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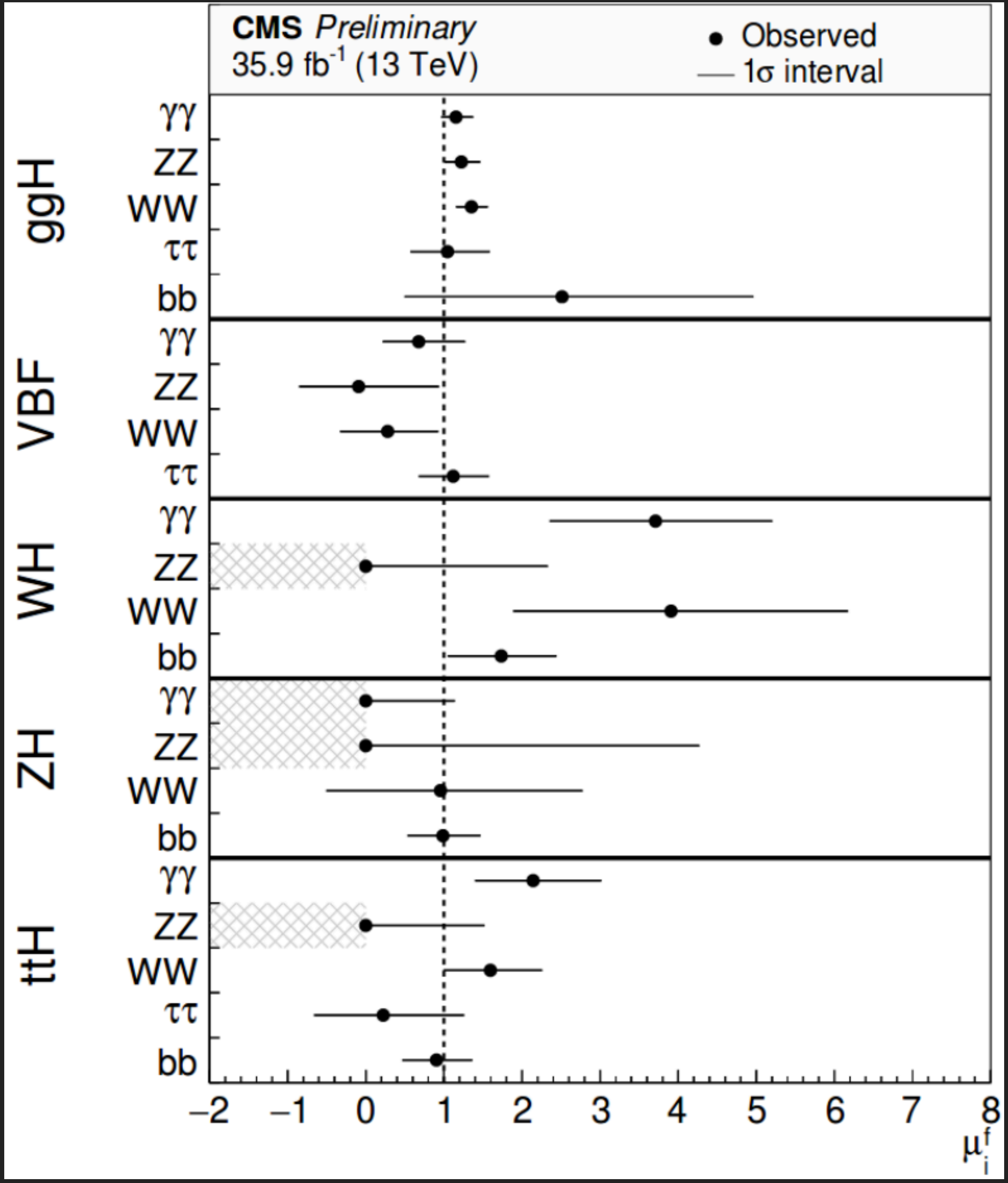
CHRIS MURPHY

EFT FOR HIGGS PHYSICS

John Ellis, CM, Verónica Sanz, & Tevong You: 1803.03252

HIGGS PHYSICS

- Many good measurements at LHC
- No evidence of BSM physics
- Λ ~ TeV



EFFECTIVE FIELD THEORY

- Most useful when UV and IR scales are well-separated

$$\mathcal{L}_{EFT} = \sum_{n,i} \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n)}(x)$$

- EFT is a full-fledged QFT provided one works to finite order in Λ
  - No reference to or input from UV physics needed
  - Advantages over ad-hoc BSM parameterization

STANDARD MODEL EFFECTIVE FIELD THEORY

- Given SM particle content, write down all terms allowed by SM 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**	$\frac{1}{2}$

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

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D_\mu^L Q_L + \bar{q}_R i\gamma^\mu D_\mu^R q_R + \bar{L}_L i\gamma^\mu D_\mu^L L_L + \bar{l}_R i\gamma^\mu D_\mu^R l_R$$

$$\mathcal{L}_G = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^a W^{a\mu\nu}$$

$$\mathcal{L}_H = (D_\mu^L \phi)^\dagger (D^{L\mu}\phi) - V(\phi)$$

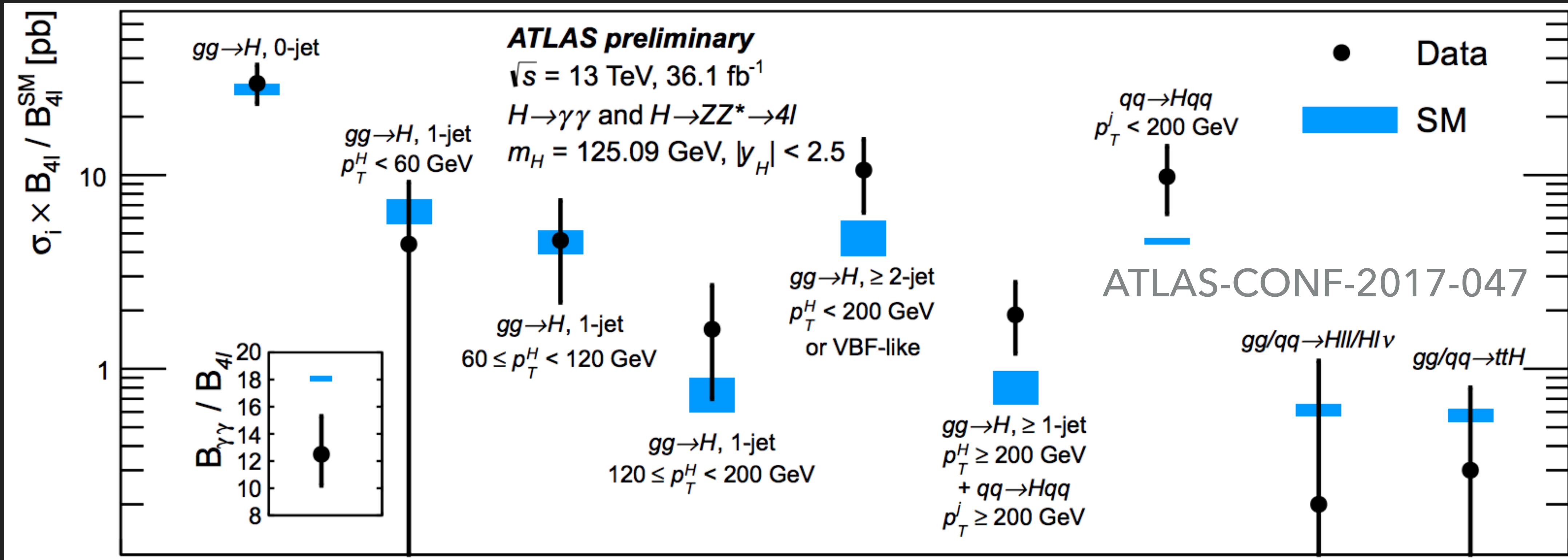
$$\mathcal{L}_Y = y_d \bar{Q}_L \phi q_R^d + y_u \bar{Q}_L \phi^c q_R^u + y_L \bar{L}_L \phi l_R + \text{h.c.} \quad ,$$

