恭贺邝宇平院士八十华诞

Happy Birthday, Professor Kuang!

ZHEJIANG UNIVERSITY

Revisit to Non-decoupling MSSM

Mingxing Luo

Zhejiang Institute of Modern Physics
Zhejiang University

Tsinghua University Nov.13, 2012

with Jiwei Ke, Hui Luo, Kai Wang, Liucheng Wang and Guohuai Zhu

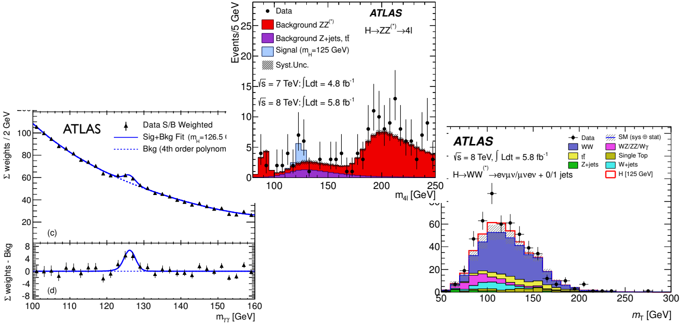
hep-ph/1211.XXXX

Discovery of a Higgs-like Boson at the LHC

Two cleanest channels $\gamma\gamma$, 4ℓ:

reconstruction masses at 125 GeV

Dilepton also consistent with $ZZ^* \to 4\ell$ at 125 GeV



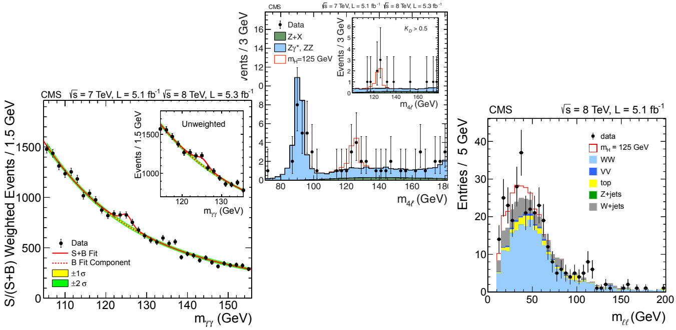
- $\gamma\gamma$: spin 0 or 2 (Landau-Yang)
- couples to weak gauge bosons (ZZ^*/WW^*)
- if it is spin-zero, production from gluon fusion

Discovery of a Higgs-like Boson at the LHC

Two cleanest channels $\gamma\gamma$, 4ℓ:

reconstruction masses at 125 GeV

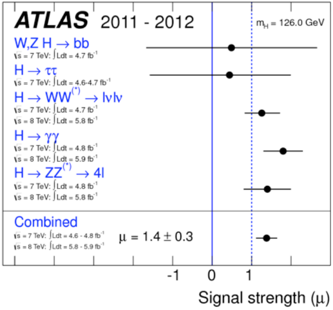
Dilepton also consistent with $ZZ^* \to 4\ell$ at 125 GeV



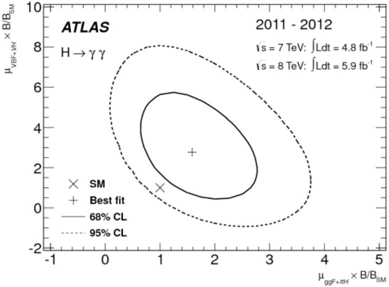
- $\gamma\gamma$: spin 0 or 2 (Landau-Yang)
- couples to weak gauge bosons (ZZ^*/WW^*)
- if it is spin-zero, production from gluon fusion

The SM Higgs? Likely

Signal strength of individual channels (SM: μ=1)

