# The Higgs Legacy of the LHC Run I

Juan González Fraile

Universität Heidelberg

Tyler Corbett, O. J. P. Éboli, Dorival Gonçalves, J. G–F,
M. C. Gonzalez–Garcia, Tilman Plehn and Michael Rauch

arXiv:1207.1344, 1211.4580, 1304.1151, **1505.05516**

# How to access the EWSB mechanism?

- **Run I**: the Higgs boson was discovered $\rightarrow$ **a particle directly related to the EWSB.**

  Many studies of the Higgs properties have been performed: that could be afterall one of the fastest track to understand the origin of the EWSB.

# How to access the EWSB mechanism?

- **Run I**: the Higgs boson was discovered $\rightarrow$ **a particle directly related to the EWSB.**

  Many studies of the Higgs properties have been performed: that could be afterall one of the fastest track to understand the origin of the EWSB.

  $\diamond$ Is there a preferred framework to study the Higgs interactions?

  $\diamond$ How can we exploit all available data?

# How to access the EWSB mechanism?

- **Run I**: the Higgs boson was discovered $\rightarrow$ **a particle directly related to the EWSB.**

  Many studies of the Higgs properties have been performed: that could be afterall one of the fastest track to understand the origin of the EWSB.

  $\diamond$ Is there a preferred framework to study the Higgs interactions?

  $\diamond$ How can we exploit all available data?

- **Run II**: *Kick off!*

# How to access the EWSB mechanism?

- **Run I**: the Higgs boson was discovered $\rightarrow$ **a particle directly related to the EWSB.**

  Many studies of the Higgs properties have been performed: that could be afterall one of the fastest track to understand the origin of the EWSB.

  $\diamond$ Is there a preferred framework to study the Higgs interactions?

  $\diamond$ How can we exploit all available data?

- **Run II**: *Kick off!*

**Outline**

- $\Delta$-framework for Higgs interactions.
- Effective Lagrangian approach for the Higgs.
- Adding distributions: $p_T$, $\Delta\phi_{jj}$ and off-shell–$m_{4\ell}$.

# ∆–framework: rate–based analysis

Study the Higgs interactions using as a parametrization the SM operators with free couplings:

$$g_x = g_x^{\text{SM}}\ (1+\Delta_x)$$
$$g_\gamma = g_\gamma^{\text{SM}}\ (1+\Delta_\gamma^{\text{SM}}+\Delta_\gamma) \equiv g_\gamma^{\text{SM}}\ (1+\Delta_\gamma^{\text{SM+NP}})$$
$$g_g = g_g^{\text{SM}}\ (1+\Delta_g^{\text{SM}}+\Delta_g) \equiv g_g^{\text{SM}}\ (1+\Delta_g^{\text{SM+NP}})\ ,$$

Thus, the Lagrangian is:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W\ g m_W H\ W^\mu W_\mu + \Delta_Z\ \frac{g}{2c_w} m_Z H\ Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f\ \frac{m_f}{v} H\left(\bar{f}_R f_L + \text{h.c.}\right)$$
$$+ \Delta_g F_G\ \frac{H}{v}\ G_{\mu\nu}G^{\mu\nu} + \Delta_\gamma F_A\ \frac{H}{v}\ A_{\mu\nu}A^{\mu\nu} + \text{invisible decays}\ ,$$

Can be linked to extended Higgs sectors, 2HDM, Higgs Portals etc → see 1308.1979

Can also be almost directly linked to the LO non–linear Effective Lagrangian → see 1504.01707

# SFITTER

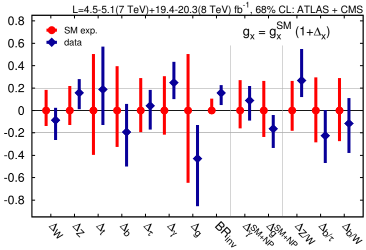
- For the analyses based on event rates (159 measurements):

| Modes | ATLAS | CMS |
|---|---|---|
| $H \to WW$ | 1412.2641 | 1312.1129 |
| $H \to ZZ$ | 1408.5191 | 1312.5353 |
| $H \to \gamma\gamma$ | 1408.7084 | 1407.0558 |
| $H \to \tau\bar{\tau}$ | 1501.04943 | 1401.5041 |
| $H \to b\bar{b}$ | 1409.6212 | 1310.3687 |
| $H \to Z\gamma$ | ATLAS-CONF-2013-009 | 1307.5515 |
| $H \to$ invisible | 1402.3244, ATLAS-CONF-2015-004 | 1404.1344 |
| | 1502.01518, 1504.04324, | CMS-PAS-HIG-14-038 |
| $t\bar{t}H$ production | 1408.7084,1409.3122 | 1407.0558,1408.1682 |
| | | 1502.02485 |
| kinematic distributions | 1409.6212,1407.4222 | |
| off-shell rate | ATLAS-COM-CONF-2014-052 | 1405.3455 |

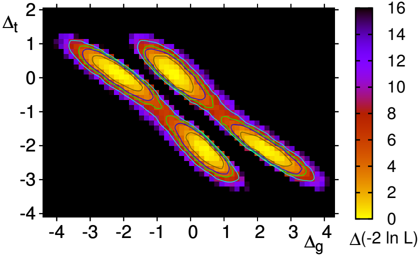
- Correlated experimental uncertainties
- Default: Box shaped theoretical uncertainties
- Default: Uncorrelated production theoretical uncertainties

# ∆–framework: results

◇ 68% CL error bars:

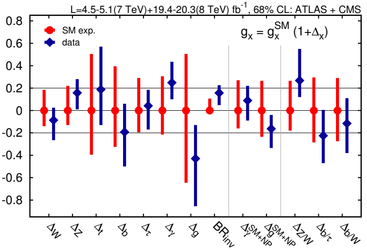



◇ Well understood correlations:

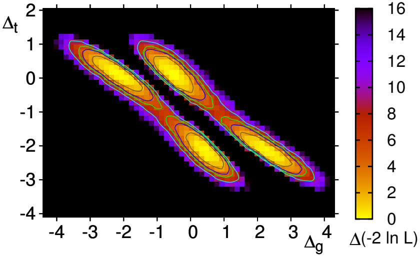


# ∆–framework: results

◇ 68% CL error bars:



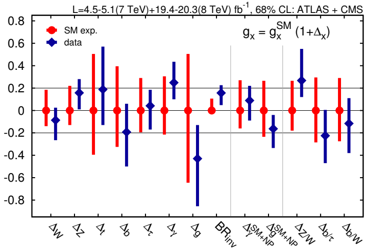

◇ Well understood correlations:



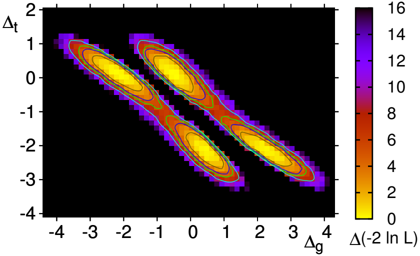

- ◇ Everything consistent with the SM (what a surprise...)
- ◇ ∆–framework is well aligned with experimental measurements. Suitable for testing different analysis details→ **1505.05516**
  Correlated vs. Uncorrelated theoretical uncertainties
  Box-shaped vs. Gaussian theoretical uncertainties
  Passarino estimates, $N^3LO$ for gluon fusion.
- ◇ ∆–framework only suitable for event -rate analysis.

# Δ–framework: results

◇ 68% CL error bars:




◇ Well understood correlations:




◇ Everything consistent with the SM (what a surprise...)

◇ Δ–framework is well aligned with experimental measurements. Suitable for testing different analysis details→ **1505.05516**

Correlated vs. Uncorrelated theoretical uncertainties
Box-shaped vs. Gaussian theoretical uncertainties
Passarino estimates, $N^3LO$ for gluon fusion.

