Higgs Discovery and an Enhanced $\gamma\gamma$ Rate in the MSSM

Nausheen R. Shah
University of Michigan

M. Carena, S. Gori, N. R. S & C. E. M. Wagner, **arXiv:1112.3336** [hep-ph]
M. Carena, S. Gori, N. R. S, C. E. M. Wagner & L. Wang, **arXiv:1205.5842** [hep-ph]
M. Carena, S. Gori, I. Low, N. R. S & C. E. M. Wagner, **arXiv:1211.6136** [hep-ph]
M. Carena, S. Gori, N. R. S, C. E. M. Wagner & L. Wang, **In Preperation**

Outline

- Motivation:
  - Recent Atlas/CMS Results
- MSSM:
  - Higgs Mass
  - ~125 GeV Higgs
- Production and Decays:
  - Staus & Stops
- Vaccum Stability:
  - Limits on possible effects
- NMSSM
- Conclusions and Outlook

Motivation

Recent Experimental Results

Higgs Discovery!

- CMS: $m_h \sim 126.2$ GeV (ZZ), 124.9 GeV ($\gamma\gamma$)
- ATLAS: $m_h \sim 123.5$ GeV (ZZ), 126.6 GeV ($\gamma\gamma$)

- Possible Enhanced $\gamma\gamma$ Rate:
  - $\mu = 1.8$ ATLAS ($\sim 2.4\ \sigma$)
  - $\mu = 1.5$ CMS (July 4th)

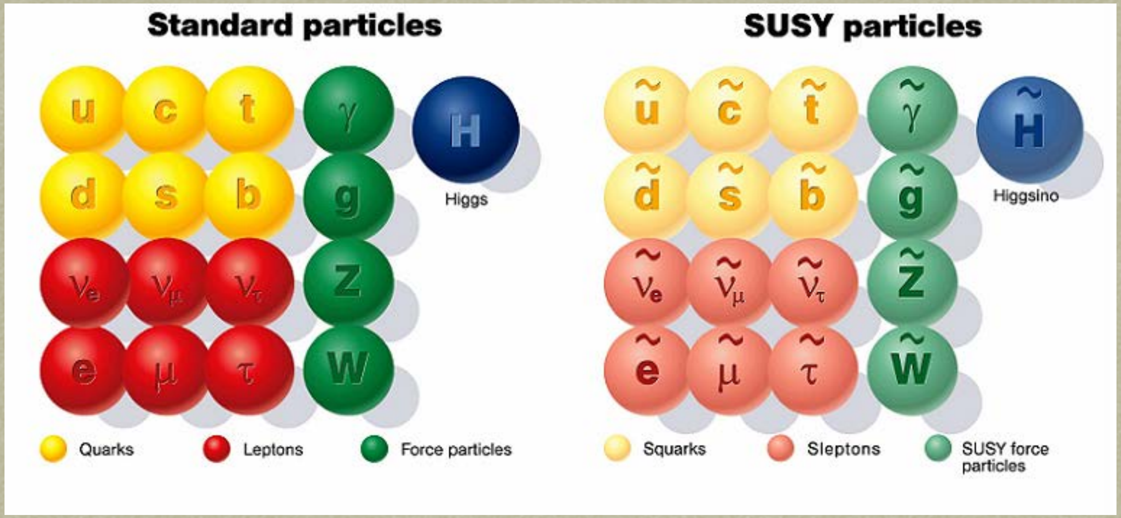
Can SUSY Accommodate:

- $m_h \sim 125$ GeV
- Enhanced $\gamma\gamma$ rate decoupled from WW and ZZ rate

Supersymmetry

Fermion-Boson Symmetry

Minimal Particle Content



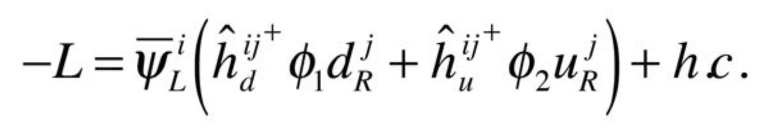
- For every fermion there is a boson of equal mass and couplings and visa versa.
- No new dimensionless couplings.
- Couplings of SUSY particles equal to couplings of SM particles.
- Helps stabilize the weak scale-Planck scale hierarchy.
- Provides a good Dark Matter candidate (the lightest SUSY Particle).
- Allows for gauge coupling unification.
- Radiatively Induces electroweak symmetry breaking.

Higgs Mass

Dependence on MSSM Parameters

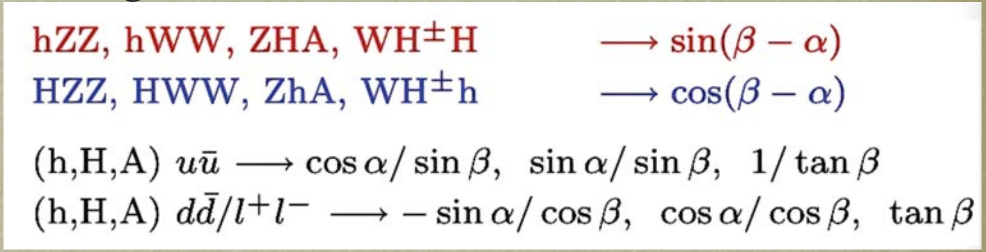
What does the MSSM imply for the Higgs Sector?

- 2 Higgs *SU(2)* doublets: ϕ_1 and ϕ_2
  - 2 CP-even (*h, H*) with mixing angle α.
  - 1 CP-odd (*A*) and a charged pair H^{+-}
    - tan $\beta = v_2/v_1,\qquad v^2 = v_1^2 + v_2^2 = 246$ GeV
- At tree level, one Higgs doublet couples only to *down* quarks and the other couples only to *up* quarks:



$$-L = \overline{\psi}_L^i \left(\hat{h}_d^{ij^+} \phi_1 d_R^j + \hat{h}_u^{ij^+} \phi_2 u_R^j \right) + h.c.$$

- Up and down sectors diagonalized independently:
  - Higgs interactions remain flavor diagonal at tree-level.
- Couplings :
  - Gauge bosons and fermions (SM normalized)



hZZ, hWW, ZHA, $WH^{\pm}H$	$\longrightarrow \sin(\beta-\alpha)$
HZZ, HWW, ZhA, $WH^{\pm}h$	$\longrightarrow \cos(\beta-\alpha)$
(h,H,A) $u\bar{u}$	$\longrightarrow \cos\alpha/\sin\beta,\quad \sin\alpha/\sin\beta,\quad 1/\tan\beta$
(h,H,A) $d\bar{d}/l^+l^-$	$\longrightarrow -\sin\alpha/\cos\beta,\quad \cos\alpha/\cos\beta,\quad \tan\beta$

- Lightest (SM-like) Higgs naturally light due to SUSY, $m_h \leq m_Z$. (tree)
  - Others may be heavy and roughly degenerate (decoupling limit).

Radiative Corrections to the SM-like Higgs Boson Mass

Important corrections due to incomplete cancellations of particles & sparticles in loops.

- Main effect due to *stops*:

$$X_t = A_t - \mu^* / \tan\beta$$

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

- Moderate / large values of tan β, large non-standard Higgs masses & $M_{SUSY} \sim m_Q \sim m_u$:

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

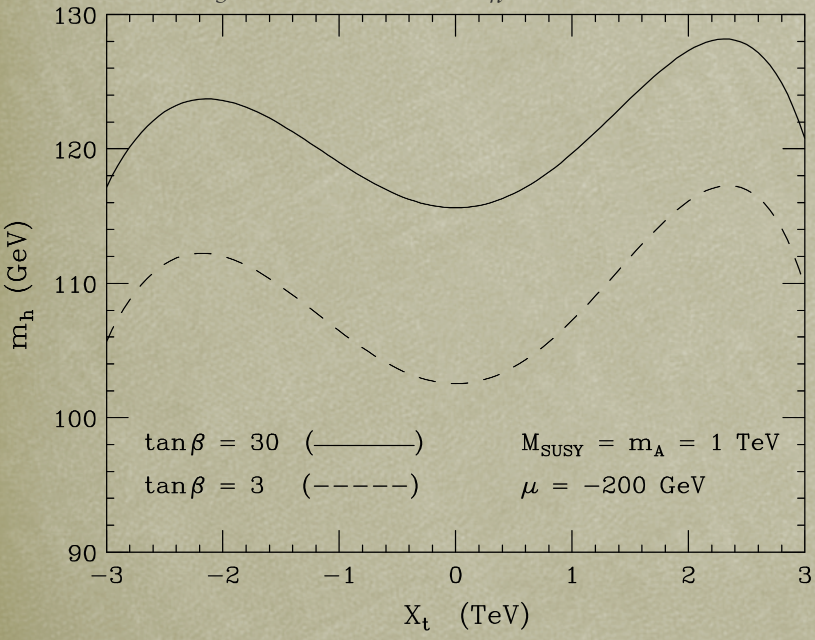
$$t = \log\frac{M^2_{\mathrm{SUSY}}}{m_t^2} \qquad \tilde{A}_t = A_t - \mu\cot\beta \qquad \tilde{X}_t = \frac{2\tilde{A}_t^2}{M^2_{\mathrm{SUSY}}}\left(1 - \frac{\tilde{A}_t^2}{12M^2_{\mathrm{SUSY}}}\right)$$

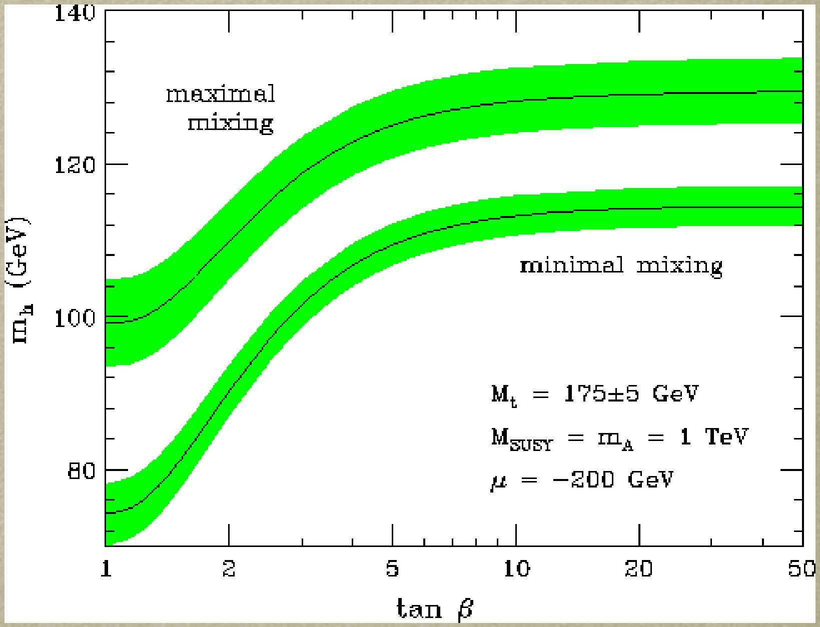
- m_h:
  - Quadratic and quartic dependence on the stop mixing parameter, A_t
  - Log dependence on averaged stop mass scale, M_{SUSY}

Standard Model-like Higgs Mass

- Long list of 2-loop computations:
  - Carena, Degrassi, Ellis, Espinoza, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, Wagner, Weiglein, Zhang, Zwirner.
- 2-loop corrections: $m_h \lesssim 130$ GeV
  - $M_S = 1 - 2$ TeV, $\Delta m_h \sim 2 - 5$ GeV

Carena and Haber, hep-ph/0208209





$X_t = A_t - \mu/\tan\beta, \quad X_t = 0:$ No mixing; $\quad X_t = \sqrt{6}M_S:$ Max. Mixing

- **$m_h \sim 125$ GeV: Large X_t and Moderate/Large $\tan\beta$**

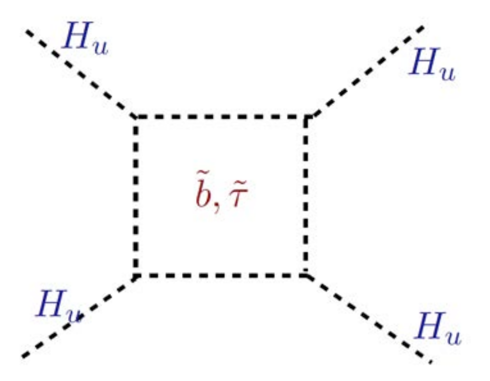
Additional Affects at Large tan β

- Sbottoms: $$\Delta m_h^2 \simeq -\frac{h_b^4 v^2}{16\pi^2}\frac{\mu^4}{M_{\mathrm{SUSY}}^4}\left(1+\frac{t}{16\pi^2}\left(9h_b^2 - 5\frac{m_t^2}{v^2} - 64\pi\alpha_3\right)\right)$$
  - h_b recieves 1-loop corrections that depend on sign of $\mu M_{\tilde{g}}$

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

- Staus: $$\Delta m_h^2 \simeq -\frac{h_\tau^4 v^2}{48\pi^2}\frac{\mu^4}{M_{\tilde{\tau}}^4}$$
  - h_τ corrections depend on the sign of μM_2

$$h_\tau \simeq \frac{m_\tau}{v\cos\beta(1+\tan\beta\Delta h_\tau)}$$



- Both corrections give negative contributions to the Higgs mass
  - Positive values of $\mu M_{\tilde{g}}$ and μM_2 enhance the value of the Higgs mass.

A_t Dependence

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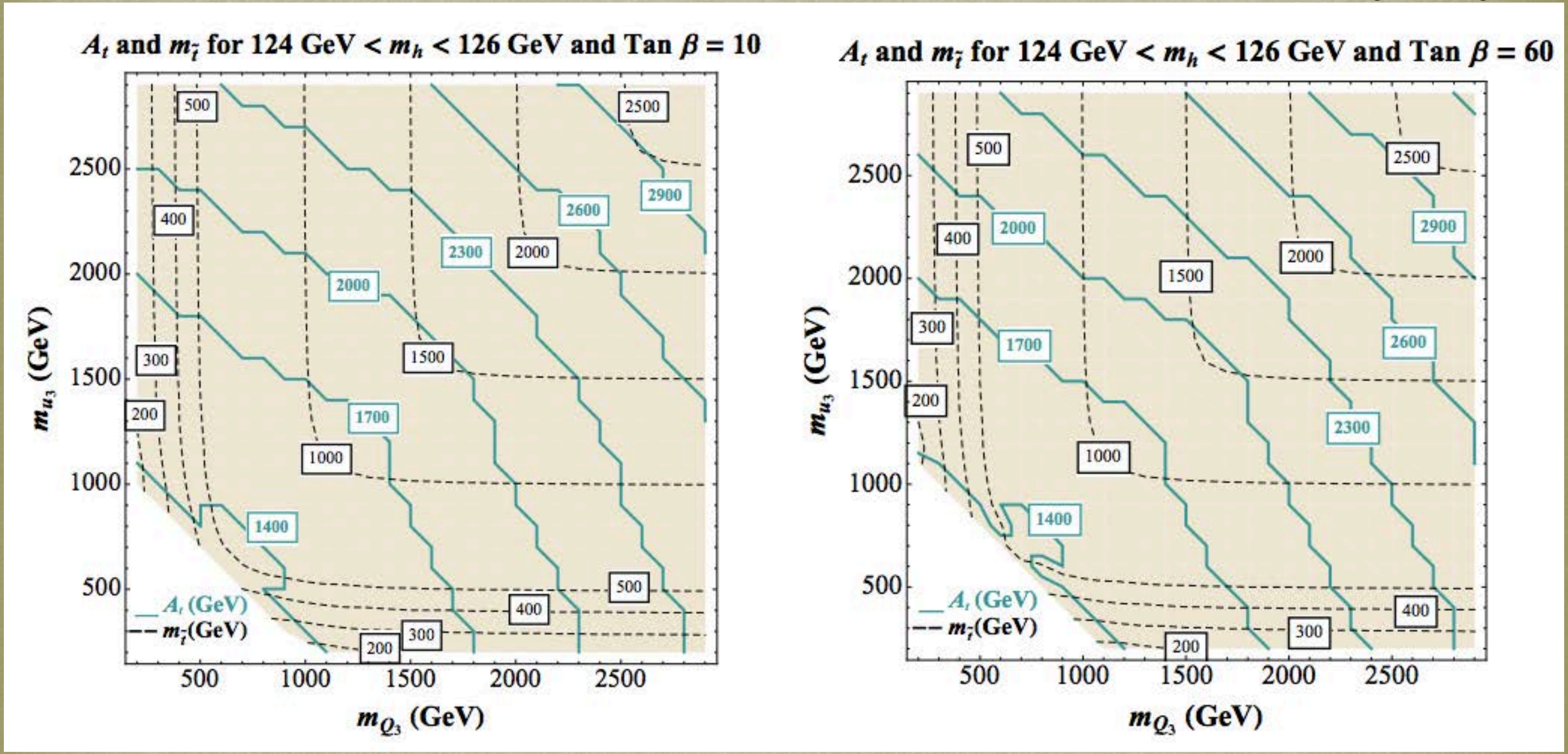
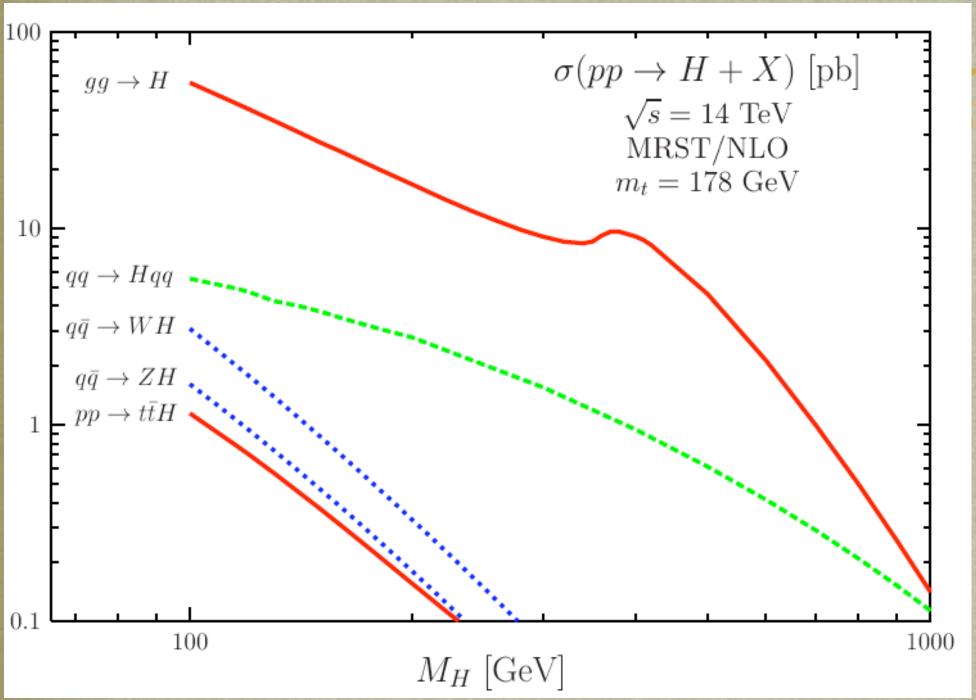


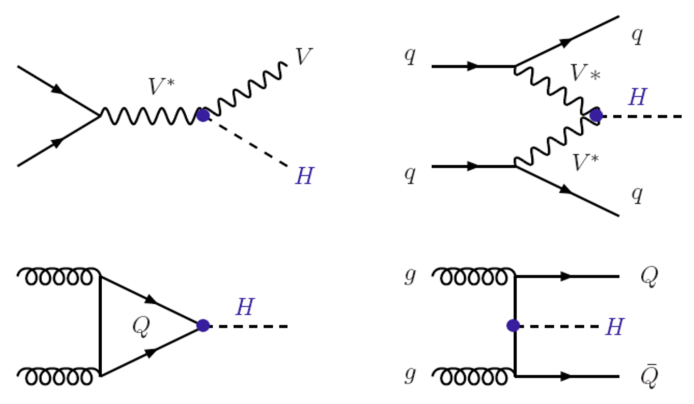
- Contours of A_t needed to obtain 124 GeV < m_h < 126 GeV.
  - Associated stop mass contours in black.
- Illustrates the requirement for large A_t.
  - No hard lower bound for stop masses

Cross-sections and Rates

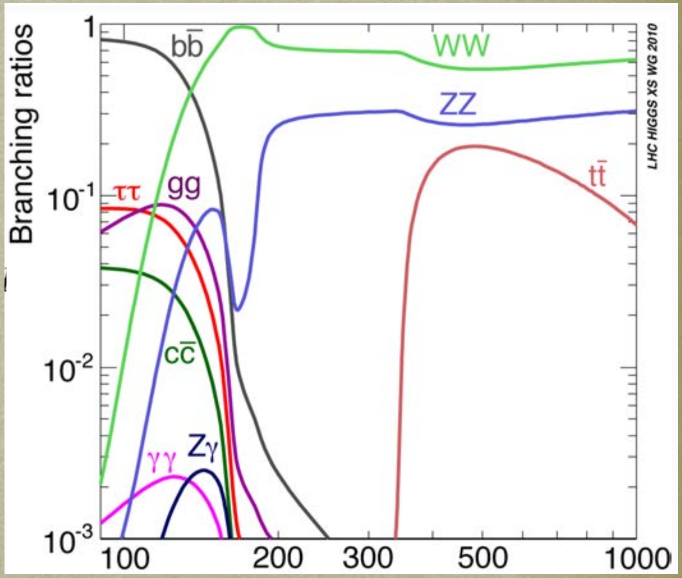
Higgs Production Mechanisms at the LHC

Main Higgs Production channels at the LHC





A. Djouadi, 0503172



- The event rate depends on 3 quantities:

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

- These may be affected by new physics.
- If SM rate modified ➔ total width is modified as well.
- Particularly true for *WW* rate for high Higgs masses and for *bb* rate for low Higgs masses.

