SUSY Prediction for the ILC

Sven Heinemeyer, IFCA (CSIC, Santander)

Geneva, 10/2010

based on collaboration with
O. Buchmüller, R. Cavanaugh, A. de Roeck, J. Ellis, H. Flächer, G. Isidori, K. Olive, S. Rogerson, F. Ronga, G. Weiglein

1. Introduction and motivation
2. The models and the tools
3. Predictions for the ILC
4. The future: GigaZ/Z factory
5. Conclusions

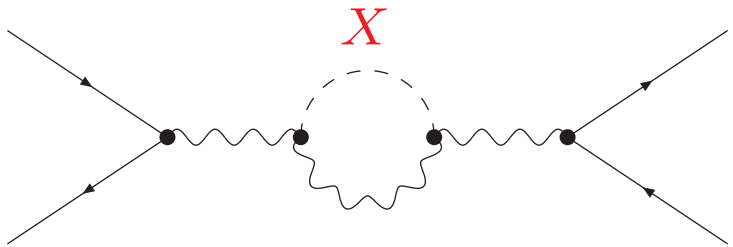
1. Introducion: How to make a prediction?

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



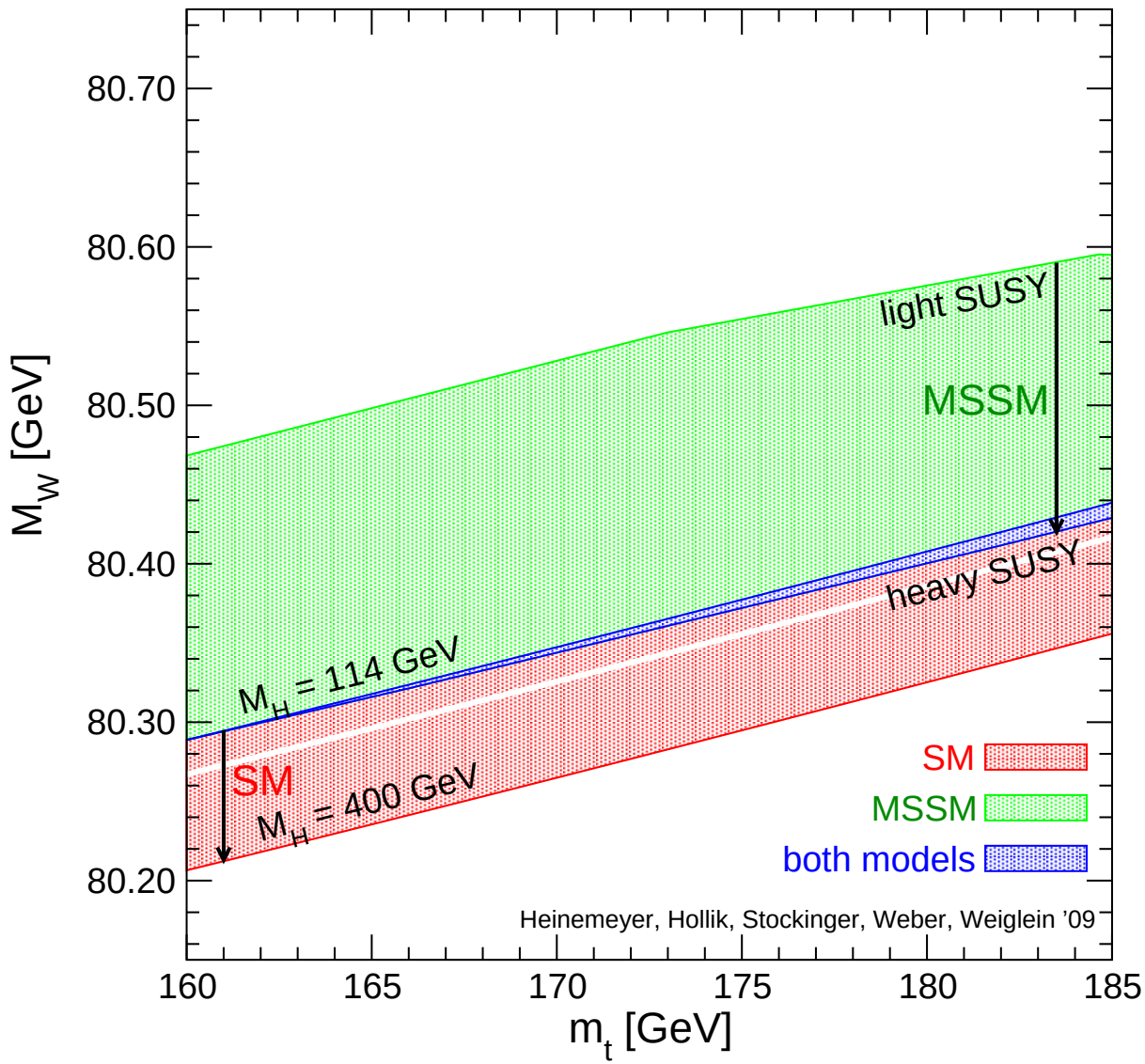
$\Downarrow$

$\Rightarrow$ Information about unknown parameters

Very high accuracy of measurements and theoretical predictions needed

Example: Prediction for M_W in the SM and the MSSM :

[S.H., W. Hollik, D. Stockinger, A. Weber, G. Weiglein '07]



MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of $M_H^{\rm SM}$

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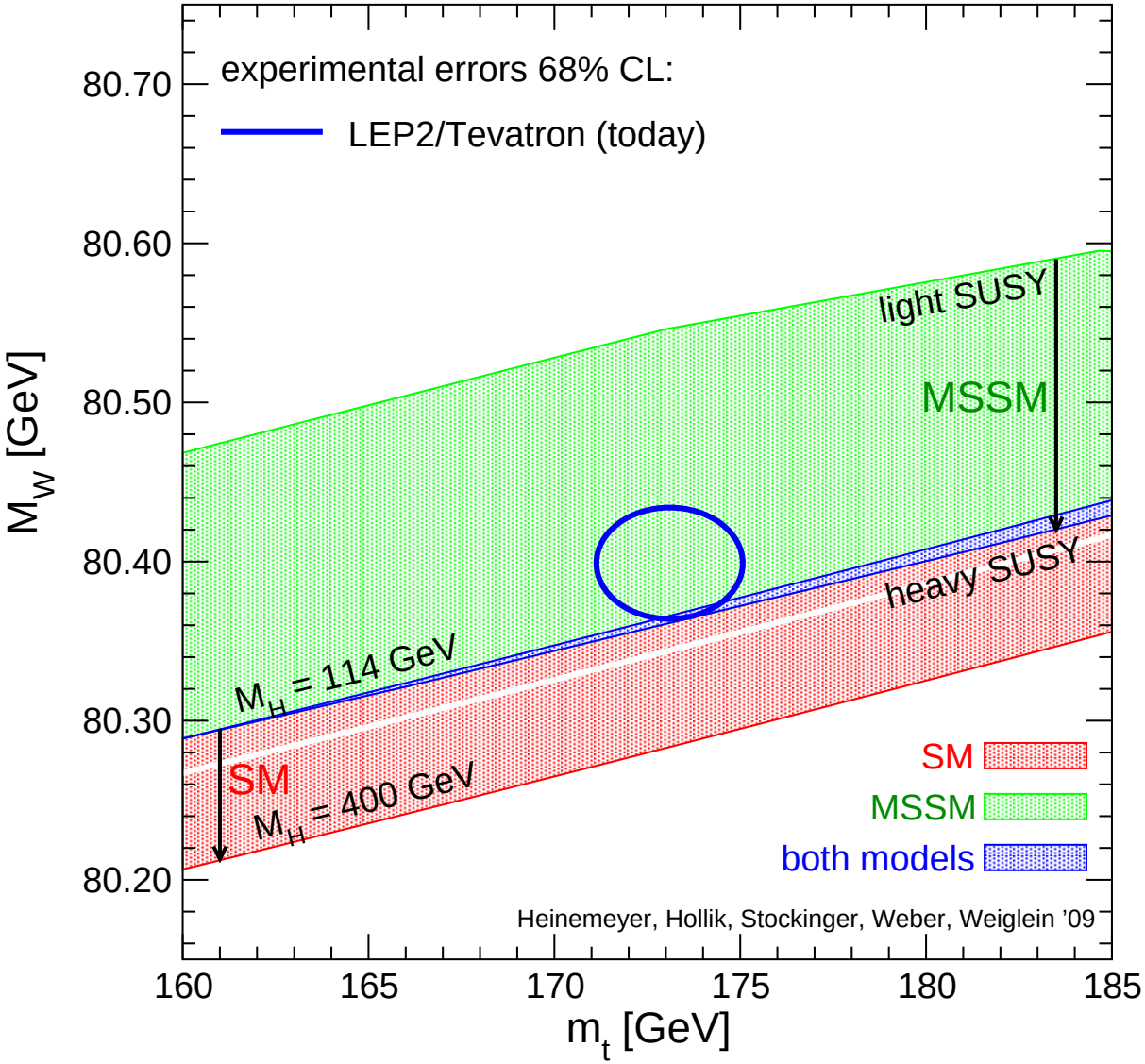

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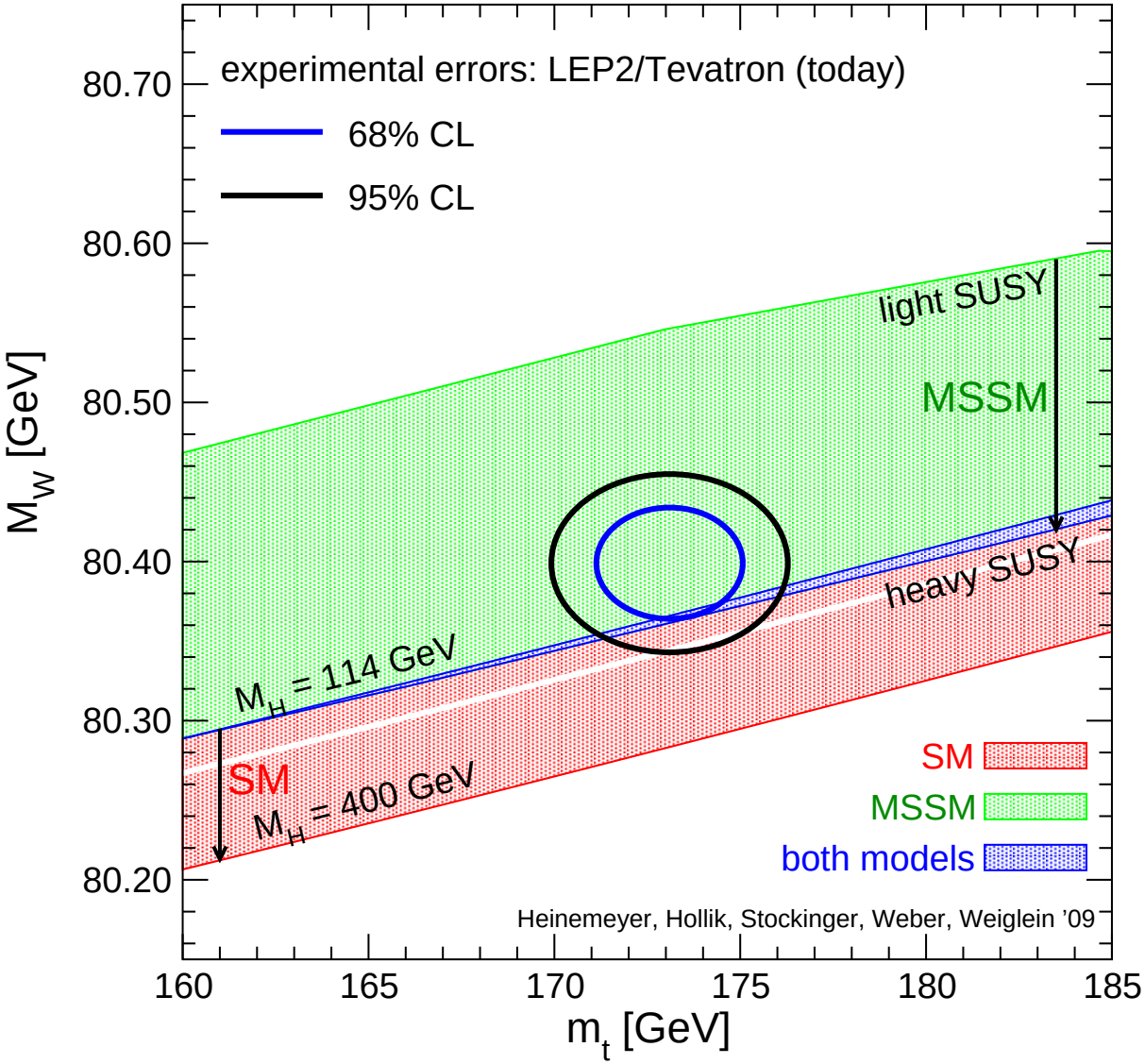