◇ Δ–framework only suitable for event -rate analysis.

How could we add the information from kinematic distributions?→ Effective Lagrangian!

# Effective Lagrangian Approach

Common idea $\sim O(30)$ years: SM success (lack of unexpected) motivates model independent parametrization for NP $\to \mathcal{L}_{\rm eff}$

Based on symmetries and particle content at low energy:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_0^{\rm SM} + \sum_{m=1}^{\infty} \sum_n \frac{f_n^{(4+m)}}{\Lambda^m} \mathcal{O}_n^{(4+m)}$$

First flavor, then LEP/2 and EWPD, TGV, also Higgs at LEP and Tevatron

# Effective Lagrangian Approach

Common idea $\sim O(30)$ years: SM success (lack of unexpected) motivates model independent parametrization for NP $\rightarrow \mathcal{L}_{\rm eff}$

Based on symmetries and particle content at low energy:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_0^{\rm SM} + \sum_{m=1}^{\infty} \sum_n \frac{f_n^{(4+m)}}{\Lambda^m} \mathcal{O}_n^{(4+m)}$$

First flavor, then LEP/2 and EWPD, TGV, also Higgs at LEP and Tevatron

**Apply it to the Higgs sector!**

1207.1344

# Effective Lagrangian Approach

Common idea $\sim O(30)$ years: SM success (lack of unexpected) motivates model independent parametrization for NP $\to \mathcal{L}_{\rm eff}$

Based on symmetries and particle content at low energy:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_0^{\rm SM} + \sum_{m=1}^{\infty} \sum_n \frac{f_n^{(4+m)}}{\Lambda^m} \mathcal{O}_n^{(4+m)}$$

First flavor, then LEP/2 and EWPD, TGV, also Higgs at LEP and Tevatron

**Apply it to the Higgs sector!**

1207.1344


Alternative to the $\Delta$ setup:

- **Correlations** between different sectors: EWPD, TGV and now Higgs!

# Effective Lagrangian Approach

Common idea $\sim O(30)$ years: SM success (lack of unexpected) motivates model independent parametrization for NP $\to \mathcal{L}_{\rm eff}$

Based on symmetries and particle content at low energy:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_0^{\rm SM} + \sum_{m=1}^{\infty} \sum_n \frac{f_n^{(4+m)}}{\Lambda^m} \mathcal{O}_n^{(4+m)}$$

First flavor, then LEP/2 and EWPD, TGV, also Higgs at LEP and Tevatron

**Apply it to the Higgs sector!**

1207.1344


Alternative to the $\Delta$ setup:

- **Correlations** between different sectors: EWPD, TGV and now Higgs!→ 1304.1151 (Higgs-TGV)
- **Correlations** between different Higgs couplings → analysis gets convoluted

# Effective Lagrangian Approach

Common idea $\sim O(30)$ years: SM success (lack of unexpected) motivates model independent parametrization for NP $\to \mathcal{L}_{\rm eff}$

Based on symmetries and particle content at low energy:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_0^{\rm SM} + \sum_{m=1}^{\infty} \sum_n \frac{f_n^{(4+m)}}{\Lambda^m} \mathcal{O}_n^{(4+m)}$$

First flavor, then LEP/2 and EWPD, TGV, also Higgs at LEP and Tevatron

**Apply it to the Higgs sector!**

1207.1344


Alternative to the $\Delta$ setup:

- **Correlations** between different sectors: EWPD, TGV and now Higgs! $\to$ 1304.1151 (Higgs-TGV)
- **Correlations** between different Higgs couplings $\to$ analysis gets convoluted
- New Lorentz structures: potential to break/increase sensitivity with kinematics!

# Effective Lagrangian: the linear realization

Bottom-up model-independent effective Lagrangian approach:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_0^{\text{SM}} + \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$$

Particle content ($SU(2)_L$ doublet), Symmetries (SM, lepton, baryon, CP)

[1] $D_\mu \Phi = \left(\partial_\mu + i\frac{1}{2}g' B_\mu + ig\frac{\sigma_a}{2}W^a_\mu\right)\Phi$, $\hat{B}_{\mu\nu} = i\frac{g'}{2}B_{\mu\nu}$, $\hat{W}_{\mu\nu} = i\frac{g}{2}\sigma^a W^a_{\mu\nu}$

# Effective Lagrangian: the linear realization

**Bottom-up model-independent** effective Lagrangian approach:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_0^{\rm SM} + \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$$

Particle content ($SU(2)_L$ doublet), Symmetries (SM, lepton, baryon, CP)

Choice of basis (not for today): EOM, huge variety of data **(DATA–DRIVEN)**, focus measurable at LHC:

[1] $D_\mu\Phi = \left(\partial_\mu + i\frac{1}{2}g' B_\mu + ig\frac{\sigma_a}{2}W^a_\mu\right)\Phi$, $\hat{B}_{\mu\nu} = i\frac{g'}{2}B_{\mu\nu}$, $\hat{W}_{\mu\nu} = i\frac{g}{2}\sigma^a W^a_{\mu\nu}$

# Effective Lagrangian: the linear realization

**Bottom-up model-independent** effective Lagrangian approach:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_0^{\rm SM} + \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$$

Particle content ($SU(2)_L$ doublet), Symmetries (SM, lepton, baryon, CP)

Choice of basis (not for today): EOM, huge variety of data **(DATA–DRIVEN)**, focus measurable at LHC:[1]

$$\begin{array}{lll}\mathcal{O}_{GG} = \Phi^\dagger\Phi\, G^a_{\mu\nu}G^{a\mu\nu}, & \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi, & \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi, \\ \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right), & \mathcal{O}_W = (D_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\Phi), & \mathcal{O}_B = (D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\Phi), \\ \mathcal{O}_{e\Phi,33} = (\Phi^\dagger\Phi)(\bar{L}_3\Phi e_{R,3}), & \mathcal{O}_{u\Phi,33} = (\Phi^\dagger\Phi)(\bar{Q}_3\tilde{\Phi}u_{R,3}), & \mathcal{O}_{d\Phi,33} = (\Phi^\dagger\Phi)(\bar{Q}_3\Phi d_{R,3})\ ,\end{array}$$

Thus, 9 parameters for Higgs interactions:

$$\frac{f_{GG}}{\Lambda^2}, \frac{f_{WW}}{\Lambda^2}, \frac{f_{BB}}{\Lambda^2}, \frac{f_{\phi,2}}{\Lambda^2}, \frac{f_W}{\Lambda^2}, \frac{f_B}{\Lambda^2}, \frac{f_\tau}{\Lambda^2}, \frac{f_b}{\Lambda^2}, \frac{f_t}{\Lambda^2}$$

[1] $D_\mu\Phi = \left(\partial_\mu + i\frac{1}{2}g' B_\mu + ig\frac{\sigma_a}{2}W^a_\mu\right)\Phi$, $\hat{B}_{\mu\nu} = i\frac{g'}{2}B_{\mu\nu}$, $\hat{W}_{\mu\nu} = i\frac{g}{2}\sigma^a W^a_{\mu\nu}$

# Effective Lagrangian: the linear realization

**Bottom-up model-independent** effective Lagrangian approach:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_0^{\rm SM} + \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$$

Particle content ($SU(2)_L$ doublet), Symmetries (SM, lepton, baryon, CP)

Choice of basis (not for today): EOM, huge variety of data **(DATA–DRIVEN)**, focus measurable at LHC:[1]

$$\begin{array}{lll}
\mathcal{O}_{GG} = \Phi^\dagger \Phi \; G^a_{\mu\nu} G^{a\mu\nu}, & \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi, & \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi, \\
\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu \left(\Phi^\dagger \Phi\right) \partial_\mu \left(\Phi^\dagger \Phi\right), & \mathcal{O}_{W} = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi), & \mathcal{O}_{B} = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi), \\
\mathcal{O}_{e\Phi,33} = (\Phi^\dagger \Phi)(\bar{L}_3 \Phi e_{R,3}), & \mathcal{O}_{u\Phi,33} = (\Phi^\dagger \Phi)(\bar{Q}_3 \tilde{\Phi} u_{R,3}), & \mathcal{O}_{d\Phi,33} = (\Phi^\dagger \Phi)(\bar{Q}_3 \Phi d_{R,3}) \;,
\end{array}$$

