Higgs: Interpretation and Implications

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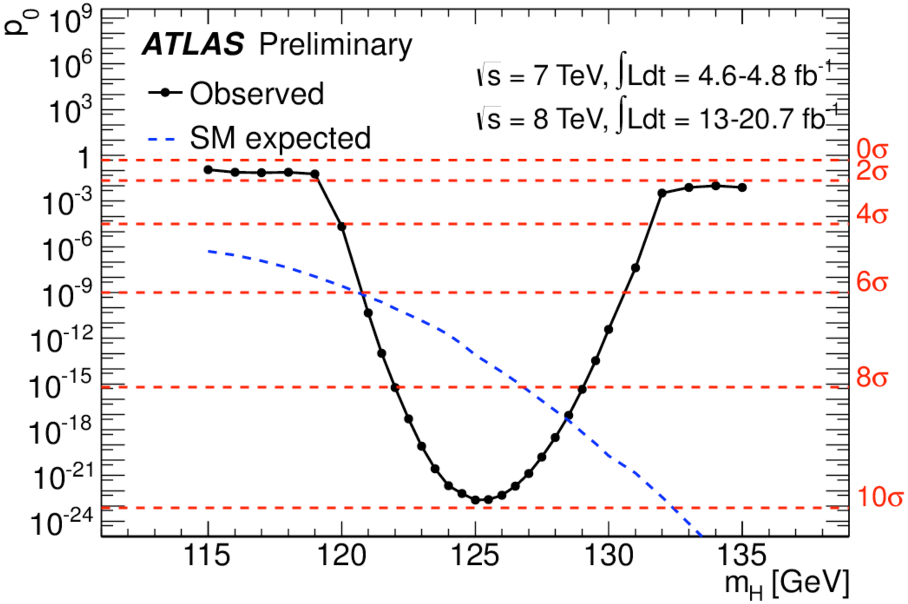
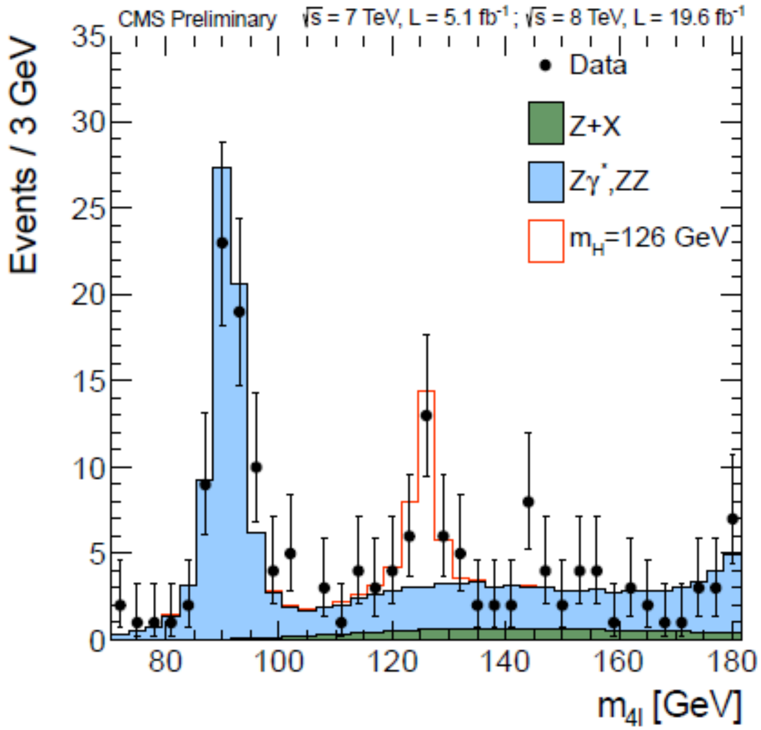
April 19, 2013

Discovery!

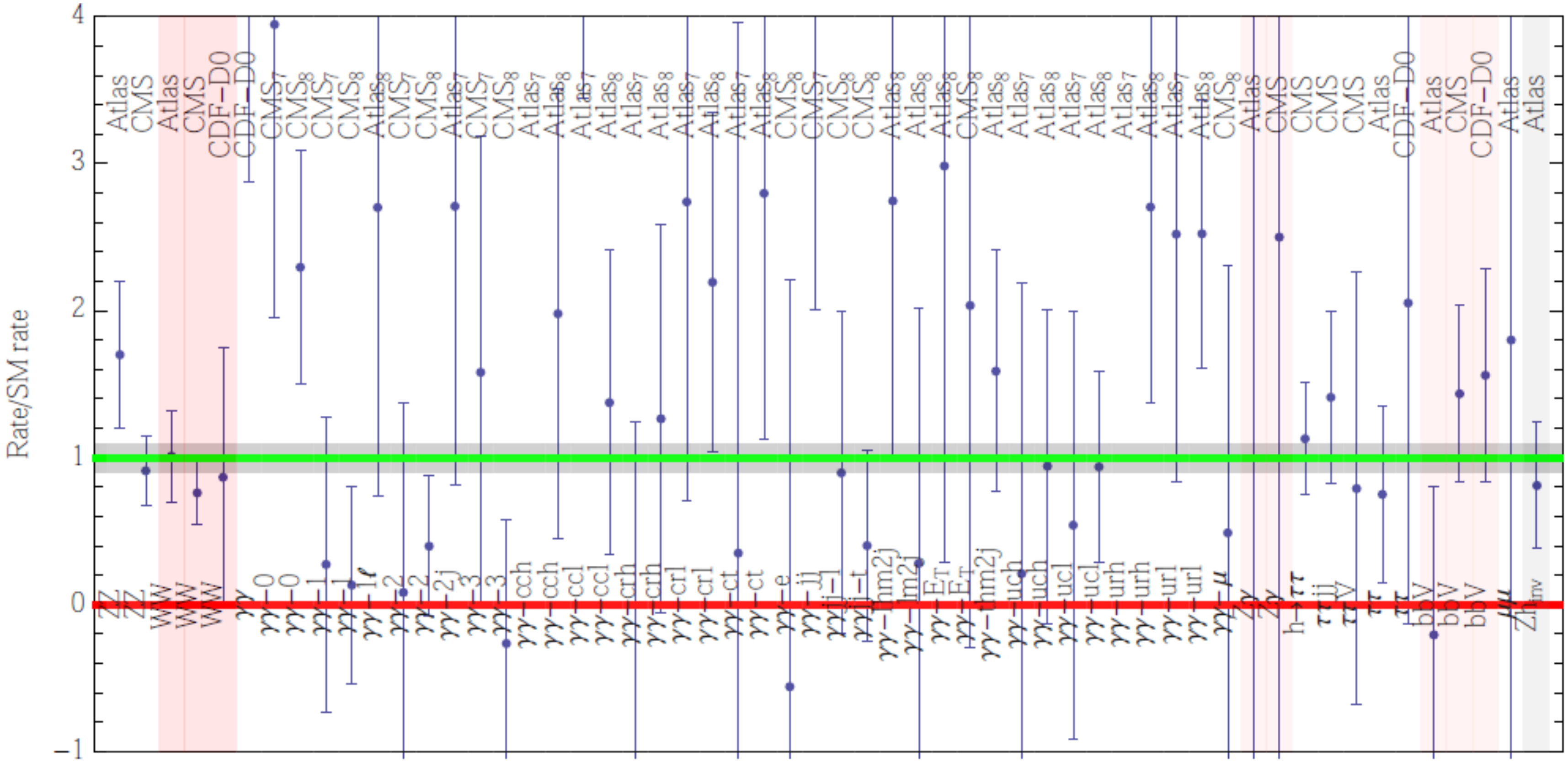


ATLAS coll. ATLAS-CONF-2013-034.



CMS coll. CMS-PAS-HIG-13-002

Data



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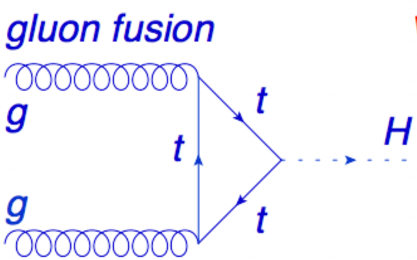
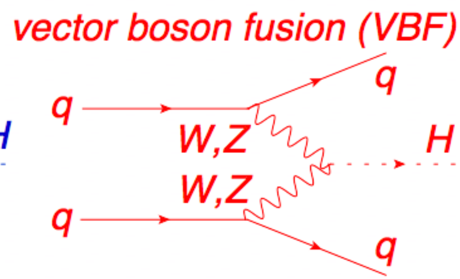
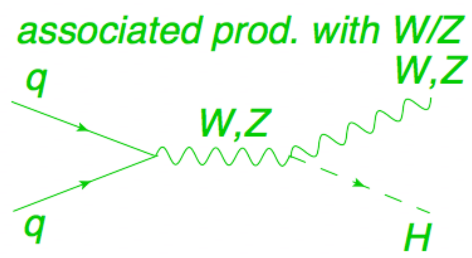
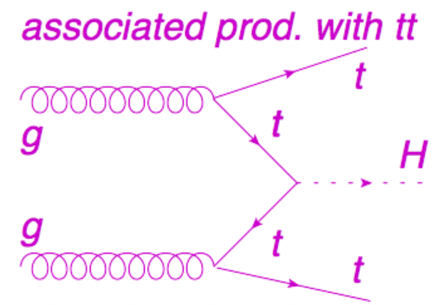
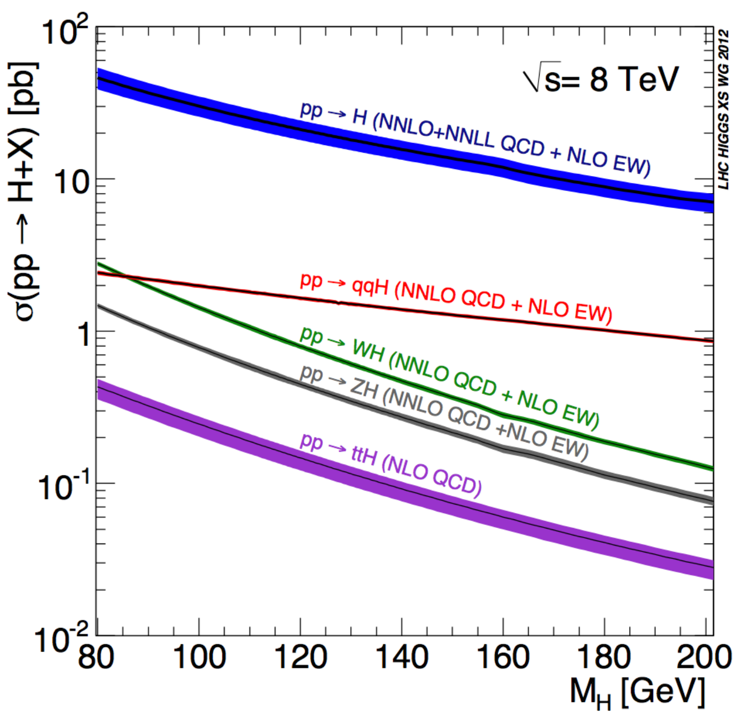
Higgs Production





