

Signatures of GMSB SUSY particles in the CMS detector at the LHC

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Abstract

This thesis presents an analysis of the ability of the CMS detector to detect particles originating from the Gauge Mediation Supersymmetry Breaking models, GMSB.

The CMS, Compact Muon Detector, is one of two general purpose experiments at the LHC, Large Hadron Collider, accelerator. When in 2007 proton beam collisions at an energy of 14 TeV will be switched on, a new high energy range for particle physics will be open for searches, inter alia, the supersymmetry.

In framework of the GMSB, the supersymmetric cascade ends on decay of the, so-called, Next to Lightest Supersymmetry Particle, NLSP, to its Standard Model partner and undetectable gravitino, which is the Lightest Supersymmetry Particle, LSP. The NLSP lifetime depends on the scale of the SUSY breaking. The nature of NLSP, which could be neutralino or slepton, is determined by model parameters (number of messengers and $\tan\beta$). Because of that, detection of the NLSP and determination of its properties are important for the physics program at LHC.

The observability of an end-point signatures within GMSB models have been performed. The signal was defined as the difference of the invariant mass distributions of the same and different flavour pairs of electrons and muons: $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$. Both cases of neutral and charge NLSP have been discussed. As a result a subset of the GMSB parameter space in which end-point signals could be observed was given. The analysis has been based on the fast simulation of the CMS detector and has taken into account all possible kinds of Standard Model background. The background has been eliminated by series of kinematic cuts which had used the overall hardness of the supersymmetric event.

Two scenarios with different implications on the signal detection have been also considered. In the first, a long-lived stau played the rôle of the NLSP. It has been proven that CMS muon system was able to detect stau, determine its mass, and put lower limit on the stau lifetime via time of flight measurement. In the second case, the neutralino decaying in flight into gammas non-pointing to the main vertex, was the NLSP. It has been demonstrated that non-pointing gammas could be identified in the system of the calorimeters of the CMS and that late electromagnetic showers could be seen in the CMS muon system.

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Chapter 1

Introduction

The aim of this work is to precisely define the potential for observation of a low-energy supersymmetry at the CMS detector.

Despite a lot of effort, it is not possible to predict how supersymmetry would be realized in Nature, if it really exists. That is why all variants of supersymmetric models should be considered. It is very important to verify if detectors, which are now under construction, will be able to find at least some phenomena of all conceivable supersymmetry models.

Those facts influenced our strategy of the search for the supersymmetry:

- First, the Gauge Mediated Supersymmetry Breaking (GMSB) models were chosen. At the time (in 1997) when this analysis started other supersymmetric models (MSSM, SUGRA) had been widely studied. The GMSB was then a recent theoretical solution, which had not been explored yet in the CMS.
- Next, the different phenomenological implications were taken into account. The most promising experimental signatures have been considered.
- The results of dedicated analyses for a few characteristic model points of the GMSB parameters space, were finally extended into a range of parameters, which could be accessible in proton-proton collisions at LHC accelerator.

In this thesis, the step by step realization of the above plan will be shown.

1.1 Motivation

Developments in High Energy Physics in the last decades of the XX century established a *Standard Model* (SM) of elementary interactions. Despite extensive searches for phenomena contradicting prediction of the SM no significant deviations have been found. The Standard Model can precisely describe experimental results up to maximal experimentally accessible energy scale (of the order of 200 GeV). However, it is hard to imagine that SM is the end of the story of discovering the mystery of the microscopic world. The SM goes a step further over the Maxwell's unification of electric and magnetic forces into electromagnetism, and unifies electromagnetic and weak interactions. However, the electroweak symmetry is not exact symmetry and it has to be broken. It is realized by a *Higgs mechanism*, which at the same time gives masses to elementary fermions. The mechanism of electroweak symmetry breaking manifests itself by masses of intermediate bosons W^+ , W^- and Z^0 and unknown scalar particle – the *Higgs boson* – which remains after the breaking. This particle is intensively searched for. Its mass cannot be calculated from first principles. There are bounds from the SM renormalization on Higgs mass which set

the limit, namely Higgs mass is less $1\text{ TeV}/c^2$. Global fits to electroweak data (sensitive to the logarithm of Higgs mass) favorites a light Higgs, e.g. provided by LEP experiments. Theory of interactions provides an effective Higgs mass, to which 1-loop (fermion, gauge boson and scalar) diagrams contribute and generate large radiative mass corrections. Summed corrections give divergences which grow quadratically with the cut-off scale, which limits the validity of the SM. Although not experimentally reachable, the Planck scale ($M_{\text{PL}} \sim 10^{19}\text{ GeV}$) is the furthest force scale of particle (gravitational) interaction. Setting that fundamental scale as a cut-off scale, the Higgs mass-squared would be at level of M_{PL}^2 instead of demanded mass near electroweak scale $(100\text{ GeV})^2$. One needs an extreme fine-tuning over a dozen orders of magnitude. This technical difficulty is known as a *hierarchy problem*.

The systematical solution of the hierarchy problem, which yields precise and testable predictions, exploits a new symmetry, called a *supersymmetry* (SUSY). Supersymmetry assumes the spin symmetry between fermions and bosons. All SM fermions (bosons) acquire new bosonic (fermionic) partners with the same masses and quantum numbers, which allow for almost exact cancellation of dangerous divergences in Higgs mass corrections. The natural solution of hierarchy problem was one of the reasons for extending the Standard Model.

The supersymmetric partners have not been experimentally observed yet, what implies the condition that if supersymmetry exists, it must be broken and supersymmetric particles should be heavier, out of the reach of present experiments. Unfortunately, for arbitrarily large mass splitting of superpartners, one loses property for hierarchy cancellation. Because of that the scale of the supersymmetry need to be imposed for so-called low-energy supersymmetry:

$$M_{\text{SUSY}} \lesssim \mathcal{O}(1\text{ TeV}).$$

There are several variants of supersymmetry discussed in the literature. A basic model is a minimal extension of the SM, namely *Minimal Supersymmetry Standard Model* (MSSM). The MSSM provides gauge couplings unification and theory of Grand Unification (GUT). The electroweak symmetry breaking occurs naturally as a radiative effect in Supersymmetric Grand Unification Theory and light Higgs boson is predicted.

The MSSM contains more than hundred *a priori* free parameters (all masses, couplings, mixing parameters). Most of those parameters are connected to the spontaneous symmetry breaking mechanism, the least understood part of the SM. To further constrain MSSM different models with limited number of parameters of the supersymmetry breaking mechanism were proposed:

- Minimal SuperGravity (SUGRA) [1]–[9],
- Gauge Mediated Supersymmetry Breaking (GMSB) [10]–[15],
- Anomaly Mediated Supersymmetry Breaking (AMSB) [16]–[19].

Those three models moves the SUSY breaking into a *hidden sector* which can communicate with a *visible sector* of observable particles by respectively: *gravitational*, *gauge* interactions¹ or *anomalies* in the supergravity Lagrangian.

There are many more alternative models such as:

- Model with *D*-term contribution of scalar mass [20]–[22],
- Model with not universal GUT scale of supersymmetry breaking [23, 24]

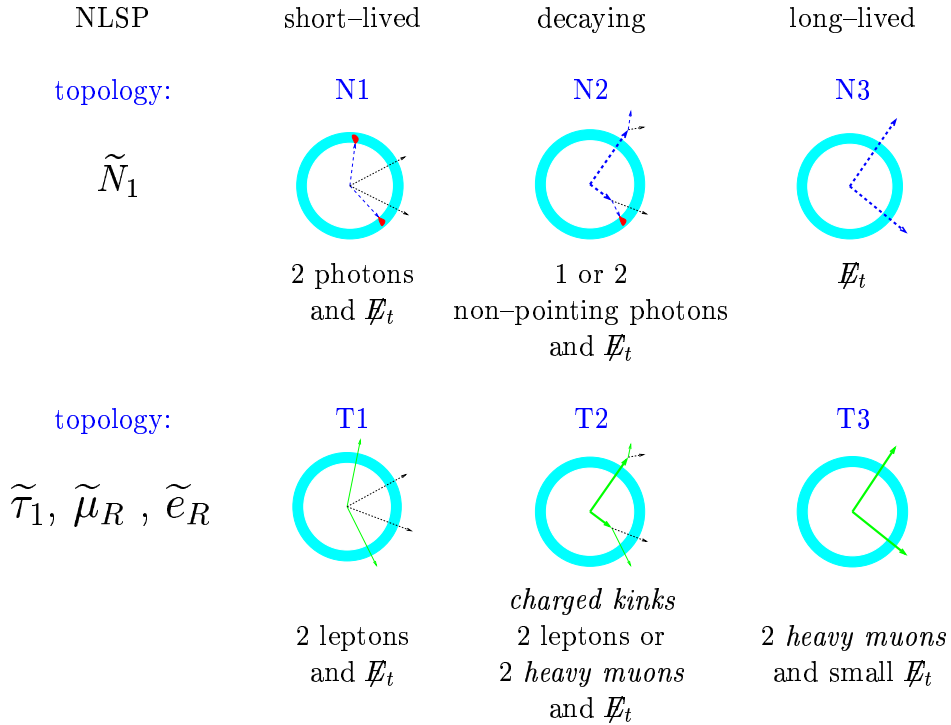
¹ Namely, *Gauge* theory of interactions. The structure and properties of interactions are recalculated from a given potential, which could be suitably modified or *gauge transformed* by arbitrary functions in a way that conserves equations (for example Maxwell's equations); the equations remains *gauge invariant*.

- MSSM with R -parity violation [25]–[29],
- The Next-to-MSSM [30]–[32].

All the solutions of the SUSY breaking have advantages and some disadvantages, but every one of them leads to interesting phenomenological implications.

The canonical scenario is determined by R -parity which distinguish between SM and SUSY particles. If R -parity is conserved supersymmetric particles are produced in pairs and any decay chain of superpartners end on at least two stable Lightest Supersymmetric Particles (LSPs). To satisfy cosmological requirements for Dark Matter constituents, the LSP need to be neutral, free of colour charge and weakly interacting with matter. For many choices of SUSY parameters (e.g.: MSSM, SUGRA) the lightest neutralino (superpartner of neutral bosons) is the LSP. It escapes detection and its signal is the missing energy (or in hadron colliders – the missing transverse energy which is calculated from energy registered in calorimeters).

In models with the GMSB, which are subject of this thesis, gravitino is the LSP. Its mass is small (a few keV), hence the life time $c\tau$ of the Next to Lightest Supersymmetric Particle (NLSP), which decays to its SM partner and gravitino, can span the wide range. Event topology is $c\tau$ -dependent. If the NLSP is short-lived, it decays immediately. Long-lived NLSPs decaying outside the volume of the detector are considered as stable particles (supersymmetric decay cascades are very similar or the same as in the canonical MSSM) unlike NLSPs decaying inside. Apart from neutralino NLSP, the GMSB models allow for electrically charge NLSP, the lightest slepton which could be $\tilde{\tau}_1$ or $\tilde{\mu}_R$, $\tilde{e}_R$. Characteristic topologies are given by schemes:



The most interesting signatures are chosen for the full analysis.

1.2 In short

The thesis is organized as follows:

- In Chapter 1, the main motivation for the current subject (supersymmetry searches in the framework of the GMSB models) was given.
- Chapter 2 provides the description of the LHC accelerator and the CMS detector main properties.
- Chapter 3 contains the theoretical introduction to supersymmetry.
- The simulation of the Standard Model background is described in Chapter 4.
- Chapter 5 contains original analyses of the GMSB (topology: N1, N2, N3 and T1) which are based on the edge signatures in mass distributions of leptons coming from supersymmetric cascades.
- Selected topologies of SUSY particles are presented in Chapter 6.

Methods for detection of

★ the long-lived stau detection (topology: T3)

and

★ the decaying NLSP (neutralino topology: N2 and stau topology: T2) detection.

- Chapter 7 summarizes the thesis.

The work described in the thesis can be assumed to have been performed in its majority by the author unless specific citations are provided.

One of the major difficulties encountered by the author during the work on the thesis was a transition from Fortran based to C++ based software undertaken by the CMS Collaboration. This is a serious endeavor which has started a few years ago and it is not yet completely finished.

The new software in principle offers more detailed simulation of the CMS detector, but it became functional only recently and some important features are still missing. The old software in the meantime became obsolete and it is no longer supported.

As a result, different parts of the presented work had to be done within different frameworks. The part concerning long-lived staus (Sec. 6.1) was done with the Fortran based detailed simulation called CMSIM. Overall scan of GMSB parameter space to evaluate visibility of leptonic endpoints (Sec. 5) was based on fast Fortran simulation CMSJET. Finally, the part describing decays in flight of the NLSPs (Sec. 6.2) was based on a parton level simulation package SPYTHIA and detector parametrization.

Using those mixed techniques it was possible to build quite consistent picture of the phenomena in question. However, as soon as the new generation software tools became available with all needed functionality, the author plans to redo the most critical parts and publish the results elsewhere.

Chapter 2

The CMS Detector at the LHC

The search for new physics is the main reason for continuous strife to increase the energy of accelerators. At present a new powerful accelerator, the Large Hadron Collider (LHC) is being built. The LHC enables investigating elementary fermion interactions in the energy range of the order of 1 TeV, never achieved before. The LHC is expected to start data taking in 2007.

2.1 The LHC overview

The LHC replaces the LEP (Large Electron Positron) [33] in the underground tunnel in the European Laboratory for Particle Physics (CERN) near Geneva, Switzerland. The proton beams will be collided with a center of mass energy of 14 TeV. Collisions of heavy ion nuclei are also foreseen. Six experiments are planned for the LHC. Two of them are general purpose ones:

- CMS, a Compact Muon Solenoid,
- ATLAS, A Toroidal LHC ApparatuS,

and four are dedicated ones:

- ALICE, A Large Ion Collider Experiment, adapted to the heavy ion physics,
- LHC-b, aimed to study CP violation in b-quark sector,
- TOTEM, a TOTal and Elastic Measurement, designated to measure total cross section (using the luminosity independent method), elastic scattering and diffraction dissociation at the LHC; with an experimental set-up (CSC and silicon trackers) integrated with the beam pipe at the location of the CMS detector.
- CASTOR, a Centauro And STRange Object Research, a specialized (electromagnetic and hadron) calorimetry system to probe the very forward phase space region in central Pb-Pb and p-p collisions; with
 - ★ ZDC, a Zero Degree Calorimeter at 140 m from the CMS interaction point.

The experiments will be located at the beam crossing points show in Figure 2.1.

The small cross-sections for new phenomena require an extremely high interaction rates. In the LHC bunches will be colliding every 25 ns. In the p-p case, the initial luminosity is foreseen to be $10^{32} - 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. During the low luminosity period, the SM theory, especially heavy quarks properties, will be studied. Furthermore, some searches of the Higgs and light supersymmetric

particles should be possible. Luminosity will increase to the designed $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ or 100 fb^{-1} per year¹ of the integrated luminosity.

Ultimately, the LHC should also operate in the heavy ion mode, testing the existence of the quark gluon plasma (QGP). The ion beams will reach energy of $2.7 \div 7 \text{ TeV}$ per nucleon depending on the nucleus: O, Ar, Kr, Sn, Pb. The luminosity will be from $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ for Pb-Pb collisions with bunch spacing of 125 ns, up to $2.9 \cdot 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ for the lightest ions.

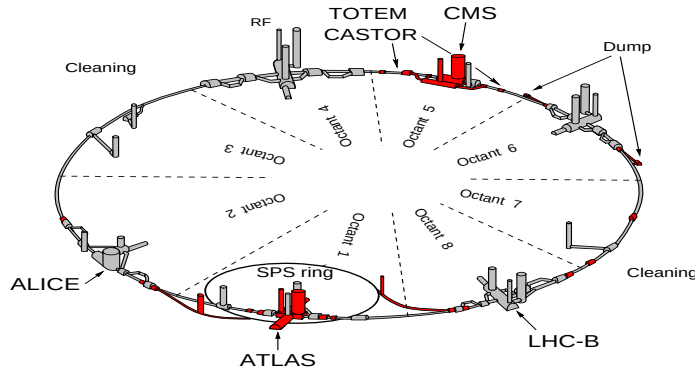


Figure 2.1: Layout of the CERN tunnel which includes the existing LEP structure in gray and the LHC improvements in red.

2.2 The Compact Muon Solenoid detector

The CMS detector was optimized for the identification and the precise measurement of muons, electrons, photons and jets at high luminosity.

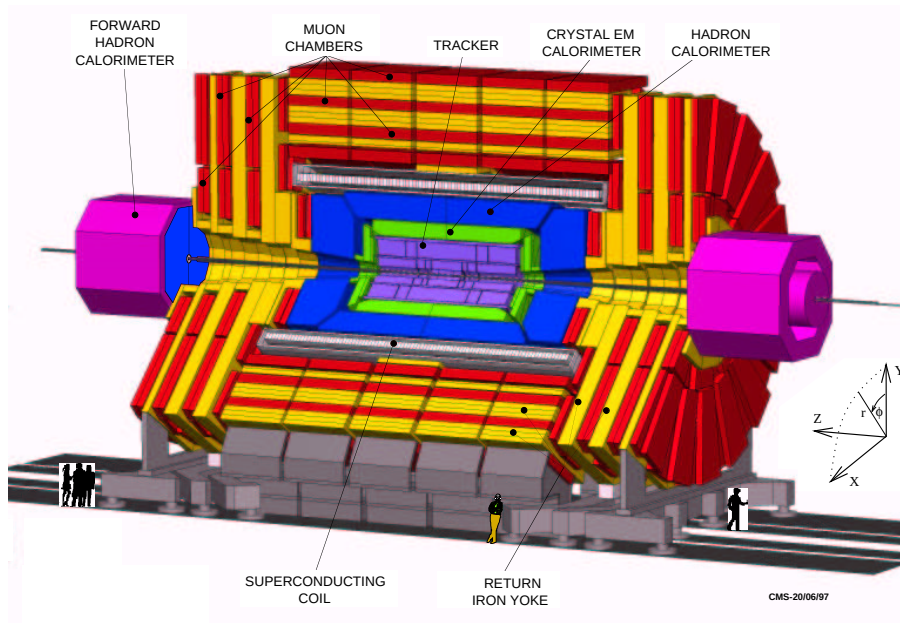


Figure 2.2: Three-dimensional scheme of the CMS detector.

The main feature of CMS detector is the muon system based on a solenoid [34] with a multilayer structure. The detector is shown in Figure 2.2. It is constructed of five wheels

¹The LHC year is assumed to be 10^7 seconds.

of barrel and two endcaps divided into twelve ϕ -sectors, having the overall 21.6 m length and 14.6 m diameter and a total weight 14.500 t.

The choice of the magnet system determined the design of the whole detector. The superconducting coil, 13.5 m long and 6.2 m wide, which provides the solenoidal magnetic field of 4 Tesla has been chosen. The solenoid hosts sub-detectors: an inner tracker and electromagnetic and hadronic calorimeters. The muon system is placed outside the coil.

The detailed description of the CMS detector and dedicated software can be found in the Technical Proposal [35] and in the stout volumes of technical design reports of sub-detectors as well as data acquisition and trigger system [34, 36, 47, 48, 50, 51]. In this thesis only basic, indispensable information of CMS elements will be given.

2.3 The Muon System (MS) [36, 37]

The Muon System consists of four Muon Stations placed in every barrel wheel and both endcaps. The stations are placed in between the iron yoke slabs, which play the role of absorber. The iron yoke contains the magnetic field of the solenoid, and absorbs electromagnetic cascades.

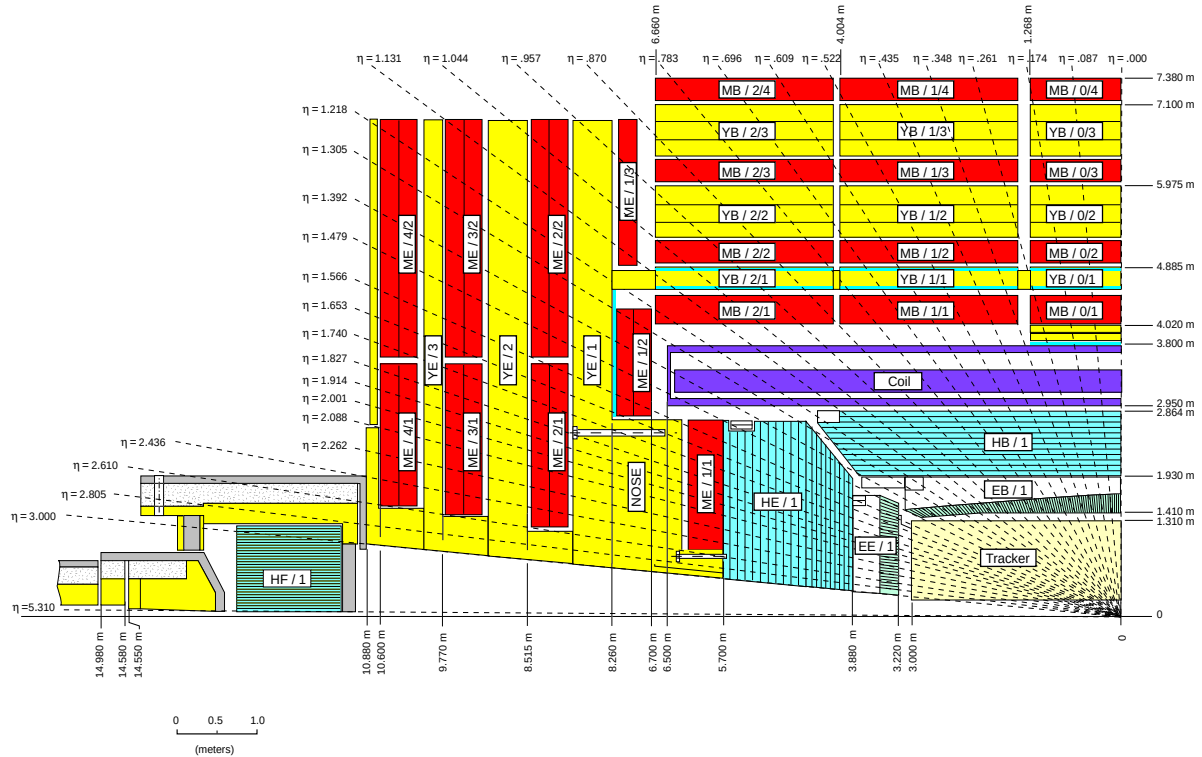


Figure 2.3: Longitudinal view of the CMS detector. Position of sub-detectors is indicated by the appropriate abbreviations (M – muon station, Y – iron yoke, E – electromagnetic calorimeter, H – hadron calorimeter, HF – very forward calorimeter). The second letter, B or E, denotes the barrel or the endcap.

The muon system aims at the identification of muons, their momentum measurement and the trigger and provides:

geometric coverage up to pseudorapidity ² $|\eta| < 2.1$,

² The pseudorapidity $\eta = -\ln(\tan(\theta/2))$ is a function of the particle production angle θ with respect to the beam axis.

muon identification based on the fact that no electrons, gammas or hadrons can penetrate muon sectors after crossing 16λ nuclear interaction length of material,

precise tracking with the spatial resolution of the order of $75 \div 150 \mu\text{m}$ per tracking point,

transverse momentum measurement over a wide range of transverse momentum p_t from a few GeV up to a few TeV with resolution:

$$\text{for } 0 < |\eta| < 2$$

$$\frac{\Delta p_t}{p_t} \simeq 6\text{-}10 \% \text{ for } p_t \leq 10 \text{ GeV}, 7\text{-}20 \% \text{ for } p_t \leq 100 \text{ GeV} \text{ and } 15\text{-}35 \% \text{ for } p_t \leq 1 \text{ TeV},$$

and after matching with the inner tracker:

$$\text{for } 0 < |\eta| < 2.1$$

$$\frac{\Delta p_t}{p_t} \simeq 0.5\text{-}1 \% \text{ for } p_t \leq 10 \text{ GeV}, 1.5\text{-}5 \% \text{ for } p_t \leq 100 \text{ GeV} \text{ and } 5\text{-}20 \% \text{ for } p_t \leq 1 \text{ TeV}.$$

muon charge assignment,

bunch crossing identification for every muon track with efficiency $> 99 \%$,

first level (L1) muon trigger.

Those tasks are fulfilled by three types of gaseous detectors: the drift tubes (DTs), the cathode strip chambers (CSCs) and the resistive plate chambers (RPCs). They have to cope with high occupancy, and avoid problems with false signals from large area of the muon system.

2.3.1 Drift Tubes [38, 39]

Each Barrel Muon Station MB1÷MB4 is equipped with DTs. There are 12 layers of DTs grouped into three super-layers (SL) per station.³ In each station two outer SLs are parallel to the beam pipe and measure $R\phi$ coordinate. The middle SL measures $z(\theta)$ coordinate. The $R\phi$ cross-section of one station is shown in Figure 2.4b. The tubes within one SL are shifted by half of its width with respect to the next SL. The wires of the middle SL are perpendicular to the wires of outer SLs. Mechanical stiffness is provided by 10 cm aluminum honeycomb plane between the θ -SL and the $R\phi$ -SL.

The Drift Tubes provide measurement of the position of a muon in the barrel detector. In the same time they give trigger information and the bunch crossing identification.

Single DT (Figure 2.4a) has a cross-section of $4 \times 1.1 \text{ cm}^2$. Length of the DT layer in the muon station is 2.56 m and its width may range from 2 m to 4 m. The cell is filled with the mixture of Ar-CO₂ giving the maximal drift time about 350 ns.

The DT is the only CMS muon detector which determines the position of muon track by time measurement. This property could be used for identification of exotic heavy, weakly interacting particles which can penetrate the muon detector. A related analysis will be presented in Section 6.1.1.

The DTs identify muon tracks and the bunch crossings using a Meantimer electronics (MT) [40]. The wires have one-side electronic readout. An avalanche generated by a particle crossing a given cell at $t = 0$ is registered after drift time inside the cell and propagation time along

³The most outer station is an exception because the SL for the z measurement is absent there.

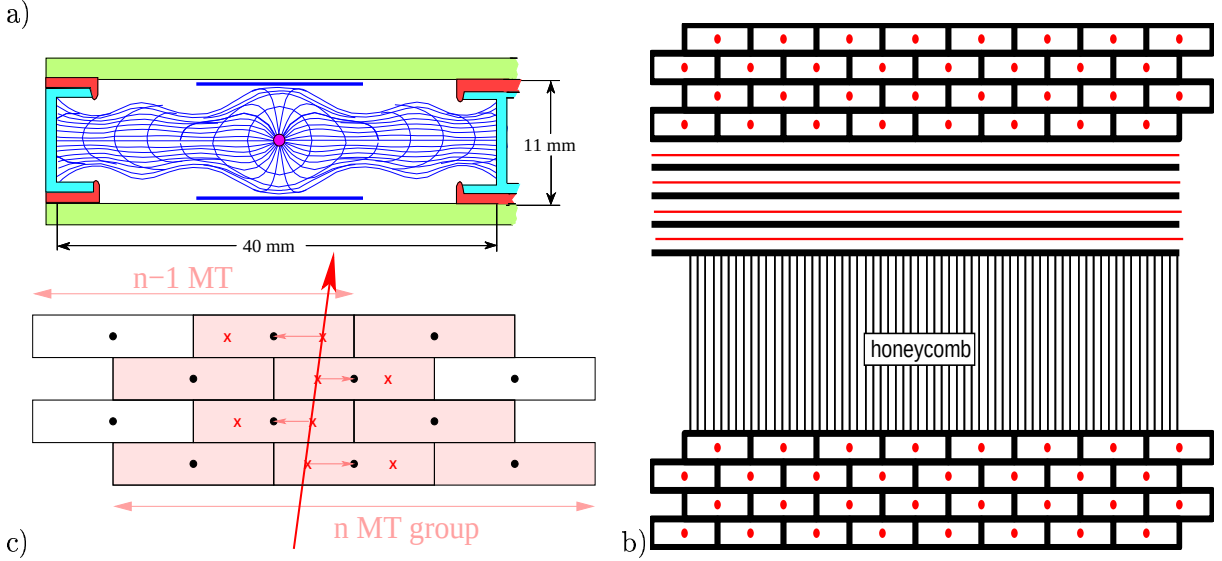


Figure 2.4: Layout of Drift Tubes. a) Single cell showing drift lines.

- b) The $R\phi$ view of the Drift Tube Station with the bunch crossing point below the station. Wires are marked with red colour. c) The meantimer technique scheme in the single super-layer.

the wire. The shift register is also synchronized with bunch crossing time according to the cell position within the detector. It compensates for a total delay of signal. While the hit position in single tube is reconstructed, the left-right ambiguity doubles number of hits. However, fake hits are rejected by alignment procedure given by the meantimer.

Scheme of this technique is shown in Figure 2.4c. The candidate of muon track is search if at least three out of four DT layers have been hit. Single not correlated hits are rejected.⁴ The analogous MT circuit works on nine wires form four layers. It checks which cells have been switched to fit a muon track to all possible combinations. The MTs overlaps by every five wires what ensures that one track is contained in one MT. Finally, the dedicated electronical correlators use the MTs of the inner SL and the outer SL with a proper overlap. The track coordinates can be maximally given by 8 hits $r\phi$ plane and 4 his in θ one. The correlation of track of two SLs improves an angular resolution to 12.5mrad whereas single SL has the resolution better than 50 mrad and a spatial resolution of 1.25 mm.

All reconstructed track are sorted by their angle with respect to radial direction. Two with the smallest angles are transmitted to the DT trigger server.

2.3.2 Cathodes Strip Chambers [41, 42]

The CSCs are used in the Endcap Muon Stations ME1÷ME4. Their goal is the same as DTs in the barrel. They precisely measure muon momentum and identify associated bunch crossing in region with high particle rates of the order of 1 kHz/cm², 100 times greater rates then in the barrel. The CSCs are crucial for the Level-1 trigger supplied by the CSC Local Trigger electronics in each muon station.

The CSC is a multiwire proportional chamber with 30 μ m diameter gold wires forming anode planes. Wires are parallel arranged with the 3.12 mm spacing. A single 9.5 mm gas gap is shown in Figure 2.5a. One of two cathodes is divided into strips perpendicular to the wires. Strips run radially (which causes differences in strips width from 3 to 16 mm). The single chamber

⁴Muon detection is impaired by δ -radiation and electromagnetic cascades originating in the iron yoke. Its probability is of order of 5.5 % per one cell, and rapidly increases for muon of $p_t > 300$ GeV/c.

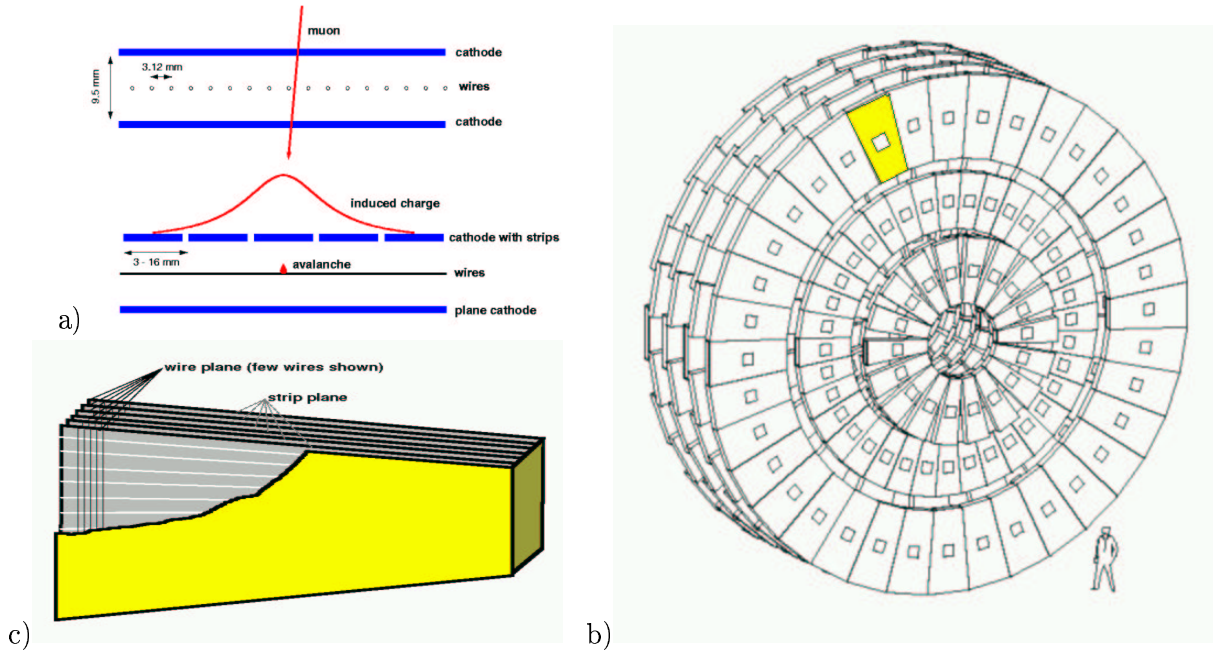


Figure 2.5: Layout of Cathodes Strip Chambers. a) Single cell in two perpendicular cross sections. b) The trapezoidal CSC chamber. c) The endcap perspective from the inner side.

(Figure 2.5b) consists of 6 gaps placed into a sandwiched honeycomb mechanical structure. The gas vessel is filled by mixture of Ar-CO₂-CF₄ providing the maximal drift time equal to the time of p-p bunches collisions at the accelerator.

Chambers have a trapezoidal shape (Figure 2.5c) which cover 10° or 20° ϕ -sectors and allow the azimuth continuous coverage due to overlapping. The first muon station consist of three rings, the others are set up by two rings. Theirs length ranges 1.7 m to 3.4 m and width is 50 cm to 130 cm the most outer stations.

The CSCs operate on the cathode strip technique which is the measurement of the position of charge deposition induced on several strips by crossing particle. (It works better then drift time measurement in presence of high momentum muon bremsstrahlung.) The scheme is shown in Figure 2.5a. Six layers of radial cathode strips precisely measure the ϕ coordinate and six layers of anode wires are used to measure the η coordinate. A reconstruction of muon track is given by a χ^2 linear fit to all hits. The single hit spatial resolution is foreseen to be about 120–250 μm to provide a track segment precision of 75 μm for the closest to interacting point chambers (ME1/1 and ME1/2) and 150 μm for others.

The CSC trigger relies on the coincidence of track signals in both perpendicular coordinates. The efficiency is close to 100 % at low p_t , and decreases to 80–90 % at about $p_t=1 \text{ TeV}/c$.

2.3.3 Resistive Plate Chambers [43, 44, 45]

All muon station have the fast-response RPCs providing fast Level-1 trigger and timing signal. The main properties of the RPCs is the time resolution of the order 1 ns. This is crucial for trigger performance.

An active element of RPC is a gas gap, 2 mm wide, formed by two resistive plane electrodes. The planes are made of bakelite with a bulk resistivity of a few $10^{10} \Omega\text{cm}$. The outer surface of bakelite is coated with graphite to form the high voltage and ground electrodes. The improvement of efficiency and resolution is achieved by placing two gap with a common read-out plane of

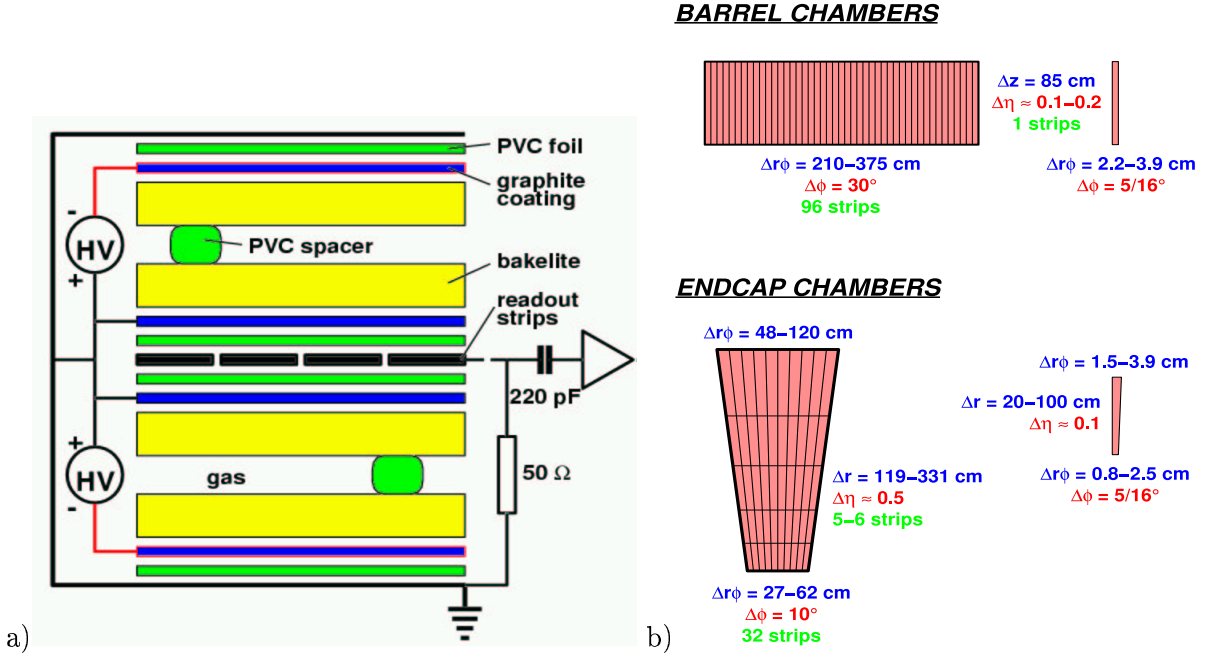


Figure 2.6: Layout of Resistive Plate Chambers. a) The double gap scheme. b) RPC chambers: θ -plane of barrel where 6 layers of RPCs will be allocated and ϕ -sector of endcap with one RPC layer per the muon station.

aluminum strips (35 mm) in the middle (Figure 2.6a).

The crossing particle ionizes gas (mixture of gases: $\text{C}_2\text{H}_2\text{F}_4$, iC_4H_{10} and SF_6 with a typical percentage composition 96.5–3.0–0.5 %) inside the gap. Then liberated electrons discharge electrodes. An avalanche is generated inside the chamber and detected on strips. Highly resistive electrodes and the small admixture of freon (SF_6) contain lateral dimensions of an avalanche. Detectors remain effective (with efficiency $> 95\%$) in avalanche mode for rates as high as a few kHz/cm^2 .

The 1656 chambers amounts to the total area of 3400m^2 . The sizes of single barrel and endcap RPCs are shown in Figure 2.6b. In the barrel, there is six layers of RPCs, whereas endcaps are equipped with four RPC stations. A candidate muon tracks are reconstructed from at least three and at most six hits (for the barrel) or three of four hits (for endcaps) by the dedicated Pattern Comparator Trigger(PACT) electronics [46]. The PACT compares patterns of hits on read-out strips with predefined patterns corresponding to muons with well defined transverse momentum.

2.4 Calorimeter system

The calorimeter system measures energy and direction of electromagnetic cascades or particle jets. It determines the missing transverse energy flow. It provides the identification of gammas, electrons, isolated muons, hadrons and hadronic jets, and measurement of missing energy. The precise measurements of leptons, hadrons and the event missing energy are crucial in searches for the new phenomena.

One of the searches of the GMSB model based on transverse missing energy cut combined with other kinematical cut will be presented in Section 4.3. The possibility of non standard use of calorimeter system is also analyzed in Section 6.2.3.

A placement of all calorimeters in the CMS (HB, HO, HE, HF, EB, EE) is shown in Figure 2.3.

2.4.1 Hadronic calorimeter [47]

A Hadronic calorimeter (HCAL=HB+HE) fills the layer closest to the CMS coil. Its aim is the jet detection and measurement of its energy and position. The HCAL consists of three segments: the central (barrel) sub-detector (HB) and the forward (endcap) calorimeter (HE) in the range of $|\eta| < 3$. A supplementary part of the hadronic system is a very forward calorimeter (HF) located outside the endcap muon detectors, 11 m from the interaction point, which covers pseudorapidity range of $3 < |\eta| < 5$.

The HB and HE are constructed of scintillator tiles read out by embedded wavelength shifting fibers which transmit captured light to hybrid photo diodes (HPD). The HPDs transform light into electric pulses. Pulses are amplified and converted into digital signals which are then sent by optical links from the inside of the detector to the counting room. Fibers form towers of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ granularity. The readout is sampled in depth by two separate electronic channels. The first channel reads the scintillator layer placed immediately after the electromagnetic calorimeter. The second channel reads 17 or 18 sampling scintillator layers.

The HF calorimeter is based on scintillating high-purity quartz fibers which are embedded in the absorber plates. The extreme radiation hardness of silica is desirable for proper operation in a strong radiation field, and in an area with very high occupancy. The HF uses the Cherenkov light produced by hadron showers in fibers. The optic signal is guided into photomultiplier tubes (PMTs).

The HE/HB system works in 4 T magnetic field. It requires non-magnetic absorber which does not distort the uniformity of the field, and has a short interacting length. Those requirements are satisfied by brass, namely by an alloy of 90 % Cu and 10 % Zn. The few centimeters thick absorber plates provide the mechanical strength and stability. In gaps between them the scintillating plates are mounted. Effective thickness (in the nuclear interaction length) for HB varies from 5.5λ at $\eta = 0$ to 10.8λ at $\eta = 1.3$ and is on average 11λ in the endcaps and very forward HCAL parts. The transition region between the barrel and endcaps is relatively small.

The Outer Hadron Calorimeter (HO) was built to add extra thickness in the central rapidity region. It consists of an additional layer of scintillator tiles placed behind the crystals in the middle wheel of the detector.

The expected energy resolution for this structure is: ⁵

$$\begin{aligned} \sigma_E/E &= 70 \% / \sqrt{E/\text{GeV}} \oplus 9.5 \% && \text{for the barrel HB,} \\ \text{and } \sigma_E/E &= 75 \% / \sqrt{E/\text{GeV}} \oplus 7 \% && \text{for endcaps HEs} \\ \sigma_E/E &= 100 \% / \sqrt{E/\text{GeV}} \oplus 5 \% && \text{for very forward HCAL HF.} \end{aligned}$$

2.4.2 Electromagnetic calorimeter [48]

The Electromagnetic Calorimeter (ECAL) is composed of barrel part (EB) covering the pseudorapidity interval $|\eta| < 1.48$ and endcap calorimeters (EE) which complete the detector space up to $|\eta| = 3$. Endcap is also equipped with a preshower (SE) in $1.65 < |\eta| < 2.60$ located in the front of the ECAL.

