Exploring Two Higgs Doublet Models Through Higgs Production

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Outline

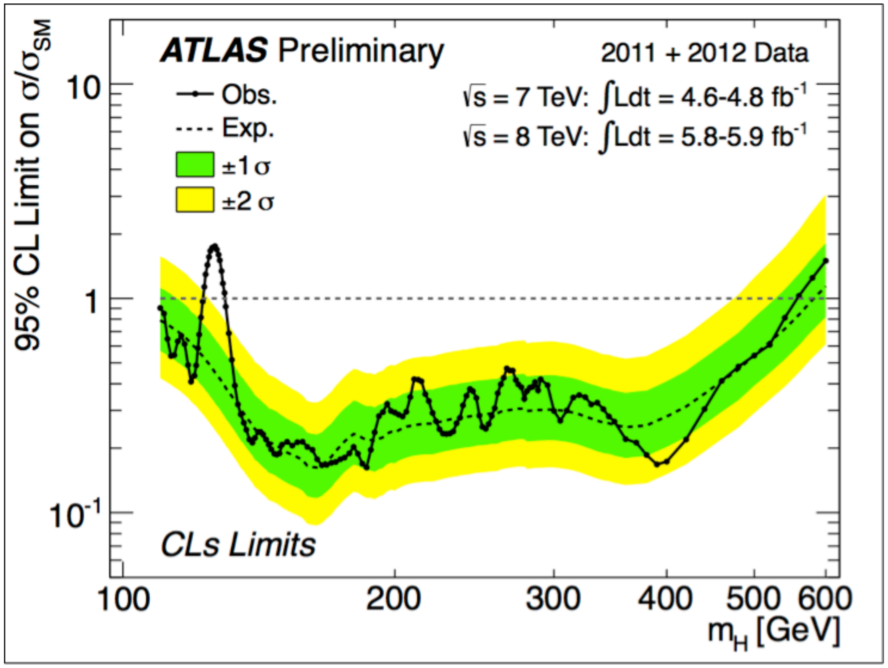
- Higgs production and decay
- Introduction to two Higgs doublet models (2HDMs.)
- LHC limits
- Flavor constraints
- Conclusions

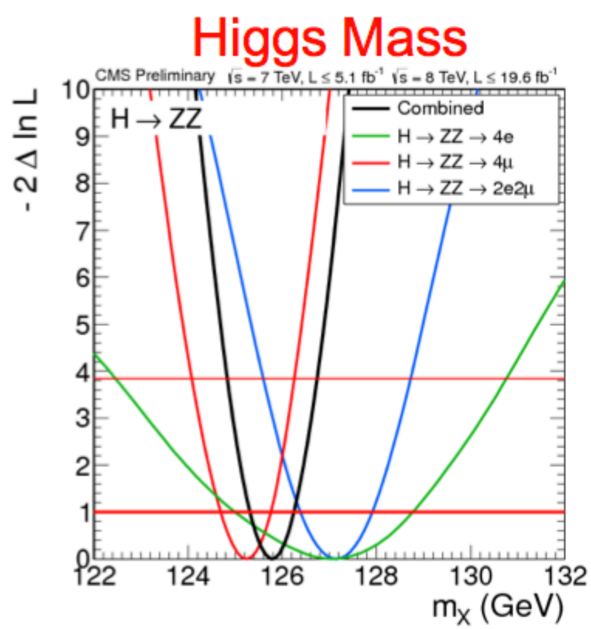
Purpose and assumptions

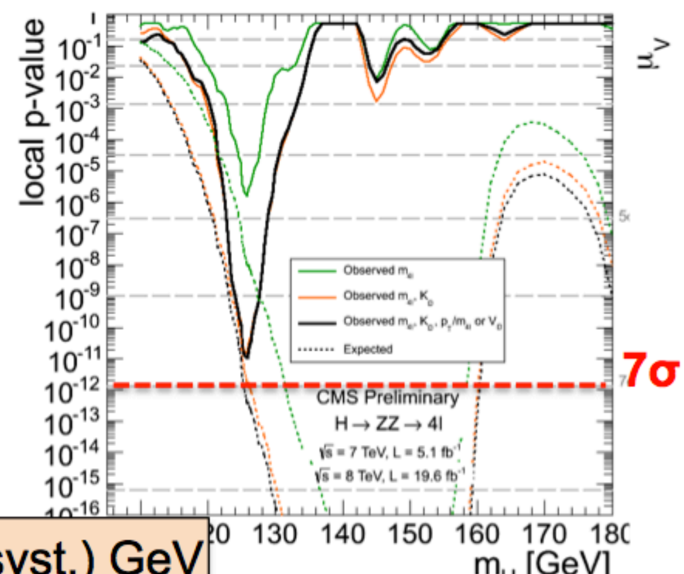
- Discuss the connection between the recently observed Higgs-like particle and rare B decays in the context of 2HDMs.
- Assume that the discovered Higgs is the lightest Higgs boson.
- Study physics in the non-decoupling limit.
- No tree-level FCNC

Higgs Discovery

4th July 2012: ATLAS and CMS have observed a new particle, with mass ~ 125 GeV.



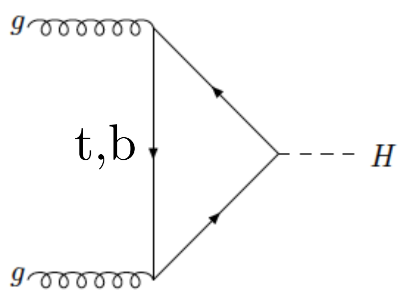




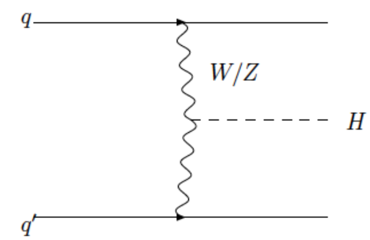
m_H = 125.8 ± 0.5(stat.) ± 0.2(syst.) GeV

Higgs productions at the LHC

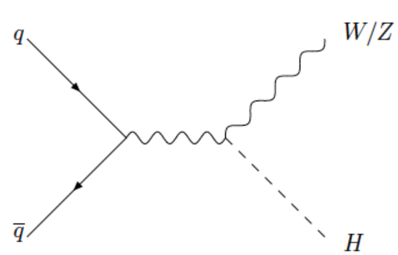
- Gluon fusion (ggF)



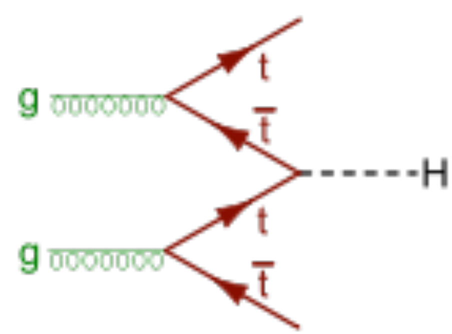
- Vector boson fusion (VBF)



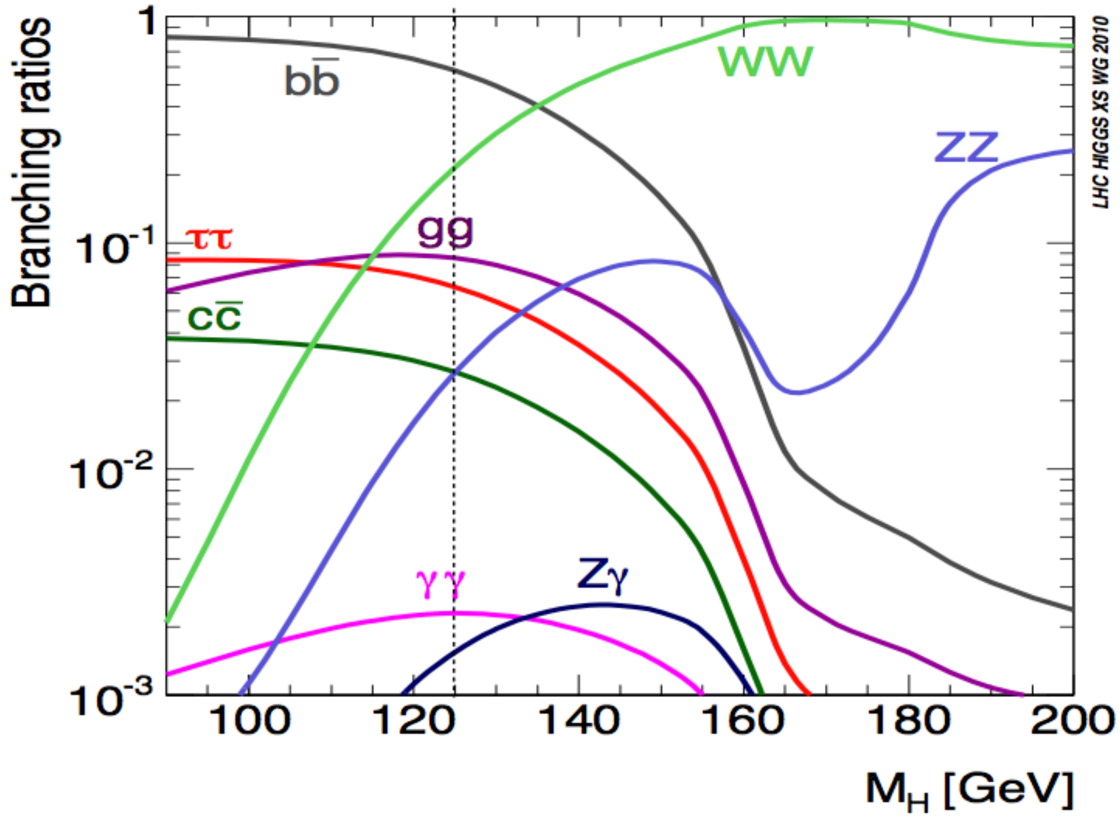
- Associated production (WH/ZH)



