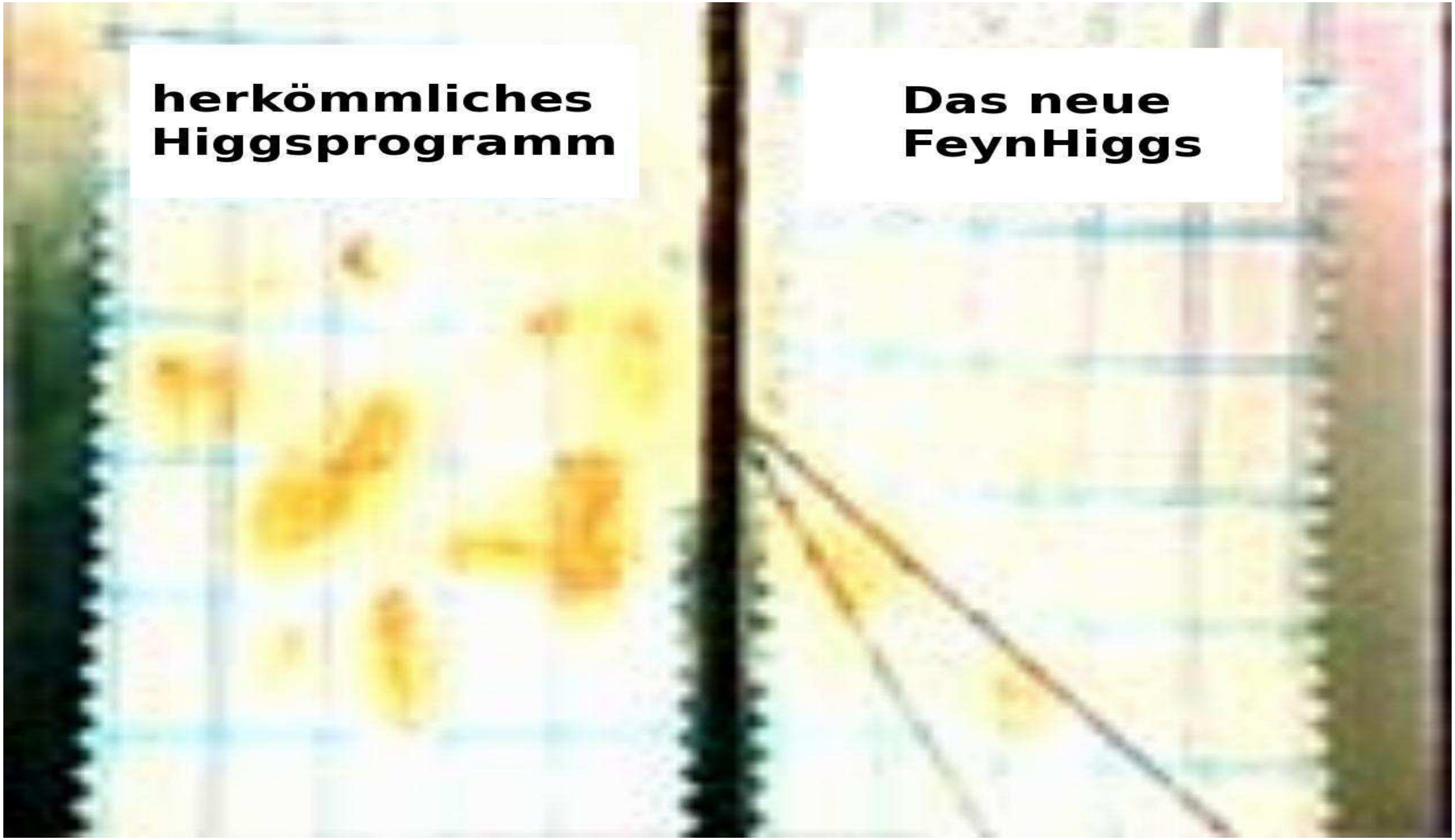
herkömmliches
Higgsprogramm
Das neue
FeynHiggs

SUSY Prediction for the LHC

Sven Heinemeyer, IFCA (CSIC, Santander)

Boston, 06/2009

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

1. Introduction and motivation
2. The MasterCode
3. Models & Methods
4. Predictions for the LHC
5. Conclusions

1. Introduction

The LHC is coming . . .
first collisions by the end of this year?

The ILC is still coming . . .
. . . a bit later than anticipated

Worldwide Study of
the Physics and Detectors
for Future Linear
$e^+ e^-$ Colliders

⇒ New Physics is certainly around the corner

⇒ Time to get ready

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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$\Rightarrow$ is there any possibility to know what to expect?

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It is a supersymmetric one

⇒ concentrate on the MSSM from now on

(other people ⇒ other guesses ⇒ other priorities . . .)

⇒ is there any possibility to know what to expect?

Let's see . . .

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

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

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

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

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

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

Problem in the MSSM: complex phases (← neglected here)

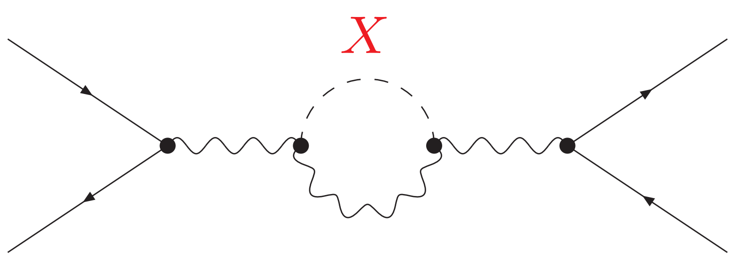
How to make a prediction?

