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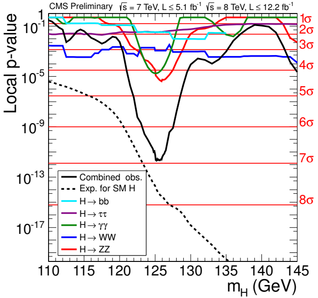
Higgs Fits

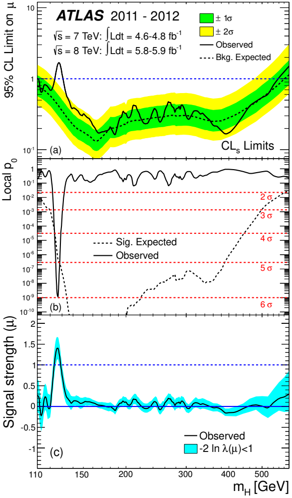
Michael Rauch | Higgs Couplings, 09 November 2017

INSTITUTE FOR THEORETICAL PHYSICS

Found a Resonance

Resonance at ∼ 125 GeV found





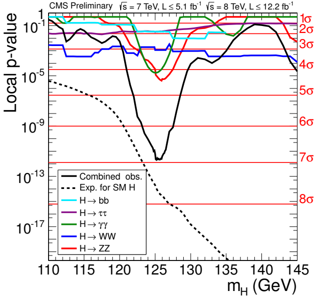
Assuming SM is correct, full theory:

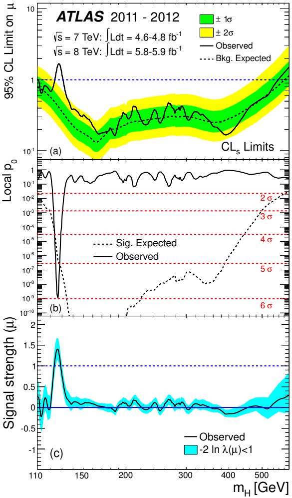
⇒ Job done

- must be Higgs
  (only missing but expected particle)
- mass only remaining unknown parameter
- couplings and quantum numbers fixed by theory prediction

Found a Resonance

Resonance at $\sim$ 125 GeV found





Assuming SM is correct, full theory:

$\Rightarrow$ Job done

- must be Higgs
  (only missing but expected particle)
- mass only remaining unknown parameter
- couplings and quantum numbers fixed by theory prediction

$\leftrightarrow$ test predictions

Parametrizing Higgs Couplings

Discrete quantum numbers (CP-even scalar) those of SM Higgs
Measured rates in reasonable agreement with SM expectation

- $\Rightarrow$ Constraints on new-physics models

- $\Rightarrow$ SM(-Higgs) + X
  - (linear) SM Effective Field Theory – dimension-6 operators

    [Buchmüller, Wyler; Grzadkowski *et al.* ; Giudice *et al.* ; Contino *et al.* ; Passarino; Gonzalez Garcia *et al.* ; Trott *et al.* ; . . .]

    new-physics heavy and can be integrated out
    $\rightarrow$ reasonable assumption, but should be tested

  - Higgs EFT

    Dimension-4 contributions to renormalizable Lagrangian + non-decoupling dimension-6 operators

    [Zeppenfeld *et al.* ; Duehrssen *et al.* ; Lafaye, Plehn, MR, Zerwas; LHC HXSWG]

    can be seen as LO contribution of chiral Lagrangian [Buchalla *et al.* ; . . .]

