

# The Higgs Legacy of the LHC Run I

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# Outline

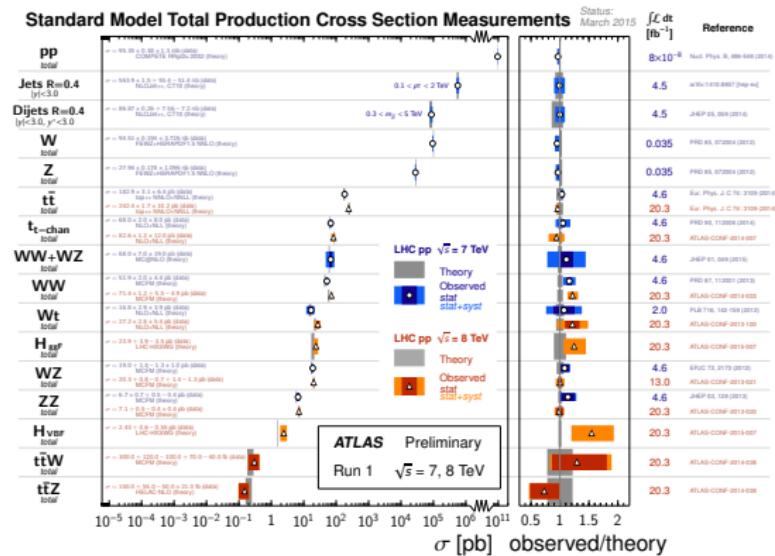
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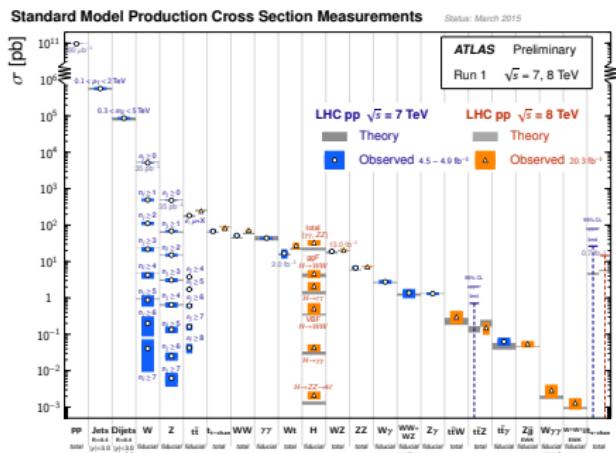
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# Stairway to Heaven or Highway to Hell?

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With all the amazing measurements and with the Higgs discovery, Run I of the LHC kept us on the way.



- We lack understanding of OPEN questions: dark matter, neutrino masses, Hierarchy issue..
  - Very interesting models: SUSY, Composite etc
- They are being tested, but so far, we lack of any other new resonance or appealing deviation...
- We do have a new player in the game.

# Outline

- ◊  $\Delta$ -framework for Higgs interactions.

Simplest (yet powerful) framework: extended Higgs sector, Higgs portals, 2HDM.

**T. Corbett, O. J. P. Éboli, D. Gonçalves, J. G–F, T. Plehn, M. Rauch,  
arXiv: 1505.05516**

- ◊ Effective Lagrangian approach (linear).

The role of kinematic distributions,

Off-shell measurements The role of correlations (Higgs –TGV)

**T. Corbett, O. J. P. Éboli, D. Gonçalves, J. G–F, M. C. Gonzalez–Garcia, T. Plehn, M. Rauch,  
arXiv: 1207.1344, 1211.4580, 1304.1151, 1505.05516**

- ◊ Non-linear EFT.

Decorrelating Higgs – TGV

**I. Brivio, T. Corbett, O. J. P. Éboli, M. B. Gavela, D. Gonçalves, J. G–F,  
M. C. Gonzalez–Garcia, L. Merlo, T. Plehn, M. Rauch, S. Rigolin, J. Yepes,  
arXiv: 1311.1823, 1406.6367, 1511.08188**

# $\Delta$ -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:

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

Can be linked to extended Higgs sectors, 2HDM, Higgs Portals etc → see Lopez–Val *et al*  
1308.1979

Can also be linked to the non-linear Effective Lagrangian → see Buchalla *et al*

1504.01707

# SFITTER

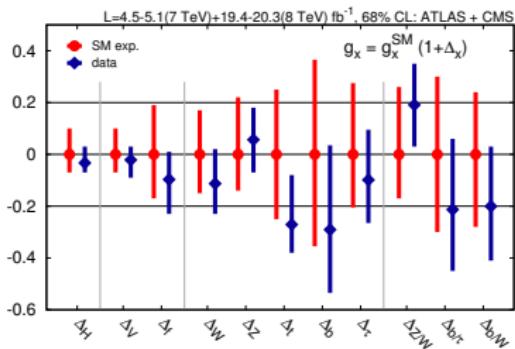
- For the analyses based on event rates (159 measurements):

Modes	ATLAS	CMS
$H \rightarrow WW$	1412.2641	1312.1129
$H \rightarrow ZZ$	1408.5191	1312.5353
$H \rightarrow \gamma\gamma$	1408.7084	1407.0558
$H \rightarrow \tau\bar{\tau}$	1501.04943	1401.5041
$H \rightarrow b\bar{b}$	1409.6212	1310.3687
$H \rightarrow Z\gamma$	ATLAS-CONF-2013-009	1307.5515
$H \rightarrow$ invisible	1402.3244, ATLAS-CONF-2015-004 1502.01518, 1504.04324,	1404.1344 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

# $\Delta$ -framework: results

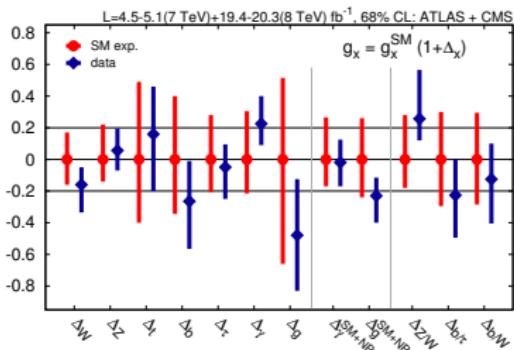
- ◊ 68% CL error bars:



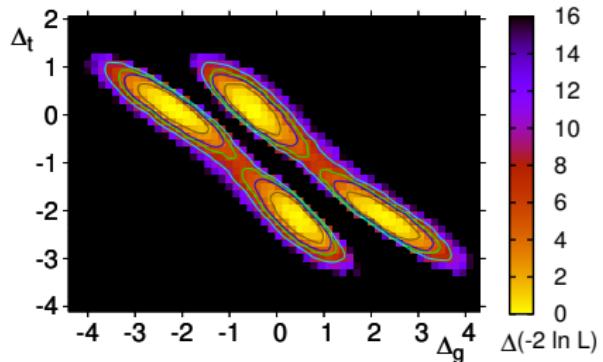
- ◊ Extended Higgs sectors, e. g. extra Singlet:  
 $\cos \alpha = 1 + \Delta_H \in [0.93, 1.]$  at 68% CL.
- ◊ Simple 2HDM, Composite Higgs:  
 $\Delta_V \in 6\%$  and  $\Delta_f \in 12\%$  at 68% CL.

