Probing new physics through Higgs couplings

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Higgs couplings and New Physics

- Higgs sector is a affected by many BSM theories
  - Important modifications can occur (4^{th} generation, 2 Higgs Doublets Model ...)
  - Impact is different according to production/decay mode
    ➙ Variety of signatures
    ➙ 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.

BSM exploration in Higgs phenomenology

There are two approaches to the search for NP effects :

- Study the effects of a specific model
  - Choose a UV completion with new particles
    (W', vector-like fermions, etc...)

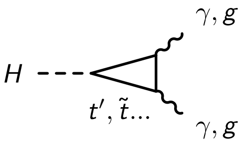
    ➞ can provide a reasonable fit with few parameters

- Model-independent
  - EFT (Effective Field Theory) :
    keep SM particle spectrum
    add higher-order operators

    ➞ 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

- Allow for tree-level couplings modification

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

- Generic parameterisation $\kappa_g^2 = \frac{\Gamma_{H\to gg}}{\Gamma^{SM}_{H\to gg}}$, $\kappa_\gamma^2 = \frac{\Gamma_{H\to\gamma\gamma}}{\Gamma^{SM}_{H\to\gamma\gamma}}$
  - Hide interferences with SM particles

$$\to \Gamma \propto |A(W) + A(t) + A(NP)|^2$$

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- "top-inspired" parameterisation :

$$\Gamma_{gg} \propto \left| C_t^g A_t (1 + \kappa_{gg}) \right|^2$$
$$\Gamma_{\gamma\gamma} \propto \left| A_w + \frac{4}{9} C_t^\gamma A_t (1 + \kappa_{\gamma\gamma}) \right|^2$$

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- Easy interpretation for top partners

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

- Avoids correlations if tree-level parameters κ_V, κ_b, ... are introduced.

Theoretical motivation

- Contribution of a new particle depends on
  $\Rightarrow$ charge (Q), color, loop form factor, Higgs coupling
- Usually loop form factor is asymptotic if $2m_X^2 > m_H^2$:

$$\begin{array}{ll} \mathcal{F} = 1 & \text{spin } 1/2 \\ \mathcal{F} = -\frac{21}{4} & \text{spin } 1 \\ \mathcal{F} = \frac{1}{4} & \text{spin } 0 \end{array}$$

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

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

Testing compatibility Model v.s. Data

The statistical treatment is the following :

$\mathcal{L}(\text{data}|\text{model})$ ➞ $\boxed{\begin{array}{c}\text{Test Statistic}\\ \chi^2,\ \Delta\chi^2\end{array}}$ ➞ p-value

- p-value $\equiv$ compatibility
  - $p_X > 1 - 0.68 \Leftrightarrow$ model X compatible at 1σ level
  - $p_X > 1 - 0.95 \Leftrightarrow$ model X compatible at 2σ level...

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

Extracting $\mathcal{L} \equiv \chi^2$

- Input : Set of measured cross-sections.

  Usually $\hat{\mu}_i = \frac{\sigma_{pp \to h \to X_i}}{\sigma^{\mathrm{SM}}_{pp \to h \to X_i}}$, 1σ error band $[\hat{\mu}_i - \sigma_-, \hat{\mu}_i + \sigma_+]$.
- Using a gaussian approximation for χ^2 in channel i

$$\chi^2 = \left(\frac{\mu_i \mid_{\text{model}} - \hat{\mu}_i}{\sigma_i} \right)^2$$

  - Valid if $n_{\text{obs}} \sim n_{\text{exp}}$.
  - True in most channels except ZZ and some $\gamma\gamma$ subchannels.
- Using a decorrelated approximation, the full χ^2 is

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

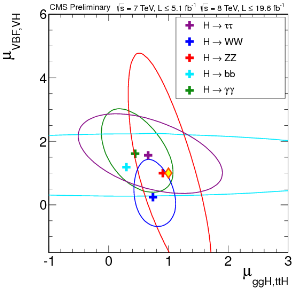
  - Valid if statistical errors dominate. (Still the case ?)