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



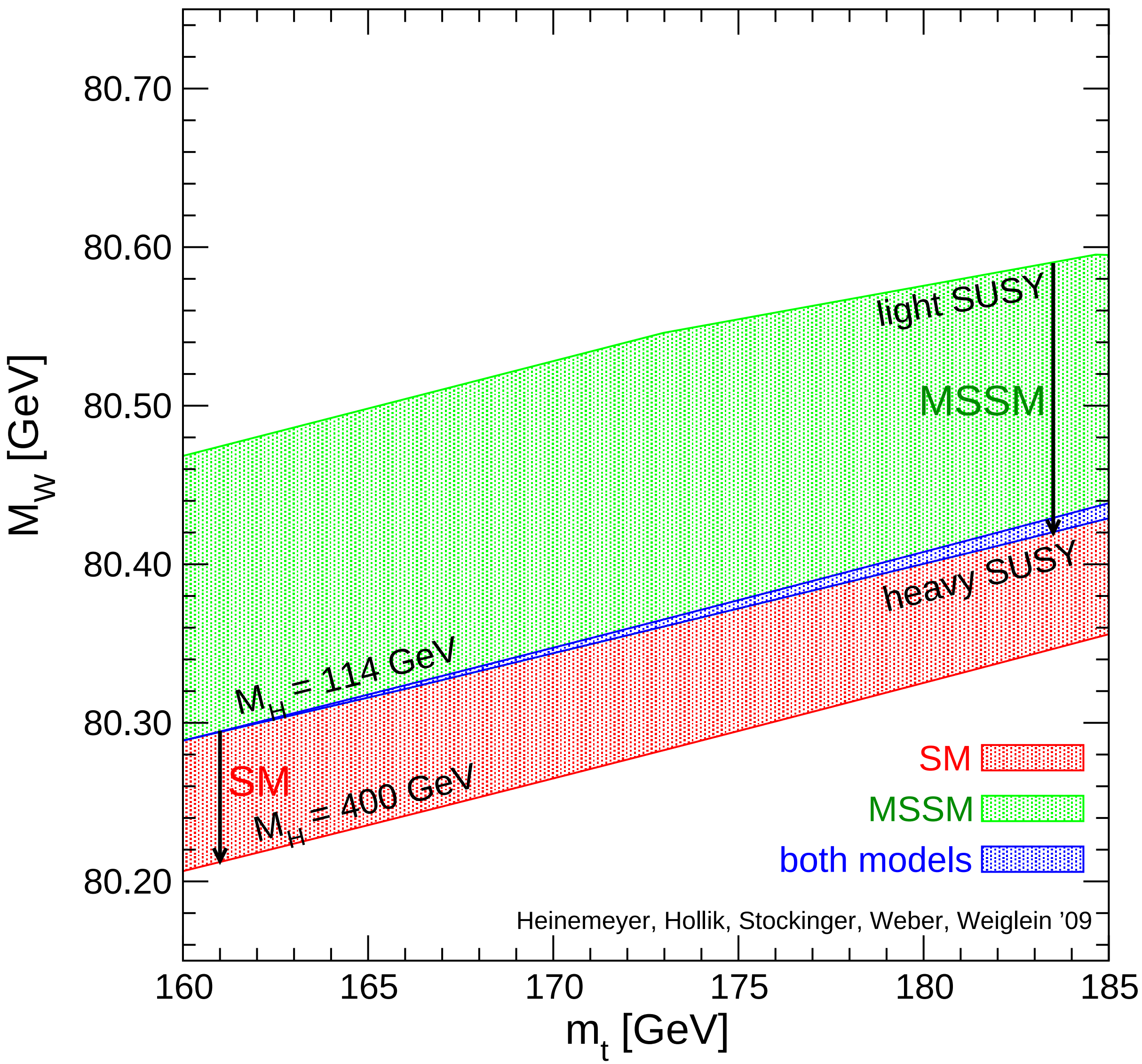
$\Downarrow$

$\Rightarrow$ 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^{SM}

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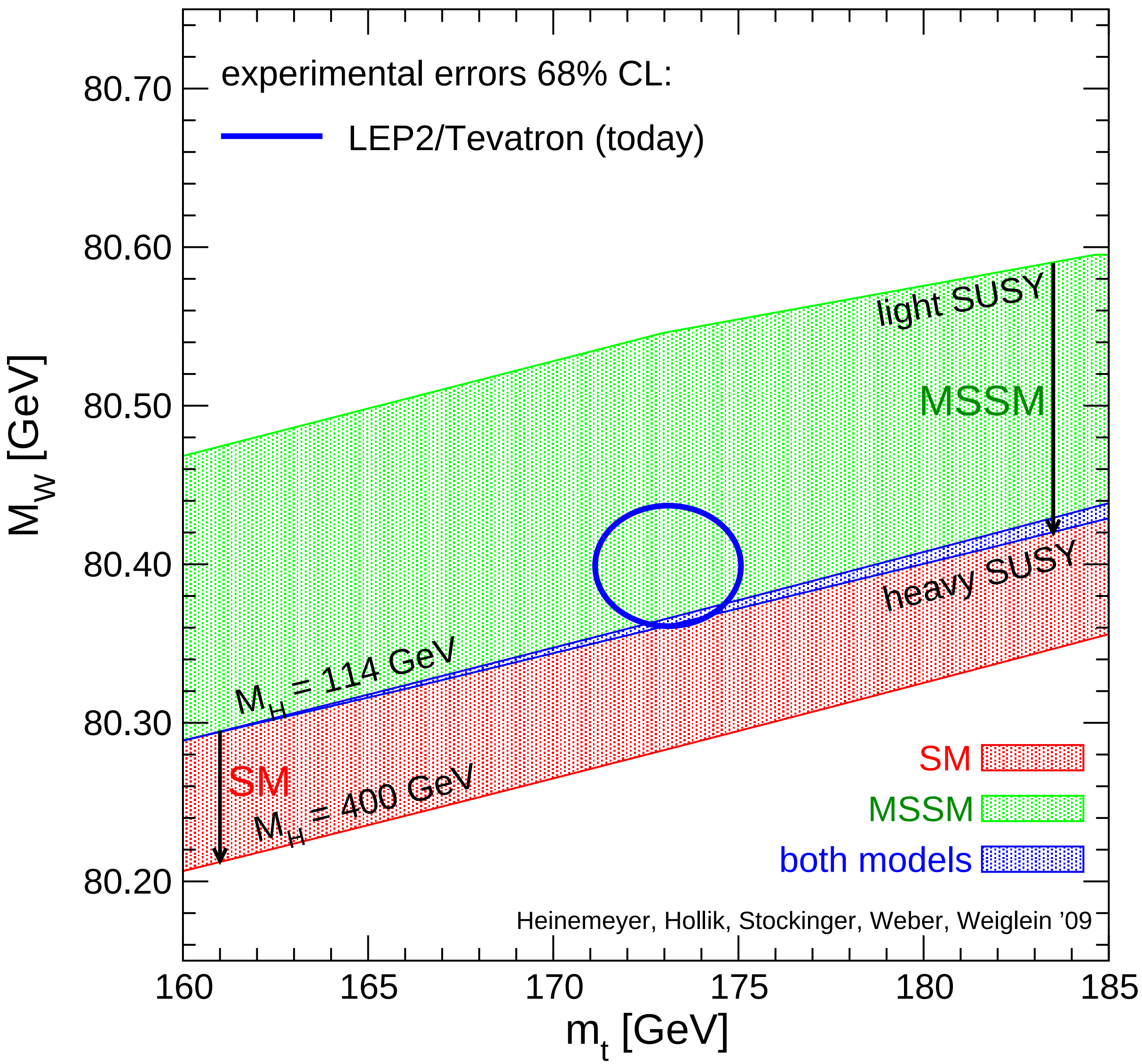

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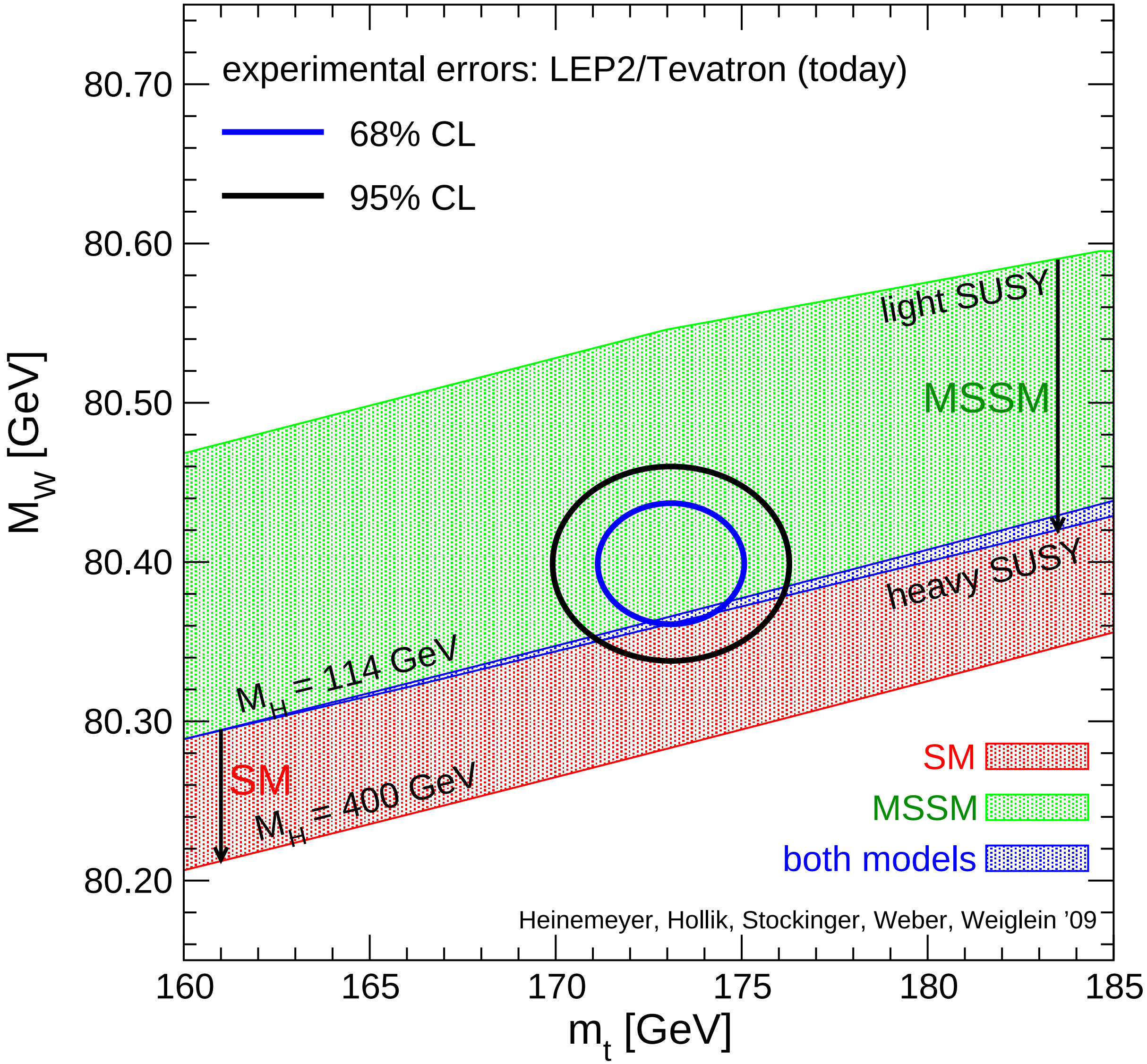

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2. The MasterCode

⇒ collaborative effort of theorists and experimentalists

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

Über-code for the combination of different tools:

– tools 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

⇒ consistent evaluation with the best codes available

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 (SUSYPope)*]
  - 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*]

    → see S.H.'s talk at SUSY 09
- planned: inclusion of more tools / more models

Example: B/K physics observables in the MasterCode

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

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

3. Models & methods

Indirect constraints on $M_{\rm SUSY}$ 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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$\Rightarrow$ combination of EWPO, BPO, CDM ?

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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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 ...

$\Rightarrow$ 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]*

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]

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]*

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

→ Myriam Mondragon's talk at SUSY 09

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

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

$\Rightarrow$ besides the CMSSM parameters

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

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

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

Different methods:

1.) Scanning:

– 3-dim scans (possibly with CDM fixing one dimension)

[J. Ellis, T. Hahn, SH, K. Olive, A. Weber, G. Weiglein '04, '06, '07]

– multi-dim scans

[O. Buchmueller et al. '07] *[S.H., X. Miao, S. Su, G. Weiglein '08]*

– multi-dim scans (with Markov Chain Monte Carlo technique)

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

⇒ here: results using last one

2.) Fitting:

– Frequentist

[J. Ellis, T. Hahn, SH, K. Olive, A. Weber, G. Weiglein '04, '06, '07]

[O. Buchmueller et al. '07, '08] *[S.H., X. Miao, S. Su, G. Weiglein '08]*

– Bayesian

[R. Ruiz de Austri, R. Trotta and L. Roszkowski '06, '07]

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

⇒ focus on Frequentist here

3.) Priors . . . (none)

χ^2 calculation:

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

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

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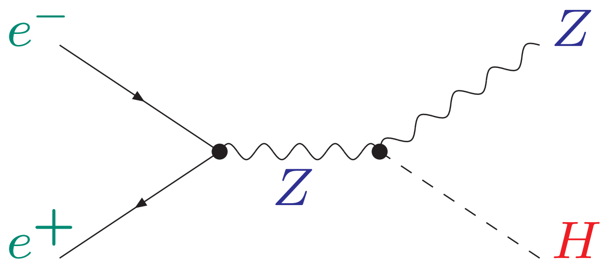
What to do if only a lower/upper bound exists?

$\rightarrow$ especially important: M_h

SM Higgs search at LEP:

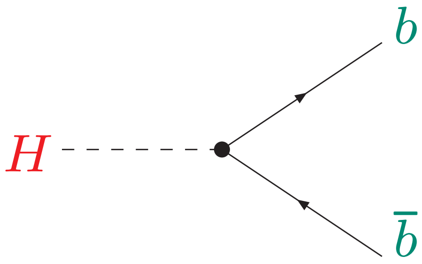
Dominant SM production process:

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



Dominant decay process:

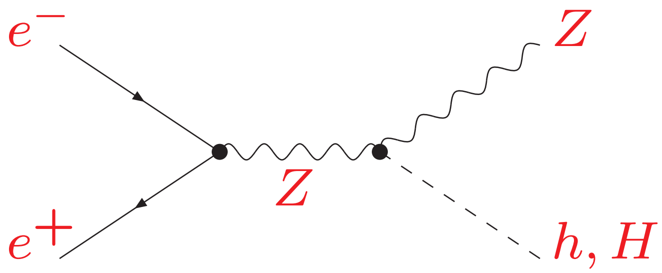
$H \to b\bar{b}$:



Bounds valid in the CMSSM? NUHM1? MSSM?

