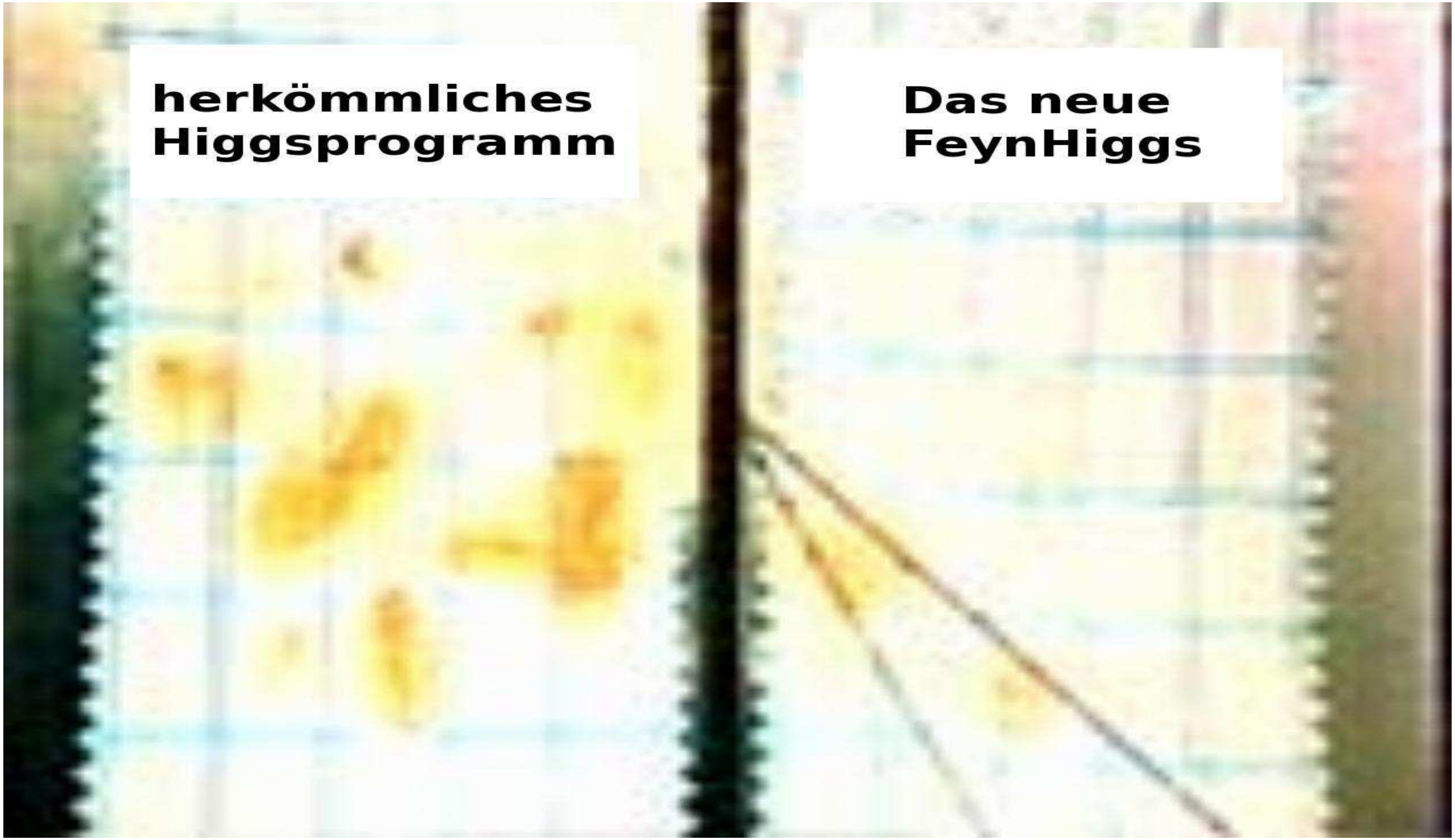

herkömmliches
Higgsprogramm
Das neue
FeynHiggs

SUSY Prediction for the LHC and the ILC

Sven Heinemeyer, IFCA (CSIC, Santander)

Bonn, 08/2010

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 LHC/ILC
4. Conclusions

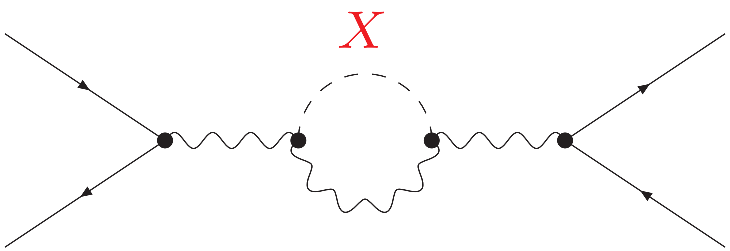
1. Introducion: How to make a prediction?

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



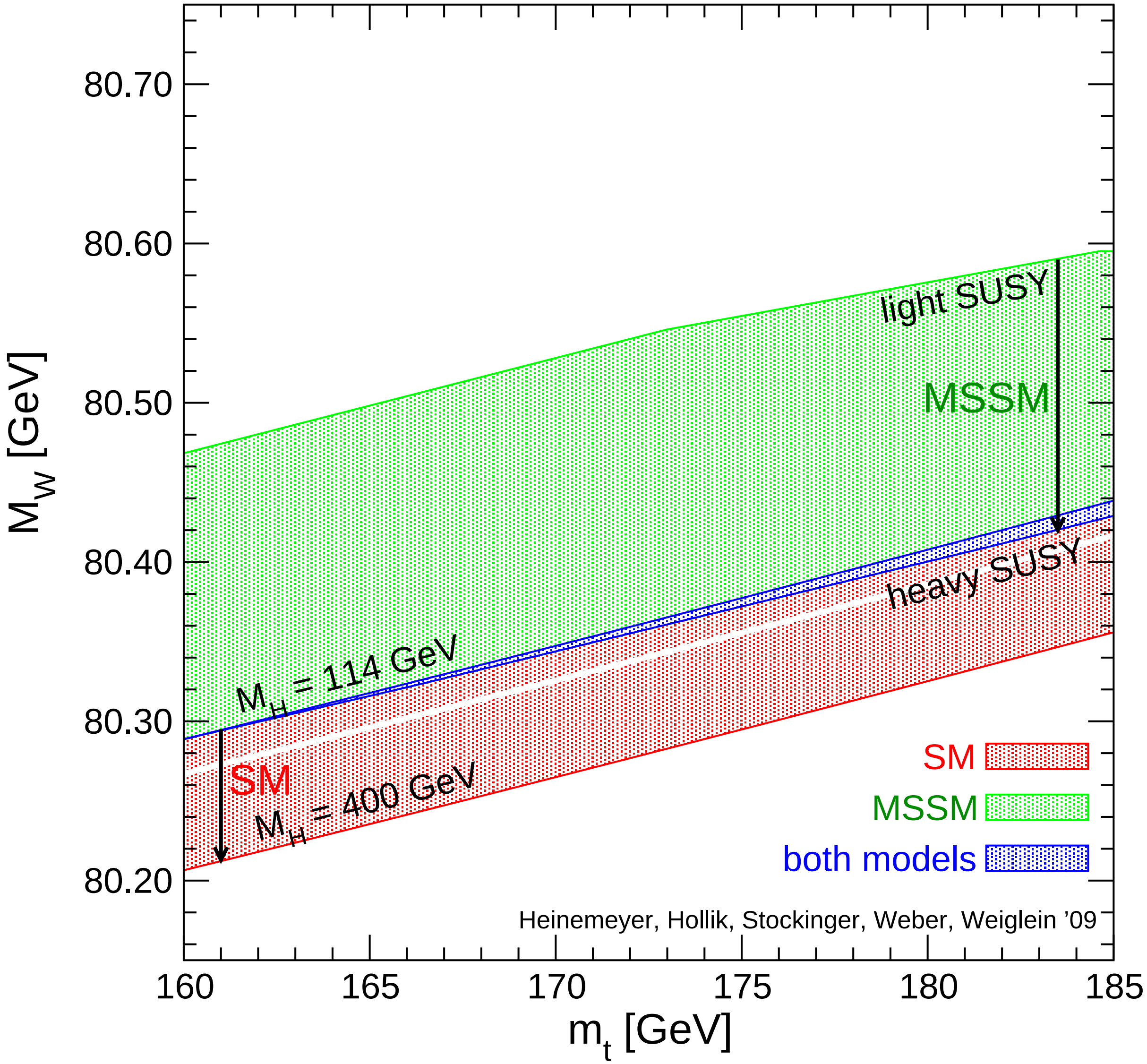
$\Downarrow$

$\Rightarrow$ 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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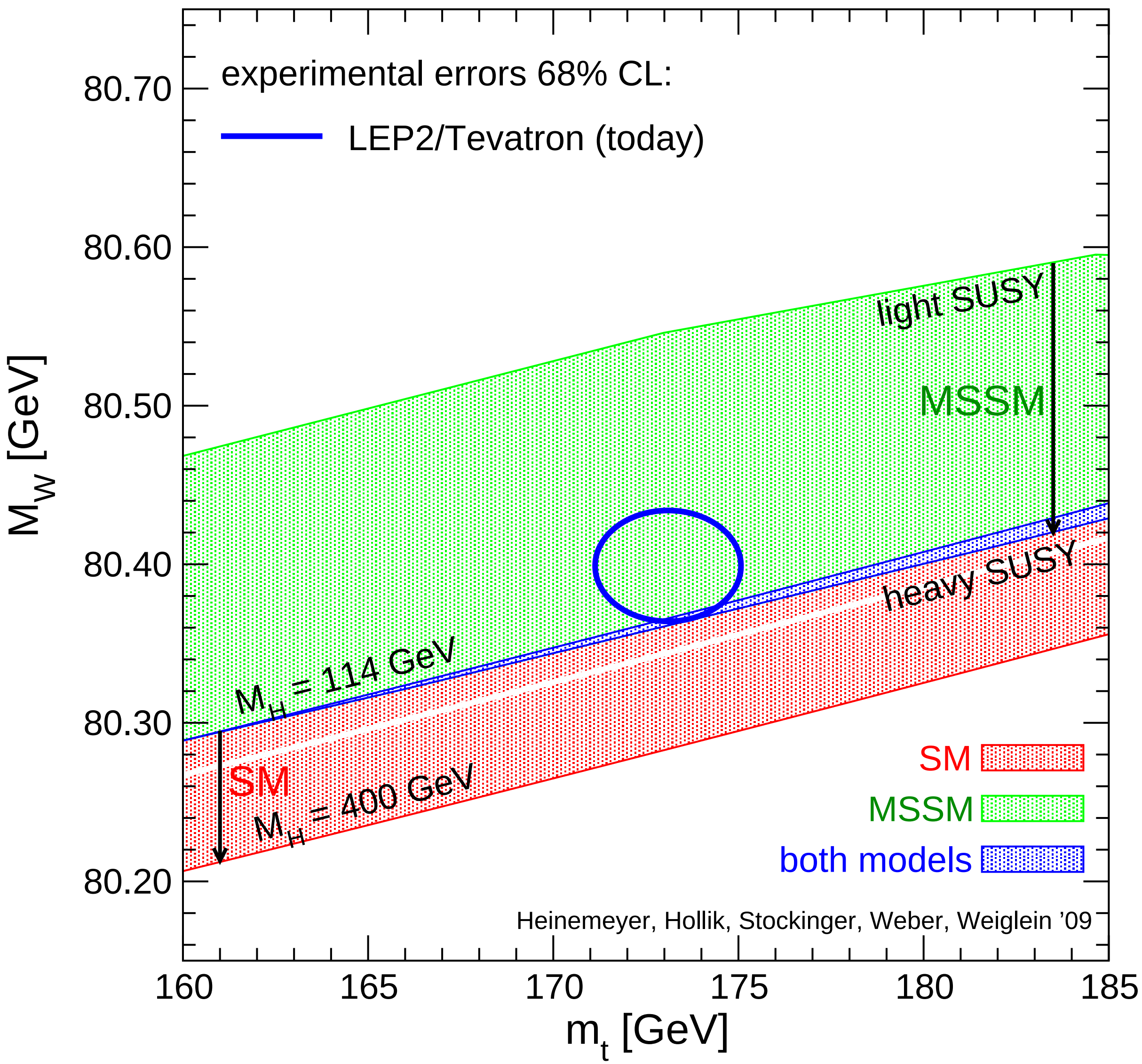

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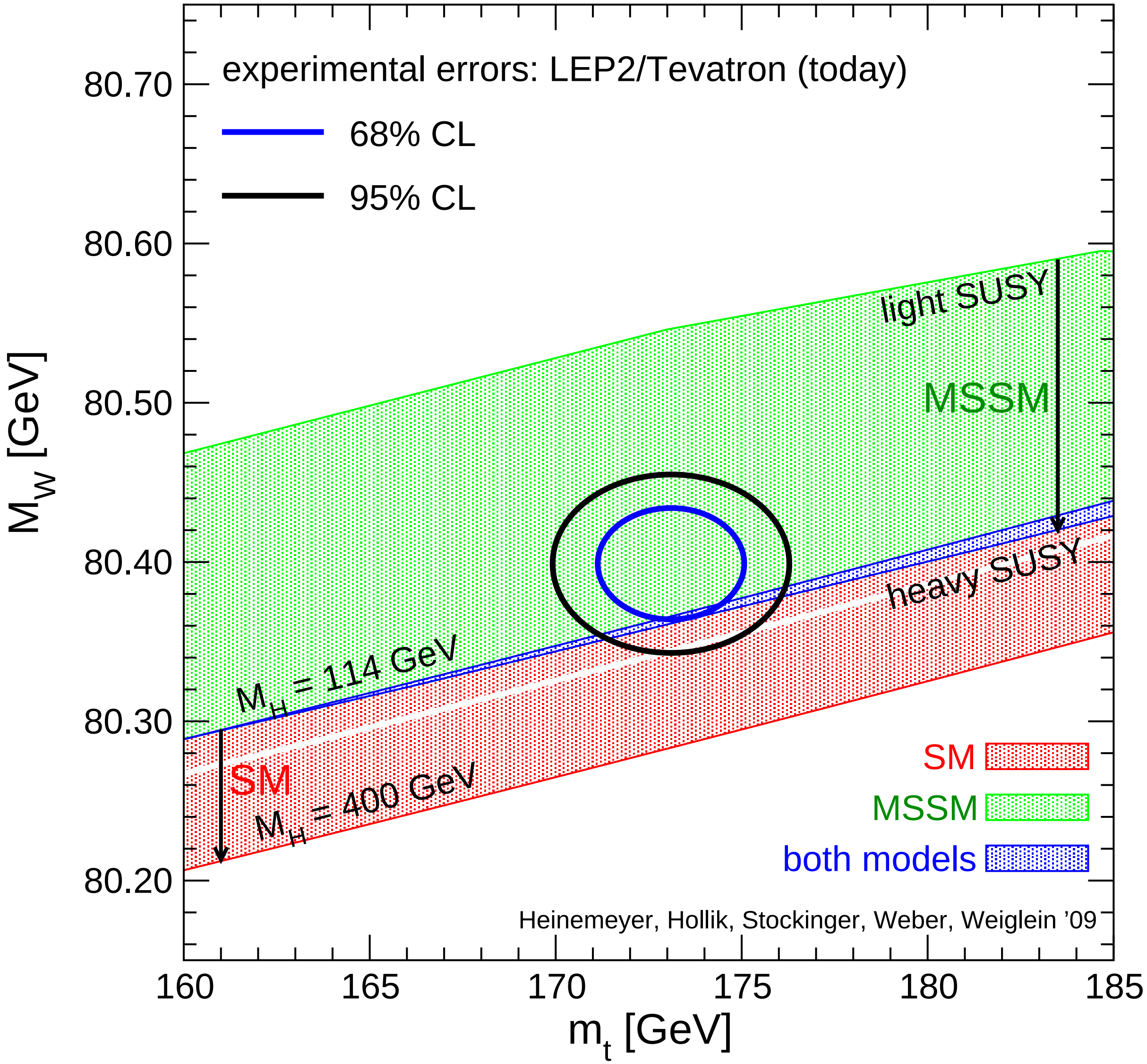

