Higgs Measurements in and beyond the SM at the LHC in the Forward Proton Mode

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based on collaboration with
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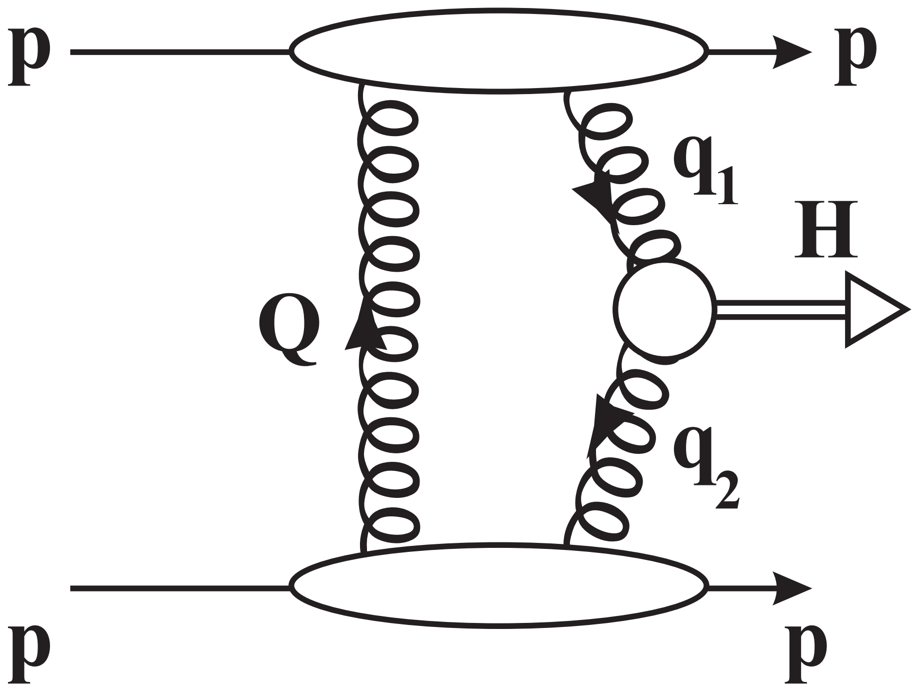
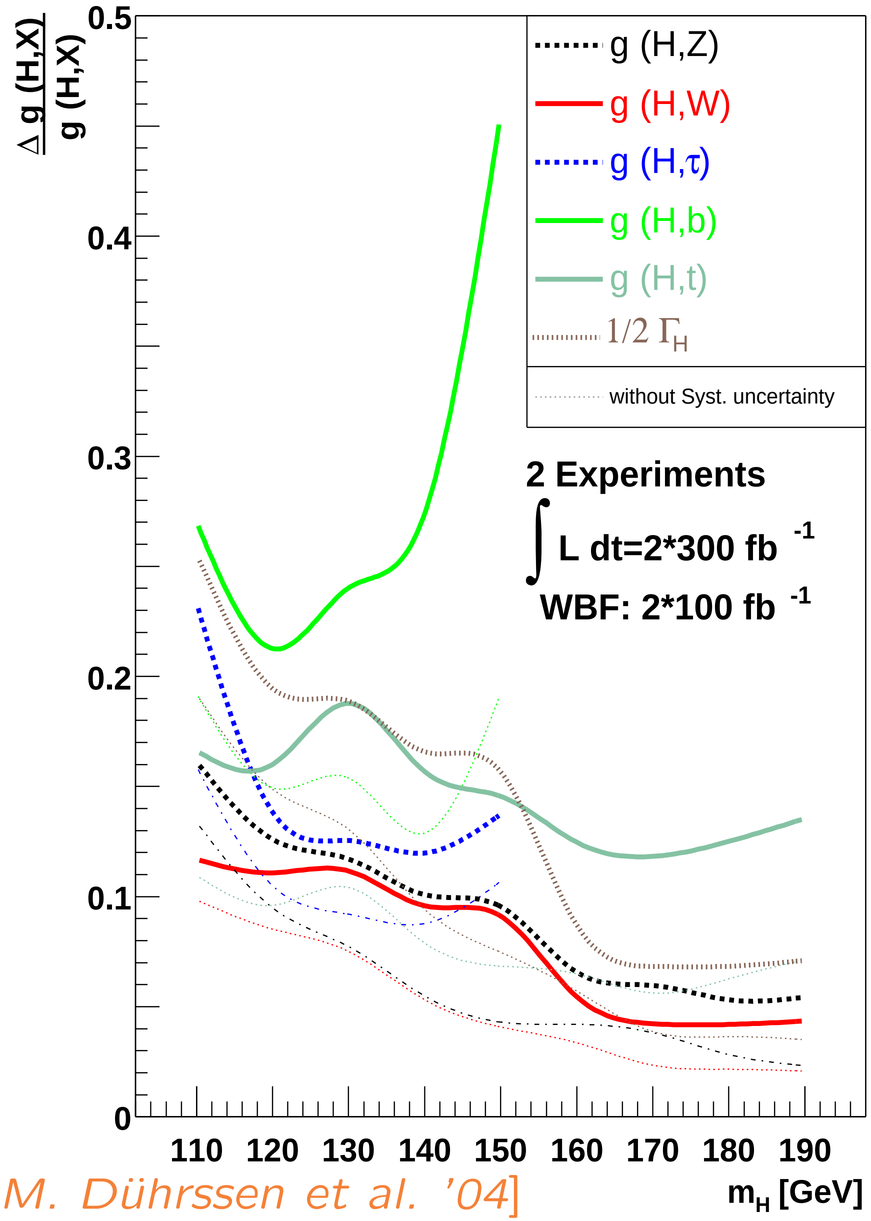
1. Introduction

$pp \rightarrow p \oplus H \oplus p, \quad H \rightarrow b\bar{b}, \tau^+\tau^-, W^+W^-, \ldots$ (protons remain intact)



The LHC will find a SM-like Higgs and measure its characteristics:



[M. Dührssen et al. '04]

– mass: $\delta M_h \approx 200$ MeV

– couplings: $(2*300+2*100)$ fb^{-1} :

typical: 20-30% for $m_H \leq 150$ GeV

10% accuracies for HVV couplings above WW threshold

Assumption:

– $g^2_{HVV} \leq g^2_{HVV,\text{SM}} \times 1.05$

– SM rates for the Higgs

Problem: $Hb\bar{b}$ crucial!

$Hb\bar{b}$ situation unclear:

old: $t\bar{t}H, H \to b\bar{b}$

signal shape $\approx$ background shape

$\Rightarrow$ no longer viable

new: $WH, H \to b\bar{b}$ (boosted)

$\Rightarrow$ up to $\sim 3.5\,\sigma$ possible?

$\Rightarrow$ other possibilities for $Hb\bar{b}$?

Some details ($\phi = h^{\text{MSSM}}, H^{\text{MSSM}}, H^{\text{4th gen}}$):

1. Proton detection: in Forward Proton Taggers at 220 m, 420 m

2. Higgs decay: (here only) $\phi \to b\bar{b}$
   two high p_T b jets, measured in ATLAS or CMS

3. Trigger to keep signal (2):
   "cocktail" of triggers: FP @ 220m, high p_T jets, high p_T leptons, . . .

4. Identification of signal: (1) and (2) have to match in mass

5. Cross section calculation: $\sigma_{\text{SM}} \times \frac{\Gamma(gg\to\phi)_{\text{NP}}}{\Gamma(gg\to H)_{\text{SM}}}$

6. Decay calculation: $\text{BR}_{\text{NP}}(\phi \to b\bar{b})$ $\Rightarrow$ FeynHiggs (MSSM: incl. Δ_b dep.)
   advantage over SM: possibly enhanced decay rates

7. Backgrounds:
   taken into account according to recent analyses/
   best available estimates

$\Rightarrow$ $5\,\sigma$ discovery contours, $3\,\sigma$ significance sensitivities

Four luminosity assumptions:

$60\ \ \mathrm{fb}^{-1}$:

$\mathcal{L} = 2 \times 30\ \ \mathrm{fb}^{-1}$: three years of low-luminosity running

$60\ \ \mathrm{fb}^{-1}$ eff $\times$ 2:

as “60”, but assuming an improvement in signal efficiency etc.

effectively: signal rates doubled

$600\ \ \mathrm{fb}^{-1}$:

$\mathcal{L} = 2 \times 300\ \ \mathrm{fb}^{-1}$: three years of high-luminosity running

$600\ \ \mathrm{fb}^{-1}$ eff $\times$ 2:

as “600”, but assuming an improvement in signal efficiency etc.

effectively: signal rates doubled

2. MSSM analysis update

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)

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

Update with respect to 2007 analysis:

– Update of background estimates: NLO for $gg \to b\bar{b}$

– Update of LEP and Tevatron exclusion bounds
$\Rightarrow$ HiggsBounds [*B. Bechtle, O. Brein, S.H., G. Weiglein, K. Williams '08*]

– Update of σ and BR calculation
$\Rightarrow$ FeynHiggs [*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '98 - '10*]
$\to$ small changes in Δ_b, $gg \to h$ improved
(still working on further $gg \to h$ improvement, possibly large impact!)

