Higgs Couplings, Tokyo, 27th November 2018

The Branco Weiss Fellowship Society in Science

Global SMEFT Fit

Tevong You

UNIVERSITY OF CAMBRIDGE

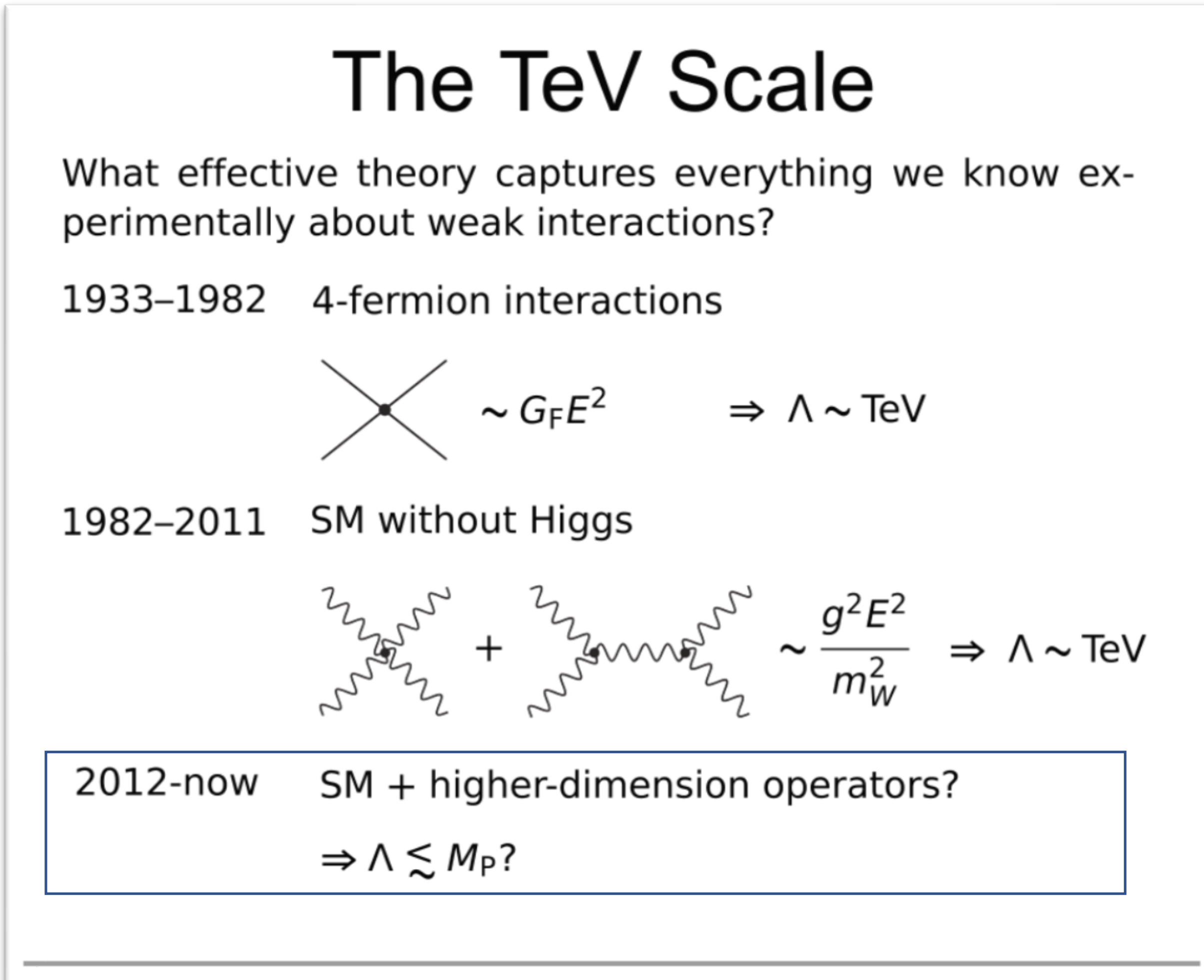
Based on J. Ellis, C. Murphy, V. Sanz and TY, JHEP (1803.03252)

Introduction

- Motivation
- SM EFT framework
- EWPT and TGCs
- Updated Run 2 SM EFT fit
- Conclusion

Why SM EFT?

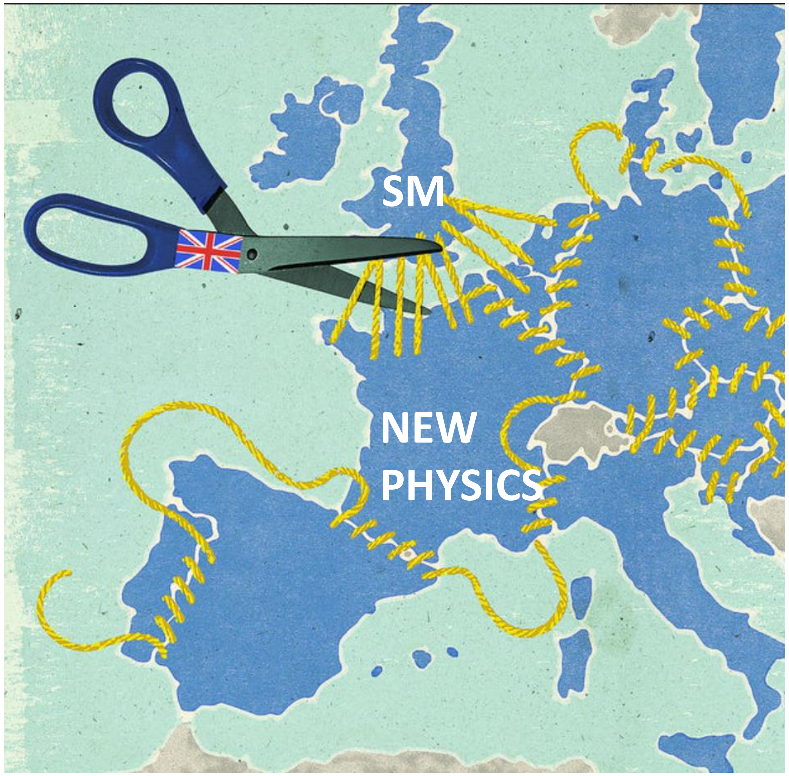
Assuming a SM Higgs and **decoupled new physics** at higher energies, the SM EFT is the next phenomenological framework



Markus Luty PASCOS 2015 slide

SMEXIT:

decoupling new physics



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**	$\frac{1}{2}$

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

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

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

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

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

SMEFT framework

- Unique dim-5 Weinberg operator, violates lepton number, predicts neutrino masses
- Modulo 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

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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

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Operators benefit from per mille precision at LEP

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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

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

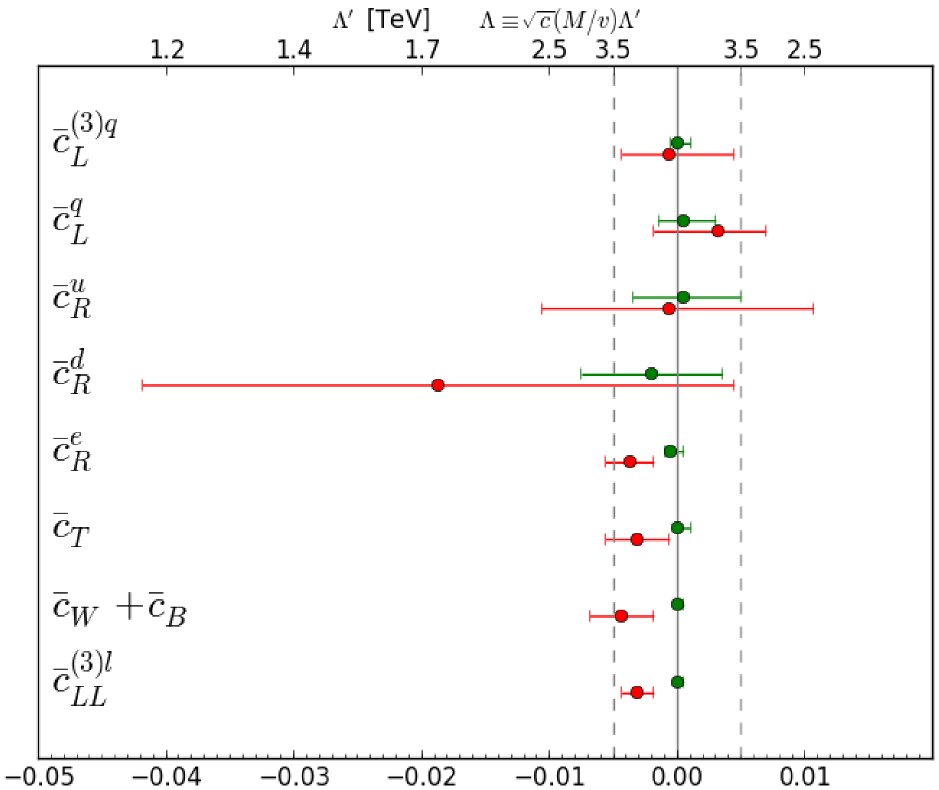
$$g^f = T_f^3 - Q_f s_W^2 \qquad s_W^2 = \frac{1}{2} - \frac{1}{2}\sqrt{1 - \frac{4\pi\alpha}{\sqrt{2} G_F m_Z^2}}$$

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

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

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

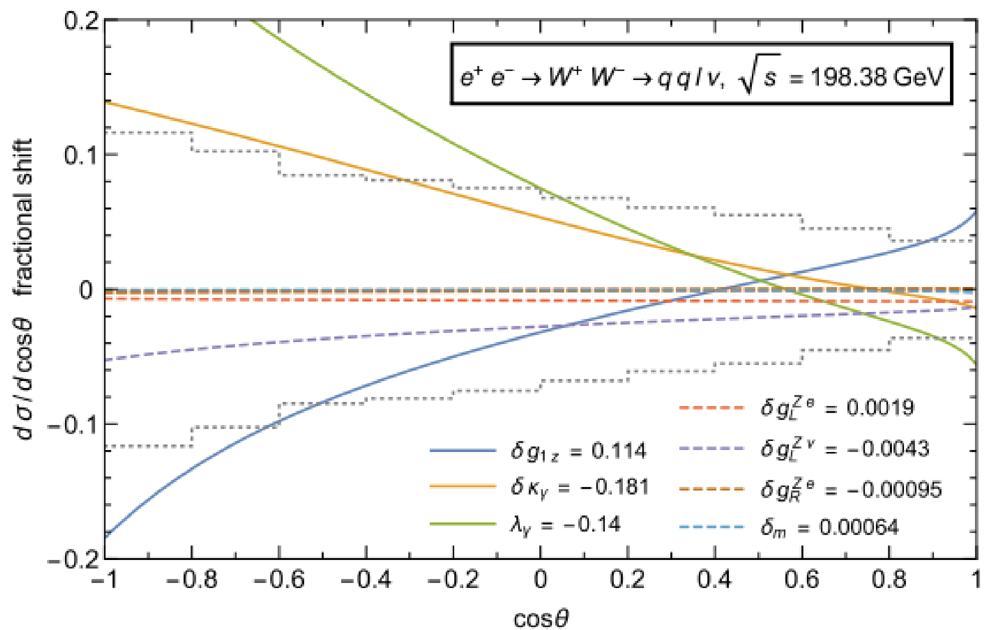
Triple-Gauge-Couplings in Diboson

- 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

- Justified at LEP:



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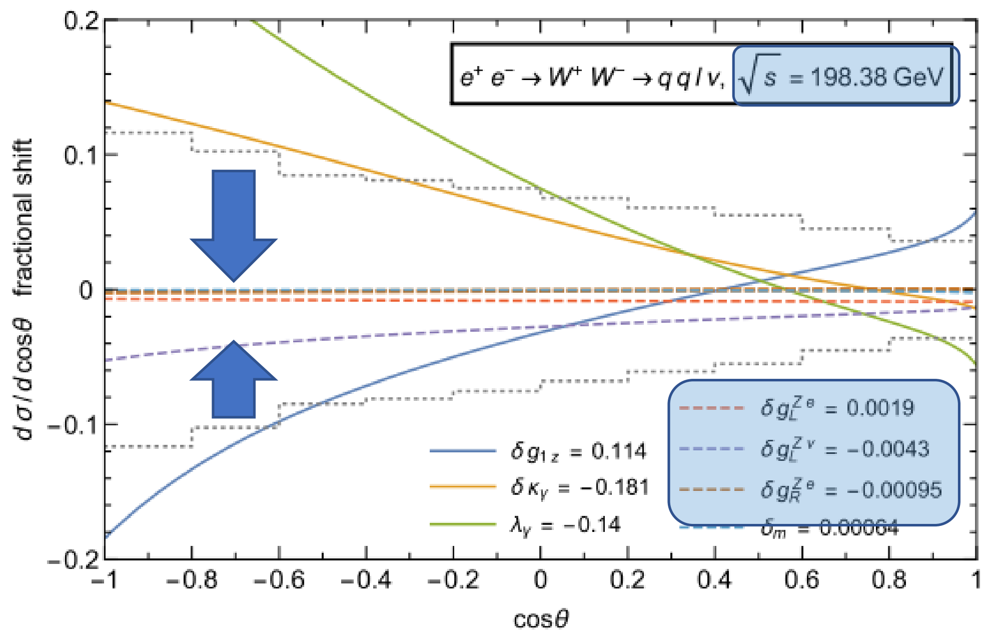

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- But not at high pT:

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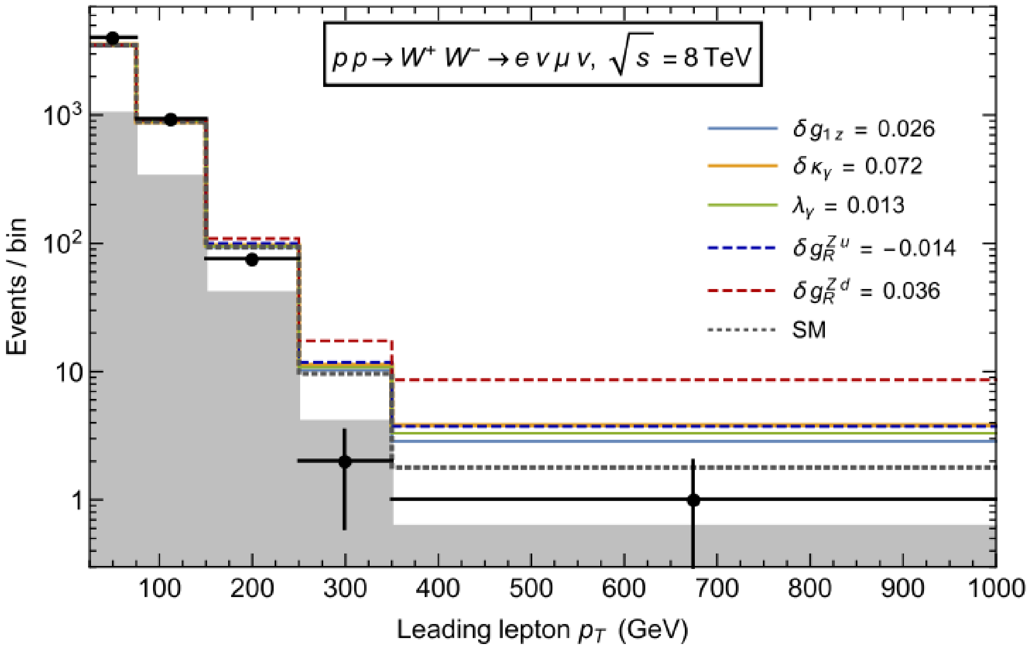

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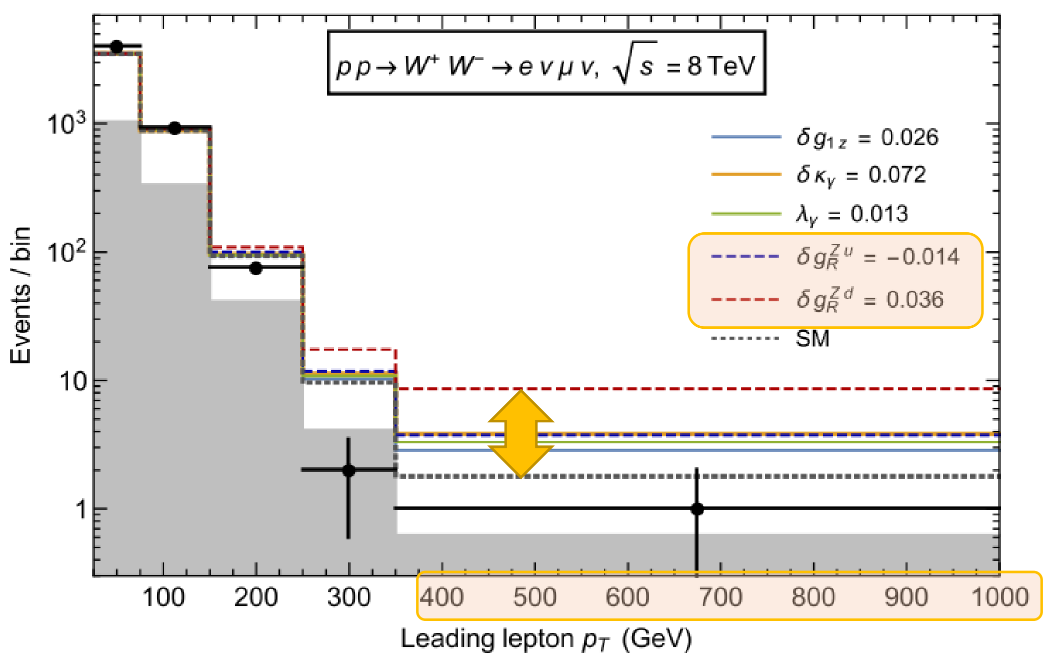


Note: quadratic dim-6 effect unless diboson SM-BSM interference recovered

Azatov et al 1607.05236, 1707.08060, Panico, Riva, Wulzer 1708.07823, Bellazzini, Riva 1806.09640

Updated Global SMEFT Fit

J. Ellis, C. Murphy, V. Sanz and TY, JHEP 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**

Updated Global SMEFT Fit

- SILH basis

$$
\begin{aligned}
\mathcal{L}_{\mathrm{SMEFT}}^{\mathrm{SILH}} \supset\ & \frac{\bar{c}_W}{m_W^2}\frac{ig}{2}\left(H^\dagger\sigma^a\overleftrightarrow{D}^\mu H\right)D^\nu W^a_{\mu\nu} + \frac{\bar{c}_B}{m_W^2}\frac{ig'}{2}\left(H^\dagger\overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu} + \frac{\bar{c}_T}{v^2}\frac{1}{2}\left(H^\dagger\overleftrightarrow{D}_\mu H\right)^2 \\
&+ \frac{\bar{c}_{ll}}{v^2}2(\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L) + \frac{\bar{c}_{He}}{v^2}(iH^\dagger\overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R) + \frac{\bar{c}_{Hu}}{v^2}(iH^\dagger\overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R) \\
&+ \frac{\bar{c}_{Hd}}{v^2}(iH^\dagger\overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R) + \frac{\bar{c}'_{Hq}}{v^2}(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L) \\
&+ \frac{\bar{c}_{Hq}}{v^2}(iH^\dagger\overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L) + \frac{\bar{c}_{HW}}{m_W^2}ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu} + \frac{\bar{c}_{HB}}{m_W^2}ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
&+ \frac{\bar{c}_{3W}}{m_W^2}g^3\epsilon_{abc}W^{a\,\nu}_{\mu}W^b_{\nu\rho}W^{c\,\rho\mu} + \frac{\bar{c}_g}{m_W^2}g_s^2|H|^2G^A_{\mu\nu}G^{A\mu\nu} + \frac{\bar{c}_\gamma}{m_W^2}g'^2|H|^2B_{\mu\nu}B^{\mu\nu} \\
&+ \frac{\bar{c}_H}{v^2}\frac{1}{2}(\partial^\mu|H|^2)^2 - \sum_{f=e,u,d}\frac{\bar{c}_f}{v^2}y_f|H|^2\bar{F}_L H^{(c)}f_R \\
&+ \frac{\bar{c}_{3G}}{m_W^2}g_s^3 f_{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho} - \frac{\bar{c}_{uG}}{m_W^2}4g_s y_u H^\dagger\cdot\bar{Q}_L\gamma^{\mu\nu}T_a u_R G^A_{\mu\nu}\,. \qquad (6)
\end{aligned}
$$

Updated Global SMEFT Fit

- Warsaw basis

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

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

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]
$\mathcal{A}_\ell\,$(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

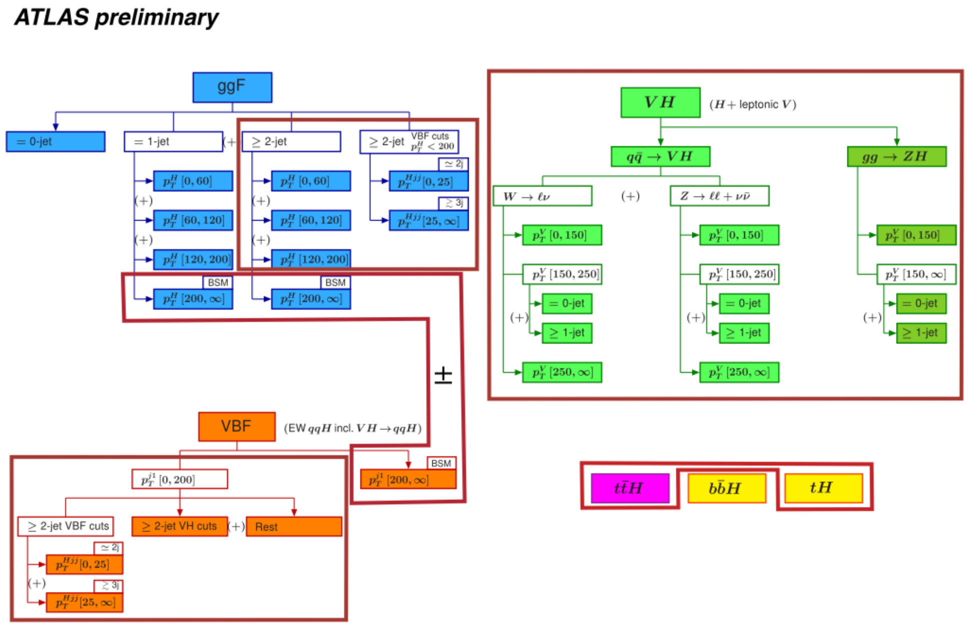
- ATLAS+CMS Higgs Run 2

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]	$B(h \to \gamma\gamma)/\ B(h \to 4\ell)$		$0.69^{+0.15}_{-0.13}$
[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

