Contextualizing the Higgs at the LHC

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Implications of LHC results for TeV-scale physics
CERN July 13-17

Collaboration with Contino, Galloway, Del Re, Rahatlou, Grassi, Craig, Chang

Outline

Searching for new physics through higgs couplings

- Recently both CMS and ATLAS reported 5σ access for the new resonance at 125 GeV, which can be the Higgs boson of the Standard Model.
- Most of the BSM models predict a spin 0 field with couplings to the SM fields which are generically different than in the Standard Model: Composite Higgs, dilaton, 2HDM, SUSY
- Scalar particle with couplings different from the SM Higgs might be the first indication of the new physics
- New physics states are too heavy for the direct production at the collider but their indirect effects like modification of the Higgs couplings can be already probed.

Single scalar effective lagrangian

- Write down most general effective theory that describes EW symmetry breaking with additional scalar field.
- Longitudinal components of W, Z(Goldstone bosons) of $SU(2)_L \times SU(2)_R/SU(2)_V$ can be described by

$$\Sigma(x) = \exp\left(i\sigma^a\chi^a(x)/v\right)$$

- We can classify operators of the effective Higgs lagrangian in number of derivatives

$$\mathcal{L} = -V(h) + \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \dots$$

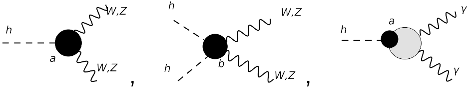
$$\mathcal{L}^{(2)} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4} Tr\left(D_\mu\Sigma^\dagger D^\mu\Sigma\right)\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \cdots\right)$$

$$\mathcal{L}^{(2)}_{unit.gauge} = \frac{1}{2}(\partial_\mu h)^2 + \left(m_W^2 W_\mu W^\mu + \frac{1}{2}m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \dots\right)$$

If $a = b = 1$ exchange of the h cancels the growth of the scattering amplitudes of the NG bosons χ

Chiral lagrangian for light Higgs

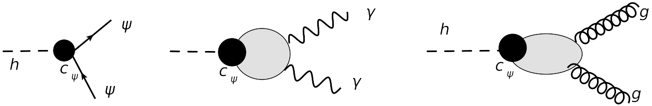
- $$\mathcal{L} = \frac{1}{2}\left(\partial_\mu h\right)^2 - \frac{1}{2} m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^3}{v}\right) h^3 - \frac{d^4}{24}\left(\frac{3m_h^2}{v^2}\right) h^4$$
  $$- \left(m_W^2 W_\mu W^\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \dots\right)$$

- 

Coupling to fermions

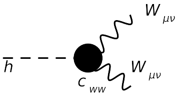
$$\mathcal{L}_{ferm} = -\sum_{\psi=u,d,l} m_\psi \bar{\psi}_i \psi_j \left(\delta_{ij} + c_{\psi_{ij}}\frac{h}{v} + c_{2\psi_{ij}}\frac{h^2}{v^2}\right)$$

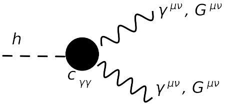
Generically higgs couplings can be non-diagonal, but FCNC($\epsilon_K, B-\bar{B}$) constraints require all c^{ij} to be diagonal



Four Derivative interactions

$$\mathcal{L}^{(4)} = \frac{g^2}{16\pi^2}\left(c_{ww}W^+_{\mu\nu}W^-_{\mu\nu} + c_{ZZ}Z^2_{\mu\nu} + c_{Z\gamma}Z_{\mu\nu}\gamma_{\mu\nu}\right)h + \ldots$$
$$+\frac{g^2}{16\pi^2}\left(\gamma^2_{\mu\nu}(c_{\gamma\gamma}\frac{h}{v} + \ldots) + G^2_{\mu\nu}\left(c_{gg}\frac{h}{v} + c_{2gg}\frac{h^2}{v^2}\ldots\right)\right)$$

- 

- 

- c_{ww} will effect final state distributions
- $c_{gg}, c_{\gamma\gamma}$ direct modification of the $h\gamma\gamma$ coupling without effecting Higgs coupling to the SM fields, (integrating out heavy fields which do not mix with SM)

Choice of the operators

- Coupings that are probed at LHC: $hbb, hgg, h\gamma\gamma, h\tau\tau, hWW(ZZ)$, so really we want to find constraints in this 5D parameter space of the couplings.

