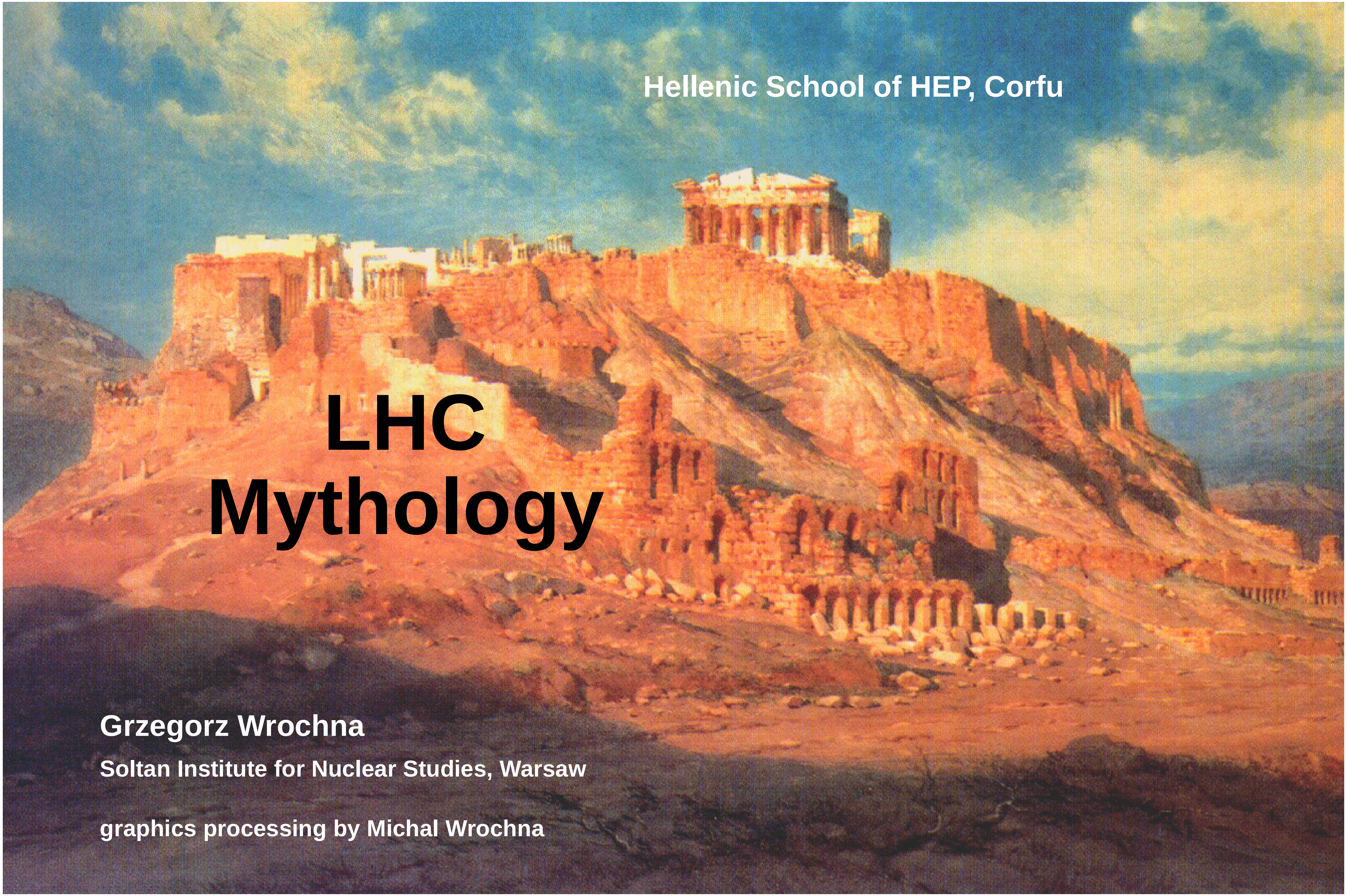


Hellenic School of HEP, Corfu

LHC Mythology

Grzegorz Wrochna

Soltan Institute for Nuclear Studies, Warsaw

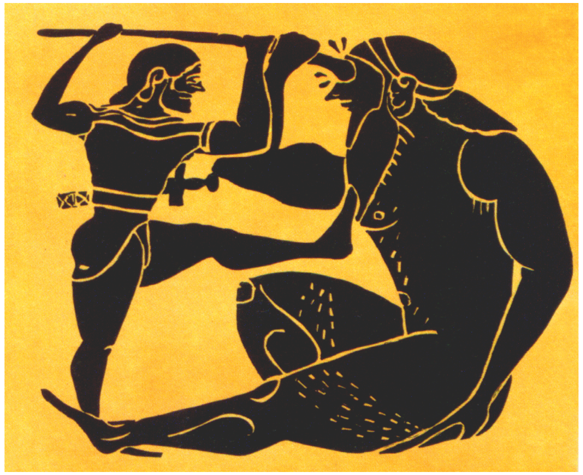
graphics processing by Michal Wrochna

6 stories about LHC physics

Hades - nothing, but SM

Trojan Horse - SM higgs

Pandora's box - SUSY



Odyssey - exotics

Sphinx - new physics

Olympus - extra dimensions

How to learn what will happen at LHC?

Ask PYTHIA !

Most of the results presented here comes from this source.

Particle physics today

The Standard Model precisely describes both electroweak and strong interactions. No significant deviation from its predictions was observed so far.

But:

- **it has ~20 free parameters**
- **particle masses are generated by Higgs mechanism, not determined within the Standard Model**
- **Higgs particle was not observed so far**
- **Standard Model does not explain**
  – existence of 3 generations of fermions
  – mixing between different generations

Strategy for the near future:

- **find Higgs particle or exclude its existence in the region allowed by theory (~1 TeV)**
- **look for deviations from the Standard Model**
- **search for new particles (~50 GeV — ~5 TeV)**

Needed tools

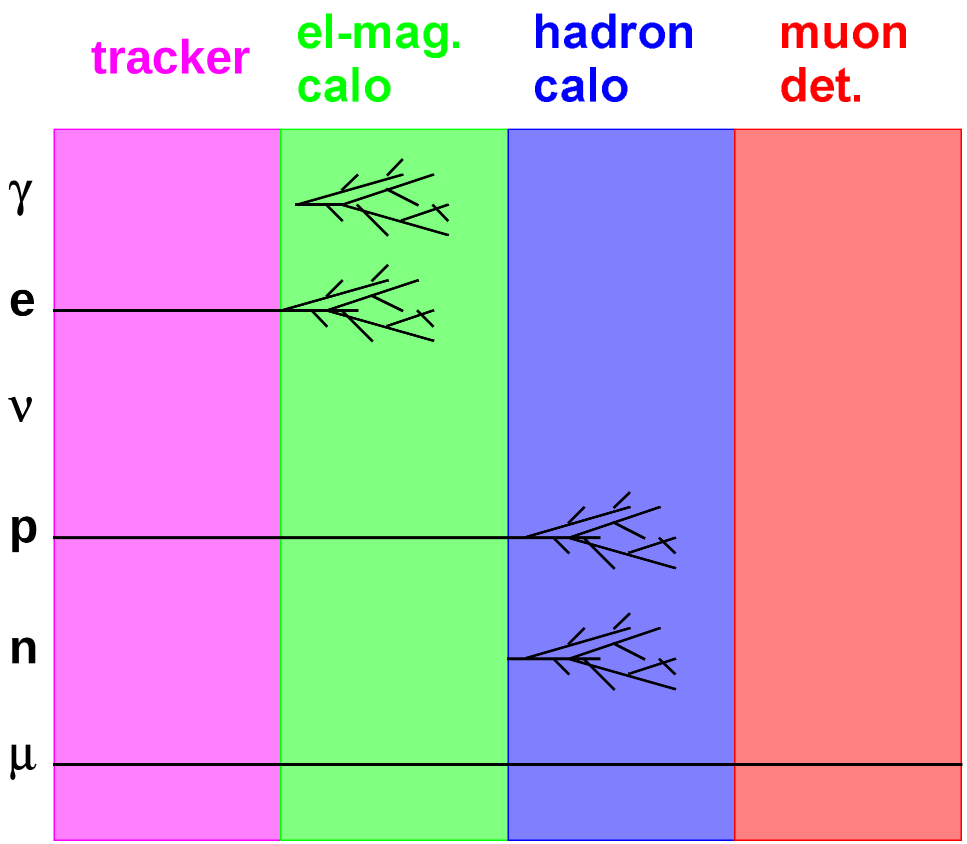
- **accelerator:** **LHC**
  – high energy: **14 TeV**
  – wide energy range "for free" in **pp beams**
  – high luminosity **$10^{34}cm^{-2}s^{-1}$**
- **detectors:** **ATLAS, CMS, LHC-B, ALICE**
  – universal (e, γ, μ, jets, missing energy)
  – fine grained (large number of particles): **~10^7 channels**
  – fast (high luminosity): **25 ns bunch crossing**


Area map of CERN site
Paris
Jura Mountain
SWITZERLAND
FRANCE
Nyon
LAC LEMAN
Divonne
Gex
CMS
ALEPH
OPAL
LHC
Versoix
N
Ferney Voltaire
St.Genis
L3
DELPHI
Airport
CERN
Meyrin
ATLAS
SWITZERLAND
FRANCE
GENEVA
Annemasse
Legend:
CERN sites
accelerator
LEP experiment
motorway
road
city
border
St. Julien
Lyon
0
5
km
Annecy (LAPP)
Chamonix (Mont Blanc)

Detectors (for theorists :-)

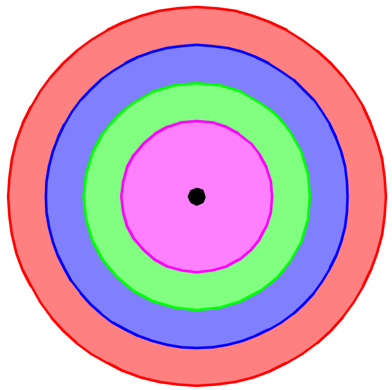
Only γ, $e^{\pm}$, $p^{\pm}$, n, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, K^{0}_{L} can be detected directly.

A universal detector must have four componetns to distinguish them:



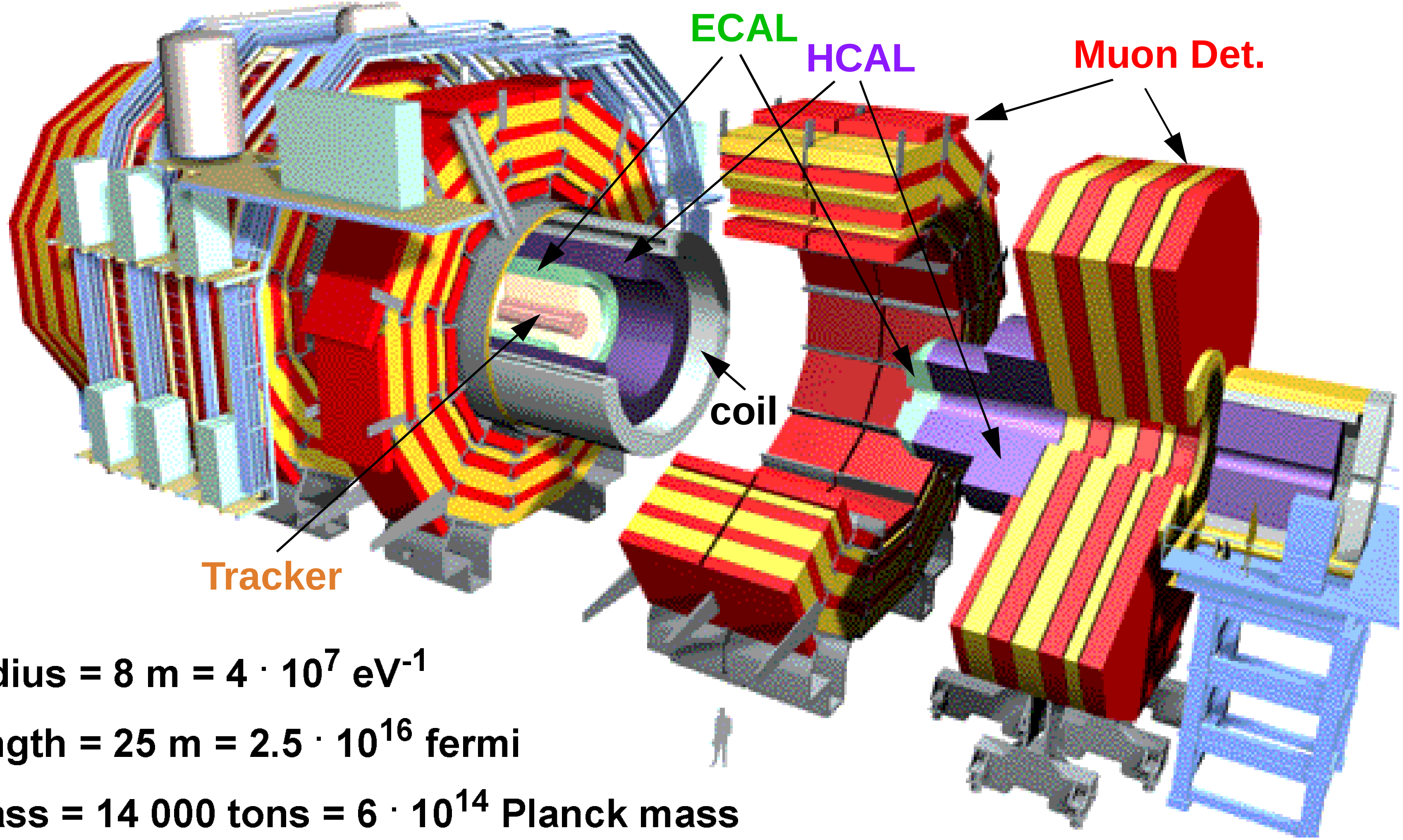
Usually the components are compactified to form a cylinder

(see e.g. Compact Muon Solenoid)



ATLAS uses similar approach, but it is compactified to larger dimensions.

Compact Muon Solenoid — CMS



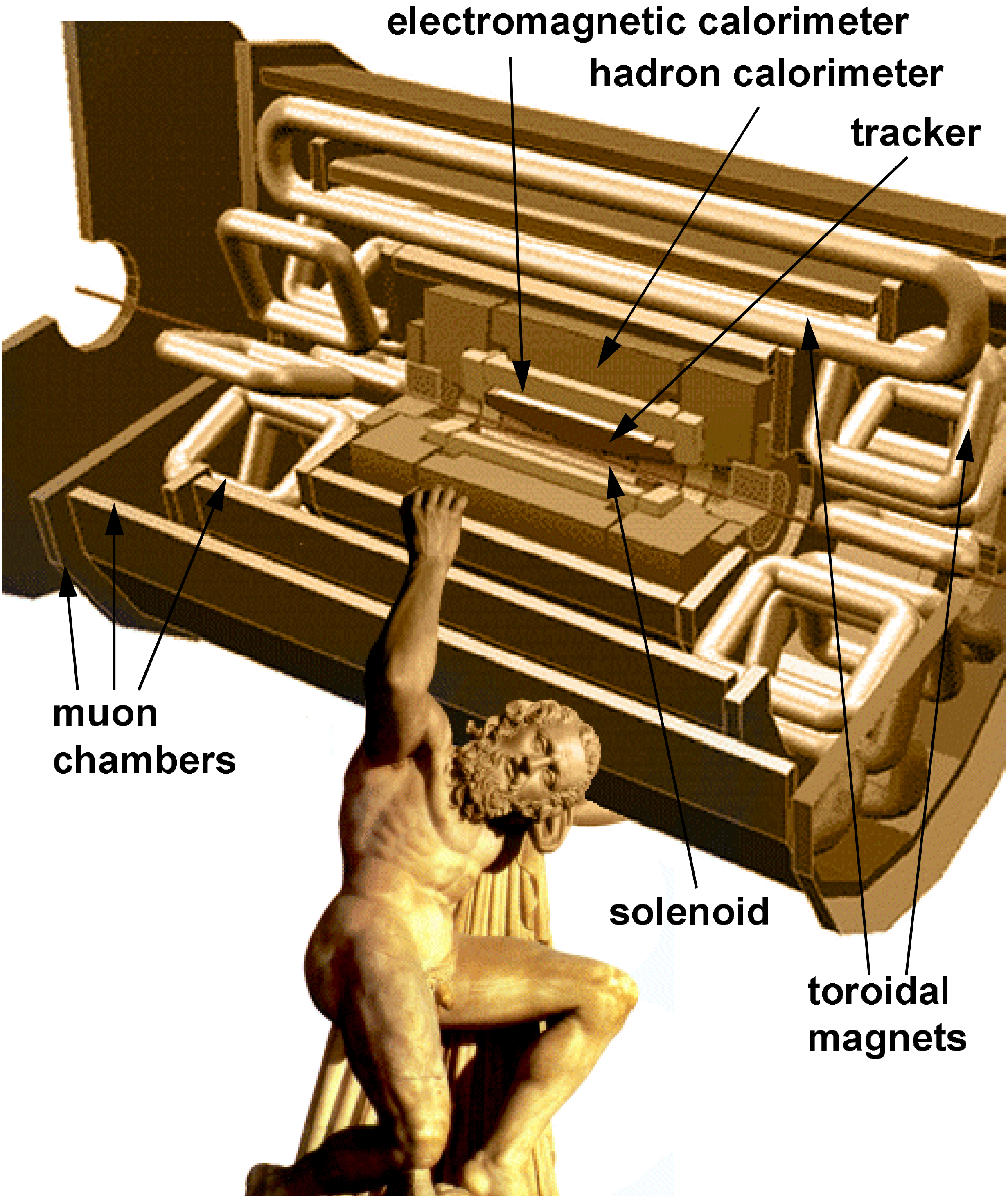
radius = 8 m = 4 · 10^7 eV^{-1}

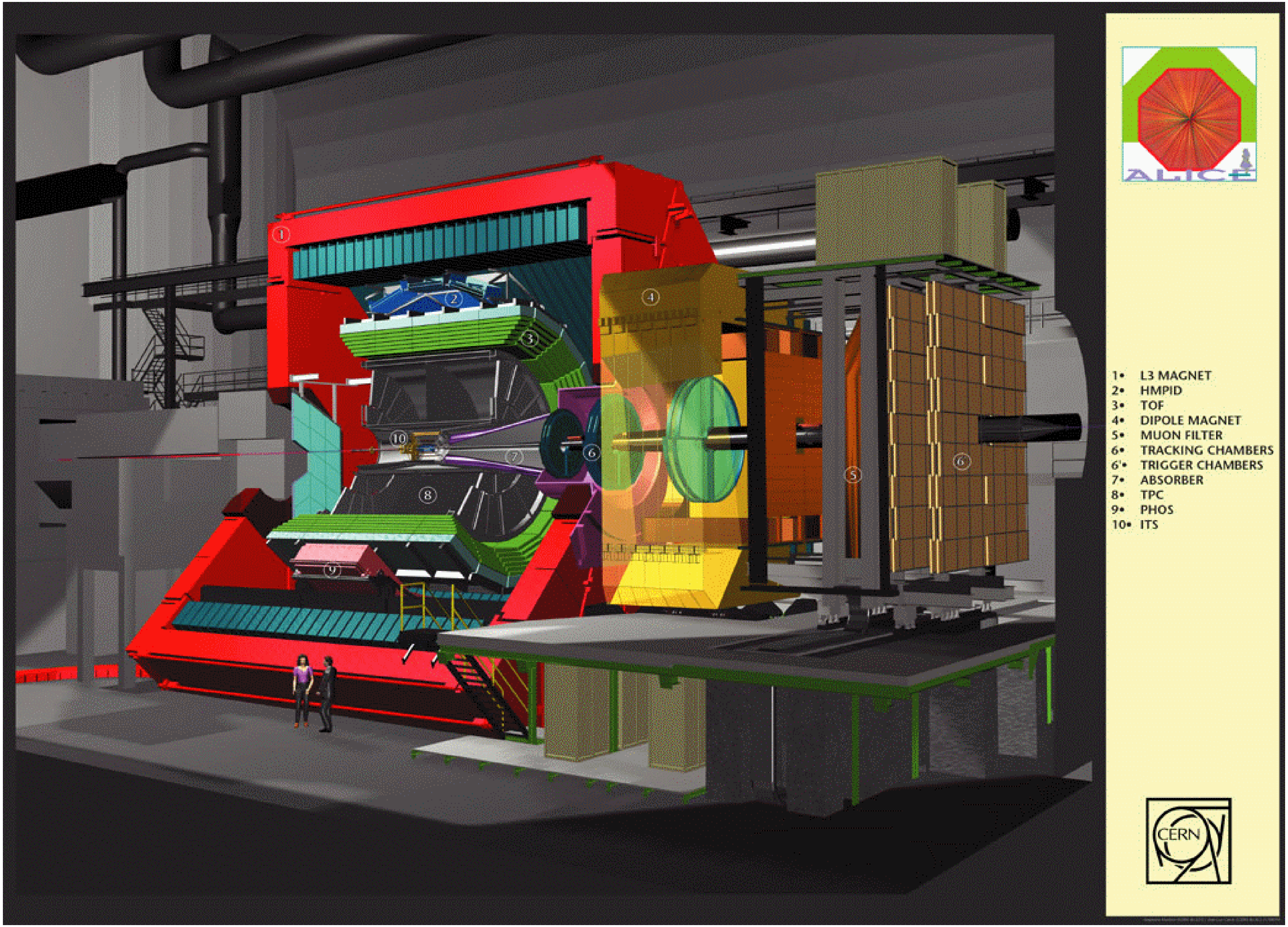
length = 25 m = 2.5 · 10^{16} fermi

mass = 14 000 tons = 6 · 10^{14} Planck mass

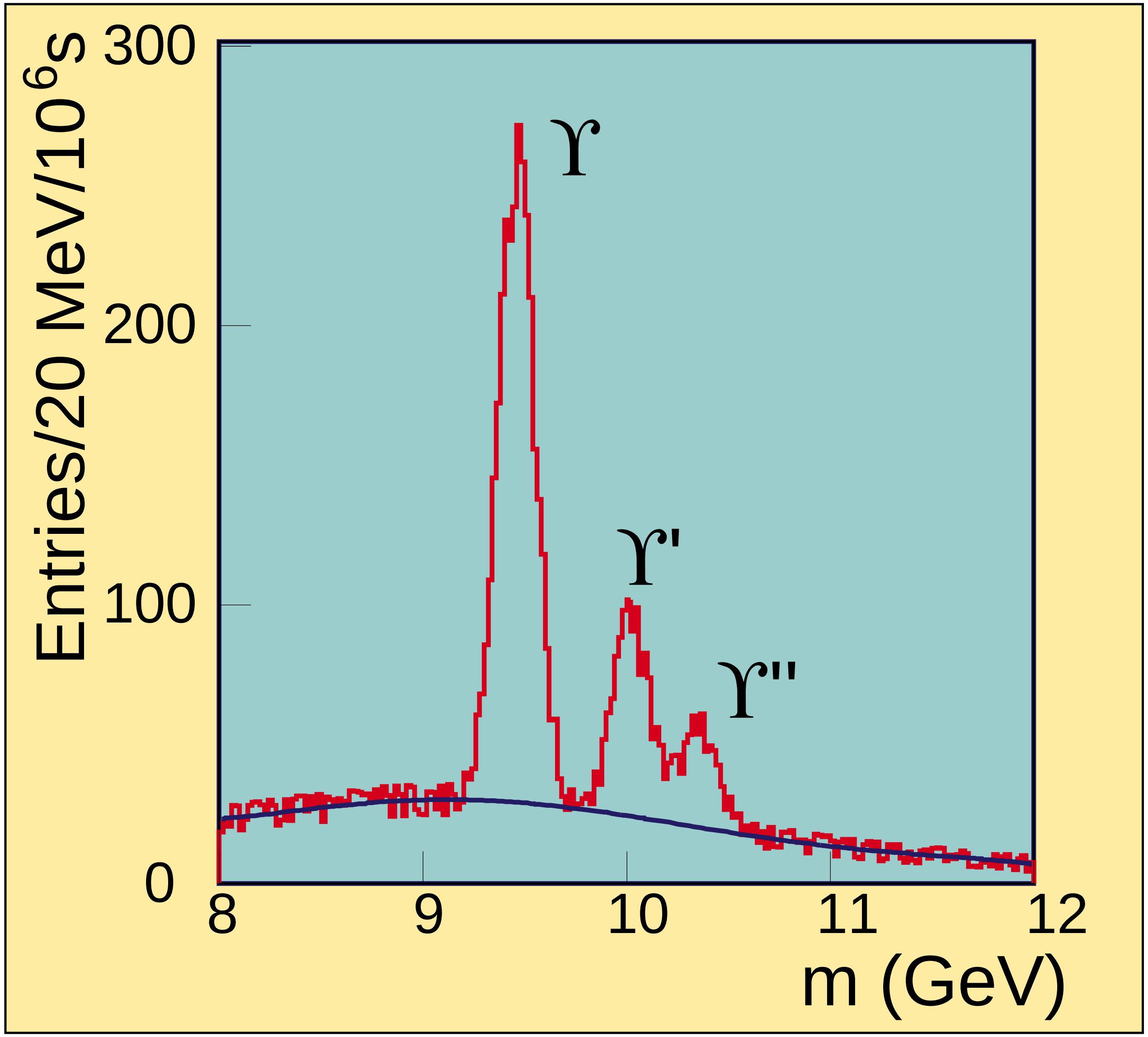
mag. field = 4 T

ATLAS


electromagnetic calorimeter
hadron calorimeter
tracker
muon
chambers
solenoid
toroidal
magnets


ALICE
1• L3 MAGNET
2• HMPID
3• TOF
4• DIPOLE MAGNET
5• MUON FILTER
6• TRACKING CHAMBERS
6'• TRIGGER CHAMBERS
7• ABSORBER
8• TPC
9• PHOS
10• ITS
CERN

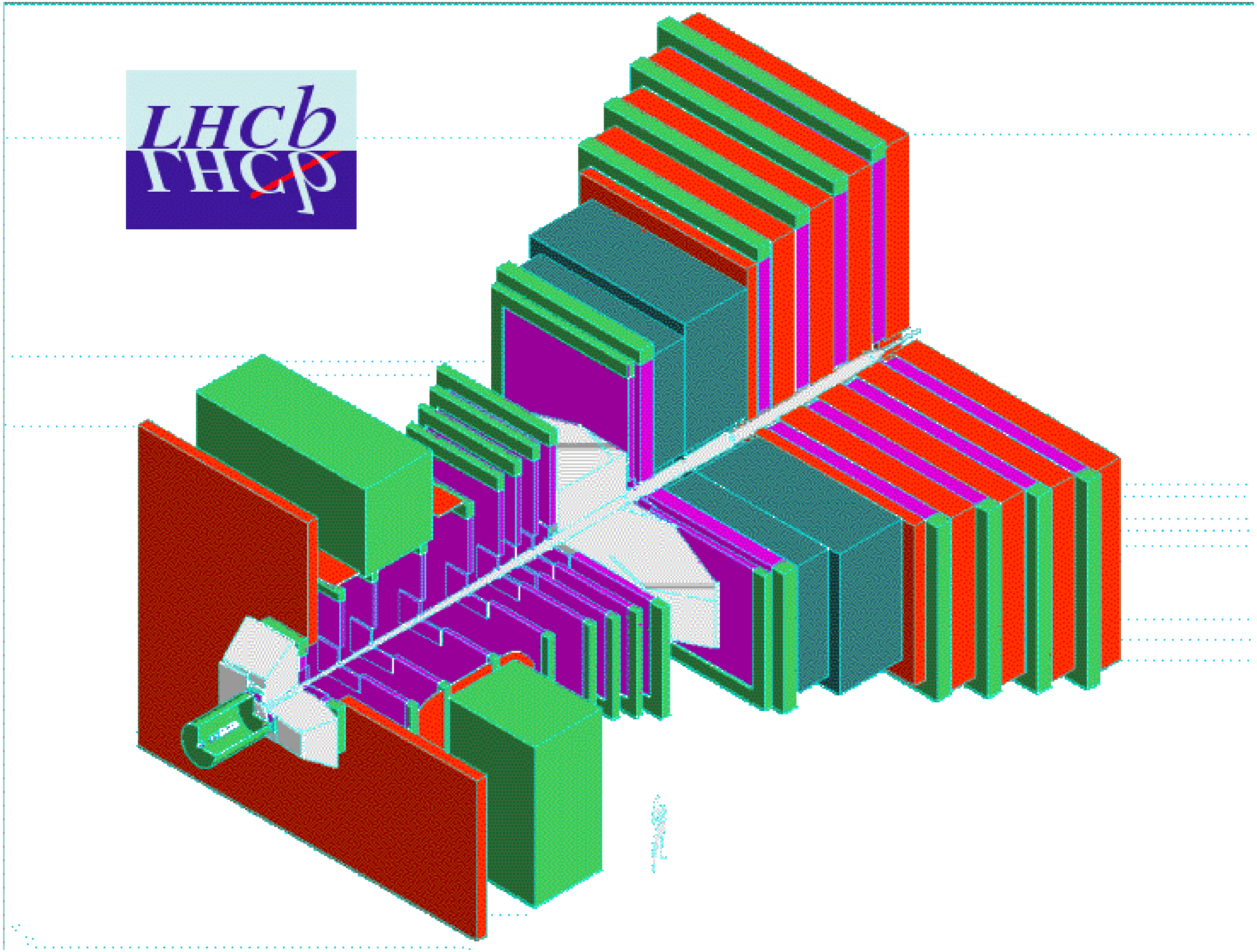
ϒ family: mass region



ALICE

mass spectra after one month of Pb-Pb running

Change in *Y, Y', Y''* production rates might be a sign of Quark-Gluon Plasma.