Is it Possible to Enhance Di-Photon Rate Without Affecting Higgs into *WW* and ZZ Rate?

- Higgs decay into photons proceeds via charged particle loops.
- If colorless, only $\gamma\gamma$ impacted.
- $\tilde{\tau}$:
  - For equal soft masses:
  - Enhancement for large mixing.
  - *WW* and top SM cont. = *-13*

$$b_{\tilde{\tau}} \frac{\partial \log \det \left(M_{\tilde{\tau}}^2\right)}{\partial \log v} \simeq -\frac{2}{3} \frac{m_\tau^2}{m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2} \mu^2 \tan^2 \beta$$

$$\Delta A_{\gamma\gamma} \propto -\frac{m_{\tilde{\tau}_2}^2}{6\, m_{\tilde{\tau}_1}^2} \left(1 - \frac{m_{\tilde{\tau}_1}^2}{m_{\tilde{\tau}_2}^2}\right)^2$$

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

- Large mixing here means:

Large μ and Large tan β

$m_h \sim 125$ GeV: Light Stops and the $\gamma\gamma$ Rate

$$\delta A^{\tilde t}_{\gamma\gamma,gg} \propto \frac{m_t^2}{m_{\tilde t_1}^2 m_{\tilde t_2}^2}\left[m_{\tilde t_1}^2 + m_{\tilde t_2}^2 - X_t^2\right]$$

$$\delta A^{\tilde t}_{\gamma\gamma,gg} \propto \frac{m_t^2}{m_{\tilde t_1}^2}\left[1 - \frac{A_t^2}{m_Q^2}\right]$$

- **$A_t \sim m_Q >> m_u$ and large $\tan\beta$:**
  - **Sign of δA depends on A_t/m_Q > (<) 1**
- **Gluon fusion:**
  - Dominant SM contribution from t (4).
  - Stops can enhance/suppress gluon fusion: $\tilde t$ (2 δA)
- **Di-photon width:**
  - SM W loop is partially suppressed by t loop (-13).
  - Light $\tilde t$:
    - Effect Opposite as on GF
      - If add to top cont. in GF, then suppress $\gamma\gamma$ (8/9 δ A)
- **Always have trade-off between GF and $\gamma\gamma$**
- More significant impact on GF than on $\gamma\gamma$

Mixing Effects in CP-even Higgs Sector

- Mixing can have very relevant effects on the production rates and decay branching ratios.
  - In most regions of parameter space, mixing effects conspire to enhance the branching ratio into *bb*, thus suppressing the decay into photons and gauge bosons.

$$\mathcal{M}_H^2 = \left[\begin{array}{cc} m_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(m_A^2 + M_Z^2)\sin\beta\cos\beta + \mathrm{Loop}_{12} \\ -(m_A^2 + M_Z^2)\sin\beta\cos\beta + \mathrm{Loop}_{12} & m_A^2 \cos^2\beta + M_Z^2 \sin^2\beta + \mathrm{Loop}_{22} \end{array} \right]$$

$$hWW: \quad \sin(\beta-\alpha),$$

$$ht\bar{t}: \quad \frac{\cos\alpha}{\sin\beta},$$

$$hb\bar{b}: \quad -\frac{\sin\alpha}{\cos\beta}\left[1 - \frac{\Delta h_b \tan\beta}{1+\Delta h_b \tan\beta}\left(1 + \frac{1}{\tan\alpha\tan\beta}\right)\right]$$

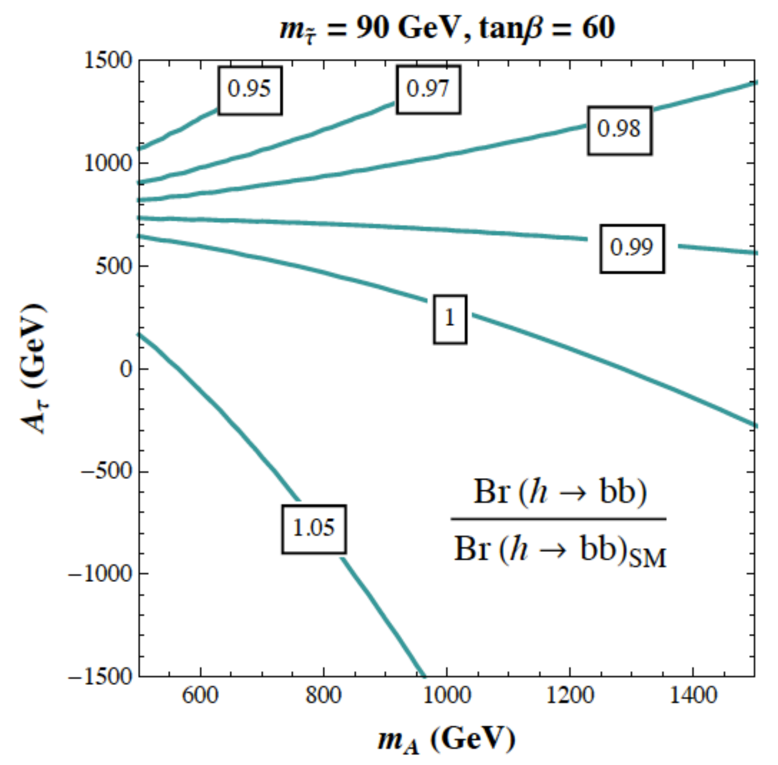
$$\sin(2\alpha) = \frac{2\,(\mathcal{M}_H^2)_{12}}{\sqrt{Tr[\mathcal{M}_H^2]^2 - det[\mathcal{M}_H^2]}},$$

$$\cos(2\alpha) = \frac{(\mathcal{M}_H^2)_{11} - (\mathcal{M}_H^2)_{22}}{\sqrt{Tr[\mathcal{M}_H^2]^2 - det[\mathcal{M}_H^2]}}$$

$$-(m_A^2 + M_Z^2)\sin\beta\cos\beta + \mathrm{Loop}_{12}$$

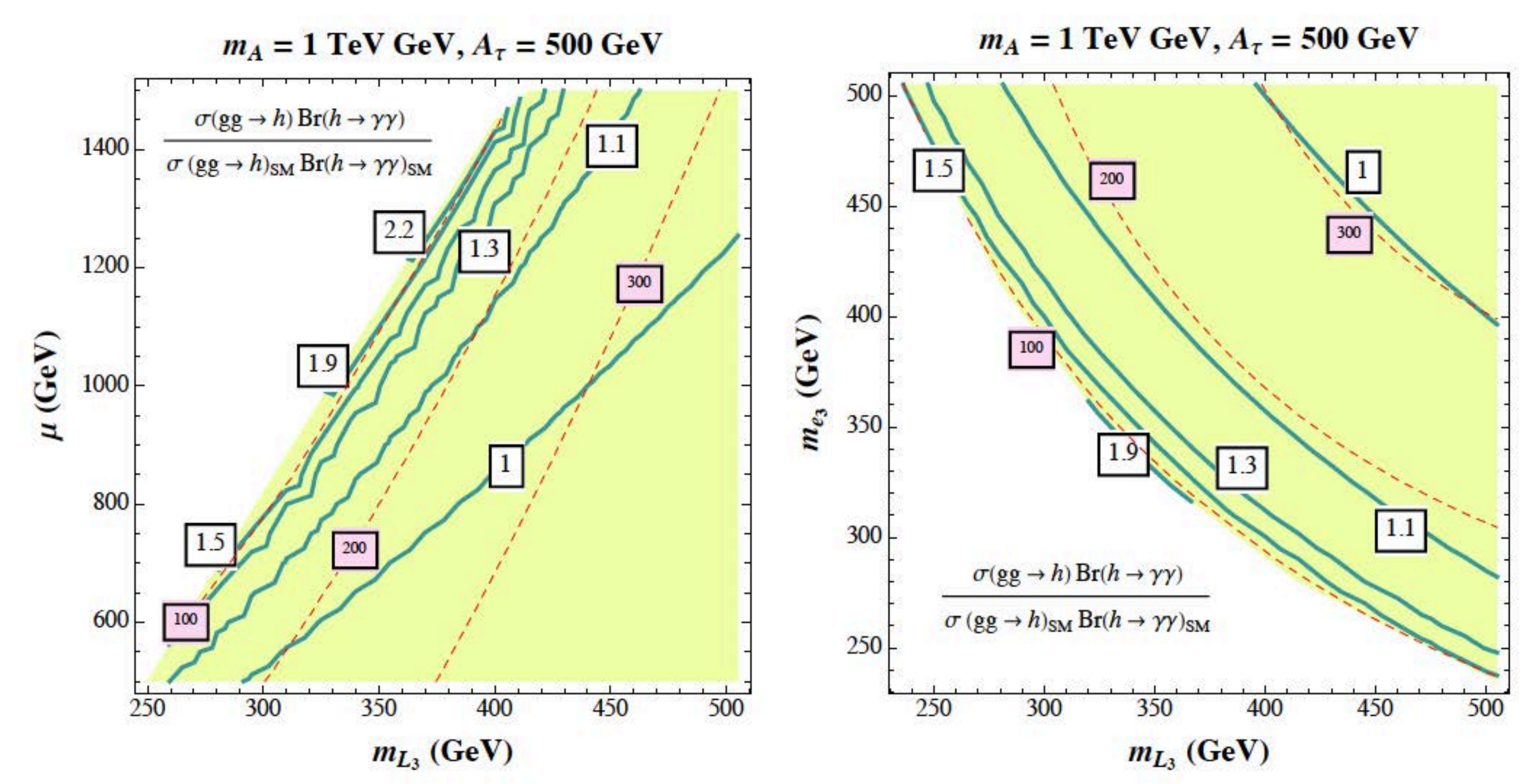
m_A, A_τ and $BR(h \to bb)$

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



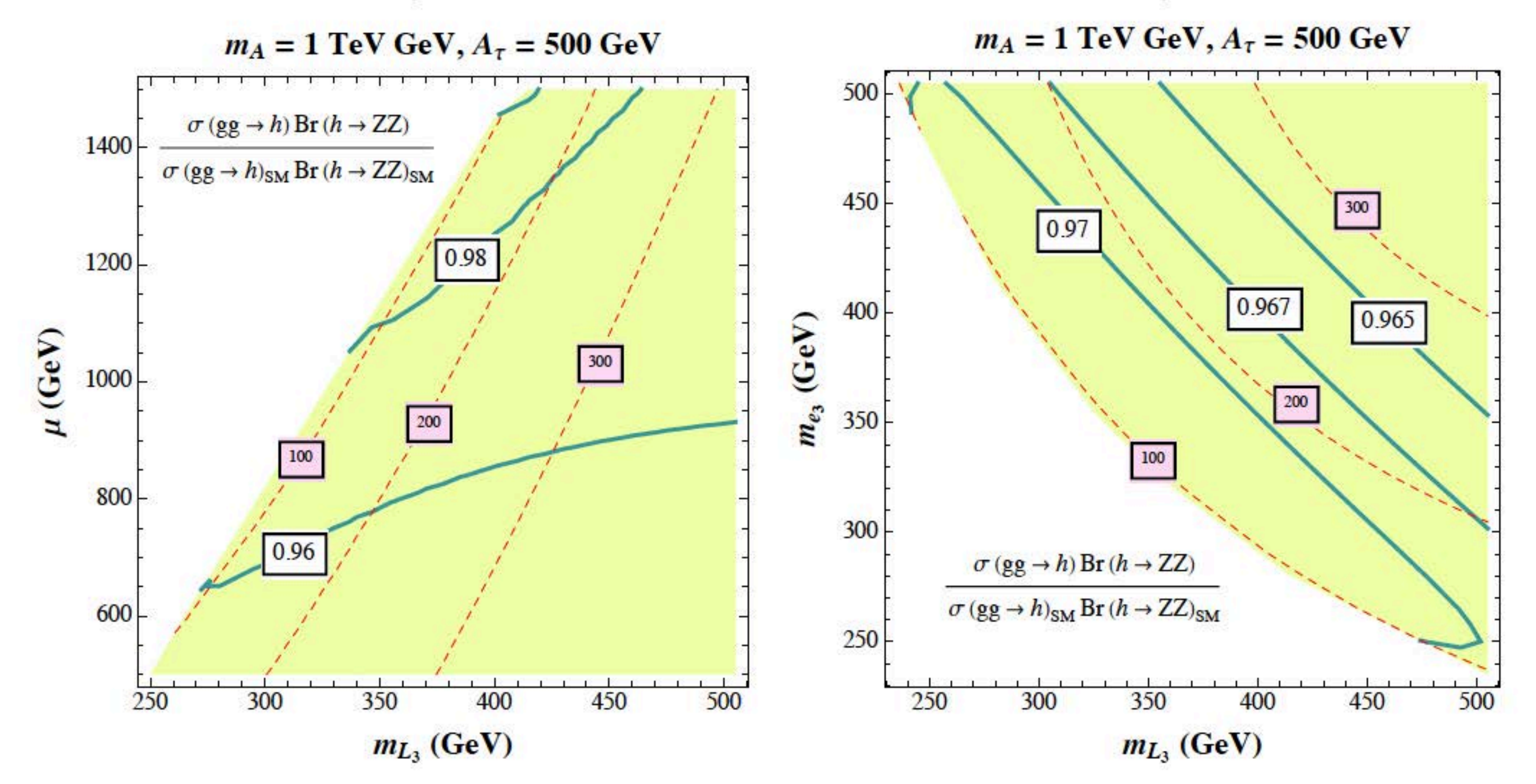
- The ratio of BR(h→ b b) to its SM value, in the (m_A, A_τ) plane.
- $\tan\beta = 60$, $m_{e3} = m_{L3} = 250$ GeV.
- We fix $m_{\tau 1} = 90$ GeV, hence μ varies in the range 500-550 GeV.
- Relevant squark parameters are $A_t = 1.8$ TeV, $m_{Q3} = m_{u3} = 1.5$ TeV corresponding to $m_{t1,2} =$ 1.4, 1.6 TeV and $m_h \sim 125$ GeV.
- *bb* suppressed → $\gamma\gamma$, *ZZ/WW* enhanced.
- Trade-off between m_A and A_τ

Light Staus:
Large μ, tan β, m_A and A_τ



- Light staus with large mixing may induce relevant enhancement of the BR of the decay of a SM-like Higgs into two photons, without affecting other decays too much.
  - A_τ changes BR into *bb*, impacting γγ, WW and ZZ together.
    - Dashed lines denote contours of stau masses

ZZ Production Minimally Impacted



$\gamma\gamma$/ ZZ Rates

tan β = 60 and μ such that light $m_{\tilde{\tau}}$ = 90 GeV.

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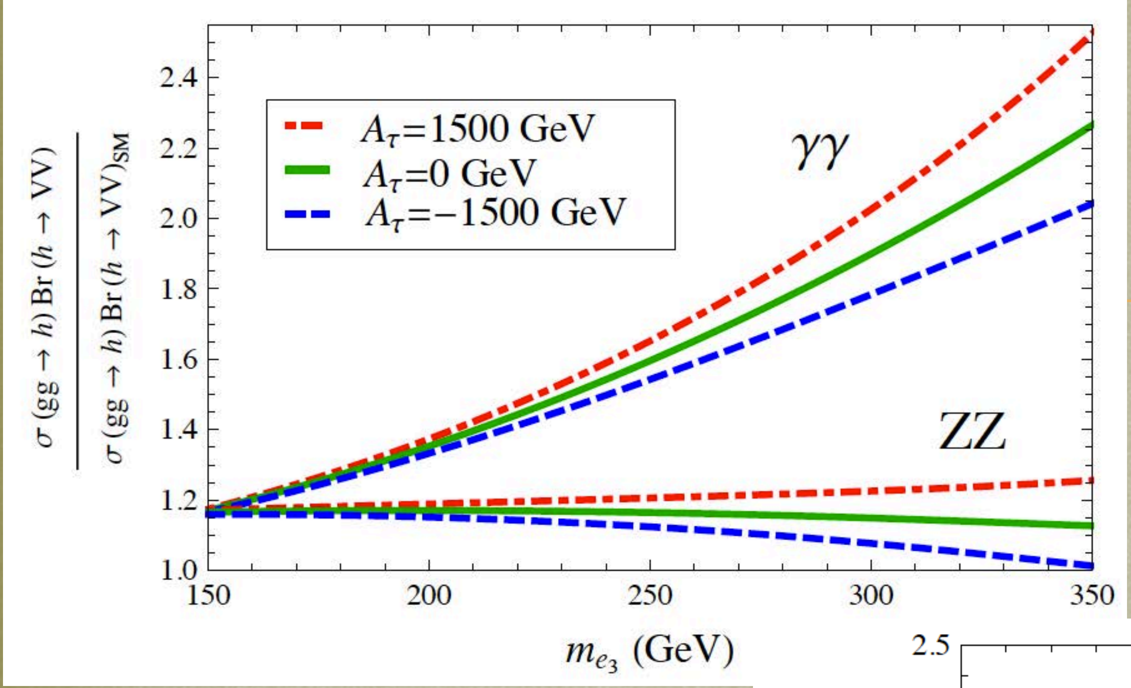
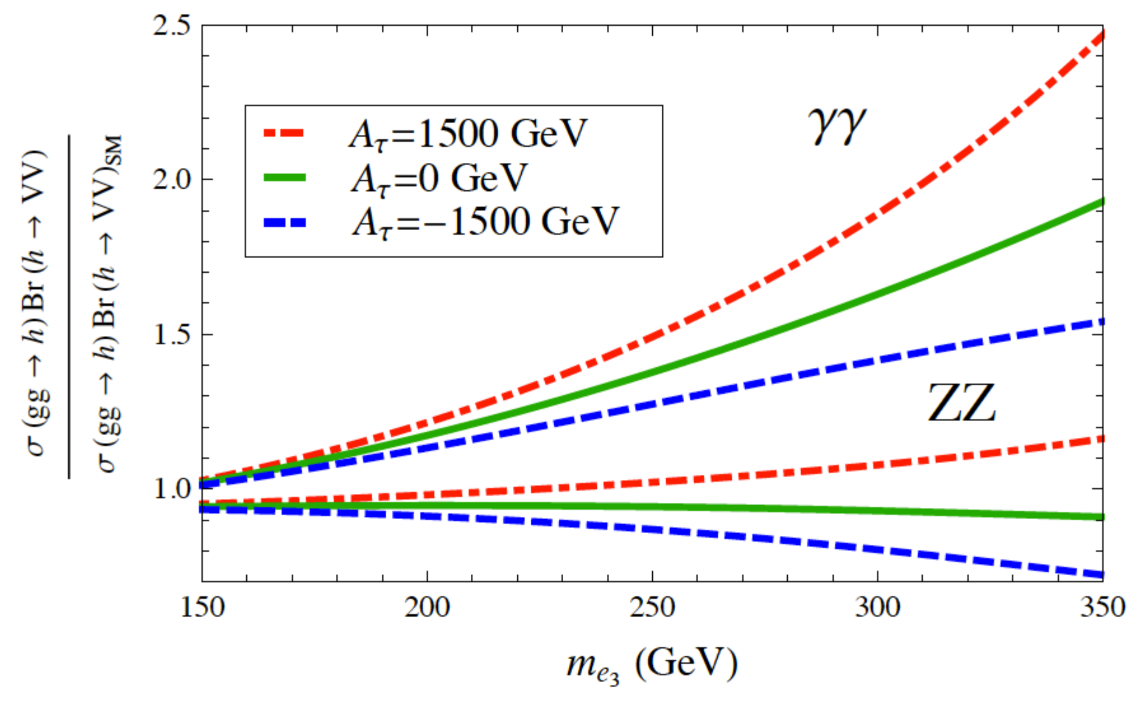
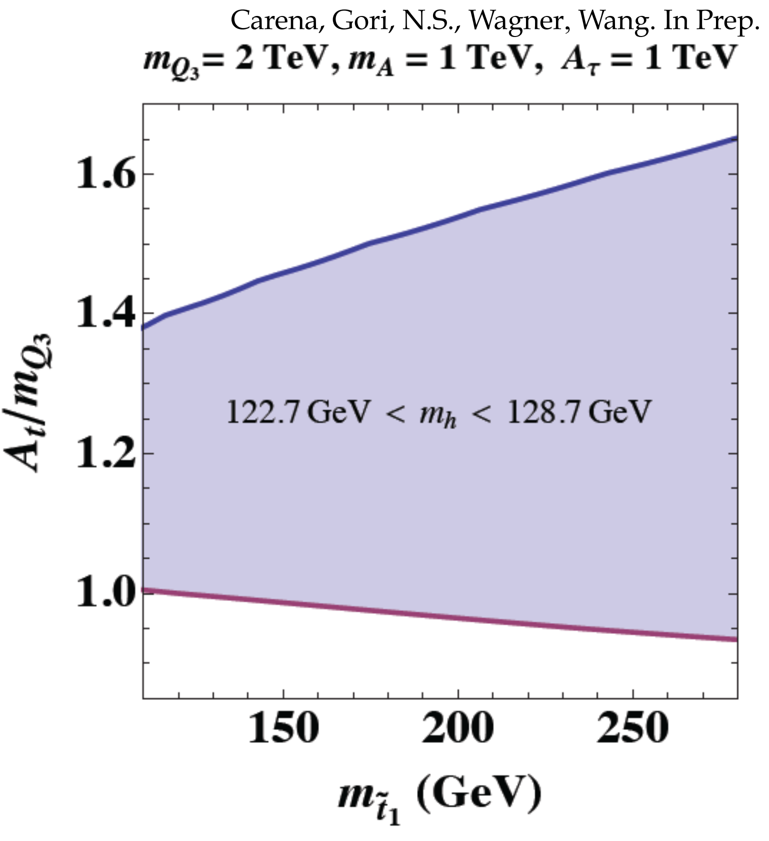