- ttH



Higgs Decays



- Tree-level: h$\rightarrow f\bar{f}$ and h$\rightarrow VV$
- Loop: h$\rightarrow gg$, h$\rightarrow \gamma\gamma$, and h$\rightarrow Z\gamma$

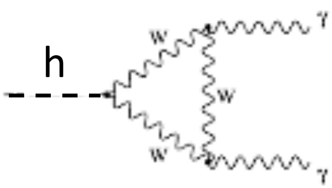
Higgs Decays to Photons

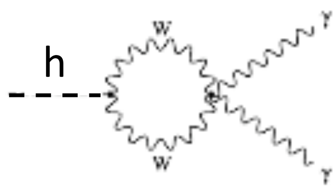
- Dominant contribution is W loops
- Contribution from top is small

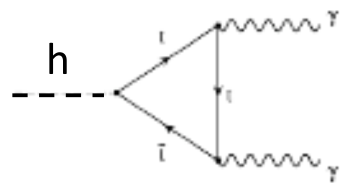
Note opposite signs of t/W loops

$$\boxed{\Gamma(h \rightarrow \gamma\gamma) \approx \frac{\alpha^3}{256\pi^2 s_W^2} \frac{M_h^3}{M_W^2} \left| 7 - \frac{16}{9} + \dots \right|^2}$$

W top







Two Higgs Doublet Models (2HDMs)

- A good review paper: [Branco, Ferreira, Lavoura, Rebelo, Sher, Silva]

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \qquad \langle \phi_i^0 \rangle = \begin{pmatrix} 0 \\ \frac{v_i}{\sqrt{2}} \end{pmatrix}$$

$$\phi_i^0 = \frac{v_i}{\sqrt{2}} + \frac{1}{\sqrt{2}}(\phi_i^{0,r} + i\phi_i^{0,i})$$

- β : $\tan\beta \equiv \frac{v_2}{v_1}$

- α : The mixing angle between two CP-even neutral Higgs bosons.

- Apply an Z_2 symmetry, such that a fermion couples only to a single Higgs doublet. Free from tree level FCNCs. [S. L. Glashow and S. Weinberg, Phys. Rev. D 15, 1958 (1977).]

$$\Phi_1 \to -\Phi_1, \Phi_2 \to \Phi_2 \quad \text{and} \quad d \to -d, u \to u, e \to -e. \quad \text{for the type II model}$$

- Five Higgs bosons: h, H, A, and $H^\pm$

- 6 parameters: $\alpha, \tan\beta, M_h, M_H, M_A$, and $M_{H^\pm}$

- Assume that M_h =125 GeV

Neutral Higgs couplings

Model	Type I	Type II	Lepton-specific	Flipped
Φ_1	-	d, ℓ	ℓ	d
Φ_2	u, d, ℓ	u	u, d	u, ℓ

Neutral Higgs couplings in the 2HDMs.

$$\mathcal{L} = -\Sigma_i g_{iih} \frac{m_i}{v} \bar{f}_i f_i h^0 - \Sigma_{V=W,Z} g_{hVV} \frac{2M_V^2}{v} V_\mu V^\mu h^0$$

	I	II	Lepton specific	Flipped
g_{hVV}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
$g_{ht\bar{t}}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
$g_{hb\bar{b}}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
$g_{h\tau^+\tau^-}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

- Universal hVV couplings $\sin(\beta-\alpha)$
- An example of Type II: Supersymmetry
- Decoupling limit: $\sin(\beta-\alpha)=1$, $\sin\alpha=-\cos\beta$ and $\cos\alpha=\sin\beta$

Charged Higgs couplings

$$\mathcal{L} = \frac{g}{\sqrt{2}M_W}\bar{t}(\lambda_{tt}m_t P_L - \lambda_{bb}m_b P_R)bH^+ - \frac{g}{\sqrt{2}M_W}\bar{\nu}\lambda_{ll}m_l P_R l H^+ + \text{H.c.},$$

Charged Higgs Couplings in the 2HDMs

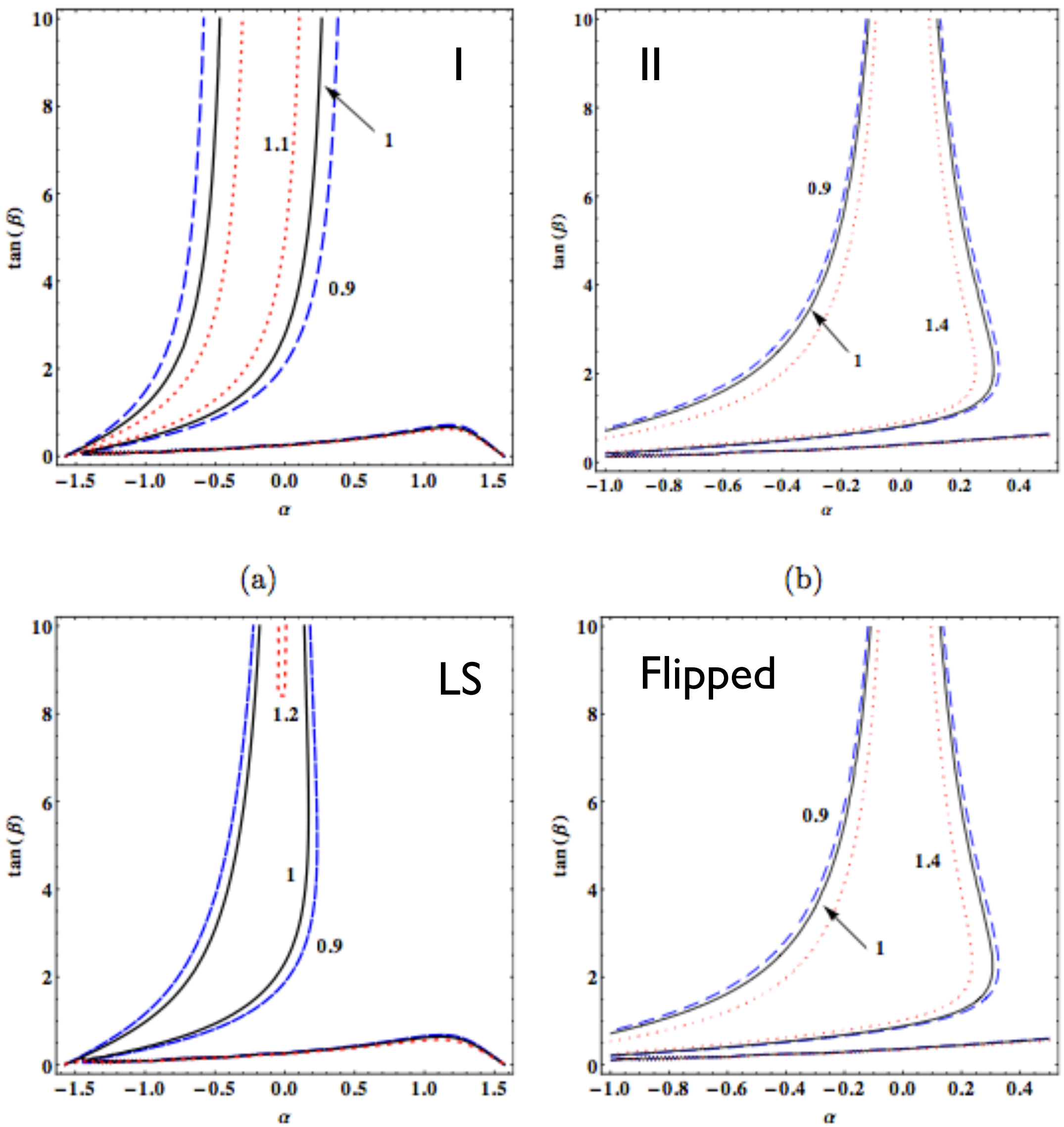
	I	II	Lepton Specific	Flipped
λ_{tt}	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
λ_{bb}	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
$\lambda_{\tau\tau}$	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$

