Higgs couplings beyond the Standard Model

Based on arXiv:1210.8120, G.Cacciapaglia, A.Deandrea, G.DLR, J-B.Flament

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Higgs couplings and New Physics

- Higgs sector is a crucial part in many BSM theories
  - Important modifications can occur (4^{th} generation, 2 Higgs Doublets Model ...)
  - Signatures can be quite different depending on the underlying physics.
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    ➞ Higgs phenomenology is a right place to look for New Physics
- Even if the Higgs ends up standard-like, we can still :
  - derive bounds on New Physics that are competitive with direct searches.
  - This requires a full recast of the SM searches.

Testing compatibility Model v.s. Data

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- Choice of the test statistics
  → It is customary to take $\Delta\chi^2$, but in some cases it is not the best choice.

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- Input : Set of measured cross-sections.

  Usually $\hat{\mu}_i = \frac{\sigma_{pp\to h\to X_i}}{\sigma^{\rm SM}_{pp\to h\to X_i}}$, 1σ error band $[\hat{\mu}_i - \sigma_-, \hat{\mu}_i + \sigma_+]$.

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- Using a decorrelated approximation, the full χ^2 is

$$\chi^2 = \sum_i \chi_i^2$$

  - Valid if statistical errors dominate. (Still the case ?)

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- Each decay mode ($\gamma\gamma$, ZZ...) can be split in subchannels
  - $WW \to WW + 0/1/2j$, $\gamma\gamma \to \gamma\gamma(\text{high } p_T/\text{low } p_T) + 0/2j$ ...

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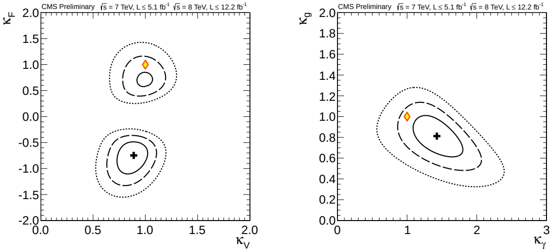
- Correlations between subchannels of a single channel :
  ➞ For instance we have $\sum_j \epsilon^{\text{ggh}}_{\gamma\gamma\ i} = \epsilon^{\text{ggh}}_{\gamma\gamma}$
  $\Rightarrow$ Exclusive uncertainties are correlated by the sum constraint.

Use simplified models (from ATLAS/CMS)

- ATLAS and CMS have provided studies of Higgs couplings, by varying some sets of parameters

$$(\kappa_V, \kappa_F),\ (\kappa_u, \kappa_d),\ (\kappa_Z, \kappa_W),\ (\kappa_g, \kappa_\gamma)\ldots$$



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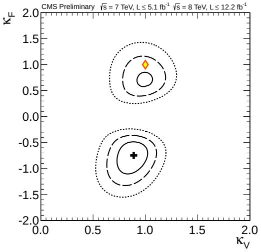

- Approximation-free result! This is the best one can achieve.
- But, only available as 2D contours ➞ useless for more complex models.

Improved χ^2 extraction

- Instead of giving all subchannels, give the χ^2 as a function of the production modes.

$$
\begin{array}{c}
(\hat{\mu}_{WW}, \sigma_{WW}) \\
\downarrow \\
(\hat{\mu}^{0j}_{WW}, \sigma^{0j}_{WW}), (\hat{\mu}^{1j}_{WW}, \sigma^{1j}_{WW}) \ldots \\
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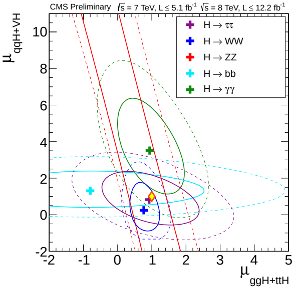

- 2D gaussian approximation

$$\chi^2 = \begin{pmatrix} \mu_{\text{ggh,tth}} \\ \mu_{\text{VBF,VH}} \end{pmatrix}^T V^{-1} \begin{pmatrix} \mu_{\text{ggh,tth}} \\ \mu_{\text{VBF,VH}} \end{pmatrix}$$

Improved χ^2 extraction (II)

- Requires that 4 production modes ($gg \to h$, $\bar{t}th$, VBF, VH) can be related to 2 parameters ($\mu_{\mathrm{ggh,tth}}, \mu_{\mathrm{VBF,VH}}$)
  - If custodial symmetry is preserved VBF and VH are rescaled in the same way.
  $$R_{VBF} = R_{VH}$$
  - So far $\bar{t}th$ production not crucial $\rightarrow$ $\sigma_{\bar{t}th}$ can be neglected, except for $h \to \bar{b}b$, where $gg \to h$ does not contribute.

- It yields χ^2 only up to an additive constant.

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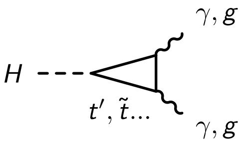
  - Choose a UV completion with new particles
    (W', vector-like fermions, etc...)
  - Pros : can provide a reasonable fit with few parameters
- Model-independent
  - EFT (Effective Field Theory) :
    keep SM spectrum (no new particles)
    add higher-order operators
  - Pros : Accounts for most cases of heavy new physics.

Specialised Parametrisation

- Our aim : New Physics models contributing mostly via loop-induced couplings
  - It is a broad class (extra dimensions, vector-like fermions, top partners ...)



  - Keep only a few parameters

- In a larger view, allow for tree-level couplings modification

Effective parametrisation $\kappa_{gg}, \kappa_{\gamma\gamma}$

- Naive parameterisation $\kappa_g^2 = \frac{\Gamma_{H\to gg}}{\Gamma^{\mathrm{SM}}_{H\to gg}}, \; \kappa_\gamma^2 = \frac{\Gamma_{H\to\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{H\to\gamma\gamma}}$
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$$\longrightarrow \Gamma \propto |A(W) + A(t) + A(NP)|^2$$

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- "top-inspired" parameterisation :

$$\Gamma_{gg} \propto \left| C_t^g A_t (1 + \kappa_{gg}) \right|^2$$
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- Easy interpretation for top partners

$$\kappa_{gg} = \kappa_{\gamma\gamma} = f(1/M)$$

- Avoids correlations if tree-level parameters k_W, k_b, ... are introduced.

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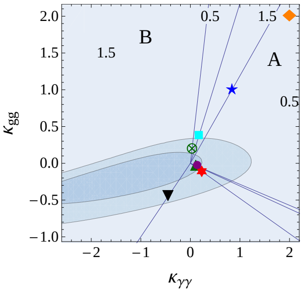
- $g_{HXX} = g_{HXX}(1/M)$: decoupling limit
- Correlations

$$\boxed{\frac{\kappa_{\gamma\gamma}}{\kappa_{gg}} = \frac{3}{8}\frac{N_c Q^2}{C_{\text{color}}}}$$

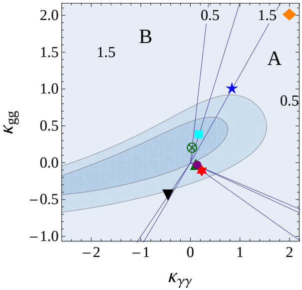
Specific realisations

- Models to be tested:
  - Extra-dimensional models
    5D-UED ($\otimes$),6D-UED ($\bigstar$),Brane Higgs ($\blacktriangledown$,$\spadesuit$)
  - Colour octect ($\blacksquare$)
  - Minimal Composite Higgs model ($\bullet$)
  - Little Higgs model
    Littlest Higgs ($*$), Simplest Little Higgs ($\blacktriangle$)
  - 4^{th} generation ($\blacklozenge$)
- All models lie on a line starting at SM point, except 4^{th} generation.

Excluding New Physics



CMS



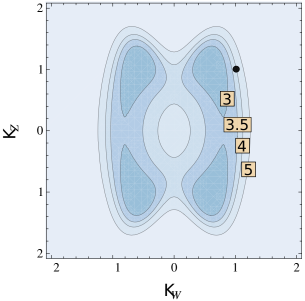
ATLAS

Excluded at 95% C.L.

- 4^{th} generation
- 6D UED up to M_{up}

Fermiophobic model

- Study the k_W, k_Z fermiophobic models
  - No couplings to fermions ($\mu_{ggh} = 0,\ \mu_f = 0$)



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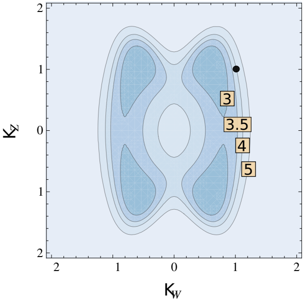


- In this case we use the χ^2 test instead of the $\Delta\chi^2$
  ➞ This is due to the poor quality of the best fit itself.

Dilaton model

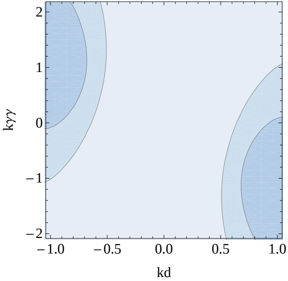
- A dilaton-like impostor would be characterised by a common rescaling factor

$$\kappa_Z = \kappa_W = \kappa_f = \kappa_d = \frac{v}{f}$$

- It would be also modified by extra particles in loop-induced couplings

$\rightarrow$ Parameter set $(\kappa_d, \kappa_{gg}, \kappa_{\gamma\gamma})$

- Fit when κ_{gg} is marginalised



Conclusion

- Summary
  - Parametrisation with few parameters, but covering many models.
  - Advocate for such a fit by ATLAS and CMS collaborations.
  - This is a powerful way to set limits on new heavy particles.

- Development
  - Complete experimental input ($Z\gamma$)
  - Compare with bounds from direct searches

Add-Ons

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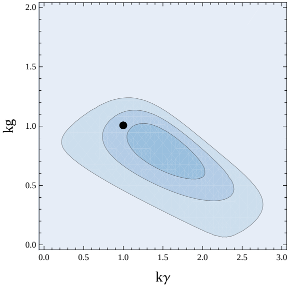
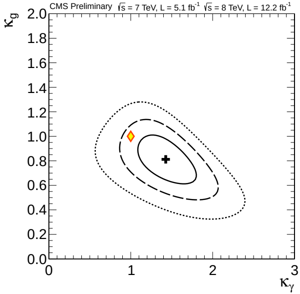
Check of the χ^2 extraction

- The simplest check we can do is compare our $\kappa_{gg}, \kappa_{\gamma\gamma}$ fit to the one performed by CMS, with the same dataset.





Importance of correlations

- Correlations among signals due to Systematics + Theory
- Compare our two approaches
  - $\Delta\chi^2$: sum of all subchannels (no correlations)
  - $\Delta\chi^2$ obtained from $\Delta\chi^2(\mu_{VBF}, \mu_{ggH})$
- The second χ^2 is more peaked
  $\Rightarrow$ Stronger exclusion
- *Example :* Uncertainties on migration coefficients.

χ^2 v.s. $\Delta\chi^2$ tests

- Likelihood ratio test ($\Delta\chi^2$) is optimal for test H_0/H_1
  - H_0 is taken as the best fit hypothesis (alternate hypothesis)
  - H_1 is the test hypothesis
- However this cannot exclude the model itself
- Single experiment test χ^2
  - H_0 is the best fit hypothesis

Pros

- Stronger limits
- Possibility to compare two models with different parameters.