Assumptions:

- single narrow resonance at $\sim$ 125 GeV
- width negligible
  $\Rightarrow (\sigma \cdot \mathrm{BR})(ii \to H \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$
- tensor structure identical to SM

Generalized Higgs sector

- for Higgs couplings present in the Standard Model $x = W, Z, t, b, \tau, c, \mu$

$$g_{xxH} \equiv g_x \longrightarrow g_x^{\text{SM}} \ (1 + \Delta_x) \equiv g_x^{\text{SM}} \ \kappa_x$$

- for loop-induced Higgs couplings $x = \gamma, g$

$$g_x \longrightarrow g_x^{\text{SM}} \ \left(1 + \Delta_x^{\text{SM}} + \Delta_x\right) = g_x^{\text{SM}} \ \left(1 + \Delta_x^{\text{SM+NP}}\right) \equiv \kappa_x g_x^{\text{SM}}$$

where g_x^{SM}: (loop-induced) coupling in the Standard Model
Δ_x^{SM}: contribution from modified tree-level couplings to Standard-Model particles
Δ_x : additional (dimension-five) contribution

- ratios

$$\frac{g_x}{g_y} = \frac{g_x^{\text{SM}}}{g_y^{\text{SM}}}(1 + \Delta_{x/y})$$

- ignore Higgs self-couplings (g_{HHH}, g_{HHHH})

SFitter

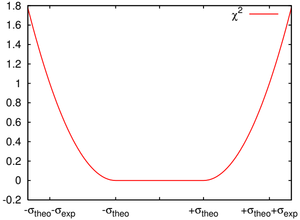
Algorithms:

- Weighted Markov chain
- Cooling Markov chain ($\sim$ simulated annealing)
- Modified gradient fit (Minuit)
- Grid scan
- Nested Sampling [Skilling; Feroz, Hobson]

[Lafaye, Plehn, MR,Zerwas]
[Eur.Phys.J.C54:617-644,2008, [arXiv:0709.3985 [hep-ph]]]
[JHEP08(2009)009 [arXiv:0904.3866 [hep-ph]]]

Errors:

- three types:
  - Gaussian – arbitrary correlations possible ($\rightarrow$ systematic errors)
  - Poisson
  - box-shaped (RFit) [CKMFitter]
- assignment as in exp. studies
- adaption to likelihood input easy



Output of SFitter:

- fully-dimensional log-likelihood map
- one- and two-dimensional distributions via
  - marginalization (Bayesian)
  - profile likelihood (Frequentist)
- list of best points

Experimental Input

[Corbett, Eboli, Goncalves, Gonzalez-Fraile, Plehn, MR]

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Higgs data

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

- rates and backgrounds from experimental papers
  $\sim$ 200 channels in total

Higgs theory

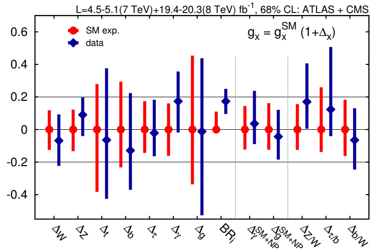
Couplings from modified versions of

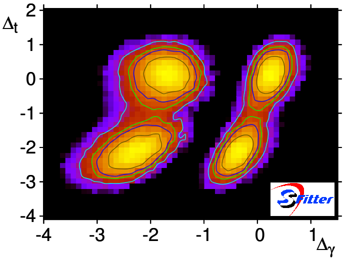
- HDecay [Djouadi, Kalinowski, Mühlleitner, Spira]
- eHDecay [Contino, Ghezzi, Grojean, Mühlleitner, Spira]
- private code [Corbett, Gonzalez-Fraile]

Results in Δ-Framework

Run-I Results

[Corbett, Eboli, Goncalves, Gonzalez-Fraile, Plehn, MR]

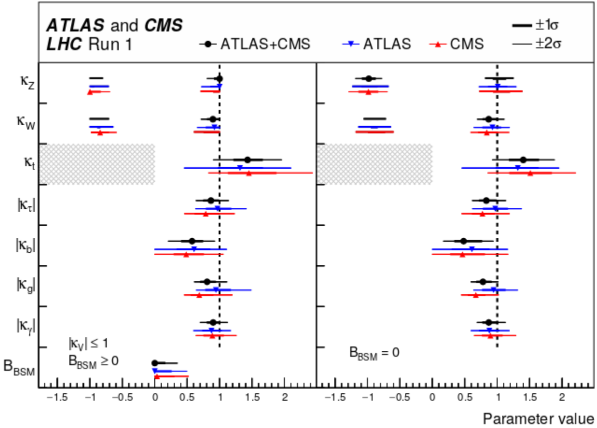




- tested precision on couplings up to $\mathcal{O}(10\%)$
- good agreement with SM expectation
- sign ambiguities

