“Higgs Boson Discovery” and Supersymmetry at the LHC

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Higgs Hunting 2012,
Orsay, July 2012
The LHC experiments have discovered a new particle

- The evidence is strong that the new particle decays to $\gamma\gamma$ and $ZZ$ with rates roughly consistent with those predicted for the SM Higgs boson.

- There are also indications that the new particle decays to $W^+W^-$

- The observed decay modes indicate that the new particle is a boson.
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- There are also indications that the new particle decays to $W^+W^-$.
- The observed decay modes indicate that the new particle is a boson.
The Signal strength may be computed in all different production and decay channels and is consistent with SM

However,
A di-photon rate enhancement is the most visible feature at both experiments.
The WW rates look/ed somewhat small
There is an apparent suppression of tau production in VBF.

Present experimental uncertainties allow for a wide variety of new physics alternatives.
From the Tevatron:

Combination of searches for Higgs decaying to WW and bb shows a clear excess in the 115 GeV to 135 GeV mass region.

For a Higgs mass of 125 GeV, the combined production rates are consistent with the SM ones within 1 σ, but the bb rate appears to be enhanced.
What does a 125 GeV Higgs mean for the different BSM frameworks?

For No Higgs models these are bad news.

For Composite Higgs/Pseudo-Goldstone Higgs models it depends on the scenario.

What about SUSY?

Also, many recent studies consider effective theory approaches and investigate the best fit to the data in a more model independent way.

see Espinosa’s talk
What about the Higgs in Supersymmetry?

- **Minimal** Higgs Sector: Two Higgs doublets
  \[ \tan \beta = \frac{v_2}{v_1} \]
  \[ v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV} \]

  - 2 CP-even \( h \) (SM-like), \( H \) with mixing angle \( \alpha \)
  - 1 CP-odd \( A \) + 1 charged pair \( H^+ \)

- One Higgs doublet couples to up quarks, the other to down quarks/leptons only

  Higgs interactions flavor diagonal if SUSY preserved

- Quartic Higgs couplings determined by SUSY as a function of the gauge couplings
  
  -- lightest (SM-like) Higgs strongly correlated to Z mass (naturally light!)
  
  -- other Higgs bosons can be as heavy as the SUSY breaking scale

- Important quantum corrections to the lightest Higgs mass due to incomplete cancellation of top and stop contributions in the loops
  
  -- also contributions from sbottoms and staus for large \( \tan \beta \) --
Lightest SM-like Higgs mass strongly depends on:

* CP-odd Higgs mass $m_A$
* $\tan\beta$
* the top quark mass
* the stop masses and mixing

$$M^2_{\tilde{t}} = \left( \begin{array}{ccc} m^2_Q + m^2_t + D_L & m_t X_t \\ m_t X_t & m^2_U + m^2_t + D_R \end{array} \right)$$

$M_h$ depends logarithmically on the averaged stop mass scale $M_{\text{SUSY}}$ and has a quadratic and quartic dep. on the stop mixing parameter $X_t$. [and on sbottom/stau sectors for large tan beta]

For moderate to large values of $\tan\beta$ and large non-standard Higgs masses

$$m^2_h \approx M^2_Z \cos^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[ \frac{1}{2} \tilde{X}_t + t + \frac{1}{16\pi^2} \left( \frac{3}{2} \frac{m_t^2}{v^2} - 32\pi\alpha_3 \right)(\tilde{X}_t + t^2) \right]$$

$$t = \log(M^2_{\text{SUSY}}/m^2_t) \quad \tilde{X}_t = \frac{2X^2_t}{M^2_{\text{SUSY}}} \left(1 - \frac{X^2_t}{12 M^2_{\text{SUSY}}} \right) \quad X_t = A_t - \mu/\tan\beta \rightarrow \text{LR stop mixing}$$

Analytic expression valid for $M_{\text{SUSY}} \sim m_Q \sim m_U$

M.C. Espinosa, Quiros, Wagner '95
M.C. Quiros, Wagner '95
Additional effects at large tan beta from sbottoms:

\[ \Delta m_h^2 \approx - \frac{h_b^4 v^2 \mu^4}{16 \pi^2 M_{\text{SUSY}}^4} \]

with

\[ h_b \approx \frac{m_b}{v \cos \beta (1 + \tan \beta \Delta h_b)} \]

receiving one loop corrections that depend on the sign of \( \mu M_{\tilde{g}} \).

and staus:

\[ \Delta m_h^2 \approx - \frac{h_{\tau}^4 v^2 \mu^4}{48 \pi^2 M_{\tilde{\tau}}^4} \]

with

\[ h_{\tau} \approx \frac{m_{\tau}}{v \cos \beta (1 + \tan \beta \Delta h_{\tau})} \]

Dep. on the sign of \( \mu M_2 \).

