A lighter Higgs in 2HDMs

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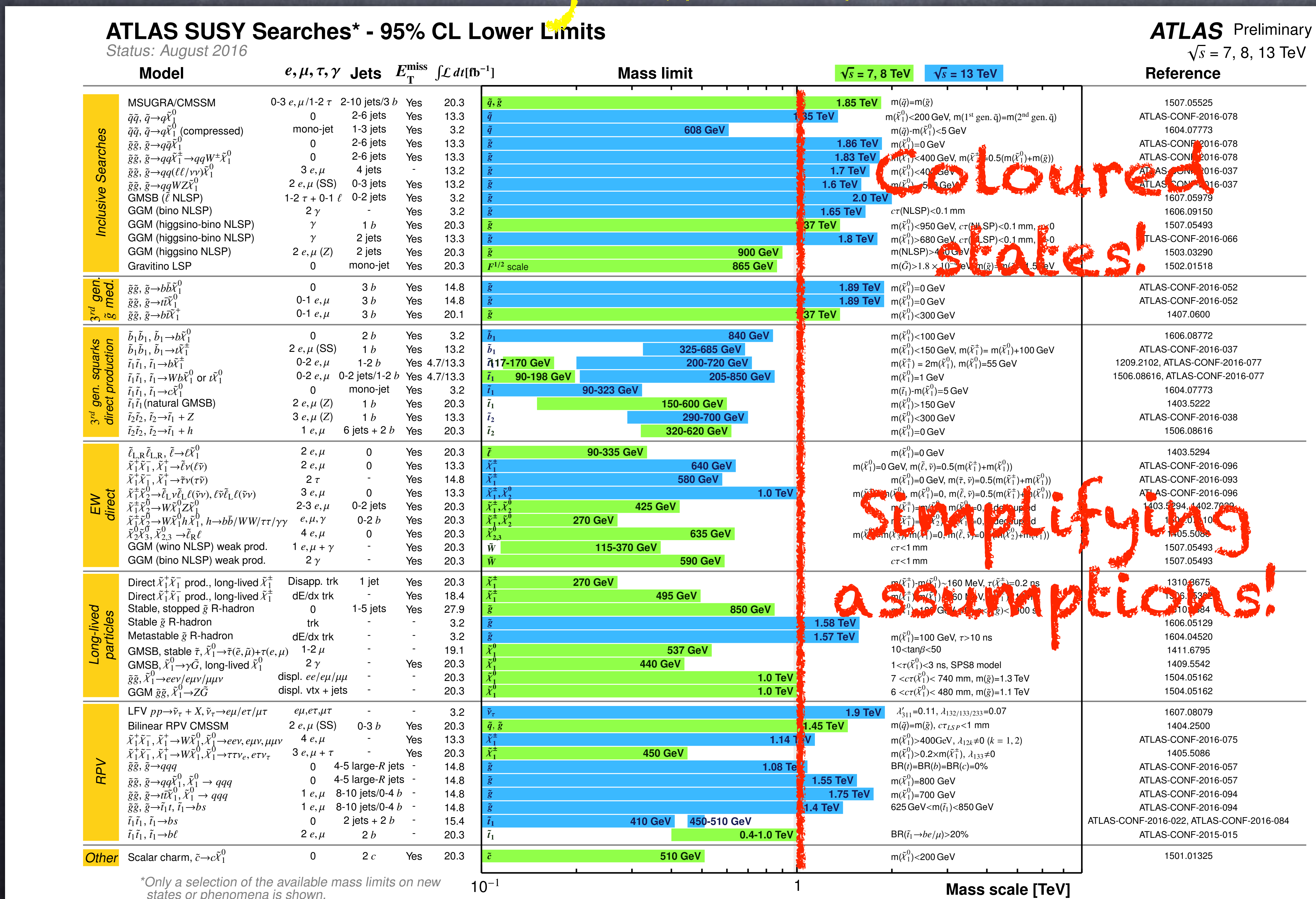
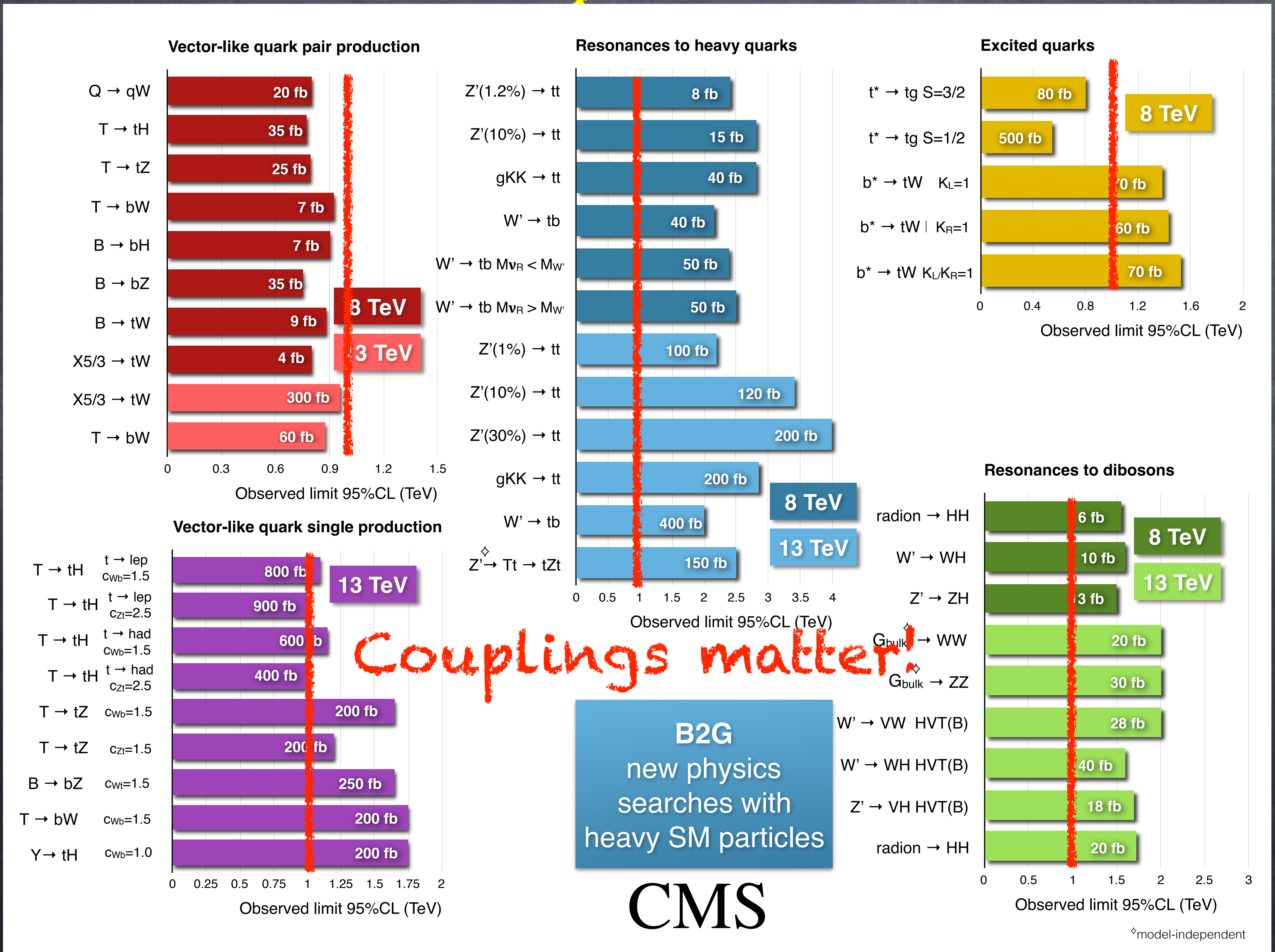
No new physics below 1 TeV? Hold your horses!



