Electroweak Symmetry Breaking, the Higgs Mass and the New Era of Physics

Marcela Carena
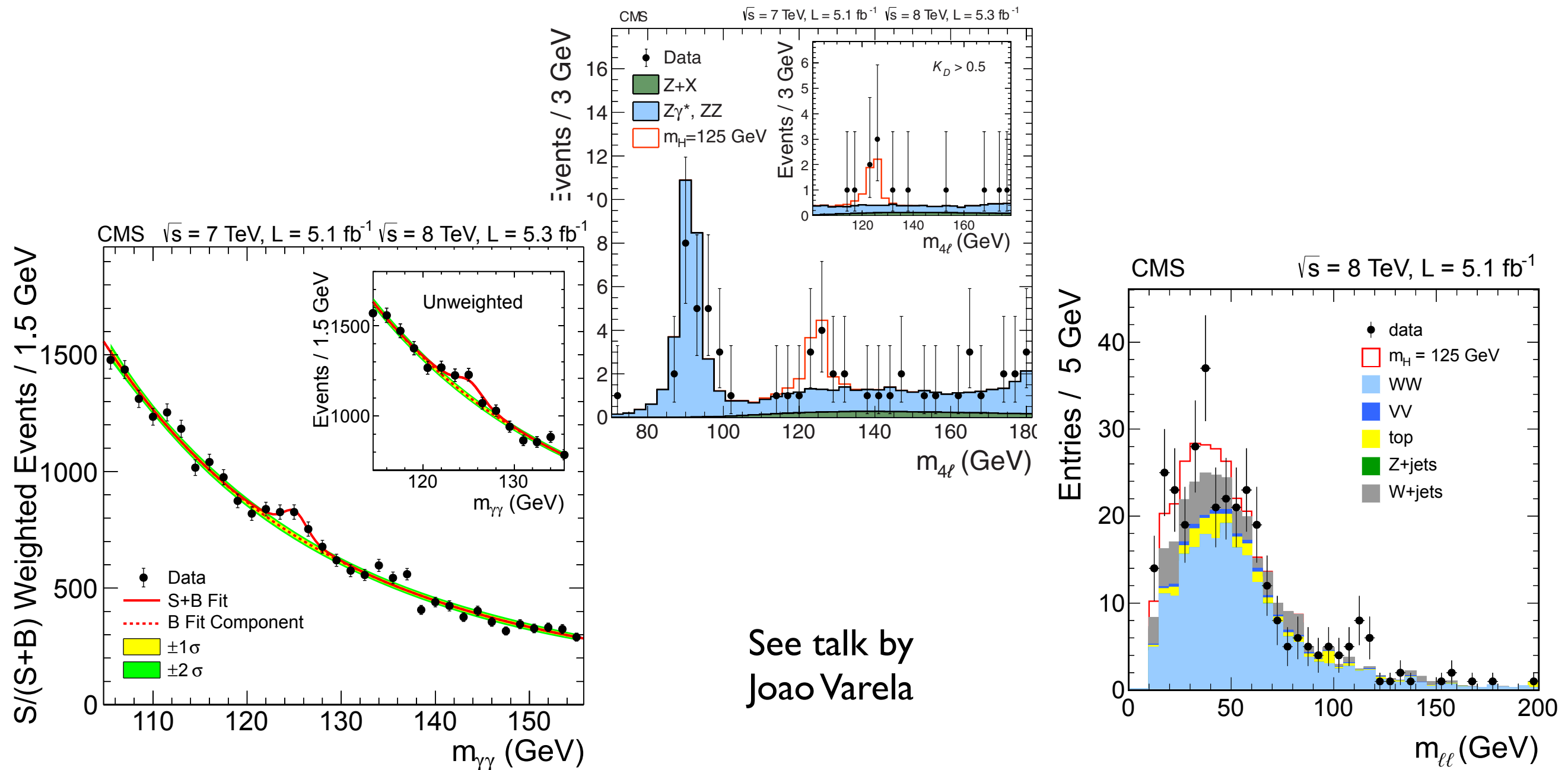### Fermilab and U. of Chicago.

US LHC Users Organization Annual Meeting
Fermilab, October 19, 2012

The LHC experiments have discovered a new particle

- **The evidence is strong that the new particle decays to γγ, ZZ and WW with rates roughly consistent with those predicted for the SM Higgs boson.**
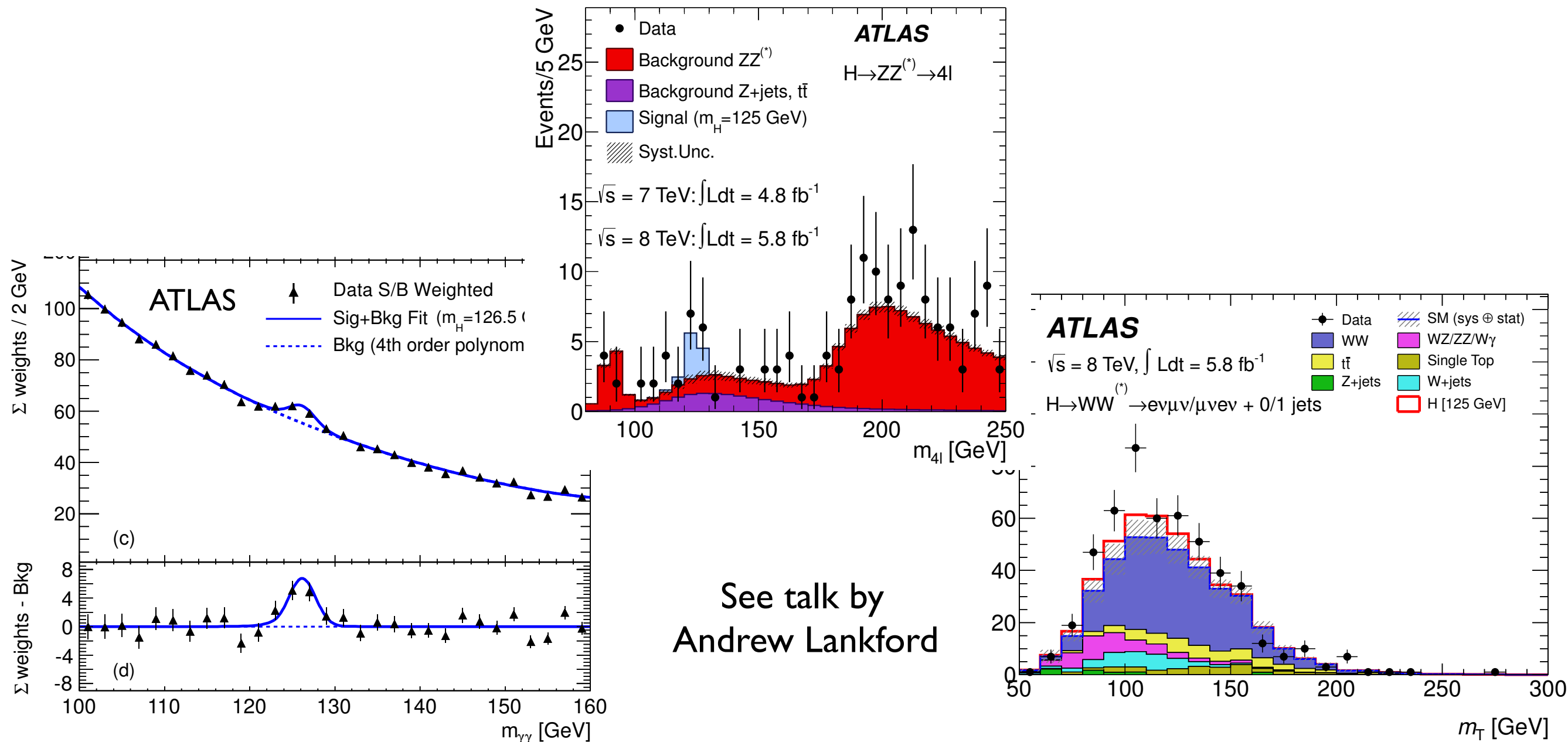

See talk by
Joao Varela

- **The observed decay modes indicate that the new particle is a boson.**

eriments have discovered a new particle

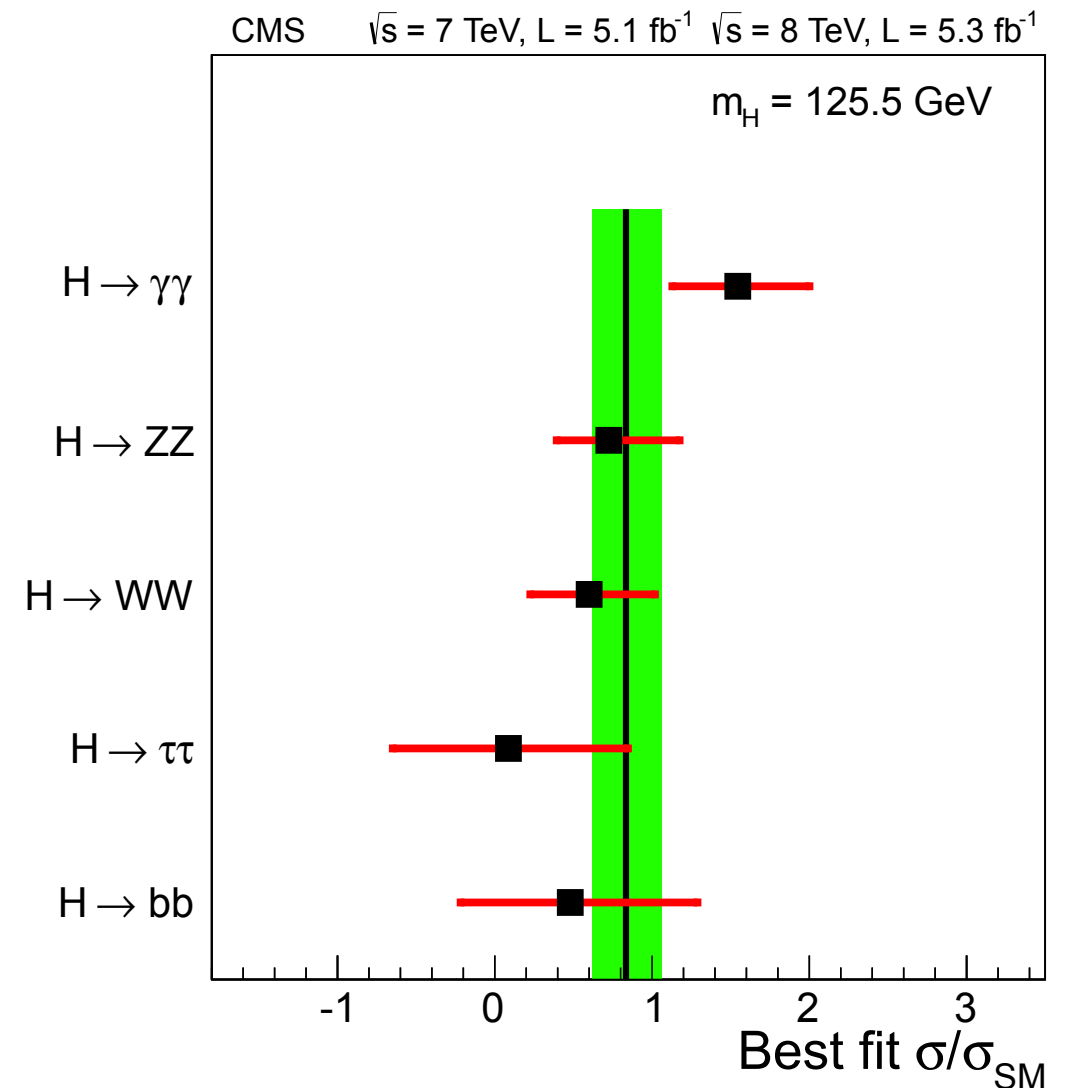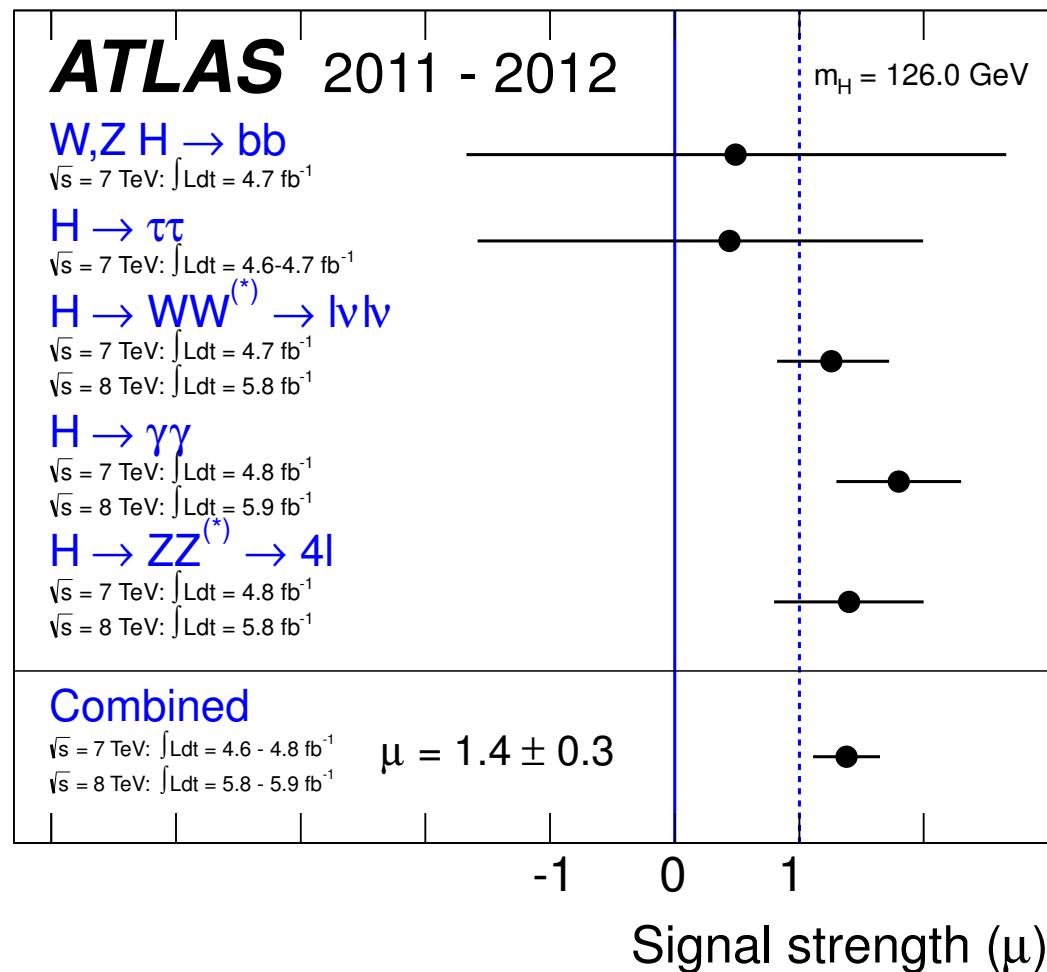**...ong that the new particle decays to γγ, ZZ and WW with rates roughly consistent with those predicted for the SM Higgs boson.**

See talk by
Andrew Lankford

- **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 the SM

However
A di-photon rate enhancement is the most visible feature at both experiments.
The WW/ZZ rates in average are at the SM value
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
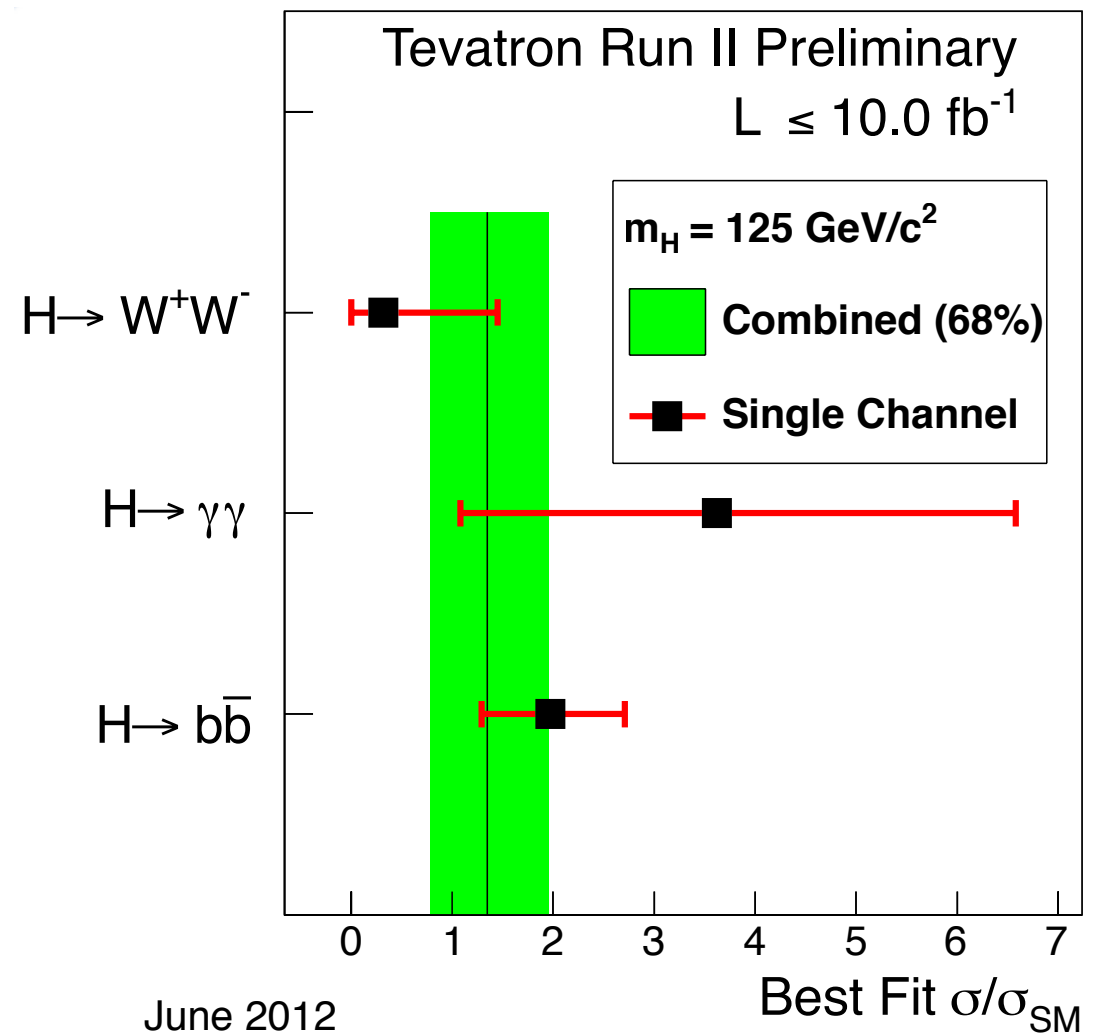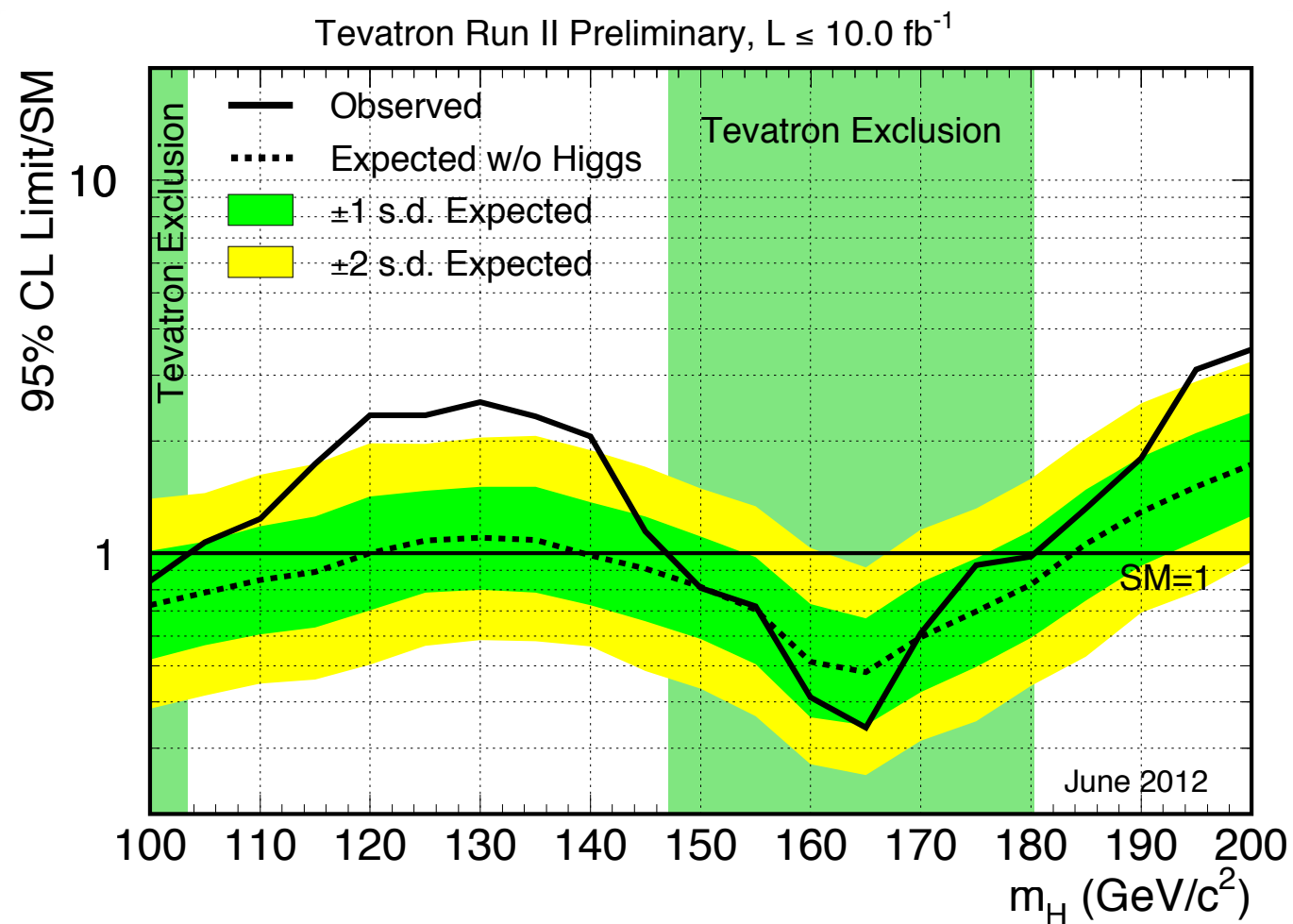
For a Higgs mass of 125 GeV, the **combined** production rates
are consistent with the SM ones within 1σ,
but the bb rate appears to be enhanced

