MasterCode: Status and Prospects

Sven Heinemeyer, IFCA (CSIC, Santander)

CERN, 02/2011

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

1. Introduction
2. Codes and predictions
3. Models & Methods
4. Predictions for the LHC
5. Prospects
6. Conclusions

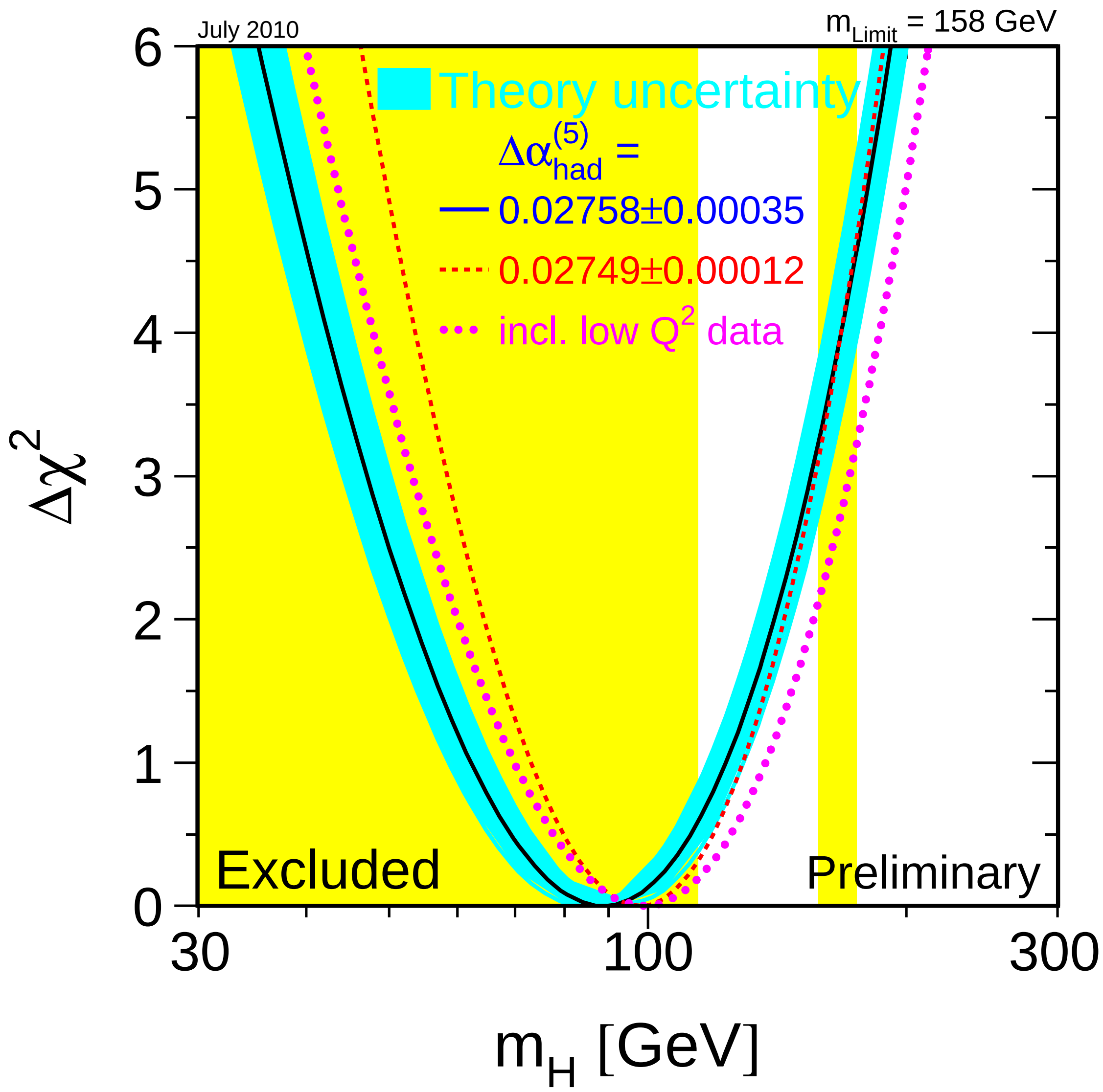
1. Introduction

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

Global fit to all SM data incl. direct searches:

[*GFitter '10*]

$\Rightarrow M_H = 119.1^{+13.5}_{4.0}$ GeV

$M_H < 157$ GeV, 95% C.L.

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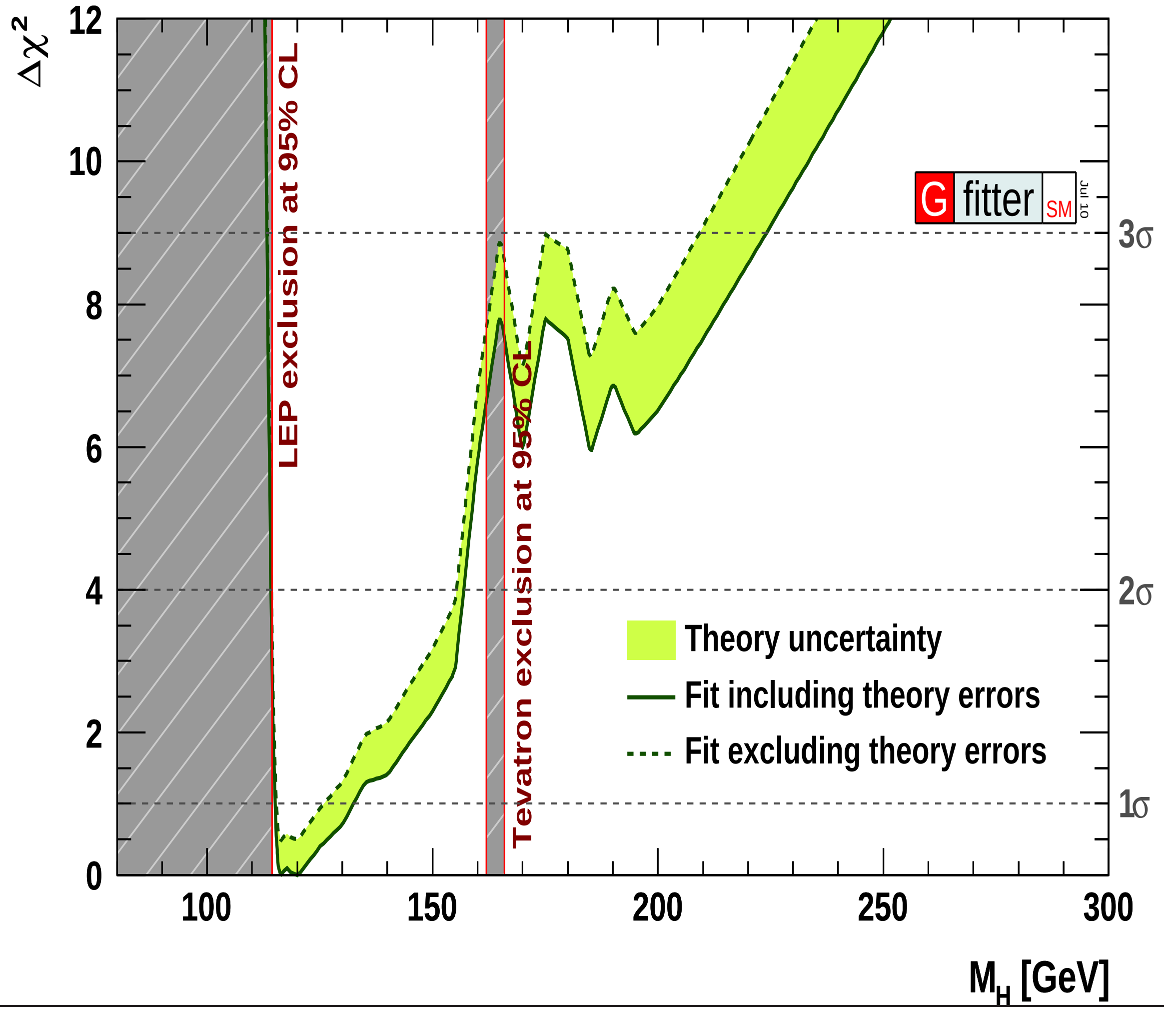

Main idea of the MasterCode: do “the same” in Supersymmetry!

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 $\Rightarrow$ LHC reach

2. Codes and predictions

Our tool:

The "MasterCode"

⇒ collaborative effort of theorists and experimentalists

[*O. Buchmüller, R. Cavanaugh, D. Colling, A. De Roeck, M. Dolan, J. Ellis, H. Flächer, S.H., G. Isidori, K. Olive, S. Rogerson, F. Ronga, G. 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 next section)

– 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*]

⇒ 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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(Some) Electroweak precision observables in the MasterCode

($\rightarrow$ as for blue band analysis, except Γ_W)

1. M_W (LEP/Tevatron)

2. A^e_{LR} (SLD)

3. A^b_{FB} (LEP)

4. A^c_{FB} (LEP)

5. A^l_{FB}

6. A_b, A_c

7. R_b, R_c

8. σ^0_{had}

$\Rightarrow$ largest impact: (1), (2), (3)

(Some) B/K physics observables in the MasterCode

1. BR($b \to s\gamma$) (MSSM/SM)
2. BR($B_s \to \mu^+\mu^-$)
3. ΔM_s
4. R($\Delta M_s/\Delta M_d$)
5. BR($B_u \to \tau\nu_\tau$) (MSSM/SM)
6. BR($B \to X_x\ell^+\ell^-$)
7. BR($K \to \ell\nu$) (MSSM/SM)
8. BR(ΔM_K) (MSSM/SM)

$\Rightarrow$ largest impact: (1) and (2)

Further low-energy observables

– anomalous magnetic moment of the muon: $(g-2)_\mu$

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Higgs physics observables in the MasterCode

– lightest Higgs mass: M_h

– effective mixing angle: α_{eff} , especially for $\sin^2(\beta - \alpha_{\text{eff}})$

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– CDM density: $\Omega_\chi h^2$

– Direct detection cross section: σ_p^{SI} (prediction; not incl. in the fit yet)

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SM parameters

– top mass: m_t

– Z boson mass: M_Z

– hadronic contribution to fine structure constant: $\Delta\alpha_{\text{had}}$

3. Models & methods

Indirect constraints on M_{SUSY} from existing data?

- Electroweak precision observables (EWPO) ?
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$\Rightarrow$ combination of EWPO, BPO, CDM ?

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EWPO M_W : information on $m_{\tilde{t}}$, $m_{\tilde{b}}$ or M_A, $\tan\beta$ or . . .

EWPO $(g-2)_\mu$: information on $\tan\beta$ and/or $m_{\tilde{\chi}^0}$, $m_{\tilde{\chi}^\pm}$ and/or $m_{\tilde{\mu}}$, $m_{\tilde{\nu}_\mu}$

BPO $\text{BR}(b \to s\gamma)$: information on $\tan\beta$ and/or $M_{H^\pm}$ and/or $m_{\tilde{t}}$, $m_{\tilde{\chi}^\pm}$

CDM (LSP gives CDM) : information on $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}}$ or M_A or . . .

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CDM (LSP gives CDM) : information on $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}}$ or M_A or ...

$\Rightarrow$ combination (so far) makes only sense if all parameters are connected!
$\Rightarrow$ GUT based models, ...

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
- . . .

The models: 1.) CMSSM (or 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

The models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameter at the GUT scale

⇒ effectively M_A or μ as free parameters at the EW scale

> ⇒ besides the CMSSM parameters
>
> M_A or μ

Further extension: NUHM2:

Assumption: no unification of the Higgs parameters at the GUT scale

⇒ effectively M_A and μ as free parameters at the EW scale

> ⇒ besides the CMSSM parameters
>
> M_A and μ

The models: 3.) VCMSSM: (Very Constrained MSSM)

⇒ In addition to CMSSM: assume relation between A_0 and m_0:

$$A_0 = m_0 + B_0$$

tan β fixed (e.g. via CDM constraint)

Free parameters: $m_{1/2}$, A_0, m_0

Lightest SUSY particle (LSP) is the lightest neutralino

The models: 4.) mSUGRA: (Gravitino DM in mSUGRA)

⇒ In addition to CMSSM: assume relation between A_0 and m_0:

$$A_0 = m_0 + B_0$$

mSUGRA: $m_{\text{gravitino}} = m_0$ ⇒ gravitino can be the LSP

Free parameters: $m_{1/2}$, A_0, m_0

Lightest SUSY particle (LSP) is the gravitino

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)

⇒ MasterCode: multi-dim scans with MCMC technique

2.) Fitting:

– Frequentist
– Bayesian

⇒ MasterCode: Frequentist

⇒ χ^2 function to include all experimental results

3.) Priors . . . (none)

χ^2 calculation:

$\rightarrow$ global χ^2 likelihood function
combines all theoretical predictions with experimental constraints:

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{(f^{\rm obs}_{{\rm SM}_i} - f^{\rm fit}_{{\rm SM}_i})^2}{\sigma(f_{{\rm SM}_i})^2}$$

N: number of observables studied

M: SM parameters: $\Delta\alpha_{\rm had}, m_t, M_Z$

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 → see the back-up

4. Predictions for the LHC

– 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, $\Delta\alpha_{\rm had}$

⇒ χ^2 function

→ scan over the full CMSSM/NUHM1/VCMSSM/mSUGRA parameter space

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

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

→ final minimum: Minuit

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

⇒ preferred CMSSM/NUHM1 parameters
⇒ LHC reach

Best-fit points:

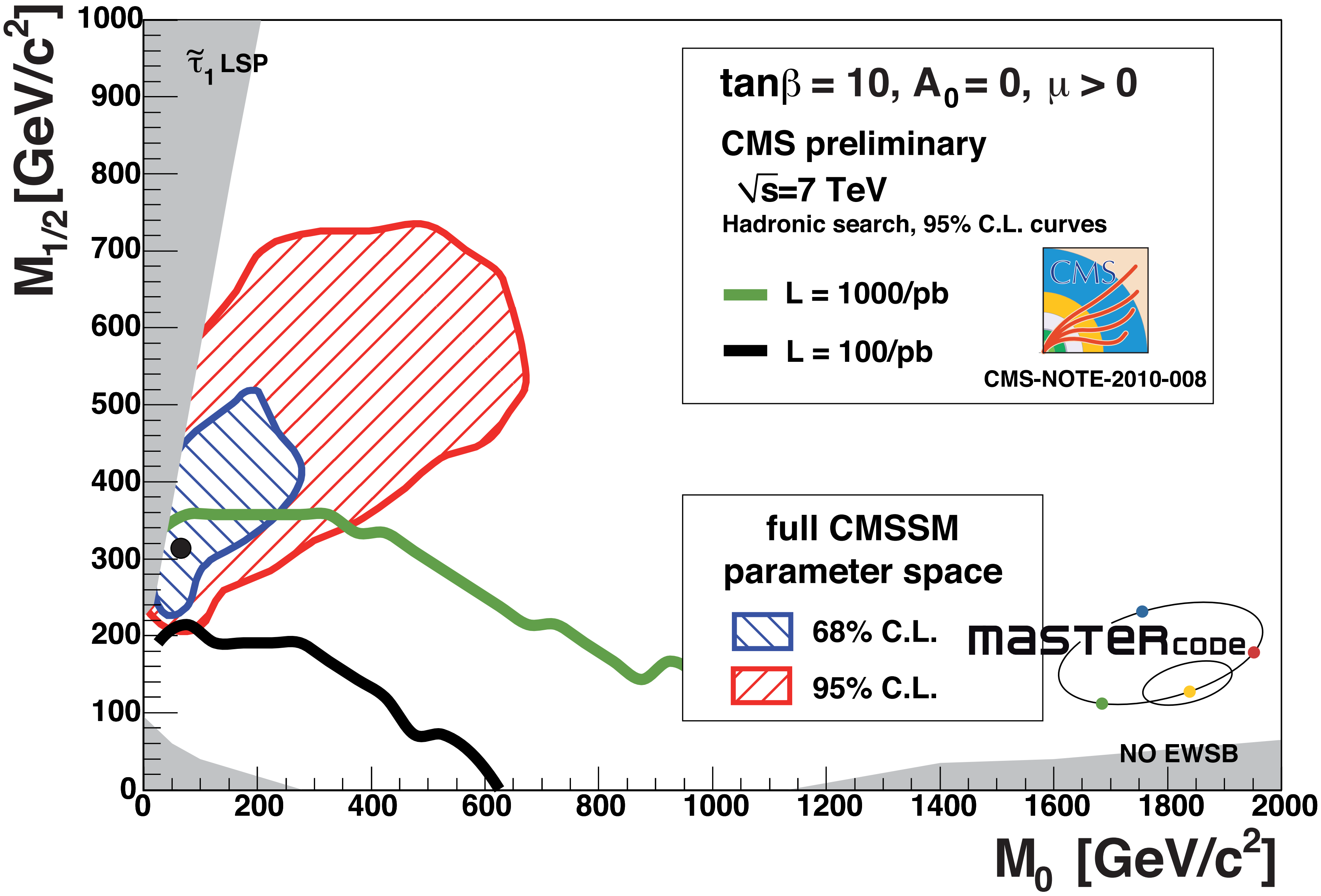
[2010]

