Implications of SUSY Searches at the LHC for the ILC

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Granada, 09/2011

1. Motivation

2. SUSY predictions for and from the LHC

3. Implications for the (I)LC

4. Conclusions

1. Motivation ;-)

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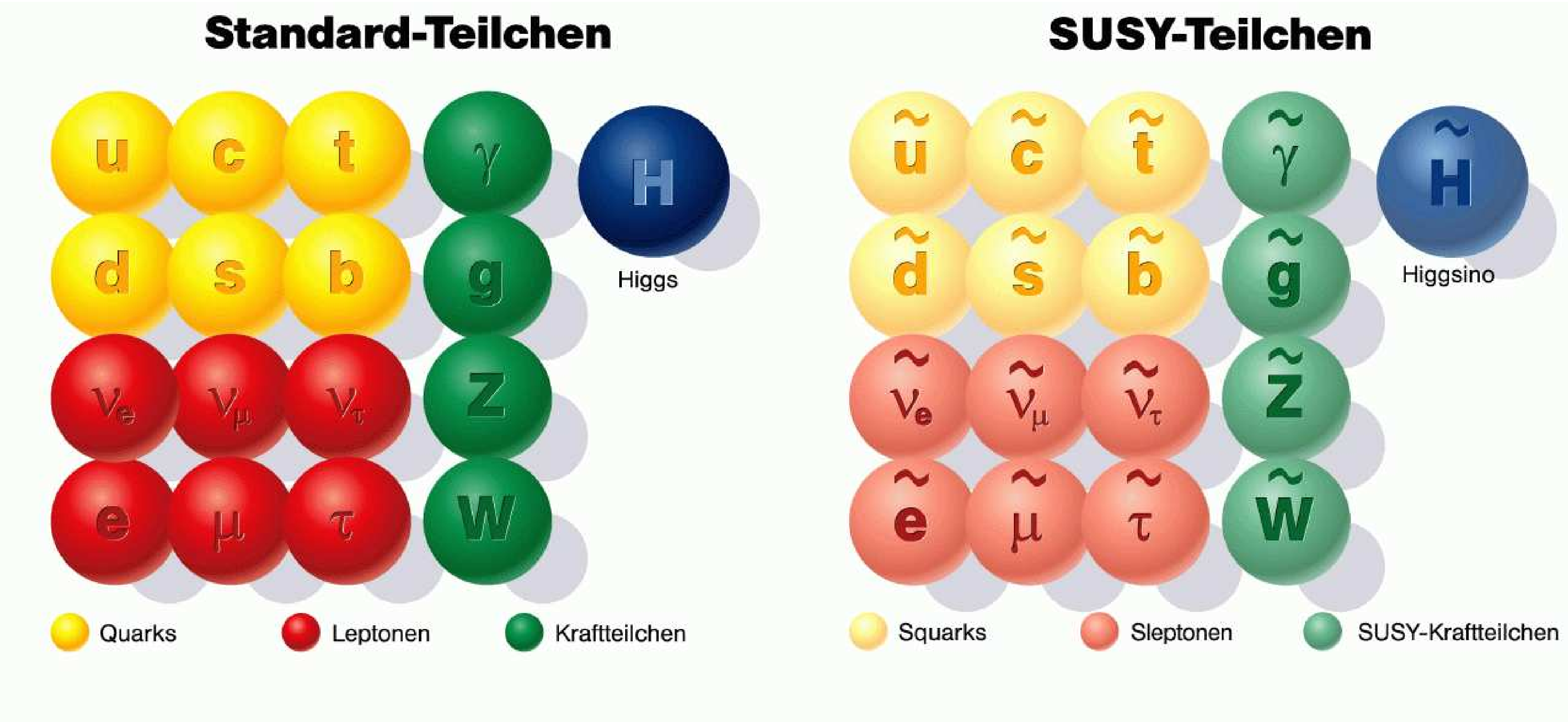


SUSY needs not motivation here :-)

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

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

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

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

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

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: 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):

⇒ 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

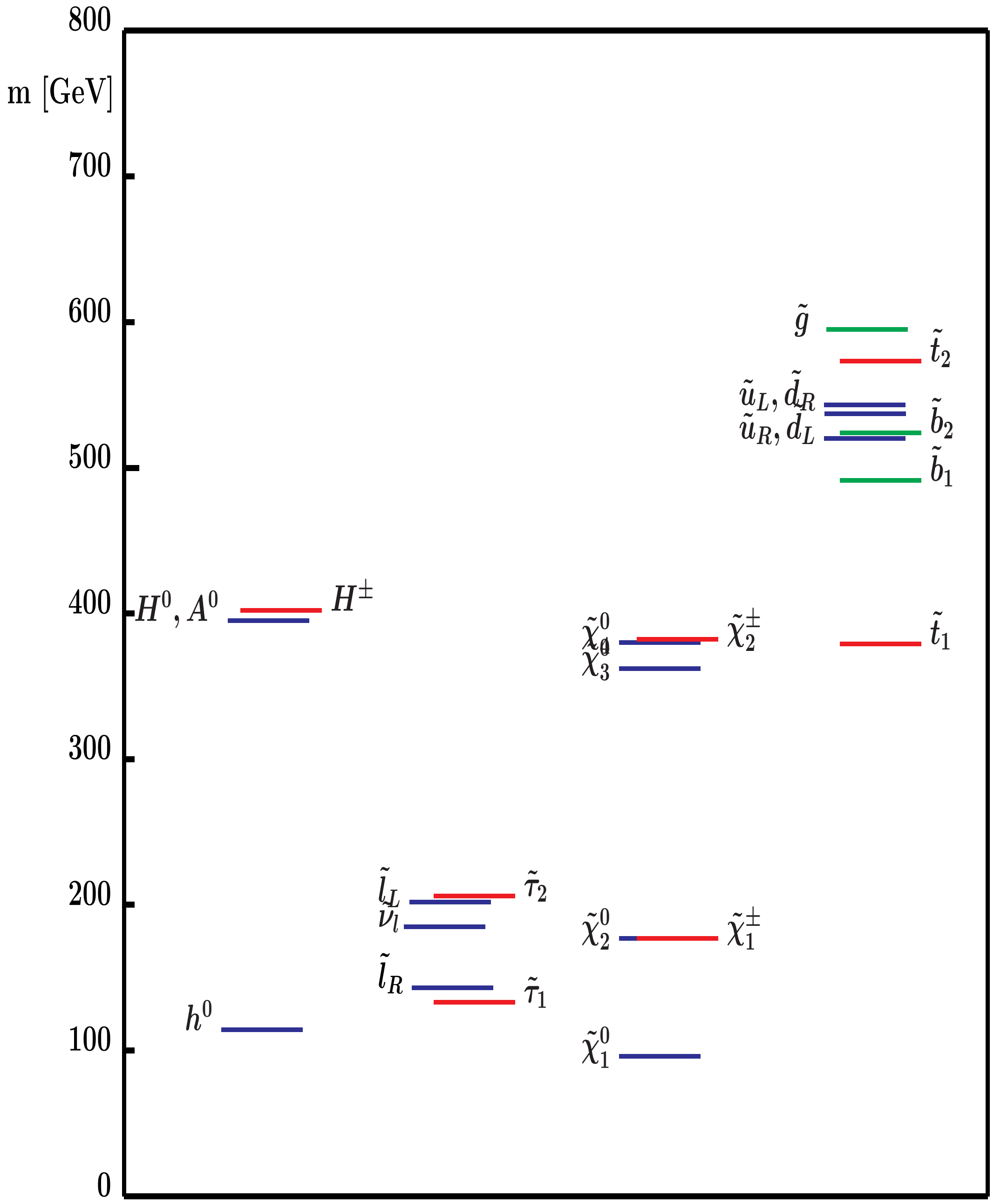
⇒ Lightest SUSY particle (LSP) is the lightest neutralino

"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 . . .

