LHC Higgs — some theory issues

Georg Weiglein

DESY

Hamburg, 06 / 2012

- LHC Higgs XS WG: MSSM
- LHC Higgs XS WG: properties of a light Higgs
- Implications from Higgs search results
- A light Higgs in SUSY cascades?
- Should the benchmark scenarios used for SUSY Higgs searches at the LHC be updated?

LHC Higgs XS WG: MSSM

Predictions for MSSM cross sections and branching ratios:

Both SM cross sections dressed with effective MSSM couplings and dedicated cross section predictions in the MSSM are used

Higgs masses, effective couplings and branching ratios (partially) in predictions for LHC Higgs XS WG evaluated with *FeynHiggs*

FeynHiggs: Higgs phenomenology in the SM and the MSSM; extension to the NMSSM in preparation

www.feynhiggs.de

[*T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. W., K. Williams*]

LHC Higgs XS WG: properties of a light Higgs

- Mass: finite width effects assumed to be negligible
- Couplings:

  What is actually meant by a Higgs coupling measurement?

  - Use tree-level relations

    $\Rightarrow$ Misses large higher-order corrections

    Compatibility of the results with the SM?

  - Full SM predictions $+$ anomalous couplings

    $\Rightarrow$ Appropriate tools needed

    Anomalous couplings would in general change kinematic distributions

    $\Rightarrow$ no simple rescaling of MC predictions possible

Determination of the properties of a light Higgs-like state

- - Scaling of couplings + free parameters for additional (loop) contributions
    Note: scaling of couplings is in general not possible if higher-order electroweak corrections are included
  - Coupling ratios vs. absolute coupling determination: assumption on total width needed
- Higgs spin an $\mathcal{CP}$ properties [*M. Schumacher '12*]

Production in gluon fusion:
H→γγ: discriminate spin 0 and 2 from Gottfried Jackson angle
H→VV→4l: discriminate spin 0,1,2 and CP structures from invariant di-lepton mass and up to 5 decay angles
H→ττ discriminate CP (and spin) from decay angle correlations

Production in association with two jets / vector boson fusion, decays H→γγ,VV,ττ
discriminate spin and CP structure from azimuthal angle difference of two jets, event shapes (thrust, ...) + other observables

other possibilities:
- ttH, H→γγ or bb: angular angle correlations
- H produced in central exclusive diffration
- ...

Implications from Higgs search results

Limits for different production and decay channels have been presented in two ways:

- For a specific model: SM, MSSM benchmark scen., ...

  $\Rightarrow$ combination of different channels possible

  difficult to interpret for other models or w.r.t. changes in the input parameters or the theoretical predictions

- As cross section limits for a certain search topology

  $\Rightarrow$ exclusion bounds have to be tested channel by channel

  fairly model-independent and generally applicable

  $\Rightarrow$ Implemented in program *HiggsBounds*

  [*P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., K. Williams '08, '12*]

HiggsBounds: determination of 95% C.L. exclusion region from given cross section limits

In order to obtain an exclusion limit having the correct statistical interpretation as a 95% C.L.:

- On the basis of the expected search limits for different channels in a given model one needs to determine for every parameter point the search channel having the highest statistical sensitivity for setting an exclusion limit

- For this single channel only one needs to compare the observed limit with the theory prediction for the Higgs production cross section times decay branching ratio to determine whether or not the considered parameter point of the model is excluded at 95% C.L.

Interpretation of the results of the searches for a SM-like Higgs

- Limits from the SM Higgs searches have constrained the allowed region for a light SM-like Higgs to about $123 \text{ GeV} \lesssim M_{\mathrm{H_{SM}}} \lesssim 127 \text{ GeV}$
- Excess reported by ATLAS and CMS in the unexcluded region near $M_{\mathrm{H_{SM}}} \approx 125 \text{ GeV}$, supported by several channels (in particular $\gamma\gamma$, ZZ^*)

  Slight excess observed also at the Tevatron

  Statistical significance not yet conclusive

$\Rightarrow$ Investigate MSSM (and also NMSSM) interpretation of assumed Higgs signal at $\approx 125 \text{ GeV}$

Here: assumed signal at $125 \pm 1 \text{ GeV}$, theoretical uncertainties from unknown higher-order corr., $\Delta M_{\mathrm{h}}^{\mathrm{intr}} \sim 2 \text{ GeV}$, and parametric uncertaintes (m_{t} varied by $\pm 1\sigma$) taken into account

Interpretation of an assumed Higgs signal at $\sim 125~\mathrm{GeV}$ *in terms of the light MSSM CP-even Higgs* h

Assumed signal would imply a lower bound on M_h

$\Rightarrow$ Set parameters entering via higher-order corrections such that M_h is maximised ($m_\mathrm{h}^\mathrm{max}$ benchmark scenario)

