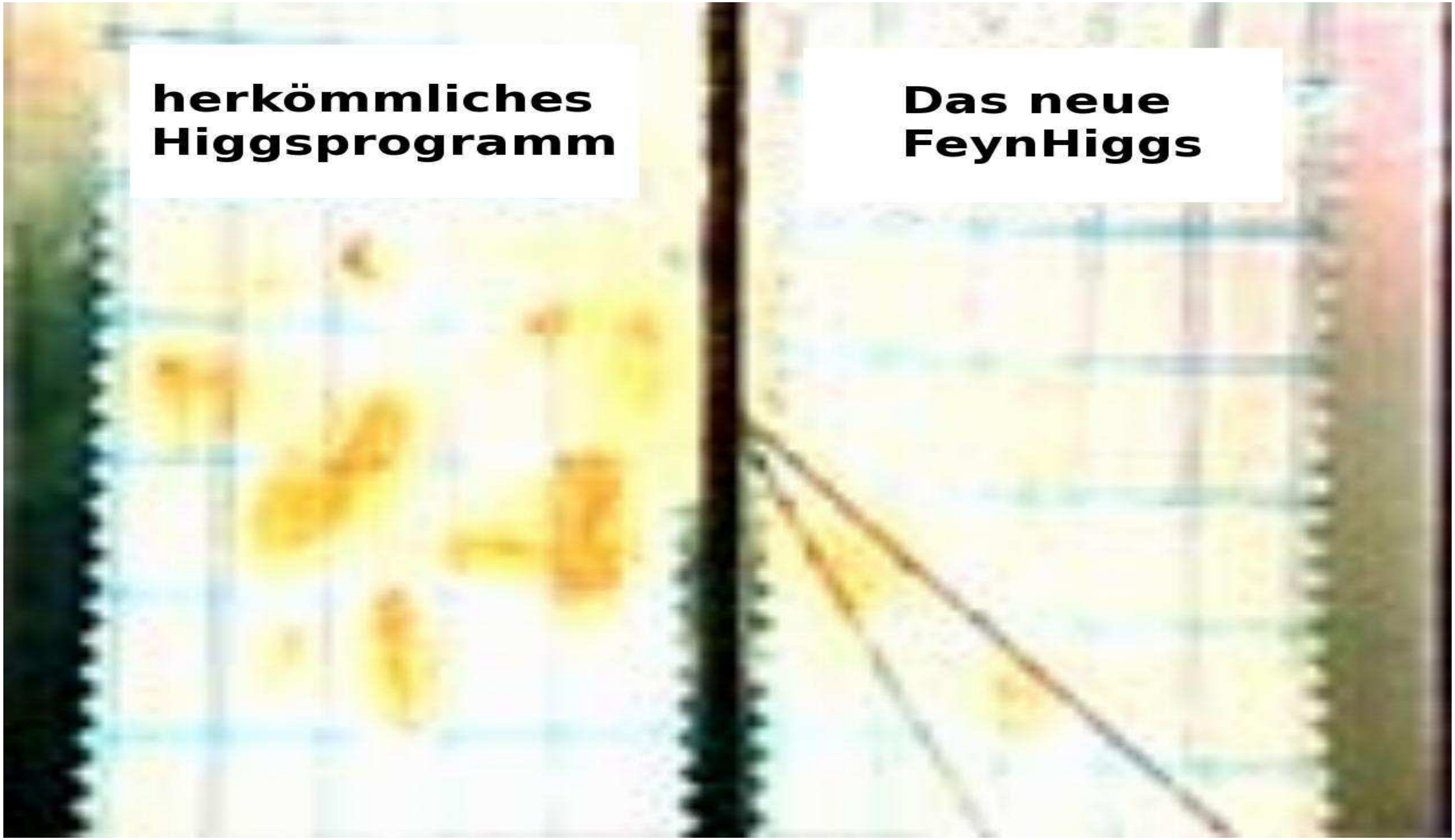
herkömmliches
Higgsprogramm
Das neue
FeynHiggs

SUSY Prediction for the LHC

Sven Heinemeyer, IFCA (CSIC, Santander)

DESY Hamburg, 06/2010

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

1. Introduction and motivation
2. The models and the tools
3. Predictions for the LHC
4. Conclusions

1. Introduction

The big question:

Which Lagrangian describes the world?

My guess:

It is a supersymmetric one

$\Rightarrow$ concentrate on the MSSM from now on

(other people $\Rightarrow$ other guesses $\Rightarrow$ other priorities . . .)

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Let's see . . .

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

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

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

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

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

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

Problem in the MSSM: complex phases ($\leftarrow$ neglected here)

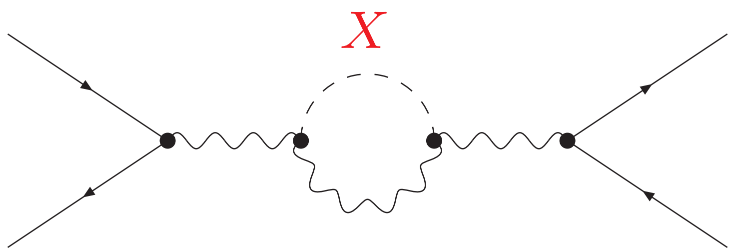
How to make a prediction?

Comparison of precision observables with theory:

Precision data:		Theory:
$M_W, \sin^2\theta_{\rm eff}, a_\mu, \ldots$	$\leftrightarrow$	SM, MSSM , . . .

$$\Downarrow$$

Test of theory at quantum level: Sensitivity to loop corrections



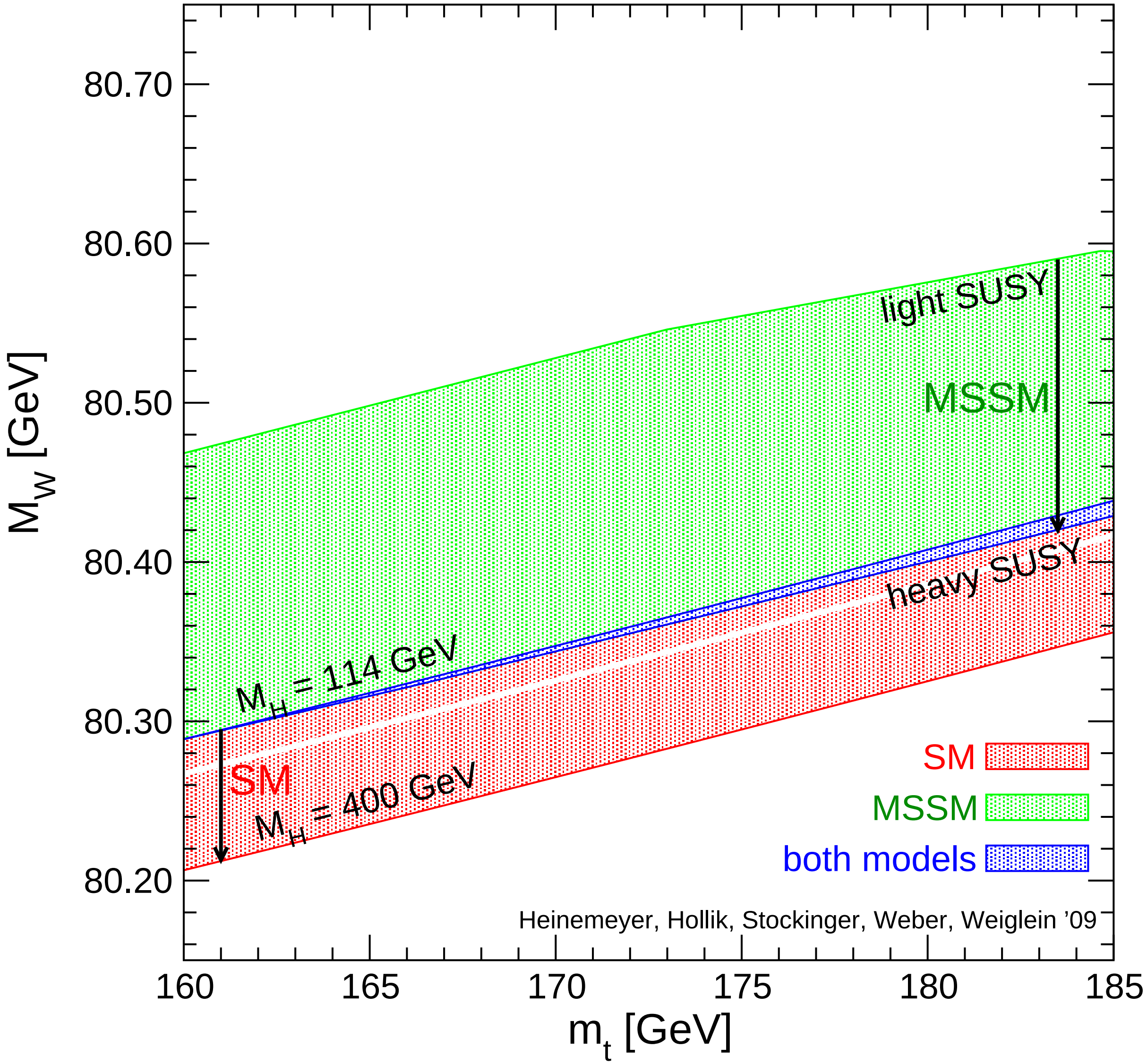
$$\Downarrow$$

$\Rightarrow$ 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^{SM}

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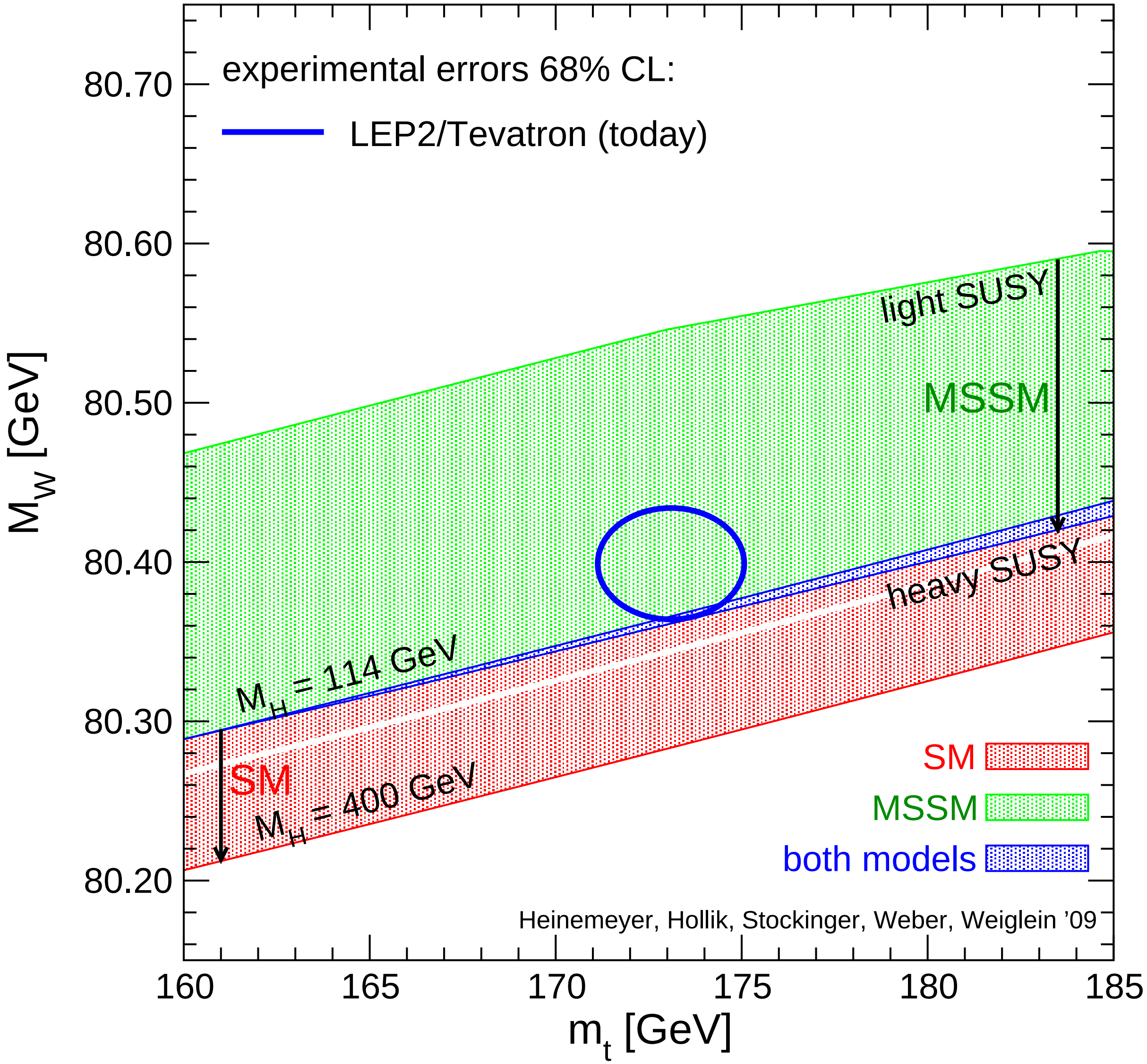

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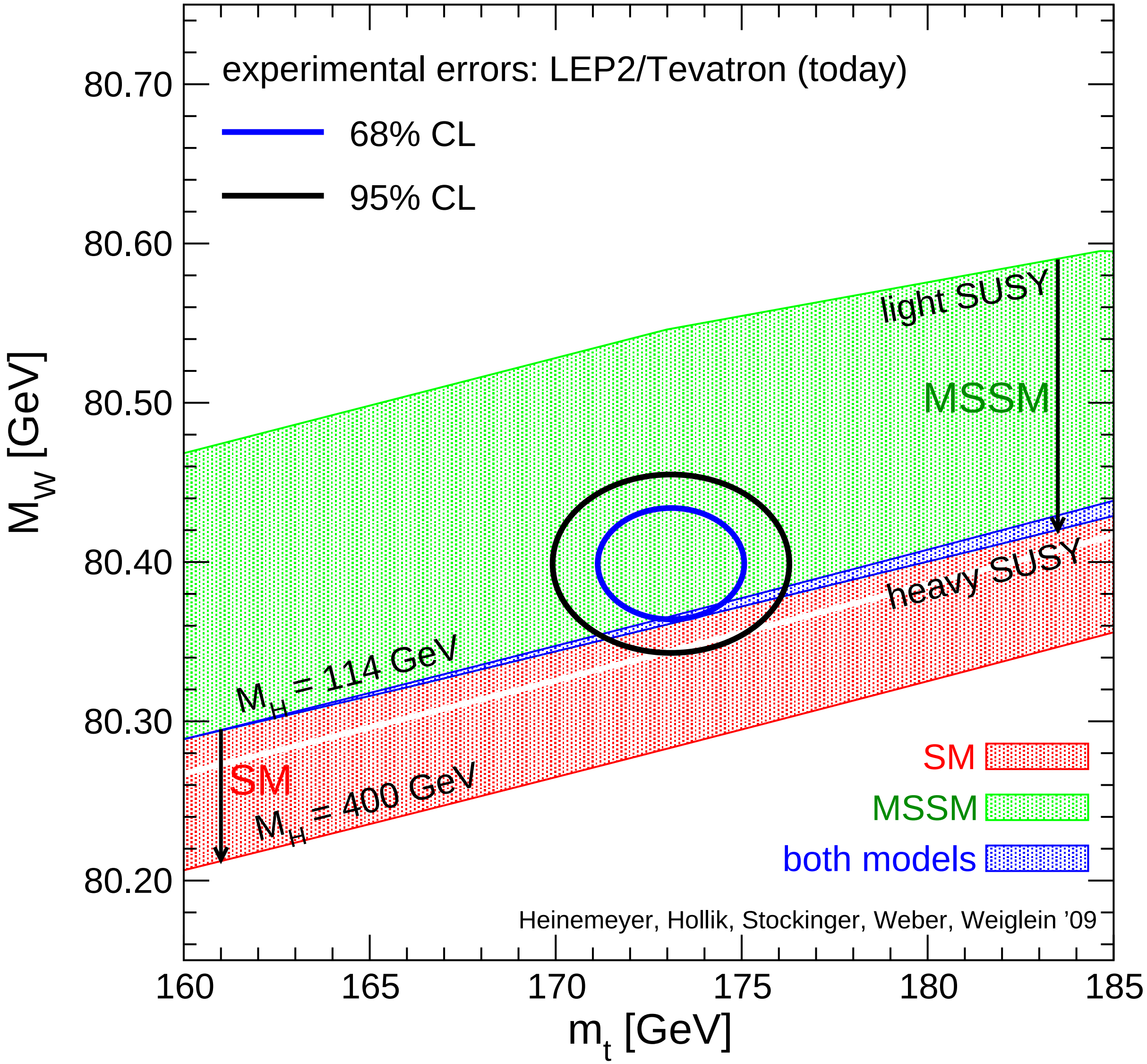