Model	Min. χ^2	Probability	$m_{1/2}$	m_0	A_0	$\tan\beta$	M_h
mSUGRA	29.3	6.0%	550	230	430	28	
	33.2	2.2%	130	2110	980	7	
VCMSSM	22.5	31%	300	60	30	9	109
CMSSM	22.4	26%	330	70	-260	11	106
NUHM1	19.7	29%	260	100	9300	7	120

– VCMSSM, CMSSM, NUHM1 have similar high probabilities

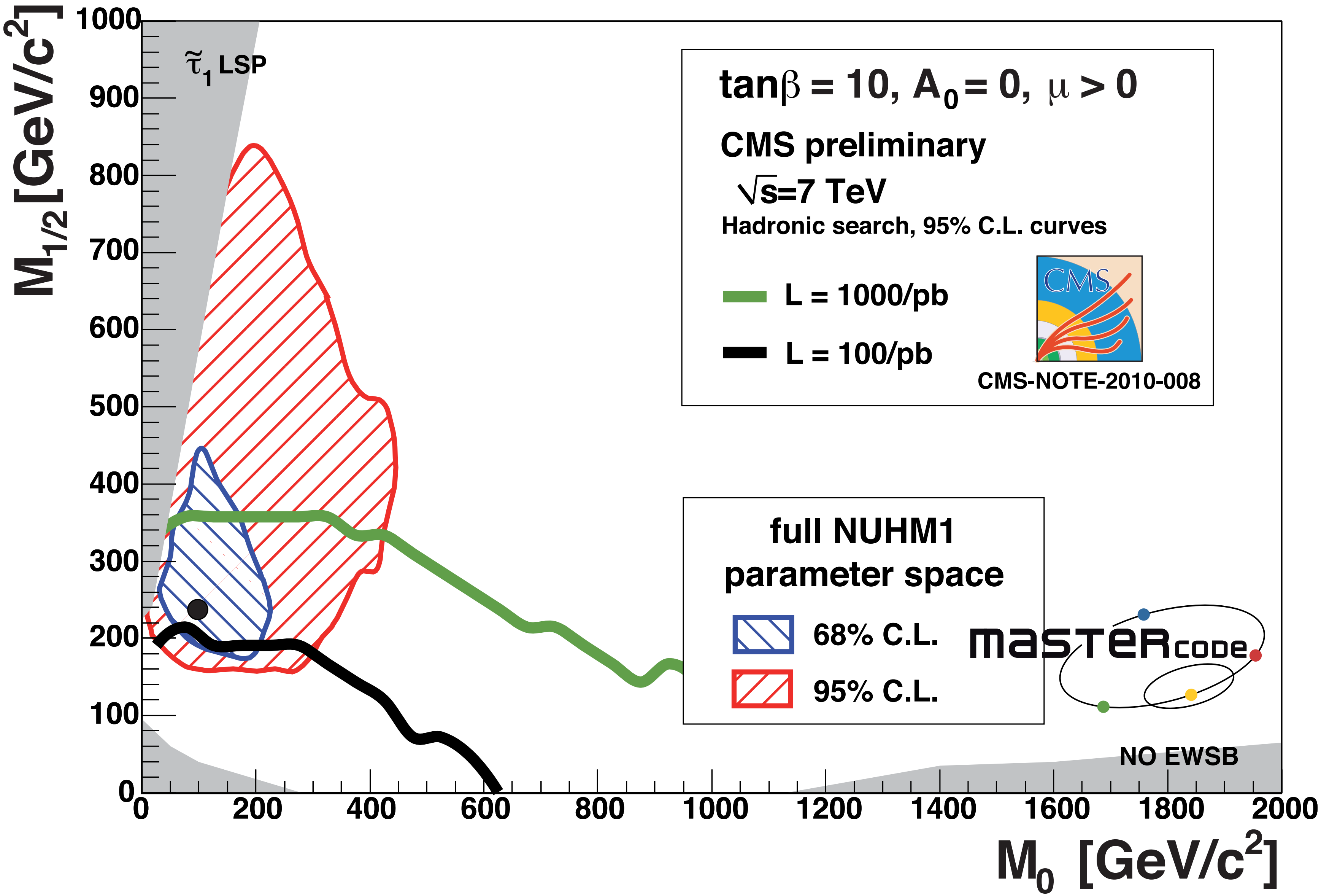
– M_h does not include direct LEP constraints
$\Rightarrow$ no severe tension between the models and LEP bound

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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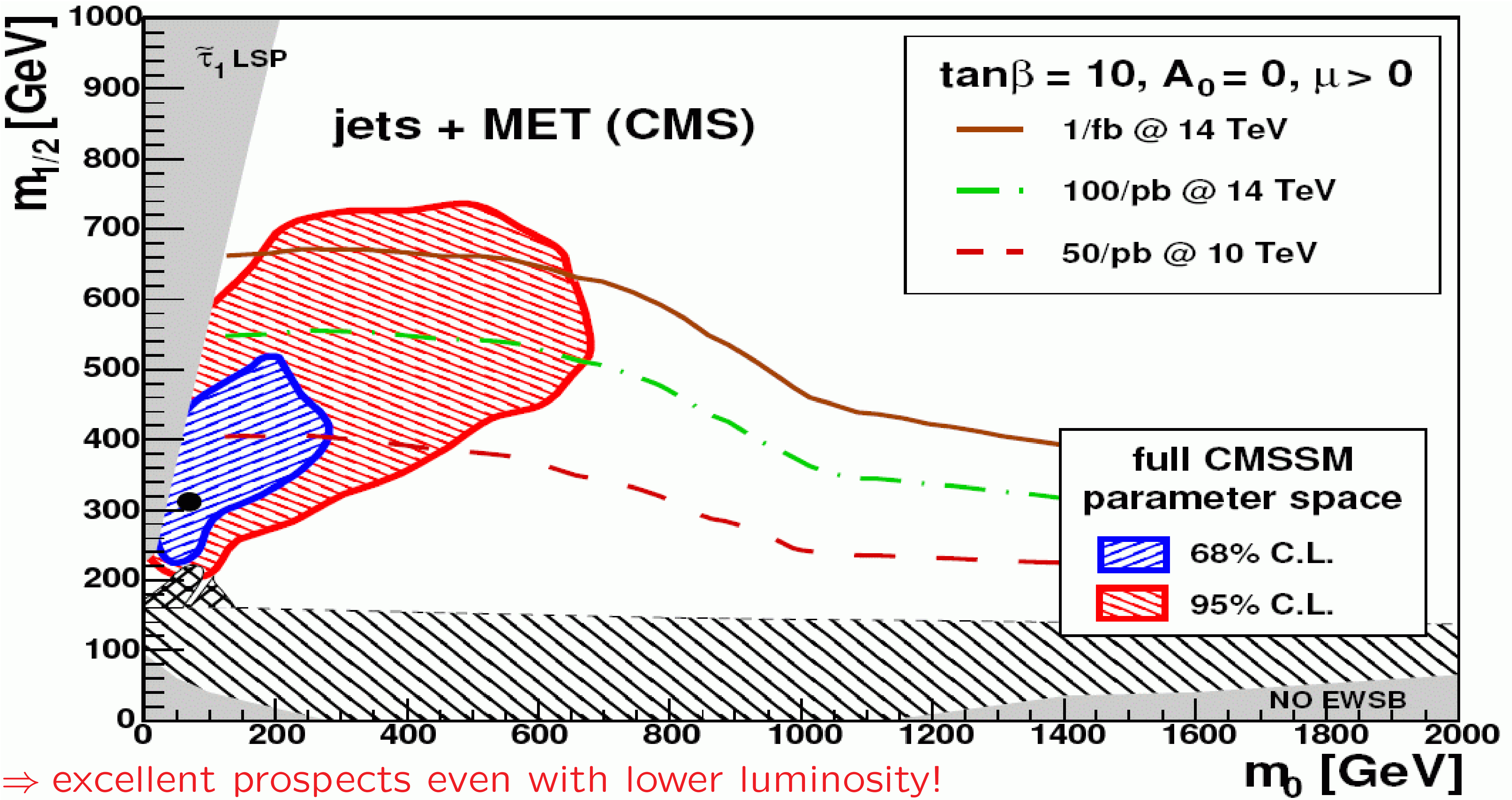
LHC (CMS) ⊕ CMSSM analysis:

[*CMS '07*]

[*2008*]



⇒ excellent prospects even with lower luminosity!

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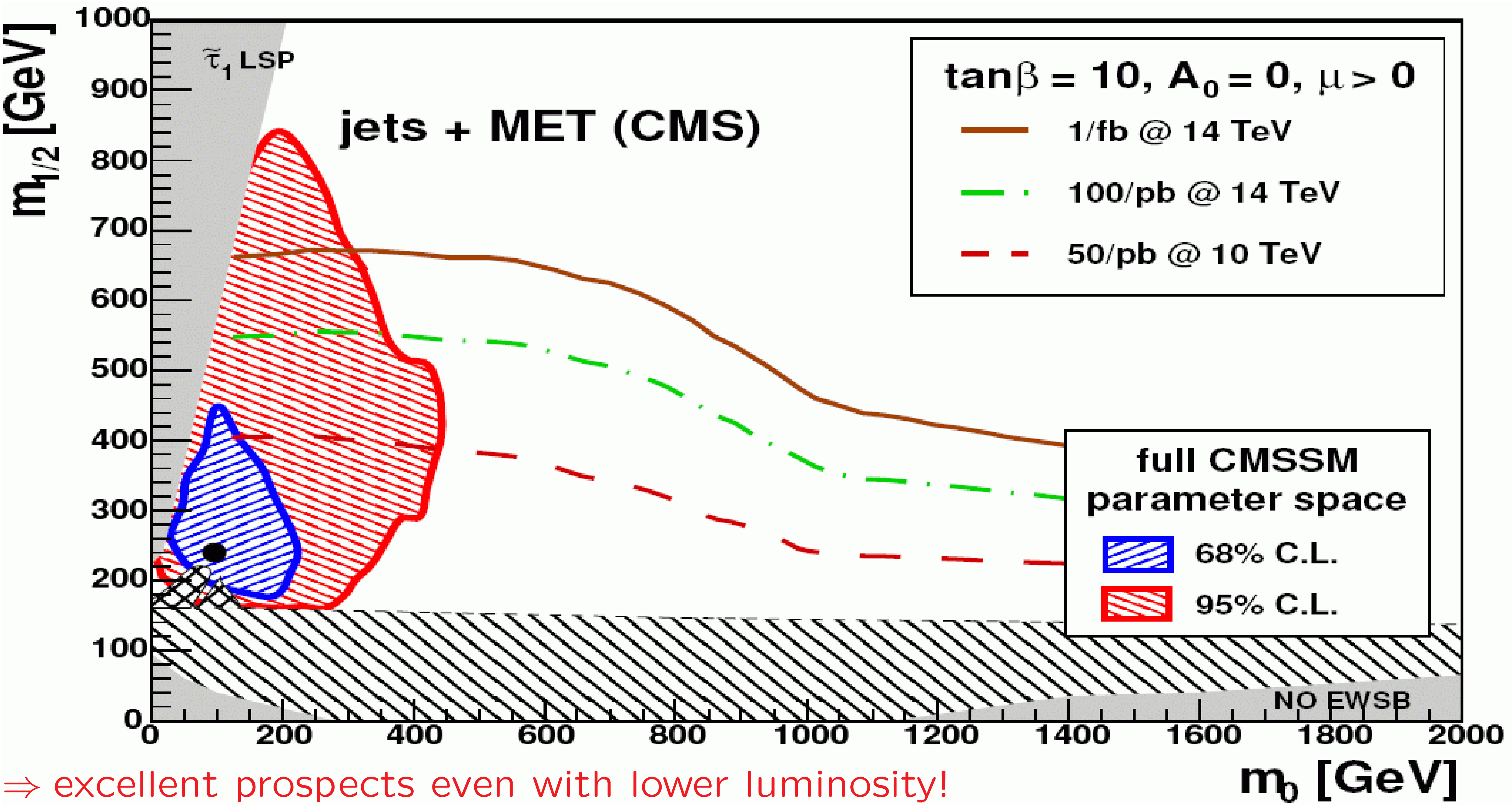

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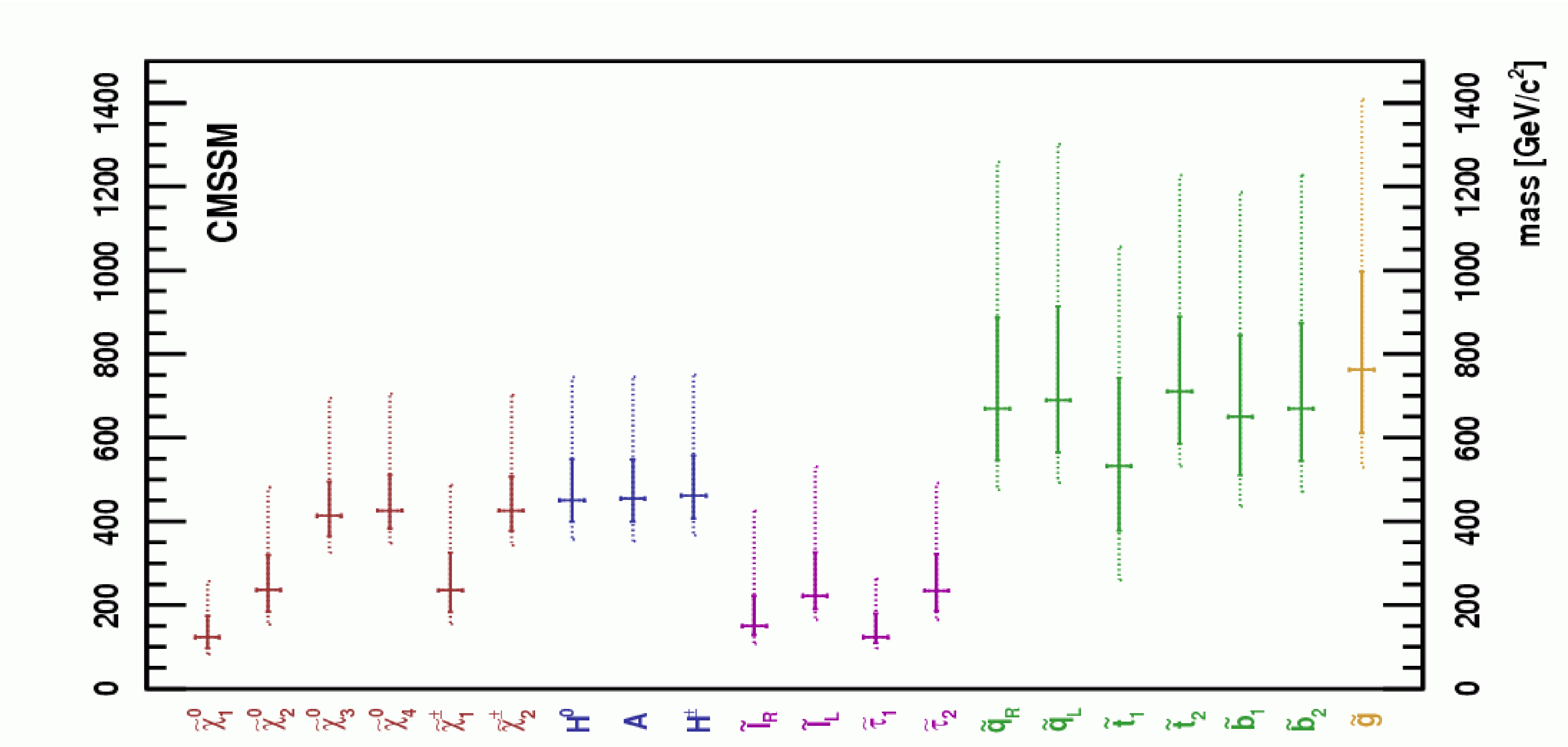
Masses for best-fit points: CMSSM