Thus, 9 parameters for Higgs interactions:

$$\frac{f_{GG}}{\Lambda^2}, \frac{f_{WW}}{\Lambda^2}, \frac{f_{BB}}{\Lambda^2}, \frac{f_{\phi,2}}{\Lambda^2}, \frac{f_{W}}{\Lambda^2}, \frac{f_{B}}{\Lambda^2}, \frac{f_{\tau}}{\Lambda^2}, \frac{f_{b}}{\Lambda^2}, \frac{f_{t}}{\Lambda^2}$$

Let's see them in unitary gauge

[1] $D_\mu \Phi = \left(\partial_\mu + i\frac{1}{2} g' B_\mu + i g \frac{\sigma_a}{2} W^a_\mu\right)\Phi$, $\hat{B}_{\mu\nu} = i\frac{g'}{2} B_{\mu\nu}$, $\hat{W}_{\mu\nu} = i\frac{g}{2}\sigma^a W^a_{\mu\nu}$

# Effective Lagrangian for Higgs Interactions

$$\begin{aligned}
\mathcal{L}_{\rm eff}^{\rm HVV} &= g_{Hgg}\ HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\ HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\ A_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZ\gamma}\ HA_{\mu\nu}Z^{\mu\nu} \\
&+ g^{(1)}_{HZZ}\ Z_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZZ}\ HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\ HZ_{\mu}Z^{\mu} \\
&+ +g^{(1)}_{HWW}\left(W^+_{\mu\nu}W^{-\,\mu}\partial^{\nu}H + \text{h.c.}\right) + g^{(2)}_{HWW}\ HW^+_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\ HW^+_{\mu}W^{-\,\mu}
\end{aligned}$$

$$\mathcal{L}_{\rm eff}^{Hff} = g^f_{Hij}\bar{f}_L f_R H + \text{h.c.}$$

$$\begin{aligned}
g_{Hgg} &= -\frac{\alpha_s}{8\pi}\frac{f_{GG}v}{\Lambda^2} &, g_{H\gamma\gamma} &= -\left(\frac{g^2 v s^2}{2\Lambda^2}\right)\frac{f_{WW}+f_{BB}}{2}\ , \\
g^{(1)}_{HZ\gamma} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s(f_W-f_B)}{2c} &, g^{(2)}_{HZ\gamma} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s[2s^2 f_{BB}-2c^2 f_{WW}]}{2c}\ , \\
g^{(1)}_{HZZ} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{c^2 f_W + s^2 f_B}{2c^2} &, g^{(2)}_{HZZ} &= -\left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s^4 f_{BB}+c^4 f_{WW}}{2c^2}\ , \\
g^{(1)}_{HWW} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{f_W}{2} &, g^{(2)}_{HWW} &= -\left(\frac{g^2 v}{2\Lambda^2}\right) f_{WW}\ , \\
g^f_{Hij} &= -\frac{m^f_i}{v}\left(1-\frac{v^2}{\sqrt{2}\Lambda^2}f_f\right) &, g^{\Phi,2}_{Hxx} &= g^{\rm SM}_{Hxx}\left(1-\frac{v^2}{2}\frac{f_{\Phi,2}}{\Lambda^2}\right)
\end{aligned}$$

# Effective Lagrangian for Higgs Interactions

$$\begin{aligned}
\mathcal{L}_{\rm eff}^{\rm HVV} &= g_{Hgg}\; HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\; HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\; A_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZ\gamma}\; HA_{\mu\nu}Z^{\mu\nu} \\
&+ g^{(1)}_{HZZ}\; Z_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZZ}\; HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\; HZ_{\mu}Z^{\mu} \\
&+ +g^{(1)}_{HWW}\left(W^{+}_{\mu\nu}W^{-\,\mu}\partial^{\nu}H + \mathrm{h.c.}\right) + g^{(2)}_{HWW}\; HW^{+}_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\; HW^{+}_{\mu}W^{-\,\mu}
\end{aligned}$$

$$\mathcal{L}_{\rm eff}^{Hff} = g^{f}_{Hij}\bar{f}_L f_R H + \mathrm{h.c.}$$

$$g_{Hgg} = -\frac{\alpha_s}{8\pi}\frac{f_{GG}v}{\Lambda^2} \quad , g_{H\gamma\gamma} = -\left(\frac{g^2 v s^2}{2\Lambda^2}\right)\frac{f_{WW}+f_{BB}}{2} \;,$$

$$g^{(1)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s(f_W - f_B)}{2c} \quad , g^{(2)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s[2s^2 f_{BB} - 2c^2 f_{WW}]}{2c} \;,$$

$$g^{(1)}_{HZZ} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{c^2 f_W + s^2 f_B}{2c^2} \quad , g^{(2)}_{HZZ} = -\left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2} \;,$$

$$g^{(1)}_{HWW} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{f_W}{2} \quad , g^{(2)}_{HWW} = -\left(\frac{g^2 v}{2\Lambda^2}\right)f_{WW} \;,$$

$$g^{f}_{Hij} = -\frac{m^f_i}{v}\left(1 - \frac{v^2}{\sqrt{2}\Lambda^2}f_f\right) \quad , g^{\Phi,2}_{Hxx} = g^{\rm SM}_{Hxx}\left(1 - \frac{v^2}{2}\frac{f_{\Phi,2}}{\Lambda^2}\right)$$

# Effective Lagrangian for Higgs Interactions

$$\begin{aligned}
\mathcal{L}_{\rm eff}^{\rm HVV} &= g_{Hgg}\; HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\; HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\; A_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZ\gamma}\; HA_{\mu\nu}Z^{\mu\nu} \\
&+ g^{(1)}_{HZZ}\; Z_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZZ}\; HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\; HZ_{\mu}Z^{\mu} \\
&+ +g^{(1)}_{HWW}\left(W^{+}_{\mu\nu}W^{-\,\mu}\partial^{\nu}H + \text{h.c.}\right) + g^{(2)}_{HWW}\; HW^{+}_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\; HW^{+}_{\mu}W^{-\,\mu}
\end{aligned}$$

$$\mathcal{L}_{\rm eff}^{Hff} = g^{f}_{Hij}\bar{f}_L f_R H + \text{h.c.}$$

$$g_{Hgg} = -\frac{\alpha_s}{8\pi}\frac{f_{GG}v}{\Lambda^2} \quad , g_{H\gamma\gamma} = -\left(\frac{g^2 v s^2}{2\Lambda^2}\right)\frac{f_{WW}+f_{BB}}{2} \quad ,$$

$$g^{(1)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s(f_W - f_B)}{2c} \quad , g^{(2)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s[2s^2 f_{BB} - 2c^2 f_{WW}]}{2c} \quad ,$$

$$g^{(1)}_{HZZ} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{c^2 f_W + s^2 f_B}{2c^2} \quad , g^{(2)}_{HZZ} = -\left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2} \quad ,$$

$$g^{(1)}_{HWW} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{f_W}{2} \quad , g^{(2)}_{HWW} = -\left(\frac{g^2 v}{2\Lambda^2}\right)f_{WW} \quad ,$$

$$g^{f}_{Hij} = -\frac{m_i^f}{v}\left(1 - \frac{v^2}{\sqrt{2}\Lambda^2}f_f\right) \quad , g^{\Phi,2}_{Hxx} = g^{\rm SM}_{Hxx}\left(1 - \frac{v^2}{2}\frac{f_{\Phi,2}}{\Lambda^2}\right)$$