Signal strength

$$R_{\mathtt{decay}}^{\mathtt{production}} \equiv \frac{\sum_j \sigma(pp \to j \to h) \times \mathrm{B}(h \to \mathtt{decay})|_{\mathrm{observed}}}{\sum_j \sigma(pp \to j \to h) \times \mathrm{B}(h \to \mathtt{decay})|_{\mathrm{SM}}}$$

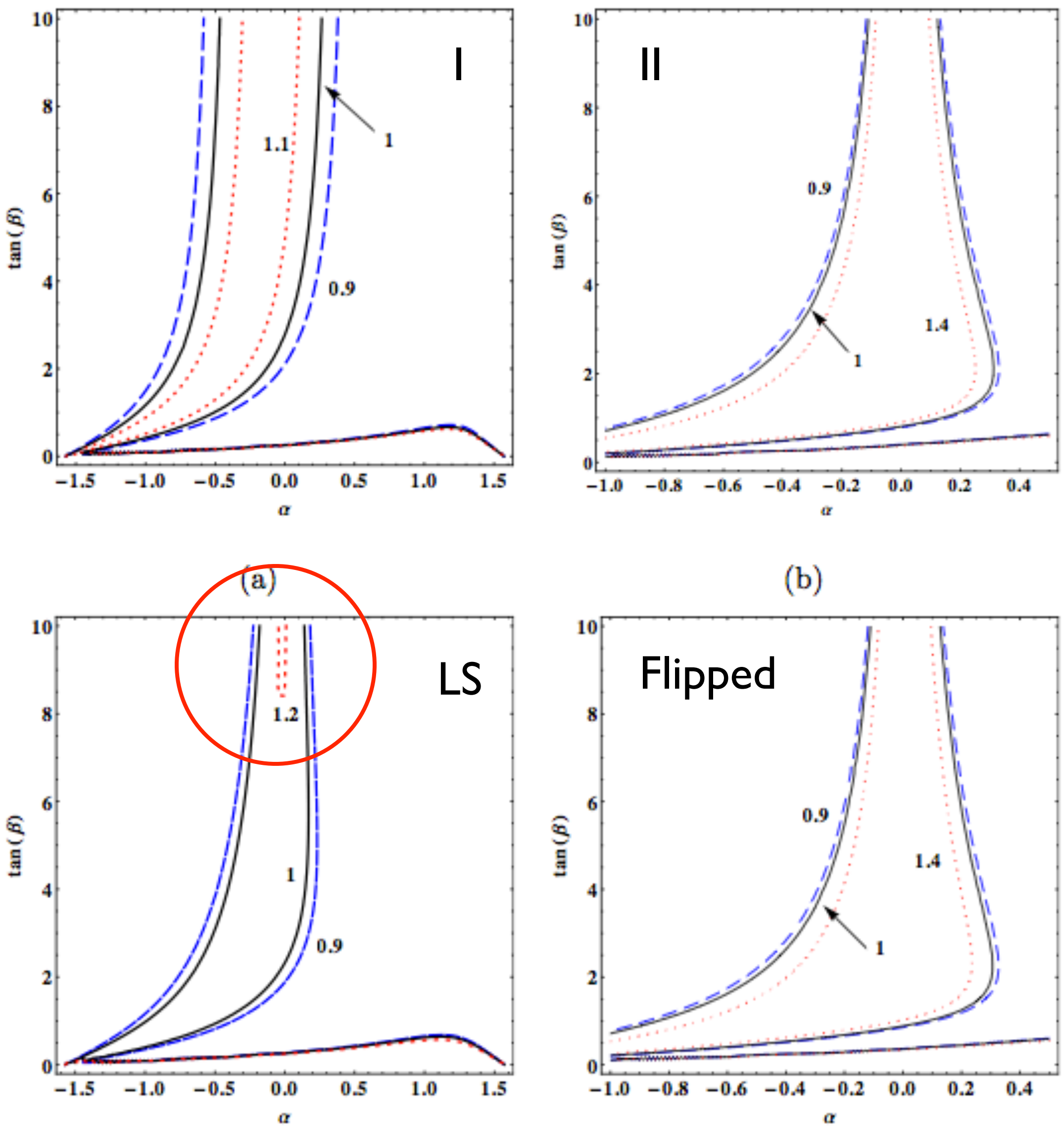
- R=1 : Standard Model Higgs
- Measuring deviations of the couplings from the SM
- Ratio: avoid the large uncertainties

Higgs to diphoton through ggF: $R_{\gamma\gamma}^{ggF}$



- $g_{hVV}=\sin(\beta-\alpha)$ changes sign at large α and small tanβ.
- Not possible to obtain $R_{\gamma\gamma}^{ggF}$ larger than 1.2 for the type I.
- For the lepton specific model, at large tanβ the contours get narrower because of the $h \to \tau\bar{\tau}$ contributions to the total width $\propto (\sin\alpha/\cos\beta)^2$, except for $\alpha \sim 0$.
- $R_{\gamma\gamma}^{ggF} > 1.2$ requires $\alpha \sim 0$ and tan$\beta > 8$.
- Similarly, for the type II and flipped models, the total widths are enhanced by the large ratio to $b\bar{b}$ and $\tau\bar{\tau}$, respectively, so the contours becomes narrower at large tanβ.

Higgs to diphoton through ggF: $R_{\gamma\gamma}^{ggF}$



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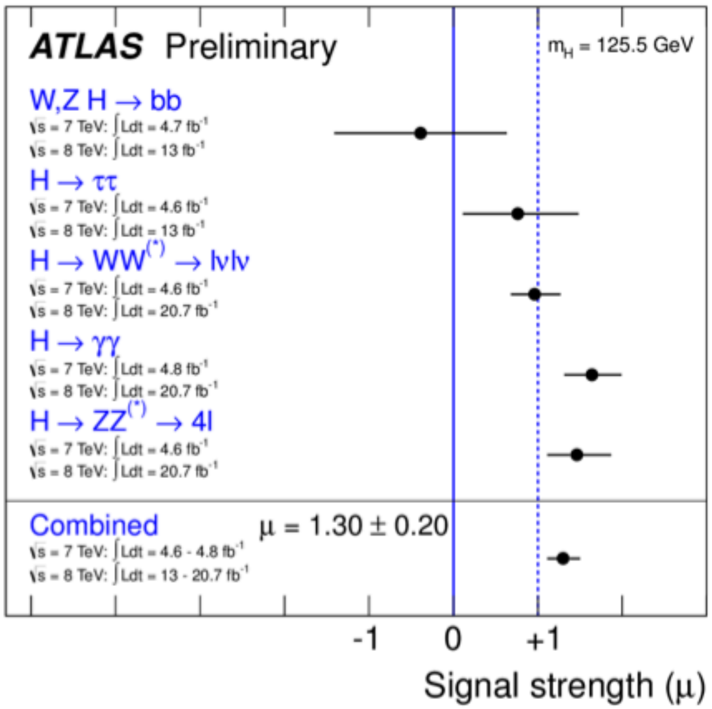
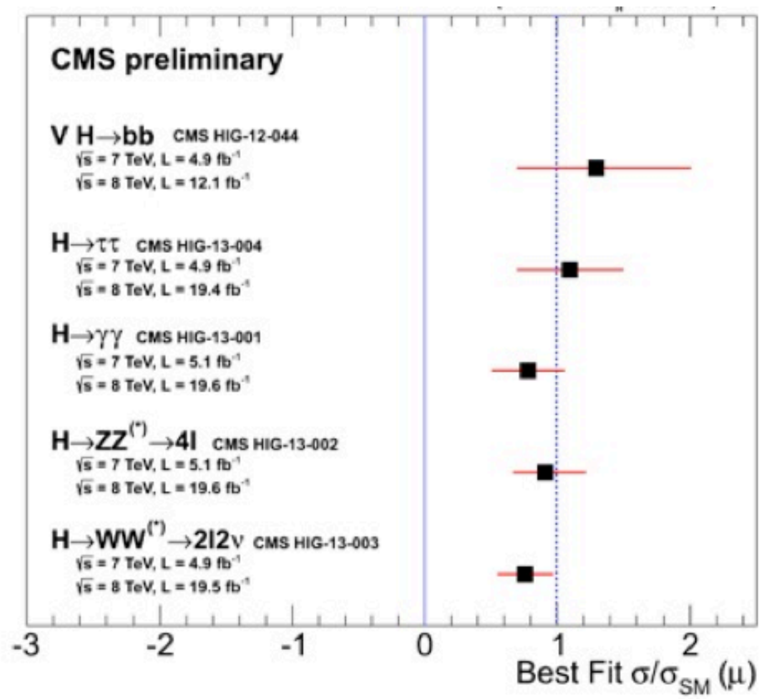
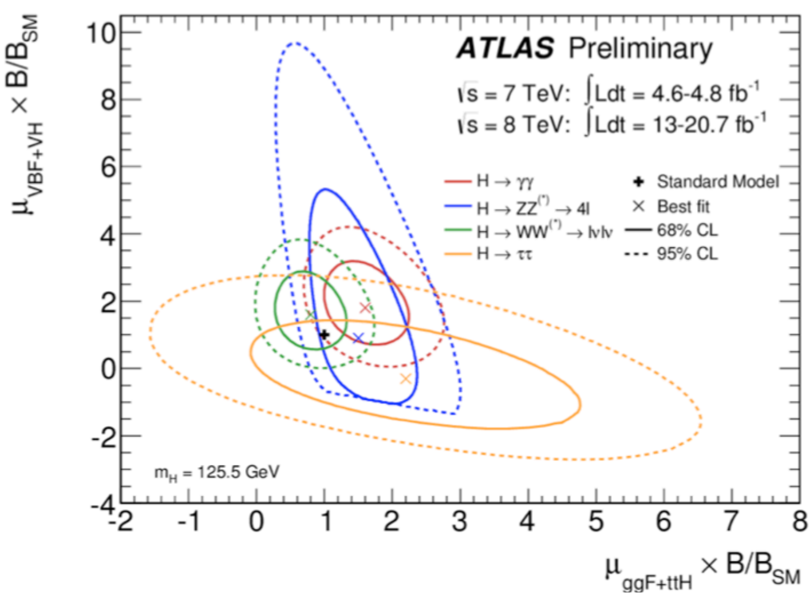
Measured signal strength

