Today is March 11th.
Hope the Dead Rest in Peace

Revisit to Non-decoupling MSSM

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Kavli IPMU, Tokyo Univ. 03/11/2013

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

arXiv:1211.2427, 1212.6311

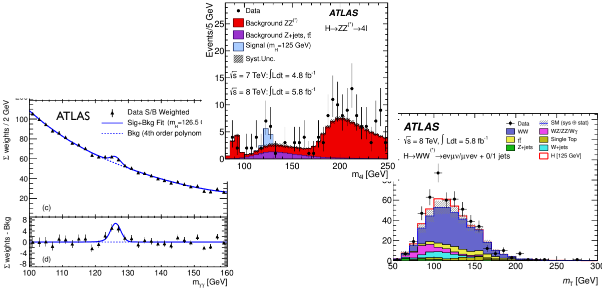
Partially overlaps with 1211.1955 [hep-ph] by Bechtle, Heinemeyer, Stal, Stefaniak, Weiglein and Zeune (Two days)

Discovery of a Higgs-like Boson at the LHC

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

reconstruction masses at 125 GeV

Dilepton $WW^* \to 2\ell 2\nu$ also consistent with $ZZ^* \to 4\ell$ at 125 GeV



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

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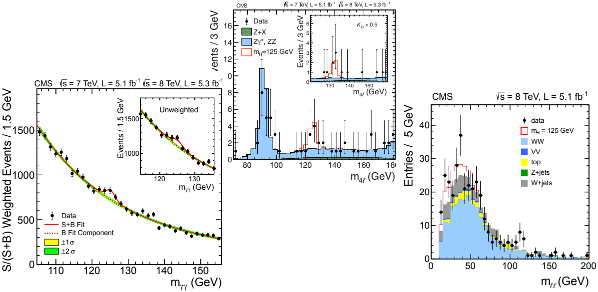

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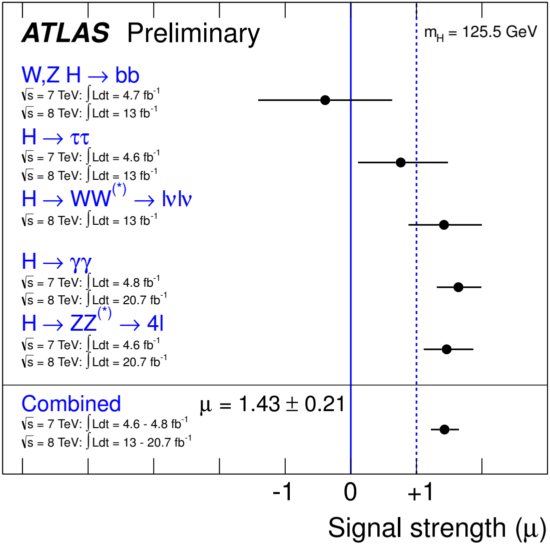
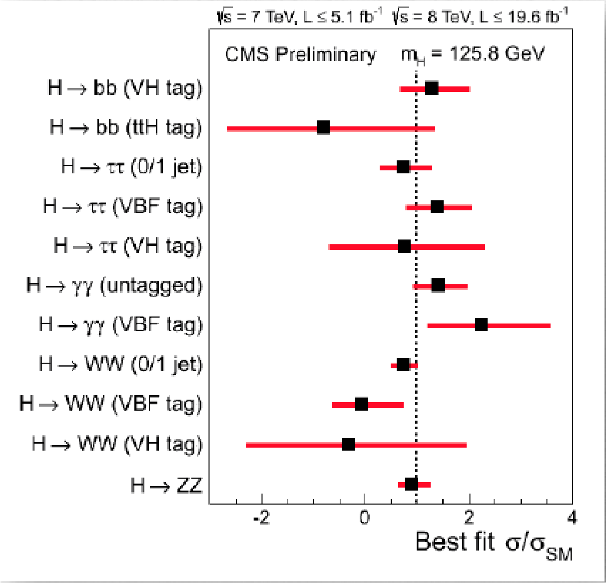
SM Higgs? Likely