Search for neutral SUSY Higgs bosons:

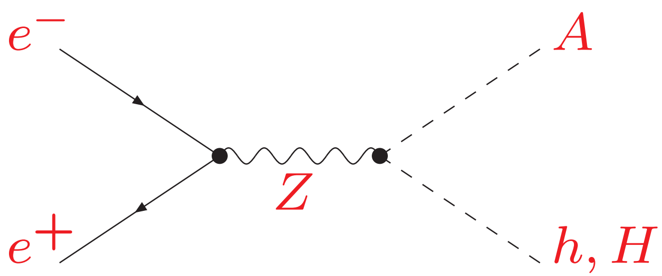
$e^+e^- \to Zh, ZH$



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

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

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



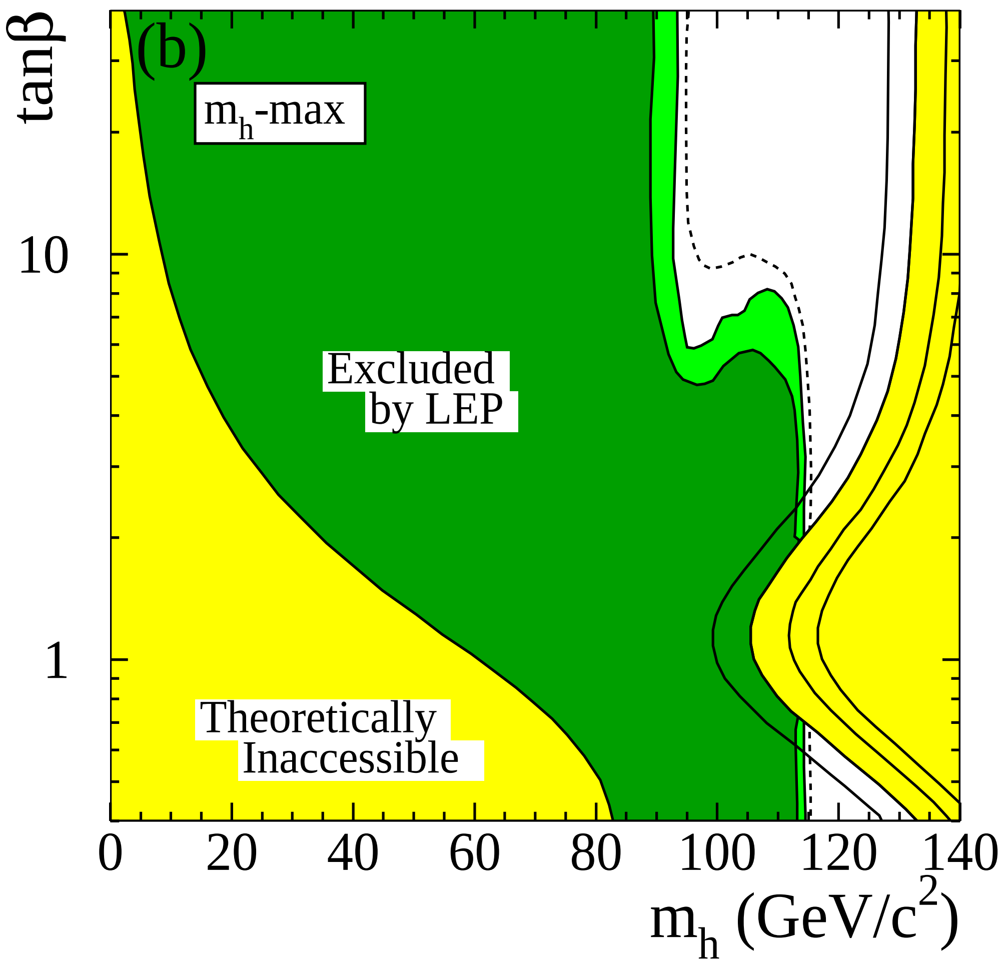
$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}})\sigma^{\text{SM}}_{hZ}$$

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

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

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

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

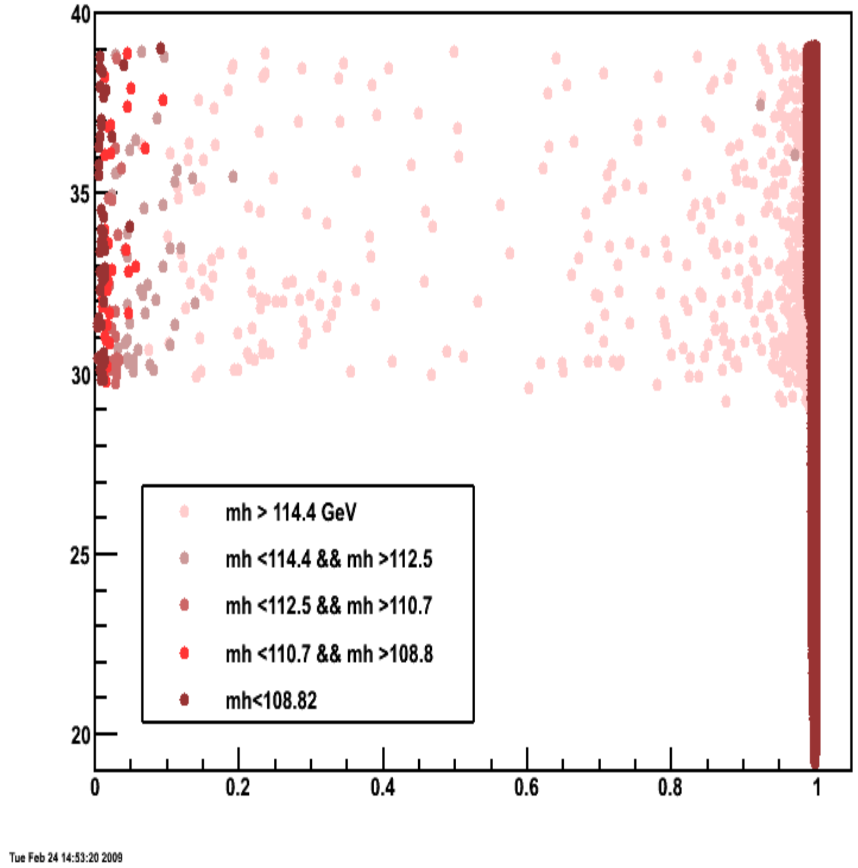


$m_h > 92.8$ GeV
(expected: 94.9 GeV), 95% C.L.

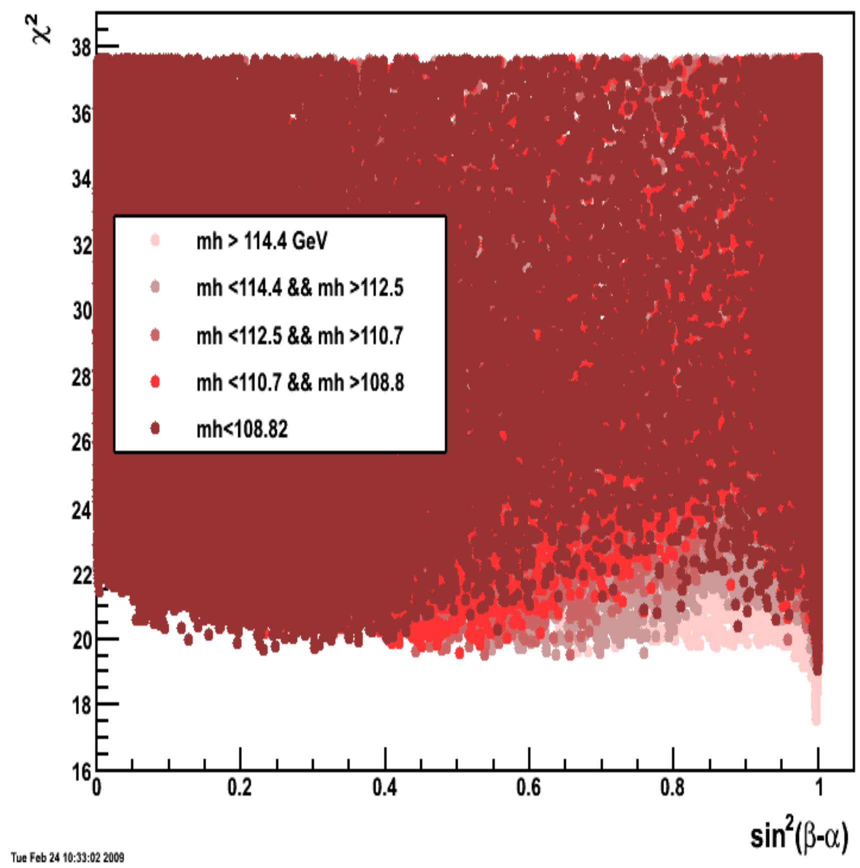
$M_A > 93.4$ GeV
(expected: 95.2 GeV)