Moriond results







$\chi^2\ fit$

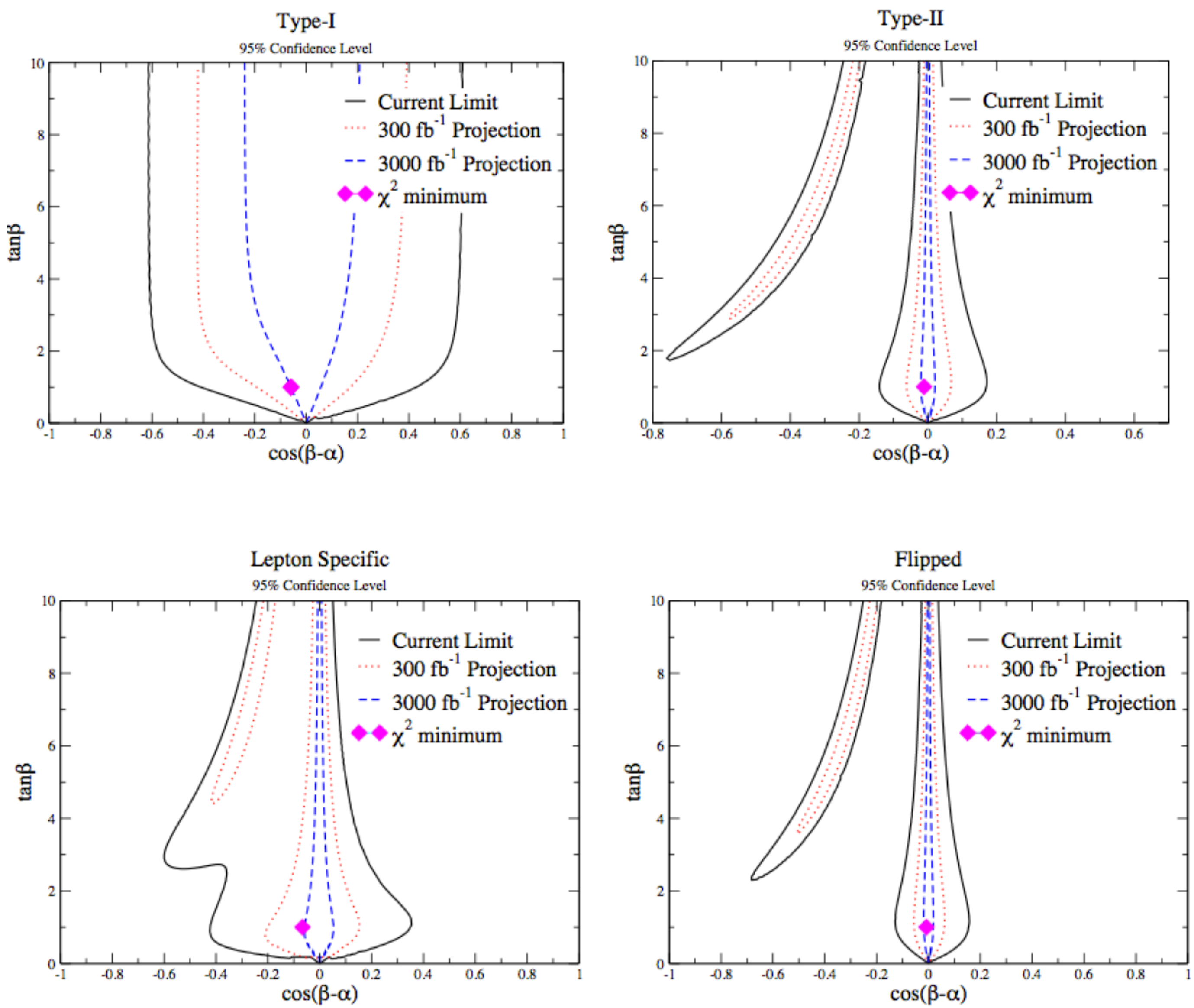
$$\chi^2 = \sum_i \frac{(R_i^{\text{2HDM}} - R_i^{\text{meas}})^2}{(\sigma_i^{\text{meas}})^2}$$

R_i^{meas} : Measured Higgs signal strengths.

σ_i^{meas} : The uncertainty of R_i^{meas}

R_i^{2HDM} : Theoretical prediction from 2HDMs

$\chi^2 \ fit$



- SM limit is $\cos(\beta - \alpha) = 0$
- Projection: assume that the SM is correct.
- systematics $\sim \dfrac{1}{\sqrt{(N)}}$
- These best fit values will be used as input parameters for the flavor bounds later.

Other constraints

- Flavor constraints:
  - $BR(B \to X_s \gamma)$
  - $BR(B_s \to \mu^+ \mu^-)$

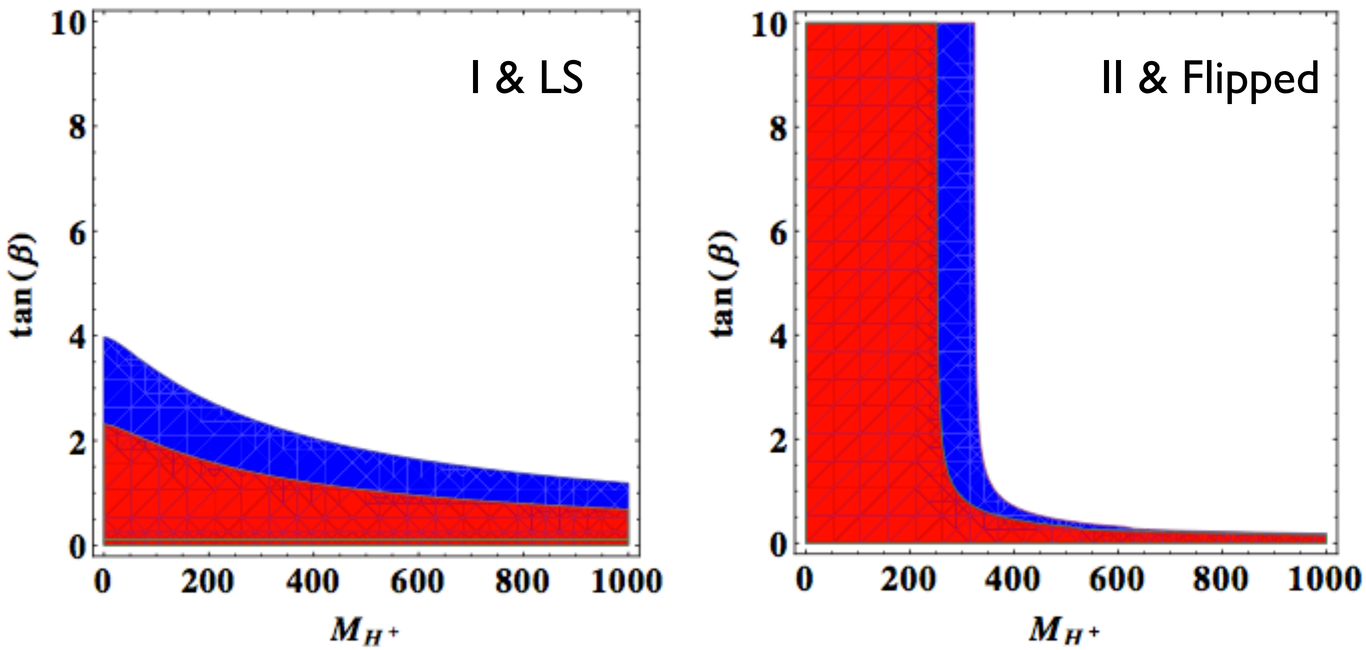
- LEP II direct search:

$$e^+e^- \to H^+H^- \text{ with } H^+ \to \tau\nu \text{ or } c\bar{s} \text{ at 95\% CL}$$

$$M_{H^\pm} \geq 78.6 \text{ GeV to } 89.6 \text{ GeV}$$

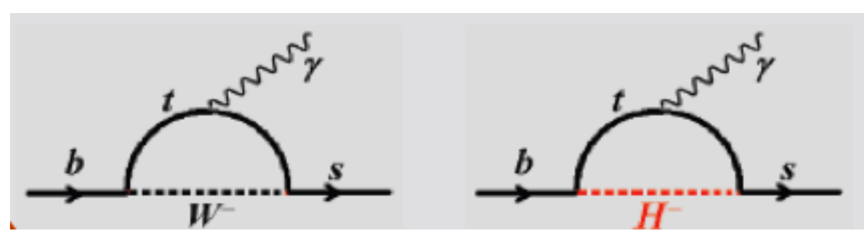
[hep-ex/0107031, hep-ex/1301.6065]

Flavor constraints: $B \to X_s\gamma$



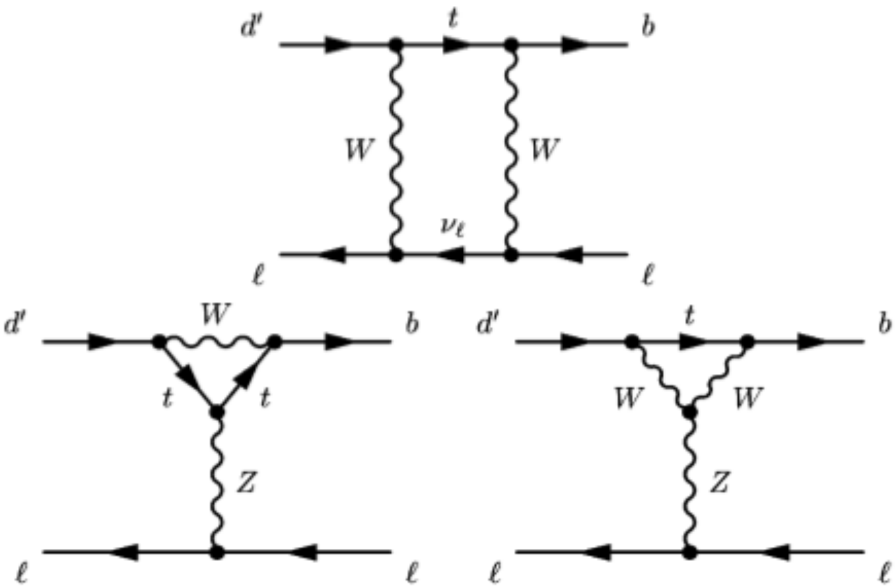
$BR(B \to X_s\gamma)\,|_{exp} = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$ hep-ex/0711.4889

Blue+Red: excluded at 2 sigma.
Red: excluded at 3 sigma.

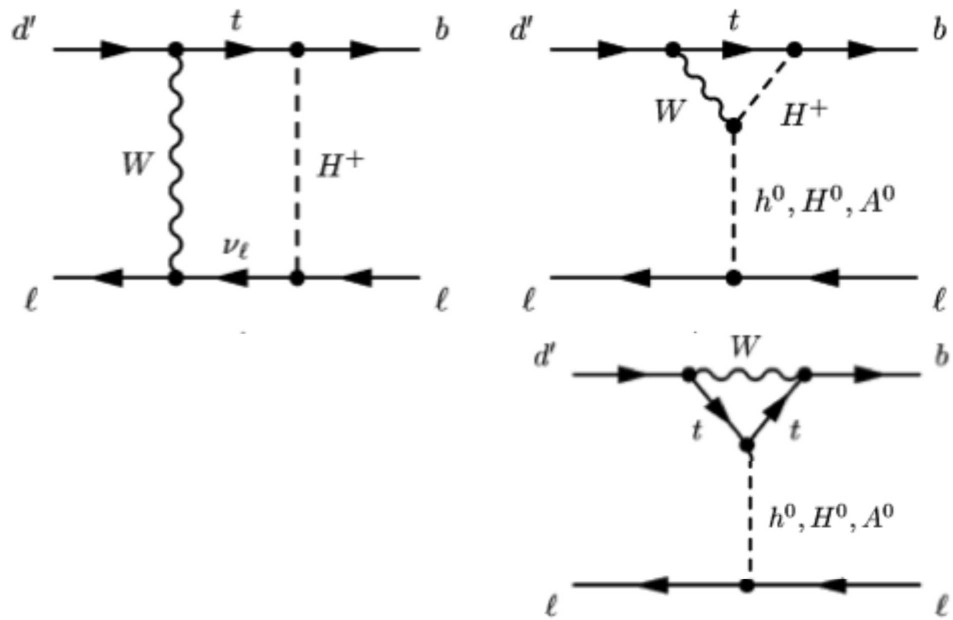


Flavor constraints: $B_s \to \mu^+\mu^-$

SM



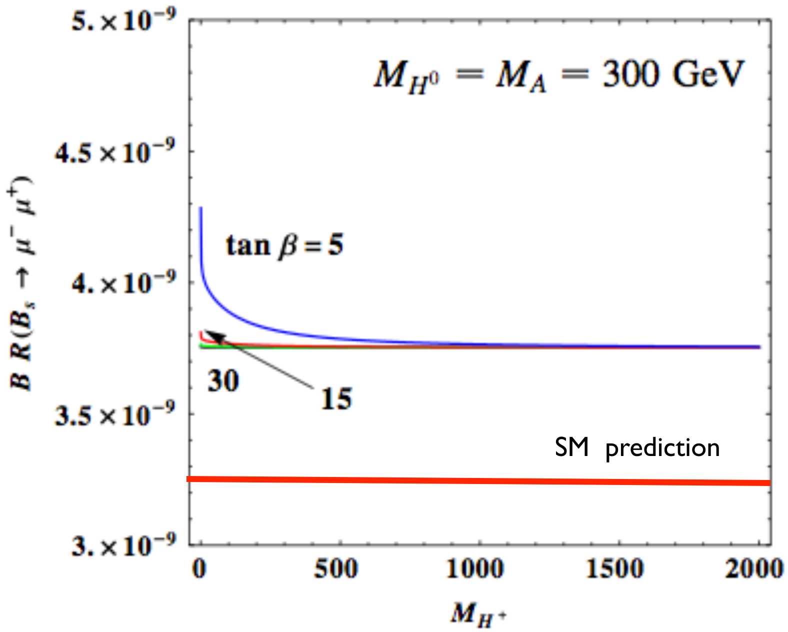
2HDMs

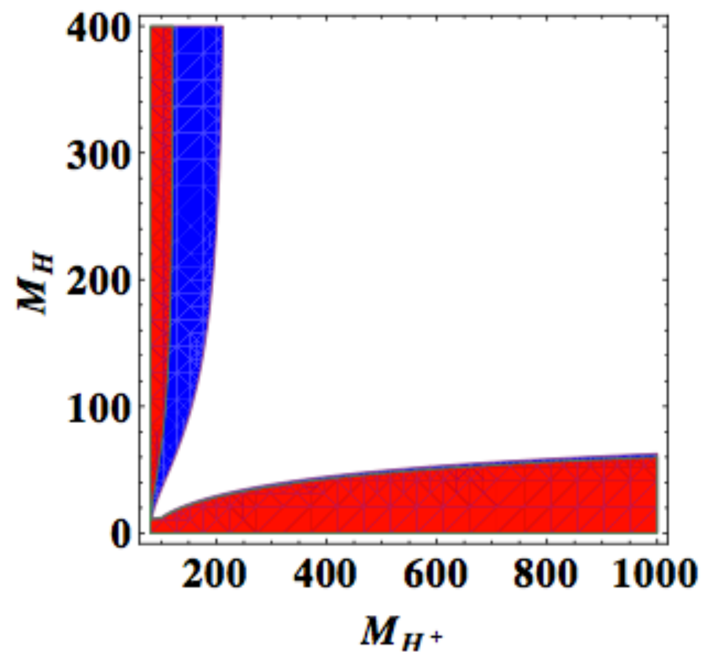


$$\mathrm{BR}\,(B_s \to \mu^+\mu^-)|_{\mathrm{exp}} = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$ R. Aaij *et al.* (LHCb Collaboration)

$$\mathrm{BR}\,(B_s \to \mu^+\mu^-)|_{\mathrm{SM}} = (3.23 \pm 0.27) \times 10^{-9}$$