masterCODE

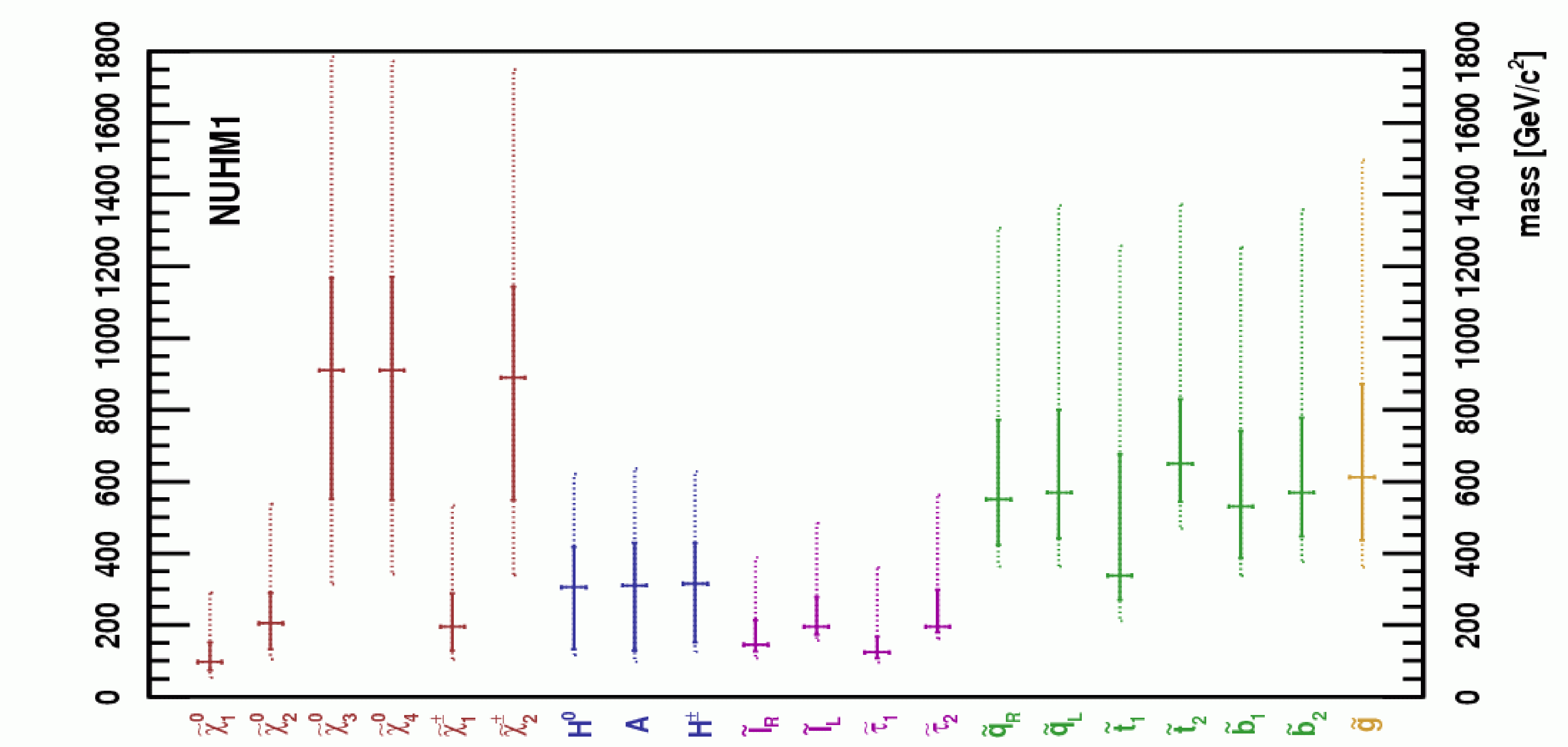
[2009]



$\Rightarrow$ largely accessible spectrum for LHC and ILC

Masses for best-fit points: NUHM1

[2009]



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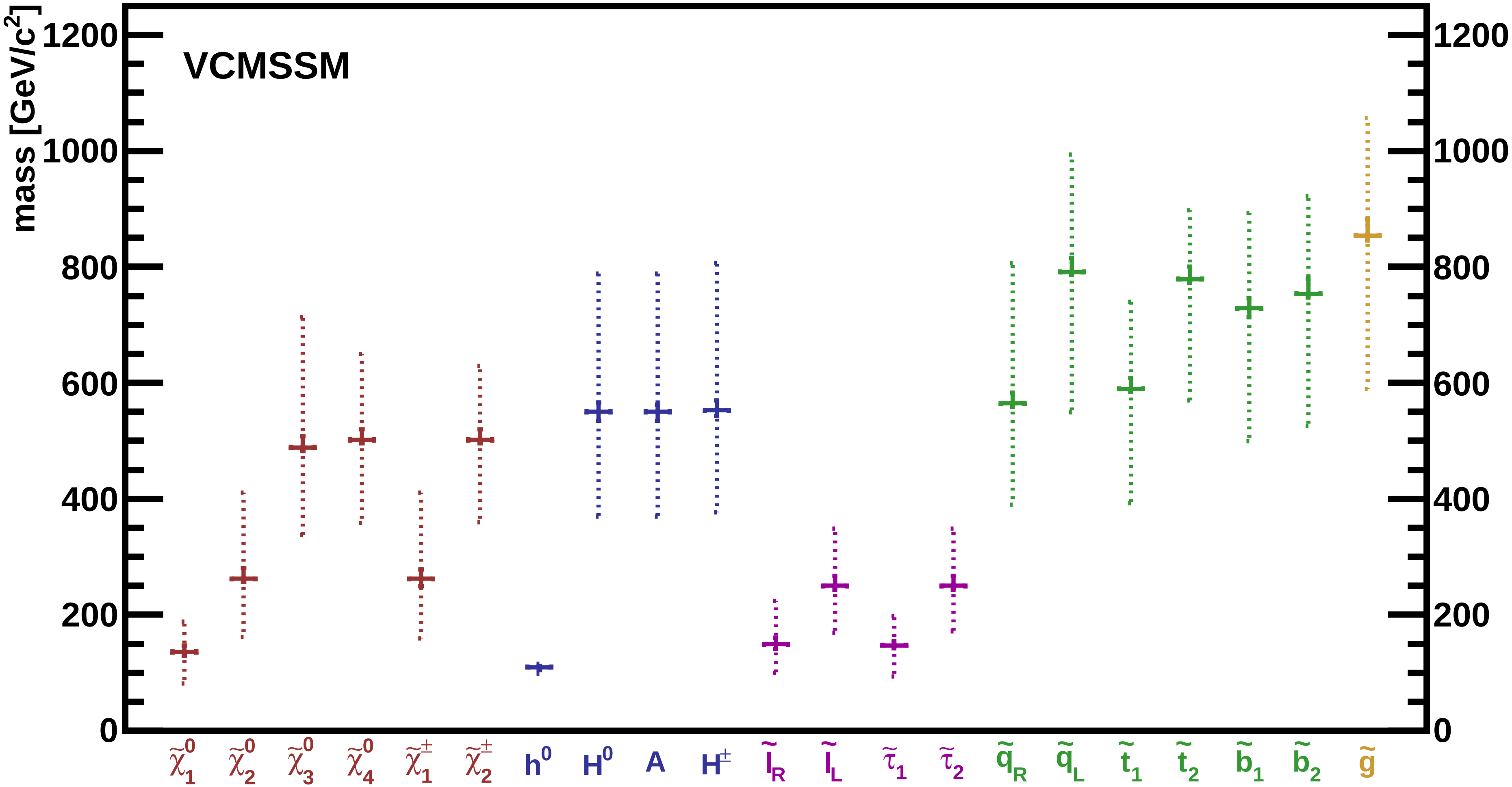
Masses for best-fit points: VCMSSM

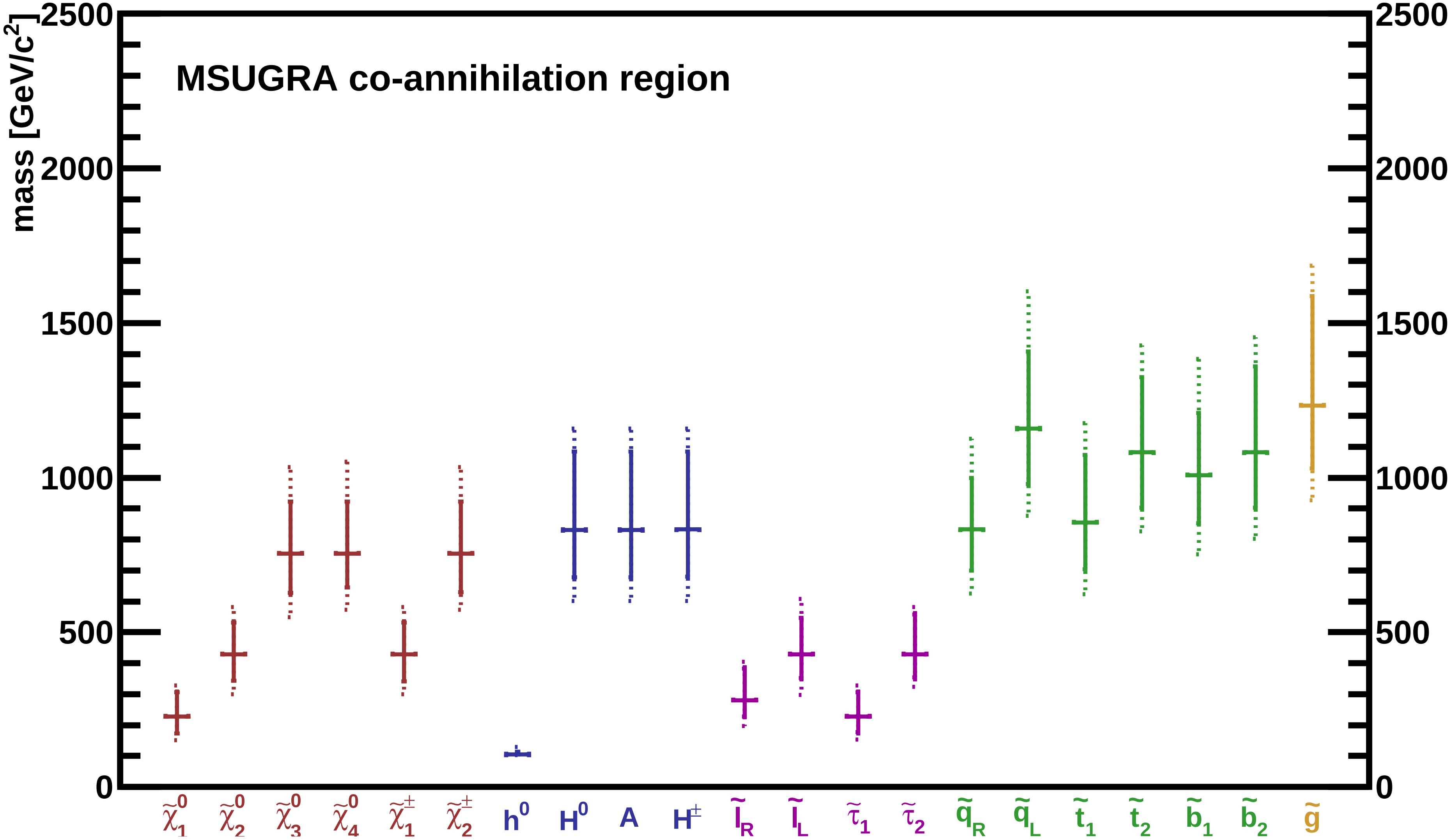
[2010]



⇒ largely accessible spectrum for LHC and ILC

Masses for best-fit points: mSUGRA (co-annihilation region)

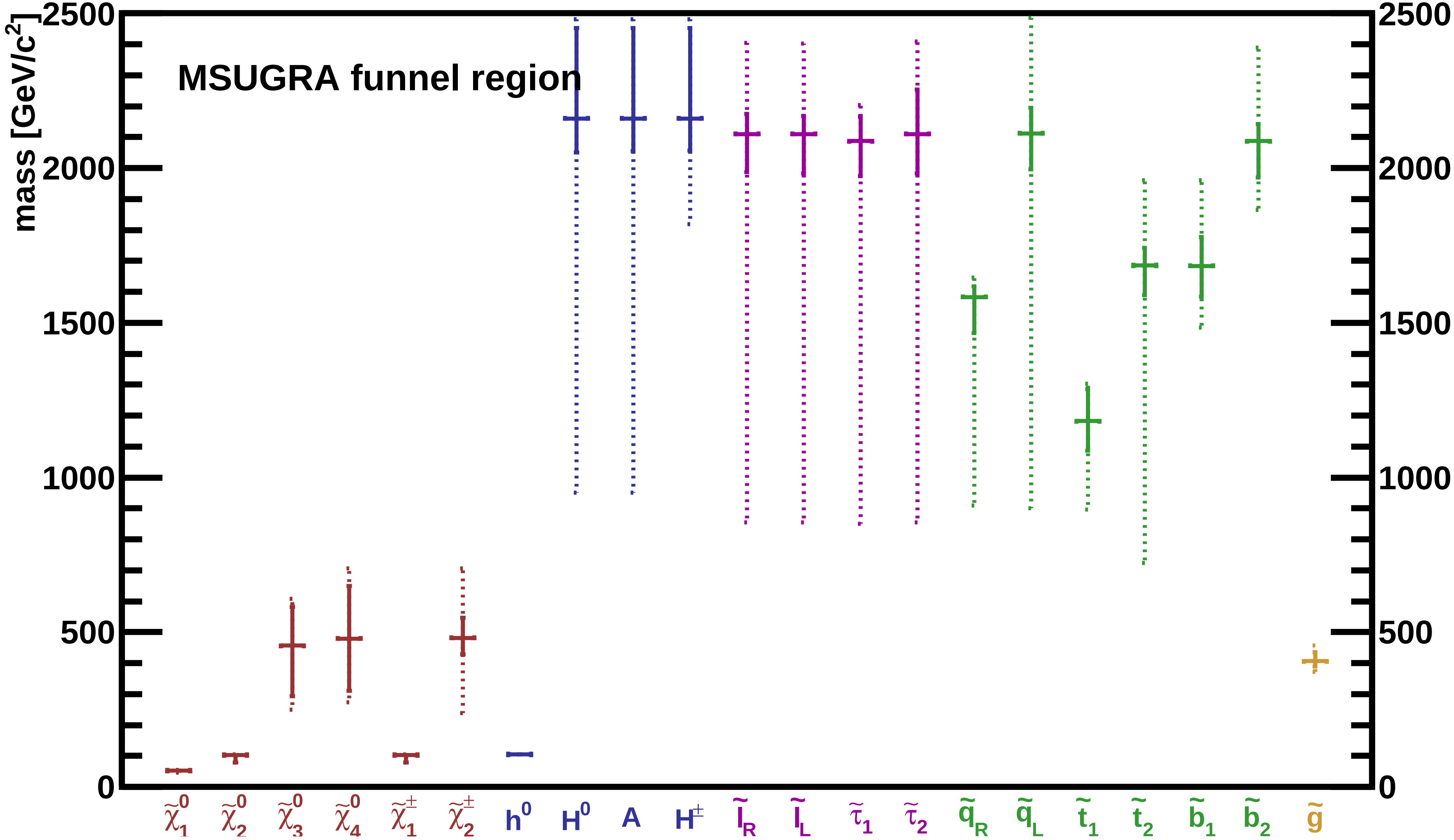
[2010]