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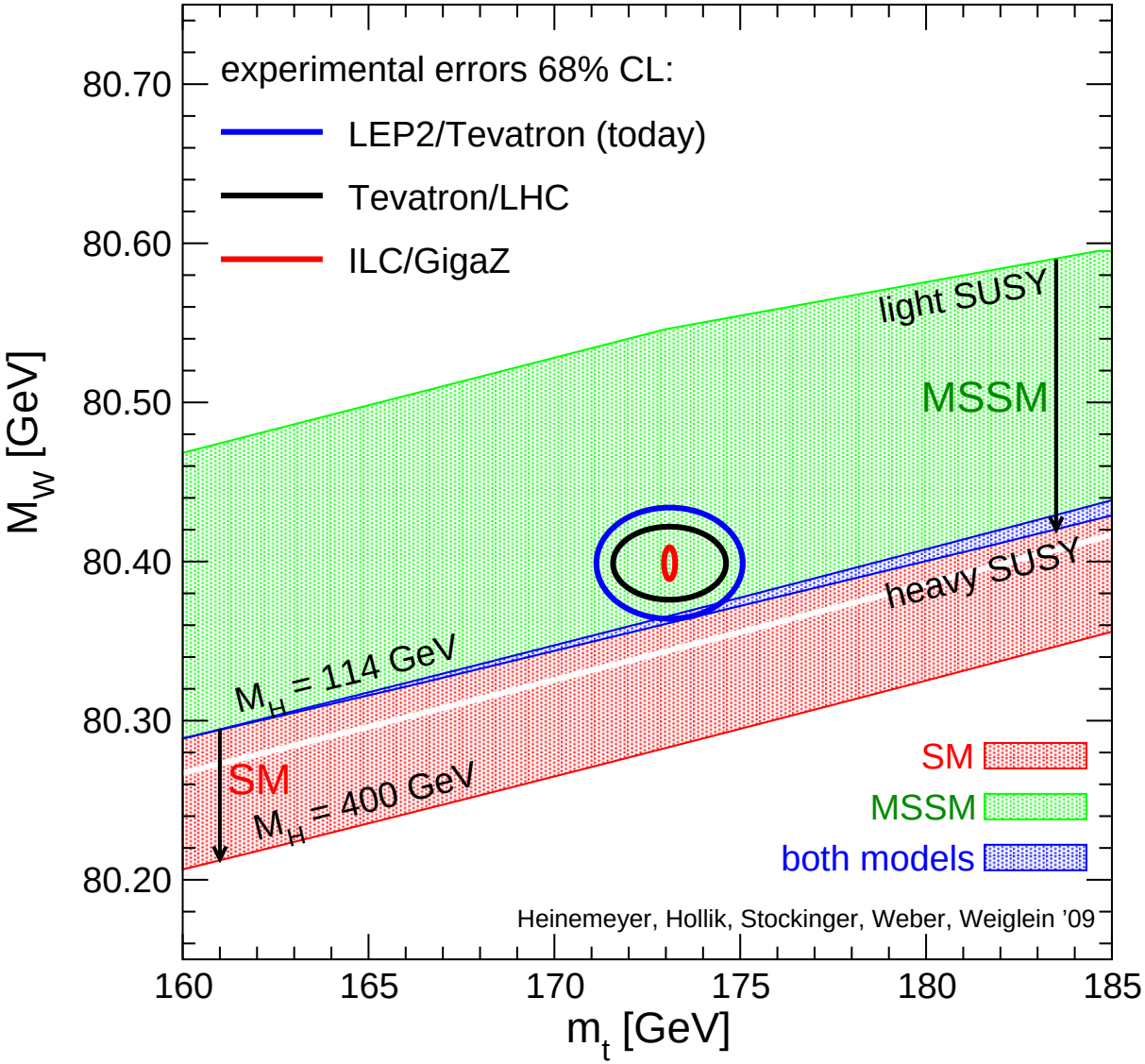

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overlap:
SM is MSSM-like
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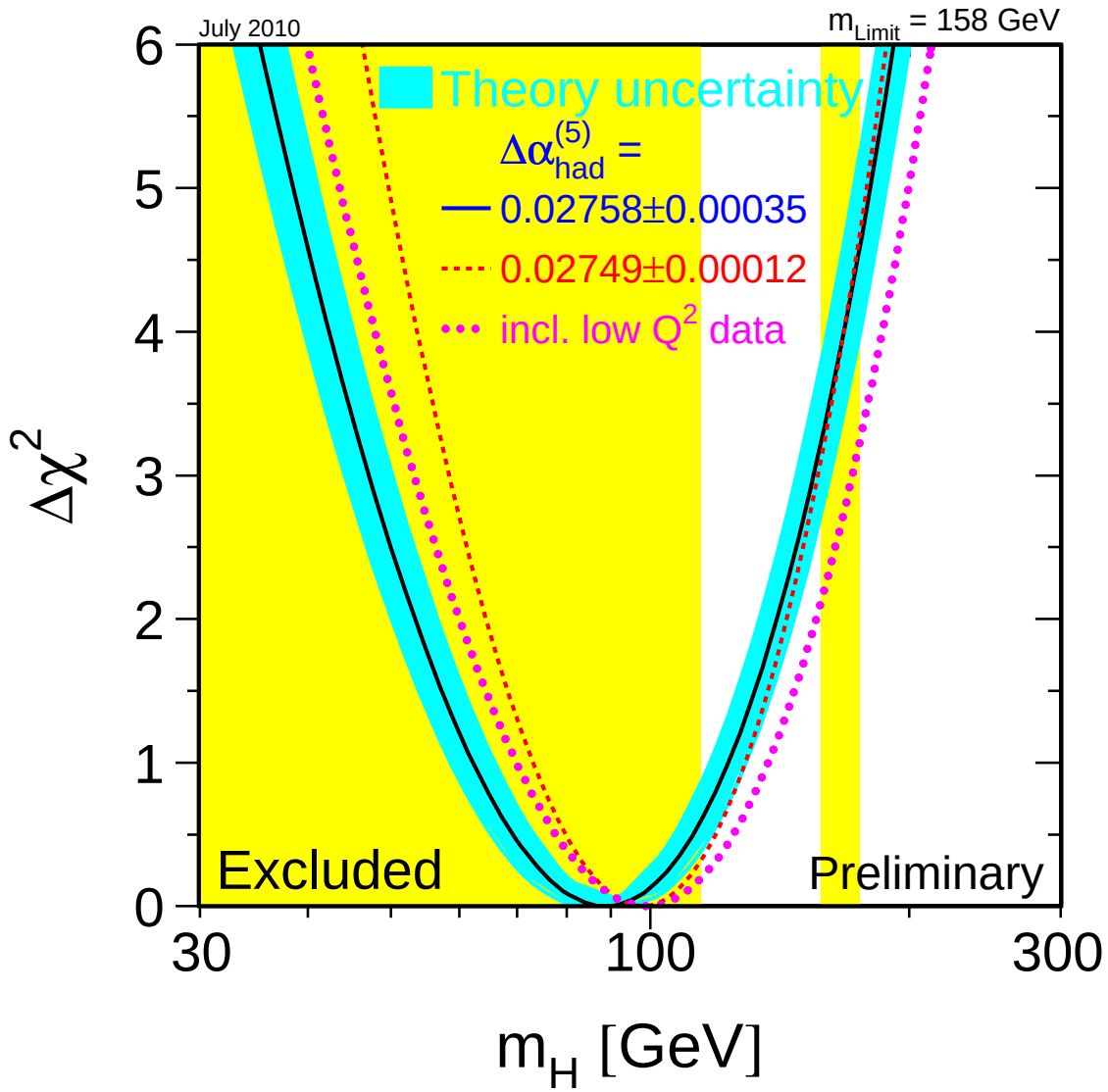
SM band:
variation of $M_H^{\rm SM}$

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 the MasterCode: do "the same" in Supersymmetry!

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. The models and the tools

Our tool:

The "MasterCode"

⇒ collaborative effort of theorists and experimentalists

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

Über-code for the combination of different tools:

- Über-code original in Fortran, now re-written in C++
- tools are included as subroutines
- compatibility ensured by collaboration of authors of "MasterCode" and authors of "sub tools" /SLHA(2)
- sub-codes in Fortran or C++

⇒ evaluate observables of one parameter point consistently with various tools

cern.ch/mastercode

Status of the "MasterCode":

- one model: (MFV) MSSM (see below)

- tools included:
  - B-physics observables [*SuFla*]
  - more B-physics observables [*SuperIso*]
  - Higgs related observables, $(g-2)_\mu$ [*FeynHiggs*]
  - Electroweak precision observables [*FeynWZ*]
  - Dark Matter observables [*MicrOMEGAs, DarkSUSY*]
  - for GUT scale models: RGE running [*SoftSusy*]

$\Rightarrow$ all most-up-to-date codes on the market!

- added: χ^2 analysis code [*Minuit*]

- currently being implemented:
  - Higgs constraints (for χ^2 contributions . . .) [*HiggsBounds*]

- planned: inclusion of more tools / more models

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Different methods:

1.) Scanning:

- 3-dim scans (possibly with CDM fixing one dimension)
- multi-dim scans
- multi-dim scans (with Markov Chain Monte Carlo technique)

$\Rightarrow$ MasterCode: multi-dim scans with MCMC technique

2.) Fitting:

- Frequentist
- Bayesian

$\Rightarrow$ MasterCode: Frequentist

$\Rightarrow$ χ^2 function to include all experimental results

3.) Priors . . . (none)

In general:

The MasterCode can perform fits in the (MFV) MSSM

(ready for NMFV MSSM: [*FeynHiggs, SuFla*])

However:

Concentrating on existing experimental data fits make sense only in GUT based models:

- CMSSM
- NUHM1, NUHM2
- mSUGRA
- VCMSSM
- ...

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- NUHM1, NUHM2
- mSUGRA
- VCMSSM
- ...

⇒ analyses exist already, to be shown here

⇒ analyses currently performed

3. Predictions for the ILC

[*Buchmüller, Cavanaugh, De Roeck, Ellis, Flächer, S.H., Isidori, Olive, Ronga, Weiglein '09*]

– combine all electroweak precision data as in the SM
– combine with B physics observables
– combine with CDM and $(g-2)_\mu$
– include SM parameters with their errors: m_t, M_Z, $\Delta\alpha_{\text{had}}$

$\Rightarrow \chi^2$ function

$\rightarrow$ scan over the full CMSSM/NUHM1 parameter space

$\sim 2.5\ 10^7$ points samples with MCMC

statistical measure: χ^2 function (Frequentist, no priors)

$\rightarrow$ final minimum: Minuit

$\Delta\chi^2$: 68, 95% C.L. contours

$\Rightarrow$ preferred CMSSM/NUHM1 parameters $\boxed{\Rightarrow \text{ILC reach / } \mathcal{L}_{\text{SUSY}}}$

Best-fit points:

[2009]

CMSSM:

$m_{1/2} = 310$ GeV, $m_0 = 60$ GeV, $A_0 = 130$ GeV,

$\tan\beta = 11$, $\mu = 400$ GeV, $M_A = 450$ GeV

$\chi^2/N_{\text{dof}} = 20.6/19$ (36 % probability)

$\Rightarrow$ very similar to SPS 1a :-)

NUHM1:

$m_{1/2} = 270$ GeV, $m_0 = 150$ GeV, $A_0 = -1300$ GeV,

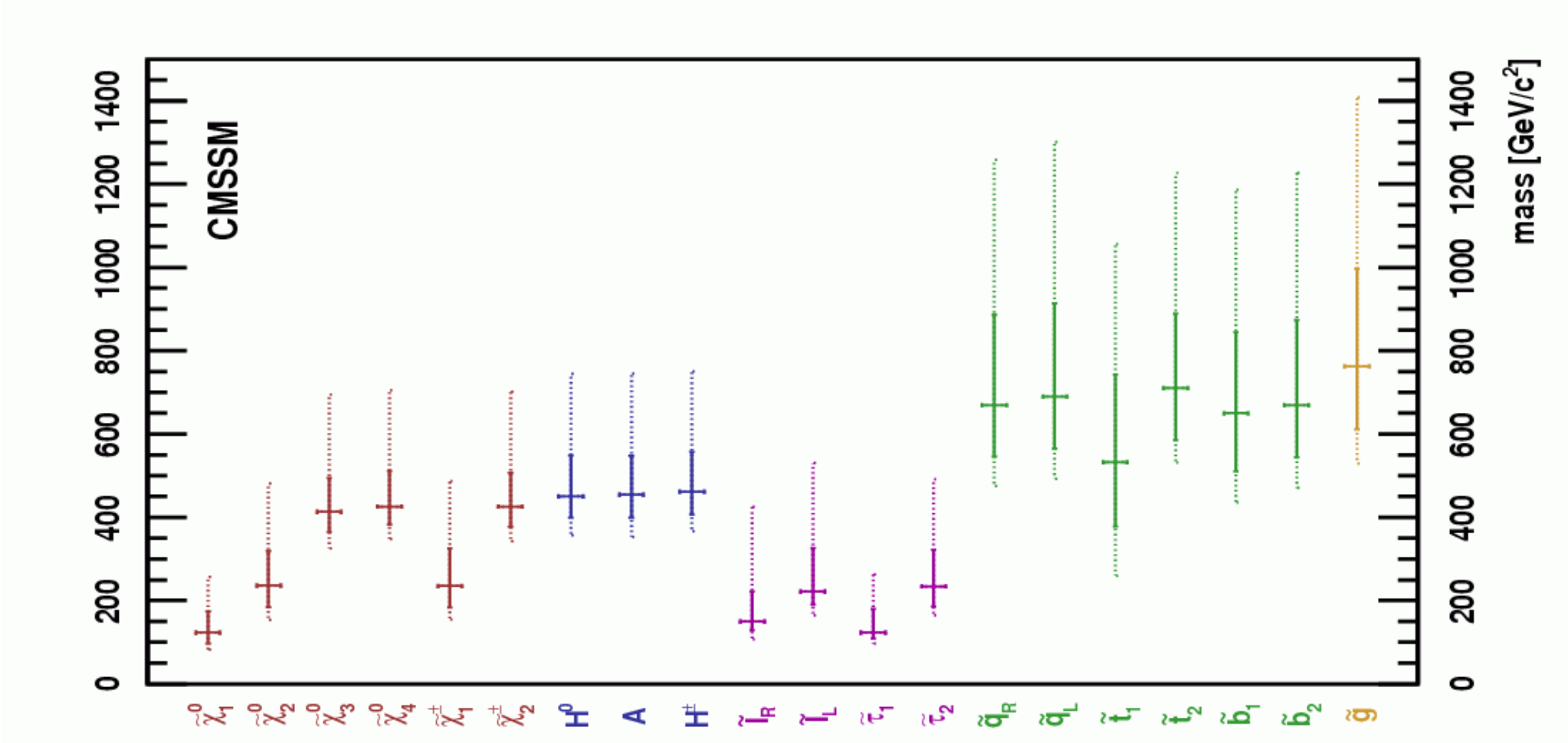
$\tan\beta = 11$, $\mu = 1140$ GeV, $M_A = 310$ GeV

(similar probability)

$\Rightarrow \mathcal{L}_{\text{SUSY}}$

Masses for best-fit points: CMSSM

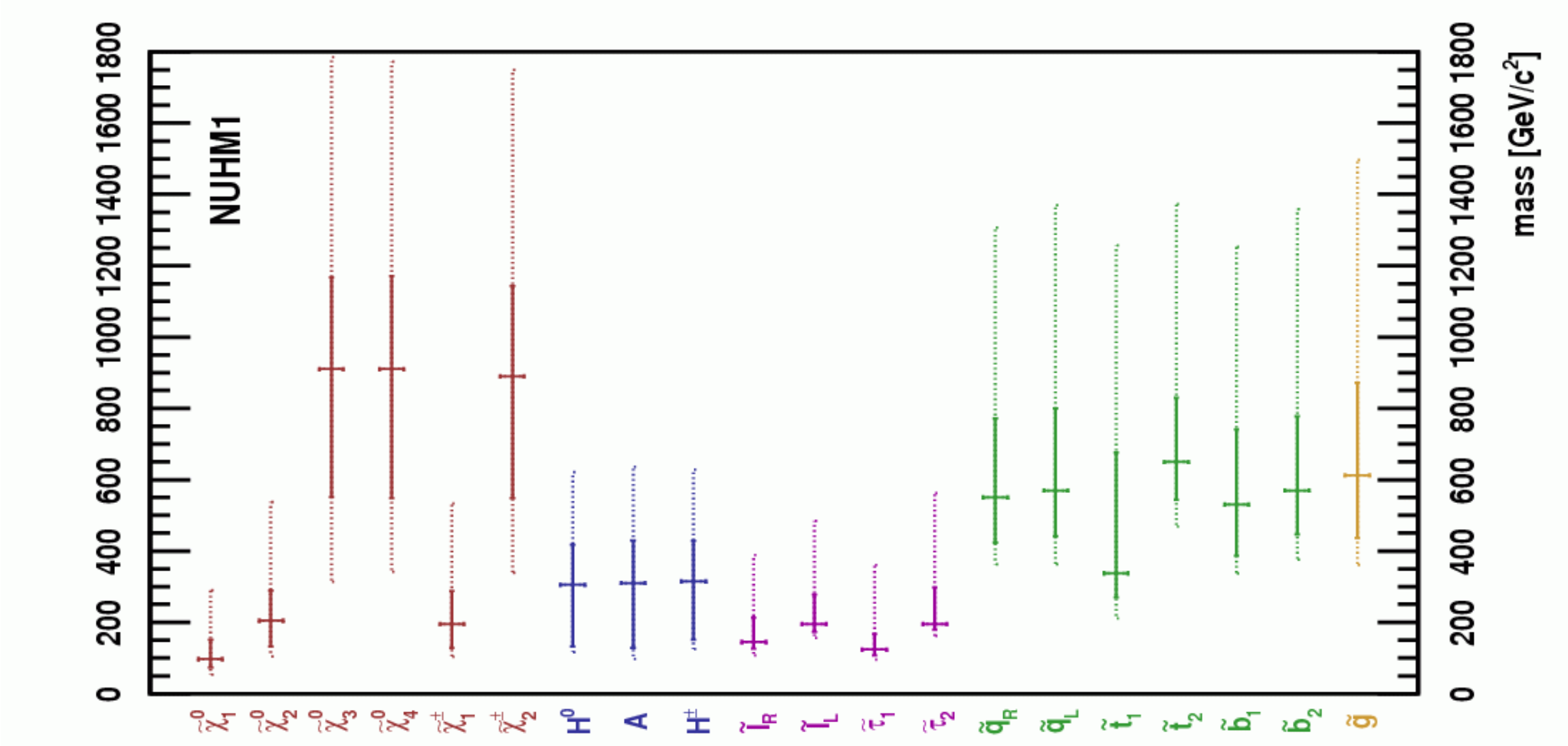
[2009]



⇒ largely accessible spectrum for ILC (confirmation from LHC!)

Masses for best-fit points: NUHM1

[2009]



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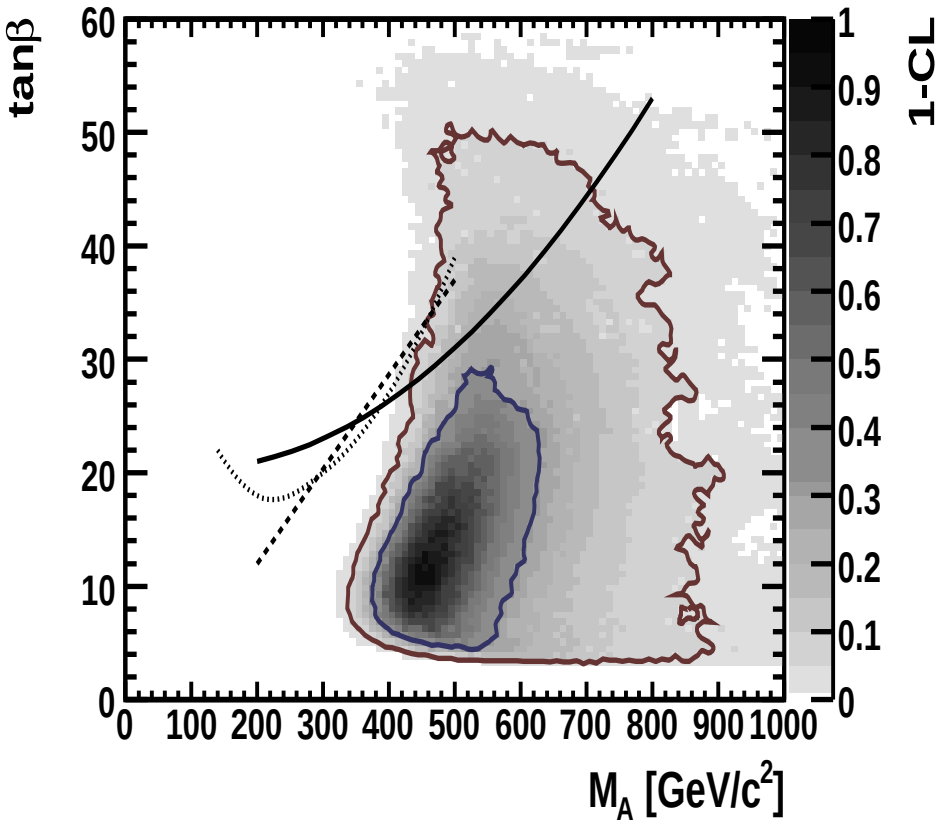
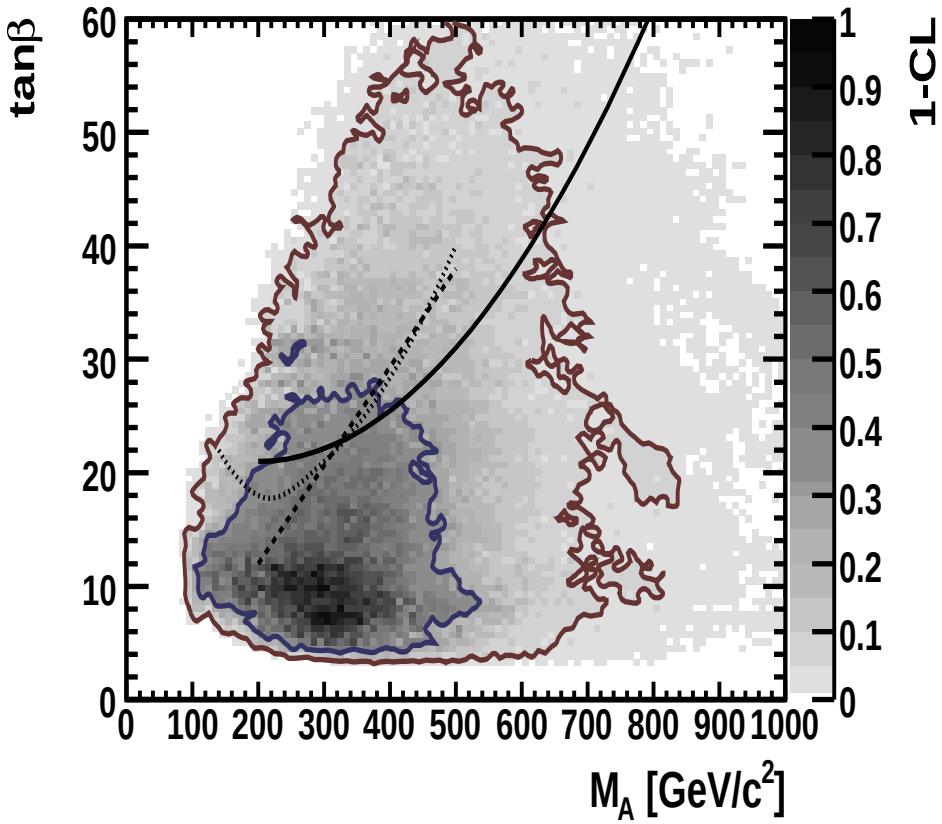
Some more predictions: preferred M_A–tan β parameter space

[2009]