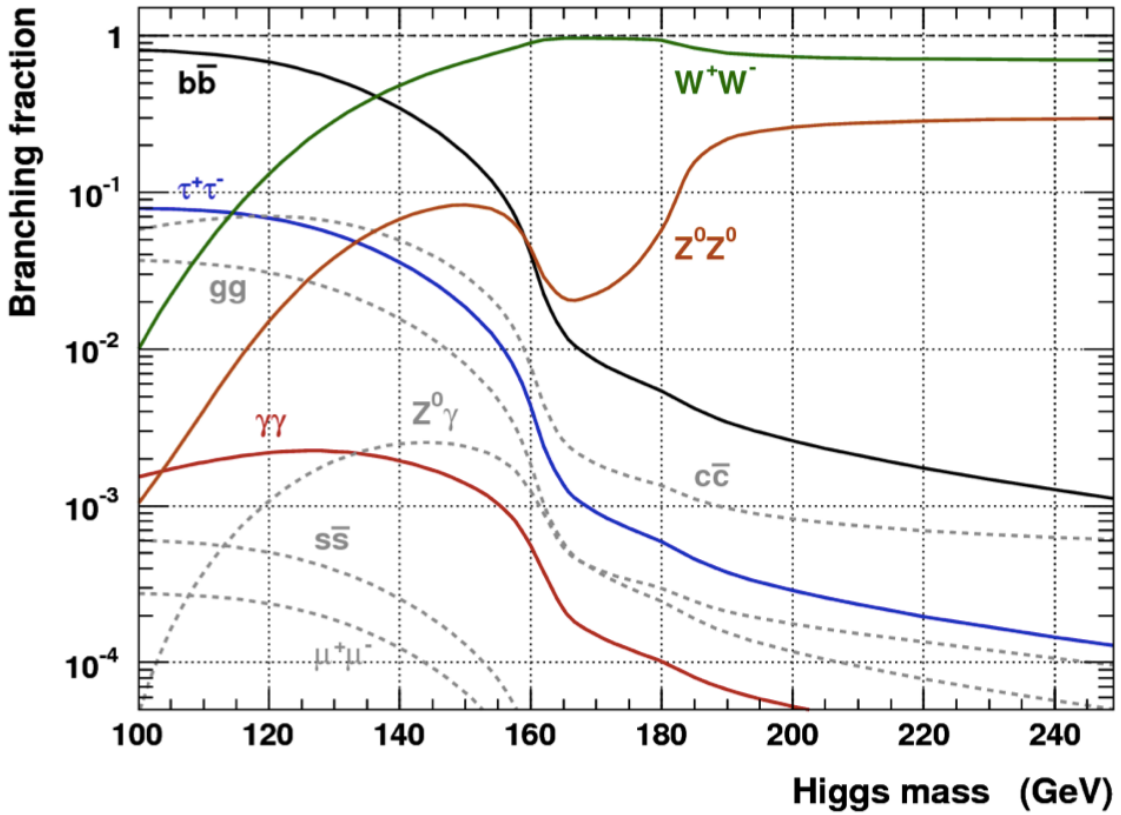




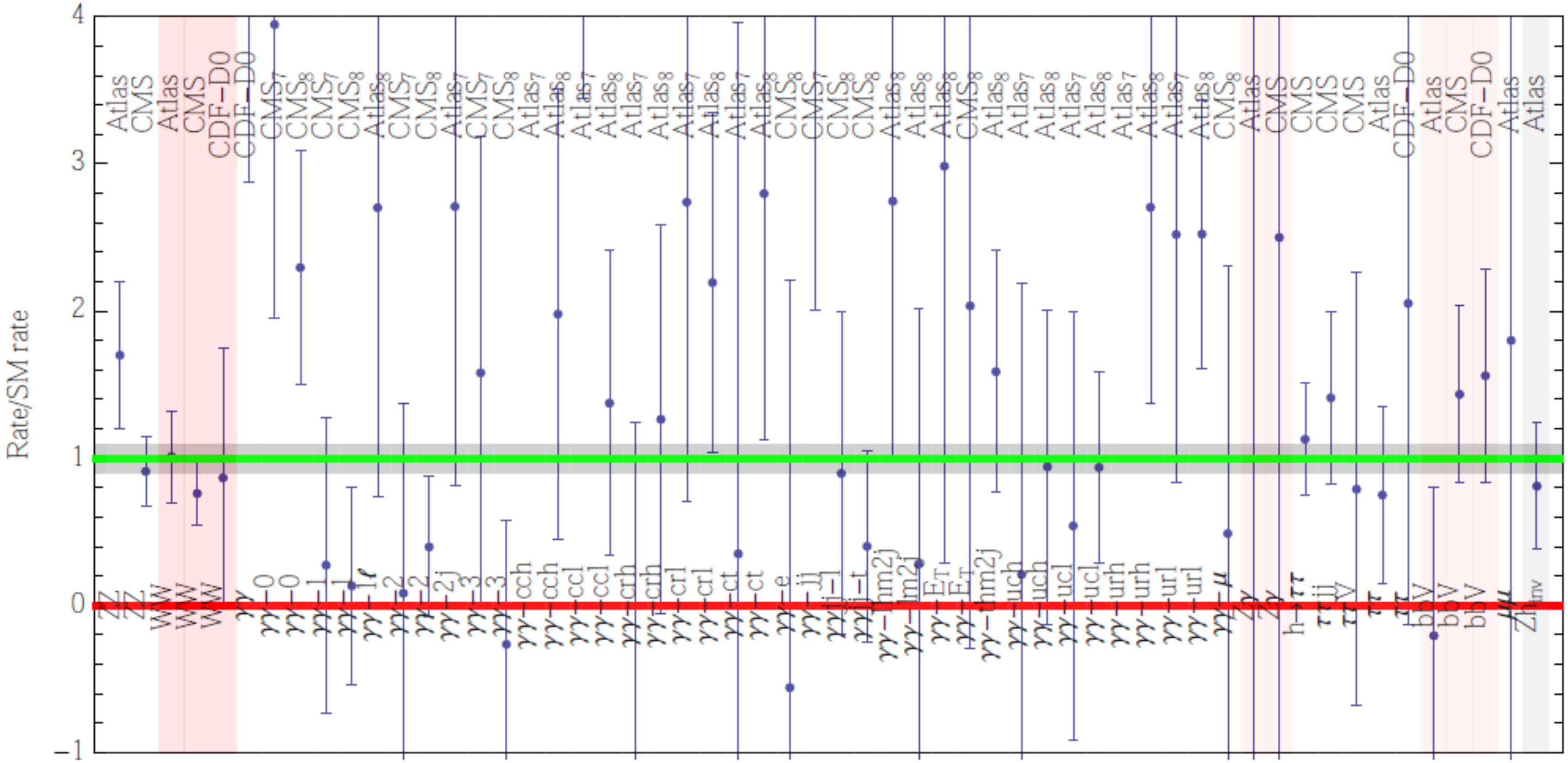


- Access to top, Z and W couplings.
- Loops sensitive to new particles

Higgs Decays



Data



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$$R_f = \frac{\sum_p \sigma\left(pp \to h + X^{(p)}\right) \times \zeta_f^{(p)} \times \mathrm{BR}(h \to f)}{\sum_p \sigma\left(pp \to h + X^{(p)}\right)_{\mathrm{SM}} \times \zeta_f^{(p)} \times \mathrm{BR}(h \to f)_{\mathrm{SM}}}$$

How to make a fit

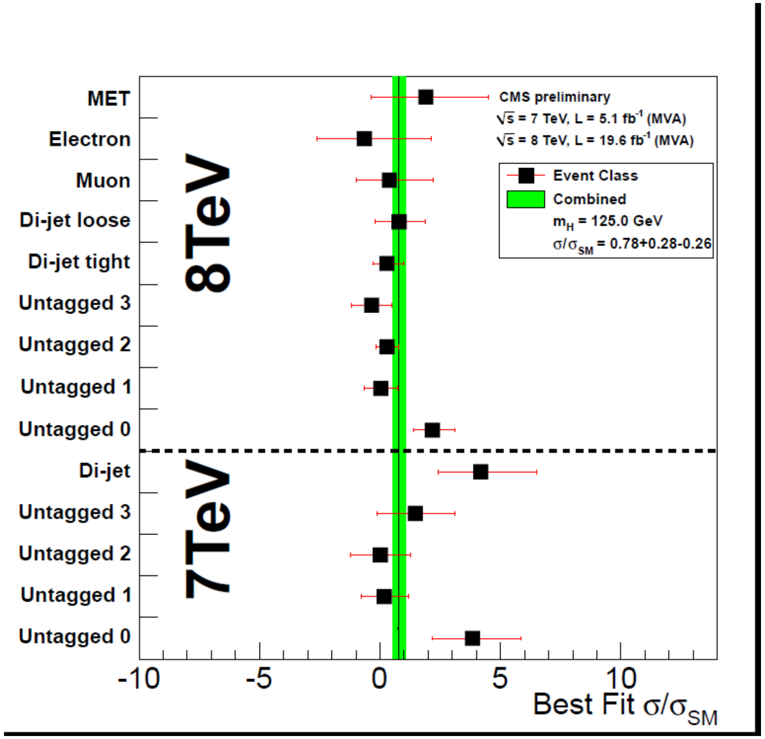
Is it really the SM higgs?
Simple recipe:

- Take your favorite set of parameters

- Define rates as function

- Construct $\chi^2(\{p_i\}) = \sum_j \left(\frac{R_j(\{p_i\}) - R_j^{exp}}{\sigma_j} \right)^2$

$$R_f = \frac{\sum_p \sigma\left(pp \to h + X^{(p)}\right) \times \zeta_f^{(p)} \times \mathrm{BR}(h \to f)}{\sum_p \sigma\left(pp \to h + X^{(p)}\right)_{\mathrm{SM}} \times \zeta_f^{(p)} \times \mathrm{BR}(h \to f)_{\mathrm{SM}}}$$



CMS coll. CMS-PAS-HIG-13-001

Issues: no correlation, data taking, uncertainties in the production efficiencies, "cherry picking"

Minimal Lagrangian

Assuming:

- A unique neutral scalar, color-singlet, CP-even, near 126 GeV

$$\mathcal{L}_{(0)} = \frac{h}{v}\left[c_V\left(2m_W^2 W_\mu^\dagger W^\mu + m_Z^2 Z_\mu Z^\mu\right) - c_t \sum_{f=u,c,t} m_f \bar{f} f - c_b \sum_{f=d,s,b} m_f \bar{f} f - c_\tau \sum_{f=e,\mu,\tau} m_f \bar{f} f\right]$$

$$\mathcal{L}_{(2)} = -\frac{h}{4v}\left[2c_{WW} W_{\mu\nu}^\dagger W^{\mu\nu} + c_{ZZ} Z_{\mu\nu} Z^{\mu\nu} + 2c_{Z\gamma} A_{\mu\nu} Z^{\mu\nu} + c_{\gamma\gamma} A_{\mu\nu} A^{\mu\nu} - c_{gg} G_{\mu\nu}^a G^{a,\mu\nu}\right]$$

Standard Model

$$c_V = c_t = c_b = c_\tau = 1$$

$$c_{\gamma\gamma} = c_{Z\gamma} = c_{gg} = 0$$

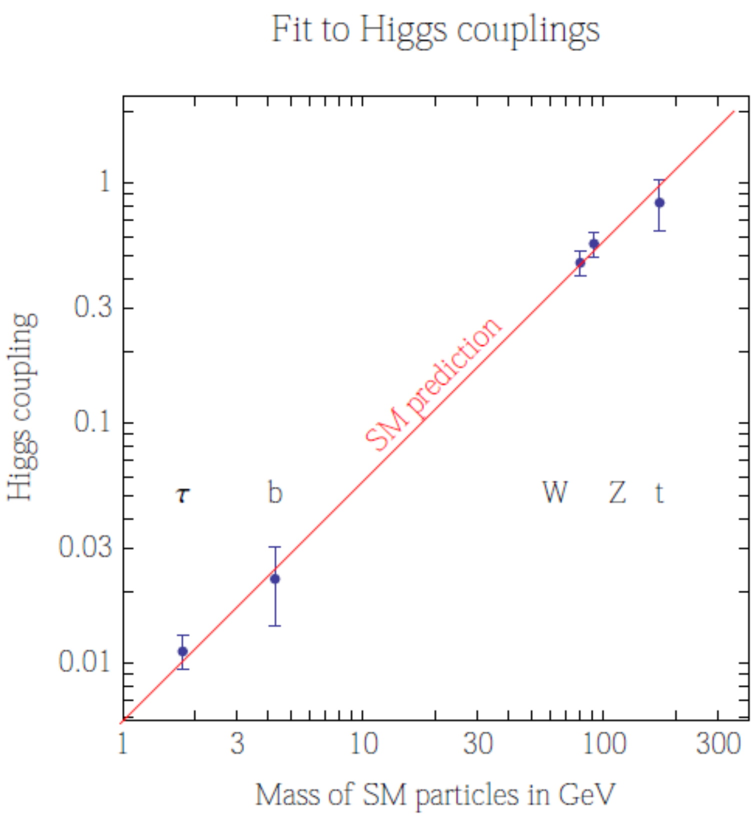
Taming the fit

O(10) parameters: too many!

To have more handle:

- Fix parameters and relations
- Marginalize

$$\chi^2(\{p_i\}) = \min_{\{p_j\}} \chi^2(\{p_i\}, \{p_j\})$$



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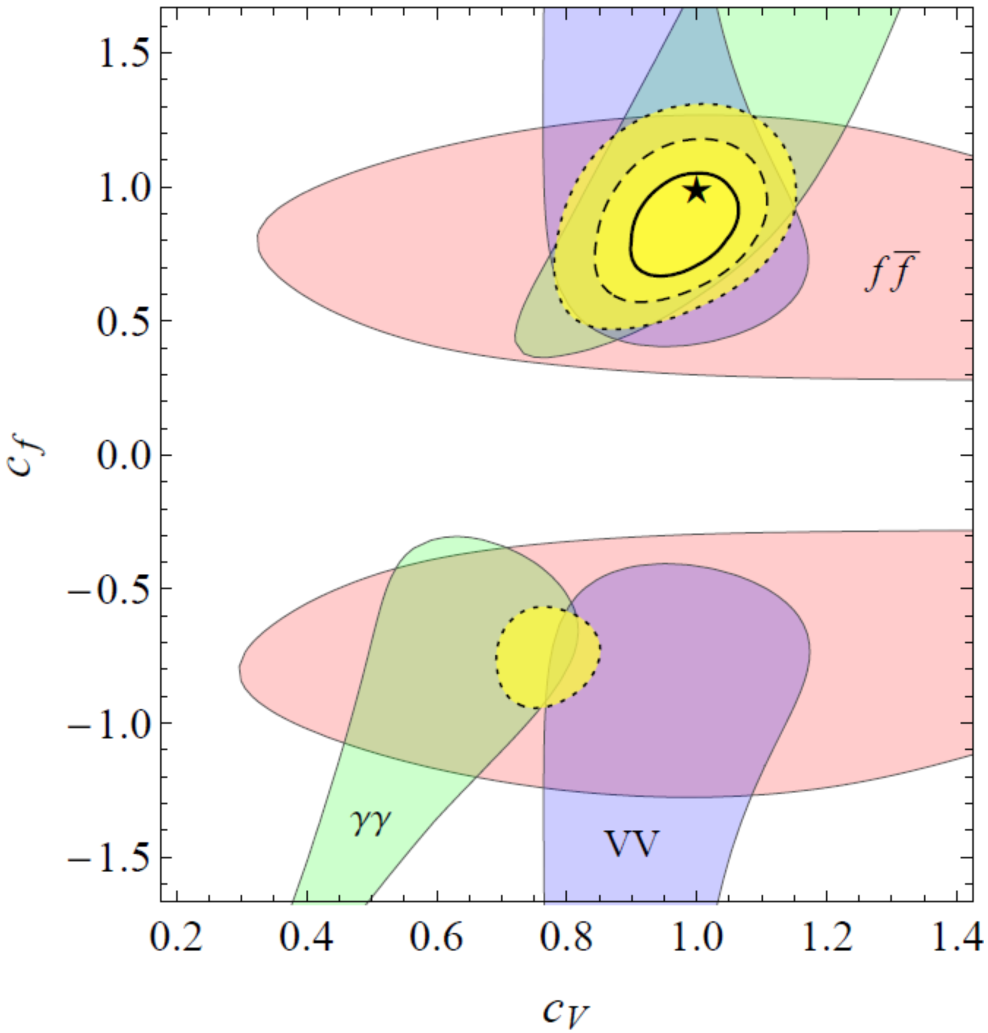
Composite Higgs Inspired Fit