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scan over
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MSSM is SM-like

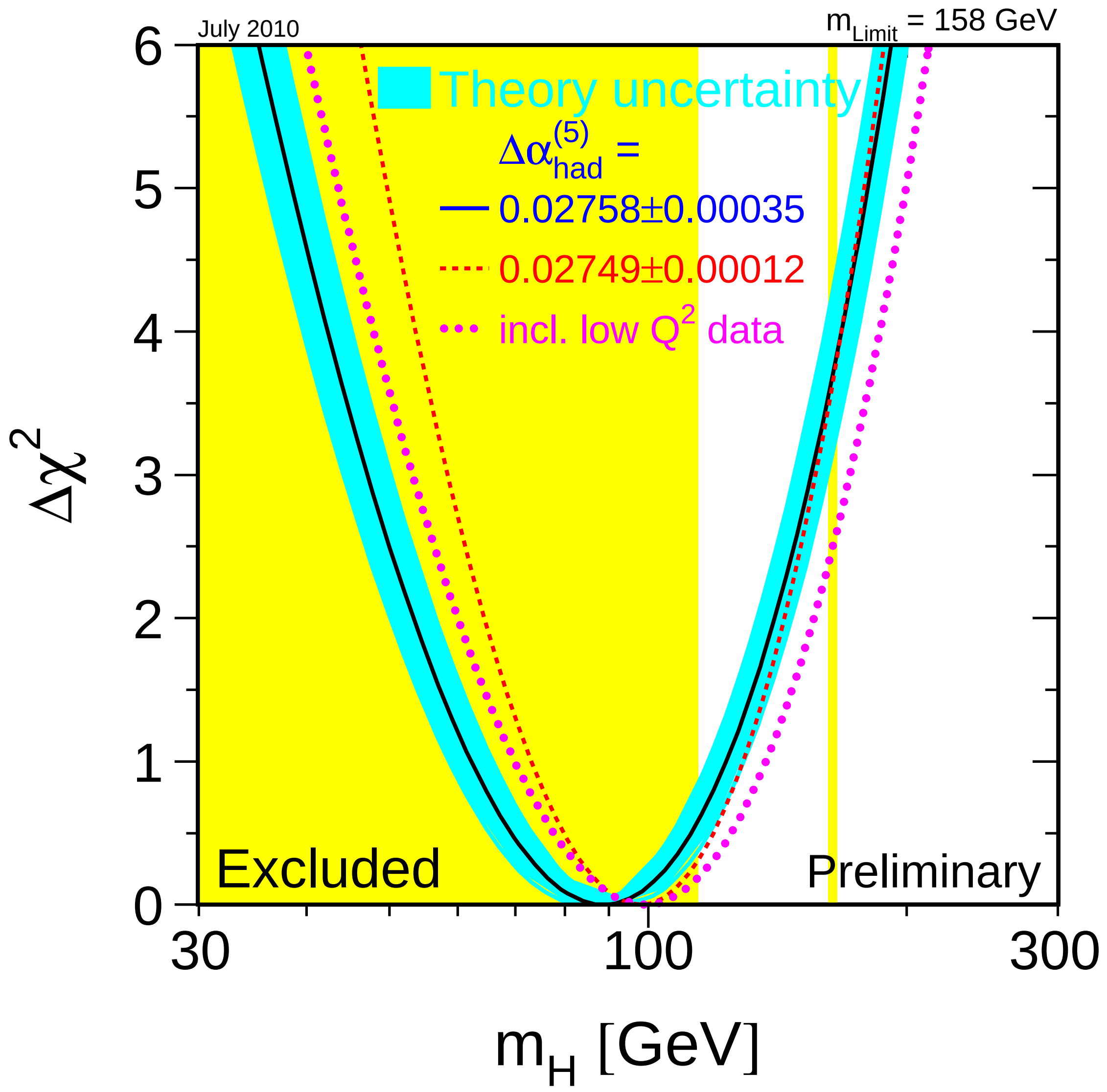
SM band:
variation of M_H^{SM}

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

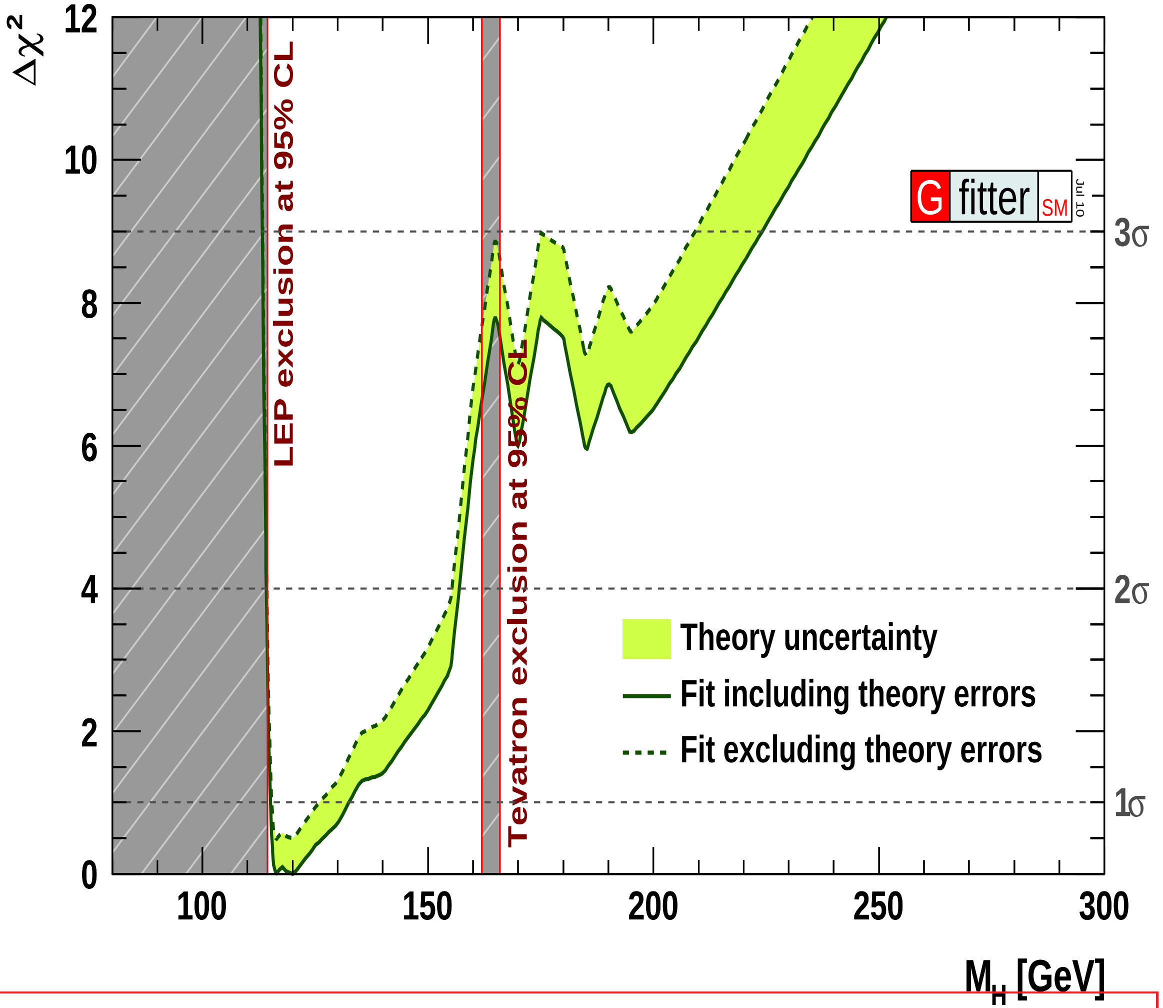
$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 160$ GeV

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

$\Rightarrow$ no confirmation of Higgs mechanism

$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 150$ 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 $\Rightarrow$ LHC/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*]

⇒ 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!

- added: χ^2 analysis code *[Minuit]*

- currently being implemented:
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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 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)

⇒ MasterCode: multi-dim scans with MCMC technique

2.) Fitting:

– Frequentist
– Bayesian

⇒ MasterCode: Frequentist

⇒ 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
- . . .

In general:

The MasterCode can perform fits in the (MFV) MSSM

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However:

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

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

⇒ analyses exist already, to be shown here

⇒ analyses currently performed, to be shown at SUSY11

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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P_i: MSSM parameter-dependent prediction for the corresponding constraint

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

→ especially important: M_h

→ backup

3. Predictions for the LHC and 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, $\Delta\alpha_{\text{had}}$

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

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

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

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

NUHM1:

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

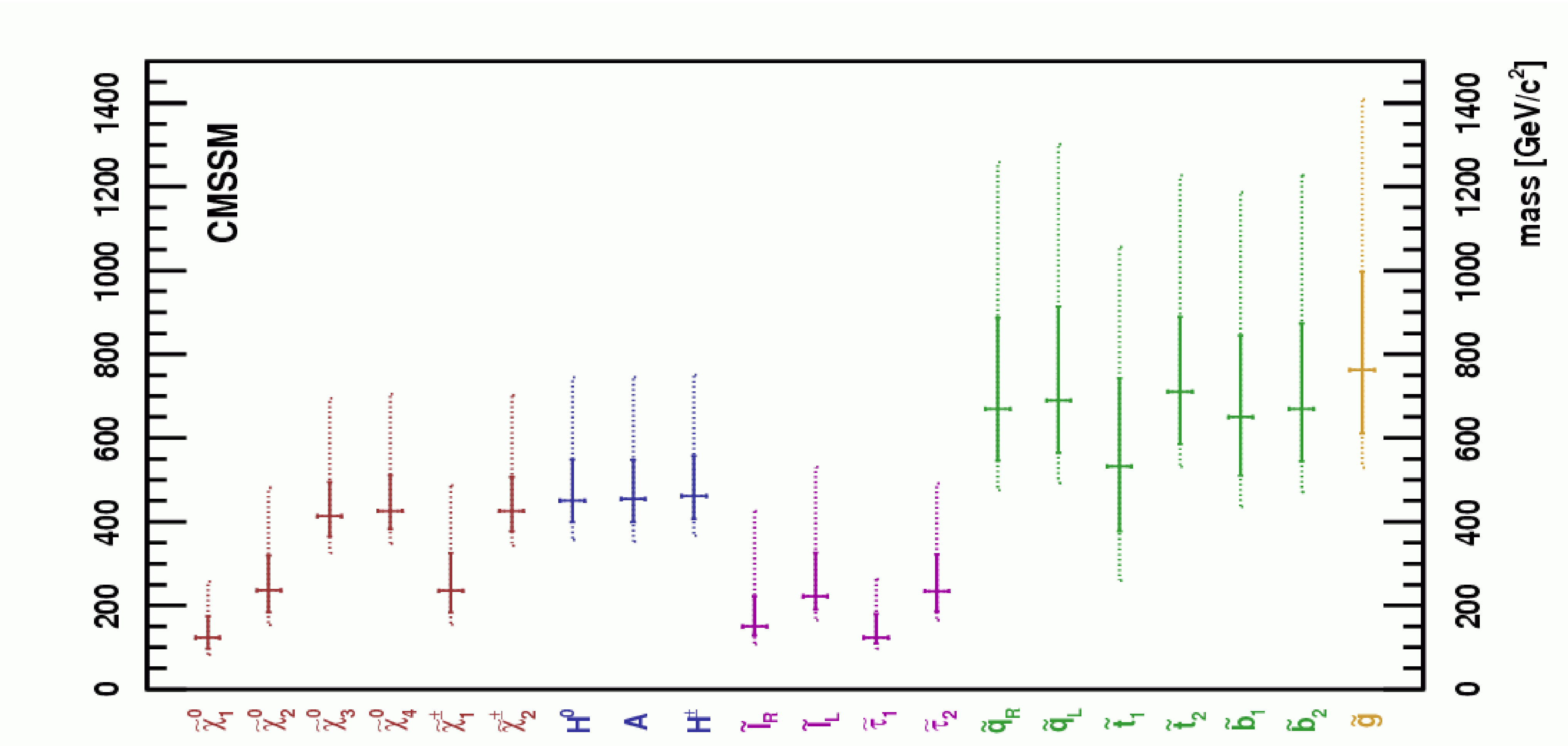
$\tan\beta = 11$, $\mu = 1140$ GeV, $M_A = 310$ GeV

(similar probability)

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

Masses for best-fit points: CMSSM

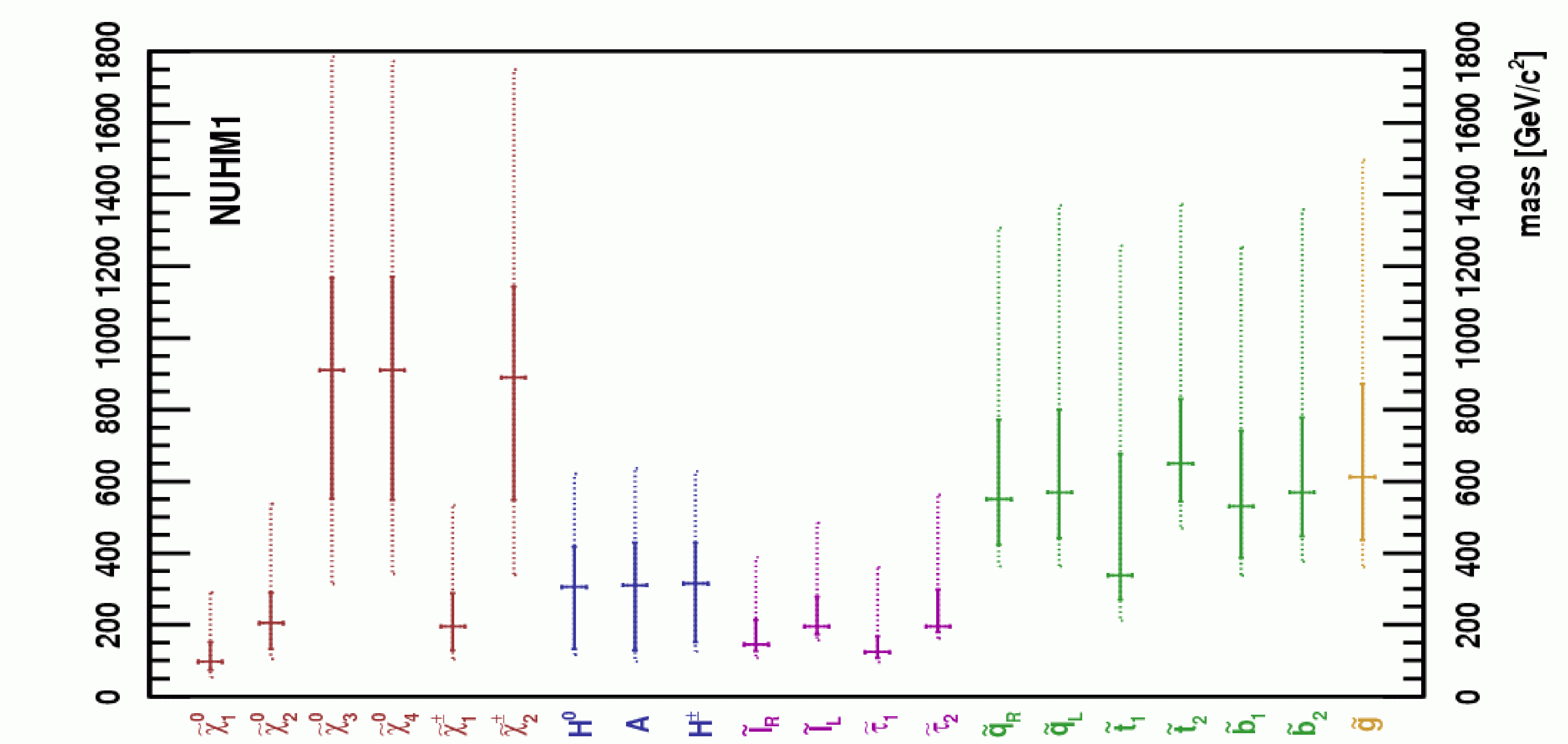
[2009]



