# The Gauge-Higgs Legacy of the LHC Run I

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Based on JHEP **1607**, 152 (2016) [arXiv:1604.03105]
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# Motivation

- 2012 Higgs discovery $\rightarrow$ new particle directly related to EWSB
- Connection to new physics?
- Model independent framework to parametrize new physics effects at low scale

**EFT approach:**

$$\mathcal{L} = \sum_x \frac{f_x}{\Lambda^2} \mathcal{O}_x$$

- Advantages: gauge invariance, renormalizability, ...
- Common operators $\rightarrow$ use EFT approach to correlate Higgs sector and triple gauge vertices (TGV)

J. Ellis, V. Sanz and T. You,1404.3667, 1410.7703; E. Massó and V. Sanz,1211.1320; A. Falkowski, M. Gonzalez-Alonso, A. Greljo and D. Marzocca, 1508.00581; G. Brooijmans *et al.*,1405.1617 ; M. Trott,1409.7605; A. Falkowski and F. Riva,1411.0669

# Theory

- $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$-symmetry, SM particles
- Dim6: 59 baryon/lepton number conserving operators
- P and C - even operators
- Data driven approach

## Dimension 6 operators

$$\mathcal{O}_{GG} = \phi^\dagger \phi \; G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi$$

$$\mathcal{O}_W = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_B = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right)$$

$$\mathcal{O}_{e\phi,33} = (\phi^\dagger \phi)(\bar{L}_3 \phi e_{R,3}) \qquad \mathcal{O}_{u\phi,33} = (\phi^\dagger \phi)(\bar{Q}_3 \tilde{\phi} u_{R,3}) \qquad \mathcal{O}_{d\phi,33} = (\phi^\dagger \phi)(\bar{Q}_3 \phi d_{R,3})$$

$$\mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^\mu_\rho\right) \; .$$

$\rightarrow$ 10 parameters for global fit, 3 parameters for TGV-only fit

# Data for TGV

Data for TGV analysis:

| Channel | Distribution | Data set | |
|---|---|---|---|
| $WW \to \ell^+\ell'^- + \not{E}_T$ (0$j$) | Leading lepton $p_T$ | ATLAS 8 TeV, 20.3 fb$^{-1}$ | 1603.01702 |
| $WW \to \ell^+\ell^{(\prime)-} + \not{E}_T$ (0$j$) | $m_{\ell\ell^{(\prime)}}$ | CMS 8 TeV, 19.4 fb$^{-1}$ | 1507.03268 |
| $WZ \to \ell^+\ell^-\ell^{(\prime)\pm}$ | $m_T^{WZ}$ | ATLAS 8 TeV, 20.3 fb$^{-1}$ | 1603.02151 |
| $WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$ | $Z$ candidate $p_T^{\ell\ell}$ | CMS 8 TeV, 19.6 fb$^{-1}$ | CMS-PAS-SMP-12-006 |
| $WV \to \ell^\pm jj + \not{E}_T$ | $V$ candidate $p_T^{jj}$ | ATLAS 7 TeV, 4.6 fb$^{-1}$ | 1410.7238 |
| $WV \to \ell^\pm jj + \not{E}_T$ | $V$ candidate $p_T^{jj}$ | CMS 7 TeV, 5.0 fb$^{-1}$ | 1210.7544 |
| $WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$ | $Z$ candidate $p_T^{\ell\ell}$ | ATLAS 7 TeV, 4.6 fb$^{-1}$ | 1208.1390 |
| $WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$ | $Z$ candidate $p_T^{\ell\ell}$ | CMS 7 TeV, 4.9 fb$^{-1}$ | CMS-PAS-SMP-12-006 |