MSSM band:
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overlap:
SM is MSSM-like
MSSM is SM-like

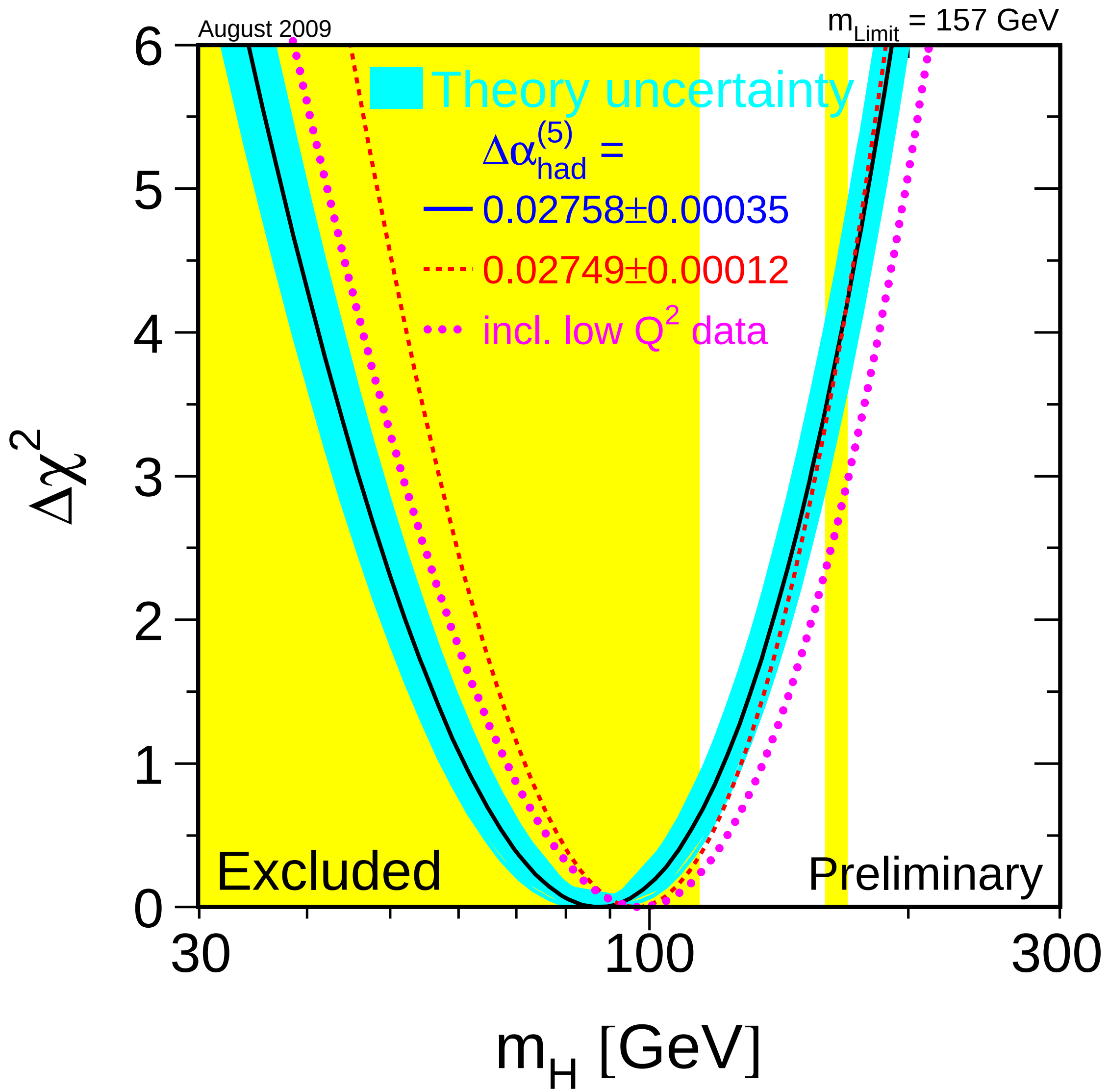
SM band:
variation of $M_H^{\rm SM}$

Global fit to all SM data:

[*LEPEWWG '09*]

$\Rightarrow M_H = 87^{+35}_{-26}$ GeV

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



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

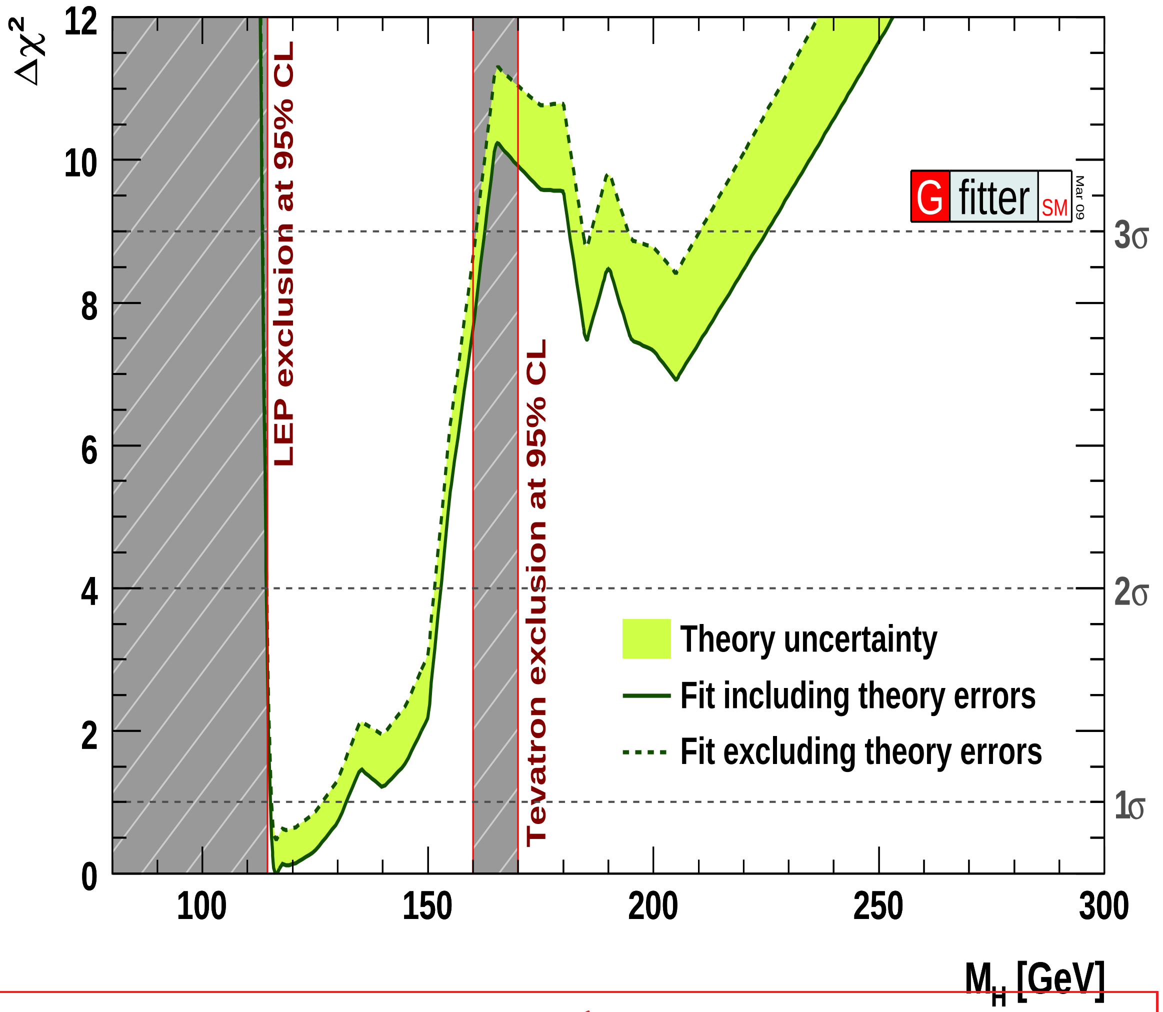
$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 160$ GeV

Global fit to all SM data incl. direct searches:

[*GFitter '09*]

$\Rightarrow M_H = 116.4^{+18.3}_{-1.4}$ GeV

$M_H < 152$ 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, $M_H \lesssim 150$ GeV

2. The models and the tools

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 $\text{BR}(b \to s\gamma)$: 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 makes only sense if all parameters are connected!
$\Rightarrow$ GUT based models, . . .

Existing analyses for GUT based models: (involving precision observables)

CMSSM/mSUGRA:

[J. Ellis, S.H., K. Olive, G. Weiglein '04, '06, '07] *[J. Ellis, S.H., K. Olive, A. Weber, G. Weiglein '07]*

[E. Baltz, P. Gondolo '04] *[R. Ruiz de Austri, R. Trotta and L. Roszkowski '06, '07]*

[B. Allanach, C. Lester and A. Weber '06, '07]

[F. Feroz, M. Hobson, L. Roszkowski and R. Ruiz de Austri, R. Trotta '08]

[O. Buchmueller et al. '07] *[O. Buchmueller et al. '08]* *[O. Buchmueller et al. '09]*

[M. Cabrera, A. Casas, R. Ruiz de Austri '09] *[Y. Akrami, P. Scott, J. Edsjo, J. Conrad, L. Bergstrom '09]*

NUHM (Non-Universal Higgs Mass model):

[J. Ellis, S.H., K. Olive, G. Weiglein '06] *[J. Ellis, S.H., K. Olive, A.M. Weber, G. Weiglein '07]*

[J. Ellis, T. Hahn, S.H., K. Olive, G. Weiglein '07]

[O. Buchmueller et al. '08] *[O. Buchmueller et al. '09]*

VCMSSM (Very Constrained MSSM):

[J. Ellis, S.H., K. Olive, G. Weiglein '06]

[L. Roszkowski, R. Ruiz de Austri, R. Trotta, Y. Tsai, T. Varley '09]

mSUGRA (GDM) (Gravitino Dark Matter): *[J. Ellis, S.H., K. Olive, G. Weiglein '06]*

CMSSM, mGMSB, mAMSB: *[S.H., X. Miao, S. Su, G. Weiglein '08]*

CNMSSM: *[D. Lopez-Fogliani, L. Roszkowski, R. Ruiz de Austri, T. Varley '09]*

Finite Unified Theories: *[S.H., M. Mondragón, G. Zoupanos '07]*

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)

⇒ here: results using last two

2.) Fitting:

– Frequentist
– Bayesian

⇒ focus on Frequentist here

3.) Priors . . . (none)

The models: 1.) CMSSM (or mSUGRA):

$\Rightarrow$ Scenario characterized by

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

$$\left.\begin{array}{l} m_0 : \text{universal scalar mass parameter} \\ m_{1/2} : \text{universal gaugino mass parameter} \\ A_0 : \text{universal trilinear coupling} \end{array}\right\} \text{at the GUT scale}$$

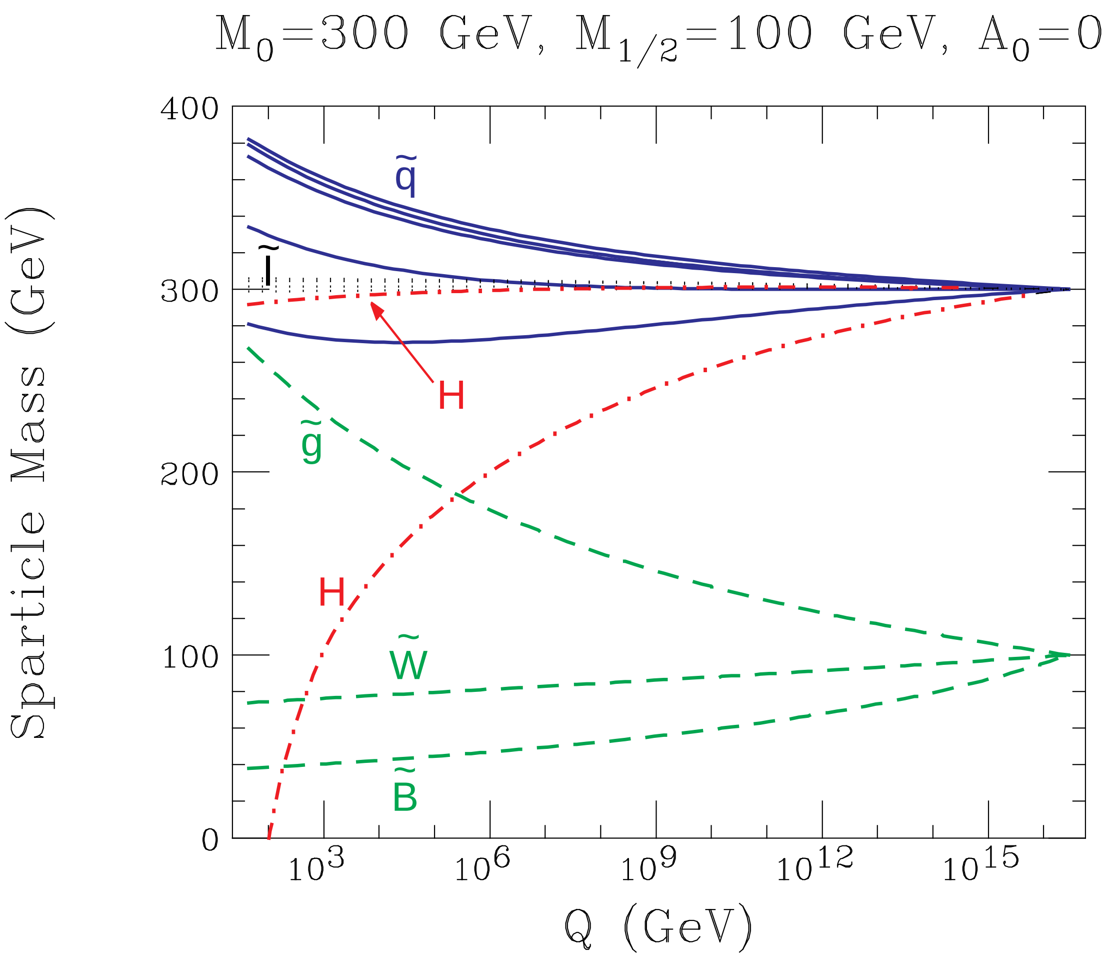
$\tan\beta$: ratio of Higgs vacuum expectation values