Choice of the operators

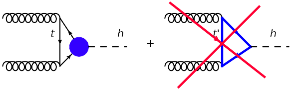
- Coupings that are probed at LHC: $hbb, hgg, h\gamma\gamma, h\tau\tau, hWW(ZZ)$, so really we want to find constraints in this 5D parameter space of the couplings.
- For simplicity reasons let us assume that we have only two independent parameters

$$\mathcal{L}_W = -\left(m_W^2 W_\mu W^\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2a\frac{h}{v}\right)$$
$$\mathcal{L}_\psi = -\frac{v}{\sqrt{2}}\lambda_i \bar{\psi}_i \psi_i (1 + c\frac{h}{v})$$

- a- modification of the Higgs coupling to W, Z, $SU(2)$ custodial requires it to be the same
- c- modification of the Higgs coupling to fermions
  Standard Model corresponds to the $a = 1, c = 1$

Why a,c?

- FCNC constraints prefer flavor universal rescaling of the fermion couplings $c_i = c$, however nothing requires $c_\tau = c_b = c_t$, but good starting point
- Example models: Holographic composite Higgs models based on the $SO(5)/SO(4)$, MCHM5,MCHM4 (Agashe,Contine,Pomarol), 2HDM where only one Higgs couples to fermions.
- Modification of the Hgg, $H\gamma\gamma$ couplings comes ONLY from the modification of the top and W couplings.



$c_g = c_\gamma = 0$

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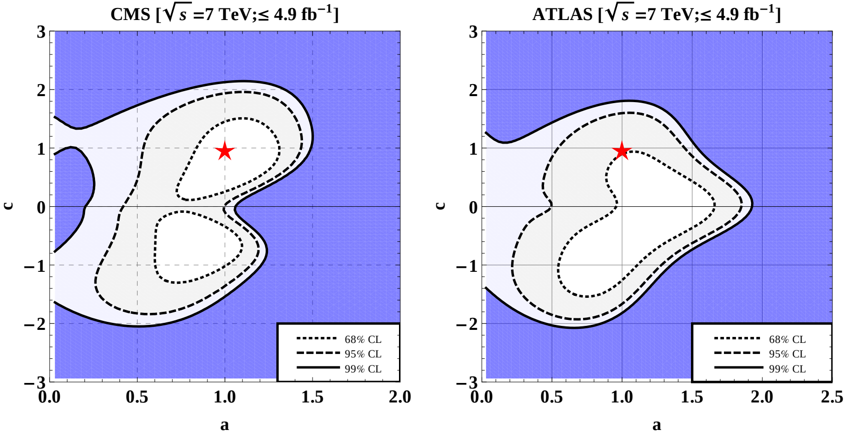
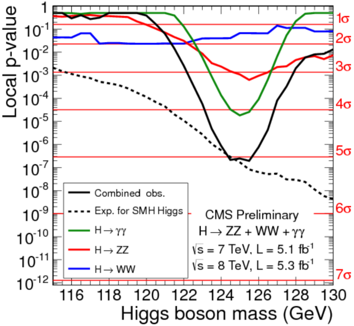
$$c_{g,\gamma}^{\text{top}+\text{New Physics}} / c_{g,\gamma}^{\text{SM(top)}} = c_b = c_\tau$$

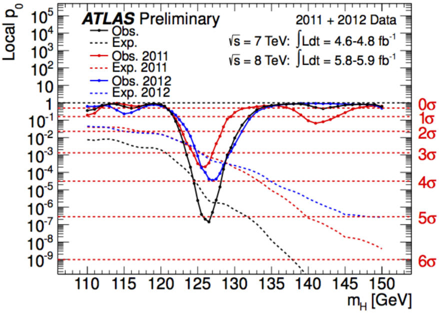
Couplings after Moriond '12



68, 95, 99% contours in (a, c) plane after Moriond'12

Resonance at 125 GeV

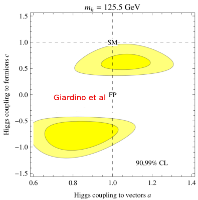


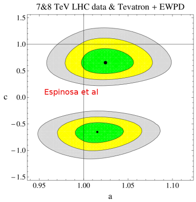


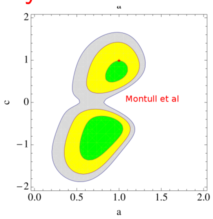
PAS-HIG-12-020, ATLAS-CONF-2012-093

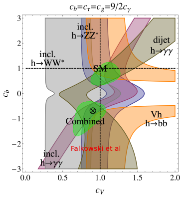
Theorists fitting couplings of the resonance at 125GeV, 2D fits