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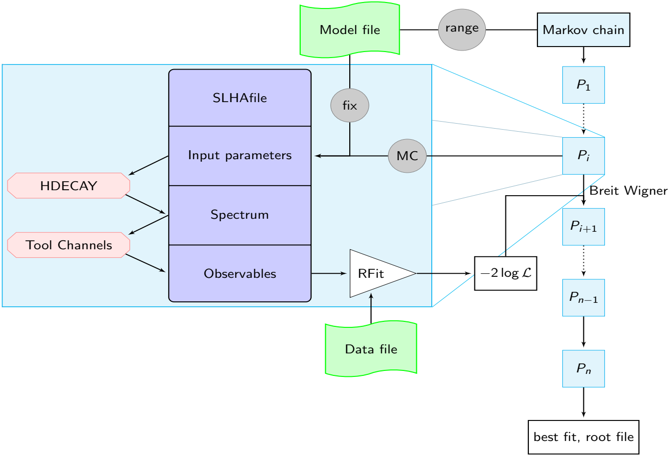
## Higgs Fit:

| Production/Decay mode | 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 | 1402.3244,1502.01518,1504.04324 | 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 |

Previous publication: The Higgs Legacy of the LHC Run I, T. Corbett et al. [arXiv:1505.05516]


Model file
range
Markov chain
SLHAfile
fix
$P_1$
Input parameters
MC
$P_i$
HDECAY
Breit Wigner
Spectrum
$P_{i+1}$
Tool Channels
Observables
RFit
$-2 \log \mathcal{L}$
$P_{n-1}$
Data file
$P_n$
best fit, root file

# SFitter Highlights

- Input: Model, Data
- Output:
  - best fit points
  - fully-dimensional log-likelihood map
  - likelihood projections on one and two dimensional plane (Bayesian and Frequentist)
- Algorithms:
  - Weighted Markov chain
  - Cooling Markov chain
  - Modified gradient fit (Minuit)
  - ...
- Errors
  - Gaussian
  - Poisson
  - box-shaped

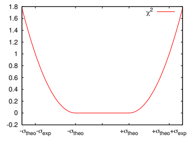
# Uncertainty treatment

## Types of uncertainties

- Systematic - Gaussian - correlated
- Statistic - Poisson - uncorrelated
- Theory - flat - partially correlated via nuisance parameters

## RFit scheme (Profiling over theory uncertainty)

$$-2\log\mathcal{L} = \begin{cases} \frac{\left|x_{meas,i} - x_{pred,i}\right| - \sigma_{theo,i}}{\sigma_{exp,i}} & \text{for} \quad \left|x_{meas,i} - x_{mod,i}\right| > \sigma_{theo,i} \\ 0 & \text{for} \quad \left|x_{meas,i} - x_{mod,i}\right| < \sigma_{theo,i} \end{cases}$$



# Correlation of uncertainties

## Theory uncertainties

Global nuisance parameter for each channel:
*WW* 5%, *WZ* 4%, *WV*-semileptonic 4%

## Systematic uncertainties

Correlate uncertainties on luminosity, lepton reconstruction, ...

$$-2\log\mathcal{L} = \vec{\chi}_d^T C^{-1} \vec{\chi}_d$$

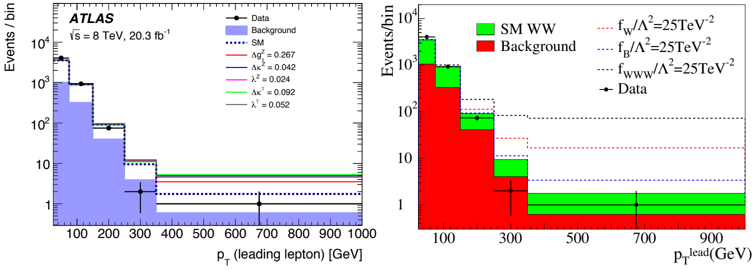
$$C_{i,j} = \frac{\sigma_i^l \sigma_j^l + \sigma_i^j \sigma_j^j + \dots}{\sigma_i^{(exp)} \sigma_j^{(exp)}}$$

| Channel | Exp | Lumi | Detector eff | Lepton eff | Background rate |
|---|---|---|---|---|---|
| $WW \to \ell^+\ell'^- + \not{E}_T$ (0$j$) | ATLAS | 2.0% | 1.4% | 1.4% | 2.0% |
| $WW \to \ell^+\ell^{(\prime)-} + \not{E}_T$ (0$j$) | CMS | 2.6% | 1.0% | 3.8% | 2.0% |
| $WZ \to \ell^+\ell^-\ell^{(\prime)\pm}$ | ATLAS | 2.8% | 0.5% | 1.7% | 1.6% |
| $WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$ | CMS | 4.4% | 3.1% | 2.0% | 2.5% |
| ... | | | | | |