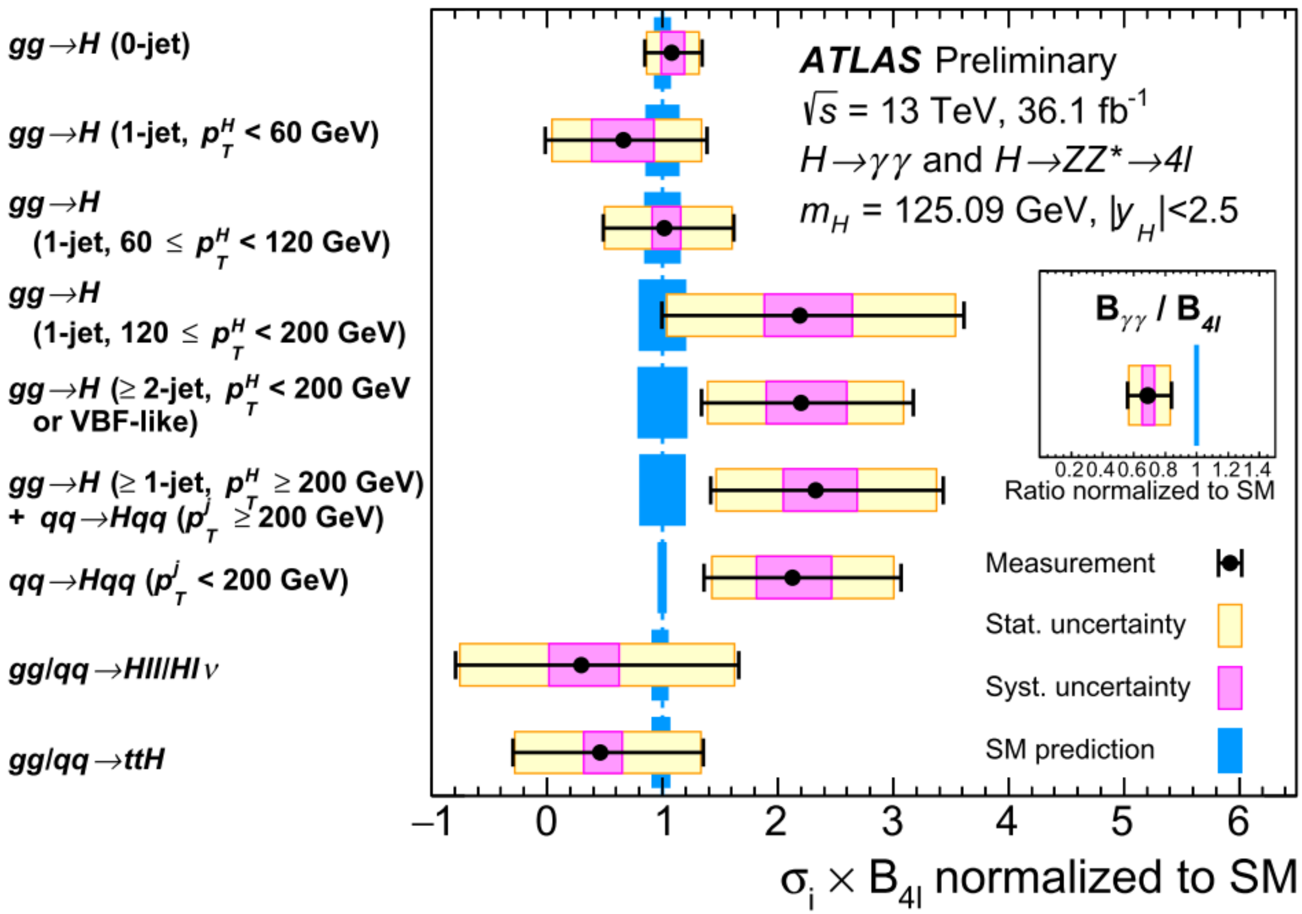


ATLAS-CONF-2017-047

- Facilitates combination and interpretation

STXS

- STXS measurements



ATLAS-CONF-2017-047

STXS

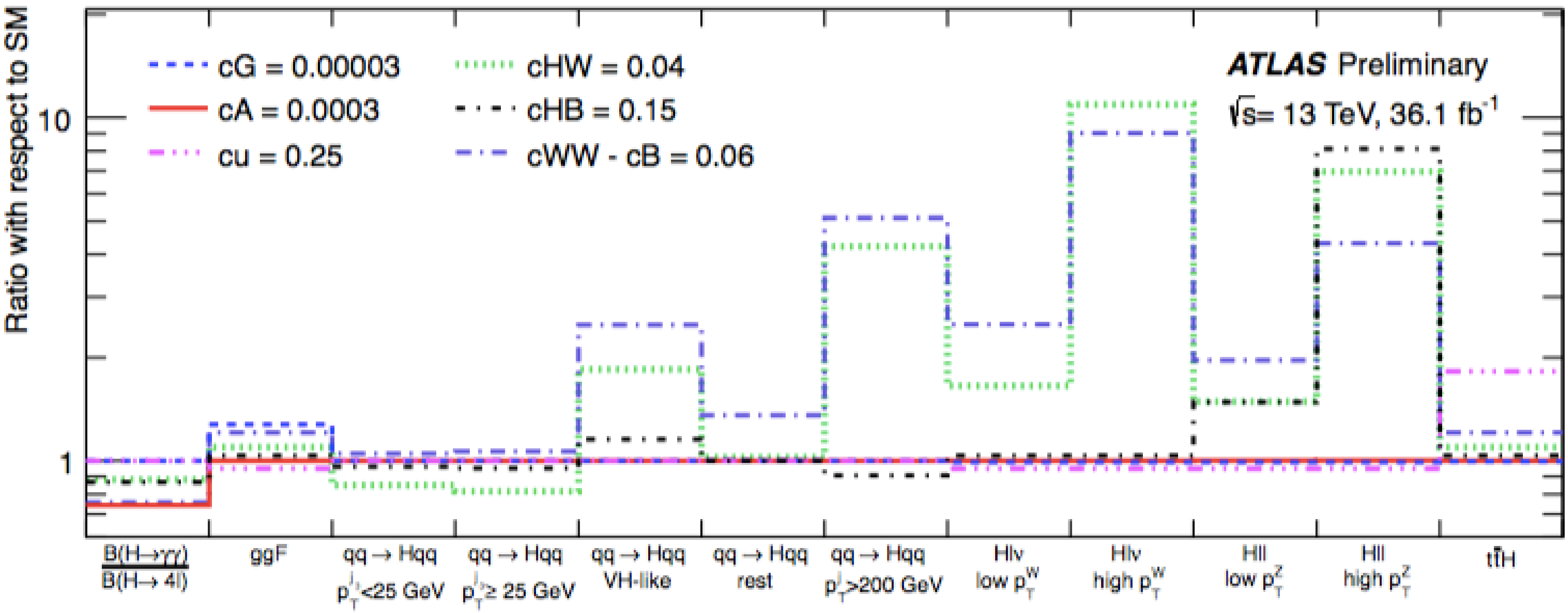
- STXS dim-6 predictions

Cross-section region	$\sum_i A_i c_i$
$gg \to H$ (0-jet)	
$gg \to H$ (1-jet, $p_T^H < 60$ GeV)	$56c'_g$
$gg \to H$ (1-jet, $60 \le p_T^H < 120$ GeV)	
$gg \to H$ (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

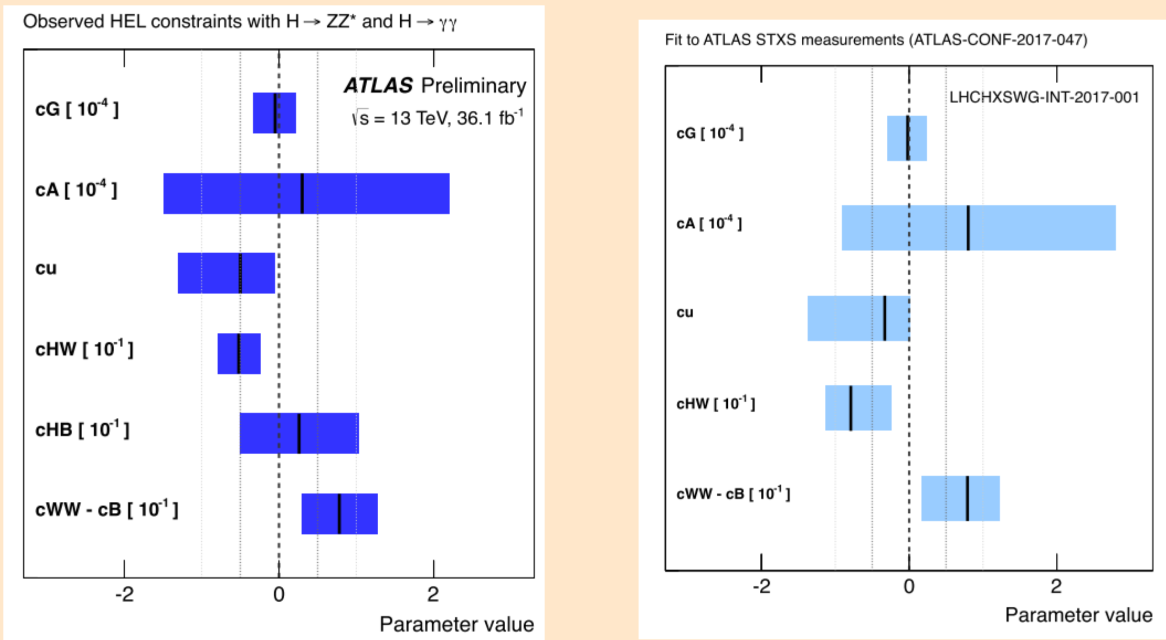
- STXS dim-6 predictions



Tevong You (Cambridge)

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

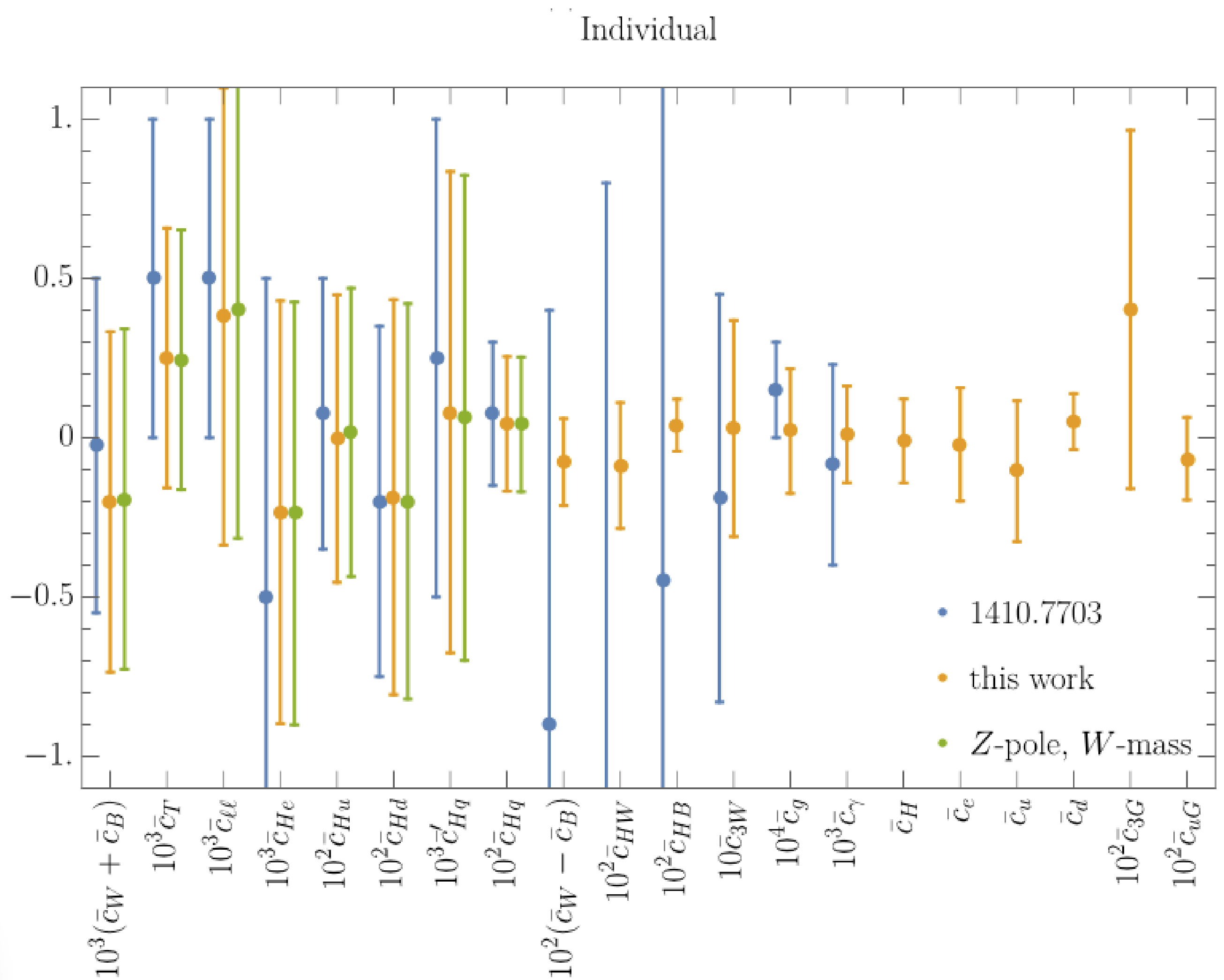
- See also VHbb case (ATLAS-CONF-2018-053)