- **Top:**
  - $m_{\tilde{t}}$ ~ 140 GeV
  - m_{Q3} ~ 2.5 TeV
  - A_t ~ 2 TeV
  - m_A ~ 1.5 TeV

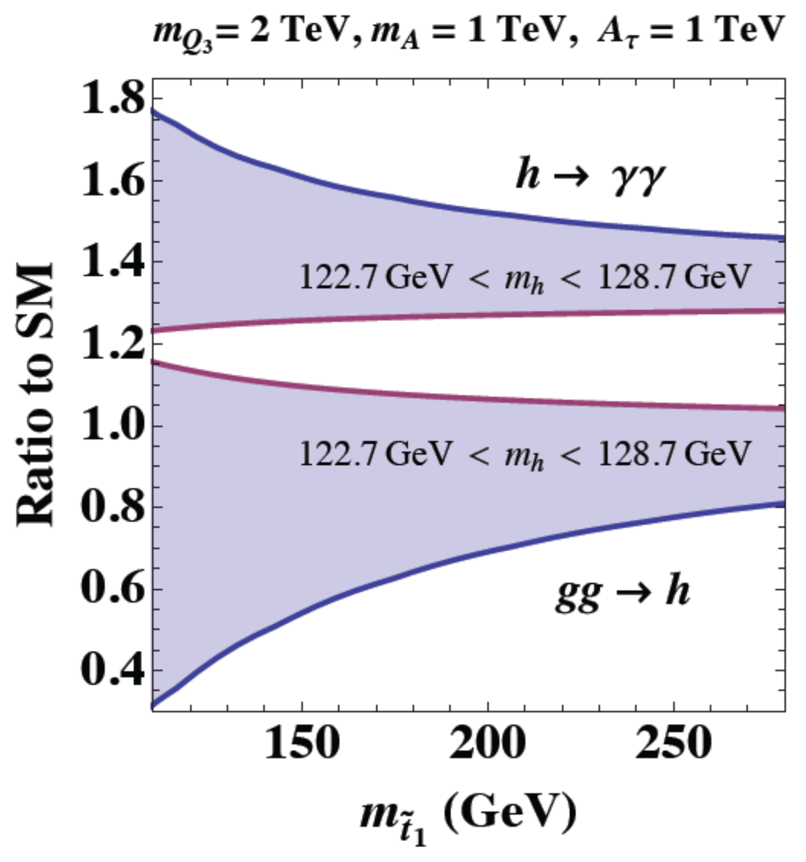
- **Right:**
  - $m_{\tilde{t}}$ ~ 500 GeV
  - m_{Q3} ~ 1.5 TeV
  - A_t ~ 1.4 TeV
  - m_A ~ 1 TeV





$\tan\beta = 70,\ m_{\tau 1} = 95$ GeV

Left:
A_t/m_Q consistent with Higgs mass
Bottom:
Corresponding GF and $\gamma\gamma$ (SM normalized)



Light Stops/Staus & Higgs Mixing

Vacuum Stability

Light Staus and Large $\mu \tan\beta$

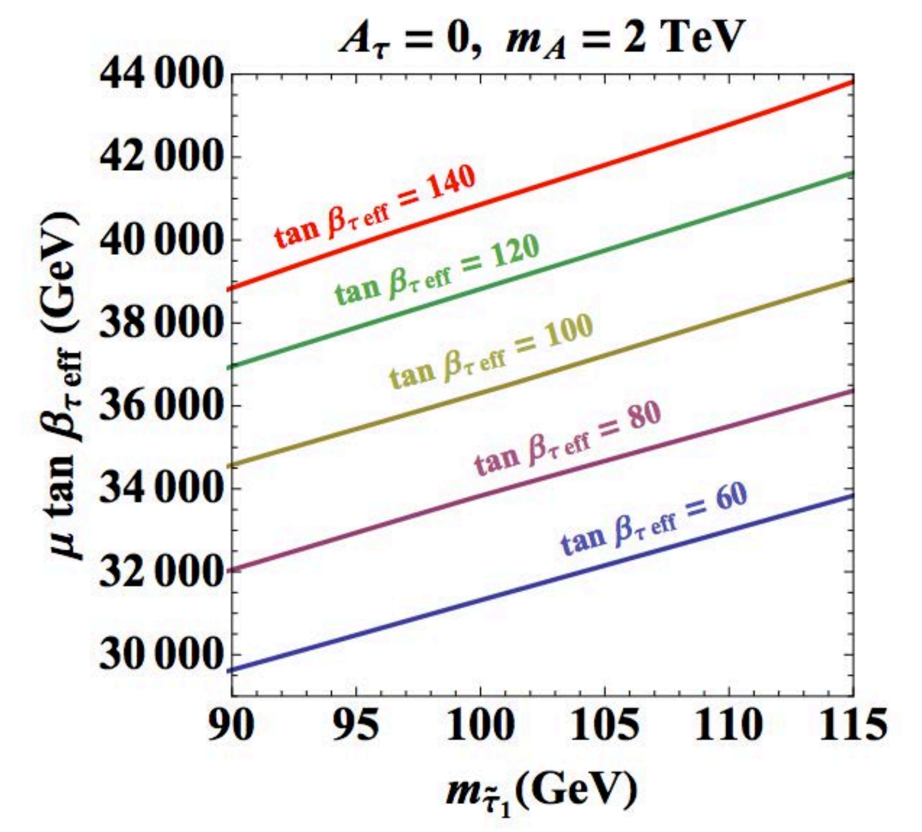
$$y_\tau = \sqrt{2}\,\frac{m_\tau}{v\cos\beta(1+\Delta_\tau)} \approx \frac{\tan\beta}{100(1+\Delta_\tau)}$$

$$\begin{aligned} V \;=\; & |\mu\, h_u - y_\tau \tilde{\tau}_L \tilde{\tau}_R^*|^2 + \frac{g_2^2}{8}\left(|\tilde{\tau}_L|^2 + |h_u|^2\right)^2 + \frac{g_1^2}{8}\left(|\tilde{\tau}_L|^2 - 2|\tilde{\tau}_R|^2 - |h_u|^2\right)^2 \\ & + m_{H_u}^2 |h_u|^2 + m_{L_3}^2 |\tilde{\tau}_L|^2 + m_{E_3}^2 |\tilde{\tau}_R|^2 + \frac{g_1^2 + g_2^2}{8}\,\delta_H\,|h_u|^4\;, \end{aligned}$$

$$\tan\beta_{\tau\,\mathrm{eff}} \equiv \frac{\tan\beta}{1+\Delta_\tau}$$

$$\begin{aligned} \Delta V \;\simeq\; & m_A^2 |h_d|^2 - \frac{m_A^2}{\tan\beta}(h_d h_u + \mathrm{h.c.}) + \frac{m_A^2}{\tan^2\beta}|h_u|^2 + (y_\tau A_\tau h_d \tilde{\tau}_L \tilde{\tau}_R^* + \mathrm{h.c.}) \\ & + \; |y_\tau|^2 |h_d|^2 \left(|\tilde{\tau}_L|^2 + |\tilde{\tau}_R|^2\right) + D\text{-terms.} \end{aligned}$$

- $\gamma\gamma$ rate depends dominantly on $\mu \tan\beta$
- EW vacuum stability depends dominantly on $\mu\, y_\tau$ and y_τ
- Δ_τ effects become important



$\Delta\tau \sim -0.15$ to -0.25

$\tan\beta \sim (0.85$ to $0.75)\tan\beta_{eff}$

μ destabilizes vacuum

Larger $\tan\beta$ and m_A stabilize vacuum

Positive A_τ further destabilizes

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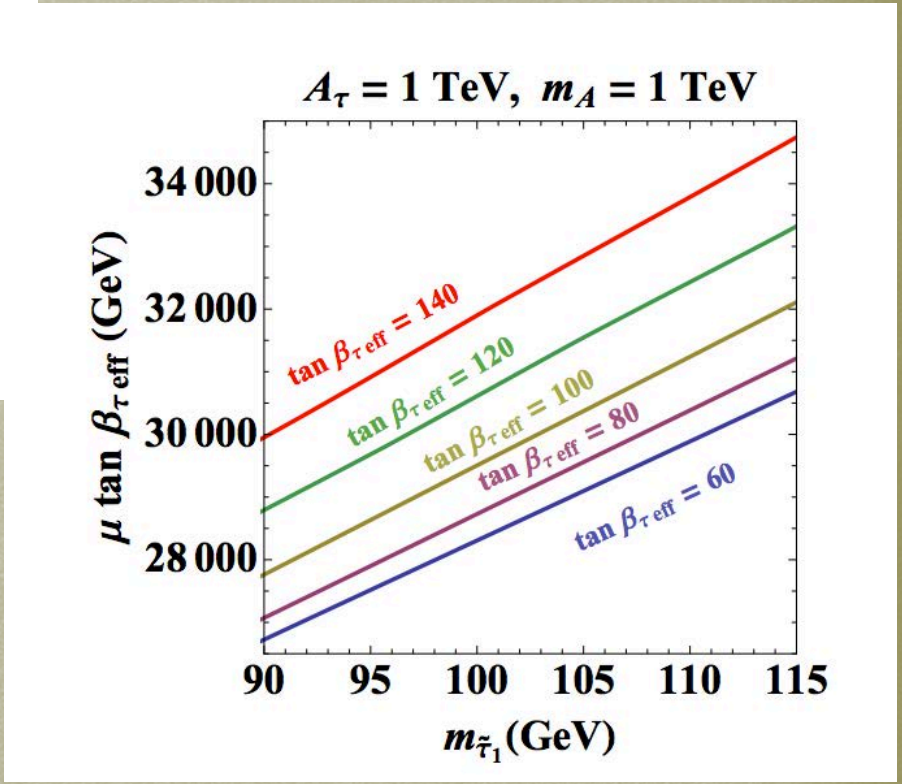
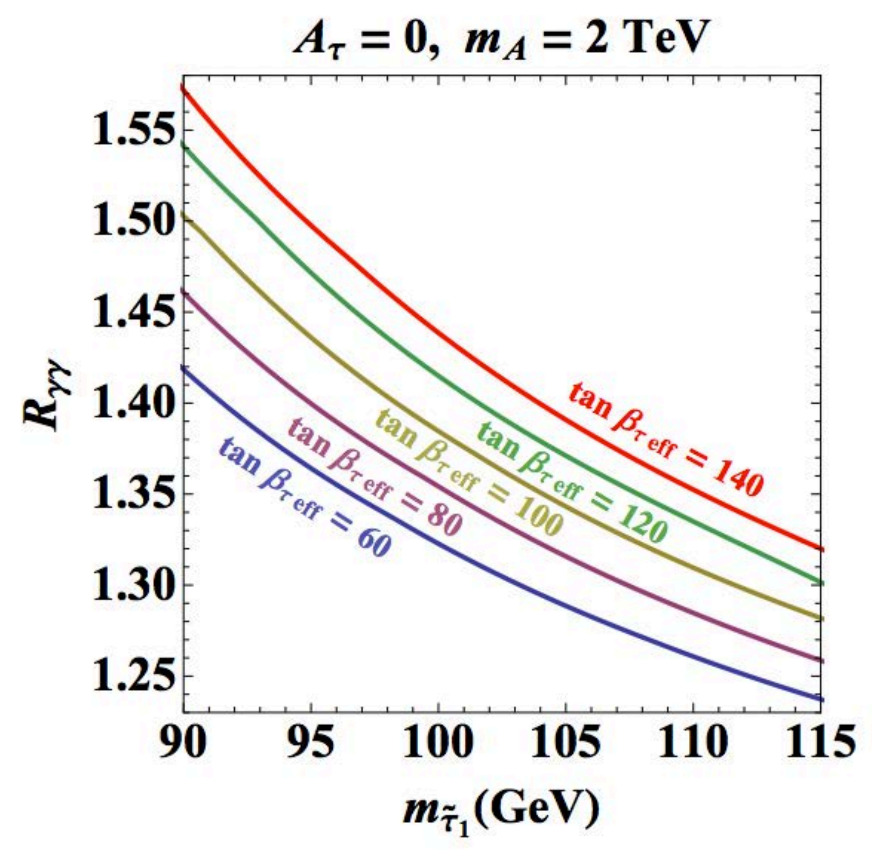


Ratios of $\gamma\gamma$ Consistent with Vacuum Stability



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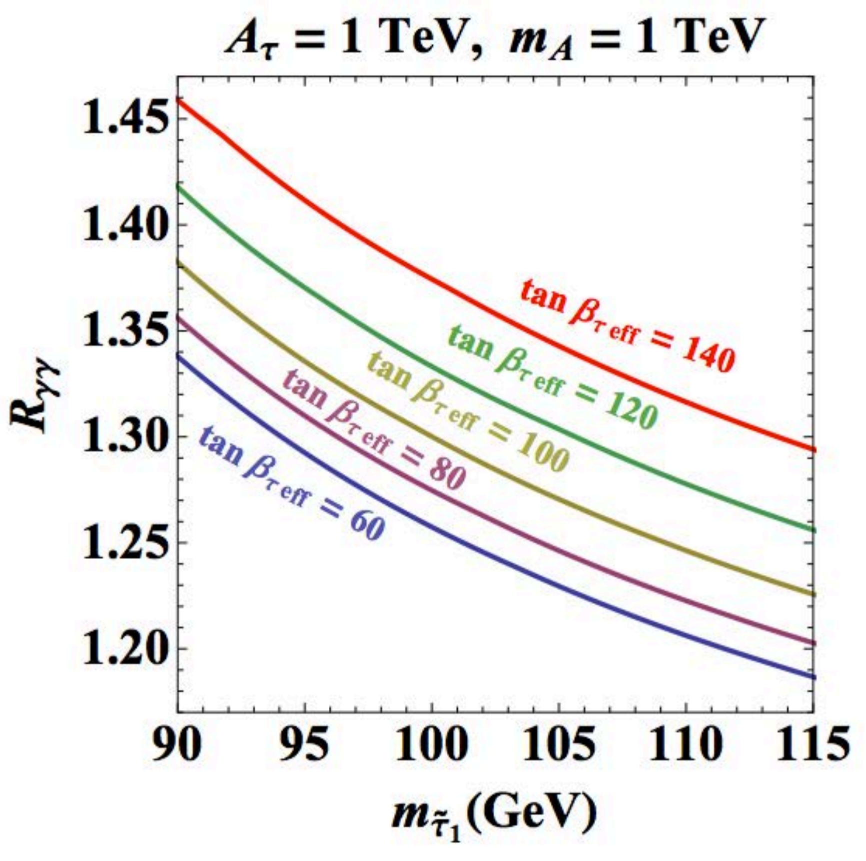
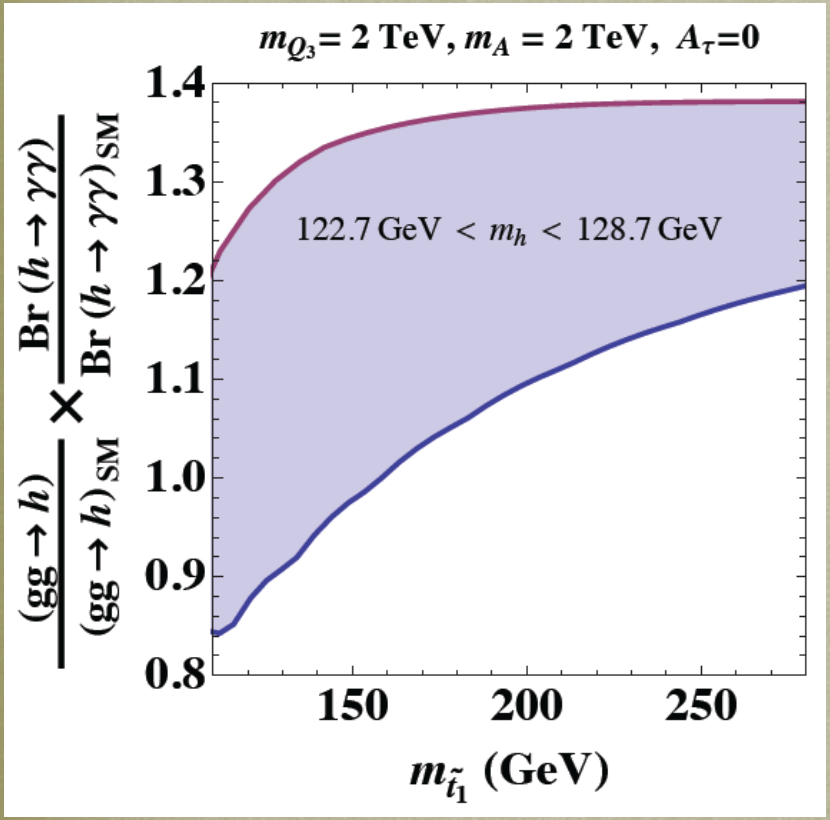
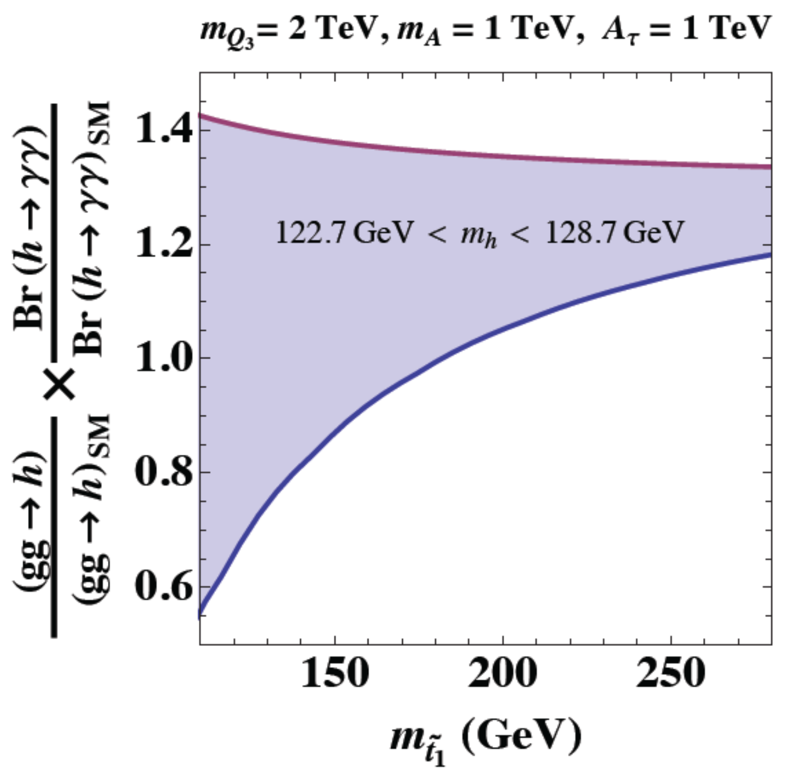


Even though $\mu\ tan\ \beta$ much lower for positive A_τ
Lower m_A partially compensates in $R_{\gamma\gamma}$

GF x $\gamma\gamma$ satisfying VS
$\tan\beta = 70$

Carena, Gori, N.S., Wagner, Wang. In Prep.





