The MasterCode

Sven Heinemeyer, IFCA (CSIC, Santander)

DESY Hamburg, 07/2010

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

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

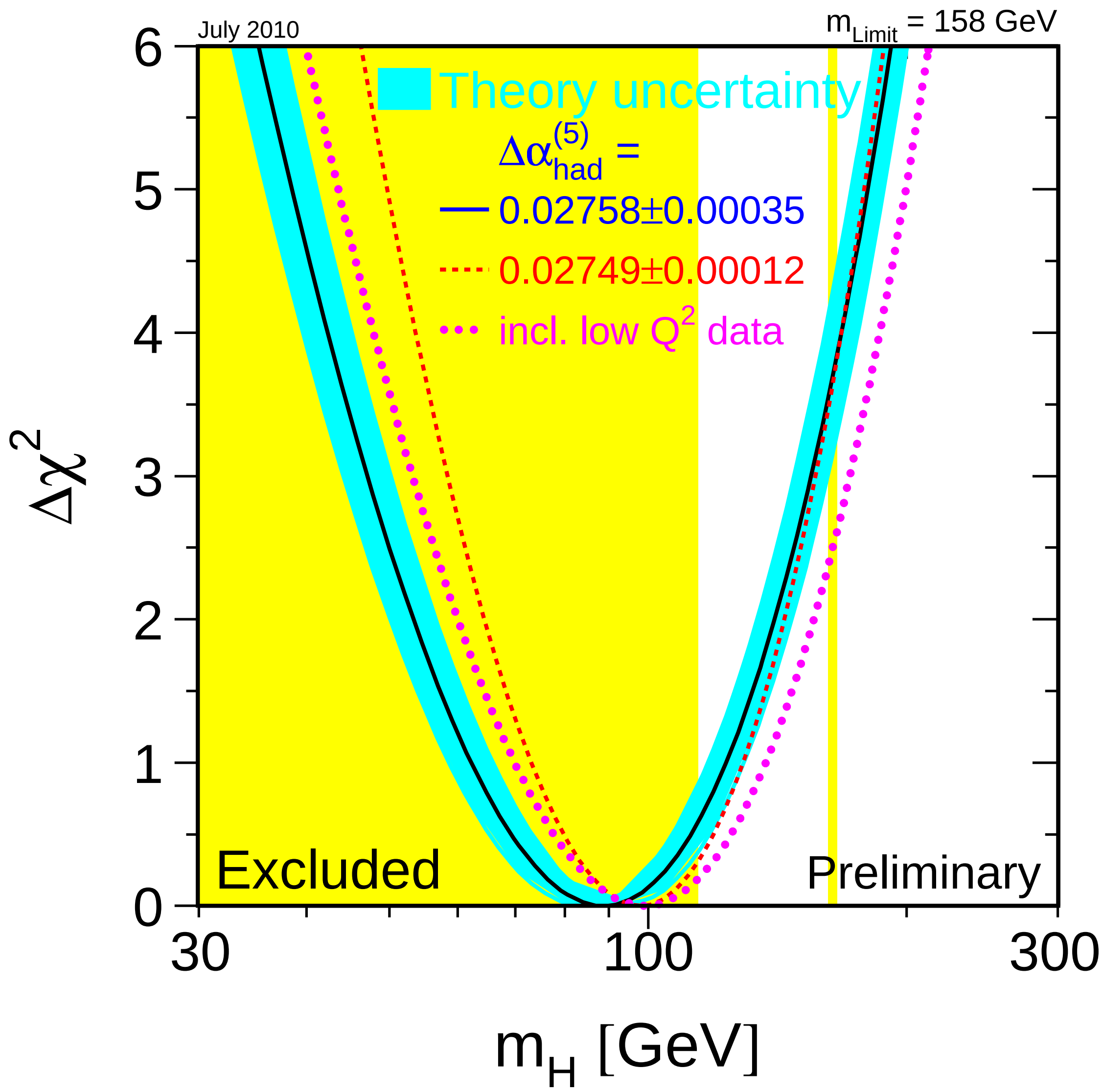
1. Introduction

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

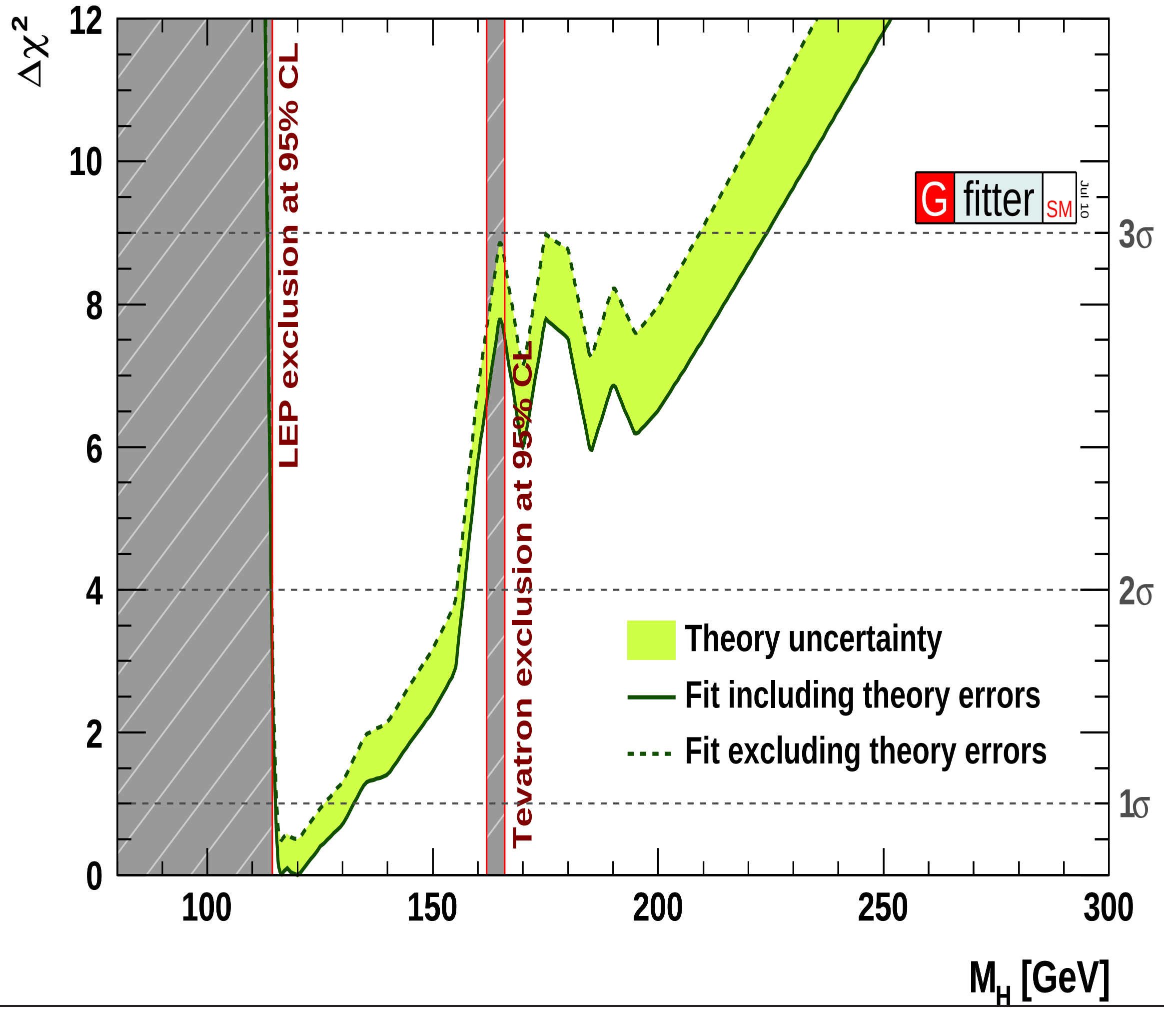
$\Rightarrow$ no confirmation of
Higgs mechanism

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.



Assumption for the fit:
SM incl. Higgs boson

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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/ILC reach

2. Codes and predictions

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 next section)

– tools included:
  – B-physics observables [*SuFla*]
  – more B-physics observables [*SuperIso*]
  – Higgs related observables, $(g-2)_\mu$ [*FeynHiggs*]
  – Electroweak precision observables [*FeynWZ (SUSYPope)*]
  – 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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⇒ all most-up-to-date codes on the market!   ⇒ crucial for precision!

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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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SM parameters

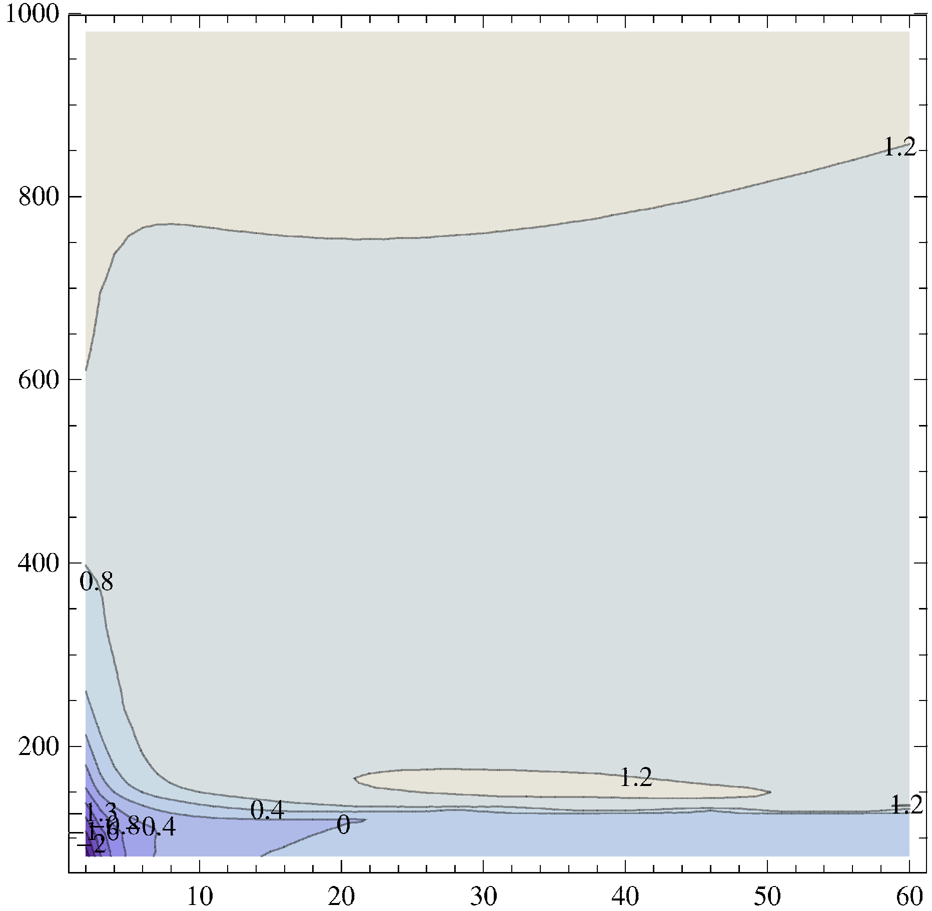
– top mass: m_t

– Z boson mass: M_Z

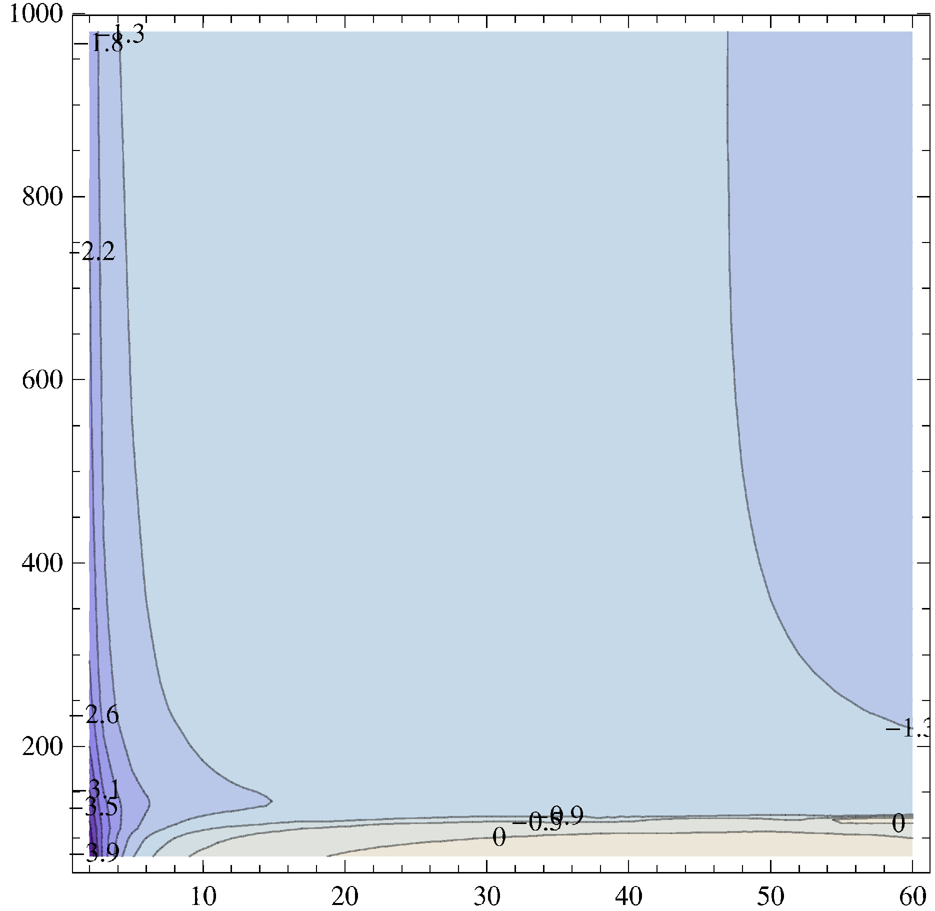
– hadronic contribution to fine structure constant: $\Delta\alpha_{\text{had}}$