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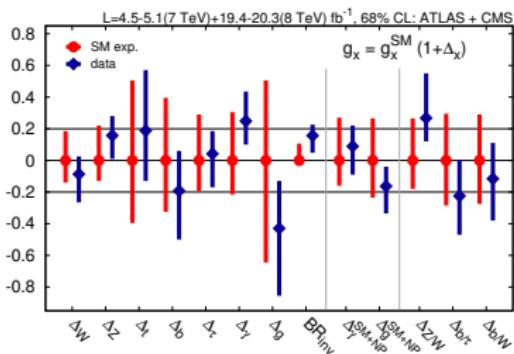
- ◊ Well understood correlations:



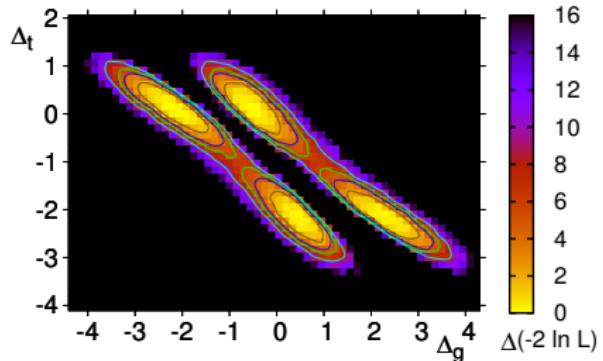
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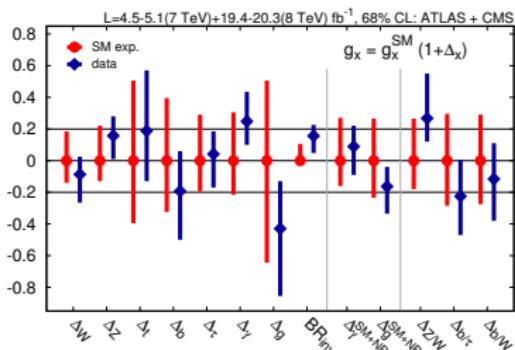
- ◊ Higgs Portals:

$$\text{BR}_{\text{inv}} < 30.6\% \text{ at 95\% CL.}$$

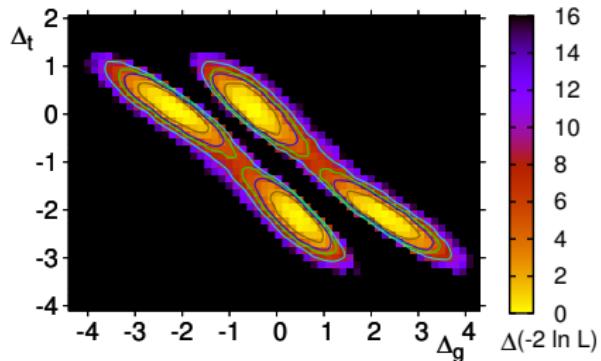
More details e. g. Lopez–Val *et al* 1308.1979

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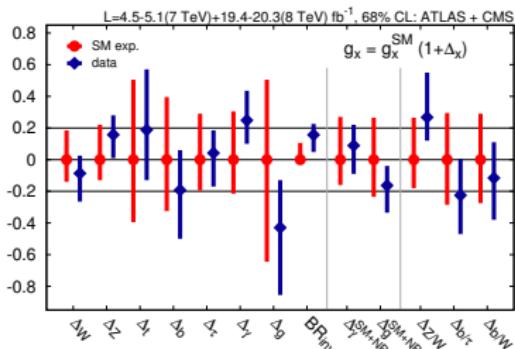
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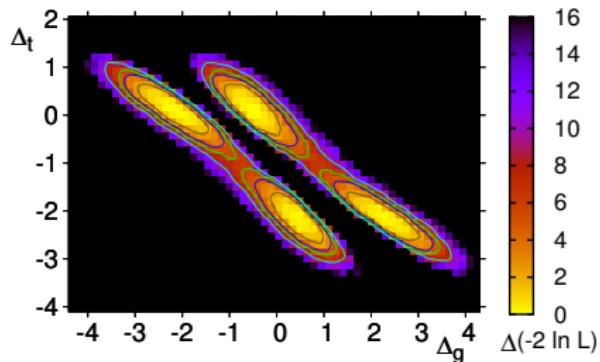
- ◊ Everything consistent with the SM.
- ◊ Δ-framework is well aligned with experimental measurements. Suitable for testing different analysis details → **1505.05516**
- Correlated theory uncertainties, Gaussian vrs flat, N<sup>3</sup>LO for gluon fusion ...
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How to add information from kinematic distributions? EWSB sector? → Effective Lagrangian!

# Effective Lagrangian Approach

$\sim O(30)$  years: SM success motivates model independent parametrization for  $\text{NP} \rightarrow \mathcal{L}_{\text{eff}}$

**Key principle:** To describe physics at some scale (for us, LHC), we do not need to know all the details of the dynamics at a much higher scale.

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

Based on symmetries and particle content at low energy.

**Model Independent:** Captures (almost) any NP BSM without committing to a specific BSM extension. If no NP appears quantify the exclusion accuracy on NP.

Provides a clear **ordering**/hierarchy in terms of  $\Lambda$ .

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

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

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- **Correlations** between different sectors: EWPD, TGV and now Higgs!  $\rightarrow$  Higgs-TGV
- 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)

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

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

Thus, 9 parameters for Higgs interactions:

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Let's see them in unitary gauge

---


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# Effective Lagrangian for Higgs Interactions

$$\begin{aligned}
 \mathcal{L}_{\text{eff}}^{\text{HVV}} &= g_{Hgg} HG_{\mu\nu}^a G^{a\mu\nu} + g_{H\gamma\gamma} HA_{\mu\nu} A^{\mu\nu} + g_{HZ\gamma}^{(1)} A_{\mu\nu} Z^\mu \partial^\nu H + g_{HZ\gamma}^{(2)} HA_{\mu\nu} Z^{\mu\nu} \\
 &+ g_{HZZ}^{(1)} Z_{\mu\nu} Z^\mu \partial^\nu H + g_{HZZ}^{(2)} HZ_{\mu\nu} Z^{\mu\nu} + g_{HZZ}^{(3)} HZ_\mu Z^\mu \\
 &+ +g_{HWW}^{(1)} \left( W_{\mu\nu}^+ W^{-\mu} \partial^\nu H + \text{h.c.} \right) + g_{HWW}^{(2)} HW_{\mu\nu}^+ W^{-\mu\nu} + g_{HWW}^{(3)} HW_\mu^+ W^{-\mu} \\
 \mathcal{L}_{\text{eff}}^{Hff} &= g_{Hij}^f \bar{f}_L f_R H + \text{h.c.}
 \end{aligned}$$

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 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} , \\
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 g_{Hij}^f &= -\frac{m_i^f}{v} \left(1 - \frac{v^2}{\sqrt{2}\Lambda^2} f_f\right) & , g_{Hxx}^{\Phi,2} &= g_{Hxx}^{\text{SM}} \left(1 - \frac{v^2}{2} \frac{f_{\Phi,2}}{\Lambda^2}\right)
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# Effective Lagrangian for Higgs Interactions

$$\begin{aligned}
 \mathcal{L}_{\text{eff}}^{\text{HVV}} &= g_{Hgg} HG_{\mu\nu}^a G^{a\mu\nu} + g_{H\gamma\gamma} HA_{\mu\nu} A^{\mu\nu} + \textcolor{red}{g_{HZ\gamma}^{(1)}} A_{\mu\nu} Z^\mu \partial^\nu H + \textcolor{red}{g_{HZ\gamma}^{(2)}} HA_{\mu\nu} Z^{\mu\nu} \\
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 &+ \textcolor{red}{+ g_{HWW}^{(1)} \left( W_{\mu\nu}^+ W^{-\mu} \partial^\nu H + \text{h.c.} \right) + g_{HWW}^{(2)} HW_{\mu\nu}^+ W^{-\mu\nu} + g_{HWW}^{(3)} HW_\mu^+ W^{-\mu}} \\
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# Global analysis of the Higgs interactions I

