# *Prospects for SUSY and Higgs Phenomenology at the LHC*

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DESY

CERN, 06 / 2010

# *Introduction*

The LHC is about to open up the new territory of TeV-scale physics

Many open questions:

- How does electroweak symmetry breaking work?
- How is the hierarchy of scales stabilised?
- What is dark matter? Can it be produced in the laboratory?
- Are there new sources of $\mathcal{CP}$-violation?
- ...

# What to expect?

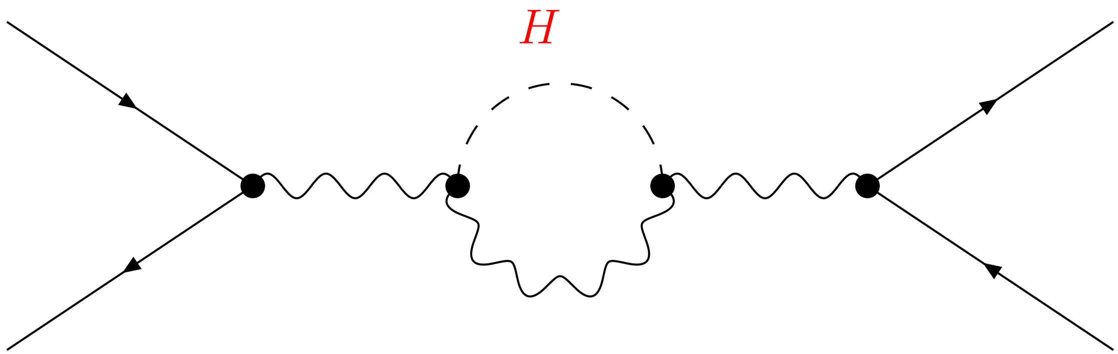
# Information from electroweak precision physics

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

Theory:
SM, MSSM, ...

$\Downarrow$

Test of theory at quantum level: loop corrections




$\Downarrow$

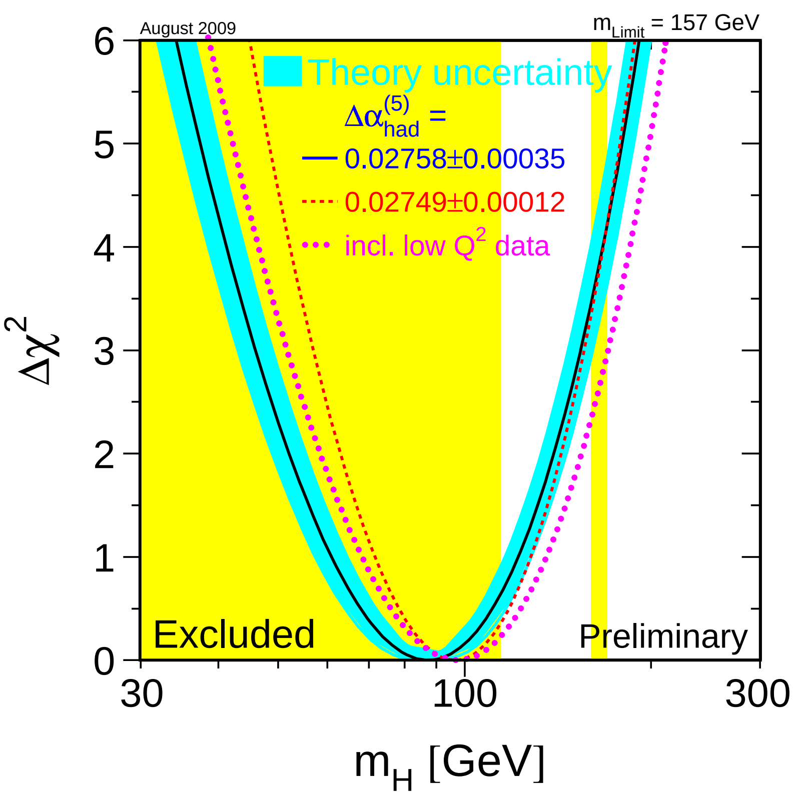
Sensitivity to effects from unknown parameters: $M_H$, $M_{\tilde{t}}$, ...

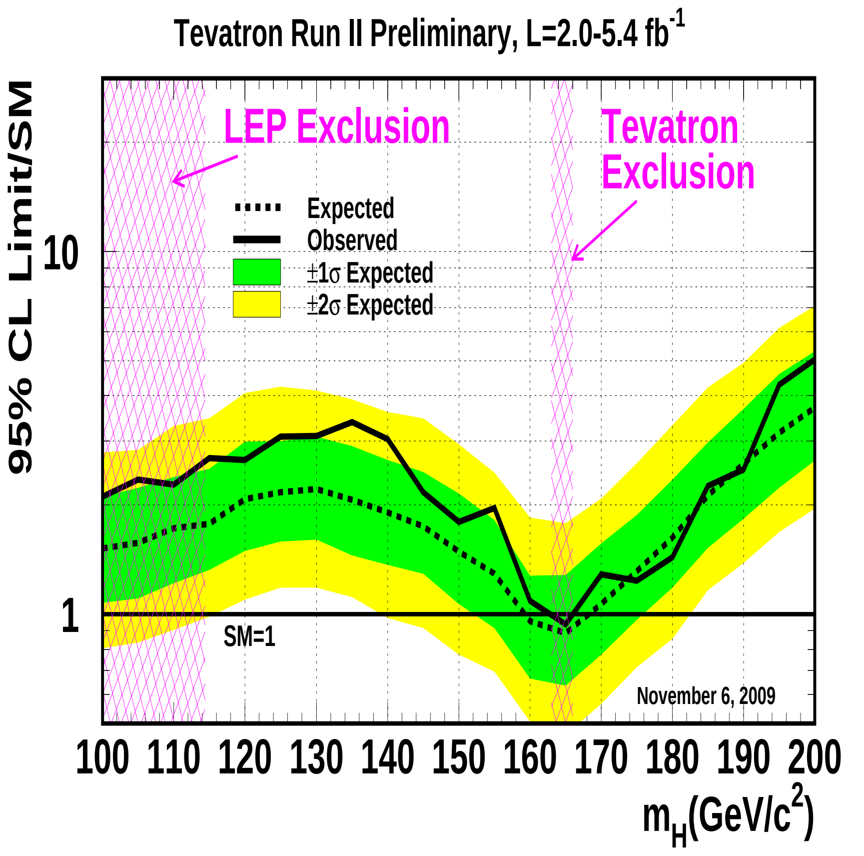
Window to “new physics”

# 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

# The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles:

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

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

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

$\tilde{g}$ $\tilde{\chi}^\pm_{1,2}$ $\tilde{\chi}^0_{1,2,3,4}$ 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

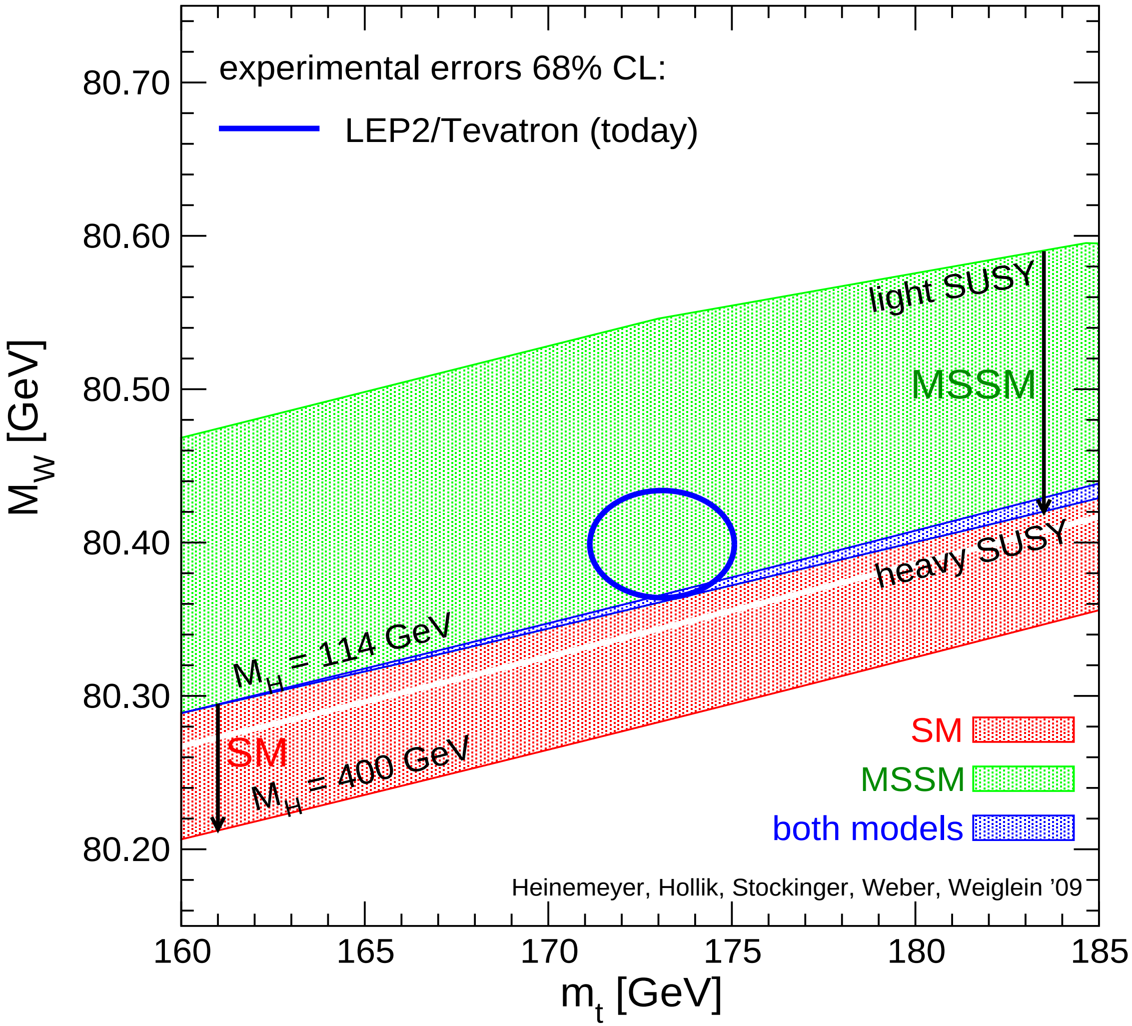
Hierarchy problem $\Rightarrow$ expect observable effects at TeV scale

# *Most sensitive precision observables*

- W-boson mass: $M_{\mathrm{W}}$
- Effective weak mixing angle: $\sin^2 \theta_{\mathrm{eff}}$
- Anomalous magnetic moment of the muon: $(g-2)_\mu$
- FCNC $b$ decay: $\mathrm{BR}(b \to s\gamma)$
- Cold dark matter (CDM) density: $\Omega_{\mathrm{CDM}}$
- ...