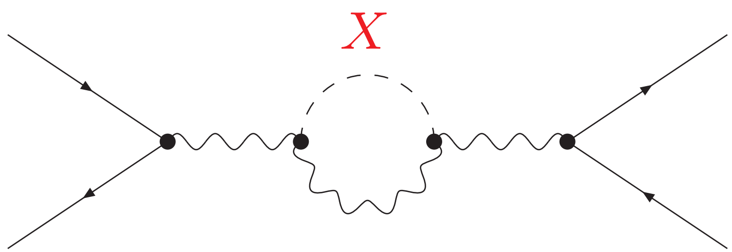
2. SUSY prediction for and from the LHC

How to make predictions: Comparison of precision observables with theory:

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

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections

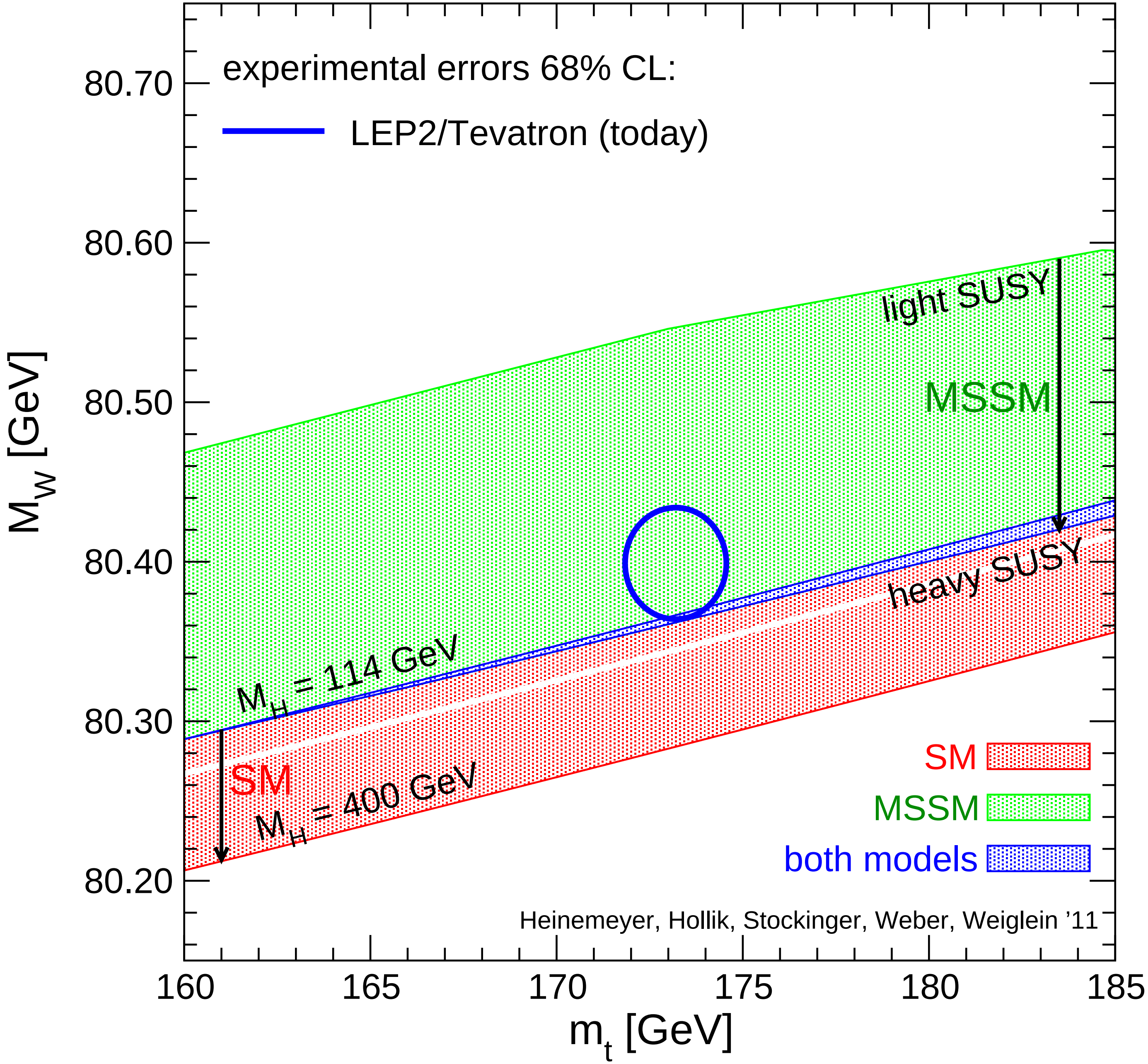


$\Downarrow$

$\Rightarrow$ Information about unknown parameters

Very high accuracy of measurements and theoretical predictions needed

The most beautiful example:

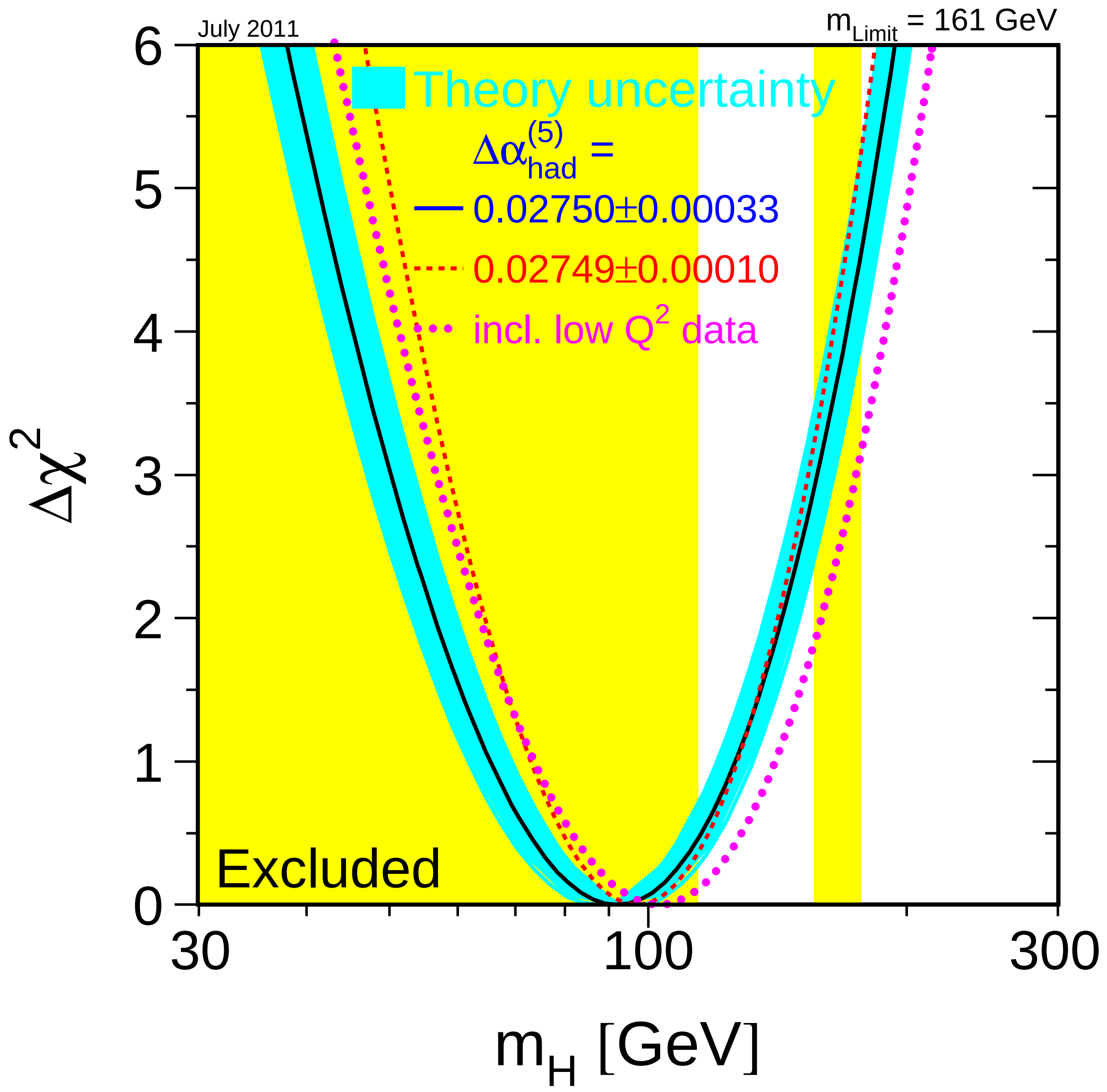


Global fit to all SM data:

[*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 analysis:

Combine all existing precision data:

- Electroweak precision observables (EWPO)
- B physics observables (BPO)
- Astrophysical data (CDM, DD)
- LHC searches for SUSY

Predict:

- best-fit points
- ranges for Higgs masses
- ranges for SM parameters
- ranges for SUSY masses

$\Rightarrow$ LC implications

Our tool:

The "MasterCode"

⇒ collaborative effort of theorists and experimentalists

[*O. Buchmüller, R. Cavanaugh, A. De Roeck, M. Dolan, J. Ellis, H. Flächer, SH, G. Isidori, D. Martinez Santos, K. Olive, S. Rogerson, F. Ronga, G. 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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Assumption: measurements are uncorrelated - fulfilled to a high degree

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

$\rightarrow$ especially important: M_h $\rightarrow$ no time - ask me over coffee