# Effective Lagrangian for Higgs Interactions

$$\begin{aligned}
\mathcal{L}_{\rm eff}^{\rm HVV} &= g_{Hgg}\; HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\; HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\; A_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZ\gamma}\; HA_{\mu\nu}Z^{\mu\nu} \\
&+ g^{(1)}_{HZZ}\; Z_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZZ}\; HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\; HZ_\mu Z^\mu \\
&+ +g^{(1)}_{HWW}\left(W^+_{\mu\nu}W^{-\,\mu}\partial^\nu H + \text{h.c.}\right) + g^{(2)}_{HWW}\; HW^+_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\; HW^+_\mu W^{-\,\mu}
\end{aligned}$$

$$\mathcal{L}_{\rm eff}^{Hff} = g^f_{Hij}\bar{f}_L f_R H + \text{h.c.}$$

$$g_{Hgg} = -\frac{\alpha_s}{8\pi}\frac{f_{GG}v}{\Lambda^2} \quad , g_{H\gamma\gamma} = -\left(\frac{g^2 v s^2}{2\Lambda^2}\right)\frac{f_{WW}+f_{BB}}{2} \quad ,$$

$$g^{(1)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s(f_W - f_B)}{2c} \quad , g^{(2)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s[2s^2 f_{BB} - 2c^2 f_{WW}]}{2c} \quad ,$$

$$g^{(1)}_{HZZ} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{c^2 f_W + s^2 f_B}{2c^2} \quad , g^{(2)}_{HZZ} = -\left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2} \quad ,$$

$$g^{(1)}_{HWW} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{f_W}{2} \quad , g^{(2)}_{HWW} = -\left(\frac{g^2 v}{2\Lambda^2}\right) f_{WW} \quad ,$$

$$g^f_{Hij} = -\frac{m_i^f}{v}\left(1 - \frac{v^2}{\sqrt{2}\Lambda^2}f_f\right) \quad , g^{\Phi,2}_{Hxx} = g^{\rm SM}_{Hxx}\left(1 - \frac{v^2}{2}\frac{f_{\Phi,2}}{\Lambda^2}\right)$$

# Effective Lagrangian for Higgs Interactions

$$
\begin{aligned}
\mathcal{L}_{\rm eff}^{\rm HVV} &= g_{Hgg}\; HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\; HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\; A_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZ\gamma}\; HA_{\mu\nu}Z^{\mu\nu} \\
&+ g^{(1)}_{HZZ}\; Z_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZZ}\; HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\; HZ_{\mu}Z^{\mu} \\
&+ +g^{(1)}_{HWW}\left(W^{+}_{\mu\nu}W^{-\,\mu}\partial^{\nu}H + \text{h.c.}\right) + g^{(2)}_{HWW}\; HW^{+}_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\; HW^{+}_{\mu}W^{-\,\mu}
\end{aligned}
$$

$$
\mathcal{L}_{\rm eff}^{Hff} = g^{f}_{Hij}\bar{f}_L f_R H + \text{h.c.}
$$

$$
g_{Hgg} = -\frac{\alpha_s}{8\pi}\frac{f_{GG}v}{\Lambda^2} \quad , g_{H\gamma\gamma} = -\left(\frac{g^2 v s^2}{2\Lambda^2}\right)\frac{f_{WW}+f_{BB}}{2} \;,
$$

$$
g^{(1)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s(f_W - f_B)}{2c} \quad , g^{(2)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s[2s^2 f_{BB} - 2c^2 f_{WW}]}{2c} \;,
$$

$$
g^{(1)}_{HZZ} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{c^2 f_W + s^2 f_B}{2c^2} \quad , g^{(2)}_{HZZ} = -\left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2} \;,
$$

$$
g^{(1)}_{HWW} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{f_W}{2} \quad , g^{(2)}_{HWW} = -\left(\frac{g^2 v}{2\Lambda^2}\right) f_{WW} \;,
$$

$$
g^{f}_{Hij} = -\frac{m^f_i}{v}\left(1 - \frac{v^2}{\sqrt{2}\Lambda^2}f_f\right) \quad , g^{\Phi,2}_{Hxx} = g^{\rm SM}_{Hxx}\left(1 - \frac{v^2}{2}\frac{f_{\Phi,2}}{\Lambda^2}\right)
$$

# Effective Lagrangian for Higgs Interactions

$$\begin{aligned}\mathcal{L}_{\rm eff}^{\rm HVV} &= g_{Hgg}\, HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\, HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\, A_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZ\gamma}\, HA_{\mu\nu}Z^{\mu\nu} \\ &+ g^{(1)}_{HZZ}\, Z_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZZ}\, HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\, HZ_\mu Z^\mu \\ &+ +g^{(1)}_{HWW}\left(W^+_{\mu\nu}W^{-\,\mu}\partial^\nu H + \text{h.c.}\right) + g^{(2)}_{HWW}\, HW^+_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\, HW^+_\mu W^{-\,\mu}\end{aligned}$$

$$\mathcal{L}_{\rm eff}^{Hff} = g^f_{Hij}\bar{f}_L f_R H + \text{h.c.}$$

$$g_{Hgg} = -\frac{\alpha_s}{8\pi}\frac{f_{GG}v}{\Lambda^2} \quad , g_{H\gamma\gamma} = -\left(\frac{g^2vs^2}{2\Lambda^2}\right)\frac{f_{WW}+f_{BB}}{2} \quad ,$$

$$g^{(1)}_{HZ\gamma} = \left(\frac{g^2v}{2\Lambda^2}\right)\frac{s(f_W-f_B)}{2c} \quad , g^{(2)}_{HZ\gamma} = \left(\frac{g^2v}{2\Lambda^2}\right)\frac{s[2s^2f_{BB}-2c^2f_{WW}]}{2c} \quad ,$$

$$g^{(1)}_{HZZ} = \left(\frac{g^2v}{2\Lambda^2}\right)\frac{c^2f_W+s^2f_B}{2c^2} \quad , g^{(2)}_{HZZ} = -\left(\frac{g^2v}{2\Lambda^2}\right)\frac{s^4f_{BB}+c^4f_{WW}}{2c^2} \quad ,$$

$$g^{(1)}_{HWW} = \left(\frac{g^2v}{2\Lambda^2}\right)\frac{f_W}{2} \quad , g^{(2)}_{HWW} = -\left(\frac{g^2v}{2\Lambda^2}\right)f_{WW} \quad ,$$

$$g^f_{Hij} = -\frac{m_i^f}{v}\left(1-\frac{v^2}{\sqrt{2}\Lambda^2}f_f\right) \quad , g^{\Phi,2}_{Hxx} = g^{\rm SM}_{Hxx}\left(1-\frac{v^2}{2}\frac{f_{\Phi,2}}{\Lambda^2}\right)$$

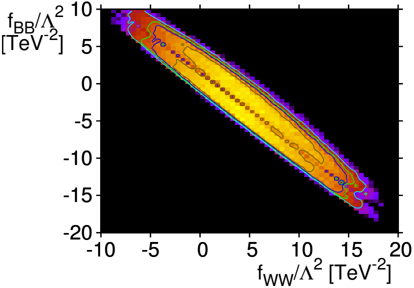
# Effective Lagrangian for Higgs Interactions