LHCb

CP Physics Performance (LoI)

LHCb

$L = 1.5 \times 10^{32}$ one year $= 10^{7}$ s

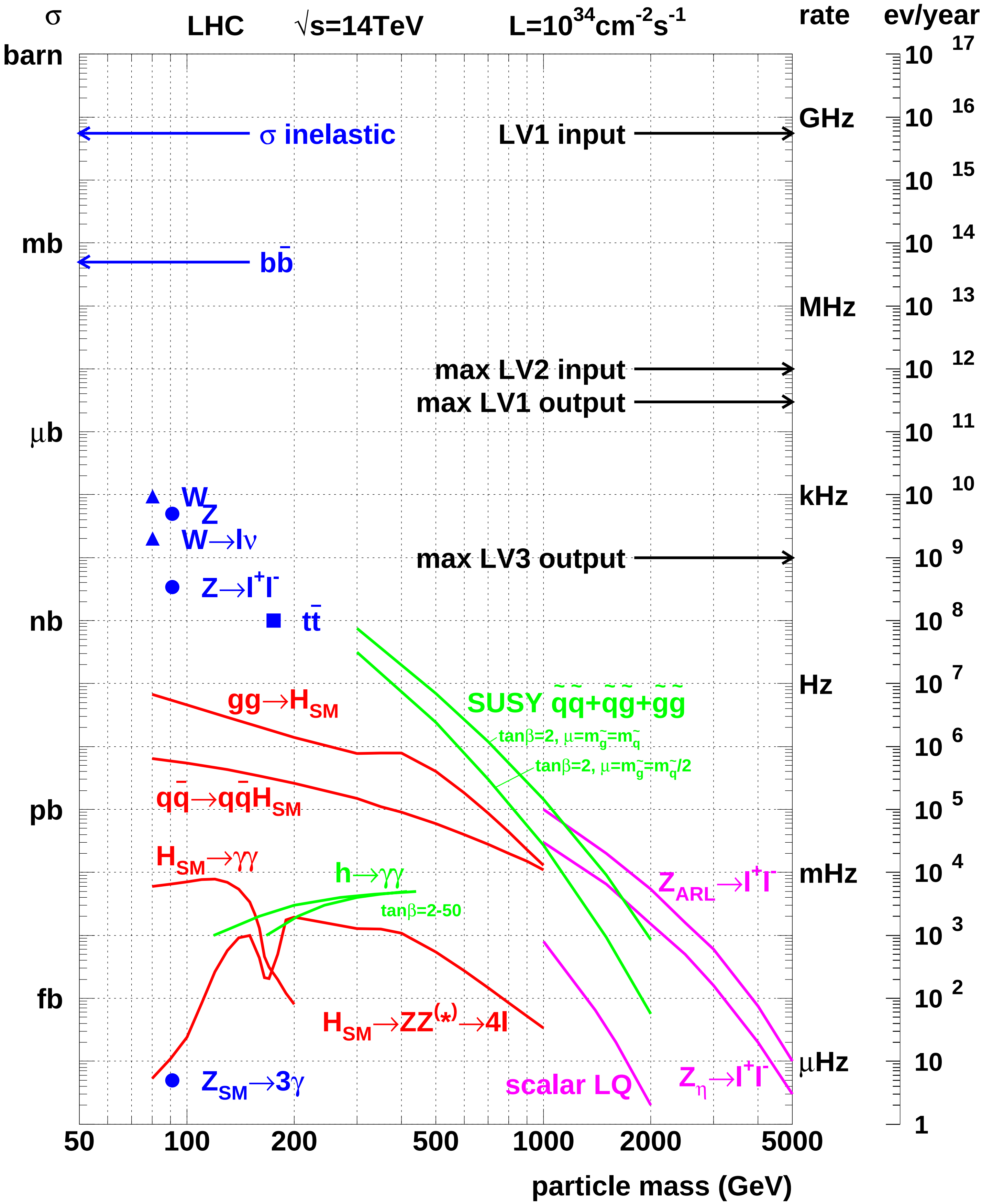
	decay mode	No. of events	uncertainty in one year
$\sin 2\alpha$	$B_d \to \pi^+\pi^-$	14 k	$\sigma(\sin 2\alpha) = 0.039$ (if no penguin)
$\sin 2\beta$	$B_d \to J/\psi K_S$	55 k	$\sigma(\sin 2\beta) = 0.023$ ATLAS: 0.017 CMS: 0.015
γ'	$B_s \to D_s K$	3.3 k	$\sigma(\gamma) = 6° \sim 16°$
γ	$B_d \to DK^*$	0.9 k	$\sigma(\gamma) = 7° \sim 12°$
$\sin 2\delta\gamma$	$B_s \to J/\psi\,\phi$	44 k	$\sigma(2\delta\gamma) \leq 0.02$
x_s	$B_s \to D_s\pi$	35 k	$x_s \leq 55$

- Our measurements are not systematic limited

(particle ID, good mass and decay time resolutions)

→ error will be reduced by $1/\sqrt{n(\text{years})}$

- LHC-B will run many years to study CP violation



σ
barn
LHC
√s=14TeV
L=10^34 cm^-2 s^-1
rate
ev/year
σ inelastic
LV1 input
GHz
mb
bb̄
MHz
max LV2 input
max LV1 output
μb
kHz
W
Z
W→lν
max LV3 output
Z→l+l-
nb
tt̄
Hz
gg→HSM
SUSY q̃q̃+q̃g̃+g̃g̃
tanβ=2, μ=mg̃=mq̃
tanβ=2, μ=mg̃=mq̃/2
qq̄→qq̄HSM
pb
HSM→γγ
h→γγ
tanβ=2-50
ZARL→l+l-
mHz
fb
HSM→ZZ(*)→4l
ZSM→3γ
scalar LQ
Zη→l+l-
μHz
50
100
200
500
1000
2000
5000
particle mass (GeV)
10 17
10 16
10 15
10 14
10 13
10 12
10 11
10 10
10 9
10 8
10 7
10 6
10 5
10 4
10 3
10 2
10
1

The Kingdom of Hades

Imagine, that nothing new will be discovered at LHC.

Not even the SM higgs.

Silent and empty Elysian Fields from 175 GeV to a few TeV ...

What will we do?

Standard Model at LHC

QCD

- **proton structure:** DY (incl. W & Z), jet & top production
- **min. bias studies:** σ_{tot}, particle spectra
- **jet structure and fragmentation, σ, α_S**
- **hard diffraction:** η-gaps, pomeron, ...
- **photon physics:** γ, $\gamma\gamma$, γj, γb γc
- **heavy flavour production**

electroweak physics

- **Wγ & WZ production**
- **W mass**
- **triple gauge couplings**

b-quark physics

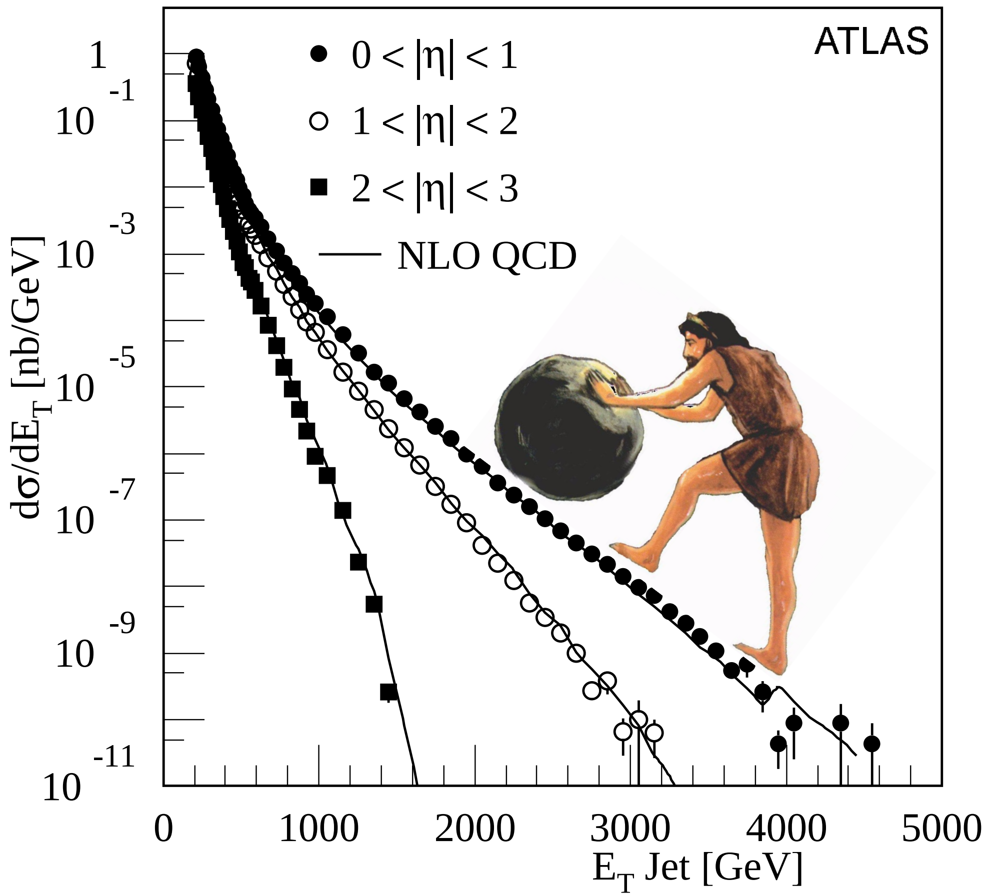
- **CP violation**
- **oscillations**
- **rare decays**

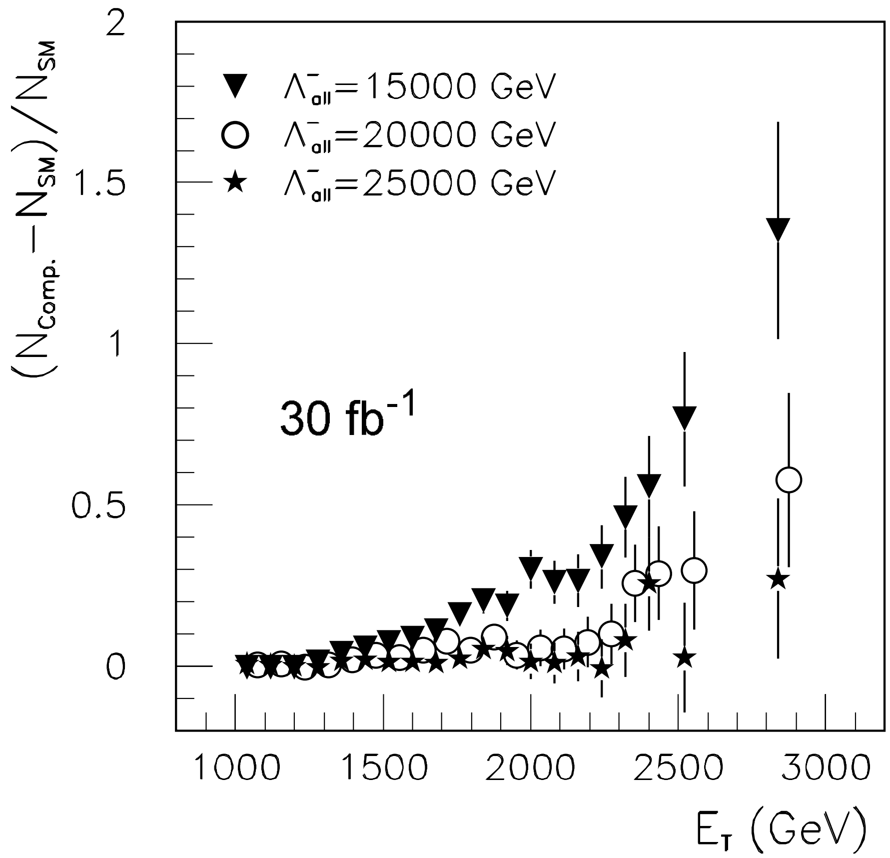
top quark physics

Is it a Sisyphus work? Hopefully not!

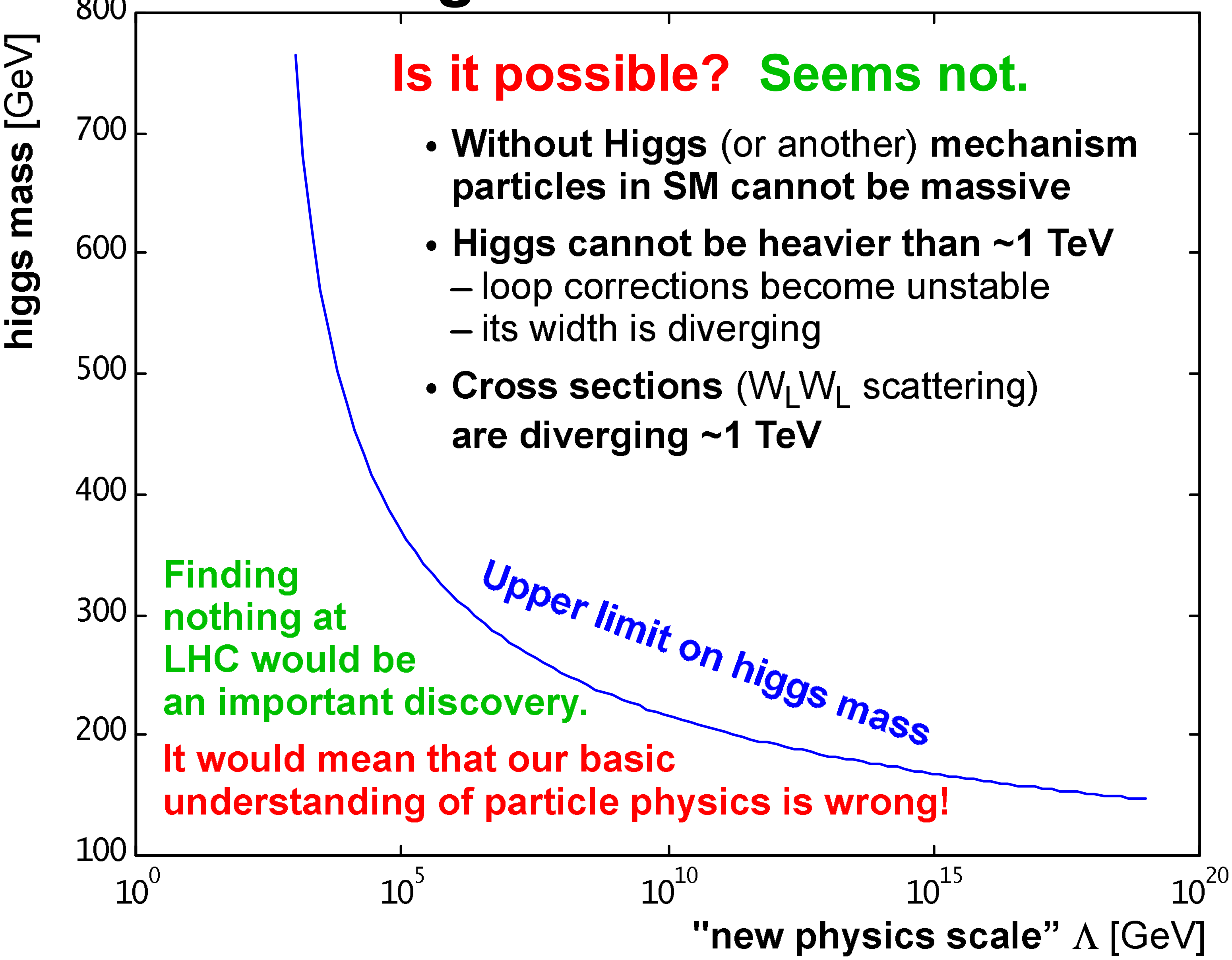
Jet spectra and compositness

Deviation from SM can be a sign of internal structure of quarks.

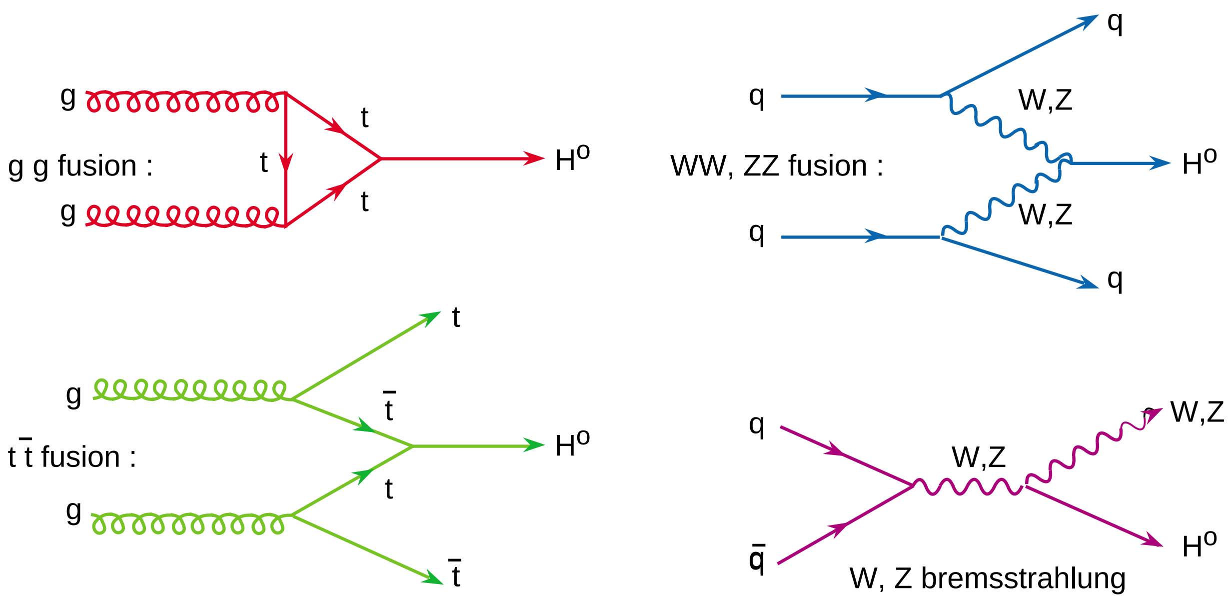


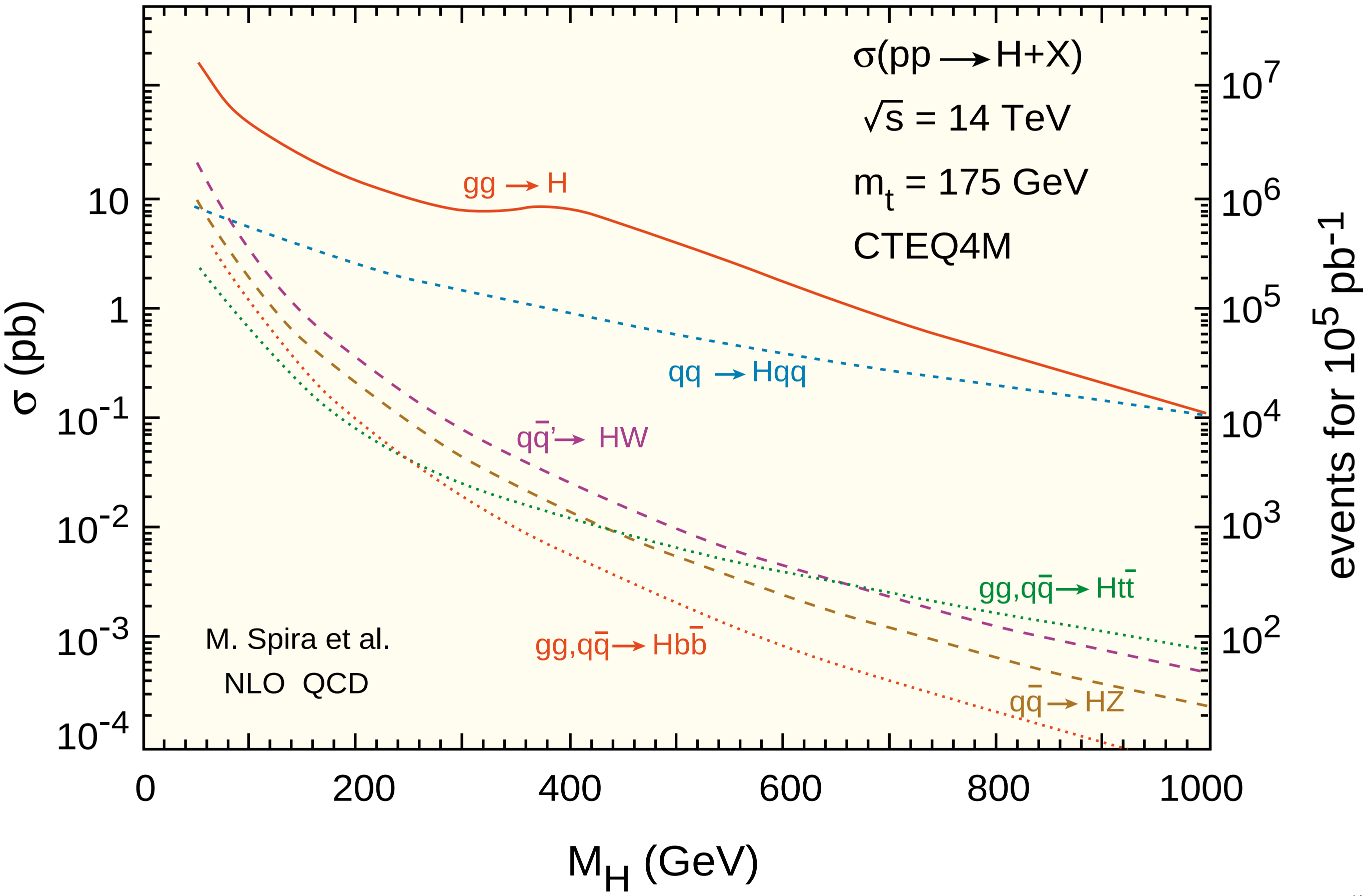


Nothing discovered at LHC ?



