A 125 GeV Higgs and the $\gamma\gamma$ Rate in the MSSM

Nausheen R. Shah
FNAL

M. Carena, S. Gori, N. R. Shah & C. Wagner, **arXiv:1112.3336** [hep-ph]
M. Carena, S. Gori, N. R. Shah C. Wagner & L. Wang, **arXiv:1204.SOON** [hep-ph]

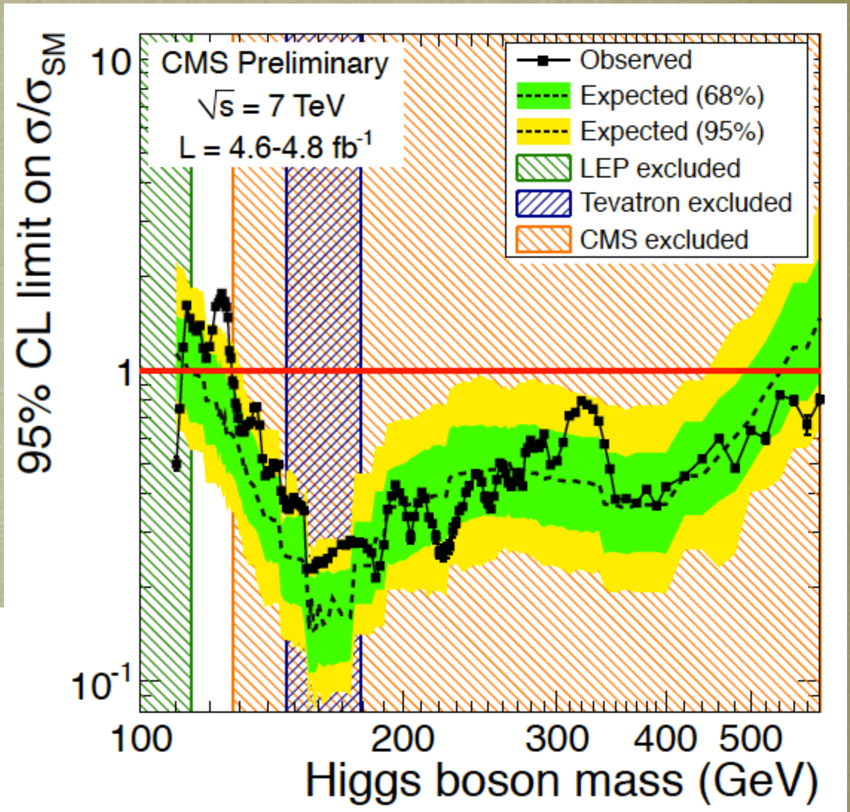
Outline

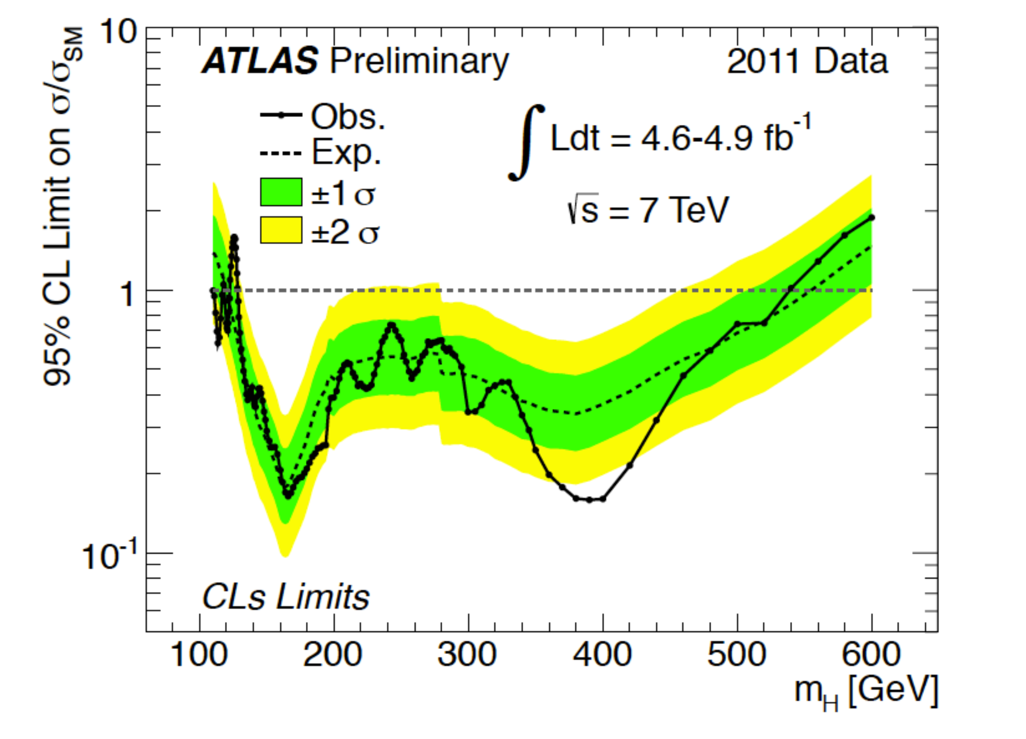
- Motivation:
  - Recent Atlas/CMS Results
- MSSM
- Higgs Mass in the MSSM
- Production Cross-Sections
- Constraints on MSSM parameter space due to EWPT.
- Implications for messenger scale/soft masses assuming flavor universality at high scale.
- Preliminary Collider study results.
- Conclusions and Outlook

