Predicting the Scale of Supersymmetry

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DESY

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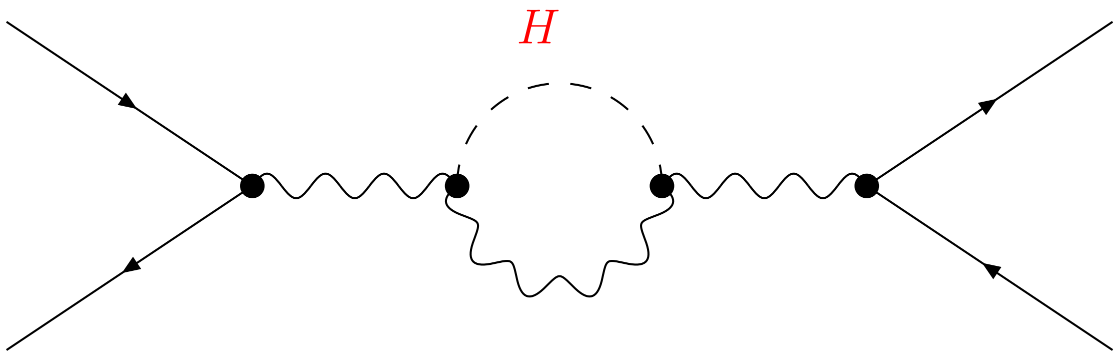
Introduction: what is the scale of new physics?

EW precision data:
$M_Z, M_W, \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}, \ldots$

Theory:
SM, MSSM, ...

$\Downarrow$

Test of theory at quantum level: loop corrections



$\Downarrow$

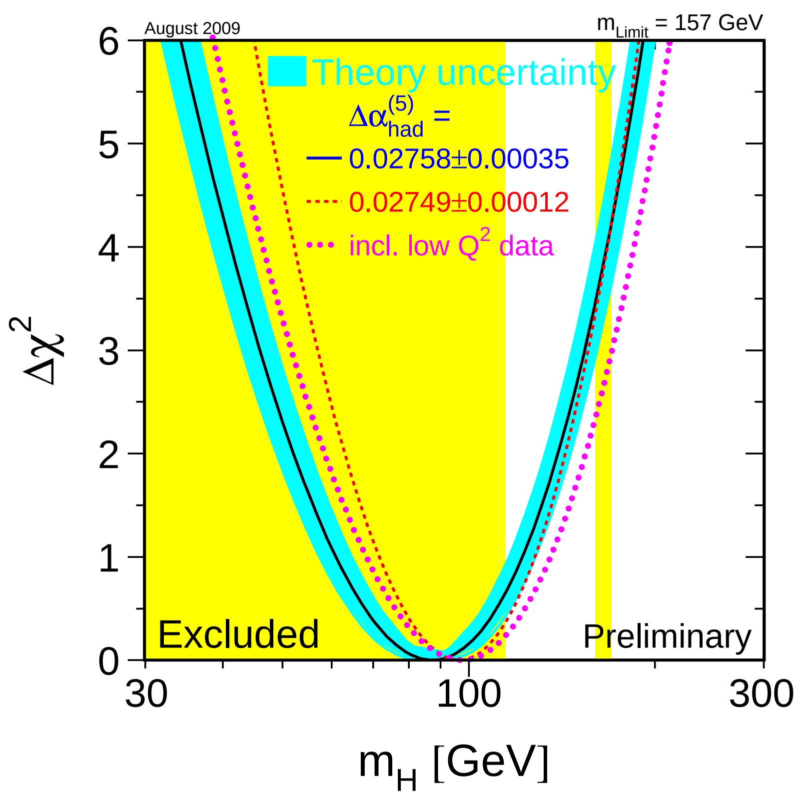
Sensitivity to effects from unknown parameters: M_{H}, $M_{\tilde{t}}$, ...

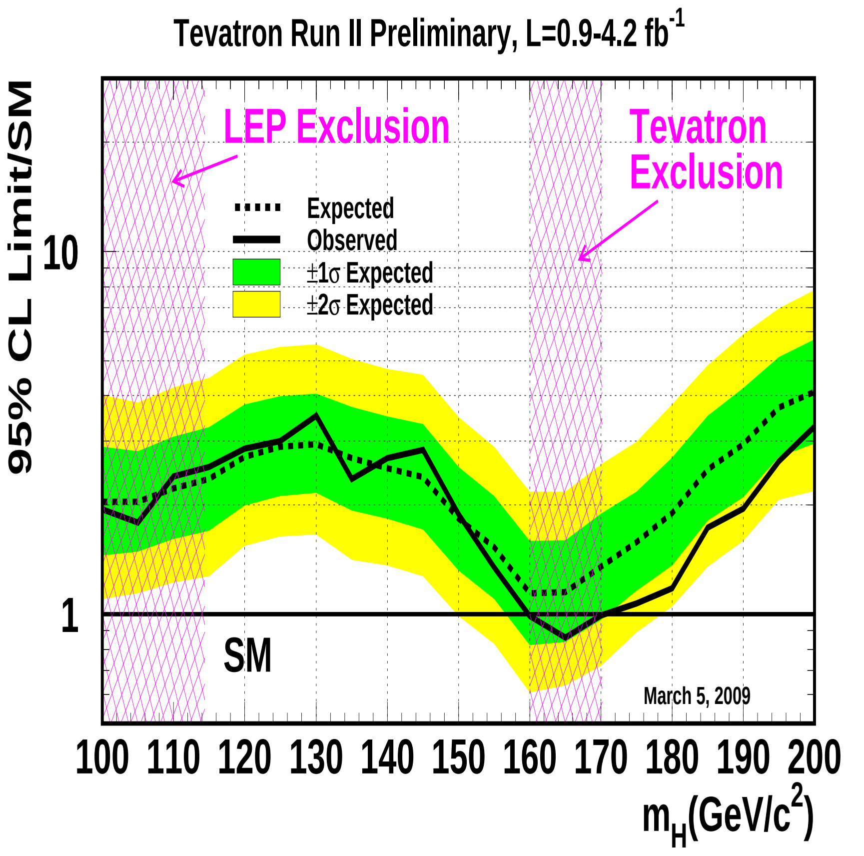
Window to “new physics”

Constraints on the SM Higgs from electroweak precision data and direct searches

SM Higgs: ew. prec. data + direct search at LEP & Tevatron

[*LEPEWWG '09*] [*TEVNPH Working Group '09*]