⇒ largely accessible spectrum for LHC (and ILC)

Masses for best-fit points: NUHM1

[2009]



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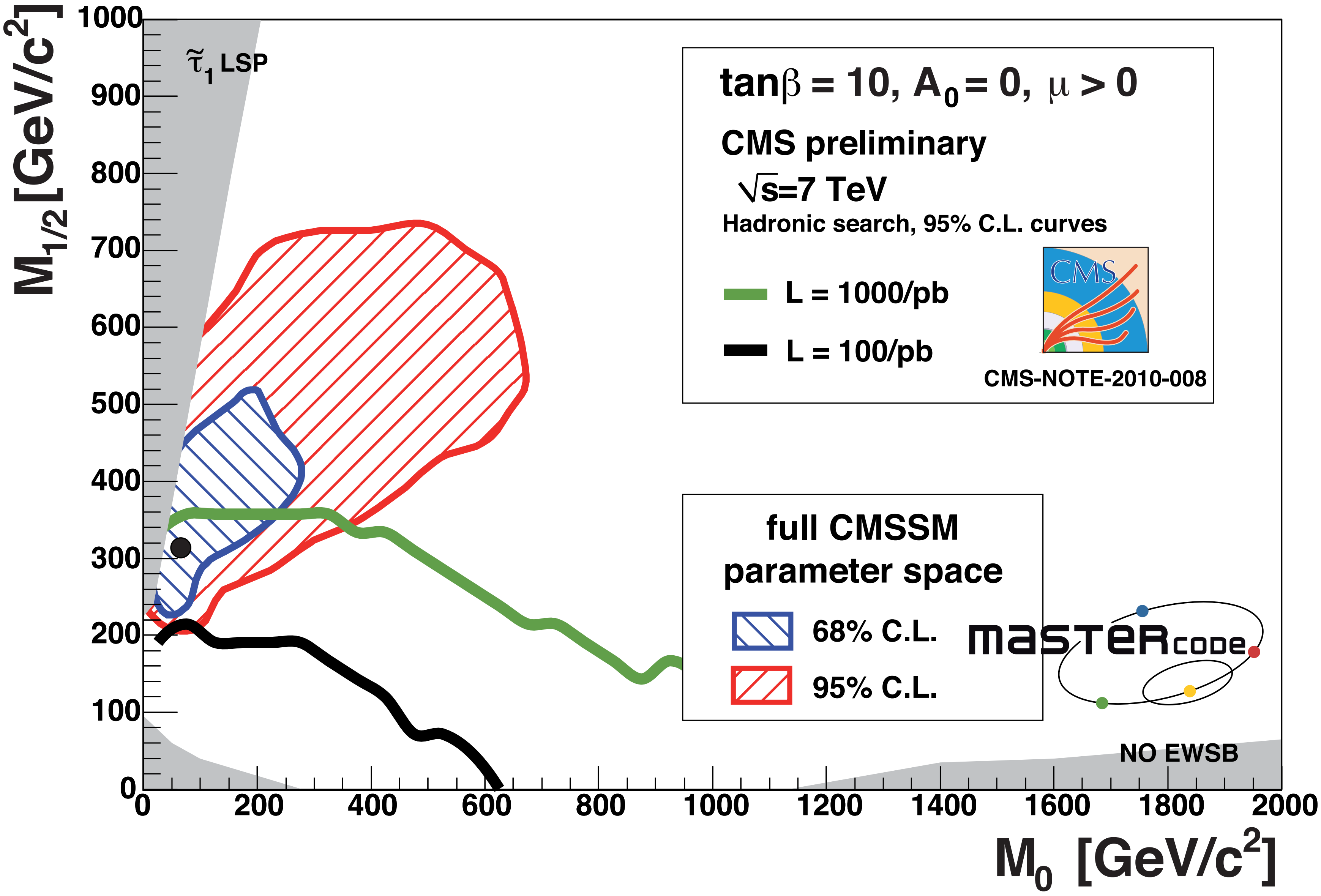
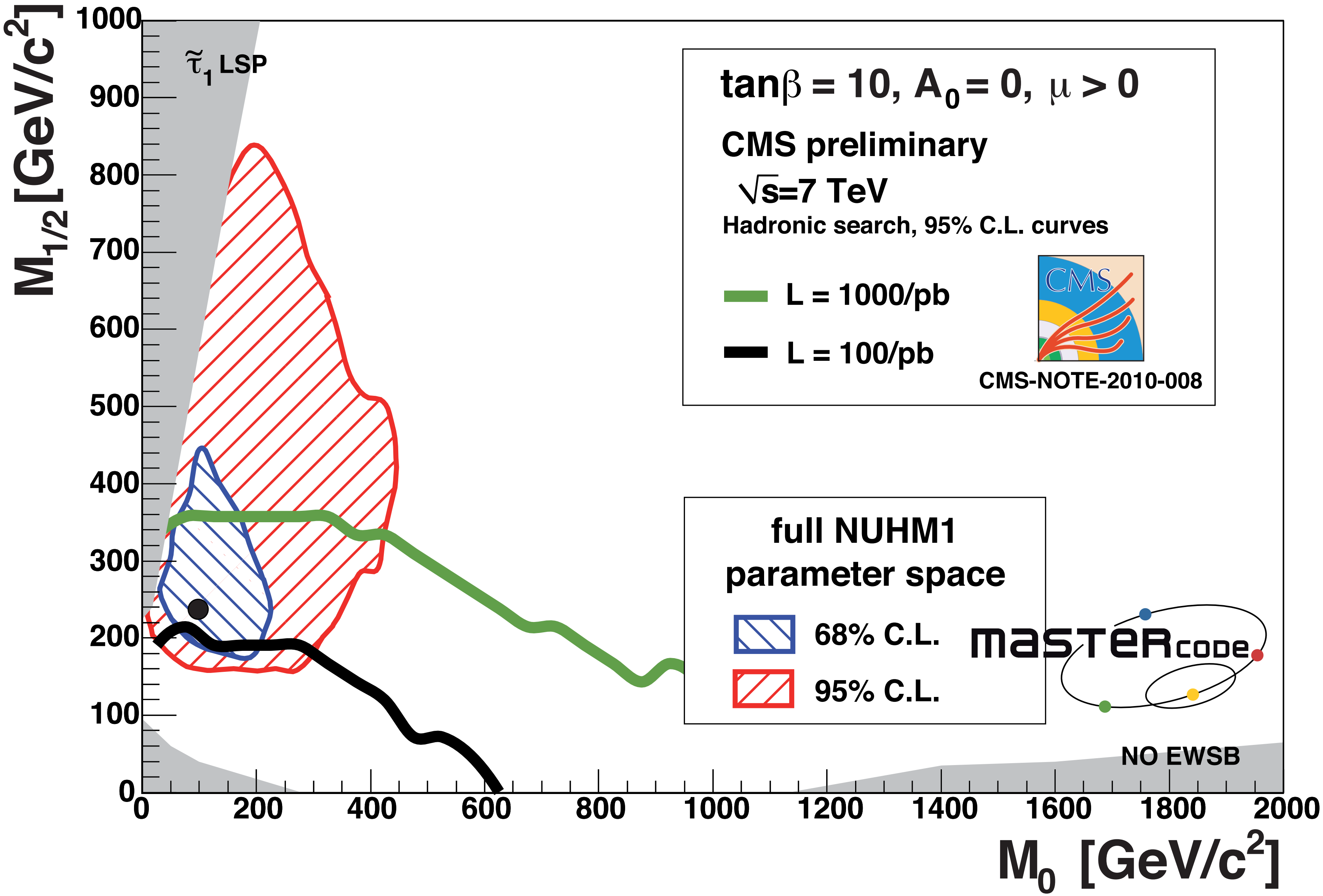
LHC (CMS) $\oplus$ CMSSM analysis:



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

LHC (CMS) ⊕ NUHM1 analysis:

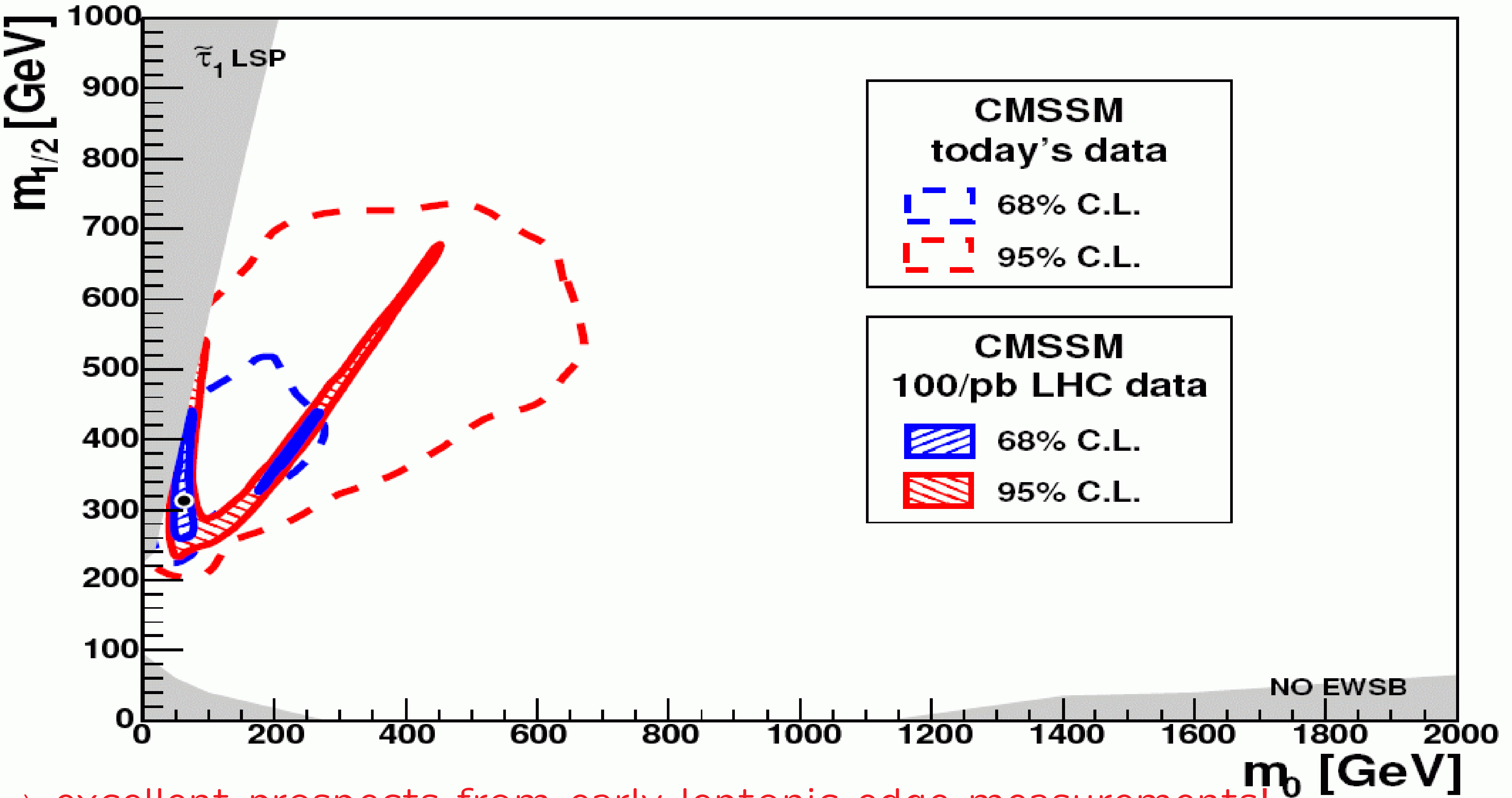


⇒ best-fit point and part of 68% C.L. are can be tested in 2011

LHC (CMS) ⊕ CMSSM analysis:

[2008]

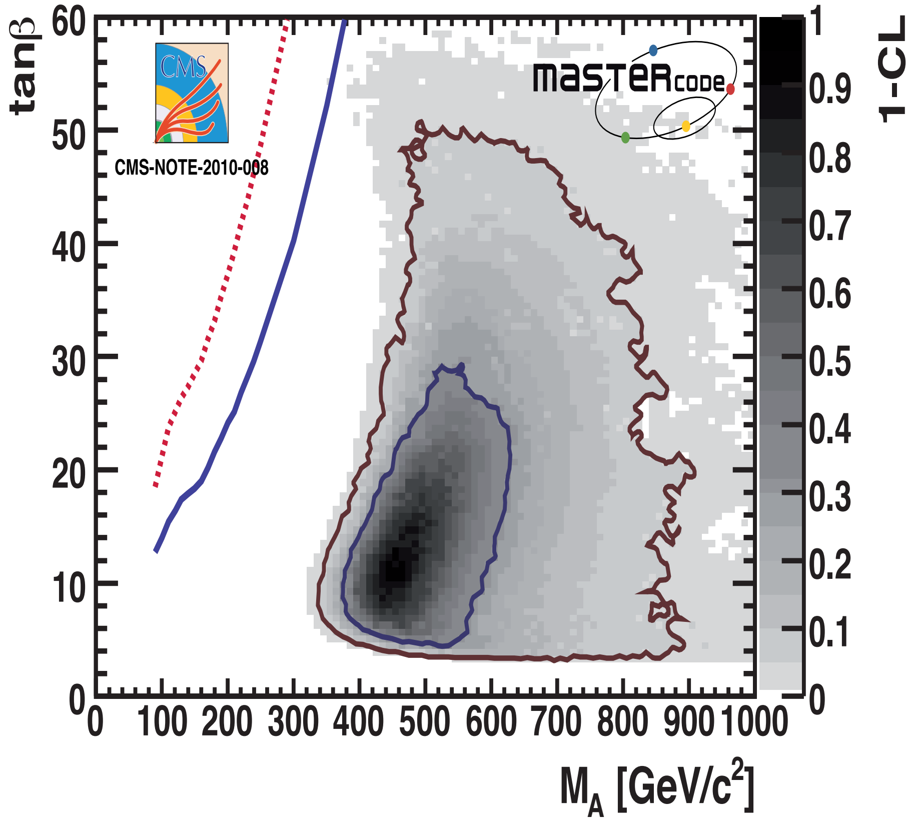
reach with 1 fb^{-1} @ 14 TeV incl. leptonic edge measurements