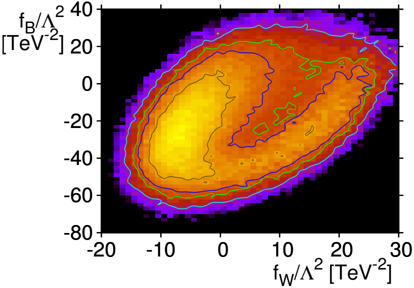
$$
\begin{aligned}
\mathcal{L}_{\rm eff}^{\rm HVV} &= g_{Hgg}\, HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\, HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\, A_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZ\gamma}\, HA_{\mu\nu}Z^{\mu\nu} \\
&+ g^{(1)}_{HZZ}\, Z_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZZ}\, HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\, HZ_{\mu}Z^{\mu} \\
&+ +g^{(1)}_{HWW}\left(W^{+}_{\mu\nu}W^{-\,\mu}\partial^{\nu}H + \text{h.c.}\right) + g^{(2)}_{HWW}\, HW^{+}_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\, HW^{+}_{\mu}W^{-\,\mu}
\end{aligned}
$$

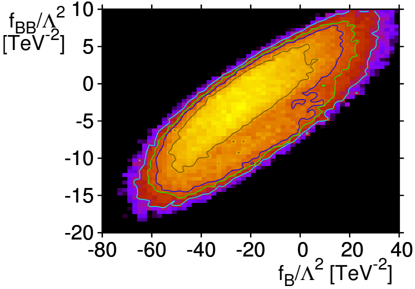
$$
\mathcal{L}_{\rm eff}^{Hff} = g^{f}_{Hij}\bar{f}_L f_R H + \text{h.c.}
$$

$$
\begin{aligned}
g_{Hgg} &= -\frac{\alpha_s}{8\pi}\frac{f_{GG}v}{\Lambda^2} &, g_{H\gamma\gamma} &= -\left(\frac{g^2vs^2}{2\Lambda^2}\right)\frac{f_{WW}+f_{BB}}{2}\,, \\
g^{(1)}_{HZ\gamma} &= \left(\frac{g^2v}{2\Lambda^2}\right)\frac{s(f_W-f_B)}{2c} &, g^{(2)}_{HZ\gamma} &= \left(\frac{g^2v}{2\Lambda^2}\right)\frac{s[2s^2f_{BB}-2c^2f_{WW}]}{2c}\,, \\
g^{(1)}_{HZZ} &= \left(\frac{g^2v}{2\Lambda^2}\right)\frac{c^2f_W+s^2f_B}{2c^2} &, g^{(2)}_{HZZ} &= -\left(\frac{g^2v}{2\Lambda^2}\right)\frac{s^4f_{BB}+c^4f_{WW}}{2c^2}\,, \\
g^{(1)}_{HWW} &= \left(\frac{g^2v}{2\Lambda^2}\right)\frac{f_W}{2} &, g^{(2)}_{HWW} &= -\left(\frac{g^2v}{2\Lambda^2}\right)f_{WW}\,, \\
g^{f}_{Hij} &= -\frac{m^f_i}{v}\left(1-\frac{v^2}{\sqrt{2}\Lambda^2}f_f\right) &, g^{\Phi,2}_{Hxx} &= g^{\rm SM}_{Hxx}\left(1-\frac{v^2}{2}\frac{f_{\Phi,2}}{\Lambda^2}\right)
\end{aligned}
$$

# A variety of correlations

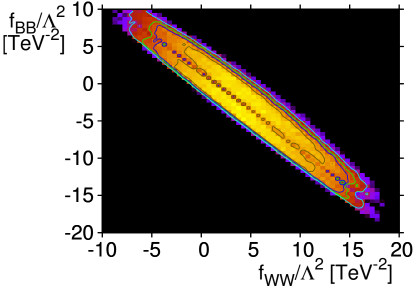


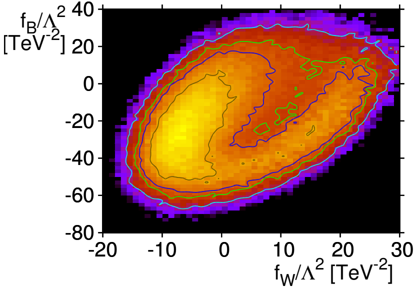



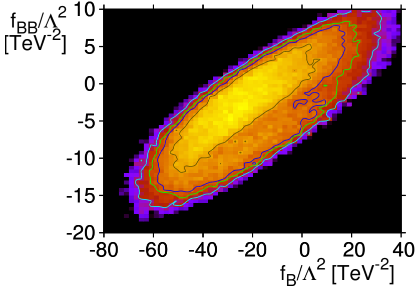




2-d correlations with 68%, 90%, 95% and 99% CL allowed regions in the planes $f_{WW} \times f_{BB}$, $f_W \times f_B$, and $f_B \times f_{BB}$ (TeV$^{-2}\times$ TeV$^{-2}$).

# A variety of correlations



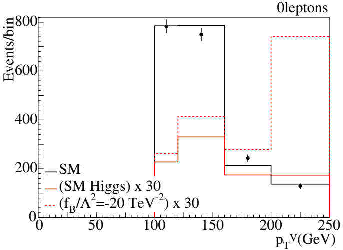



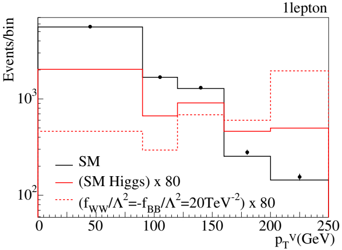

2-d correlations with 68%, 90%, 95% and 99% CL allowed regions in the planes $f_{WW} \times f_{BB}$, $f_W \times f_B$, and $f_B \times f_{BB}$ (TeV$^{-2}\times$ TeV$^{-2}$).

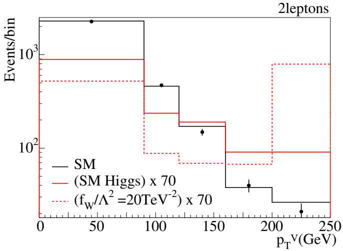
Lorentz structures not exploited so far...

Add kinematic distributions!

# $p_T^V$ in associated production



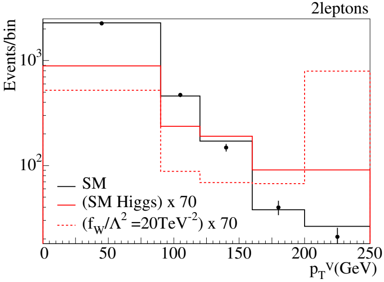

ATLAS $H \to b\bar{b}$ (1409.6212)

$p_T^V$ is sensitive to maximum energy flow of the event

Background rapidly decreases, while enhancement for dimension-6 operators

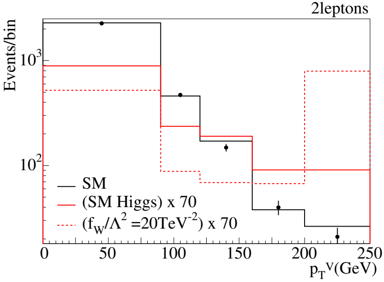
# $p_T^V$ implementation

Simulation with usual tools: FeynRules, MadGraph5, Pythia, PGS4/DELPHES



# $p_T^V$ implementation

Simulation with usual tools: FeynRules, MadGraph5, Pythia, PGS4/DELPHES



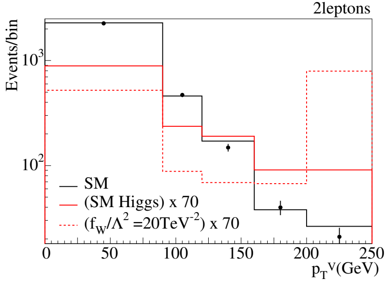

- Distributions for cut–based cross check
  - ◇ Less precise
  - ◇ Shifted central measurement

MVA–8 TeV: $\mu = 0.65 \pm 0.4$
Cut–based–8TeV: $\mu = 1.23 \pm 0.6$

Thus, combination is not straightforward.

