“Higgs Boson Discovery” and Supersymmetry at the LHC

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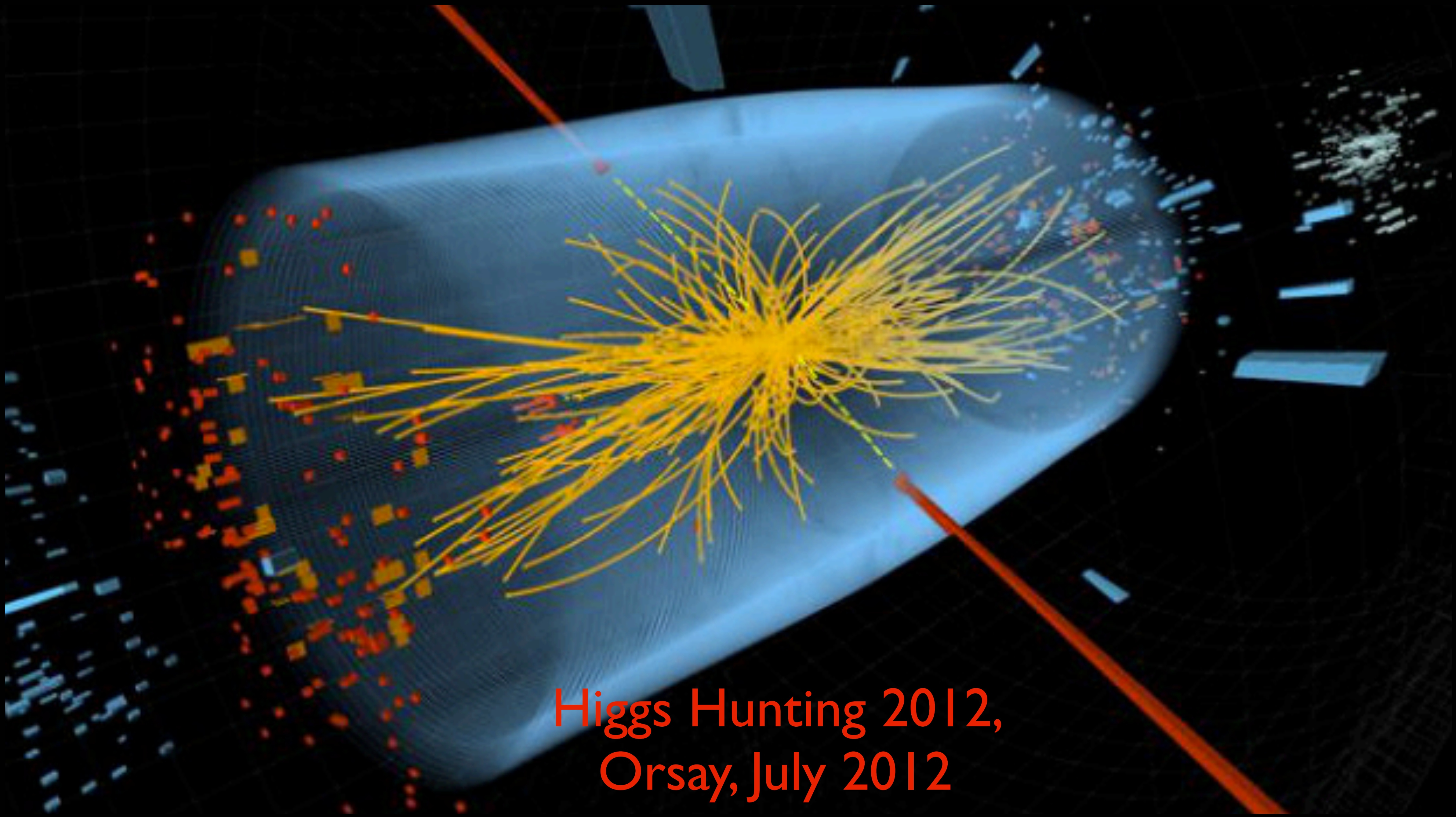
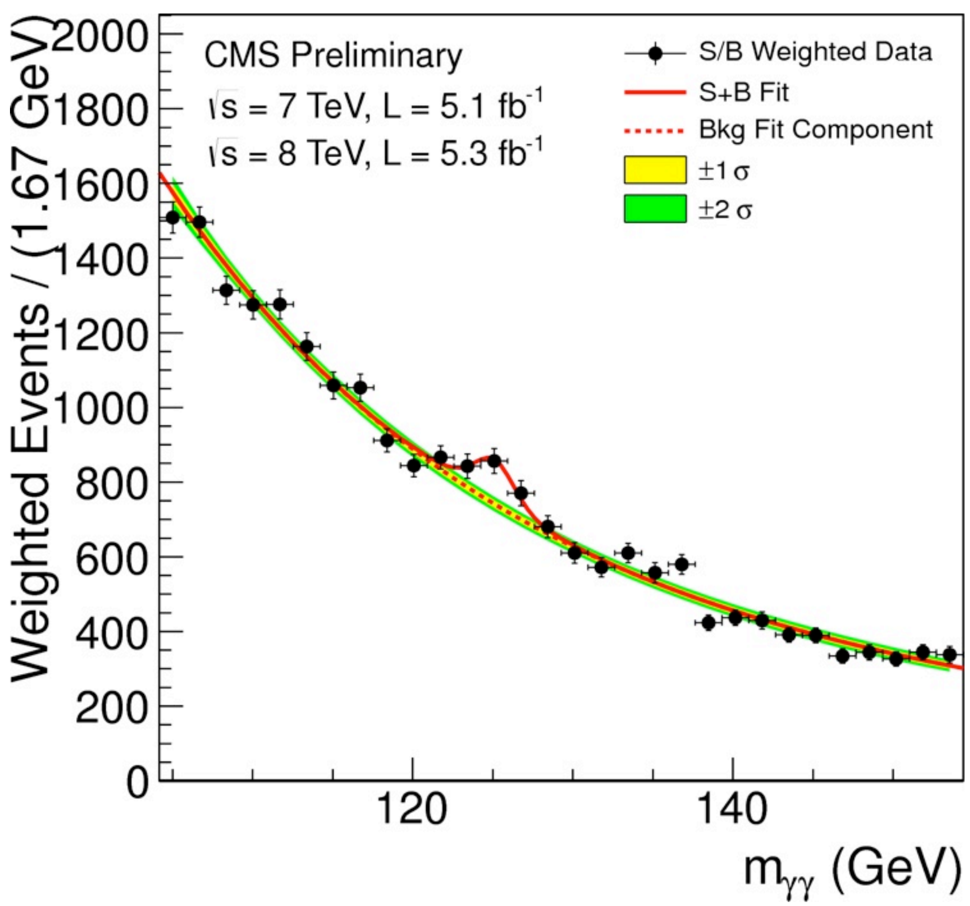
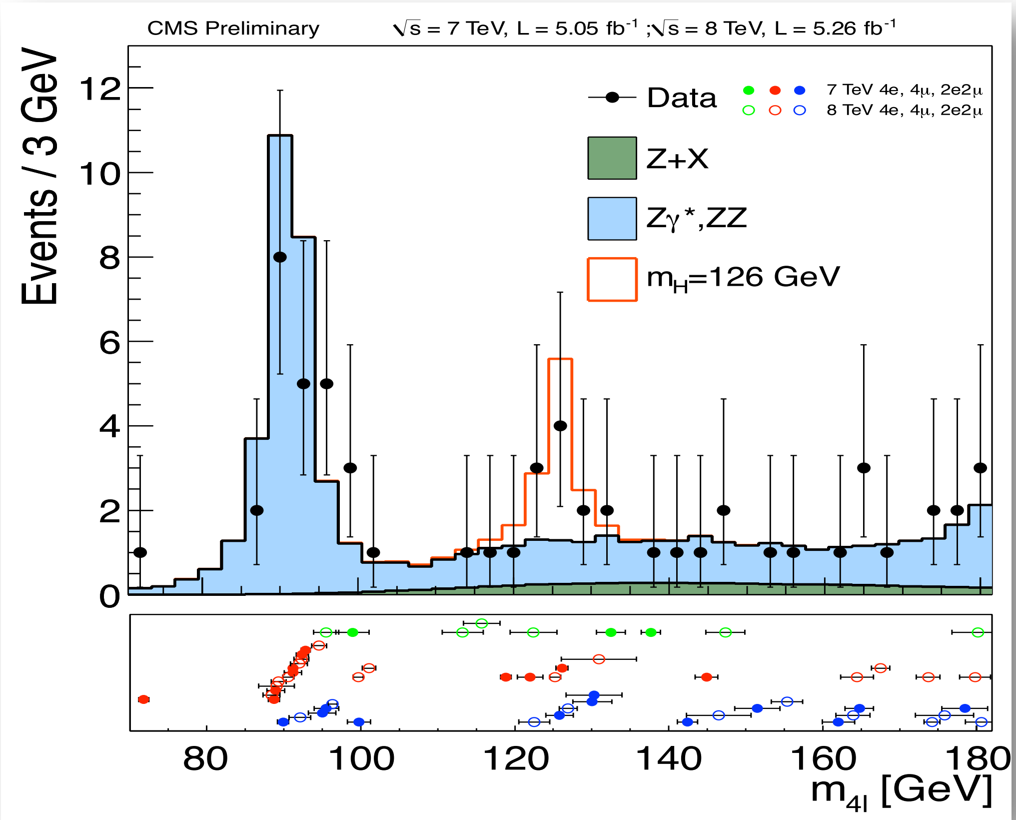


Higgs Hunting 2012,
Orsay, July 2012

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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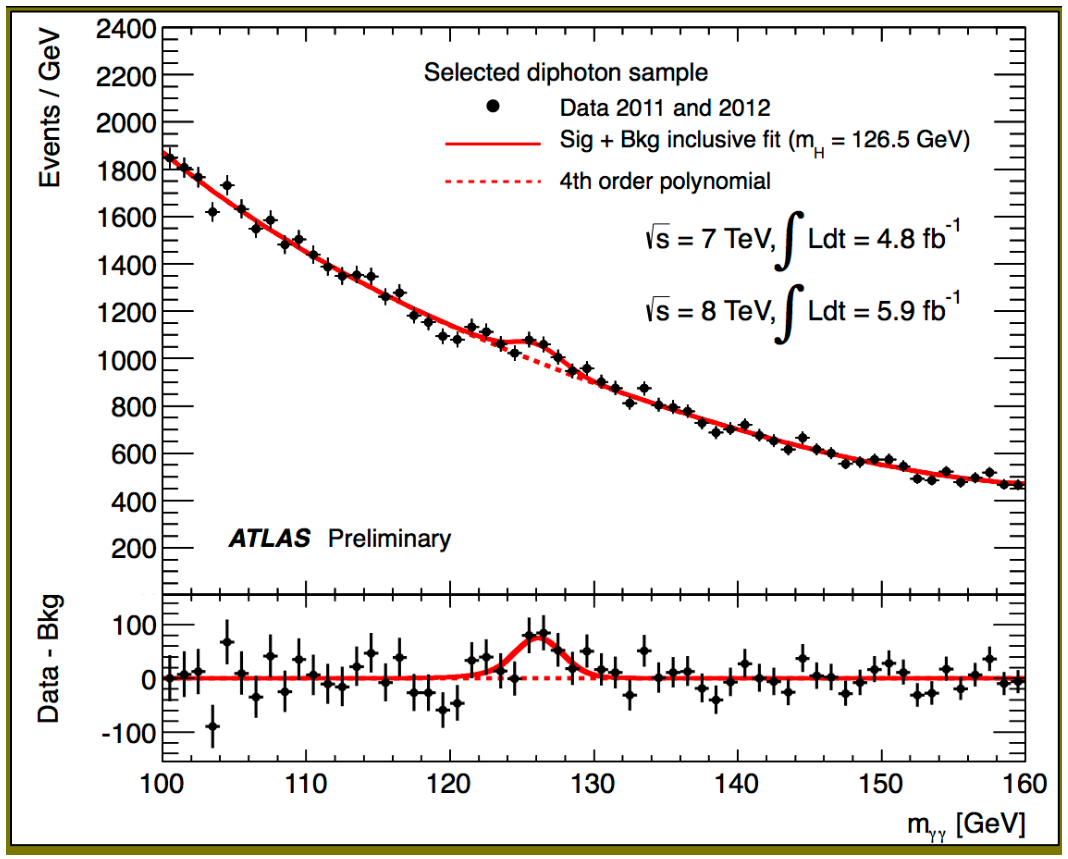