H^o production at hadron colliders:



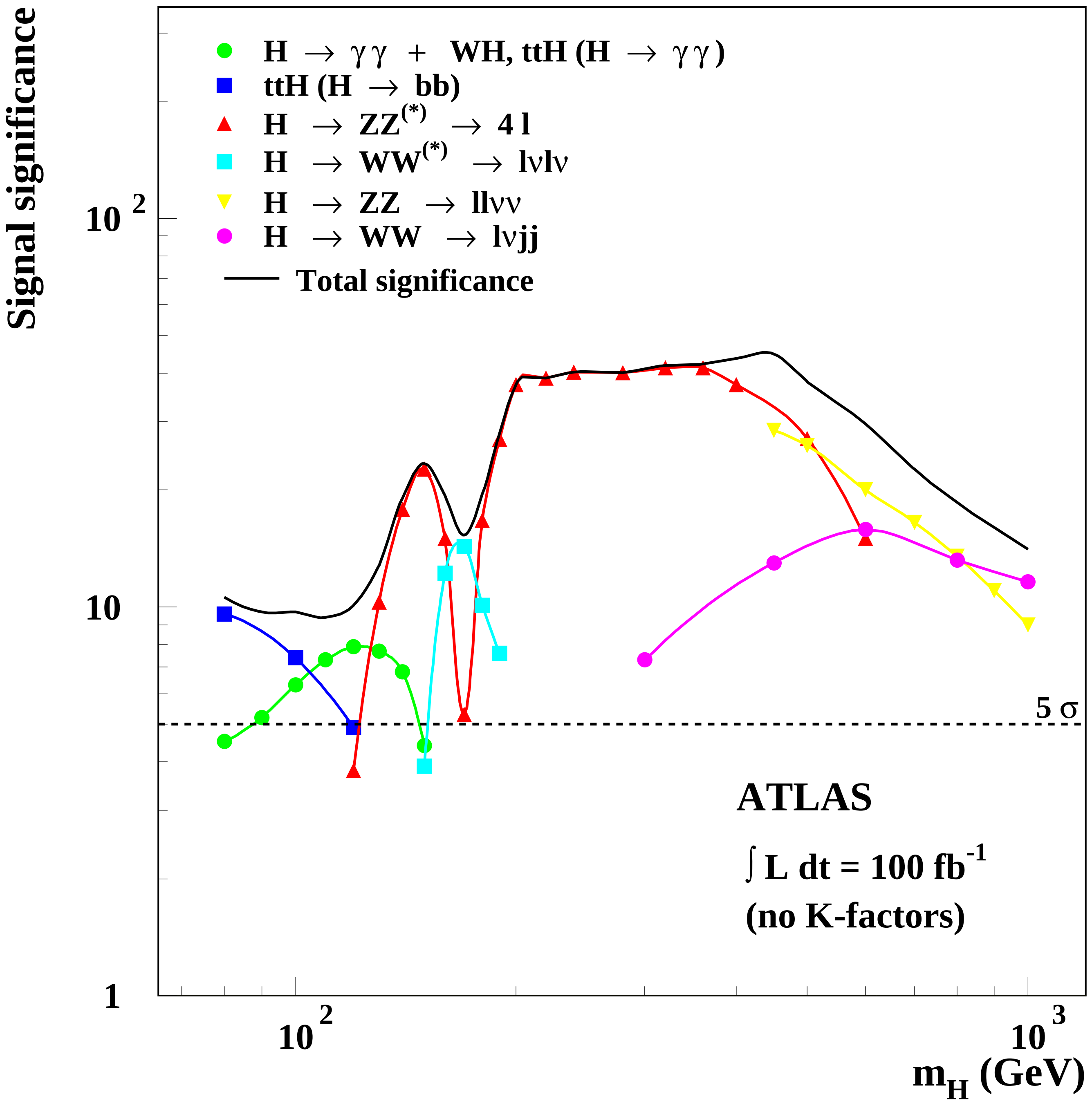


But : BR (H → Z¡Z¡ → 4l¯) = 1.4 ¥ 10^{-3}

BR (H → Z¡Z¡ → 4∝¯) = 3 ¥ 10^{-4}

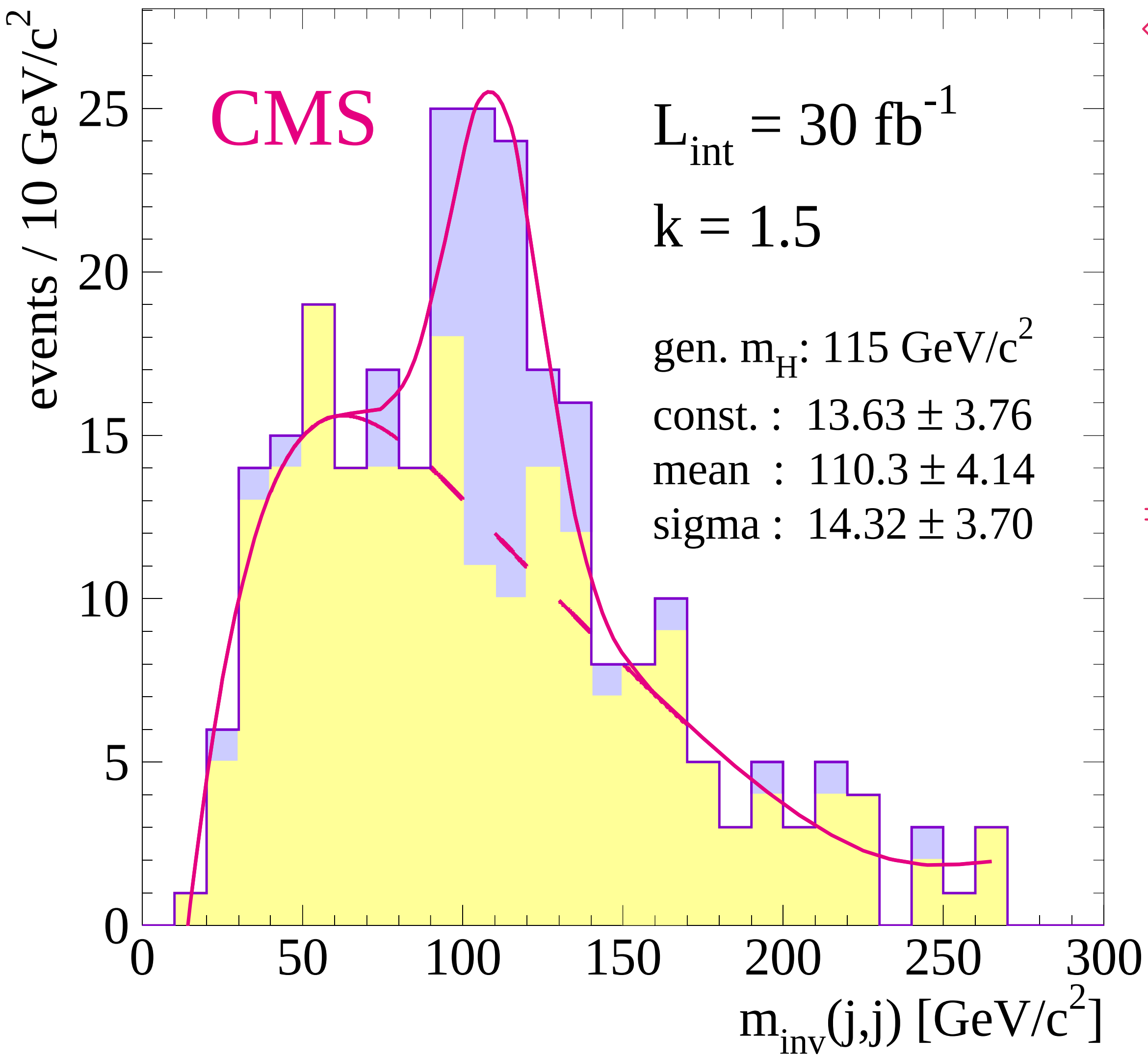
D_D_1186 .c

Standard Model Higgs



$$t\bar{t}H^0_{SM} \rightarrow l^{\pm}\nu q\bar{q}b\bar{b}b\bar{b}$$

$$m_{H^0} = 115\ GeV/c^2$$



◇ $90 < m < 130\ GeV/c^2$:

N_{H115}	=	38
$N_{t\bar{t}Z^0}$	=	3
$N_{t\bar{t}b\bar{b}}$	=	23
$N_{t\bar{t}jj}$	=	26
N_{BG}	=	52

⇒ results (stat.):

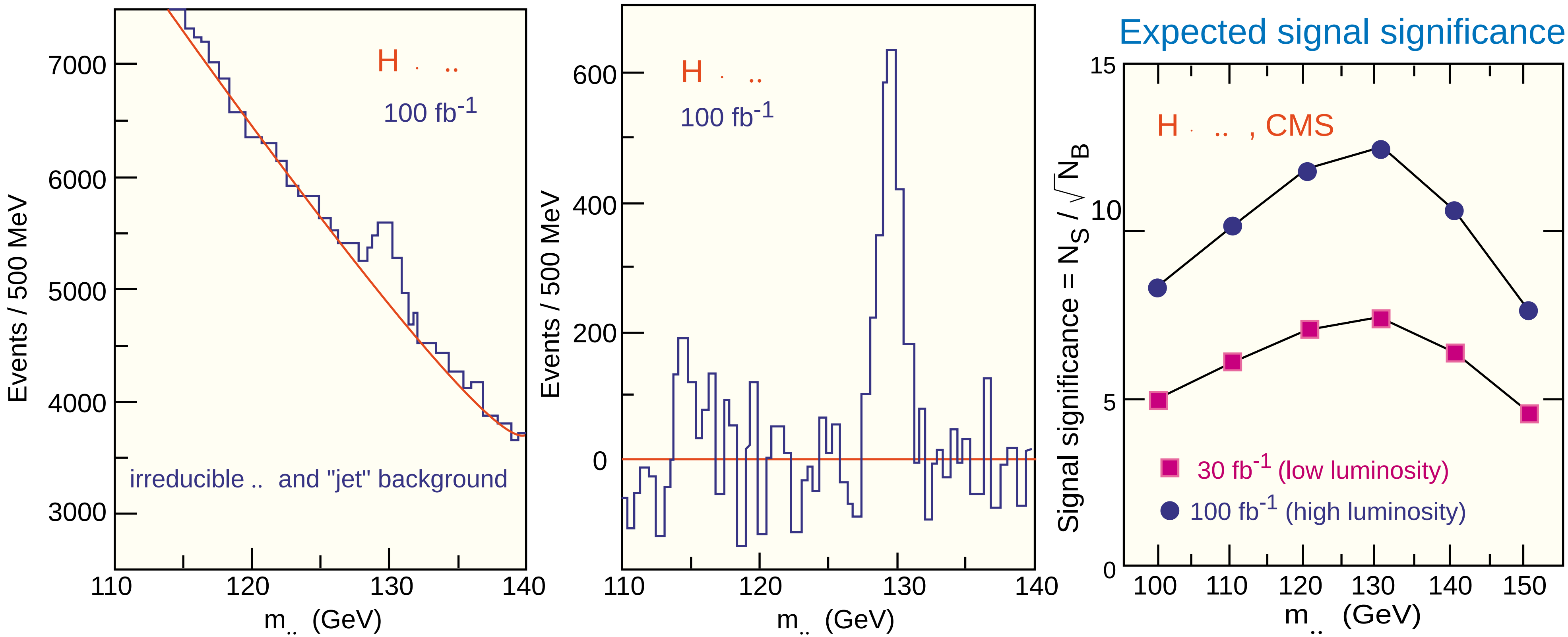
$S/B = 73\%$

$S/\sqrt{B} = 5.3$

$\Delta y_t/y_t = 13\%$

$\Delta m/m = 3.8\%$

H_{SM} .. in CMS $PbWO_4$ calorimeter



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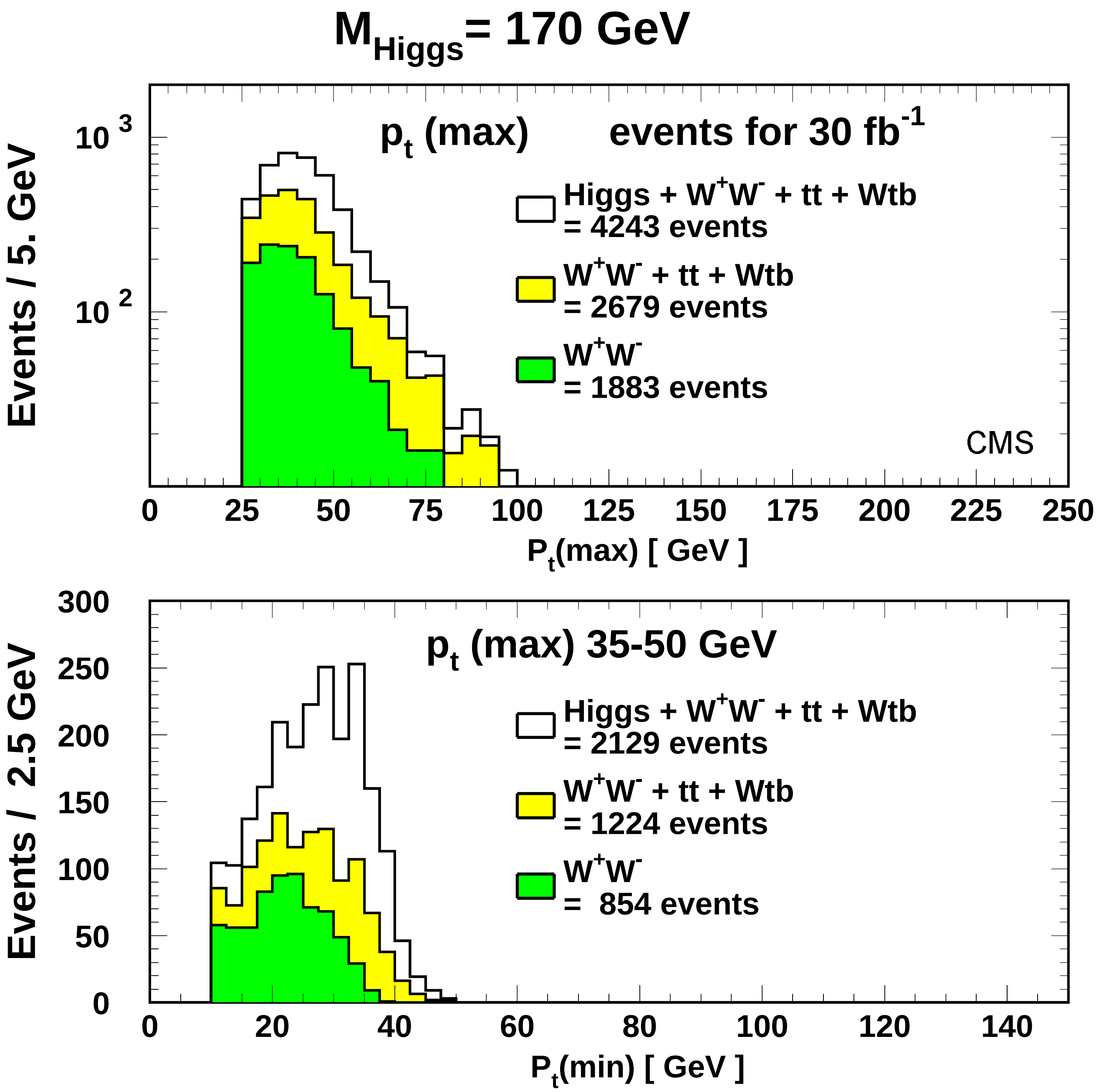
$H_{SM} \to WW \to l\nu\, l\nu$

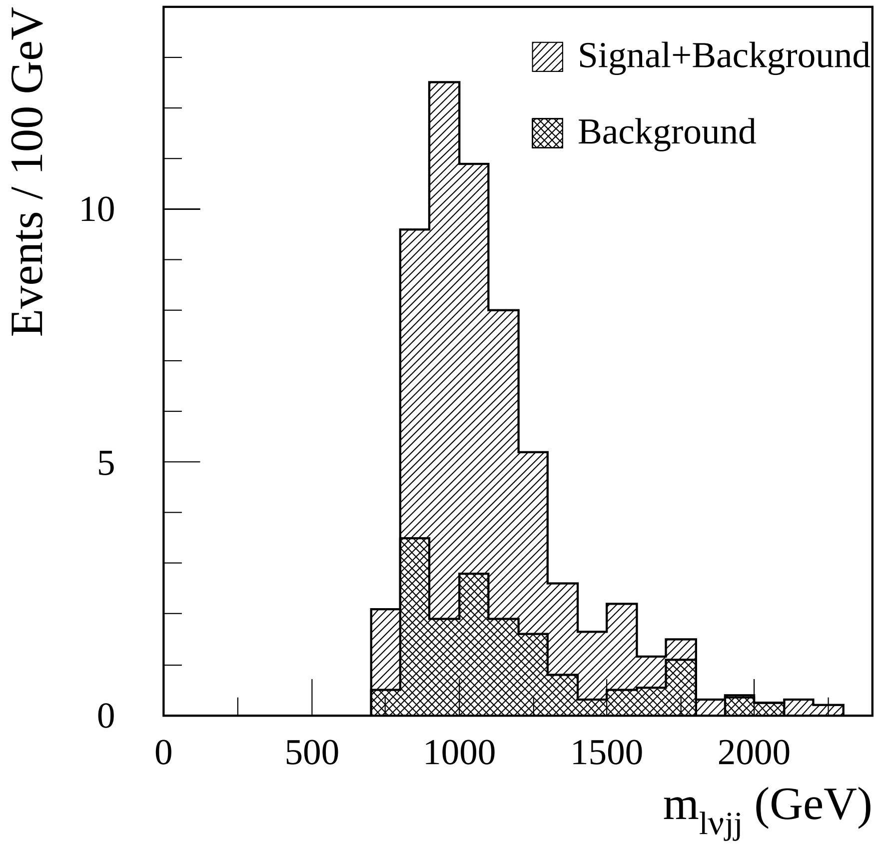
lepton p_T distributions



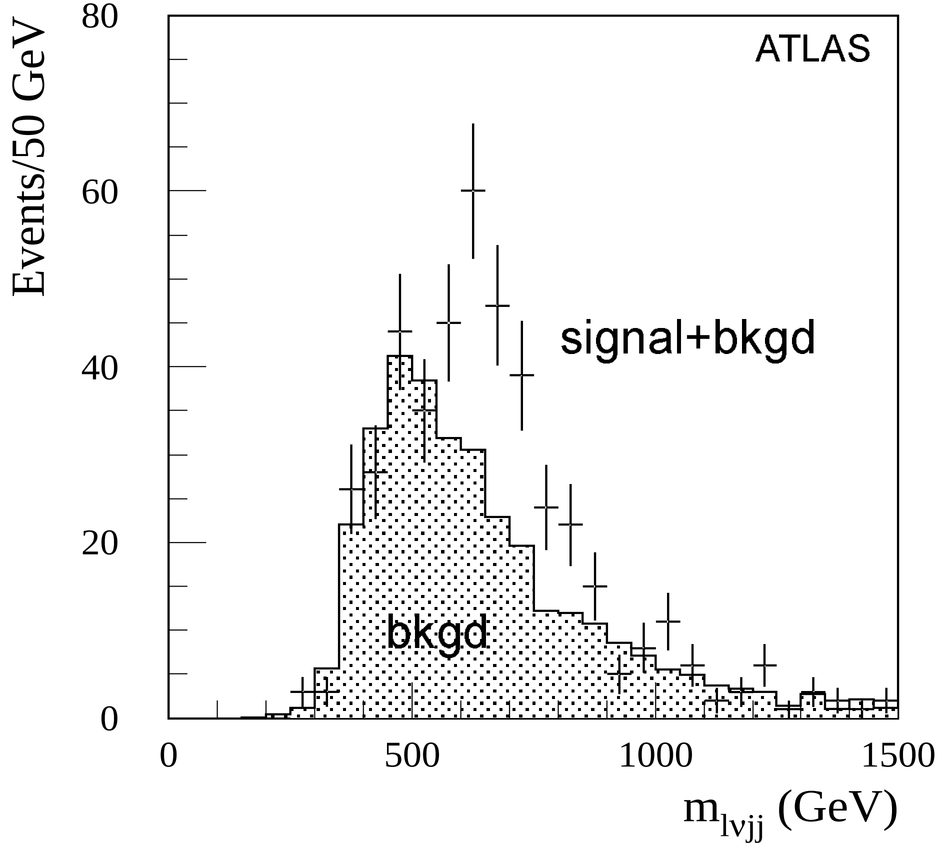
$H_{SM} \to WW \to l\nu\, jj$

30 fb^{-1}

M_H = 1000 GeV



M_H = 600 GeV



$H \to WW^{(*)} \to l\nu l\nu$ selection criteria

1. Two isolated leptons:

   $P_T^1 > 20$ GeV, $P_T^2 > 15$ GeV and $|\eta| < 2.5$;

2. Two tag jets:

   $P_T^1 > 40$ GeV, $P_T^2 > 20$ GeV and $\Delta\eta_{tags} = |\eta_{tag}^1 - \eta_{tag}^2| > 3.8$;

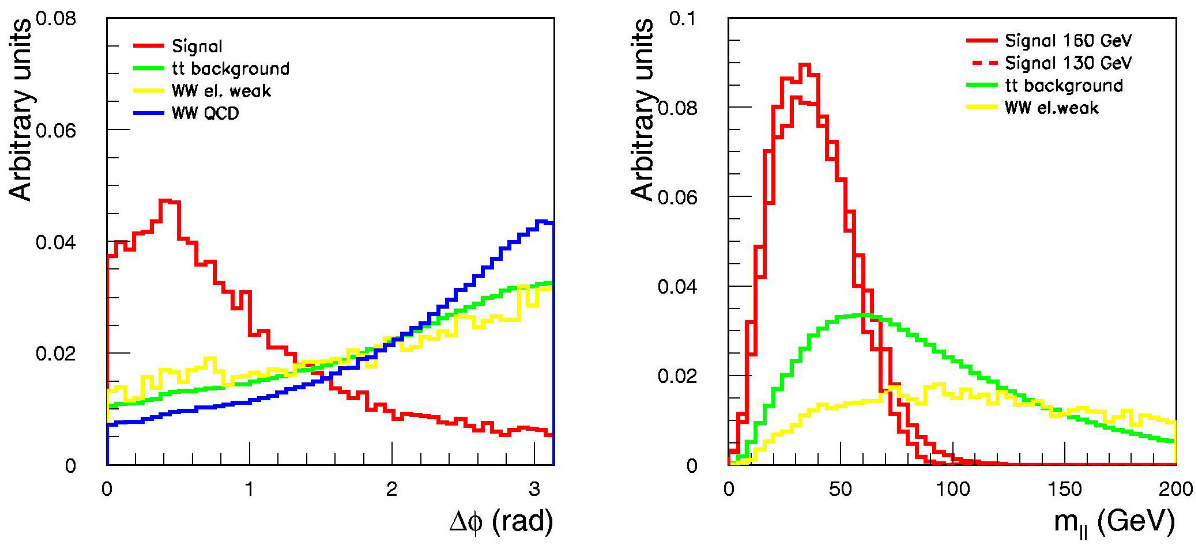
   $\eta_{tag}^{min} < \eta_{l_{1,2}} < \eta_{tag}^{max}$;

   Tag jets should not be b-jets
   $\Rightarrow$ b-jet veto ($\epsilon_b = 0.70$) for tag jets within $|\eta| < 2.5$

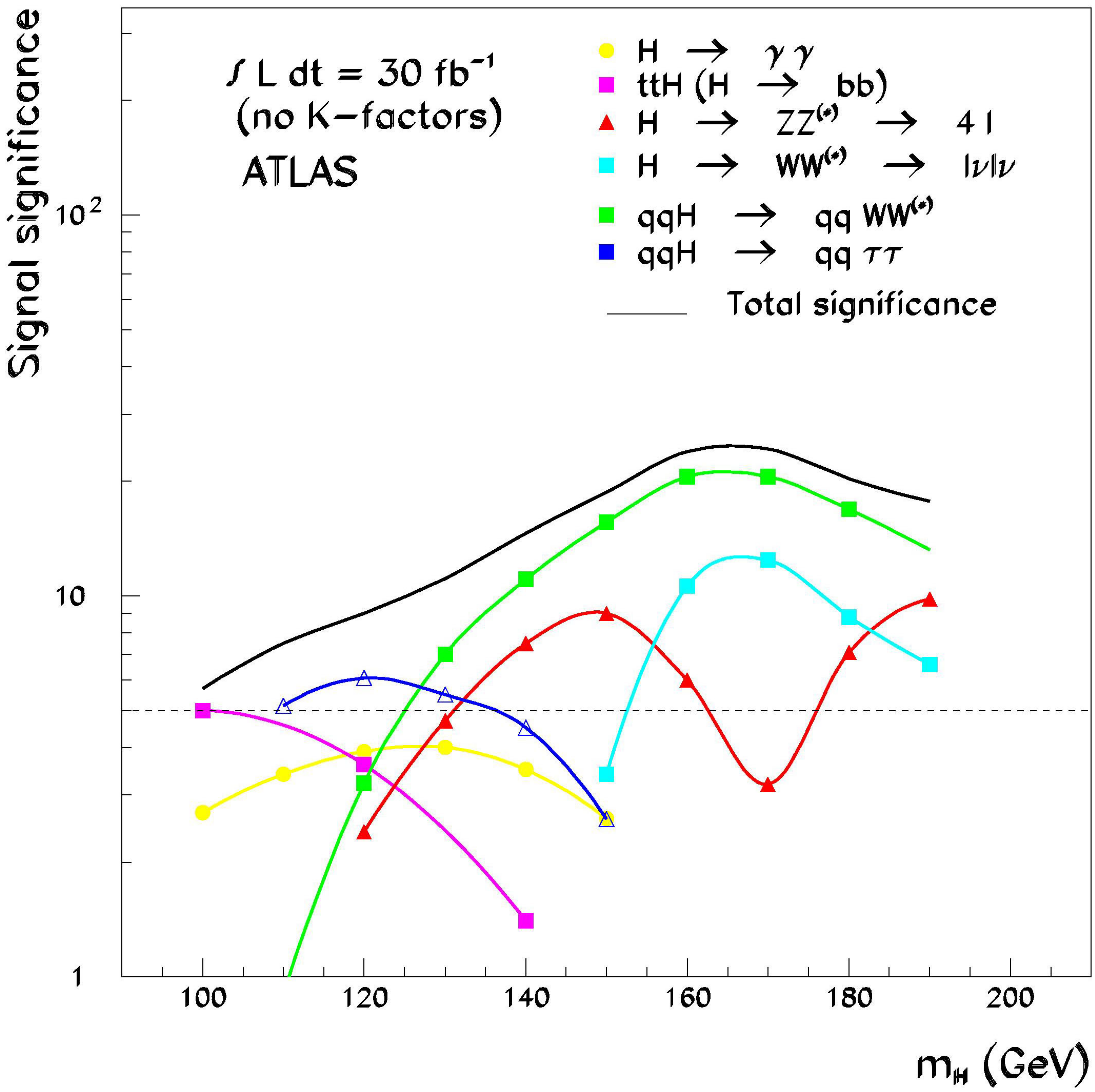
3. Lepton Angular and Di-lepton mass cuts:

   (exploit angular correlations (Spin-0 Higgs $\to$ Spin-1 W's)
   $\Rightarrow$ leptons are expected to have a small angular separation)

   $\Delta\phi_{ll} \leq 1.05$, $\Delta R_{ll} \leq 1.8$, $\cos\theta_{ll} \geq 0.2$
   $M_{ll} < 85$ GeV, $P_T(l_{1,2}) < 120$ GeV



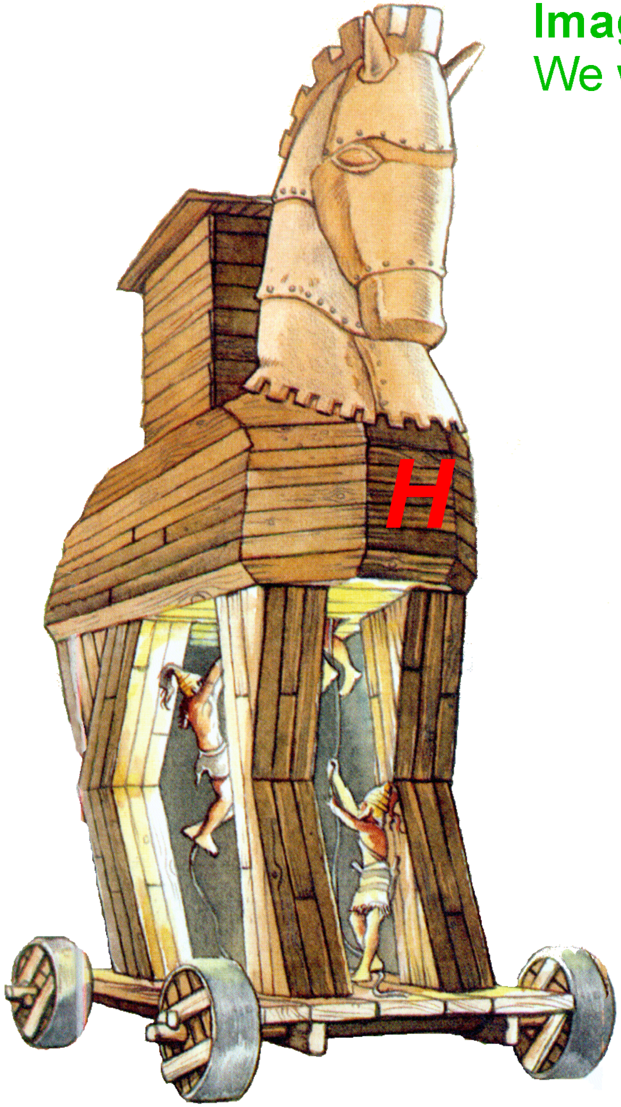
ATLAS Higgs discovery potential for 30 fb^{-1}



- Vector boson fusion channels improve the sensitivity significantly in the low mass region
- Several channels available over the full mass range

  (important for Higgs boson parameter determination)

SM higgs — The Trojan Horse



Imagine, that we turn on LHC and we find just SM higgs.
We will behave like Trojans finding the Wooden Horse:

- **We will anounce it to the world.**
- **We will celebrate our great victory.**
- **There will be laurel wreaths for heroes** (Nobel) **and festivities for the crowd,**
- **TV shows and newspaper covers ...**

But this will be the begining of the end ...