# Prediction for $M_\mathrm{W}$ (parameter scan): SM vs. MSSM

Prediction for $M_\mathrm{W}$ in the SM and the MSSM:




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

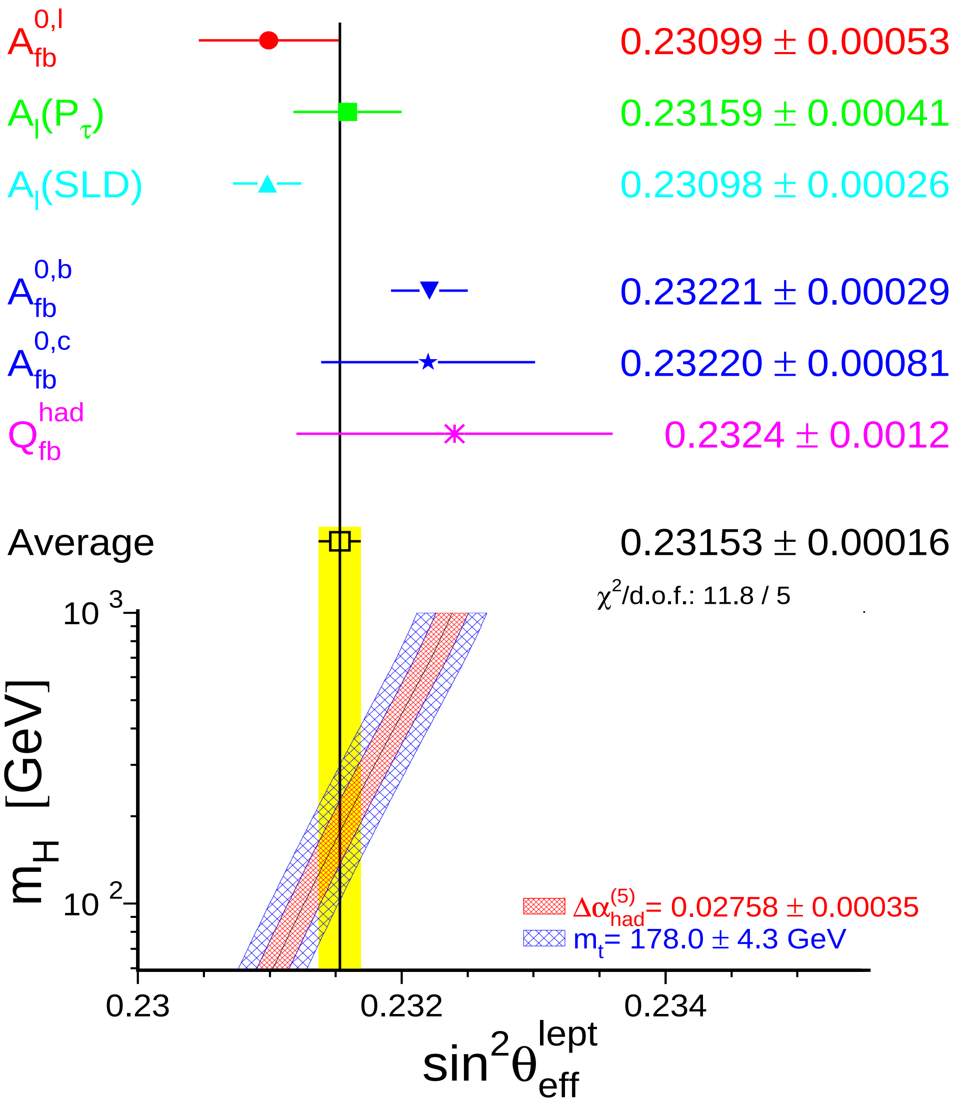
MSSM: SUSY parameters varied

SM: $M_\mathrm{H}$ varied

Tevatron result for $m_\mathrm{t}$ interpreted (perturb.) as pole mass

$\Rightarrow$ Slight preference for MSSM over SM

# $\sin^2\theta_{\rm eff}$: *an old (but still relevant) story*




[*LEPEWWG '05*]

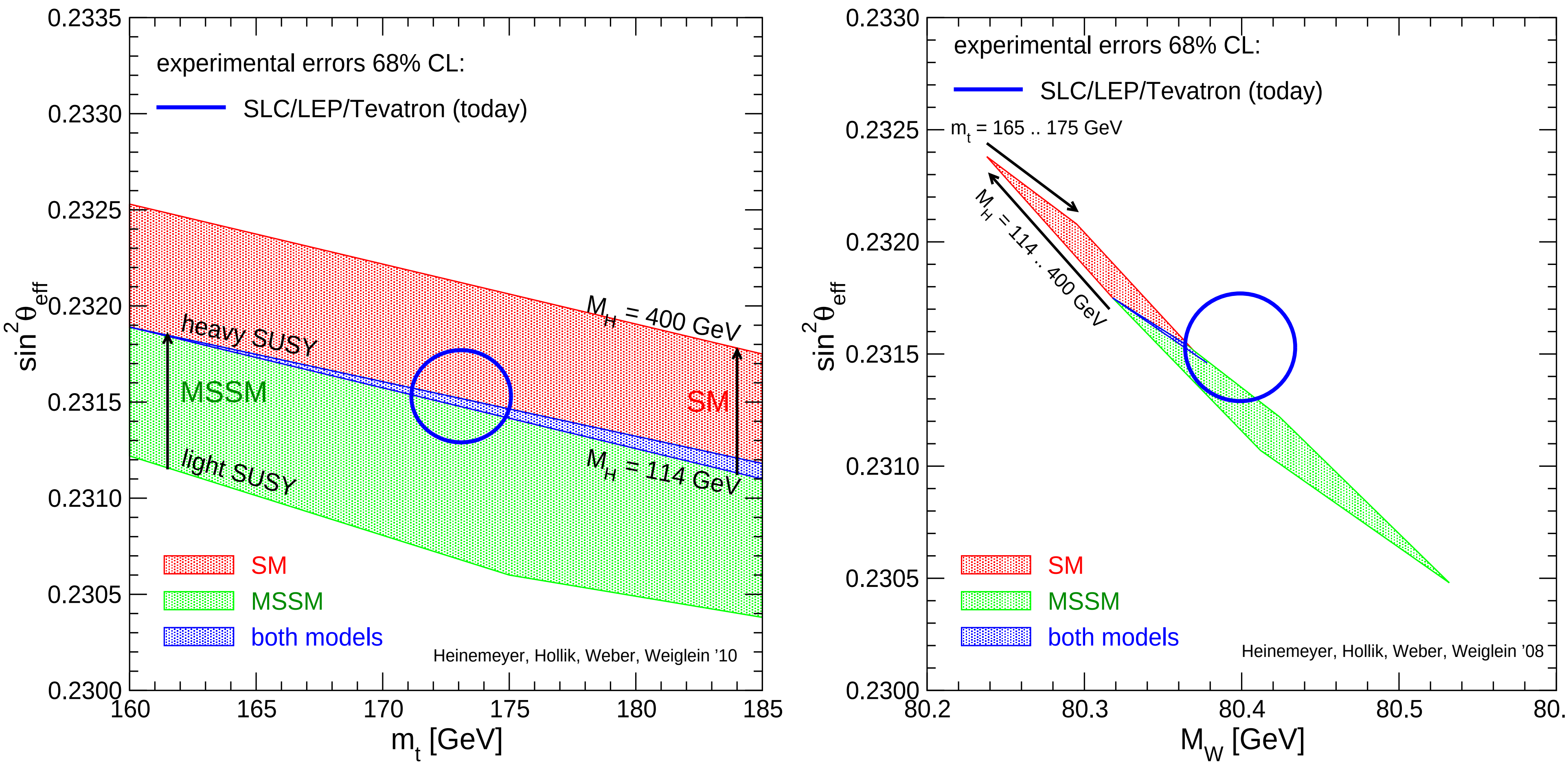
$\sin^2\theta_{\rm eff}$ has a high sensitivity to $M_{\rm H}$ and effects of new physics

But:
large discrepancy between $A_{\rm LR}$ (SLD) and $A_{\rm FB}$ (LEP),

has big impact on constraints on new physics

# $\sin^2\theta_{\rm eff} = 0.23153 \pm 0.00016$: *central value, errors added in quadrature*

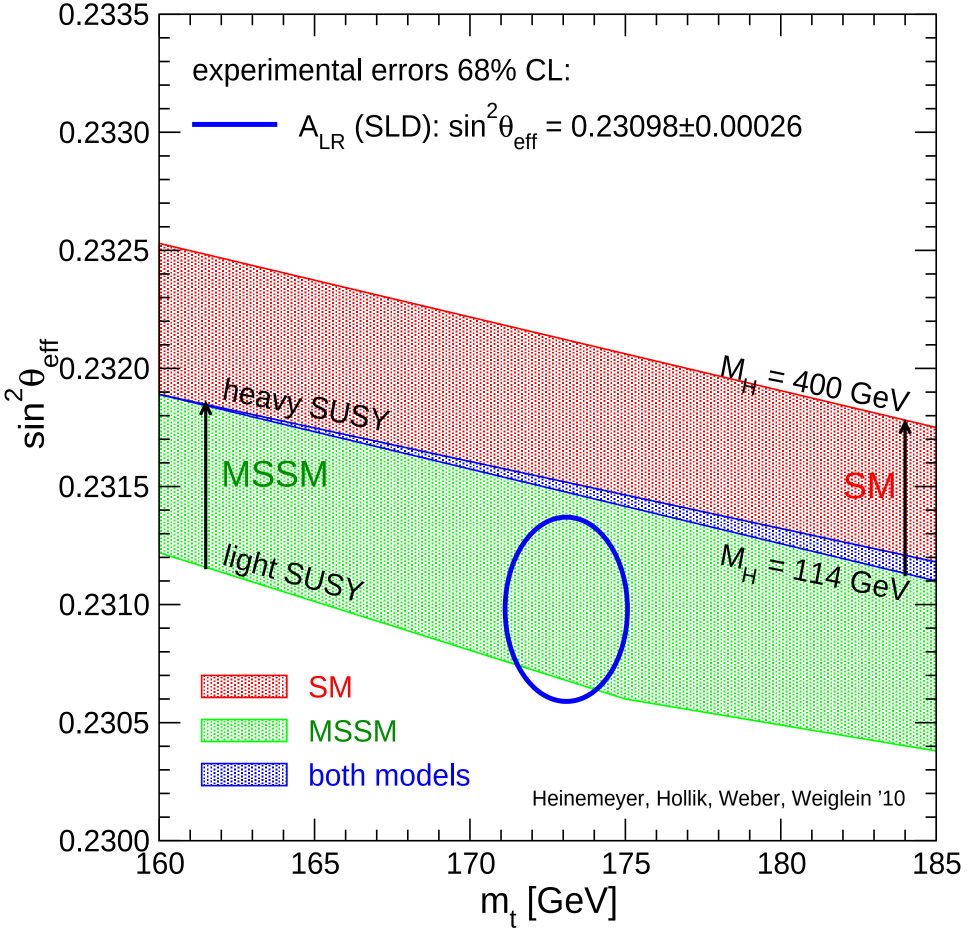
[*S. Heinemeyer, W. Hollik, A.M. Weber, G. W. '10*]