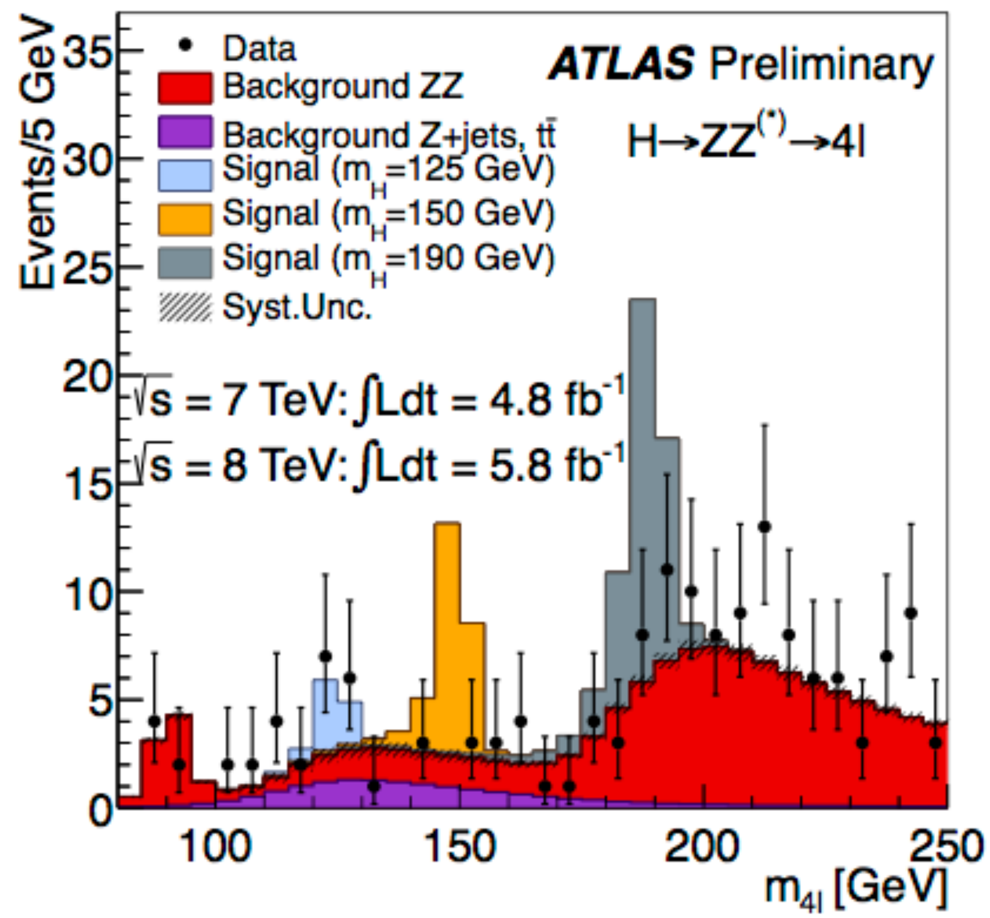

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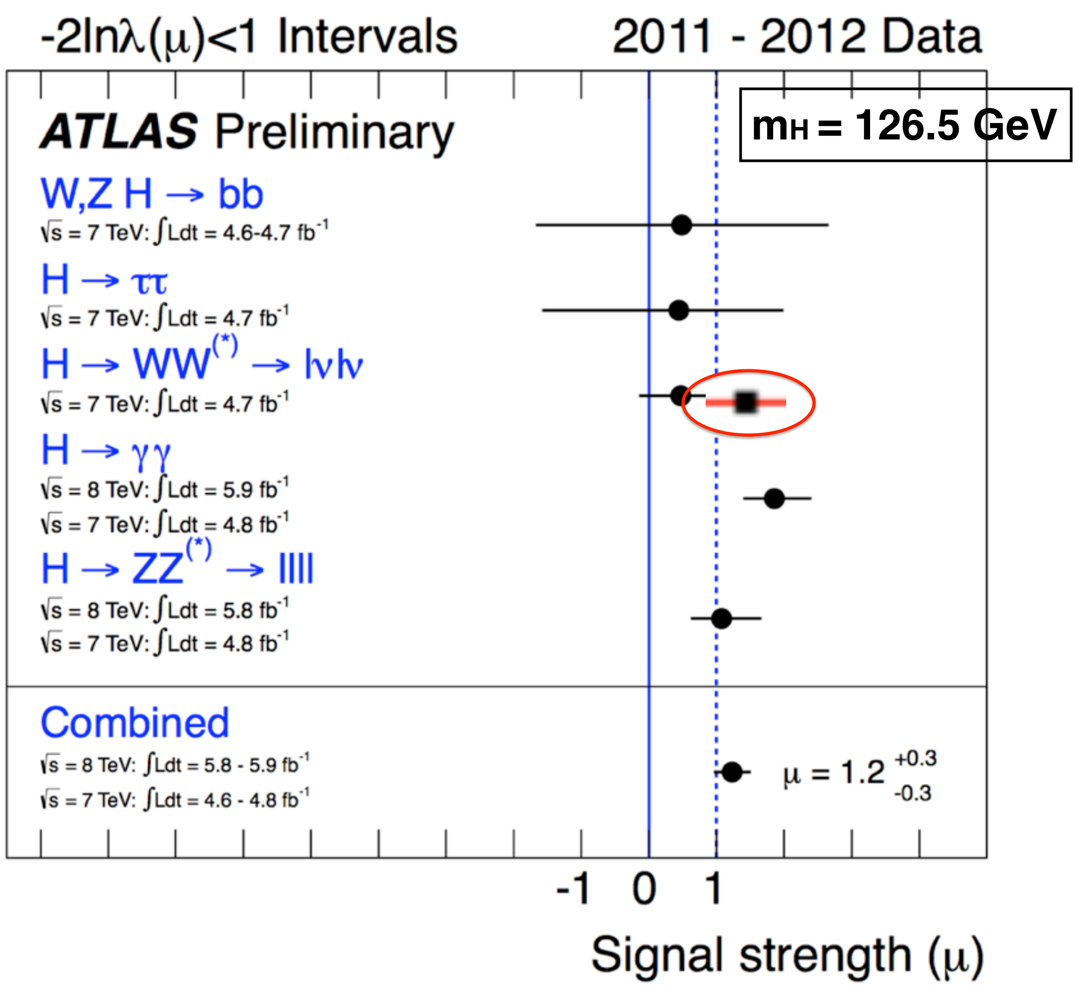
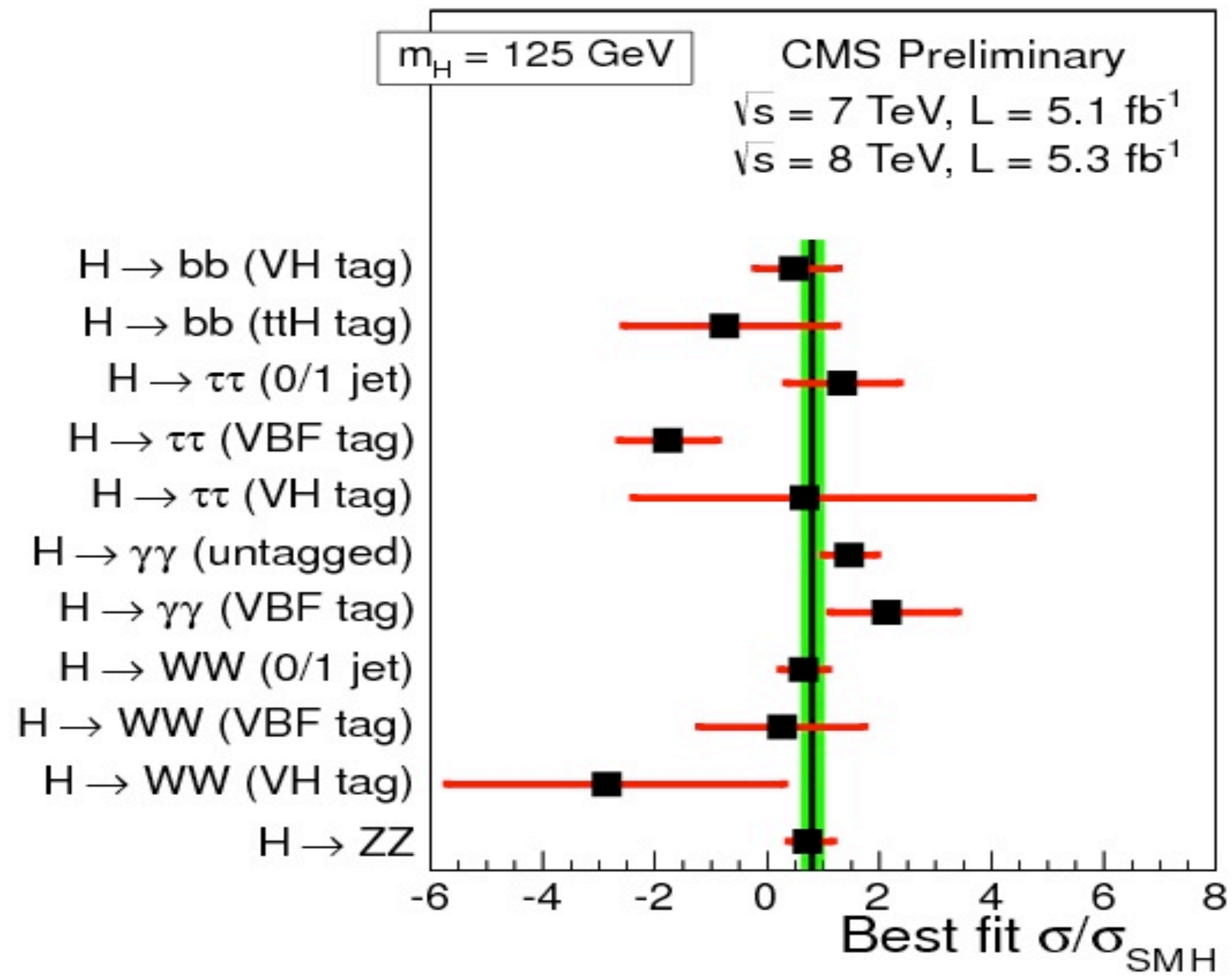
The Signal strength may be computed in all different production and decay channels and is consistent with SM





However,

A di-photon rate enhancement is the most visible feature at both experiments.

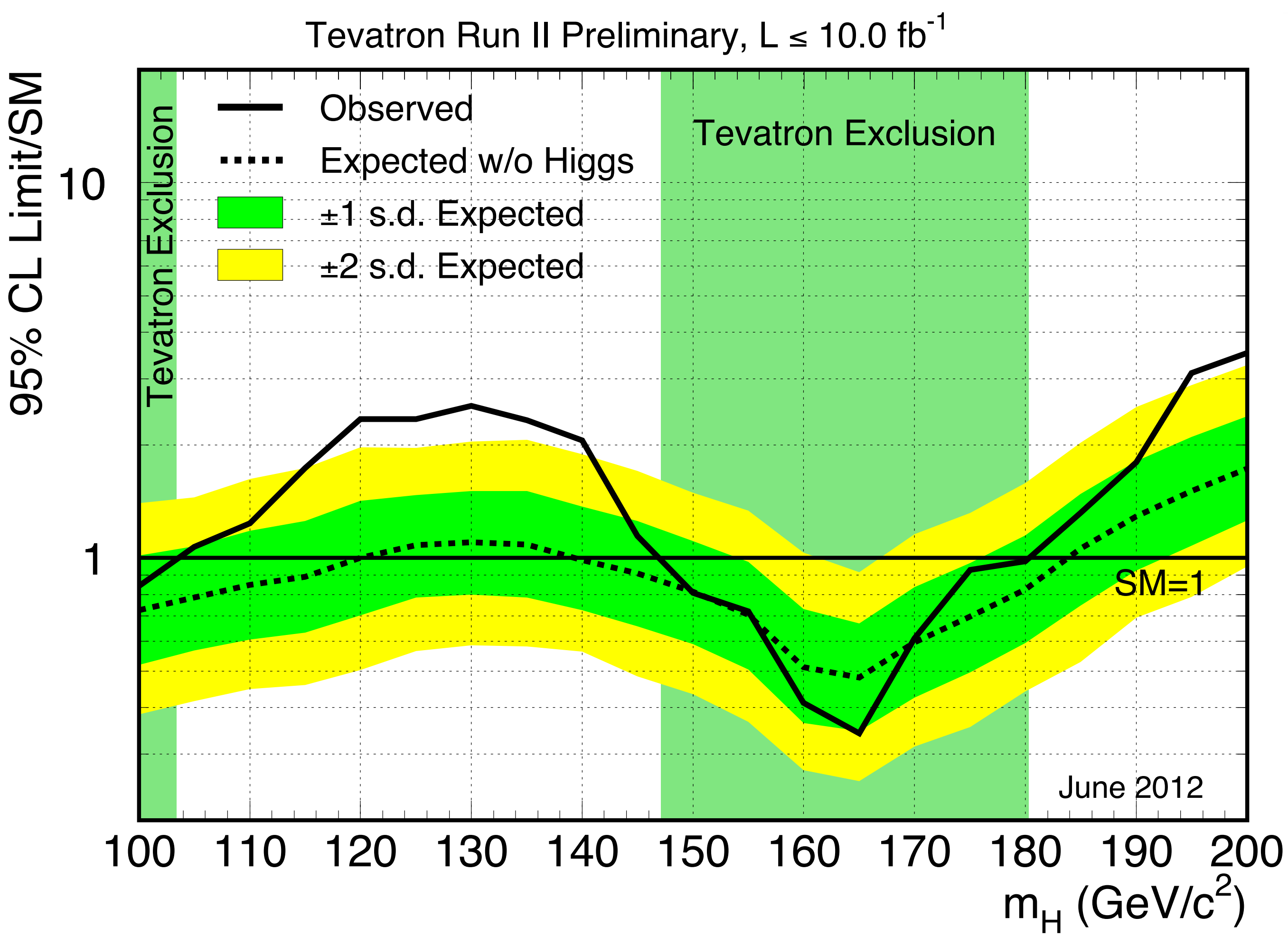
The WW rates look/ed somewhat small

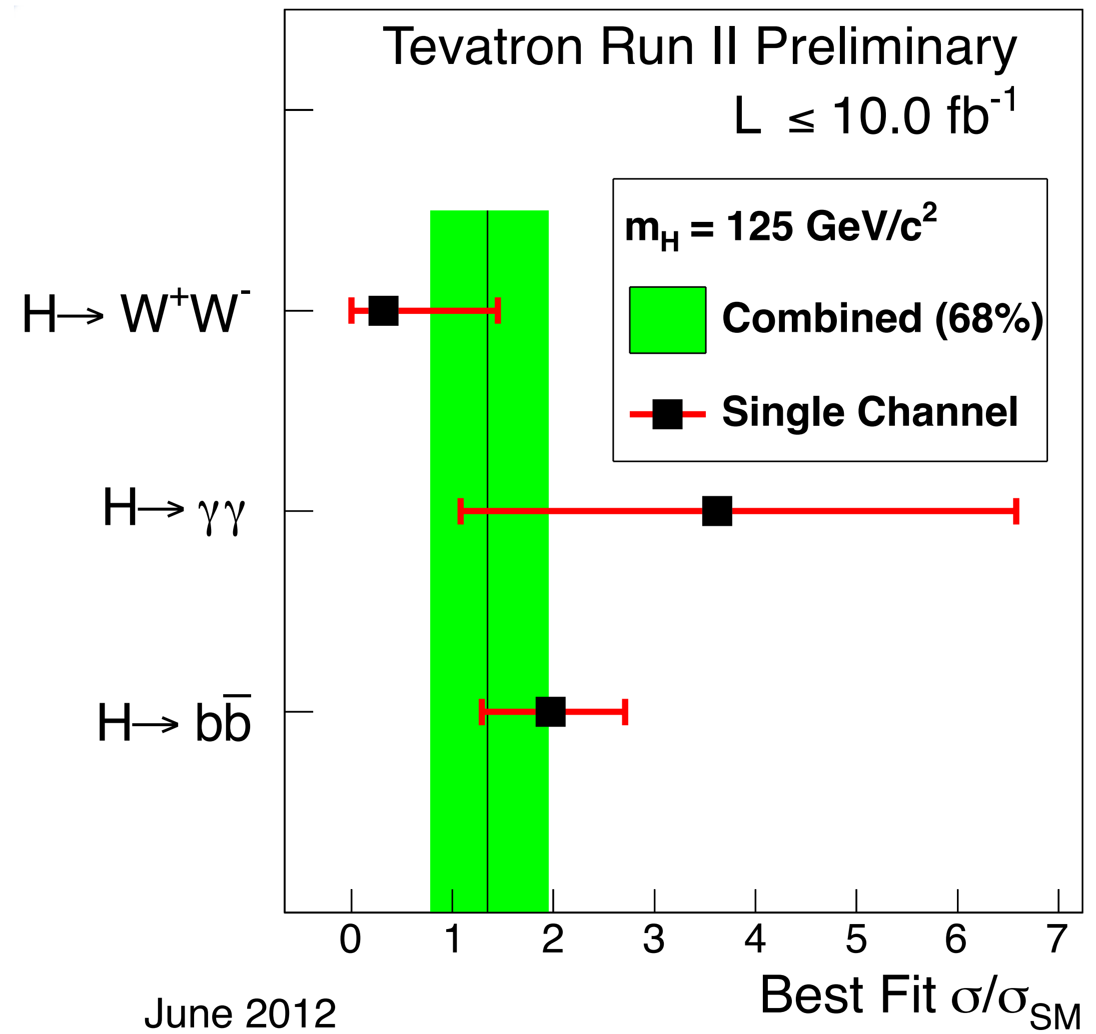
There is an apparent suppression of tau production in VBF.