CMSSM



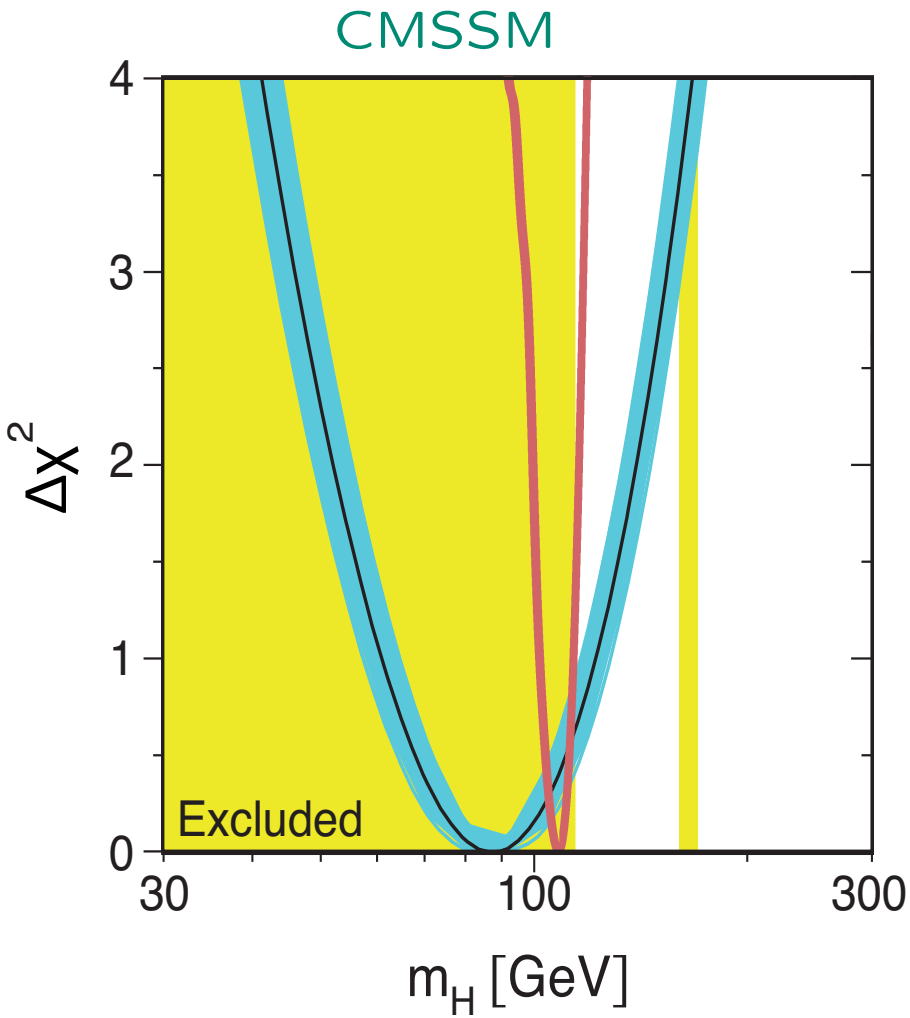
NUHM1

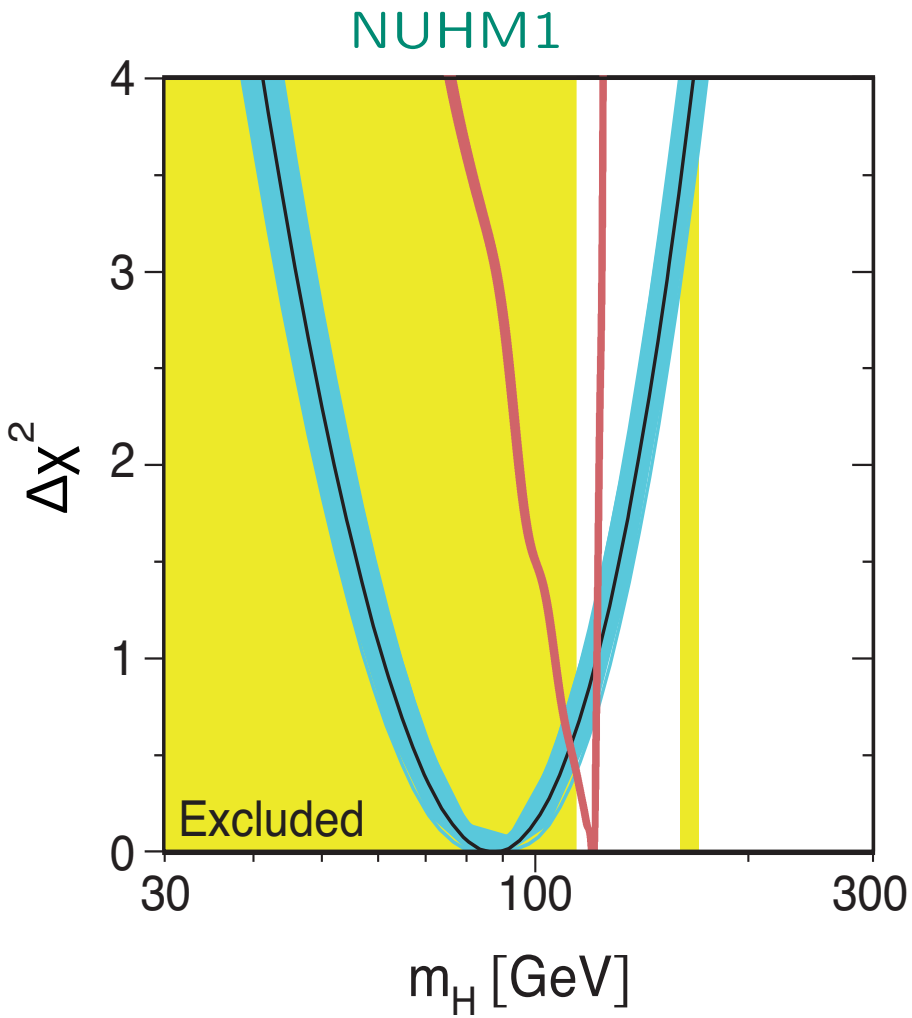


$\Rightarrow$ best-fit regions missed by LHC, better for ILC(1000)

Prediction of $M_H^{\rm SM}$ (blue band) and M_h in the MSSM (red band):

[2009]





$M_h^{\rm CMSSM} = 108.5 \pm 6 \pm 1.5$ GeV

$\Rightarrow$ as good as the SM

$M_h^{\rm NUHM1} = 121^{+1}_{-14} \pm 1.5$ GeV

$\Rightarrow$ above the LEP limit

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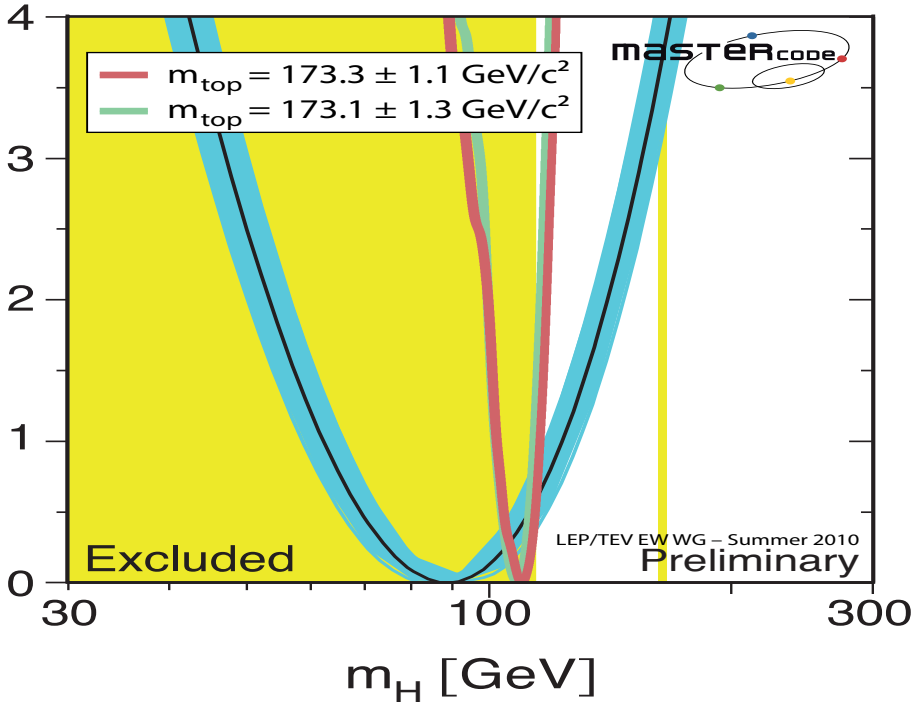

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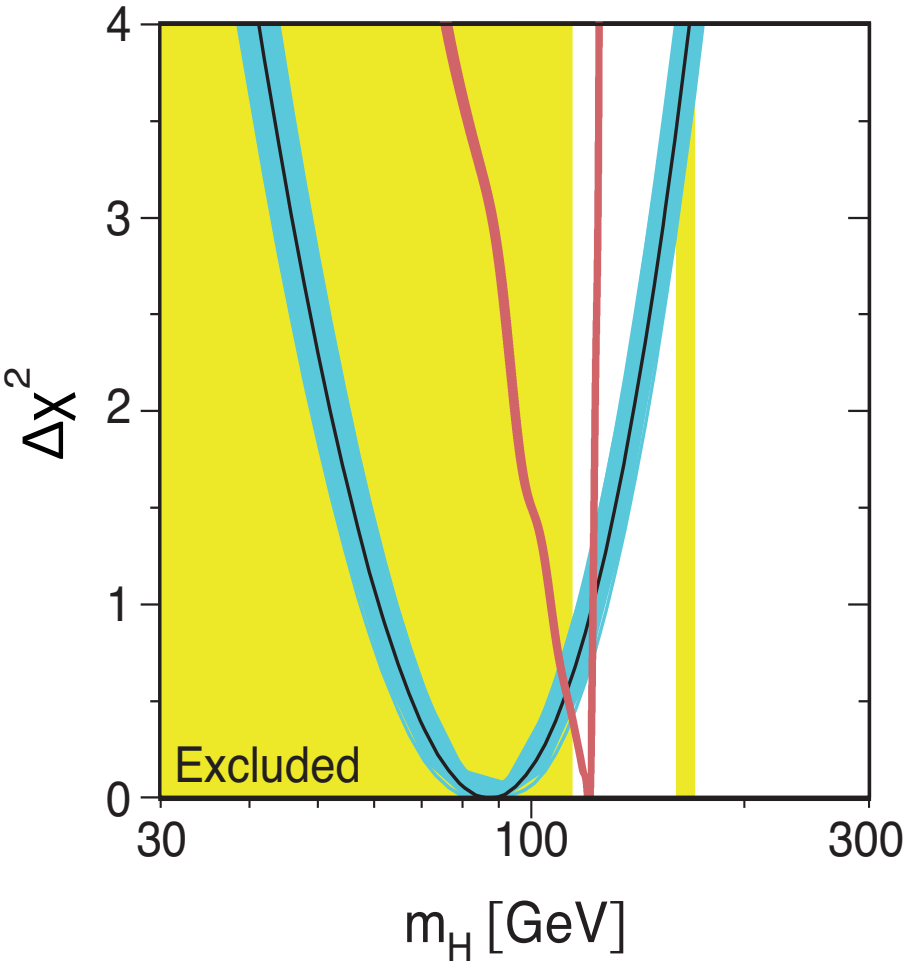
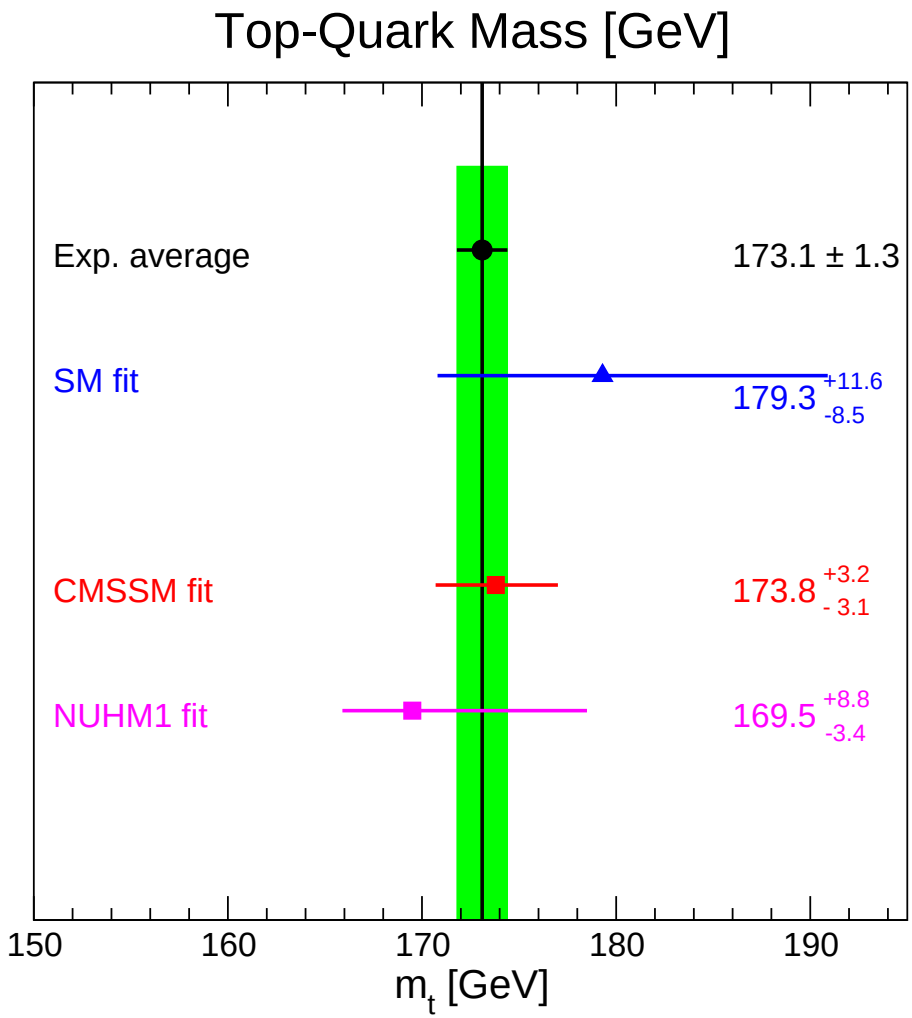


