Heavy MSSM Higgs Bosons at the LHC

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1. Introduction & Motivation
2. "Conventional" production of H, A at the LHC
3. CED production of MSSM Higgs bosons at the LHC
4. Conclusions

1. Introduction & Motivation

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

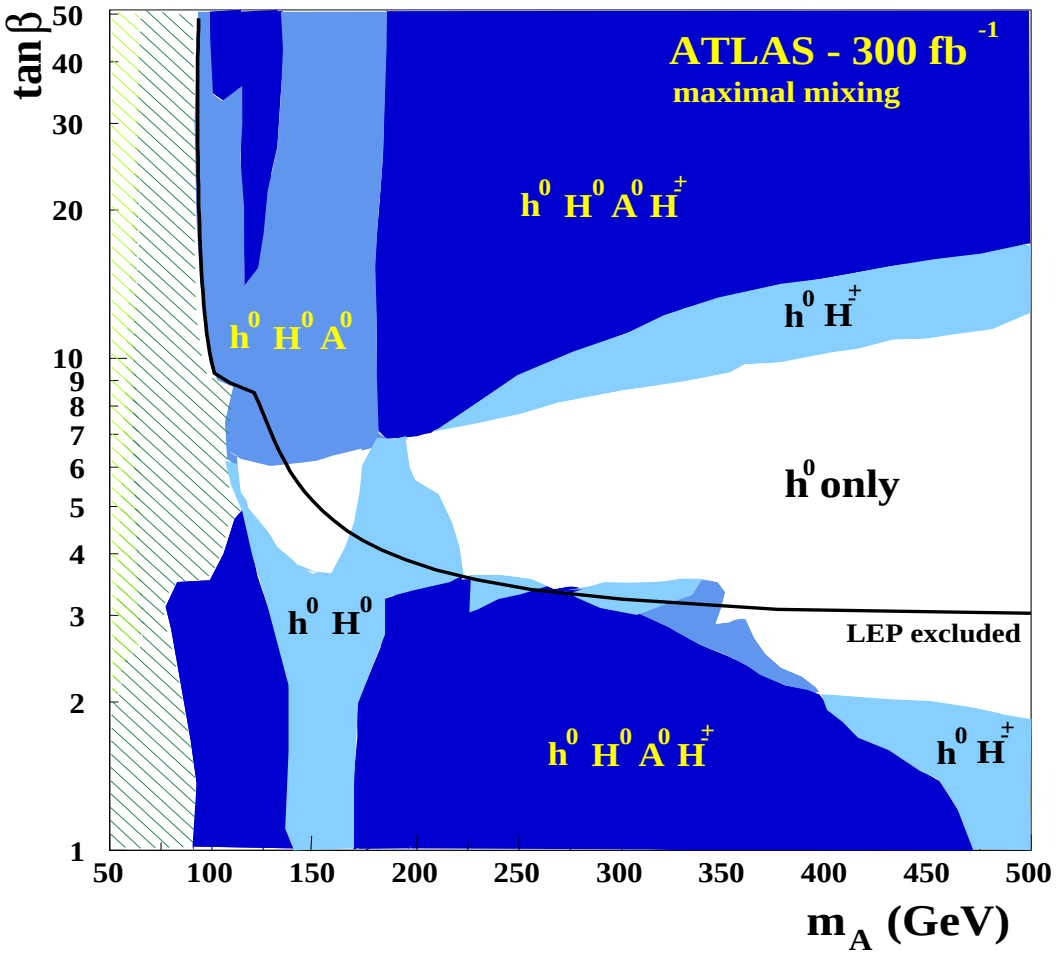
physical states: $h^0, H^0, A^0, H^\pm$ Goldstone bosons: $G^0, G^\pm$

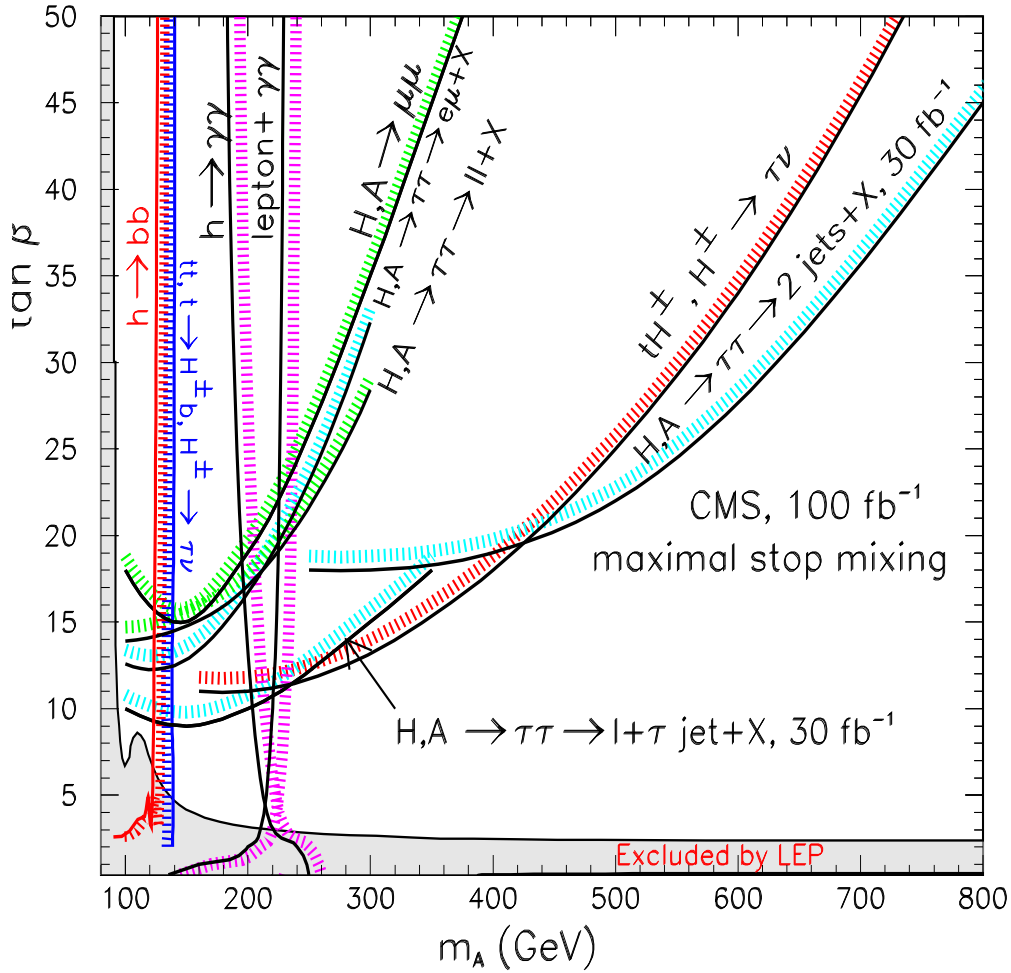
Input parameters: (to be determined experimentally)

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

"Heavy" MSSM Higgs searches:

