Implications of LHC searches for the ILC

Sven Heinemeyer, IFCA (CSIC, Santander)

Granada, 05/2011

1. Why SUSY?

2. Predictions for the ILC before the LHC

3. Impact of LHC searches

4. Conclusions

1. Why SUSY?

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⇒ **Supersymmetry (SUSY)**

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The Standard Model has fermions: u, d, e, ν_e, $\ldots$

The Standard Model has bosons: γ, $W^{\pm}$, Z, g, H

$\Rightarrow$ there should be a symmetry connecting them
$\Rightarrow$ **Supersymmetry (SUSY)**

On a more theoretical basis:

Haag-Lopuszanski-Sohnius theorem:
maximal gauge symmetry for a QFT:
inner gauge symmetry $\otimes$ (local) SUSY

More than four reasons as a SUSY motivation

The SM is in a pretty good shape.

Why MSSM? (Is it worth to double the particle spectrum?)

1.) Stability of the Higgs mass against higher-order corr.

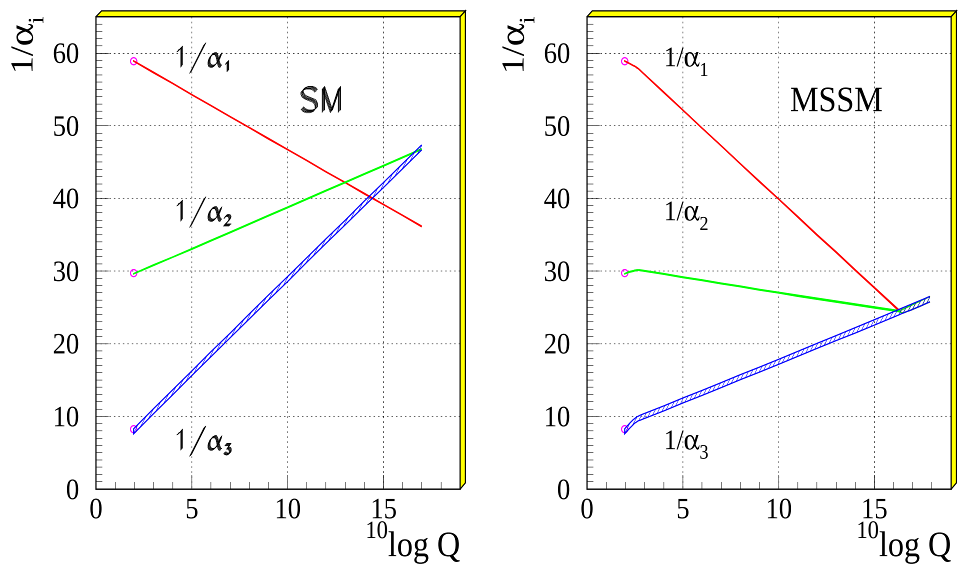
2.) Unification of gauge couplings: Not possible in the SM, but in the MSSM (although it was not designed for it.)

3.) SUSY provides CDM candidate

4.) Spontaneous symmetry breaking via Higgs mechanism is automatic in SUSY GUTs

5.) . . .

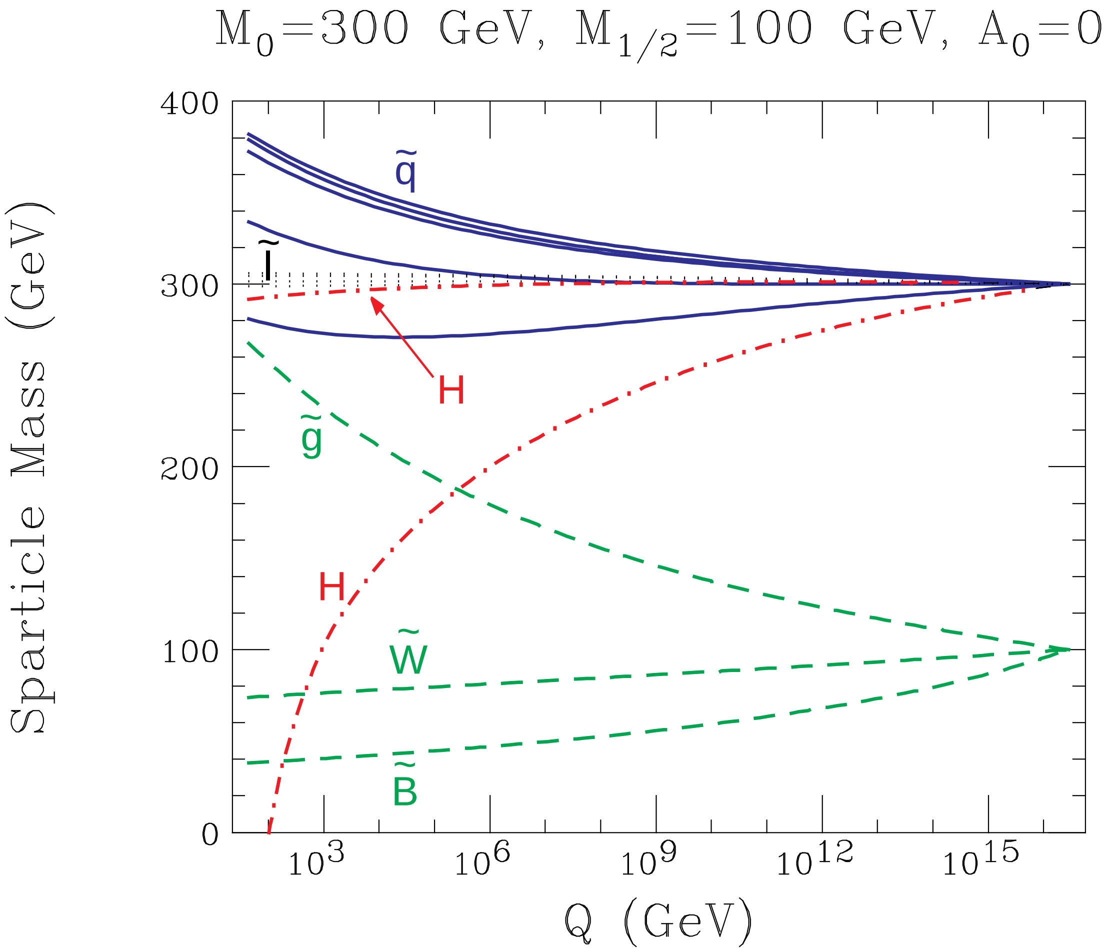
Unification of the Coupling Constants in the SM and the minimal MSSM



[*Amaldi, de Boer, Fürstenau '92*]

Take the most simple MSSM version: CMSSM/mSUGRA
→ just three GUT scale parameters + $\tan\beta$

⇒ particle spectra from renormalization group running to weak scale



⇒ one parameter turns negative ⇒ Higgs mechanism for free

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

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

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

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

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

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM $\Rightarrow m_h \leq M_Z$

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta)$$

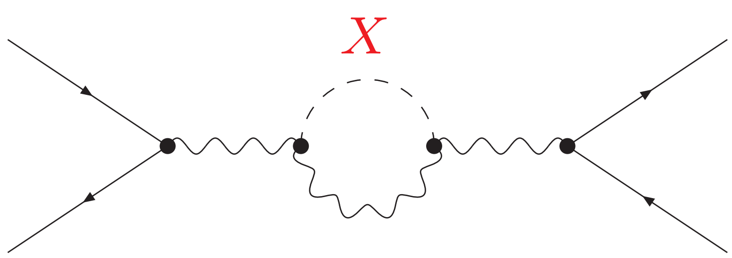
How to make a prediction?