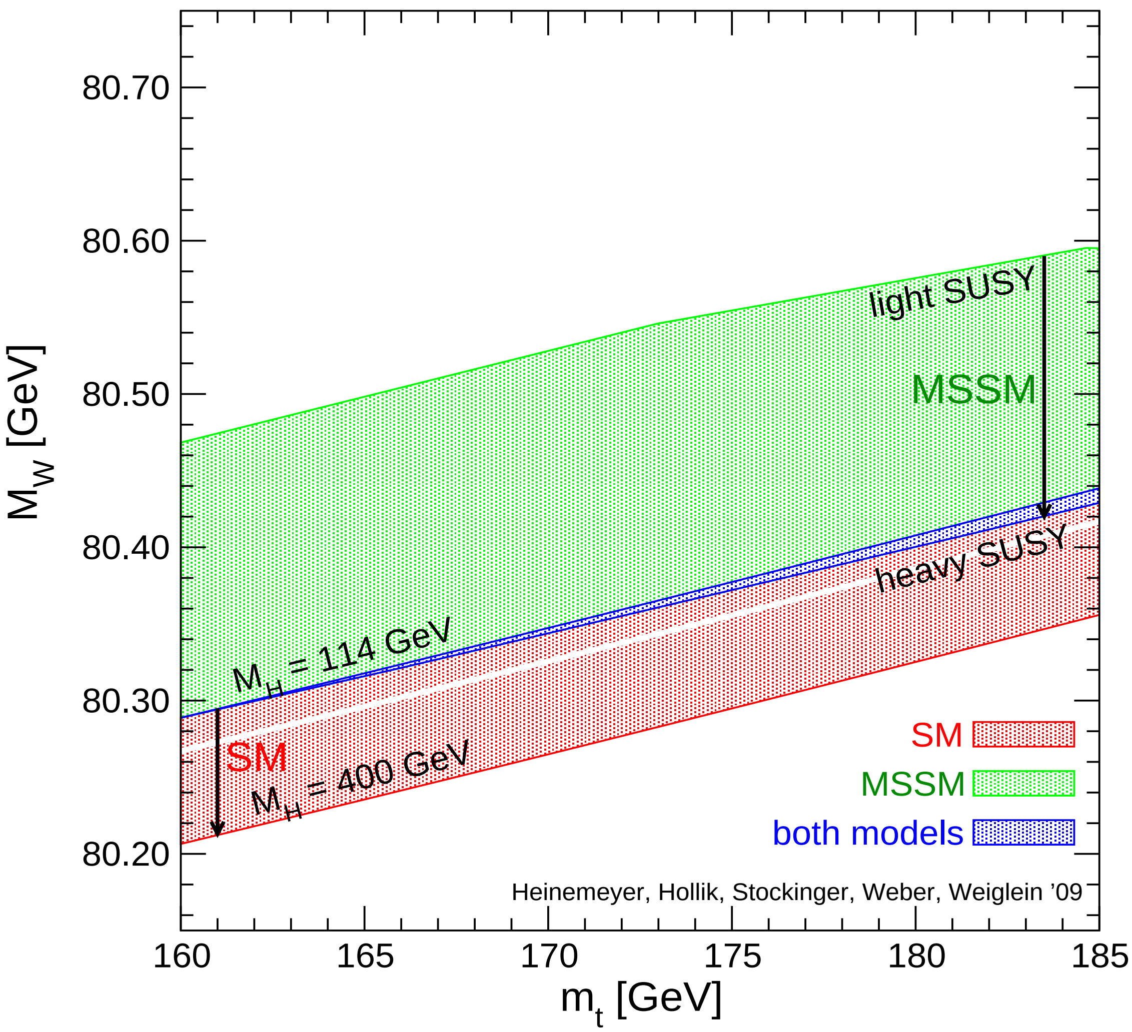




⇒ Preference for a light Higgs

Prediction for M_W (parameter scan): SM vs. MSSM

Prediction for M_W in the SM and the MSSM:



[*S. Heinemeyer, W. Hollik, A.M. Weber, G. W. '09*]

MSSM: SUSY parameters varied

SM: M_H varied

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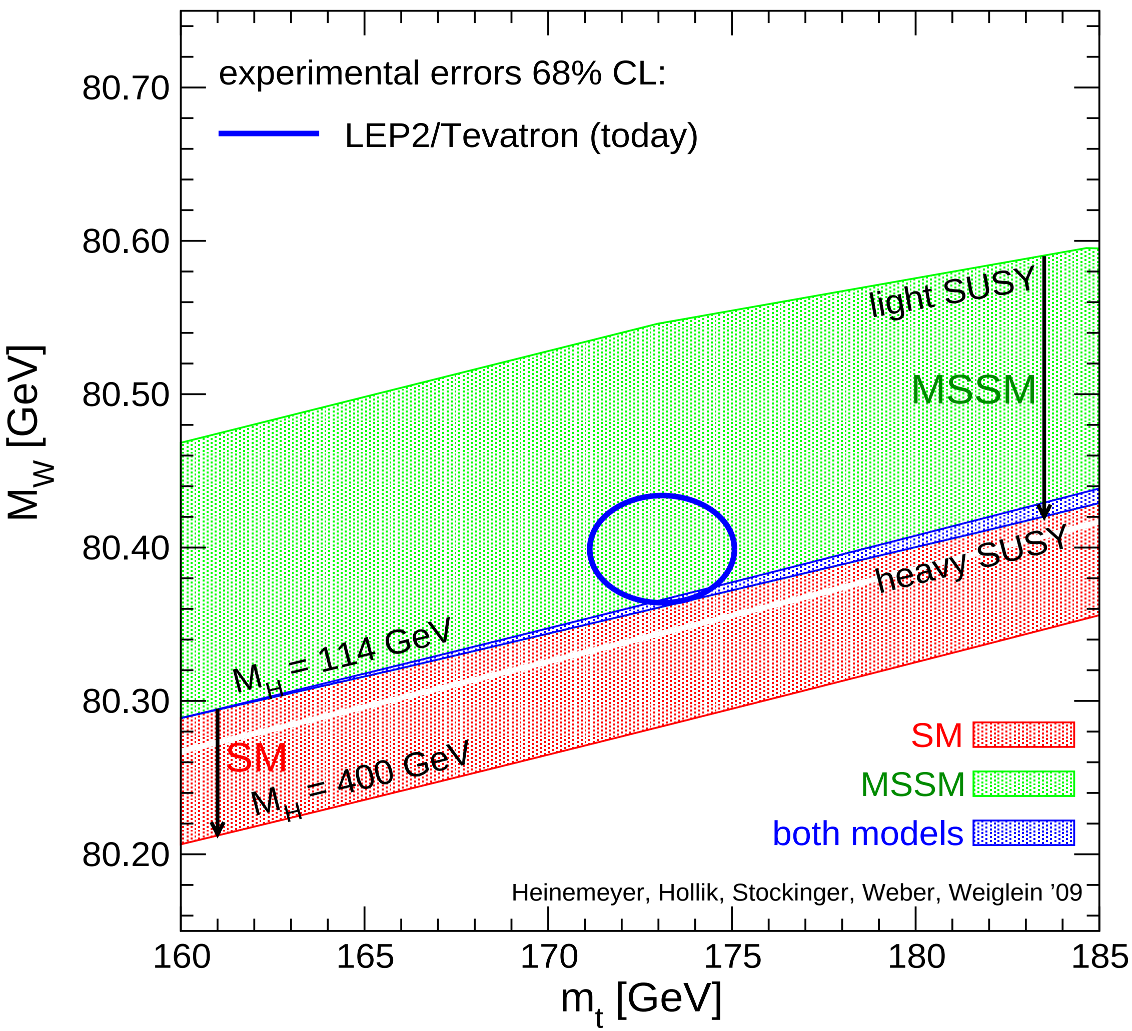

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MSSM: SUSY parameters varied

SM: M_H varied

⇒ Slight preference for MSSM over SM

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles:

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

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

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

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

Two Higgs doublets, physical states: $h^0, H^0, A^0, H^{\pm}$

General parametrisation of possible SUSY-breaking terms
$\Rightarrow$ free parameters, no prediction for SUSY mass scale

Hierarchy problem $\Rightarrow$ expect observable effects at TeV scale

How does SUSY breaking work?

Exact SUSY $\Leftrightarrow m_{\mathrm{e}} = m_{\tilde{\mathrm{e}}}, \ldots$

$\Rightarrow$ SUSY can only be realised as a broken symmetry

MSSM: no particular SUSY breaking mechanism assumed, parameterisation of possible soft SUSY-breaking terms

$\Rightarrow$ relations between dimensionless couplings unchanged

$\Rightarrow$ cancellation of large quantum corrections preserved

Most general case: 105 new parameters

Strong phenomenological constraints on flavour off-diagonal and $\mathcal{CP}$-violating SUSY-breaking terms

$\Rightarrow$ Good phenomenological description for universal SUSY-breaking terms ($\approx$ diagonal in flavour space)

Simplest ansatz: the Constrained MSSM (CMSSM)

Assume universality at high energy scale ($M_{\rm GUT}$, $M_{\rm Pl}$, ...)
renormalisation group running down to weak scale
require correct value of M_Z

$\Rightarrow$ CMSSM characterised by

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

CMSSM is in agreement with all experimental constraints:
Electroweak precision observables (EWPO) $+$ flavour physics $+$ cold dark matter density $+$ ...

