Ultimate precision workshop, Paris Saclay Institut Pascal, 5th December 2019

The Branco Weiss Fellowship Society in Science

Current BSM global (EFT) interpretation efforts

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CERN

Outline

- SM EFT fits
- BSM matching and constraints
- SM EFT at higher energies
- SM EFT positivity bounds

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We've always been doing EFTs

- QED EFT = QED + Euler-Heisenberg + Fermi theory

$$\mathcal{L}^{EFT}_{QED} = \bar{\Psi} i\gamma^\mu D_\mu \Psi - m\bar{\Psi}\Psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Fermi theory (1933)

$$+ \sum_i \frac{c_6^{(i)}}{\Lambda^2}(\bar{\Psi}\Gamma^2\Psi)(\bar{\Psi}\Gamma^2\Psi)$$

$$\Gamma^2 = \{\mathbb{1}, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}$$

Euler-Heisenberg (1936)

$$+ \frac{c_8^{(1)}}{\Lambda^4}(F_{\mu\nu}F^{\mu\nu})^2 + \frac{c_8^{(2)}}{\Lambda^4}F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu} + \dots$$

- EFT fits to experimental data established V-A structure
- (Light-by-light scattering observed 80 years later)

D'Enterria, Silveira 1305.7142
ATLAS 1702.01625
CMS 1810.04602

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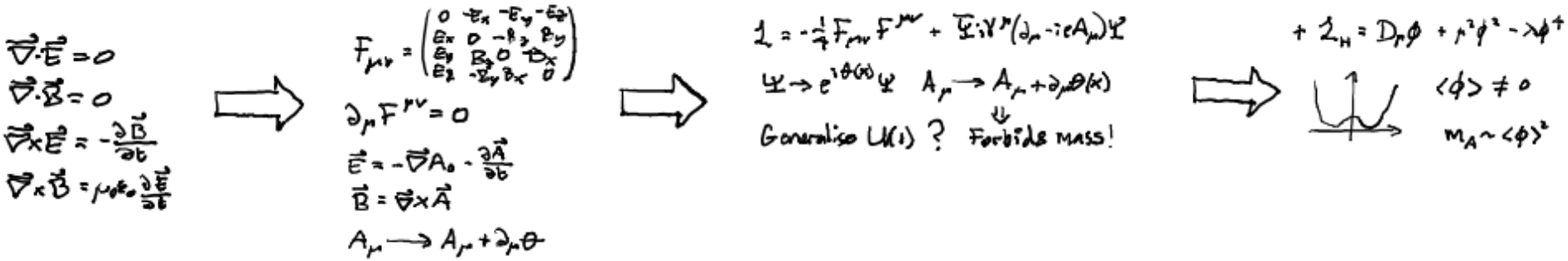
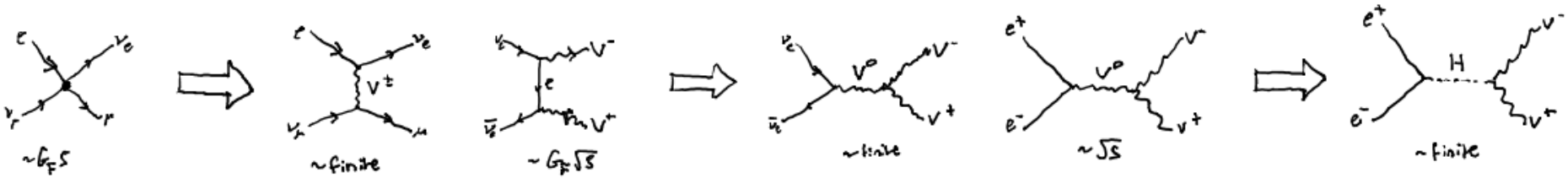
EFT to the SM

- EFT led to non-abelian gauge theory and Higgs
- Historically:



- Inevitably:

Llewellyn Smith 1973
Joglekar 1974



- Structure also enforced by little group scaling

Electroweak fits *nailed* non-abelian gauge structure

- Started in 1980s, see e.g.

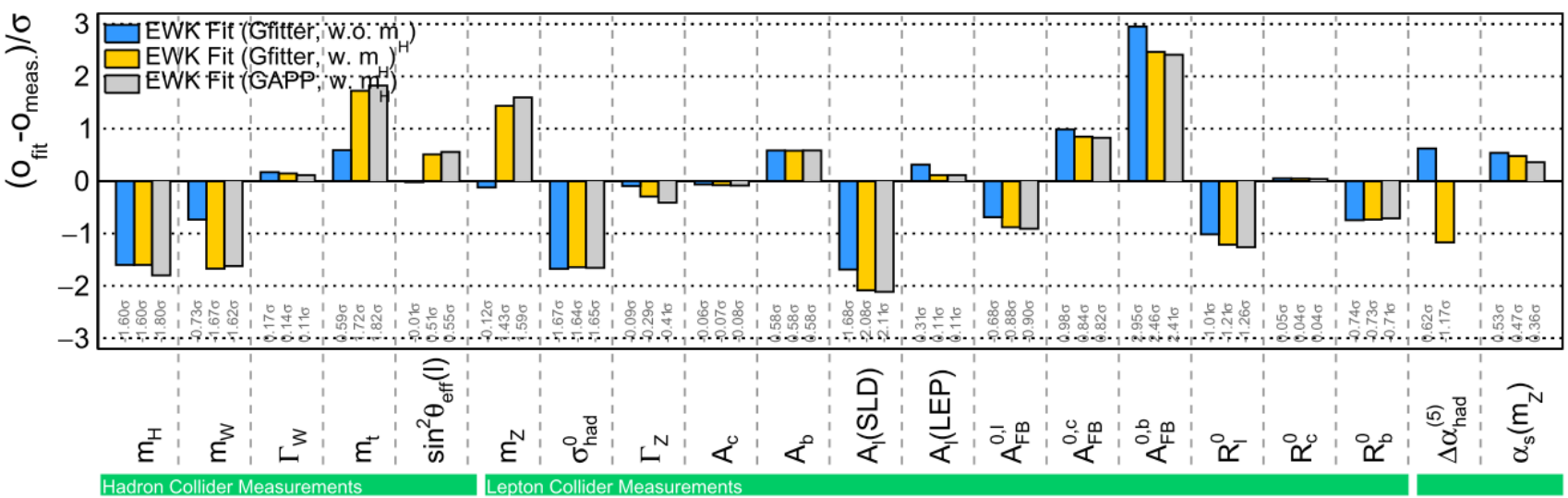
  J. E. Kim, P. Langacker, M. Levine and H. H. Williams, *Rev. Mod. Phys.* **53**, 211 (1981).

  U. Amaldi *et al.*, *Phys. Rev.* **D36**, 1385 (1987).

  G. Costa, J. R. Ellis, G. L. Fogli, D. V. Nanopoulos and F. Zwirner, *Nucl. Phys.* **B297**, 244 (1988).

- Recent electroweak fits:
  - **GAPP** (1710.06503)
  - **Gfitter** (1407.3792)
  - **HEPfit** (1710.05402)
  - **Zfitter** (1302.1395)

See e.g. review by Erler & Scott 1902.05142



SM to SMEFT framework

- New physics appear to be decoupled at higher energies
- Given particle content, write down *all* terms allowed by symmetries…

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q_L	**3**	**2**	$\frac{1}{6}$
q_R^u	**3**	**1**	$\frac{2}{3}$
q_R^d	**3**	**1**	$-\frac{1}{3}$
L_L	**1**	**2**	$-\frac{1}{2}$
l_R	**1**	**1**	-1
ϕ	**1**	**2**	$\frac{1}{2}$

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad ,$$

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D_\mu^L Q_L + \bar{q}_R i\gamma^\mu D_\mu^R q_R + \bar{L}_L i\gamma^\mu D_\mu^L L_L + \bar{l}_R i\gamma^\mu D_\mu^R l_R$$
$$\mathcal{L}_G = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu}$$
$$\mathcal{L}_H = (D_\mu^L\phi)^\dagger(D^{L\mu}\phi) - V(\phi)$$
$$\mathcal{L}_Y = y_d\bar{Q}_L\phi q_R^d + y_u\bar{Q}_L\phi^c q_R^u + y_L\bar{L}_L\phi l_R + \text{h.c.} \quad ,$$

- …Including **higher-dimensional** operators!

$$+ \quad \boxed{\mathcal{L}_{\text{SM}}^{\text{dim-6}} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i}$$

- Generated by new physics at scale $\Lambda \gg v$

Global **SMEFT** fit examples

Tevong You

- **(Electroweak):** *Han & Skiba* 0412166, *Efrati, Falkowski, Soreq* 1503.07872*
- **(Higgs)**: *Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia* 1211.4580
- **(Electroweak)**+**(Higgs+TGC)**: *Pomarol & Riva* 1308.2803
- **(Electroweak)**+**(Higgs+TGC+differential)**: *Ellis, Sanz, TY* 1410.7703
- **(LEP TGC)**: *Berthier, Bjorn, Trott* 1606.06693
- **(electroweak + LEP TGC)**: *Falkowski & Riva* 1411.0669
- **(Four-fermion)**: *Falkowski, Gonzalez-Alonso, Mimouni* 1706.03783*
- **(Electroweak+Higgs+TGC+differential)**: *Ellis, Murphy, Sanz, TY* 1803.03252, *Biekotter, Corbett, Plehn* 1812.07587, *Almeida et al* 1812.01009
- **(Electroweak+Higgs+LEP TGC)**: *Falkowski & Straub* 1911.07866*
- **Top, flavour, future colliders...**

*general flavour structure

SMEFT framework

- Unique dim-5 Weinberg operator, violates lepton number, predicts neutrino masses
- Up to flavour structure, there are **59** dim-6 (CP-even) operators in a **non-redundant** basis

Buchmuller and Wyler (Nucl. Phys. B 268 (1986) 621)
Gradkowski et al [arXiv:1008.4884]

- **~19** operators relevant for EWPT, TGC, and Higgs physics

EWPTs	Higgs Physics	TGCs
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$		
$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$		$\mathcal{O}_{3W} = g\frac{\epsilon_{abc}}{3!} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	
$\mathcal{O}^{(3)\,l}_{LL} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	
$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$	$\mathcal{O}_g = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	
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In SILH basis (Giudice et al. hep-ph/0703164), adopted from Pomarol and Riva (1308.1426)

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Combinations of operators constrained in EWPT more easily set to zero in Higgs and TGCs

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Operators constrained by measurements at per cent level or worse

In SILH basis (Giudice et al. hep-ph/0703164), adopted from Pomarol and Riva (1308.1426)

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Operators benefit from per mille precision at LEP

In SILH basis (Giudice et al. hep-ph/0703164), adopted from Pomarol and Riva (1308.1426)

LEP EWPT Example

- (Pseudo-)Observables

$$\Gamma_Z = \Gamma_{had} + 3\Gamma_\ell + 3\Gamma_\nu \qquad R_\ell = \frac{\Gamma_{had}}{\Gamma_\ell} \qquad \sigma_{had} = 12\pi \frac{\Gamma_e \Gamma_{had}}{\hat{m}_Z^2 \Gamma_Z^2} \qquad A_{FB}^f = \frac{3}{4} A_e A_f \qquad M_W = c_W M_Z$$

$$R_q = \frac{\Gamma_q}{\Gamma_{had}}$$

- Depends on

$$\Gamma_f = \frac{\sqrt{2} G_F M_Z^2 \hat{M}_Z}{6\pi} \left[(g_L^f)^2 + (g_R^f)^2 \right] \qquad A_f = \frac{(g_L^f)^2 - (g_R^f)^2}{(g_L^f)^2 + (g_R^f)^2}$$

$$g^f = T_f^3 - Q_f s_W^2 \qquad s_W^2 = \frac{1}{2} - \frac{1}{2}\sqrt{1 - \frac{4\pi\alpha}{\sqrt{2} G_F M_Z^2}}$$

- Dim-6 operators can modify observables directly through Zff couplings contributions or indirectly through redefinitions of input observables

$$m_Z^2 = (m_Z^2)^0 (1 + \Pi_{ZZ}) \qquad G_F = G_F^0 (1 - \Pi_{WW}^0) \qquad \alpha(m_Z) = \alpha^0(m_Z)(1 + \Pi'_{\gamma\gamma})$$

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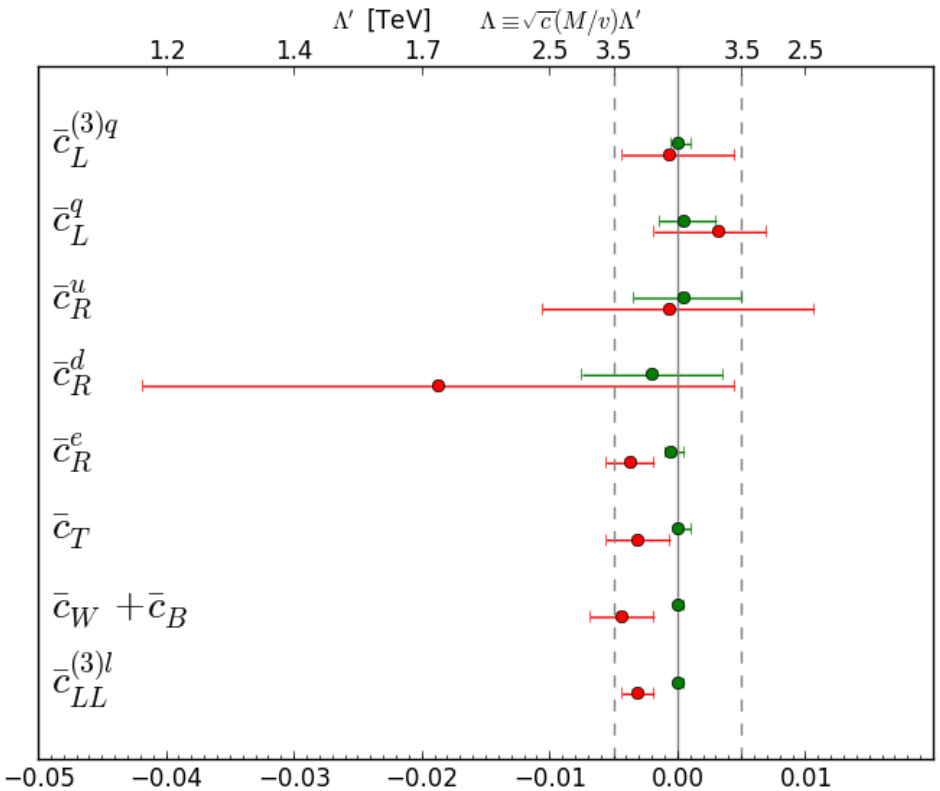
LEP EWPT Example