Comparison of M_h: FH - CPsH

$m_h^{\rm max}$

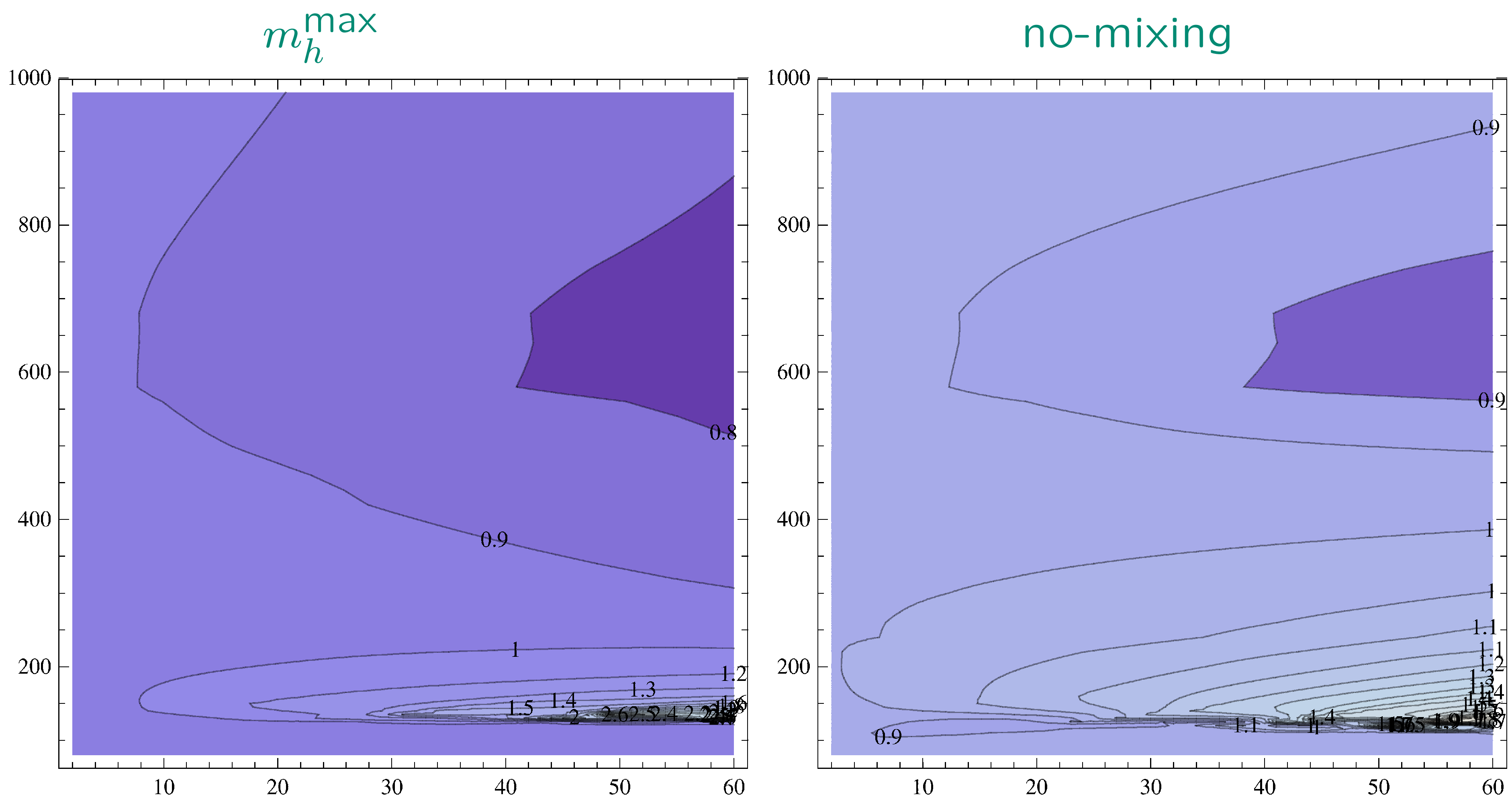


no-mixing



$\Rightarrow$ Differences of up to $\sim$ 1.2 GeV for "non-extreme" parameters

Comparison of $\sin^2\alpha_{\rm eff}$: FH/CPsH



⇒ Sizable differences for "relevant" parameters

3. Models & methods

Indirect constraints on M_{SUSY} from existing data?

- Electroweak precision observables (EWPO) ?

- B physics observables (BPO) ?

- Cold dark matter (CDM) ?

$\Rightarrow$ 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 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):

$\Rightarrow$ 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

$\Rightarrow$ 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

$$M_A \text{ or } \mu$$

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

$$M_A \text{ and } \mu$$

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

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

$$A_0 = m_0 + B_0$$

$\tan\beta$ 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:

→ global χ^2 likelihood function
combines all theoretical predictions with experimental constraints:

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

N: number of observables studied
M: SM parameters: $\Delta\alpha_{\text{had}}, m_t, M_Z$
C_i: experimentally measured value (constraint)
P_i: MSSM parameter-dependent prediction for the corresponding constraint

χ^2 calculation:

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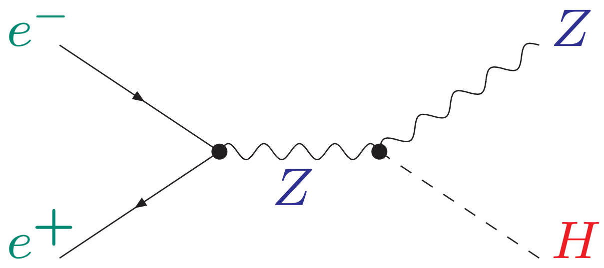
What to do if only a lower/upper bound exists?

$\rightarrow$ especially important: M_h

SM Higgs search at LEP:

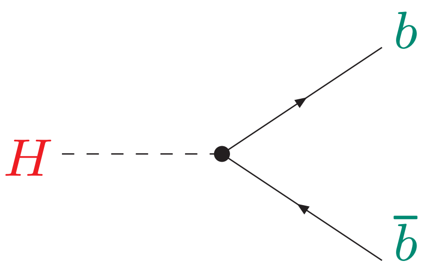
Dominant SM production process:

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



Dominant decay process:

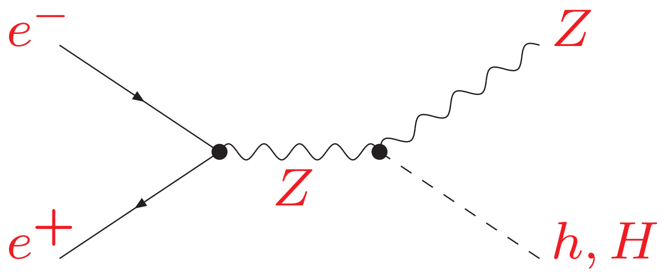
$H \to b\bar{b}$:



Bounds valid in the CMSSM? NUHM1? MSSM?

Search for neutral SUSY Higgs bosons:

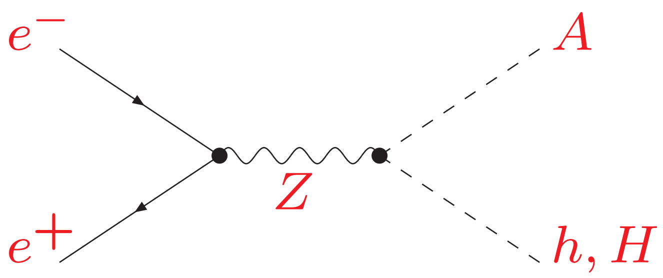
$e^+e^- \to Zh, ZH$



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

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

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

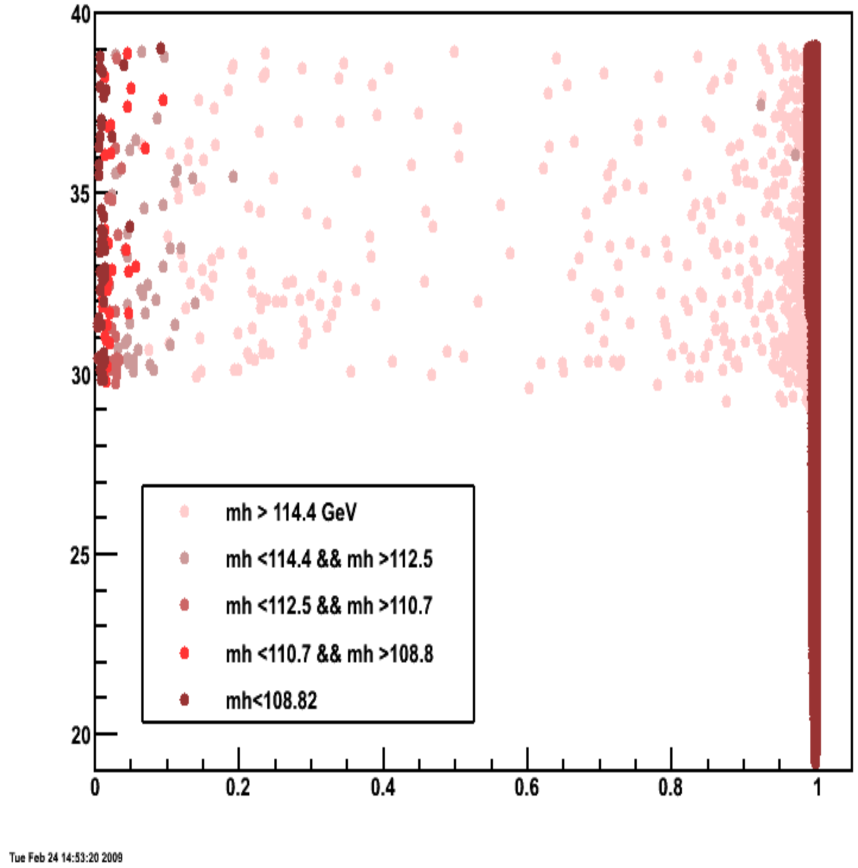


$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\rm eff})\sigma_{hZ}^{\rm SM}$$

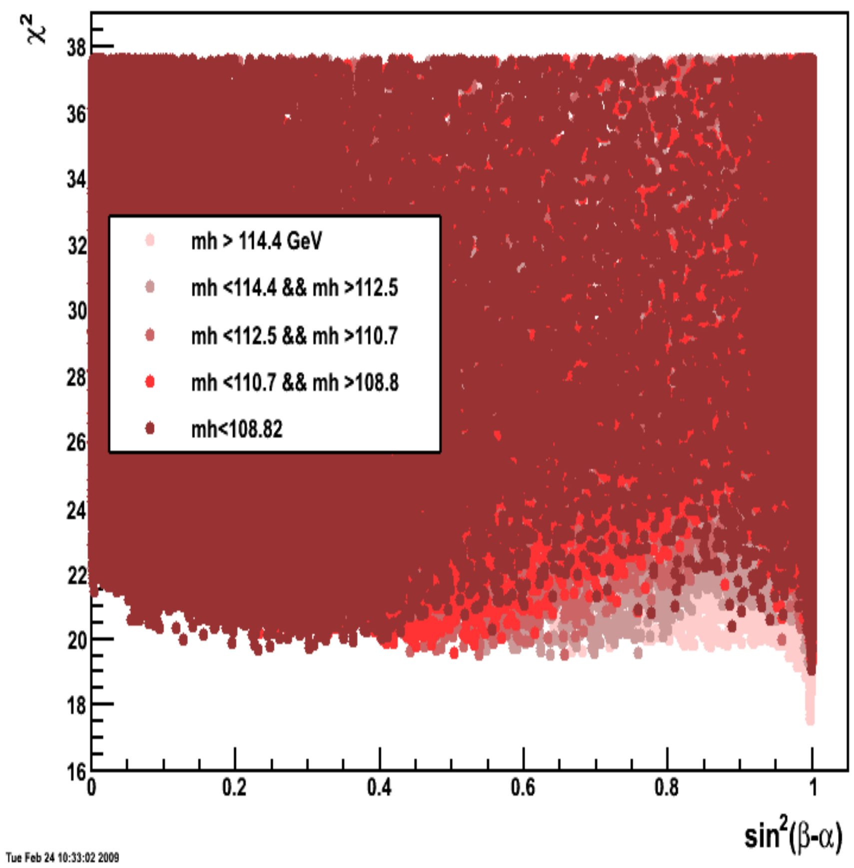
$$\sigma_{HA} \propto \sin^2(\beta - \alpha_{\rm eff})\sigma_{hZ}^{\rm SM}$$

