BSM Physics at the LHC

Sven Heinemeyer, IFCA (CSIC, Santander)

Barcelona, 09/2010

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1. Introduction

2. Introduction to Supersymmetry

3. Supersymmetry at the LHC

4. More BSM phenomenology at the LHC

5. Conclusions

BSM Physics at the LHC (II)

Supersymmetry at the LHC

1. SUSY Higgs physics at the LHC
2. Colored Sparticles at the LHC
3. SUSY fits and predictions for the LHC

1. SUSY Higgs at the LHC

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2(\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) + \underbrace{\frac{g'^2 + g^2}{8}}(H_1\bar{H}_1 - H_2\bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}|H_1\bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

2 $\mathcal{CP}$-violating phases: ξ, $\arg(m_{12})$ $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2$$

Discovering the Higgs boson

What has to be done?

1. Find the new particle

Discovering the Higgs boson

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1. Find the new particle
2. measure its mass ($\Rightarrow$ ok?)

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What has to be done?

1. Find the new particle
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4. measure couplings to fermions
5. measure self-couplings
6. measure spin, . . .

Discovering the Higgs boson

What has to be done?

1. Find the new particle	T
2. measure its mass ($\Rightarrow$ ok?)	T
3. measure coupling to gauge bosons	
4. measure couplings to fermions	
5. measure self-couplings	
6. measure spin, ...	

T = Tevatron,

Discovering the Higgs boson

What has to be done?

1. Find the new particle	T	L
2. measure its mass ($\Rightarrow$ ok?)	T	L
3. measure coupling to gauge bosons		L
4. measure couplings to fermions		L
5. measure self-couplings		
6. measure spin, ...		

T = Tevatron, L = LHC,

Discovering the Higgs boson

What has to be done?

	T	L	I
1. Find the new particle	T	L	I
2. measure its mass ($\Rightarrow$ ok?)	T	L	I
3. measure coupling to gauge bosons		L	I
4. measure couplings to fermions		L	I
5. measure self-couplings			I
6. measure spin, . . .			I

T = Tevatron, L = LHC, I = ILC

We need the ILC to find the Higgs
and to establish the Higgs mechanism!
But the LHC can do a crucial part already!

Contrary to the SM:

m_h is not a free parameter

MSSM tree-level bound: $m_h < M_Z$ $\Rightarrow$ SUSY always requires a light Higgs!

Large radiative corrections:

Dominant one-loop corrections:

$$\Delta M_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Measurement of M_h, Higgs couplings $\Rightarrow$ test of the theory

Upper bound on M_h in the MSSM:

"Unconstrained MSSM":

M_A, $\tan\beta$, 5 parameters in $\tilde{t}$–$\tilde{b}$ sector, μ, $m_{\tilde{g}}$, M_2

$$M_h \lesssim 135 \text{ GeV}$$

for $m_t = 173.3 \pm 1.1\,\text{GeV}$

(including theoretical uncertainties from unknown higher orders)
⇒ observable at the LHC

Obtained with:

FeynHiggs

[*S.H., W. Hollik, G. Weiglein '98 – '02*]

[*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '03 – '10*]

`www.feynhiggs.de`

→ all Higgs masses, couplings, BRs, XSs (easy to link, easy to use :-)

Higgs couplings, tree level:

$$
\begin{aligned}
g_{hVV} &= \sin(\beta-\alpha)\, g_{HVV}^{\text{SM}}, \qquad V = W^{\pm}, Z \\
g_{HVV} &= \cos(\beta-\alpha)\, g_{HVV}^{\text{SM}} \\
g_{hAZ} &= \cos(\beta-\alpha)\, \frac{g'}{2\cos\theta_W} \\
g_{hb\bar{b}}, g_{h\tau^+\tau^-} &= -\frac{\sin\alpha}{\cos\beta}\, g_{Hb\bar{b},H\tau^+\tau^-}^{\text{SM}} \\
g_{ht\bar{t}} &= \frac{\cos\alpha}{\sin\beta}\, g_{Ht\bar{t}}^{\text{SM}} \\
g_{Ab\bar{b}}, g_{A\tau^+\tau^-} &= \gamma_5 \tan\beta\, g_{Hb\bar{b}}^{\text{SM}}
\end{aligned}
$$

$\Rightarrow$ $g_{hVV} \le g_{HVV}^{\text{SM}}$, g_{hVV}, g_{HVV}, g_{hAZ} cannot all be small

$g_{hb\bar{b}}, g_{h\tau^+\tau^-}$: significant suppression or enhancement w.r.t. SM coupling possible

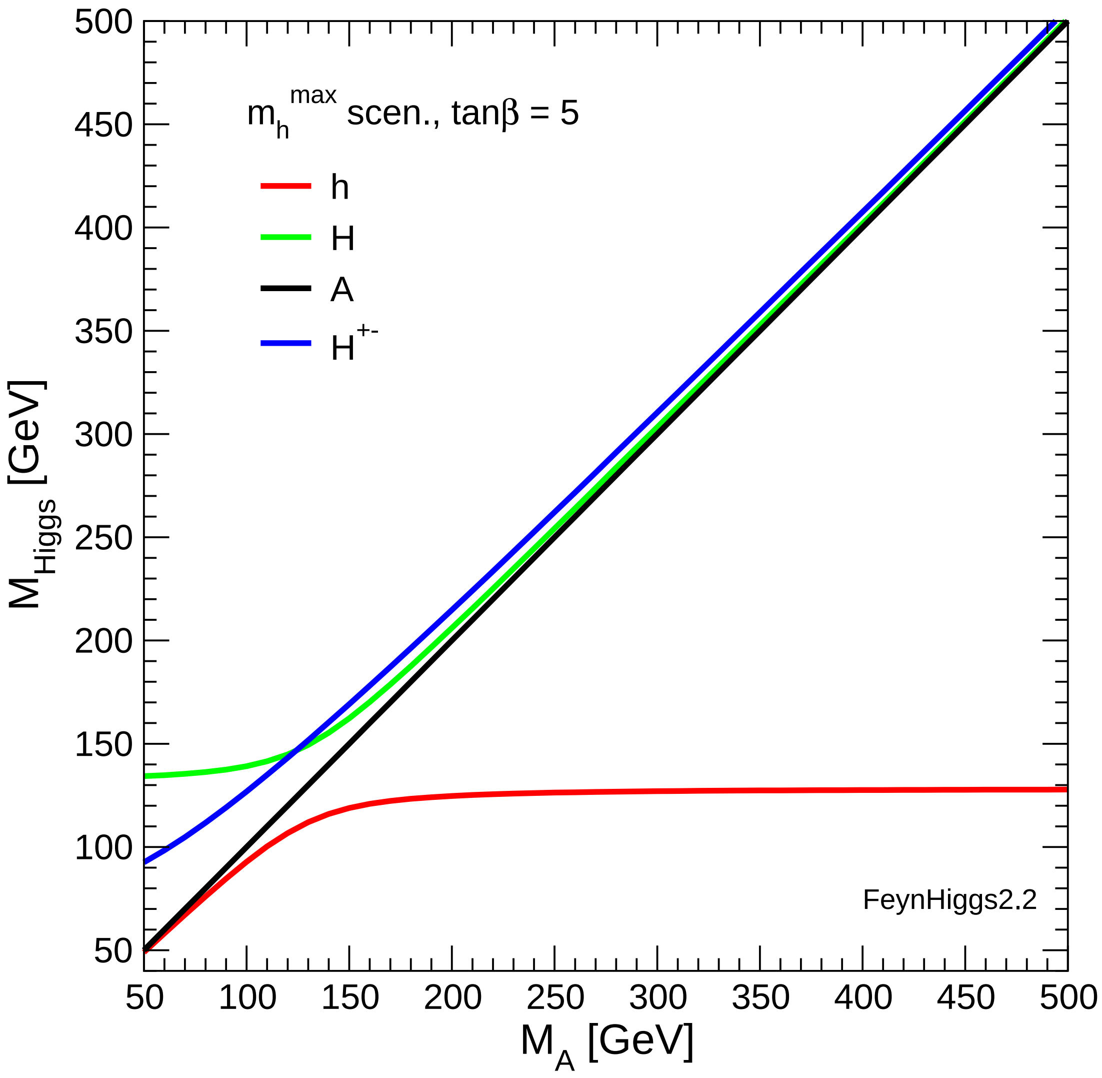
The decoupling limit:

For $M_A \gtrsim 150$ GeV:

The lightest MSSM Higgs is SM-like

The heavy MSSM Higgses:
$M_A \approx M_H \approx M_{H^\pm}$

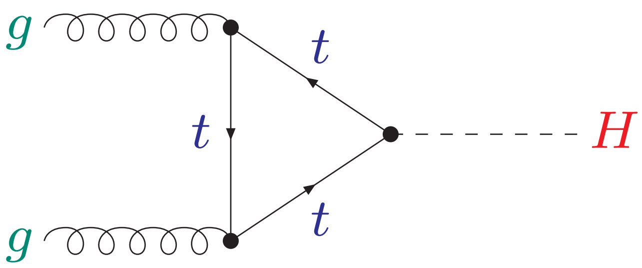
of course there are exceptions . . .



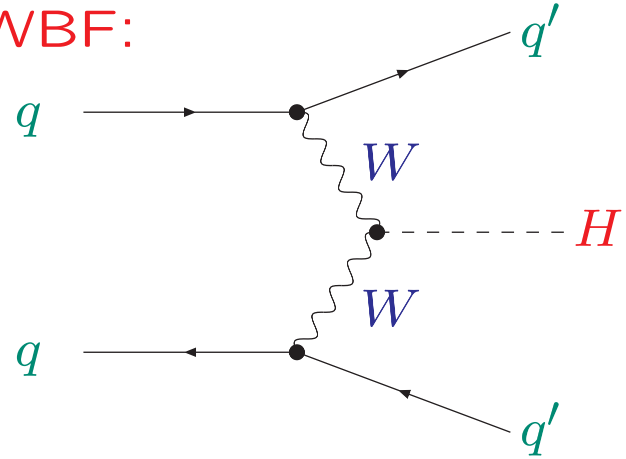
Higgs search at the LHC:

Important SM production channel at the LHC:

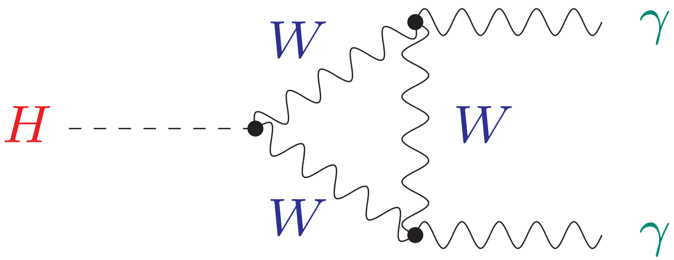
Gluon-Fusion:

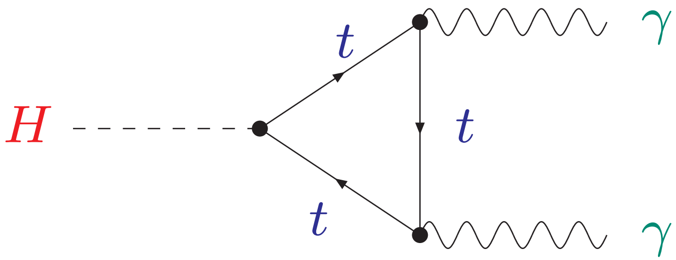


WBF:



Important decay for Higgs mass measurement:

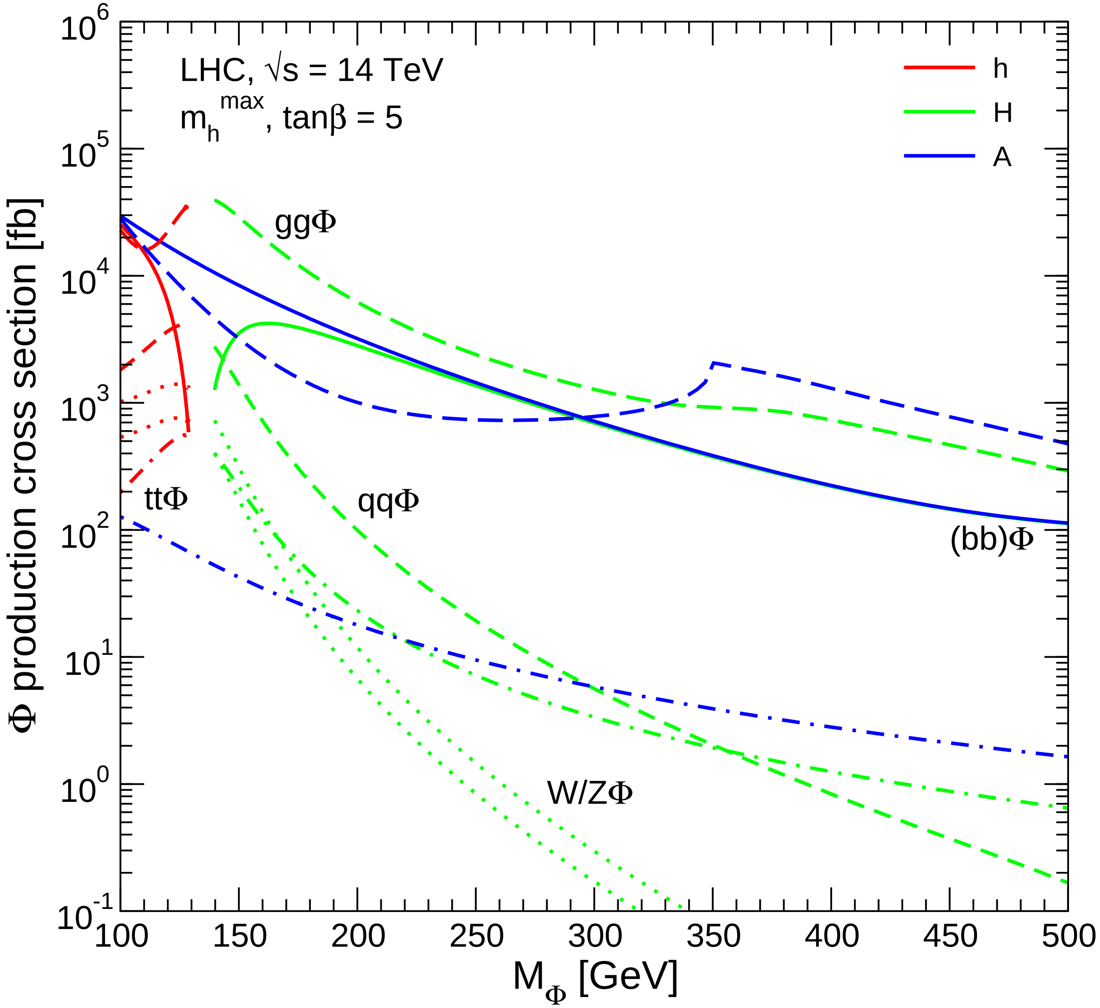




SM Higgs search at the LHC: ⇒ full parameter accessible

Overview about SUSY Higgs production cross sections $(\phi = h, H, A)$

[*Tev4LHC Higgs working group report '06*]



gluon fusion: $gg \to \phi$

weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'\phi$

top quark associated production: $gg, q\bar{q} \to t\bar{t}\phi$

weak boson associated production: $q\bar{q}' \to W\phi, Z\phi$

NEW: $b\bar{b}\phi$

Search for the lightest MSSM Higgs at the LHC:

⇒ full parameter accessible   But there might be problems . . .