We will be left with

- **the Standard Model which works perfectly, but we do not understand why,**
- **the Higgs mechanism which we do not know where it comes from,**
- **nonunified forces, random symmetries, and ~20 arbitrary parameters,**
- **with no hint what is behind,**
- **no idea what to do next ...**

Supersymmetry - the Box of Pandora

Physicists are curious about the nature of symmetries observed in particle world,

likewise Pandora was curious about the content of the beautiful box.

One can suspect existence of even higher symmetry — the supersymmetry.

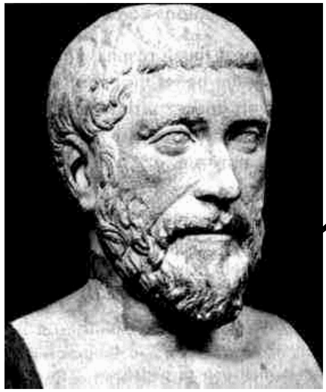
However, to appear in our world it must be broken.

It may release

- **dozens of new particles**
- **hundreds of production modes**
- **thousands of decay channels**

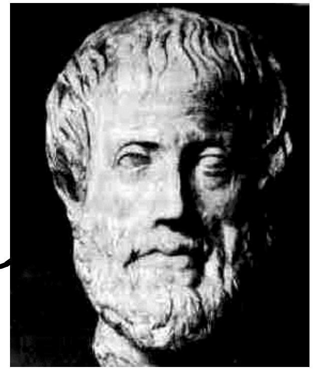
to be studied at LHC ...

Philosophers on Supersymmetry

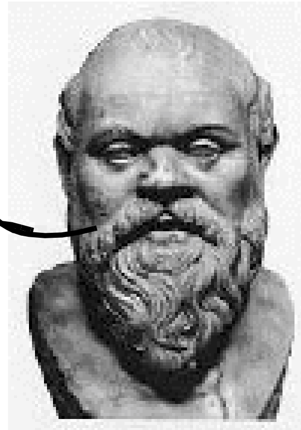


Each fermion has corresponding boson and vice versa.

Each discovered particle has undiscovered supersymmetric partner.

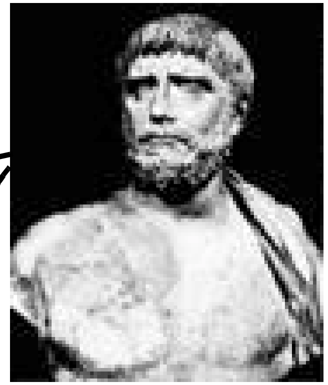


Each existing particle has nonexistent supersymmetric partner.



No supersymmetric particle have been discovered so far.

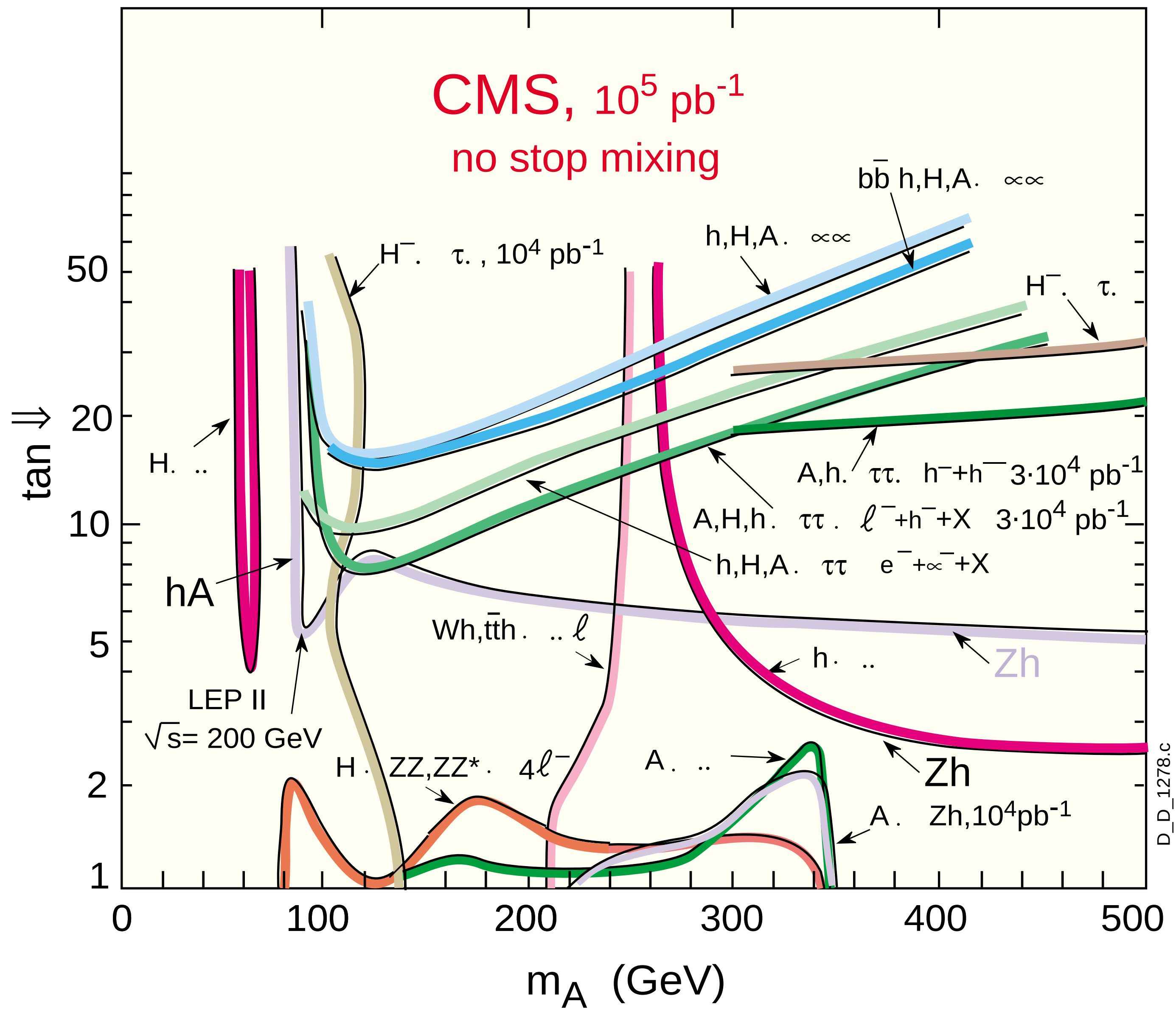
Half of all particles predicted by supersymmetry have been already discovered.



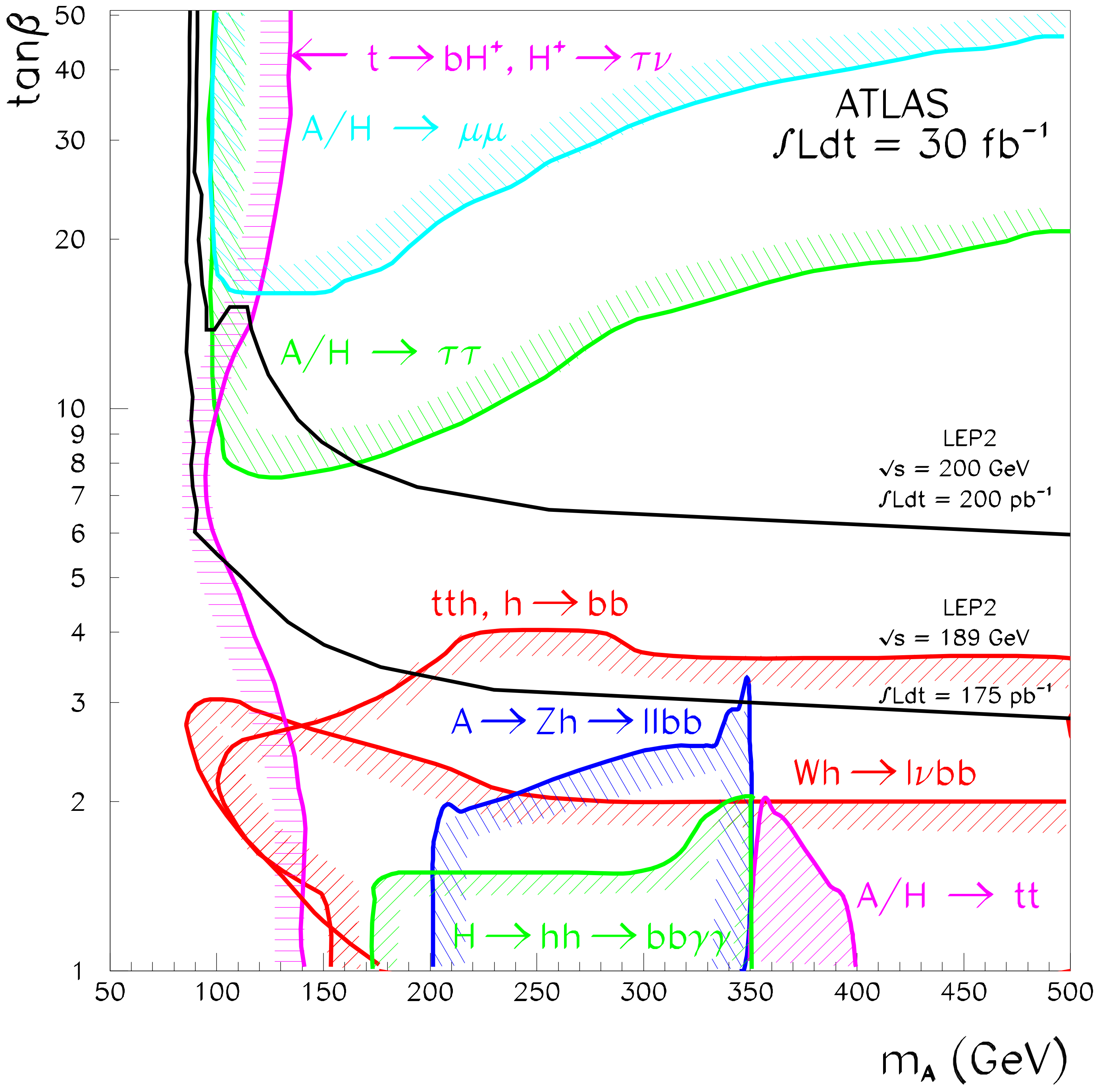
Significance contours for SUSY Higgses

Regions of the MSSM parameter space (m_A, tg⇓) explorable through various SUSY Higgs channels

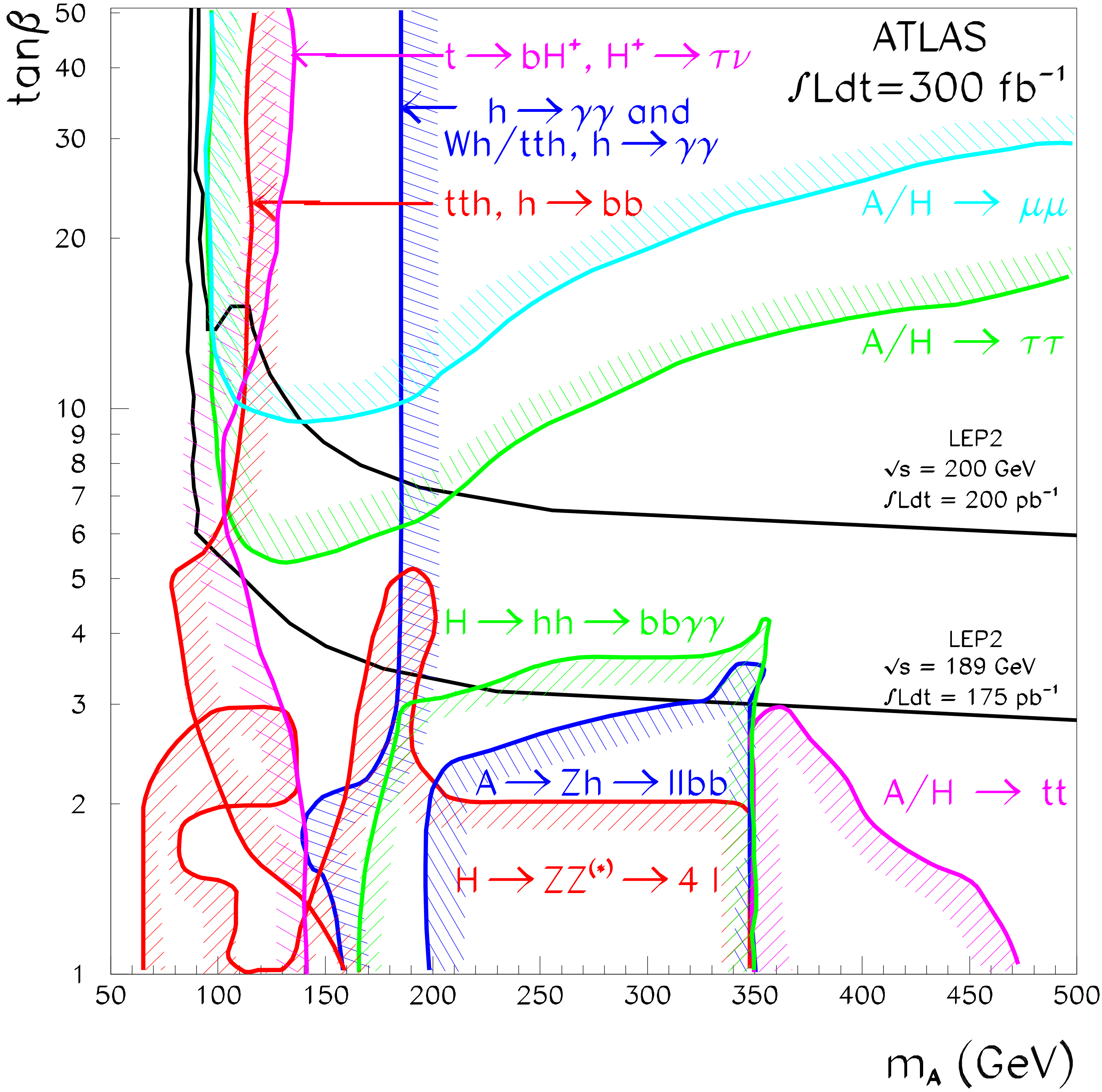
- 5 σ significance contours
- two-loop / RGE-improved radiative corrections
- m_{top} = 175 GeV, m_{SUSY} = 1 TeV



MSSM higgses



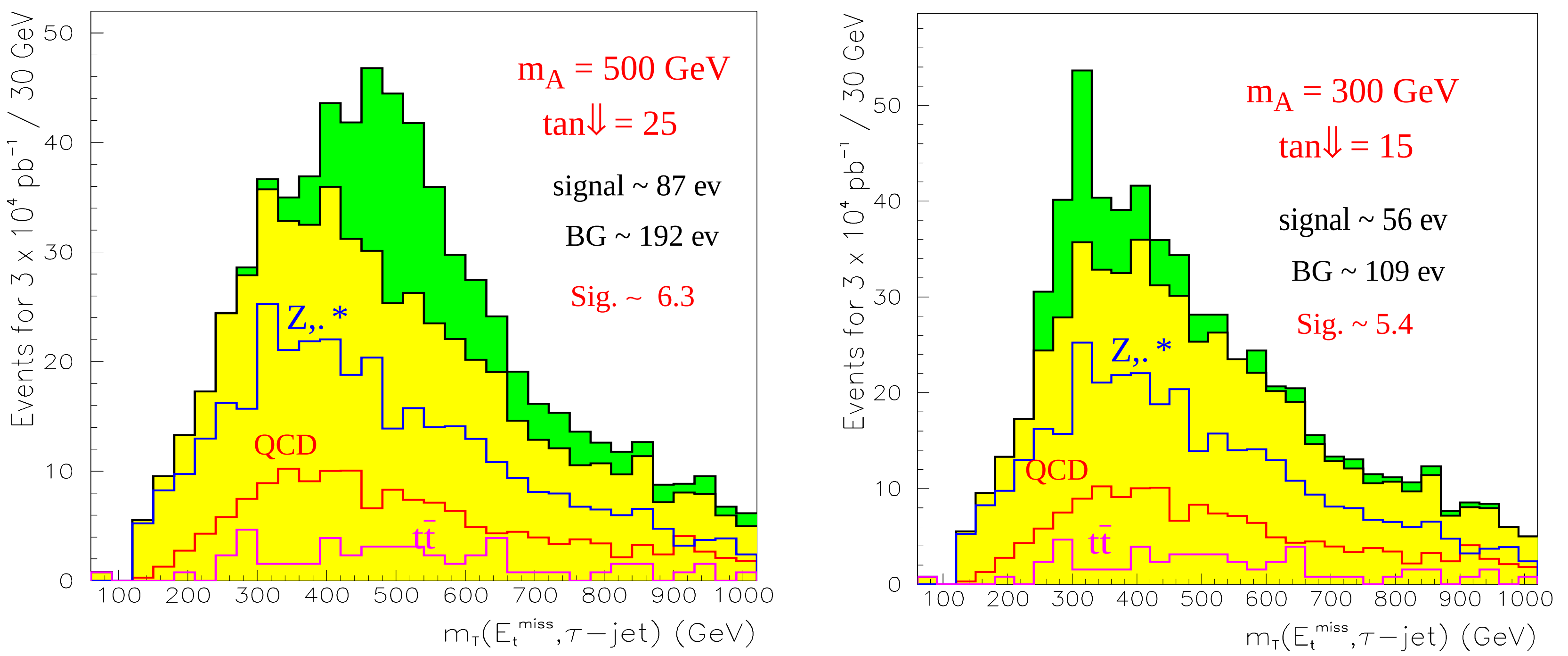
MSSM higgses



Signal superimposed on the total background for 30 fb^{-1}

A, H -> ττ -> 2 τ-jets + E_t^{miss} + X

E_t^{miss} rejection factor for QCD ~ 20 (present ORCA study)



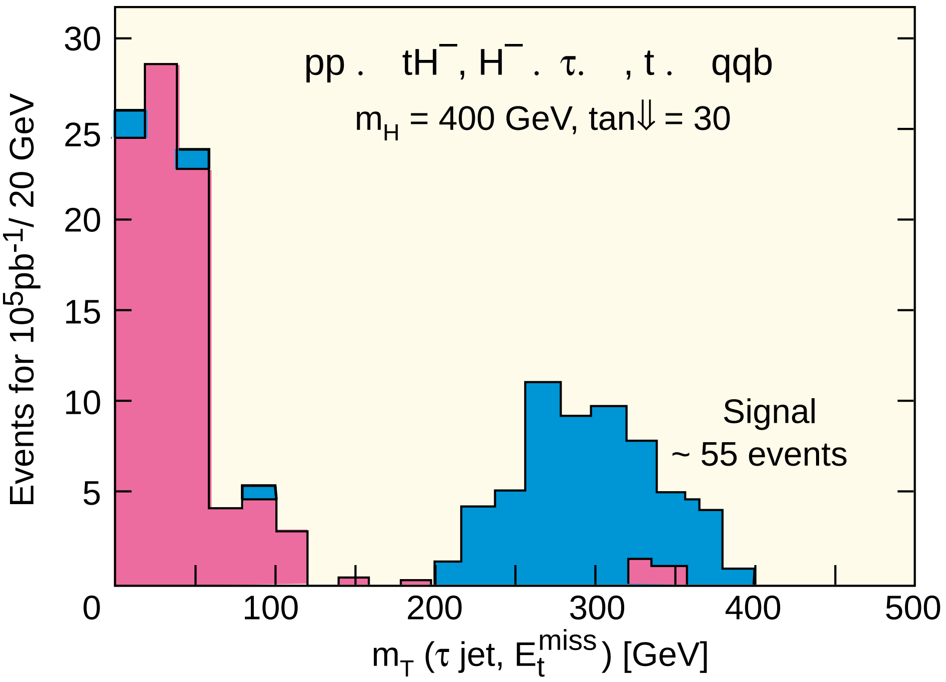
$E_t^{\tau\text{-jet}}$ > 60 GeV, 1/3 prong sel. with p_t^h(max)> 40 GeV, E_t^{miss} > 40 GeV, .ϕ (j_1,j_2) < 175^0