Flavor constraints: $B_s \to \mu^+\mu^-$ (Type I)



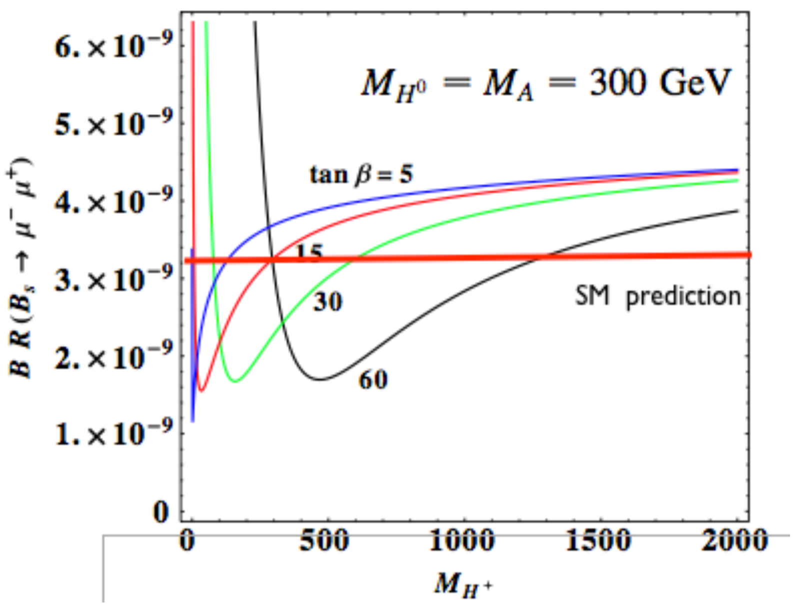


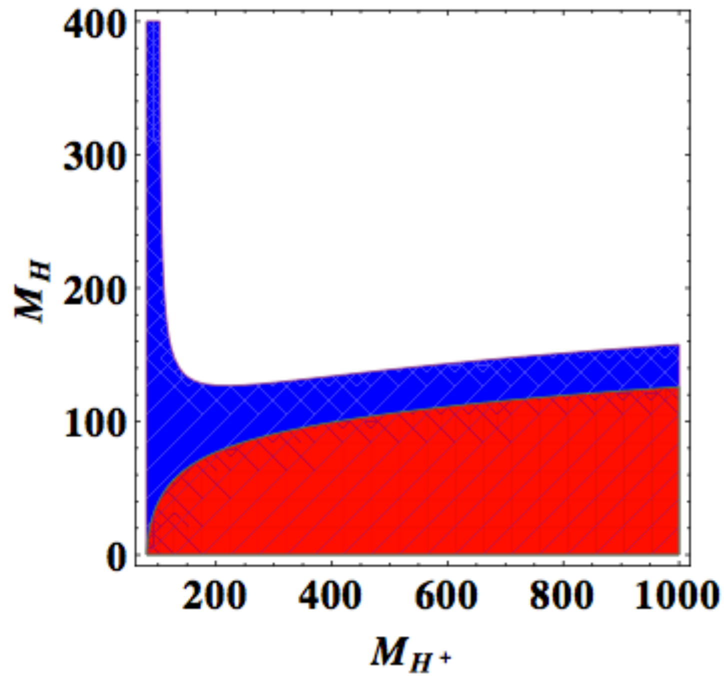
Assume $M_H = M_A$

Blue+Red: excluded at 2 sigma.
Red: excluded at 3 sigma.

For MH+> 500 GeV, the BR is almost a constant independent of MH+.

Flavor constraints: $B_s \to \mu^+\mu^-$ (Type II)





Blue+Red: excluded at 2 sigma.
Red: excluded at 3 sigma.

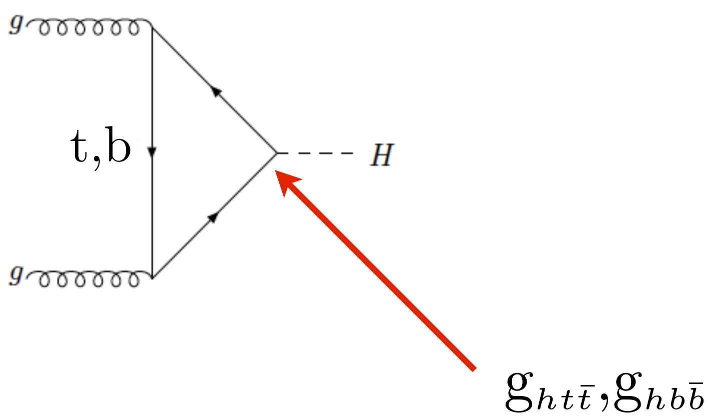
Conclusions

- We have considered four variations of 2HDMs, which have a Z_2 Symmetry.
- Only small regions of $\alpha - \tan\beta$ can produce rates which are consistent with the experimental results from the LHC.
- The parameters of these models are strongly constrained by measurements.
- None of the models we studied can be excluded by current measurements.

Backup slides

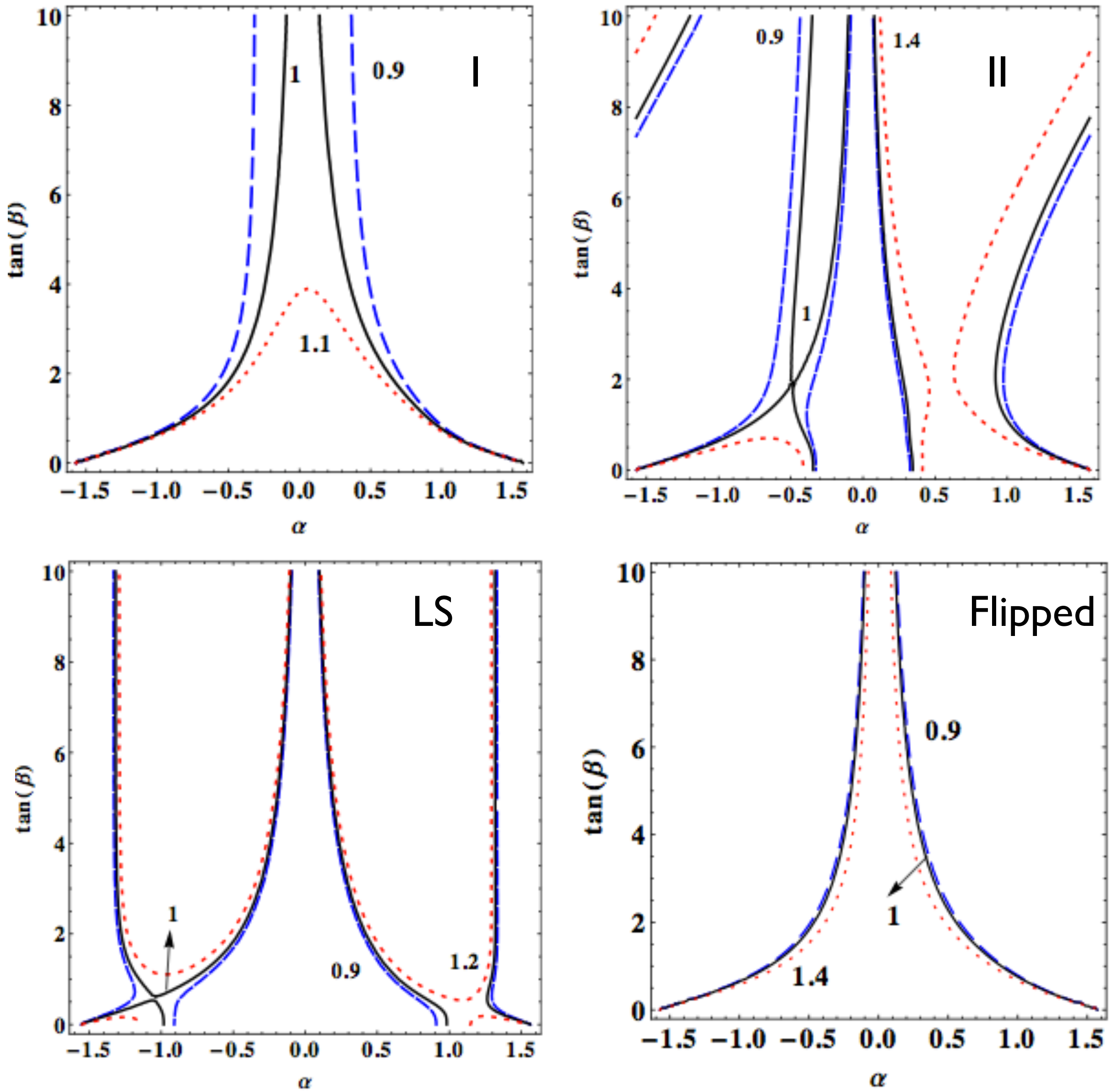
Gluon fusion production

- gluon fusion (ggF)



- For the type II and flipped models, the bottom loop is proportional to $-\frac{\sin\alpha}{\cos\beta}$ and can have large contributions in the large $\tan\beta$ regions.