Results in κ-Framework

Official combination from ATLAS & CMS



- difficult to relate to electroweak sector
  → try other approach

Effective Field Theory

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- integrate out heavy, non-SM degrees of freedom
  higher-dimensional operators appearing in Lagrangian

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_{i} \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- a priori 59 operators when assuming flavour and CP symmetry [Grzadkowski *et al.*]
- use HISZ basis [Hagiwara, Ishihara, Szalapski, Zeppenfeld]
  operators contributing to Higgs physics

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

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{W} = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \qquad \mathcal{O}_{B} = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \, \Phi \, \Phi^\dagger \, (D^\mu \Phi) \qquad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left(\Phi^\dagger \Phi\right) \partial_\mu \left(\Phi^\dagger \Phi\right) \qquad \mathcal{O}_{\Phi,4} = (D_\mu \Phi)^\dagger \, (D^\mu \Phi) \left(\Phi^\dagger \Phi\right)$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3} \left(\Phi^\dagger \Phi\right)^3$$

fermionic couplings

Final Set

- rotate to basis without blind directions linked to electroweak precision data
- restrict fermion couplings to SM-like set
- ignore Higgs self-couplings
- $\Rightarrow$

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

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

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

- gauge-boson part can be translated to general *HVV* vertex structure

  $\Rightarrow$ 7 κ-like coupling modifications (W=Z, γ, $Z\gamma$, g, t, b, τ)

  $\Rightarrow$ 5 new Lorentz structures

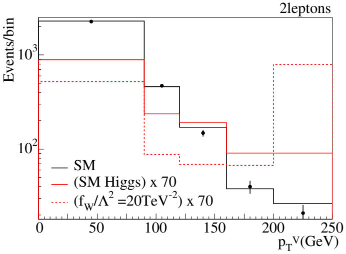
  ($V_{\mu\nu} V^\mu \partial^\nu H$, $V_{\mu\nu} V^{\mu\nu} H$ with $V = W, Z$; $\quad A_{\mu\nu} Z^\mu \partial^\nu H$)

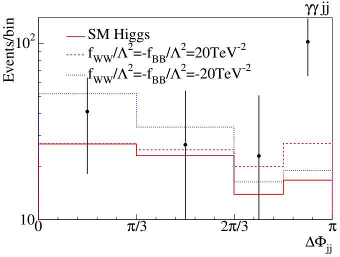
- kinematic distributions become relevant

Kinematic Distributions

Two kinematic distributions used:

- transverse momentum of the vector boson in VH, $H \to b\bar{b}$ production
- azimuthal angle separation of two jets in $\gamma\gamma jj$ production



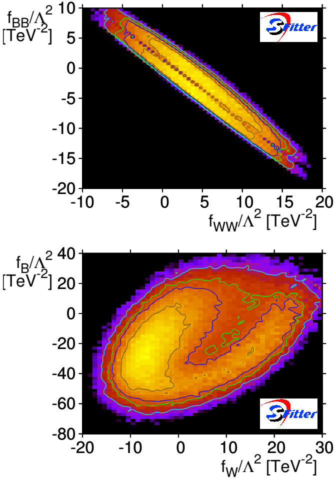


Analysis

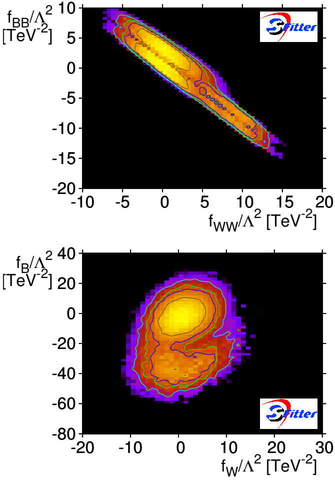
[Corbett, Eboli, Goncalves, Gonzalez-Fraile, Plehn, MR]