SM Higgs? Likely



How to interpret the 125 GeV resonance

- Standard Model Higgs boson?
- Composite Higgs?
- ....
- Higgs boson in MSSM
  - the light Higgs boson h at 125 GeV (nontrival)

$$m_h = 125\text{GeV} < M_H \sim M_A \sim M_{H^\pm}$$

  - the heavy Higgs boson H at 125 GeV while h evades all direct searches (or h around 98 GeV)

$$m_h < M_H = 125\text{GeV} \sim M_A \sim M_{H^\pm}$$

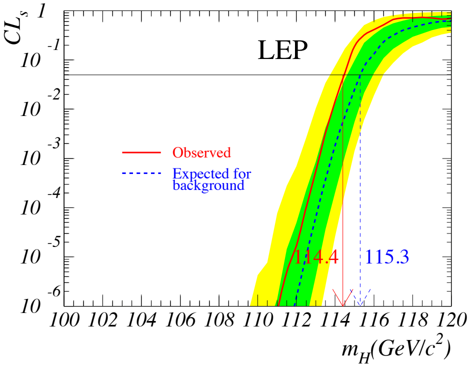
- A. Belyaev, Q. -H. Cao, D. Nomura, K. Tobe and C. -P. Yuan, Phys. Rev. Lett. **100**, 061801 (2008).
- N. D. Christensen, T. Han and S. Su, Phys. Rev. D **85**, 115018 (2012).
- K. Hagiwara, J. S. Lee and J. Nakamura, JHEP 1210 (2012) 002.
- R. Benbrik, M. G. Bock, S. Heinemeyer, O. Stal, G. Weiglein 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 excludes a SM-like Higgs to 114.4 GeV (in both SM and MSSM)

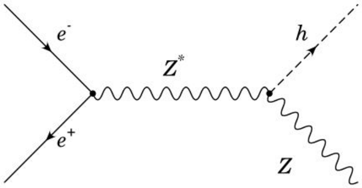
Higgs Mass Lower Bound

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}



Since m_t arises from H_u, $v_u >> v_d$ (a large $\tan\beta$).

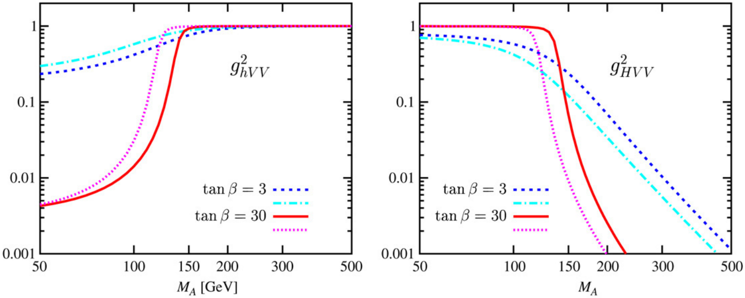
A simple realization: to make h H_d-like, then $g_{ZZh} \propto$ a small v_d

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

$$\begin{pmatrix} \text{Re } H_u \\ \text{Re } H_d \end{pmatrix} = \begin{pmatrix} \sin\beta & -\cos\beta \\ \cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} H_{\text{SM}} \\ H_\perp \end{pmatrix}$$

large $\tan\beta \Rightarrow \beta \to \pi/2$; h is H_d-like $\Rightarrow \alpha \to \pm\pi/2$. So

$$g_{ZZh} \propto \sin(\beta - \alpha) \to 0$$

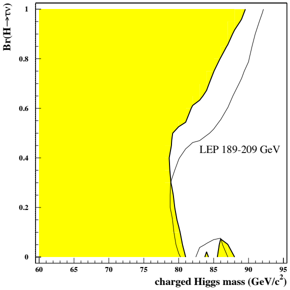


Qualitatively, smaller $M_A \to$ smaller g_{ZZh}
large $\tan\beta \Rightarrow \beta \to \pi/2$

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

Taking $M_A \to 0$, $\sin\alpha \to -1$, $g_{ZZh} \propto \sin(\beta - \alpha) \to 0$

Lower bound of M_A from LEP bound on charged Higgs



Charged Higgs may also close to M_A. At tree level:

$$M_{H^{\pm}}^2 = M_A^2 + m_W^2$$

$M_A > 80$ GeV is required to survive the LEP direct search bound (via Zh) and LEP charged Higgs search.

Since H is H_u-like and h is H_d-like, $M_h \simeq \mathcal{M}_{11}, M_H \simeq \mathcal{M}_{22}$.