⇒ largely accessible spectrum for LHC and ILC

Masses for best-fit points: mSUGRA (funnel region)

[2010]

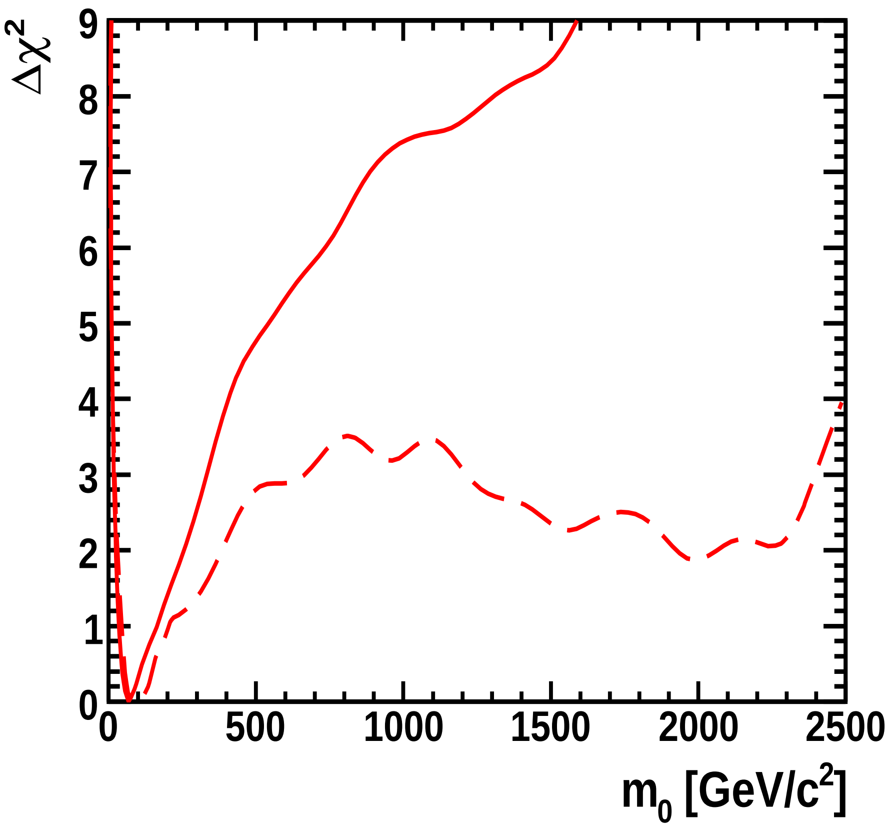


⇒ possibly much more difficult for the LHC (but high χ^2!)

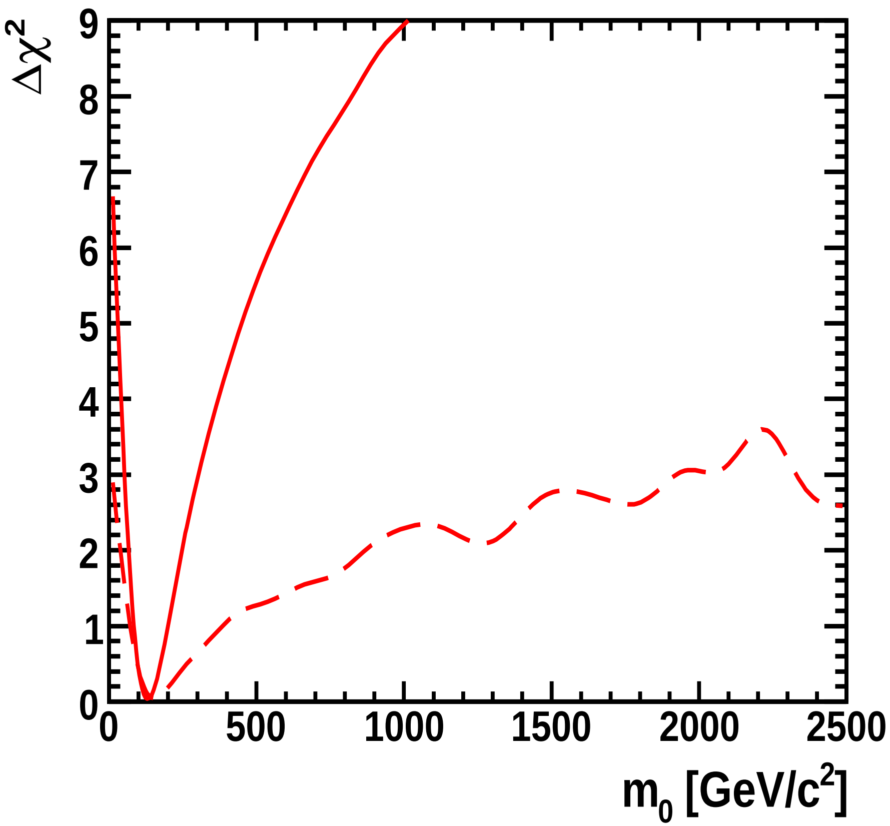
Relevance of $(g-2)_\mu$: m_0 with and without:

[2009]

CMSSM



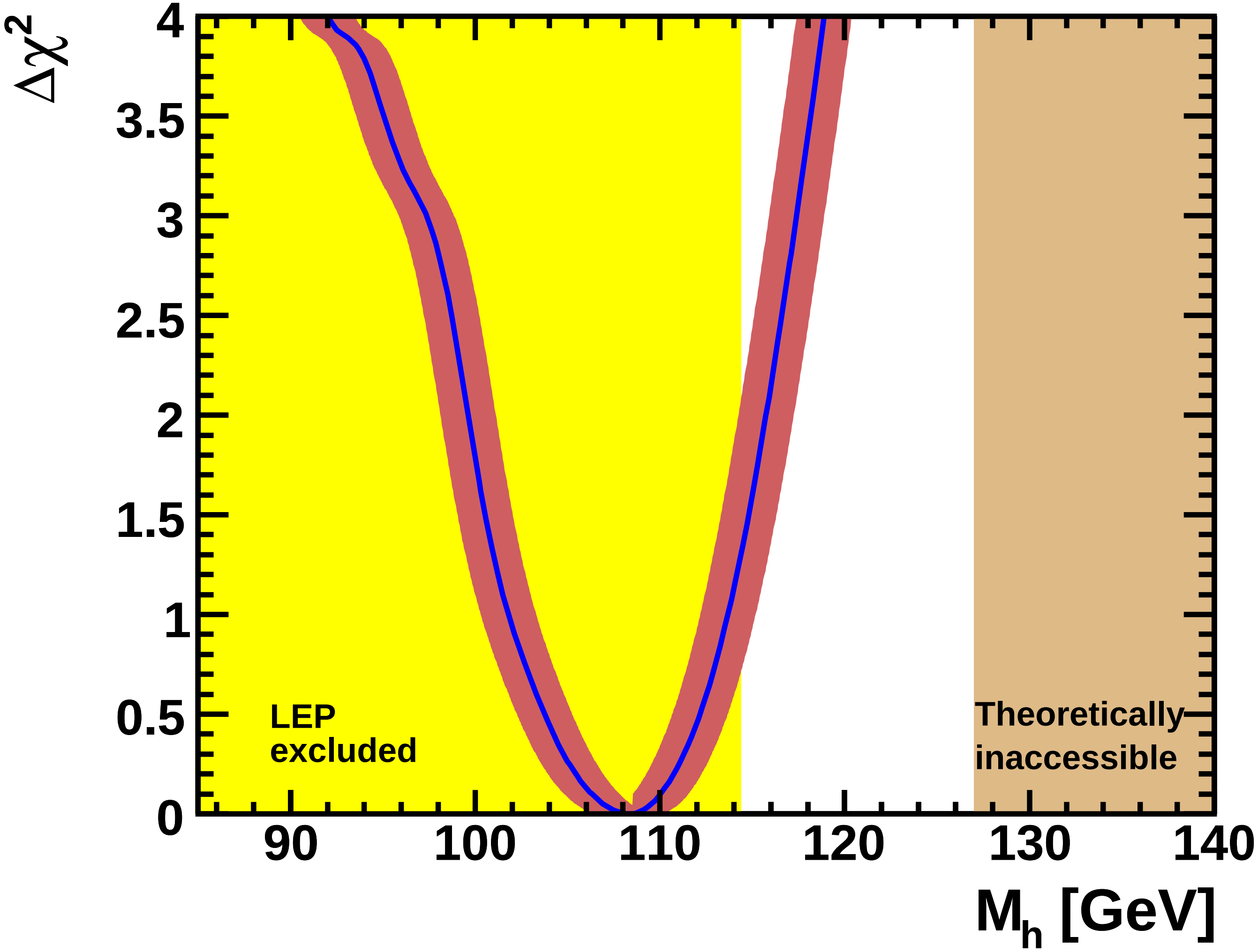
NUHM1



$\Rightarrow$ same minimum, but much more shallow

CMSSM: red band plot: (LEP bounds not included!)

[2009]



$M_h = 109 \pm 6\,(\text{exp}) \pm 1.5(\text{theo})$ GeV

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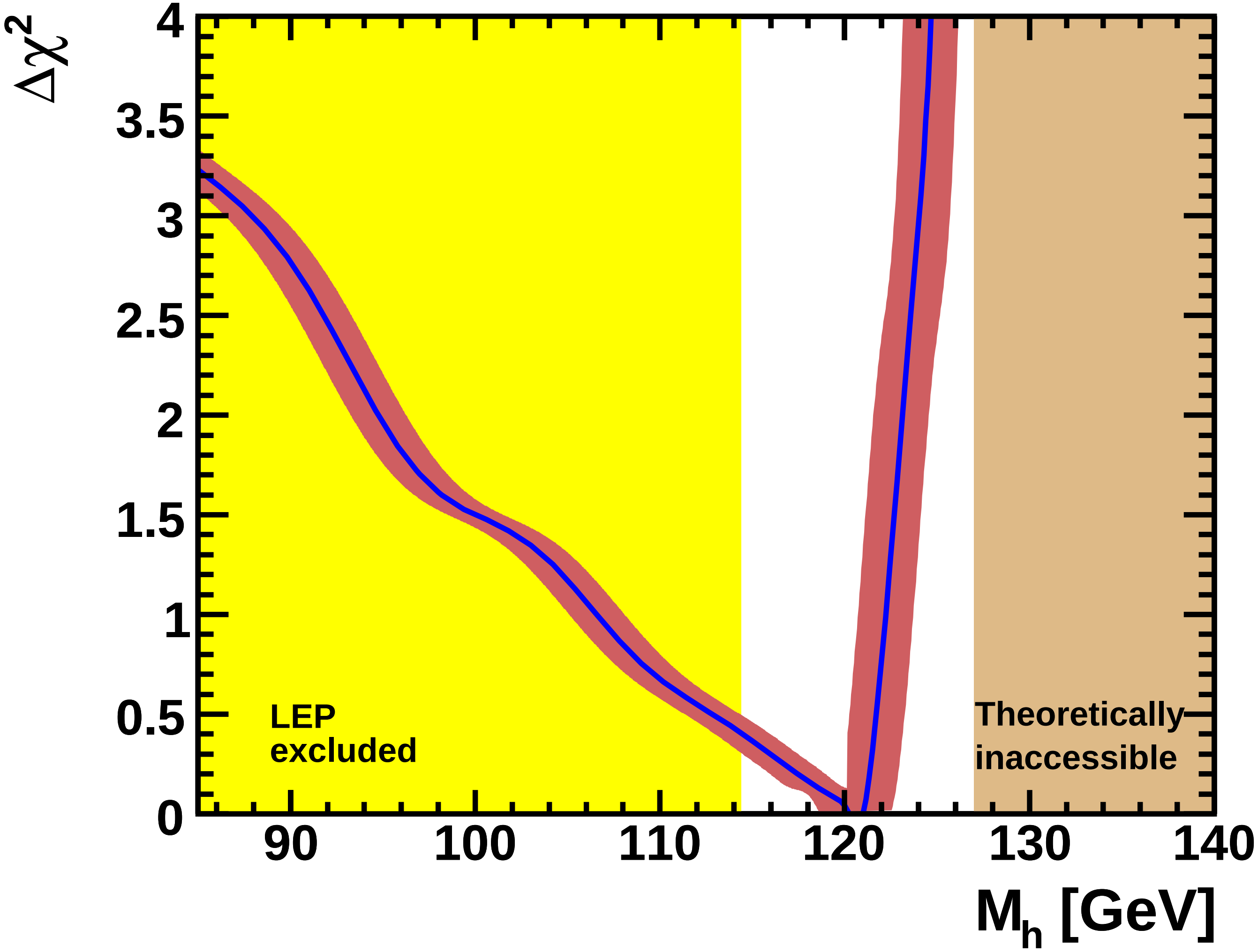
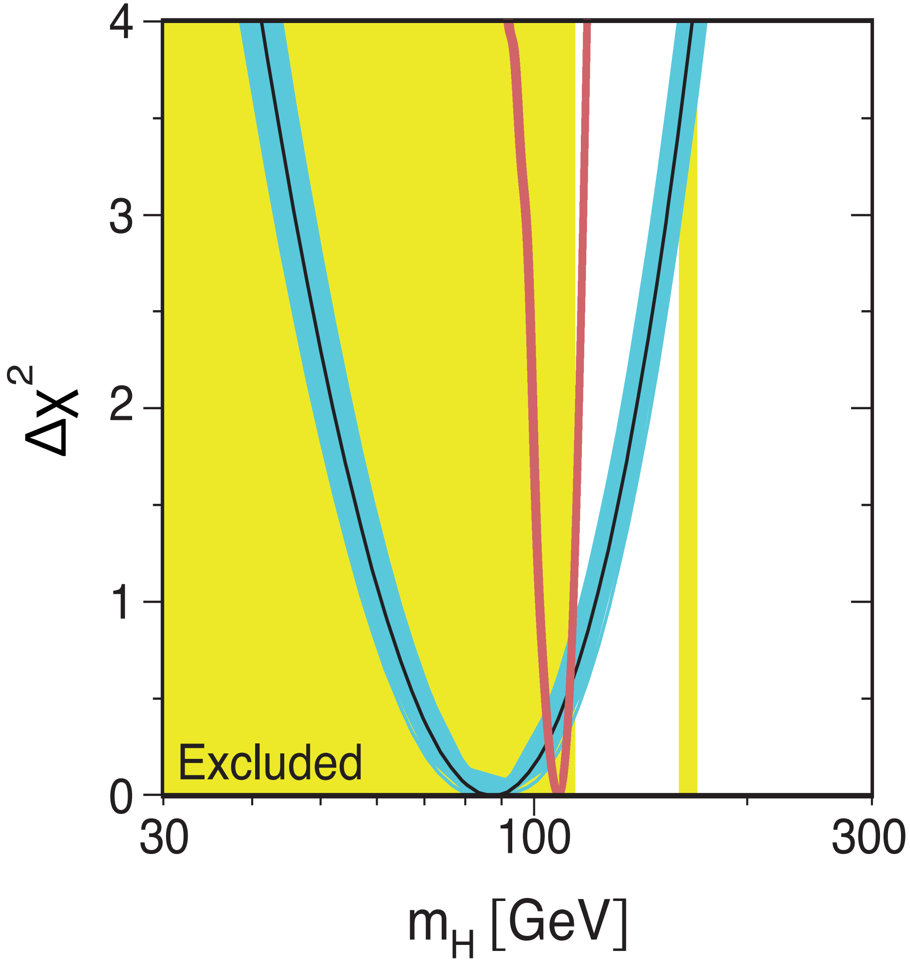