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

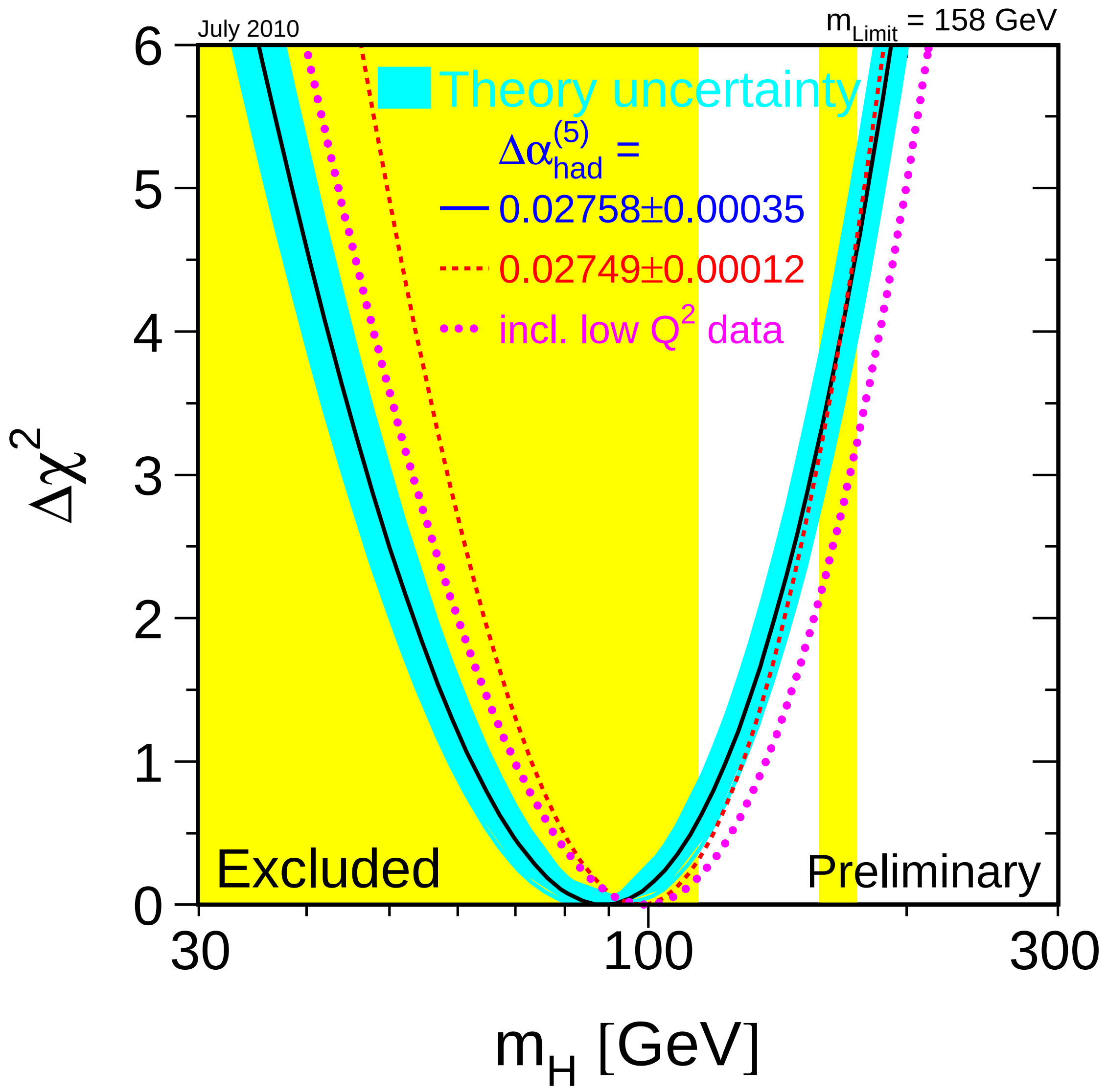
Very high accuracy of measurements and theoretical predictions needed

Global fit to all SM data:

[*LEPEWWG '10*]

$\Rightarrow M_H = 89^{+35}_{-26}$ GeV

$M_H < 158$ 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 analysis:

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 $\Rightarrow$ ILC reach

2. Predictions for the ILC before the LHC

Indirect constraints on M_{SUSY} from existing data?

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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 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 $m_{\tilde{\chi}^0_1}$ and $m_{\tilde{\tau}}$ or M_A or ...

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

$\Rightarrow$ combination makes only sense if all parameters are connected!
$\Rightarrow$ GUT based models, . . .

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)

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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

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

⇒ 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

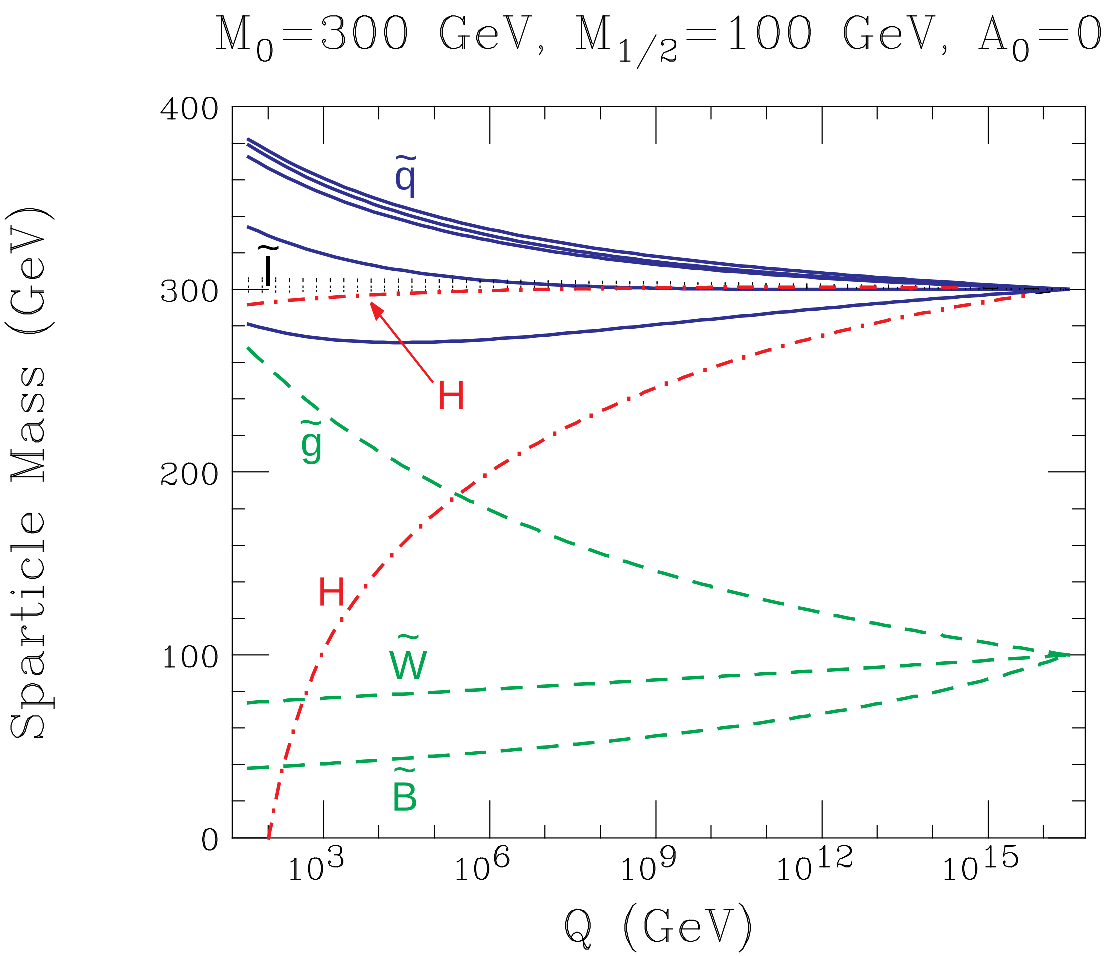
$\tan\beta$: ratio of Higgs vacuum expectation values

sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

⇒ Lightest SUSY particle (LSP) is the lightest neutralino

⇒ particle spectra from renormalization group running to weak scale



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“Typical” CMSSM scenario
(SPS 1a benchmark scenario):

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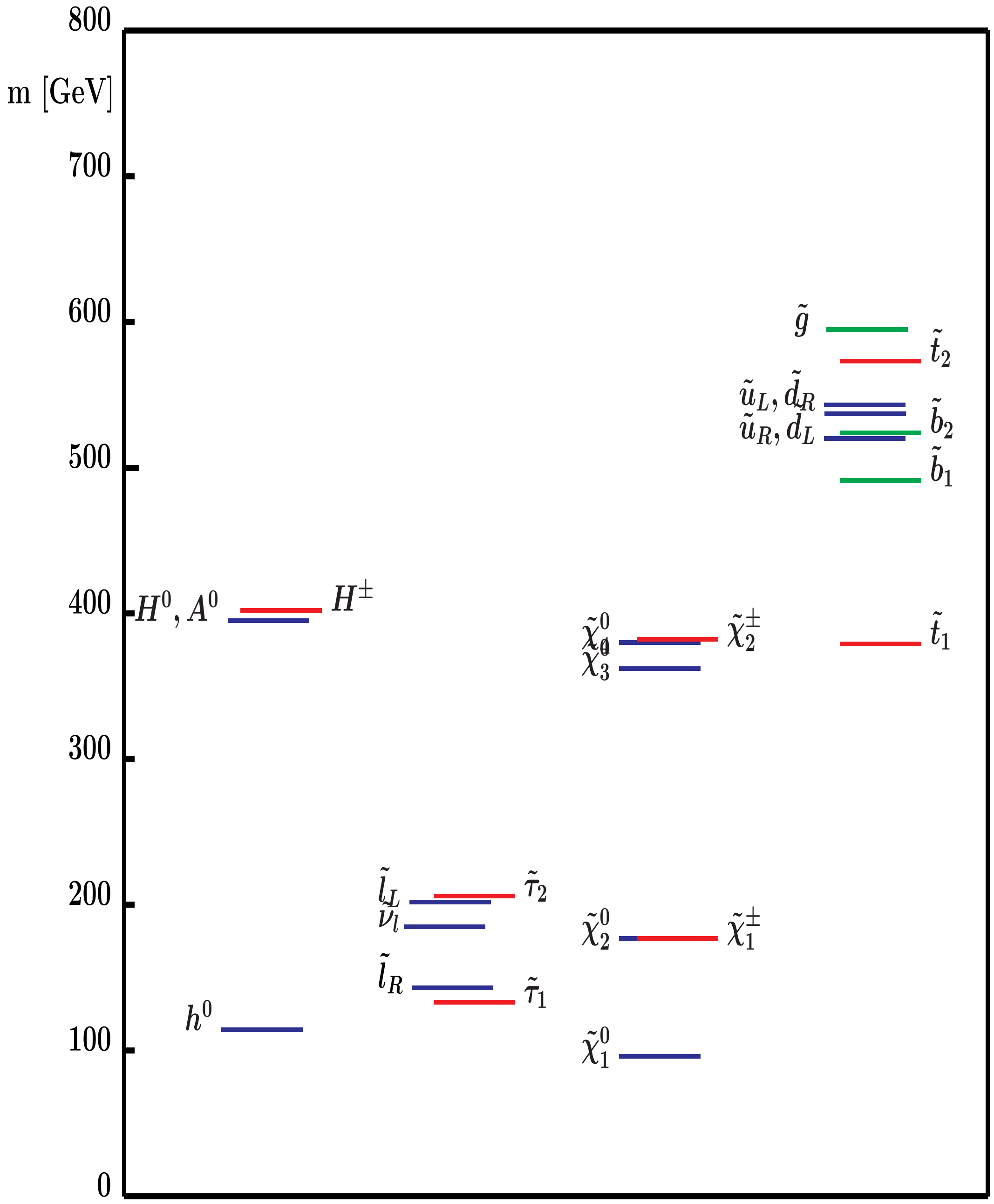