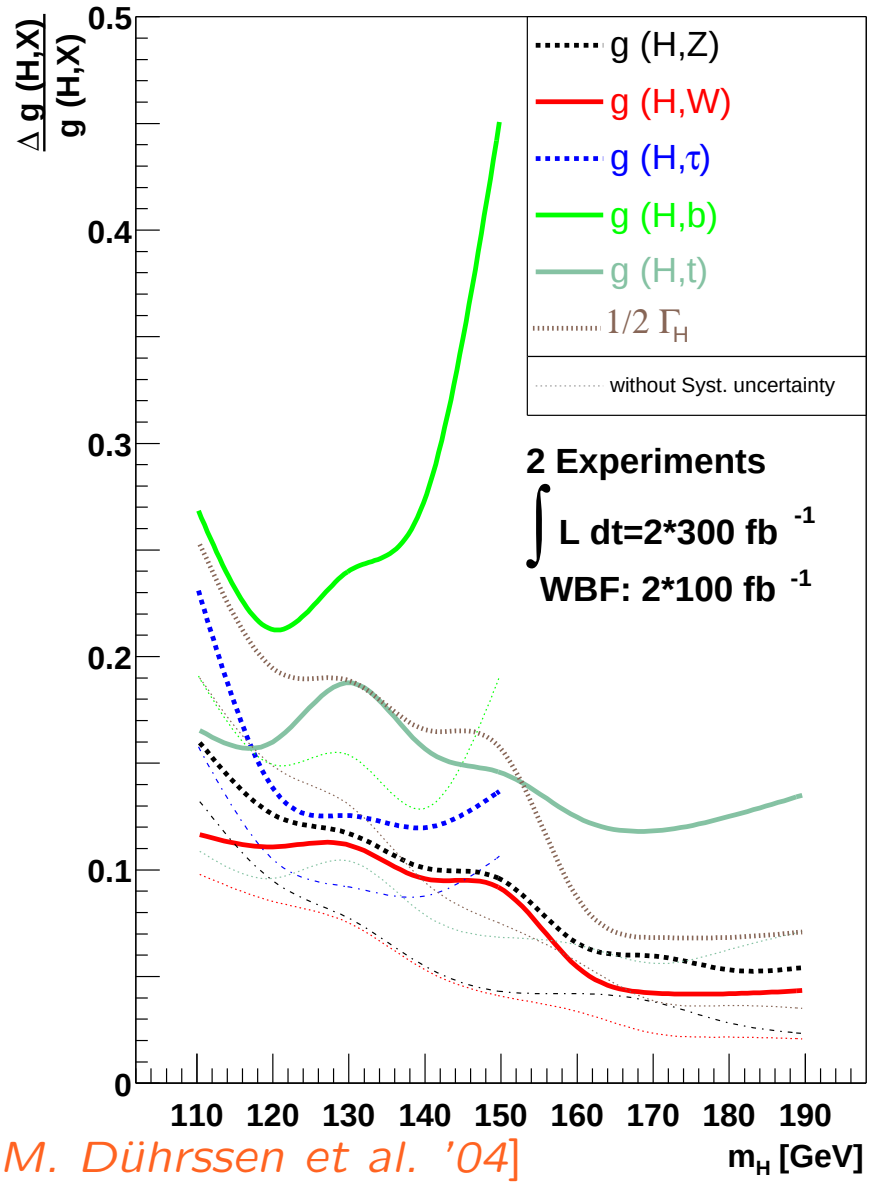
MSSM Higgs discovery contours in M_A–$\tan\beta$ plane ($m_h^{\max}$ benchmark scenario): [ATLAS '99] [CMS '03]





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

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 accuracies of 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:

$Hb\bar{b}$ only via $t\bar{t} \to H \to b\bar{b}$

signal shape $\approx$ background shape

$\Rightarrow$ reduced signal in new analyses (for ATLAS and CMS)

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

2. "Conventional" production of H, A at the LHC

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

Enhancement factors compared to the SM case:

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

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

$\Rightarrow$ Δ_b effects so far neglected by ATLAS/CMS

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

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

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

Analyzed search channels ($\phi = H, A$):

$$b\bar{b}\phi, \phi \to \tau^+\tau^- \to 2\,\text{jets}$$

$$b\bar{b}\phi, \phi \to \tau^+\tau^- \to \mu + \text{jet}$$

$$b\bar{b}\phi, \phi \to \tau^+\tau^- \to e + \text{jet}$$

$5\,\sigma$ discovery contours = lower edge of LHC wedge

Analyzed search channels ($\phi = H, A$):

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$$b\bar{b}\phi, \phi \to \tau^+\tau^- \to \mu + \text{jet}$$

$$b\bar{b}\phi, \phi \to \tau^+\tau^- \to e + \text{jet}$$

$\phi \to \tau^+\tau^- \to$ jets, 60 fb^{-1}			
M_A [GeV]	200	500	800
N_S	63	35	17
ε_{exp}	2.5×10^{-4}	2.4×10^{-3}	3.6×10^{-3}
R_{M_ϕ}	0.176	0.171	0.187
$\Delta M_\phi / M_\phi$ [%]	2.2	2.8	4.5

ε_{exp}: experimental selection efficiency

R_{M_ϕ}: di-τ mass resolution over Higgs boson mass

[*S. Gennai, A. Nikitenko, L. Wendland '06*]

Analyzed search channels ($\phi = H, A$):

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$$b\bar{b}\phi, \phi \to \tau^+\tau^- \to \mu + \text{jet}$$

$$b\bar{b}\phi, \phi \to \tau^+\tau^- \to e + \text{jet}$$

$\phi \to \tau^+\tau^- \to \mu + \text{jet}$, 30 fb^{-1}		
M_A [GeV]	200	500
N_S	79	57
ε_{exp}	7.0×10^{-3}	2.0×10^{-2}
R_{M_ϕ}	0.210	0.200
$\Delta M_\phi / M_\phi$ [%]	2.4	2.6

ε_{exp}: experimental selection efficiency

R_{M_ϕ}: di-τ mass resolution over Higgs boson mass

[*A. Kalinowski, M. Konecki, D. Kotlinski '06*]

Analyzed search channels ($\phi = H, A$):

$$b\bar{b}\phi, \phi \to \tau^+\tau^- \to 2\,\text{jets}$$

$$b\bar{b}\phi, \phi \to \tau^+\tau^- \to \mu + \text{jet}$$

$$b\bar{b}\phi, \phi \to \tau^+\tau^- \to e + \text{jet}$$

$\phi \to \tau^+\tau^- \to e +$ jet, 30 fb^{-1}			
M_A [GeV]	200	300	500
N_S	72.9	45.5	32.8
ε_{exp}	3.0×10^{-3}	6.4×10^{-3}	1.0×10^{-2}
R_{M_ϕ}	0.216	0.214	0.230
$\Delta M_\phi / M_\phi$ [%]	2.5	3.2	4.0

ε_{exp}: experimental selection efficiency

R_{M_ϕ}: di-τ mass resolution over Higgs boson mass

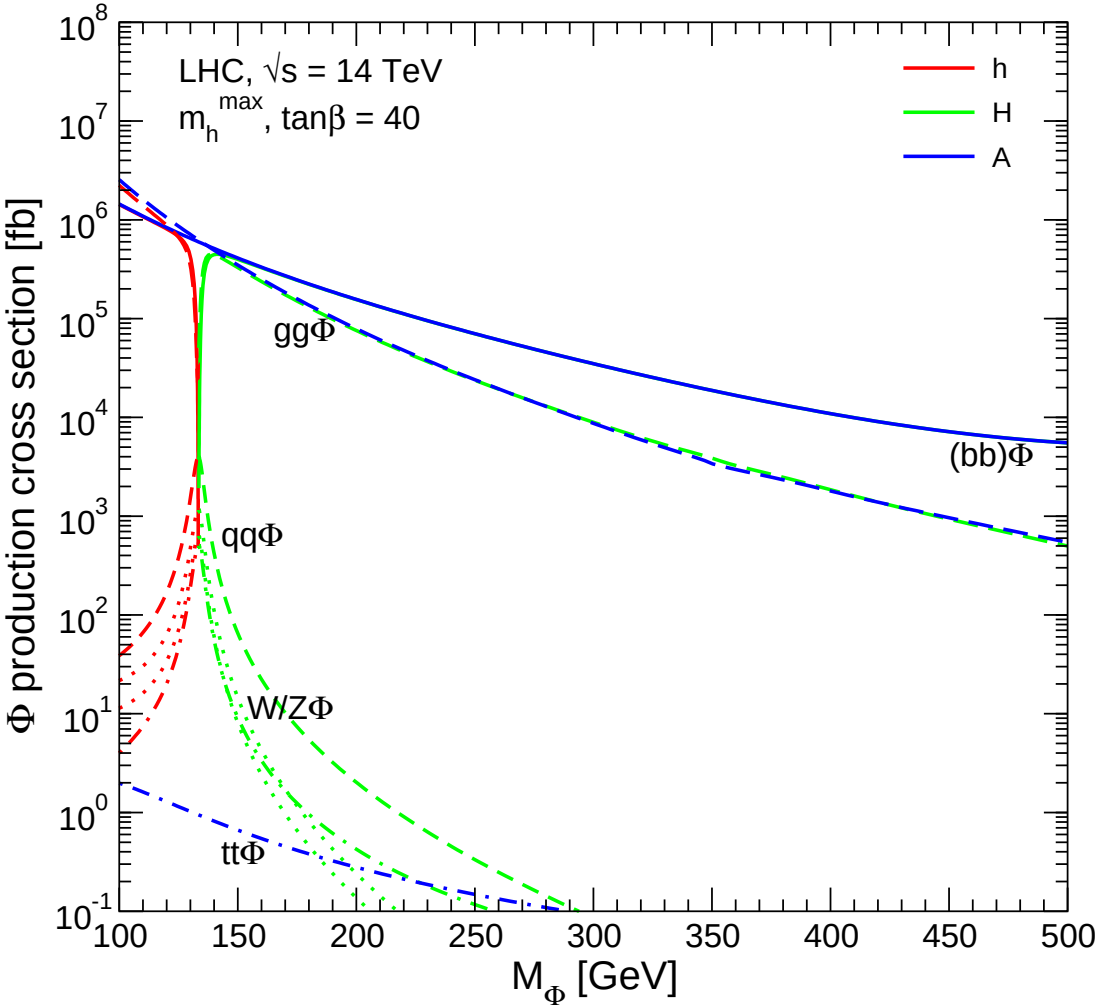
[*R. Kinnunen, S. Lethi '06*]