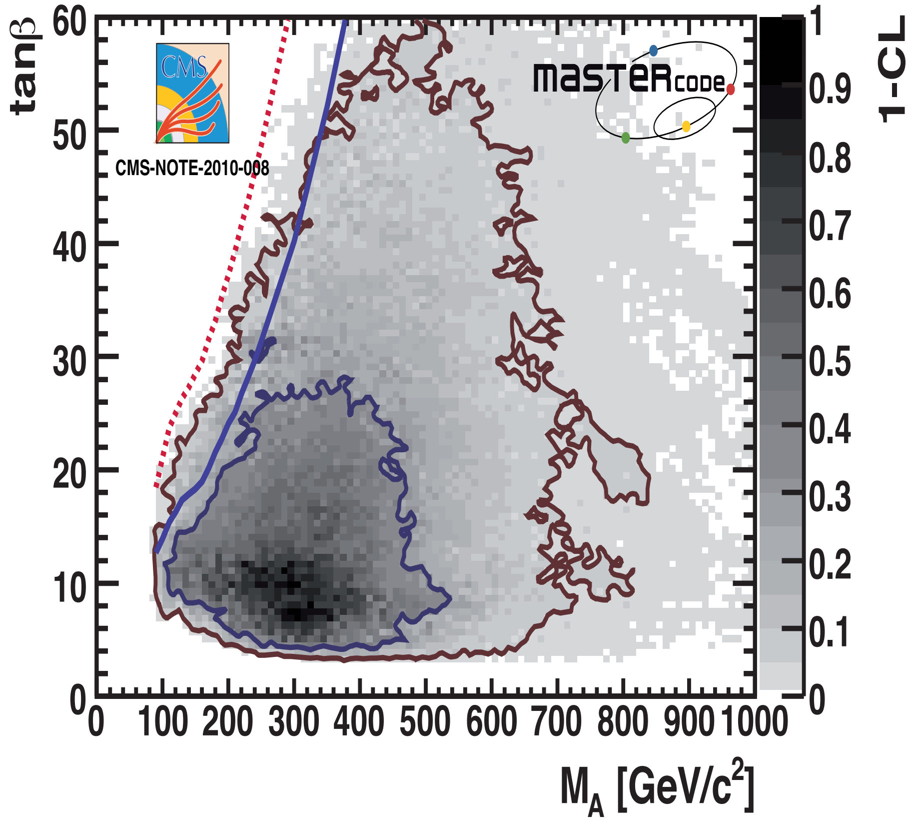
⇒ excellent prospects from early leptonic edge measurements!

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

CMSSM



NUHM1

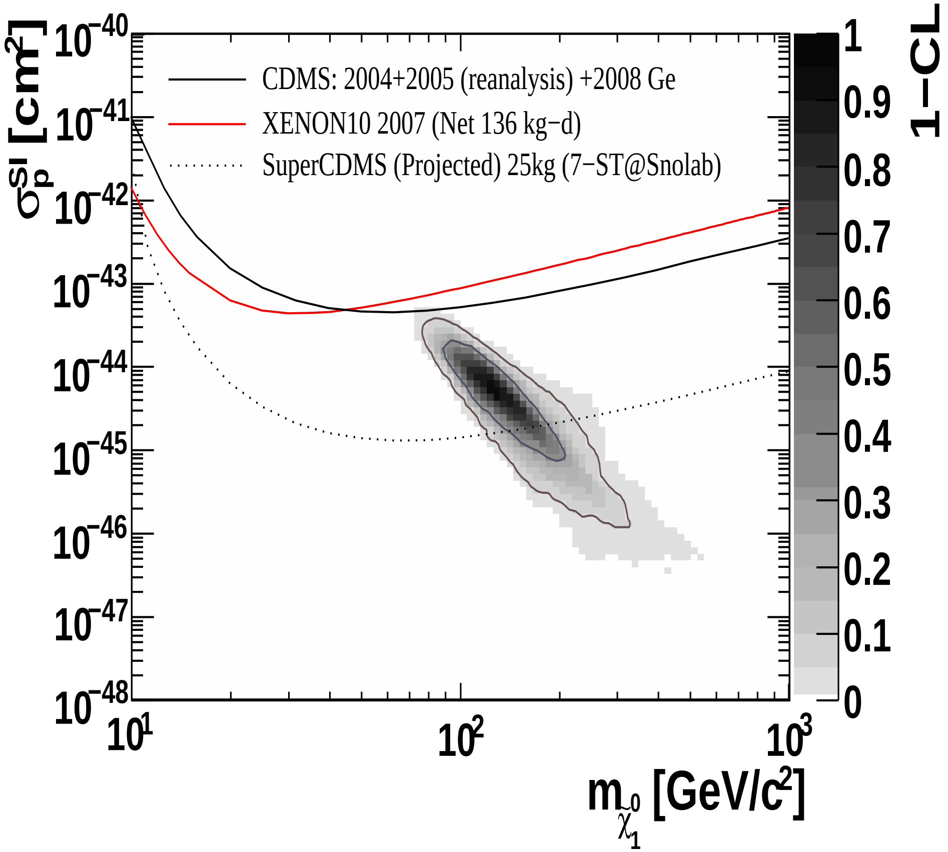


red dotted: discovery with 1 fb^{-1} @ 7 TeV
blue solid: 95% C.L. exclusion with 1 fb^{-1} @ 7 TeV

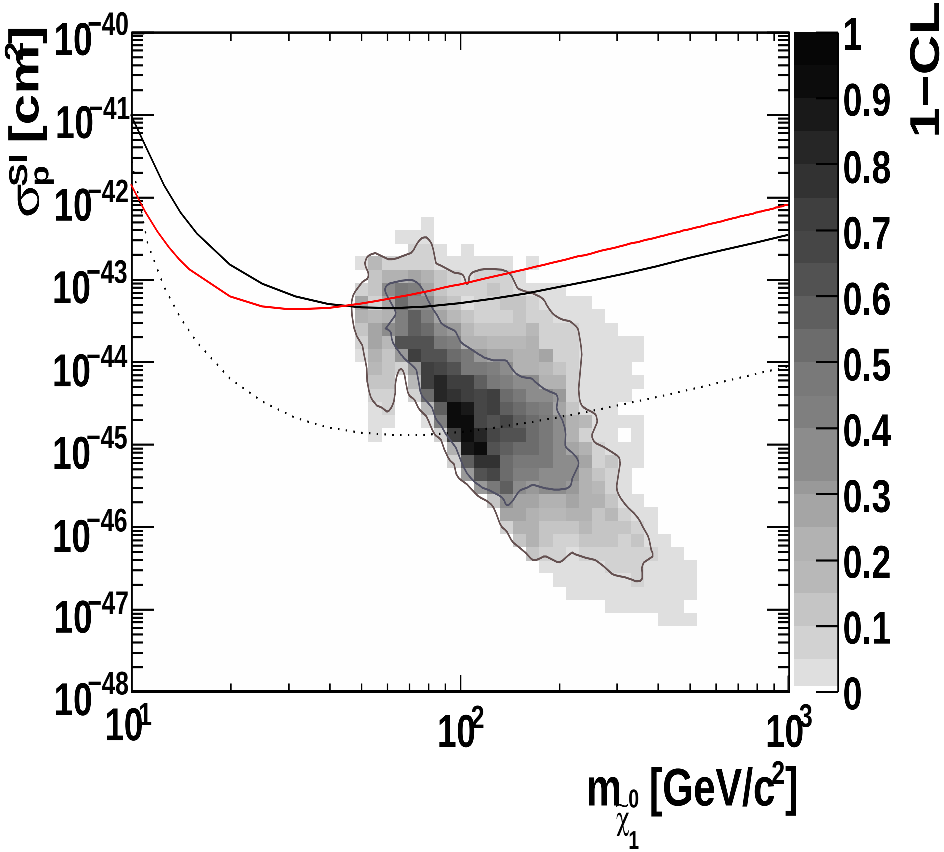
⇒ preferred regions missed in 2010-2011 run

[2009]

CMSSM



NUHM1

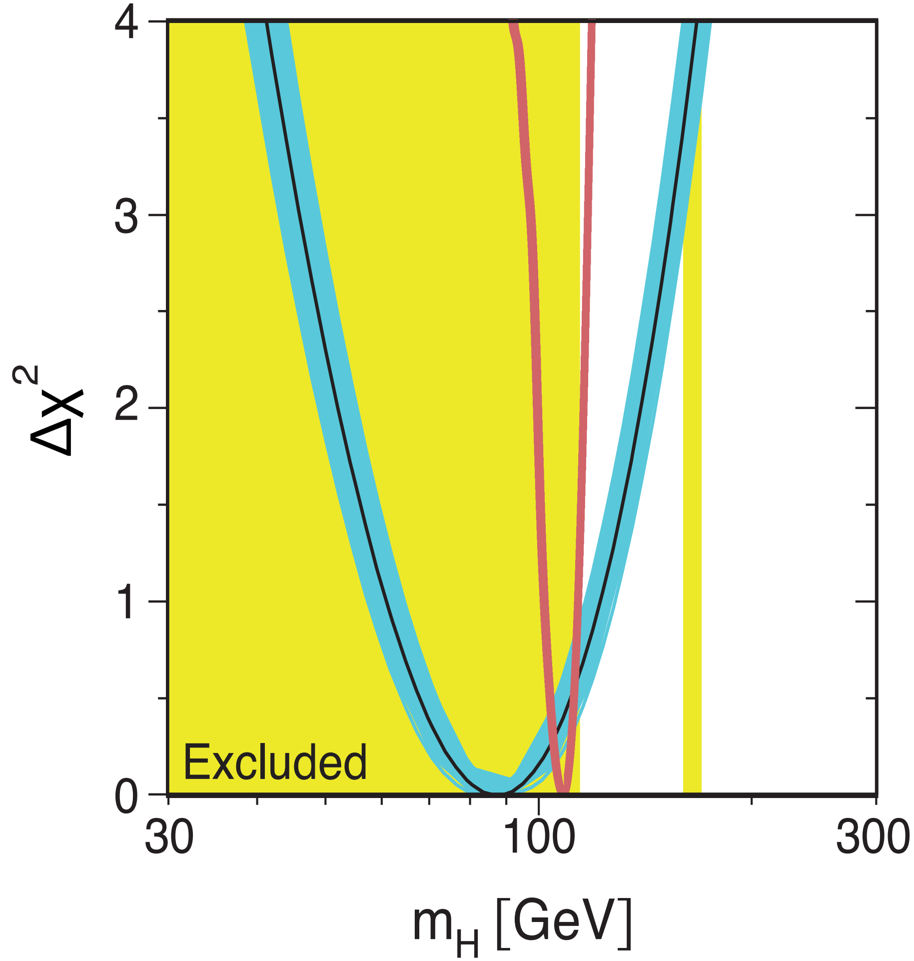


⇒ only partially covered by future experiments

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

[2009]

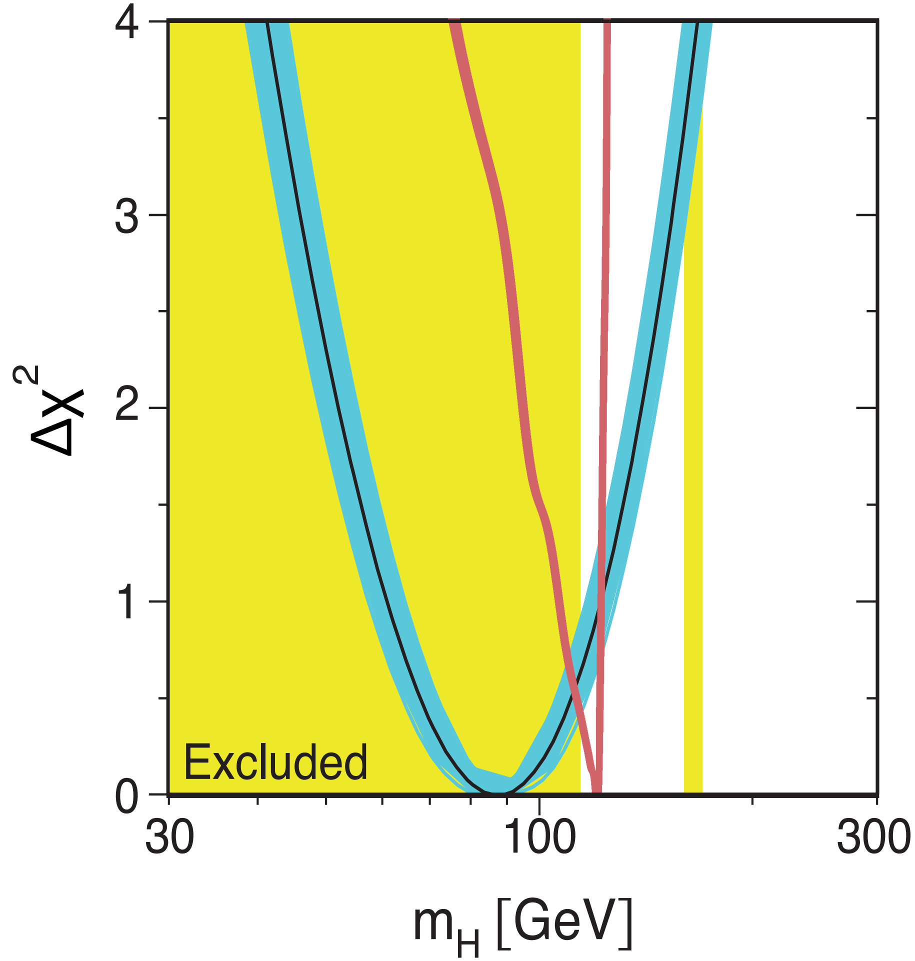
CMSSM



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

$\Rightarrow$ as good as the SM

NUHM1



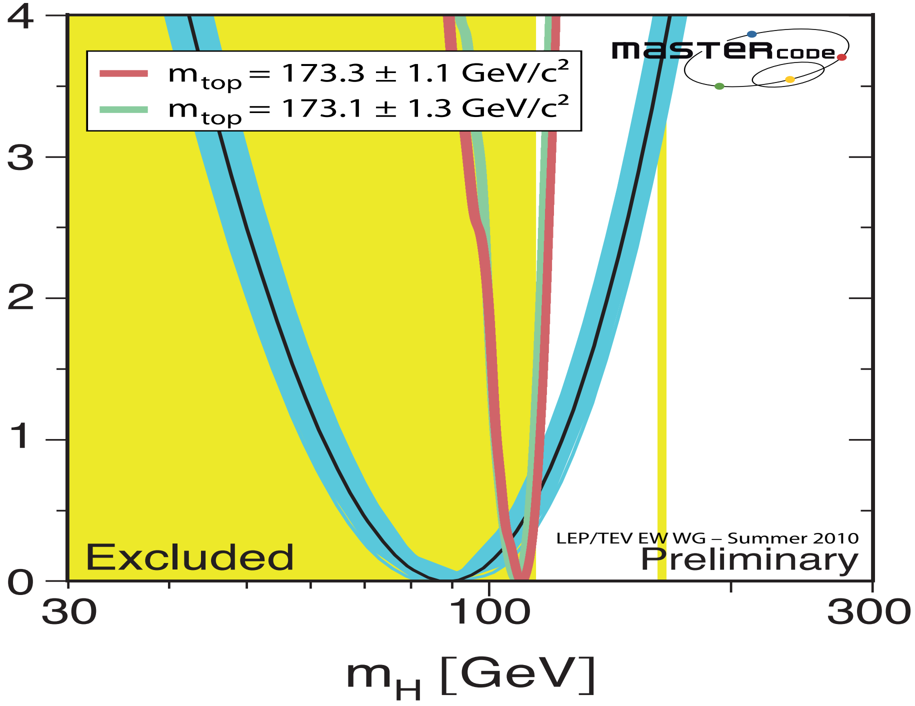
$M_h^{\rm NUHM1} = 121^{+1}_{-14} \pm 1.5$ GeV

$\Rightarrow$ above the LEP limit

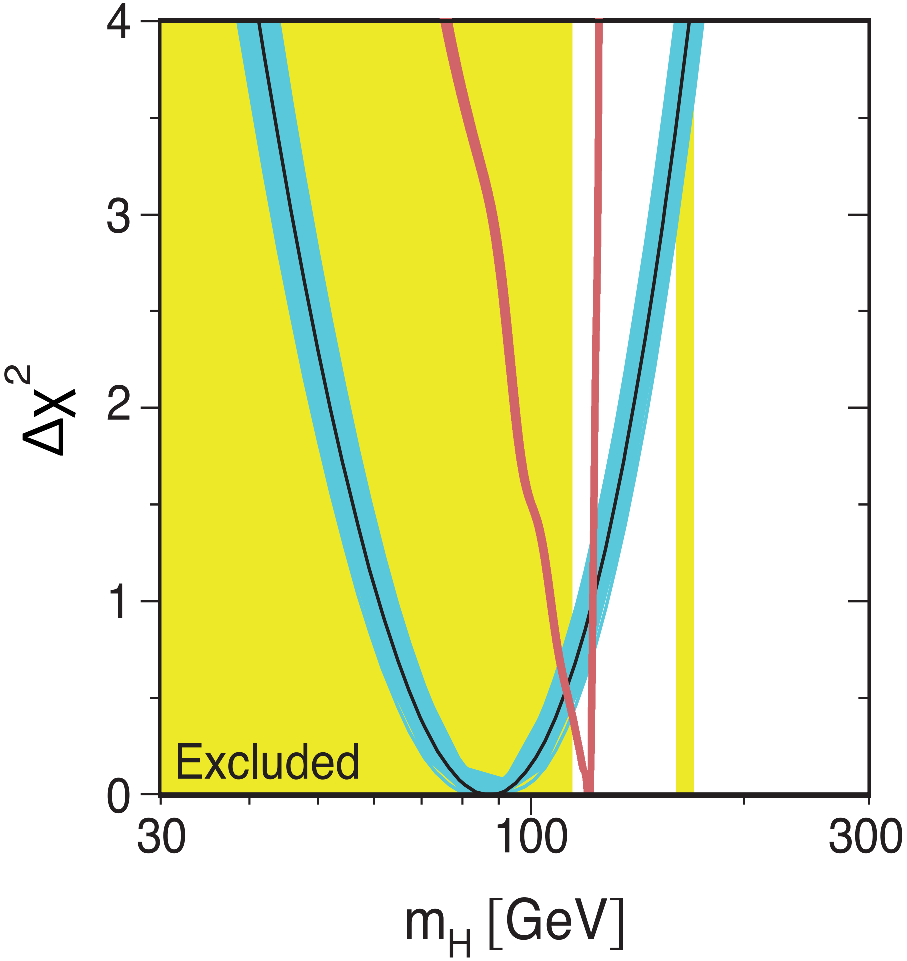
Prediction of $M_H^{\rm SM}$ (blue band) and M_h in the MSSM (red band):

[2010]

CMSSM



NUHM1



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

$\Rightarrow$ as good as the SM

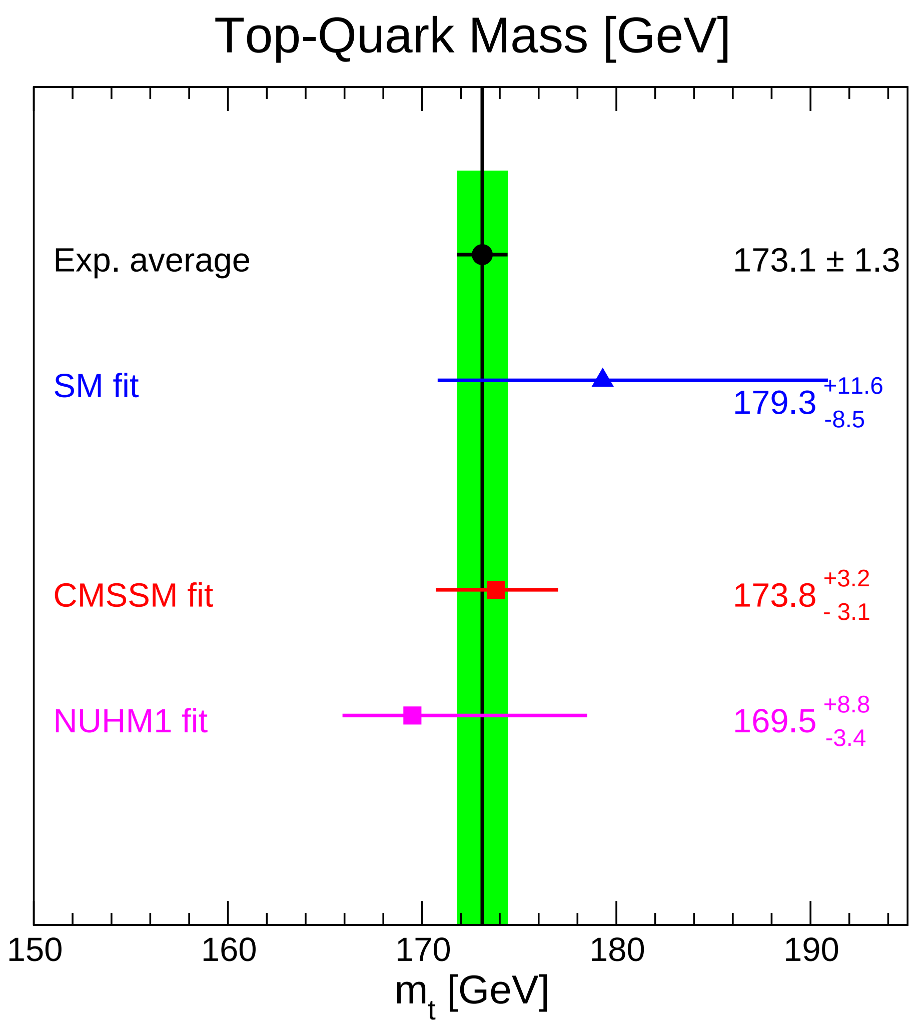
$M_h^{\rm NUHM1} = 121^{+1}_{-14} \pm 1.5$ GeV

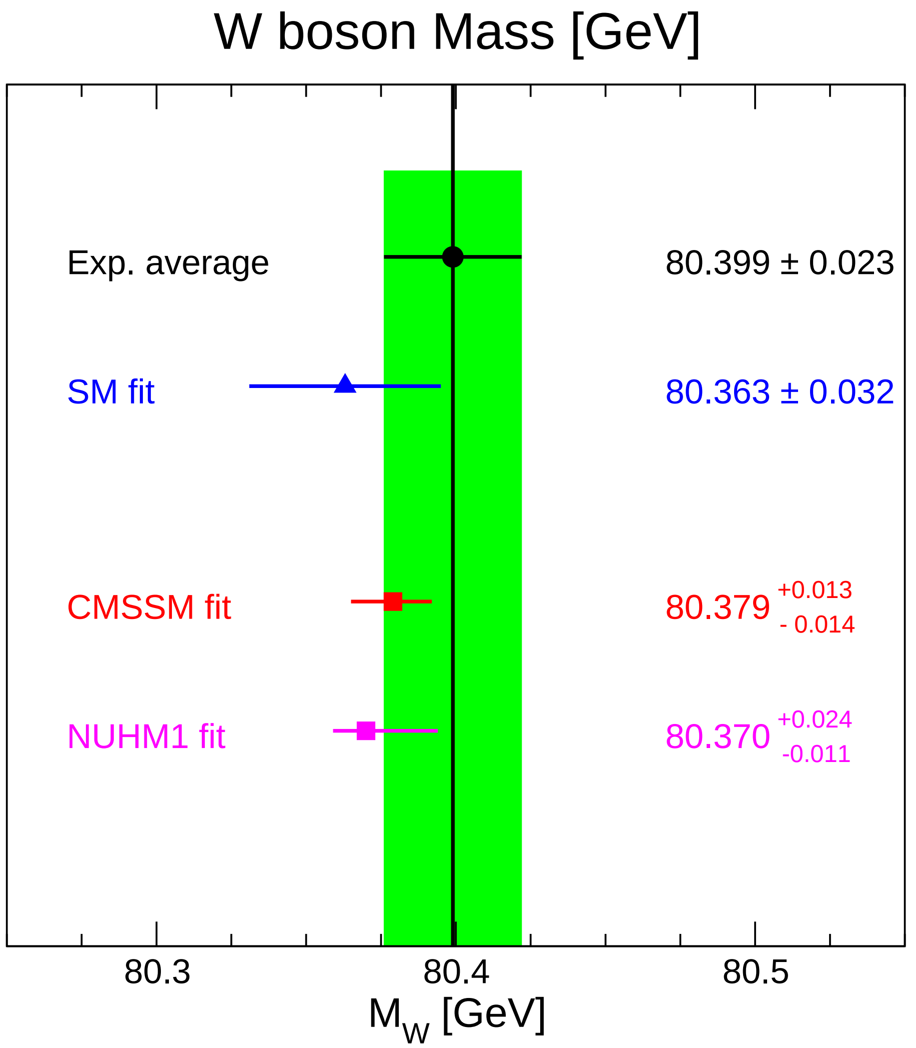
$\Rightarrow$ above the LEP limit

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

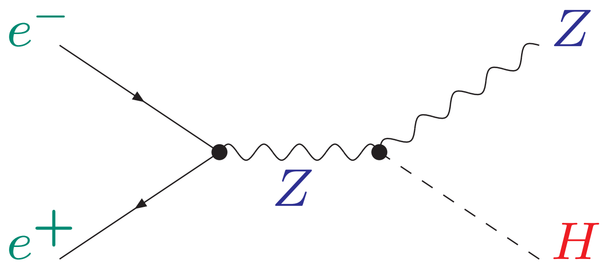

Higgs Days at Santander 2010
Theory meets Experiment
13.-16. October
HEPTOOLS
IFCA
Instituto de Física de Cantabria
CSIC
UC
UNIVERSIDAD DE CANTABRIA
contact: Sven.Heinemeyer@cern.ch
http://www.ifca.es/HDays10
Photo: Philip Bechtle HDays09

Back-up

SM Higgs search at LEP:

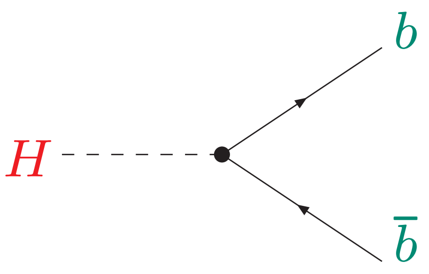
Dominant SM production process:

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



Dominant decay process:

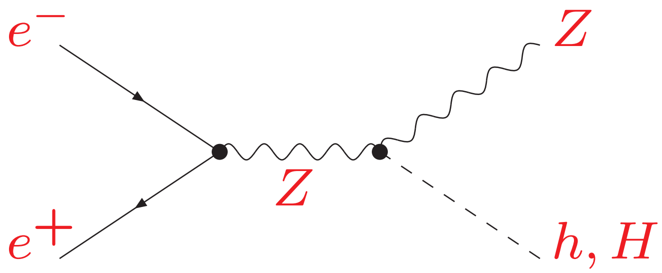
$H \to b\bar{b}$:



Bounds valid in the CMSSM? NUHM1? MSSM?

Search for neutral SUSY Higgs bosons:

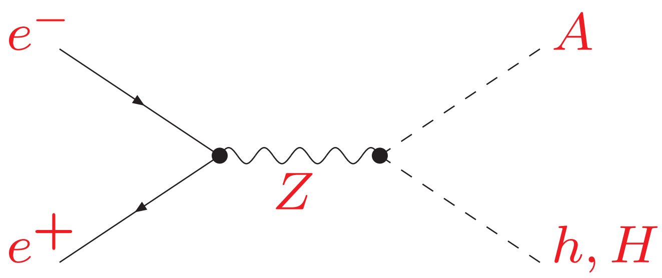
$e^+e^- \to Zh, ZH$



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

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

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

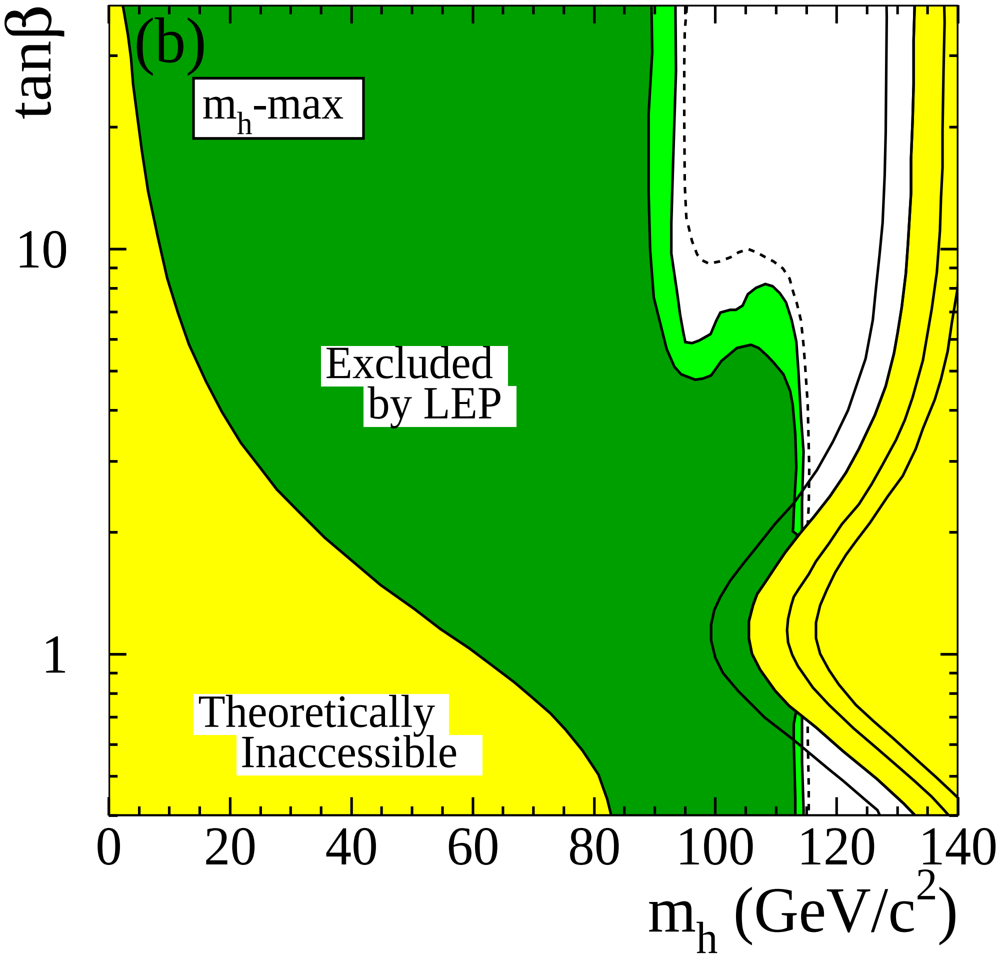


$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

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

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):