Event rates (159 measurements) from ATLAS  
and CMS analyses:

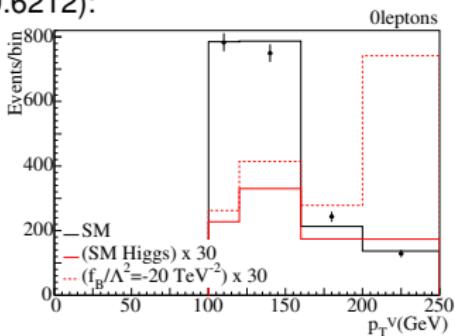
Modes
$H \rightarrow WW$
$H \rightarrow ZZ$
$H \rightarrow \gamma\gamma$
$H \rightarrow \tau\bar{\tau}$
$H \rightarrow b\bar{b}$
$H \rightarrow Z\gamma$
$H \rightarrow \text{invisible}$
$t\bar{t}H$ production

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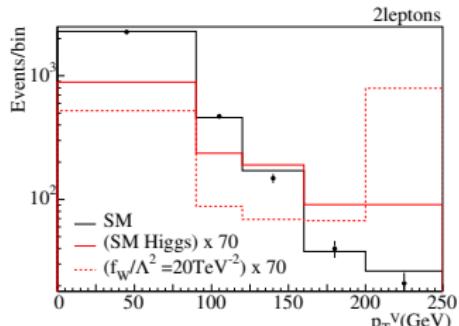
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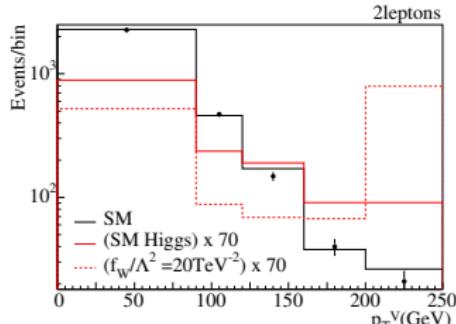


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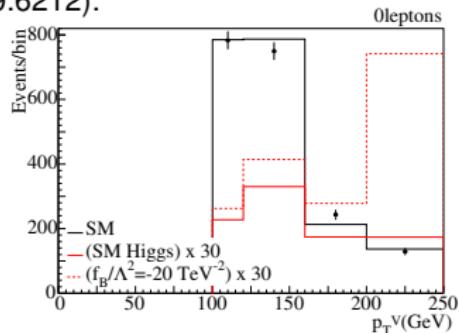
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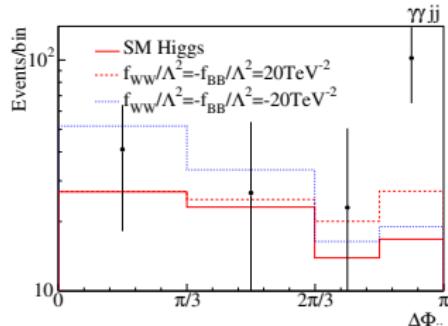
Kinematic distributions from ATLAS  $H \rightarrow b\bar{b}$  (1409.6212):



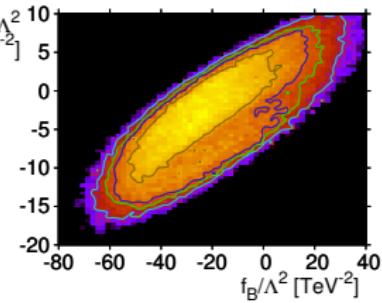
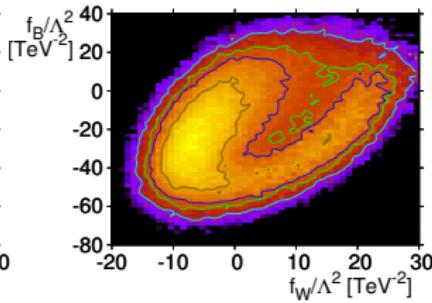
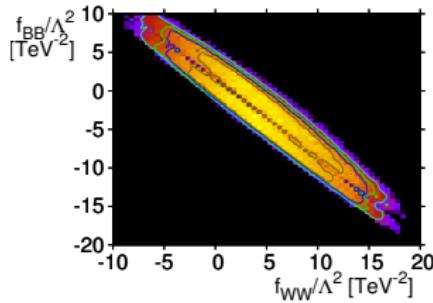
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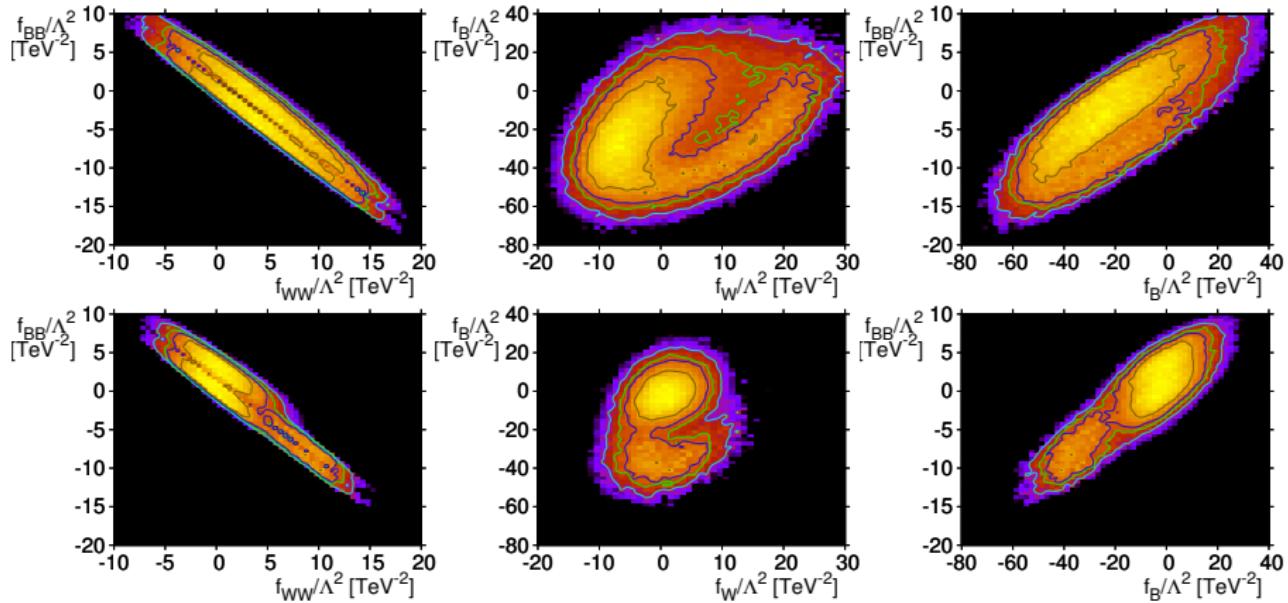
From ATLAS differential  $H \rightarrow \gamma\gamma$  (1407.4222):



