Non-standard signatures in GMSB

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OUTLINE:

- GMSB – introduction
- Why GMSB is interesting from the detection point of view?
- What was done by ATLAS?
- Why is not so simple?
- Discussion LEP–TeVatron–LHC–NLC

Gauge Mediated Supersymmetry Breaking

SUSY is broken in a so called Secluded Sector at scale $\sqrt{F}$ and transmitted to SM particles via Messenger Sector.
Messenger sector contains n flavours of vector GUT representations (eg. SU(5)). Via interaction with SM singlet scalar field from Secluded sector Messengers acquire mass M and soft supersymmetry breaking masses squared proportional to $F_M < F$.
This effect feeds down to the MSSM through loop corrections. Gauginos acquire majorana masses at one loop

$$m_j(M) = n\frac{\alpha_j(M)}{4\pi}\Lambda$$

while sfermions acquire SUSY-breaking masses-squared at two loops

$$m^2_{\tilde{f}_i}(M) = 2n\sum_{j=1}^{3} C_{ij}\left(\frac{\alpha_j(M)}{4\pi}\right)^2\Lambda^2$$

where $\Lambda = F_M/M$ sets the effective scale of SUSY breaking in MSSM.
The superpartner mass depends on its SM coupling. Eg. the heaviest scalars are $\tilde{q}_L$, then $\tilde{q}_R$, $\tilde{l}_L$, $\tilde{l}_R$. Gaugino masses are related to sfermion masses via factor $\sqrt{n}$.
Because squarks of different families are degenerate at relatively low scale M, there is no large FCNC effects.
The splitting of masses is obtained via RGE and depends on $\tan\beta$ the hierarchy M/Λ and a value of the μ parameter (μ^2 is determined by EW symmetry breaking: only sign of μ is free).
The most important difference between the GMSB and the mSUGRA models is that in the GMSB scenario gravitino is the LSP

$$m_{\tilde{G}} = \frac{F}{\sqrt{3}M_P}$$

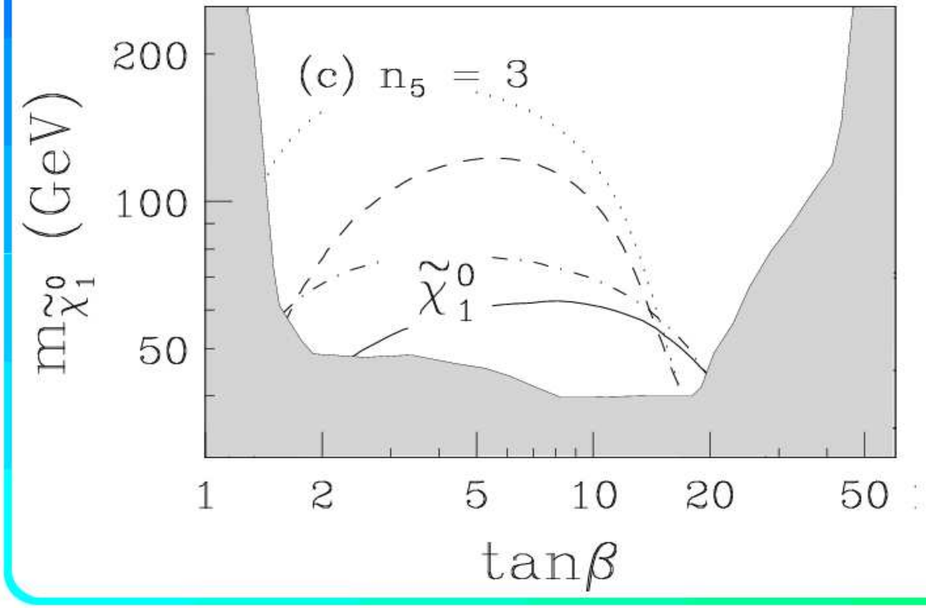
GMSB – introduction

MSSM LSP becomes GMSB NLSP and decays to its SM partner and gravitino with $c\tau$ from microns to hundreds of meters. For $n = 1$ and low $\tan\beta$ neutralino is the NLSP whereas for high $\tan\beta$ or high n stau is the NLSP.

It can be seen below for $n = 3$

NLSP lifetime is proportional to the gravitino mass squared for fixed NLSP mass.