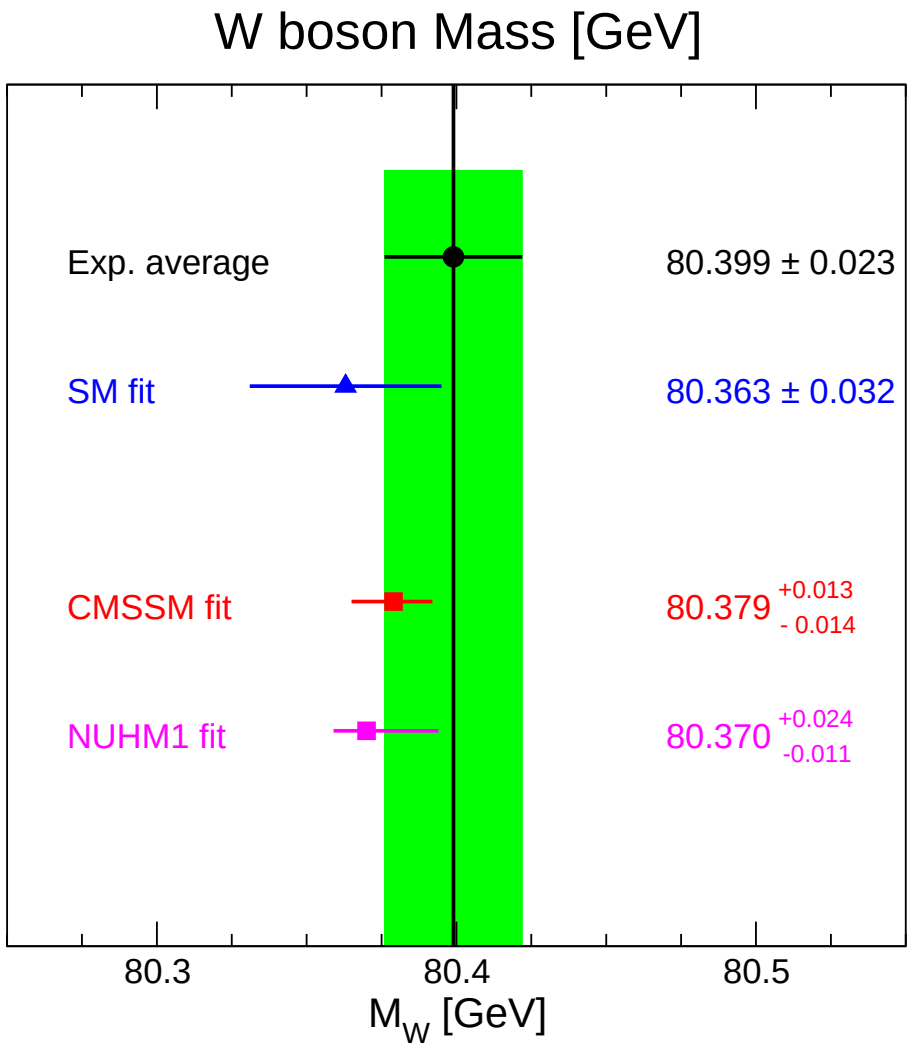
$M_h^{\rm NUHM1} = 121^{+1}_{-14} \pm 1.5$ GeV

$\Rightarrow$ above the LEP limit

M_W fit: M_W not included, m_t fit: m_t not included

(SM fit: M_H not included – CMSSM/NUHM1 fit: M_h included) [2009]





⇒ CMSSM and NUHM1 fit amazingly well m_t and M_W

⇒ better than the SM: smaller errors, better best-fit points

4. The future: GigaZ/Z factory

Experimental errors of the precision observables:

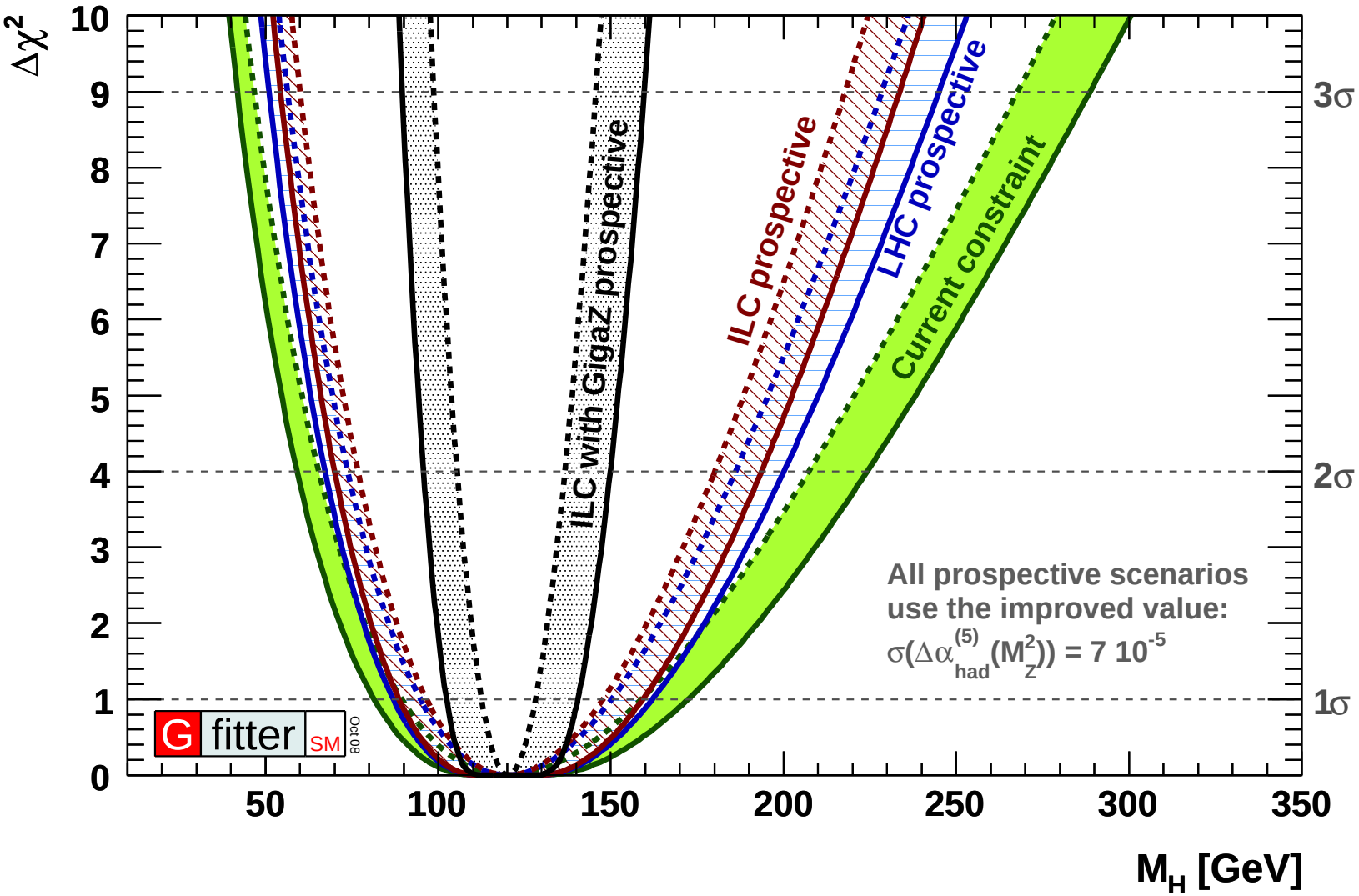
	today	Tev./LHC	ILC	GigaZ	Z factory
$\delta \sin^2\theta_{\text{eff}} (\times 10^5)$	16	16	–	1.3	3
δM_W [MeV]	23	15	10	7	–
δm_t [GeV]	1.3	1-2	0.2	0.1	–

Relevant SM parametric errors: $\delta(\Delta\alpha_{\text{had}}) = 5 \times 10^{-5}$, $\delta M_Z = 2.1$ MeV

	$\delta m_t = 2$	$\delta m_t = 1$	$\delta m_t = 0.1$	$\delta(\Delta\alpha_{\text{had}})$	δM_Z
$\delta \sin^2\theta_{\text{eff}}$ [10^{-5}]	6	3	0.3	1.8	1.4
ΔM_W [MeV]	12	6	1	1	2.5

GigaZ: Improvement in the Blue Band plot:

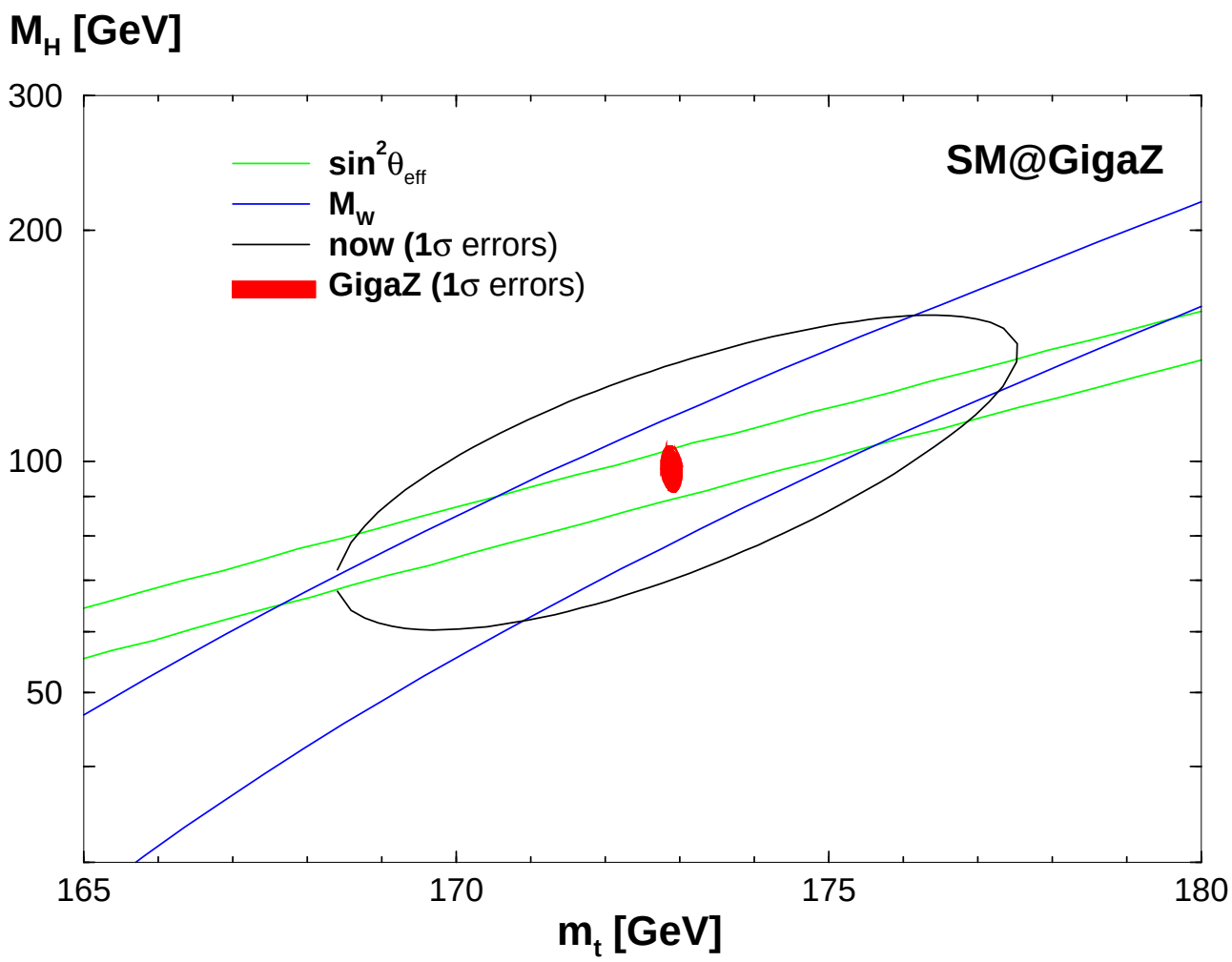
[*GFitter '09*]



(note: artificially $M_H^{\rm SM} = 120$ GeV)