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

CMSSM

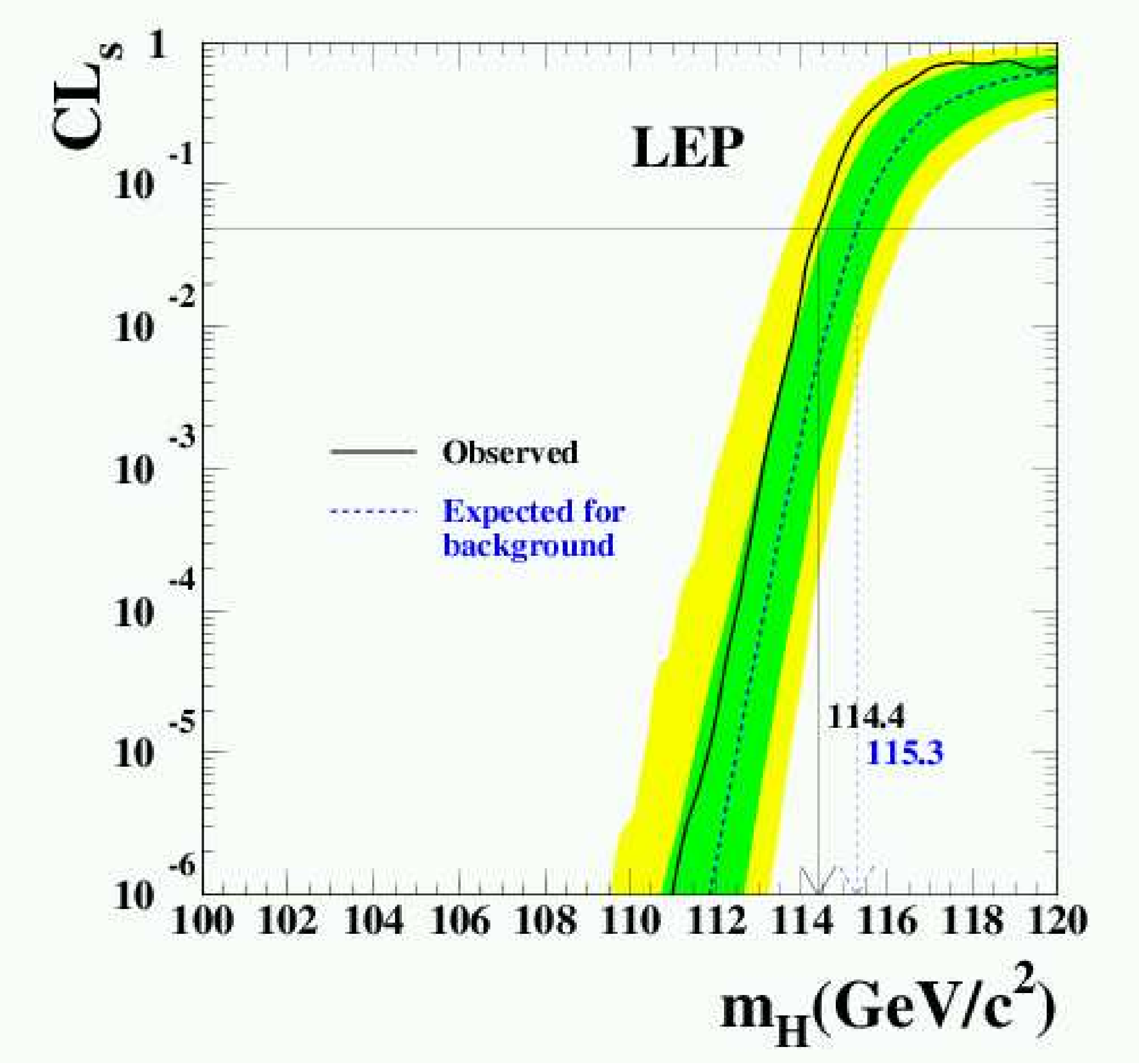


NUHM1



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

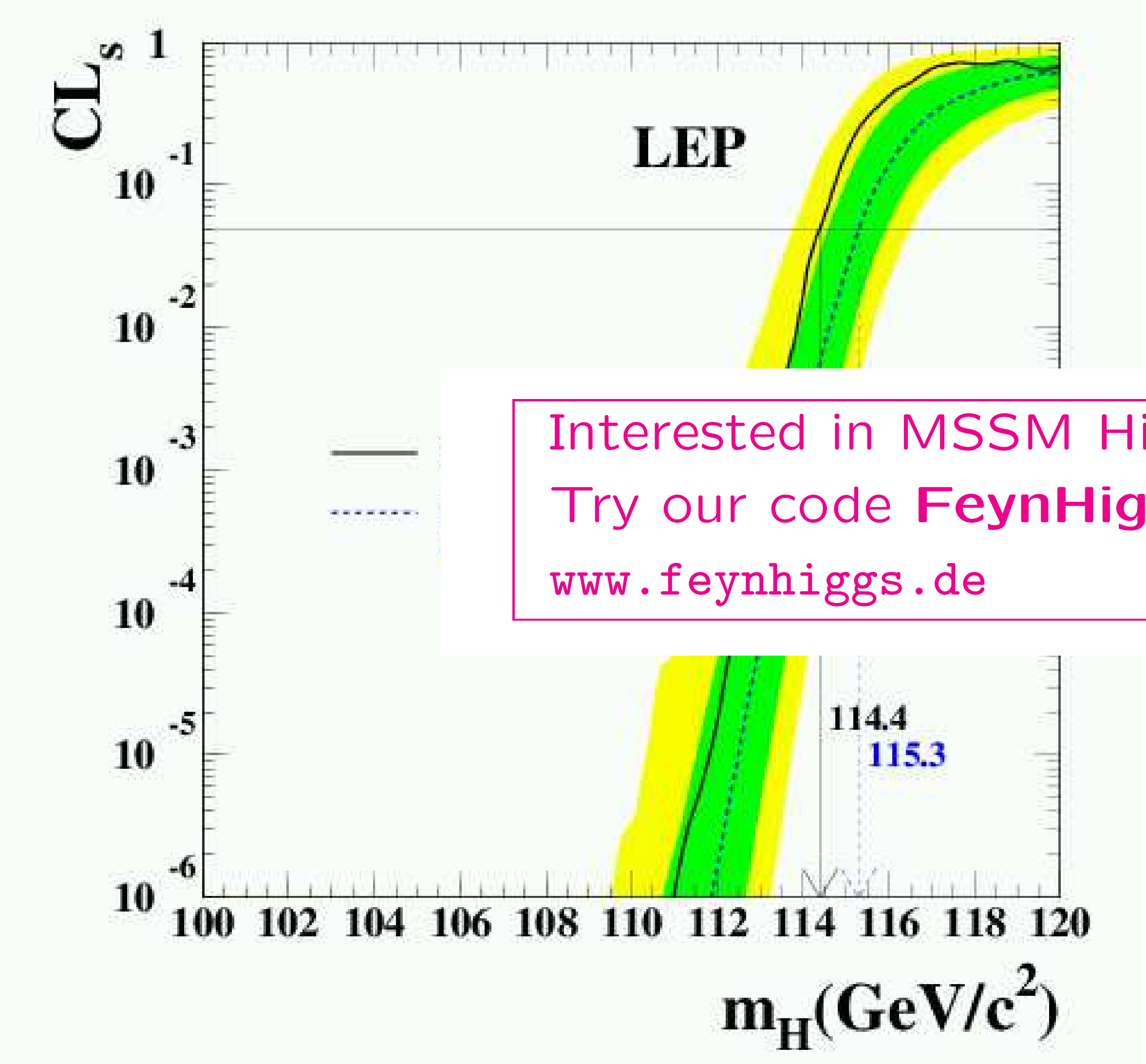
$\Rightarrow$ can be included into χ^2 evaluation

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

Interested in MSSM Higgs physics?

Try our code **FeynHiggs**

`www.feynhiggs.de`

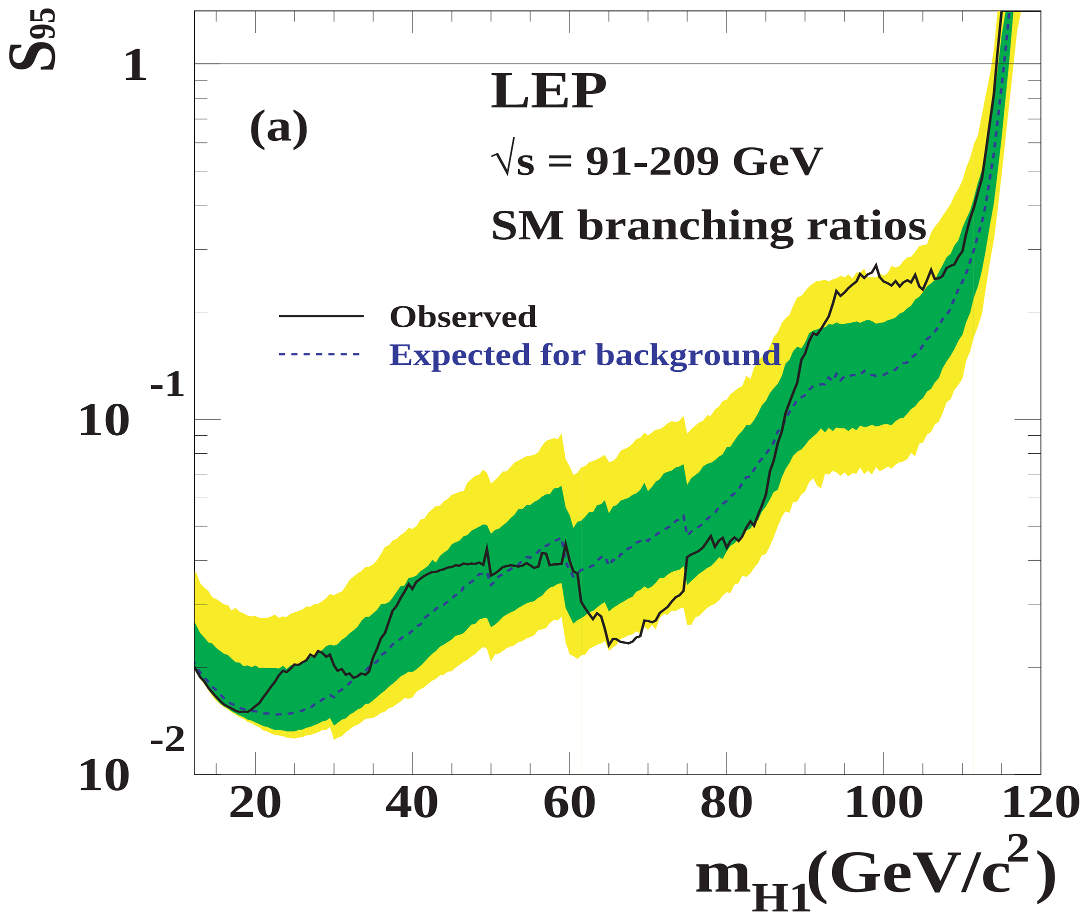
...ed into

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

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 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/ILC reach

→ not yet existing results in Henning Flächer's talk at SUSY 09

Best-fit points:

[*MasterCode '08*]

CMSSM:

$m_{1/2} = 310$ GeV, $m_0 = 60$ GeV, $A_0 = 240$ GeV,

$\tan\beta = 11$, $\mu = 380$ GeV, $M_A = 410$ GeV

$\chi^2/N_{\rm dof} = 20.4/19$ (37.3 % probability)

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

NUHM1:

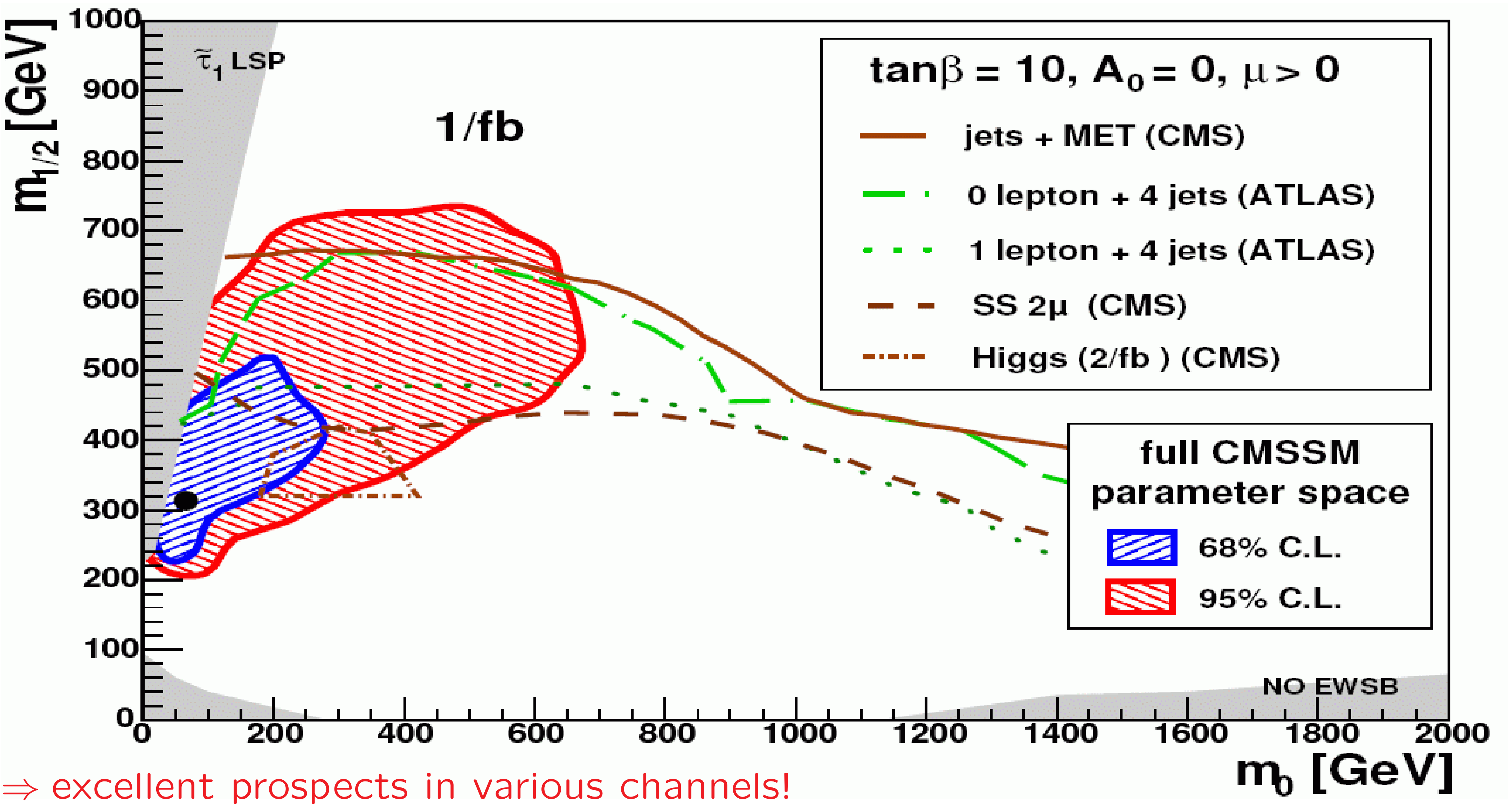
$m_{1/2} = 240$ GeV, $m_0 = 100$ GeV, $A_0 = -930$ GeV,