- …including higher-dimensional operators

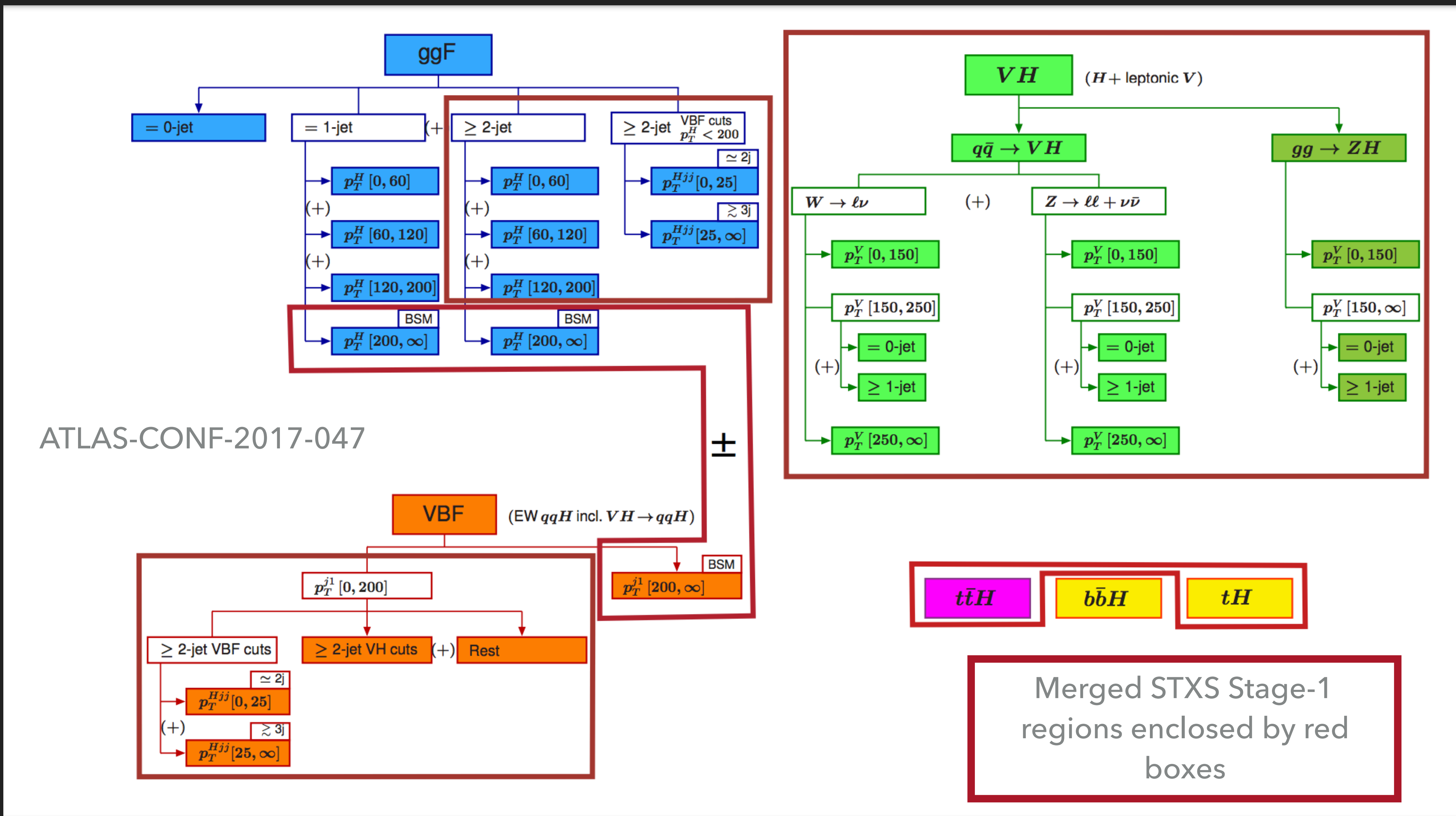
$$+ \quad \mathcal{L}_{\text{SM}}^{\text{dim-6}} = \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

NEXT-GENERATION ANALYSIS

- Previously assumed:
  - EWPD >> diboson >> Higgs
- No longer justified, theoretically unsatisfactory
- Kinematic information encoded in Simplified Template Cross Sections (STXS)



SIMPLIFIED TEMPLATE CROSS SECTIONS



ANALYSIS FRAMEWORK

- Focus on leading dimension-6 operators

$$\mathcal{L}_{\mathrm{SMEFT}} \supset \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda_i^2} \mathcal{O}_i$$

- Work to linear order in Wilson coefficients
- Impose $U(3)^5$ symmetry, broken by SM Yukawas
- Use α_{EM}, G_F, M_Z, as input parameters

DIMENSION-6 OPERATORS IN WARSAW BASIS

$$\bar{C} \equiv \frac{v^2}{\Lambda^2} C$$

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

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

results of EMSY 1803.03252 expressed in both SILH and Warsaw bases

PRECISION ELECTROWEAK MEASUREMENTS USED IN SMEFT FIT

- 12 Z-pole measurements
- 74 LEP 2 W^+W^- measurements
- New M_W measurement from ATLAS
- Probes 11 SMEFT directions

Observable	Measurement	Ref.	SM Prediction	Ref.
Γ_Z [GeV]	2.4952 ± 0.0023	[41]	2.4943 ± 0.0005	[40]
σ^0_{had} [nb]	41.540 ± 0.037	[41]	41.488 ± 0.006	[40]
R^0_ℓ	20.767 ± 0.025	[41]	20.752 ± 0.005	[40]
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010	[41]	0.01622 ± 0.00009	[118]
$\mathcal{A}_\ell\,(P_\tau)$	0.1465 ± 0.0033	[41]	0.1470 ± 0.0004	[118]
$\mathcal{A}_\ell\,(\text{SLD})$	0.1513 ± 0.0021	[41]	0.1470 ± 0.0004	[118]
R^0_b	0.021629 ± 0.00066	[41]	0.2158 ± 0.00015	[40]
R^0_c	0.1721 ± 0.0030	[41]	0.17223 ± 0.00005	[40]
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016	[41]	0.1031 ± 0.0003	[118]
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	[41]	0.0736 ± 0.0002	[118]
$\mathcal{A}_b$	0.923 ± 0.020	[41]	0.9347	[118]
$\mathcal{A}_c$	0.670 ± 0.027	[41]	0.6678 ± 0.0002	[118]
M_W [GeV]	80.387 ± 0.016	[42]	80.361 ± 0.006	[118]
M_W [GeV]	80.370 ± 0.019	[98]	80.361 ± 0.006	[118]

ATLAS+CMS HIGGS DATA FROM 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

RUN 2 HIGGS MEASUREMENTS USED IN SMEFT FIT

- Include all available kinematical information
- Include 1 W^+W^- measurement at high p_T
- Probe 13 SMEFT directions