The Non-Universal Higgs Model (NUHM)

Universality of soft SUSY-breaking contributions to the Higgs scalar masses is less motivated than universality between squarks and sleptons

$\Rightarrow$ NUHM:

two additional parameters (can be traded for M_A and μ after imposing the electroweak vacuum conditions)

Simplest realisation:

$$m_{H_1}^2 = m_{H_2}^2 \equiv m_H^2$$

Common soft SUSY-breaking contribution to Higgs scalar masses squared: “NUHM1”

Global CMSSM and NUHM1 fits using indirect experimental and cosmological constraints

Global χ^2 fit in the CMSSM ($m_{1/2}$, m_0, A_0 (GUT scale), $\tan\beta$, $\mathrm{sign}(\mu)$ (weak scale)) and the NUHM1 (m_H^2 as add. param.)

Fit includes (*MasterCode*, Markov-chain Monte Carlo sampling):
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '08*]

- All observables used in the SM fit of the LEPEWWG
- $+$ Cold dark matter (CDM) density (WMAP, ...), $\Omega_{\mathrm{CDM}}\, h^2 = 0.1099 \pm 0.0062$
- $+ \, (g-2)_\mu$
- $+$ BPO: $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$, $\mathrm{BR}(B \to \tau\nu)$, ...
- $+$ Kaon decay data: $\mathrm{BR}(K \to \mu\nu)$, ...

Method: predictions

- *MasterCode:* Consistent set of predictions
  - RGE running and spectrum calculators:

    SoftSUSY, *SuSpect*
  - SUSY observables:

    Higgs sector: *FeynHiggs* (soon: *HiggsBounds*)

    Electroweak physics: *FeynHiggs*, *FeynWZ*

    Flavour physics: *SuFla*, *SuperIso*

    CDM: *MicrOMEGAs, DarkSUSY*
  - Interface: SLHA

$\Rightarrow$ State-of-the art predictions, well tested, modular structure

Method: statistics and parameter space sampling

- Frequentist statistical method: global χ^2 likelihood function

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \chi^2(M_\mathrm{h}) + \chi^2(\mathrm{BR}(\mathrm{B_s} \to \mu\mu))$$

$$+ \chi^2(\text{SUSY search limits}) + \sum_i^M \frac{(f^{\mathrm{obs}}_{\mathrm{SM}_i} - f^{\mathrm{fit}}_{\mathrm{SM}_i})^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

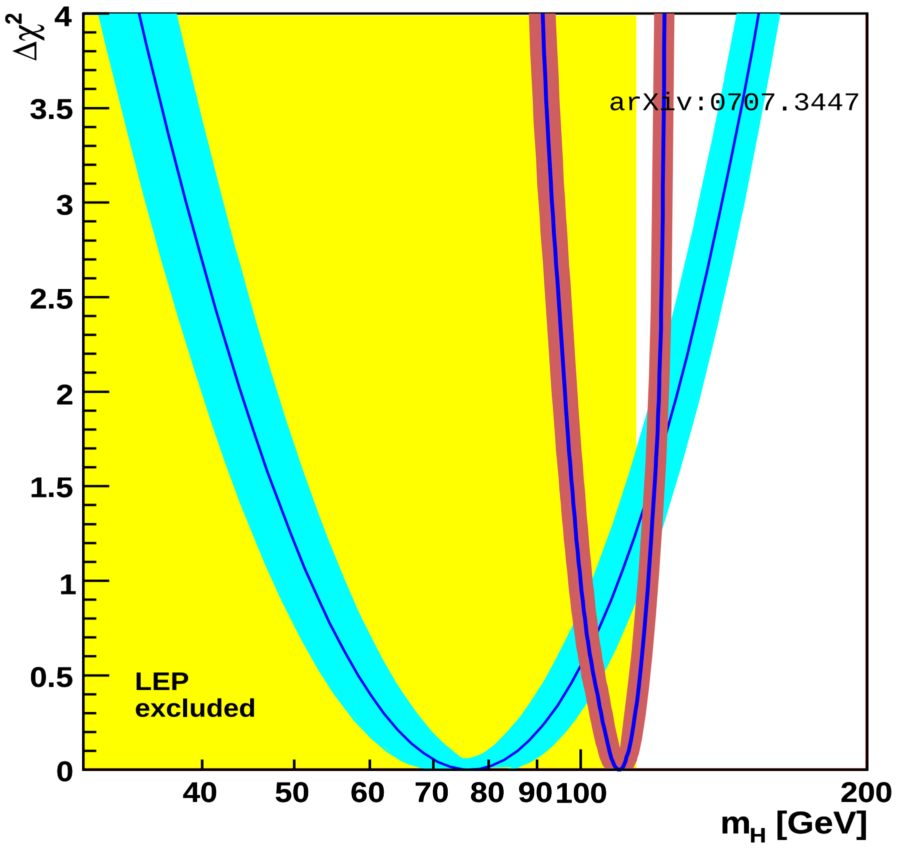
Fit parameters: SUSY parameters $m_{1/2}$, m_0, A_0, $\tan\beta$, m^2_H
$+$ SM parameters $\Delta\alpha_\mathrm{had}$, m_t, M_Z (simultaneous fit)
$\Rightarrow$ χ^2 distribution is quantitative measure of goodness-of-fit

- Markov-chain Monte Carlo (MCMC) sampling
  $\Rightarrow$ Thorough sampling of multi-dim. parameter space
  25 million points

Indirect prediction for the Higgs mass in the SM and the constrained MSSM (CMSSM) from precision data

χ^2 fit for $M_{\rm h}$, without imposing direct search limit [*O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07*]

SM CMSSM



⇒ Accurate indirect prediction; Higgs "just around the corner"?

Predictions for the SUSY scale from precision data

Comparison: preferred region for the SUSY mass scale vs. LHC discovery reach for $1, 0.1, 0.05 \ \text{fb}^{-1}$ of understood data