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

CMSSM

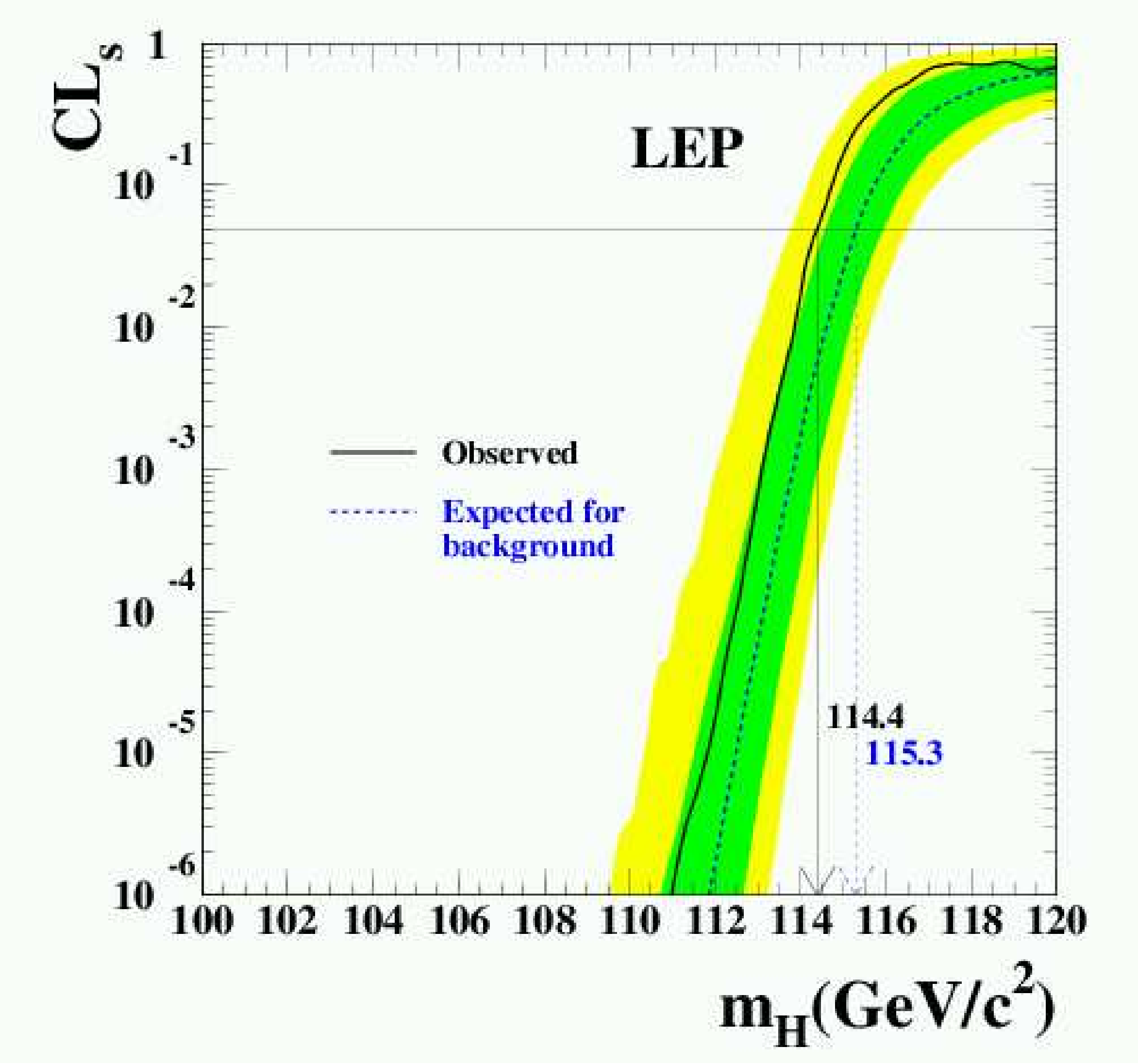


NUHM1



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

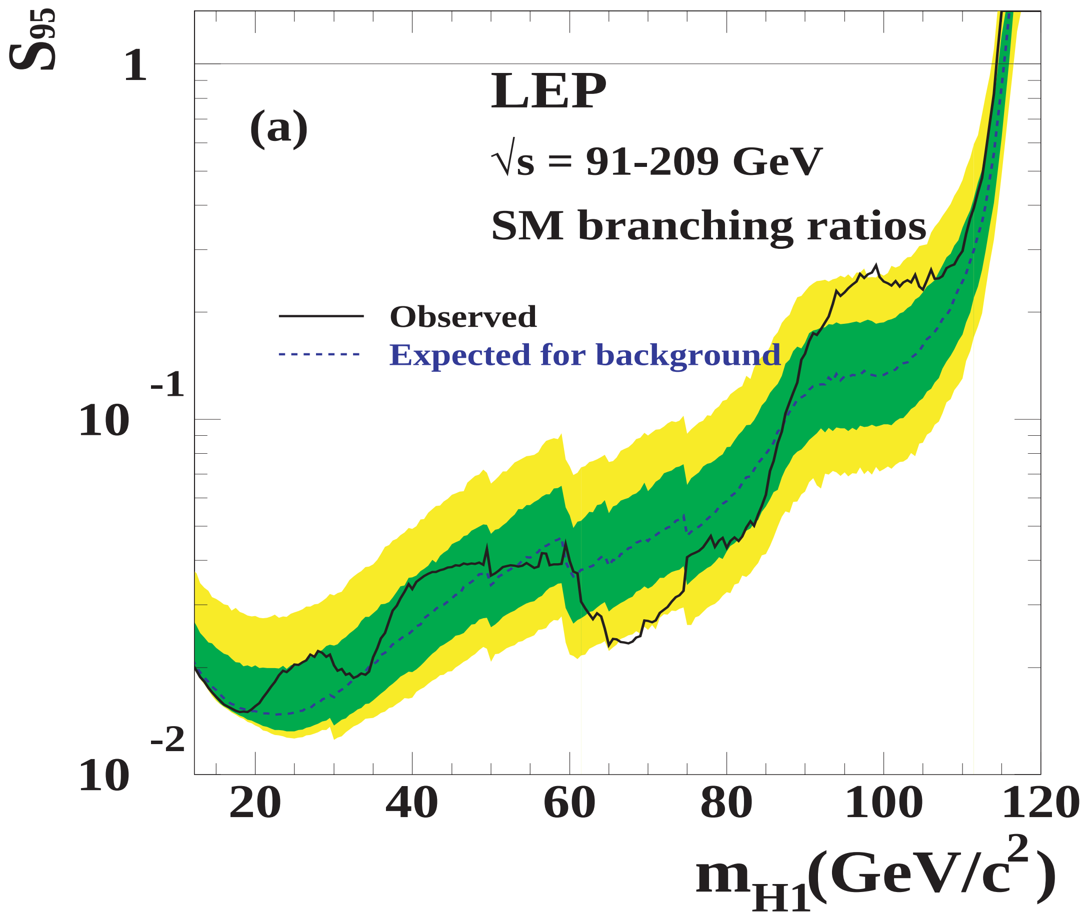
$\Rightarrow$ can be included into χ^2 evaluation

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

4. Predictions for the LHC and the ILC

– 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, $\Delta\alpha_{\rm had}$

$\Rightarrow$ χ^2 function

$\longrightarrow$ 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)

$\longrightarrow$ final minimum: Minuit

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

$\Rightarrow$ preferred CMSSM/NUHM1 parameters
$\Rightarrow$ LHC/ILC reach

Best-fit points:

[2008]

CMSSM:

$m_{1/2} = 310$ GeV, $m_0 = 60$ GeV, $A_0 = 130$ GeV,
$\tan\beta = 11$, $\mu = 400$ GeV, $M_A = 450$ GeV

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

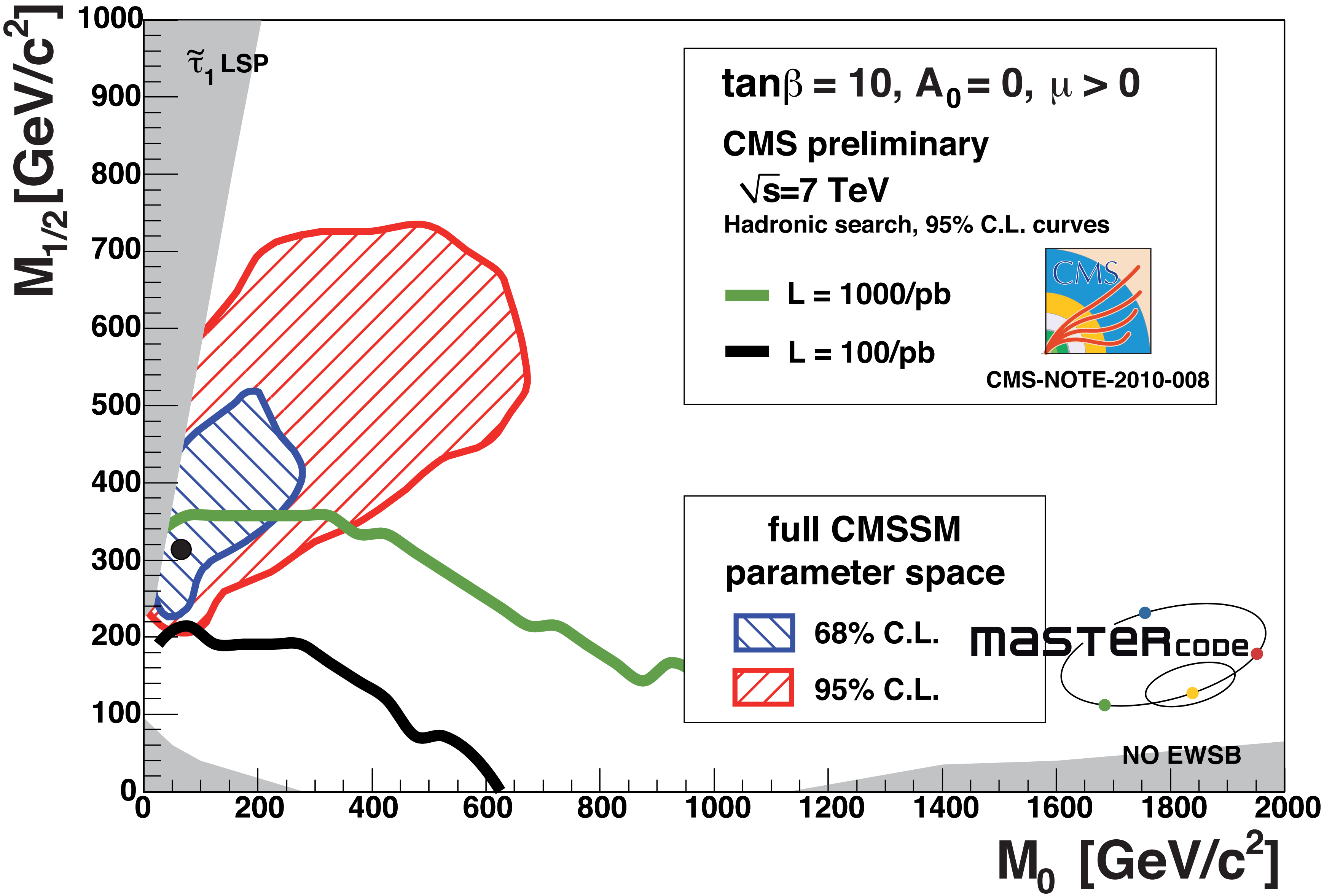
$\Rightarrow$ very similar to SPS 1a :-)

NUHM1:

$m_{1/2} = 270$ GeV, $m_0 = 150$ GeV, $A_0 = -1300$ GeV,
$\tan\beta = 11$, $\mu = 1140$ GeV, $M_A = 310$ GeV

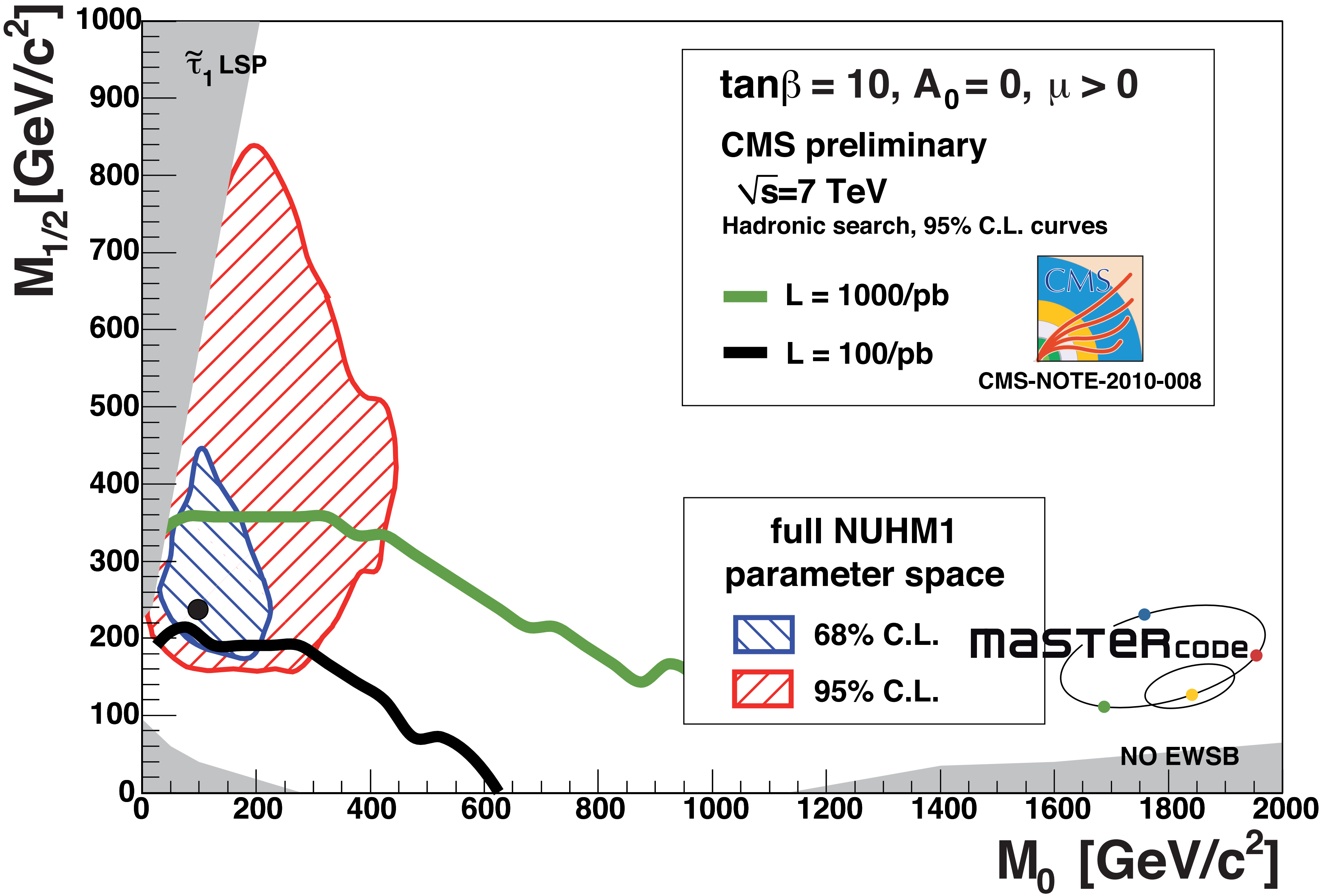
(similar probability)

LHC (CMS) $\oplus$ CMSSM analysis:



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

LHC (CMS) $\oplus$ NUHM1 analysis:



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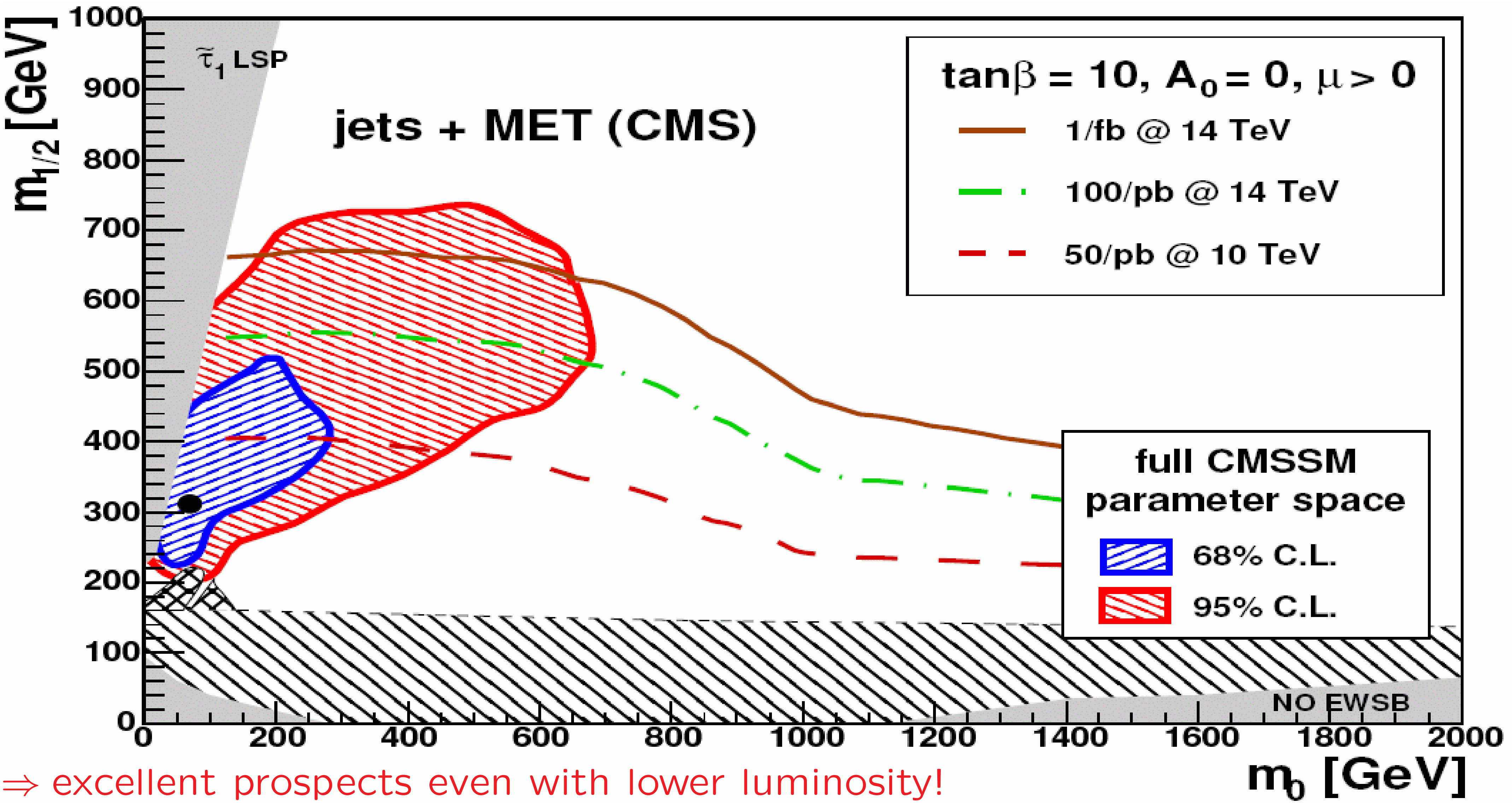
LHC (CMS) $\oplus$ CMSSM analysis:

[*CMS '07*]

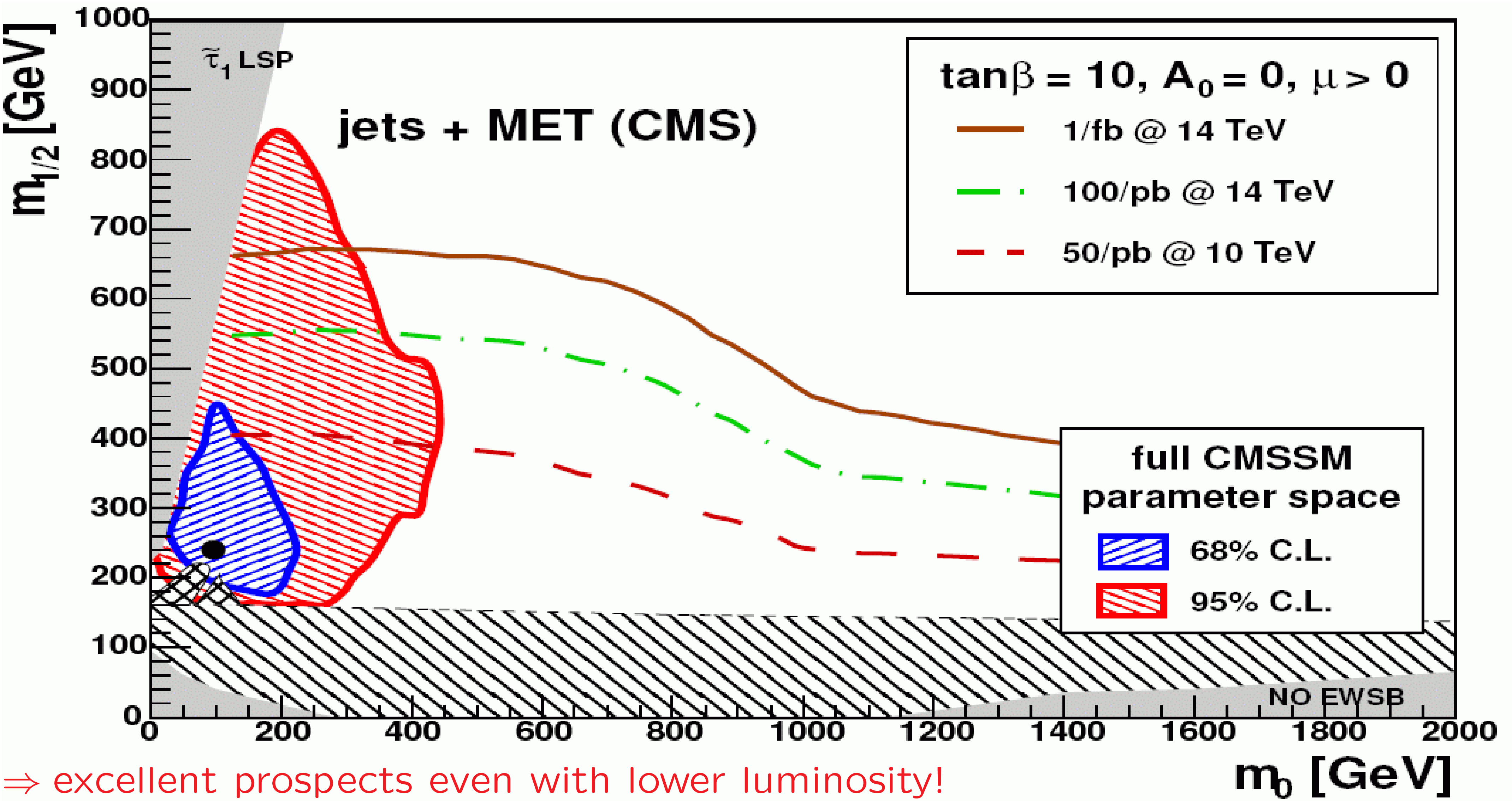
[*2008*]



$\Rightarrow$ excellent prospects even with lower luminosity!

LHC (CMS) ⊕ NUHM1 analysis:

[*CMS '07*] [*2008*]



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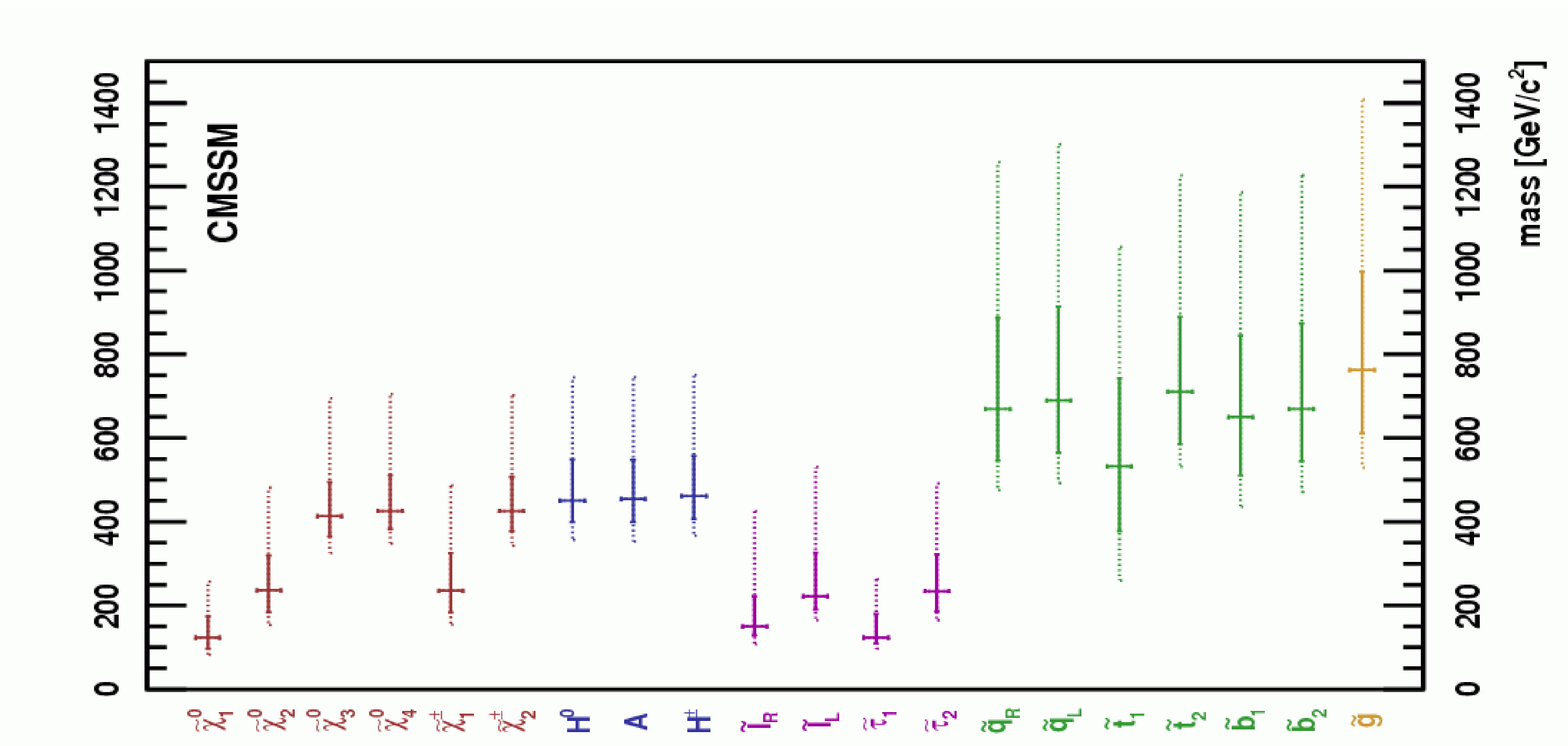
Masses for best-fit points: CMSSM

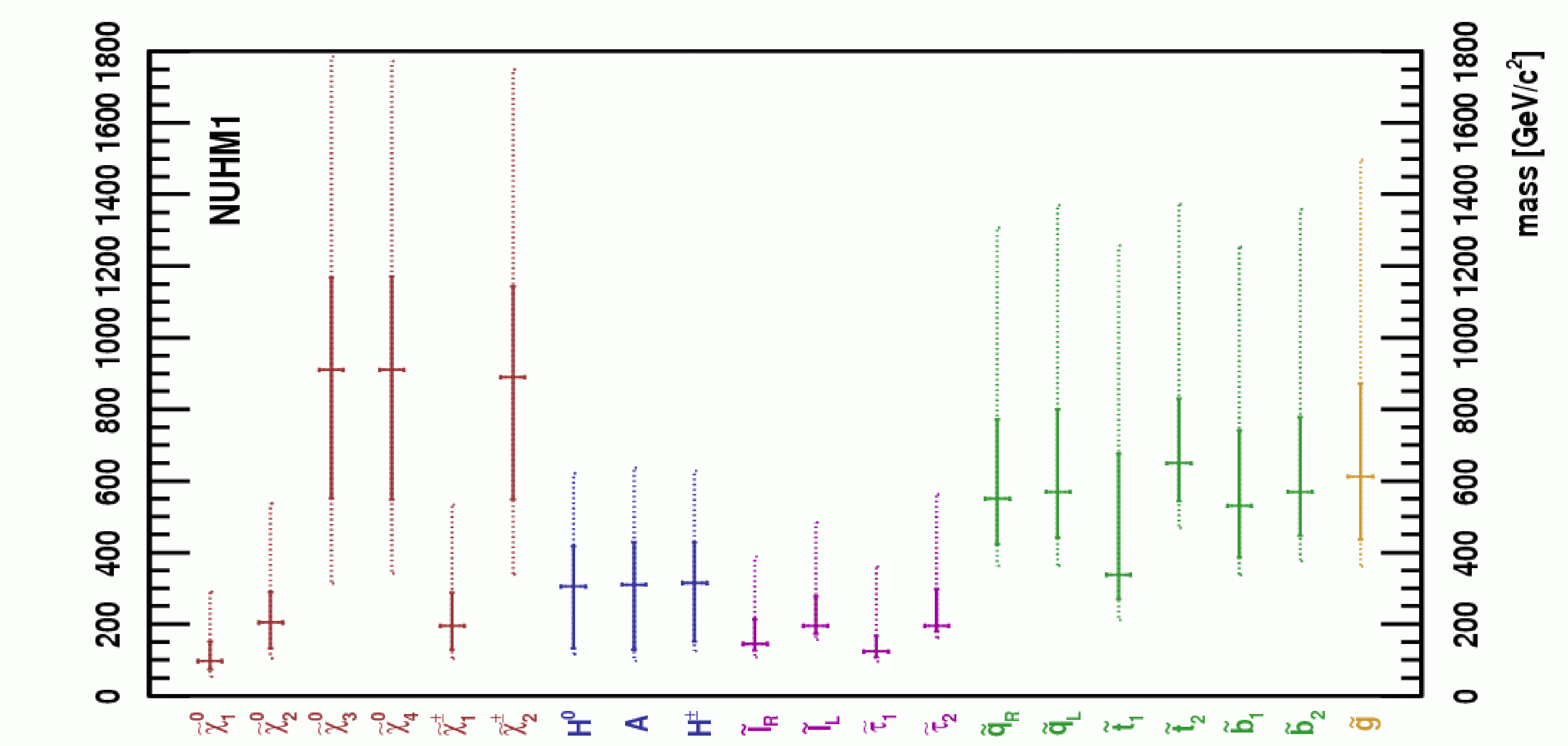
[2009]



$\Rightarrow$ largely accessible spectrum for LHC and ILC

Masses for best-fit points: NUHM1

[2009]

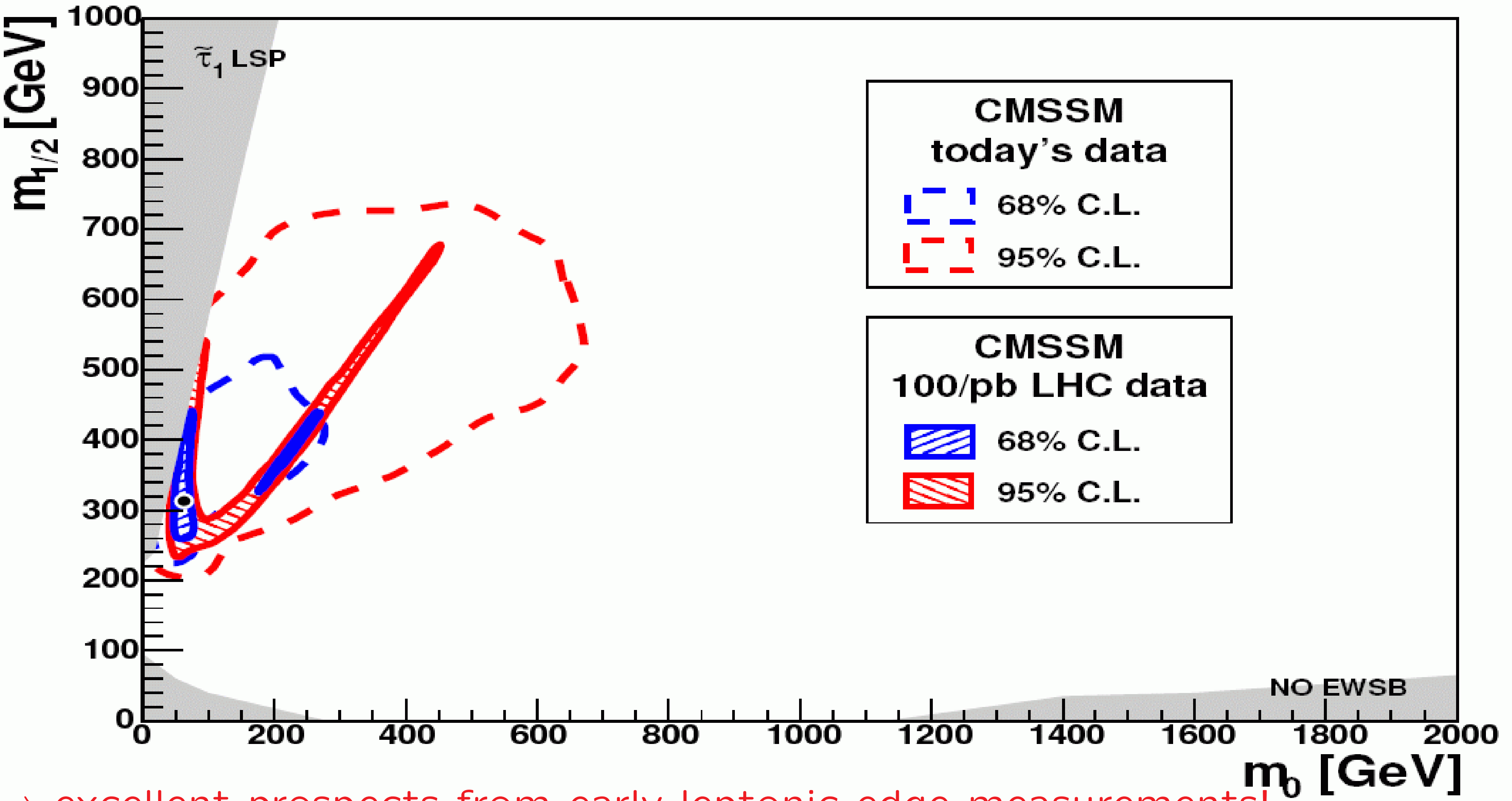


$\Rightarrow$ largely accessible spectrum for LHC and ILC

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

[2008]