Simplest thing to do:

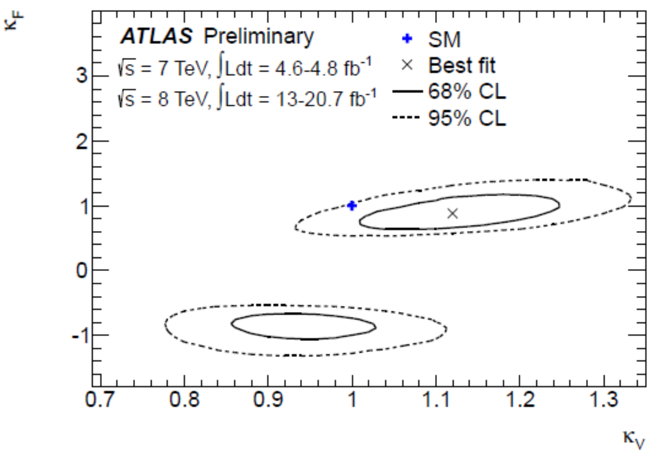
- Bosons VS Fermions

$$c_V\,, \quad c_f = c_b = c_t = c_\tau$$

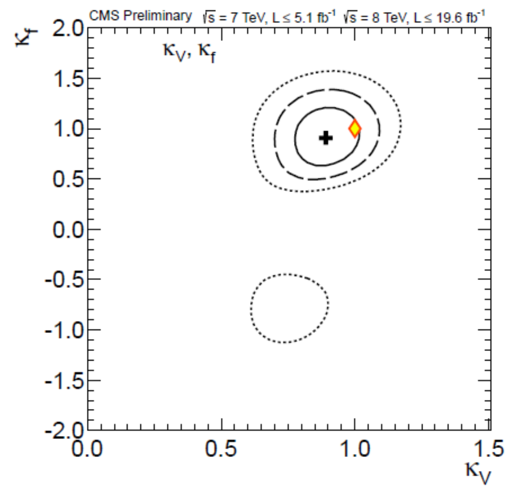
- No new particle in the loop

$$c_{\gamma\gamma} = c_{\gamma Z} = c_{gg} = 0$$

Confused?



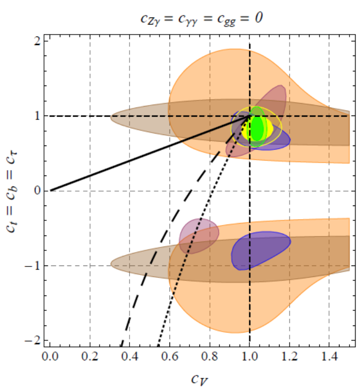
ATLAS coll. ATLAS-CONF-2013-034.



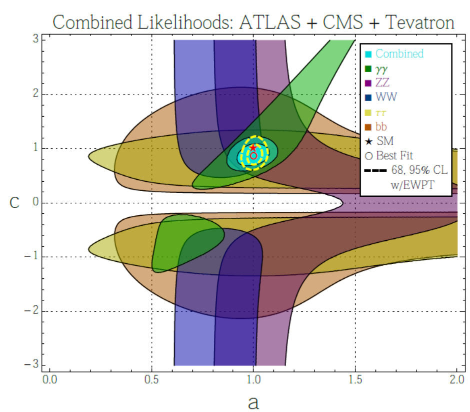
CMS coll. HIG-13-005-pas

- Collaborations follow "LHC HXSWG interim recommendation" (1209.0040)

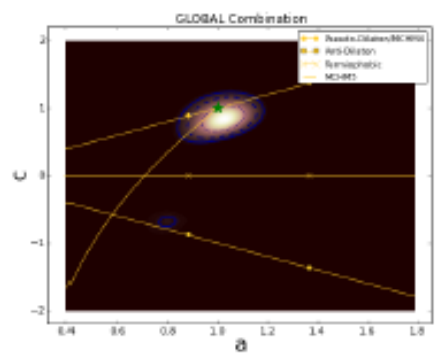
- Theorist don't



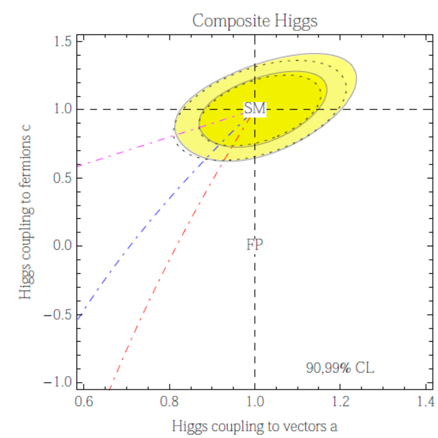
Falkowski,Riva,Urbano. 1303.1812



Azatov, Galloway 1212.1380v3



Ellis, You 1303.3879



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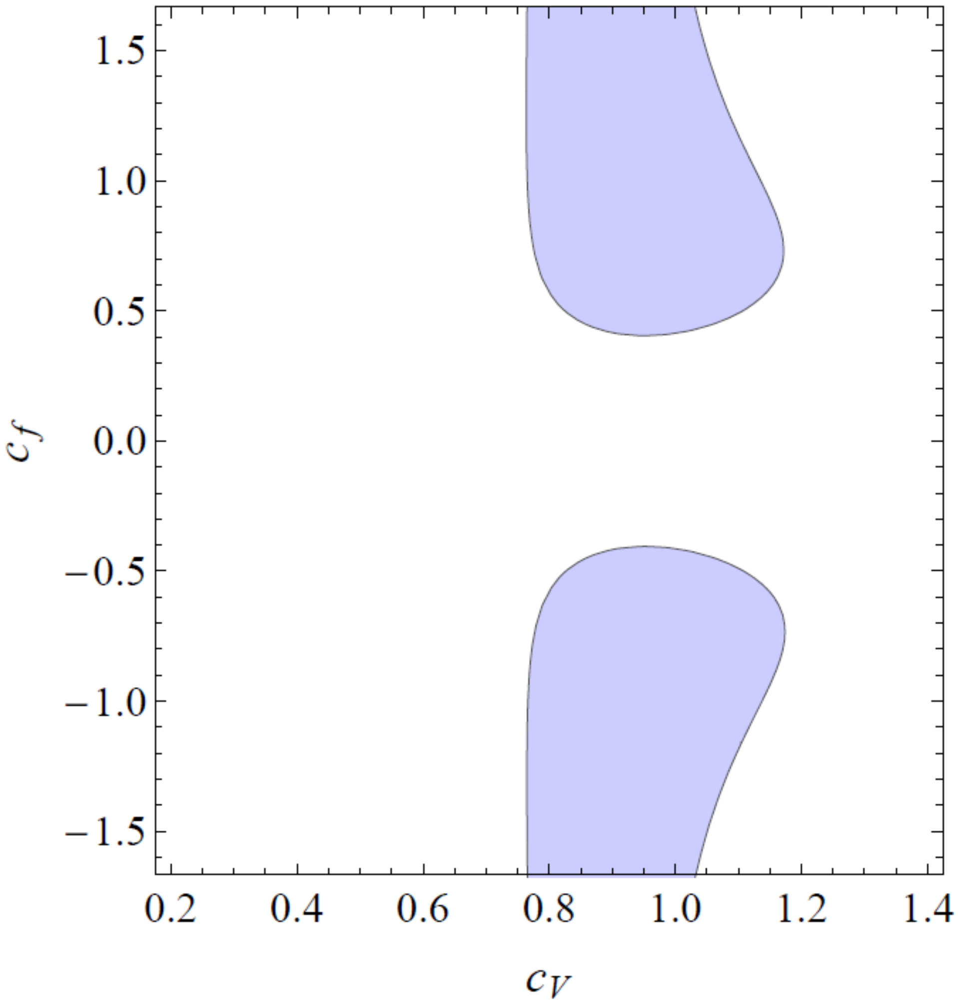
Dissecting the fit: vectors

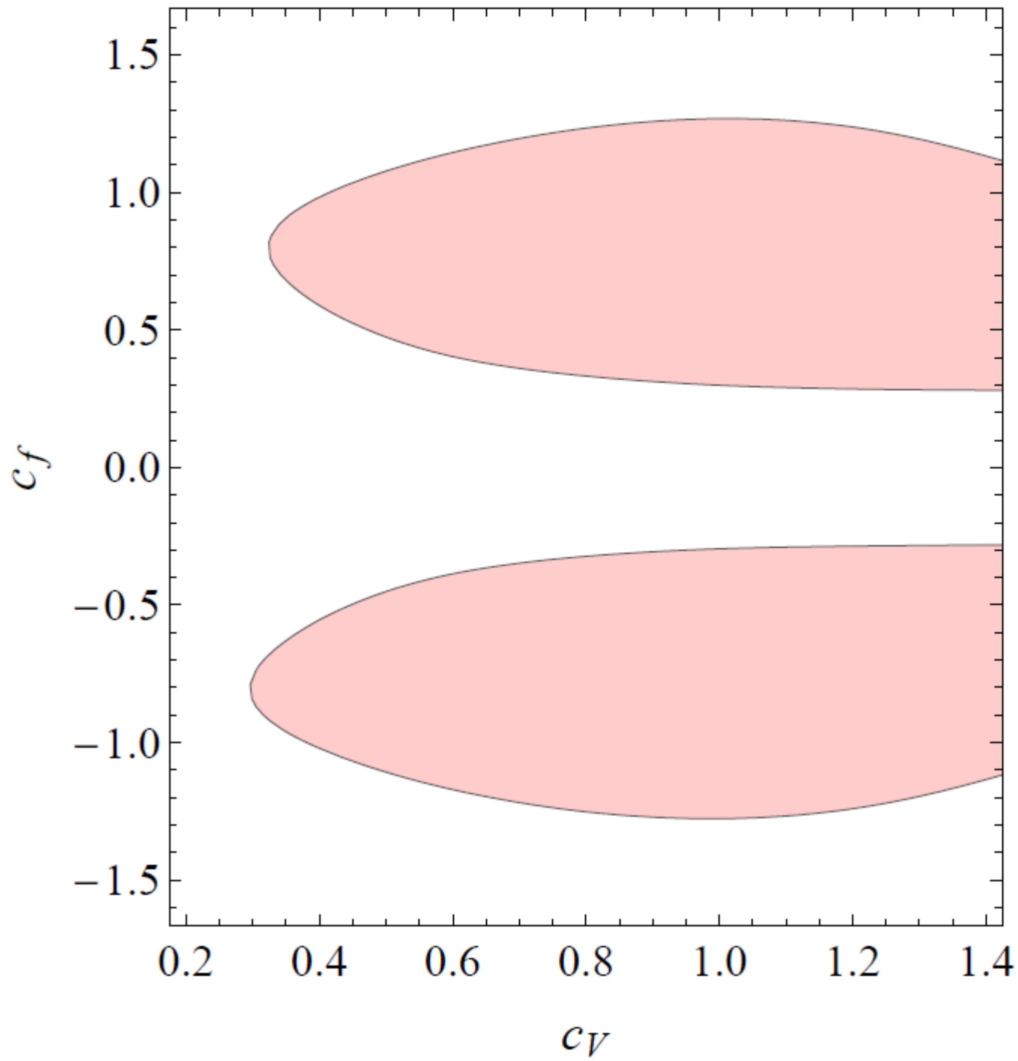


Each channel sensitive to a combination of production and decay

$$\frac{\Gamma_{VV}}{\Gamma_{VV}^{SM}} \propto c_V^2$$

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} \propto c_f^2$$

Dissecting the fit: fermions

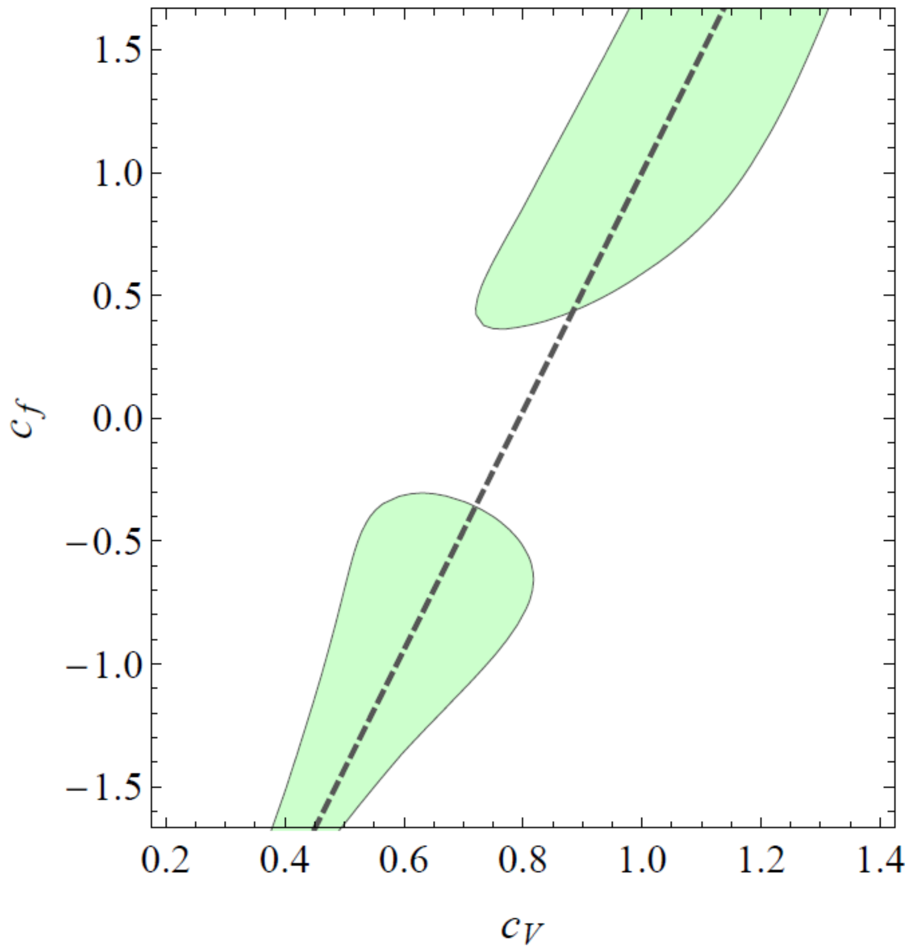


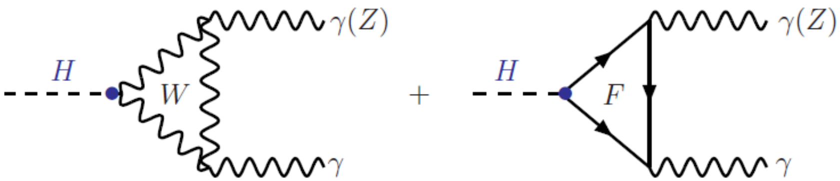
Each channel sensitive to a combination of production and decay

