Higgs Couplings Beyond the Standard Model

Guillaume Drieu La Rochelle, IPNL, Lyon

HPNP 2013, 富山 - Toyama

Why is the Higgs crucial for New Physics?

- Higgs sector modified in many BSM set-ups
  - Subject to important modifications
    - 4^{th} generation, 2 Higgs Doublets Model, …
  - Novel signatures that depend on underlying Physics

⇒ **Higgs sector is the right place to look for New Physics**

Why is the Higgs crucial for New Physics?

- Higgs sector modified in many BSM set-ups
  - Subject to important modifications
    - 4th generation, 2 Higgs Doublets Model, …
  - Novel signatures that depend on underlying Physics

⇒ **Higgs sector is the right place to look for New Physics**

- Still, if the Higgs is Standard-like :
  - Derive bounds on extra Physics : competitive with direct search
  - This requires a full recast of the SM Higgs searches

Higgs couplings from the data

- Data = Set of measurements in a multi-analysis framework
- Model = Set of predictions for values of the Higgs couplings

⇒ **Test compatibility of a model with data**

Higgs couplings from the data

- Data = Set of measurements in a multi-analysis framework
- Model = Set of predictions for values of the Higgs couplings

→ **Test compatibility of a model with data**

- This requires a statistical treatment :

$\mathcal{L}(\text{data}|\text{model})$ → Test Statistic $\chi^2,\ \Delta\chi^2$ → p-value

  – p-value ≡ compatibility
    - $p_X > 1 - 0.68$ model compatible at 1 sigma level

  – Choice of the test statistics.

Extracting the likelihood $\mathcal{L}$

- Input : set of measured cross-sections :
  - $\hat{\mu}_i = \frac{\sigma_{pp \to H \to X_i}}{\sigma^{SM}_{pp \to H \to X_i}}$, given with 1 σ range [$\hat{\mu}_i - \sigma_i^-, \hat{\mu}_i + \sigma_i^+$]

Extracting the likelihood $\mathcal{L}$

- Input : set of measured cross-sections :
  - $\hat{\mu}_i = \frac{\sigma_{pp\to H\to X_i}}{\sigma^{SM}_{pp\to H\to X_i}}$, given with 1 σ range [$\hat{\mu}_i - \sigma_i^-, \hat{\mu}_i + \sigma_i^+$]

- First approximation : Gaussian form

$$\chi_i^2 = \left(\frac{\mu_{i|\,model} - \hat{\mu}_i}{\sigma_i}\right)^2$$

  - Valid if $n_{obs} \sim n_{exp}$
  - True in most channels except $H \to ZZ$ or some $H \to \gamma\gamma$ subchannels.

Extracting the likelihood $\mathcal{L}$

- Input : set of measured cross-sections :
  - $\hat{\mu}_i = \frac{\sigma_{pp\to H\to X_i}}{\sigma^{SM}_{pp\to H\to X_i}}$, given with 1 σ range [$\hat{\mu}_i - \sigma_i^-$, $\hat{\mu}_i + \sigma_i^+$]

- First approximation : Gaussian form

$$\chi_i^2 = \left(\frac{\mu_{i|\,model} - \hat{\mu}_i}{\sigma_i}\right)^2$$

  - Valid if $n_{obs} \sim n_{exp}$
  - True in most channels except $H \to ZZ$ or some $H \to \gamma\gamma$ subchannels.

- Second approximation : Decorrelated channels

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

  - Valid if statistical errors dominate (But is it still the case?).

Trouble with the likelihood

- The issue of mass
  - Most channels compatible with $m_H = 126$ GeV, BUT Atlas ZZ : $m_H = 123.5$ GeV

Trouble with the likelihood

- The issue of mass
  - Most channels compatible with $m_H = 126$ GeV, BUT Atlas ZZ : $m_H = 123.5$ GeV
- Different subchannels require different treatments :
  - For $H \to WW$ decay $WW + 0j/1j/2j$

$$\left.\begin{array}{l} \mu_{0j} = \mu_{incl.} \times \varepsilon_{0j} \\ \mu_{1j} = \mu_{incl.} \times \varepsilon_{1j} \\ \mu_{2j} = \mu_{incl.} \times \varepsilon_{2j} \end{array}\right\} \text{ requires } \begin{array}{l} \hat{\mu}_{0j}, \hat{\mu}_{1j}, \hat{\mu}_{2j} \\ \varepsilon_{0j}, \varepsilon_{1j}, \varepsilon_{2j} \end{array}$$

  - $H \to \gamma\gamma$, 11 subchannels.