new: Moriond EW '18

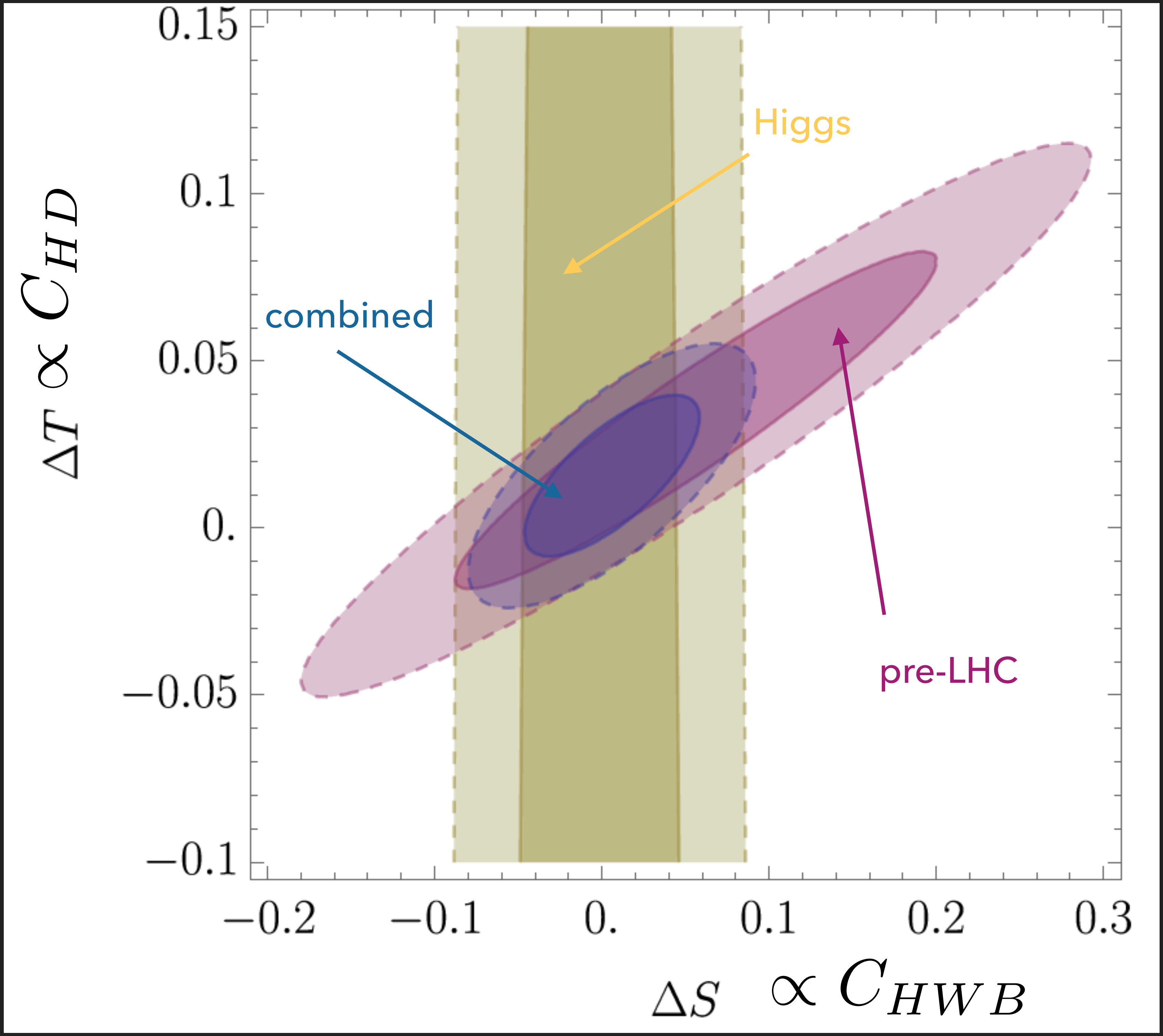
CMS

	Production	Decay	Sig. Stren.
[102]	1-jet, $p_T > 450$	$b\bar{b}$	$2.3^{+1.8}_{-1.6}$
[103]	Zh	$b\bar{b}$	0.9 ± 0.5
[103]	Wh	$b\bar{b}$	1.7 ± 0.7
[104]	$t\bar{t}h, \geq 1\ell$	$b\bar{b}$	0.72 ± 0.45
[105]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-1.52^{+1.76}_{-1.72}$
[105]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$0.94^{+0.80}_{-0.67}$
[105]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.34^{+1.42}_{-1.07}$
[105]	$t\bar{t}h$	$2\ell ss$	$1.61^{+0.58}_{-0.51}$
[105]	$t\bar{t}h$	3ℓ	$0.82^{+0.77}_{-0.71}$
[105]	$t\bar{t}h$	4ℓ	$0.9^{+2.3}_{-1.6}$
[106]	0-jet DF	WW	$1.30^{+0.24}_{-0.23}$
[106]	1-jet DF	WW	$1.29^{+0.32}_{-0.27}$
[106]	2-jet DF	WW	$0.82^{+0.54}_{-0.50}$
[106]	VBF 2-jet	WW	$0.72^{+0.44}_{-0.41}$
[106]	Vh 2-jet	WW	$3.92^{+1.32}_{-1.17}$
[106]	Wh 3-lep	WW	$2.23^{+1.76}_{-1.53}$
[107]	ggF	$\gamma\gamma$	$1.10^{+0.20}_{-0.18}$
[107]	VBF	$\gamma\gamma$	$0.8^{+0.6}_{-0.5}$
[107]	$t\bar{t}h$	$\gamma\gamma$	$2.2^{+0.9}_{-0.8}$
[107]	Vh	$\gamma\gamma$	$2.4^{+1.1}_{-1.0}$
[108]	ggF	4ℓ	$1.20^{+0.22}_{-0.21}$
[109]	0-jet	$\tau\tau$	0.84 ± 0.89
[109]	boosted	$\tau\tau$	$1.17^{+0.47}_{-0.40}$
[109]	VBF	$\tau\tau$	$1.11^{+0.34}_{-0.35}$
[106]	Zh 4-lep	WW	$0.77^{+1.49}_{-1.20}$

ATLAS

	Production	Decay	Sig. Stren.
[110]	pp	$\mu\mu$	-0.1 ± 1.5
[111]	Zh	$b\bar{b}$	$1.12^{+0.50}_{-0.45}$
[111]	Wh	$b\bar{b}$	$1.35^{+0.68}_{-0.59}$
[112]	$t\bar{t}h$	$b\bar{b}$	$0.84^{+0.64}_{-0.61}$
[113]	$t\bar{t}h$	$2\ell os + 1\tau_h$	$1.7^{+2.1}_{-1.9}$
[113]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-0.6^{+1.6}_{-1.5}$
[113]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.6^{+1.8}_{-1.3}$
[113]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$3.5^{+1.7}_{-1.3}$
[113]	$t\bar{t}h$	3ℓ	$1.8^{+0.9}_{-0.7}$
[113]	$t\bar{t}h$	$2\ell ss$	$1.5^{+0.7}_{-0.6}$
[114]	ggF	WW	$1.21^{+0.22}_{-0.21}$
[114]	VBF	WW	$0.62^{+0.37}_{-0.36}$
[115]	$B(h \to \gamma\gamma)/\ B(h \to 4\ell)$		$0.69^{+0.15}_{-0.13}$
[115]	0-jet	4ℓ	$1.07^{+0.27}_{-0.25}$
[115]	1-jet, $p_T < 60$	4ℓ	$0.67^{+0.72}_{-0.68}$
[115]	1-jet, $p_T \in (60, 120)$	4ℓ	$1.00^{+0.63}_{-0.55}$
[115]	1-jet, $p_T \in (120, 200)$	4ℓ	$2.1^{+1.5}_{-1.3}$
[115]	2-jet	4ℓ	$2.2^{+1.1}_{-1.0}$
[115]	"BSM-like"	4ℓ	$2.3^{+1.2}_{-1.0}$
[115]	VBF, $p_T < 200$	4ℓ	$2.14^{+0.94}_{-0.77}$
[115]	Vh lep	4ℓ	$0.3^{+1.3}_{-1.2}$
[115]	$t\bar{t}h$	4ℓ	$0.51^{+0.86}_{-0.70}$
[116]	Wh	WW	$3.2^{+4.4}_{-4.2}$

CONSTRAINTS ON OBLIQUE PARAMETERS



GLOBAL FIT RESULTS

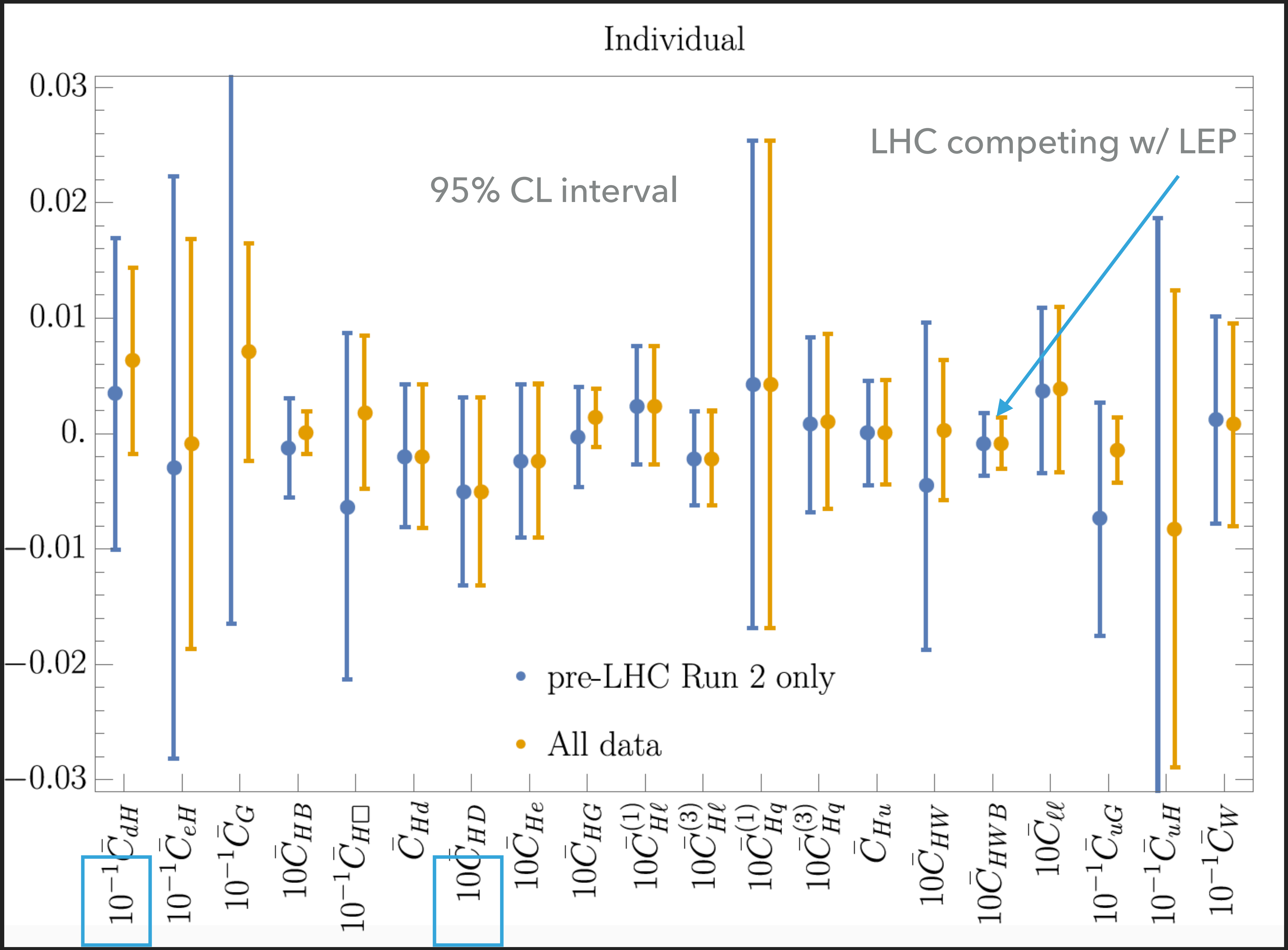
Theory	χ^2	χ^2/n_d	p-value
SM	157	0.987	0.532
SMEFT	137	0.987	0.528
SMEFT*	143	0.977	0.564