- Individual (green) and marginalised (red) 95% CL limits



Ellis, Sanz and T.Y. 1410.7703

- 8 (combinations of) operators probed by EWPT

Triple-Gauge-Couplings in Diboson

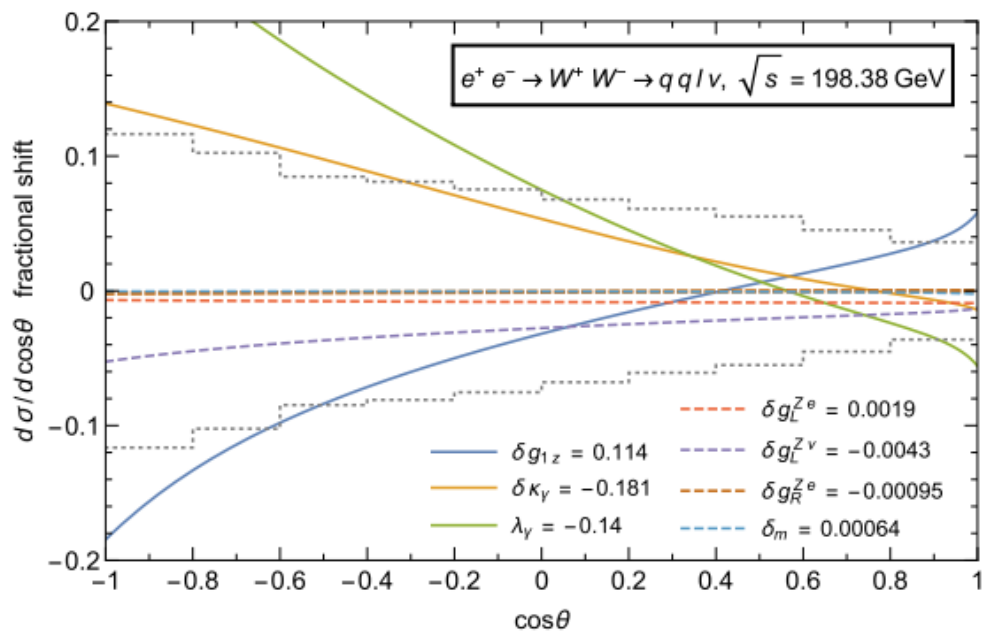
- Assume SM Z and W couplings to fermions in diboson measurements
- Interpret in anomalous TGC framework:

$$\mathcal{L}_{\rm TGC} = ig\Big\{(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})\big[(1+\delta g_{1z})\,c_\theta Z^\nu + s_\theta A^\nu\big] + \frac{1}{2}W^+_{[\mu,}W^-_{\nu]}\big[(1+\delta\kappa_z)\,c_\theta Z^{\mu\nu} + (1+\delta\kappa_\gamma)\,s_\theta A^{\mu\nu}\big] + \frac{1}{m_W^2}W^{+\nu}_{\mu}W^{-\rho}_{\nu}(\lambda_z c_\theta Z_\rho{}^\mu + \lambda_\gamma s_\theta A_\rho{}^\mu)\Big\},$$

Z. Zhang, 1610.01618

(See also Grojean et al 1810.05149)

- Justified at LEP:



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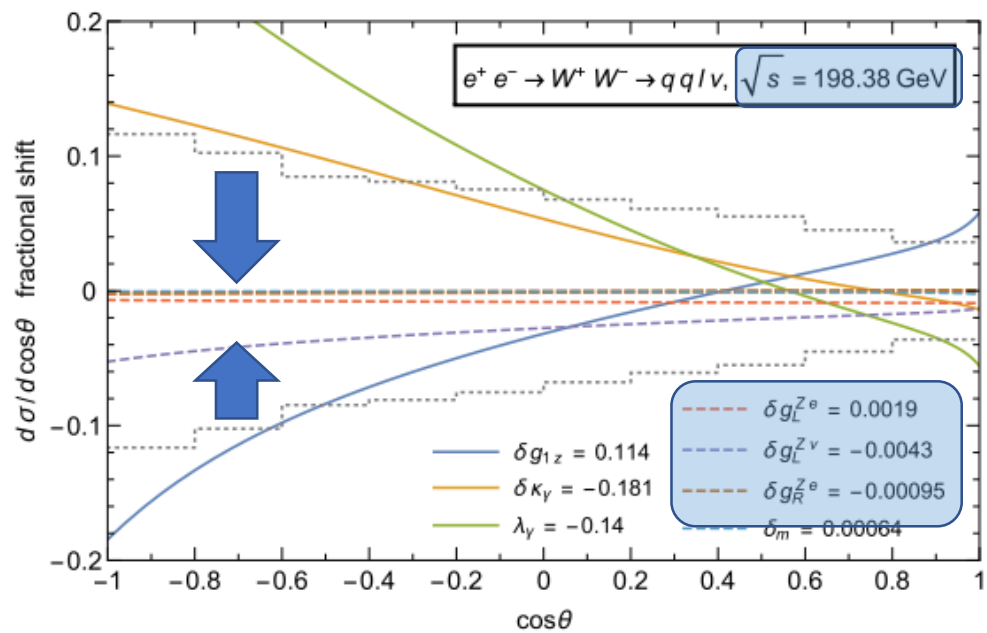

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Z. Zhang, 1610.01618

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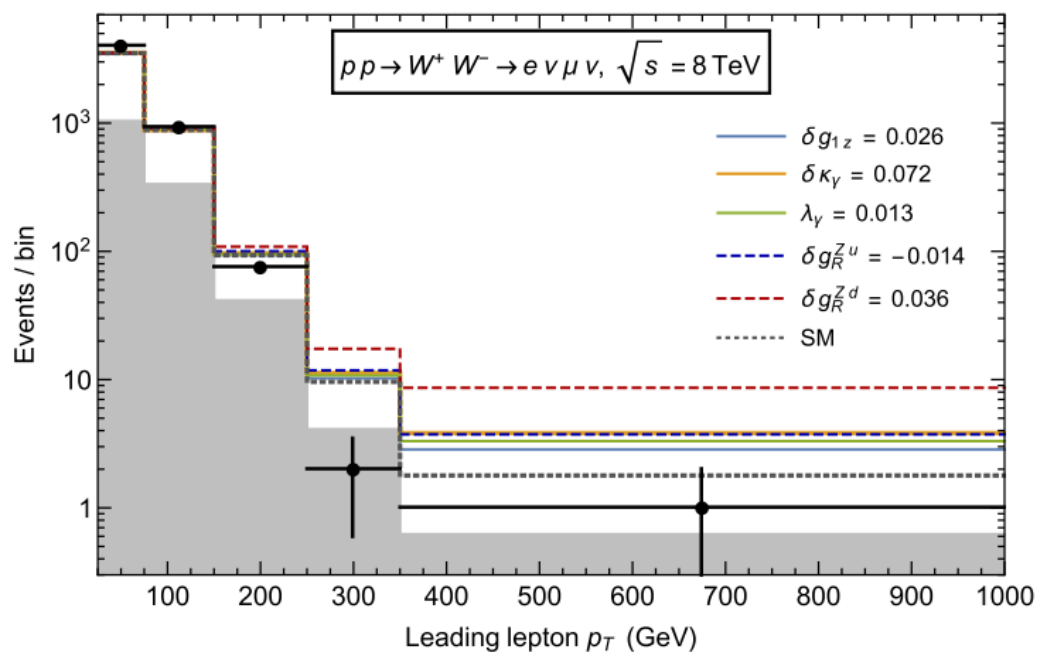
- But not at high pT:



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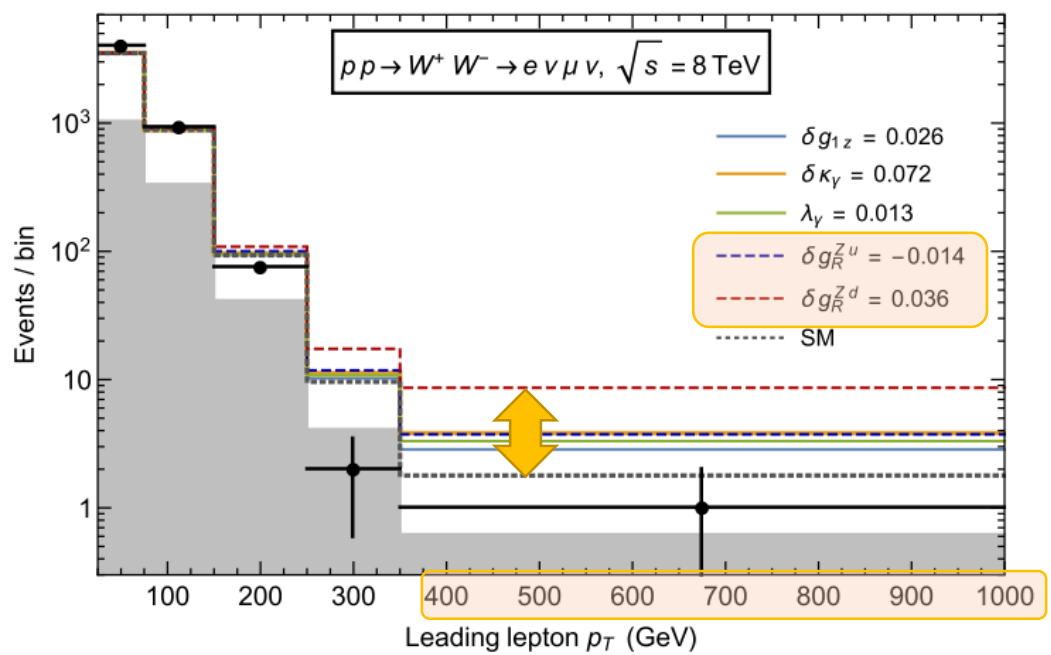


Note: quadratic dim-6 effect unless diboson SM-BSM interference recovered

Azatov et al 1607.05236, 1707.08060, Panico, Riva, Wulzer 1708.07823

Updated Global SMEFT Fit

J. Ellis, C. Murphy, V. Sanz and TY, 1803.03252

- Combine **EWPT, diboson, Higgs** data
- Fit to 20 dim-6 CP-even operators **simultaneously**
- Present results in **Warsaw** and **SILH** basis
- Match to **simplified models**
- See also similar recent fits:
  - 1906.05296 van Beek, Nocera, Rojo, Slade
  - 1812.07587 Biekotter, Corbett, Plehn
  - 1812.01009 Almeida, Alves, Rosa-Agostinho, Eboli, Gonzalez-Garcia

Updated Global SMEFT Fit

- Warsaw basis

$$\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset \frac{\bar{C}_{Hl}^{(3)}}{v^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}\tau^I\gamma^\mu l) + \frac{\bar{C}_{Hl}^{(1)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l) + \frac{\bar{C}_{ll}}{v^2}(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$$
$$+ \frac{\bar{C}_{HD}}{v^2}\left|H^\dagger D_\mu H\right|^2 + \frac{\bar{C}_{HWB}}{v^2}H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$$
$$+ \frac{\bar{C}_{He}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e) + \frac{\bar{C}_{Hu}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u) + \frac{\bar{C}_{Hd}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$$
$$+ \frac{\bar{C}_{Hq}^{(3)}}{v^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q) + \frac{\bar{C}_{Hq}^{(1)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q) + \frac{\bar{C}_W}{v^2}\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$$

$$\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset \frac{\bar{C}_{eH}}{v^2}(H^\dagger H)(\bar{l}eH) + \frac{\bar{C}_{dH}}{v^2}(H^\dagger H)(\bar{q}dH) + \frac{\bar{C}_{uH}}{v^2}(H^\dagger H)(\bar{q}u\widetilde{H})$$
$$+ \frac{\bar{C}_G}{v^2}f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho + \frac{\bar{C}_{H\Box}}{v^2}(H^\dagger H)\Box(H^\dagger H) + \frac{\bar{C}_{uG}}{v^2}(\bar{q}\sigma^{\mu\nu}T^A u)\widetilde{H}\, G^A_{\mu\nu}$$
$$+ \frac{\bar{C}_{HW}}{v^2}H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu} + \frac{\bar{C}_{HB}}{v^2}H^\dagger H\, B_{\mu\nu}B^{\mu\nu} + \frac{\bar{C}_{HG}}{v^2}H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}\,.$$

Observables

- LEP and SLC EWPTs, M_W from ATLAS, Tevatron

Observable	Measurement	Ref.	SM Prediction	Ref.
Γ_Z [GeV]	2.4952 ± 0.0023	[39]	2.4943 ± 0.0005	[38]
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	[39]	41.488 ± 0.006	[38]
R^0_ℓ	20.767 ± 0.025	[39]	20.752 ± 0.005	[38]
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	[39]	0.01622 ± 0.00009	[114]
$\mathcal{A}_\ell\,(P_\tau)$	0.1465 ± 0.0033	[39]	0.1470 ± 0.0004	[114]
$\mathcal{A}_\ell\,(\mathrm{SLD})$	0.1513 ± 0.0021	[39]	0.1470 ± 0.0004	[114]
R^0_b	0.021629 ± 0.00066	[39]	0.2158 ± 0.00015	[38]
R^0_c	0.1721 ± 0.0030	[39]	0.17223 ± 0.00005	[38]
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	[39]	0.1031 ± 0.0003	[114]
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	[39]	0.0736 ± 0.0002	[114]
$\mathcal{A}_b$	0.923 ± 0.020	[39]	0.9347	[114]
$\mathcal{A}_c$	0.670 ± 0.027	[39]	0.6678 ± 0.0002	[114]
M_W [GeV]	80.387 ± 0.016	[40]	80.361 ± 0.006	[114]
M_W [GeV]	80.370 ± 0.019	[94]	80.361 ± 0.006	[114]

- LEP WW measurements
- ATLAS WW high pT overflow bin

Observables

- ATLAS+CMS Higgs Run 1

Production	Decay	Signal Strength	Production	Decay	Signal Strength
ggF	$\gamma\gamma$	$1.10^{+0.23}_{-0.22}$	Wh	$\tau\tau$	-1.4 ± 1.4
ggF	ZZ	$1.13^{+0.34}_{-0.31}$	Wh	bb	1.0 ± 0.5
ggF	WW	0.84 ± 0.17	Zh	$\gamma\gamma$	$0.5^{+3.0}_{-2.5}$
ggF	$\tau\tau$	1.0 ± 0.6	Zh	WW	$5.9^{+2.6}_{-2.2}$
VBF	$\gamma\gamma$	1.3 ± 0.5	Zh	$\tau\tau$	$2.2^{+2.2}_{-1.8}$
VBF	ZZ	$0.1^{+1.1}_{-0.6}$	Zh	bb	0.4 ± 0.4
VBF	WW	1.2 ± 0.4	tth	$\gamma\gamma$	$2.2^{+1.6}_{-1.3}$
VBF	$\tau\tau$	1.3 ± 0.4	tth	WW	$5.0^{+1.8}_{-1.7}$
Wh	$\gamma\gamma$	$0.5^{+1.3}_{-1.2}$	tth	$\tau\tau$	$-1.9^{+3.7}_{-3.3}$
Wh	WW	$1.6^{+1.2}_{-1.0}$	tth	bb	1.1 ± 1.0
pp	$Z\gamma$	$2.7^{+4.6}_{-4.5}$	pp	$\mu\mu$	0.1 ± 2.5