$\gamma\gamma$ Enhancement > 40%
Larger *tan β*

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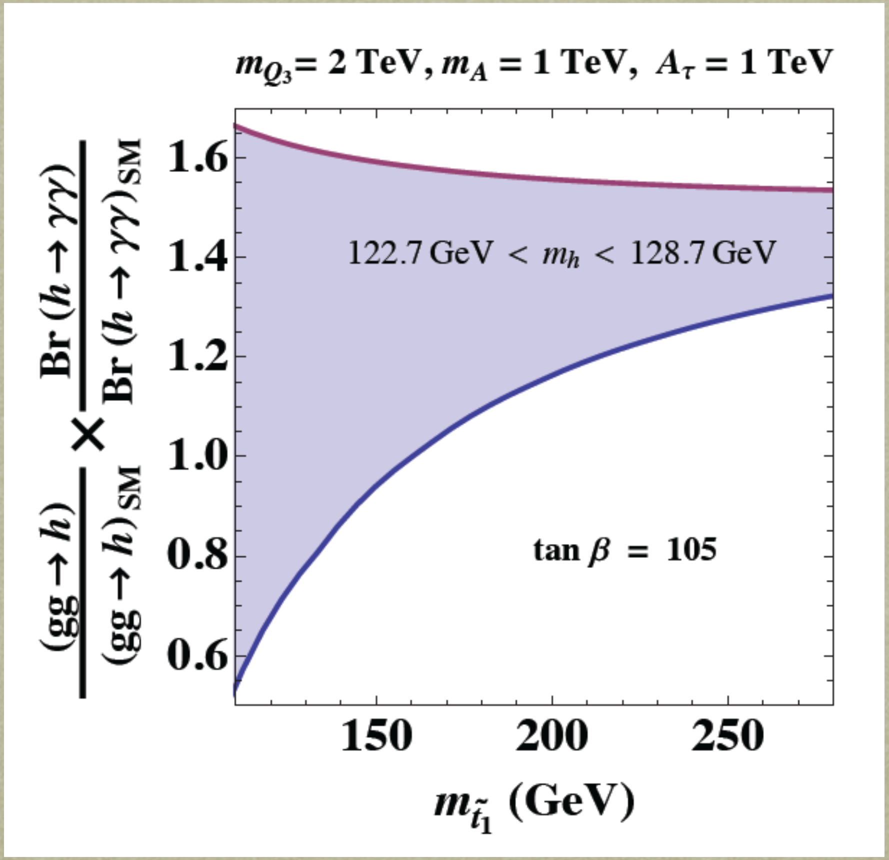

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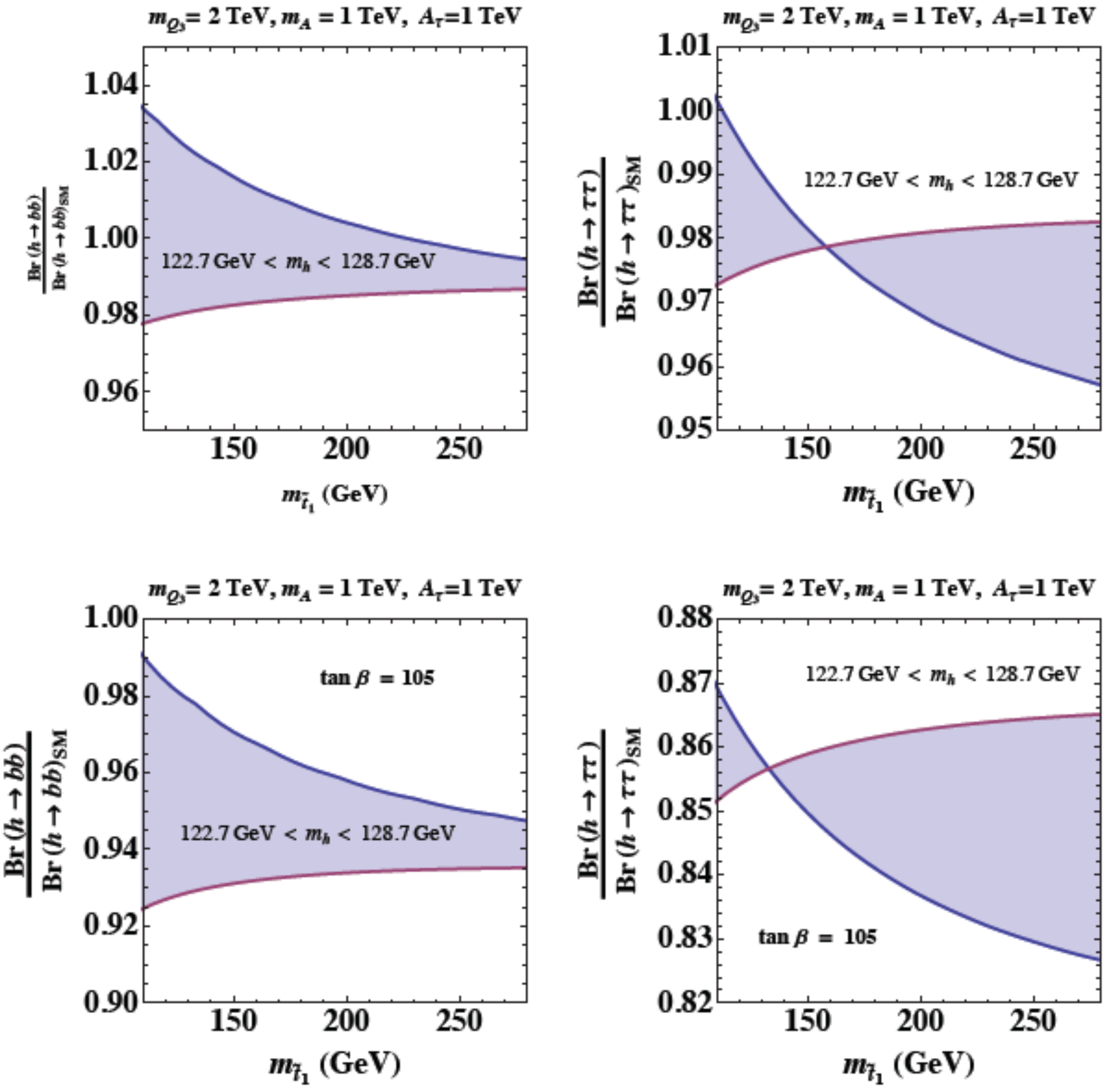
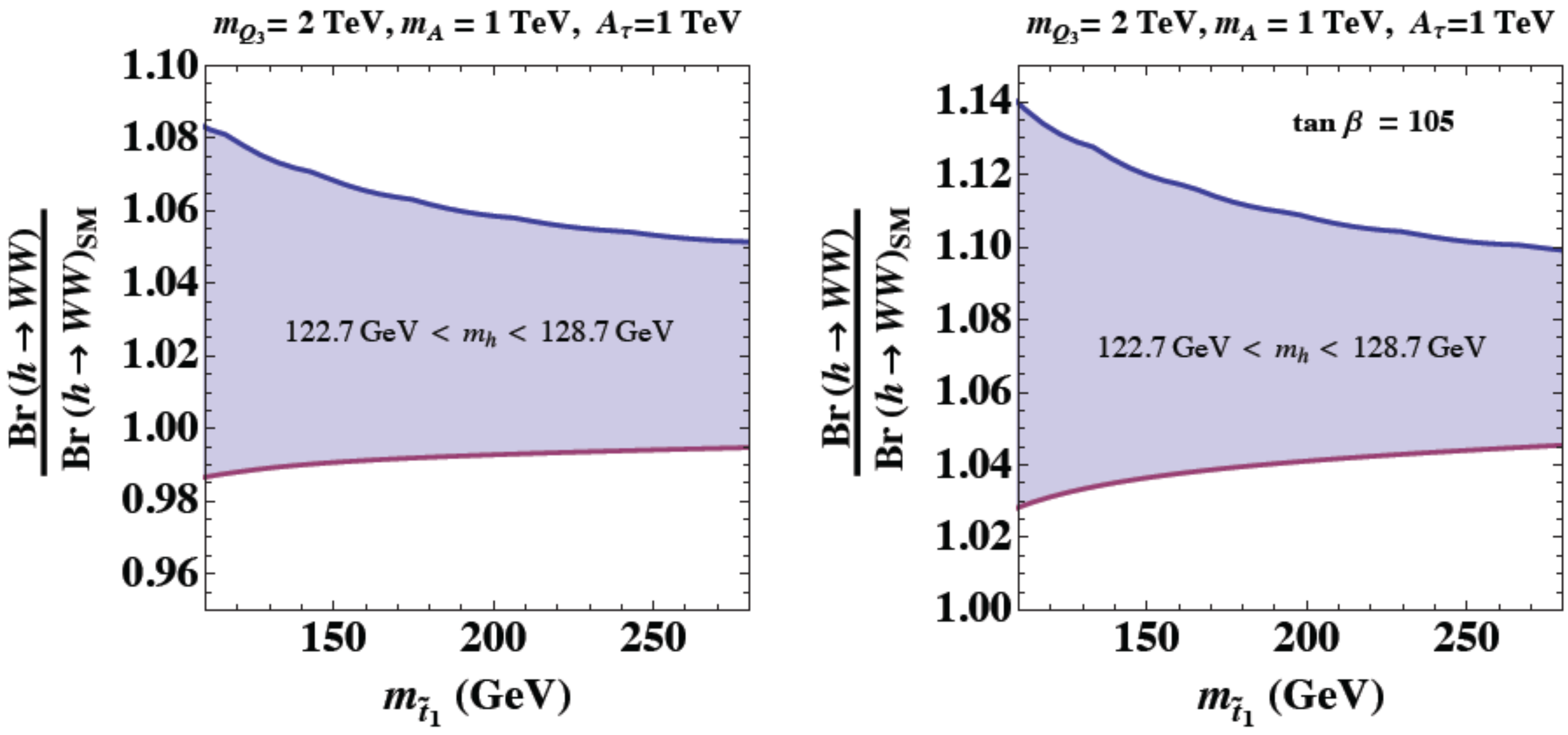


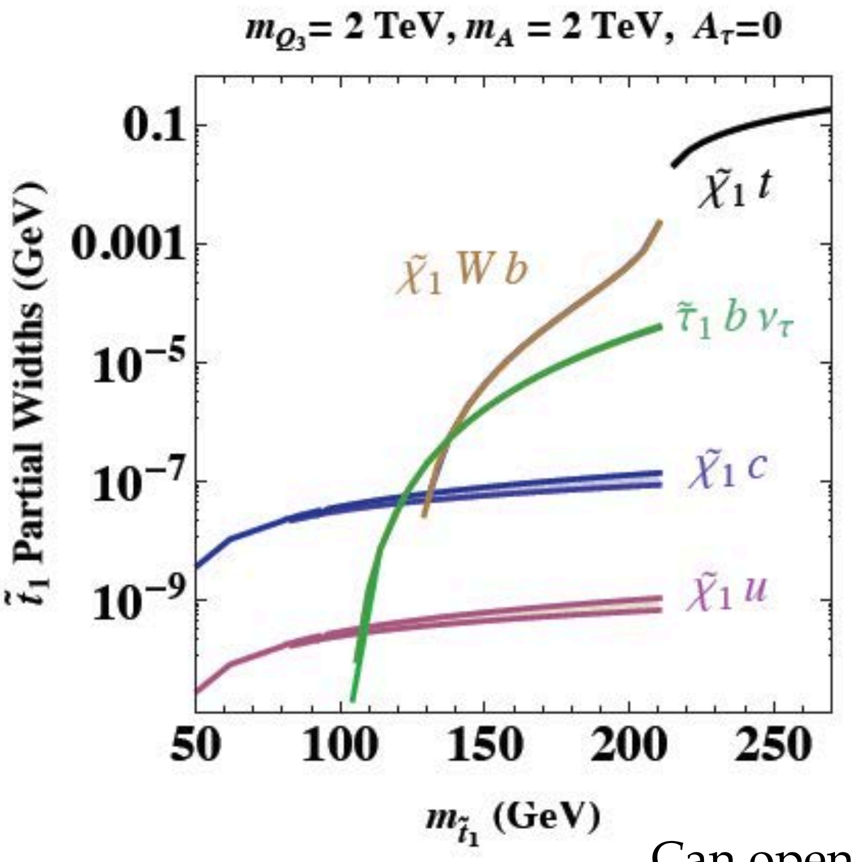
bb and *ττ* ?

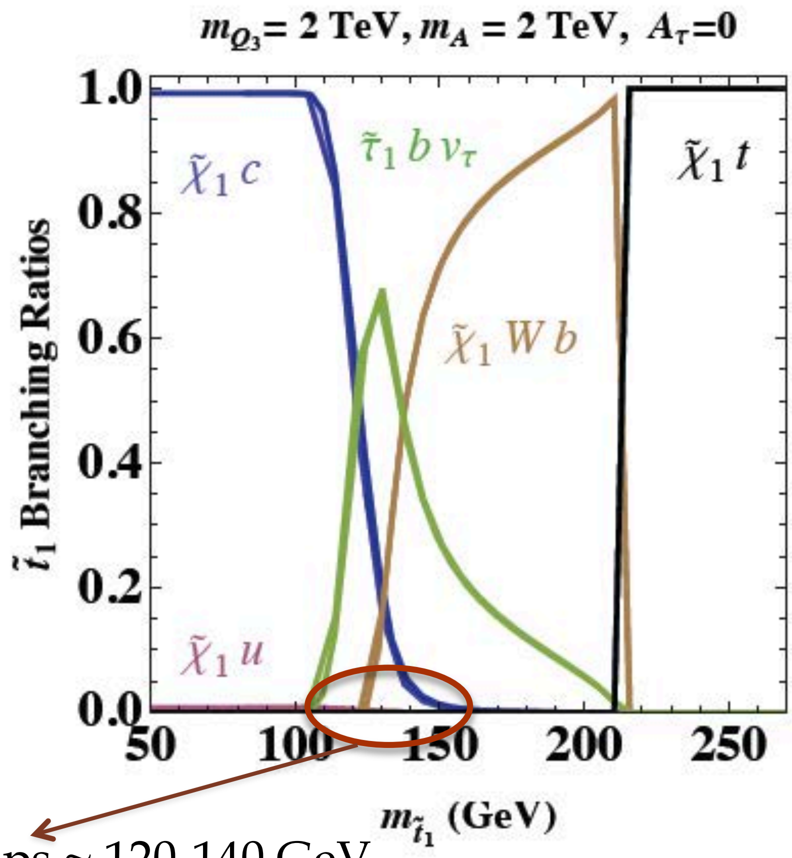
WW ?



m_{Q_3}= 2 TeV, m_A = 1 TeV, A_τ=1 TeV
$\frac{\mathrm{Br}(h \to WW)}{\mathrm{Br}(h \to WW)_{\mathrm{SM}}}$
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.96
122.7 GeV < m_h < 128.7 GeV
150
200
250
$m_{\tilde{t}_1}$ (GeV)
m_{Q_3}= 2 TeV, m_A = 1 TeV, A_τ=1 TeV
tan β = 105
$\frac{\mathrm{Br}(h \to WW)}{\mathrm{Br}(h \to WW)_{\mathrm{SM}}}$
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
122.7 GeV < m_h < 128.7 GeV
150
200
250
$m_{\tilde{t}_1}$ (GeV)

Stop BR Impacted by Light Staus

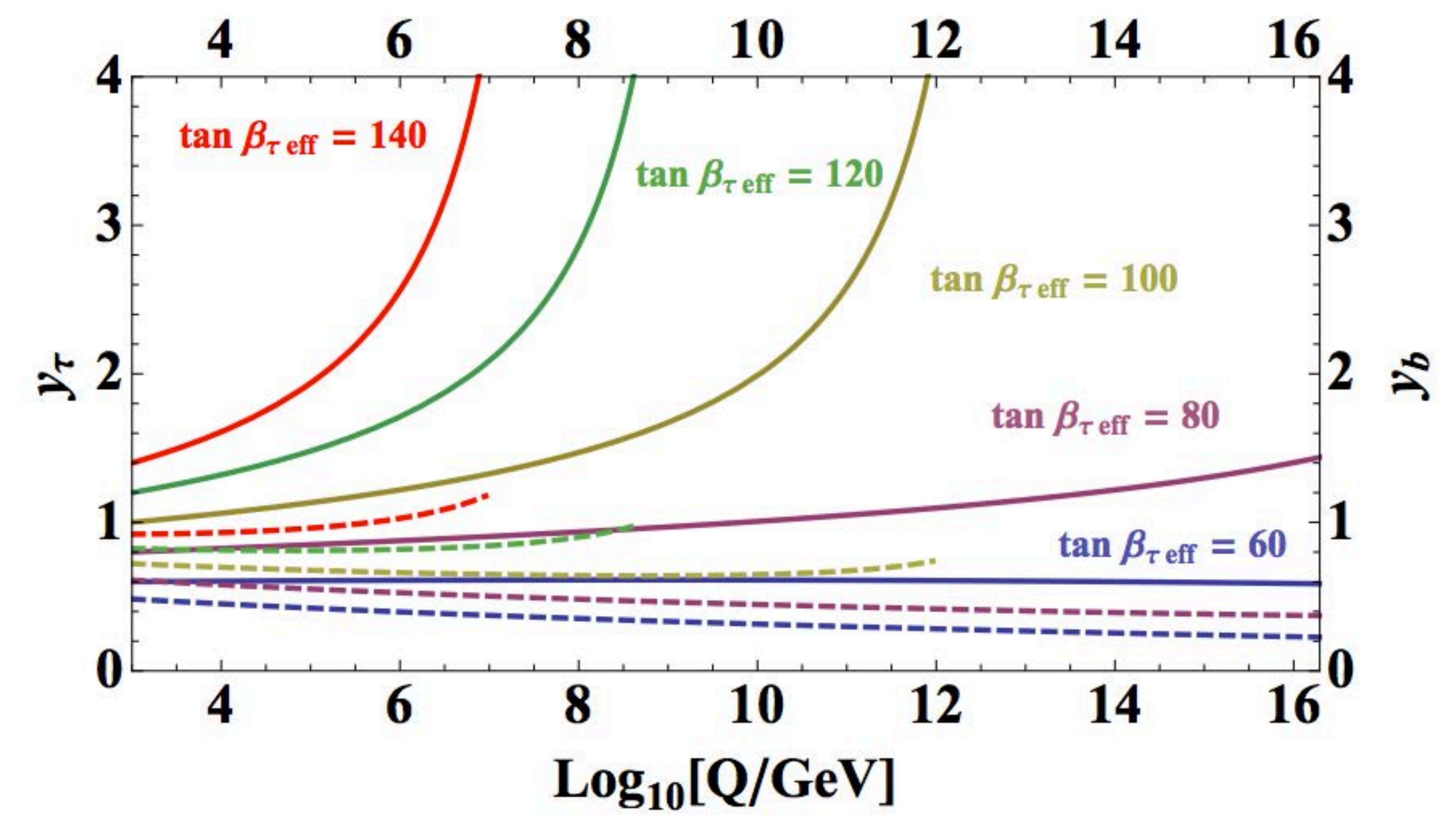




Can open up stops ~ 120-140 GeV

Perturbativity??