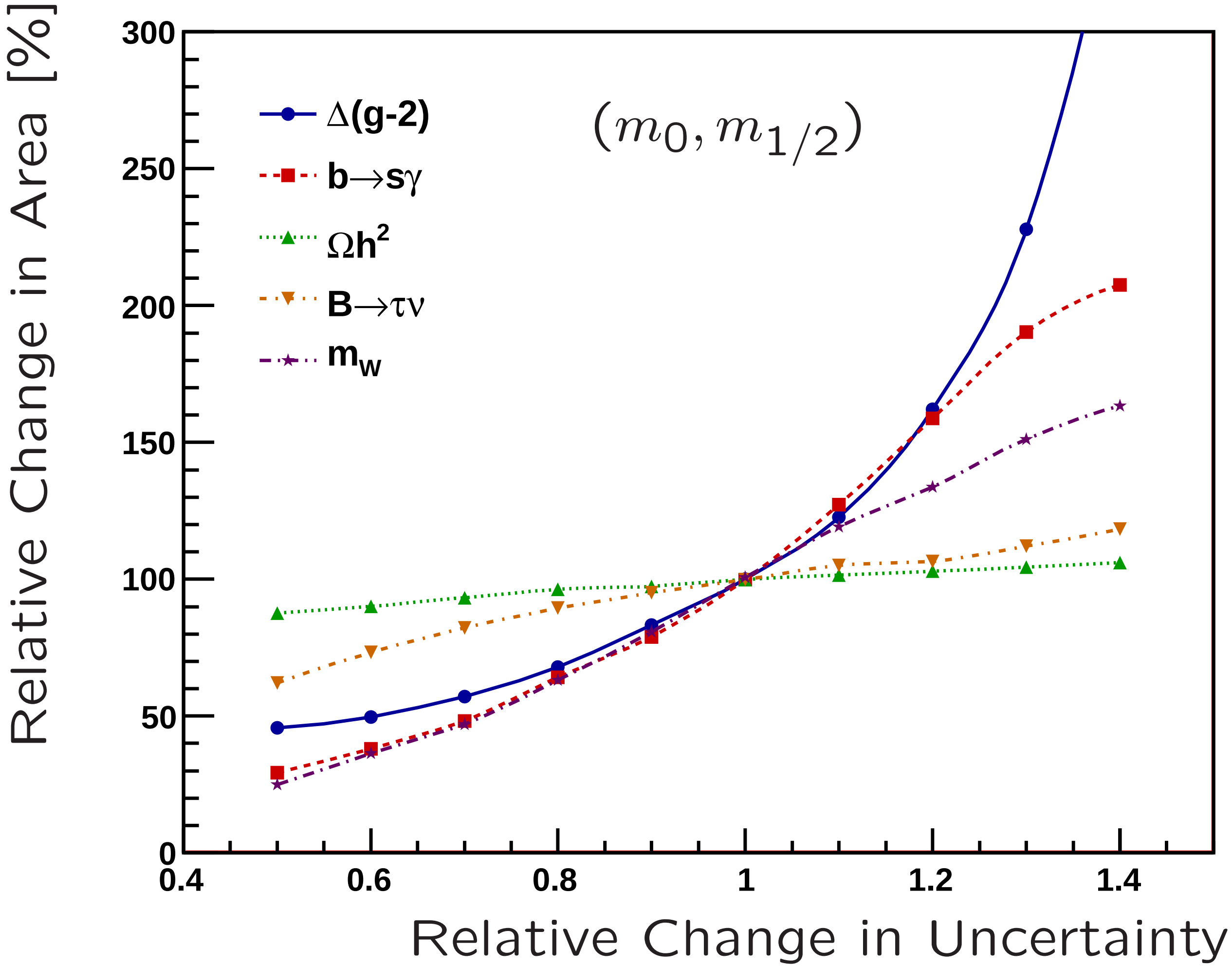
CMSSM analysis incl. leptonic edge measurements



⇒ 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($B_u \to \tau\nu$)

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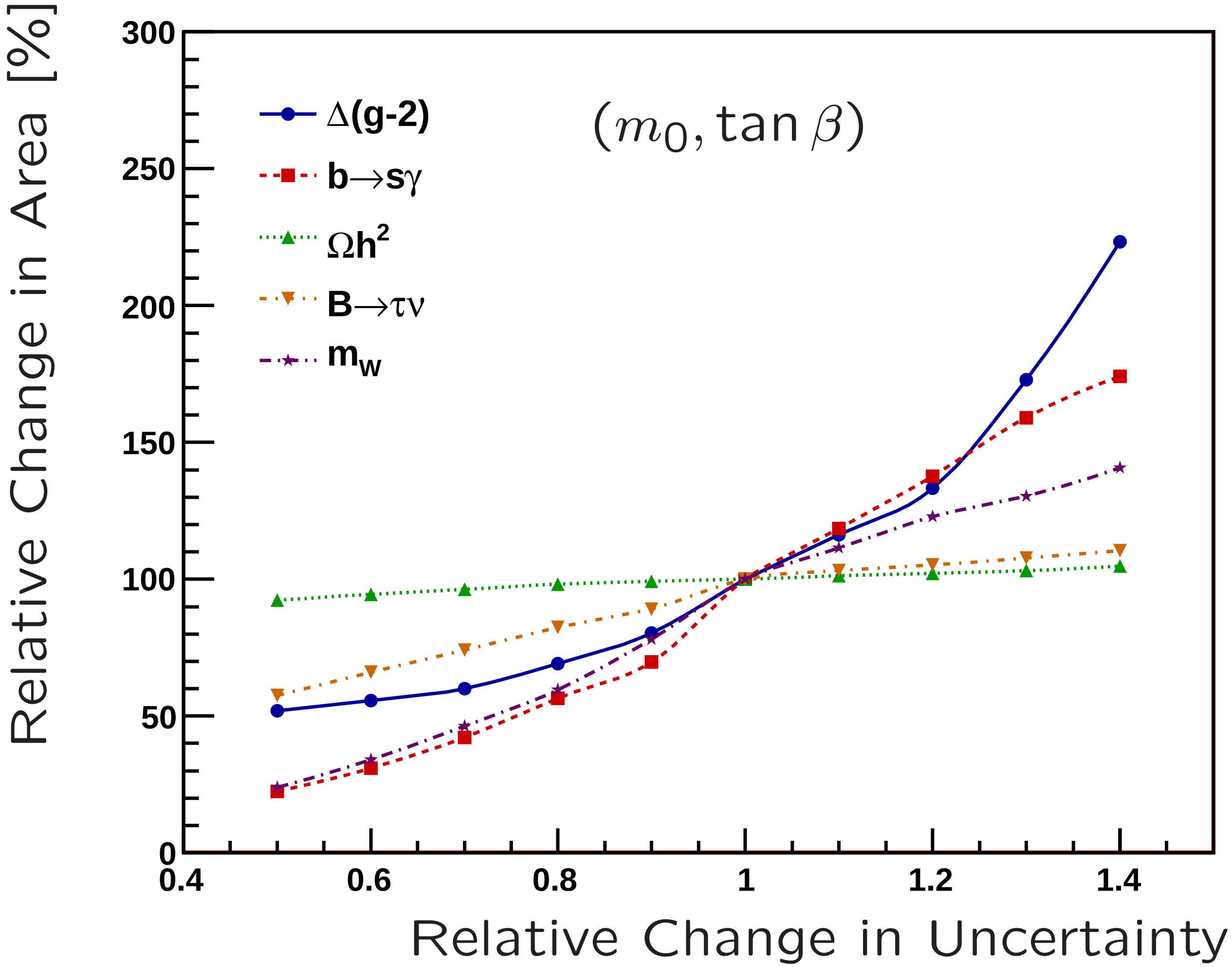

⇒ strong impact of $(g-2)_\mu$

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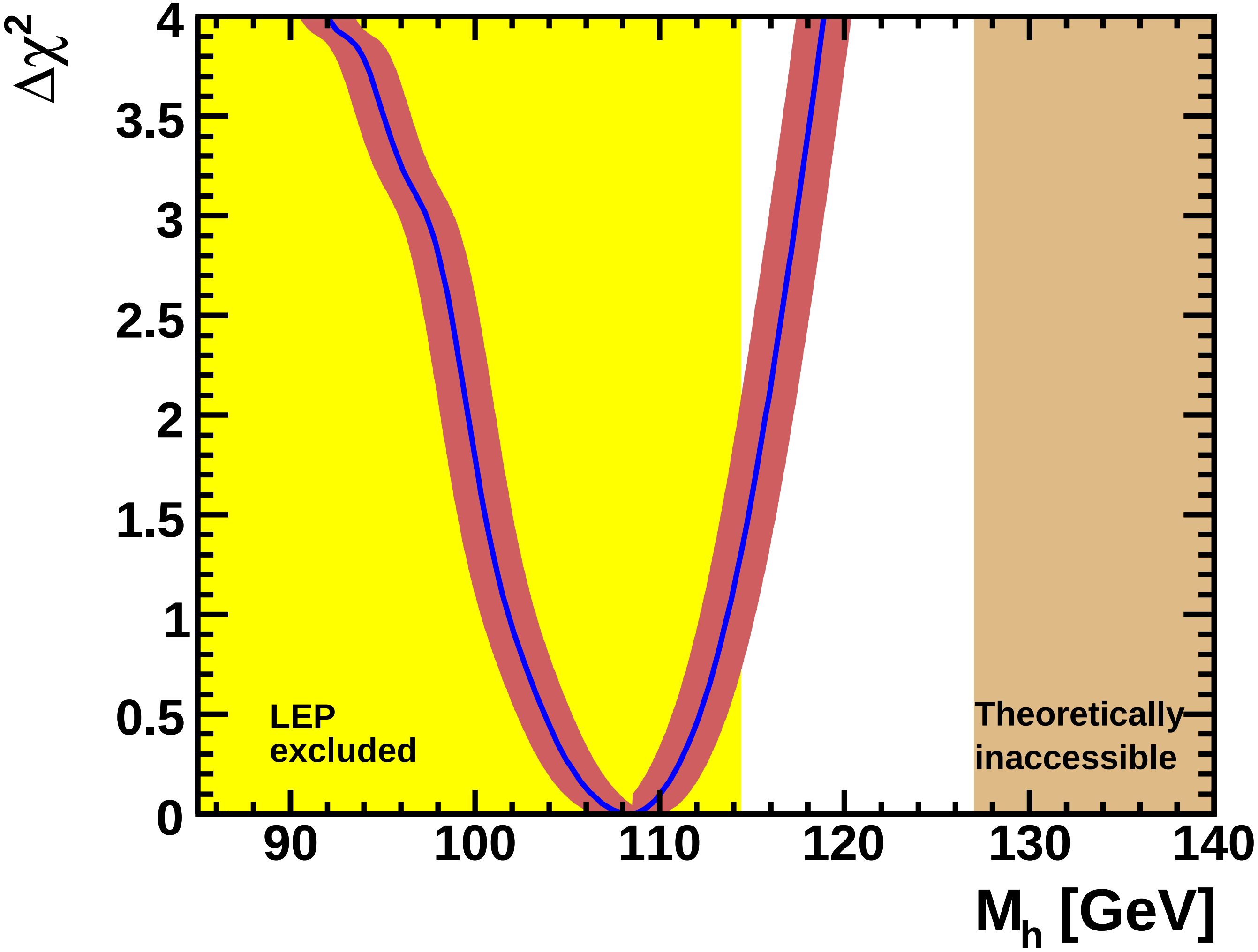
CMSSM: red band plot: (LEP bounds not included!)

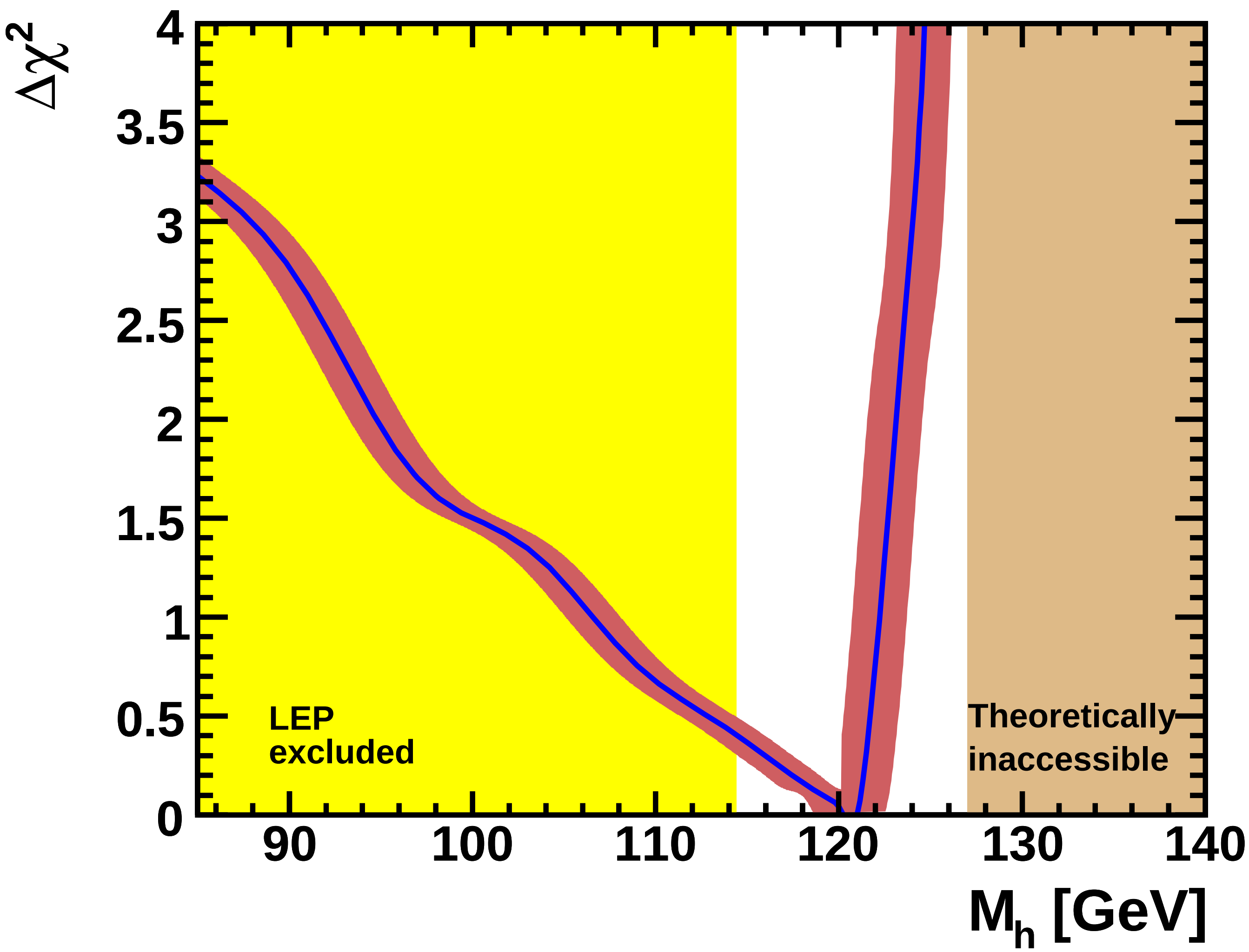
[2009]



$M_h = 108 \pm 6\,(\text{exp}) \pm 1.5(\text{theo})$ GeV

NUHM1: red band plot: (LEP bounds not included!)