Latest ingredient: 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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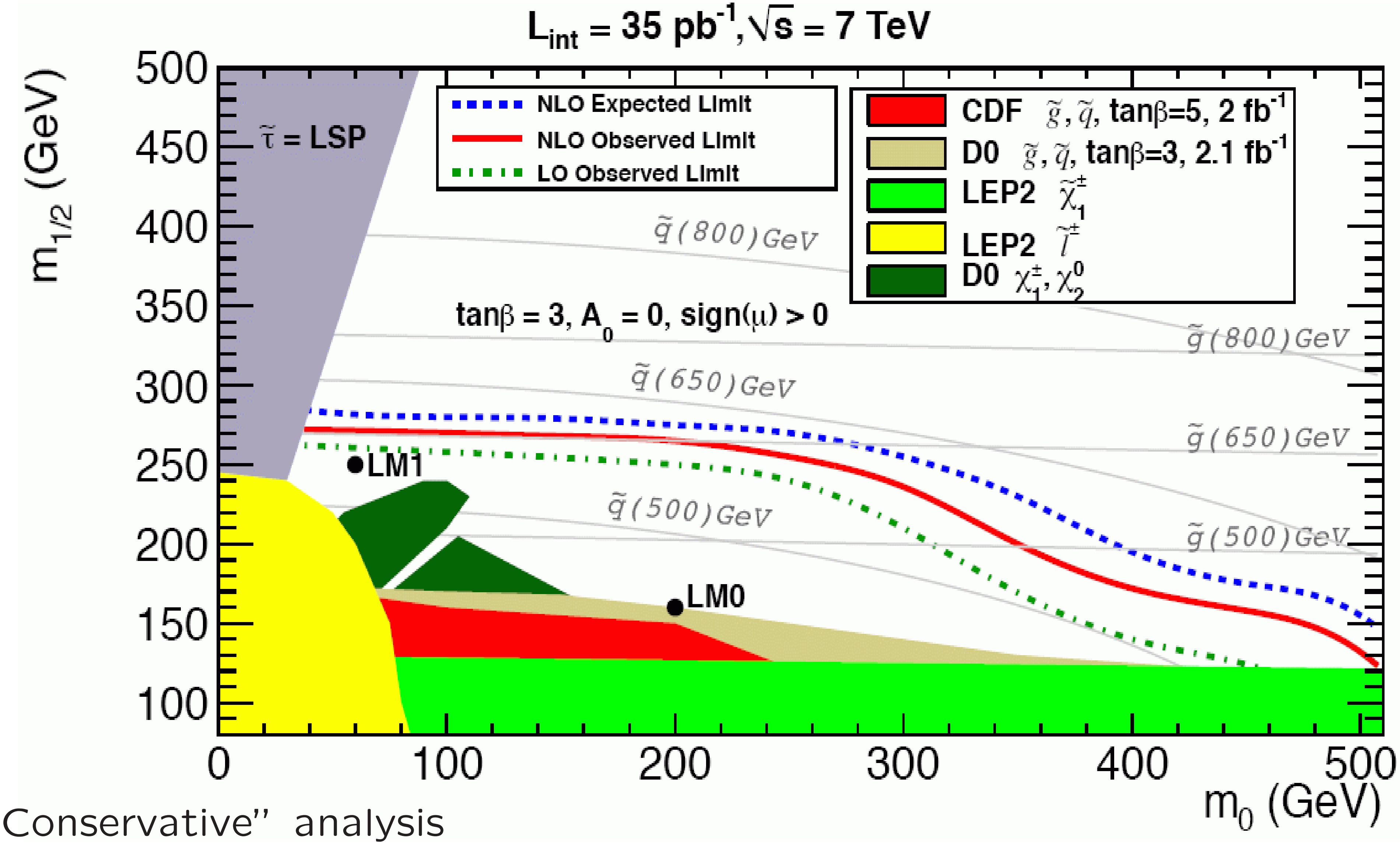
$\Rightarrow$ Implications for the ILC?

$\Rightarrow$ not as trivial as you might think!

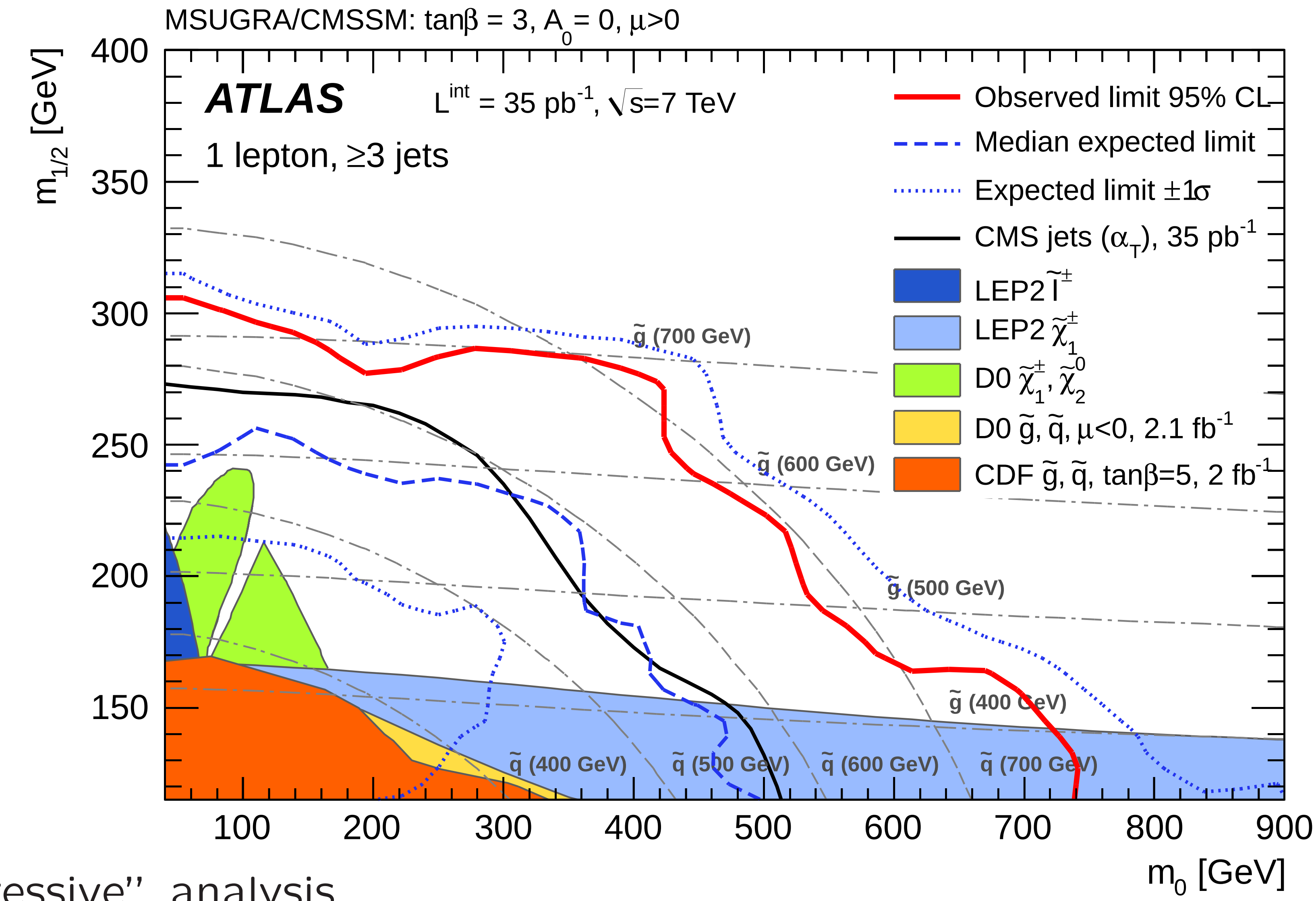


"Conservative" analysis

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

First ATLAS results: 1 lepton

[*ATLAS '11*]