20 coefficients → SMEFT

13 coefficients → SMEFT*

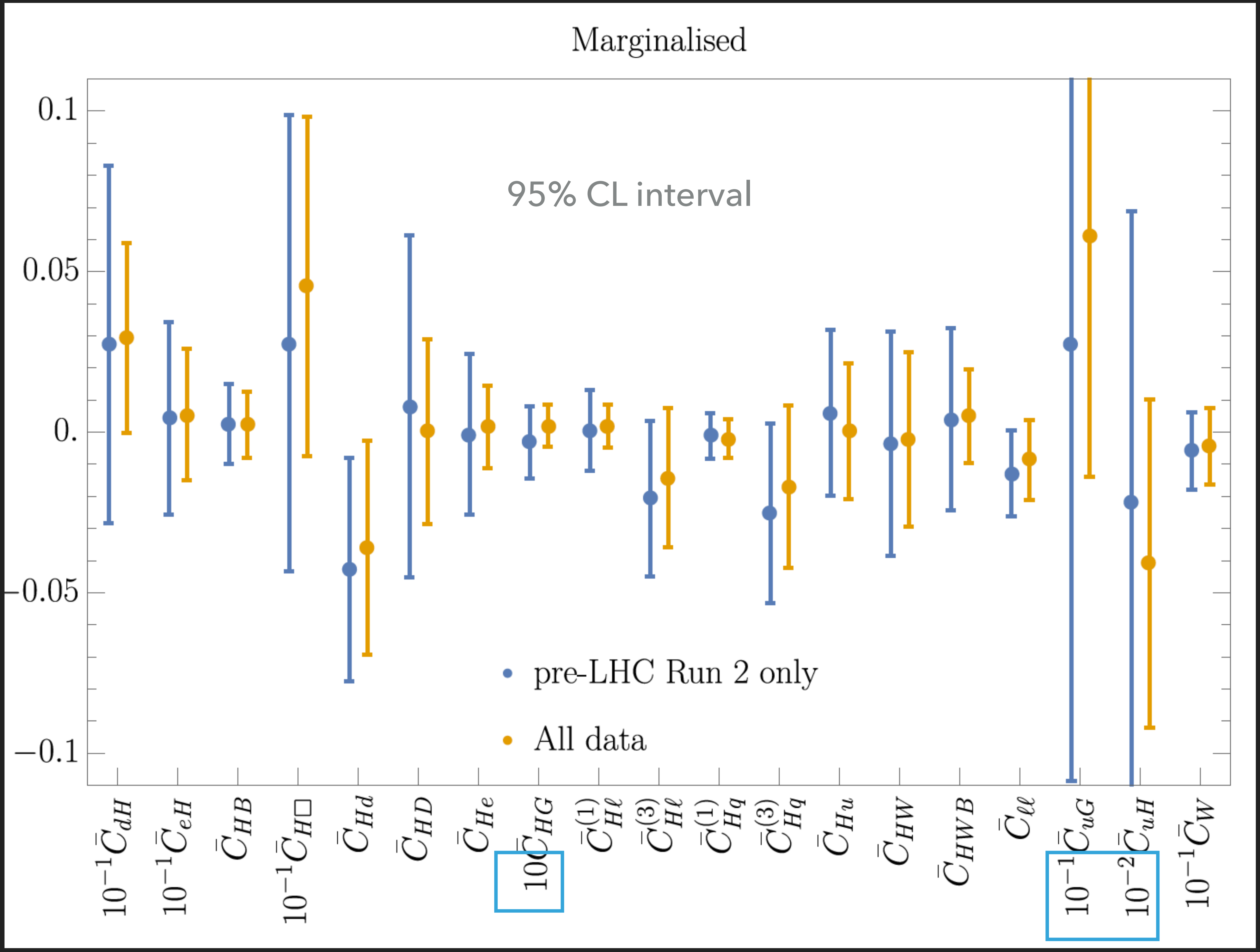
*assumes SMEFT is UV-completed by a renormalizable, weakly-coupled theory