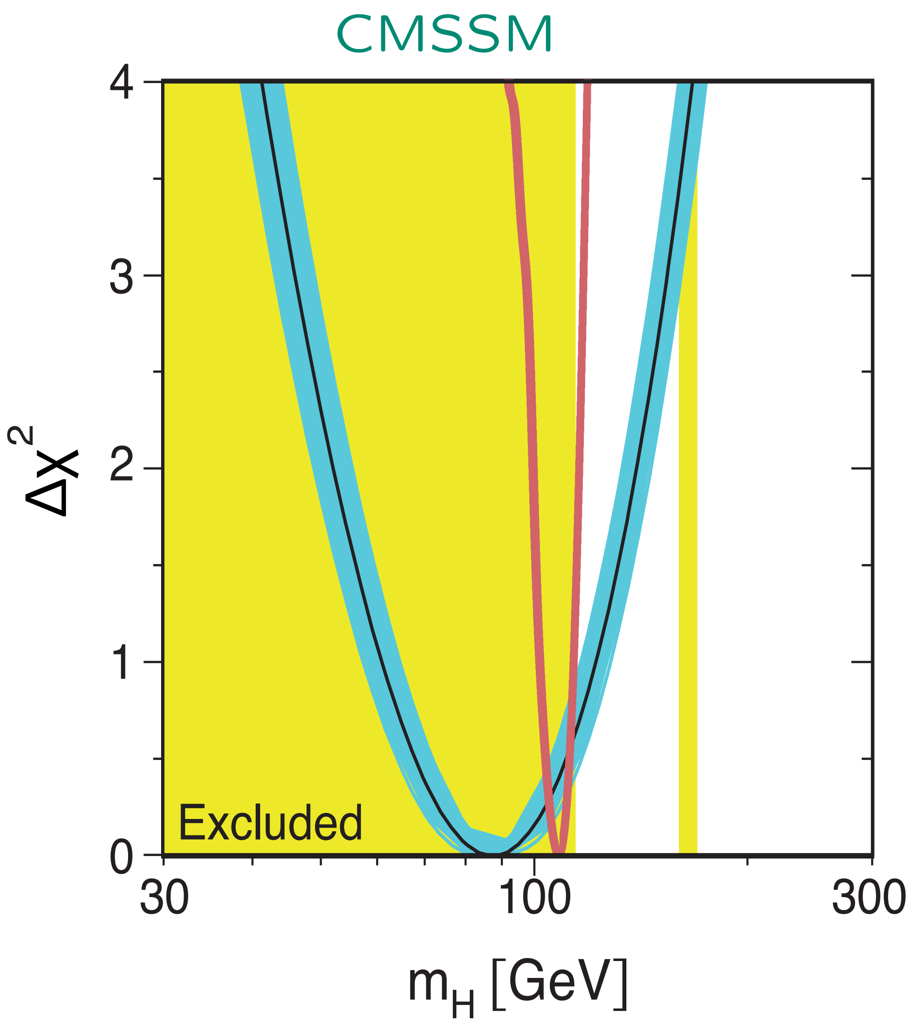
[2009]

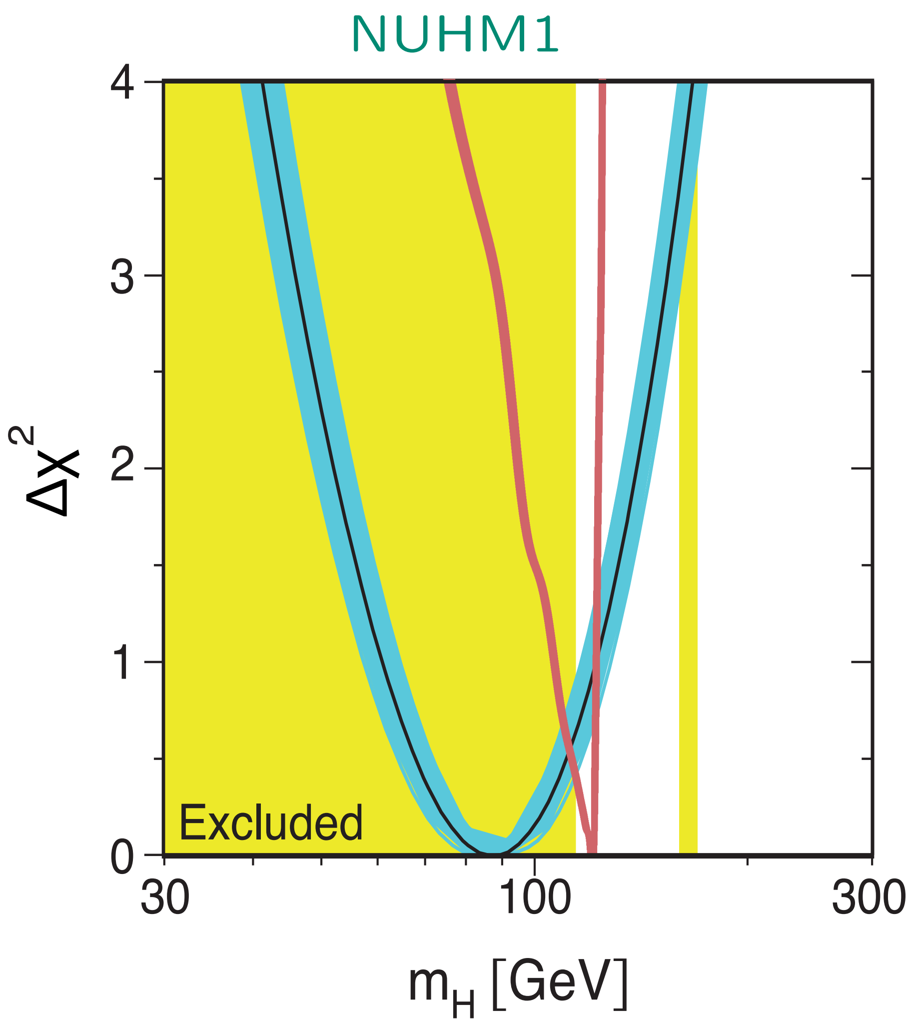


$M_h = 121^{+1}_{-14}$ (exp) $\pm$ 1.5(theo) GeV $\Rightarrow$ naturally above LEP limit

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

[2009]





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

$\Rightarrow$ as good as the SM

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

$\Rightarrow$ above the LEP limit

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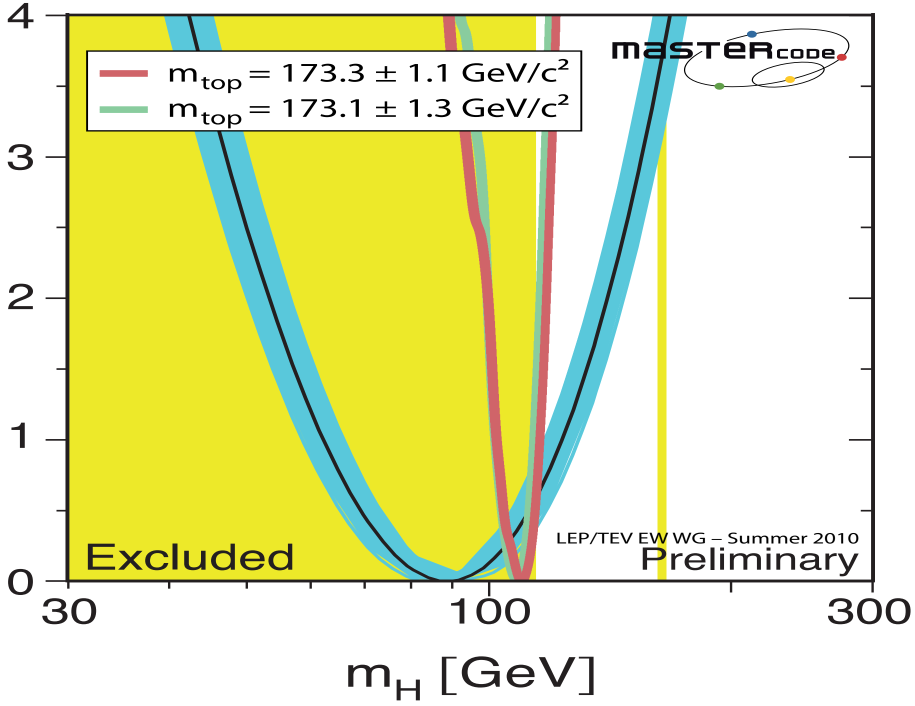
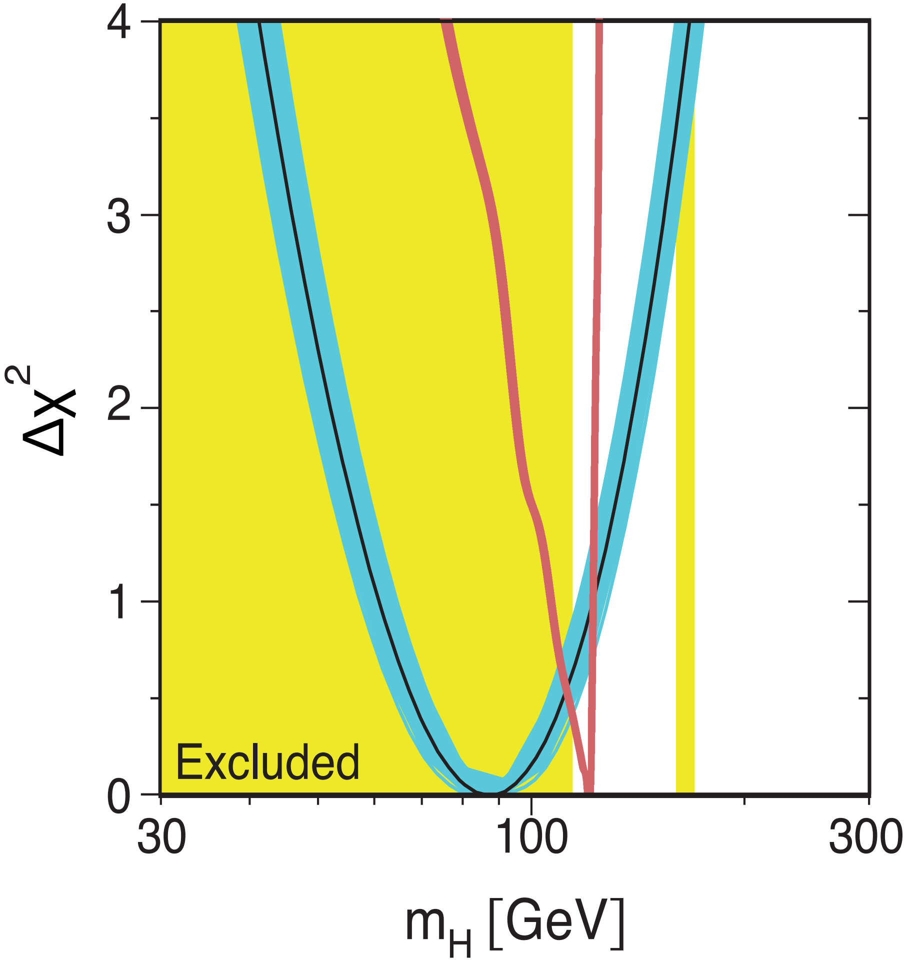
CMSSM



NUHM1



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$\Rightarrow$ as good as the SM

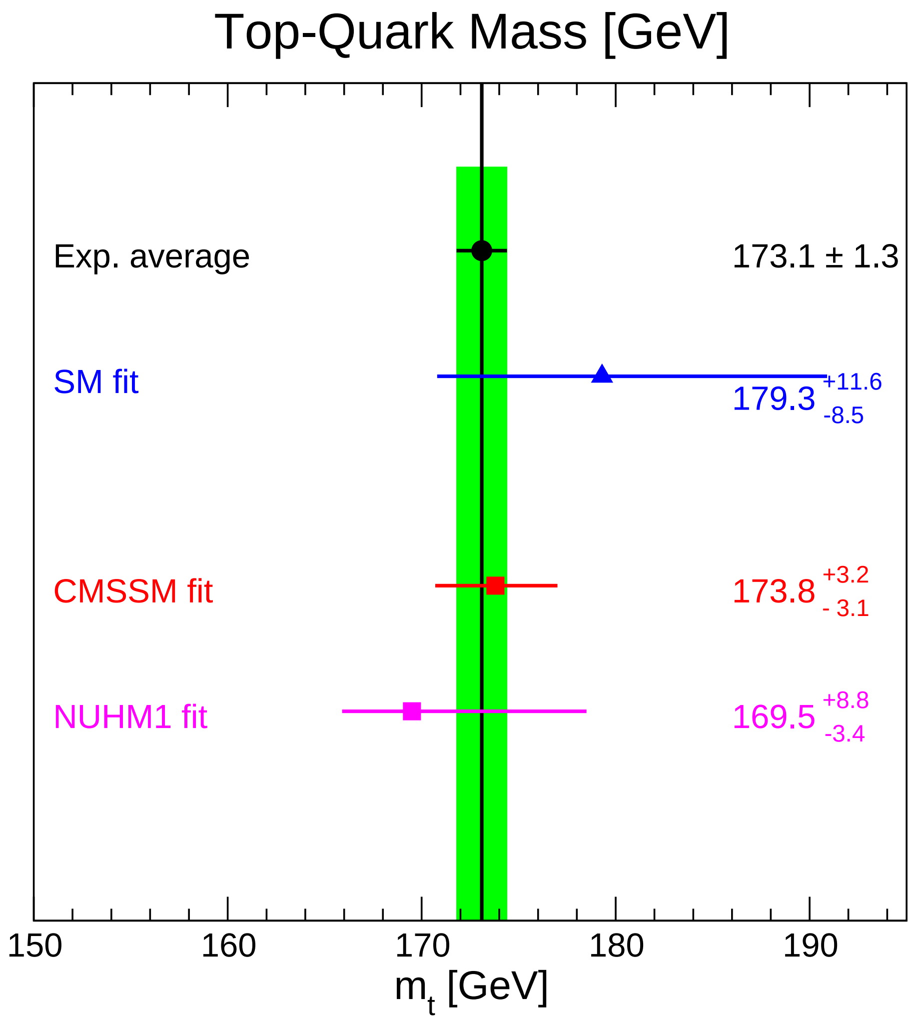
$M_h^{\rm NUHM1} = 121^{+1}_{-14} \pm 1.5$ GeV