Both corrections give negative contributions to the Higgs mass hence smaller values of \( \mu \) and positive values of \( \mu M_2 \) and \( \mu M_{\tilde{g}} \) enhance the value of the Higgs mass.

Maximal effect: lower \( m_h \) by several GeV.
SM-like MSSM Higgs Mass:

Many contributions to two-loop calculations
Brignole, M.C., Degrassi, Diaz, Ellis, Haber, Hempfling, Heinemeyer, Hollik, Espinosa, Martin, Quiros, Ridolfi, Slavich, Wagner, Weiglein, Zhang, Zwirner, …

Figure r–

The maximal value of the $h$ boson mass as a function of $X_t/M_S$ in the pMSSM when all other soft SUSY–breaking parameters and $\tan\beta$ are scanned in the range Eqm fsg fleftg and the contours for $pqr < M_h < pqv$ GeV in the $[M_S, X_t]$ plane for some selected range of $\tan\beta$ values frightgm

The theoretical uncertainties in the determination of $M_h$ are includedo Hencem only the scenarn ios with large $X_t/M_S$ values andm in particularm those close to the maximal mixing scenario

$A_t/M_S \approx \sqrt{w}$ surviveo The no–mixing scenario is ruled out for $M_S < \sim t TeVm while the typical mixing scenario needs large $M_S$ and moderate to large $\tan\beta$ valueso We obtain

$M_{\text{max}}^h = rtw$ and $rs$ GeV inm the maximalm zero and typical mixing scenariosm respectively

The right–hand side of Figo r shows the contours in the $[M_S, X_t]$ plane where we obtain the mass range $rst$ GeV $< M_h < rsx$ GeV from our pMSSM scan with $X_t/M_S < \sim t; the regions in

which $\tan\beta < \sim t$ van dw a r eh i g h l i g h t e do O n e s e e sa g a i nt h a tal a r ge p a r m e t e r space is excluded if the Higgs mass constraint is imposed

3. Implications for constrained MSSM scenarios

In constrained MSSM scenarios hcMSSMi

5 the various soft SUSY–breaking parameters obey a number of universal boundary conditions at a high energy scale such as the GUT scalem thus reducing the number of basic input parameters to a handfulo These inputs are evolved via the MSSM renormalisation group equations down to the low energy scale

$M_S$ where the conditions

of proper electroweak symmetry breaking hEWSBi are imposedo The Higgs and superparticle

3 We have checked that the program

FeynHiggs [pw] gives comparable values for $M_h$ within $\approx q$ GeV which we consider to be our uncertainty as in Eqm ftgm

4 Note that the $M_{\text{max}}^h$ values given above are obtained with a heavy superparticle spectrumk for which the constraints from flavour physics and sparticle searches are evadedk and in the decoupling limit in which the $h$ production cross sections and the decay branching ratios are those of the SM Higgs bosonm Howeverk we also searched for points in the parameter space in which the boson with mass $\sim pqt$ GeV is the heavier CP–even $H_0$ boson which corresponds to values of $M_A$ of order $po$ GeVm Among the $\sim po$ valid MSSM points of the scank only $\sim pt \times po^{-4}$ correspond to this scenariom Howeverk if we impose that the $H_0$ cross sections times $branching ratios$ are compatible with the SM values within a factor of $q$ and include the constraints from MSSM

Higgs searches in the $\tau^+\tau^-$ channelk only $\sim sp \times po^{-5}$ of the points survivem These are all excluded once the $b \to s\gamma$ and $B_s \to \mu^+\mu^-$ constraints are imposedm A detailed study of the pMSSM Higgs sector including the dark matter and flavour constraints as well as LHC Higgs and SUSY search limits is presented in Refm [px]m

In this paper cMSSM denotes all constrained MSSM scenariosk including GMSB and AMSBm

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Soft supersymmetry Breaking Parameters

At large $\tan \beta$, light staus/sbottoms can decrease $m_h$ by several GeV's via Higgs mixing effects and compensate $\tan \beta$ enhancement.