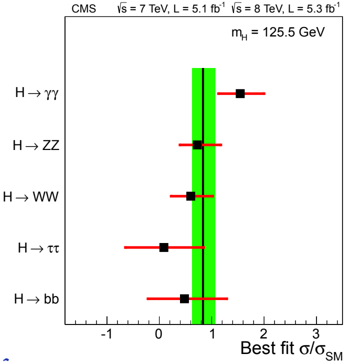


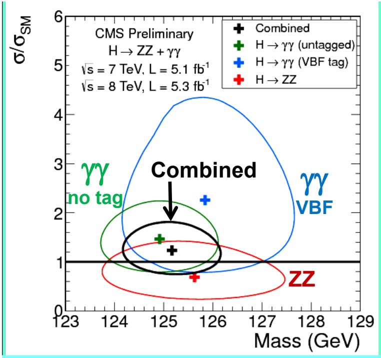
top-related production (gluon fusion + ttH) vs W/Z-related production (VBF, VH) in H→γγ



- $\sigma(gg \to h \to \gamma\gamma)/\sigma_{SM} \simeq 1.9 \pm 0.5$
- $\sigma(gg \to h \to ZZ^* \to 4\ell)/\sigma_{SM} \gtrsim 1$
- $\sigma(gg \to h \to WW^* \to 2\ell 2\nu)/\sigma_{SM} \gtrsim 1$

The SM Higgs? Likely





- $\sigma(gg \to h \to \gamma\gamma)/\sigma_{SM} \simeq 1.5 \pm 0.4$
- $\sigma(gg \to h \to ZZ^* \to 4\ell)/\sigma_{SM} \lesssim 1$
- $\sigma(gg \to h \to WW^* \to 2\ell 2\nu)/\sigma_{SM} \lesssim 1$

How to interprete the 125 GeV resonance

- Standard Model Higgs boson?
- Composite Higgs?
- ....
- Higgs boson in MSSM
  - the light Higgs boson h at 125 GeV? (push the limit)
  - the heavy Higgs boson H at 125 GeV? while h evades all direct searches (or h around 98 GeV?)

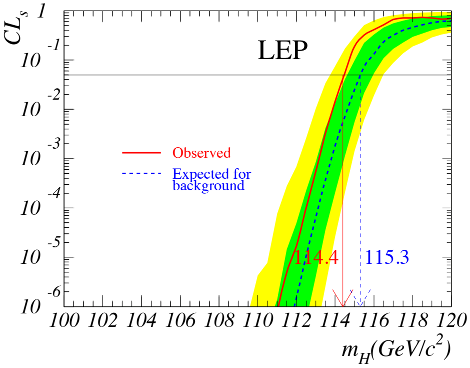
- A. Belyaev, Q. -H. Cao, D. Nomura, K. Tobe and C. -P. Yuan, Phys. Rev. Lett. **100**, 061801 (2008) [hep-ph/0609079].
- N. D. Christensen, T. Han and S. Su, Phys. Rev. D **85**, 115018 (2012) [arXiv:1203.3207 [hep-ph]].
- K. Hagiwara, J. S. Lee and J. Nakamura, arXiv:1207.0802 [hep-ph].
- R. Benbrik, M. G. Bock, S. Heinemeyer, O. Stal, G. Weiglein and L. Zeune, arXiv:1207.1096 [hep-ph].
- G. Belanger, U. Ellwanger, J. F. Gunion, Y. Jiang, S. Kraml and J. H. Schwarz, arXiv:1210.1976 [hep-ph].
- M. Drees, arXiv:1210.6507 [hep-ph].
- P. Bechtle, S. Heinemeyer, O. Stal, T. Stefaniak, G. Weiglein and L. Zeune, arXiv:1211.1955 [hep-ph].