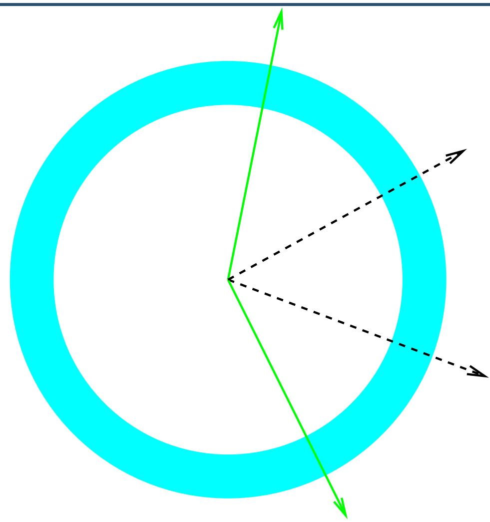
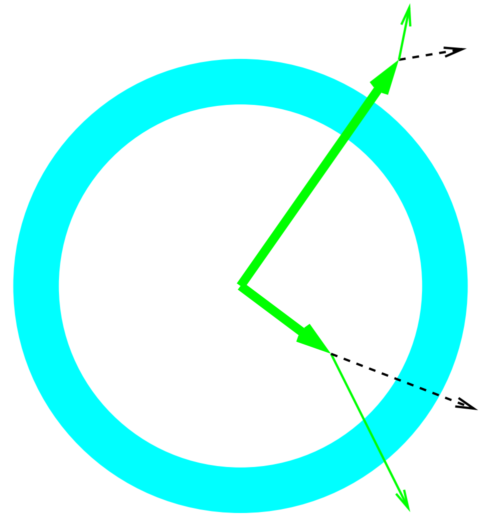
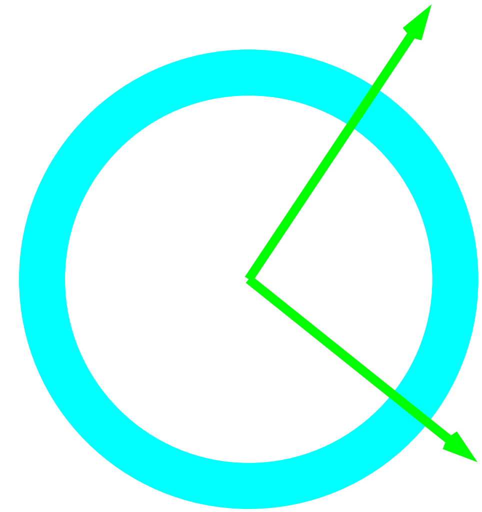
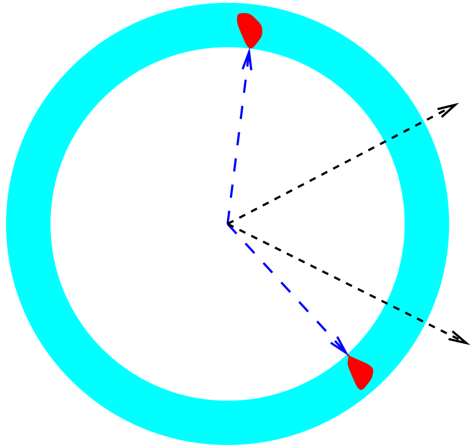
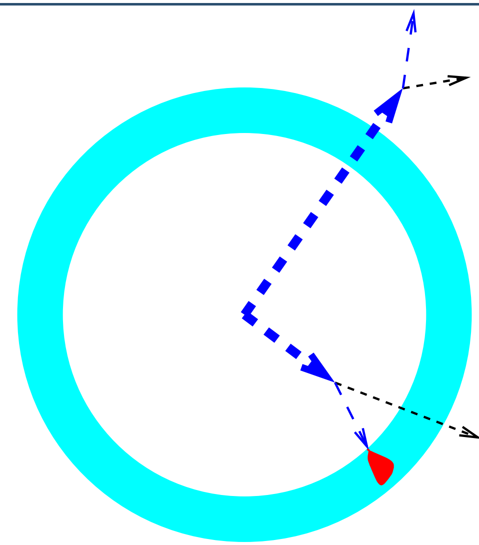
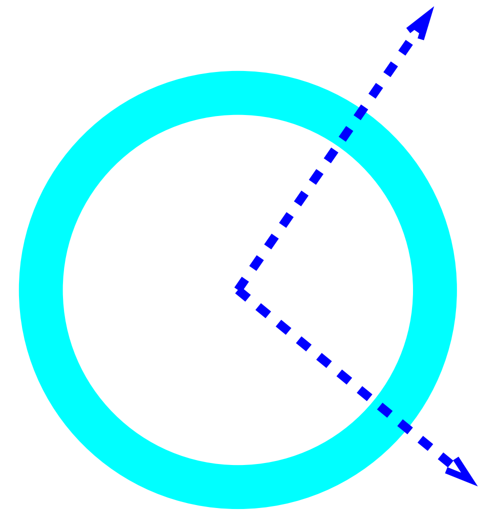
$$c\tau \approx (1.3\mathrm{m}) \left(\frac{100\mathrm{GeV/c^2}}{\mathrm{m(NLSP)}}\right)^5 \left(\frac{\sqrt{\mathrm{F}}}{1000\mathrm{TeV/c^2}}\right)^4$$

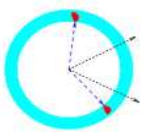


$(\mathrm{sgn}\mu, M/\Lambda)$: $(+, 2)$ solid, $(+, 10^4)$ dashed, $(-, 2)$ dot-dashed and $(-, 10^4)$ dotted; lines are drown for equal masses of stau and neutralino.

(The plot is taken from hep-ph/9609444)

Why GMSB?