$$\frac{\Gamma_{bb}}{\Gamma_{bb}^{SM}} \propto c_f^2$$

$$\frac{\sigma_{VH}}{\sigma_{VH}^{SM}} \propto c_V^2$$

Dissecting the fit: photons

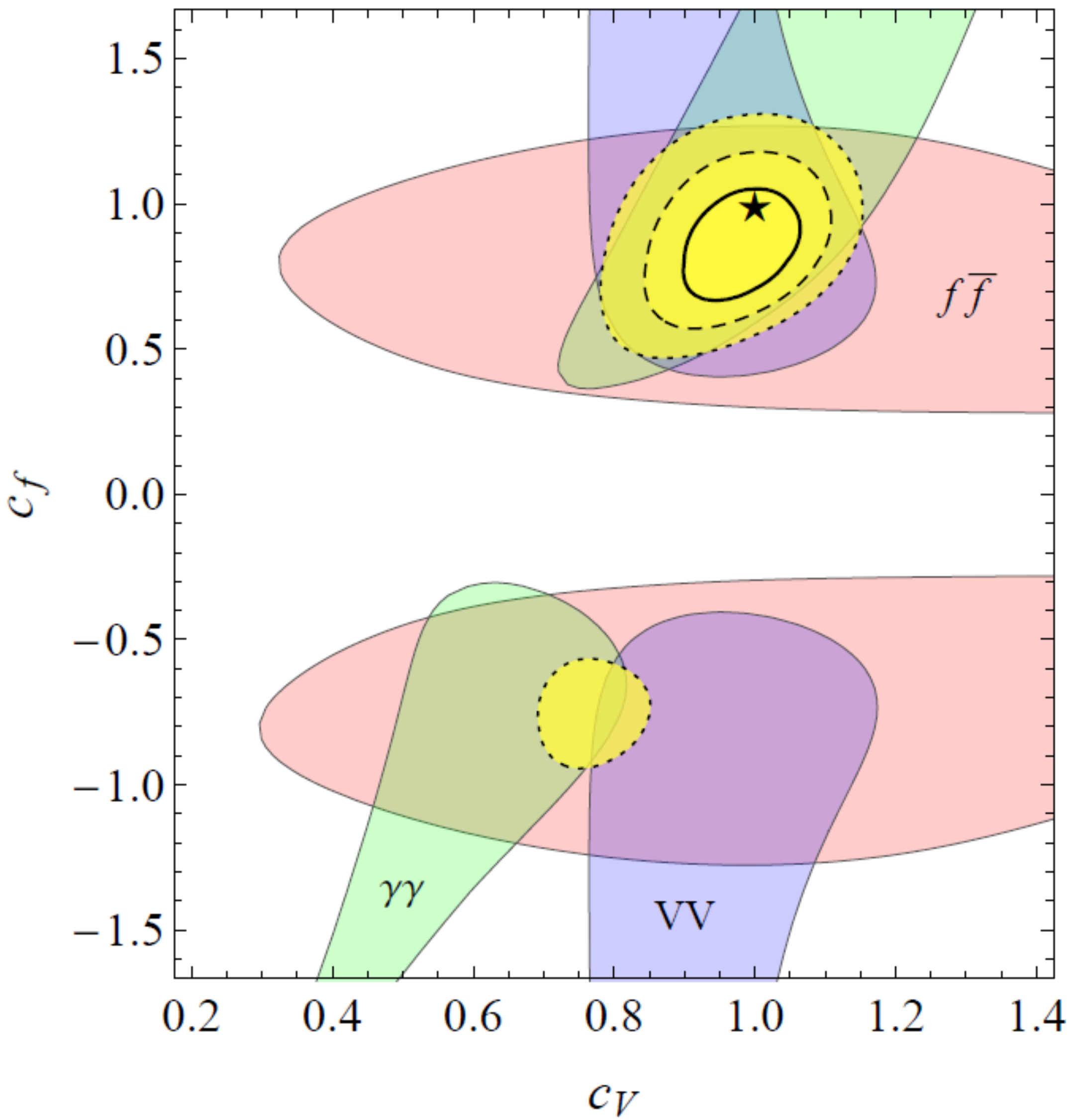




$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} \propto c_\gamma^2$$

$$c_{\gamma\gamma} \propto |A_W c_V + A_t c_f| \simeq |0.97 c_V - 0.21 c_f|$$

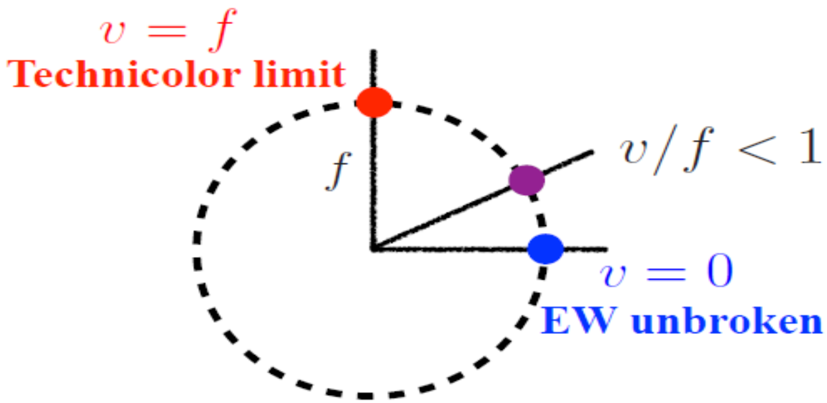
Composite Higgs Inspired Fit



- Best Fit (0.98, 0.86)
- SM well within 68% CL

Composite Higgs

Higgs remnant of strong dynamic with global symmetry pattern G/H



$$\Lambda \sim 4\pi f$$

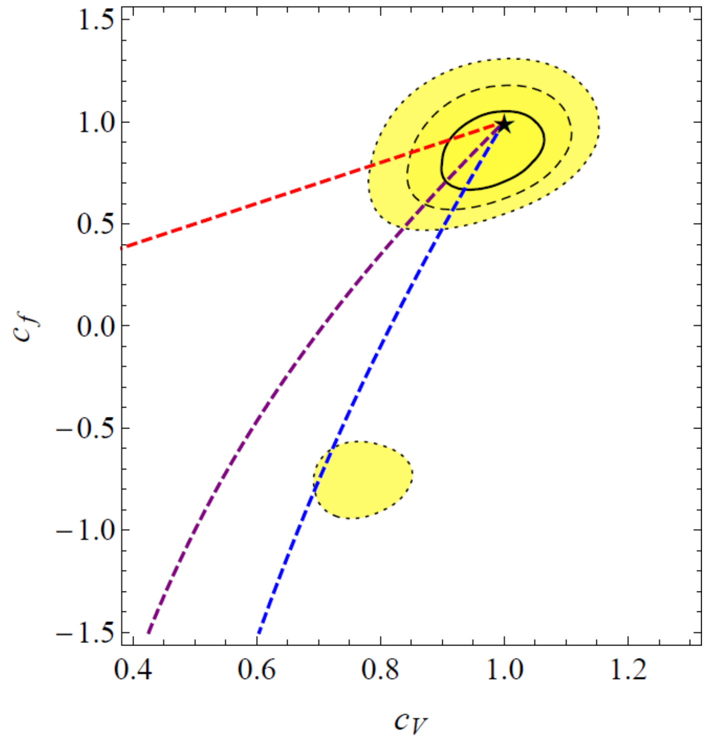
$$m_\rho = g_\rho f$$

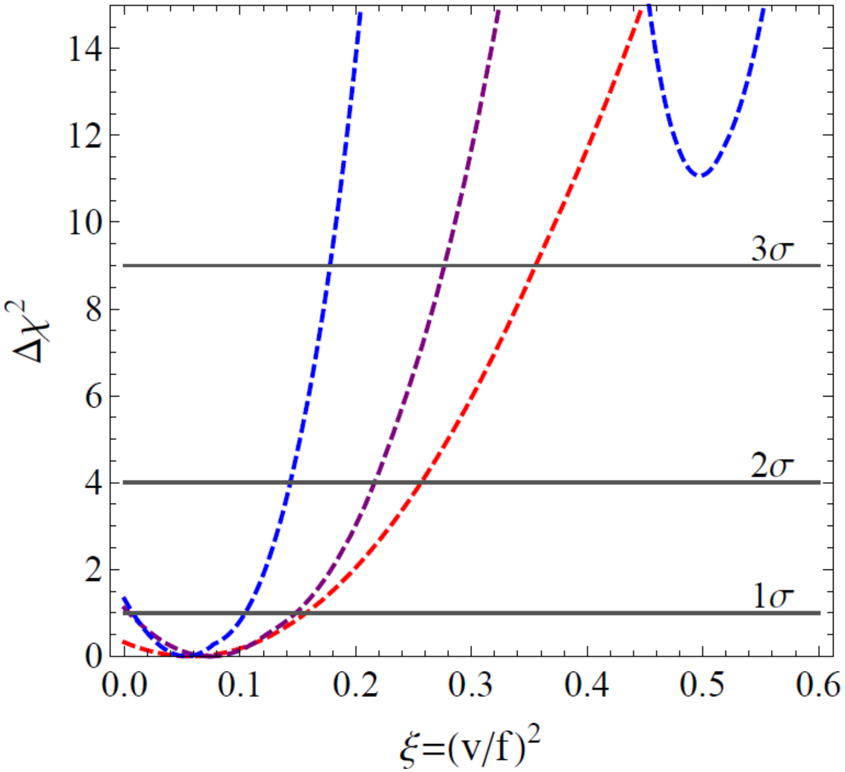
SO(5)/SO(4)

$$c_V = \sqrt{1 - v^2/f^2}$$ ← ~ Model independent

$$c_f = \frac{1 - (1+n)v^2/f^2}{\sqrt{1 - v^2/f^2}}$$ ← Model dependent

Composite Higgs Implications





SO(5)/SO(4)

$$c_V = \sqrt{1 - v^2/f^2}$$

$$c_f = \frac{1-(1+n)v^2/f^2}{\sqrt{1-v^2/f^2}}$$

- n fixes the trajectory (n=0,1,2)
- Fine tuning ~v/f

Two Higgs Doblet Models

- Extra doublet describe many models (SUSY included)
- Details of the potential are not important
- Couplings described by 2 parameters only

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

$$\langle H_1^0 \rangle = \frac{v_1}{\sqrt{2}} \quad , \quad \langle H_2^0 \rangle = \frac{v_2}{\sqrt{2}}$$

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

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$$

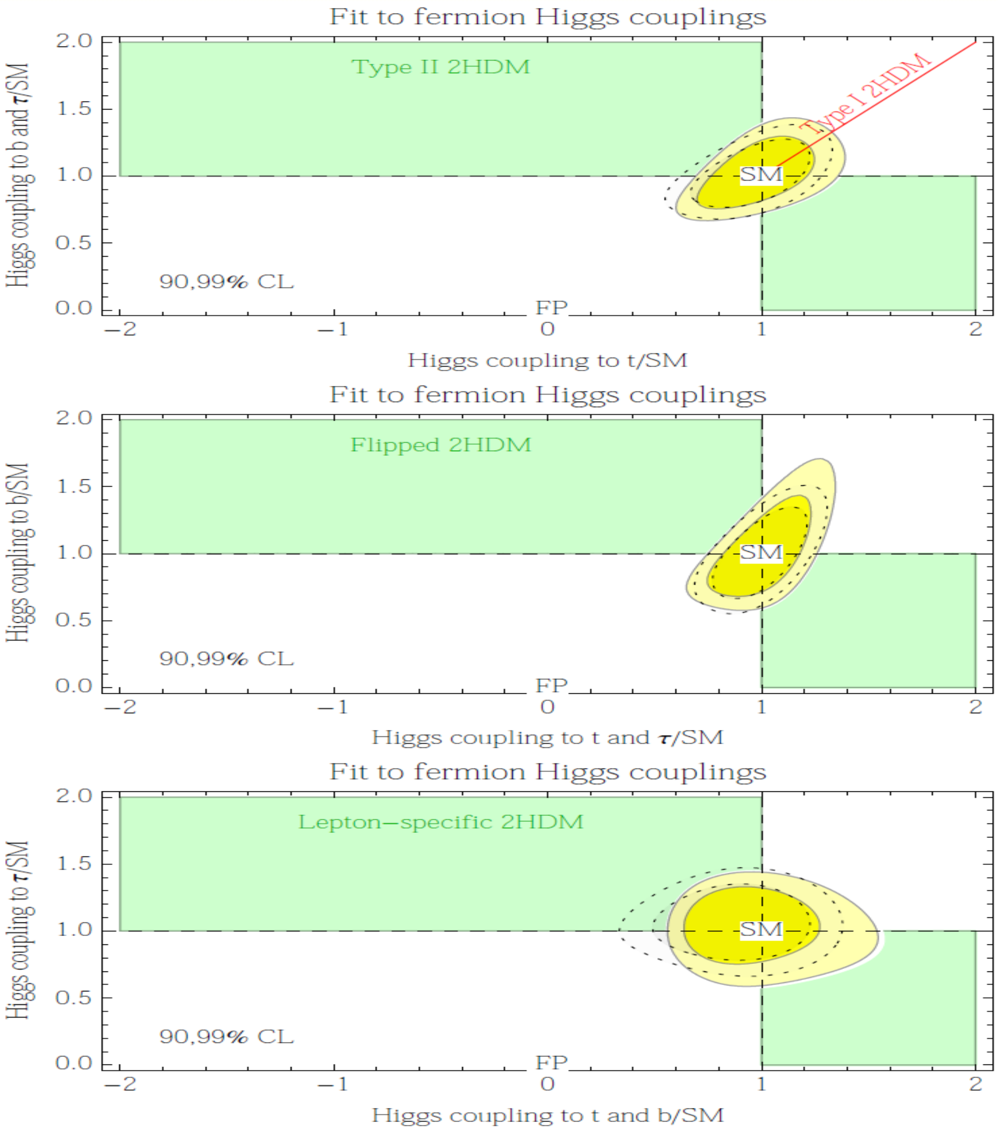
2HDM

Given the angles remains to assign doublet-fermion couplings

	Type I	Type II	Type X (lepton-specific)	Type Y (flipped)
r_t	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
r_b	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
r_τ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