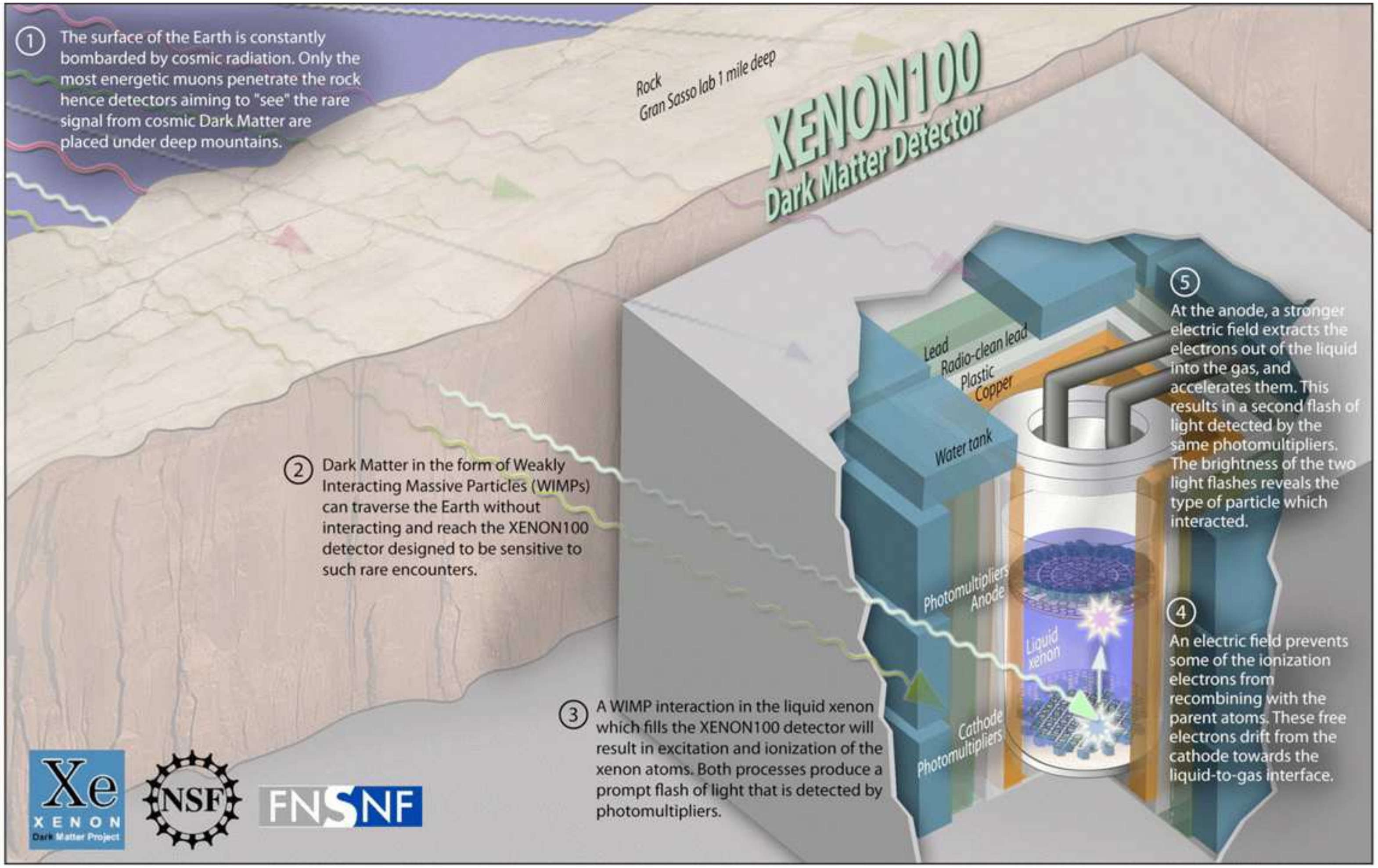


"Aggressive" analysis

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

Additional new constraint:

Direct Dark Matter detection: Xenon100



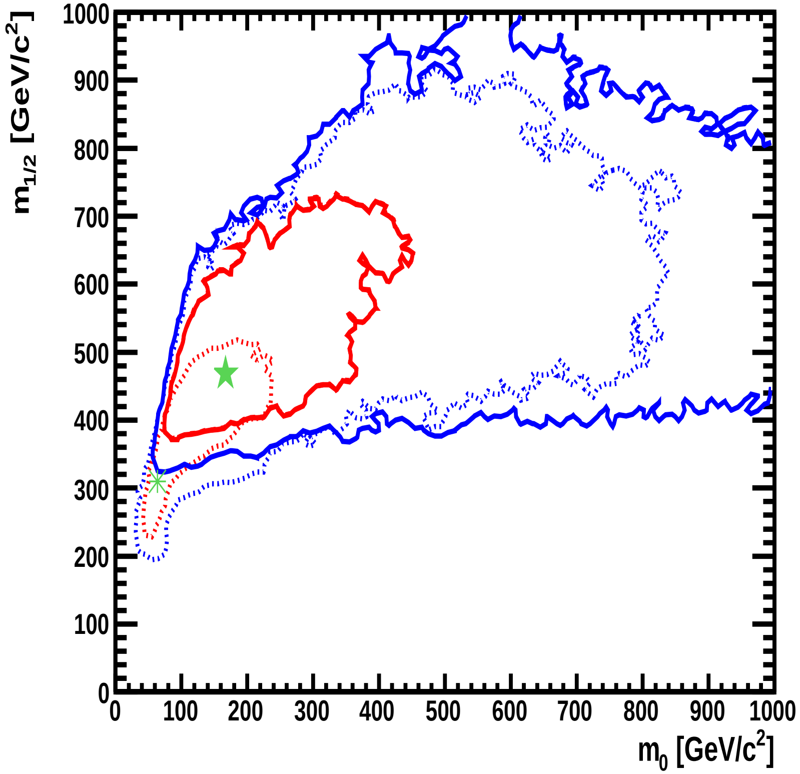
expected: 1.8 ± 0.6 events

observed: 3 events

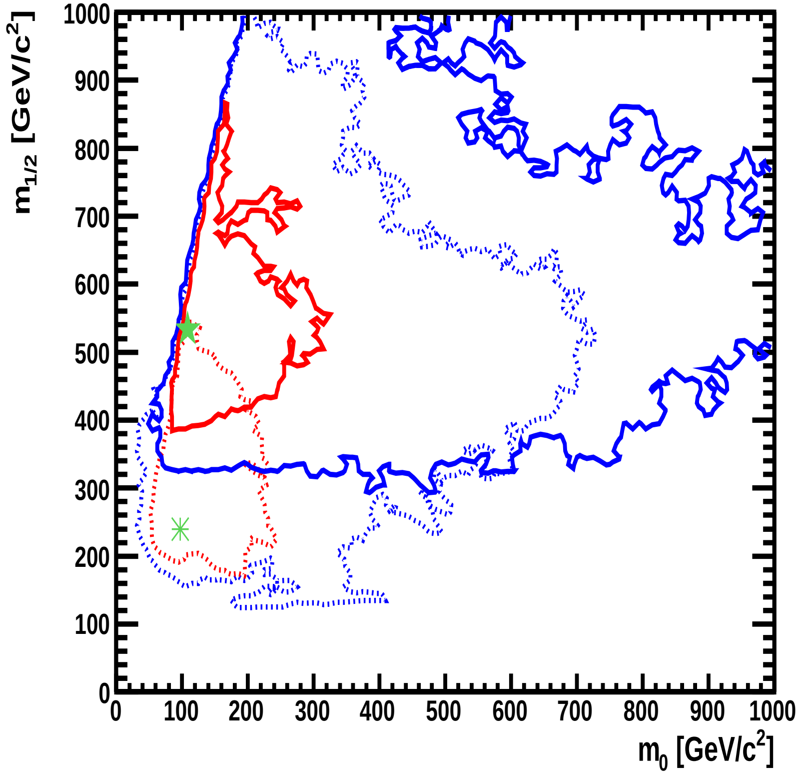
m_0-$m_{1/2}$ plane:

[2011]

CMSSM



NUHM1



dotted: pre-LHC/Xenon, solid: post-LHC/Xenon

⇒ new best-fit point within old 68% CL area

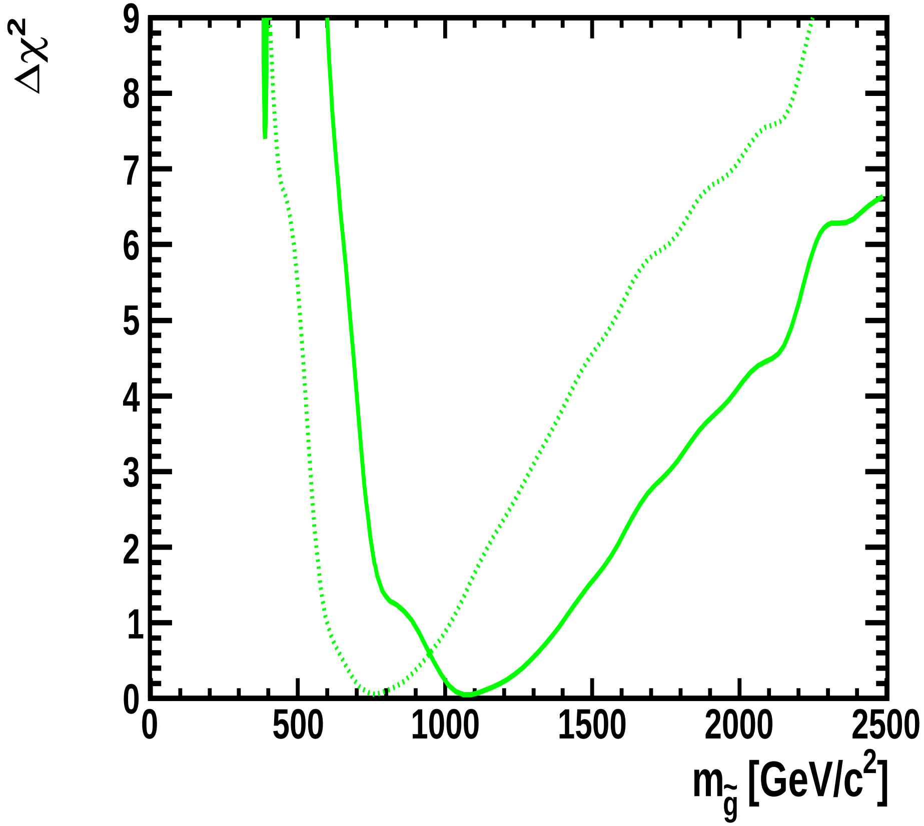
⇒ old best-fit point ruled out at 95% CL

⇒ shift to higher masses

Starting point of the cascade: gluino

[2011]