The Higgs Discovery puts the final piece of the Standard Model in place

and marks the birth of the hierarchy problem: one of the main motivations for physics beyond the SM

The SM works beautifully, explaining all experimental phenomena to date with great precision no compelling hints for deviations

But many questions remain unanswered:

Dynamical Origin of electroweak symmetry breaking

Origin of generations and structure of Yukawa interactions

Matter-antimatter asymmetry

Unification of forces

Neutrino masses

Dark matter and dark energy

Hence, the "prejudice" (the hope) that there must be "New Physics"

The Higgs naturalness or hierarchy problem: $\text{Why } v \ll M_{Pl}?$

$\Lambda_{eff.}$

$$V(\Phi) = m^2\,\Phi^\dagger\Phi + \frac{\lambda}{2}\left(\Phi^\dagger\Phi\right)^2 \qquad m^2 < 0$$

The Higgs mass parameter
$\Lambda_{eff.}$

$|m|^2 = 2\,\lambda\,v^2 = 1/2\,m_h^2$

has maximum sensitivity to the unknown UV physics $\mu_{eff.}^2 \; v^2 = |\mu|^2/2\lambda$

Quantum corrections diverge quadratically with the scale of new physics : Λ_{eff}

μ^2

$$m^2 = m^2(\Lambda_{eff.}) + \Delta m^2$$

$_{eff.}) + \Delta\mu^2$

$$\to \Delta m^2 \approx \frac{n_W\,g_{hWW}^2 + n_h\,\lambda\; - n_f\,g_h^2 ff}{16\pi^2}\,\Lambda_{eff}^2 \quad \mu \qquad v^2 = |\mu|^2/2\lambda$$

$,,^2$

$O(m_W)$

$$\mu^2 = \mu \qquad \frac{\lambda^2 - n_f g_{hf\bar f}^2}{\tau^2}\Lambda^2{}_{eff.}$$
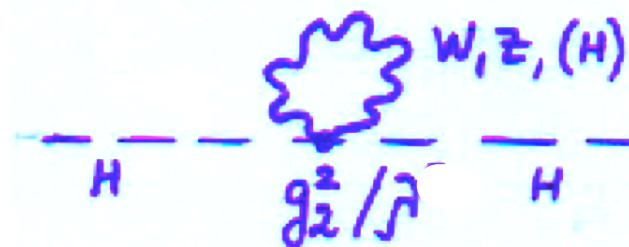
to explain $v \approx O(m_W)$ either New Physics at the TeV scale

$\Lambda_{eff.} \leq$ **or fine tuning to achieve cancellation**

The Higgs naturalness or hierarchy problem: Why $v \ll M_{Pl}$?

New Degrees of freedom at a scale ~ TeV that
through symmetry conditions identify couplings and degrees of freedom
of the SM particles with those of new particles, and
allow the automatic cancellation of loop corrections to the Higgs mass parameter

Example:
Supersymmetry is a symmetry between bosons and fermions
that ensures the equality of couplings (and masses)

The Higgs is not a fundamental scalar but rather a composite state
- QCD-like technicolor, top-condensate/top color, Little Higgs, Gauge-Higgs Unification...-

Possible realization: theories of **Warped Extra Dimensions** in which
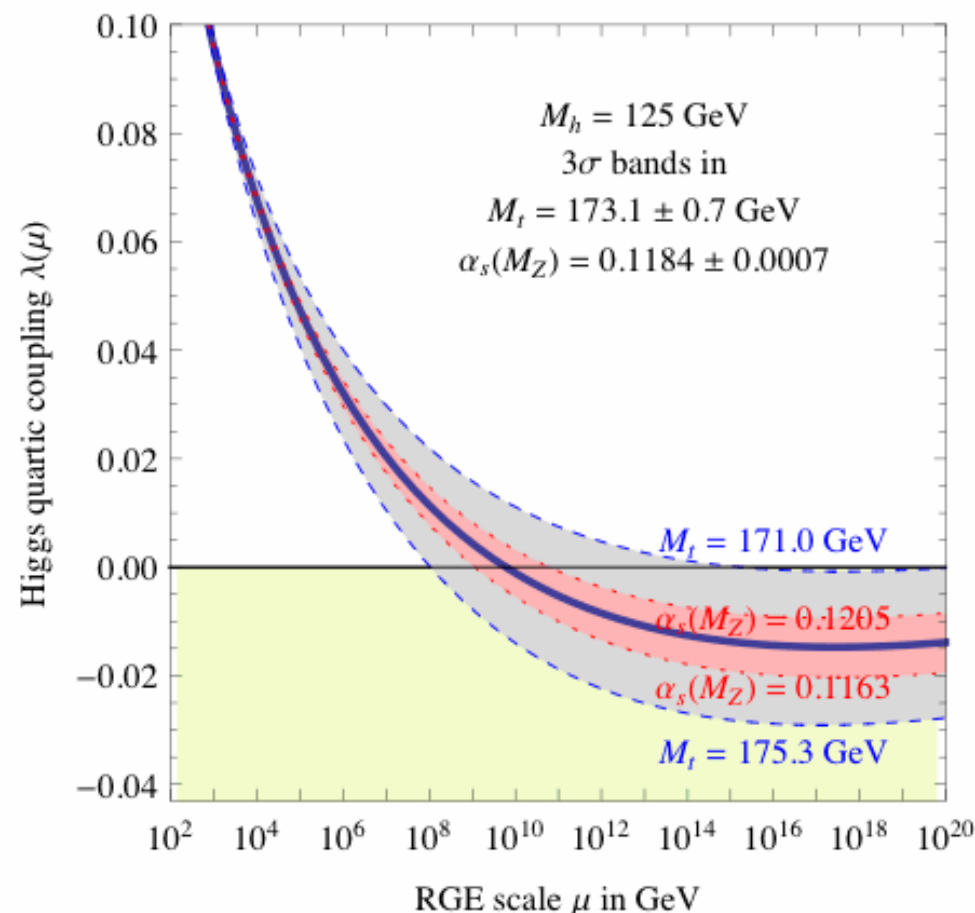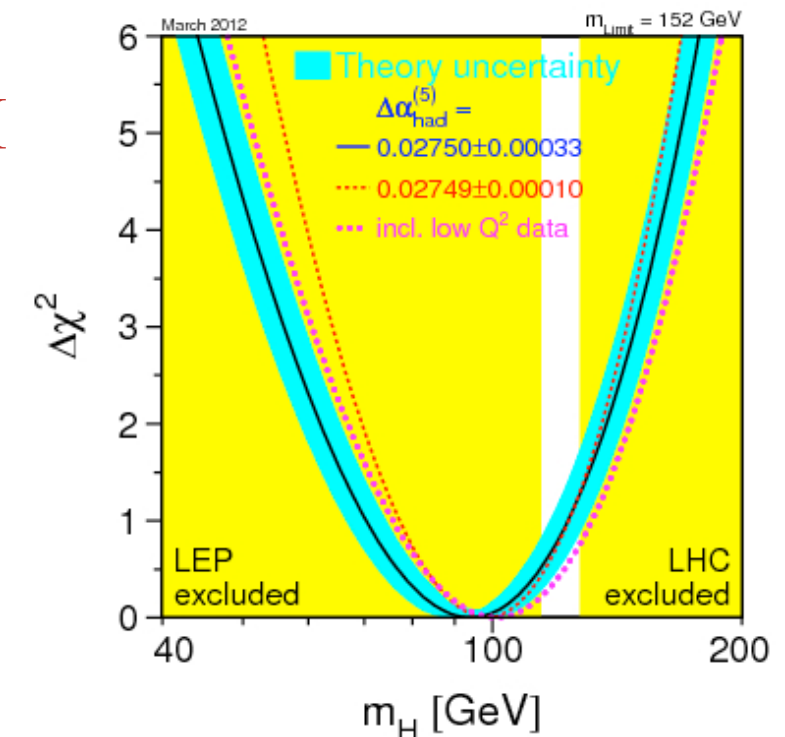the **fundamental** Planck scale ~ $v \ll M_{Pl}$.

A SM-like Higgs mass in the range 124-127 GeV

Is in good agreement with Higgs mass expectations from indirect Precision Electroweak Observables within the SM
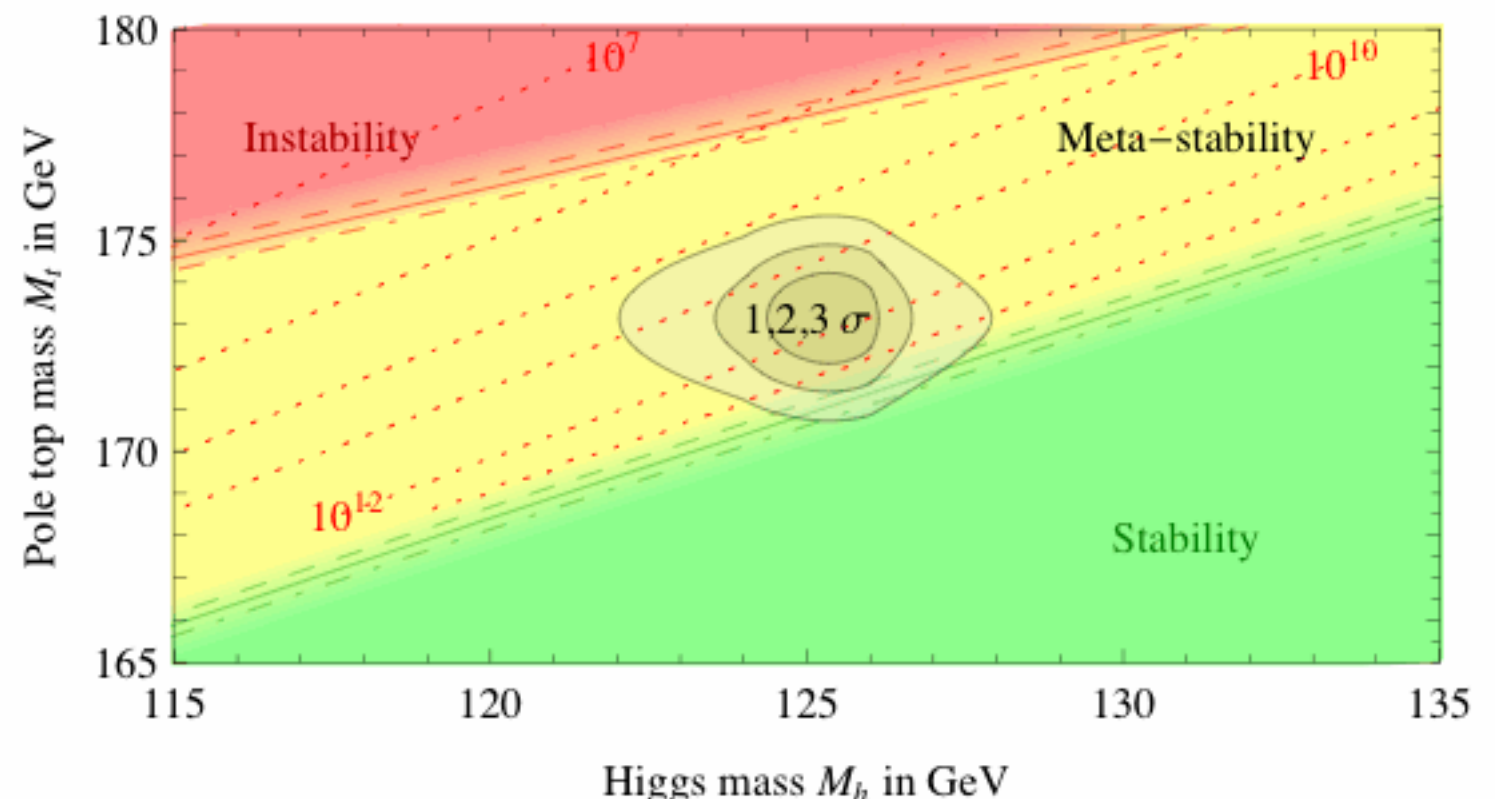
Preferred value: $M_H = 94^{+29}_{-24}$ GeV

but
The stability of our universe prefers new physics at a scale below M_{Pl}.

Degrassi et al, '12; Berzukov et al '12

What if the newly discovered particle is not the SM Higgs?

- it can still be the Higgs boson of EWSB -

The SM Higgs Boson:

Spin 0

Neutral CP even component of a complex $SU(2)_L$ doublet with Y=1

Singlet under the residual SU(2) custodial symmetry after EWSB

==> $g_{WWH}/g_{ZZH} = m_W^2/m_Z^2$ at tree level

Couplings to SM fermions proportional to fermion masses

Self-coupling strength determined in terms of its mass and v = 174 GeV

A *SM-like* Higgs Boson:

Could be a mixture of CP even and CP odd states

Could have non-SM couplings to vector bosons and fermions

==> non-SM decay widths and production cross sections in many/all channels

Could have decays into new particles

Could be partly singlet or triplet instead of an $SU(2)_L$ doublet ?

Could be composite

Effective Theory Analyses

Chiral Lagrangian for a light Higgs-like scalar

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 \ldots$$

$$- \left(m_W^2 W_\mu^+ W_\mu^- + \frac{1}{2}m_Z^2 Z_\mu Z_\mu\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right)$$

$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}} \bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + c_{2\psi}\frac{h^2}{v^2} + \ldots\right)$$

$$+ \frac{g^2}{16\pi^2}\left(c_{WW} W_{\mu\nu}^+ W_{\mu\nu}^- + c_{ZZ} Z_{\mu\nu}^2 + c_{Z\gamma} Z_{\mu\nu}\gamma_{\mu\nu}\right)\frac{h}{v} + \ldots$$
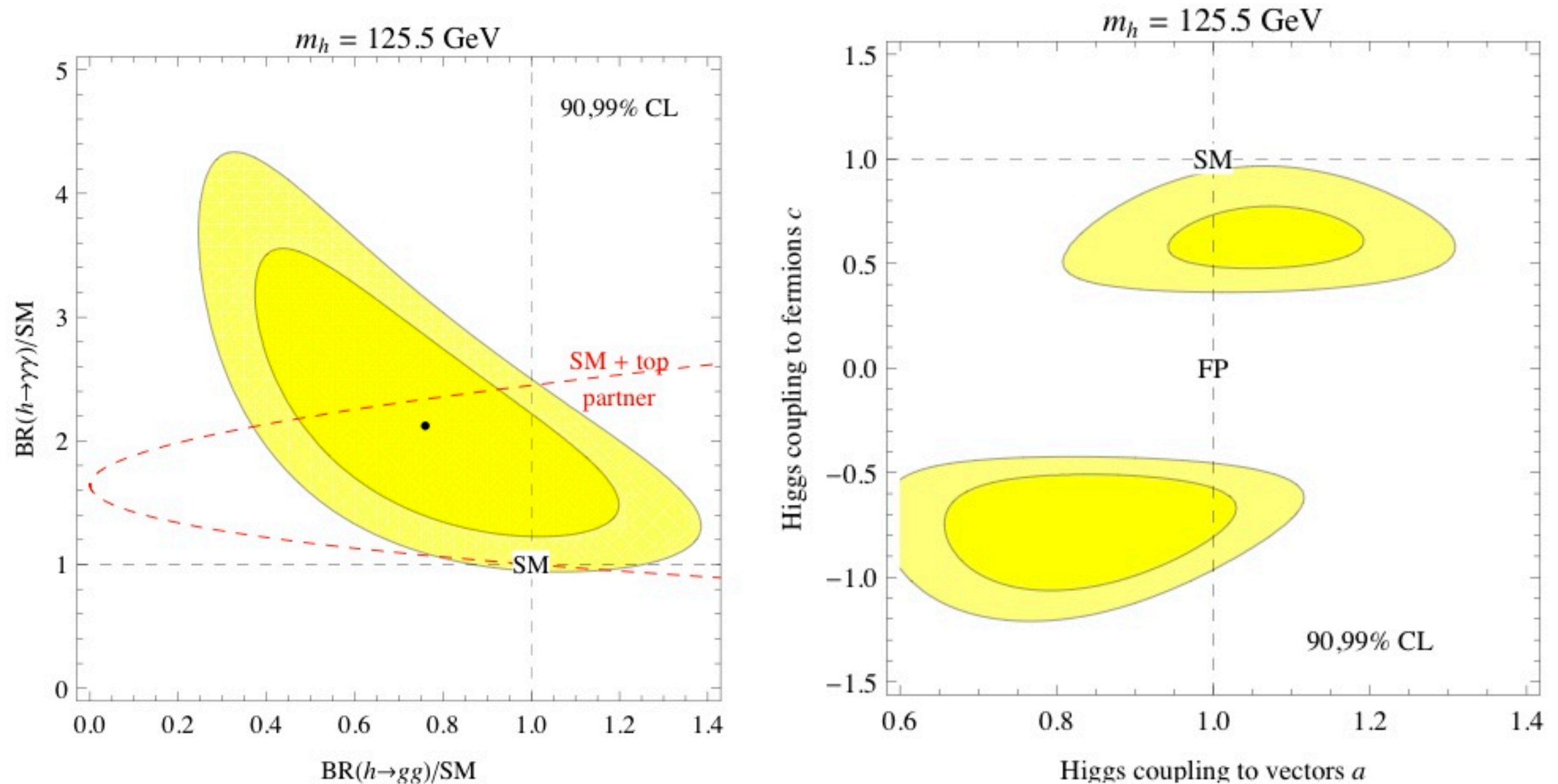
$$+ \frac{g^2}{16\pi^2}\left[\gamma_{\mu\nu}^2\left(c_{\gamma\gamma}\frac{h}{v} + \ldots\right) + G_{\mu\nu}^2\left(c_{gg}\frac{h}{v} + c_{2gg}\frac{h^2}{v^2}\ldots\right)\right]$$

$$+ \ldots$$

} dimension 6 operators

Contino et al '10

In the SM

a=b=c=d₃=d₄=1

$a = b = c = d_3 = d_4 = 1$

$c_{2\psi} = c_{WW} = c_{ZZ} = c_{Z\gamma} = c_{\gamma\gamma} = \ldots = 0$

all the rest = 0

linear realization of the SU(2)_L x U(1)_Y impose relations among coefficients

$$+ \frac{g^2}{16\pi^2}\left[\frac{c_{hhgg}}{\Lambda^2}G_{\mu\nu}^2\frac{(\partial_\rho h)^2}{v^2} + \frac{c_{hhgg}}{\Lambda^2}G_{\mu\rho}G_{\rho\nu}\frac{\partial_\mu h\partial_\nu h}{v^2}\right] + \ldots$$

Many recent studies consider effective theory approaches and investigate the best fit to the data in a model independent way
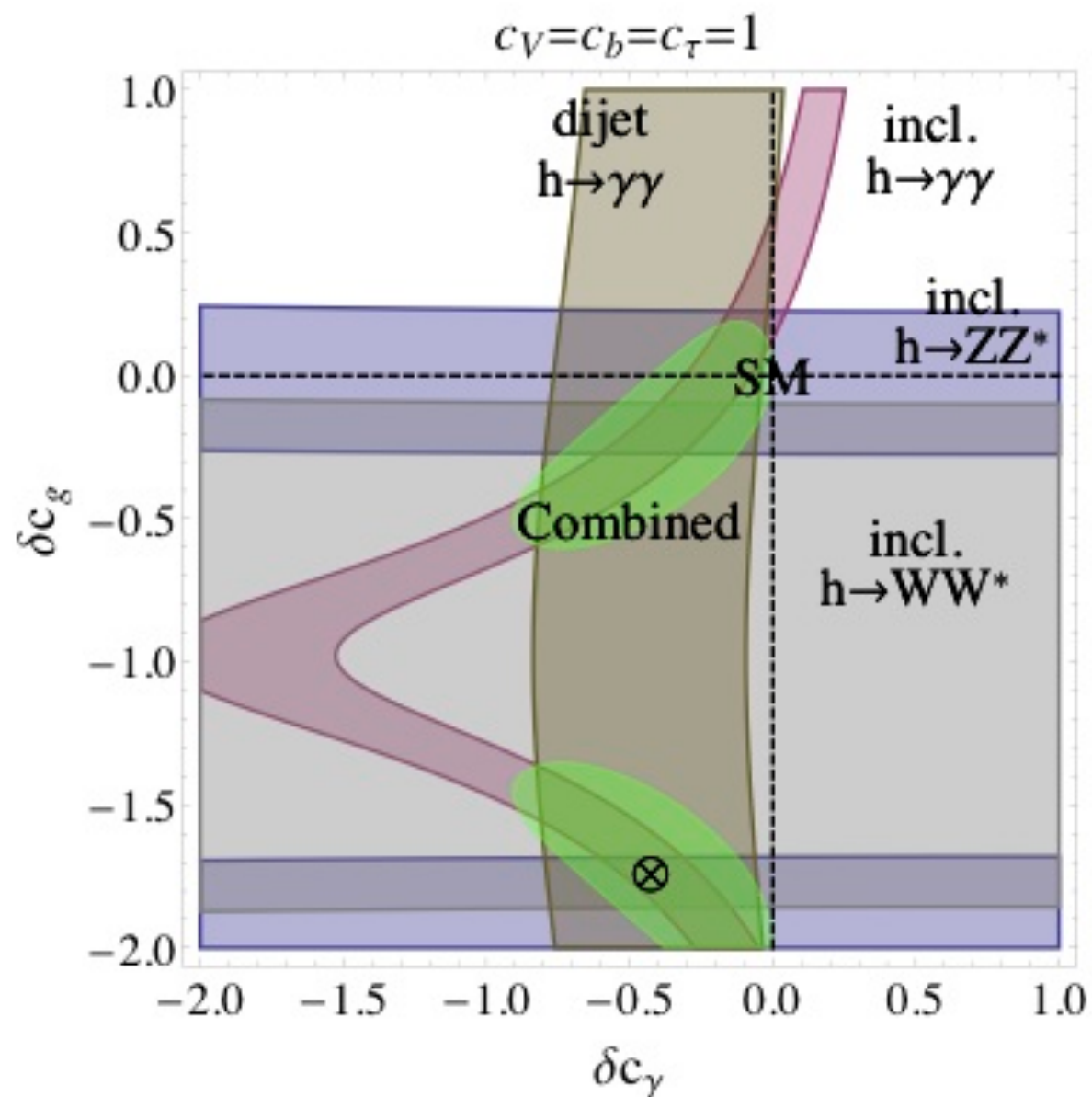