Carena, Gori, Low, N.S., Wagner

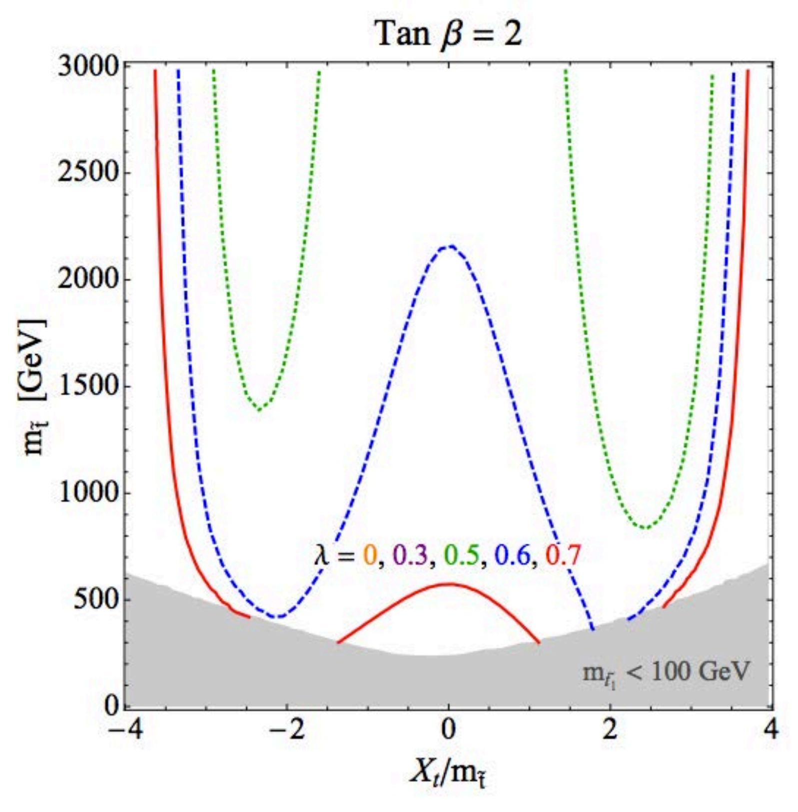


NMSSM

Higgs Mass

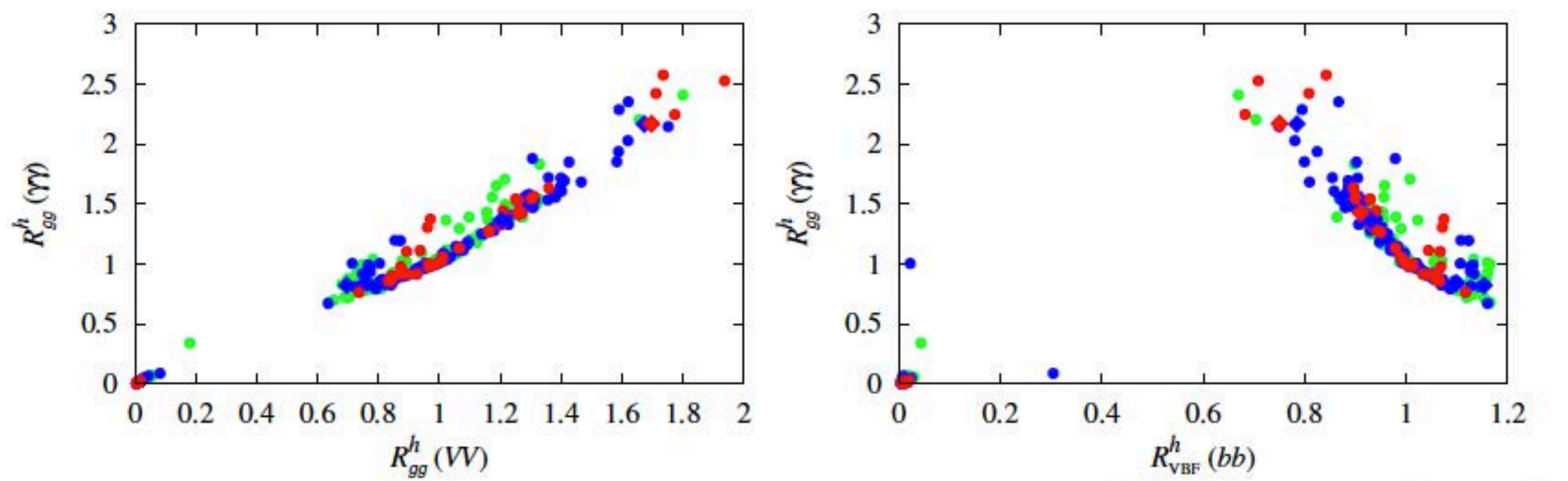
- Extra degree of freedom
  - $m_h \sim 125$ GeV for low *tan β*
  - Chargino contribution to $\gamma\gamma$ can be relevant
  - Tree-level contributions to Higgs Mixing impacting *bb*

Hall, Pinner, Ruderman'11



Modification of Higgs into VV via mixing in Higgs Sector: doublet-singlet mixing induced via λ

Ellwanger. '12
Benbrick, Bock, Heinemeyer, Stal, Weiglien, Zeune, '12
Gunion, Jian, Kraml, '12



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

Varying BR(h->bb) induces significant and correlated variations in the other Higgs BR.

Conclusions and Outlook

- ~125 GeV Higgs consistent with light stops and large stop mixing:
  - $A_t \sim m_Q >> m_u$.
- Rates may be modified by mixing or by light sfermions.
  - **Light Staus.**
    - Large $\mu \tan\beta$ can enhance diphoton rate without modifying other rates in a significant way
  - **Light Stops** can suppress/enhance the photon rate: ($A_t/m_Q <$ (>) 1)
    - Always coupled with opposite effect on GF
  - Suppression of the bottom quark rates via Higgs sector mixing (m_A, A_τ).
    - Further enhancement of the di-photon rate.

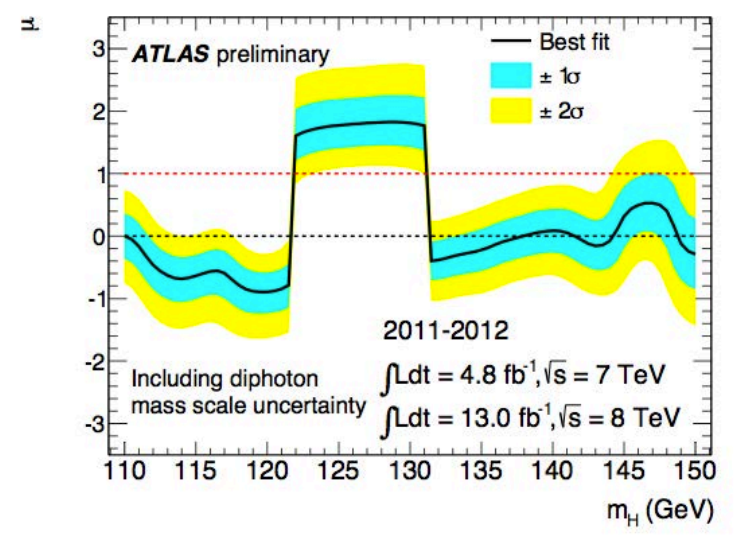
      Less dramatic enhancement of the WW and ZZ rates.

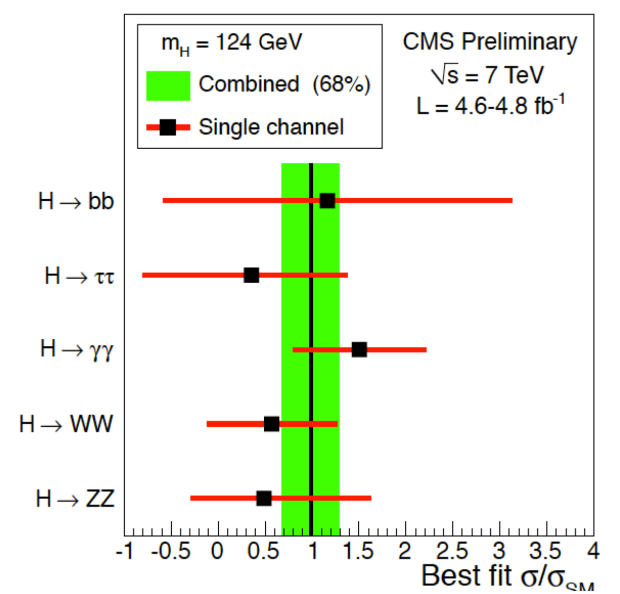
Difference in diphoton due to GF and VBF could point to light stops

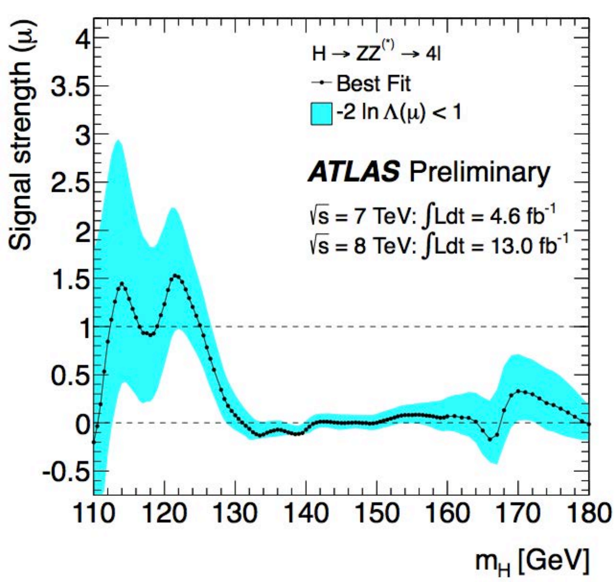
- Charge breaking vacuum??
  - Constrains maximal enhancement
  - Δ_τ effects important
  - Perturbativity
- NMSSM introduces extra degrees of freedom: λ

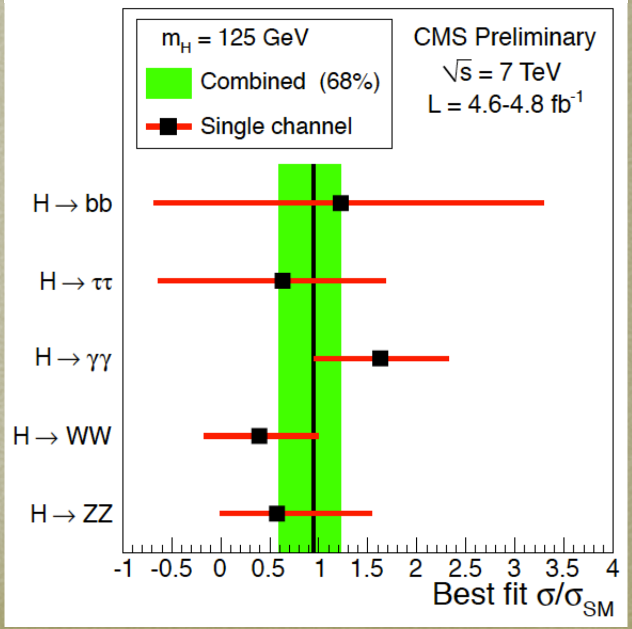
Backup Slides

The $h \to \gamma\gamma$ rate looks high at this point, but more data is necessary in order to reach a robust conclusion.

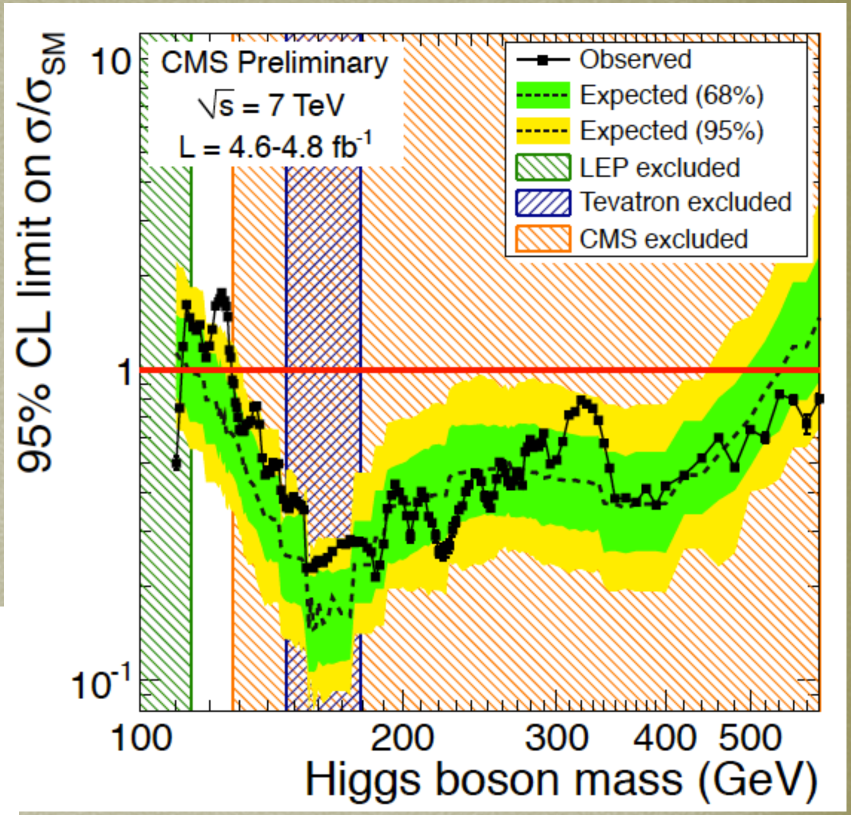


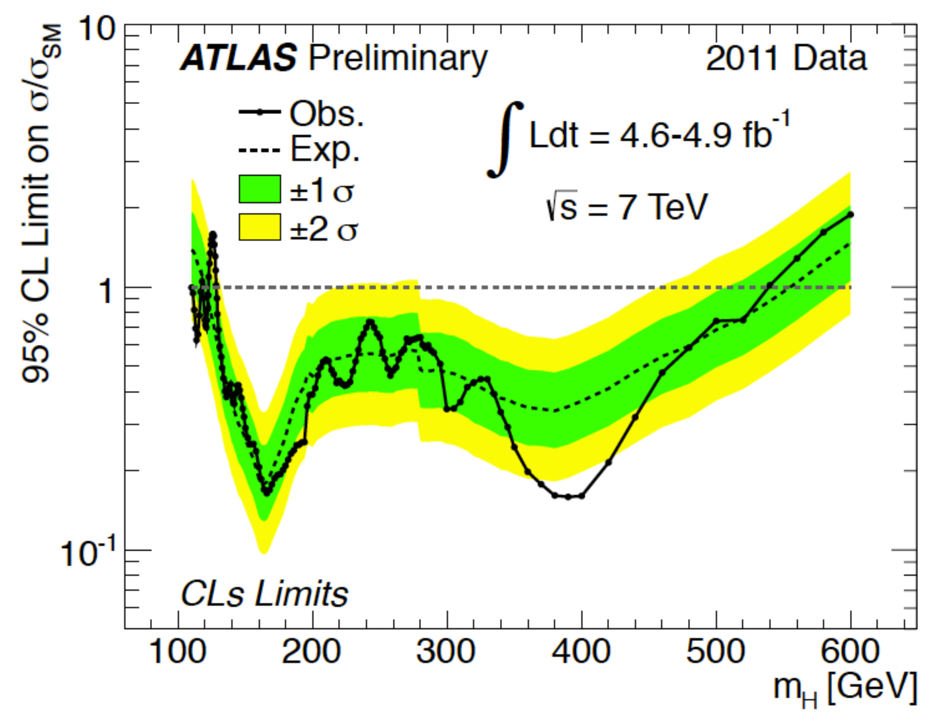






We are living in very interesting times: A light SM-like Higgs is beginning to be probed by present data.





Excluded at 95% CL

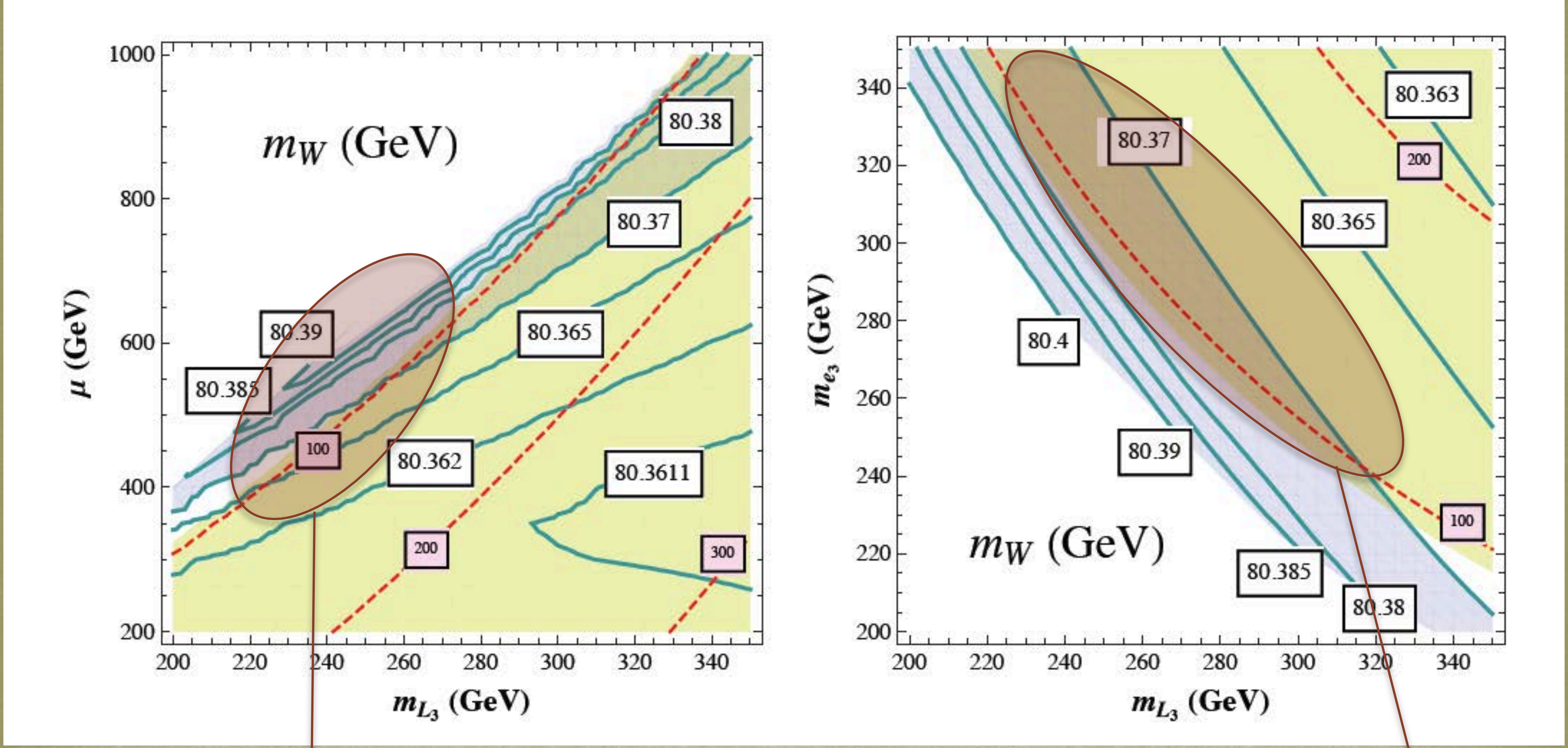
CMS:
127.5-600 GeV

ATLAS:
110-117.5 GeV
118.5-122.5 GeV
129-539 GeV

Electroweak Constraints

m_W and (g_μ-2)

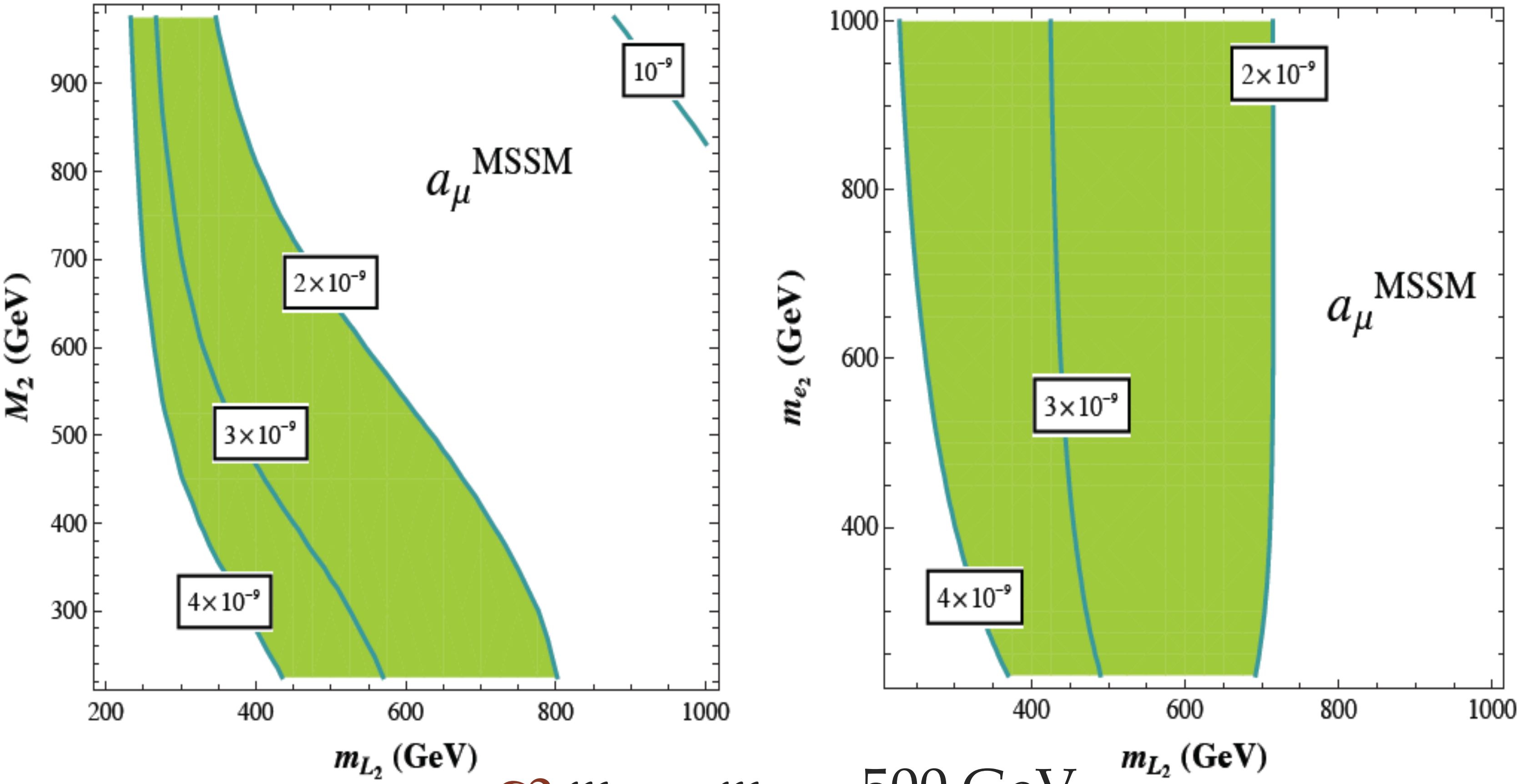
$m_W = 80.385 +/- 0.015$ GeV



$m_{L3} = m_{e3}$,
$\mu > 500$ GeV.

m_{L3} and m_{e3} ~ few hundred GeV,
$m_{L3} < m_{e3}$.