Motivation

Recent Experimental Results

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



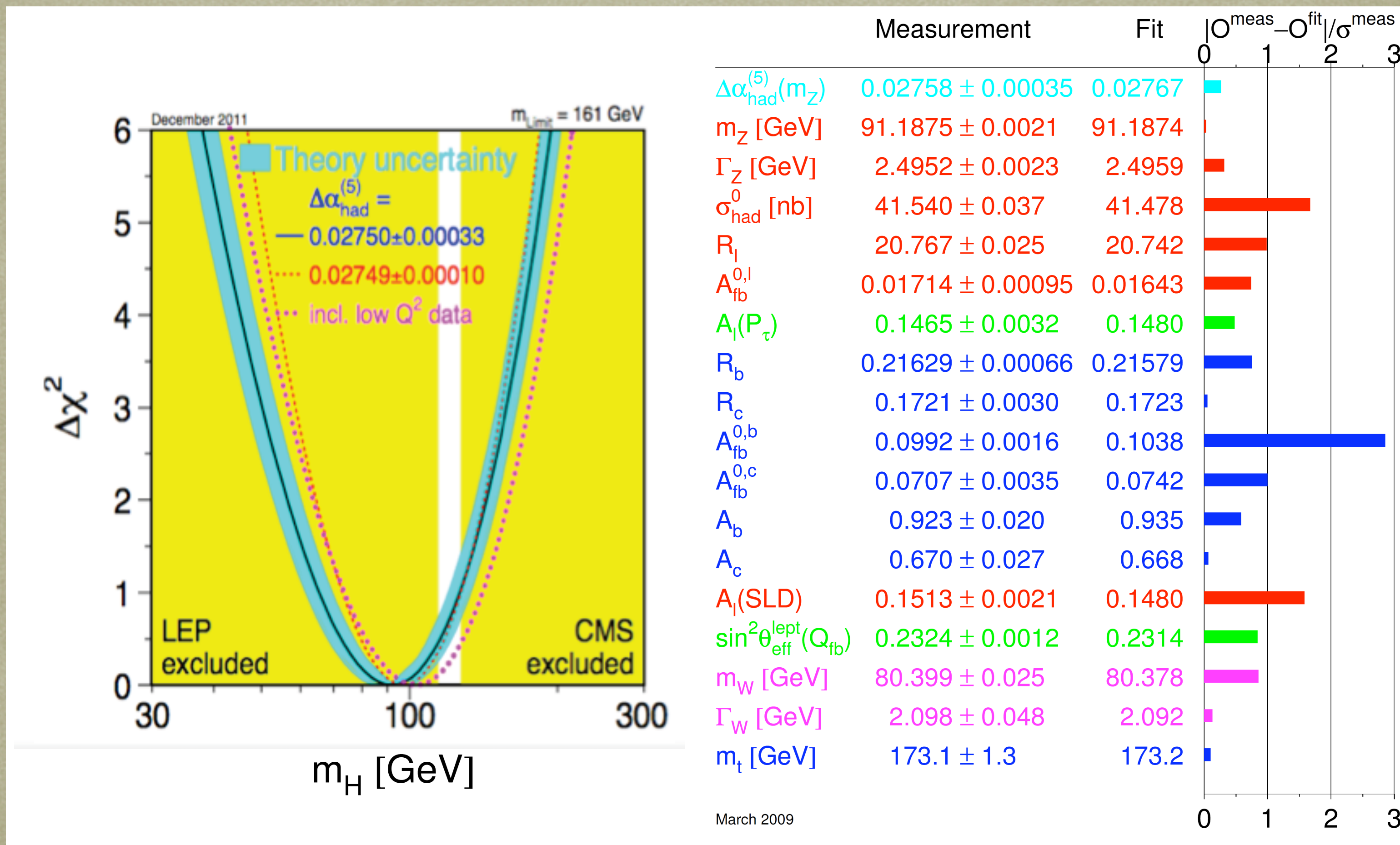


<u>Excluded at 95% CL</u>

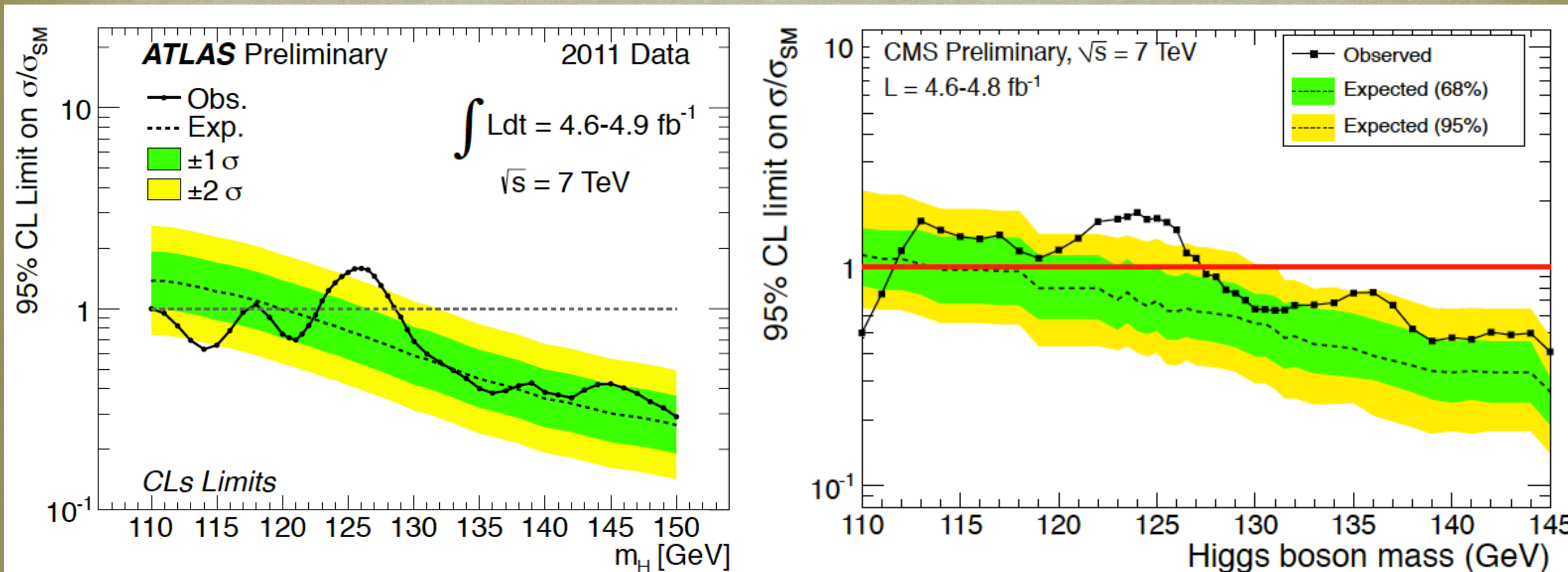
CMS:
127.5-600 GeV

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

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

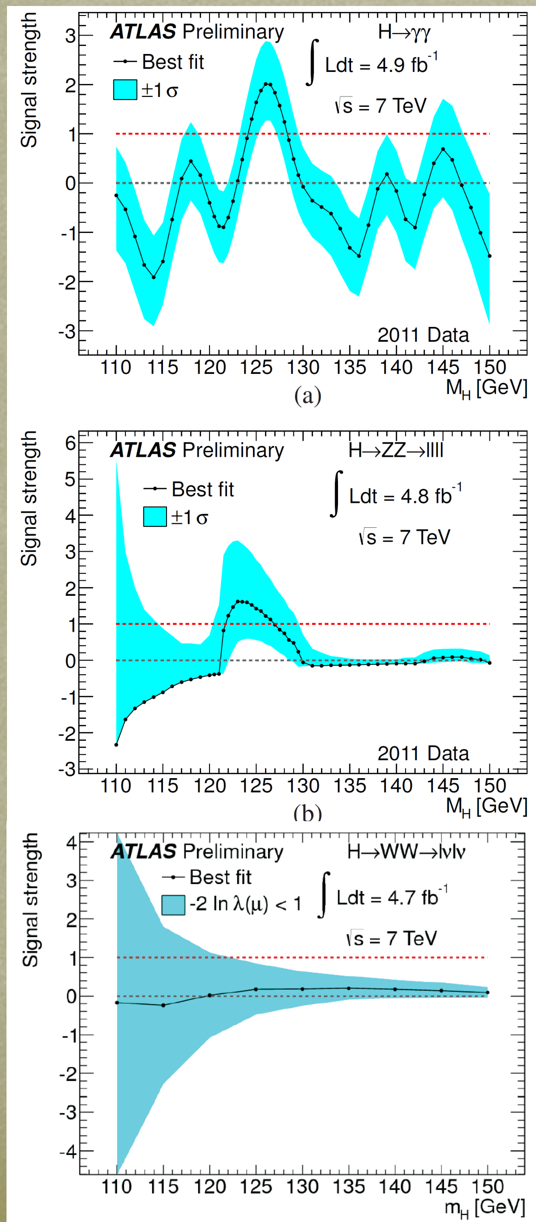


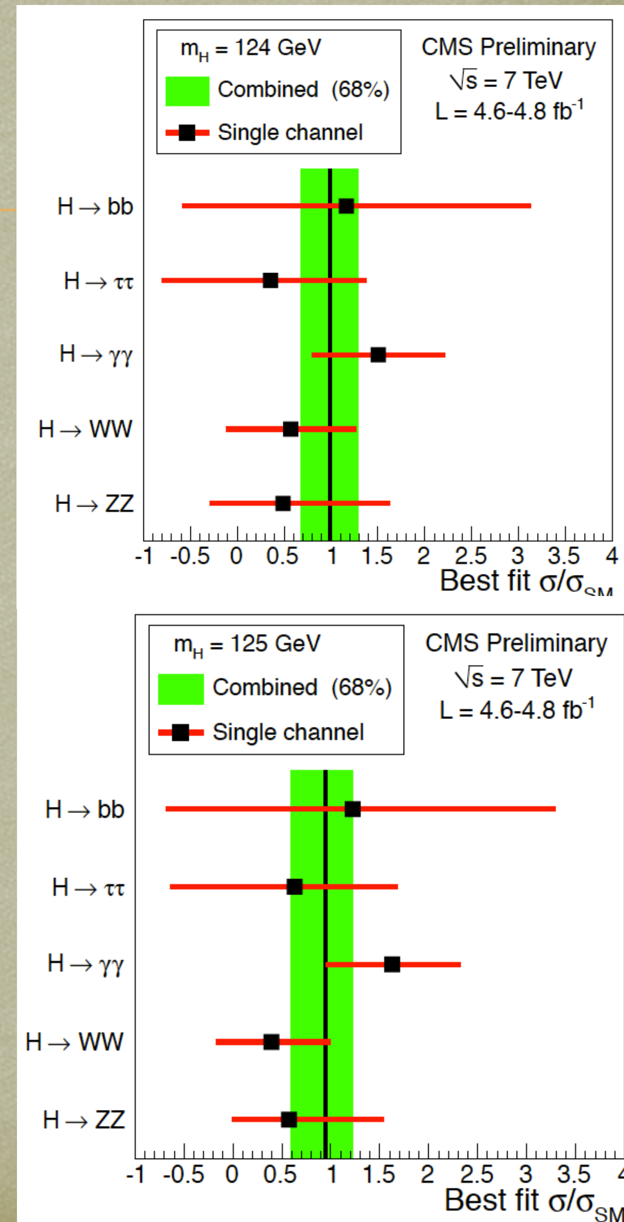
Zoom in on Low Higgs Mass



- 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.

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





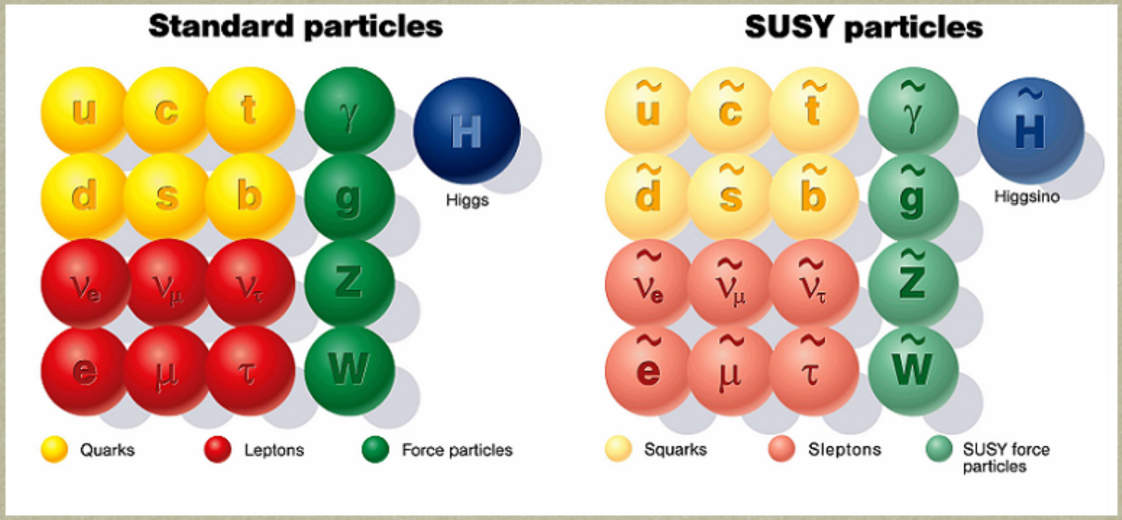
Goals

- $m_h \sim 125$ GeV
- $\gamma\gamma$ 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.
- Induces electroweak symmetry breaking radiatively.

Higgs Mass

Dependence on MSSM Parameters

What does SUSY 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^{+-}
    - $\tan\beta = v_2/v_1$, $v^2 = v_1^2 + v_2^2 = 246$ 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) $u\bar{u} \longrightarrow \cos\alpha/\sin\beta,\ \ \sin\alpha/\sin\beta,\ \ 1/\tan\beta$

(h,H,A) $d\bar{d}/l^+l^- \longrightarrow -\sin\alpha/\cos\beta,\ \ \cos\alpha/\cos\beta,\ \ \tan\beta$

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

Radiative Corrections to the SM-like Higgs Boson Mass

- Important quantum corrections due to incomplete cancellation of particles and sparticles in loops.
- Main effect due to *stops*:

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

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

- m_h depends logarithmically on averaged stop mass scale, M_{SUSY}, and has a quadratic and quartic dependence on the stop mixing parameter, A_t.
- For moderate to large values of tan β, large non-standard Higgs masses and $M_{SUSY} \sim m_Q \sim m_u$:

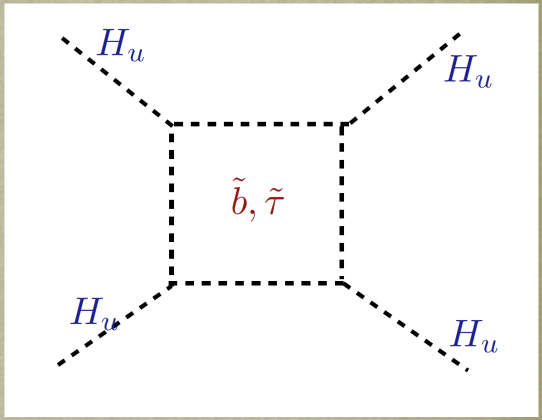
$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

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

Additional Affects at Large tan β

- Sbottoms: $$\Delta m_h^2 \simeq -\frac{h_b^4 v^2}{16\pi^2}\frac{\mu^4}{M_{\rm SUSY}^4}\left(1+\frac{t}{16\pi^2}(9h_b^2 - 5\frac{m_t^2}{v^2} - 64\pi\alpha_3)\right)$$
  - 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

