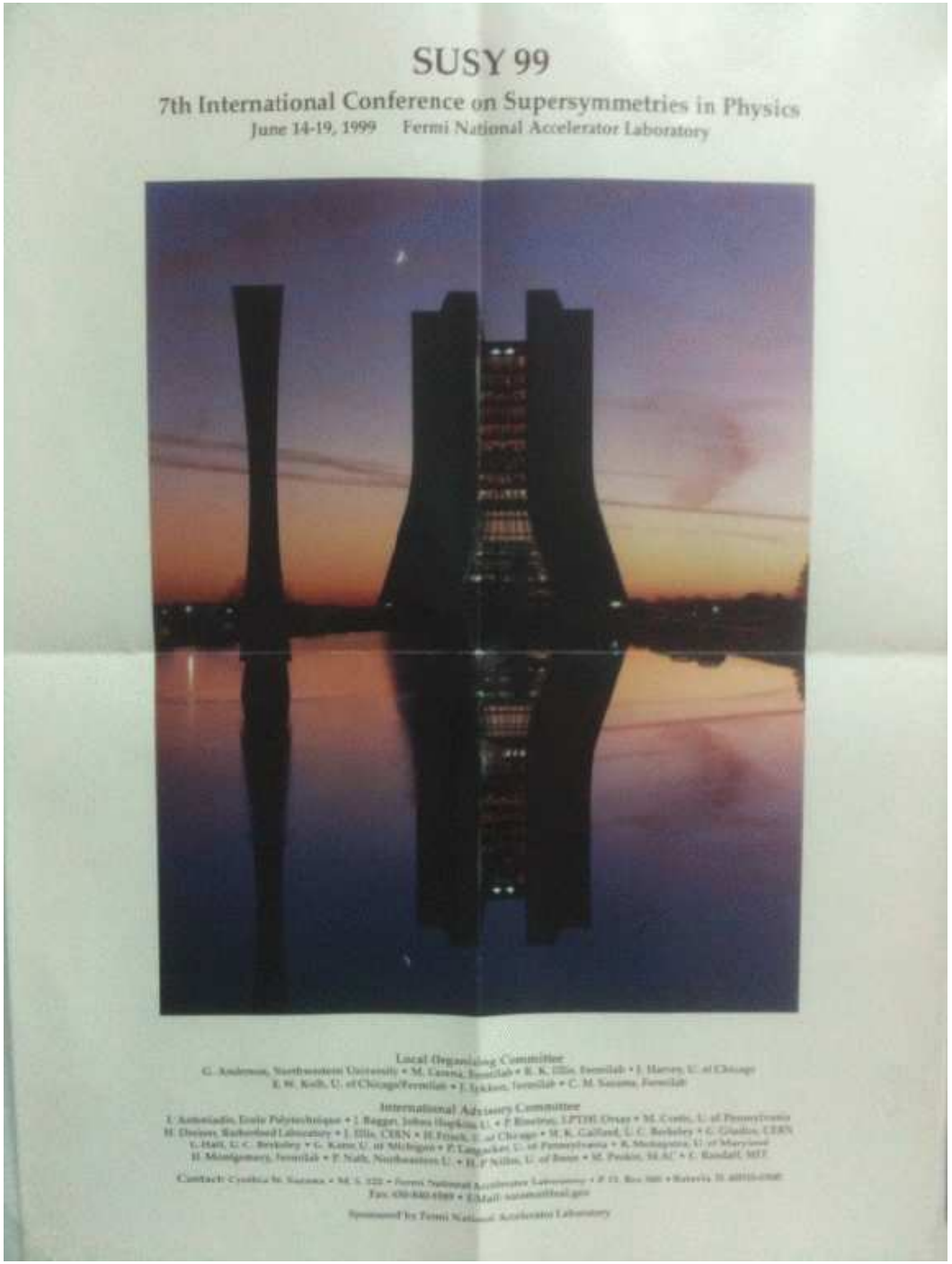
SUSY 99
7th International Conference on Supersymmetries in Physics
June 14-19, 1999 Fermi National Accelerator Laboratory
Local Organizing Committee
International Advisory Committee

SUSY 11
19th International Conference on Supersymmetry and Unification of Fundamental Interactions
August 28 - September 2, 2011
Fermi National Accelerator Laboratory
Includes Particle Astrophysics & Cosmology Day at the KICP, U. of Chicago
TOPICS
SUSY formal aspects and model building
SUSY phenomenology and experimental searches
Higgs Physics: from theory to experiment
Alternatives: model building and searches
New Physics at the Intensity Frontier
Dark Matter
Cosmic Particles
Inflation & Dark Energy
Additional information & registration
Fermilab
ENERGY

SUSY at the LHC

Sven Heinemeyer, IFCA (CSIC, Santander)

Fermilab, 08/2011

1. Motivation ;-)
2. Searches for signs of SUSY at the LHC
3. SUSY fits
4. Implications for future e^+e^- colliders
5. Conclusions

1. Motivation ;-)

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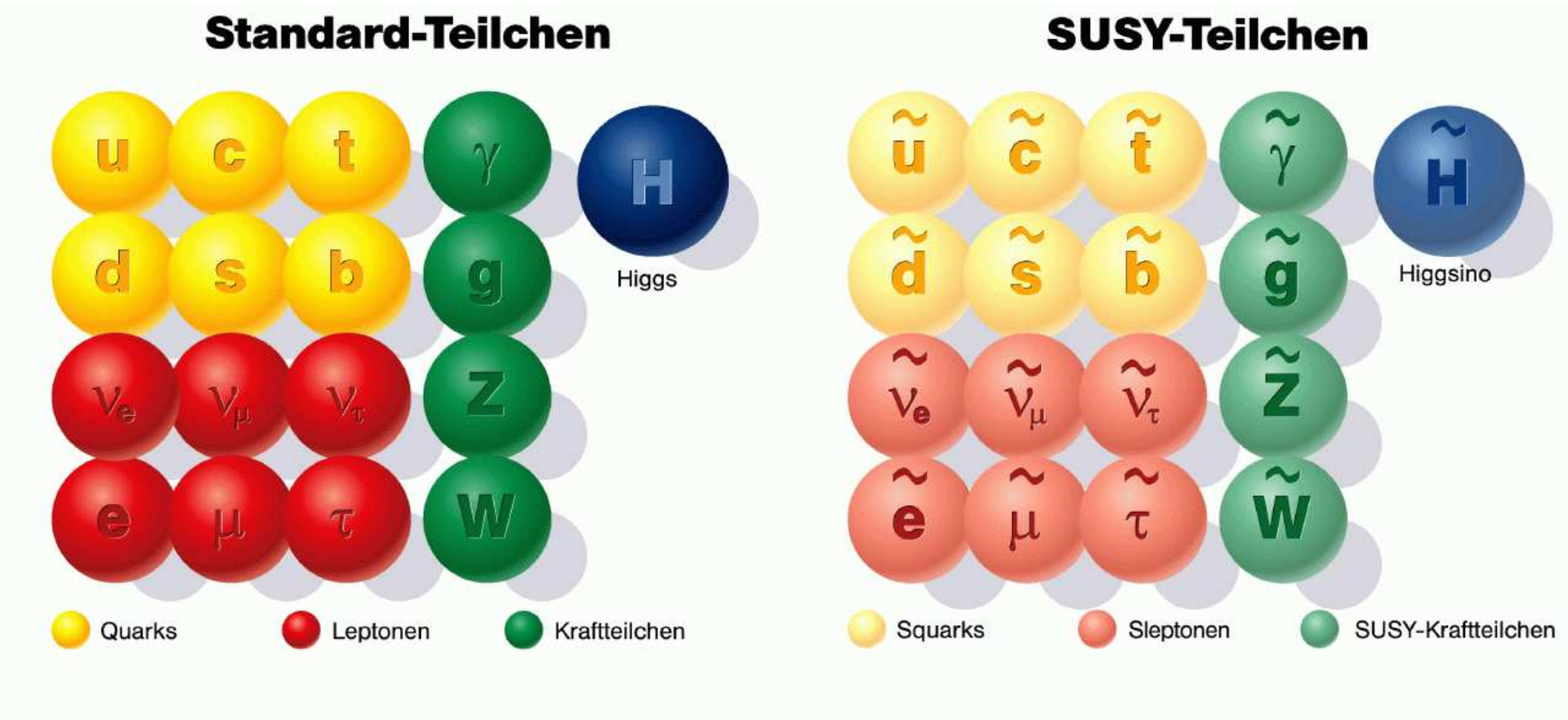


SUSY needs not motivation here :-)

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin } 1 \text{ / Spin } 0$$

$$\tilde{g} \quad \tilde{\chi}_{1,2}^{\pm} \quad \tilde{\chi}_{1,2,3,4}^{0} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature
has so many free parameters!

Simplified models: 1.) CMSSM (sometimes wrongly called mSUGRA):

$\Rightarrow$ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

m_0 : universal scalar mass parameter

$m_{1/2}$: universal gaugino mass parameter

A_0 : universal trilinear coupling

} at the GUT scale

$\tan\beta$: ratio of Higgs vacuum expectation values

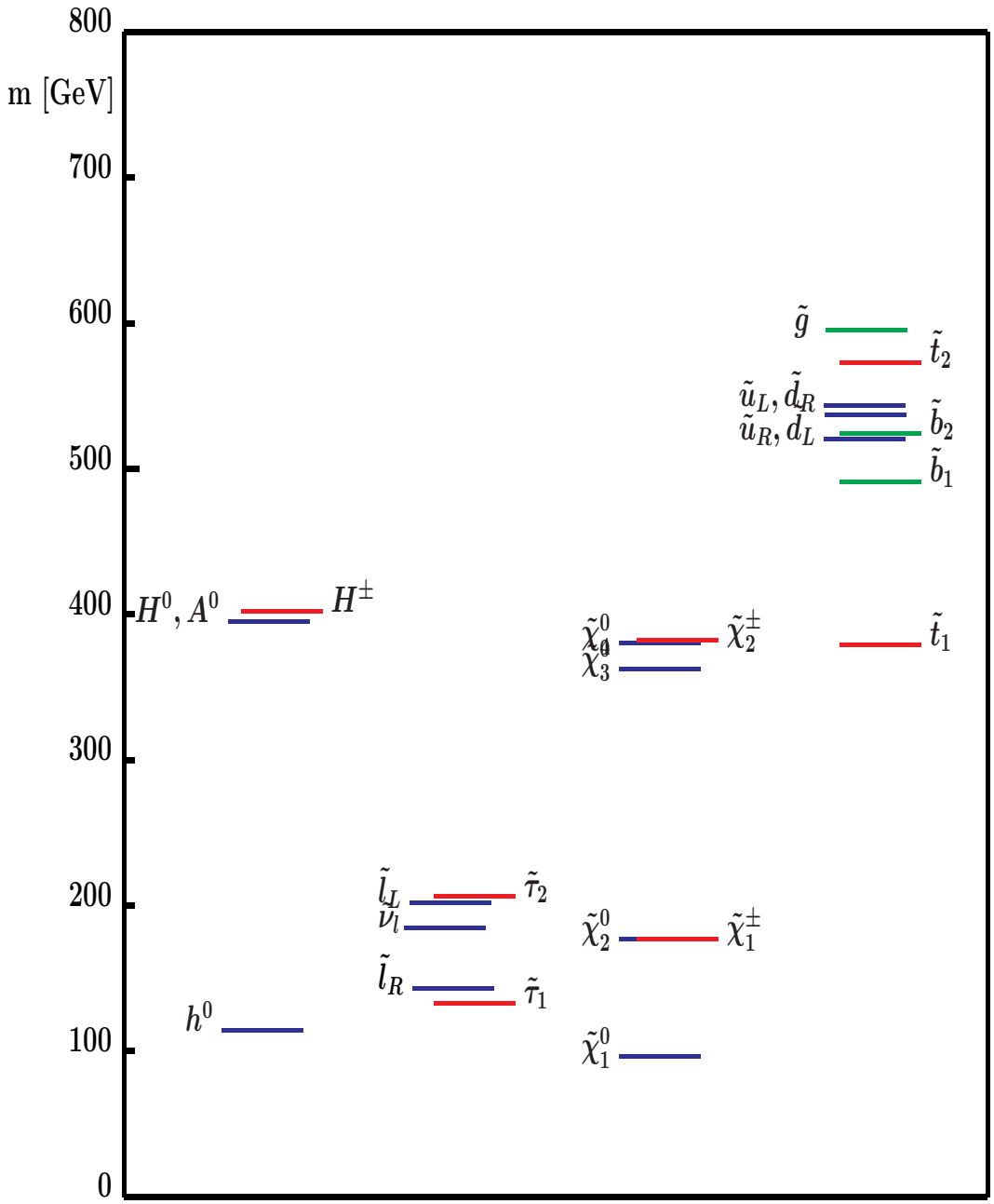
$\text{sign}(\mu)$: sign of supersymmetric Higgs parameter

$\Rightarrow$ particle spectra from renormalization group running to weak scale

$\Rightarrow$ Lightest SUSY particle (LSP) is the lightest neutralino

"Typical" CMSSM scenario (SPS 1a benchmark scenario):

Strong connection between all the sectors



Simplified models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameter at the GUT scale

$\Rightarrow$ effectively M_A or μ as free parameters at the EW scale

$\Rightarrow$ besides the CMSSM parameters

$$M_A \text{ or } \mu$$

And there is more: 3.) VCMSSM
4.) mSUGRA
5.) NUHM2

. . . no time here . . .