The models: 2.) NUHM1: (Non-universal Higgs mass model)

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

⇒ effectively M_A or μ as free parameters at the EW scale

⇒ besides the CMSSM parameters

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

And we have more: 3.) VCMSSM
4.) mSUGRA

- no time here
- qualitative results (very) similar

Our tool:

The "MasterCode"

⇒ collaborative effort of theorists and experimentalists

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

Über-code for the combination of different tools:

– tools are included as subroutines

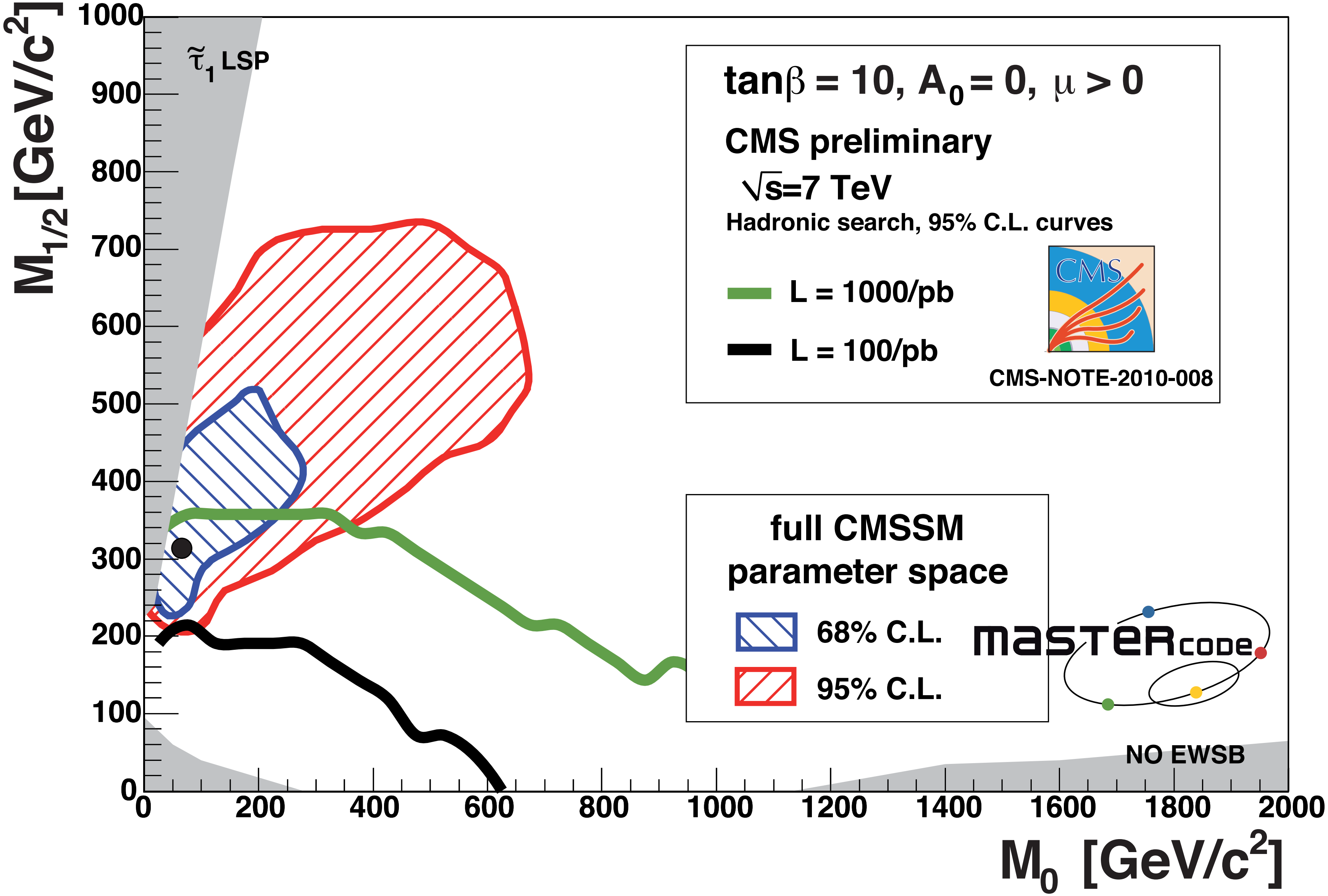
– compatibility ensured by collaboration of authors of "MasterCode" and authors of "sub tools" /SLHA(2)

– one "MasterCode" for one model . . .

⇒ evaluate observables of one parameter point consistently with various tools

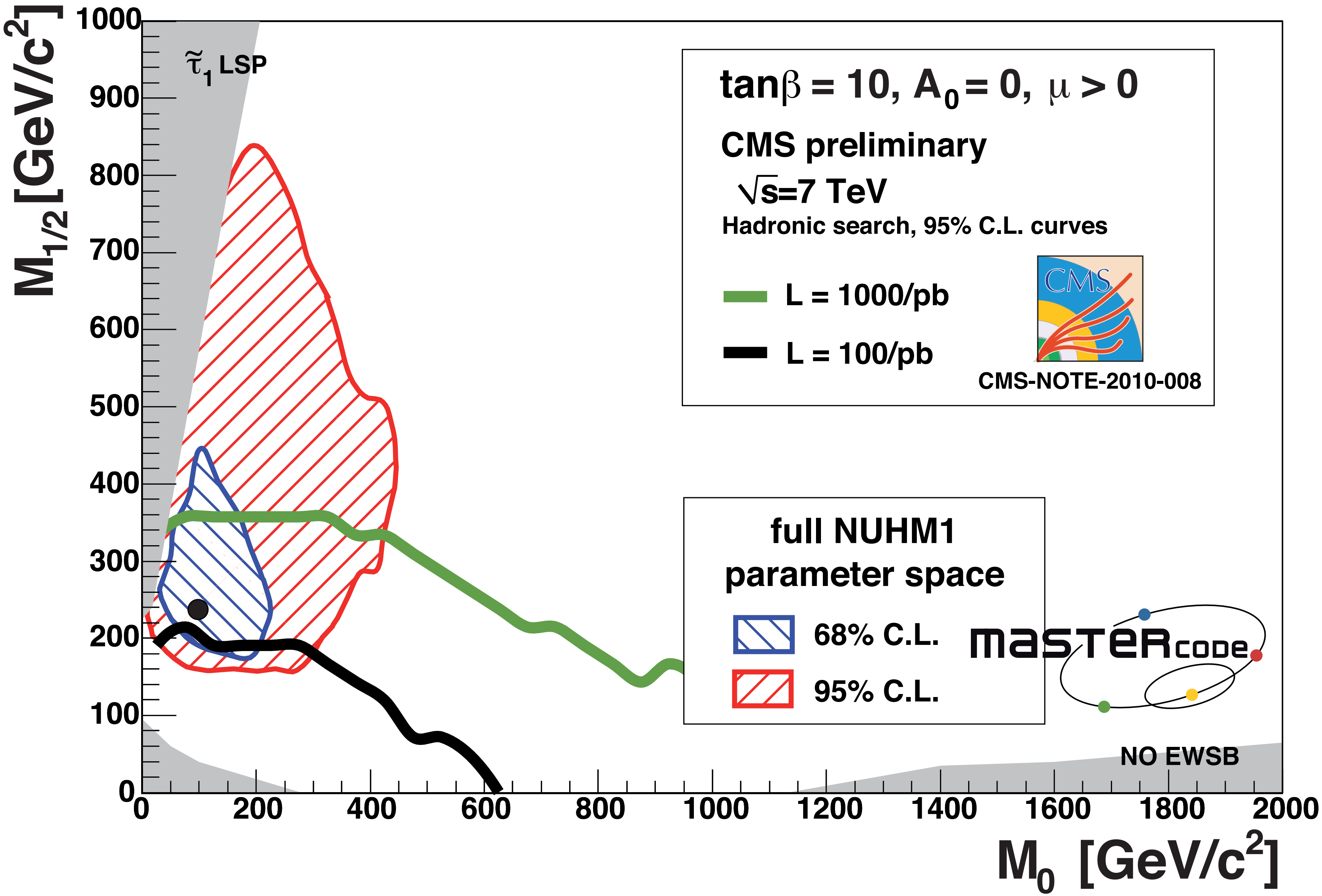
cern.ch/mastercode

LHC (CMS) $\oplus$ CMSSM analysis:



$\Rightarrow$ best-fit point and part of 68% C.L. are can be tested in 2011

LHC (CMS) ⊕ NUHM1 analysis:



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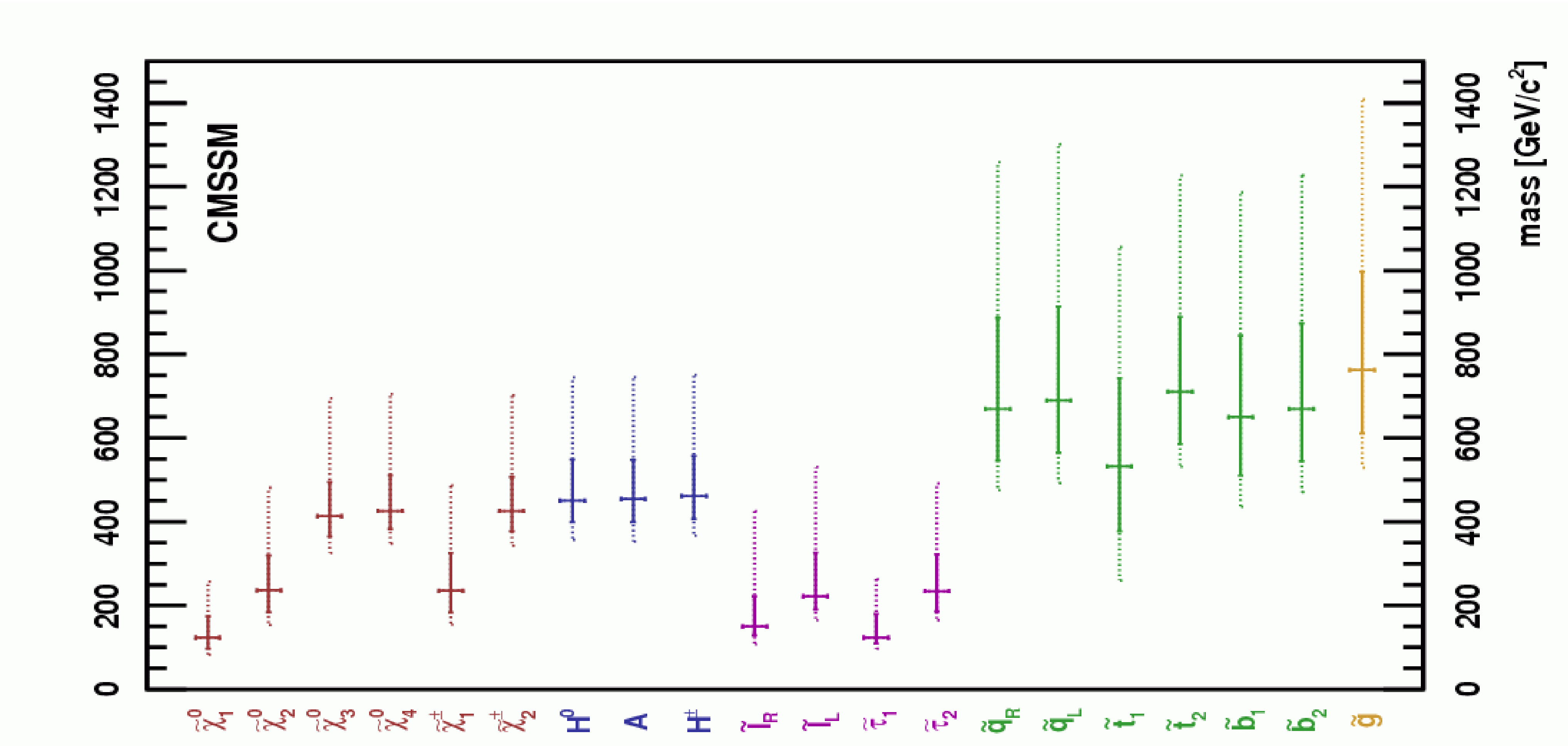
Preferred ranges for SUSY masses: CMSSM

[2009]



$\Rightarrow$ largely accessible spectrum for ILC

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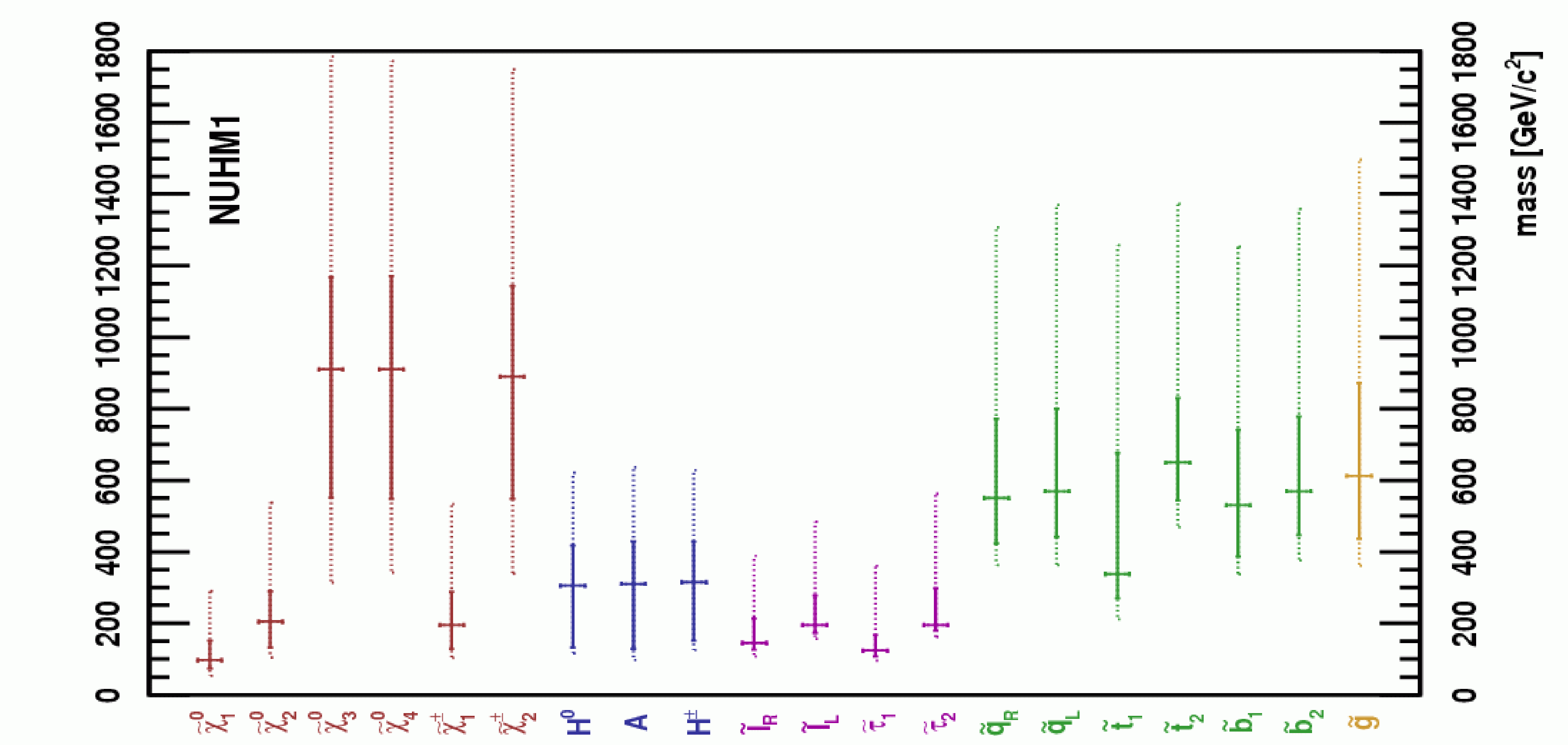

⇒ largely accessible spectrum for ILC

3. Impact of LHC searches

Obvious idea:

(so far) negative search results for SUSY particles yield

new χ^2(LHC, SUSY) contribution

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

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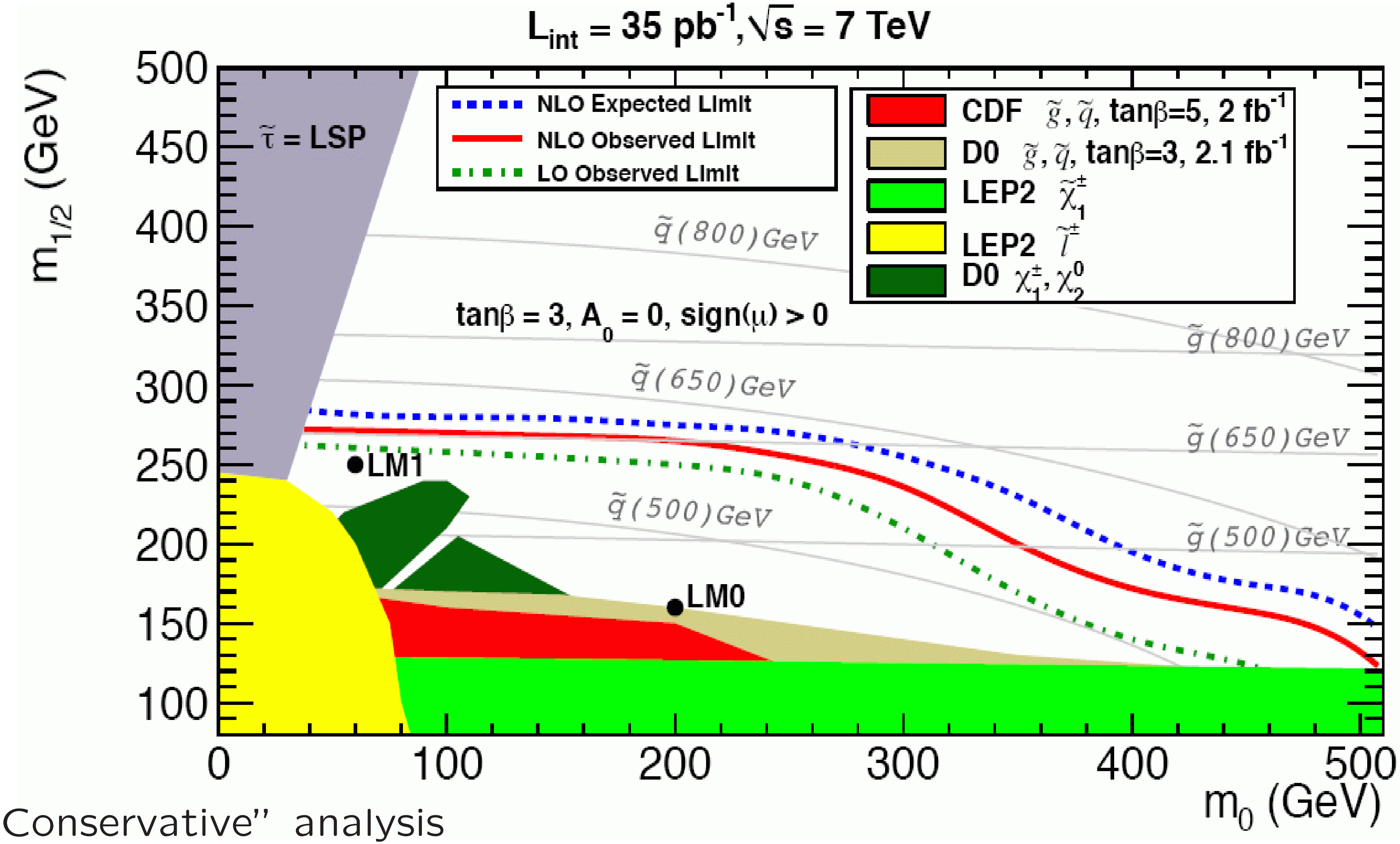
⇒ Implications for the ILC?

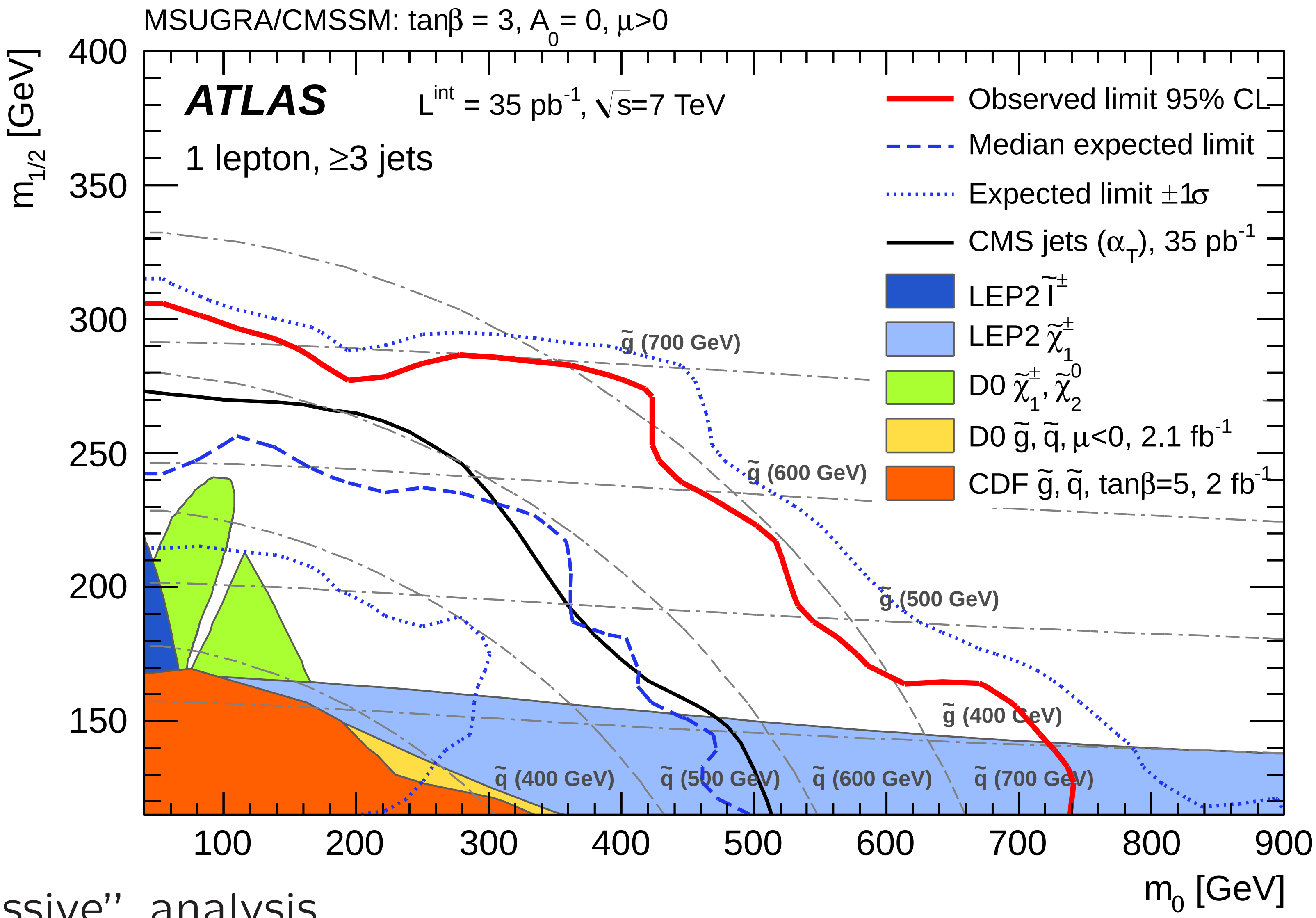
⇒ not as trivial as you might think!



"Conservative" analysis

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

First ATLAS results: 1 lepton



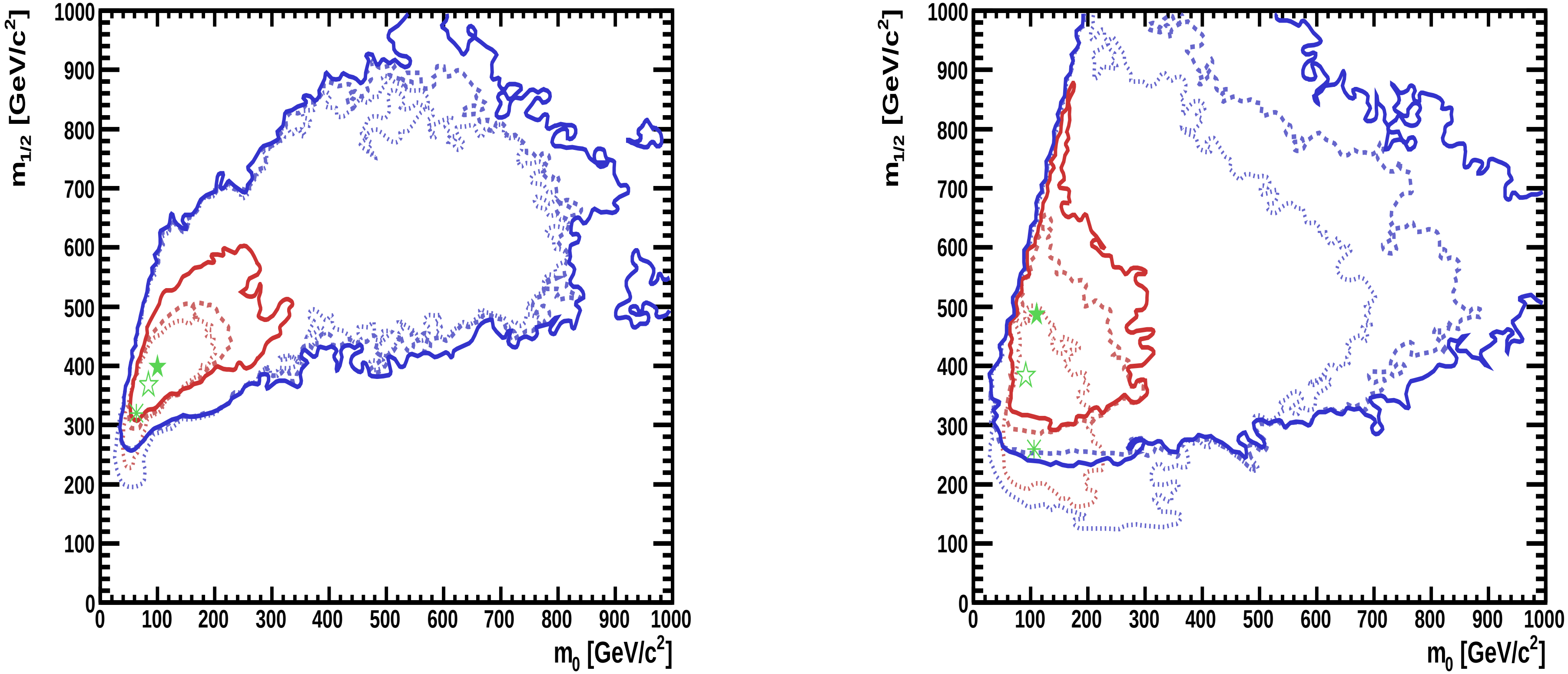
"Aggressive" analysis

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

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

[2011]