1 σ Preference for enhancement of diphoton width, with or without small suppression of gluon width.
(results from Mid-July'12)

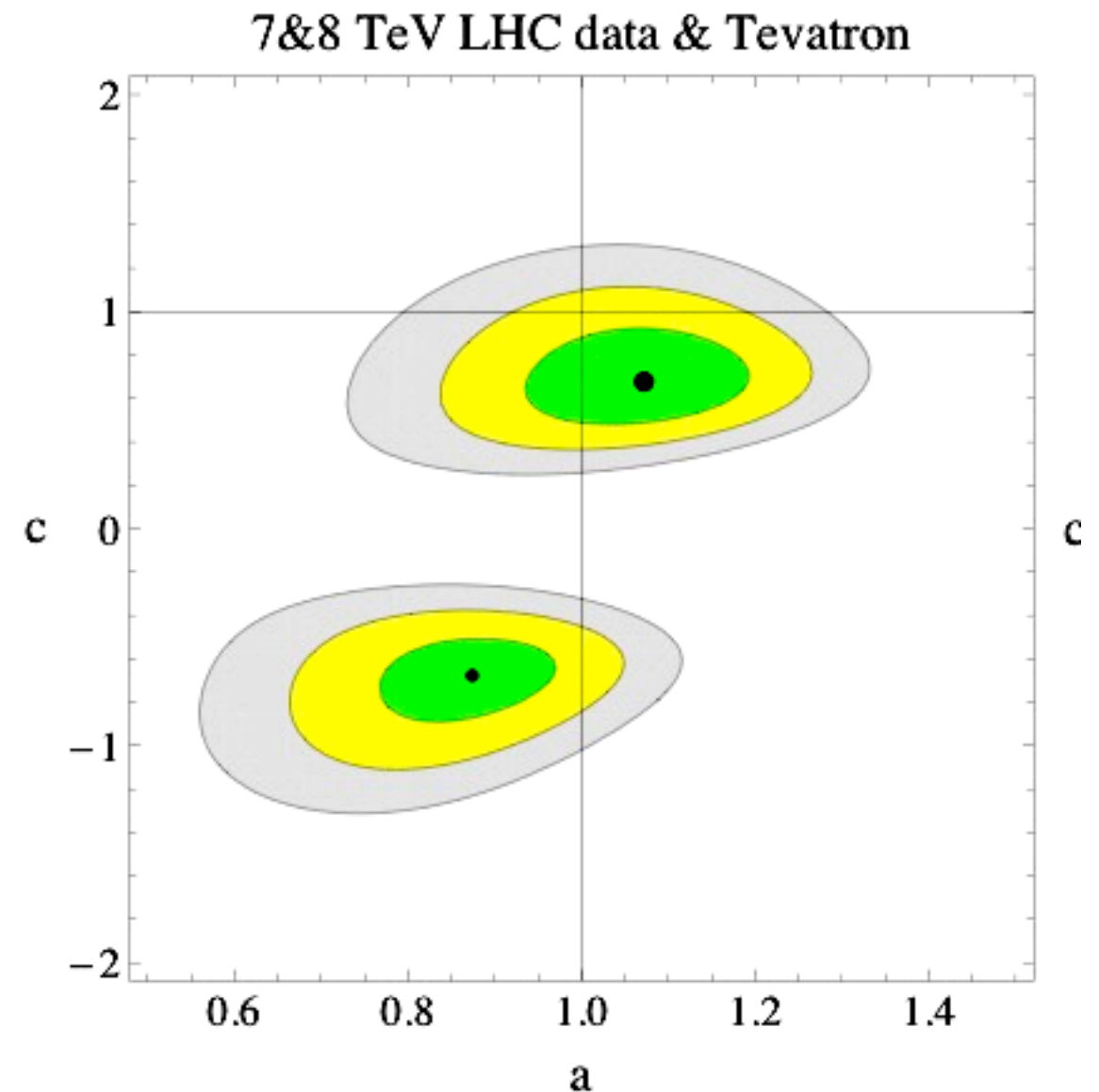Giardino, Kannike, Raidal, Strumia
arXiv:1207.1347

Many recent studies consider effective theory approaches and investigate the best fit to the data in a model independent way

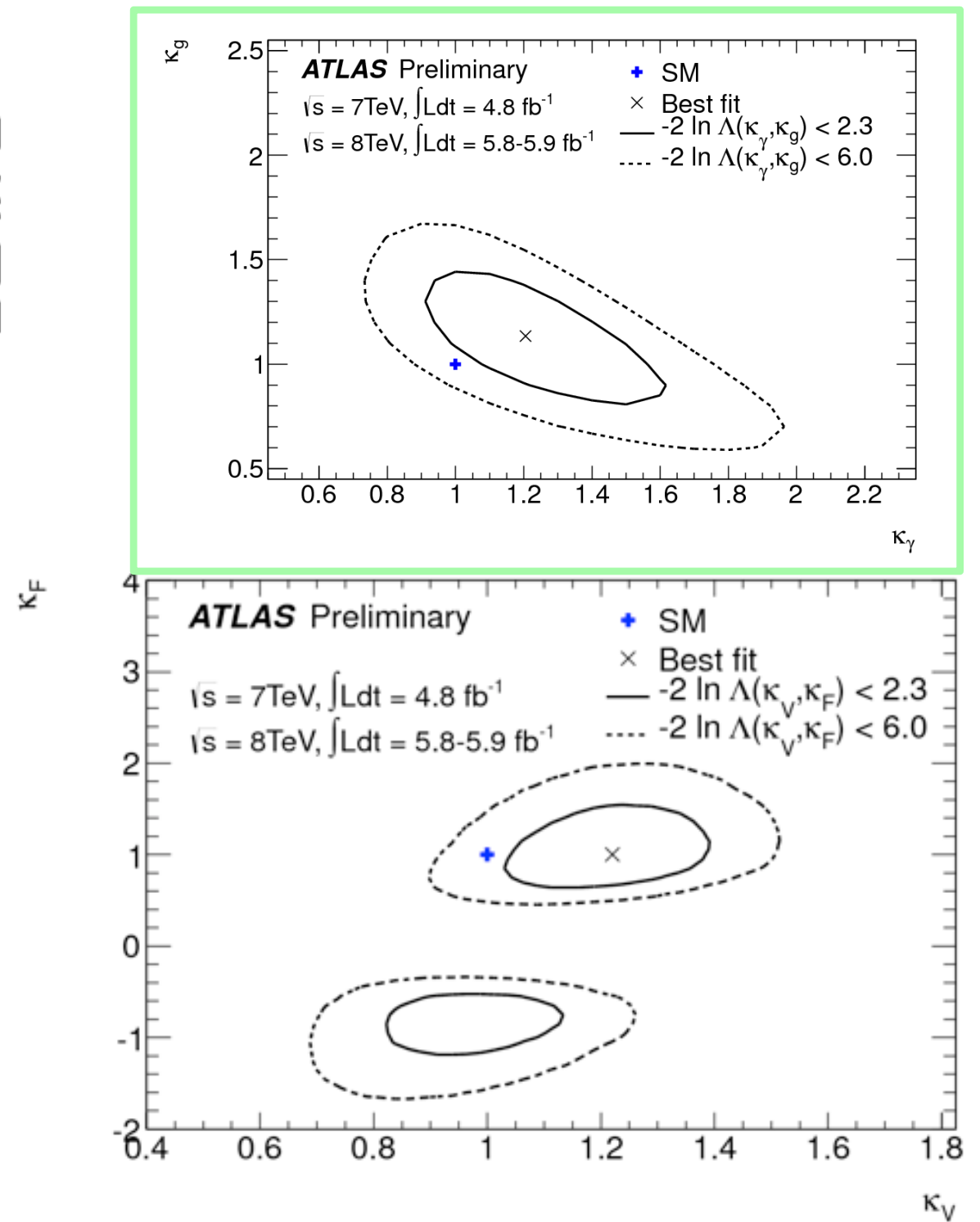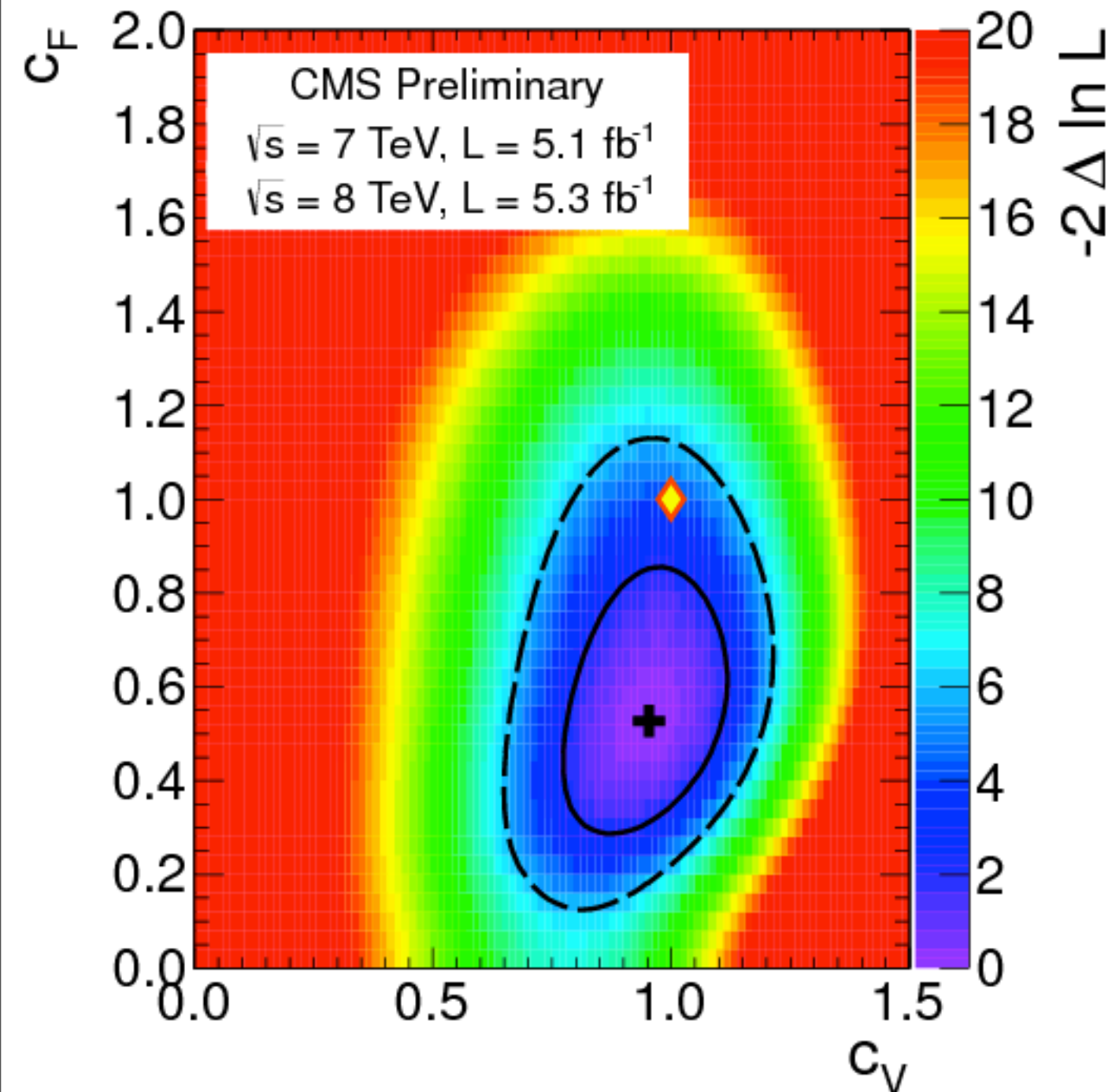Carmi, Falkowski, Kuflik, Volansky, Zupan, arXiv:1207.1718

Espinosa, Grojean, Muhlleitner, Trott, arXiv:1207.1717

Similar analyses by Corbet, Eboli, Gonzalez-Fraile, Gonzalez Garcia '12; Montul, Riva '12

Fit to two parameter space couplings by CMS and ATLAS

Official results differ in each experiment due to different results in WW/ZZ/di-taus

What does a 125 GeV Higgs mean
for specific 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?

What about the Higgs in Supersymmetry?

- **Minimal** Higgs Sector: Two Higgs doublets

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

$$\tan\beta = v_2 / v_1$$

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

- 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

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t\,X_t \\ m_t\,X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

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

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

$$t = \log(M_{SUSY}^2/m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12M_{SUSY}^2}\right) \qquad X_t = A_t - \mu/\tan\beta \rightarrow \text{LR stop mixing}$$
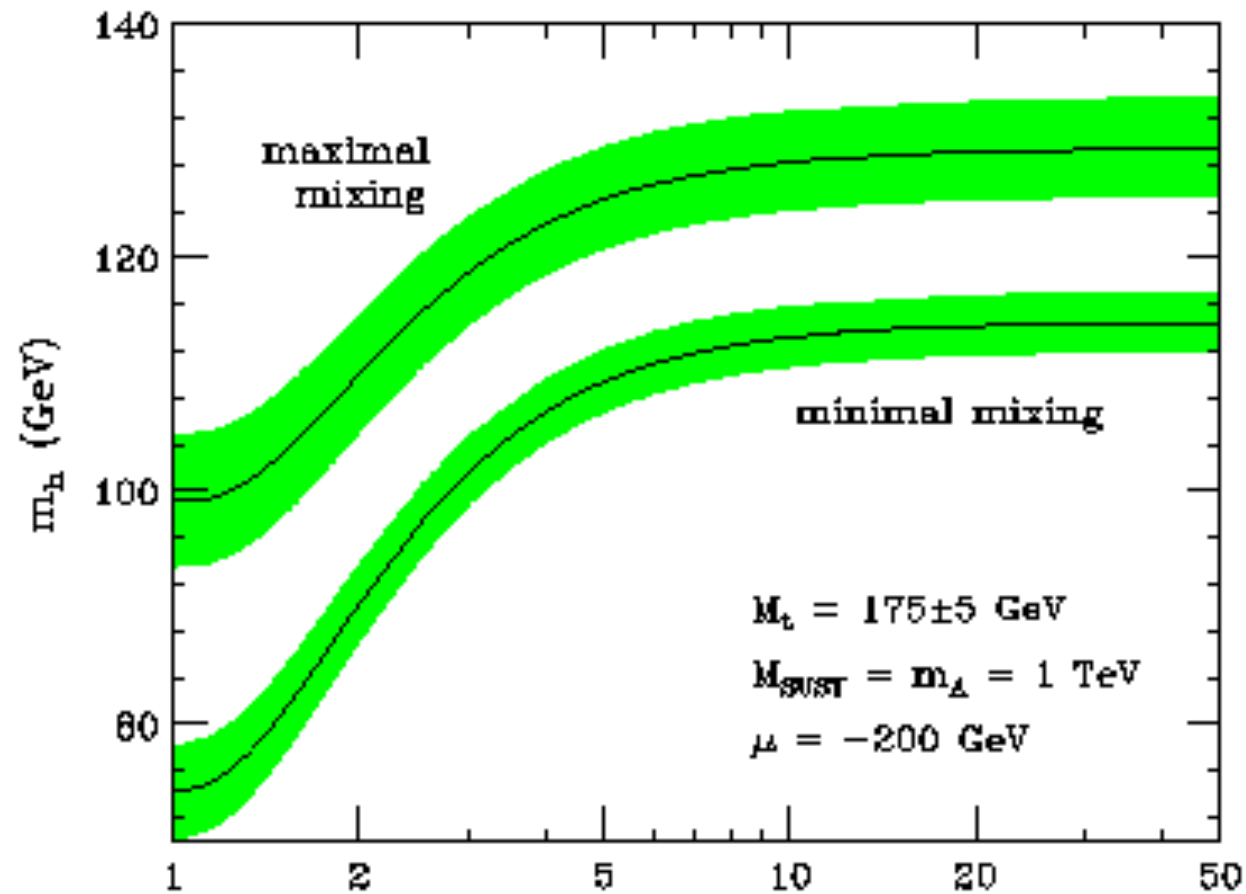
$M_{SUSY} \sim m_Q \sim m_U$
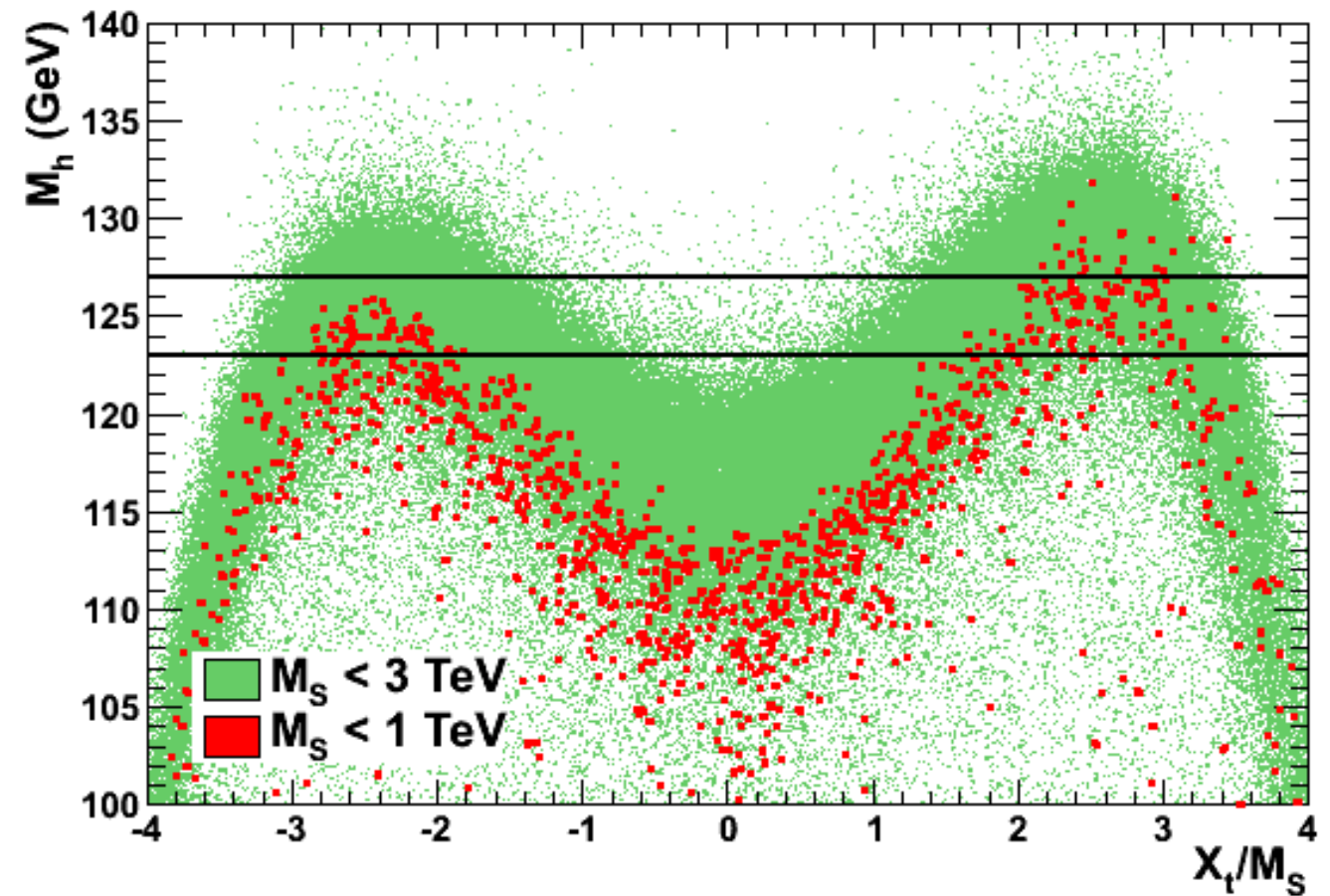
M.C. Espinosa, Quiros, Wagner '95; M.C. Quiros, Wagner '95

Additionl NEGATIVE contributions from light sbottoms/staus at large tan beta
$\longrightarrow$ can lower m_h by several GeV

SM-like MSSM Higgs Mass:

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

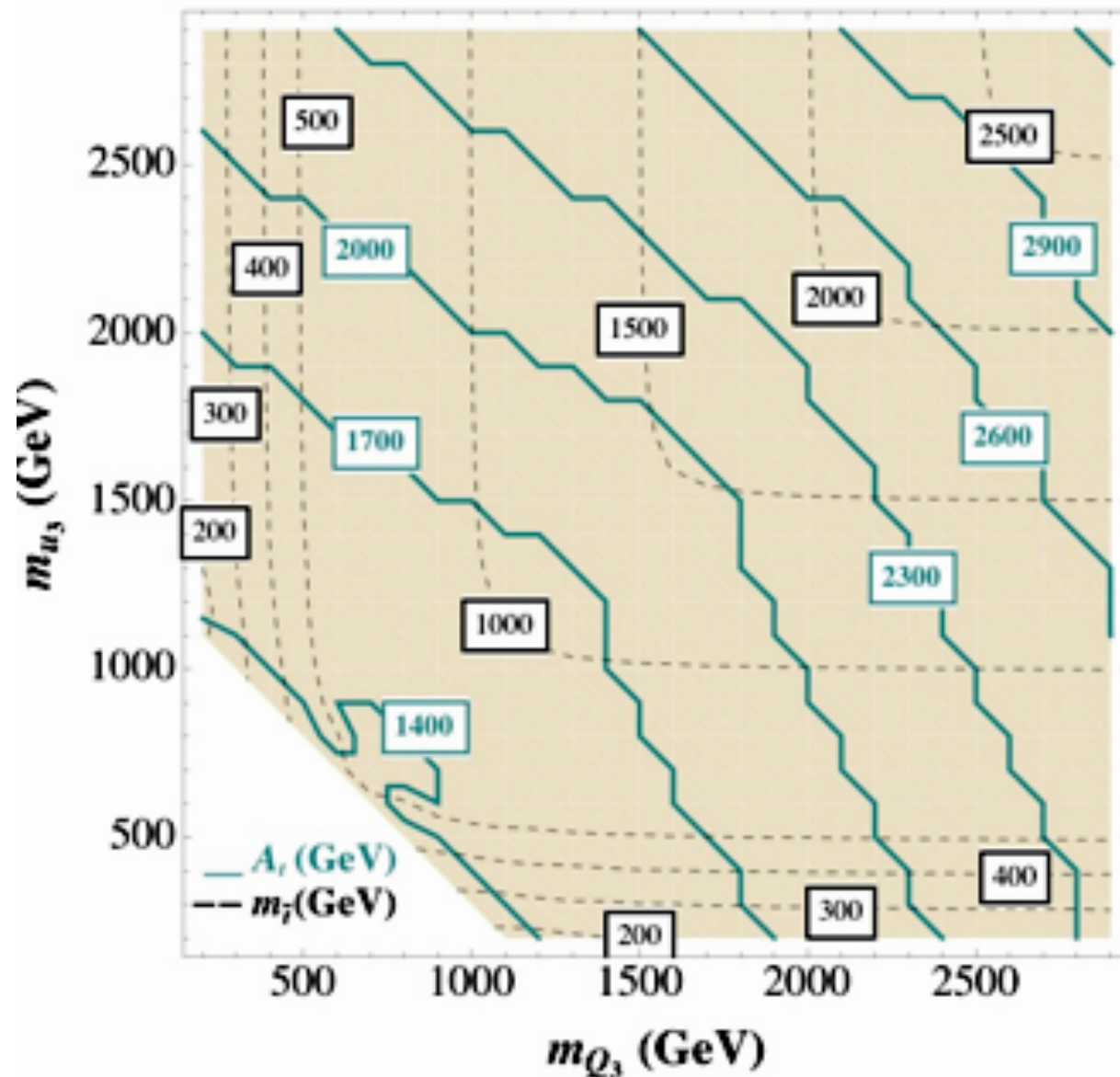Arbeya, Battaglia, Djouadi, Mahmoudi, Quevillon'11

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

(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

A_t and $m_{\tilde{t}}$ for 124 GeV < m_h < 126 GeV and Tan β = 60

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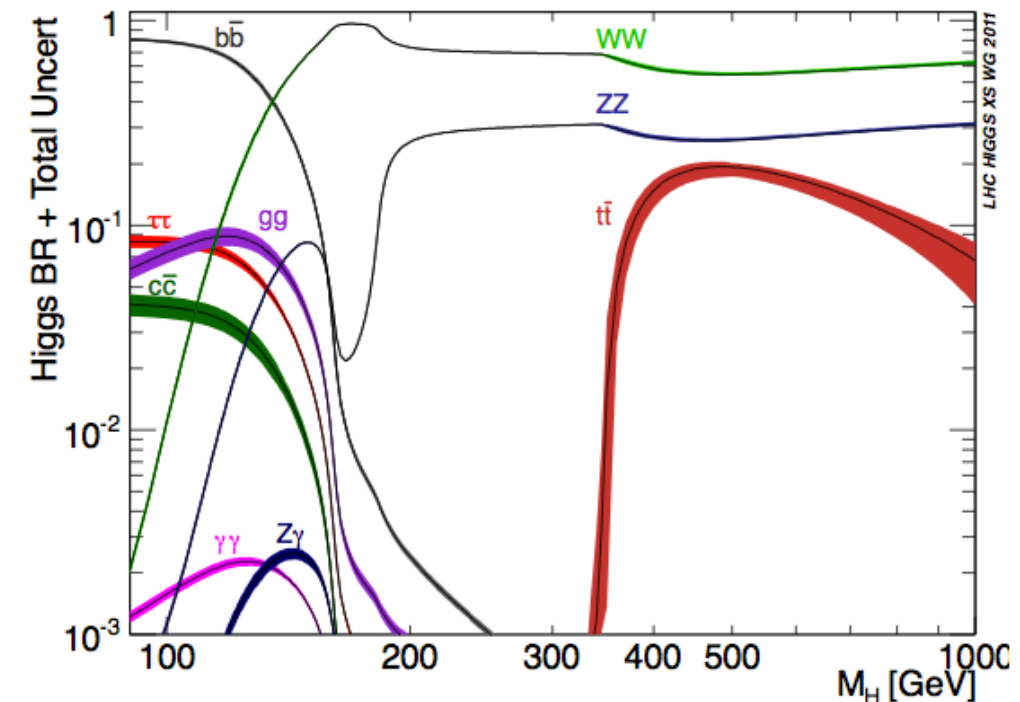
The event rates: $$B\sigma(p\bar{p} \to h \to X_{\rm SM}) \equiv \sigma(p\bar{p} \to h)\frac{\Gamma(h \to X_{\rm SM})}{\Gamma_{\rm total}}$$

- All three quantities may be affected by new physics.
- If one partial width is modified, the total width is modified as well, modifying all BR's.
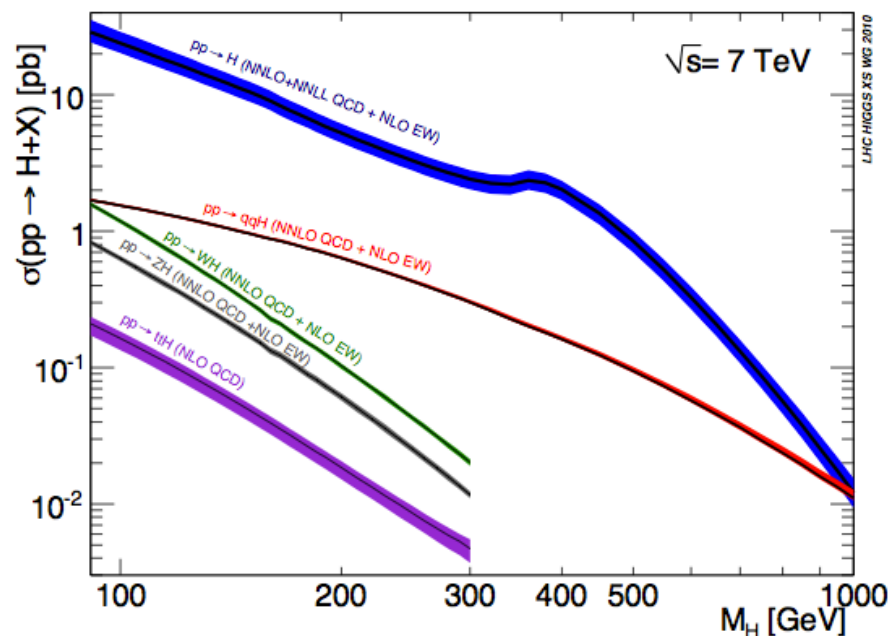
Main production channel: Gluon Fusion

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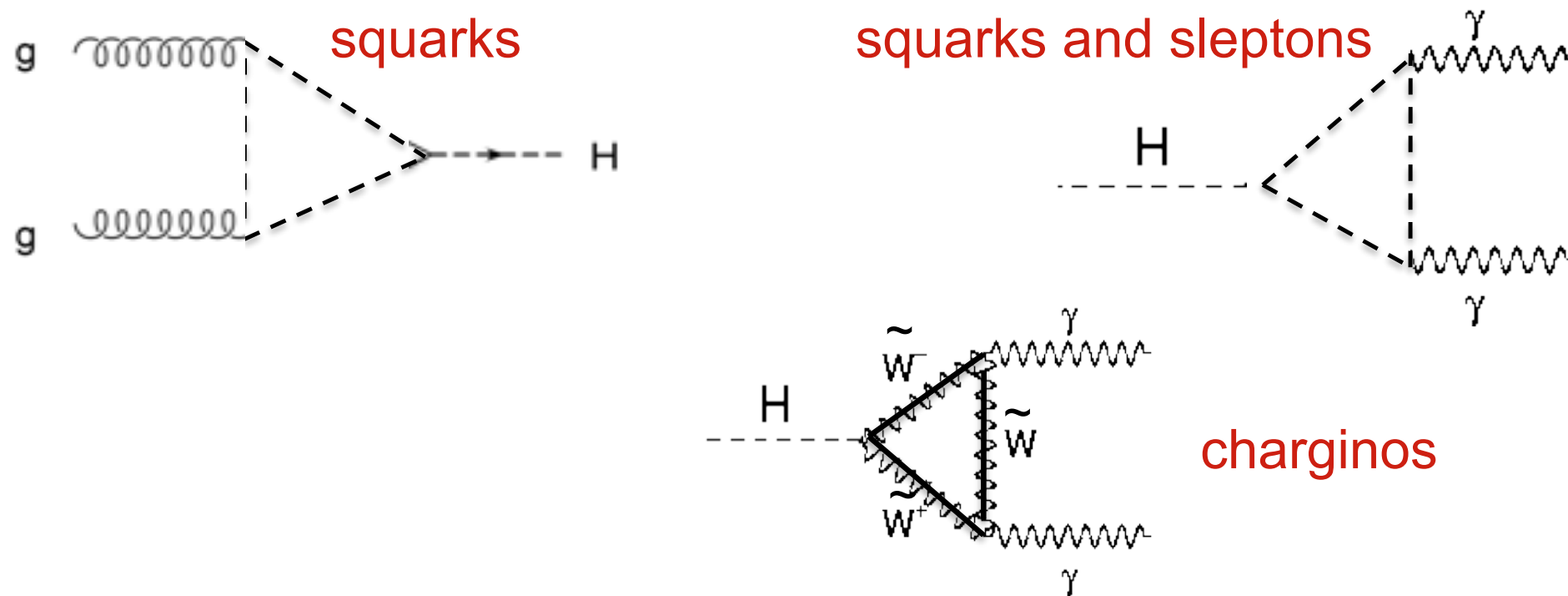
◆ Through enhancement/suppression of the Higgs-bb and Higgs-di-tau
coupling strength via mixing in the Higgs sector :
This affects in similar manner BR's into all other particles

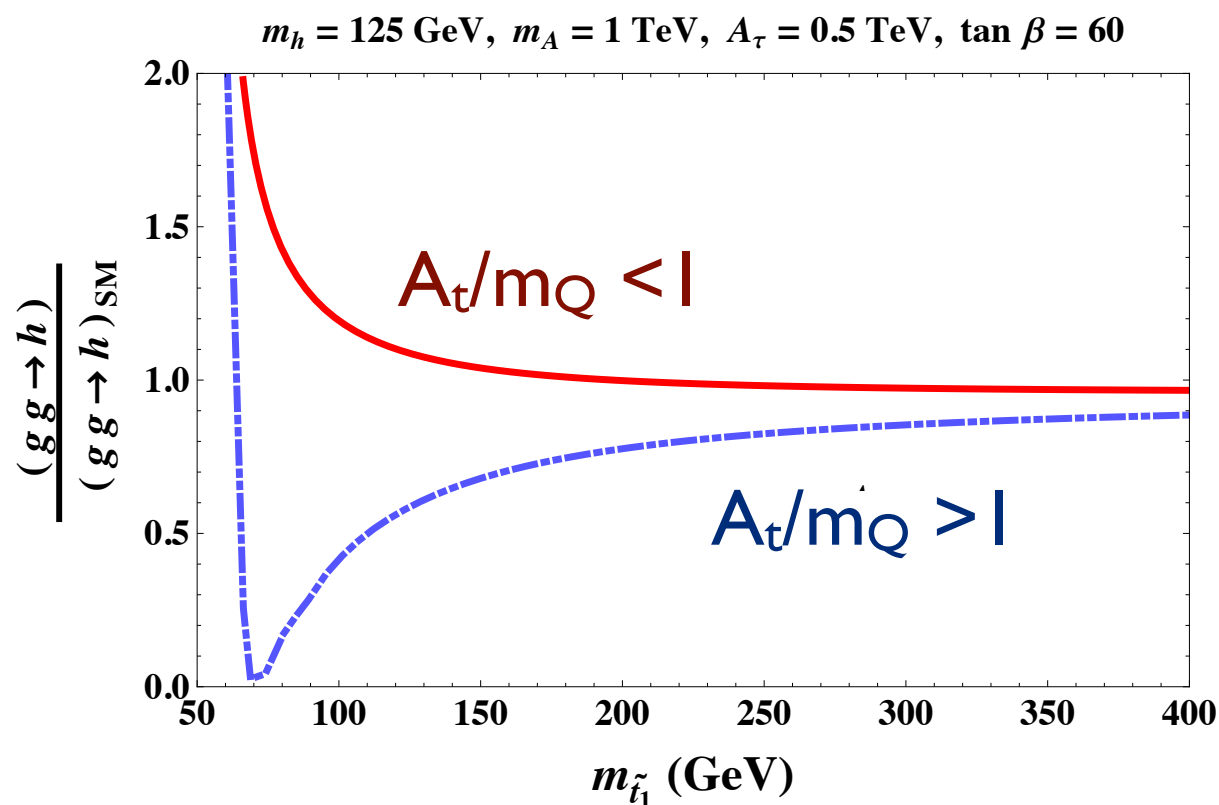❖ Through vertex corrections to Yukawa couplings: different for bottoms and taus
This destroys the SM relation BR(h → bb)/BR(h → ττ) ~ m_b^2/m_τ^2

❖ Through decays to new particles (including invisible decays)
This affects in similar manner BR's to all SM particles

Gluon Fusion in the MSSM

Light stops can increase the gluon fusion rate, but for large stop mixing X_t as required for $m_h \sim 125$ GeV mostly leads to moderate suppression

[light sbottoms lead to suppression for large tanβ]

$m_h = 125$ GeV, $m_A = 1$ TeV, $A_\tau = 0.5$ TeV, $\tan\beta = 60$

$$\delta A^{\tilde{t}}_{\gamma\gamma,gg} \propto \frac{m_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} \left[m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - X_t^2 \right]$$

If one stop much heavier: $m_Q \gg m_U$ and large tanβ

$$\delta A^{\tilde{t}}_{\gamma\gamma,gg} \propto \frac{m_t^2}{m_{\tilde{t}_1}^2} \left[1 - \frac{A_t^2}{m_Q^2} \right]$$

M.C., Gori, Shah, Wagner, Wang in prep.
See also Dermisek, Low '07.
Natural SUSY fit: Espinosa, Grojean, Saenz, Trotta '12

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

Squark effects in gluon fusion overcome opposite effects in di-photon decay rate:

If $\dfrac{\sigma(gg \to h)}{\sigma(gg \to h)_{SM}} < (>)1$

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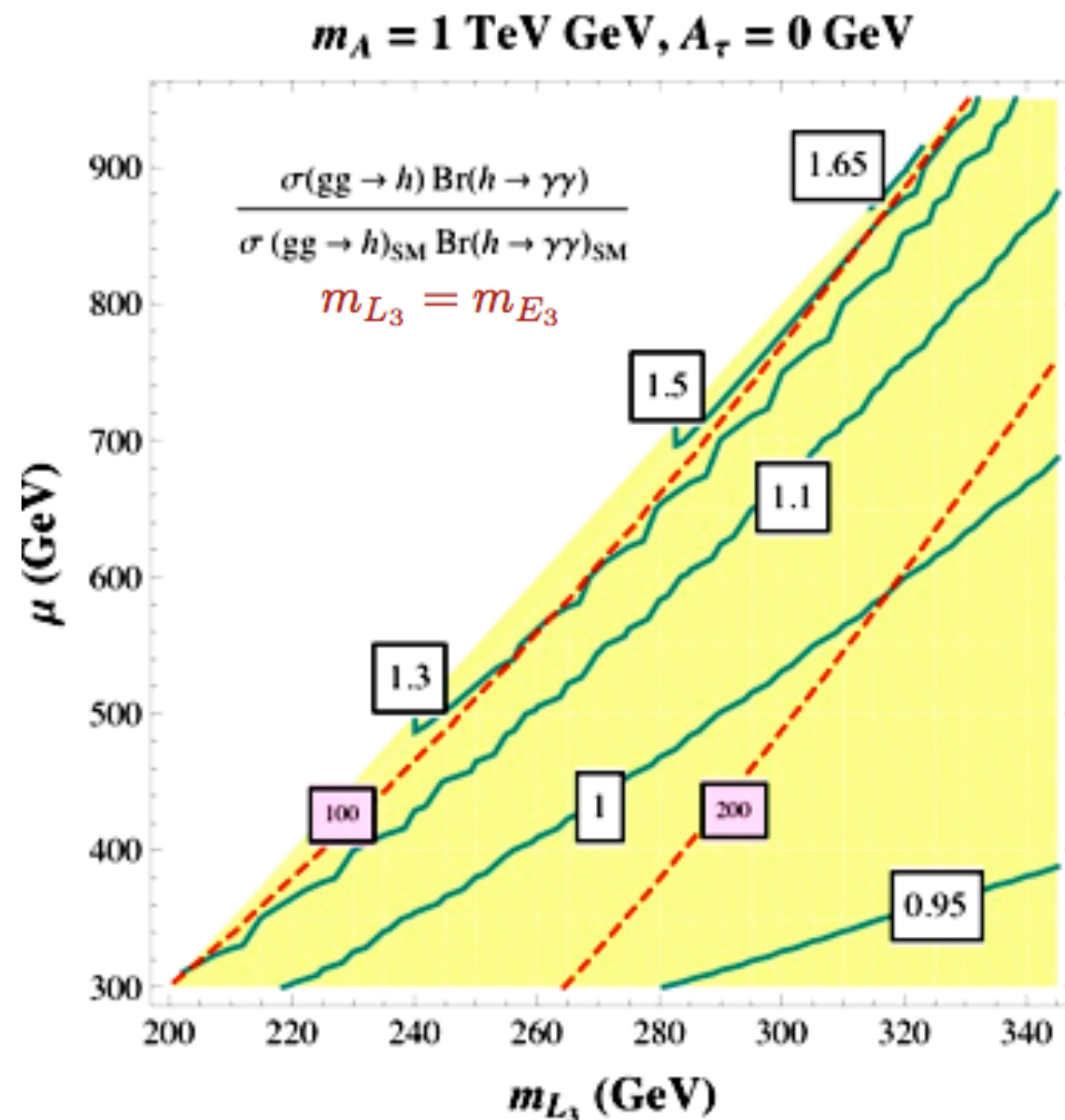
$$\mathcal{M}_{\tilde\tau}^2 \simeq \left[\begin{array}{cc} m_{L_3}^2 + m_\tau^2 + D_L & h_\tau v(A_\tau \cos\beta - \mu \sin\beta) \\ h_\tau v(A_\tau \cos\beta - \mu \sin\beta) & m_{E_3}^2 + m_\tau^2 + D_R \end{array} \right]$$

$$m_A = 1 \text{ TeV GeV}, A_\tau = 0 \text{ GeV}$$

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

$$m_{L_3} = m_{E_3}$$

Light staus with large mixing

[sizeable μ and tan beta]:

➔ **enhancement of the**

Higgs to di-photon decay rate

Contours of constant

$$\frac{\sigma(gg \to h)Br(h \to \gamma\gamma)}{\sigma(gg \to h)_{SM} Br(h \to \gamma\gamma)_{SM}}$$
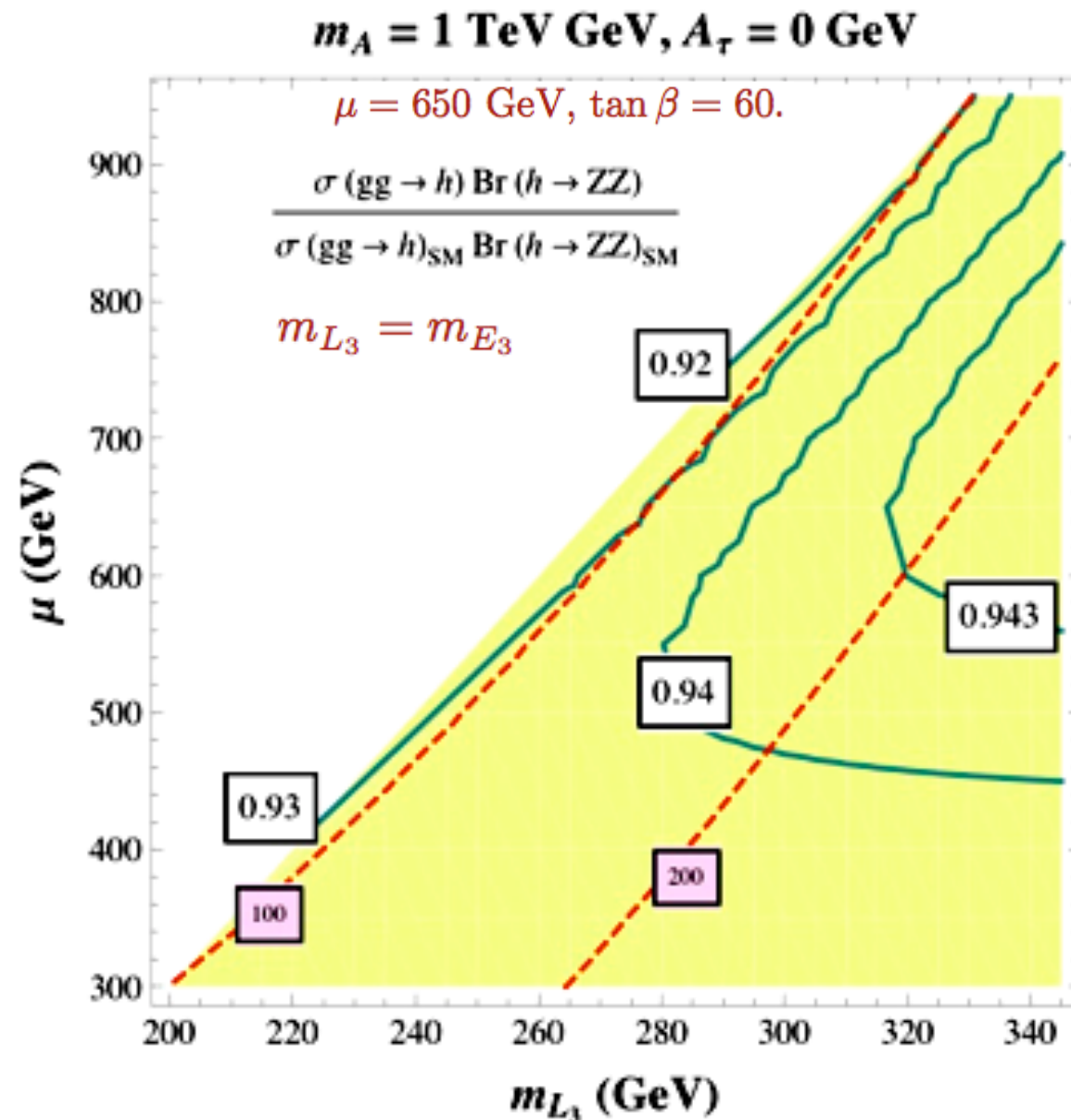
for $M_h \sim 125$ GeV

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

For a generic discussion of modified γγ and Zγ widths by new charged particles, see M. C. , Low and C. Wagner'12; for specific connection with light staus: Giudice, Paradisi, Strumia'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

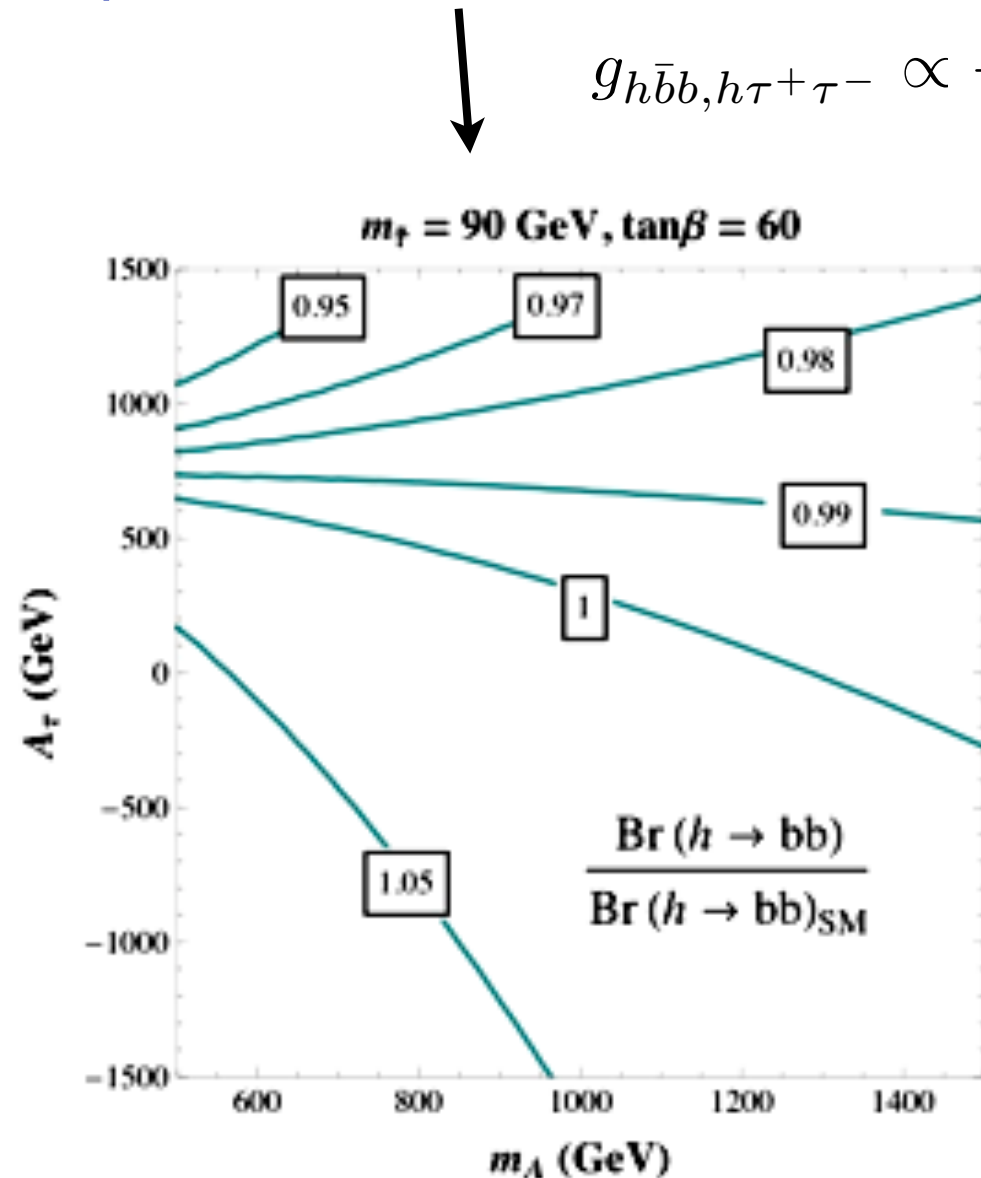$$\frac{\sigma(gg \to h) Br(h \to ZZ)}{\sigma(gg \to h)_{SM} Br(h \to ZZ)_{SM}}$$

for $M_h \sim 125$ GeV

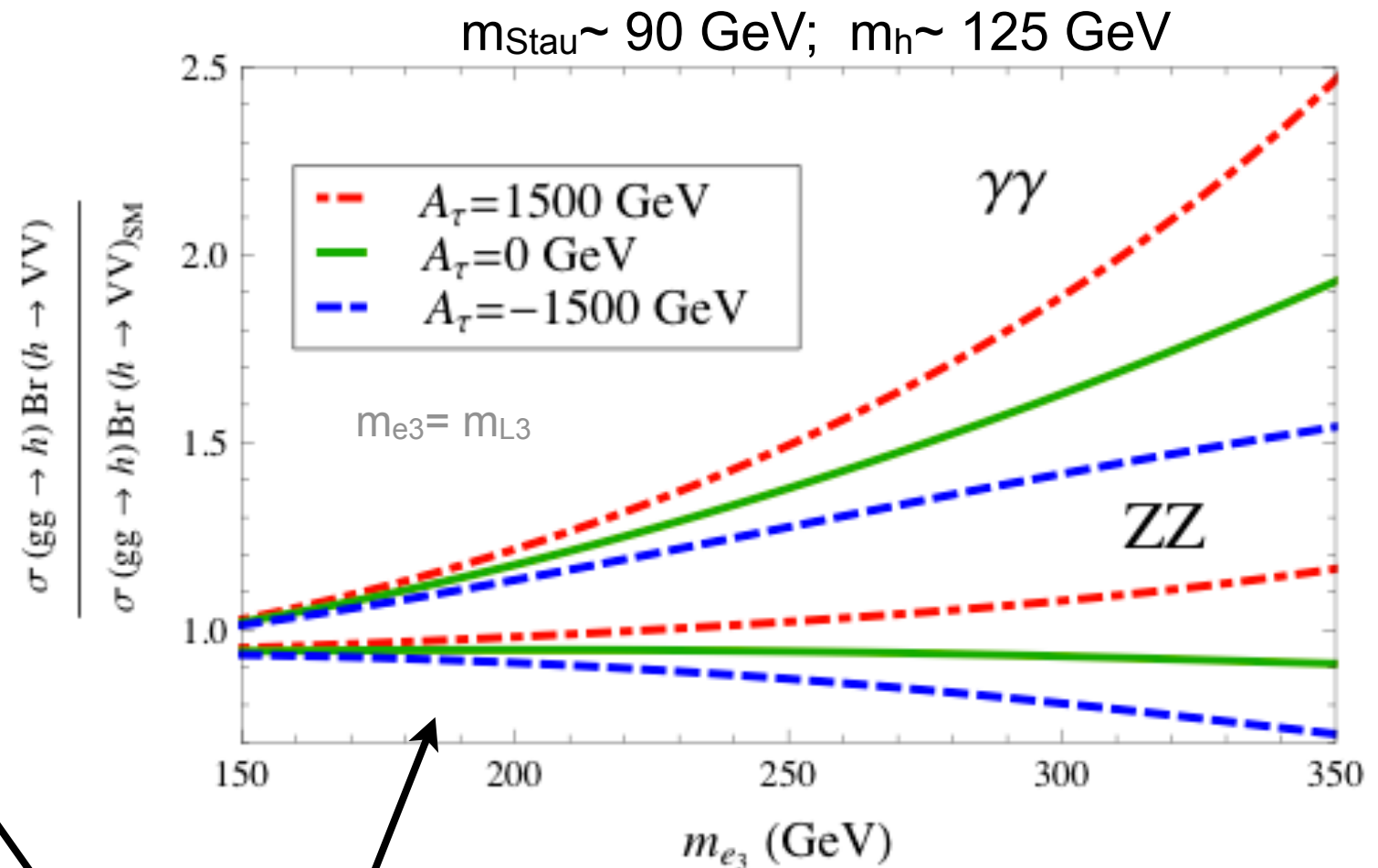M. C., Gori, Shah, Wagner'11 + Wang'12

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

$$g_{h\bar{b}b,h\tau^+\tau^-} \propto -\sin\alpha/\cos\beta$$

$m_{Stau} \sim$ 90 GeV; $m_h \sim$ 125 GeV

$m_{\tilde{\tau}} = 90$ GeV, $\tan\beta = 60$

0.95   0.97   0.98   0.99   1   1.05

$$\frac{\text{Br}(h \to bb)}{\text{Br}(h \to bb)_{SM}}$$

$A_\tau(\text{GeV})$

m_A (GeV)

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

- $A_\tau = 1500$ GeV
- $A_\tau = 0$ GeV
- $A_\tau = -1500$ GeV

$m_{e3} = m_{L3}$

$\gamma\gamma$

ZZ

m_{e_3} (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, Battagllia, Djouadi, Mahmoudi '12
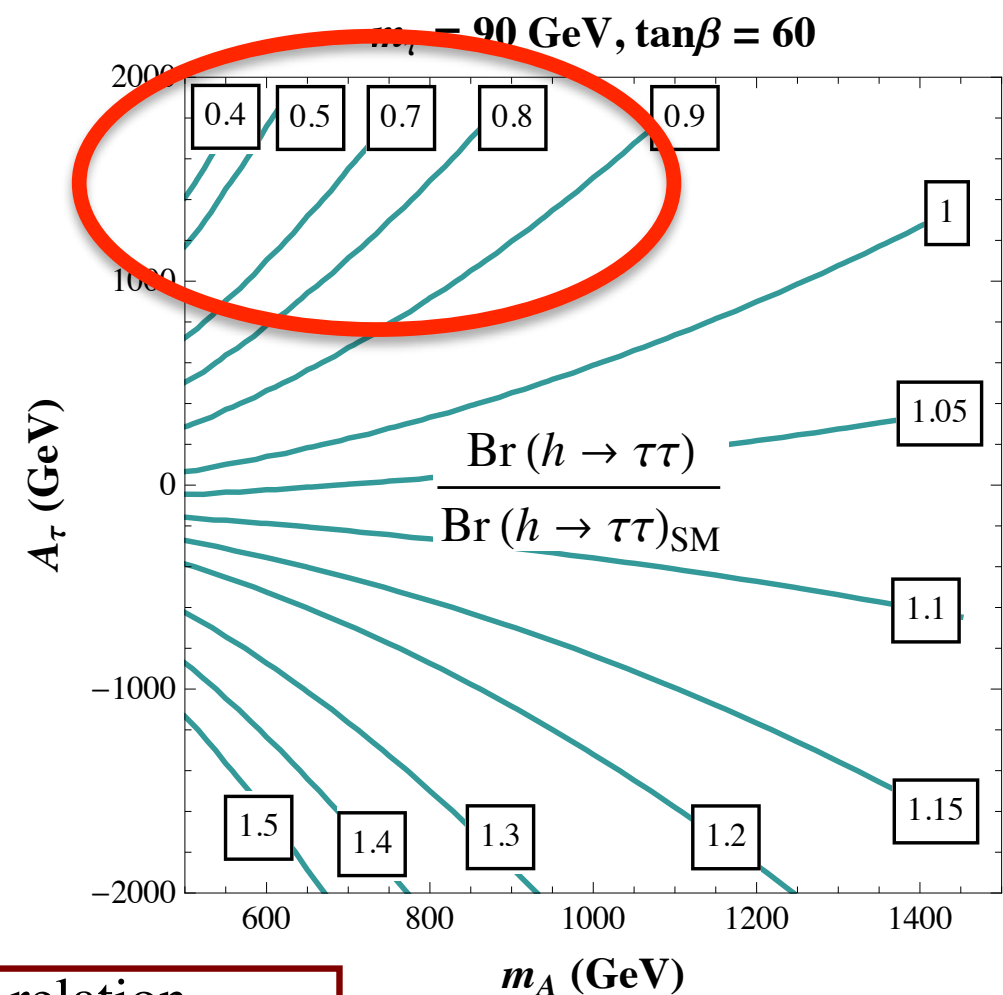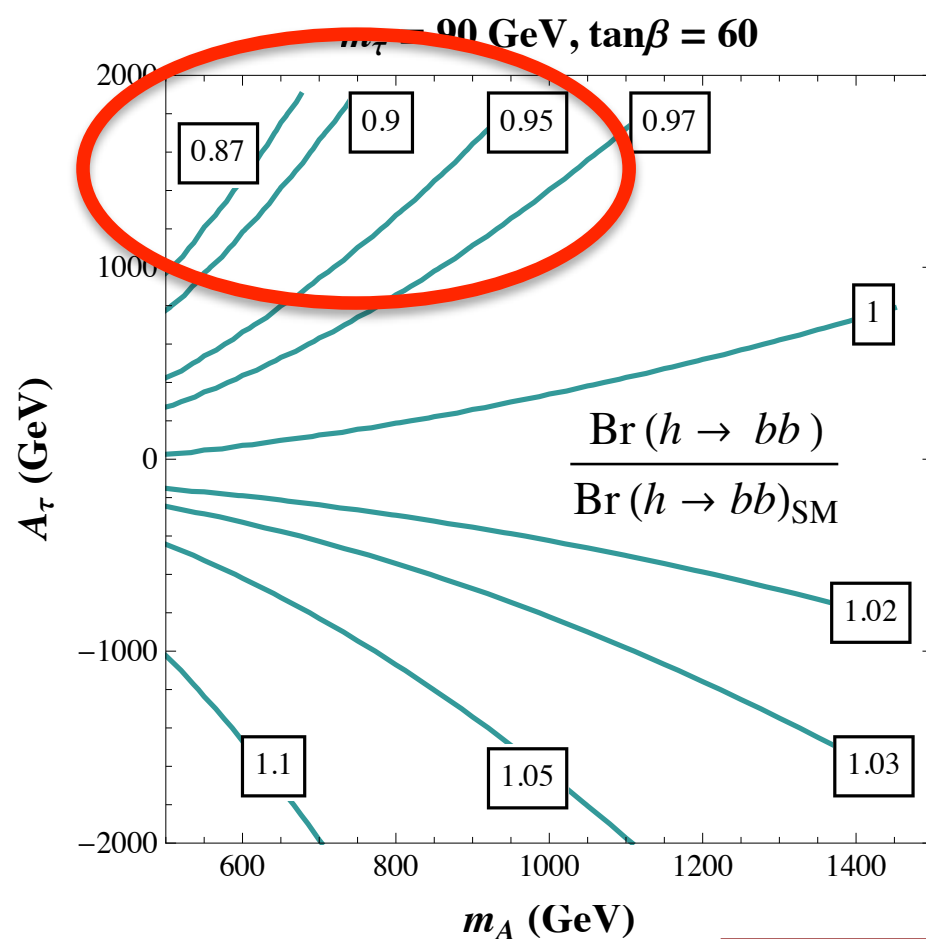Benbrik, Gomez Bock, Heinemeyer, Stal, Weigein, Zeune'12

Suppression of the h to taus to h to b's ratio
due to different radiative SUSY corrections to higgs-fermion couplings

$$m_{b,\tau} \simeq \frac{h_{b,\tau} v}{\sqrt{2}} \cos\beta \left(1 + \frac{\Delta_{h_{b,\tau}}}{h_{b,\tau}} \tan\beta\right)$$

$\Delta_{b,\tau}$

$$g_{hbb,h\tau\tau} = -\frac{m_{b,\tau} \sin\alpha}{v \cos\beta (1 + \Delta_{b,\tau})} \left[1 - \frac{\Delta_{b,\tau}}{\tan\beta \tan\alpha}\right]$$

$m_\tau = 90$ GeV, $\tan\beta = 60$

$\dfrac{\text{Br}(h \to bb)}{\text{Br}(h \to bb)_{\text{SM}}}$

$\dfrac{\text{Br}(h \to \tau\tau)}{\text{Br}(h \to \tau\tau)_{\text{SM}}}$
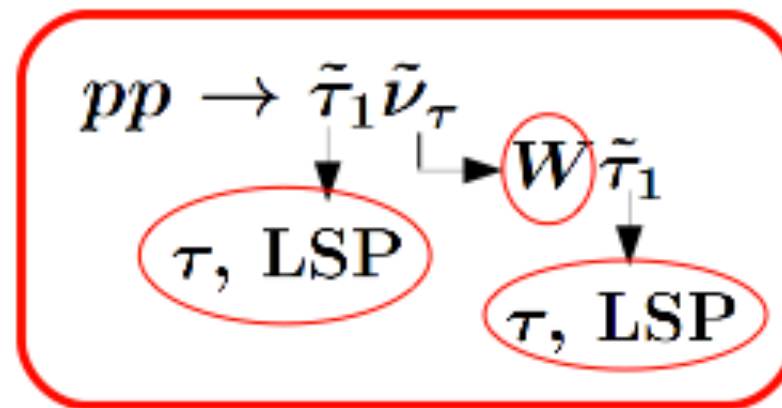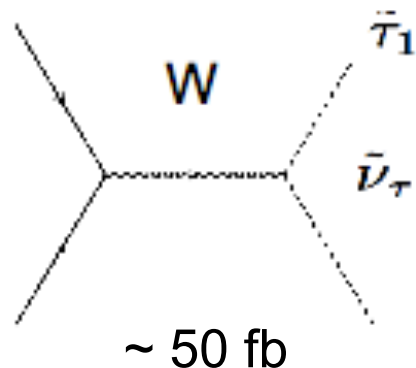
destroy basic relation

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

M. C., Gori, Shah, Wagner, Wang

Possible scenario with suppression or small enhancement
of gluon fusion and enhancement of diphoton rate and SM-like VBF

Stau Searches at the LHC

- LHC looks for staus produced through SUSY cascade decays
- LHC looks at long-lived staus
- Interesting channel to look for:

~ 50 fb

signature:
Lepton, 2 taus, missing energy

Physical background: Wγ*, WZ*Final
Fake background: W+jets

Estimation at the parton level shows promising results at 8 TeV LHC

- In principle also $pp \rightarrow \tilde{\tau}_1 \tilde{\tau}_1 \rightarrow (\tau\,\mathrm{LSP})(\tau\,\mathrm{LSP})$ can be interesting, but much more challenging

M. C., Gori, Shah, Wagner, Wang

- Another interesting possibility: Staus in "light" Stop decays $\tilde{t}_1 \rightarrow b\tilde{\chi}^+ \rightarrow b\tilde{\tau}\nu$

Many Minimal SUSY models can produce m_h=125 GEV

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

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

Tan $\beta = 2$

$\lambda = 0, 0.3, 0.5, 0.6, 0.7$

$m_{\tilde{t}_1} < 100$ GeV

$m_{\tilde{t}}$ [GeV]

$X_t / m_{\tilde{t}}$

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 cannot enhance the di-photon rate (at low tanβ stau mixing is negligible)