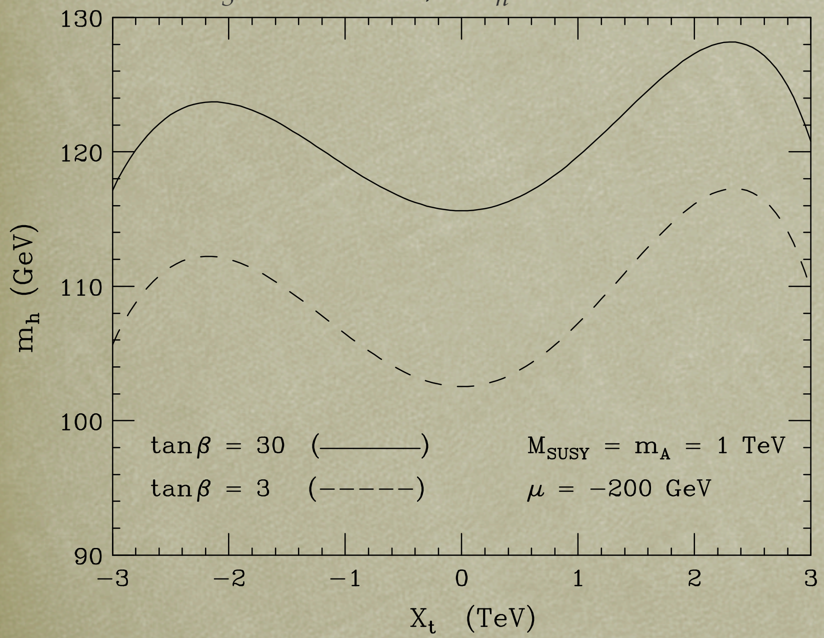
$$h_\tau \simeq \frac{m_\tau}{v\cos\beta(1+\tan\beta\Delta h_\tau)}$$

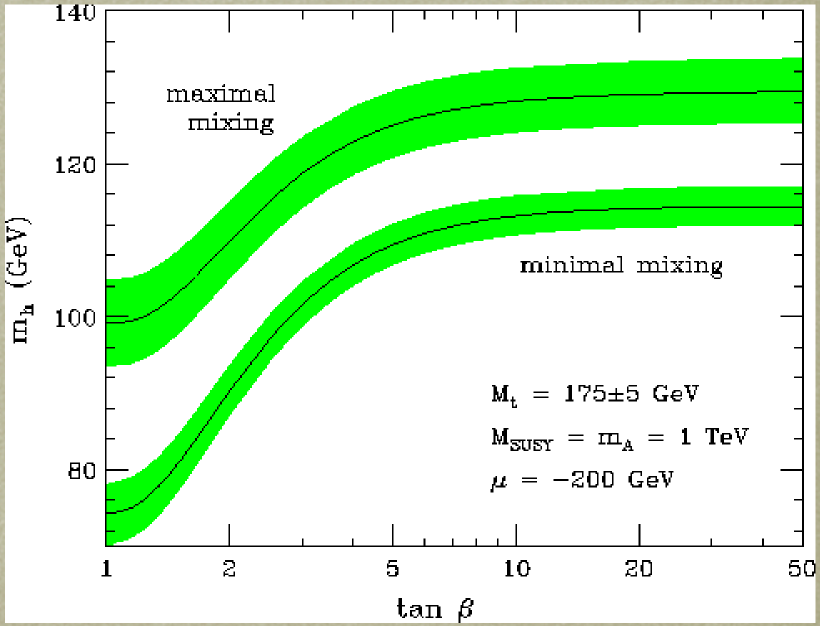
- Both corrections give negative contributions to the Higgs mass
  - Positive values of $\mu M_{\tilde{g}}$ and μM_2 enhance the value of the Higgs mass.

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: $m_h \leq 130$ GeV
  - M_S = 1 – 2 TeV, $\Delta m_h \sim$ 2 – 5 GeV

Carena and Haber, hep-ph/0208209

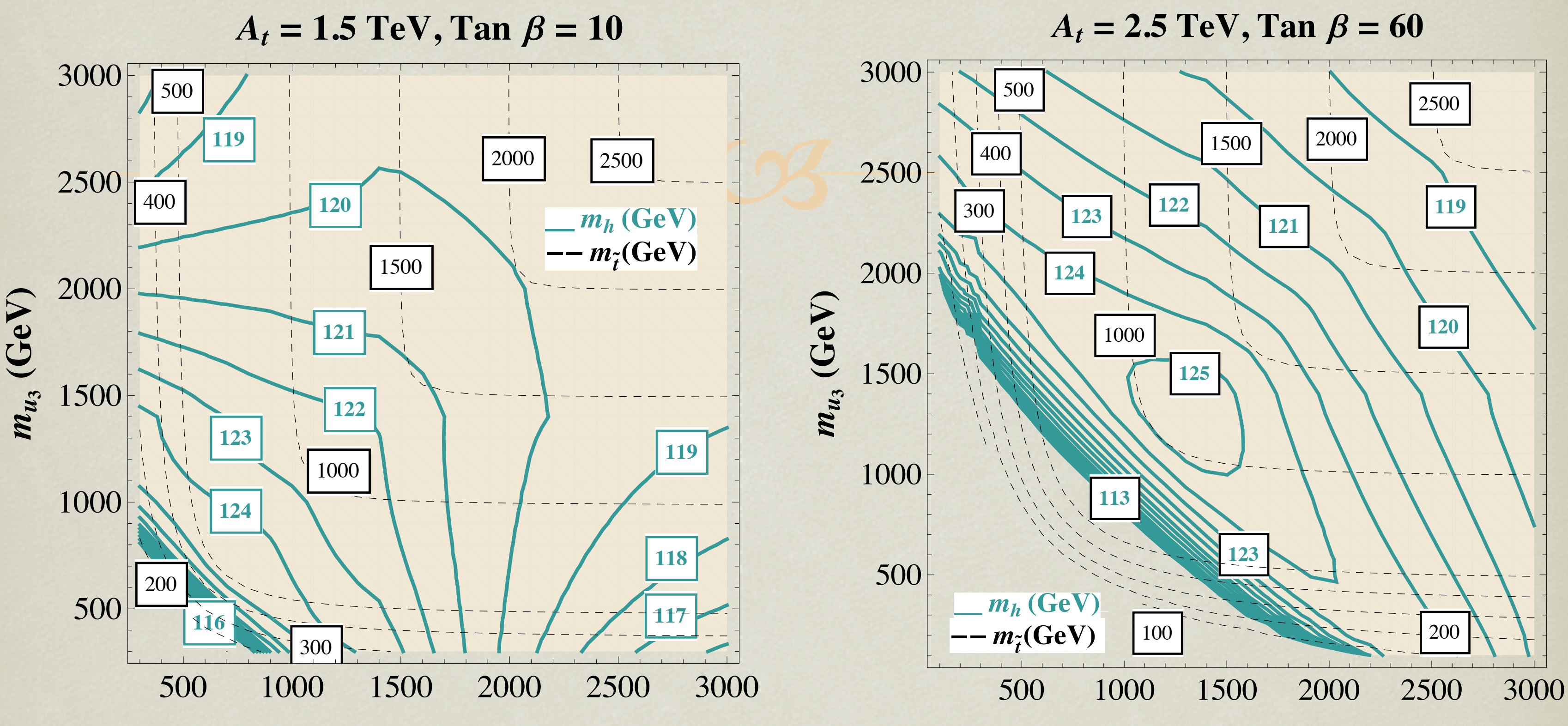




$X_t = A_t - \mu/\tan\beta, \quad X_t = 0$: No mixing; $\quad X_t = \sqrt{6}M_S$: Max. Mixing

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

125 GeV Higgs Boson and the Stop Spectrum



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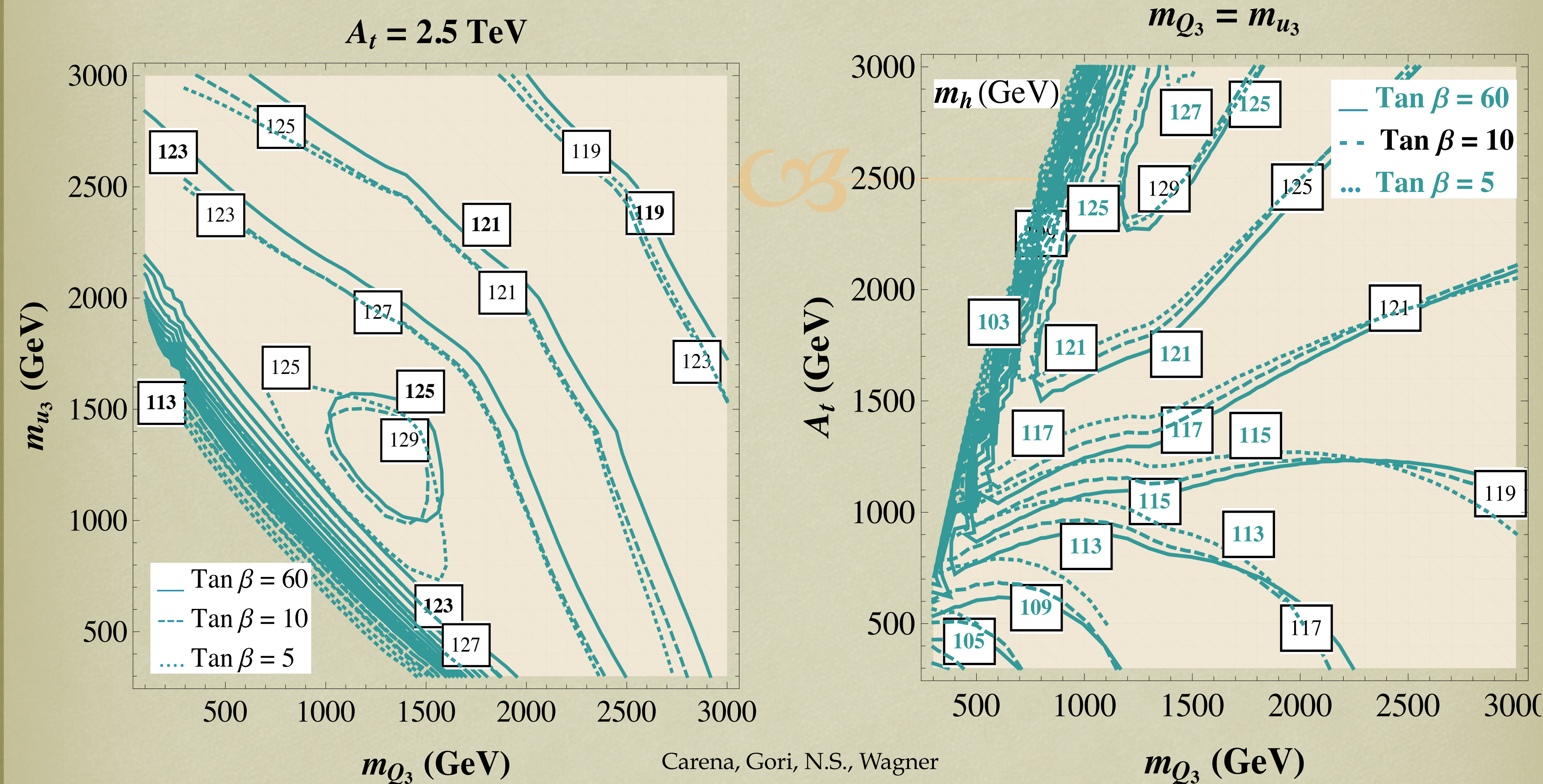
$\mu = 1030$ GeV $m_{e_3} = m_{L_3} = 340$ GeV