Trouble with the likelihood

- The issue of mass
  - Most channels compatible with $m_H = 126$ GeV, BUT Atlas ZZ : $m_H = 123.5$ GeV
- Different subchannels require different treatments :
  - For $H \to WW$ decay $WW + 0j/1j/2j$

$$\left.\begin{array}{l} \mu_{0j} = \mu_{incl.} \times \varepsilon_{0j} \\ \mu_{1j} = \mu_{incl.} \times \varepsilon_{1j} \\ \mu_{2j} = \mu_{incl.} \times \varepsilon_{2j} \end{array}\right\} \text{ requires } \begin{array}{l} \hat{\mu}_{0j}, \hat{\mu}_{1j}, \hat{\mu}_{2j} \\ \varepsilon_{0j}, \varepsilon_{1j}, \varepsilon_{2j} \end{array}$$

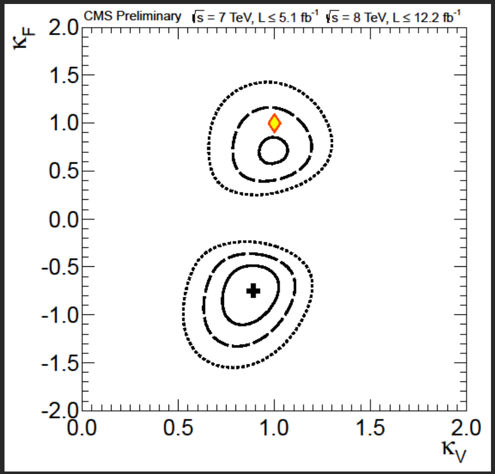
  - $H \to \gamma\gamma$, 11 subchannels.
- All necessary information may not be available
- May underestimate correlations
  - Non negligible error comes from estimations of $\varepsilon_{i,1}, \varepsilon_{i,2} \ldots$
  - However, the sum of the exclusive efficiencies if more precise

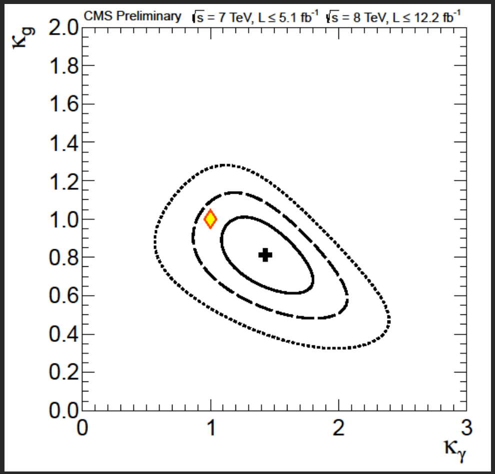
→ The errors on each efficiency are correlated

Trouble-free likelihood

- ATLAS and CMS provide likelihoods for various simplified models
  - $(\kappa_V, \kappa_F), (\kappa_u, \kappa_d), (\kappa_Z, \kappa_W), (\kappa_g, \kappa_\gamma), \dots$

CMS-PAS-HIG-12-045
ATLAS-CONF-2012-127



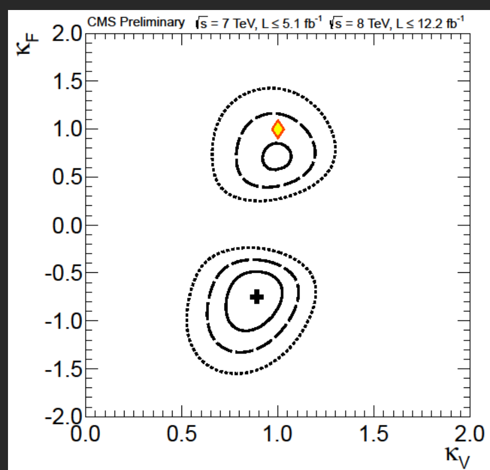


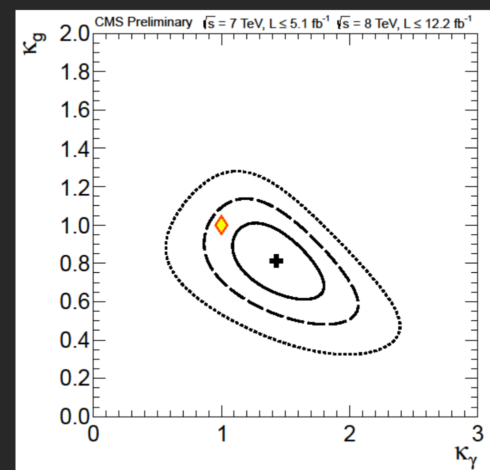
- No approximations ! This is the best one can achieve.