Combination of latest experimental and theoretical results

Prediction for Higgs production cross sections at the LHC:

⇒ implemented into **FeynHiggs**

[*T. Hahn, S.H., F. Maltoni, G. Weiglein, S. Willenbrock '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: $b\bar{b}\phi$

(5 flavor scheme)

Combination of latest experimental and theoretical results

1. latest CMS results for $b\bar{b}\phi, \phi \to \tau^+\tau^-$

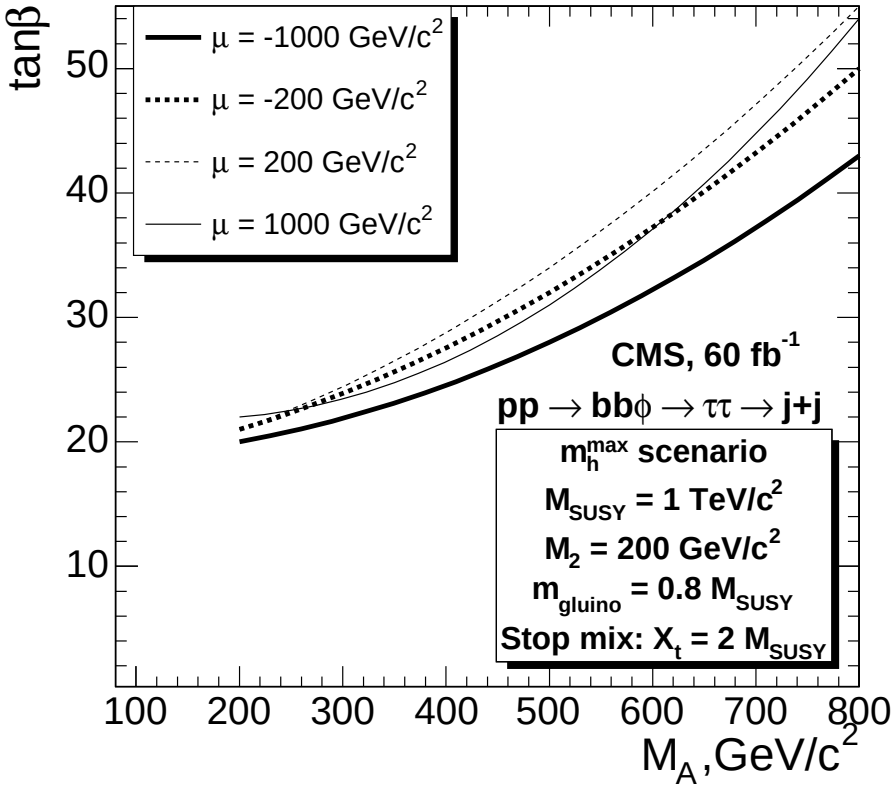
2. cross section results as implemented into `FeynHiggs`
   - five flavor scheme for SM result
   - effective coupling approximation for SUSY correction:

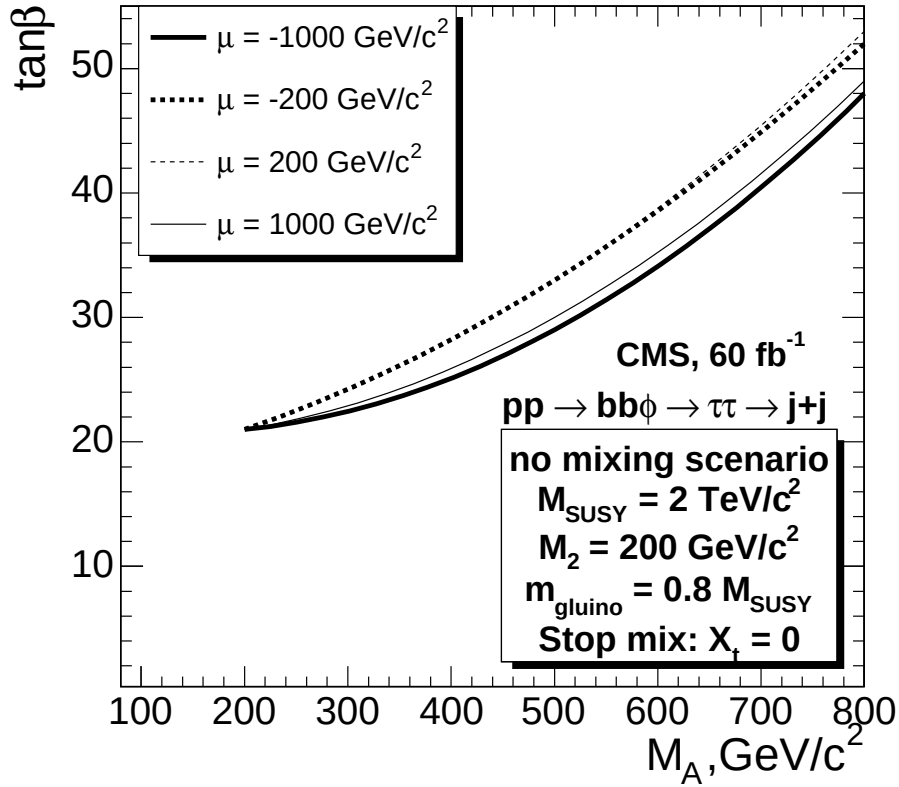
$$\frac{\Gamma(\phi \to b\bar{b})_{\text{MSSM}}}{\Gamma(\phi \to b\bar{b})_{\text{SM}}}$$

3. evaluation of BR$(H/A \to \tau^+\tau^-)$ as implemented into `FeynHiggs` included:
   - Δ_b corrections
   - Higgs wave function corrections
   - decay to SUSY particles
   - ...

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

[*S.H., A. Nikitenko, G. Weiglein et al. '07*]