Correlations between different operators → distributions crucial

rate only:

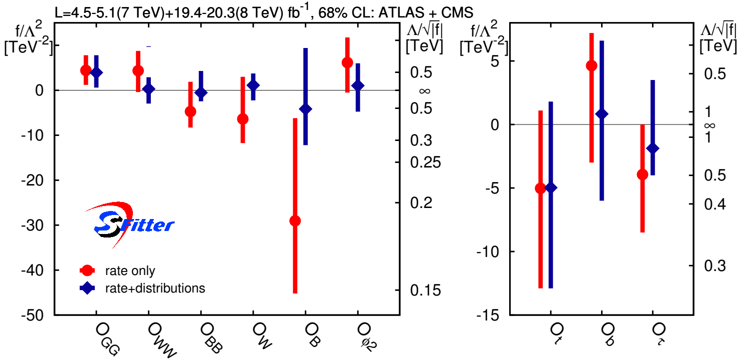


plus distributions:



Results

[Corbett, Eboli, Goncalves, Gonzalez-Fraile, Plehn, MR]



- secondary solutions for $\mathcal{O}_{GG}$, fermion couplings (not shown)
- information from distributions helps
- probed energy scales 300-500 GeV for $\mathcal{O}(1)$ Wilson coefficients
- good agreement with SM limit

Is fitting Higgs couplings useful?

Is fitting only Higgs couplings useful?

D6 Higgs-Gauge Operators

- SU(2) connects Higgs and gauge sector
- $\rightarrow$ also consider modifications to triple gauge couplings (TGC)
- modification of corresponding TGC vertices:

	$\mathcal{O}_{WWW}$	$\mathcal{O}_{W}$	$\mathcal{O}_{B}$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{\phi,2}$
WWZ	X	X	X			
$WW\gamma$	X	X	X			
HWW		X		X		X
HZZ		X	X	X	X	X
$HZ\gamma$		X	X	X	X	(X)
$H\gamma\gamma$				X	X	(X)

- one more relevant operator

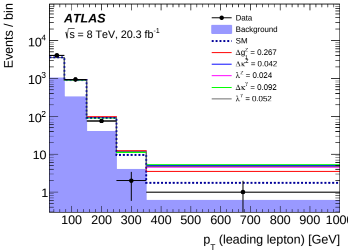
$$\mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}^{\mu}{}_{\nu}\hat{W}^{\nu}{}_{\rho}\hat{W}^{\rho}{}_{\mu}\right)$$

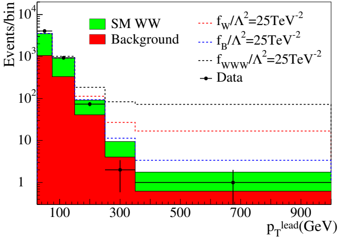
Experimental Input

[Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, MR]

need distributions from Gauge boson data

Channel	Distribution	Data set	Reference
$WW \to \ell^+\ell'^- + \not{E}_T$ (0j)	Leading lepton p_T	ATLAS 8 TeV, 20.3 fb^{-1}	1603.01702
$WW \to \ell^+\ell^{(\prime)-} + \not{E}_T$ (0j)	$m_{\ell\ell^{(\prime)}}$	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

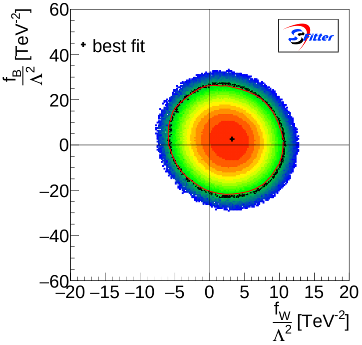


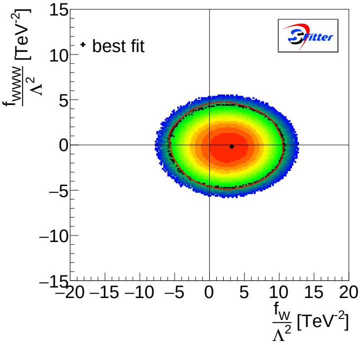


Cross-check

[Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, MR]