$$r_W = r_Z = \sin(\beta - \alpha)$$

2HDM



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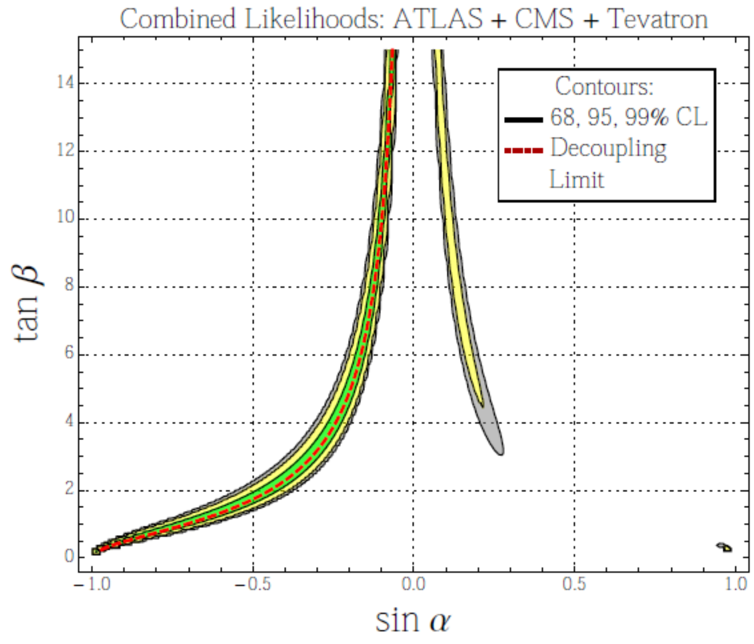
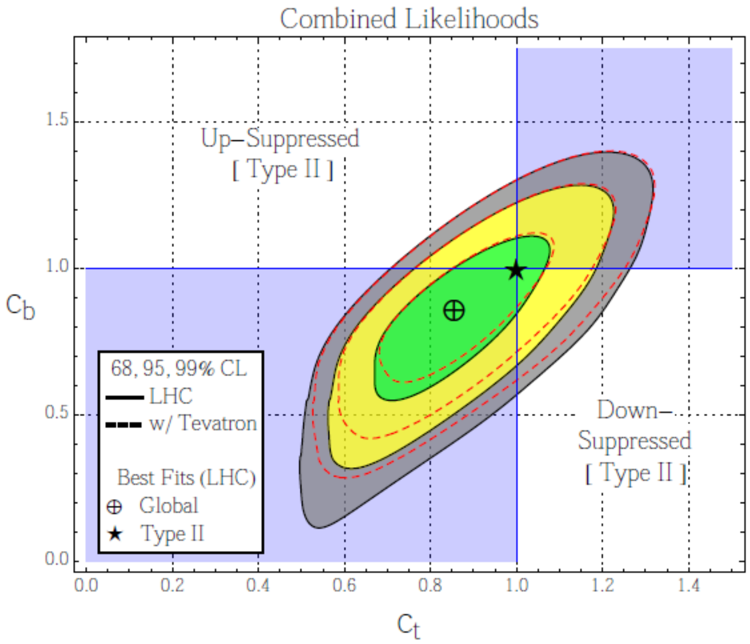
2HDM Type-II - MSSM

Type-II describes MSSM like Higgs Doublets





Azatov, Galloway 1212.1380v3

MSSM Heavier Scalar

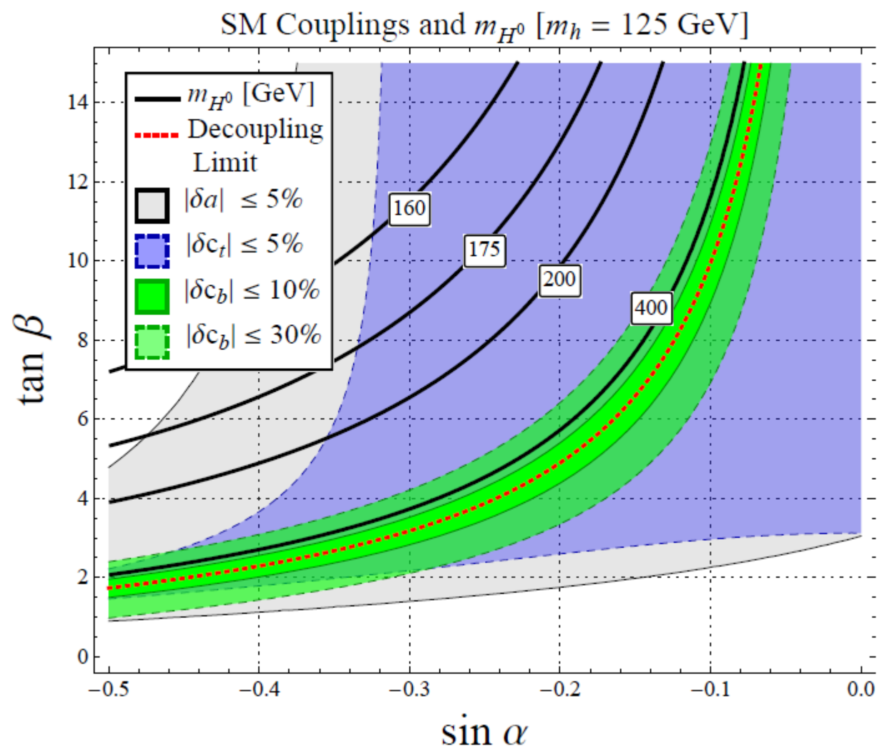
SUSY constraints the potential

⇩

Fixed Higgs mass: prediction for the heavier scalar mass

⇩

Fit gives a lower bound on mH



Azatov, Galloway 1212.1380v3

Decoupling limit is favored

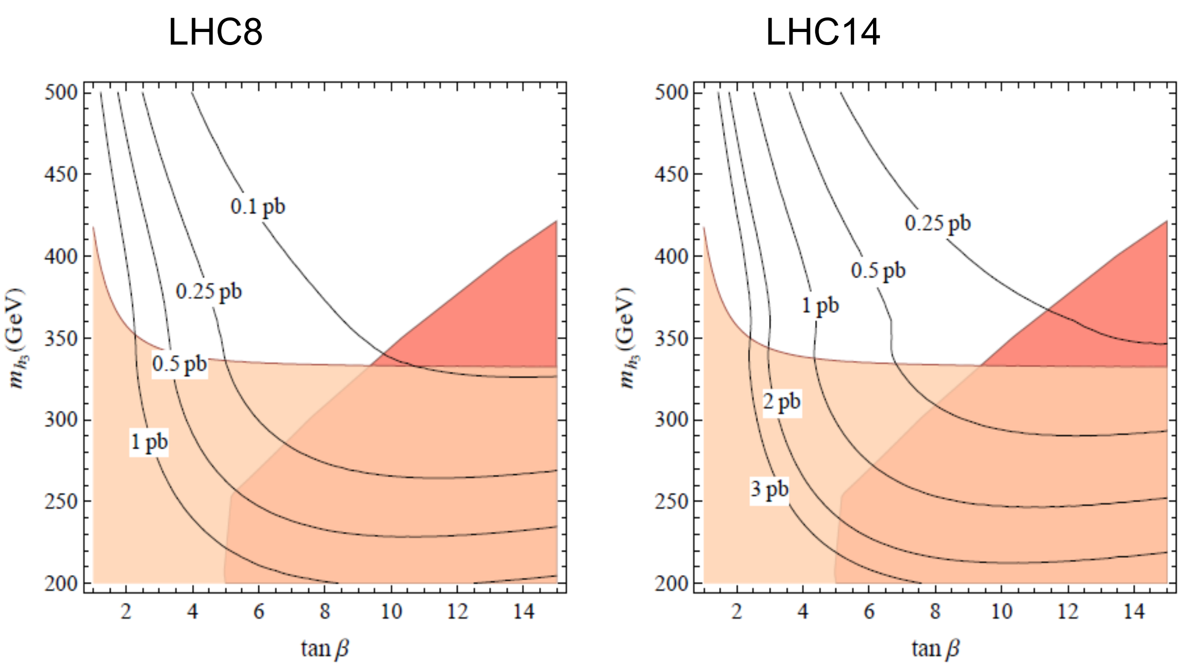
$$M_H \simeq M_{H^\pm} \simeq M_A$$

MSSM Heavier Scalar

Fit gives a lower bound on mH

Prediction on production cross section

Interplay between direct searches and Higgs data fits



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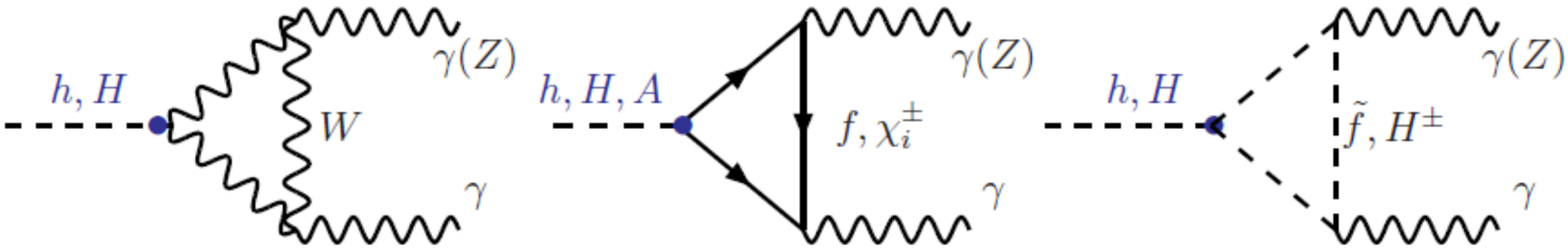
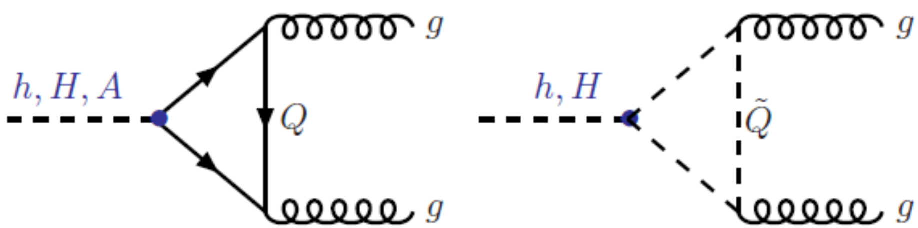
Darker red: excluded by pseudoscalar direct searches

Loop corrections

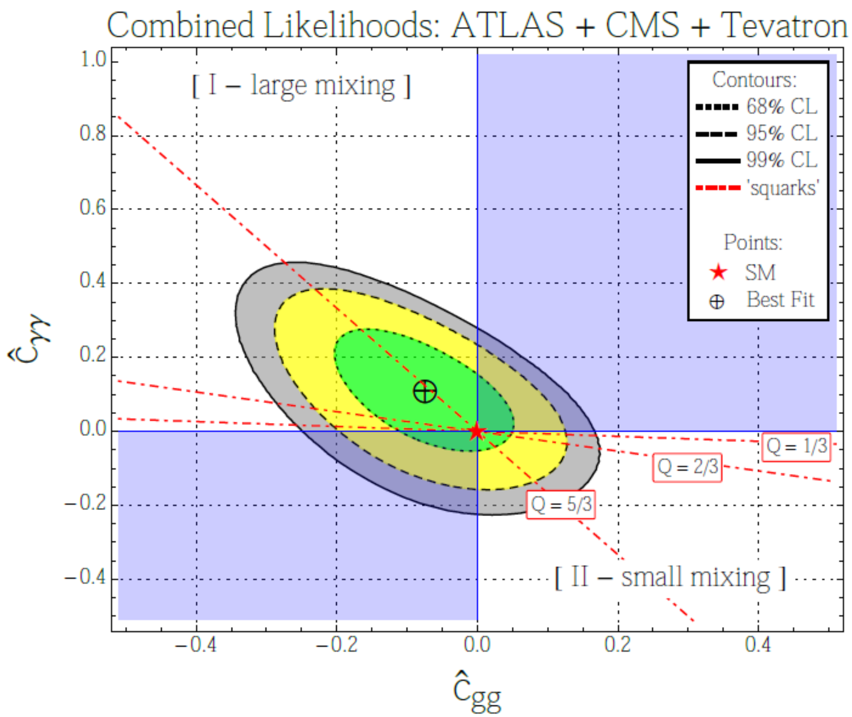


Loop corrections
encode new particles
information
e.g. superpartners



$$\mathcal{L}_{(2)} = -\frac{h}{4v}\left[2c_{WW}W^{\dagger}_{\mu\nu}W^{\mu\nu} + c_{ZZ}Z_{\mu\nu}Z^{\mu\nu} + 2c_{Z\gamma}A_{\mu\nu}Z^{\mu\nu} + c_{\gamma\gamma}A_{\mu\nu}A^{\mu\nu} - c_{gg}G^{a}_{\mu\nu}G^{a,\mu\nu}\right]$$