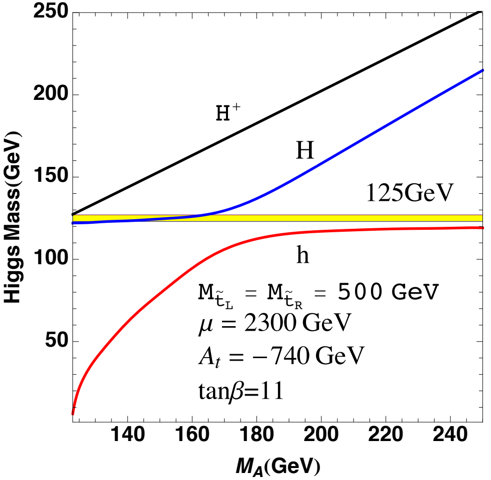
$$
\begin{aligned}
M_H^2 \simeq \mathcal{M}_{22}^2 \quad \simeq \quad & M_A^2 \cos^2\beta + m_Z^2 \sin^2\beta \left(1 - \frac{3}{8\pi^2} y_t^2 t\right) \\
+ \quad & \frac{y_t^4 v^2}{16\pi^2} 12 \sin^2\beta \left\{ t \left[1 + \frac{t}{16\pi^2} \left(1.5 y_t^2 + 0.5 y_b^2 - 8 g_3^2\right) \right] \right.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

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

At tree level, $M_A \to m_Z$, $M_h \to M_H \to M_Z$: nondecoupling

One may always realize a 125 GeV heavy Higgs boson in nondecoupling MSSM scenario.

$$m_h < M_H = 125\text{GeV} \sim M_A \sim M_{H^\pm}$$

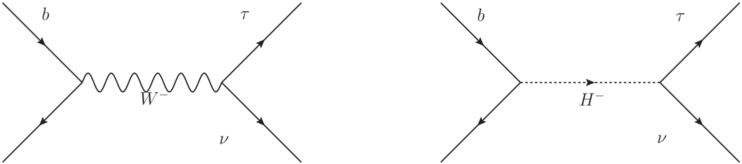


Consequences of Non-decoupling

One may always realize a 125 GeV heavy Higgs boson. And non-decoupling scenario may evade all constraints from LEP but ....

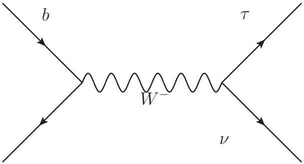
- However, is the scenario flavor safe as $m_{H^+} \sim m_A$?
  - $B^+ \to \tau^+ \nu$; $B \to D^{(*)} \tau \nu_\tau$;
  - $\mu \to e\gamma$
  - $b \to s$ transition: $b \to s\gamma$; $B_s \to \mu^+ \mu^-$;
  - $t \to bH^+$ with $H^+ \to \tau^+ v$;
- In addition, light h and H can enhance spin-independent neutralino-nuclei scattering. If DM consists of only neutralino, how about bounds from direct detection?

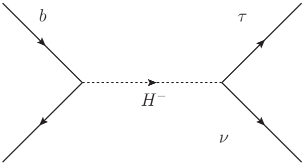
$B_u \to \tau\nu$ in general 2HDM and SUSY



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

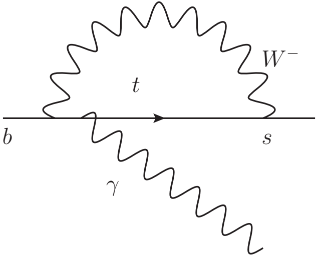
$B_u \to \tau\nu$ in general 2HDM and SUSY

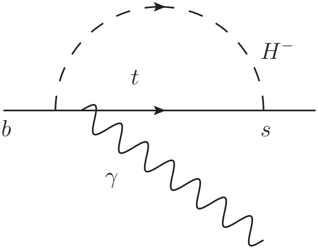




- MSSM prediction in nondecoupling limit: 20$\%$ $-$ 30% smaller than the SM, consistent with the new Belle data
  SM prediction: $(0.95 \pm 0.27) \times 10^{-4}$
  world average before 2012: $(1.65 \pm 0.34) \times 10^{-4}$
  Belle: $0.72^{+0.29}_{-0.27} \times 10^{-4}$ (new)
- Similarly, the charged Higgs contribution to $B \to D^{(*)}\tau\nu_\tau$ and $\mu \to e\gamma$ are not very significant in the interesting region of $M_{H^\pm}$ and $\tan\beta$.