Cross-check results for agreement, e.g. with ATLAS 8 TeV WW



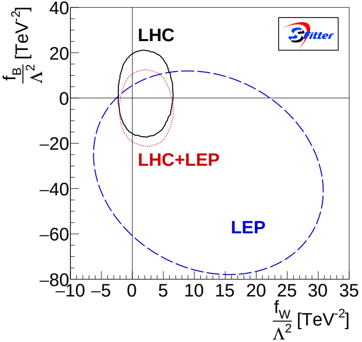


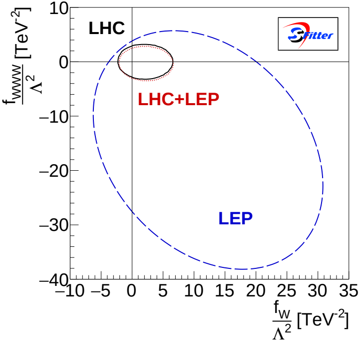
- colour: profile likelihood of our implementation
- black dots: $\Delta(-2\log L) = 5.99$
- red solid contour: ATLAS 95% CL result $\to$ good agreement

Comparison and Combination with LEP

[see also Falkowski *et al.* ; Riva *et al.*]

TGC measurements available also from LEP



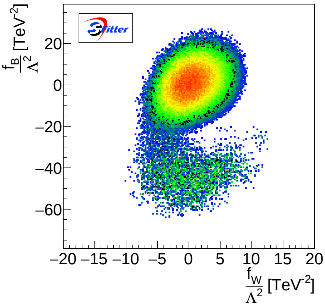


- LHC precision dominates
- no significant improvement when adding LEP data (slight shift for f_B)

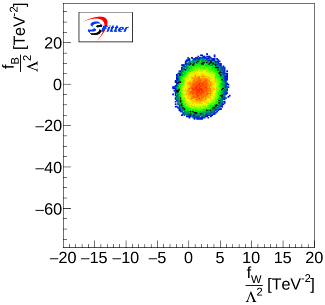
Correlation Plots

[Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, MR]

Higgs data only
(rates and distributions):



Higgs + TGC + LEP data:



Data (95% CL; f/Λ^2 [TeV^{-2}])	$\mathcal{O}_B$	$\mathcal{O}_W$
Higgs	[-52;-38] ∪ [-15.5;18.1]	[-5.2;6.4]
TGC	[-14.3;15.9]	[-1.5;6.3]
Higgs+TGC+LEP	[-11.8;8.8]	[-0.98;5.0]

Correlation Plots

[Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, MR]

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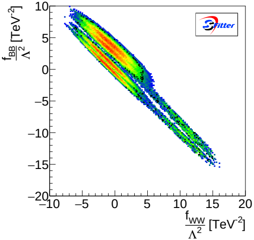
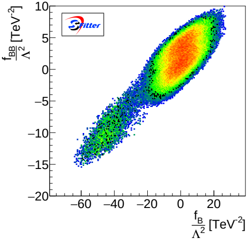
(rates and distributions):





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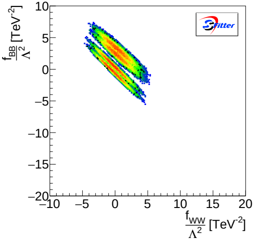
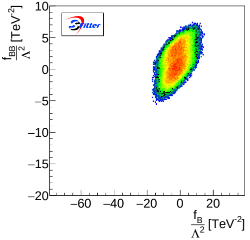
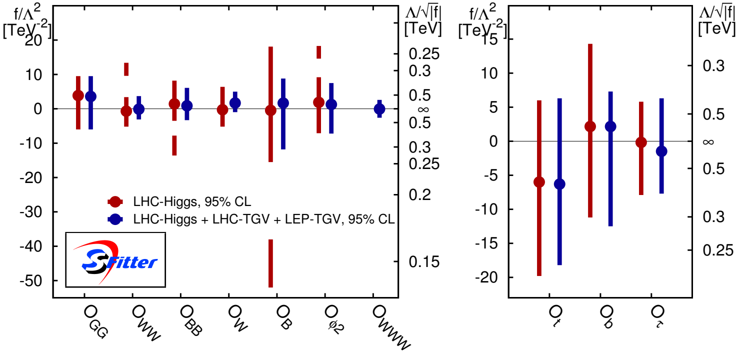