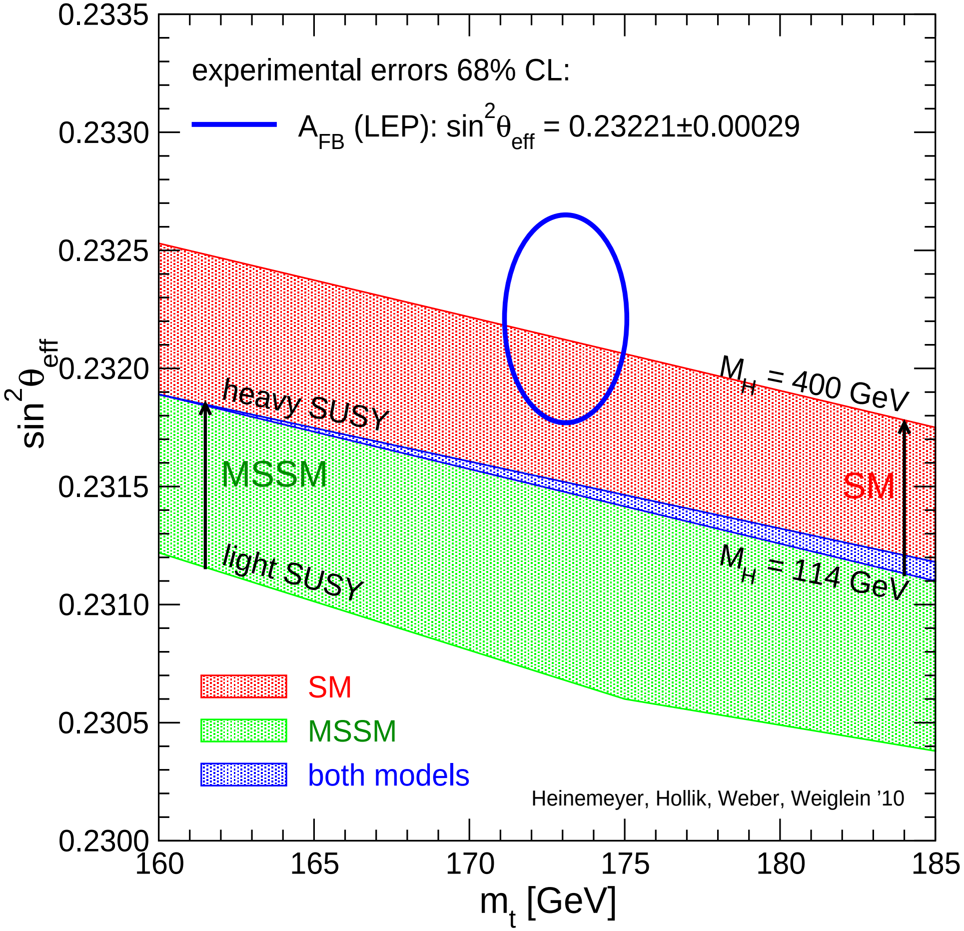



$\Rightarrow$ Good agreement of indirect prediction with experimental result for both models

# $\sin^2\theta_{\rm eff}$ *prediction vs. measured values from* $A_{\rm LR}$ *(SLD) and* $A_{\rm FB}$ *(LEP)*

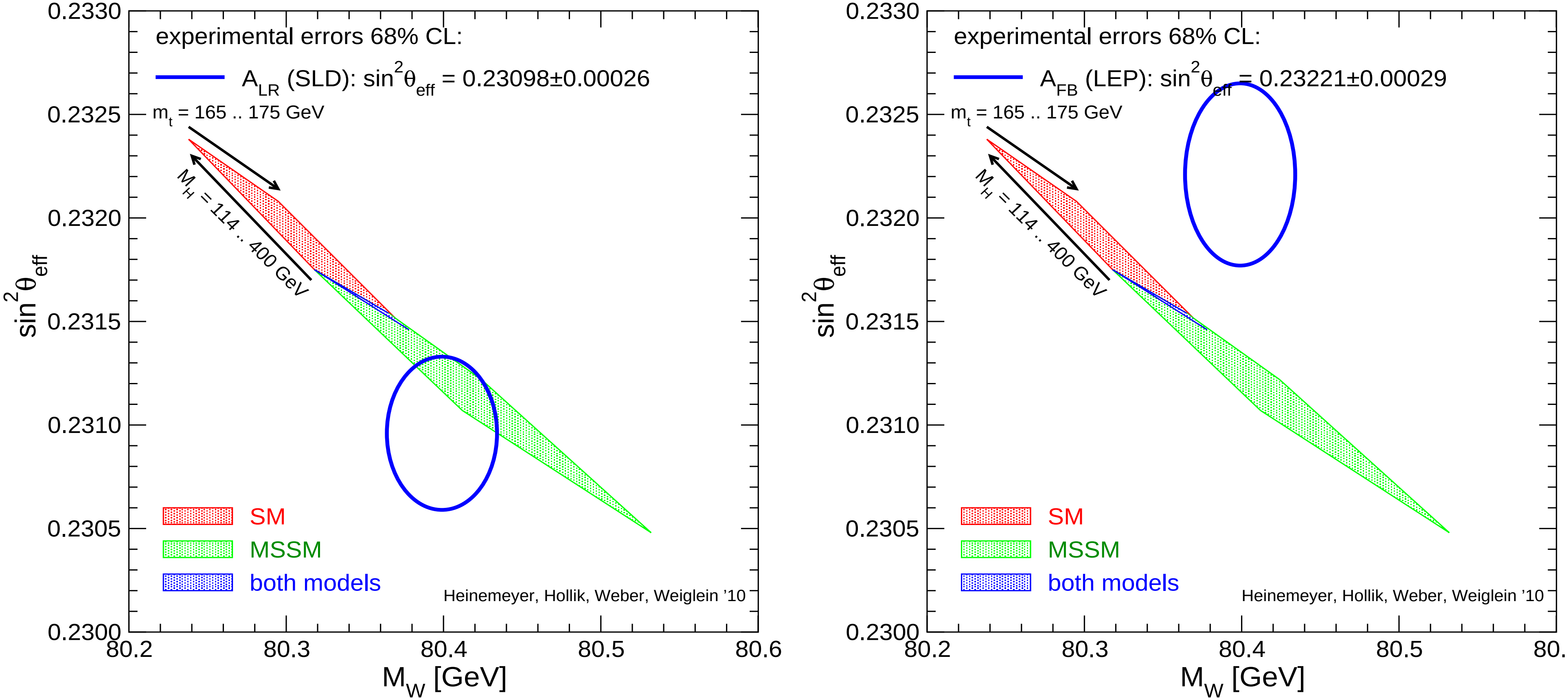
*[S. Heinemeyer, W. Hollik, A.M. Weber, G. W. '10]*




$\Rightarrow$ Large impact on indirect constraints

# $\sin^2\theta_{\text{eff}}$ *prediction vs. measured values from* $A_{\text{LR}}$ *(SLD) and* $A_{\text{FB}}$ *(LEP)*




$\Rightarrow$ Precise $\sin^2\theta_{\text{eff}}$ measurement has the potential to rule out the SM and the MSSM in one go!

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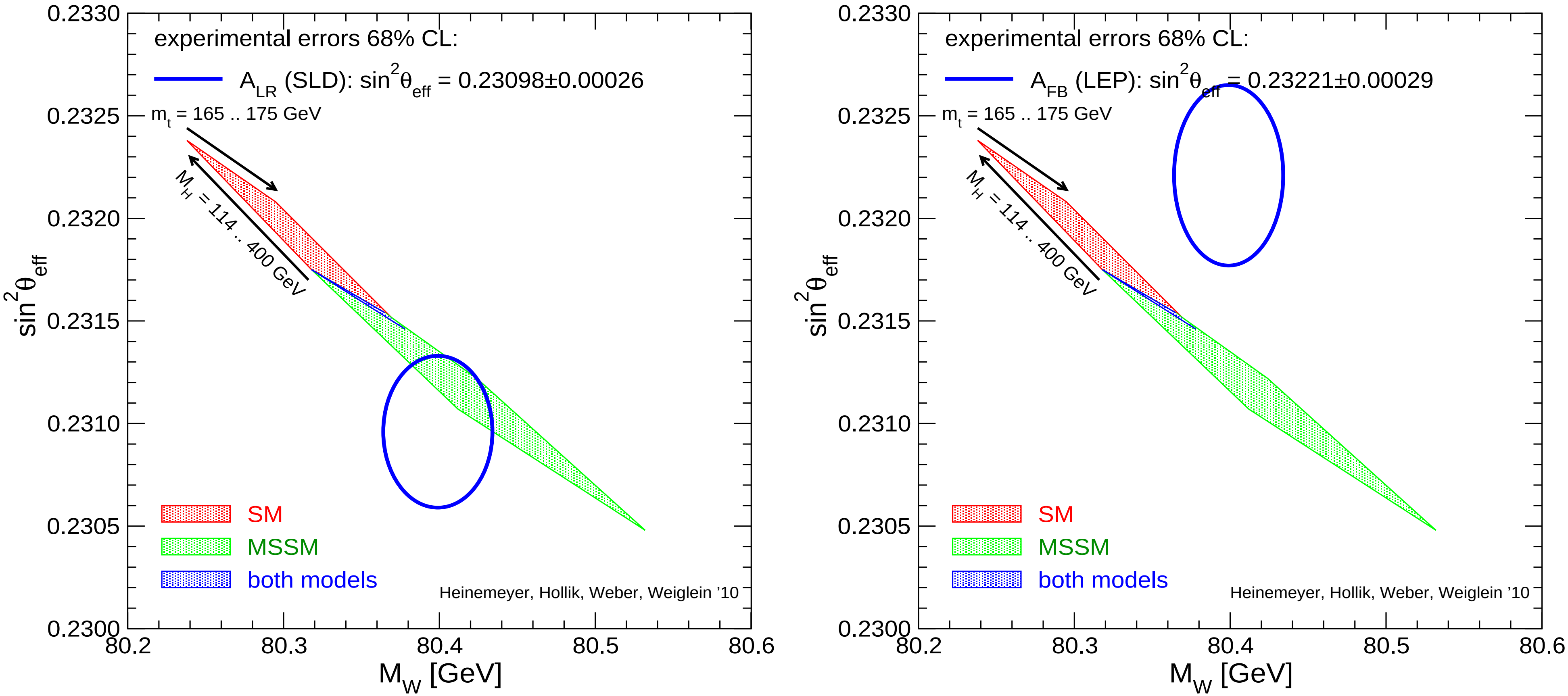


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Any input on this from the LHC?

