Does the LHC exclude SUSY Particles at the ILC?

Sven Heinemeyer, IFCA (CSIC, Santander)

Tokyo, 11/2013

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NO!

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1. Introduction

2. Messages from Electoweak precision observables

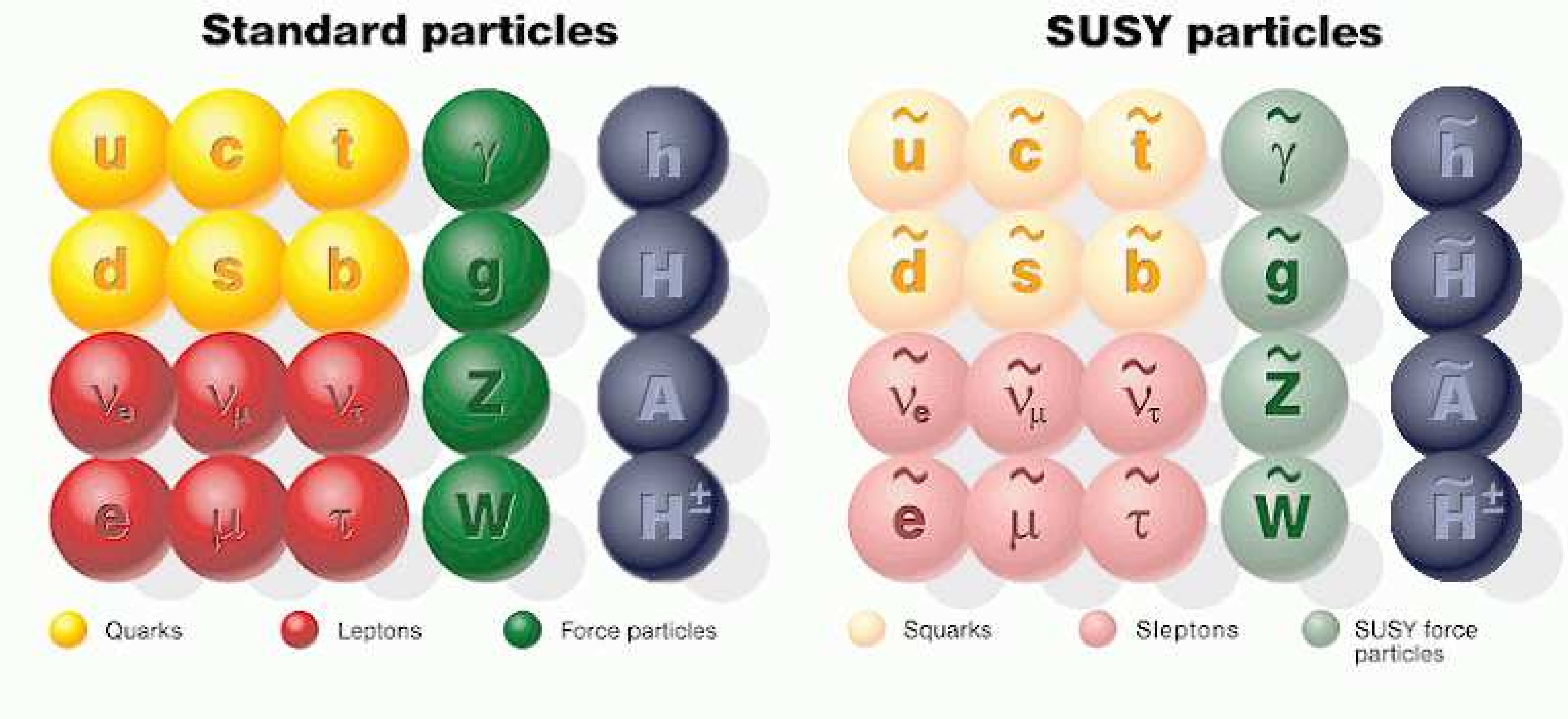
3. What does the LHC exclude?

4. Conclusions

1. Introduction

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



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

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

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

Input parameters: (to be determined experimentally)

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

Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

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

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

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

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

2 $\mathcal{CP}$-violating phases: ξ, arg(m_{12}) $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2$$

Complex parameters:

- μ : Higgsino mass parameter
- $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b} - \mu^*\{\cot\beta\,, \tan\beta\}$ complex
- $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)
- $m_{\tilde{g}}$: gluino mass

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

Effects of complex parameters in the Higgs sector:

Complex parameters enter via loop corrections:

Result:

$$(A, H, h) \to (h_3, h_2, h_1(= \phi))$$

with

$$M_{h_3} > M_{h_2} > M_{h_1}$$

Neutralinos and charginos:

Higgsinos and electroweak gauginos mix

charged:

$$\tilde{W}^{+}, \tilde{h}_u^{+} \to \tilde{\chi}_1^{+}, \tilde{\chi}_2^{+}, \qquad \tilde{W}^{-}, \tilde{h}_d^{-} \to \tilde{\chi}_1^{-}, \tilde{\chi}_2^{-}$$

$\Rightarrow$ charginos: mass eigenstates

mass matrix given in terms of M_2, μ, $\tan\beta$

neutral:

$$\underbrace{\tilde{\gamma}, \tilde{Z},}_{\tilde{W}^0, \tilde{B}^0} \tilde{h}_u^0, \tilde{h}_d^0 \to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

$\Rightarrow$ neutralinos: mass eigenstates

mass matrix given in terms of M_1, M_2, μ, $\tan\beta$

$\Rightarrow$ only one new parameter

$\Rightarrow$ MSSM predicts mass relations between neutralinos and charginos

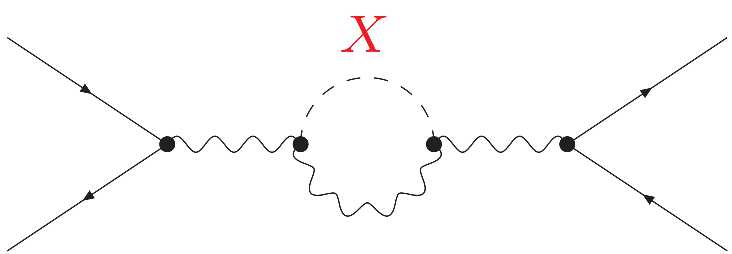
2. Messages from Electroweak Precision Observables

Comparison of electro-weak precision observables with theory:

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

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. M_X



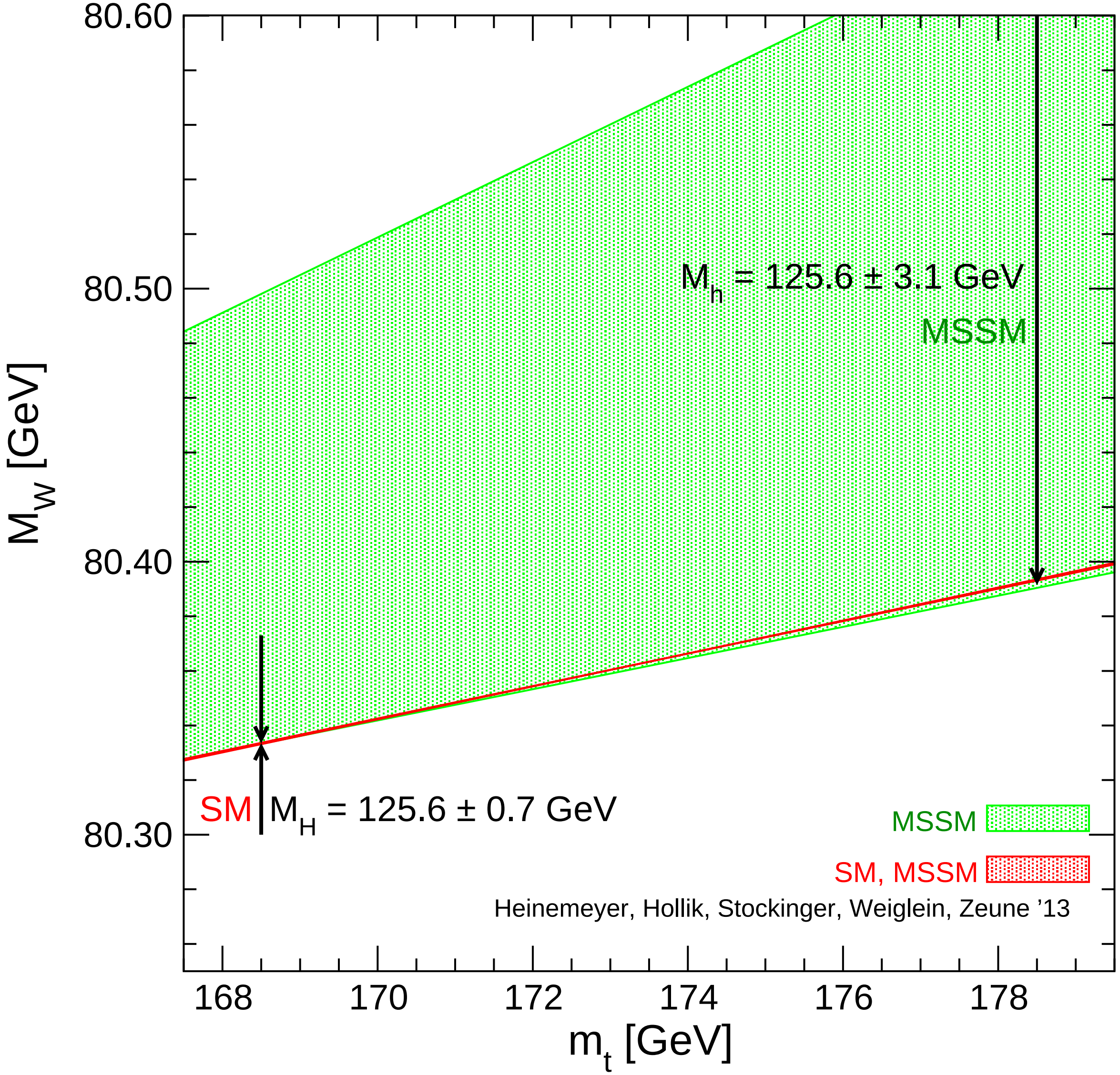
$\Downarrow$

MSSM: limits on M_X

Very high accuracy of measurements and theoretical predictions needed

Prediction for M_W in the SM and the MSSM :

[*S.H., W. Hollik, D. Stockinger, G. Weiglein, L. Zeune '13*]



MSSM band:
scan over
SUSY masses

SM band/overlap:
SM is MSSM-like
MSSM is SM-like

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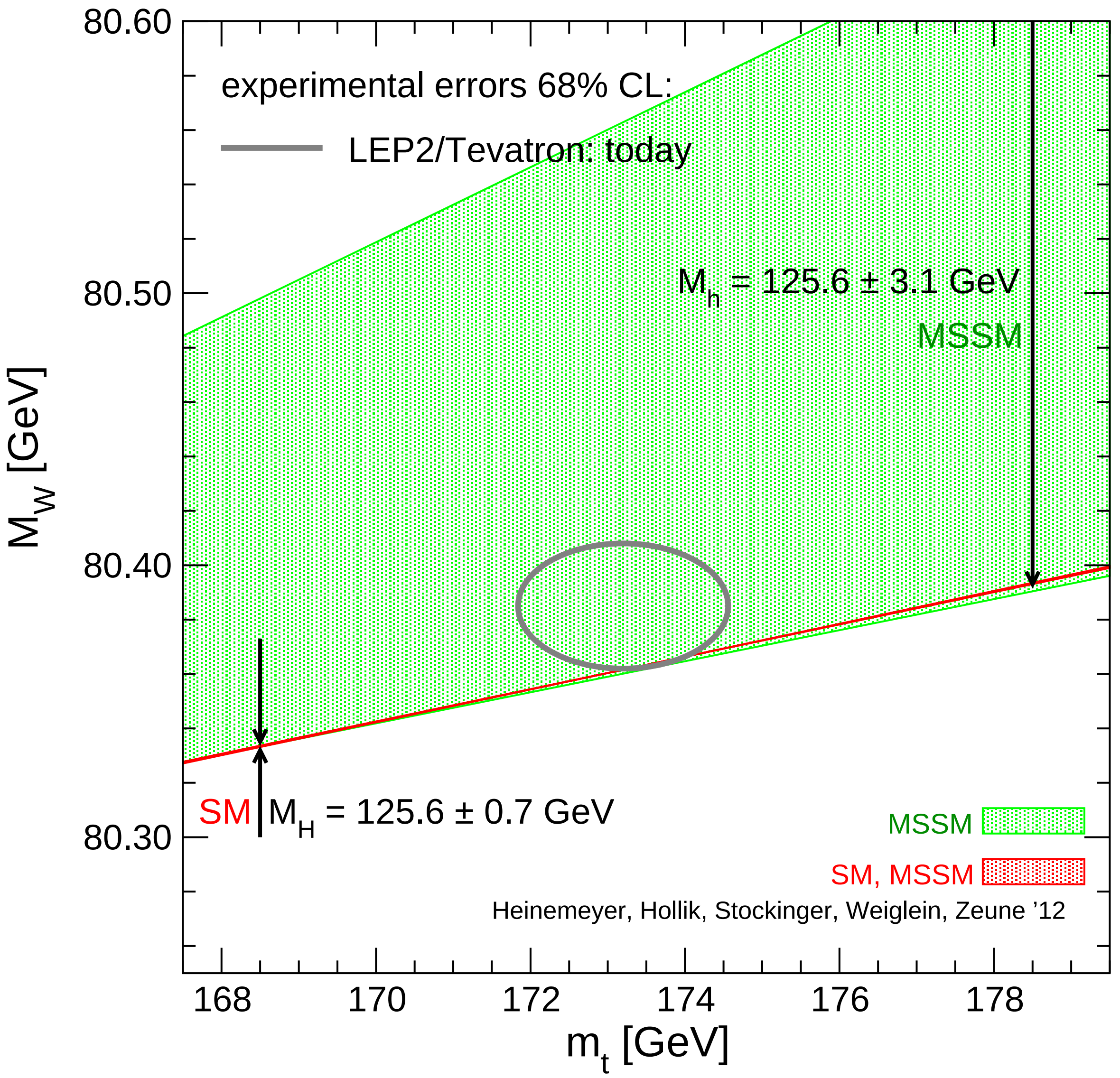

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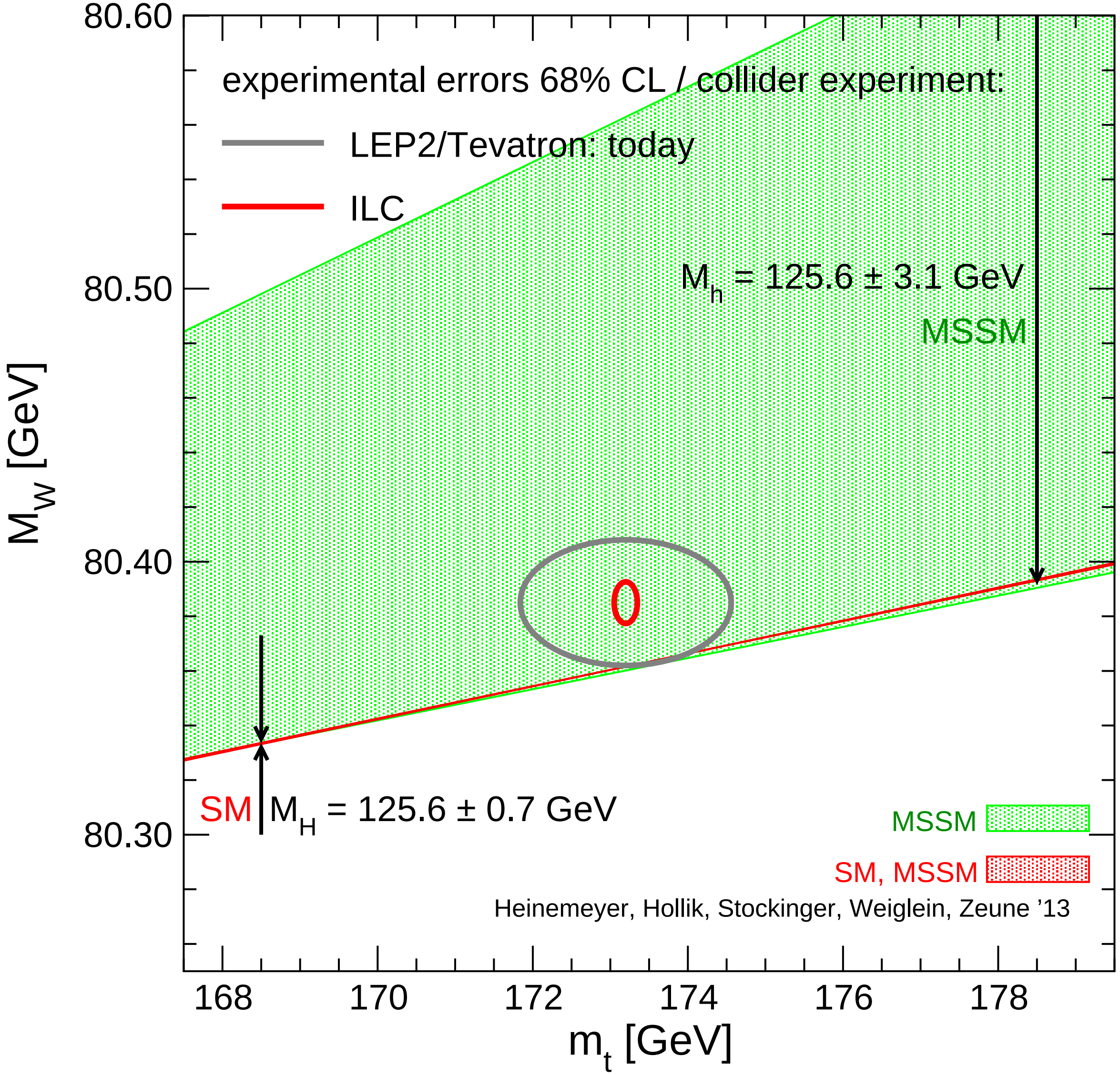