Intermediate values of $\tan \beta$ lead to the largest values of $m_h$ for the same values of stop mass parameters.

Large stop sector mixing $A_t > 1$ TeV

Similar results from Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon '11
Draper Meade, Reece, Shih '11

No lower bound on the lightest stop
One stop can be light and the other heavy or in the case of similar stop soft masses, both stops can be below 1 TeV

Intermediate values of $\tan \beta$ lead to the largest values of $m_h$ for the same values of stop mass parameters.

At large $\tan \beta$, light staus/sbottoms can decrease $m_h$ by several GeV's via Higgs mixing effects and compensate $\tan \beta$ enhancement.
Can departures in the production/decay rates at the LHC disentangle among different SUSY spectra?

The event rate depends on three quantities:

\[ B\sigma(p\bar{p} \rightarrow h \rightarrow X_{SM}) \equiv \sigma(p\bar{p} \rightarrow h) \frac{\Gamma(h \rightarrow X_{SM})}{\Gamma_{total}} \]

- The three of them may be affected by new physics.
- If one partial width is modified, then the total width is modified as well, producing modifications of all BR’s.

How much can we perturb the gluon production mode?
Is it possible to change WW and ZZ decay rates independently?
Can we vary the Higgs rate into di-photons independently from the rate into WW/ZZ?
Can we change the ratio of b-pair to tau pair decay rates?
Departures in the production and decay rates at the LHC

- Through SUSY particle effects in loop induced processes

\[
\begin{align*}
\text{squarks} & \quad \Rightarrow \quad \text{squarks and sleptons} \\
\text{g} & \quad \Rightarrow \quad \text{charginos}
\end{align*}
\]

- Through enhancement/suppression of the Higgs-bb and Higgs-di-tau coupling strength via mixing in the Higgs sector:
This affects in similar manner BR’s into all other particles

- Through vertex corrections to Yukawa couplings: different for bottoms and taus
This destroys the SM relation \( \text{BR}(h\rightarrow bb)/\text{BR}(h\rightarrow \tau\tau) \sim m_b^2/m_\tau^2 \)
Gluon Fusion in the MSSM

Light 3\textsuperscript{rd} gen. squarks
[stops and sbottoms] can increase the gluon fusion rate, but for stop mixing $X_t$ as required for $m_h$ values of interest, tend to lead to suppression

Squark suppression effects in gluon fusion yield small enhancement in di-photon decay rate but

$$\frac{\sigma(gg \rightarrow h)}{\sigma(gg \rightarrow h)_{SM}} \frac{BR(h \rightarrow \gamma\gamma)}{BR(h \rightarrow \gamma\gamma)_{SM}} \leq 1$$

mh $\sim$ 124-126 GeV range

Dermisek, Low’07
Higgs Production in the di-photon channel in the MSSM

Charged scalar particles with no color charge can change di-photon rate without modification of the gluon production process.

\[ m_A = 1 \text{ TeV GeV}, \ A_T = 0 \text{ GeV} \]

\[ \frac{\sigma(gg \to h) \, Br(h \to \gamma\gamma)}{\sigma(gg \to h)_{\text{SM}} \, Br(h \to \gamma\gamma)_{\text{SM}}} \]

\[ m_{L_3} = m_{E_3} \]

Light staus with large mixing [sizeable \( \mu \) and tan beta]:

\[ \Rightarrow \text{enhancement of the Higgs to di-photon decay rate} \]

\[ M_\gamma^2 \simeq \left[ \frac{m_{L_3}^2 + m_{\tau}^2 + D_L}{m_{E_3}^2 + m_{\tau}^2 + D_R} \right] h \nu (A_{\tau} \cos \beta - \mu \sin \beta) \]

Contours of constant

\[ \frac{\sigma(gg \to h) \, Br(h \to \gamma\gamma)}{\sigma(gg \to h)_{\text{SM}} \, Br(h \to \gamma\gamma)_{\text{SM}}} \]

for \( M_h \sim 125 \text{ GeV} \)