No new physics below 1 TeV? Hold your horses!



No new physics below 1 TeV? Hold your horses!

- The call for New Physics mainly comes from the Higgs sector (and DM?)
- It's a logical possibility to have weakly coupled light states:

"Non-minimal" composite Higgs models!

EW-inos in SUSY

Axions (R-axion...)


No new physics below 1 TeV?
Hold your horses!
multi-TeV horizon
Light stuff may still be there!

2 Higgs Doublet Models

- Minimal extension of the SM Higgs sector

$$V = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - m_{12}^2 \left(\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1 \right) + \frac{\lambda_1}{2} \left(\phi_1^\dagger \phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\phi_2^\dagger \phi_2 \right)^2 + \lambda_3 \left(\phi_1^\dagger \phi_1 \right) \left(\phi_2^\dagger \phi_2 \right) + \lambda_4 \left(\phi_1^\dagger \phi_2 \right) \left(\phi_2^\dagger \phi_1 \right) + \frac{\lambda_5}{2} \left[\left(\phi_1^\dagger \phi_2 \right)^2 + \left(\phi_2^\dagger \phi_1 \right)^2 \right] ,$$

Z_2 symmetric (except m_{12})

- "physical" basis

$$\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5,\ m_{11}^2,\ m_{22}^2,\ m_{12}^2$$
$$\Updownarrow$$
$$m_h,\ m_H,\ m_A,\ m_{H^\pm},\ \tan\beta,\ \sin(\beta-\alpha),\ v,\ m_{12}^2$$

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

$\alpha \Rightarrow h \leftrightarrow H$ mixing

2 Higgs Doublet Models

- Couplings to fermions define 4 flavour-safe scenarios

		Type I	Type II	Flipped	Lepton Specific
Up-Type quark	h	$\frac{\cos\alpha}{\sin\beta}$			
	H	$\frac{\sin\alpha}{\sin\beta}$			
	A	$\cot\beta$			
Down-Type quark	h	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$
	H	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$
	A	$\cot\beta$	$\tan\beta$	$\tan\beta$	$\cot\beta$
Lepton	h	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
	H	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$
	A	$\cot\beta$	$\tan\beta$	$\cot\beta$	$\tan\beta$
WW and ZZ	h	$\sin(\beta-\alpha)$			
	H	$\cos(\beta-\alpha)$			
	A	0			

Higgs couplings

A lighter Higgs?

- The spectrum may contain a lighter Higgs-like state:

$$\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5,\ m_{11}^2,\ m_{22}^2,\ m_{12}^2$$
$$\Updownarrow$$
$$m_h,\ m_H,\ m_A,\ m_{H^\pm},\ \tan\beta,\ \sin(\beta-\alpha),\ v,\ m_{12}^2$$

125

$h \to \gamma\gamma$

below 125 GeV?

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Strategy:

- Preliminary scan of the parameter space

m_h (GeV)	m_H (GeV)	m_A (GeV)	$m_{H^\pm}$ (GeV)	$\sin(\beta-\alpha)$	$\tan\beta$	m_{12}^2 (GeV)^2
[80;110]	125	[60;1000]	[80;1000]	[-1;1]	[1/50;50]	[-(300)^2;+(200)^2]

Strategy:

- Preliminary scan of the parameter space
- Impose existing constraints (using existing tools):

  1* Indirect constraints
  2* LEP bounds (on scalars)
  3* LHC bounds (on Higgs couplings)

1* Indirect constraints

- EWPTs (S and T parameters) - 2 sigma limit
- Stability of the potential, and perturbativity of all couplings

Computed with 2HDMC

- flavour bounds (charged Higgs)

Computed with SuperIso

Process	Experimental values	Theoretical computation	Combined error at 1σ
$\mathcal{BR}(\overline{B} \to X_s\gamma)$	$(3.43 \pm 0.22) \times 10^{-4}$ [20]	$(3.40 \pm 0.19) \times 10^{-4}$ [21]	0.29×10^{-4}
$\mathcal{BR}(B_s \to \mu^+\mu^-)$	$(2.9 \pm 0.7) \times 10^{-9}$ [22, 23]	$(3.54 \pm 0.27) \times 10^{-9}$ [21]	0.8×10^{-9}
$\Delta_0(B \to K^*\gamma)$	$(5.2 \pm 2.6) \times 10^{-2}$ [24]	$(5.1 \pm 1.5) \times 10^{-2}$ [21]	3.0×10^{-2}
ΔM_d	0.510 ± 0.003 ps^{-1} [20]	0.543 ± 0.091 ps^{-1} [25]	0.091 ps^{-1}

2* LEP constraints

- Direct bounds on scalars (HiggsBounds at 95% C.L.)

3* LHC constraints

- Fit of signal strengths using kappa's (8TeV legacy data - 1606.02266)

$$\kappa_{XY}^2 = \frac{\Gamma(H \to YX)}{\Gamma^{\rm SM}(H \to XY)} \qquad \text{N.B.} \quad \kappa_{WW} = \kappa_{ZZ} = \cos(\beta - \alpha)$$

- Gaussian fit of signal strengths (1504.07919)