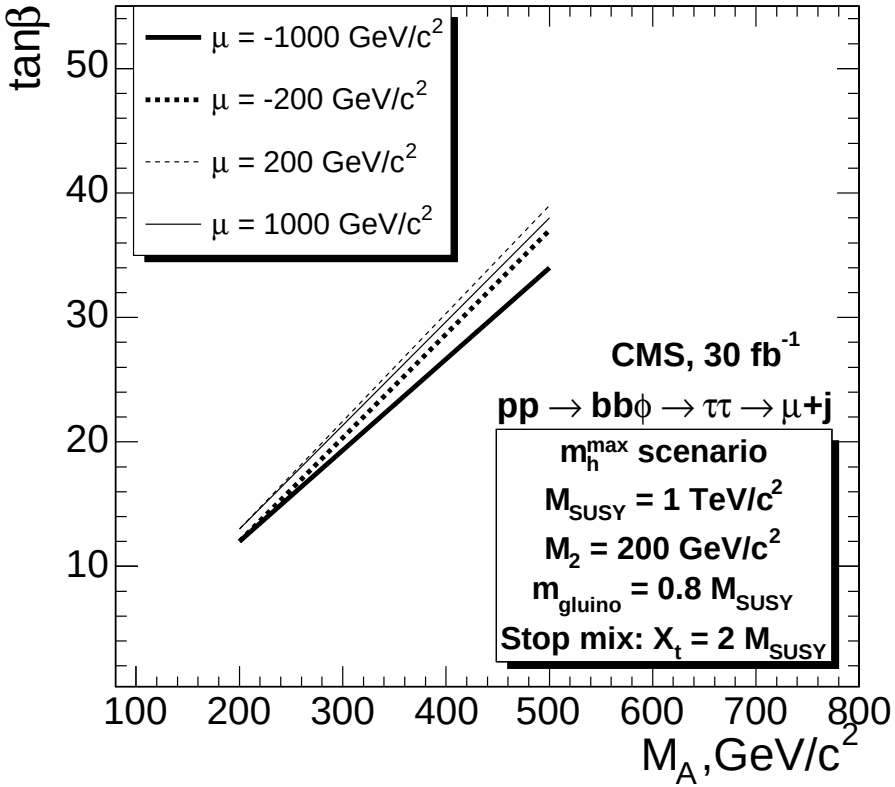


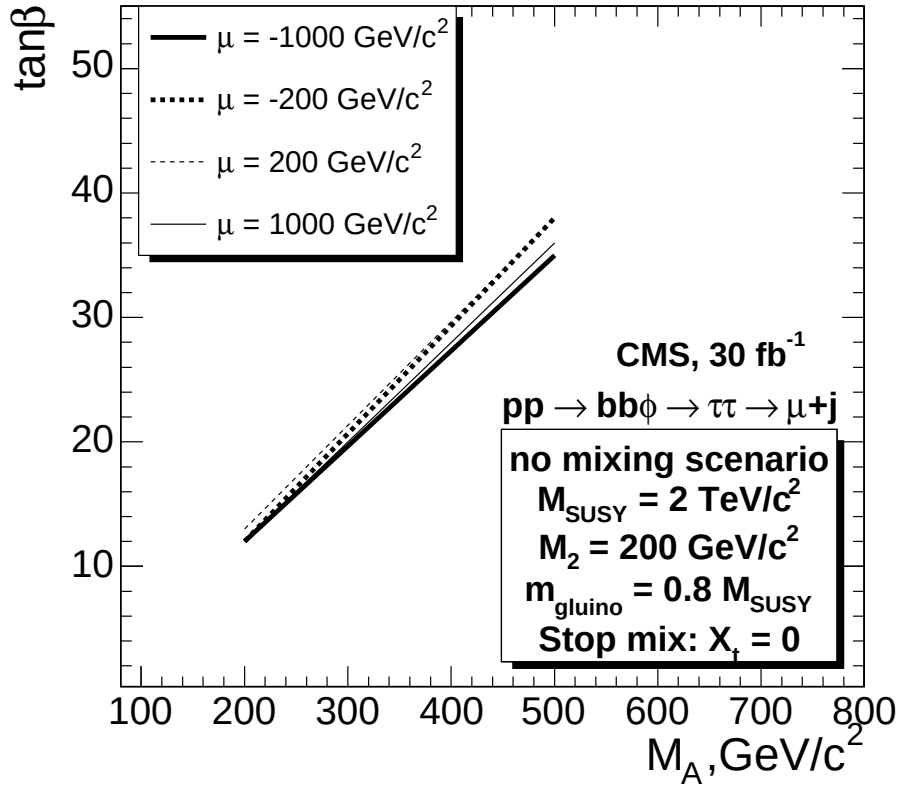
$\Rightarrow$ non-negligible variation with the sign and absolute value of μ

($\to$ numerical compensations in production and decay)

Dependence on μ of LHC wedge from $b\bar{b} \to H/A \to \tau^+\tau^- \to \mu +$ jet:

[*S.H., A. Nikitenko, G. Weiglein et al. '07*]



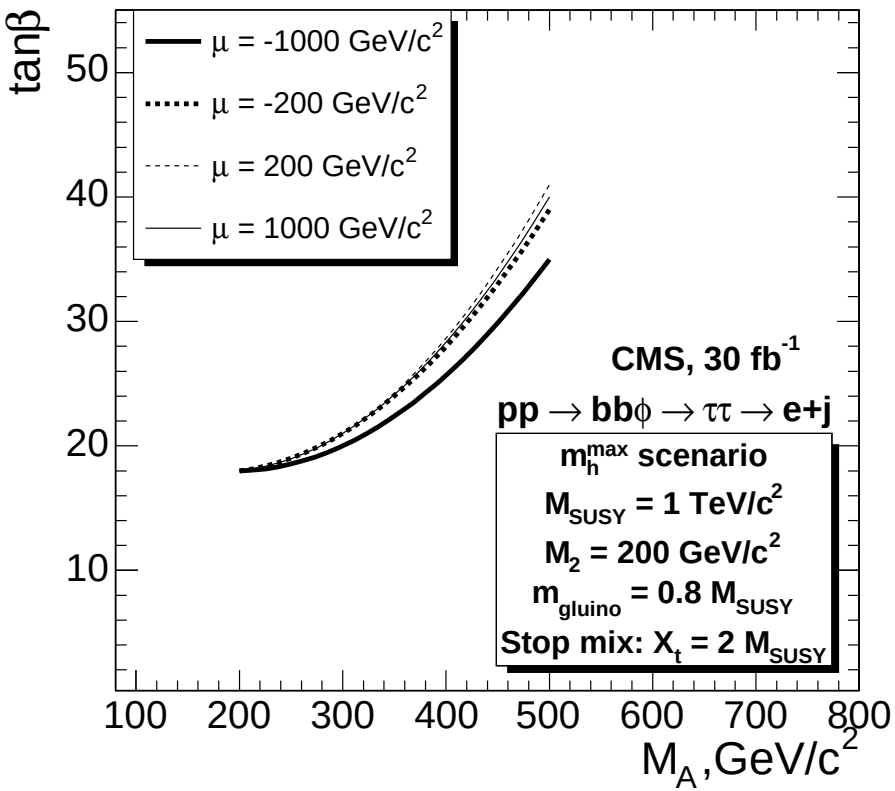


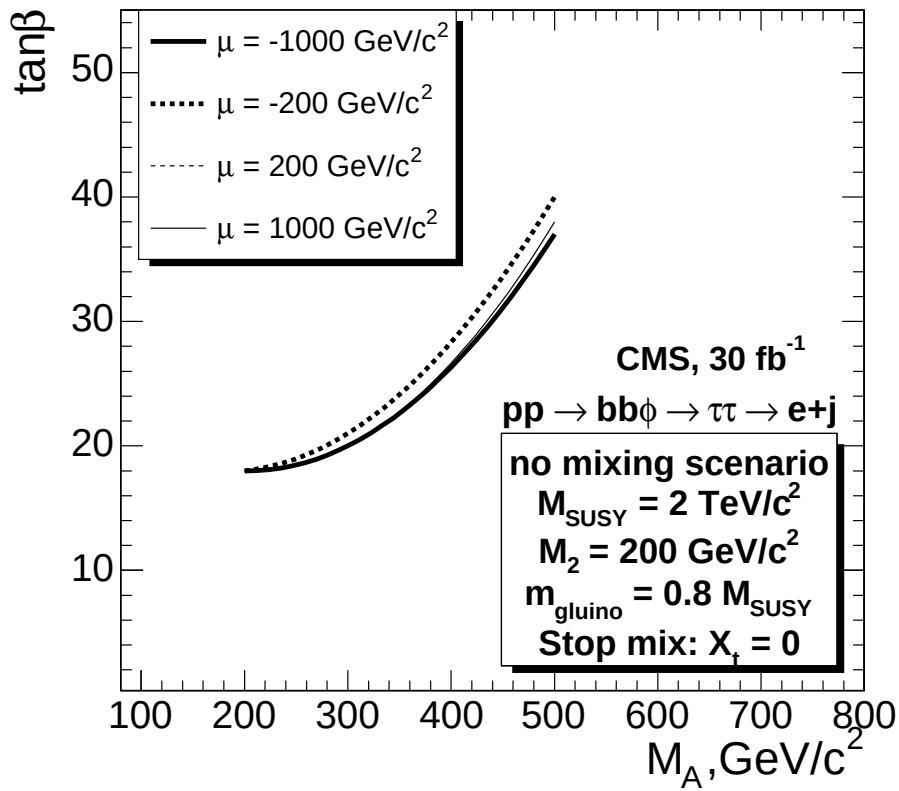
$\Rightarrow$ non-negligible variation with the sign and absolute value of μ