Observables

- ATLAS+CMS Higgs Run 2

	Production	Decay	Sig. Stren.		Production	Decay	Sig. Stren.
[96]	1-jet, $p_T > 450$	$b\bar{b}$	$2.3^{+1.8}_{-1.6}$	[105]	pp	$\mu\mu$	-0.1 ± 1.4
[97]	Zh	$b\bar{b}$	0.9 ± 0.5	[106]	Zh	$b\bar{b}$	$0.69^{+0.35}_{-0.31}$
[97]	Wh	$b\bar{b}$	1.7 ± 0.7	[106]	Wh	$b\bar{b}$	$1.21^{+0.45}_{-0.42}$
[98]	$t\bar{t}h$	$b\bar{b}$	$-0.19^{+0.80}_{-0.81}$	[107]	$t\bar{t}h$	$b\bar{b}$	$0.84^{+0.64}_{-0.61}$
[99]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-1.20^{+1.50}_{-1.47}$	[108]	$t\bar{t}h$	$2\ell os + 1\tau_h$	$1.7^{+2.1}_{-1.9}$
[99]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$0.86^{+0.79}_{-0.66}$	[108]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-0.6^{+1.6}_{-1.5}$
[99]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.22^{+1.34}_{-1.00}$	[108]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.6^{+1.8}_{-1.3}$
[100]	$t\bar{t}h$	$2\ell ss$	$1.7^{+0.6}_{-0.5}$	[108]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$3.5^{+1.7}_{-1.3}$
[100]	$t\bar{t}h$	3ℓ	$1.0^{+0.8}_{-0.7}$	[108]	$t\bar{t}h$	3ℓ	$1.8^{+0.9}_{-0.7}$
[100]	$t\bar{t}h$	4ℓ	$0.9^{+2.3}_{-1.6}$	[108]	$t\bar{t}h$	$2\ell ss$	$1.5^{+0.7}_{-0.6}$
[101]	0-jet	WW	$0.9^{+0.4}_{-0.3}$	[109]	VBF	WW	$1.7^{+1.1}_{-0.9}$
[101]	1-jet	WW	1.1 ± 0.4	[109]	Wh	WW	$3.2^{+4.4}_{-4.2}$
[101]	2-jet	WW	1.3 ± 1.0	[110]	$\mathrm{B}(h \to \gamma\gamma)/\ \mathrm{B}(h \to 4\ell)$		$0.69^{+0.15}_{-0.13}$
[101]	VBF 2-jet	WW	1.4 ± 0.8	[110]	0-jet	4ℓ	$1.07^{+0.27}_{-0.25}$
[101]	Vh 2-jet	WW	$2.1^{+2.3}_{-2.2}$	[110]	1-jet, $p_T < 60$	4ℓ	$0.67^{+0.72}_{-0.68}$
[101]	Wh 3-lep	WW	-1.4 ± 1.5	[110]	1-jet, $p_T \in (60, 120)$	4ℓ	$1.00^{+0.63}_{-0.55}$
[102]	ggF	$\gamma\gamma$	$1.11^{+0.19}_{-0.18}$	[110]	1-jet, $p_T \in (120, 200)$	4ℓ	$2.1^{+1.5}_{-1.3}$
[102]	VBF	$\gamma\gamma$	$0.5^{+0.6}_{-0.5}$	[110]	2-jet	4ℓ	$2.2^{+1.1}_{-1.0}$
[102]	$t\bar{t}h$	$\gamma\gamma$	2.2 ± 0.9	[110]	"BSM-like"	4ℓ	$2.3^{+1.2}_{-1.0}$
[102]	Vh	$\gamma\gamma$	$2.3^{+1.1}_{-1.0}$	[110]	VBF, $p_T < 200$	4ℓ	$2.14^{+0.94}_{-0.77}$
[103]	ggF	4ℓ	$1.20^{+0.22}_{-0.21}$	[110]	Vh lep	4ℓ	$0.3^{+1.3}_{-1.2}$
[104]	0-jet	$\tau\tau$	0.84 ± 0.89	[110]	$t\bar{t}h$	4ℓ	$0.51^{+0.86}_{-0.70}$
[104]	boosted	$\tau\tau$	$1.17^{+0.47}_{-0.40}$				
[104]	VBF	$\tau\tau$	$1.11^{+0.34}_{-0.35}$				

Observables

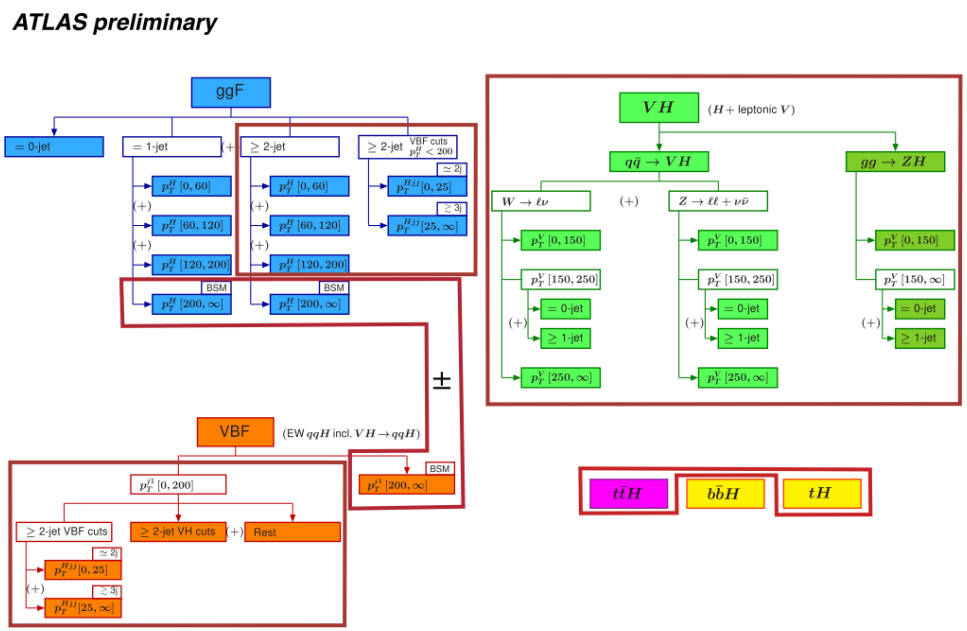
- ATLAS+CMS Higgs Run 2

Including kinematical information facilitated by **STXS**

	Production	Decay	Sig. Stren.		Production	Decay	Sig. Stren.
[96]	1-jet, $p_T > 450$	$b\bar{b}$	$2.3^{+1.8}_{-1.6}$	[105]	pp	$\mu\mu$	-0.1 ± 1.4
[97]	Zh	$b\bar{b}$	0.9 ± 0.5	[106]	Zh	$b\bar{b}$	$0.69^{+0.35}_{-0.31}$
[97]	Wh	$b\bar{b}$	1.7 ± 0.7	[106]	Wh	$b\bar{b}$	$1.21^{+0.45}_{-0.42}$
[98]	$t\bar{t}h$	$b\bar{b}$	$-0.19^{+0.80}_{-0.81}$	[107]	$t\bar{t}h$	$b\bar{b}$	$0.84^{+0.64}_{-0.61}$
[99]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-1.20^{+1.50}_{-1.47}$	[108]	$t\bar{t}h$	$2\ell os + 1\tau_h$	$1.7^{+2.1}_{-1.9}$
[99]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$0.86^{+0.79}_{-0.66}$	[108]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-0.6^{+1.6}_{-1.5}$
[99]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.22^{+1.34}_{-1.00}$	[108]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.6^{+1.8}_{-1.3}$
[100]	$t\bar{t}h$	$2\ell ss$	$1.7^{+0.6}_{-0.5}$	[108]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$3.5^{+1.7}_{-1.3}$
[100]	$t\bar{t}h$	3ℓ	$1.0^{+0.8}_{-0.7}$	[108]	$t\bar{t}h$	3ℓ	$1.8^{+0.9}_{-0.7}$
[100]	$t\bar{t}h$	4ℓ	$0.9^{+2.3}_{-1.6}$	[108]	$t\bar{t}h$	$2\ell ss$	$1.5^{+0.7}_{-0.6}$
[101]	0-jet	WW	$0.9^{+0.4}_{-0.3}$	[109]	VBF	WW	$1.7^{+1.1}_{-0.9}$
[101]	1-jet	WW	1.1 ± 0.4	[109]	Wh	WW	$3.2^{+4.4}_{-4.2}$
[101]	2-jet	WW	1.3 ± 1.0	[110]	$\mathrm{B}(h \to \gamma\gamma)/\ \mathrm{B}(h \to 4\ell)$		$0.69^{+0.15}_{-0.13}$
[101]	VBF 2-jet	WW	1.4 ± 0.8	[110]	0-jet	4ℓ	$1.07^{+0.27}_{-0.25}$
[101]	Vh 2-jet	WW	$2.1^{+2.3}_{-2.2}$	[110]	1-jet, $p_T < 60$	4ℓ	$0.67^{+0.72}_{-0.68}$
[101]	Wh 3-lep	WW	-1.4 ± 1.5	[110]	1-jet, $p_T \in (60, 120)$	4ℓ	$1.00^{+0.63}_{-0.55}$
[102]	ggF	$\gamma\gamma$	$1.11^{+0.19}_{-0.18}$	[110]	1-jet, $p_T \in (120, 200)$	4ℓ	$2.1^{+1.5}_{-1.3}$
[102]	VBF	$\gamma\gamma$	$0.5^{+0.6}_{-0.5}$	[110]	2-jet	4ℓ	$2.2^{+1.1}_{-1.0}$
[102]	$t\bar{t}h$	$\gamma\gamma$	2.2 ± 0.9	[110]	"BSM-like"	4ℓ	$2.3^{+1.2}_{-1.0}$
[102]	Vh	$\gamma\gamma$	$2.3^{+1.1}_{-1.0}$	[110]	VBF, $p_T < 200$	4ℓ	$2.14^{+0.94}_{-0.77}$
[103]	ggF	4ℓ	$1.20^{+0.22}_{-0.21}$	[110]	Vh lep	4ℓ	$0.3^{+1.3}_{-1.2}$
[104]	0-jet	$\tau\tau$	0.84 ± 0.89	[110]	$t\bar{t}h$	4ℓ	$0.51^{+0.86}_{-0.70}$
[104]	boosted	$\tau\tau$	$1.17^{+0.47}_{-0.40}$				
[104]	VBF	$\tau\tau$	$1.11^{+0.34}_{-0.35}$				

STXS

- Simplified Template Cross-Sections
- Sub-division into kinematic regions for production processes