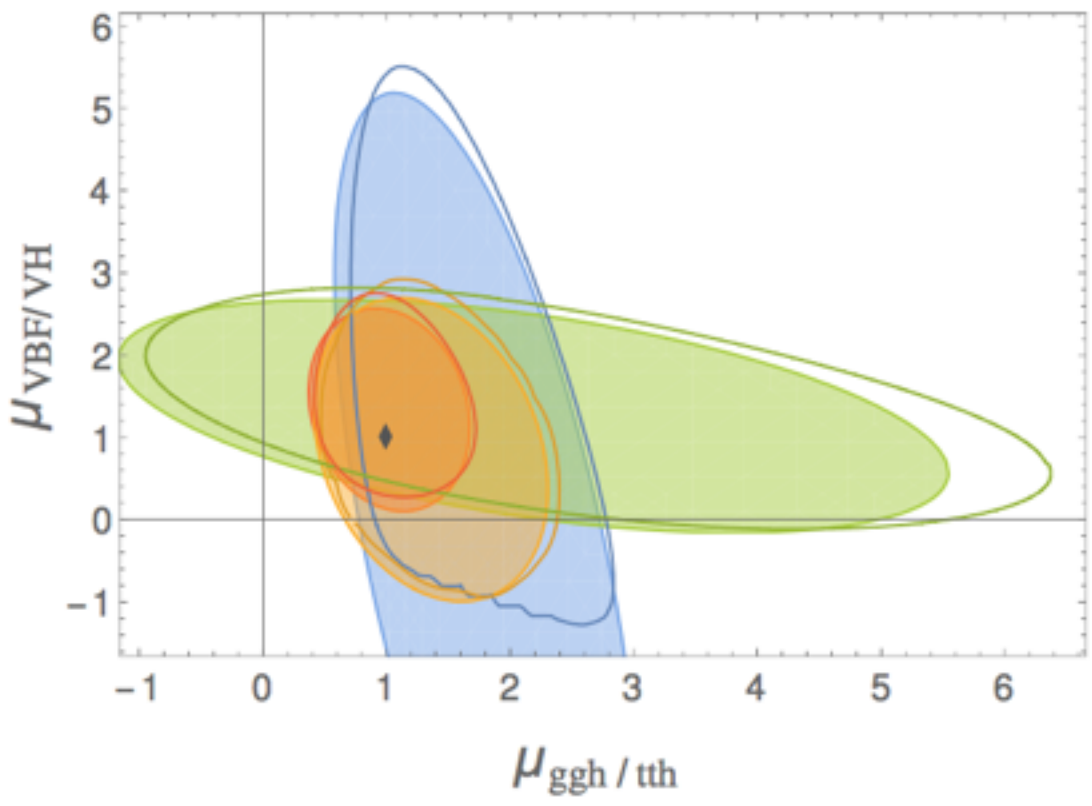


Figure 2: Relevance of the hypothesis of a Gaussian likelihood: comparison of experimental 95%$C.L.$ exclusion contours with contours extrapolated from the 68%$C.L.$ fit (ATLAS only). Colour code per final state: yellow: $\gamma\gamma$, green: $\tau\tau$, red: WW, blue: ZZ. Gray rhombus: SM

$$\kappa_{XY}^2 = \frac{\Gamma(H \to YX)}{\Gamma^{\rm SM}(H \to XY)}$$ N.B. $\kappa_{WW} = \kappa_{ZZ} = \cos(\beta - \alpha)$

- Gaussian fit of signal strengths (1504.07919)

Cross section calculation

- We use the same "kappa trick" to calculate production cross sections for the lighter Higgs.