Trouble-free likelihood

- ATLAS and CMS provide likelihoods for various simplified models
  - $(\kappa_V, \kappa_F), (\kappa_u, \kappa_d), (\kappa_Z, \kappa_W), (\kappa_g, \kappa_\gamma), \ldots$

CMS-PAS-HIG-12-045
ATLAS-CONF-2012-127





- No approximations ! This is the best one can achieve.
- But, only available as 2D contours

→ Useless for more complex models

Improved extraction

- Instead of giving all subchannels . . .

$$(\hat{\mu}_{WW}, \sigma_{WW})$$

$$\downarrow$$

$$(\hat{\mu}_{WW,0j}, \sigma_{WW,0j}, \varepsilon_{0j})$$

$$(\hat{\mu}_{WW,0j}, \sigma_{WW,0j}, \varepsilon_{0j})$$

. . .

Improved extraction

- Instead of giving all subchannels . . .

  . . . Use χ^2 as a function of production modes

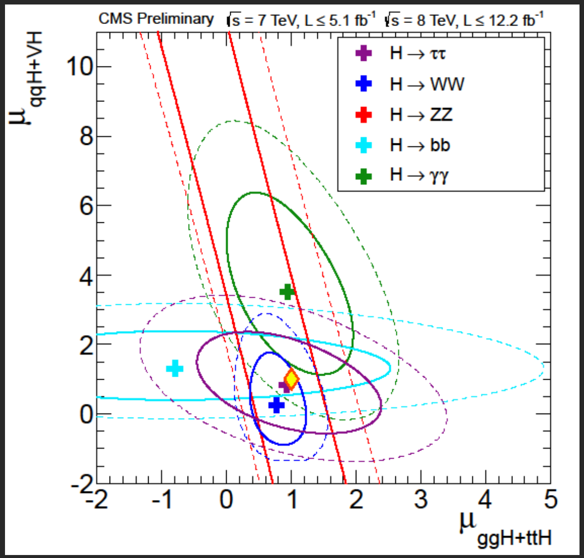
$$(\hat{\mu}_{WW}, \sigma_{WW})$$

$$\downarrow$$

$$(\hat{\mu}_{WW,0j}, \sigma_{WW,0j}, \varepsilon_{0j})$$

$$(\hat{\mu}_{WW,0j}, \sigma_{WW,0j}, \varepsilon_{0j})$$

$$\ldots$$



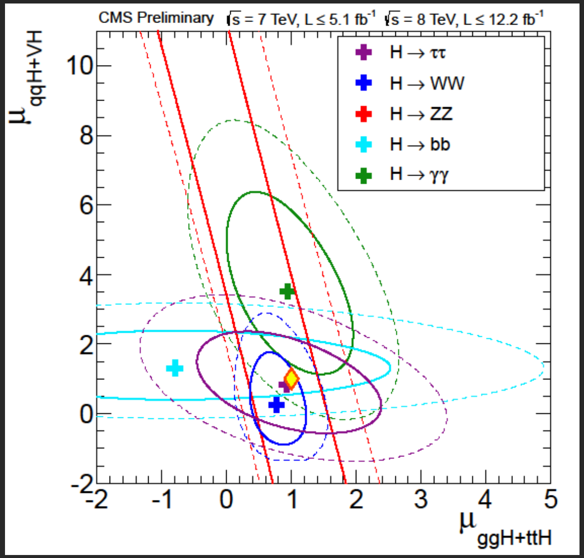
Improved extraction

- Instead of giving all subchannels . . .
  . . . Use χ^2 as a function of production modes

$$(\hat{\mu}_{WW}, \sigma_{WW})$$

↓

$$(\hat{\mu}_{WW,0j}, \sigma_{WW,0j}, \varepsilon_{0j})$$
$$(\hat{\mu}_{WW,0j}, \sigma_{WW,0j}, \varepsilon_{0j})$$
$$\ldots$$



- 2D Gaussian approximation

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

→ See also Belanger et al. arXiv:1212.5244

What do we gain ?

- Simplifies significantly the data processing (from theory side) & keeps part of the correlations.
- Requires that 4 production modes $(gg \to H, \bar{t}tH, VBF, VH)$ are related to 2 parameters $(\mu_{ggH,ttH}, \mu_{VBF,VH})$
  - If custodial symmetry is preserved, VBF and VH scales identically

$$R_{VBF} = R_{VH}$$

  - So far $\bar{t}tH$ production is small, so can be neglected

  Except for $H \to \bar{b}b$, but then $gg \to H$ does not contribute.