- 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



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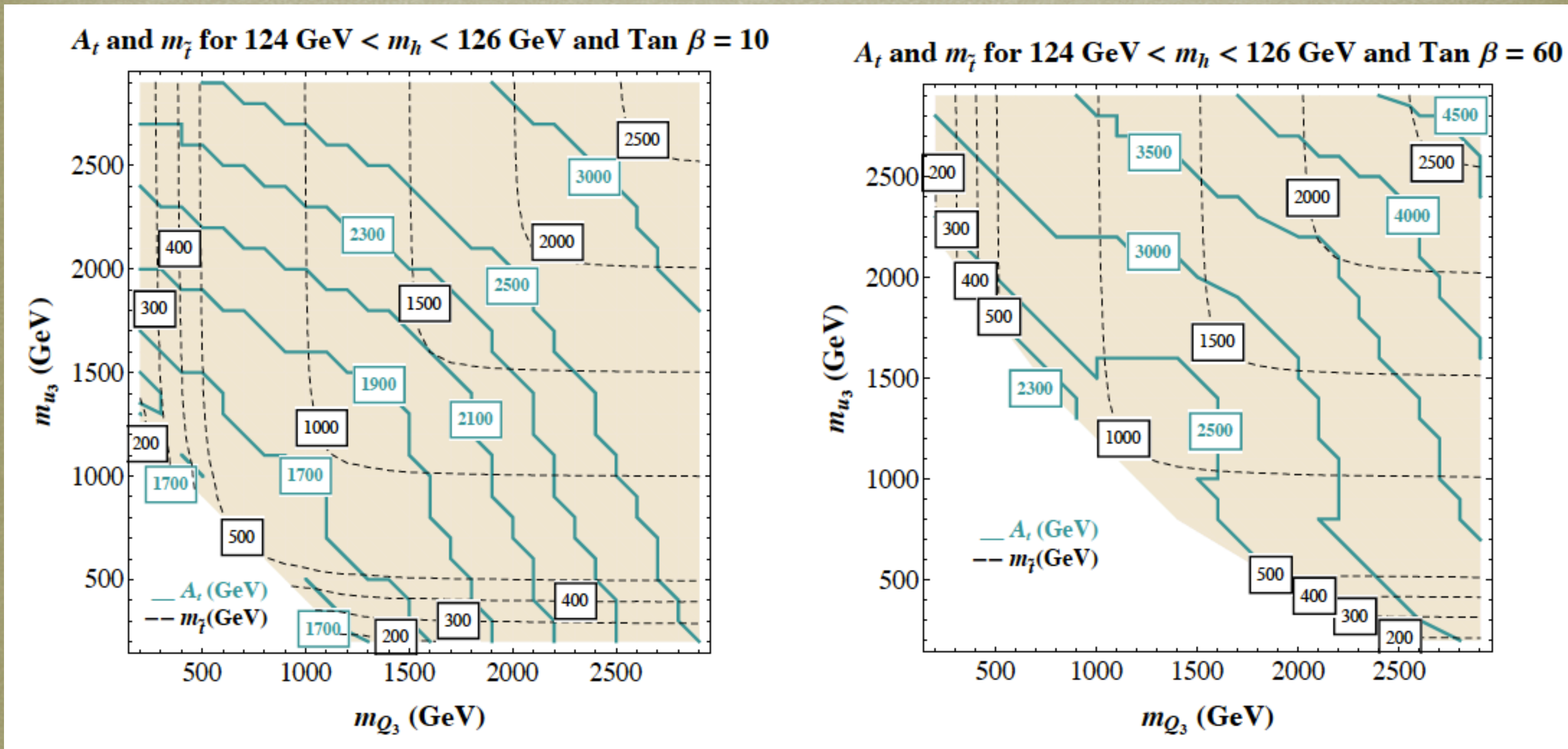
- Intermediate tan β leads to largest m_h for same values of soft stop mass parameters.
  - Gain in tree-level Higgs mass from moving tan β from 5 to 60 compensated by the negative stau effects.
- In case of degenerate soft masses,
  - A_t above ~ 1.5 TeV needed to achieve m_h ~ 125 GeV.
  - The lightest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

A_t Dependence



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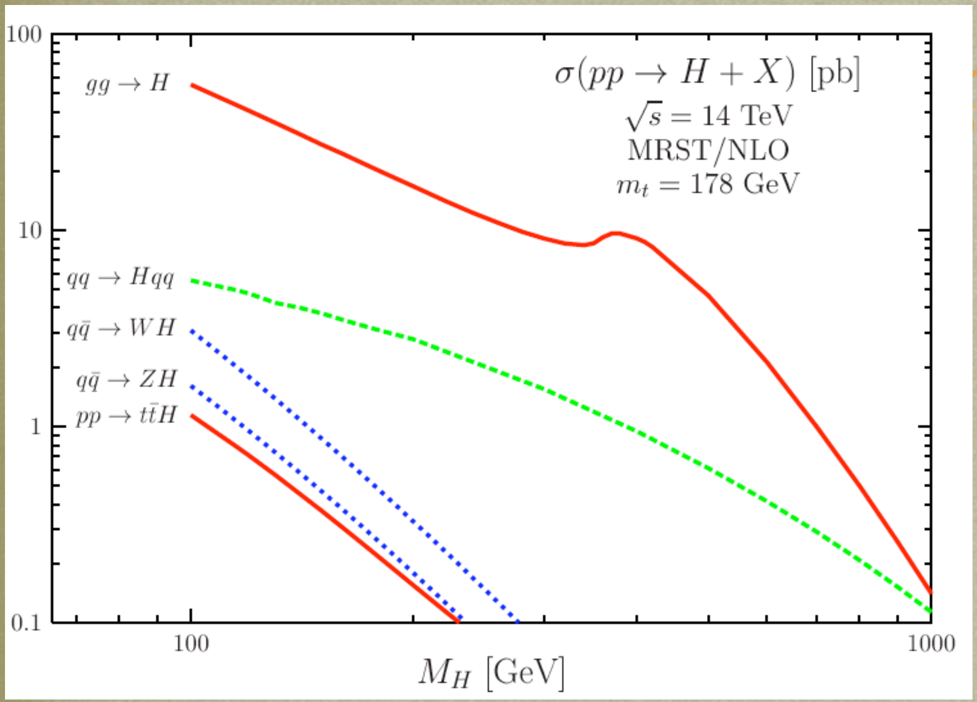
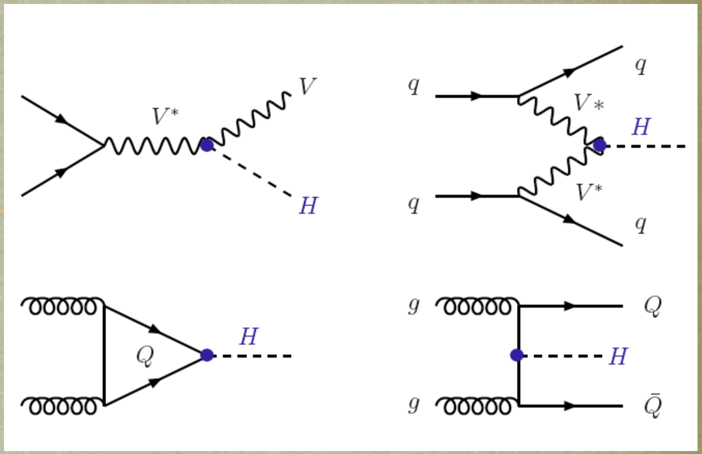
- Contours of A_t needed to obtain 124 GeV < m_h < 126 GeV.
  - Associated stop mass contours in black.
- Illustrates the requirement for A_t large.

Cross-sections and Rates

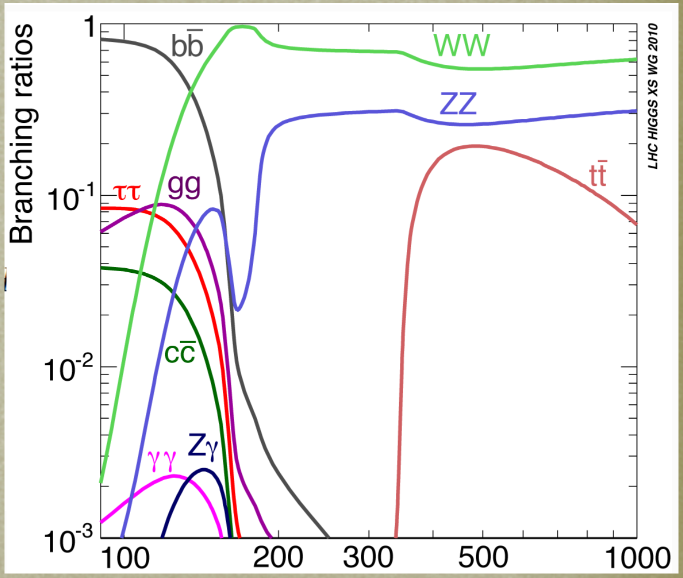
Higgs Production Mechanisms at the LHC

Main Higgs Production channels at the LHC





A. Djouadi, 0503172



- The event rate depends on three quantities:

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

- 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.

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.