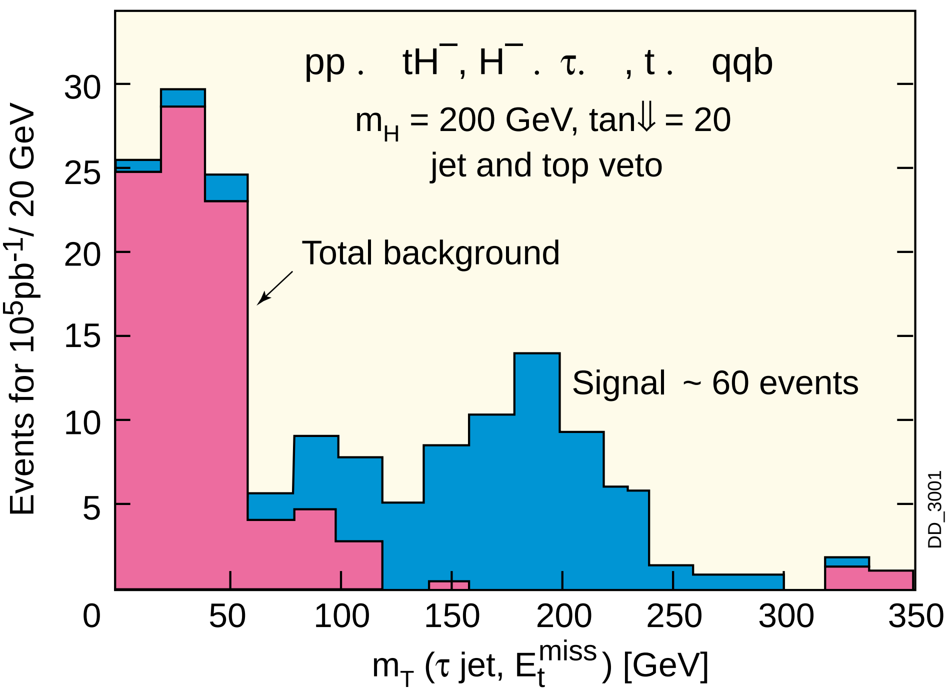
$H^- . \tau .$ in H^-tb

m_T (τ jet, E_t^{miss}), Lt = 100 fb^{-1}

with veto on a central jet, E_t^{jet} > 40 GeV, .. ^{jet}. < 2.5

and veto on a second top, . $m_{\tau. j}$ - m_{top} . > 130 GeV

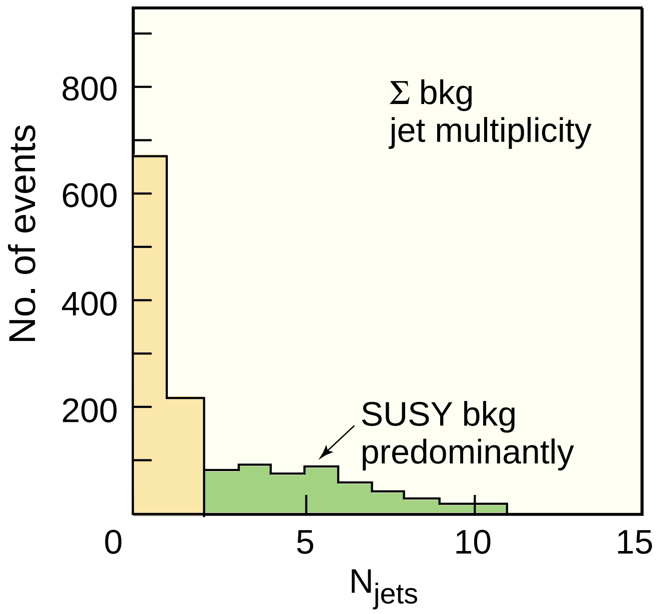


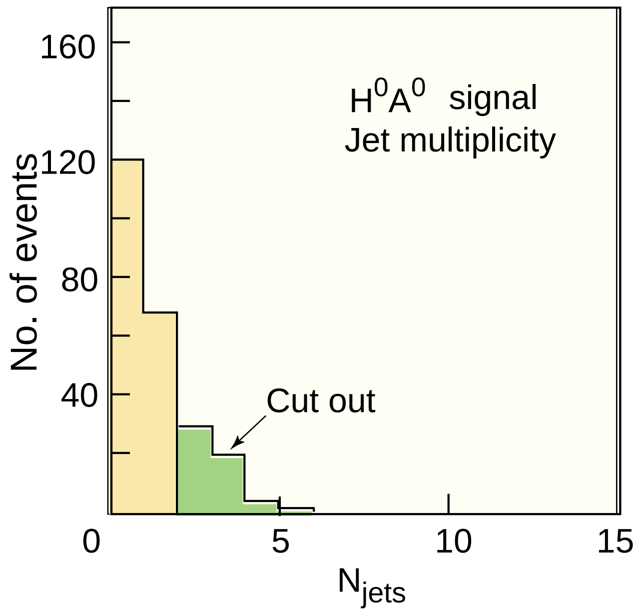


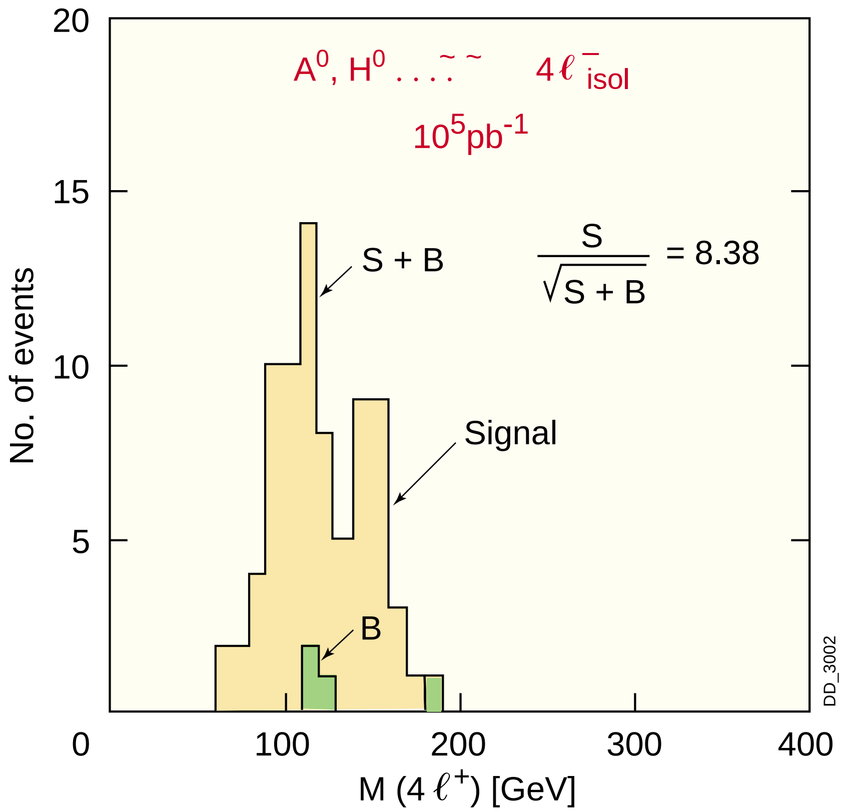
A, H . . . . $\tilde{}\ \tilde{}$ 4 ℓ_{isol} + E_t^{miss}

$m_{\tilde{g},\tilde{q}}$ = 1 TeV, m($\tilde{l}$) = 250 GeV, tg⇓ = 3, ∝ = -500 GeV

For background rejection: jet multiplicity, E_t^{miss}, p_t^l, presence of top in tH⁻b production etc.







MSSM point:

$m_{A,H}$ = 350 GeV

m($\tilde{.}^0_1$) = 60 GeV

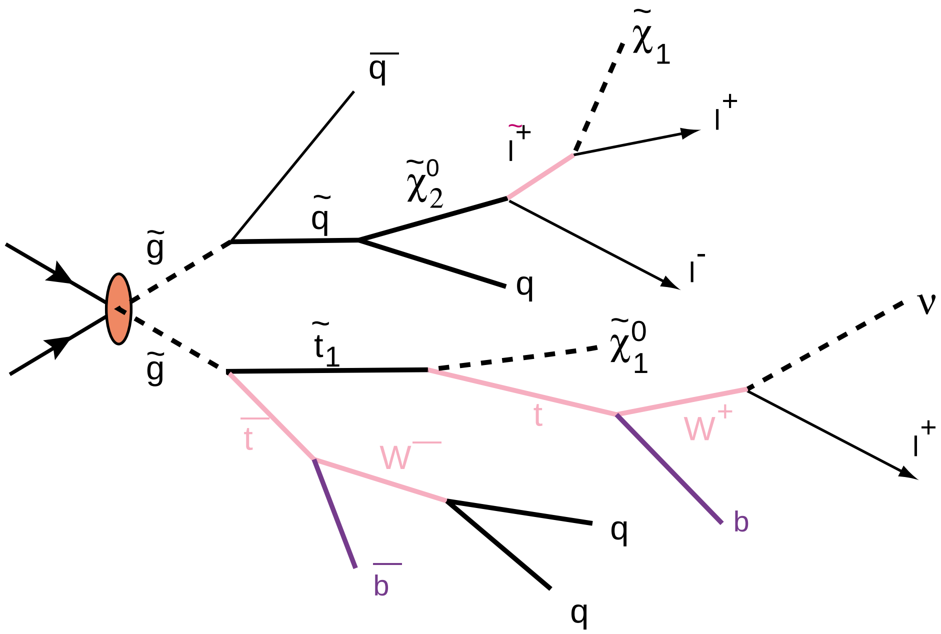
m($\tilde{.}^0_2$) =120 GeV

use:

$\tilde{.}^0_2$. $\tilde{.}^0_1$ $\ell^+\ell^-$

SUSY cascade decays

Gluino/squark production event topology allowing sparticle mass reconstruction



3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

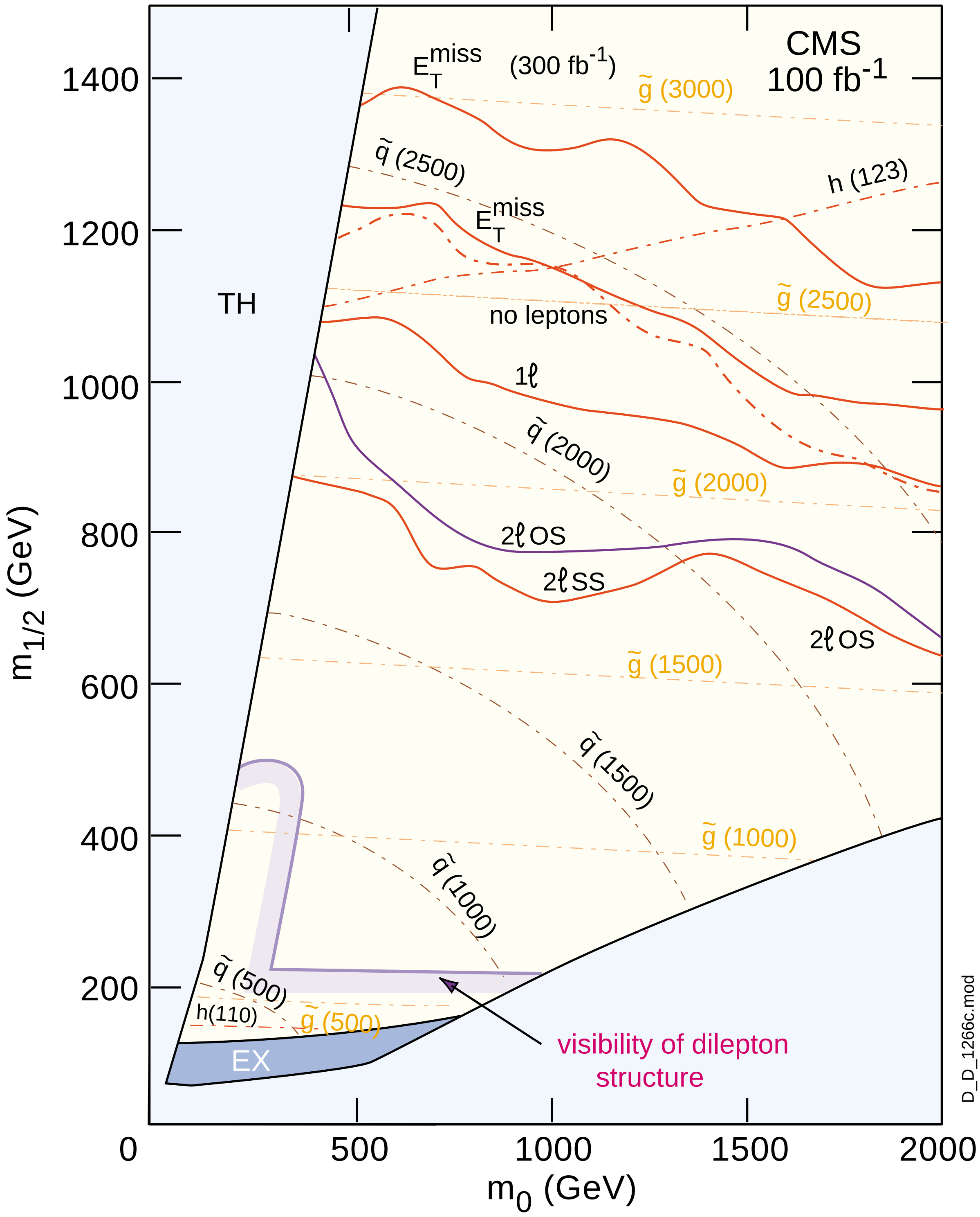
Such cascade decays allow to reconstruct sleptons, neutralinos, squarks, gluinos... in favorable cases with %level mass resolutions

D_D_2047.c.1

Explorable domain in $\tilde{q}$, $\tilde{g}$ seaches
in n leptons + E_t^{miss} + $\geq$ 2 jets final states

m SUGRA, A_0 = 0, tan ⇓= 35, ∝ > 0

5 σ contours ; non - isolated muons

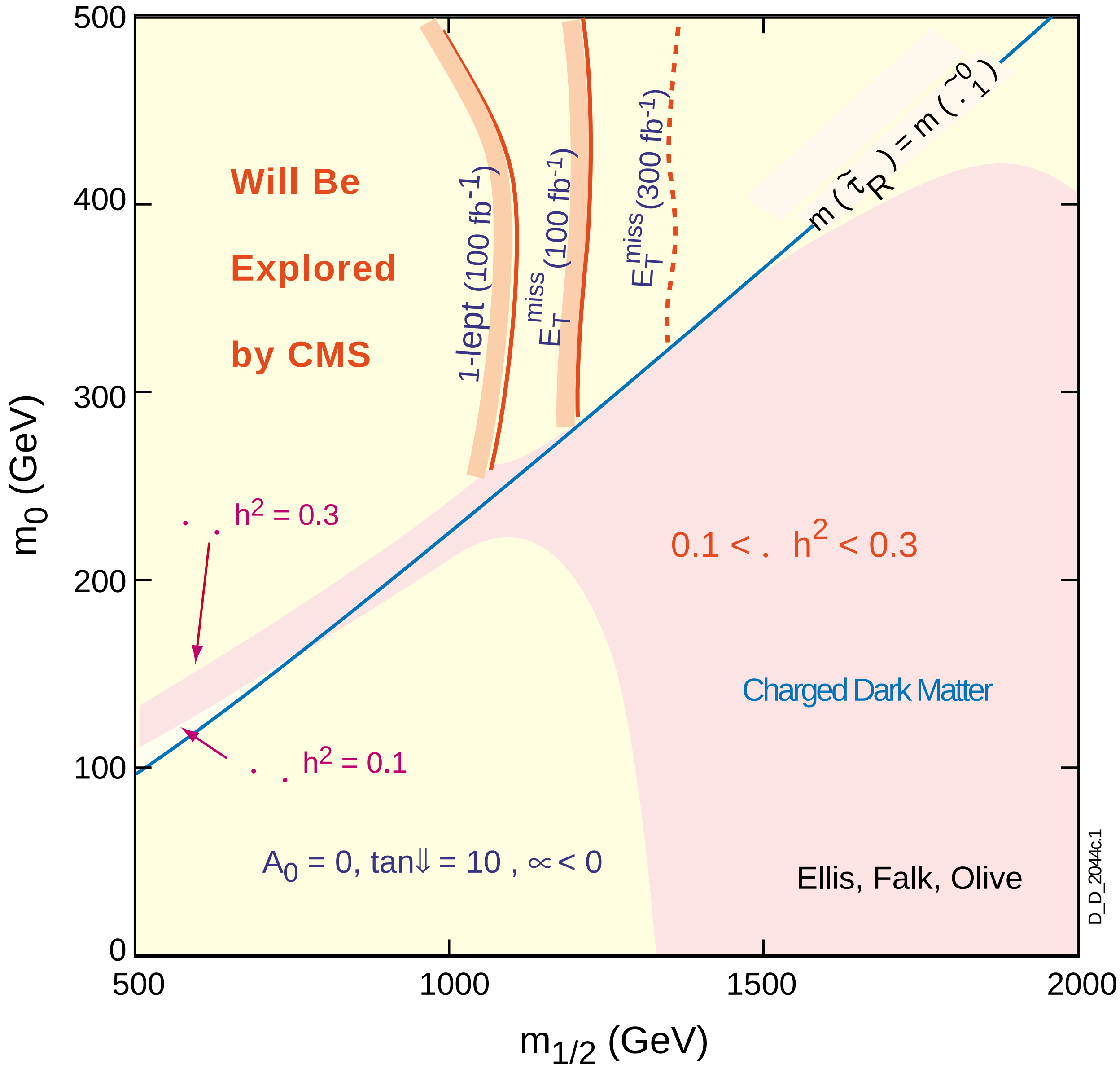


Relic $\tilde{\chi}_1^0$ density contours in mSUGRA

after inclusion of $\tilde{\tau}_R \tilde{\chi}_1^0$ + ...co-annihilation channels -

- upper limit on cosmologically acceptable m($\tilde{\chi}_1^0$)

- reach at LHC/CMS in various final state topologies



→ upper limit on $m_{1/2} \approx$ 1400GeV

thus on m($\tilde{\chi}_1^0$) ≈ 600 GeV

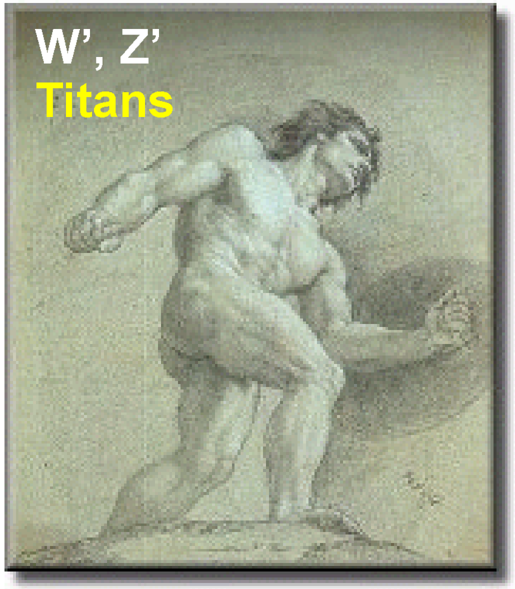
Conclusions on SUSY searches

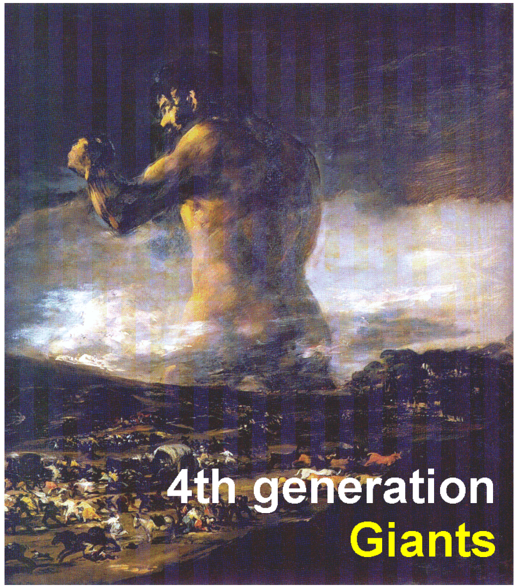
- The ultimate SUSY reach in terms of squark/gluino masses is 2.5 - 3 TeV (mSUGRA) with 300 fb^{-1}; in the worst case of degenerate gaugino masses (and heavy squarks and sleptons) the gluino mass reach is still expected to be ~ 1.5 TeV.
- The cosmologically preferred region of mSUGRA parameter space ($0.1 < \Omega h^2 < 0.3$) is found to be within the LHC ultimate reach.
- Large domain of mSUGRA parameter space where $\tilde{\chi}_2^0$ decays into leptons (direct 3-body decay or cascade one via sleptons) is explorable in 2(3) leptons (+ $\not{E}_T$ + jets) channels with corresponding observation of dilepton mass edge used in various mass reconstruction methods.
- With integrated luminosity of 100 fb^{-1} the $\tilde{l}_L$ mass reach in 2 leptons + no jets + $\not{E}_T$ channel is ~ 340 GeV (up to 440 GeV if $m_{LSP} \sim (0.45 - 0.6) \cdot m_{\tilde{l}_L}$).

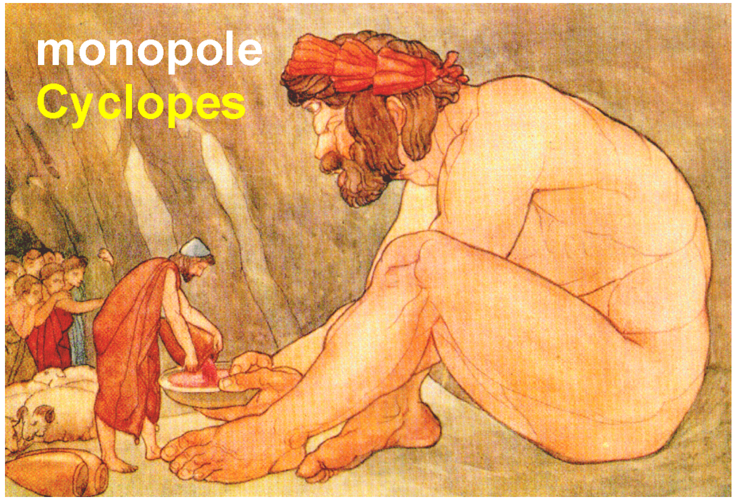
Conclusions on SUSY searches

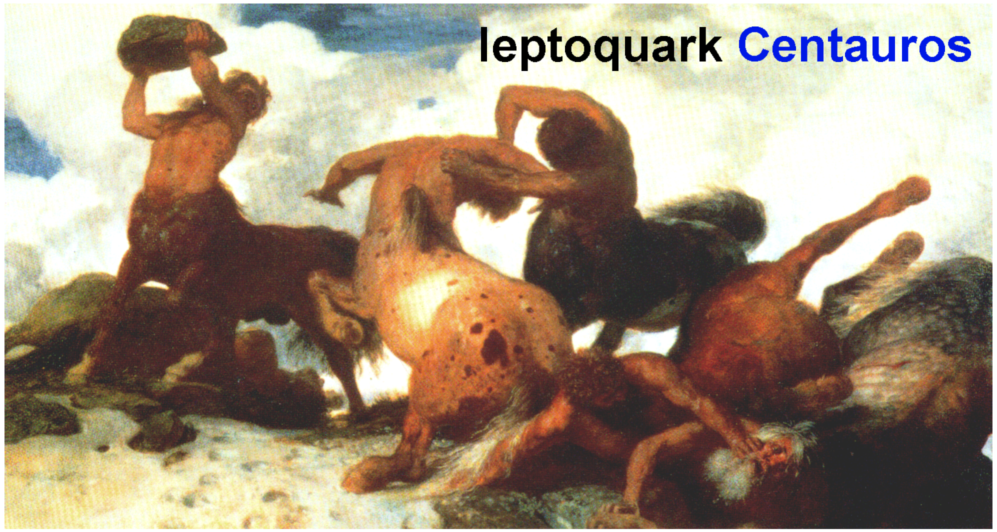
- For moderate values of $\tan\beta$ the range of $\tilde{\chi}_2^0$ mass explorable in 3 leptons + no jets + $\not{E}_T$ reaches 150-155 GeV with 100 fb^{-1}.
- Decay of the lightest SUSY Higgs into $b\bar{b}$ can be observed with S/B ratio of ~1 in a wide range of mSUGRA parameter space (where $\tilde{\chi}_2^0 \longrightarrow \tilde{\chi}_2^0$ h).
- With integrated luminosity of 100 fb^{-1} stau mass in the minimal GMSB model (for high $\tan\beta$, $M/\Lambda = 200$, $\Lambda = 50$ -300 TeV) can be measured in the range from 90 to 700 GeV. The $\tilde{\chi}_1^0$ lifetime can be measured from 1cm to 1 km for $\sigma_{SUSY} > 100\ fb^{-1}$.
- In a R-parity violation scenario with $\lambda_{ijk} \neq 0$ (purely leptonic decay) the parameter region explorable with integrated luminosity of 10 fb^{-1} extends up to masses of squark/gluino of ~ 1.5-1.8 TeV.

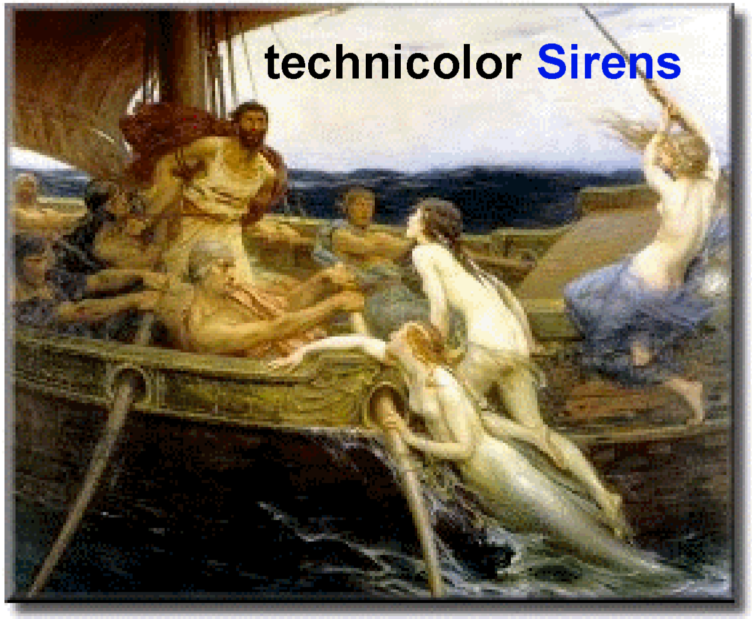
Odyssey - exotica







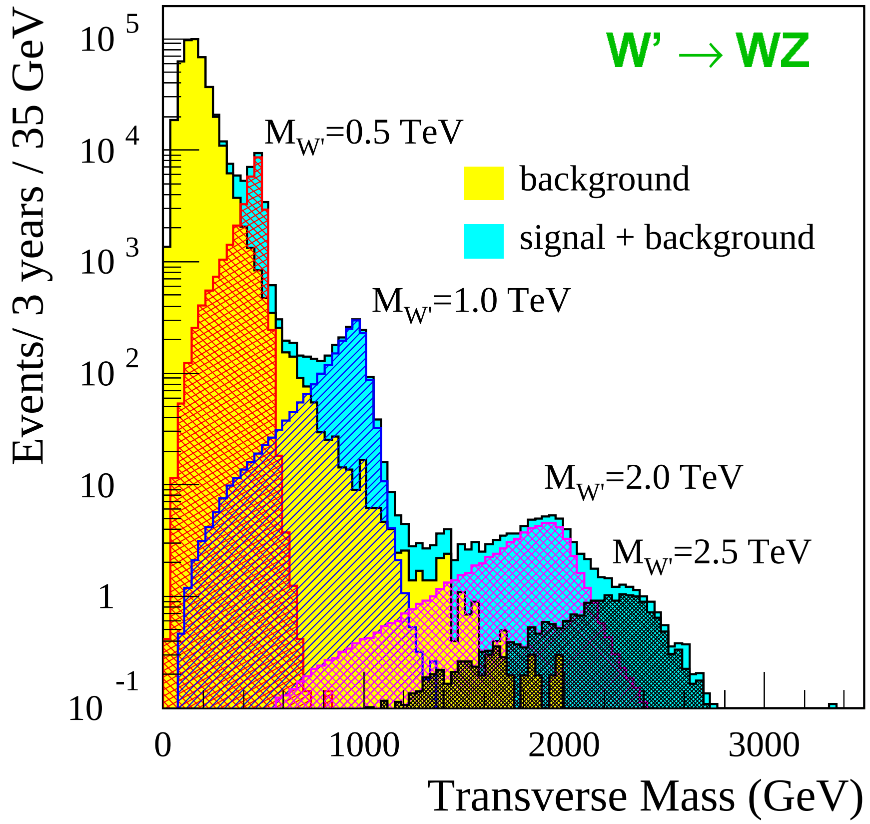


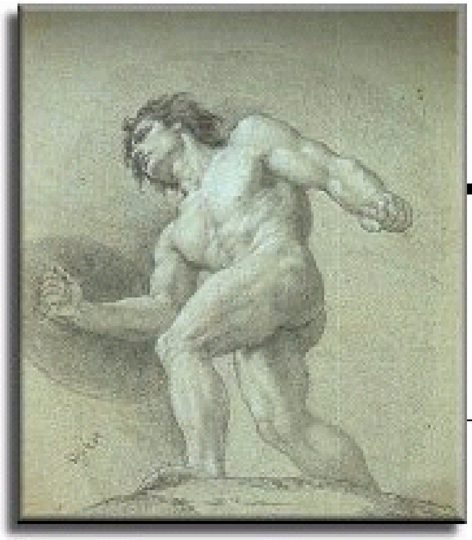


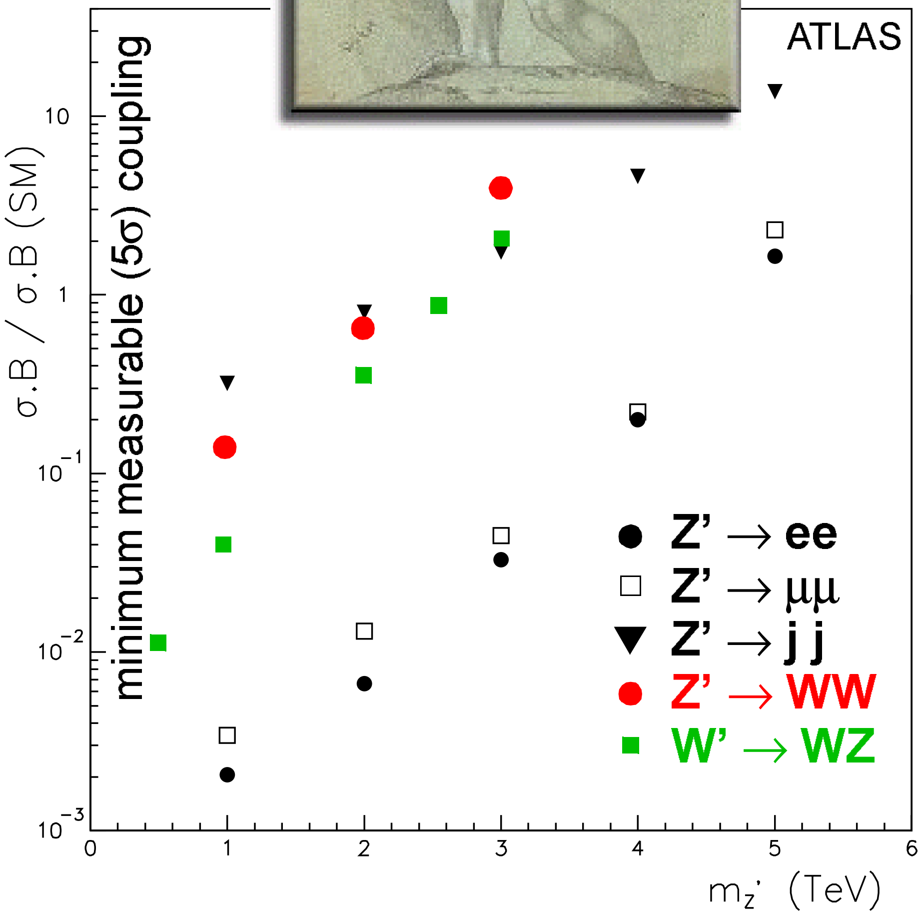
W', Z' Titans

Extension of the Standard Model symmetry group might introduce new, massive gauge bosons.