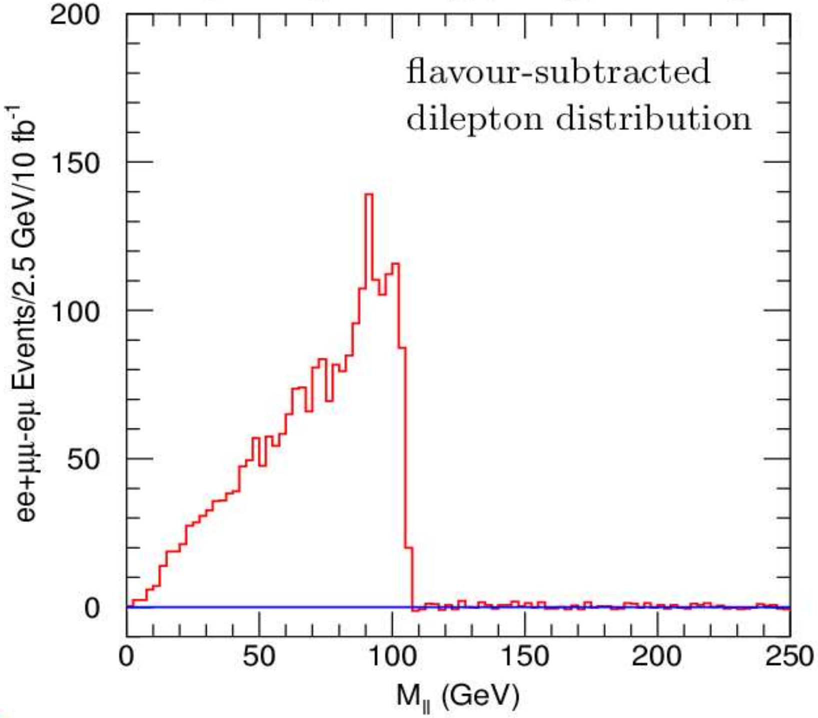
NLSP	$c\tau \simeq 0$	$c\tau \simeq$ det. size	$c\tau >> $ det. size
$\widetilde{\tau}_1 \to \widetilde{G}\tau$			
$\widetilde{\mathbf{N}}_1 \to \widetilde{G}\gamma$			

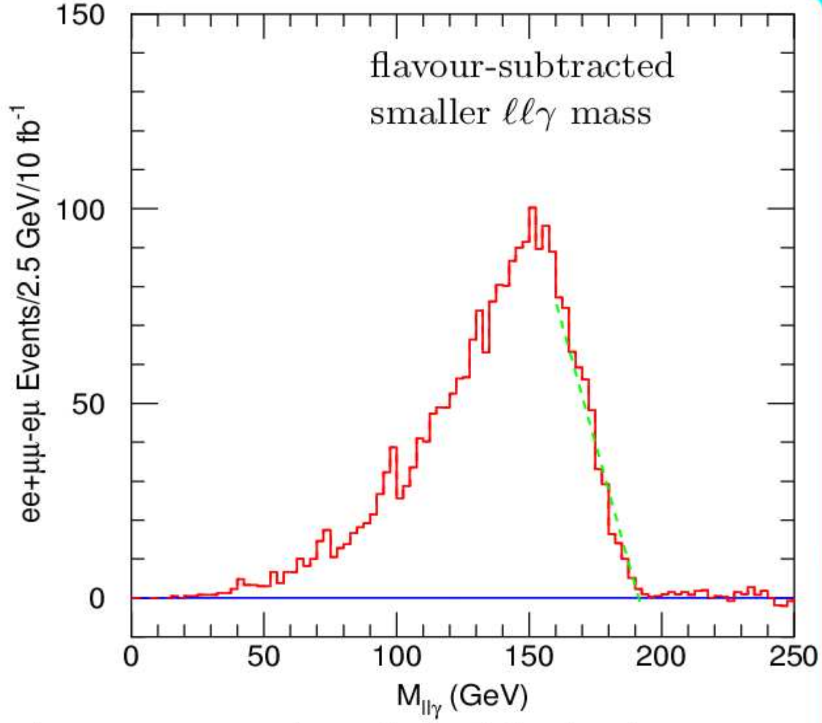


ATLAS point G1a

NLSP: $\widetilde{N}_1$, 119 GeV; short-lived; 7.6 pb

At this point: $\widetilde{N}_1 \to \widetilde{G}\gamma$ and
$\widetilde{N}_2 \to \widetilde{\ell}^{\pm}\ell^{\mp} \to \widetilde{N}_1 \ell^+\ell^- \to \widetilde{G}\ell^+\ell^-\gamma$
In the flavour-subtracted distribution
$e^+e^- + \mu^+\mu^- - e^{\pm}\mu^{\mp}$ one can very sharp
endpoint $\sqrt{M^2_{\widetilde{N}_2} - M^2_{\widetilde{\ell}_R}}\sqrt{M^2_{\widetilde{\ell}_R} - M^2_{\widetilde{N}_1}}/M_{\widetilde{\ell}_R}$.





Taking into account the whole 4-body decay chain one can measure 3 more endpoints

$M_{\ell\ell\gamma} = \sqrt{M^2_{\widetilde{N}_2} - M^2_{\widetilde{N}_1}}$ (linear – figure)

$M^{(1)}_{\ell\gamma} = \sqrt{M^2_{\widetilde{\ell}_R} - M^2_{\widetilde{N}_1}}$ (edge)

$M^{(2)}_{\ell\gamma} = \sqrt{M^2_{\widetilde{N}_2} - M^2_{\widetilde{\ell}_R}}$ (linear)

Which is sufficient to determine $\widetilde{N}_2, \widetilde{\ell}_R$ and $\widetilde{N}_1$ masses