sign(μ) : sign of supersymmetric Higgs parameter

$\Rightarrow$ particle spectra from renormalization group running to weak scale

$\Rightarrow$ Lightest SUSY particle (LSP) is the lightest neutralino

⇒ particle spectra from renormalization group running to weak scale



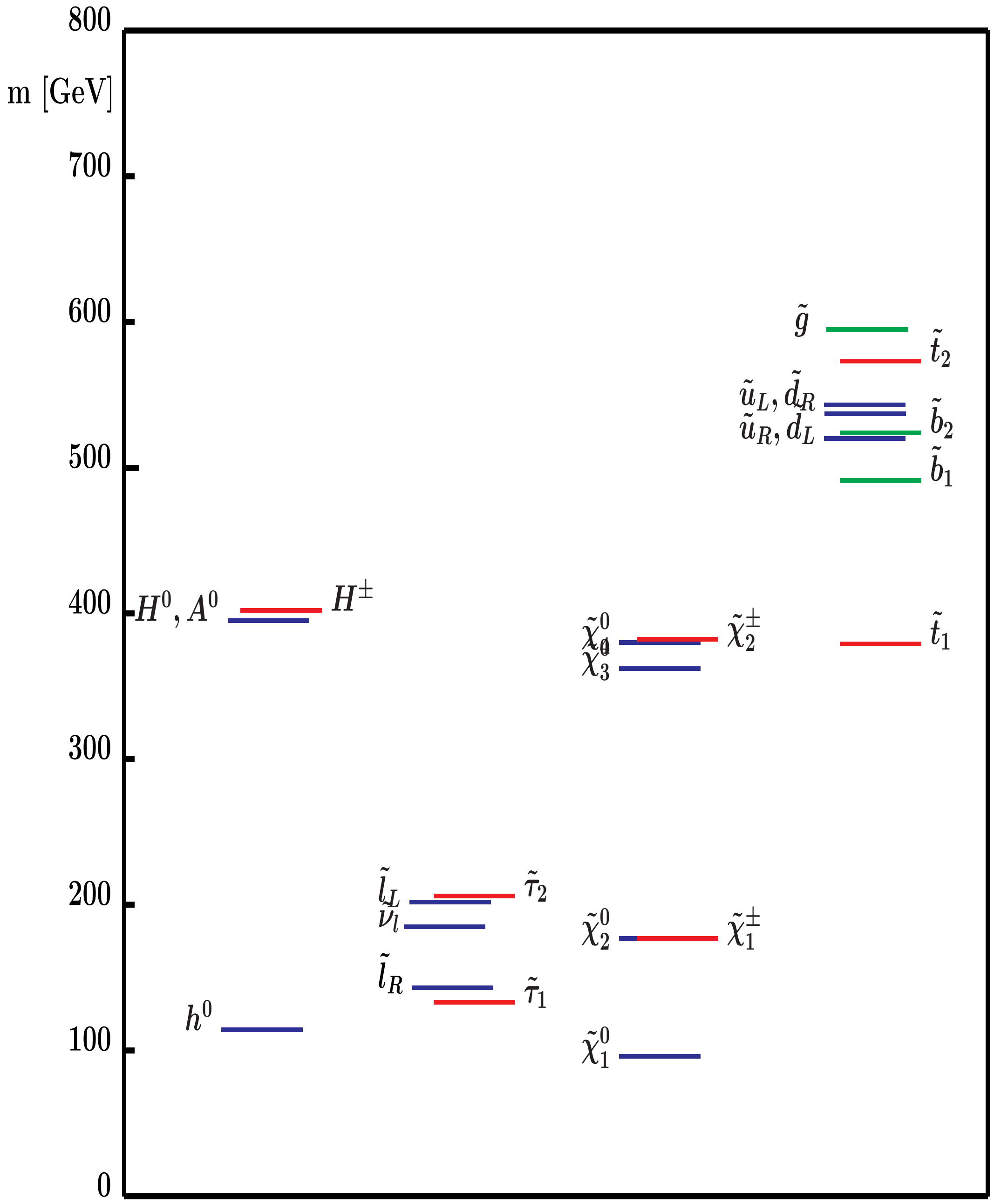
⇒ one parameter turns negative ⇒ Higgs mechanism for free

“Typical” CMSSM scenario

(SPS 1a benchmark scenario):

SPS home page:

`www.ippp.dur.ac.uk/~georg/sps`



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

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

$\Rightarrow$ effectively M_A or μ as free parameters at the EW scale

$\Rightarrow$ besides the CMSSM parameters

M_A or μ

Further extension: NUHM2:

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

$\Rightarrow$ effectively M_A and μ as free parameters at the EW scale

$\Rightarrow$ besides the CMSSM parameters

M_A and μ

Our tool:

The "MasterCode"

⇒ collaborative effort of theorists and experimentalists

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

Über-code for the combination of different tools:

– calculations of POs are included as subroutines

– compatibility ensured by collaboration of authors of "MasterCode" and authors of "sub tools" /SLHA(2)

– one "MasterCode" for one model . . .

⇒ evaluate observables of one parameter point consistently with various tools

cern.ch/mastercode

Status of the “MasterCode”:

– one model: (MFV) MSSM

– 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*]

– added: χ^2 analysis code
  (→ similar directions as SFitter, Fittino)

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

– planned: inclusion of more tools
  inclusion of more models

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?

$\rightarrow$ especially important: M_h

$\rightarrow$ backup

3. Predictions for the LHC

[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, $\Delta\alpha_{\rm had}$

$\Rightarrow$ 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 $\boxed{\Rightarrow \mathcal{L}_{\rm SUSY}}$

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

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

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

NUHM1:

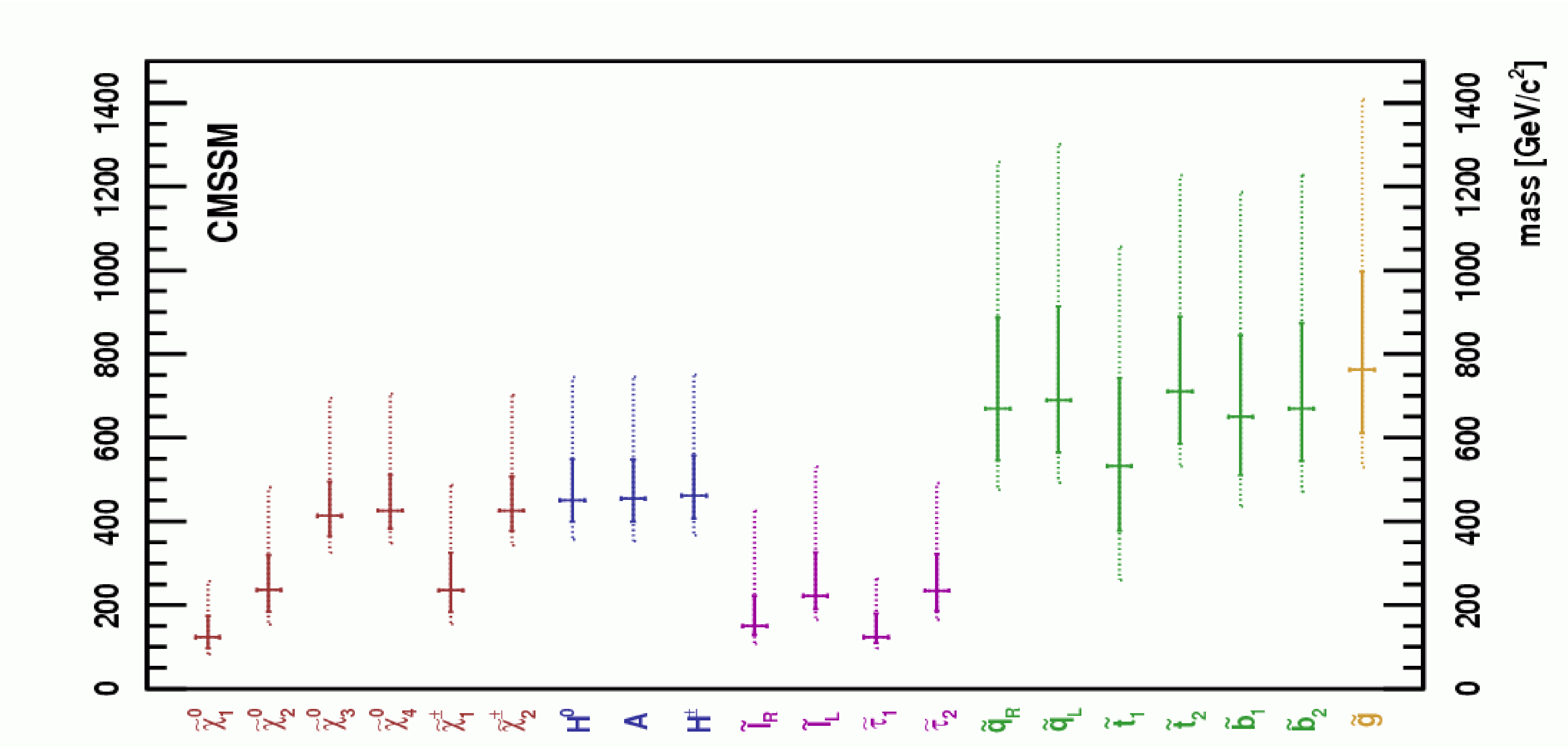
$m_{1/2} = 270$ GeV, $m_0 = 150$ GeV, $A_0 = -1300$ GeV,
$\tan\beta = 11$, $\mu = 1140$ GeV, $M_A = 310$ GeV

(similar probability)

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

Masses for best-fit points: CMSSM

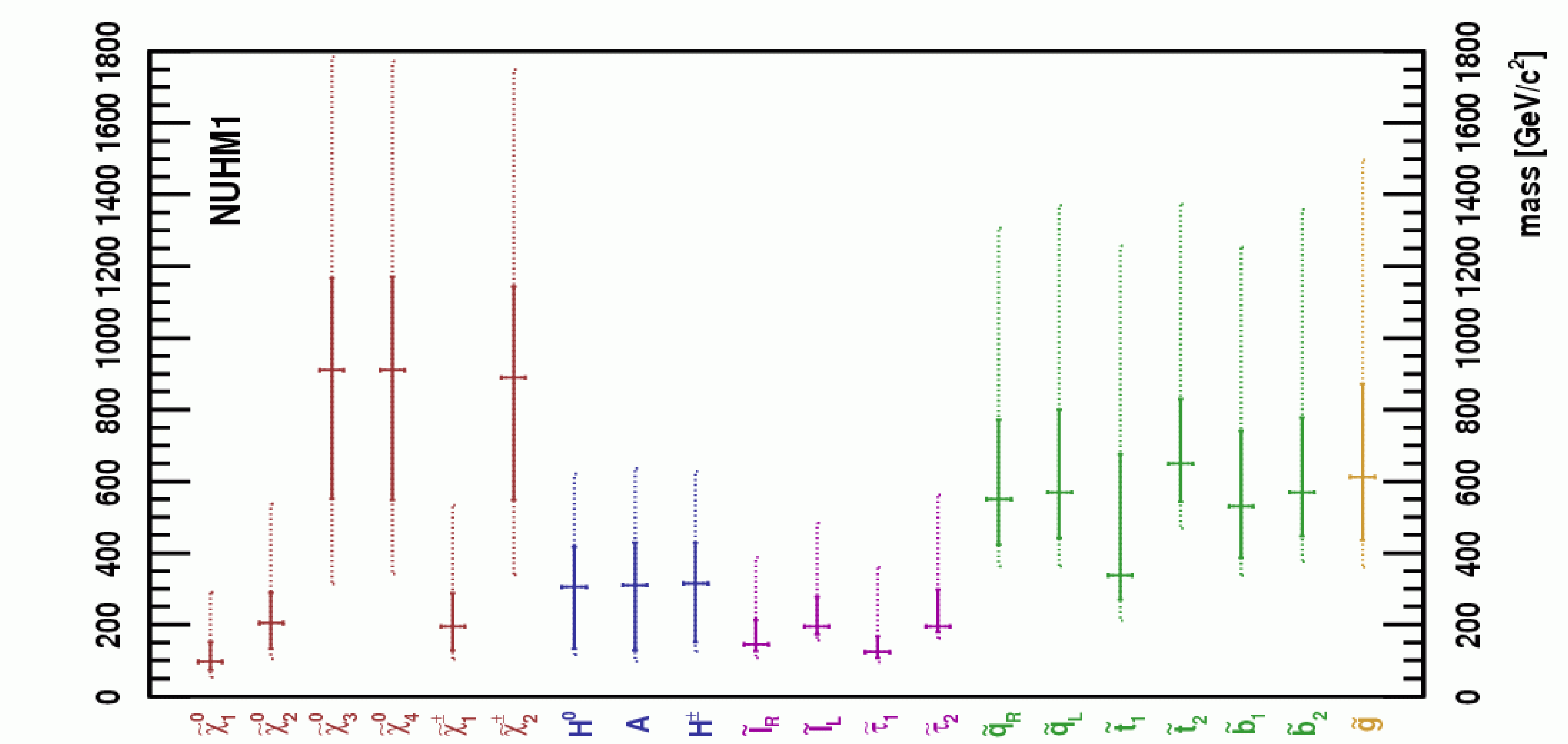
[2009]



⇒ largely accessible spectrum for LHC (and ILC)

Masses for best-fit points: NUHM1

[2009]