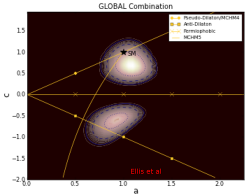
talks by E.Kuflik, C. Grojean today



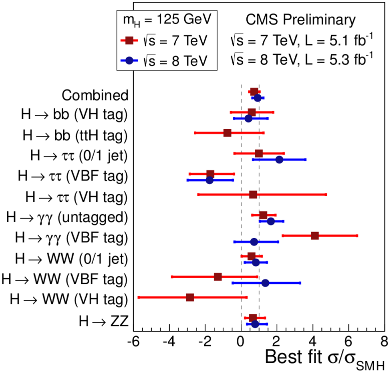




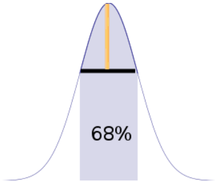




Constructing likelihoods



(CMS note PAS-HIG-12-020)



Symmetrizing errors we can reconstruct likelihood assuming gaussian distribution

Signal rescaling/cut efficiencies

- We need to know modification of the number of signal events for every channel i. For this we need : production cross section for each production mode σ_p, the efficiencies ζ_i^p of the kinematic cuts, and the Higgs decay branching fraction:

$$\left(n_s^i\right)^{New\ \ Physics} = \left(n_s^i\right)^{SM} \frac{\sum_p \sigma_p \times \zeta_i^p}{\sum_p \sigma_p^{SM} \times \zeta_i^p} \times \frac{BR_i}{BR_i^{SM}}$$

- Dominant production modes at LHC for 125 GeV Higgs are ggH, VBF, VH
  - $\gamma\gamma$ official CMS efficiencies from *PAS-HIG-12-015*

Fitting CMS and ATLAS

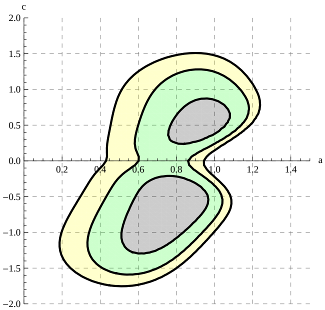


Figure: CMS fit for 125 GeV Higgs, Grey,Green,Yellow -68, 95, 99% areas

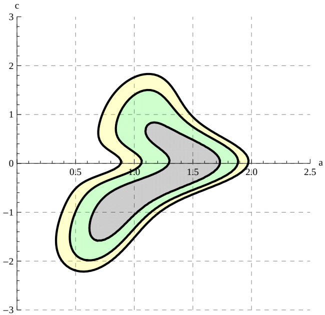


Figure: ATLAS fit for 126.5 GeV Higgs, Grey,Green,Yellow -68, 95, 99% areas

Checking our prediction with official fit

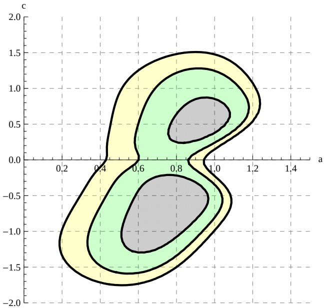
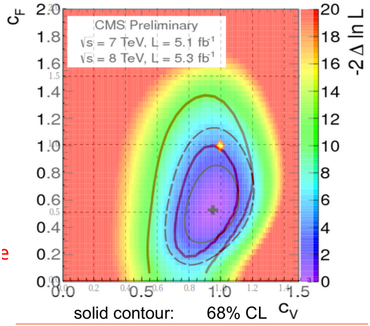


Figure: Grey,Green,Yellow -68, 95, 99% areas

- We can compare our prediction with official CMS combination. We change priors to be $a \in [0, 3], c \in [0, 3]$



Going further, three parameter fit (AA,S.Chang,N.Craig,J.Galloway)

- So far all our fits were presented assuming condition $c_b = c_t$
- In one of the most popular BSM scenarios, supersymmetry

$$\tan\beta = \frac{v_u}{v_d}$$

$$a = \sin(\beta - \alpha), \;\; c_t = \frac{\cos\alpha}{\sin\beta}, \;\; c_b = c_\tau = -\frac{\sin\alpha}{\cos\beta}$$