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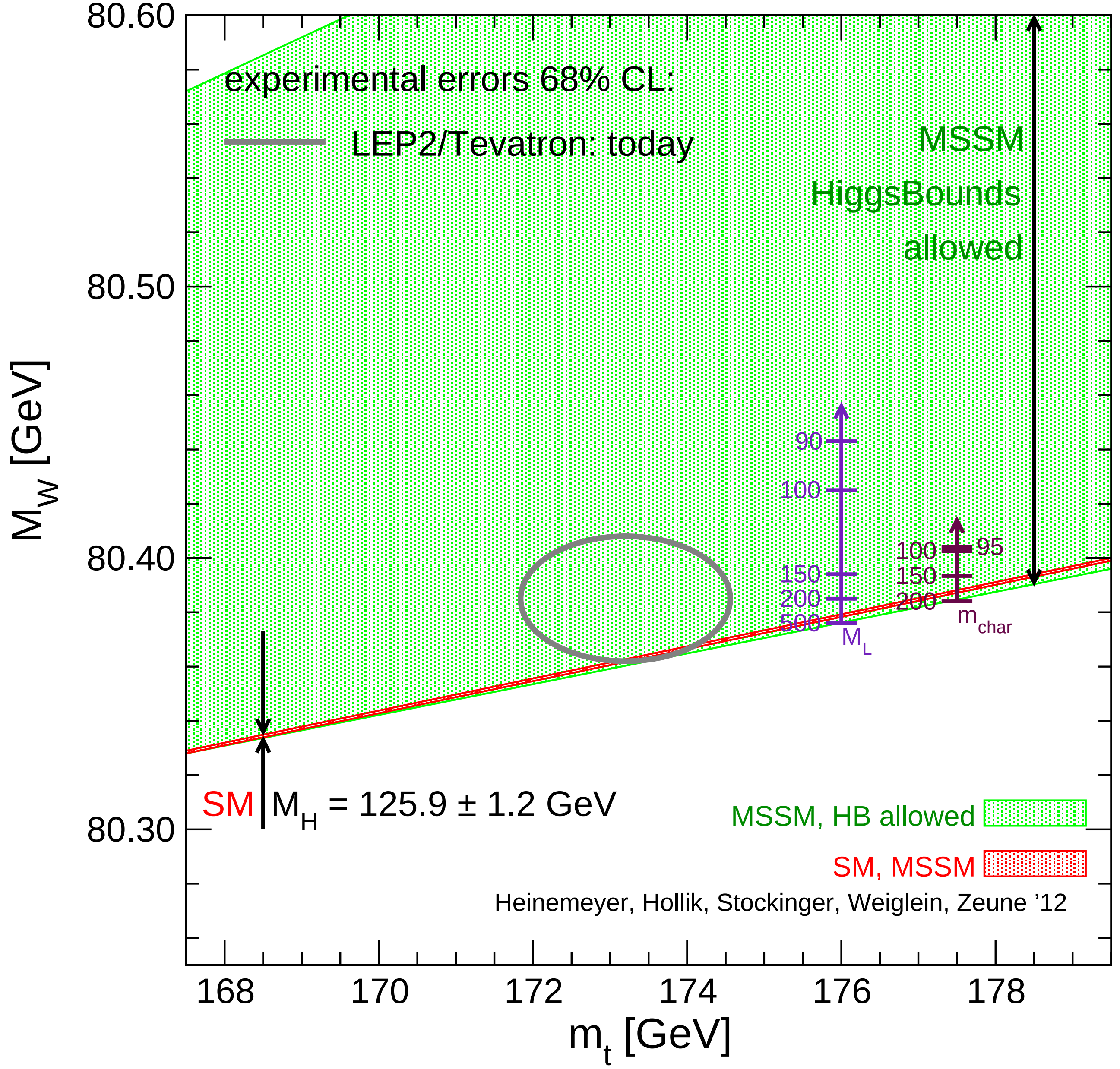
Effects of charginos and staus: [S.H., W. Hollik, G. Weiglein, L. Zeune '13]



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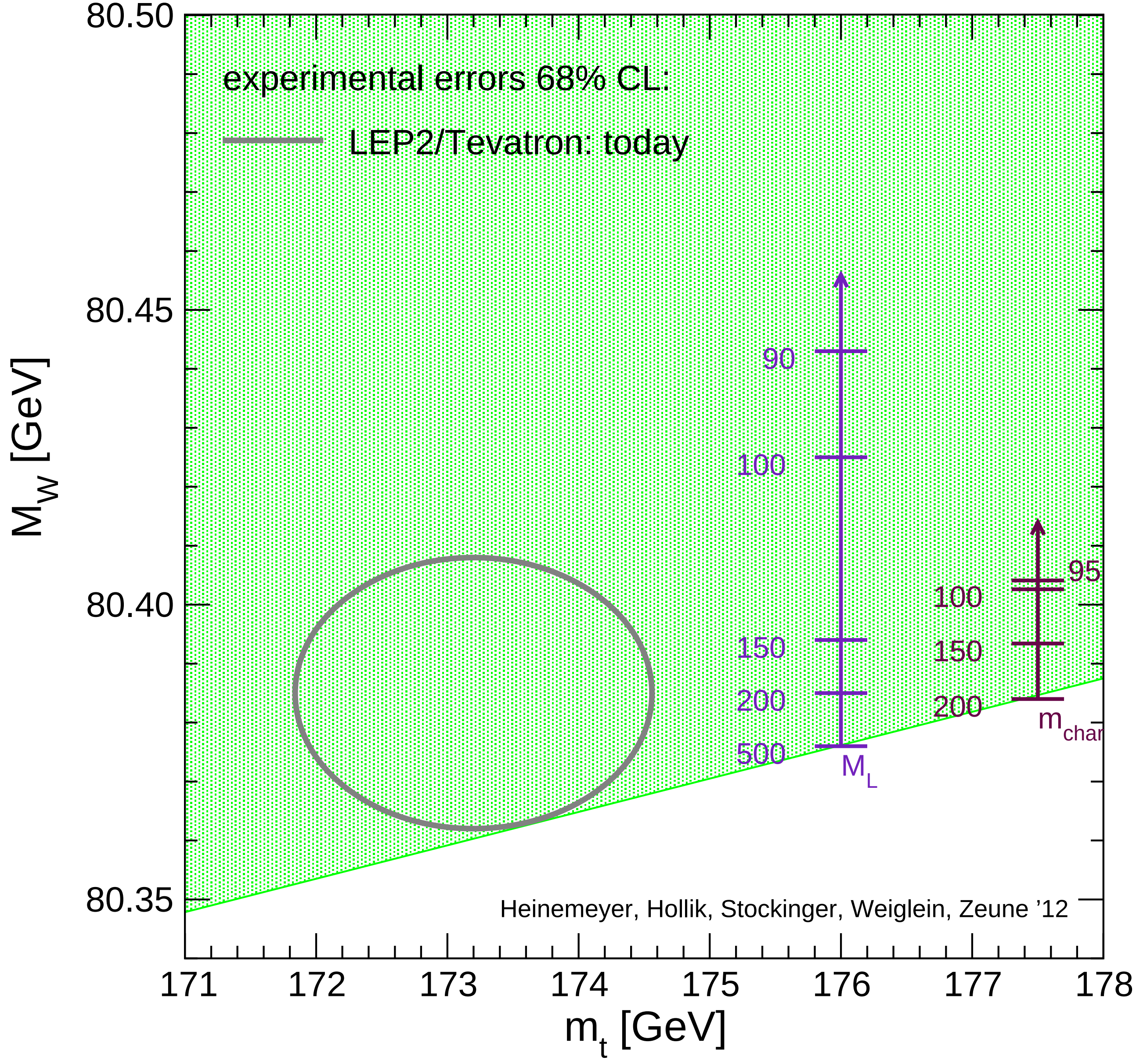
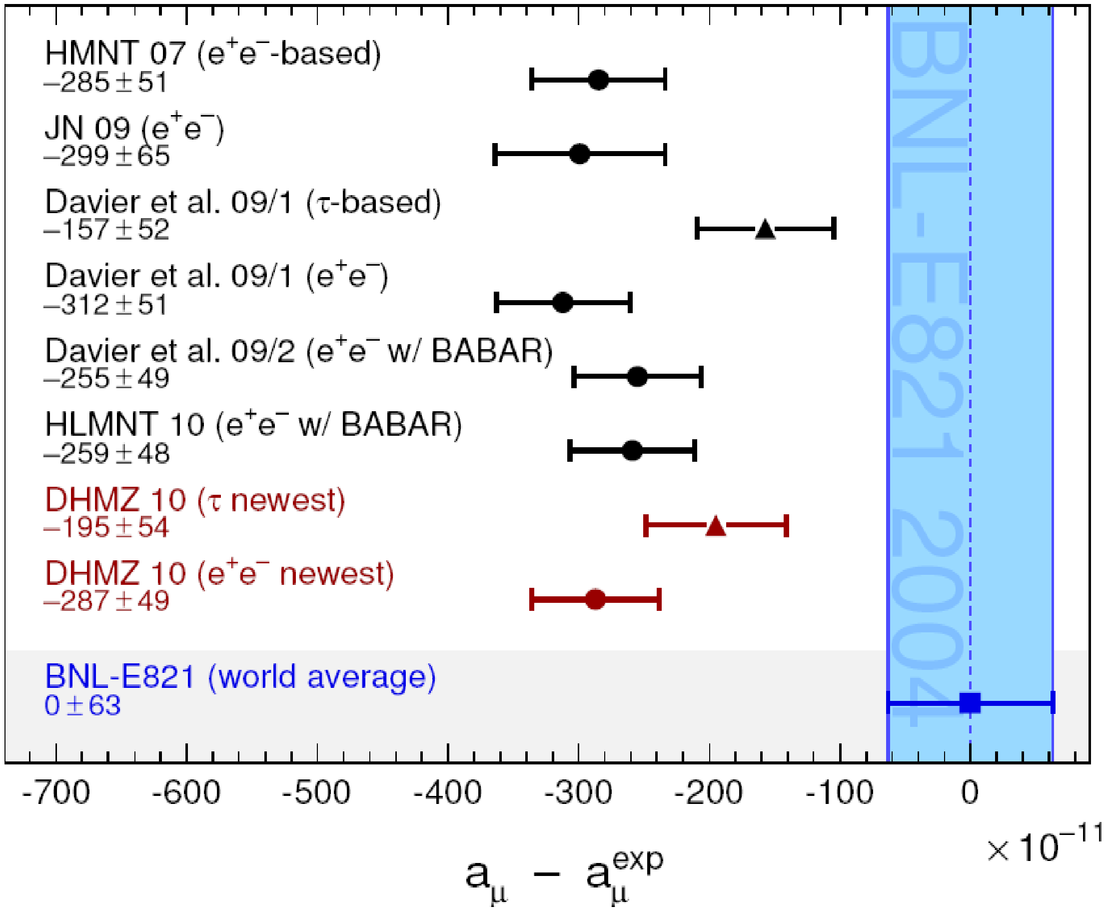