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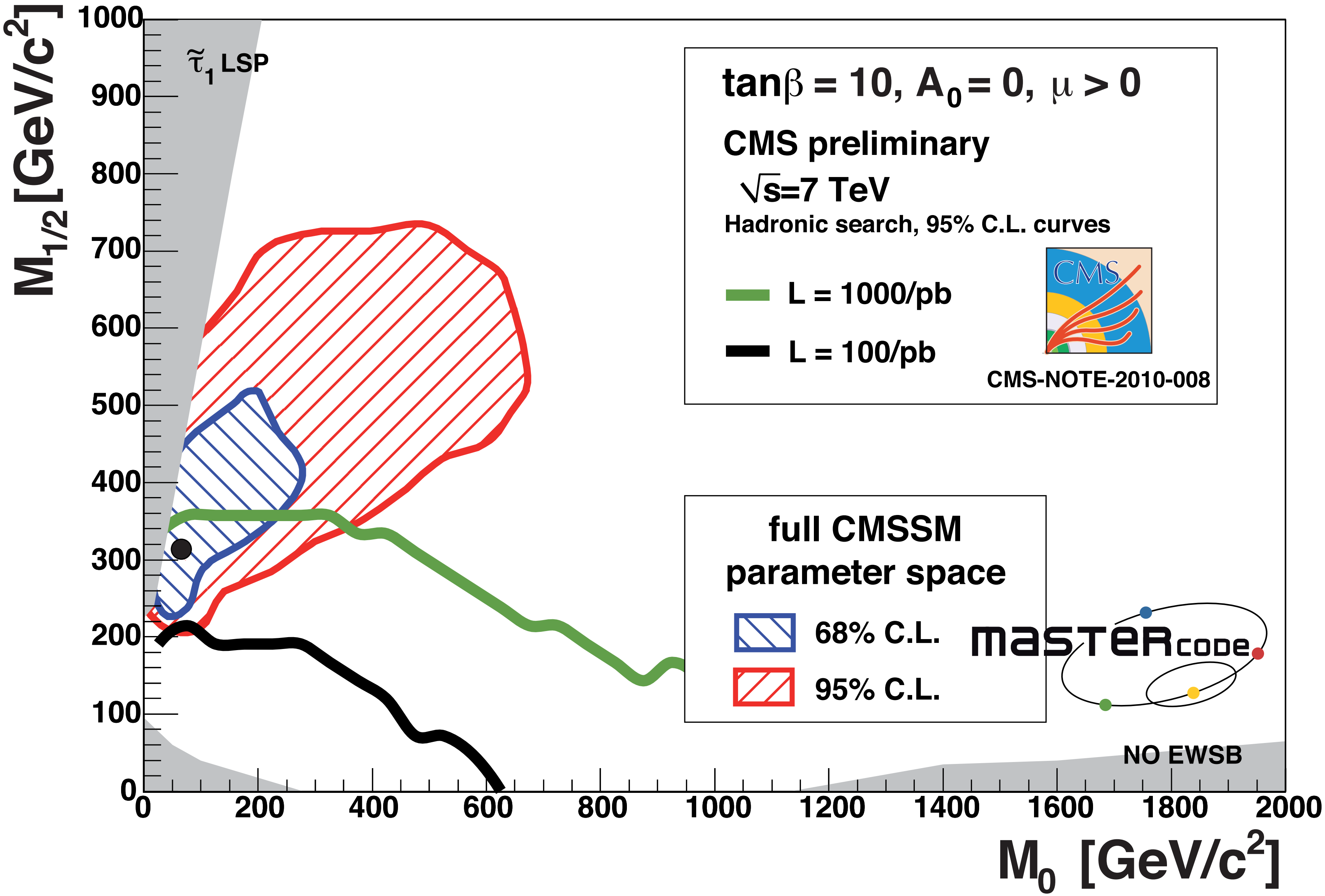
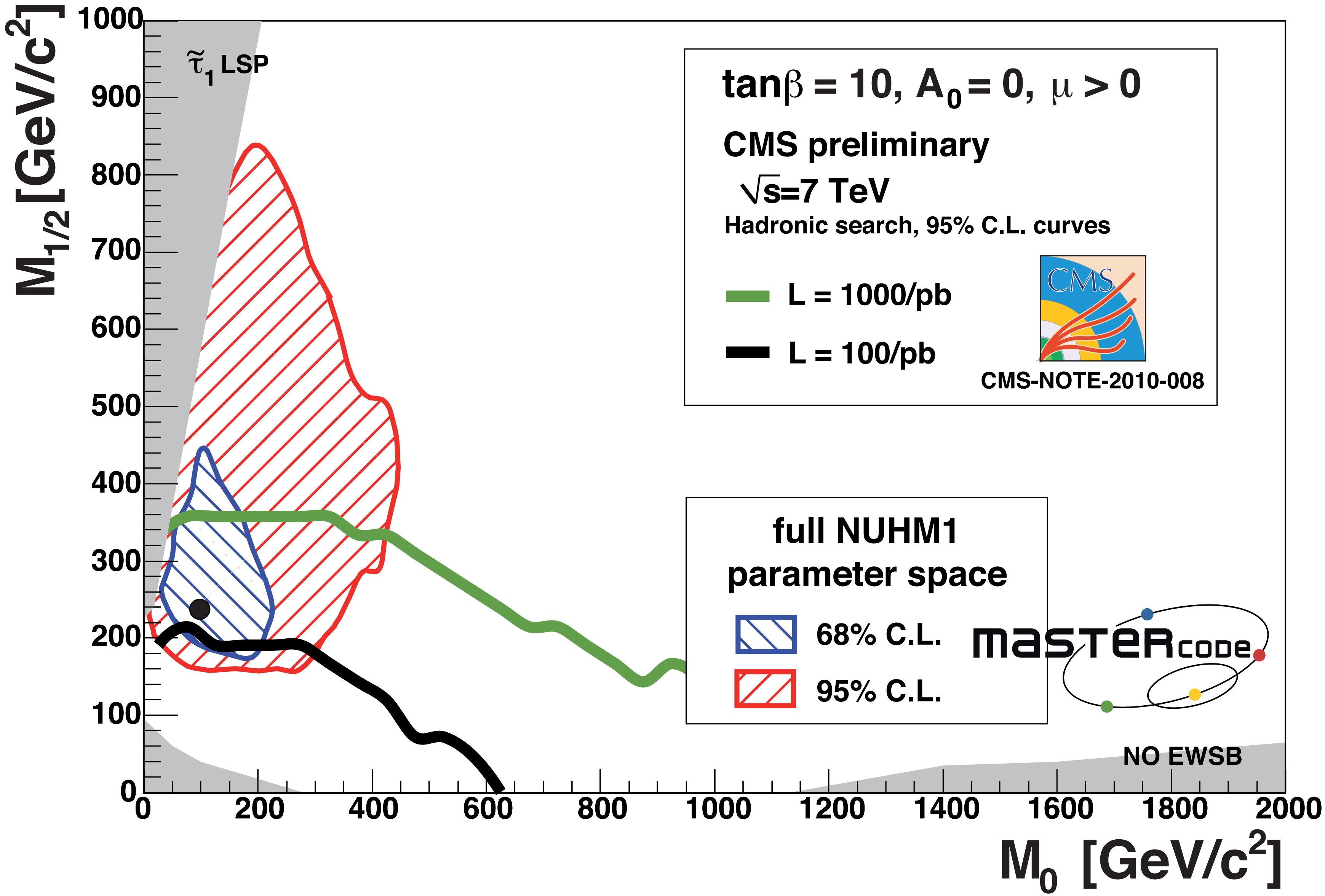
LHC (CMS) $\oplus$ CMSSM analysis:



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

LHC (CMS) ⊕ NUHM1 analysis:

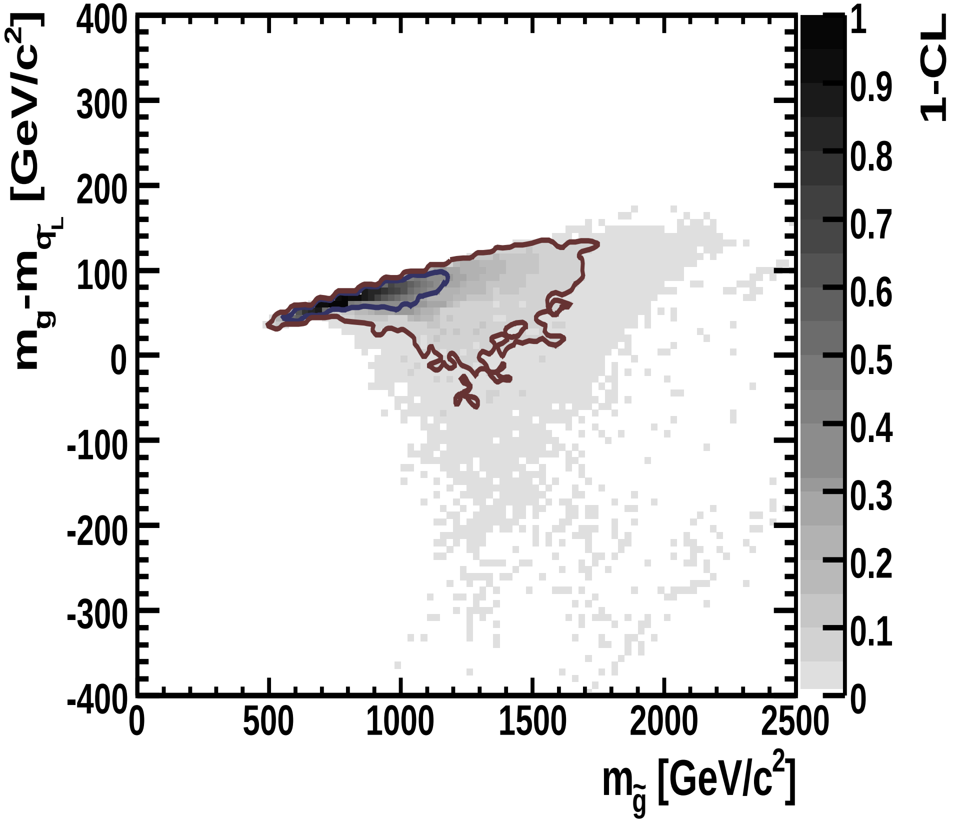


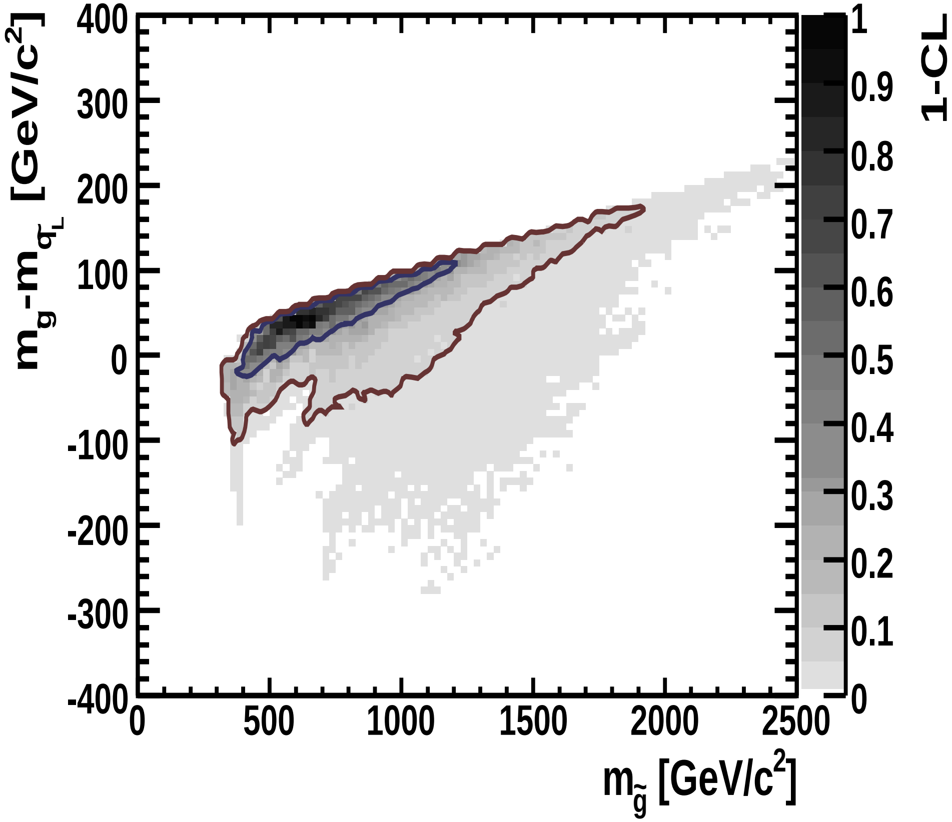
⇒ best-fit point and part of 68% C.L. are can be tested in 2011

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

[2009]

CMSSM   NUHM1



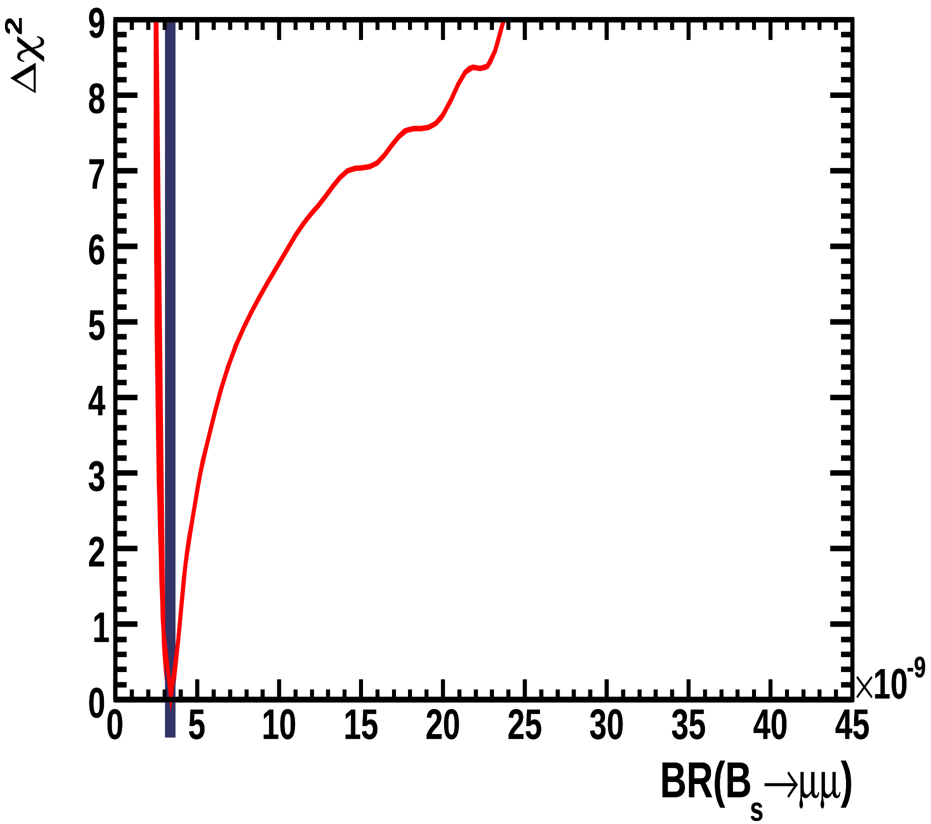


$\Rightarrow m_{\tilde{g}}$ often largest mass, but exceptions are possible

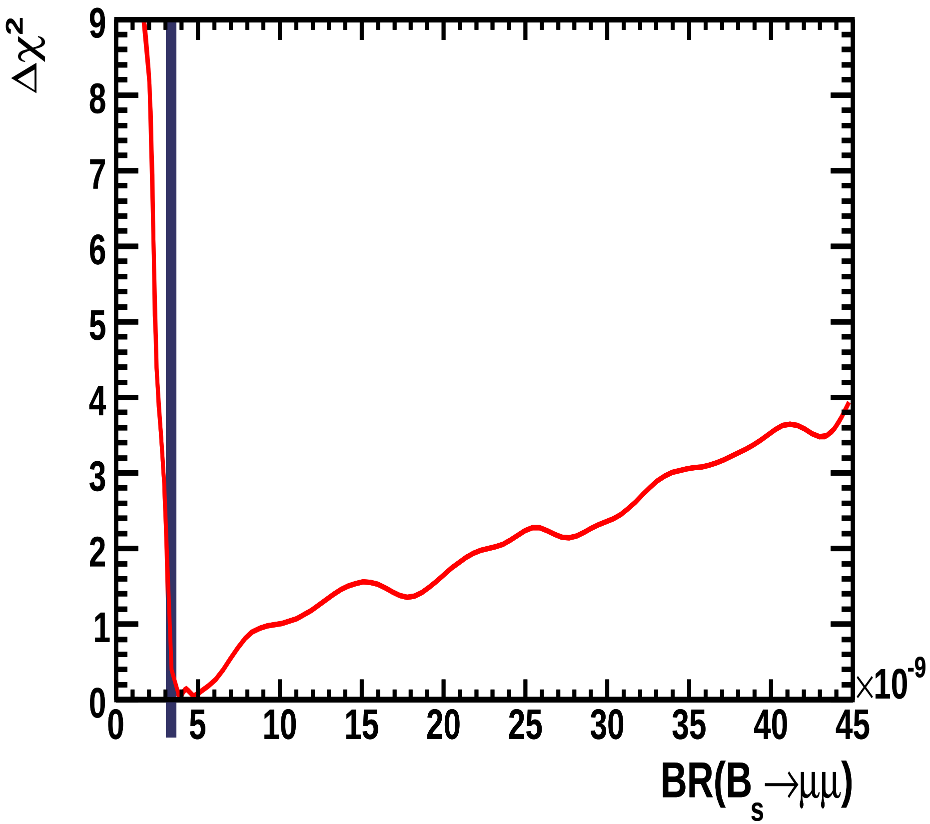
Some more predictions: BR($B_s \to \mu^+\mu^-$)