For a generic discussion of modified \( \gamma\gamma \) and \( Z\gamma \) widths by new charged particles, see M. C. ,Low and C. Wagner '12

Recent MSSM scan: Benbrik, Gomez Bock, Heinemeyer, Stal, Weigein, Zeune '12
Higgs into di-photon rate can be enhanced via Staus without changing the Higgs into WW/ZZ rates

Contours of constant

\[ \frac{\sigma (gg \to h) \text{Br}(h \to ZZ)}{\sigma (gg \to h)_{\text{SM}} \text{Br}(h \to ZZ)_{\text{SM}}} \]

for \( M_h \sim 125 \text{ GeV} \)

M. C., Gori, Shah, Wagner’11 + Wang’12
Mixing Effects in the CP-even Higgs Sector
can have relevant effects in the production and decay rates

\[
M_H^2 = \begin{bmatrix}
  m_A^2 \sin^2 \beta + M_Z^2 \cos^2 \beta \\
-(m_A^2 + M_Z^2) \sin \beta \cos \beta + \text{Loop}_{12}
\end{bmatrix}
\]

\[
\text{Loop}_{12} = \frac{m_t^4}{16 \pi^2 v^2 \sin^2 \beta} \frac{\mu A_t}{M_{\text{SUSY}}^2} \left[ A_t \tilde{A}_t - 6 \right] + \frac{h_b^2 v^2}{16 \pi^2 \sin^2 \beta} \frac{\mu^3 A_b}{M_{\text{SUSY}}^4} + \frac{h_{\tilde{t}}^2 v^2}{48 \pi^2} \sin^2 \beta \frac{\mu^3 A_\tau}{M_{\tilde{t}}^4}
\]

effects through radiative corrections to the CP-even mass matrix which defines the mixing angle alpha

\[
\sin \alpha \cos \alpha = M_{12}^2 / \sqrt{\left( \text{Tr } M^2 \right)^2 - 4 \det M^2}
\]

destroy basic relation

\[
g_{h,H,Abb} / g_{h,H,\tau} \propto m_b / m_\tau
\]

M.C. Mrenna, Wagner ’98
Haber,Herrero, Logan, Penaranda, Rigolin, Temes ’00

Radiative corrections ==> main decay modes of the SM-like MSSM Higgs into b- and tau-pairs can be drastically changed
Additional modifications of the Higgs rates into gauge bosons via stau induced mixing effects in the Higgs sector

Important $A_t$ induced radiative corrections to the mixing angle $\alpha$ together with loop vertex corrections to $hbb$ coupling, $\Delta b$

$m_{\text{Stau}} \approx 90 \text{ GeV}; \ m_h \approx 125 \text{ GeV}$

Small variations in BR $[Hbb]$ induce significant variations in the other Higgs BR's

M. C. Gori, Shah, Wagner,'11 + Wang'12

Similar results for example within pMSSM/MSSM fits:  Arbey, Battaglia, Djouadi, Mahmoudi ’12
Benbrik, Gomez Bock, Heinemeyer, Stal, Weigein, Zeune’12

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Scenario with suppression of gluon fusion and enhancement of diphoton rate 
+ suppression of the h to taus to h to b’s ratio 
due to different radiative SUSY corrections to higgs-fermion couplings

Further suppression of gluon fusion is possible due to light stops, with mass ~150 GeV

M. C., S. Gori, N. Shah, C. Wagner
Many minimal SUSY models can produce $m_h=125$ GEV

NMSSM: extra singlet $S$ with extra parameter $\lambda$

$$W \supset \lambda S H_u H_d + \mu H_u H_d + \frac{M}{2} S^2 + \frac{\kappa}{3} \hat{S}^3 + \ldots$$

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \text{rad. corrections}$$

SM + singlet limit

$$M^2 = \begin{pmatrix} 
\lambda^2 v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta & \lambda v(\mu, M_S, A_\lambda) \\
\lambda v(\mu, M_S, A_\lambda) & m_S^2
\end{pmatrix}$$