χ^2 extraction

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

$$(\hat{\mu}_{WW}, \sigma_{WW})$$
$$\downarrow$$
$$(\hat{\mu}^{0j}_{WW}, \sigma^{0j}_{WW}), (\hat{\mu}^{1j}_{WW}, \sigma^{1j}_{WW})\ldots$$
$$+\ \epsilon^{ggh}_{0j},\ \epsilon^{VBF}_{0j}, \ldots$$

$$\longrightarrow$$



- 2D gaussian approximation

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

χ^2 extraction (II)

- Requires that 4 production modes ($gg \to h$, $\bar{t}th$, VBF, VH) can be related to 2 parameters ($\mu_{\text{ggh,tth}}, \mu_{\text{VBF,VH}}$)
  - 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 ➡ $\sigma_{\bar{t}th}$ 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.

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.

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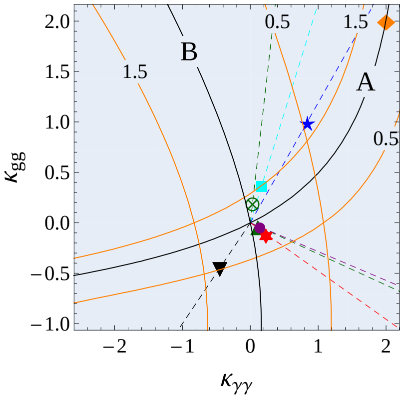

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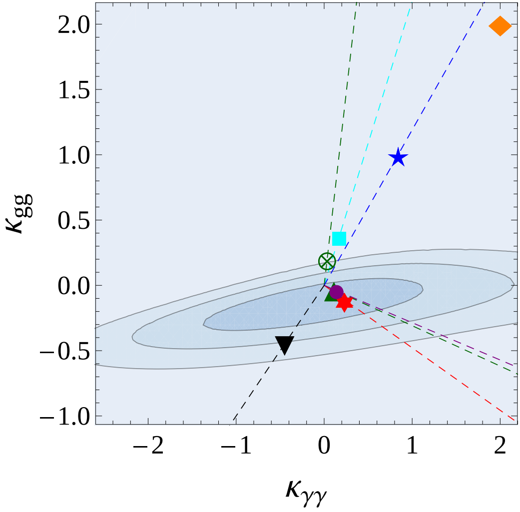
Excluding New Physics



Excluded at 95% C.L.

- 4^{th} generation
- other models up to some parameter value

CMS

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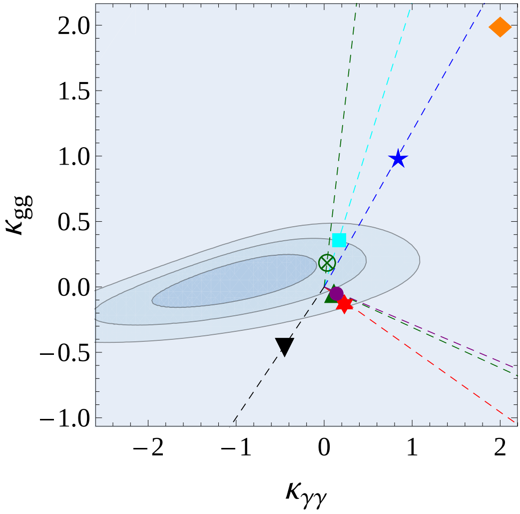

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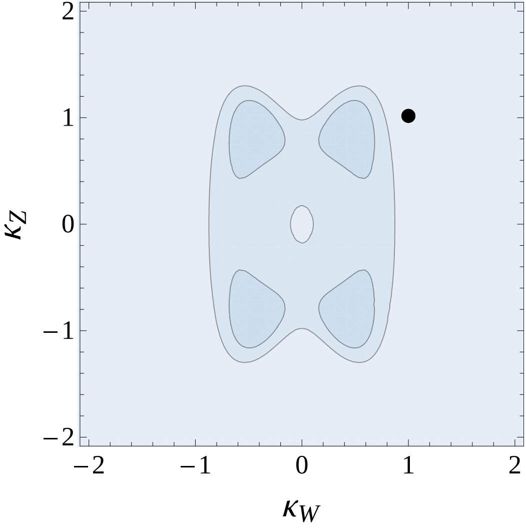
Other frameworks : Fermiophobic Higgs model