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

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

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

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

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

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

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

m_h ~125 GeV: Squarks and the Di-Photon Production Rate

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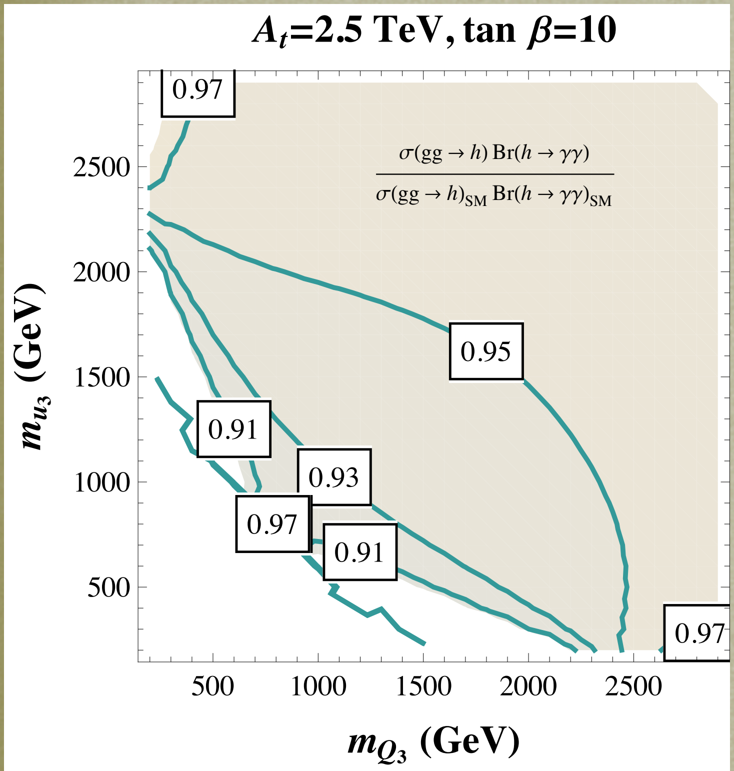
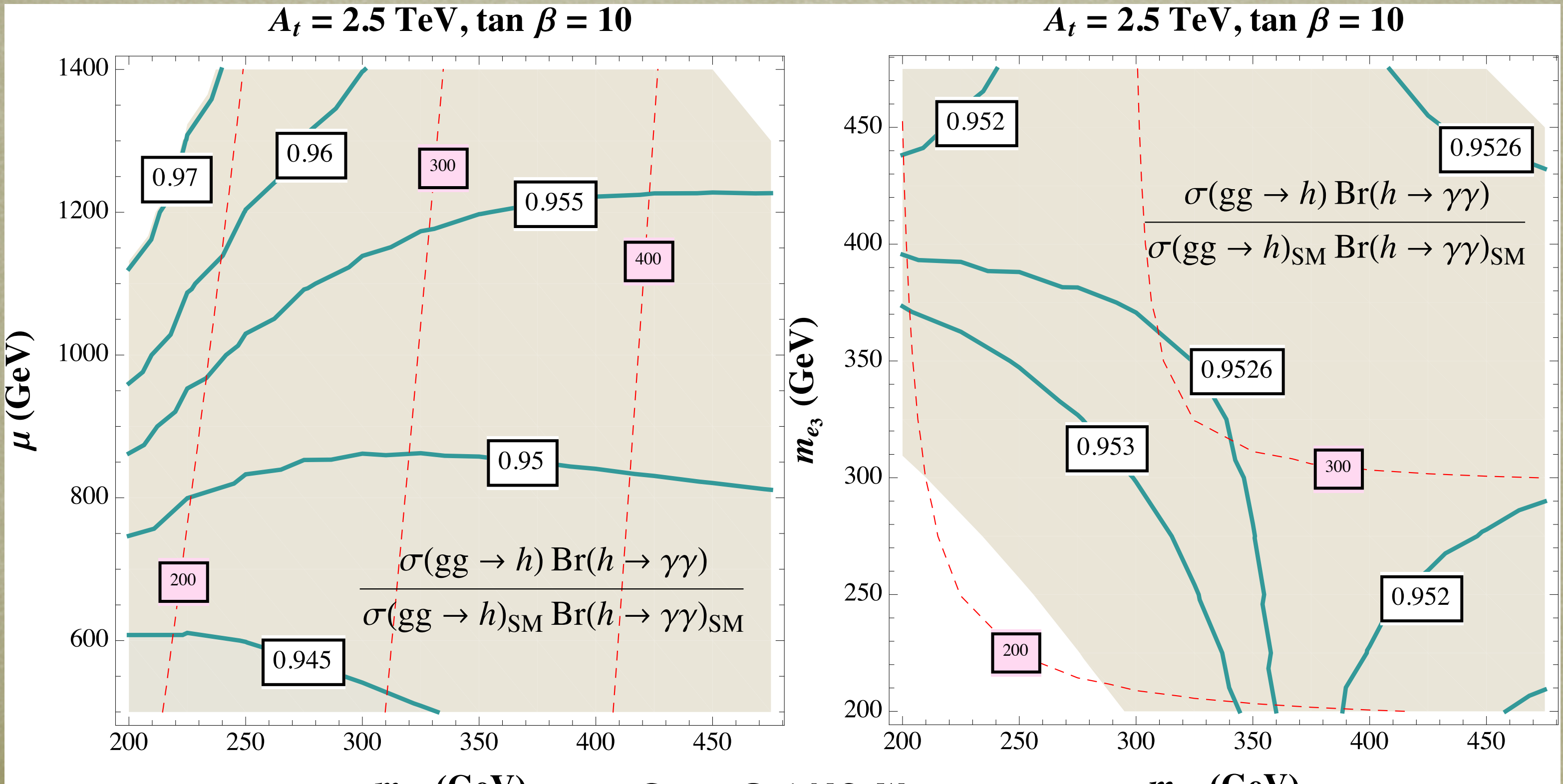


- Gluon fusion:
  - Receives contributions from top/bottom and stops/sbottoms.
  - Light 3rd generation squarks can increase gluon fusion rate, but large mixing is required for m_h masses of interest
    - Always leads to suppression.
- Di-photon rate:
  - W loop is partially suppressed by top loop.
  - Light stops/sbottoms
    - Can add to this suppression
    - Can produce enhancement if mixing large.
      - Usually overcompensated by suppression of gluon fusion.
  - Heavy 3rd generation squarks consistent with 125 GeV Higgs, lead to suppression in di-photon production

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

Sleptons

- At moderate values of tan β and small stau mixing, light staus tend to induce a slight suppression in $\gamma\gamma$ production:



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

- Higgs decay into photons proceeds via charged particle loops.
- Light staus would have the same effect as light stops
  - Enhancement for large mixing.
  - Do not effect the gluon fusion rate.

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

- Large mixing here means:
  - Large μ and Large $\tan\beta$

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

A_τ

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

- 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

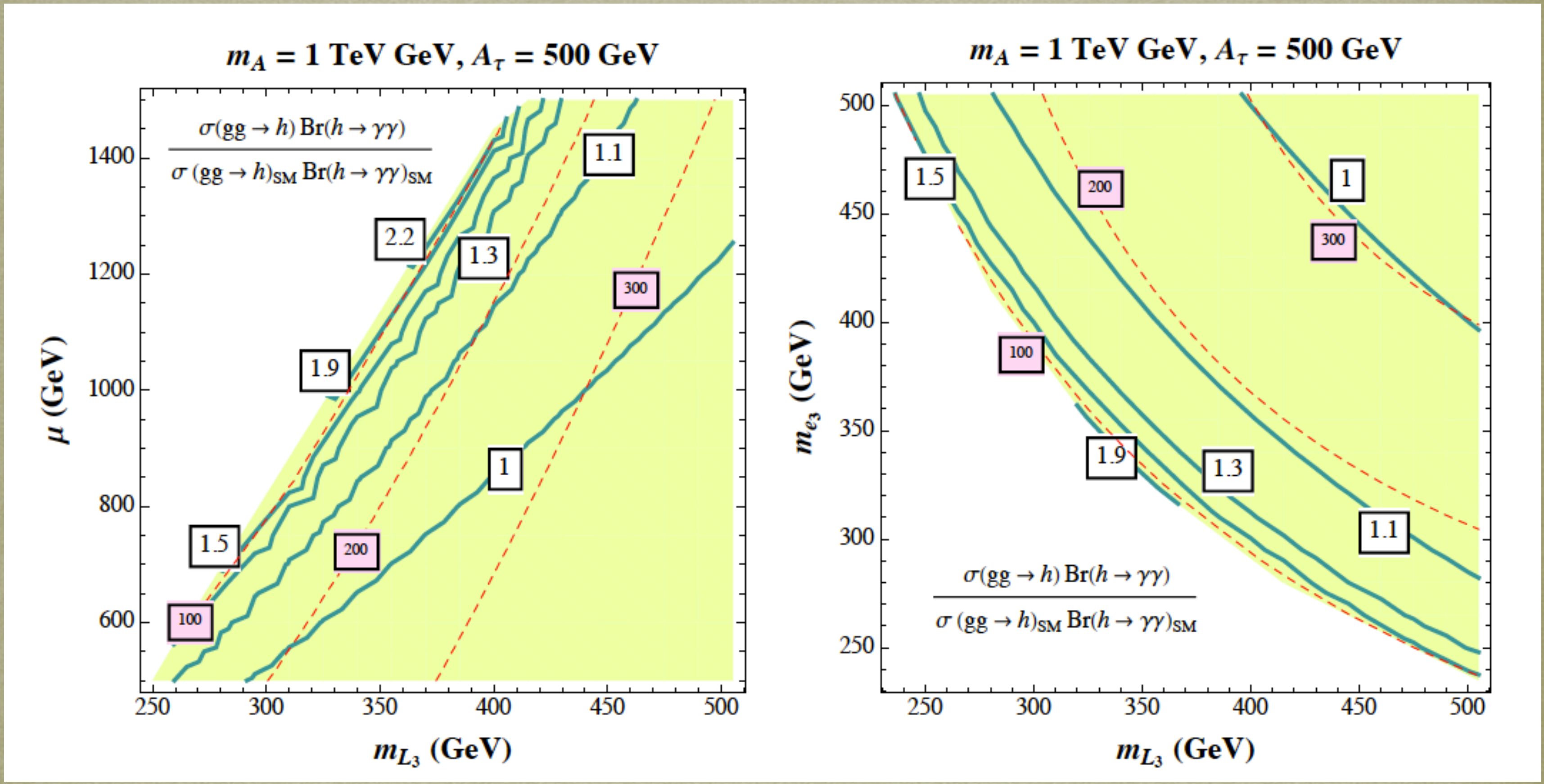
$$\text{BR}(h \to b\bar{b}) \simeq 0.8\text{BR}(\text{h} \to \text{b}\bar{\text{b}})_{\text{SM}}$$