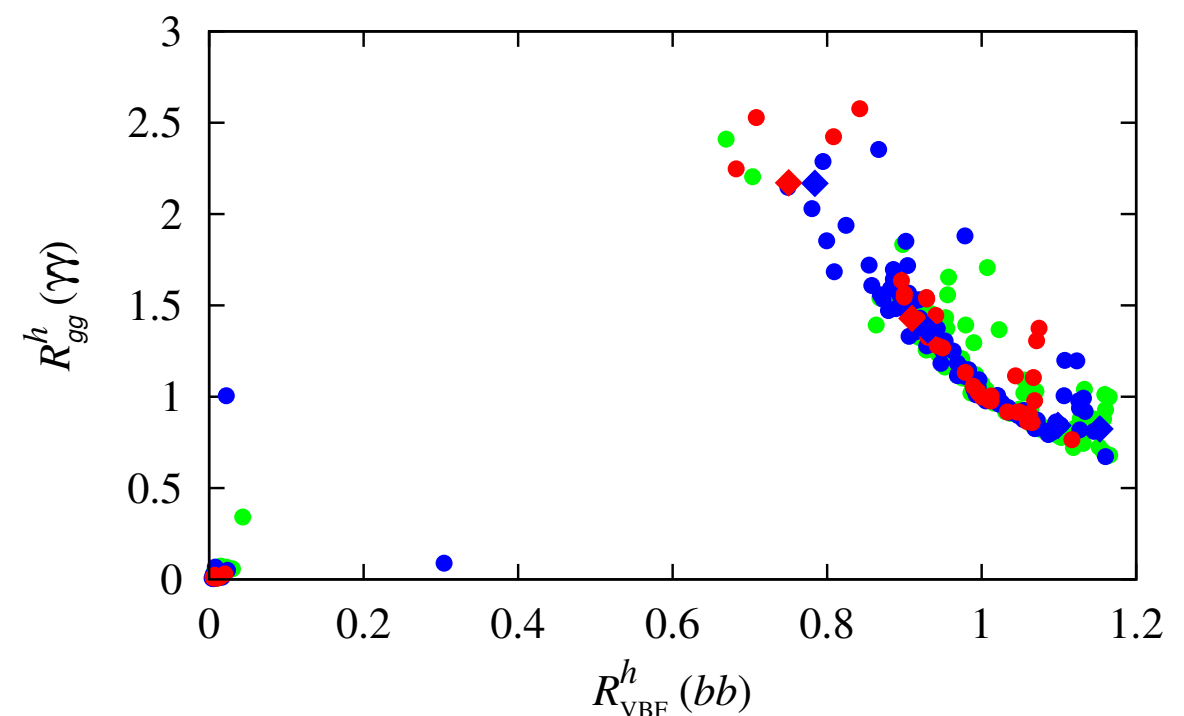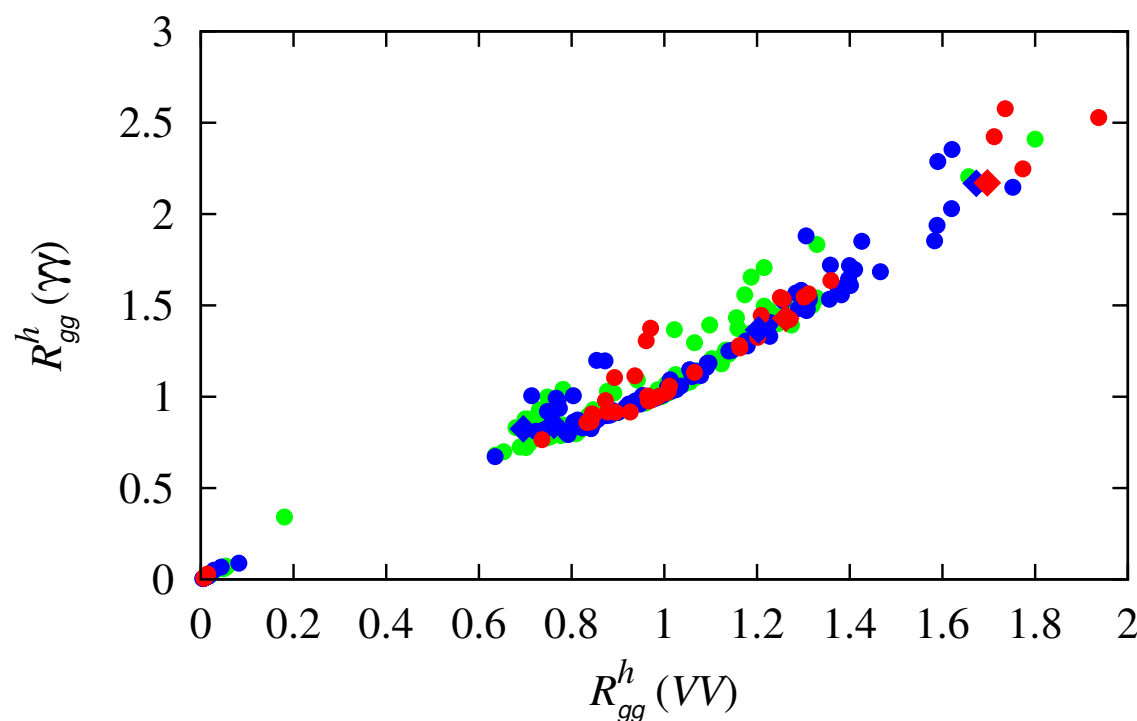- Light chargino at low tanβ can contribute to enhance the di-photon rate
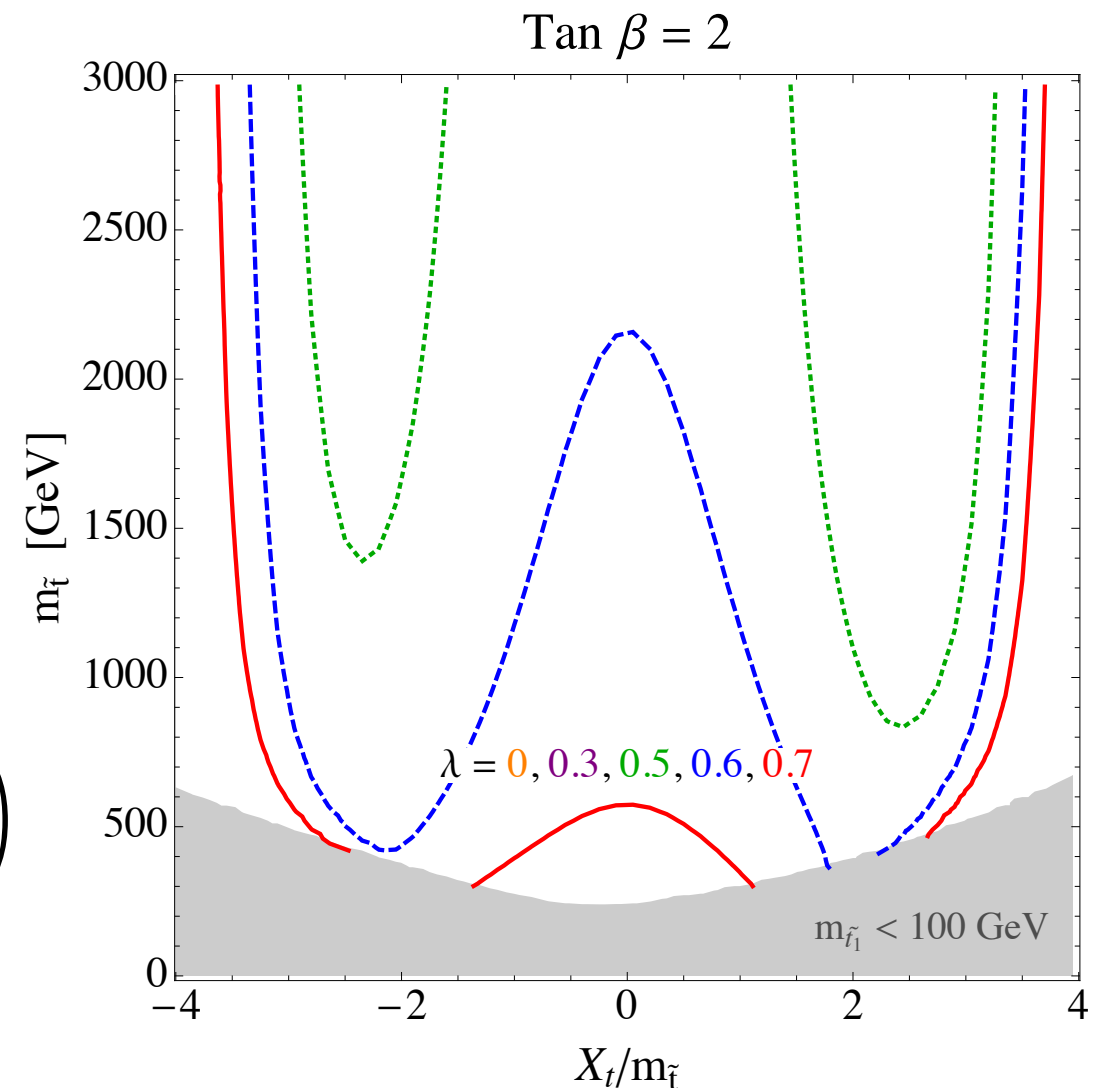
Analogous to MSSM, modifications of the Higgs rates into gauge bosons via mixing effects in the Higgs sector

genuine NMSSM effect from doublet-singlet mixing induced by λ

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

$$R_{gg}^{h_i}(X) \equiv \frac{\Gamma(gg \to h_i)\ \mathrm{BR}(h_i \to X)}{\Gamma(gg \to h_{\mathrm{SM}})\ \mathrm{BR}(h_{\mathrm{SM}} \to X)};$$

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

Suppression in BR [H ⟶ bb] induces
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

$\tan\beta = 20, M = 1\,\text{TeV}, \mu = m_S = 200\,\text{GeV}, M_{\text{SUSY}} = 300\,\text{GeV}, A_t = A_b = 0$
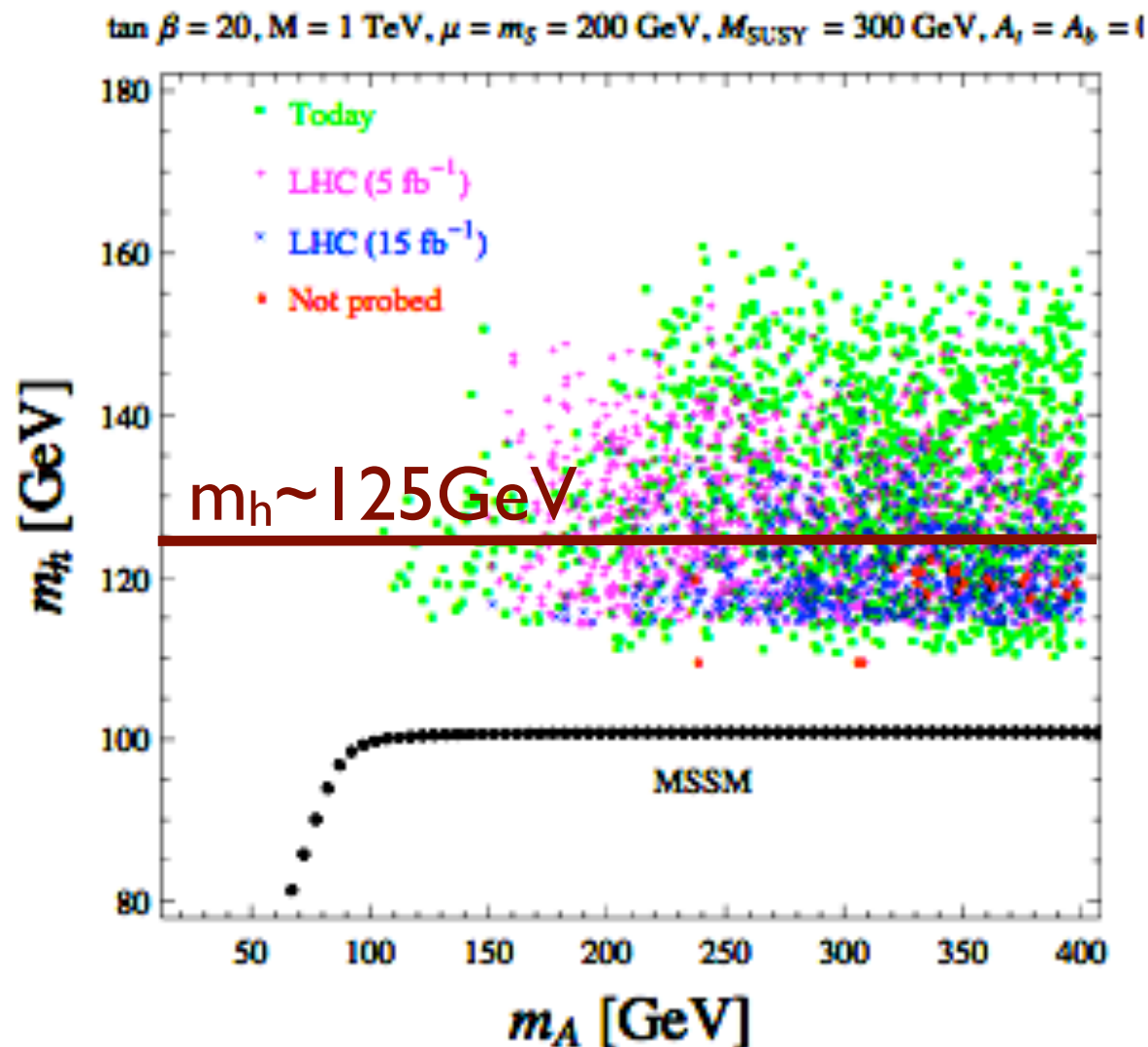
Scan over parameters including all possible dimension 5 and 6, SUSY Higgs operators

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
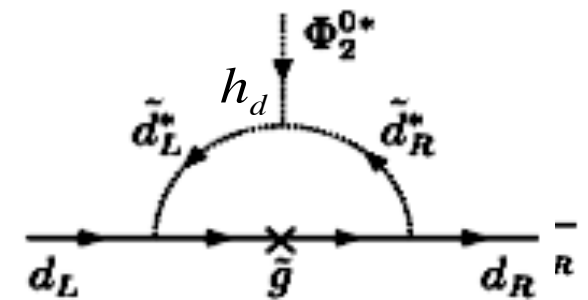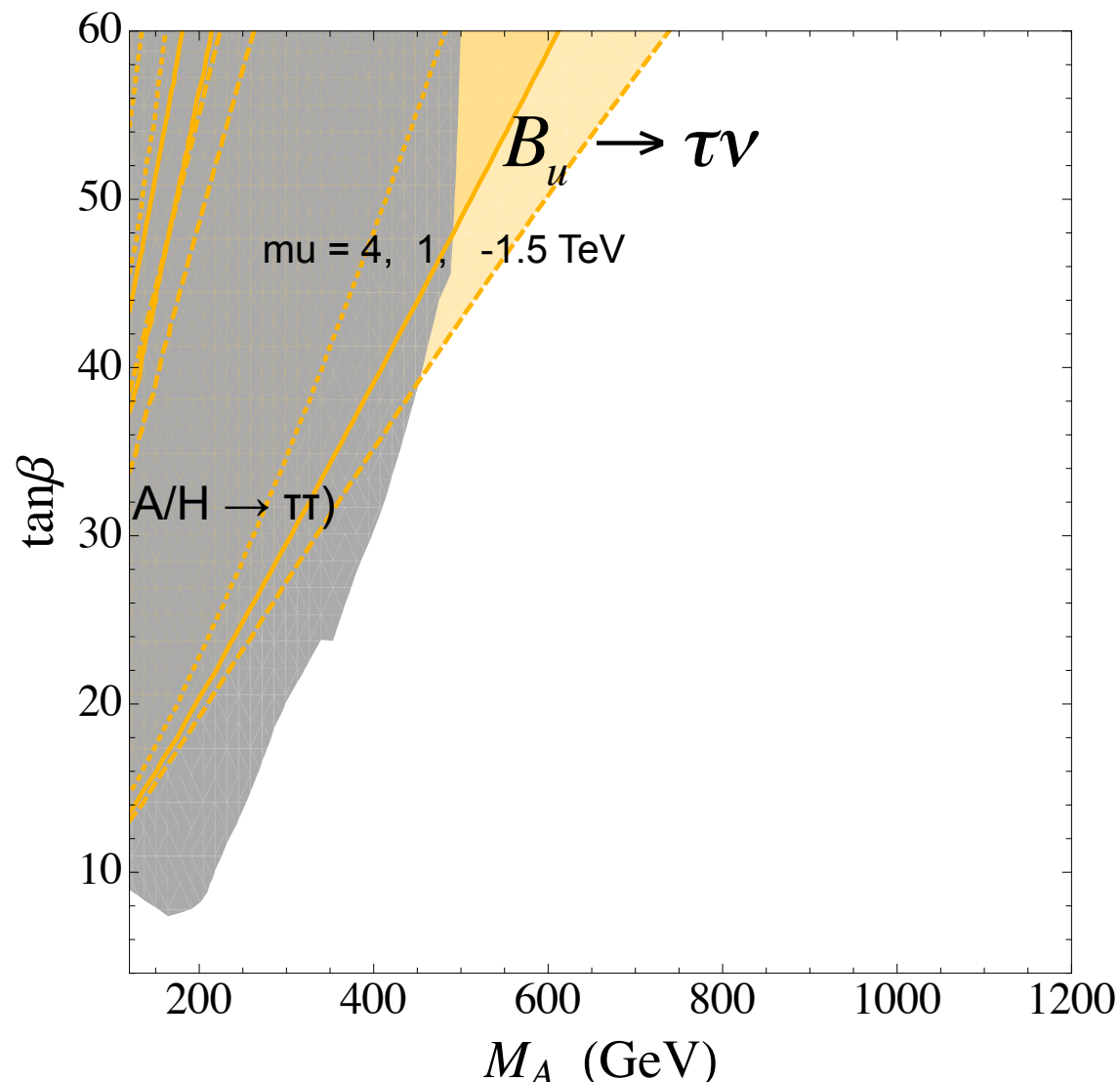
The Flavor-Higgs Connection

M_h ~ 125 GeV and flavor in the MSSM

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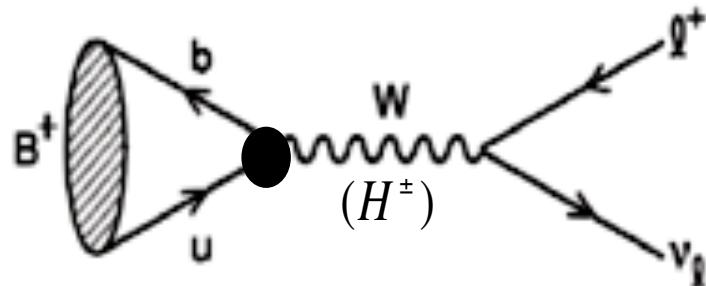
$$R_{B_u \to \tau\nu} = \frac{\mathrm{BR}(B_u \to \tau\nu)^{MSSM}}{\mathrm{BR}(B_u \to \tau\nu)^{SM}} = \left[1 - \left(\frac{m_B^2}{m_{H^\pm}^2} \right) \frac{\tan\beta^2}{(1 + \varepsilon_0^3 \tan\beta)} \right]^2$$

$B_u \to \tau\nu$
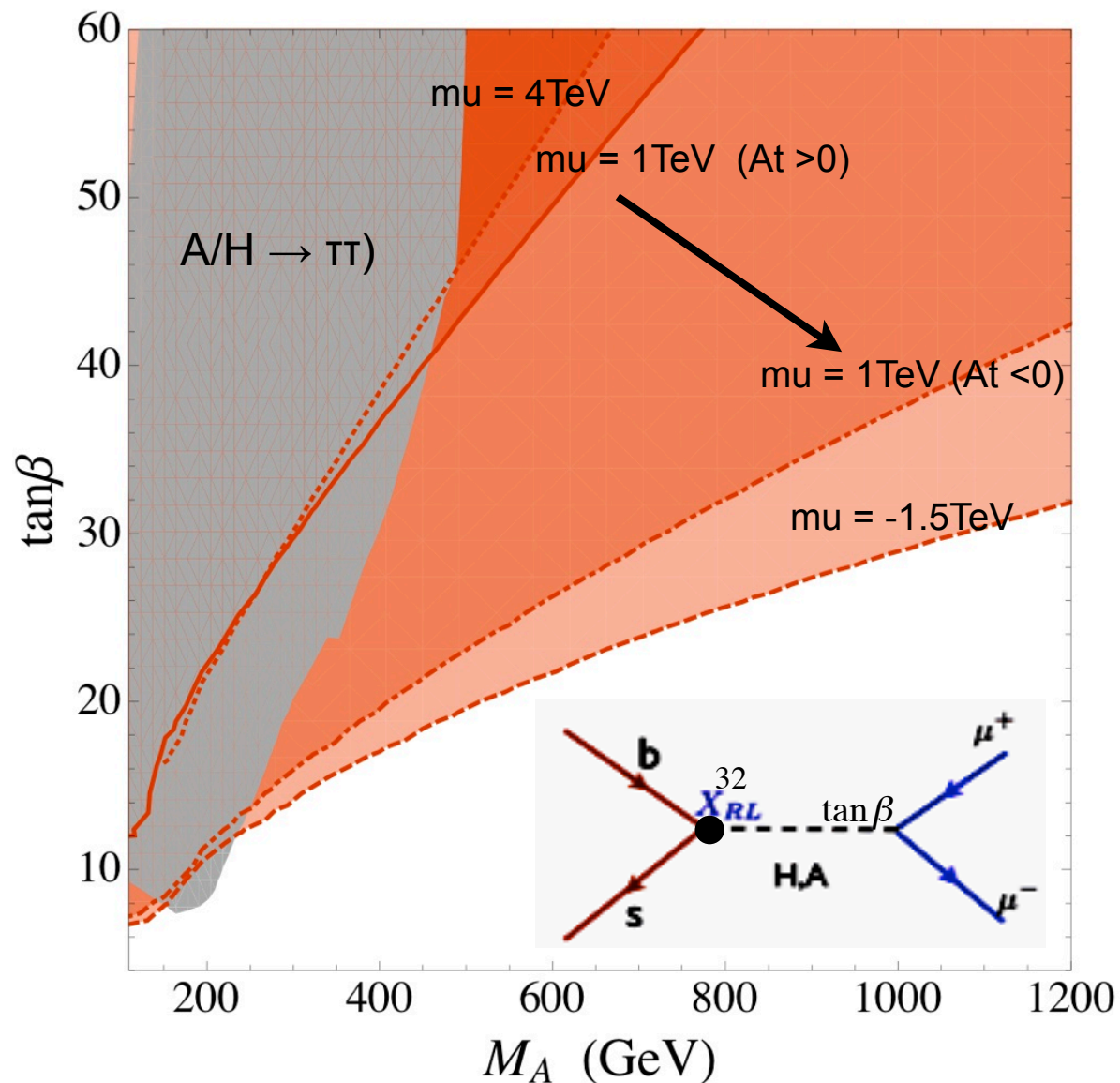
mu = 4, 1,   -1.5 TeV

A/H → ττ)