$$\kappa_{XY}^2 = \frac{\Gamma(h \to YX)}{\Gamma^{\rm SM}(H \to XY)}$$

N.B. $\kappa_{VV}^{\rm light} = \sin(\beta - \alpha)$

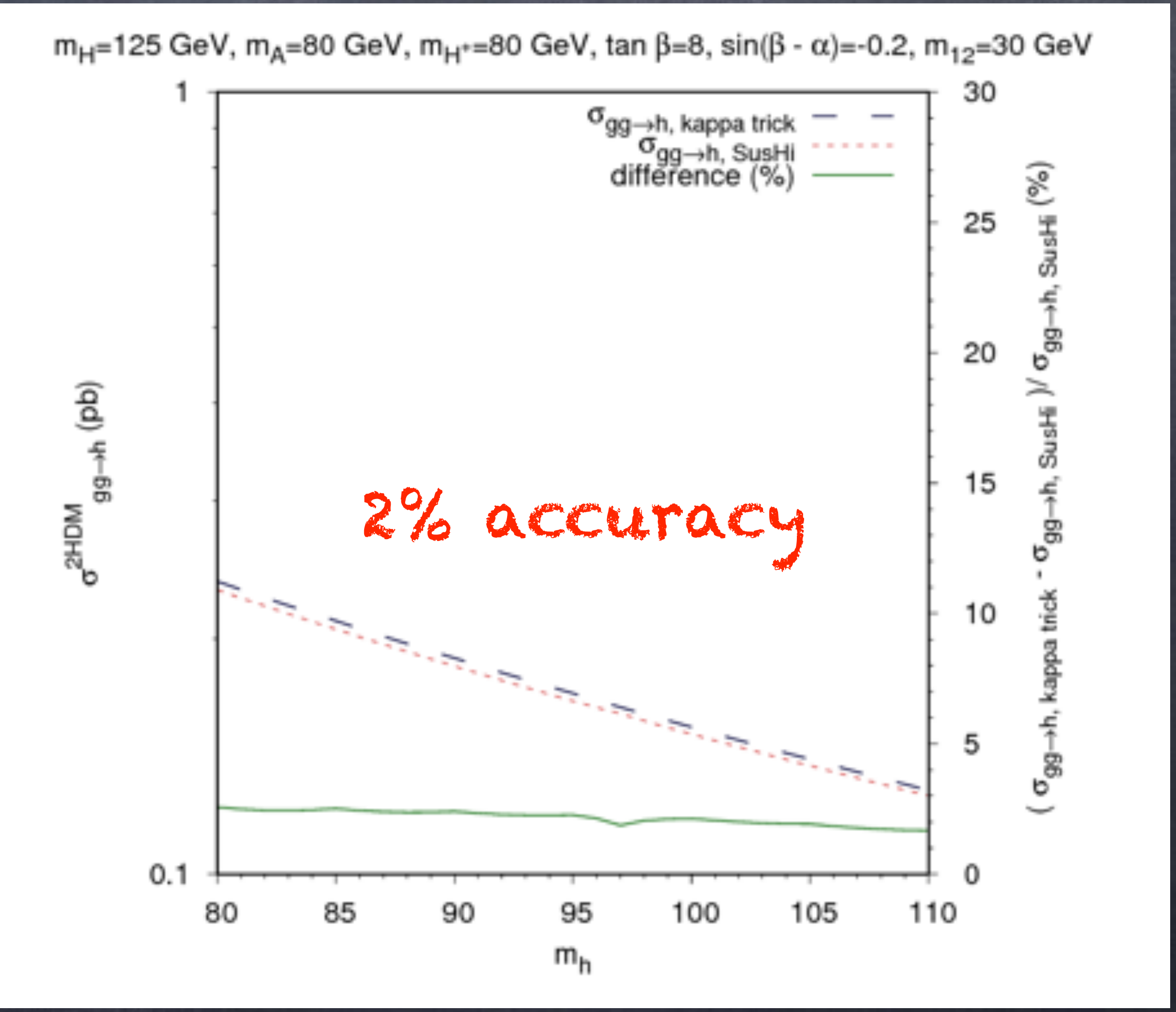
Approximate cross sections

$$\sigma(gg \to h) = \kappa_{gg}^2 \times \sigma^{\rm SM}$$

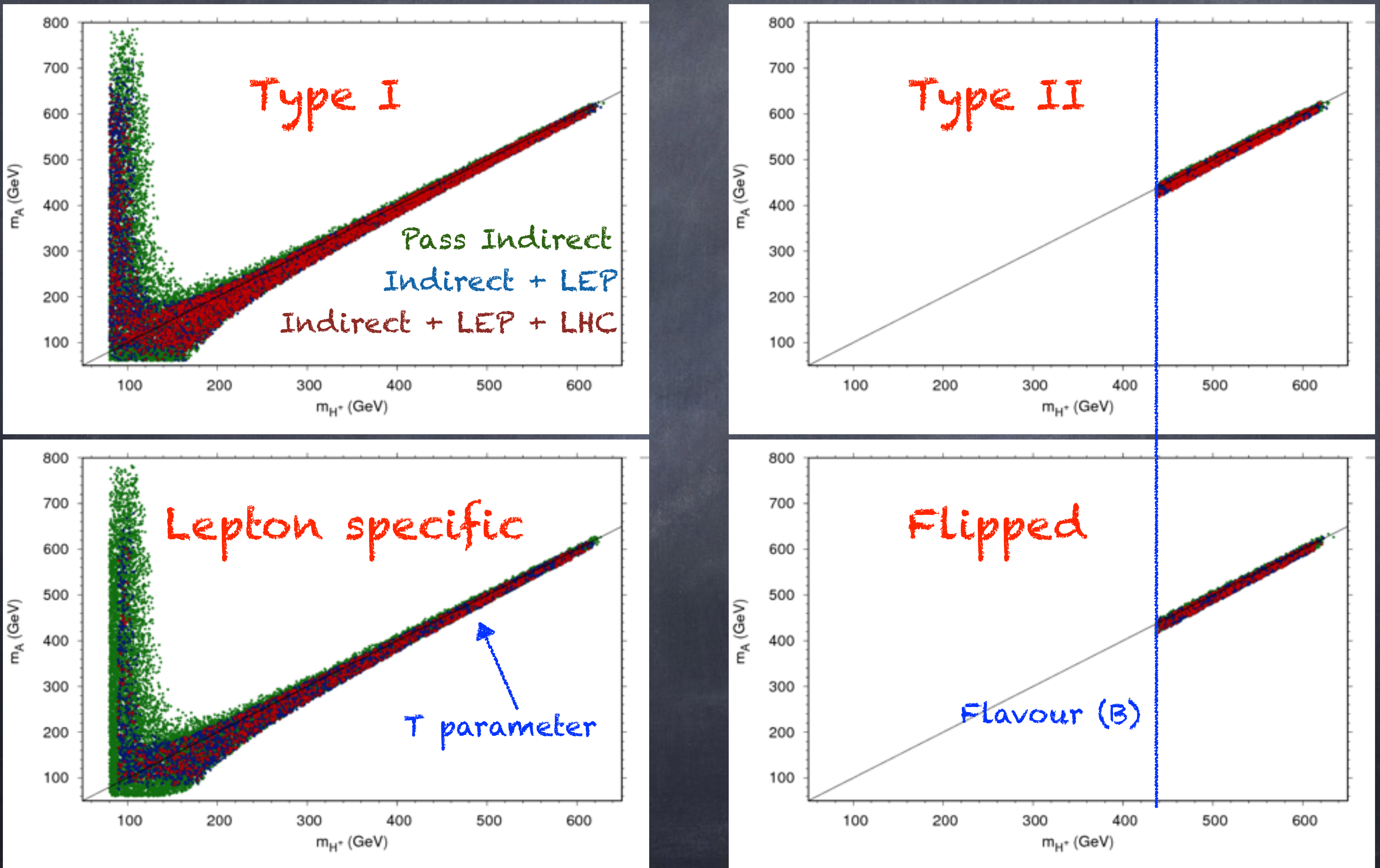
$$\sigma(VBF + Vh) = \kappa_{VV}^2 \times \sigma^{\rm SM}$$

compared with SusHi

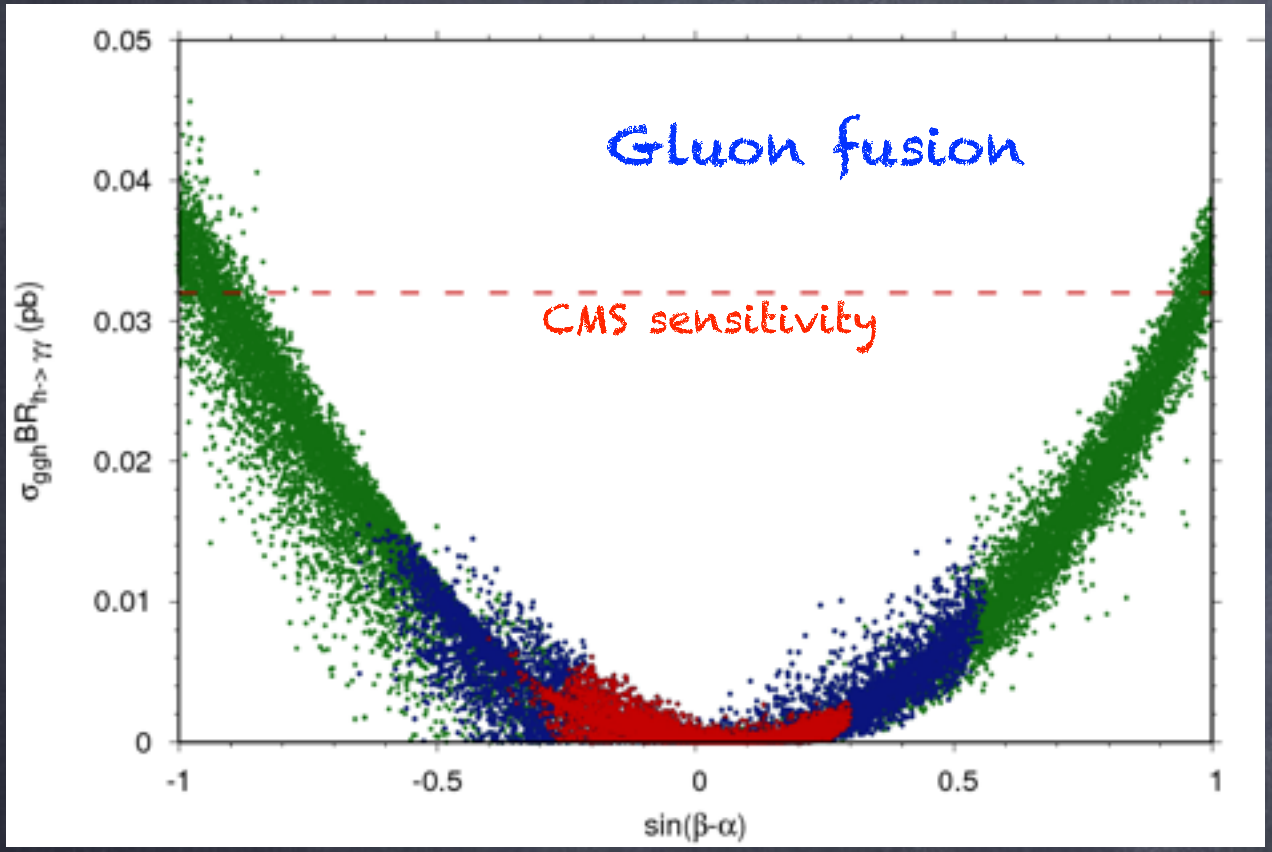
N.B.: no VBF nor Vh in SusHi!