($\rightarrow$ numerical compensations in production and decay)

Dependence on μ of LHC wedge from $b\bar{b} \to H/A \to \tau^+\tau^- \to e +$ jet:

[*S.H., A. Nikitenko, G. Weiglein et al. '07*]



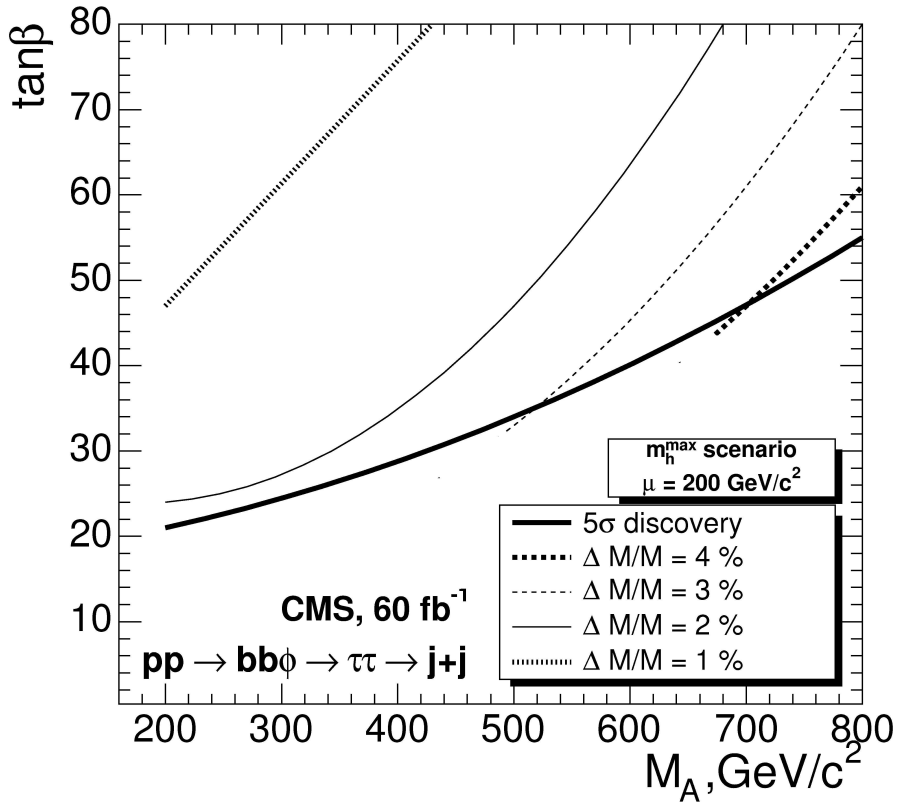


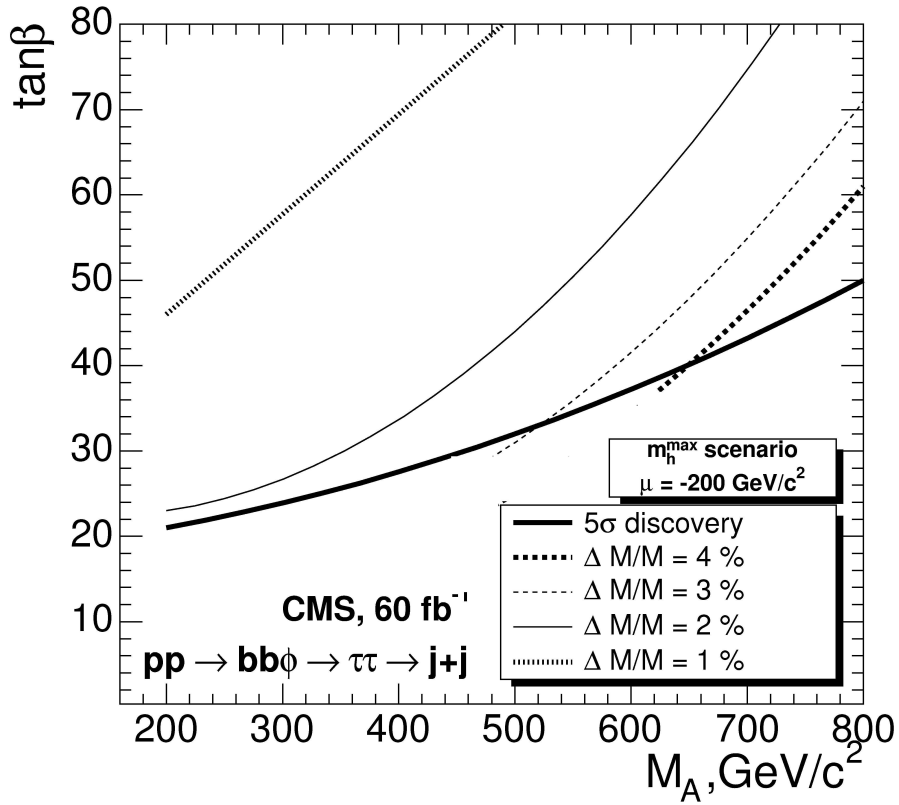
$\Rightarrow$ non-negligible variation with the sign and absolute value of μ

($\rightarrow$ numerical compensations in production and decay)

Precision of $\delta M/M$ from $b\bar{b} \to H/A \to \tau^+\tau^- \to 2\,\text{jets}$:

[*S.H., A. Nikitenko, G. Weiglein et al. '07*]





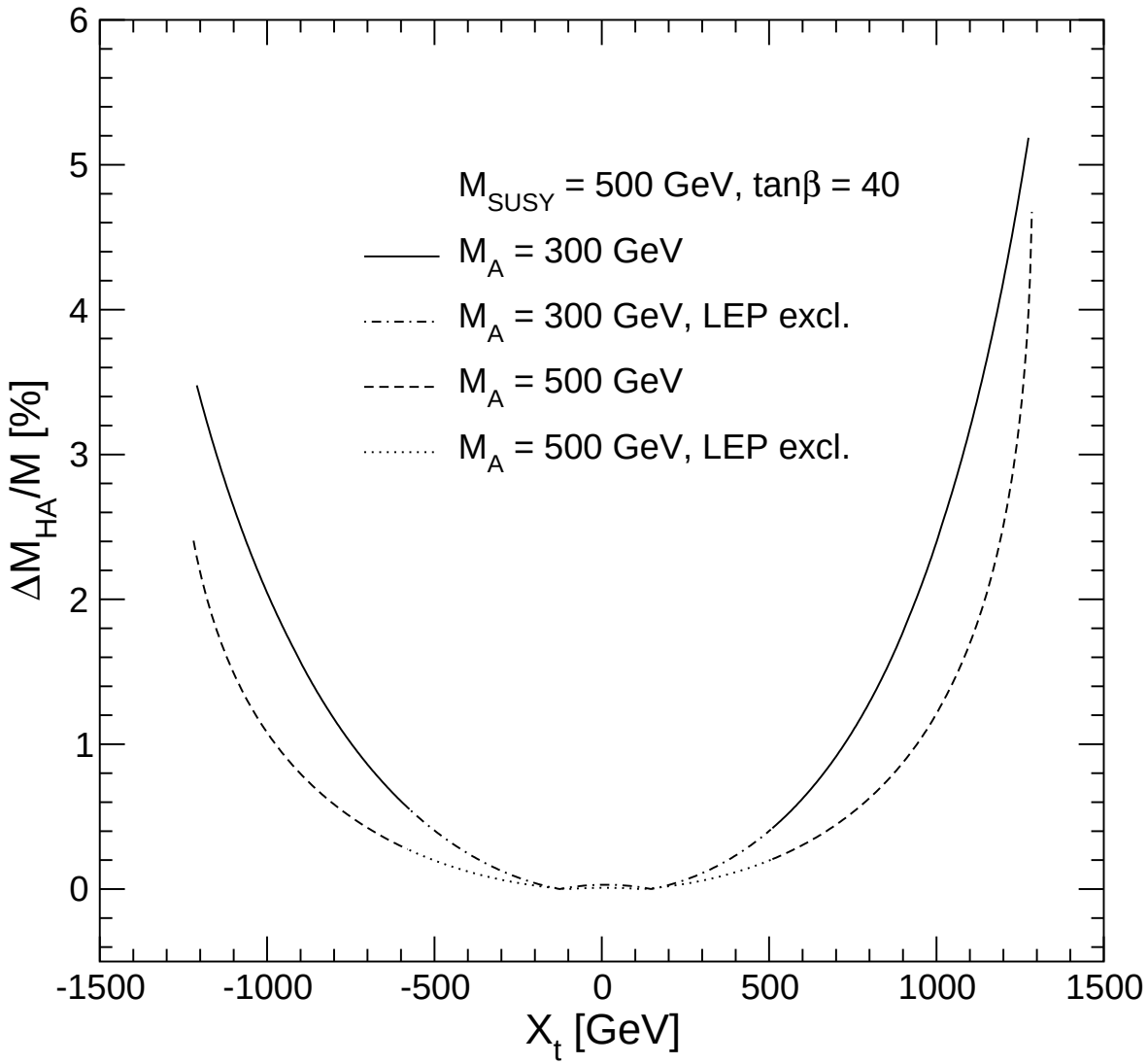
$\Rightarrow$ high precision measurement of heavy Higgs boson masses possible