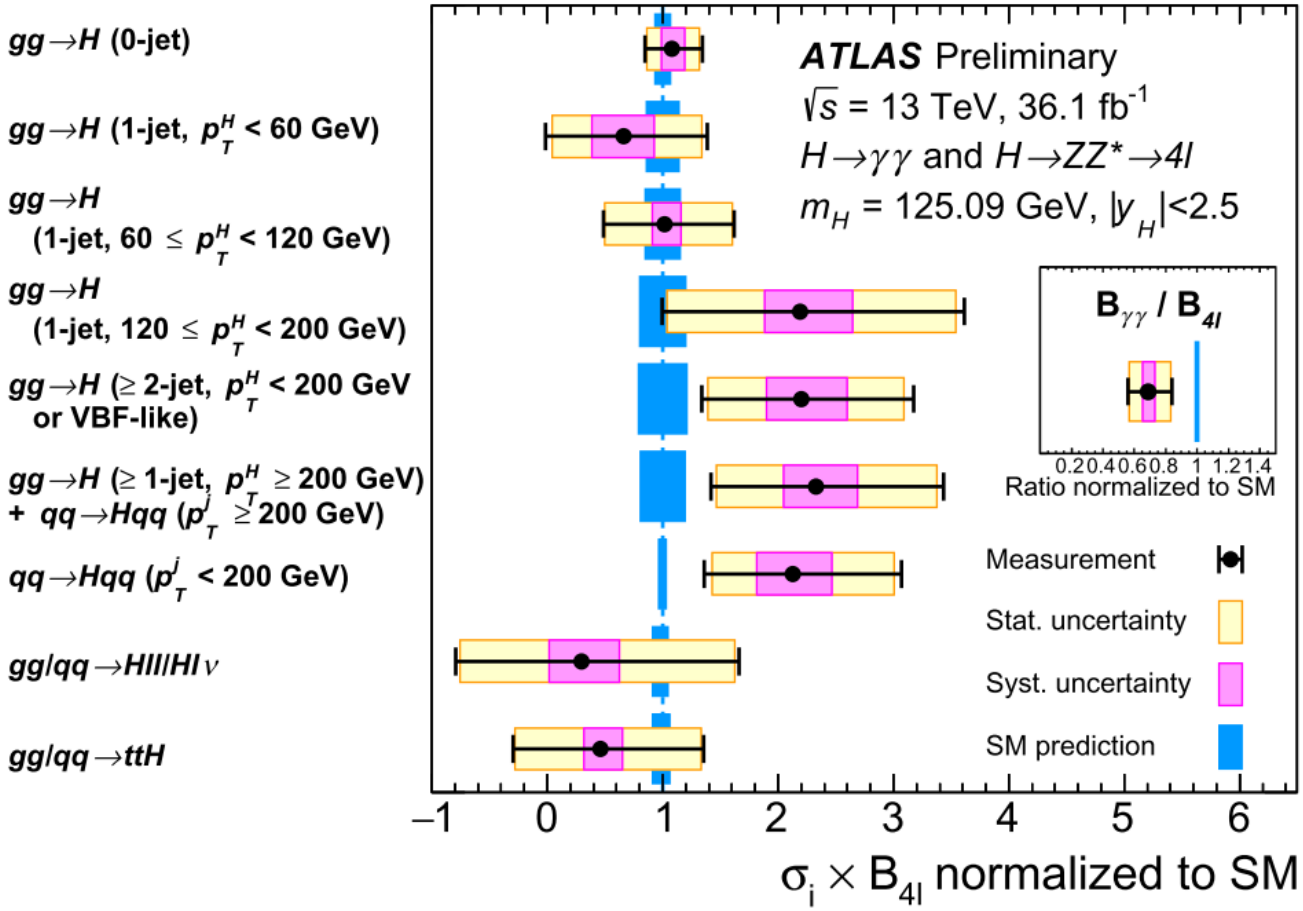


ATLAS-CONF-2017-047

- Facilitates combination and interpretation

STXS

- STXS measurements



ATLAS-CONF-2017-047

STXS

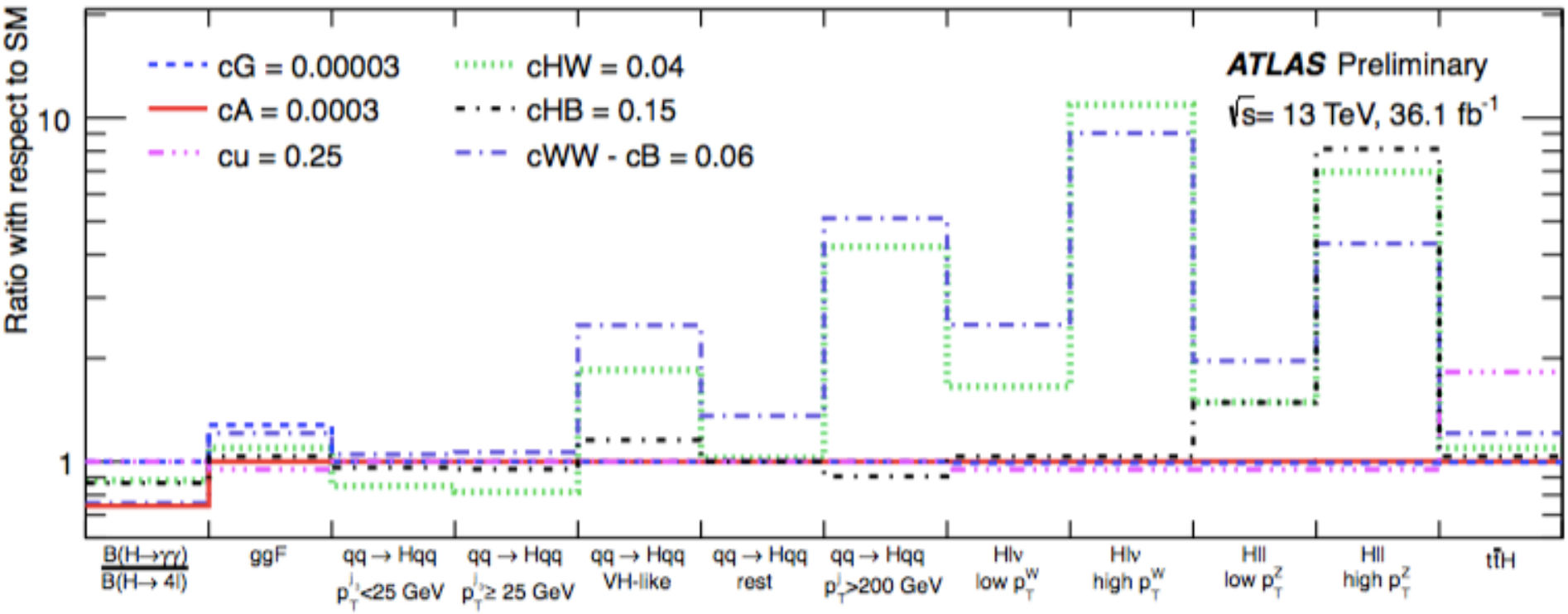
- STXS dim-6 predictions

Cross-section region	$\sum_i A_i c_i$
$gg \to H$ (0-jet) $gg \to H$ (1-jet, $p_T^H < 60$ GeV) $gg \to H$ (1-jet, $60 \le p_T^H < 120$ GeV)	$56c_g'$
$gg \to H$ (1-jet, $120 \le p_T^H < 200$ GeV)	$56c_g' + 18\mathtt{c3G} + 11\mathtt{c2G}$
$gg \to H$ (1-jet, $p_T^H \ge 200$ GeV)	$56c_g' + 52\mathtt{c3G} + 34\mathtt{c2G}$
$gg \to H$ ($\ge$ 2-jet, $p_T^H < 60$ GeV)	$56c_g'$
$gg \to H$ ($\ge$ 2-jet, $60 \le p_T^H < 120$ GeV)	$56c_g' + 8\mathtt{c3G} + 7\mathtt{c2G}$
$gg \to H$ ($\ge$ 2-jet, $120 \le p_T^H < 200$ GeV)	$56c_g' + 23\mathtt{c3G} + 18\mathtt{c2G}$
$gg \to H$ ($\ge$ 2-jet, $p_T^H \ge 200$ GeV)	$56c_g' + 90\mathtt{c3G} + 68\mathtt{c2G}$
$gg \to H$ ($\ge$ 2-jet VBF-like, $p_T^{j_3} < 25$ GeV)	$56c_g'$
$gg \to H$ ($\ge$ 2-jet VBF-like, $p_T^{j_3} \ge 25$ GeV)	$56c_g' + 9\mathtt{c3G} + 8\mathtt{c2G}$
$qq \to Hqq$ (VBF-like, $p_T^{j_3} < 25$ GeV)	$-1.0\mathtt{cH} - 1.0\mathtt{cT} + 1.3\mathtt{cWW} - 0.023\mathtt{cB} - 4.3\mathtt{cHW}$ $-0.29\mathtt{cHB} + 0.092\mathtt{cHQ} - 5.3\mathtt{cpHQ} - 0.33\mathtt{cHu} + 0.12\mathtt{cHd}$
$qq \to Hqq$ (VBF-like, $p_T^{j_3} \ge 25$ GeV)	$-1.0\mathtt{cH} - 1.1\mathtt{cT} + 1.2\mathtt{cWW} - 0.027\mathtt{cB} - 5.8\mathtt{cHW}$ $-0.41\mathtt{cHB} + 0.13\mathtt{cHQ} - 6.9\mathtt{cpHQ} - 0.45\mathtt{cHu} + 0.15\mathtt{cHd}$
$qq \to Hqq$ ($p_T^j \ge 200$ GeV)	$-1.0\mathtt{cH} - 0.95\mathtt{cT} + 1.5\mathtt{cWW} - 0.025\mathtt{cB} - 3.6\mathtt{cHW}$ $-0.24\mathtt{cHB} + 0.084\mathtt{cHQ} - 4.5\mathtt{cpHQ} - 0.25\mathtt{cHu} + 0.1\mathtt{cHd}$
$qq \to Hqq$ ($60 \le m_{jj} < 120$ GeV)	$-0.99\mathtt{cH} - 1.2\mathtt{cT} + 7.8\mathtt{cWW} - 0.19\mathtt{cB} - 31\mathtt{cHW}$ $-2.4\mathtt{cHB} + 0.9\mathtt{cHQ} - 38\mathtt{cpHQ} - 2.8\mathtt{cHu} + 0.9\mathtt{cHd}$
$qq \to Hqq$ (rest)	$-1.0\mathtt{cH} - 1.0\mathtt{cT} + 1.4\mathtt{cWW} - 0.028\mathtt{cB} - 6.2\mathtt{cHW}$ $-0.42\mathtt{cHB} + 0.14\mathtt{cHQ} - 6.9\mathtt{cpHQ} - 0.42\mathtt{cHu} + 0.16\mathtt{cHd}$
$gg/q\bar{q} \to ttH$	$-0.98\mathtt{cH} + 2.9\mathtt{cu} + 0.93\mathtt{cG} + 310\mathtt{cuG}$ $+27\mathtt{c3G} - 13\mathtt{c2G}$

Hays, Sanz, Zemaityte
[LHCHXSWG-INT-2017-01]

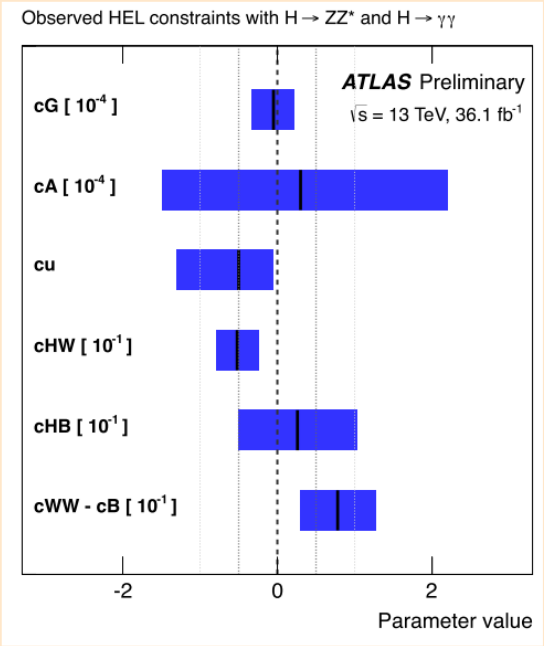
STXS

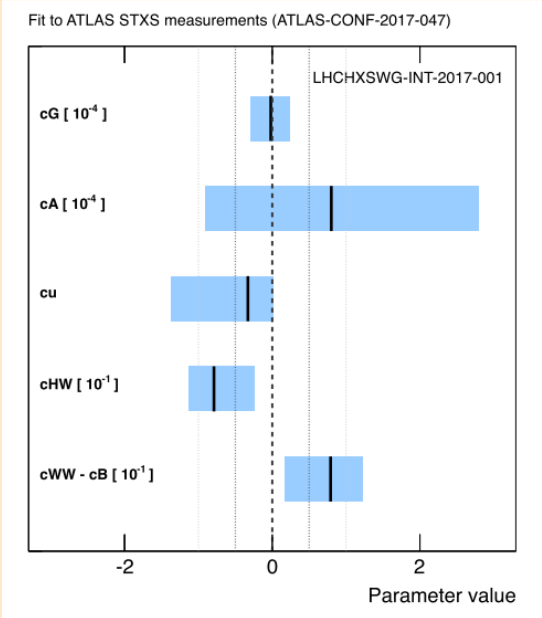
- STXS dim-6 predictions



STXS

- Good agreement with optimised non-STXS fit





ATLAS fit uses more categories than measured STXS

Fit to STXS measurement can only constrain five parameters

https://indico.cern.ch/event/682466/contributions/2796820/attachments/1573120/2482936/WG211Dec2017.pdf

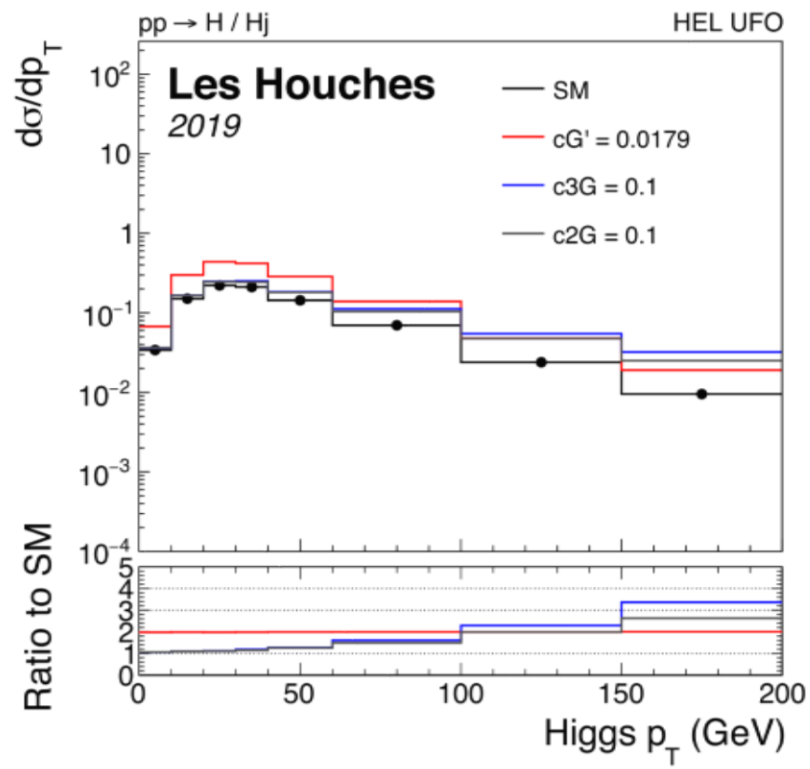
27 Mar 2018 C. Hays, Oxford University 13

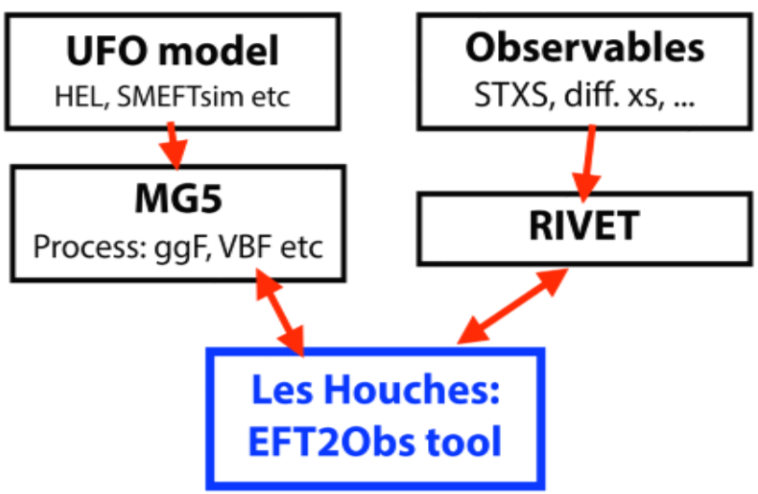
- VHbb now also available ATLAS 1903.04618

EFT⟺STXS mapping

- **General problem:** how do the operators of my favourite EFT affect the **STXS** / **diff. x-secs** measured by the experiments?
- **Solution:** develop new tool to automatically determine linear (and eventually quadratic) coefficients for scaling of ***any observable*** as a function of EFT params from ***any UFO model***
- First demo version produced
  - **https://github.com/ajgilbert/EFT2Obs-Demo**

Demo: ggF Higgs p_T distribution



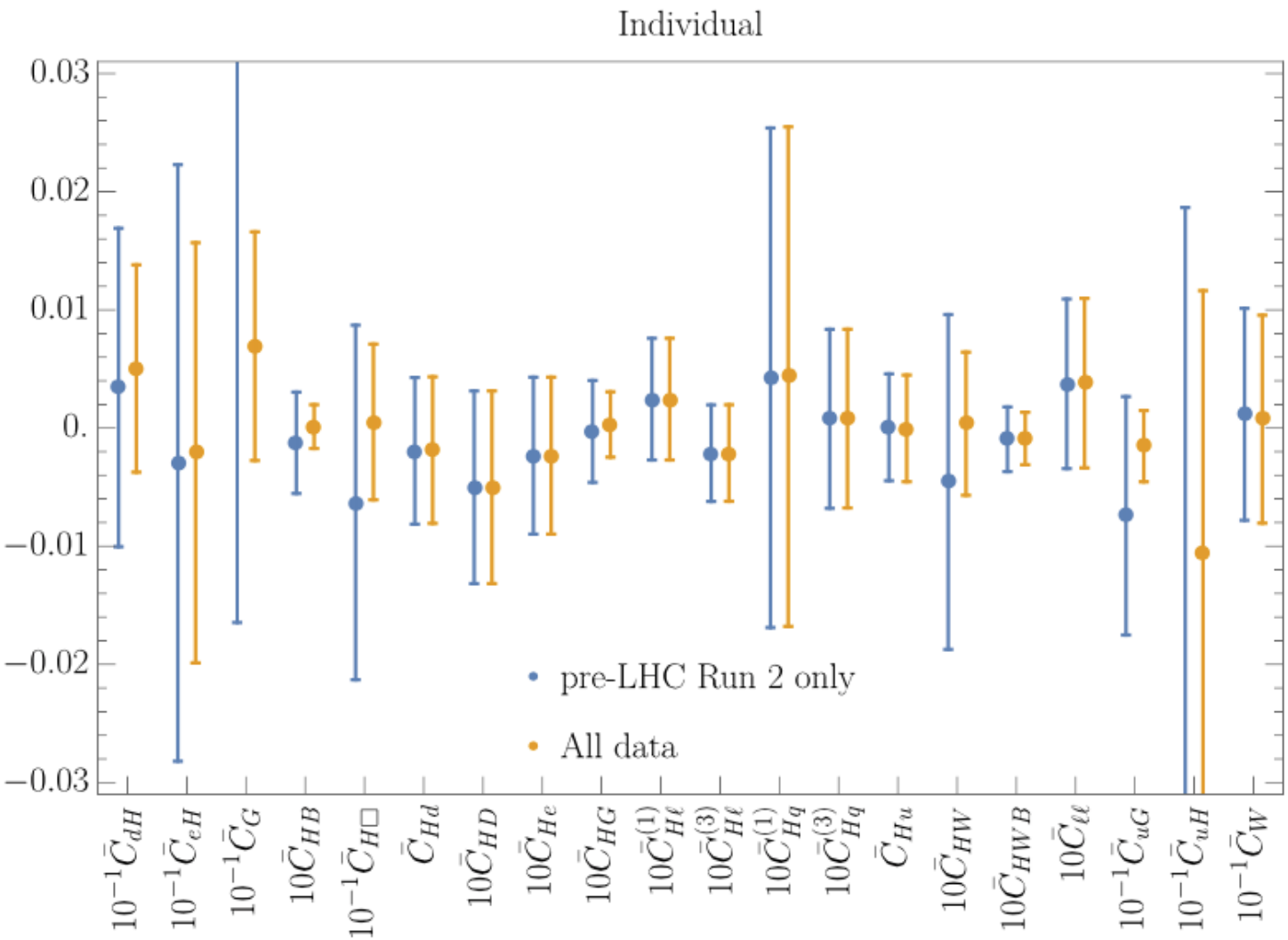



```
xsec / SM for bin 1 [0, 10] = 1.0 + 54.9*cG' + 0.605*c3G + 0.64*c2G
xsec / SM for bin 2 [10, 20] = 1.0 + 55.2*cG' + 0.986*c3G + 0.957*c2G
xsec / SM for bin 3 [20, 30] = 1.0 + 55*cG' + 1.22*c3G + 1.11*c2G
xsec / SM for bin 4 [30, 40] = 1.0 + 55.2*cG' + 1.93*c3G + 1.53*c2G
xsec / SM for bin 5 [40, 60] = 1.0 + 55.6*cG' + 2.75*c3G + 2.59*c2G
xsec / SM for bin 6 [60, 100] = 1.0 + 55.6*cG' + 6.1*c3G + 4.9*c2G
xsec / SM for bin 7 [100, 150] = 1.0 + 55.7*cG' + 12.9*c3G + 9.9*c2G
xsec / SM for bin 8 [150, 200] = 1.0 + 56*cG' + 23.7*c3G + 16.3*c2G
```