$M_h = 121^{+1}_{-14}\,(\text{exp}) \pm 1.5(\text{theo})$ GeV $\Rightarrow$ naturally above LEP limit

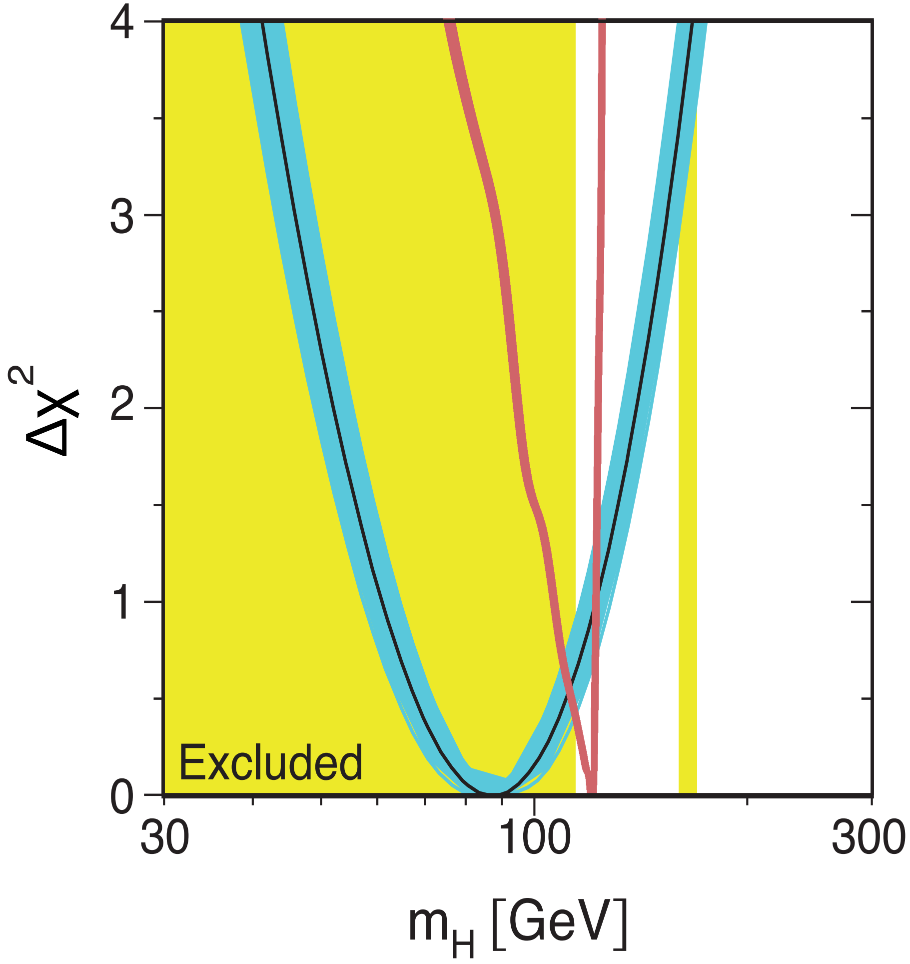
Prediction of $M_H^{\rm SM}$ (blue band) and M_h in the MSSM (red band):

[2009]

CMSSM



NUHM1



$M_h^{\rm CMSSM} = 109.5 \pm 6 \pm 1.5$ GeV

⇒ as good as the SM

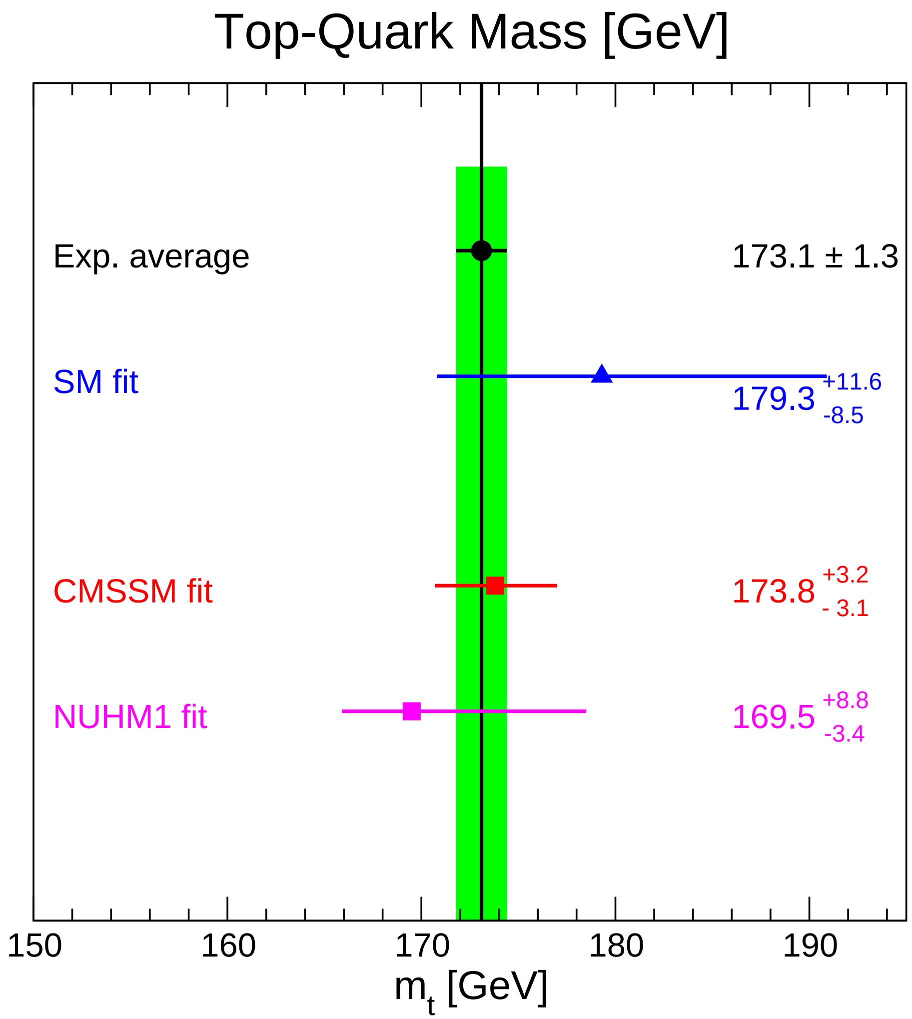
$M_h^{\rm NUHM1} = 121^{+1}_{-14} \pm 1.5$ GeV

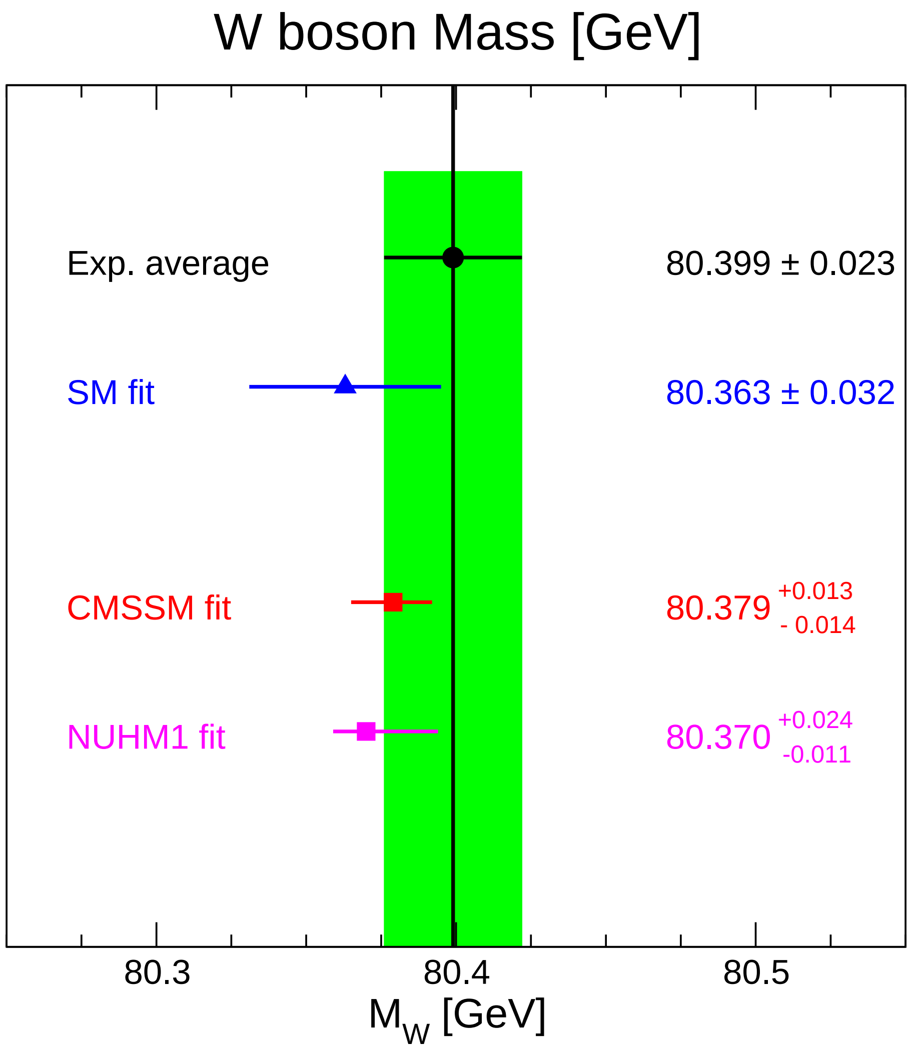
⇒ above the LEP limit

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]



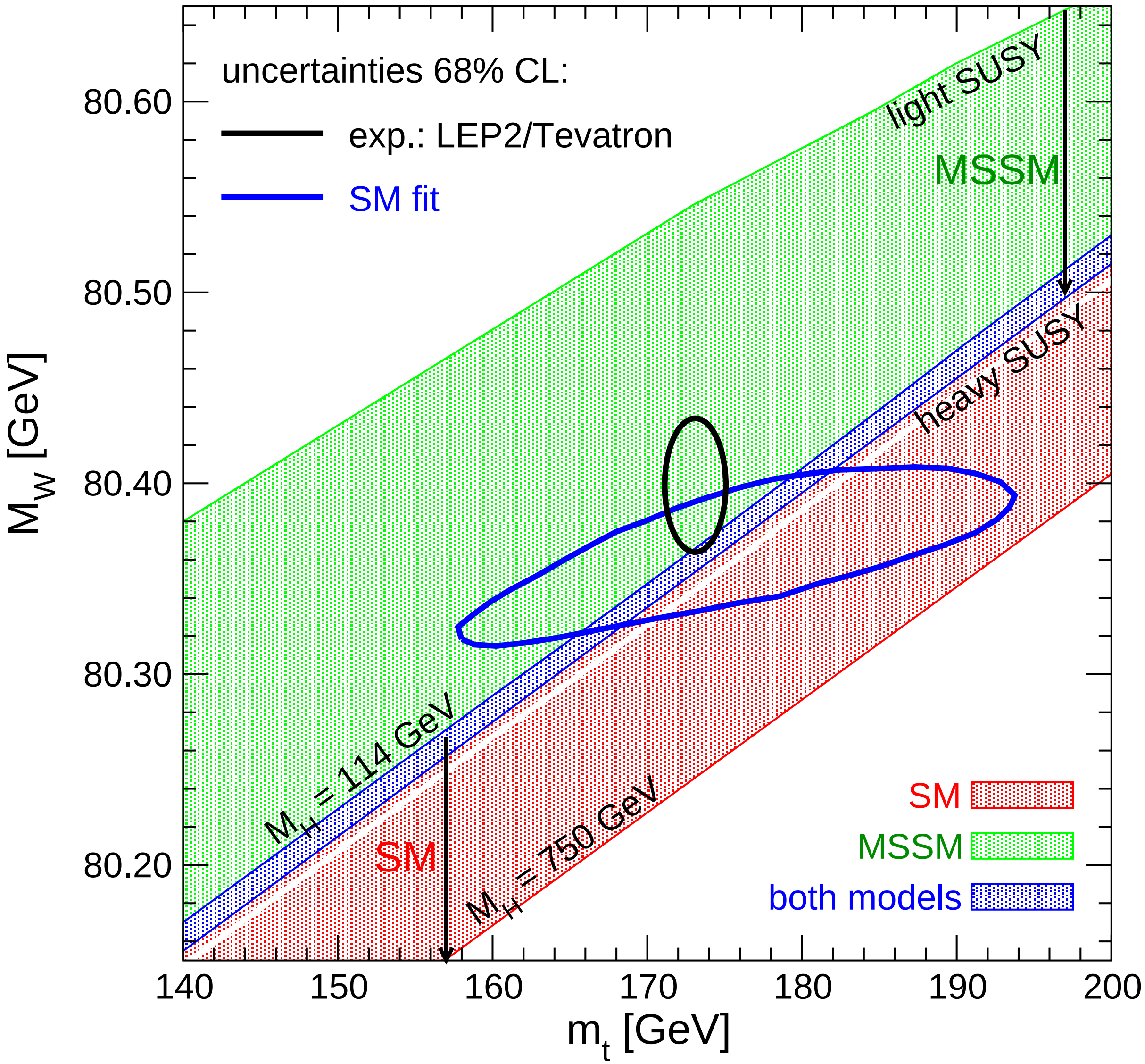


⇒ CMSSM and NUHM1 fit amazingly well m_t and M_W

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

Comparison of direct and indirect determination of m_t and M_W in the SM and the MSSM :

[2009]



MSSM band:
scan over
SUSY masses

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

SM band:
variation of M_H^{SM}

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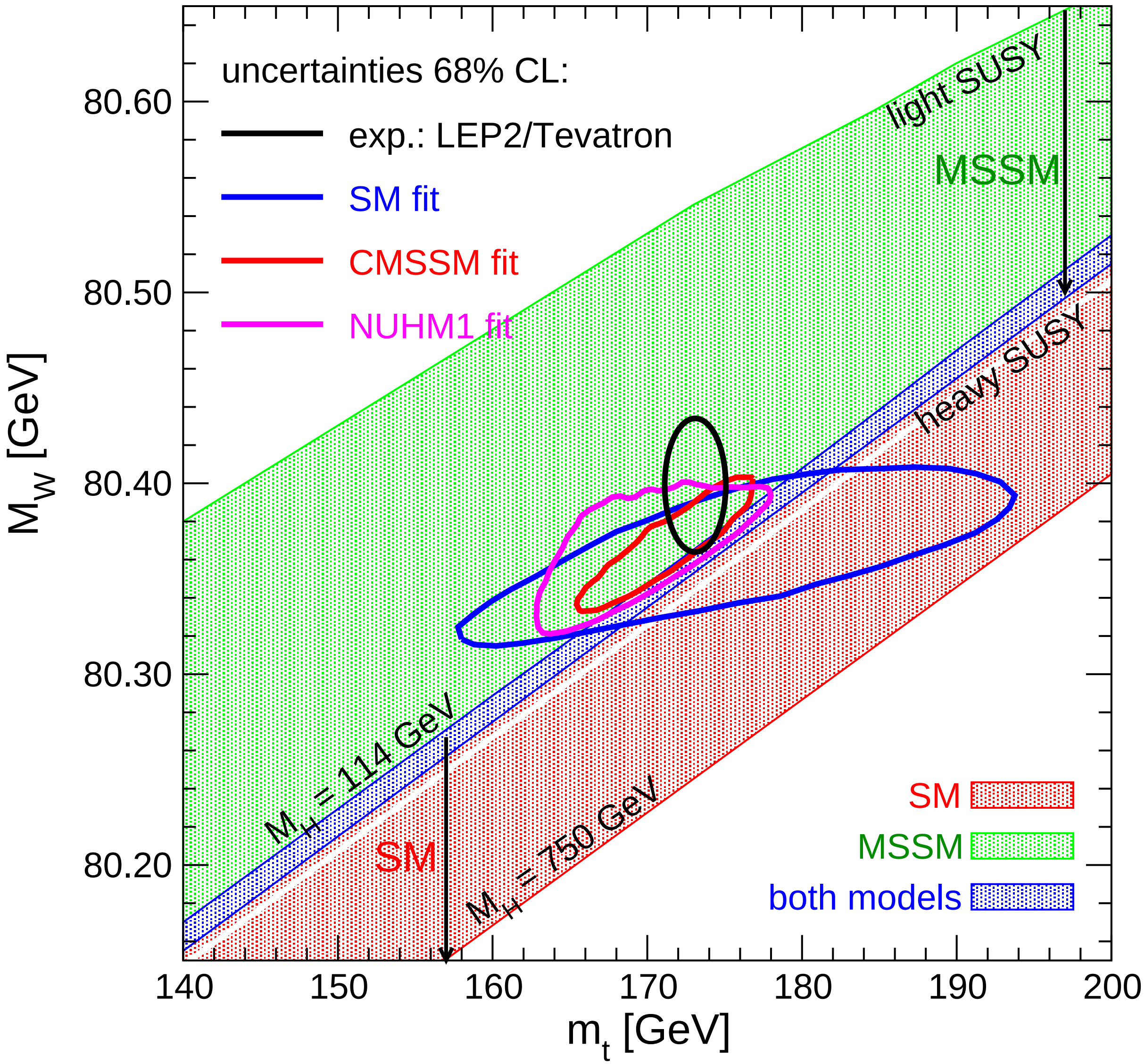