Distinguish between H and A:

$\delta M/M$ resolution of 1–4% possible

$\Rightarrow$ possibly enough to resolve H and A

($M_{\text{SUSY}} = 500$ GeV,
$A_{t,b} = 1000$ GeV
$\mu = 1000$ GeV,
$M_2 = 500$ GeV
$m_{\tilde{g}} = 500$ GeV
$\rightarrow$ "normal" scenario)

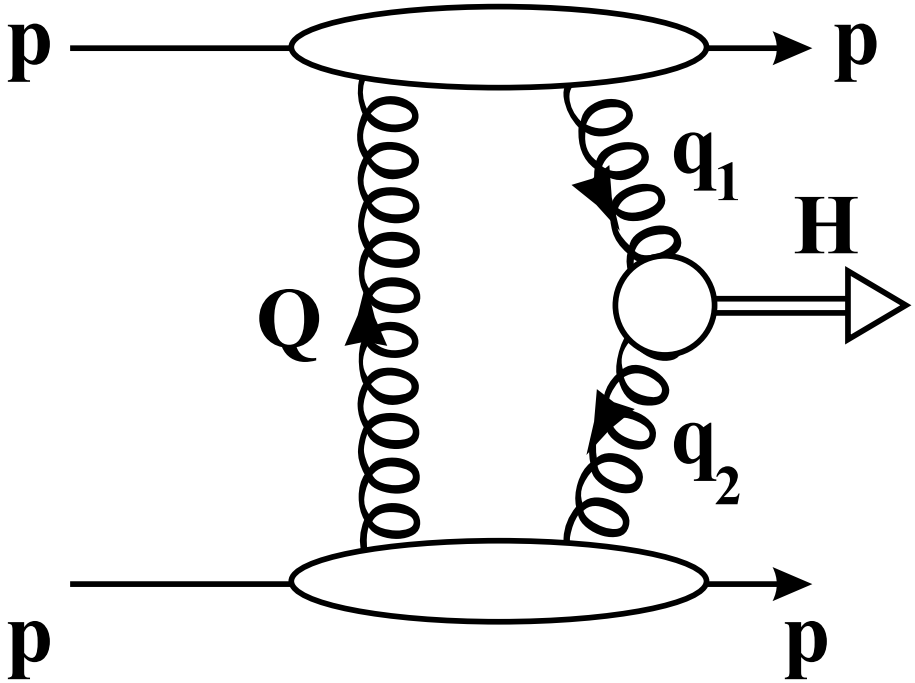


$\Rightarrow$ detailed analysis in progress [*S.H., A. Nikitenko, G. Weiglein '07*]

3. CED production of MSSM Higgs bosons at the LHC

[*S.H., V. Khoze, M. Ryskin, W. Stirling, M. Tasevsky, G. Weiglein '07*]

$pp \;\rightarrow\; p \oplus h, H \oplus p, \quad h, H \rightarrow b\bar{b}$ (protons remain intact)



Some details ($\phi = h, H$):

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: 220, high p_T jets, high p_T leptons, ...

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

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

6. Decay calculation: BR($\phi \to b\bar{b}$) $\Rightarrow$ `FeynHiggs`, incl. Δ_b dependence
   advantage over SM: enhanced decay rates

7. Backgrounds and pile-up:
   taken into account according to recent analyses/
   best available estimates

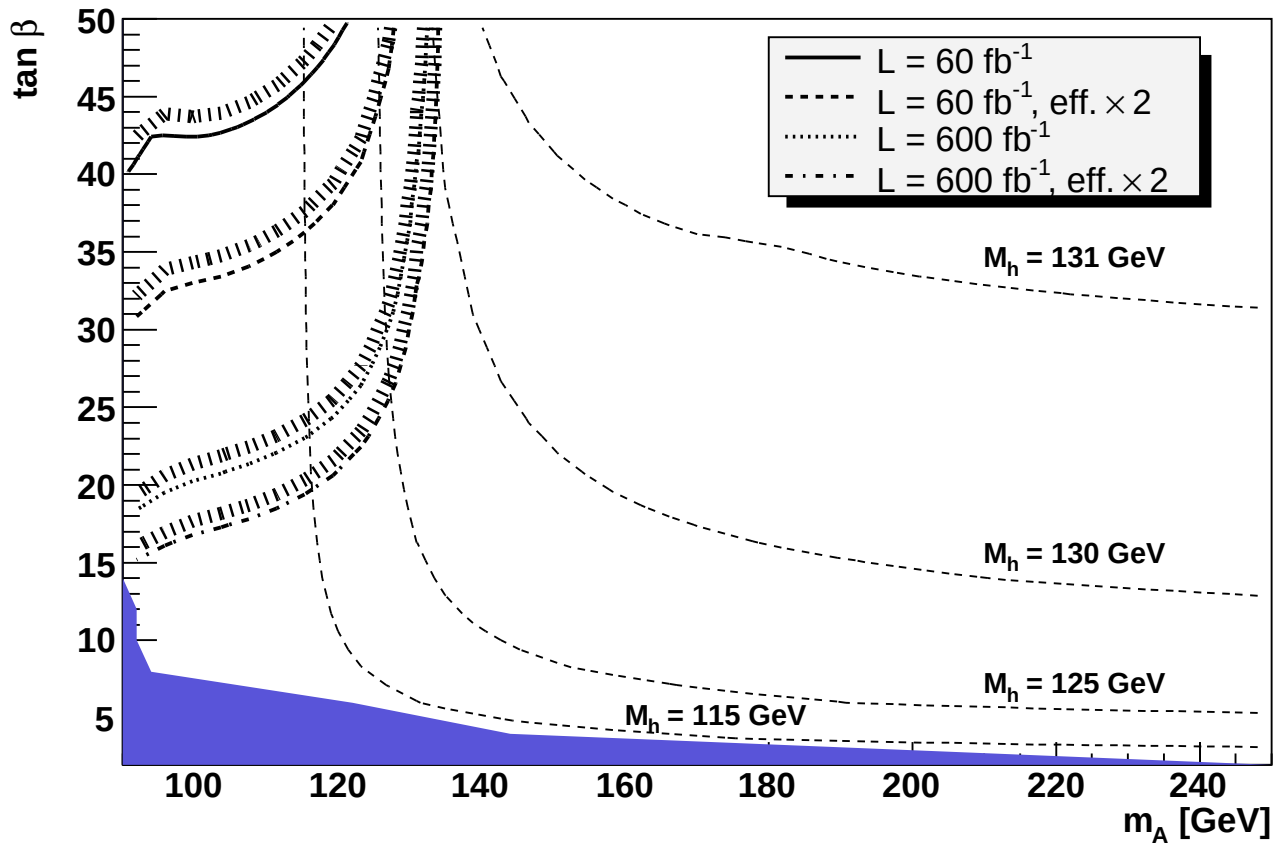
$\Rightarrow$ 5 σ discovery contours, 3 σ significance bounds