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

Going Beyond the SM

There are two approaches towards non-standard effects :

- Model specific
  - One chooses a **UV completion**, with new particles (W', vector-like fermions, and so on)
  - Pros : reasonnable number of parameters ➡ reasonnable fit

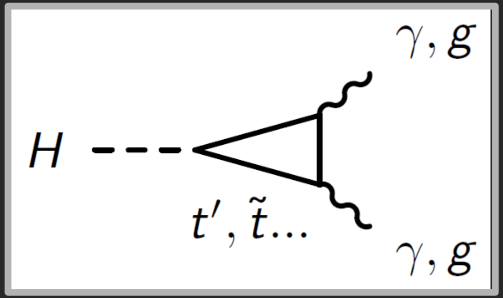
Going Beyond the SM

There are two approaches towards non-standard effects :

- Model specific
  - One chooses a **UV completion**, with new particles (W’, vector-like fermions, and so on)
  - Pros : reasonnable number of parameters ➡ reasonnable fit
- 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

- Target : New Physics contributing mostly via loop-induced couplings
  - This encompasses many models
    - Extra dimensions
    - Vector-like fermions
    - Top partners



  - Keep the number of free parameters small

- Then, for a better description, include also tree-level modifications.

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

- Differs from the recommended parametrisation $(\kappa_g, \kappa_\gamma)$ where

$$\kappa_g^2 = \frac{\Gamma_{H\to gg}}{\Gamma_{H\to gg}^{SM}},\ \kappa_\gamma^2 = \frac{\Gamma_{H\to\gamma\gamma}}{\Gamma_{H\to\gamma\gamma}^{SM}}$$

→ HWSWG arXiv:1209.0040

  - Hide interferences with SM particles since

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

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

- Differs from the recommended parametrisation $(\kappa_g, \kappa_\gamma)$ where

$$\kappa_g^2 = \frac{\Gamma_{H\to gg}}{\Gamma_{H\to gg}^{SM}}, \; \kappa_\gamma^2 = \frac{\Gamma_{H\to\gamma\gamma}}{\Gamma_{H\to\gamma\gamma}^{SM}}$$

HWSWG arXiv:1209.0040

  - Hide interferences with SM particles since

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

- « Top-inspired » parametrisation :

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

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

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

- Differs from the recommended parametrisation $(\kappa_g, \kappa_\gamma)$ where

$$\kappa_g^2 = \frac{\Gamma_{H\to gg}}{\Gamma_{H\to gg}^{SM}}, \ \kappa_\gamma^2 = \frac{\Gamma_{H\to\gamma\gamma}}{\Gamma_{H\to\gamma\gamma}^{SM}}$$

HWSWG arXiv:1209.0040

  - Hide interferences with SM particles since

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

- « Top-inspired » parametrisation :

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

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

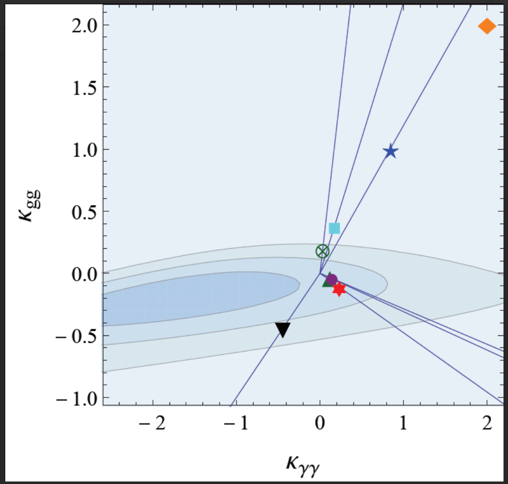
- Easy interpretation for top partners : $\kappa_{gg} = \kappa_{\gamma\gamma} = f(1/M)$
- Avoids correlations when introducing κ_V, κ_b