- In the fits we will assume SUSY inspired condition

$$a \neq c_t \neq c_b = c_\tau$$

Fit with $c_b \neq c_t$

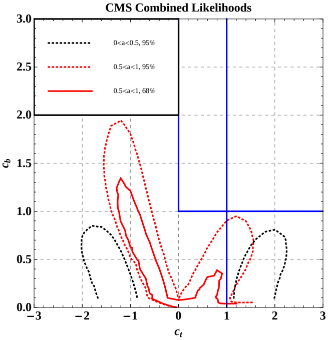
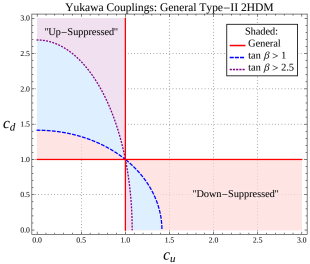


Figure: Black dotted -95% contour for $0 < a < 0.5$,red dotted -95% contour for $0.5 < a < 1$, red solid -68% contour for $0.5 < a < 1$

- To simplify analysis we will assume $a \in [0, 1]$(*Rychkov, Falkowski, Urbano*)

2HDM implications



$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \sqrt{2}\begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix}\begin{pmatrix} \mathrm{Re}\, H_d^0 \\ \mathrm{Re}\, H_u^0 \end{pmatrix}$$

$$\tan\beta = \frac{v_u}{v_d}$$

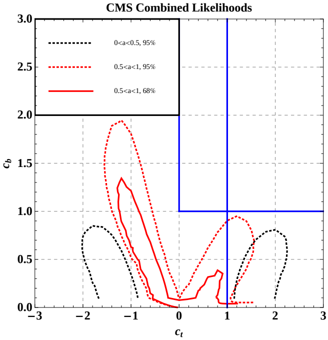
$$a = \sin(\beta - \alpha)$$

$$c_t = \frac{\cos\alpha}{\sin\beta}$$

$$c_b = -\frac{\sin\alpha}{\cos\beta}$$

Only small part of the c_u, c_d plane is covered by type II 2HDM

(c_u, c_d) fits for 2HDM

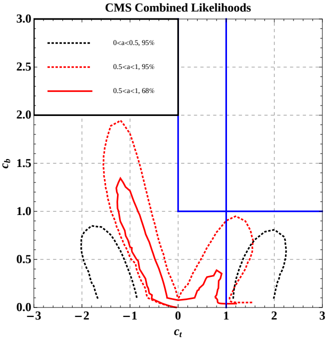


c

(c_d, c_u) fit

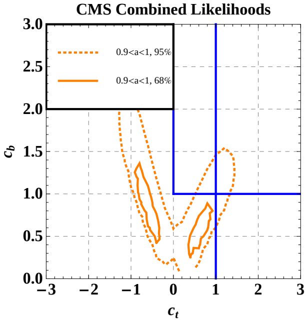
- Only half of the c_b, c_t plane is available
- We have a slight "preference" towards $c_b < 1$ region

(c_u, c_d) fits for 2HDM



c

(c_d, c_u) fit

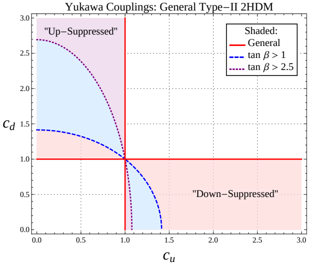


- Only half of the c_b, c_t plane is available
- We have a slight "preference" towards $c_b < 1$ region

Conditions for b phobic higgs

- $$\Delta V = \lambda_1 \left|H_u^0\right|^4 + \lambda_2 \left|H_d^0\right|^4 - 2\lambda_3 \left|H_u^0\right|^2 \left|H_d^0\right|^2 + \left[\lambda_4 \left|H_u^0\right|^2 H_u^0 H_d^0 + \lambda_5 \left|H_d^0\right|^2 H_u^0 H_d^0 + \lambda_6 (H_u^0 H_d^0)^2 + \text{c.c.}\right].$$