The anomalous magnetic moment of the muon

$$a_\mu \equiv (g-2)_\mu/2$$

Overview about the current experimental and SM (theory) result:

[*M. Davier, A. Hoecker, B. Malaescu, Z. Zhang '10*] $\to$ T



$$a_\mu^{\rm exp} - a_\mu^{\rm theo,SM} \approx (28.7 \pm 8) \times 10^{-10} \quad : \; 3.6\,\sigma$$

Most recent development for τ data:

[F. Jegerlehner, R. Szafron '10]

[M. Benayoun, P. David, L. DelBuono, F. Jegerlehner '11, '12]

Re-evaluation of τ data:

– improved evaluation of ρ–γ mixing

– some other (so far neglected) effects

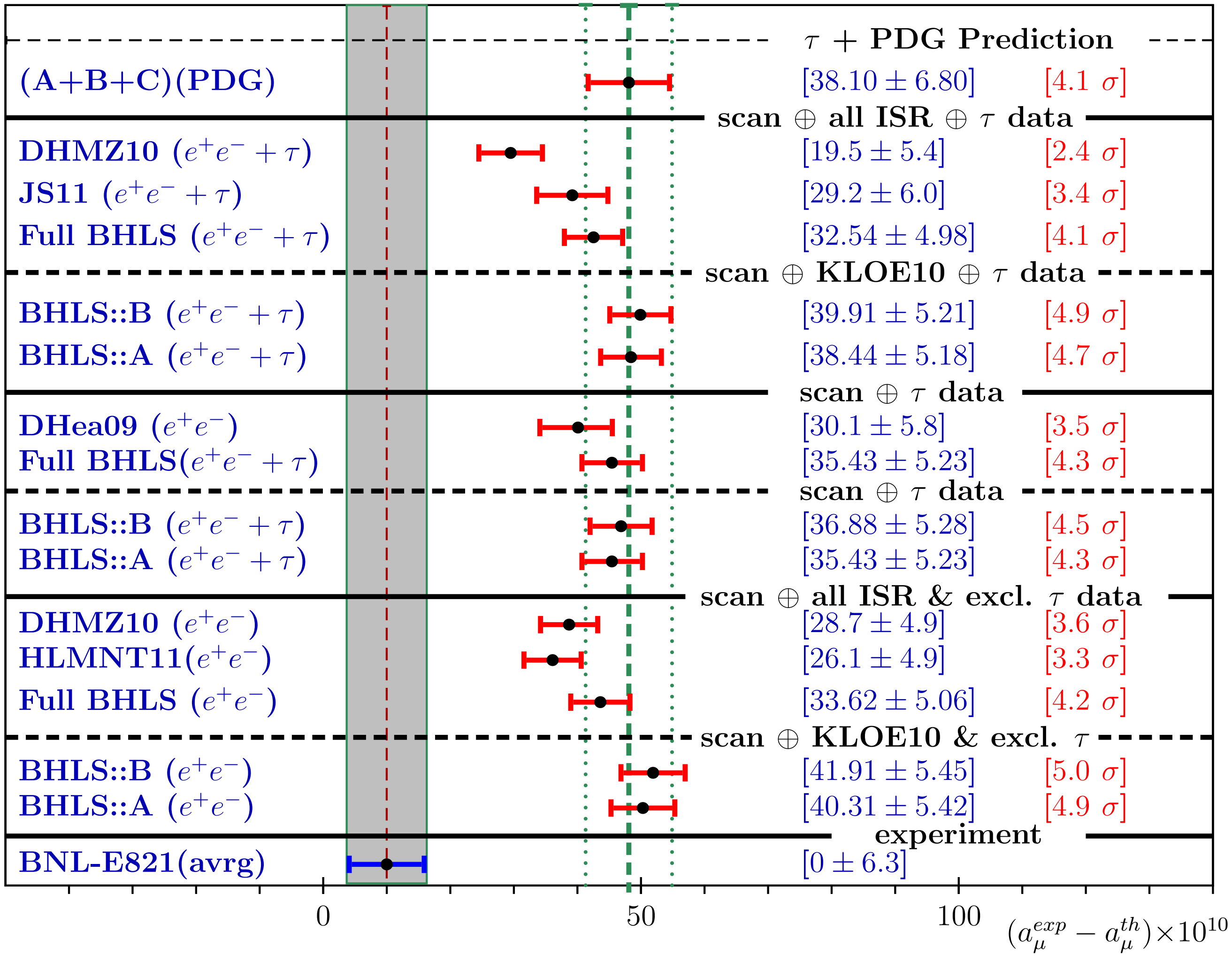
$\Rightarrow$ shift in τ data:

Now: agreement with e^+e^- data! $\Rightarrow$ still tbc!

If correct: $\Rightarrow$ new average of all data possible . . .

New overview:

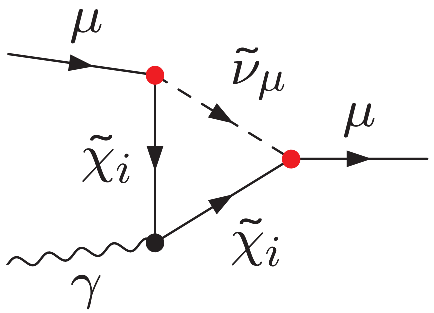
[*M. Benayoun, P. David, L. DelBuono, F. Jegerlehner '12*]

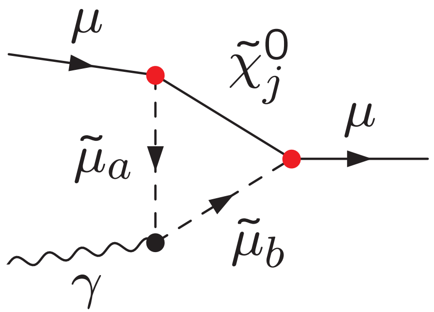


⇒ more than 4 σ deviation!