$\Rightarrow$ Lower bounds on M_A, $\tan\beta$

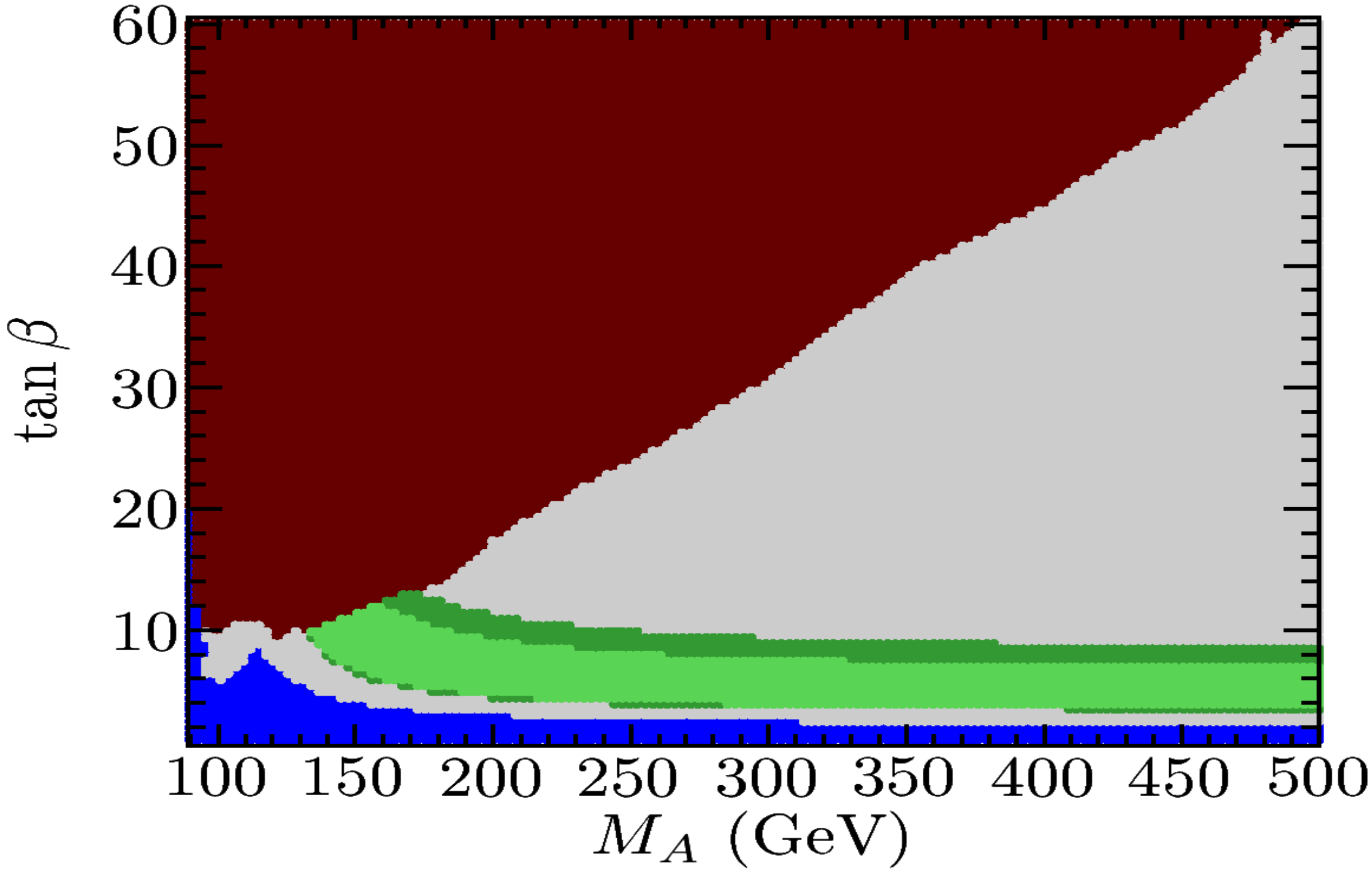
Search limits from LEP and from LHC $H, A \to \tau^+\tau^-$ search taken into account:

HiggsBounds

[*P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., K. Williams '08, '12*]

Lower bounds on M_{A} *and* $\tan\beta$ *from assumed Higgs signal at* ~ 125 GeV

Green region: compatible with assumed Higgs signal with / without m_{t} variation [*S. Heinemeyer, O. Stål, G. W. '11*]

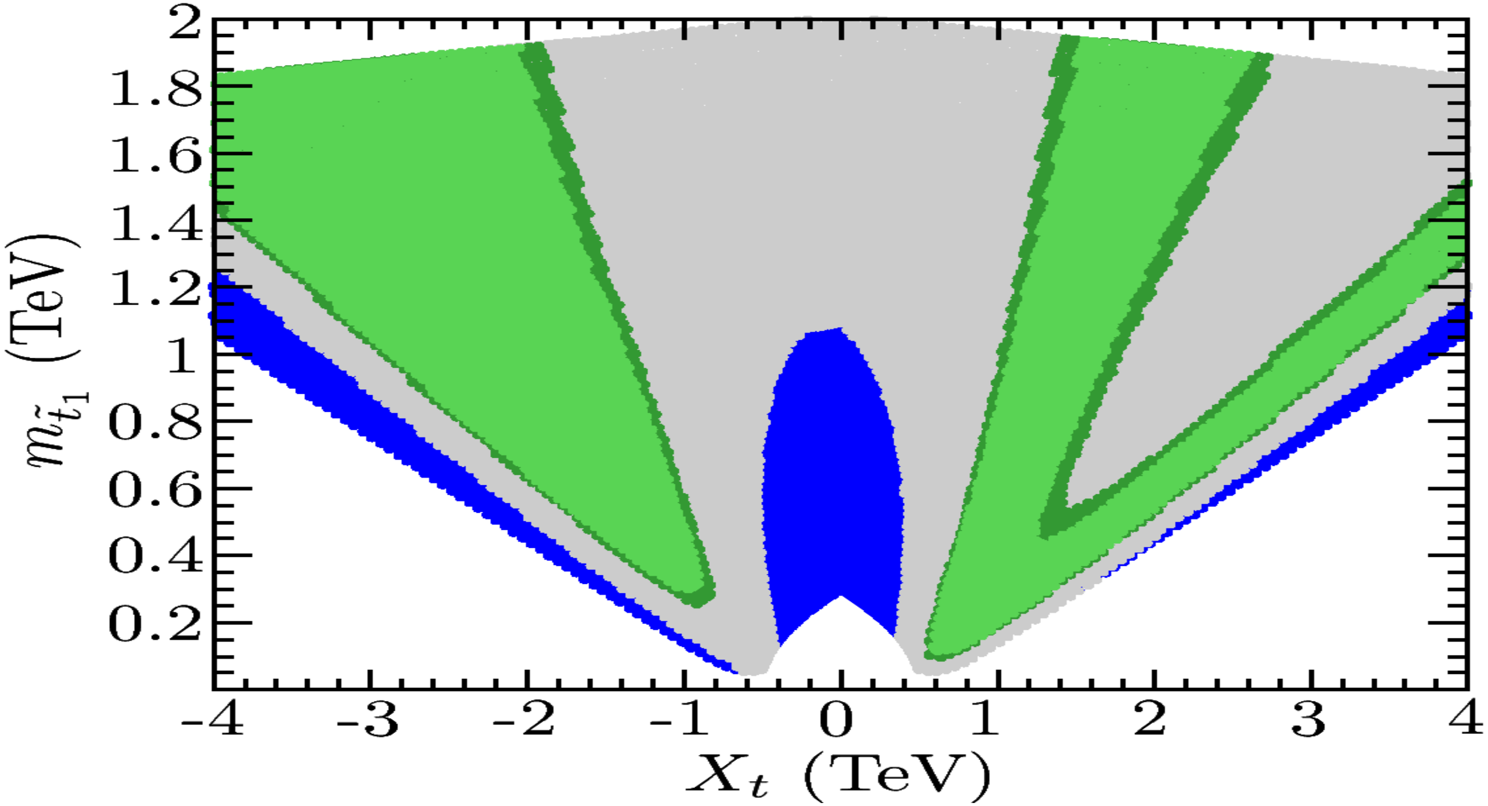


$\Rightarrow \tan\beta \gtrsim 3$, $M_{\mathrm{A}} \gtrsim 130$ GeV, $M_{\mathrm{H}^\pm} \gtrsim 152$ GeV

Lower bound on the lightest stop mass from assumed Higgs signal at ~ 125 GeV

M_A, $\tan\beta$ chosen in decoupling region: $M_\mathrm{A} = 1$ TeV, $\tan\beta = 20$

[S. Heinemeyer, O. Stål, G. W. '11]