The base for operating of ECAL as a photon/electron detector is determined by lead-tungstate PbWO_4 scintillating crystals which had been chosen by CMS collaboration because

⁵ $a \oplus b = \sqrt{a^2 + b^2}$

they are intrinsically radiation hard and have the fastest light output relatively to other crystals. Typical dimensions of crystals, $0.22 \times 0.22 \times 23 \text{ cm}^3$ in the barrel $0.25 \times 0.25 \times 22 \text{ cm}^3$ in the endcaps, were matched to sizes of typical electromagnetic shower in lead–tungstate given by transverse Molière radius of 2.2 cm and longitudinal length limited to $26 X_0$ radiation lengths with $X_0 = 0.89 \text{ cm}$.

Compact calorimeter system offers an excellent performance for energy resolution:

$$\frac{\sigma E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \quad (E \text{ in GeV}),$$

where a ($\sim 0.025 \text{ GeV}^{1/2}$) is a stochastic term, which includes photo–statistical fluctuations and variations in the shower containment, b ($< 0.2 \text{ GeV}$) represents the electronic noise and pileup energy and c (~ 0.005) is the constant term. The beam test of the 6×5 crystal matrix [49] confirmed appropriate values of parameters: $a=0.0273 \text{ GeV}^{1/2}$, $b=0.142 \text{ GeV}$, $c=0.0042$. The angular resolution is expected to be:

$$m(\sigma) \sim 50 \text{ mrad}/\sqrt{E} \quad (E \text{ in GeV}).$$

Crystals are embedded in the on–detector light–to–light readout consisting of avalanche photodiodes (ADPs: silicon in the barrel and vacuum in endcaps), transimpedance preamplifiers and floating–point (to 12–bit, 40 MHz voltage–sampling) ADC. After digitization the signal is transmitted by fiber–optic links to upper level readout located in the counting room.

The substructure of the ECAL is shown in Figure 2.7.

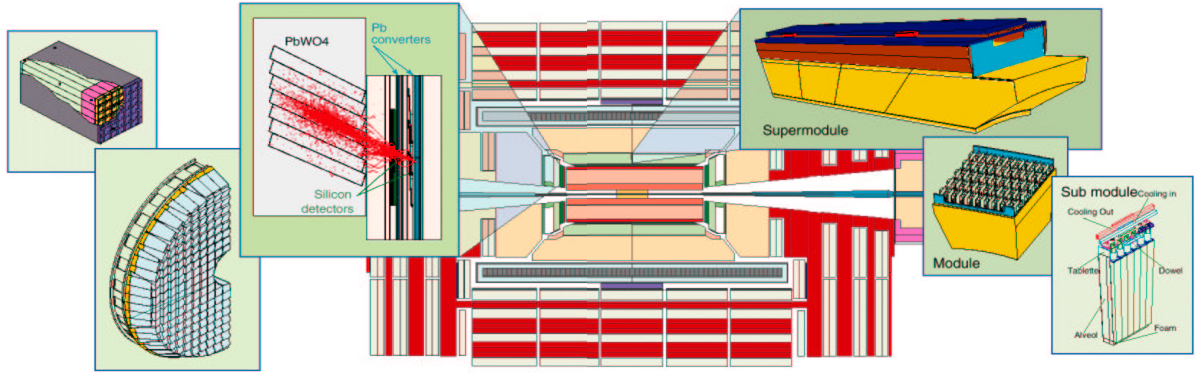


Figure 2.7: The electromagnetic calorimeter barrel and endcap substructure.

The barrel part of ECAL consists of 61 thousands of trapezoidal crystals which form semi–projective geometry pointing to the primary interaction vertex with $\Delta\eta \times \Delta\phi = 0.0175 \times 0.0175$ granularity. Crystals are mounted in sub–modules of 2×5 crystals by fixing them to 0.2 mm wall structure. Sub–modules are combined into modules which form 36 supermodules. Single supermodule contains 1700 crystals, 20 in ϕ and 85 in η .

Crystals of endcaps have the same truncated pyramid shape and dimensions. The group of 6×6 crystals set up a supercrystal units which form Dee–shaped sections. There is four Dees, two for one endcap. Both endcaps have identical granularity of the $\Delta\eta \times \Delta\phi$ which range form 0.0175×0.0175 to 0.05×0.05 . The total number of crystal in endcaps exceeds 21 thousands.

Endcaps are equipped with preshowers based on silicon detectors. The preshower consists of two active silicon tiles equipped with digital electronics plates and sandwiched between absorber layers (lead converters) and mechanical frames. Single $0.61 \times 0.61 \text{ cm}^2$ silicon module is subdivided into 32 strips at 1.9 mm pitch. An energy deposition is measured and typical very good accuracy of $300 \mu\text{m}$ at 50 GeV for an impact position of electromagnetic shower is achieved. A charge–weight–average algorithm allows to distinguish between single photons and pair of photons coming from π_0 decay.

2.5 Central Tracking System [50]

The aim of central tracking system is to identify and to measure the momentum tracks of muons, electrons and jets over a large energy range with a very high precision with efficiency better than 98 % in the range $|\eta| < 2.5$. The tracker should also provide secondary detached vertex identification.

The whole Central Tracker is build of silicon detectors, the pixel and the strip modules shown in Figure 2.8. There are 25 thousands silicon sensors controlled by almost 10 million readout channels. A covered area has 210 m^2 and is contained inside the inner barrel having a diameter of 2.4 m and a length of 5.4 m.

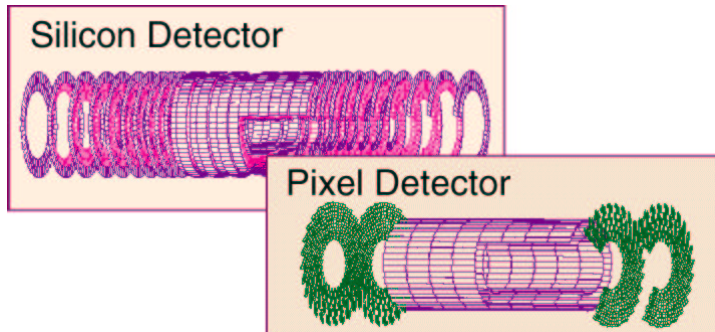


Figure 2.8: The Central Tracker detectors of the CMS.

The interaction point is surrounded by three cylindrical layers of the pixel detectors and two disks for both endcaps. The cell size of pixel detector is $150 \times 150 \mu\text{m}^2$. They are arranged in modular units equipped with very thin ($180 \mu\text{m}$) readout chip wall. Pixels provide excellent spatial resolution $10 \mu\text{m}$ in the ϕ coordinate and $15 \mu\text{m}$ in the z .

Next, ten cylindrical layers of the barrel and three mini-rings and nine disk for each endcaps are constructed of single-sided or double-sided silicon strip detectors. Their small pitches, in between 80 to $200 \mu\text{m}$, and very fast response are suitable for providing 1 % electronic occupancy and achieving very high spatial resolution at the level of $10 \mu\text{m}$ (for $50 \mu\text{m}$ pitch sensor). The silicon detectors are $300 \mu\text{m}$ thick (or $500 \mu\text{m}$ for outer region) and are readout by front-end electronics. They form modules of one or two detectors with overall strip length from 7 to 12.5 cm .

The momentum resolution of the tracker system is better than

$$\frac{\Delta p_t}{p_t} \approx (15 \cdot \frac{p_t}{\text{TeV}} \oplus 0.5) \% \text{ for } |\eta| \leq 1.6,$$

and decrease to

$$\frac{\Delta p_t}{p_t} \approx (60 \cdot \frac{p_t}{\text{TeV}} \oplus 0.5) \% \text{ for } |\eta| = 2.5.$$

2.6 Trigger [51]

With the high bunch-crossing, high event rates and potentially large event sizes, experiments at the LHC impose severe demands on the data acquisition and trigger systems. A multi-level trigger system based on hardware and software is necessary to cope with the task of event-rate reduction.

The system must analyze almost 100 million of electronic channels to select the most interesting events arriving to the detector with a 40 MHz frequency. The problem is illustrated in Figure 2.9. Only 100 Hz of data can be stored for the off-line analysis. If one event requires 1 Megabyte then the total data volume reaches about 100 MB/s and 1 Petabyte/year. This gives four fully stored 100 GB disk per hour.

For the CMS experiment two levels trigger are foreseen: the First Level Trigger (L1) and the High Level Trigger (HLT).

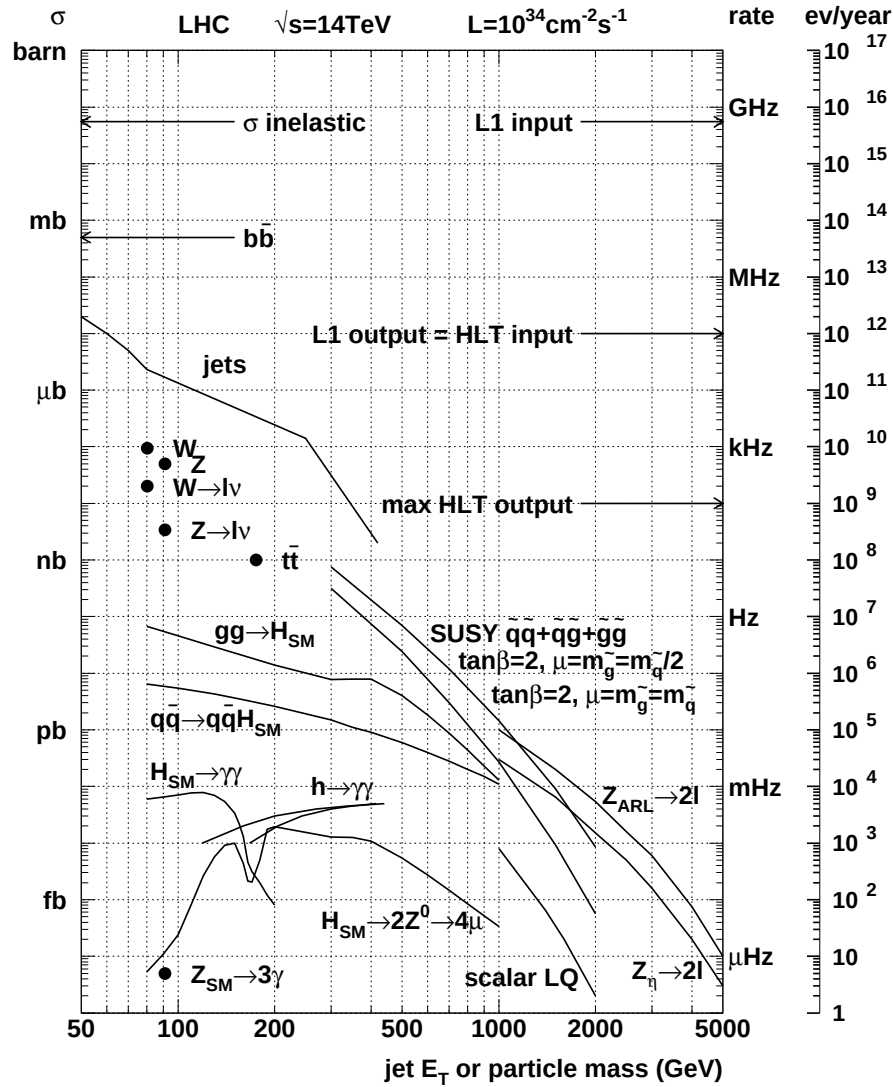


Figure 2.9: The rates and cross sections of selected processes of p-p collisions at the LHC for the final luminosity, $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

Figure taken from [52].

Hardware L1 trigger reduce rate of 1 GHz to 100 kHz. It has about $3 \mu\text{s}$ for its decision. The L1 merges information from the Calorimeter Trigger (CT) and Global Muon Trigger (GMT) into final Global Trigger (GT). The CT and the GMT require a single-object such as muon, photon/electron, jet, single hadron. Each subsystem provides list of four the most energetic objects with additional info about their position in the detector, energy or momentum, isolation criteria and the bunch crossing identification. Adjustable threshold cuts are applied only at the GT level. The GT delivers an estimated value of total and missing E_t and applies required selection cuts on single object or their combination (for example: lepton or jets pairs, jets with missing energy or leptons, etc). The GT can also calculate spatial correlation between objects and make an event topology cuts directly achievable at the first level of trigger. The trigger processors are planed to be flexible enough to allows improvements during the real data taking in case of different physics requirements.

Software HLT will reside on a computer farm. It will reduce the rate from 100 kHz to 100 Hz. It will be subdivided into at least two levels, each of them realizing progressively more complex reconstruction algorithms.

Chapter 3

Theoretical Introduction

In this Chapter the advantages of including of the supersymmetry in the theory of elementary particles will be given. At the beginning, main features of the Standard Model (SM) and some of its problems will be outlined. Supersymmetry will be shortly reviewed. Finally, one of the most promising realization of the low-energy supersymmetry, a Gauge Mediated Supersymmetry Breaking (GMSB) Model will be described.

3.1 Open issues in the Standard Model

According to the SM [53, 54], elementary particles are point-like objects without substructure at least up to the present experimental limits (10^{-18} m). There are two types of particle: *fermions*, the constituents of matter which are divided into leptons and quarks, and *bosons* mediating the strong, weak, electromagnetic or gravitational interactions. Fermions and bosons differ by their intrinsic angular momentum, the spin. The spin can be an odd (for fermions) or even (for bosons) multiple of a $\frac{1}{2}\hbar$ unit.¹

Interaction					Strength	Range [m]	Mediator				² Mass [GeV/c ²]	Spin [$\hbar$]
Gravitational		G_N	$\sim$	$6.7 \cdot 10^{-39}$	$\frac{\hbar c}{(\text{GeV}/c^2)^2}$	∞	Gravition		G	0	2	
Weak		@ M_Z	α_2	$\sim$	10^{-6}	10^{-17}	Bosons		$Z^0, W^\pm$	91.2, 80.4	1	
Elmag.		@ M_Z	α_1	$\sim$	1/128	∞	Photon		γ	0	1	
Strong		@ M_Z	α_3	$\sim$	0.117	10^{-15}	Gluons		8 g's	0	1	

Table 3.1: Fundamental interaction and their carriers – the SM bosons.

The first group of matter particles consists of the $\frac{1}{2}$ -spin fermions while the second the 1-spin bosons. The only exception is a graviton with the spin of 2. Gravity can and will be neglected because its strength is at least 10^{34} times weaker than other interactions. Forces and particles are listed in Table 3.1 and Table 3.2. Each particle has its antiparticle with an opposite sign of all charges.

The SM is consistent with experiments. Basic symmetries (Lorentz invariance, CPT) are

¹ $\hbar = \frac{h}{2\pi} = 1.055 \cdot 10^{-34}$ J·s, where h is a Planck's constant. ² $c = 299\,792\,458$ m/s – speed of light in vacuum.

Family	Leptons				Quarks			
		Q		Mass [MeV/c ²]		Q		Mass [MeV/c ²]
1 st	electron	e	-1	0.511	up	u	+2/3	1.5 – 4.5
	e-neutrino	ν_e	0	$< 3 \cdot 10^{-6}$	down	d	-1/3	5.0 – 8.5
2 nd	muon	μ	-1	106	charm	c	+2/3	$(1.0 - 1.4) \cdot 10^3$
	μ -neutrino	ν_μ	0	< 0.19	strange	s	-1/3	80 – 155
3 rd	tau	τ	-1	1777	top	t	+2/3	$(174 \pm 5) \cdot 10^3$
	τ -neutrino	ν_τ	0	< 18.2	bottom	b	-1/3	$(4.0 - 4.5) \cdot 10^3$

Table 3.2: Fermions of the Standard Model; the particle masses taken from the PDG review [55].

imposed to construct a Lorentz invariant Lagrangian which conserves discrete quantum numbers (hypercharge Y , weak isospin I , colour c). Local *gauge* symmetry group:

$$U(1)_Y \times SU(2)_I \times SU(3)_c$$

defines electromagnetic, weak and strong interactions. Exact gauge invariance requires massless bosons and fermions. Thus, gauge symmetry has to be broken to allow for the proper values of masses of intermediated bosons W^+ , W^- , Z^0 and massive fermions. The elegant solution is called *spontaneous symmetry breaking* (SSB) of electroweak symmetry into electromagnetic symmetry:

$$U(1)_Y \times SU(2)_I \rightarrow U(1)_{em}.$$

That scheme was implemented in the SM by so-called *Higgs Mechanism* [56, 57].

Higgs Mechanism

The concept of the Higgs Mechanism is based on the spontaneous symmetry breaking due to asymmetry of the ground state. In the SM, a new doublet field Φ is induced to the $U(1)_Y \times SU(2)_I$ gauge invariant Lagrangian of the electroweak symmetry with the simplest form:

$$L_{SSB} = |D\Phi|^2 - V(\Phi),$$

where $\Phi = (\phi_1^+ + i\phi_2^+, \phi_3^0 + i\phi_4^0)/\sqrt{2}$ is a fundamental doublet of complex scalars, $D\Phi$ is its covariant derivative and the operation $|\varphi|^2$ of any field denotes $|\varphi|^2 = \varphi^\dagger \varphi$. Neutral components of Φ preserve $U(1)_{em}$ and acquire non-vanishing vacuum expectation value (v.e.v.).

A potential $V(\Phi)$ is given by:

$$V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4,$$

where a self-coupling $\lambda > 0$ imposes the vacuum stability. The potential must be renormalizable to make the SM predictive up to very high energies. The μ is the Higgs mass parameter. If $\mu^2 < 0$ then non-zero v.e.v is generated for $v = \sqrt{-\mu^2/\lambda}$ in the ground state $\Phi = (0, v/\sqrt{2})$. It gives infinite number of equally expected physical vacuums, with the only one state (a concrete argument of the field, $\arg \Phi$) to finally realized. The SSB transmit the Lagrangian with additional four degrees of freedom into three massive vector (which are identified with bosons: $W^\pm, Z^0$) and one massless vector bosons (photon γ), and a new neutral scalar boson, which is called a *Higgs particle* (m_H).

The masses of particles in the SM are given by:

$$m_W = vg/2, \quad m_Z = m_W/\cos\theta_W \quad 3$$

and

$$m_H = \sqrt{2\lambda v^2} \equiv \sqrt{-2\mu^2}.$$

Vector boson masses can be expressed by measurable parameters:

$$v = (\sqrt{2}G_F)^{-\frac{1}{2}}, \quad \alpha = g^2 \sin^2\theta_W/4\pi, \quad 4$$

where G_F is the Fermi constant determined from the muon lifetime in the decay ($\mu \rightarrow \nu_\mu \bar{\nu}_e e$) and Weinberg's angle measured from the relative cross section of two processes of the neutral current ($\nu_\mu p \rightarrow \nu_\mu X$) and the charge current ($\nu_\mu p \rightarrow \mu X$). The v.e.v was extracted to the value of:

$$v = (\sqrt{2}G_F)^{-\frac{1}{2}} = 2m_W/g = 246 \text{ GeV}/c^2.$$

Although, masses of W, Z were properly predicted, the Higgs mass is undetermined. The m_H depends on two parameters: λ and v , and the value of the self-coupling λ is unknown. The Higgs mass can be only constrained by the sinus of the Weinberg's angle and the mass of boson W . The latest global $\Delta\chi^2$ fit to all experimental data predicts the central value of the SM Higgs mass to be [58]:

$$m_H = 98_{-35}^{+51} \text{ GeV}/c^2$$

and the upper limit for standard Higgs, including also the theoretical uncertainty provided by [58] is:

$$m_H \leq 204 \text{ (176, 267) GeV}/c^2 \quad \text{at 95 \% (90, 99) \% CL.}$$

When the SSB Lagrangian is induced into the full SM Lagrangian for the fermion fields, their masses are generated via couplings to the Higgs field given by Yukawa constants g_i . Masses are proportional to the values of Yukawa couplings. The quark mass eigenstates differ from weak eigenstates. They are translated one to another by the famous Cabibbo–Kobayashi–Maskawa mixing matrix [60, 61], which also properly reconstructs the symmetry CP (the space and particle – antiparticle parity) violation by a single complex phase. In the SM neutrinos are assumed to be massless. Recent experimental evidence for the neutrino oscillations [62, 63] requires incorporating the neutrino masses into the model. It is not a problem. From the technical point of view one can introduce a mixing matrix for neutrinos. Such matrix is already known in the literature as the Maki–Nakagawa–Sakata matrix [64].

The SM allows for precise prediction of a large set of the SM quantities such as partial widths, cross-sections, branching ratios, asymmetries or vector and axial couplings. Experimental results are in agreement with the SM prediction. Any observable shows the significant deviation, the largest is at the level of 1.7 pull (i.e. $R_b = \Gamma(b\bar{b})/\Gamma(\text{had})$), which is reasonably assumed to be consistent with the SM [58].

The Higgs particle is the only missing ingredient of the Standard Model. Any present experiments (from LEP or TeVatron colliders) showed the evidence for Higgs. The direct searches at LEP had only yielded the limit on the Higgs mass at [59]:

$$m_H \geq 114.4 \text{ GeV}/c^2 \text{ (95\% CL).}$$

The Higgs search is an exciting challenge for experiments, and is the main argument for constructing the LHC, described in previous Section 2.1.

³ By definition, Weinberg's angle: $\theta_W = \arctan \frac{g'}{g}$, where g and g' are gauge couplings constants representing, respectively, the SU(2) and U(1) gauge groups. $\sin\theta_W = \frac{e}{g}$, where e is the positron electric charge.

⁴ $\alpha = e^2/4\pi\epsilon_0\hbar c$ – the fine-structure constant.

Gray holes of Standard Model

The SM provides explicit and consistent formulas for measured observables. Agreement between the SM prediction and experiment is excellent. However, the SM is not satisfactory because it produces new questions. The main unsolved conceptual problems are [57]:
the quantum gravity, which is not included in the SM,

the *hierarchy problem*,

commonly regarded as the most important one (see below),

existence and number of fermions generations is not explained
(experimentally there are three generation of leptons and quarks),

quantization of electric charge

Experimental data and phenomenological indications, such as:
non exact unification of all forces in a Grand Unification Theory (GUT) scale,

baryogenesis generating matter – antimatter asymmetry at the Universe,

no dark matter candidates among the SM particles,

small cosmological constant,

non zero neutrino masses.

strongly suggest the existence of deeper, more profound theory behind the SM.

Hierarchy problem and SuperSYmmetrical solution

The full Lagrangian of electroweak theory contains terms describing interactions of Higgs sector with bosons, fermions and self interactions, which are proportional to the masses. In consequence the Higgs mass requires additional not negligible contributions from loop diagrams:

$$m_H^2 = m_H^2 + \Sigma(\delta m_{H \text{ fermion/scalar}}^2) \text{ with}$$

$$\delta m_{H \text{ fermion}}^2 = \frac{|\lambda_f|^2}{16\pi^2} \left[-2\Lambda^2 + 6m_f^2 \ln\left(\frac{\Lambda}{m_f}\right) + \dots \right]$$

and

$$\delta m_{H \text{ scalar}}^2 = \frac{\lambda_s}{16\pi^2} \left[\Lambda^2 - 2m_s^2 \ln\left(\frac{\Lambda}{m_s}\right) + \dots \right],$$

(3.1)

where fermions and scalars can give large radiative corrections proportional to their couplings λ_f , λ_s and masses m_f and m_s . Moreover Higgs mass should be of the order of the cut-off scale Λ , to which the SM should be the circumscription of particle interaction. There is any reason why should not be a fundamental physics, such as the Planck scale $M_{PL} \sim 10^{19}$ GeV. Simultaneously, the Higgs mass increases many orders of magnitude (at least $\sim 10^{15}$) the foreseen value of Higgs mass (less then 1 TeV/c²) from electroweak theory. It is refereed as a *hierarchy problem*.

Within the SM the unnatural fine-tuning is necessary to establish the loop corrections to the Higgs mass. That means that should be no new particles, which couple to the Higgs field, up to the Planck scale.

One can notice from formulas for fermion and scalar Higgs mass corrections (Equation 3.1), that the Λ divergences could be canceled if SM fermion is accompanied by two (complex) scalars with equal couplings $\lambda_s = |\lambda_f|^2$.

One of the most popular solutions to the hierarchy puzzle comes with the *supersymmetry* [66], which fulfills above requirements for new particles.

3.2 The idea of the Supersymmetry

The supersymmetry is last symmetry which can be incorporated into the field theory of particles. It predict chiral multiplets containing fermionic and bosonic degrees of freedom. Mathematically the symmetry is circumvented by the Lie's algebra [65].

The supersymmetry introduces partners to all known particles. Its generator $\hat{Q}$ communicates with generators of the $U(1) \times SU(2) \times SU(3)$ gauge group. In simplest case ($N = 1$ SUSY) there is one distinct set of $\hat{Q}$ and its hermitian conjugate $\hat{Q}^\dagger$, which transform each particle state into one other state differing by a half of spin, boson into fermion and vice verse:

$$\hat{Q} | boson \rangle = | fermion \rangle, \quad \hat{Q} | fermion \rangle = | boson \rangle.$$

The new *supersymmetric particles* (or in short *sparticles*) should retain all quantum numbers and mass of their respective SM-partners except the spin, which should differ by a $\frac{1}{2}\hbar$ unit of the angular momentum. The spectrum of elementary particles is duplicated, and the Higgs sector is also extended. Expected sparticles are listed in Table 3.3.

In simplest supersymmetric scenario the electroweak symmetry breaking is realized by two complex Higgs doublets $H_1 = (H_1^+, H_1^0)$ and $H_2 = (H_2^0, H_2^-)$, which construct classical scalar potential:

$$V = (|\mu|^2 + m_{H_1}^2)|H_1^0|^2 + (|\mu|^2 + m_{H_2}^2)|H_2^0|^2 - (bH_1^0 H_2^0 + c.c) + \frac{1}{8}(g^2 + g'^2)(|H_1^0|^2 - |H_2^0|^2)^2$$

with already set to zero Higgs charge components ($H_1^+ = H_2^- = 0$) at the minimum of the potential without loss of generality. To get non zero v.e.v's for neutral components:

$$\langle H_1^0 \rangle = v_1 \quad \text{and} \quad \langle H_2^0 \rangle = v_2 \quad (3.2)$$

one have to be established necessary conditions for gauge invariance of the terms and the stabilization of the potential by so called D -flat direction in the field space for $|H_1^0| = |H_2^0|$. Values of v.e.v's are required to agree with the measurable parameters of electroweak symmetry breaking:

$$v_1^2 + v_2^2 = v^2 = 2m_Z^2/(g^2 + g'^2) \approx (174 \text{ GeV}/c^2)^2,$$

but the ratio of v.e.v's remains free parameter of SUSY models. Traditionally, it is written as:

$$\tan\beta = \frac{v_1}{v_2}. \quad (3.3)$$

Supersymmetric Higgs potential is directly derived from the part of the SUSY superpotential:

$$W = \mu H_1 H_2, \quad (3.4)$$

where parameter μ is an effective parameter of Higgs mixing in the supersymmetry. The sign of μ determines the space configuration of the SUSY Higgs potential.

The supersymmetric Higgs mechanism provides a doublet of charged scalars $H^\pm$, two neutral scalars h , H and one neutral pseudoscalar A . The masses of H , A and $H^\pm$ are in principle large, but h is bounded: $m_h < |\cos 2\beta| m_Z$ and with radiative corrections, h should remain light. If the lightest of supersymmetric Higgses will not be observed below about $\lesssim 130 \text{ GeV}/c^2$ [67], the SUSY model could be falsified.

3.3 The MSSM

That minimal extension of the Standard Model without any additional constraints, is called:

the Minimal Supersymmetric Standard Model (MSSM).

	SM	Superpartner s-SM interaction $\leftrightarrow$ mass eigenstate	Name of s-SM	Quantum numbers $SU_c(3), SU_I(2), U_Y(1)$ $i = 1, 2, 3 - \text{generation}$	Spin	Type	
SM-fermions	u	$\tilde{u}_{L,R}$	s-up	doublet $\tilde{Q}_i = (\tilde{u}_i, \tilde{d}_i)_L$	0	squarks	
	d	$\tilde{d}_{L,R}$	s-down	3, 2, 1/3			
	c	$\tilde{c}_{L,R}$	s-charm	up singlet $\tilde{U}_i = \tilde{u}_{iR}$			
	s	$\tilde{s}_{L,R}$	s-strange	3, 1, 4/3			
	t	$\tilde{t}_{L,R} \quad \} \quad \tilde{t}_{1,2}$	stop	down singlet $\tilde{D}_i = \tilde{d}_{iR}$			
	b	$\tilde{b}_{L,R} \quad \} \quad \tilde{b}_{1,2}$	sbottom	3, 1, -2/3			
	e	$\tilde{e}_{L,R}$	selectron	doublet $\tilde{L}_i = (\tilde{\nu}_{\tilde{e}_i}, \tilde{e}_i)_L$	0	sleptons	
	ν_e	$\tilde{\nu}_{\tilde{e}R}$	selectron sneutrino	1, 2, -1			
	μ	$\tilde{\mu}_{L,R}$	smuon	singlet $\tilde{E}_i = \tilde{e}_{iR}$			
	ν_μ	$\tilde{\nu}_{\tilde{\mu}R}$	smuon sneutrino	1, 1, -2			
	τ	$\tilde{\tau}_{L,R} \quad \} \quad \tilde{\tau}_{1,2}$	stau				
	ν_τ	$\tilde{\nu}_{\tilde{\tau}R}$	stau sneutrino				
SM-bosons	$W^\pm$	$\tilde{W}^\pm$	wino	1, 3, 0	1/2	gauginos	
	$H^\pm$	$\tilde{H}^\pm \quad \} \quad \tilde{C}_{1,2}^\pm$	CHARGINOS charge higgsinos	1, 2, -1			
	γ	$\tilde{\gamma}$	photino	1, 1, 0	1/2		
	Z	$\tilde{Z}$	zino	1, 3, 0			
	h	$\tilde{h} \quad \} \quad \tilde{N}_{1,2,3,4}$	NEUTRALINOS	1, 2, -1			
	H	$\tilde{H}$	$\}$ neutral higgsinos				
	A	$\tilde{A}$					
	g	$\tilde{g}$	gluino	8, 1, 0	1/2		
	G	$\tilde{G}$	gravitino	0, 0, 0	3/2		

Table 3.3: The particle spectrum in the MSSM.

The first column corresponds to the particles present in the Standard Model (SM), next columns contain properties of their supersymmetric partners (s-SM).

Supersymmetric bosons (L or R) are the interaction eigenstates and they have names from the SM fermion helicity states: left-handed or right-handed. The only exception are sneutrinos. Interaction eigenstates can mix into mass eigenstates. Generally, the mixing is substantial for third family, which is point out in Table. Mass matrices in Appendix A. The supersymmetric fermion are also mixed and charge gauginos occur as charginos $\tilde{C}_{1,2}^\pm$ and neutral ones as neutralinos $\tilde{N}_{1,2,3,4}$. Their properties (especially, decay channels) depend on the main constituent. Their behavior is determined by gauginos coming from Goldston bosons forming elementary carriers, as follows:

$W^\pm = (W_\mu^1 + iW_\mu^2)/\sqrt{2}$ $Z = -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W$ $\gamma = B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W$			
Goldston bosons	goldstinos		Quan. Num.
$W_\mu^i, i=1,2,3$	$\tilde{W}_\mu^i, i=1,2,3$	wino	1, 3, 0
B_μ	$\tilde{B}_\mu$	bino	1, 1, 0

Supersymmetric elementary particles have not been observed, what means they must have higher masses. Because of that, the supersymmetry cannot be an exact symmetry of Nature. It cannot be also spontaneously broken in the SM-sector, without reintroducing the problems that were to be cured. One is forced to introduce so called *soft* supersymmetry breaking terms which are related to superpartner masses and their couplings. The soft terms involves only scalars and gauginos and not their respective superpartners, which indeed breaks the supersymmetry.

The origin of *soft* parameters (sparticles masses and couplings) is not defined within the MSSM. Our present knowledge constraints the values of parameters which give rise to the flavour changing neutral current (FCNC) processes. The best way of introducing relevant constraint is to postulate new conserved multiplicative quantum number called R-parity:

$$R = (-1)^{3(B-L)+2S}$$

where B – baryon number, L – lepton number and S – spin.

By definition, SM-particles are R-even, whereas superpartners are R-odd. As a consequence, superpartners can be produced only in even number, and there should be the *lightest supersymmetric particle*, the LSP. If R-parity is exact symmetry then the LSP should be stable and neutral. The last constraint comes from the cosmology, in which the LSP is considered to be the dark matter candidate.

Supersymmetry has many more appealing features. Local supersymmetry opens the way for introducing gravity into the particle physics, and is unavoidable ingredient of the *superstring* models.

The theoretical motivation for supersymmetry imposed many searches for supersymmetric particles. No convincing evidence for SUSY production have been found. Experiments derived limits on the sparticle production. Table 3.4 summarizes the searches performed in e^+e^- collider by the LEP experiments (ALEPH, DELPHI, L3, OPAL) [68, 69, 70] and in p^+p^- accelerator by Tevatron experiments (CDF, DØ) [71, 72, 73, 74] The low-energy supersymmetry was not ruled out and the highly required verification will be provided by the LHC.

3.4 Mechanisms of supersymmetry breaking

The MSSM with conserved R-parity has 105 free parameters in addition to 21 SM undetermined ones. Although there is nothing wrong with such a model, it is not very predictive. To increase the predictability one should propose some mechanism responsible for the breaking of supersymmetry. Many theoretical effort was concentrated on understanding the structure of *soft* terms, which connect the theory with experiments.

An elegant and theoretically appealing mechanism for many years was the *gravity mediation*. That solution relies on assuming that supersymmetry is spontaneously broken in the *hidden sector*, and then transmitted to the *visible sector* via some flavour blind interaction, e.g. gravity. This scenario is called a *supergravity* (SUGRA). The SSB in the hidden sector should occur at the Planck scale. Requiring the experimentally observable sparticles at the electroweak scale:

$$M_{\text{SUSY}} = \frac{F}{M_{\text{PL}}} \sim 1 \text{ TeV}/c^2$$

one determines an intermediate scale of SUSY breaking to be of the order of $\sqrt{F} \sim 10^{11} \text{ GeV}$. As a result FCNC may be reintroduced via renormalization group equations (RGE) evolution of the soft terms from the Planck scale down to the electroweak scale. To solve the problem with gravity mediation one should control the dynamics beyond M_{PL} .

The better possible solution to the FCNC problem is to lower the scale at which MSSM soft supersymmetry breaking terms do not mix flavours. It can be done by postulating a *messenger*

particle		Condition	Lower limit (GeV/c ²)	Source
$\tilde{\chi}_1^\pm$	gaugino	$M_{\tilde{\nu}} > 200 \text{ GeV}/c^2$	103	LEP 2
		$M_{\tilde{\nu}} > M_{\tilde{\chi}^\pm}$	85	LEP 2
		any $M_{\tilde{\nu}}$	45	Z width
	Higgsino	$M_2 < 1 \text{ TeV}/c^2$	99	LEP 2
	GMSB		150	DØ isolated photons
	RPV	$LL\bar{E}$ worst case	87	LEP 2
		$LQ\bar{D}$ $m_0 > 500 \text{ GeV}/c^2$	88	LEP 2
$\tilde{\chi}_1^0$	indirect	any $\tan\beta$, $M_{\tilde{\nu}} > 500 \text{ GeV}/c^2$	39	LEP 2
		any $\tan\beta$, any m_0	36	LEP 2
		any $\tan\beta$, any m_0 , SUGRA Higgs	59	LEP 2 combined
	GMSB		93	LEP 2 combined
	RPV	$LL\bar{E}$ worst case	23	LEP 2
$\tilde{e}_R$	$e\tilde{\chi}_1^0$	$\Delta M > 10 \text{ GeV}/c^2$	99	LEP 2 combined
$\tilde{\mu}_R$	$\mu\tilde{\chi}_1^0$	$\Delta M > 10 \text{ GeV}/c^2$	95	LEP 2 combined
$\tilde{\tau}_R$	$\tau\tilde{\chi}_1^0$	$M_{\tilde{\chi}_1^0} < 20 \text{ GeV}/c^2$	80	LEP 2 combined
$\tilde{\nu}$			43	Z width
$\tilde{\mu}_R, \tilde{\tau}_R$		stable	86	LEP 2 combined
$\tilde{t}_1$	$c\tilde{\chi}_1^0$	any θ_{mix} , $\Delta M > 10 \text{ GeV}/c^2$	95	LEP 2 combined
		any θ_{mix} , $M_{\tilde{\chi}_1^0} \sim \frac{1}{2}M_{\tilde{t}}$	115	CDF
		any θ_{mix} and any ΔM	59	ALEPH
	$b\bar{\ell}\tilde{\nu}$	any θ_{mix} , $\Delta M > 7 \text{ GeV}/c^2$	96	LEP 2 combined
$\tilde{g}$	any $M_{\tilde{q}}$		195	CDF jets+ $\cancel{E}_T$
$\tilde{q}$	$M_{\tilde{q}} = M_{\tilde{g}}$		300	CDF jets+ $\cancel{E}_T$

Table 3.4: Lower limits on supersymmetric particle masses. Taken from PDG [75].
RPV stands for the R -parity violation model. $\tilde{\chi}^0$ denotes neutralino $\tilde{N}$ and $\tilde{\chi}^\pm$ – chargino $\tilde{C}$.

secluded sector which separately communicates itself with other sectors. The SUSY breaking is felt at tree level by messenger particles of mass M and then transmitted to the visible sector via loop diagrams of the SM gauge interactions. The scale of supersymmetry breaking in the messenger sector can be much lower, because gauge interactions are much stronger than gravity, and the amount of RGE running of soft breaking terms can be much smaller. Thus effectively the FCNC processes are under control. This scenario is called *Gauge Mediated Supersymmetry Breaking* model (GMSB).

3.5 Gauge Mediated Supersymmetry Breaking models

In GMSB models [76, 77] the role of the messenger is played by gauge fields, e.g. by number N of singlet representations of the $\mathbf{5} \oplus \bar{\mathbf{5}} \subset SU(5)$ to preserve the unification of coupling constants. In the act of the SUSY breaking messengers acquire the mass M . That process is schematically shown in Figure 3.1. Subsequently MSSM gauginos obtain mass as a one loop correction:

$$m_{\lambda_i} = N \frac{\alpha_i}{4\pi} \Lambda, \quad (3.5)$$

while sfermions acquire mass at the two loops level:

$$\tilde{m}^2 = 2N\Lambda^2 \sum_{i=1}^3 \left[c_i \left(\frac{\alpha_i}{4\pi} \right)^2 \right], \quad (3.6)$$

where λ_i are the SM Yukawa gauge couplings constants and c_i are the corresponding quadratic Casimir coefficients. In the above Λ is an effective scale of supersymmetry breaking $\Lambda = F/M$, where F is an auxiliary field messenger mass splitting parameter.

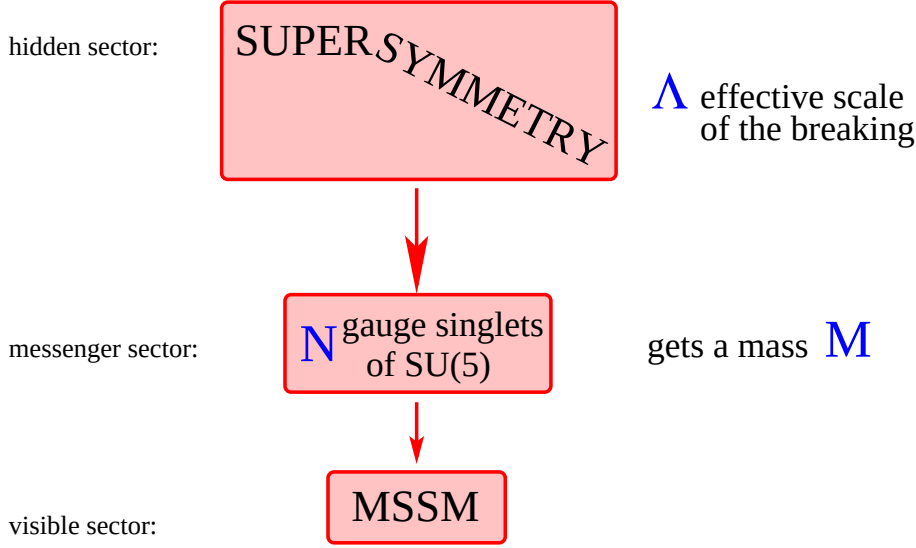


Figure 3.1: The GMSB scheme.

The mass formulas (3.5, 3.6) imply a distinctive mass hierarchy of GMSB SUSY particles. The superpartner mass depends on the SM couplings to which the given particle couples. Because of that left-handed sfermions are heavier than right-handed. Among gauginos photino is the lightest, gluino the heaviest. On the average gaugino masses are larger by factor $\sqrt{N}$. An additional mass splitting comes from the Higgs sector parameters: $\tan\beta$ and $\text{sign}(\mu)$.

The whole mass spectrum can be obtain by using five GMSB model parameters, which are:

N	–	number of singlet representation of the group $SU(5) \times SU(5)$,
Λ	–	effective scale of the SUSY breaking,
M	–	messenger mass scale,
$\tan\beta$	–	ratio of Higgs vacuum expectation values, (Eq. 3.3)
$\text{sign}(\mu)$	–	sign of Higgs sector mixing parameter. (Eq. 3.4)

The super-Higgs mechanism provides the GMSB with a very light gravitino as opposed to the SUGRA models, where its mass can reached even a few TeV/c^2 . The GMSB gravitino has mass (and couplings) closely related to the scale of SUSY breaking:

$$m_{\tilde{G}} = \frac{M\Lambda}{\sqrt{3}M_P} \simeq 2.4 \left(\frac{M\Lambda}{(100 \text{ TeV})^2} \right) \text{ eV}/c^2 \quad (3.7)$$

where $M_P = 2.4 \cdot 10^{18} \text{ GeV}$ is the reduced Planck scale.