SUSY can easily explain the deviation:

Feynman diagrams for MSSM 1L corrections:





- Diagrams with chargino/sneutrino exchange
- Diagrams with neutralino/smuon exchange

Enhancement factor as compared to SM:

$$\mu - \tilde{\chi}^\pm_i - \tilde{\nu}_\mu \quad : \quad \sim m_\mu \tan\beta$$
$$\mu - \tilde{\chi}^0_j - \tilde{\mu}_a \quad : \quad \sim m_\mu \tan\beta$$

SM, EW 1L: $\frac{\alpha}{\pi} \frac{m_\mu^2}{M_W^2}$

MSSM, 1L: $\frac{\alpha}{\pi} \frac{m_\mu^2}{M_{\text{SUSY}}^2} \times \tan\beta$

SUSY corrections at 1L:

$$a_\mu^{\mathrm{SUSY,1L}} \approx 13 \times 10^{-10} \left(\frac{100 \text{ GeV}}{M_{\mathrm{SUSY}}}\right)^2 \tan\beta \,\mathrm{sign}(\mu)$$

$M_{\mathrm{SUSY}}(= m_{\tilde{\mu}} = m_{\tilde{\nu}} = m_{\tilde{\chi}})$: generic SUSY mass scale

$$a_\mu^{\mathrm{SUSY,1L}} = (-100 \ldots + 100) \times 10^{-10}$$

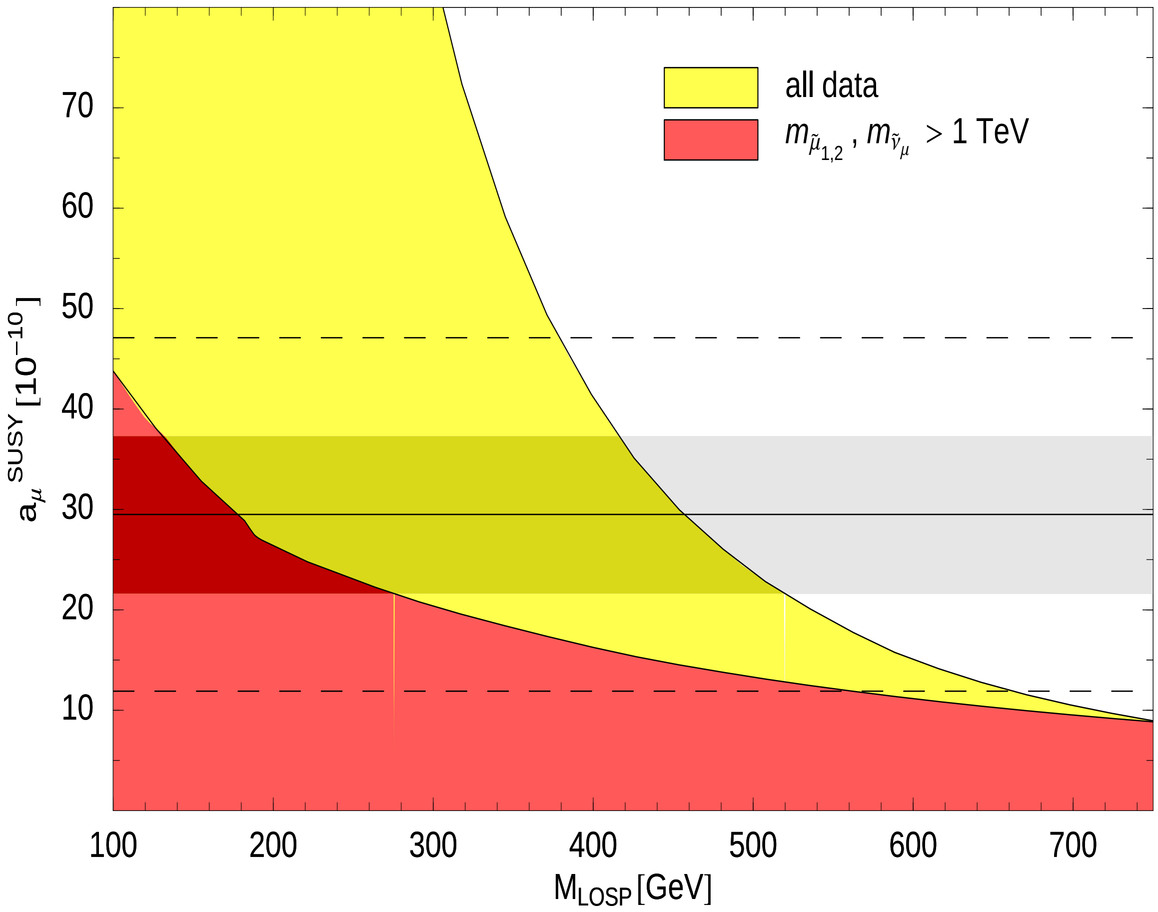
$$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{theo,SM}} \approx (28 \pm 8) \times 10^{-10}$$

⇒ SUSY could easily explain the "discrepancy"

⇒ a_μ can provide bounds on SUSY parameter space

(by requiering agreement at the 95% C.L.)

Example: Scan over SUSY parameter space



Scan over

μ, M_2, $m_{\tilde{\mu}}$, A_μ

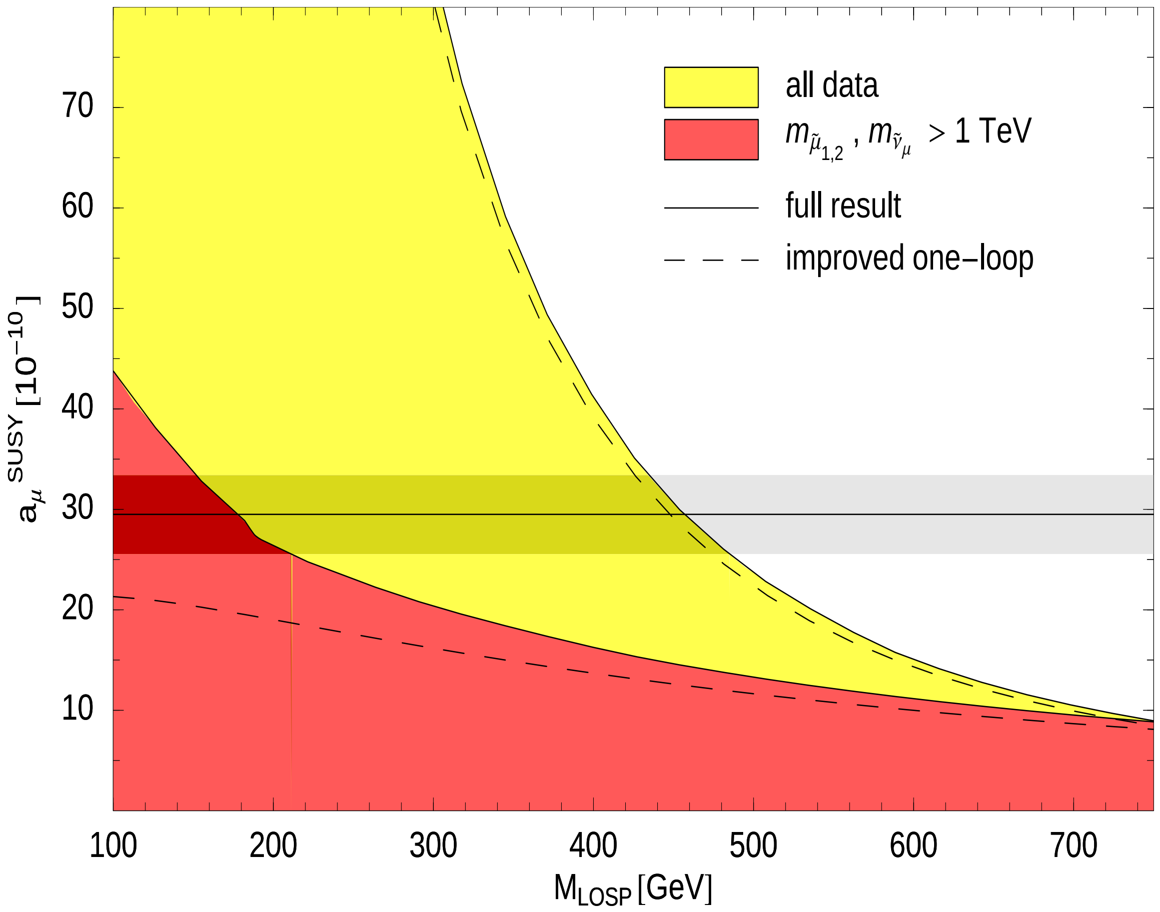
LOSP = lightest observable SUSY particle

LOSP = $\tilde{\mu}$ or $\tilde{\chi}$

[*D. Stöckinger '06*]

SUSY could easily explain discrepancy

New example: Scan over SUSY parameter space



Scan over

μ, M_2, $m_{\tilde{\mu}}$, A_μ

LOSP = lightest observable SUSY particle

LOSP = $\tilde{\mu}$ or $\tilde{\chi}$

[*D. Stöckinger '06*]

SUSY could easily explain discrepancy

With improved precision (and similar central value):

$\Rightarrow$ strong bounds on the MSSM parameter space

3. What does the LHC exclude?

Production of EW SUSY particles at the LHC:

$$pp \to \tilde{\chi}_1^{\pm}\,\tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\,\tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\,Z/h\tilde{\chi}_1^0$$

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Possible: production of Higgs bosons: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$, . . .

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Always: production of the lightest SUSY particle: $\tilde{\chi}_1^0$

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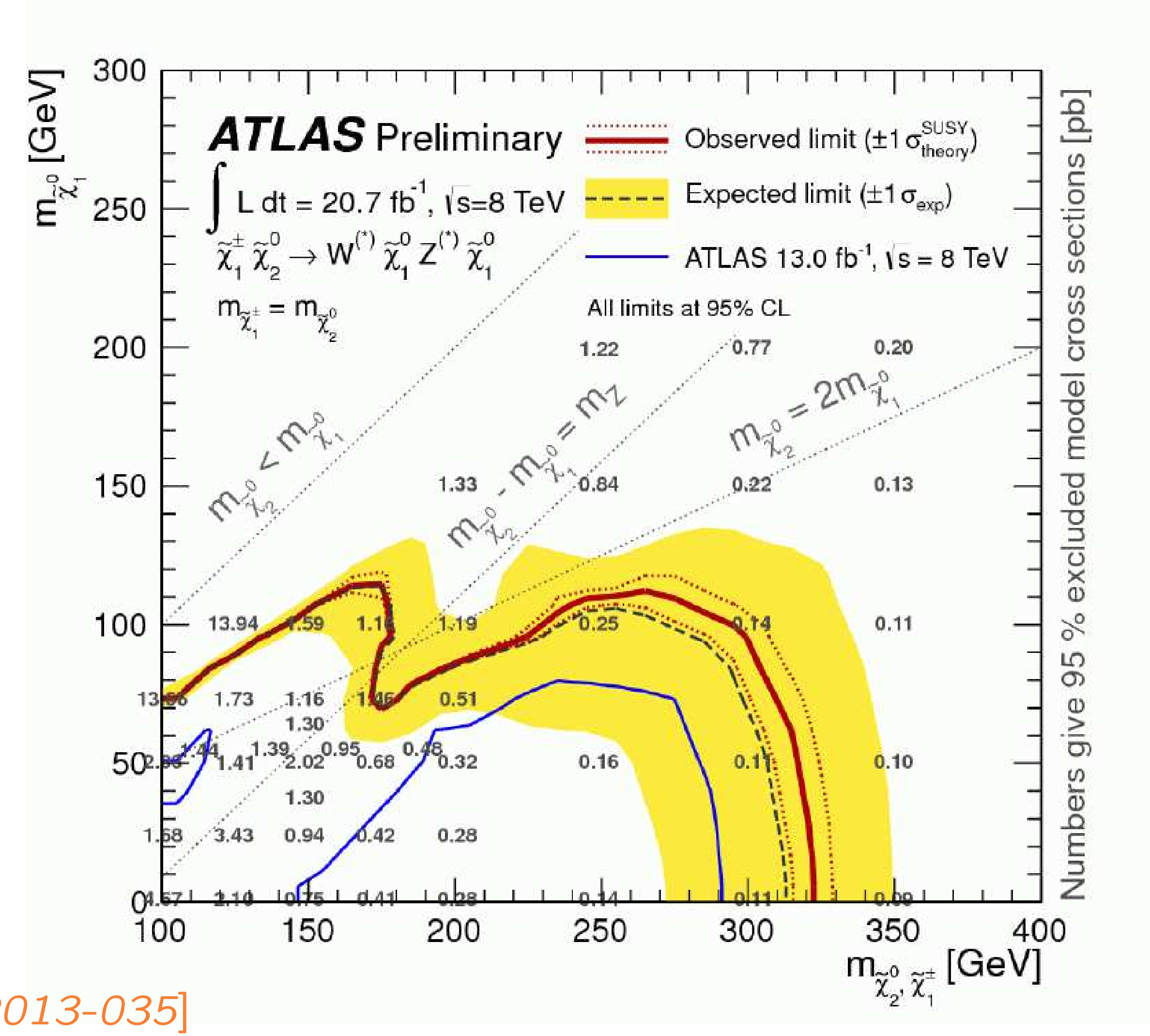
Always: production of the lightest SUSY particle: $\tilde{\chi}_1^0$

⇒ important source for information on Higgs, LSP

⇒ precision prediction (at least) of BR's necessary

Effects on SUSY exclusion regions

LHC is looking for $pp \to \tilde{\chi}_1^{\pm}\,\tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\,Z\tilde{\chi}_1^0$



[ATLAS-CONF-2013-035]

Assumptions in the limit setting:

– BR($\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$) = 1

$\Rightarrow$ largely correct due to kinematical constraints

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  NEVER correct, because $\tilde{\chi}_2^0 \to h \tilde{\chi}_1^0$ possible
  ⇒ include precision calculation of all relevant decay modes

Assumptions in the limit setting:

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  NEVER correct, because $\tilde{\chi}_2^0 \to h \tilde{\chi}_1^0$ possible
  $\Rightarrow$ include precision calculation of all relevant decay modes

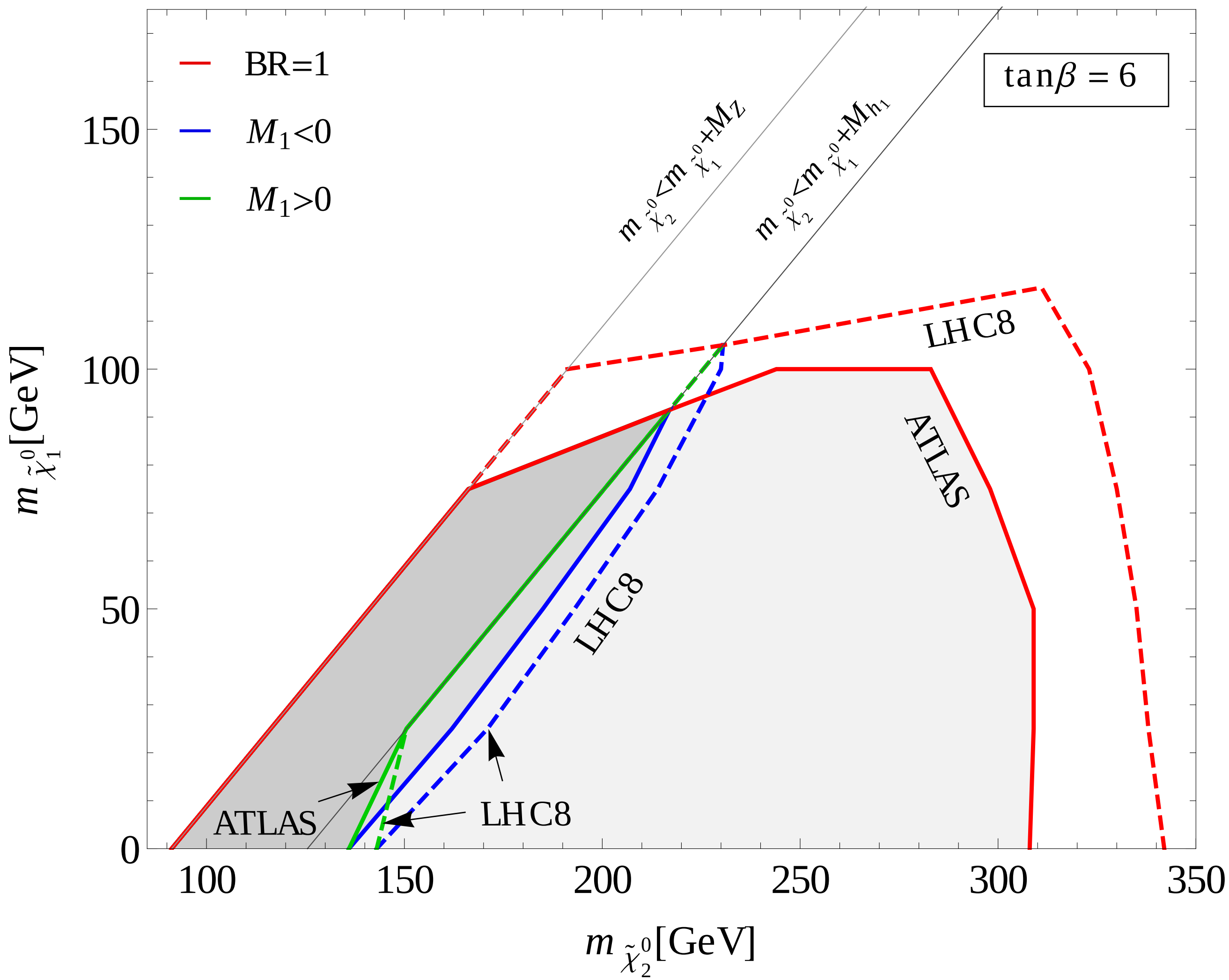
Procedure:

based on [*ATLAS-CONF-2013-035*]

- start with ATLAS scenario
  ($M_{\text{SUSY}} = 2000$ GeV, $\mu = 1000$ GeV, $\tan\beta = 6$) $\to$ vary M_2 and M_1
- use ATLAS result as cross section limit on $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production
- as ATLAS (and CMS): display results in $m_{\tilde{\chi}_2^0}$–$m_{\tilde{\chi}_1^0}$ plane
- compare ATLAS exclusion to "real" exclusion
  including precision calculation for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$
- vary parameters: phase of M_1, $\tan\beta$, . . .

Comparison of ATLAS vs. "real" exclusion (I)

[*A. Bharucha, S.H., F. v.d. Pahlen '13*]



$\Rightarrow$ huge reduction of exclusion region (where $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ allowed)

Comparison of ATLAS vs. "real" exclusion (II)

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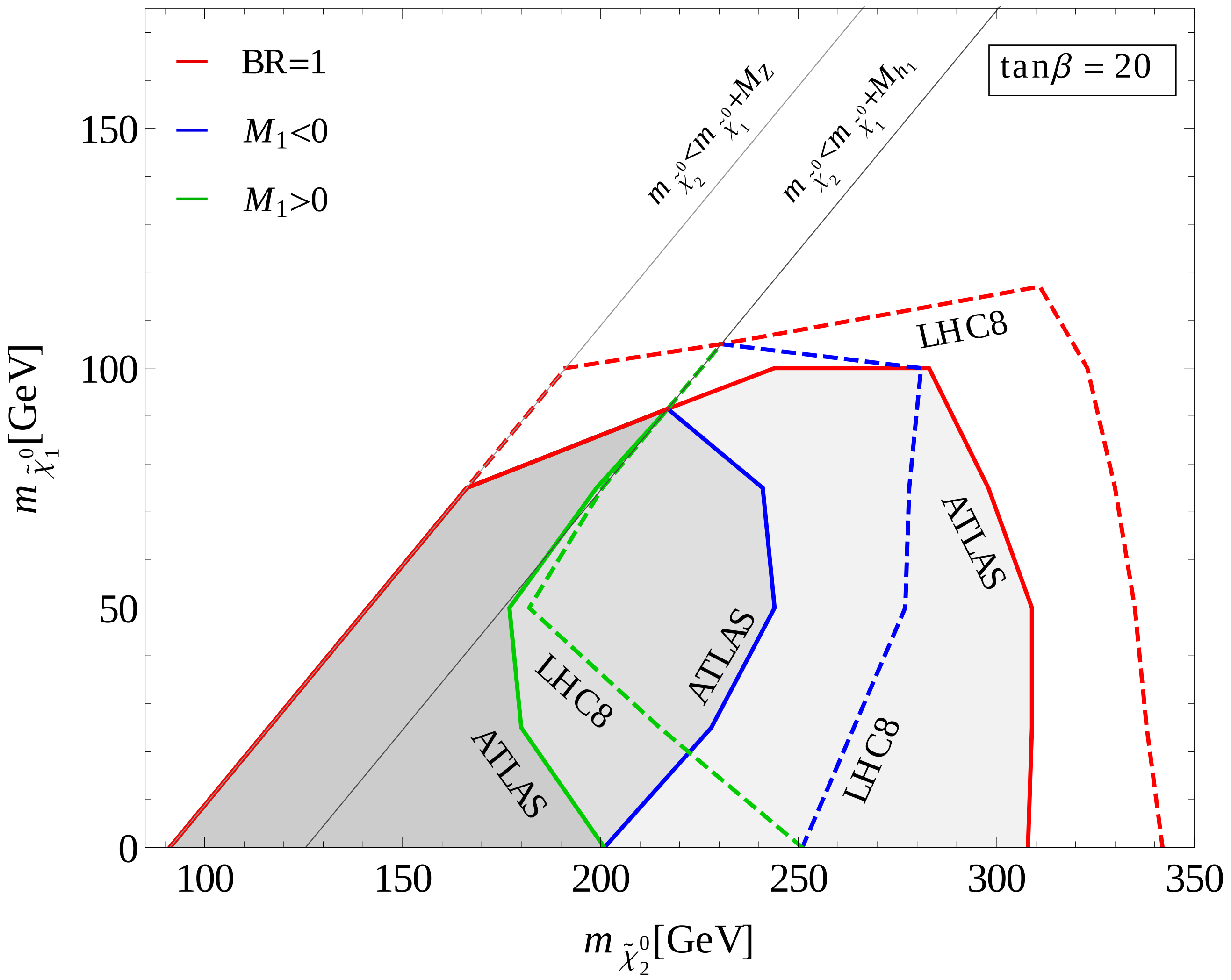
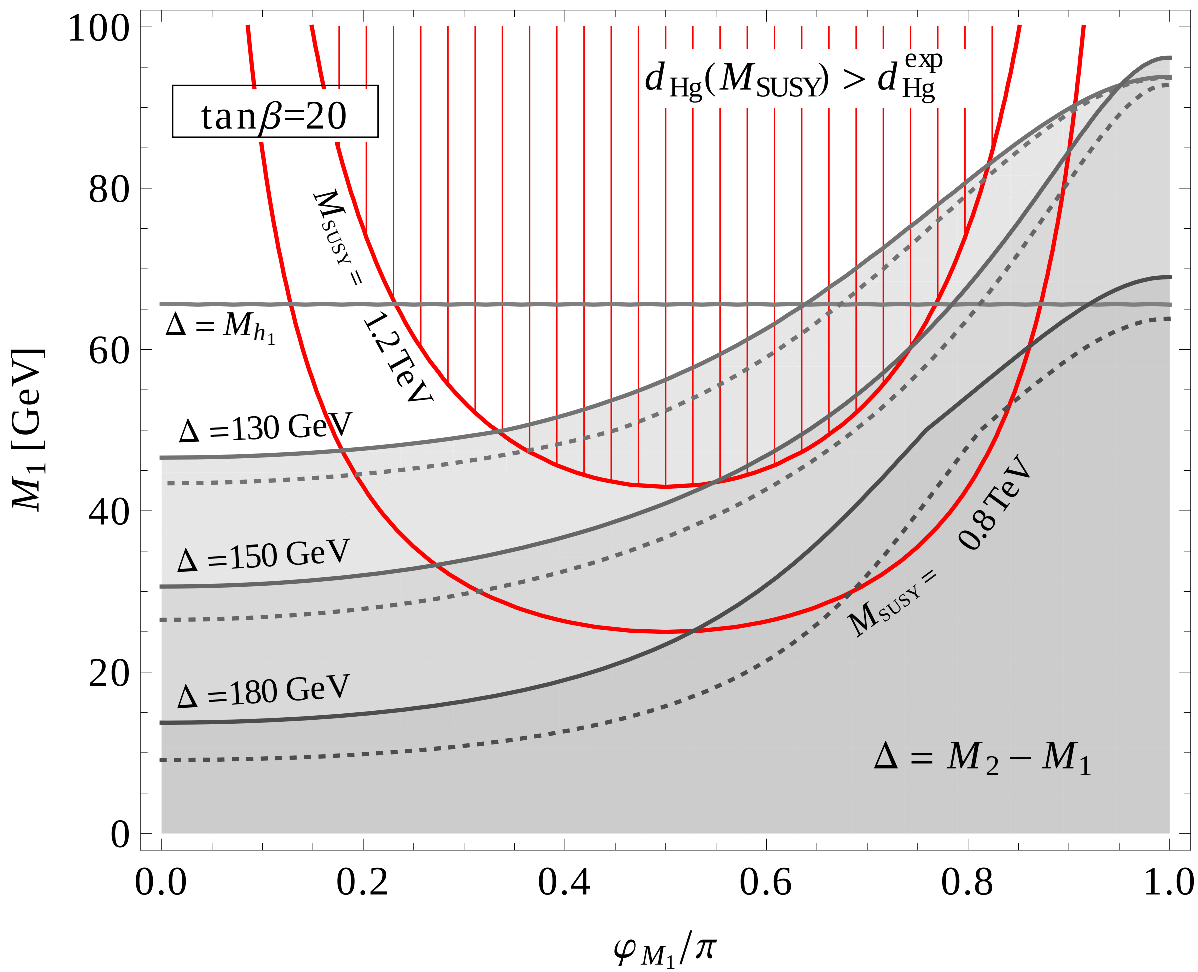


$\Rightarrow$ huge reduction of exclusion region (where $\tilde\chi_2^0 \to \tilde\chi_1^0 h$ allowed)

Effects of complex M_1 and higher-order corrections:

[A. Bharucha, S.H., F. v.d. Pahlen '13]