Loop coefficients fit



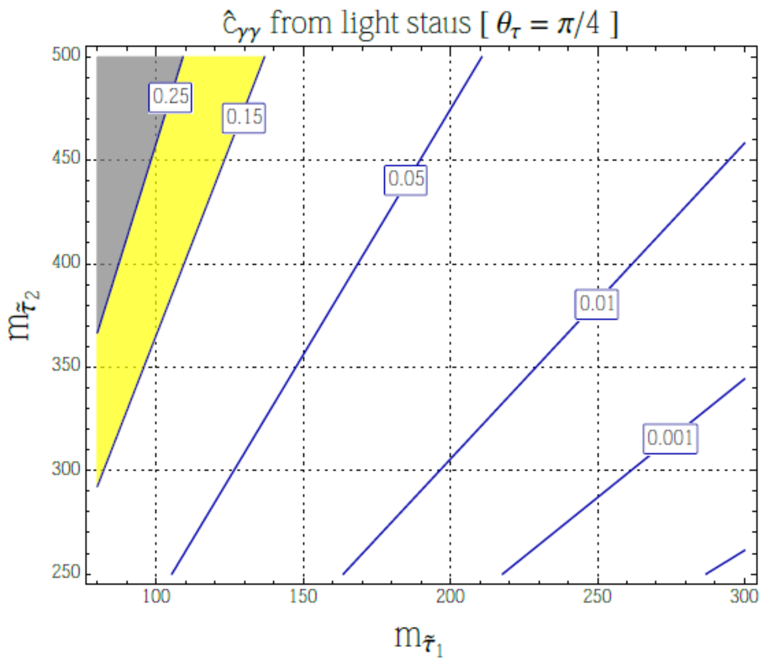
Azatov, Galloway 1212.1380v3

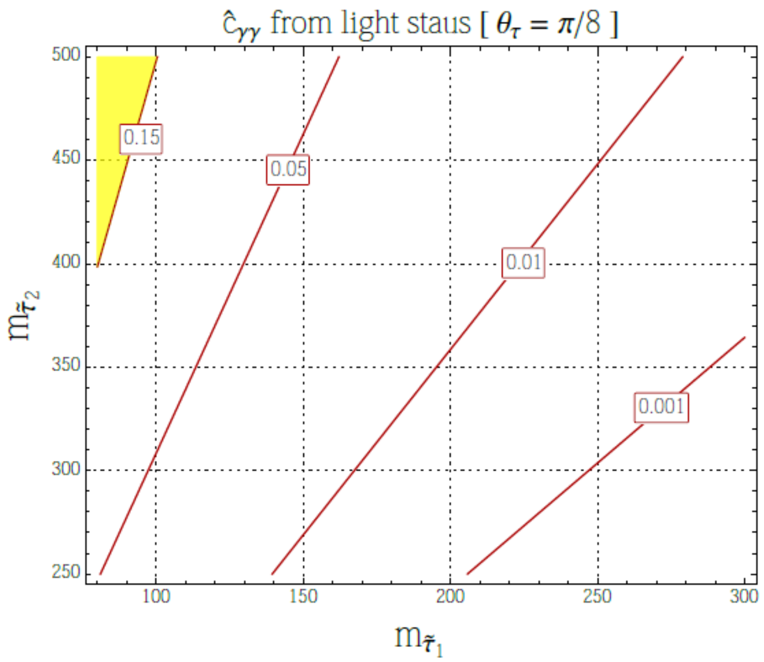
- Slope is set by representation
- Position on the line depends on the model (mass of the particle, etc.)

$$c_{\gamma\gamma} = -\frac{d(r)Q^2}{C_2(r)}\frac{\alpha}{\alpha_s}c_{gg}$$

Loop in susy - e.g. Stau

Light Stau enter only in correction to diphoton decay
Popular given last year excess





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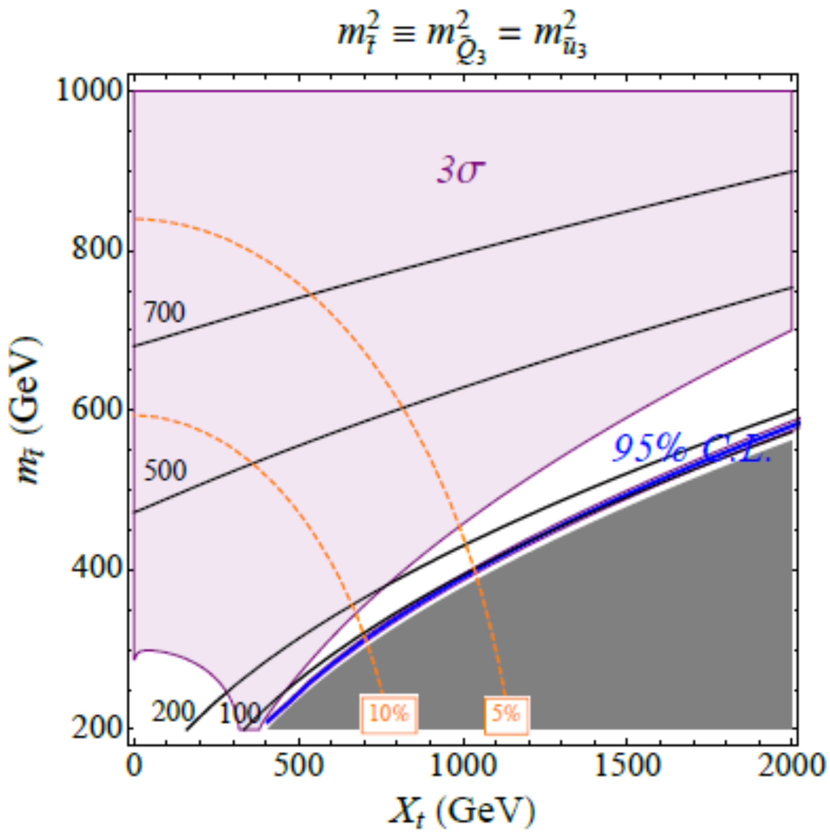
Loop in susy - e.g. Stops

tanβ>>1 limit used to study stops

$$\hat{c}_{gg} \approx \frac{m_t^2}{4}\left[\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right]$$



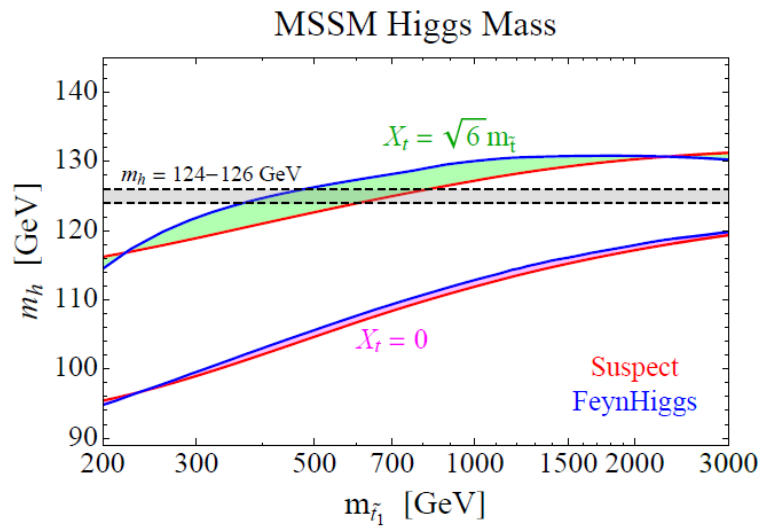
D'Agnolo, Kuflik, Zanetti 1212.1165

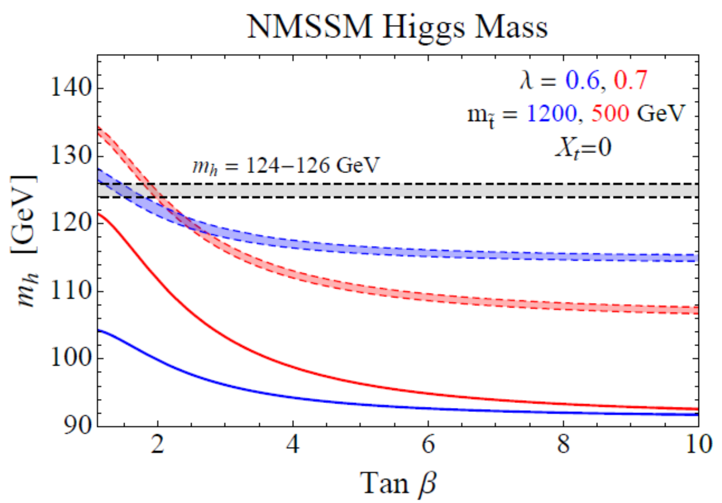
What the mass is telling us

Different ways to get 125 GeV:

- heavy stops
- large stop mixing
- extended scalar sector (NMSSM)

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$





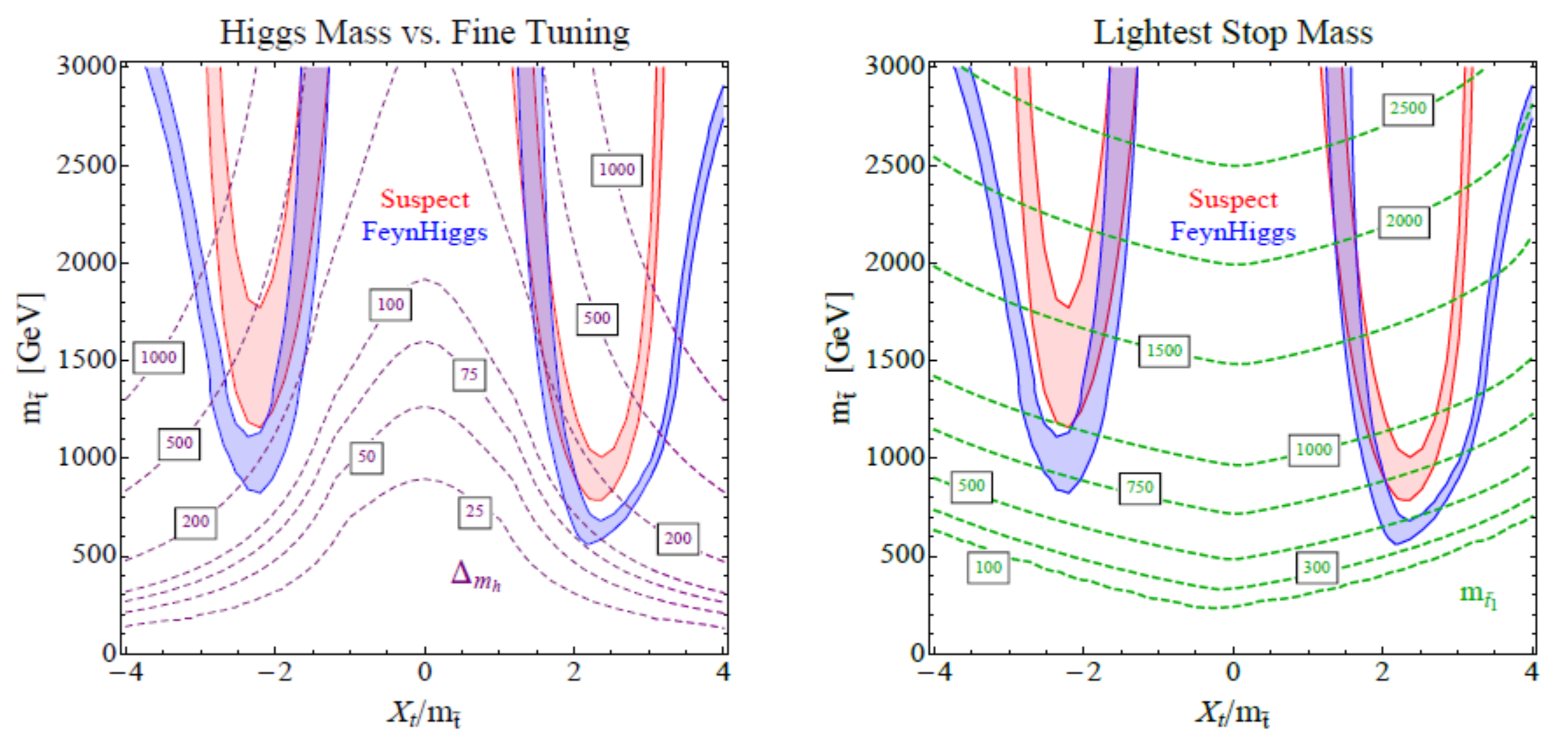
Hall, Pinner, Ruderman 1112.2703

Stops and Naturalness

If too large ⇨ tuned parameters to get correct EWSB scale

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$



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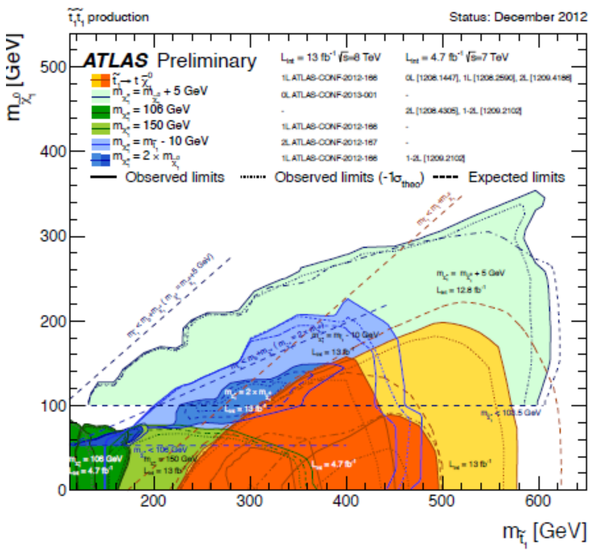
1112.2703