[2009]

CMSSM

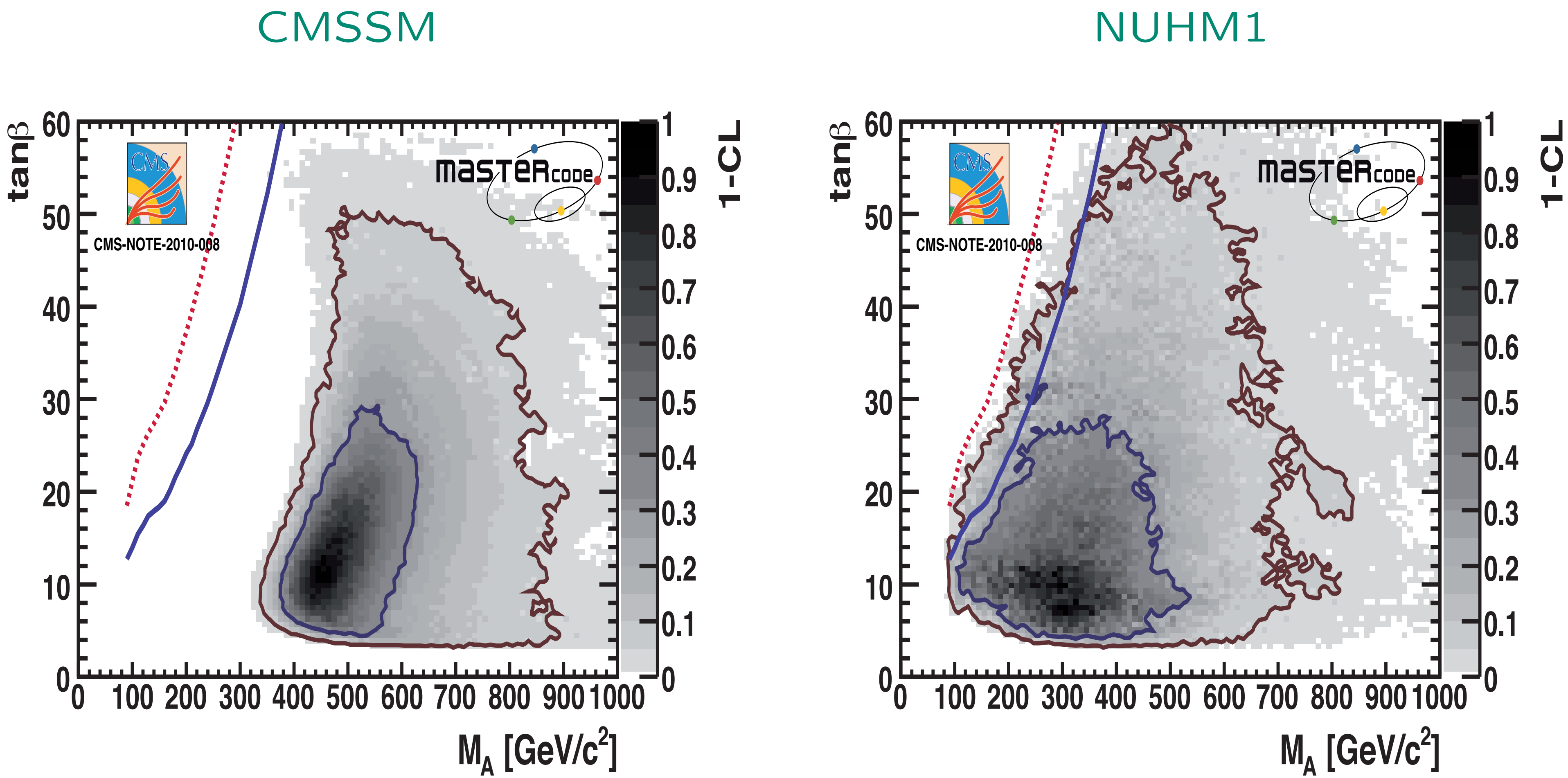


NUHM1



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

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



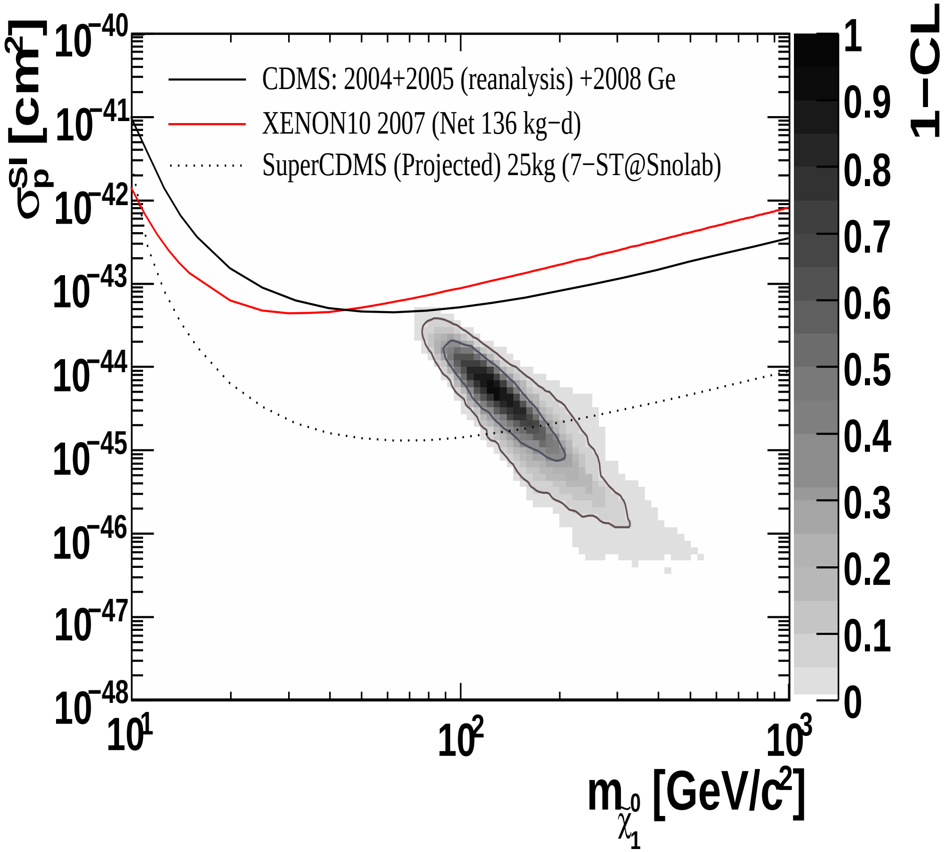
red dotted: discovery with 1 fb^{-1} @ 7 TeV
blue solid: 95% C.L. exclusion with 1 fb^{-1} @ 7 TeV

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

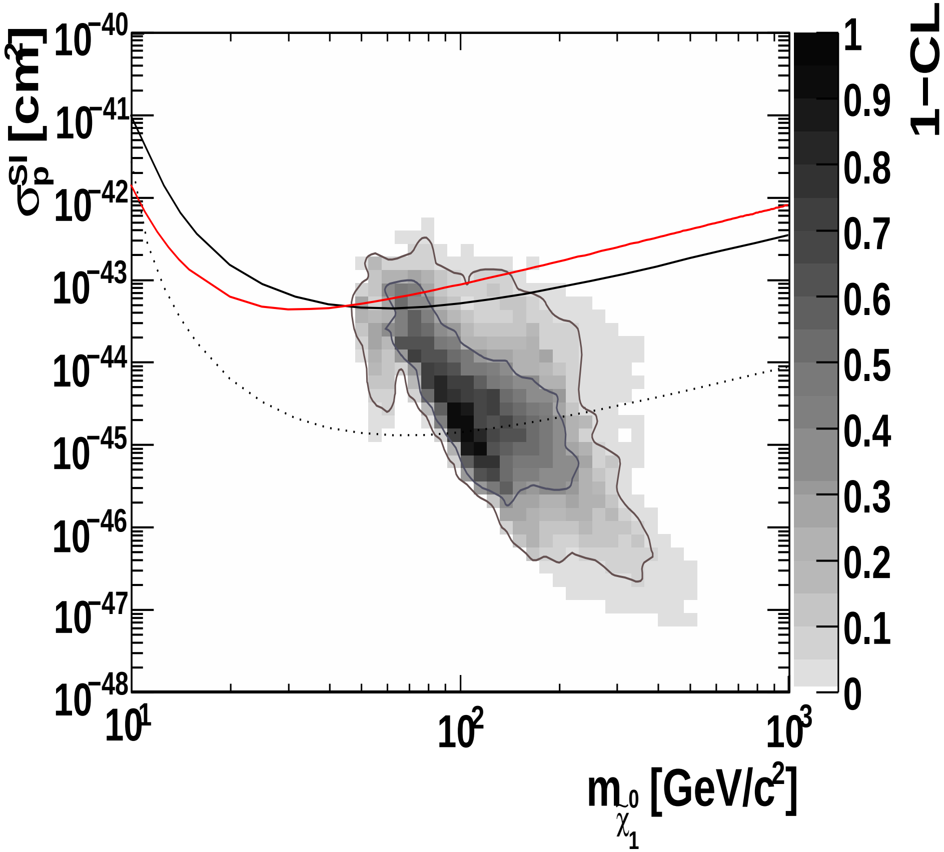
Some more predictions: direct search for dark matter

[2009]

CMSSM



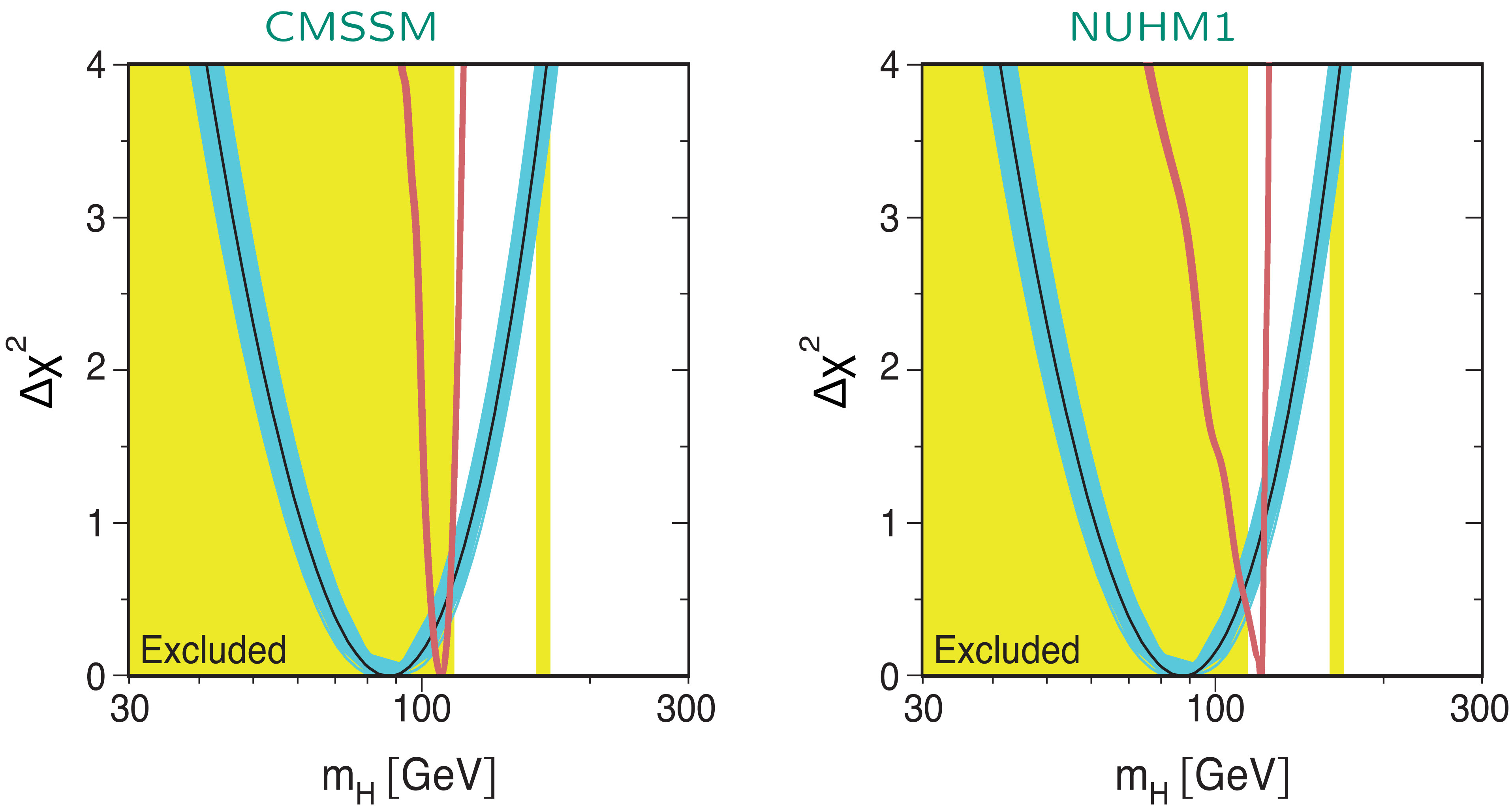
NUHM1



⇒ only partially covered by future experiments

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

[2009]