De Blas, Lohwasser, Musella, Mimasu (1803.10379)

Talks by Douglas Schaefer and Chris Hays

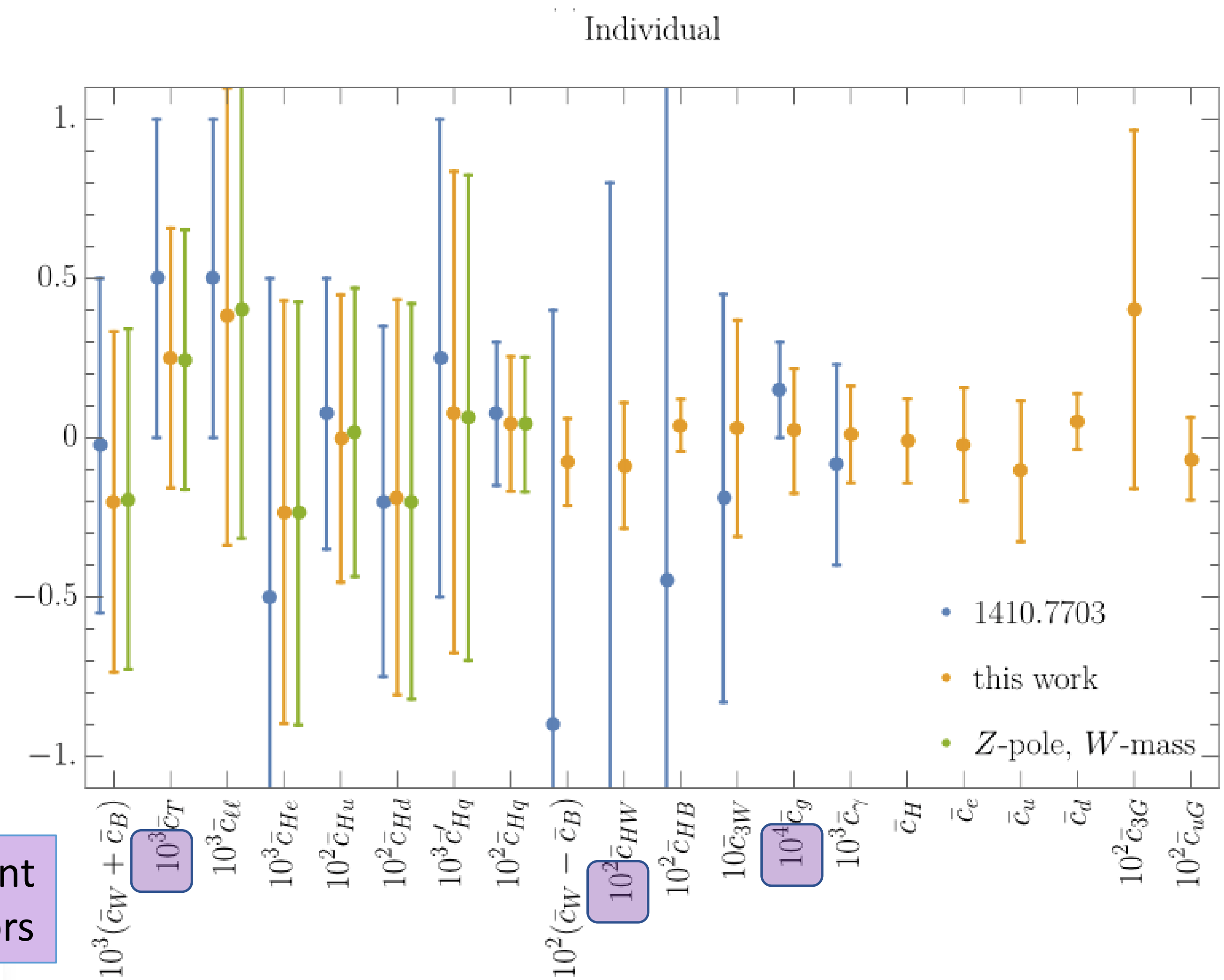
Results

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



Results

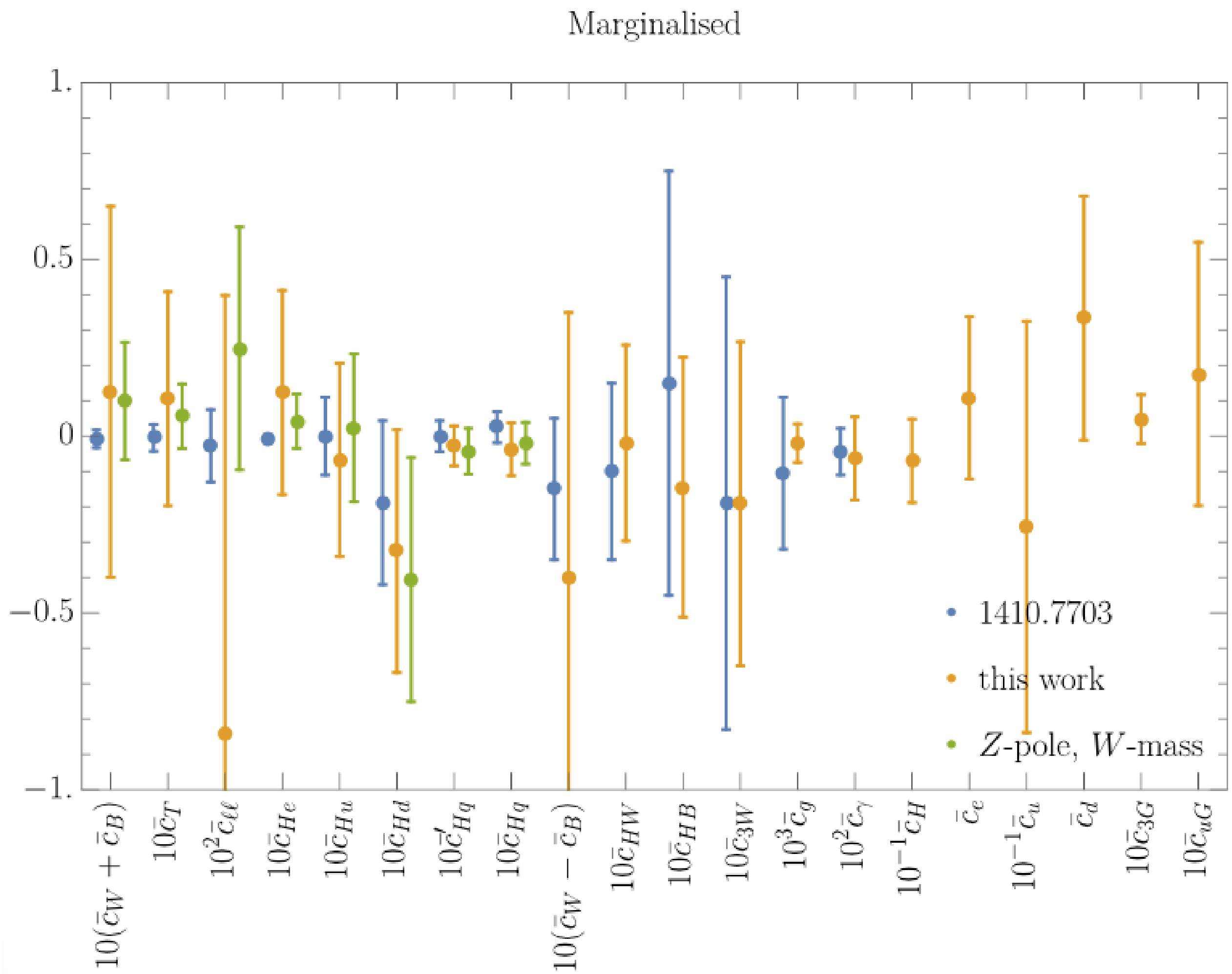
- **SILH** basis, fit each operator **individually**