# $p_T^V$ implementation

Simulation with usual tools: FeynRules, MadGraph5, Pythia, PGS4/DELPHES




- Distributions for cut–based cross check
  - ◇ Less precise
  - ◇ Shifted central measurement

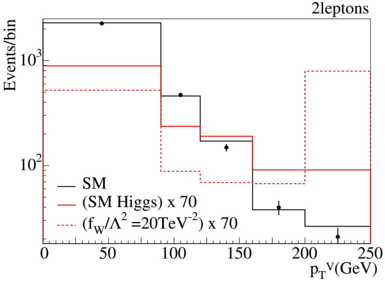
MVA–8 TeV: $\mu = 0.65 \pm 0.4$
Cut–based–8TeV: $\mu = 1.23 \pm 0.6$

Thus, combination is not straightforward.

- Optimal:
  - ◇ fix normalization from MVA

# $p_T^V$ implementation

Simulation with usual tools: FeynRules, MadGraph5, Pythia, PGS4/DELPHES




- Distributions for cut–based cross check
  - ◇ Less precise
  - ◇ Shifted central measurement

MVA–8 TeV: $\mu = 0.65 \pm 0.4$
Cut–based–8TeV: $\mu = 1.23 \pm 0.6$

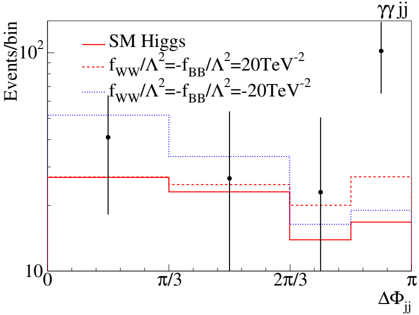
Thus, combination is not straightforward.

- Optimal:
  - ◇ fix normalization from MVA
  - ◇ define *asymmetries*

$$A_i = \frac{\text{bin}_{i+1} - \text{bin}_i}{\text{bin}_{i+1} + \text{bin}_i} \ .$$

Added to the likelihood function propagating the uncertainties

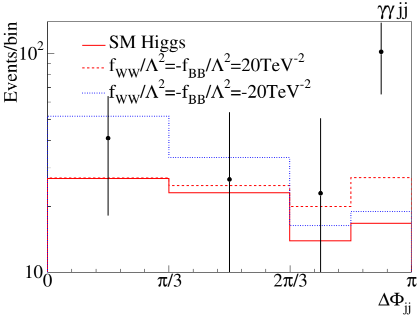
# $\Delta\Phi_{jj}$ in weak boson fusion




ATLAS $H \to \gamma\gamma$ differential study (1407.4222)

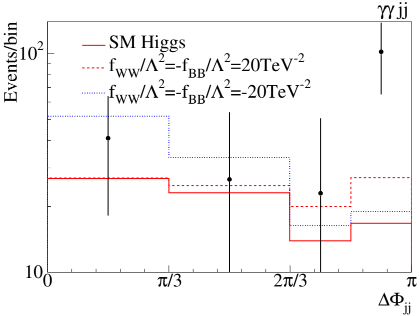
# $\Delta\Phi_{jj}$ in weak boson fusion

- Dimension-6 contributions peak at 0 or $\pi$.




ATLAS $H \to \gamma\gamma$ differential study (1407.4222)

# $\Delta\Phi_{jj}$ in weak boson fusion

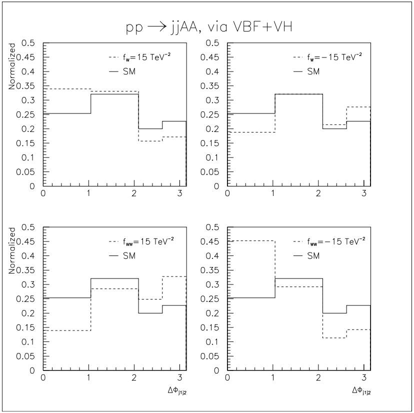



ATLAS $H \to \gamma\gamma$ differential study (1407.4222)

- Dimension-6 contributions peak at 0 or $\pi$.
- **Keep in mind**

  ⋄ WBF better for WW and $\tau\tau$,
  ⋄ No WFB specific cuts: both GGF and VH mess up

# $\Delta\Phi_{jj}$ in weak boson fusion

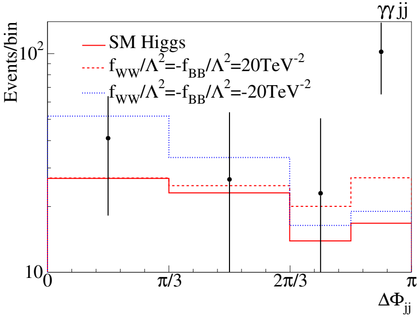



- Dimension-6 contributions peak at 0 or $\pi$.
- **Keep in mind**

  ⋄ WBF better for WW and $\tau\tau$,
  ⋄ No WFB specific cuts: both GGF and VH mess up

  Thus, power dramatically diminished.

# $\Delta\Phi_{jj}$ in weak boson fusion




ATLAS $H \to \gamma\gamma$ differential study (1407.4222)

- Dimension-6 contributions peak at 0 or $\pi$.
- **Keep in mind**

  ◇ WBF better for WW and $\tau\tau$,
  ◇ No WFB specific cuts: both GGF and VH mess up

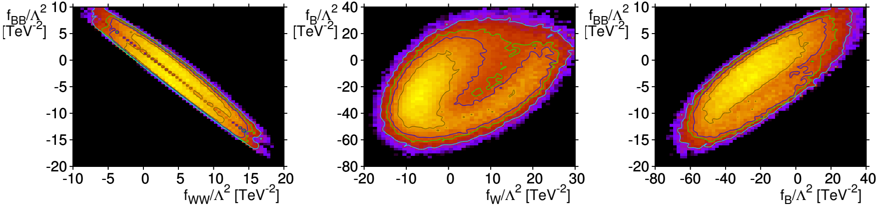
  Thus, power dramatically diminished.
- Combination: again, fix normalization and define sensitive *asymmetries*:

$$A_1 = \frac{(\sigma < \frac{\pi}{3}) + (\sigma > \frac{2\pi}{3}) - (\frac{\pi}{3} < \sigma < \frac{2\pi}{3})}{(\sigma < \frac{\pi}{3}) + (\sigma > \frac{2\pi}{3}) + (\frac{\pi}{3} < \sigma < \frac{2\pi}{3})},$$

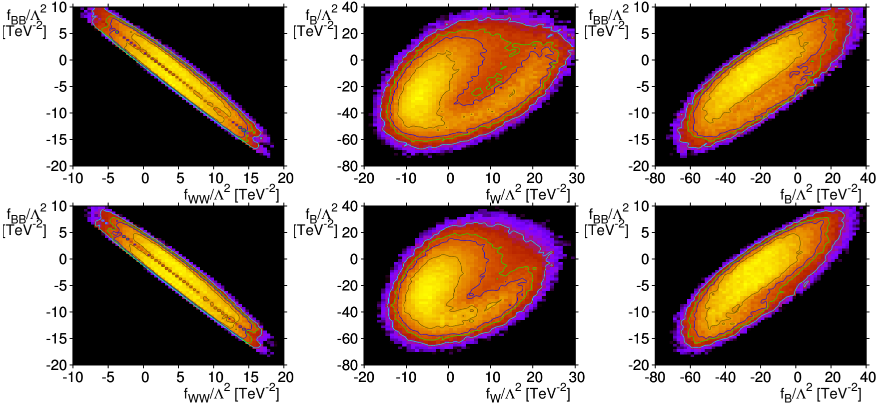
$$A_2 = \frac{(\sigma > \frac{2\pi}{3}) - (\sigma < \frac{\pi}{3})}{(\sigma > \frac{2\pi}{3}) + (\sigma < \frac{\pi}{3})}$$

$$A_3 = \frac{(\sigma > \frac{5\pi}{6}) - (\frac{2\pi}{3} < \sigma < \frac{5\pi}{6})}{(\sigma > \frac{5\pi}{6}) + (\frac{2\pi}{3} < \sigma < \frac{5\pi}{6})}.$$