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 1σ, **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

$\tan\beta = v_2/v_1$

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

$\Rightarrow v = \sqrt{v_1^2 + v_2^2} = 246$ GeV

- 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

$$\mathbf{M}^2_{\tilde{t}} = \begin{pmatrix} \mathbf{m}_Q^2 + \mathbf{m}_t^2 + \mathbf{D}_L & \mathbf{m}_t \mathbf{X}_t \\ \mathbf{m}_t \mathbf{X}_t & \mathbf{m}_U^2 + \mathbf{m}_t^2 + \mathbf{D}_R \end{pmatrix}$$

M_h depends logarithmically on the averaged stop mass scale M_{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

$$m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{\mathrm{v}^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{\mathrm{v}^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

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

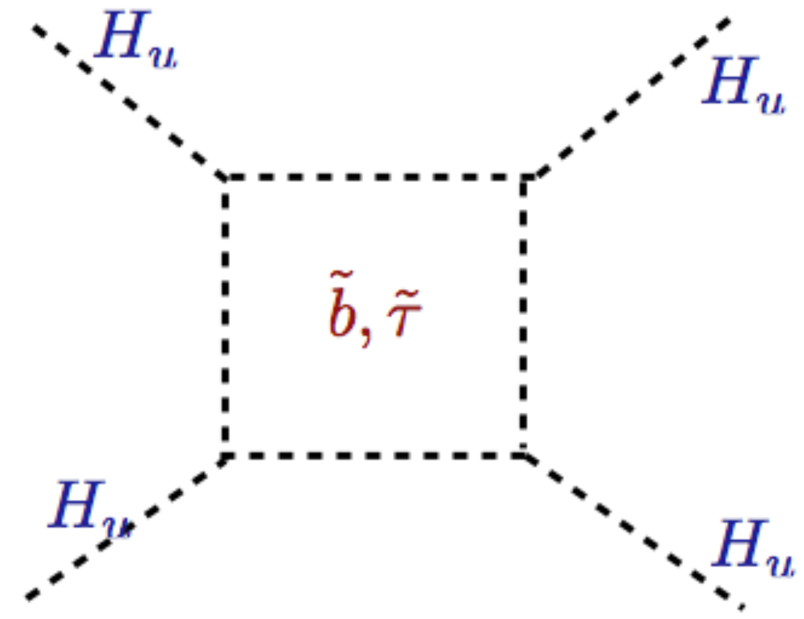
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

M.C. Espinosa, Quiros, Wagner '95
M.C. Quiros, Wagner '95

Additional effects at large tan beta from sbottoms:

$$\Delta m_h^2 \simeq -\frac{h_b^4 v^2}{16\pi^2}\frac{\mu^4}{M_{\rm SUSY}^4}$$

with $h_b \simeq \dfrac{m_b}{v\cos\beta(1+\tan\beta\Delta h_b)}$



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

and staus: $$\Delta m_h^2 \simeq -\frac{h_\tau^4 v^2}{48\pi^2}\frac{\mu^4}{M_{\tilde{\tau}}^4}$$

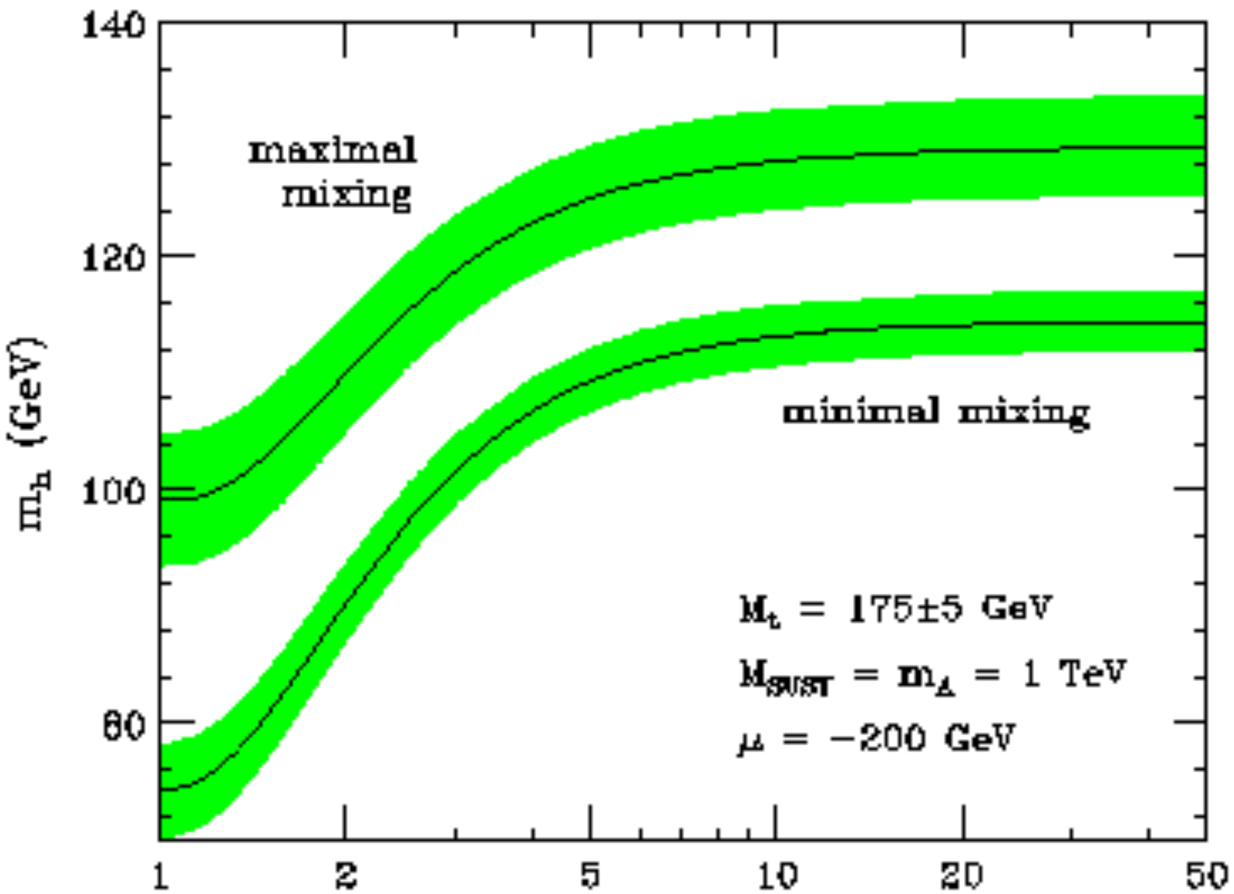
with $h_\tau \simeq \dfrac{m_\tau}{v\cos\beta(1+\tan\beta\Delta h_\tau)}$ Dep. on the sign of μM_2

Both corrections give negative contributions to the Higgs mass
hence smaller values of μ and positive values of μM_2 and $\mu M_{\tilde{g}}$ enhance the value of the Higgs mass

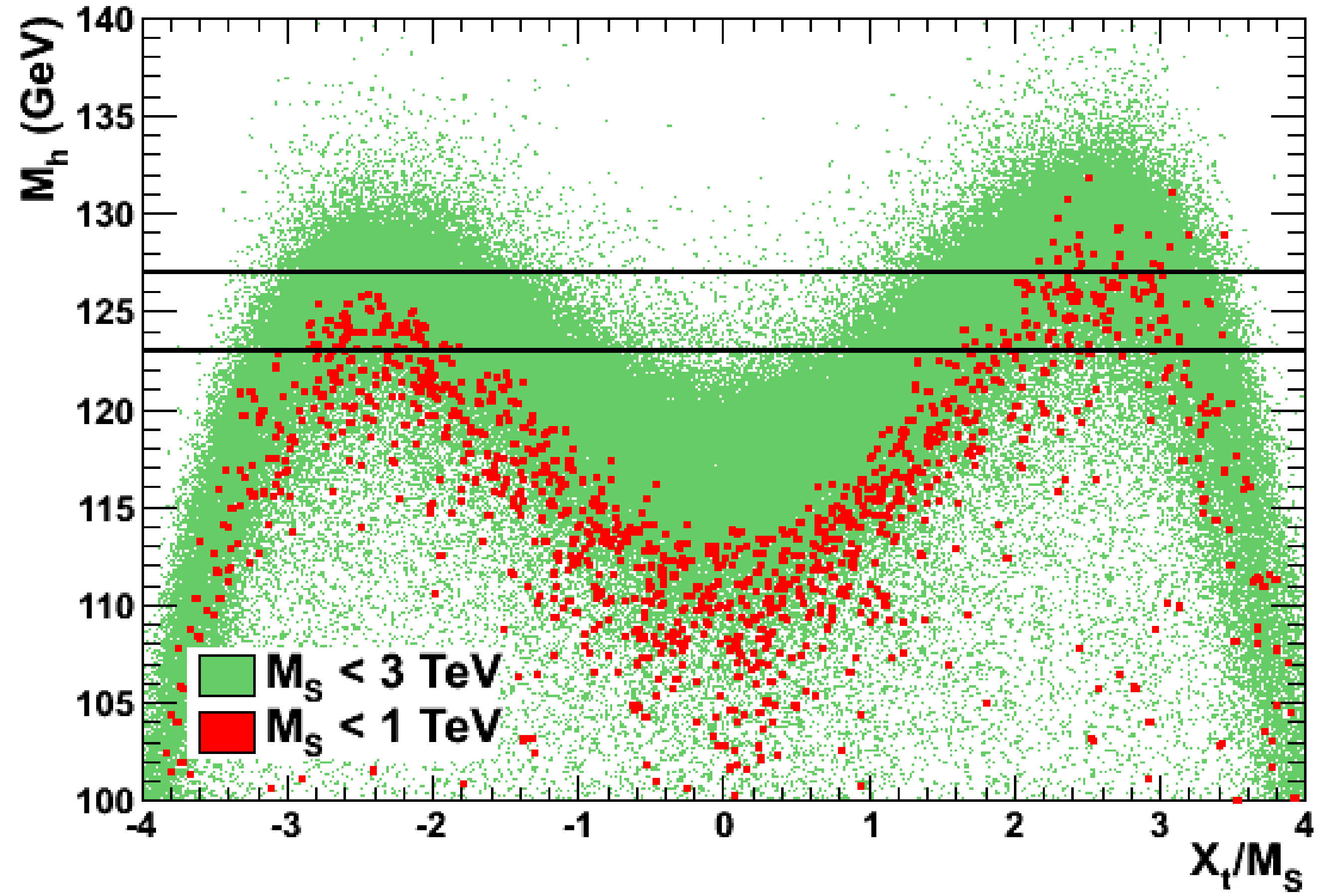
Maximal effect: lower m_h by several GeV

SM-like MSSM Higgs Mass:

M.C, Haber, Heinemeyer, Hollik,Weiglein,Wagner'00



Arbeya, Battaglia, Djouadi, Mahmoudi, Quevillon'11



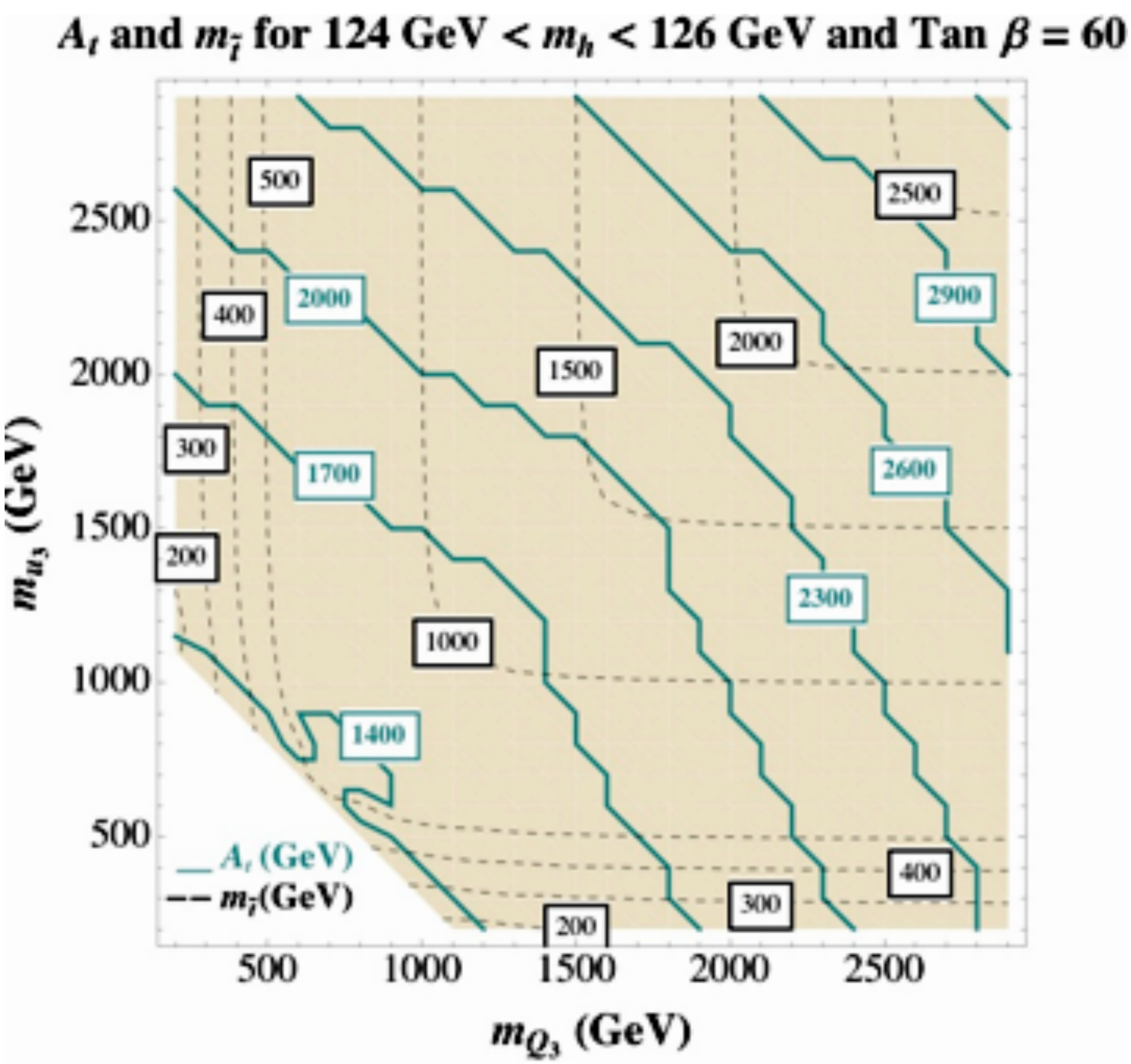
$$m_h \leq 130 \text{ GeV}$$

(for sparticles of ~ 1 TeV)

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, …

Soft supersymmetry Breaking Parameters



M. C., S. Gori, N. Shah, C.Wagner '11
+L.T.Wang '12

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 1TeV

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

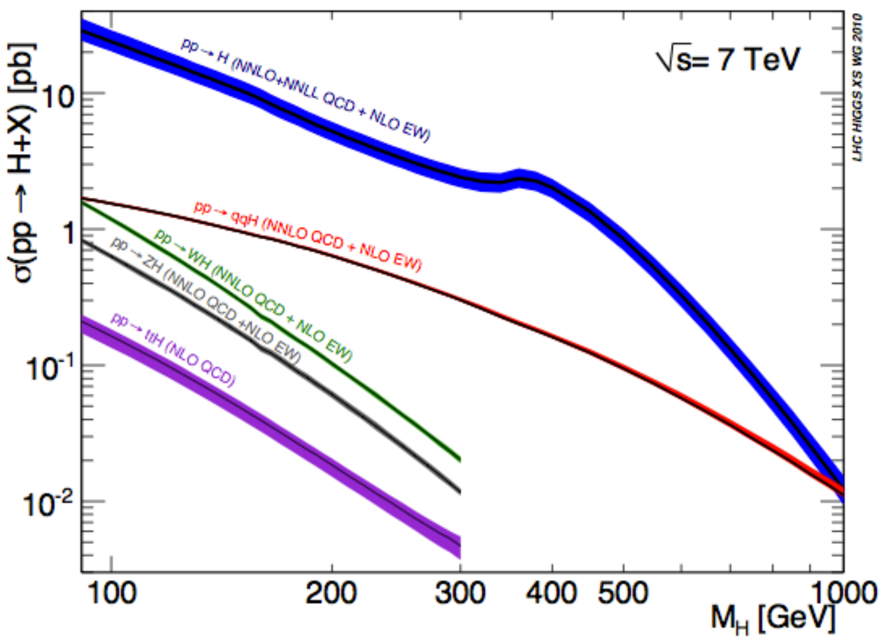
At large tan beta, light staus/sbottoms can decrease mh by several GeV's via Higgs mixing effects and compensate tan beta enhancement

Can departures in the production/decay rates at the LHC disentangle among different SUSY spectra?