ATLAS – fit

Fitting GMSB parameters by ATLAS

Point G1A 7.6 pb, short-lived $\widetilde{N}_1$

quantity	low-lumi	ultimate
$M_h(GeV)$	109.47 ± 3.0	109.27 ± 0.2
$M_{\ell\ell}^{max}(GeV)$	105.1 ± 0.1	same
$M_{\ell\ell\gamma}^{max}(GeV)$	189.7 ± 0.3	189.7 ± 0.3
$M_{\ell\gamma}^{(1)}(GeV)$	112.7 ± 0.15	112.7 ± 0.1
$M_{\ell\gamma}^{(2)}(GeV)$	152.6 ± 0.3	152.6 ± 0.2

parameter	low-lumi	high-lumi	ultimate
$\Lambda(TeV)$	90 ± 1.7	90 ± 0.89	same
$M(TeV)$	500 ± 170	500 ± 110	same
n	1.0 ± 0.014	1.0 ± 0.011	same
$\tan\beta$	5.0 ± 1.3	5.0 ± 0.4	5.0 ± 0.14

Point G2A 23 pb, short-lived $\widetilde{\tau}_1$

quantity	low-lumi	ultimate
$M_h(GeV)$	106.6 ± 3.0	106.6 ± 0.2
$M_{\ell\ell}^{max(1)}(GeV)$	52.21 ± 0.05	same
$M_{\ell\ell}^{max(2)}(GeV)$	175.94 ± 0.18	same
$M_{\ell\ell q}^{max}(GeV)$	640 ± 7	same
$M_{\ell q}^{max}/M_{\ell\ell q}^{max}$	0.450 ± 0.004	same

parameter	low-lumi	high-lumi	ultimate
$\Lambda(TeV)$	30 ± 0.54	same	same
$M(TeV)$	250 ± 60	same	same
n	3.0 ± 0.05	same	same
$\tan\beta$	5.0 ± 1.0	5.0 ± 1.0	5.0 ± 0.06

Point G1B 7.6 pb, long-lived $\widetilde{N}_1$

quantity	low-lumi	ultimate
$M(\tilde{g}) - M(\widetilde{N}_2)(GeV)$	189.7 ± 0.3	189.7 ± 0.3
$M(\widetilde{q}_L)(GeV)$	112.7 ± 0.15	112.7 ± 0.1

(M_h & $M_{\ell\ell}^{max}$ as in point G1A)

For 30/fb the fit gives (for $\mu > 0$:

$n \times \Lambda = (90 \pm 0.88)\,TeV$, $\Lambda = (90 \pm 11.5)\,TeV$

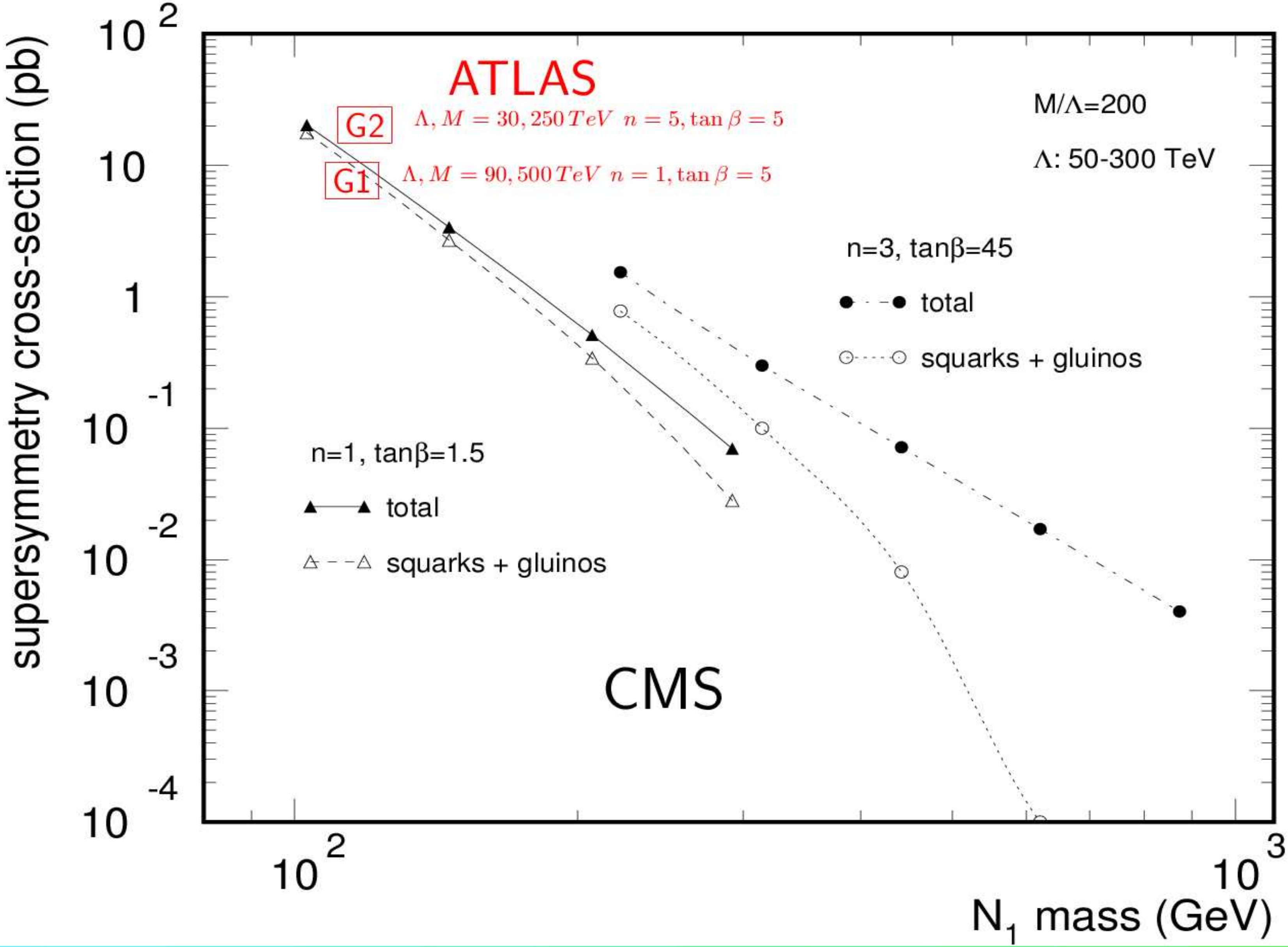
$M < 7 \times 10^5\,TeV$, $\tan\beta = 5.0^{+2.7}_{-1.8}$