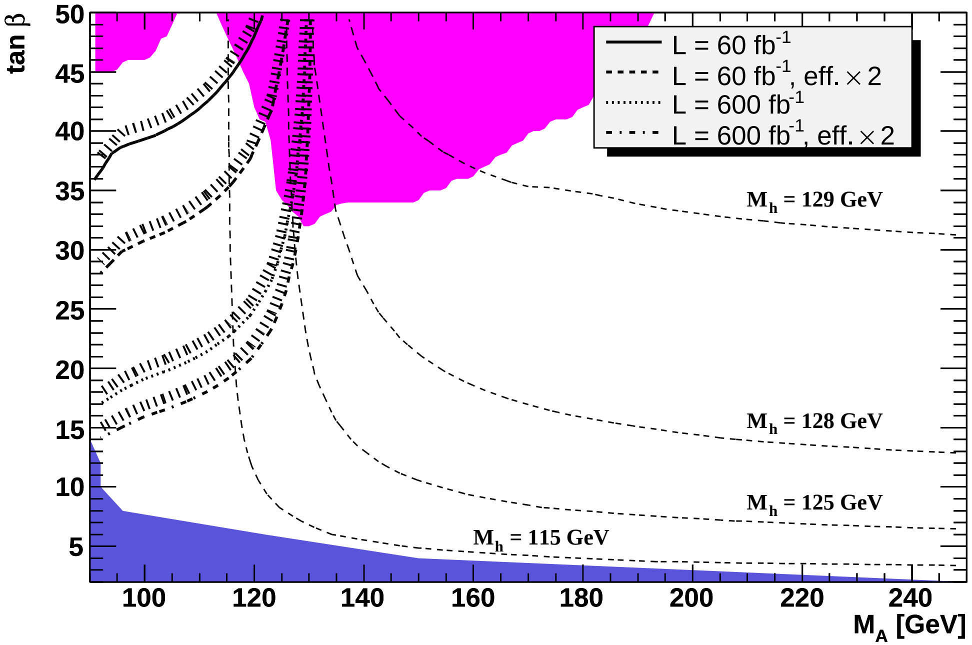
MSSM scenarios:

– "normal" benchmarks: m_h^{max}, no-mixing ($\mu = +200$ GeV)

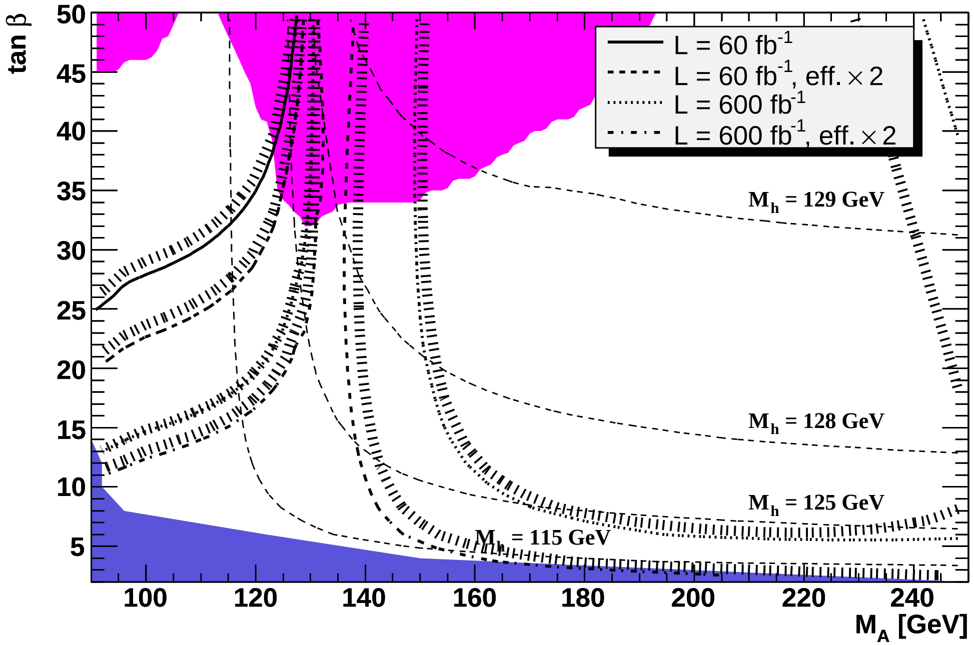
– CDM benchmarks: M_A-$\tan\beta$ planes in agreement with CDM
[*J. Ellis, T. Hahn, S.H., K. Olive, G. Weiglein '07*] $\longrightarrow$backup

Results for h in the $m_h^{\rm max}$ scenario:

5 σ discovery



3 σ sensitivity



pink: Tevatron exclusion bounds

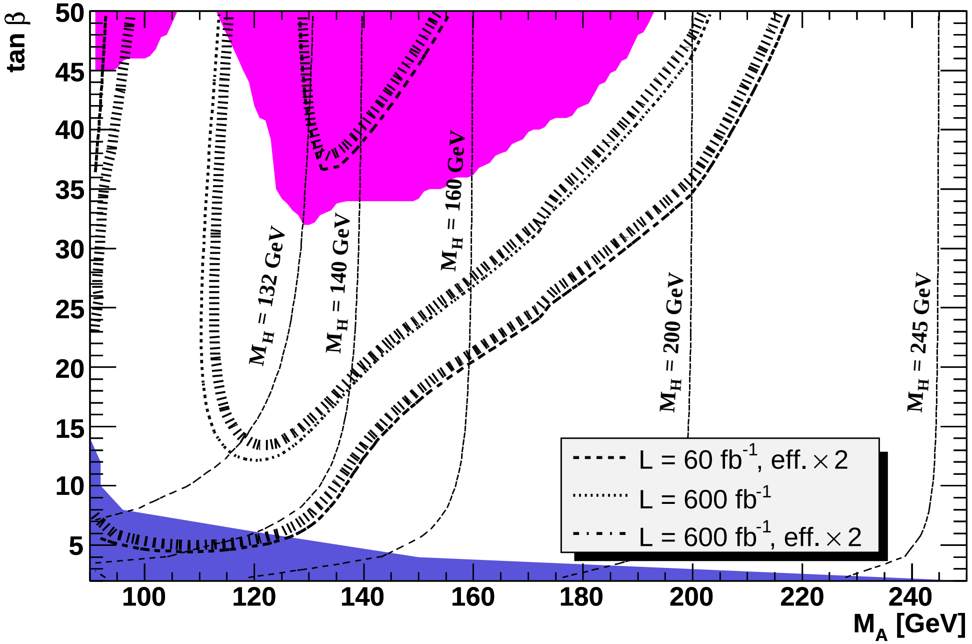
blue: LEP exclusion bounds

$\Rightarrow$ large parts can be covered at 3 σ!

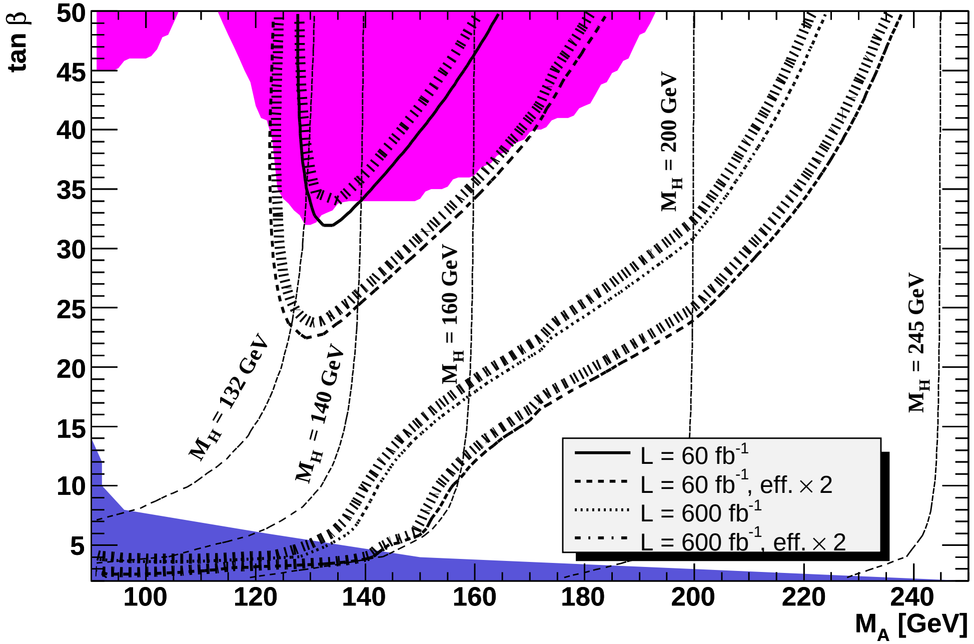
$\Rightarrow$ access to $hb\bar{b}$ coupling?!