CMSSM



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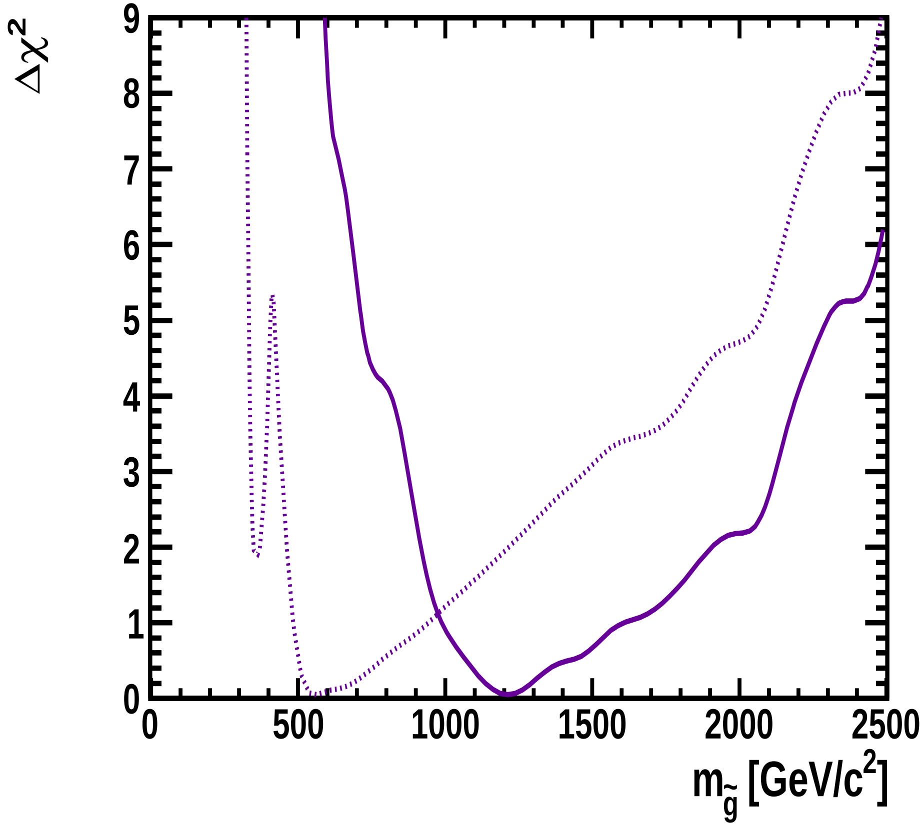


dotted: pre-LHC/Xenon, solid: post-LHC/Xenon

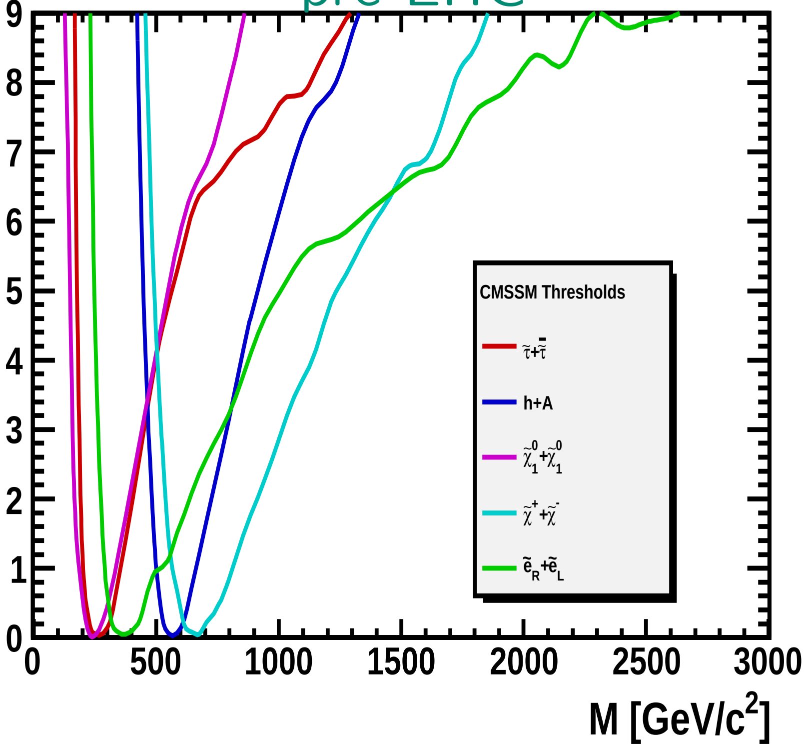
⇒ substantial upward shift

3. Implications for the (I)LC

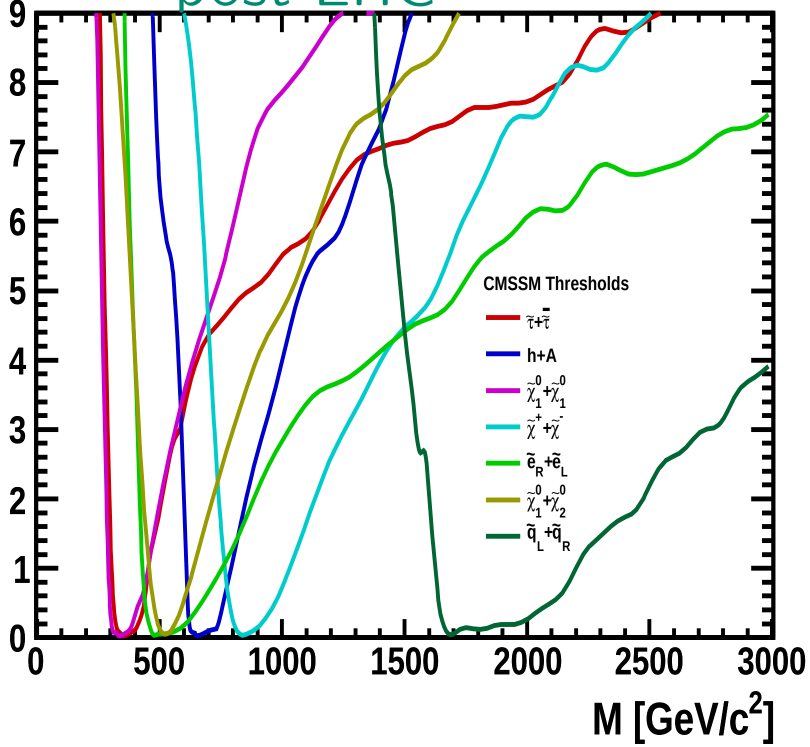
e^+e^- production thresholds in the CMSSM: [PRELIMINARY]

[2011]

pre LHC



post LHC



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

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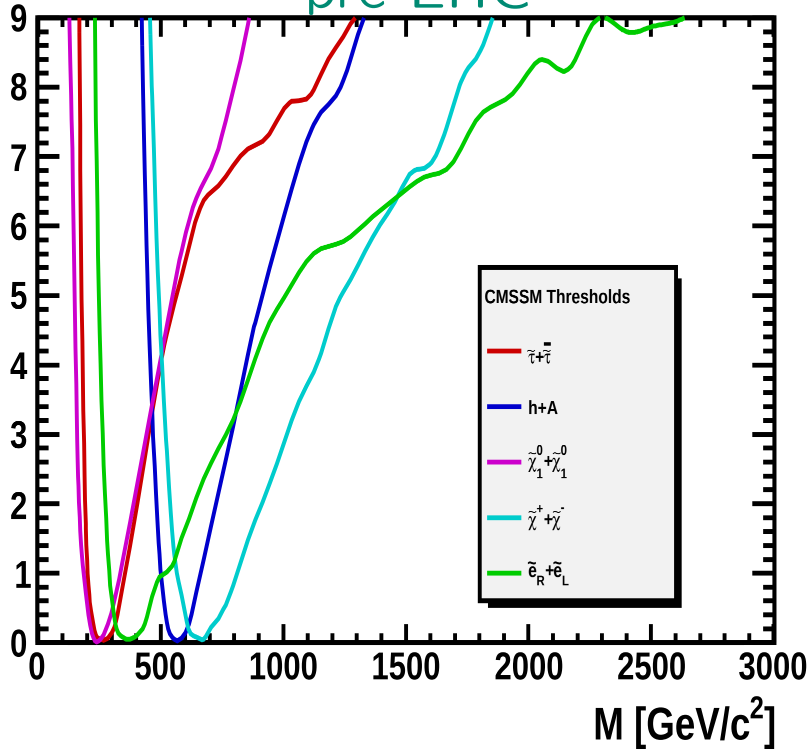
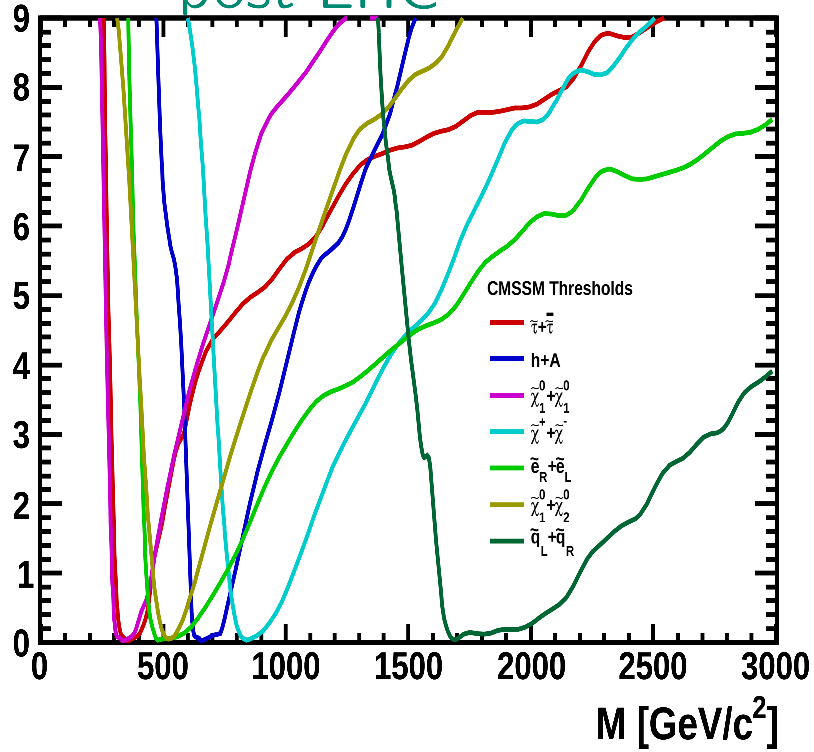


post LHC



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

And this is WRONG!