Point G2B 23 pb, long-lived $\widetilde{\tau}_1$

Quasi-stable sleptons:
many precise mass measurements

parameter	low-lumi	high-lumi	ultimate
$\Lambda(TeV)$	30 ± 0.25	same	same
$M(TeV)$	250 ± 32	same	same
n	3.0 ± 0.02	same	same
$\tan\beta$	5.0 ± 0.3	5.0 ± 0.3	5.0 ± 0.03

GMSB X-sections



SUSY GMSB event: cascade decays to

Next to the Lightest Supersymmetry Particle

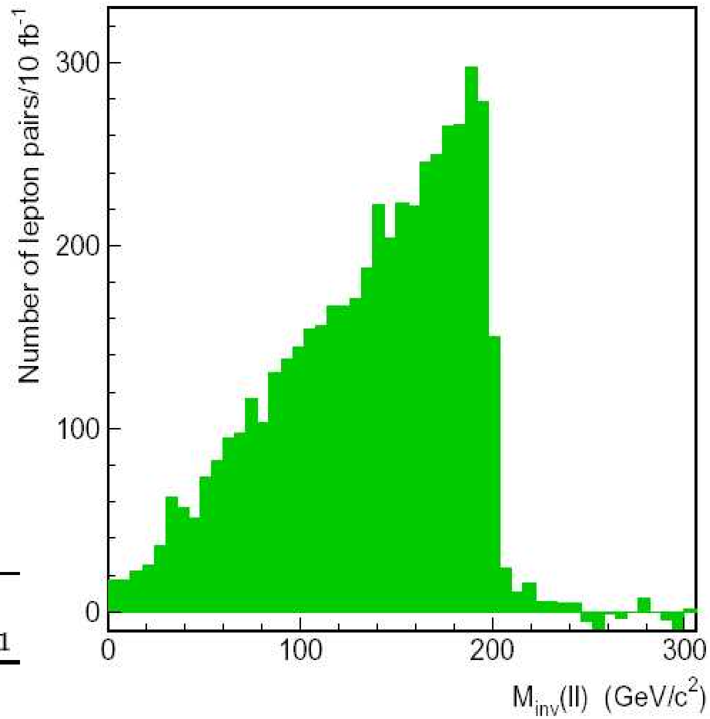
↙ ↘

neutralio $\widetilde{N}_1$

In $M_{inv}(\ell\bar{\ell})$ of
$\mu^+\mu^- + e^+e^- - \mu^+e^- - e^+\mu^-$

sleptons: $\widetilde{\tau}_1$ **or** $\widetilde{e}_R\, \widetilde{\mu}_R$

$$\widetilde{N}_2 \to \widetilde{\ell}^{\pm}_R + \ell^{\mp}$$
$$\hookrightarrow \widetilde{N}_1 + \ell^{\pm}$$