LEP exclueds a SM-like Higgs to 114.4 GeV (in both SM and MSSM)

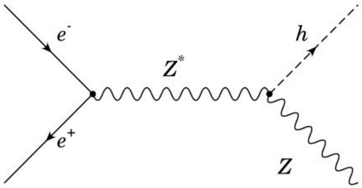
Higgs Mass Lower Bound

LEP excludes a 114.4 GeV Higgs boson @ 95% CL. (expected 115.3 GeV)

	Exp.	Obs.
ALEPH	113.5	111.4
DELPHI	113.3	114.1
L3	112.4	112.0
OPAL	112.7	112.7



To evade the LEP bound: reducing g_{ZZh}



A simple realization: to make h H_d-like and take a small v_d

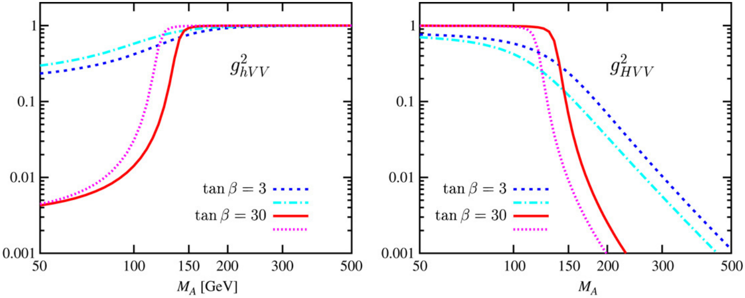
$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} \text{Re } H_d \\ \text{Re } H_u \end{pmatrix}$$

$$\frac{\tan 2\alpha}{\tan 2\beta} = \frac{M_A^2 + m_Z^2}{M_A^2 - m_Z^2}$$

In the limit of small v_d (large $\tan\beta$, $\sin\beta \to 1$)
Taking $M_A \to 0$, $\sin\alpha \to -1$

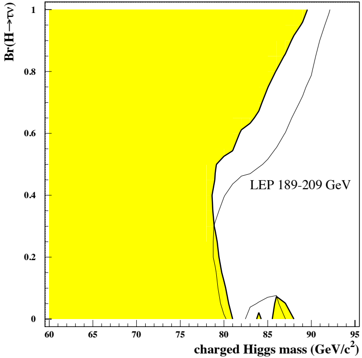
$$\beta \to \frac{\pi}{2}, \alpha \to -\frac{\pi}{2}, g_{ZZh} \sim \sin(\beta - \alpha) \to 0$$

A. Djouadi / Physics Reports 459 (2008) 1–241



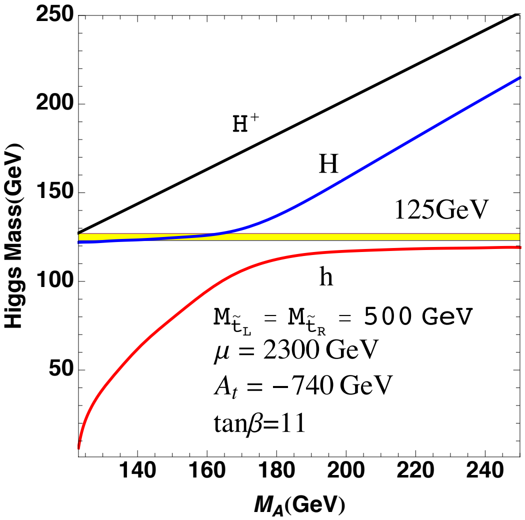
Qualitatively, smaller $M_A \to$ smaller g_{ZZh}

Lower bound of M_A from LEP bound on charged Higgs



non-decoupling limit ($M_A \to m_Z$) may survive the LEP direct search bound (via Zh) and charged Higgs search

At tree level, $M_A \to m_Z$, $M_h \to M_H$: nondecoupling
With radiative corrections:



Large $\tan\beta$ and $\sin\alpha \to -1$ lead to $M_h \simeq \mathcal{M}_{11}, M_H \simeq \mathcal{M}_{22}$