Slide by Andrew Gilbert

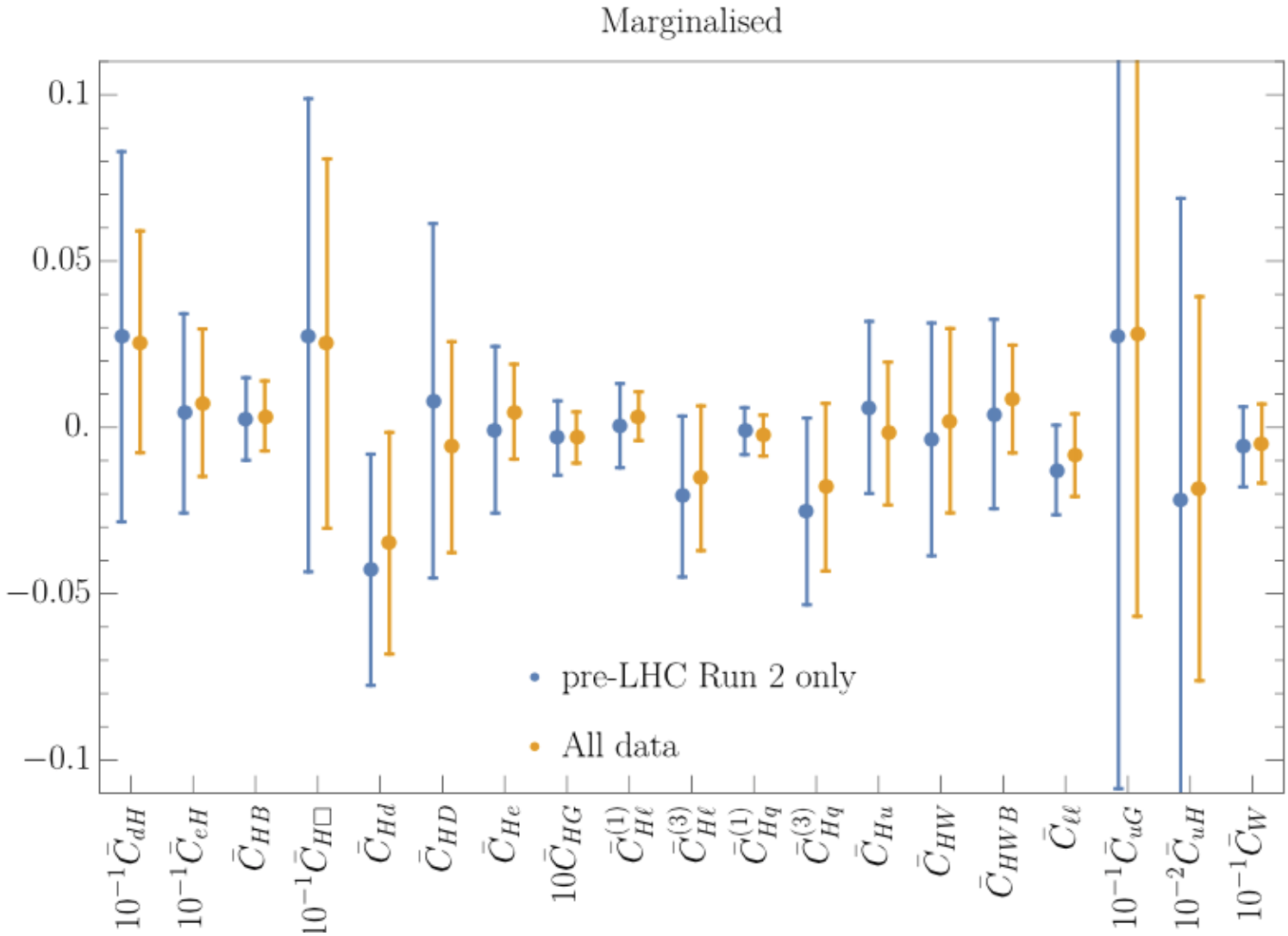
Results

- **Warsaw** basis, fit each operator **individually**



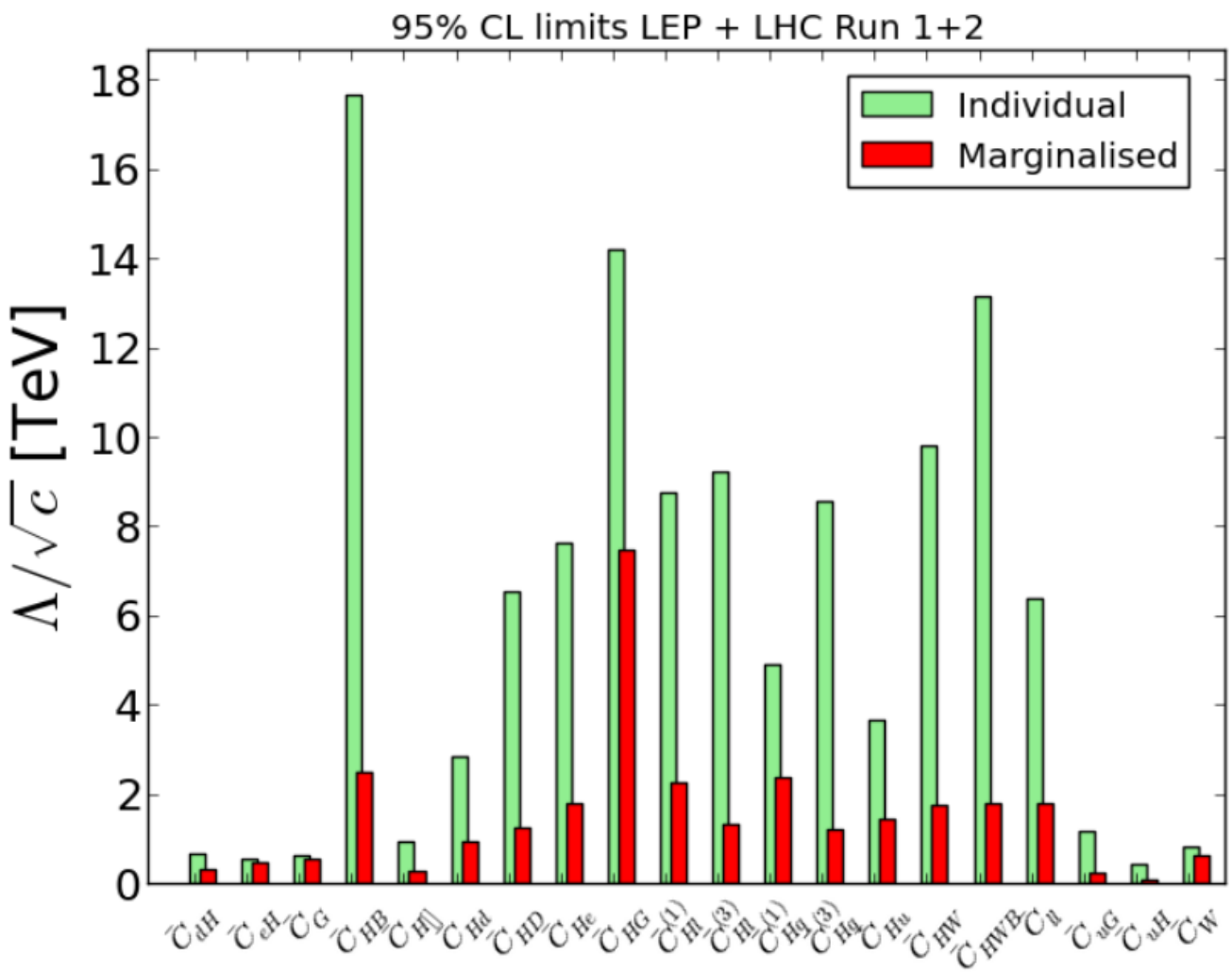
Results

- **Warsaw** basis, fit *all* operators **simultaneously**



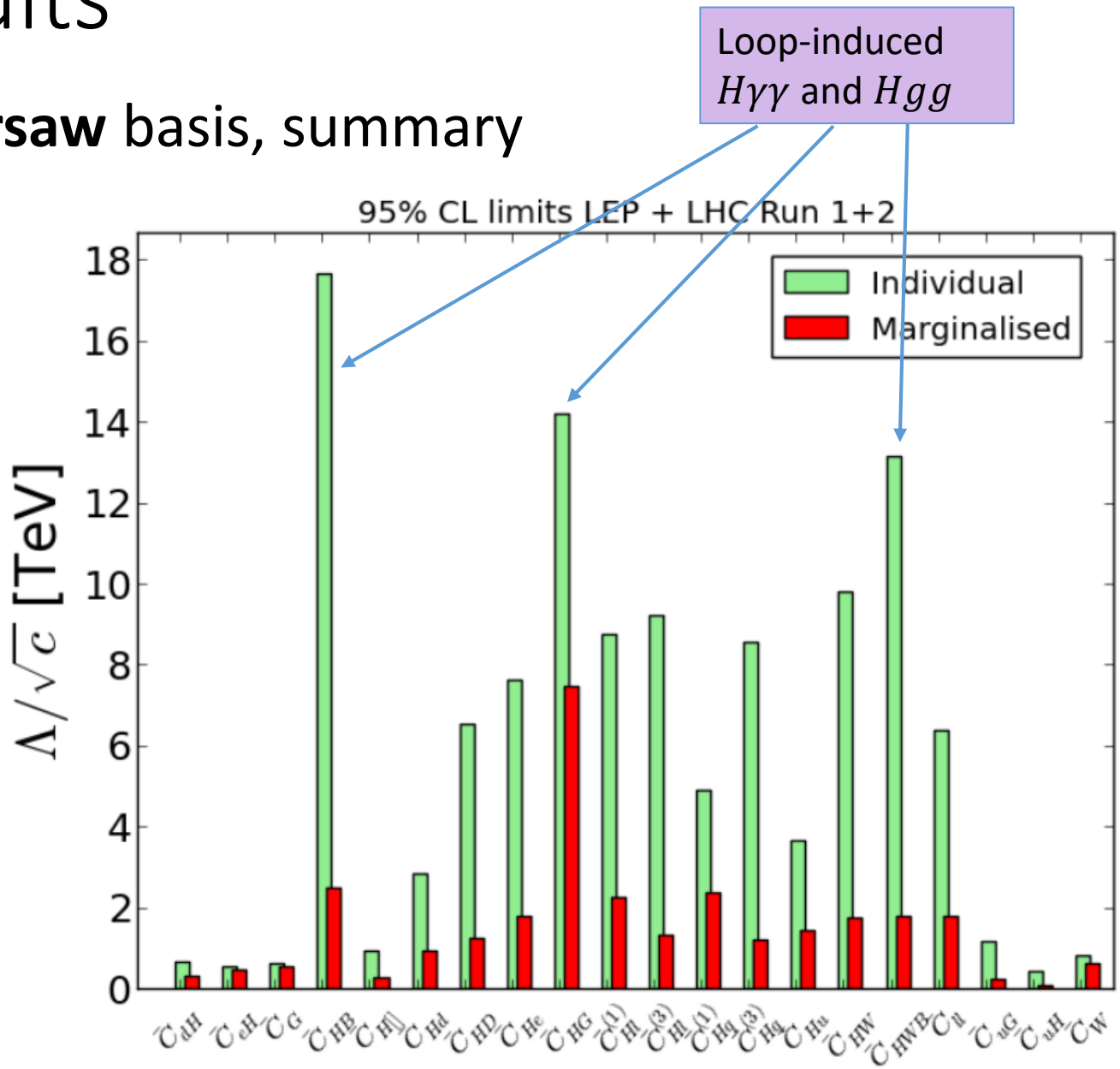
Results

- **Warsaw** basis, summary



Results

- **Warsaw** basis, summary



Outline

- SM EFT fits
- **BSM matching and constraints**
- SM EFT at higher energies
- SM EFT positivity bounds

Matching SMEFT to BSM

- Tree-level matching dictionary

  De Blas, Criado, Perez-Victoria, Santiago 1711.10391

- Automated tree-level matching tool

  Criado 1710.06445

- One-Loop matching - using Universal One-Loop Effective Action (UOLEA)

  Henning, Lu, Murayama, 1412.1837;
  Drozd, J. Ellis, Quevillon, TY, 1512.03003;
  S.A.R. Ellis, Quevillon, TY, Z. Zhang, 1604.02445, 1706.07765
  S.A.R. Ellis, Quevillon, Vuong, TY, Z. Zhang, in progress

- Automated one-loop matching tool

  Das Bakshi et al, CoDex, 1808.04403 (using UOLEA results)
  Santiago et al, Matchmaker, in progress

Application of the UOLEA: MSSM Stops

- Write UV Lagrangian for heavy multiplet in appropriate form to extract U matrix, mass matrix, and covariant derivative:

$$\boxed{\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm SM} + \cancel{(\Phi^\dagger F(x) + \text{h.c.})} + \Phi^\dagger (P^2 - M^2 - U(x))\Phi + \mathcal{O}(\Phi^3)}$$