# Analysis framework

- Tools: FeynRules, MadGraph5, Pythia, DELPHES
- Example: ATLAS 8 TeV WW

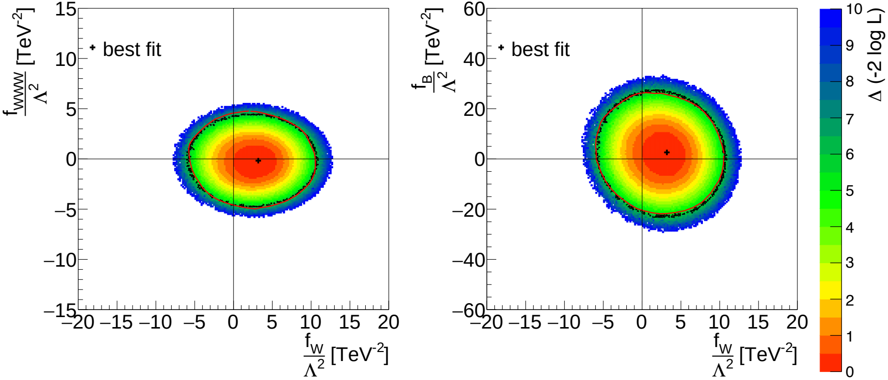
0. Read off background estimation
1. Reproduce SM distribution
2. Determine correction factors with respect to ATLAS/CMS
3. Parametrize bin dependence on operators
    - linear, quadratic, interference



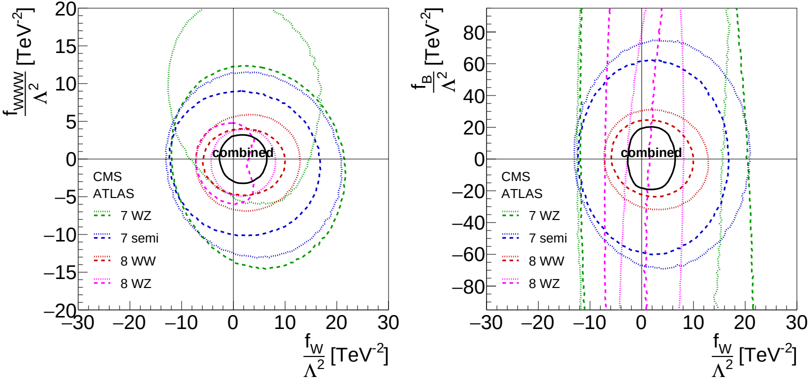

$\rightarrow$ strongest constraint from last bin

# Cross–check results

4. Implement parametrization in SFitter
5. Profile likelihood fit
6. Compare with ATLAS/CMS results [here: ATLAS 8 TeV WW]
   Color-coded log-Likelihood, black dots/red line: 95%CL



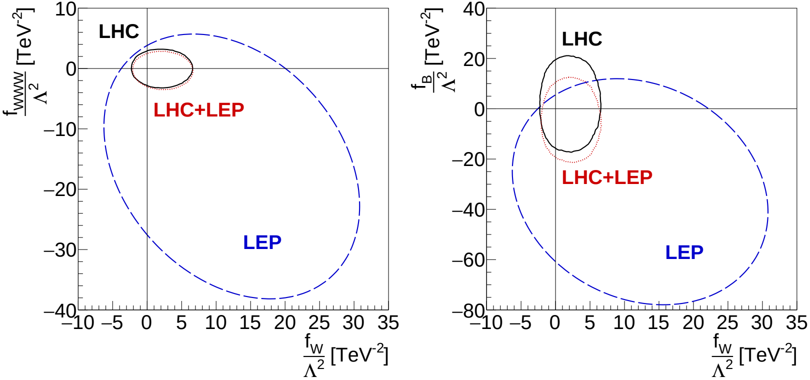
# Results from LHC Run I




- Stronger constraint on $\frac{f_{W/WWW}}{\Lambda^2}$ than $\frac{f_B}{\Lambda^2}$ [WWZ suppressed by $s_w^2/c_w^2$]
- $\frac{f_B}{\Lambda^2}$ main constraint by semileptonic (7TeV) and WW channel
- Semileptonic channel update?!