What is happening to the χ^2?

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

LHC data favors higher (colored) 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	22.3/20	32%	360	90	-400	15	109
$\text{LHC}_{1/\text{fb}}$	29.3/22	14%	780	450	-1100	41	119
NUHM1	20.8/18	29%	340	110	520	13	119
$\text{LHC}_{1/\text{fb}}$	27.4/21	16%	730	150	-910	41	119

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

Not finding SUSY early does not make the ILC looks bad,
makes some very constrained models look bad!

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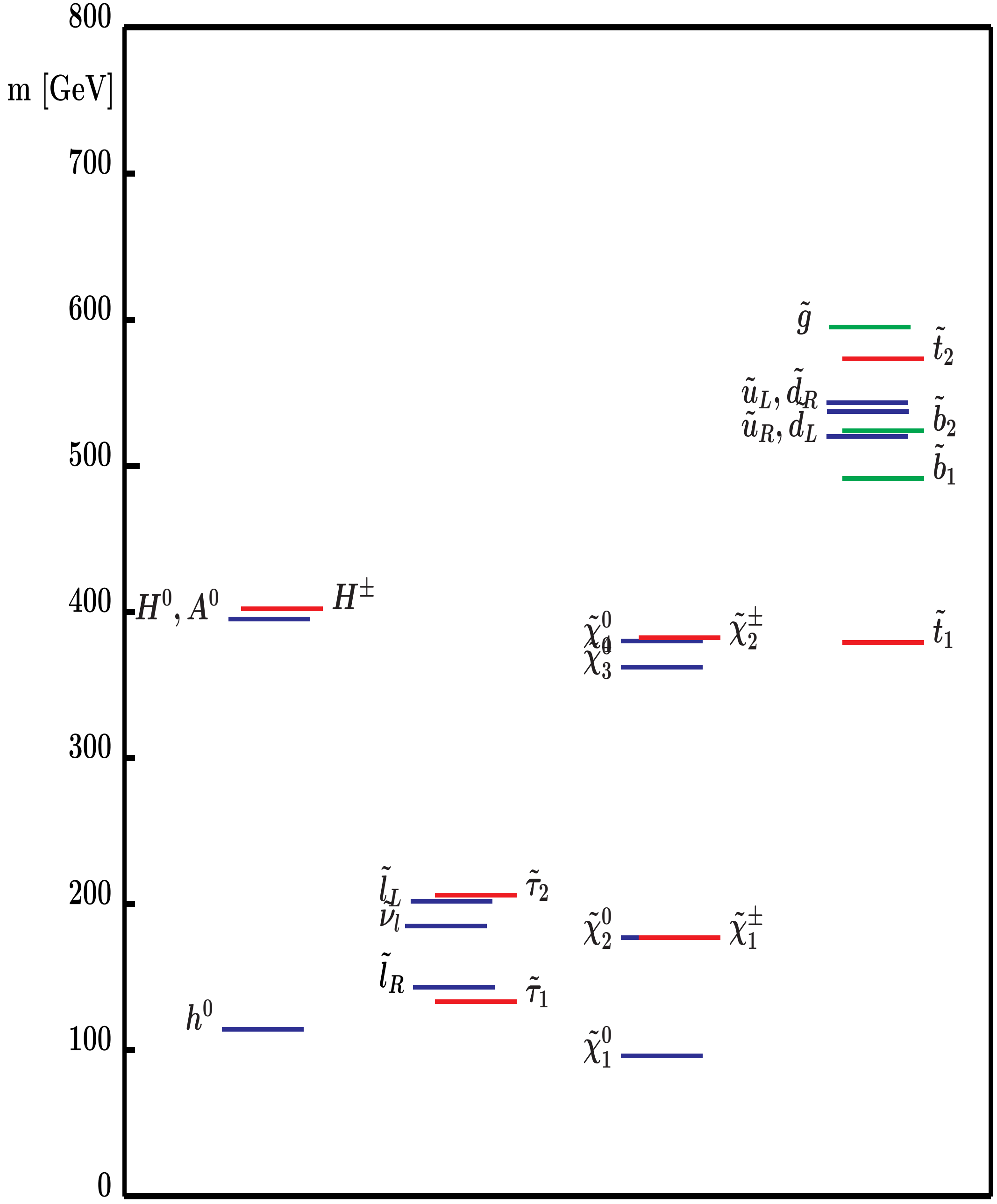
Any inference from one sector to the other is strongly model dependent!

"Typical" CMSSM scenario

(SPS 1a benchmark scenario):

SPS home page:

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



Free parameters in the MSSM

- mass matrices are 3 x 3 hermitian

  → $m^2_{\tilde Q}$, $m^2_{\tilde u}$, $m^2_{\tilde d}$, $m^2_{\tilde L}$, $m^2_{\tilde e}$: 45 parameters

- gaugino masses M_1, M_2, M_3 are complex numbers: 6
- trilinear couplings a_u, a_d, a_e are 3 x 3 complex matrices: 54
- bilinear coupling b is 2 x 2 matrix: 4
- Higgs masses m^2_{Hu}, m^2_{Hd} : 2

  → altogether 111 parameter ???

Symmetries (lepton + baryon number, Peccei-Quinn, R symmetry) lead to'rotations':

-4 non-trivial field redifinitions

-2 in the Higgs sector (since minimal model only 2 parameters in the Higgs sector)

→ **remain 105 free new parameters in the MSSM!**

LHC4TSP, CERN, 2.9.2011 G. Moortgat-Pick 4

SUSY breaking

`Hidden sector':	→	Visible sector:
SUSY breaking		MSSM

` Gravity-mediated': mSUGRA

`Gauge-mediated': GMSB

`Anomaly-mediated': AMSB

.....

- **SUGRA:** mediating interactions are gravitational m_0, $m_{1/2}$, $\tan\beta$, A_0, sign(μ)
- **GMSB:** mediating interactions are ordinary electroweak and QCD gauge interactions Λ, M_{mess}, N_{mess}, $\tan\beta$, sign(μ)
- **AMSB:** SUSY breaking happens on a different brane in a higher-dimensional theory m_0, m_{aux}, $\tan\beta$, sign(μ)