  " Down-Suppressed " conditions

- 

If $\tan\beta \gtrsim 5$

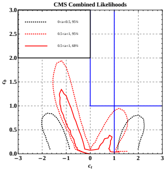
$$\lambda_3 \lesssim -\lambda_1 + \frac{\lambda_4}{2}\tan\beta$$

$$\lambda_3 \gtrsim -\frac{B\mu}{v^2}\tan\beta + \lambda_1 - \lambda_4 \tan\beta$$

$$\lambda_3 \cos 2\beta > \lambda_1 \sin^2\beta - \lambda_2 \cos^2\beta + \lambda_4 \frac{\sin 3\beta}{2\cos\beta} + \lambda_5 \frac{\cos 3\beta}{2\sin\beta}$$

$$\lambda_3 \cos 2\beta < -\frac{2B\mu}{v^2 \tan 2\beta} + \lambda_2 \cos^2\beta - \lambda_1 \sin^2\beta - \lambda_5 \frac{\cos^2\beta}{\tan\beta} + \lambda_4 \sin^2\beta \tan\beta$$

MSSM and b phobic Higgs



$$\lambda_3 \lesssim -\lambda_1 + \frac{\lambda_4}{2} \tan\beta$$
$$\lambda_3 \gtrsim -\frac{B\mu}{v^2} \tan\beta + \lambda_1 - \lambda_4 \tan\beta$$

- MSSM tree level

$\lambda_{1,2,3} = \frac{1}{8}(g^2 + g'^2), \quad \lambda_{4,5,6} = 0,$ we are always up suppressed region

- 1 -loop

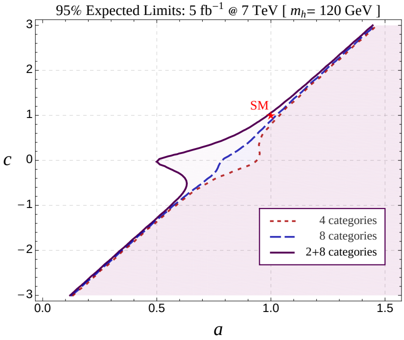
$$\delta\lambda_1 = \frac{3y_t^4}{16\pi^2}\left(\bar{A}_t^2 - \bar{A}_t{}^4/12\right), \ \delta\lambda_3 = \frac{3y_t^4\bar{\mu}^2}{64\pi^2}\left(\bar{A}_t^2 - 2\right)$$
$$\delta\lambda_4 = \frac{y_t^4\bar{\mu}}{32\pi^2}\left(\bar{A}_t^3 - 5\bar{A}_t\right)$$

(*Carena,Espinosa,Quiros,Wagner*)

- Only corrections from λ_4 can push us towards down suppressed region

The power of exclusive analysis, $\gamma\gamma$

(AA,DelRe,Contino,Galloway,Grassi,Rahatlou)



- Expected exclusion curves (background only) for $m_h = 120$ GeV based on the simulation with 4, 8 and 10 categories
- 4 categories- cuts based on R_9 and photon pseudorapidity,
- 8 categories- same cuts + photon are differentiated based on $P_t(\gamma\gamma)$ cut on $P_t(\gamma\gamma)$ helps to differentiate between VBF and gluon fusion we are more sensitive in the fermiophobic region
- 10 categories - 2 additional categories based on the VBF and HSTRA cuts

Injecting SM signal

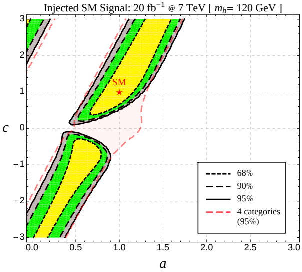
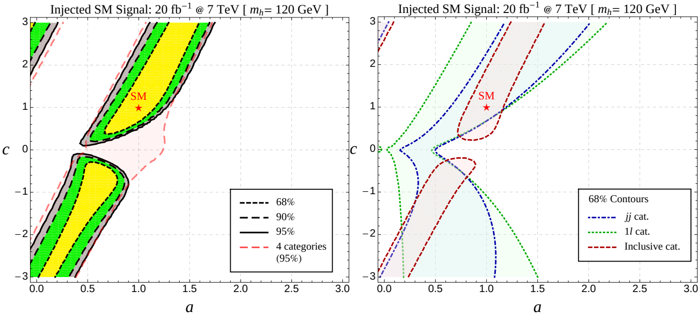


Figure: 95% and 68% exclusion contours for the simulation based on $m_h = 120$ GeV, $20fb^{-1}$, injecting SM signal, only $h \to \gamma\gamma$

- Simulation for the $m_h = 120$ GeV higgs with exclusive $\gamma\gamma$ channels, with 10 categories defined by kinematic cuts in order to differentiate between , VBF, HSTRA, GGH production mechanisms.
- Probability is always peaked along the constant R value

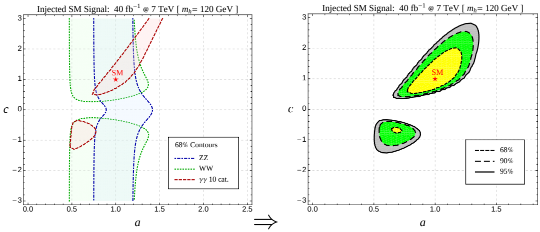
$$R^i(\gamma\gamma) \propto \sigma^i \times Br(h \to \gamma\gamma)$$
$$\sigma^i \propto \alpha^i c^2 + \beta^i a^2$$
$$Br(h \to \gamma\gamma) \propto \frac{|8.3a - 1.78c|^2}{0.84c^2 + 0.16a^2} \Rightarrow$$
$$\left|\frac{a_1}{c_1}\right| = \left|\frac{a_2}{c_2}\right|,$$
$$|8.3a_1 - 1.78c_1| = |8.3a_2 - 1.78c_2|$$

Breakdown by channels



Combining $\gamma\gamma$ WW and ZZ analisys

- Can we rule out one solution my measuring precisely a ? For example by adding WW or ZZ channels ?



- unfortunately even $40 fb^{-1}$ are not enough to rule out negative c solution at 68% level.

$\gamma\gamma$ signal at 125 GeV analysis

Expected signal and estimated background

Event classes		SM Higgs boson expected s				
		Total	ggH	VBF	VH	ttH
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61%	17%	19%	3%
	Untagged 1	16.3	88%	6%	6%	1%
	Untagged 2	21.5	91%	4%	4%	–
	Untagged 3	32.8	91%	4%	4%	–
	Dijet tag	2.9	27%	73%	1%	–
8 TeV 5.3 fb^{-1}	Untagged 0	6.1	68%	12%	16%	4%
	Untagged 1	21.0	88%	6%	6%	1%
	Untagged 2	30.2	92%	4%	3%	–
	Untagged 3	40.0	92%	4%	4%	–
	Dijet tight	2.6	23%	77%	–	–
	Dijet loose	3.0	53%	45%	2%	–

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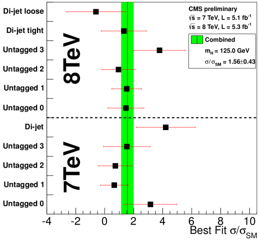

- for the CMS $\gamma\gamma$ analysis all the efficiencies and SM signal rates are public, to simulate observed signal we can inject SM signal modified by best fit values .

$\gamma\gamma$ signal at 125 GeV analysis

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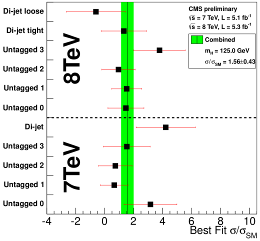

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- for the CMS $\gamma\gamma$ analysis all the efficiencies and SM signal rates are public, to simulate observed signal we can inject SM signal modified by best fit values .
- 7 TeV $\sigma_{ggh} : \sigma_{VBF} : \sigma_{VH} = 1 : 0.08 : 0.058$
- 8 TeV $\sigma_{ggh} : \sigma_{VBF} : \sigma_{VH} = 1 : 0.08 : 0.056$
- efficiencies of different production mechanism for untagged subchannels are different

Channel breakdown in $\gamma\gamma$ search 68% contours

- 7 TeV search

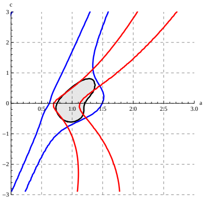


Figure: Red -dijet tagged, Blue-untagged, Black-combination

- the largest excess was reported in the categories, which have the largest contamination by VBF events ("Fermiophobic Higgs" see talk by Gabrielli)