2. Searches for signs of SUSY at the LHC

Two possible ways:

1.) Search for SUSY particles

2.) Search for indirect effects of SUSY particles

$\Rightarrow$ both are important

$\Rightarrow$ both will be explored

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2.) Search for indirect effects of SUSY particles

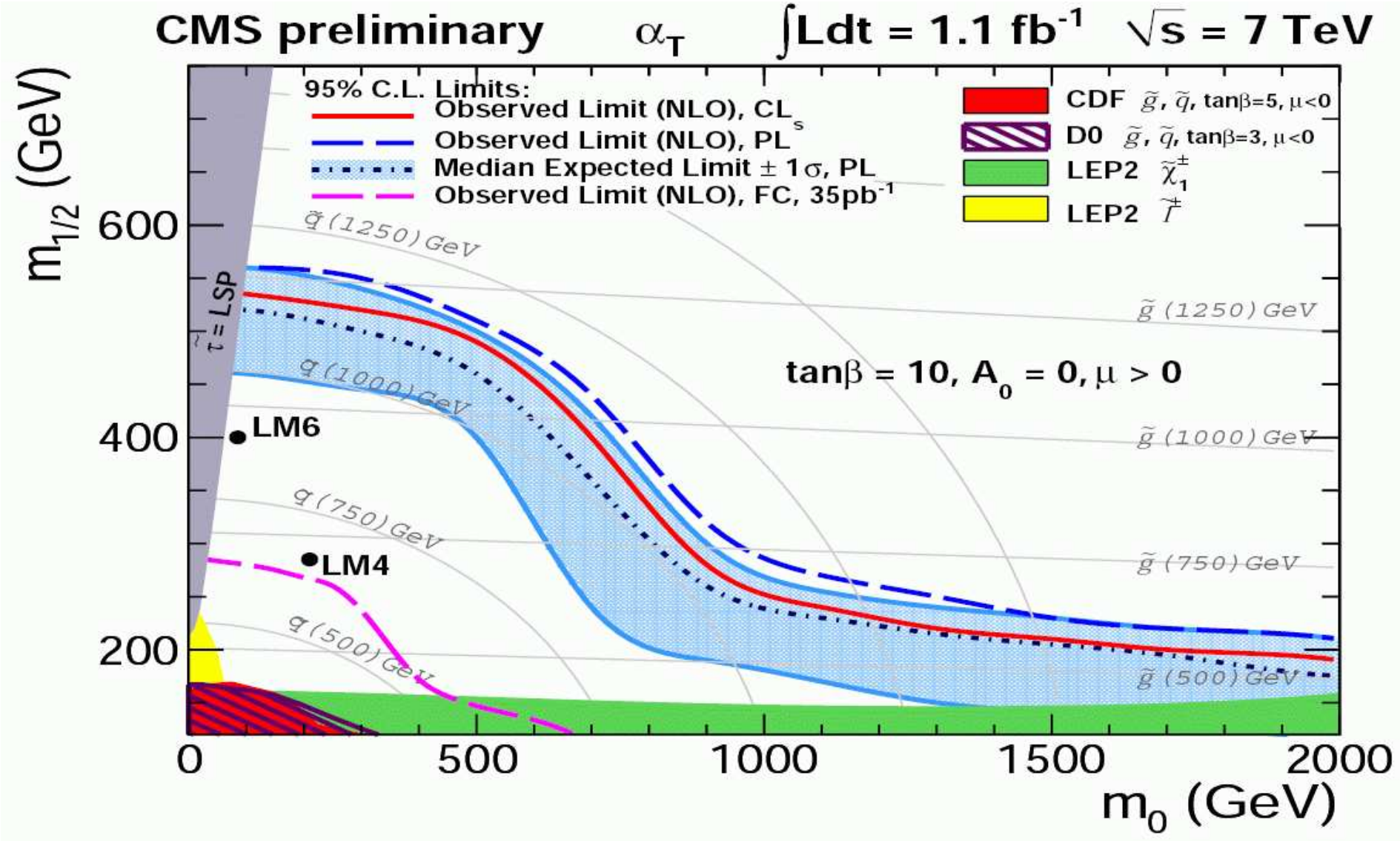
$\Rightarrow$ both are important

$\Rightarrow$ both will be explored

$\Rightarrow$ both will have to be combined

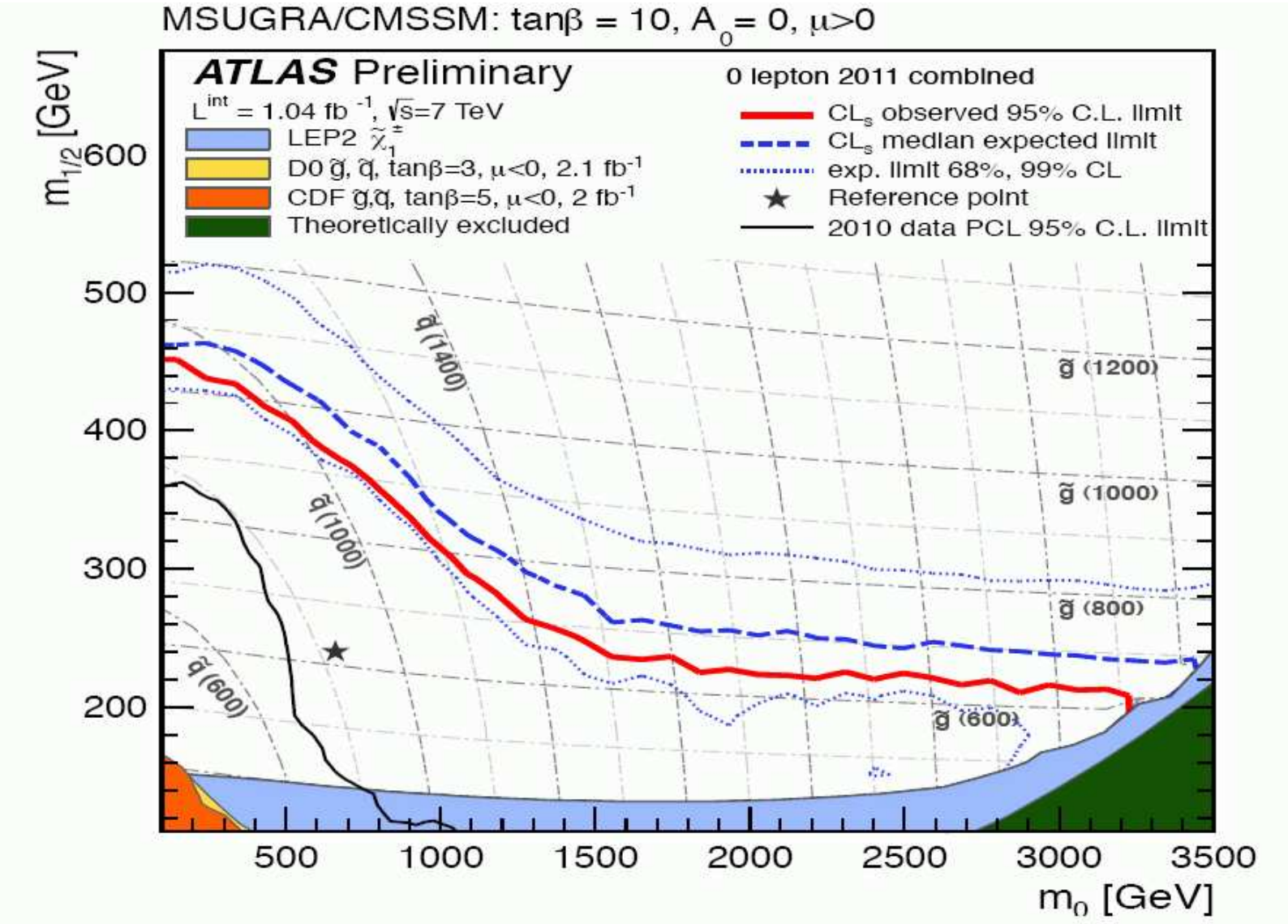
$\Rightarrow$ both will have to give (eventually) the same answer
$\Rightarrow$ crucial test of the model!

Search for SUSY particles: first CMS results: 0 lepton [*CMS '11*]



⇒ valid also for other $\tan\beta$ and A_0 values ??

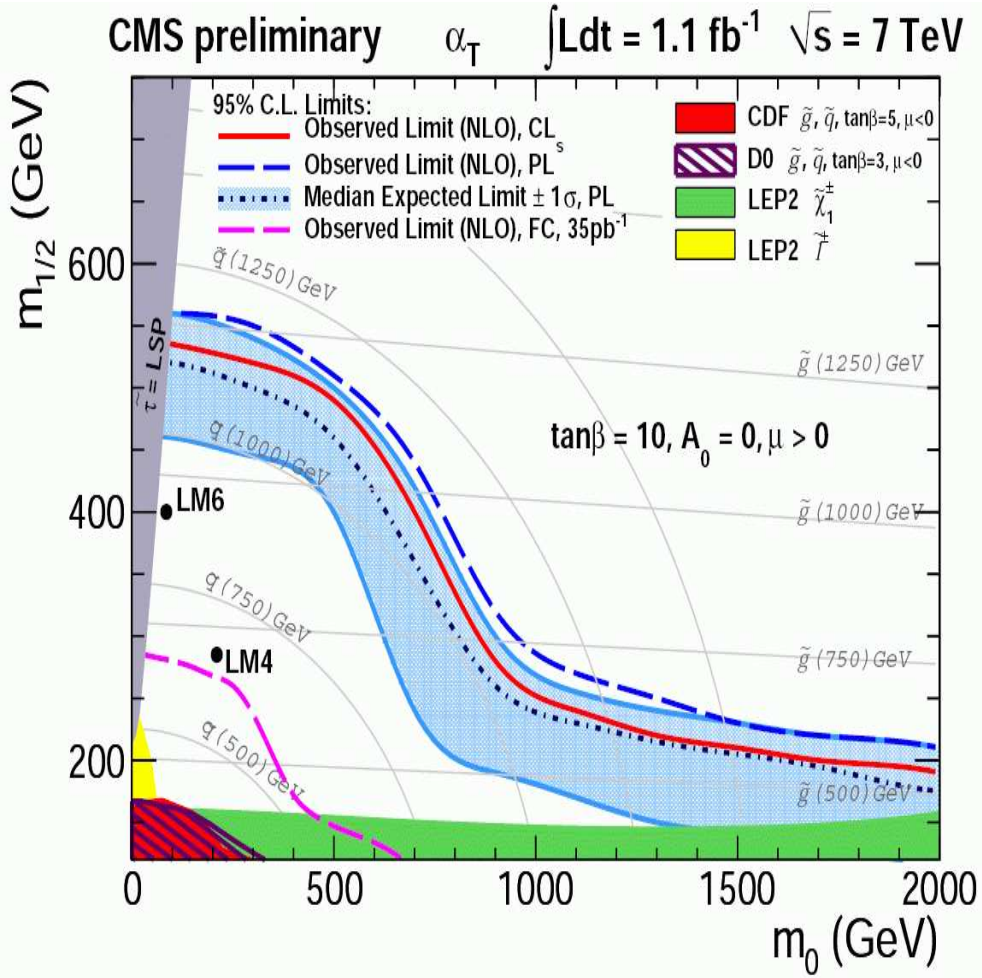
Search for SUSY particles: first ATLAS results: 0 lepton [*ATLAS '11*]



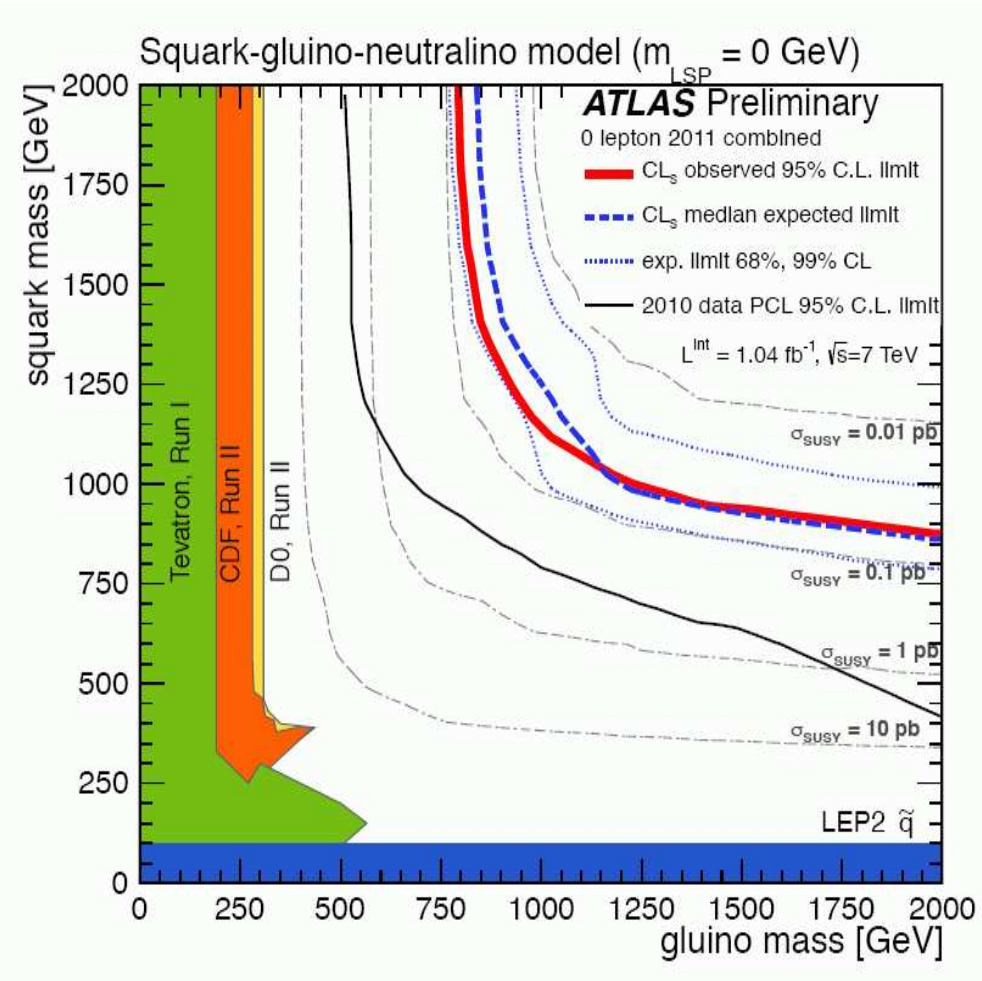
⇒ valid also for other $\tan\beta$ and A_0 values ??

The results are presented in two ways:

CMSSM



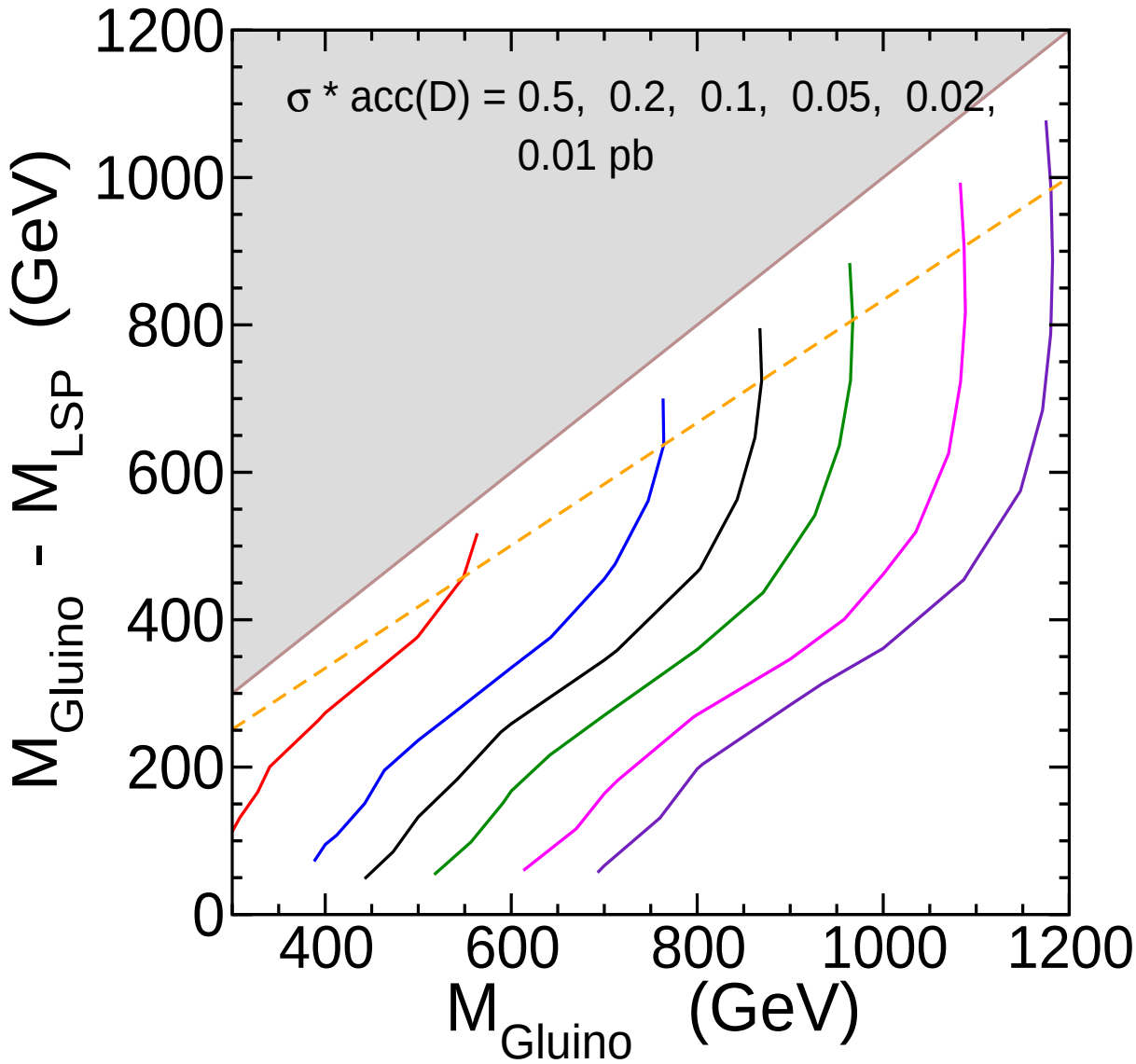
"simplified model"



⇒ How general is this? How useful is this?