$$
\begin{aligned}
M_H^2 \simeq \mathcal{M}_{22}^2 \quad \simeq \quad & M_A^2 \cos^2\beta + m_Z^2 \sin^2\beta \left(1 - \frac{3}{8\pi^2} y_t^2 t\right) \\
+ \quad & \frac{y_t^4 v^2}{16\pi^2} 12 \sin^2\beta \left\{ t \left[1 + \frac{t}{16\pi^2} \left(1.5 y_t^2 + 0.5 y_b^2 - 8 g_3^2\right)\right] \right. \\
+ \quad & \left. \frac{A_t \tilde{a}}{M_{SUSY}^2} \left(1 - \frac{A_t \tilde{a}}{12 M_{SUSY}^2}\right) \left[1 + \frac{t}{16\pi^2} \left(3 y_t^2 + y_b^2 - 16 g_3^2\right)\right] \right\} \\
- \quad & \frac{v^2 y_b^4}{16\pi^2} \sin^2\beta \frac{\mu^4}{M_{SUSY}^4} \left[1 + \frac{t}{16\pi^2} \left(9 y_b^2 - 5 y_t^2 - 16 g_3^2\right)\right] + \mathcal{O}(y_t^2 m_Z^2)
\end{aligned}
$$

M. S. Carena, J. R. Espinosa, M. Quiros and C. E. M. Wagner, Phys. Lett. B **355**, 209 (1995) [hep-ph/9504316].

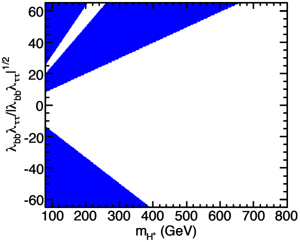
Consequences of Non-decoupling

Non-decoupling scenario may evade all constraints from direct search experiments but ....

- $H^{\pm}$ are around ($M_{H^{\pm}}^2 = M_A^2 + m_W^2$ at tree level)
  Is the scenario flavor safe?

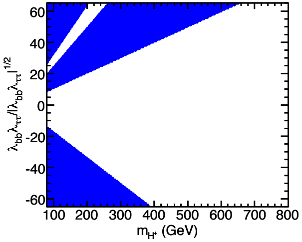
- Light Higgs bosons can enhance spin-independent neutralino-nuclei scattering
  If DM consists of only neutralino, how about bounds from direct detection?

Tree level $H^{\pm}$: $B_u \to \tau\nu$ in 2HDM and SUSY



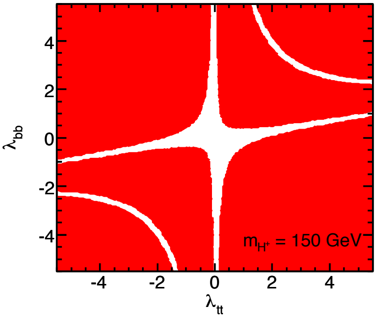
- $$\frac{BR(B^+ \to \tau^+\nu)_{\text{MSSM}}}{BR(B^+ \to \tau^+\nu)_{\text{SM}}} = \left| 1 - \frac{m_B^2}{M_{H^+}^2} \frac{\tan^2\beta}{(1+\epsilon_0^* \tan\beta)(1+\epsilon_l \tan\beta)} \right|^2$$
- $\tan\beta \sim$10: ϵ_0^* and ϵ_l below 1%
  MSSM corrections to d-type quarks and lepton mass matrix have been neglected
- nondecoupling: $M_{H+} \sim$ 130 GeV
  MSSM prediction: 20$\% - 30\%$ smaller than the SM value