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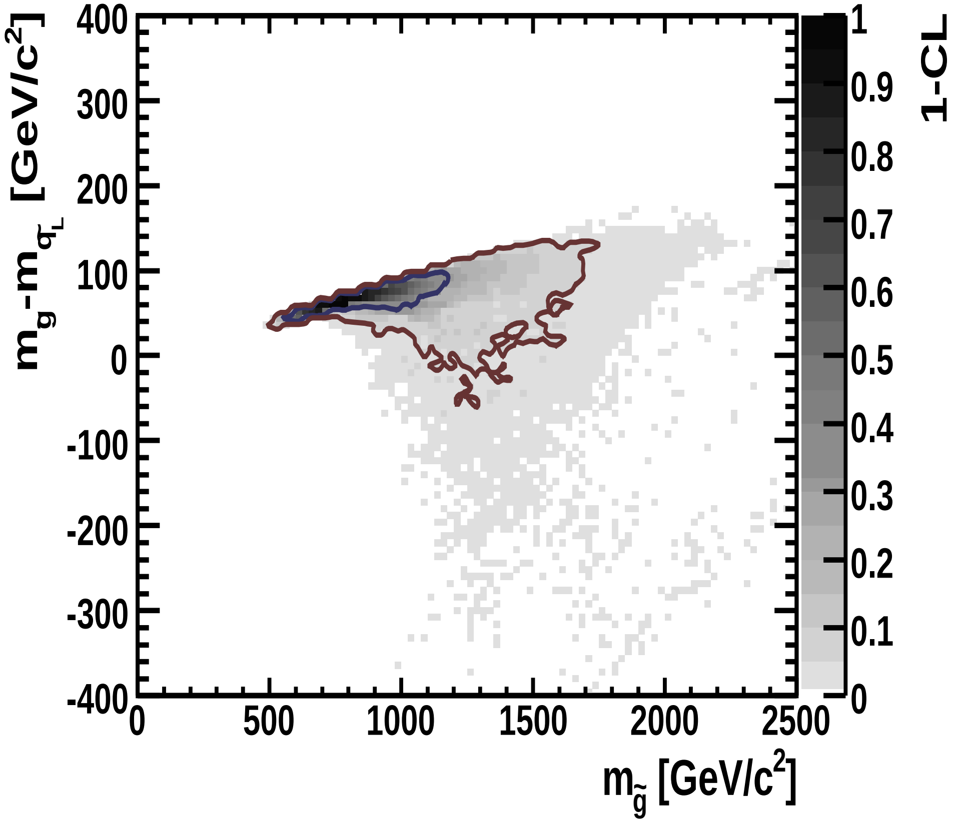
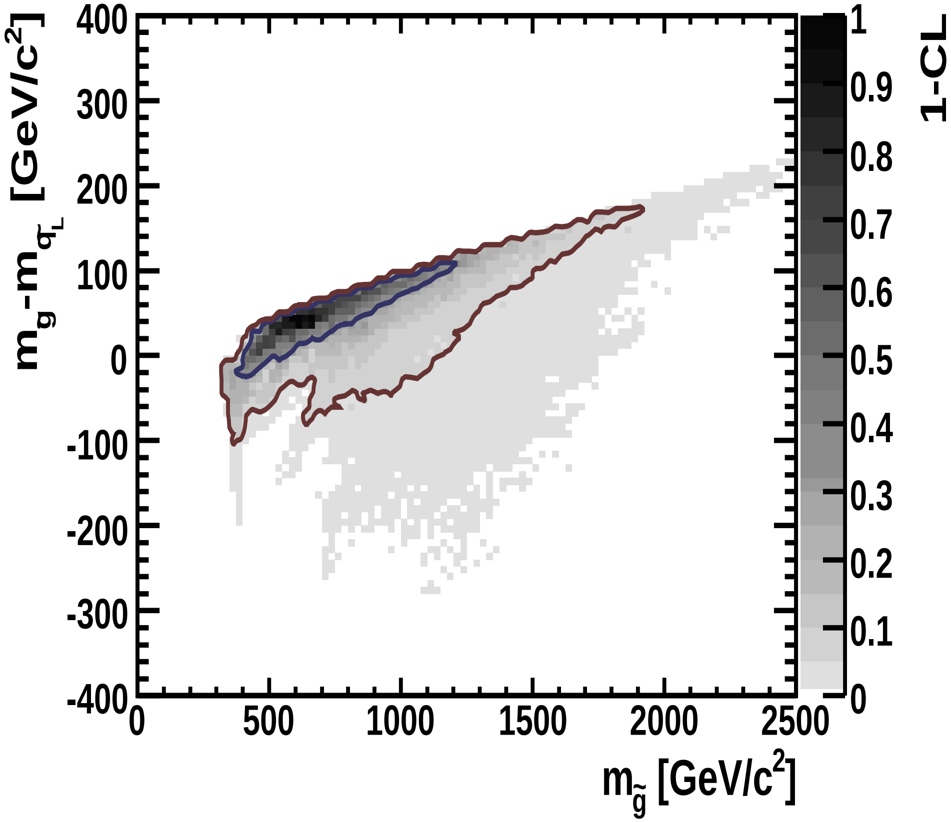
Some more predictions: $m_{\tilde{g}} - m_{\tilde{q}_L}$

[2009]

CMSSM



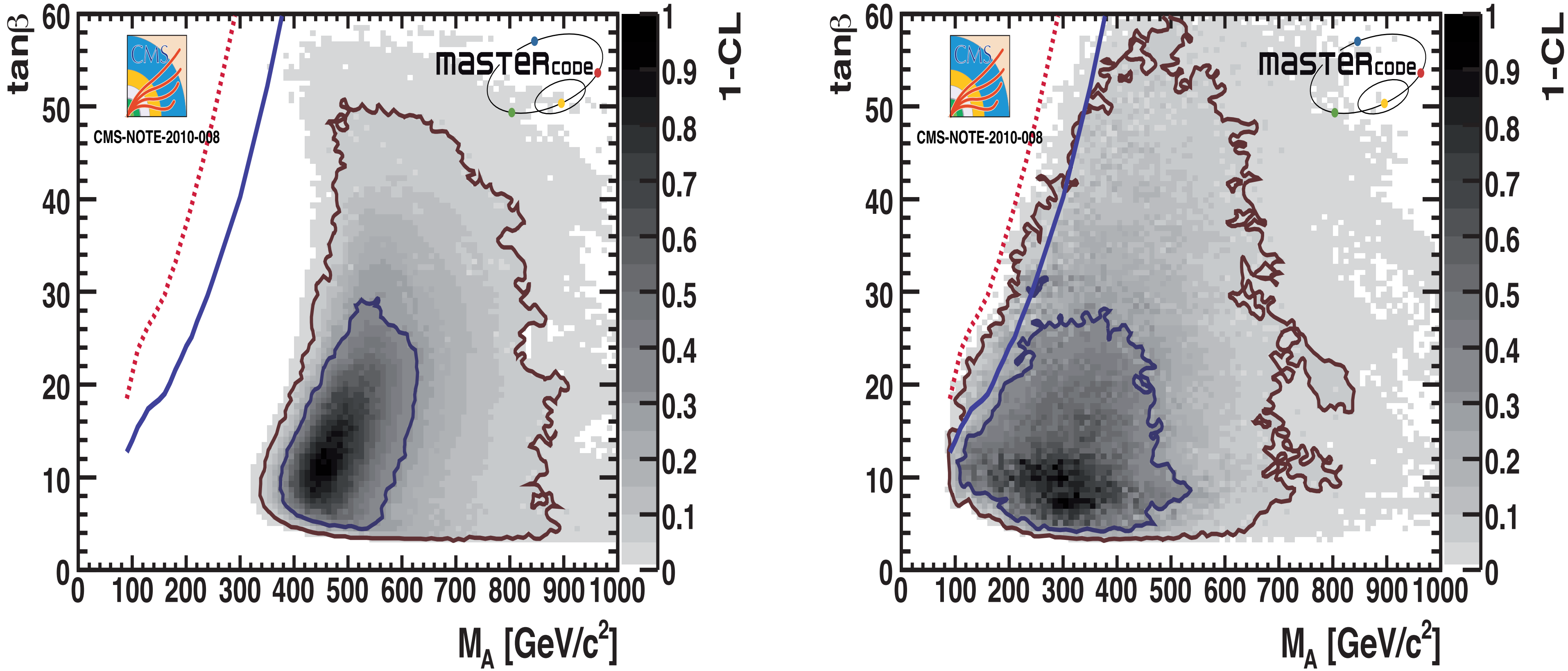
NUHM1



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

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

CMSSM NUHM1



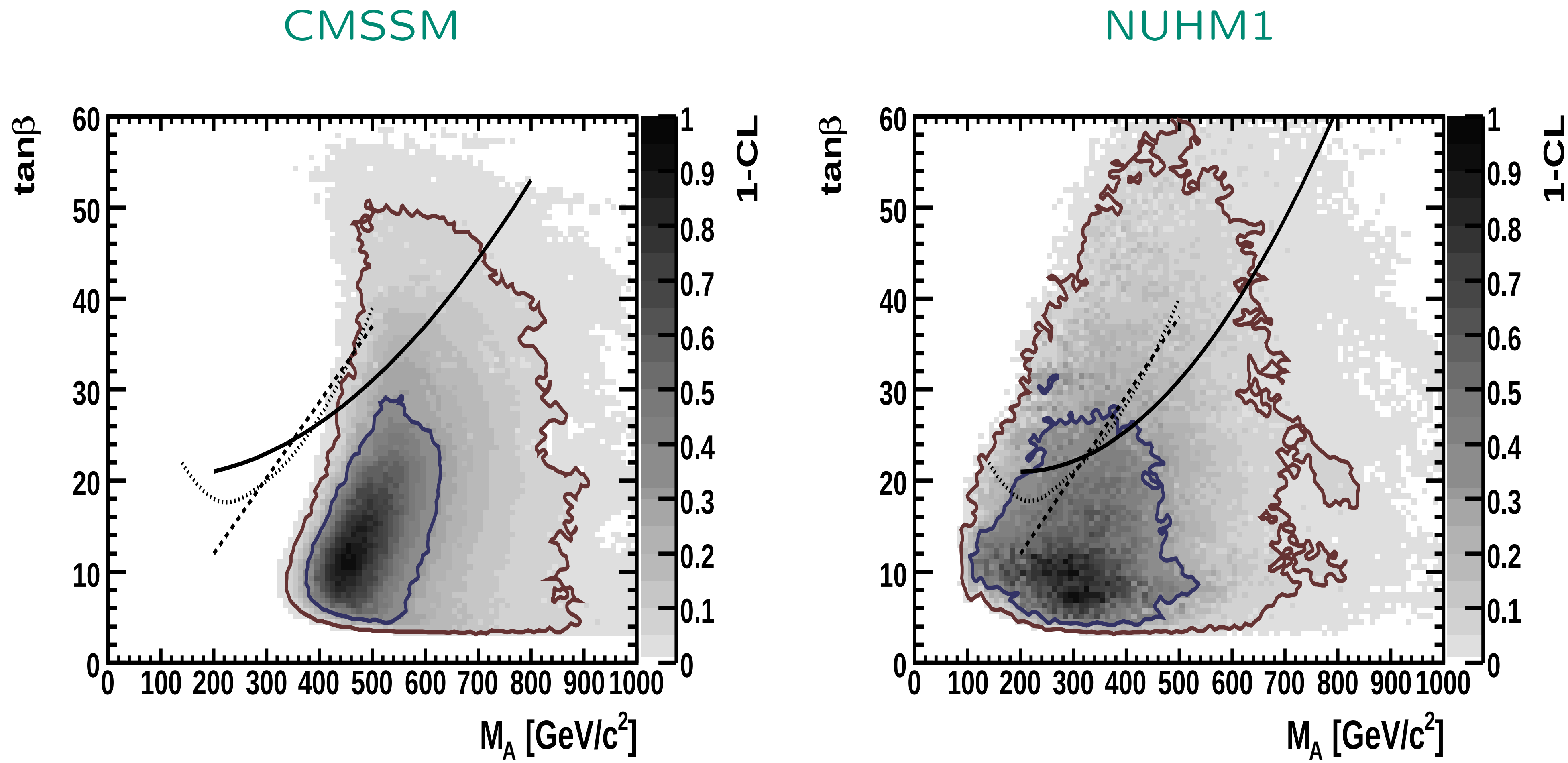
red dotted: discovery with 1 fb^{-1} @ 7 TeV

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

⇒ preferred regions missed in 2010-2011 run

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

[2009]



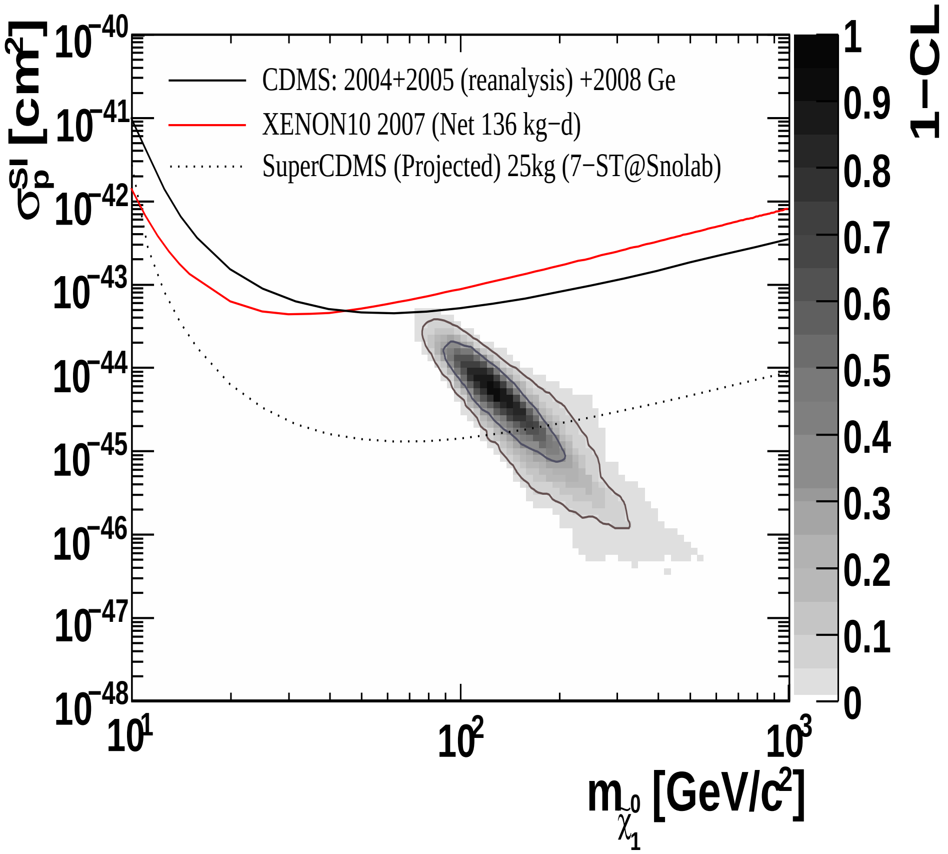
CMS analysis for 30 fb^{-1} @ 14 TeV

⇒ still best-fit regions missed by LHC, better for ILC(1000)