Note different scaling factors

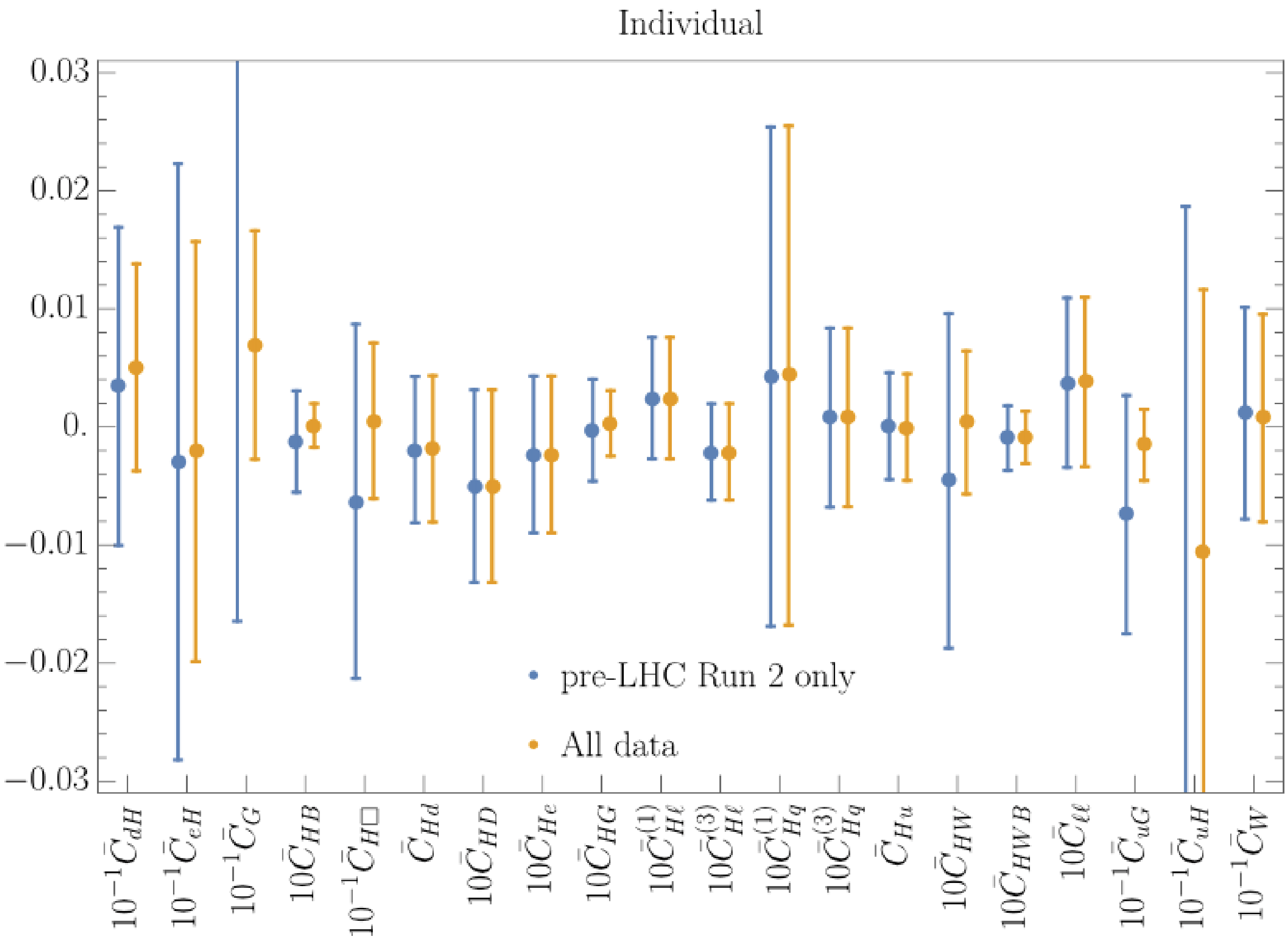
Results

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



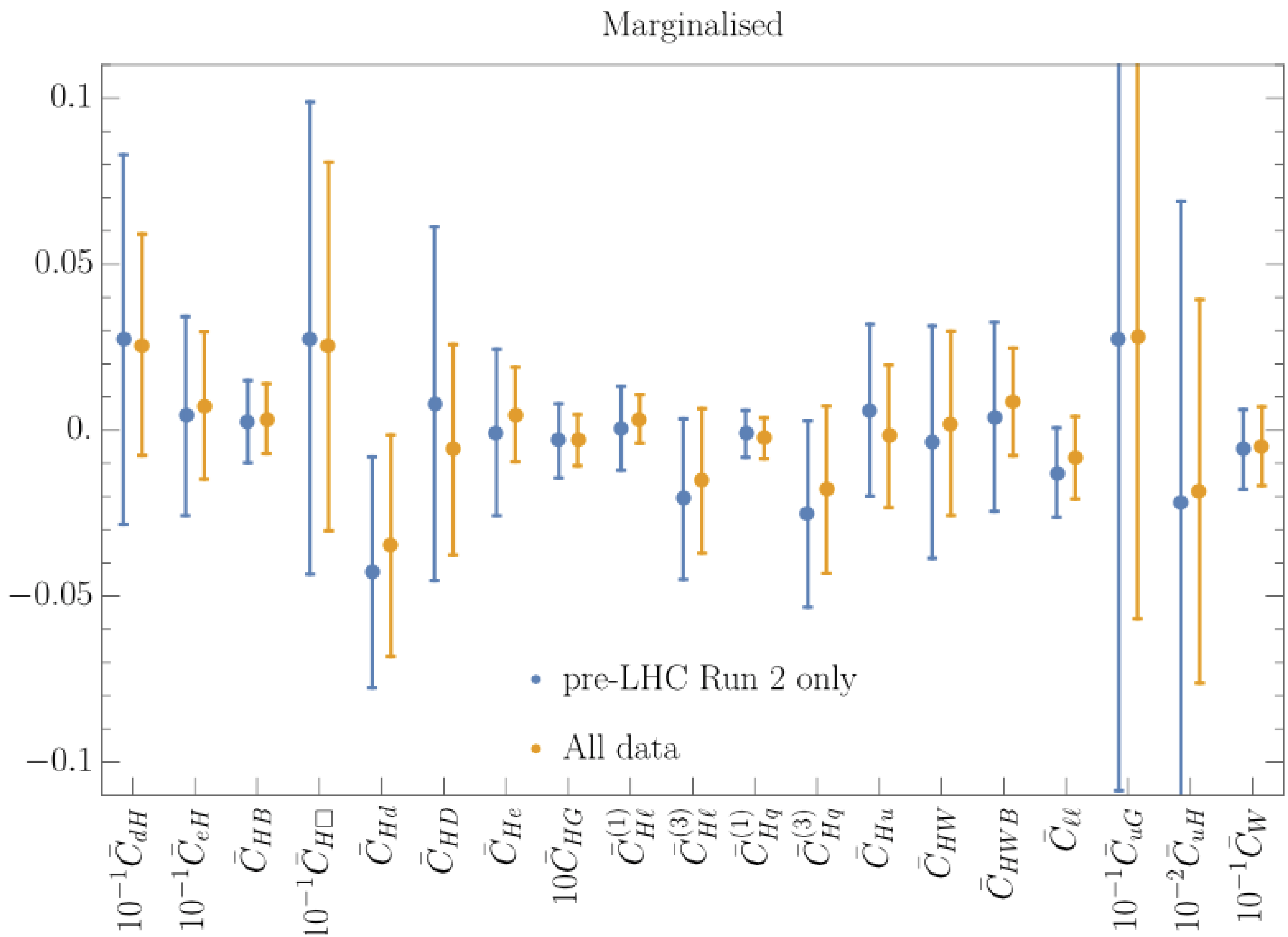
Results

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



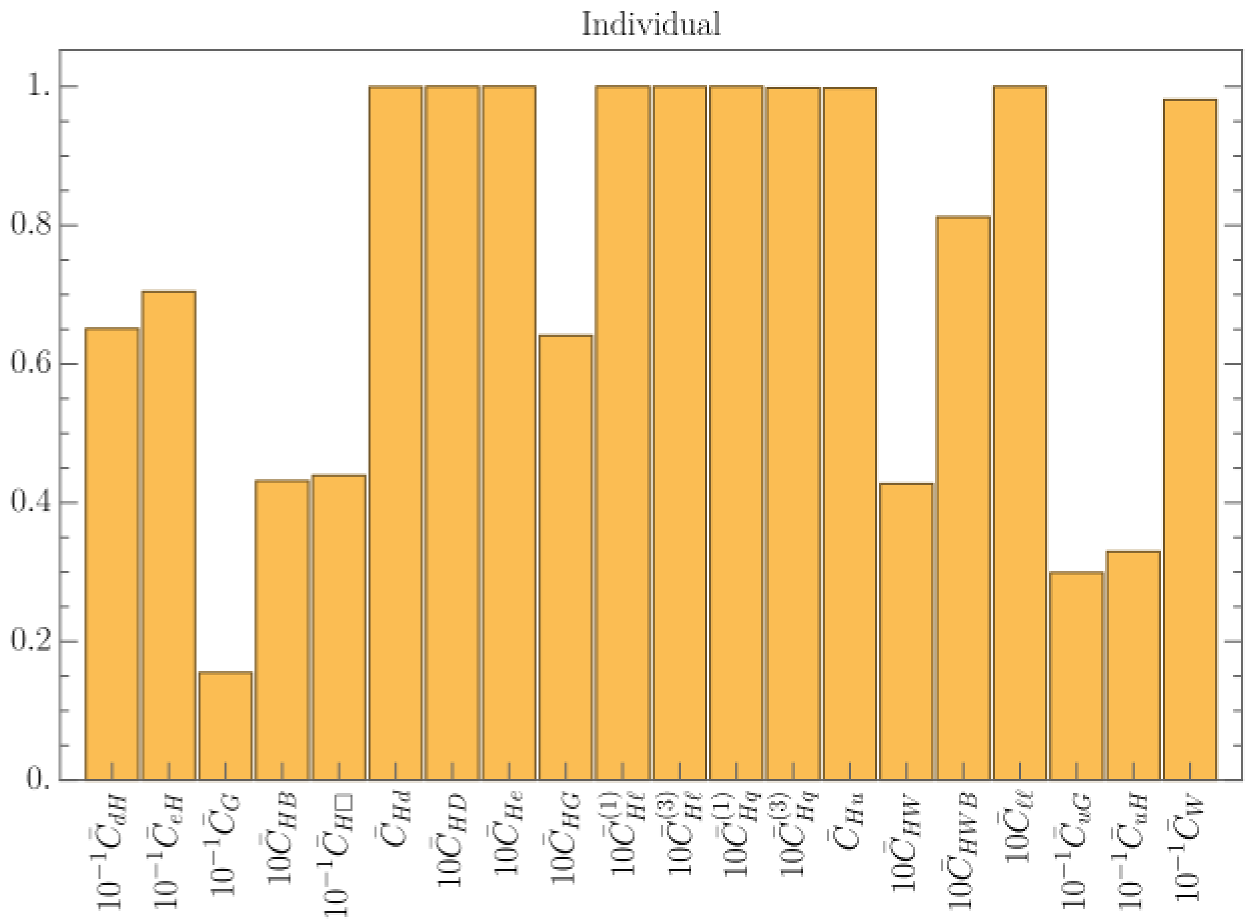
Results

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



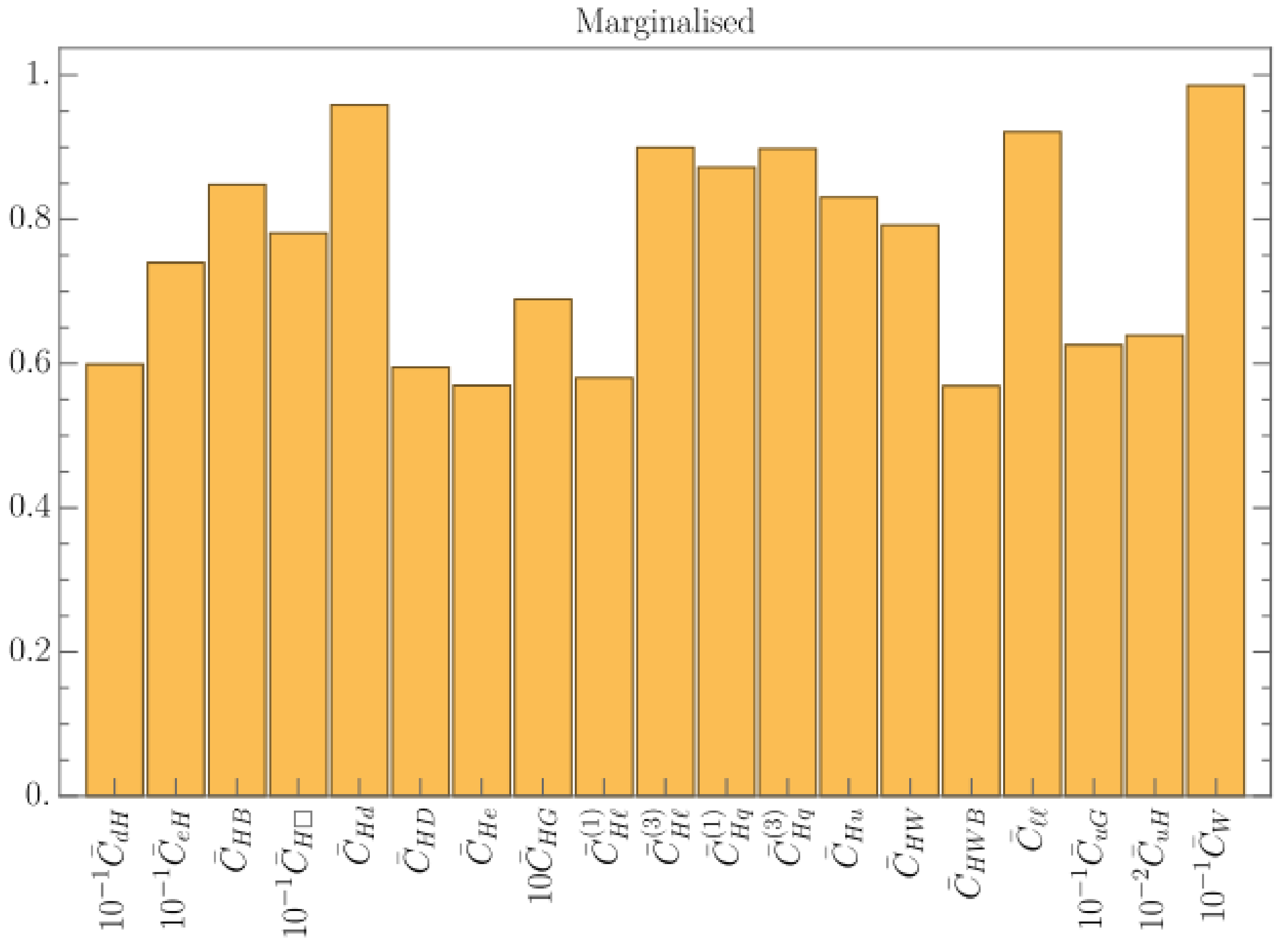
Results

- **Warsaw** basis, improvement from Run 1 to 2 (lower is better) for **individual** fit