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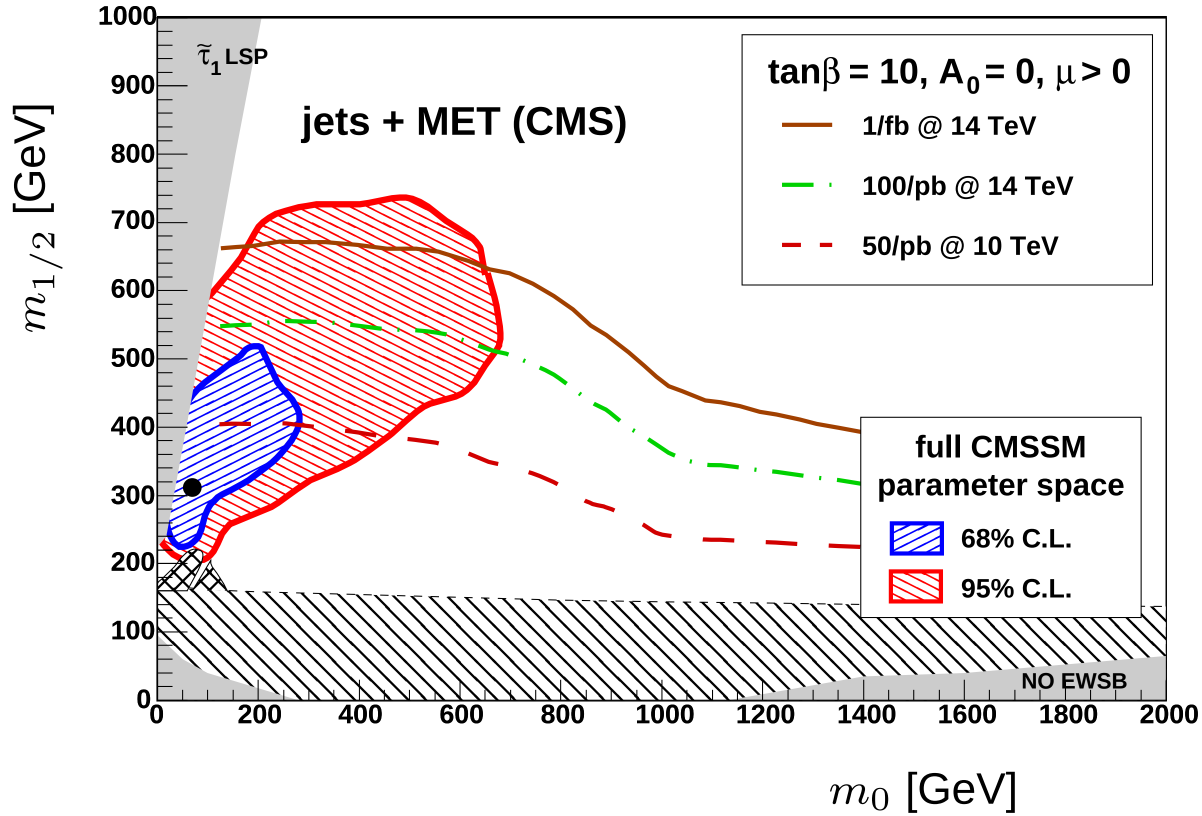

⇒ Preferred region would lead to early discovery

Preferred region in the m_0–$m_{1/2}$ plane of the NUHM1 vs. LHC discovery reach

68% and 95% C.L. contours from the fit vs. LHC discovery reach for $1, 0.1, 0.05\ \text{fb}^{-1}$ of understood data

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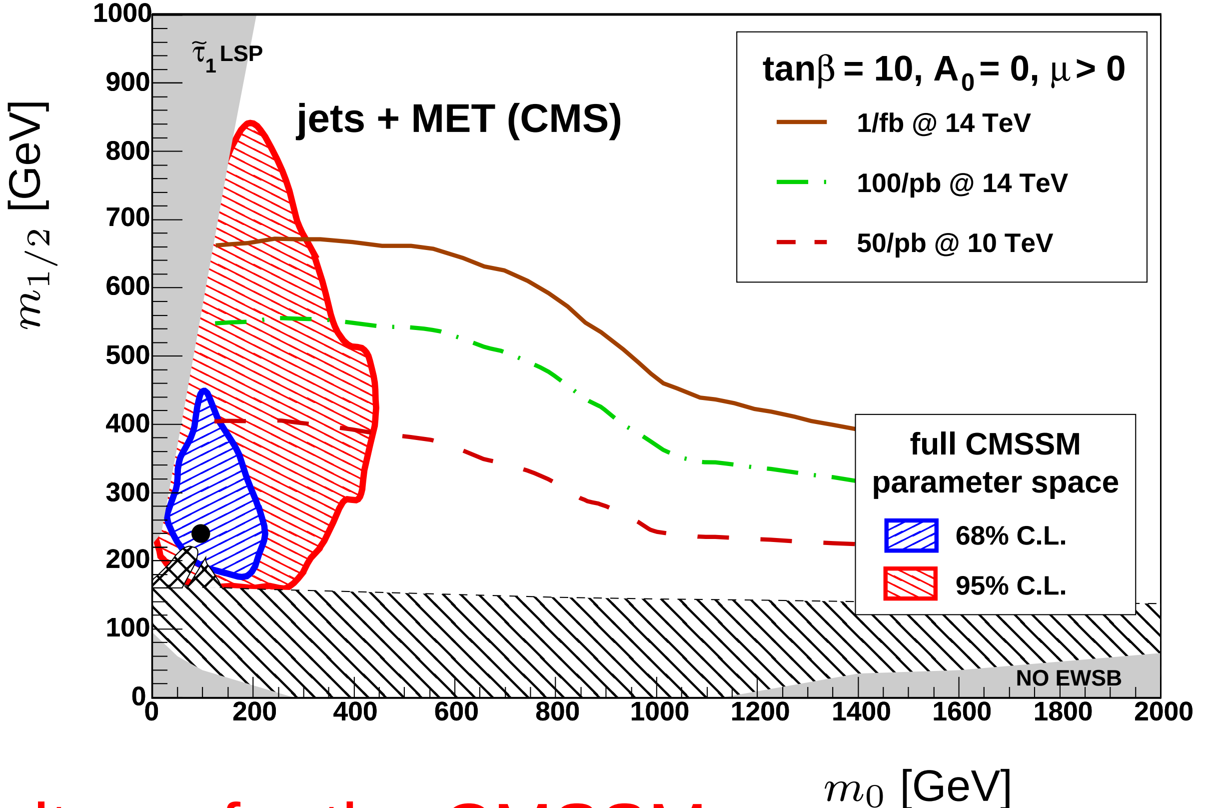
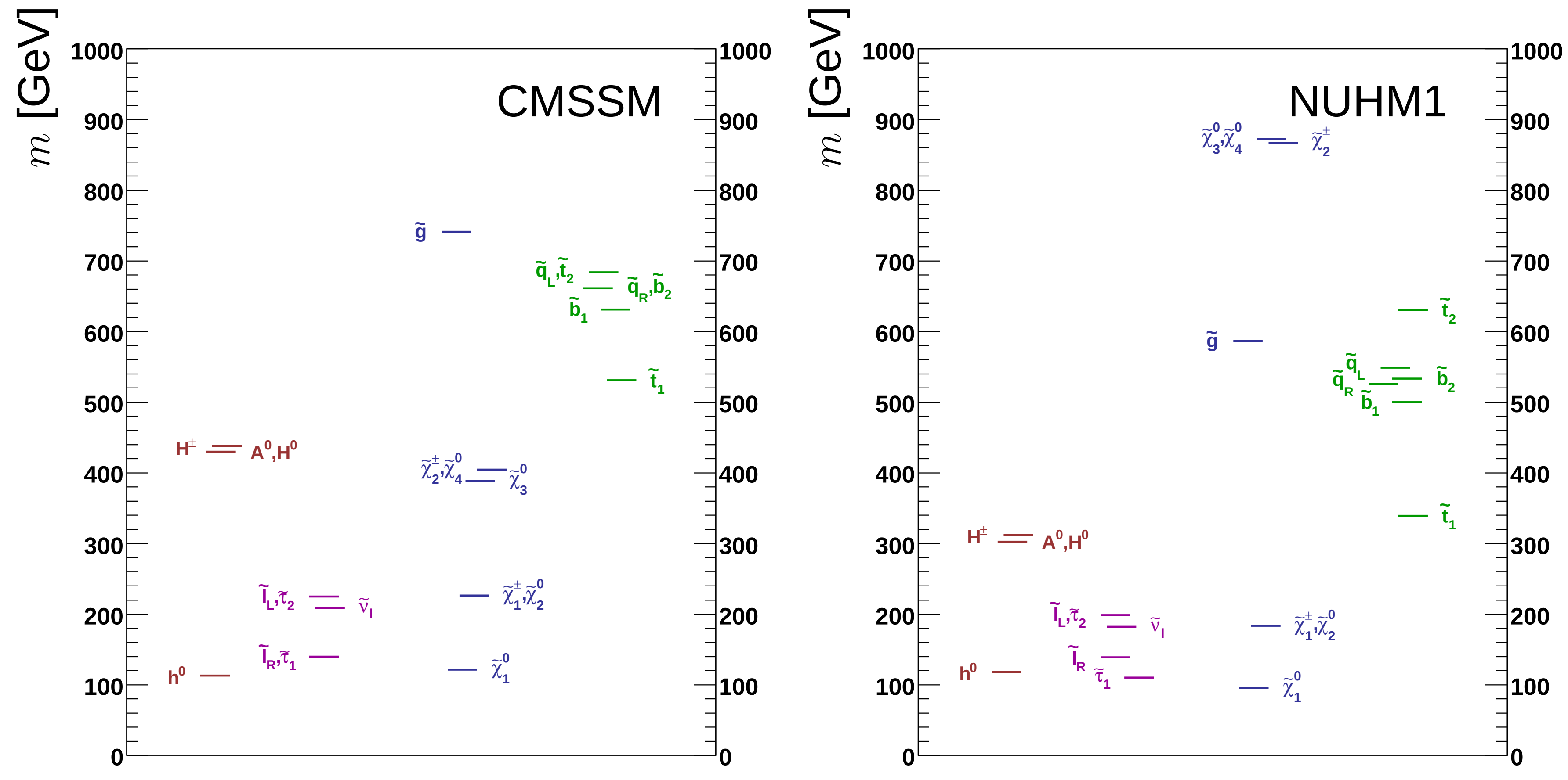