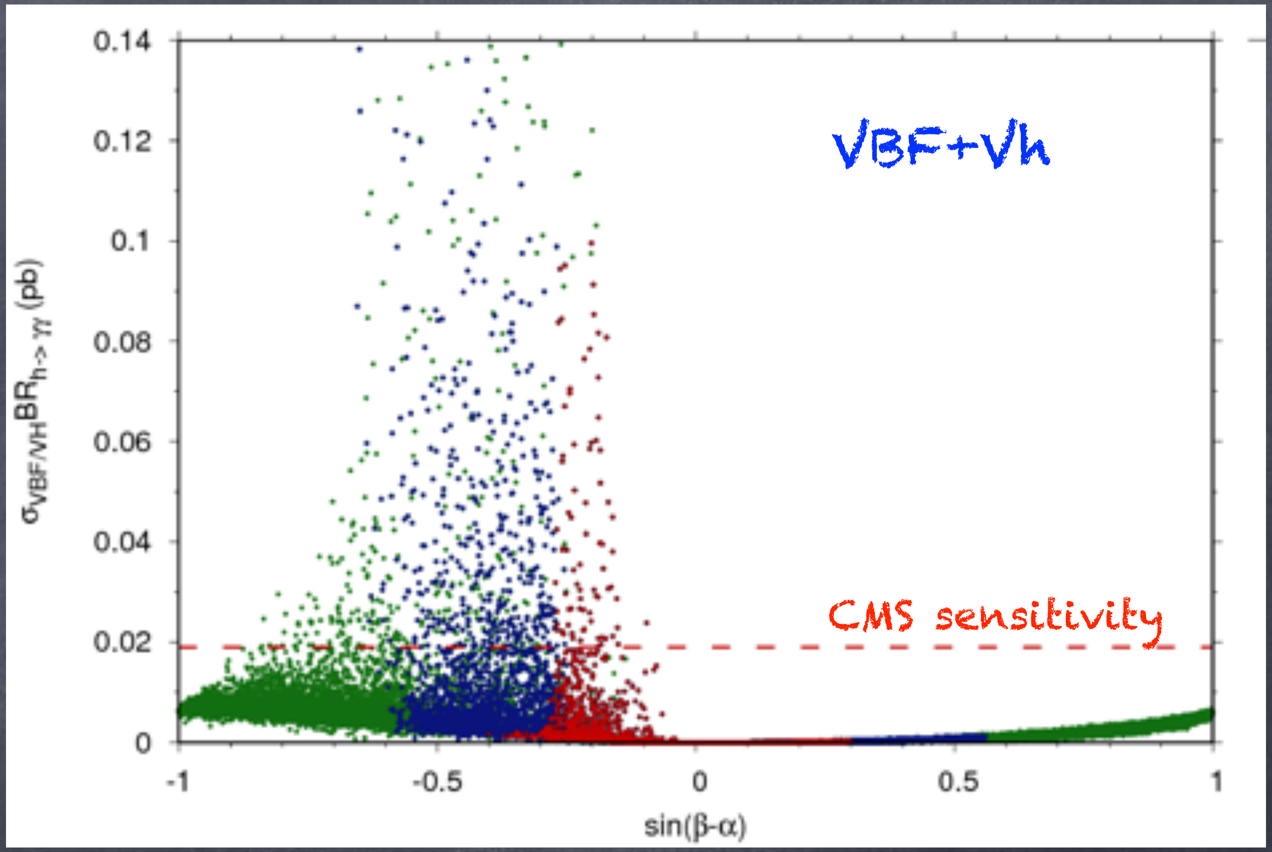


Results


Type I
Pass Indirect
Indirect + LEP
Indirect + LEP + LHC
Type II
Lepton specific
T parameter
Flipped
Flavour (B)
m_A (GeV)
m_{H^+} (GeV)
100
200
300
400
500
600
700
800

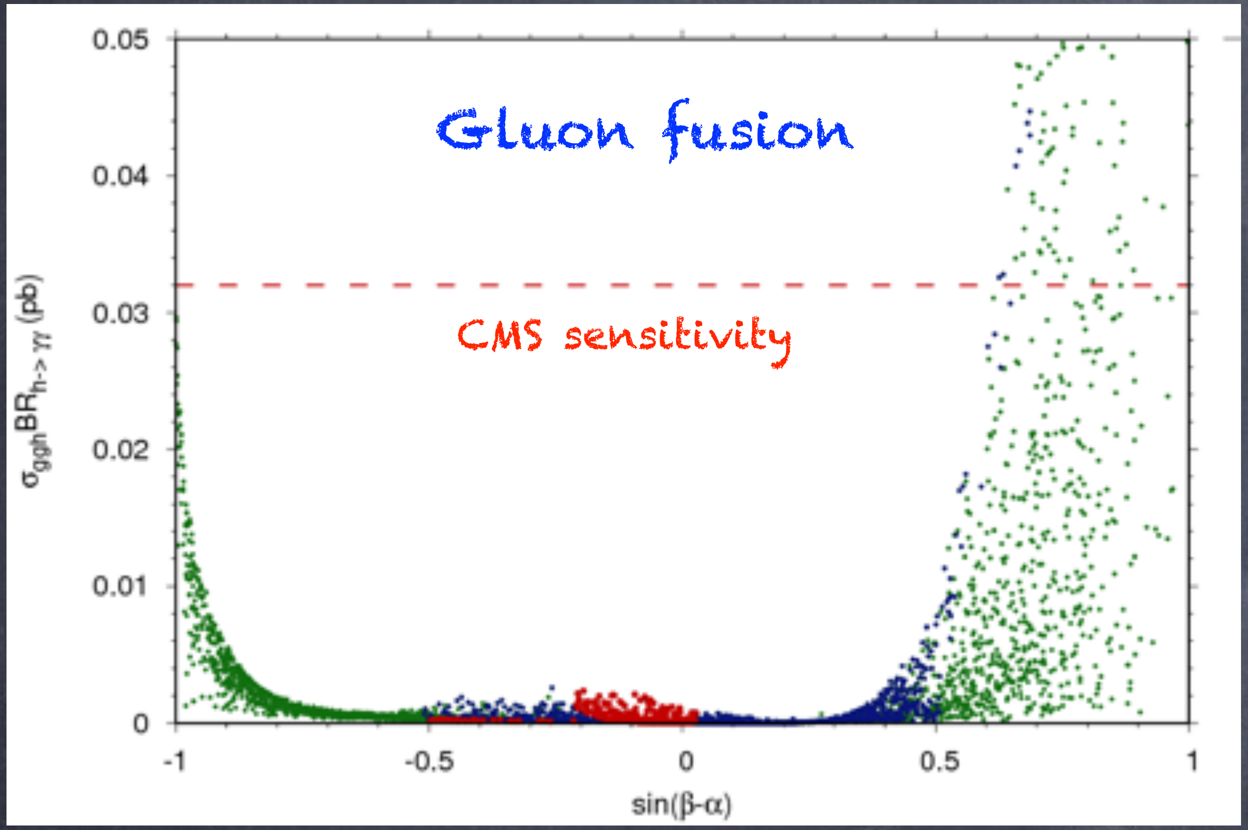
Results
Di-photon signal (type I)