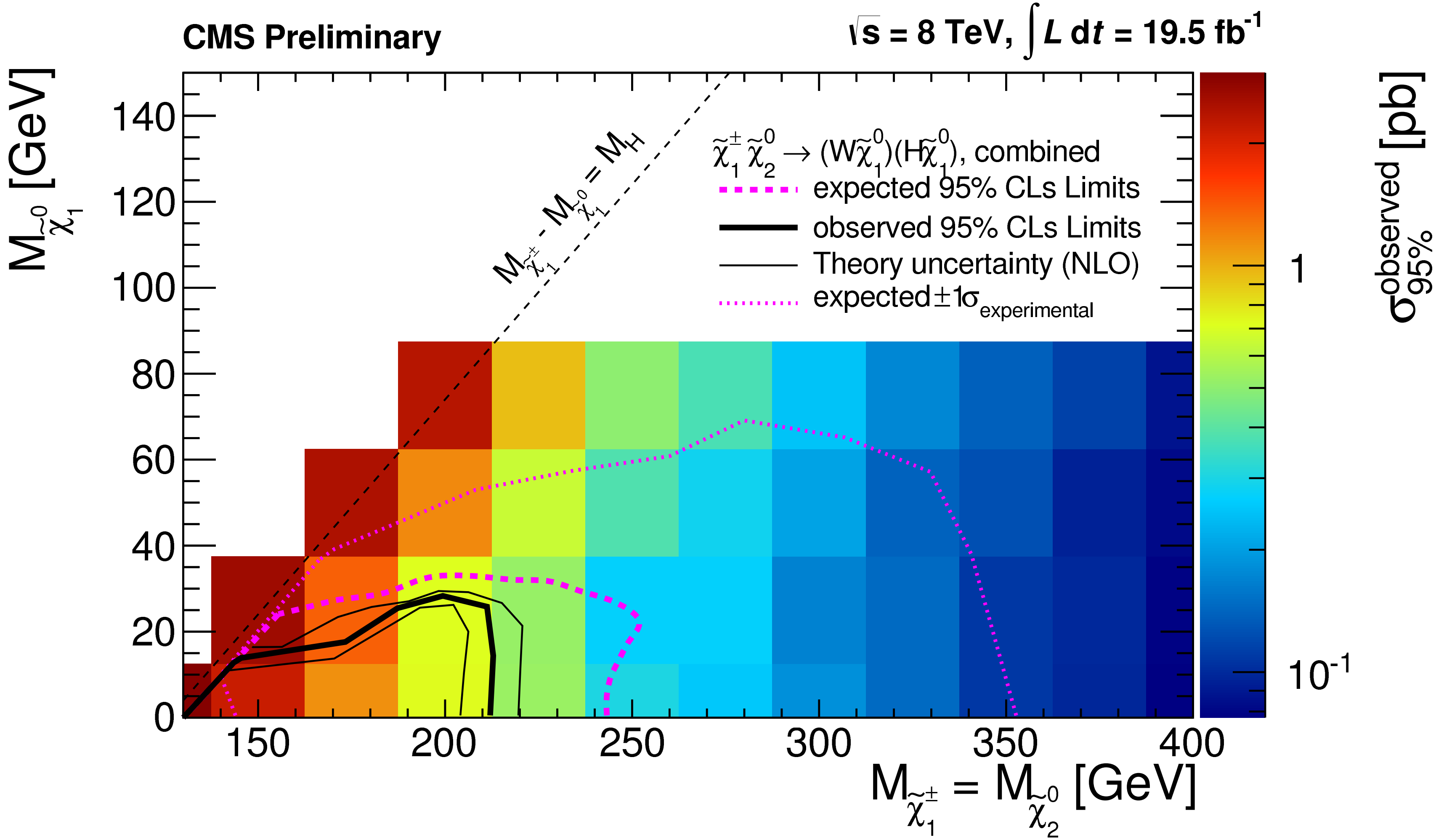
$\Delta := M_2 - M_1$, solid: NLO, dotted: tree

$\Rightarrow$ strong phase dependence, NLO not negligible

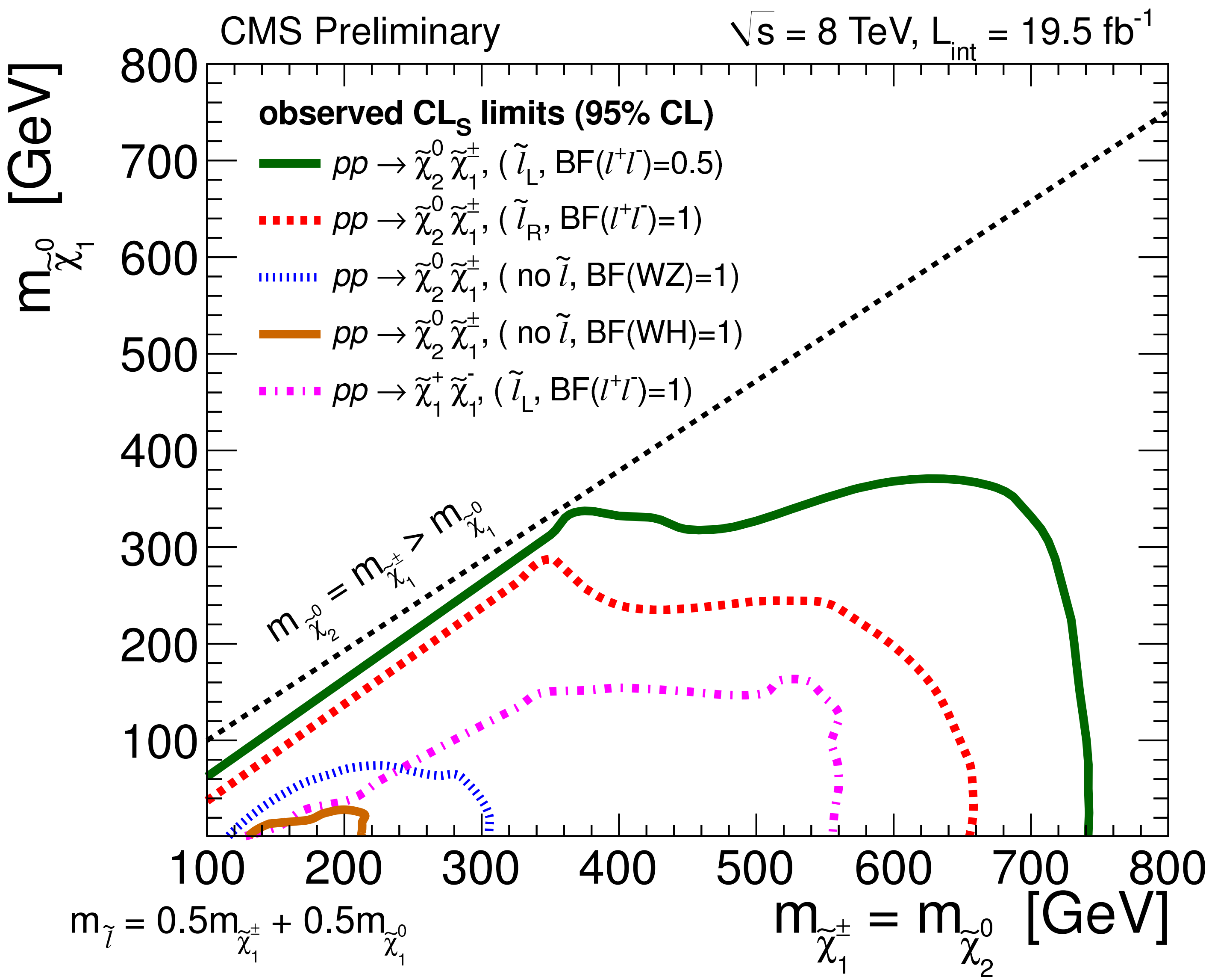
New development:

ATLAS and CMS are now also searching for

$$pp \to \tilde{\chi}_1^{\pm}\, \tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\, \tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\, h\tilde{\chi}_1^0 \to W^{\pm}\tilde{\chi}_1^0\, b\bar{b}\tilde{\chi}_1^0$$



Exclusion bounds from $h \to b\bar{b}$:



$\Rightarrow$ rather small exclusion regions . . .

4. Conclusinos

- Electroweak precision data: M_W, $(g-2)_\mu$, . . .
  $\Rightarrow$ some discrepancies with experimental data . . .
  $\Rightarrow$ fixed with relatively light EW SUSY particles

- Effects on SUSY exclusion regions: $pp \to \tilde{\chi}_1^\pm \tilde{\chi}_2^0$
  Used for interpretation so far: $\mathrm{BR}(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0) = \mathrm{BR}(\tilde{\chi}_2^0 \to Z \tilde{\chi}_1^0) = 1$
  $\Rightarrow$ take all decay channels into account: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$
  $\Rightarrow$ huge reduction of excluded parameter space
  $\Rightarrow$ strong dependence on phase of M_1

- New: search for decay to Higgs:
  $\Rightarrow$ so far only very weak bounds

$\Rightarrow$ the LHC does not exclude the production of SUSY particles at the ILC!