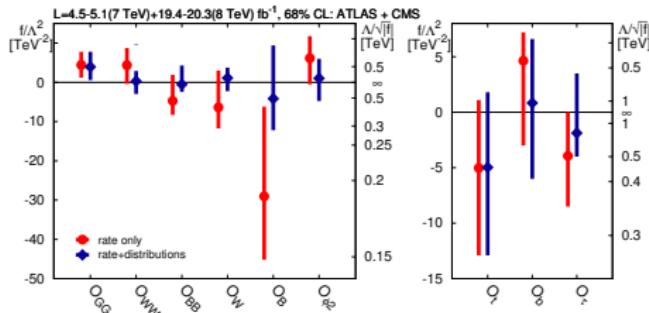
# Full dimension-6 analysis



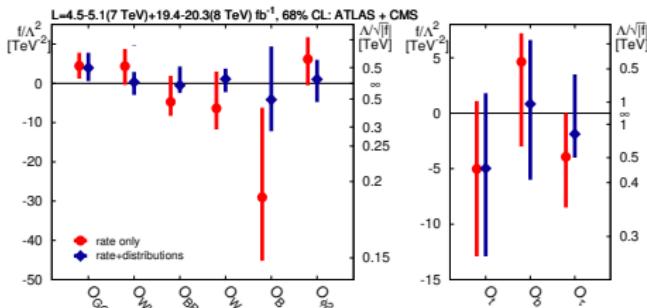
# Full dimension-6 analysis



# EFT from Effective?



# EFT from Effective?



With the current sensitivity, this is model dependent dimension-6 Lagrangian.

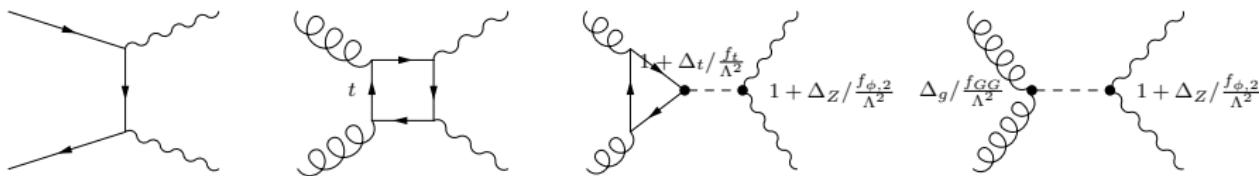
EFT vrs. full model: Biekoetter *et al* 1406.7320, Gorbhan *et al* 1502.07352, Dawson *et al* 1501.04103, Craig *et al* 1411.0676, Drozd *et al* 1504.02409 etc

Brehmer *et al* 1510.03443:

- Several weakly interacting extensions: extra singlet, extra doublet, vector triplet, colored scalar partner
- Several Higgs channels: Associated production, WBF, decays to photons,  $4\ell$ , hh
- Several variables:  $m_{4\ell}$ ,  $m_{VH}$ ,  $p_{T,j}$ ,  $\Delta\Phi_{jj}$  etc

Interesting questions raise about how to perform the matching.

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

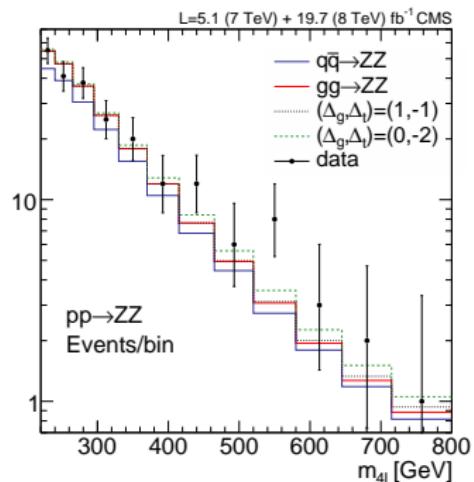


Continuum background  $q\bar{q}(gg) \rightarrow ZZ$  (left) and Higgs signal  $gg \rightarrow H \rightarrow ZZ$  (right).

$$\mathcal{M}_{gg \rightarrow ZZ} = (1 + \Delta_Z) [(1 + \Delta_t) \mathcal{M}_t + \Delta_g \mathcal{M}_g] + \mathcal{M}_c$$

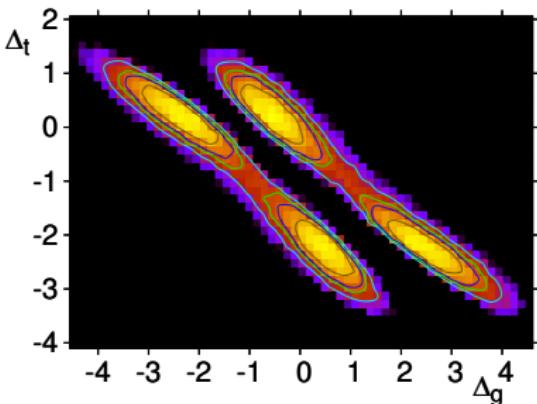
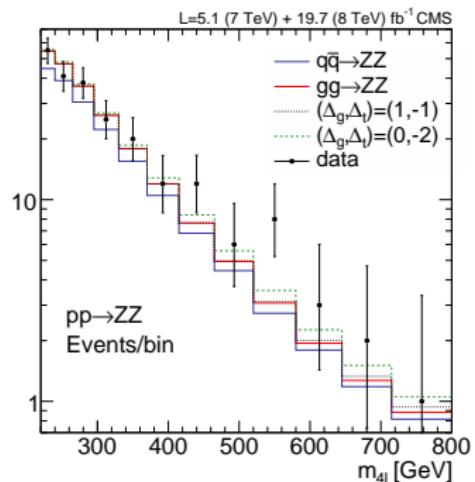
$$\begin{aligned} \frac{d\sigma}{dm_{4\ell}} &= (1 + \Delta_Z) \left[ (1 + \Delta_t) \frac{d\sigma_{tc}}{dm_{4\ell}} + \Delta_g \frac{d\sigma_{gc}}{dm_{4\ell}} \right] \\ &\quad + (1 + \Delta_Z)^2 \left[ (1 + \Delta_t)^2 \frac{d\sigma_{tt}}{dm_{4\ell}} + (1 + \Delta_t) \Delta_g \frac{d\sigma_{tg}}{dm_{4\ell}}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