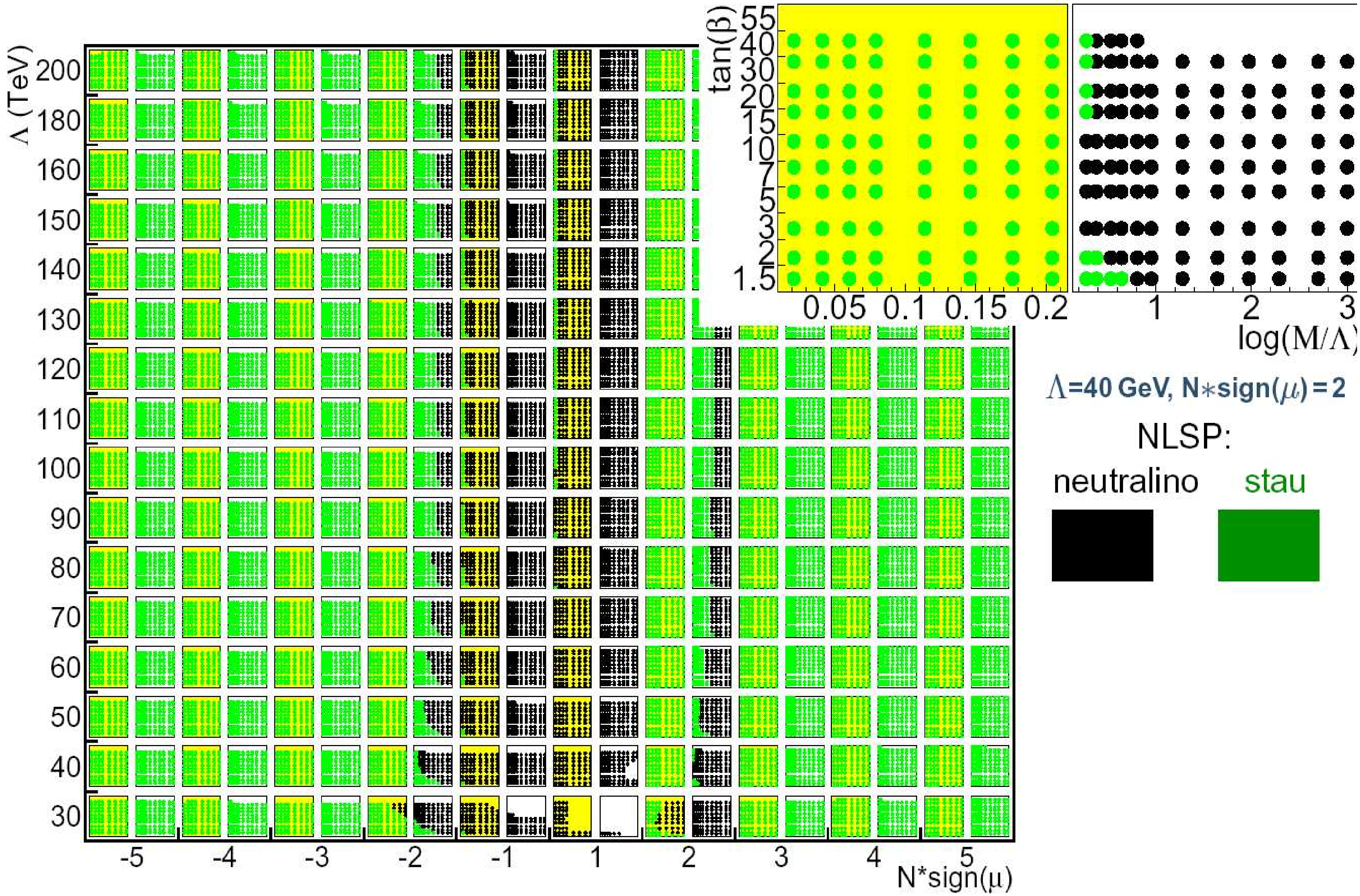


$$\widetilde{N}_1 \to \widetilde{\ell}^{\pm}_R + \ell^{\mp}$$
$$\hookrightarrow \tilde{G} + \ell^{\pm}$$

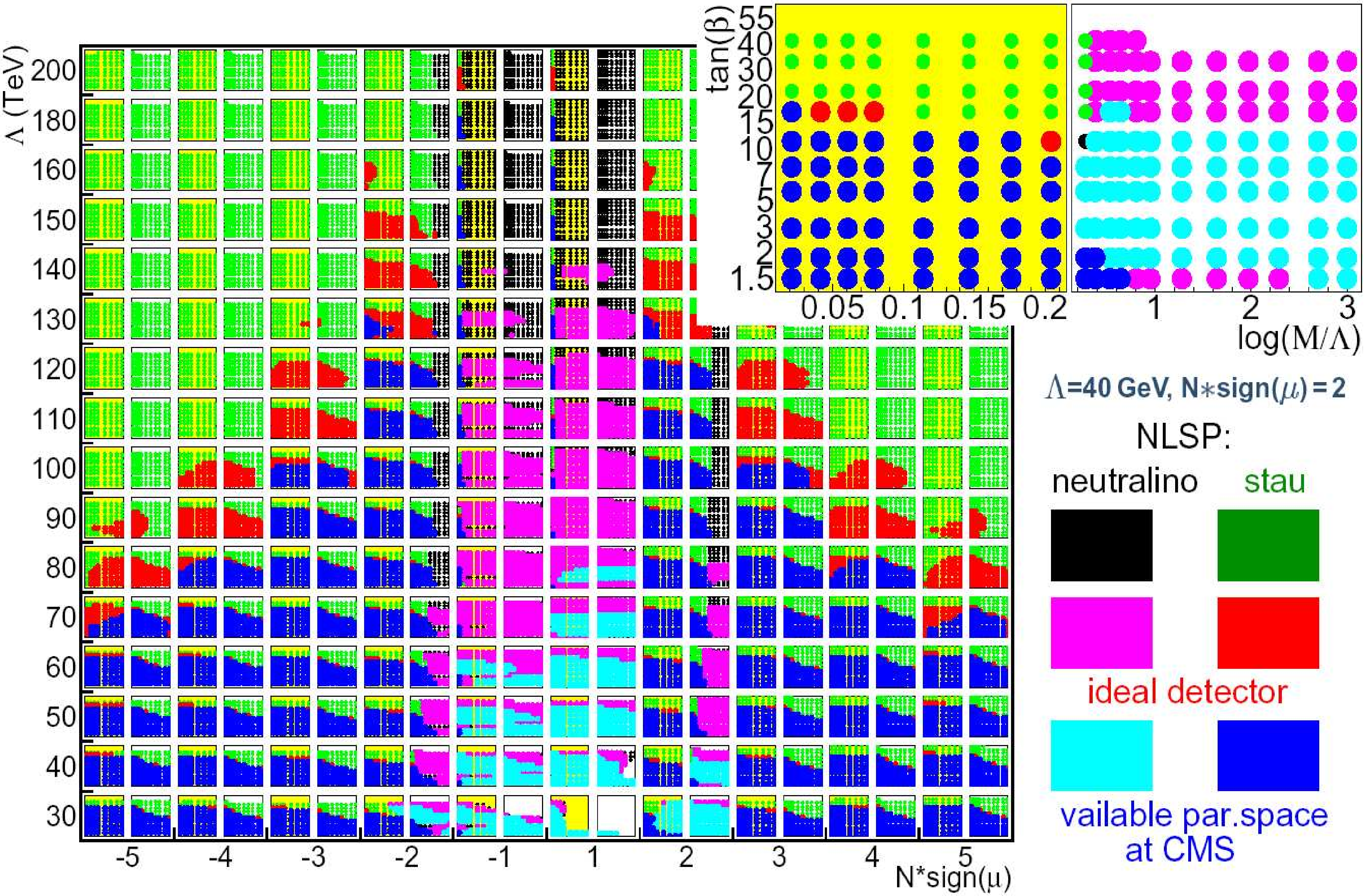
$$M_{inv}(\ell\bar{\ell}) = \frac{\sqrt{m^2_{\widetilde{N}_2} - m^2_{\widetilde{\ell}_R}}\sqrt{m^2_{\widetilde{\ell}_R} - m^2_{\widetilde{N}_1}}}{m_{\widetilde{\ell}_R}}$$