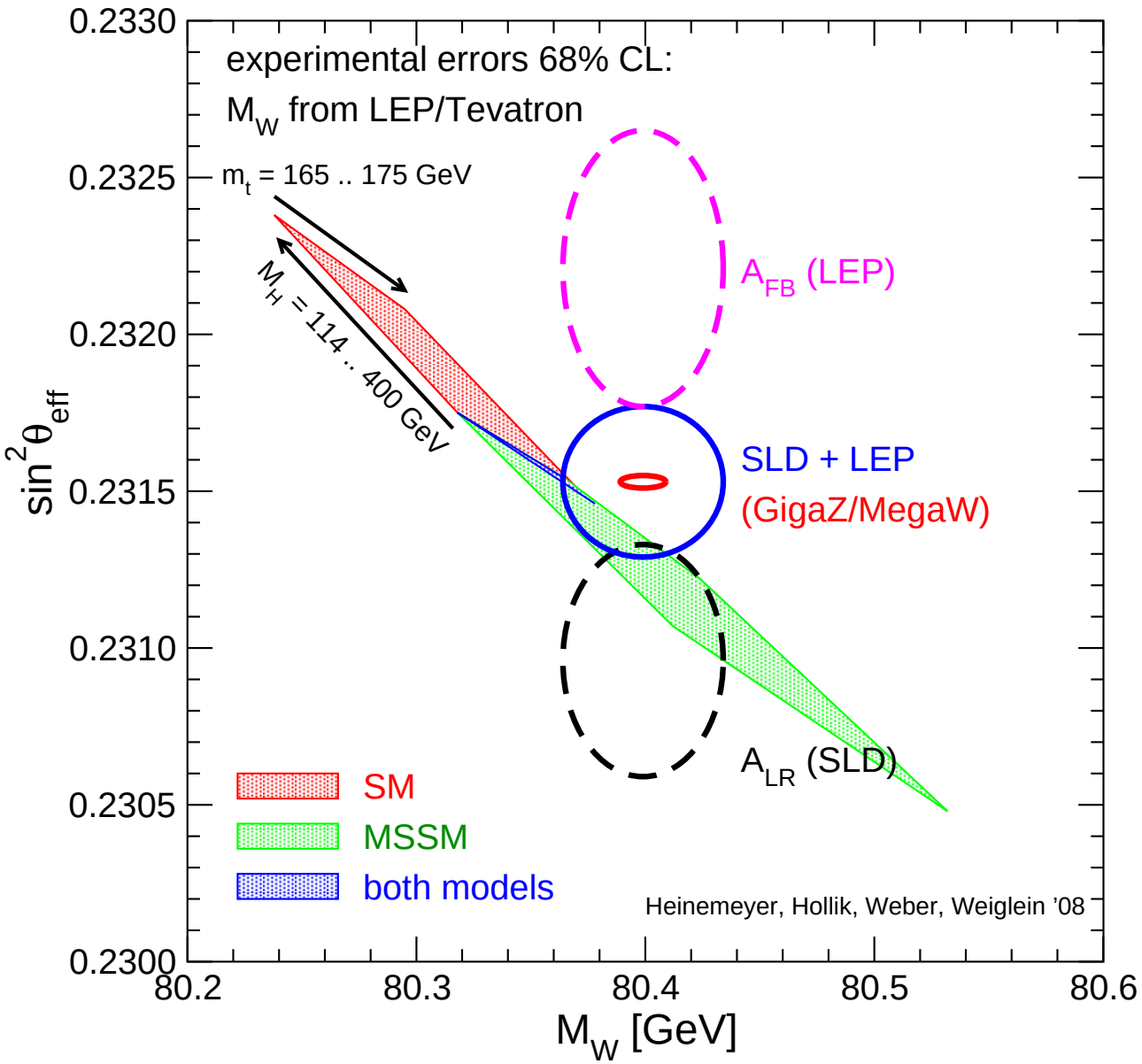
GigaZ: $\Rightarrow$ Improvement in M_H determination:

[*J. Erler, S.H., W. Hollik, G. Weiglein, P. Zerwas '00*]



GigaZ: Most sensitive test of SM or MSSM:

[*S.H., W. Hollik, A. Weber, G. Weiglein '08*]



5. Conclusinos

- Idea: Predict most probable MSSM parameter regions using existing data: EWPO, BPO, CDM, ...
- Models: CMSSM, NUHM1
- statistical measure: χ^2 function (Frequentist, no priors)
  $\sim 2.5\ 10^7$ points samples with MCMC
  $\Delta\chi^2$: 68, 95% C.L. contours
- Best-fit points:
  CMSSM: $m_{1/2} = 310$ GeV, $m_0 = 60$ GeV, $A_0 = 240$ GeV,
  $\tan\beta = 11$, $\mu = 380$ GeV, $M_A = 410$ GeV
  $\Rightarrow$ very similar to SPS 1a :-)
  Prediction of M_h (no LEP bound): $M_h = 109.5 \pm 6 \pm 1.5$ GeV
  NUHM1: $m_{1/2} = 270$ GeV, $m_0 = 150$ GeV, $A_0 = -1300$ GeV,
  $\tan\beta = 11$, $\mu = 1140$ GeV, $M_A = 310$ GeV
  Prediction of M_h (no LEP bound): best fit: $M_h \approx 121$ GeV
- $\Rightarrow$ large parts of the parameter space accessible at the ILC
- $\Rightarrow$ strong future improvements via GigaZ/Z factory

Back-up

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

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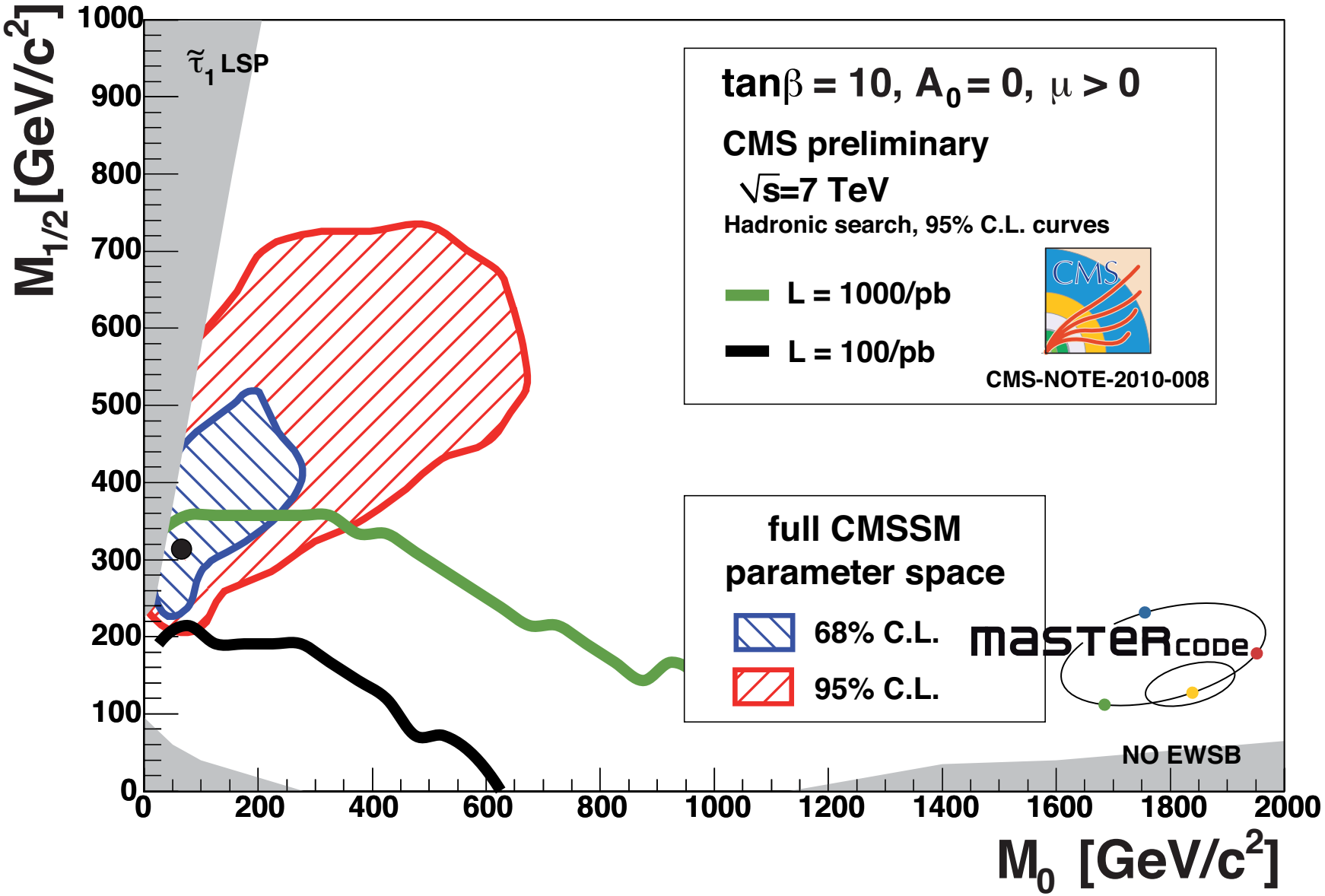
What to do if only a lower/upper bound exists?

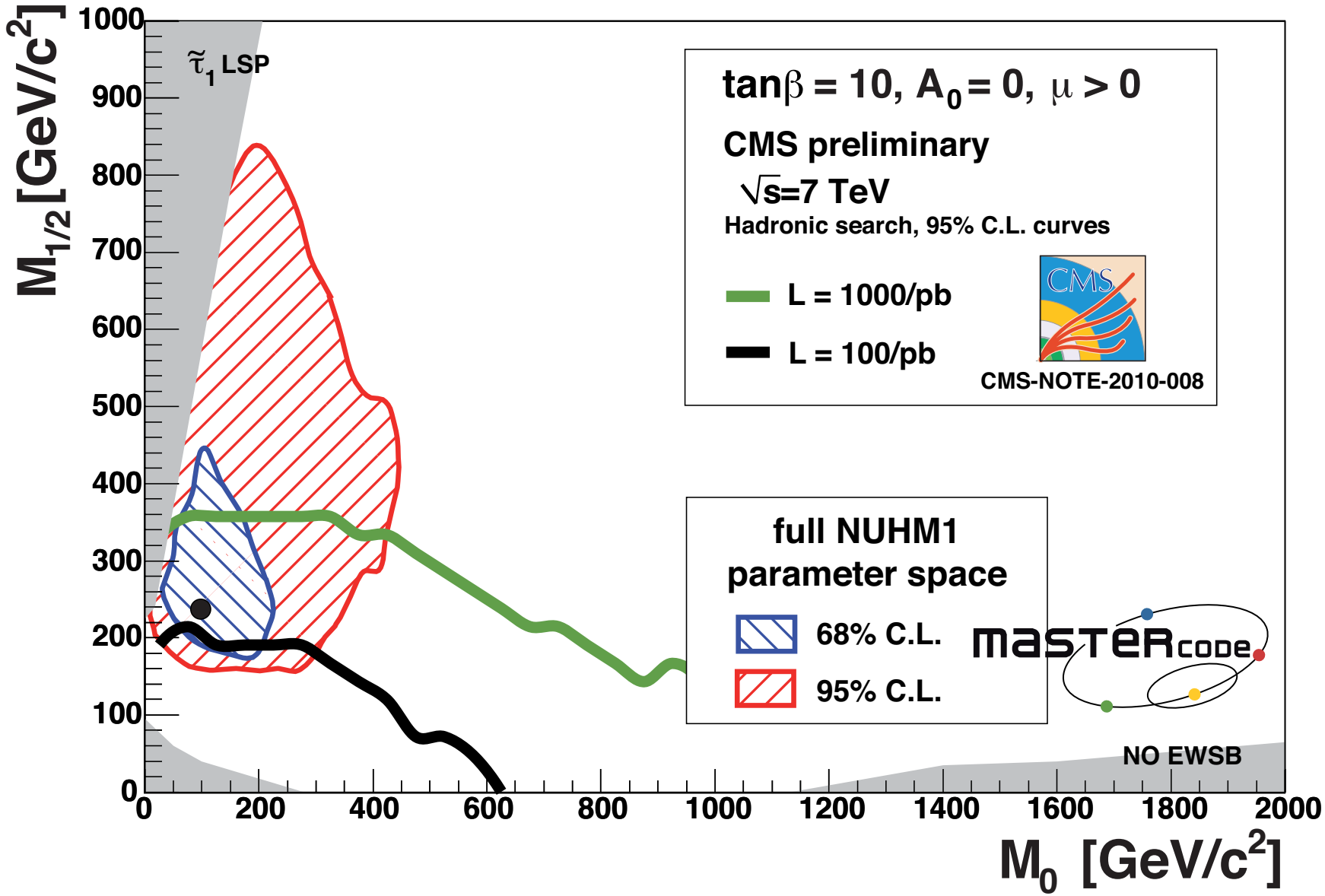
→ especially important: M_h

LHC (CMS) ⊕ CMSSM analysis:



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

LHC (CMS) ⊕ NUHM1 analysis:



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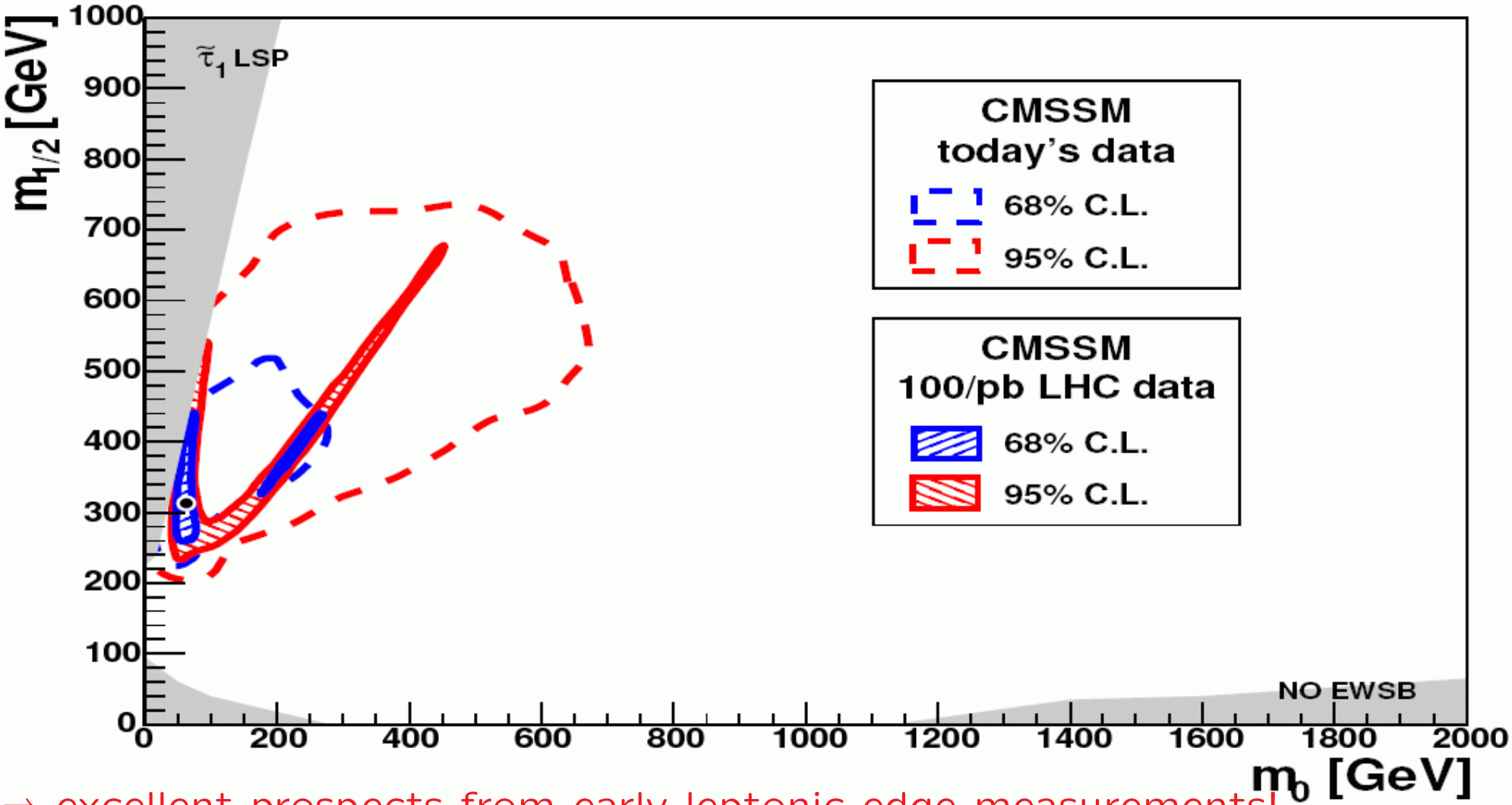
LHC (CMS) ⊕ CMSSM analysis:

[2008]

reach with 1 fb^{-1} @ 14 TeV incl. leptonic edge measurements

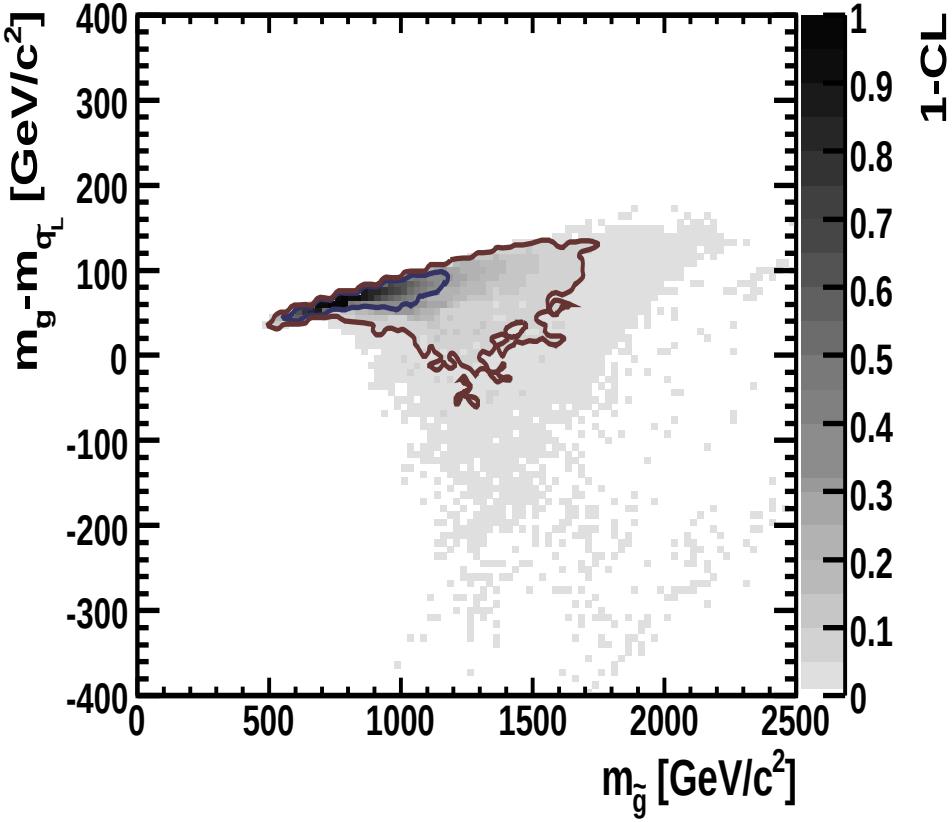


⇒ excellent prospects from early leptonic edge measurements!

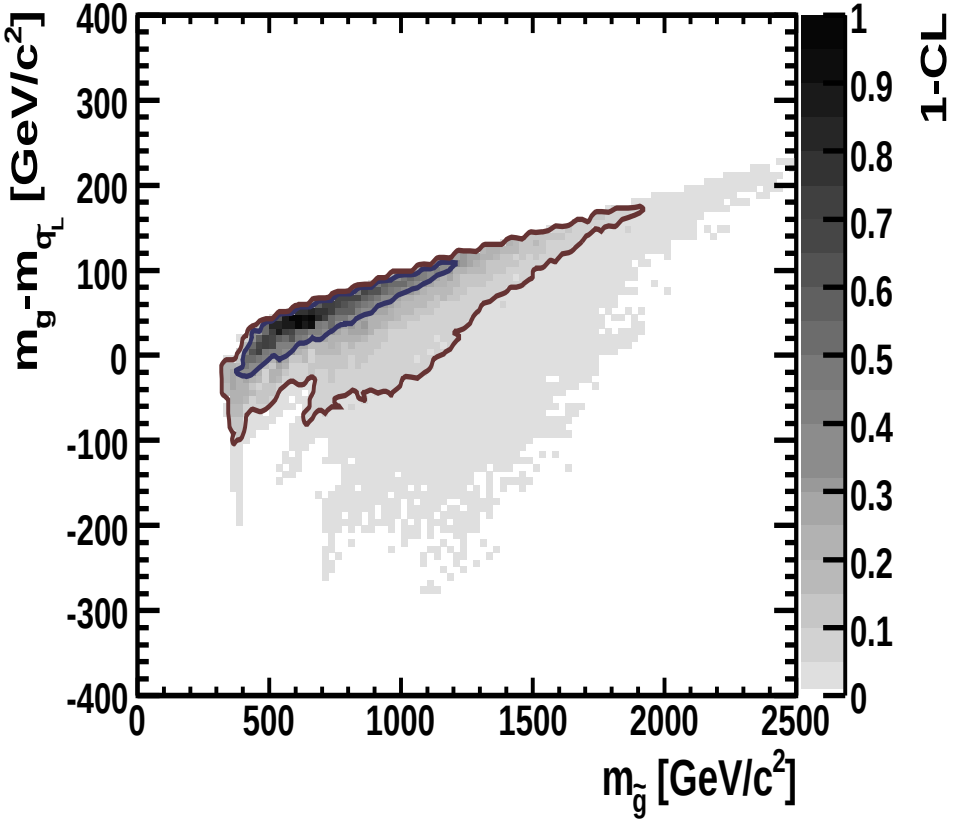
Some more predictions: $m_{\tilde{g}} - m_{\tilde{q}_L}$

[2009]

CMSSM



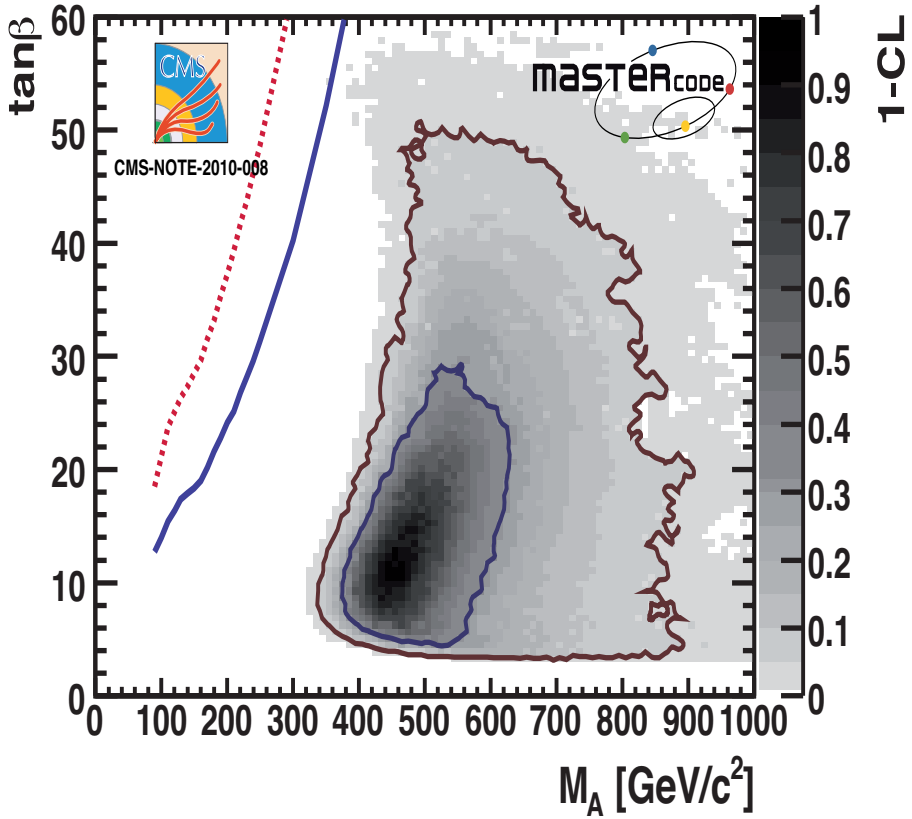
NUHM1



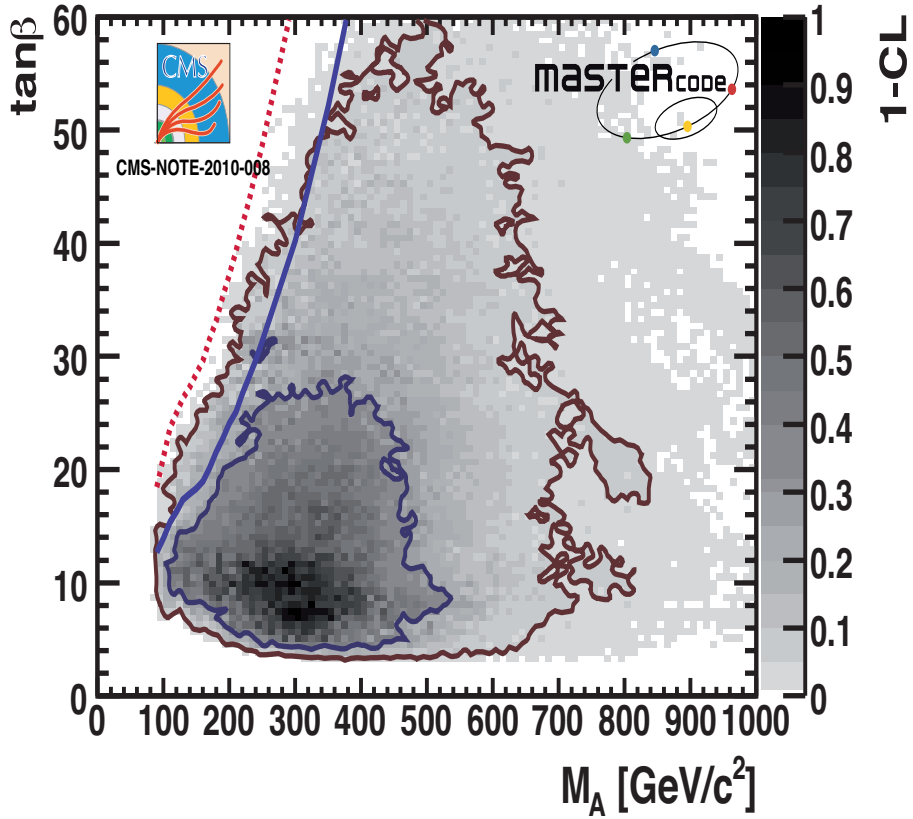
$\Rightarrow m_{\tilde{g}}$ often largest mass, but exceptions are possible