Results for h (I):

$m_h^{\max}$ scenario

4 luminosity assumptions:
$60, 60$ eff $\times 2$,
$600, 600$ eff $\times 2$

$\Rightarrow 5\,\sigma$ contours



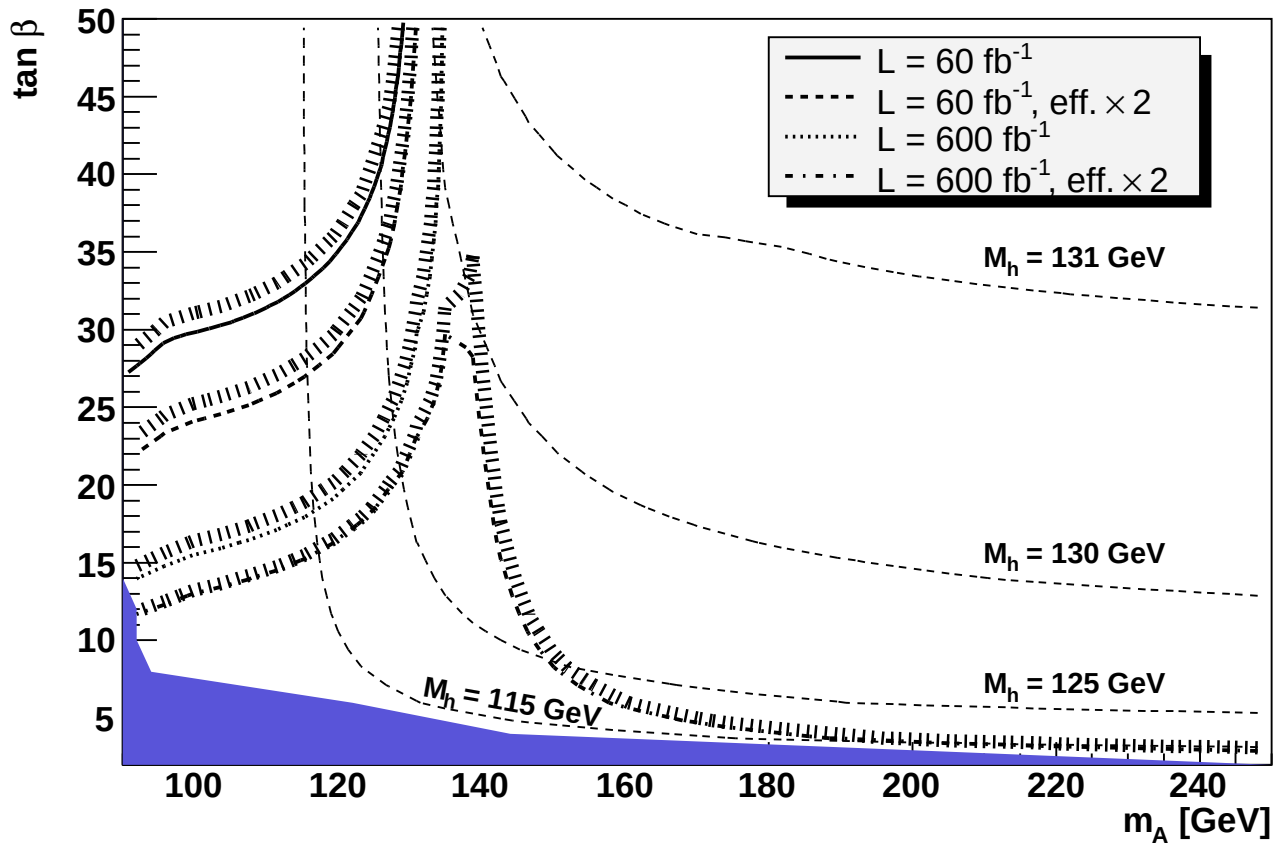
$\Rightarrow$ some coverage for low M_A and large $\tan\beta$

Results for h (II):