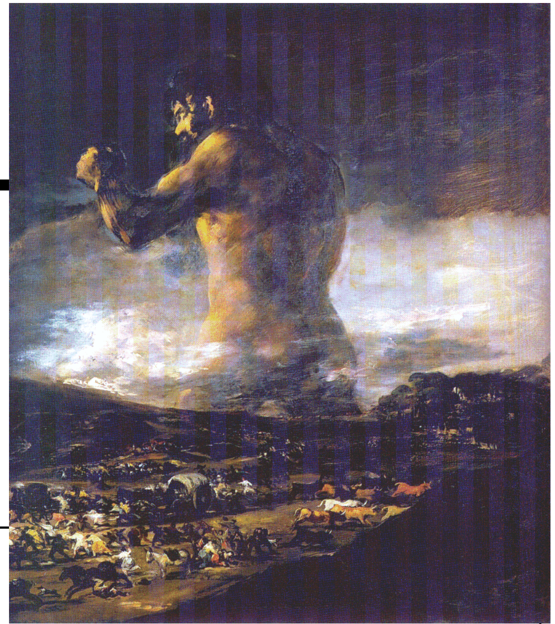
Bosonic decay plots - 300 fb^{-1}, fermionic - 100 fb^{-1}





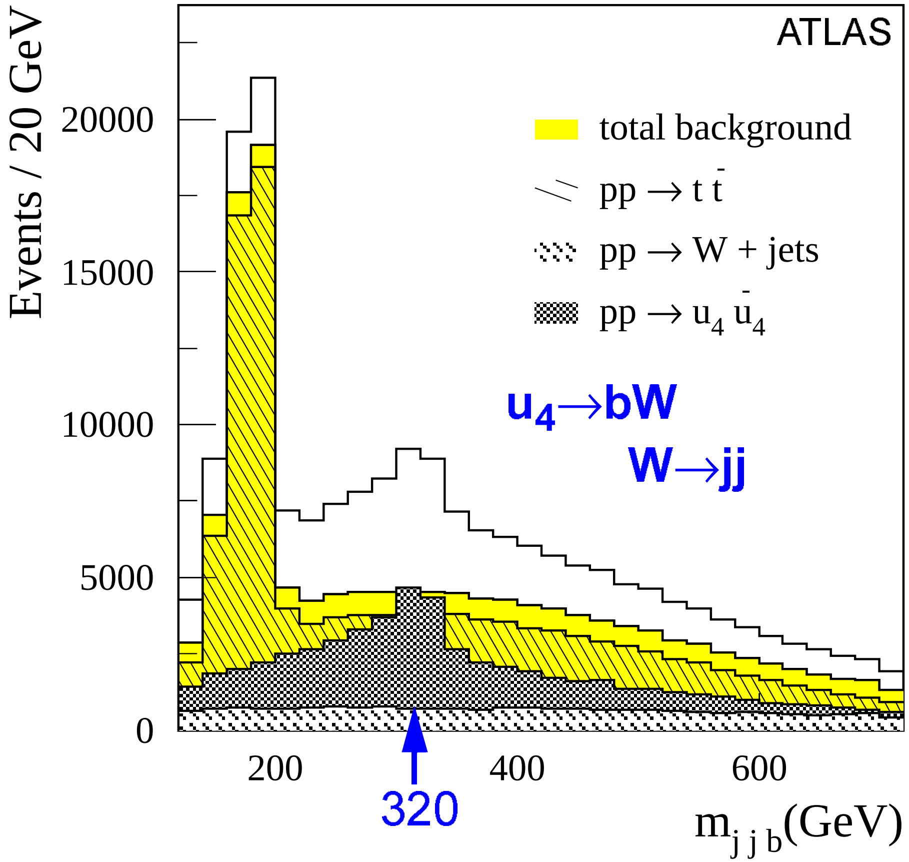


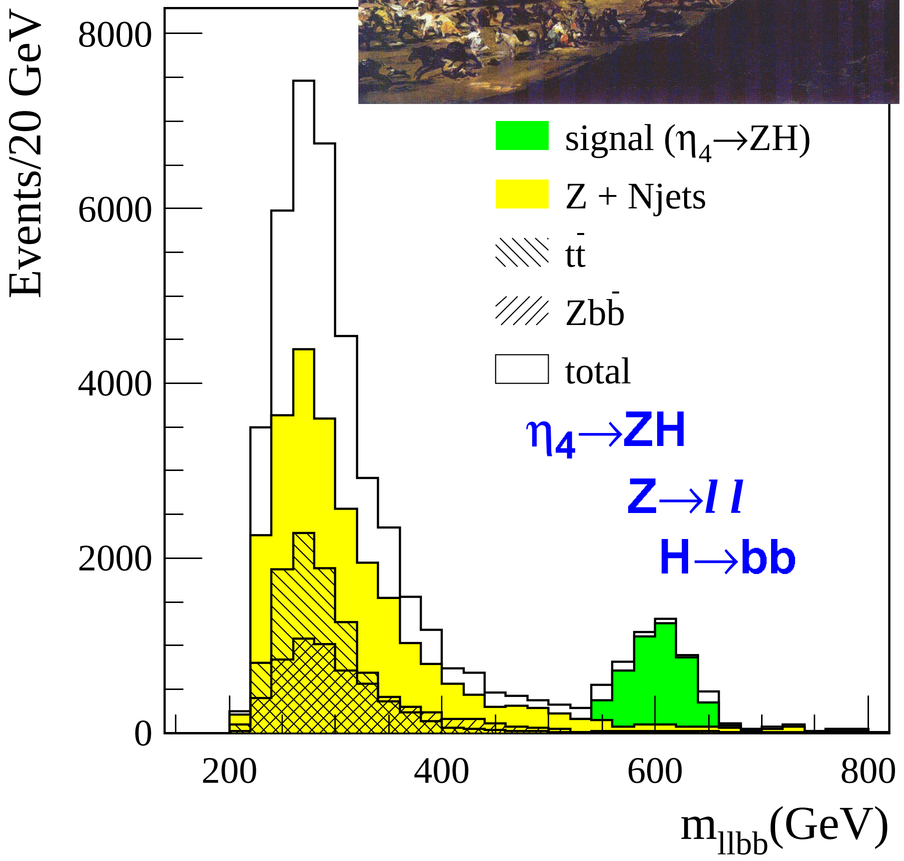
4^{th} generation fermion Giants



Several models containing 4th generation leptons and quarks with a gigantic mass have been proposed.

Plots for 100 fb^{-1}

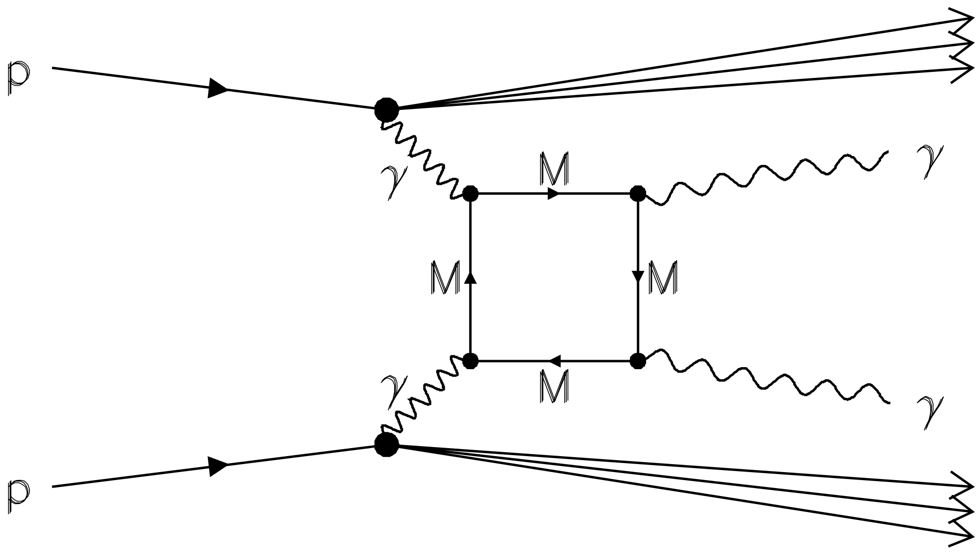




Monopole Cyclopes

Monopoles are particles with only one magnetic pole instead of two.

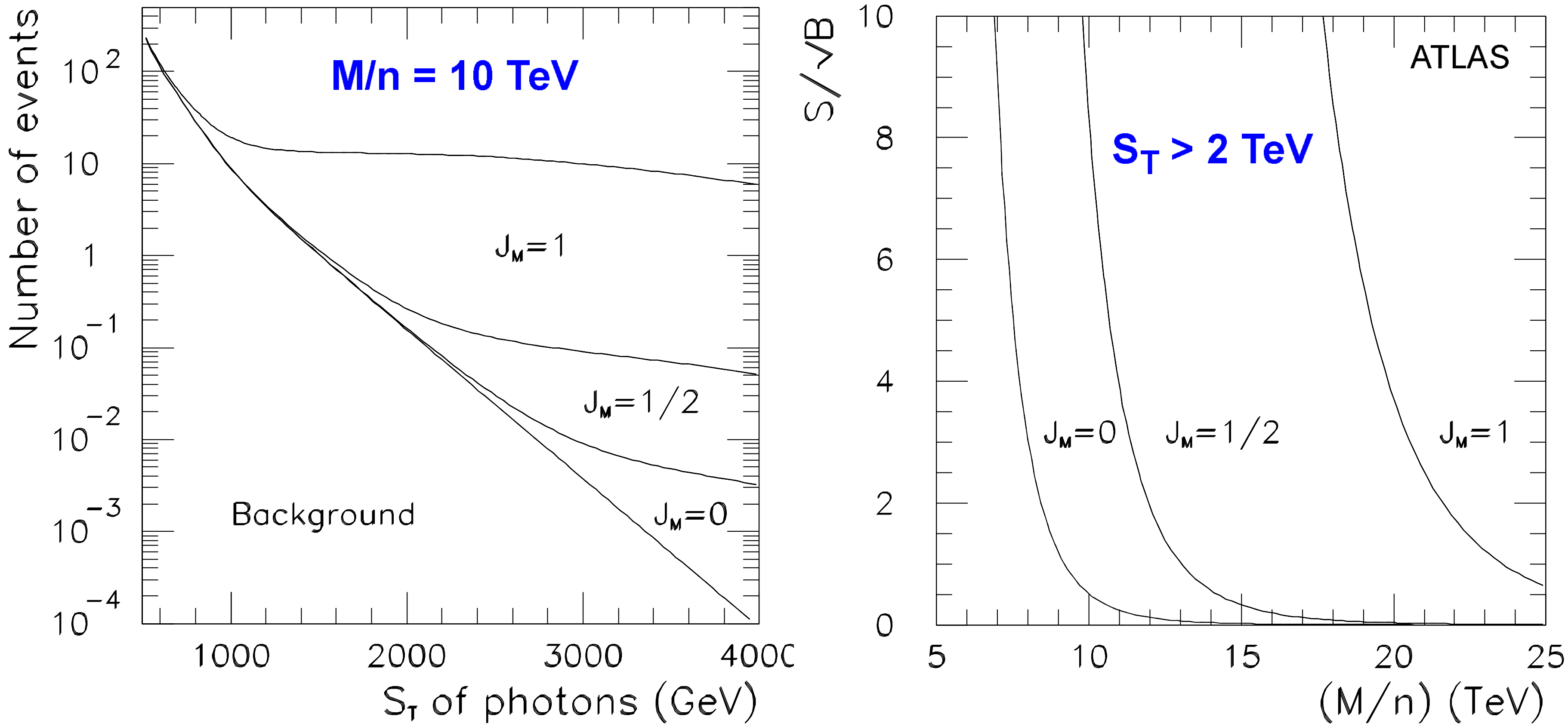
They could be observed at LHC through hard photons produced in the process:



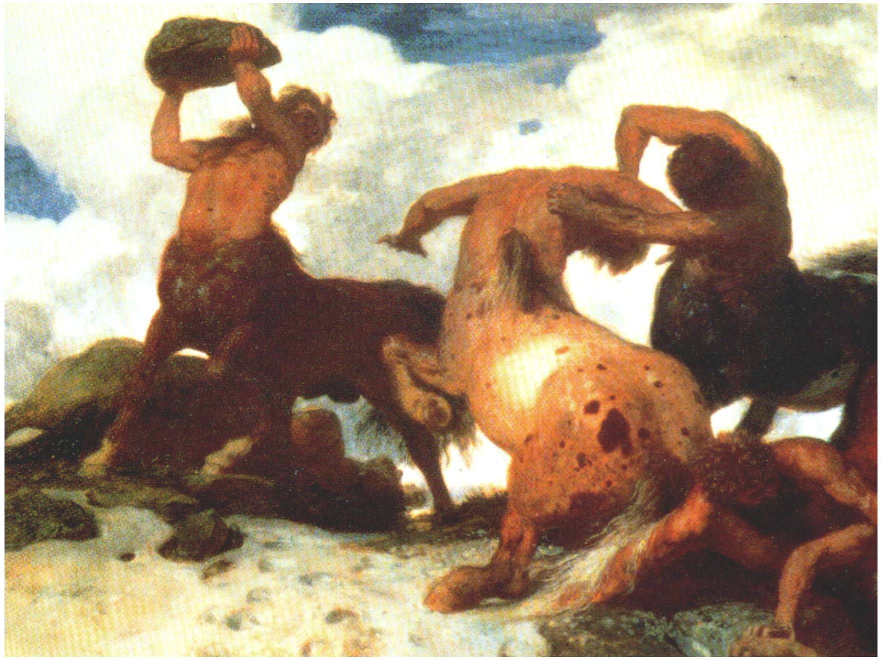
Hard photon pairs from monopoles

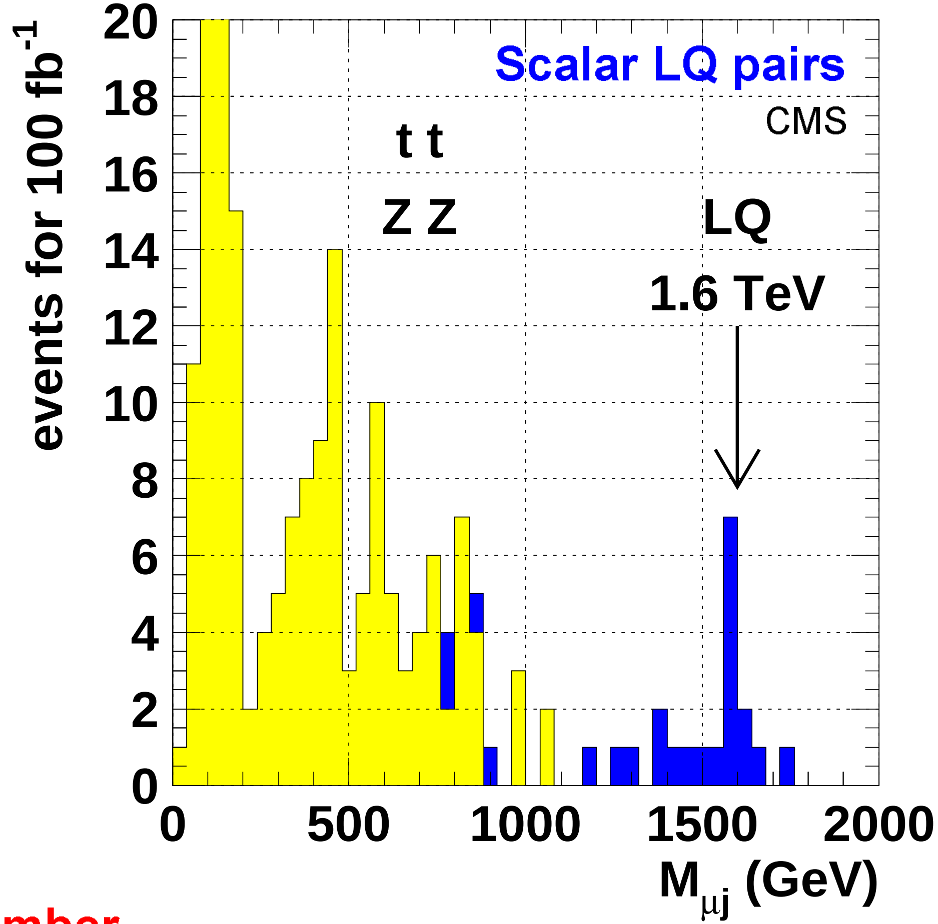
M - monopole mass, n - monopole charge, $S_T = |p_T(\gamma 1)| + |p_T(\gamma 2)|$

Plots for 100 fb^{-1}



Leptoquark Centauros





LQ are half lepton, half quark hybrids, appearing in models with symmetry of leptons & quarks.

They carry both leptonic & barionic number.

Production: qq → LQ LQ, qg → LQ Decay: LQ → *l* q

LQ can be discovered at LHC up to M_{LQ}~1.6 GeV.

Technicolor Sirens

Technicolor is a new strong interaction at high scale.

It provides an alternative to higgs mechanism of EW symmetry breaking by means of technipions (conndensates of technifermions).

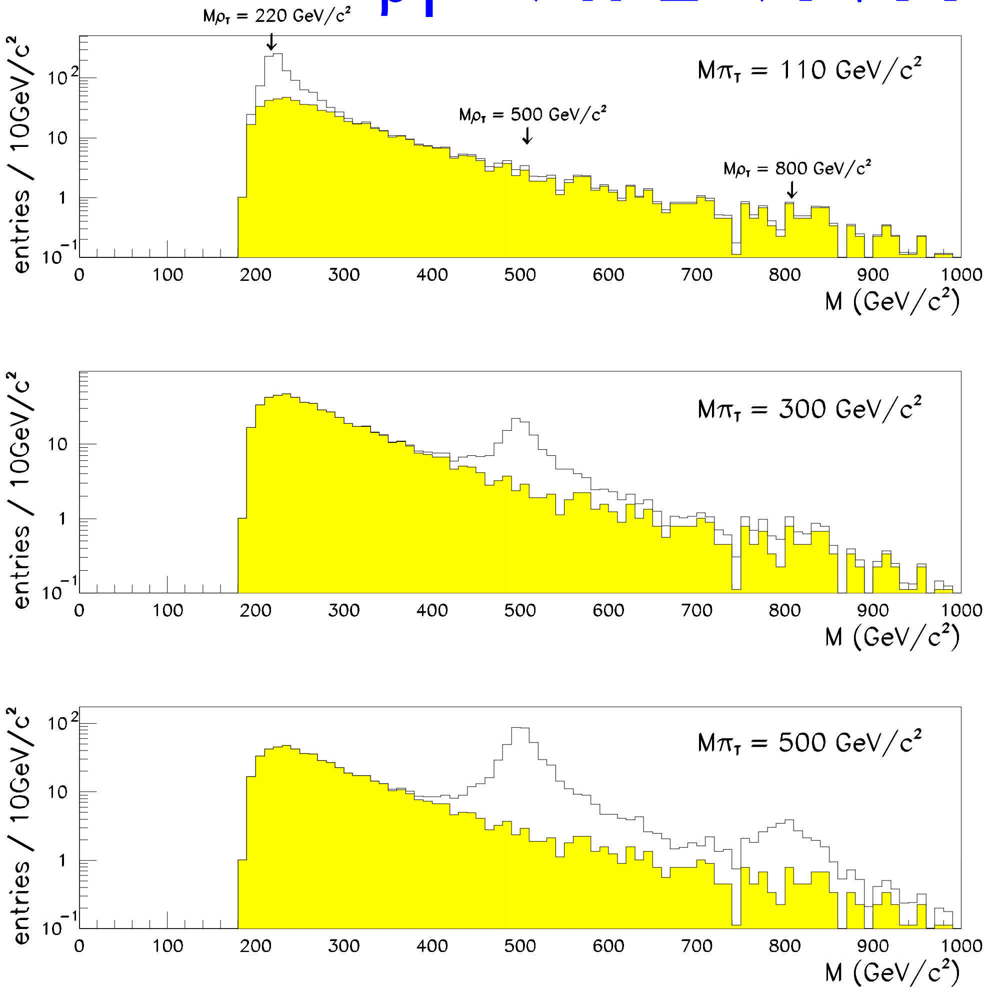
Technihadron resonances, could be observed at LHC.

Some theorists loose their lives attracted by this alluring theory like Odysseus by Sirens. But it seems to be a dead end ...

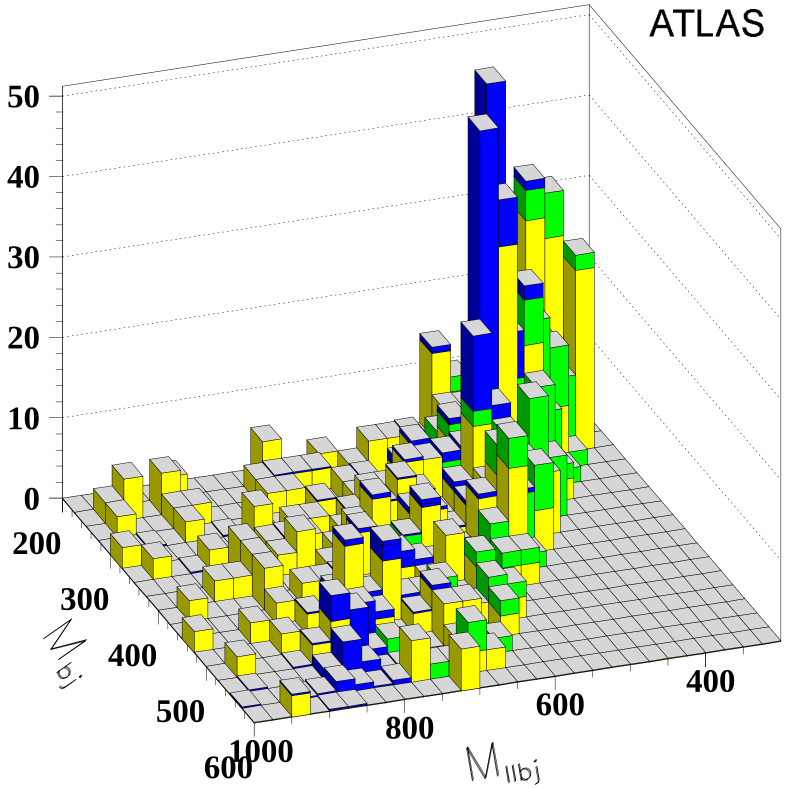
Technicolor resonances

30 fb^{-1}

$\rho_T^{\pm} \to W^{\pm}Z \to l^{\pm}\nu\, l^{+}l^{-}$



$\rho_T^{\pm} \to \pi_T^{\pm}Z \to bq\, l^{+}l^{-}$



signal, t t, Z j

“New Physics” — the Sphinx puzzle

Can we discover at LHC something unexpected?

Detectors were optimized for discovery of higgs.