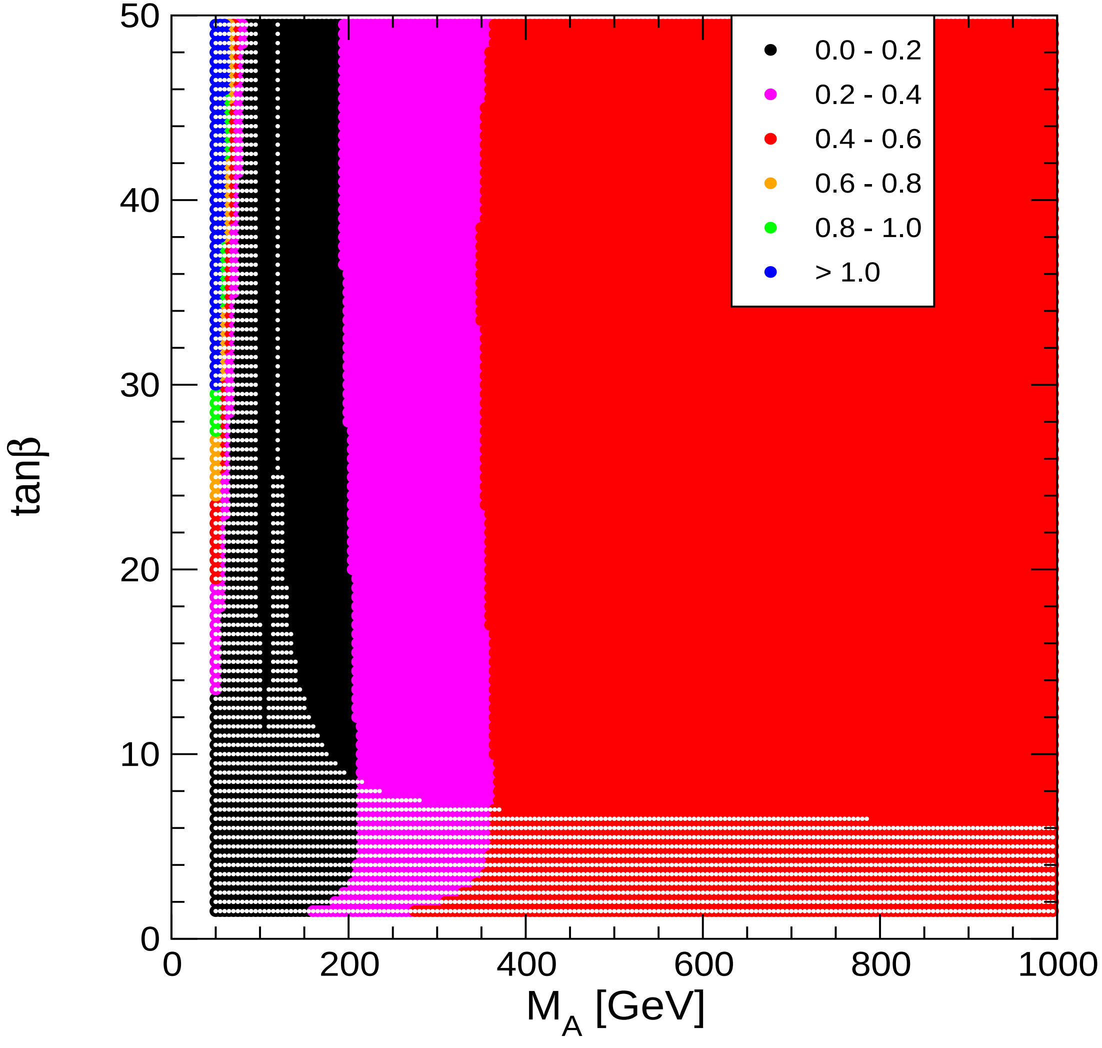
Possible problem in SUSY:

$$gg \to h \to \gamma\gamma$$

can be strongly suppressed

$\to$ "gluophobic Higgs scenario"

[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

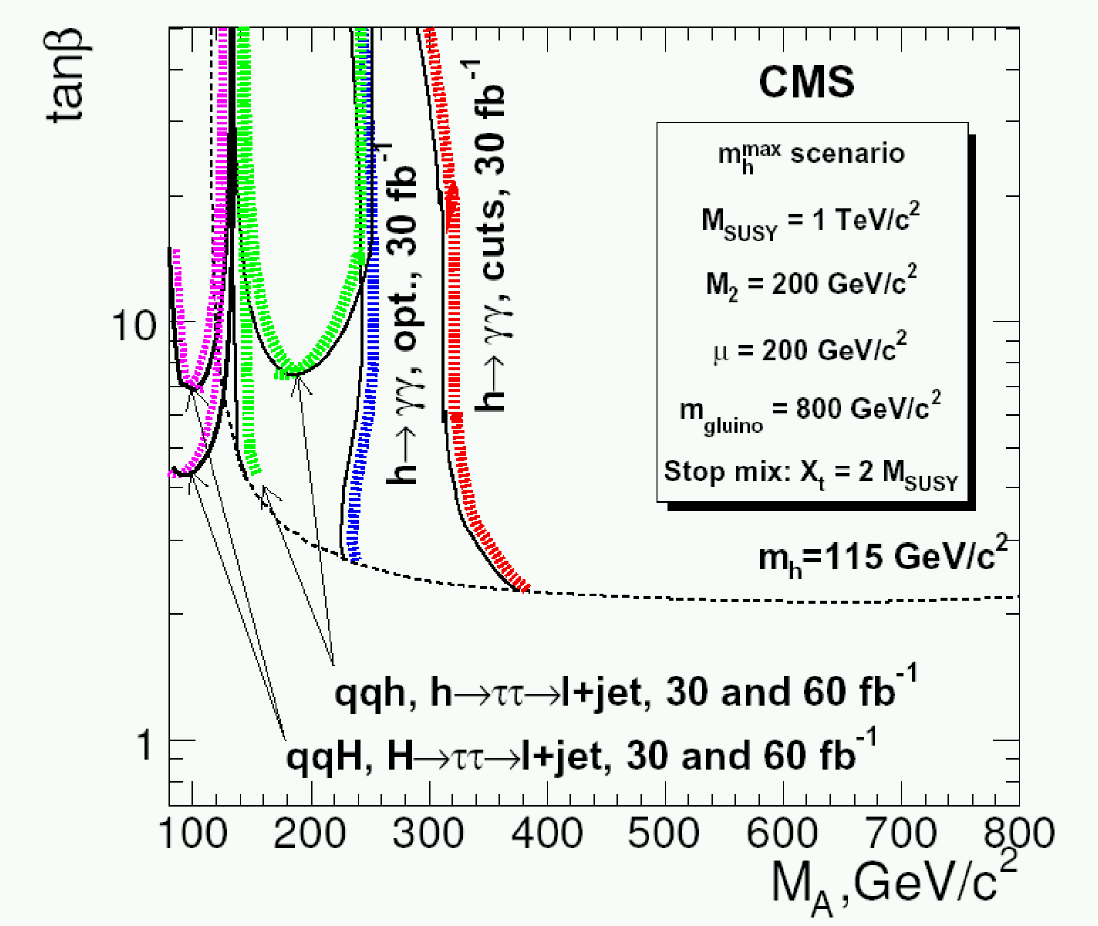


$\Rightarrow$ Strong suppression of $gg \to h \to \gamma\gamma$ possible over the whole parameter space

(not realized in mSUGRA/CMSSM, GMSB, AMSB, . . .)

M_h measurement in the "nice" $m_h^{\max}$ scenario:

[*CMS '06*]



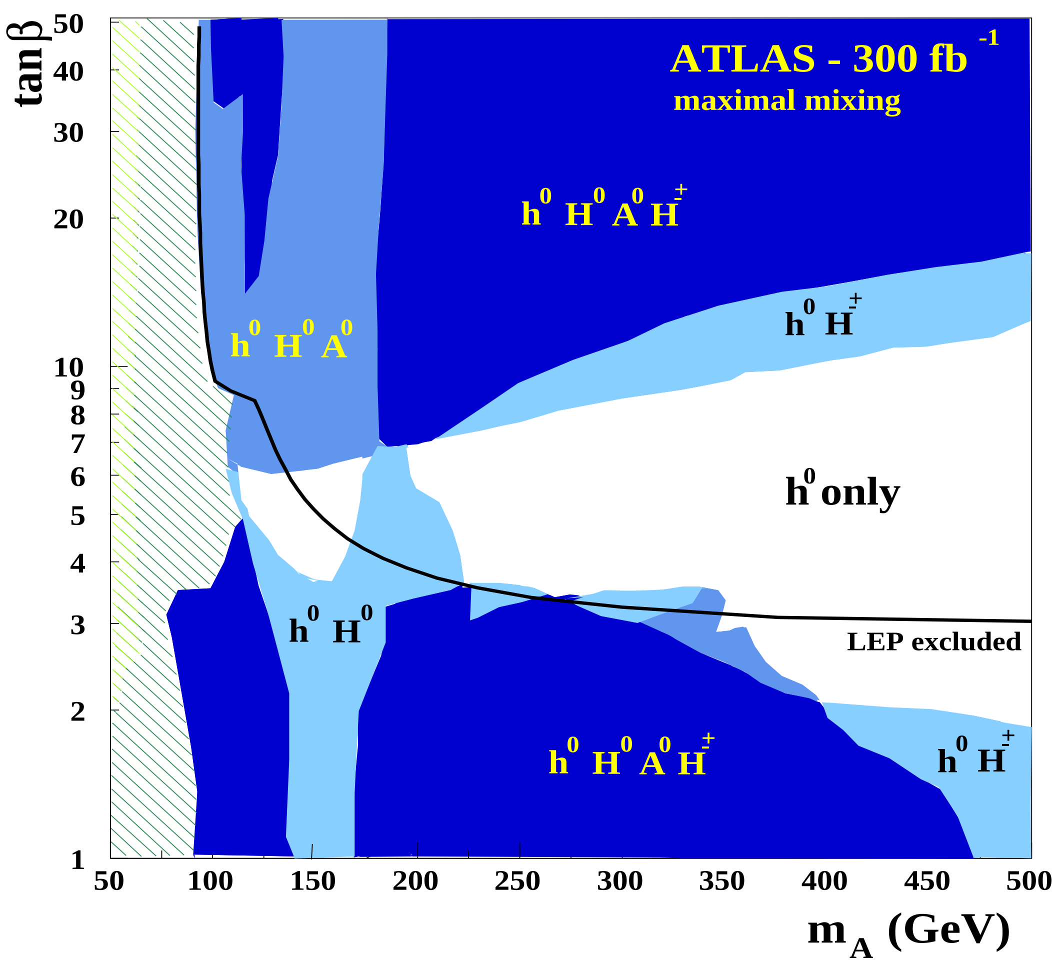
Measurement possible only for
$M_A \gtrsim 250$ GeV
$\Rightarrow \delta M_h \approx 200$ MeV

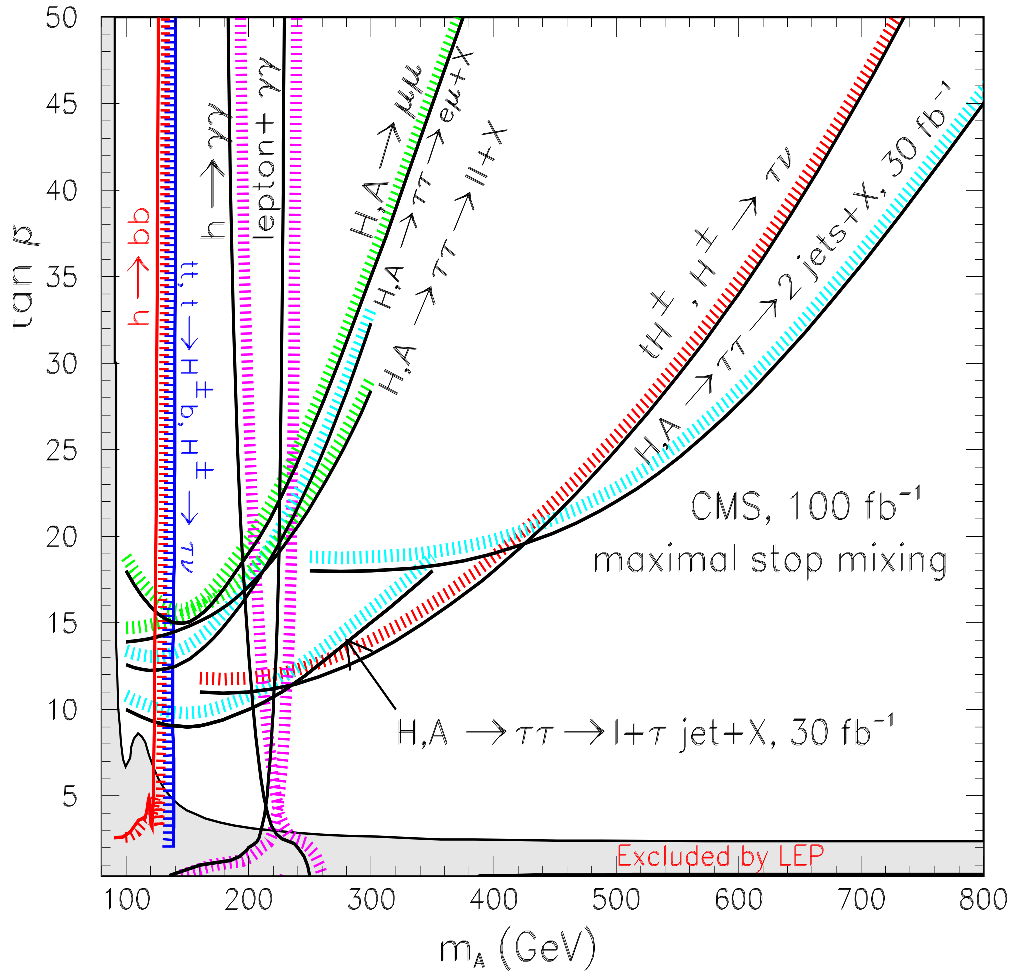
other channels:
$h \to ZZ^* \to 4\mu$ ($M_h \gtrsim 130$ GeV)

otherwise: $\delta M_h \gtrsim 1-2$ GeV

The heavy MSSM Higgs bosons

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane
($m_h^{\rm max}$ benchmark scenario): [*ATLAS '99*] [*CMS '03*]