Some more predictions: preferred M_A–$\tan\beta$ parameter space

CMSSM



NUHM1



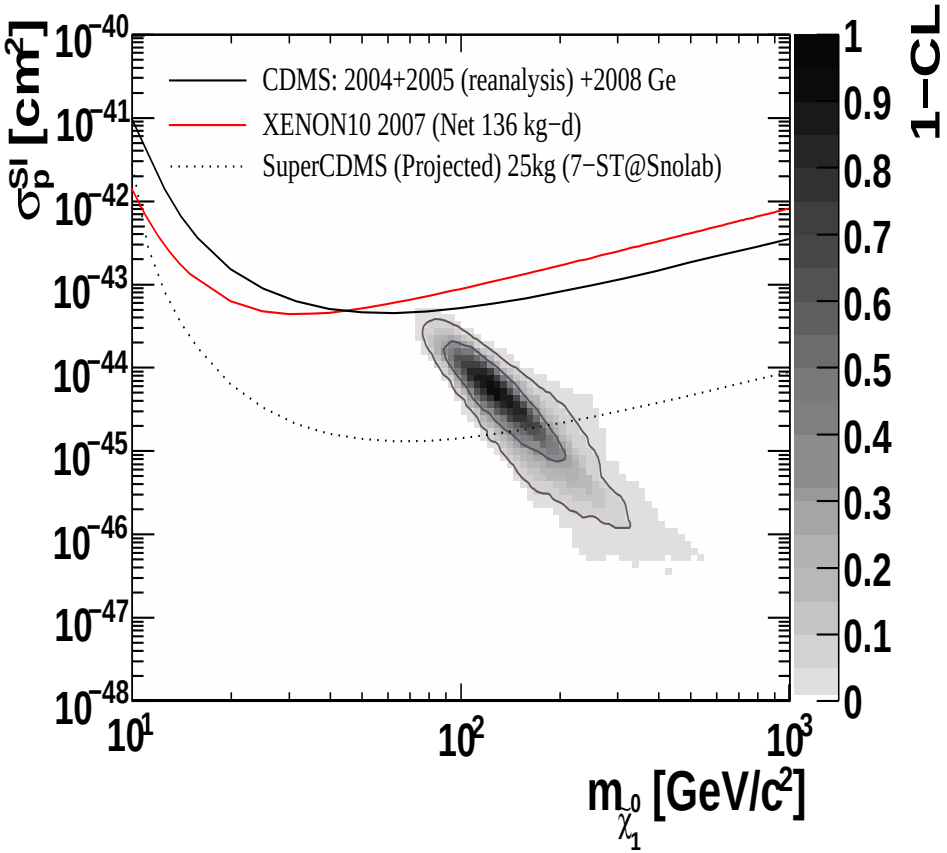
red dotted: discovery with 1 fb^{-1} @ 7 TeV
blue solid: 95% C.L. exclusion with 1 fb^{-1} @ 7 TeV

$\Rightarrow$ preferred regions missed in 2010-2011 run

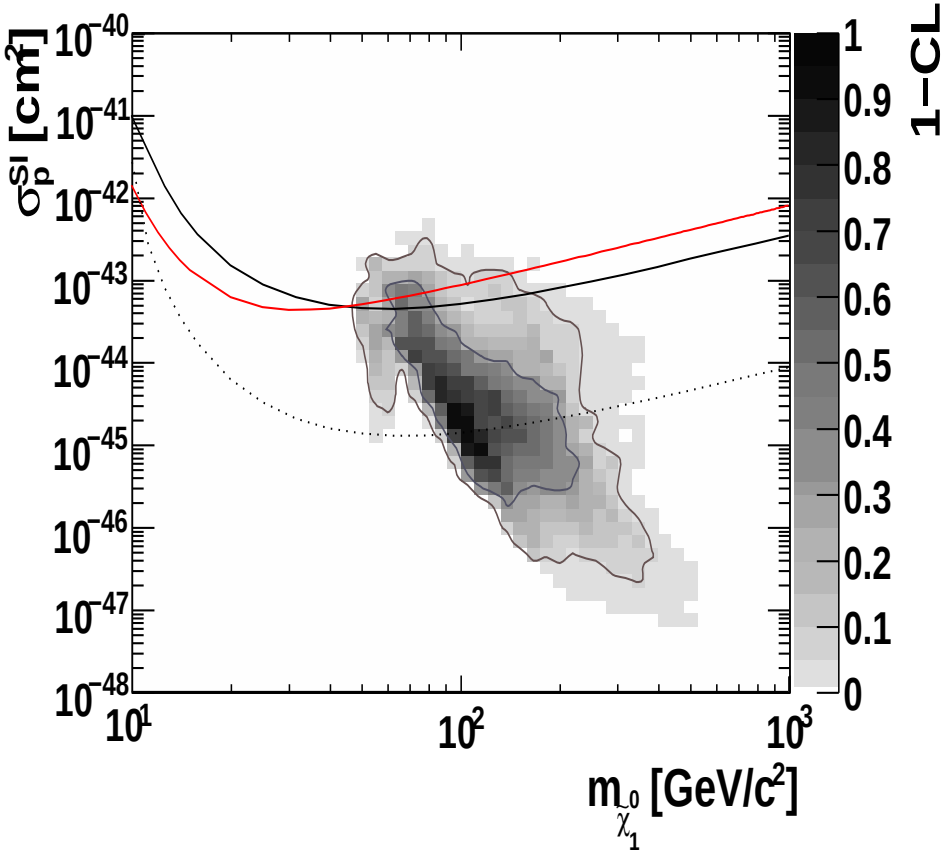
Some more predictions: direct search for dark matter

[2009]

CMSS M



NUHM1

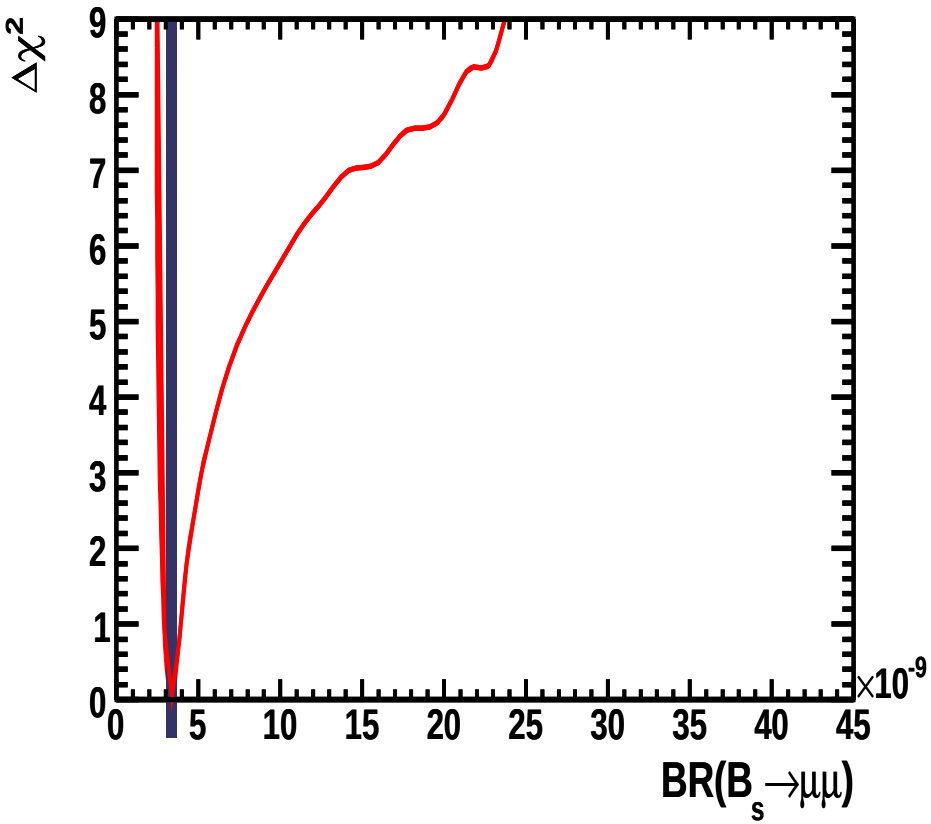


⇒ only partially covered by future experiments

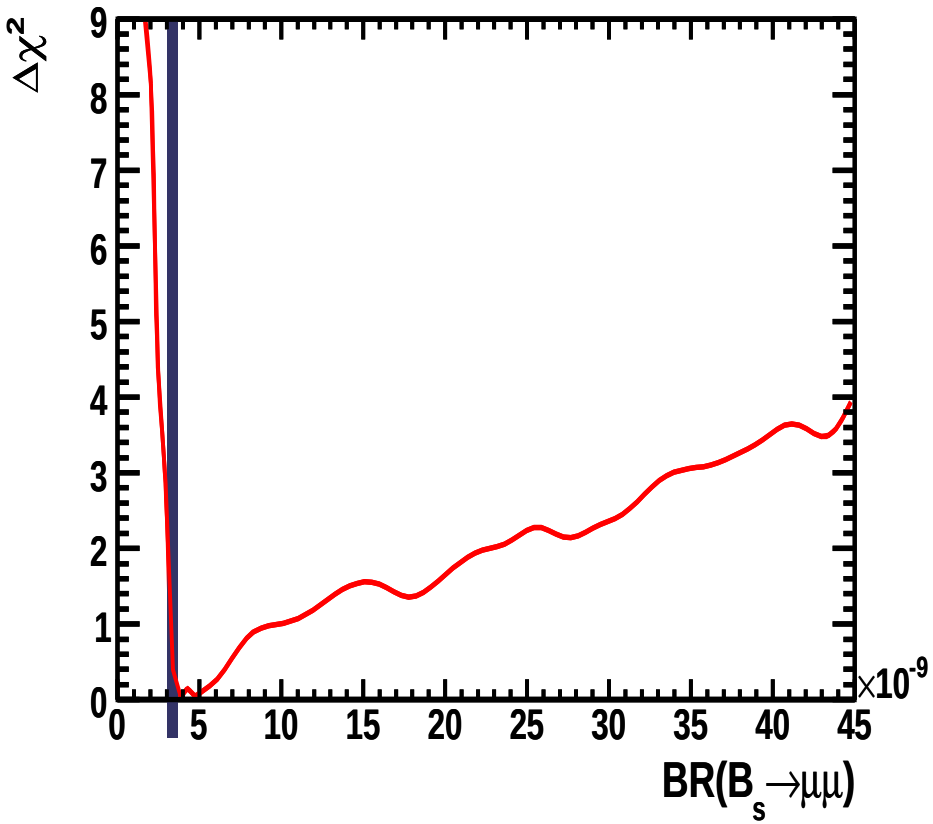
Some more predictions: BR($B_s \to \mu^+\mu^-$)

[2009]

CMSSM



NUHM1



$\Rightarrow$ best-fit similar to SM, larger value would favor NUHM1

Current and future errors:

Current:

$$\delta m_t^{\text{exp}} = 1.3 \text{ GeV}, \qquad \delta(\Delta\alpha_{\text{had}}) = 3.5 \times 10^{-4}$$

$$\delta M_W^{\text{theory,SM}} \approx \pm 4 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{theory}} \approx \pm 10 \times 10^{-5}$$

$$\delta m_t: \quad \delta M_W^{\text{para}} \approx \pm 13 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{para}} \approx \pm 7 \times 10^{-5}$$

$$\delta(\Delta\alpha_{\text{had}}): \quad \delta M_W^{\text{para}} \approx \pm 6.5 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{para}} \approx \pm 13 \times 10^{-5}$$

$$\delta M_W^{\text{exp}} \approx \pm 23 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{exp}} \approx \pm 16 \times 10^{-5}$$

Future:

$$\delta M_W^{\text{theory}} \gtrsim \pm 2 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{theory}} \gtrsim \pm 2 \times 10^{-5}$$

$$\delta m_t: \quad \delta M_W^{\text{para}} \approx \pm 1 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{para}} \approx \pm 0.4 \times 10^{-5}$$

$$\delta(\Delta\alpha_{\text{had}}): \quad \delta M_W^{\text{para}} \approx \pm 1 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{para}} \approx \pm 1.8 \times 10^{-5}$$

$$[\text{GigaZ}]: \quad \delta M_W^{\text{exp}} \approx \pm 7 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{exp}} \approx \pm 1.3 \times 10^{-5}$$