→ New results for $\frac{f_B}{\Lambda^2}$ : [-14,17] (CMS), [-19,20] (ATLAS)

# Comparison and combination with LEP

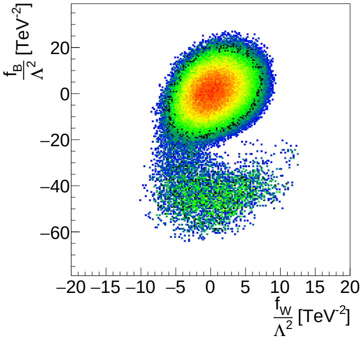



- LHC much more precise
- No significant improvement from including LEP

$\rightarrow$ slight shift of $f_B$

- With the current precision interpretation in terms of an EFT becomes model-dependent

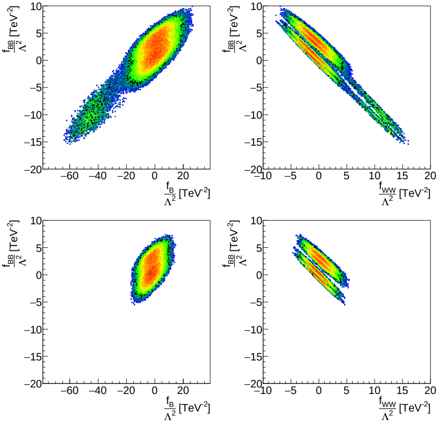
# Gauge Higgs combination I




1-D exclusion limits, 95% CL:

| Data | $\mathcal{O}_B$ | $\mathcal{O}_W$ |
|---|---|---|
| LHC-Higgs | $(-52, -38) \cup (-15.5, 18.1)$ | $(-5.2, 6.4)$ |
| LHC-TGV | $(-14.3, 15.9)$ | $(-1.5, 6.3)$ |
| Higgs+TGV+LEP | $(-11.8, 8.8)$ | $(-0.98, 5.0)$ |

# Gauge Higgs combination II

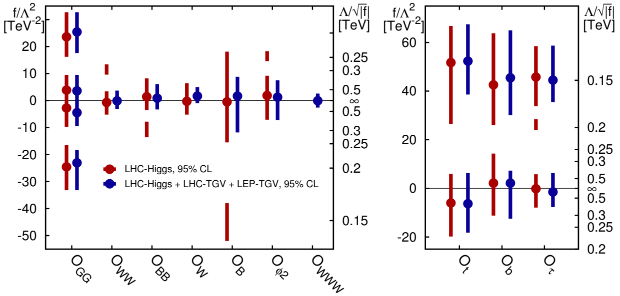



- Correlation between $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$ due to $H_{\gamma\gamma}$ decay rate

$\rightarrow$ illustrates the importance of profiling

- Secondary solution in $\mathcal{O}_B$ has vanished $\rightarrow$ propagates to $\mathcal{O}_{BB}$ and $\mathcal{O}_{WW}$ via correlation

# Combined results




- First combination of all the di-boson production channels at LHC Run I in combination with Higgs channels [1604.03105]
- secondary solutions are excluded for $\mathcal{O}_{WW}, \mathcal{O}_{BB}, \mathcal{O}_{B}$ and $\mathcal{O}_{\phi 2}$
- strongly increased precision for $\mathcal{O}_{B}$ and $\mathcal{O}_{W}$
- $\mathcal{O}_{WWW}$ among best measured dimension–six operators
- improvements on all operators due to correlations

# Summary

- First combination of all the di-boson production channels at LHC Run I in combination with Higgs channels [1604.03105]
- $\mathcal{O}_{WWW}$ among best measured dim 6 operator
- Already more precise than LEP
- Major improvements from latest and future results
- LHC di-boson data should be included into Higgs sector analysis