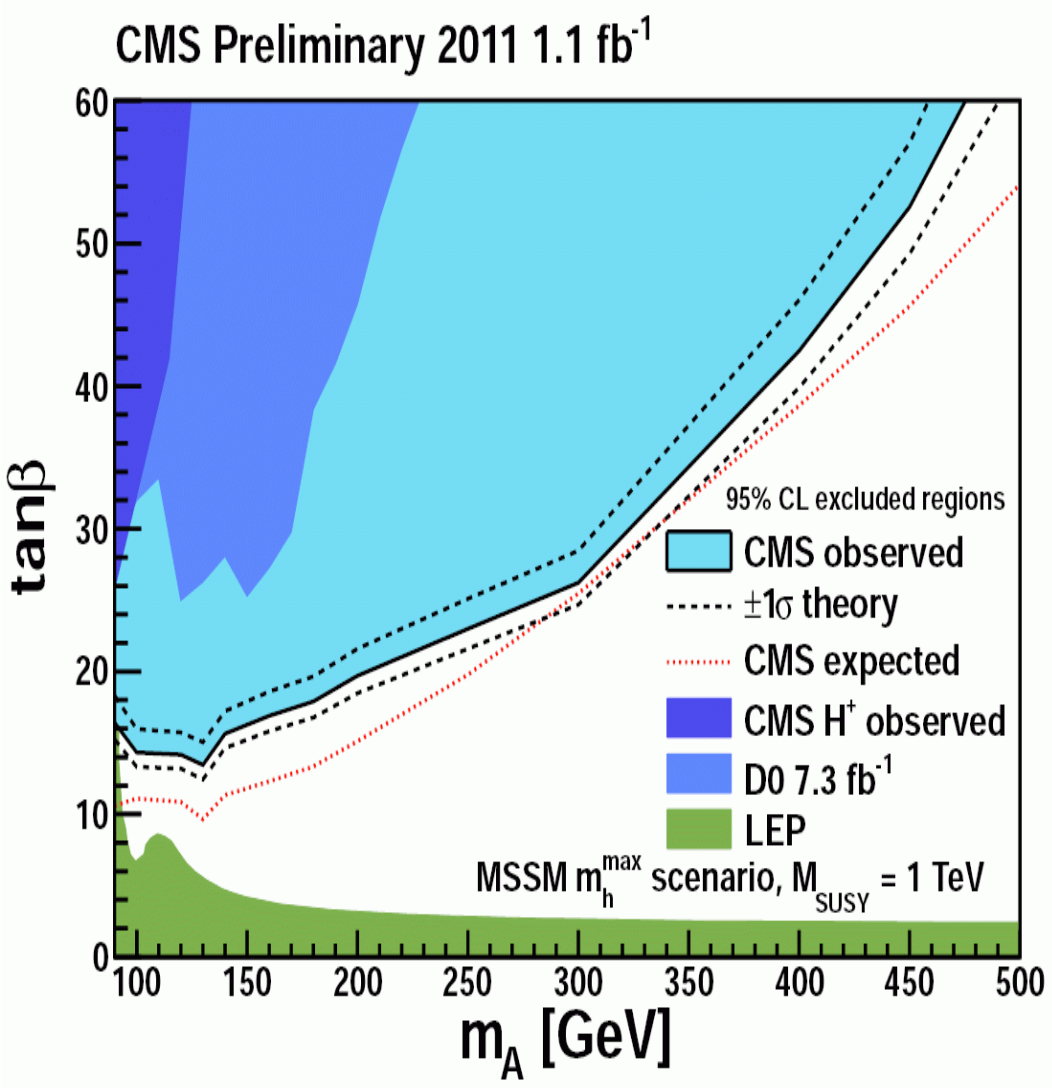
Three "easy" ways to "avoid" these constraints

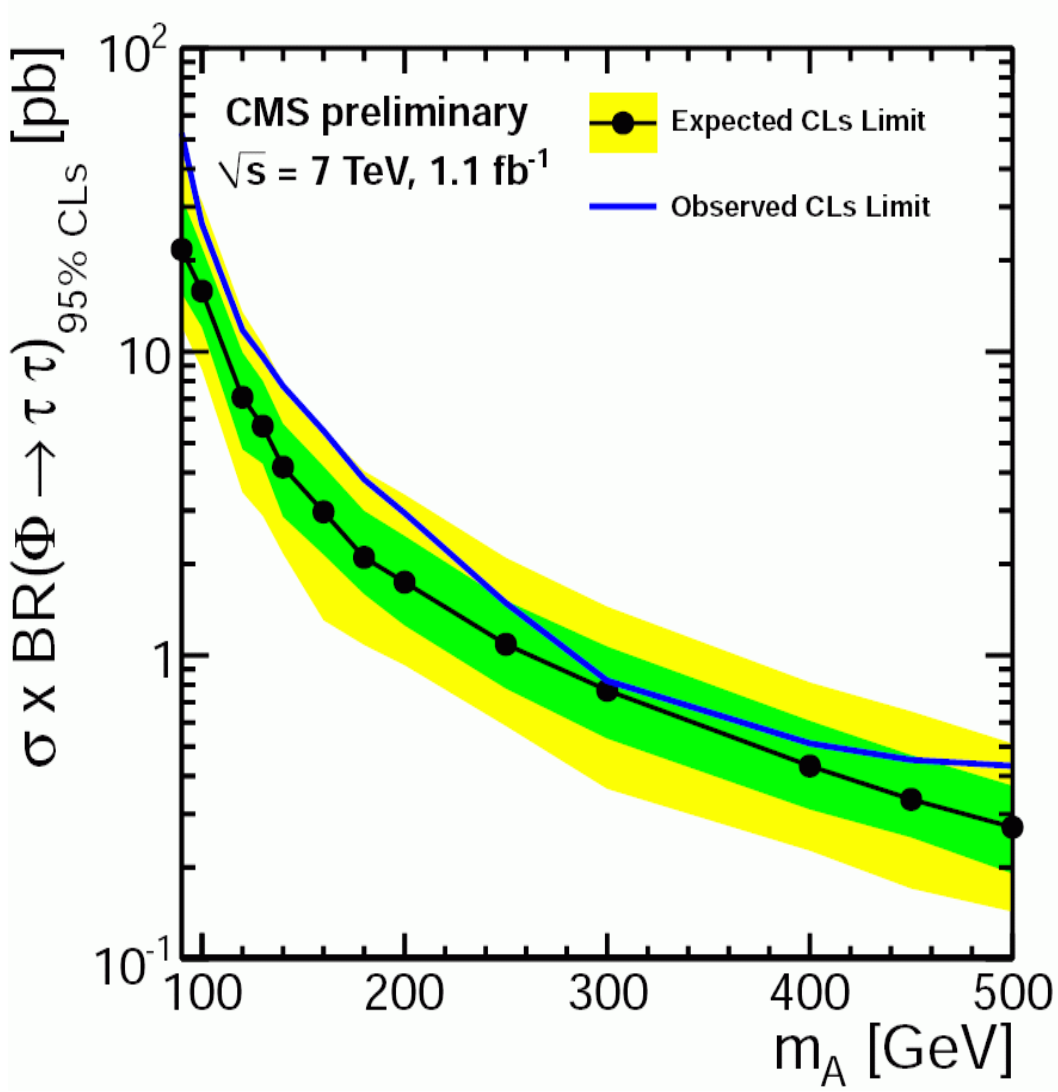
1. not valid for stops and sbottoms (→ excess? :-)
2. compressed spectrum
3. "extended" spectrum → wait a moment



[*T. LeCompte, S. Martin '11*]

Searches for $H/A \to \tau^+\tau^-$ at ATLAS/CMS:





⇒ model independet results preferred!

SUSY/Higgs bounds from a theory perspective

SUSY/Higgs bounds from a theory perspective

SUSY limits

What is the best way to present the results?

Cross section $\times$ BR limits possible?

Limits incl. cuts, but with detector effects folded out?

$\Rightarrow$ theorists need limits that can be applied to any model!

. . . or at least limits in more benchmark models

$\Rightarrow$ theorists also need "as much likelihood information as possible"

not only 95% CL, not for fixed A_0, $\tan\beta$, . . .

SUSY/Higgs bounds from a theory perspective

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Higgs limits

The situation is partially better :-)
(nearly) model indepent limits on $\sigma \times$ BR available

. . . but we need more than just the 95% CL exclusion bound!
$\Rightarrow$ HiggsBounds!

More benchmark scenarios?

Request by ATLAS/CMS in early 2011:
"Please provide us models in which you want us to present the results!"

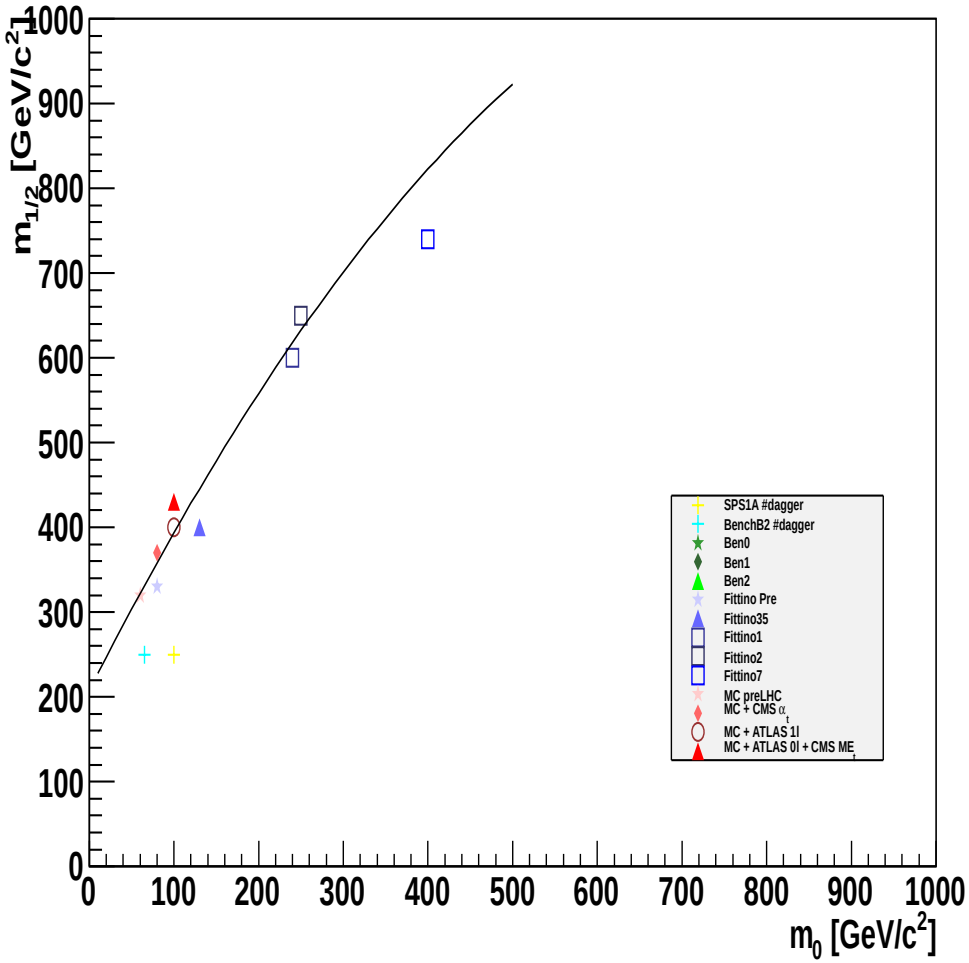
⇒ Innitiative for a new benchmark proposal (work in progress . . .)
[*S.S. AbdusSalam, B.C. Allanach, H. Dreiner, J. Ellis, S.H., M. Krämer, M. Mangano, K.A. Olive, S. Rogerson, L. Roszkowski, G. Weiglein*]

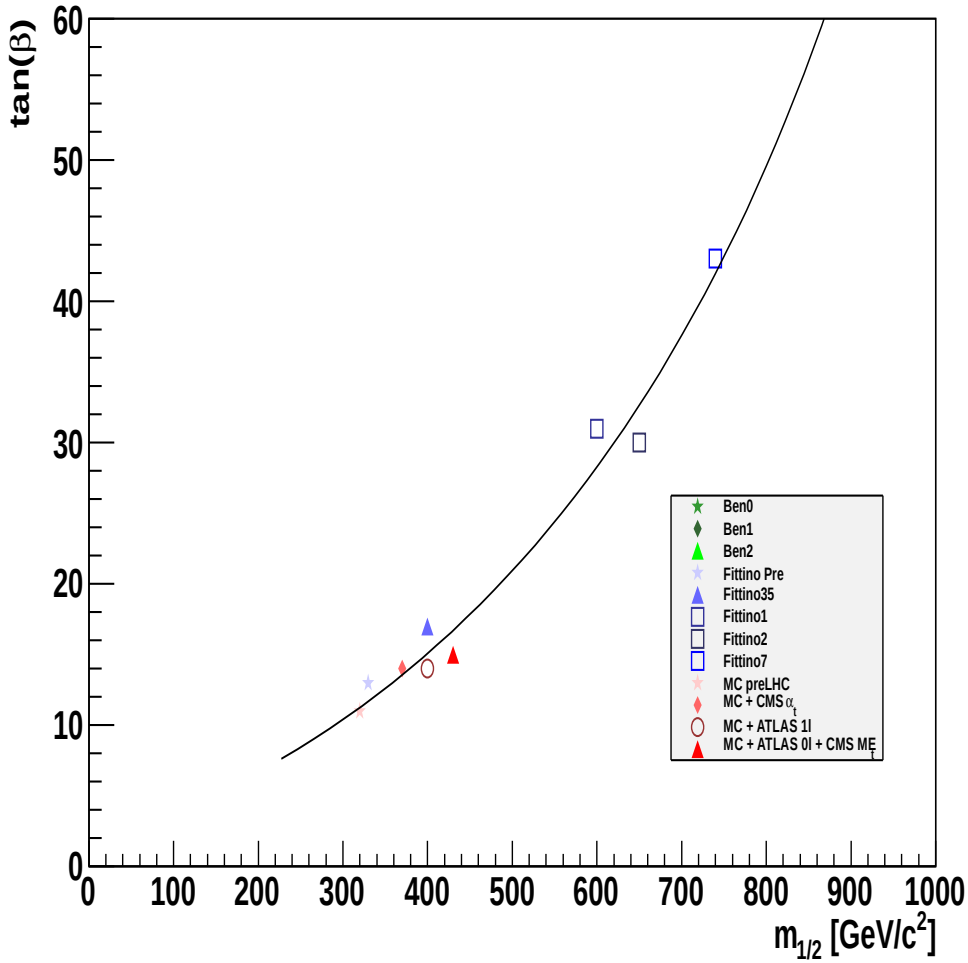
1. Clear definition of models:
   (why is it called CMSSM and not mSUGRA?)
2. Benchmark models:
   - CMSSM
   - NUHM1, NUHM2
   - RPV-CMSSM
   - mGMSB
   - mAMSB
   - p19MSSM
3. Model planes: either based on the old SPS points or . . .
4. Model lines: within the planes
   ⇒ (infinitely) new points are defined along the (infinite) lines

or . . .

planes based on best-fit points (details in a minute!)