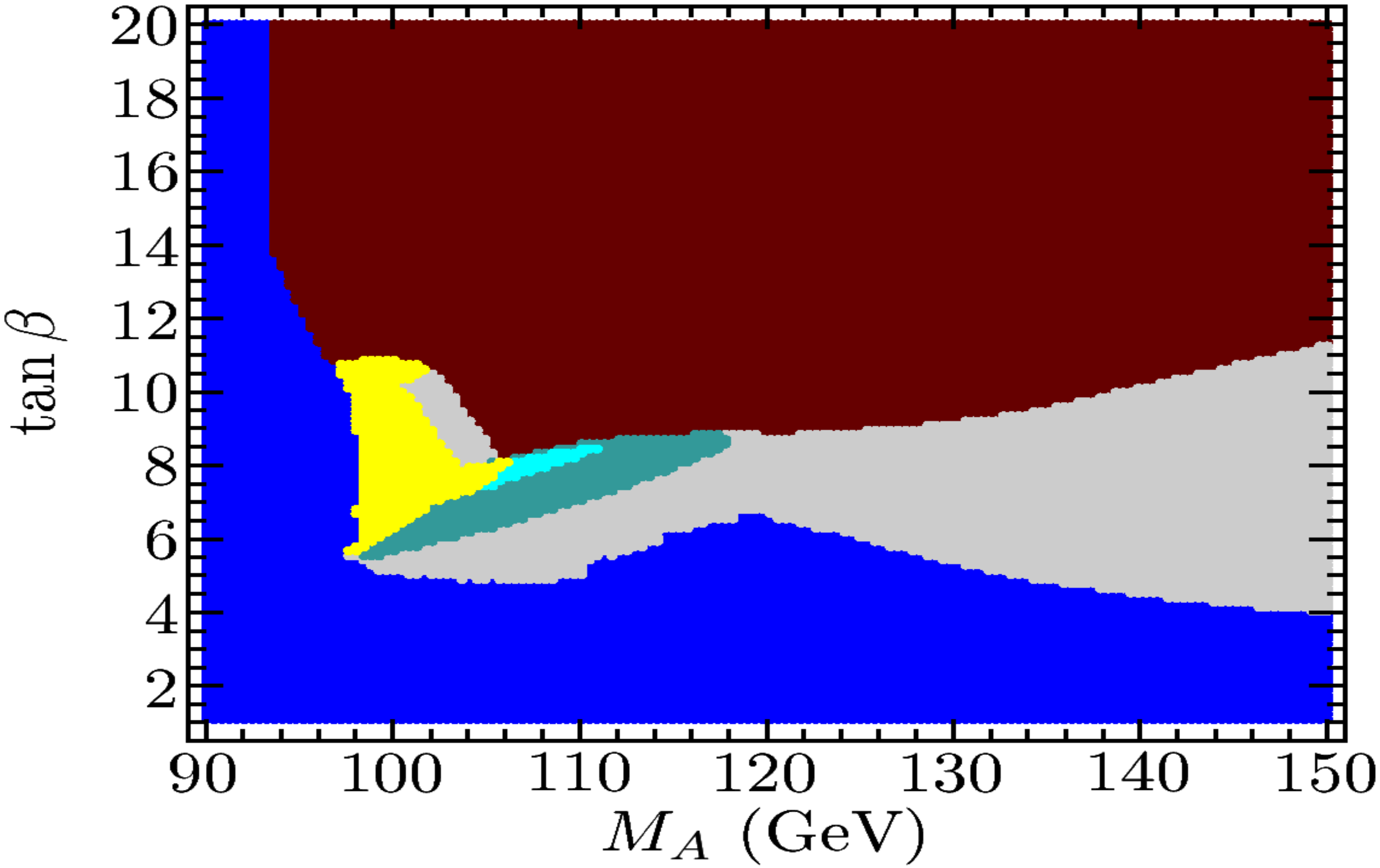


$\Rightarrow m_{\tilde{\mathrm{t}}_1} > 100\ (250)$ GeV for positive (negative) X_t

Compatibility with assumed signal would be difficult in constrained models: mGMSB, mAMSB, ...

Interpretation of an assumed Higgs signal at $\sim 125\ \mathrm{GeV}$ *in terms of the heavy MSSM CP-even Higgs* H

Scan over M_A, $\tan\beta$, M_SUSY, X_t [*S. Heinemeyer, O. Stål, G. W. '11*]



$\Rightarrow$ possible for low M_A, moderate $\tan\beta$
(in yellow region: $\gamma\gamma$ rate compatible with LHC results)

Interpretation of an assumed Higgs signal at $\sim 125\ \mathrm{GeV}$ in terms of the heavy MSSM CP-even Higgs H

The light Higgs h in this scenario has a mass that is often below the LEP limit of $M_{\mathrm{H_{SM}}} > 114.4\ \mathrm{GeV}$ (with reduced couplings to gauge bosons, in agreement with LEP bounds)

Could have, for instance, $M_{\mathrm{H}} \sim 125\ \mathrm{GeV}$, $M_{\mathrm{h}} \sim 98\ \mathrm{GeV}$ (slight excess observed at LEP at $M_{\mathrm{h}} \sim 98\ \mathrm{GeV}$)

$\Rightarrow$ It is important to extend the LHC Higgs searches to the region below $114\ \mathrm{GeV}$!

The best way of experimentally proving that an observed state is not the SM Higgs is to find in addition (at least one) non-SM like Higgs!

A light Higgs in SUSY cascades?

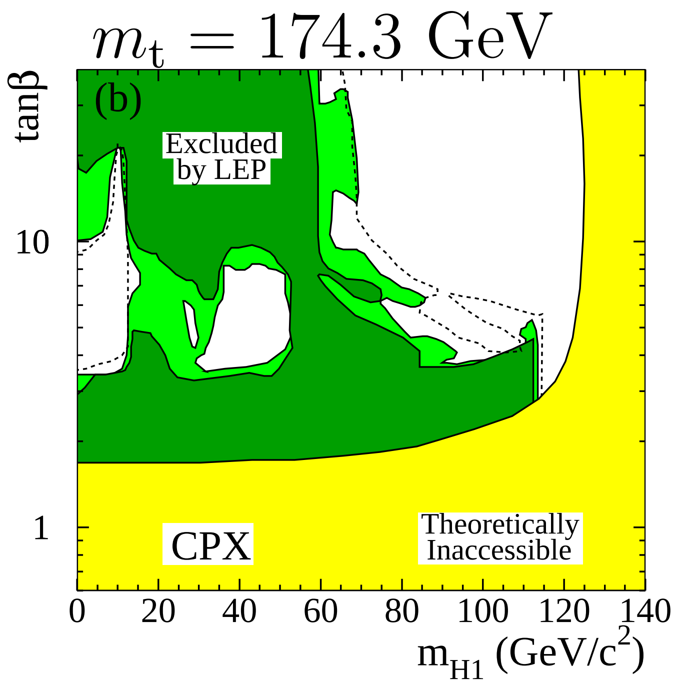
MSSM with $\mathcal{CP}$-violating phases (CPX scenario):

Light Higgs, h_1: strongly suppressed h_1VV couplings

Second-lightest Higgs, h_2, possibly within LEP reach (with reduced VVh_2 coupling), h_3 beyond LEP reach

Large $\mathrm{BR}(h_2 \to h_1 h_1) \Rightarrow$ difficult final state

[*LEP Higgs WG '06*]



$\Rightarrow$ Light SUSY Higgs not ruled out!

A light Higgs in SUSY cascades

Example: NMSSM scenario, light $\mathcal{CP}$-even Higgs,
$20 \text{ GeV} < M_{\mathrm{h}_1} < 110 \text{ GeV}$, in agreement with all search limits (large singlet component)

$\mu_{\mathrm{eff}} = -200 \text{ GeV}$, $M_1 = 300 \text{ GeV}$, $M_2 = 600 \text{ GeV}$

$M_{\mathrm{SUSY}} = 750 \text{ GeV}$, $m_{\tilde{\mathrm{g}}} = 1 \text{ TeV}$

$\Rightarrow$ Higgs production in chargino and neutralino decays in SUSY cascades

$$\tilde{q} \to q\tilde{\chi}_i^0 \to q\tilde{\chi}_1^0 h_k \to q\tilde{\chi}_1^0 b\bar{b}$$

$$\tilde{g} \to g\tilde{q} \to gq\tilde{\chi}_i^0 \to gq\tilde{\chi}_1^0 h_k \to gq\tilde{\chi}_1^0 b\bar{b}$$

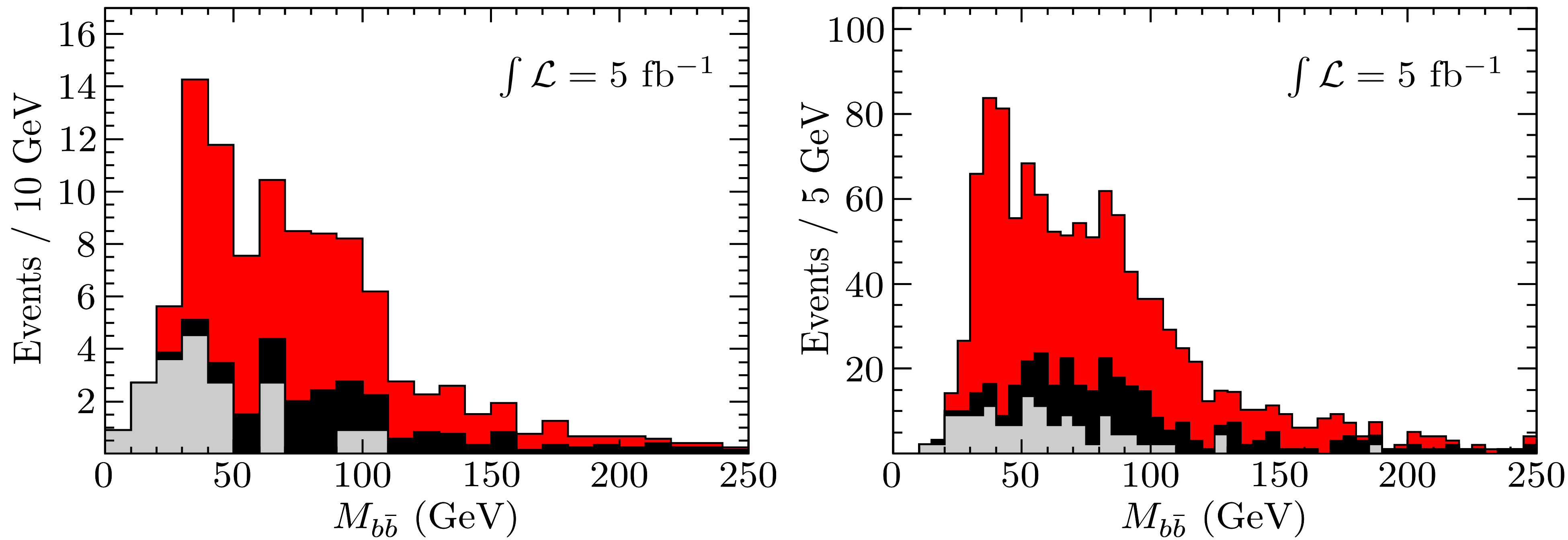
$\ldots$

Results for $b\bar{b}$ jet invariant mass distribution:

SUSY signal, SUSY background, SM $t\bar{t}$ background (grey)

$\int \mathcal{L} = 5\ \mathrm{fb}^{-1}$, $M_{\mathrm{h}_1} \approx 40$ GeV [*O. Stål, G. W. '11*]

$\sqrt{s} = 7$ TeV $\sqrt{s} = 14$ TeV



$\Rightarrow$ Signal over background ratio looks encouraging
h_1 peak and Z peak visible

$\Rightarrow$ We could get a signal for SUSY $+$ Higgs at once
"A double Nobel Prize discovery" [*D. Shih*]

Should the benchmark scenarios used for SUSY Higgs searches at the LHC be updated?

- Experimental results are usually interpreted in the M_A–$\tan\beta$ plane

  Search for heavy SUSY Higgs bosons has highest sensitivity for small M_A and large $\tan\beta$

- Higher-order corrections, Higgs decays into SUSY particles

  $\Rightarrow$ full structure of the SUSY model enters

  $\Rightarrow$ other parameters are fixed in certain "benchmark scenarios"

How robust are limits / discovery reach in the M_A–$\tan\beta$ plane w.r.t. other SUSY effects?

What about the LHC bounds from SUSY / Higgs searches?