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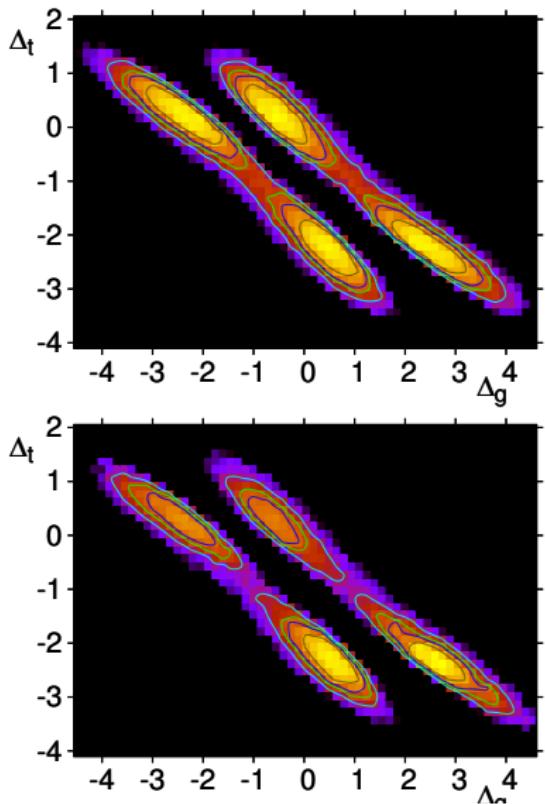
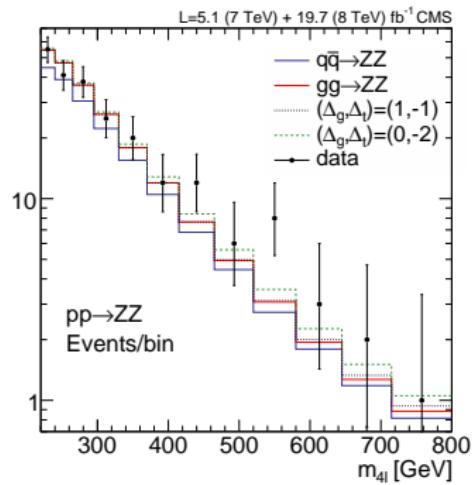
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# $\Gamma_H$ from off-shell measurements

$$\sigma_{i \rightarrow H \rightarrow f}^{\text{on-shell}} \propto \frac{g_i^2(m_H) g_f^2(m_H)}{\Gamma_H} \quad \text{vrs.} \quad \sigma_{i \rightarrow H^* \rightarrow f}^{\text{off-shell}} \propto g_i^2(m_{4\ell}) g_f^2(m_{4\ell}) .$$

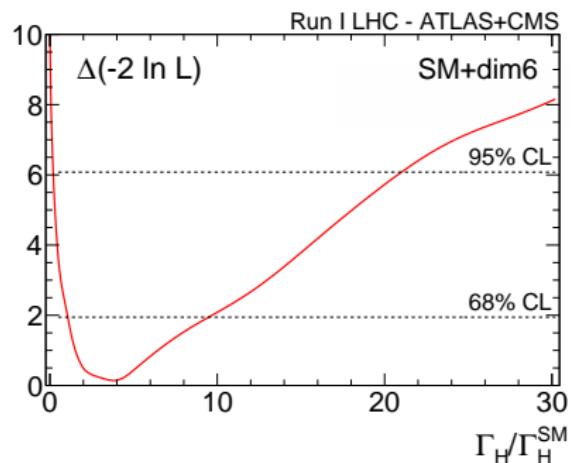
- May allow to bound the Higgs total decay width under certain assumptions.
- Here including effective operators (and not only the gluon fusion top-loop induced production).

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

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- $\Gamma_H < 9.3\Gamma_H^{\text{SM}}$  68% CL
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# Effective Lagrangian for TGV interactions

The usual Lagrangian to study TGV<sup>2</sup> interactions since LEP:

$$\begin{aligned}\mathcal{L}_{\text{eff}}^{WWV} = & g_{WWV} \left( -ig_1^V \left( W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger W^{\mu\nu} V_\nu \right) - i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} \right. \\ & \left. - i \frac{\lambda_V}{M_W^2} W_{\rho\mu}^\dagger W_\nu^\mu V^{\nu\rho} - g_5^V \epsilon^{\mu\nu\rho\sigma} (W_\mu^\dagger \partial_\rho W_\nu - \partial_\rho W_\mu^\dagger W_\nu) V_\sigma \right)\end{aligned}$$

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<sup>2</sup>Triple Gauge boson Vertex.

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Where is  $g_5^Z$ ? Comes from dim-8, but wait...

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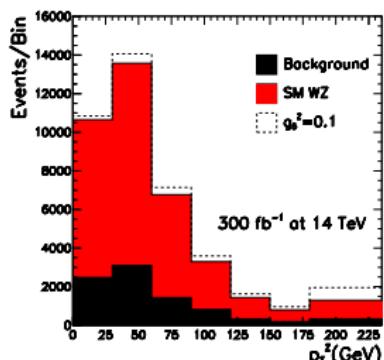
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The usual Lagrangian to study TGV<sup>2</sup> interactions since LEP:

$$\begin{aligned} \mathcal{L}_{\text{eff}}^{WWV} = & g_{WWV} \left( -ig_1^V (W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger W^{\mu\nu} V_\nu) - i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} \right. \\ & \left. - i \frac{\lambda_V}{M_W^2} W_{\rho\mu}^\dagger W_\nu^\mu V^{\nu\rho} - g_5^V \epsilon^{\mu\nu\rho\sigma} (W_\mu^\dagger \partial_\rho W_\nu - \partial_\rho W_\mu^\dagger W_\nu) V_\sigma \right) \end{aligned}$$

These can be directly measured at Colliders in gauge boson production, poor theorist's attempt:



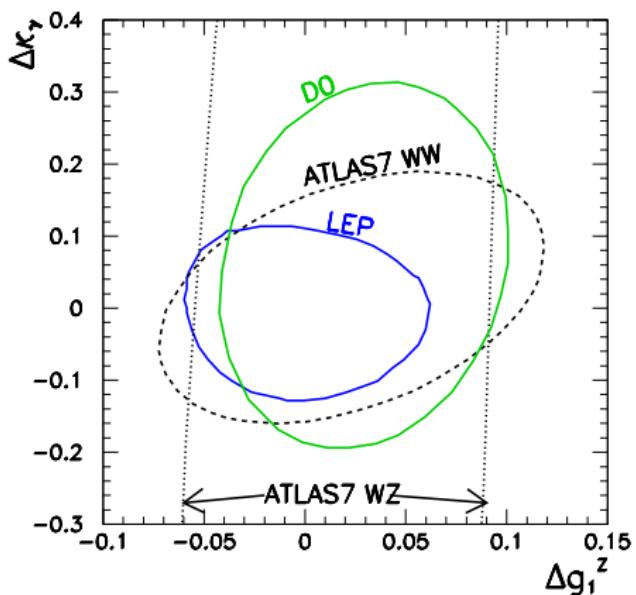
$$\begin{aligned} \Delta g_1^Z &= g_1^Z - 1 = \frac{g^2 v^2}{8c^2 \Lambda^2} f_W , \\ \Delta \kappa_\gamma &= \kappa_\gamma - 1 = \frac{g^2 v^2}{8\Lambda^2} (f_W + f_B) , \\ \Delta \kappa_Z &= \kappa_Z - 1 = \frac{g^2 v^2}{8c^2 \Lambda^2} (c^2 f_W - s^2 f_B) , \\ \lambda_\gamma &= \lambda_Z = \frac{3g^2 M_W^2}{\Lambda^2} f_{WWW} . \end{aligned}$$

Where is  $g_5^Z$ ? Comes from dim-8, but wait...

<sup>2</sup>Triple Gauge boson Vertex.

# Determining TGV

arxiv:1304.1151



$$\begin{aligned}\Delta g_1^Z &= g_1^Z - 1 = \frac{g^2 v^2}{8c^2 \Lambda^2} f_W , \\ \Delta\kappa_\gamma &= \kappa_\gamma - 1 = \frac{g^2 v^2}{8\Lambda^2} (f_W + f_B) , \\ \Delta\kappa_Z &= \kappa_Z - 1 = \frac{g^2 v^2}{8c^2 \Lambda^2} (c^2 f_W - s^2 f_B) .\end{aligned}$$

For the plane:

- ◊ Measurements with only two of the three aTGV independent.
- ◊ Additional assumption:  
 $\lambda_V = 0 \Leftrightarrow f_{WWW} = 0$ .