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





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

$B \to X_s\gamma$ in MSSM

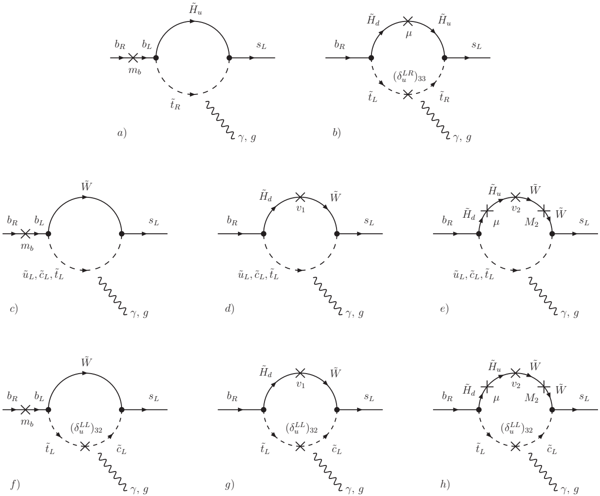
Helicity must be flipped in the involved quark states:
m_b insertion in SM

- $U(3)_Q \times U(3)_d$ chiral symmetry breaking
- Electroweak symmetry breaking

SUSY contributions:

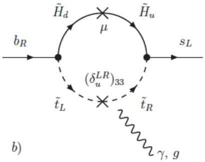
- $C_{7,8}^{\mathrm{SUSY}} = C_{7,8}^{H^\pm} + C_{7,8}^{\tilde{\chi}^\pm} + C_{7,8}^{\tilde{g}} + C_{7,8}^{\tilde{\chi}^0}$
- $C_{7,8}^{H^\pm}$ is also suppressed by m_b insertion, and has the same sign as the SM amplitude.
- $C_{7,8}^{\tilde{\chi}^0}$ is a negligible contribution.
- $C_{7,8}^{\tilde{\chi}^\pm}$ and $C_{7,8}^{\tilde{g}}$ are the squark contributions. They are not necessarily suppressed by m_b, which is helpful to cancel the SM and charged Higgs amplitudes. (m_b insertion, v_u insertion and v_d insertion).

$B \to X_s\gamma$ in MSSM



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

$B \to X_s\gamma$ in MSSM



- $C_{7,8}^{\tilde{\chi}^\pm}$:
  - m_b insertion: suppressed by m_b
  - v_d insertion: not important due to large $\tan\beta$
  - v_u insertion (effectively $\mathbf{10}\cdot\mathbf{5}^c\cdot H_u^*$-like: $Qd^c\bar{H}_u$)
  - Higgsino penguins from v_u insertion destructively interfere with the SM and charged Higgs contribution if $\mu A_t < 0$
  - light stop helps the cancellation as $\frac{\mu A_t}{M_{\tilde{t}}^2}$
  - wino-stop contribution suppressed by Super-GIM if degenerate squark masses (MFV).
- $C_{7,8}^{\tilde{g}}$ is also important: enhanced by $\mu\tan\beta$, M_3/m_b

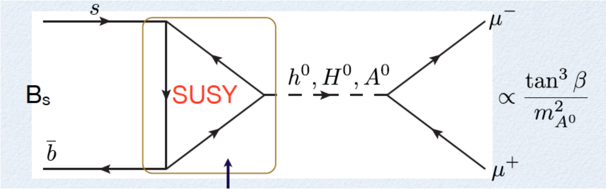
$B \to X_s\gamma$ in MSSM

Field	Q	u^c	e^c	d^c	ℓ	H_u	H_d	θ
R-charge	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{7}{5}$	$\frac{7}{5}$	$\frac{8}{5}$	$\frac{2}{5}$	1
PQ	0	0	0	-1	-1	0	1	0

$$R[Qd^c\bar{H}_u]: \quad \frac{1}{5}+\frac{7}{5}-\frac{8}{5}=0$$
$$\mathrm{PQ}[Qd^c\bar{H}_u]: \quad 0+(-1)+0=-1$$