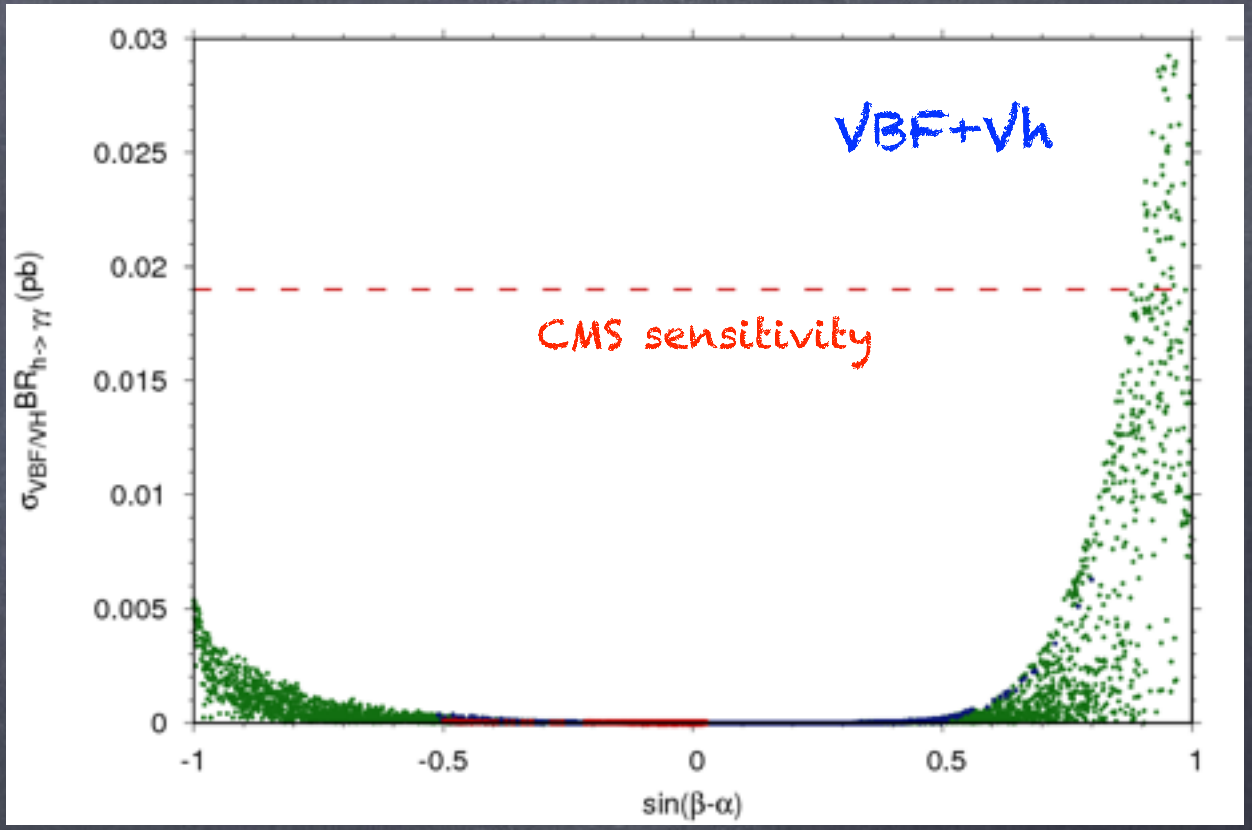




- Search sensitive to VBF+Vh for $-0.3 \lesssim \sin(\beta-\alpha) \lesssim 0$

Results
Di-photon signal (type II)