The event rate depends on three quantities:

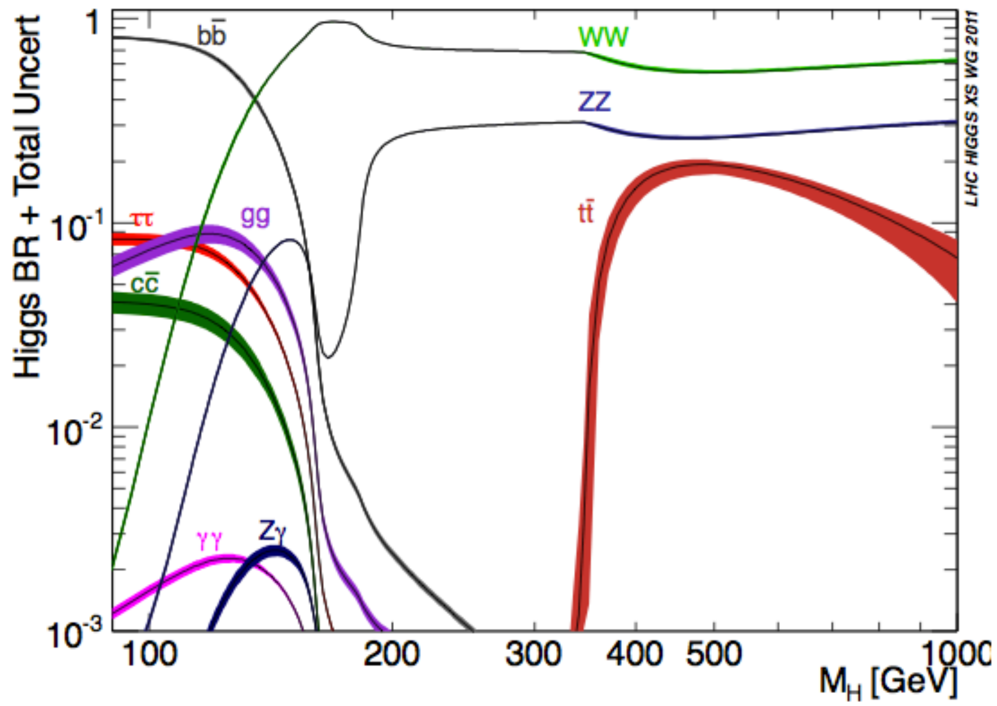
$$B\sigma(p\bar{p} \to h \to X_{\rm SM}) \equiv \sigma(p\bar{p} \to h) \frac{\Gamma(h \to X_{\rm SM})}{\Gamma_{\rm total}}$$

- 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.



Main production channel: Gluon Fusion

Main/first search modes: decay into γγ/ZZ/WW



How much can we perturb the gluon production mode?

Is it possible to change WW and ZZ decay rates independently?

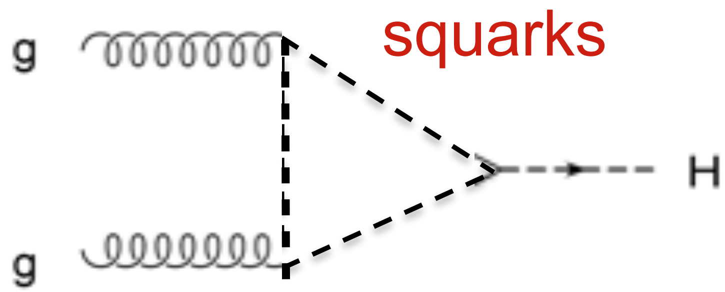
Can we vary the Higgs rate into di-photons independently from the rate into WW/ZZ?

Can we change the ratio of b-pair to tau pair decay rates?

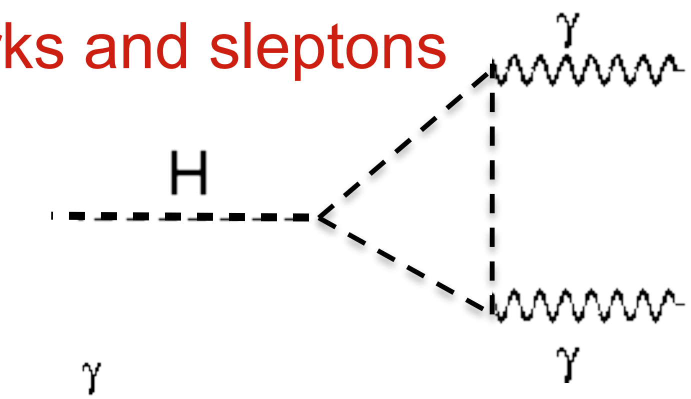
Departures in the production and decay rates at the LHC

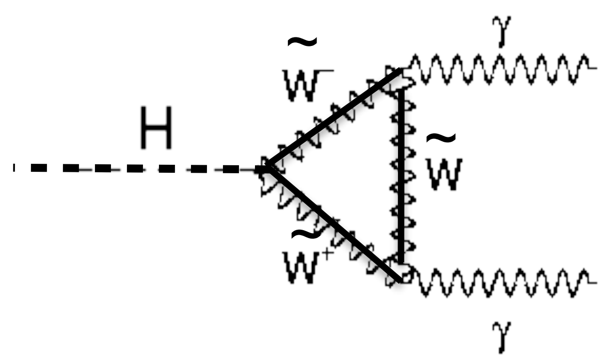
- Through SUSY particle effects in loop induced processes

squarks



squarks and sleptons





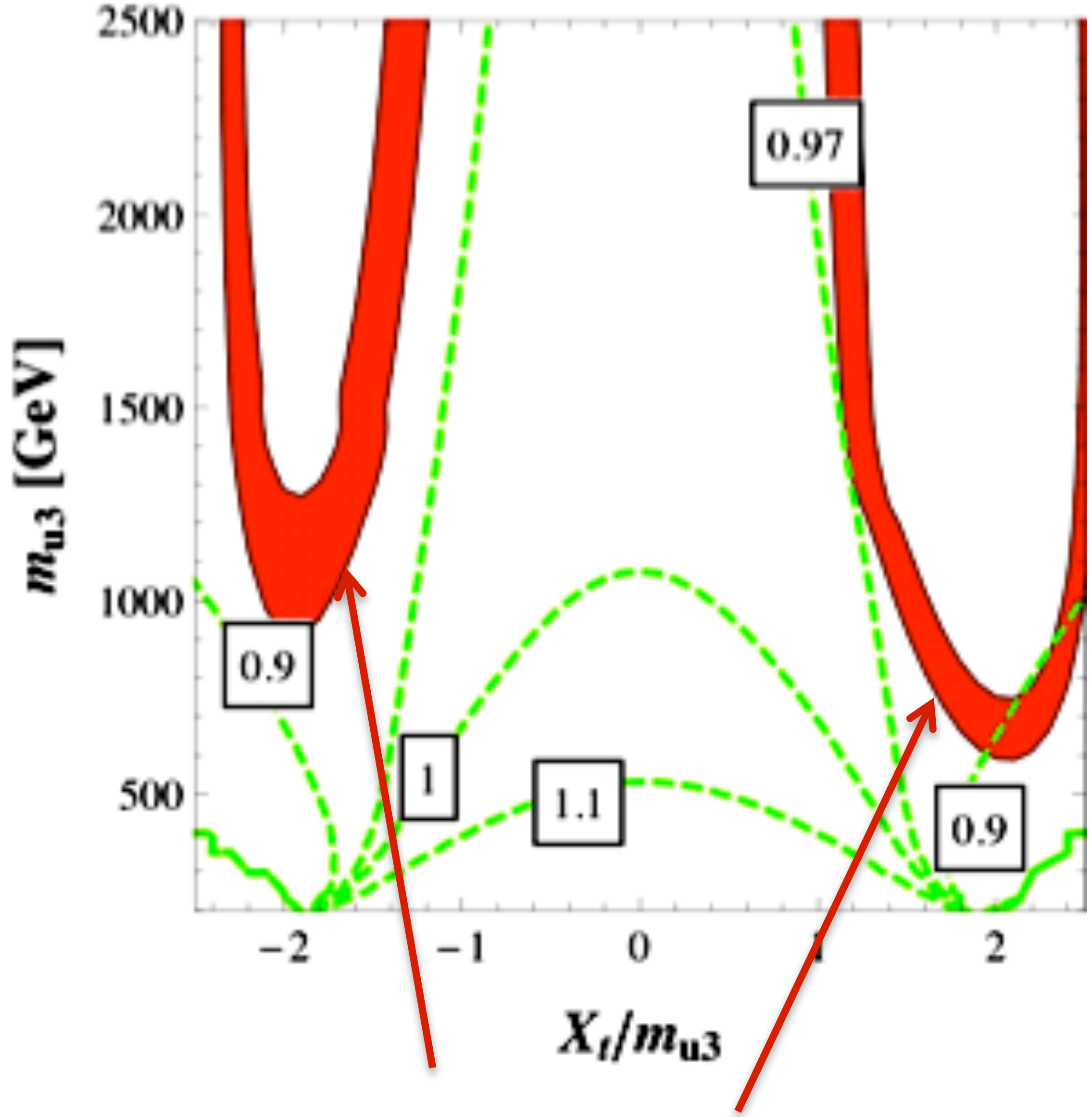
charginos

- 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 $BR(h \rightarrow bb)/BR(h \rightarrow \tau\tau) \sim m_b^2/m_\tau^2$

Gluon Fusion in the MSSM

----- contours of $\sigma(gg \to h)/\sigma(gg \to h)_{SM}$



mh ~ 124-126 GeV range

Dermisek, Low'07

Light 3rd 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**

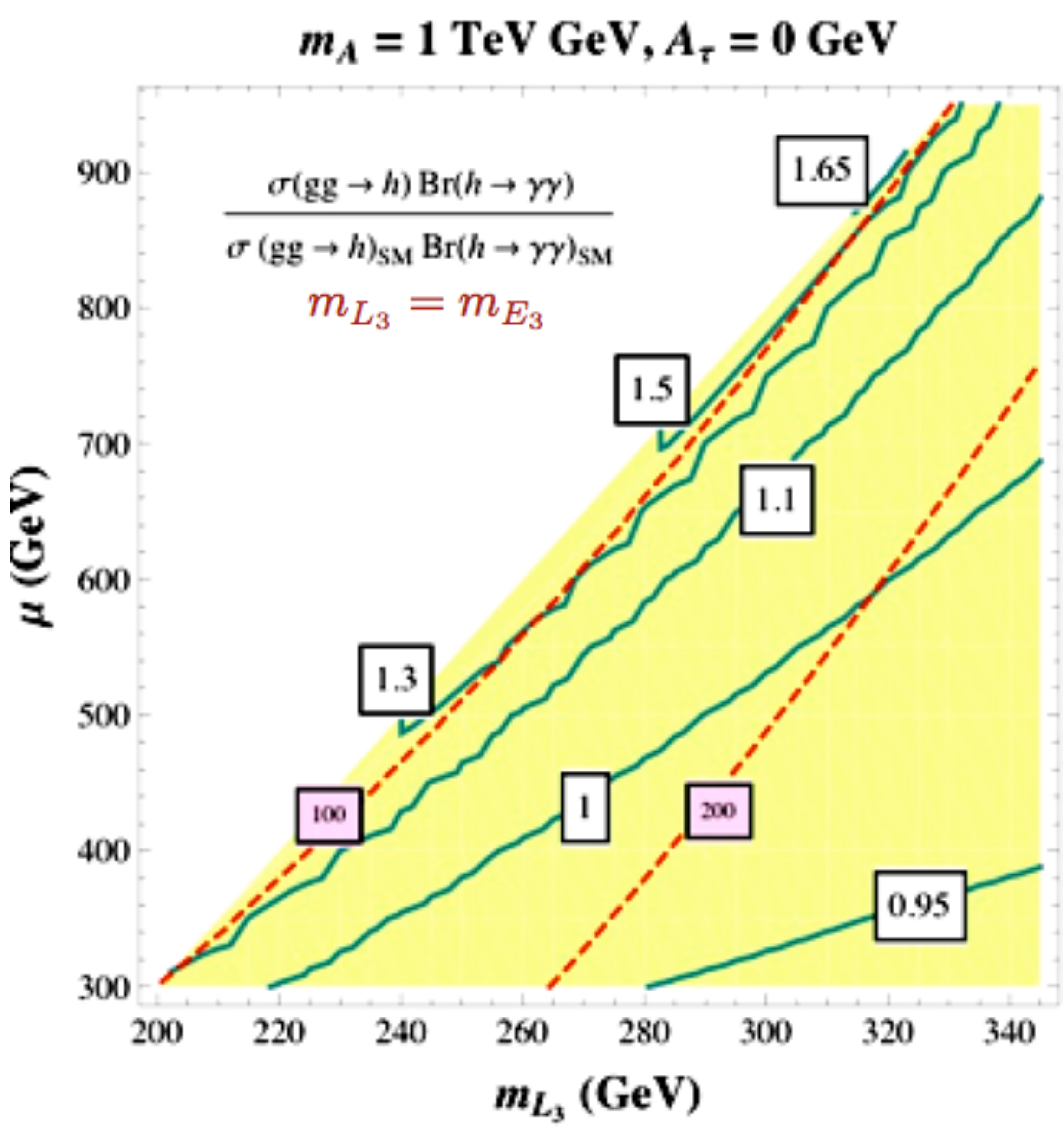
Squark suppression effects in gluon fusion yield small enhancement in di-photon decay rate but

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

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

$$\mathcal{M}_{\tilde{\tau}}^2 \simeq \begin{bmatrix} m_{L_3}^2 + m_\tau^2 + D_L & h_\tau v(A_\tau \cos\beta - \mu \sin\beta) \\ h_\tau v(A_\tau \cos\beta - \mu\sin\beta) & m_{E_3}^2 + m_\tau^2 + D_R \end{bmatrix}$$



M. C, S. Gori, N. Shah, C. Wagner,'11 +L.T.Wang'12

Light staus with large mixing

[sizeable μ and tan beta]:

➔ enhancement of the Higgs to di-photon decay rate

Contours of constant

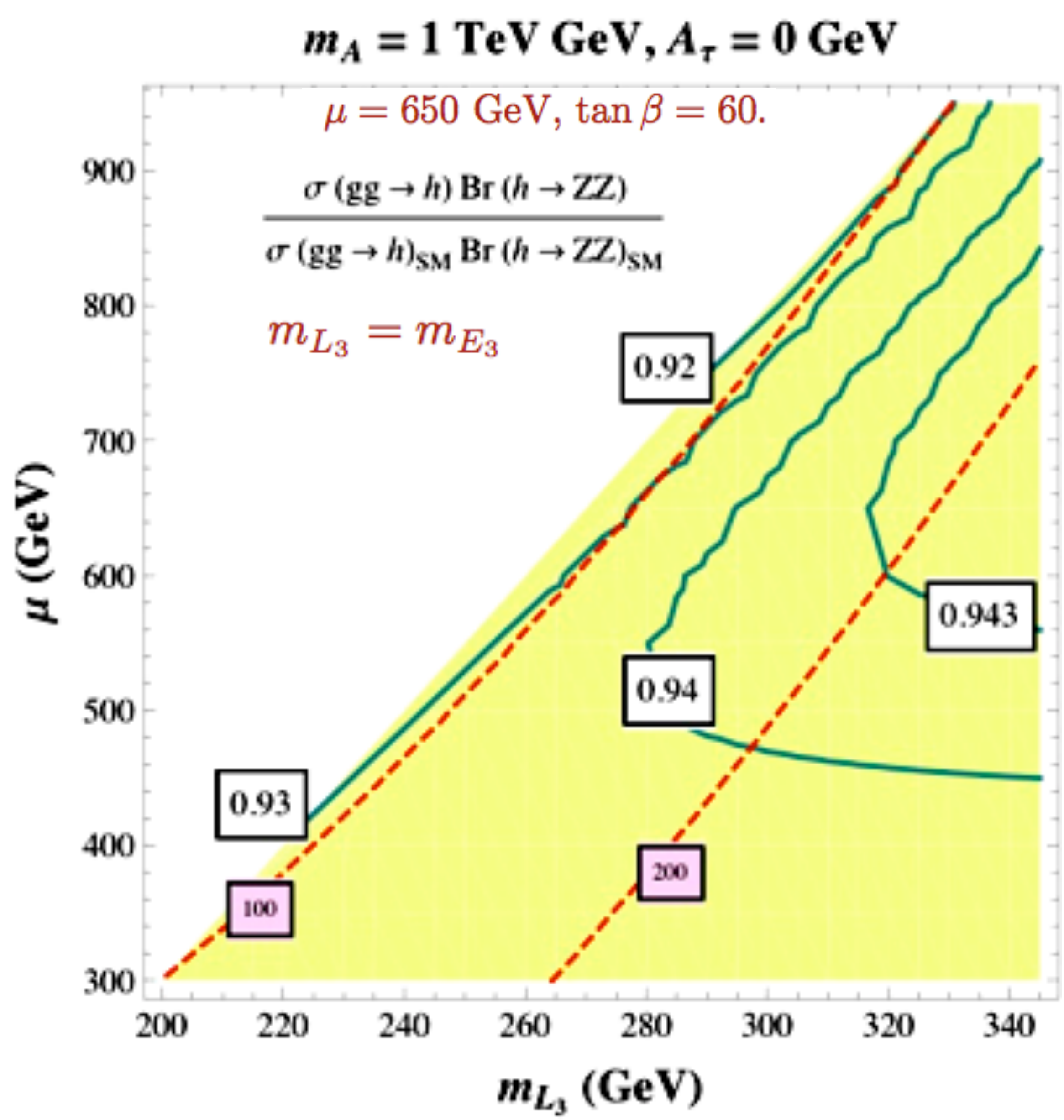
$$\frac{\sigma(gg \to h) Br(h \to \gamma\gamma)}{\sigma(gg \to h)_{SM} Br(h \to \gamma\gamma)_{SM}}$$

for $M_h \sim 125$ GeV

For a generic discussion of modified γγ and Zγ 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



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

Contours of constant

$$\frac{\sigma(gg \to h)Br(h \to ZZ)}{\sigma(gg \to h)_{SM}\,Br(h \to ZZ)_{SM}}$$

for M_h ~ 125 GeV

Mixing Effects in the CP- even Higgs Sector

can have relevant effects in the production and decay rates

$$\mathcal{M}_H^2 = \begin{bmatrix} m_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(m_A^2 + M_Z^2)\sin\beta\cos\beta + \text{Loop}_{12} \\ -(m_A^2 + M_Z^2)\sin\beta\cos\beta + \text{Loop}_{12} & m_A^2 \cos^2\beta + M_Z^2 \sin^2\beta + \text{Loop}_{22} \end{bmatrix}$$

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

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

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

$$g_{hbb} \approx \frac{-m_b \sin\alpha}{(1+\Delta_b)\ \text{v}\cos\beta}\left(1 - \Delta_b / \tan\alpha\tan\beta\right)$$

$$g_{Hbb} \approx \frac{m_b \cos\alpha}{(1+\Delta_b)\ \text{v}\cos\beta}\left(1 - \Delta_b \tan\alpha / \tan\beta\right)$$

$$g_{Abb} \approx \frac{m_b \tan\beta}{(1+\Delta_b)\text{v}}$$

destroy basic relation

$$g_{\text{h,H,Abb}} / g_{h,H,A\,\tau\tau} \propto m_b / m_\tau$$

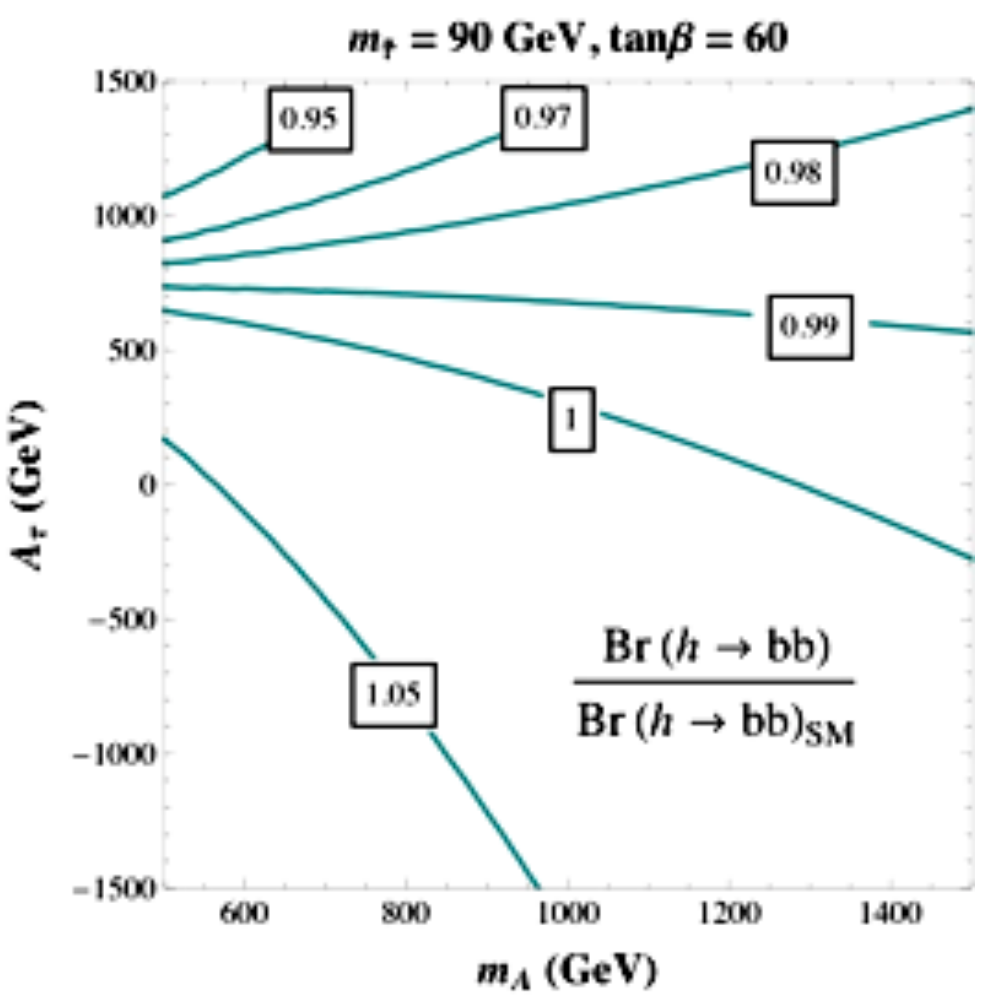
M.C. Mrenna, Wagner '98
Haber,Herrero, Logan, Penaranda, Rigolin, Temes '00

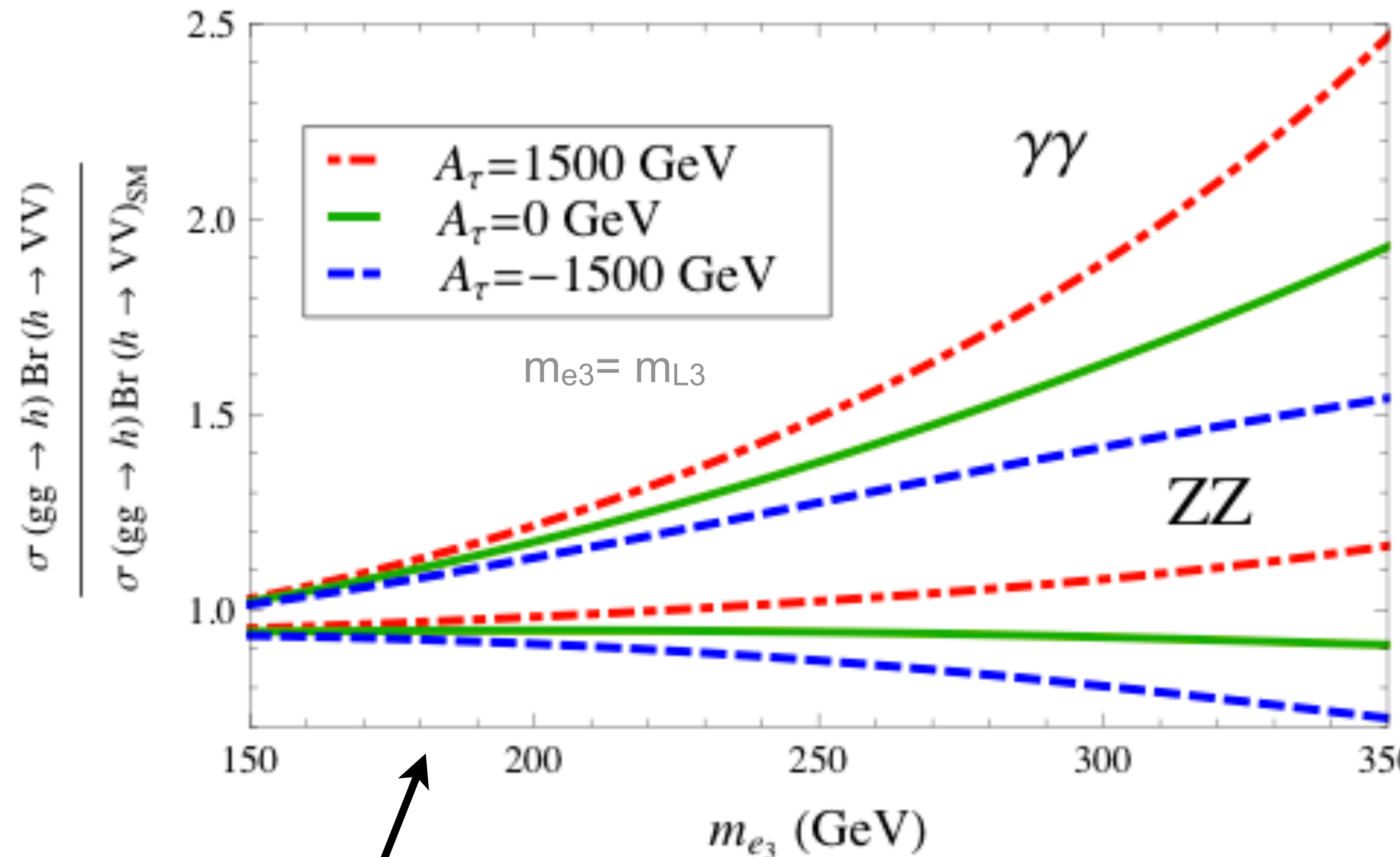
Radiative corrections ==> main decay modes of the SM-like MSSM Higgs into b- and tau-pairs can be drastically changed

Additional modifications of the Higgs rates into gauge bosons via stau induced mixing effects in the Higgs sector

Important A_τ induced radiative corrections to the mixing angle α together with loop vertex corrections to hbb coupling, Δb

m_{Stau}~ 90 GeV; m_h~ 125 GeV





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

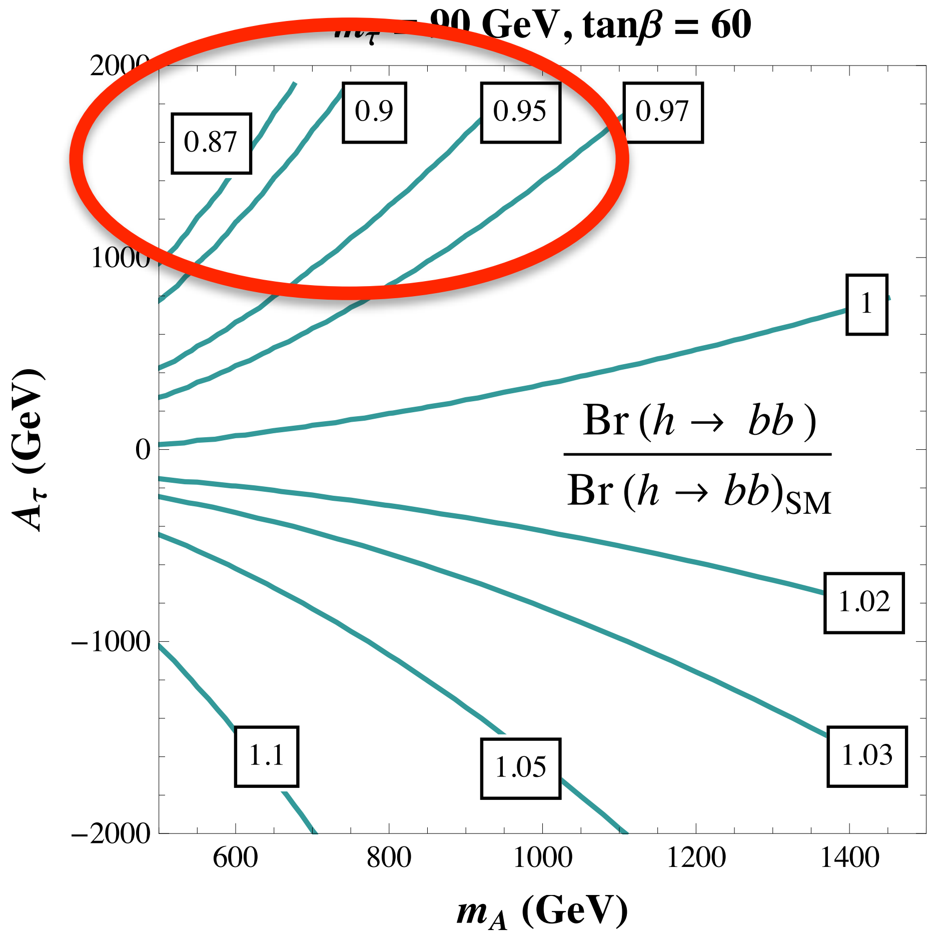
Small variations in BR [Hbb] induce significant variations in the other Higgs BR's