Results for the CMSSM only:





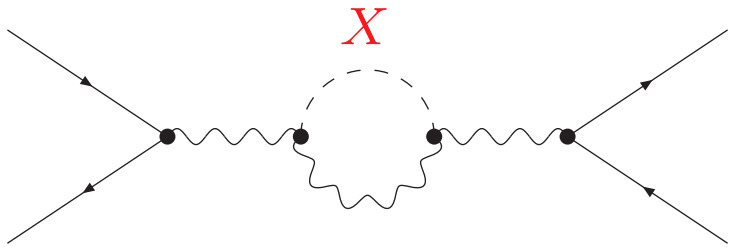
3. SUSY fits

Comparison of precision observables with theory:

Precision data:		Theory:
$M_W, \sin^2\theta_{\text{eff}}, a_\mu, \ldots$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections

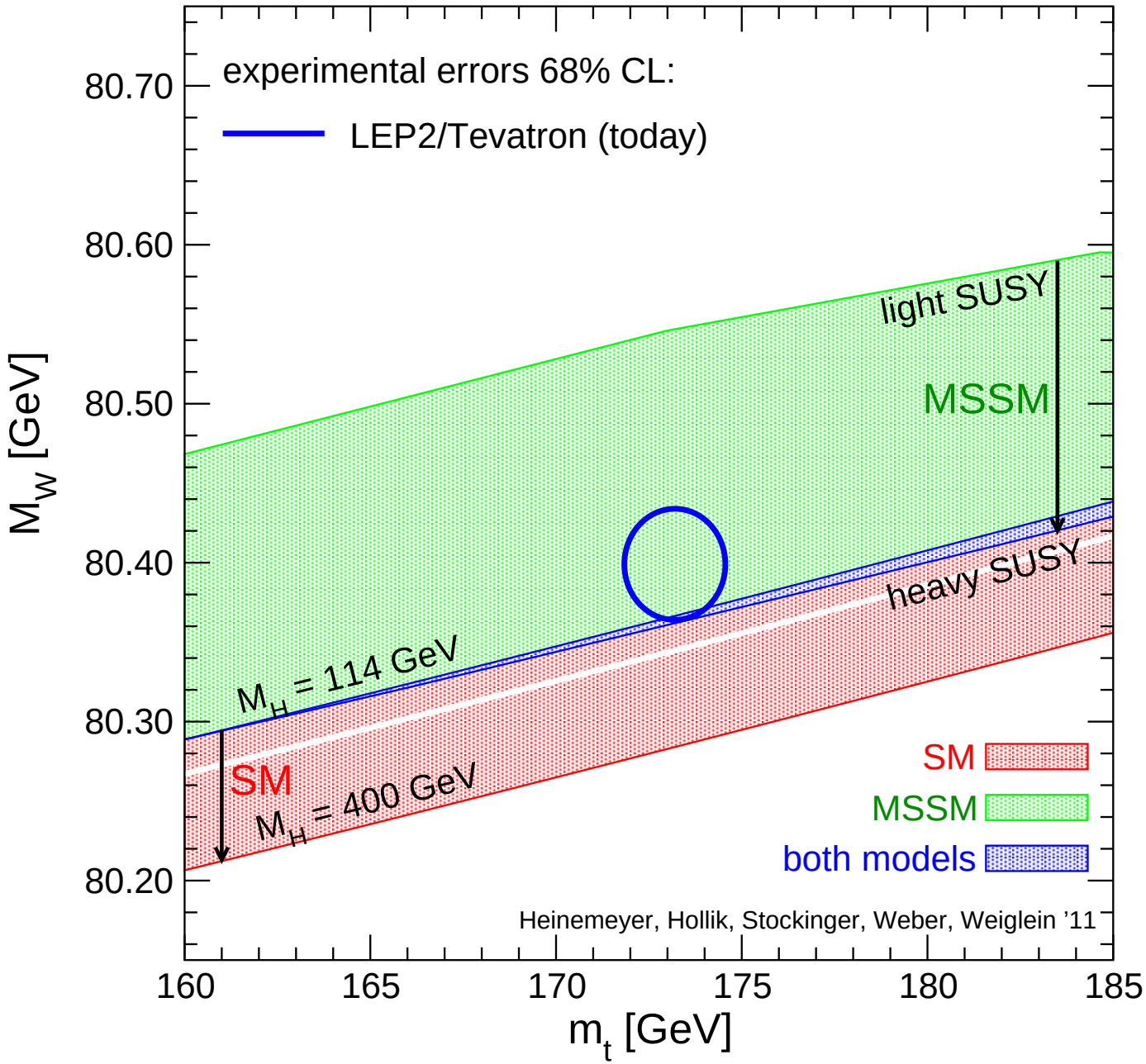


$\Downarrow$

$\Rightarrow$ Information about unknown parameters

Very high accuracy of measurements and theoretical predictions needed

The most beautiful example:

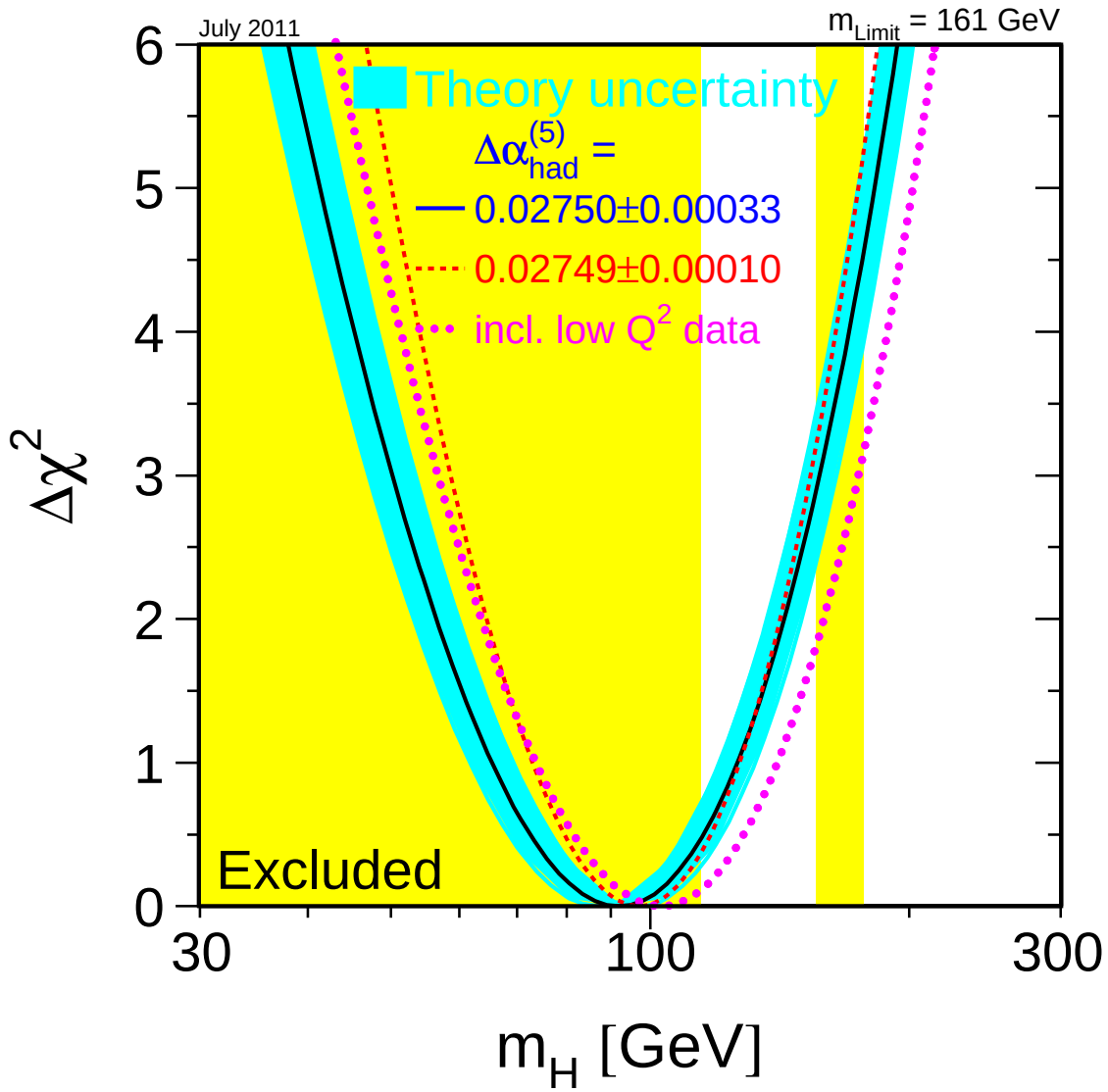


Global fit to all SM data:

[*LEPEWWG '11*]

$\Rightarrow M_H = 92^{+34}_{-26}$ GeV

$M_H < 161$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of Higgs mechanism

$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 160$ GeV

Main idea of SUSY fits:

Combine all existing precision data:

- Electroweak precision observables (EWPO)
- B physics observables (BPO)
- Cold dark matter (CDM)
- ...

Predict:

- best-fit points
- ranges for Higgs masses
- ranges for SM parameters
- ranges for SUSY masses
  $\Rightarrow$ Implications for current and future experiments

Indirect constraints on M_{SUSY} from existing data?

- Electroweak precision observables (EWPO) ?
- B physics observables (BPO) ?
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$\Rightarrow$ combination of EWPO, BPO, CDM ?

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EWPO M_W : information on $m_{\tilde{t}}$, $m_{\tilde{b}}$ or M_A, $\tan\beta$ or ...

EWPO $(g-2)_\mu$: information on $\tan\beta$ and/or $m_{\tilde{\chi}^0}$, $m_{\tilde{\chi}^\pm}$ and/or $m_{\tilde{\mu}}$, $m_{\tilde{\nu}_\mu}$

BPO $\text{BR}(b \to s\gamma)$: information on $\tan\beta$ and/or $M_{H^\pm}$ and/or $m_{\tilde{t}}$, $m_{\tilde{\chi}^\pm}$

CDM (LSP gives CDM) : information on $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}}$ or M_A or ...

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CDM (LSP gives CDM) : information on $m_{\tilde{\chi}^0_1}$ and $m_{\tilde{\tau}}$ or M_A or ...

$\Rightarrow$ combination makes only sense if all parameters are connected!

$\Rightarrow$ this brings us back to GUT based models: CMSSM, NUHM1, ...

The results presented here are based on:

The "MasterCode"

⇒ collaborative effort of theorists and experimentalists

[*Buchmüller, Cavanaugh, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Olive, Rogerson, Ronga, Weiglein*]

Über-code for the combination of different tools:

- tools are included as subroutines
- compatibility ensured by collaboration of authors of "MasterCode" and authors of "sub tools" /SLHA(2)
- one "MasterCode" for one model . . .

⇒ evaluate observables of one parameter point consistently with various tools

cern.ch/mastercode

χ^2 calculation:

$\rightarrow$ global χ^2 likelihood function
combines all theoretical predictions with experimental constraints:

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{(f_{\mathrm{SM}_i}^{\mathrm{obs}} - f_{\mathrm{SM}_i}^{\mathrm{fit}})^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

N: number of observables studied
M: SM parameters: $\Delta\alpha_{\mathrm{had}}, m_t, M_Z$
C_i: experimentally measured value (constraint)
P_i: MSSM parameter-dependent prediction for the corresponding constraint

Assumption: measurements are uncorrelated - fulfilled to a high degree

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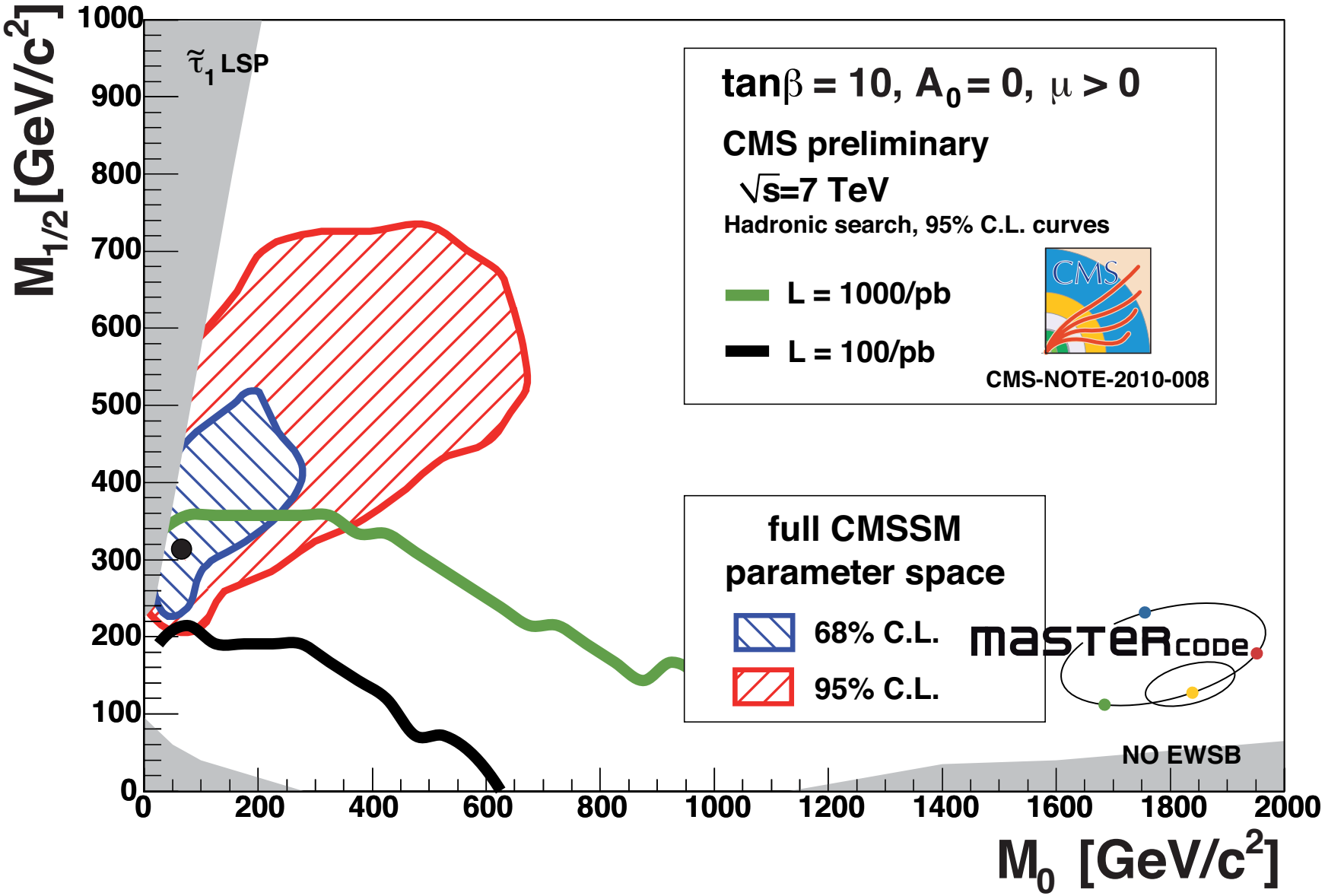
What to do if only a lower/upper bound exists?