Tree level $H^{\pm}$: $B_u \to \tau\nu$ in 2HDM and SUSY



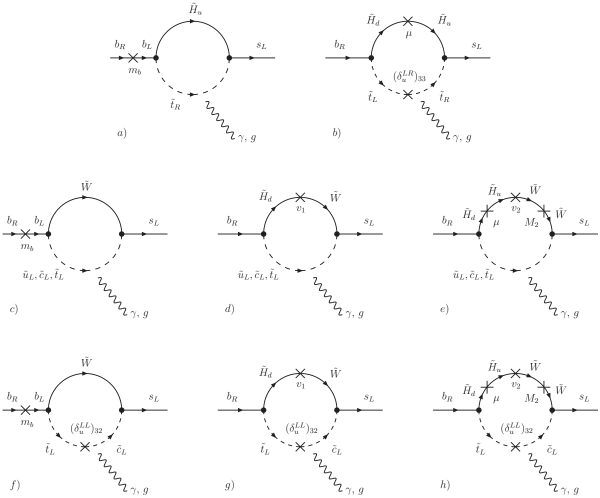
- $\frac{BR(B^+\to\tau^+\nu)_{\rm MSSM}}{BR(B^+\to\tau^+\nu)_{\rm SM}} = \left|1 - \frac{m_B^2}{M_{H^+}^2}\frac{\tan^2\beta}{(1+\epsilon_0^*\tan\beta)(1+\epsilon_l\tan\beta)}\right|^2$
- nondecoupling: $M_{H^+} \sim$ 130 GeV, $\tan\beta \sim 10$
  MSSM prediction: 20% − 30% smaller than the SM, consistent with the new Belle data
  SM prediction: $(0.95 \pm 0.27) \times 10^{-4}$
  world average before 2012: $(1.65 \pm 0.34) \times 10^{-4}$
  Belle: $0.72^{+0.29}_{-0.27} \times 10^{-4}$ (new)

$B \to X_s\gamma$ in general 2HDM



- light H^+ enhances $B \to X_s\gamma$
- type-II 2HDM: M_{H^+} > 300 GeV
- nondecoupling: $M_{H^+} \sim$ 130 GeV
  non-trival SUSY setup to cancel H^+ contribution

$B \to X_s \gamma$ in MSSM



Light stop helps to cancel the $H^{\pm}$ contribution [Top right figure]

$B \to X_s \gamma$ in MSSM

Helicity must be flipped in involved quark states
Breaking $U(3)_Q \times U(3)_d$ chiral and electroweak symmetries

- m_b insertion
  wino-stop contribution suppressed by Super-GIM if degenerate squark masses.
- v_d insertion (not important due to large $\tan\beta$)
- v_u insertion (effectively $\mathbf{10} \cdot \mathbf{5}^c \cdot H_u^*$-like coupling)
- chargino penguins from v_u insertion destructively interfere with the SM and charged Higgs if $\mu A_t < 0$
- light stop helps the cancellation as $\frac{\mu A_t}{M_{\tilde{t}}^2}$
- gluino penguins important: enhanced by $\mu \tan\beta$, $M_{\tilde{g}}/m_b$

$B_s \to \mu^+\mu^-$ in MSSM

- SM: (3.27±0.23)$\times 10^{-9}$ due to small muon mass $m_\mu^2/m_{B_S}^2$
- LHCb: $3.2^{+1.5}_{-1.2} \times 10^{-9}$ (Nov. 12, 2012)
- MSSM: leading Higgs penguin diagrams $\propto \tan^6\beta$
- if $\tan$ ~10, all 1-loop diagrams have to be considered: e.g., charged Higgs diagrams $\propto \tan^4\beta$
- nondecoupling $\to$ light M_A
  $B_s \to \mu^+\mu^-$ is even more sensitive as the neutral Higgs bosons are all light: $\tan^6\beta/M_A^4$

General Constraints

- M_H : 125 ± 2 GeV
- $R_{\gamma\gamma} = \sigma^{\gamma\gamma}_{\rm obs}/\sigma^{\gamma\gamma}_{\rm SM}$: $1 \sim 2$
- LEPII+Tevatron+LHC Higgs search bounds
- BR$(B \to X_s\gamma) < 5.5 \times 10^{-4}$
  Experimental: $(3.43 \pm 0.22) \times 10^{-4}$
  SM NNLO: $(3.15 \pm 0.23) \times 10^{-4}$
  FeynHiggs SM NLO predicton: $(3.8) \times 10^{-4}$
- BR$(B_s \to \mu^+\mu^-) < 6 \times 10^{-9}$
  Experimental upper limit: 4.2×10^{-9}
  SM prediction $(3.27 \pm 0.23) \times 10^{-9}$
  SUSYFlavor SM predicton 4.8×10^{-9} (Hadronic parameters ?)
- SUSYFlavor2.01, FeynHiggs2.9.2, HiggsBound3.8.0