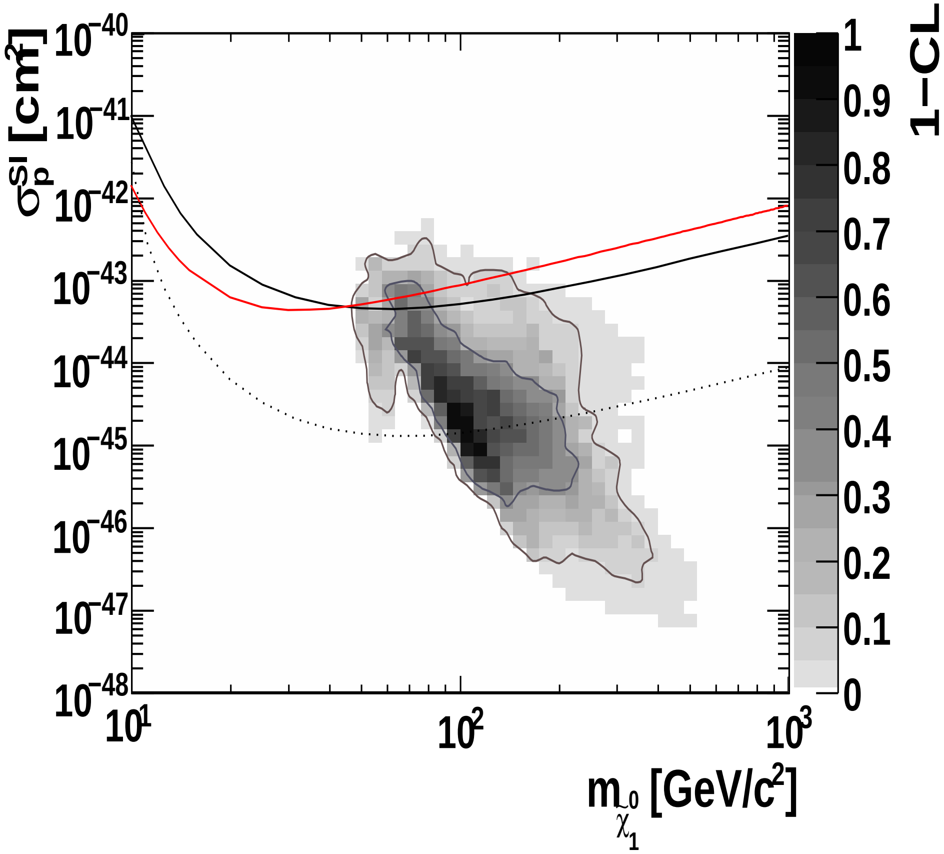
Some more predictions: direct search for dark matter

[2009]

CMSSM



NUHM1



⇒ only partially covered by future experiments

5. Prospects

Plans for the near future:

- Include ATLAS/CMS data on SUSY searches
  Needed: – exclusion bounds as model independent as possible
  – at least exclusion bounds in "our" models
  – more detailed information than "just" 95% CL exclusion bounds

- Include LHCb data

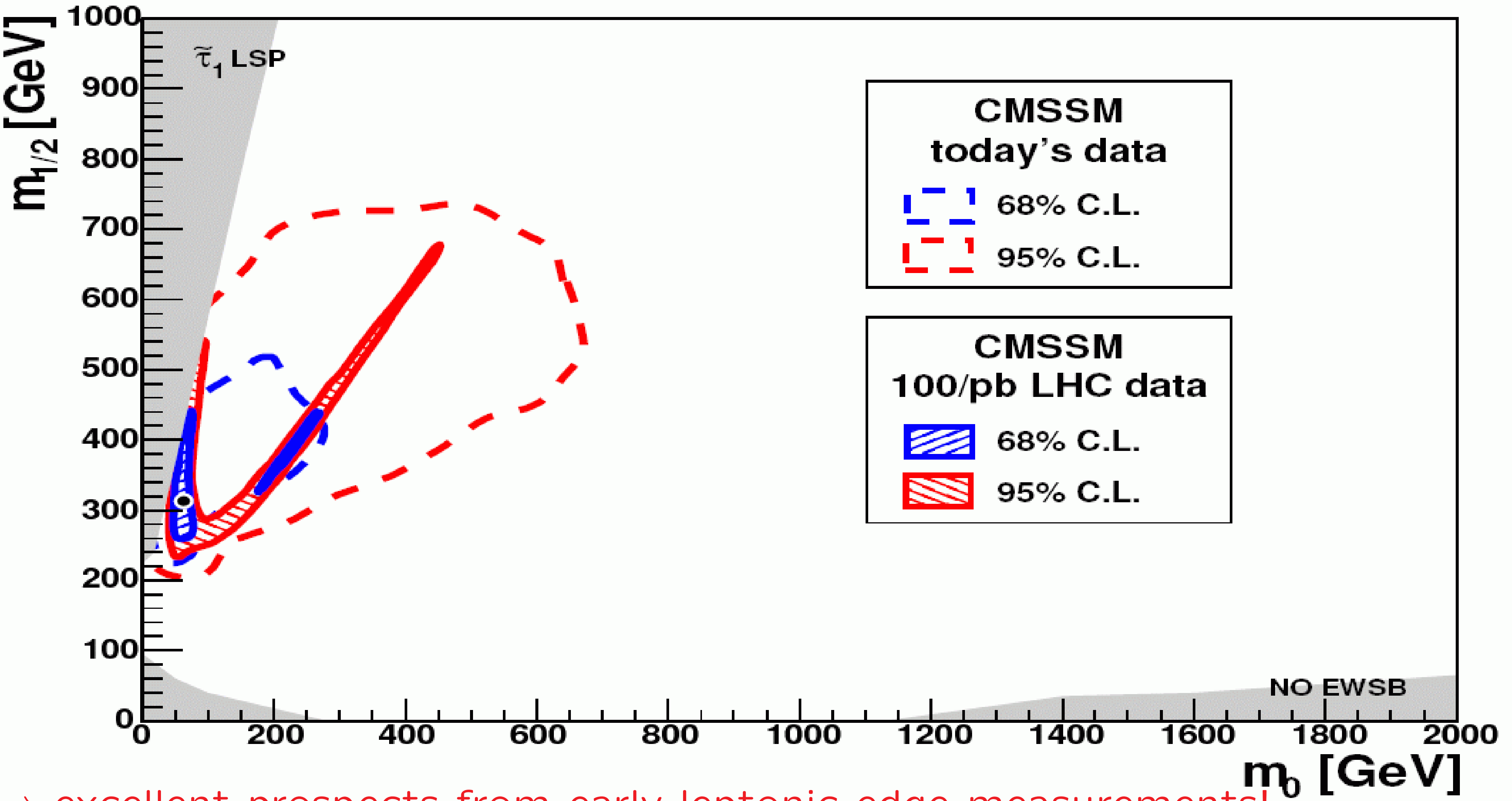
- Include DM search data (Xenon100, . . .)

- In case of a "SUSY-like" signal:
  go beyond the simple GUT based models

LHC (CMS) reach with 1 fb^{-1}:

[2008]

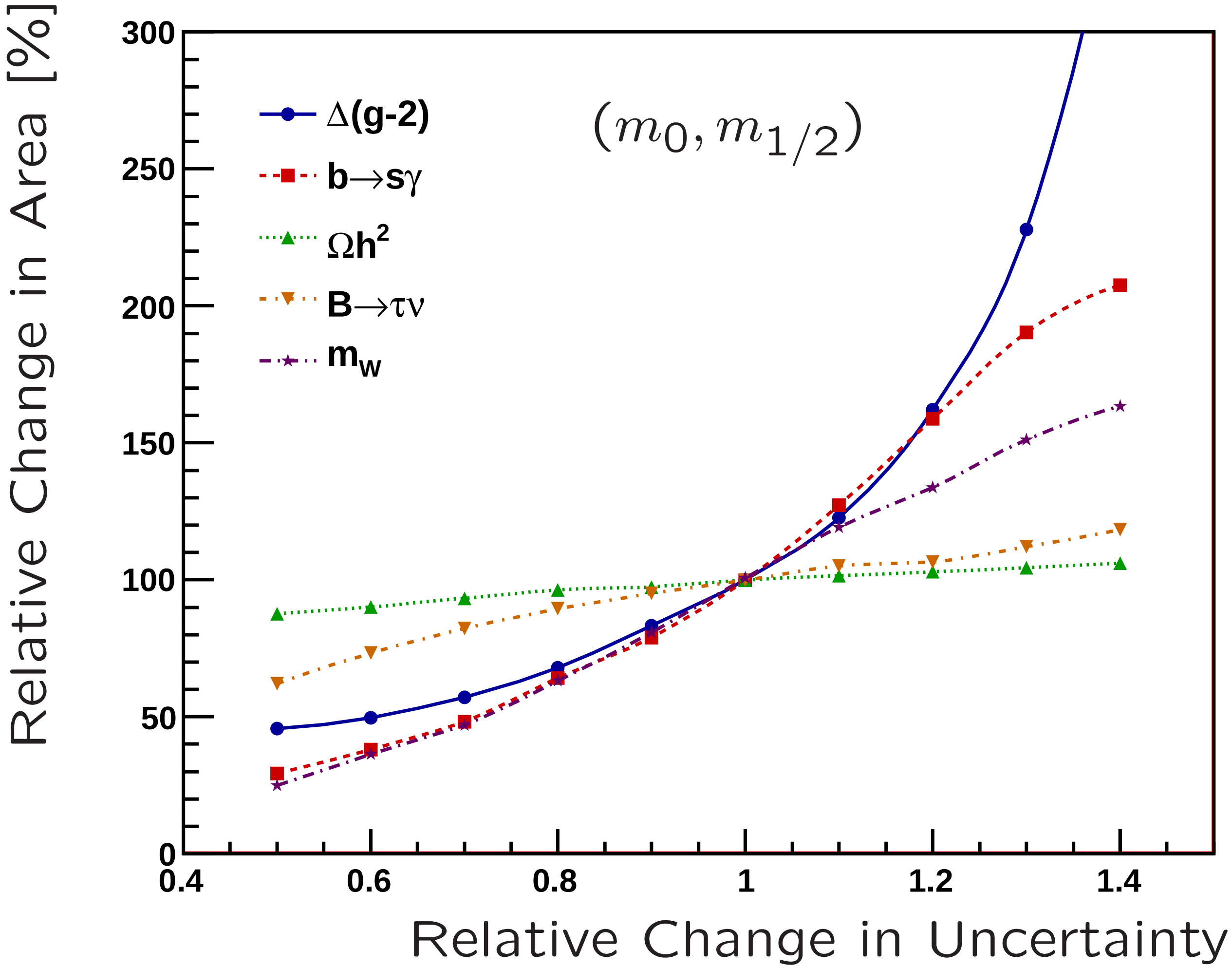
CMSSM analysis incl. leptonic edge measurements



⇒ excellent prospects from early leptonic edge measurements!

Impact of various constraints (CMSSM):

[2008]

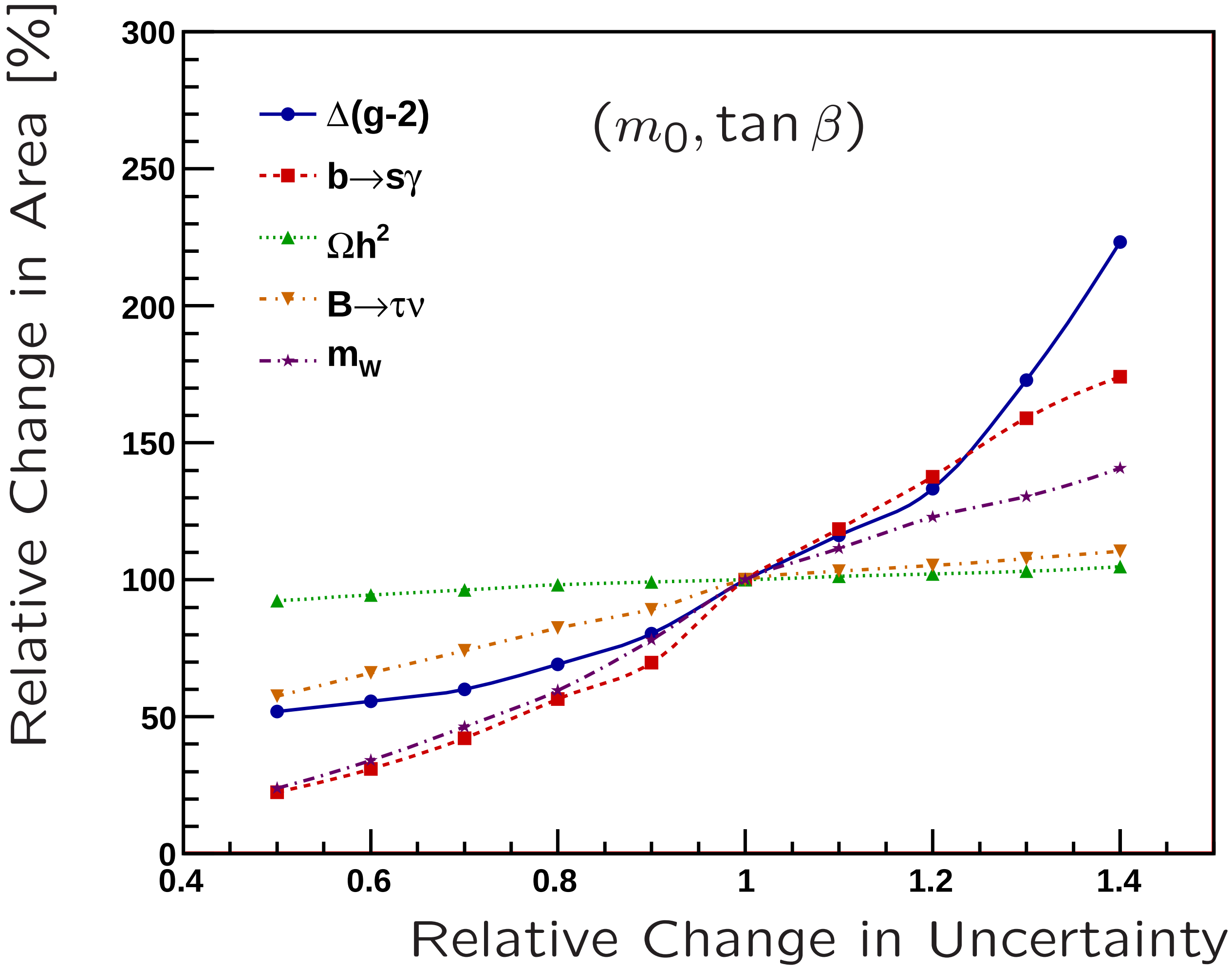


⇒ strong impact of $(g-2)_\mu$

⇒ strong improvement possible from
M_W, BR($b \to s\gamma$), $(g-2)_\mu$, BR($B_u \to \tau\nu$)

Impact of various constraints (CMSSM):

[2008]



⇒ strong impact of $(g-2)_\mu$

⇒ strong improvement possible from
M_W, BR$(b \to s\gamma)$, $(g-2)_\mu$, BR$(B_u \to \tau\nu)$

6. Conclusinos

- Models: (MFV) MSSM
  Analyses: CMSSM, NUHM1, mSUGRA, VCMSSM

- Codes included: SuFla, SuperIso, FeynHiggs, FeynWZ, MicrOMEGAs, DarkSUSY, SoftSUSY, Minuit (HiggsBounds)

  ⇒ all most-up-to-date codes on the market! ⇒ crucial for precision!