- secondary solutions removed

Complete Higgs-Gauge Analysis

[Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, MR]



- secondary solutions for $\mathcal{O}_{WW}$, $\mathcal{O}_{BB}$, $\mathcal{O}_{B}$, $\mathcal{O}_{\phi,2}$ removed
- significantly increased precision for $\mathcal{O}_{W}$, $\mathcal{O}_{B}$
- $\mathcal{O}_{WW}$, $\mathcal{O}_{BB}$ improve despite no direct contribution to TGC data (correlations!)

Chiral Lagrangian

[see talks by Francesco and Ilaria for more detailed theory discussion]

- two approaches to count dimensions:
  - canonical (energy) dimension $\rightarrow$ linear realization $\rightarrow$ shown so far
  - chiral dimension (loop dimension) $\rightarrow$ non-linear/chiral realization
- equivalent when considering all orders
- different contributions for leading terms only

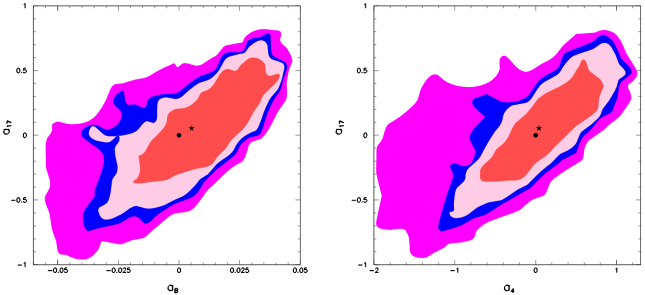
global Higgs and gauge couplings analysis also possible in this framework

[Brivio, Gonzalez-Fraile, Gonzalez-Garcia, Merlo]

Results

[Brivio, Gonzalez-Fraile, Gonzalez-Garcia, Merlo]

Constraints from Higgs data including kinematic distributions: 68%, 90%, 95%, 99% CL

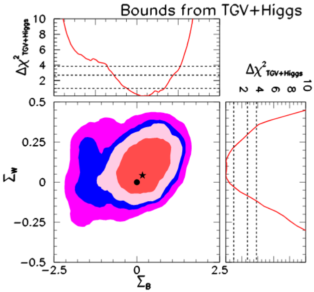


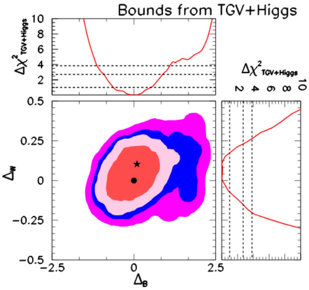
- SM limit good solution
- one bosonic parameter more (10) than in linear EFT fit
  $\rightarrow$ slightly wider parameter ranges, otherwise equivalent

Results (2)

[Brivio, Gonzalez-Fraile, Gonzalez-Garcia, Merlo]

Constraints from Higgs+TGC data incl. kin. dists: 68%, 90%, 95%, 99% CL





- 13 parameter fit
- significant improvement compared to Higgs data alone also here
- comparison linear $\leftrightarrow$ non-linear:
  investigate nature of electroweak symmetry breaking
  $\rightarrow$ higher precision necessary

Towards Run-II Results

LHC luminosity of 2016 run already exceeding run-I
(plus larger cross sections due to increased centre-of-mass energy)

$\rightarrow$ include run-II data in analyses

on-going work [$\rightarrow$ yesterday's parallel session]