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

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

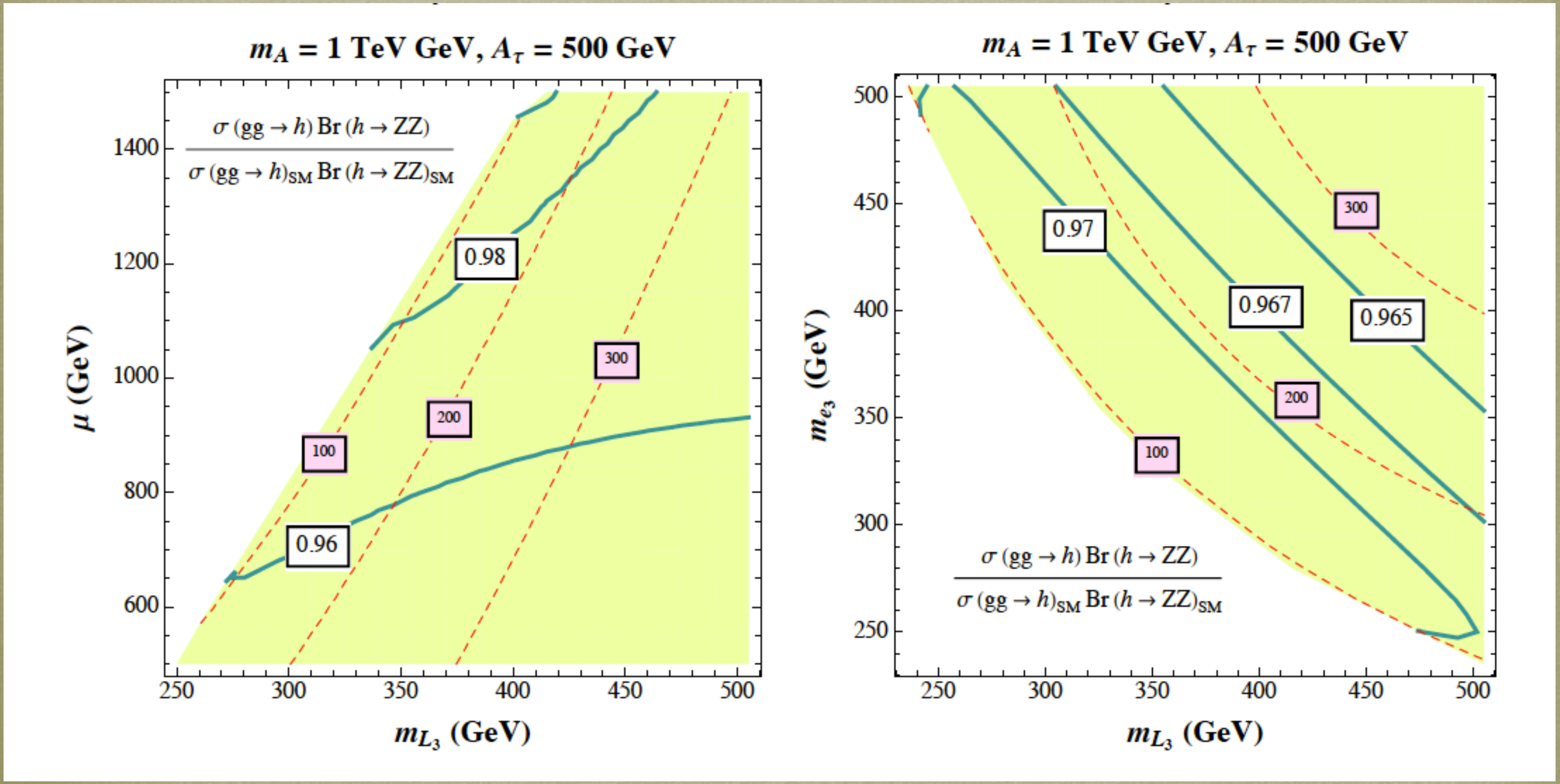
$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\text{SM}}} \frac{\text{BR}(h \to VV^*)}{\text{BR}(h \to VV^*)_{\text{SM}}} = 1.25 \qquad (V = W, Z)$$

Light Staus: Large μ, tan β and A_τ

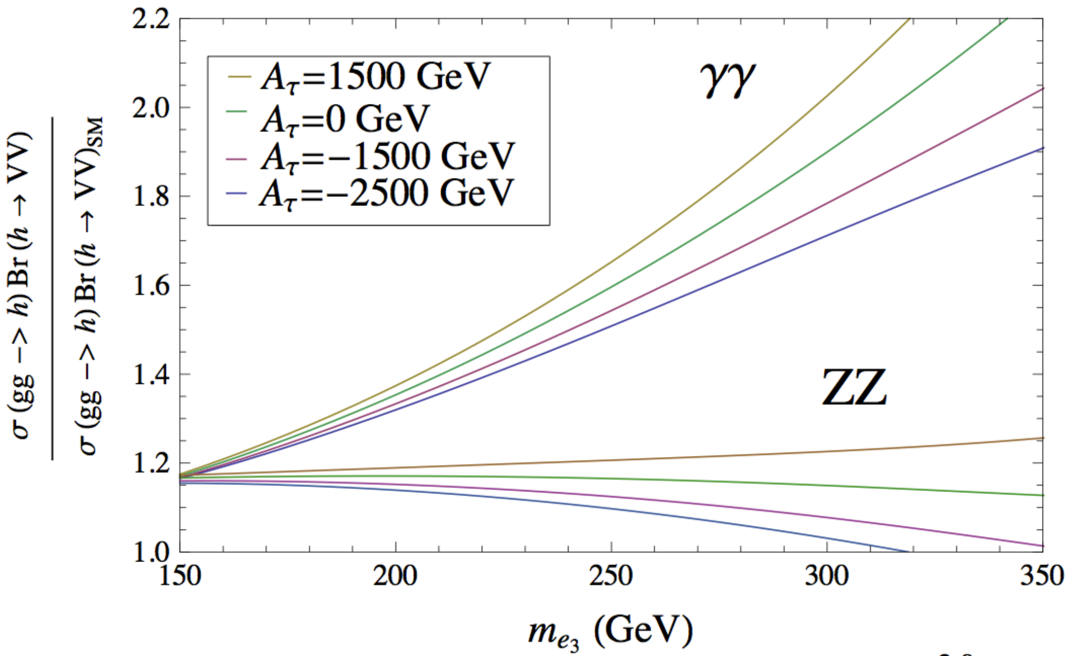


- Light staus with large mixing may induce relevant enhancement of the BR of the decay of a SM-like Higgs into two photons without affecting too much other decays.
  - A_τ changes BR into *bb*, impacting γγ, WW and ZZ together.
    - Dashed lines denote contours of stau masses

ZZ Production minimally impacted



Light Staus: A_τ and $m_{\tilde{t}}$ affect on $\gamma\gamma$ / ZZ



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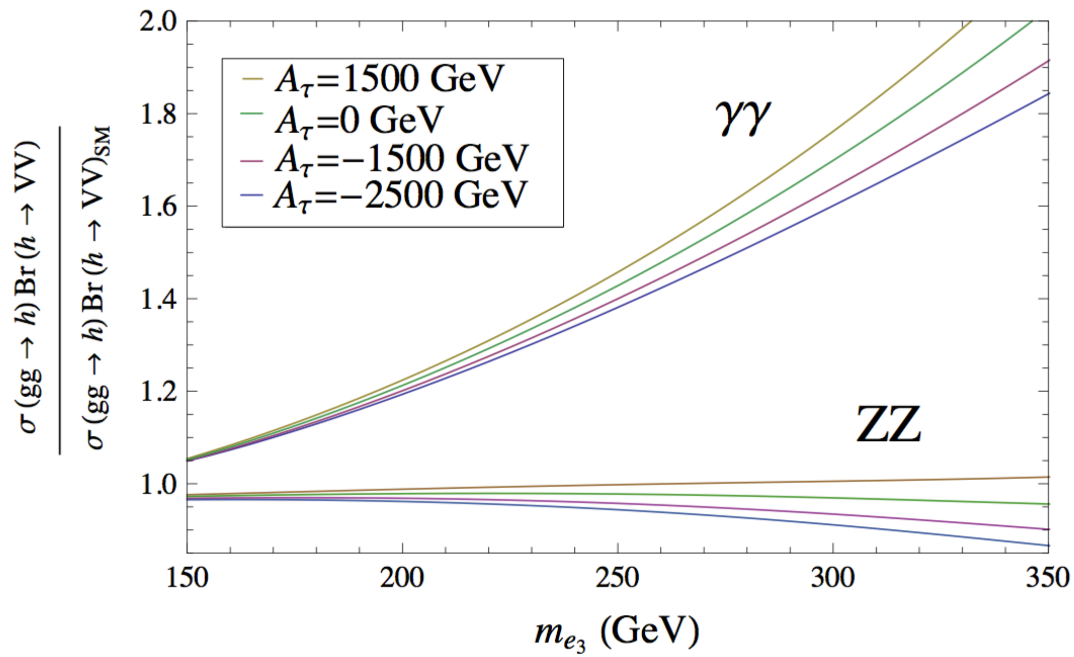
- $\tan\beta$ = 60 and μ such that light $m_{\tilde{\tau}}$ = 90 GeV.

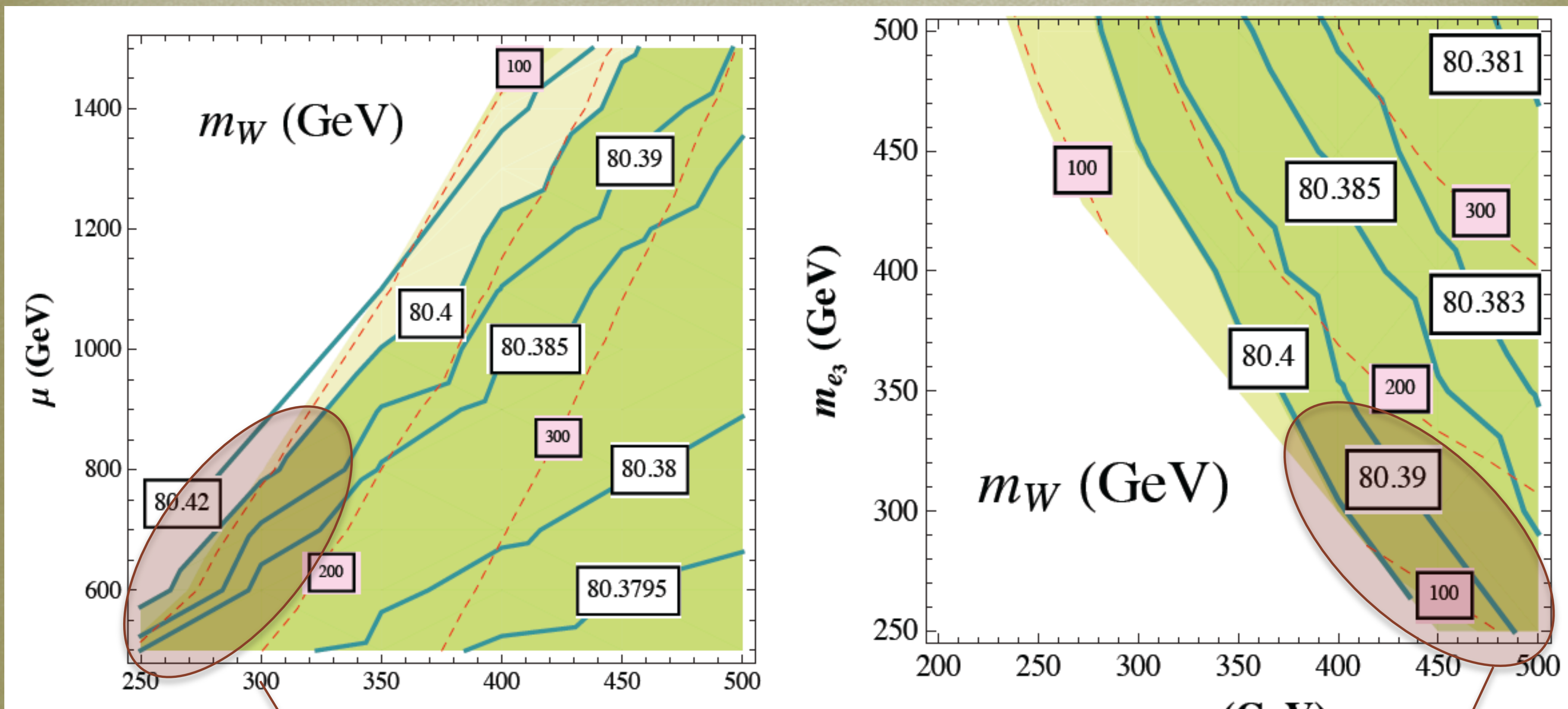
- Top: $m_{\tilde{t}} \sim$ 140 GeV
- Right: $m_{\tilde{t}} \sim$500 GeV