Stops and Naturalness

Summary Plots

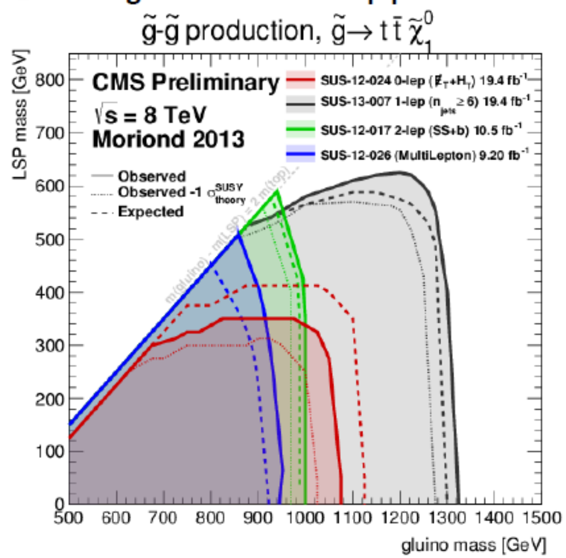
100% BR

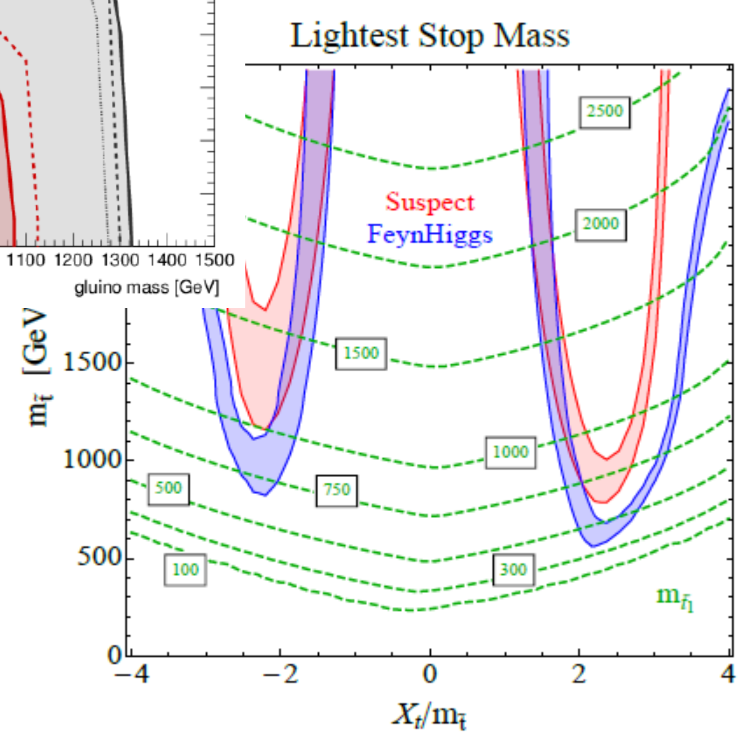
ATLAS direct stop production



Jad Marrouche @ Moriond 2013

CMS gluino-induced stop production





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There are more things

Not enough time to talk about:

- Non minimal scalar sector (SUSY or Composite Higgs)
- Non minimal composite partners
- Invisible Width
- Dilaton
- Social Higgs (more than one scalar @125GeV)
- EWPT
- Vacuum stability
- More...

Conclusions

- Light Higgs driving EWSB. Consistent with SM prediction.
- Current Higgs data can be used to extract information about EWSB and beyond the SM physics.
Precision era is approaching fast.
- Interplay between direct searches and fits
- Discovery+Naturalness VS Fine Tuning

Backup

Atlas Channels

Channel	ggF	VBF	VH	ttH	Mass	Spin	Dataset
$\gamma\gamma$	✓	✓	✓		✓	✓	25 fb^{-1}
$Z \rightarrow 4\ell$	✓	✓	✓		✓	✓	25 fb^{-1}
$WW \rightarrow \ell\ell + 2\nu$	✓	✓				✓	25 fb^{-1}
$\tau\tau$	✓	✓	✓				18 fb^{-1}
bb			✓	✓			18 fb^{-1}
$\mu\mu$	✓						21 fb^{-1}
$Z\gamma$	✓						25 fb^{-1}
2HDM (WW)	✓	✓					13 fb^{-1}
Invisible			✓				18 fb^{-1}

Heavier Higgs 2

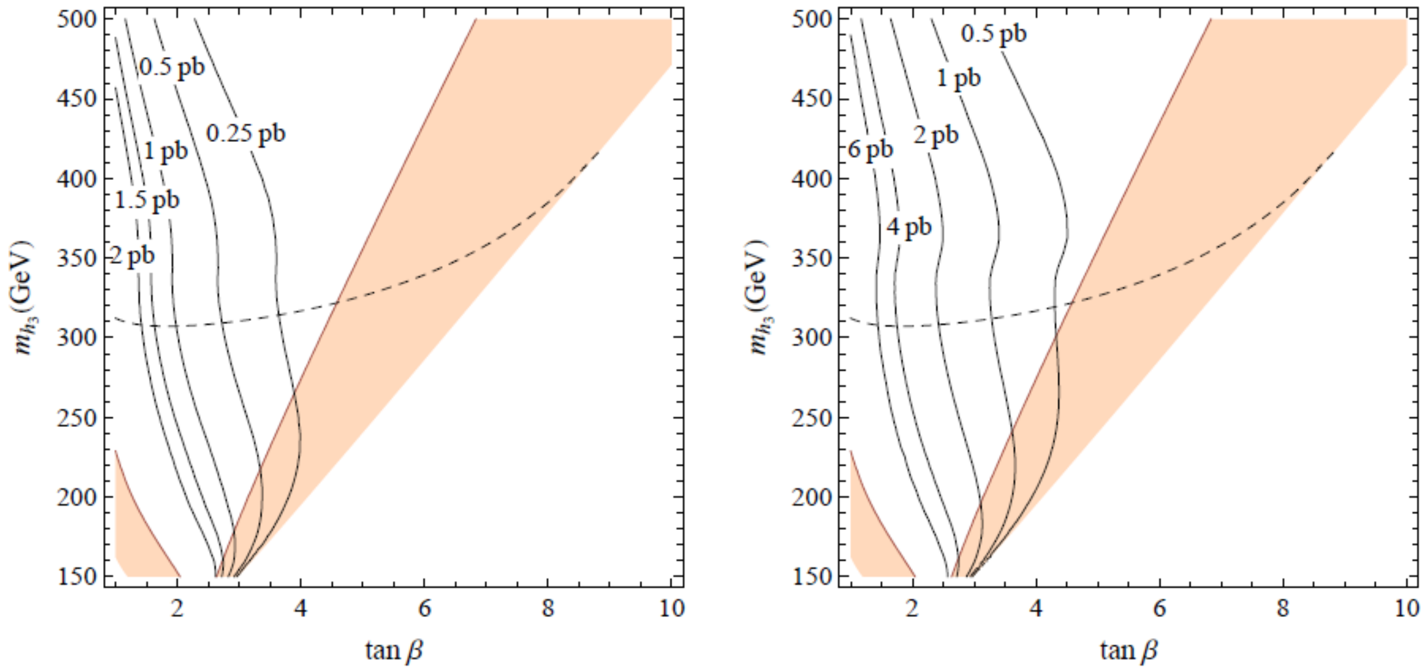


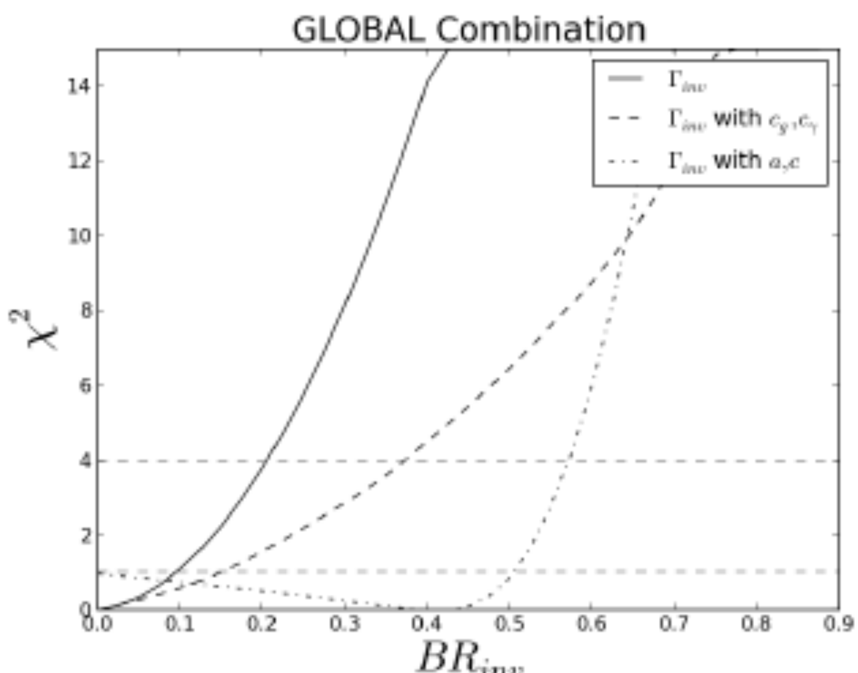
Figure 10. Singlet decoupled. Isolines of gluon fusion production cross section $\sigma(gg \to h_3)$. The colored regions are excluded at 95%C.L., and the dashed line shows $m_{H^\pm} = 300$ GeV. Left: LHC8. Right: LHC14.

Barbieri et al. 1304.3670

Lagrangian 2HDM MSSM

$$\begin{aligned}\Delta V &= m_{H_u}^2 \left|H_u^0\right|^2 + m_{H_d}^2 \left|H_d^0\right|^2 - B\mu \left(H_u^0 H_d^0 + \text{c.c.}\right) \\ &\quad + \frac{1}{8}\left(g^2 + g'^2\right)\left[\left(1 + \delta\lambda_1\right)\left|H_u^0\right|^4 + \left|H_d^0\right|^4 - 2\left|H_u^0\right|^2\left|H_d^0\right|^2\right]\end{aligned}$$

Invisible Width



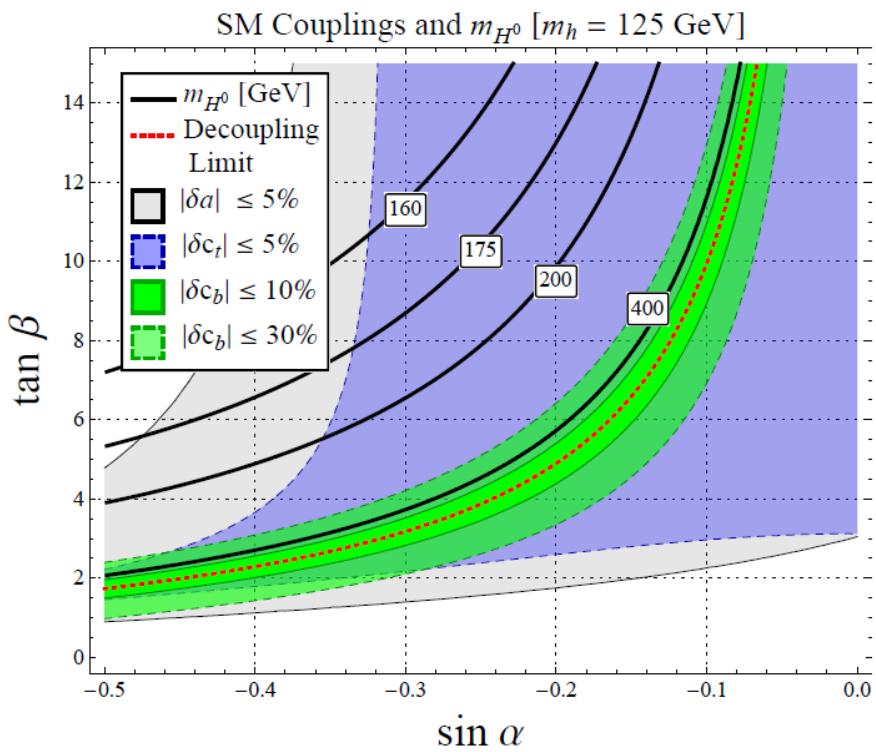
Ellis, You 1303.3879

Various models predict light particles leading to invisible decay, e.g.:

- DM models
- Non-minimal Supersymmetry
- Composite Models with extended scalar sector
- More...