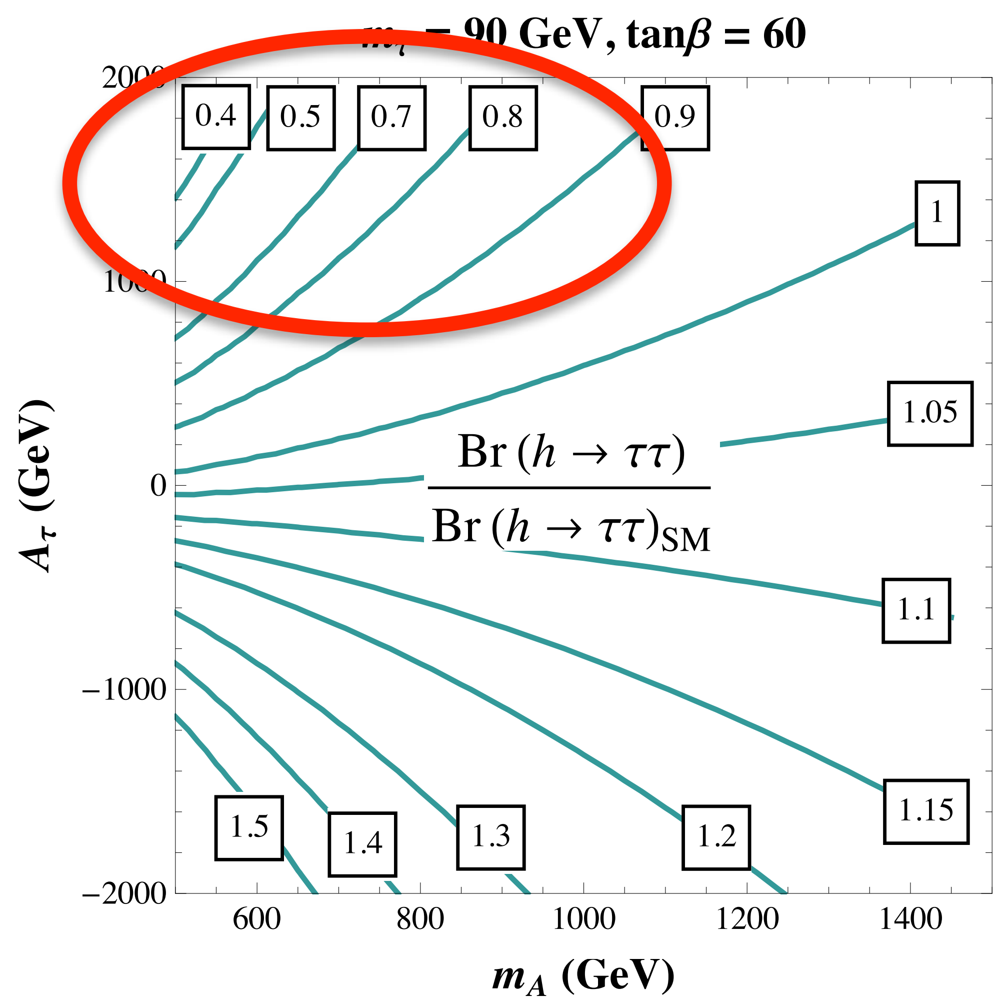
Similar results for example within pMSSM/MSSM fits: Arbey, Battagllia, Djouadi,Mahmoudi '12
Benbrik, Gomez Bock, Heinemeyer, Stal, Weigein, Zeune'12

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





futher 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

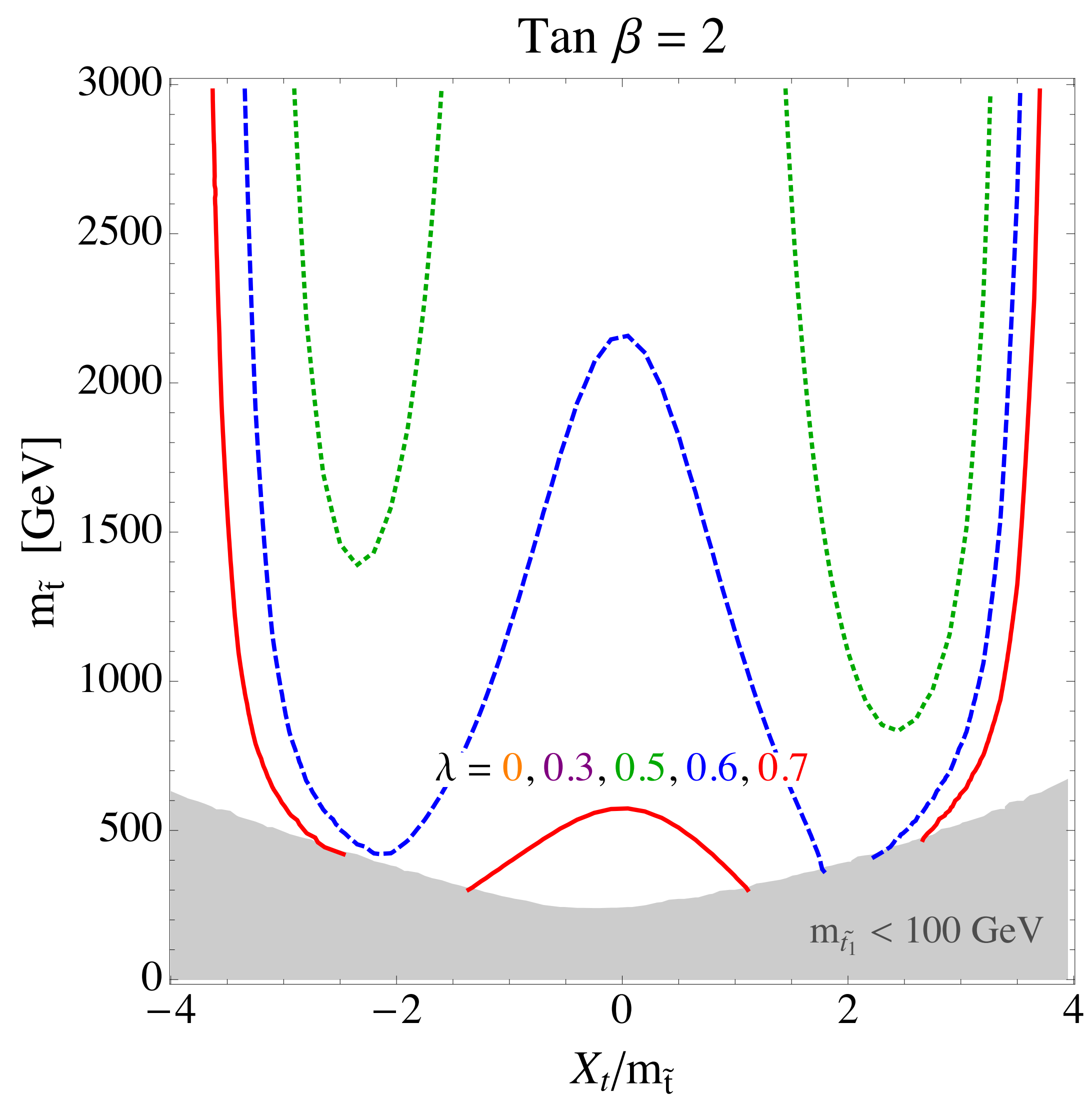
NMSSM: extra singlet S with extra parameter λ

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

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

SM + singlet limit

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



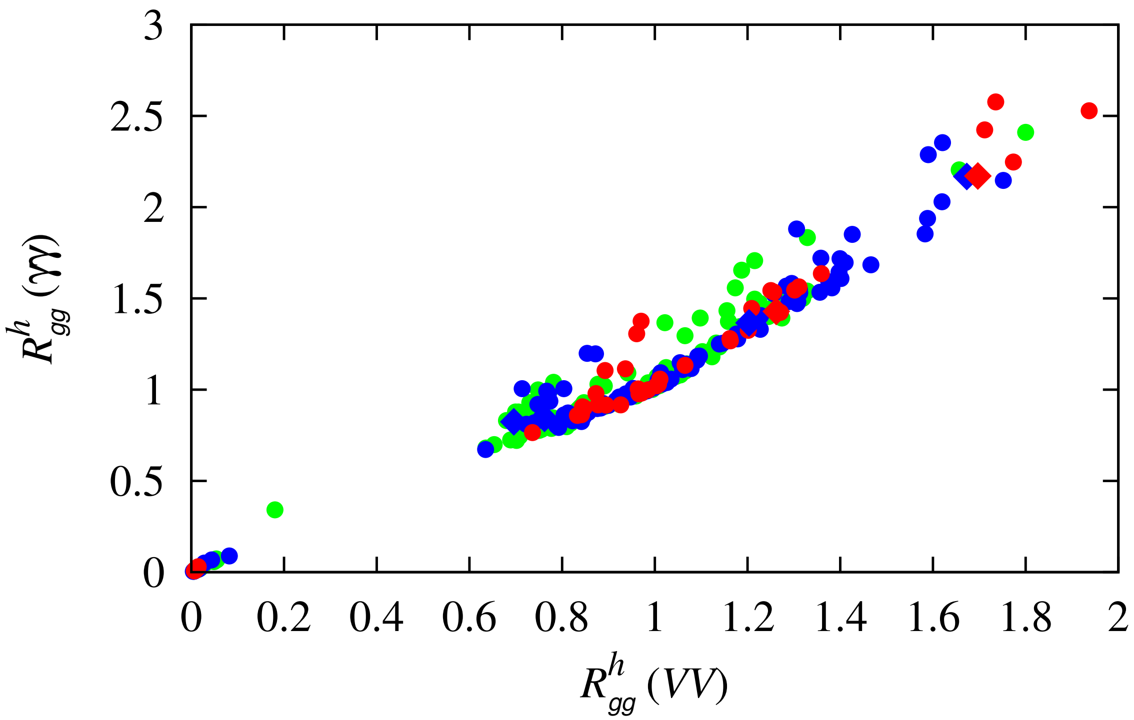
Hall, Pinner, Ruderman'11

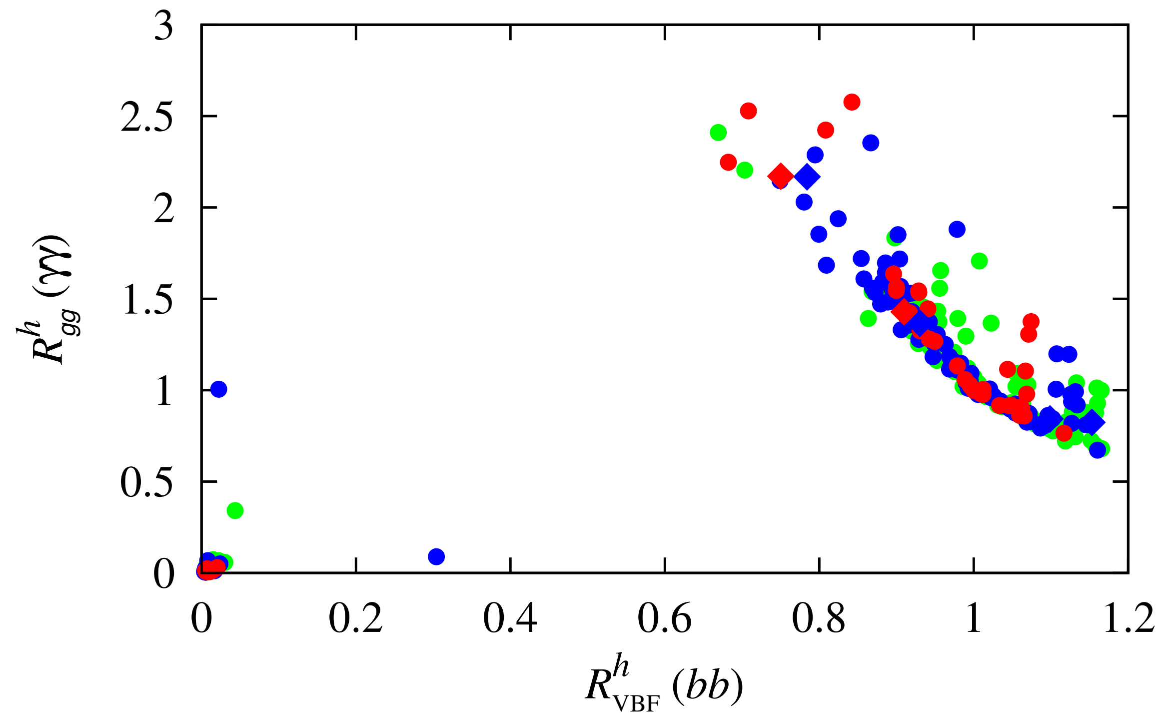
- Large effect on the mass only for low tan beta
- More freedom in gluon fusion production
- **Higgs mixing effects can be also triggered by extra new parameter λ**
- Light staus would not enhance di-photon rate since at low tan beta there is negligible mixing in the stau sector.

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 λ

Ellwanger. 12
Benbrik, Bock, Heinemeyer, Stal, Weiglein, Zeune'12
Gunion, Jiang, Kraml '12





$$R^{h_i}_{gg}(X) \equiv \frac{\Gamma(gg \to h_i)\ \mathrm{BR}(h_i \to X)}{\Gamma(gg \to h_{\rm SM})\ \mathrm{BR}(h_{\rm SM} \to X)},$$

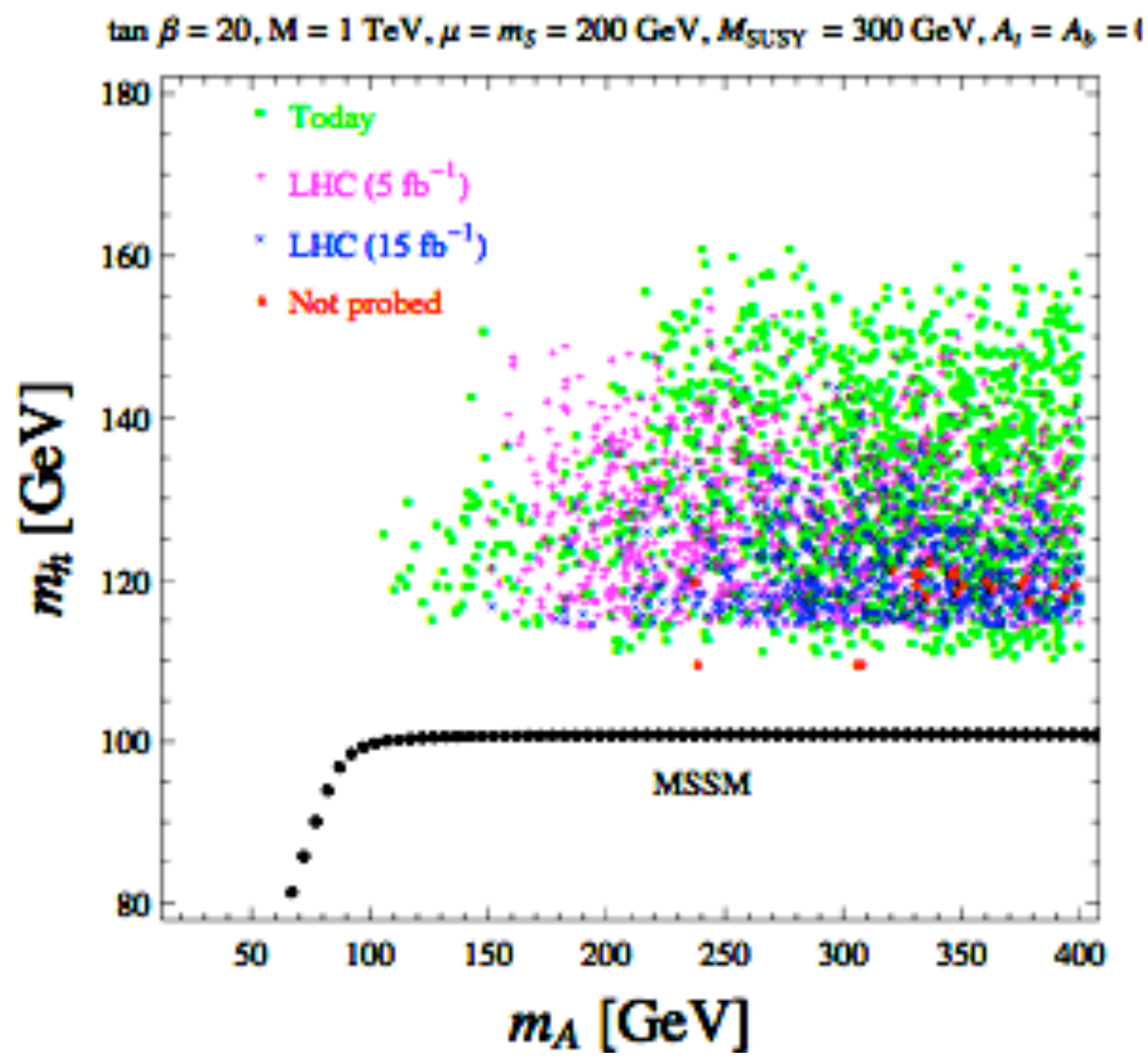
$$R^{h_i}_{\rm VBF}(X) \equiv \frac{\Gamma(WW \to h_i)\ \mathrm{BR}(h_i \to X)}{\Gamma(WW \to h_{\rm SM})\ \mathrm{BR}(h_{\rm SM} \to X)}$$

Suppression in BR [Hbb] induce
significant and correlated variations in the other Higgs BR's

More general MSSM Higgs extensions: EFT approach

$$W = \mu H_u H_d + \frac{\omega_1}{2M}(H_u H_d)^2 \qquad W_X \supset \frac{\omega_1}{2M} X (H_u H_d)^2$$

Dine, Seiberg, Thomas;
Antoniadis, Dudas, Ghilencea, Tziveloglou
M.C, Kong, Ponton, Zurita



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

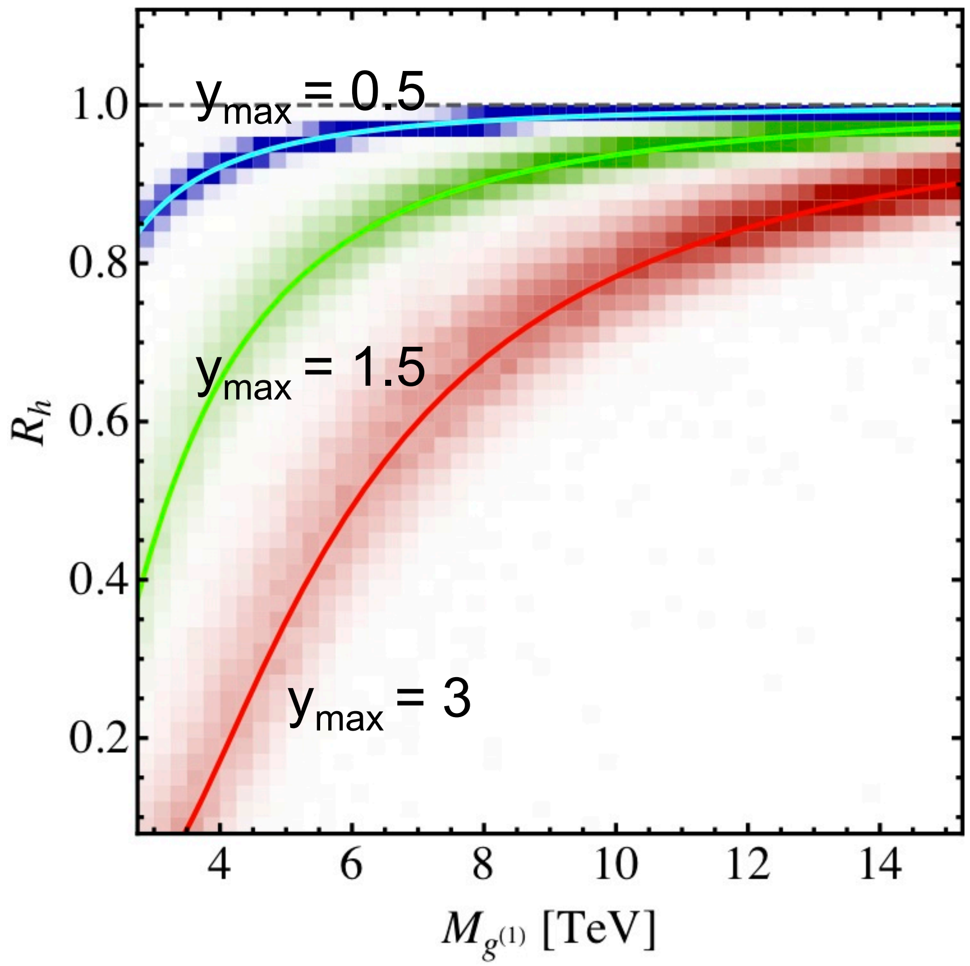
Higgs cascade decays from large splitting in masses : h/H to AA

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 hγγ & hgg couplings
Effect even more pronounced in models with custodial protection

MC, Casagrande, Goertz, Haisch, Neubert'12



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

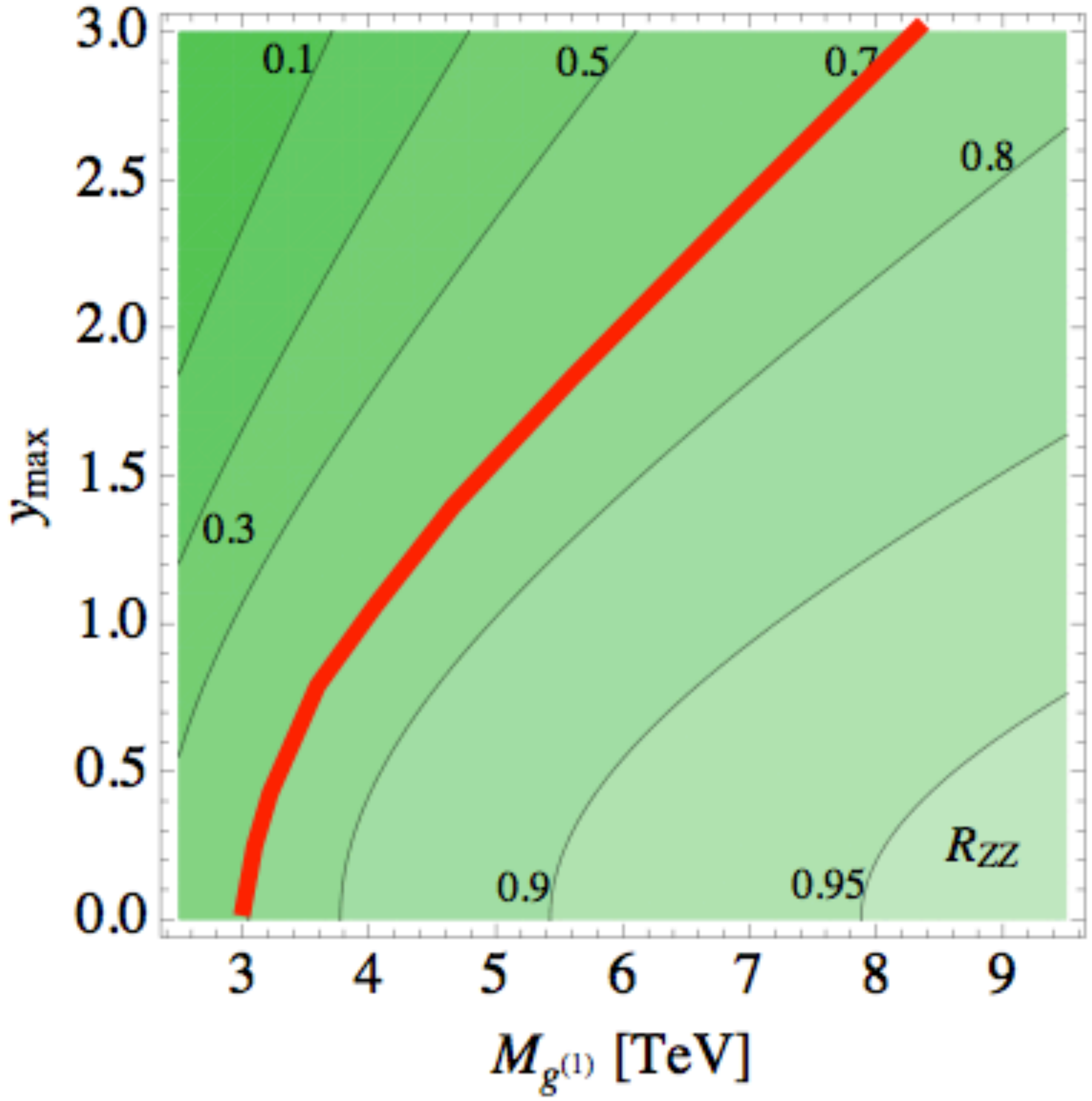
Suppression

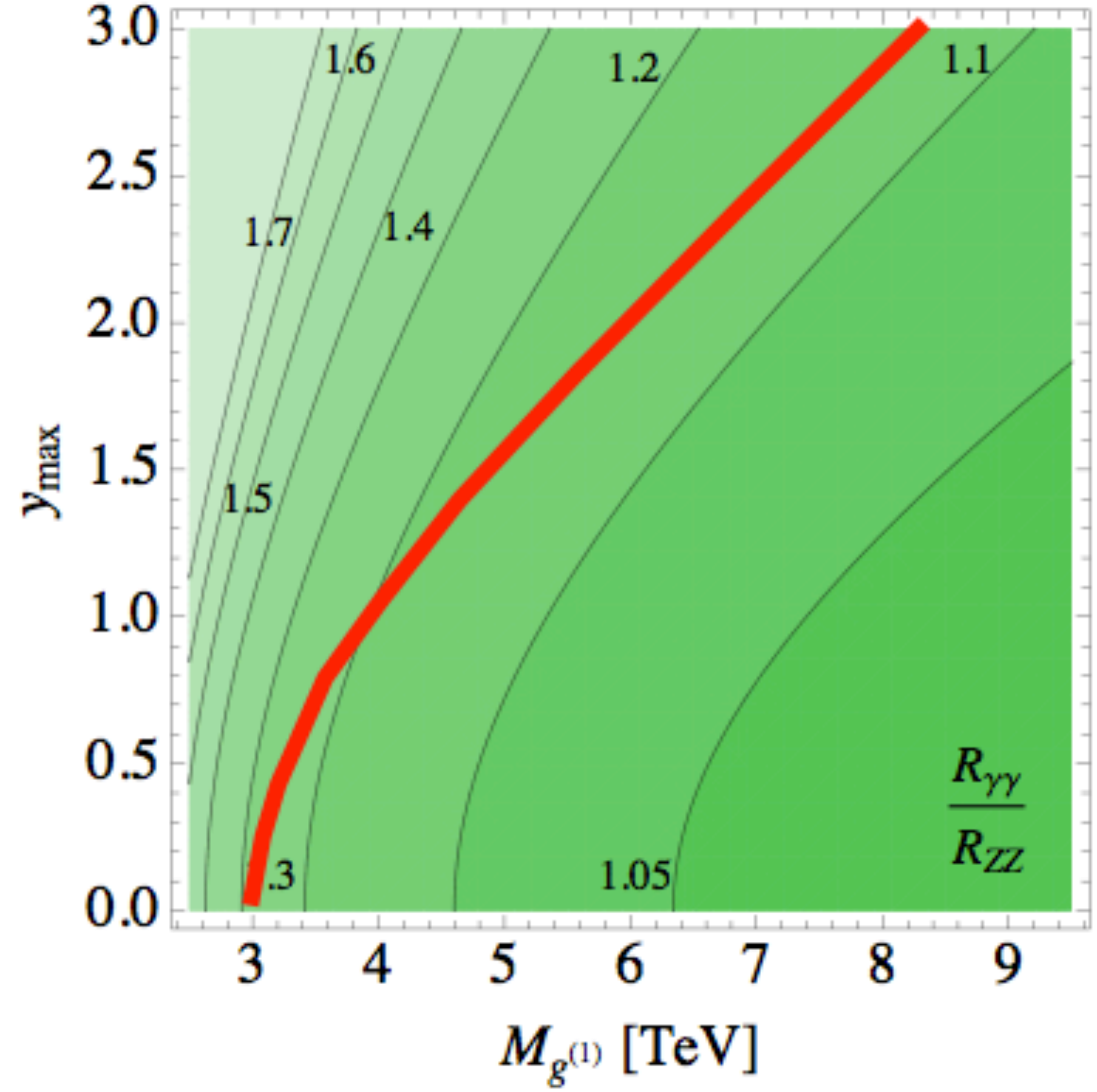
$R_h = \sigma(gg \to h)_{WED} / \sigma(gg \to h)_{SM}$

Significant enhancement of the BR (h→γγ) also possible depending on the values of leptonic 5D Yukawas

Higgs Phenomenology in Minimal RS model: Decay

Goertz, Haisch, Neubert





Higgs to diphotons can be larger than HZZ but below SM value

A measurement of R_{ZZ} **≈ 0.7 along with a slight enhancement of the di-photon over the ZZ channel would then imply (for y_{max} =3) KK masses ≈ 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

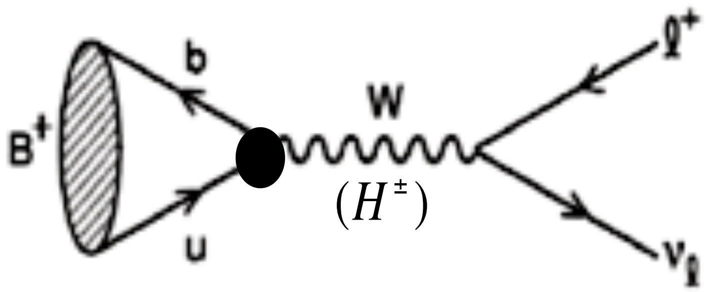
and/or

direct observation of new physics

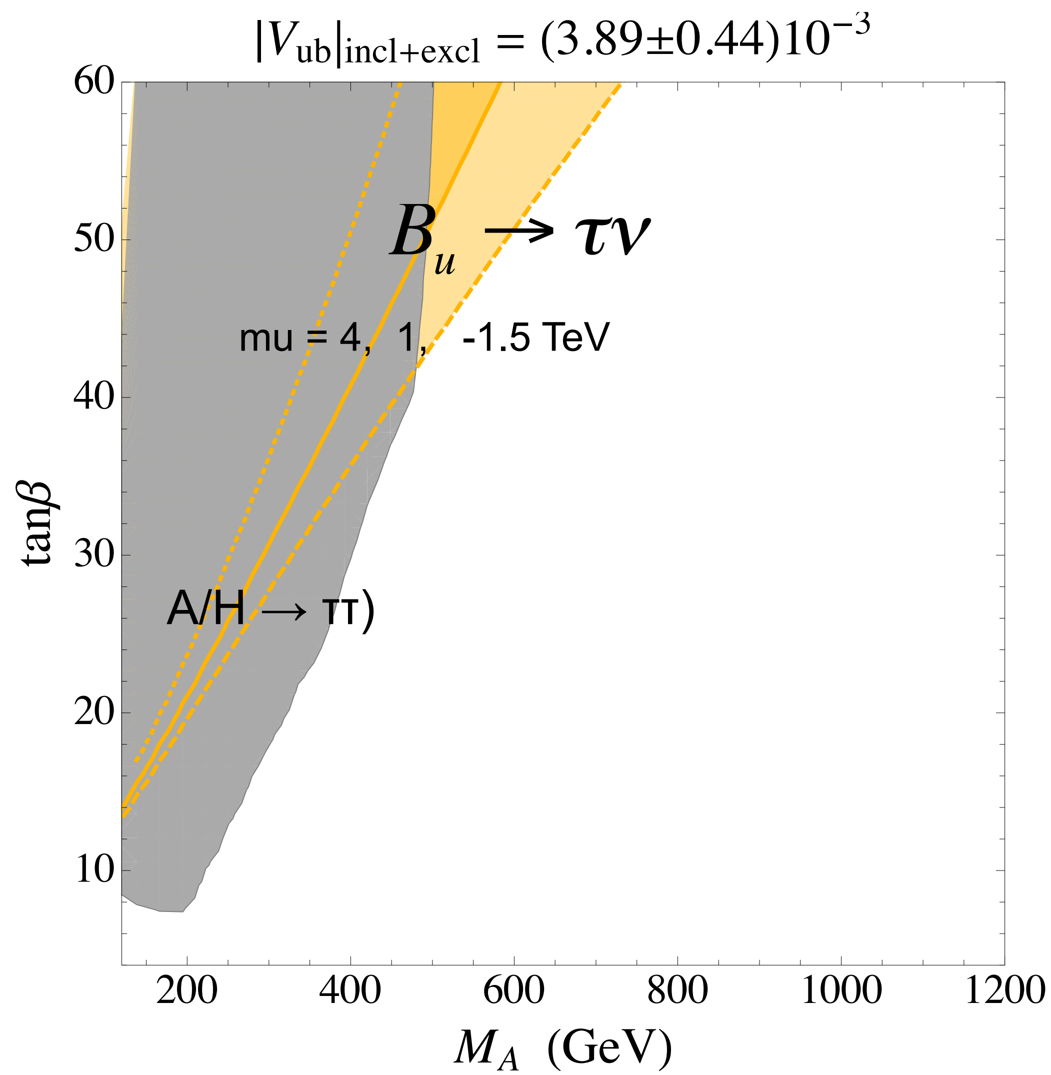
to further advance in our understanding of EWSB