- TGC fits [Falkowski *et al.* ; Riembau *et al.*]
- Higgs fits
  - HiggsSignals [Stefaniak *et al.*]
  - 5-parameter EFT fit from STXS [Zemaityte, Hays, Sanz]
  - HEPfit, Bayesian fit for chiral Lagrangian [Krause *et al.*]
- Combined Higgs+TGC fits
  - SFitter, Higgs+TGC update [Corbett, Plehn, MR *et al.*]

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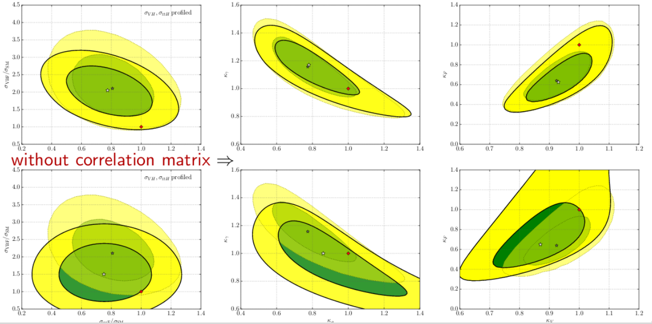
    using STXS results looks promising, correlation information crucial



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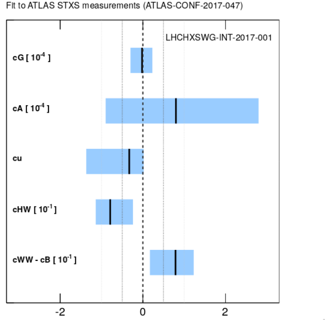

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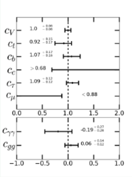
- Higgs fits
  - HiggsSignals [Stefaniak *et al.*]
  - 5-parameter EFT fit from STXS [Zemaityte, Hays, Sanz]
  - HEPfit, Bayesian fit for chiral Lagrangian [Krause *et al.*]
    prior dependence

For a Gaussian prior with $\sigma \approx 0.5$, we find:

$$c_V = 1.00 \pm 0.06 \quad c_t = 0.92^{+0.15}_{-0.17} \quad c_b = 1.07^{+0.17}_{-0.16}$$

$$c_\tau = 1.09 \pm 0.12 \quad c_g = 0.06^{+0.14}_{-0.12} \quad c_\gamma = -0.19^{+0.27}_{-0.26}$$

$$(c_\mu < 0.88 \,@\, 68\% \quad c_c > 0.68 \,@\, 68\%)$$



- Combined Higgs+TGC fits
  - SFitter, Higgs+TGC update [Corbett, Plehn, MR *et al.*]

Towards Run-II Results

LHC luminosity of 2016 run already exceeding run-I
(plus larger cross sections due to increased centre-of-mass energy)

$\rightarrow$ include run-II data in analyses

on-going work [$\rightarrow$ yesterday's parallel session]

- TGC fits [Falkowski *et al.* ; Riembau *et al.*]
- Higgs fits
  - HiggsSignals [Stefaniak *et al.*]
  - 5-parameter EFT fit from STXS [Zemaityte, Hays, Sanz]
  - HEPfit, Bayesian fit for chiral Lagrangian [Krause *et al.*]
- Combined Higgs+TGC fits
  - SFitter, Higgs+TGC update [Corbett, Plehn, MR *et al.*]

Conclusions

- combined analysis of Higgs-gauge sector working
- both linear and non-linear formulation
- information from distributions crucial for precision
- work on using run-II data started

Higgs Width

at LHC total width not directly measurable

- indirect limits:
  compare on-shell and off-shell region in $pp \to 4\ell$ production

  [Caola, Melnikov]

- limit on Higgs-gauge coupling from sum rule:
  $\Delta_W < 0$, $\Delta_Z < 0$

$\Rightarrow$ typical assumption

$$\Gamma_{\text{tot}} = \Sigma_{\text{obs}} \Gamma_x \quad \text{(plus generation universality)}$$