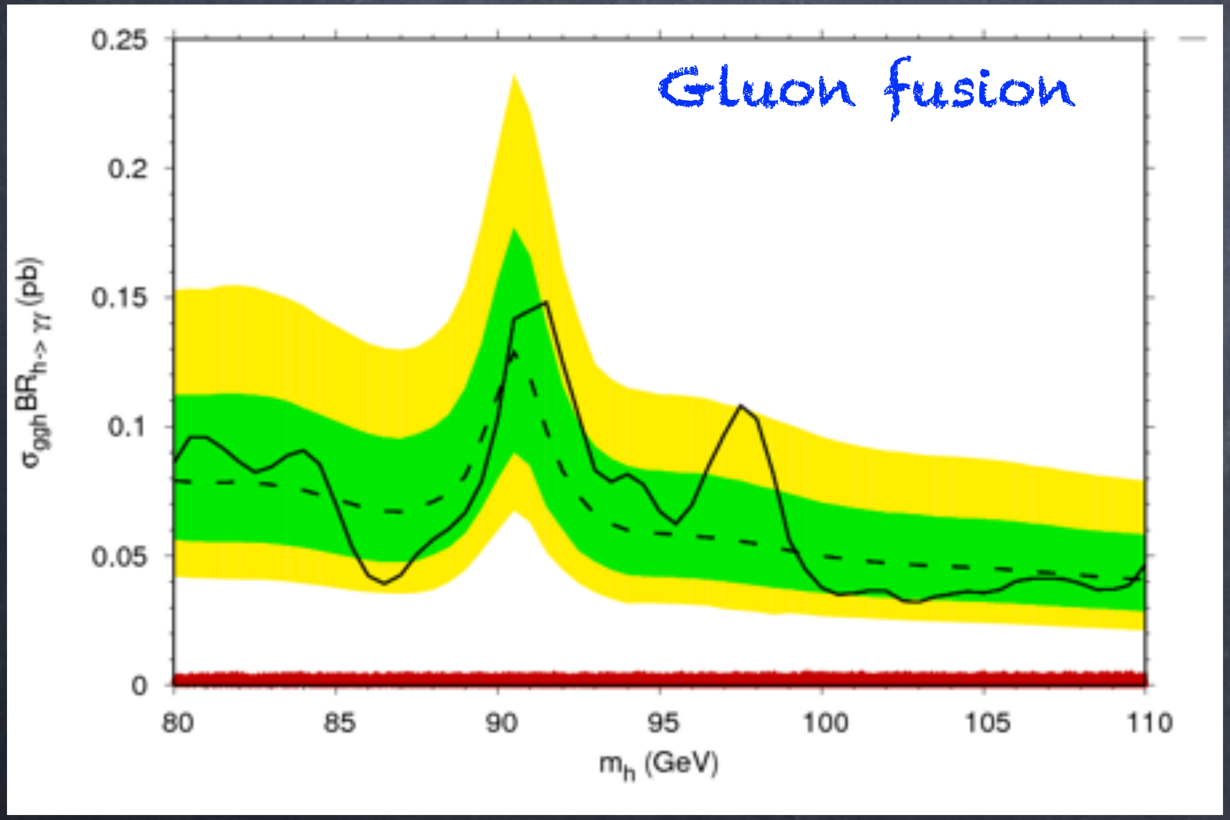


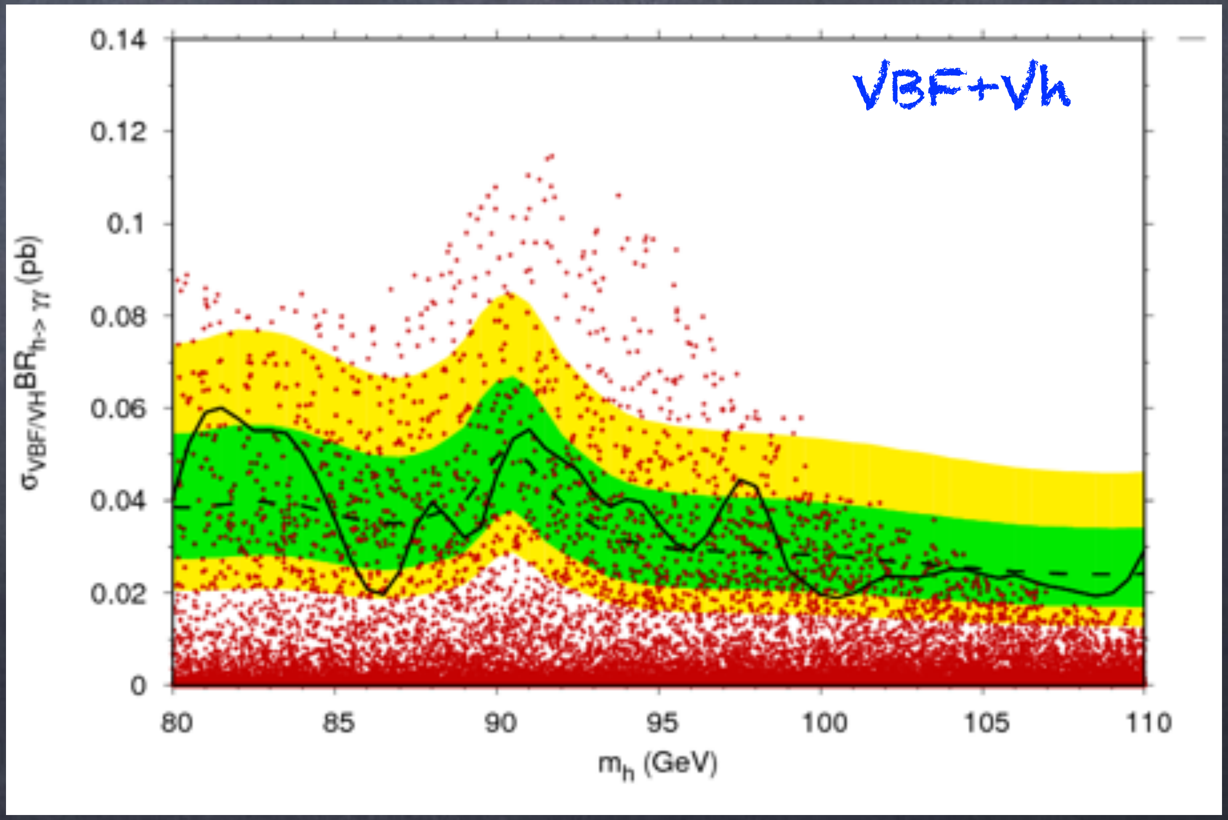
- Very far from sensitivity! We focus on Type I!

Focused scan

m_h (GeV)	m_H (GeV)	m_A (GeV)	$m_{H^\pm}$ (GeV)	$\sin(\beta-\alpha)$	$\tan\beta$	$m12^2$
[80;110]	125	[60;650]	[80;630]	[-0.3;-0.05]	[2;12]	$[-(100)^2;+(100)^2]$

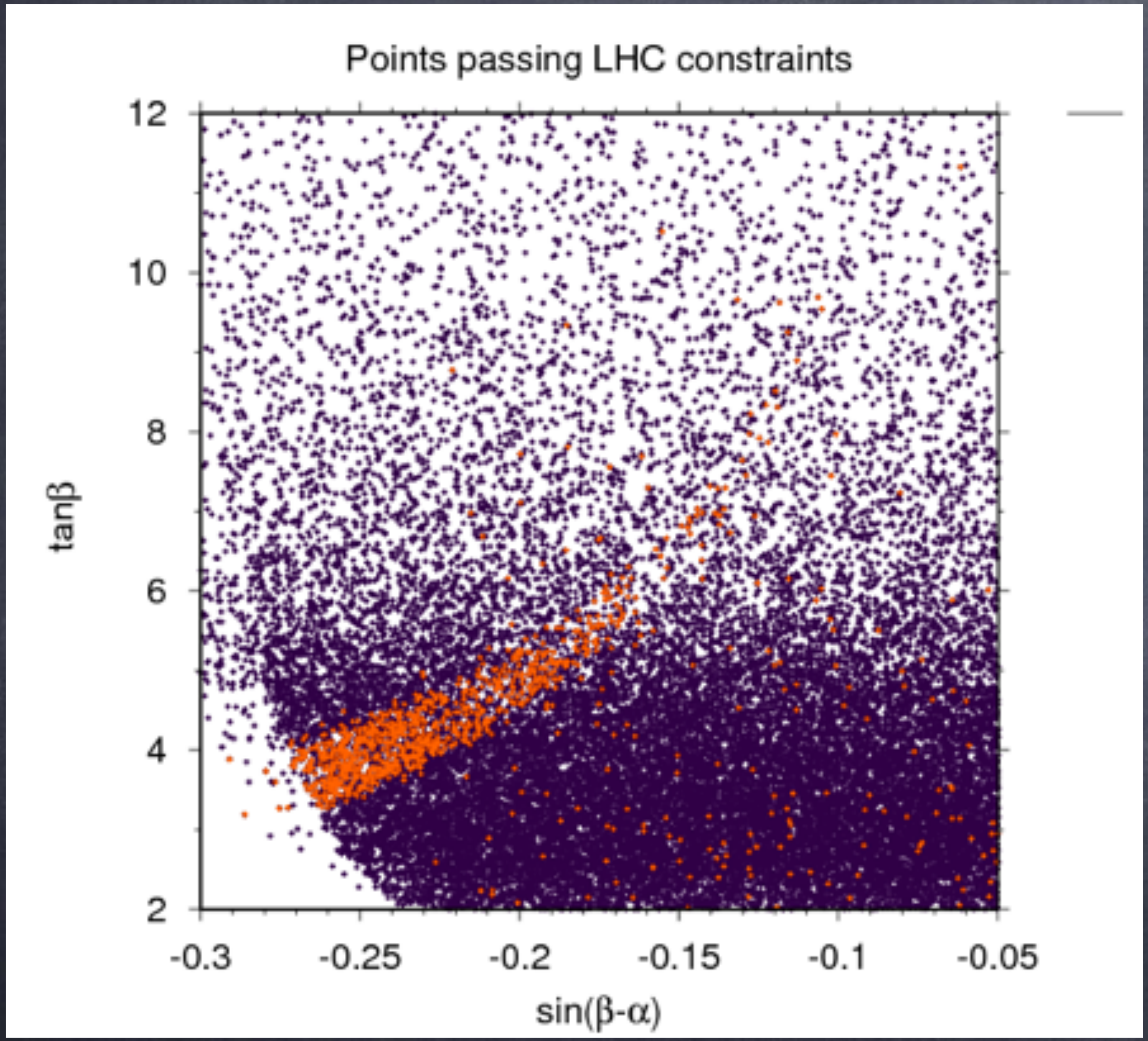
- Comparison with CMS cross section bounds.