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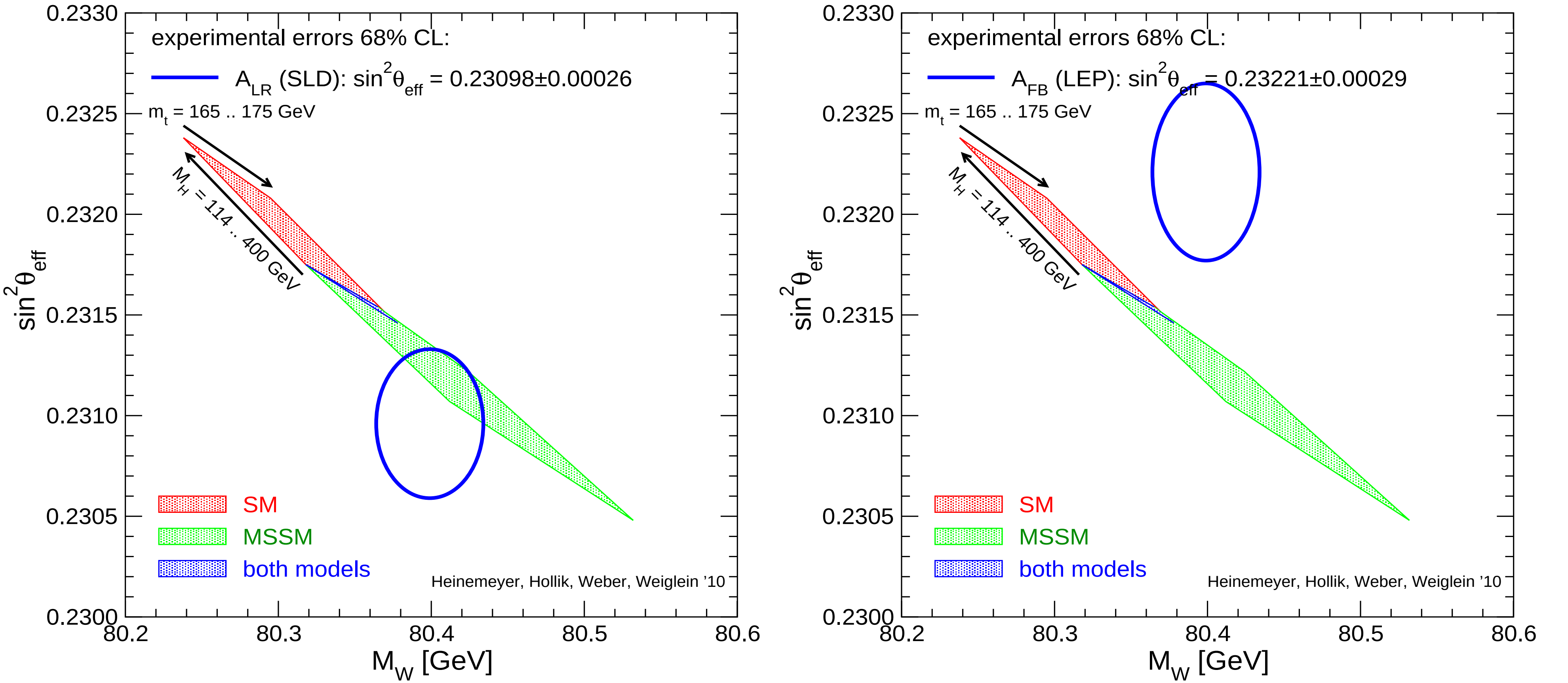


$\Rightarrow$ Precise $\sin^2\theta_{\rm eff}$ measurement has the potential to rule out the SM and the MSSM in one go!

Any input on this from the LHC?

$\Rightarrow$ An $e^+e^-$ Z factory may be needed to resolve the issue!

# *SUSY breaking*

## *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 $M_{\rm Z}$

$\Rightarrow$ 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 $M_{\rm A}$ and $\mu$ after imposing the electroweak vacuum conditions)

Simplest realisation:

$$m^2_{H_1} = m^2_{H_2} \equiv m^2_H$$

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

# Global CMSSM and NUHM1 fits using indirect experimental and cosmological constraints

Global $\chi^2$ 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, ...), $\Omega_{\rm CDM}\, h^2 = 0.1099 \pm 0.0062$
- $+$ $(g-2)_\mu$
- $+$ 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*
  - 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 $\chi^2$ likelihood function

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

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

  Fit parameters: SUSY parameters $m_{1/2}$, $m_0$, $A_0$, $\tan\beta$, $m_H^2$
  $+$ SM parameters $\Delta\alpha_\mathrm{had}$, $m_\mathrm{t}$, $M_\mathrm{Z}$ (simultaneous fit)
  $\Rightarrow$ $\chi^2$ 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

# *SUSY fits*

Various approaches in the literature:

*Fittino*, *SFITTER*, *GFITTER*, *SuperBayeS*, . . .

- Frequentist method / Bayesian method with different priors
- Different predictions for precision observables
- Different ways to sample the parameter space
- Different fit methods
- . . .

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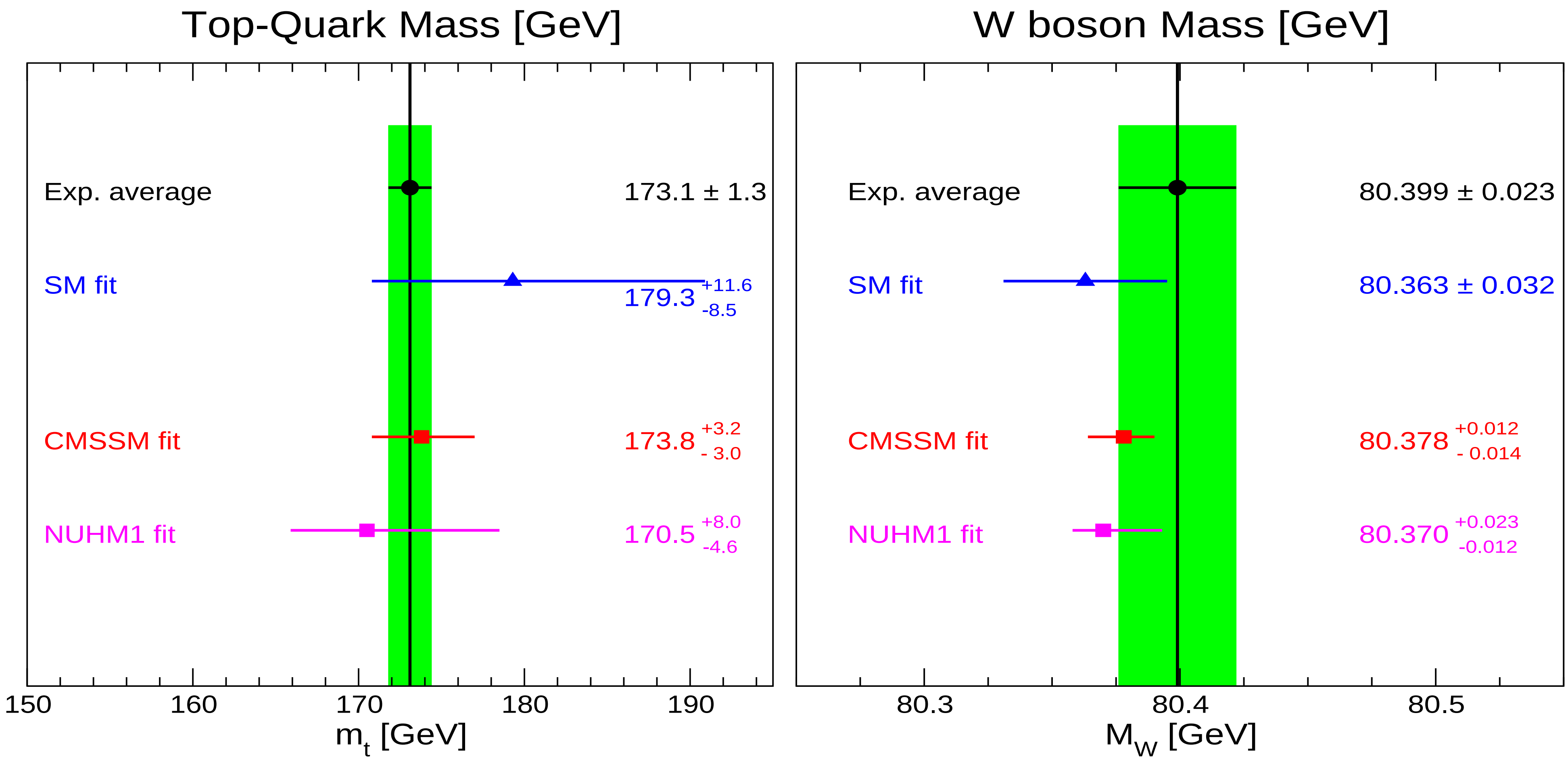
- . . .

$\Rightarrow$ SUSY / BSM Fit Workshop
DESY, Hamburg, July 26–28, 2010

# *Indirect predictions for $M_W$ and $m_t$ in the SM, the CMSSM and the NUHM1 vs. experimental results*

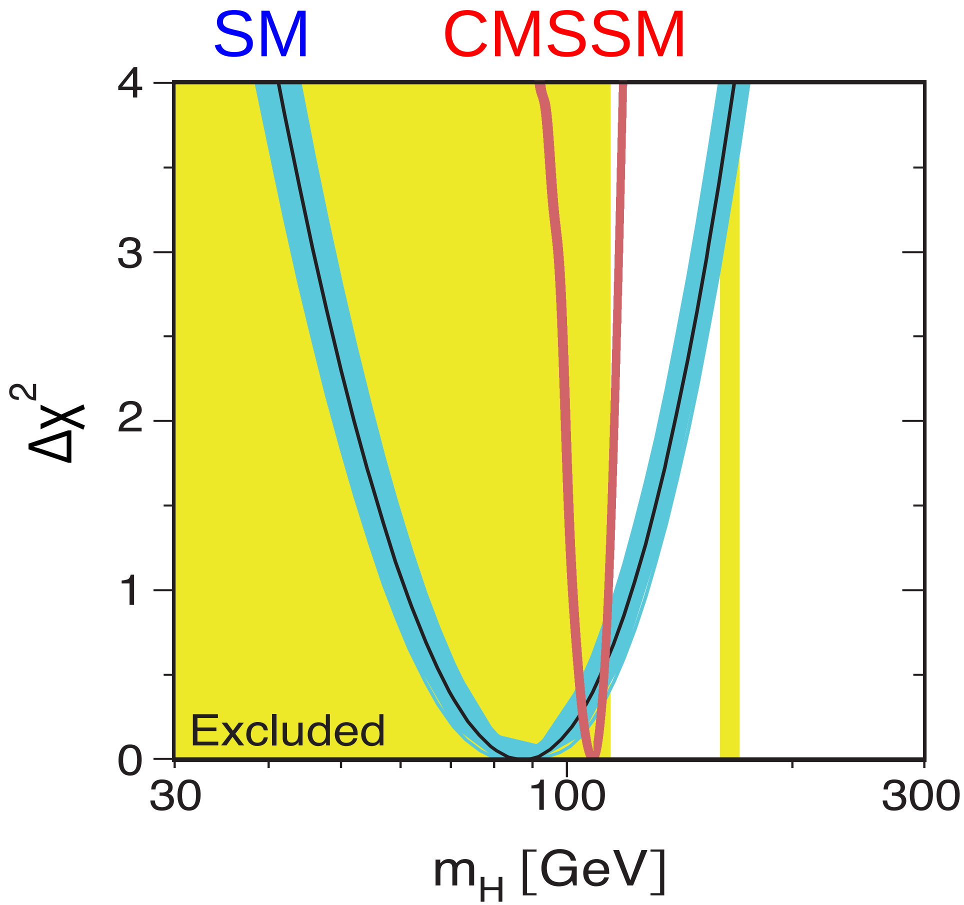
*[O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, F. Ronga, G. W. '09]*