Electroweak Constraints

m_W and $(g_\mu\text{-}2)$

$m_W = 80.385$ +-0.015 GeV



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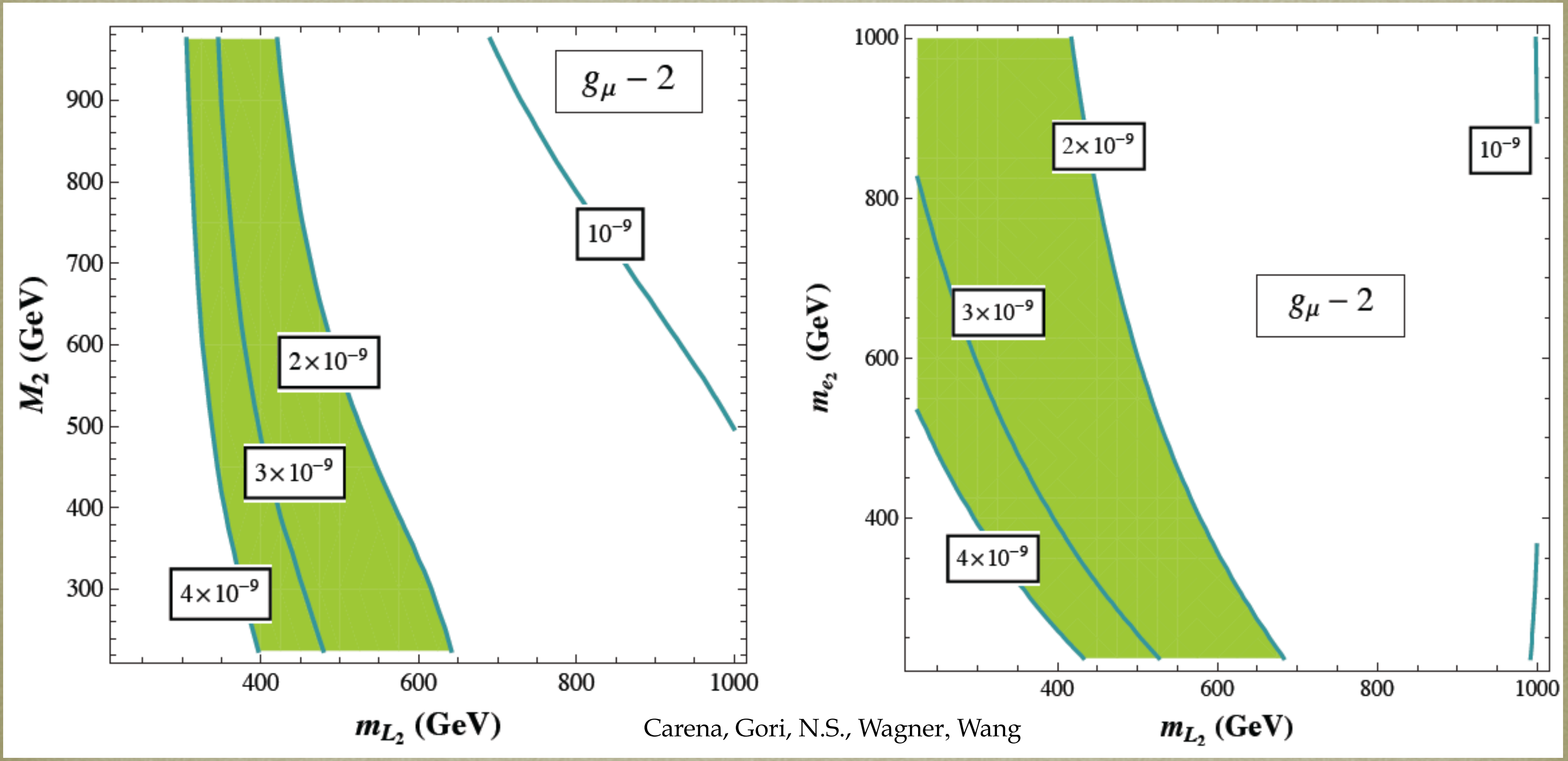
$m_{L3} = m_{e3}$,
μ < 800 GeV.

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

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

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



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Messenger Scale

Light Sleptons

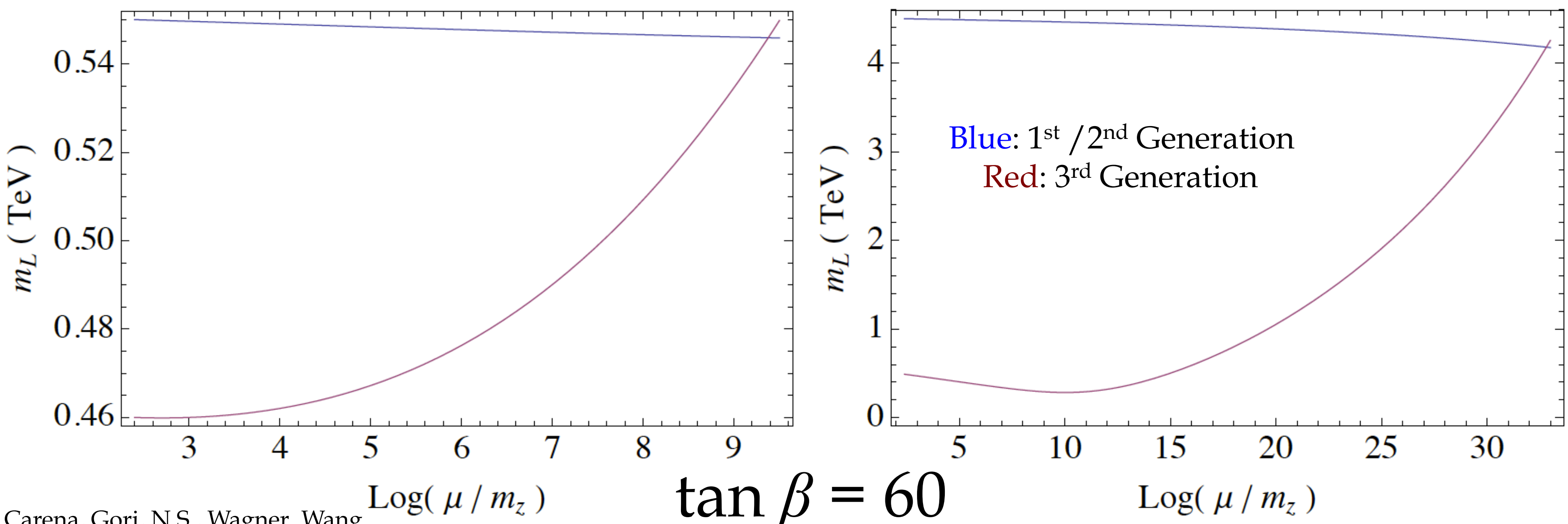
- Assuming
  - Flavor blindness
  - Both 1st/2nd and 3rd generations light at TeV scale
    - 3rd generation sleptons run strongly with Yukawas
      - Yukawas scaled by tan β
    - 1st and 2nd generation barely affected by running.

Moderate tan β and High Messenger scale ~ M_{GUT}

OR

Large tan β and Low Messenger scale

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



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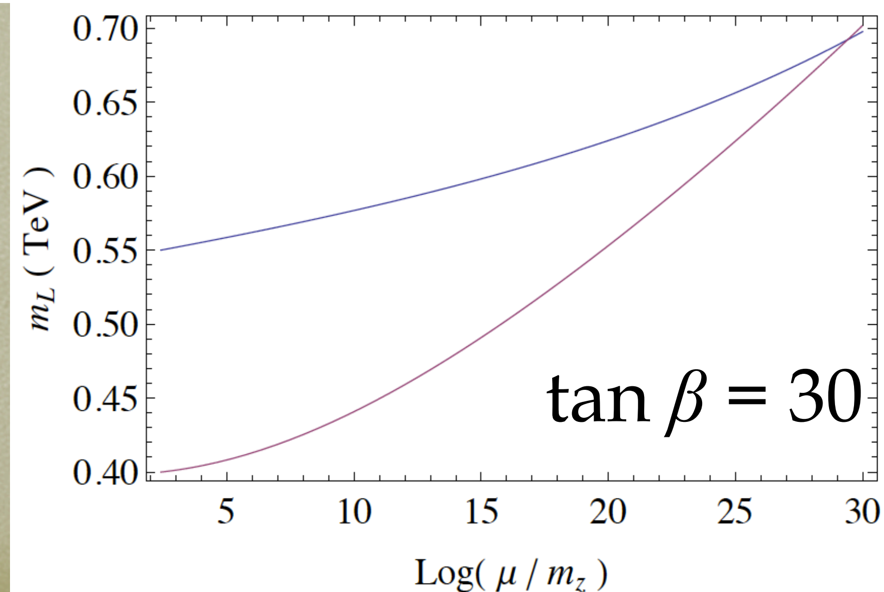
m_e runs similarly

m_{L3} running >> m_{L2}/ m_{L1} running.
m_{L2} (TeV) ~ m_{L2} (M)

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

Point III: $A_\tau = 500$ GeV, $m_{L_3} = m_{E_3} = 280$ GeV $\mu = 625$ GeV, $\tan\beta = 60$, $M_1 = 10\,\text{GeV}$, $m_A = 1$ TeV that gives $m_{\tilde{\tau}_1} = 94$ GeV, $m_{\tilde{\tau}_2} = 484$ GeV, $m_{\tilde{\nu}_\tau} = 272$ GeV, $m_{\tilde{\chi}_1} = 9$ GeV

$\tilde{\tau}_1 \rightarrow \tilde{\chi}_1 \tau$ or $\tilde{\tau}_1 \rightarrow \tilde{G}\,\tau$

$$pp \rightarrow \tilde{\tau}_1 \tilde{\nu}_\tau \text{ with } \tilde{\nu}_\tau \rightarrow W \tilde{\tau}_1 \text{ and } \tilde{\tau}_1 \rightarrow \tau \tilde{\chi}_1.$$

$$E_T^\ell > 70 \text{ GeV},\ \not{E}_T > 70 \text{ GeV and } p_T^{j,\tau} < 90 \text{ GeV}$$

- $m_{\tilde{\tau}}$~100 GeV >> m_χ
  - Hard τ
- $\tilde{\tau}_1\,\tilde{\tau}_1$ production overwhelmed by background.
- $\tilde{\tau}_1$ produced in association with $\tilde{\nu}_1$, situation better.
  - Leptonically decaying *W*
  - Large missing E_T, => $\not{E}_T$ ~> 70 GeV