- Feature of schemes: lead to 'characteristic' mass spectra

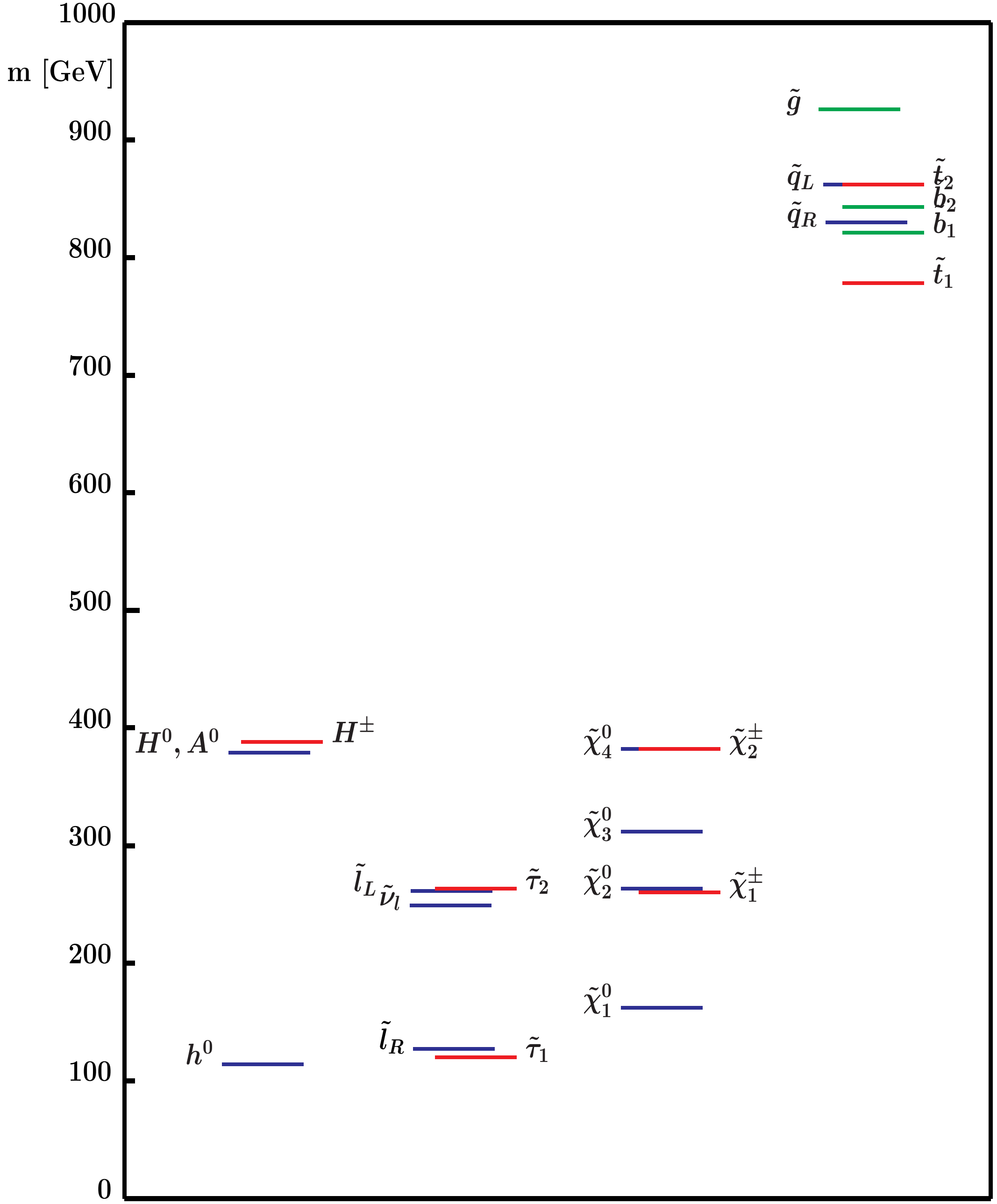
"Typical" GMSB scenario

(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`

<u>One</u> possible example
for natural larger splitting
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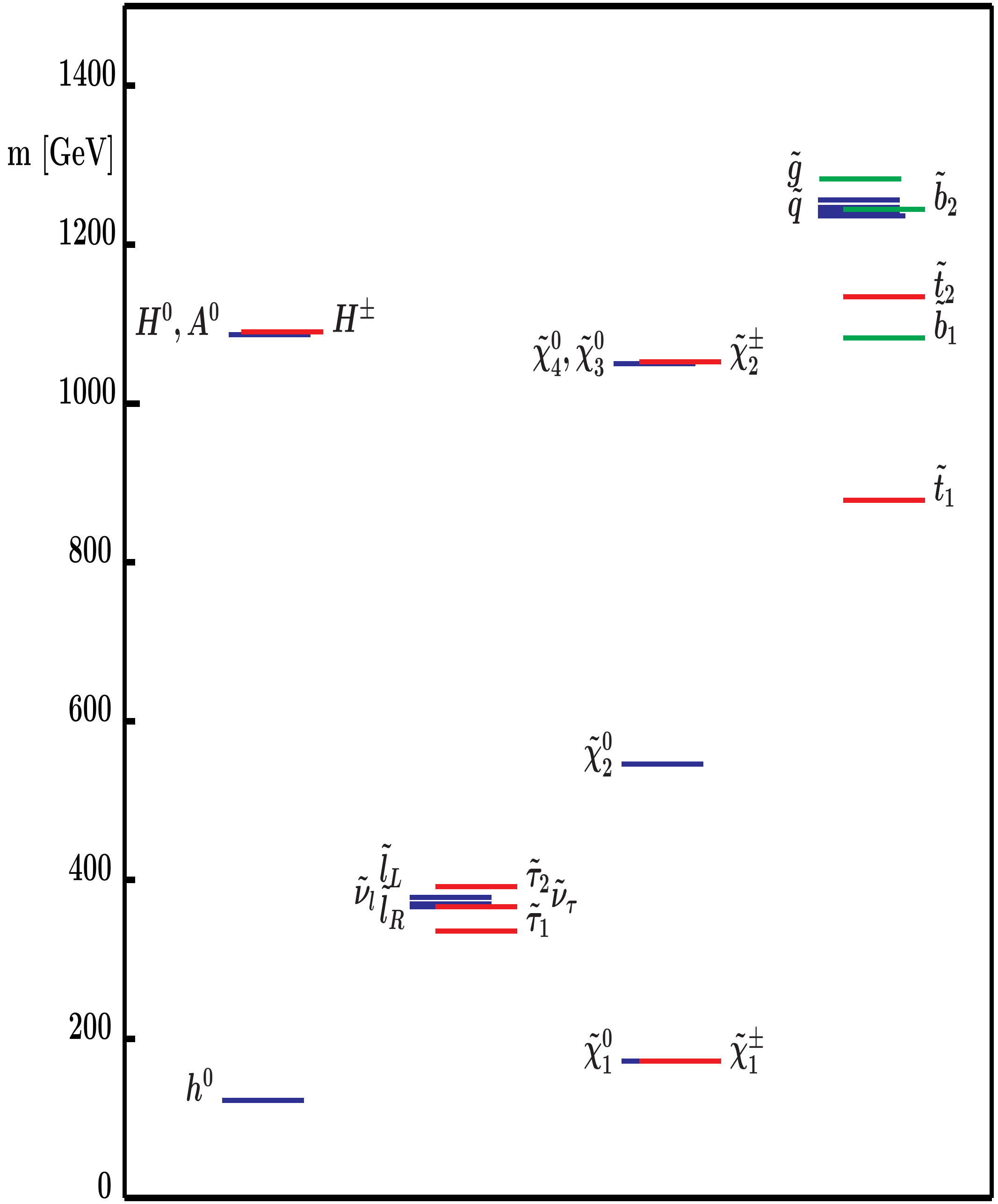
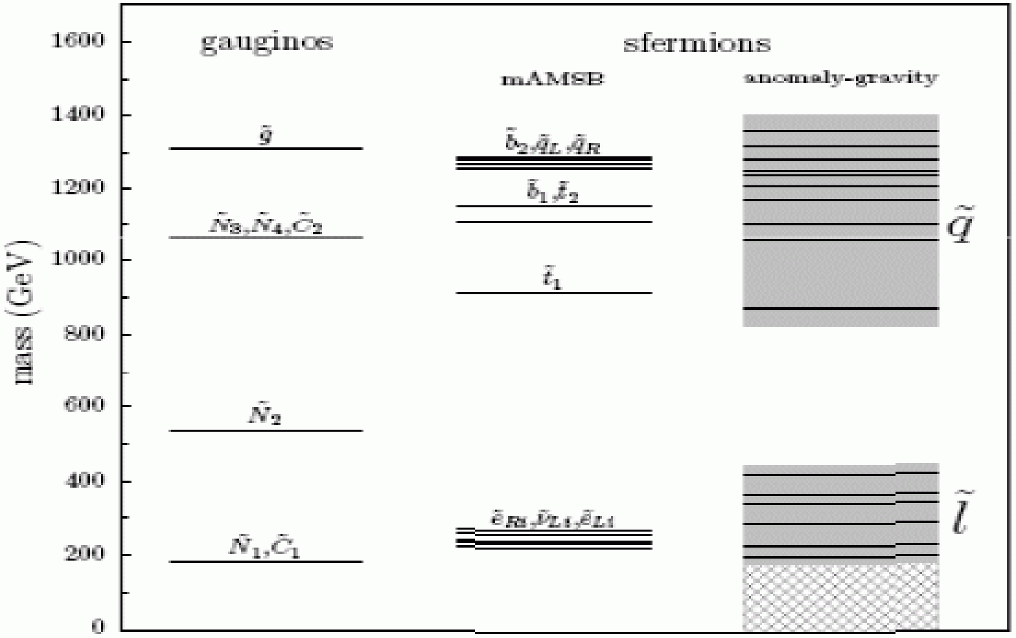
uncolored sector



New SUSY breaking developments

- For instance, hybrid models: flavourful anomaly-gravity mediation



C. Gross, G. Hiller, arXiv: 1101.5352

- heavy coloured sector
- 'light' electroweak sector

Further advantages:

- no tachions due to flavour dependence
- heavy gravitino: benefitial for cosmology

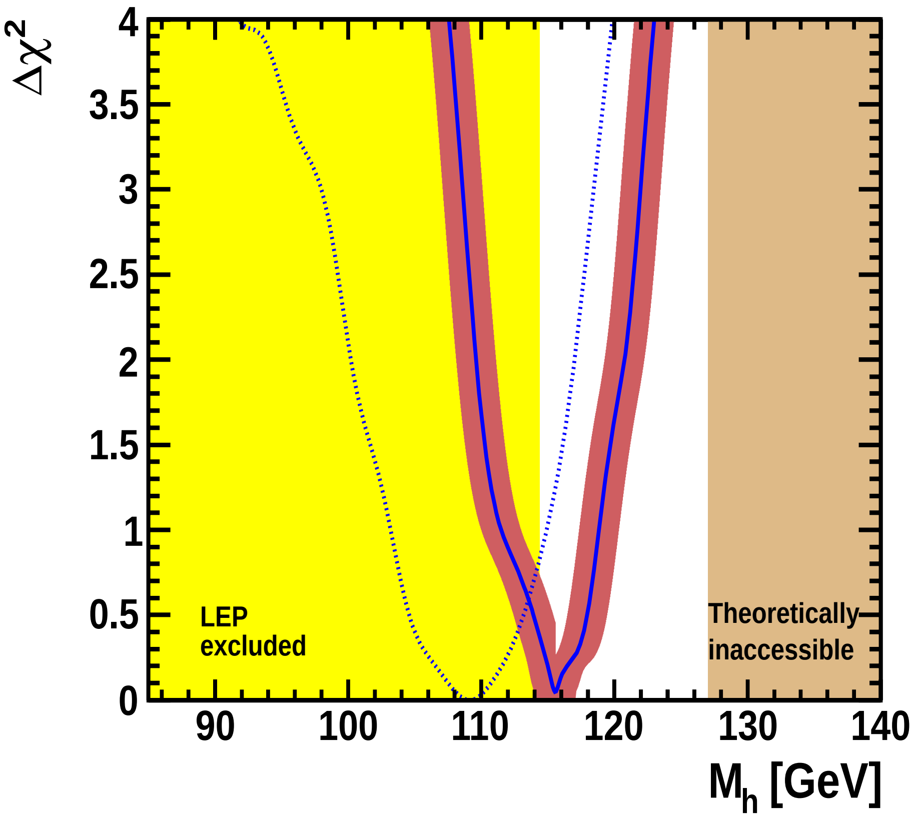
Not yet many phenomenolgy studies available ....