Input

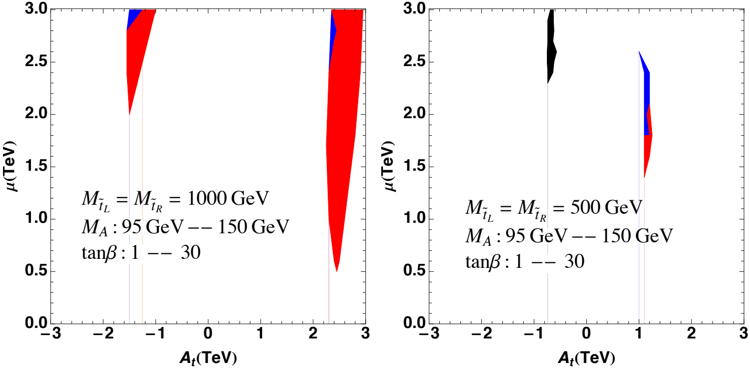
$$M_{\tilde{Q}_{1,2}} = M_{\tilde{u}_{1,2}} = M_{\tilde{d}_{1,2,3}} = M_{\tilde{L}_{1,2,3}} = M_{\tilde{e}_{1,2,3}} = 1 \text{ TeV} ,$$

$$M_1 = 200 \text{ GeV}, M_2 = 400 \text{ GeV}, M_3 = 1200 \text{ GeV} .$$

$$M_{\tilde{Q}_3} = M_{\tilde{t}} = 200 \text{ GeV}, \; 300 \text{ GeV} , 500 \text{ GeV and } 1\text{TeV}.$$

$$\begin{aligned} M_A &: \quad 95 \sim 150 \text{ GeV} \\ \tan\beta &: \quad 1 \sim 30 \\ \mu &: \quad 200 \text{ GeV} \sim 3 \text{ TeV} \\ A_u = A_d = A_\ell &: \quad -3 \sim 3 \text{ TeV} \end{aligned}$$

Light stau enhances the diphoton but irrelevant to $b \to s$ transition

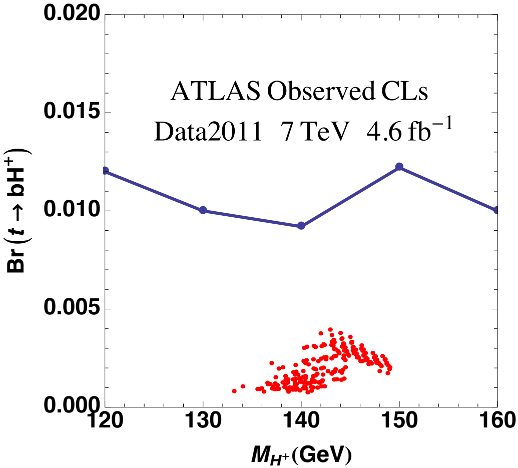


- no survivors when assuming 200GeV and 300GeV stop, reduced $gg \to H$ (cancels top-quark loop)
- red: $M_H : 125 \pm 2$ GeV, $R_{\gamma\gamma} : 1 - 2$, and combined direct search bounds
- blue: $B \to X_s \gamma$
- black: $B_s \to \mu^+ \mu^-$