Specific realisations

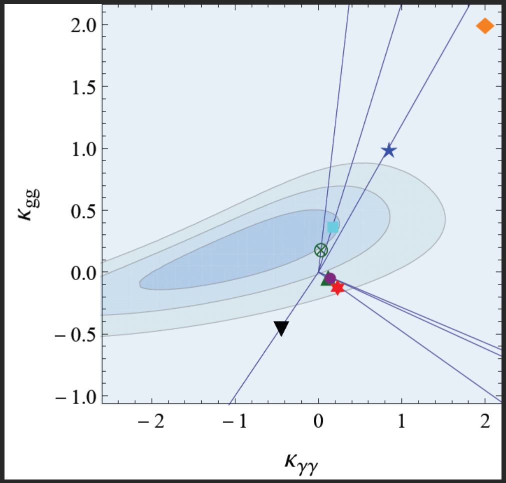
- Benchmark models
  - Extra-dimensional models
    - 5D-UED (⊗)
    - 6D UED (★)
    - Brane Higgs (▼,♠)
  - Colour octet (■)
  - Minimal Composite Higgs Model (●)
  - Little Higgs models
    - Littlest Higgs (*)
    - Simplest Little Higgs (▲)
  - 4^{th} generation (♦)

- All models lie on a line, starting at the Standard Model point
  - Except the 4^{th} generation

Constraining New Physics

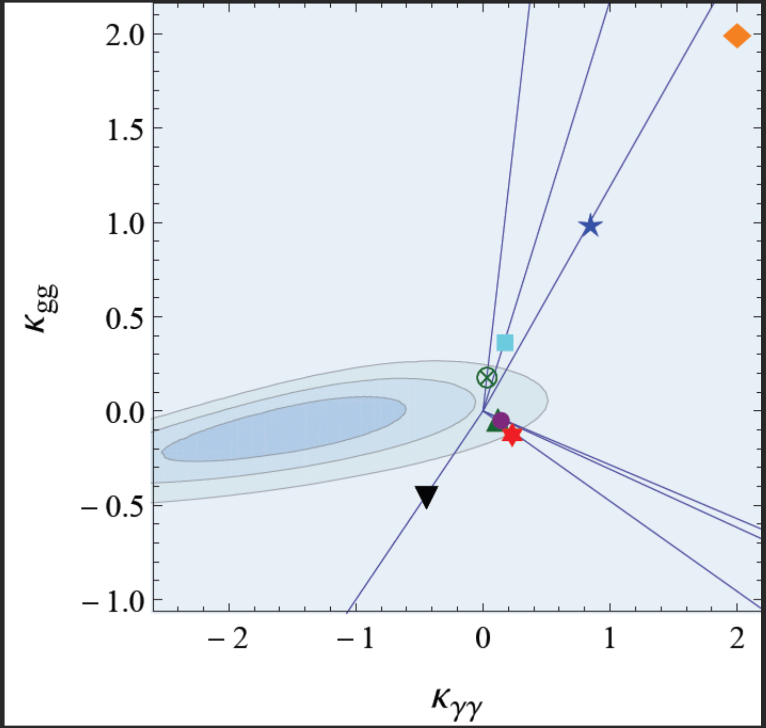


CMS



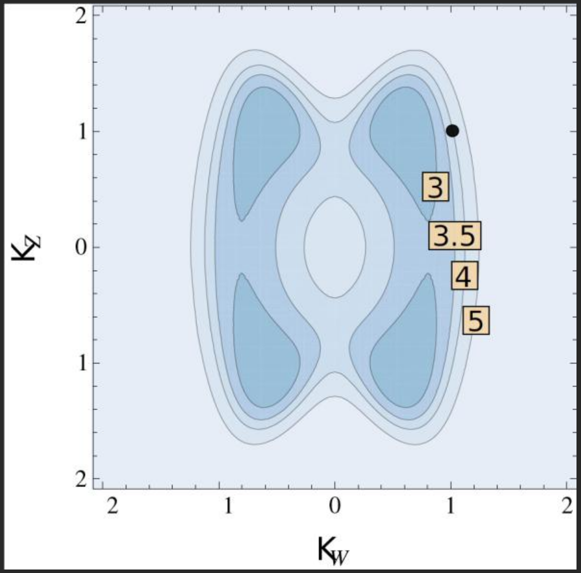
ATLAS

- Excluded at 95% C.L.
  - 4th generation
  - 6D UED up to M_{up}



Fermiophobic model

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



- Change of the statistical test : χ^2 instead of $\Delta\chi^2$
  - Due to the poor quality of the best fit itself.

Conclusion

- Summary
  - The Higgs is certainly a boon in constraining New Physics, but how to do so?
  - Choice of a parametrisation in-between a specific model and an EFT
    - Keeps few parameters
    - Account for different types of New Physics
  - The fit to such a parametrisation should be carried by ATLAS and CMS collaborations
  - Until so, one has to rely on some approximations to derive the constraints

- Prospects
  - Compare systematically with bounds from direct searches
  - Include more experimental input (as for $H \to Z\gamma$)

- Questions ?