$2 \times 10^{-9} < (g_\mu-2)/2 < 4 \times 10^{-9}$



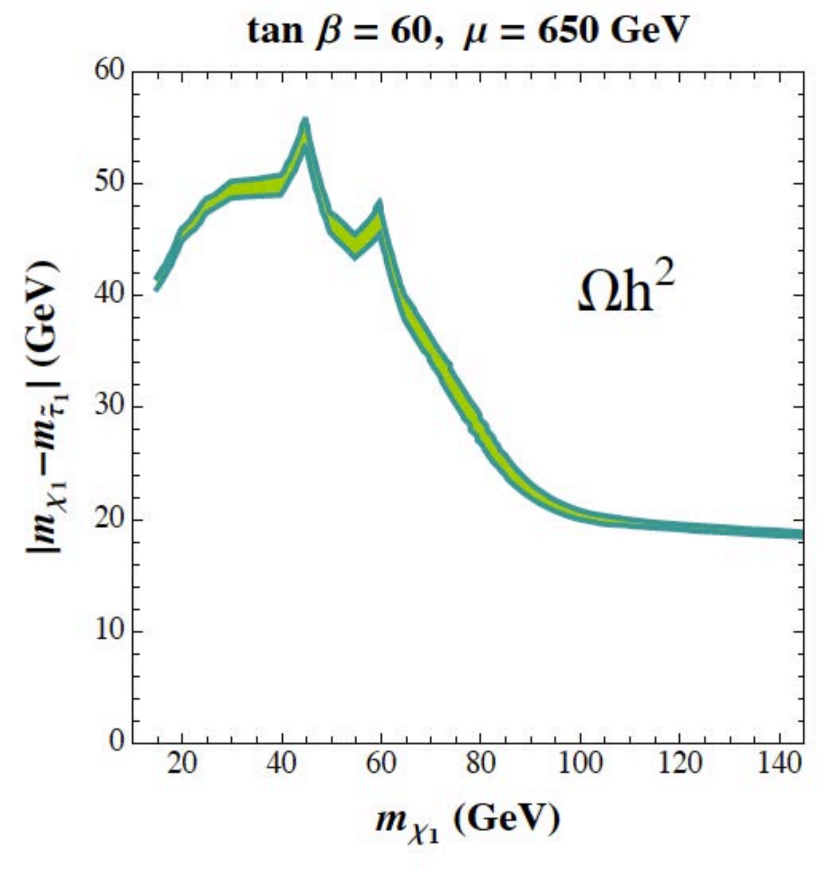
- $m_{L2} \sim m_{e2} \sim 500$ GeV

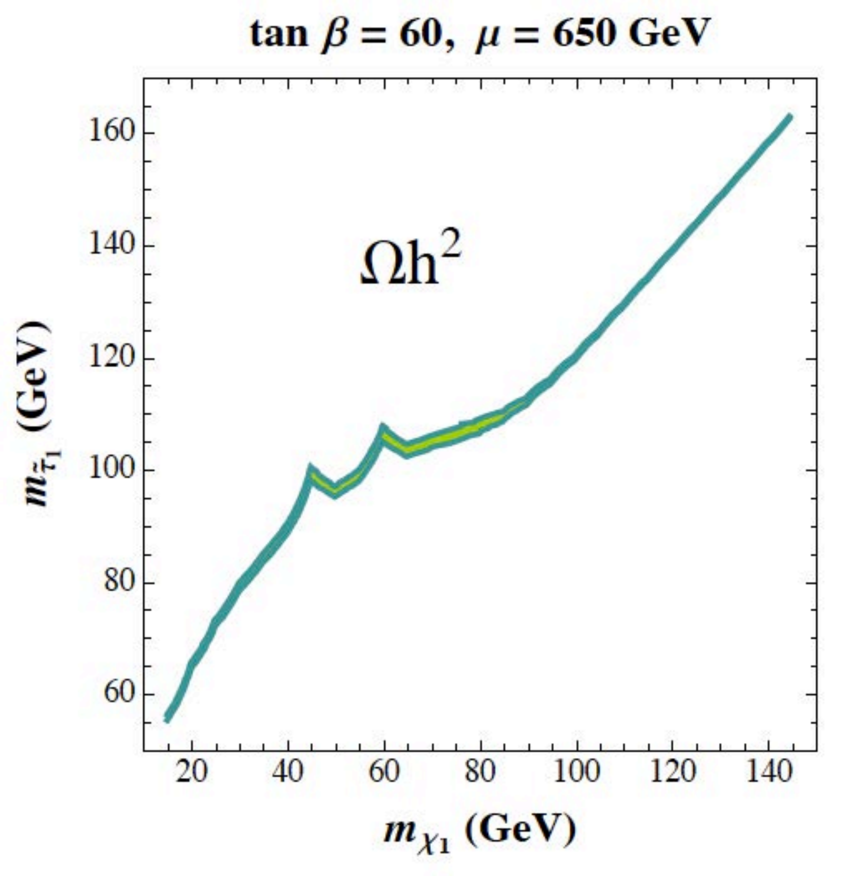
Dark Matter

LSP-NLSP Co-annihilation

Neutralino LSP and stau NLSP

$m_\tau \sim 90$ GeV => $m_{\chi 1} \sim 30 - 40$ GeV





Messenger Scale

Light Sleptons

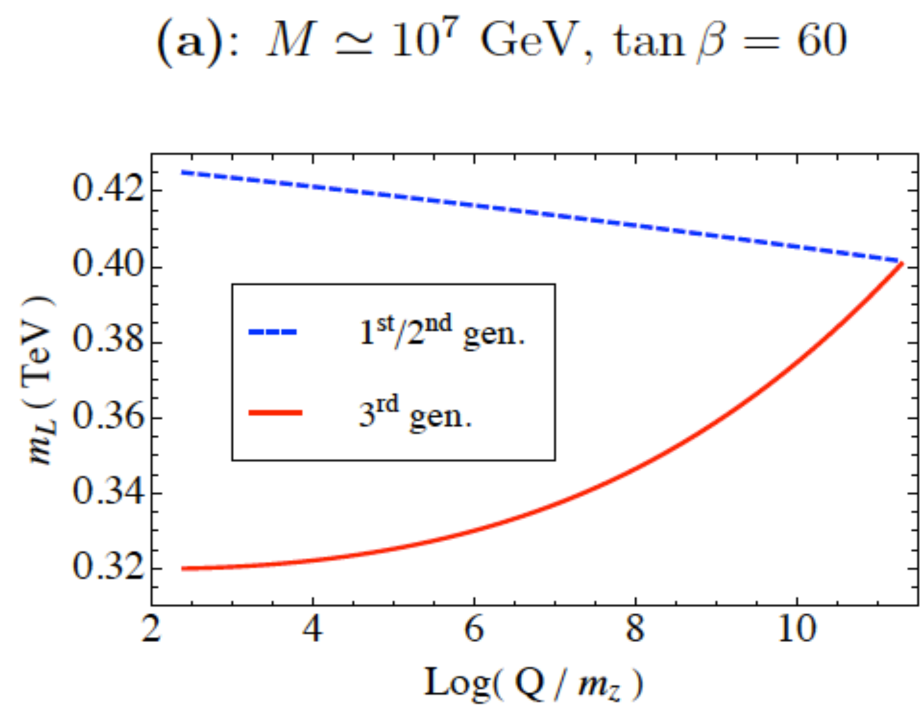
- Assuming
  - Flavor blindness
  - 1st/2nd and 3rd generations light at TeV scale
    - 3rd generation sleptons run strongly with Yukawas
      - Yukawas scaled by $\tan\beta$
    - 1st/2nd generation barely affected by running.

Large $\tan\beta$ and Low Messenger scale

OR

Moderate $\tan\beta$ and High Messenger scale ~ M_{GUT}

Running of m_L with scale, t = Log(Q / m_Z)



m_e runs similarly

m_{L3} running >> m_{L2}/ m_{L1} running.

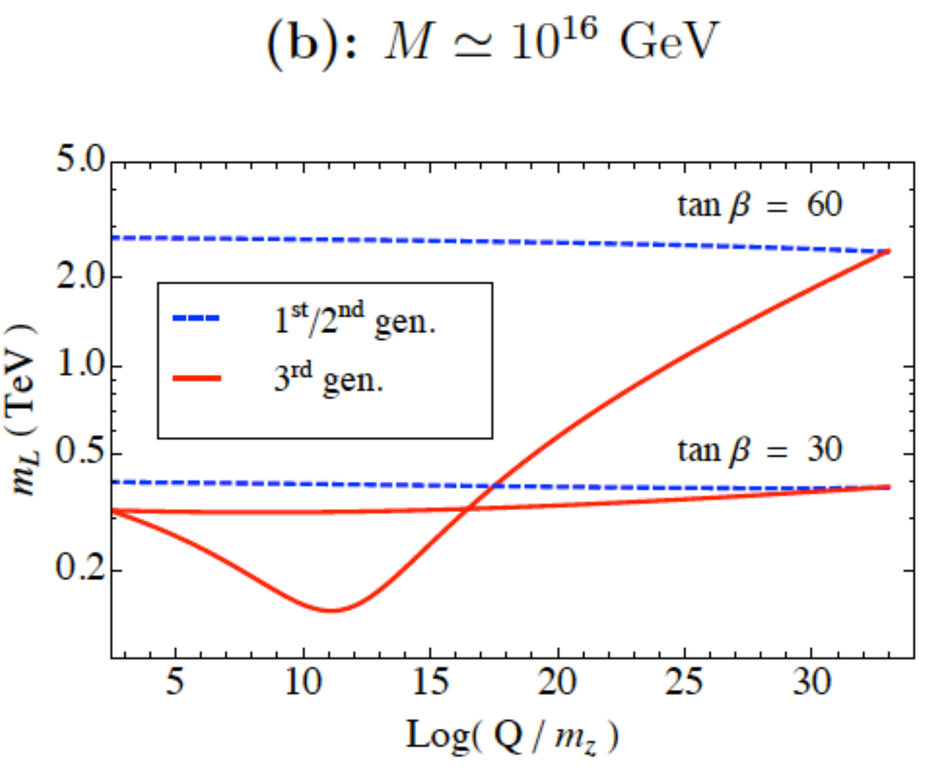
m_{L2} (TeV) ~ m_{L2} (M)

Carena, Gori, N.S., Wagner, Wang

FLAVOR BLINDNESS

Large tan β :
small m_{L2} forces low unification scale.

Lowering tan β:
reduces running of m_{L3}
Can have unification at ~ M_{GUT}



Collider Prospects

Preliminary Results for Light Staus

Probing Light Staus:

Direct weak production of a **stau + tau sneutrino** through the s-channel exchange of a *W*.

- **Quite model independent:**
  - Depends only on masses and mixings of staus and sneutrinos.
  - Would be open even in scenario with very heavy squarks/gluinos.
- **Typical signature:**
  - Multi-taus,
  - Missing energy and
  - Weak gauge bosons, giving rise to additional leptons.

- **We used parton level results from `Madgraph 5`.**
- **A more realistic simulation should include:**
  - Parton showering,
  - Hadronization, and
  - Detector simulation.

- Properly matched matrix element + parton shower simulation particularly important for estimation of *W+jets* background.
- However, our analysis sufficient to obtain a rough order of magnitude estimate of the discovery reach.

Current LHC Search Status

- Final states containing taus, leptons, hard jets and large missing energy, arising from (relatively light) squarks/gluinos decaying directly or through cascades into the stau NLSP.
  - This channel complementary to the ones we investigate, but more model dependent.
- Final states similar to the ones we analyze have been investigated in the context of searches for charginos and neutralinos.
  - Comparing the cross sections of the LHC searches, we note that the multilepton searches are still not sensitive to our scenario.

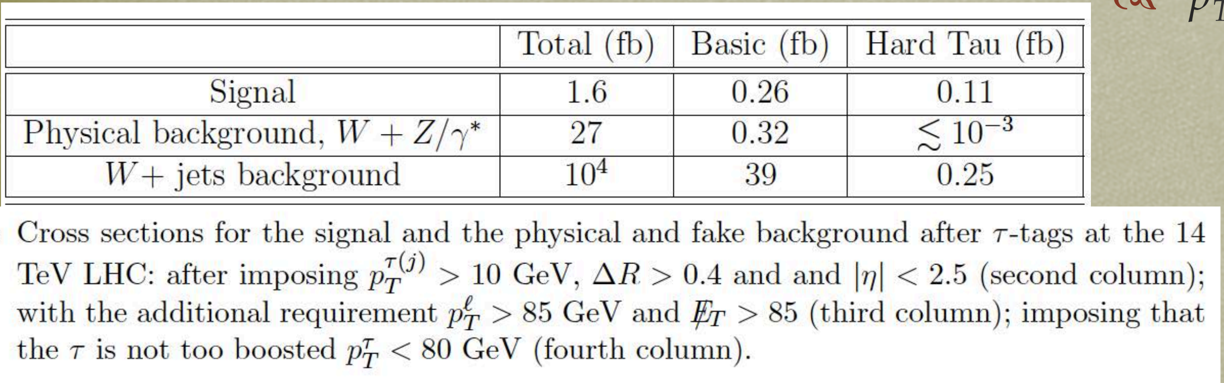
Most stringent constraint on the stau mass given by LEP bound ~ 85-90 GeV for the case of the split stau-neutralino spectrum.

$m_{L3} = m_{e3} = 280$ GeV, $\tan\beta = 60$, $\mu = 650$ GeV, $M_1 = 35$ GeV,
giving a light stau, $m_{\tau 1} \sim 95$ GeV, a very light LSP, $m_{\chi 1} \sim 35$ GeV and
a light sneutrino, $m_{\nu\tau} \sim 270$ GeV for 8 TeV LHC.

$$pp \to \tilde{\tau}_1 \tilde{\nu}_\tau \to \tilde{\tau}_1 (W \tilde{\tau}_1) \to \tau \chi_1 W \tau \chi_1$$

- $\tilde{\tau}_1 \tilde{\tau}_1$ production overwhelmed by background.
- Better situation: $\tilde{\tau}_1 \tilde{\nu}_\tau$ with leptonically decaying *W*.
- 2 loose τ tags:
  - 60% τ identification
  - Jet Background rejection factor: 20-50

- Background: $pp \to W\tau\bar{\tau}$
  - *l* from *W* in signal more boosted:
    - Large missing E_T, => $E_T > 70$ GeV
    - $p_T > 70$ GeV
  - τ mostly from Z^*/γ^*,
    - exclude 80 GeV < $m_{\tau\tau}$ <120 GeV
    - low statistics => marginal improvement.
  - Fake τ from *Wjj*
    - Veto hard jets recoiling from *W*
    - $p_T^j < 75$ GeV

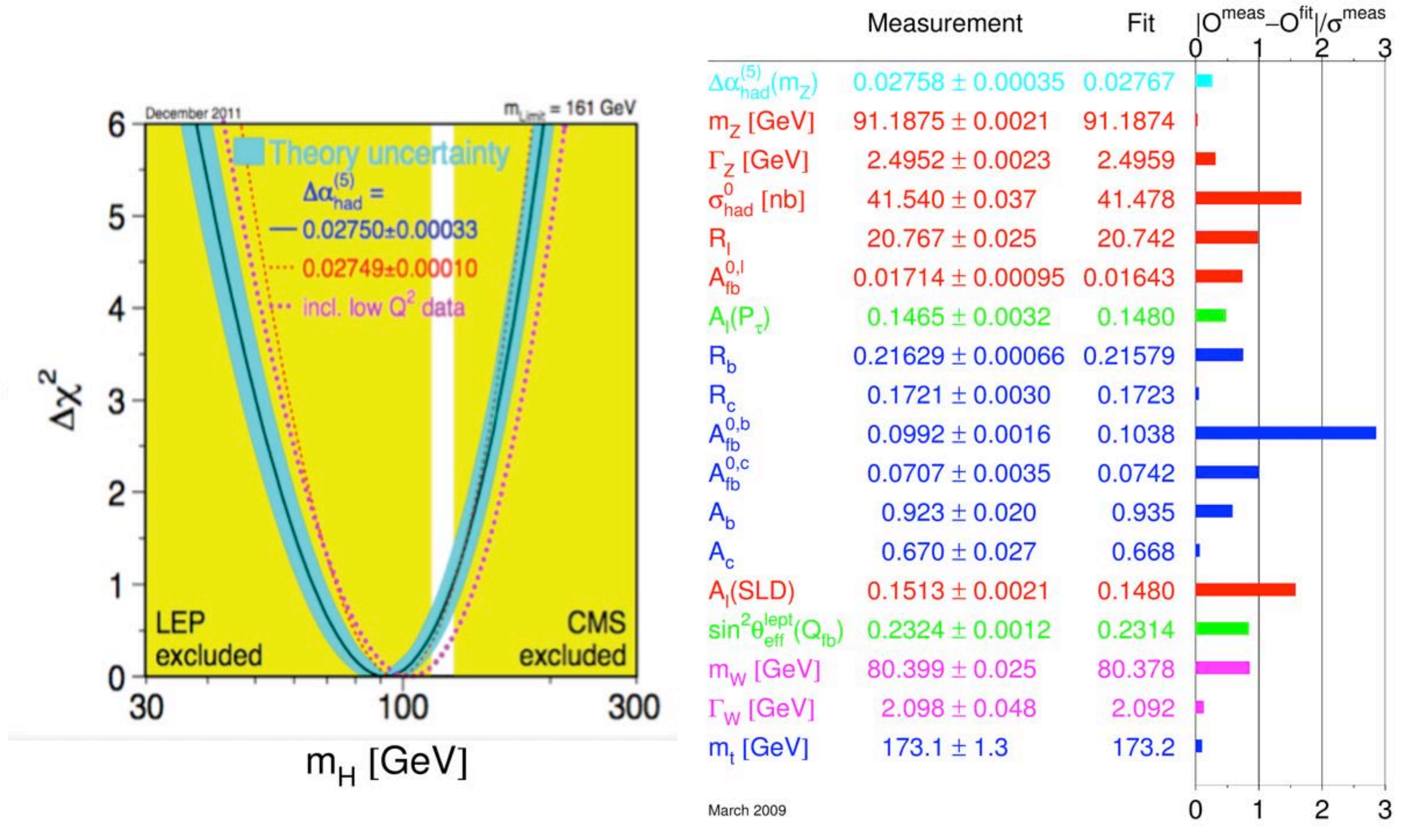


	Total (fb)	Basic (fb)	Hard Tau (fb)
Signal	1.6	0.26	0.11
Physical background, $W + Z/\gamma^*$	27	0.32	$\lesssim 10^{-3}$
$W+$ jets background	10^4	39	0.25

Cross sections for the signal and the physical and fake background after τ-tags at the 14 TeV LHC: after imposing $p_T^{\tau(j)} > 10$ GeV, $\Delta R > 0.4$ and and $|\eta| < 2.5$ (second column); with the additional requirement $p_T^\ell > 85$ GeV and $\not{E}_T > 85$ (third column); imposing that the τ is not too boosted $p_T^\tau < 80$ GeV (fourth column).