$M_h^{\text{CMSSM}} = 108 \pm 6 \pm 1.5$ GeV

$\Rightarrow$ as good as the SM

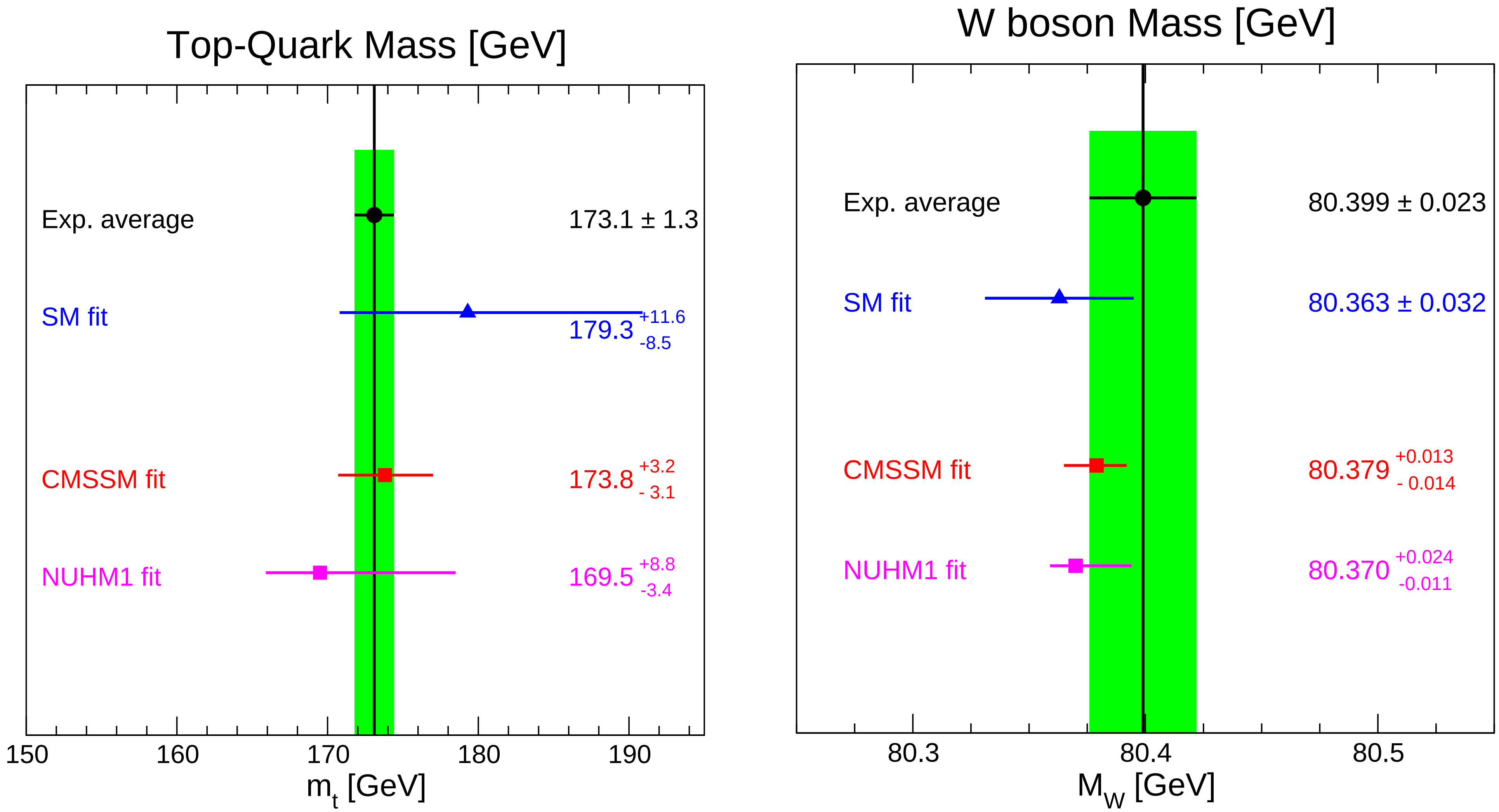
$M_h^{\text{NUHM1}} = 121^{+1}_{-14} \pm 1.5$ GeV

$\Rightarrow$ above the LEP limit

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]



$\Rightarrow$ CMSSM and NUHM1 fit amazingly well m_t and M_W

$\Rightarrow$ better than the SM: smaller errors, better best-fit points

4. 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): $M_h = 108 \pm 6 \pm 1.5$ 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
- 68% C.L. areas: partially covered with $\sim 1\ \text{fb}^{-1}$ @ 7 TeV (u.d.!)
  $\Rightarrow$ early LHC data could be very conclusive!

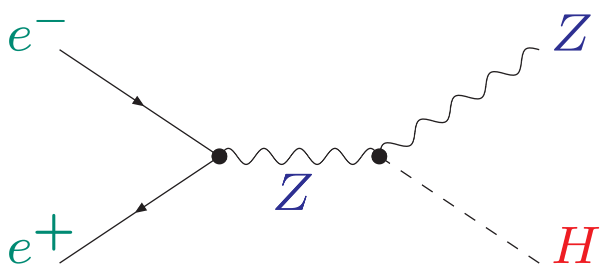

Higgs Days at Santander 2010
Theory meets Experiment
13.-16. October
HEPTOOLS
IFCA
Instituto de Física de Cantabria
CSIC
UC
UNIVERSIDAD DE CANTABRIA
contact: Sven.Heinemeyer@cern.ch
http://www.ifca.es/HDays10
Photo: Philip Bechtle HDays09

Back-up

SM Higgs search at LEP:

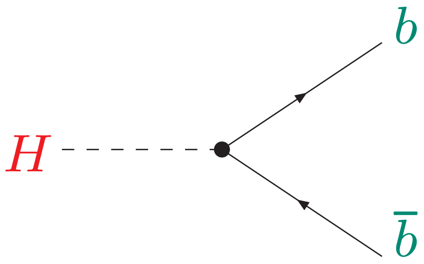
Dominant SM production process:

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



Dominant decay process:

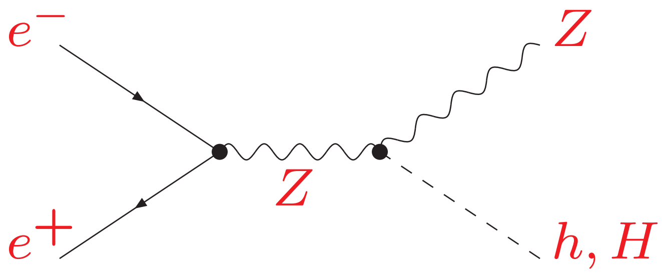
$H \to b\bar{b}$:



Bounds valid in the CMSSM? NUHM1? MSSM?

Search for neutral SUSY Higgs bosons:

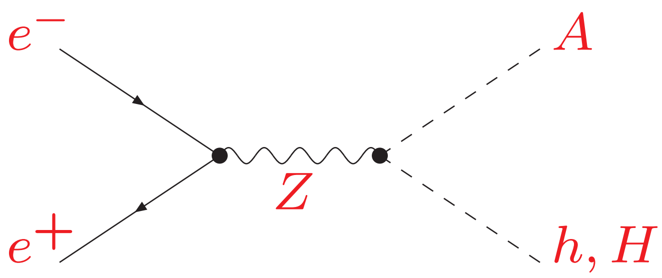
$e^+e^- \to Zh, ZH$



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

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

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



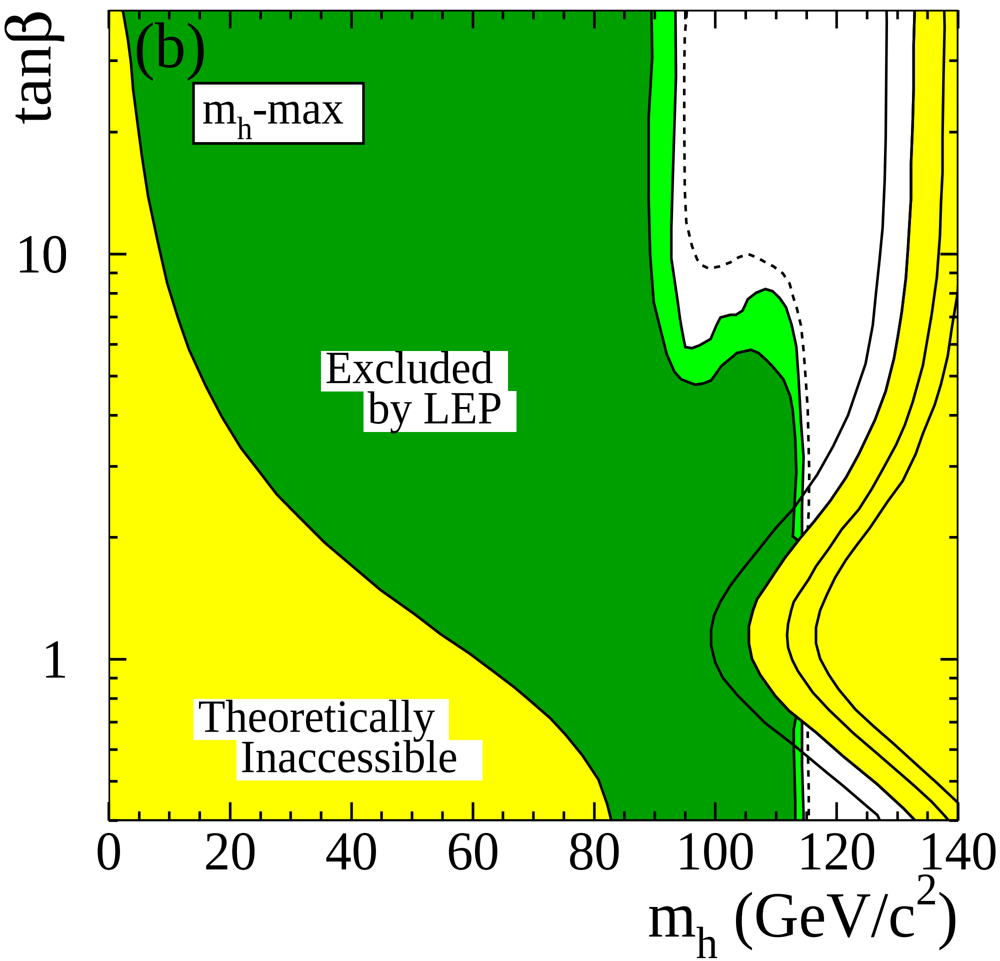
$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\rm eff})\sigma^{\rm SM}_{hZ}$$

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

Constraints from the Higgs search at LEP [*LEP Higgs Working Group '06*]

Experimental search vs. upper M_h-bound (*FeynHiggs* 2.0)

$m_h^{\rm max}$-scenario ($m_t = 174.3$ GeV, $M_{\rm SUSY} = 1$ TeV):

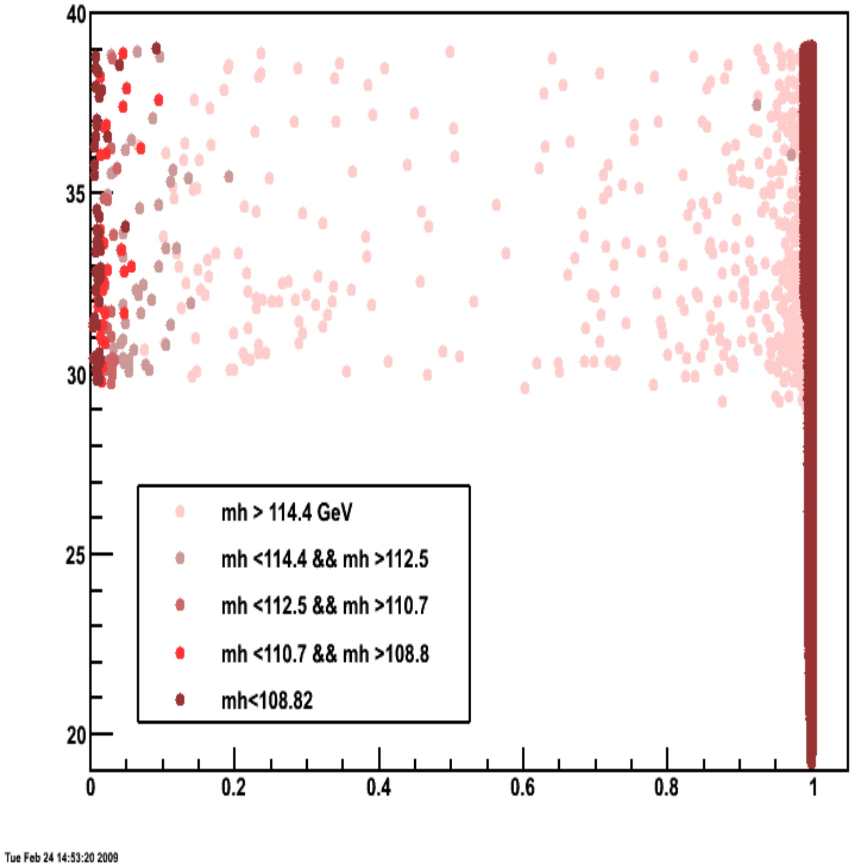


$m_h > 92.8$ GeV (expected: 94.9 GeV), 95% C.L.

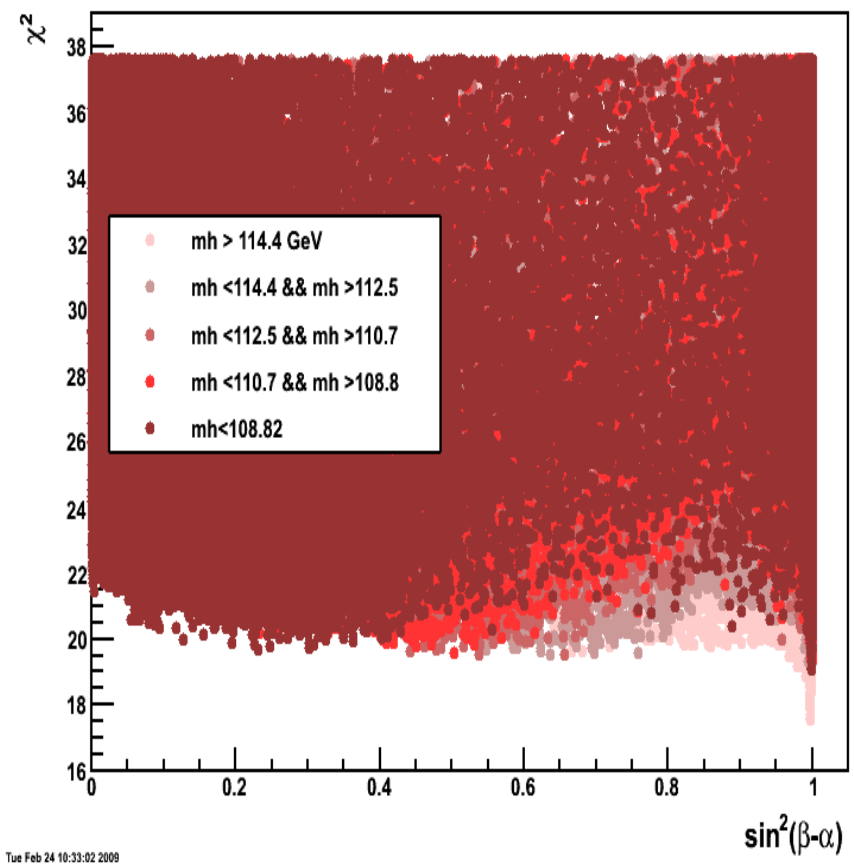
$M_A > 93.4$ GeV (expected: 95.2 GeV)