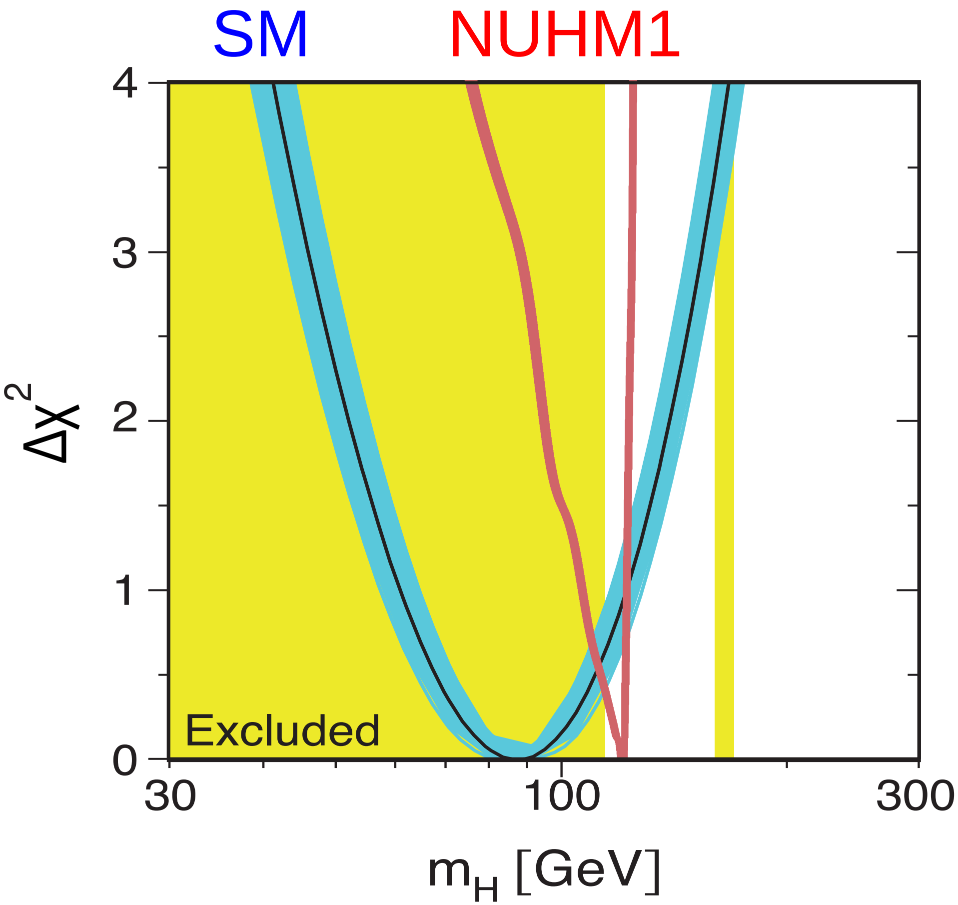



⇒ Remarkable agreement in the CMSSM and the NUHM1

# *Indirect prediction for the Higgs mass in the SM and the CMSSM / NUHM1 from precision data*

$\chi^2$ fit for $M_\mathrm{h}$, without imposing direct search limit



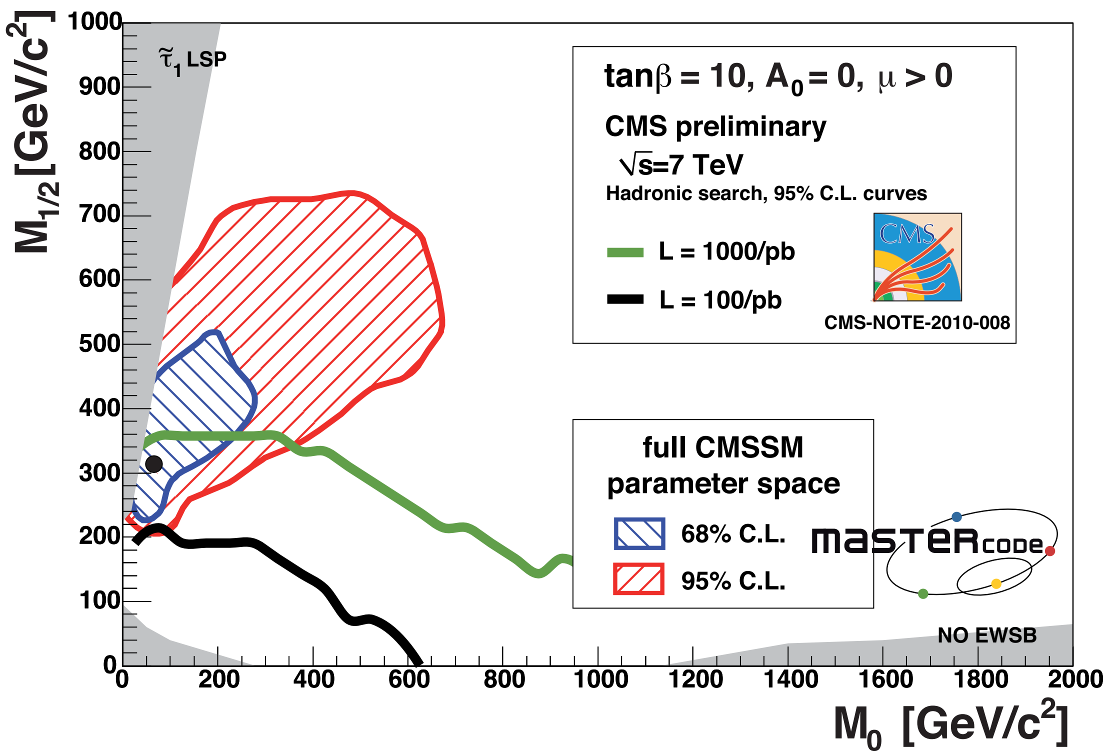

$$M_\mathrm{h}^{\mathrm{CMSSM}} = 108 \pm 6\ \mathrm{GeV} \qquad M_\mathrm{h}^{\mathrm{NUHM1}} = 121^{+2}_{-14}\ \mathrm{GeV}$$

$\Rightarrow$ Accurate indirect prediction; Higgs “just around the corner”?

# Predictions for the SUSY scale from precision data: CMSSM

Comparison: preferred region in the $m_0$–$m_{1/2}$ plane vs. CMS 95% C.L. reach (→ *F. Ronga's talk, Thu.*) for $0.1, 1\ \mathrm{fb}^{-1}$ at $7\ \mathrm{TeV}$

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '10*]

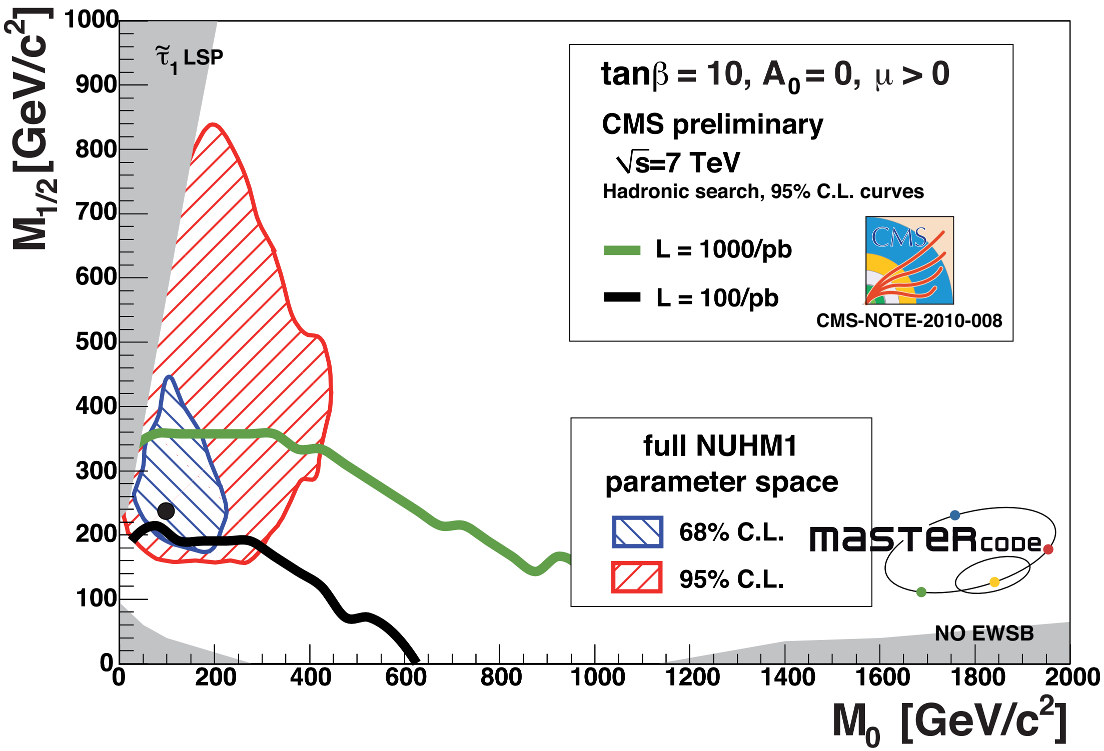



⇒ Good prospects for early discovery! Get hint in first run?

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

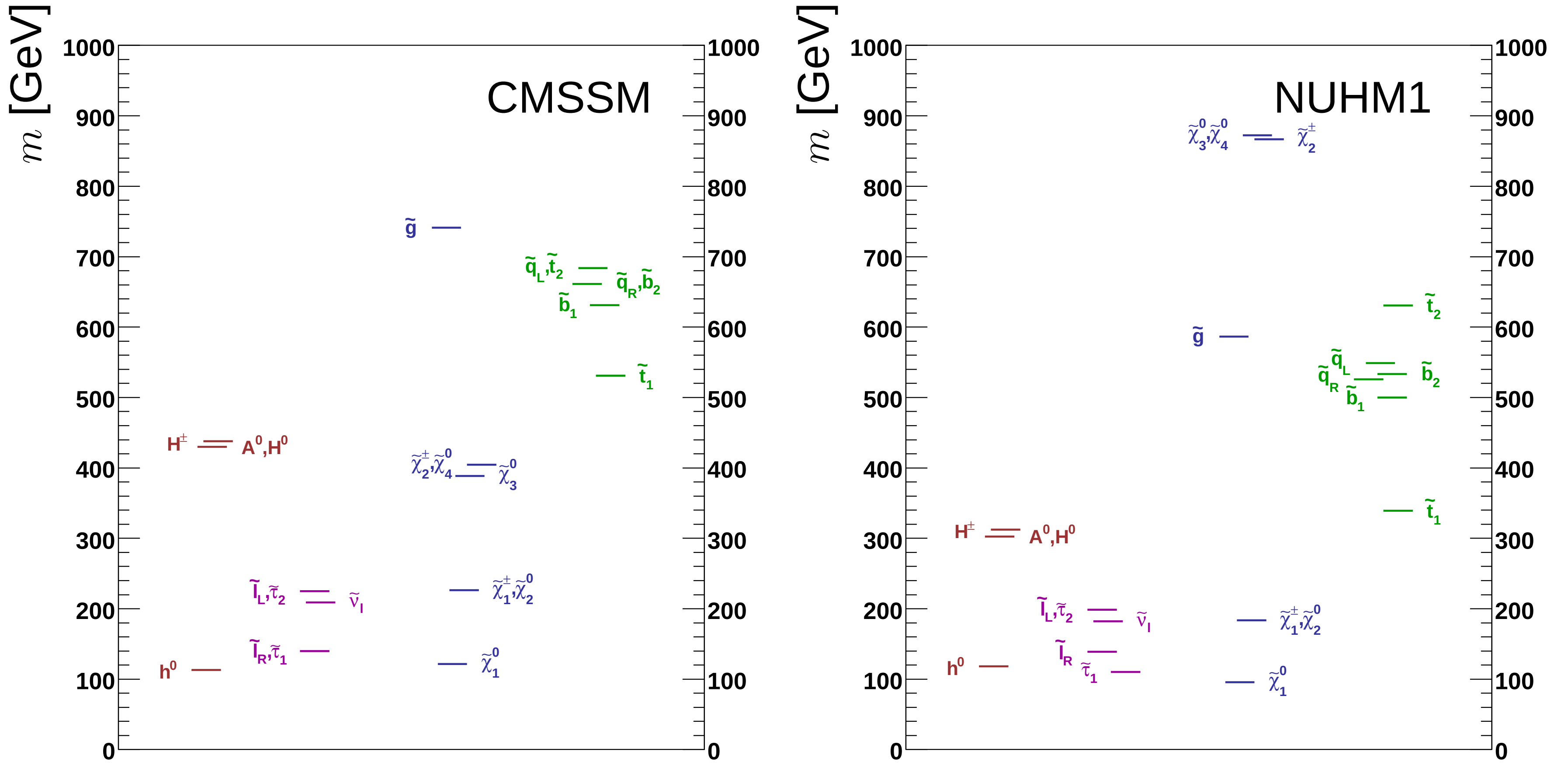
68% and 95% C.L. contours from the fit vs. CMS sensitivities for $0.1, 1\ \mathrm{fb}^{-1}$ at $7\ \mathrm{TeV}$