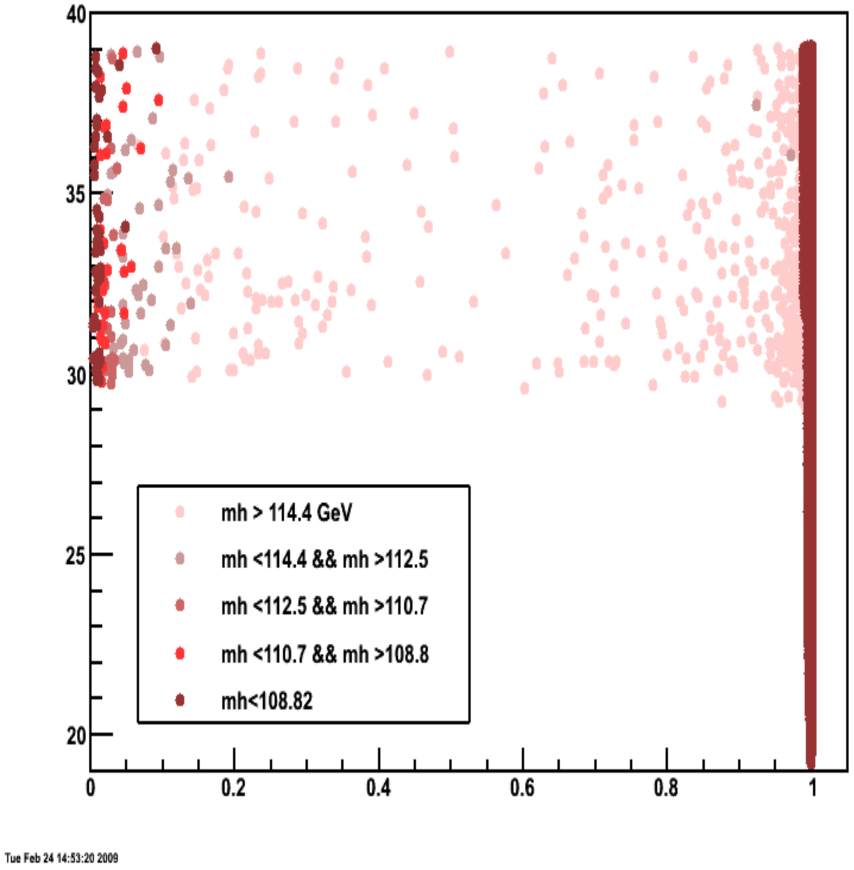
$m_h > 92.8$ GeV
(expected: 94.9 GeV), 95% C.L.

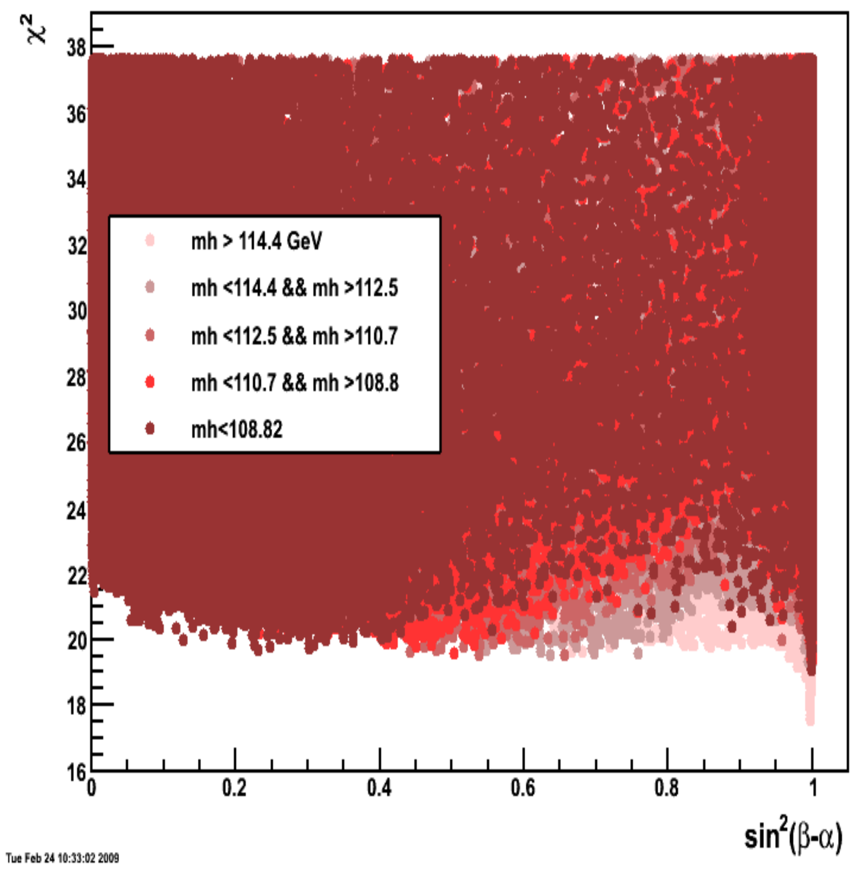
$M_A > 93.4$ GeV
(expected: 95.2 GeV)

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

CMSSM

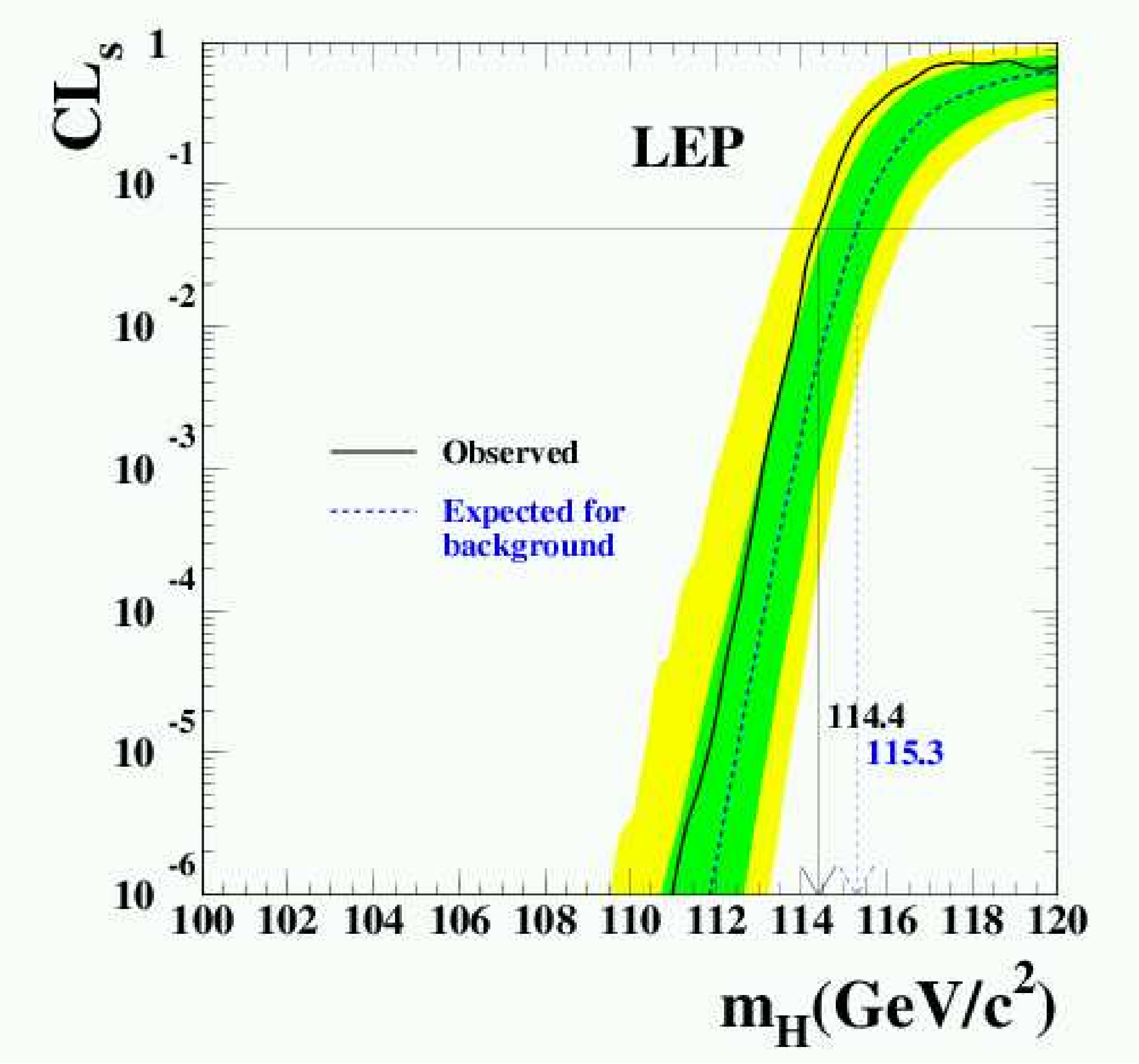
NUHM1





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

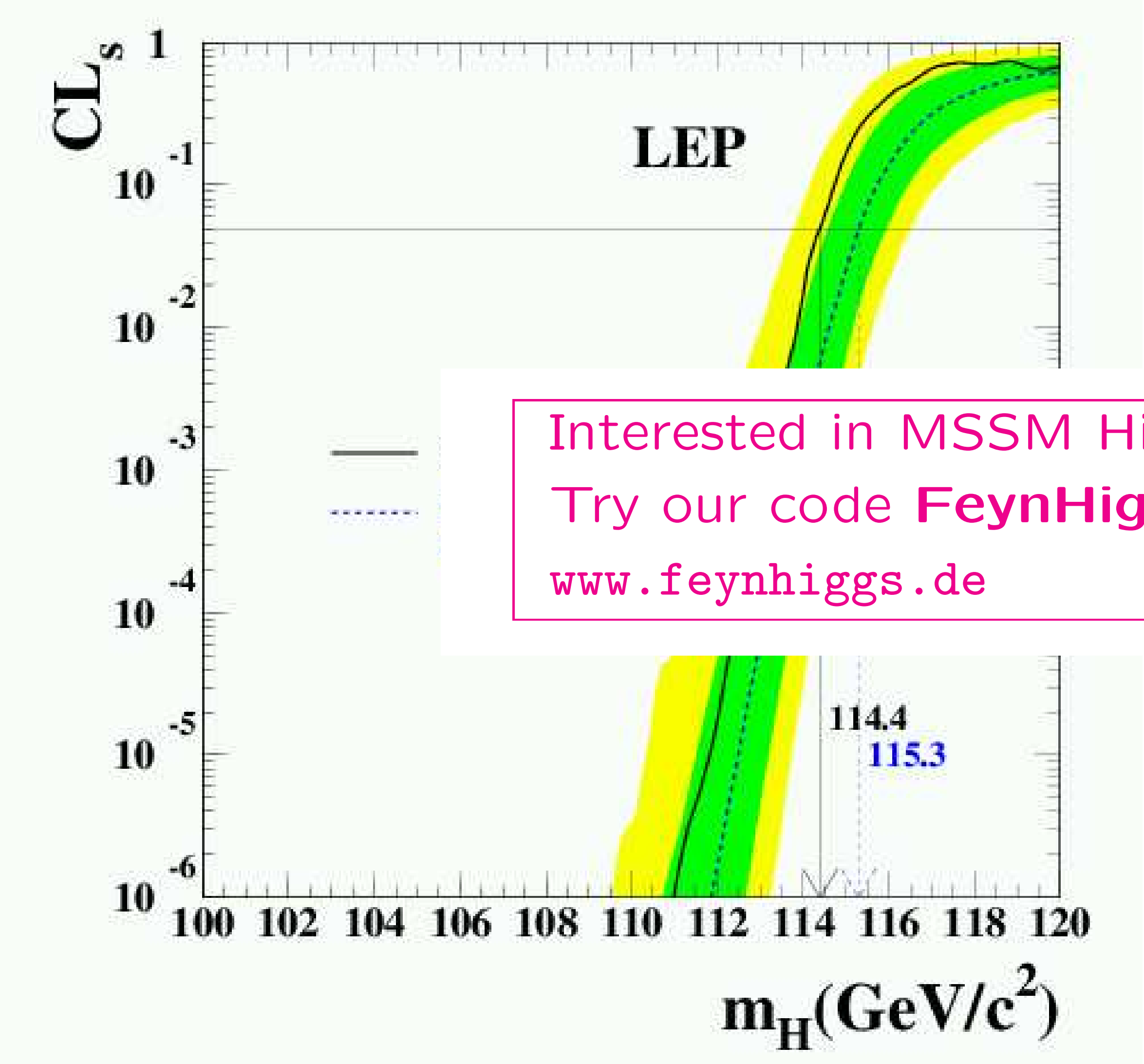
$\Rightarrow$ can be included into χ^2 evaluation

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

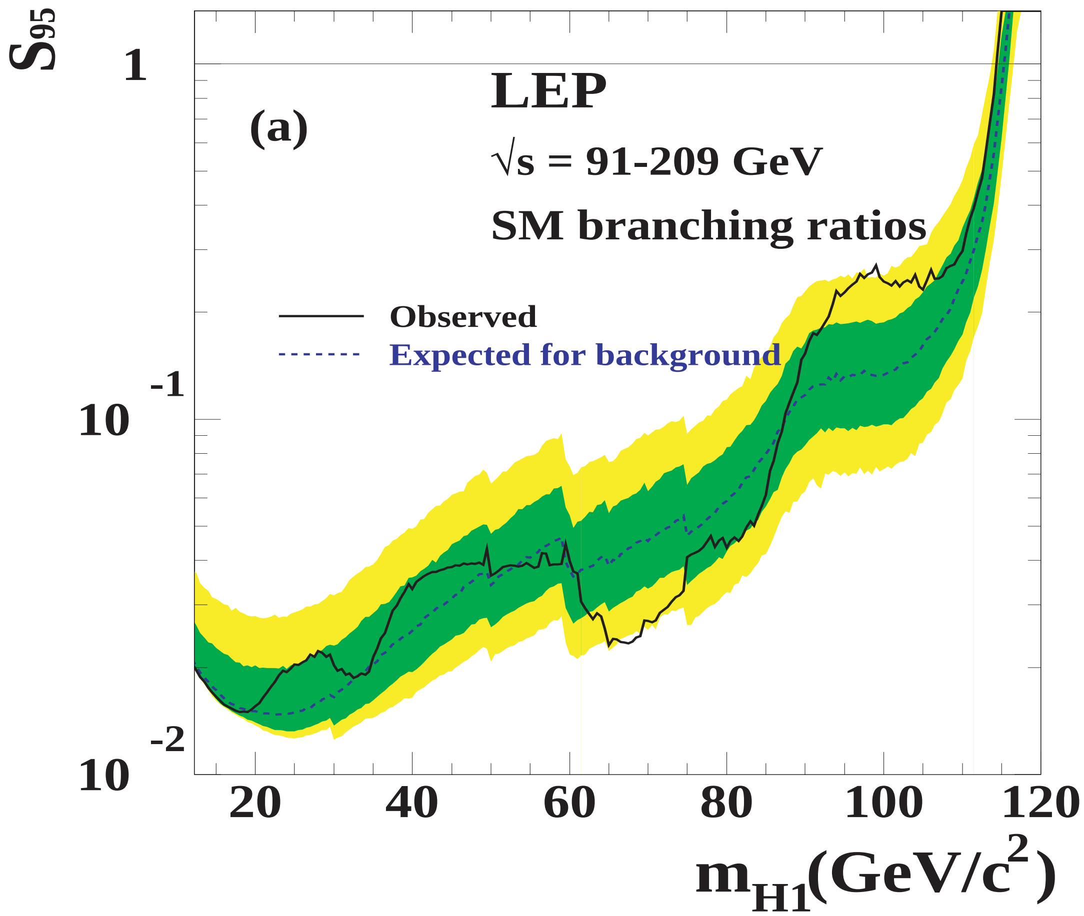
$\delta M_h^{\rm intr.} \approx 3$ GeV

We use *FeynHiggs*

Interested in MSSM Higgs physics?
Try our code **FeynHiggs**
`www.feynhiggs.de`

In the NUHM1:

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

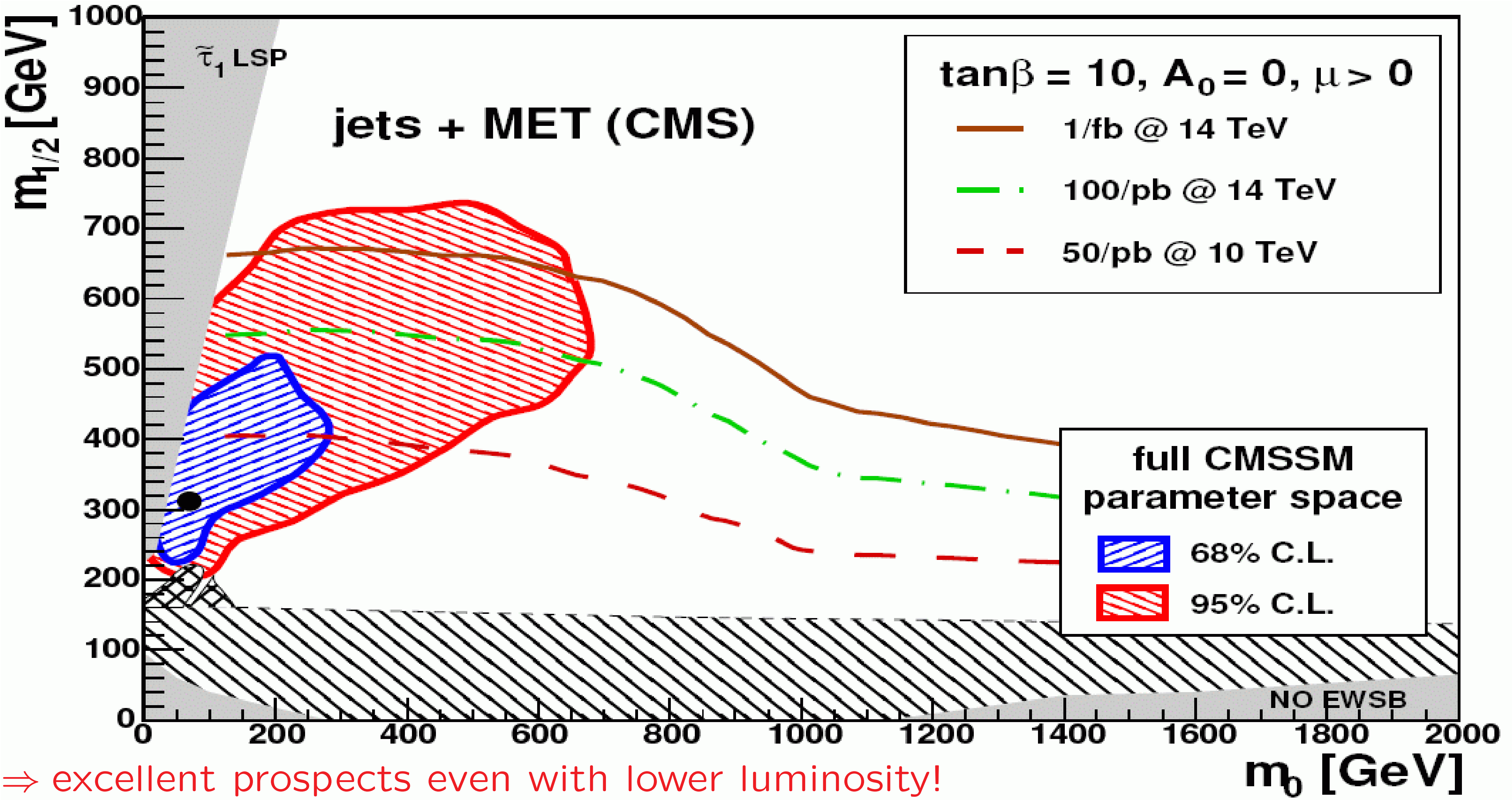


⇒ take into account the LEP SM Higgs bound ...

... but shifted according to the reduced coupling

LHC (CMS) ⊕ CMSSM analysis:

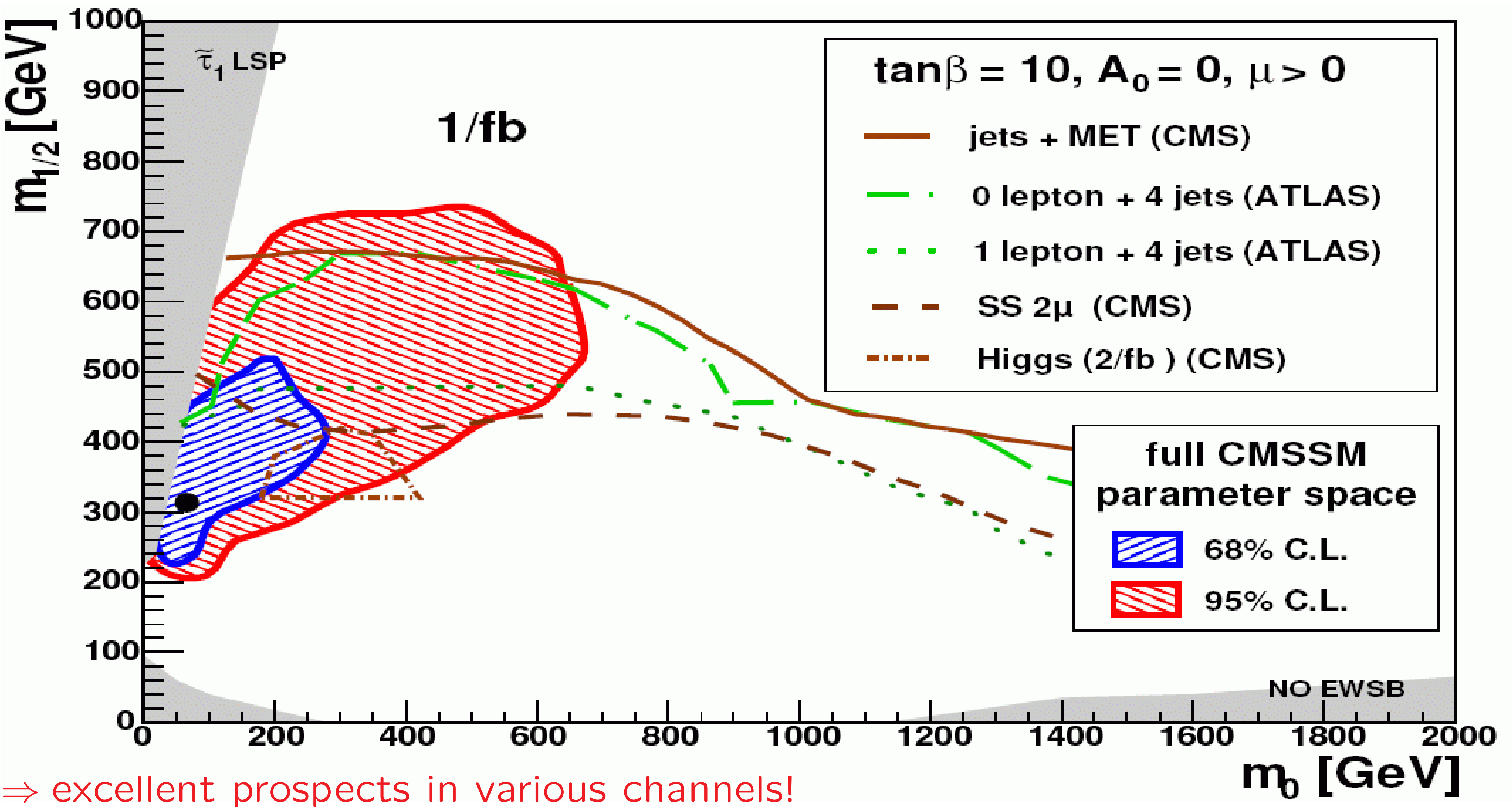
[*CMS '07*] [*2008*]



⇒ excellent prospects even with lower luminosity!

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

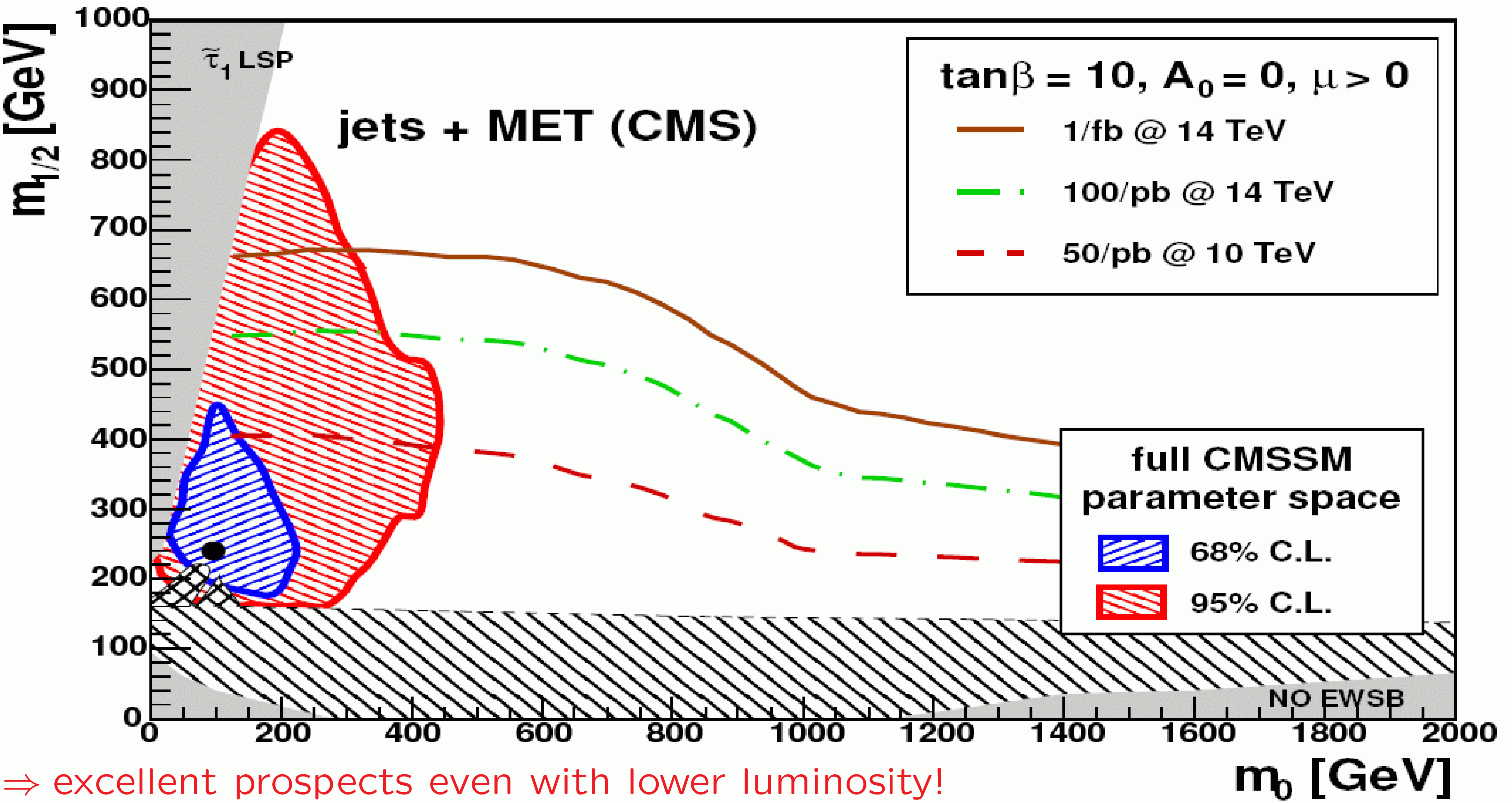
[*MasterCode '08*] [*CMS '07*]



⇒ excellent prospects in various channels!

LHC (CMS) ⊕ NUHM1 analysis:

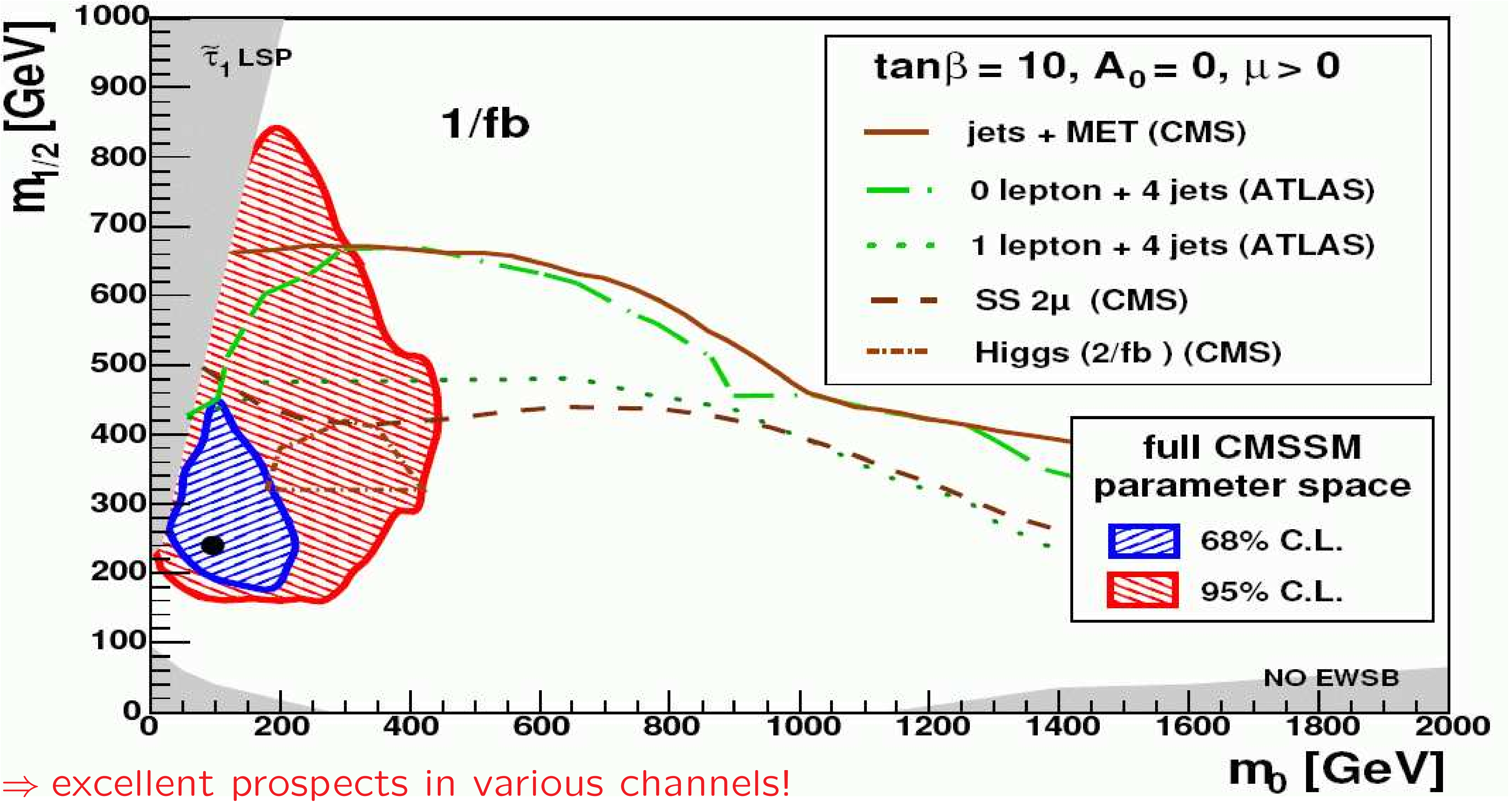
[*CMS '07*] [*2008*]



⇒ excellent prospects even with lower luminosity!