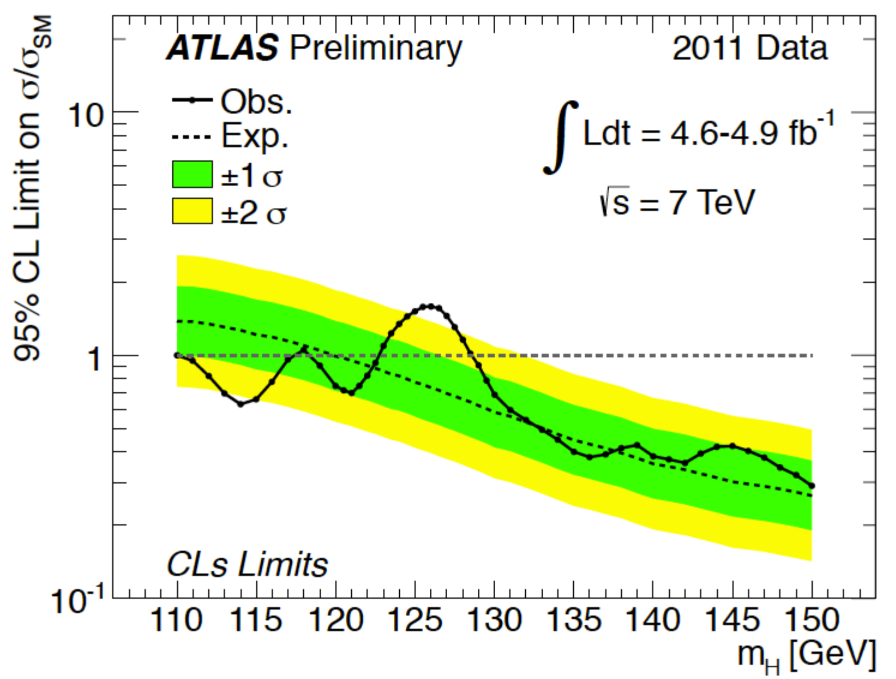
Similar cuts for 14 TeV LHC:
Can get S/B ~ 1
with σ ~ 1 fb
(low statistics)

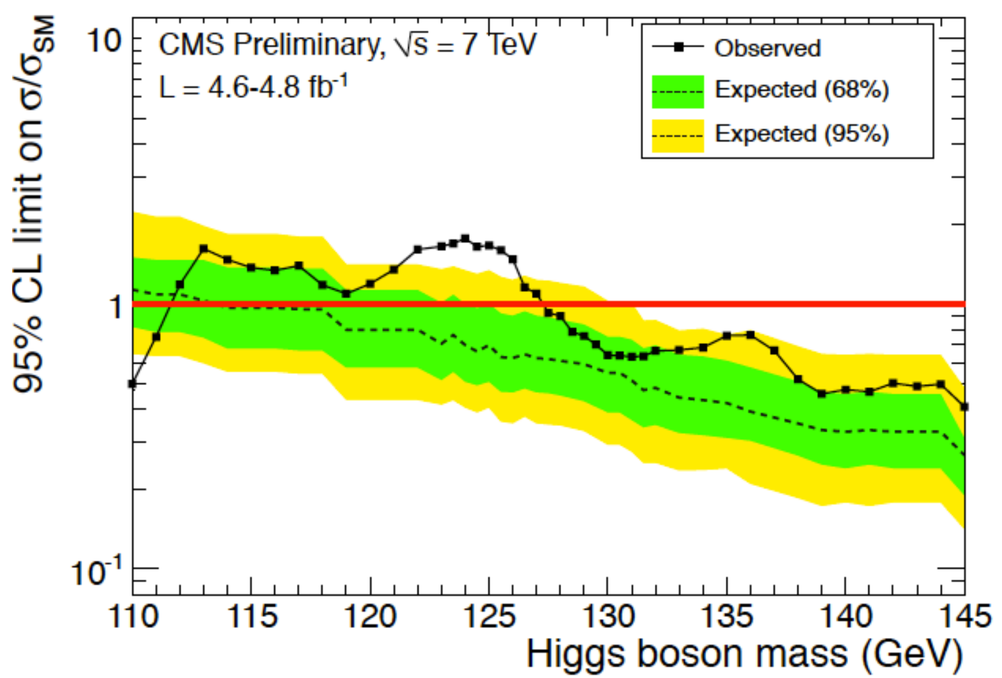
Allowed region also overlaps with region preferred by SM Precision Electroweak Data



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.025	80.378
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2

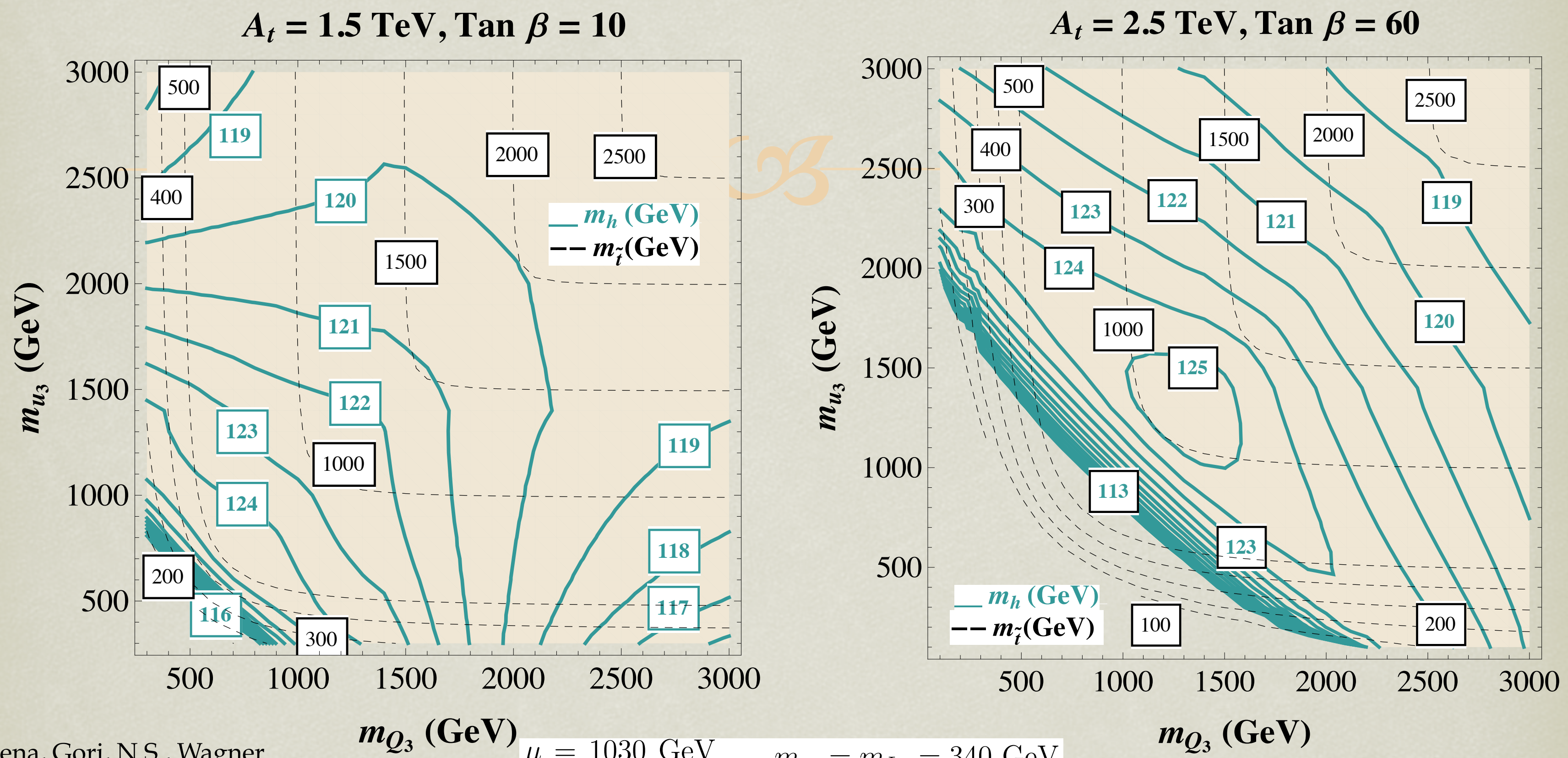
Zoom in on Low Higgs Mass





- If the Higgs is SM-like, mass range between ~ 115 – 130 GeV is preferred both from direct searches as well as from indirect precision tests.
- Interesting excess in the region of the Higgs masses close to 125 GeV.

125 GeV Higgs Boson and the Stop Spectrum



A_t = 1.5 TeV, Tan β = 10

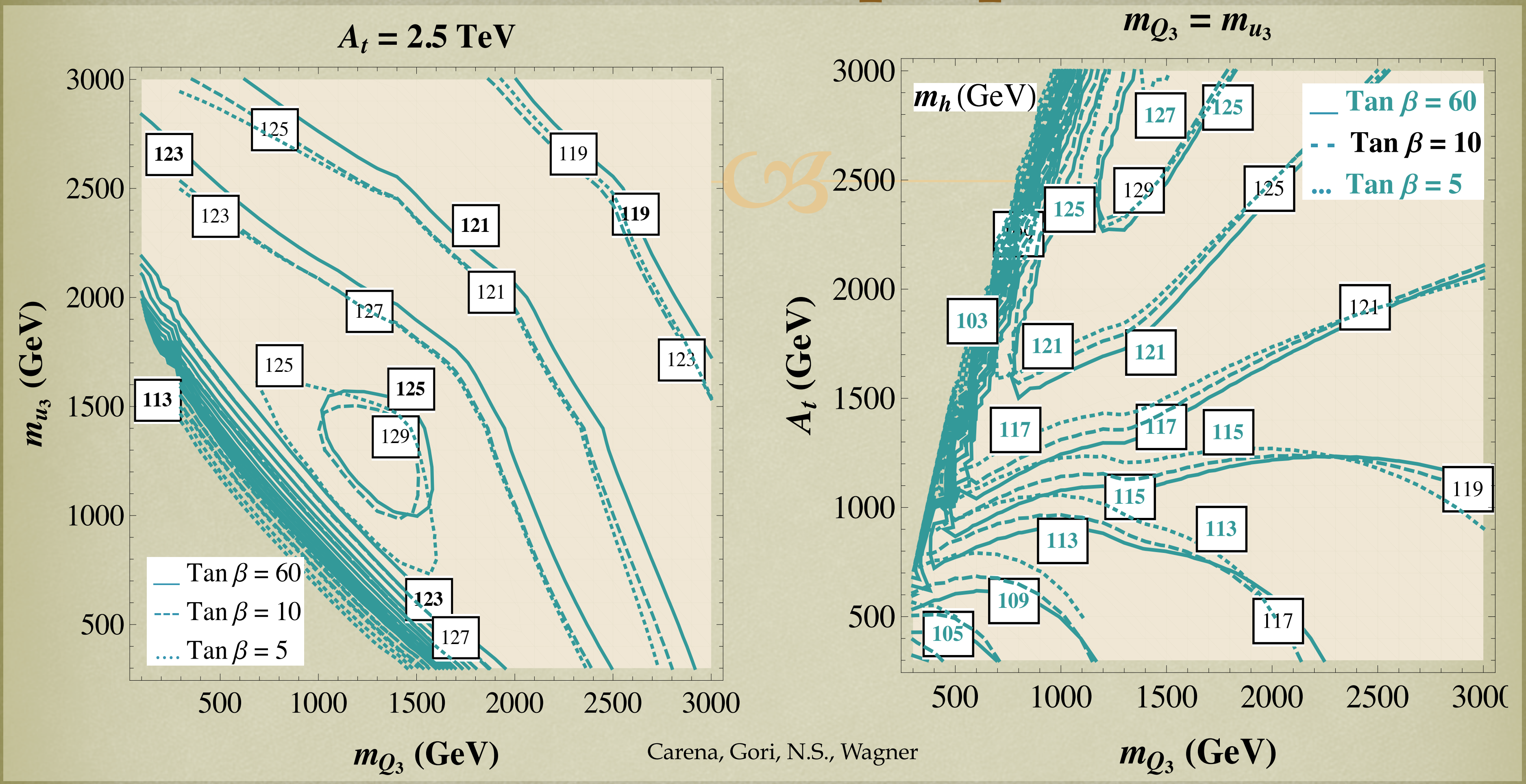
A_t = 2.5 TeV, Tan β = 60

Carena, Gori, N.S., Wagner

$\mu = 1030$ GeV $m_{e3} = m_{L3} = 340$ GeV

- Contour plots of Higgs and stop masses in m_{Q3}-m_{u3} plane, for two values of A_t and tan β.
  - Lightest stau mass is ~ 135 GeV for tan β = 60.
- Large splitting: heaviest stop mass is of the order of the heaviest soft stop parameter.
  - Light stop ~ 100 GeV can be obtained.
  - No hard lower bound on the stop mass.
- Large value of A_t ~ 1.5 TeV always necessary to achieve m_h ~ 123 - 127 GeV .
  - Larger for larger tan β to compensate for the negative corrections from the sbottom/staus.

More on the Stop Spectrum

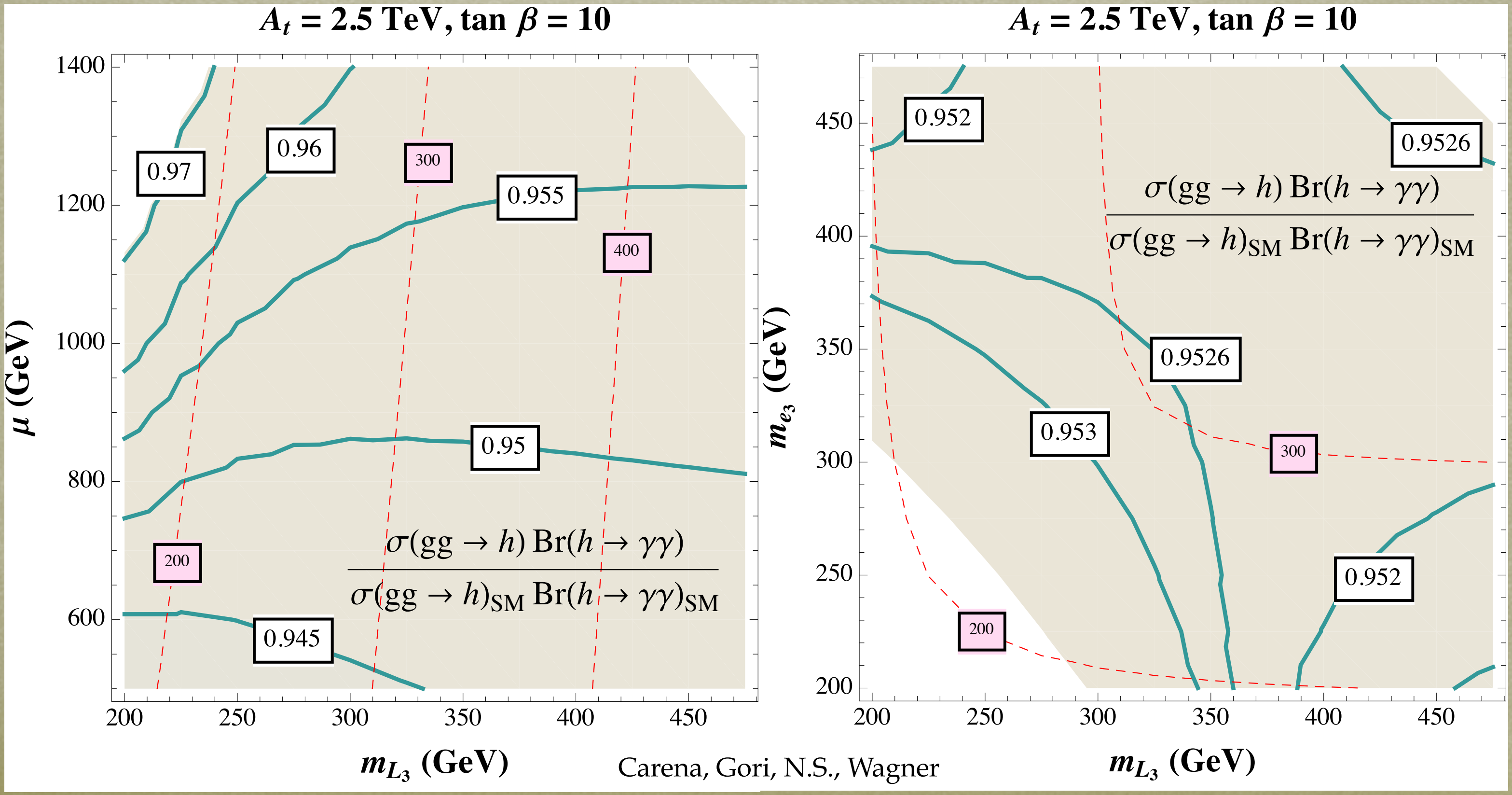


Carena, Gori, N.S., Wagner

- Intermediate tan β leads to largest m_h for same values of soft stop mass parameters.
  - Gain in tree-level Higgs mass from moving tan β from 5 to 60 compensated by the negative stau effects.
- In case of degenerate soft masses,
  - A_t above ~ 1.5 TeV needed to achieve m_h ~ 125 GeV.
  - The lightest stop mass is naturally above ~ 500 GeV.

Sleptons

- Moderate values of tan β and small stau mixing:
  - Light $\tilde{\tau}$ tend to induce slight suppression in $\gamma\gamma$ production:



Carena, Gori, N.S., Wagner

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

A_τ

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

- Higgs mixing effects depend relevantly on A_τ for $m_A \sim < 1$ TeV
- $\tan\beta = 60$; $A_\tau = 1500$ GeV; $m_A = 700$ GeV; $\mu = 1030$ GeV; $m_{e3} = m_{L3} = 340$ GeV
- $m_{\tilde\tau} = 106$ GeV

$$\text{BR}(h \to b\bar{b}) \simeq 0.8\,\text{BR}(\text{h} \to \text{b}\bar{\text{b}})_{\rm SM}$$

- CONSEQUENCE
  - Further enhancement of $\gamma\gamma$ and also WW and ZZ!

$$\frac{\sigma(gg\to h)}{\sigma(gg\to h)_{\rm SM}}\frac{\text{BR}(h\to\gamma\gamma)}{\text{BR}(h\to\gamma\gamma)_{\rm SM}} = 1.96$$

$$\frac{\sigma(gg\to h)}{\sigma(gg\to h)_{\rm SM}}\frac{\text{BR}(h\to VV^*)}{\text{BR}(h\to VV^*)_{\rm SM}} = 1.25 \qquad (V = W, Z)$$