CMSSM NUHM1

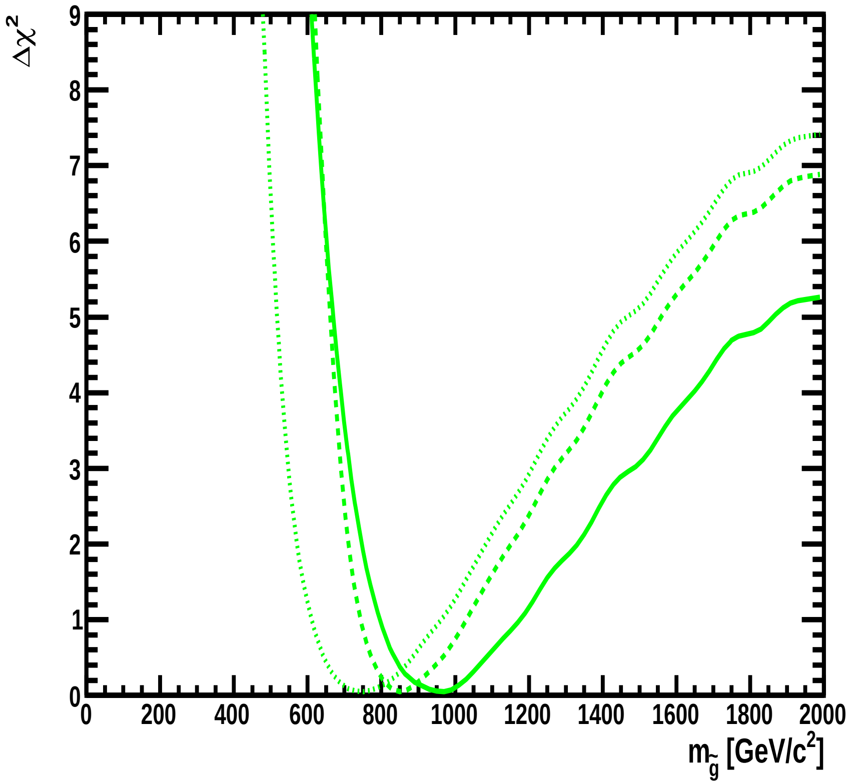


solid: ATLAS – dashed: CMS – dotted: no LHC

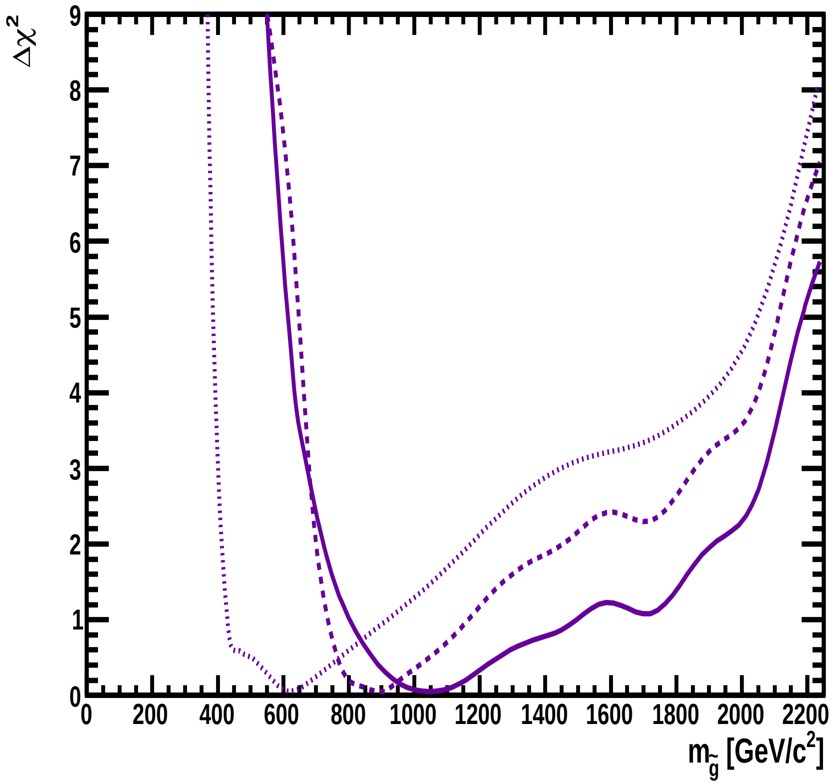
$\Rightarrow$ shift to higher mass scales

[2011]

CMSSM



NUHM1



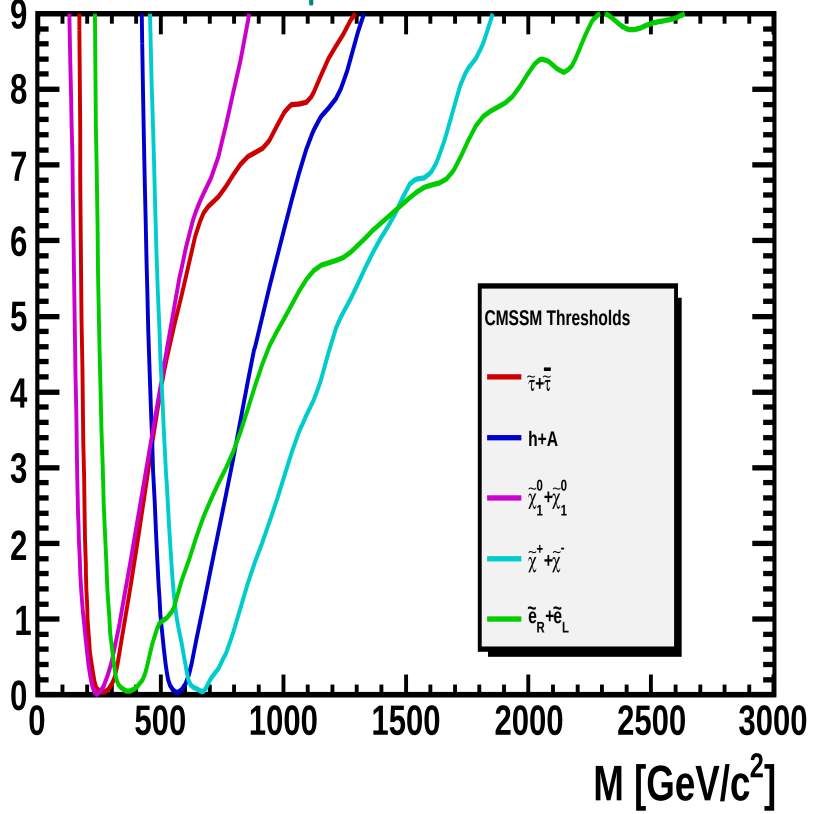
solid: ATLAS – dashed: CMS – dotted: no LHC

⇒ upward shift by 100 – 200 GeV

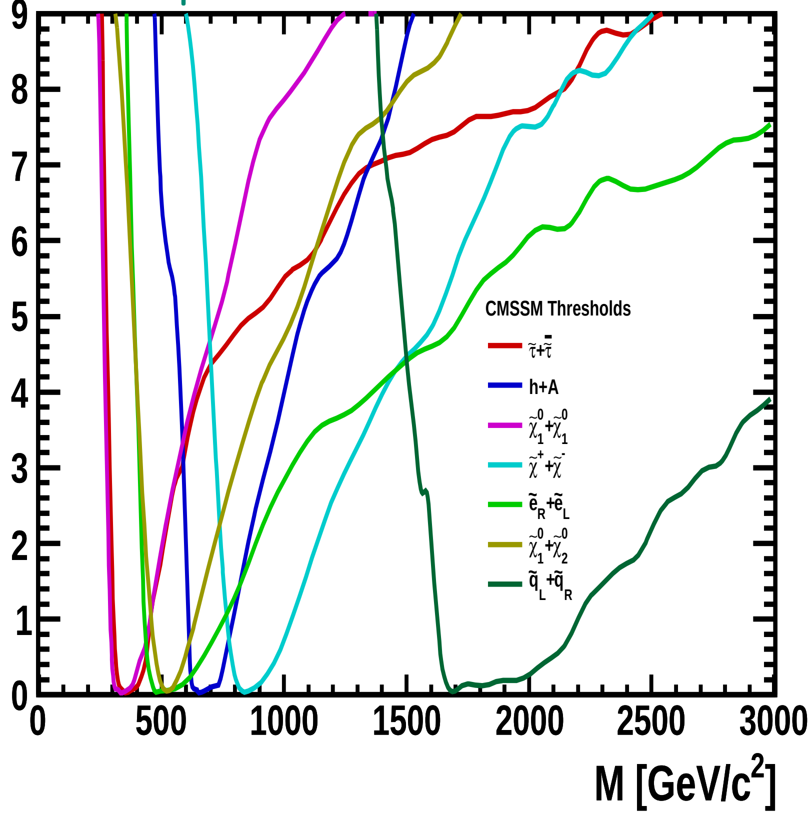
e^+e^- production thresholds in the CMSSM: [PRELIMINARY]