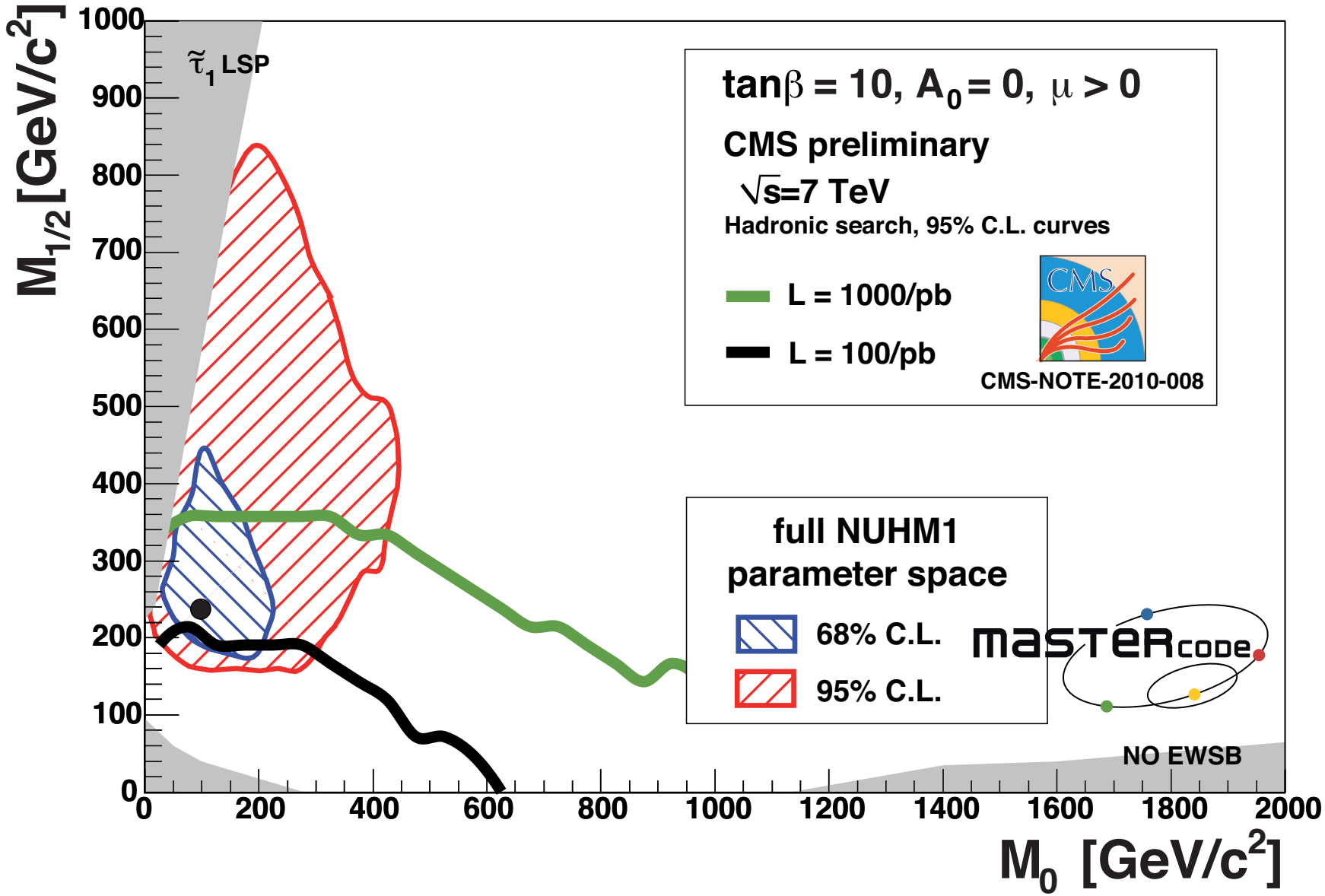
→ especially important: M_h → no time - ask me over coffee

pre-LHC predictions: CMSSM:



⇒ "best-fit point and part of 68% C.L. are can be tested in 2011"

pre-LHC predictions: NUHM1:



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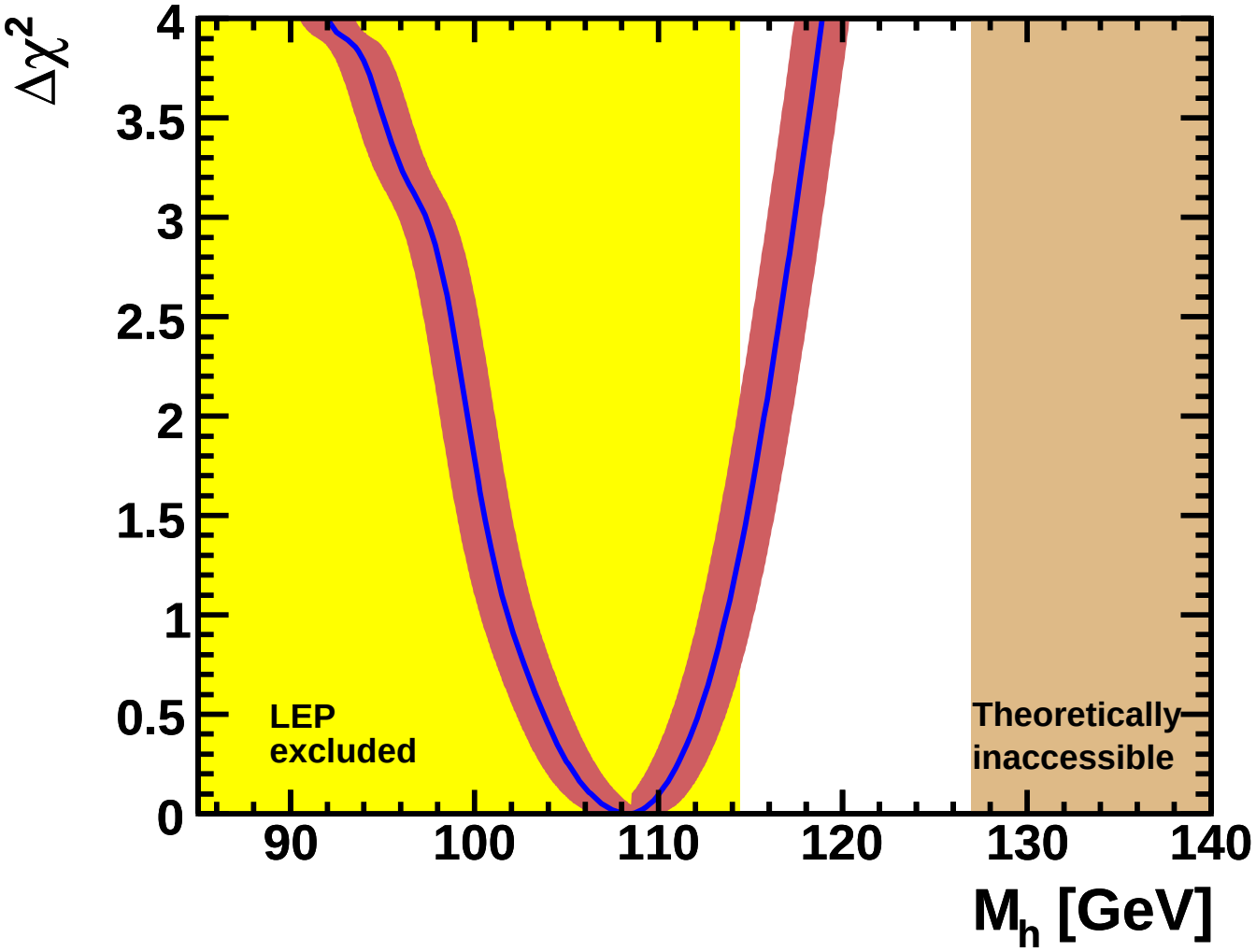
pre-LHC-CMSSM: red band plot:

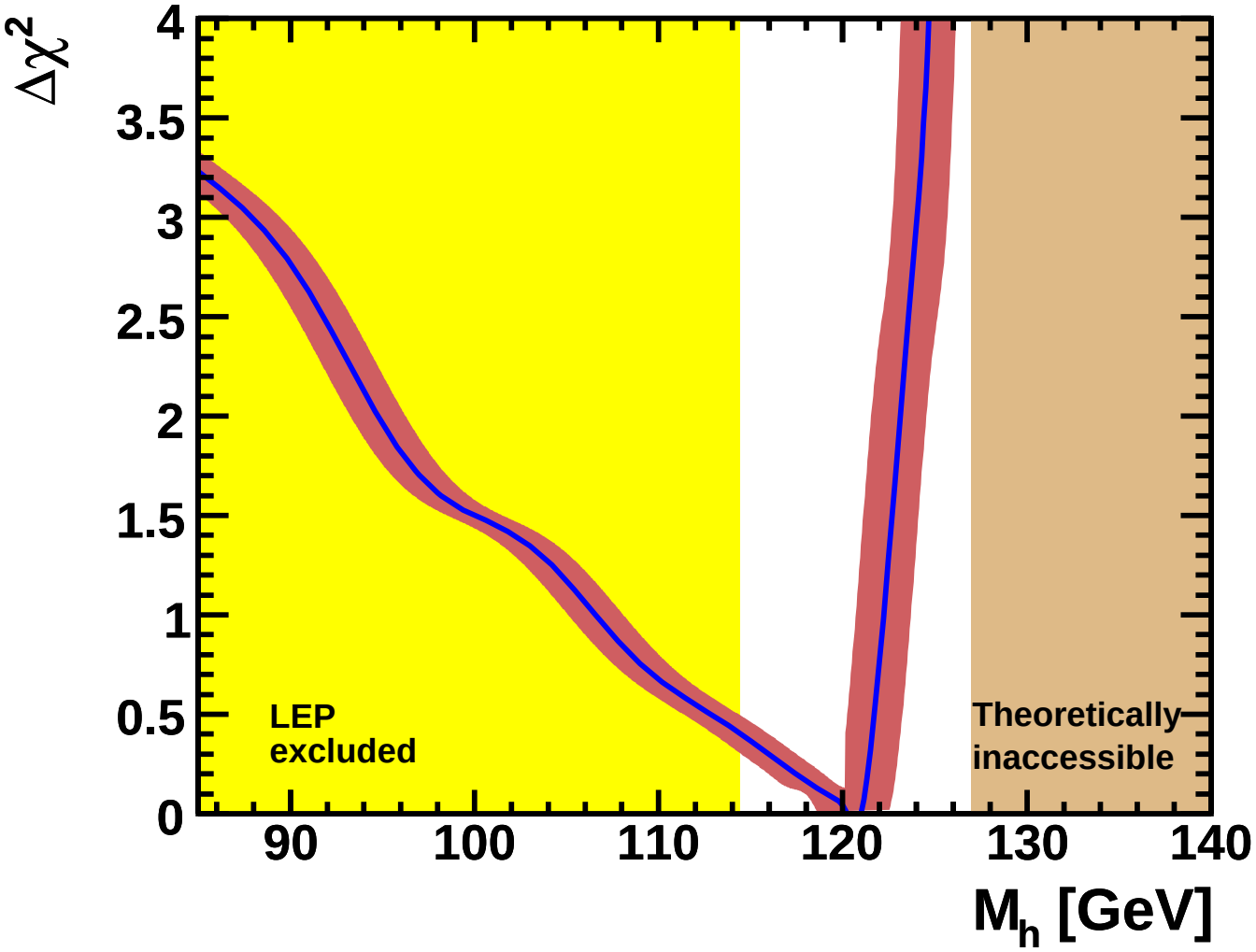
[2009]



$M_h = 108 \pm 6\,(\text{exp}) \pm 1.5(\text{theo})$ GeV

pre-LHC-NUHM1: red band plot:

[2009]



$M_h = 121^{+1}_{-14}\,(\text{exp}) \pm 1.5(\text{theo})$ GeV

$\Rightarrow$ naturally above LEP limit

Inclusion of LHC searches

Obvious idea:

(so far) negative search results for SUSY particles/effects yield

$$\boxed{\text{new } \chi^2(\text{LHC-SUSY, LHC-Higgs, } \ldots) \text{ contribution}}$$

Expected effect: disfavor low m_0-$m_{1/2}$ values

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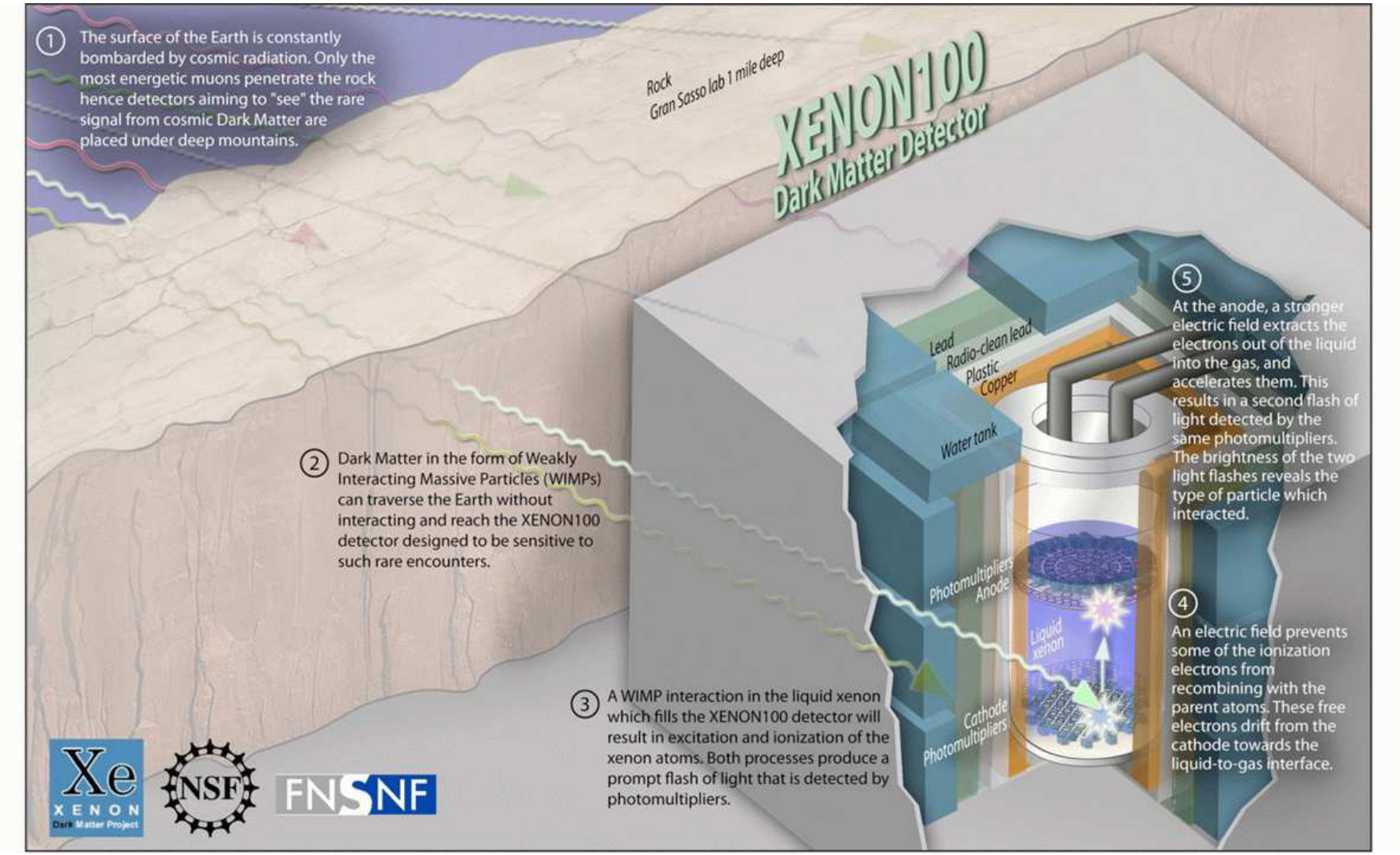
$\Rightarrow$ Implications for SUSY fits?

$\Rightarrow$ Implications for future colliders?

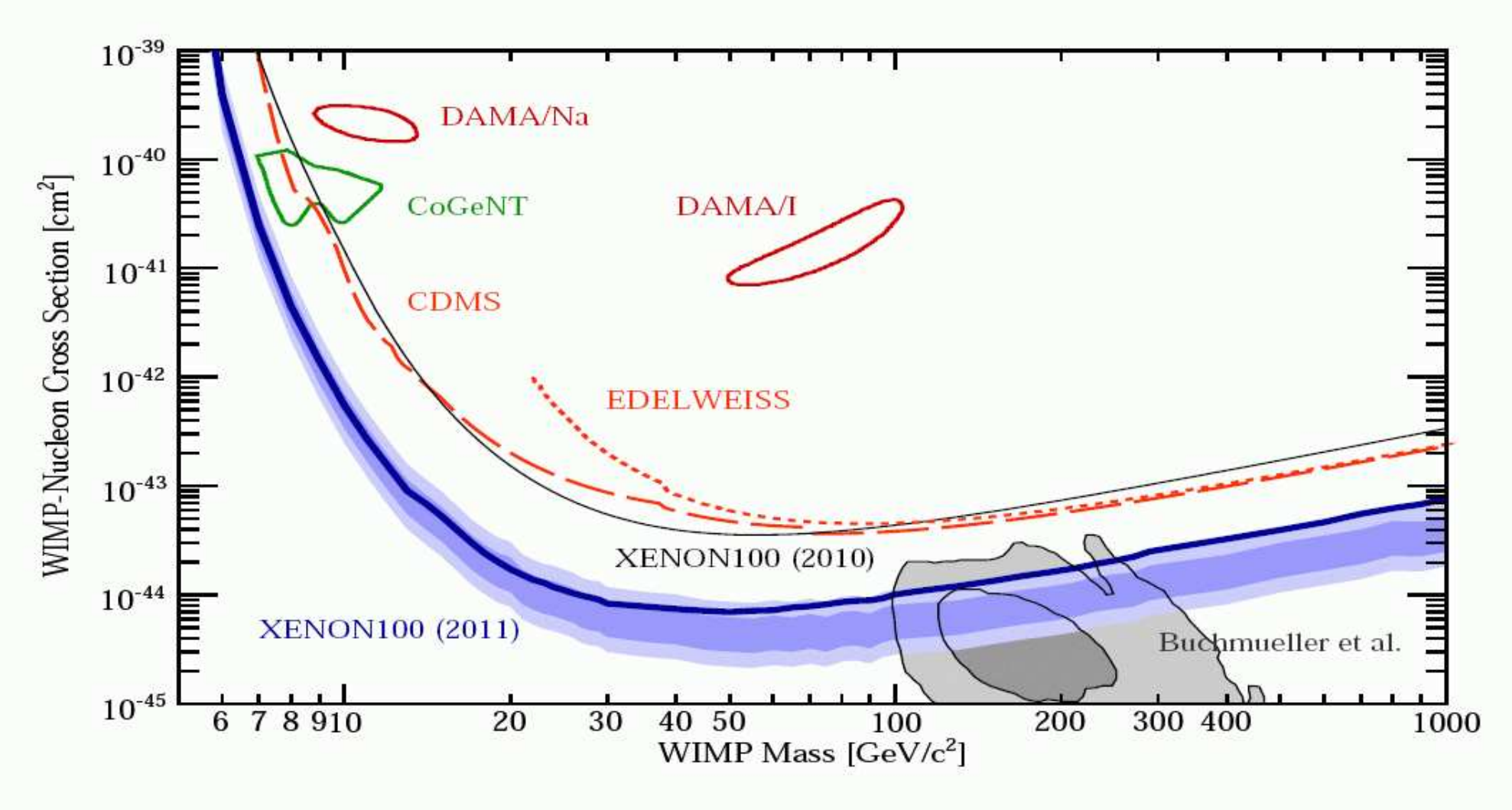
Additional new constraint:

Direct Dark Matter detection: Xenon100



Xenon100 results:

[*Xenon100 collaboration '11*]



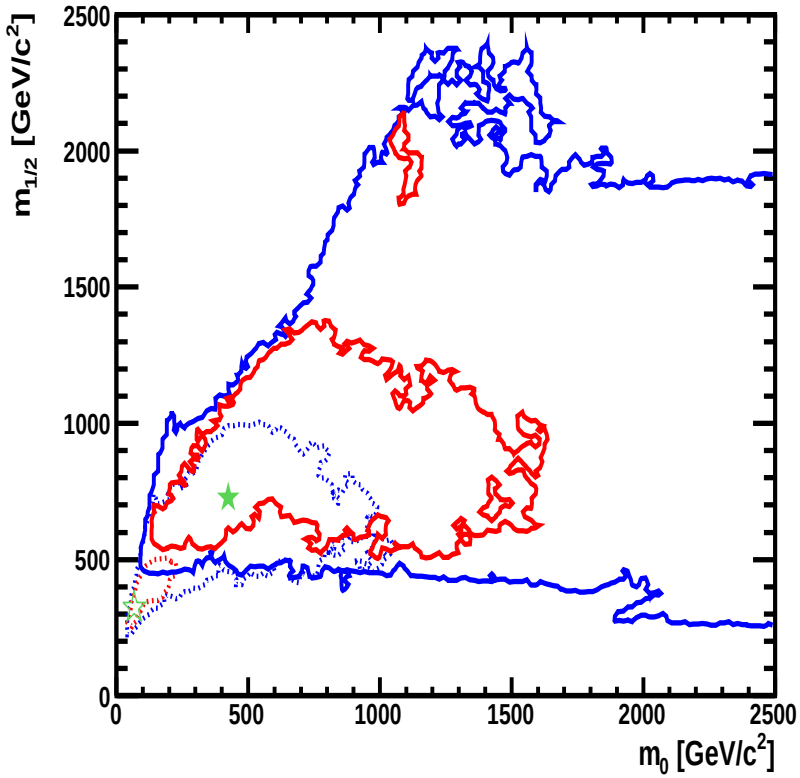
expected: 1.8 ± 0.6 events

observed: 3 events

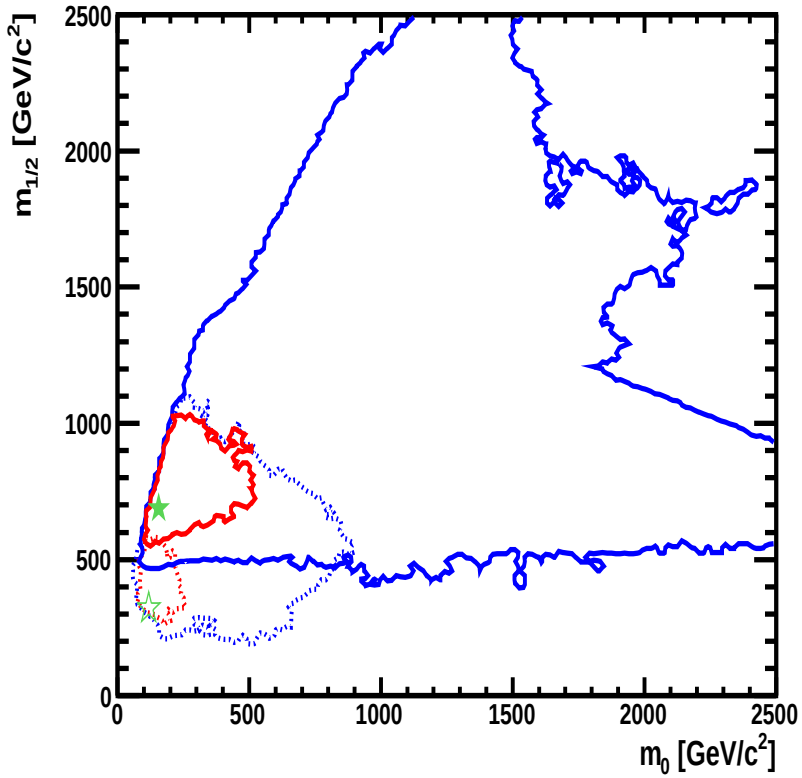
m_0-$m_{1/2}$ plane:

[2011]

CMSSM



NUHM1



dotted: pre-LHC/Xenon, solid: post-LHC (1 fb^{-1})/Xenon

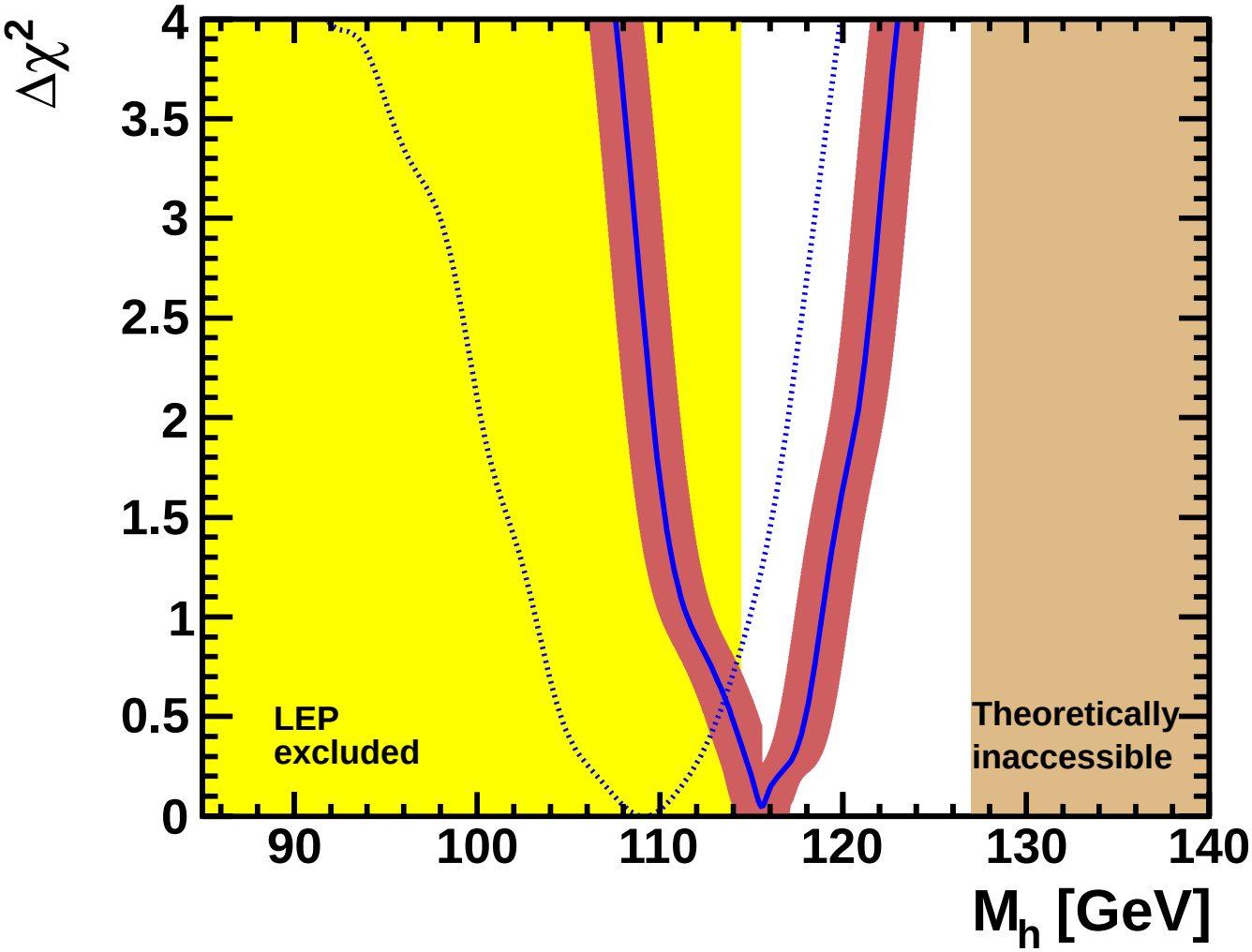
⇒ new best-fit point within old 95% CL area

⇒ hardly any overlap between old and new 68% CL areas

⇒ shift to higher masses

CMSSM: post-LHC (35 pb^{-1}) red band plot:

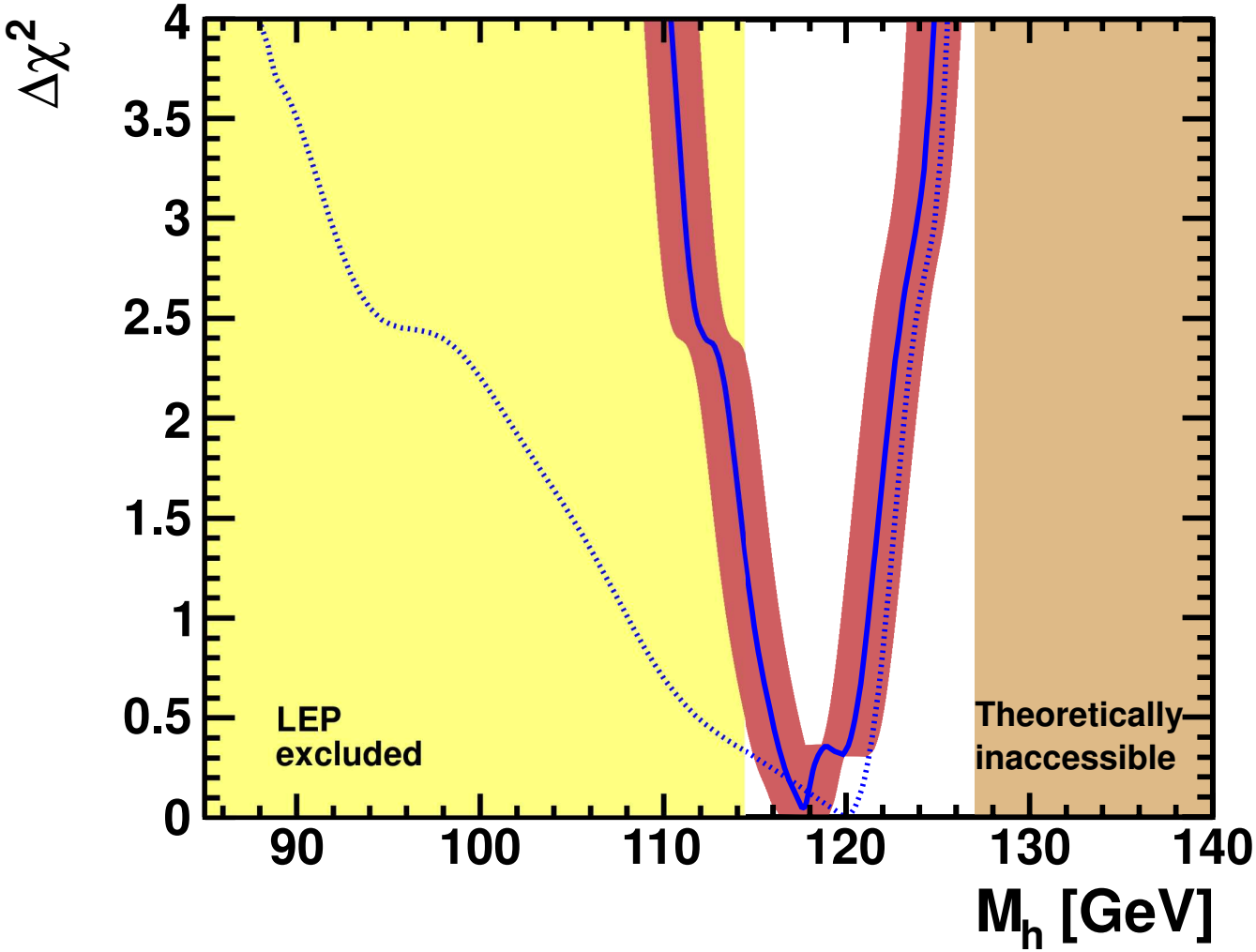
[2011]