Results for H in the m_h^{max} scenario:

5 σ discovery



3 σ sensitivity



pink: Tevatron exclusion bounds

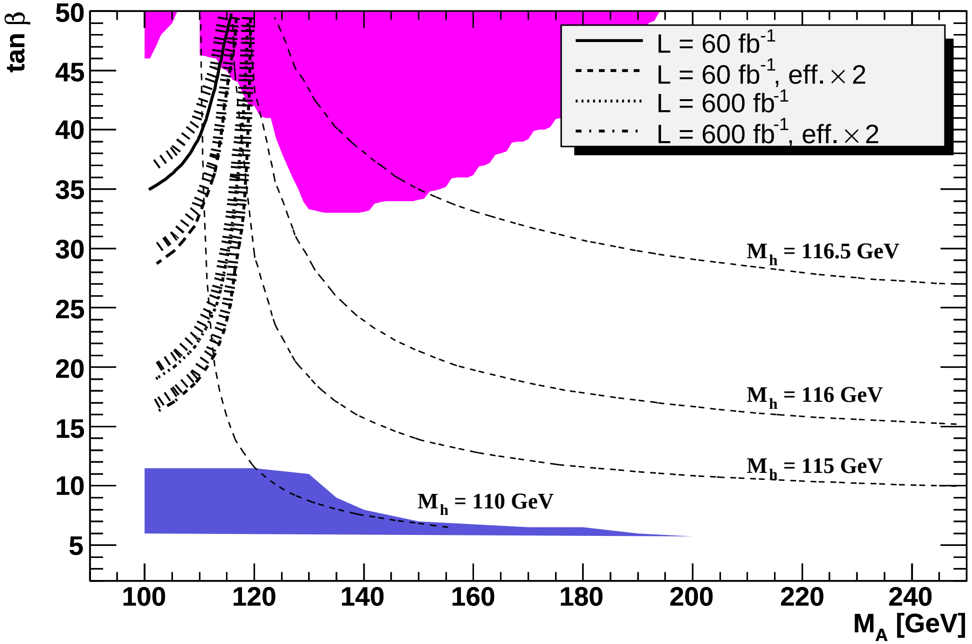
blue: LEP exclusion bounds

⇒ large discovery regions, but no "LHC wedge" coverage →backup

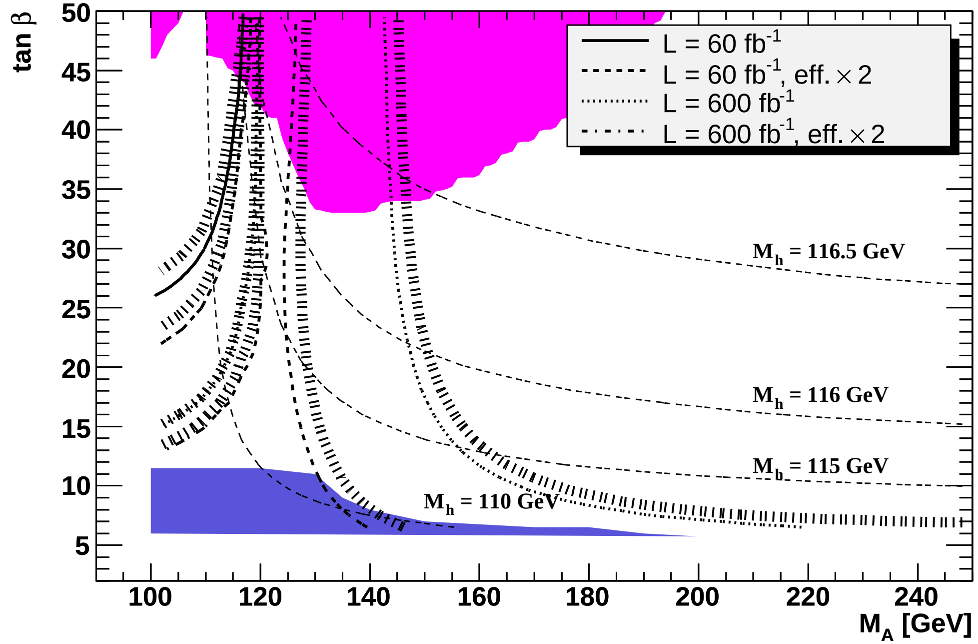
⇒ access to $Hb\bar{b}$ coupling?!

Results for h in the CDM scenario (#3):

5 σ discovery



3 σ sensitivity



pink: Tevatron exclusion bounds

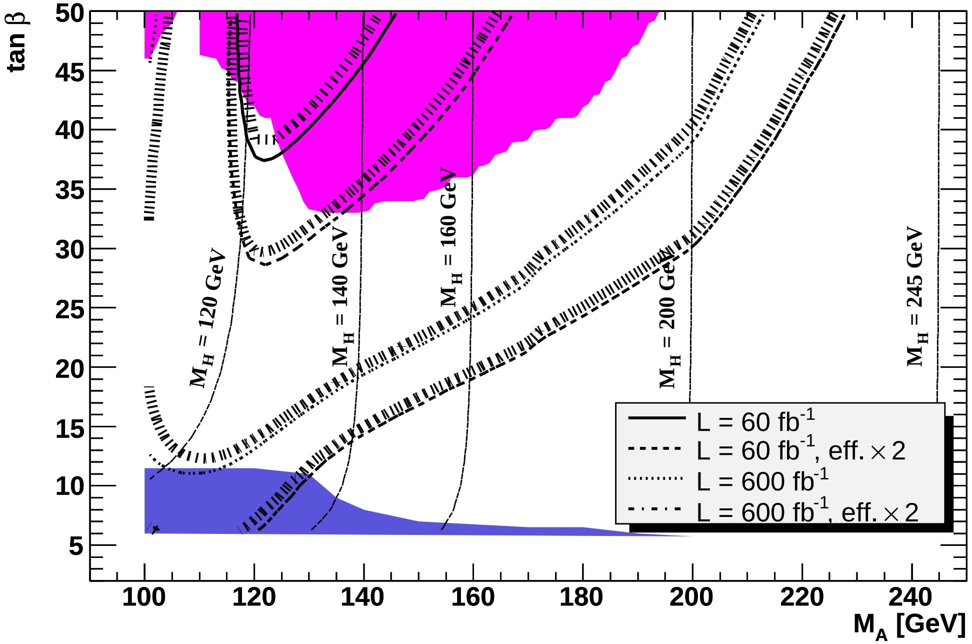
blue: LEP exclusion bounds

$\Rightarrow$ large parts allowed by CDM can be covered at 3 σ!

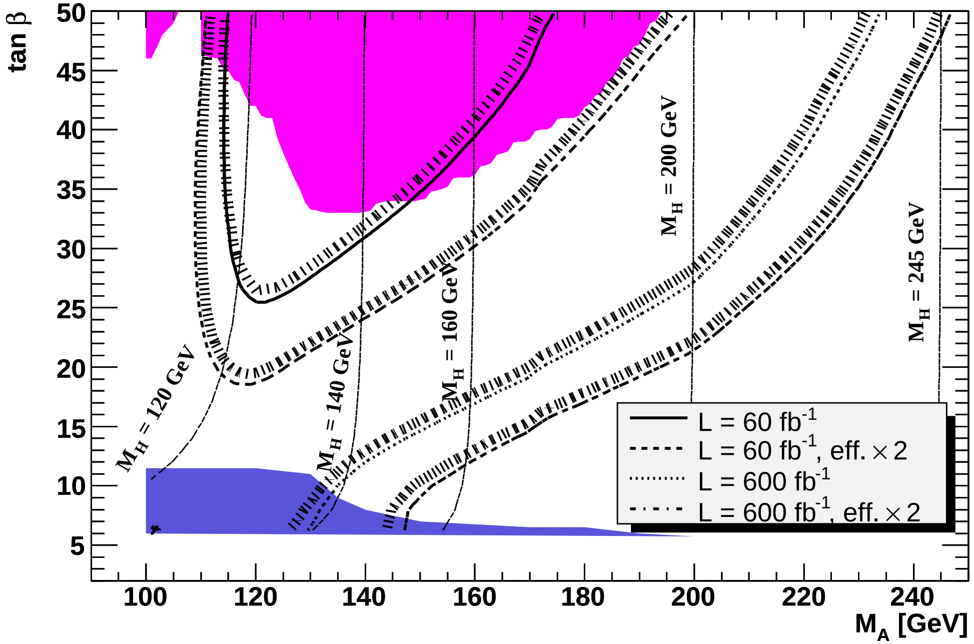
$\Rightarrow$ access to $hb\bar{b}$ coupling? (5 σ slightly worse than in $m_h^{\max}$)

Results for H in the CDM scenario (#3):

$5\,\sigma$ discovery



$3\,\sigma$ sensitivity



pink: Tevatron exclusion bounds

blue: LEP exclusion bounds

$\Rightarrow$ large discovery regions, but no "LHC wedge" coverage

$\Rightarrow$ access to $Hb\bar{b}$ coupling? (slightly better than in m_h^{max})

3. Determination of spin and $\mathcal{CP}$ properties

Existing analyses for the LHC:

rely largely on the coupling of the Higgs to heavy gauge bosons:

$$\begin{aligned} (gg,)\, WW \to H &\to ZZ \to 4\ell \\ (gg,)\, WW \to H &\to WW \to \ell\nu\,\ell\nu \\ WW \to H &\to \tau^+\tau^- \end{aligned}$$

($gg \to H$ as background)

Needed for these SM(-like) analyses: a Higgs with

– a sufficiently large $HV_\mu V^\mu$ coupling
  i.e. no large suppression with respect to the SM value

– a sufficiently large BR($H \to VV$)
  $\Rightarrow M_H \gtrsim 140$ GeV to suppress $H \to b\bar{b}$

– possibly a large BR($H \to \tau^+\tau^-$)

SM analyses for the structure of the $HV_\mu V^\mu$ coupling:

$\mathcal{CP}$-even vs. $\mathcal{CP}$-odd

[*T. Plehn, D. Rainwater, D. Zeppenfeld '01*] (theory)
[*V. Hankele, G. Klämke, D. Zeppenfeld '06*] (theory)
[*C. Ruwiedel, M. Schumacher, N. Wermes '07*] (experimental)

Problem: Assumption often made:

$H^{\mathcal{CP}-\text{even}} V_\mu V^\mu$ has the same strength as $H^{\mathcal{CP}-\text{odd}} V_\mu V^\mu$

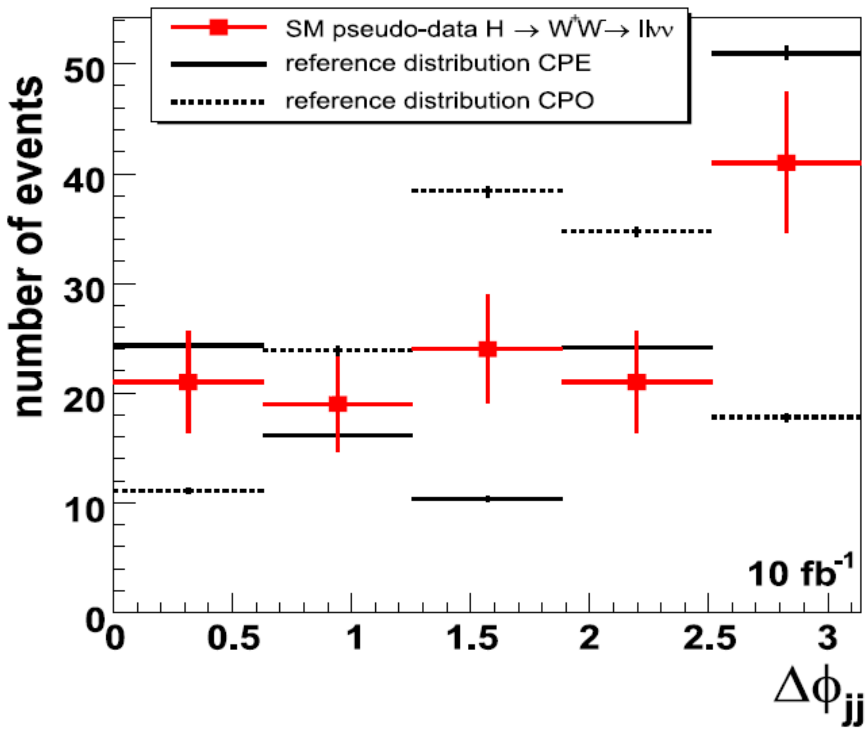
MSSM:

$$\frac{H^{\mathcal{CP}-\text{odd}} V_\mu V^\mu}{H^{\mathcal{CP}-\text{even}} V_\mu V^\mu} \approx 10^{-11}$$

Higgs coupling structure determination?

[*C. Ruwiedel, M. Schumacher, N. Wermes '07*]

$\Rightarrow$ explore $HW_\mu W^\mu$ coupling



Φ_{jj}: angle between the two tagging jets (WBF: signal, gg background)

$M_H = 160$ GeV

$\Rightarrow$ BR($H \to WW$) is maximal

$H \to WW \to e\mu\, p_T^{\rm miss}$

Two extreme cases:

$\mathcal{CP}$-even and -odd tensor structures

(assumed to have the same strength!)

$\Rightarrow$ discrimination at $\sim 5\,\sigma$ possible with 10 fb^{-1}

Situation in MSSM: *

Light Higgs: $M_h \lesssim 135$ GeV

$\Rightarrow$ light Higgs h has too small BR($h \to VV^{(*)}$)

Heavy Higgses:

$$g_{hVV} = g_{HVV}^{\text{SM}} \times \sin(\beta - \alpha)$$
$$g_{HVV} = g_{HVV}^{\text{SM}} \times \cos(\beta - \alpha)$$
$$g_{AVV} = 0 \qquad \text{at tree-level}$$

$M_H \approx M_A \gtrsim 150$ GeV:

$\Rightarrow \beta - \alpha \to \pi/2$

$\Rightarrow h$ has substantial VV coupling

$\Rightarrow H$ and A have negligible VV coupling

$\Rightarrow$ no heavy Higgs with substantial coupling to VV in the MSSM

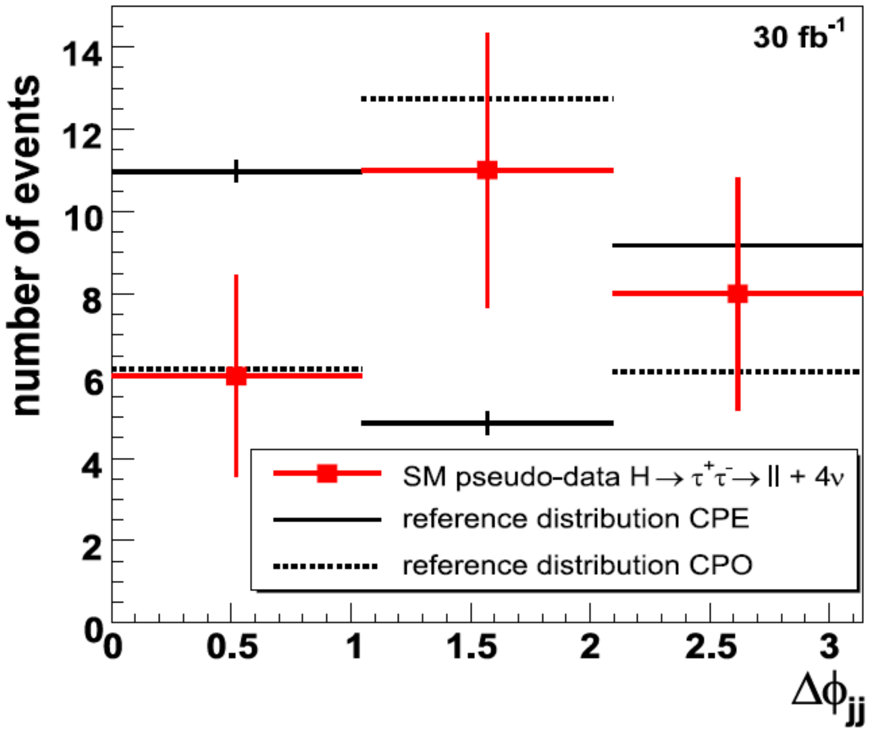
$\Rightarrow$ method relying on $H \to VV$ cannot be applied

* α diagonalizes the neutral $\mathcal{CP}$-even Higgs sector

Higgs coupling structure determination in $WW \to H \to \tau^+\tau^-$

[C. Ruwiedel, M. Schumacher, N. Wermes '07]

$\Rightarrow$ explore $HV_\mu V^\mu$ coupling



$M_H = 120$ GeV
exploiting
$WW \to H \to \tau^+\tau^- \to \ell\ell\, 4\nu$

Two extreme cases:
$\mathcal{CP}$-even and -odd tensor structures

$\Rightarrow$ discrimination at $\sim 2\,\sigma$
possible with 30 fb^{-1}

Φ_{jj}: angle between the two tagging jets

Situation in MSSM: *

$$g_{hVV} = g_{HVV}^{\text{SM}} \times \sin(\beta - \alpha)$$
$$g_{HVV} = g_{HVV}^{\text{SM}} \times \cos(\beta - \alpha)$$
$$g_{AVV} = 0 \qquad \text{at tree-level}$$

$M_H \approx M_A \gtrsim 150$ GeV $\Rightarrow M_h \lesssim 135$ GeV ($M_h \approx 120$ GeV "easy")
$\Rightarrow h$ has substantial VV coupling
but no (sufficient) $h \to \tau^+\tau^-$ enhancement

$M_H \approx M_A \lesssim 130$ GeV $\Rightarrow |\sin(\beta - \alpha)| \ll 1$ possible
$\Rightarrow H$ has substantial VV coupling
but no (sufficient) $H \to \tau^+\tau^-$ enhancement

$\Rightarrow$ no improvement with respect to SM analysis

* α diagonalizes the neutral $\mathcal{CP}$-even Higgs sector

Situation in other models beyond the SM:

If:

- Higgs sector consists of doublets and singlets
- one has one light SM-like Higgs, $M_H^{\text{SM-like}} \lesssim 140$ GeV

then:

- BR($H^{\text{SM-like}} \to VV^{(*)}$) is too small
- the following sum rule for the New Physics (NP) Higgs couplings holds:

$$\sum_i (g_{H_iVV})^2 = (g_{HVV}^{\text{SM}})^2$$

Since the light Higgs is SM like all other Higgses have small H_iVV coupling

$H \to VV^{(*)}$: method cannot be applied

$H \to \tau^+\tau^-$: large enhancement of $\Gamma(H \to \tau^+\tau^-)$ needed ...

Situation with CED Higgs production:

$$pp \ \longrightarrow \ p \oplus H \oplus p$$

protons remain intact

⇒ the primary active di-gluon system obeys a
$J_z = 0$, $\mathcal{CP}$-even selection rule
(J_z is the projection of the total angular momentum along the proton beam axis)

⇒ permits a clean determination of the quantum numbers of the observed Higgs

Further advantage:
leading order $gg^{PP} \to b\bar{b}$ QCD background subprocess have to vanish in the limit of massless quarks and forward outgoing protons

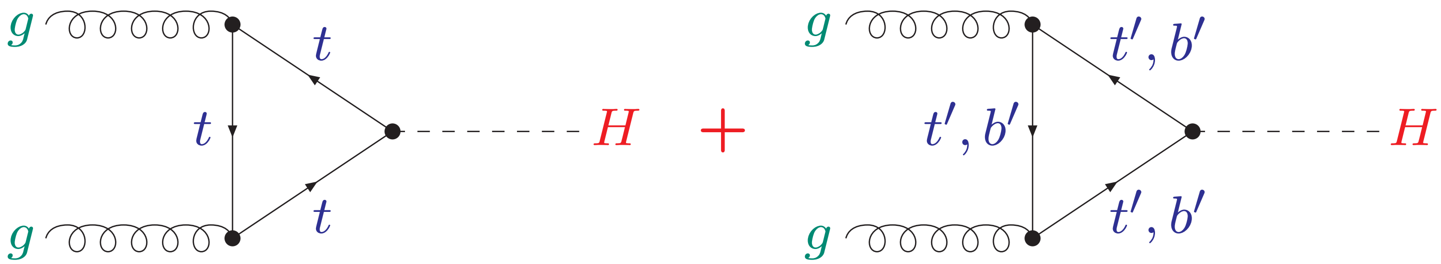
Corresponding MSSM advantage: $h, H \to b\bar{b}$ enhanced!

4. 4th generation model

Assume the SM with a 4th generation of heavy fermions

Relevant changes:

1. additional contribution to $gg \to H$:



$\Rightarrow$ factor of ~ 9 in Higgs production cross section

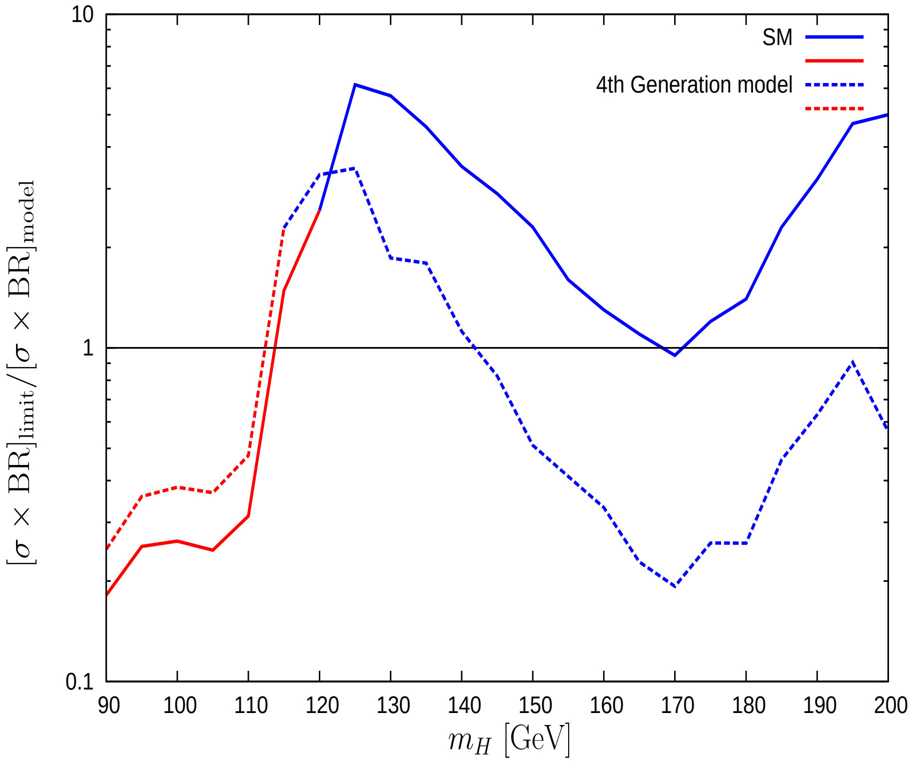
2. $\Rightarrow$ factor of ~ 9 in $\Gamma(H \to gg)$

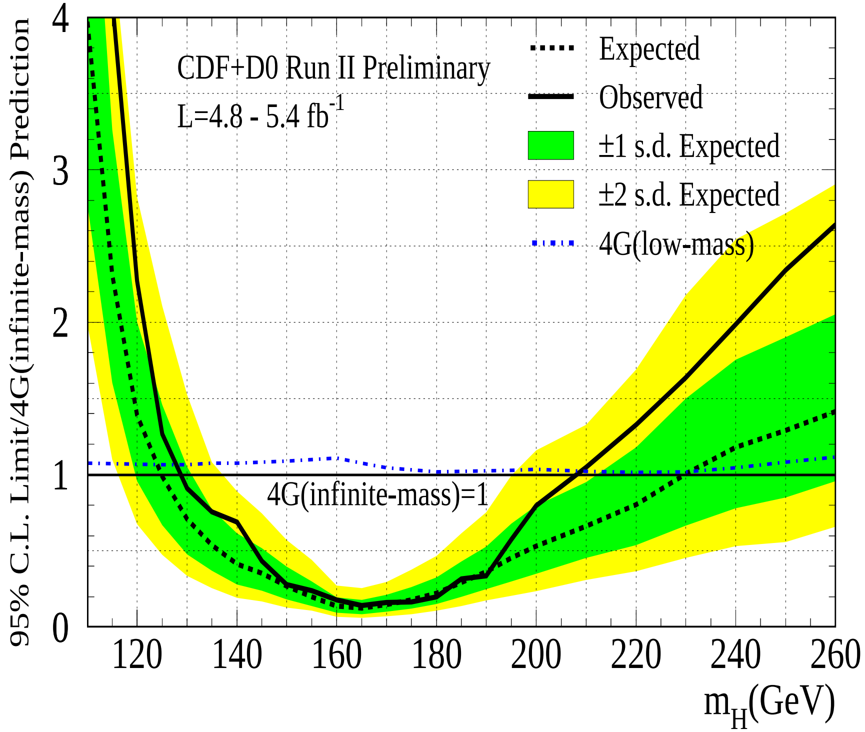
   $\Rightarrow$ reduced BR$(H \to b\bar{b})$, BR$(H \to \tau^+\tau^-)$

Evaluation of SM quantities with FeynHiggs
subsequent application of reduction and enhancement factors

LEP and Tevatron limits for 4th generation model

[P. Bechtle, O. Brein, S.H., G. Weiglein, K. Williams '08] [CDF, DØ '10]

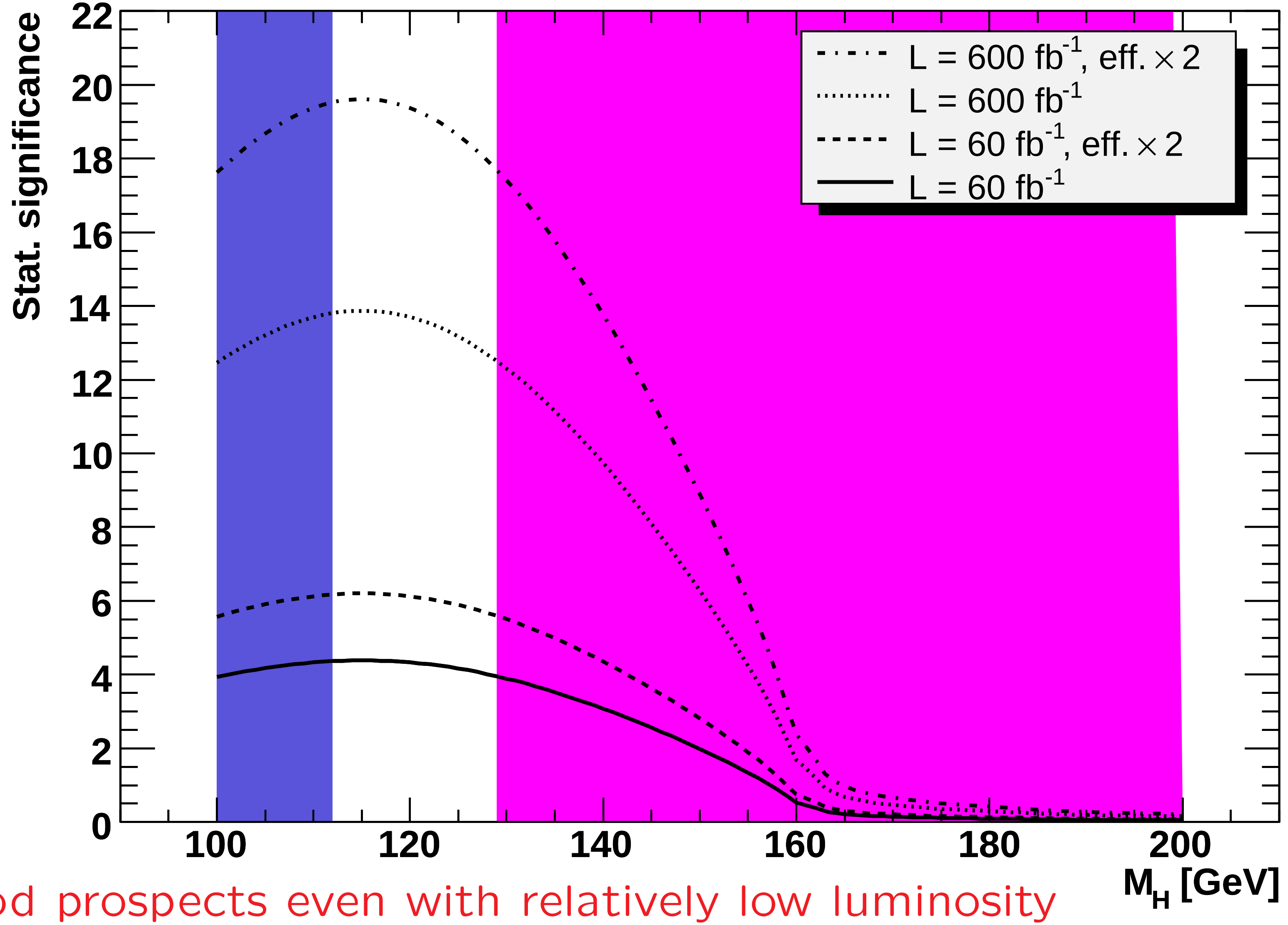




⇒ only 112 GeV $\lesssim M_H \lesssim$ 130 GeV, $M_H \gtrsim$ 210 GeV still allowed

⇒ will be tested very soon by the Tevatron

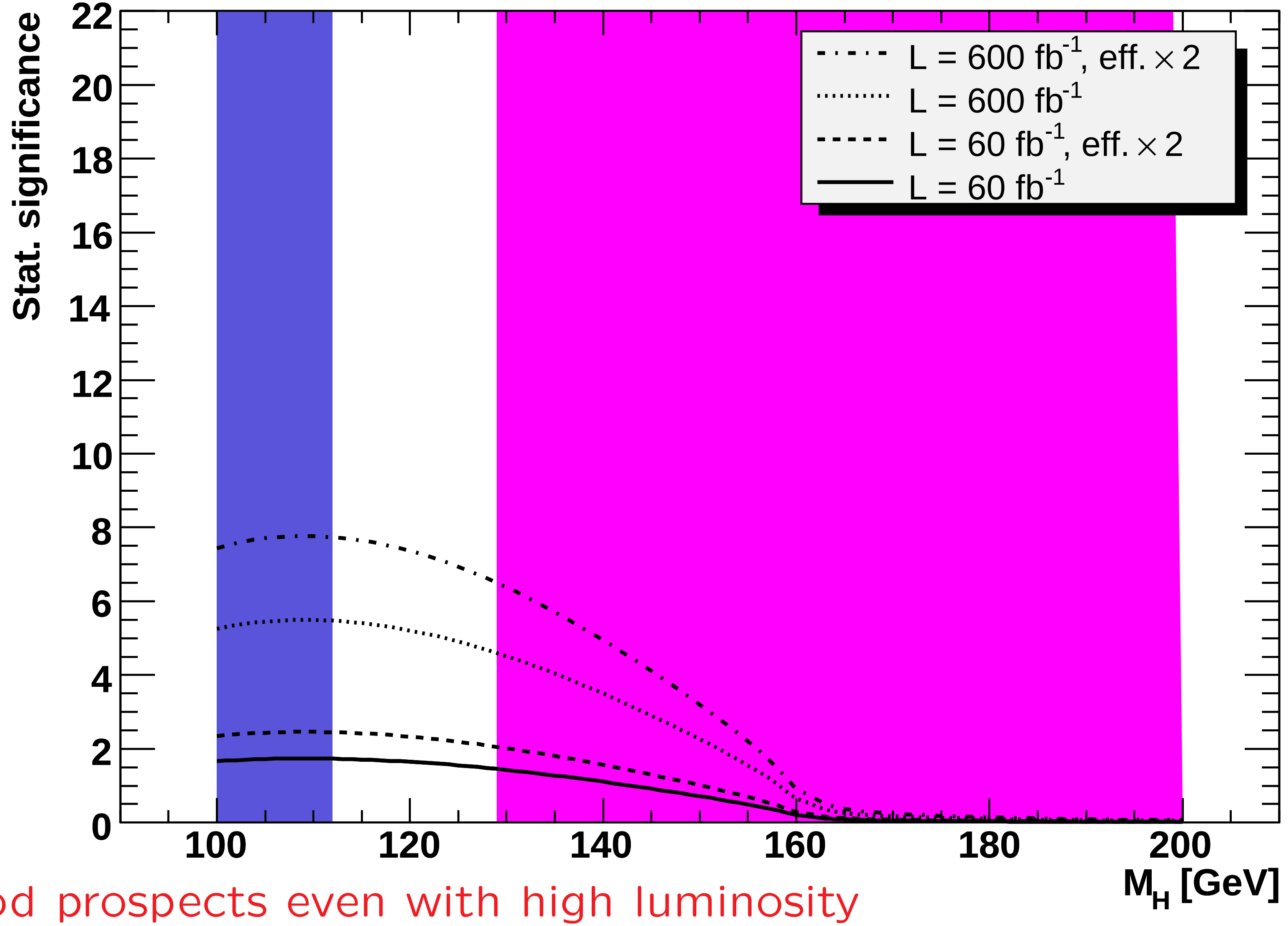
CED Higgs production in 4th generation model



⇒ good prospects even with relatively low luminosity

$M_H \gtrsim$ 200 GeV ⇒ BR($H \to b\bar{b}$) too small

CED Higgs production in 4th generation model



⇒ good prospects even with high luminosity

$M_H \gtrsim 200$ GeV ⇒ BR($H \to \tau^+\tau^-$) too small

5. Conclusions

- CED Higgs production

  $pp \rightarrow p \oplus \Phi \oplus p, \quad \Phi \rightarrow b\bar{b}, \tau^+\tau^-, W^+W^-$

  – extended discovery reach (in BSM models)?

  – new handle for bottom Yukawa coupling: y_b

- CED production of MSSM Higgs bosons:

  update of 2007 analysis:

  – background: NLO for $gg \rightarrow b\bar{b}$

  – LEP/Tevatron exclusion bounds (`HiggsBounds`)

  – theory calculation (`FeynHiggs`)

  – new CDM benchmark planes

  $\Rightarrow$ at very high luminosity: good chances for $hb\bar{b}$ coupling

  $\Rightarrow$ possibly access to $Hb\bar{b}$ coupling

- CED production of 4th generation Higgs boson:

  LEP/Tevatron searches: 112 GeV $\lesssim M_H \lesssim$ 130 GeV still allowed

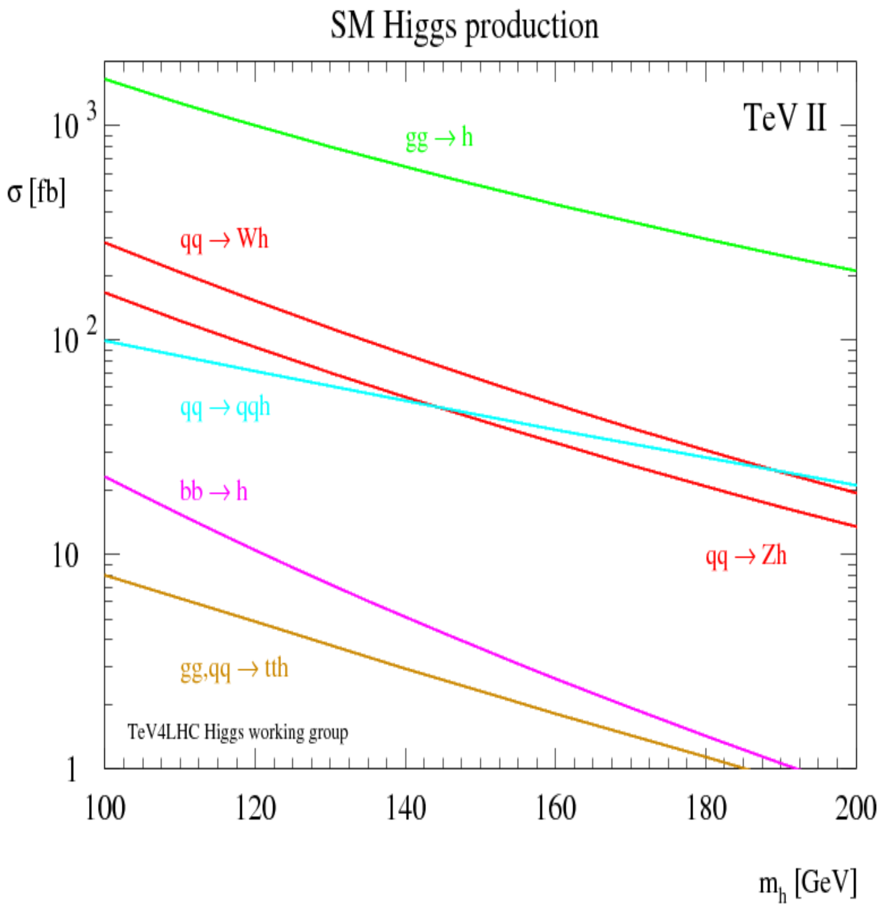
  $\Rightarrow$ good chances for $H \rightarrow b\bar{b}$ already at low luminosity

  $\Rightarrow$ good chances for $H \rightarrow \tau^+\tau^-$ at high luminosity

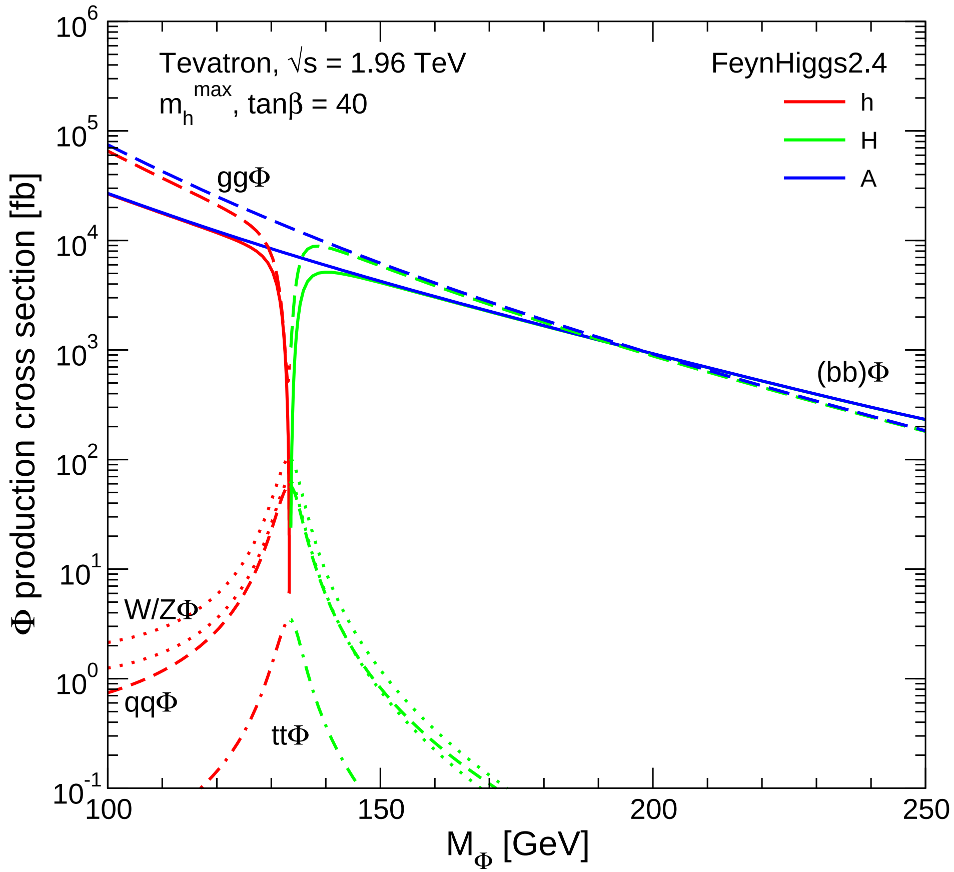
Back-up

Higgs production cross sections at the Tevatron:

SM



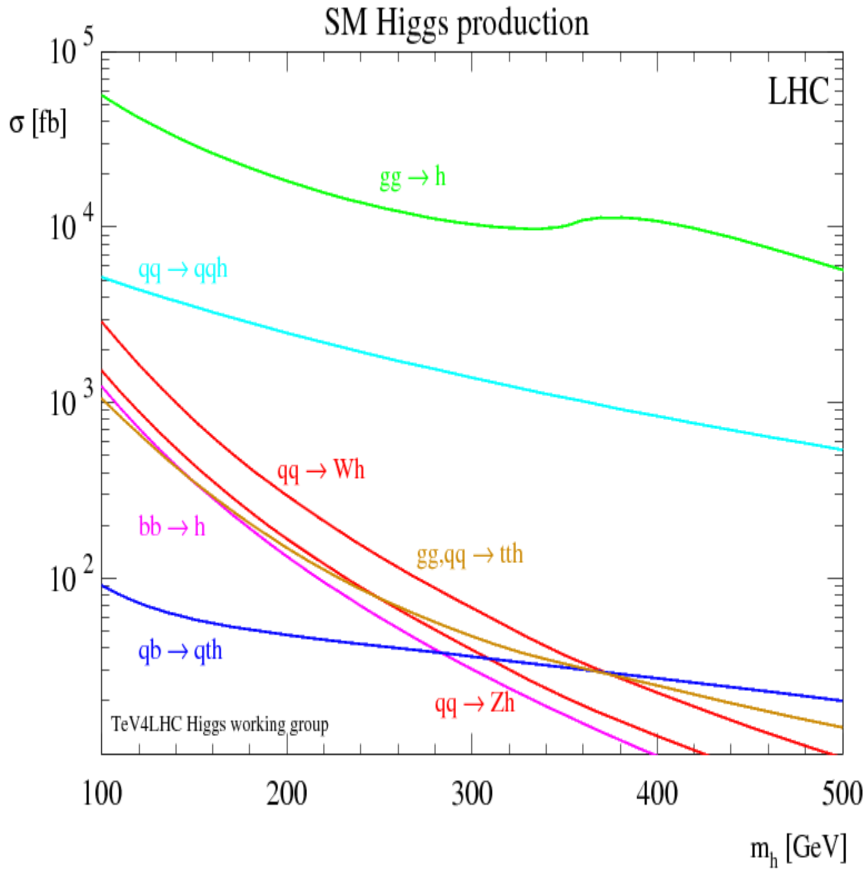
MSSM



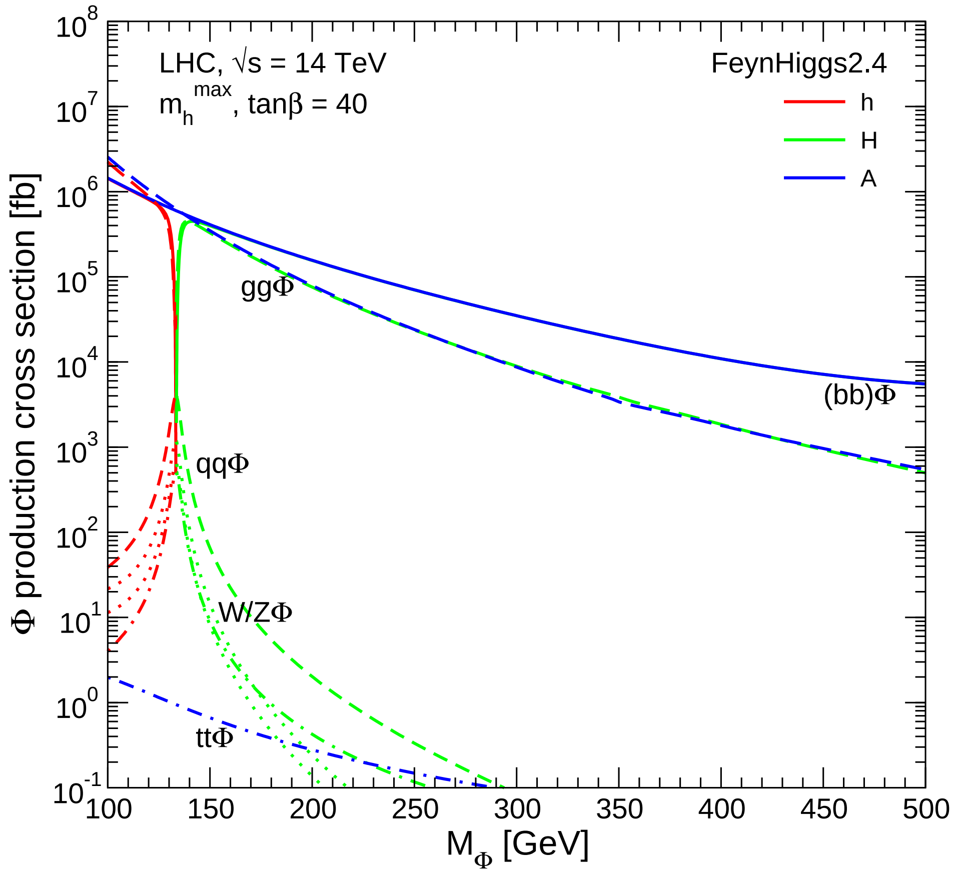
MSSM: possibly enhanced rates at high $\tan\beta$

Higgs production cross sections at the LHC:

SM



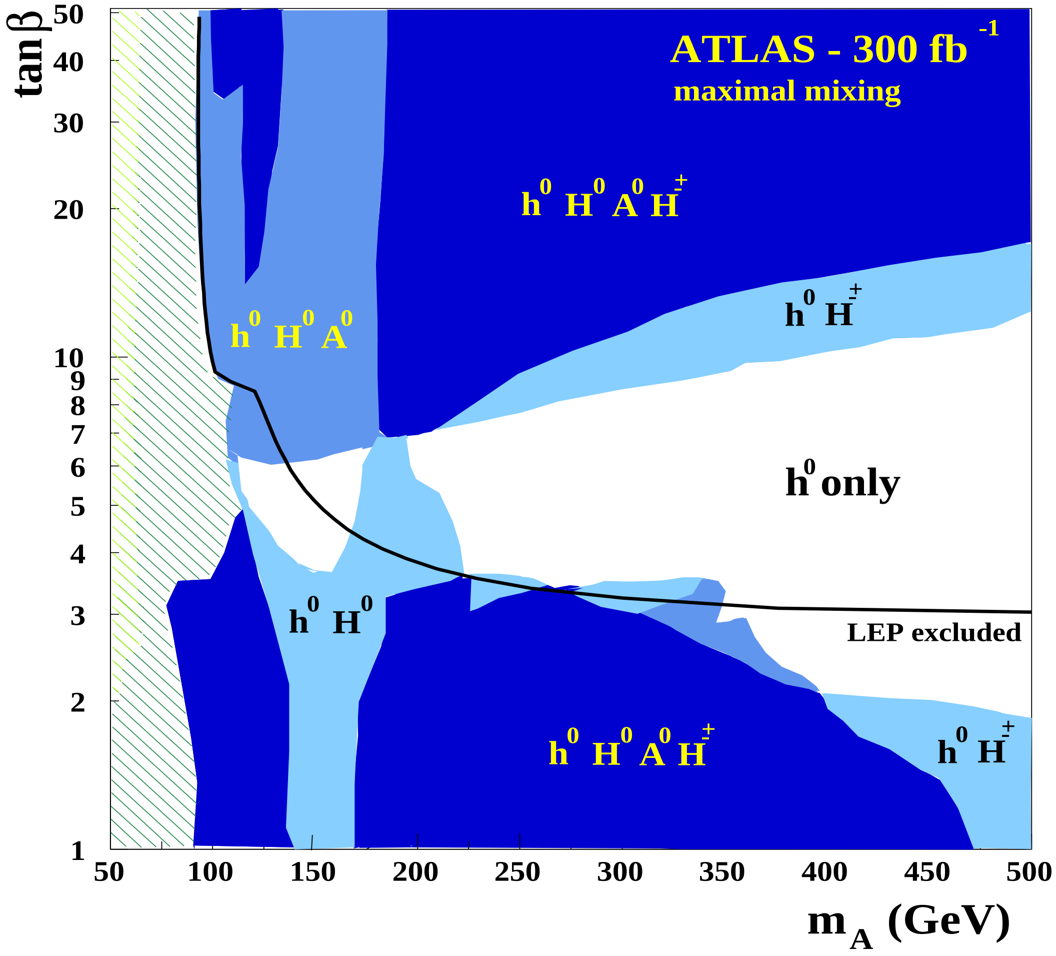
MSSM

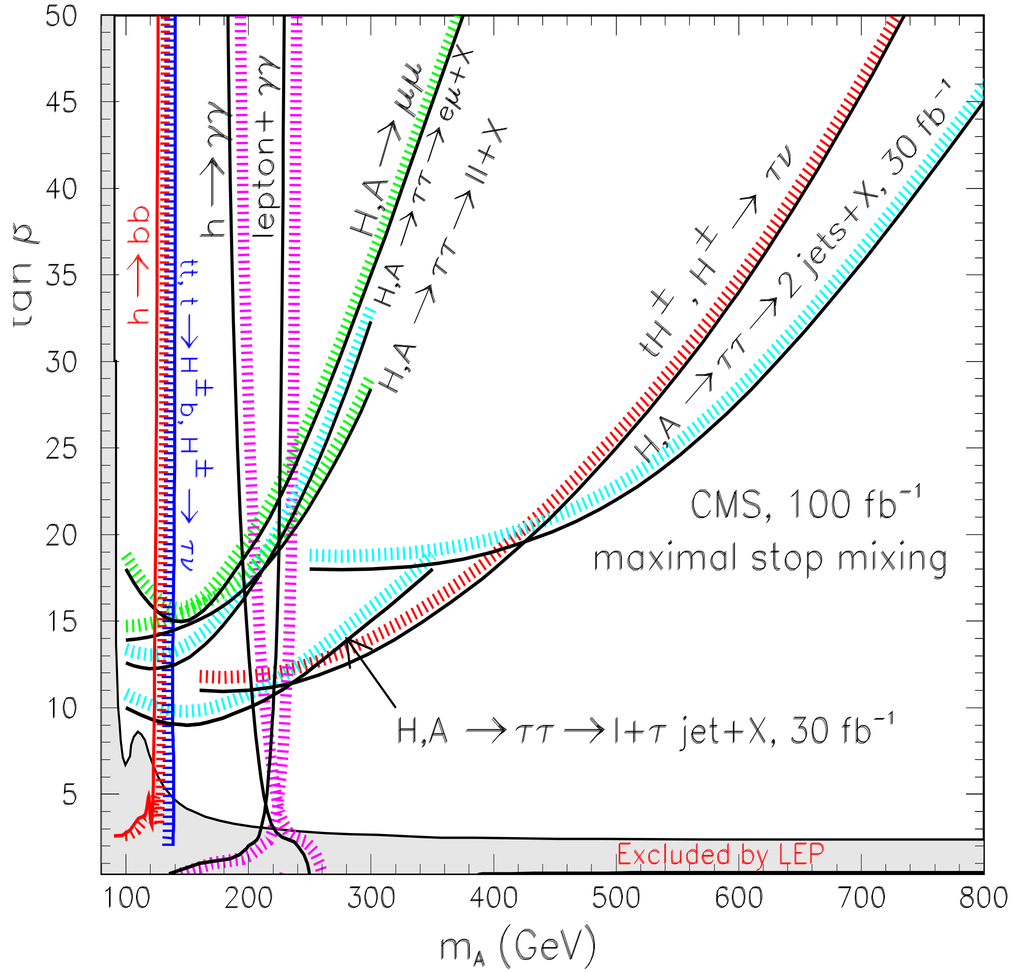


MSSM: possibly enhanced rates at high $\tan\beta$

“Heavy” MSSM Higgs searches:

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





Where can the heavy Higgses be observed? With which precision?

The Charged MSSM Higgs boson and CDM benchmarks

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

NUHM: (Non-universal Higgs mass model)

$\Rightarrow$ besides the CMSSM parameters (m_0, $m_{1/2}$, A_0, $\tan\beta$)

M_A and μ

Assumption:

no unification of scalar fermion and scalar Higgs parameters at the GUT scale

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

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

Lightest SUSY particle (LSP) is the lightest neutralino

$\Rightarrow$ possible: M_A–$\tan\beta$ planes in agreement with CDM :-)

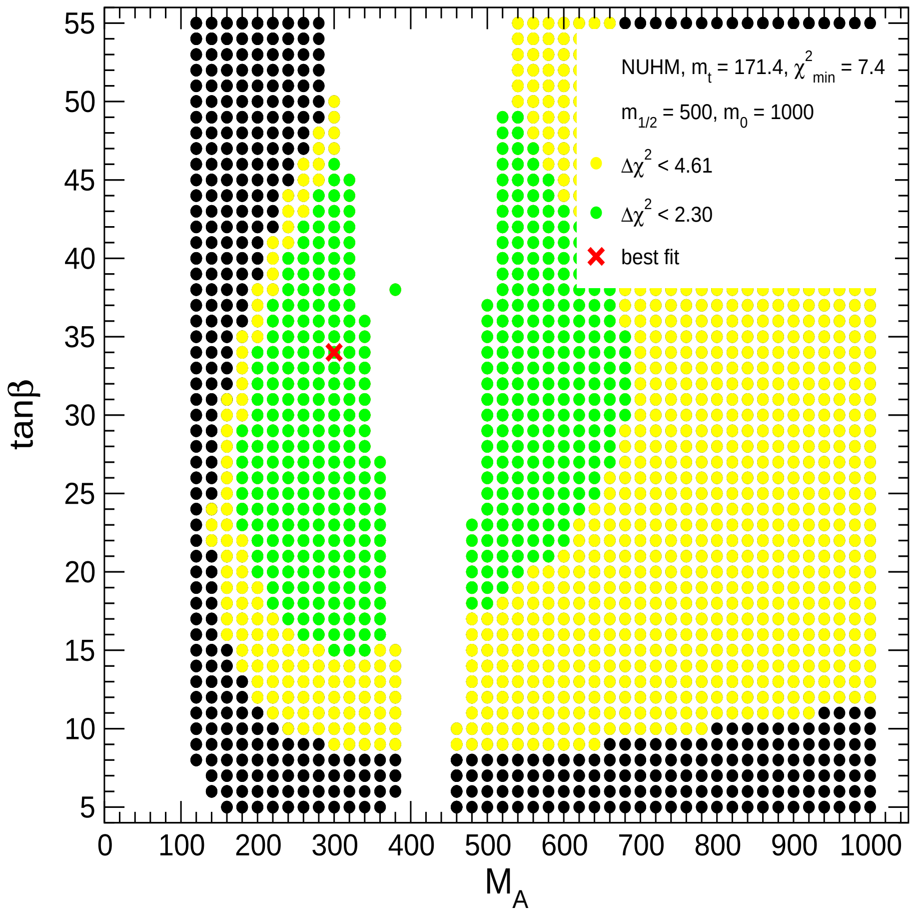
$\Rightarrow M_A$–tan β planes in agreement with CDM possible!

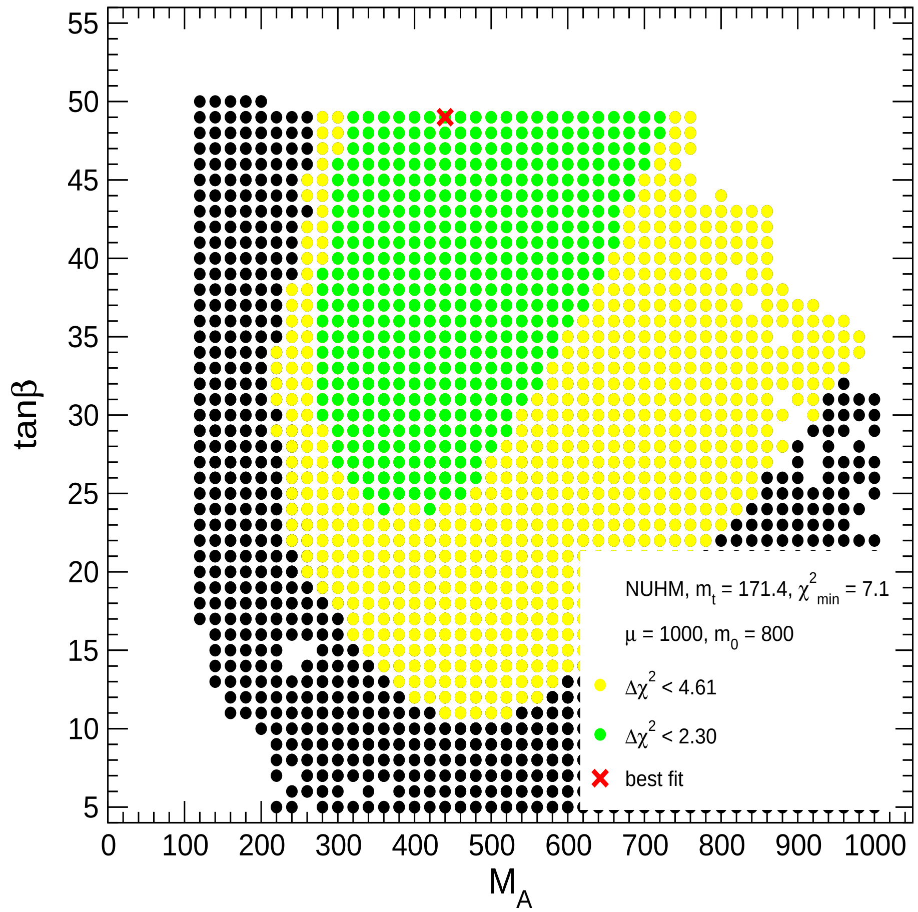
Also in agreement with other constraints from
electroweak precision observables and B physics observables:

$\Rightarrow \chi^2$ test with:

1. W boson mass M_W
2. effective leptonic weak mixing angle $\sin^2\theta_{\rm eff}$
3. total Z boson width Γ_Z
4. lightest Higgs boson mass M_h
5. anomalous magnetic moment of the muon $(g-2)_\mu$
6. b decay BR$(b \to s\gamma)$
7. b decay BR$(B_s \to \mu^+\mu^-)$
8. b decay BR$(B_u \to \tau\nu_\tau)$
9. B_s mixing ΔM_{B_s}

Example: NUHM planes 2,3





$\Rightarrow$ good χ^2 (M_W, $\sin^2\theta_{\rm eff}$, Γ_Z, M_h, $(g-2)_\mu$, BR($b \to s\gamma$) and other BPO)

$\Rightarrow$ larger regions o.k.