For low energy GMSB supersymmetry breaking, realized when

$$\Lambda \sim 10 - 1000 \text{ TeV} \quad \text{and} \quad M > \Lambda$$

gravitino mass is of order of $1 \text{ eV}/c^2 - 1 \text{ keV}/c^2$, what set it up to be the Lightest Supersymmetric Particle.

3.5.1 The role of the NLSP

Light and practically non-interacting gravitino is not detectable. The GMSB phenomenology is largely defined by the Next to the Lightest Supersymmetric Particle, NLSP.

The candidates are:
the lightest neutralino $\tilde{N}_1$ or

the lightest slepton $\tilde{\tau}_1$ ⁵

degenerated sleptons $\tilde{\tau}_1, \tilde{\mu}_R, \tilde{e}_R$, called co-NLSP.

An appropriate relation between masses of neutralino and stau is illustrated on Figure 3.2. The author generated a large sample of the GMSB models using the ISAJET 7.53 package. Details will be provided in Section 5.1. On Figure one point denotes a GMSB model with the defined set of parameters: $N, \Lambda, M, \tan\beta, \text{sign}\mu$. As can be seen, the scenario which is realized depends on parameters. The large part of parameter space is covered by stau $\tilde{\tau}_1$ as the NLSP.

Zooms of Figure 3.2 are presented in Figure 3.3. Sequentially, there are separated plots for different values of N and $\text{sign}(\mu)=1$. In the range of generated parameters, neutralino $\tilde{N}_1$ is the NLSP mainly for $N = 1$ and small values of $\tan\beta < 10$ or large values of M , for $N = 2$ only for the largest M . The same dependency between neutralino and stau masses is for $\text{sign}(\mu)=-1$. With the Λ growth (for $N>3$), the splitting by M/Λ is wider and inverted for $\tan\beta$. In case of $N = 5$ for very high (not reachable for the LHC) masses (of the order of a few TeV), the NLSP occurs to be neutralino for intermediary values of $\tan\beta$.

The next to lightest supersymmetric particle in the framework of the GMSB scenario decays to its SM partner and gravitino with $c\tau$ ranging from microns to hundreds of meters:

$$c\tau \approx (1.3 \text{ m}) \left(\frac{100 \text{ GeV}}{\tilde{m}_{\text{NLSP}}} \right)^5 \left(\frac{\sqrt{F}}{1000 \text{ TeV}} \right)^4.$$

The NLSP lifetime is proportional to the gravitino mass squared for fixed NLSP mass, and is almost completely unconstrained. Very short lifetimes (very large coupling between matter and gravitino) are excluded by direct gravitino searches. The simplest inflationary scenarios put an upper limit on the gravitino mass at $1 \text{ keV}/c^2$, which correspond to an upper limit on NLSP $c\tau$ of 10 m, but this constraint can be overcome within more elaborated cosmological models. On the other hand, from the experimental point of view it is better to check even what is forbidden from the theoretical point of view [78].

From the experimental point of view there are three possibilities

1. $c\tau$ is (very) large compared to the detector dimensions.
In this case:
2. stau NLSP will look like *heavy muon*; (topology: T3, Sec.1.1)
3. neutralino NLSP will escape detection, (topology: N3)
the phenomenology will be similar to the SUGRA.
4. $c\tau$ is of the order of the detector dimensions.
In this case both (topologies: T2, N2) types of NLSP may decay inside the detector, and the NLSP lifetime could be directly measured.
5. $c\tau$ is (very) small with respect to detector dimensions.
In this case all NLSPs will decay inside the detector giving rise to spectacular signal of additional 2γ ($\tilde{N}_1$ NLSP; topology: N1) or 2τ ($\tilde{\tau}_1$ NLSP; topology: T1).

⁵ The particle $\tilde{\tau}_1$ is lighter of two massive (the heavier is $\tilde{\tau}_2$) combination of the helicity eigenstates: a right-handed $\tilde{\tau}_R$ and a left-handed $\tilde{\tau}_L$. For clarification see Tab. 3.3.

At accelerators, only gravitino couplings, not its mass, can be measured. The measurement of the NLSP lifetime is equivalent to the estimate of an effective scale of supersymmetry breaking. Any limit will significantly constrain the SUSY breaking mechanism.

$\Lambda=30\text{-}1000\text{ TeV}$, $M=40\text{-}30000\text{ TeV}$, $\tan\beta=1.5\text{-}55$, $\text{sign}(\mu)=\pm 1$

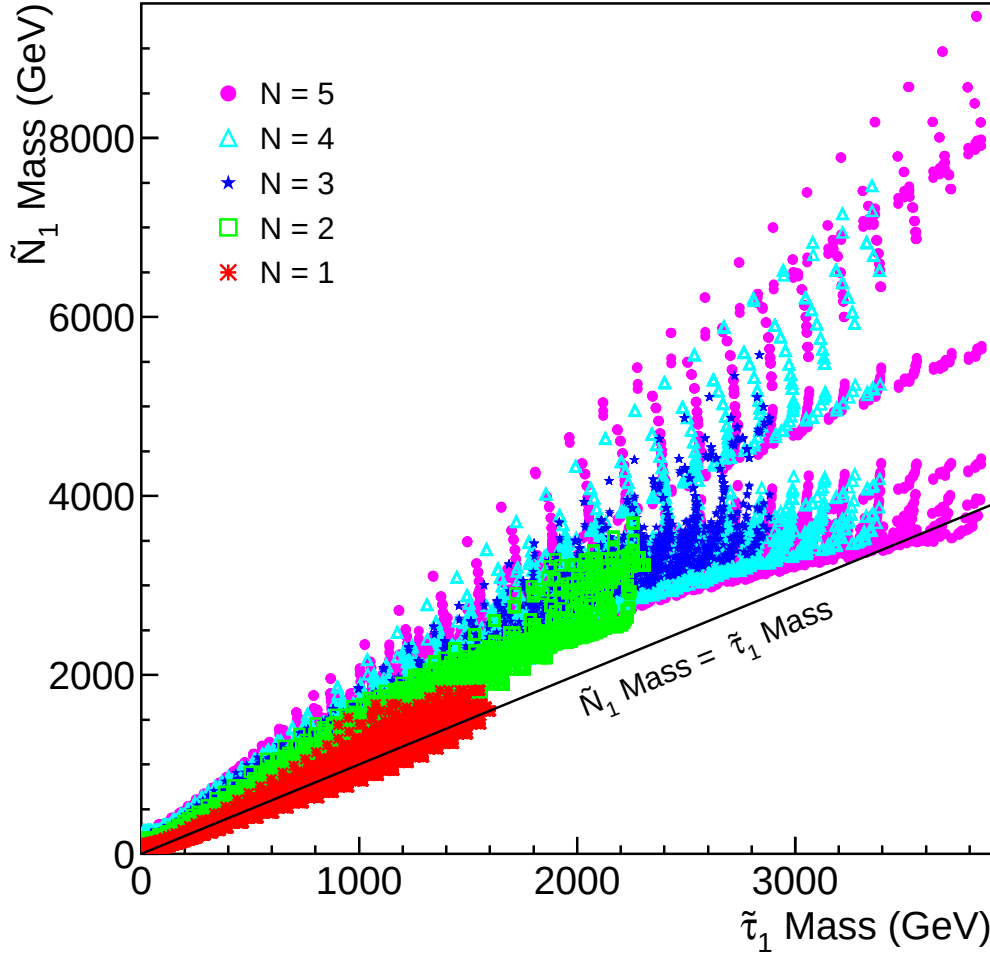


Figure 3.2: The masses of neutralino $\tilde{N}_1$ and stau $\tilde{\tau}_1$ for sample of GMSB models. The lightest particle is the NLSP. Every point on Figure corresponds to model with well defined parameters.

Details of simulation are given in Section 5.1. The range of parameters is following:

- Λ is changed from 30 TeV to 1000 TeV.

Lines of the constant Λ value increase in an right-up aslant direction.

- M is calculated from the ratio $1.1 < M/\Lambda < 10^3$ and it stretches along the diagonal lines.

The greater M the smaller neutralino $\tilde{N}_1$ mass for a given Λ .

- The different *diagonal lines* correspond to different values of $\tan\beta$ and $\text{sign}(\mu)$.

The parameter $\tan\beta$ is in a range $1.5 < \tan\beta < 60$. The discrete values of $\tan\beta$: 1.5, 1.7, 2, 3, 5, 7, 10, 15, 20, 30, 40, 55 have been chosen for both ± 1 values of $\text{sign}(\mu)$ parameter.

- Integer numbers for N : 1, 2, 3, 4, 5 are taken into consideration. They are marked by different colours and marker types. The widest mass splitting is for $N = 5$.

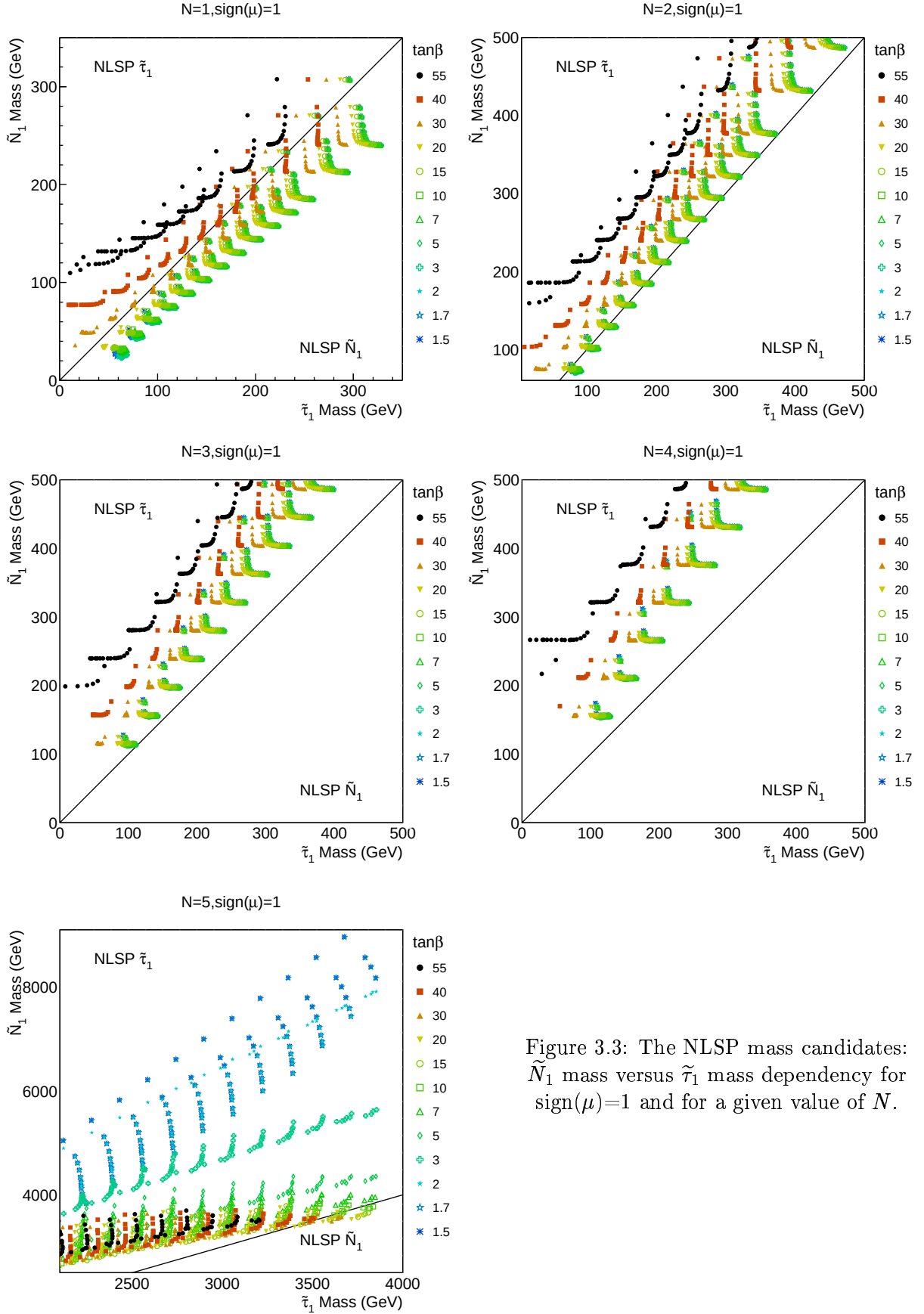


Figure 3.3: The NLSP mass candidates: $\tilde{N}_1$ mass versus $\tilde{\tau}_1$ mass dependency for $\text{sign}(\mu)=1$ and for a given value of N .

3.5.2 Physics reach of the LHC

The reach of the LHC depends on the average mass of sparticles [79, 80]. The overall supersymmetric cross-section falls with that mass as can be seen in the Figure 3.4.

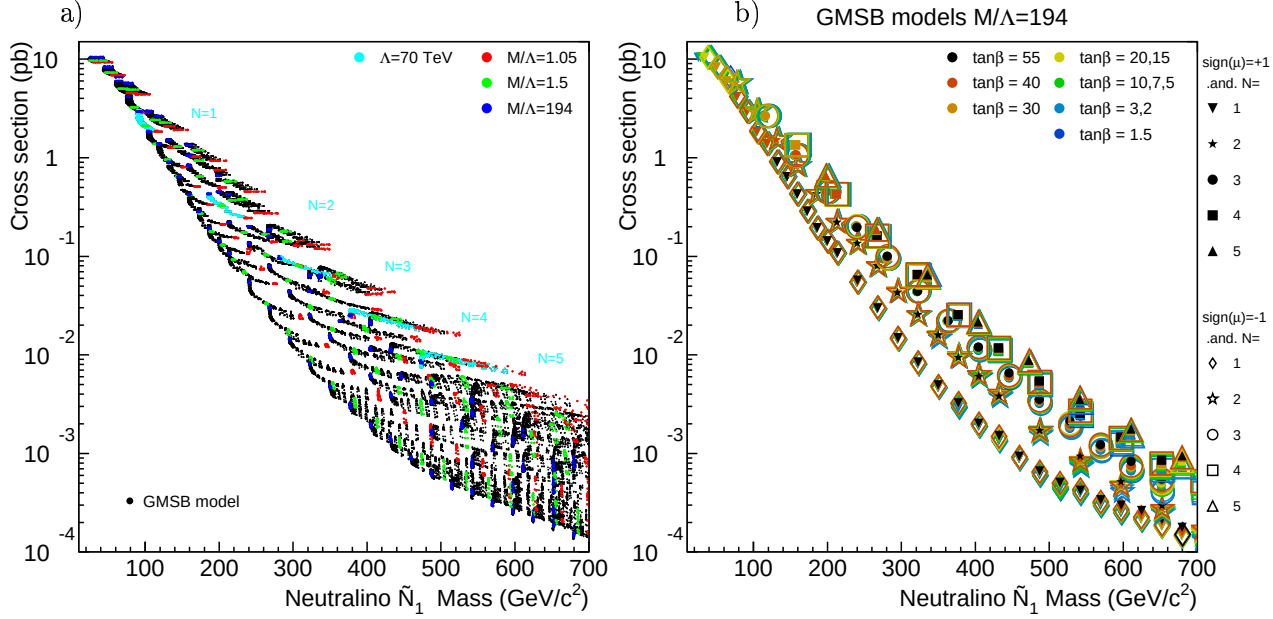


Figure 3.4: GMSB models cross-sections at LHC. Model parameters are specified on pictures.

a) Red, green and blue dots refer to given values of M/Λ . One value of parameter Λ was chosen to show the dependence of parameter N (cyan dots). b) The plot is drawn only for one M/Λ . Open and close marks stand for different N and $\pm \text{sign}(\mu)$. Dots are coloured according to $\tan\beta$.

Three classes of measurements which provide an insight into SUSY breaking mechanism should be possible at the LHC:

1. the determination of an overall mass scale of superpartners;
2. the measurement of the mass ratios, in particular sfermion/gaugino;
3. the determination of strength of the gravitino (goldstino) couplings.

The first two classes are common to all SUSY breaking models. In the GMSB case, however, specific relations between the masses should allow to distinguish that model from other scenarios [81, 82]. The third point is characteristic for the GMSB, because the $c\tau$ measurement determines directly the gravitino coupling.

Chapter 4

Simulation of the GMSB models and SM Background

4.1 Standard Model background generation procedure

Generation of the LHC SM background is one of the most complicated technical issues. The enormous rate of the LHC prohibits direct background simulation, well known strategy of the LEP era. The only practical way to deal with the LHC rate is to divide the background into groups of growing *hardness*, simulate a given amount of events for each group, weight these groups by the cross-section, and finally add them up. The result is approximate, but the *hardest*, and potentially the most harmful background may be simulated in the most precise and appropriate way. The number of simulated background events is chosen as a compromise between required precision of the background estimate and the available CPU time.

For the purpose of the background estimate the following Standard Model processes for the p-p collision at the center of mass energy $\sqrt{S} = 14$ TeV were simulated

minimum bias, $b\bar{b}$, γ , $t\bar{t}$, W, WW, WZ, Z, ZZ.

These processes were generated separately with the PYTHIA 6.157 [83] event generator and then processed by the CMSJET 4.703 [84] fast detector simulation. Each of the background process was simulated in several $\hat{p}_t$ intervals,¹ at least 50k events per interval. The details of the background simulation process are given in Table 4.1. All sources of SM background were preselected with a requirement of a presence of at least one *hard object* in every event. The requirement will be called:

- **CUT0:** at least one *hard object* in the event
 - electron, muon, gamma: $p_t > 20$ GeV/c and $|\eta| < 2.4$ ²
 - jet: $p_t > 40$ GeV/c and $|\eta| < 4.5$

Distributions of the missing transverse energy³ $\cancel{E}_t$ for these sources of background and distributions of the transverse momentum of the 4th most energetic jet p_t^{4j} in the event are shown in Figures 4.1 – 4.18. Events in all figures were selected with an additional criterion:

- **CUT1:** at least four jets with $p_t > 40$ GeV/c reconstructed.

¹ $\hat{p}_t$ – the transverse momentum defined in the rest frame of the hard interaction, here for 2→2 processes.

² During the preparation time of this thesis, the η coverage of the CMS muon was suppressed to $|\eta| < 2.1$. It was decided to keep the limitation: $|\eta| < 2.4$ for the present of the thesis.

³ The missing transverse energy $\cancel{E}_t = E_t^{total} - E_t^{visible}$ ($E_t = p_z / \sinh \eta$) reconstruction, provided by the CMSJET, is done using the transverse energy contents of calorimeters cells in the CMS detector, smeared according to the expected experimental resolution.

Background Type	PYTHIA Subprocess	$\hat{p}_t$ Intervals [GeV/c]: Number of Events					
		$\hat{p}_{t \min}$	$\hat{p}_{t \max}$	Nev	$\hat{p}_{t \min}$	$\hat{p}_{t \max}$	Nev
minimum bias Fig. 4.1 4.2	11: $f_i f_j \rightarrow f_i f_j$	0 – 10	:	5.M	200 – 400	:	50k
	12: $f_i f_i \rightarrow f_k f_k$	10 – 25	:	5.M	400 – 600	:	50k
	13: $f_i \bar{f}_i \rightarrow gg$	25 – 50	:	500k	600 – 1000	:	200k
	28: $f_i g \rightarrow f_k \bar{f}_k$	50 – 100	:	50k	1000 – 2000	:	150k
	53: $gg \rightarrow f_i f_j$	100 – 150	:	50k	2000 – ∞	:	50k
	68: $gg \rightarrow gg$	150 – 200	:	50k			
$b\bar{b}$ Fig. 4.3 4.4		0 – 15	:	5.M	100 – 200	:	50k
	81: $f_i \bar{f}_i \rightarrow Q_k \bar{Q}_k$	15 – 25	:	1.M	200 – 400	:	50k
	82: $gg \rightarrow Q_k \bar{Q}_k$	25 – 50	:	500k	400 – ∞	:	250k
		50 – 100	:	50k			
γ Fig. 4.5 4.6	14: $f_i \bar{f}_i \rightarrow g\gamma$	0 – 10	:	5.M	100 – 200	:	50k
	18: $f_i \bar{f}_i \rightarrow \gamma\gamma$	10 – 25	:	10.M	200 – 1000	:	50k
	29: $f_i g \rightarrow f_i \gamma$	25 – 50	:	50k	1000 – ∞	:	50k
	114: $gg \rightarrow \gamma\gamma$	50 – 100	:	50k			
	115: $gg \rightarrow g\gamma$						
$t\bar{t}$ Fig. 4.7 4.8	81: $f_i \bar{f}_i \rightarrow Q_k \bar{Q}_k$	0 – 200	:	50k	400 – 1000	:	240k
	82: $gg \rightarrow Q_k \bar{Q}_k$	200 – 400	:	300k	1000 – ∞	:	150k
W Fig. 4.9 4.10	2: $f_i \bar{f}_j \rightarrow W^+$						
	16: $f_i \bar{f}_j \rightarrow gW^+$	0 – 50	:	500k	200 – 400	:	50k
	20: $f_i \bar{f}_j \rightarrow \gamma W^+$	50 – 100	:	50k	400 – 1000	:	50k
	31: $f_i g \rightarrow f_k W^+$	100 – 200	:	50k	1000 – ∞	:	50k
	36: $f_i \gamma \rightarrow f_k W^+$						
WW Fig. 4.11 4.12	25: $f_i \bar{f}_i \rightarrow W^+ W^-$	0 – 100	:	500k	200 – 400	:	50k
	69: $\gamma\gamma \rightarrow W^+ W^-$	100 – 200	:	50k	400 – ∞	:	50k
WZ Fig. 4.13 4.14	23: $f_i \bar{f}_j \rightarrow ZW$	0 – 100	:	1.M	400 – 1000	:	50k
	70: $\gamma W \rightarrow ZW$	100 – 200	:	50k	1000 – ∞	:	50k
		200 – 400	:	50k			
Z Fig. 4.15 4.16	1: $f_i \bar{f}_i \rightarrow \gamma^*/Z$						
	15: $f_i \bar{f}_i \rightarrow gZ$	0 – 25	:	1.M	100 – 200	:	50k
	19: $f_i \bar{f}_i \rightarrow \gamma^* Z$	25 – 50	:	500k	200 – 400	:	50k
	30: $f_i g \rightarrow f_i Z$	50 – 100	:	50k	400 – ∞	:	50k
	35: $f_i \gamma \rightarrow f_i Z$						
ZZ Fig. 4.17 4.18		0 – 200	:	50k	400 – ∞	:	50k
		200 – 400	:	50k			

Table 4.1: The SM processes generated in several $\hat{p}_t$ intervals with the PYTHIA 6.157. The fast event reconstruction provided by the CMSJET 4.703.

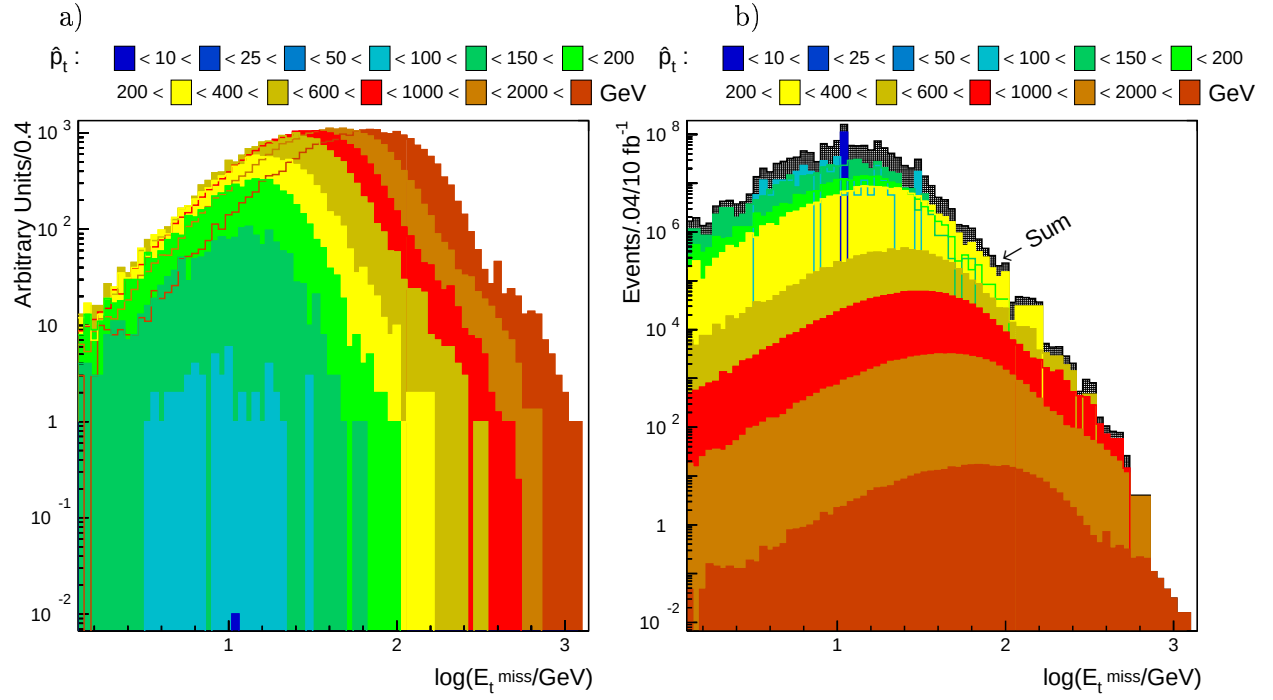


Figure 4.1: The E_t distribution for minimum bias production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

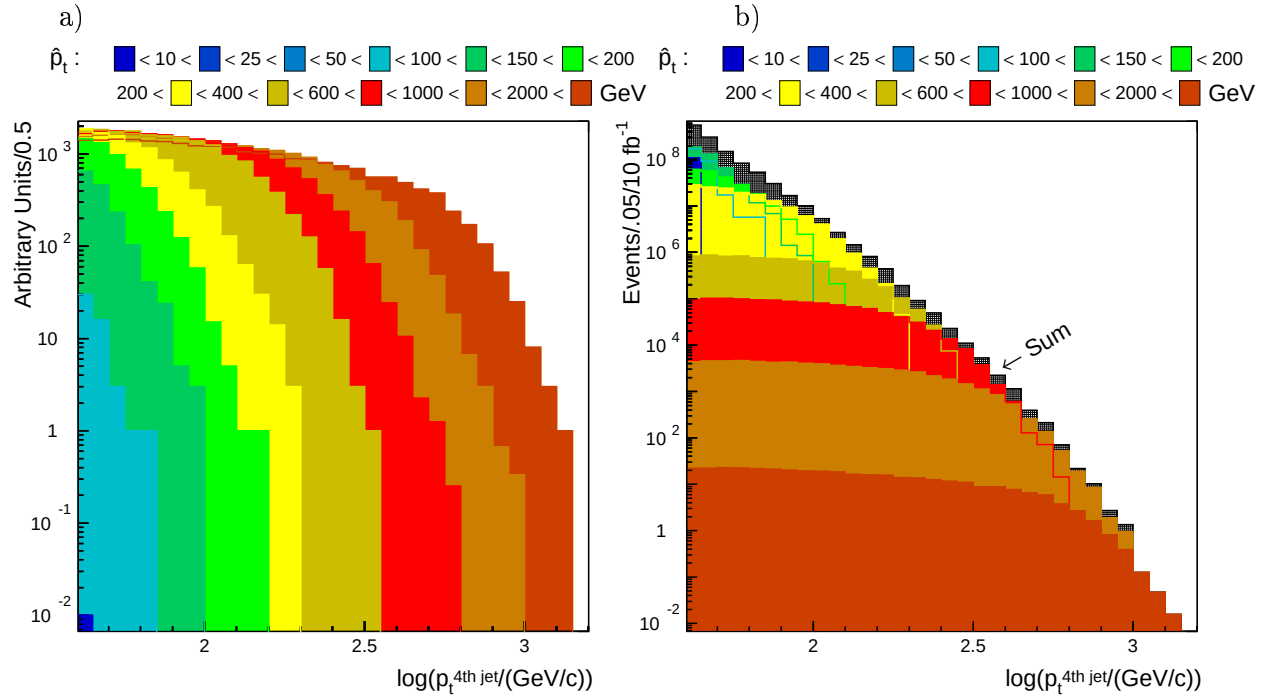


Figure 4.2: The p_t^{4j} distribution for minimum bias production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

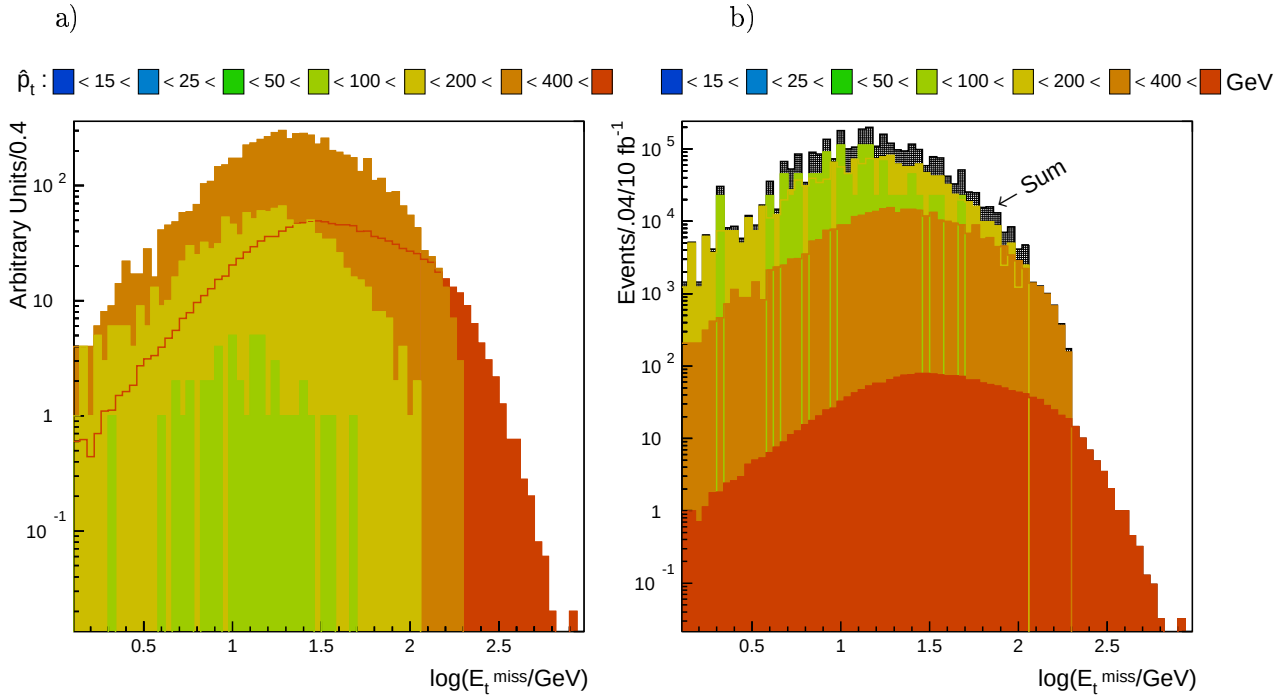


Figure 4.3: The $\cancel{E}_t$ distribution for $b\bar{b}$ production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

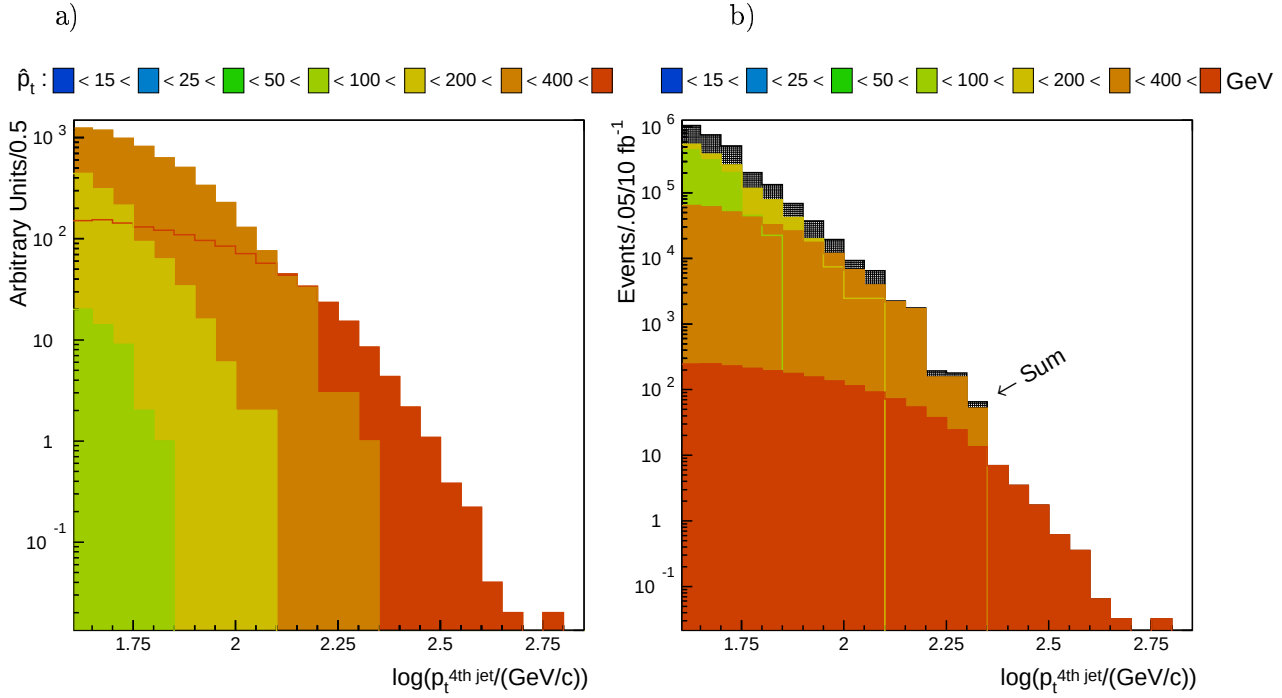


Figure 4.4: The p_t^{4j} distribution for $b\bar{b}$ production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

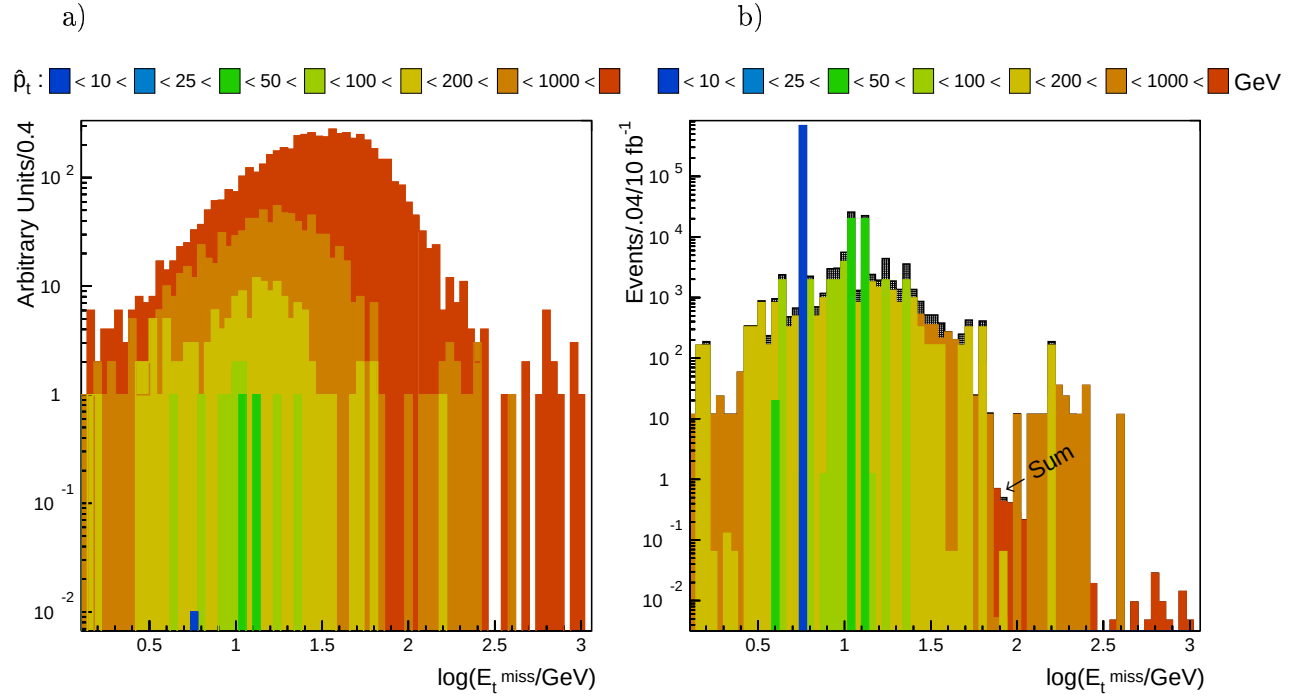


Figure 4.5: The E_t distribution for γ production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

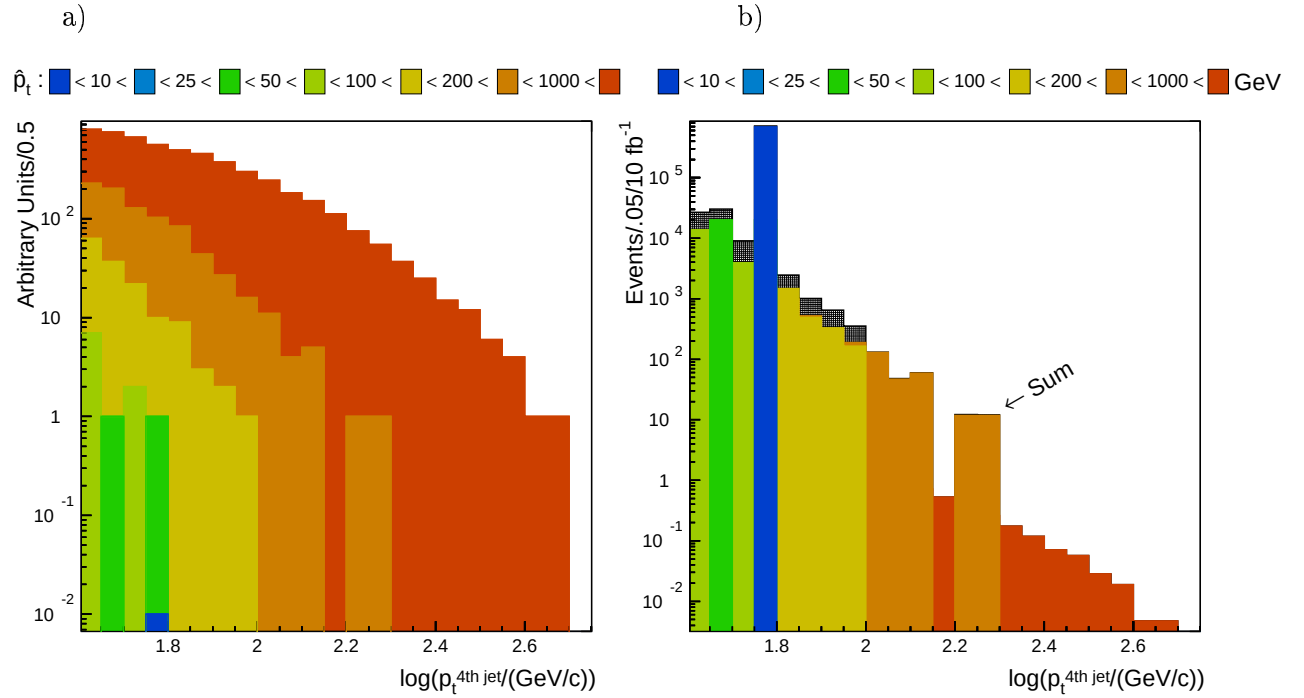


Figure 4.6: The p_t^{4j} distribution for γ production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

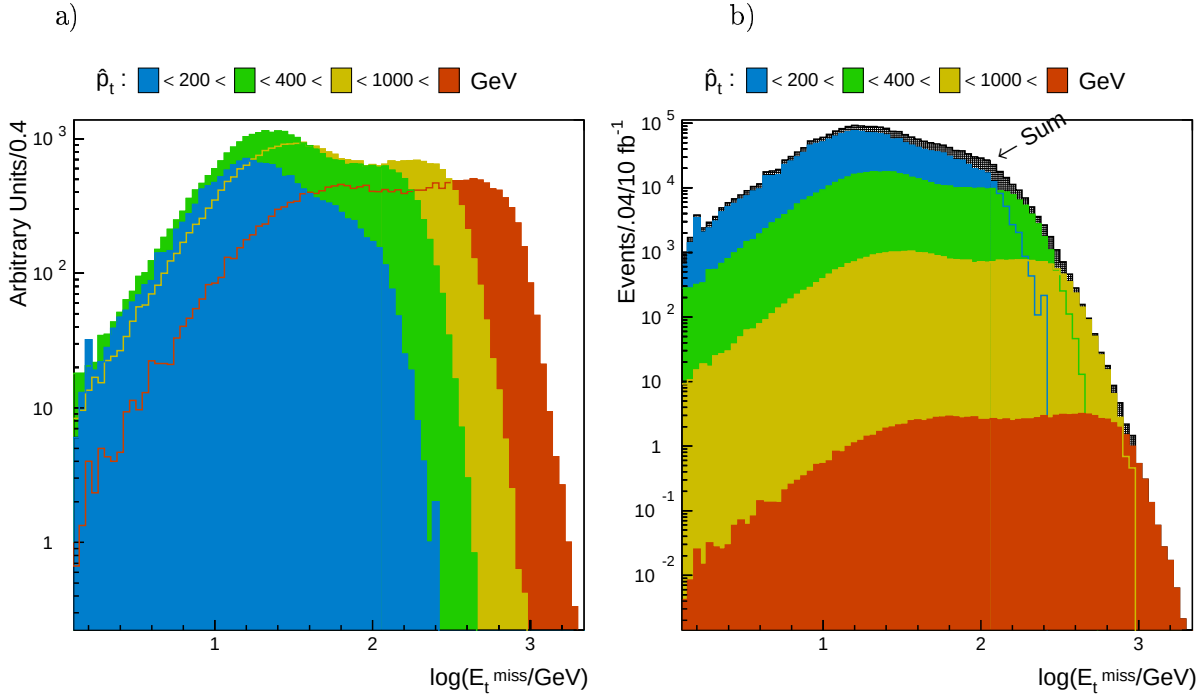


Figure 4.7: The $\cancel{E}_t$ distribution for $t\bar{t}$ production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

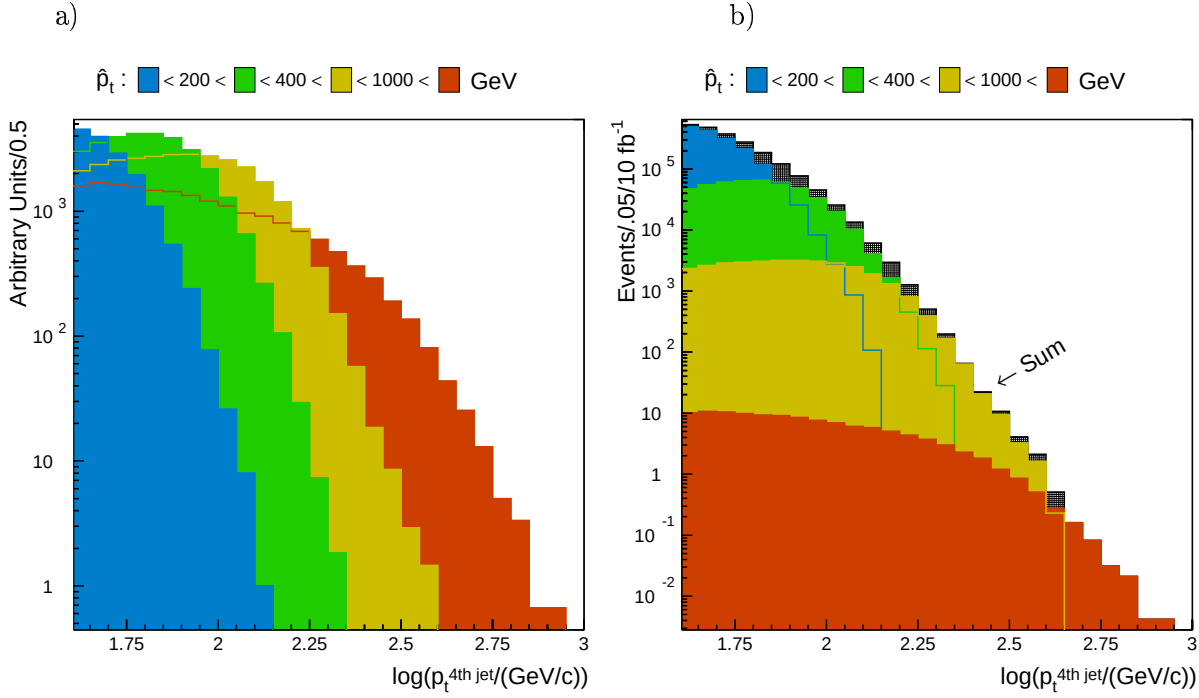


Figure 4.8: The p_t^{4j} distribution for $t\bar{t}$ production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

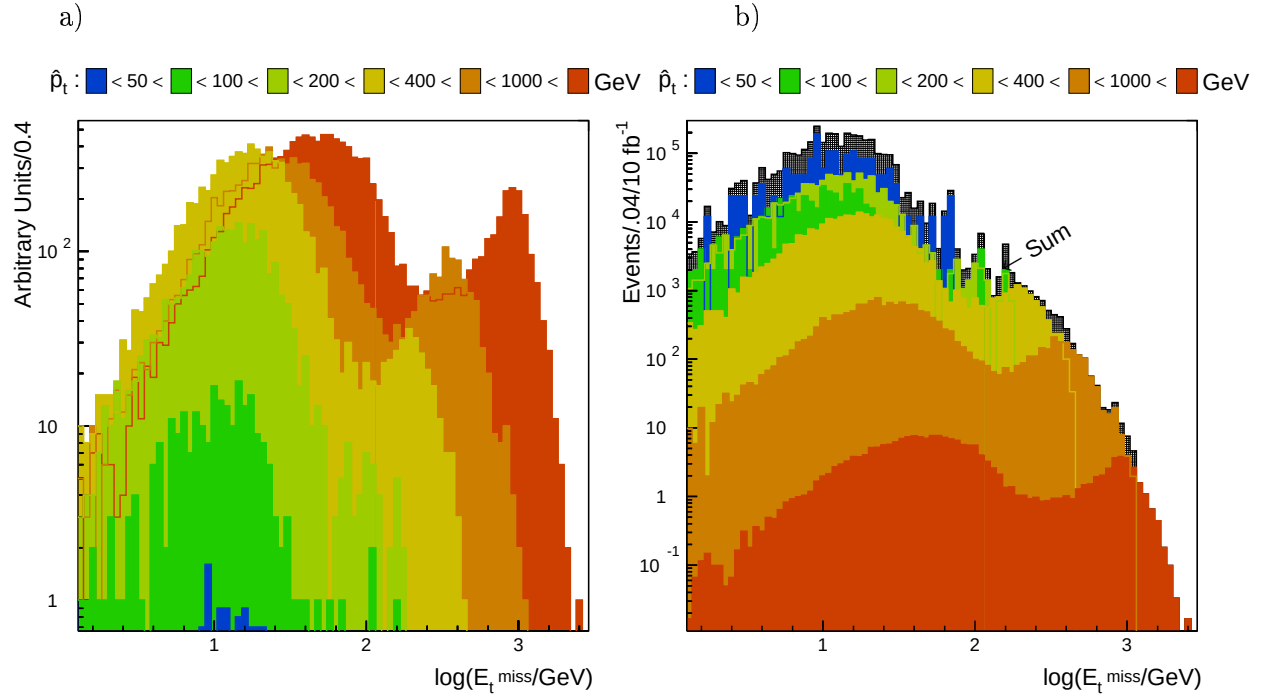


Figure 4.9: The $\cancel{E}_t$ distribution for W production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

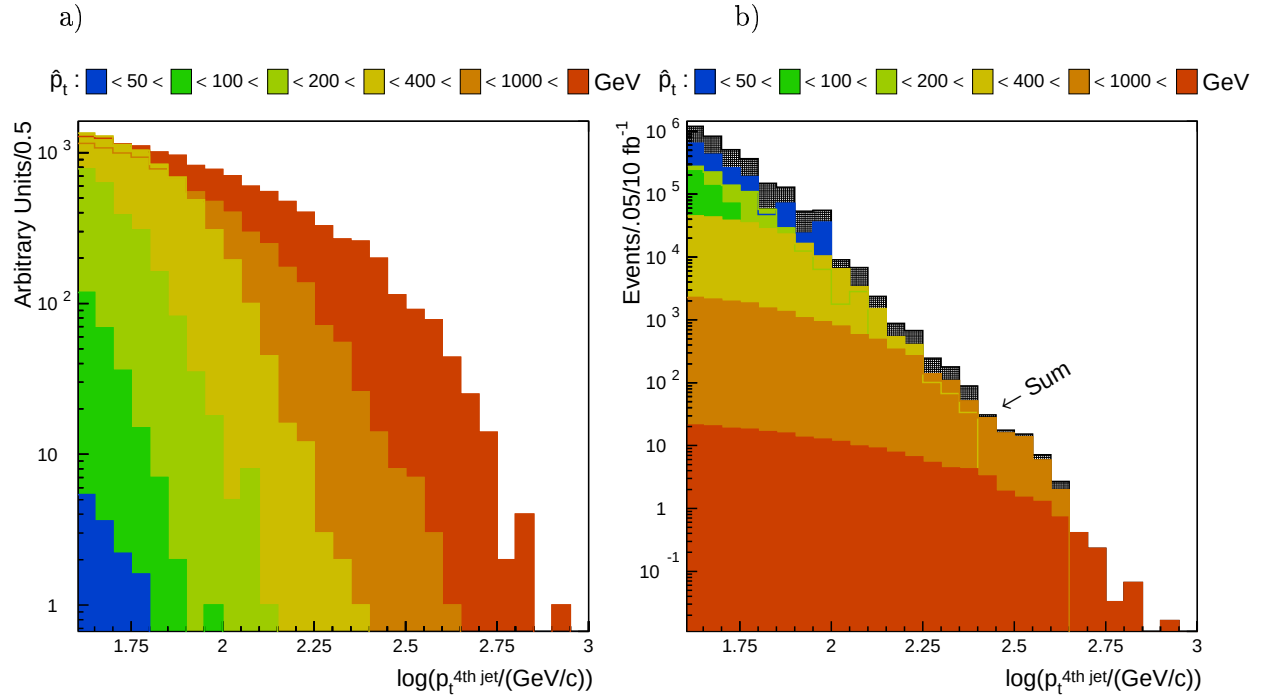


Figure 4.10: The p_t^{4j} distribution for W production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

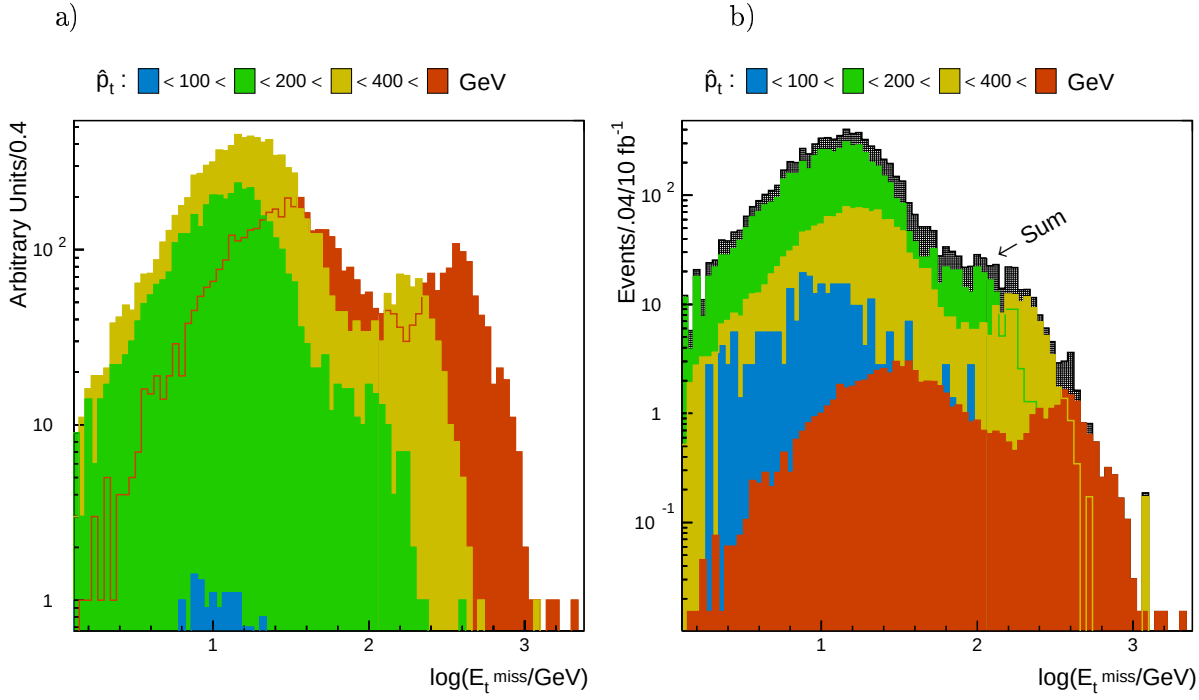


Figure 4.11: The E_t distribution for WW production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

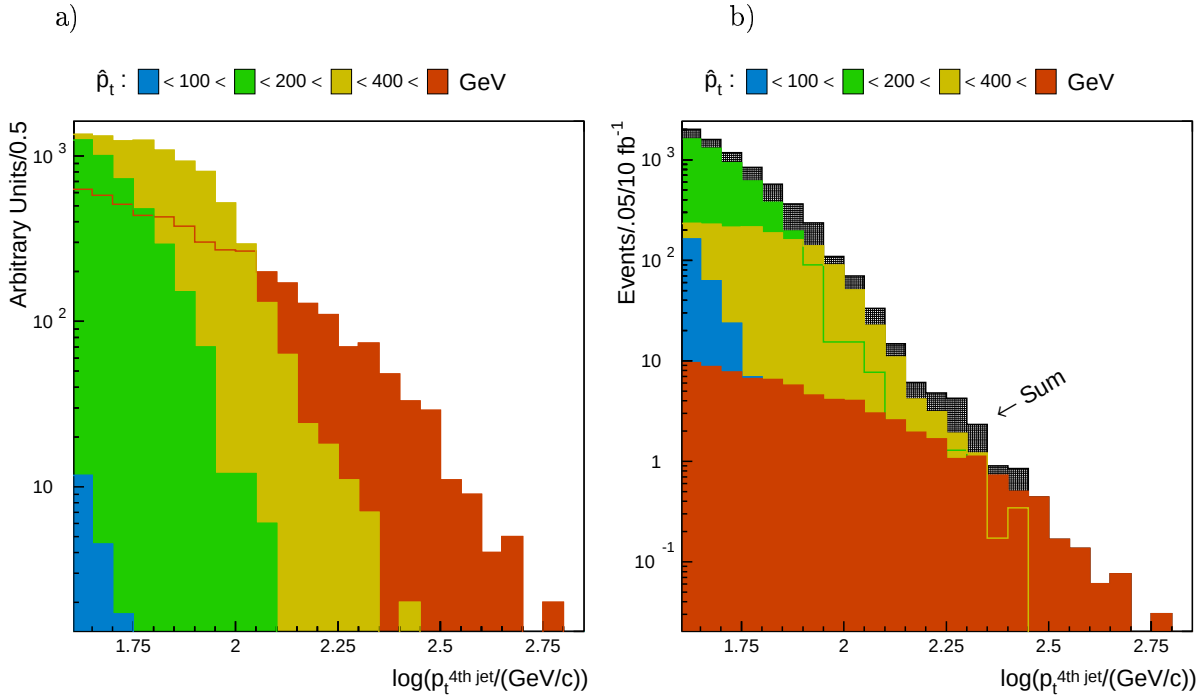


Figure 4.12: The p_t^{4j} distribution for WW production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

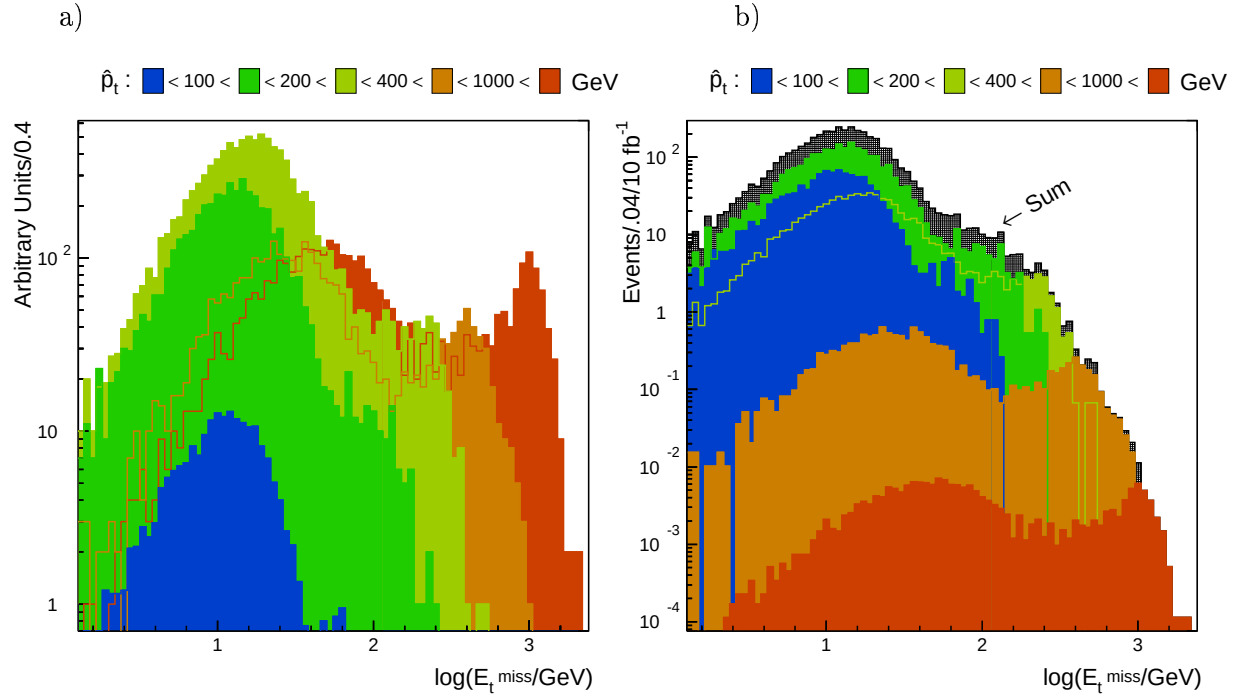


Figure 4.13: The $\cancel{E}_t$ distribution for WZ production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

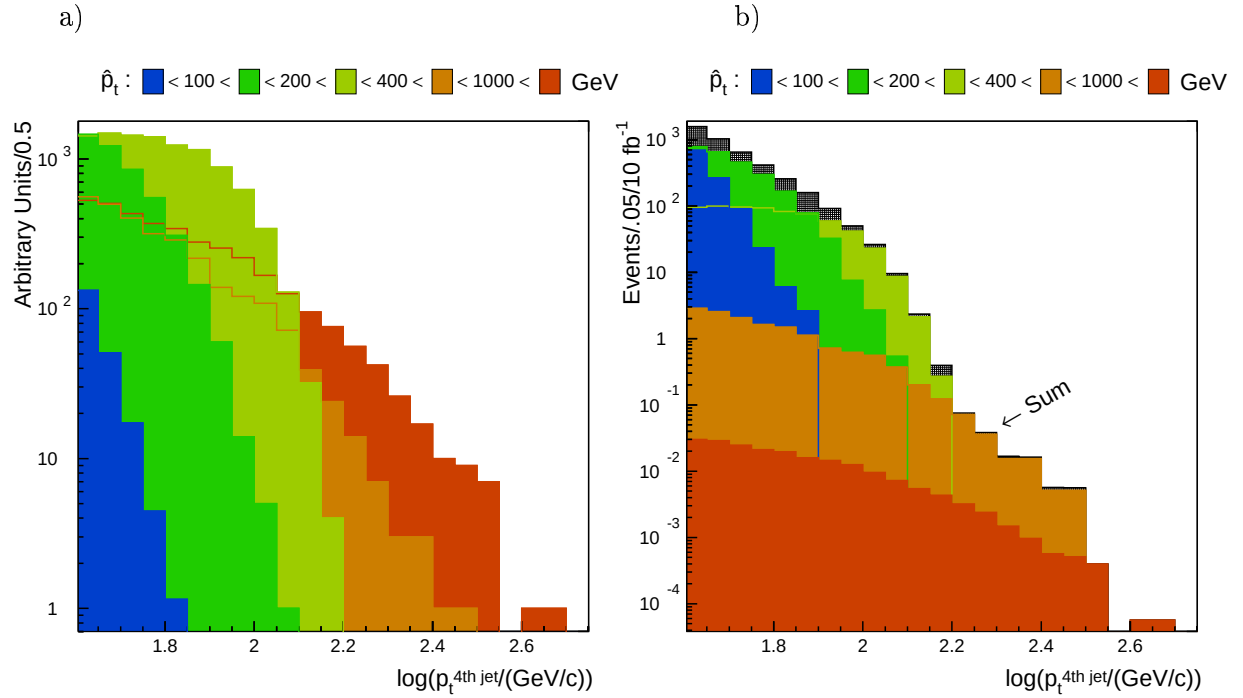


Figure 4.14: The p_t^{4j} distribution for WZ production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

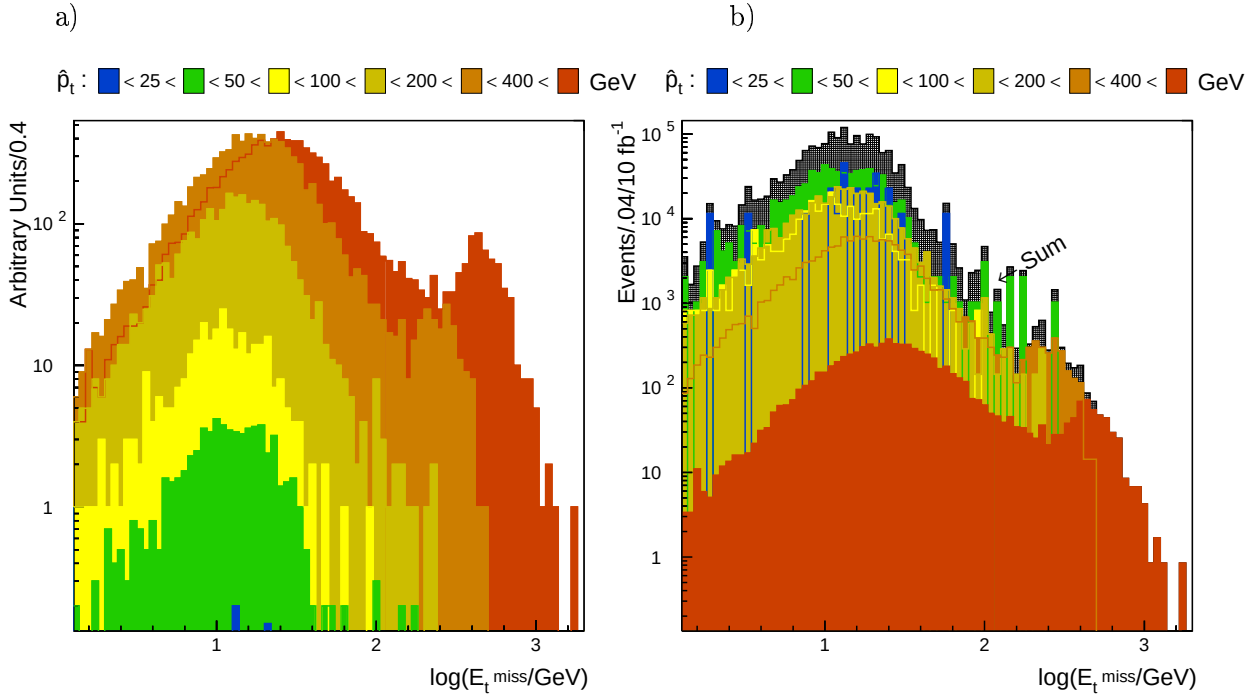


Figure 4.15: The $\cancel{E}_t$ distribution for Z production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

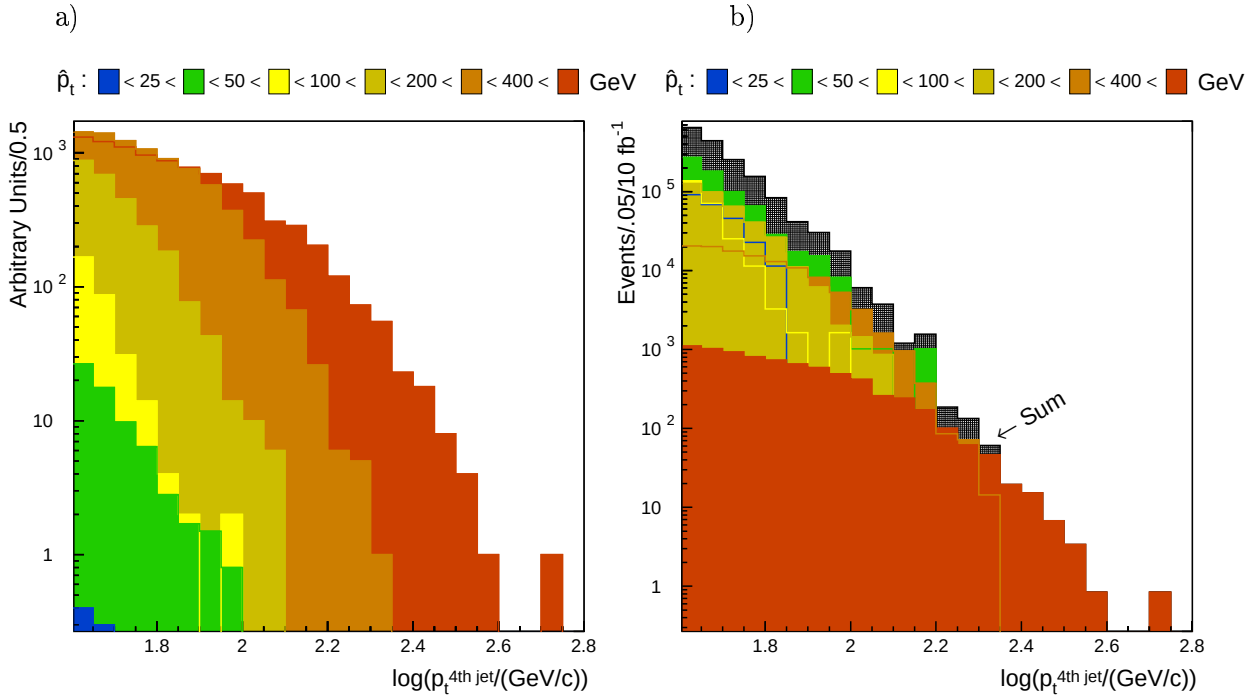


Figure 4.16: The p_t^{4j} distribution for Z production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

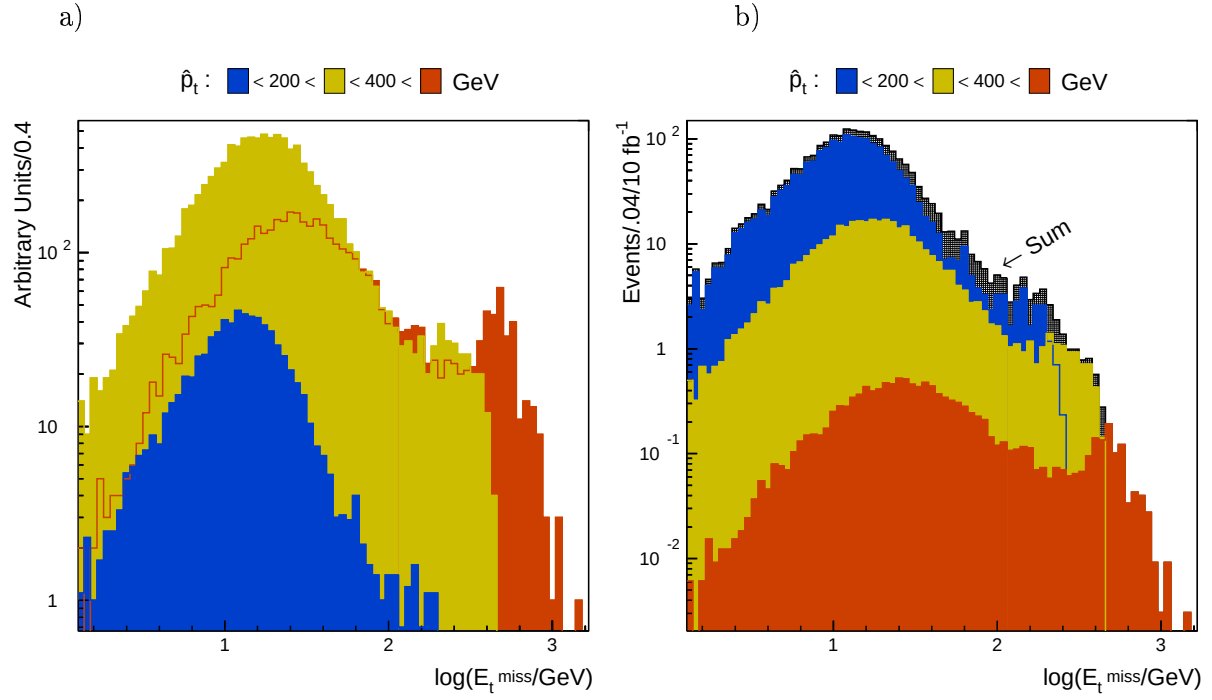


Figure 4.17: The $\cancel{E}_t$ distribution for ZZ production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

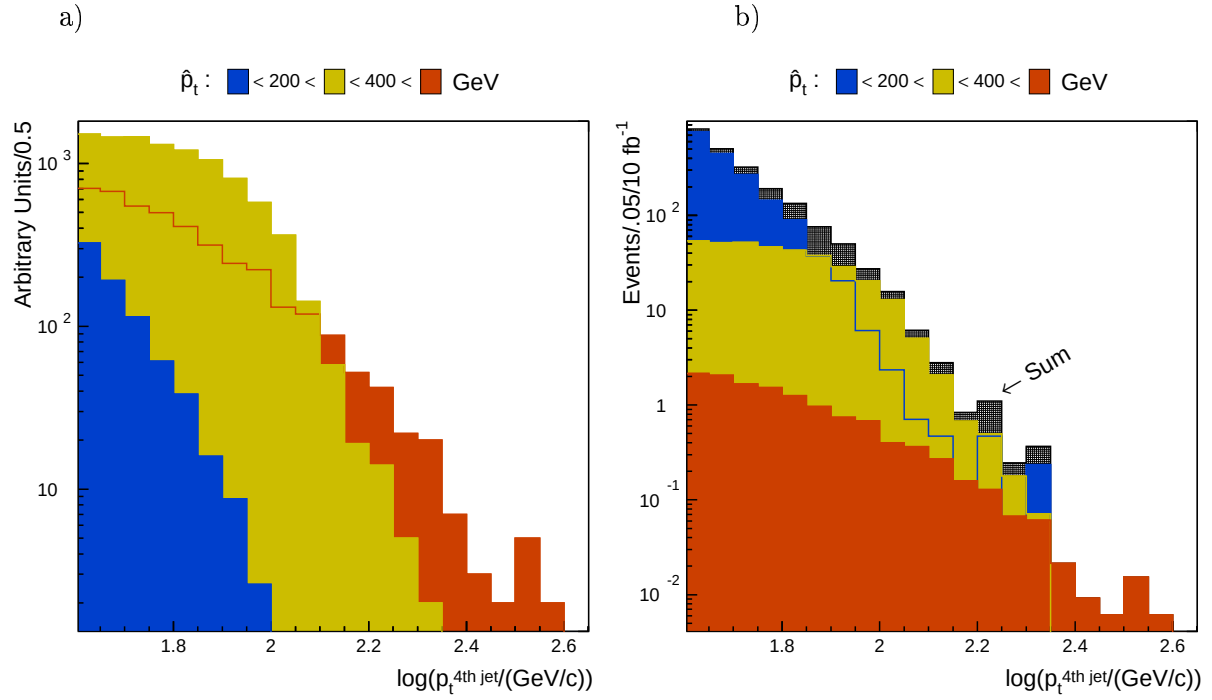


Figure 4.18: The p_t^{4j} distribution for ZZ production as a sum of the $\hat{p}_t$ intervals. Left: raw data. Right: samples weighted by the cross sections.

On the left side of each Figure 4.1 – 4.18, raw distributions are shown, whereas on the right side the distributions are weighted by the partial cross sections to provide an appropriate contributions to total cross section.

The CUT1 eliminates majority of low $\hat{p}_t$ background, as can be seen from Figures. Remainder, however, was potentially harmful, because – after weighting by the cross-section – it could give spikes in the final distributions. The example of such effect can be seen in Figure 4.1, where single minimum bias event around $\cancel{E}_t \sim 10$ GeV, from the interval $\hat{p}_t < 10$ GeV/c, dominated the rate in the summary (right) plot. Because of such effects some intervals were simulated with much higher statistics than the others (see Table 4.1).

The total background is given by the sum of all processes. The cumulative distribution of missing energy for the total background is shown in Figure 4.19, with only CUT0 criterion (at least one hard object in the event) on the left side and with CUT1 requirement on the right.

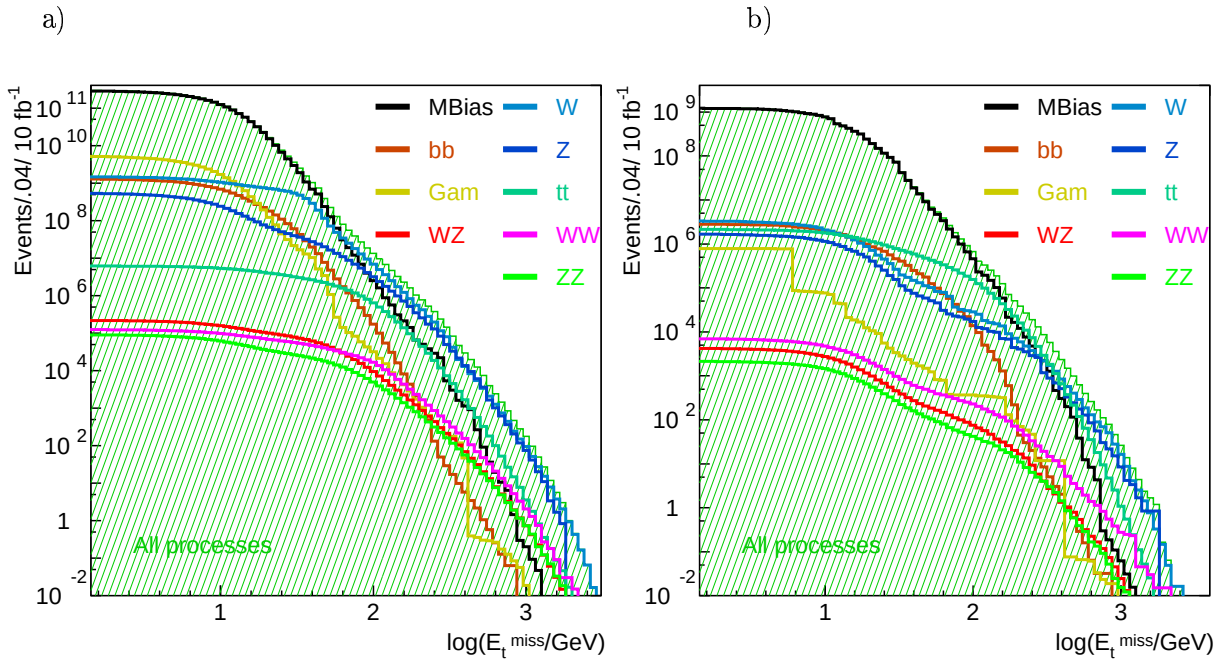


Figure 4.19: The Standard Model contributions to the total background, $\cancel{E}_t$ distributions.

Left: after CUT0 only. Right: after CUT1

The cumulative distribution of the transverse momentum of the fourth most energetic jet is shown on the left side of the Figure 4.20. On the right side of that figure additional requirement was applied, called:

- **CUT2:** $\cancel{E}_t > 200$ GeV

The CUT2 reduces the background rate by a factor of 10^6 with respect to the rate with the requirement of the reconstruction of at least one hard object in the event (CUT0).

In addition to already defined CUT0 (p.29), CUT1 (p.29) and CUT2 (p.40), the following cuts were applied to further background reduce:

- **CUT3:** $p_t^{4j} > 80$ GeV/c
- **CUT4:** at least 2 opposite sign leptons with $p_t > 20$ GeV/c

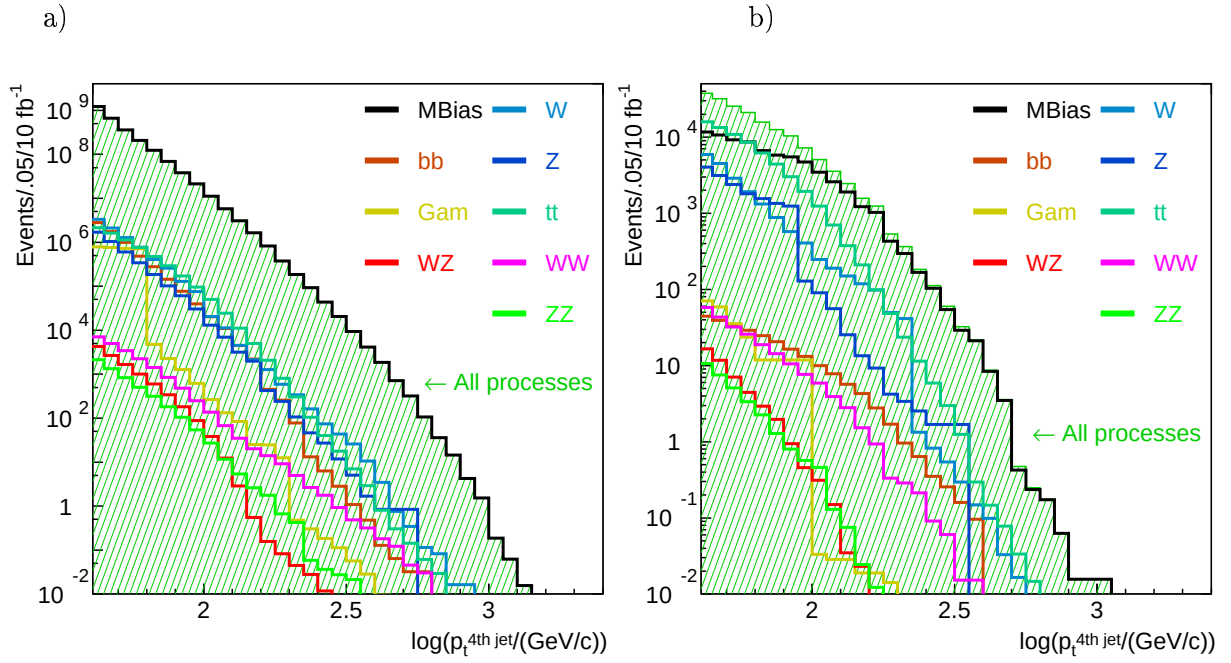


Figure 4.20: The Standard Model contributions to the total background, p_t^{4j} distributions. Left: after CUT1. Right: after CUT2.

All the kinematical cuts are summarized in Table 4.2. Their efficiency of for the SM background suppression is giving by the number of events remaining after the cut in Table 4.3.

No. of CUT	Requirements:		
	object	p_t range [GeV/c]	$ \eta $ range
CUT 0	electron	> 20	< 2.4
	muon	> 20	< 2.4
	gamma	> 20	< 2.4
	jet	> 40	< 4.5
CUT 1	at least 4 jets	> 40	< 4.5
CUT 2	transverse missing energy	$\cancel{E}_t > 200$ GeV	
CUT 3	4th jet	$p_t^{4j} > 80$	
CUT 4	2 other sign leptons	> 20	< 2.4

Table 4.2: Summary of kinematical cuts. The cuts (2÷4) include all the previous ones.

Background Type	low luminosity case: $\mathcal{L} = 10/\text{fb}$					
	Number of Events after:					
	no CUTs	CUT0	CUT1	CUT2	CUT3	CUT4
min. bias	$(6.770 \pm .003) \cdot 10^{+14}$	$(2.914 \pm .015) \cdot 10^{+11}$	$(1.22 \pm .11) \cdot 10^{+9}$	$(1.13 \pm .18) \cdot 10^{+4}$	$(3.1 \pm 0.1) \cdot 10^{+3}$	198 ± 16
$b\bar{b}$	$(8.019 \pm .004) \cdot 10^{+12}$	$(1.302 \pm .012) \cdot 10^{+09}$	$(2.82 \pm .16) \cdot 10^{+6}$	$(4.44 \pm .01) \cdot 10^{+1}$	7.4 ± 0.5	$1.6 \pm .2$
γ	$(3.462 \pm .002) \cdot 10^{+12}$	$(7.97 \pm .06) \cdot 10^{+09}$	$(8.4 \pm 6.9) \cdot 10^{+5}$	$(1.06 \pm .35) \cdot 10^{+2}$	12 ± 12	$.014 \pm .008$
$t\bar{t}$	$(6.22 \pm .02) \cdot 10^{+06}$	$(6.19 \pm .02) \cdot 10^{+06}$	$(2.15 \pm .13) \cdot 10^{+6}$	$(1.59 \pm .03) \cdot 10^{+4}$	$(1.11 \pm .04) \cdot 10^{+3}$	128 ± 10
W	$(6.09 \pm .08) \cdot 10^{+09}$	$(1.490 \pm .004) \cdot 10^{+09}$	$(3.33 \pm .15) \cdot 10^{+6}$	$(5.91 \pm .38) \cdot 10^{+3}$	218 ± 50	$.25 \pm .06$
WW	$(7.68 \pm .01) \cdot 10^{+05}$	$(1.25 \pm .04) \cdot 10^{+05}$	$(7.03 \pm .08) \cdot 10^{+3}$	$(5.81 \pm .35) \cdot 10^{+1}$	3.9 ± 0.7	$.18 \pm .05$
WZ	$(2.927 \pm .003) \cdot 10^{+05}$	$(2.21 \pm .03) \cdot 10^{+05}$	$(4.26 \pm .04) \cdot 10^{+3}$	$(1.66 \pm .14) \cdot 10^{+1}$	$(.25 \pm .10) \cdot 10^{-2}$	$.011 \pm .007$
Z	$(1.197 \pm .001) \cdot 10^{+10}$	$(5.42 \pm .02) \cdot 10^{+08}$	$(1.69 \pm .06) \cdot 10^{+6}$	$(4.0 \pm 1.1) \cdot 10^{+3}$	75 ± 21	5.9 ± 2.2
ZZ	$(1.194 \pm .002) \cdot 10^{+05}$	$(9.128 \pm .015) \cdot 10^{+04}$	$(2.15 \pm .02) \cdot 10^{+3}$	$(1.06 \pm .08) \cdot 10^{+1}$	$(.43 \pm .25) \cdot 10^{-2}$	$.009 \pm .005$
SM total	$(6.885 \pm .003) \cdot 10^{+14}$	$(3.027 \pm .015) \cdot 10^{+11}$	$(1.23 \pm .12) \cdot 10^{+9}$	$(3.72 \pm .21) \cdot 10^{+4}$	$(4.5 \pm 0.1) \cdot 10^{+3}$	334 ± 19

Table 4.3: The SM background sensitivity to the kinematical set of cuts defined in Table 4.2.

Columns give the number of event which remains after a given cut.

4.2 Signal generation

Two classes of signal are considered, GMSB models with the short-lived NLSP:

- with neutralino $\tilde{N}_1$ as the NLSP

and

- with stau $\tilde{\tau}_1$ as the NLSP.

A dozen of different GMSB models was generated by ISAJET 7.53 [85] (see Sec. 5.1). The detector response was simulated using CMSJET 4.703 [84].

The CMSJET is the fast non-GEANT simulation of the CMS detector oriented on the SM physics and Beyond the SM studies. Program has interfaces to PYTHIA, ISAJET or HERWIG generators. The helix parametrization is used to the 4 Tesla magnetic field retracing. Energy is smeared according to the GEANT simulation with respect to full granularity of calorimeters: HCAL, ECAL and VFCAL. Electromagnetic and hadron showers are longitudinally and transversally parametrized. There are special routines for the best lepton/gamma/ π^0 treatment. Momenta in the tracker and in the muon system relates $\Delta p_t/p_t$ distribution (MS in Sec. 2.3, Tracker in Sec. 2.5). Cone (CDF) and chain-like (UA2) finders with merging and splitting are used to shape jets. Dead cells and towers of subdetector are included to provide the best approximation to the CMS detector. The pile-up can be added to the signal. In the thesis, the low luminosity LHC run was considered with no pile-up. The CMSJET performs the *full* but *fast* events reconstruction and the missing transverse energy $\cancel{E}_t$ calculation.

For the clarity only ten selected GMSB models,⁴ listed in Tables 4.4 and 4.5 are presented. First Table refers to the set of GMSB models in which neutralino $\tilde{N}_1$ is the NLSP, in the second Table include GMSB models in which stau $\tilde{\tau}_1$ plays the role of the NLSP.

GMSB	Λ [TeV]	M [TeV]	N^* sgn(μ)	$\tan \beta$	$m_{\tilde{N}_1}$ [GeV/c ²]	$m_{\tilde{\tau}_1}$ [GeV/c ²]	$m_{\tilde{u}_L}$ [GeV/c ²]	σ [pb]	edge [GeV/c ²]
GMSB 1	70	630	1	1.5	89	124	754	2810	81
GMSB 2	80	96	-1	15	123	134	891	1420	84
GMSB 3	120	228	-1	10	169	207	1281	322	141
GMSB 4	160	256	1	7	230	275	1678	68	180
GMSB 5	200	380	1	3	281	364	2054	19	231

Table 4.4: The parameters of selected GMSB models with $\tilde{N}_1$ as the NLSP.

4.3 Kinematical selection

The effects of kinematical cuts can be noticed in Figures: 4.21, 4.22, 4.23 (the $\tilde{N}_1$ -NLSP case) and Figures: 4.24, 4.25, 4.26 (the $\tilde{\tau}_1$ -NLSP case). Models are denoted by appropriate colour lines. The total SM background is drawn with the black line. The preselection, called CUT0, has already eliminated a large amount of low p_t processes, as it was mentioned above. All plotted

⁴ Models were chosen in regard to the *edge* observable explained in Chap. 5

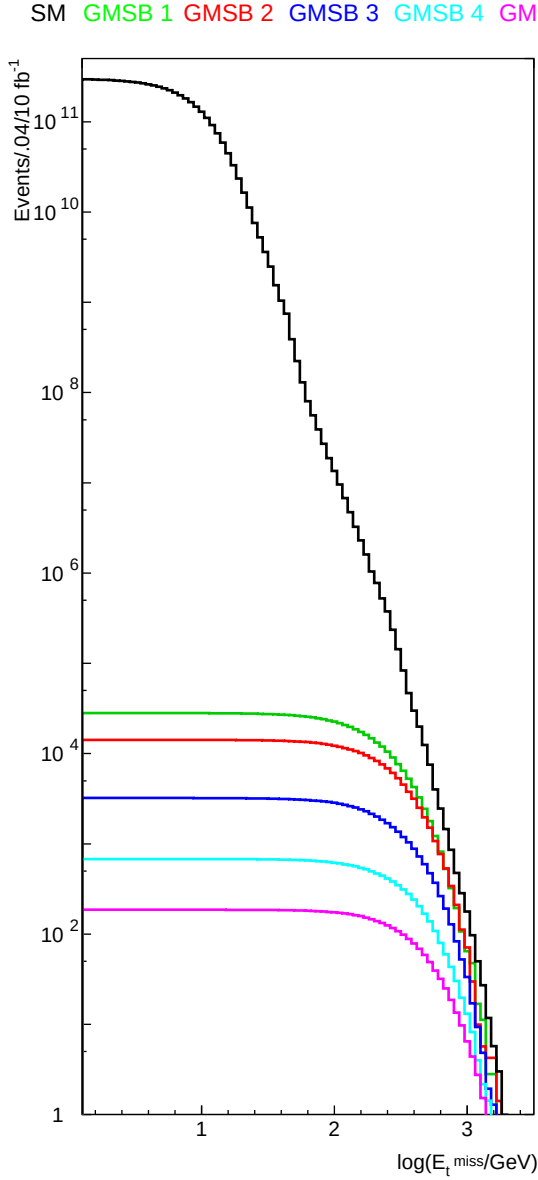


Figure 4.21: The cumulative E_t^{miss} distribution after CUT0 for models listed in Table 4.4 and background.
GMSB models with $\tilde{N}_1$ as the NLSP.

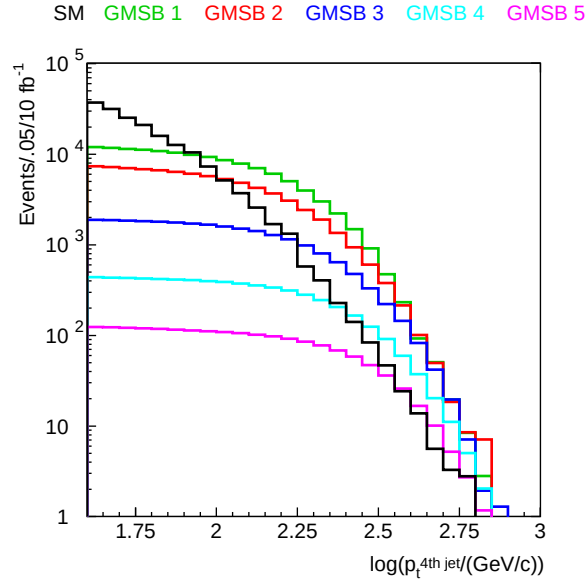


Figure 4.22: The cumulative p_t^{4j} distribution after CUT2 for models listed in Table 4.4 and background.
GMSB models with $\tilde{N}_1$ as the NLSP.

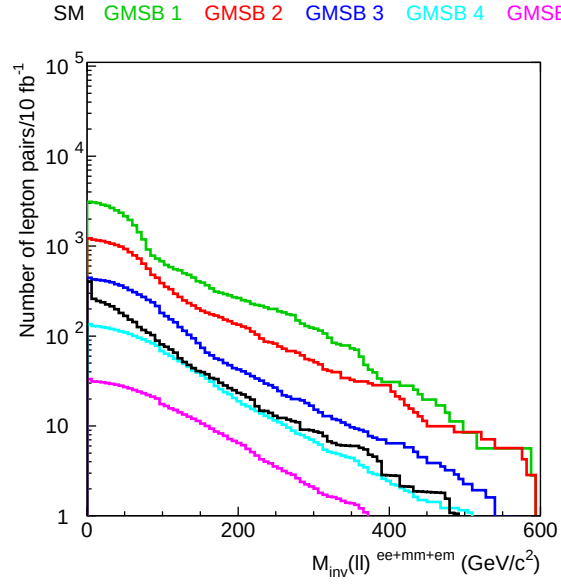


Figure 4.23: The cumulative difference of invariant mass distribution of the same and different flavour pair of leptons of opposite signs after CUT4 for models listed in Table 4.4 and background.
GMSB models with $\tilde{N}_1$ as the NLSP.

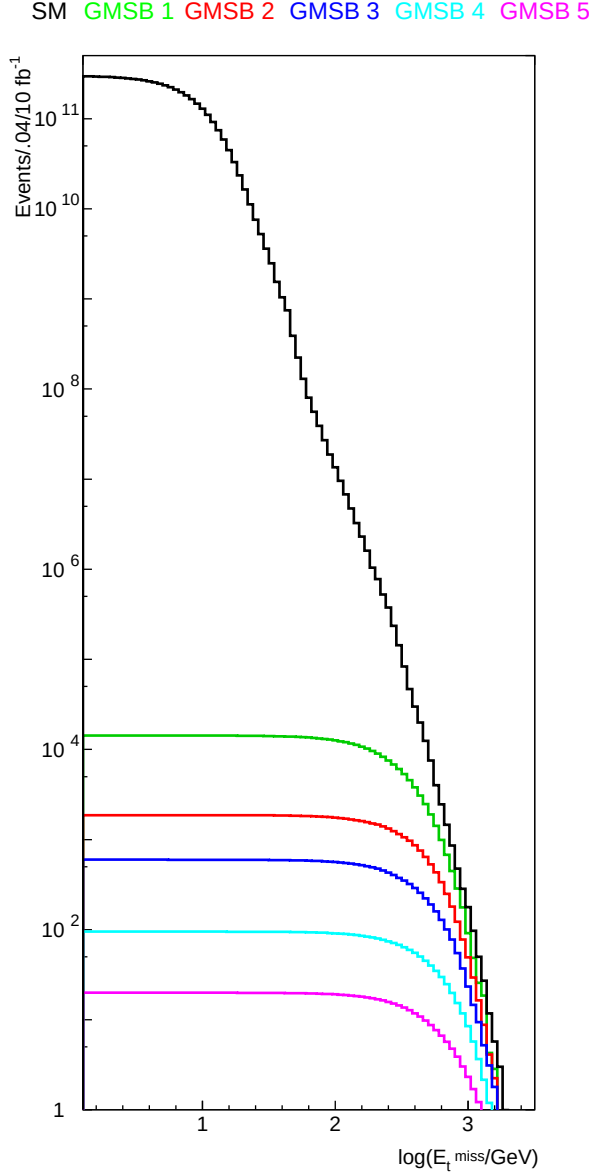


Figure 4.24: The cumulative E_t^{miss} distribution after CUT0 for models listed in Table 4.5 and background.
GMSB models with $\tilde{\tau}_1$ as the NLSP.

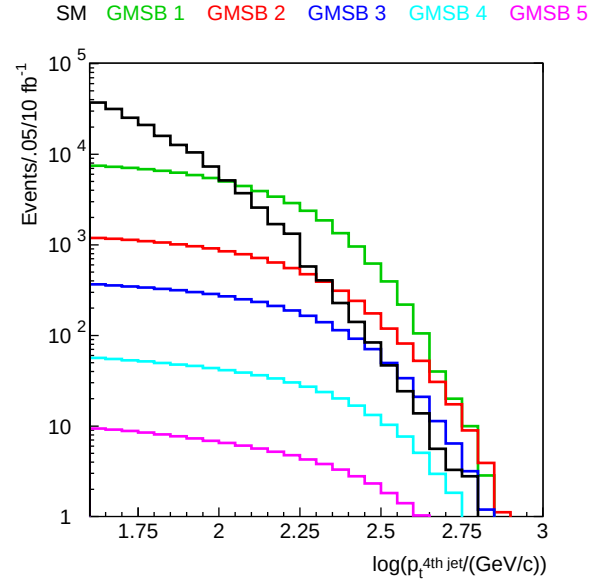


Figure 4.25: The cumulative p_t^{4j} distribution after CUT2 for models listed in Table 4.5 and background.
GMSB models with $\tilde{\tau}_1$ as the NLSP.

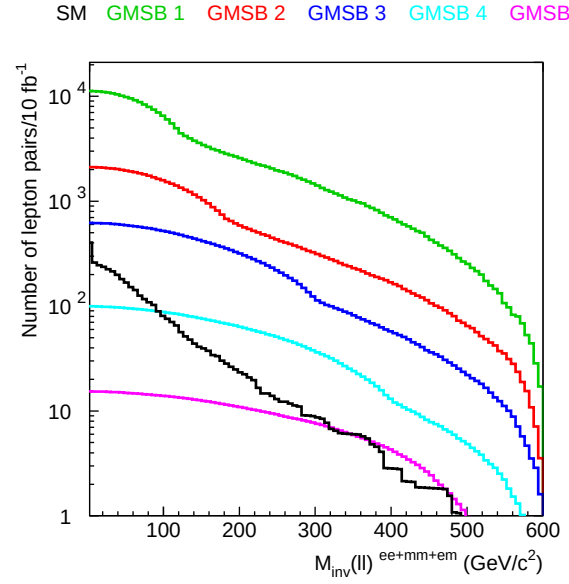


Figure 4.26: The cumulative difference of invariant mass distribution of the same and different flavour pair of leptons of opposite signs after CUT4 for models listed in Table 4.5 and background.
GMSB models with $\tilde{\tau}_1$ as the NLSP.

GMSB	Λ [TeV]	M [TeV]	N^* sgn(μ)	$\tan \beta$	$m_{\tilde{N}_1}$ [GeV/c ²]	$m_{\tilde{\tau}_1}$ [GeV/c ²]	$m_{\tilde{u}_L}$ [GeV/c ²]	σ [pb]	edge [GeV/c ²]
GMSB 1	30	120	-4	2	165	111	781	1400	122
GMSB 2	60	114	-3	2	257	183	1247	190	180
GMSB 3	70	73.5	-3	3	365	207	1466	60	300
GMSB 4	80	104	4	2	490	283	1957	9.5	400
GMSB 5	90	306	5	2	621	366	2447	2	501

Table 4.5: The parameters of selected GMSB models with $\tilde{\tau}_1$ as the NLSP.

distributions are cumulative – integrated in a way that gives the number of events remaining after cut for a given value. The flatter distribution the less sensitive to the cut.

Picture 4.21 and picture 4.24 present the transverse missing energy $\cancel{E}_t$ distribution after the CUT0. On a large range of $\cancel{E}_t$ the GMSB curves are flat whereas the SM background rate falls by several orders of magnitude. As a compromise between loosing signal and reducing background the defined before CUT2 was set to be $\cancel{E}_t > 200$ GeV, ($\log(\cancel{E}_t/\text{GeV}) > 2.3$).

Figure 4.22 and Figure 4.25 are drawn after the application of the CUT2. Again, the GMSB curves are flat for low values of p_t^{4j} , whereas SM curve falls continuously. By setting the CUT3 at $p_t^{4j} > 80$ GeV/c (e.i. $\log(p_t^{4j}/(\text{GeV}/c)) > 1.6$) one can decrease the level of background by another factor of ten. Is is due to the fact that supersymmetric cascades are usually rich in jets.

It is clear from there Figures, that by cutting harder on transverse momentum of the 4th jet p_t^{4j} e.g. $p_t^{4j} > 250$ GeV/c (e.i. $\log(p_t^{4j}/(\text{GeV}/c)) > 2.4$), one can obtain 5σ significance of the supersymmetry signal for GMSB models with cross-section at least at the level of 50 pb. Those models are GMSB 4 from the Table 4.4 (Fig. 4.22) and GMSB 3 from the Table 4.5 (Fig. 4.25). It means that GMSB models with squark masses of the order of 1.5 TeV/c² can be discovered using only $\cancel{E}_t$ and p_t^{4j} as the selection variables.

Instead of cutting so hard on the transverse momentum of the fourth jet one can impose some kind of requirements concerning the searched decay chain. An example is shown in the Figure 4.23 (Figure 4.26). As can be seen from the Figures, the requirement of a presence of a pair of sufficiently energetic leptons of opposite signs allows for discovering all models. For models (e.g. GMSB's 5) for which only few dozens of events expected at the preselection level (CUT0) an excess of events above the SM prediction can be achieved.

The model survival against cuts is demonstrated in Table 4.3 for GMSBs with the $\tilde{N}_1$ NLSP and in Table 4.3 for GMSBs with the $\tilde{\tau}_1$ NLSP. Because of direrences in kinemtics between those types of models set of cut work better (about three times) for stau-like models then neutralino-like GMSBs.

In next Chapter the analysis of the supersymmetry search will be presented, and the main observable – an end-point from the combined invariant mass distribution of lepton pairs will be explained.

GMSB $\tilde{N}_1$ NLSP	N _{gen} = 10 k low luminosity case: $\mathcal{L} = 10/\text{fb}$ Efficiency $eff_i = \frac{\text{N after CUT}_i}{N_{\text{total}}}$						
	no CUTs	eff_0	eff_1	eff_2	eff_3	eff_4	S/ $\sqrt{B}$
GMSB 1	28130 $\pm$ 280	1.00	.920	.425	.218	.068	105
GMSB 2	14200 $\pm$ 140	1.00	.903	.518	.268	.051	40
GMSB 3	3220 $\pm$ 30	1.00	.949	.586	.371	.079	14
GMSB 4	680 $\pm$ 7	1.00	.937	.645	.433	.101	4.0
GMSB 5	22.7 $\pm$ 0.2	.995	.648	.560	.350	.732	.09

Table 4.6: GMSB models with the $\tilde{N}_1$ NLSP from Table 4.4. Their sensitivity to the kinematical set of cuts defined in Table 4.2. Columns give the fraction of events which remains after a given cut. The last column shows the conventionally defined significance for the signal S and the SM background B.

GMSB $\tilde{\tau}_1$ NLSP	N _{gen} = 10 k low luminosity case: $\mathcal{L} = 10/\text{fb}$ Efficiency $eff_i = \frac{\text{N after CUT}_i}{N_{\text{total}}}$						
	no CUTs	eff_0	eff_1	eff_2	eff_3	eff_4	S/ $\sqrt{B}$
GMSB 1	14280 $\pm$ 140	1.00	.834	.524	.255	.222	172
GMSB 2	1870 $\pm$ 20	1.00	.808	.637	.340	.304	32
GMSB 3	598 $\pm$ 6	1.00	.759	.611	.339	.301	10
GMSB 4	95 $\pm$ 1	.998	.682	.591	.332	.296	1.5
GMSB 5	20.0 $\pm$ 0.2	.998	.519	.469	.254	.226	.23

Table 4.7: GMSB models with the $\tilde{\tau}_1$ NLSP from Table 4.5. Their sensitivity to the kinematical set of cuts defined in Table 4.2. Columns give the fraction of events which remains after a given cut. The last column shows the conventionally defined significance for the signal S and the SM background B.

Chapter 5

Visibility of the leptonic edge signature

Cascade decays of heavy particles are characteristic features of supersymmetry. In several regions of SUSY parameter space sparticles manifest themselves by presence of end-points in some kinematic distributions. One of the most spectacular signals of that kind is the edge in the invariant mass distributions of the same and different flavour pairs of electrons and muons: $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$.

In the SUGRA models, the edge is due to the heavier neutralino decay into the pair slepton-lepton and successively slepton into lepton and lighter neutralino (e.g. at the SUGRA Point 5 [86] the decay chain is $q_L \rightarrow \tilde{N}_2 q \rightarrow \tilde{l}_R^\pm l^\mp q \rightarrow \tilde{N}_1 l^+ l^- q$).

Within Gauge Mediated Supersymmetry Breaking models the origin of such signature depends on the NLSP nature. If neutralino is the NLSP, then the situation is the same as in SUGRA models apart from the fact, that NLSP can decay into gravitino and standard model NLSP partner. If slepton plays the role of the NLSP, the signal is due to cascade decays of neutralino via NLSP slepton to gravitino.

Detection of such edge allows for precise determination of the mass differences of relevant neutralinos taking part in the decay chain. The end-point is regarded as a *golden* signature of the supersymmetry. However, it is not clear, if leptonic edge exists and/or it could be detected in randomly chosen model, namely the supersymmetric model which hopefully appears in Nature.

In present Chapter, as far as the GMSB models are concerned, a systematic search for leptonic edges in the CMS detector will be provided via scan over wide range of parameter space of the GMSB models [87].

5.1 Wide simulation of GMSB models

The GMSB models were simulated using the Monte Carlo program ISAJET 7.53. [85].

ISAJET is based on perturbative quantum chromodynamics (QCD) and phenomenological models for parton and beam jet fragmentation. The program incorporates a package ISASUSY for the supersymmetry calculation of sparticles masses and their branching ratios in terms of the MSSM parameters. In peculiarity, using ISAJET one can specify different supersymmetric frameworks: SUGRA, GMSB, AMSB, RPV, Technicolor or Extra-Dimension models with limited number of parameters. Technically, those parameters are translated into MSSM ones.

The GMSB routine needs five parameters (defined at page 24):

$$N, \quad \Lambda = F/M, \quad M, \quad \tan\beta, \quad \text{sign}(\mu)$$

and additional parameter C_{grav} which defines the ratio of gravitino mass to its mass at scale

of the SUSY breaking F . Effectively, $C_{grav} \geq 1$ is used to verified the gravitino mass and the lifetime of the NLSP. Here, the minimal-GMSB case was assumed with $C_{grav} = 1$.

A custom made interface allowed to generate a large sample of GMSB models at once with limited number of events per one model. The knowledge of sparticle mass hierarchy, branching ratios and (total and partial) cross-sections was sufficient.

Almost 90,000 models were generated in following range of parameters:

- $N = 1, 2, 3, 4, 5$ of equivalent number of messenger field representation is possible,
- Λ : from 30 TeV to 1000 TeV, with the 10 TeV step in between 30–160 TeV and 20 TeV 160 TeV,
- M/Λ from 1.1 to $< 10^3$,
- $\tan\beta \in (1.5, 60)$, discrete values were chosen: 1.5, 1.7, 2, 3, 5, 7, 10, 15, 20, 30, 40, 55,
- $\text{sign}(\mu) = +1$ or $\text{sign}(\mu) = -1$.

5.2 The origin of the leptonic edge

A leptonic edge is the name for an abrupt drop in the difference of invariant mass distributions of the same and different flavour lepton pairs:

$$\mu^+\mu^- + e^+e^- - \mu^+e^- - e^+\mu^-.$$

An example of it is shown in Figure 5.1. Decay chains generating such end-point start from one of the neutralino which decays to a slepton and their antilepton partner. Then slepton decays to its SM partner (lepton) and a sfermion (neutralino or gravitino). Direct three-body decays of neutralino, in which case slepton is virtual, to a sfermion and lepton-antilepton pair are also possible.

The hierarchy of masses or, equivalently, the NLSP type determines the sign and flavour of the last fermion in the cascade. In GMSB models two cases are differentiated:

Case 1: if $\tilde{N}_1$ is the NLSP then sparticle decay chain ends on:

$$\begin{array}{lcl} \tilde{N}_2 \rightarrow \tilde{\ell}_R + \bar{\ell} & \text{or} & \tilde{N}_2 \rightarrow \tilde{N}_1 + \ell\bar{\ell} \\ \tilde{\ell}_R \rightarrow \tilde{N}_1 + \ell & & \end{array}$$

Case 2: if $\tilde{\tau}_1$ is the NLSP (or sleptons¹ and stau are degenerated in so-called the co-NLSP state) then the sparticle decay chain end on gravitino:

$$\begin{array}{lcl} \tilde{N}_1 \rightarrow \tilde{\ell}_R + \bar{\ell} & \text{or} & \tilde{N}_1 \rightarrow \tilde{G} + \ell\bar{\ell} \\ \tilde{\ell}_R \rightarrow \tilde{G} + \ell & & \end{array}$$

Two body decays prevail over the three body decays, which have negligible branching ratios. The evidence of the case 2 edge is qualified by the lifetime of the NLSP. It exists if stau is short-lived (topology T1 : Sec.1.1). In case 1, the neutralino $\tilde{N}_1$ lifetime has no influence on end-point existence. Technically, the study has been performed for models with very light gravitino, in which the NLSP immediately decays.

The position of the end-point in the invariant mass of pair of leptons is given by the following formulas:

¹ Here, sleptons are lighter selectrons $\tilde{e}_R$ and smuons $\tilde{\mu}_R$.

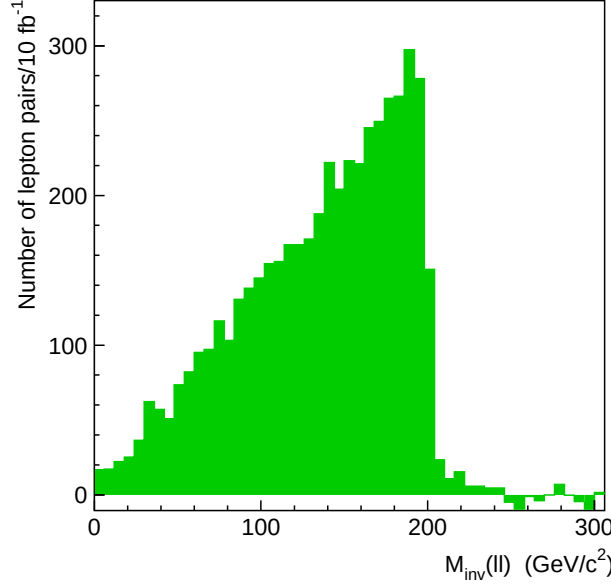


Figure 5.1: The difference of the invariant mass distributions of the same and different flavour lepton pairs: $\mu^+\mu^- + e^+e^- - \mu^+e^- - e^+\mu^-$. There is only the signal and no SM background. Only the detector acceptance cuts are applied. (GMSB: $\Lambda = 40$ TeV, $M = 52$ TeV, $N \cdot \text{sign}(\mu) = -4$, $\tan\beta = 2$.)

case 1, an end-point of type 1:

$$M_{\text{inv}}(\ell\bar{\ell})_1 = \frac{\sqrt{m_{N_2}^2 - m_{\tilde{\ell}_R}^2} \sqrt{m_{\tilde{\ell}_R}^2 - m_{N_1}^2}}{m_{\tilde{\ell}_R}}, \quad (5.1)$$

case 2, an end-point of type 2:

$$M_{\text{inv}}(\ell\bar{\ell})_2 = \sqrt{m_{N_1}^2 - m_{\tilde{\ell}_R}^2}. \quad (5.2)$$

Detection of the end-point allows for determination of constraints on masses of these sparticles.

5.2.1 Sleptons degeneracy

The observability of the leptonic end-point depends mainly on one feature of the given GMSB model. It is heavily affected by the degeneracy of sleptons. In the first approximation, right sleptons (staus, smuons, sleptons) are degenerate, because they share the same SM Yukawa couplings, what provides adequate formula (Eq. 3.6). However, the left-right mixing in third generation of sfermions is substantial, (Appendix A.1). The mixing is mainly affected by supersymmetric Higgs sector, represented by the ratio of v.e.v's $\tan\beta$ and mixing parameter μ . Left-right staus $\tilde{\tau}_L$, $\tilde{\tau}_R$ evolve to mass eigenstates: lighter $\tilde{\tau}_1$ and heavier $\tilde{\tau}_2$.

It is shown in Figure 5.2, which depicts relations between $\tilde{\mu}_R$ and $\tilde{e}_R$ masses and $\tilde{\tau}_1$ mass as a function of the model parameters $\tan\beta$, Λ and M/Λ , for both sign of $\text{sign}(\mu)$ in $N = 3$ GMSB models. The similar dependence is for other values of parameter N . In the upper-left part of the picture, where μ is positive, the $\tilde{\tau}_1$ mass is given on the horizontal axis, whereas in the lower-right part ($\mu < 0$) on the vertical one. This was done in order to exhibit the symmetry

to the $\text{sign}(\mu)$ if it exists. As one can see the $\text{sign}(\mu)$ symmetry between is not complete. It is especially apparent for large $\tan\beta = 55$, where $\text{sign}(\mu) = -1$ models have lost self-consistency and only $\text{sign}(\mu) = +1$ are allowed. Substantial stau mixing can be observed for models with large values of $\tan\beta$, especially for large values of M/Λ .

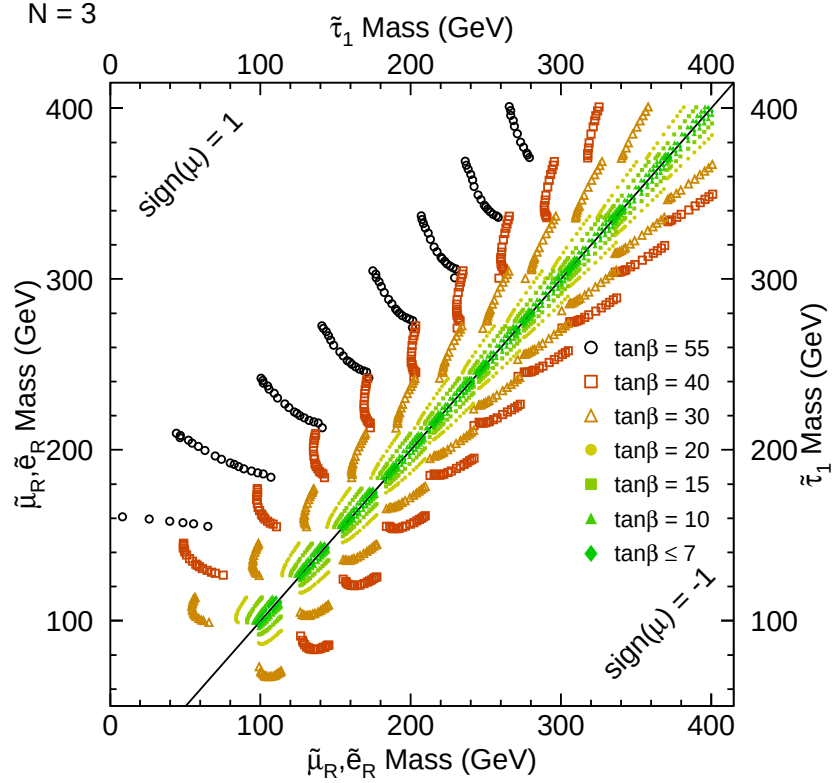


Figure 5.2: The dependence of the relation between sleptons and stau masses on $\tan\beta$, Λ and M/Λ for $N = 3$ and $\text{sign}(\mu) = \pm 1$. In the upper-left part of the picture $\tilde{\tau}_1$ mass is given on the horizontal axis, whereas in the lower-right part ($\text{sign}(\mu) = \pm 1$) on the vertical one. Different values of $\tan\beta$ are shown with different markers. Models with the same $\tan\beta$ form colour branches. Parameter Λ grows from the left-bottom to the right-top part of Figure, so groups of $\tan\beta$ branches reduplicate if masses are growing up. Each branch consist of points representing models differing only by the value of M/Λ parameters. Values of M/Λ increase symmetrically from the middle to outside. The higher the M/Λ ratio the higher the level of slepton degeneracy.

5.2.2 Neutralino Branching ratios

Slepton degeneracy determine the extent of neutralino decays into sleptons. This is necessary for the edge existence. Then, approximately, the following ratios are the same:

$$\text{BR}_1(\tilde{N}_1 \text{ or } 2 \rightarrow \tilde{\tau}_1 \tau) \approx \text{BR}_2(\tilde{N}_1 \text{ or } 2 \rightarrow \tilde{\mu}_R \mu) \approx \text{BR}_3(\tilde{N}_1 \text{ or } 2 \rightarrow \tilde{e}_R e).$$

Only in that case production of smuons and selectrons can be enhanced making the leptonic edge visible. To be mode specified, one needs to consider slepton mixing and neutral gaugino mixing (Appendix A.1, A.3)

For models with the NLSP stau $\tilde{\tau}_1$, the lightest neutralino $\tilde{N}_1$ behavior is crucial. It was check that $\tilde{N}_1$ decays (dominantly, other decays are negligible) only to sleptons and all branching ratios

sum up to 1:

$$\text{BR}_1(\tilde{N}_1 \rightarrow \tilde{\tau}_1 \tau) + \text{BR}_2(\tilde{N}_1 \rightarrow \tilde{\mu}_R \mu) + \text{BR}_3(\tilde{N}_1 \rightarrow \tilde{e}_R e) = 1.$$

Figure 5.3 shows for which GMSB parameters, ratios: BR_1 , BR_2 , BR_3 are at the same level. In that Figure the variable defined as follows:

$$\text{ratio BRs} = \frac{\text{BR}_2(\tilde{N}_1 \rightarrow \tilde{\mu}_R \mu) + \text{BR}_3(\tilde{N}_1 \rightarrow \tilde{e}_R e)}{\text{BR}_1(\tilde{N}_1 \rightarrow \tilde{\tau}_1 \tau)}, \quad (5.3)$$

is shown. With increasing degeneracy the ratio BRs approaches 2. One can see, that the ratio BRs grows with diminishing M/Λ and diminishing $\tan\beta$.

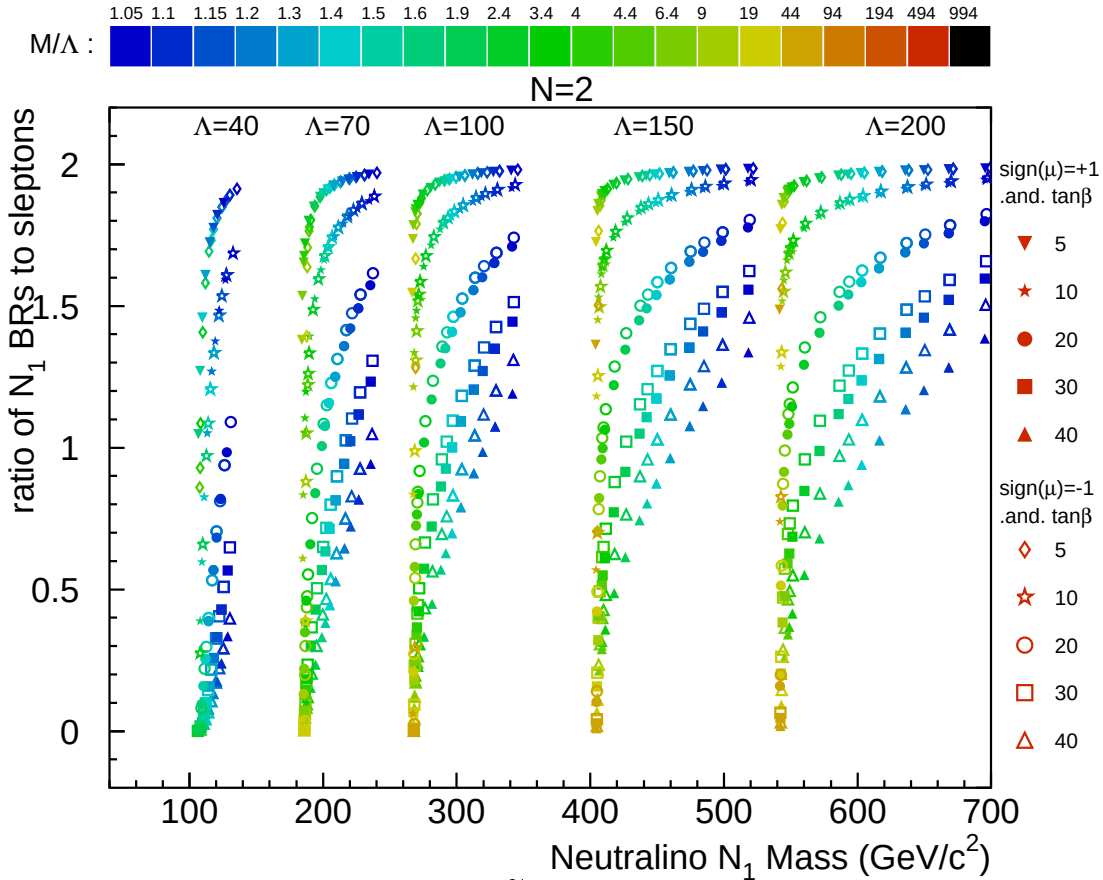


Figure 5.3: Branching ratios (Eq. 5.3) of $\tilde{N}_1$ versus its mass for models with stau $\tilde{\tau}_1$ as the NLSP. The end-point of type 2.

Conditions are less optimistic for models with the $\tilde{N}_1$ NLSP because there is an additional decay mode $\tilde{N}_2 \rightarrow \tilde{N}_1 X$, which dominates for large values of Λ . Figure 5.4 show sum of branching ratios to selectrons and smuons:

$$\text{BR}_2(\tilde{N}_2 \rightarrow \tilde{\mu}_R \mu) + \text{BR}_3(\tilde{N}_2 \rightarrow \tilde{e}_R e). \quad (5.4)$$

Above $\Lambda = 150$ TeV ($\tilde{N}_1$ mass above $250 \text{ GeV}/c^2$) there is no model with this BR above 10%.

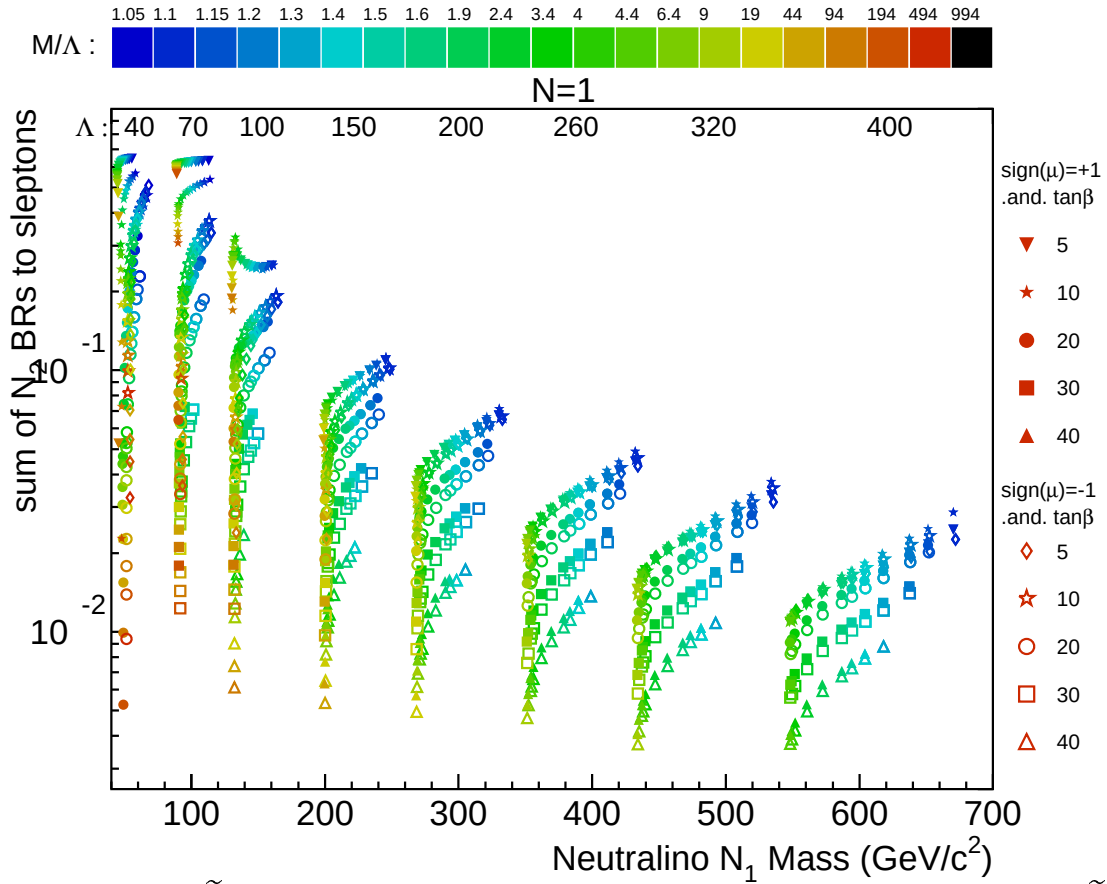


Figure 5.4: Sum of $\tilde{N}_2$ branching ratios to sleptons and smuons (Eq. 5.4) for model with $\tilde{N}_1$ as the NLSP. The end-point of type 1.

5.2.3 Dilepton end-points

In principle, every model has one of the two possible end-points as defined above (Eq. 5.1, 5.2). Its type depends on the NLSP type. Figure 5.5 illustrates which kind of the end-point is expected for a given GMSB model. The plot is a multidimensional table-diagram of all five GMSB parameters. Each dot indicates one model. Position of the double-square cell in the diagram corresponds to parameters $N \times \text{sign}(\mu)$ and Λ , whereas distribution of points inside each double-square cell corresponds to parameters $\tan\beta$ and $\log(M/\Lambda)$. The left cell of the double-square cell (with yellow background) is for small, whereas the right one (without coloured background) is for large values of $\log(M/\Lambda)$. An enlargement of some double-square cells is shown in Figure 5.6. The colour pattern refers to the kind of the NLSP for a given choice of parameters. Black points mark models with the $\tilde{N}_1$ NLSP, whereas green points mark models with the $\tilde{\tau}_1$ NLSP. The empty spaces denote models which are not self-consistent.

It can be seen that $\tilde{N}_1$ is the NLSP for $N = 1, 2$ and large values of the M/Λ parameter. For $N = 1$ only for the smallest possible values of M/Λ $\tilde{N}_1$ is not the NLSP.

The $N = 2, 3, 5$ space is dominated by edges of type 2 for models with the $\tilde{\tau}_1$ NLSP.

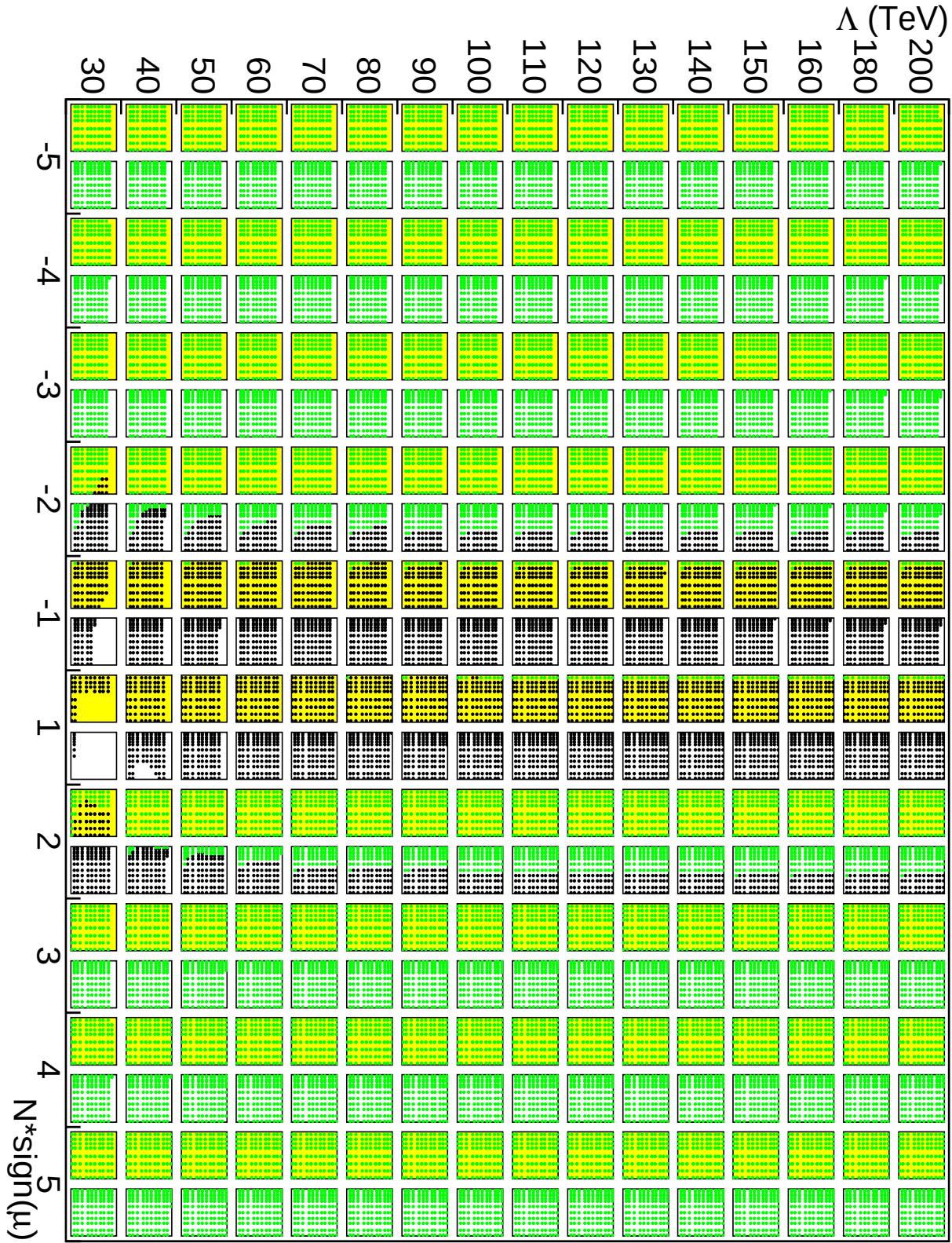


Figure 5.5: Multidimensional table-diagram for all 5 GMSB parameters. Black marks denote models with the case 1 of the end-point with $\tilde{N}_1$ NLSP. Green marks denote the case 2 of the end-point and $\tilde{\tau}_1$ NLSP. Enlargements of some double cells are in Figure 5.6.

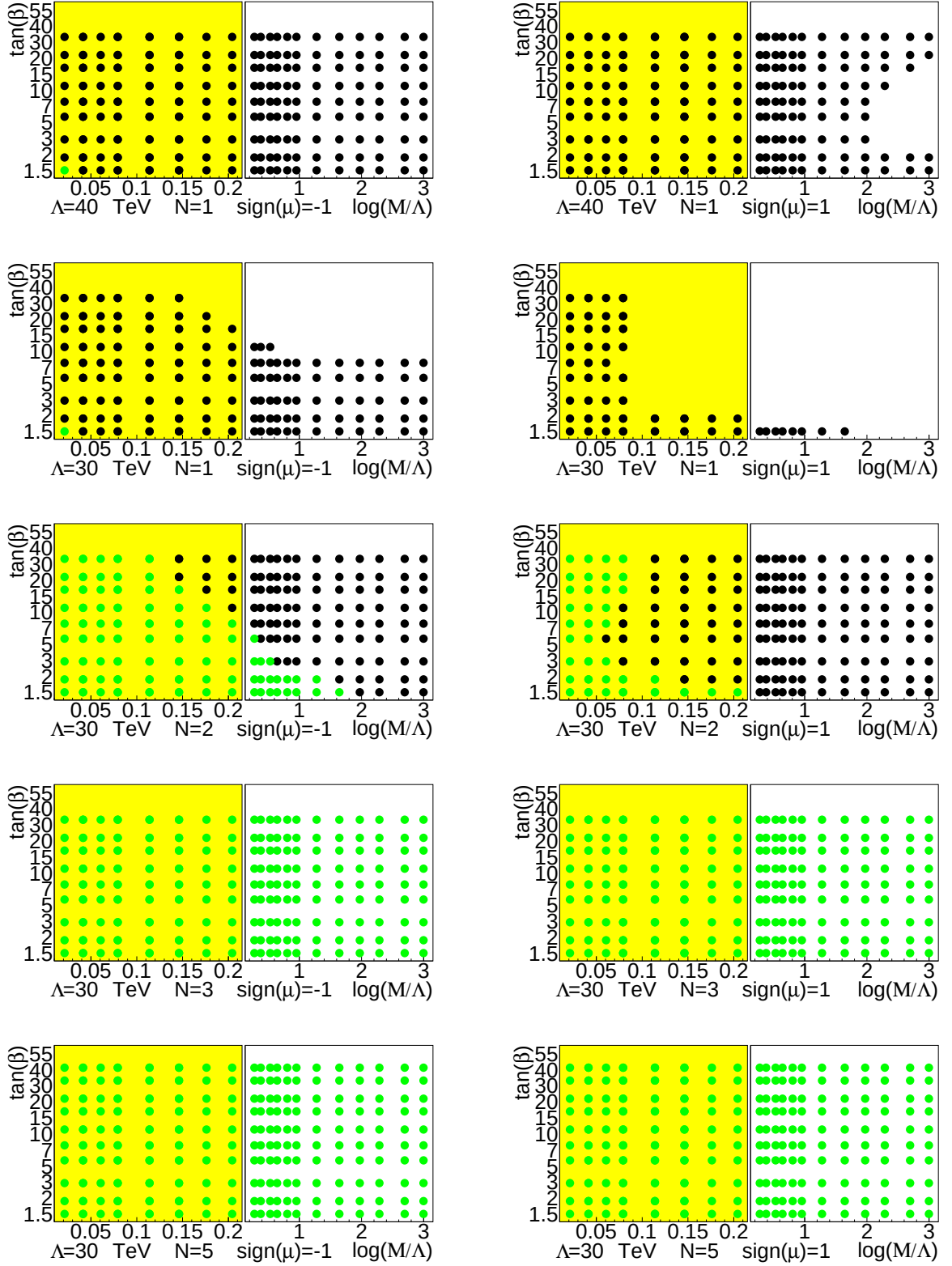


Figure 5.6: Enlargement of some pairs of cells from Figure 5.5. The pattern of colours as in Figure 5.5.

5.3 The definition of the end-point observability

This Section provides definition of observability of the lepton-lepton end-points:

type 1: $M_{\text{inv}}(\ell\bar{\ell})_1$ given by Equation 5.1

and

type 2: $M_{\text{inv}}(\ell\bar{\ell})_2$ given by Equation 5.2.

In Figure 5.7 the level of the SM background after the final selection is shown. Because there is no source for the edge signature it fluctuates around zero. In Figure also fit of constant function to the background is presented. The value of the fitted constant: $N = (0.9 \pm 0.8) \cdot 10^{-3}$, as well as the value of $\chi^2 = 1.1$ (per degree of freedom) confirms, that the background is consistent with zero.

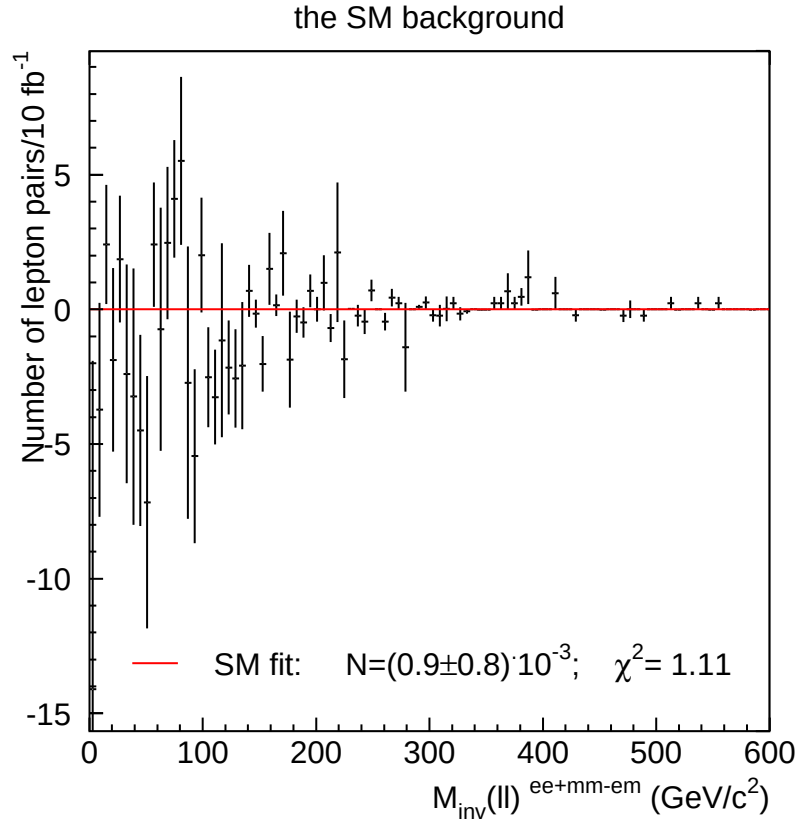


Figure 5.7: The SM background in the difference of the invariant mass distributions of the same and different flavour lepton pairs: $\mu^+\mu^- + e^+e^- - \mu^\pm e^\mp$ after application of kinematical cuts (which are defined in Tab. 4.2; number of events, which passed the cuts in Tab 4.3.)

The characteristic end-points in the difference of the invariant mass distribution of same and different flavour lepton pairs $\mu^+\mu^- + e^+e^- - \mu^\pm e^\mp$ are shown for both types of end-point: in Figure 5.8 for neutralino and in Figure 5.10 for stau NLSP.

The integrated (from the left to the right) distributions are shown in Figures 5.9 and 5.11, respectively. These distribution fluctuate around zero from left down to the end-point position where the curves start to grow up.

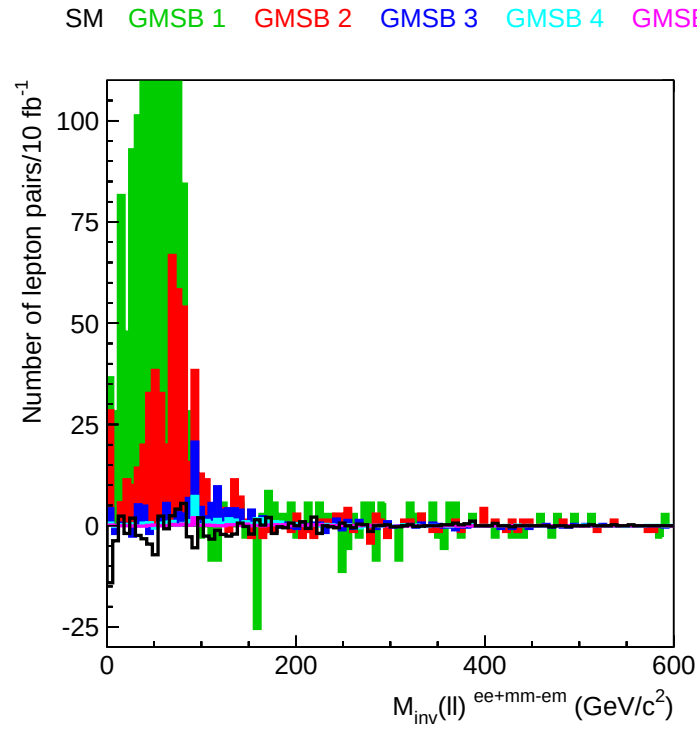


Figure 5.8: The difference of the invariant mass distributions of pairs of leptons of same and different flavour for models with $\tilde{N}_1$ NLSP.

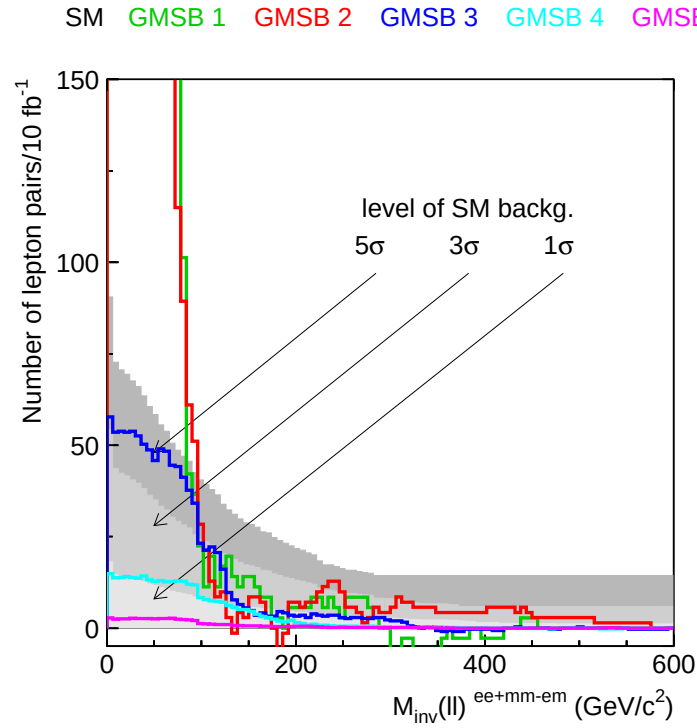


Figure 5.9: The cumulative difference of the invariant mass distributions of pairs of leptons of same and different flavour for models with $\tilde{N}_1$ NLSP.

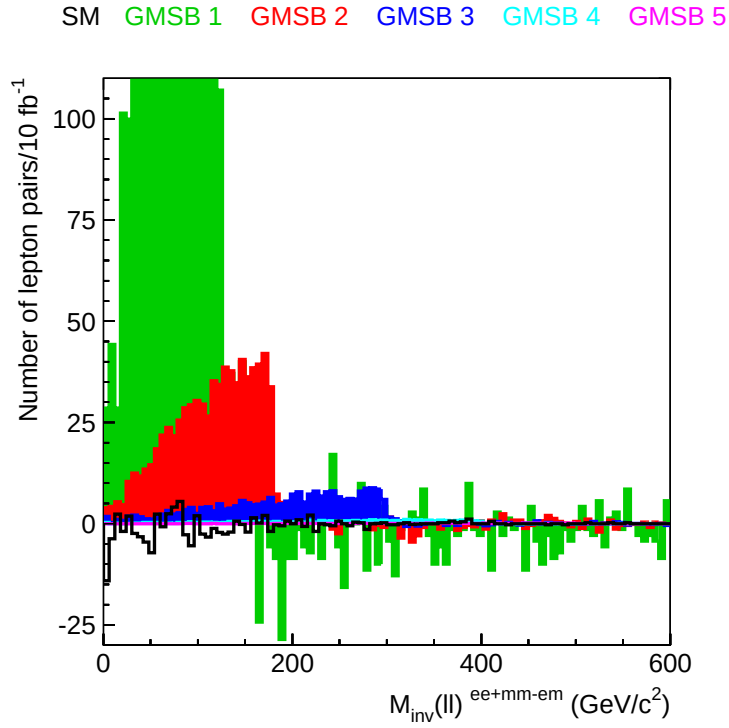


Figure 5.10: The difference of the invariant mass distributions of pairs of leptons of same and different flavour for models with $\tilde{\tau}_1$ NLSP.

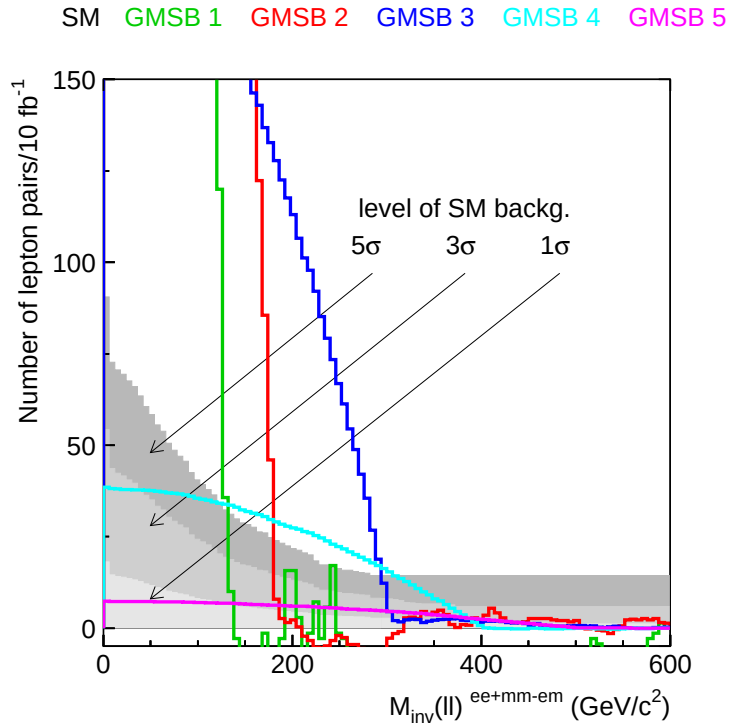


Figure 5.11: The cumulative difference of the invariant mass distributions of pairs RD leptons of same and different flavour for models with $\tilde{\tau}_1$ NLSP.

In these Figures the distributions of the level of the statistical fluctuation of the expected background (at 10/fb of integrated luminosity) corresponding to 5σ , 3σ and 1σ are shown with different levels of shadow. The observability is defined as a requirement that integrated signal distribution shown in Figures 5.9 and 5.11 are, at least in the part, above given level of shadowed background.

In the following we also want to have definition of the observability for points of the GMSB parameter space, for which the detector simulation was not performed (about 90,000 such points, Sec. 5.1) and the exact shape of their distributions is not known.

For these points the shape is parametrized by the distribution in question, by a parabola $P(M_{\ell\bar{\ell}})$. The parabola is defined by

the expected number of excess events N_E

and the expected position of the end-point M_{end}

(type 1: $M_{\text{inv}}(\ell\bar{\ell})_1$ or type 2: $M_{\text{inv}}(\ell\bar{\ell})_2$):

$$P(M_{\ell\bar{\ell}}) = N_E \cdot (1 - (M_{\ell\bar{\ell}}/M_{\text{end}})^2) \text{ for } M_{\ell\bar{\ell}} < M_{\text{end}}$$

and

$$P(M_{\ell\bar{\ell}}) = 0 \text{ for } M_{\ell\bar{\ell}} \geq M_{\text{end}}.$$

It was checked, that for GMSB points for which the simulation of the detector response had been performed, the parametrization is in agreement with their (fully simulated) distribution.

From Figures 5.9 and 5.11 it is clear that models GMSB1, GMSB2, GMSB3 in the case of $\tilde{N}_1$ NLSP and models GMSB1, GMSB2, GMSB3, GMSB4 in the case of $\tilde{\tau}_1$ NLSP fulfill above definition of the observability.

An estimate of the selection efficiency for models for which the detector response was not simulated will be given in Section 5.5 after the circumscription of the detector efficiency in next Section.

5.4 The detector efficiency

For each model simulated in the detector (by CMSJET 4.703) described in Section 4.2 the set of cuts was applied. Detection efficiency was evaluated as a ratio of an excess in the distribution $\mu^+\mu^- + e^+e^- - \mu^\pm e^\mp$ after all cuts, to the same excess after CUT0 (the preselection) and CUT4 (the requirement of, at least, two other sign leptons) only. This efficiency is presented as the blue triangles in Figures 5.12 and 5.13 for models with $\tilde{N}_1$ and $\tilde{\tau}_1$ NLSP, respectively. It can be seen that defined in such a way efficiency varies between a few and a few tens of percents. Its dependence on $\tilde{N}_1$ mass is more regular for the models with $\tilde{\tau}_1$ NLSP.

Green dots in these Figures (5.12 5.13) represent the ratio of the excess after all cuts to the number of generated events. This ratio estimates the product of efficiency and branching ratio into the decay we are searching for. It is slightly higher than detector efficiency for models with $\tilde{\tau}_1$ NLSP. It is because the BR for these models is close to the 100 % and there are two possible decay chains per event. For models with $\tilde{N}_1$ NLSP the BR is of the order of 10 %.

To each set of the green points a line is fitted. In Figure 5.12 the line represents the lower bound on the value of the excess, in Figure 5.13 – the *average* value of expected excess.

These lines were used as an estimate of the efficiency for all models for which the simulation of the detector response have not been performed.

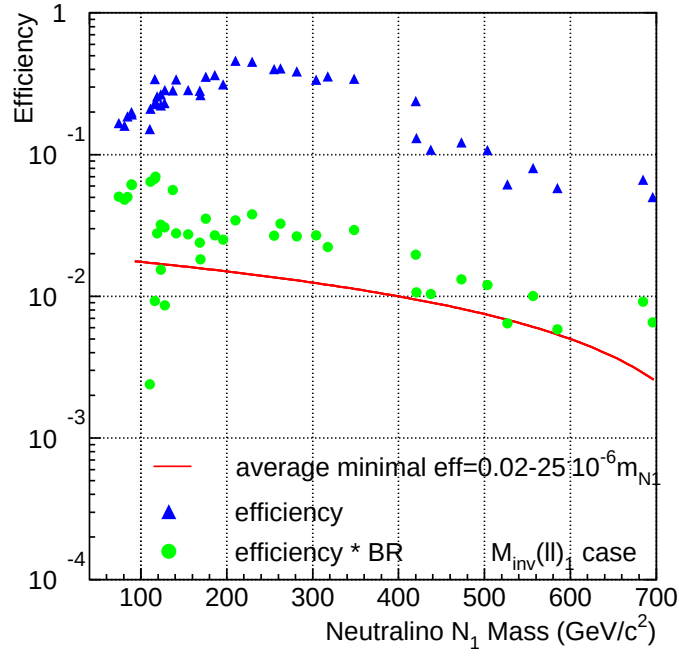


Figure 5.12: The detector efficiency in the case of $\tilde{N}_1$ as the NLSP.

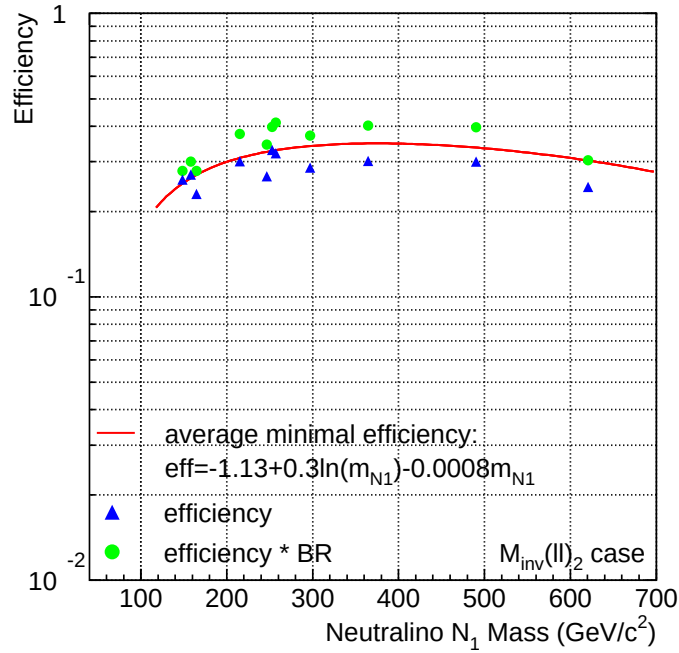


Figure 5.13: The detector efficiency in the case of $\tilde{\tau}_1$ as the NLSP.

5.5 The exploration of the GMSB parameters space

The estimate of the selection efficiency found in the preceding section can be used to evaluate the regions of the GMSB parameters space in which detection of the leptonic edges would be possible at LHC in the CMS detector. For the purpose of such evaluation 10/fb of the integrated luminosity was assumed, which correspond to one or two years of operation at low luminosity (an order of magnitude lower than the designed luminosity). The results cannot be directly interpreted in the case of the high luminosity because in the present study the influence of pile-up events have been neglected. One should not expect significant decrease of the efficiency due to the pile-up, because the selection is based on presence of large number of hard objects in the event, but only detailed simulation can fully answer such questions.

We start the evaluation from plots showing expected number of pair of opposite sign leptons in function of the lightest neutralino mass of the model. The $\tilde{N}_1$ NLSP case is shown in Figures 5.14, 5.15, whereas $\tilde{\tau}_1$ NLSP case is shown in Figures 5.16, 5.17.

In Figures 5.14, 5.16 small dots represent models from the wide simulation of GMSBs. The efficiency evaluated in the preceding section is already taken into account, and different colours correspond to different $\tan\beta$ ranges. Large full squares denote models simulated with the CMSJET. In Figures 5.15, 5.17 only a subset of considered models is shown, what allows for more detailed inspection of the dependence of the result on GMSB model parameters. The colour pattern differentiates between the values of M/Λ , while $\tan\beta$ is depicted using different kind of markers. Full symbols mark models with $\mu > 0$, while the empty ones are used for models with $\mu < 0$. The position of the group of points corresponding to different values of N and Λ are denoted by appropriate labels.

5.5.1 Results

The information about the observability of GMSB models (defined in the Sec. 5.3) is shown in more systematic way in the multidimensional table-diagram shown in Figure 5.18, constructed in the same way as Figure 5.5.

Green (black) points mark $\tilde{\tau}_1$ ($\tilde{N}_1$) NLSP models. Overprinted red (magenta) circles correspond to models in which the leptonic edge of type 2 (type 1) would be detected if selection efficiency could amount to 100%. Overprinted blue (cyan) circles mark models in which the edge of type 2 (type 1) will be detected if selection efficiency corresponds to the estimate from Figure 5.13 (5.12) represented by the red curve.

Enlargements of some double-cells are shown in following Figures:
5.19 for $N = 1$, 5.20 for $N = 2$, 5.21 for $N = 3$, 5.22 for $N = 4$ and 5.23 for $N = 5$.

Results for GMSBs with the neutralino $\tilde{N}_1$ NLSP

Main conclusions for the $\tilde{N}_1$ NLSP case (type 1) are:

$$\left. \begin{array}{l} \Lambda < 40 \text{ TeV for } N \cdot \text{sign}(\mu) = -2 \\ \Lambda < 50 \text{ TeV for } N \cdot \text{sign}(\mu) = +2 \\ \Lambda < 70 \text{ TeV for } N \cdot \text{sign}(\mu) = -1 \\ \Lambda < 90 \text{ TeV for } N \cdot \text{sign}(\mu) = +1 \end{array} \right\} \text{ for } \tan\beta \text{ not greater then } \tan\beta < 30.$$

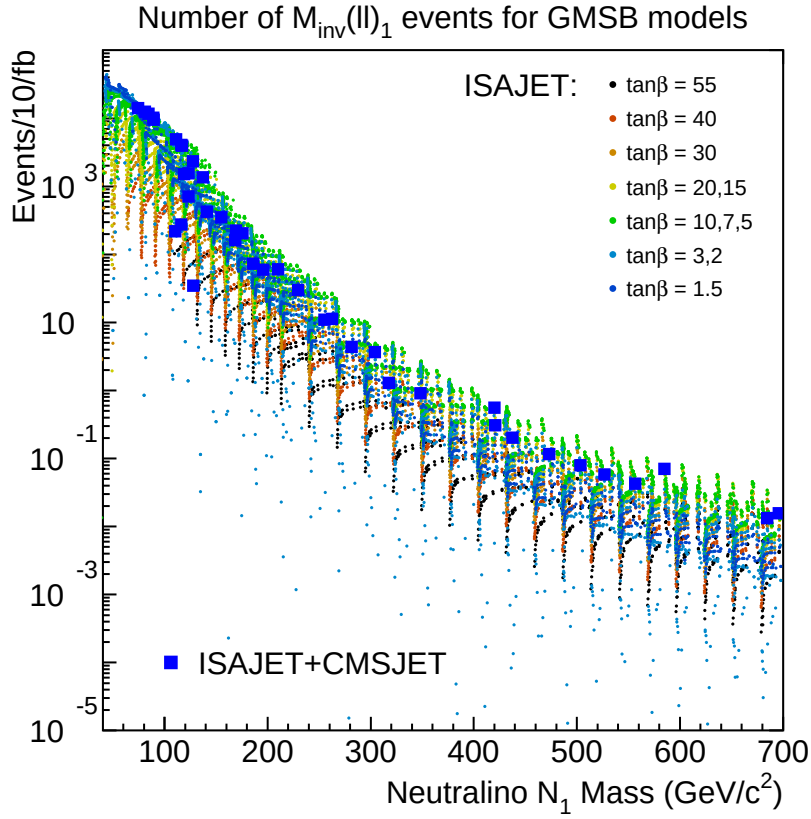


Figure 5.14: Number of $\ell^+\ell^-$ pairs expected for all models with $\tilde{N}_1$ NLSP taken into account. The efficiency is included.

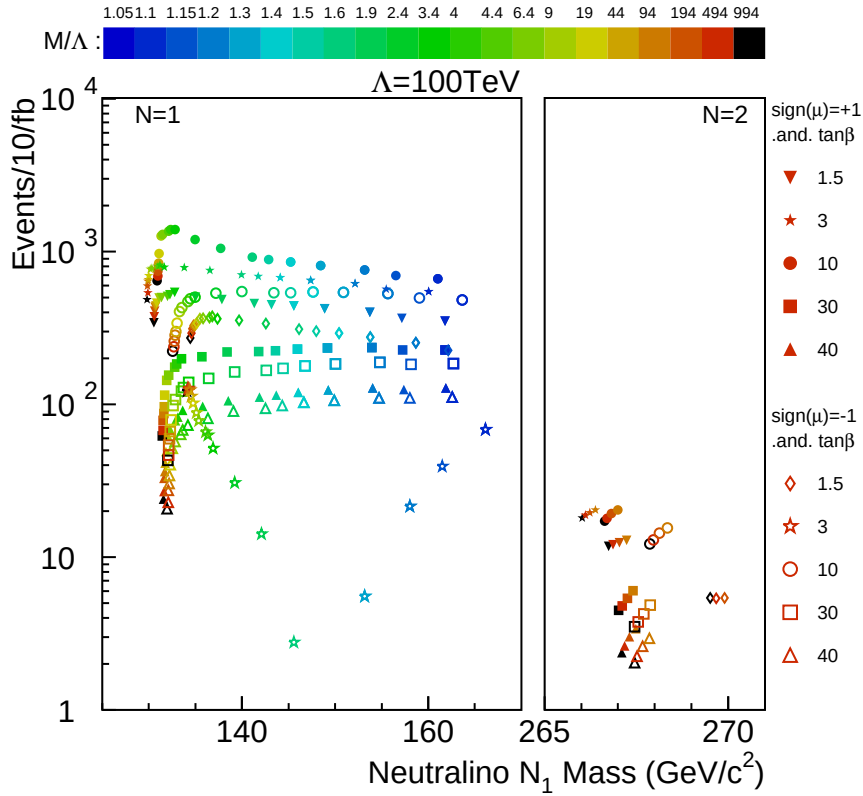


Figure 5.15: Number of $\ell^+\ell^-$ pairs expected for models with $\tilde{N}_1$ NLSP for $\Lambda = 100\text{TeV}$.

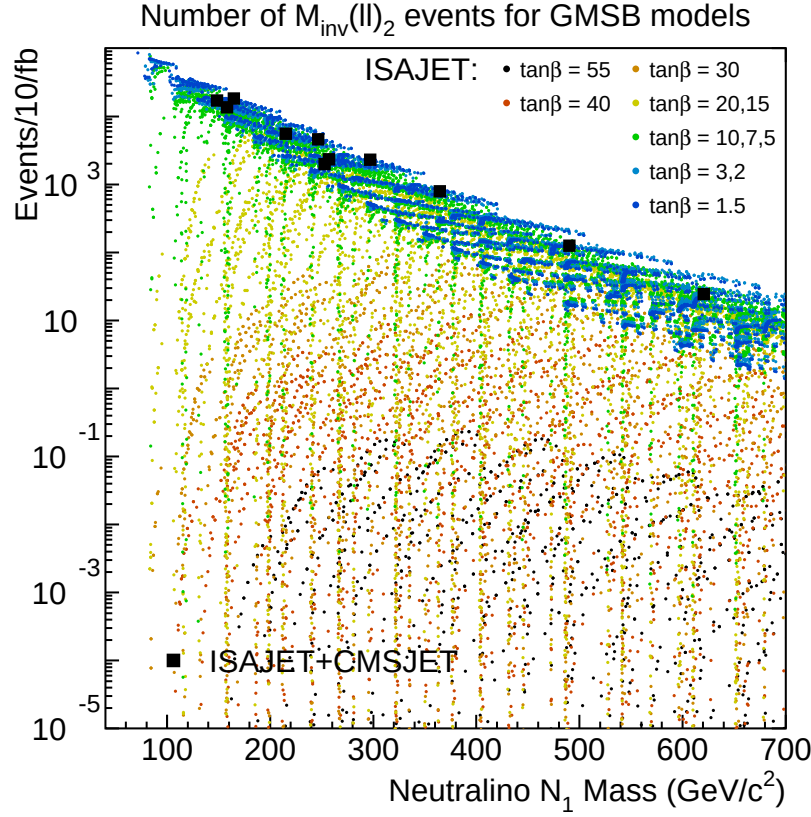


Figure 5.16: Number of $\ell^+\ell^-$ pairs expected for all models with $\tilde{\tau}_1$ NLSP taken into account. The efficiency is included.

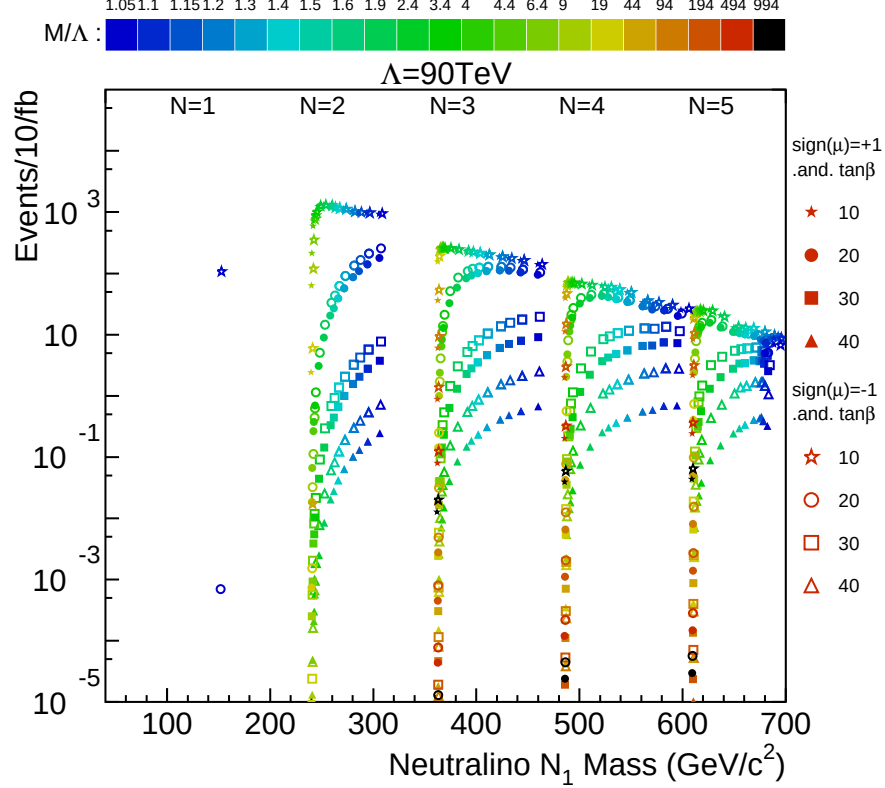


Figure 5.17: Number of $\ell^+\ell^-$ pairs expected for models with $\tilde{\tau}_1$ NLSP for $\Lambda = 90 \text{ TeV}$.

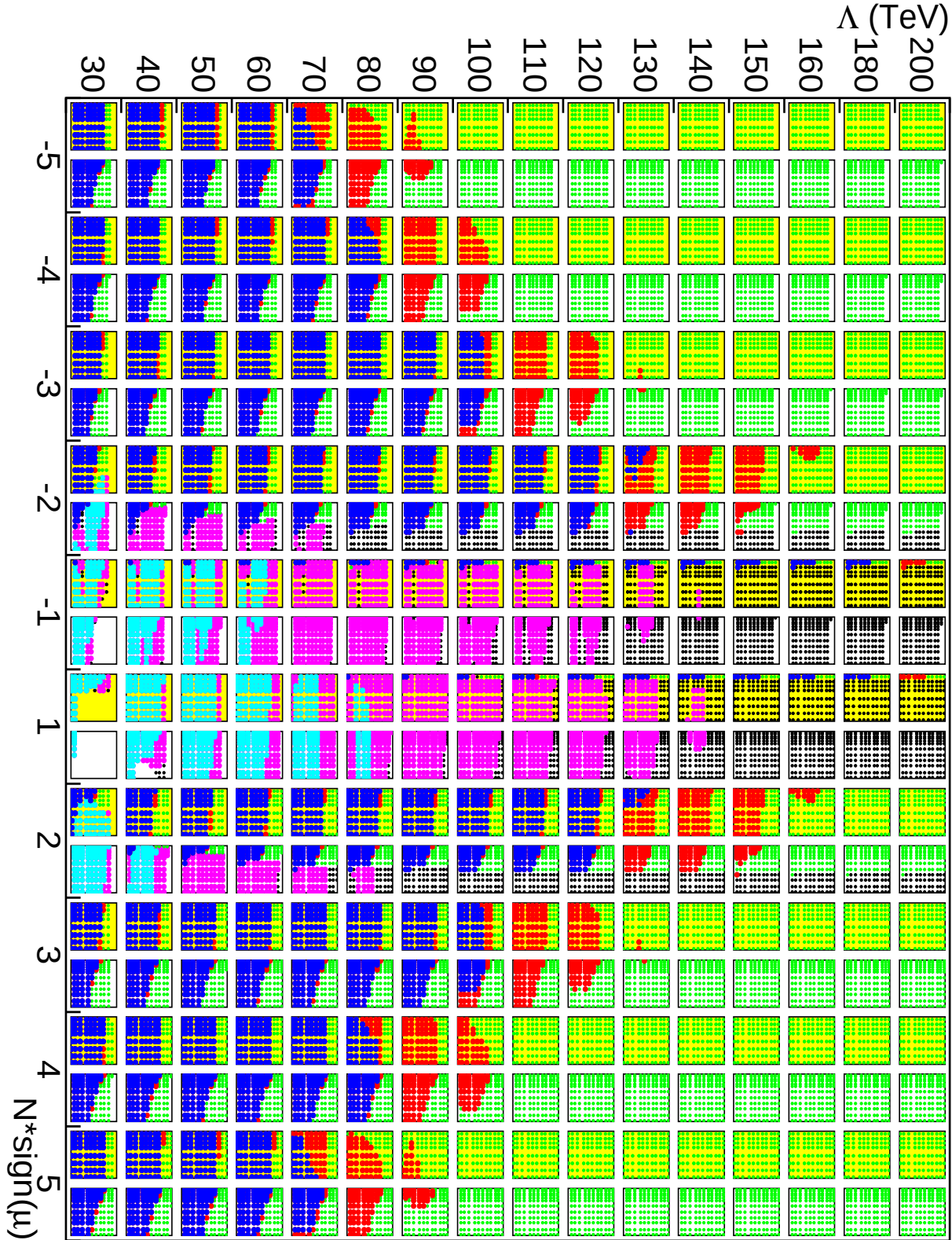


Figure 5.18: End-point evidence for $\tilde{N}_1$ NLSP models. The result. Green (black) points mark $\tilde{\gamma}_1$ ($\tilde{N}_1$) NLSP models. Overprinted red (magenta) circles correspond to models in which the leptonic edge of type 2 (type 1) would be detected if selection efficiency could amount to 100%.

Overprinted blue (cyan) circles mark models in which the edge of type 2 (type 1) will be detected if selection efficiency will correspond to the estimate from Figure 5.13 (5.12) represented by the red curve in that Figure. Details are shown in following Figures:

5.19 ($N = 1$), 5.20 ($N = 2$), 5.21 ($N = 3$), 5.22 ($N = 4$) and 5.23 ($N = 5$).

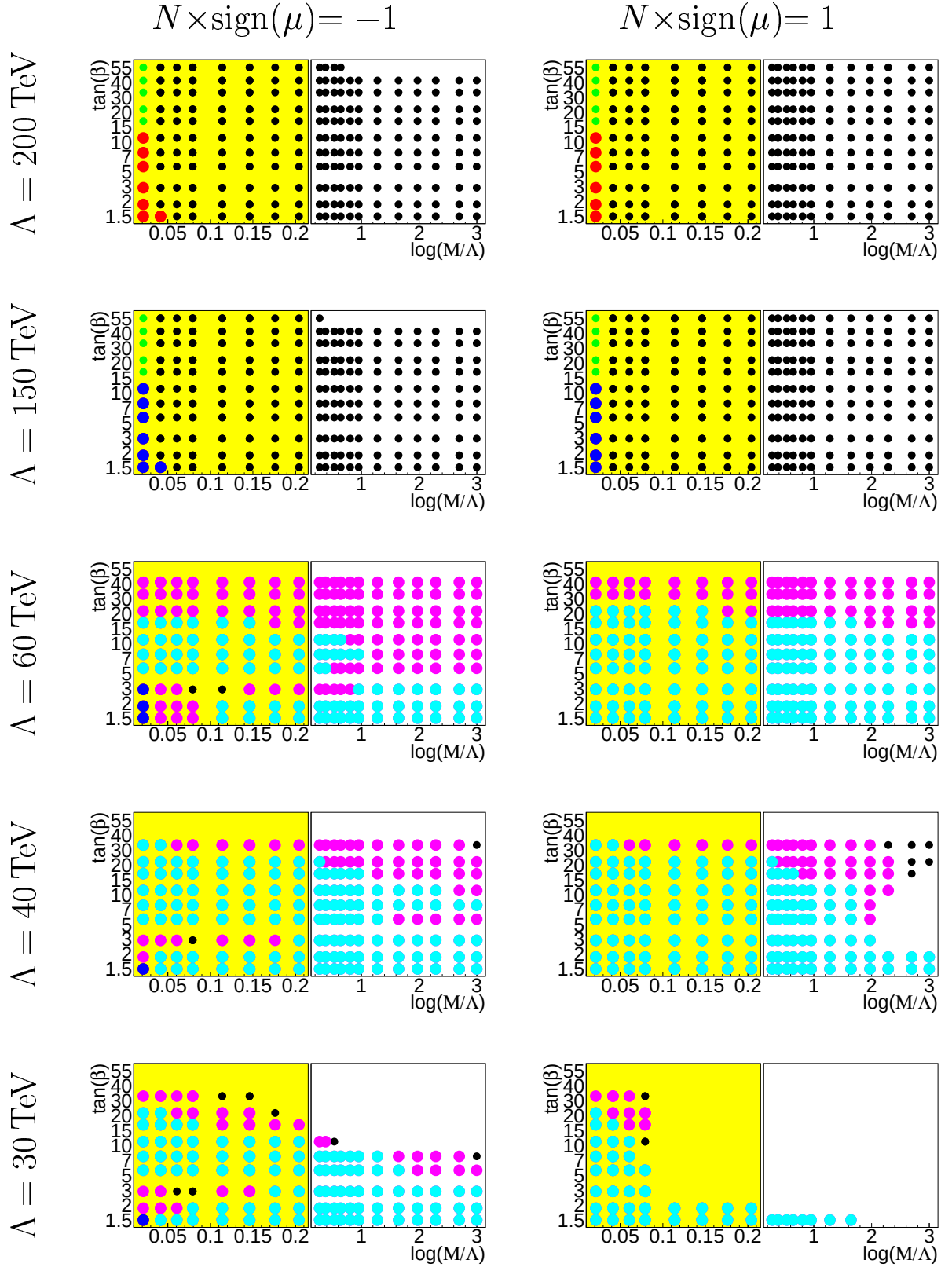


Figure 5.19: Enlargement of some pairs of cells from the Figure 5.18 for $N = 1$. The pattern of colours as in Figure 5.18.

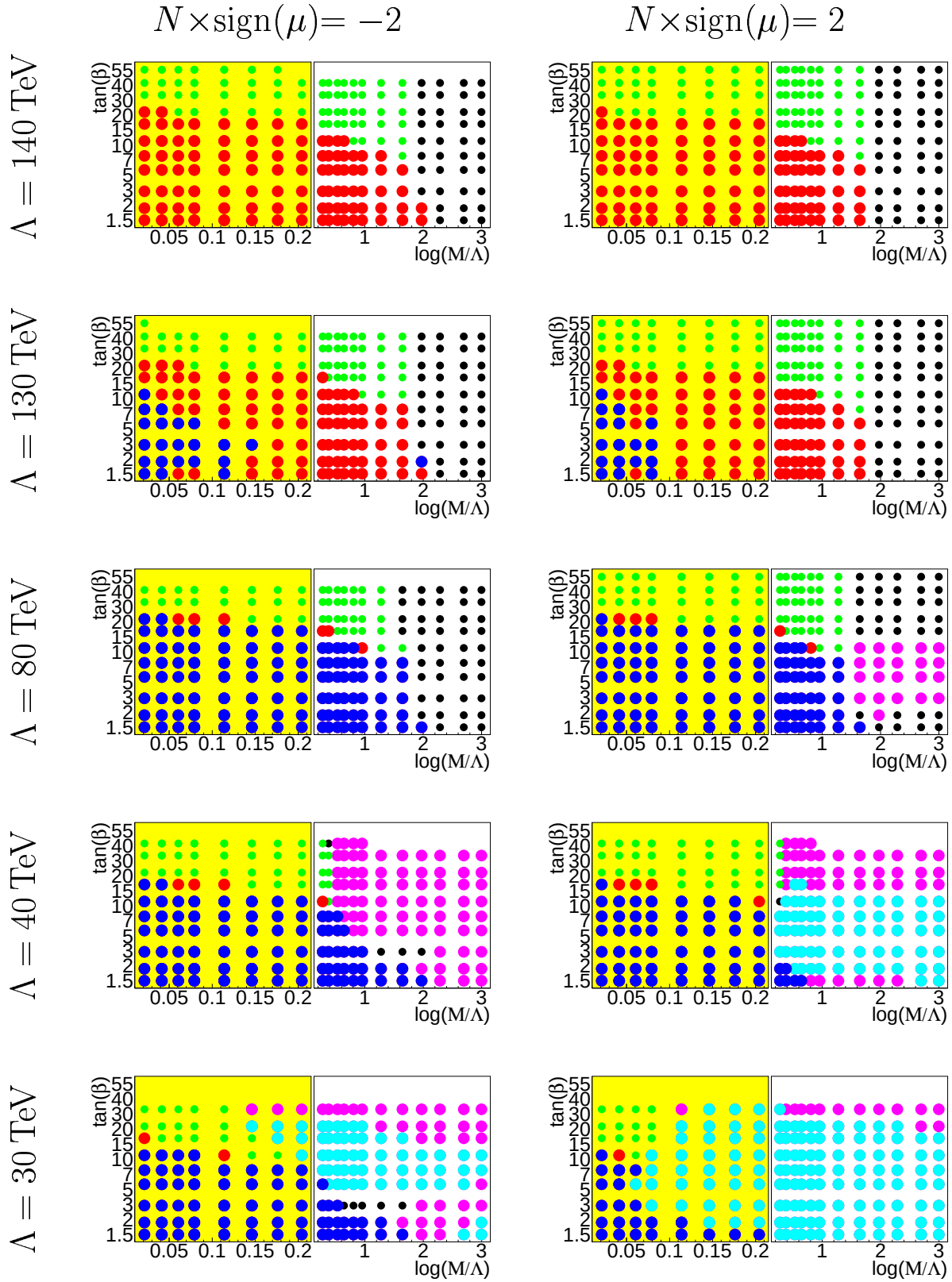


Figure 5.20: Enlargement of some pairs of cells from the Figure 5.18 for $N = 2$. The pattern of colours as in Figure 5.18.

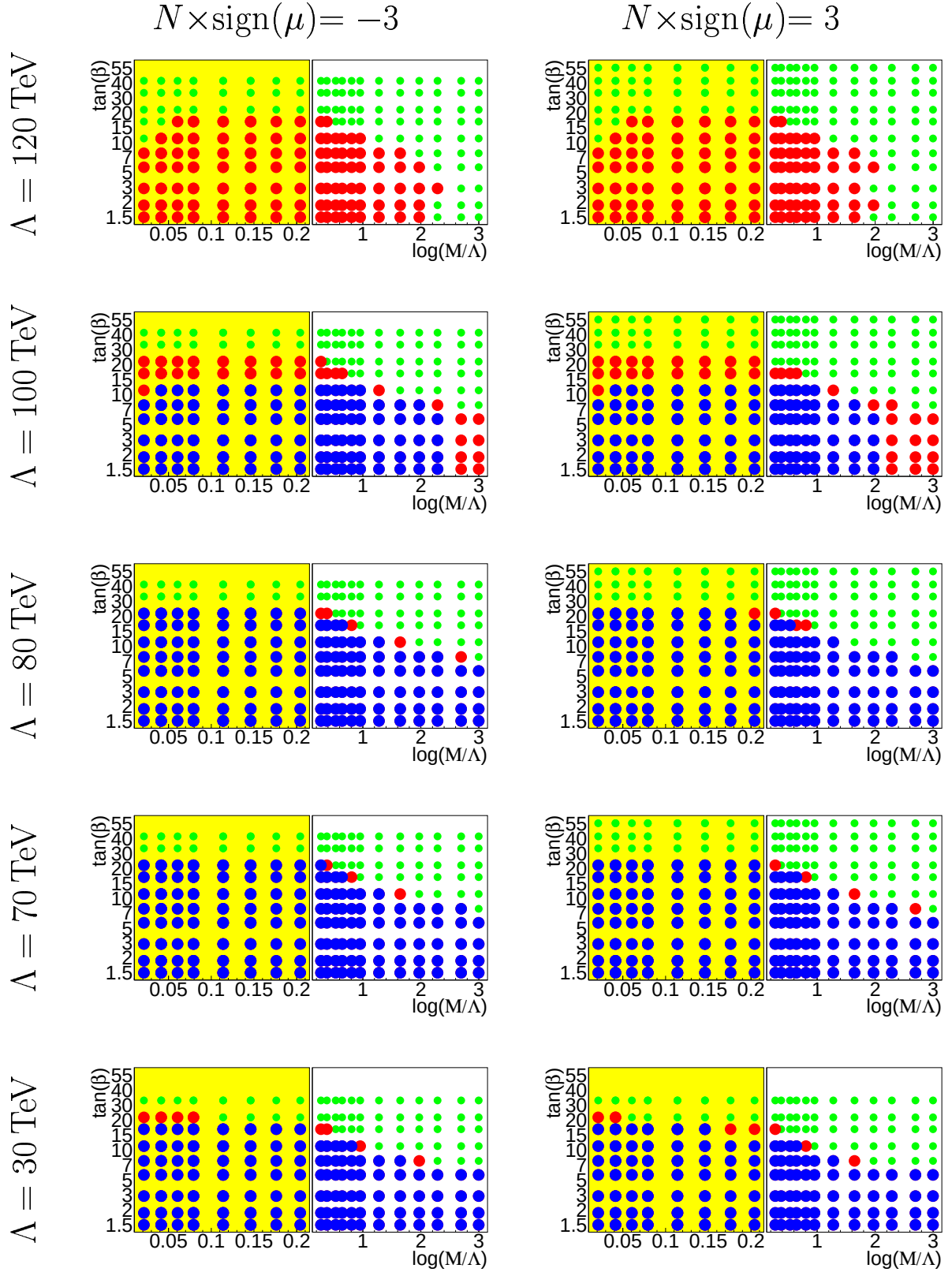


Figure 5.21: Enlargement of some pairs of cells from the Figure 5.18 for $N = 3$. The pattern of colours as in Figure 5.18.

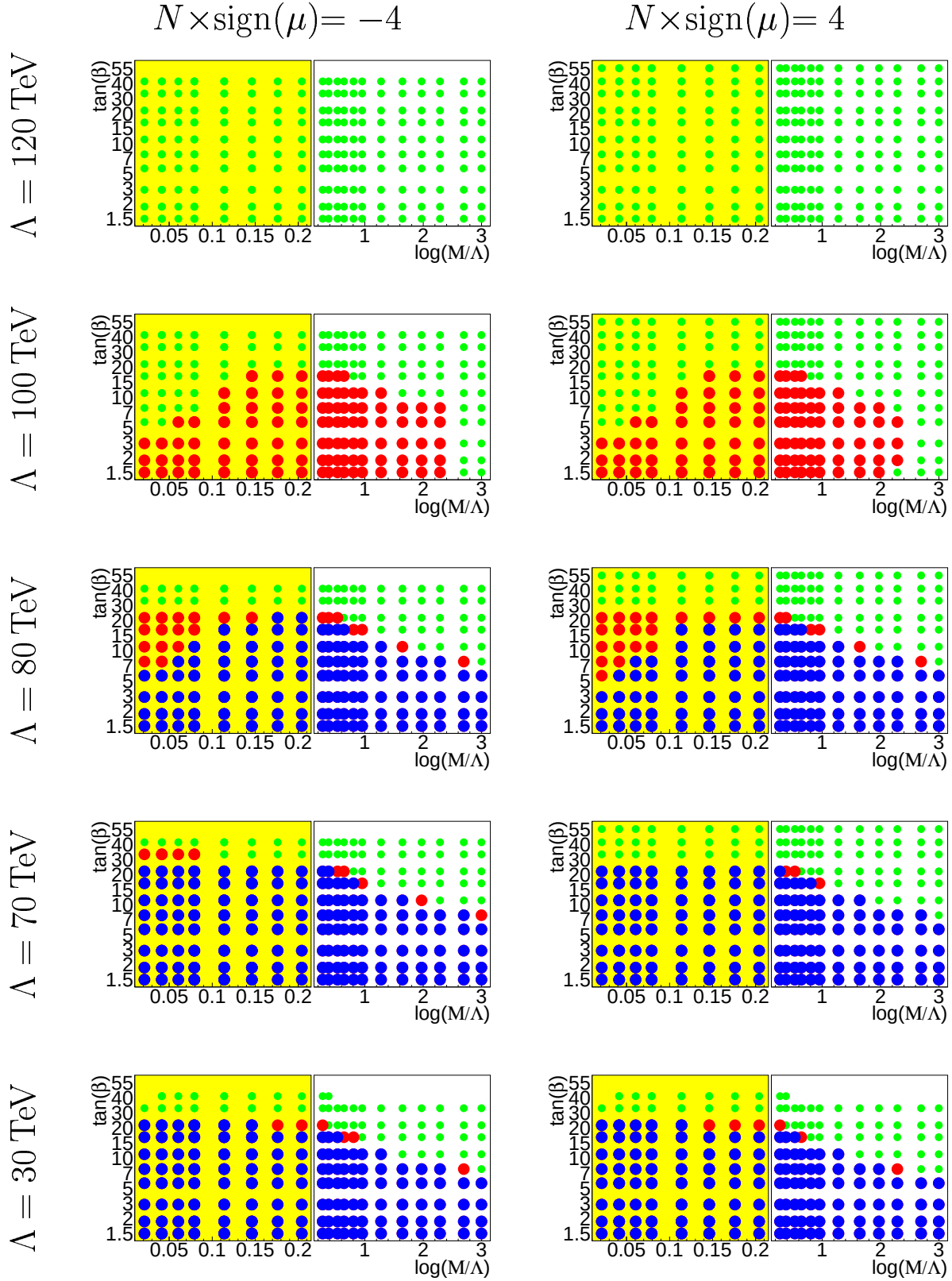


Figure 5.22: Enlargement of some pairs of cells from the Figure 5.18 for $N = 4$. The pattern of colours as in Figure 5.18.

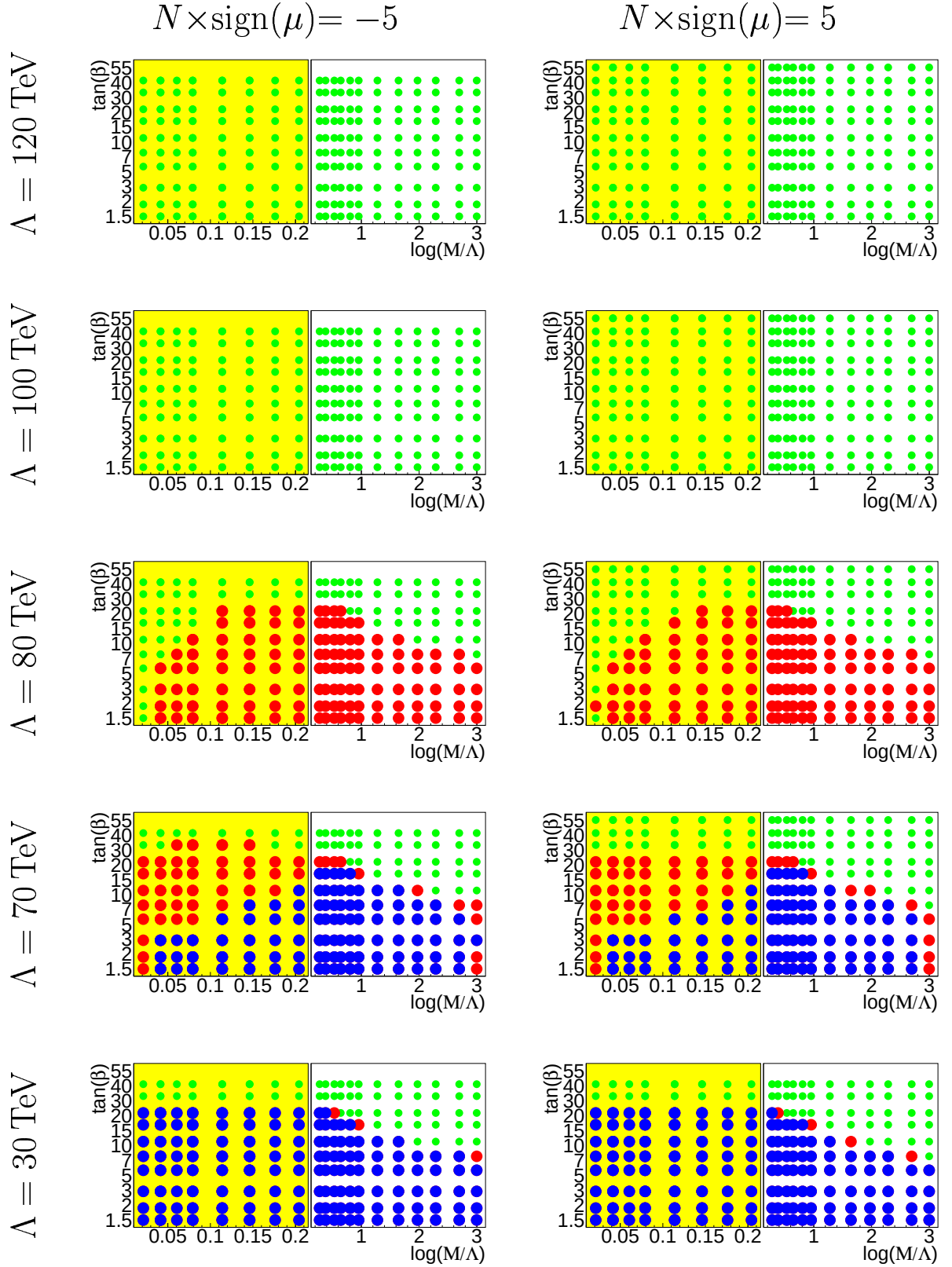


Figure 5.23: Enlargement of some pairs of cells from the Figure 5.18 for $N = 5$. The pattern of colours as in Figure 5.18.

Results for GMSBs with the stau $\tilde{\tau}_1$ NLSP

Main conclusions for the $\tilde{\tau}_1$ NLSP case (type 2) are:

the end-point is detectable at the 5σ level for $\int \mathcal{L} dt = 10/\text{fb}$ if:

$$\tan\beta < 30 \quad \left\{ \begin{array}{ll} \Lambda < 80 & \text{TeV for } N \cdot \text{sign}(\mu) = \pm 5 \\ \Lambda < 90 & \text{TeV for } N \cdot \text{sign}(\mu) = \pm 4 \\ \Lambda < 110 & \text{TeV for } N \cdot \text{sign}(\mu) = \pm 3 \\ \Lambda < 130 & \text{TeV for } N \cdot \text{sign}(\mu) = \pm 2 \text{ and for } \Lambda = 130 \text{ only for } M/\Lambda < 10 \\ \Lambda < 170 & \text{TeV for } N \cdot \text{sign}(\mu) = \pm 1 \text{ only for } M/\Lambda < 1.15. \end{array} \right.$$

Neutralino and stau mass ranges

The limitation can be translated into the ranges of masses of supersymmetric particles. Figure 5.24 shows masses of $\tilde{\tau}_1$ and neutralino $\tilde{N}_1$, where the same colour codes as in Figure 5.18 are used. The range of masses where the end-point is detectable is:

neutralino $m_{\tilde{N}_1} < 600 \text{ GeV}/c^2$,

stau $m_{\tilde{\tau}_1} < 350 \text{ GeV}/c^2$.

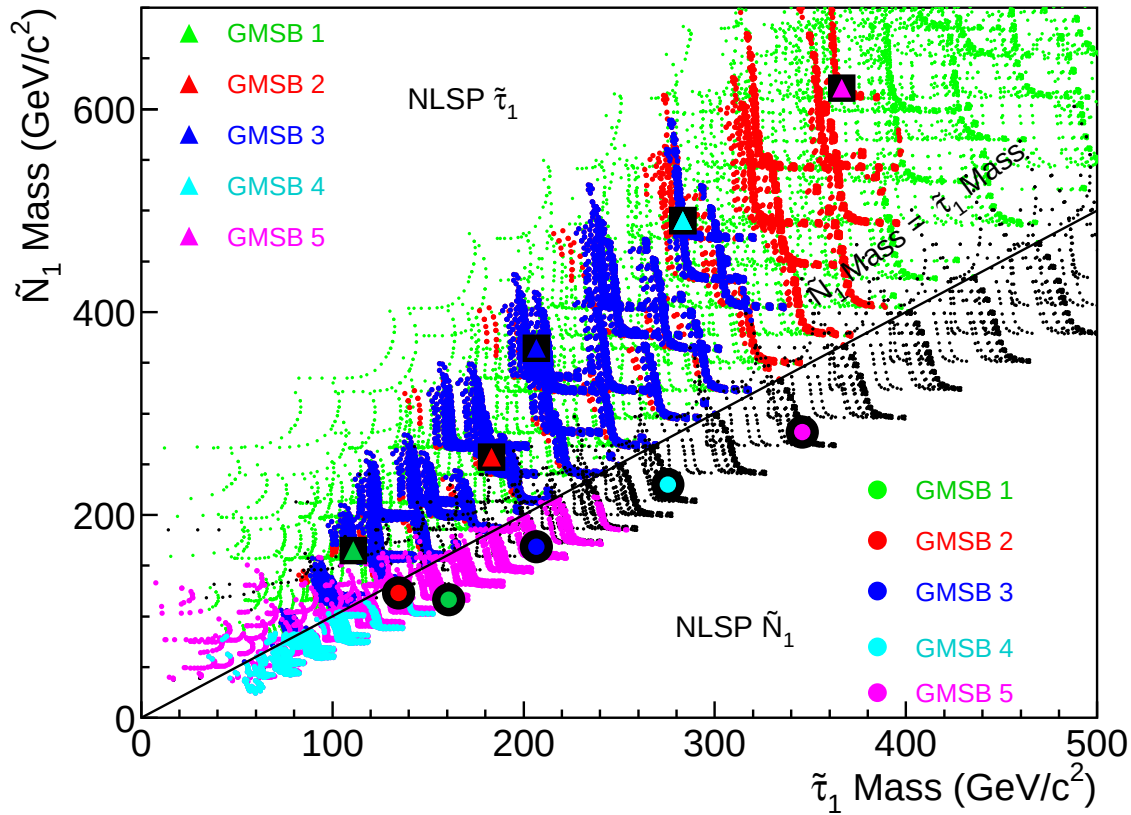


Figure 5.24: The masses of candidates for NLSP. Figure related to Figure 3.2 but marked according to colour symbols of the observability in Figures 5.18. Ten considered GMSB models is pointed out by triangles (the $\tilde{\tau}_1$ NLSP from Tab. 4.5) circles (the $\tilde{N}_1$ NLSP from Tab. 4.4).

Chapter 6

Characteristic signatures of the GMSB models

6.1 Long-lived stau detection

The GMSB NLSP staus with the long time of life behaves as *heavy muons*. They differ from muons by lower velocity $\beta = v/c$. The CMS detector can directly determine their velocity by time of flight measurement using the Drift Tubes (DT) of the Muon Barrel Stations (MB).

6.1.1 Time of flight measurement with Drift Tubes

Time measurement is needed to determine the particle velocity. In the CMS detector the only possibility is given by muon subdetector, the drift tubes (DT), which is described in Chapter 2.3.1. What the drift tubes actually measure is not a position of the through going charged track but drift time. To estimate precise coordinate along the drift direction, the time of the arrival of the particle at the tube must be known. Knowledge of a coarse coordinate along the sensitive wire is sufficient for muons, because the position of the tube, the velocity of muon ($\beta \sim 1$) and velocity of a signal propagation along the wire are all known. If the particle velocity is significantly lower than the speed of light, then the points reconstructed in successive DT layers with the assumption $\beta = 1$ do not align. The signals arrive at wires late exactly by the difference of the time of flight between non-relativistic and relativistic particles. The time of flight measurement technicalities are described in [88, 89]. These results were based on the full detector simulation done by the author of this thesis.

In the analysis one specific point of the GMSB parameter space was chosen. It was the model with the stau as the NLSP with the mass of 90 GeV/c². The reason is that the smaller the mass of the stau the higher the background from a wrongly measured muons.

The overall cross section at the chosen point is 9.6 pb, and each event cascades into stau anti-stau pair. The staus are *stable*, i.e. they do not decay inside the CMS detector.

In order to estimate the resolution of the DT system:

SPYTHIA 5.7 [90] was modified to allow for stable staus;

new stable muon (with the appropriate mass) was added as a particle to the list of particles in the detailed CMS simulation program CMSIM 117 [91].

The DT response was subsequently simulated with the CMSIM program for staus and background muons. Production of secondary particles was turned on.

$\Lambda = 85 \text{ TeV}; M/\Lambda = 300; \mu < 0; \tan \beta = 45; N = 1.$ $m(h) = 120 \text{ GeV}/c^2; m(H, A, H^\pm) = 450 \text{ GeV}/c^2;$ $m(\tilde{G}) = 1 \text{ keV}/c^2; c\tau(\tilde{\tau}_1) = 10 \text{ m}; m(\tilde{\tau}_{1,2}) = (90, 320) \text{ GeV}/c^2;$ $m(\tilde{N}_{1,2,3,4}) = (121, 240, 363, 370) \text{ GeV}/c^2; m(\tilde{C}_{1,2}) = (240, 500) \text{ GeV}/c^2;$ $m(\tilde{l}_{R,L}) = (140, 310) \text{ GeV}/c^2; m(\tilde{\nu}_{L(\tilde{l}, \tilde{\tau})}) = (304, 313) \text{ GeV}/c^2;$ $m(\tilde{g}_{1,2}) = 720 \text{ GeV}/c^2; m(\tilde{q}_{R,L}) = (900, 960) \text{ GeV}/c^2;$ $m(\tilde{t}_{1,2}) = (840, 913) \text{ GeV}/c^2; m(\tilde{b}_{1,2}) = (901, 902) \text{ GeV}/c^2.$
--

Table 6.1: Parameters of the GMSB model.

The background consisted of wrongly measured muons. To suppress overwhelming low energy muons the presence of at least two muons in the event with transverse momentum greater than 40 GeV/c and $|\eta| < 2.4$ was required. Such requirement assures that the event is triggered by muons (or staus) alone.

The main source of the background after this cut were $Z^0 \rightarrow \mu^+ \mu^-$ events. To suppress these events the following cuts to the pair of muons were applied:

transverse momentum of the pair $p_{\text{Tpair}} > 45 \text{ GeV}/c$;

invariant mass of the pair $m_{\text{inv}} > 97 \text{ GeV}/c$. After this selection both signal and background $Z^0 \rightarrow \mu^+ \mu^-$ cross sections were at the level of 5 pb. Other backgrounds: supersymmetry, top pair production and Drell-Yan muon pair production, were at the level of 2 pb in total.

Finally, the severe DT acceptance criteria was applied to each of the muons (staus) of the pair separately:

to accept the information from the muon station we required at least 7 associated hits in 8 $R\phi$ DT layers with straight line fit with $\chi^2 < 10$ and at least 3 associated hits in the 4 z DT layers;

at least 3 stations had to fulfill the above described criteria to accept the particle

pseudorapidity $|\eta| < 1$.

For each muon station $1/\beta$ was determined. The final results were obtained by averaging over all selected stations.

The separation between muons and staus can be clearly seen in the scatter plot (Fig. 6.1) which shows measured $1/\beta$ as a function of the particle momentum.

6.1.2 Mass measurement

The resolution of the time of flight measurement is estimated to be 1 ns plus 1 ns of a systematic shift toward negative values of the time delay. A possible origin of this shift comes from production of secondaries [88]. Muon inducing electromagnetic showers or δ electrons can mimic *tachions* but not low β particles, because only the hit closest to the wire is digitalized (two hit resolution is of the order of 15 ns). After correcting for the systematic shift the square of mass of the particle is calculated from the $1/\beta$ measurement. It is shown in Figure 6.2 where the statistics correspond to the integrated luminosity of 500/pb (only one week of data taking at low luminosity $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$). The signal significance is unquestionable.

Taking into account excellent performance of the search for stable staus it is interesting find the maximal effective low energy supersymmetry scale at which the stable stau signal would be

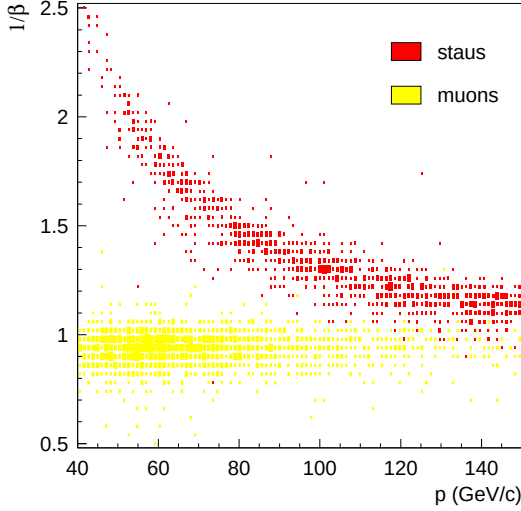


Figure 6.1: Measured $1/\beta$ as a function of the particle momentum [88].

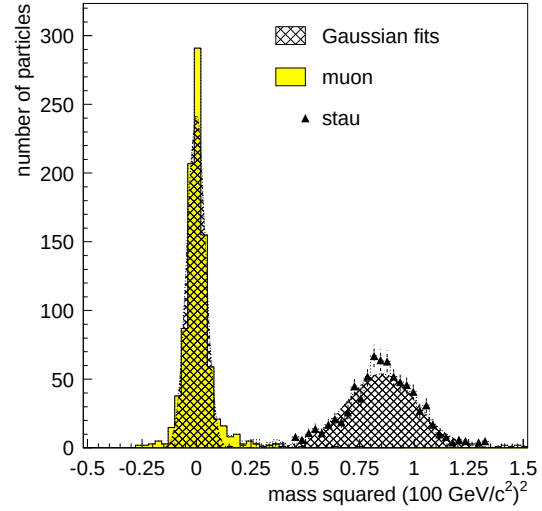


Figure 6.2: Squared mass distributions obtained from the $1/\beta$ measurement [88].

visible. To do that the resolution was parameterized as a function of the particle velocity and applied to the samples of staus generated in several points of the GMSB parameter space. The result for three of these points are shown in Figures 6.3,6.4. For the final plot (Fig. 6.4) and efficiency evaluation only particles satisfying the following criteria were used:

$1/\beta < 2$. — because slower particles start to escape the time window in the central tracker;

$p < 1.5 \cdot m_{\tilde{\tau}_1}$ — where $m_{\tilde{\tau}_1}$ is determined from the fit to the band shown in Figure 6.3 (this cut is applied to eliminate the fragment of the stau band which is closer than 4σ to the line $1/\beta = 1$). As one can see the efficiency grows with the stau mass. The effect is mainly due to the last applied cut. The signal for the heaviest stau corresponds to one year of data taking at nominal luminosity. At this GMSB point squarks and gluinos have masses of the order of $4 \text{ TeV}/c^2$. Although they are not directly produced (the cross-sections for gauginos production dominates) this is the supersymmetry scale to which presented search is sensitive. To see the signal it is sufficient that overall cross-section for super-partner production exceeds 1 fb .

6.2 Detection of the NLSP decays

In this Section, the NLSPs, which could decay inside the detector, are considered. The main decay mode of neutralino NLSP is $\tilde{N}_1 \rightarrow \tilde{G}\gamma$. It will be shown, that the determination of the $\tilde{N}_1$ lifetime is possible. Such determination would be very important, since it is equivalent to an estimate of the supersymmetry breaking scale.

6.2.1 Detection of $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ decays

Flight path probability distribution $P(l)$ for a particle with life time τ , mass m , and momentum p is given by the formula:

$$P(l) = \frac{1}{\lambda} e^{-\frac{l}{\lambda}}, \quad \text{where} \quad \lambda = c\tau \frac{p}{m} \quad (6.1)$$

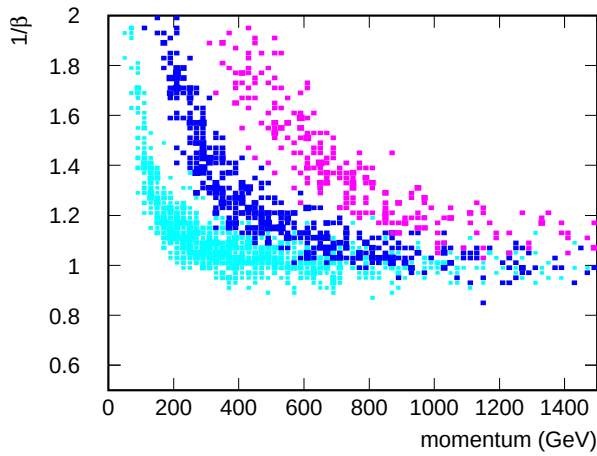


Figure 6.3: Measured $1/\beta$ as a function of the $\tilde{\tau}_1$ momentum for three chosen GMSB points [89].

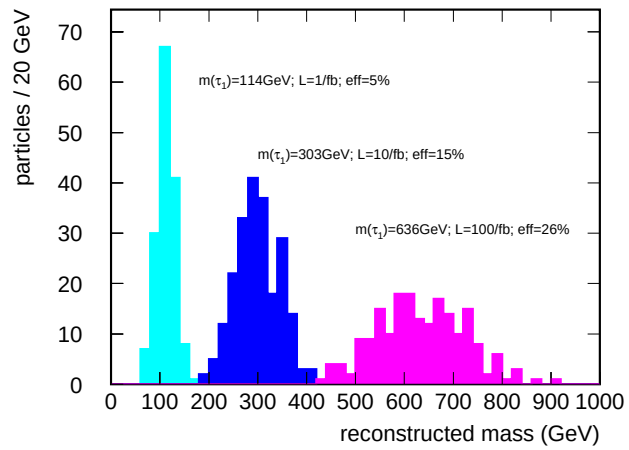


Figure 6.4: Mass distributions obtained from the $1/\beta$ measurement for three chosen GMSB points [89].

Possibility of detecting the $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ decay depends on the average flight path λ . The decay may happen in different parts of CMS (Fig. 2.3).

- for $\lambda > 100$ m most of the decays happen outside of CMS. In this case the missing energy is the only measurable quantity. Nothing can be said about the $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ decay itself. The maximal $c\tau(\tilde{N}_1)$ which still allows to see the $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ signal is determined in Section 6.2.4.
- For $\lambda < 1$ m most of the decays take place within the Inner Tracker volume. In such a case the photon can be detected in the electromagnetic calorimeter ECAL and its energy can be precisely measured. The photons do not point to the interaction point but limited angular resolution of the ECAL do not allow for the lifetime measurement. The minimal λ for which this effect can be observed is given in Section 6.2.4.
- If $1 \text{ m} < \lambda < 100 \text{ m}$, a large fraction of decays take place inside the muon detector or within Central Tracker. In the following (Sec. 6.2.2, 6.2.3) we argue that this is the most favorable situation for the determination of the $\tilde{N}_1$ lifetime.

6.2.2 CMS muon system as a late decay counter

Photon created inside the iron yoke produces an electromagnetic shower. Its profile is characterized by the radiation length of iron $X_0 = 1.76$ cm. If shower leaks to the muon station (which has small average density and so, large radiation length), the particles spread out and the muon chamber registers from a few tens to few hundreds of hits. This can be seen in Figure 6.5 where simulated 300 GeV muon emits a 22 GeV photon 8 cm before the iron surface.

The idea is to look at such huge accumulation of hits in one muon station. There are three immediate questions:

what is the acceptance?

can the $\tilde{N}_1$ lifetime be estimated?

what are the background sources?

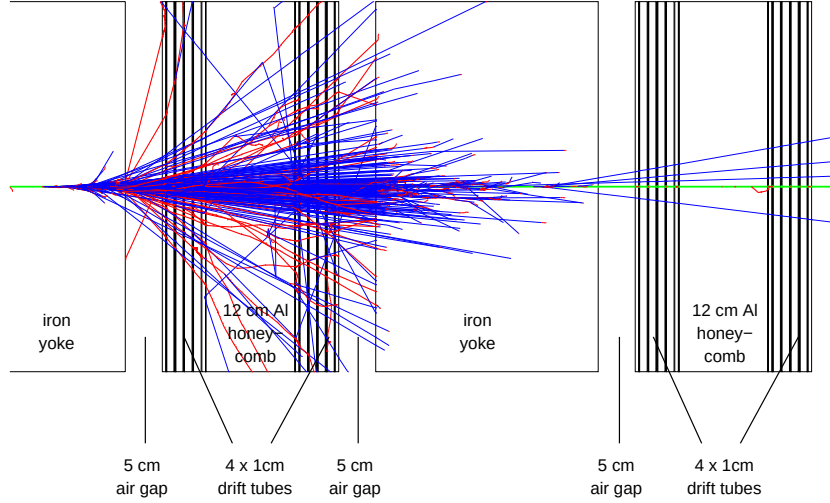


Figure 6.5: Electromagnetic shower in CMS Muon Detector caused by a 22 GeV photon. GEANT simulation.

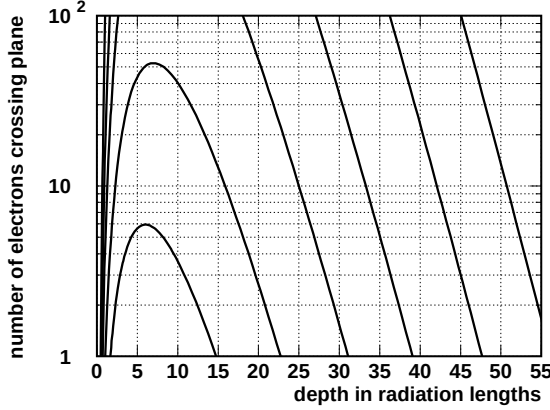


Figure 6.6: Parameterization of an average number of electrons in an electromagnetic shower as a function of the shower depth for several shower energies.

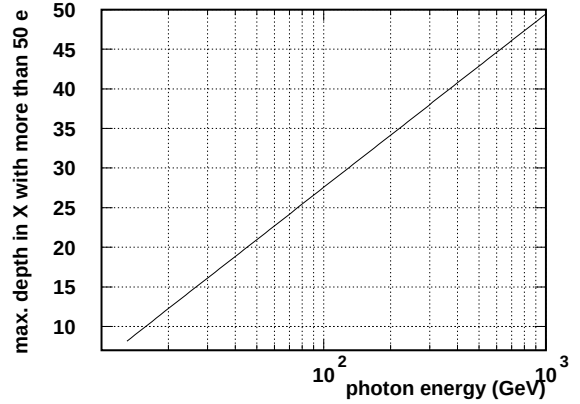


Figure 6.7: Parameterization of the shower energy dependence of the maximal shower depth at which expected number of electrons exceeds 50.

Acceptance

We use the average number of secondary electrons in the electromagnetic shower at its given depth. This number can be reasonably parameterized with a use of the information from ref. [55]. Figure 6.6 shows a parameterization of shower profiles for several energies chosen to have the shower maximum at 6,7,...,11 radiation lengths. In Figure 6.7 the depth (in radiation lengths) for which the expected average number of electrons with energy greater than 1.5 MeV exceeds 50 is plotted as a function of shower energy.

The photon (from neutralino decay inside an iron slab) is assumed to give detectable signal in the muon detector if its shower leaves at the end of the iron slab on average at least 50 electrons. According to this definition a 100 GeV photon is detected if it travels less than ~ 50 cm of iron.

This definition was implemented in the specially written Monte Carlo simulation. A modified SPYTHIA was used to generate supersymmetric events with a stable $\tilde{N}_1$ as the NLSP. These NLSPs were allowed to decay with different lifetimes. The results are shown in Figure 6.8.

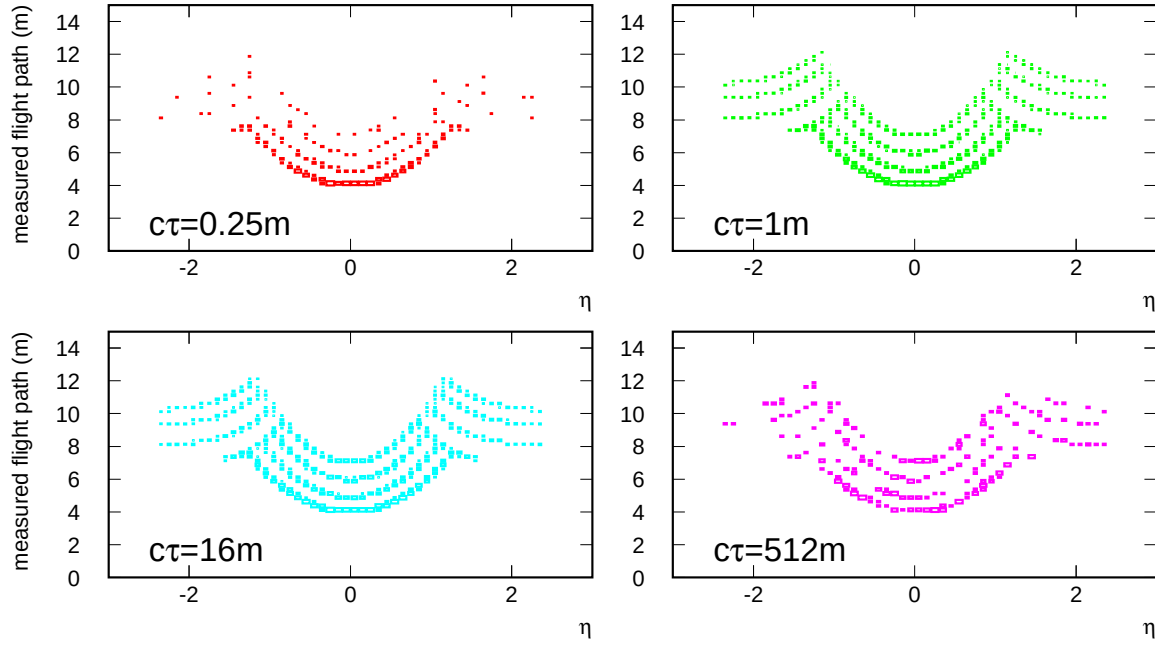


Figure 6.8: Measured flight path as a function of η for four $\tilde{N}_1$ lifetimes.

A measured flight path of the NLSP is the distance from the interaction point to the entrance point of the muon station which is plotted as a function of η . The specific shape on the plot reproduces the configuration of muon stations. For the smallest used lifetime ($c\tau = 25\text{ cm}$) the muon systems starts to see decaying neutralinos. Significant accumulation of hits is seen in the first barrel muon station. There are two reasons for that. First, it is the station closest to the interaction point. Second, immediately before the station there is a lot of partially empty space (Fig. 2.3). The effective density of this space housing coil and cables is assumed to amount to a half of that of iron. As a result, photons have there acceptance two times greater than in the following muon stations.

With $c\tau = 1\text{ m}$ (second frame in the Fig. 6.8) all muon stations have hits, but still there is more photons detected at the beginning of the muon system than at the end. The points corresponding to detection of neutralinos of $c\tau = 16\text{ m}$ lifetime are almost evenly distributed, and finally for $c\tau = 512\text{ m}$ the majority of neutralinos escape from the detector.

Lifetime – qualitative estimate

It is evident from the Figure 6.8 that the present analysis is sensitive to the $\tilde{N}_1$ lifetime. This is shown more qualitatively in the Figure 6.9 which shows detected flight distributions for three different $c\tau$. It can be seen that around $c\tau = 4\text{ m}$ the acceptance of the muon system is maximal (two upper frames), and that the ratio of the distribution of the measured flight path to the reference distribution ($c\tau = 4\text{ m}$) is sensitive to the $\tilde{N}_1$ lifetime. This is seen as the difference of slopes shown in the two lower frames of Figure 6.9.

Background sources

There are two kinds of background to the late electromagnetic showers originating from $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ decays:

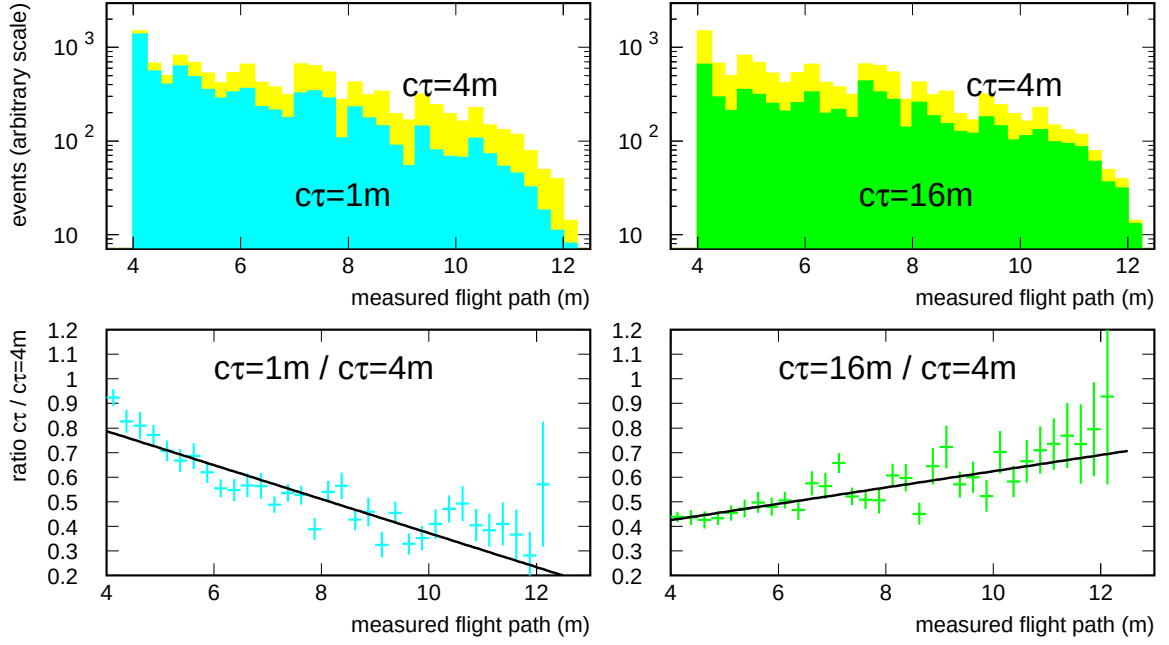


Figure 6.9: Comparison of the measured flight path distributions for different $\tilde{N}_1$ lifetimes.

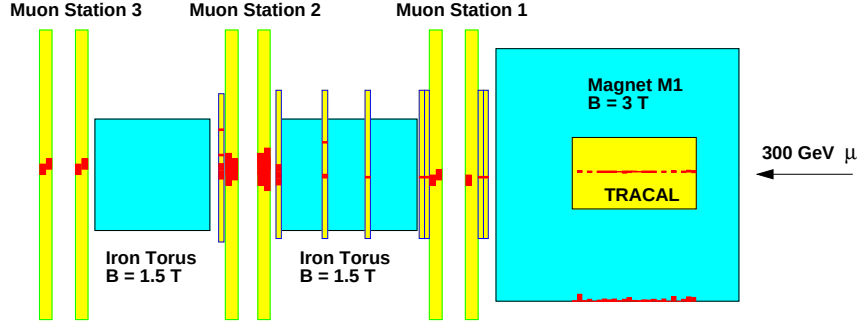


Figure 6.10: Electromagnetic shower observed in a muon station of RD5 experiment.

hard electromagnetic radiation from energetic muons (including cosmic muons);

late hadron showers, mainly due to fly-through K_L^0 and neutrons, but also from the HCAL punch-through.

The detection of electromagnetic showers caused by energetic photons was extensively studied in the past by RD5 and CMS collaborations. Measurement of high energy muons, crucial for the LHC physics, can be spoiled by emission of hard electrons and photons developing showers inside the muon detector. Therefore, a lot of experimental and simulation results on the subject already exists. If one neglects the parent muon, the situation is very similar to this in $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ decays. An example is shown in Fig. 6.10. This is an event display of the RD5 experiment. A 300 GeV muon traverses Tracking Calorimeter (TRACAL) and Muon Stations interleaved with iron yoke. Large concentration of hits (dark spots in the Figure) in Muon Station 2 indicates the presence of an electromagnetic shower.

The hadronic background on the other hand is especially dangerous in the first station, where the punch-through of hadronic showers may mimic the γ signature. An example is shown

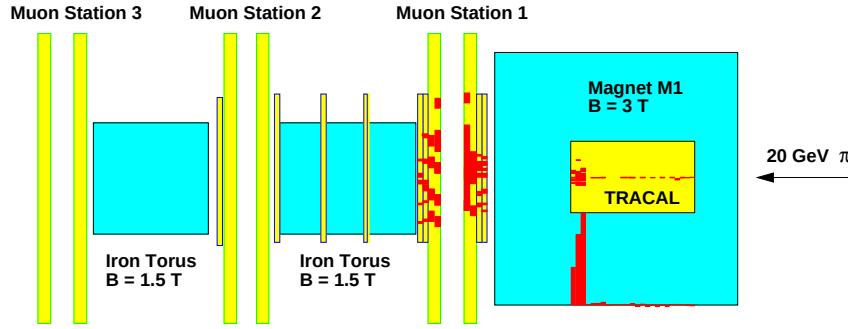


Figure 6.11: Late hadronic shower observed in a muon station of RD5 experiment.

in Figure 6.11. A 20 GeV pion interacts late in the calorimeter and remnants of the hadronic shower are seen in the Muon Station 1.

Both types of background, muon induced electromagnetic showers and late hadronic showers can be significantly suppressed if one requires that, respectively:

there is no muon track pointing to or going through the late shower;

there is no jet activity in the $\eta\phi$ region of the detected accumulation of hits in the muon station.

The second requirement is necessary for punch-through muons as well.

The signal is almost completely background free when it is combined with some isolation criteria, at least for the outer muon stations. The background which remain is the K_L^0 flux [92]. We found that a simple Monte Carlo study shows that the flux amounts to 100/fb per pseudorapidity unit in the 3rd Barrel Muon station. To that one should add secondary kaons which are not only more difficult to simulate accurately, but also more difficult to eliminate with separation criteria. They can emerge from hadron detector interaction at any angle, and provoke the occupation signal in a $\eta\phi$ cone where there is no other activity.

The background can be suppressed using using kinematic cuts described in the Section 4. We estimated that a probability that a primary K_L^0 provoke large accumulation of hits in the first muon station in a $\eta\phi$ cone free from other activity is less than 10^{-6} . We expect no more than 1 fake signature per 10^4 pp beam crossing at high luminosity.

6.2.3 Detection of non-pointing γ with CMS calorimetry

For small lifetimes, substantial fractions of the NLSPs decay before the electromagnetic calorimeter ECAL, giving spectacular signal of very energetic γ or $\gamma\gamma$ pair. In this section, we estimate what is the minimal $\tilde{N}_1$ lifetime which is still measurable by the CMS detector.

CMS calorimeters are able to determine photon direction. The situation is relatively simple in the endcap ECAL, which is equipped with the preshower. The designed angular resolution amounts to $\sigma_\theta = 45\text{mrad}/\sqrt{E_\gamma/\text{GeV}}$ [48].

The signature of non-pointing gamma in the barrel ECAL is a large energy deposit in several aligned crystals. Taking into account the fact that photons originating from $\tilde{N}_1$ decays are very energetic we define a non-pointing gamma as a shower which leaks to the hadron calorimeter (HCAL) giving an angular difference between nominal gamma entrance points to ECAL and HCAL greater than the HCAL tower width. A leaking shower is defined in analogy to what is used for the muon system in the Section 6.2.2. To accept the photon as non-pointing candidate in the barrel we required that for average electromagnetic shower induced by this photon there is at

least 50 electrons with energy greater than 1.5 MeV expected at the end of the barrel ECAL. Such definition prefers photons with energy greater than 100 GeV, so we apply a direct cut at 100 GeV for photons in the endcap ECAL. Further, we require for endcap non-pointing candidates the significance of the angular difference between reconstructed photon direction and the direction from the detector center to the energy deposit in the calorimeter to be greater than 5. The $R\phi$ resolution is taken to be nominal, whereas θ resolution is assumed to be dominated by the beam spot size along beam direction (RMS=5 cm).

Performance of the method

In Figure 6.12 we show distributions of the impact parameter for three different $\tilde{N}_1$ lifetimes (from left to right $c\tau = 6.25, 25, 400$ cm) and two GMSB points. At the first (second) point the $\tilde{N}_1$ mass is equal to 291 GeV/c² (102 GeV/c²), and the total supersymmetry cross-section amounts to 70 fb (21 pb). The histograms are normalized to a common number of 6k initial events (10% of the total 60k events simulated for each lifetime and GMSB point). They correspond to an integrated luminosity of 90/fb (300/pb). It is clearly seen that an average impact parameter grows with the $\tilde{N}_1$ lifetime. It also grows with the particle mass. The plot for $c\tau = 4$ m and $m(\tilde{N}_1) = 291$ GeV shows a steep-like structure at impact parameter of 50 cm. It is because the histogram is a sum of two distributions. One for the endcap ECAL, and one for the barrel ECAL. The later has no entries below ~ 50 cm, because we require that the difference between pointing directions going through ECAL and HCAL deposits is greater than HCAL tower angular dimension which corresponds to indirect selection of impacts greater than about 50 cm. Such structure is less pronounced for smaller masses or smaller lifetimes which means that barrel the ECAL contributes less and less to the selection of the signal there.

In Figure 6.13 gamma energy distributions are shown for the same sets of simulated data. An abrupt drop of the efficiency below 100 GeV is caused by the explicit cut for the endcaps and the selection in the barrel. In the first approximation the distributions corresponding to $c\tau = 6.25$ cm and 25 cm differ only by an overall normalization factor (for each $\tilde{N}_1$ mass separately). The distributions in the third plot, however, fall down faster. This is because $c\tau = 4$ m is already greater than the dimensions of the inner surface of the ECAL. Thus the less energetic neutralinos have greater probability to decay before ECAL than more energetic ones.

Finally, in Figure 6.14 we show the $\gamma\gamma$ mass distribution. The second γ is only required to fall into active volume of the ECAL or the HCAL (the second $\tilde{N}_1$ is required to decay before or inside calorimeters, but is not required to give non-pointing signature). The second γ can be seen in the calorimeters with efficiency of the order of 60% (45%) for $c\tau = 6.25$ cm and 45% (15%) $c\tau = 4$ m for $\tilde{N}_1$ mass of 291 GeV/c² (102 GeV/c²). There are two lines in Figure 6.14. They show the expected contribution from 2γ background events. Dash-dotted (dotted) lines correspond to the level of background at integrated luminosity of the order of 90/fb (300/pb). The lines are the extrapolation of background evaluated for the purpose of the $H \rightarrow \gamma\gamma$ search [35].

6.2.4 Combined $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ decay detection efficiency

A combined $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ decay detection efficiency is shown in Figure 6.15. In the lower frame a probability of tagging at least one neutralino decay is presented. In the upper frame both neutralinos are tagged. The overall efficiency for the scenario with $m(\tilde{N}_1) = 291$ GeV/c² is shown with upper-most lines. Dashed lines show the $m(\tilde{N}_1) = 102$ GeV/c² case. The label “ μ CAL” stands for the method described in the Section 6.2.2. As one can see the two methods: non-pointing γ in the ECAL and late decays in the muon system (μ CAL) are complementary.

To proceed to the more quantitative evaluation of the resolution of the $\tilde{N}_1$ lifetime mea-

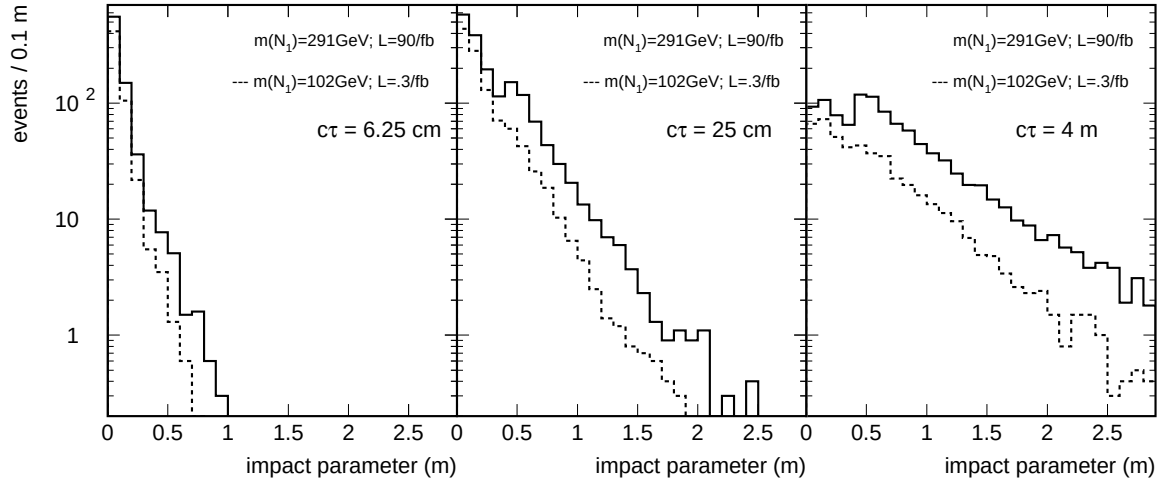


Figure 6.12: Distributions of the impact parameter of non-pointing photons for three different $\tilde{N}_1$ lifetimes.

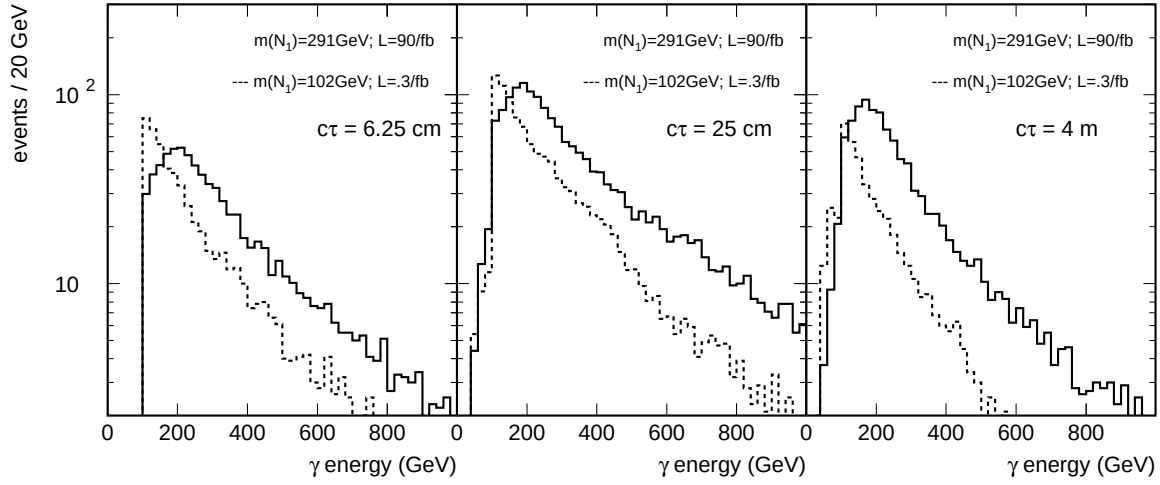


Figure 6.13: Distributions of the energy of non-pointing photons for three different $\tilde{N}_1$ lifetimes.

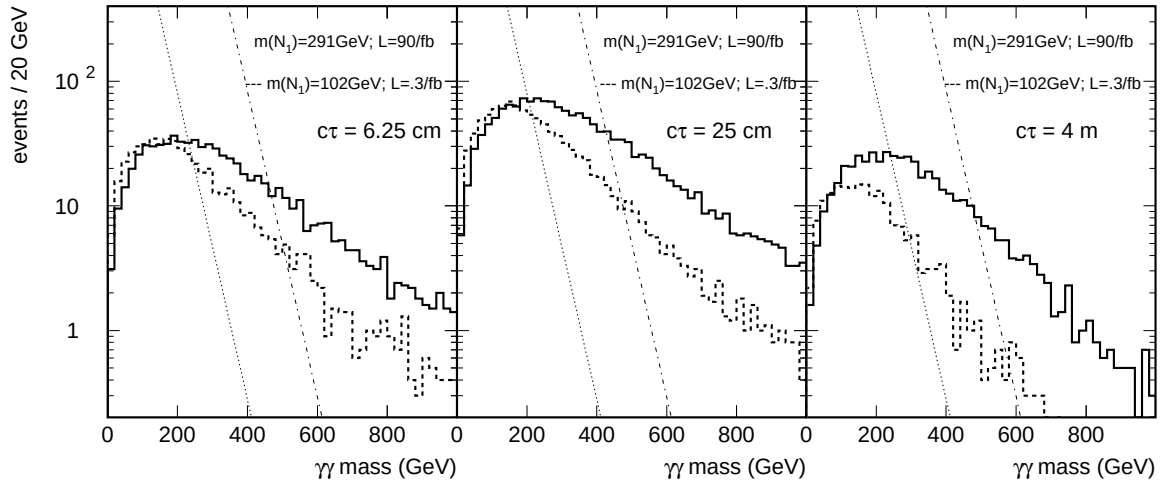


Figure 6.14: Distributions of the $\gamma\gamma$ mass for events with at least one tagged non-pointing photon for three different $\tilde{N}_1$ lifetimes.

surement we suppose that prior to the decay-in-flight requirement we select 1000 signal events, and that the decay-in-flight requirement eliminates the background to the level that can be ignored for the purpose of the present study. Such assumption correspond to about 143/fb of integrated luminosity and kinematic selection efficiency at the level of 10% for the scenario with $m(\tilde{N}_1) = 291 \text{ GeV}/c^2$. In this GMSB scenario squarks (gluinos) have masses of the order of 2.1 TeV (1.7 TeV).

In Figure 6.16 we show the evaluation of the CMS sensitivity to the $\tilde{N}_1$ lifetime. We used several complementary methods to extract lifetime information from the data. Each method is based on some quantity Q which is sensitive to the $\tilde{N}_1$ lifetime. Taking the value of Q for two consecutive lifetimes τ_i and τ_{i+1} we estimate relative error of the lifetime measurement at the geometric average $\tau = \sqrt{\tau_i \cdot \tau_{i+1}}$

$$\frac{\sigma_+(c\tau)}{c\tau} = \left| \frac{\tau_{i+1} - \tau_i}{\tau} \cdot \frac{\langle \sigma_Q \rangle}{Q(\tau_{i+1}) - Q(\tau_i)} \right|, \quad (6.2)$$

where $\langle \sigma_Q \rangle = (\sigma_Q(\tau_{i+1}) + \sigma_Q(\tau_i))/2$ is the average error of the measurement of the quantity Q . The smaller the error on Q , and the greater the absolute value of the difference $|Q(\tau_{i+1}) - Q(\tau_i)|$, the smaller the error on the lifetime. Implemented methods and corresponding to them quantities Q are listed below.

1. *ECAL counting* method (sensitivity shown with the solid squares connected by a dashed line) relies on the Q -quantity being the number of non-pointing photons detected by calorimeters (Sec. 6.2.3).
2. *μ CAL counting* method (solid triangles connected by a dotted line) refers to the Q -quantity being the number of the late decays detected by the observation of an accumulation of hits in one muon station (Sec. 6.2.2).
3. *ECAL/ μ CAL* method (solid bullets connected by a dash-dotted line) relies on the Q -quantity being the ratio of events tagged by ECAL and μ CAL.
4. *ECAL impact* method (empty squares connected by a dashed line) uses the Q -quantity being the mean value of the impact parameter distributions of tagged by ECAL non-pointing photons (such distributions are shown in Figure 6.12 at the top of the page 80).
5. *μ CAL slope* method (empty triangles connected by a dotted line) uses the Q -quantity being the slope of the ratio of the distribution of the flight path measured by the muon system to the reference distribution (Figure 6.9 at the top of the page 77).
6. Finally the combined sensitivity is shown with the encircled solid stars (the *sheriff stars*) connected by the solid line.

For the derivation of the sensitivity of the simple counting methods (solid squares for the ECAL and solid triangles for the μ CAL) we assume that the overall supersymmetry cross-section is known with a factor of 2 accuracy. The performance of such counting experiments depends heavily on this assumption. If the knowledge of the overall cross-section will be better the method will perform also better and vice verse.

For the rest of methods no prior knowledge on the overall supersymmetry production rate is required.

It can be seen that both CMS systems: calorimetry (solid and empty squares connected by dashed lines) as well as muon chambers (solid and empty triangles connected by dotted lines), can perform a lifetime estimation over a wide range of $\tilde{N}_1$ lifetimes.

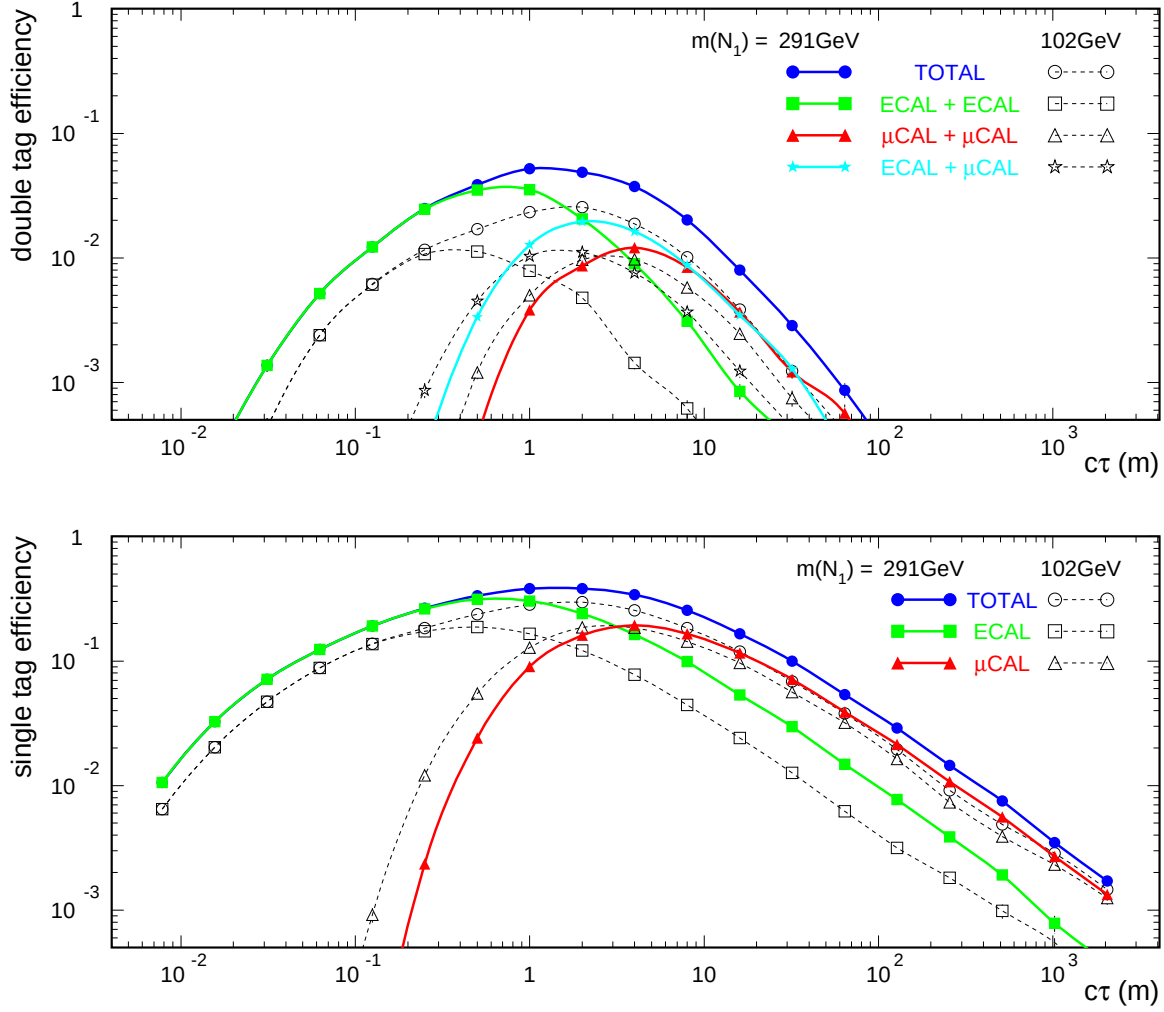


Figure 6.15: Combined $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ decay detection efficiency. (See text for explanations.)

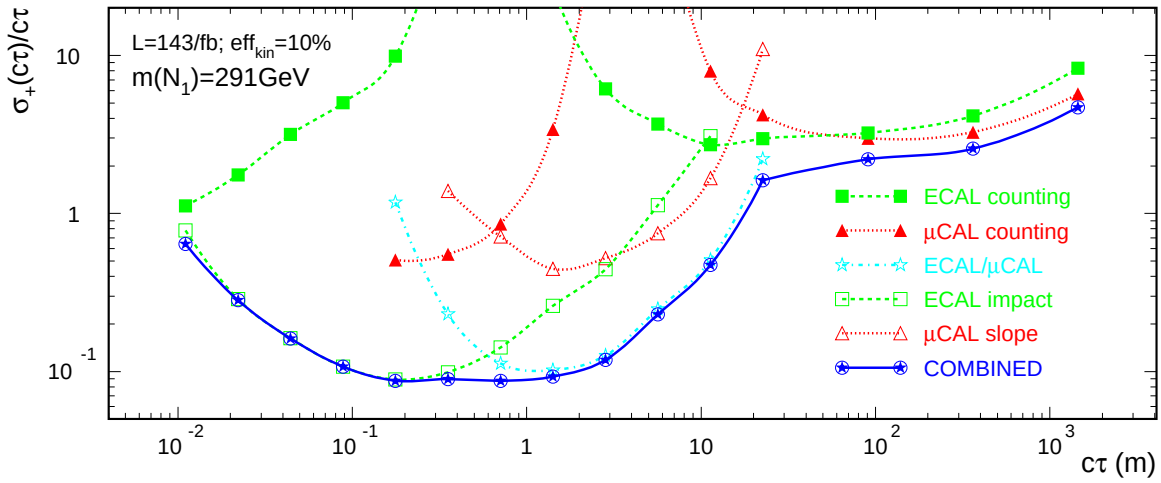


Figure 6.16: CMS sensitivity to $\tilde{N}_1$ lifetime. (See text for explanations.)

The impact parameter measurement in the ECAL is a method which is sensitive to small lifetimes down to $c\tau = 1$ cm. For even smaller lifetimes the ECAL counting method could be better. However, with the initial assumption that we have selected about 1000 signal events we expect for such lifetime only a few photons to be tagged as non-pointing. With 1000 events the sensitivity stops at that point. We should notice, that at the edge of the resolution the systematic effects (not taken into account in the present evaluation) dominate the accuracy of lifetime estimate. It means that the sensitivity for the smallest lifetimes shown in Figure 6.16 is worse.

At $c\tau$ of about 20 cm the μ CAL starts to be sensitive. First as a counting device, but already at about $c\tau = 1$ m the slope measurement performs better. At $c\tau = 10$ m again counting method prevails. It is interesting to see that for such large lifetimes the ECAL counting methods performs almost as well as μ CAL counting one. The answer to this astonishing performance can be derived from a comparison of the shapes of curves displaying counting methods sensitivity with efficiency curves shown immediately above in Figure 6.15. The maximal efficiency correspond to the striking degradation of the counting method sensitivity. This is because the sensitivity of these methods is related to the ratio of the absolute value of derivative of the tagging efficiency to the total error. At the efficiency maximum the derivative is zero, and so counting gives no (local) sensitivity. On the other hand the performance of direct lifetime measurements is the best at the point of maximal efficiency.

It can also be noted that the most efficient method for the lifetimes from $c\tau = 60$ cm to 20 m is the ratio of events tagged by ECAL and μ CAL. This method does not suffer from the necessity of a prior knowledge of the overall supersymmetry cross-section but is exposed to the difference in systematic effects specific for ECAL and μ CAL separately. It introduces an additional (and not possible to evaluate without full detector simulation) systematic error, but on the other hand allows to cross-check the performance of both considered systems.

Finally, the maximal lifetime we are sensitive to is around $c\tau = 1$ km. We are able to estimate it with an order of magnitude accuracy. Above this point the detection efficiency falls below 10^{-3} .

To summarize this Section we can say that CMS detector is able to estimate/measure the $\tilde{N}_1$ lifetime with a sample of 1000 signal events. At $c\tau \sim 1$ cm, the precision is about 0.7. The performance improves for greater lifetimes, and from $c\tau = 10$ cm to 3 m we find the best sensitivity of 10%. For greater lifetimes the resolution gradually decreases. From 20 m to about 1 km the accuracy is expected to change from a factor of two to a factor of 5. (The factor of two precision means, that $(\sigma_+(c\tau))/c\tau = 2$.)

6.2.5 Detection of $\tilde{\tau}_1 \rightarrow \tilde{G}\tau$ decays

Detection of the long-lived $\tilde{\tau}_1$ was already discussed in the Section 6.1. In the present Section we would like to comment on a possibility to extend the methods developed for the search for $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ decay to $\tilde{\tau}_1 \rightarrow \tilde{G}\tau$ decays detection. In this case the final topology depends on the τ decay mode. There are three possibilities:

1. $\tau \rightarrow e$
2. $\tau \rightarrow \text{hadron}(s)$
3. $\tau \rightarrow \mu$

Let us consider them in a sequence.

$\tau \rightarrow e$

For the late decays this case is very similar to $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ decay. The electron created by late $\tilde{\tau}_1$ decay produces an electromagnetic shower inside the detector. The only difference lays in the energy of the shower. Electron takes in average only one third of the tau lepton energy. It means that the acceptance is about $\sqrt{3}$ smaller. On the other hand, if the decay happens after at least one barrel muon station, then the method developed for the long-lived staus (Sec. 6.1) can be used. There are two possible signatures:

delayed track seen in one to three barrel muon stations causes accumulation of hits in the next station;

delayed track seen in one to three barrel muon stations disappears in the iron. Both signatures are subject to an instrumental background (chamber inefficiency) as well as a physical one (i.e. muon induced electromagnetic showers).

On the other hand an appearance of a non-pointing energetic electron in the middle of the central tracker is very spectacular. The impact parameter can be measured with a great precision. It means, that for small values of the NLSP lifetimes, a scenario with stau NLSP allows for more precise $c\tau$ determination. Since impact parameters of the order of tens of microns can be measured, the lower edge of the lifetime sensitivity extends down by about two orders of magnitude.

$\tau \rightarrow \text{hadron(s)}$

From the point of view of μCAL method application this case is different from the previous one by the fact that the electromagnetic shower is replaced by a hadronic one. Hadronic shower may extend over more than one muon station. It could enlarge the acceptance but also the level of background.

For decays inside the central tracker there are three kinds of hadronic decays of tau lepton to be considered.

One prong decays without neutral mesons. Only the impact parameter can be accurately measured.

One prong decays with one or more π^0 . It is similar to the $\tau \rightarrow e$ decay. The impact parameter can be precisely measured. For the energetic hadron a precise E/p measurement with the ECAL allows to distinguish between $\tau \rightarrow e$ and $\tau \rightarrow \pi\pi^0$ decays.

Three prong (multi prong) decays. In this case a reconstruction of the secondary vertex is affordable. The lifetime measurement is the most precise, but less effective, because only about one out of ten taus decays into three prongs.

$\tau \rightarrow \mu$

The only signature of this channel is a kink on the charged track trajectory, or impact parameter of the muon track. The precision of the impact parameter measurement depends on the precision of the determination of the interaction point. In this case precise impact parameter measurement give the same possibilities as in the case of electrons in the final state. Muon identification allows for further background suppression.

Performance in the $\tilde{\tau}_1 \rightarrow \tilde{G}\tau$ channel

It is evident that $\tilde{\tau}_1 \rightarrow \tilde{G}\tau$ decays gives similar to $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ channel performance. The efficiency reduction due to larger missing energy taken off by neutrinos is compensated by more precise impact parameter determination for small lifetimes and time of flight signature for late decays or non-decaying inside the detector status.

Summary

In the thesis the visibility of the most characteristic signatures of the GMSB SuperSYmmetry in the CMS detector at the LHC was investigated.

In Section 5 the method using the end-point in the difference of invariant mass distributions of the same and different flavour leptons $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$ was described. Next, it was used for the wide range of the GMSB parameter space and particles masses. Accessible ranges of GMSB parameters: N , $\Lambda = F/M$, M , $\tan\beta$, $\text{sign}(\mu)$ are presented in plots in the Figures 5.18 and 5.19–5.23. The visibility of this spectacular signature depends not only on the interplay between the overall GMSB SUSY cross-section and integrated luminosity, but also on the properties of the sparticle decays. In particular these signatures will not be visible if stau is much lighter than other sleptons. Such situation occurs for large $\tan\beta$ and/or large M/Λ .

In Section 6.1 the detailed simulation of the CMS detector was used to show that the Drift Tubes of the barrel Muon System could be used to measure the time of flight of the long-lived weakly interacting charged particles with 1 ns precision. Such measurement allows to extract very clean signal of long-lived stau NLSP. With 100/fb of integrated luminosity it is possible to discover the GMSB SUSY and estimate stau mass even if its overall cross-section is as small as 1 fb. Such cross-section corresponds to squark and gluino masses of the order of 4 TeV/c² in GMSB models.

In Section 6.2.2 the possibility of detecting late $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ decays in the Muon System of the CMS detector was described. The visibility of non-pointing photons in the CMS detector calorimetry was studied in Section 6.2.3. In Section 6.2.4 it was shown that combining the information from the calorimetry and the muon system of the CMS detector it is possible to estimate the lifetime of the $\tilde{N}_1$. The relative precision of such estimate changes from 0.7 at $c\tau = 1$ cm to 0.1 in the $c\tau$ range from 10 cm to 1 m. At $c\tau = 100$ m the precision deteriorates to a factor of 2 and at $c\tau = 1$ km to a factor of 5. Accessible range of $c\tau$ spans over 5 orders of magnitude. In the case of very long lifetime ($c\tau$ in a kilometers range) a lower limit at the level of $c\tau > 100$ m can be obtained. In the opposite case of very short lifetimes ($c\tau < 1$ cm) the lower limit at $c\tau < 10$ cm is affordable.

Presented study leads to the conclusion that the CMS detector can cope with unusual signatures like semi-relativistic ($\beta < 1$) particles and non-pointing photons. This enlarges spectrum of features that can be used for the exploration of physics beyond the Standard Model. In particular it was shown, that all signatures specific to the GMSB SUSY, can be observed for a wide range of model parameters.

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To My Family and Friends.

How good that you have been.

I believe You are still there.

How good that you have been patiently waiting without any inquiries.

Appendix A

Supersymmetric Flavour Conserving Mixing

Below the tree-level mass matrices are given [93].

A.1 Slepton Mixing

Every fermion has two bosonic supersymmetric partners, which are the scalar interaction eigenstates $\tilde{f}_L, \tilde{f}_R$ referred to the $SU(2)$ doublet of left- and right-handed fermions. In general, those eigenstates are not the mass eigenstates. However, the left-right mixing is substantial for the third generation of sfermions $f \in \{t, b, \tau\}$. Respectively, mass eigenstates $\tilde{f}_1, \tilde{f}_2$ correspond to lighter and heavier mass eigenstates.

The mass matrix, if flavour mixing among sfermions is neglected, is given in the $(\tilde{f}_L, \tilde{f}_R)$ basis by:

$$\mathcal{M}_{\tilde{f}}^2 = \begin{pmatrix} \tilde{m}_{\tilde{f}_L}^2 + m_f^2 + m_Z^2 \cos 2\beta (\sin^2 \theta_W - 1/2) & m_f (A_f - \mu \tan \beta) \\ m_f (A_f - \mu \tan \beta) & \tilde{m}_{\tilde{f}_R}^2 + m_f^2 - m_Z^2 \cos 2\beta \sin^2 \theta_W \end{pmatrix}. \quad (\text{A.1})$$

The first term of the diagonal elements is the soft scalar mass term evaluated at the weak scale, and the second is the mass squared of the the corresponding slepton, and the last comes from the the Higgs electroweak symmetry breaking. $\tan \beta$ is the ratio v_2/v_1 of the vacuum expectation values of the two neutral Higgs fields and μ is the supersymmetric higgsino mass parameter describing the mixing of two Higgs doublets. The trilinear term A_f causing left-right mixing is due to the soft-breaking Yukawa-type interaction. $\sin \theta_W$ is known as a Weinberg's angle.

The sfermion mass eigenstates can be obtained by diagonalizing the above mass matrix with a unitary matrix.

Above mass matrix stand for sleptons. Matrices for squarks stop $\tilde{t}$ and sbottom $\tilde{b}$ differ by coefficients standing before $\sin^2 \theta_W$ ($2/3$ for $\tilde{t}$ and $1/3$ for $\tilde{b}$) and for $\tilde{t}$ one has $\cot \beta$ instead of $\tan \beta$.

A.2 Chargino Mixing

In supersymmetric theories, the spin-1/2 partners of the W bosons and the charged Higgs bosons, $\widetilde{W}^\pm$ and $\widetilde{H}^\pm$, mix to form chargino mass eigenstates $\widetilde{C}_{1,2}^\pm$. The chargino mass matrix is given

in the $(\widetilde{W}^-, \widetilde{H}^-)$ basis by:

$$\mathcal{M}_{\widetilde{C}} = \begin{pmatrix} M_2 & \sqrt{2}m_W \cos \beta \\ \sqrt{2}m_W \sin \beta & \mu \end{pmatrix}, \quad (\text{A.2})$$

which is built up by the fundamental SUSY parameters; the $SU(2)$ gaugino mass M_2 and the parameter μ and the ratio $\tan \beta$.

Since the chargino mass matrix $\mathcal{M}_C$ is not symmetric, two different unitary matrices acting on the left- and right- chiral $(\widetilde{W}, \widetilde{H})$ states are needed to diagonalize the matrix, in a way that $U_R \mathcal{M}_C U_L^\dagger = \text{diag}(m_{\widetilde{C}_1^\pm}, m_{\widetilde{C}_2^\pm})$ with the ordering $m_{\widetilde{C}_1^\pm} \leq m_{\widetilde{C}_2^\pm}$.

A.3 Neutralino Mixing

The neutral supersymmetric fermionic partners of the B and W^3 gauge bosons, $\widetilde{B}$ and $\widetilde{W}^3$, can mix with the neutral supersymmetric fermionic partners of the Higgs bosons, $\widetilde{H}_1^0$ and $\widetilde{H}_2^0$, to form the mass eigenstates. Hence the physical states, $\widetilde{N}_i$, called neutralinos, are found by diagonalizing the 4×4 mass matrix

in the $(\widetilde{B}, \widetilde{W}^3, \widetilde{H}_1^0, \widetilde{H}_2^0)$ basis:

$$\mathcal{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta s_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}, \quad (\text{A.3})$$

where $s_\beta = \sin \beta$, $c_\beta = \cos \beta$ and $s_W = \sin \theta$, $c_W = \cos \theta$. M_1 and M_2 are the gaugino mass parameters, corresponding to $U(1)$ and $SU(2)$ groups, respectively.

The neutralino mass matrix $\mathcal{M}_N$ is a complex, symmetric matrix so that it can be diagonalized by just one unitary matrix N such that $N^* \mathcal{M}_N N^\dagger = \text{diag}(m_{\widetilde{N}_1}, m_{\widetilde{N}_2}, m_{\widetilde{N}_3}, m_{\widetilde{N}_4})$ with the ordering $m_{\widetilde{N}_1} \leq m_{\widetilde{N}_2} \leq m_{\widetilde{N}_3} \leq m_{\widetilde{N}_4}$.

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