(R-parity)

$$\Phi = (\tilde{Q}\,, \tilde{t}_R^*), \qquad M^2 = \begin{pmatrix} m^2_{\tilde{Q}} & 0 \\ 0 & m^2_{\tilde{t}_R} \end{pmatrix} \qquad G'_{\mu\nu} = \begin{pmatrix} W'^a_{\mu\nu}\tau^a + Y_{\tilde{Q}} B'_{\mu\nu}\mathbb{1} & 0 \\ 0 & -Y_{\tilde{t}_R} B'_{\mu\nu} \end{pmatrix}$$

$$U = \begin{pmatrix} (h_t^2 + \frac{1}{2}g_2^2 c_\beta^2)\tilde{H}\tilde{H}^\dagger + \frac{1}{2}g_2^2 s_\beta^2 H H^\dagger - \frac{1}{2}(g_1^2 Y_{\tilde{Q}} c_{2\beta} + \frac{1}{2}g_2^2)|H|^2 & h_t X_t \tilde{H} \\ h_t X_t \tilde{H}^\dagger & (h_t^2 - \frac{1}{2}g_1^2 Y_{\tilde{t}_R} c_{2\beta})|H|^2 \end{pmatrix}$$

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Application of the UOLEA: MSSM Stops

- Pick the relevant operators by counting operator dimensions

Universal coefficient	Operator
$f_2^i = \mathcal{I}_i^1$	U_{ii}
$f_3^i = 2\,\mathcal{I}[q^4]_i^4$	$G_i'^{\mu\nu} G'_{\mu\nu,i}$
$f_4^{ij} = \frac{1}{2}\mathcal{I}_{ij}^{11}$	$U_{ij}U_{ji}$
$f_5^i = 16\,\mathcal{I}[q^6]_i^6$	$[P^\mu, G'_{\mu\nu,i}][P_\rho, G_i'^{\rho\nu}]$
$f_6^i = \frac{32}{3}\,\mathcal{I}[q^6]_i^6$	$G'^{\mu}{}_{\nu,i} G'^{\nu}{}_{\rho,i} G'^{\rho}{}_{\mu,i}$
$f_7^{ij} = \mathcal{I}[q^2]_{ij}^{22}$	$[P^\mu, U_{ij}][P_\mu, U_{ji}]$
$f_8^{ijk} = \frac{1}{3}\mathcal{I}_{ijk}^{111}$	$U_{ij}U_{jk}U_{ki}$
$f_9^i = 8\,\mathcal{I}[q^4]_i^5$	$U_{ii} G_i'^{\mu\nu} G'_{\mu\nu,i}$
$f_{10}^{ijkl} = \frac{1}{4}\mathcal{I}_{ijkl}^{1111}$	$U_{ij}U_{jk}U_{kl}U_{li}$
$f_{11}^{ijk} = 2\big(\mathcal{I}[q^2]_{ijk}^{122} + \mathcal{I}[q^2]_{ijk}^{212}\big)$	$U_{ij}[P^\mu, U_{jk}][P_\mu, U_{ki}]$
$f_{12}^{ij} = 4\,\mathcal{I}[q^4]_{ij}^{33}$	$\big[P^\mu, [P_\mu, U_{ij}]\big]\big[P^\nu, [P_\nu, U_{ji}]\big]$
$f_{13}^{ij} = 4\big(\mathcal{I}[q^4]_{ij}^{33} + 2\,\mathcal{I}[q^4]_{ij}^{42} + 2\,\mathcal{I}[q^4]_{ij}^{51}\big)$	$U_{ij}U_{ji} G_i'^{\mu\nu} G'_{\mu\nu,i}$
$f_{14}^{ij} = -8\,\mathcal{I}[q^4]_{ij}^{33}$	$[P^\mu, U_{ij}][P^\nu, U_{ji}] G'_{\nu\mu,i}$
$f_{15}^{ij} = 4\big(\mathcal{I}[q^4]_{ij}^{33} + \mathcal{I}[q^4]_{ij}^{42}\big)$	$\big(U_{ij}[P^\mu, U_{ji}] - [P^\mu, U_{ij}]U_{ji}\big)[P^\nu, G'_{\nu\mu,i}]$
$f_{16}^{ijklm} = \frac{1}{5}\mathcal{I}_{ijklm}^{11111}$	$U_{ij}U_{jk}U_{kl}U_{lm}U_{mi}$
$f_{17}^{ijkl} = 2\big(\mathcal{I}[q^2]_{ijkl}^{2112} + \mathcal{I}[q^2]_{ijkl}^{1212} + \mathcal{I}[q^2]_{ijkl}^{1122}\big)$	$U_{ij}U_{jk}[P^\mu, U_{kl}][P_\mu, U_{li}]$
$f_{18}^{ijkl} = \mathcal{I}[q^2]_{ijkl}^{2121} + \mathcal{I}[q^2]_{ijkl}^{2112} + \mathcal{I}[q^2]_{ijkl}^{1221} + \mathcal{I}[q^2]_{ijkl}^{1212}$	$U_{ij}[P^\mu, U_{jk}]U_{kl}[P_\mu, U_{li}]$
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	X_t^0	X_t^2	X_t^4	X_t^6
c_6	f_8	f_{10}	f_{16}	f_{19}
c_H	f_7	f_{11}	f_{17}, f_{18}	-
c_T	f_7	f_{11}	f_{17}, f_{18}	-
c_R	f_7	f_{11}	f_{17}	-
c_{GG}	f_9	f_{13}	-	-
c_{WW}	f_9	f_{13}, f_{14}	-	-
c_{BB}	f_9	f_{13}, f_{14}	-	-
c_{WB}	f_9	f_{13}, f_{14}	-	-
c_W	-	f_{15a}, f_{15b}	-	-
c_B	-	f_{15a}, f_{15b}	-	-
c_D	-	f_{12c}	-	-

Application of the UOLEA: MSSM Stops

- Example: $\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a,\mu\nu}$

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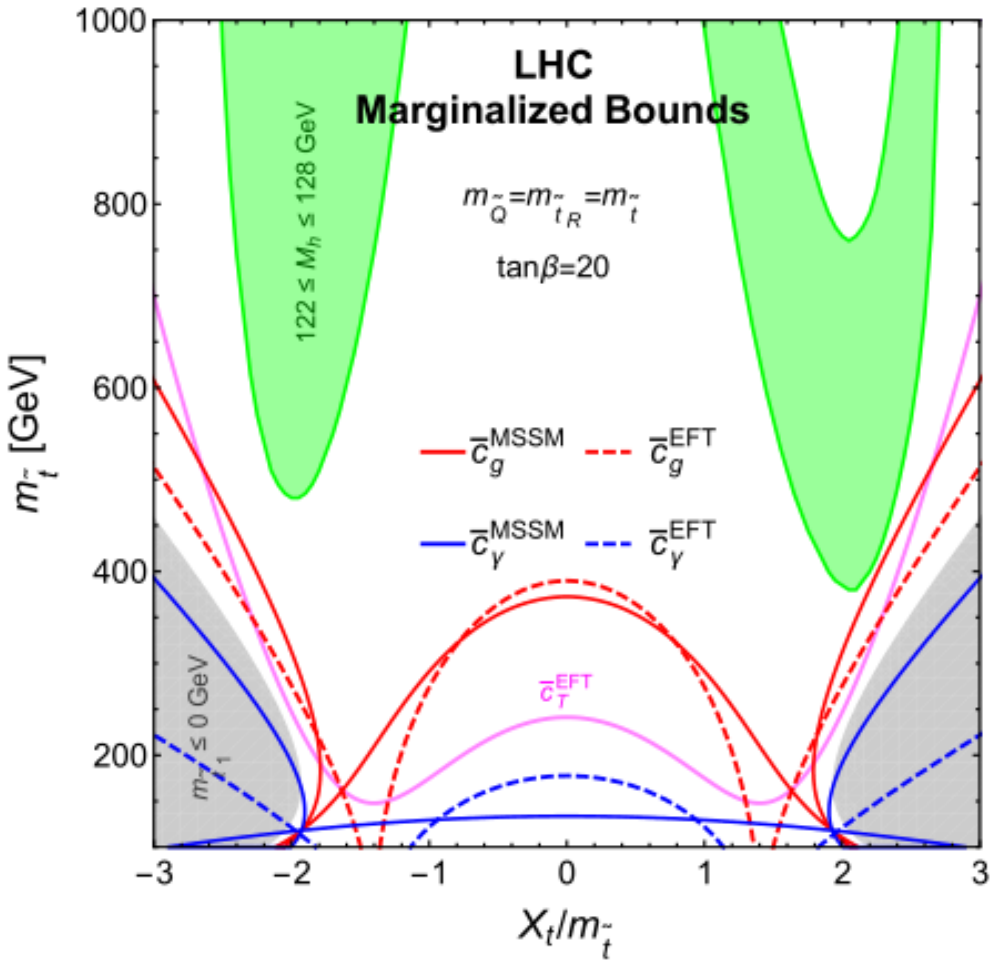
c_{BB}	f_9	f_{13}, f_{14}	-	-

$$c_{GG} = \frac{1}{24}\left(\frac{h_t^2 - \frac{1}{6}g_1^2 c_{2\beta}}{m_{\tilde{Q}}^2} + \frac{h_t^2 + \frac{1}{3}g_1^2 c_{2\beta}}{m_{\tilde{t}_R}^2} - \frac{\bar{X}_t^2}{m_{\tilde{Q}}^2 m_{\tilde{t}_R}^2}\right)$$

Results

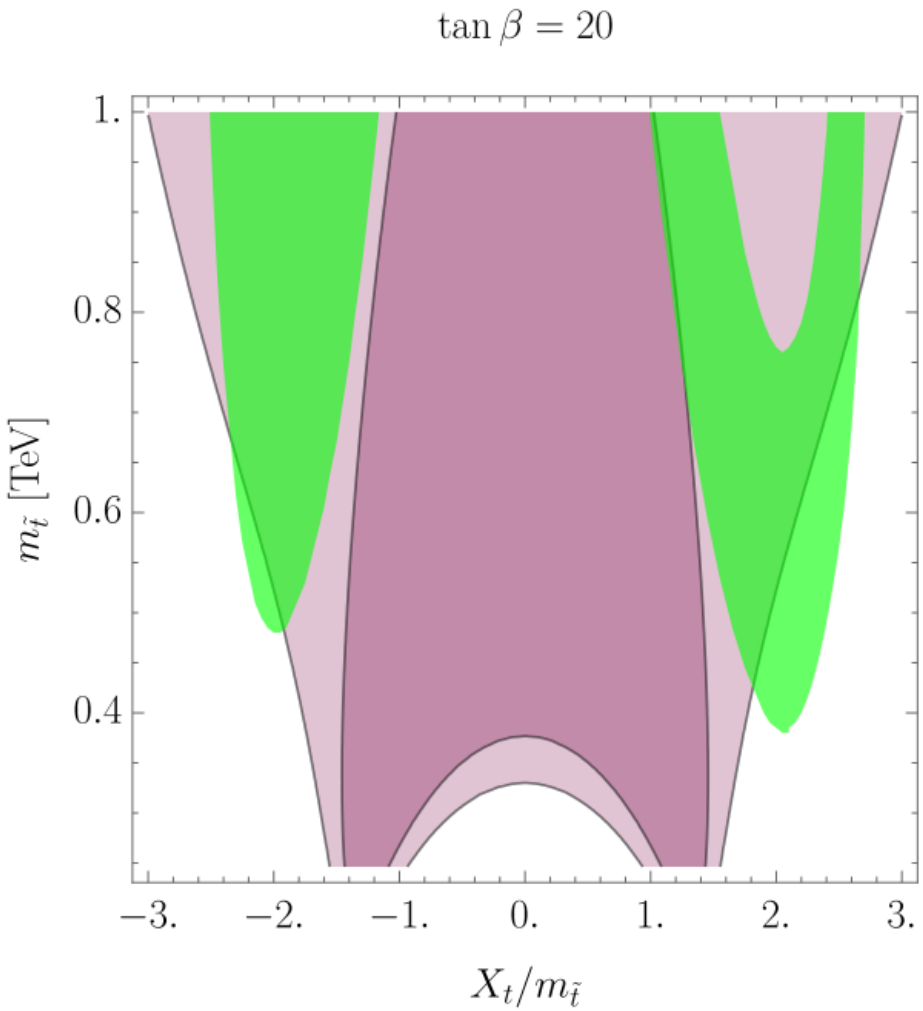
- Simplified models: **stops** (Run 1)



Drozd, Ellis, Quevillon and T.Y.
1504.02409

Results

- Simplified models: **stops** (Run 2)



Results

- Simplified models: **renormalisable SM extensions**

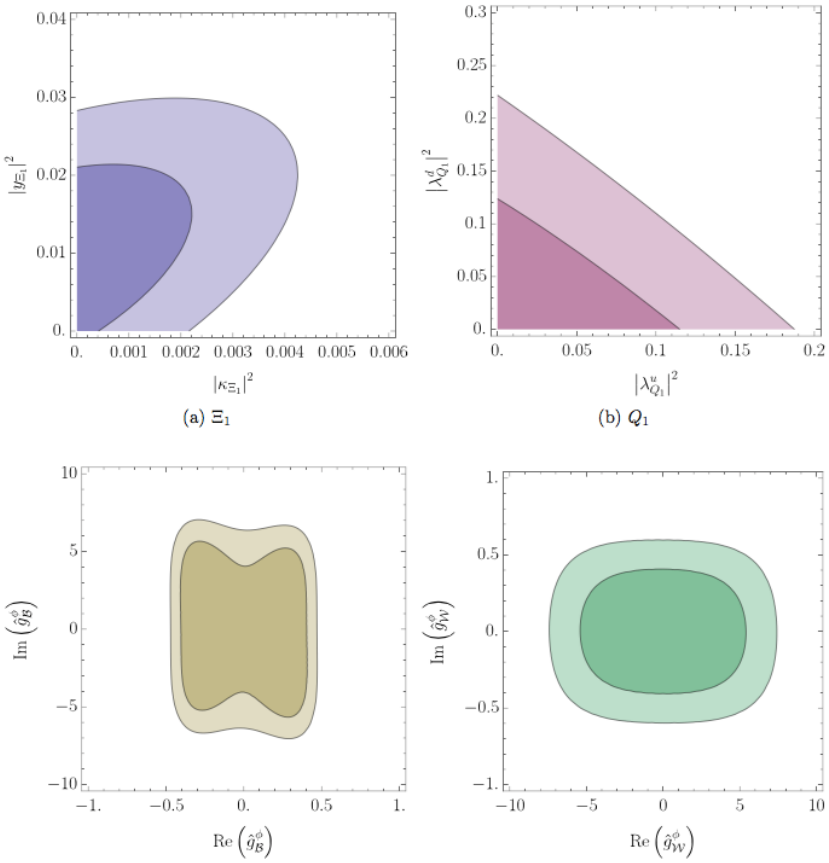
Name	Spin	$SU(3)$	$SU(2)$	$U(1)$	Name	Spin	$SU(3)$	$SU(2)$	$U(1)$
$\mathcal{S}$	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
$\mathcal{S}_1$	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	1	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
$\mathcal{B}$	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
$\mathcal{B}_1$	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
$\mathcal{W}$	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
$\mathcal{W}_1$	1	1	3	1	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$
N	$\frac{1}{2}$	1	1	0	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$
E	$\frac{1}{2}$	1	1	-1	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$

- Classification and tree-level matching dictionary

De Blas, Criado, Perez-Victoria, Santiago [1711.10391]

Results

- Simplified models: **renormalisable SM extensions**



(a) Ξ_1 (b) Q_1 (c) $\mathcal{B}$, no ψ^4 operators (d) $\mathcal{W}$, no ψ^4 operators