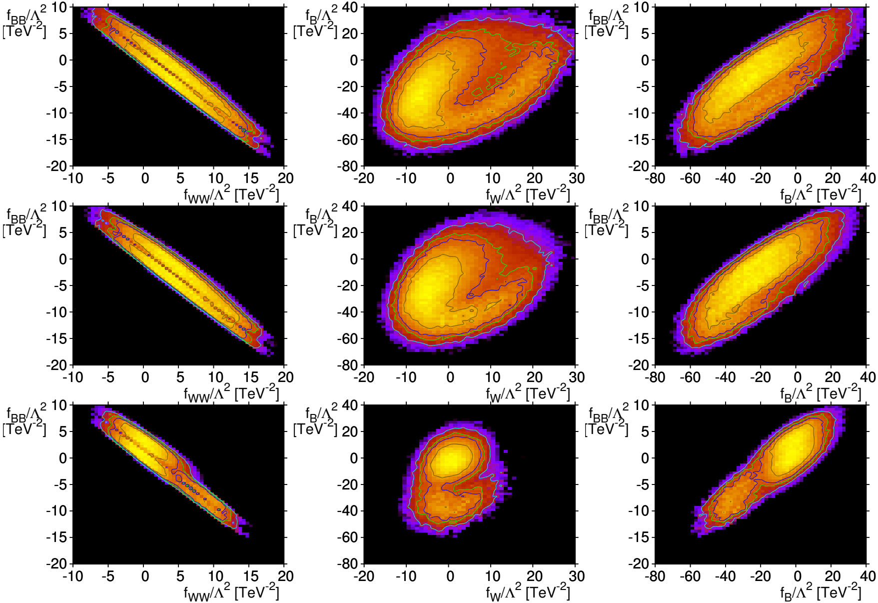
# Full dimension-6 analysis



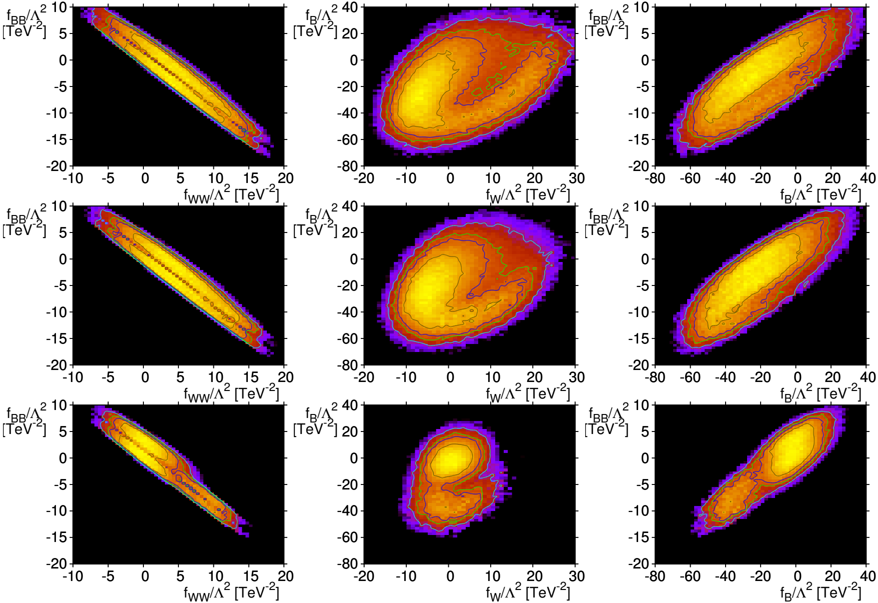
# Full dimension-6 analysis



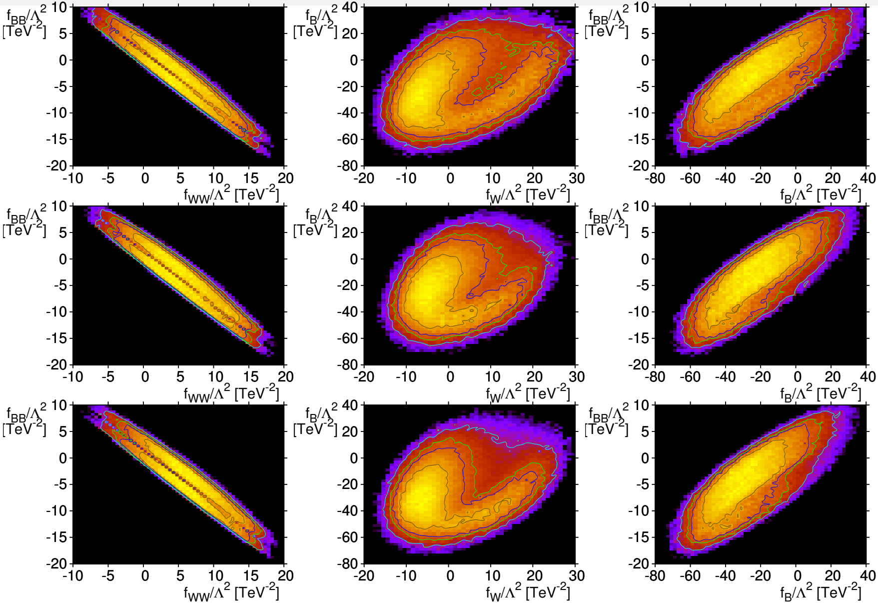
# Full dimension-6 analysis



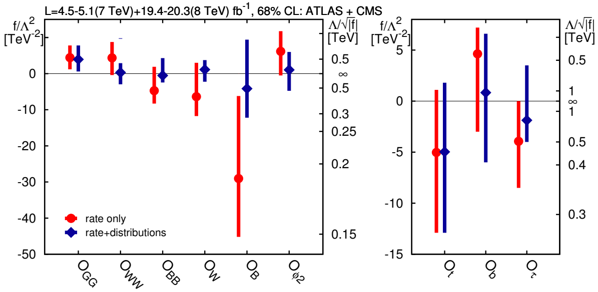
# EFT from Effective?



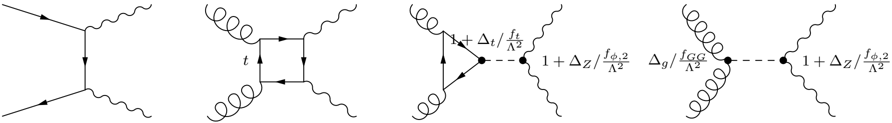
# EFT from Effective?



# 1dimensional results



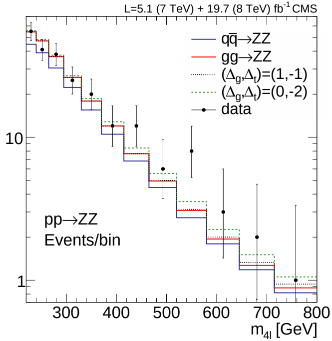
# $m_{4\ell}$ from off–shell measurements




Continuum background $q\bar{q}\,(gg) \to ZZ$ (left) and Higgs signal $gg \to H \to ZZ$ (right).