M_h ~ 125 GeV and flavor in the MSSM

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



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



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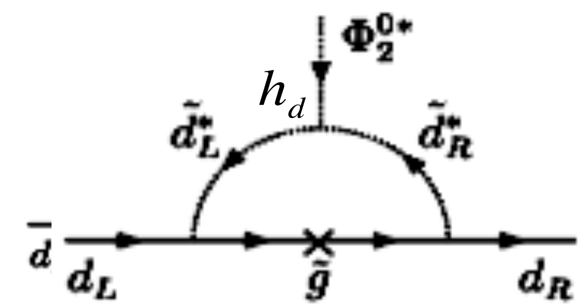
Important radiative corrections

$$\varepsilon_0^i \approx \frac{2\alpha_s}{3\pi}\frac{\mu^* M_{\tilde g}^*}{\max\left[m_{\tilde d_1^i}^2, m_{\tilde d_2^i}^2, M_{\tilde g}^2\right]}$$



ε loop factors intimately connected to the structure of the squark mass matrices

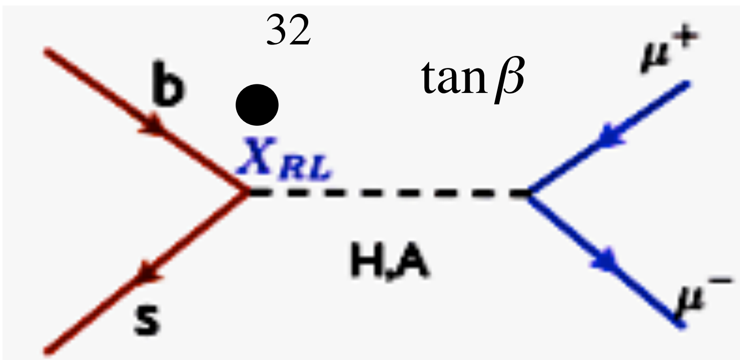
Independent on stop mixing
Almost independent of RG evolution
more powerful than Higgs searches

See Isidori's talk

M_h ~ 125 GeV and Minimal Flavor Violation in the MSSM

•**Loop-induced A/H contributions to** $B_s \to \mu^+\mu^-$

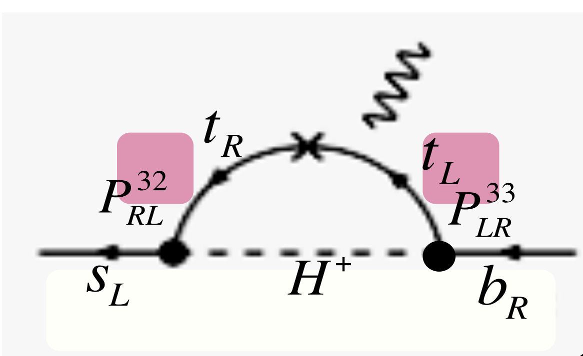
$$BR(B_S \to \mu^+\mu^-)^{SUSY} \propto \frac{\left|X_{RL}^{32}\right|^2 \tan\beta^2}{m_A^4} \propto \frac{\left|\mu A_t\right|^2 \tan\beta^6}{m_A^4}$$



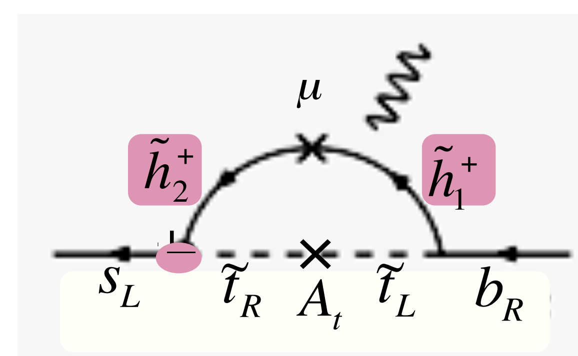
with $$\left(X_{RL}^{H/A}\right)^{bs} \approx -\frac{m_b}{v}\frac{h_t^2\ \varepsilon_Y\ \tan\beta^2}{\left(1+\varepsilon_0^3\tan\beta\right)\left(1+\Delta_b\right)} V_{CKM}^{tb^*} V_{CKM}^{ts}$$

$$\varepsilon_Y \approx \frac{\mu^* A_t^*}{16\pi^2 \max\left[m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2\right]} \qquad \Delta_b = \left(\varepsilon_0^3 + \varepsilon_y h_t^2\right)\tan\beta$$

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



$$\delta h_t \propto h_t \frac{2\alpha_S}{3\pi}\mu^* M_{\tilde{g}}$$



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

$$A_{\chi^+} \propto \frac{\mu A_t \tan\beta\ m_b}{\left(1+\Delta_b\right)} h_t^2 f[m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu]\ V_{ts}$$

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 $M \sim M_{GUT}$**

even starting with universal masses (MFV) in the supersymmetric theory:

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

Due to RG effects:

1) The effective FC strange-bottom-neutral Higgs is modified: $B_s \to \mu^+ \mu^-$

$$\left(X_{RL}^{H/A}\right)^{bs} \approx -\frac{m_b}{v} \frac{(\varepsilon_0^3 - \varepsilon_0^{1,2} + h_t^2 \varepsilon_Y)\ \tan\beta^2}{\left(1+\varepsilon_0^3 \tan\beta\right)\left(1+\Delta_b\right)} V_{CKM}^{tb^*} V_{CKM}^{ts}$$

$\varepsilon_0^3 - \varepsilon_0^{1,2} > 0$ 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 $b \to s\gamma$

$$A_{\tilde{g}} \propto \alpha_S (m_0^2 - m_{Q_3}^2) M_{\tilde{g}} \mu\ \tan\beta\ F(m_0, m_R, m_{\tilde{b}_i}, m_{\tilde{d}_i}, M_{\tilde{g}})$$

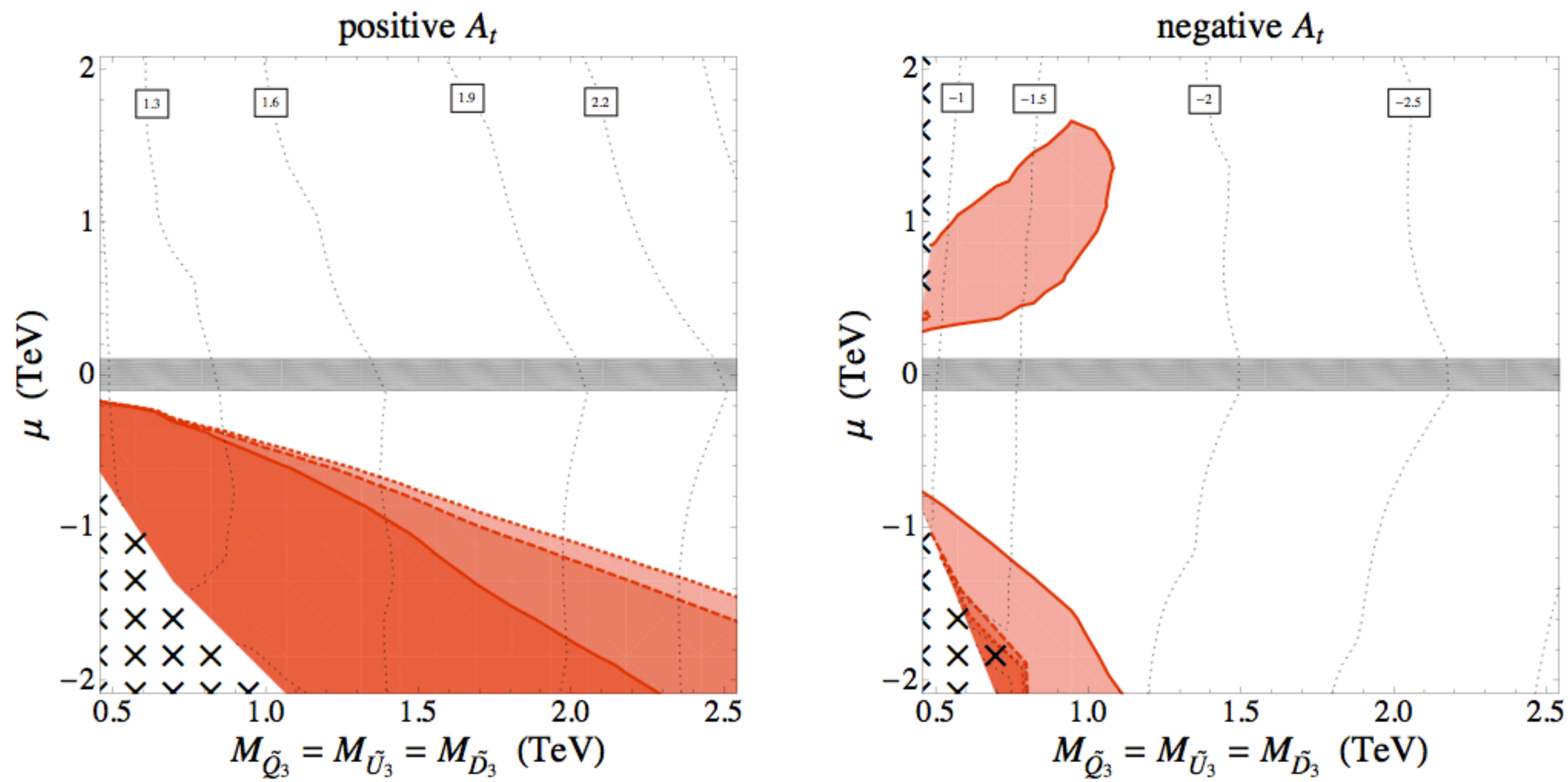
Borzumati, Bertolini, Masiero,Ridolfi

- **If ~~SUSY~~ is transmitted at low energies: $M \sim M_{SUSY}$**

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

M_h ~ 125 GeV and flavor in the MSSM

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



tan beta=20 M_A=400 GeV

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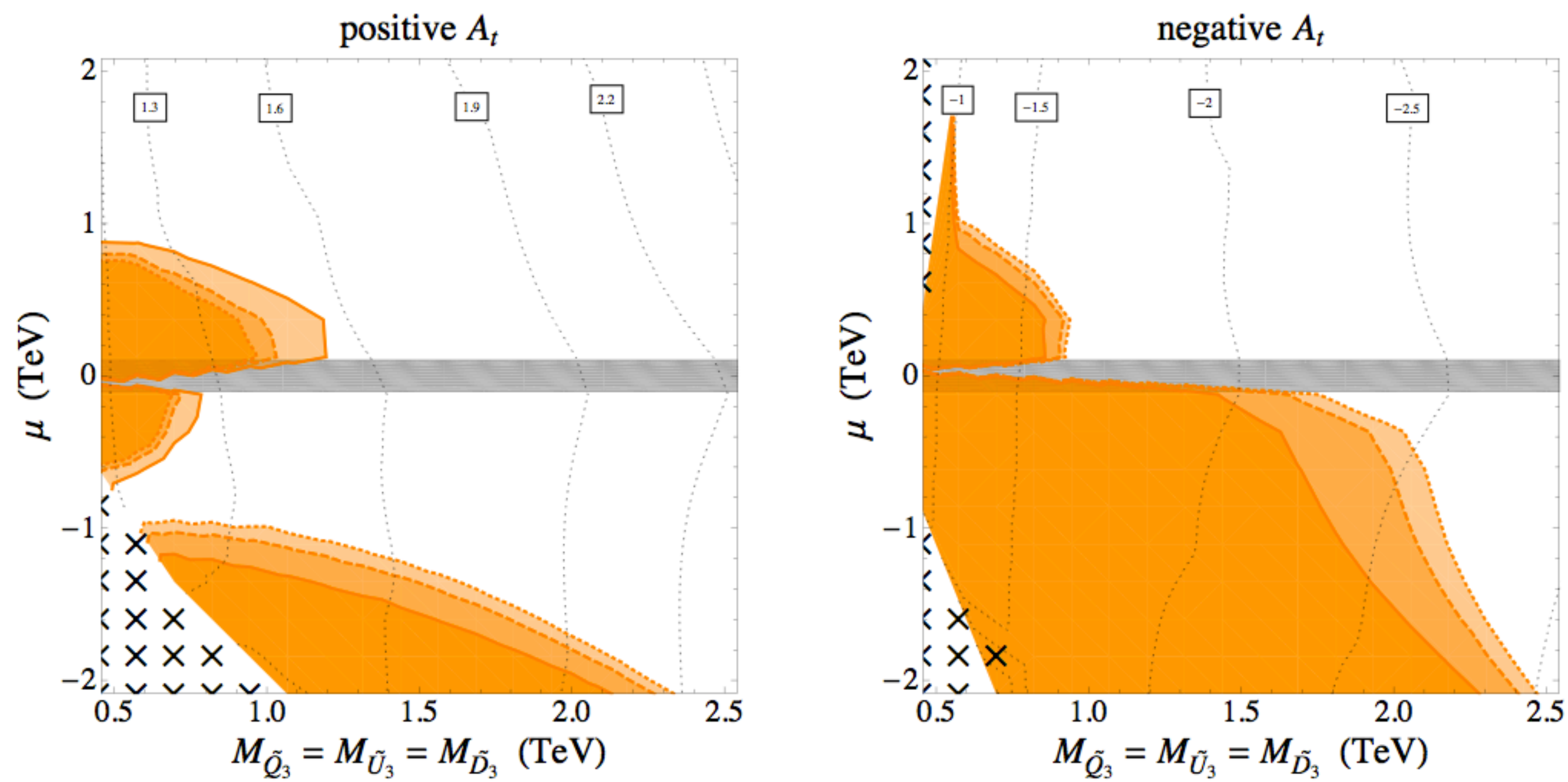
Red solid line: $B_s \to mu^+mu^-$ with low energy SUSY breaking effects
Red dashed (dotted) line has 25% (50%) splitting from RG

M_h ~ 125 GeV and flavor in the MSSM

Low Energy Vs High Energy SUSY breaking effects on B →X_s gamma



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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