SFB Block Meeting, 24.2.2011 'B1 (List, Moortgat-Pick)' 9

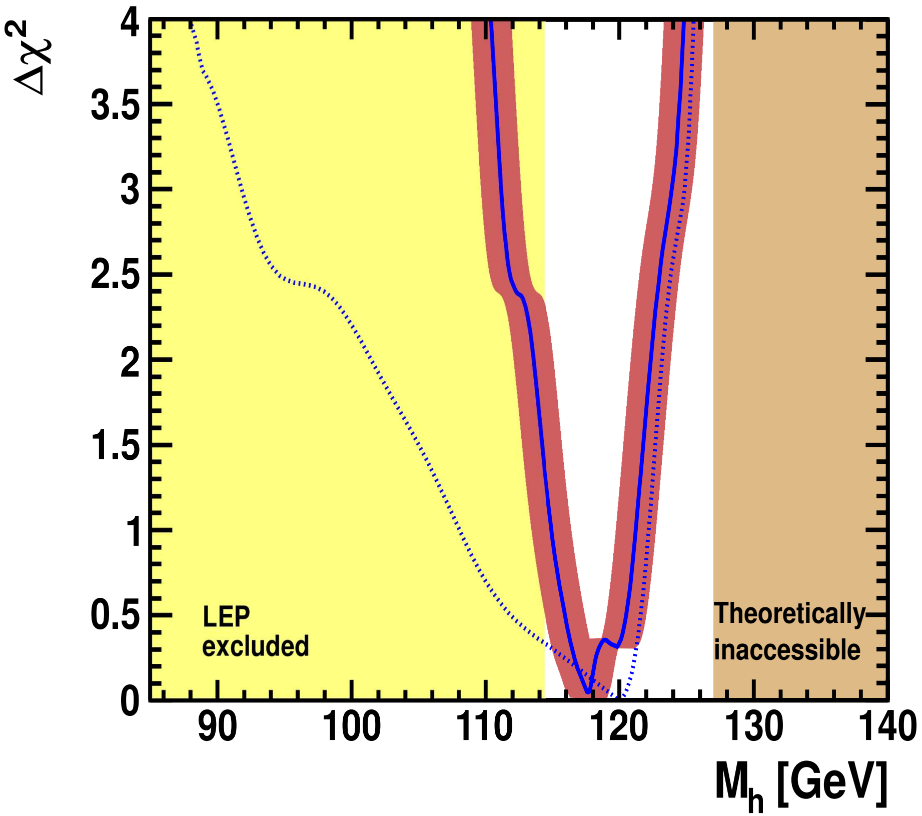
M_h prediction: post-LHC (35 pb^{-1}) red band plot:

[2011]

CMSSM



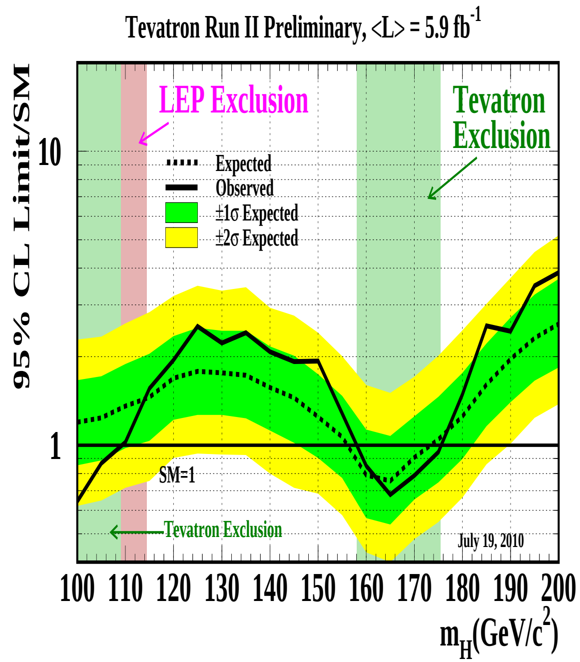
NUHM1

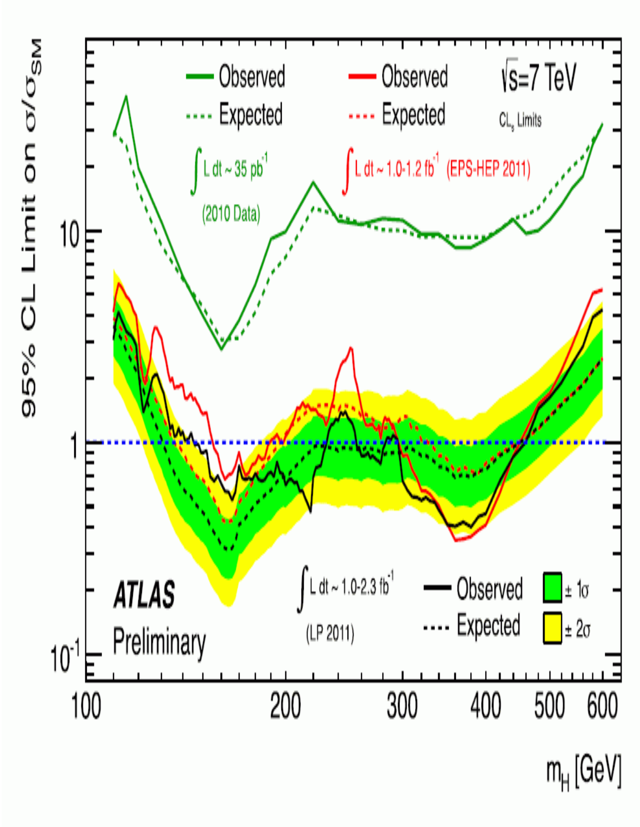


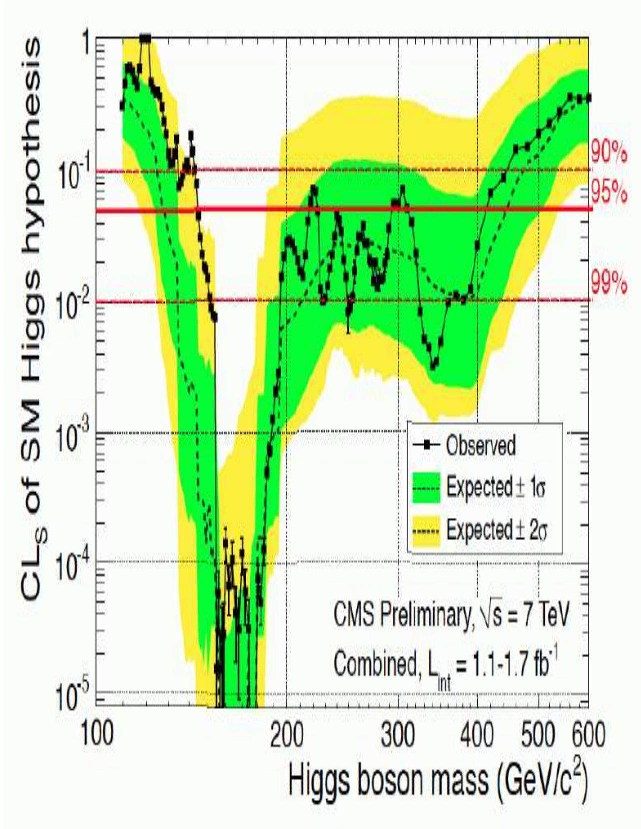
$M_h = 116 \pm 4\,(\text{exp}) \pm 1.5(\text{theo})$ GeV $118 \pm 3\,(\text{exp}) \pm 1.5(\text{theo})$ GeV

$\Rightarrow$ LEP bounds evaded! Light MSSM Higgs looks very good!

Direct Higgs searches at Tevatron and LHC:







⇒ everything points towards a low mass Higgs

⇒ low energy e^+e^+ collider IDEAL to study this scenario

We have to be prepared!

4. Conclusinos

- SUSY is (still) my (our?) best bet for physics beyond the SM

- Precision observables allow to make

- Crucial new ingredient: direct LHC searches
  $\Rightarrow$ predictions for SUSY/Higgs masses and parameters

- Our tool: MasterCode: EWPO, BPO, CDM, LHC, . . .

- 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!

- Everything points towards a low mass Higgs boson

I

I$_{\text{DEAL}}$LC is the IDEAL machine to study this scenario!