Their performance was tested with typical signatures:

- **hard μ, e, γ, jets originated from the interaction point, missing E_T, etc.**

What, if we see something unusual, like

- **hard objects (e.g. γ) created far from the IP,**
- **~stable, heavy (nonrelativistic) particles.**

It would look as strange as Sphinx — a lion with wings and women’s head.

It would presents as with a difficult puzzle.

The life of particle physics might depend on the right solution.

Gravitions in GMSB models

LSP = gravitino, NLSP = neutralino or stau

- **long lived stau looks like a heavy (nonrelativistic) muon**
- **neutralinos decaying far from IP give non-pointing photons**
- **cascade decays of neutralinos produce sharply edged distributions** (for all lifetime values)

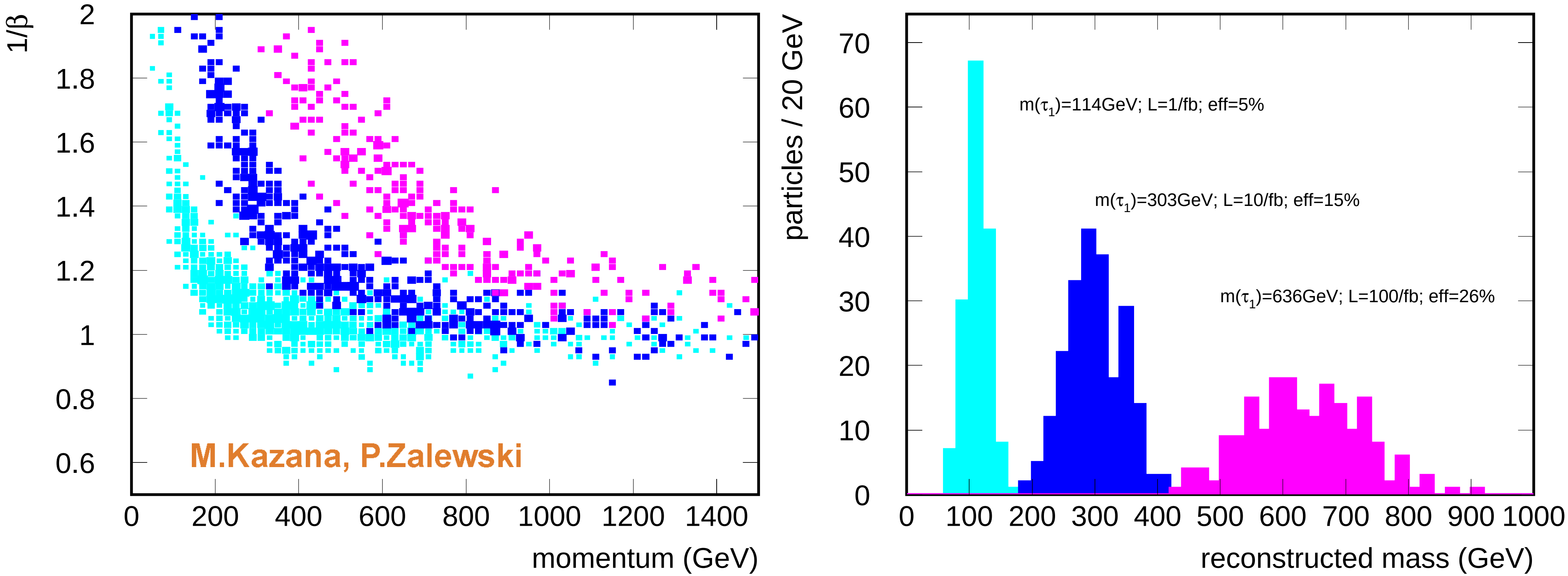
NLSP	short lived	decaying	long lived
$\tilde{N}_1 \rightarrow \tilde{G}\gamma$	like MSSM +2γ	cτ measurement by • ECAL counting • μCAL counting • ECAL/μCAL ratio • ECAL impact par. • μCAL slope	like MSSM
$\tilde{\tau}_1 \rightarrow \tilde{G}\tau$	like MSSM +2τ	both cτ and mass measurement	mass measurement by TOF method

Mass measurement of long lived staus

Specific GMSB scenarios: **n=3, tanβ=45, M/Λ=200, Λ=50-300 TeV**

σ_{SUSY} = 1 fb - 10 pb, $\tilde{q}\,\tilde{g}$ masses = 1-4 TeV, $\tilde{\tau}$ mass = 90-700 GeV

Method: **TOF**(Drift Tubes) → **1/β → mass** ***Results:***

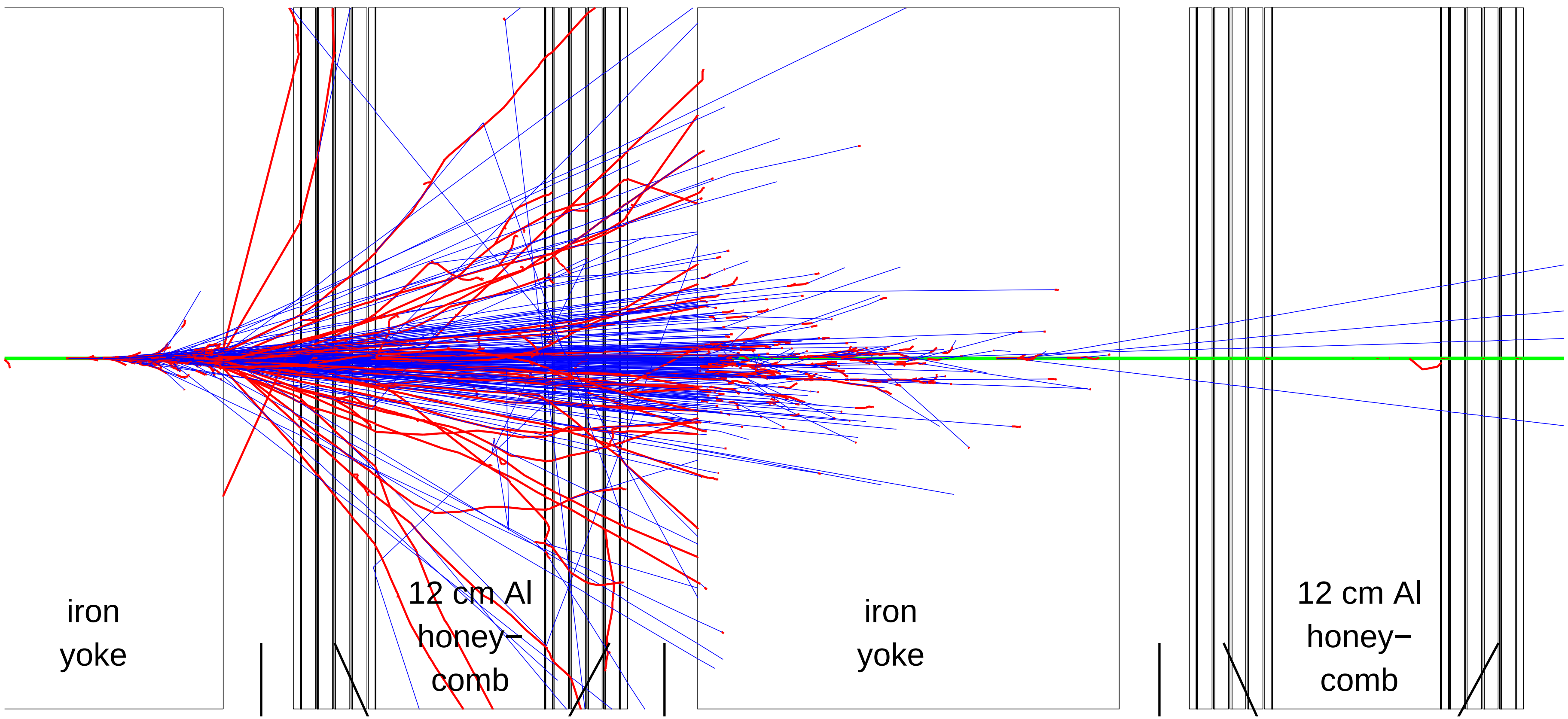


CMS can measure τ mass from 90 to ~700 GeV with ∫ L=100/fb

Upper limit corresponds to σ_{SUSY}=1fb and $\tilde{q}$ $\tilde{g}$ masses of ~4 TeV

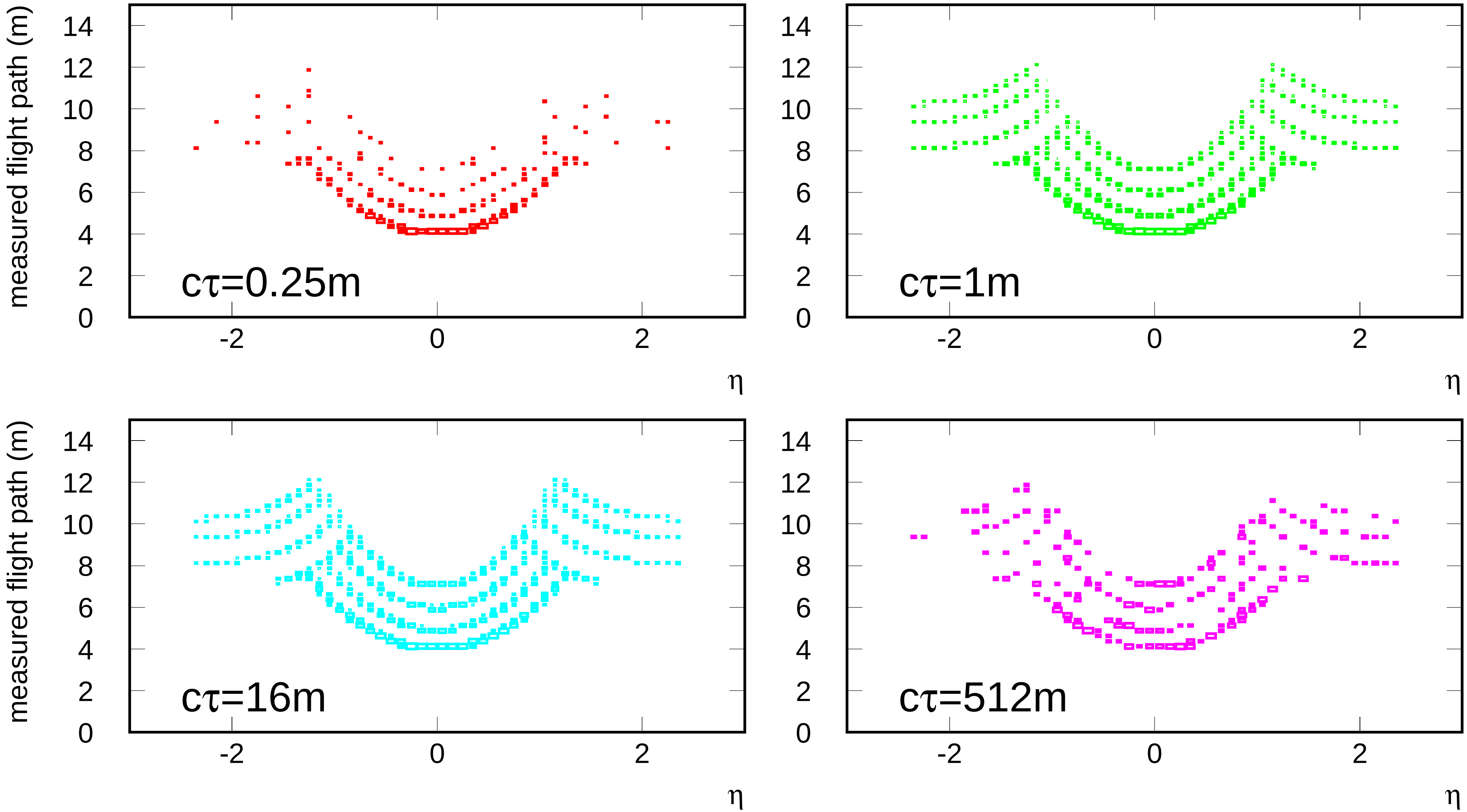
Muon system as calorimeter

If $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ decay happen inside the muon system the photon will develop an electromagnetic shower.



Electromagnetic showers in the muon system (caused by energetic muons) **were extensively studied in RD5 experiment and CMS simulation.**

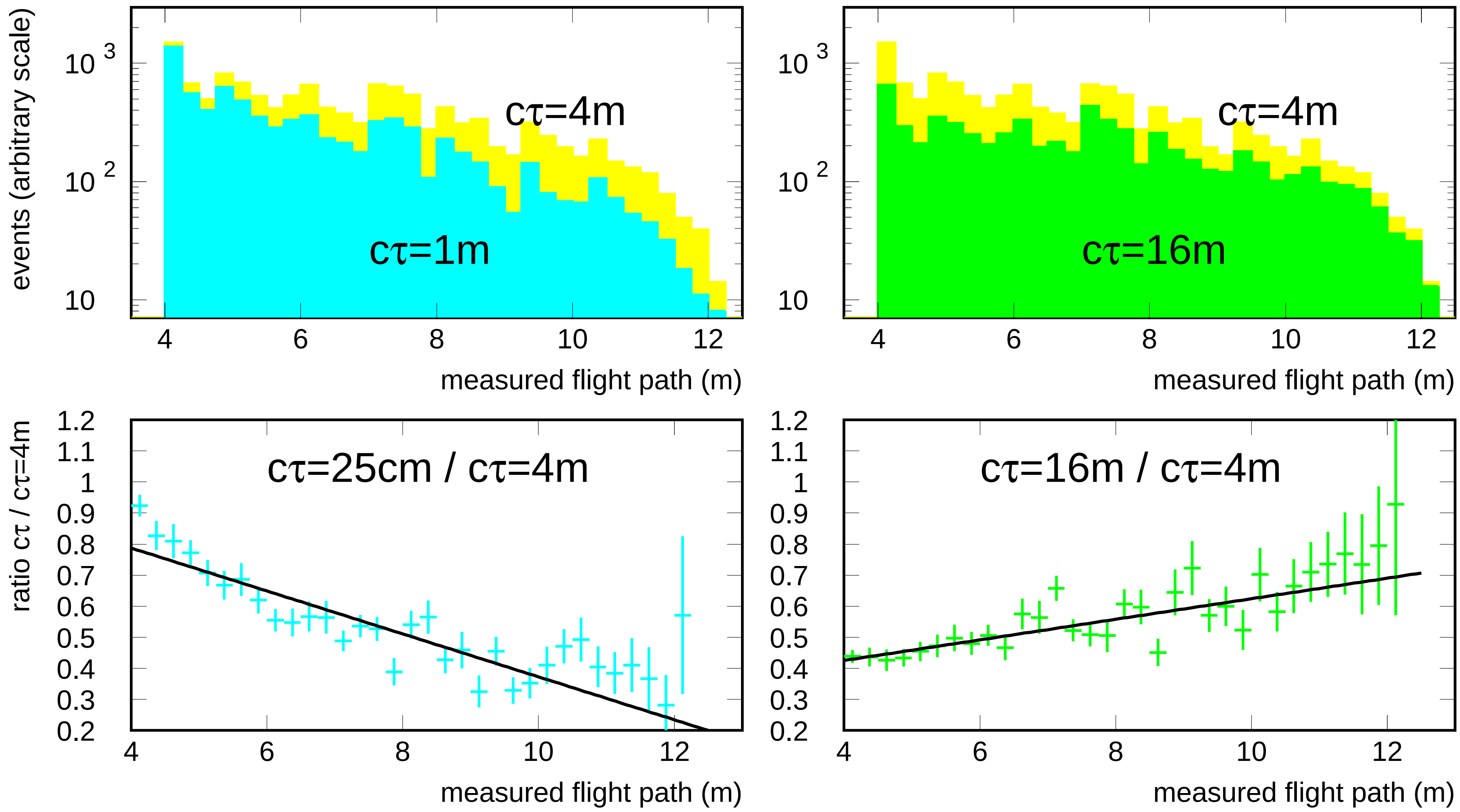
Neutralino flight path seen in μCAL



"Cheshire plot" — the smiling cat of Alice from Wonderland.

Late showers caused by $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ detected in muon stations.

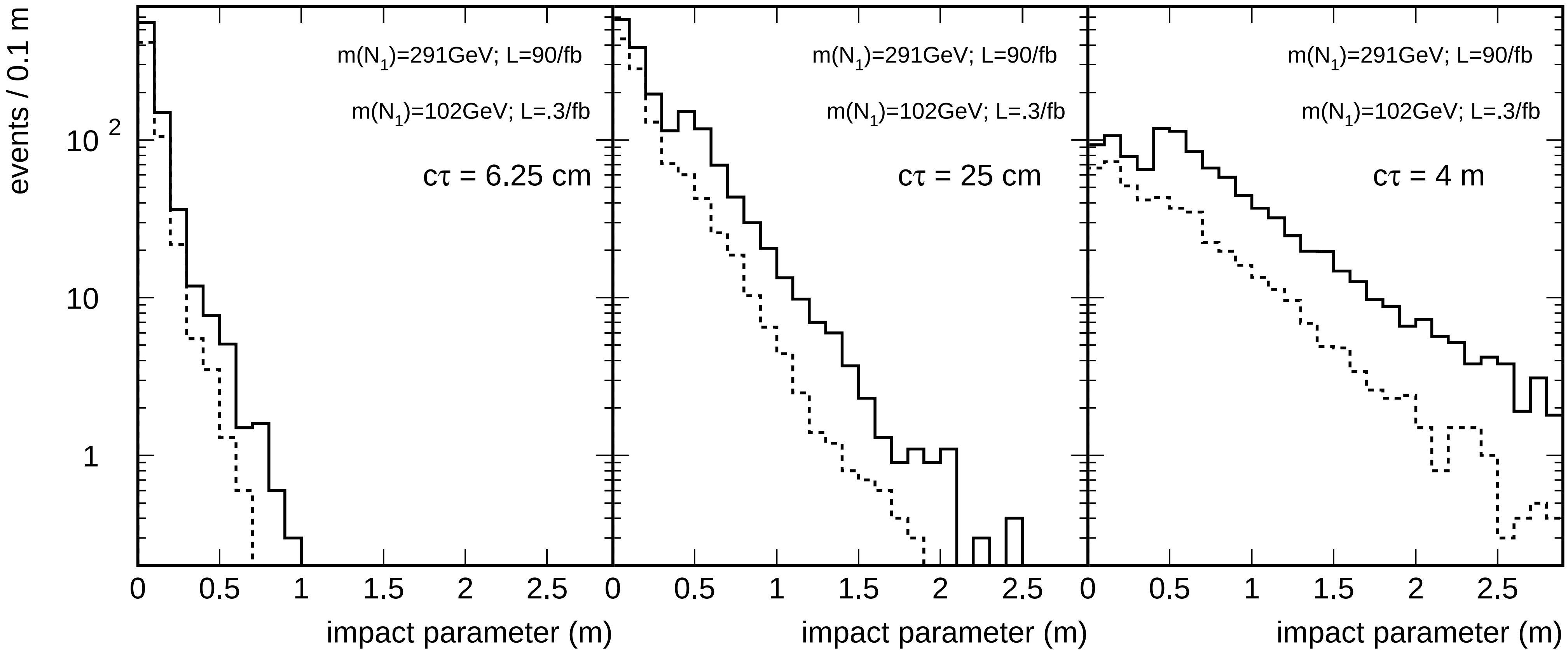
Measurement of neutralino cτ



“μCAL counting” — compare the number of events for different cτ

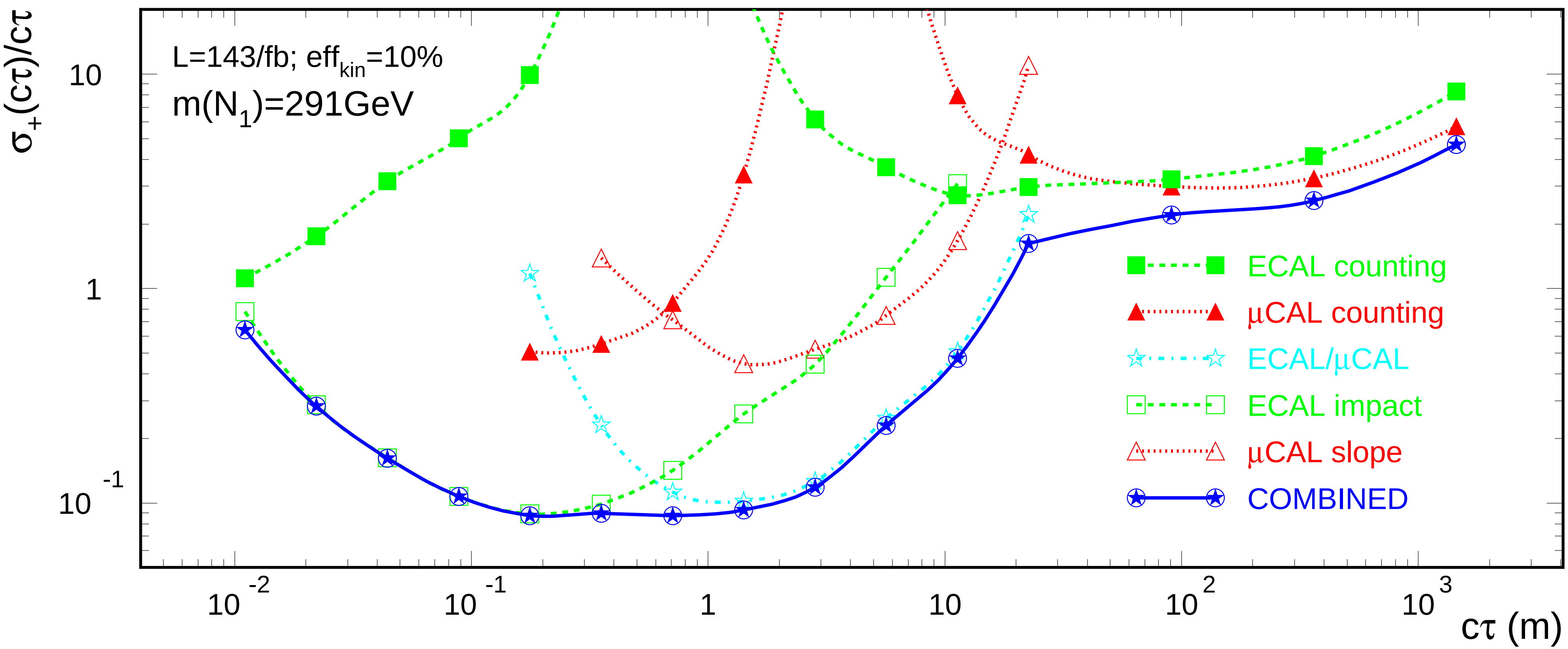
“μCAL slope” — compare the shape of $\tilde{N}_1$ flight path distributions

Non-pointing photons in ECAL



Impact parameter distribution

CMS sensitivity to neutralino life time



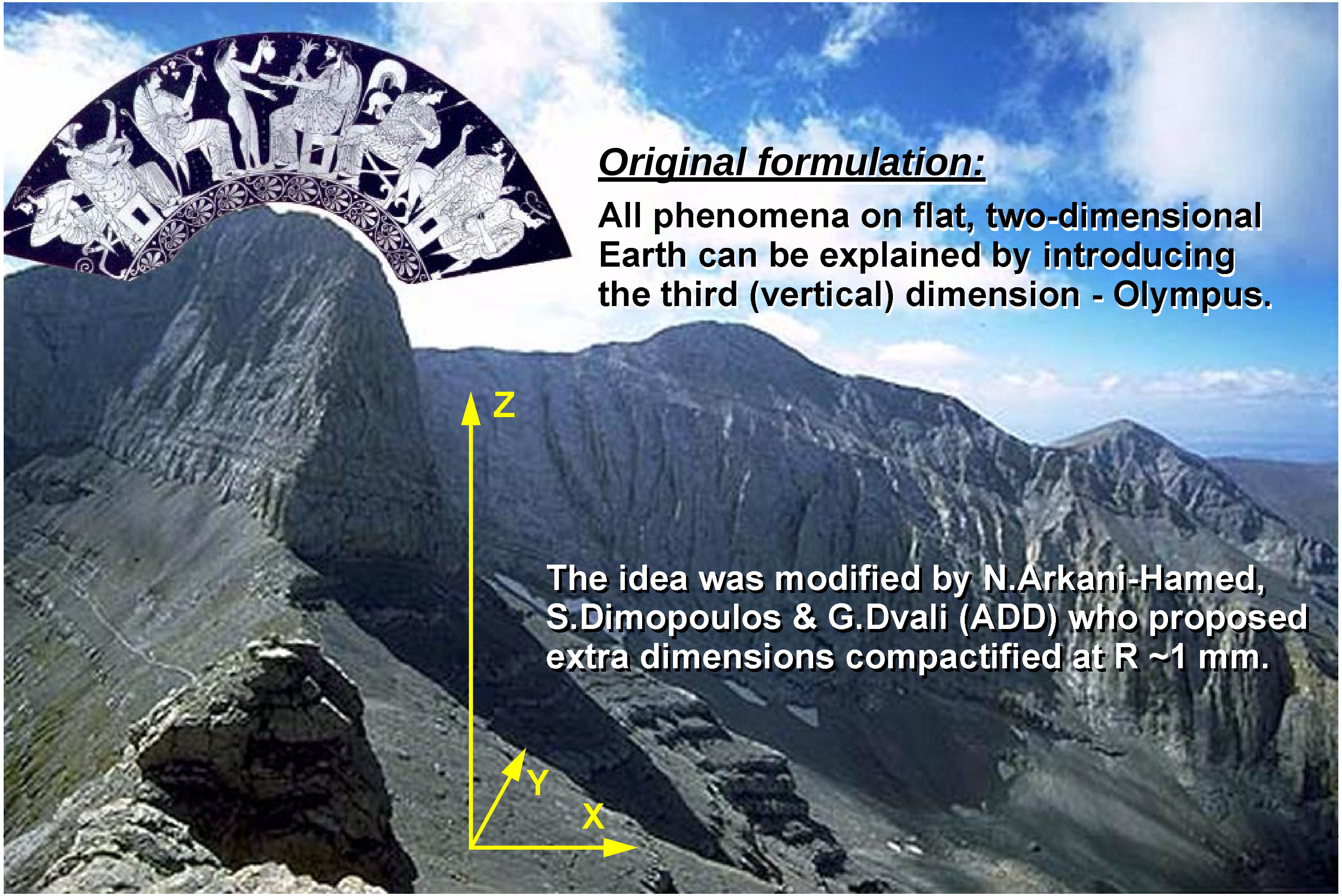
Conclusions

different ECAL and μCAL methods are complementary

CMS can measure $\tilde{N}_1$ cτ from 1cm to 1km

for scenarios with σ_{SUSY}>100fb

Extra dimensions at Olympus



Hierarchy problem

Two fundamental scales:

- **Electroweak — $M_{EW} \sim 10^2$-10^3 GeV**
- **Planck — $M_{Pl} \sim 10^{19}$ GeV**

Observation:

- **M_{EW} is established experimentaly**
  - EW interactions are tested down to distances $1/M_{EW} \sim 10^{-17}$ cm
- **M_{Pl} is just a number**
  - gravity tested only down to ~ 1 mm, far away from $1/M_{Pl} \sim 10^{-35}$ m

Solution: cut the Gordian Knot!