$$M_{inv}(\ell\bar{\ell}) = \sqrt{m^2_{\widetilde{N}_1} - m^2_{\widetilde{\ell}_R}}$$

Scan over parameters space



Scan over parameters space



Models: Case Studies

Goals:

- For more complex signals (cascades, production of multiple particles), check if consistent with various models
- Large number of models, phenomenology depends on free parameters → case studies

Projects:

- SUSY
  - mSUGRA (Alexander Belyaev, Tadas Krupovnickas)
  - MSSM (Howie Baer, Georg Weiglein, Csaba Balazs)
  - NMSSM (Sabine Kraml, Cyril Hugonie)
  - Stops (Sabine Kraml, Joe Lykken, Shoji Asai)
  - Disentangling Models (Dirk Zerwas et al. (SFITTER), Bob Kehoe, Gordon Kane)
  - Tools (Michael Spira (PROSPINO), Peter Skands (SLHA))
- Universal Extra Dimensions (Kyoungchul Kong, Konstantin Matchev, Satya Nandi)
- Signal Generators and tools for Extra Dimensions (Albert de Roeck et al.)
- Little Higgs Models with T-Parity (Jay Hubisz)
- Technicolor (Ken Lane)
- Higgsless Models (Andreas Birkedal)

Please add your name to the list!

SUSY Fits in Tevatron and LHC Data (SFITTER)