⇒ Similar results as for the CMSSM

Spectra of the best-fit points in the CMSSM and the NUHM1



$\Rightarrow$ CMSSM: similar spectrum as SPS1a benchmark point

Similar fit probabilities for the two models

$\Delta\chi^2$ *distributions: CMSSM and NUHM1*

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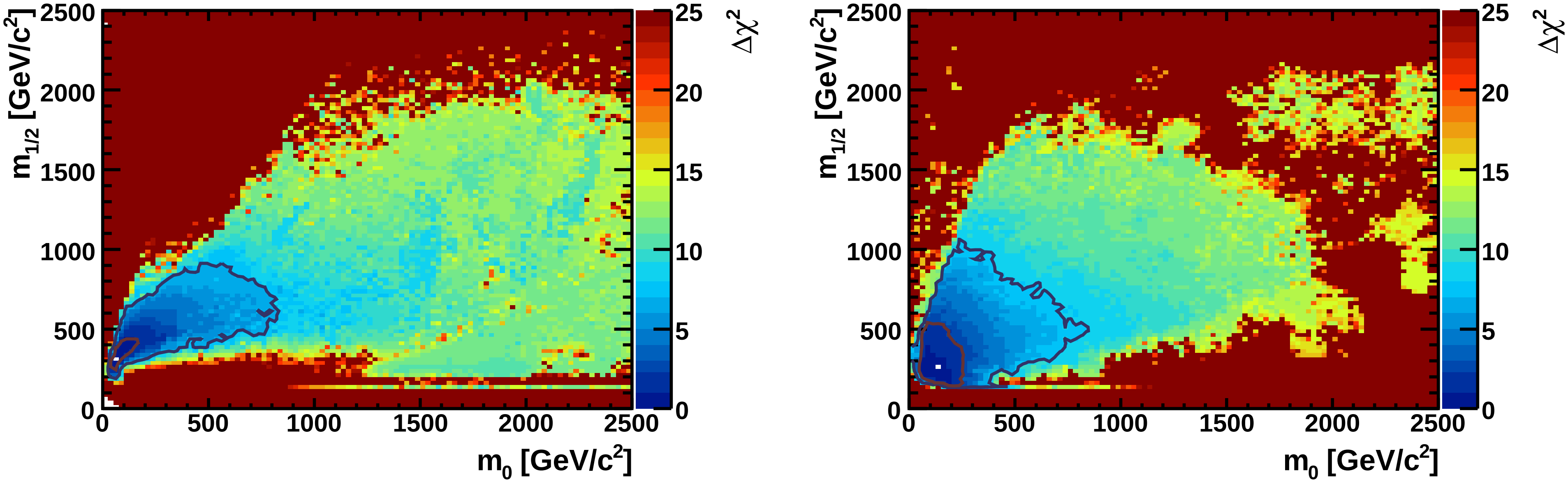


$\Rightarrow$ Preference for light SUSY scale

Focus point (FP) region is disfavoured at the 3σ level

χ^2 contributions for best fit points
Comparison with best fit in FP region

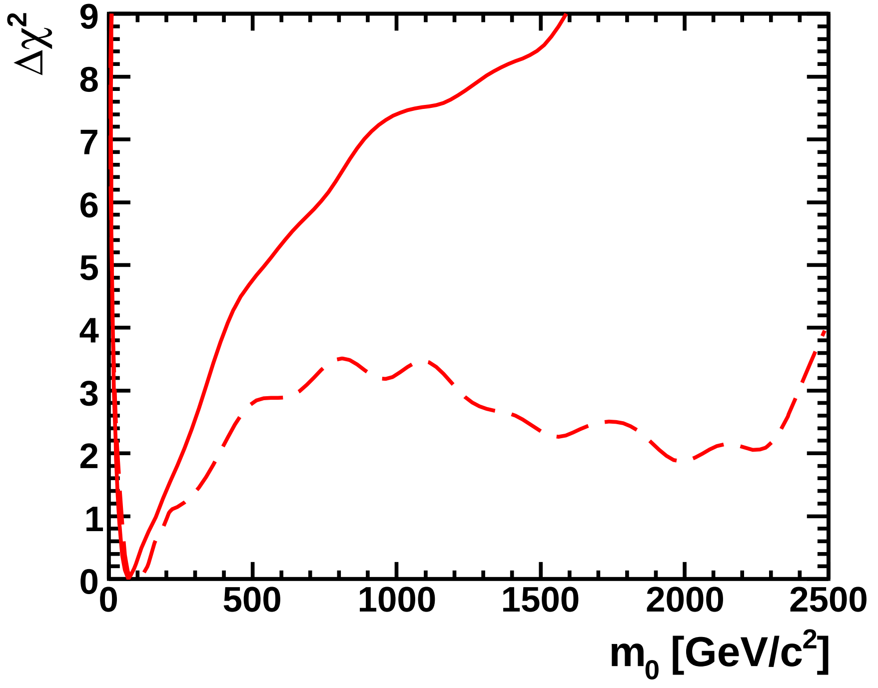
Observable	Best CMSSM fit	Best NUHM1 fit	Best CMSSM FP fit
$(g_\mu - 2)$	0.44	0.002	8.4
$\mathrm{BR}(B \to \tau\nu)$	0.20	0.41	0.85
M_W	0.53	0.08	1.5
$A_\ell(\mathrm{SLD})$	2.84	3.22	3.56
$A_\mathrm{fb}(b)$(LEP)	7.61	7.08	6.74
R_ℓ	0.96	1.01	1.05
$\mathrm{BR}^\mathrm{SUSY}_{\mathrm{b}\to\mathrm{s}\gamma}/\mathrm{BR}^\mathrm{SM}_{\mathrm{b}\to\mathrm{s}\gamma}$	1.16	0.001	0.95
M_h	0.17	0	0
χ^2_tot	20.6	18.5	29.8