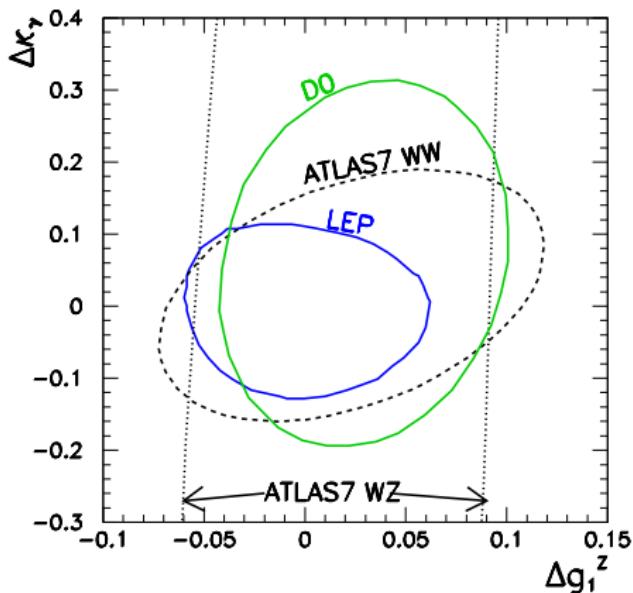
Complete 7+8 TeV LHC results are missing

# Determining TGV from Higgs data

arxiv:1304.1151

- Gauge Invariance  $\rightarrow$  TGV and Higgs couplings related:  $\mathcal{O}_W$  and  $\mathcal{O}_B$
- **Complementarity in experimental searches:** Higgs data bounds on

$$f_W \otimes f_B \Leftrightarrow \Delta\kappa_\gamma \otimes \Delta g_1^Z$$



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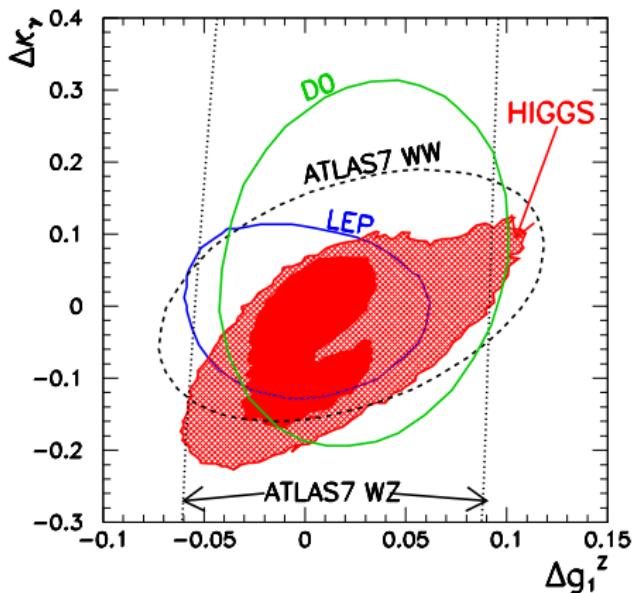
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Complete 7+8 TeV LHC results are missing

# Disentangling a dynamical Higgs

- Motivated by composite models → Higgs as a PGB of a global symmetry.
- Non-linear or “chiral” effective Lagrangian expansion including the light Higgs.

SM Gauge bosons and fermions

Light Higgs → without a given model treated as generic “singlet”  $h$

$$F_i(h) = 1 + 2a_i \frac{h}{v} + b_i \frac{h^2}{v^2} + \dots$$

↔

$h$  is not part of  $\Phi$   
More possible operators

Dimensionless unitary matrix:  $U(x) = e^{i\sigma_a \pi^a(x)/v}$

$$(V_\mu \equiv (D_\mu U) U^\dagger \text{ and } T \equiv U \sigma_3 U^\dagger)$$

↔

Relative reshuffling of the  
order at which operators  
appear

- Bosonic (pure gauge and gauge- $h$  operators) and Yukawa-like up to four derivatives

$$\mathcal{L}_{\text{chiral}} = \mathcal{L}_0 + \Delta \mathcal{L}$$

Comparison with the linear basis!

# The Non-linear Lagrangian

Alonso *et al* 1212.3305Buchalla *et al* 1307.5017

$$\mathcal{L}_{\text{chiral}} = \mathcal{L}_0 + \Delta\mathcal{L}$$

SM Lagrangian<sup>3</sup>

$$\begin{aligned} \mathcal{L}_0 = & \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \frac{1}{4}W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu} - \frac{1}{4}G_{\mu\nu}^a G^{a\mu\nu} - V(h) \\ & - \frac{(v+h)^2}{4} \text{Tr}[\nabla_\mu \nabla^\mu] + i\bar{Q}\not{D}Q + i\bar{L}\not{D}L \\ & - \frac{v+s_Y h}{\sqrt{2}} (\bar{Q}_L \mathbf{U} \mathbf{Y}_Q Q_R + \text{h.c.}) - \frac{v+s_Y h}{\sqrt{2}} (\bar{L}_L \mathbf{U} \mathbf{Y}_L L_R + \text{h.c.}) , \end{aligned}$$

Restricting to bosonic (pure gauge and gauge- $h$  operators):

$$\begin{aligned} \Delta\mathcal{L} = & \xi [c_B \mathcal{P}_B(h) + c_W \mathcal{P}_W(h) + c_G \mathcal{P}_G(h) + c_C \mathcal{P}_C(h) + c_T \mathcal{P}_T(h) \\ & + c_H \mathcal{P}_H(h) + c_{\square H} \mathcal{P}_{\square H}(h)] + \xi \sum_{i=1}^{10} c_i \mathcal{P}_i(h) \\ & + \xi^2 \sum_{i=11}^{25} c_i \mathcal{P}_i(h) + \xi^4 c_{26} \mathcal{P}_{26}(h) + \Sigma_i \xi^{n_i} c_{HH}^i \mathcal{P}_{HH}^i(h) \end{aligned}$$

---

<sup>3</sup>  $\mathbf{D}_\mu \mathbf{U}(x) \equiv \partial_\mu \mathbf{U}(x) + ig W_\mu(x) \mathbf{U}(x) - \frac{ig'}{2} B_\mu(x) \mathbf{U}(x) \sigma_3$

$\mathbf{Y}_Q \equiv \text{diag}(Y_U, Y_D)$ ,  $\mathbf{Y}_L \equiv \text{diag}(Y_\nu, Y_L)$ .