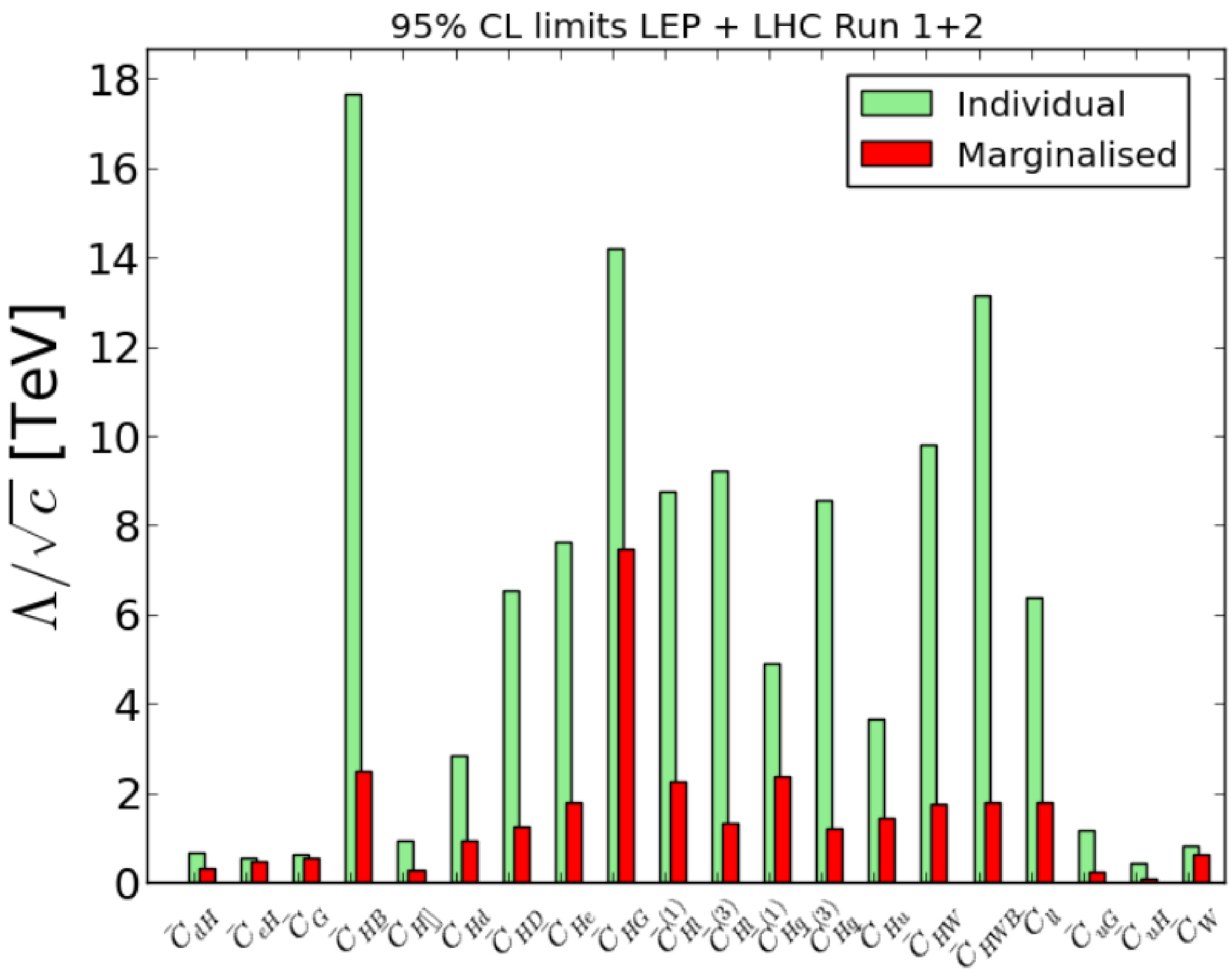
Results

- **Warsaw** basis, improvement from Run 1 to 2 (lower is better) for **marginalised** fit