- 4σ and 5σ contours
- Dot = Fermiophobic SM

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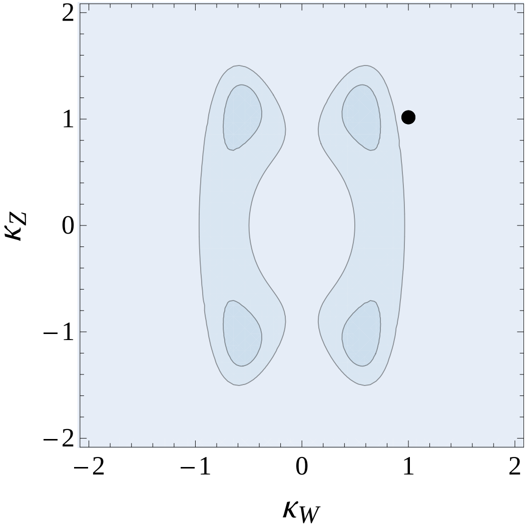

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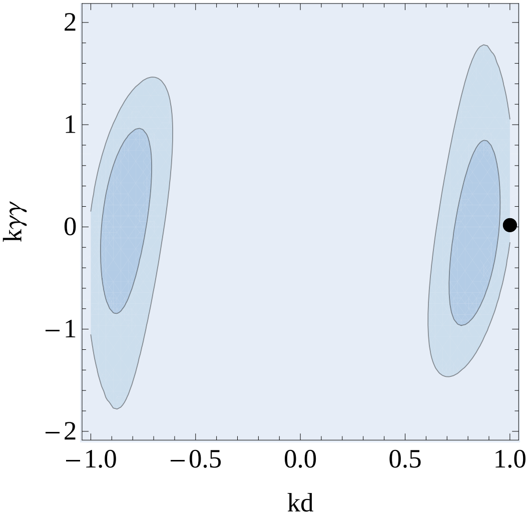

$|\kappa_d| < 1$

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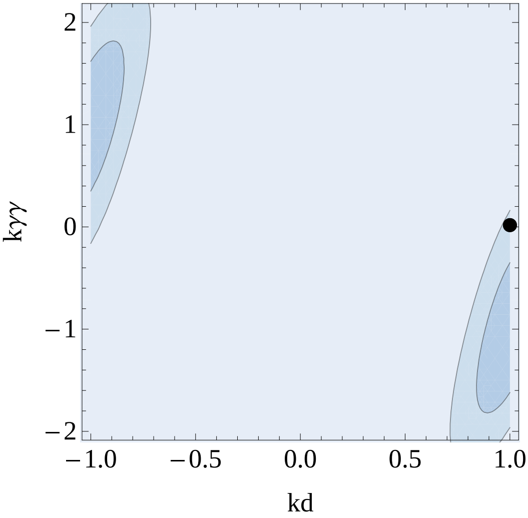

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Conclusion

- 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
  - Compare with bounds from direct searches

Add-Ons

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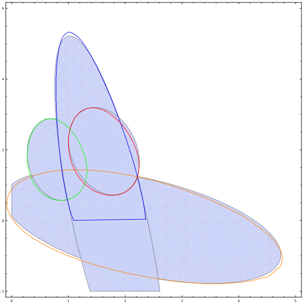
Check of the ellipse fit

After extracting the points from plots from the collaborations, we can superpose them with fitted ellipses to check the validity of the gaussian hypothesis:



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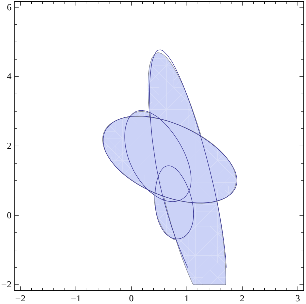

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