[2011]

pre LHC



post LHC



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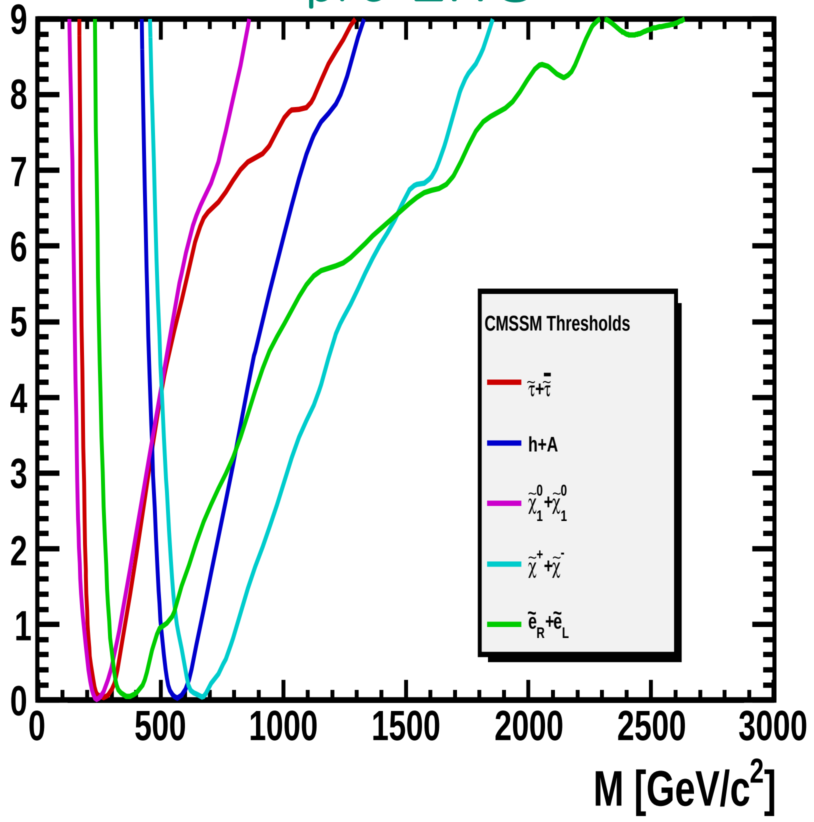

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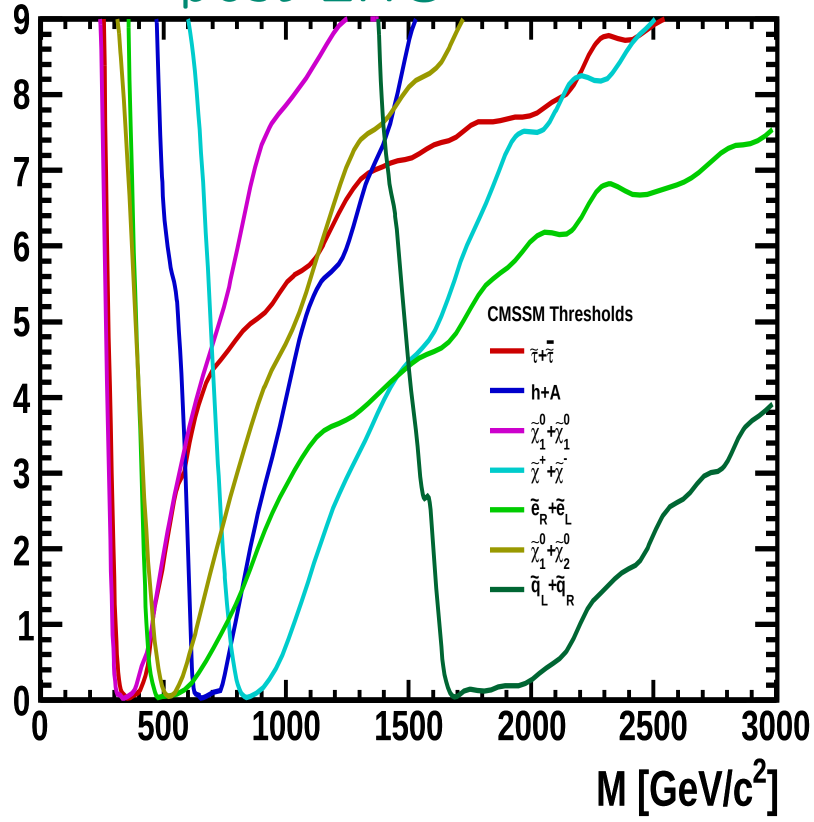

What you will hear very often now: this looks bad for the ILC

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	(21.3)	(32%)	(320)	(60)	(-170)	(11)	(107.9)
with CMS	22.0	29%	370	80	-340	14	112.6
with ATLAS	24.9	16%	400	100	-430	16	112.8
NUHM1	(19.3)	(31%)	(260)	(110)	(1010)	(8)	(121.9)
with CMS	20.9	28%	380	90	70	14	113.5
with ATLAS	23.3	18%	490	110	-630	25	116.5

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

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

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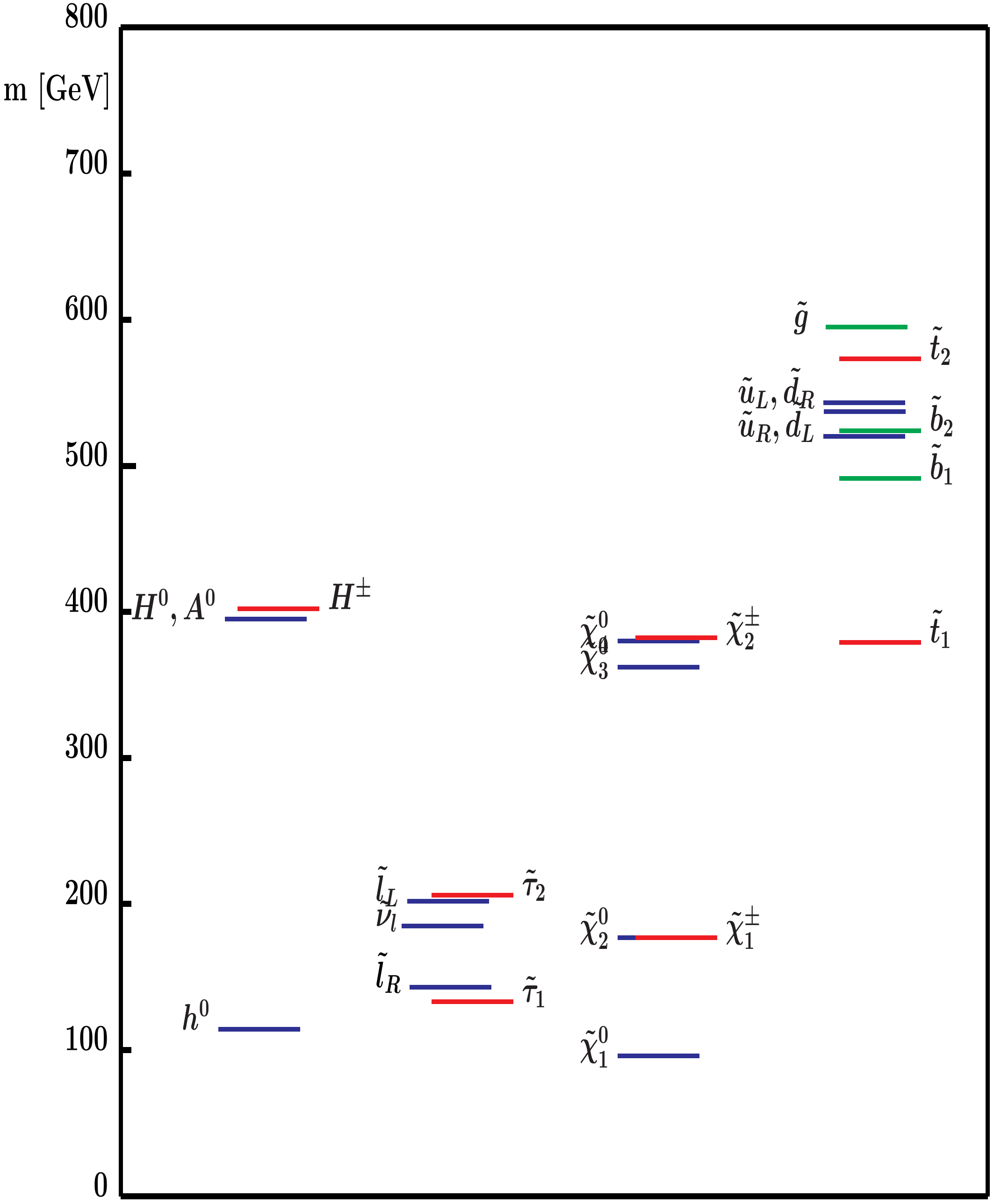
Any inference from one sector to the other is strongly model dependent!