Higgs to $\tau\bar{\tau}$ through ggF: $R_{\tau\bar{\tau}}^{ggF}$



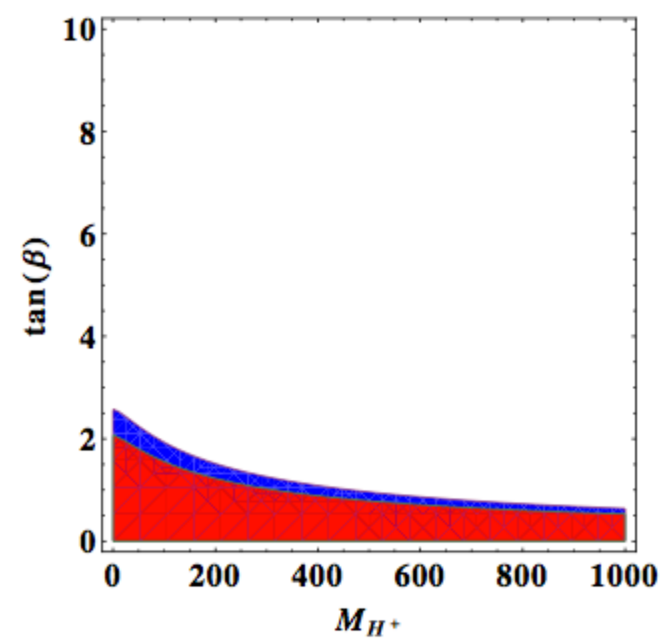
- In Model I and the Flipped Model, the SM rate can be obtained for small alpha.
- Similarity: I & Flipped
- Similarity: II & LS
- Not identical because of total width.

Flavor constraints: ΔM_{B_d}

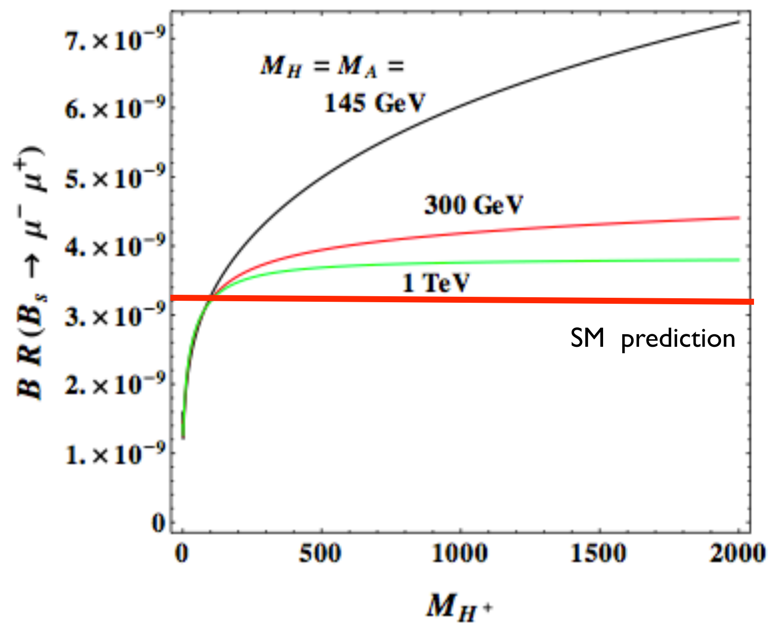
$\Delta M_{B_d}|_{\exp} = 0.507 \pm 0.004 \text{ ps}^{-1}$ hep-ex/0808.1297

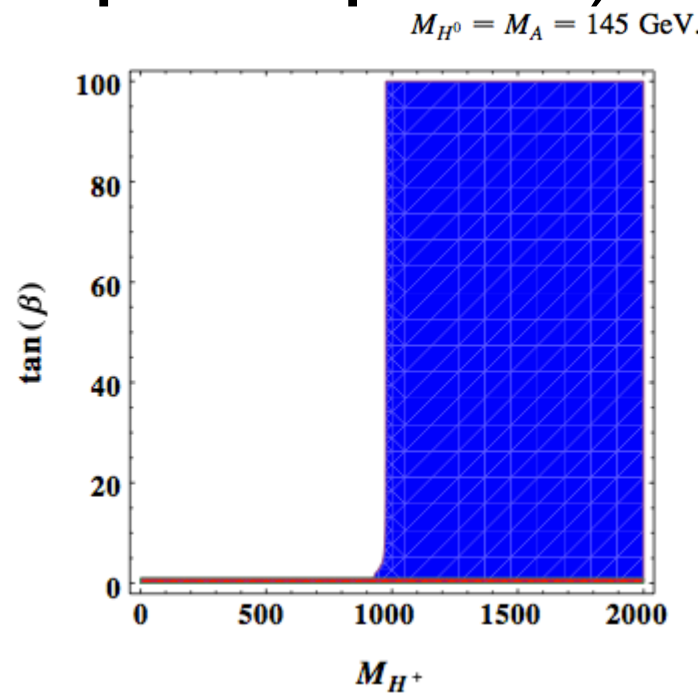
- The limits from ΔM_{B_d} are identical in all 2HDMs, because it is proportional to $\lambda_{tt}^2 = \cot^2\beta$.

Blue+Red: excluded at 2 sigma.
Red: excluded at 3 sigma.



Flavor constraints: $B_s \to \mu^+\mu^-$ (Lepton-specific)





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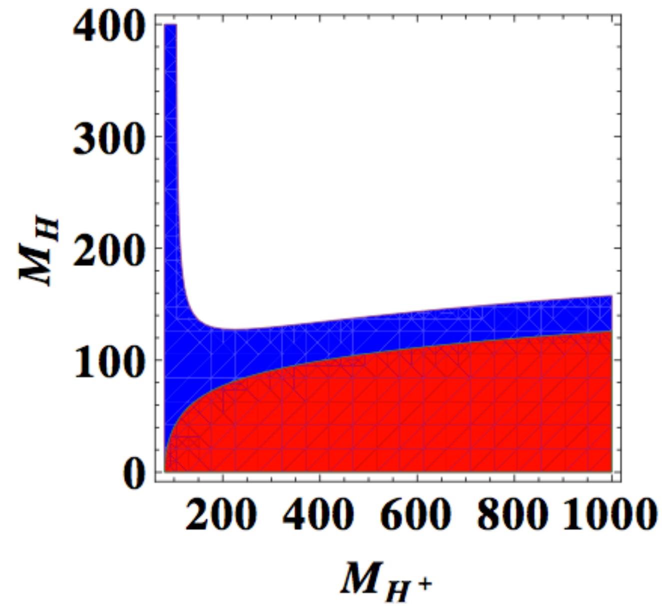
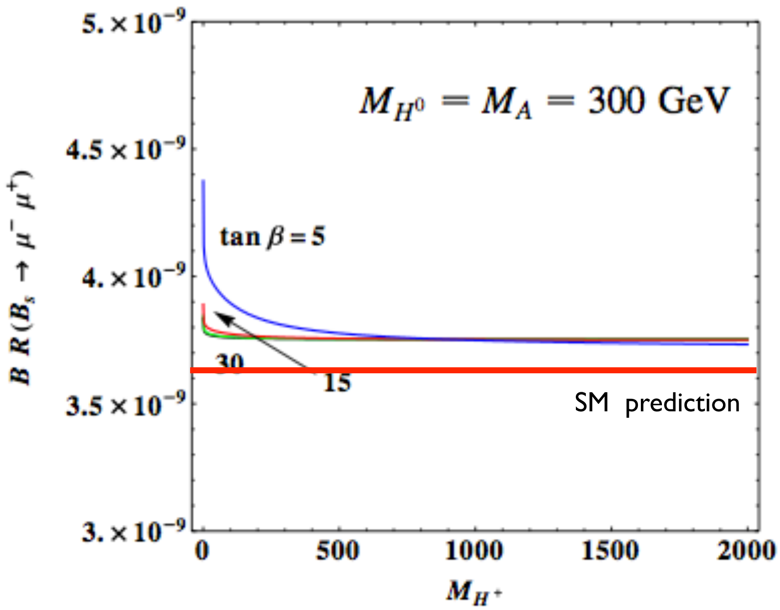
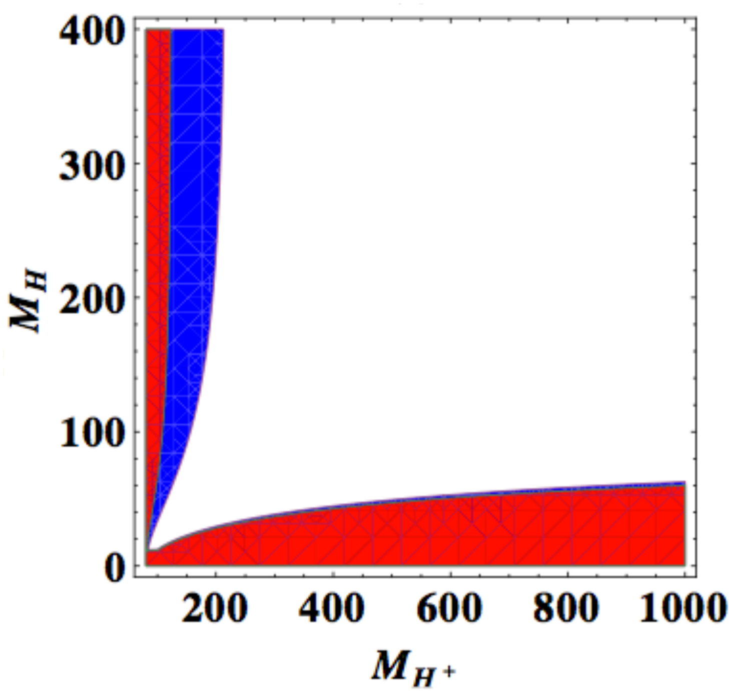
Red: excluded at 3 sigma.