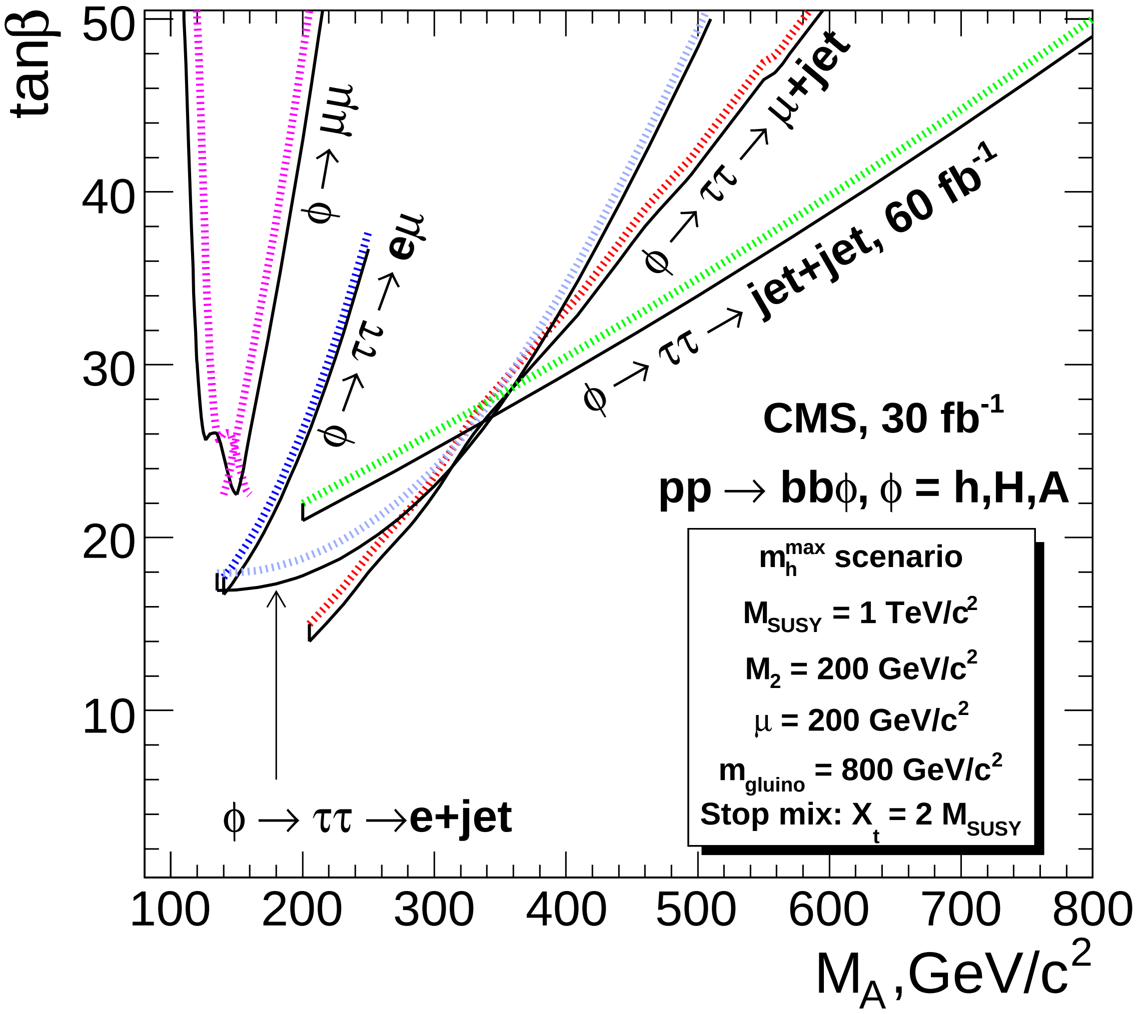




areas where only h is observable ⇒ "LHC wedge"

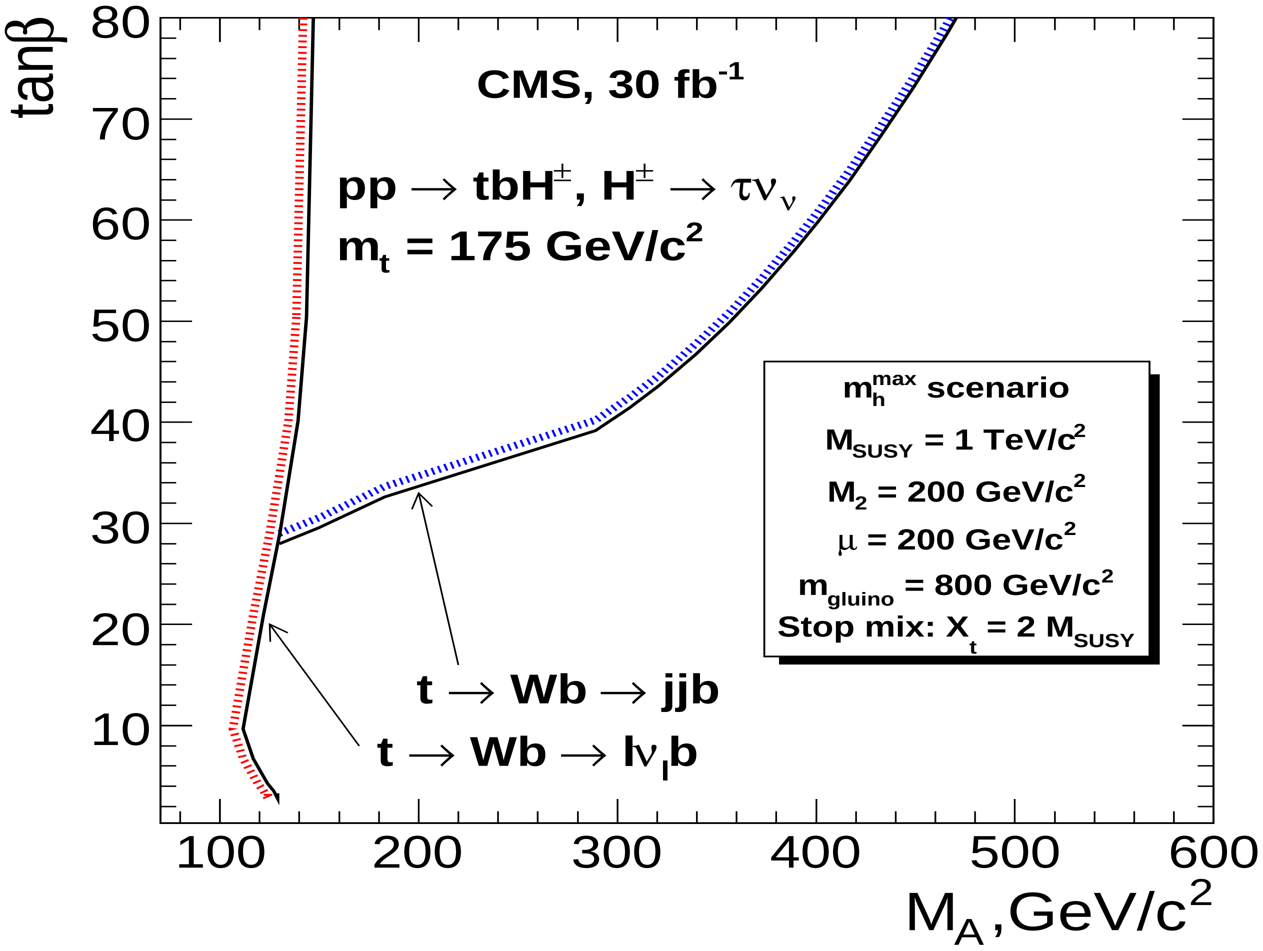
Latest results for neutral heavy Higgs bosons:

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane $(\Phi = H, A)$
($m_h^{\rm max}$ benchmark scenario): [*CMS PTDR '06*]



Charged Higgs boson searches:

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane
($m_h^{\rm max}$ benchmark scenario): [*CMS PTDR '06*]



light charged Higgs:

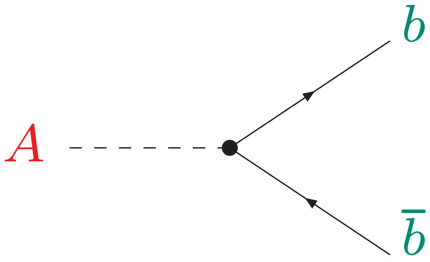
$$M_{H^\pm} < m_t$$

heavy charged Higgs:

$$M_{H^\pm} > m_t$$

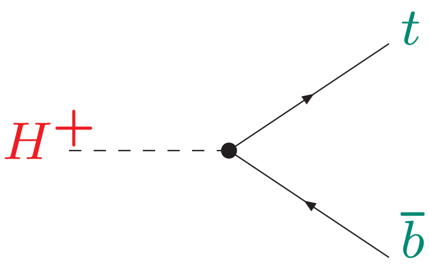
Differences compared to the SM Higgs:

Additional enhancement factors compared to the SM case:



$$y_b \quad \longrightarrow \quad y_b \, \frac{\tan\beta}{1 + \Delta_b}$$

At large $\tan\beta$: either $H \approx A$ or $h \approx A$



$$y_b \, \frac{\tan\beta}{1 + \Delta_b}$$

$$\Delta_b = \frac{2\alpha_s}{3\,\pi} m_{\tilde{g}} \, \mu \tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\,\pi} A_t \, \mu \tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$

$\Rightarrow$ other parameters enter $\Rightarrow$ strong μ dependence

Most powerful search modes for heavy MSSM Higgs bosons:

$$b\bar{b} \to H/A \to \tau^+\tau^- + X$$
$$gb \to tH^\pm + X, \;\; H^\pm \to \tau\nu_\tau$$
$$pp \to t\bar{t} \to H^\pm + X, \;\; H^\pm \to \tau\nu_\tau$$

Enhancement factors compared to the SM case:

$$H/A \;:\; \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{\text{BR}(H \to \tau^+\tau^-) + \text{BR}(A \to \tau^+\tau^-)}{\text{BR}(H \to \tau^+\tau^-)_{\text{SM}}}$$

$$H^\pm \;:\; \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \text{BR}(H^\pm \to \tau\nu_\tau)$$

$\Rightarrow$ Δ_b effects so far not included in ATLAS/CMS analyses

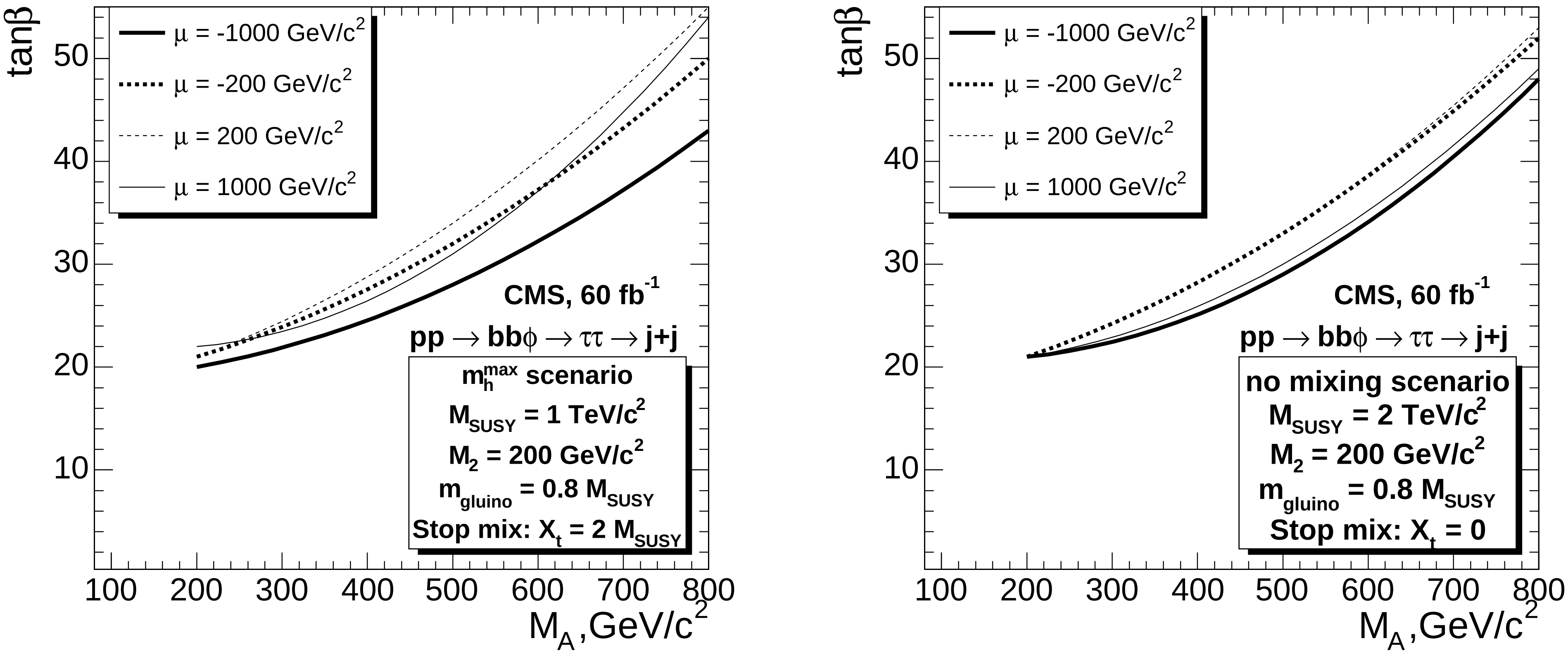
also relevant for BR($H/A \to \tau^+\tau^-$), BR($H^\pm \to \tau\nu_\tau$)

also relevant: correct evaluation of $\Gamma(H/A/H^\pm \to$ SUSY)

$\Rightarrow$ additional effects on BR($H/A \to \tau^+\tau^-$), BR($H^\pm \to \tau\nu_\tau$)

Dependence of LHC wedge from $b\bar{b} \to H/A \to \tau^+\tau^- \to 2\,\text{jets}$ on μ:

[S.H., A. Nikitenko, G. Weiglein et al. '06]