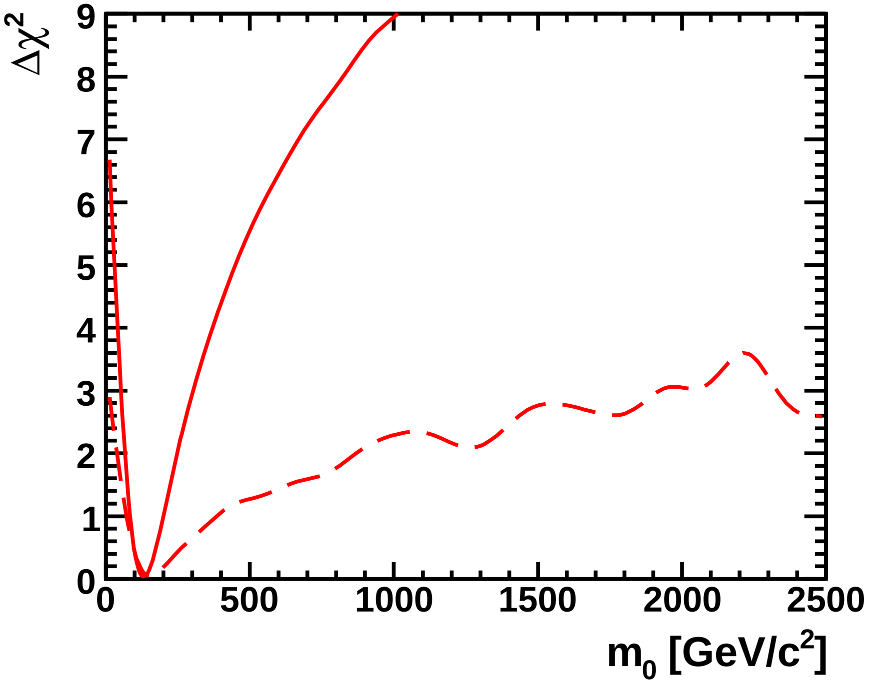
$\Rightarrow$ Clear preference for light SUSY;

Strongest contribution from $(g_\mu - 2)$

$\Delta\chi^2$ *for CMSSM and NUHM1 with (solid) and without (dashed)* $(g_\mu - 2)$ *constraint*

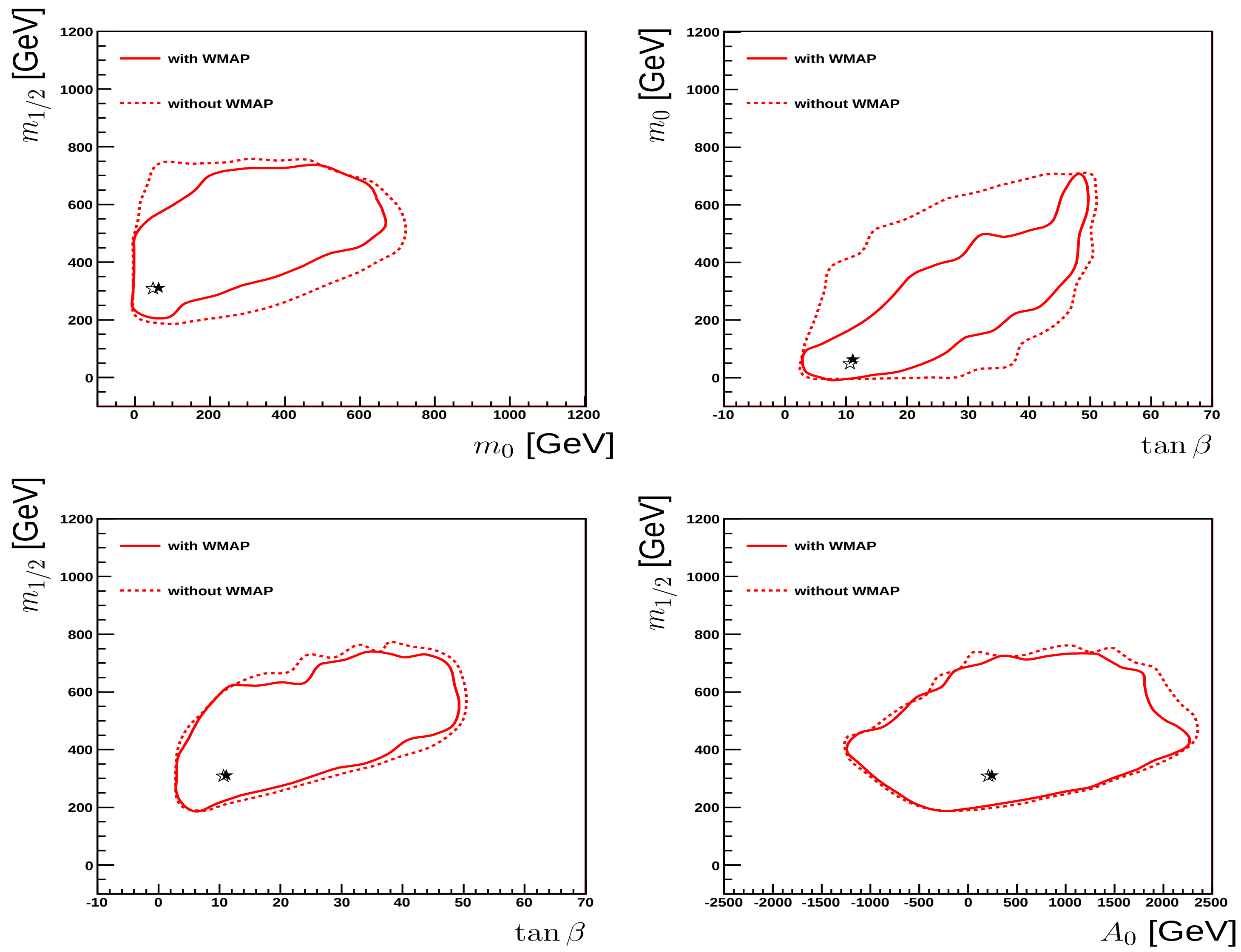
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '09*]





$\Rightarrow$ Slight Preference for light SUSY scale even if $(g_\mu - 2)$ is excluded from the fit

Impact of CDM constraint, CMSSM results



⇒ Fit results are robust w.r.t. in-/exclusion of $\Omega_{\rm CDM}$ constraint

χ^2 *functions for the relic density in the CMSSM and NUHM1 without (solid) and with (dashed) the* $\Omega_{\rm CDM}$ *constraint*