The dominant contribution to $B_s \to \mu^+\mu^-$ is proportional to $\lambda_{tt}\lambda_{\mu\mu}$ so the branching ratio is insensitive to $\tan\beta$.

Flavor constraints: $B_s \to \mu^+\mu^-$ (Flipped)





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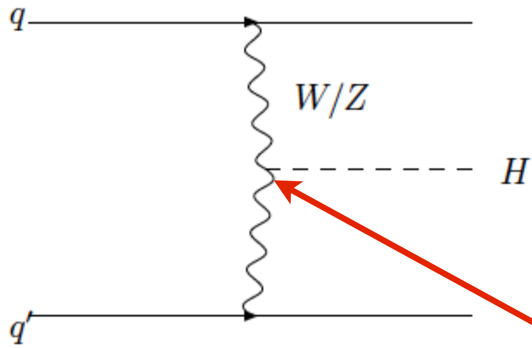
Red: excluded at 3 sigma.

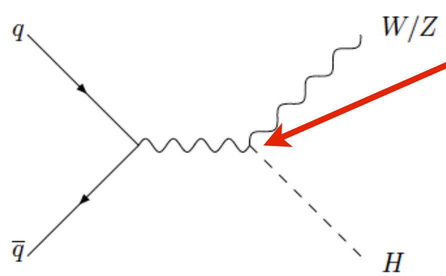
VBF/VH production

- Vector boson fusion (VBF)



$$R_{ff}^{\mathrm{VBF},Vh} \sim \sin^2(\beta-\alpha) g_{hff}^2$$

$\sin(\beta - \alpha)$



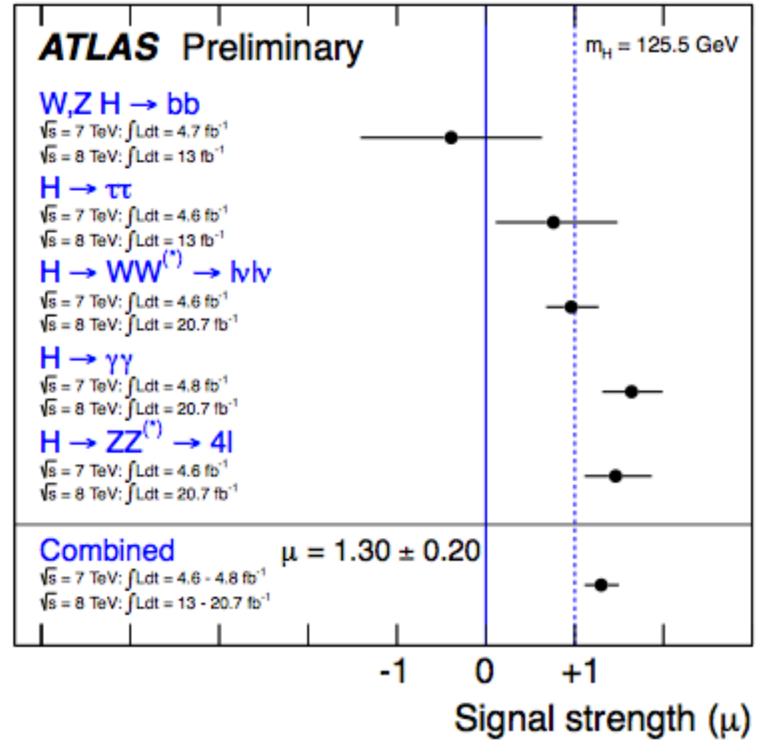
- associated production

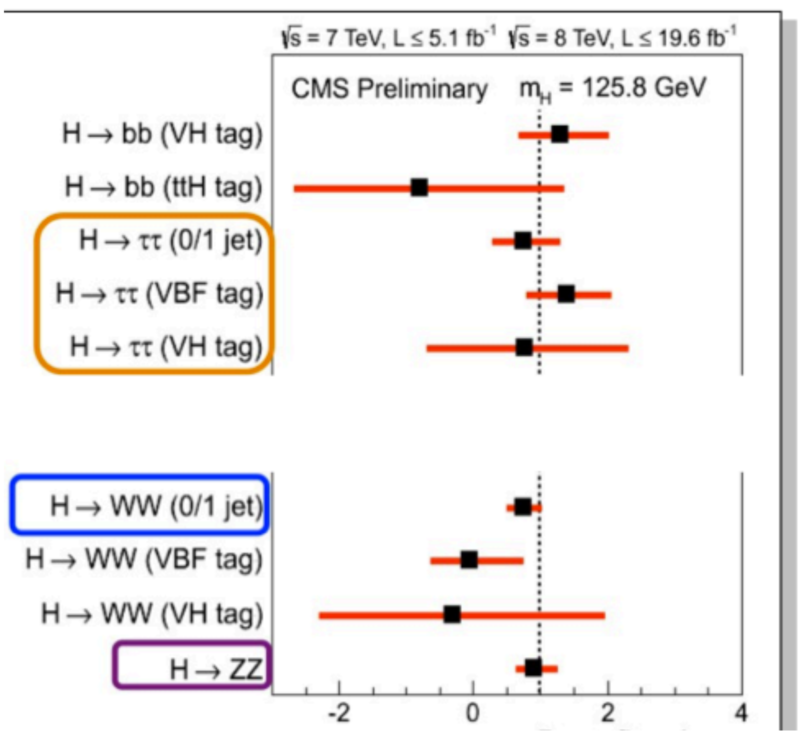
Higgs potential

$$\begin{aligned} V_{\rm 2HDM} = {} & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{H.c.}] \\ & + \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1) \\ & \times (\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 \\ & + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)](\Phi_1^\dagger\Phi_2) + \text{H.c.}\}. \quad (1) \end{aligned}$$

$\mathcal{L}_{\rm Yuk} = -Y_d\bar{Q}\Phi_1 d - Y_u\bar{Q}\Phi_2^c u - Y_l\bar{L}\Phi_1 e + \text{h.c.}$ for type II.

Higgs Decay Mode	$\hat{\mu}$ (m_H=125.5 GeV)
$VH \to Vbb$	-0.4 ± 1.0
$H \to \tau\tau$	0.8 ± 0.7
$H \to WW^{(*)}$	1.0 ± 0.3
$H \to \gamma\gamma$	1.6 ± 0.3
$H \to ZZ^{(*)}$	1.5 ± 0.4
Combined	1.30 ± 0.20





New preliminary updates from some channels with full 2011+2012 dataset

- **Updates from $H \to WW$ and $H \to \tau\tau$ channels**
- **$H \to \gamma\gamma$ Updated $\mu = 0.78 \pm 0.27$ at 125 GeV**
- **$H \to ZZ^* \to 4l$ update includes VBF tag**

ZZ(0/1 jet): $0.84^{+0.32}_{-0.26}$
ZZ(dijet): $1.22^{+0.84}_{-0.57}$

Higgs production