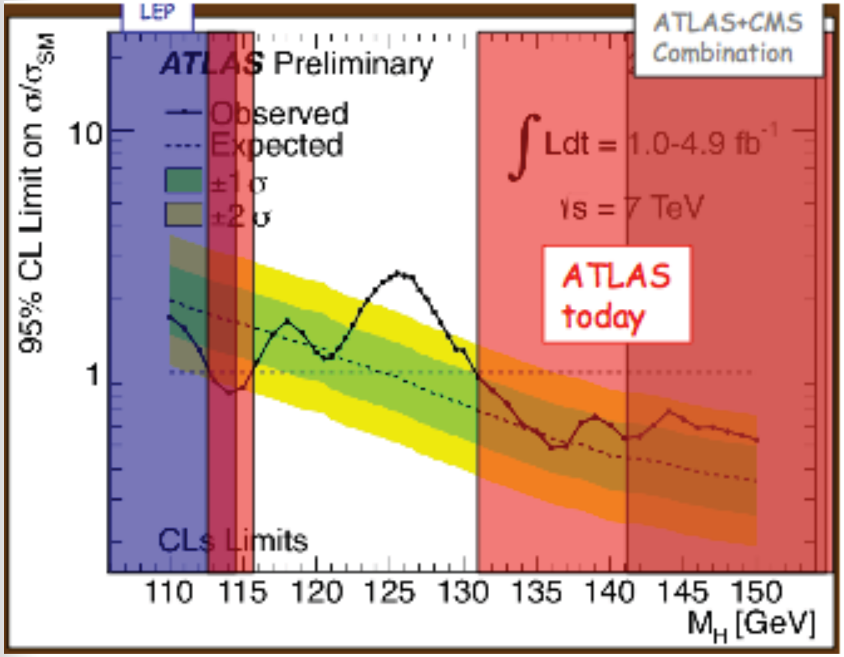
- Background: $pp \rightarrow W\tau\bar{\tau}$
  - *l* from *W* in signal has larger p_T,
    - p_T > 70 GeV
  - τ mostly from Z*/γ*,
    - exclude 80 GeV < $m_{\tau\tau}$ <120 GeV
  - Fake τ from Wjj
    - Veto hard jets recoiling from the *W*
    - p_T^j < 90 GeV
    - Can get S/B ~ 1
    - σ ~ 1 fb (low statistics)

Conclusions and Outlook

- Allowed SM-Higgs mass range at LHC:
  - Consistent with precision measurements
  - Extrapolation of SM description to very high energies.
- 125 GeV Higgs boson consistent with stops ~ 1 TeV and large stop mixing:
  - No hard bound on the lightest stop mass.
- In MSSM, rates may be modified by mixing or by light sfermions.
  - MSSM parameter region consistent with a 125 GeV Higgs:
    - Stops tend to slightly suppress the photon rate.
    - Light staus can enhance it without modifying other rates in a significant way.
  - Light staus with large mixing can also induce relevant mixing effects:
    - Suppression of the bottom quark rates.
    - Further enhancement of the photon rate.
    - Less dramatic enhancement of the *WW* and *ZZ* rates.
- EWPT combined with recent Higgs results, favor light sleptons for all three generation
  - Either large tan β with low messenger scale or moderate tan β with high messenger scale.
- Work-in-Progress: Collider signatures of light staus.

Backup Slides

Atlas results zoomed in the Low Mass region



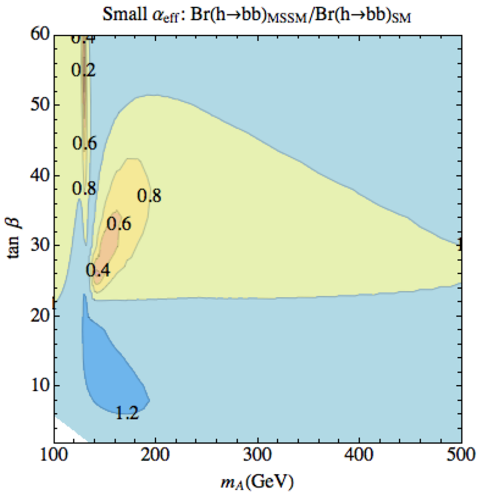
H→γγ, H→ ττ
H→ WW(*)→ lνlν
H→ ZZ(*) → 4l, H→ ZZ → llνν
H→ ZZ → llqq, H→ WW→lνqq
W/ZH→ lbb+X not included

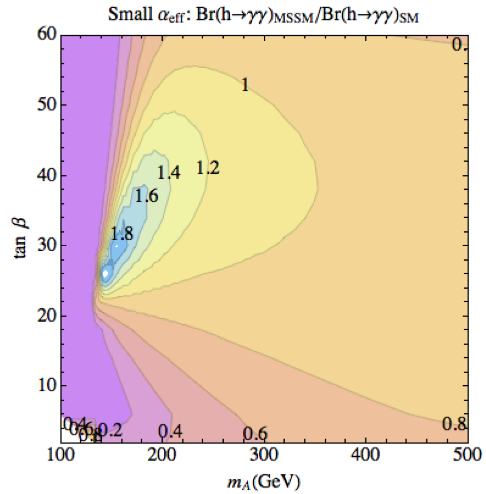
We have restricted the most likely mass region (95% CL) to

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

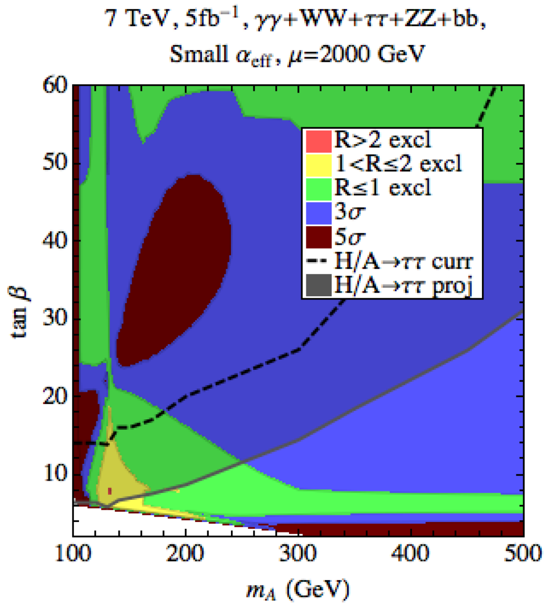




For large values of μ and A_t

one can get suppression of the Higgs decay into bottom quarks and therefore enhancement of photon decay branching ratio

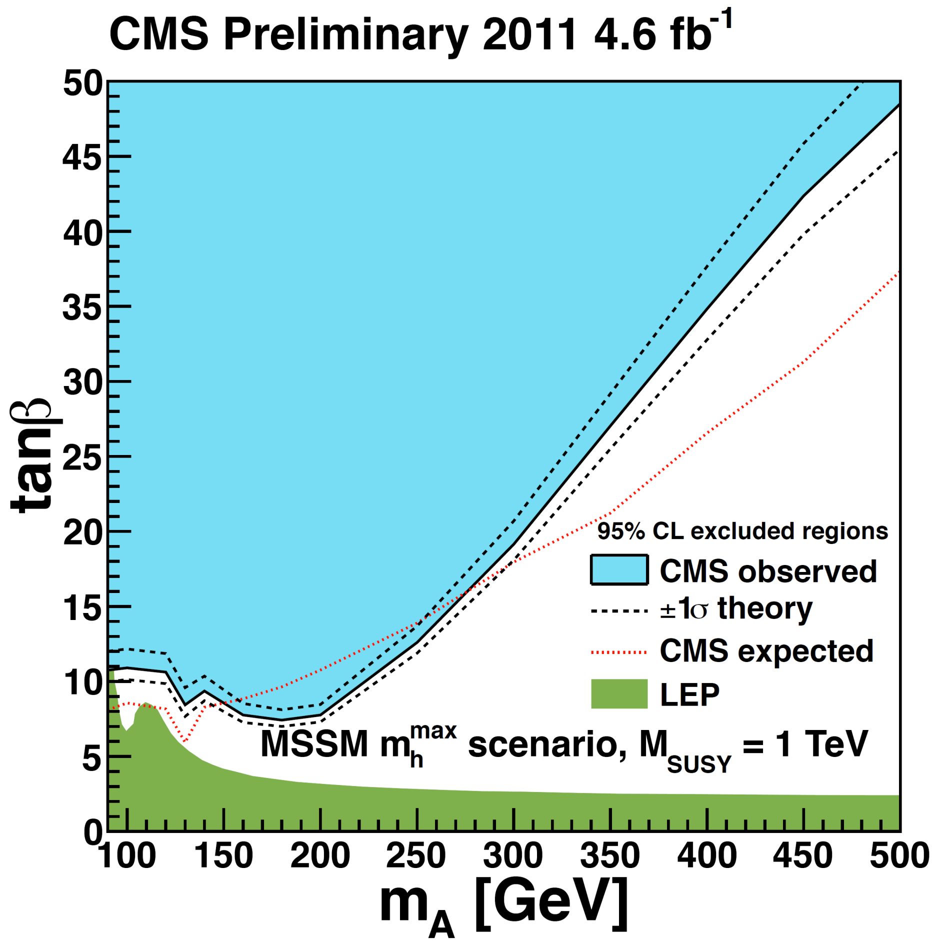
Carena, Mrenna, Wagner'99
Carena, Heinemeyer, Wagner, Weiglein'02



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

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

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

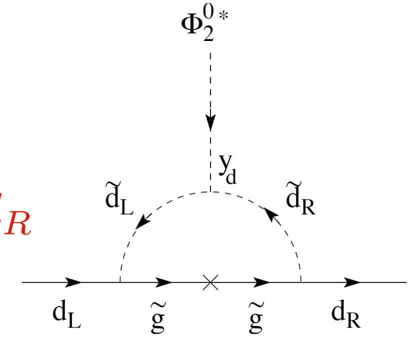
$$A_f(\tau) = 2\left[\tau + (\tau-1)f(\tau)\right]\tau^{-2}$$
$$A_W(\tau) = -\left[2\tau^2 + 3\tau + 3(2\tau-1)f(\tau)\right]\tau^{-2}$$

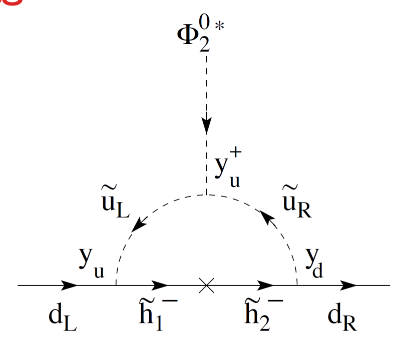
$$f(\tau) = \begin{cases} \arcsin^2\sqrt{\tau} & \tau \le 1 \\ -\frac{1}{4}\left[\ln\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \tau > 1 \end{cases}$$

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