Model	χ^2	χ^2/n_{d}	Coupling	Mass / TeV
SM	157	0.987	-	-
$\mathcal{S}_1$	156	0.986	$\lvert y_{\mathcal{S}_1}\rvert^2 = (6.3 \pm 5.9) \cdot 10^{-3}$	$M_{\mathcal{S}_1} = (9.0,\ 49)$
φ, Type I	156	0.986	$Z_6 \cdot \cos\beta = -0.64 \pm 0.59$	$M_{\varphi} = (0.9,\ 4.3)$
Ξ	155	0.984	$\lvert\kappa_{\Xi}\rvert^2 = (4.2 \pm 3.4) \cdot 10^{-3}$	$M_{\Xi} = (12,\ 35)$
N	155	0.978	$\lvert\lambda_N\rvert^2 = (1.8 \pm 1.2) \cdot 10^{-2}$	$M_N = (5.8,\ 13)$
$\mathcal{W}_1$	155	0.984	$\left\lvert\hat{g}^{\phi}_{\mathcal{W}_1}\right\rvert^2 = (3.3 \pm 2.7) \cdot 10^{-3}$	$M_{\mathcal{W}_1} = (4.1,\ 13)$
E	157	0.993	$\lvert\lambda_E\rvert^2 < 1.2 \cdot 10^{-2}$	$M_E > 9.2$
Δ_3	156	0.990	$\lvert\lambda_{\Delta_3}\rvert^2 < 1.9 \cdot 10^{-2}$	$M_{\Delta_3} > 7.3$
Σ	157	0.992	$\lvert\lambda_{\Sigma}\rvert^2 < 2.9 \cdot 10^{-2}$	$M_{\Sigma} > 5.9$
Q_5	156	0.990	$\lvert\lambda_{Q_5}\rvert^2 < 0.18$	$M_{Q_5} > 2.4$
T_2	157	0.992	$\lvert\lambda_{T_2}\rvert^2 < 7.1 \cdot 10^{-2}$	$M_{T_2} > 3.8$
$\mathcal{S}$	157	0.993	$\lvert y_{\mathcal{S}}\rvert^2 < 0.32$	$M_{\mathcal{S}} > 1.8$
Δ_1	157	0.993	$\lvert\lambda_{\Delta_1}\rvert^2 < 5.7 \cdot 10^{-3}$	$M_{\Delta_1} > 13$
Σ_1	157	0.993	$\lvert\lambda_{\Sigma_1}\rvert^2 < 7.3 \cdot 10^{-3}$	$M_{\Sigma_1} > 12$
U	157	0.993	$\lvert\lambda_U\rvert^2 < 2.8 \cdot 10^{-2}$	$M_U > 6.0$
D	157	0.993	$\lvert\lambda_D\rvert^2 < 1.4 \cdot 10^{-2}$	$M_D > 8.4$
Q_7	157	0.993	$\lvert\lambda_{Q_7}\rvert^2 < 7.7 \cdot 10^{-2}$	$M_{Q_7} > 3.6$
T_1	157	0.993	$\lvert\lambda_{T_1}\rvert^2 < 0.13$	$M_{T_1} > 3.0$
$\mathcal{B}_1$	157	0.993	$\left\lvert\hat{g}^{\phi}_{\mathcal{B}_1}\right\rvert^2 < 2.4 \cdot 10^{-3}$	$M_{\mathcal{B}_1} > 21$

- Streamlines process of interpreting limits on BSM parameter space

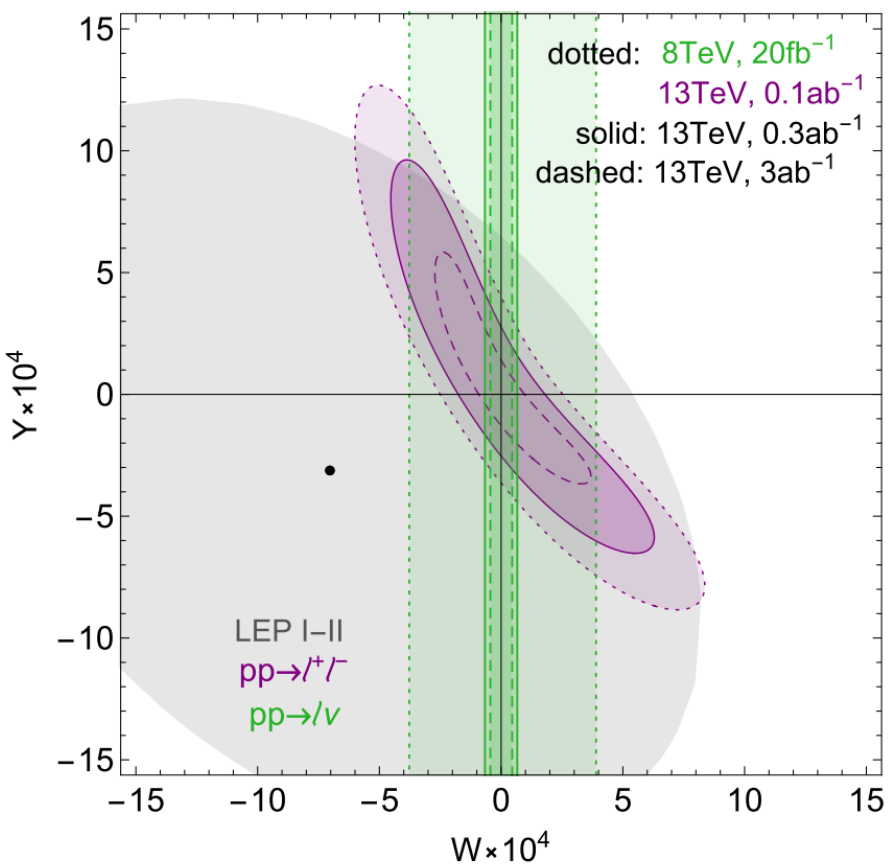
Outline

- SM EFT fits
- BSM matching and constraints
- **SM EFT at higher energies**
- SM EFT positivity bounds

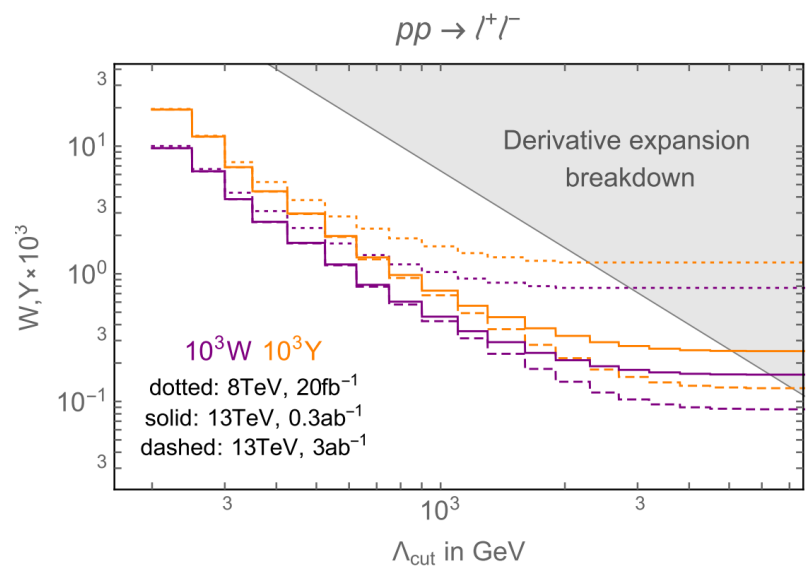
W, Y parameters: LEP vs LHC

Farina et al 1609.08157

- Dim-6 energy growth competes with precision



	universal form factor ($\mathcal{L}$)	contact operator ($\mathcal{L}'$)
W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$	$-\frac{g_2^2\mathrm{W}}{2m_W^2} J_L{}^a_\mu J_L{}^\mu_a$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$	$-\frac{g_1^2\mathrm{Y}}{2m_W^2} J_Y{}_\mu J_Y{}^\mu$



Measuring Higgs couplings without the Higgs

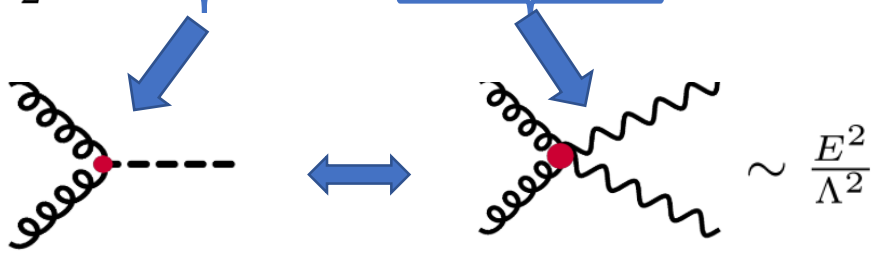
1812.09299 Henning et al

- Higgs couplings measured on-shell are related to off-shell processes

- e.g. Higgs-gluon-gluon coupling $\boldsymbol{\kappa_g}$

$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$|H|^2 = \frac{1}{2}\left(v^2 + 2hv + h^2 + 2\phi^+\phi^- + (\phi^0)^2\right)$$



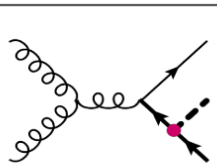
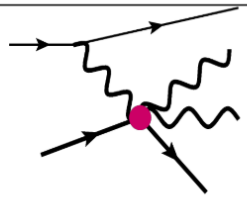
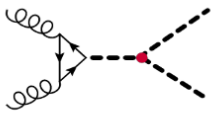
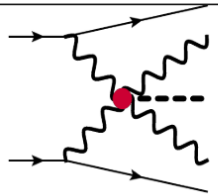
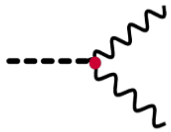
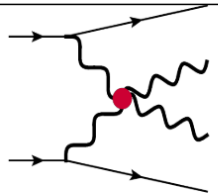
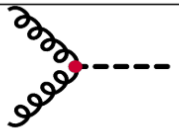
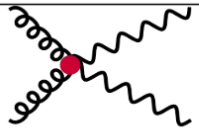
- Benefits from **energy growth** in amplitude

Tevong You

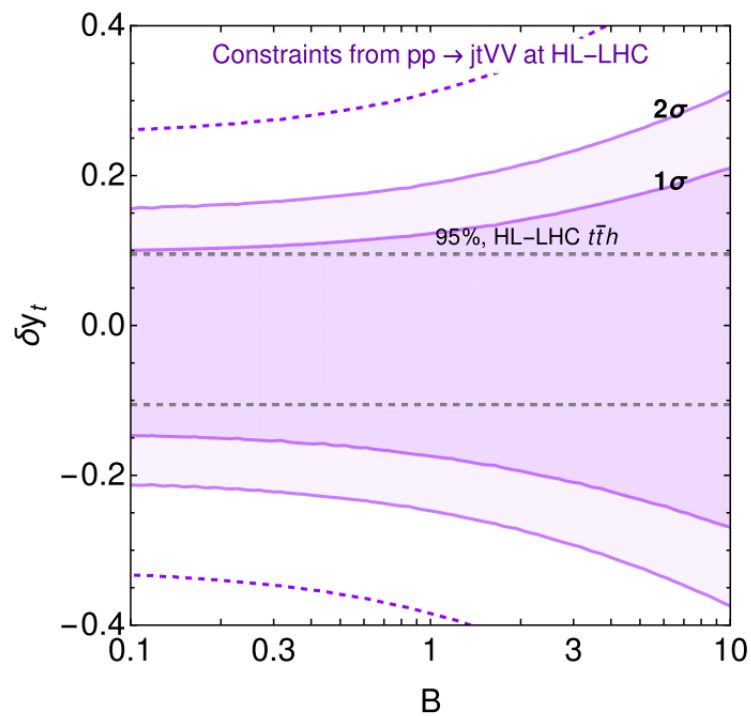
Measuring Higgs couplings without the Higgs

1812.09299 Henning et al

- Exploring the global picture of the Higgs in a holistic way

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

$$\mathcal{O}_r = |H|^2 \partial_\mu H^\dagger \partial^\mu H \qquad \mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R$$
$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \qquad \mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\,\mu\nu} \qquad \mathcal{O}_6 = |H|^6 \qquad (1)$$



- Additional input to global fits

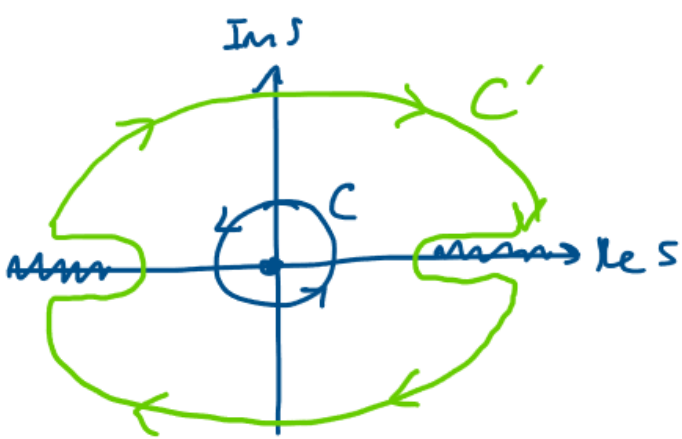
Outline

- SM EFT fits
- BSM matching and constraints
- SM EFT at higher energies
- **SM EFT positivity bounds**

SMEFT positivity bounds

- Testing fundamental principles of QFT in UV through EFT
- Analytic S-matrix constraints on EFT if UV completion respects unitarity and Lorentz invariance
- e.g. 2 → 2 scalar amplitude A(s,t) in forward limit t=0

$$\mathcal{A}(s,t=0) = \sum_i f_i s^i = f_0 + f_1 s + f_2 s^2 + \dots \qquad f_n = \frac{1}{2\pi i}\oint_C ds\, \frac{\mathcal{A}(s,0)}{s^{n+1}}$$



$$\mathcal{A}(s,0)\big|_{s\to\infty} \sim s^a \qquad a < n$$

$$\Rightarrow f_n \sim \int_{s_0}^{\infty} ds\, \frac{\mathrm{Disc}[\mathcal{A}(s,0)]}{s^{n+1}} = \int_{s_0}^{\infty} ds\, \frac{\sigma}{s^{n+1}} > 0$$