“Typical” CMSSM scenario

(SPS 1a benchmark scenario):

SPS home page:

`www.ippp.dur.ac.uk/∼georg/sps`



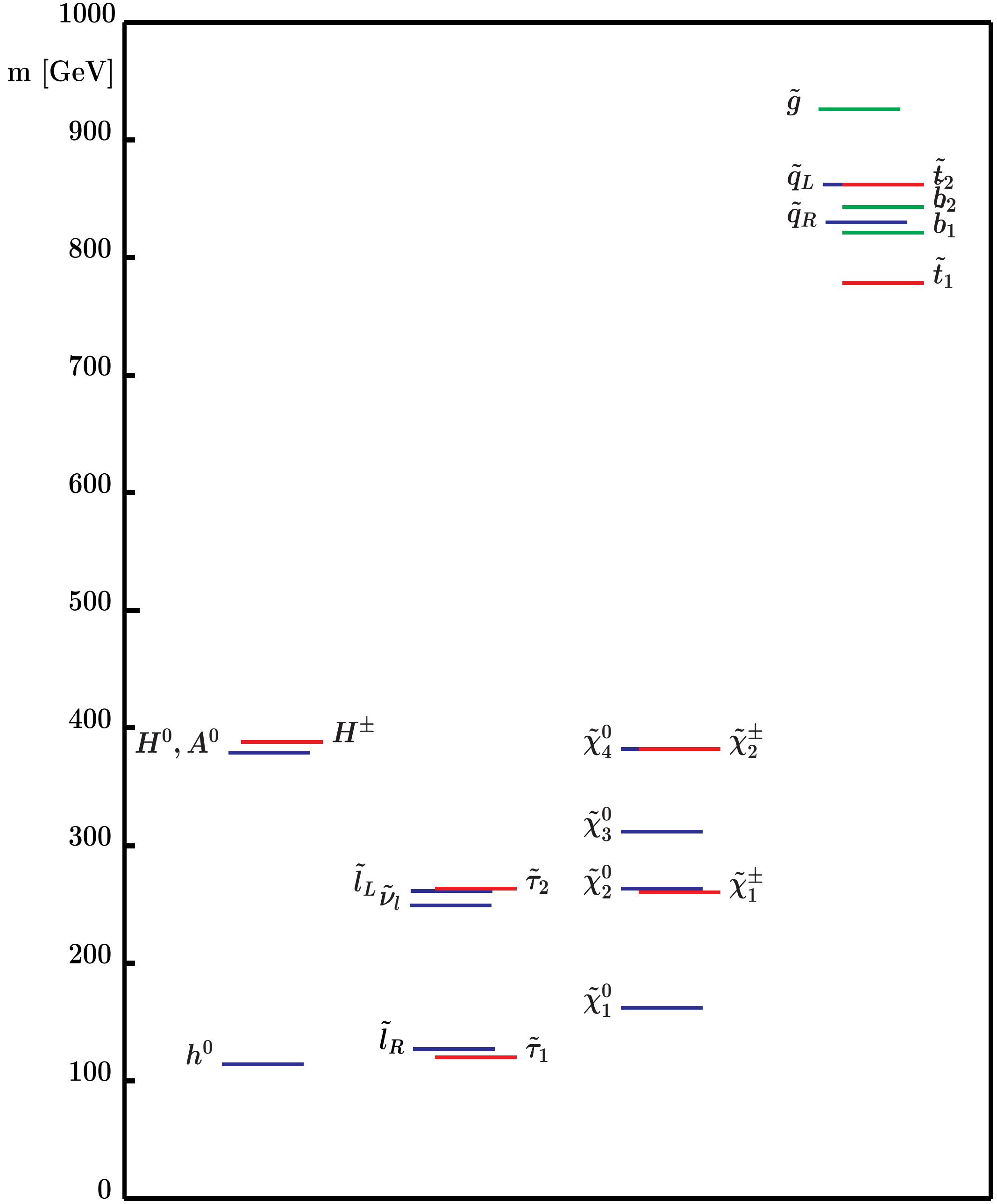
“Typical” GMSB scenario

(SPS 7 benchmark scenario):

SPS home page:

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

<u>One</u> 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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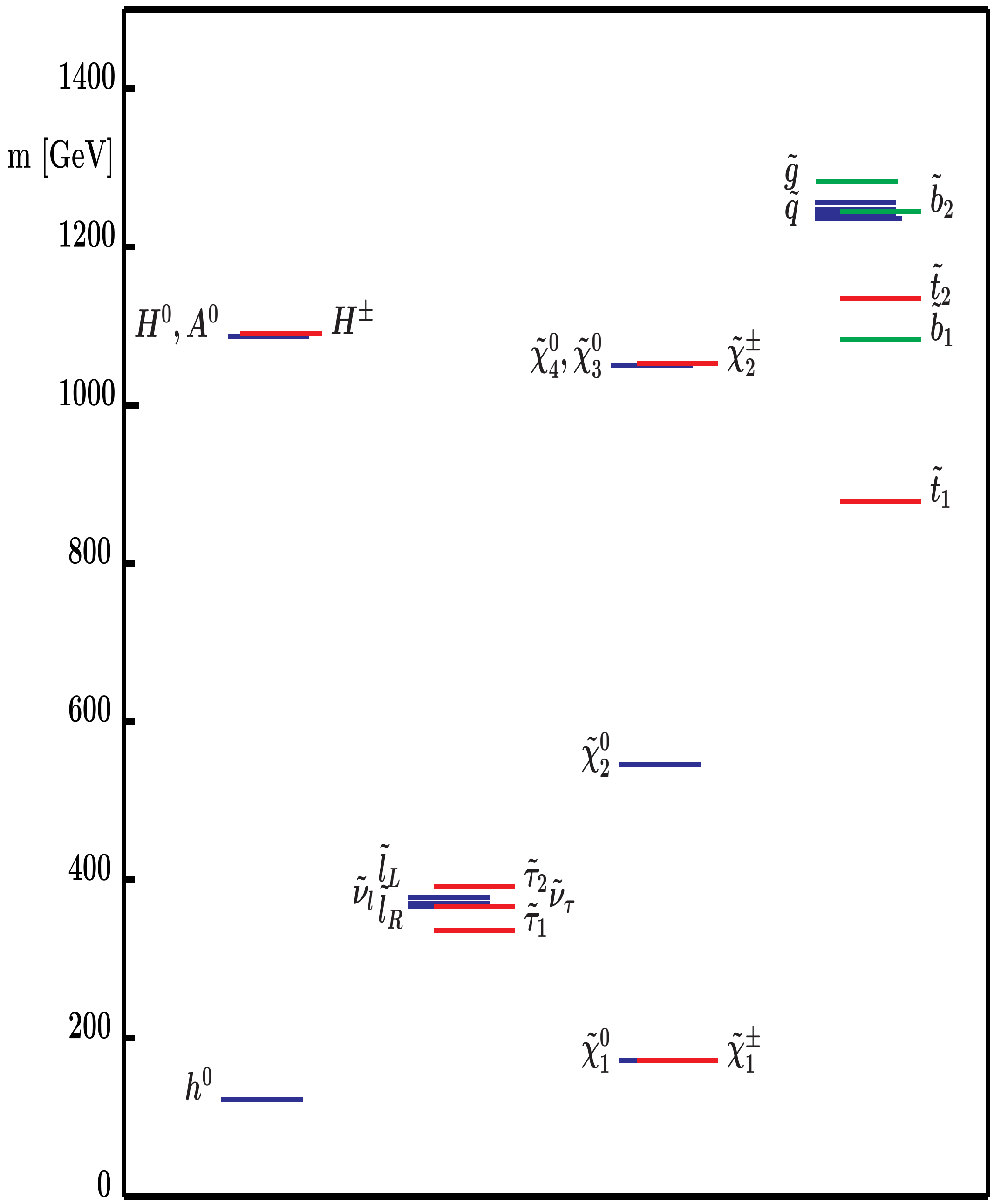

4. Conclusinos

- SUSY is (still) my (our?) best bet for physics beyond the SM
- Precision observables allow to make predictions for SUSY masses and parameters
- During the absence of a signal this is restricted to GUT based models
  $\longrightarrow$ CMSSM, NUHM1, . . .
- Our tool: MasterCode: EWPO, BPO, CDM, . . .
- pre-LHC predictions: relatively low mass scales
- post-LHC predictions: slightly higher mass scales
  CMSSM, NUHM1, . . . still fit well
  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 ILC very moderate!


Higgs Days at Santander 2011
Theory meets Experiment
19.-23. September
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UNIVERSIDAD DE CANTABRIA
contact:Sven.Heinemeyer@cern.ch
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