$M_h = 116 \pm 4\,(\text{exp}) \pm 1.5(\text{theo})$ GeV $\Rightarrow$ fits "better" than pre-LHC

NUHM1: post-LHC (35 pb^{-1}) red band plot:

[2011]

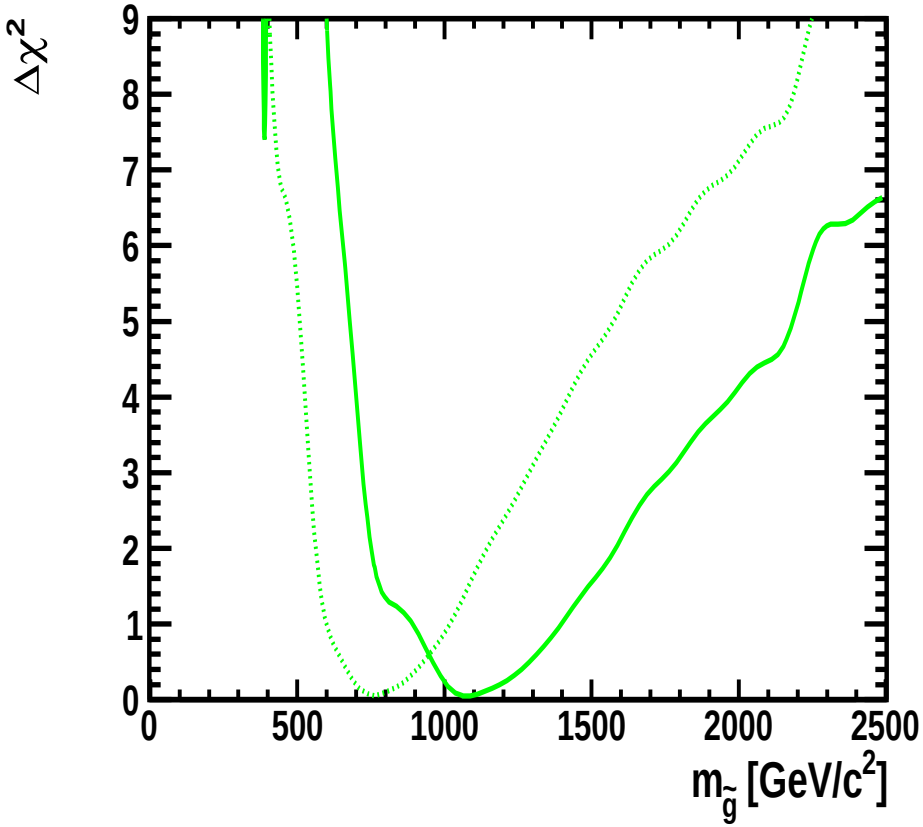


$M_h = 118 \pm 3\,(\text{exp}) \pm 1.5(\text{theo})$ GeV

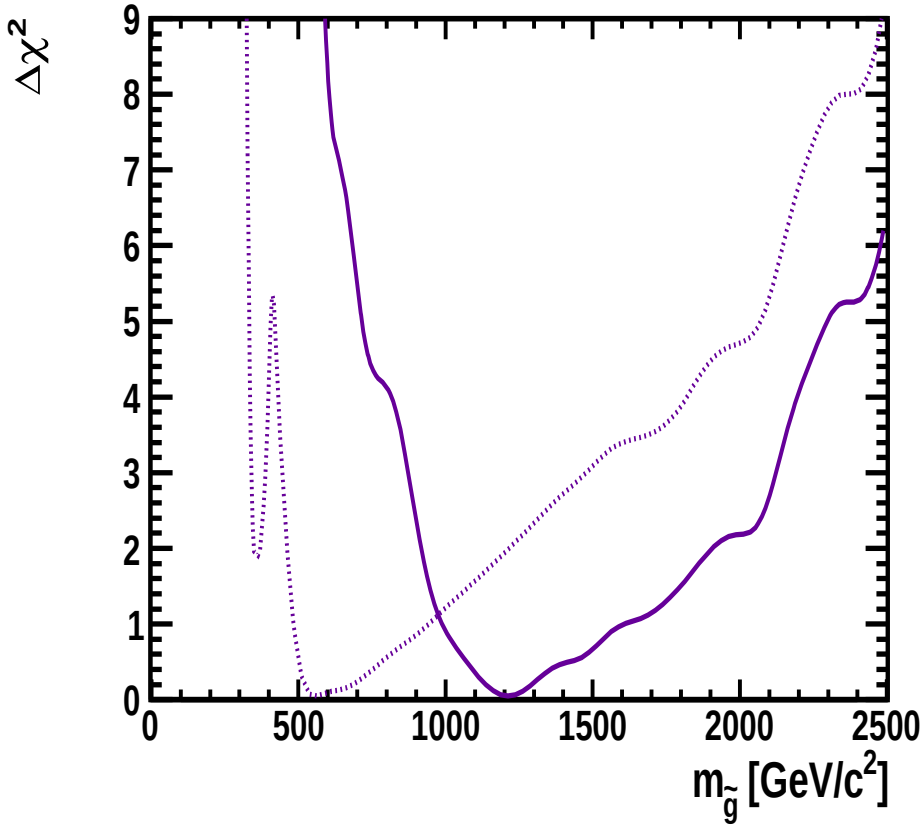
Starting point of the cascade: gluino (35 pb^{-1})

[2011]

CMSSM



NUHM1



dotted: pre-LHC/Xenon, solid: post-LHC (35 pb^{-1})/Xenon

$\Rightarrow$ substantial upward shift

What is happening to the χ^2?

Low energy data (mostly $(g-2)_\mu$) favors low SUSY mass scales

LHC data favors higher SUSY scales

$\Rightarrow$ tension, reflected in rising χ^2:

Model	Min. χ^2	Prob.	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	$M_h^{\text{no LEP}}$ (GeV)
CMSSM	22.5/19	26%	310	60	-60	10	109
LHC 2011	29.3/19	11%	730	420	-1180	40	116
NUHM1	20.5/17	25%	240	100	920	7	119
LHC 2011	27.3/18	13%	690	160	-880	33	118

4. Implications for future e^+e^- colliders

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Do we need an e^+e^- collider at all?

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Do we need an e^+e^- collider at all?

$\Rightarrow$ In order to establish SUSY experimentally:

Need to demonstrate that:
- every particle has superpartner
- their spins differ by 1/2
- their gauge quantum numbers are the same
- their couplings are identical
- mass relations hold

...

$\Rightarrow$ Precise measurements of masses, branching ratios, cross sections, angular distributions, ... mandatory for

- establishing SUSY experimentally
- disentangling patterns of SUSY breaking

4. Implications for future e^+e^- colliders

Do we need an e^+e^- collider at all?

⇒ In order to establish SUSY experimentally:

Need to demonstrate that:
- every particle has superpartner
- their spins differ by 1/2
- their gauge quantum numbers are the same
- their couplings are identical
- mass relations hold

...

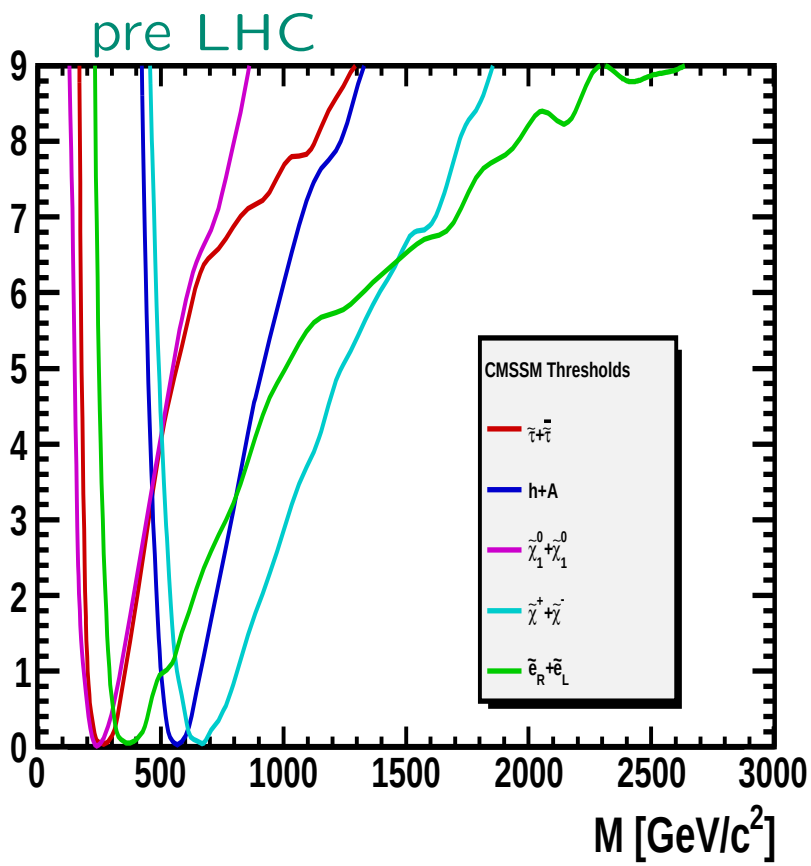
⇒ Precise measurements of masses, branching ratios, cross sections, angular distributions, ... mandatory for

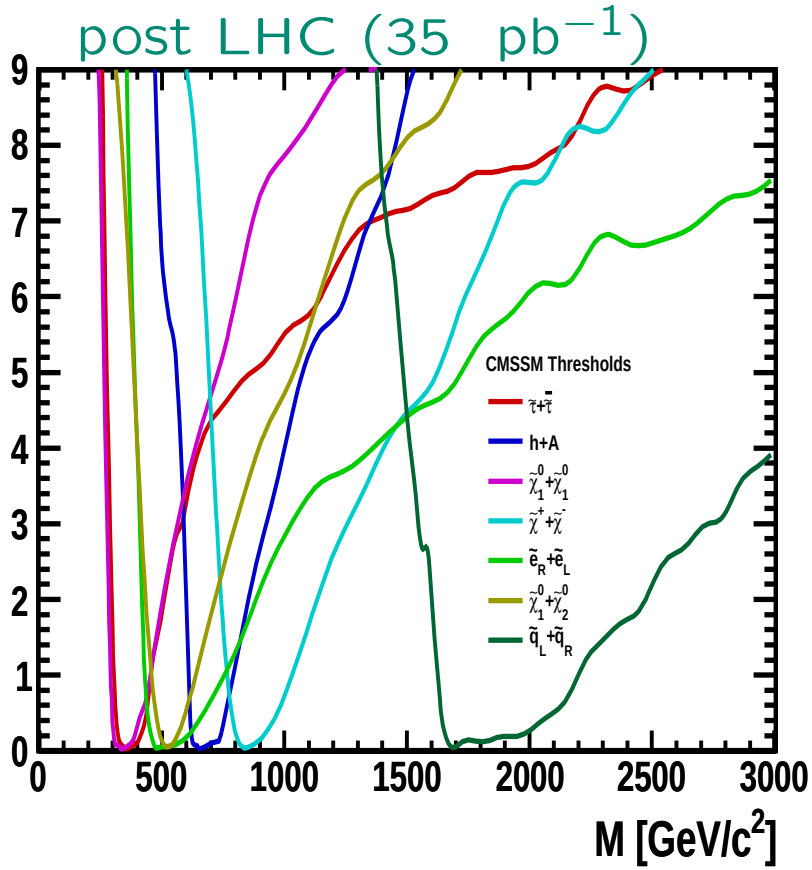
- establishing SUSY experimentally
- disentangling patterns of SUSY breaking

⇒ We need both: hadron colliders (LHC) and high luminosity LC

e^+e^- production thresholds in the CMSSM: [PRELIMINARY]

[2011]





What you will hear very often now:

this looks bad for an LC with $\sqrt{s} = 0.5 - 1$ TeV

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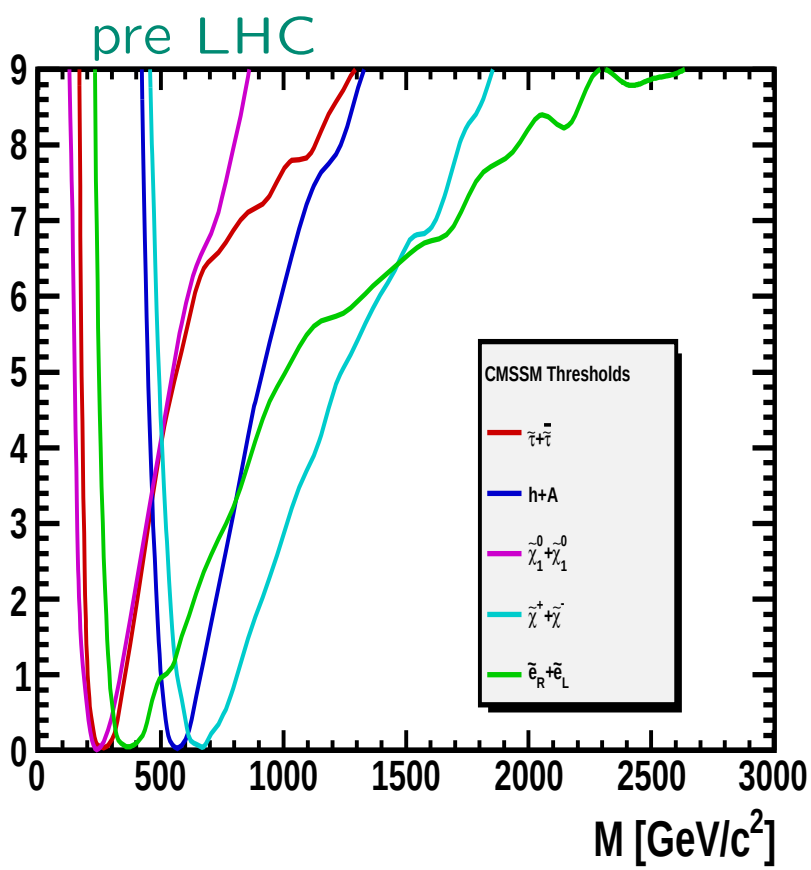

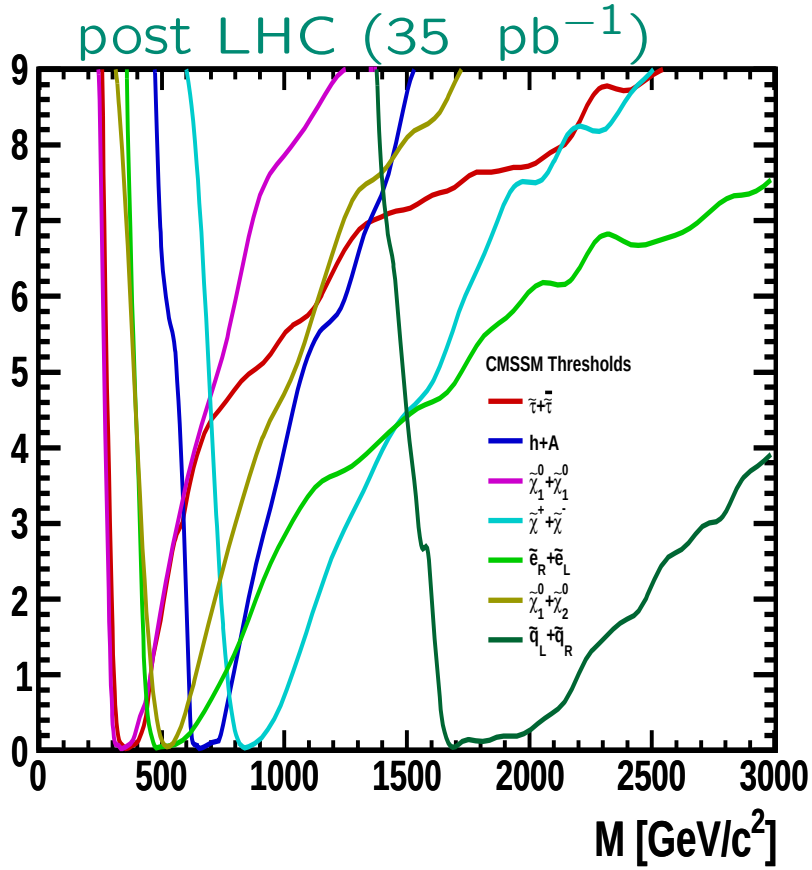

What you will hear very often now:

this looks bad for an LC with $\sqrt{s} = 0.5 - 1$ TeV

And this is WRONG!