p_T Distribution

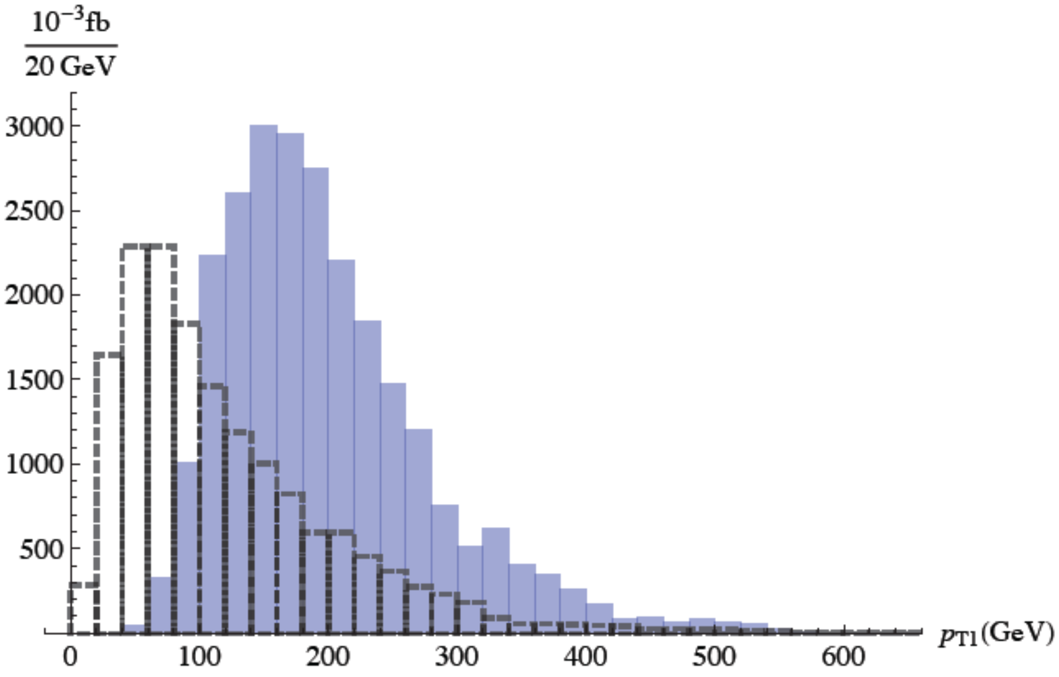
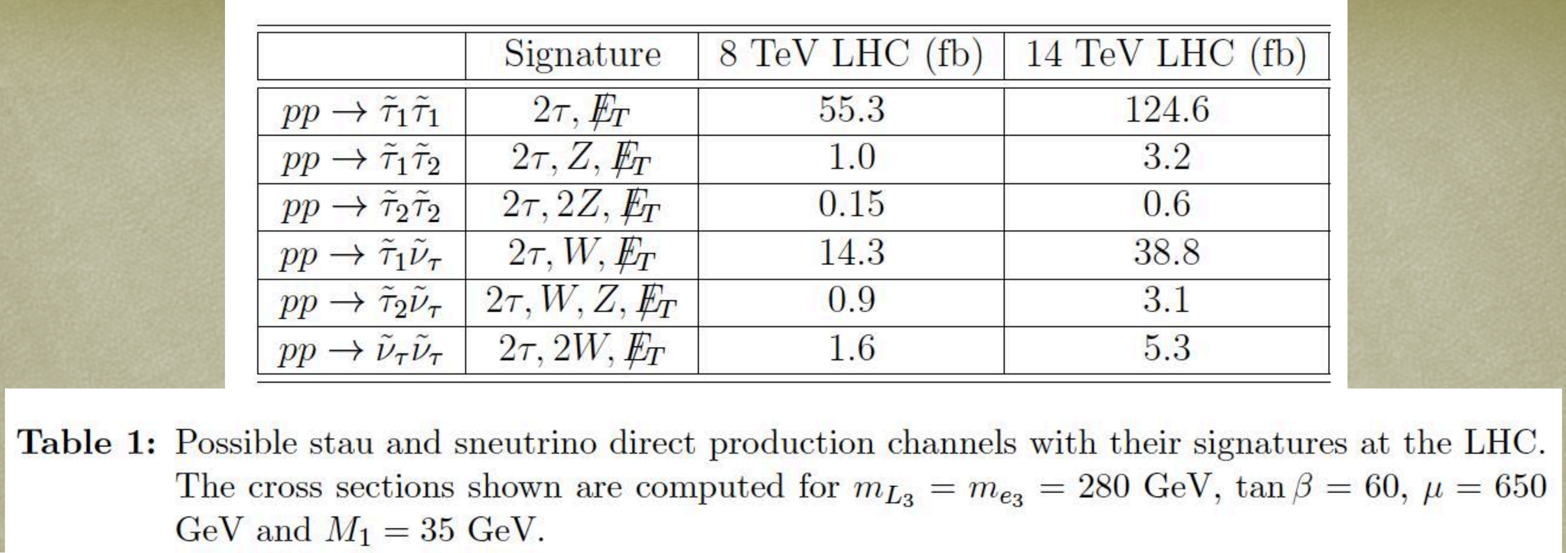
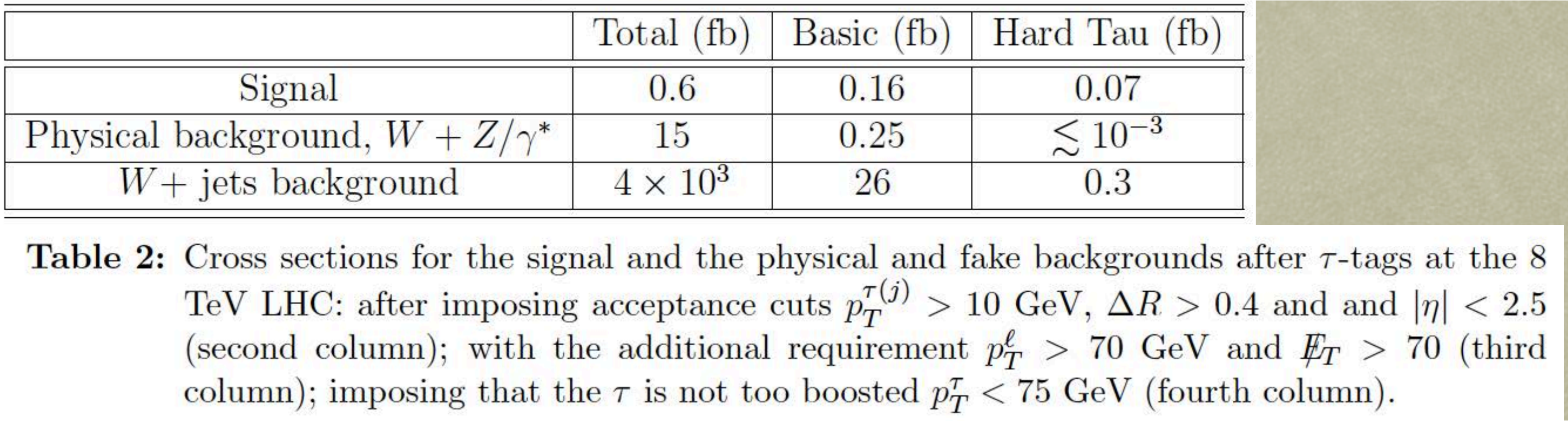


Figure 9: p_T distribution for the leading jet faking a tau of the $W+$ jets background (in blue) and for the leading tau of the signal (black dashed) at the 8 TeV LHC. The events shown satisfy the basic set of cuts ($p_T^\ell > 70$ GeV and $\not{E}_T > 70$ GeV). The signal has been scaled by a factor of 100 for visibility.



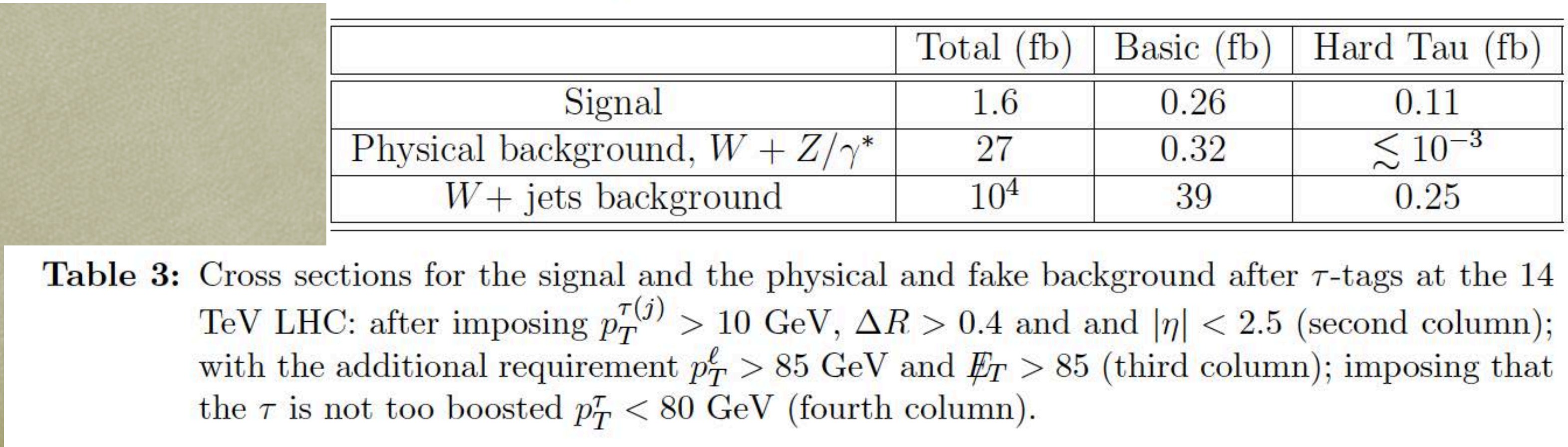
	Signature	8 TeV LHC (fb)	14 TeV LHC (fb)
$pp \to \tilde{\tau}_1\tilde{\tau}_1$	$2\tau, \not{E}_T$	55.3	124.6
$pp \to \tilde{\tau}_1\tilde{\tau}_2$	$2\tau, Z, \not{E}_T$	1.0	3.2
$pp \to \tilde{\tau}_2\tilde{\tau}_2$	$2\tau, 2Z, \not{E}_T$	0.15	0.6
$pp \to \tilde{\tau}_1\tilde{\nu}_\tau$	$2\tau, W, \not{E}_T$	14.3	38.8
$pp \to \tilde{\tau}_2\tilde{\nu}_\tau$	$2\tau, W, Z, \not{E}_T$	0.9	3.1
$pp \to \tilde{\nu}_\tau\tilde{\nu}_\tau$	$2\tau, 2W, \not{E}_T$	1.6	5.3

Table 1: Possible stau and sneutrino direct production channels with their signatures at the LHC. The cross sections shown are computed for $m_{L_3} = m_{e_3} = 280$ GeV, $\tan\beta = 60$, $\mu = 650$ GeV and $M_1 = 35$ GeV.



	Total (fb)	Basic (fb)	Hard Tau (fb)
Signal	0.6	0.16	0.07
Physical background, $W + Z/\gamma^*$	15	0.25	$\lesssim 10^{-3}$
$W+$ jets background	4×10^3	26	0.3

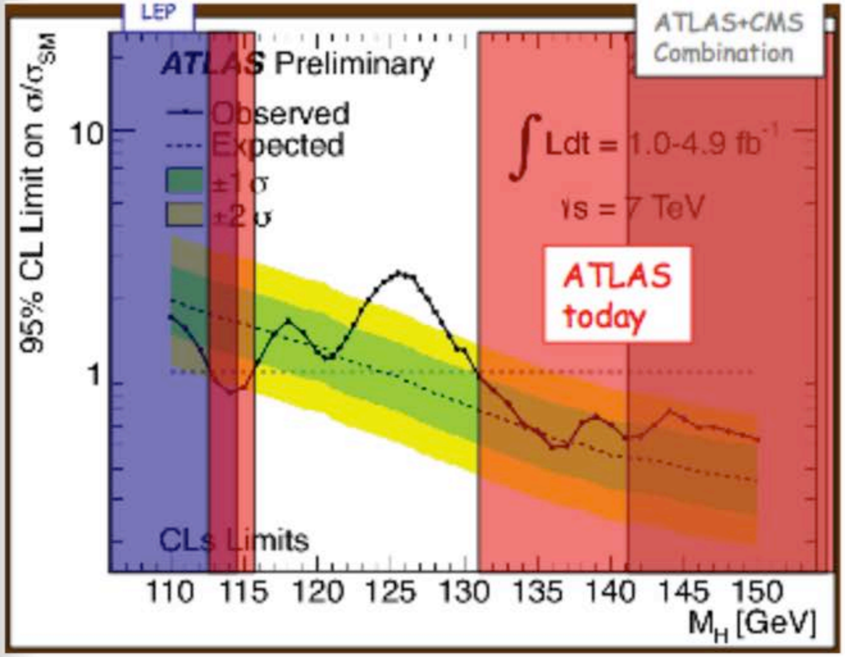
Table 2: Cross sections for the signal and the physical and fake backgrounds after τ-tags at the 8 TeV LHC: after imposing acceptance cuts $p_T^{\tau(j)} > 10$ GeV, $\Delta R > 0.4$ and and $|\eta| < 2.5$ (second column); with the additional requirement $p_T^\ell > 70$ GeV and $\not{E}_T > 70$ (third column); imposing that the τ is not too boosted $p_T^\tau < 75$ GeV (fourth column).



	Total (fb)	Basic (fb)	Hard Tau (fb)
Signal	1.6	0.26	0.11
Physical background, $W + Z/\gamma^*$	27	0.32	$\lesssim 10^{-3}$
$W+$ jets background	10^4	39	0.25

Table 3: Cross sections for the signal and the physical and fake background after τ-tags at the 14 TeV LHC: after imposing $p_T^{\tau(j)} > 10$ GeV, $\Delta R > 0.4$ and and $|\eta| < 2.5$ (second column); with the additional requirement $p_T^\ell > 85$ GeV and $\not{E}_T > 85$ (third column); imposing that the τ is not too boosted $p_T^\tau < 80$ GeV (fourth column).

Atlas results zoomed in the Low Mass region



H→γγ, H→ ττ
H→ WW$^{(*)}$→ lνlν
H→ ZZ$^{(*)}$ → 4l, H→ ZZ → llνν
H→ ZZ → llqq, H→ WW→lνqq
W/ZH→ lbb+X not included

We have restricted the most likely mass region (95% CL) to

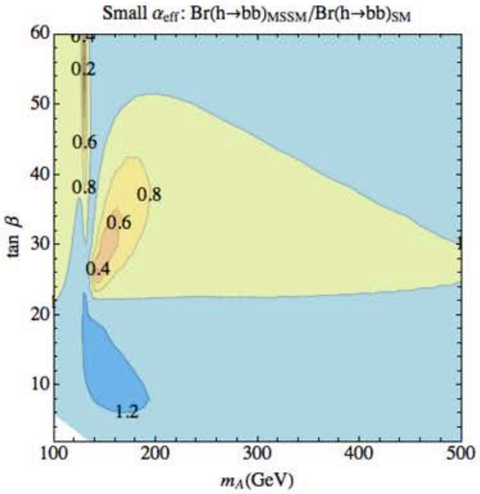
115.5-131 GeV

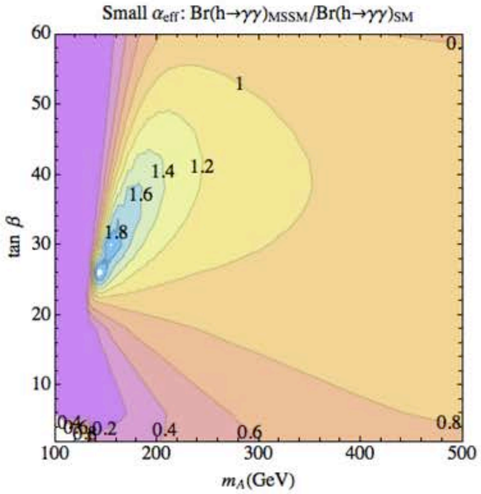
We observe an excess of events around m_H~ 126 GeV:

☐ local significance 3.6 σ, with contributions from the H→ γγ (2.8 σ), H→ ZZ* → 4l (2.1 σ), H→ WW$^{(*)}$ → lνlν (1.4 σ) analyses

☐ SM Higgs expectation: 2.4 σ local → observed excess compatible with signal strength within +1σ

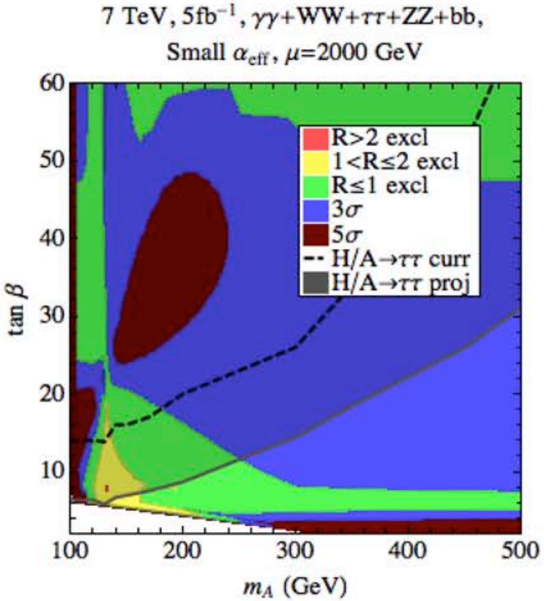
☐ the global significance (taking into account Look-Elsewhere-Effect) is ~2.3σ





For large values of μ and A_t one can get suppression of the Higgs decay into bottom quarks and therefore enhancement of photon decay branching ratio

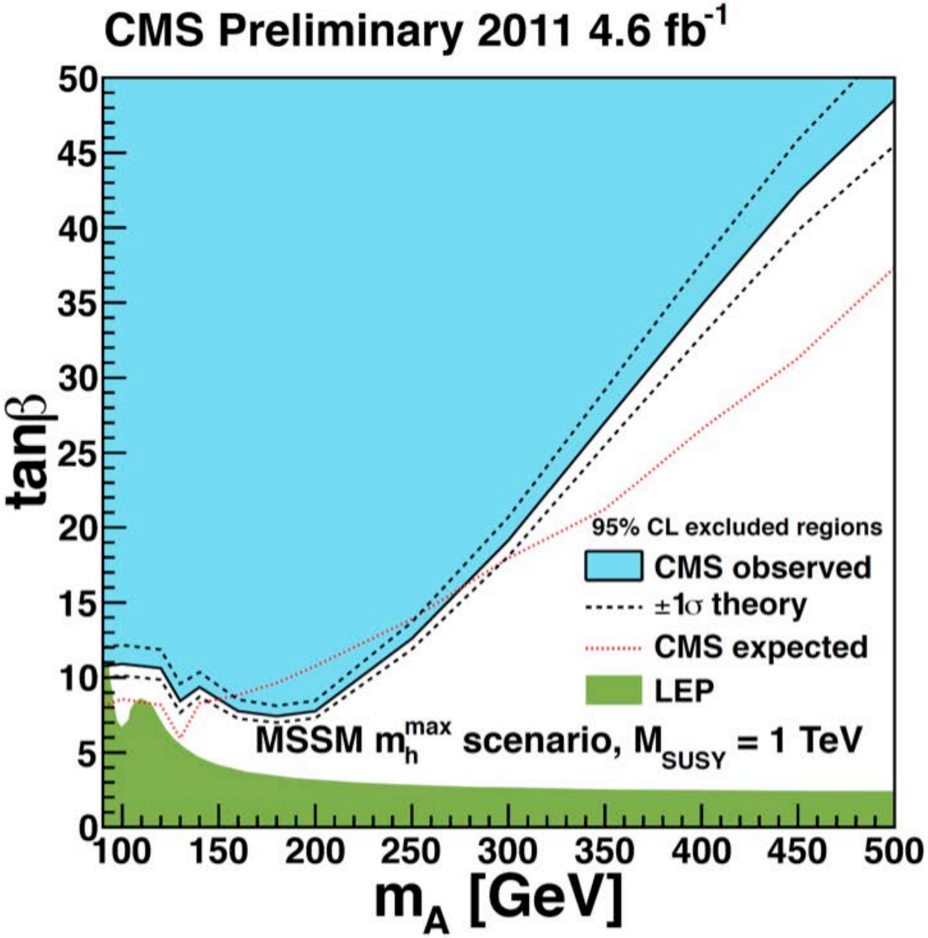
Carena, Mrenna, Wagner'99
Carena, Heinemeyer, Wagner, Weiglein'02



Such scenario, however, demands small values of the the CP-odd Higgs mass and large tanbeta and seems to be in conflict with non-standard Higgs boson searches

Carena, Draper, Liu, Wagner'11

Results did not change significantly with the datea update. Interestingly, the observed limit is somewhat weaker than the expected one.



Loop induced gluon and gamma widths

$$\Gamma_{H\to gg} = \frac{G_\mu \alpha_s^2 m_H^3}{36\sqrt{2}\pi^3}\left|\frac{3}{4}\sum_f A_f(\tau_f)\right|^2$$

$$\Gamma_{H\to\gamma\gamma} = \frac{G_\mu \alpha^2 m_H^3}{128\sqrt{2}\pi^3}\left|\sum_f N_c Q_f^2 A_f(\tau_f) + A_W(\tau_W)\right|^2$$

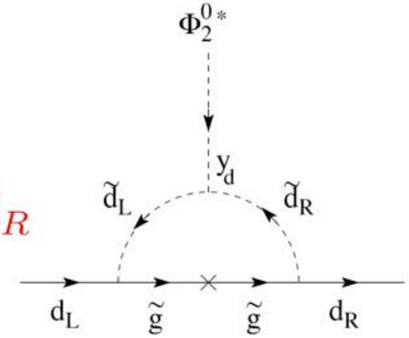
$$A_f(\tau) = 2\left[\tau + (\tau-1)f(\tau)\right]\tau^{-2}$$
$$A_W(\tau) = -\left[2\tau^2 + 3\tau + 3(2\tau-1)f(\tau)\right]\tau^{-2}$$

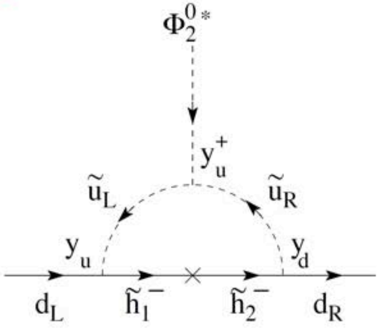
$$f(\tau) = \begin{cases} \arcsin^2\sqrt{\tau} & \tau \le 1 \\ -\frac{1}{4}\left[\ln\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \tau > 1 \end{cases}$$

Radiative Corrections to Flavor Conserving Higgs Couplings

- Couplings of down and up quark fermions to both Higgs fields arise after radiative corrections.

$$\mathcal{L} = \bar{d}_L(h_d H_1^0 + \Delta h_d H_2^0) d_R$$





- The radiatively induced coupling depends on ratios of supersymmetry breaking parameters

$$m_b = h_b v_1 \left(1 + \frac{\Delta h_b}{h_b} \tan\beta\right)$$

$$\boxed{\tan\beta = \frac{v_2}{v_1}}$$

$$\frac{\Delta_b}{\tan\beta} = \frac{\Delta h_b}{h_b} \simeq \frac{2\alpha_s}{3\pi} \frac{\mu M_{\tilde{g}}}{\max(m_{\tilde{b}_i}^2, M_{\tilde{g}}^2)} + \frac{h_t^2}{16\pi^2} \frac{\mu A_t}{\max(m_{\tilde{t}_i}^2, \mu^2)}$$

$$X_t = A_t - \mu/\tan\beta \simeq A_t \qquad \Delta_b = (E_g + E_t h_t^2) \tan\beta$$

Resummation : Carena, Garcia, Nierste, C.W.'00