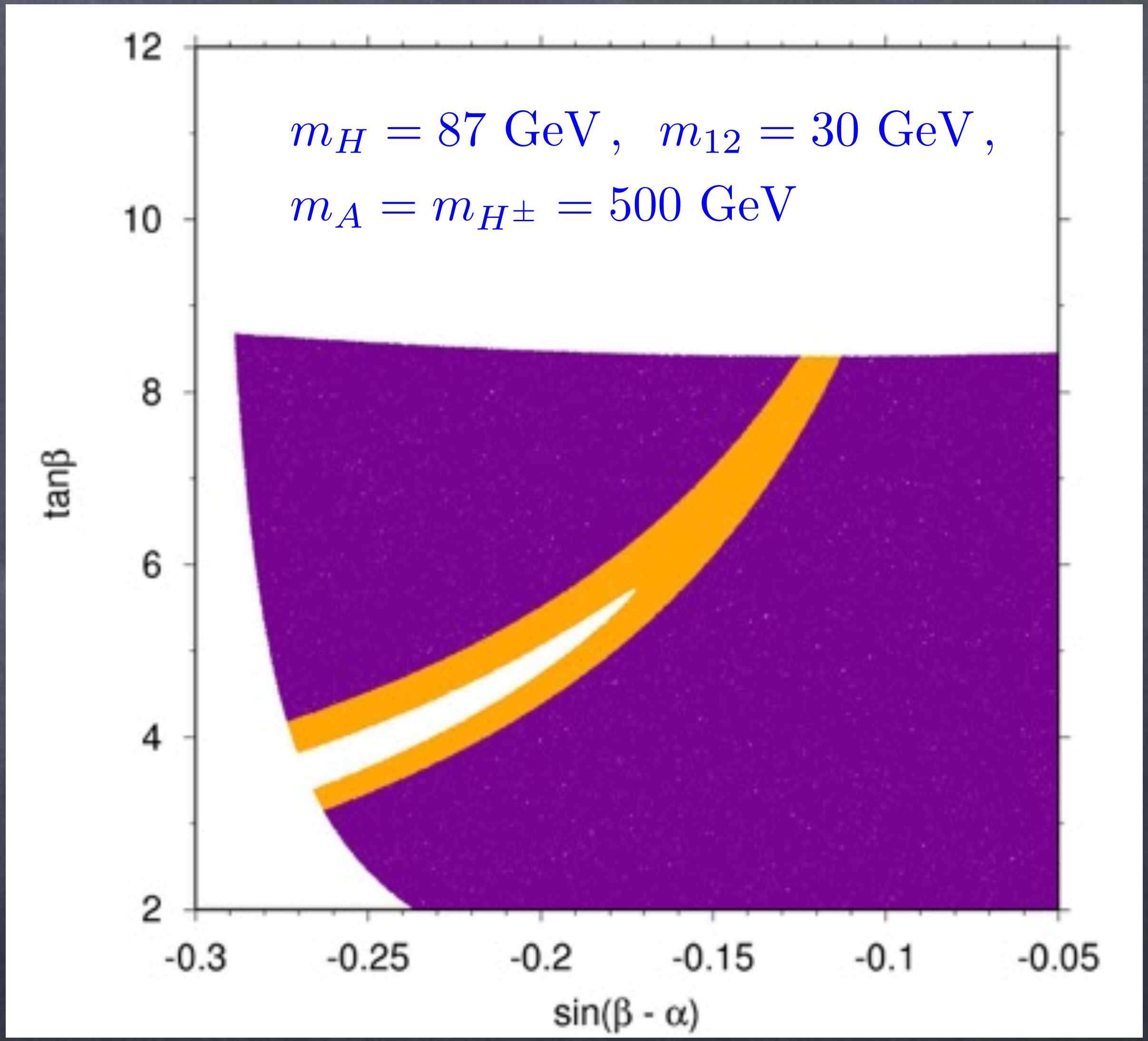




- Note: no VBF optimisation, but simple recast!

Focused scan



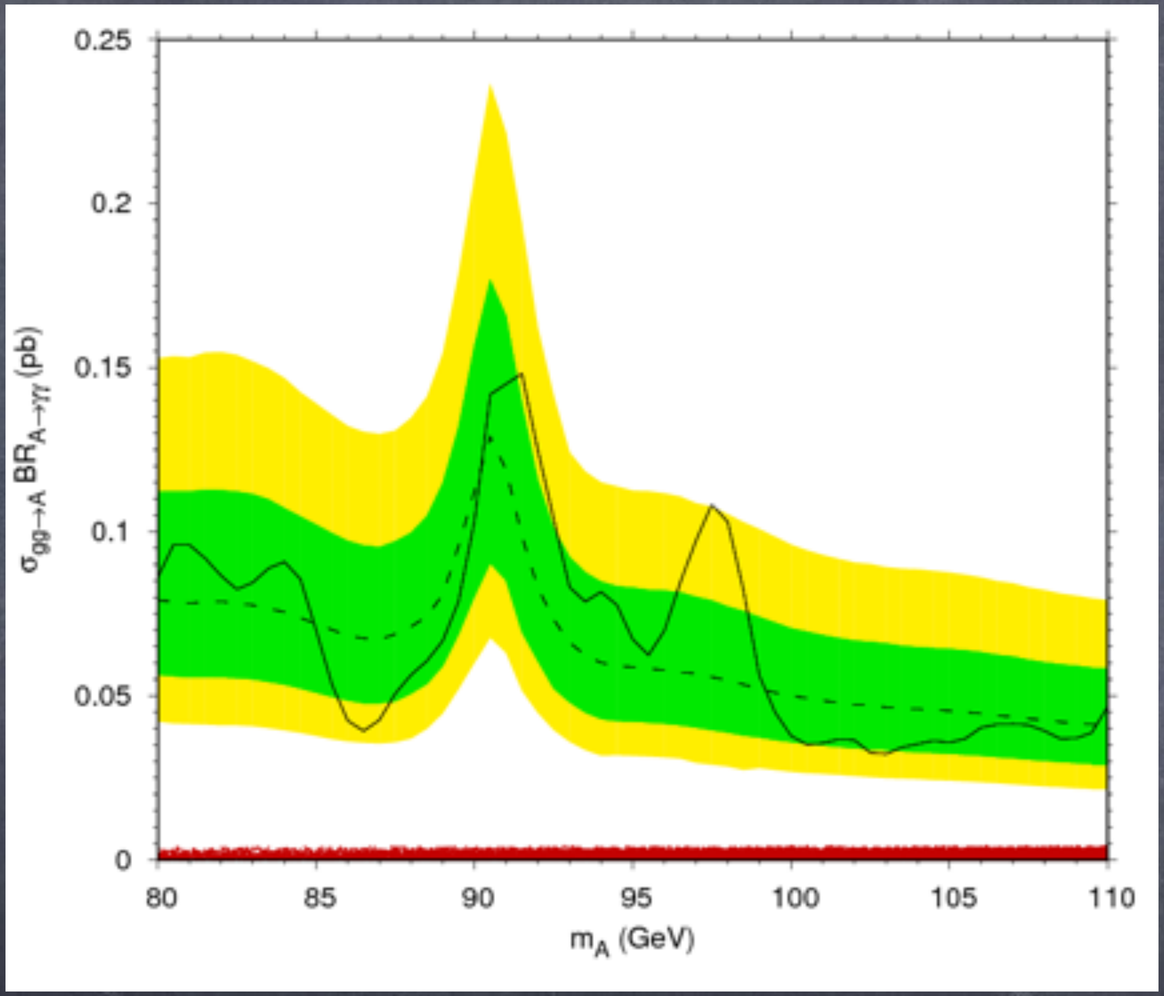


- Exclusion driven by large BR (h-> photons)

Conclusions

- 2HDMs still allow for a light CP-even Higgs
- We found that in Type-I, large diphoton signal can be obtained in VBF+Vh channel
- We also checked the pseudoscalar (no large signal)
- 2HDM Type-I is a good benchmark model for the search!
- Note: optimisation for VBF+Vh will help!

Light pseudo-scalar



m_h (GeV)	m_H (GeV)	m_A (GeV)	$m_{H^\pm}$ (GeV)	$\sin(\beta-\alpha)$	$\tan\beta$	m_{12} (GeV)
[80; 110]	125	[80; 110]	[80; 630]	[-0.4; 0.3]	[1.5; 50]	[-(300)^2; +(100)^2]