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '10*]




⇒ Similar as for CMSSM; larger coverage of 68% C.L. region

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



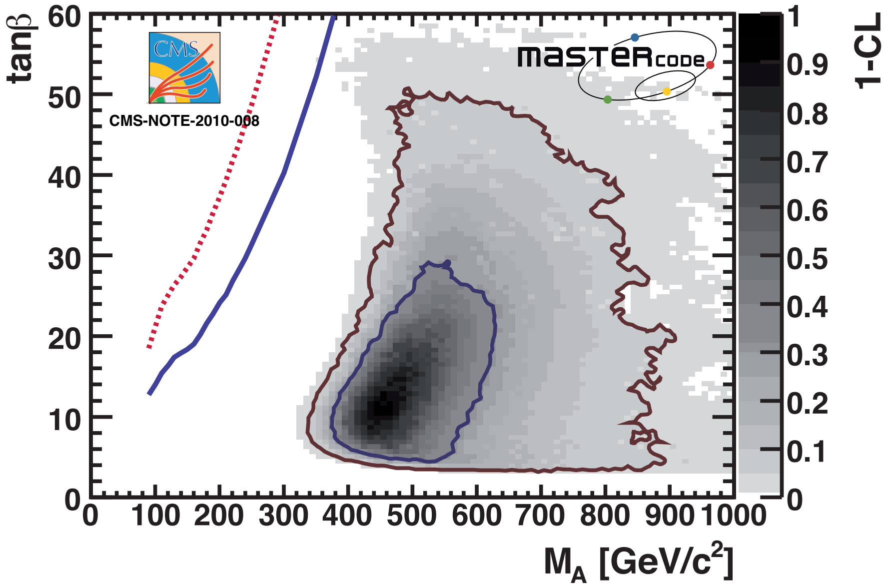

$\Rightarrow$ Similar spectra, close to SPS1a benchmark point

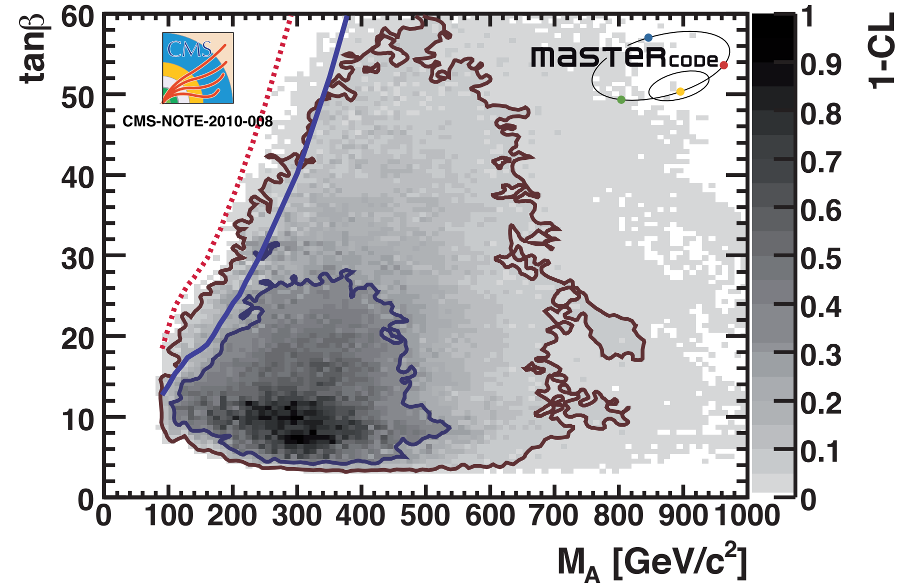
Similar fit probabilities for the two models

Good prospects for LHC and ILC

# *Prospects for SUSY Higgs searches with early LHC data*

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, F. Ronga, G. W. '10*]



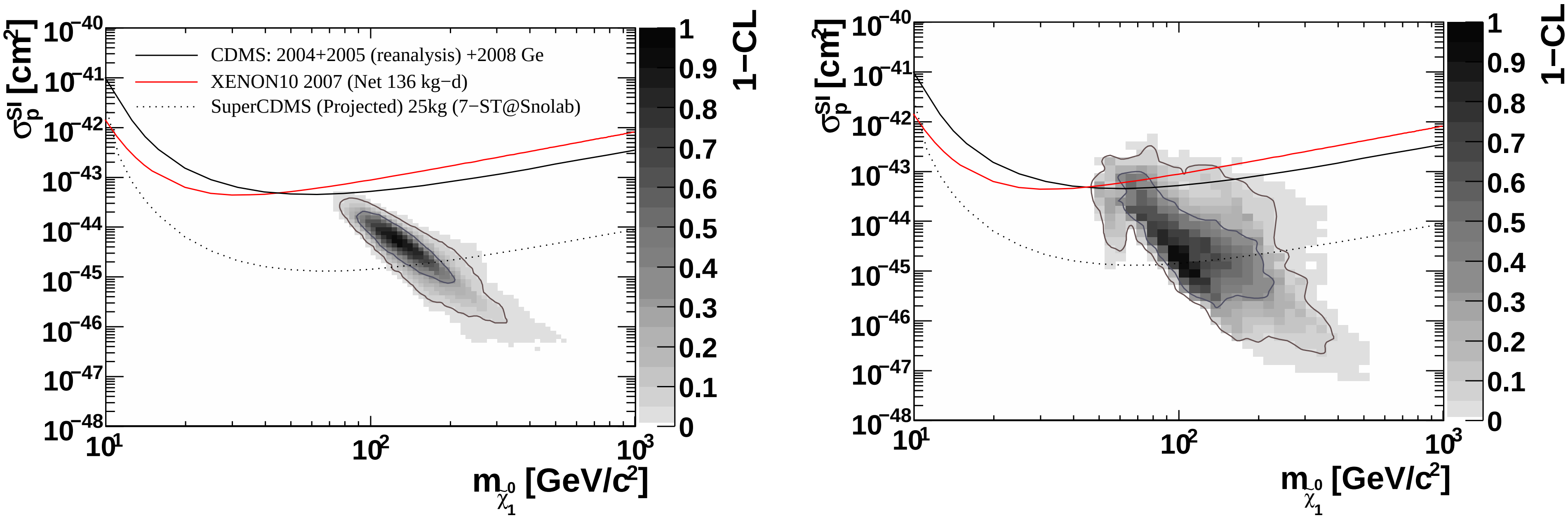




$\Rightarrow$ Chance to discover the heavy MSSM Higgses $H$, $A$ before a light SM-like Higgs $h$ is found

But: not much hope in the CMSSM and NUHM1 with the first $1\ \mathrm{fb}^{-1}$ at $7\ \mathrm{TeV}$

# *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, F. Ronga, G. W. '09*]




⇒ Projected sensitivity of the *SuperCDMS* (and *Xenon 100*) direct detection experiments will probe a sizable part of the preferred region

# *Beyond CMSSM, NUHM1, . . . ?*

What about non-minimal models, sources for $\mathcal{CP}$-violation?

A hint from D0?

[*J. Qian Planck 2010*]

## $A_{sl}^{b}$ Final Result

$$A_{sl}^{b} = \left[-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst})\right]\,\%$$

$$A_{sl}^{b}(SM) = \left[-0.023^{+0.005}_{-0.006}\right]\%$$

**The result is validated by many consistency and closure tests**

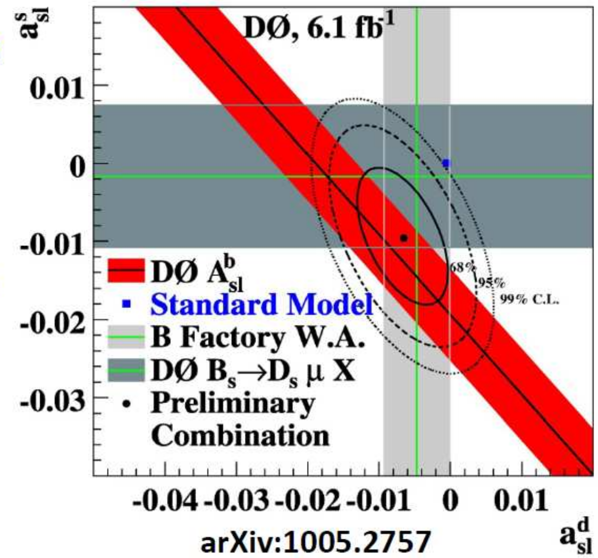
**Both $B_d^0$ and $B_s^0$ are produced at the Tevatron**

$$A_{sl}^{b} = 0.506 a_{sl}^{d} + 0.494 a_{sl}^{s}$$

$$\left( a_{sl}^{b} \equiv \frac{\Gamma(\overline{B} \to \mu^{+} X) - \Gamma(B \to \mu^{-} X)}{\Gamma(\overline{B} \to \mu^{+} X) + \Gamma(B \to \mu^{-} X)} \right)$$

**based on their relative production fractions**

**The result differs from the SM by 3.2σ. Time will tell...**




arXiv:1005.2757

Planck 2010, CERN, May 31 – June 4, 2010 Jianming Qian (University of Michigan) 24

# Sensitivity: present and future

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At present the precision observables provide little sensitivity to the structure of non-minimal SUSY models

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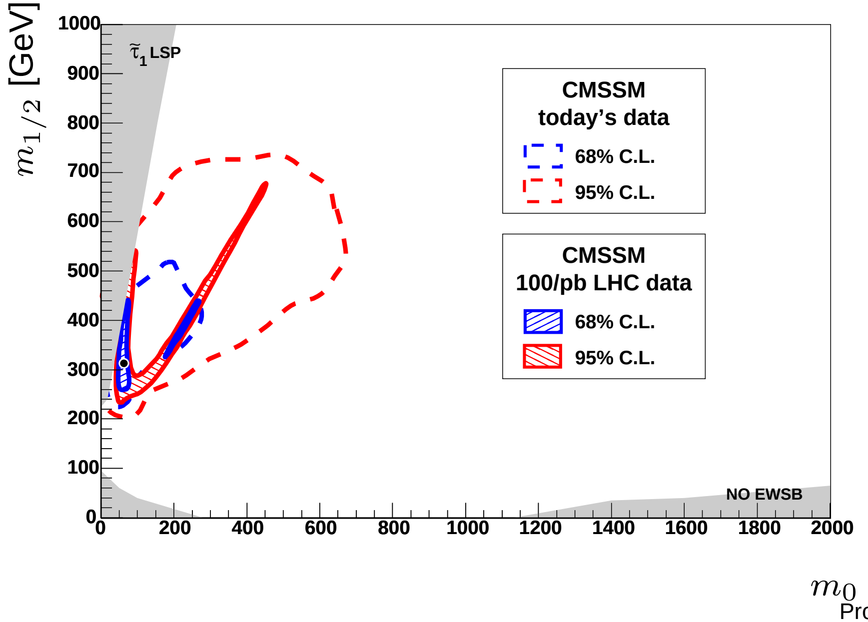
The situation will improve with input from the LHC