FIT TO EACH OPERATOR INDIVIDUALLY



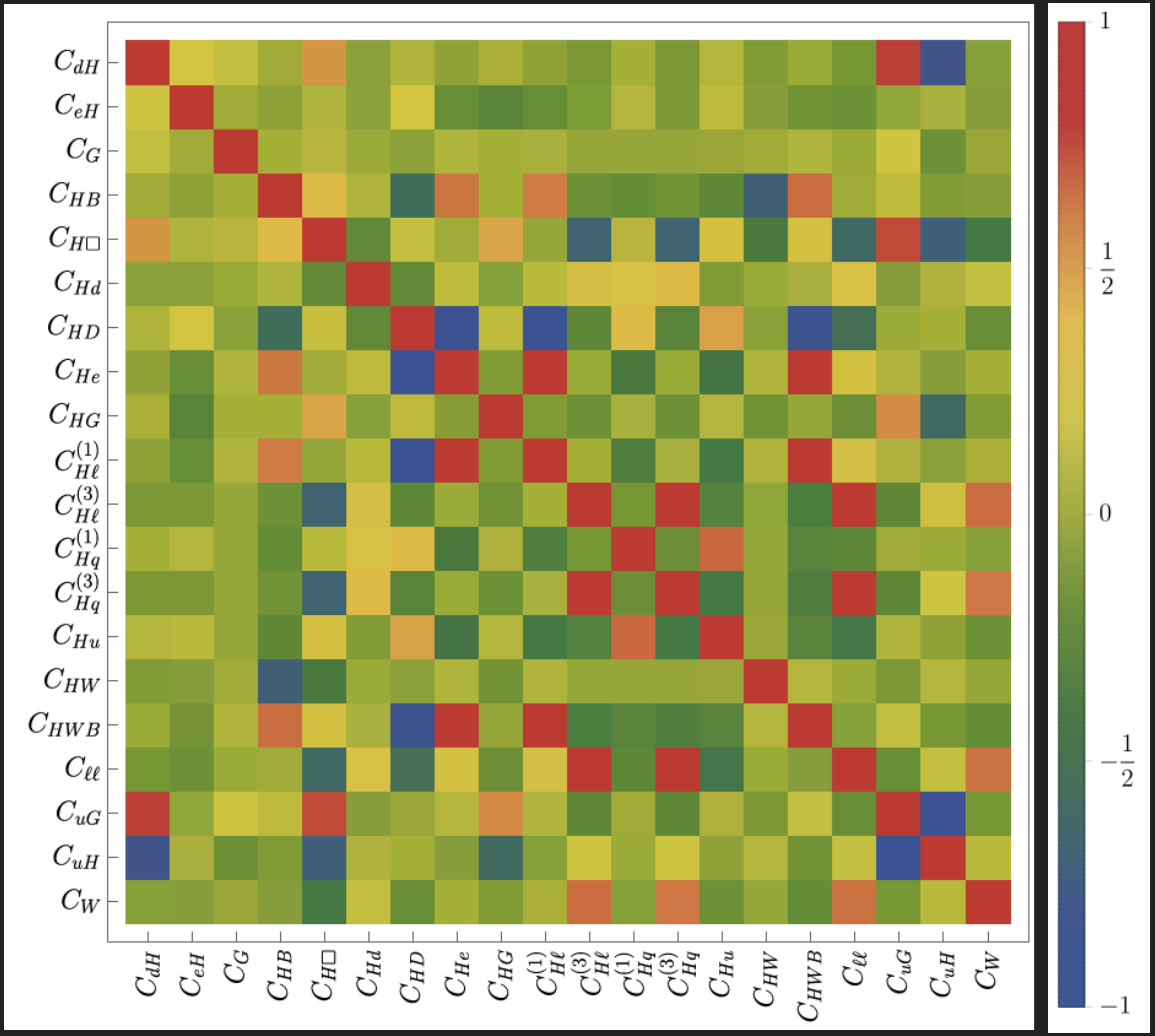
Note: different scaling factors

FIT TO ALL OPERATORS SIMULTANEOUSLY

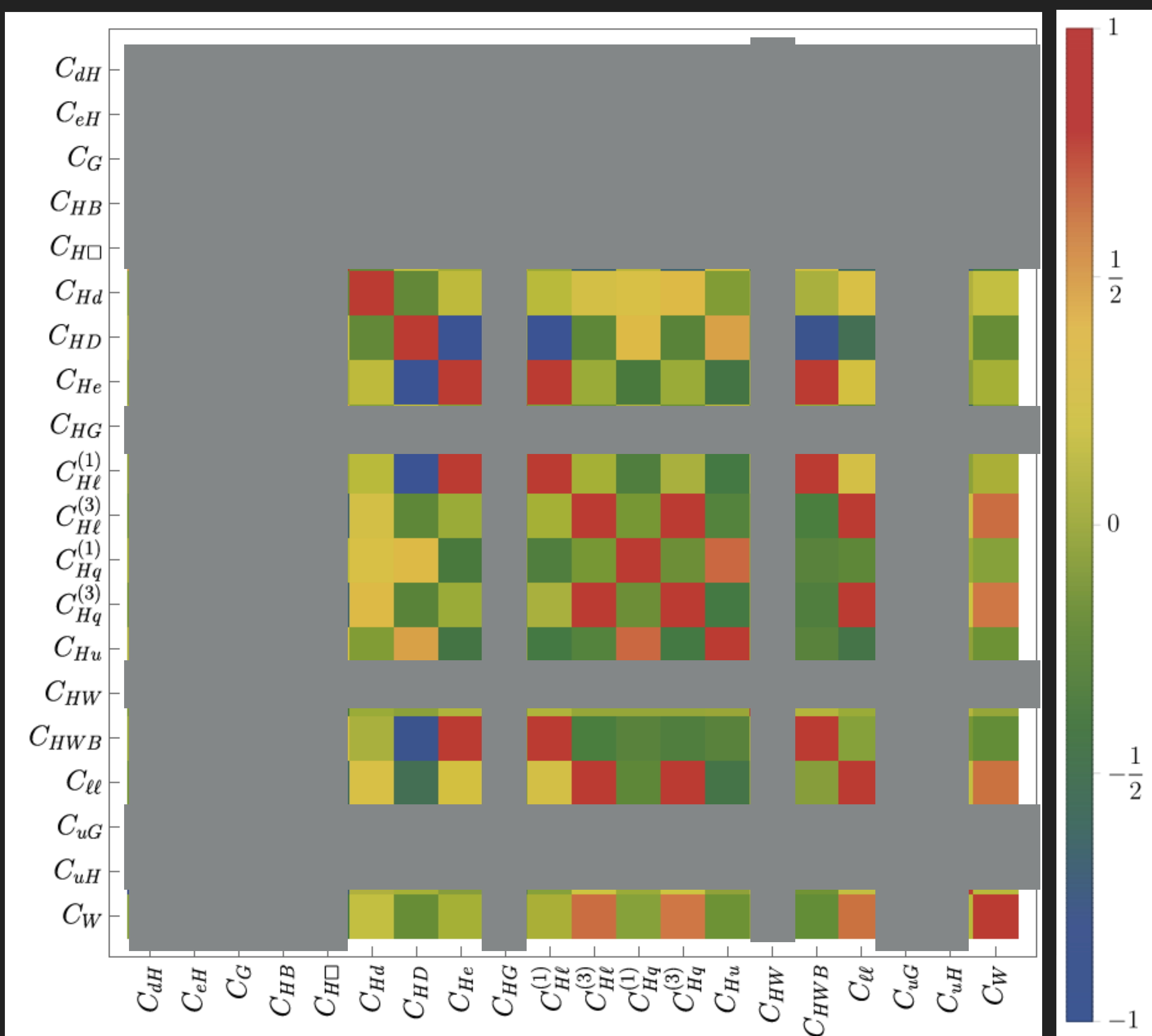


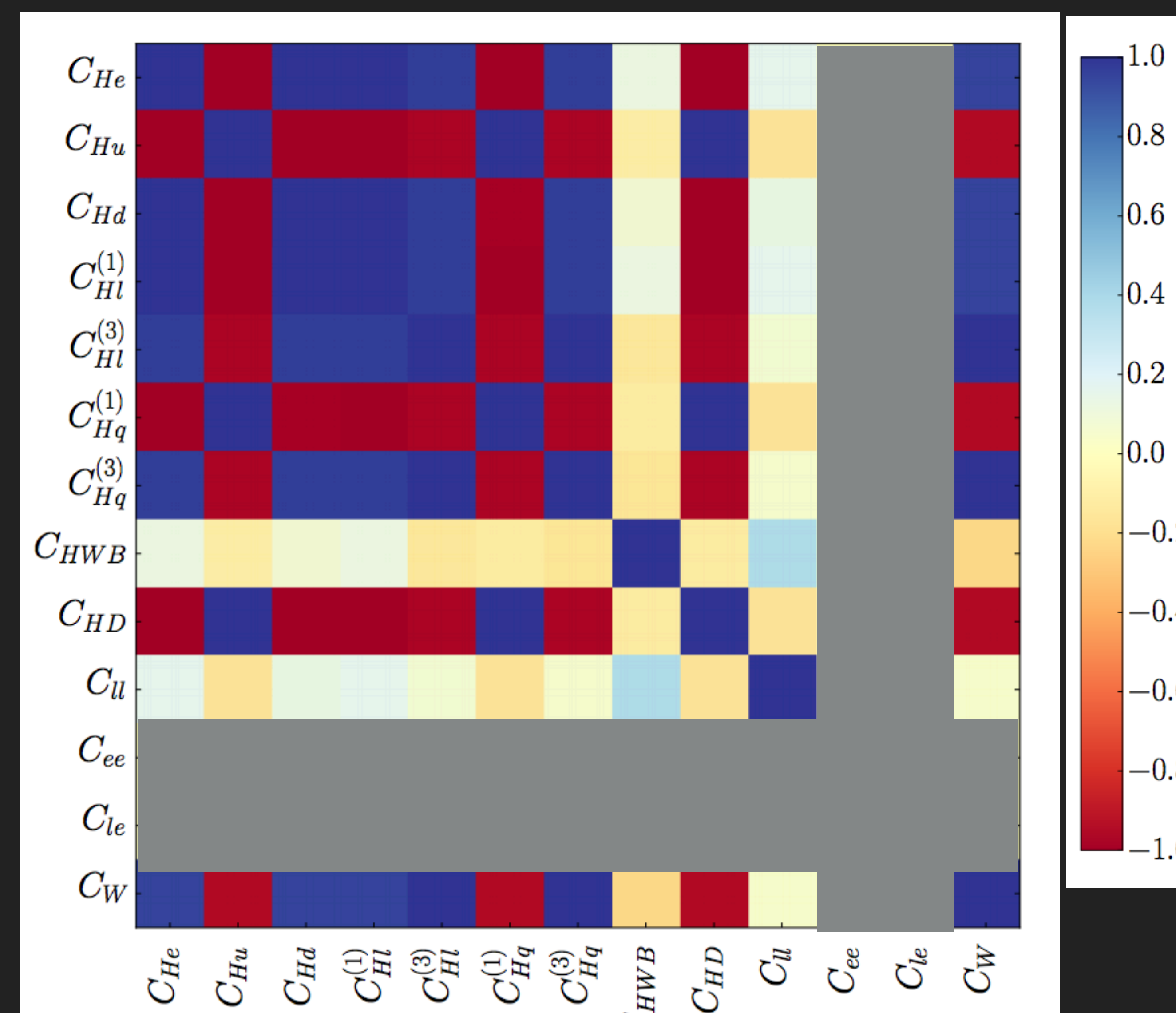
Note: different scaling factors

CORRELATION MATRIX



CORRELATION MATRIX





Brivio, Trott 1701.06424

SIMPLE EXTENSIONS OF THE SM

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	$\frac{2}{3}$

de Blas, Criado, Perez-Victoria, Santiago 1711.10391

NUMERICAL CONSTRAINTS ON EXTENSIONS

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	$\lvert\hat{g}^\phi_{\mathcal{W}_1}\rvert^2 = (3.3 \pm 2.7)\cdot 10^{-3}$	$M_{\mathcal{W}_1} = (4.1,\ 13)$
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	$\lvert\hat{g}^\phi_{\mathcal{B}_1}\rvert^2 < 2.4\cdot 10^{-3}$	$M_{\mathcal{B}_1} > 21$

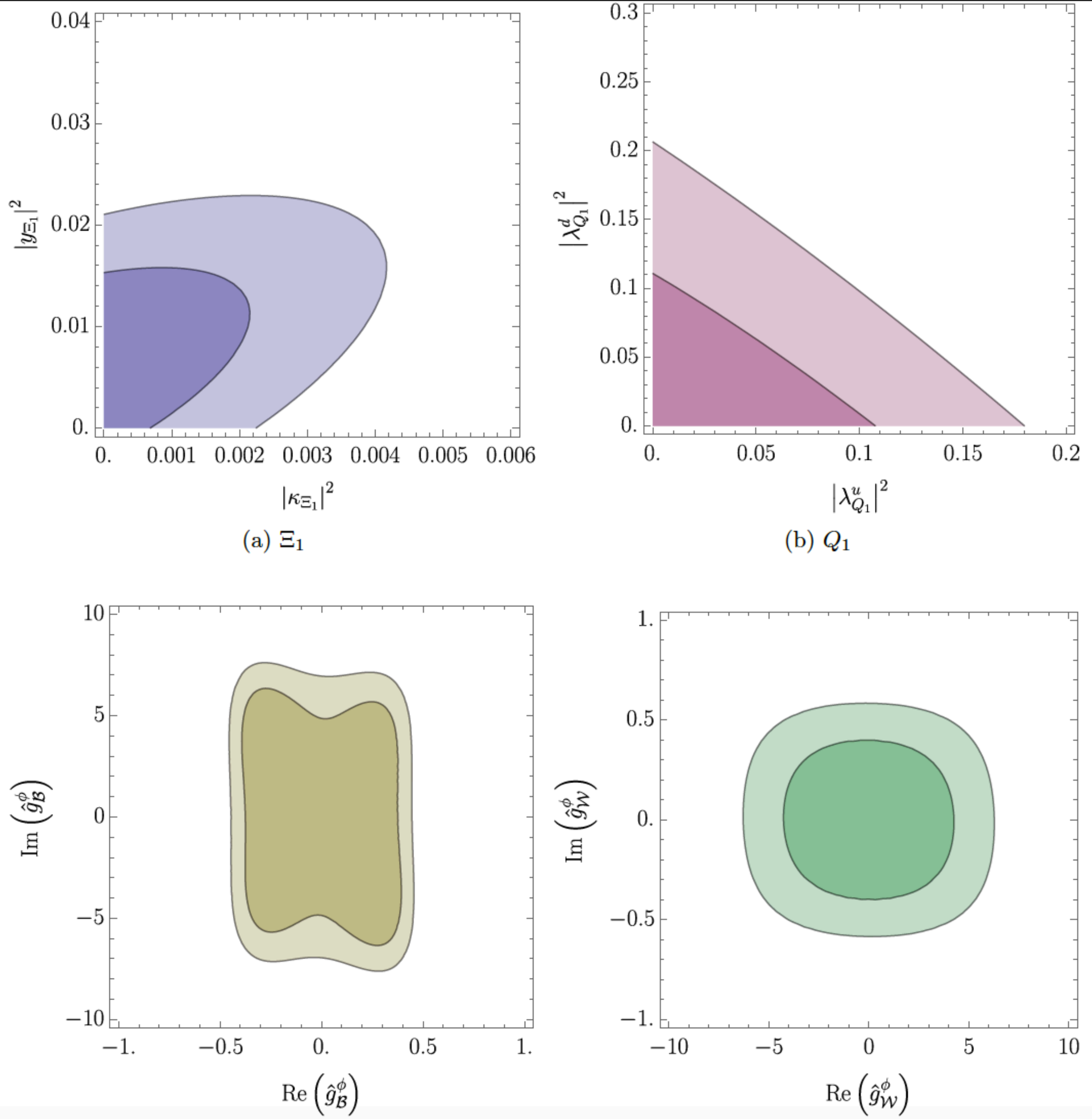
improve χ^2 & χ^2/n_d ($\mathcal{S}_1$, φ, Ξ, N, $\mathcal{W}_1$)

only improve χ^2 (E, Δ_3, Σ, Q_5, T_2)

improve neither ($\mathcal{S}$, Δ_1, Σ_1, U, D, Q_7, T_1, $\mathcal{B}_1$)