- **There is only one fundamental scale: M_{EW}**
- **M_{Pl} is just an effective constant**
- **Its high value is caused by additional spatial dimentions, compactified at radius R ~ 1 mm**

4+n dimensional gravity (ADD)

N.Arkani-Hamed, S.Dimopoulos, G.Dvali, hep-ph/9803315

R — compactification radius
M_S — 4+n dimensional "Planck scale"

Gravitational potential in 4+n dim space

for small distances r << R

$$V(r) = \frac{m_1 m_2}{M_S^{n+2}} \cdot \frac{1}{r^{n+1}}$$

for large distances r >> R

$$V(r) = \frac{m_1 m_2}{M_S^{n+2} R^n} \cdot \frac{1}{r}$$

This becomes the Newton's law with

$$M_{Pl}^2 = M_S^{n+2} R^n$$

Let us put $M_S \sim M_{EW}$
(no hierarchy!)

$$R = 10^{\frac{30}{n} - 17}\ \text{cm}$$

n=1 → R=10^8 km

- **Solar System distances, gravity very well tested**

n=2 → R=0.1 mm

- **just beyond the current limits**

ADD phenomenology

- “Tower” of graviton excitations $k \cdot m_1$
  where m_1=400eV for n=1

- ADD gravitons couple to momentum tensor and therefore contibute to most of SM processes

- Gravitons can propagate through other dimension
  ⇒ graviton emission apparently violate energy conservation

- Graviton spin of 2 can point to other dimension
  ⇒ apparent spin 0, 1 or 2

- Cross sections are divergent with s
  ⇒ explicit cut-off required

ADD signatures & limits

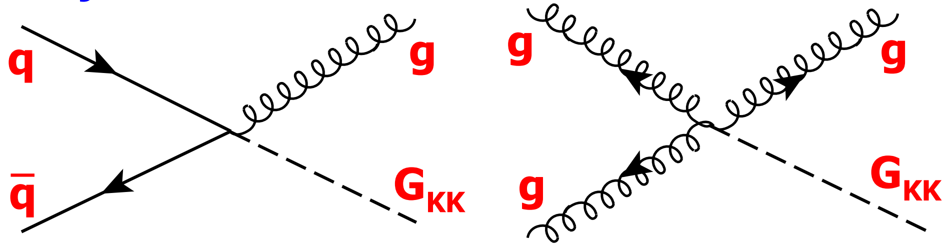
- **Supernova cooling** (Kamiokande ν)
  - $M_S > 30$ TeV (n=2)
  - $M_S > 4$ TeV (n=3)
- **Cosmic diffuse γ radiation ($G \to \gamma\gamma$)**
  - $M_S > 100$ TeV (n=2)
  - $M_S > 5$ TeV (n=3)
- **LEP2: $e^+e^- \to \gamma G, ZG$**
  - $M_S > 1.2$ TeV (n=2)
  - $M_S > 0.8$ Tev (n=4)
- **LEP2: $e^+e^- \to G \to ZZ, ff, \gamma\gamma, WW$**
  - $M_S > 1.2$ TeV
- **HERA: $ep \to G \to ep$**
  - $M_S > 0.81 - 0.93$ TeV
- **Tevatron: $e^+e^- \to G \to e^+e^-, \gamma\gamma$**
  - $M_S > 1.0 - 1.1$ TeV

Expected:

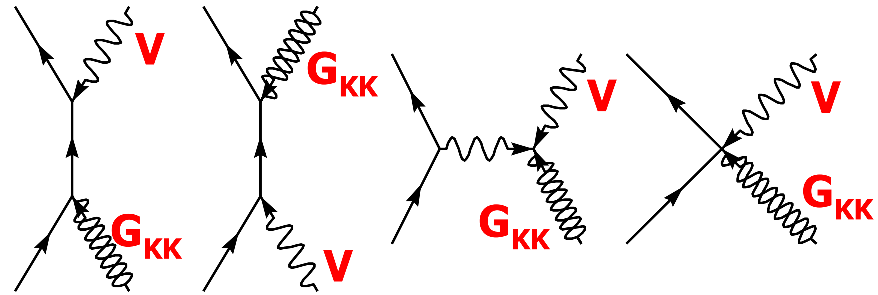
- **Tevatron run II: $e^+e^- \to gG$**
  - $M_S > 1.4$ TeV (n=2)
  - $M_S > 1.15$ TeV (n=3)
  - $M_S > 1.0$ TeV (n=4)

Real Graviton Emission

Monojets at hadron colliders

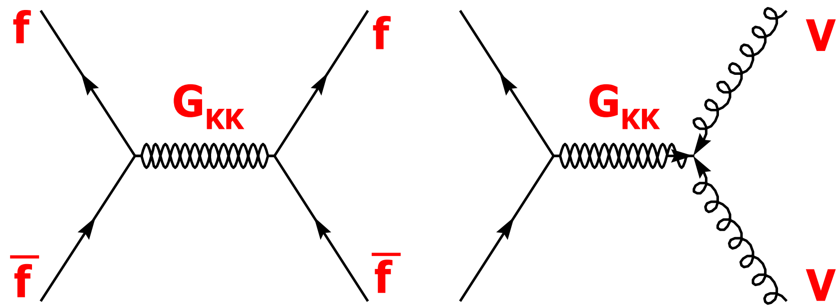


Single VB at hadron or e^+e^- colliders



Virtual Graviton Emission

Fermion or VB pairs at hadron or e^+e^- colliders



TeV^{-1} extra dimensions

Antoniadis, Benaklis, Quiros, PL B460, 176(1999)

Consider :

- p dimensions of R_1 ~ 0.1 mm
- n-p dimensions of R_2 ~ TeV^{-1}

$$M_{Pl}^2 = M_S^{n+2} R_1{}^p R_2{}^{n-p}$$

- gravity in all n extra-dimensions
- SM in n-p extra-dimensions $R_2 \Rightarrow$ ~TeV excitations of γ, W, Z, g

Build your favourite model:

- put each of $SU(3)_C$, $SU(2)_L$, $U(1)_Y$ in any subset of dimensions
- put higgses in standard dimensions, extra dimensions or both
- put fermions at "our wall", stack at other walls or let them propagate in more dimensions (in the bulk)
- study implications for LHC — will be very different !

TeV $^{-1}$ phenomenology

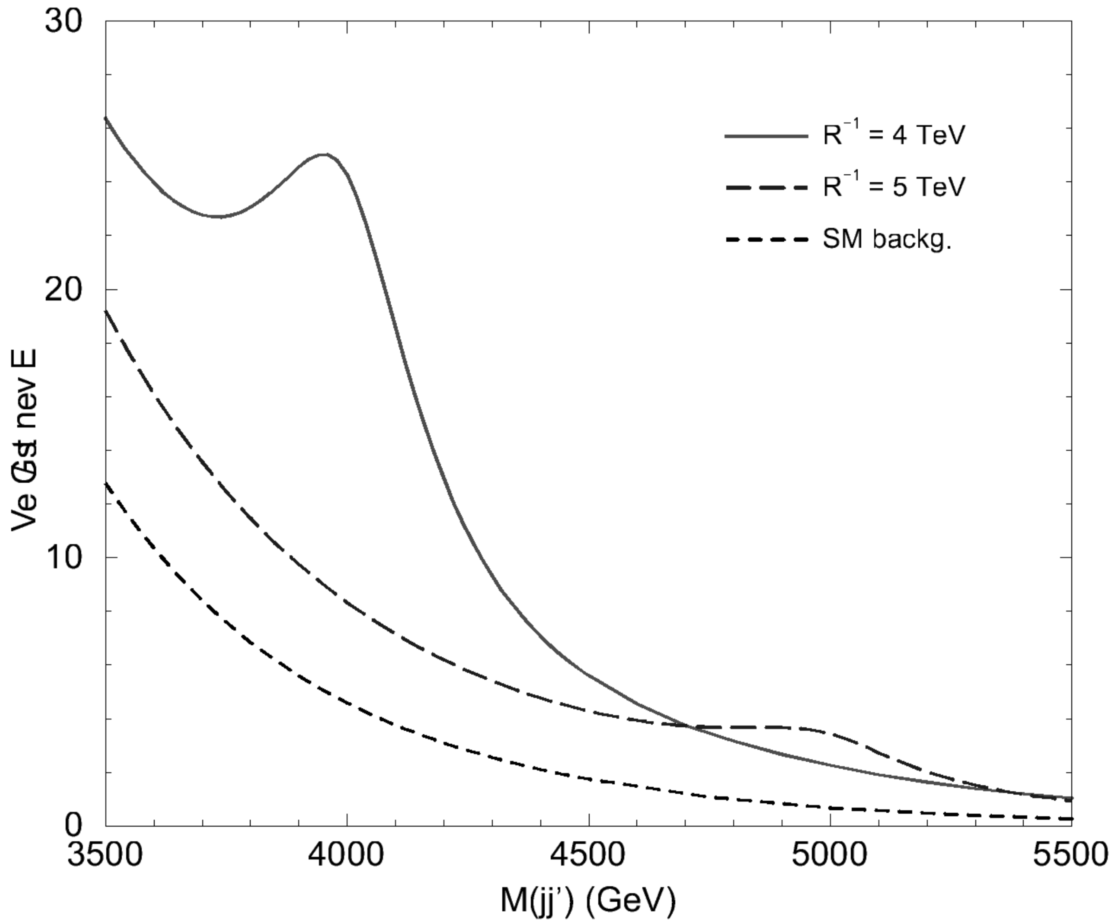
Consider the simplest case:

- **one TeV^{-1} dimension**
- **all SM in extra dimensions** (bulk)
- **all fermions at our wall**

LHC searches:

only the first resonance accessible

- **qq → $\gamma^{(1)}$ / $Z^{(1)}$ → l^+l^-**
- **qq → $W^{(1)}$ → $l^+\nu^-$**
- **qq → $g^{(1)}$ → gg**

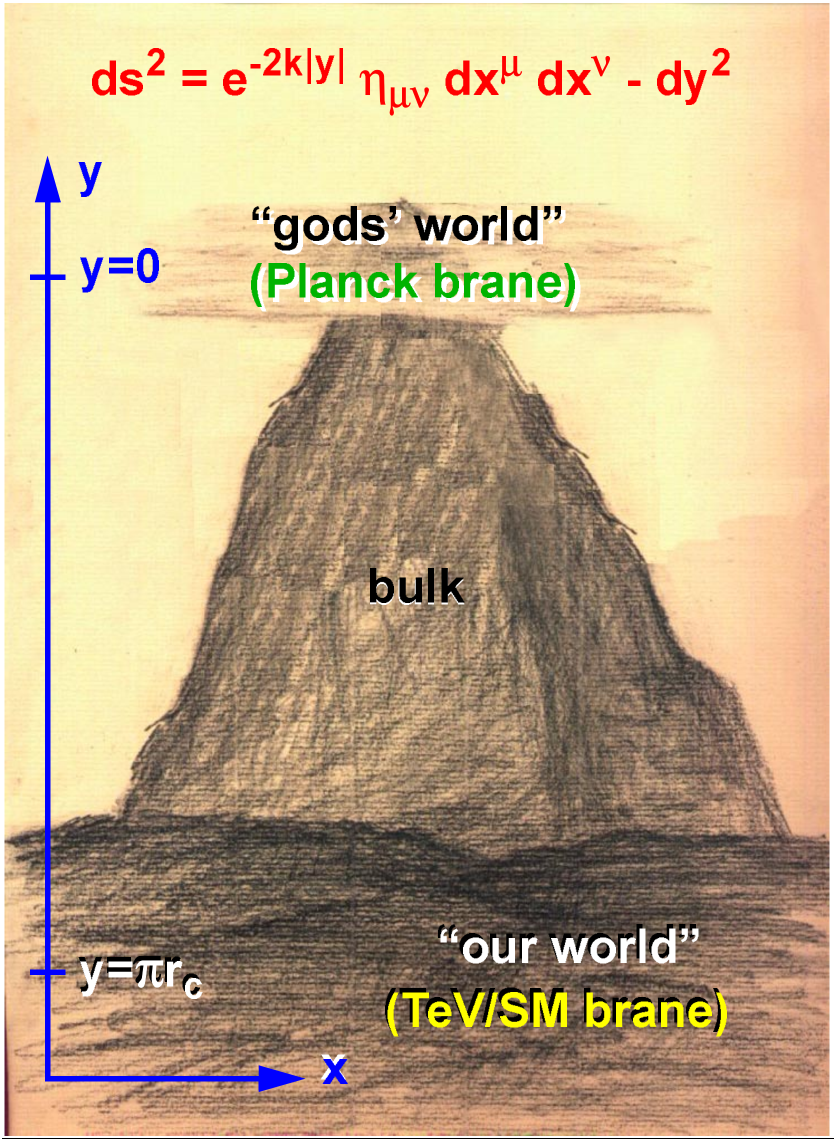


Current limit:

Tevatron:

- **$1/R_2$ > 0.8 TeV**

Randall - Sundrum Olympus



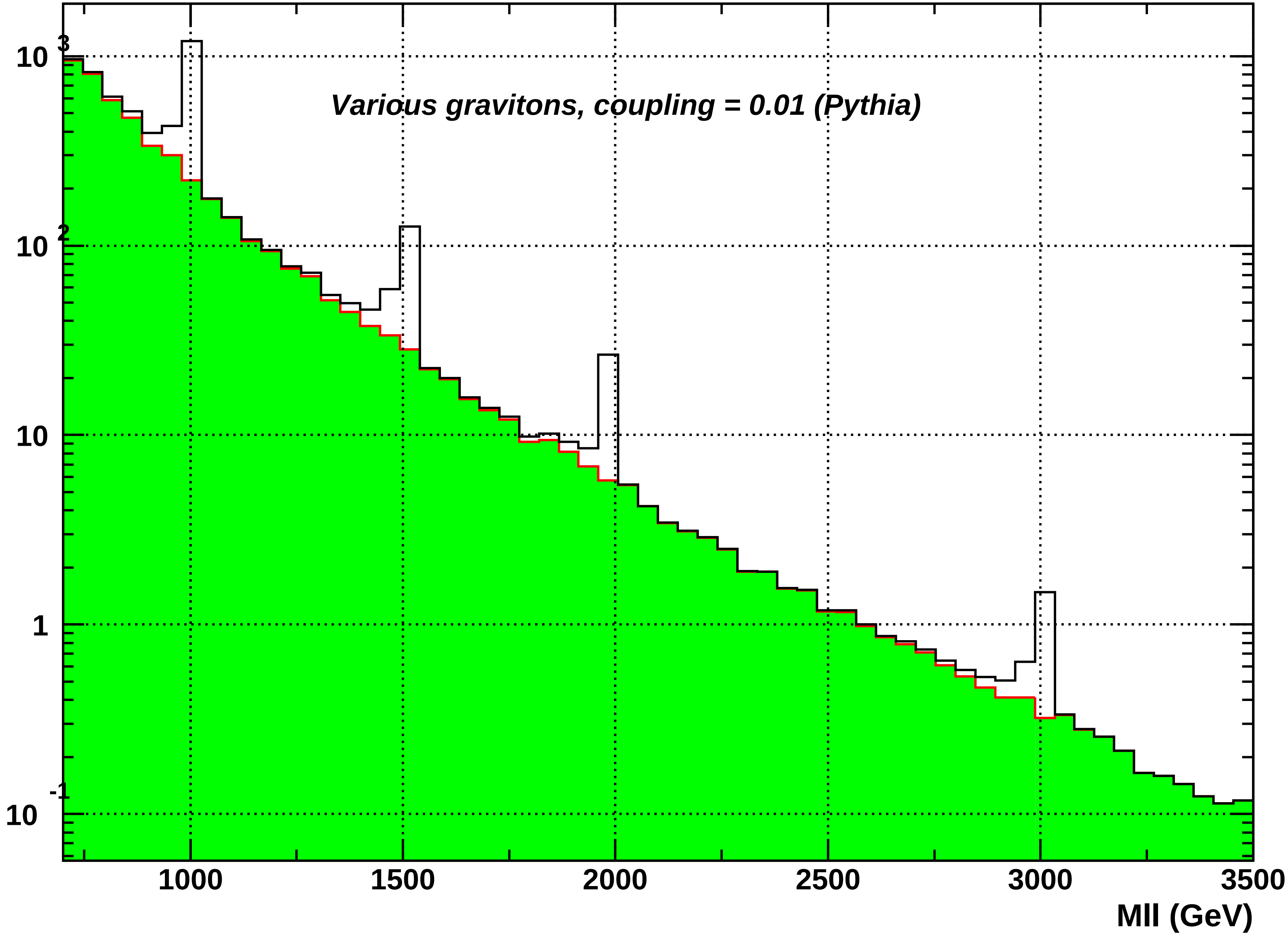
Randal and Sundrum proposed to come back to the ancien Greek idea of two worlds (branes) separated in the extra dimension (bulk).

- Gravity strong at $y=0$ and falls like $\exp(-ky)$
- Gravity scale $\Lambda_\pi = M_{Planck} \exp(-k\pi r_c)$ ~ TeV — no hierarchy
- Graviton resonances $m_n = x_n\, k \exp(-k\pi r_c)$, $J_1(x_n)=0$
- $M_{Planck}/M_{electroweak} \Rightarrow kr_c \sim 11\text{-}12$
- Newton's law $\Rightarrow |R_5| < M_{5D}^2$ $\Rightarrow$ coupling $c < 0.1$

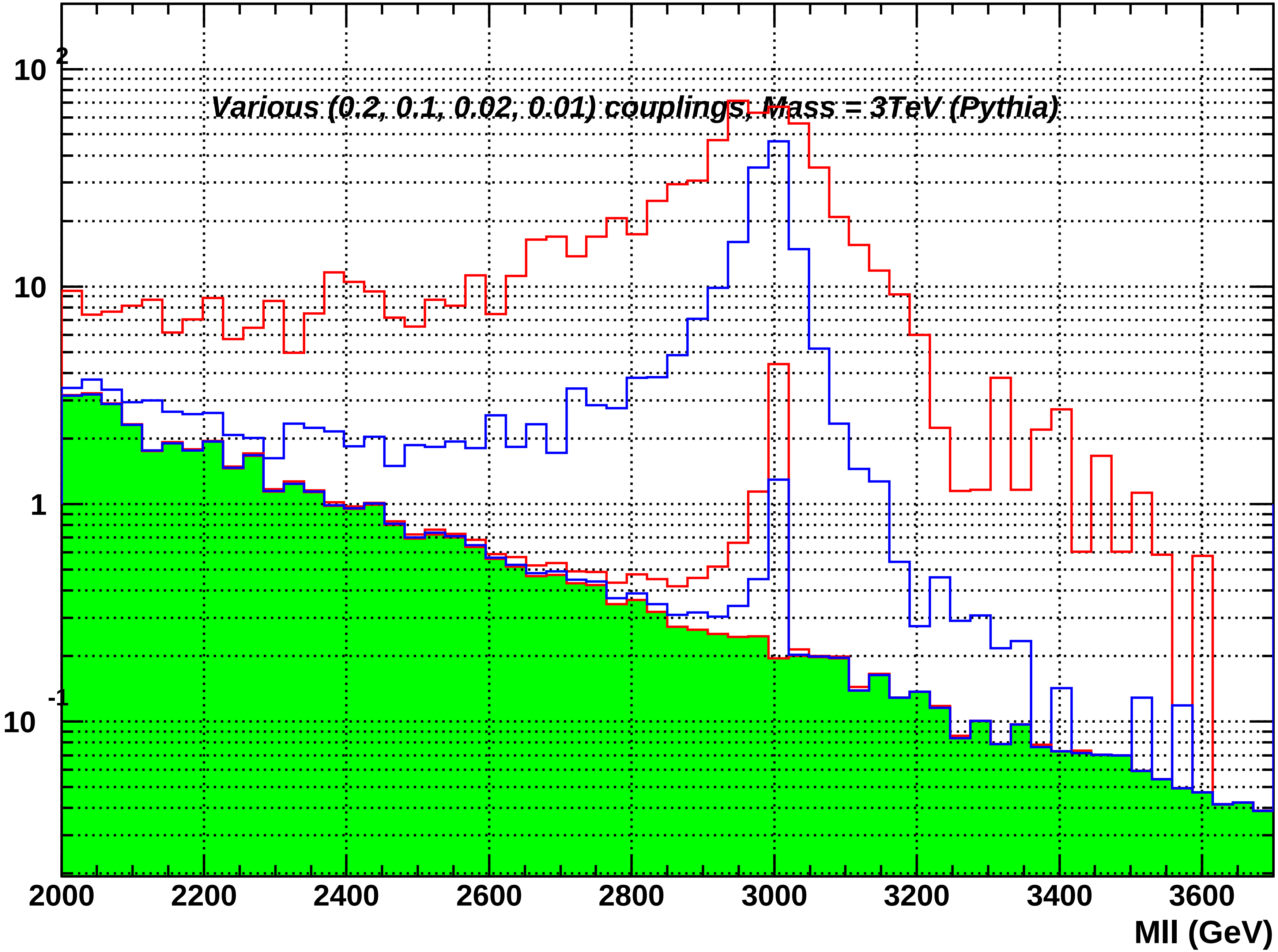
$R_5 = -20\, k^2$ k - curvature

$M_{5D}^3 = k\, M_{Planck}^2$

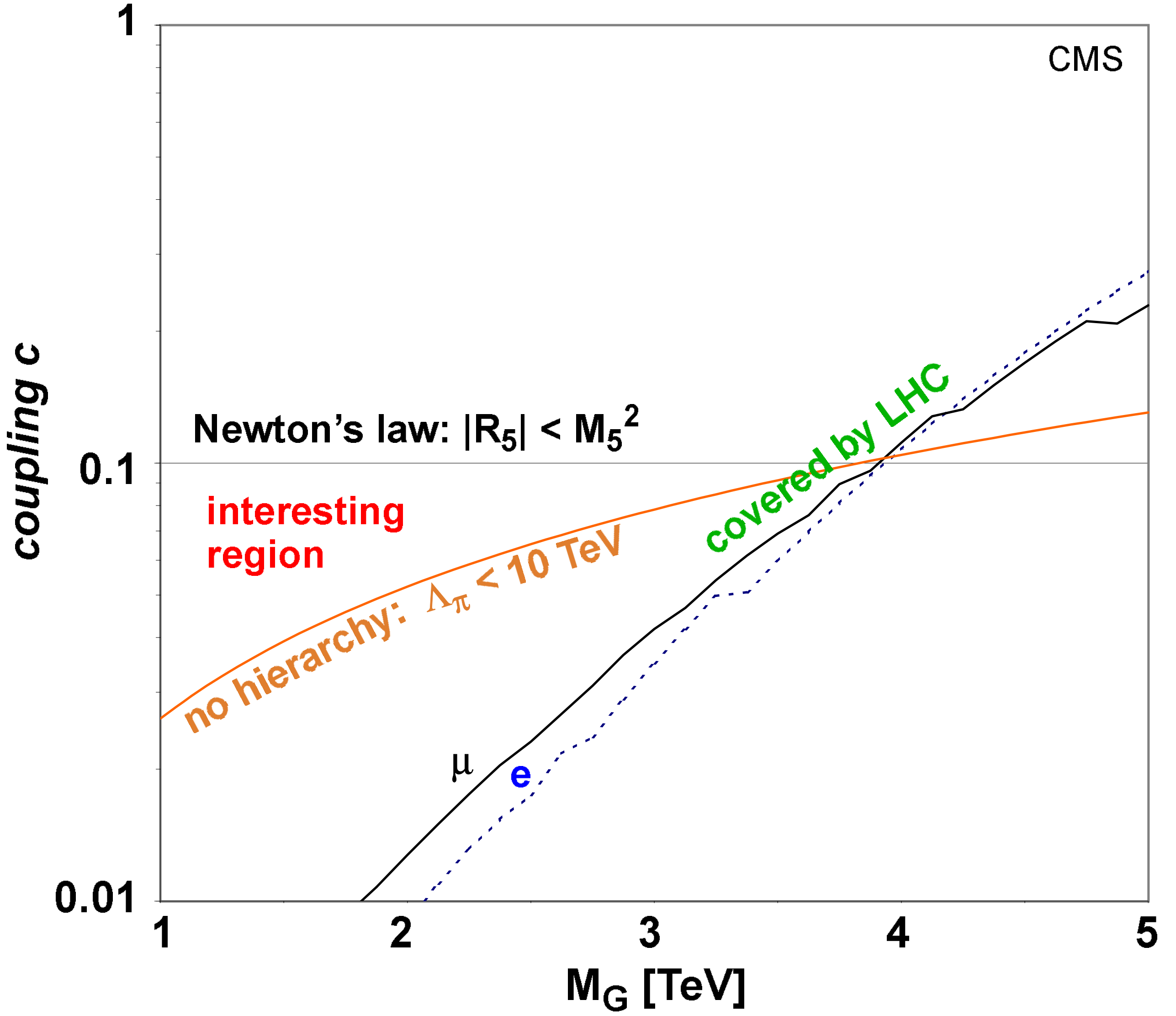
M_G = 1000, 1500, 2000, 3000 GeV



Coupling 0.2, 0.1, 0.02, 0.01



Randall - Sundrum gravitons at LHC



Extra dimension perspectives

Models with extra dimensions can

- unify all interactions
- solve the hierarchy problem
- link String Theory to Standard Model
- make Quantum Gravity and String Theory accessible at LHC
  like Prometeus made the divine fire accessible for people

Perhaps it is only a dream...

But I wish you and me this dream to come true!