  ⇒ predictions for: EWPO, BPO, CDM, . . .

  (EWPO: (nearly) as for the blue band plot)

- 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

- Results exist for:
  - best-fit points, 68, 95% C.L. areas
  - predictions for SUSY masses ⇒ LHC reach
  - predictions for M_h (red band plot)
  - predictions for SM parameters: M_W , m_t
  - predictions for flavor observables
  - predictions for astro-physical observables

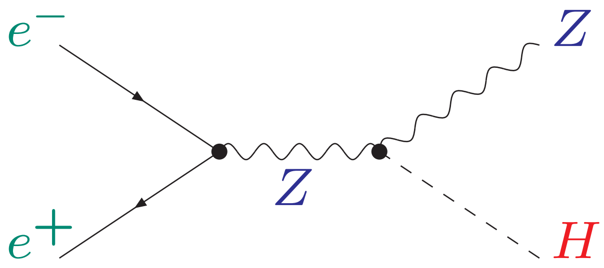
- Prospects: inclusion of ATLAS/CMS, LHCb, Xenon100 data . . .

Back-up

SM Higgs search at LEP:

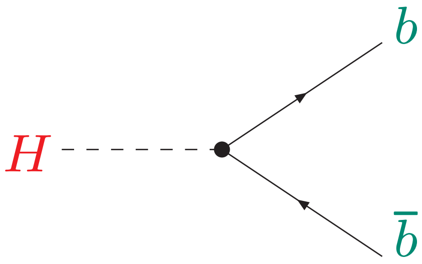
Dominant SM production process:

$e^+e^- \to ZH$:



Dominant decay process:

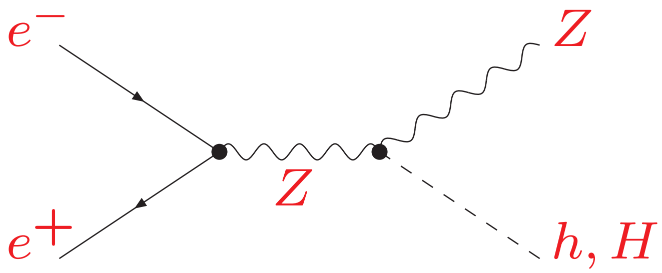
$H \to b\bar{b}$:



Bounds valid in the CMSSM? NUHM1? MSSM?

Search for neutral SUSY Higgs bosons:

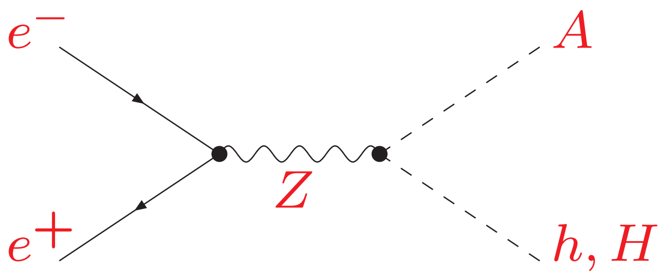
$e^+e^- \to Zh, ZH$



$$\sigma_{hZ} \approx \sin^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$$\sigma_{HZ} \approx \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$e^+e^- \to Ah, AH$

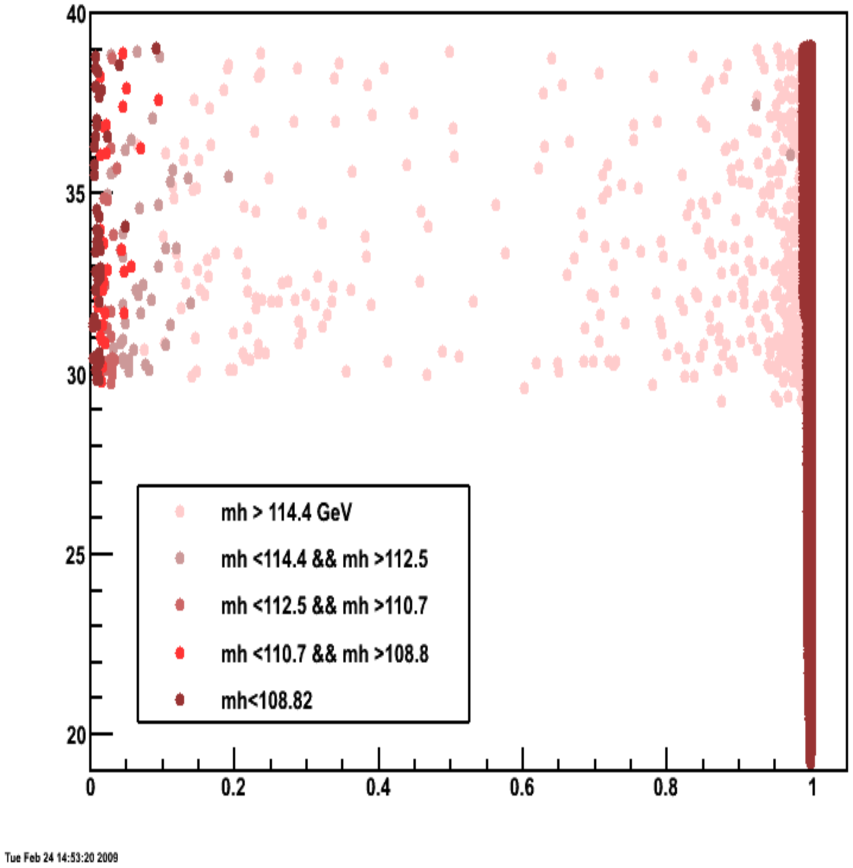


$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

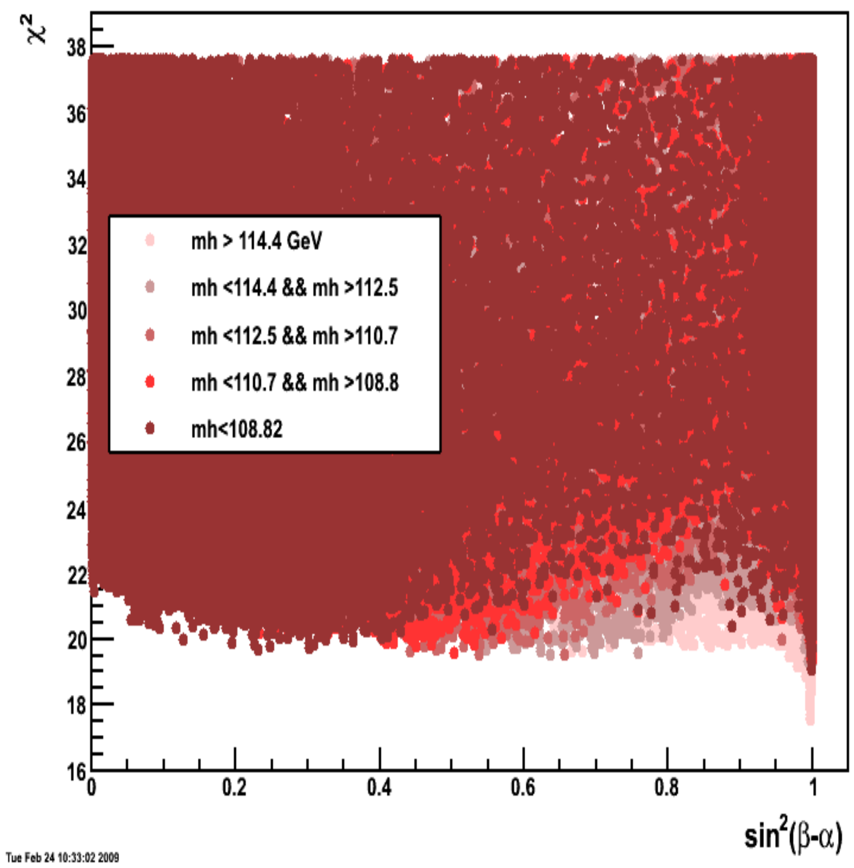
$$\sigma_{HA} \propto \sin^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$\sin^2(\beta - \alpha_{\rm eff})$ in the CMSSM, NUHM1:

CMSSM

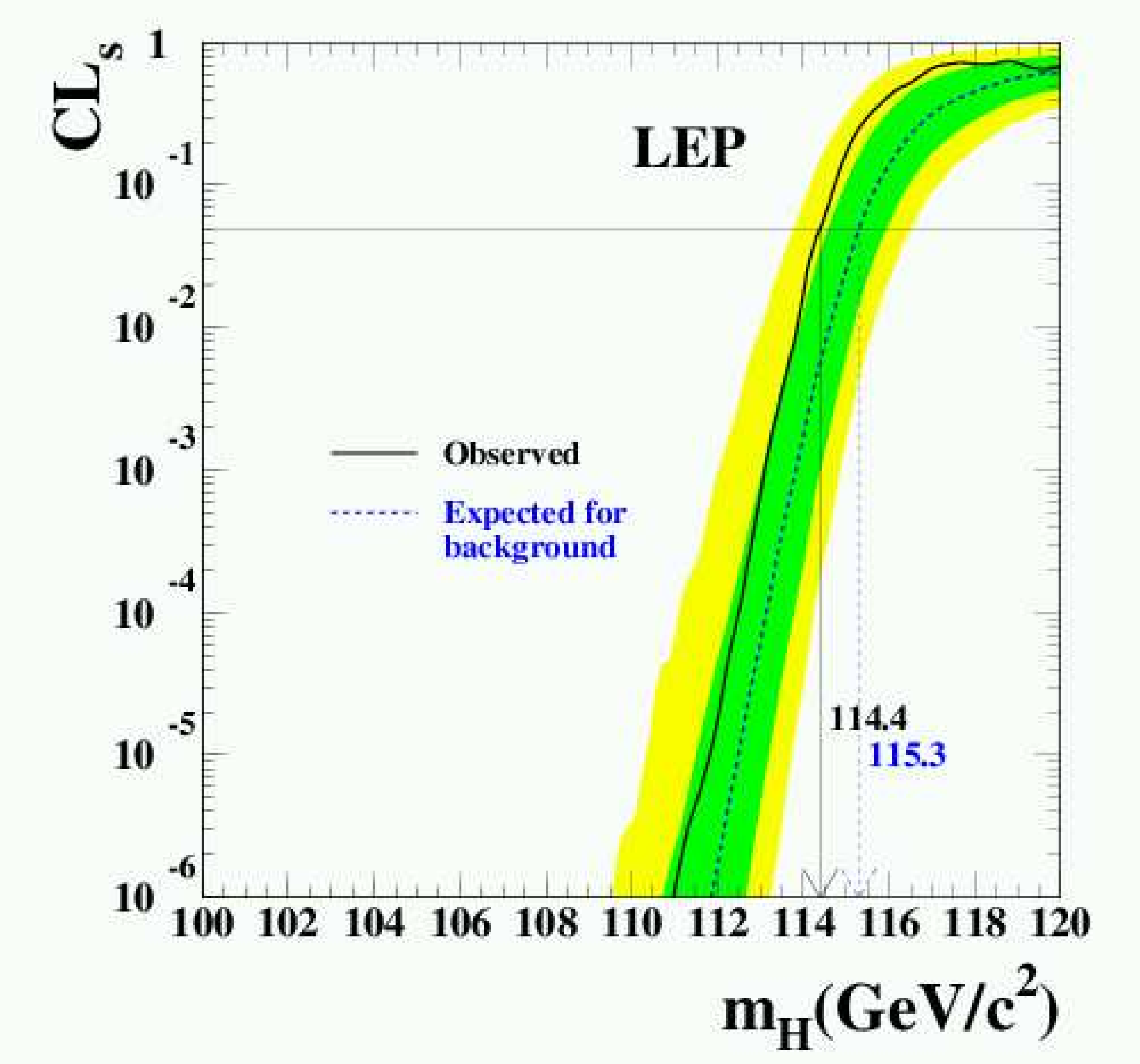


NUHM1



In CMSSM:

SM bound of M_H search can be used [*LEP Higgs Working Group '03*]



CL_s can be used/transformed into χ^2 values

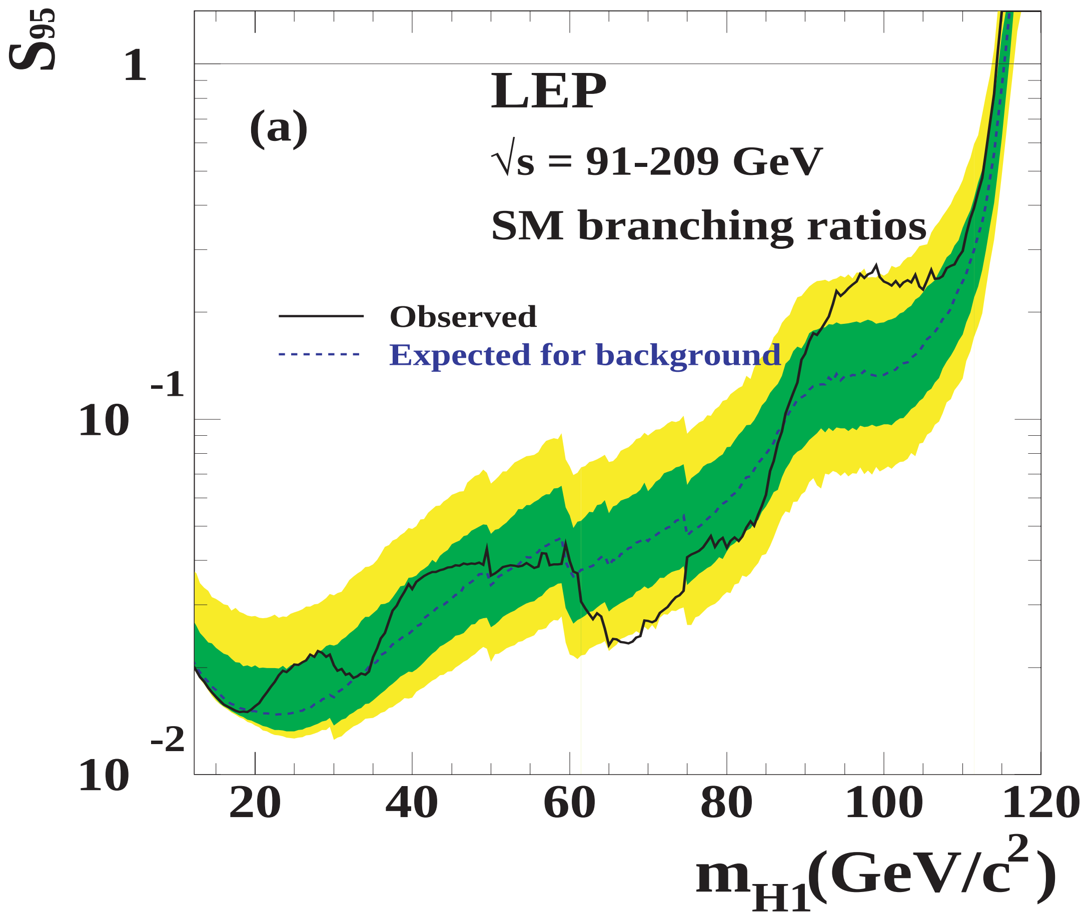
$\Rightarrow$ can be included into χ^2 evaluation

$\delta M_h^{\text{intr.}} \approx 3$ GeV

We use *FeynHiggs*

In the NUHM1:

SM bound on M_H is reduced: $S_{95} \sim \sin^2(\beta - \alpha_{\rm eff})$



⇒ take into account the LEP SM Higgs bound . . .

. . . but shifted according to the reduced coupling