2HDM ← (φ, Type I)

CONSTRAINTS ON SM EXTENSIONS



(a) Ξ_1

(b) Q_1

(c) $\mathcal{B}$, no ψ^4 operators

(d) $\mathcal{W}$, no ψ^4 operators

NON-RENORMALIZABLE MODELS

- If UV model has both super-renormalizable and non-renormalizable interactions

$$\mathcal{L} = \frac{1}{\Lambda}\left(a g_2^2 \sigma W^{a\,\mu\nu} W^a_{\mu\nu} + b g_1^2 \sigma B^{\mu\nu} B_{\mu\nu} + c g_1 g_2 \, \Sigma^a W^a_{\mu\nu} B^{\mu\nu}\right) + \Lambda\left(d\, H^\dagger H \sigma + f\, H^\dagger \tau^a H \Sigma_a\right)$$

- Low energy EFT can have higher-dimensional operators w/ arbitrary coefficients

$$\mathcal{L} = \frac{ad}{m_\sigma^2} g_2^2 H^\dagger H\, W^{a\,\mu\nu} W^a_{\mu\nu} + \frac{bd}{m_\sigma^2} g_1^2 H^\dagger H\, B^{\mu\nu} B_{\mu\nu} + \frac{cf}{m_\Sigma^2} g_1 g_2\, H^\dagger \tau^a H\, W^a_{\mu\nu} B^{\mu\nu}$$

see e.g. Jenkins, Manohar, Trott 1305.0017

NON-RENORMALIZABLE MODELS

- Subset of models: explanations of muon *g*-2

$E^{(5)}$: $C_{H\ell}^{(1)} = C_{H\ell}^{(3)}$, $\chi^2 = 157$, $\chi^2/n_d = 0.999$.

$$\begin{pmatrix} \bar{C}_{eH} \\ \bar{C}_{H\ell}^{(3)} \end{pmatrix} = \begin{pmatrix} (-0.8 \pm 8.9) \cdot 10^{-2} \\ (-0.3 \pm 1.5) \cdot 10^{-4} \end{pmatrix}$$

$\Delta_{1,3}^{(5)}$: $\chi^2 = 156$, $\chi^2/n_d = 0.996$.

$$\begin{pmatrix} \bar{C}_{eH} \\ \bar{C}_{He} \end{pmatrix} = \begin{pmatrix} (-0.8 \pm 8.9) \cdot 10^{-2} \\ (-2.3 \pm 3.3) \cdot 10^{-4} \end{pmatrix}$$

$\Sigma_1^{(5)}$: $C_{H\ell}^{(1)} = -3C_{H\ell}^{(3)}$, $\chi^2 = 155$, $\chi^2/n_d = 0.988$.

$$\begin{pmatrix} \bar{C}_{eH} \\ \bar{C}_{H\ell}^{(3)} \end{pmatrix} = \begin{pmatrix} (-0.8 \pm 8.9) \cdot 10^{-2} \\ (-1.2 \pm 0.9) \cdot 10^{-4} \end{pmatrix}$$

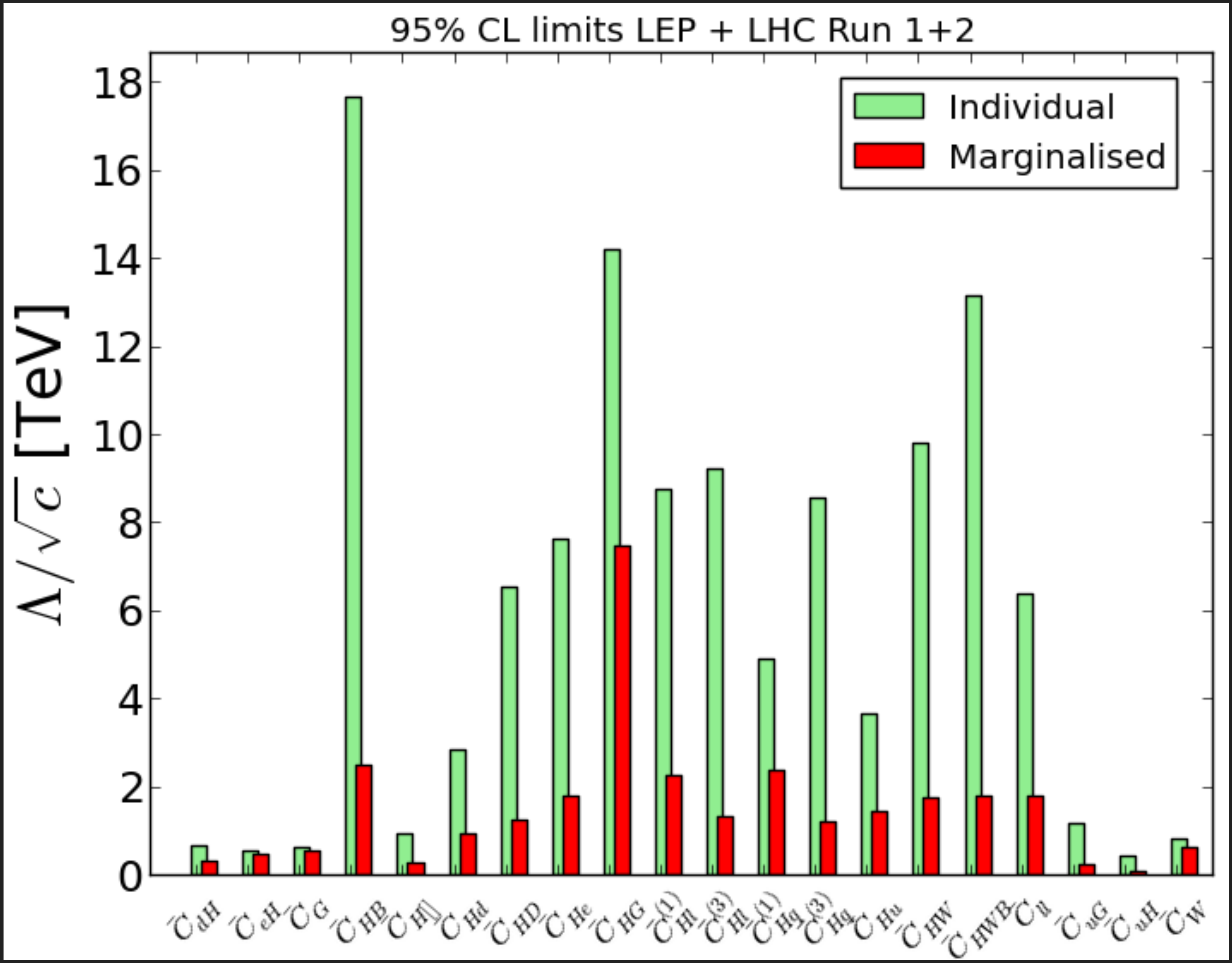
NON-RENORMALIZABLE MODELS

- Heavy scalar singlet

- $\mathcal{S}^{(5)}$: $\chi^2 = 153$, $\chi^2/n_d = 1.00$.

$$\begin{pmatrix} 0.54\bar{C}_{H\Box} - 0.05\bar{C}_{HW} + 0.01\bar{C}_{HB} + 0.08\bar{C}_{eH} + 0.84\bar{C}_{uH} + 0.03\bar{C}_{dH} \\ -0.16\bar{C}_{H\Box} + 0.75\bar{C}_{eH} + 0.64\bar{C}_{dH} \\ 0.50\bar{C}_{H\Box} - 0.04\bar{C}_{HW} + 0.01\bar{C}_{HB} + 0.57\bar{C}_{eH} - 0.36\bar{C}_{uH} - 0.54\bar{C}_{dH} \\ 0.65\bar{C}_{H\Box} - 0.06\bar{C}_{HW} + 0.02\bar{C}_{HB} - 0.32\bar{C}_{eH} - 0.42\bar{C}_{uH} + 0.54\bar{C}_{dH} \\ 0.09\bar{C}_{H\Box} + 0.95\bar{C}_{HW} - 0.29\bar{C}_{HB} \\ 0.91\bar{C}_{HG} + 0.12\bar{C}_{HW} + 0.39\bar{C}_{HB} \\ -0.39\bar{C}_{HG} + 0.27\bar{C}_{HW} + 0.88\bar{C}_{HB} \end{pmatrix} = \begin{pmatrix} -0.03 \pm 0.18 \\ 0.11 \pm 0.11 \\ (-4.1 \pm 7.9)\cdot 10^{-2} \\ (8.0 \pm 6.0)\cdot 10^{-2} \\ (1.8 \pm 9.6)\cdot 10^{-3} \\ (1.7 \pm 1.4)\cdot 10^{-4} \\ (2.0 \pm 8.4)\cdot 10^{-5} \end{pmatrix}$$

SUMMARY


95% CL limits LEP + LHC Run 1+2
$\Lambda/\sqrt{c}$ [TeV]
Individual
Marginalised
0
2
4
6
8
10
12
14
16
18
C dH
C eH
C G
C HB
C H□
C Hd
C HD
C He
C HG
C Hl (1)
C Hl (3)
C Hq (1)
C Hq (3)
C Hu
C HW
C HWB
C ll
C uG
C uH
C W