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

CMSSM

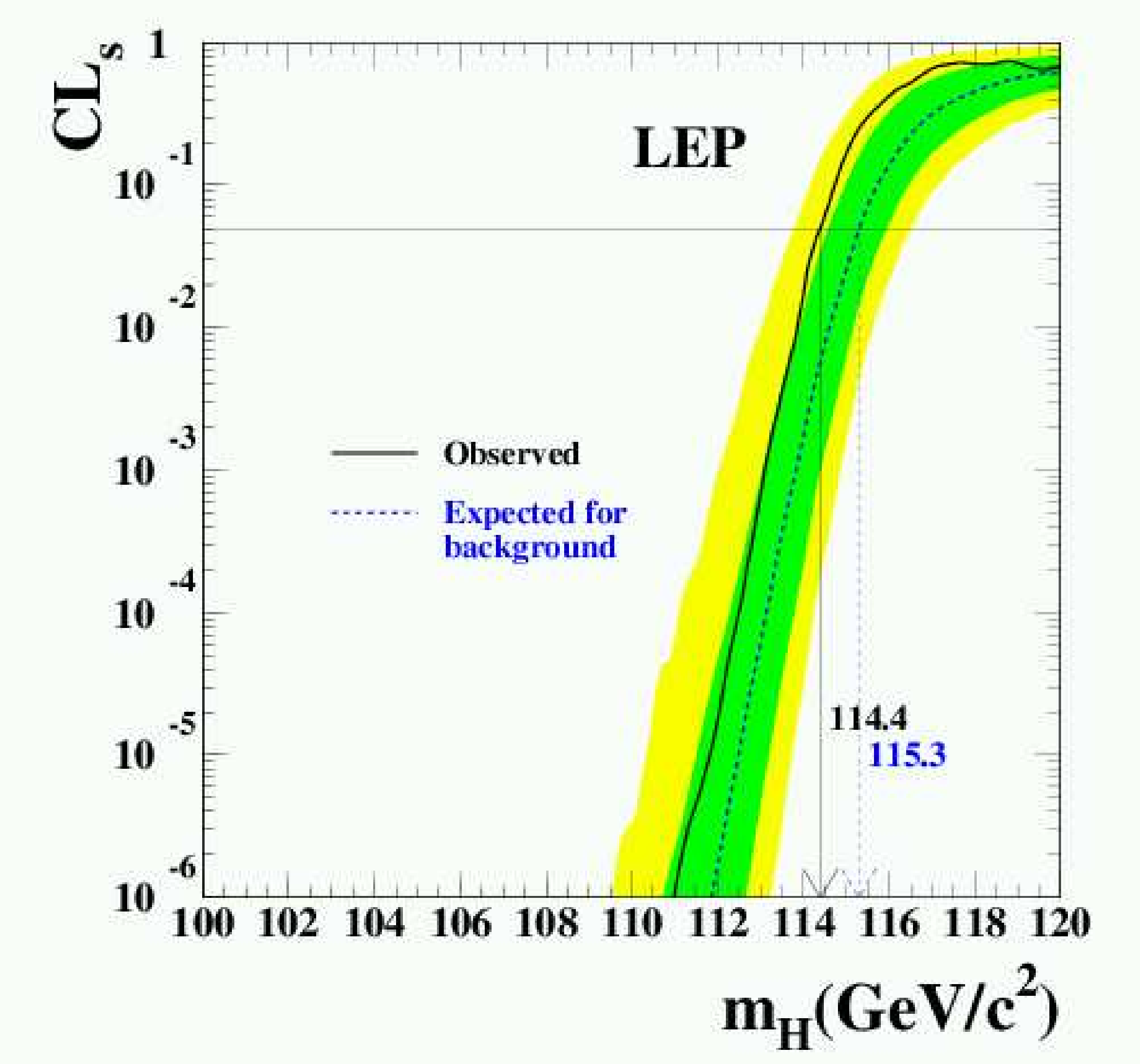


NUHM1



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

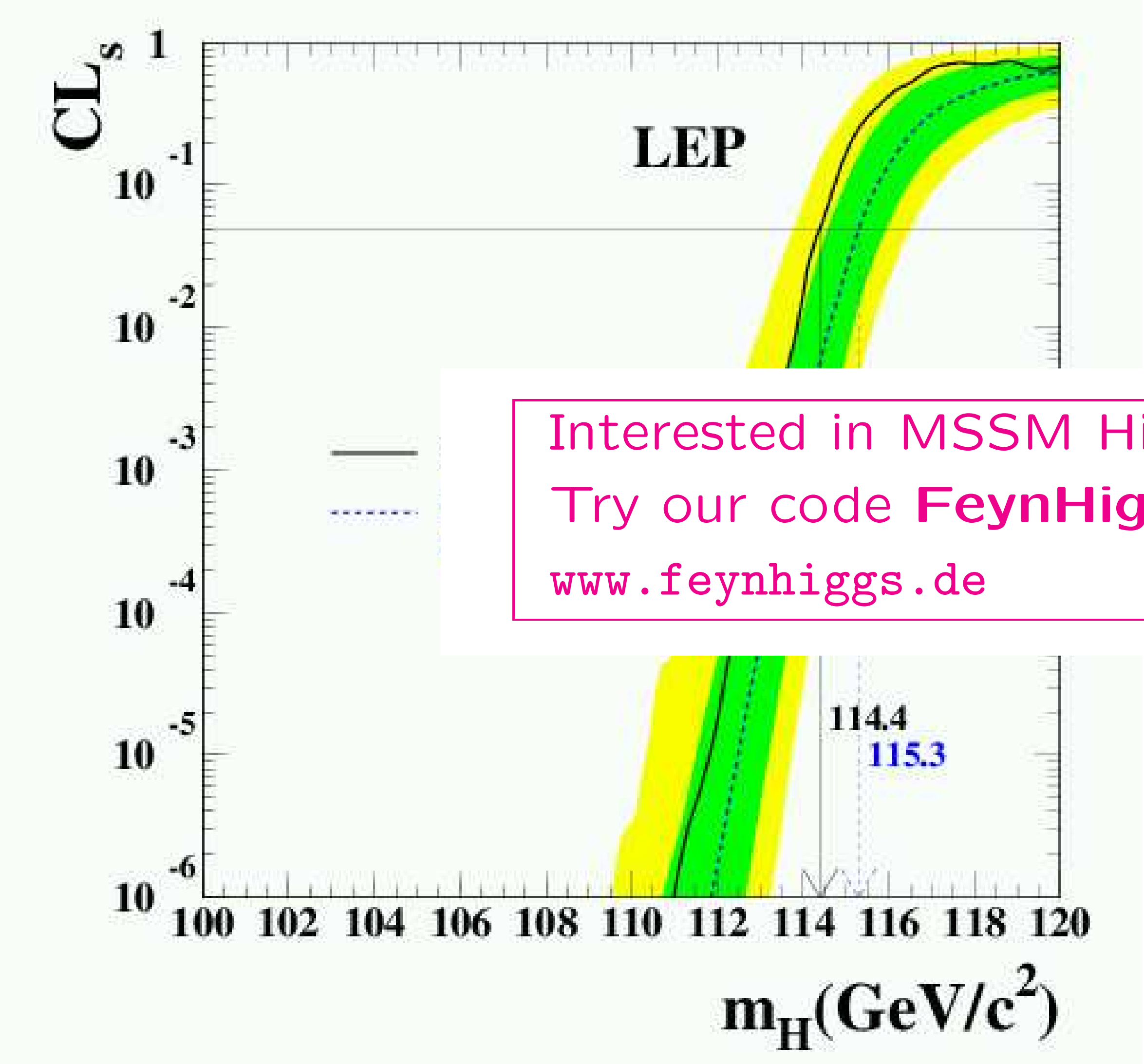
$\Rightarrow$ can be included into χ^2 evaluation

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

We use *FeynHiggs*

In 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

ed into

Interested in MSSM Higgs physics?

Try our code **FeynHiggs**

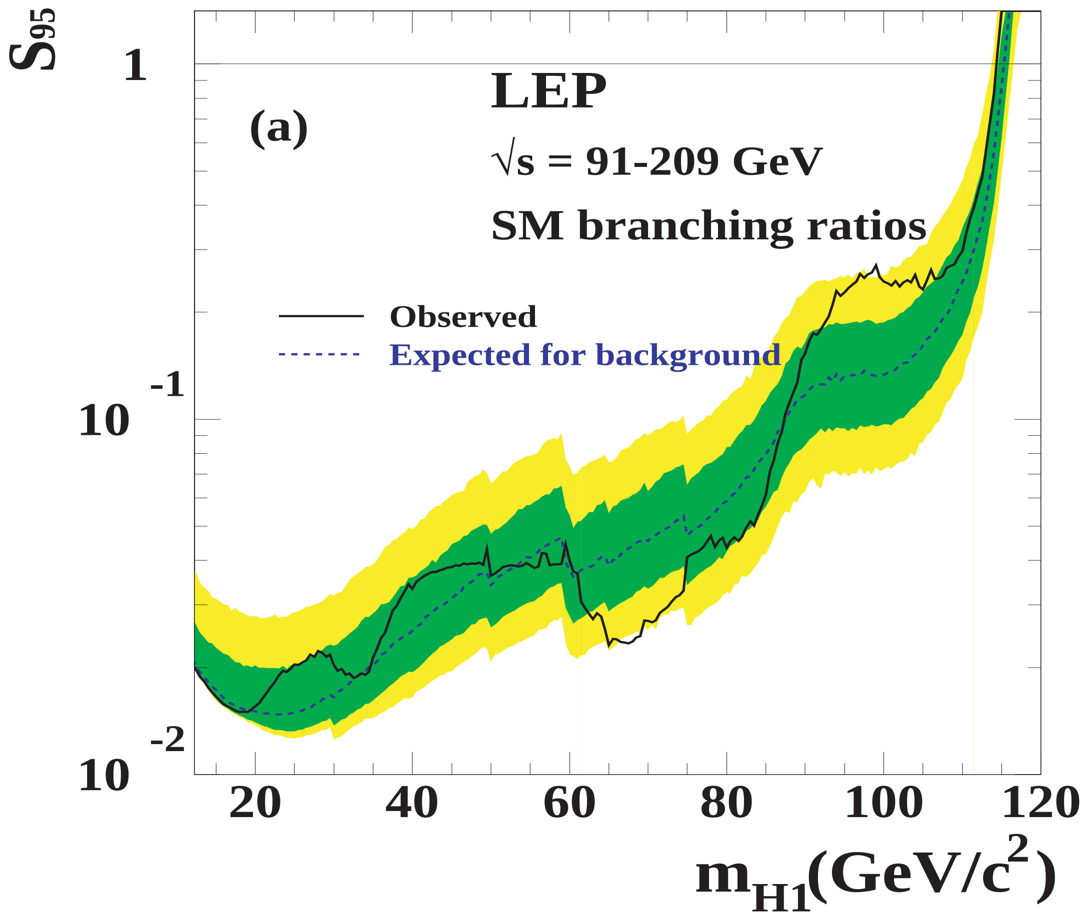
`www.feynhiggs.de`

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

We use *FeynHiggs*

In the NUHM1:

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



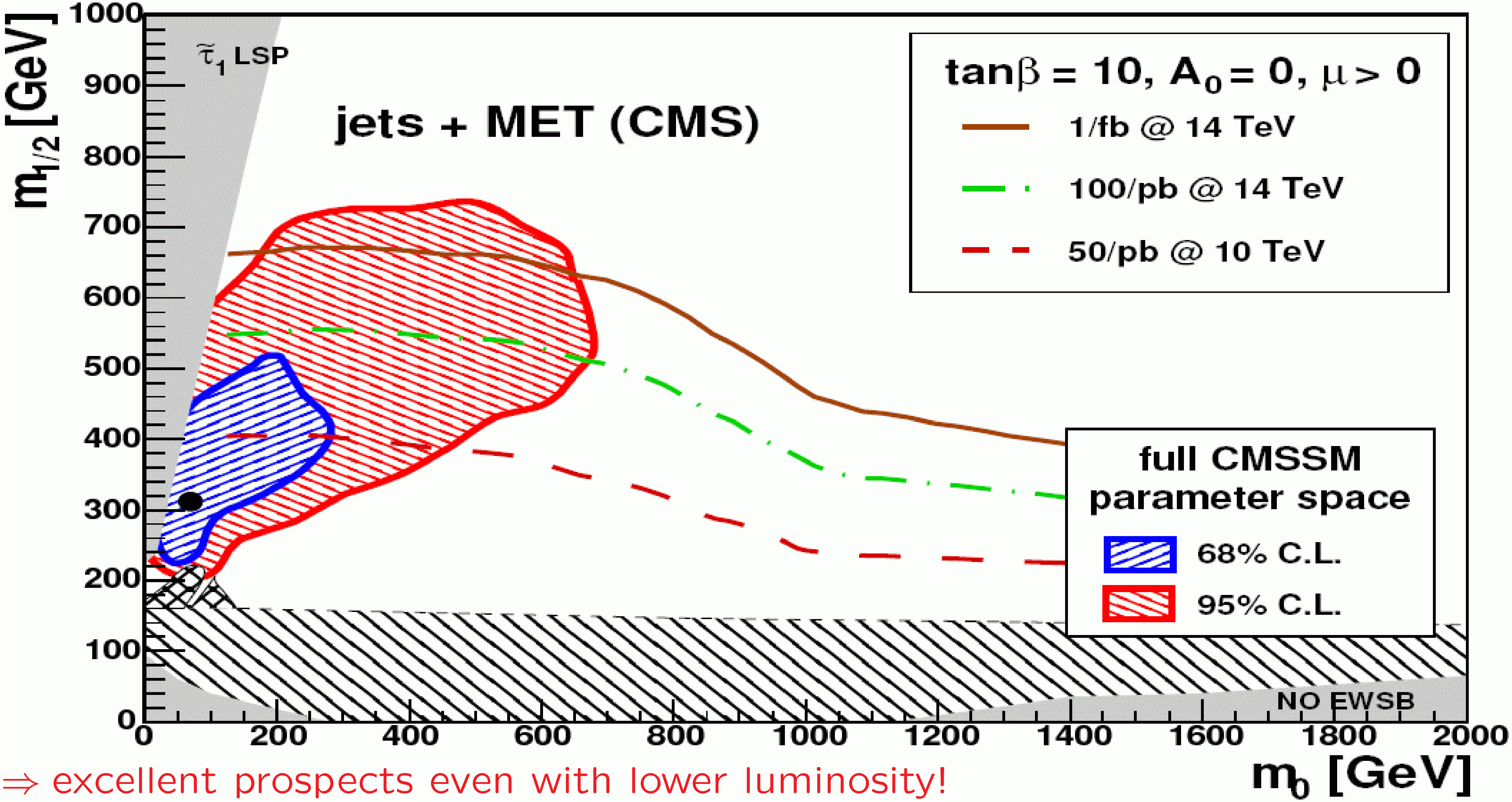
$\Rightarrow$ take into account the LEP SM Higgs bound . . .