Results

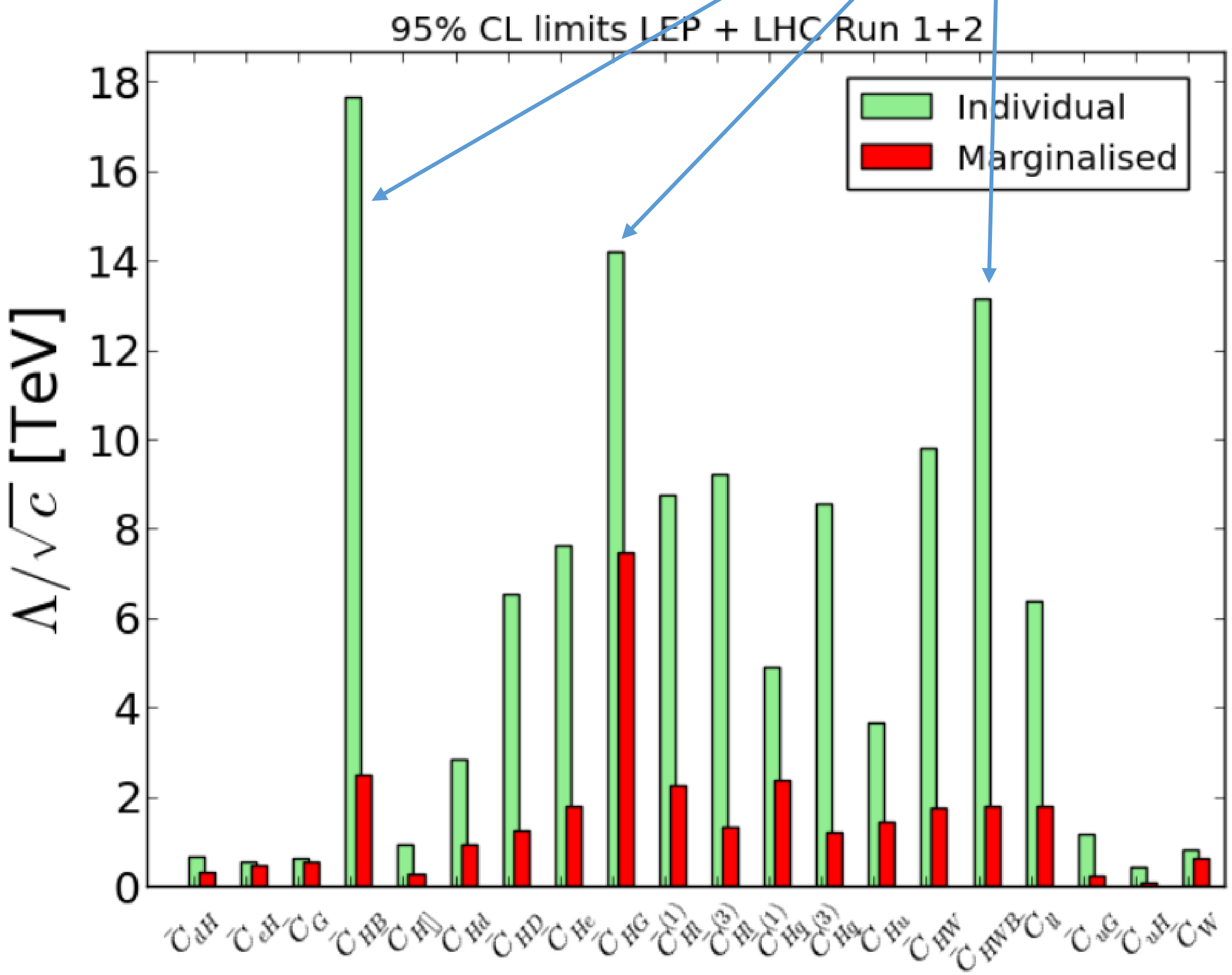
- **Warsaw** basis, summary



Results

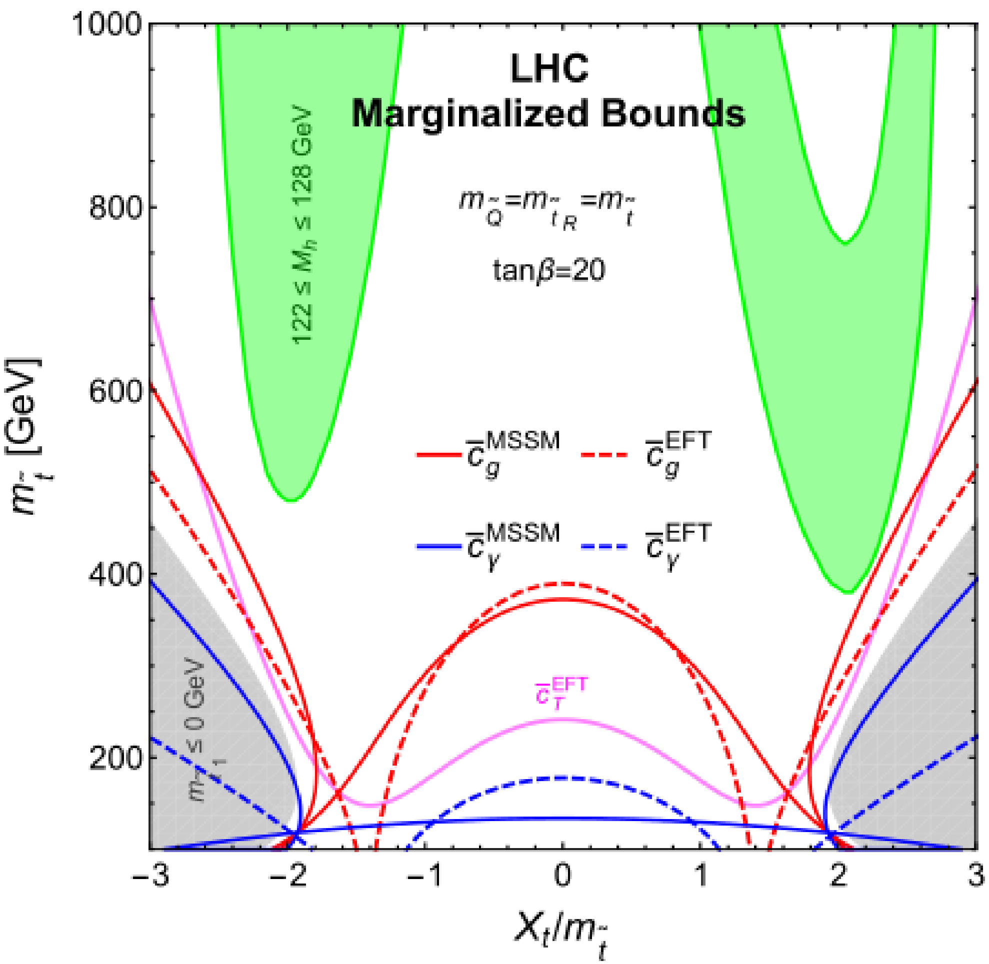
- **Warsaw** basis, summary

Loop-induced $H\gamma\gamma$ and Hgg



Results

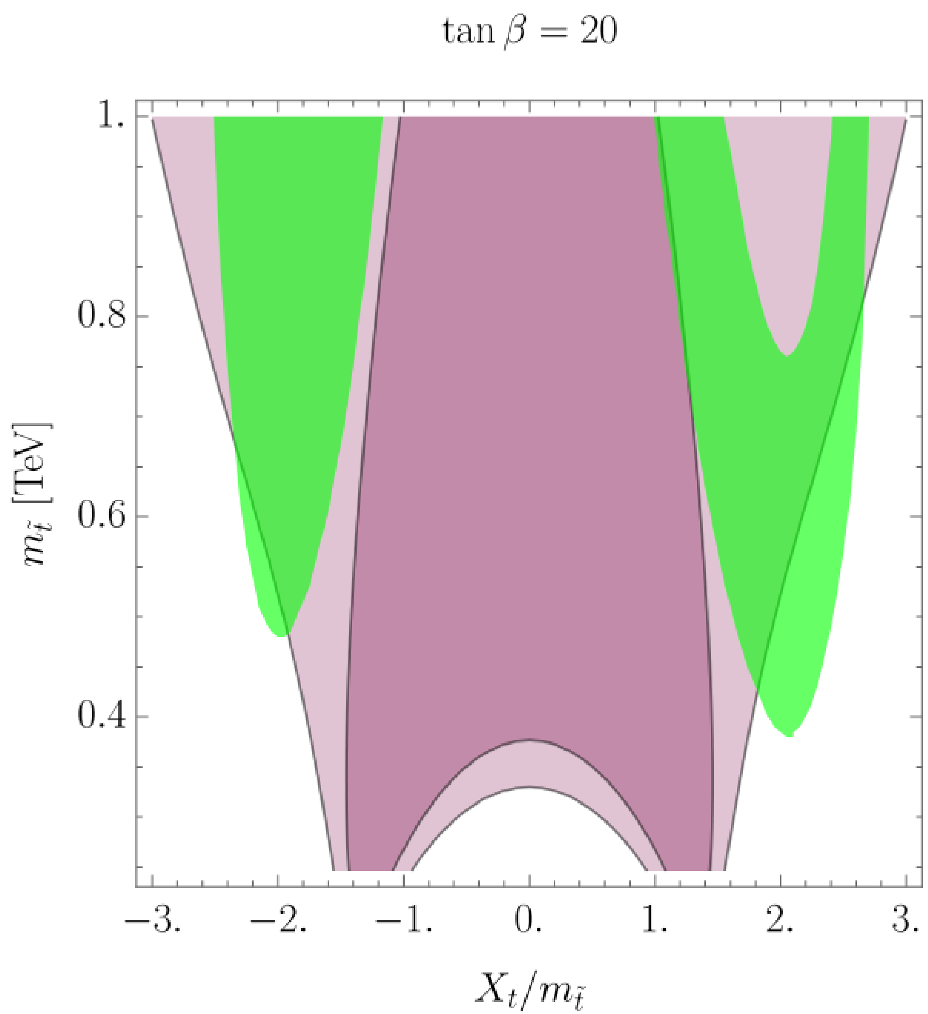
- Simplified models: **stops** (Run 1)



Drozd, Ellis, Quevillon and T.Y.
1504.02409

Results

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



Results

- Simplified models: **renormalisable SM extensions**

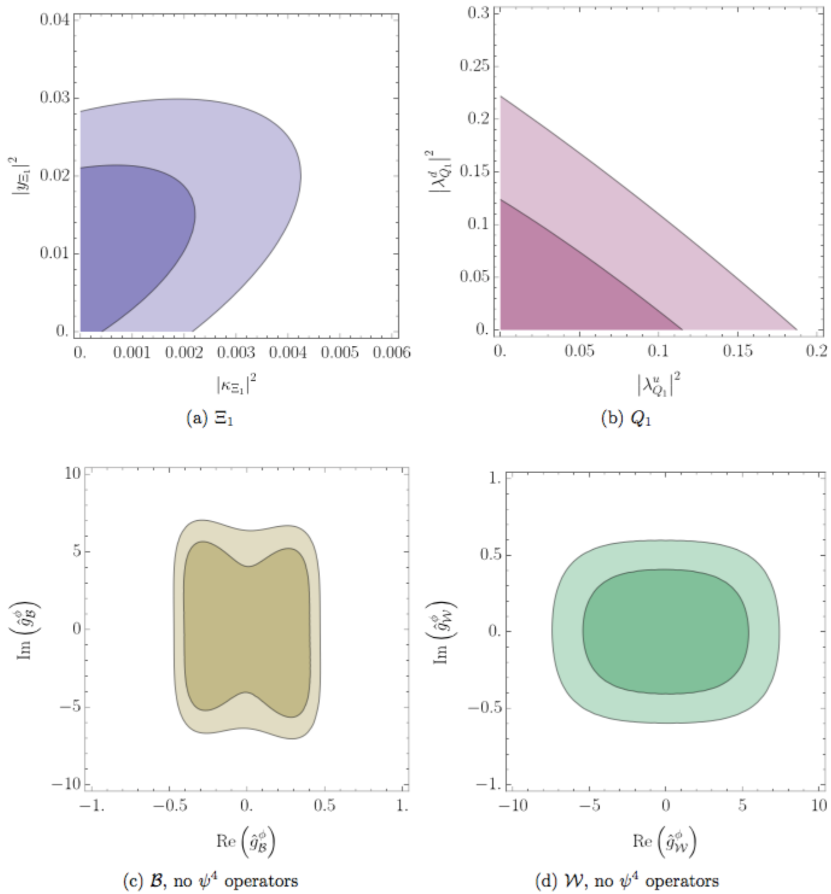
Name	Spin	$SU(3)$	$SU(2)$	$U(1)$	Name	Spin	$SU(3)$	$SU(2)$	$U(1)$
$\mathcal{S}$	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
$\mathcal{S}_1$	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	1	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
$\mathcal{B}$	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

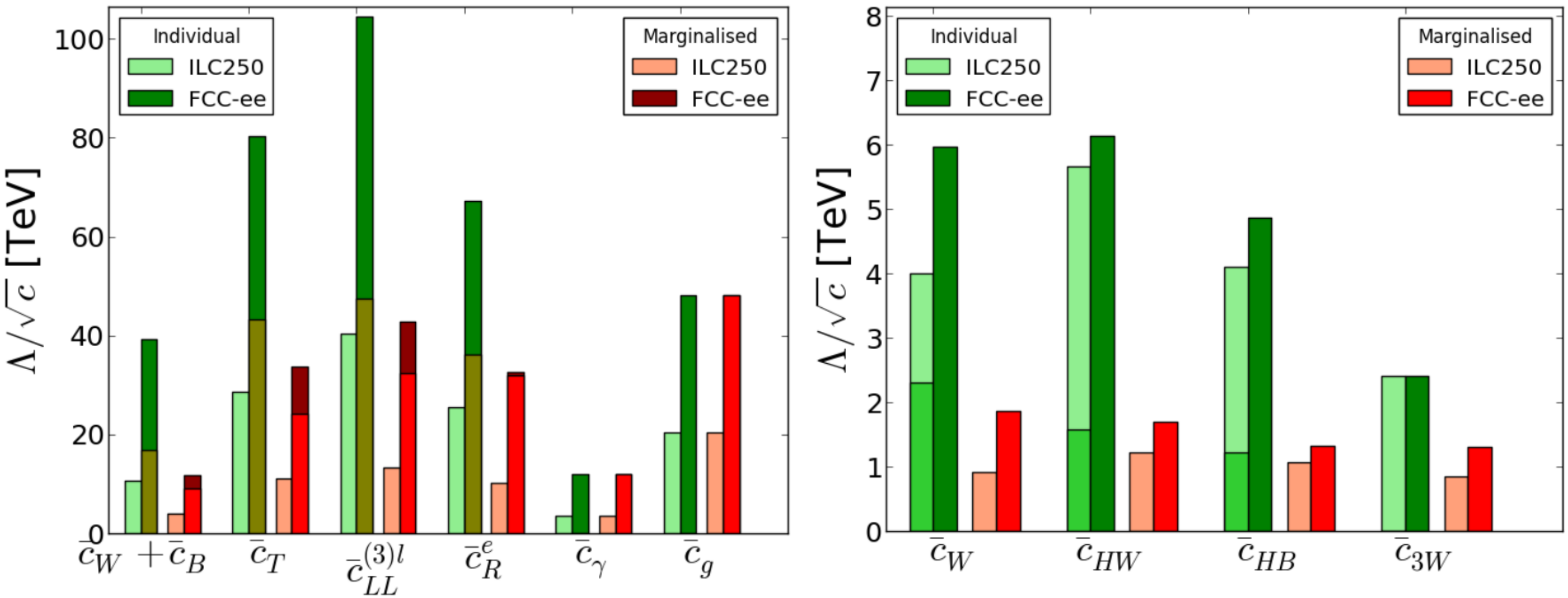
Model	χ^2	χ^2/n_{d}	Coupling	Mass / TeV
SM	157	0.987	-	-
$\mathcal{S}_1$	156	0.986	$\lvert y_{\mathcal{S}_1}\rvert^2 = (6.3 \pm 5.9)\cdot 10^{-3}$	$M_{\mathcal{S}_1} = (9.0,\ 49)$
φ, Type I	156	0.986	$Z_6 \cdot \cos\beta = -0.64 \pm 0.59$	$M_\varphi = (0.9,\ 4.3)$
Ξ	155	0.984	$\lvert\kappa_\Xi\rvert^2 = (4.2 \pm 3.4)\cdot 10^{-3}$	$M_\Xi = (12,\ 35)$
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

Future e+e- Constraints

J. Ellis and T.Y. [arXiv:1510:04561]

ILC and FCC-ee



- Future precision sensitive to TeV scale, even for loop-induced operators
- One-loop matching simplified by a **Universal One-Loop Effective Action**