$m_h^{\max}$ scenario

4 luminosity assumptions:
$60, 60$ eff $\times 2$,
$600, 600$ eff $\times 2$

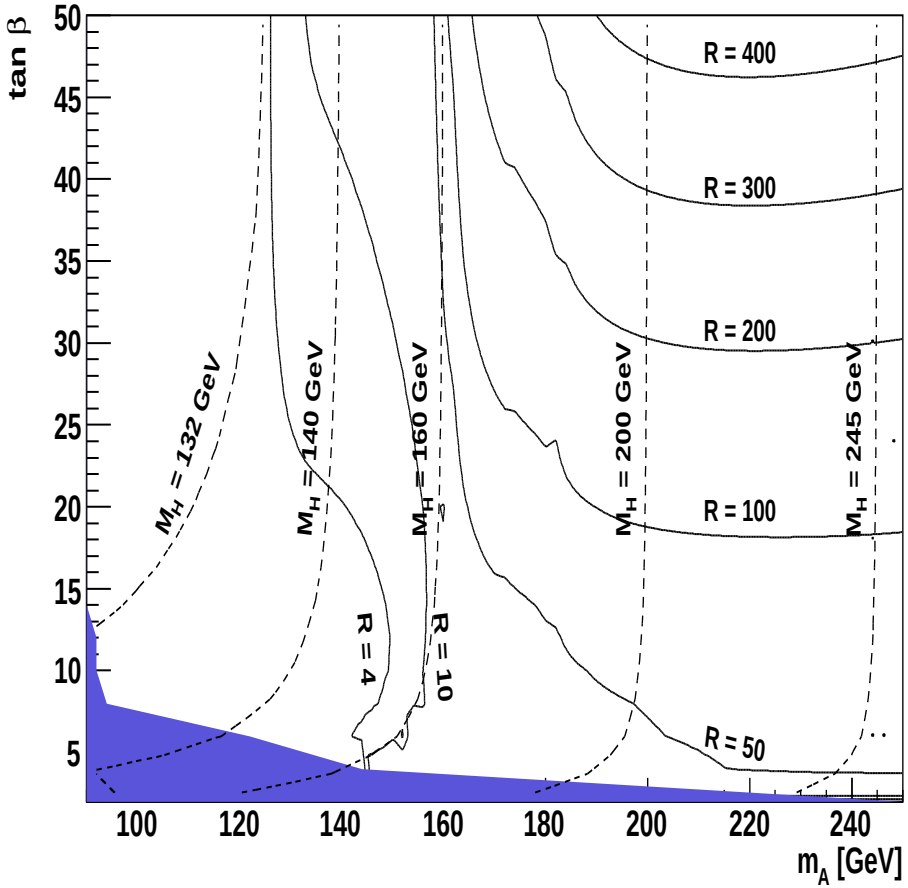
$\Rightarrow 3\,\sigma$ contours



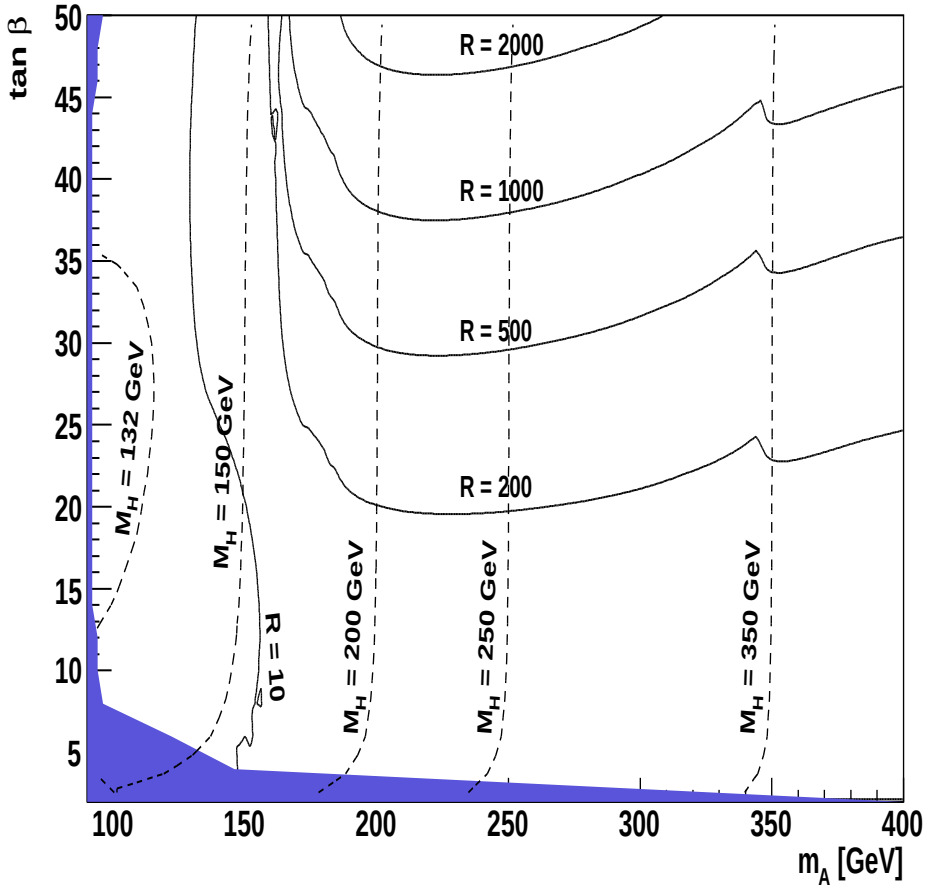
$\Rightarrow$ good coverage for high luminosity
$\Rightarrow$ determination of bottom Yukawa coupling?

Results for H: enhancement factors compared to SM

$\mu = +200$ GeV



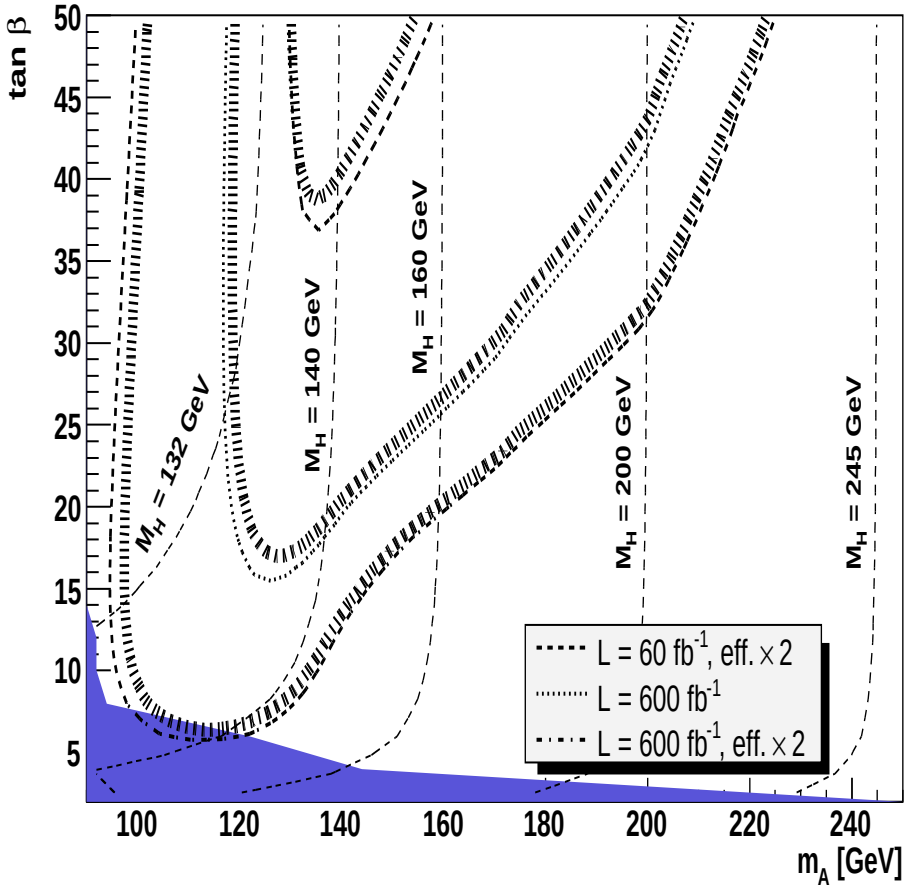
$\mu = -500$ GeV



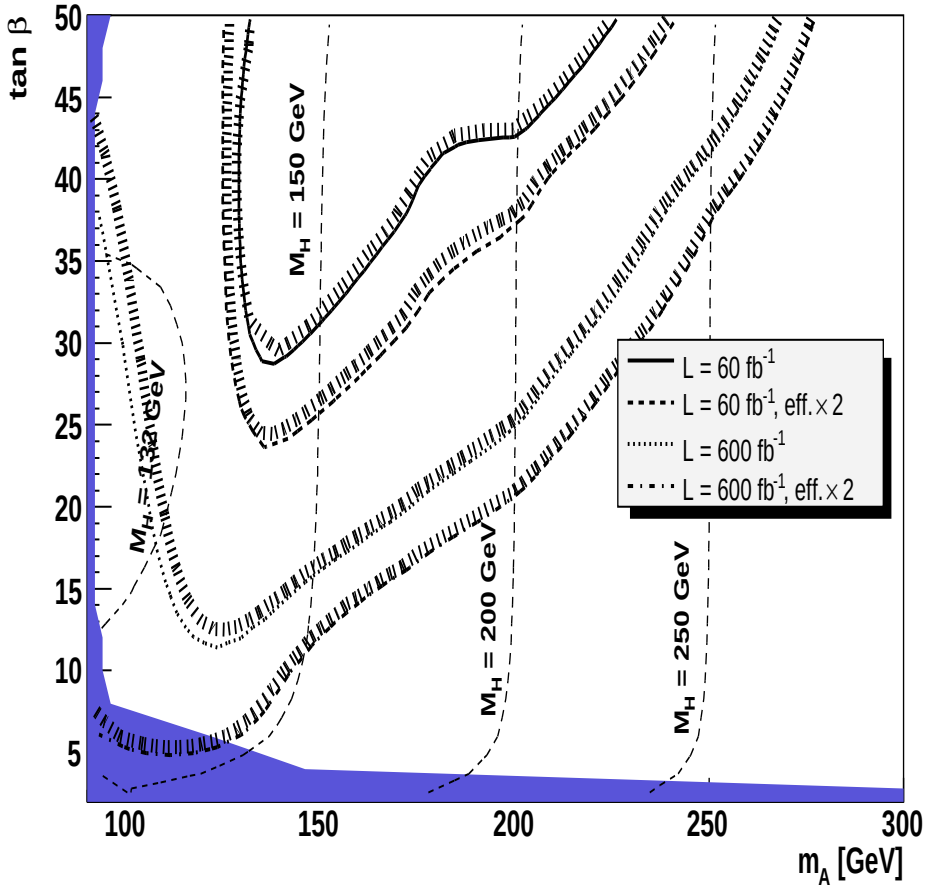
$\Rightarrow$ strong enhancement possible, especially for $\mu = -500$ GeV

Results for H: $5\,\sigma$ discovery regions

$\mu = +200$ GeV



$\mu = -500$ GeV



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

4. Conclusinos

- Important to determine:
  - Higgs boson mass scale: M_A
  - bottom Yukawa coupling: y_b

- $5\,\sigma$ discovery reach at LHC ("wedge"):

  $b\bar{b} \to H/A \to \tau^+\tau^- \to \ldots$

  Combination of
  - latest CMS analysis results (30 or 60 fb^{-1}
  - precise theory calculation: FeynHiggs

  $\Rightarrow$ precise determination of $5\,\sigma$ discovery contours

  $\Rightarrow$ strong dependence on SUSY parameters, especially on μ

- CED production of MSSM Higgs bosons:

  $pp \;\to\; p \oplus h, H \oplus p, \quad h, H \to b\bar{b}$

  Combination of experimental analyses (trigger, background, pile-up, ...), theory calculations, analyses, ...

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

  $\Rightarrow$ additional channel for H (but not reducing the LHC wedge)