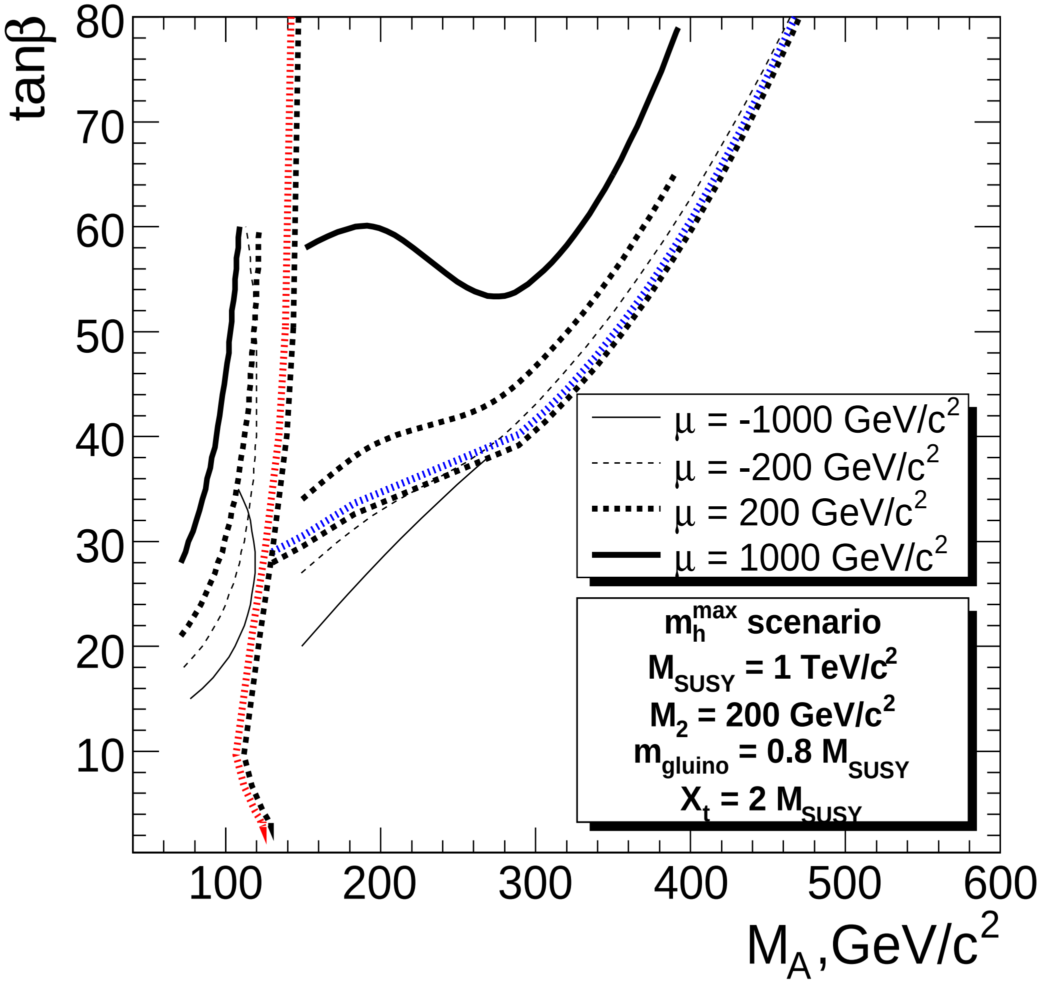


⇒ now based on full CMS simulation

⇒ non-negligible variation with the sign and absolute value of μ
(→ numerical compensations in production and decay)

Charged Higgs: comparison with CMS PTDR ($m_h^{\max}$ scenario):

[*M. Hashemi, S.H., R. Kinnunen, A. Nikitenko, G. Weiglein '07*]



→ note: M_A–$\tan\beta$ plane

light charged Higgs:

always worse than PTDR

better $M_{H^\pm}$ calculation!

inclusion of Δ_b effects

heavy charged Higgs:

PTDR in "the middle"

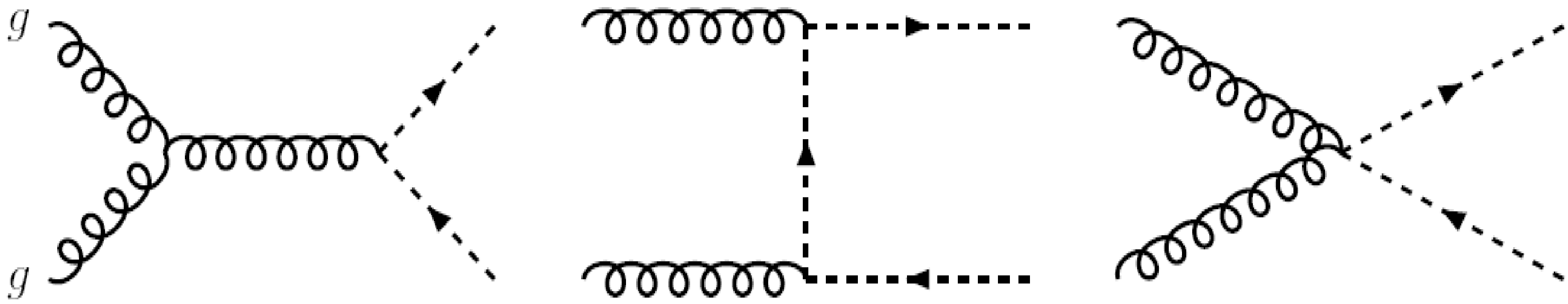
new results partially

substantially worse

2. Colored sparticles at the LHC

SUSY particle production at the LHC:

⇒ colored (s)particles are copiously produced

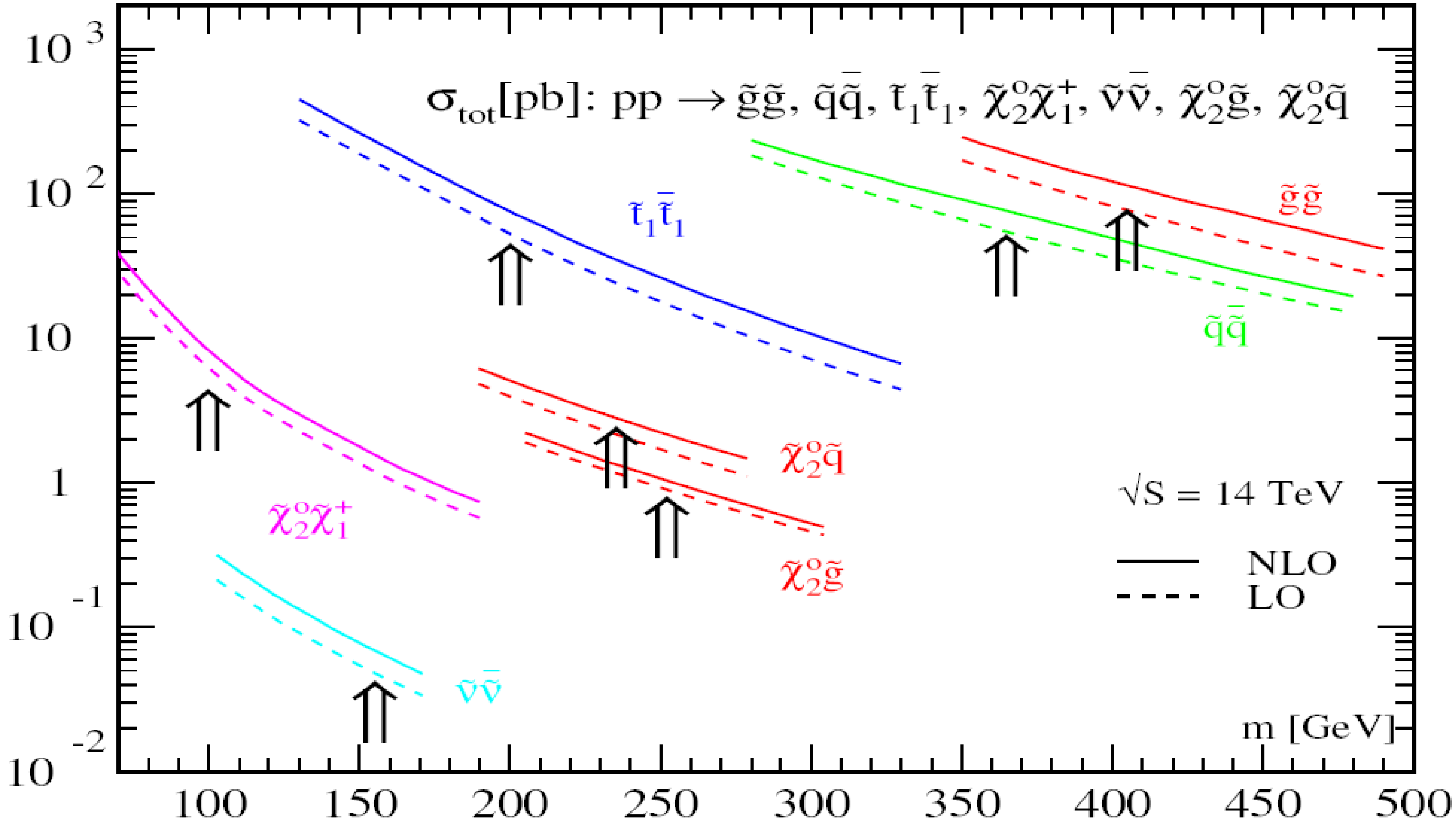


⇒ production of gluinos, squarks, . . .

As in QCD: NLO corrections are crucial!

Example for SUSY production:

[*Prospino collaboration*]



As in QCD: NLO corrections are crucial!

Production of SUSY particles at the LHC

will in general result in complicated final states

⇒ cascade decays

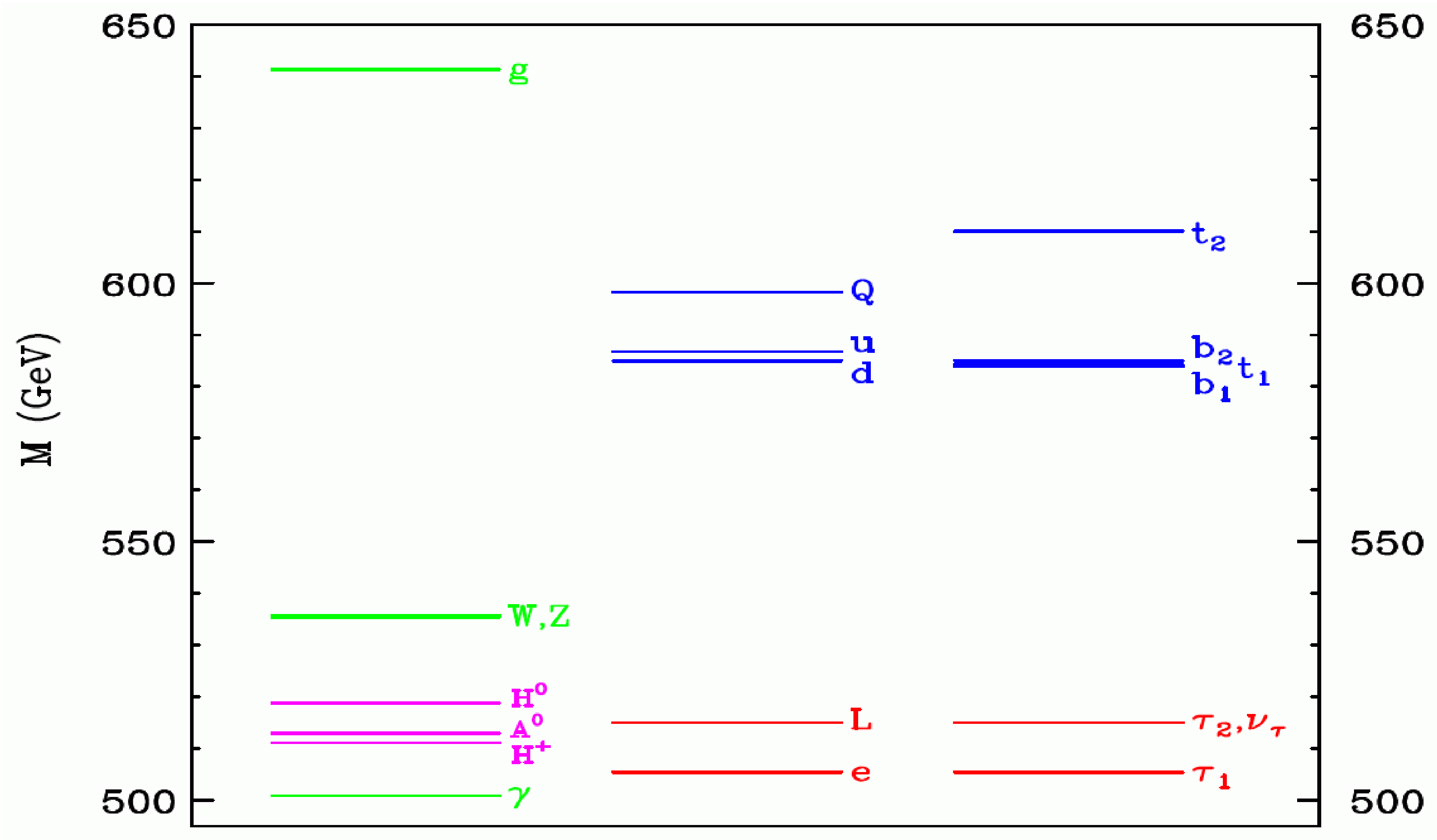
$$\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_2^0 \to \bar{q}q\tilde{\tau}\tau \to \bar{q}q\tau\tau\tilde{\chi}_1^0$$

Production of uncolored particles via cascade decays often dominates over direct production