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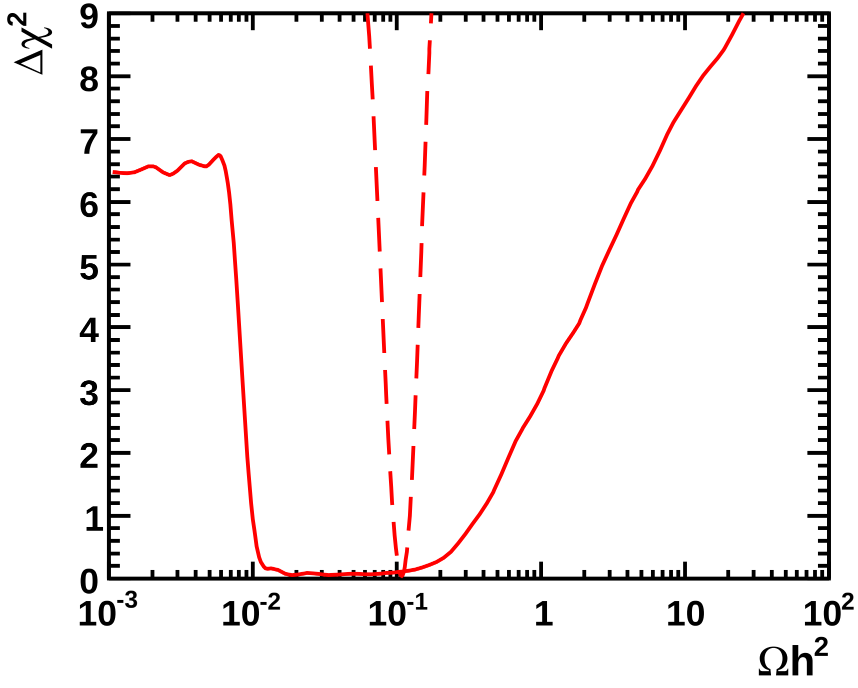
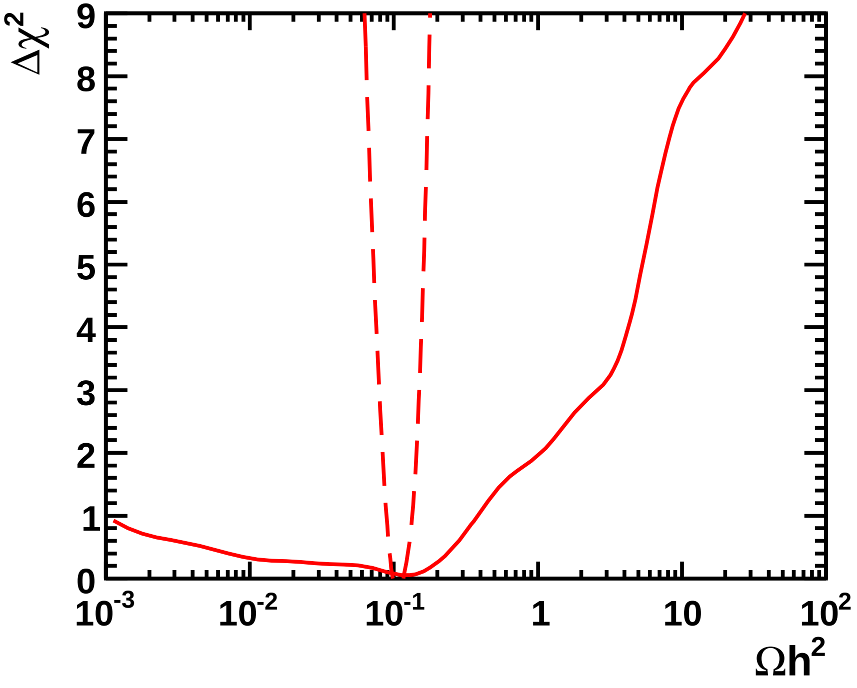
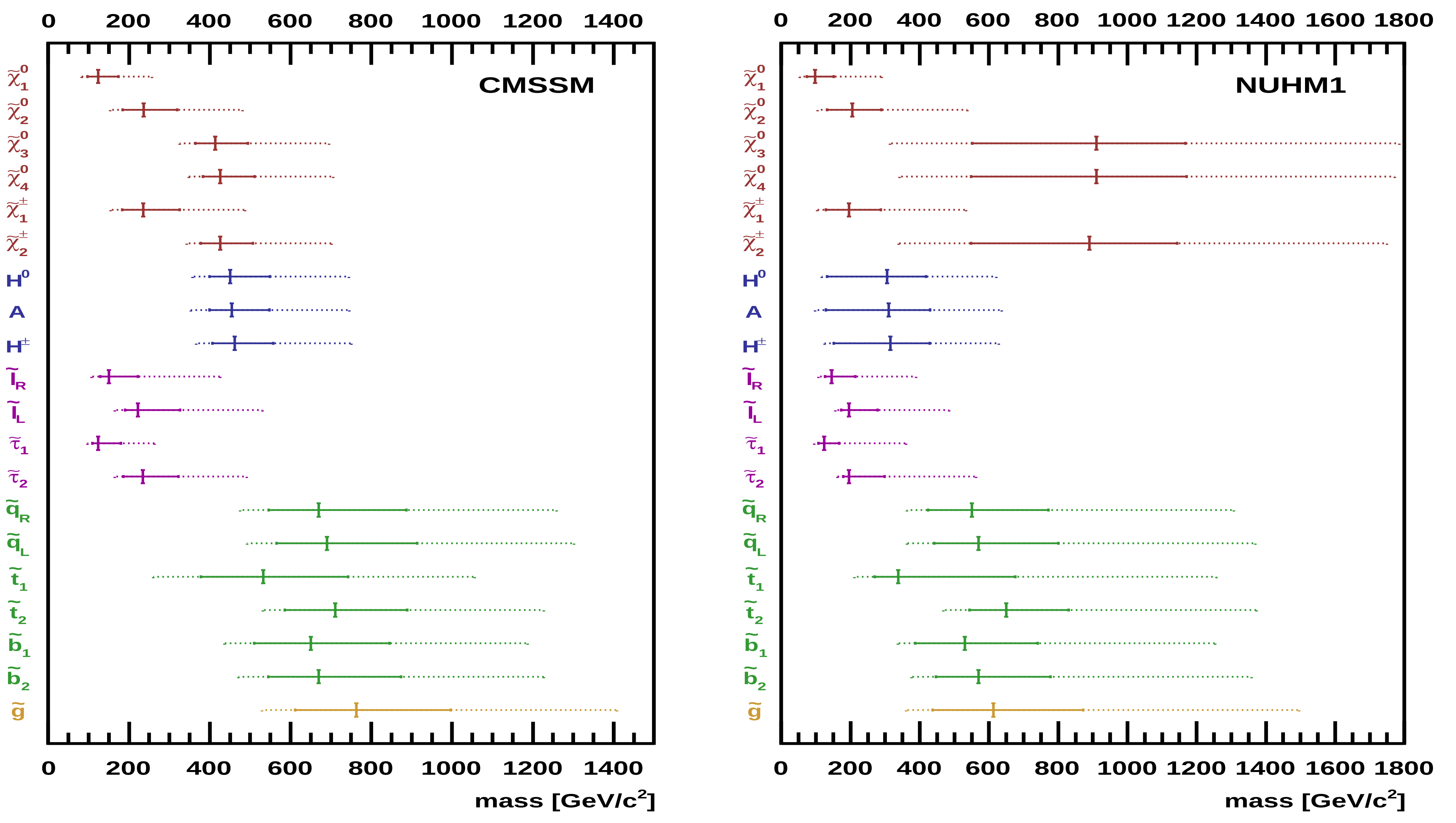




$\Rightarrow$ Indirect CDM prediction is in agreement with the measured value of the CDM relic density

Fit results for particle masses in the CMSSM and NUHM1, 68% and 95% C.L. regions



⇒ Light SUSY masses preferred

Comparison with other results in the literature

- Very good agreement with Fittino
  [*P. Bechtle, K. Desch, M. Uhlenbrock, P. Wienemann '09*]
  Frequentist method, uses previous version of *MasterCode*, different sampling

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  Stability of results based on Bayesian method w.r.t. change of priors? Theoretical uncertainties?