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

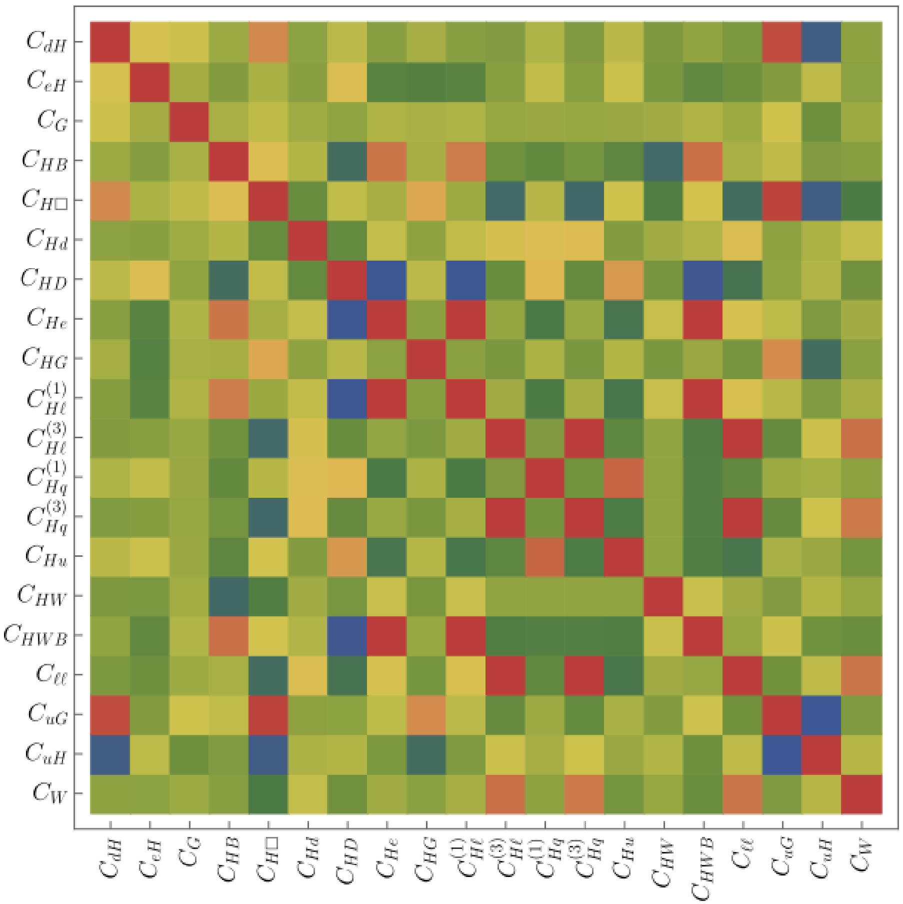
Conclusion

- SM EFT framework is the **Fermi theory of the 21st century**
- **Systematic classification** of decoupled new physics
- **Correlates measurements** and **eases interpretation**
- Finding **patterns of deviations** will give clues to a deeper underlying theory at higher energies

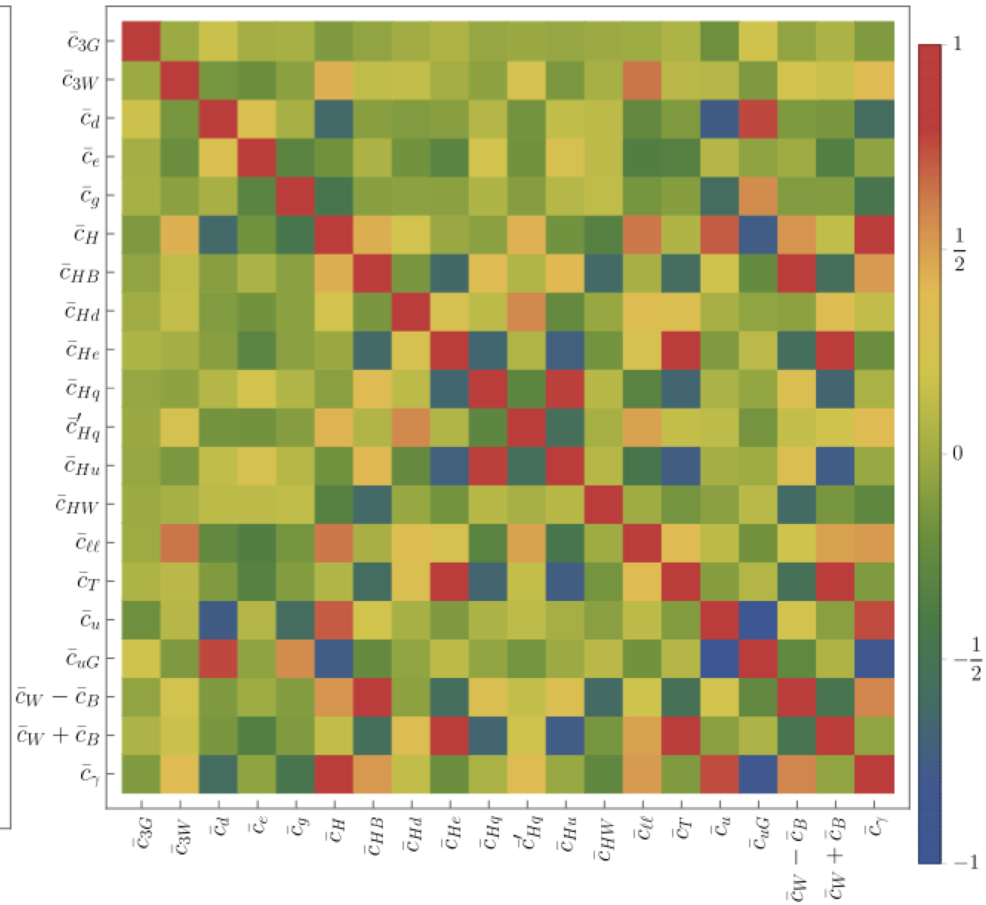
Backup

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

Backup

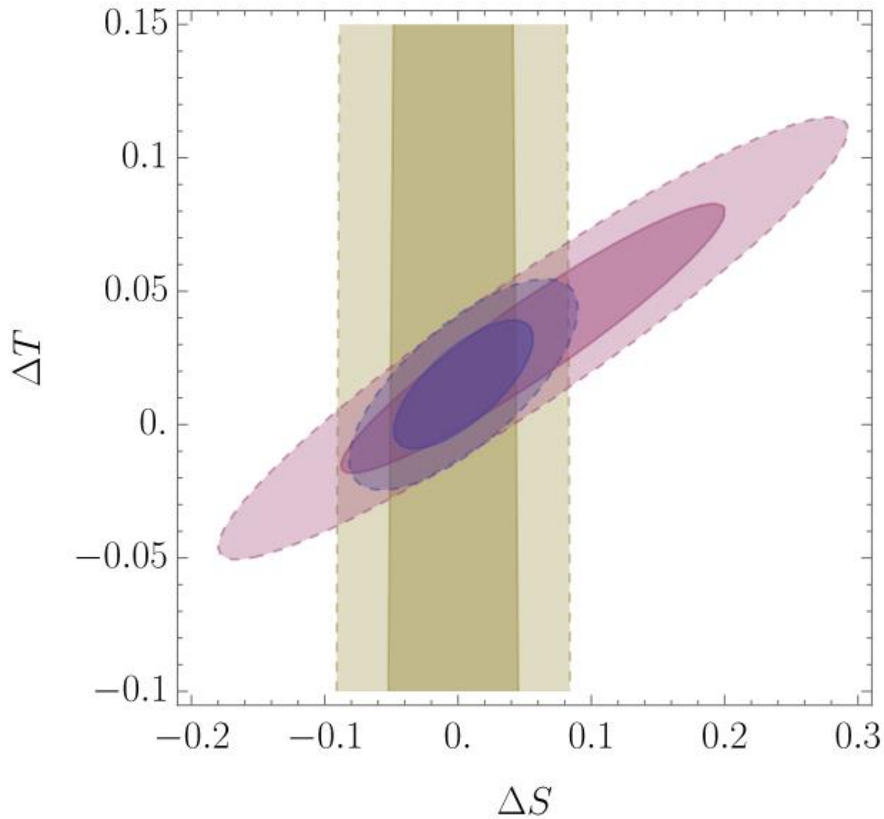


C_{dH}
C_{eH}
C_G
C_{HB}
$C_{H\Box}$
C_{Hd}
C_{HD}
C_{He}
C_{HG}
$C_{H\ell}^{(1)}$
$C_{H\ell}^{(3)}$
$C_{Hq}^{(1)}$
$C_{Hq}^{(3)}$
C_{Hu}
C_{HW}
C_{HWB}
$C_{\ell\ell}$
C_{uG}
C_{uH}
C_W



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

Backup

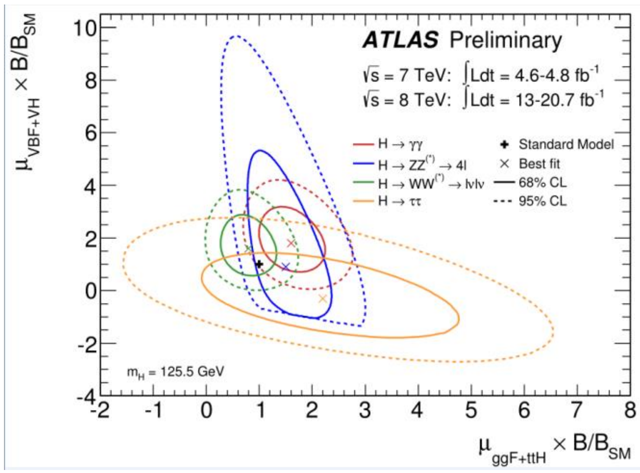


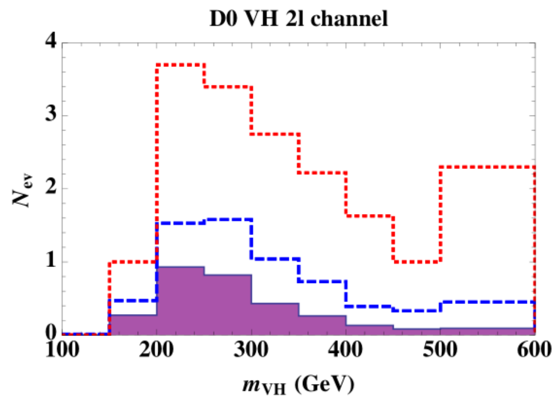
$$\frac{v^2}{\Lambda^2}C_{HWB} = \frac{g_1 g_2}{16\pi}\Delta S, \quad \frac{v^2}{\Lambda^2}C_{HD} = -\frac{g_1 g_2}{2\pi\left(g_1 + g_2\right)}\Delta T\,,$$

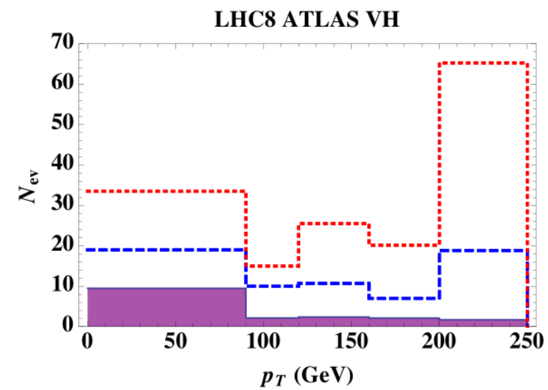
Higgs constraints on dim-6 operators

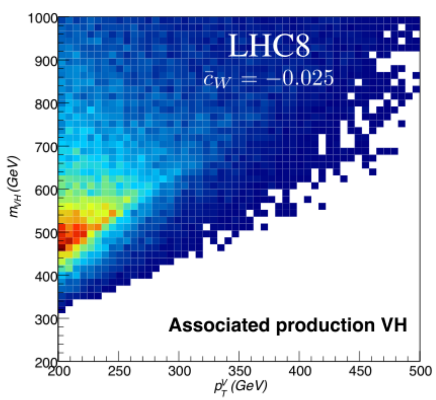
Tevong You

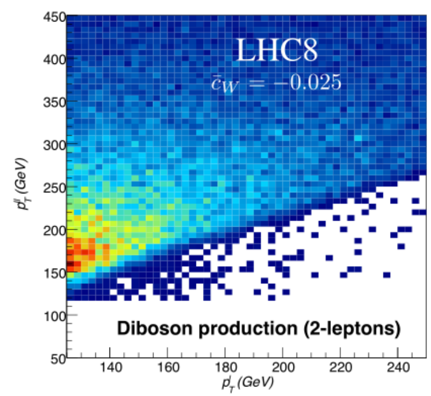
- Operators affect Higgs signal strength measurements, differential distributions











Ellis, Sanz and T.Y. 1410.7703