- 8 TeV search

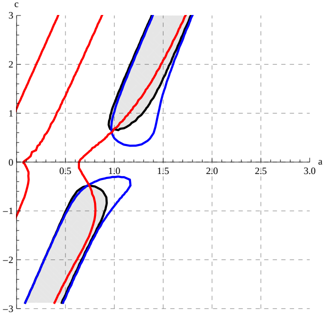


Figure: Red -dijet tagged, Blue-untagged, Black-combination

Channel breakdown in $\gamma\gamma$ search

- 7+8 TeV search

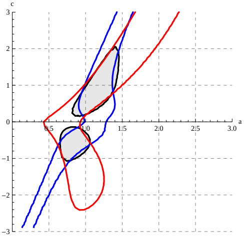


Figure: Red -dijet tagged, Blue-untagged, Black-combination

- 7+8 TeV

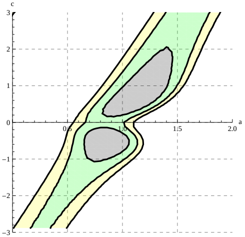
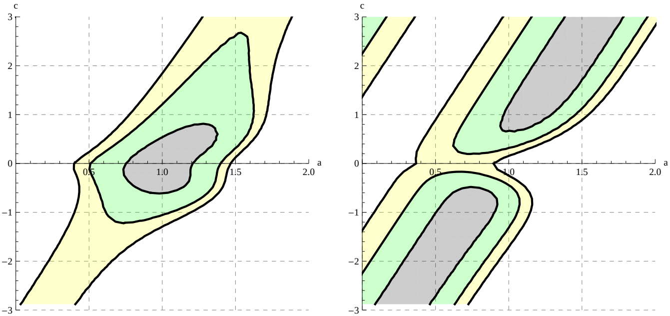


Figure: Grey,Green,Yellow -68, 95, 99% areas

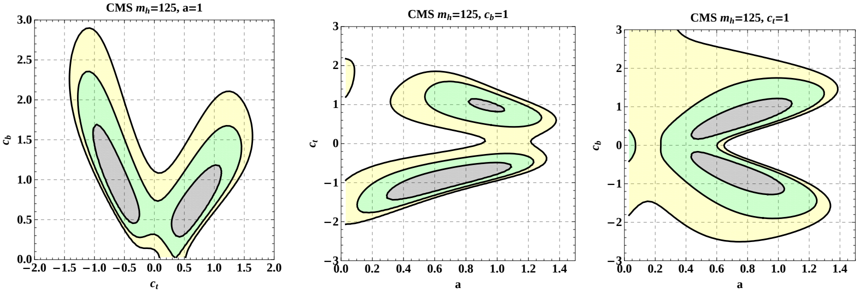
Outlook

- We presented updated fits for the Higgs couplings, 2d and 3d fits.
  - 3d fit still prefers region with suppressed bottom yukawa coupling
- SM Higgs looks good so far.
- We presented analysis of the CMS $\gamma\gamma$ channel
  - preference of the "fermiophobic" Higgs is gone
- Still need to do:
  - Exclusions for the various mass ranges, careful treatment of all the available channels, including all the efficiencies...

7 and 8 TeV best fits from CMS $\gamma\gamma$



Various 2d fits



Grey, Green, Yellow -68, 95, 99% areas

Constraints on MCHM4

Higgs is a Pseudo-Nambu-Goldstone boson of $SO(5)/SO(4)$ symmetry breaking, as a result of the nonlinear structure of the Higgs boson $m_W^2 = \frac{g^2 v^2}{4} \Rightarrow, \quad m_W^2 = \frac{g^2 f^2}{4} \sin^2(\langle h \rangle / f), \quad \xi = \sin^2(\frac{\langle h \rangle}{f})$

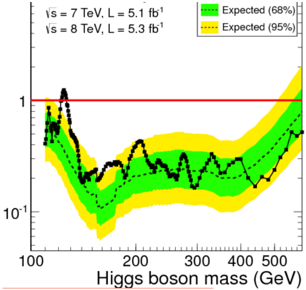


Figure: Official CMS exclusion

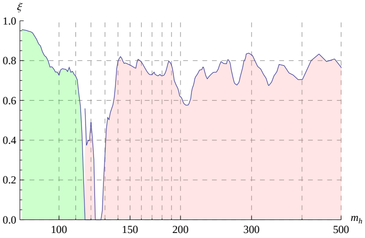


Figure: MCHM4: $a = c = \sqrt{1-\xi}$