. . . but shifted according to the reduced coupling

LHC (CMS) $\oplus$ CMSSM analysis:

[*CMS '07*]

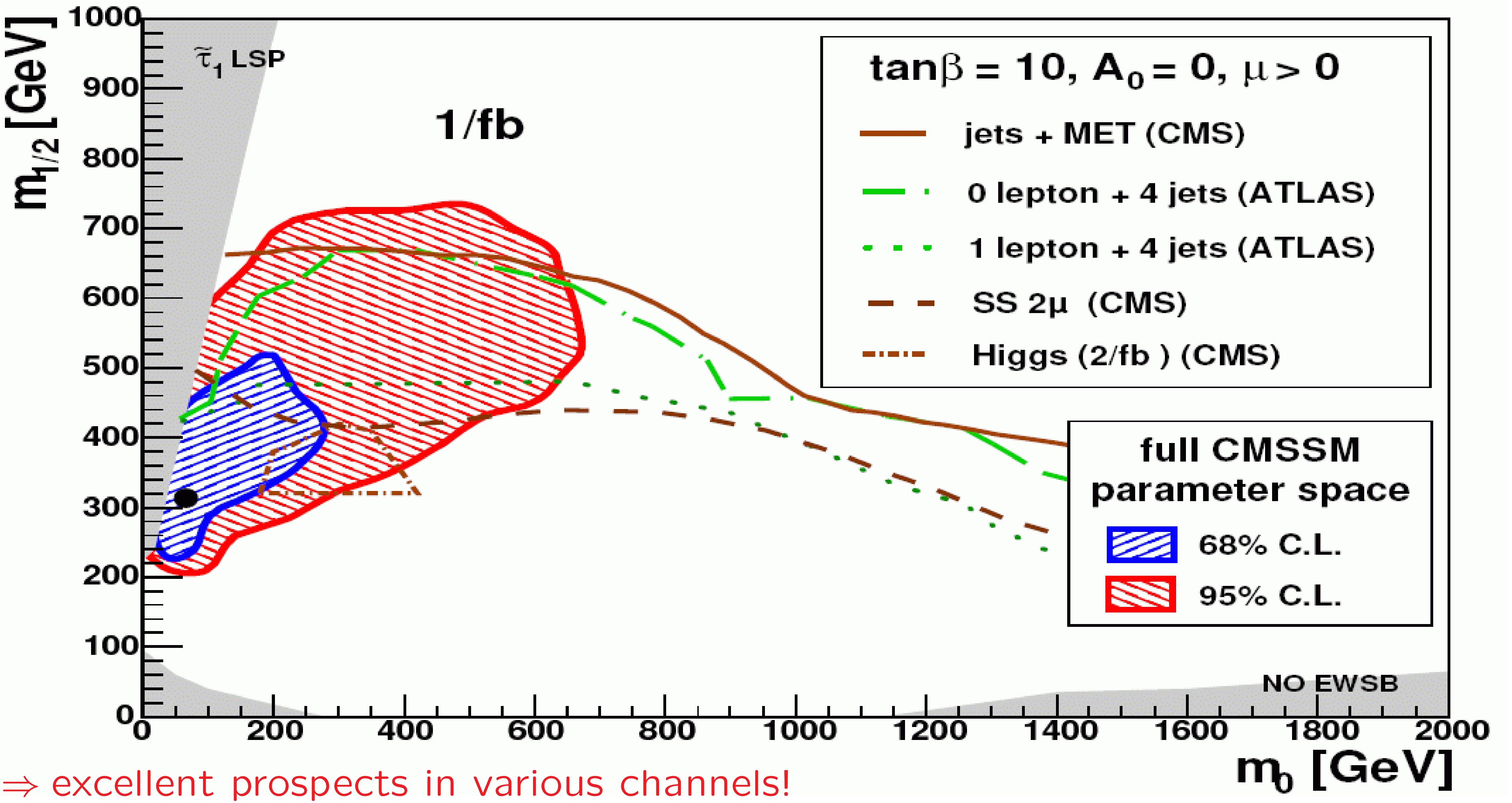
[*2008*]



$\Rightarrow$ excellent prospects even with lower luminosity!

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

[*MasterCode '08*] [*CMS '07*]

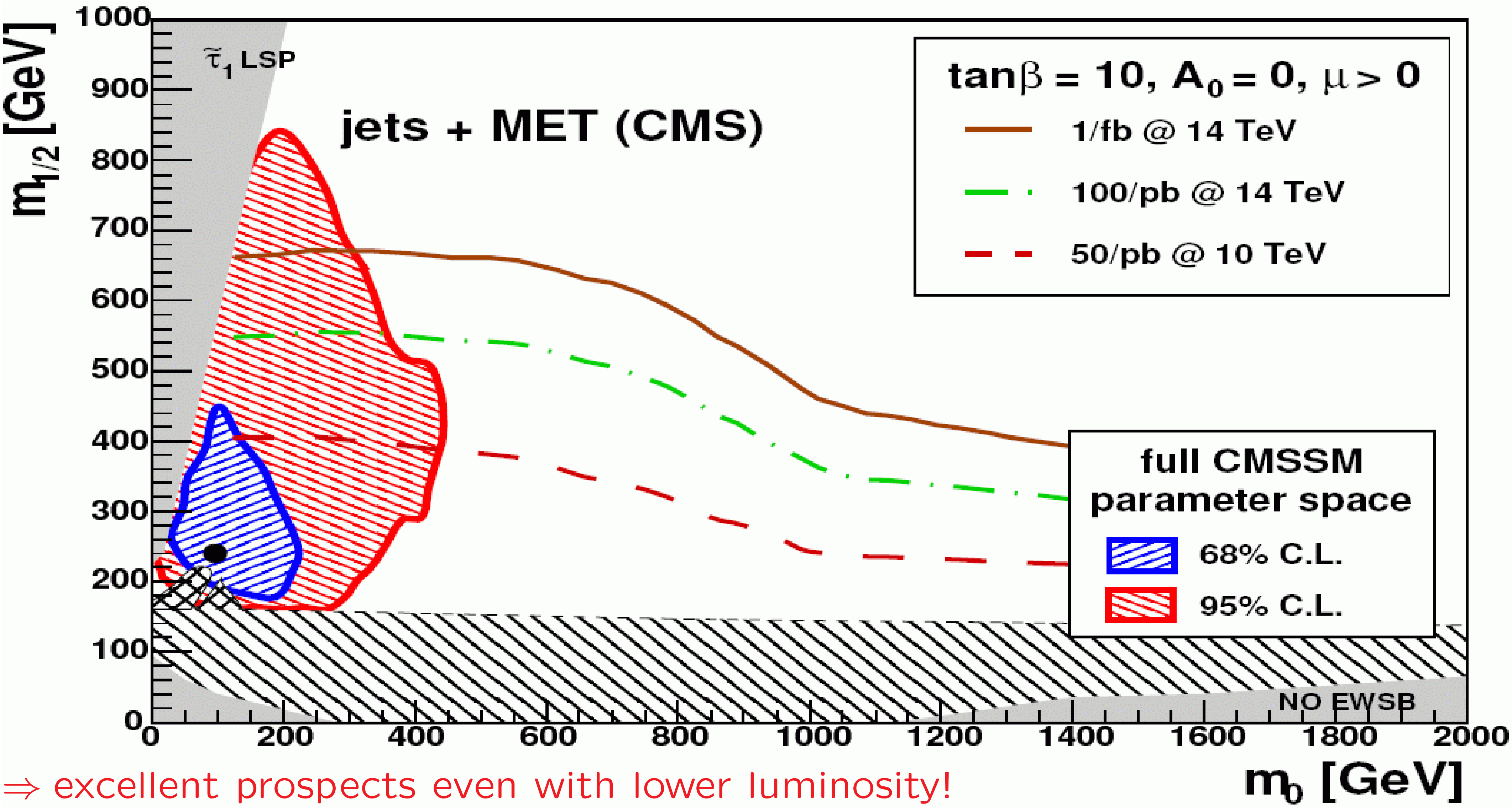


⇒ excellent prospects in various channels!

LHC (CMS) ⊕ NUHM1 analysis:

[*CMS '07*]

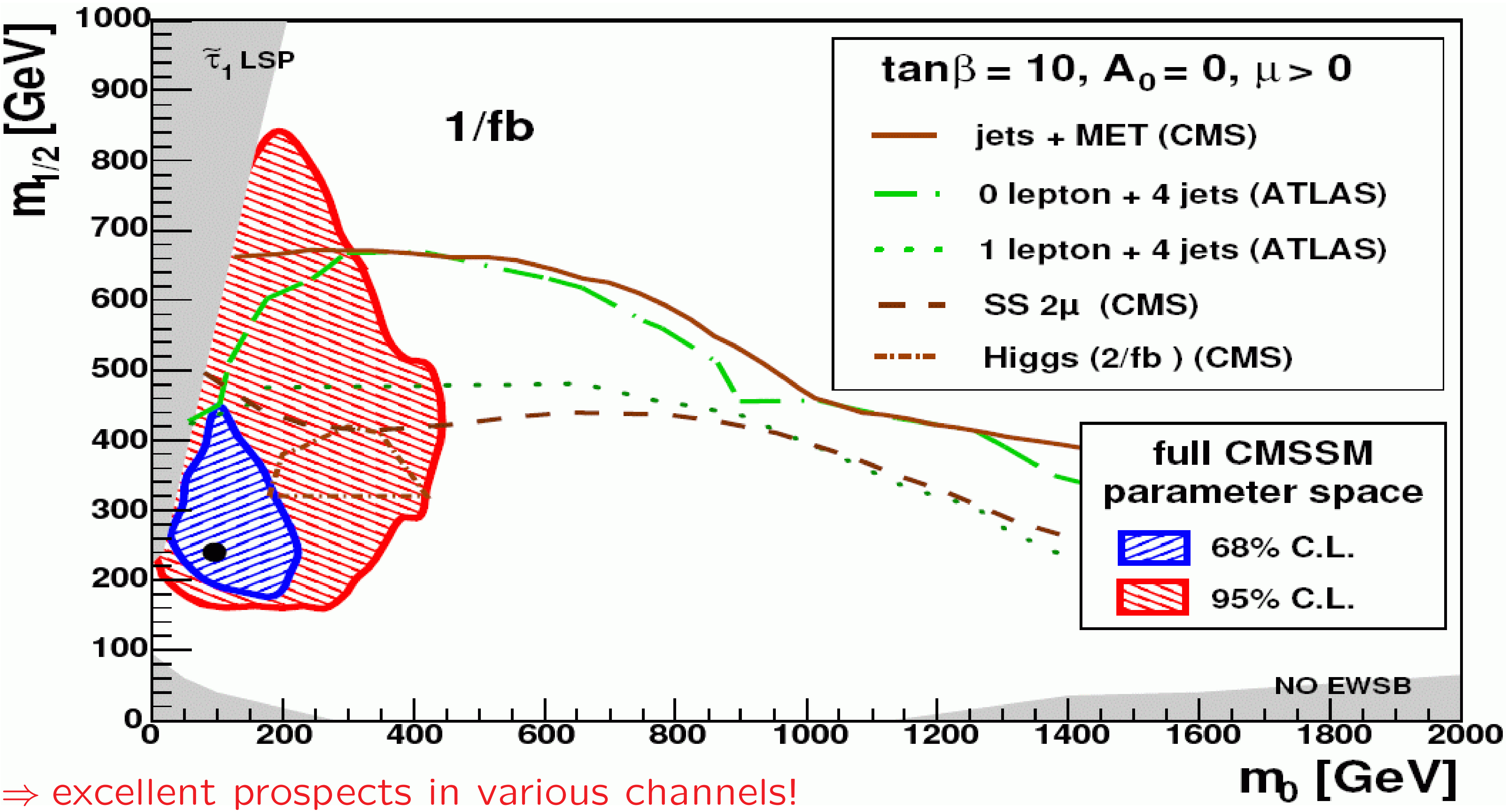
[*2008*]



$\Rightarrow$ excellent prospects even with lower luminosity!

LHC (CMS) reach with 1 fb^{-1}: NUHM1 analysis

[*MasterCode '08*] [*CMS '07*]

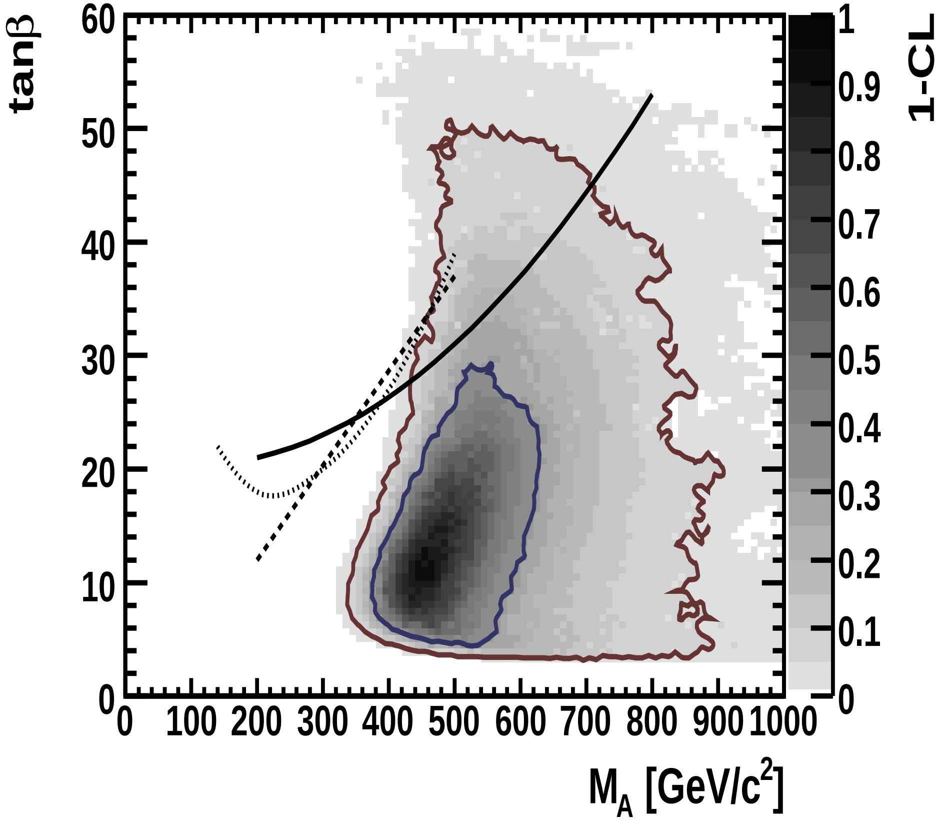


⇒ excellent prospects in various channels!

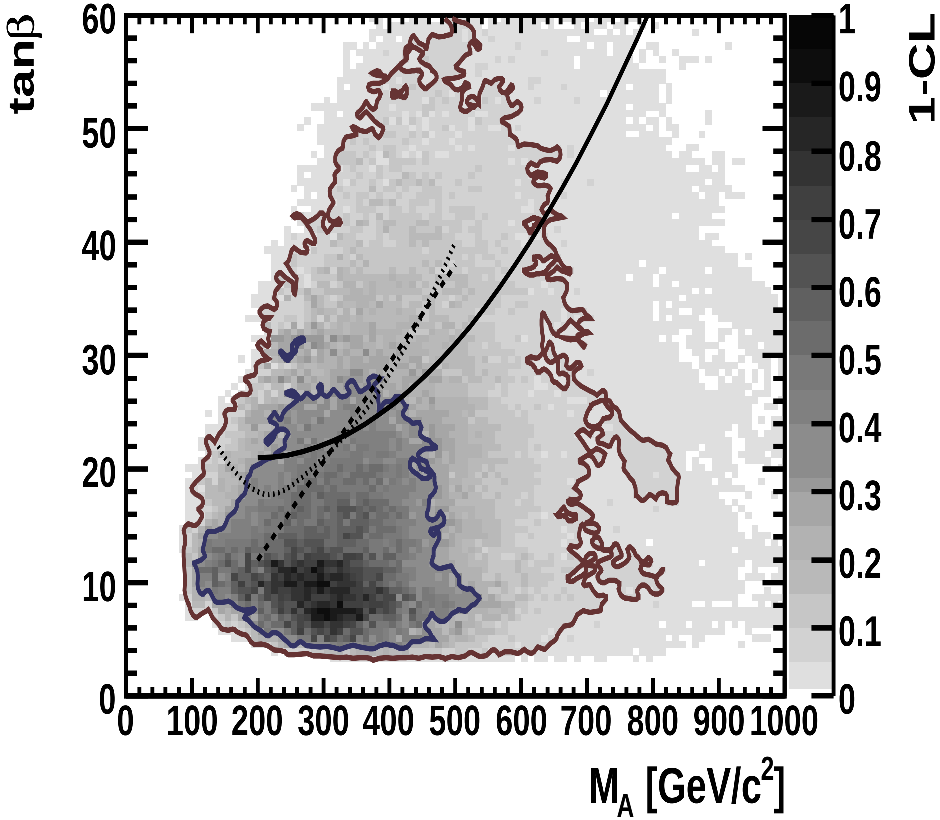
Some more predictions: preferred M_A–$\tan\beta$ parameter space

[2009]

CMSSM



NUHM1



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