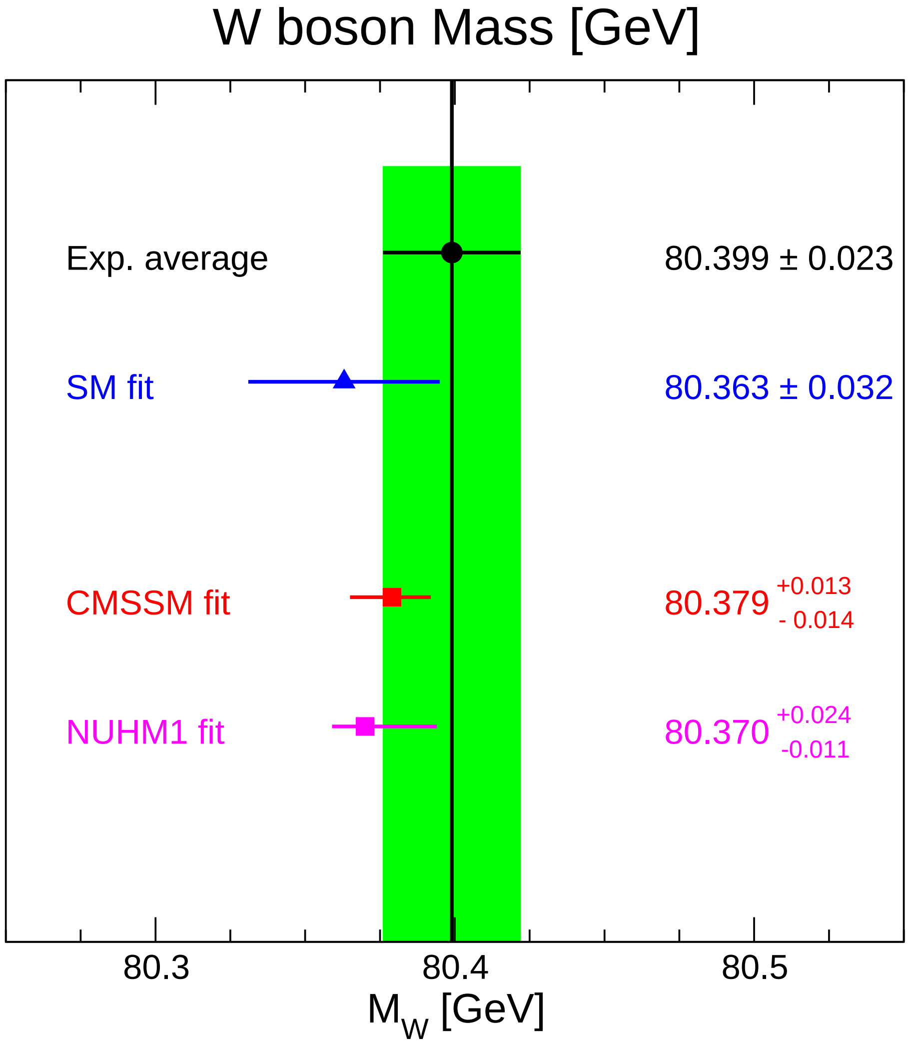
$\Rightarrow$ above the LEP limit

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]





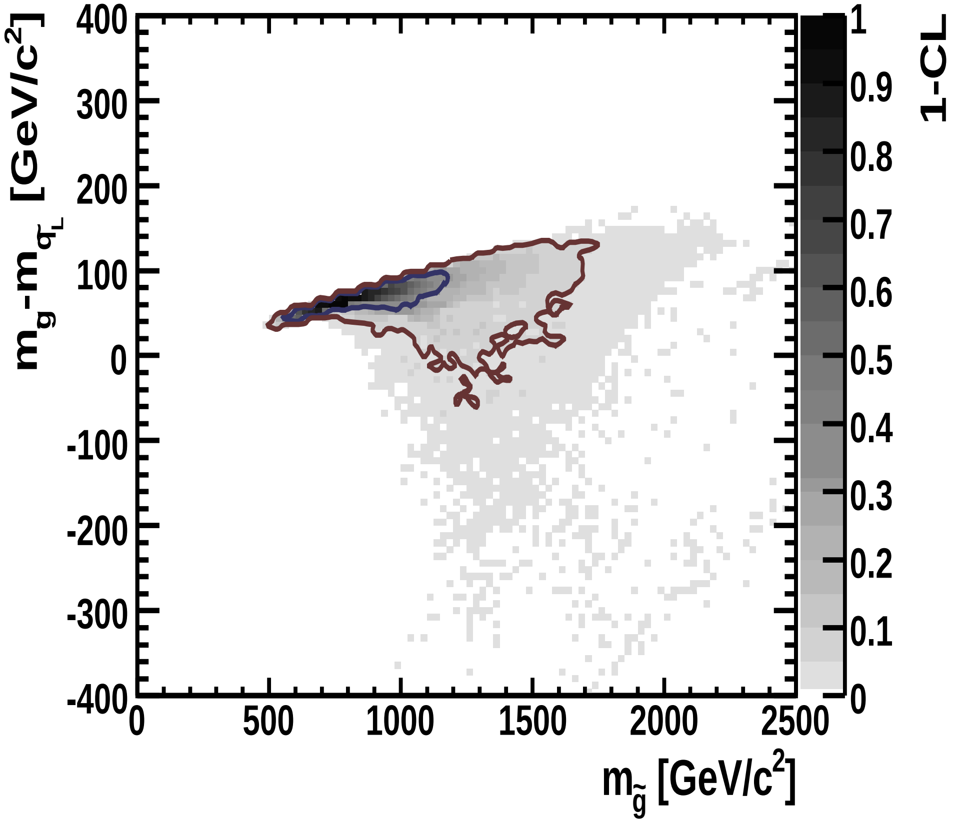
⇒ CMSSM and NUHM1 fit amazingly well m_t and M_W

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

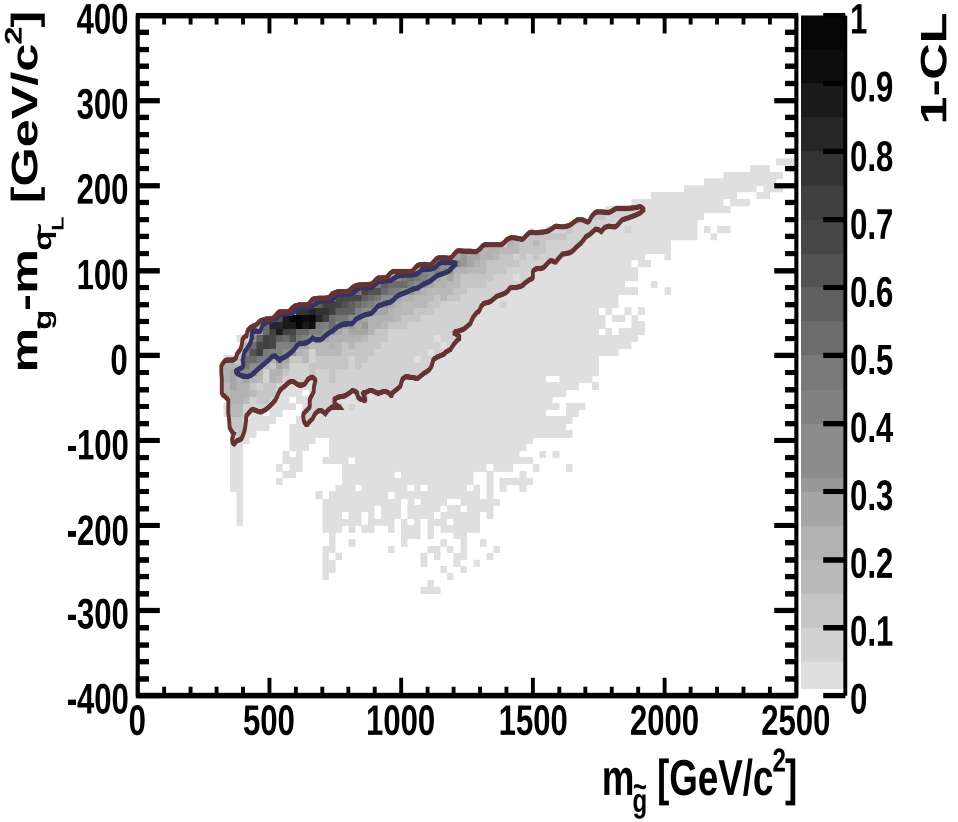
Some more predictions: $m_{\tilde{g}} - m_{\tilde{q}_L}$

[2009]

CMSSM



NUHM1

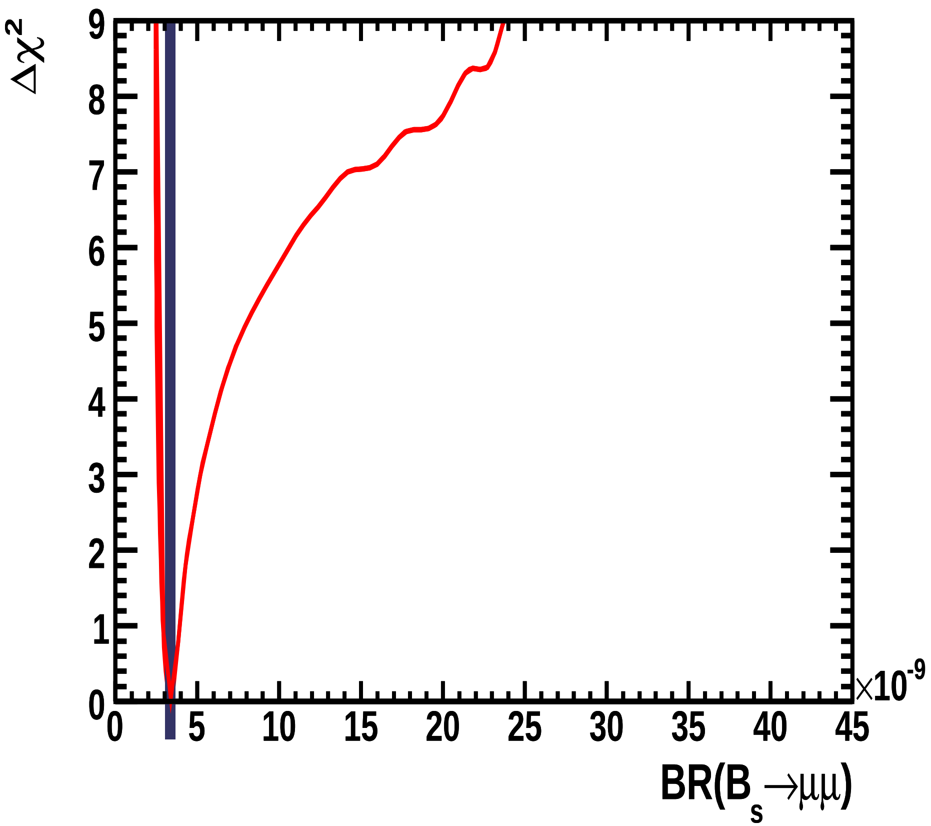


$\Rightarrow m_{\tilde{g}}$ often largest mass, but exceptions are possible

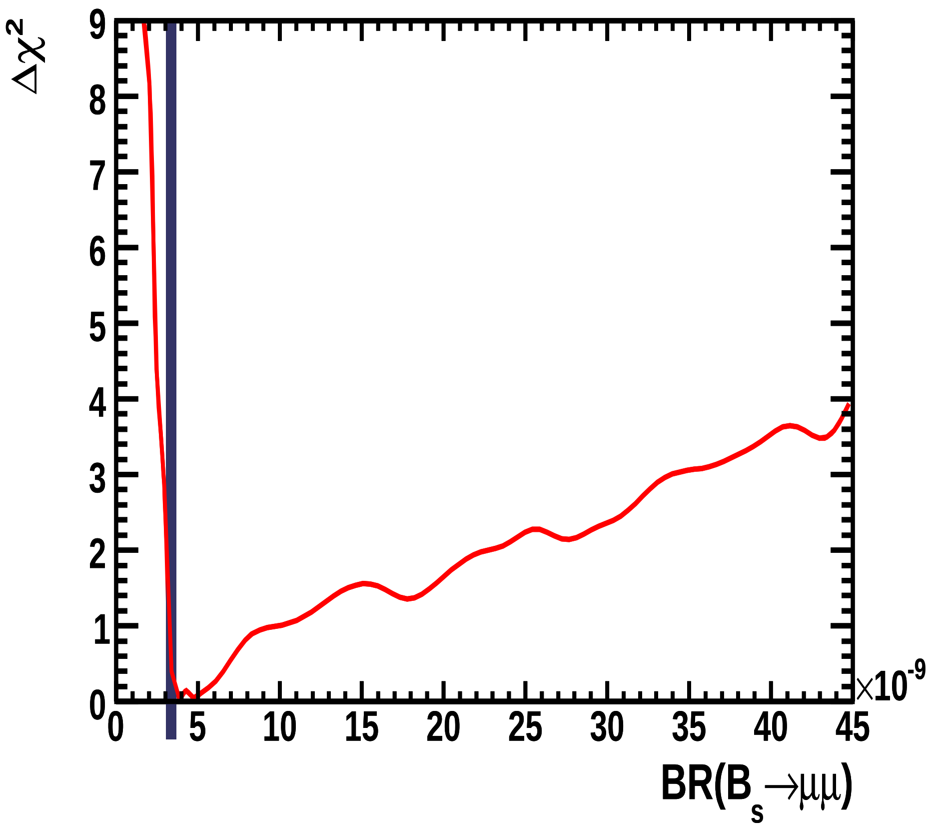
Some more predictions: BR($B_s \to \mu^+\mu^-$)

[2009]