D6 setup

Karlsruher Institut für Technologie

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

$$g_{Hgg} = -\frac{\alpha_s}{8\pi}\frac{f_{GG}v}{\Lambda^2} \qquad g^{(1)}_{HZ\gamma} = \frac{g^2 v}{2\Lambda^2}\ \frac{s_w(f_W - f_B)}{2c_w}$$

$$g_{H\gamma\gamma} = -\frac{g^2 v s_w^2}{2\Lambda^2}\ \frac{f_{BB} + f_{WW}}{2} \qquad g^{(2)}_{HZ\gamma} = \frac{g^2 v}{2\Lambda^2}\ \frac{s_w(2s_w^2 f_{BB} - 2c_w^2 f_{WW})}{2c_w}$$

$$g^{(1)}_{HZZ} = \frac{g^2 v}{2\Lambda^2}\ \frac{c_w^2 f_W + s_w^2 f_B}{2c_w^2} \qquad g^{(1)}_{HWW} = \frac{g^2 v}{2\Lambda^2}\ \frac{f_W}{2}$$

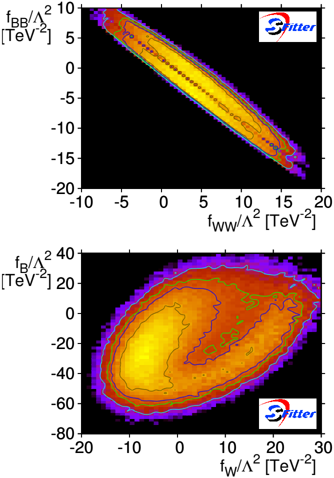
$$g^{(2)}_{HZZ} = -\frac{g^2 v}{2\Lambda^2}\ \frac{s_w^4 f_{BB} + c_w^4 f_{WW}}{2c_w^2} \qquad g^{(2)}_{HWW} = -\frac{g^2 v}{2\Lambda^2}\ f_{WW}$$

$$g^{(3)}_{HZZ} = m_Z^2(\sqrt{2}G_F)^{1/2}\left(1 - \frac{v^2}{2\Lambda^2}f_{\Phi,2}\right) \qquad g^{(3)}_{HWW} = m_W^2(\sqrt{2}G_F)^{1/2}\left(1 - \frac{v^2}{2\Lambda^2}f_{\Phi,2}\right)$$

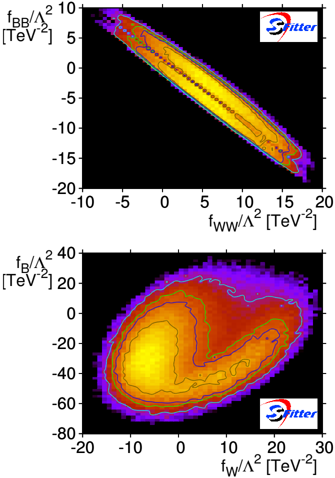
Analysis

Distributions crucial $\leftrightarrow$ sensitivity only from last p_T bin

rate only:

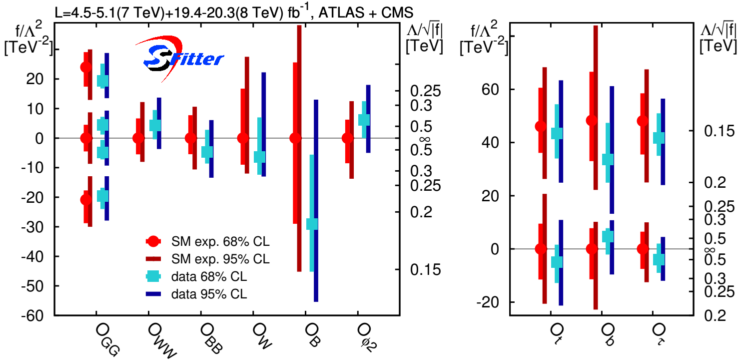


distribution without last p_T bin:



Higgs D6 Results

rate only results:



Complete Higgs-Gauge Analysis

[Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, MR]