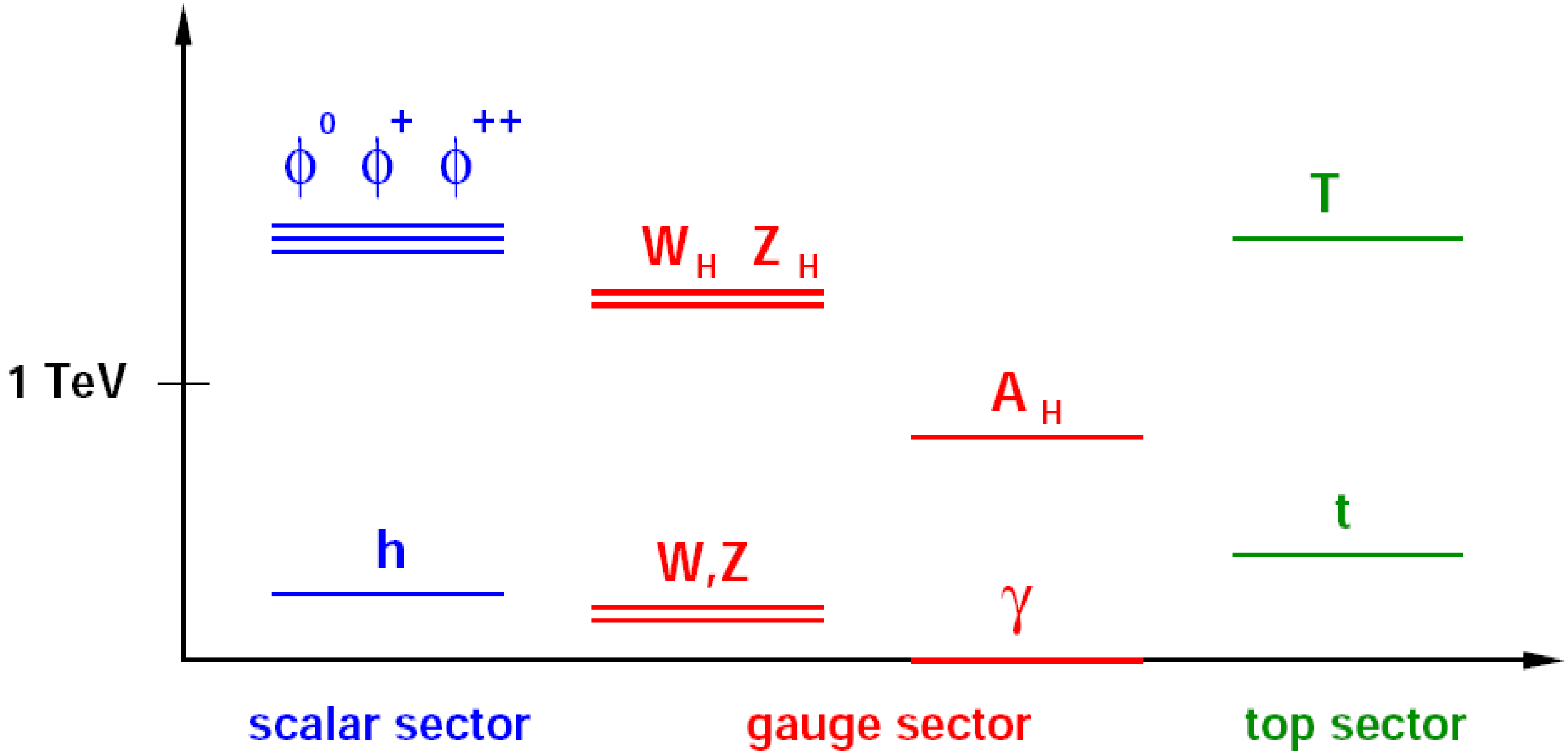
Many states are produced at once

⇒ **Main background for SUSY is SUSY itself!**

Another model beyond the SM: Extra dimensions

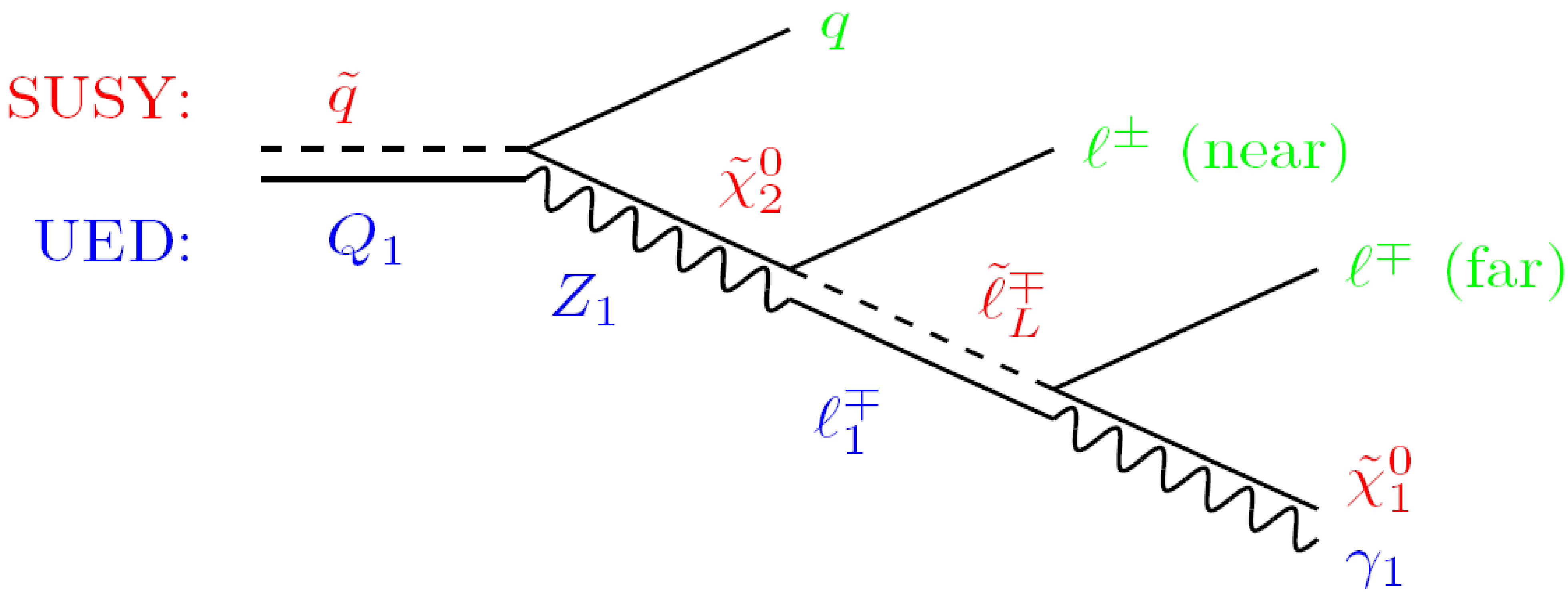


Another model beyond the SM: Little Higgs



Comparison of SUSY with e.g. Extra Dimensions:

$\Rightarrow$ cascades may look very similar:



⇒ In order to establish SUSY experimentally:

Need to demonstrate that:

– every particle has superpartner

– their spins differ by 1/2

– their gauge quantum numbers are the same

– their couplings are identical

– mass relations hold

...

⇒ Precise measurements of masses, branching ratios, cross sections, angular distributions, ... mandatory for

- establishing SUSY experimentally
- disentangling patterns of SUSY breaking

⇒ We need both: hadron colliders (Tev./LHC) and high luminosity ILC

3. SUSY fits and predictions for the LHC:

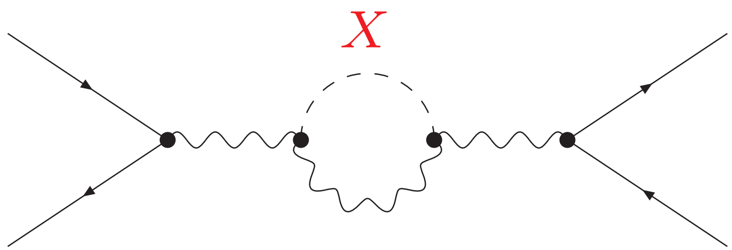
How to make a prediction?

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



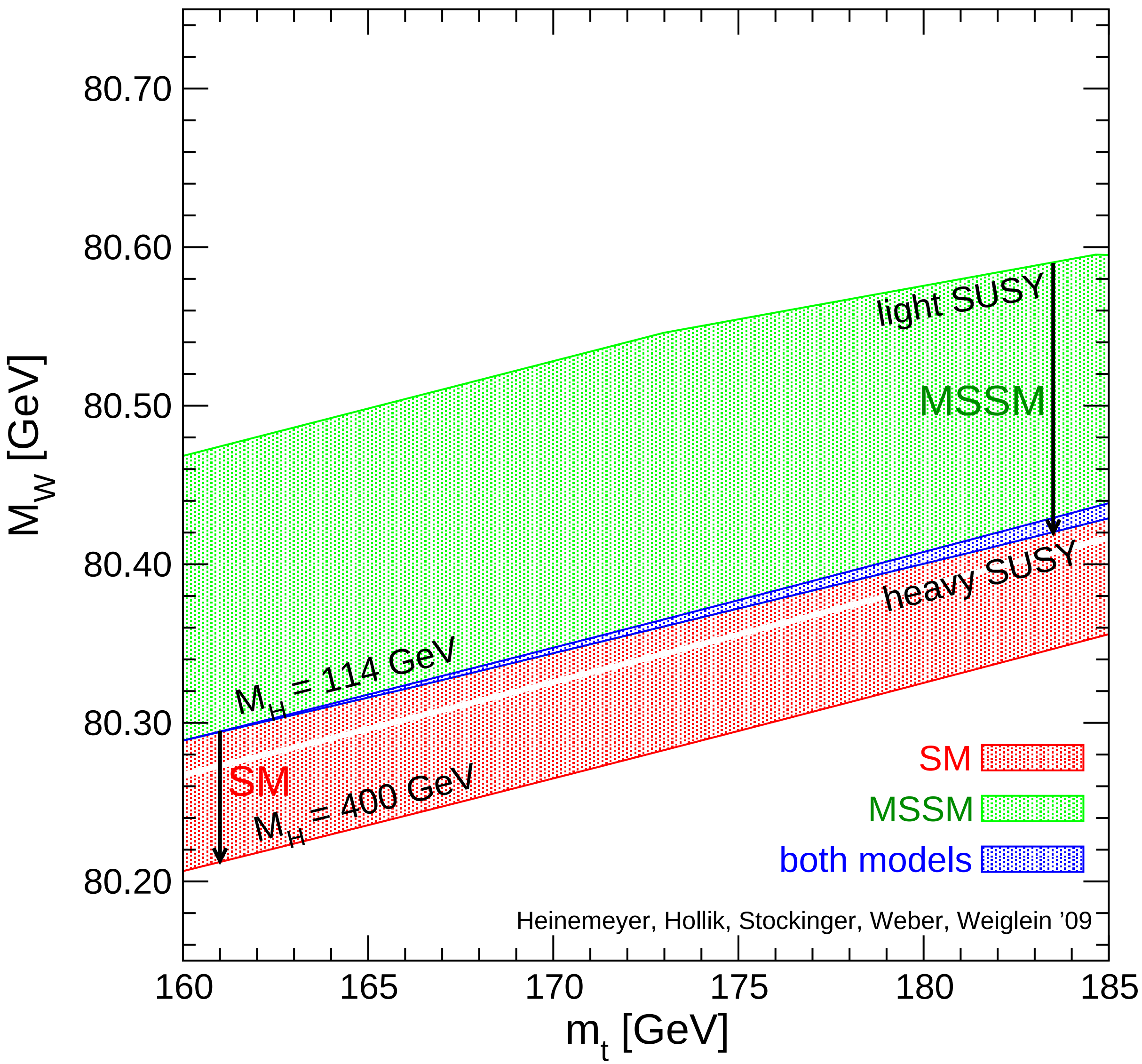
$\Downarrow$

$\Rightarrow$ 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. Weigelein '07*]



MSSM band:
scan over
SUSY masses

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

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

Example: Prediction for M_W in the SM and the MSSM :

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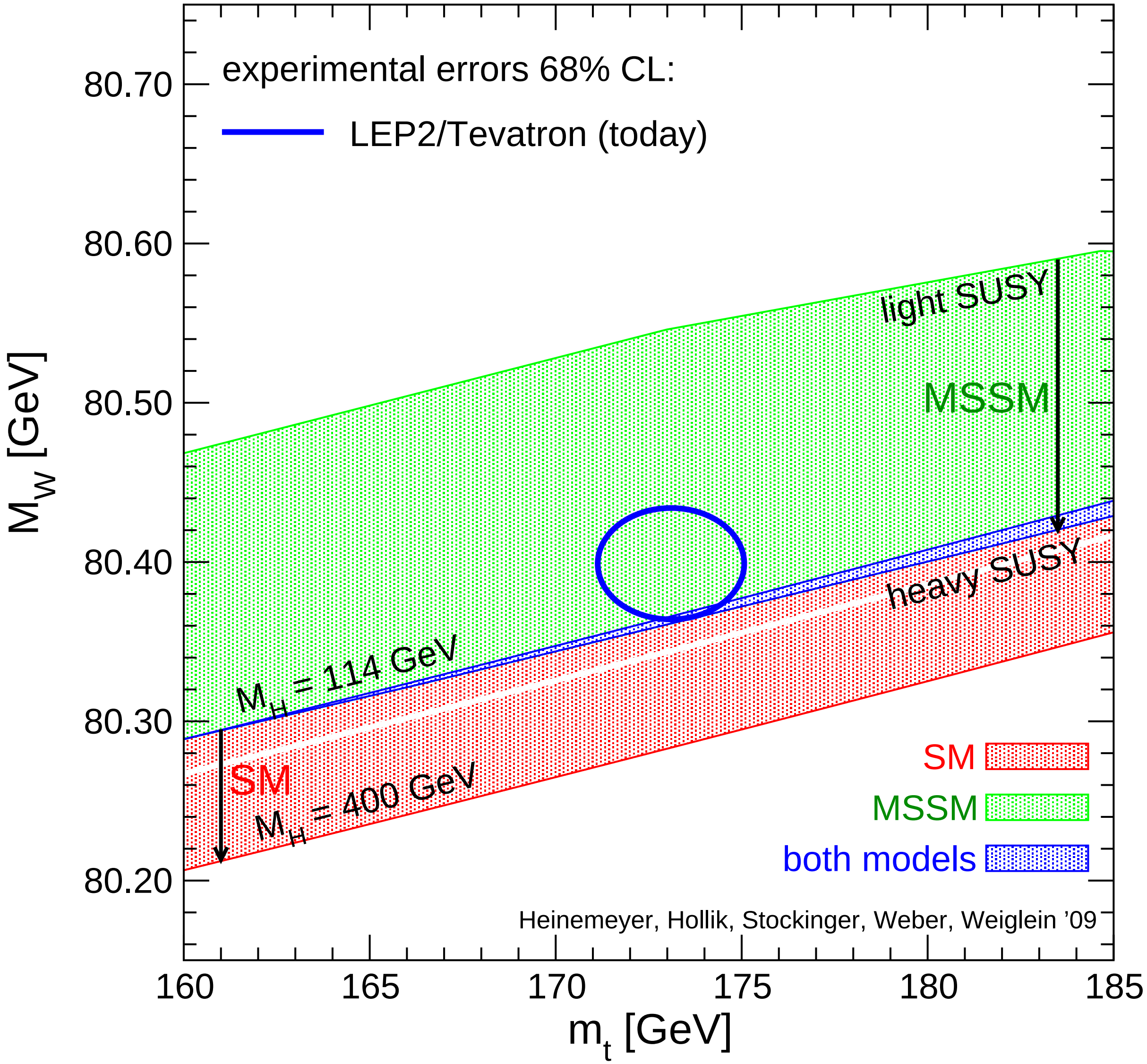

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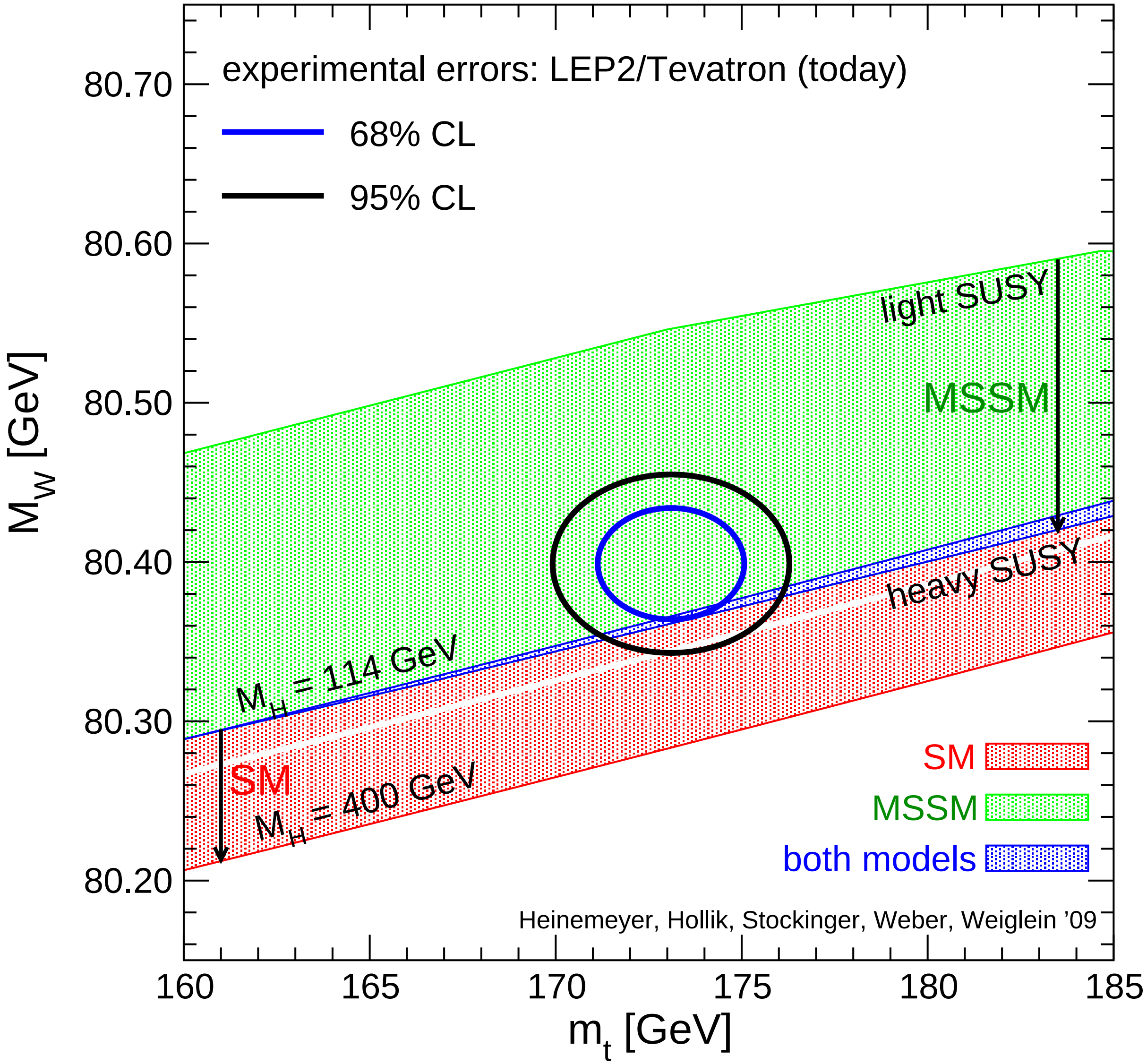

MSSM band:
scan over
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MSSM is SM-like

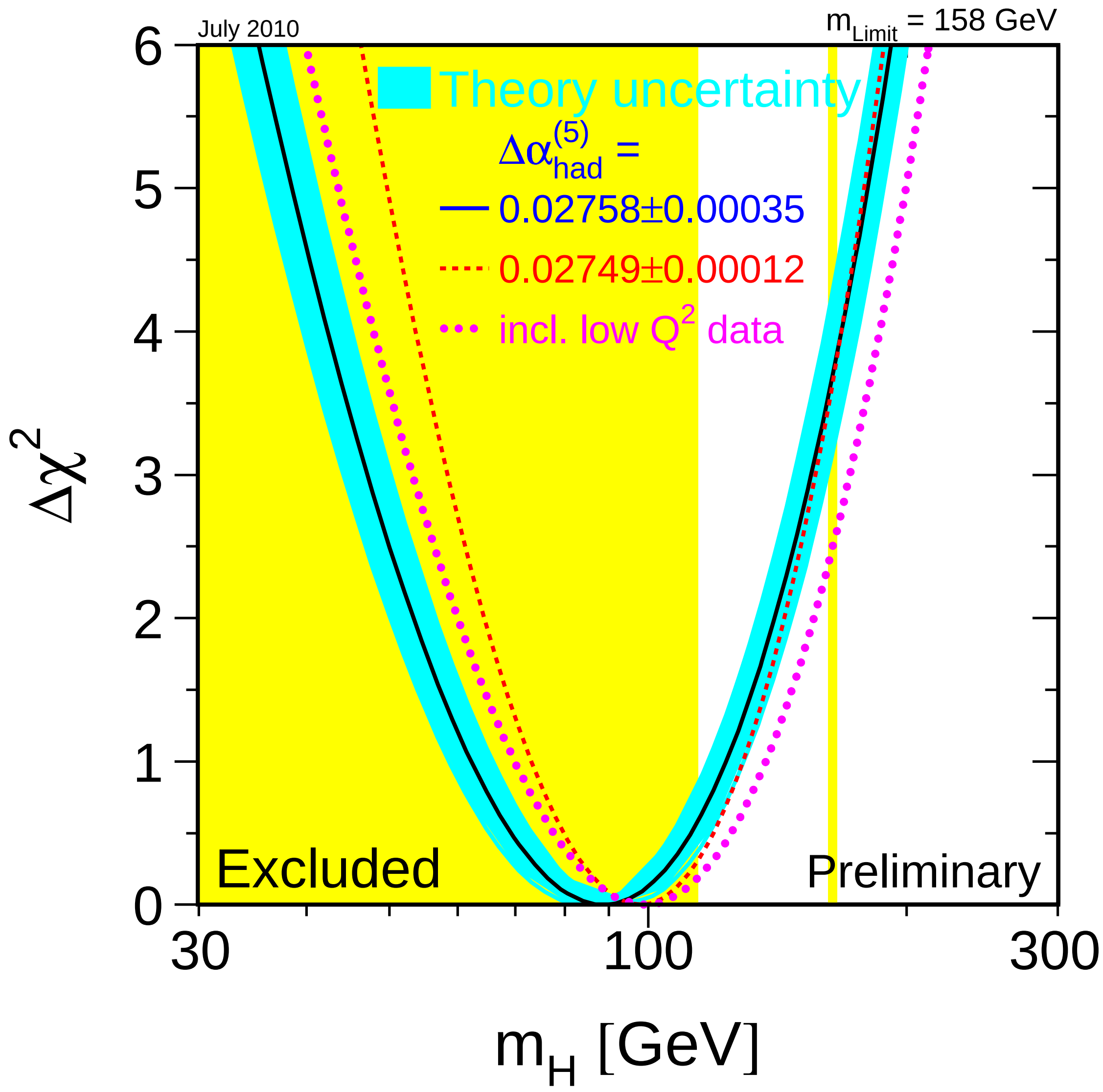
SM band:
variation of M_H^{SM}

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

Main idea of SUSY fits: 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 ⇒ LHC/ILC reach

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 ?

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 ?

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 $\mathrm{BR}(b \to s\gamma)$: 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 ...

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 ?

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 ...

$\Rightarrow$ combination makes only sense if all parameters are connected!
$\Rightarrow$ GUT based models: $\Rightarrow$ CMSSM, NUHM, ...

χ^2 calculation:

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

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

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

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:

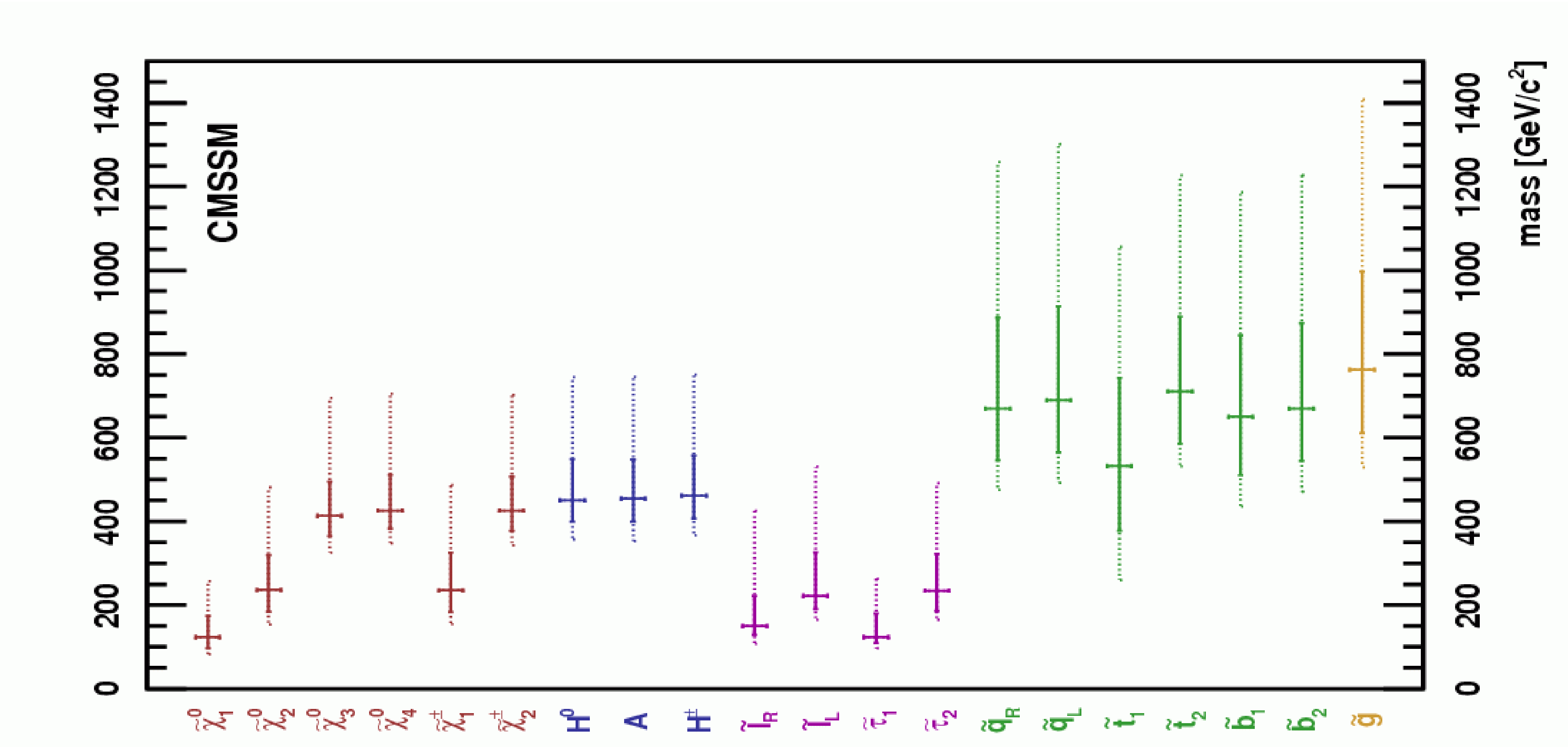
$m_{1/2} = 270$ GeV, $m_0 = 150$ GeV, $A_0 = -1300$ GeV,
$\tan\beta = 11$, $\mu = 1140$ GeV, $M_A = 310$ GeV

(similar probability)

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

Masses for best-fit points: CMSSM

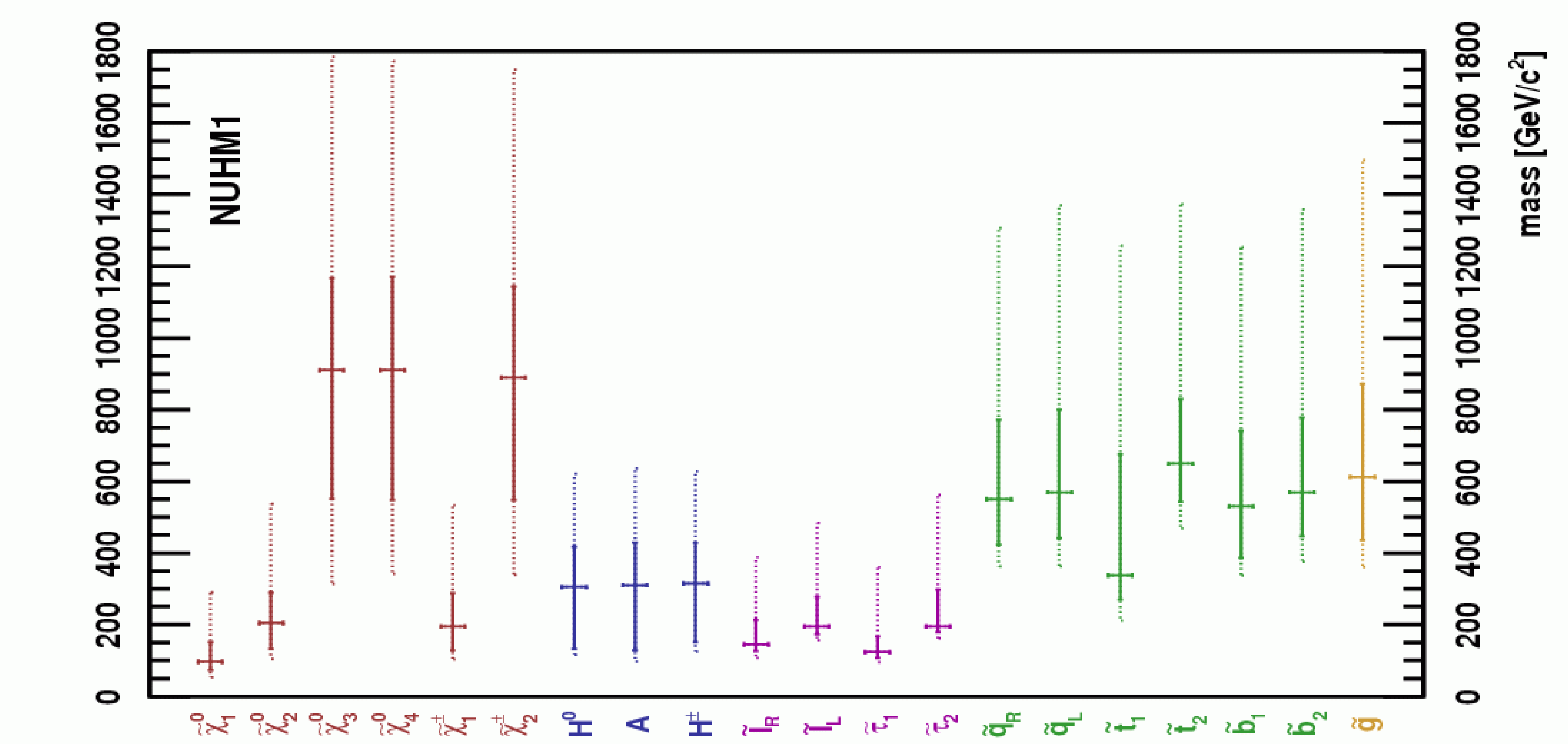
[2009]



$\Rightarrow$ largely accessible spectrum for LHC (and ILC)

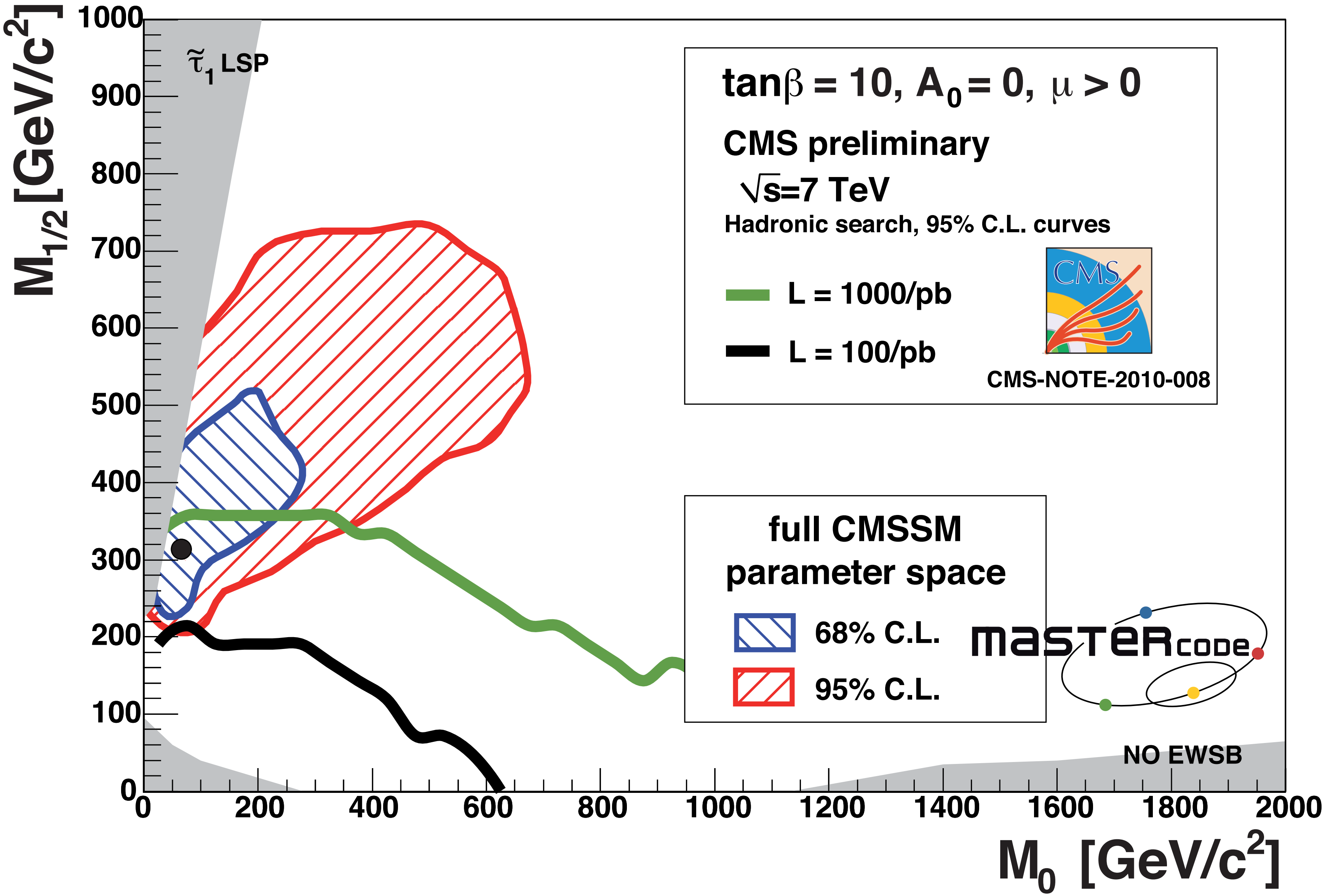
Masses for best-fit points: NUHM1

[2009]



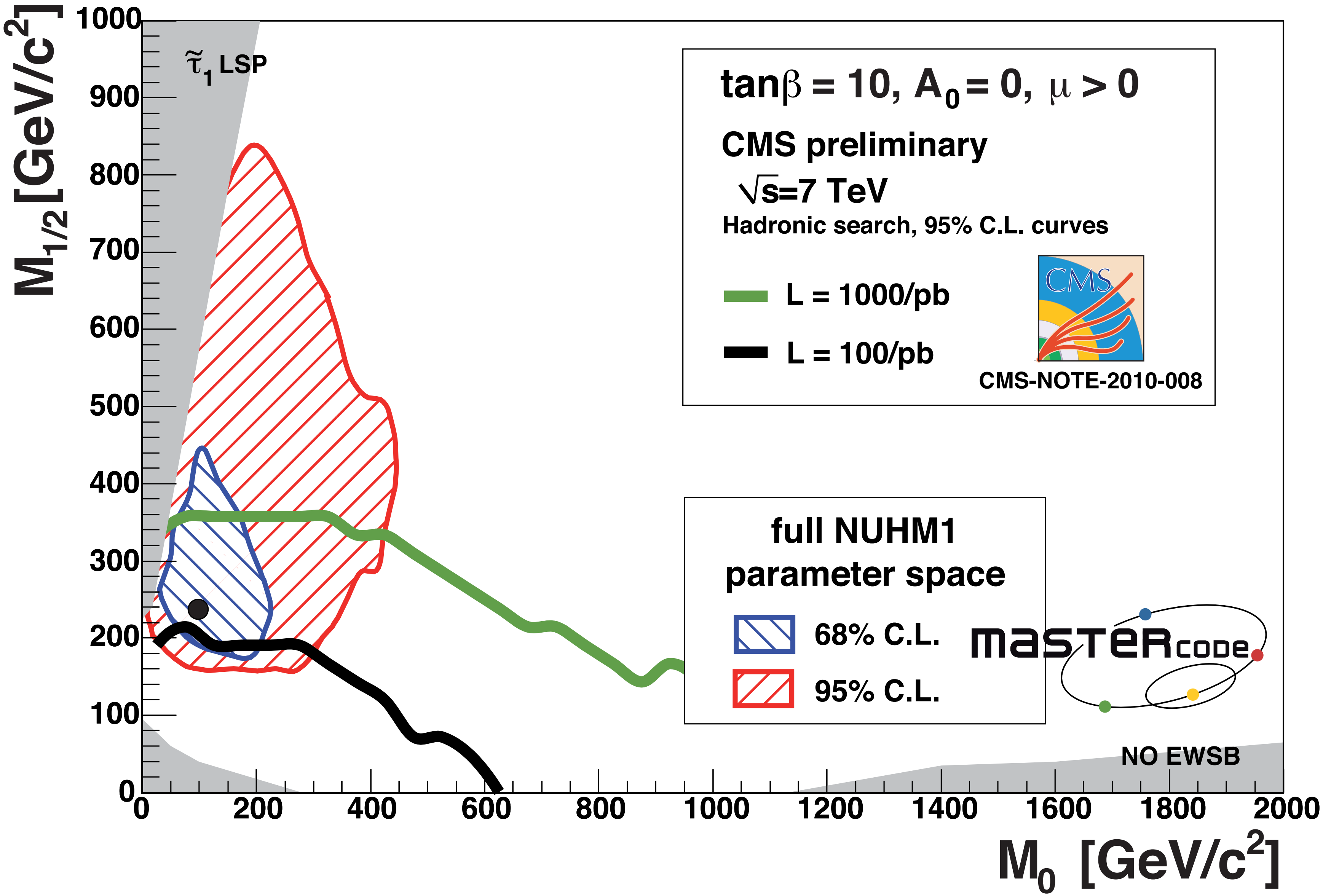
⇒ largely accessible spectrum for LHC (and ILC)

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:

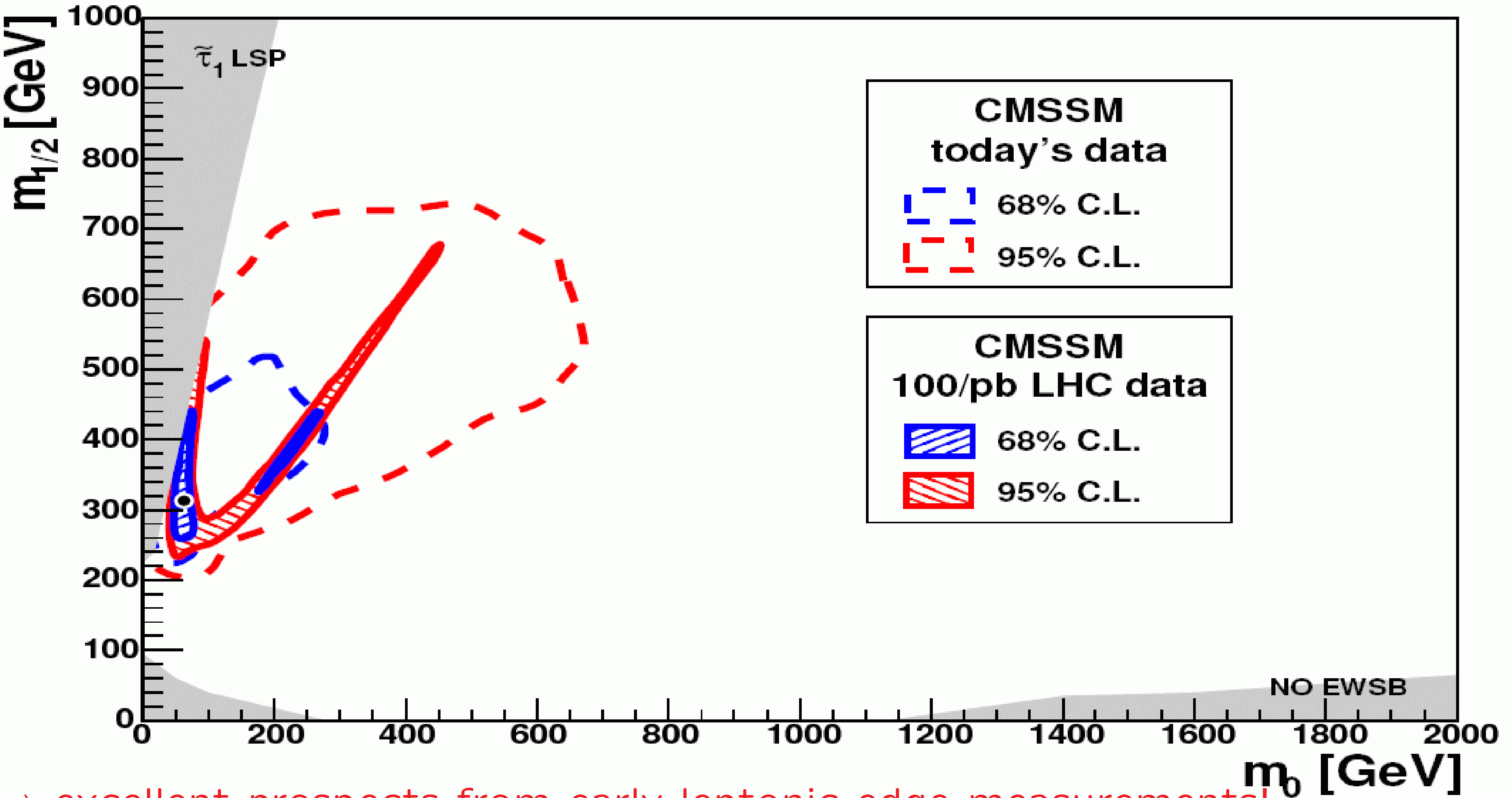


$\Rightarrow$ best-fit point and part of 68% C.L. are can be tested in 2011

LHC (CMS) $\oplus$ CMSSM analysis:

[2008]

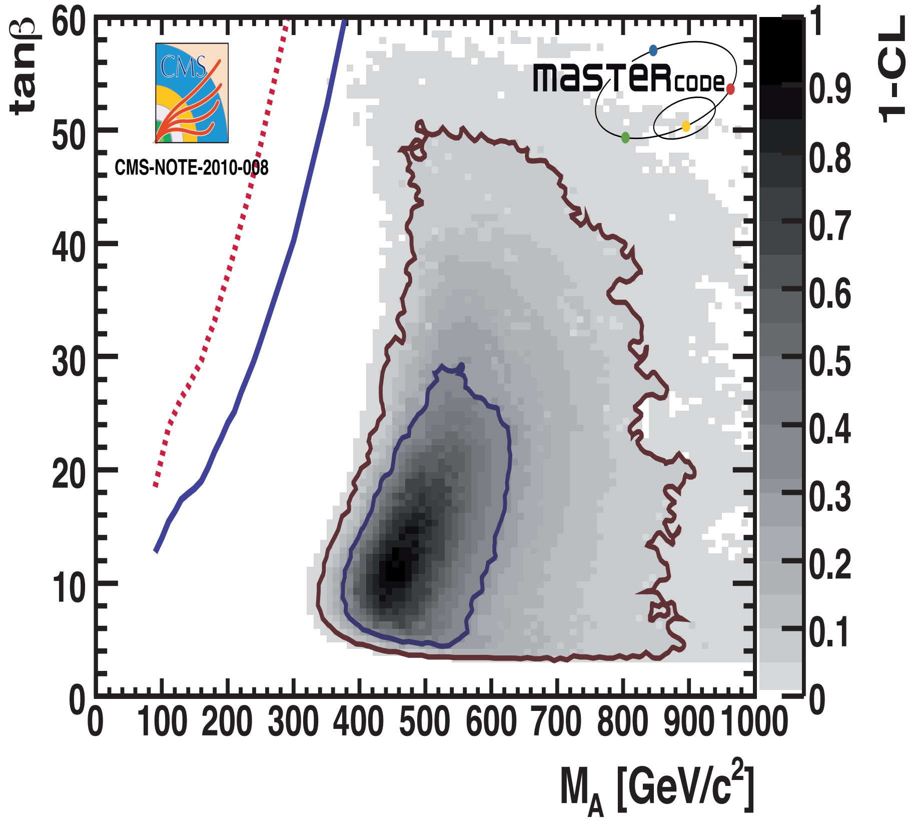
reach with 1 fb^{-1} @ 14 TeV incl. leptonic edge measurements



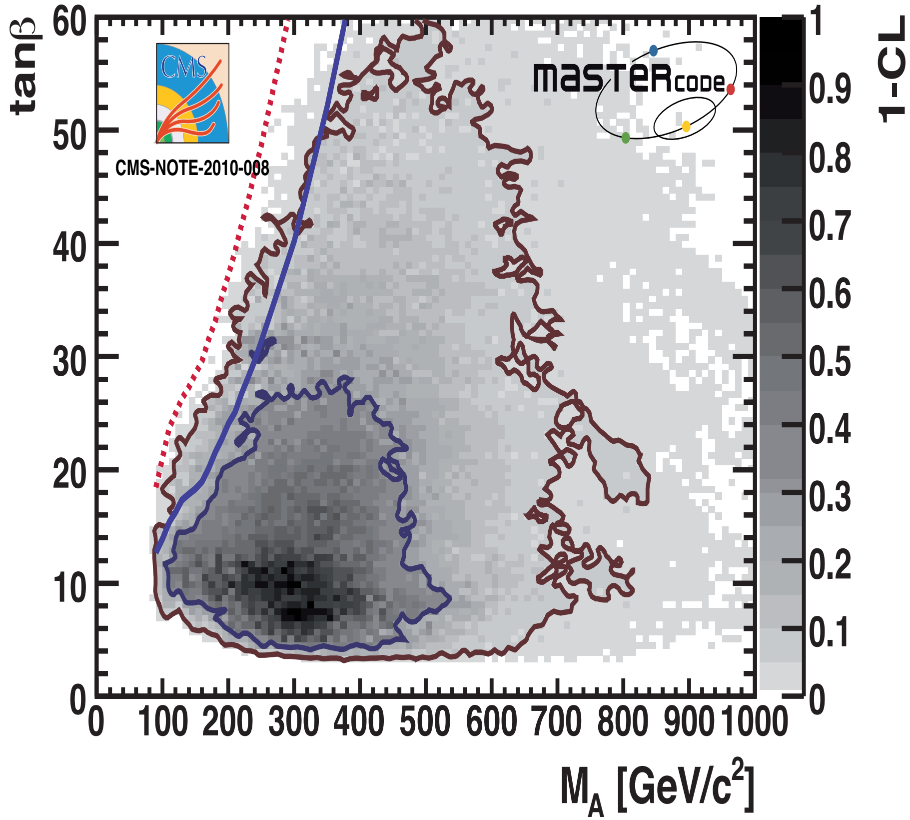
$\Rightarrow$ excellent prospects from early leptonic edge measurements!

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

CMSSM



NUHM1

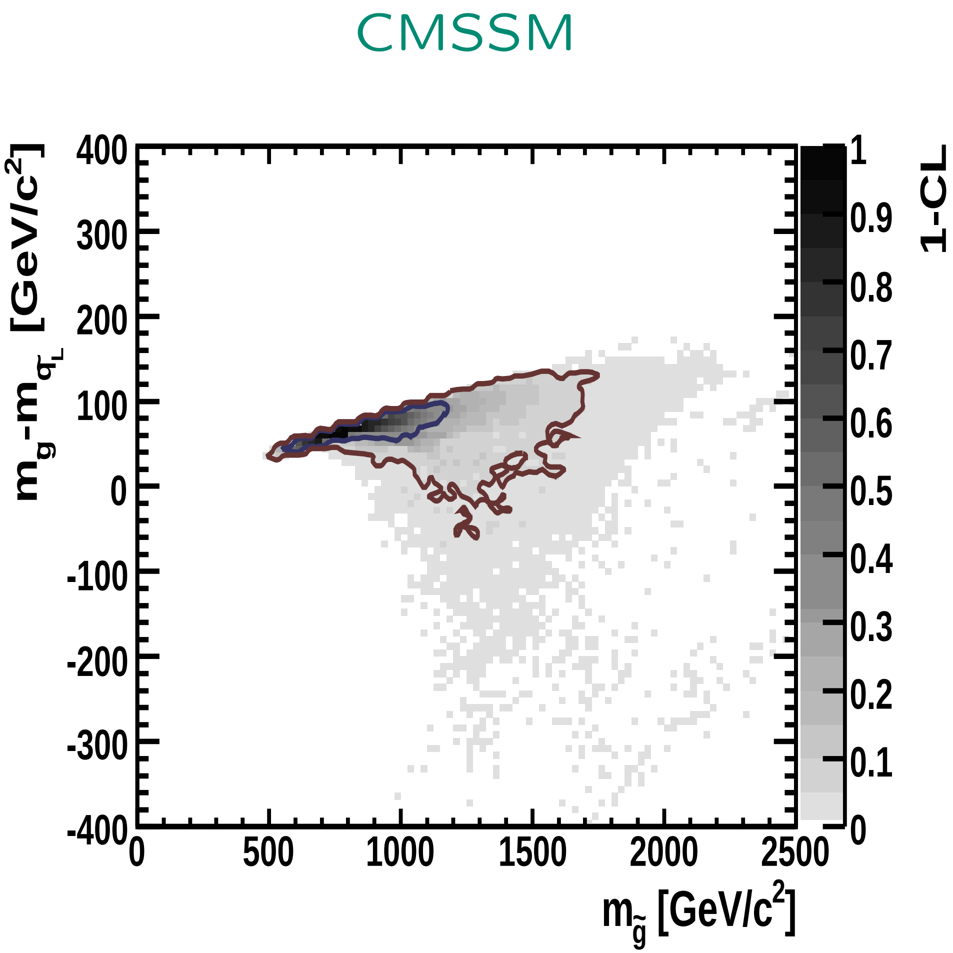


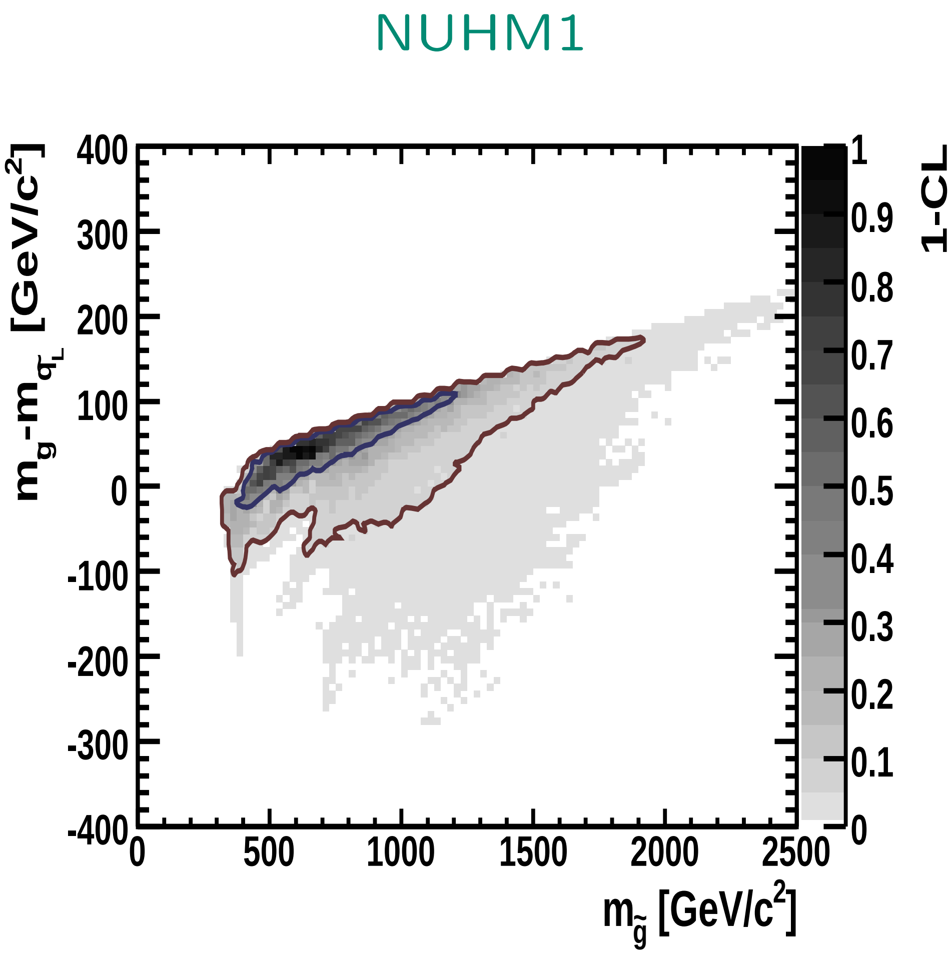
red dotted: discovery with 1 fb^{-1} @ 7 TeV
blue solid: 95% C.L. exclusion with 1 fb^{-1} @ 7 TeV

⇒ preferred regions missed in 2010-2011 run

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

[2009]

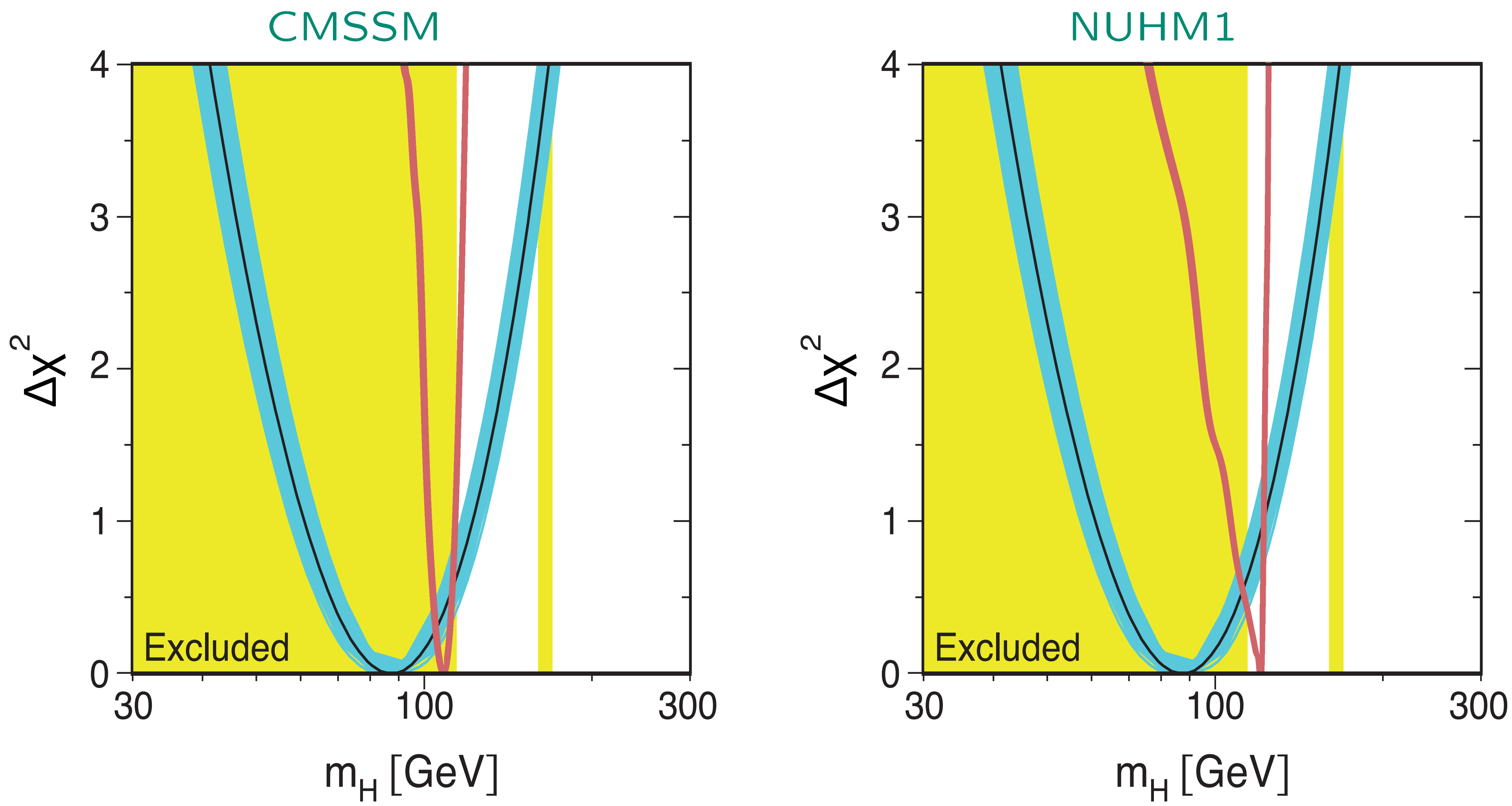




$\Rightarrow m_{\tilde{g}}$ often largest mass, but exceptions are possible

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

[2009]



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

$\Rightarrow$ as good as the SM

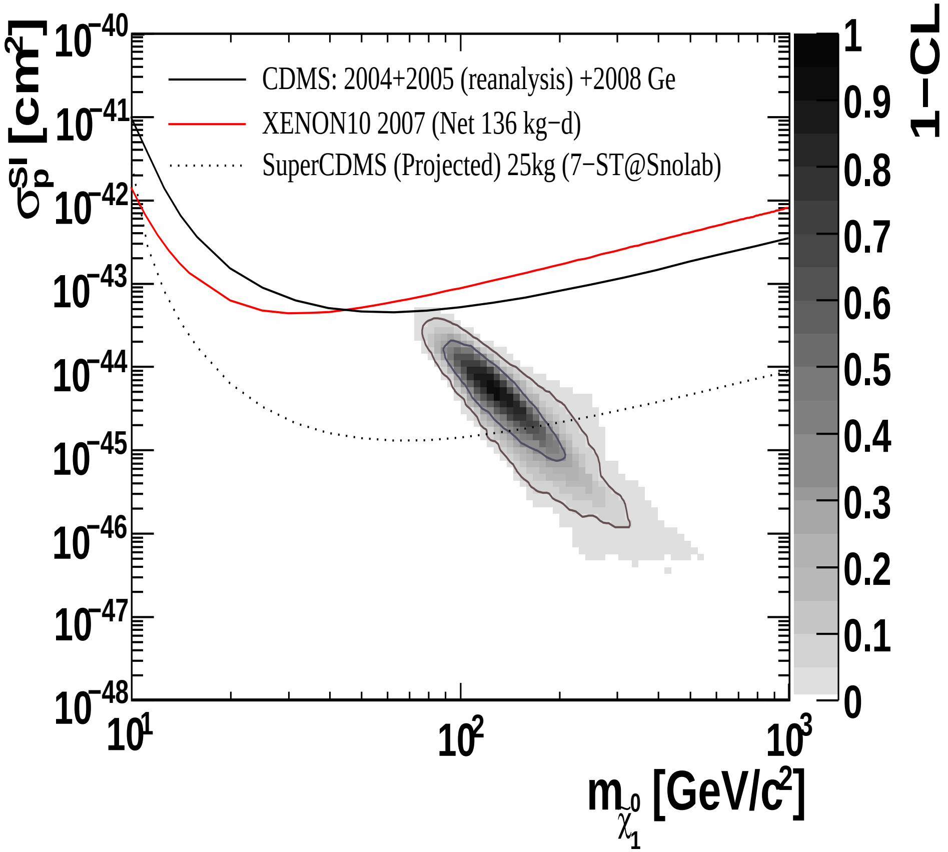
$M_h^{\rm NUHM1} = 121^{+1}_{-14} \pm 1.5$ GeV

$\Rightarrow$ above the LEP limit

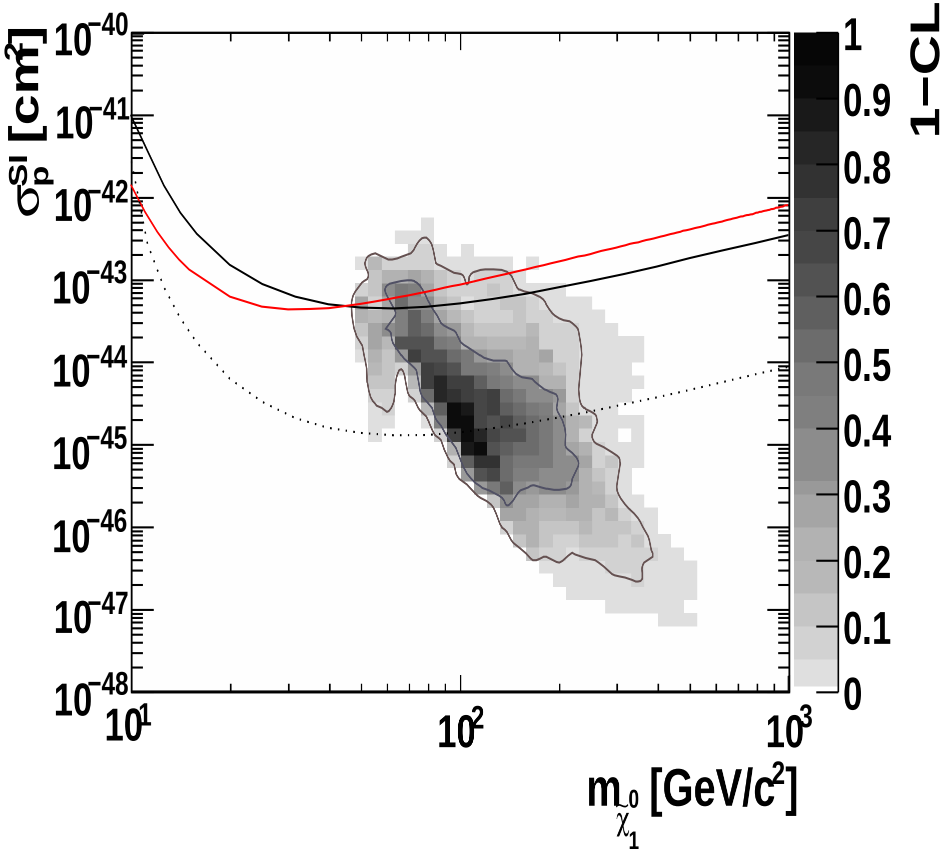
Some more predictions: direct search for dark matter

[2009]

CMSSM



NUHM1



⇒ only partially covered by future experiments