$\tan\beta = 7$, $\mu = 870$ GeV, $M_A = 300$ GeV

(39 % probability)

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

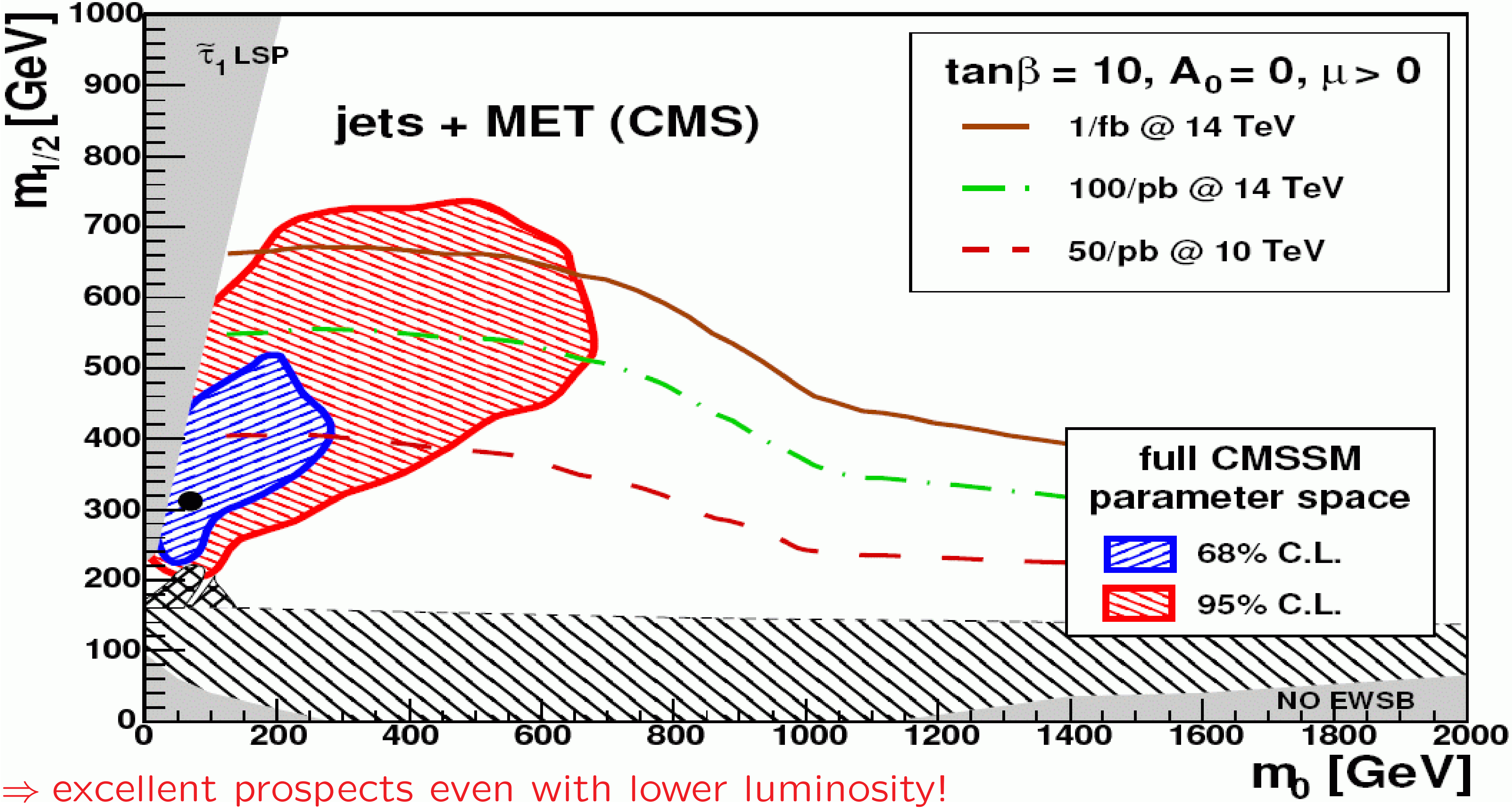
[*MasterCode '08*][*CMS '07*]



⇒ excellent prospects in various channels!

LHC (CMS):

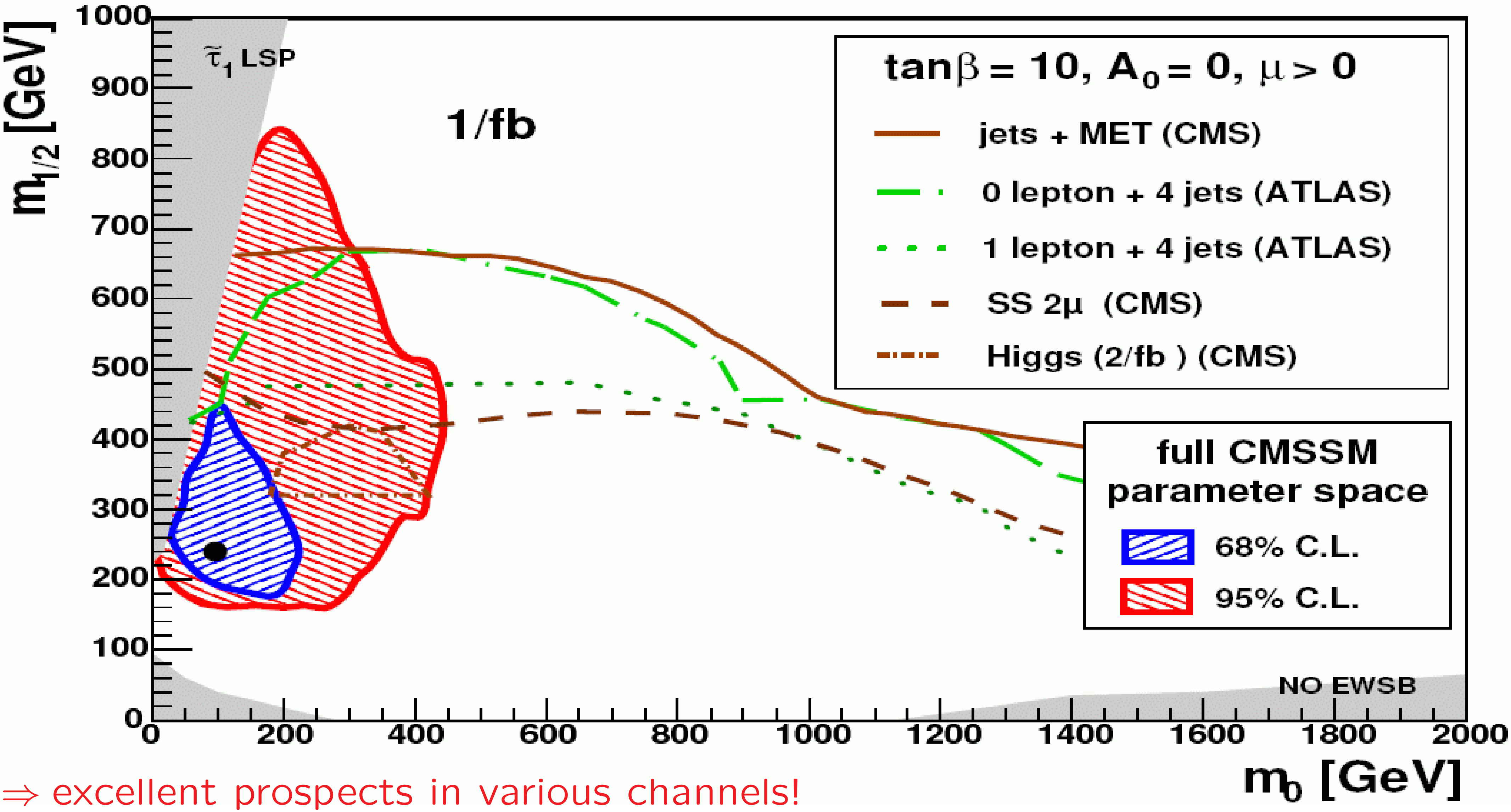
[*MasterCode '08*][*CMS '07*]



⇒ excellent prospects even with lower luminosity!