Comparison with other results in the literature, cont'd

Recent claim: overall preference for the (high-mass) focus-point region

[*Y. Akrami, P. Scott, J. Edsjo, J. Conrad, L. Bergstrom '09*]

Frequentist method, sampling with Genetic Algorithms, different treatment of SUSY observables (*SuperBayeS*)

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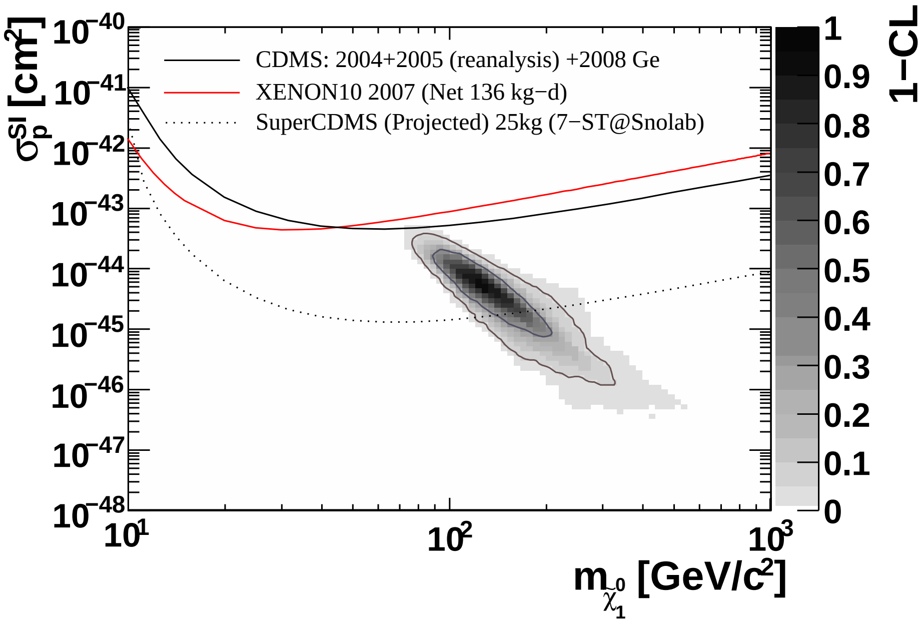
Sensitivity to numerical instabilities in the codes?

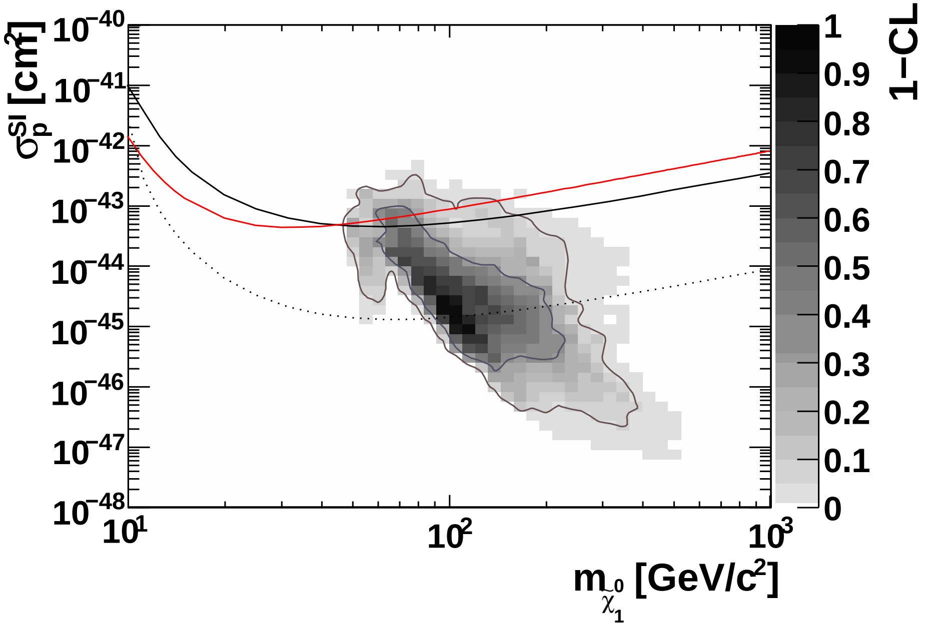
Comparison of the same parameter point yields large differences in χ^2

$\Rightarrow$ Discrepancies in evaluation of SUSY observables

Preferred regions for the spin-independent dark matter cross sections vs. present limit and future sensitivity

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '09*]

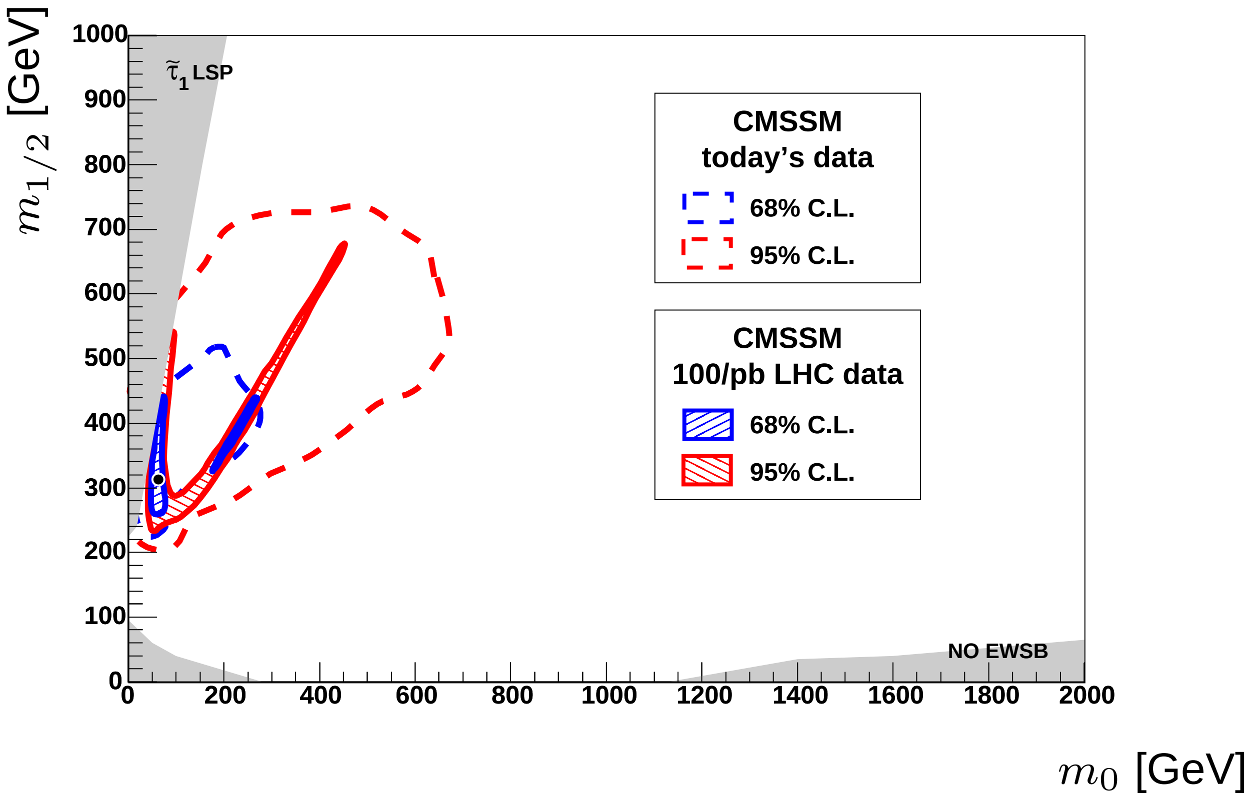




⇒ Projected sensitivity of the *SuperCDMS* direct detection experiment will probe a sizable part of the preferred region

Improvements from measuring a dilepton edge

CMSSM fit with additional information from measuring the opposite-sign dilepton edge in $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$ ($\ell = e, \mu$) with 1 fb^{-1}: [*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '08*]



$\Rightarrow$ Big improvement in determination of m_0, $m_{1/2}$

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- $(g_\mu - 2)$ has the largest impact, but qualitatively the results are stable under removing single experimental constraints

  $\Rightarrow$ There is no tension between the different constraints