Example: CMSSM fit with additional information from measuring the opposite-sign dilepton edge in $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \ell^+ \ell^-$ ($\ell = e, \mu$) with $1\ \mathrm{fb}^{-1}$: [*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 $m_0$, $m_{1/2}$ in the CMSSM

# *MSSM with complex parameters: a very light SUSY Higgs?*

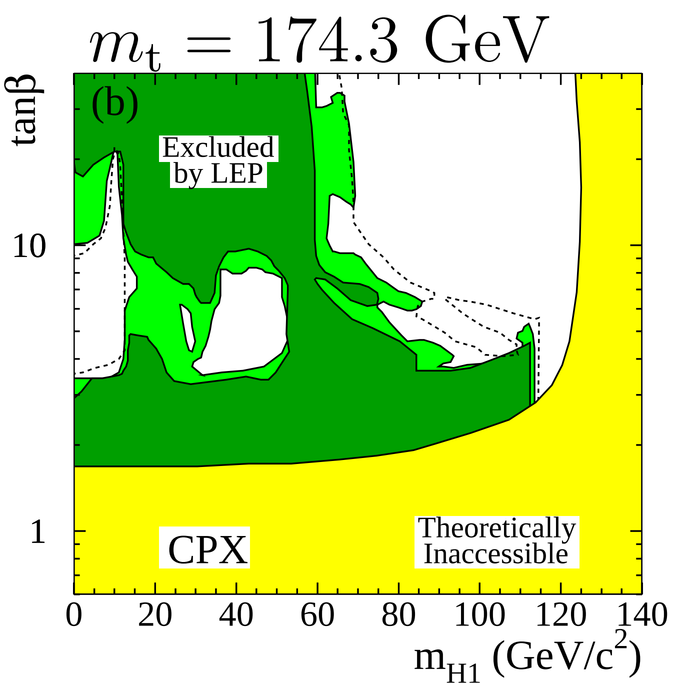
MSSM with $\mathcal{CP}$-violating phases (CPX scenario):

Light Higgs, $h_1$: strongly suppressed $h_1VV$ couplings

Second-lightest Higgs, $h_2$, possibly within LEP reach (with reduced $VVh_2$ coupling), $h_3$ beyond LEP reach

Large $\mathrm{BR}(h_2 \to h_1 h_1)$ $\Rightarrow$ difficult final state

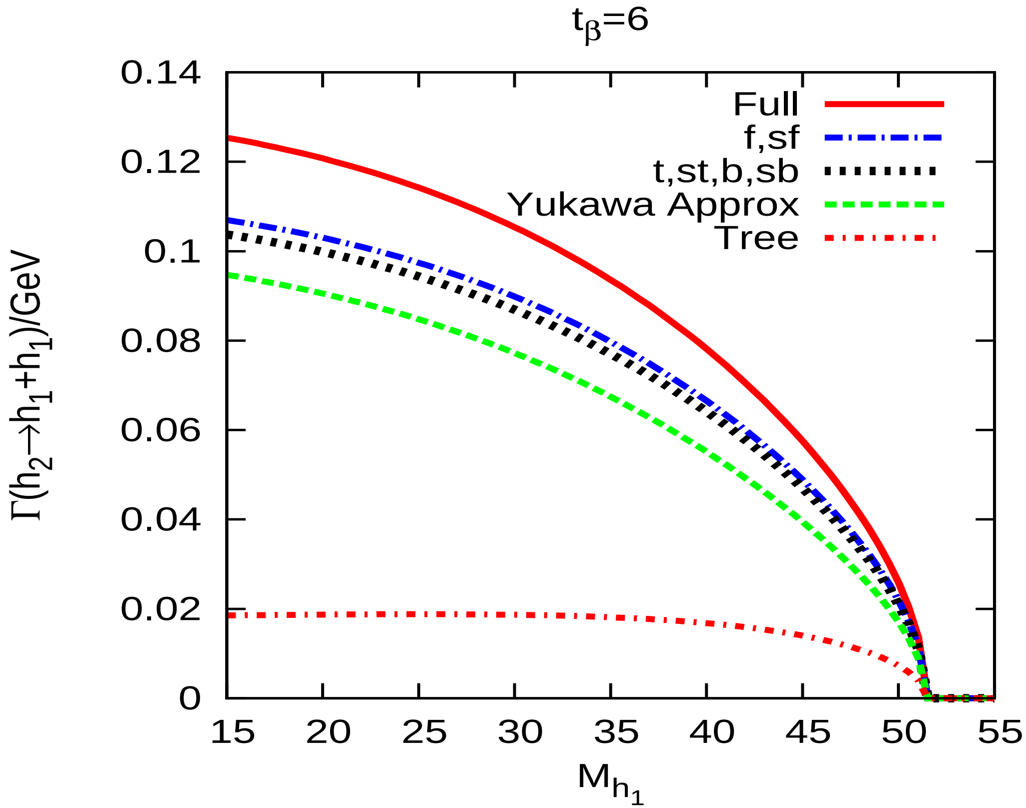
[*LEP Higgs WG '06*]




$\Rightarrow$ Light SUSY Higgs not ruled out!

# *Impact of higher-order corrections on prediction for* $\Gamma(h_2 \to h_1 h_1)$

Complete 1-loop result for $(h_2 h_1 h_1)$ vertex contribution in the MSSM with complex parameters [*K. Williams, G. W. '07*]
$+$ 2-loop propagator corrections; CPX benchmark scenario
[*S. Heinemeyer, W. Hollik, H. Rzehak, G. W. '07*]

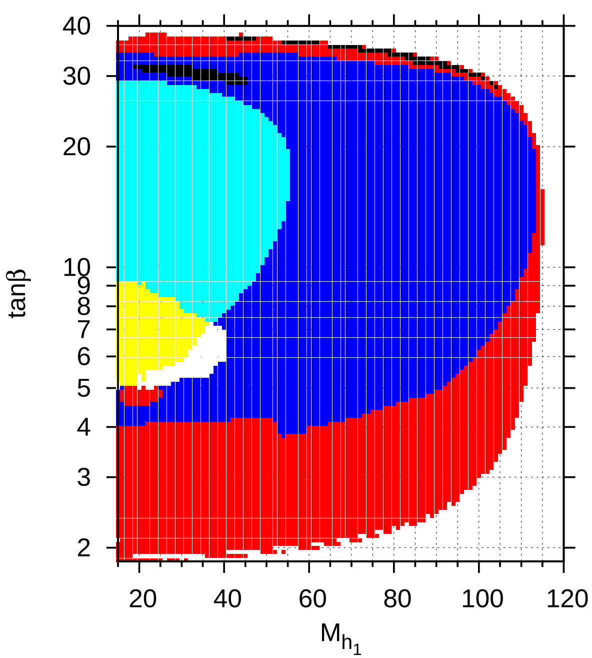



$\Rightarrow$ Huge effect from corrections to genuine $(h_2 h_1 h_1)$ vertex

# *Analysis of LEP coverage with improved theoretical prediction*

HiggsBounds [*P. Bechtle, O. Brein, S. Heinemeyer, G. W., K. Williams '08*]

Use cross section limits (expected and observed) from LEP and the Tevatron; determine for every parameter point the search channel with the highest statistical sensitivity for setting an exclusion; comparison of prediction for this channel with observed limit yields 95% C.L. exclusion contour




Channels:

(red) $= (h_1 Z) \to (b\bar{b}Z)$

(blue) $= (h_2 Z) \to (b\bar{b}Z)$

(white) $= (h_2 Z) \to (h_1 h_1 Z) \to (b\bar{b}b\bar{b}Z)$

(cyan) $= (h_2 h_1) \to (b\bar{b}b\bar{b})$

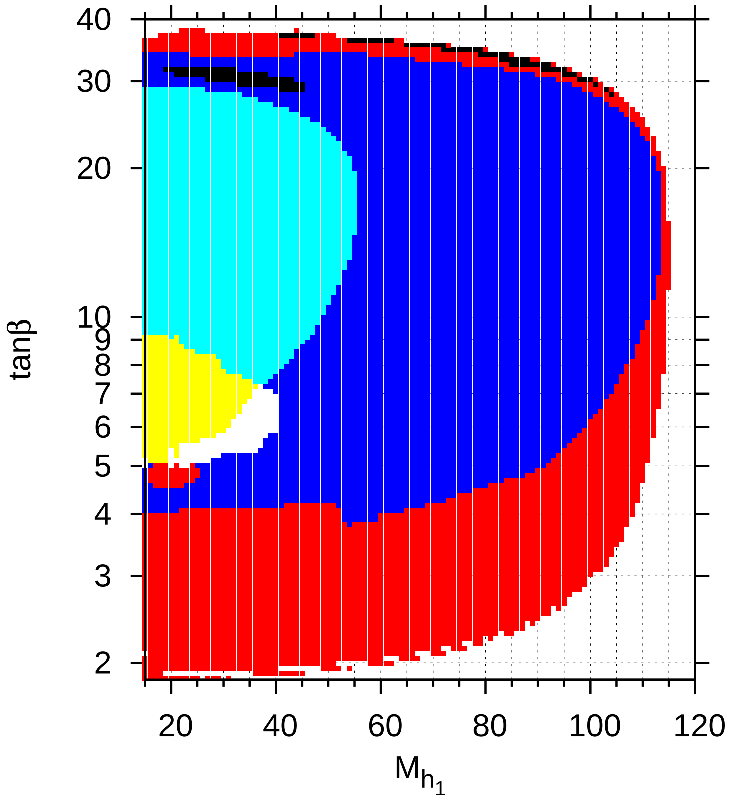
(yellow) $= (h_2 h_1) \to (h_1 h_1 h_1) \to (b\bar{b}b\bar{b}b\bar{b})$

(black) $=$ other channels

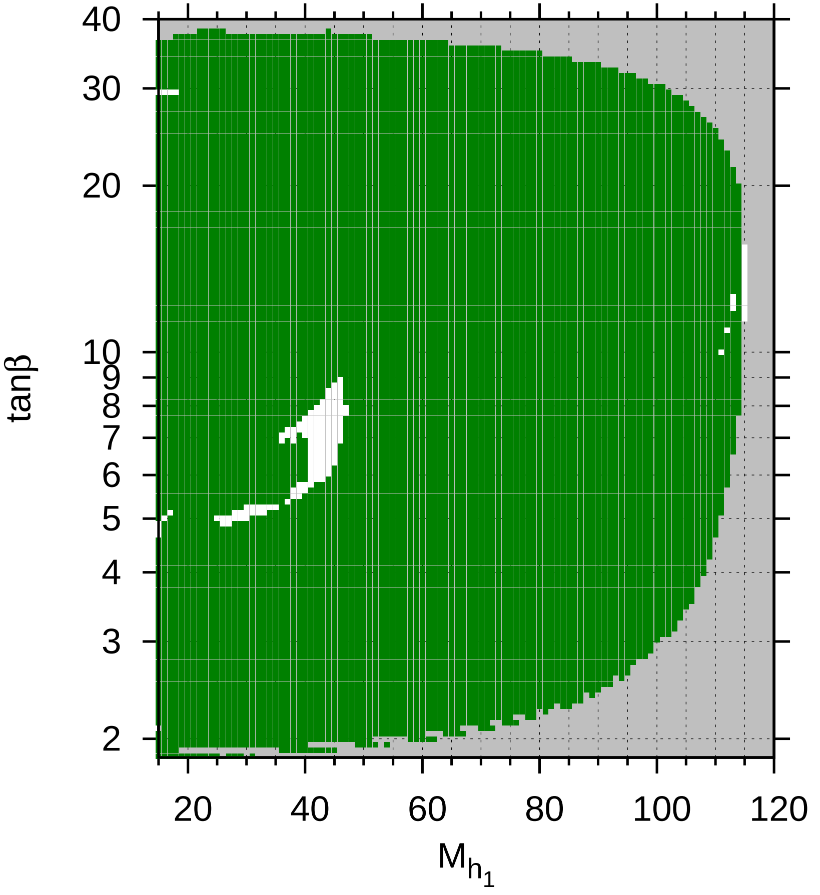
# *Impact on exclusion bounds from the LEP Higgs searches, CPX scenario,* $m_\mathrm{t} = 170.9\ \mathrm{GeV}$