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

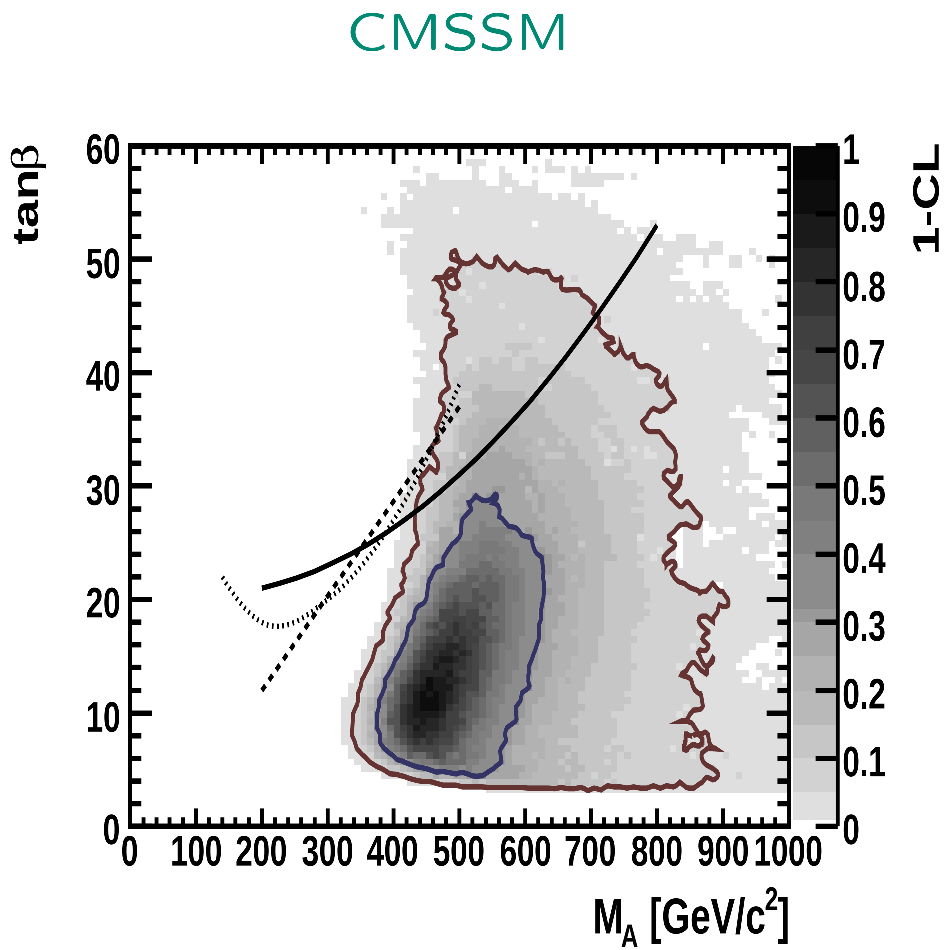
[*MasterCode '08*] [*CMS '07*]



⇒ excellent prospects in various channels!

 preferred M_A–$\tan\beta$ parameter space

[2009]

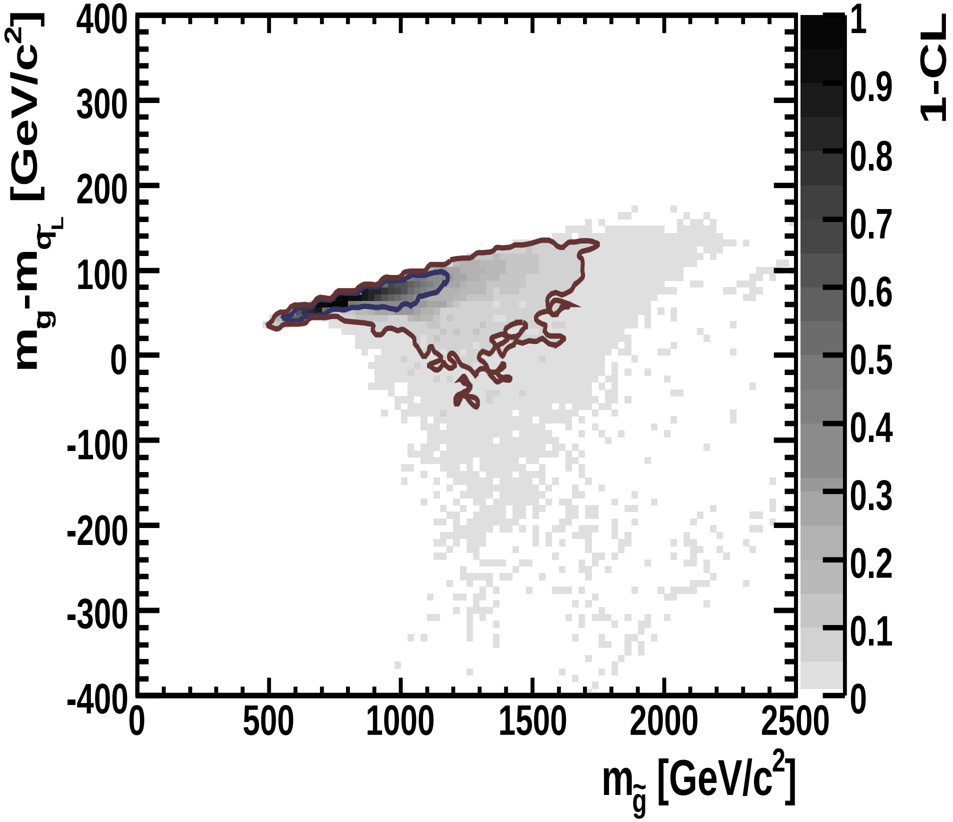


⇒ best-fit regions missed by LHC, better for ILC(1000)

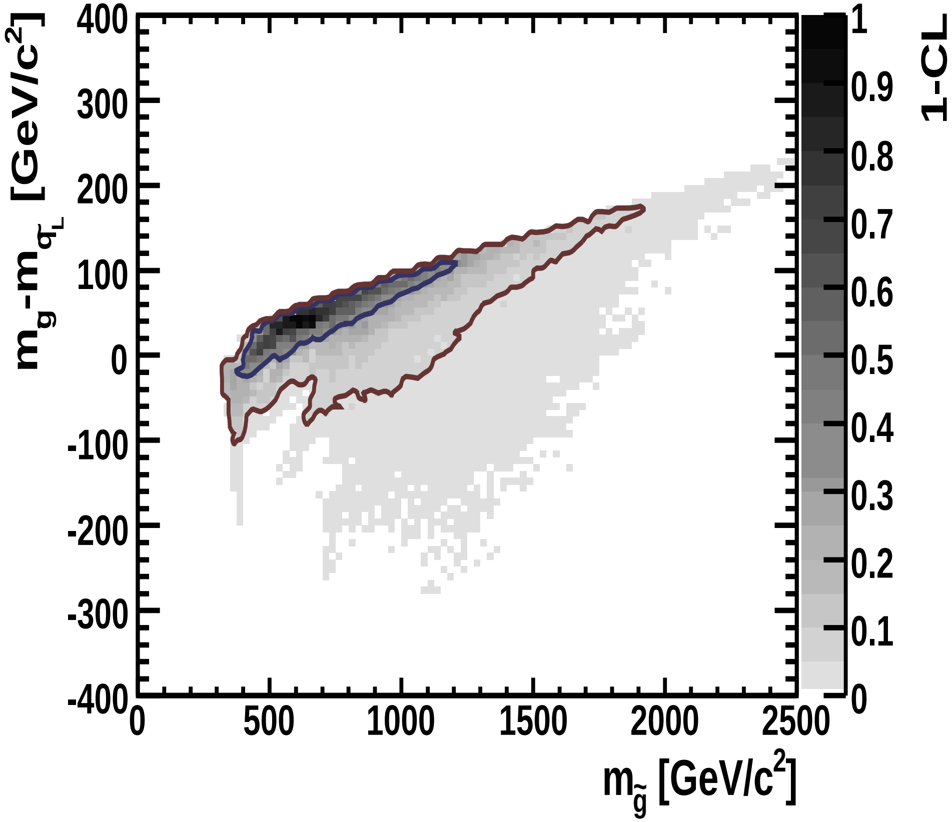
Some more predictions: $m_{\tilde{g}} - m_{\tilde{q}_L}$

[2009]

CMSSM



NUHM1

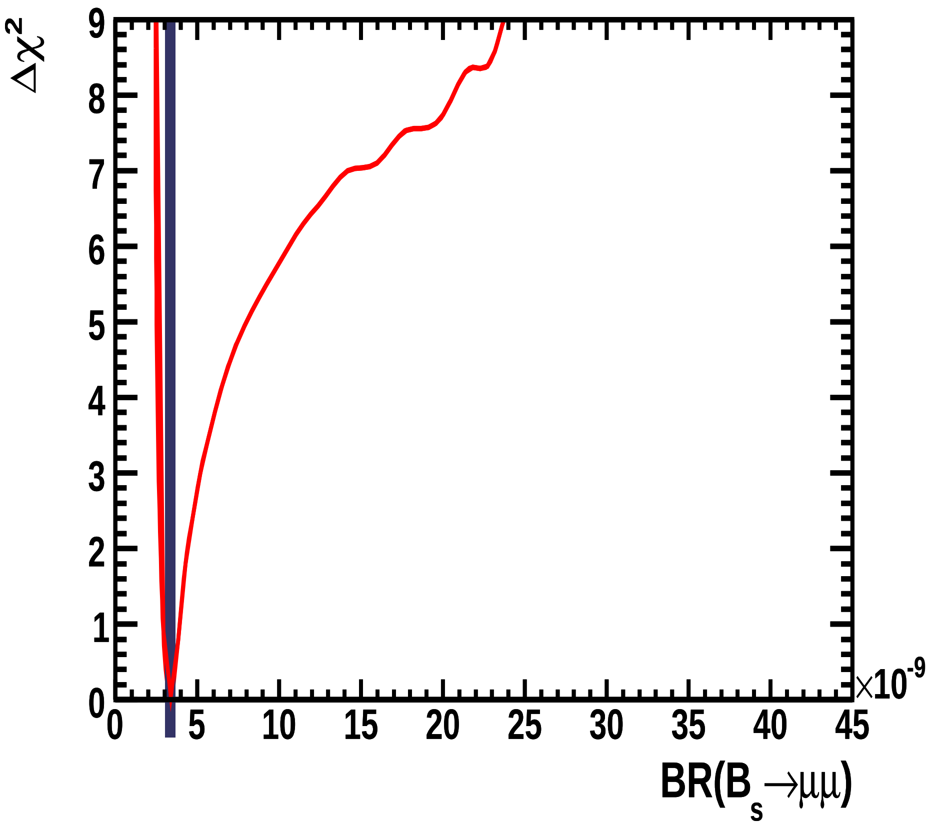


$\Rightarrow m_{\tilde{g}}$ often largest mass, but exceptions are possible

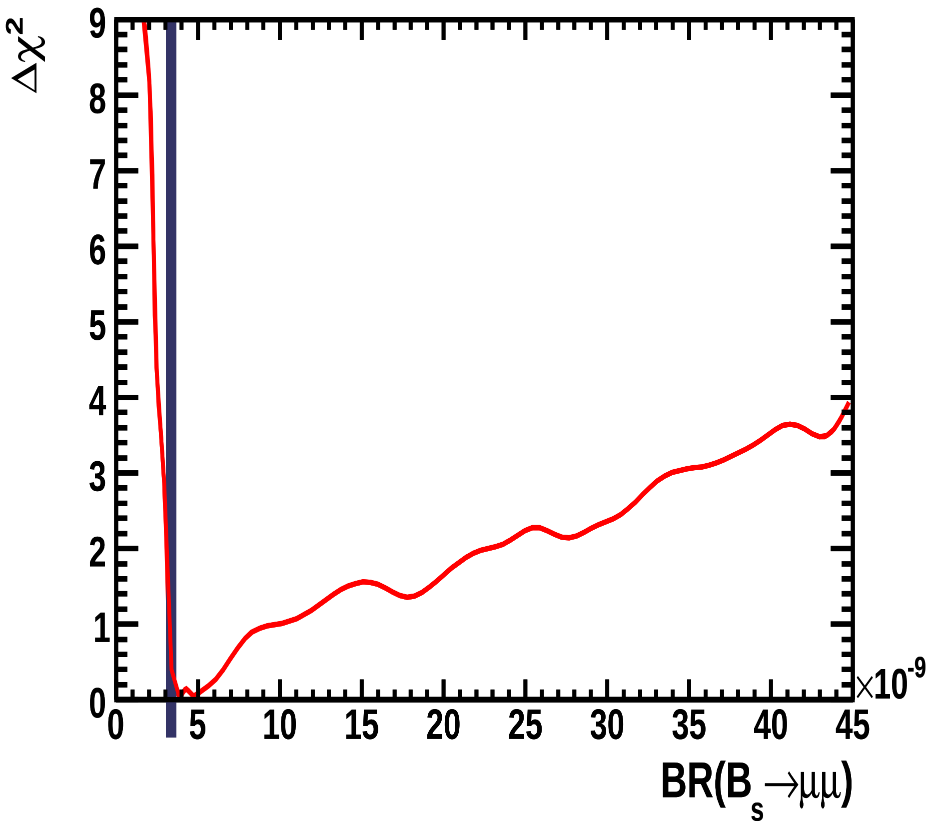
Some more predictions: BR($B_s \to \mu^+\mu^-$)

[2009]

CMSSM



NUHM1



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