# The Non-linear Lagrangian

Alonso *et al* 1212.3305

$$\mathcal{P}_C(h) = -\frac{v^2}{4} \text{Tr}(\mathbf{V}^\mu \mathbf{V}_\mu) \mathcal{F}_C(h)$$

$$\mathcal{P}_T(h) = \frac{v^2}{4} \text{Tr}(\mathbf{T} \mathbf{V}_\mu) \text{Tr}(\mathbf{T} \mathbf{V}^\mu) \mathcal{F}_T(h)$$

$$\mathcal{P}_H(h) = \frac{1}{2} (\partial_\mu h) (\partial^\mu h) \mathcal{F}_H(h)$$

$$\mathcal{P}_B(h) = -\frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h)$$

$$\mathcal{P}_W(h) = -\frac{g^2}{4} W_{\mu\nu}^a W^{a\mu\nu} \mathcal{F}_W(h)$$

$$\mathcal{P}_G(h) = -\frac{g_s^2}{4} G_{\mu\nu}^a G^{a\mu\nu} \mathcal{F}_G(h)$$

$$\mathcal{P}_1(h) = gg' B_{\mu\nu} \text{Tr}(\mathbf{T} \mathbf{W}^{\mu\nu}) \mathcal{F}_1(h)$$

$$\mathcal{P}_2(h) = ig' B_{\mu\nu} \text{Tr}(\mathbf{T} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h)$$

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$$\mathcal{P}_{10}(h) = \text{Tr}(\mathbf{V}_\nu \mathcal{D}_\mu \mathbf{V}^\mu) \partial^\nu \mathcal{F}_{10}(h)$$

$$\mathcal{P}_{\square H} = \frac{1}{v^2} (\partial_\mu \partial^\mu h)^2 \mathcal{F}_{\square H}(h).$$

$$\mathcal{P}_{11}(h) = (\text{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu))^2 \mathcal{F}_{11}(h)$$

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$$\mathcal{P}_{13}(h) = ig \text{Tr}(\mathbf{T} W_{\mu\nu}) \text{Tr}(\mathbf{T} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_{13}(h)$$

$$\mathcal{P}_{14}(h) = g \epsilon^{\mu\nu\rho\lambda} \text{Tr}(\mathbf{T} \mathbf{V}_\mu) \text{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{14}(h)$$

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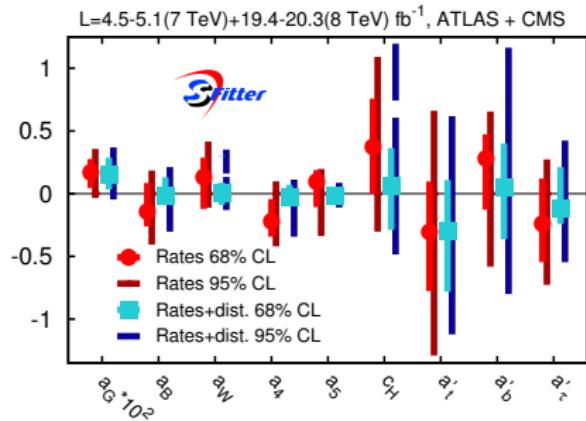
# Analysis using only Higgs data

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$$\begin{aligned} \frac{v^2}{2} \frac{f_{BB}}{\Lambda^2} &= a_B , & \frac{v^2}{2} \frac{f_{WW}}{\Lambda^2} &= a_W , \\ \frac{v^2}{(4\pi)^2} \frac{f_{GG}}{\Lambda^2} &= a_G , & \frac{v^2}{8} \frac{f_B}{\Lambda^2} &= a_4 , \\ -\frac{v^2}{4} \frac{f_W}{\Lambda^2} &= a_5 , & v^2 \frac{f_{\phi,2}}{\Lambda^2} &= c_H , \\ v^2 \frac{f_t}{\Lambda^2} &= a'_t , & v^2 \frac{f_b}{\Lambda^2} &= a'_b , \\ v^2 \frac{f_\tau}{\Lambda^2} &= a'_\tau . \end{aligned}$$



# Decorrelating Higgs and TGV

I. Brivio, T. Corbett, O. J. P. Eboli, M. B. Gavela, J. G–F, M. C. Gonzalez–Garcia, L. Merlo and S. Rigolin: → [arxiv:1311.1823](https://arxiv.org/abs/1311.1823)

In the linear case<sup>4</sup>

$$\mathcal{O}_B = \left. \begin{aligned} & \frac{ieg^2}{8} A_{\mu\nu} W^{-\mu} W^{+\nu} (v + h)^2 - \frac{ie^2 g}{8 \cos \theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} (v + h)^2 \\ & - \frac{eg}{4 \cos \theta_W} A_{\mu\nu} Z^\mu \partial^\nu h (v + h) + \frac{e^2}{4 \cos^2 \theta_W} Z_{\mu\nu} Z^\mu \partial^\nu h (v + h) \end{aligned} \right\} \text{Higgs-TGV Correlated!}$$

whereas in the non-linear case

$$\left. \begin{aligned} \mathcal{P}_2(h) &= 2ieg^2 A_{\mu\nu} W^{-\mu} W^{+\nu} \mathcal{F}_2(h) - 2 \frac{ie^2 g}{\cos \theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} \mathcal{F}_2(h) \\ \mathcal{P}_4(h) &= - \frac{eg}{\cos \theta_W} A_{\mu\nu} Z^\mu \partial^\nu \mathcal{F}_4(h) + \frac{e^2}{\cos^2 \theta_W} Z_{\mu\nu} Z^\mu \partial^\nu \mathcal{F}_4(h) \end{aligned} \right\} \text{Higgs-TGV may be decorrelated!}$$

---

<sup>4</sup>Parallel reasoning applies to  $\mathcal{O}_W$  and  $\mathcal{P}_3 - \mathcal{P}_5$

# Decorrelating Higgs and TGV

arxiv:1311.1823

Analysis using Higgs and TGV data<sup>5</sup> of

$$\mathcal{P}_G, \mathcal{P}_B, \mathcal{P}_W, \mathcal{P}_1, \mathcal{P}_2, \mathcal{P}_3, \mathcal{P}_4, \mathcal{P}_5, \mathcal{P}_T, \mathcal{P}_H, \mathcal{P}_{u,33}, \mathcal{P}_{d,33}, \mathcal{P}_{\ell,33},$$

After taking into consideration tree level contributions of  $\mathcal{P}_T$  and  $\mathcal{P}_1$  to EWPD, the relevant parameters for the analysis can be reduced. They are<sup>6</sup>:

$$a_G, a_B, a_W, c_2, c_3, a_4, a_5, c_H, a'_t, a'_b, a'_\tau$$

But we can rotate them instead to:

$$a_G, a_B, a_W, \Sigma_B, \Delta_B, \Sigma_W, \Delta_W, c_H, a'_t, a'_b, a'_\tau$$

where

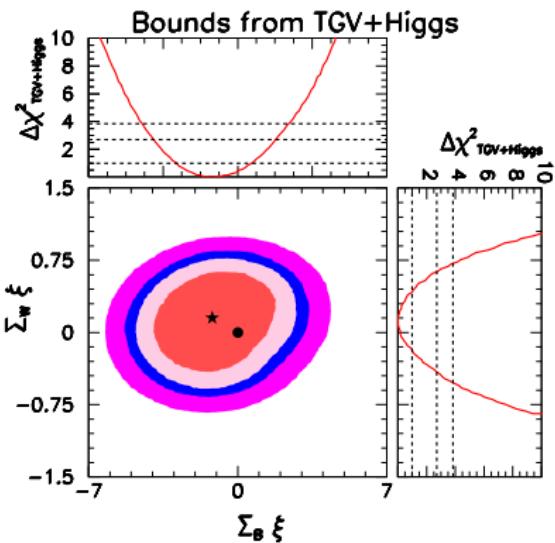
$$\begin{aligned} \Sigma_B &\equiv 4(2c_2 + a_4), & \Sigma_W &\equiv 2(2c_3 - a_5), \\ \Delta_B &\equiv 4(2c_2 - a_4), & \Delta_W &\equiv 2(2c_3 + a_5), \end{aligned}$$

defined such that at order  $d = 6$  of the linear regime  $\Sigma_B = c_B$ ,  $\Sigma_W = c_W$ , while  $\Delta_B = \Delta_W = 0$ .