Typical survival points are $M_A \sim 140 \sim 150$ GeV, $\tan\beta \sim 10$

$t \to bH^+$ at the LHC

Assuming BR$(H^+ \to \tau^+ \nu_\tau) = 100\%$



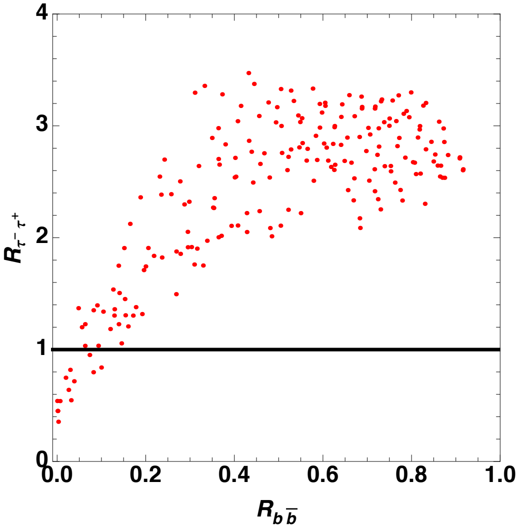
Way below the ATLAS bounds

H is most H_u and $v_u \gg v_d$ which dominates v

- Htt is close to 1: $gg \to H$ similar to SM rate
- HWW is similar to SM: $\Gamma(H \to \gamma\gamma)$ similar to SM values (W-loop dominates)
- $\Gamma(H \to WW^* \to 2\ell 2\nu)$ and $\Gamma(H \to ZZ^* \to 4\ell)$ similar to SM values

Decay BRs may be similar to SM.
Light stau can enhance the diphoton partial width.
Reduced Hbb can also enhance the $R_{\gamma\gamma}$

$$H \to \tau^+\tau^-$$



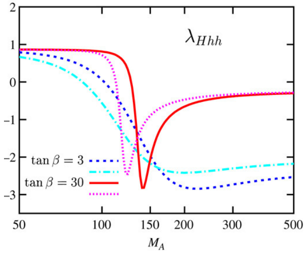
For $-\pi/2 < \alpha < 0$ when H mainly decays to bb

Enhanced $R_{\tau\tau}$:

$$R_{\tau\tau} \simeq r_{gg} \left(\frac{1+\Delta_b}{1+\Delta_b(1-\epsilon)} \right)^2$$

with $\epsilon = 1 + \tan\alpha / \tan\beta$

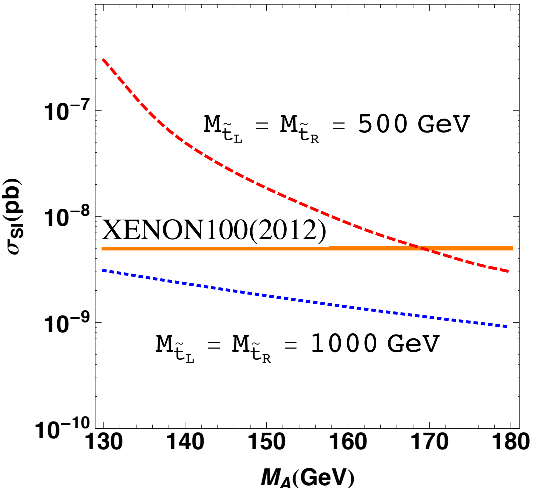
- $R_{\tau\tau} \sim 2$ consistent with ATLAS but CMS has excluded SM rate by 1 sigma
- may exist completely new decay mode $H \to hh$ (BR$\sim 50\%$, $M_h < M_H/2$): $g_{Hhh} = 2\sin 2\alpha \sin(\beta+\alpha) - \cos 2\alpha \cos(\beta+\alpha)$



- small m_A is preferred to reduce $R_{\tau\tau}$

DM

Stop may significantly enhance the scattering xsection



Irrelevant if neutralino dark matter is not the only DM component

Conclusions

- Flavor physics constraints on non-decoupling MSSM
- A small corner of parameter space with light stop, negative A_t and large μ can survive all the flavor physics bounds and consistent with all direct search experiments while getting $M_H \simeq 125$ GeV with $R_{\gamma\gamma} : 1 - 2$
- Significant enhancement in $R_{\tau\tau}$ is possible
- $R_{\tau\tau} < 1$ can be achieved if $H \to hh$ decay opens up
- If DM only consists of neutralino, direct detection experiments may put stringent bounds on the models

Thank you!

Note Added

1211.1955 [hep-ph] (BechtleHeinemeyerStalStefaniakWeigleinZeune; last Friday) agrees with our results generally but didn't point out

- $H \to hh$ possibility
- Dark Matter direct detection experiments constraint