M_A (GeV)

$\tan\beta$

Independent on stop mixing
Almost independent of
SUSY breaking scale
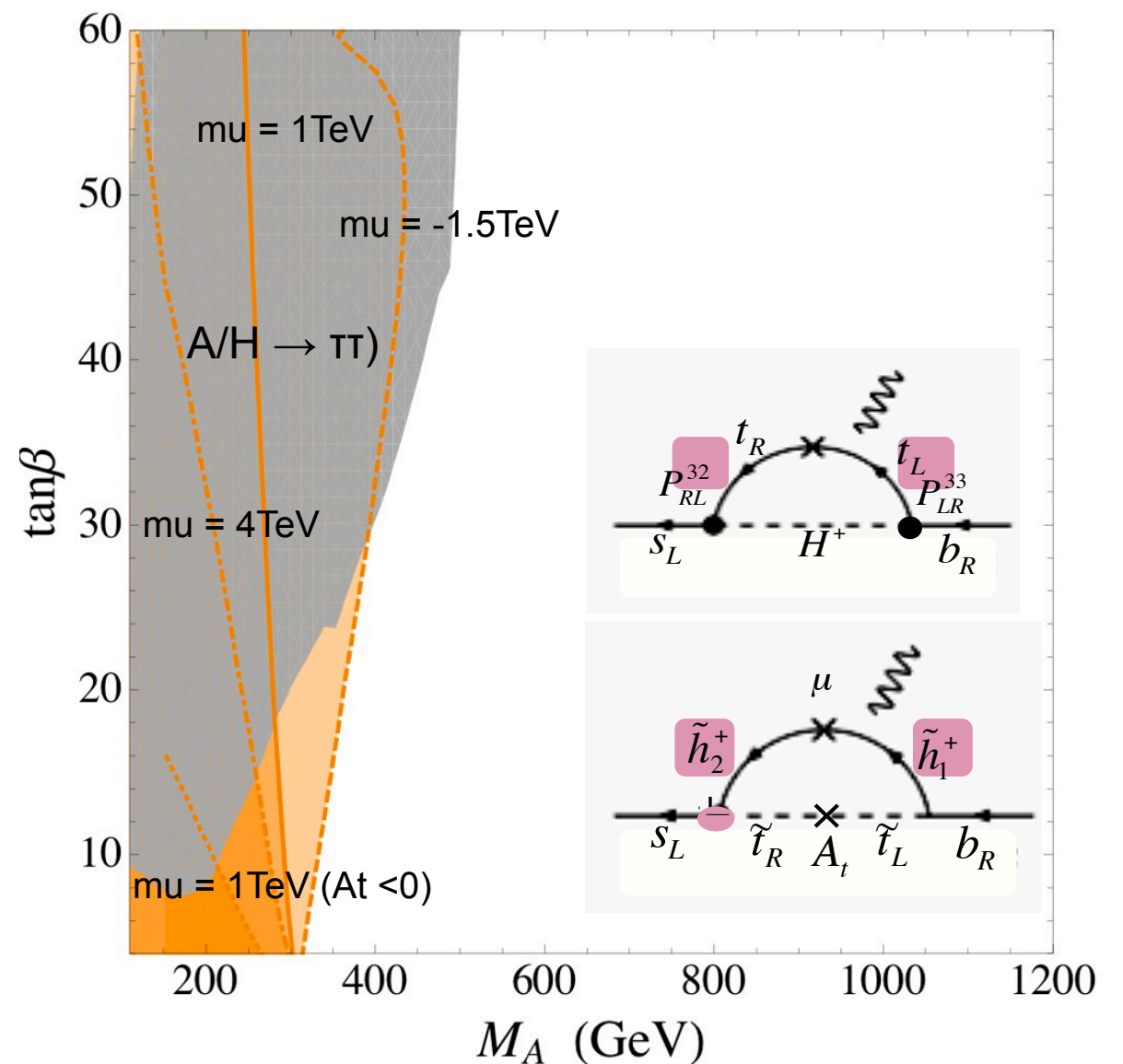More powerful than direct Heavy Higgs
searches for large tanbeta

Altmannshofer, MC, Shah, Yu, in prep.

M$_h$ ~ 125 GeV and flavor in the MSSM

## Bounds from B$_s$ →μ$^+$μ-

Bounds from B$_s$ →X$_s$ γ

SUSY effects intimately connected to the structure of the squark mass matrices

Positive values of A$_t$ less constraining for sizeable m$_A$ and large tan beta   Altmannshofer, MC, Shah,Yu

Higgs Physics in Warped Extra Dimensions

Warped Extra dimensions with Matter in the bulk

- Allowing gauge fields and matter to propagate in the bulk
  $\Rightarrow$ models of EWSB, flavor, GUTs, etc.

- Bulk Randall-Sundrum models: several possibilities for model building

ψ_{light}

W, Z, g, γ

ψ_{heavy}
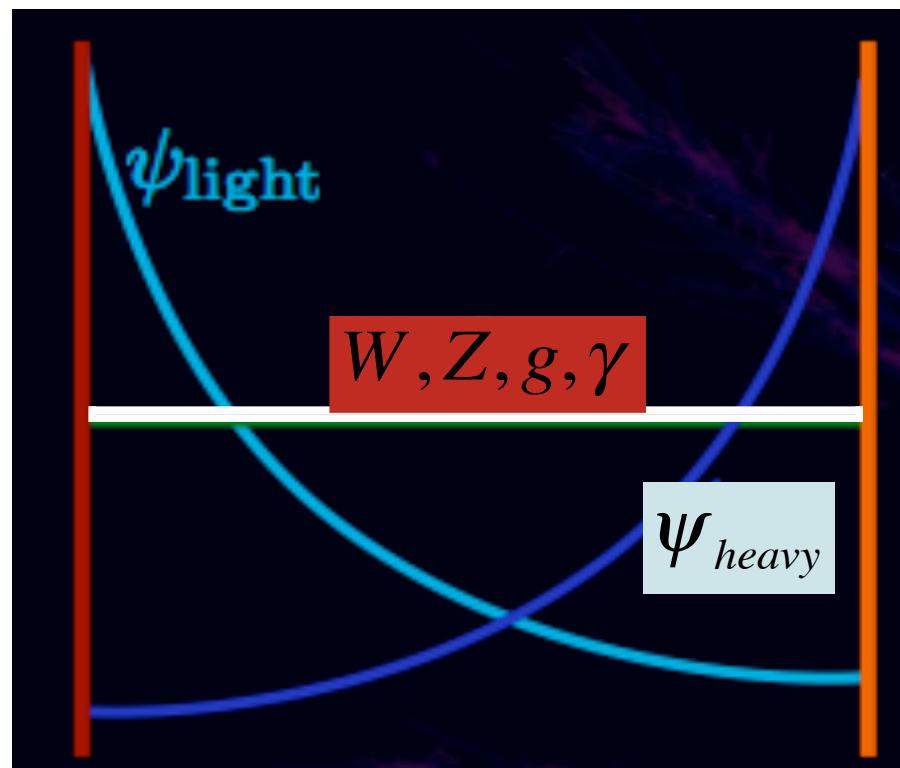
UV brane   IR brane

Higgs + KK modes

Higgs or Higgsless (b.c. EWSB)

Hierarchical fermion masses from localization

[masses depend on overlap with Higgs/TeV scale]

FCNC and higher dimensional operators

suppressed for the light fermion families

KK modes localize towards the IR for
    * Weak bosons, Gluons, Fermions
    * As well as gravitons

Large corrections to the SM gauge boson masses and couplings due to Higgs induced mixing ==> strong EW constraints on the spectrum

$$\tilde{k} \geq 1.5 \text{ TeV} \Rightarrow \text{KK gauge boson masses} > 3\text{TeV}$$

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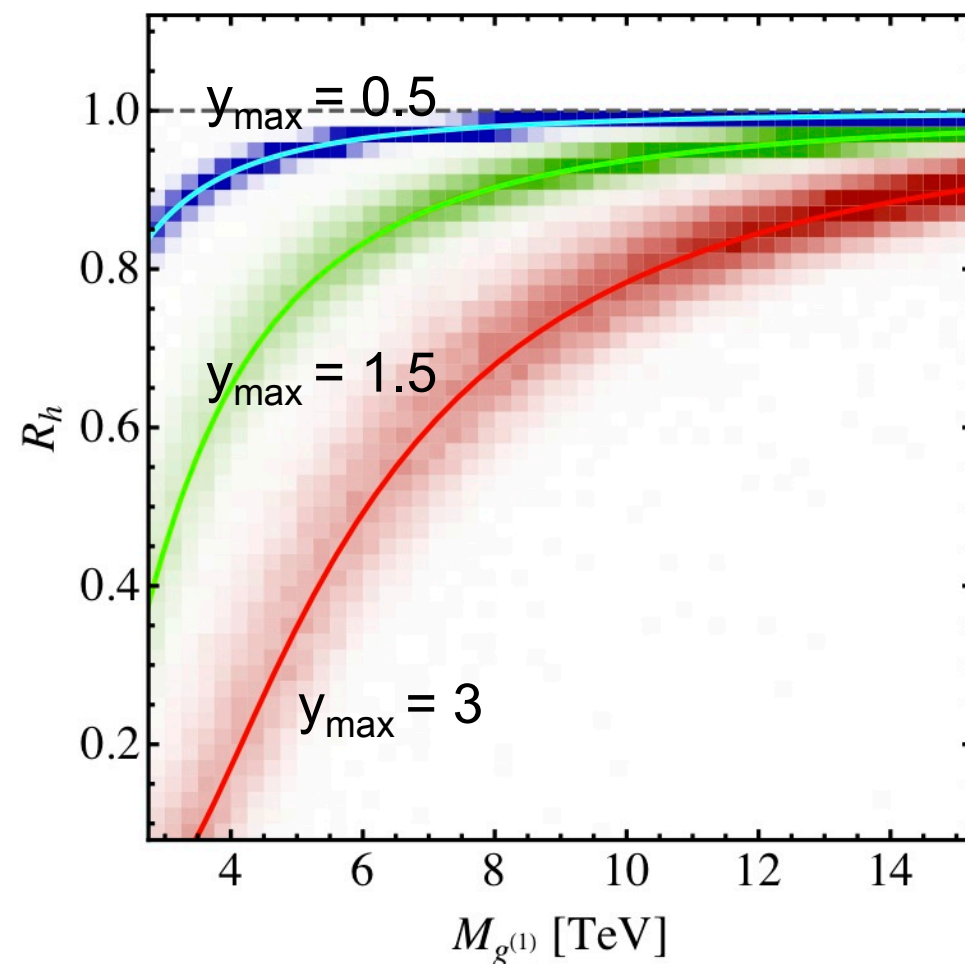
Spectacular effects on Higgs production
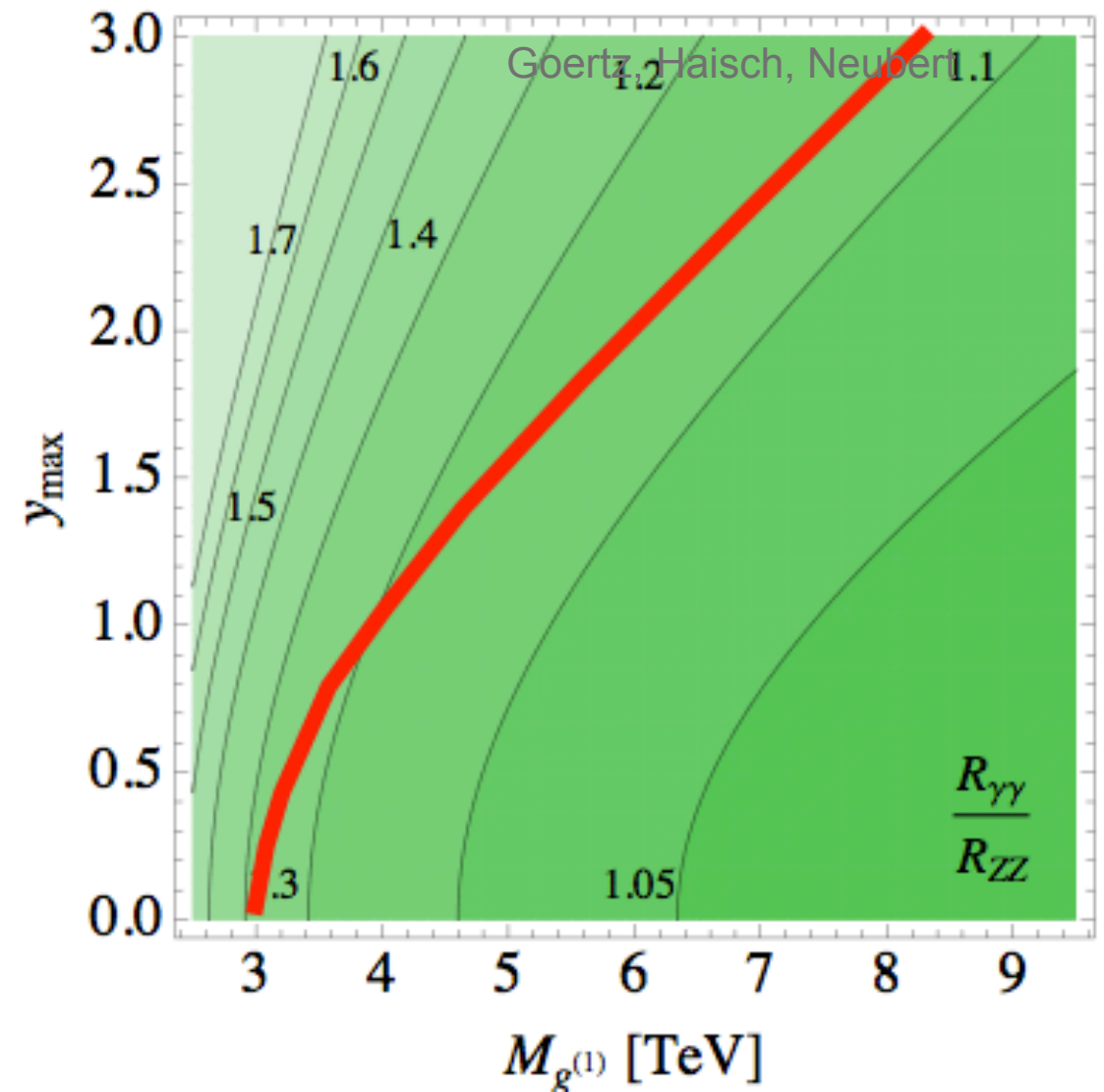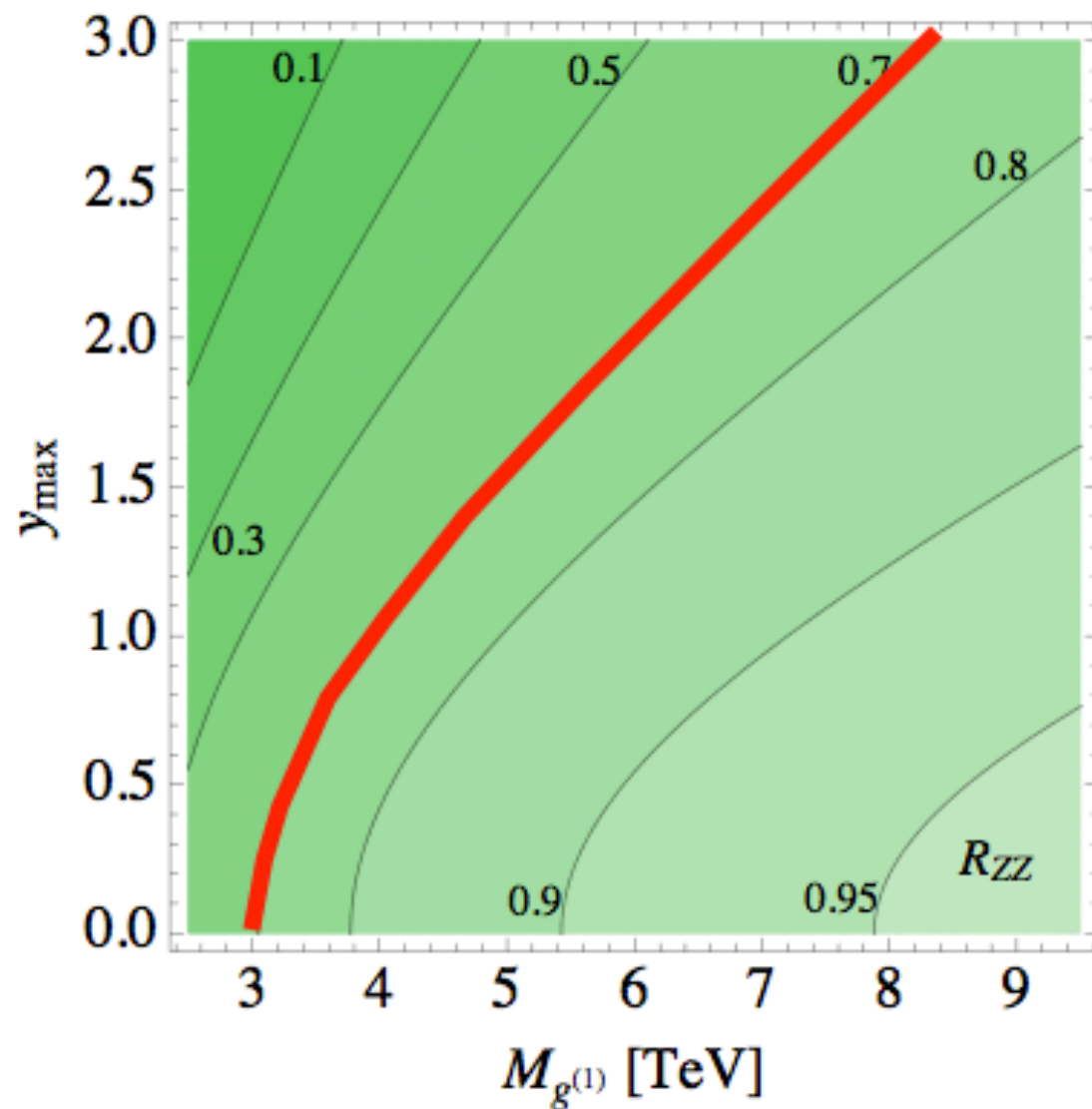via gluon fusion, even for new particle
masses well beyond direct LHC reach

Suppression

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

MC, Casagrande, Goertz, Haisch, Neubert'12

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

Higgs Phenomenology in Minimal RS model: Decay

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

Measuring $R_{ZZ} \approx 0.7$ along with a slight enhancement of $R_{\gamma\gamma}$ over R_{ZZ} would imply (for $y_{max} = 3$) KK masses ≈ 8 TeV, far outside LHC reach. ($R_{ZZ} > 0.7 \Longrightarrow$ very strong bounds)

Significant enhancement of the BR ($h \rightarrow \gamma\gamma$) possible depending on the values of leptonic 5D Yukawas

Many exotic Higgs impostor scenarios constrained by these analyses
Most recently studied example: Dilaton

Dilaton: Goldston boson associated with spontaneously broken scale invariance

Conformal breaking scale f > v ==> Dilaton is not responsible for EWSB
Introduced in the low energy L as a compensator of scale transformations

If EM and QCD (?) part of the conformal sector:

$$g_{ggh}^2/(g_{ggh}^2)^{SM} = R_g \; v^2/f^2$$

$$g_{\gamma\gamma h}^2/(g_{\gamma\gamma h}^2)^{SM} = R_\gamma \; v^2/f^2$$

$$g_{WWh,ZZh}^2/(g_{WWh,ZZh}^2)^{SM} = v^2/f^2$$

$$R_g \simeq 140; \;\; R_\gamma \simeq 2.43 \text{ for } M_\chi \simeq 125 \text{ GeV}$$

Atlas and CMS di-photon excess consistent
with f ~ 800-1300 GeV

Model Building quite involved
to make it a viable alternative

Coleppa, Gregoire, Logan '11
Lykken, Low, Shaughnessy, '12
Bellanzini, Csaki, Hubisz, Serra, Terning'12

$$\downarrow$$

$$\sigma(gg \to \chi)/\sigma(VBF \to \chi) \; 140 \times SM$$

$$BR(\chi \to \gamma\gamma)/BR(\chi \to ZZ) = 2.43 \times SM$$

Conclusions:

The Higgs discovery is of paramount importance

but

We need more precise measurements of Higgs properties
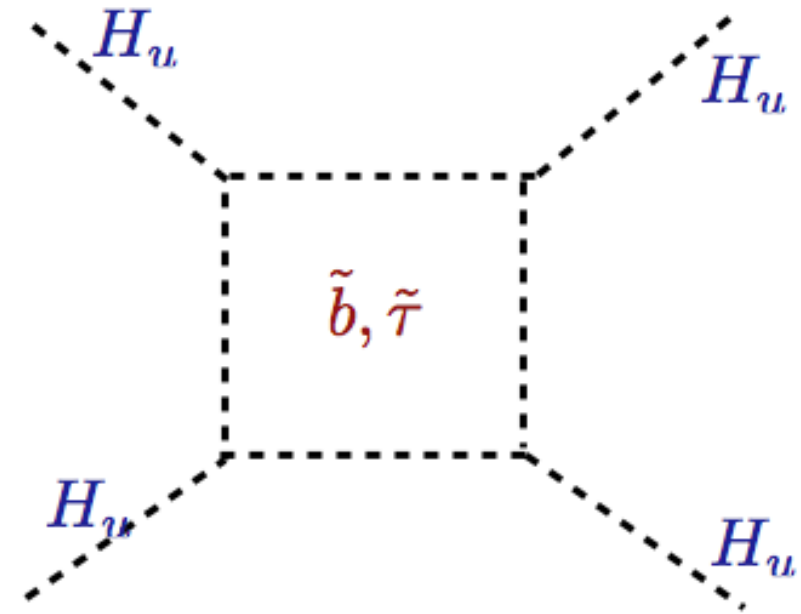
and/or

direct observation of new physics

to further advance in our understanding of EWSB

Extras

Additional effects at large tan beta from sbottoms:

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

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

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

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

with $\quad h_\tau \simeq \dfrac{m_\tau}{v \cos\beta (1 + \tan\beta \Delta h_\tau)}$ $\qquad$ 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

Mixing Effects in the CP- even Higgs Sector

can have relevant effects in the production and decay rates

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

$$\text{Loop}_{12} = \frac{h_\tau^4 v^2}{48\pi^2} \sin^2\beta \frac{\mu^3 A_\tau}{M_{\tilde{\tau}}^4}$$

Radiative corrections to the CP-even mass matrix
affect the mixing angle alpha
that governs couplings of Higgs to fermions

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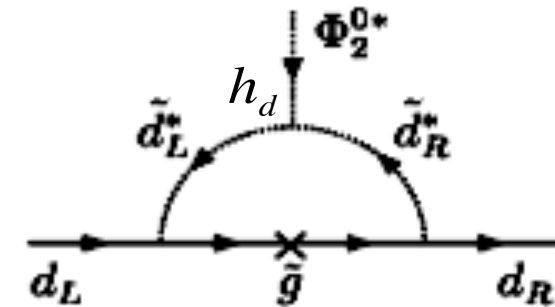
Normalized to SM ones

$$g_{hu\bar{u}, Hu\bar{u}, Au\bar{u}} \rightarrow \cos\alpha/\sin\beta, \ \sin\alpha/\sin\beta, \ 1/\tan\beta$$

$$g_{hb\bar{b}, Hb\bar{b}, Ab\bar{b}} \rightarrow -\sin\alpha/\cos\beta, \ \cos\alpha/\cos\beta, \ \tan\beta$$ (same for leptons)

If off diagonal elements **suppressed/enhanced**: same occurs for sinα or cosα

==> **suppression/enhancement** of SM-like Higgs coupling to bb and ττ

leads to enhancement/suppression of BR(h/H to WW/ZZ/γγ) for $m_{h/H}$ < 135 GeV

After SUSY breaking all fermions couple to both Higgs Doublets

$$g_{hbb,h\tau\tau} = -h_{b,\tau}\sin\alpha + \Delta h_{b,\tau}\cos\alpha$$

can change the relative strength of Higgs decays to b and tau pairs

Modification of the tree level relation between $h_{b,\tau}$ and $m_{b,\tau}$

$$m_{b,\tau} \simeq \frac{h_{b,\tau}v}{\sqrt{2}}\cos\beta\left(1 + \frac{\Delta_{h_{b,\tau}}}{h_{b,\tau}}\tan\beta\right)$$

$\Delta_{b,\tau}$

$$g_{hbb,h\tau\tau} = -\frac{m_{b,\tau}\sin\alpha}{v\cos\beta(1+\Delta_{b,\tau})}\left[1 - \frac{\Delta_{b,\tau}}{\tan\beta\tan\alpha}\right]$$

destroy basic relation

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

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

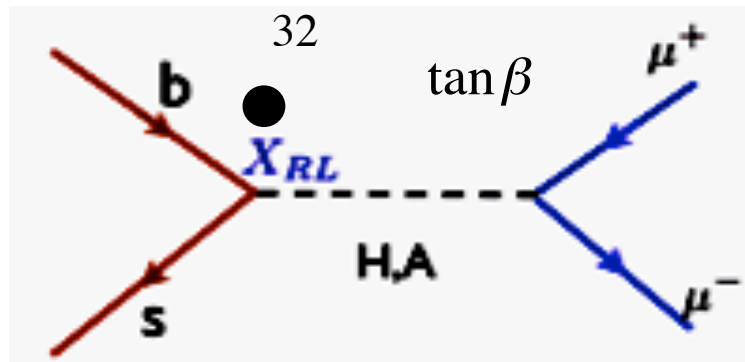**Radiative corrections ==> main decay modes of the
SM-like MSSM Higgs into b- and tau-pairs can be drastically changed**

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

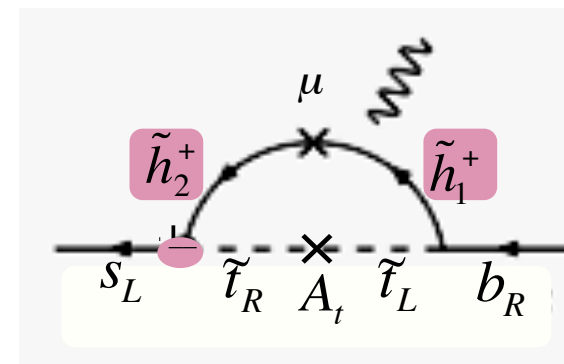$$\varepsilon_Y \approx \frac{\mu^* A_t^*}{16\pi^2 \max\left[m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2\right]} \qquad \Delta_b = \left(\varepsilon_0^3 + \varepsilon_y h_t^2\right)\tan\beta$$

• **Charged Higgs and chargino-stop contributions to** $BR(B \to X_S \gamma)$
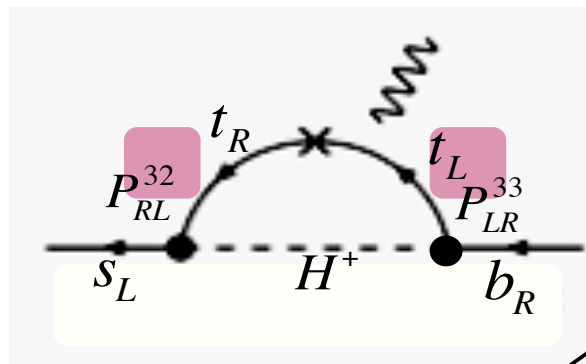
$$\delta h_t \propto h_t \frac{2\alpha_S}{3\pi} \mu^* M_{\tilde{g}}$$

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

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

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~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: $\boxed{B_s \to \mu^+ \mu^-}$

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

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

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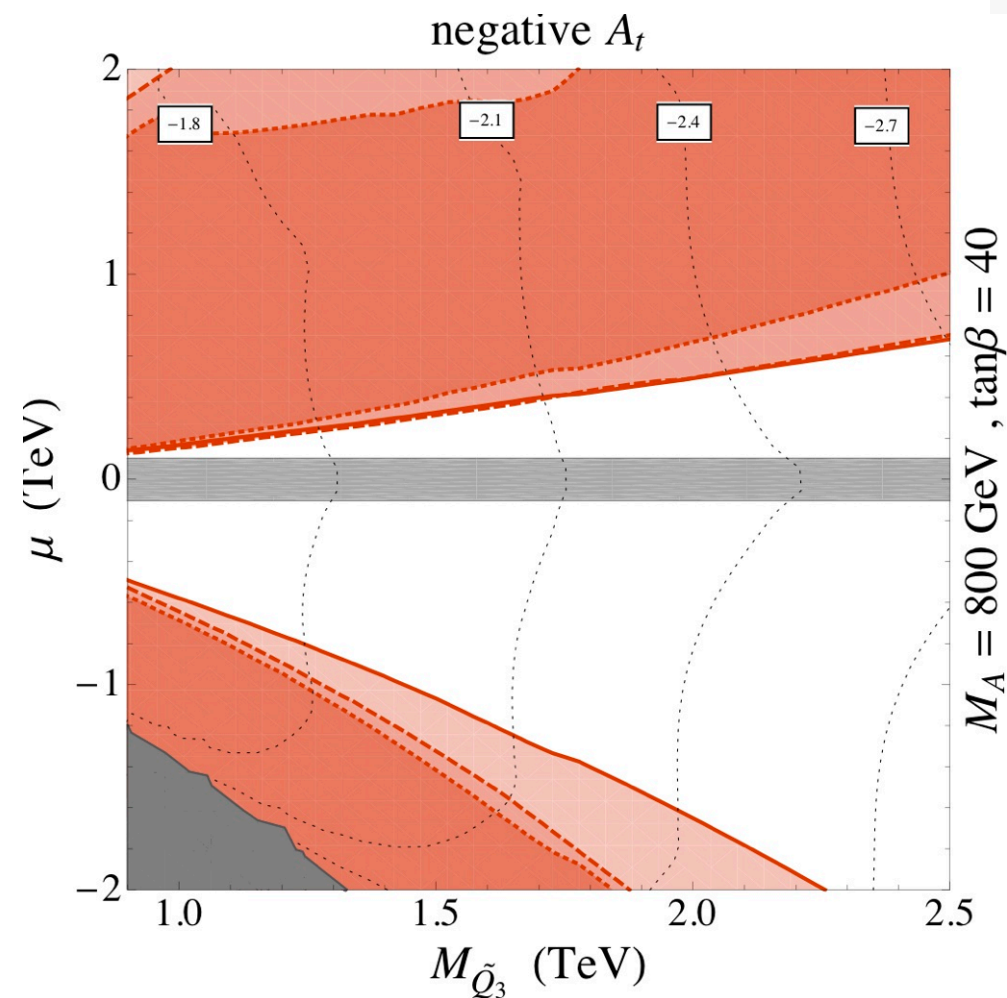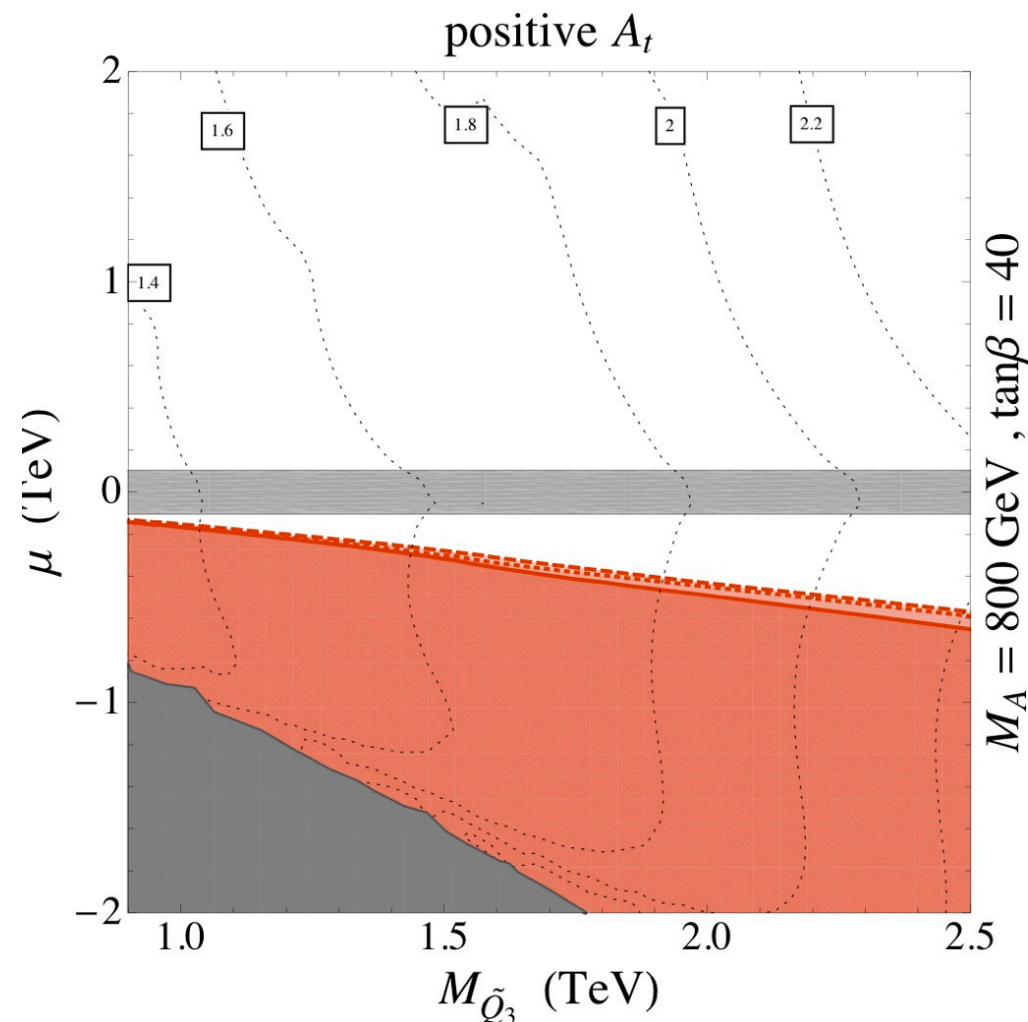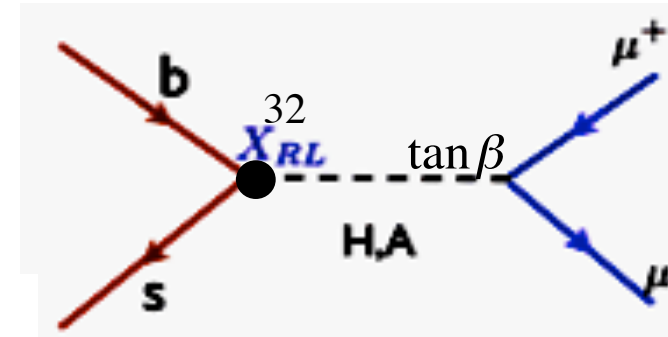
Borzumati, Bertolini,
Masiero, Ridolfi

- **If ~~SUSY~~ is transmitted at low energies: M~ M$_{SUSY}$,**
Squark mass matrices approx. block diag, only FC effects in the chargino-stop& H$^+$ loops

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

Bounds from $B_s \to \mu^+\mu^-$

Loop-induced A/H mediated FCNC's

intimately connected to the structure of the squark mass matrices
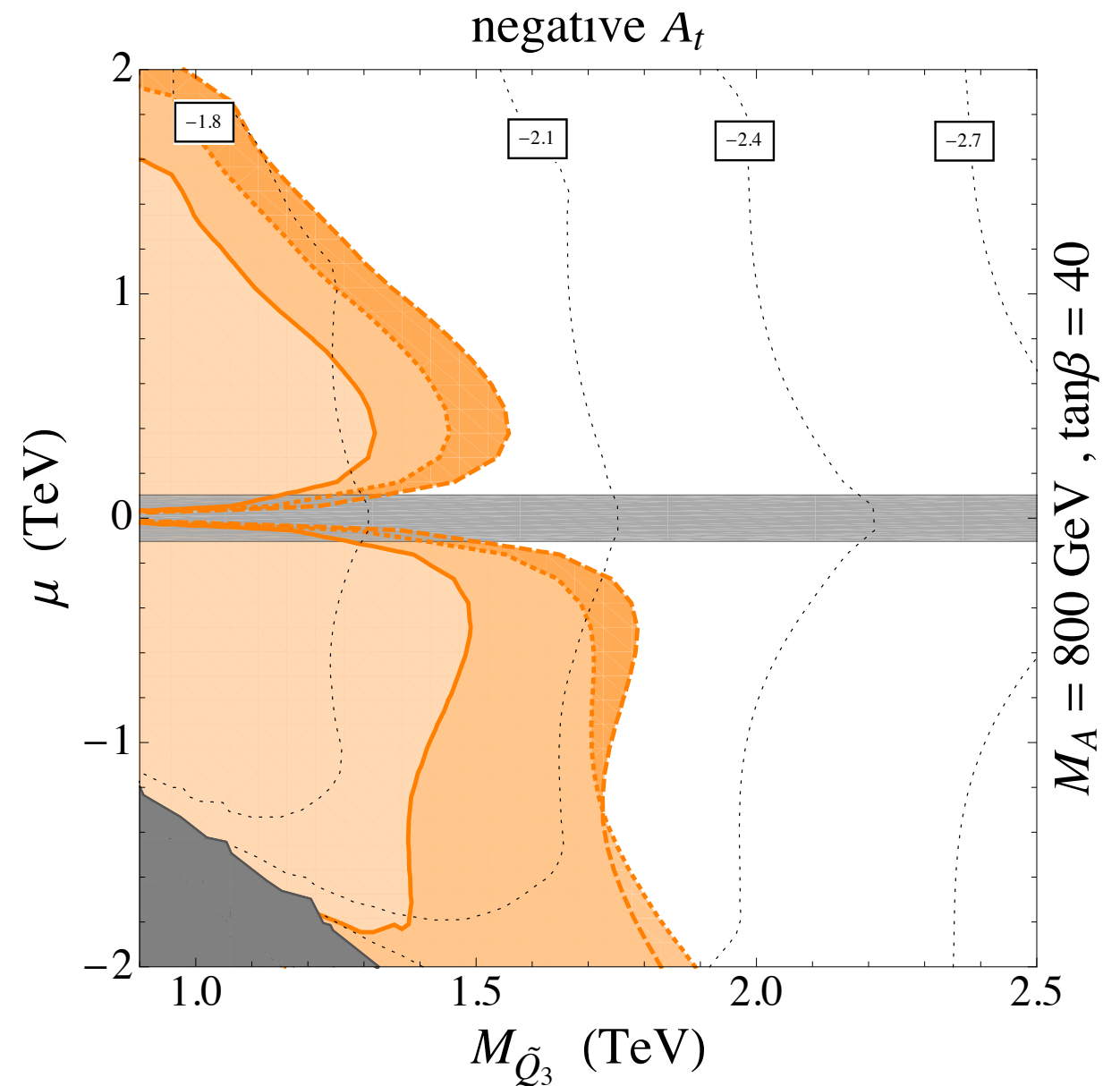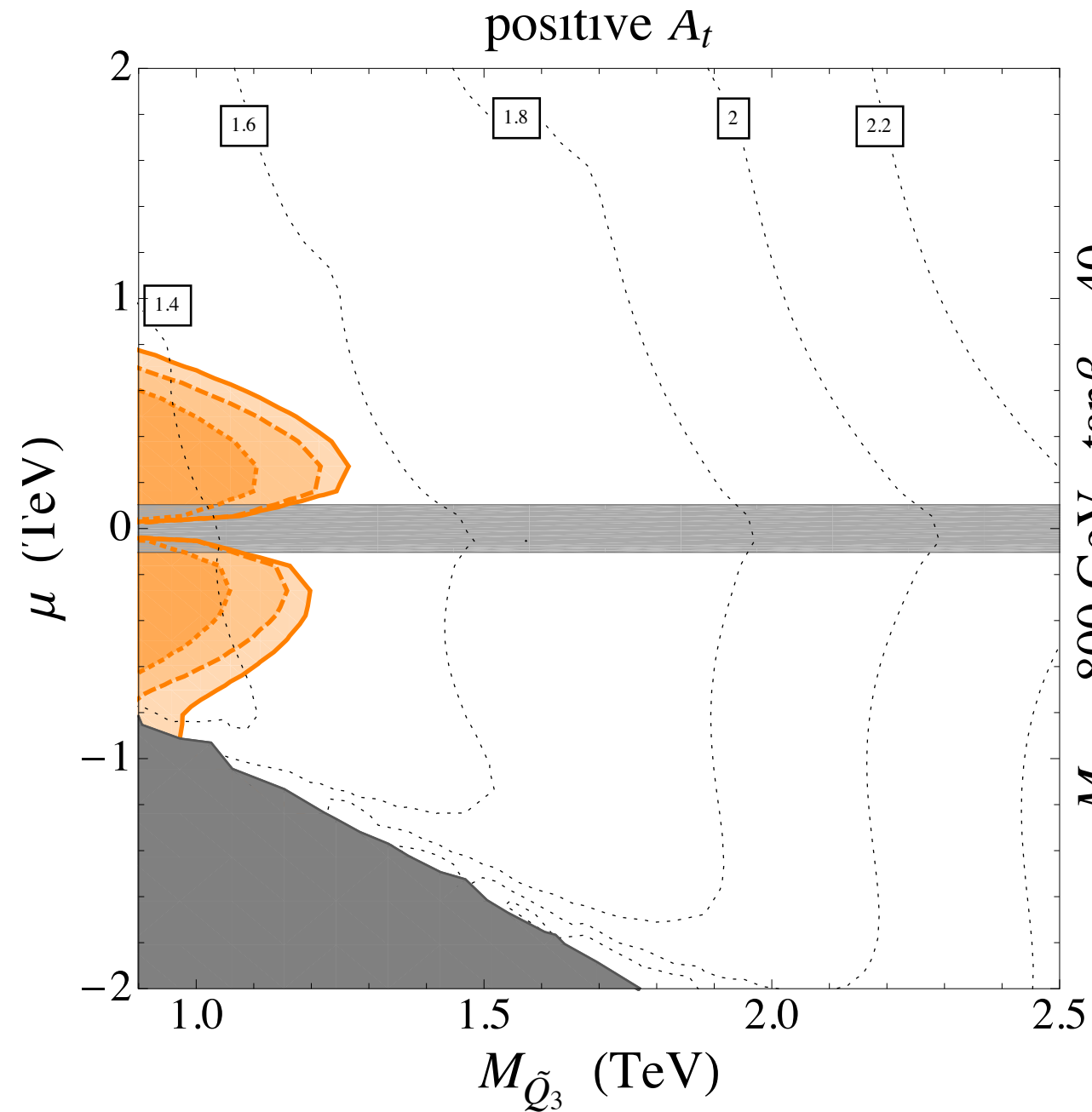
Altmannshofer, MC, Shah, Yu

Red solid line: $B_s \to mu^+mu^-$ with low energy SUSY breaking effects
Red dashed (dotted) line has high energy MFV with running of all (1st-,2nd vs 3rd gen.) parameters

Positive values of A_t less constraining for sizeable m_A and large tan beta

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

Bounds from $B_s \rightarrow X_s \gamma$

Altmannshofer, MC, Shah, Yu

Orange solid line from B X_s gamma with low energy SUSY breaking effects
Orange dashed (dotted) line has high energy MFV with running of all (1st-,2nd vs 3rd generation) parameters