- Large effect on the mass only for low tan beta
- More freedom in gluon fusion production
- **Higgs mixing effects can be also triggered by extra new parameter $\lambda$**
- Light staus would not enhance di-photon rate since at low tan beta there is negligible mixing in the stau sector.
Analogous to MSSM, modifications of the Higgs rates into gauge bosons via mixing effects in the Higgs sector

**genuine NMSSM effect from doublet-singlet mixing induced by \( \lambda \)**

\[
R_{gg}^{h_i}(X) \equiv \frac{\Gamma(gg \rightarrow h_i) \ BR(h_i \rightarrow X)}{\Gamma(gg \rightarrow h_{SM}) \ BR(h_{SM} \rightarrow X)}.
\]

\[
R_{VBF}^{h_i}(X) \equiv \frac{\Gamma(WW \rightarrow h_i) \ BR(h_i \rightarrow X)}{\Gamma(WW \rightarrow h_{SM}) \ BR(h_{SM} \rightarrow X)}
\]

Suppression in BR [Hbb] induce significant and correlated variations in the other Higgs BR’s
More general MSSM Higgs extensions: EFT approach

\[ W = \mu H_u H_d + \frac{\omega_1}{2M} (H_u H_d)^2 \quad W_X \supset \frac{\omega_1}{2M} X (H_u H_d)^2 \]

Scan over parameters including all possible dimension 5 and 6, SUSY Higgs operators

Higgs mass = 125 GeV easy to achieve for light stops, small mixing

Enhancement of h to di-photons due to \( bb \) suppression or light staus

Higgs cascade decays from large splitting in masses: \( h/H \) to \( AA \)

If the new physics is seen only indirectly via deviations from the SM Higgs properties, it will be hard to disentangle among new singlets, triplets, extra \( Z', W' \), a given mixture of the above
Higgs Phenomenology in models of Warped Extra Dimensions

Large number of new fermionic fields in the 5D theory induce large loop effects in $h\gamma\gamma$ & $hgg$ couplings
Effect even more pronounced in models with custodial protection

$y_{\text{max}} = 0.5$
$y_{\text{max}} = 1.5$
$y_{\text{max}} = 3$

Spectacular effects on Higgs production via gluon fusion, even for new particle masses well beyond direct LHC reach

Suppression

$R_h = \frac{\sigma(gg\to h)_{\text{WED}}}{\sigma(gg\to h)_{\text{SM}}}$

Significant enhancement of the BR ($h \to \gamma\gamma$) also possible depending on the values of leptonic 5D Yukawas
Higgs to diphotons can be larger than HZZ but below SM value.

A measurement of $R_{ZZ} \approx 0.7$ along with a slight enhancement of the di-photon over the ZZ channel would then imply (for $y_{\text{max}} = 3$) KK masses $\approx 8$ TeV, far outside direct reach of LHC. A lower bound $R_{ZZ} > 0.7$ would imply very strong bounds.
Conclusions:

The Higgs discovery is of paramount importance

but

We need more precise measurements of Higgs properties

and/or

direct observation of new physics

to further advance in our understanding of EWSB
$M_h \sim 125 \text{ GeV and flavor in the MSSM}$

- $B_u \rightarrow \tau \nu$ transition  MSSM charged Higgs & SM contributions interfere destructively

$$R_{B_u \rightarrow \tau \nu} = \frac{\text{BR}(B_u \rightarrow \tau \nu)^{\text{MSSM}}}{\text{BR}(B_u \rightarrow \tau \nu)^{\text{SM}}} = \left[ 1 - \left( \frac{m_B^2}{m_{H^\pm}^2} \right) \tan \beta^2 \right]^2 \left( 1 + \varepsilon_0^3 \tan \beta \right)$$

Important radiative corrections

$$\varepsilon_i \approx \frac{2\alpha_s}{3\pi} \frac{\mu^* M_{\tilde{g}}^*}{\max \left[ m_{\tilde{d}_i}^2, m_{\tilde{d}_2}^2, M_{\tilde{g}}^2 \right]}$$

$\varepsilon$ loop factors intimately connected to the structure of the squark mass matrices

Independent on stop mixing
Almost independent of RG evolution
More powerful than Higgs searches

See Isidori’s talk

Altmannshofer, MC, Shah, Yu

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\( M_h \sim 125 \text{ GeV} \) and Minimal Flavor Violation in the MSSM