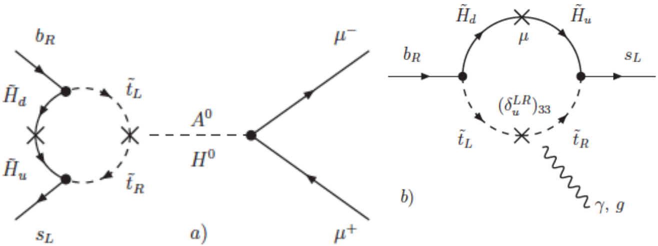
- The leading SUSY correction is $Qd^c\bar{H}_u$-like, which must break PQ and R symmetry. Their contribution are propotional to μA_t.
- SUSY correction will destructively interfere with the SM and charged Higgs contribution if $\mu A_t < 0$. Light stop helps this cancellation as $\frac{\mu A_t}{M_{\tilde{t}}^2}$.
- These SUSY correction at the same time contribute to Δm_b (cannot contribute to Δm_τ).

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

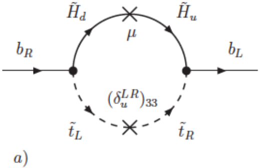


- SM: (3.27$\pm$0.23)$\times 10^{-9}$ due to small muon mass $m_\mu^2/m_{B_S}^2$
- LHCb: $3.2^{+1.5}_{-1.2} \times 10^{-9}$ (Nov. 12, 2012)
- $C^{\mathrm{SUSY}}_{\mathrm{S,P}} = C^{H^\pm}_{\mathrm{S,P}} + C^{\tilde{\chi}^\pm}_{\mathrm{S,P}} + C^{\tilde{g}}_{\mathrm{S,P}} + C^{\tilde{\chi}^0}_{\mathrm{S,P}}$
- MSSM: leading penguin diagrams $C^{\tilde{\chi}^\pm}_{\mathrm{S,P}}, C^{\tilde{g}}_{\mathrm{S,P}} \propto \tan^6\beta$
- if $\tan\beta$ ~10, all 1-loop diagrams have to be considered: e.g., charged Higgs diagrams $C^{H^\pm}_{\mathrm{S,P}} \propto \tan^4\beta$
- In nondecoupling limit, it is even worse since the neutral Higgs bosons are all light: $\tan^6\beta/M_A^4$.

SUSY corrections to the down quark mass matrix



Off-diagonal correction



Diagonal correction

General Constraints

- SUSYFlavor2.01, FeynHiggs2.9.2, HiggsBound3.8.0
- $M_H : 125 \pm 2$ 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 ?)

Input

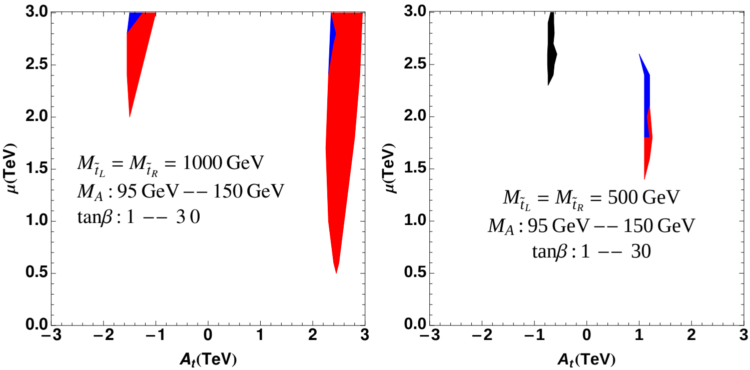
$$M_{\tilde{Q}_{1,2}} = M_{\tilde{u}_{1,2}} = M_{\tilde{d}_{1,2,3}} = M_{\tilde{L}_{1,2,3}} = M_{\tilde{e}_{1,2,3}} = 1 \text{ TeV} ,$$

$$M_{\tilde{Q}_3} = M_{\tilde{t}} = 200,\ 400,\ 500 \text{ and } 1000 \text{ GeV},$$

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

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

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

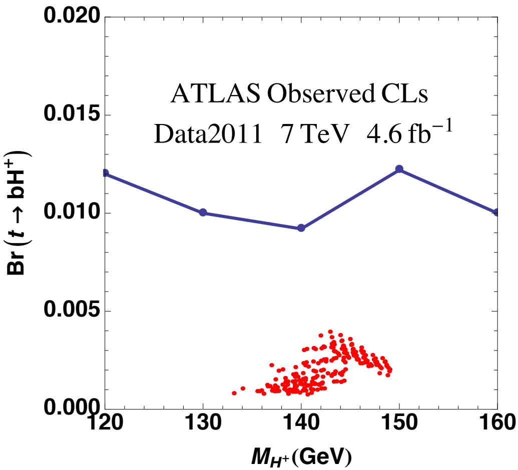


- No survivors when assuming 200GeV and 400 GeV stop, reduced $gg \to H$ (light stop loop cancels top-quark loop)
- Red: $M_H : 125 \pm 2$ GeV, $R_{\gamma\gamma} : 1 - 2$, and combined direct search bounds. Blue: $B \to X_s\gamma$. Black: $B_s \to \mu^+\mu^-$

Typical survival points are $M_{\tilde{t}} \sim 500$ GeV, $M_A \sim 140$ GeV, $\tan\beta \sim 10$, $\mu \sim 2.5$ TeV, A$_t \sim -750$ GeV.

$t \to bH^+$ at the LHC

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

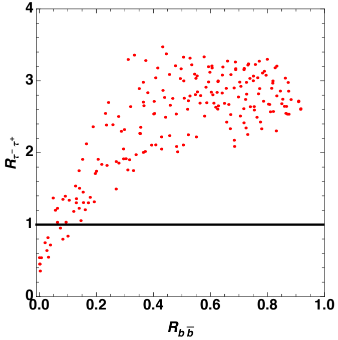


Way below the ATLAS bounds

We pay more attention to the survived corner of parameter space :

- H is SM-like (H_u-like since $v_u \gg v_d$)
  - Htt is close to 1: $gg \to H$ similar to SM rate
  - HWW is similar to SM: $\Gamma(H \to WW^* \to 2\ell 2\nu)$, $\Gamma(H \to ZZ^* \to 4\ell)$ and $\Gamma(H \to \gamma\gamma)$ (W-loop dominates) similar to SM values
- Reduced Hbb can enhance the $R_{\gamma\gamma}$ (also R_{WW} and R_{ZZ})
- Light stau can further enhance the diphoton partial width.
- bb channel and di-tau channel would be checked by further experiments

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



- The flavor constraints made the large correction in Δm_b inevitable, which leads to enhanced $\tau\tau$ (Also pointed out by K.Hagiwara et al.)

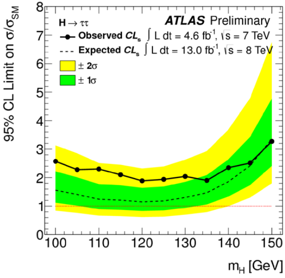
$$R_{\tau^+\tau^-} \simeq r_{gg} * r_{\tau^+\tau^-}/r_{b\bar{b}}$$

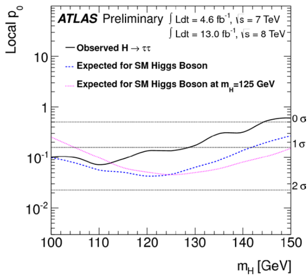
- $R_{\tau\tau} < 1$ can be achieved if a new decay $H \to hh$ opens up.

No Enhanced $\tau^+\tau^-$ observed!

Kevin Einsweiler for HCP 2012

The results are consistent with either the background hypothesis, or the SM Higgs hypothesis. The best-fit μ value at 125 GeV is $\mu = 0.7 \pm 0.7$

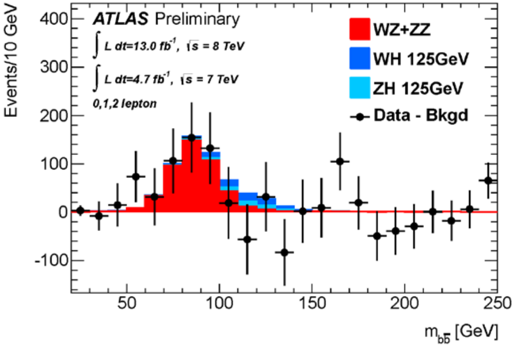




- ATLAS: $R_{\tau\tau}$=0.7 +/-0.64;
- CMS: $R_{\tau\tau}$=1.1 +/- 0.4;

$b\bar{b}$ Channel

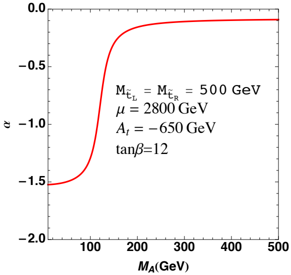
b has large error bar

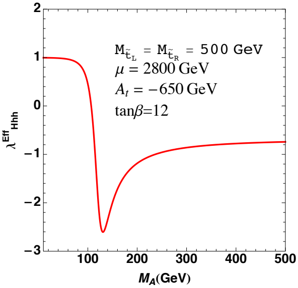


But $\mu \simeq 1$ at CMS

New $H \to hh$ Channel

$\Gamma(H \to hh) \sim \Gamma(h_{SM} \to bb)_{SM}$ is needed to compensate the total decay width (Highly fine-tuned though)

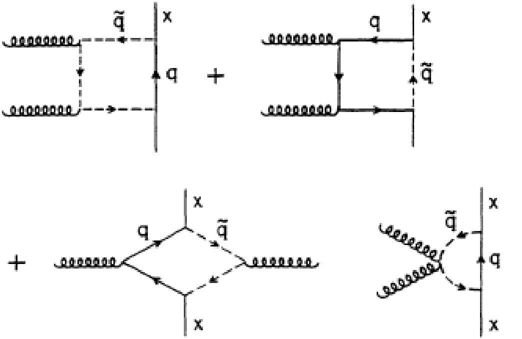




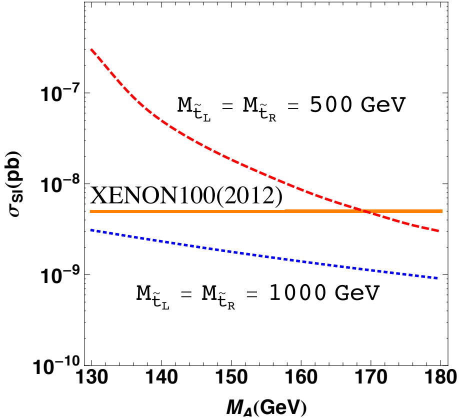
- $e^+e^- \to Ah$ with $A \to b\bar{b}$, $A \to hZ$ for $M_h \sim 20$ GeV, bs and τs are soft. Evade the LEPII search of $4b + 2b2\tau$
- WH/ZH with $H \to hh \to 2b2\tau + 4b + 4\tau$ combined requires 100 fb^{-1} at 14 TeV LHC.
- gluon fusion requires 300 fb^{-1}

Dark Matter Direct Detection

- Light higgs h and H may significantly enhance the spin-independent neutralino-nuclei cross section through Higgs exchange.
- Light Stop may further enhance this cross section due to loop contribution to neutralino-gluon scattering. Drees and Nojiri



Dark Matter Direct Detection



For 500GeV stop and $M_A <$170 GeV, XENON100 put strong constraint over this scenario.
Irrelevant if neutralino dark matter is not the only DM component.

Conclusions

- MSSM: $m_h > 120\mathrm{GeV}$ is nontrival $\Rightarrow$ nondecoupling
- LEP bounds: $\begin{cases} g_{ZZh}\downarrow & \Rightarrow \text{small } M_A \\ m_{H^+} & \Rightarrow M_A > 80\mathrm{GeV} \end{cases}$
- Is the scenario flavor safe as $m_{H^+} \sim m_A$?
- The strong constraint comes from $b \to s$ transition:
  (I) large PQ and R symmetry breaking with μA_t < 0
  (II) a light stop $M_{\tilde{t}} \sim 500$ GeV ($M_{\tilde{t}} \sim 400$ GeV excluded by collider, $M_{\tilde{t}} \sim 1$ TeV excluded by flavor)
- $\begin{cases} (I) & \Rightarrow \text{large } \Delta m_b \Rightarrow R_{\tau\tau} \uparrow \Rightarrow \text{H} \to hh \text{ to make } \mathrm{R}_{\tau\tau} < 1 \\ (II) & \Rightarrow \text{strongly constrained by XENON100} \end{cases}$

Thank you very much!