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

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



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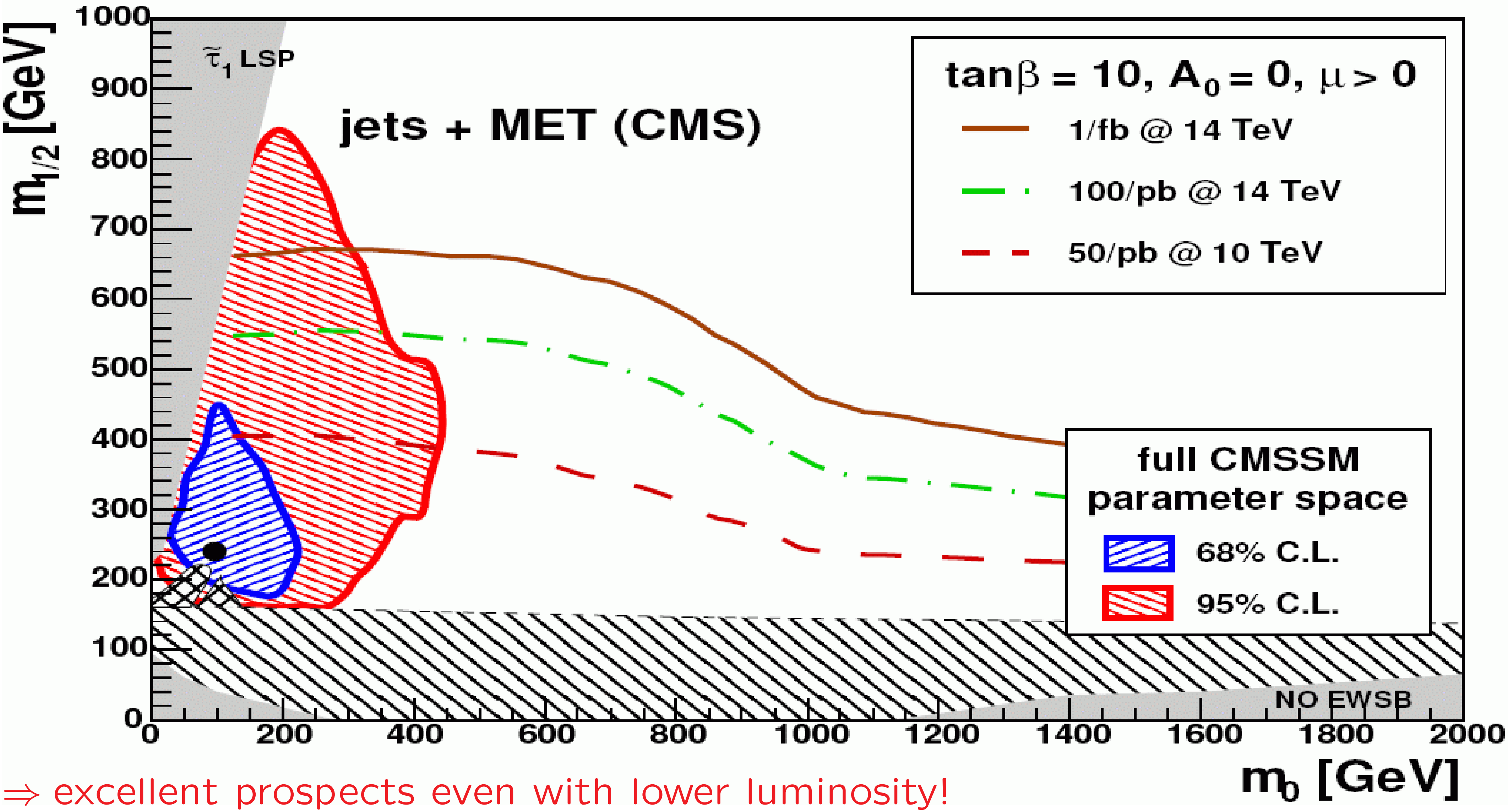
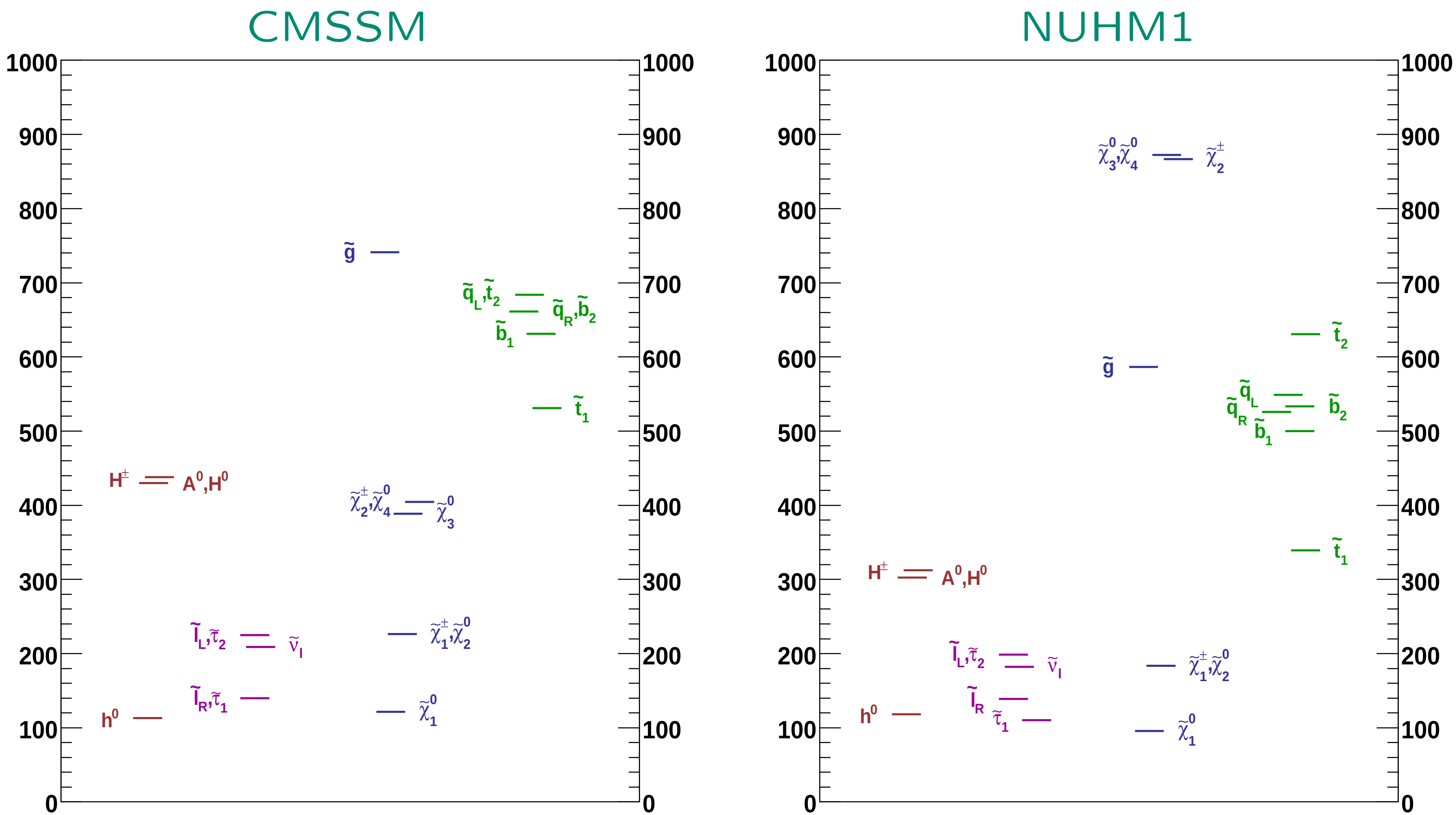
LHC (CMS): NUHM1 analysis

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



⇒ excellent prospects even with lower luminosity!

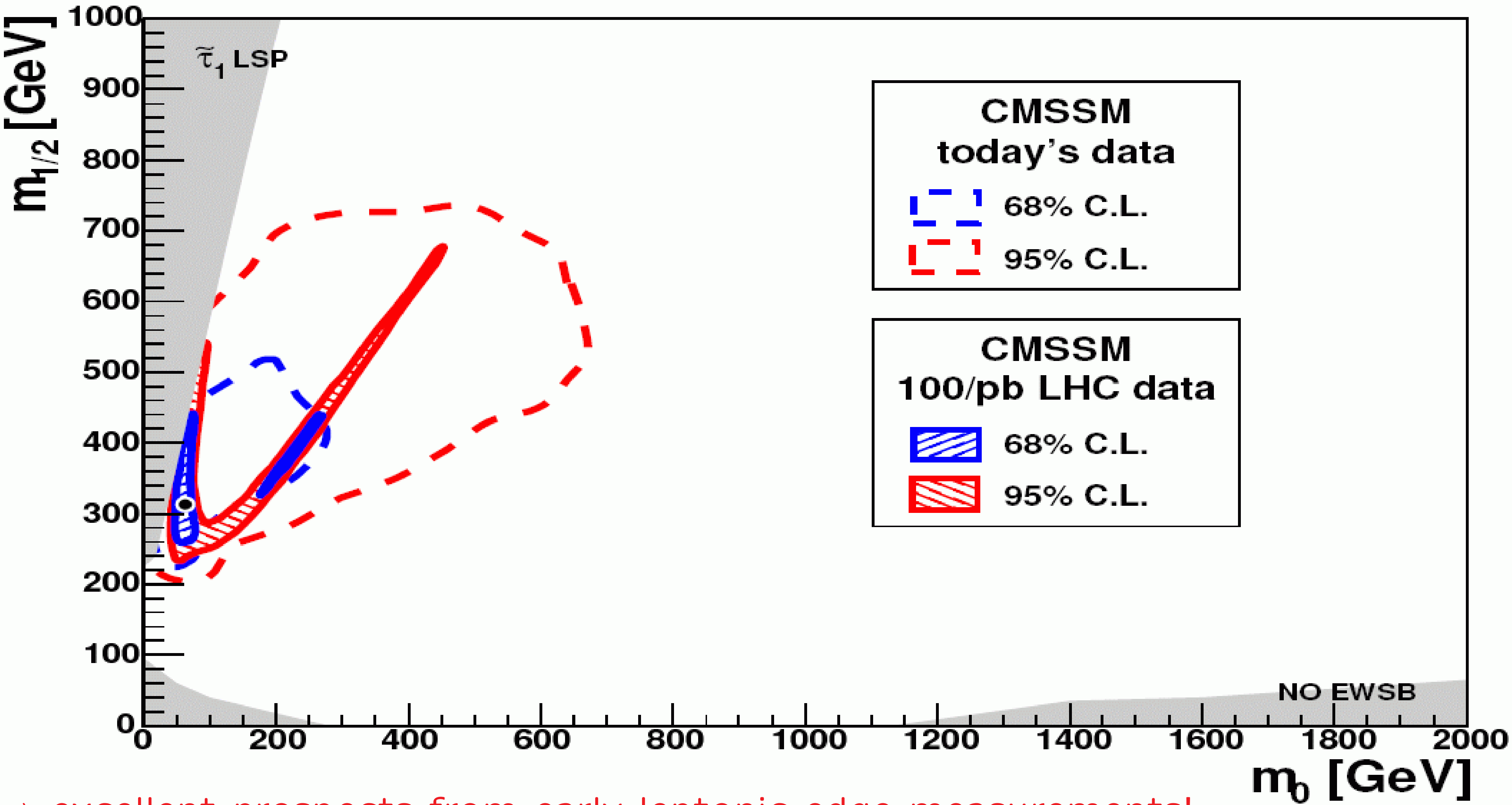
Masses for best-fit points:



⇒ largely accessible spectrum for LHC and ILC

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

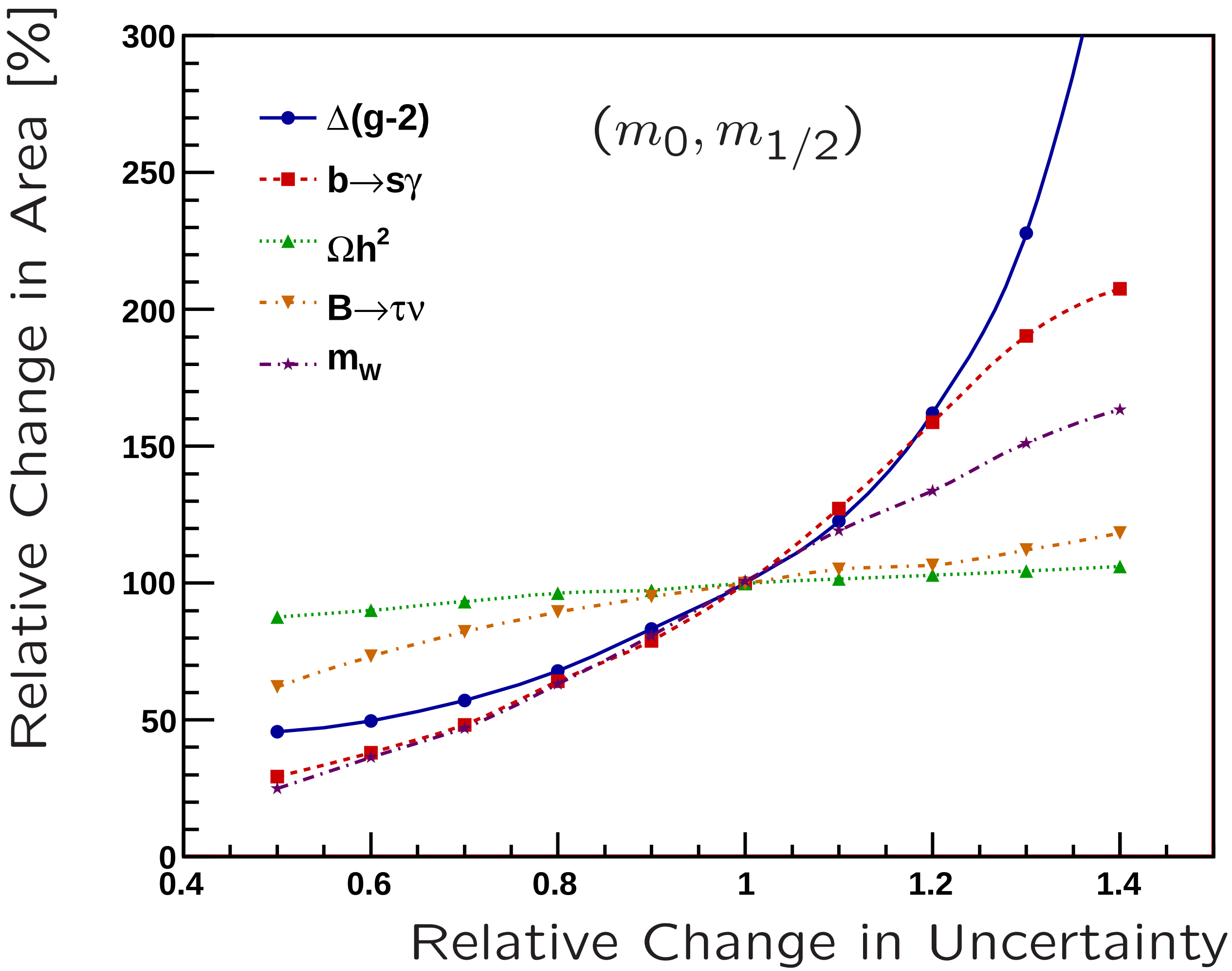
[*MasterCode '08*][*CMS '07*] CMSSM analysis incl. leptonic edge measurements



⇒ excellent prospects from early leptonic edge measurements!

Impact of various constraints (CMSSM):

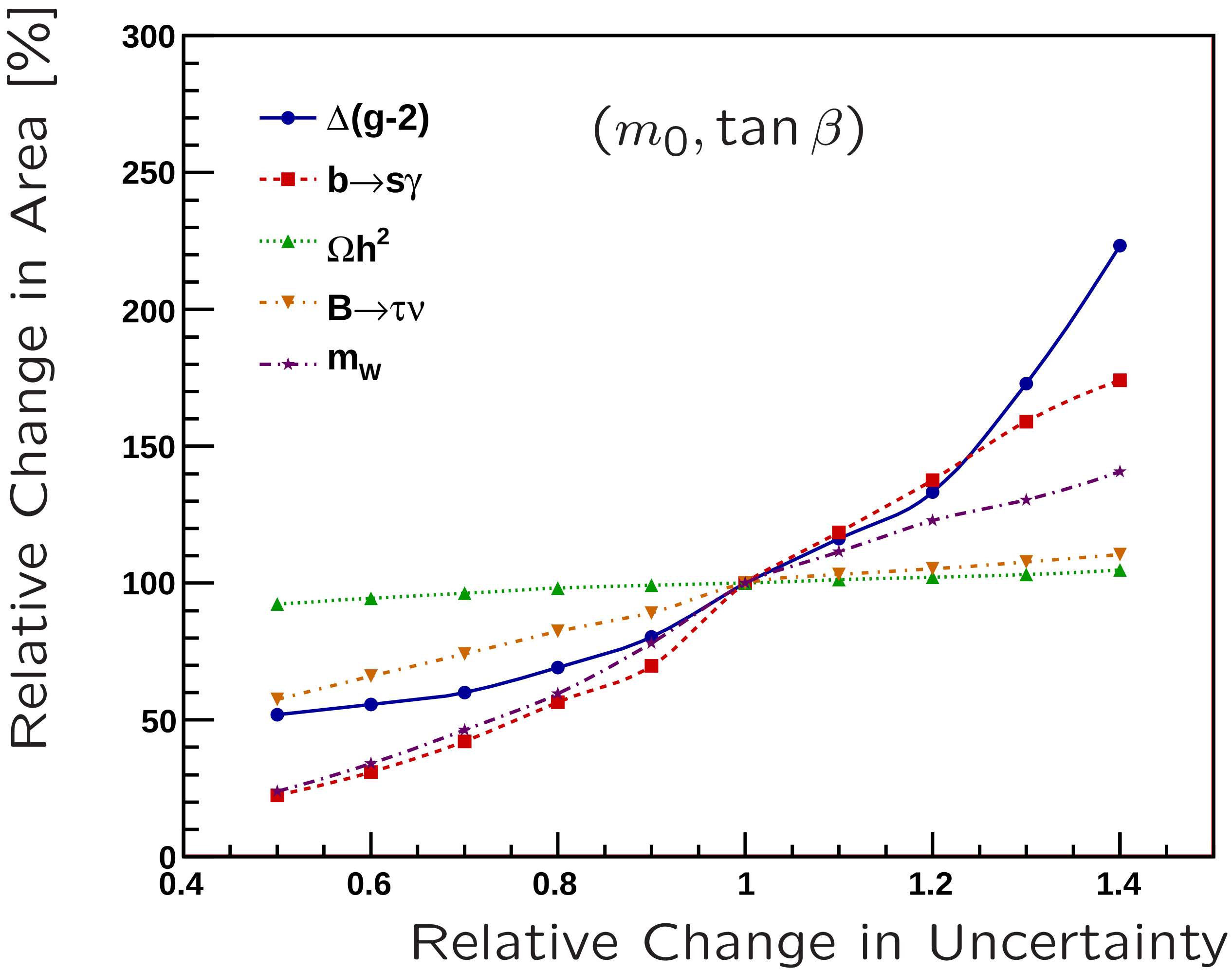
[*MasterCode '08*]



$\Rightarrow$ strong impact of $(g-2)_\mu$

$\Rightarrow$ 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): [MasterCode '08]



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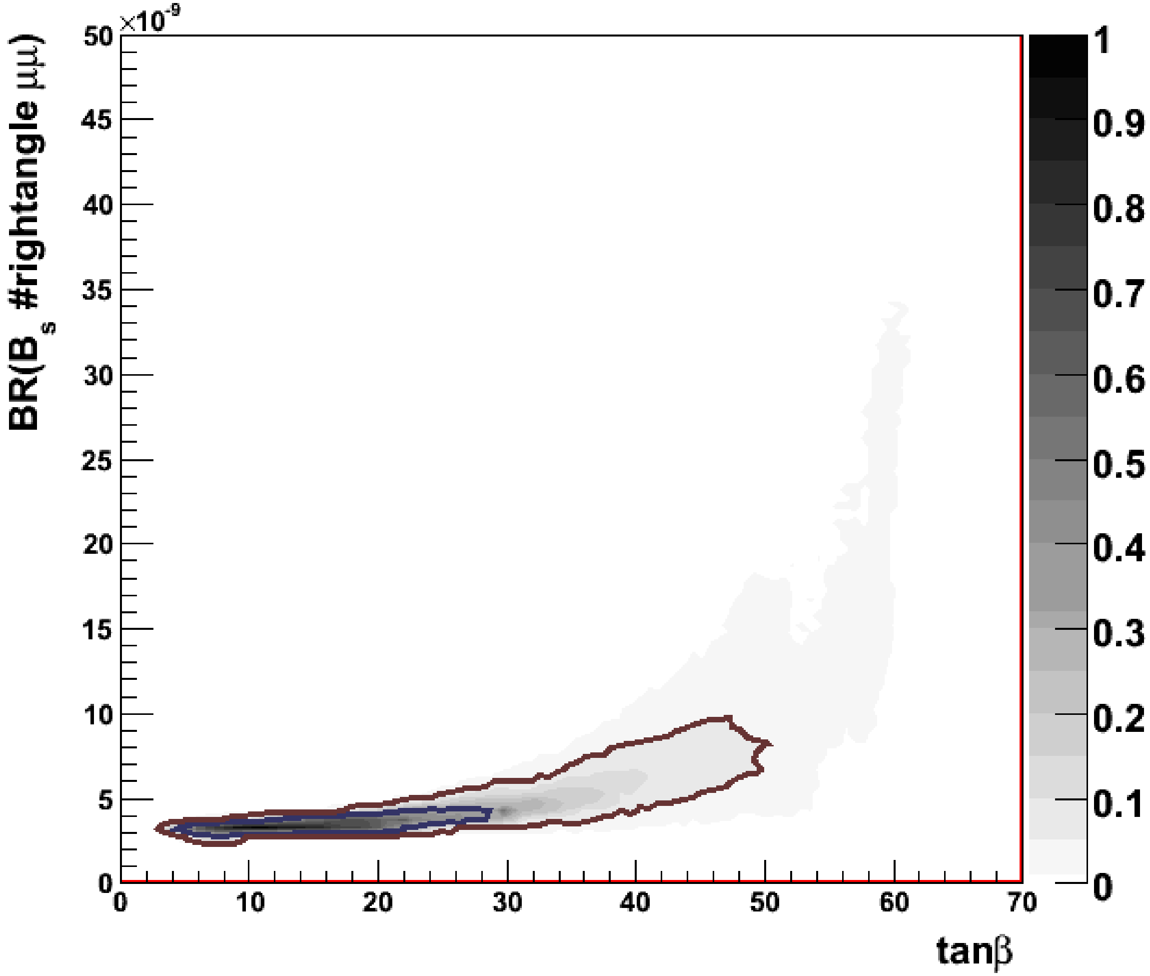
Predictions for BR($B_s \to \mu^+\mu^-$): [*MasterCode '09 PRELIMINARY*]

CMSSM:

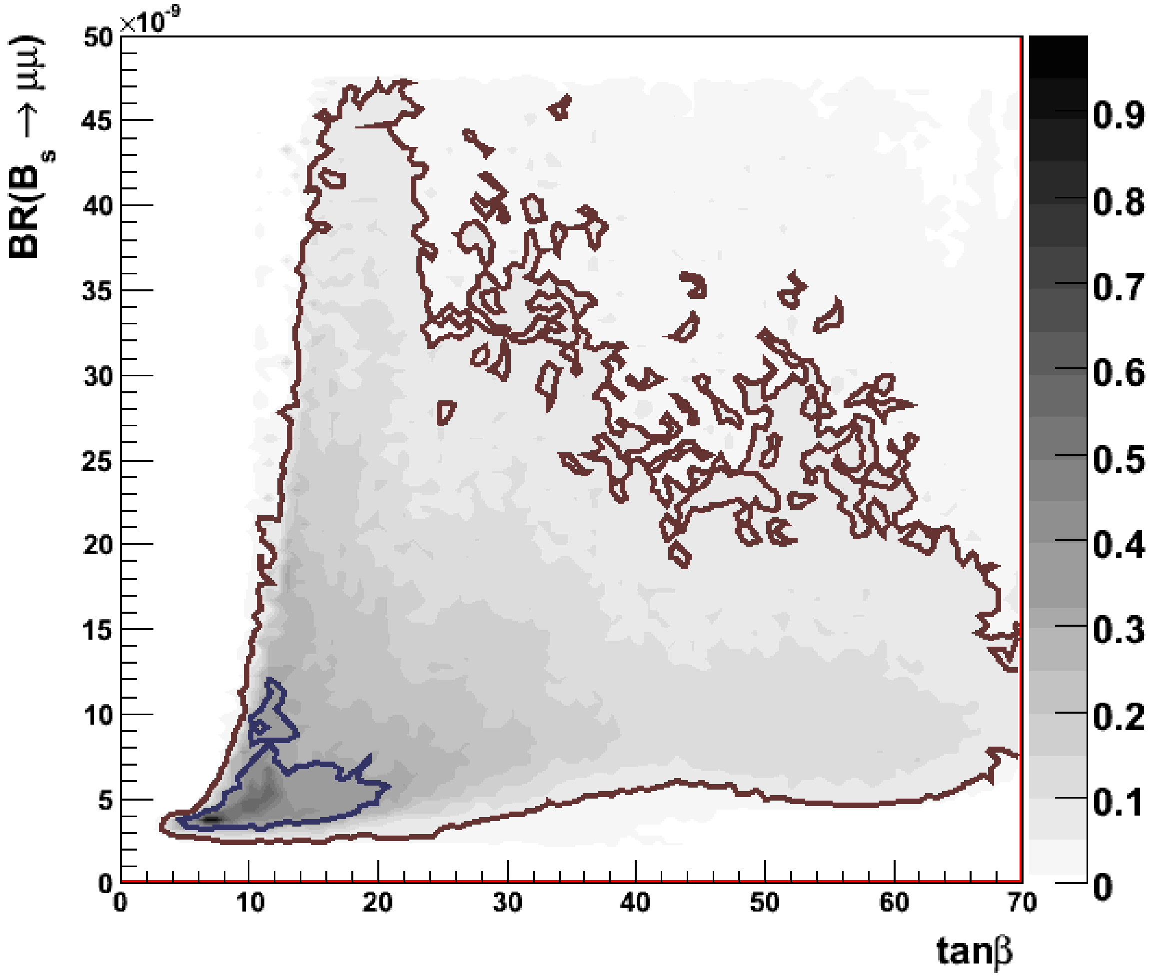


$\Rightarrow$ similar to SM

$\Rightarrow$ accessible at LHCb

Predictions for BR($B_s \to \mu^+\mu^-$): [*MasterCode '09* *PRELIMINARY*]

NUHM1:



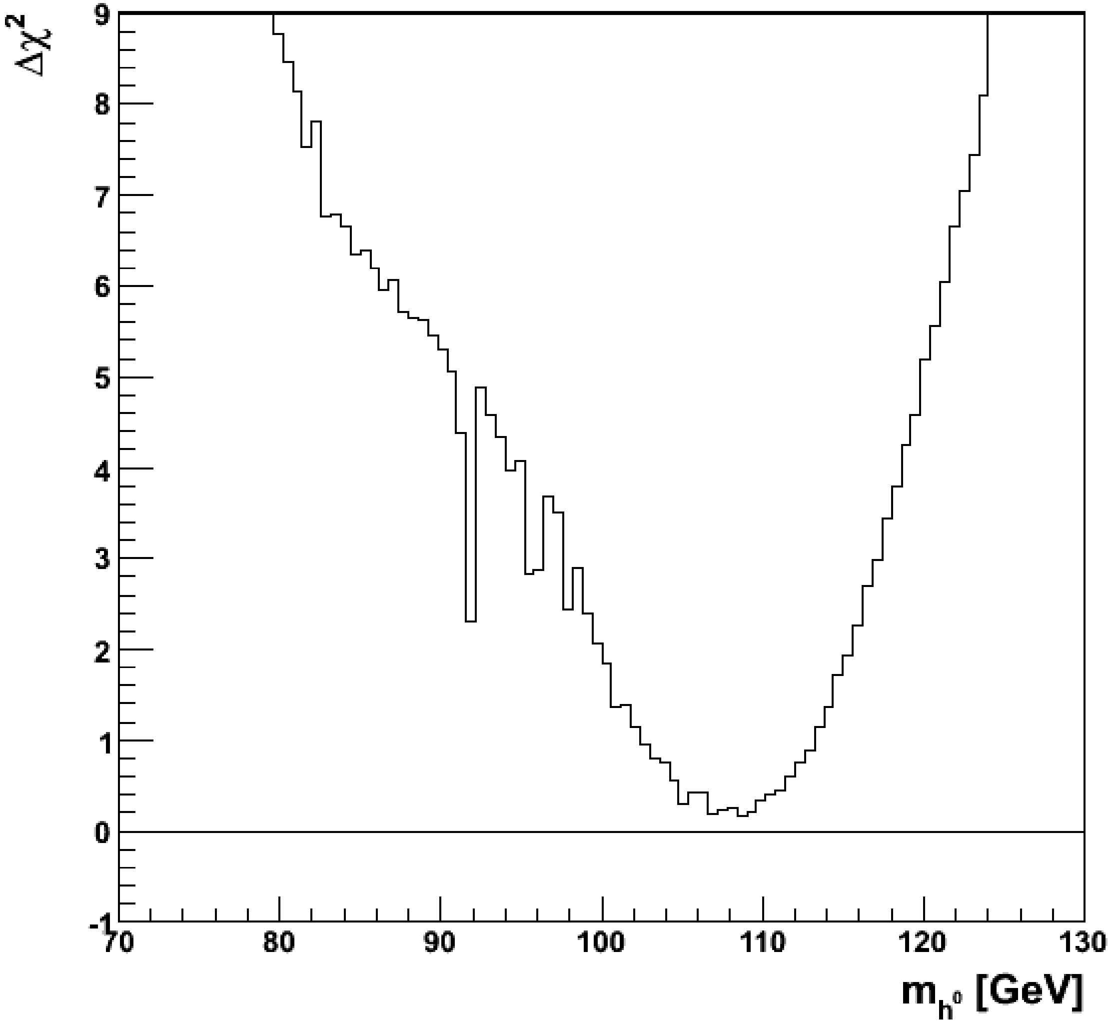
⇒ much larger than in the CMSSM possible

⇒ accessible at the Tevatron(?)/LHCb

Prediction for M_h: [*MasterCode '09 PRELIMINARY*]

(LEP bounds not included!)

CMSSM:

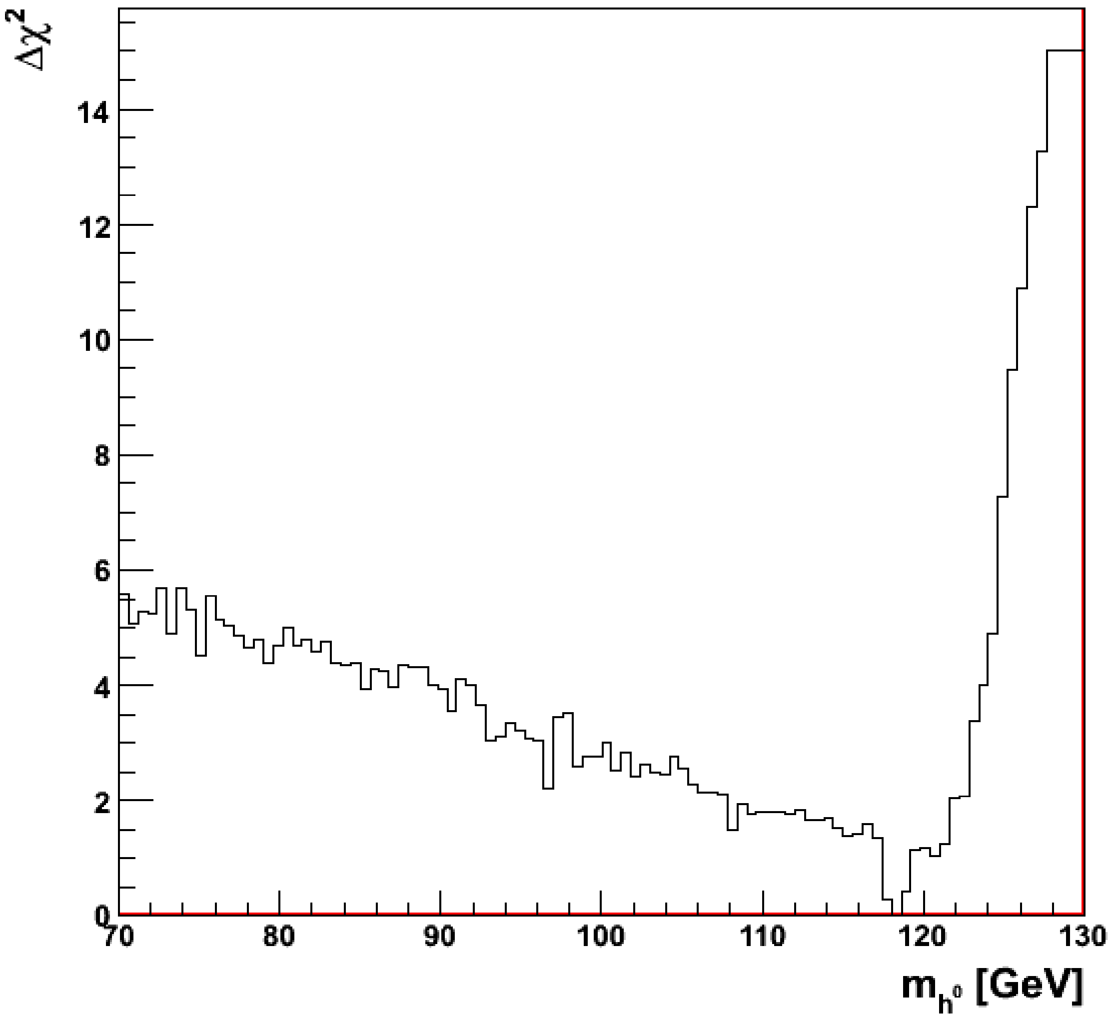


⇒ LEP bound relatively easily avoided

Prediction for M_h: [MasterCode '09 PRELIMINARY]

(LEP bounds not included!)

NUHM1:



$\Rightarrow M_h > 114.4$ GeV appears naturally

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): $M_h = 109 \pm 6 \pm 3$ GeV (prelim.!)
  NUHM1: $m_{1/2} = 240$ GeV, $m_0 = 100$ GeV, $A_0 = -930$ GeV,
  $\tan\beta = 7$, $\mu = 870$ GeV, $M_A = 300$ GeV
  Prediction of M_h (no LEP bound): best fit: $M_h \approx 120$ GeV (prelim.!)
- 95% C.L. areas: mostly covered with ~ 1 fb^{-1} (u.d.!)
  $\Rightarrow$ early LHC data could be very conclusive!

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  Brand new results:

  $\rightarrow$ Henning Flächer's talk

  P1.C, June 6, 2pm, 105 Shillman

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14.-18. September
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