SUMMARY

- SMEFT: model-independent way to search for heavy, new physics
- This work is the first combined global analysis within the SMEFT of electroweak, diboson, and Higgs data
- Higgs measurements currently compete w/ EWPD

EFT DETAILS

- *tth* production probes many coefficients not otherwise constrained by our dataset

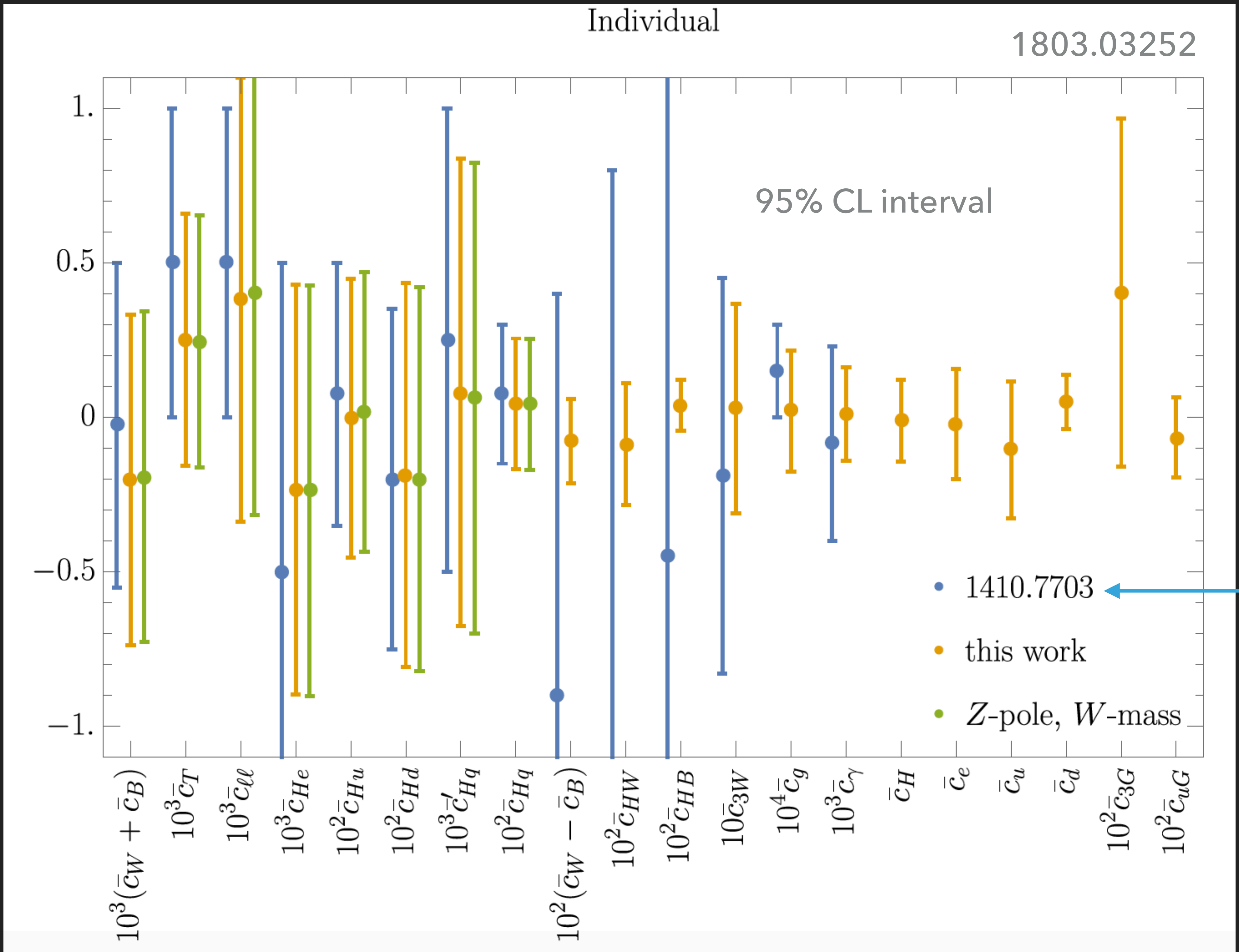
$$C_{uG} \to C_{uG} + 0.006 C_{uW} + 0.002 C_{uB} - 0.13 C_{qu}^{(8)} + \text{ additional } \psi^4 \text{ operators}$$

- Include only C_{uG} as it has the largest contribution
- Alternatively…
  - one could regularize the fit as in 1710.02008
  - add in top-quark measurements

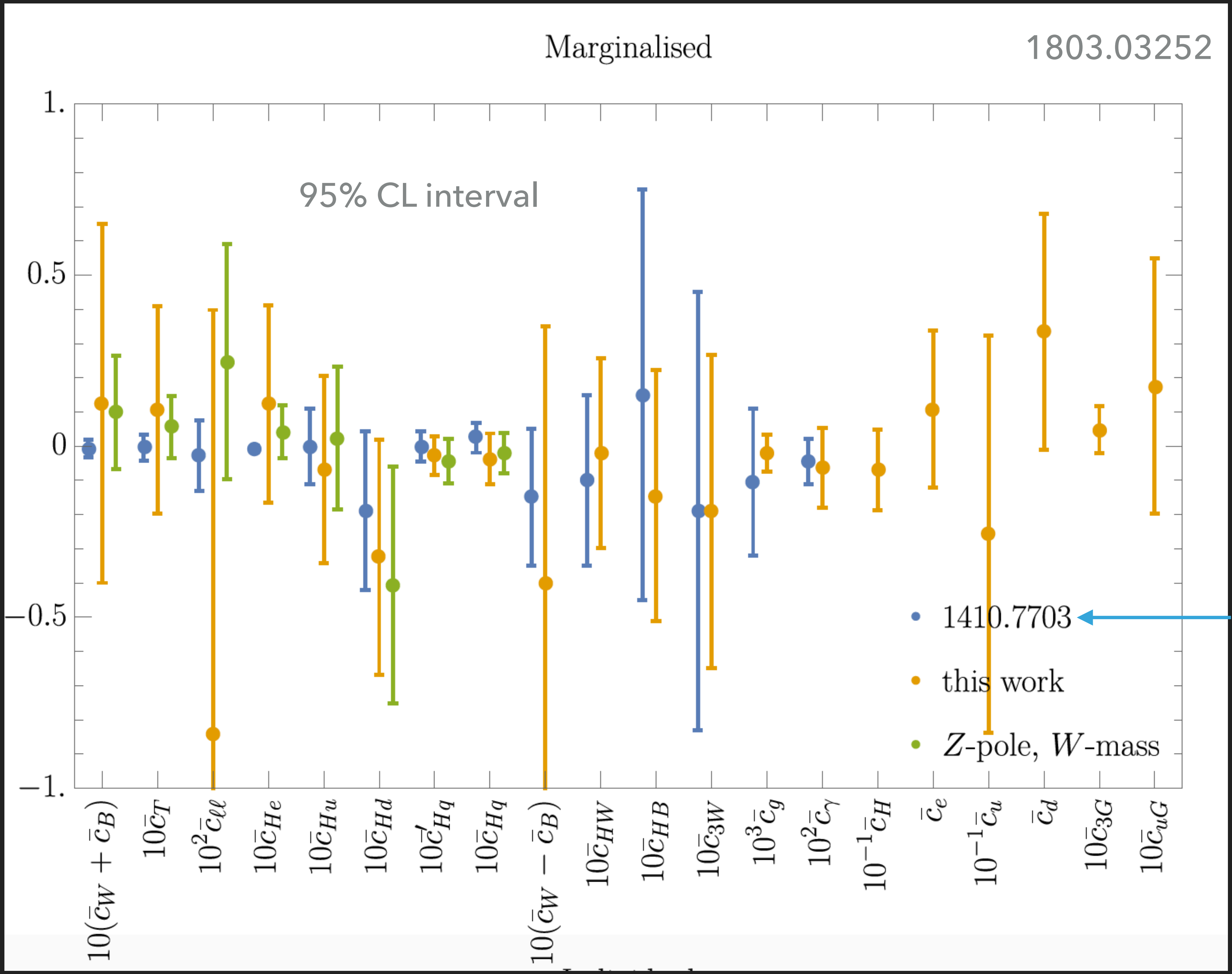
SILH BASIS

$$
\begin{aligned}
\mathcal{L}_{\rm SMEFT}^{\rm SILH} \supset\ & \frac{\bar c_W}{m_W^2}\frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu} + \frac{\bar c_B}{m_W^2}\frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu} + \frac{\bar c_T}{v^2}\frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2 \\
& + \frac{\bar c_{ll}}{v^2}(\bar L\gamma_\mu L)(\bar L\gamma^\mu L) + \frac{\bar c_{He}}{v^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar e_R\gamma^\mu e_R) + \frac{\bar c_{Hu}}{v^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar u_R\gamma^\mu u_R) \\
& + \frac{\bar c_{Hd}}{v^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar d_R\gamma^\mu d_R) + \frac{\bar c'_{Hq}}{v^2}(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar Q_L\sigma^a\gamma^\mu Q_L) \\
& + \frac{\bar c_{Hq}}{v^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar Q_L\gamma^\mu Q_L) + \frac{\bar c_{HW}}{m_W^2} ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu} + \frac{\bar c_{HB}}{m_W^2} ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
& + \frac{\bar c_{3W}}{m_W^2} g^3\epsilon_{abc}W^{a\,\nu}_\mu W^b_{\nu\rho}W^{c\,\rho\mu} + \frac{\bar c_g}{m_W^2} g_s^2|H|^2 G^A_{\mu\nu}G^{A\mu\nu} + \frac{\bar c_\gamma}{m_W^2} g'^2|H|^2 B_{\mu\nu}B^{\mu\nu} \\
& + \frac{\bar c_H}{v^2}\frac{1}{2}(\partial^\mu|H|^2)^2 + \sum_{f=e,u,d}\frac{\bar c_f}{v^2} y_f|H|^2\bar F_L H^{(c)} f_R \\
& + \frac{\bar c_{3G}}{m_W^2} g_s^3 f_{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho + \frac{\bar c_{uG}}{m_W^2} g_s y_u \bar Q_L H^{(c)}\sigma^{\mu\nu}\lambda_A u_R G^A_{\mu\nu}\,. \qquad (6)
\end{aligned}
$$