- Dim-8 constraints from n=2

SMEFT positivity bounds

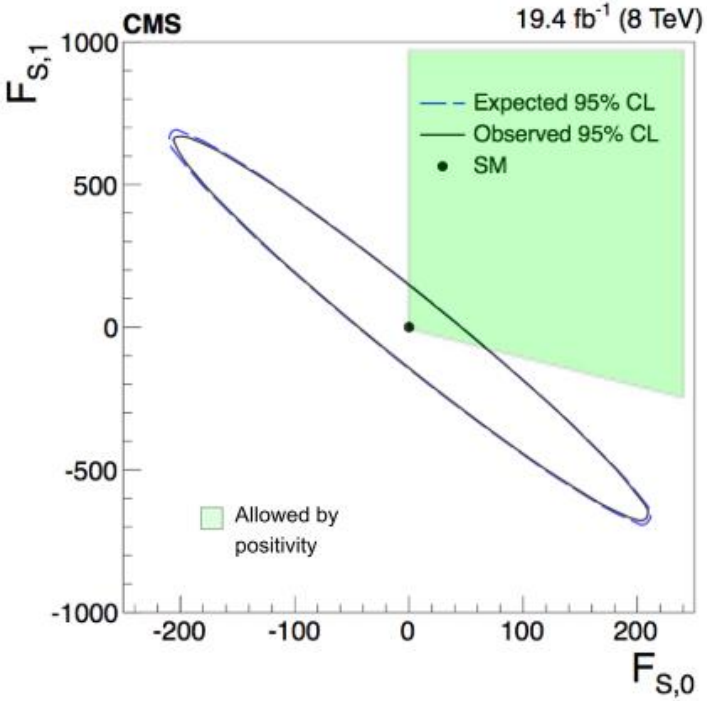
- e.g. Quartic gauge boson scattering

C. Zhang, S.-Y. Zhou 1808.00010

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum \frac{f_i O_i}{\Lambda^4}$$

$$\begin{aligned}
O_{S,0} &= [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\mu\Phi)^\dagger D^\nu\Phi] \\
O_{S,1} &= [(D_\mu\Phi)^\dagger D^\mu\Phi] \times [(D_\nu\Phi)^\dagger D^\nu\Phi] \\
O_{S,2} &= [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\nu\Phi)^\dagger D^\mu\Phi] \\
O_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
O_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
O_{M,2} &= \left[\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
O_{M,3} &= \left[\hat{B}_{\mu\nu}\hat{B}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
O_{M,4} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times \hat{B}^{\beta\nu} \\
O_{M,5} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times \hat{B}^{\beta\mu} \\
O_{M,7} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]
\end{aligned}$$

$$\begin{aligned}
O_{T,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \\
O_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \\
O_{T,2} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \\
O_{T,5} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \hat{B}_{\alpha\beta}\hat{B}^{\alpha\beta} \\
O_{T,6} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \hat{B}_{\mu\beta}\hat{B}^{\alpha\nu} \\
O_{T,7} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \hat{B}_{\beta\nu}\hat{B}^{\nu\alpha} \\
O_{T,8} &= \hat{B}_{\mu\nu}\hat{B}^{\mu\nu} \times \hat{B}_{\alpha\beta}\hat{B}^{\alpha\beta} \\
O_{T,9} &= \hat{B}_{\alpha\mu}\hat{B}^{\mu\beta} \times \hat{B}_{\beta\nu}\hat{B}^{\nu\alpha},
\end{aligned}$$



$f_{S,0}$	$f_{S,1}$	$f_{S,2}$	$f_{M,0}$	$f_{M,1}$	$f_{M,2}$	$f_{M,3}$	$f_{M,4}$	$f_{M,5}$
+	+	+	X	−	O	−	O	X
$f_{M,7}$	$f_{T,0}$	$f_{T,1}$	$f_{T,2}$	$f_{T,5}$	$f_{T,6}$	$f_{T,7}$	$f_{T,8}$	$f_{T,9}$
+	+	+	+	X	+	X	+	+

- Dim-6 constraints for n=1

See also SMEFT positivity bounds in:

Bellazzini, Riva 1806.09640
Remmen, Rodd 1908.09845
Davighi, Melville, T.Y., *in progress*

Conclusion

- **QED+Fermi theory → chiral electroweak+pion EFT**
- **Chiral electroweak EFT+Higgs → SM**
- **SM → SMEFT**
- **SMEFT** → ?
- *Only experiment can tell*

Conclusion

- Why is measuring all this stuff so important?

  - *"What would be the use of such extreme refinement in the science of measurement? […] The more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.* […]*"* –A. Michelson 1903

  - *"How can you get excited about measuring higher-dimensional operators?"* –A. Physicist 2018

Conclusion

- Why is measuring all this stuff so important?

  - *"What would be the use of such extreme refinement in the science of measurement?* ***Very briefly and in general terms the answer would be that in this direction the greater part of all future discovery must lie.*** *The more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.* ***Nevertheless, it has been found that there are apparent exceptions to most of these laws, and this is particularly true when the observations are pushed to a limit, i.e., whenever the circumstances of experiment are such that extreme cases can be examined.****"* –A. Michelson 1903

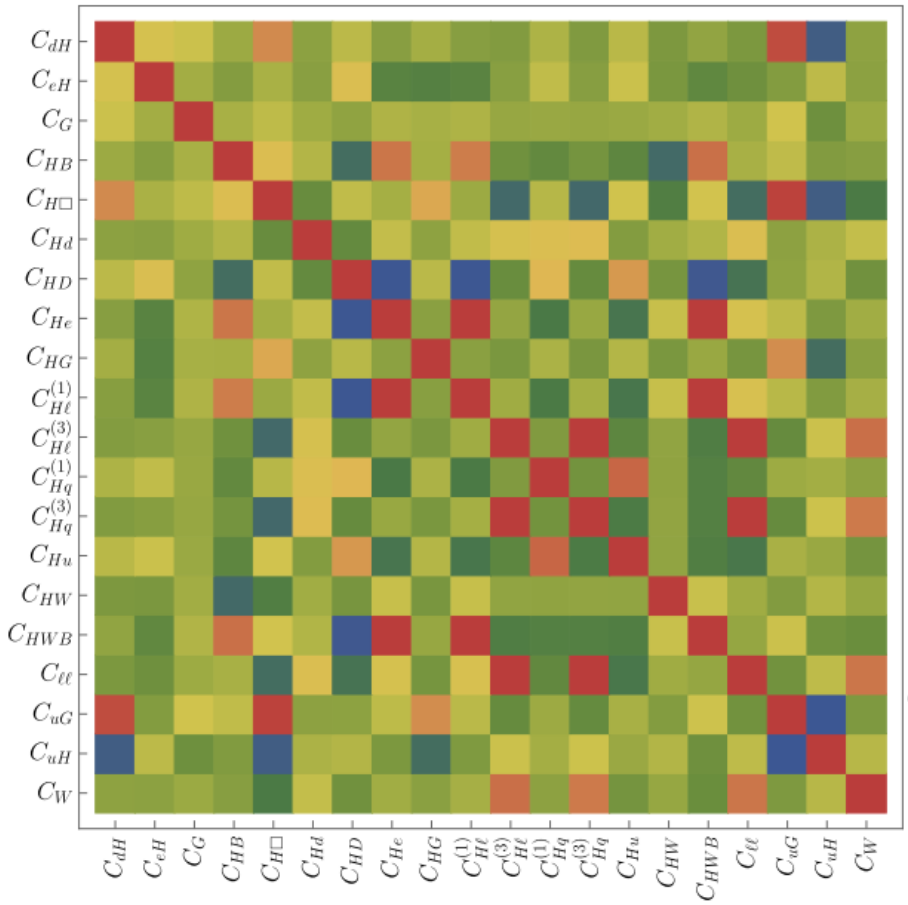
  - *"How can you get excited about measuring higher-dimensional operators?"* –A. Physicist 2018

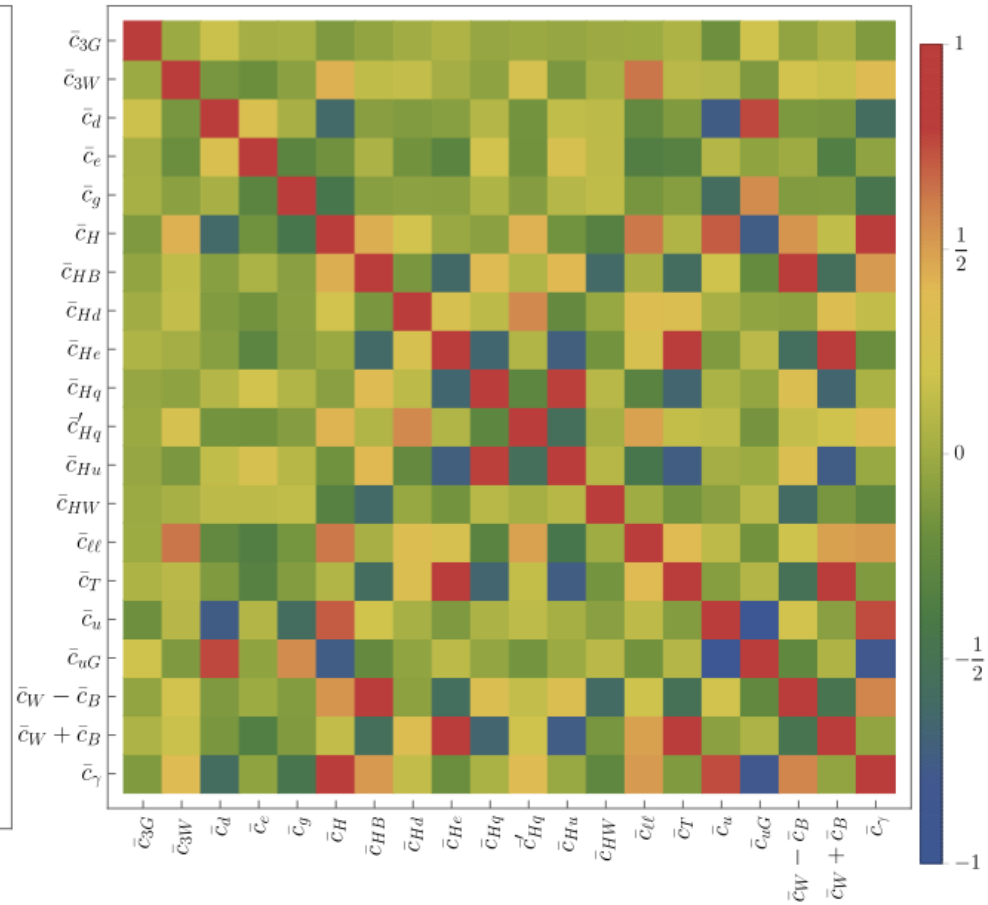
- Tera-Z and 100 TeV are the next extreme limits

Backup

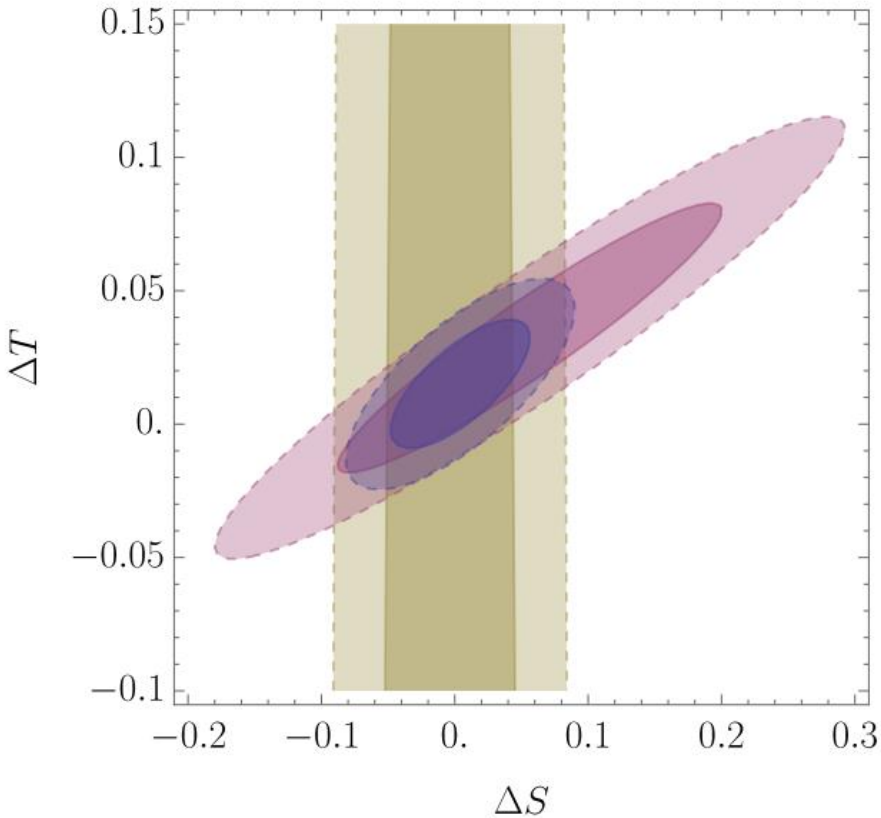
Coefficient	Z-pole + m_W	WW at LEP2	Higgs Run1	Higgs Run2	LHC WW high-p_T
$\bar{C}_{dH}$	×	×	42.4	57.6	×
$\bar{C}_{eH}$	×	×	49.6	50.4	×
$\bar{C}_{G}$	×	×	2.4	97.6	×
$\bar{C}_{HB}$	×	×	18.6	81.4	×
$\bar{C}_{H\Box}$	×	×	19.3	80.7	0.01
$\bar{C}_{Hd}$	99.85	×	0.04	0.1	×
$\bar{C}_{HD}$	99.92	0.06	×	×	×
$\bar{C}_{He}$	99.99	0.01	×	×	×
$\bar{C}_{HG}$	×	×	41.1	58.9	0.03
$\bar{C}^{(1)}_{H\ell}$	99.97	0.03	×	×	×
$\bar{C}^{(3)}_{H\ell}$	99.56	0.41	×	×	0.01
$\bar{C}^{(1)}_{Hq}$	99.98	×	×	×	×
$\bar{C}^{(3)}_{Hq}$	98.5	0.96	0.19	0.31	0.07
$\bar{C}_{Hu}$	99.3	×	0.2	0.42	0.04
$\bar{C}_{HW}$	×	×	18.3	81.7	×
$\bar{C}_{HWB}$	57.7	0.02	8.2	34.1	×
$\bar{C}_{\ell\ell}$	99.66	0.3	×	0.01	×
$\bar{C}_{uG}$	×	×	8.9	91.1	×
$\bar{C}_{uH}$	×	×	10.9	89.1	×
$\bar{C}_{W}$	×	96.2	×	×	3.8

Backup


C_{dH}
C_{eH}
C_G
C_{HB}
$C_{H\Box}$
C_{Hd}
C_{HD}
C_{He}
C_{HG}
$C_{H\ell}^{(1)}$
$C_{H\ell}^{(3)}$
$C_{Hq}^{(1)}$
$C_{Hq}^{(3)}$
C_{Hu}
C_{HW}
C_{HWB}
$C_{\ell\ell}$
C_{uG}
C_{uH}
C_W


$\bar{c}_{3G}$
$\bar{c}_{3W}$
$\bar{c}_d$
$\bar{c}_e$
$\bar{c}_g$
$\bar{c}_H$
$\bar{c}_{HB}$
$\bar{c}_{Hd}$
$\bar{c}_{He}$
$\bar{c}_{Hq}$
$\bar{c}'_{Hq}$
$\bar{c}_{Hu}$
$\bar{c}_{HW}$
$\bar{c}_{\ell\ell}$
$\bar{c}_T$
$\bar{c}_u$
$\bar{c}_{uG}$
$\bar{c}_W - \bar{c}_B$
$\bar{c}_W + \bar{c}_B$
$\bar{c}_\gamma$
1
$\frac{1}{2}$
0
$-\frac{1}{2}$
-1

Backup



$$\frac{v^2}{\Lambda^2} C_{HWB} = \frac{g_1 g_2}{16\pi} \Delta S, \quad \frac{v^2}{\Lambda^2} C_{HD} = -\frac{g_1 g_2}{2\pi\,(g_1 + g_2)} \Delta T\,,$$