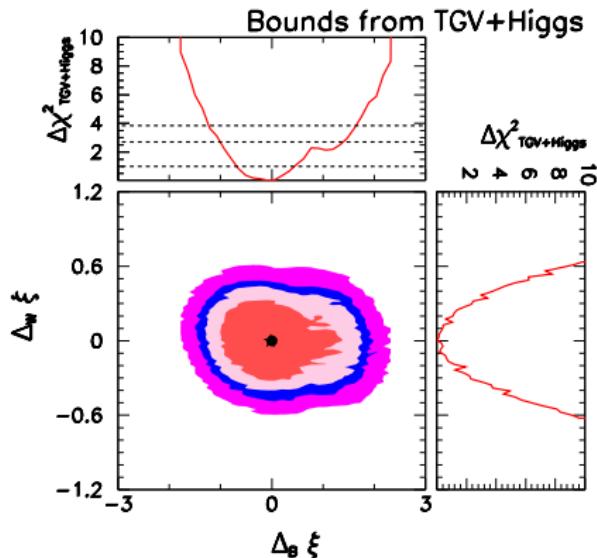
<sup>5</sup>The analysis details as in the linear fit

<sup>6</sup>For simplicity here  $a_i = c_i * a_i$

# Decorrelating Higgs and TGV



**Left:** A BSM sensor irrespective of the type of expansion: constraints from TGV and Higgs data on the combinations  $\Sigma_B = 4(2c_2 + a_4)$  and  $\Sigma_W = 2(2c_3 - a_5)$ , which converge to  $c_B$  and  $c_W$  in the linear  $d = 6$  limit.



**Right:** A non-linear versus linear discriminator: constraints on the combinations  $\Delta_B = 4(2c_2 - a_4)$  and  $\Delta_W = 2(2c_3 + a_5)$ , which would take zero values in the linear (order  $d = 6$ ) limit (as well as in the SM), indicated by the dot at  $(0, 0)$ .

# Higher order differences

arxiv:1311.1823

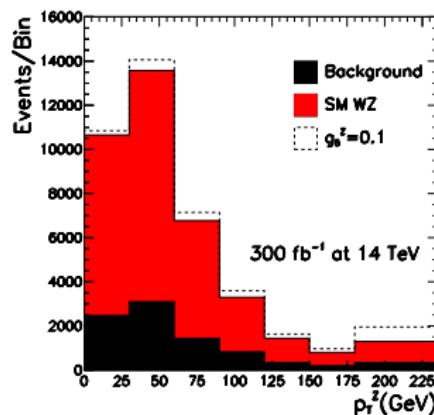
Reshuffling → interactions that are strongly suppressed in one case may be leading corrections in the other.

More on TGV!

- At *first* order in non-linear expansion (but at dim-8 in the linear one)  $\mathcal{P}_{14}$  contributes to anomalous TGV:  $g_5^Z$  (C- and P-odd but CP even).

$$\begin{aligned} \mathcal{L}_{WWV} &= -ig_5^V \epsilon^{\mu\nu\rho\sigma} \left( W_\mu^+ \partial_\rho W_\nu^- - W_\nu^- \partial_\rho W_\mu^+ \right) V_\sigma \\ &\rightarrow -\xi^2 \frac{g^3}{\cos \theta_W} \epsilon^{\mu\nu\rho\lambda} [p_{+\lambda} + p_{-\lambda}] \end{aligned}$$

- At first order in the linear expansion  $\mathcal{O}_{WWW} = i\epsilon_{ijk} \hat{W}_\mu^i \nu \hat{W}_\nu^j \rho \hat{W}_\rho^k \mu$  gives contribution to anomalous TGV  $\lambda_V$
- Chiral expansion: several operators contribute to QGVs without inducing TGVs → coefficients less constrained at present (larger deviations may be expected). Linear expansion: modifications of QGVs that do not induce changes to TGVs appear only when  $d = 8$ .



# Relaxing assumptions: $CP$ -odd

M.B. Gavela, J. G–F, M. C. Gonzalez–Garcia, L. Merlo, S. Rigolin and J. Yepes → [arxiv:1406.1823](#)

- List & applications of  $CP$ -odd non-linear operators:

$$\mathcal{L}_{\text{chiral}} = \mathcal{L}_{SM} + \Delta \mathcal{L}_{CP},$$

$$\Delta \mathcal{L}_{CP} = c_{\tilde{B}} \mathcal{S}_{\tilde{B}}(h) + c_{\tilde{W}} \mathcal{S}_{\tilde{W}}(h) + c_{\tilde{G}} \mathcal{S}_{\tilde{G}}(h) + c_{2D} \mathcal{S}_{2D}(h) + \sum_{i=1}^{16} c_i \mathcal{S}_i(h).$$

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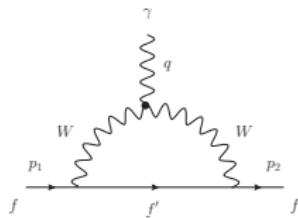
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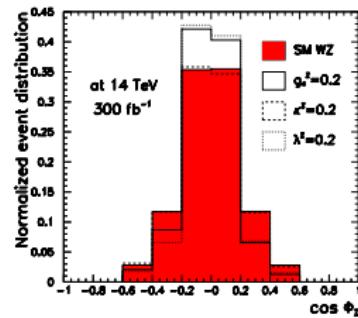
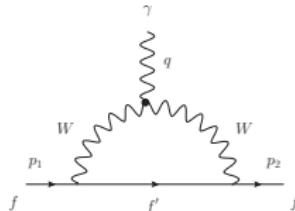
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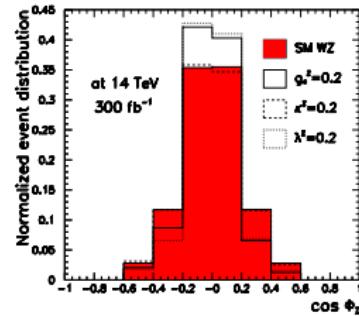
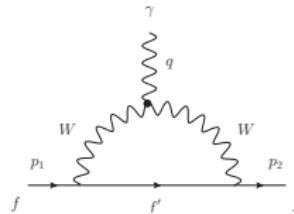
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$CP$ -violation on **Higgs physics**:  $h \rightarrow ZZ$ , e. g. CMS analysis:

$$A(h \rightarrow ZZ) = v^{-1} \left( d_1 m_Z^2 \epsilon_1^* \epsilon_2^* + d_2 f_{\mu\nu}^{*(1)} f^{\mu\nu*(2)} + d_3 f_{\mu\nu}^{*(1)} \tilde{f}^{\mu\nu*(2)} \right),$$

# Conclusions

- **$\Delta$ -framework:**
  - ◊ Test extended Higgs sectors, 2HDM, Higgs portals etc
  - ◊ Well aligned with experimental measurements: test different analysis features.
- **Effective Lagrangian approach:**
  - ◊ **Kinematic distributions** can be included, a key feature.
  - ◊ Correlations, between Higgs couplings, between different measurements.
  - ◊ Theoretical side: consistency of EFT will need to be carefully checked.  
Otherwise it is model dependent dim-6 Lagrangian.
- 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!).
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**Thank you!**