Change in best-fit points:

[2011]

Model	Min. χ^2	Prob.	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	$M_h^{\text{no LEP}}$ (GeV)
CMSSM	22.5/19	26%	310	60	-60	10	109
LHC 2011	29.3/19	11%	730	420	-1180	40	116
NUHM1	20.5/17	25%	240	100	920	7	119
LHC 2011	27.3/18	13%	690	160	-880	33	118

Probabilities still ok, but this might change with more data.

Not finding SUSY early does not make the LC looks bad,

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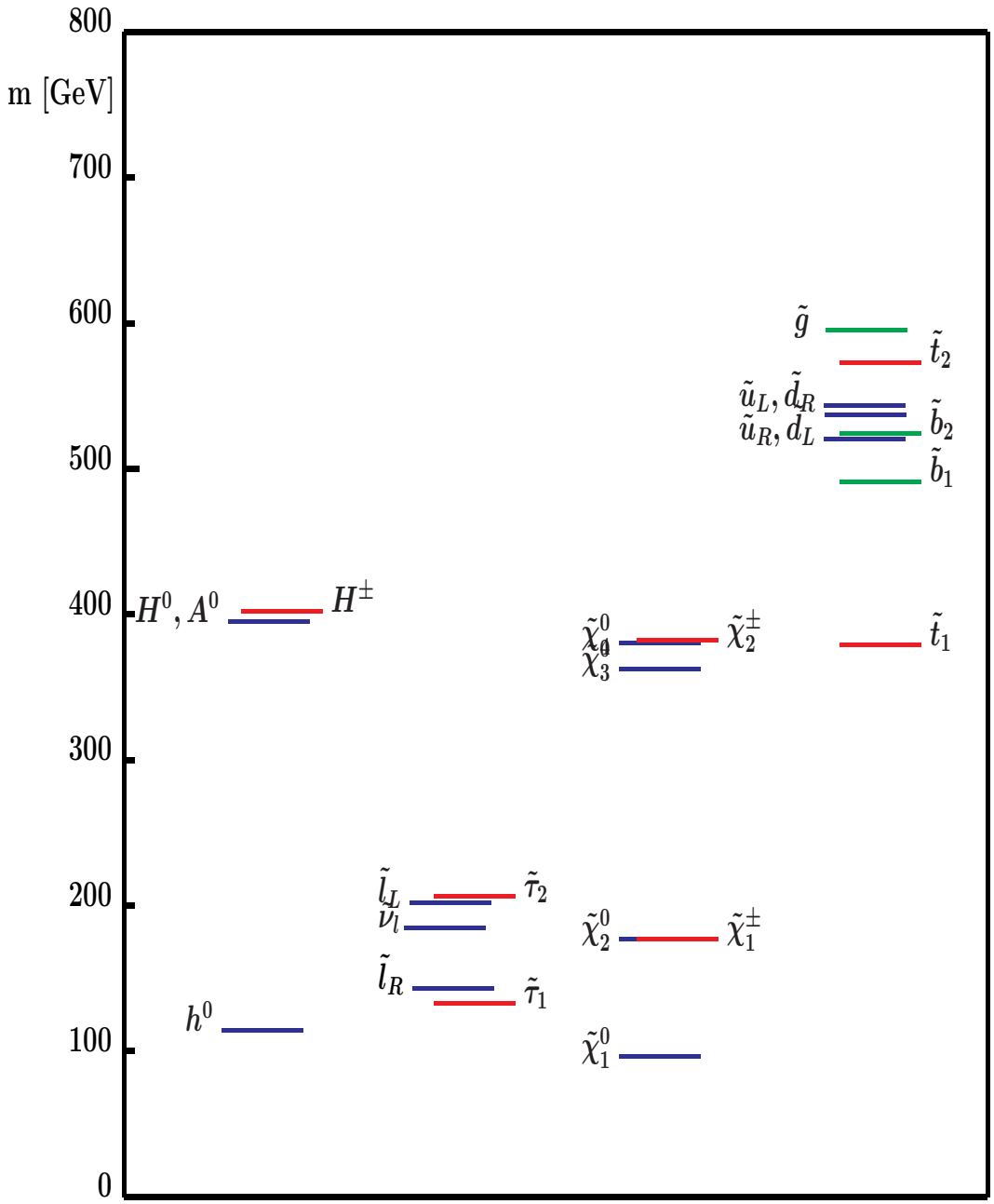
Any inference from one sector to the other is strongly model dependent!

"Typical" CMSSM scenario

(SPS 1a benchmark scenario):

Strong connection between

all the sectors



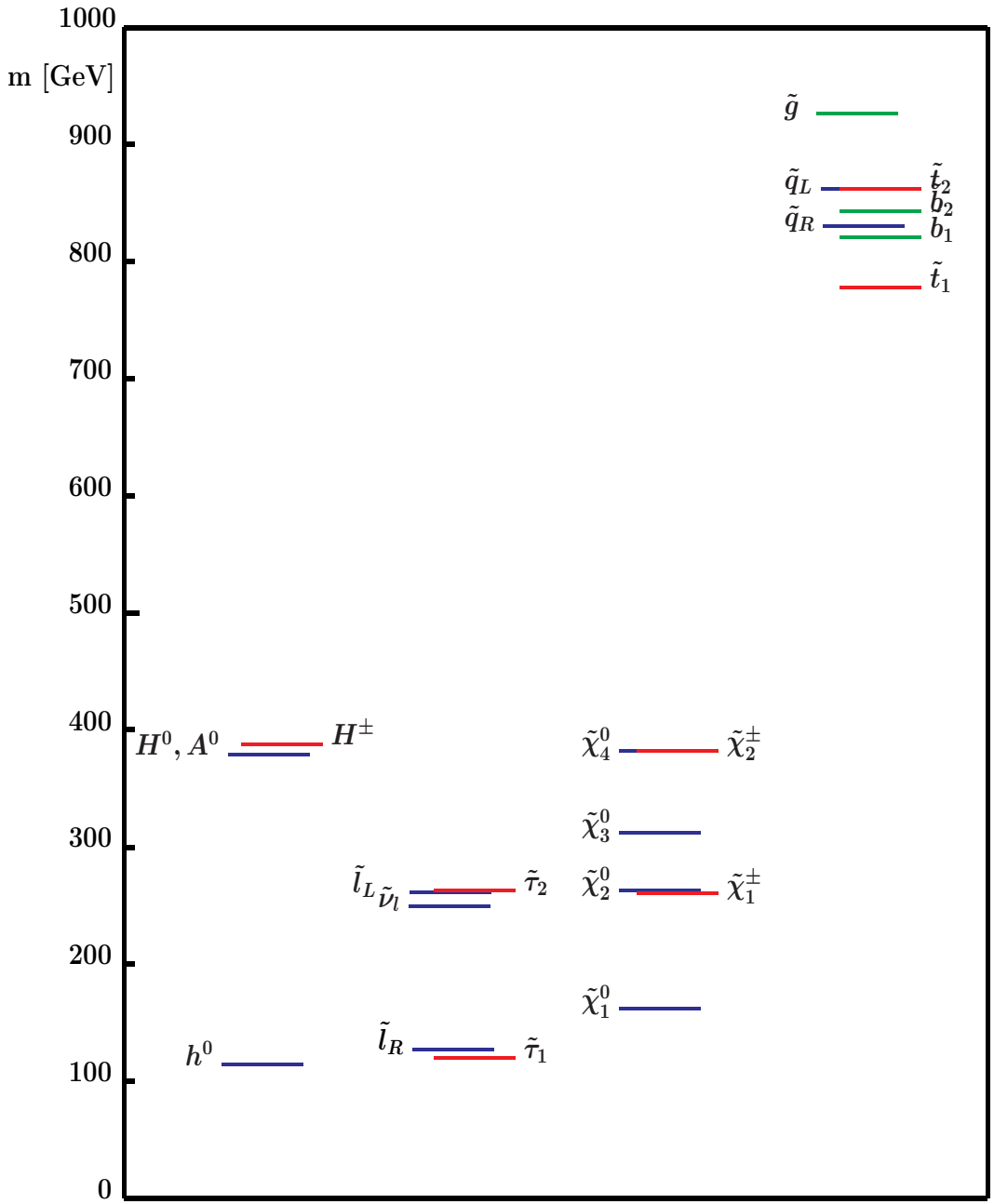
"Typical" GMSB scenario

(SPS 7 benchmark scenario):

SPS home page:

`www.ippp.dur.ac.uk/~georg/sps`

One possible example
for natural larger splitting
between colored and
uncolored sector



"Typical" AMSB scenario

(SPS 9 benchmark scenario):

SPS home page:

`www.ippp.dur.ac.uk/~georg/sps`

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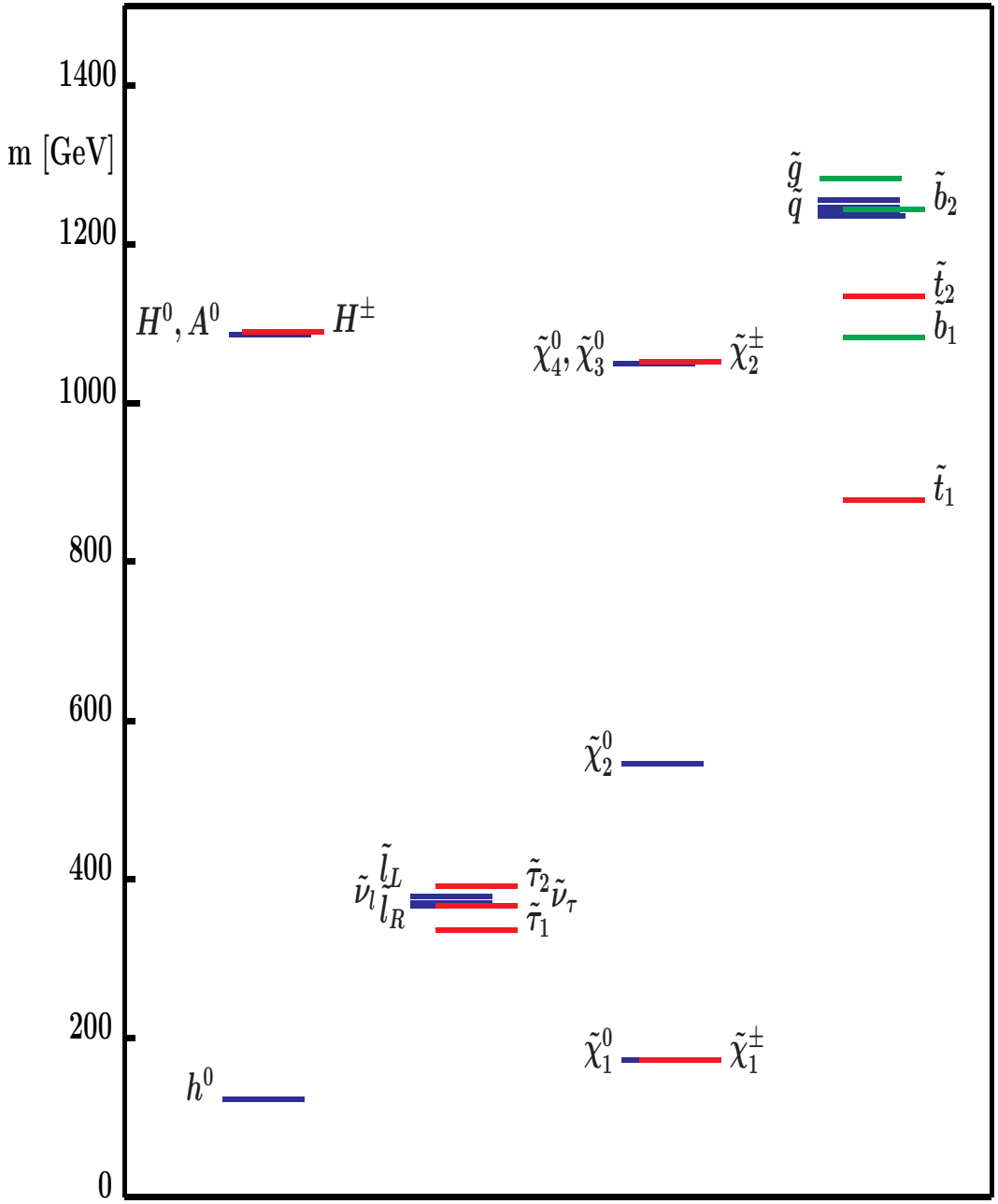

5. Conclusinos

- Finally we have the LHC running and searching for SUSY :-)

- Results are presented in the CMSSM or in "simplified models"
  - How general is this?
  - How useful is this?
  - What are better ways to provide the information (to theorists)?

- Innitiative for a new benchmark proposal (work in progress . . .)
  $\Rightarrow$ models, planes, lines, points

- SUSY fits with the MasterCode:
  post-LHC-2011 predictions: higher mass scales
  CMSSM, NUHM1, . . . still fit "so so"
  with somewhat lower probability

- What happens if in the next round of searches no SUSY is found?
  $\Rightarrow$ bad for CMSSM, NUHM1, . . .
  $\Rightarrow$ inference for LC ($\sqrt{s} = 0.5 - 1$ TeV) very moderate!

Higgs Days at Santander 2011
Theory meets Experiment
19.-23. September
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