GLOBAL FITS IN THE SILH BASIS



GLOBAL FITS IN THE SILH BASIS



previous work by JE, VS, TY

PROJECTIONS FOR HL- AND HE-LHC

- Study ongoing looking at LHC 13/14 TeV vs. 27 TeV
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop
- "It's difficult to make predictions, especially about the future" - Yogi Berra

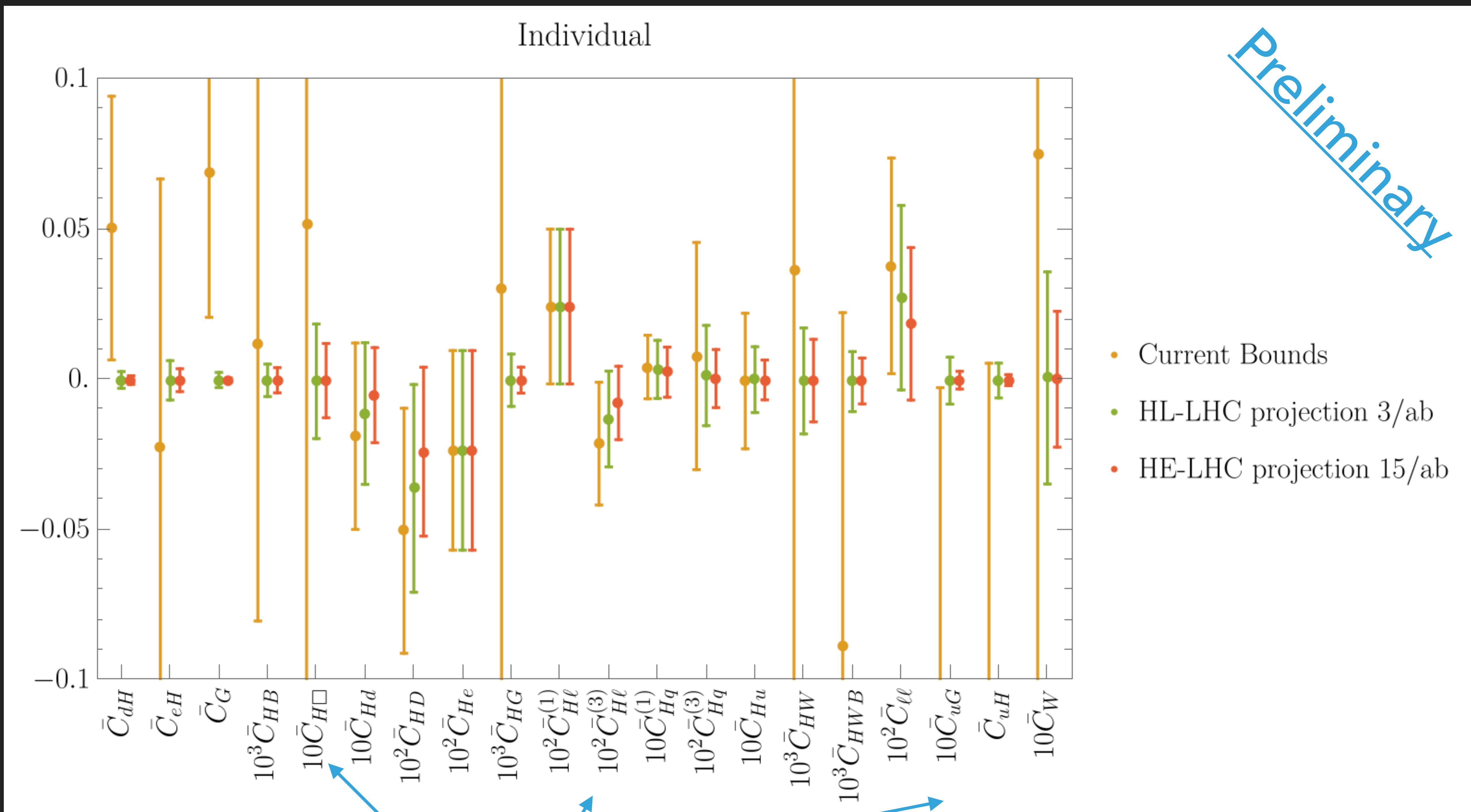
PROJECTION STRATEGY

- For each LHC Run-2 measurement used in the fit of 1803.03252
  - Set central value to SM prediction
  - Scale all uncertainties for the *i*th measurement by…
    - HL-LHC: $$\sqrt{\frac{L_i}{3/\mathrm{ab}}}$$
    - HE-LHC: $$\sqrt{\frac{\sigma_{13,i}}{\sigma_{27,i}}\frac{L_i}{15/\mathrm{ab}}}$$

most measurements currently have L_i ~ 36/fb

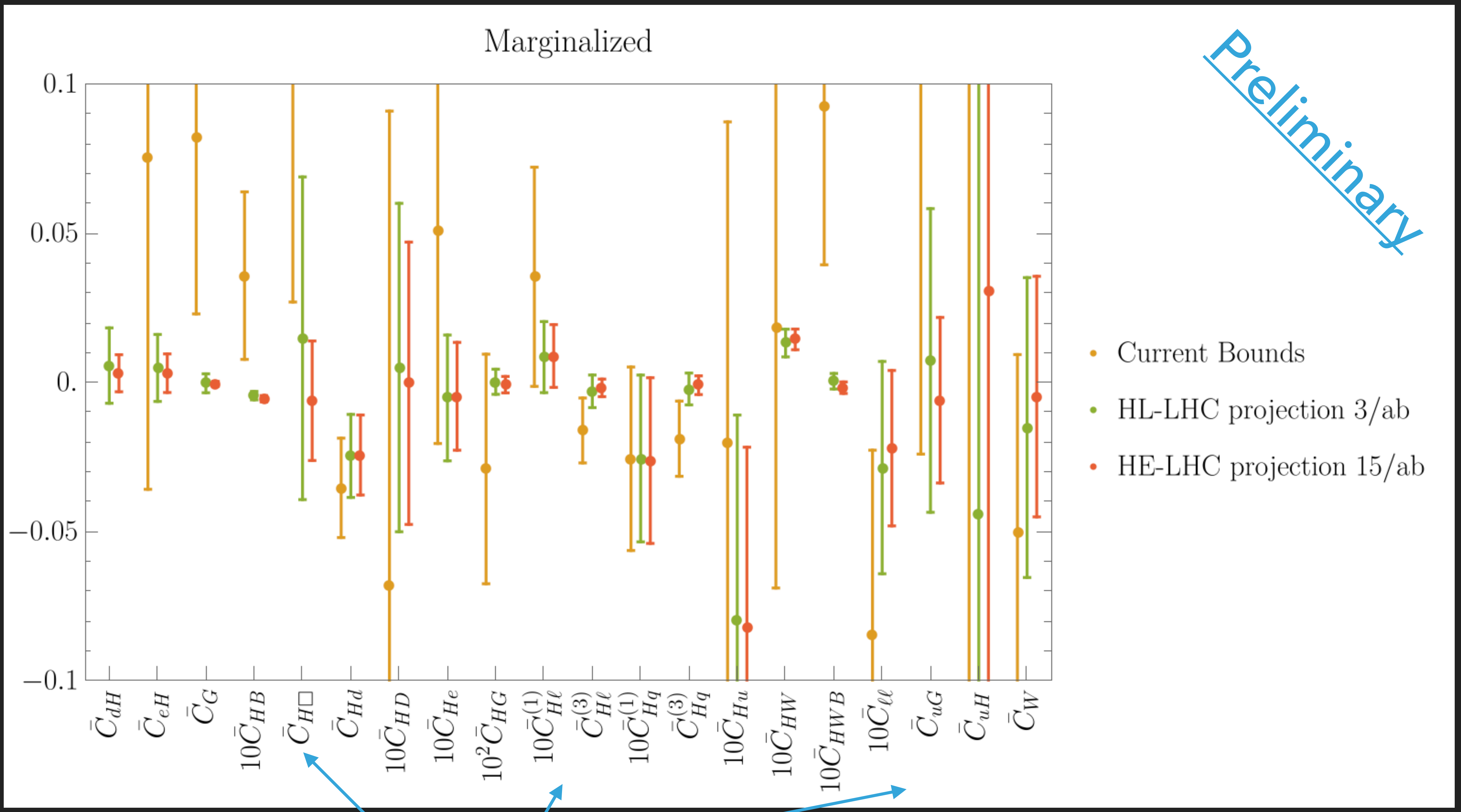
  - Leave correlations unchanged

PROJECTION: ONE COEFFICIENT AT A TIME



different powers of 10

PROJECTION: ALL COEFFICIENTS SIMULTANEOUSLY



different powers of 10