Channels (*HiggsBounds*)

$(\square) : (h_2 Z) \to (h_1 h_1 Z) \to (b\bar{b}b\bar{b}Z)$




Excluded region from LEP, 95% C.L. [*K. Williams, G. W. '07*]




$\Rightarrow$ Confirmation of the "hole" in the LEP coverage

$\Rightarrow$ Very light Higgs boson is not excluded

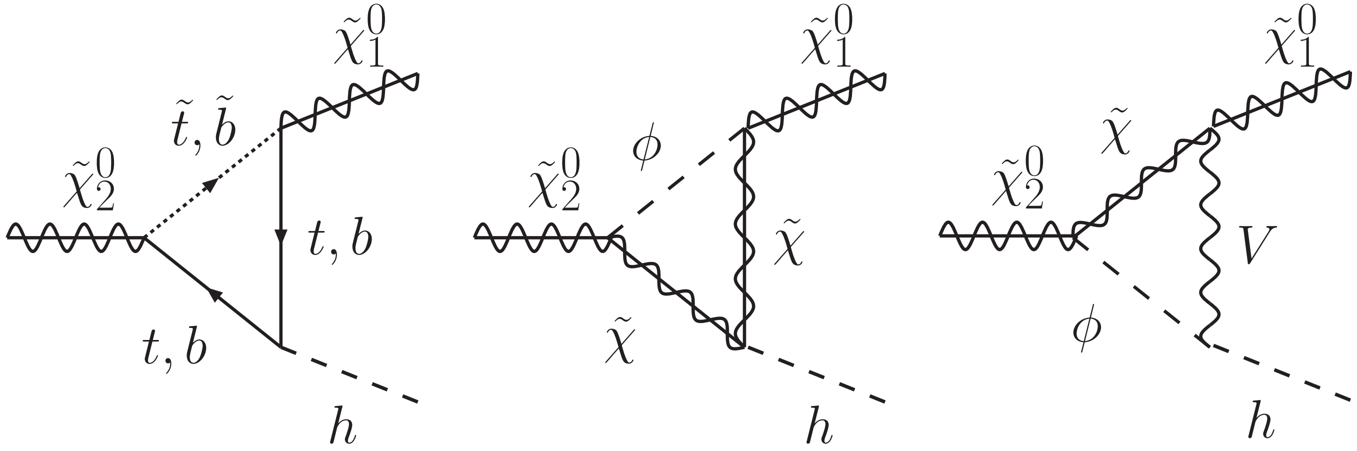
# Higgs production in SUSY cascade decays

SUSY cascade decays could be a promising Higgs source

E.g. $\mathcal{CP}$-violating scenario: very light Higgs, $M_{\mathrm{h}_1} \approx 40~\mathrm{GeV}$ not excluded by LEP, difficult to cover with standard search channels at the LHC

$\Rightarrow \tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h$ can dominate over $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 l \bar{l}$

[*A. Fowler, G. W. '09*]




$\Rightarrow$ CPX scenario: 13% of the gluinos decay into $h_1$

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  Good prospects for SUSY searches with early LHC data and for searches for direct detection of dark matter

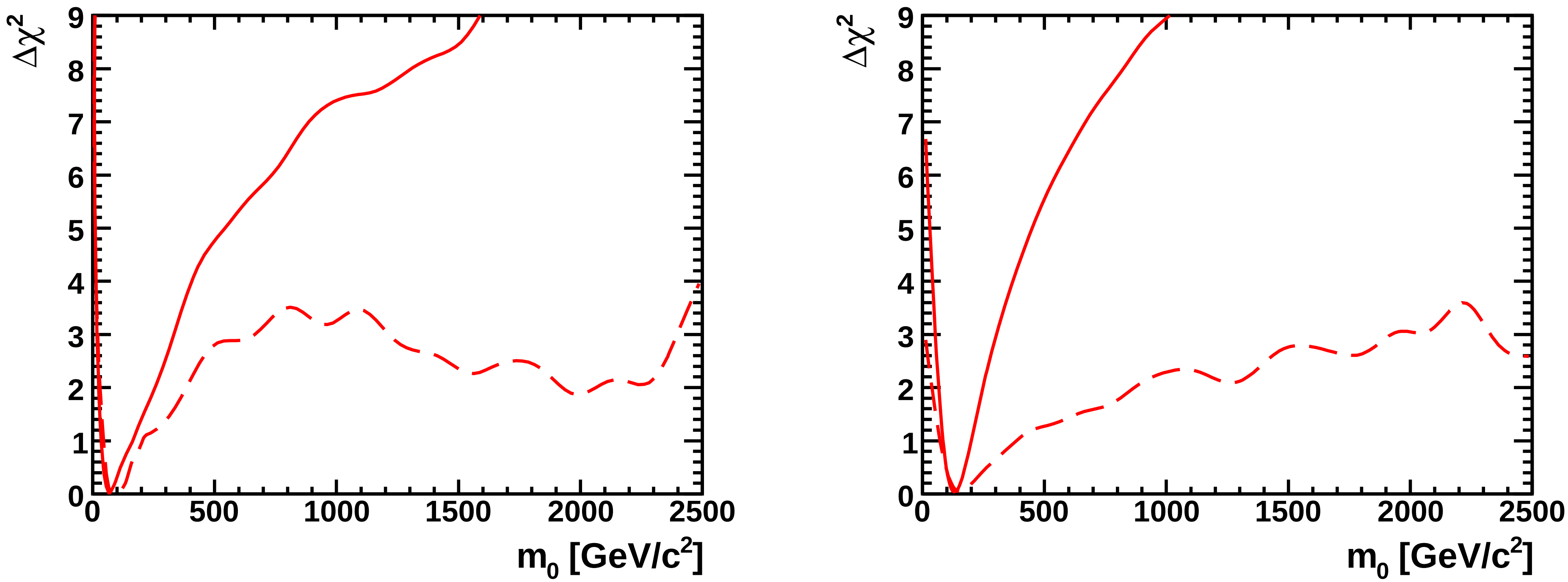
- Prospects for Higgs searches in non-minimal SUSY models:

  Chance to discover the heavy MSSM Higgses before a light SM-like Higgs (Tevatron has also search potential)

  A very light MSSM Higgs boson is not excluded
  Could be produced at LHC in SUSY cascade decays

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

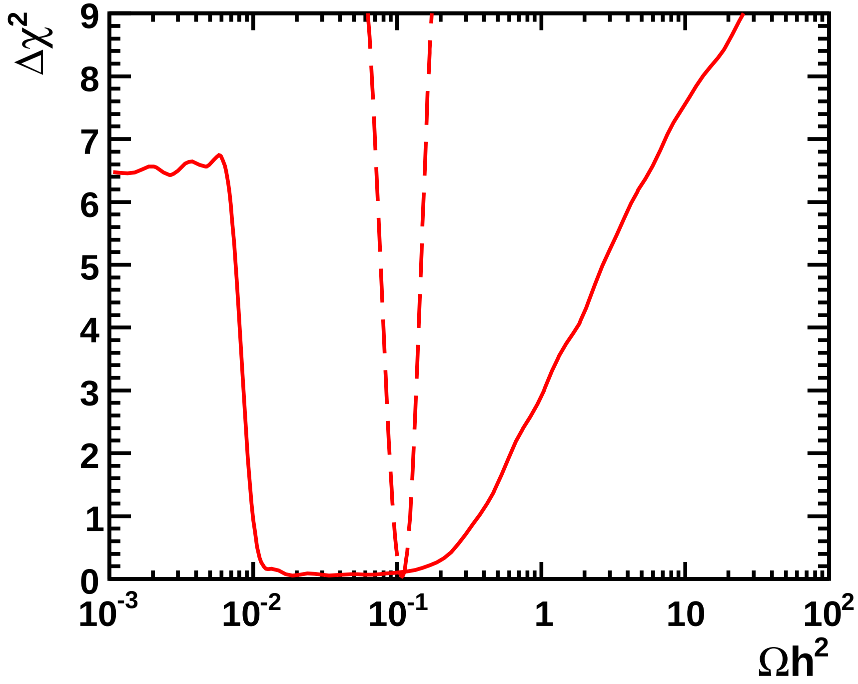
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, F. Ronga, G. W. '09*]

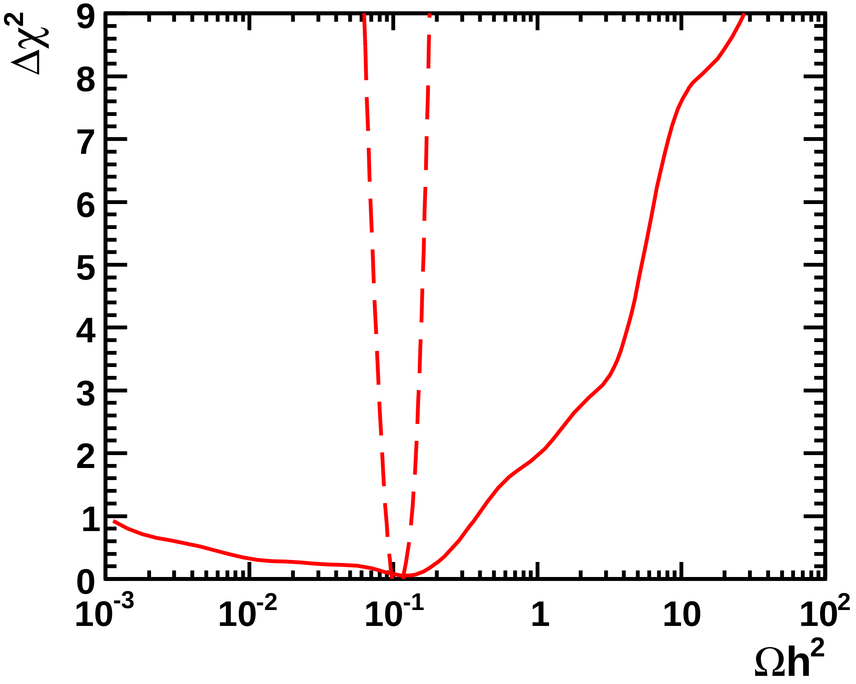



$\Rightarrow$ Slight Preference for light SUSY scale even if $(g_\mu - 2)$ is excluded from the fit

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

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




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