CMSSM



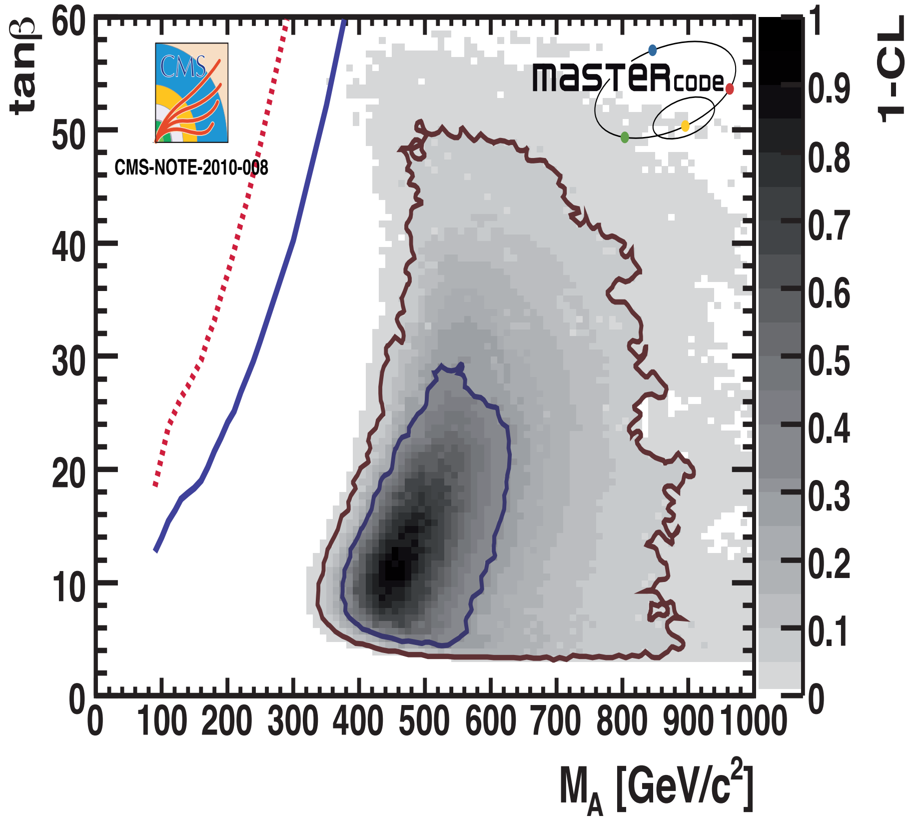
NUHM1



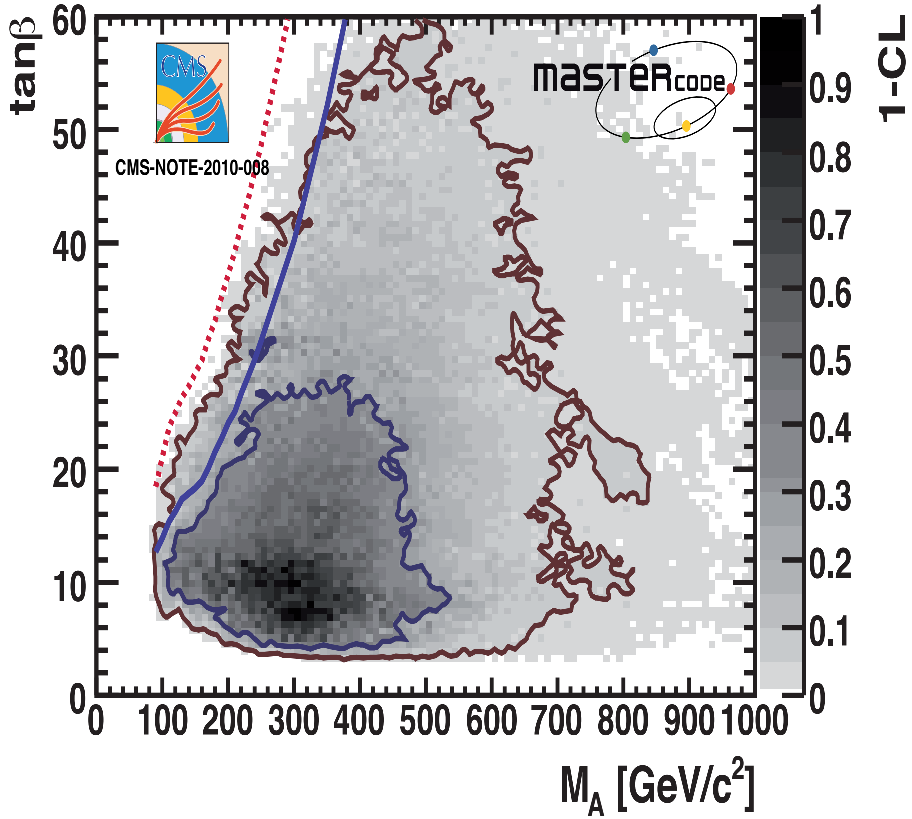
$\Rightarrow$ best-fit similar to SM, larger value would favor NUHM1

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

CMSSM



NUHM1



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

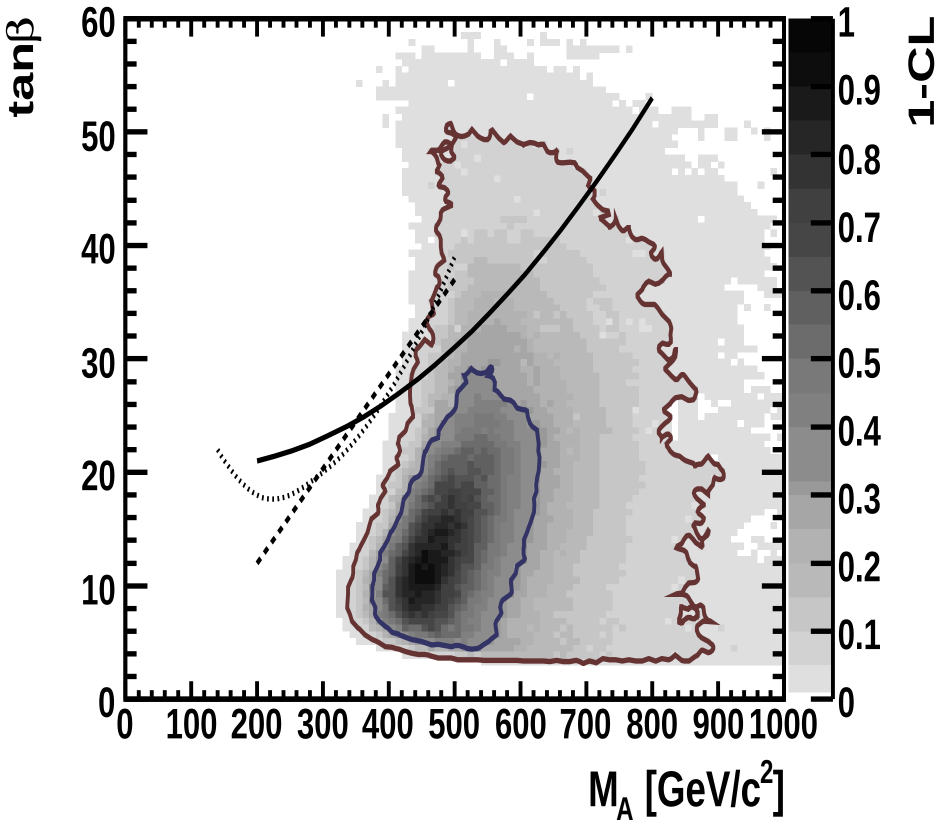
blue solid: 95% C.L. exclusion with 1 fb^{-1} @ 7 TeV

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

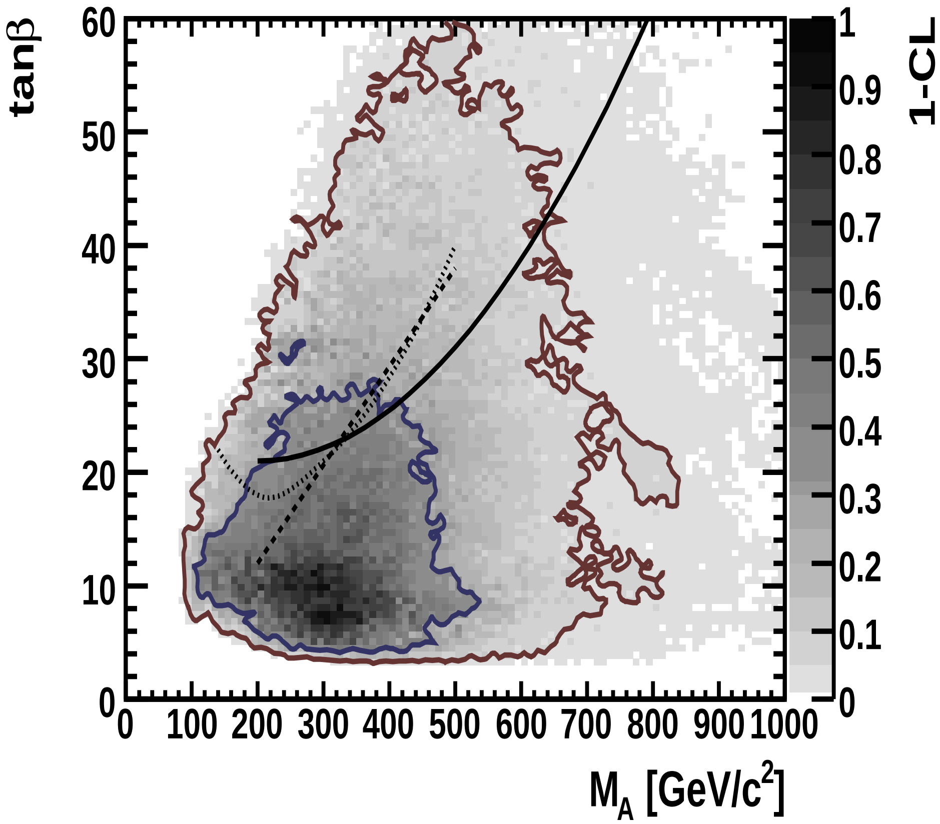
Some more predictions: preferred M_A–$\tan\beta$ parameter space

[2009]

CMSSM



NUHM1



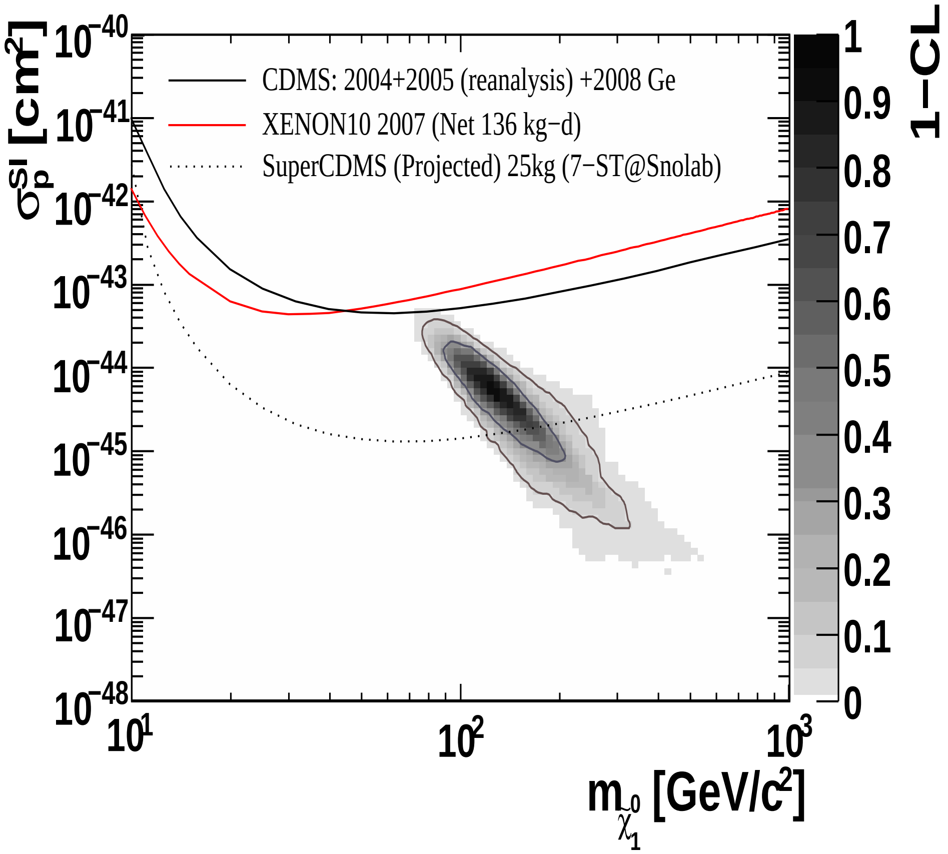
CMS analysis for 30 fb^{-1} @ 14 TeV

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

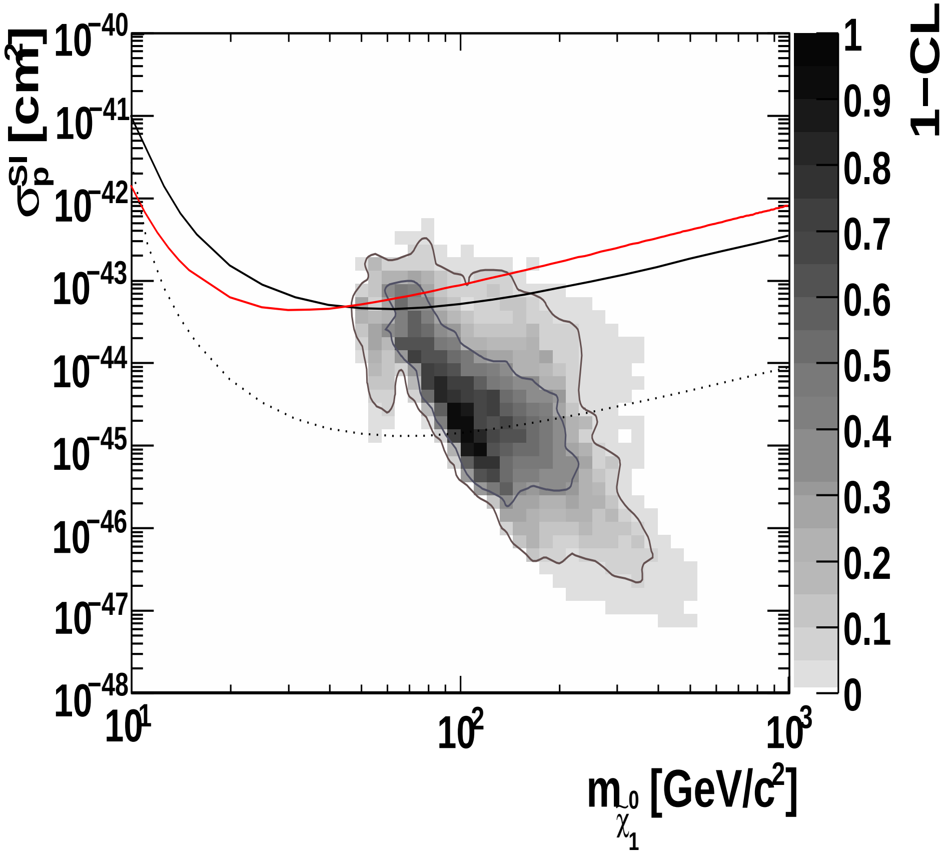
Some more predictions: direct search for dark matter

[2009]

CMSSM



NUHM1



$\Rightarrow$ only partially covered by future experiments

5. Conclusinos for the MasterCode

- Models: (MFV) MSSM
  Analyses: CMSSM, NUHM1 (, mSUGRA, VCMSSM)
- Codes included: SuFla, SuperIso, FeynHiggs, FeynWZ, MicrOMEGAs, DarkSUSY, SoftSUSY, Minuit (HiggsBounds)
  $\Rightarrow$ all most-up-to-date codes on the market! $\Rightarrow$ crucial for precision!
  $\Rightarrow$ predictions for: EWPO, BPO, CDM, ...
  (EWPO: (nearly) as for the blue band plot)
- Inclusion of "early LHC" data partially possible
- 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 $\Rightarrow$ LHC/ILC reach
  - predictions for M_h (red band plot)
  - predictions for SM parameters: M_W , bluem_t
  - predictions for flavor observables
  - predictions for astro-physical observables