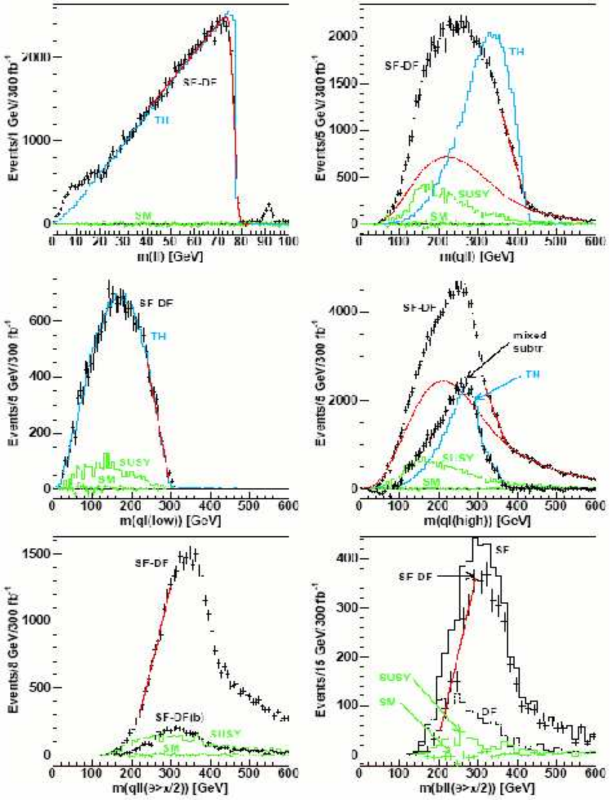
Examples of measurements at LHC

Gjelsten et al: ATLAS-PHYS-2004-007/29

$$
\begin{aligned}
(m^2_{ll})^{\text{edge}} &= \frac{(m^2_{\tilde\chi^0_2} - m^2_{\tilde l_R})(m^2_{\tilde l_R} - m^2_{\tilde\chi^0_1})}{m^2_{\tilde l_R}} \\
(m^2_{qll})^{\text{edge}} &= \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde\chi^0_1})}{m^2_{\tilde\chi^0_2}} \\
(m^2_{ql})^{\text{edge}}_{\text{min}} &= \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde l_R})}{m^2_{\tilde\chi^0_2}} \\
(m^2_{ql})^{\text{edge}}_{\text{max}} &= \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde l_R} - m^2_{\tilde\chi^0_1})}{m^2_{\tilde l_R}} \\
(m^2_{qll})^{\text{thres}} &= [(m^2_{\tilde q_L} + m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde l_R})(m^2_{\tilde l_R} - m^2_{\tilde\chi^0_1}) \\
&\quad -(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})\sqrt{(m^2_{\tilde\chi^0_2} + m^2_{\tilde l_R})^2(m^2_{\tilde l_R} + m^2_{\tilde\chi^0_1})^2 - 16 m^2_{\tilde\chi^0_2} m^4_{\tilde l_R} m^2_{\tilde\chi^0_1}} \\
&\quad +2m^2_{\tilde l_R}(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde\chi^0_1})]/(4 m^2_{\tilde l_R} m^2_{\tilde\chi^0_2})
\end{aligned}
$$

Edge	Nominal Value	Fit Value	Syst. Error Energy Scale	Statistical Error
$m(ll)^{\text{edge}}$	77.077	77.024	0.08	0.05
$m(qll)^{\text{edge}}$	431.1	431.3	4.3	2.4
$m(ql)^{\text{edge}}_{\text{min}}$	302.1	300.8	3.0	1.5
$m(ql)^{\text{edge}}_{\text{max}}$	380.3	379.4	3.8	1.8
$m(qll)^{\text{thres}}$	203.0	204.6	2.0	2.8
$m(bll)^{\text{thres}}$	183.1	181.1	1.8	6.3

plus other mass differences and edges...



From edges to masses: System overconstrained

LEP–TeVatron–LHC–NLC

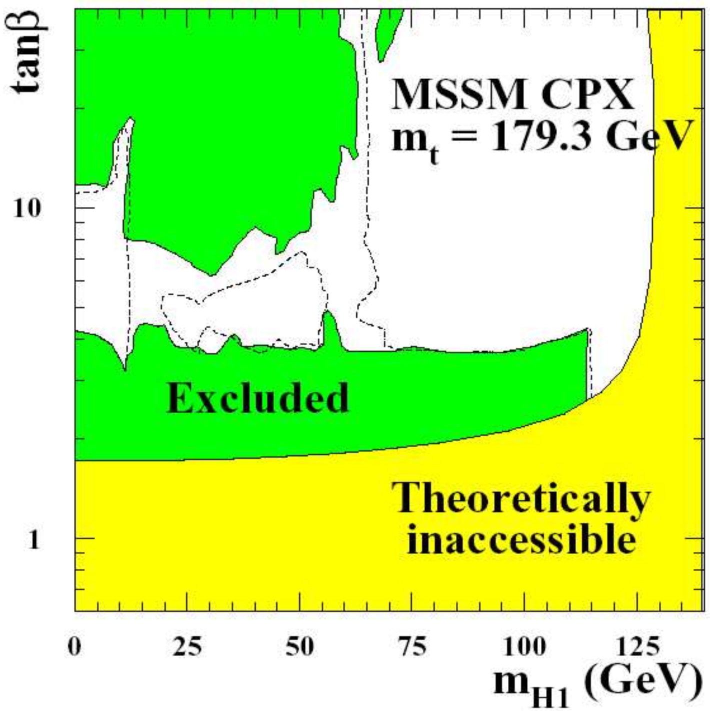
What is the problem?

CPX scenario:

→ emphasize "possible" large effects:

[M. Carena, J. Ellis, A. Pilaftsis, C. Wagner '01]

$M_{SUSY} = 500$ GeV, $|A_t| = 1$ TeV,
$A_b = A_\tau = A_t$,
$M_2 = 500$ GeV, $|m_{\tilde{g}}| = 1$ TeV,
$\mu = 2$ TeV
$\Phi = \Phi_{A_{t,b,\tau}} = \Phi_{m_{\tilde{g}}}$
$M_{H^\pm}$, $\tan\beta$ varied



LEP search left uncovered holes with low m_{h_1} ⇒ difficult for LHC

Q: Can the Tevatron cover these holes?

Sven Heinemeyer, Tev4LHC workshop, 29.04.2005 4

A": However, another thing . . .

LEP analysis:

Two codes: FeynHiggs2.0 and CPH

conservative approach (very good!):

CPX point not excluded

$\Leftrightarrow$

(point not excluded by FeynHiggs) or (point not excluded by CPH)

CPX holes "rely" heavily on large BR($h_2 \to h_1 h_1$)

CPX holes: CPH has larger BR($h_2 \to h_1 h_1$) than FeynHiggs

$\Rightarrow$ reasons for differences under investigation

$\Rightarrow$ possibly higher-order effects that are not under control

($\Rightarrow$ LEP analysis is currently the best strategy!)

Sven Heinemeyer, Tev4LHC workshop, 29.04.2005 *8*

A" ': However, yet another thing . . .

LEP analysis:

holes not excluded at the 95% C.L.
holes are excluded at the $\sim$ 75% C.L.

$\Rightarrow$ "combined" LEP/Tevatron analysis ??