MSSM Heavier Scalar

$$c_b \approx 1 - \frac{m_Z^2}{2m_H^2} \sin 4\beta \tan\beta$$
$$c_t \approx 1 + \frac{m_Z^2}{2m_H^2} \sin 4\beta \cot\beta.$$

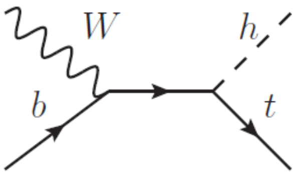


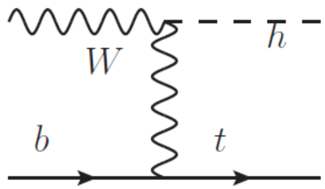
Azatov, Galloway 1212.1380v3

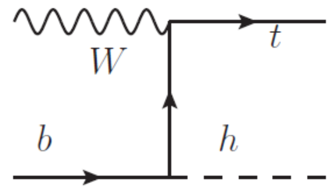
Decoupling limit is favored

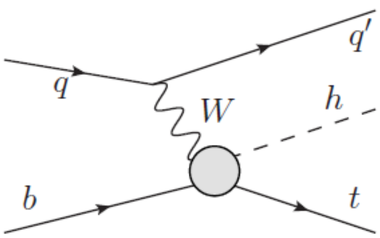
$$M_H \simeq M_{H^\pm} \simeq M_A$$

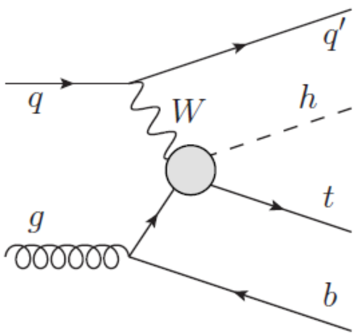
Yt<0









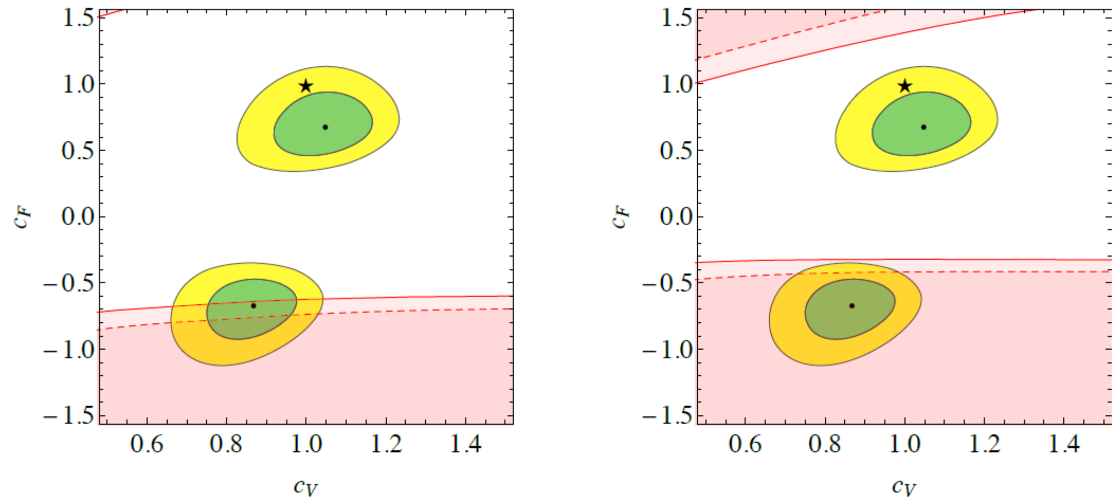


Final state

$$3\,b + 1\,\text{forward jet} + \ell^{\pm} + E_T^{miss}$$

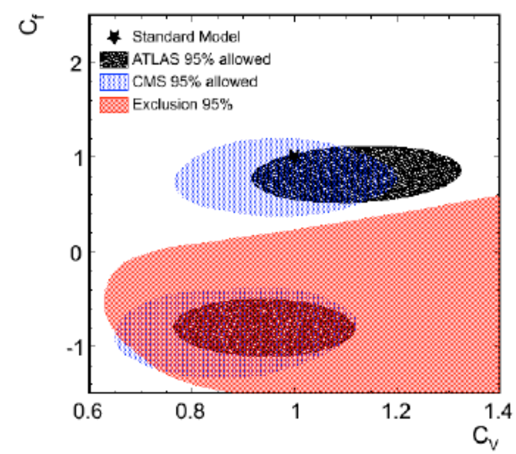
Yt<0

Final state $3\,b + 1\,\text{forward jet} + \ell^{\pm} + E_T^{miss}$



MF, Grojean, Maltoni, Salvion,Thamm. 1211.3736

$$q\,b \to t\,q'\,H \to (b\,qq')\,q'\,\gamma\gamma$$



Biswas et al. 1304.1822

Data Tables ATLAS

Channel	$\hat{\mu}$ (7 TeV)	$\zeta_i^{(G,V,T)}$ (%)	$\hat{\mu}$ (8 TeV)	$\zeta_i^{(G,V,T)}$ (%)	Refs.
$b\bar{b}$	comb. w/8	—	-0.42 ± 1.05	$(0, 100, 0)$	[66, 67]
$b\bar{b}$ (ttH)	$3.81 \pm 5.78^{**}$	$(0, 30, 70)$	—	—	
$\tau\tau$	comb. w/8	—	$0.7 \pm 0.7^{*}$	$(20, 80, 0)$	[68]
WW $(0j)$	$0.06 \pm 0.60^{*}$	inclusive	$0.92^{+0.63*}_{-0.49}$	inclusive	
WW $(1j)$	$2.04^{+1.88*}_{-1.30}$	inclusive	$1.11^{+1.20*}_{-0.82}$	inclusive	[69]
WW $(2j)$	—	—	$1.79^{+0.94*}_{-0.75}$	$(20, 80, 0)$	
ZZ	comb. w/8	—	$1.7^{+0.5}_{-0.4}$	inclusive	[70]
$\gamma\gamma_{(L)}$ (uc|ct)	$0.53^{+1.37}_{-1.44}$	$(93, 7, 0)$	0.86 ± 0.67	$(93.7, 6.2, 0.2)$	
$\gamma\gamma_{(H)}$ (uc|ct)	$0.17^{+1.94}_{-1.91}$	$(67, 31, 2)$	$0.92^{+1.1}_{-0.89}$	$(79.3, 19.2, 1.4)$	
$\gamma\gamma_{(L)}$ (uc|ec)	$2.51^{+1.66}_{-1.69}$	$(93, 7, 0)$	$2.51^{+0.84}_{-0.75}$	$(93.2, 6.6, 0.1)$	
$\gamma\gamma_{(H)}$ (uc|ec)	$10.39^{+3.67}_{-3.67}$	$(65, 33, 2)$	$2.69^{+1.31}_{-1.08}$	$(78.1, 20.8, 1.1)$	
$\gamma\gamma_{(L)}$ (c|ct)	$6.08^{+2.59}_{-2.63}$	$(93, 7, 0)$	$1.37^{+1.02}_{-0.88}$	$(93.6, 6.2, 0.2)$	
$\gamma\gamma_{(H)}$ (c|ct)	$-4.40^{+1.80}_{-1.76}$	$(67, 31, 2)$	$1.99^{+1.50}_{-1.22}$	$(78.9, 19.6, 1.5)$	
$\gamma\gamma_{(L)}$ (c|ec)	$2.73^{+1.91}_{-2.02}$	$(93, 7, 0)$	$2.21^{+1.13}_{-0.95}$	$(93.2, 6.7, 0.1)$	
$\gamma\gamma_{(H)}$ (c|ec)	$-1.63^{+2.88}_{-2.88}$	$(65, 33, 2)$	$1.26^{+1.31}_{-1.22}$	$(77.7, 21.2, 1.1)$	[71, 72]
$\gamma\gamma$ (c|trans.)	$0.35^{+3.56}_{-3.60}$	$(89, 11, 0)$	$2.80^{+1.64}_{-1.55}$	$(90.7, 9.0, 0.2)$	
$\gamma\gamma$ (dijet)	$2.69^{+1.87}_{-1.84}$	$(23, 77, 0)$	—	—	
$\gamma\gamma$ (loose high mass jj)	—	—	$2.76^{+1.73}_{-1.35}$	$(45, 54.9, 0.1)$	
$\gamma\gamma$ (tight high mass jj)	—	—	$1.59^{+0.84}_{-0.62}$	$(23.8, 76.2, 0)$	
$\gamma\gamma$ (low mass jj)	—	—	$0.33^{+1.68}_{-1.46}$	$(48.1, 49.9, 1.9)$	
$\gamma\gamma$ (E_T^{miss} significance)	—	—	$2.98^{+2.70}_{-2.15}$	$(4.1, 83.8, 12.1)$	
$\gamma\gamma$ (lepton tag)	—	—	$2.69^{+1.95}_{-1.66}$	$(2.2, 79.2, 18.6)$	

Table 2: ATLAS data used in fits. Best fits on signal strength modifier μ with efficiencies ζ (when

Data Tables CMS

Channel	$\hat{\mu}$ (7 TeV)	$\zeta_i^{(G,V,T)}$ (%)	$\hat{\mu}$ (8 TeV)	$\zeta_i^{(G,V,T)}$ (%)	Refs.
$b\bar{b}$	comb. w/8	—	$1.30^{+0.68}_{-0.59}$	$(0, 100, 0)$	[73]
$b\bar{b}$ (ttH)	$-0.81^{+2.05}_{-1.75}$	$(0, 30, 70)$	—	—	[74]
$\tau\tau$ $(0/1j)$	comb. w/8	—	$0.74^{+0.49}_{-0.52}$	inclusive	
$\tau\tau$ (VBF)	comb. w/8	—	$1.38^{+0.61}_{-0.57}$	$(0, 100, 0)$	[75]
$\tau\tau$ (VH)	comb. w/8	—	$0.76^{+1.48}_{-1.43}$	$(0, 100, 0)$	
WW $(0/1j)$	comb. w/8	—	0.76 ± 0.21	inclusive	
WW $(2j)$	comb. w/8	—	$-0.05^{+0.73}_{-0.56}$	$(17, 83, 0)$	[76]
WW (VH)	comb. w/8	—	$-0.31^{+2.24}_{-1.96}$	$(0, 100, 0)$	
ZZ (untagged)	comb. w/8	—	$0.84^{+0.32}_{-0.26}$	$(95, 5, 0)$	[77]
ZZ (dijet tag)	—	—	$1.22^{+0.84}_{-0.57}$	$(80, 20, 0)$	
$\gamma\gamma$ (untagged 0)	$3.78^{+2.01}_{-1.62}$	$(61.4, 35.5, 3.1)$	$2.12^{+0.92}_{-0.78}$	$(72.9, 24.6, 2.6)$	
$\gamma\gamma$ (untagged 1)	$0.15^{+0.99}_{-0.92}$	$(87.6, 11.8, 0.5)$	$-0.03^{+0.71}_{-0.64}$	$(83.5, 15.5, 1.0)$	
$\gamma\gamma$ (untagged 2)	-0.05 ± 1.21	$(91.3, 8.3, 0.3)$	$0.22^{+0.46}_{-0.42}$	$(91.7, 7.9, 0.4)$	
$\gamma\gamma$ (untagged 3)	$1.38^{+1.66}_{-1.55}$	$(91.3, 8.5, 0.2)$	$-0.81^{+0.85}_{-0.42}$	$(92.5, 7.2, 0.2)$	
$\gamma\gamma$ (dijet)	$4.13^{+2.33}_{-1.76}$	$(26.8, 73.1, 0.0)$	—	—	[78]
$\gamma\gamma$ (dijet loose)	—	—	$0.75^{+1.06}_{-0.99}$	$(46.8, 52.8, 0.5)$	
$\gamma\gamma$ (dijet tight)	—	—	$0.22^{+0.71}_{-0.57}$	$(20.7, 79.2, 0.1)$	
$\gamma\gamma$ (MET)	—	—	$1.84^{+2.65}_{-2.26}$	$(0.0, 79.3, 20.8)$	
$\gamma\gamma$ (Electron)	—	—	$-0.70^{+2.75}_{-1.94}$	$(1.1, 79.3, 19.7)$	
$\gamma\gamma$ (Muon)	—	—	$0.36^{+1.84}_{-1.38}$	$(21.1, 67.0, 11.8)$	

Dilaton

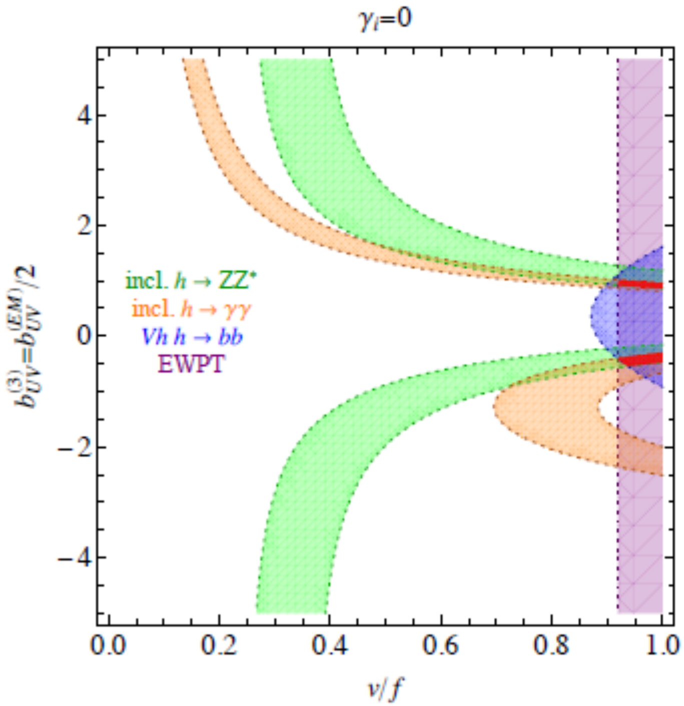
$$c_V = \frac{v}{f}$$

$$c_f = \frac{v}{f}(1+\gamma_f)$$

$$c_{\gamma\gamma,gg} = \frac{(g'^2, g_S^2)}{16\pi^2}\frac{v}{f}\left(b_{IR}^{(EM,3)} - b_{UV}^{(EM,3)}\right)$$

$$c_{Z\gamma} \sim \frac{g^2}{16\pi^2}\frac{v}{f}\left(b_{IR}^{(2)} - b_{UV}^{(2)}\right)$$

Bellazzini et al. '12



old data

EWPT