Benchmarks for Higgs searches at the Tevatron and the LHC ($\mathcal{CP}$-conserving case)

[*M. Carena, S. Heinemeyer, C. Wagner, G. W. '02*]

Scenarios for general MSSM, no specific SUSY-breaking scenario assumed, no external constraints, M_A, $\tan\beta$ varied

- $m_\mathrm{h}^\mathrm{max}$-scenario: $X_\mathrm{t} = 2\, M_\mathrm{SUSY}$, $M_\mathrm{SUSY} = 1$ TeV, $\mu = +200\ \mathrm{GeV}$

  $\Rightarrow$ maximal $m_\mathrm{h}(\tan\beta)$ for fixed m_t, M_SUSY

- no-mixing scenario: $X_\mathrm{t} = 0$, $M_\mathrm{SUSY} = 2$ TeV

- small α_eff scenario:

  $M_\mathrm{SUSY} = 800\,\mathrm{GeV}$, $\mu = 2.5\, M_\mathrm{SUSY}$, $X_\mathrm{t} = -1100$ GeV

  $\Rightarrow$ suppression of $h \to b\bar{b}$, $h \to \tau\tau$

- gluophobic Higgs scenario: $M_\mathrm{SUSY} = 350$ GeV, $X_\mathrm{t} = -750$ GeV

  $\Rightarrow$ suppression of $gg \to h$

Dependence on the parameter μ: correction to the bottom Yukawa coupling

Potentially large SUSY loop correction, Δ_b, gives rise to a large sensitivity to the parameter μ

Correction to relation between bottom mass and bottom Yukawa coupling:

$$y_b \sim \frac{m_\mathrm{b}}{1 + \Delta_b}$$

$$\Delta_b = \mu \, \tan\beta \left[\frac{2\alpha_\mathrm{s}}{3\,\pi} m_{\tilde{\mathrm{g}}} \times I(m_{\tilde{\mathrm{b}}_1}, m_{\tilde{\mathrm{b}}_2}, m_{\tilde{\mathrm{g}}}) + \frac{\alpha_\mathrm{t}}{4\,\pi} A_\mathrm{t} \times I(m_{\tilde{\mathrm{t}}_1}, m_{\tilde{\mathrm{t}}_2}, \mu) \right]$$

$\Rightarrow$ bottom Yukawa coupling can be strongly enhanced ($\mu < 0$) or suppressed ($\mu > 0$) by the Δ_b corrections

Comparison: $b\bar{b}\phi$***,*** $\phi \to b\bar{b}$ ***vs.*** $b\bar{b}\phi$***,*** $\phi \to \tau^+\tau^-$ ***channel***

$\sigma(b\bar{b}\phi)\ \mathrm{BR}(\phi \to b\bar{b})$ is fully affected by the Δ_b correction to the production process:

$$\sigma(b\bar{b}\phi)\ \mathrm{BR}(\phi \to b\bar{b}) \sim \frac{\tan^2\beta}{(1+\Delta_b)^2}\ \frac{1}{1+(1+\Delta_b)^2/9}$$

$\sigma(b\bar{b}\phi)\ \mathrm{BR}(\phi \to \tau^+\tau^-)$: Δ_b corrections to production and decay process largely compensate each other

$$\sigma(b\bar{b}\phi)\ \mathrm{BR}(\phi \to \tau^+\tau^-) \sim \tan^2\beta\ \frac{1}{(1+\Delta_b)^2+9}$$

$\Rightarrow$ Much smaller dependence of limits / discovery reach on μ

Impact of SUSY limits

- $M_{\rm SUSY}$: denotes common scalar mass parameter in the squark sector

  However: Higgs phenomenology is driven by the third generation squarks, $\tilde{\rm t}$, $\tilde{\rm b}$; squarks of the first two generations have very little impact

  LHC limits apply mostly to the first and asecond generation squarks, limits on direct $\tilde{\rm t}$, $\tilde{\rm b}$ production are much weaker

  $\Rightarrow$ Interpret $M_{\rm SUSY}$ as referring to the third generation only squarks of the first two generations may be heavier

- $m_{\tilde{\rm g}}$: Higgs phenomenology depends only mildly on $m_{\tilde{\rm g}}$

  Results for higher $m_{\tilde{\rm g}}$ would look qualitatively the same

Impact of Higgs search limits

Limits from the search for a SM-like Higgs have only moderate effect in the $m_{\mathrm{h}}^{\mathrm{max}}$ scenario, see above

Bigger impact in the other scenarios

small α_{eff} scenario:

region where the $h \to b\bar{b}$, $h \to \tau\tau$ decays are suppressed is excluded by the ATLAS and CMS searches for H, A

Backup

$b\bar{b}\phi$, $\phi \to b\bar{b}$ *vs.* $b\bar{b}\phi$, $\phi \to \tau^+\tau^-$ *channel* ($\phi = H, A$)

Production cross section:

For large $\tan\beta$: production mainly via $b\bar{b}\phi$ associated production

For large $\tan\beta$, $\mathcal{CP}$-conserving case:

$M_{\rm H} \approx M_{\rm A}$, $\sigma(b\bar{b}H) \approx \sigma(b\bar{b}A)$

$\Rightarrow \sigma_{\rm tot} \approx 2 \times \sigma(b\bar{b}A)$

$\Rightarrow \sigma_{\rm tot}$ is obtained from incoherent sum of the two cross sections

Effect of sign of μ on Tevatron exclusion bounds (D0 result from 2005) from $b\bar{b}\phi$, $\phi \to b\bar{b}$ channel

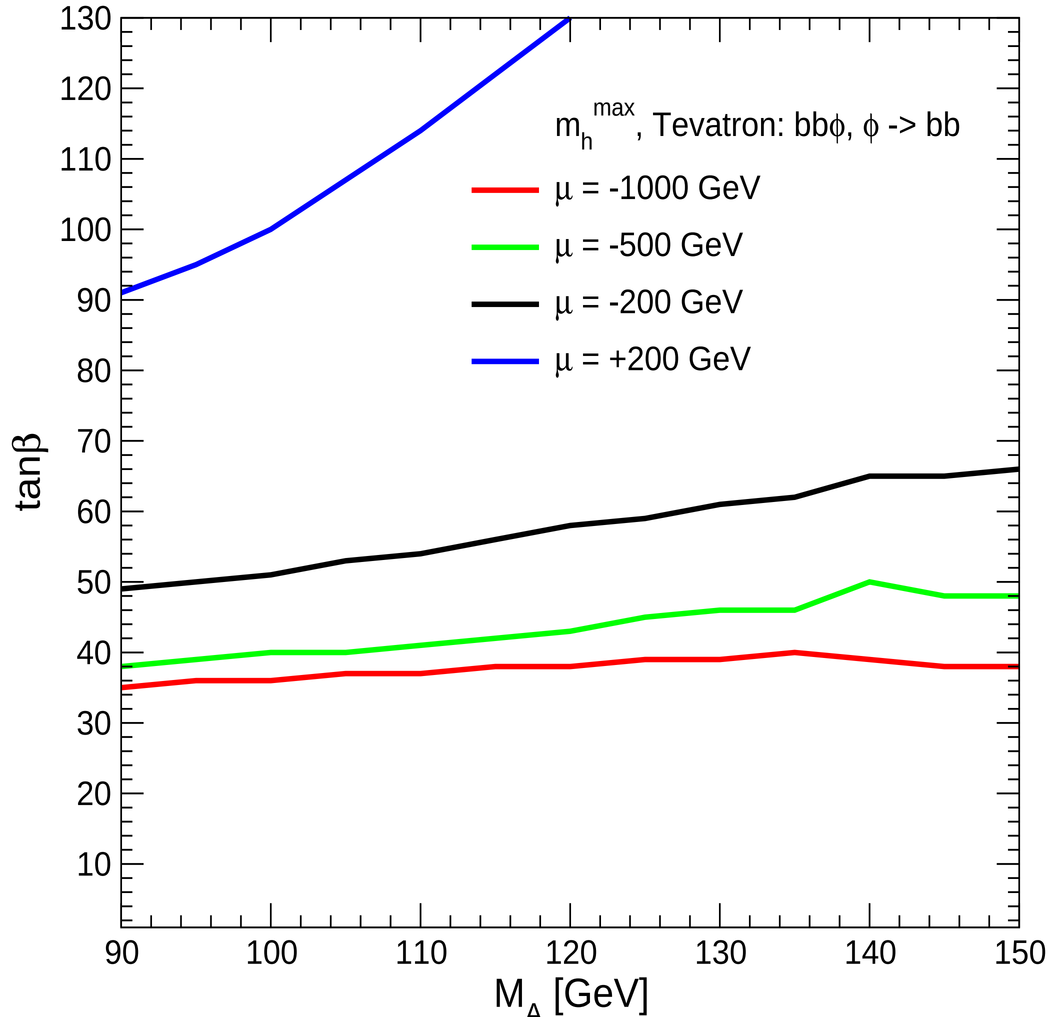
Change in the Tevatron exclusion bounds from varying μ ($m_\mathrm{h}^\mathrm{max}$ scenario) [*M. Carena, S. Heinemeyer, C. Wagner, G. W. '05*]

μ: parameter in MSSM superpotential
$\mathcal{V}_\mathrm{MSSM} = \mu H_u H_d + \ldots$

D0 published result for $\mu = -200\ \mathrm{GeV}$ in 2005
[*D0 Collab. '05*]

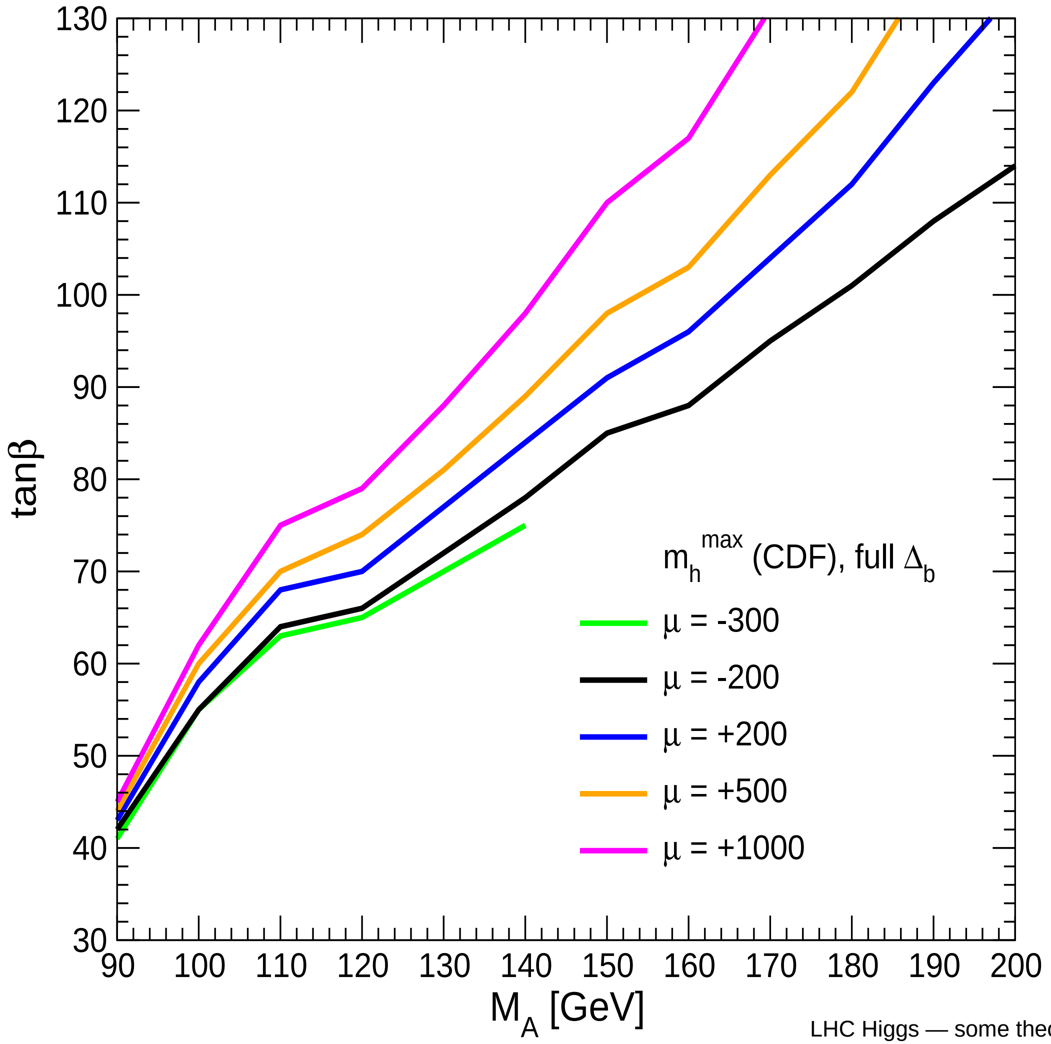
$\Rightarrow$ Change of sign of μ has drastic effect

Practically no exclusion for $\mu > 0$



Effect of variation of μ on Tevatron exclusion bounds from $p\bar{p} \to \phi \to \tau^+\tau^-$ channel

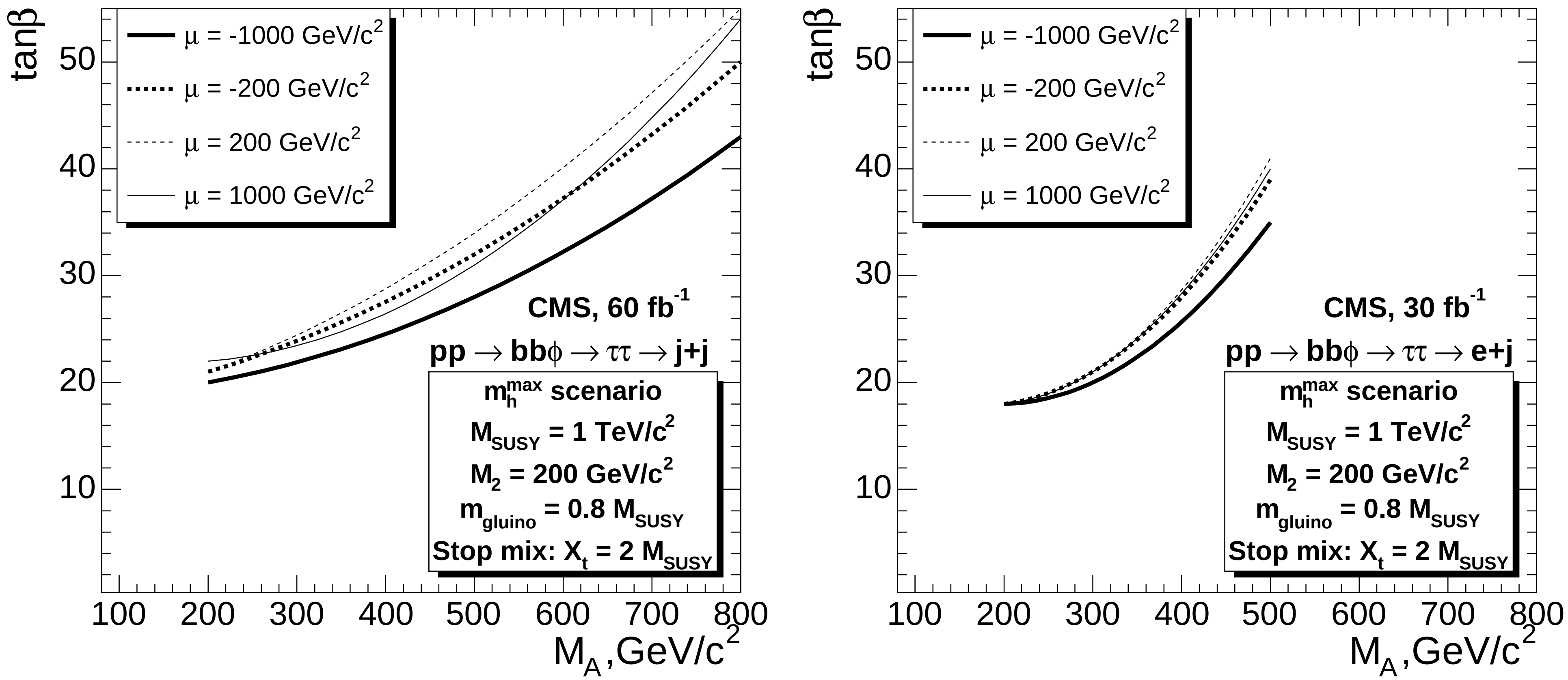
Change in the Tevatron exclusion bounds from varying μ ($m_{\mathrm{h}}^{\mathrm{max}}$ scenario) [*M. Carena, S. Heinemeyer, C. Wagner, G. W. '05*]



$\Rightarrow$ Exclusion bounds are much more stable w.r.t. variation of μ

Analysis of the CMS discovery reach in the $b\bar{b}H, A$, $H, A \to \tau^+\tau^-$ channel

Variation of the 5σ discovery contours with μ (m_h^{max} scen.): $\tau^+\tau^- \to$ jets (left) and $\tau^+\tau^- \to e +$ jet (right) [*S. Gennai, S. Heinemeyer, A. Kalinowski, R. Kinnunen, S. Lehti, A. Nikitenko, G. W. '07*]



$\Rightarrow$ Shift of discovery contour by up to $\Delta \tan\beta = 12$

Interpretation of the dependence of the discovery contours on μ

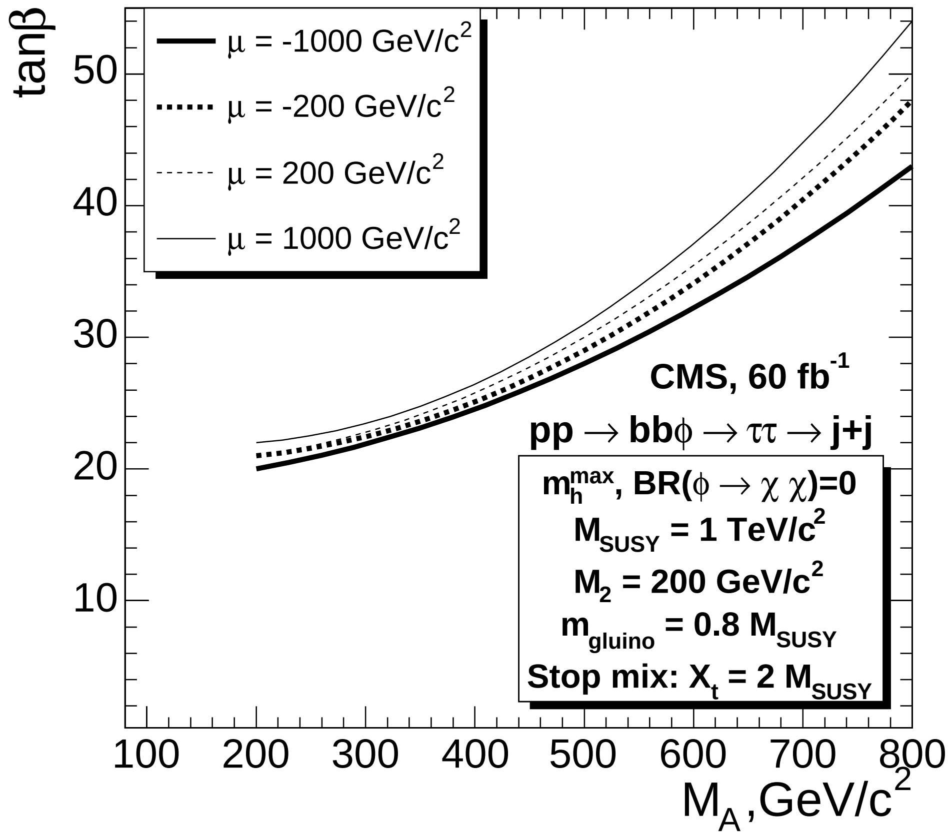
The parameter μ enters in two different ways:

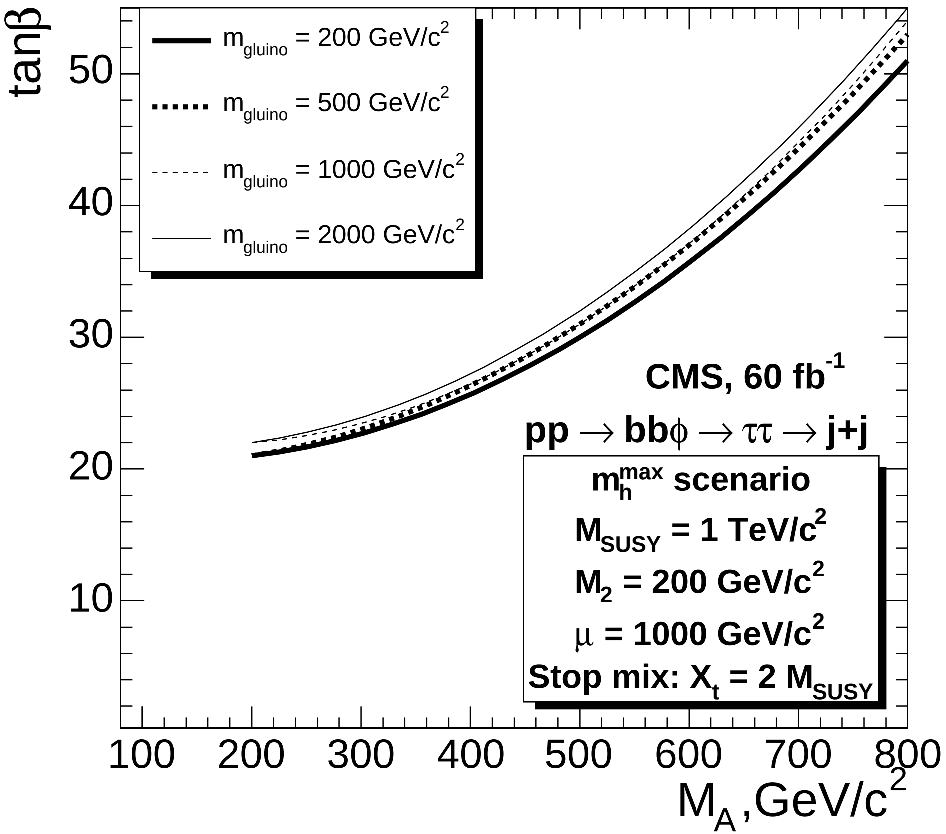
- Higher-order corrections, in particular Δ_b contribution
- Supersymmetry: Higgs bosons $\leftrightarrow$ higgsinos
  $\Rightarrow$ μ enters also the mass matrix of the higgsinos
  (mass eigenstates of higgsinos and gauginos:
  charginos and neutralinos)
  $\Rightarrow$ Small μ $\leftrightarrow$ light charginos / neutralinos

  $\Rightarrow$ For small μ Higgs decay channels into charginos and neutralinos can open up
  $\Rightarrow$ Suppression of BR$(H, A \to \tau^+\tau^-)$

$\Rightarrow$ Disentangle both effects $+$ study variation with gluino mass (enters Δ_b but no effect on Higgs decay kinematics)

$\tau^+\tau^- \to$ *jets channel: Higher-order effects induced by μ (left) and dependence on gluino mass (right)*





$\Rightarrow$ μ: higher-order effects dominate in high $\tan\beta$ region
effects on decay kinematics dominate in small $\tan\beta$ region

$\Rightarrow$ Results are stable w.r.t. varying $m_{\tilde{g}}$, $\Delta \tan\beta \lesssim 4$

General case: inclusion of interference effects

Total cross section:

$$\sigma_{\rm tot} = \sigma(b\bar{b}H) + \sigma(b\bar{b}A) \text{ (incoherent sum)}$$

holds only in the $\mathcal{CP}$-conserving case

But: in reality we don't know whether $\mathcal{CP}$ in the Higgs sector is conserved or not

In the general case:

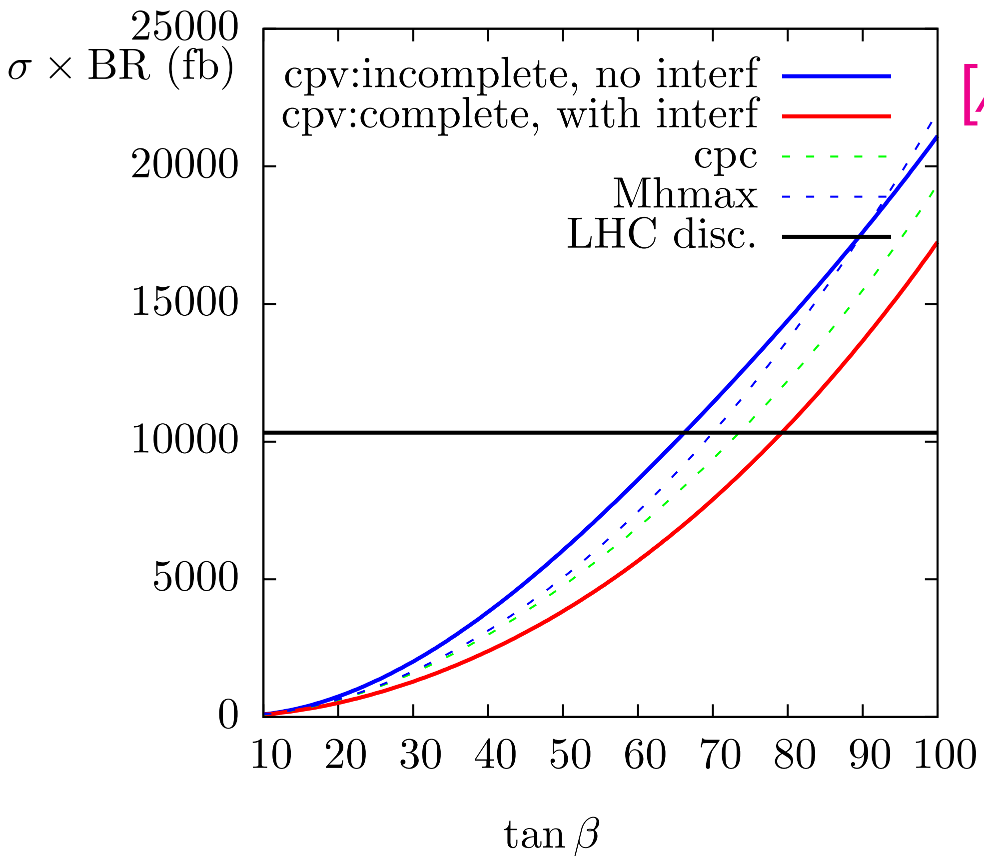
Complex parameters $\Rightarrow$ loop corrections induce $\mathcal{CP}$-violation

Two Higgs states, nearly mass degenerate, large mixing

$\Rightarrow$ Large (destructive) interference possible

Comparison: $\mathcal{CP}$-conserving case ($m_h^{\max}$ scenario) vs. $\mathcal{CP}$-violating case with and without interference contribution

CPV scenario: $|A_t| = 1200$ GeV, $\phi_{A_t} = \phi_{A_b} = \phi_{A_\tau} = \pi/5$,
$M_{H^\pm} = 340$ GeV, $M_{SUSY} = 500$ GeV, $\mu = 200$ GeV, $M_2 = 200$ GeV,
$m_{\tilde{g}} = 1$ TeV



[*A. Fowler, G. W. '10*]

$\Rightarrow$ Interference effects can have important impact on limits on $\tan\beta$ from Higgs searches at Tevatron and LHC