**Loop-induced A/H contributions to** \( B_s \rightarrow \mu^+ \mu^- \)

\[
BR(B_s \rightarrow \mu^+ \mu^-)^{\text{SUSY}} \propto \left| \frac{X_{RL}^{32}}{m_A^4} \tan \beta^2 \right| \propto \left| \frac{\mu A_t}{m_A^4} \right| \tan \beta^6
\]

with \( (X_{RL}^{32})^{hs} \approx \frac{m_b}{v} \frac{h_t^2 \varepsilon_Y \tan \beta^2}{(1+\varepsilon_0^3 \tan \beta)(1 + \Delta_b)} V_{t b}^* V_{t s} \)

\[
\varepsilon_Y \approx \frac{\mu A_t^*}{16\pi^2 \max[m_{t_1}^2, m_{t_2}^2, \mu^2]}
\]

\( \Delta_b = (\varepsilon_0^3 + \varepsilon_y h_t^2) \tan \beta \)

**Charged Higgs and chargino-stop contributions to** \( B \rightarrow X_S \gamma \)

\[
A_{H^+} \propto \frac{(h_t - \delta h_t \tan \beta) m_b}{(1 + \Delta_b)} g[m_t, m_{H^+}] V_{ts}
\]

\[
A_{\chi^+} \propto \frac{\mu A_t \tan \beta m_b}{(1 + \Delta_b)} h_t^2 f[m_{t_1}, m_{t_2}, \mu] V_{ts}
\]
**FCNC and the scale of SUSY Breaking**

- FCNC’s induced by Higgs-squark loops depend on the flavor structure of the squark soft SUSY breaking parameters.

- **If SUSY is transmitted to the observable sector at high energies** \( M \sim M_{\text{GUT}} \)
even starting with universal masses (MFV) in the supersymmetric theory:

Due to RG effects:

1) The effective FC strange-bottom-neutral Higgs is modified:

\[
\left( X_{\text{RL}}^{H/A} \right)^{bs} \approx -\frac{m_b}{v} \frac{\left( \varepsilon_0^3 - \varepsilon_0^{1,2} + h_t^2 \varepsilon_y \right) \tan^2 \beta}{(1+\varepsilon_0^3 \tan \beta)(1 + \Delta_b)} \ V_{\text{CKM}}^{tb} V_{\text{CKM}}^{ts} \ \varepsilon_0^3 - \varepsilon_0^{1,2} > 0 \ \text{and proportional to } \mu M_{\tilde{g}} \\
\]  
If \( \mu A_t < 0 \) and \( \mu M_{\tilde{g}} > 0 \)

possible cancellation of effects

2) Flavor violation in the gluino sector induces relevant contributions to \( b \rightarrow s \gamma \):

\[
A_g \propto \alpha_s \left( m_0^2 - m_{Q_3}^2 \right) M_{\tilde{g}} u \tan \beta \ F(m_0, m_R, m_{\tilde{b_i}}, m_{\tilde{d_i}}, M_{\tilde{g}}) \\
\]

**If SUSY is transmitted at low energies**: \( M \sim M_{\text{SUSY}} \)

Squark mass matrices approx. block diag, only FC effects in the chargino-stop& \( H^+ \) loops

Ellis, Heinemeyer, Olive, Weiglein
M.C, Menon, Wagner

Borzumati, Bertolini, Masiero, Ridolfi

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$M_h \sim 125$ GeV and flavor in the MSSM

Low Energy Vs High Energy SUSY breaking effects $B_s \rightarrow \mu^+\mu^-$

Red solid line: $B_s \rightarrow \mu^+\mu^-$ with low energy SUSY breaking effects

Red dashed (dotted) line has 25% (50%) splitting from RG

$\tan \beta = 20 \quad M_A = 400$ GeV

Altmannshofer, MC, Shah, Yu

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$M_h \sim 125$ GeV and flavor in the MSSM

Low Energy Vs High Energy SUSY breaking effects on $B \rightarrow X_s \gamma$

$\tan \beta = 20$ $M_A = 400$ GeV

Orange solid line from $B X_s \gamma$ with low energy SUSY breaking effects

Orange dashed (dotted) line has 25% (50%) splitting from RG

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