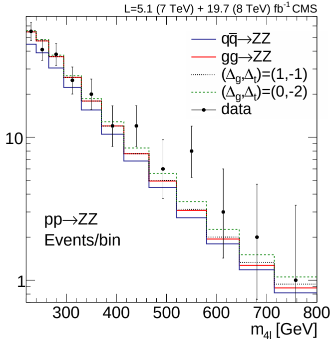
$$\begin{aligned}
\mathcal{M}_{gg\to ZZ} &= (1+\Delta_Z)\left[(1+\Delta_t)\mathcal{M}_t + \Delta_g \mathcal{M}_g\right] + \mathcal{M}_c \\
\frac{d\sigma}{dm_{4\ell}} &= (1+\Delta_Z)\left[(1+\Delta_t)\frac{d\sigma_{tc}}{dm_{4\ell}} + \Delta_g \frac{d\sigma_{gc}}{dm_{4\ell}}\right] \\
&\quad + (1+\Delta_Z)^2\left[(1+\Delta_t)^2\frac{d\sigma_{tt}}{dm_{4\ell}} + (1+\Delta_t)\Delta_g\frac{d\sigma_{tg}}{dm_{4\ell}} + \Delta_g^2\frac{d\sigma_{gg}}{dm_{4\ell}}\right] + \frac{d\sigma_c}{dm_{4\ell}}\;.
\end{aligned}$$

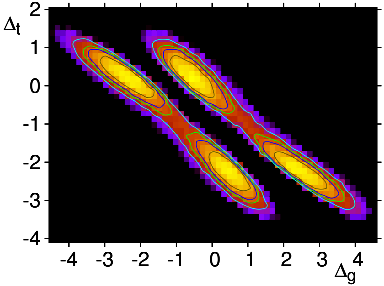
# $m_{4\ell}$ from off–shell measurements




- Here we can use ATLAS and CMS
- Bins directly into the analysis

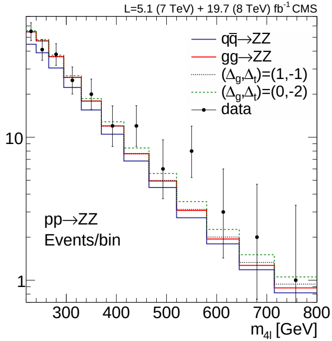
# $m_{4\ell}$ from off–shell measurements

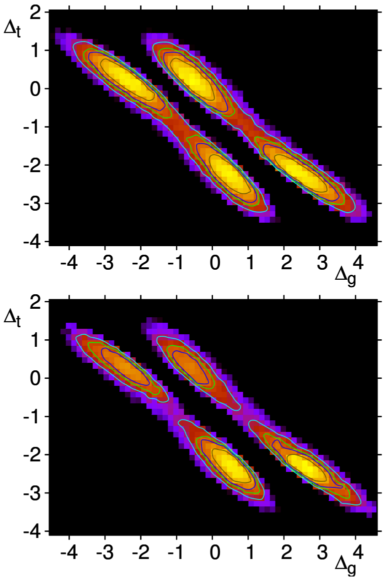



- Here we can use ATLAS and CMS
- Bins directly into the analysis

# $m_{4\ell}$ from off–shell measurements




- Here we can use ATLAS and CMS
- Bins directly into the analysis

# $\Gamma_H$ from off–shell measurements

$$\sigma^{\text{on-shell}}_{i\to H\to f} \propto \frac{g_i^2(m_H)\, g_f^2(m_H)}{\Gamma_H} \qquad \text{vrs.} \qquad \sigma^{\text{off-shell}}_{i\to H^*\to f} \propto g_i^2(m_{4\ell})\, g_f^2(m_{4\ell}) \ .$$

- May allow to bound the Higgs total decay width under certain assumptions.
- Here including effective operators (and not only the gluon fusion top-loop induced production).

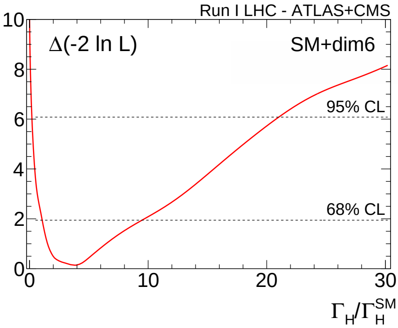
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \ g m_W H \ W^\mu W_\mu + \Delta_Z \ \frac{g}{2c_w} m_Z H \ Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \ \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.}\right)$$

$$+ \Delta_g F_G \ \frac{H}{v} \ G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \ \frac{H}{v} \ A_{\mu\nu} A^{\mu\nu} + \text{invisible decays} + \text{unobservable decays} \ .$$

# $\Gamma_H$ from off–shell measurements

$$\sigma^{\text{on-shell}}_{i\to H\to f} \propto \frac{g_i^2(m_H)\, g_f^2(m_H)}{\Gamma_H} \qquad \text{vrs.} \qquad \sigma^{\text{off-shell}}_{i\to H^*\to f} \propto g_i^2(m_{4\ell})\, g_f^2(m_{4\ell}) \;.$$

- $\Gamma_H < 9.3\Gamma_H^{SM}$ 68% CL
- May allow to bound the Higgs total decay width under certain assumptions.
- Here including effective operators (and not only the gluon fusion top-loop induced production).




$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.}\right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} + \text{invisible decays} + \text{unobservable decays} \;.$$

# Conclusions

**arXiv:1505.05516**

- So far the Higgs boson seems completely SM–like.
  $\Delta$–framework aligned with experimental measurements: test different analysis features.

- Moving to Effective Lagrangian analysis: **Kinematic distributions** essential.
  Restricting to the Higgs sector: biggest differences between EFT and $\Delta$–framework are anomalous momentum dependence on some vertices.

- Optimal implementation of kinematic distributions in a global analysis is feasible:
  ◇ **Increased sensitivity.**
  ◇ **Remove correlations.**

  We start being sensitive to more and more deviations: for instance $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$ in weak sector.
  Drawback: consistenty of EFT will need to be carefully checked.

- Off-shell distributions are also starting to be sensitive to gluon and top operators.
  ◇ Disentangle $\mathcal{O}_{GG}$ from $\mathcal{O}_t$ (and sign of top-Yukawa!).
  ◇ Total width $\Gamma_H < 9.3\Gamma_H^{SM}$ 68% CL.

# Conclusions

**arXiv:1505.05516**

- So far the Higgs boson seems completely SM–like.
  $\Delta$–framework aligned with experimental measurements: test different analysis features.

- Moving to Effective Lagrangian analysis: **Kinematic distributions** essential.
  Restricting to the Higgs sector: biggest differences between EFT and $\Delta$–framework are anomalous momentum dependence on some vertices.

- Optimal implementation of kinematic distributions in a global analysis is feasible:
  - $\diamond$ **Increased sensitivity.**
  - $\diamond$ **Remove correlations.**

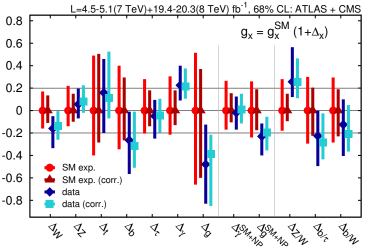
  We start being sensitive to more and more deviations: for instance $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$ in weak sector.
  Drawback: consistenty of EFT will need to be carefully checked.

- Off-shell distributions are also starting to be sensitive to gluon and top operators.
  - $\diamond$ Disentangle $\mathcal{O}_{GG}$ from $\mathcal{O}_t$ (and sign of top-Yukawa!).
  - $\diamond$ Total width $\Gamma_H < 9.3\Gamma_H^{SM}$ 68% CL.

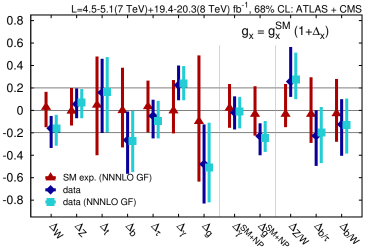
Thank you!

# Δ–framework: results II

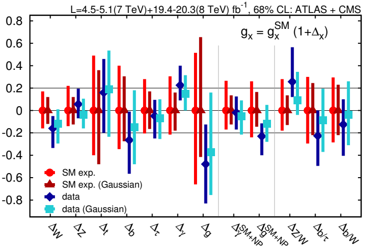
◇ Correlated theory uncertainties:




◇ $N^3LO$ for gluon fusion:




◇ Gaussian theory uncertainties:




◇ Passarino estimate: