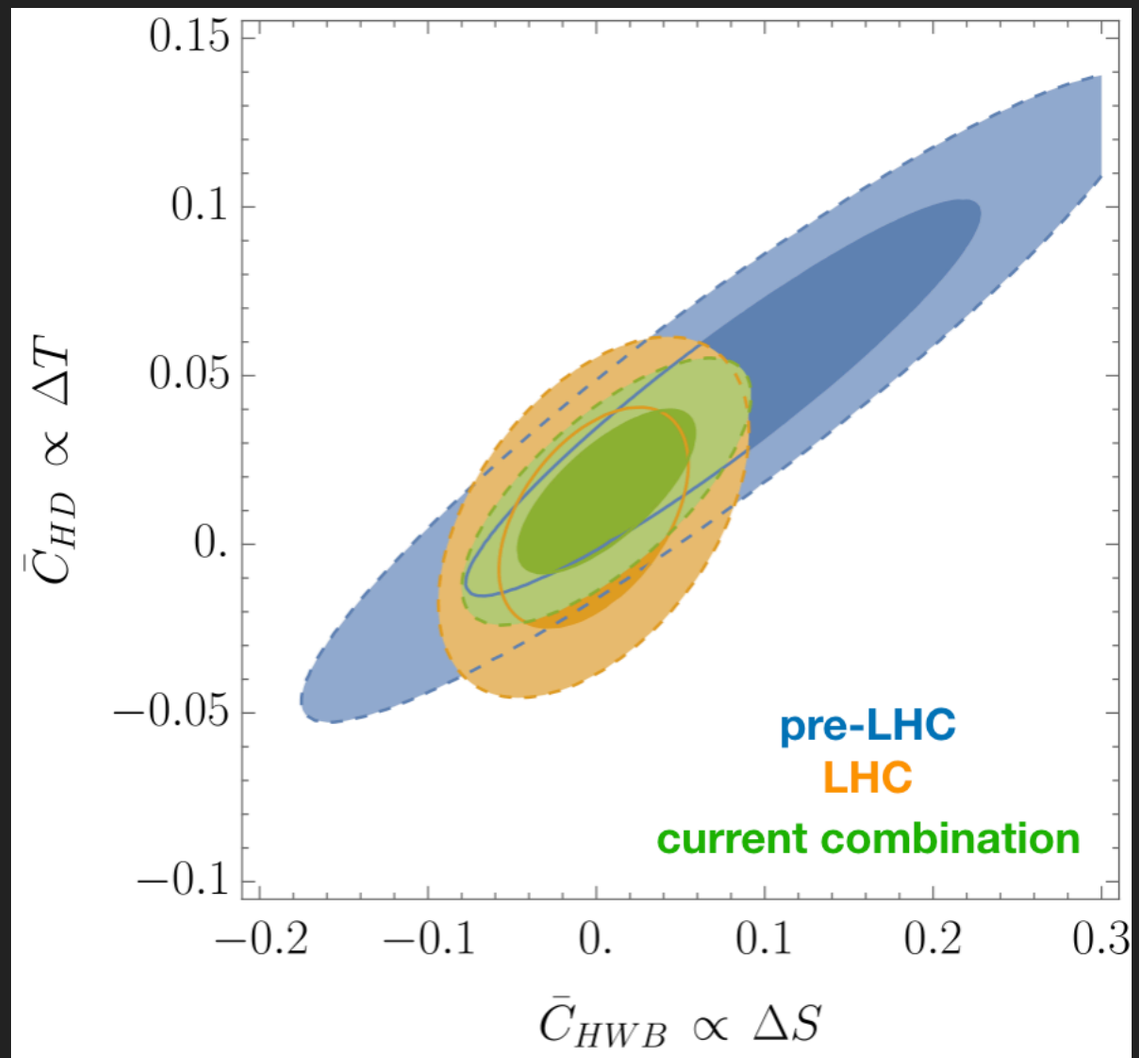
HL- / HE-LHC Study 18/06/18

CHRIS MURPHY

THEORY CHALLENGES FOR COUPLINGS

MOTIVATION

- Why do a SMEFT fit?
- Experimentally, the LHC results are very good now



based on Ellis, CM, Sanz, You: 1803.03252

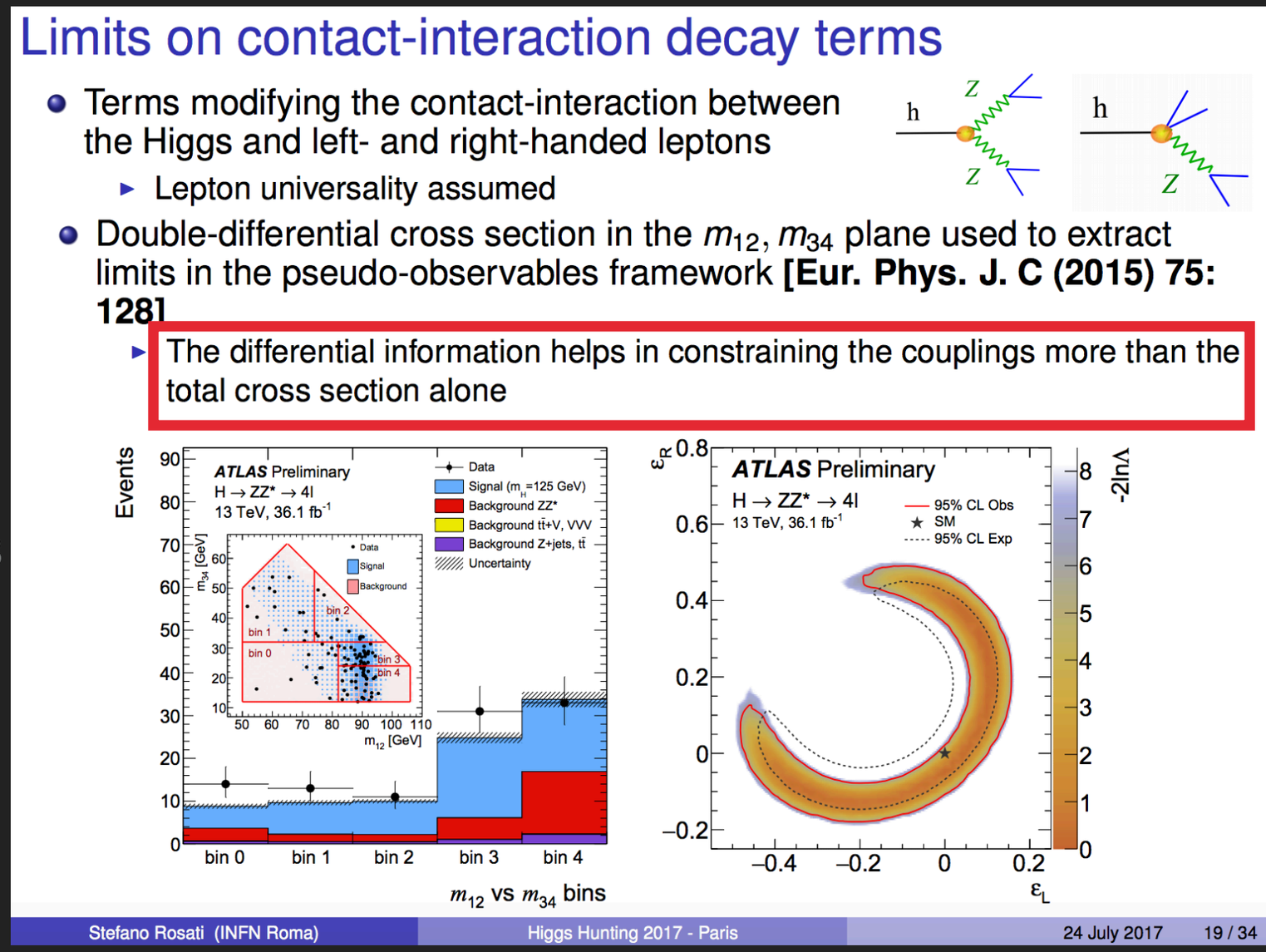
DIFFERENTIAL INFORMATION

- More constraining than total cross section alone
- This has been known for some time

  Isidori, Manohar, Trott: 1305.0663

  Grinstein, CM, Pirtskhalava: 1305.6938

  …



OUTLINE

- Standard Model Effective Field Theory
- Fit Setup and Results
- Future Projections

STANDARD MODEL EFFECTIVE FIELD THEORY

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 (non-redundant) higher-dimensional operators

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

MOTIVATION PART 2

- Fits previously assumed:
  - EWPD >> diboson >> Higgs
- Theoretically unsatisfactory, no longer justified

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
- Use α_{EM}, G_F, M_Z, as input parameters

ANALYSIS FRAMEWORK

- Assume $U(3)^5$ flavor symmetry in SMEFT, helps reduce parameters to a manageable number
- Yukawa matrices promoted to spurions, formally preserve symmetry

DIMENSION-6 OPERATORS IN WARSAW BASIS

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

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

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

results of EMSY 1803.03252 expressed in both SILH and Warsaw bases

FIT SETUP AND RESULTS

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]
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	[41]	41.488 ± 0.006	[40]
R^0_ℓ	20.767 ± 0.025	[41]	20.752 ± 0.005	[40]
$A^{0,\ell}_{\rm FB}$	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]
$\mathcal{A}_\ell$ (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]
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	[41]	0.1031 ± 0.0003	[118]
$A^{0,c}_{\rm FB}$	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]

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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

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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]	$B(h \to \gamma\gamma)/\ B(h \to 4\ell)$		$0.69^{+0.13}_{-0.13}$
[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	$3.2^{+4.4}_{-4.2}$

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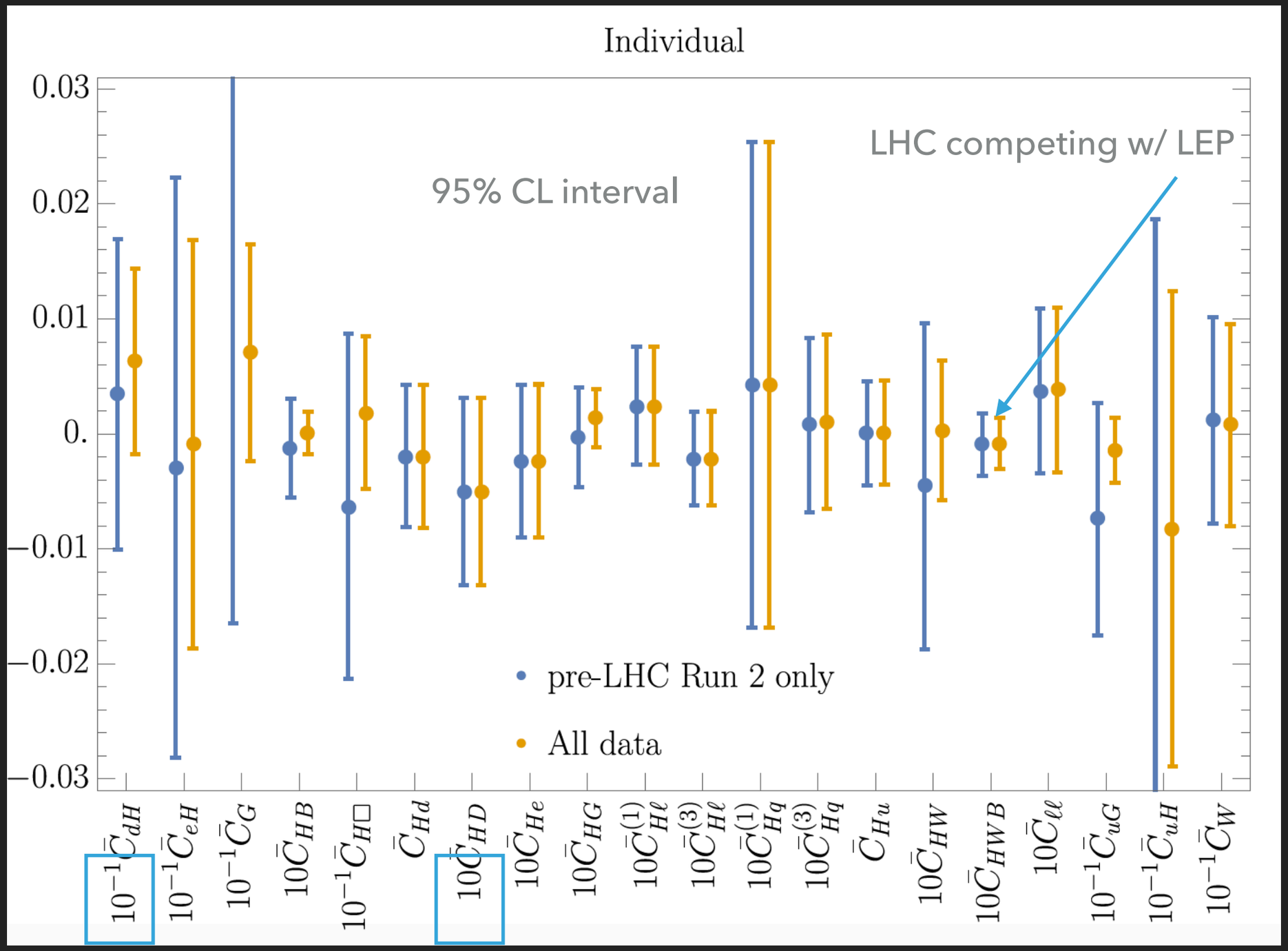
SMEFT PREDICTIONS

- pre-LHC: Berthier, Bjorn, Trott 1606.06693; Brivio, Trott 1706.08945
- LHC: Brivio, Jiang, Trott SMEFTsim 1709.06492
- Our SMEFT predictions and χ^2 are available online:
  - https://quark.phy.bnl.gov/Digital_Data_Archive/SMEFT_GlobalFit/

FIT TO EACH OPERATOR INDIVIDUALLY



Note: different scaling factors

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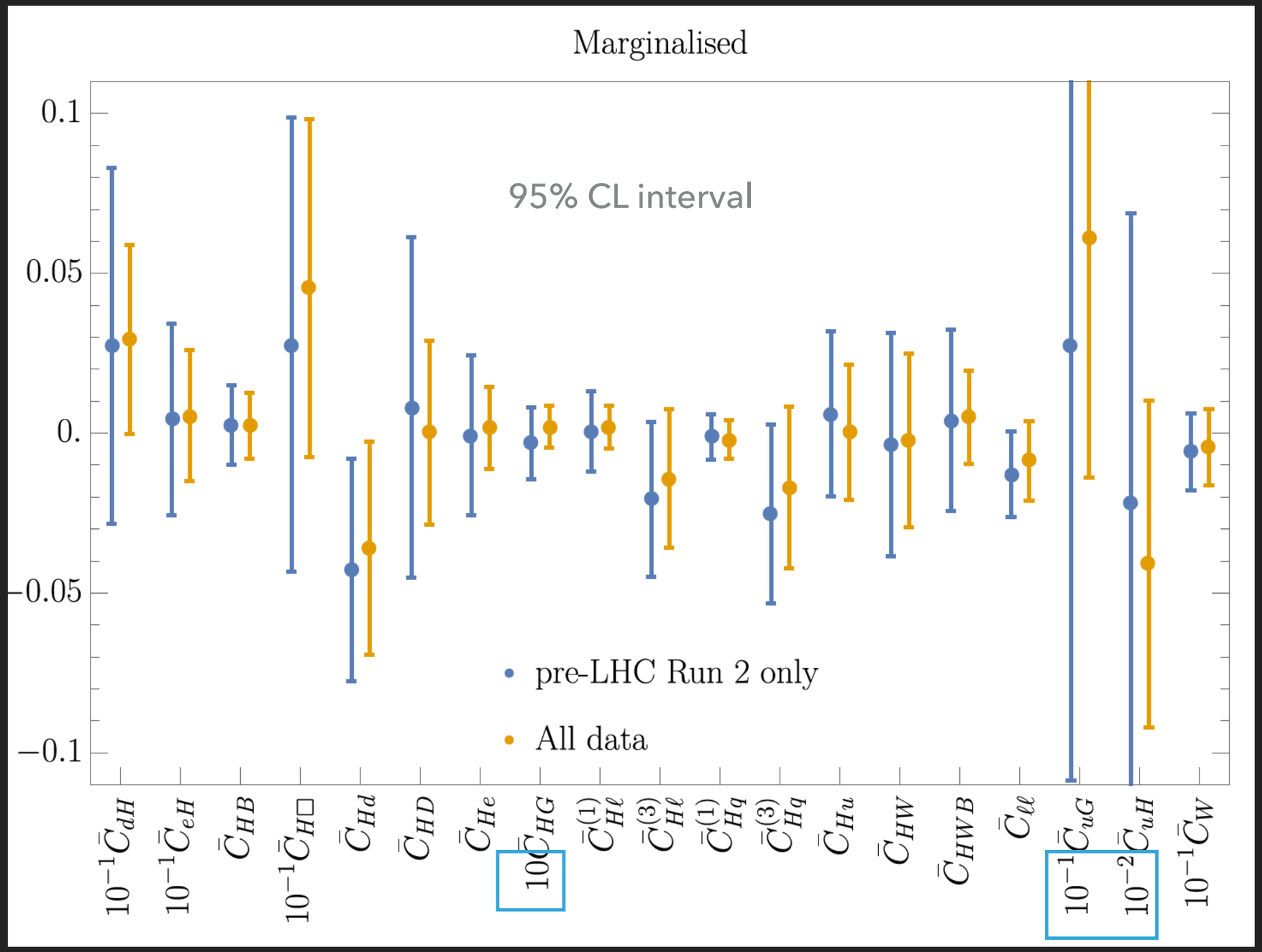
FIT TO ALL OPERATORS SIMULTANEOUSLY



Note: different scaling factors

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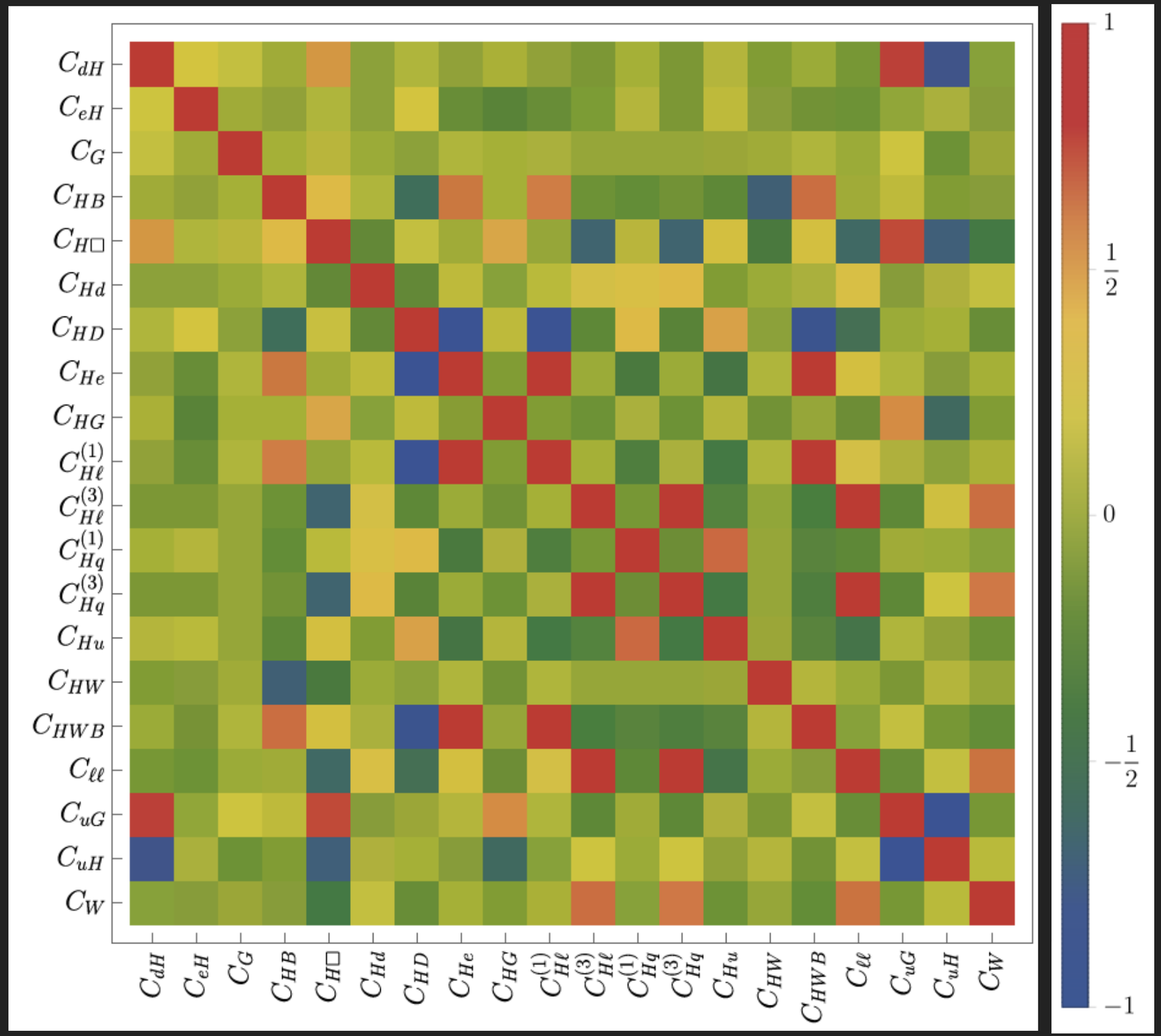
CORRELATION MATRIX



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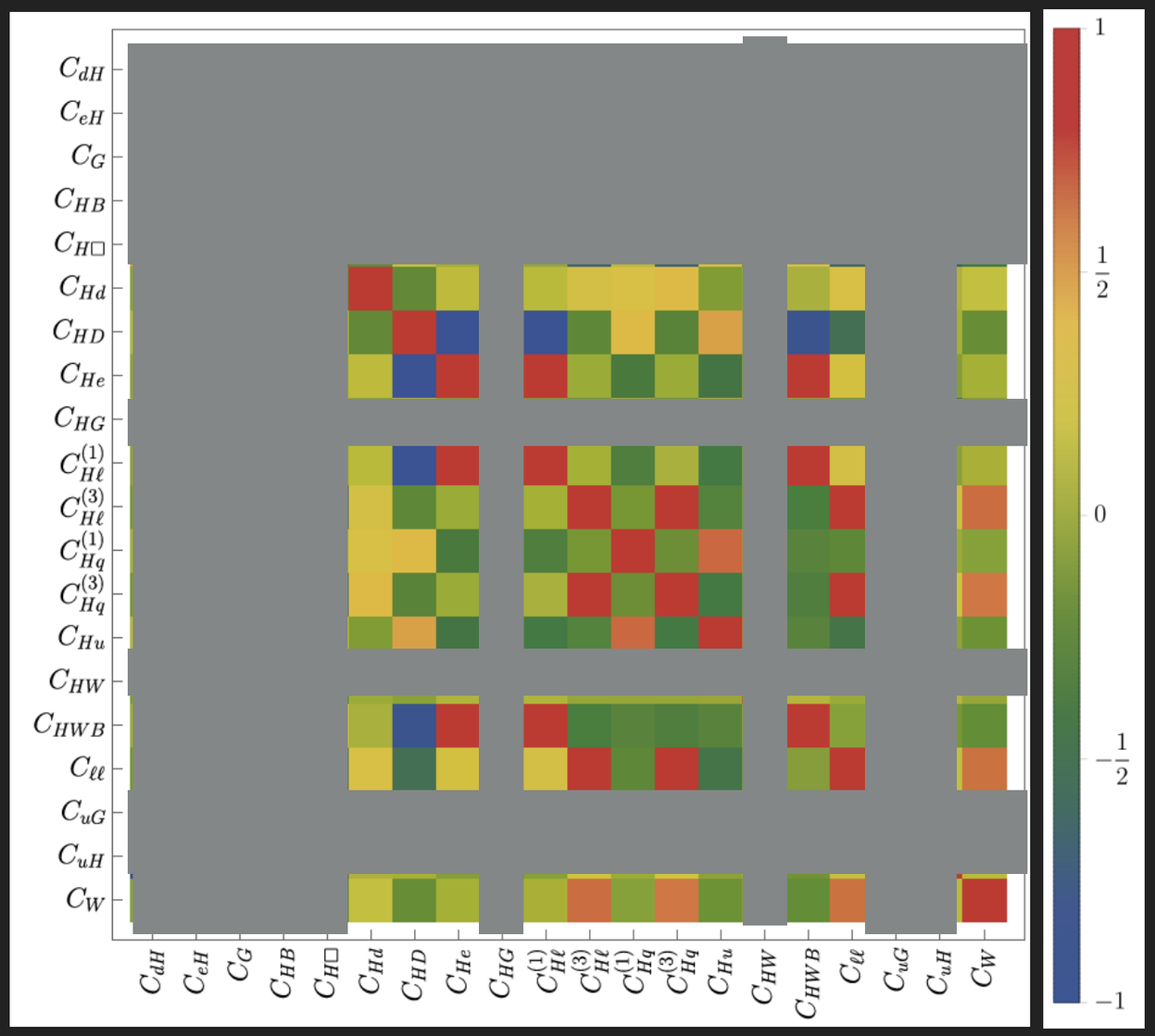
CORRELATION MATRIX

Fit to all measurements



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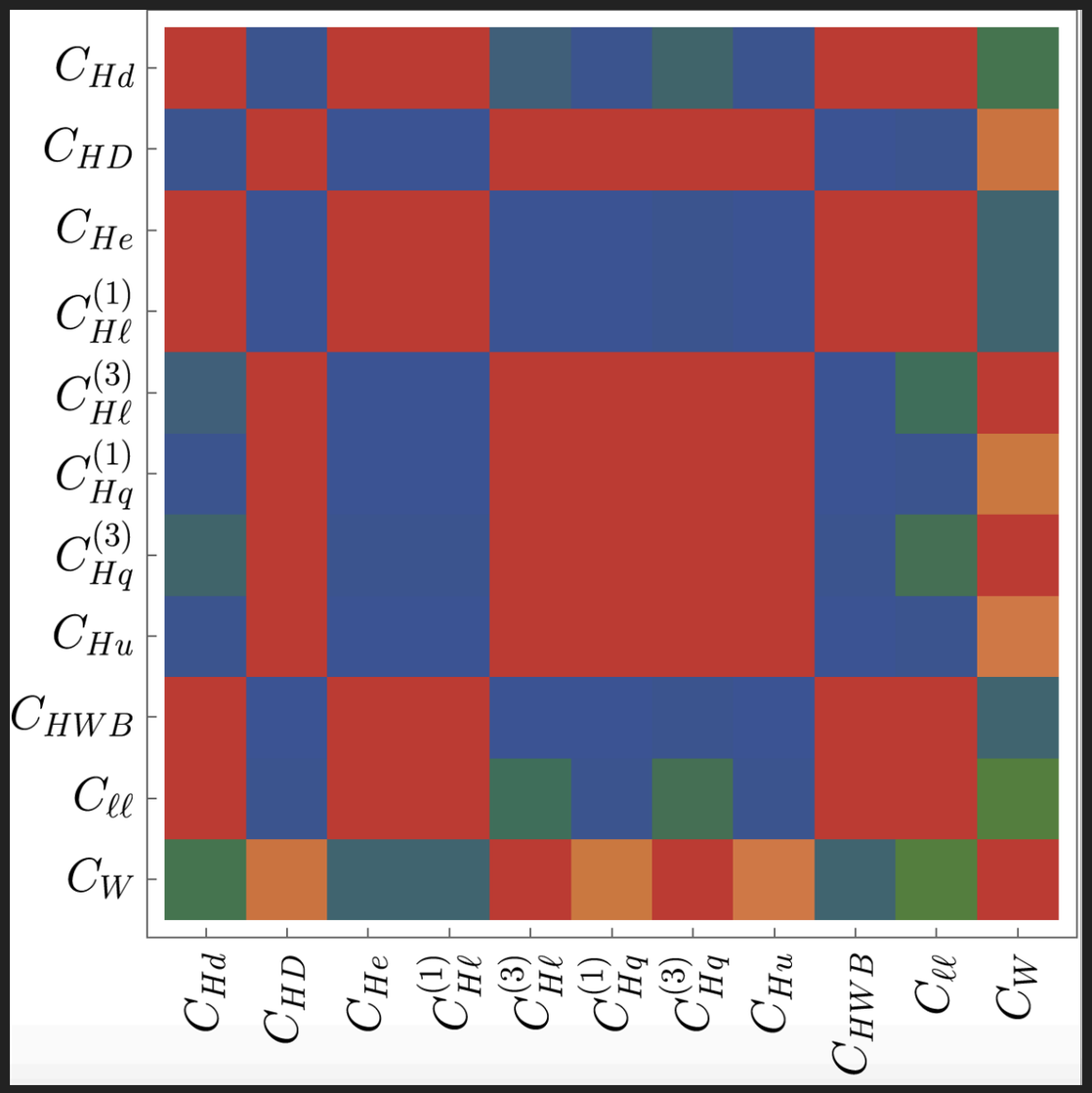
Fit to *Z*-pole, *W*-mass, & LEP2 *WW* measurements



EMSY unpublished

FUTURE PROJECTIONS

PROJECTION STRATEGY

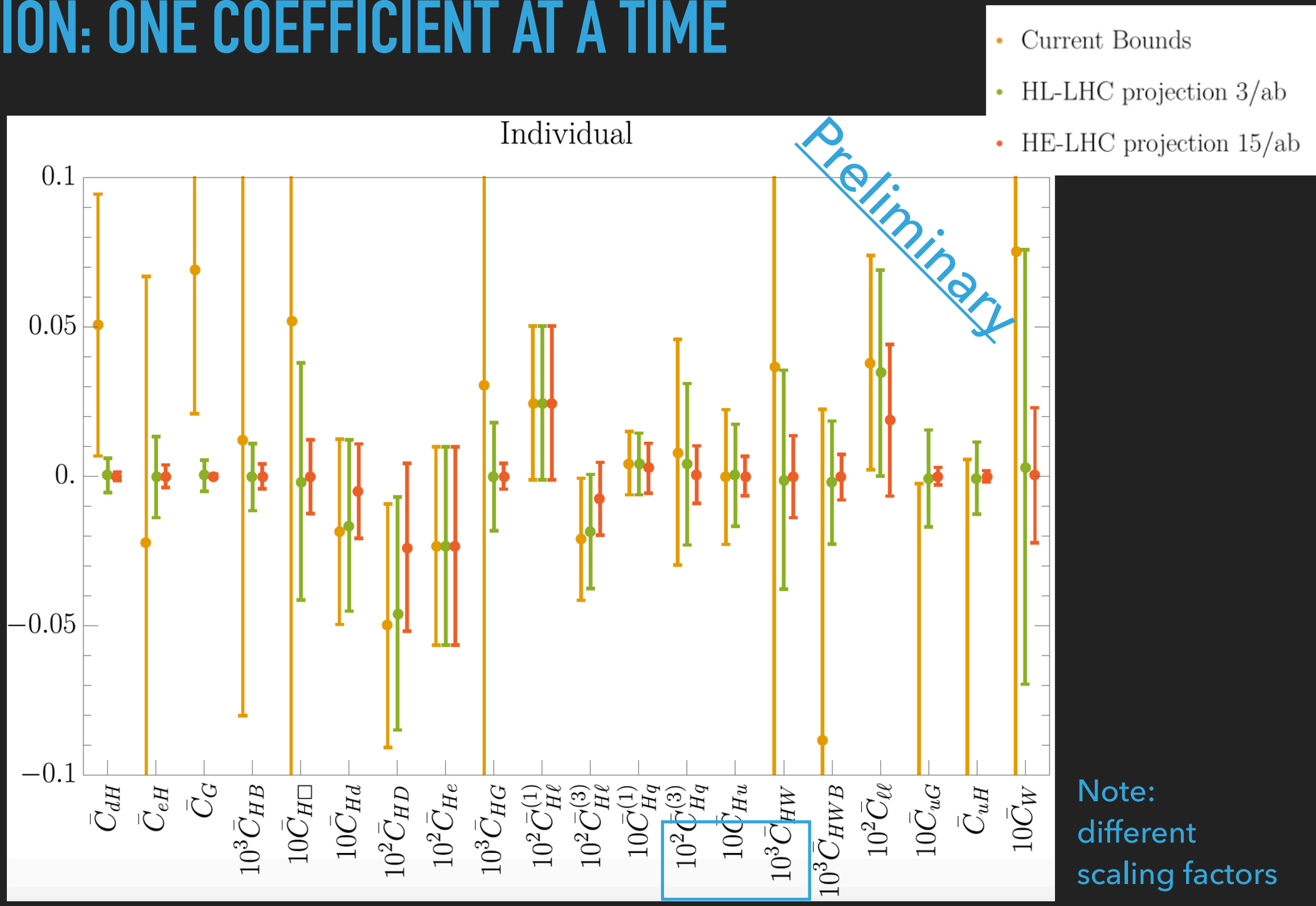
- Leave all pre-LHC, and LHC Run-1 measurements unchanged
- For each LHC Run-2 measurement used in the fit of 1803.03252...

"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 ith measurement by:
    - HL-LHC: $\sqrt{\frac{36/\text{fb}}{3/\text{ab}}}$
    - HE-LHC: $\sqrt{\frac{\sigma_{13,i}}{\sigma_{27,i}}\frac{36/\text{fb}}{15/\text{ab}}}$
  - Leave experimental correlations unchanged

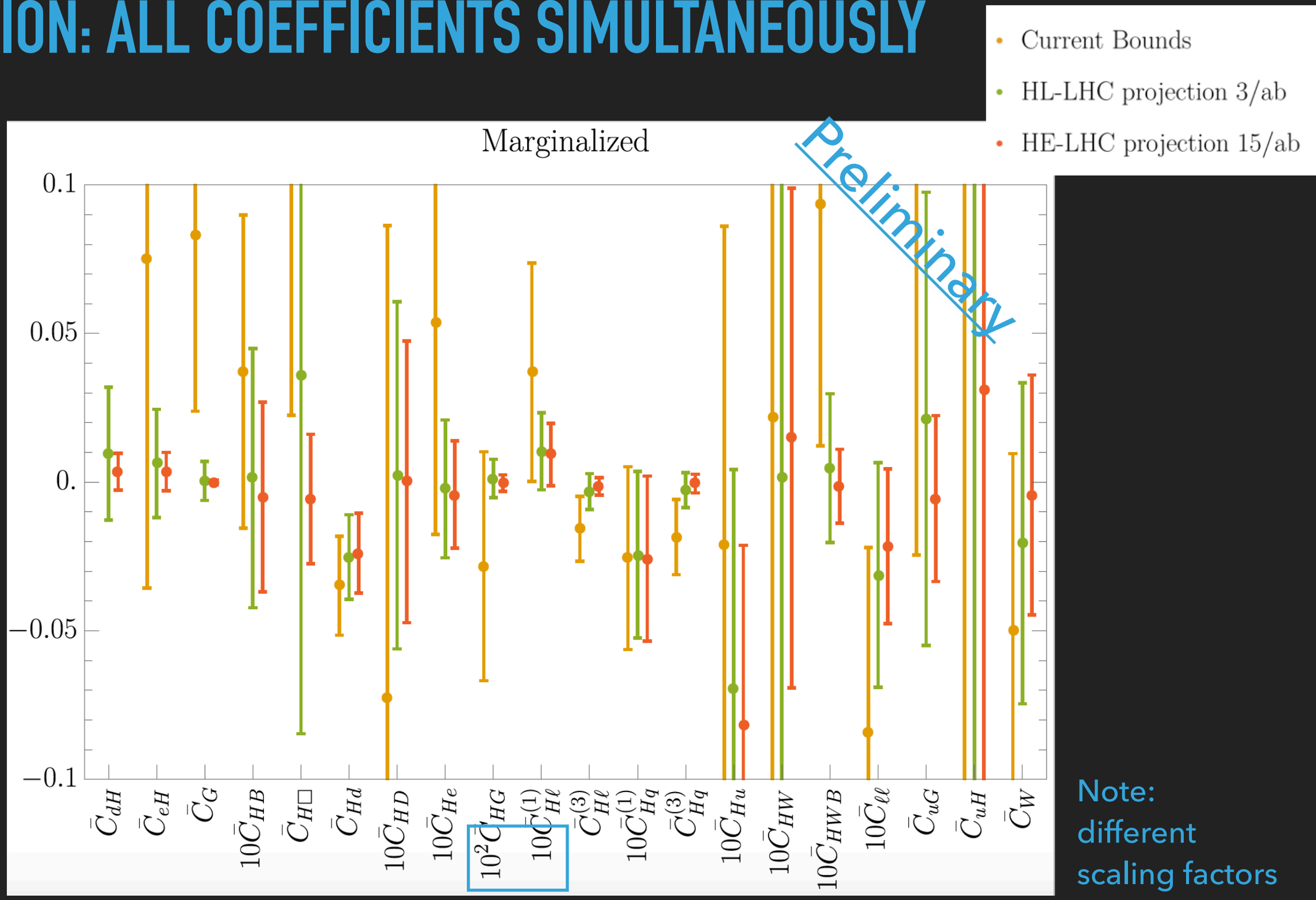
PROJECTION: ONE COEFFICIENT AT A TIME



Note: different scaling factors

CM: in progress, this plot supersedes the one presented at Fermilab on 05/04/18

PROJECTION: ALL COEFFICIENTS SIMULTANEOUSLY

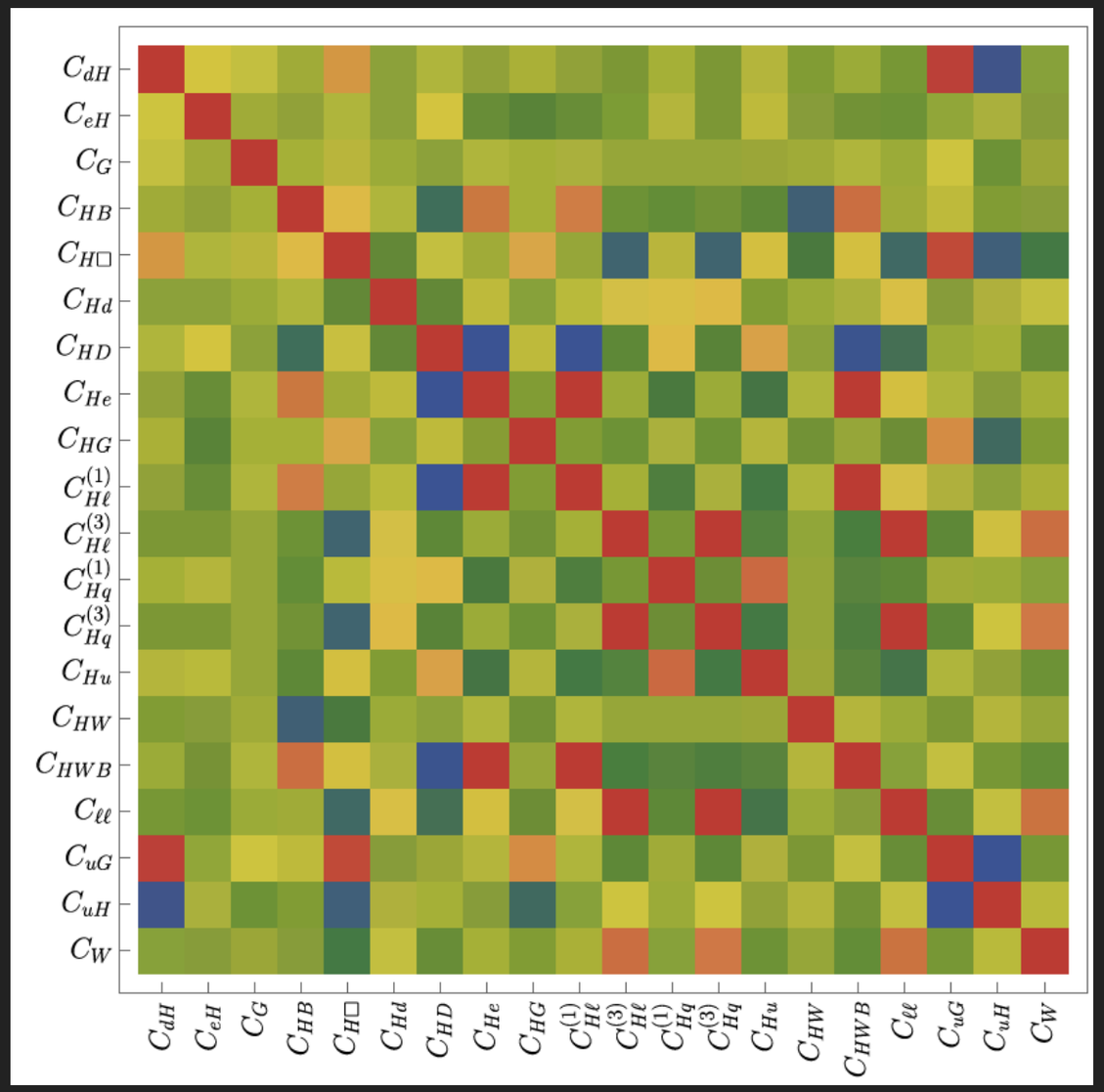


Note: different scaling factors

CM: in progress, this plot supersedes the one presented at Fermilab on 05/04/18

NEW CORRELATIONS APPEAR IN PROJECTION

Current correlations



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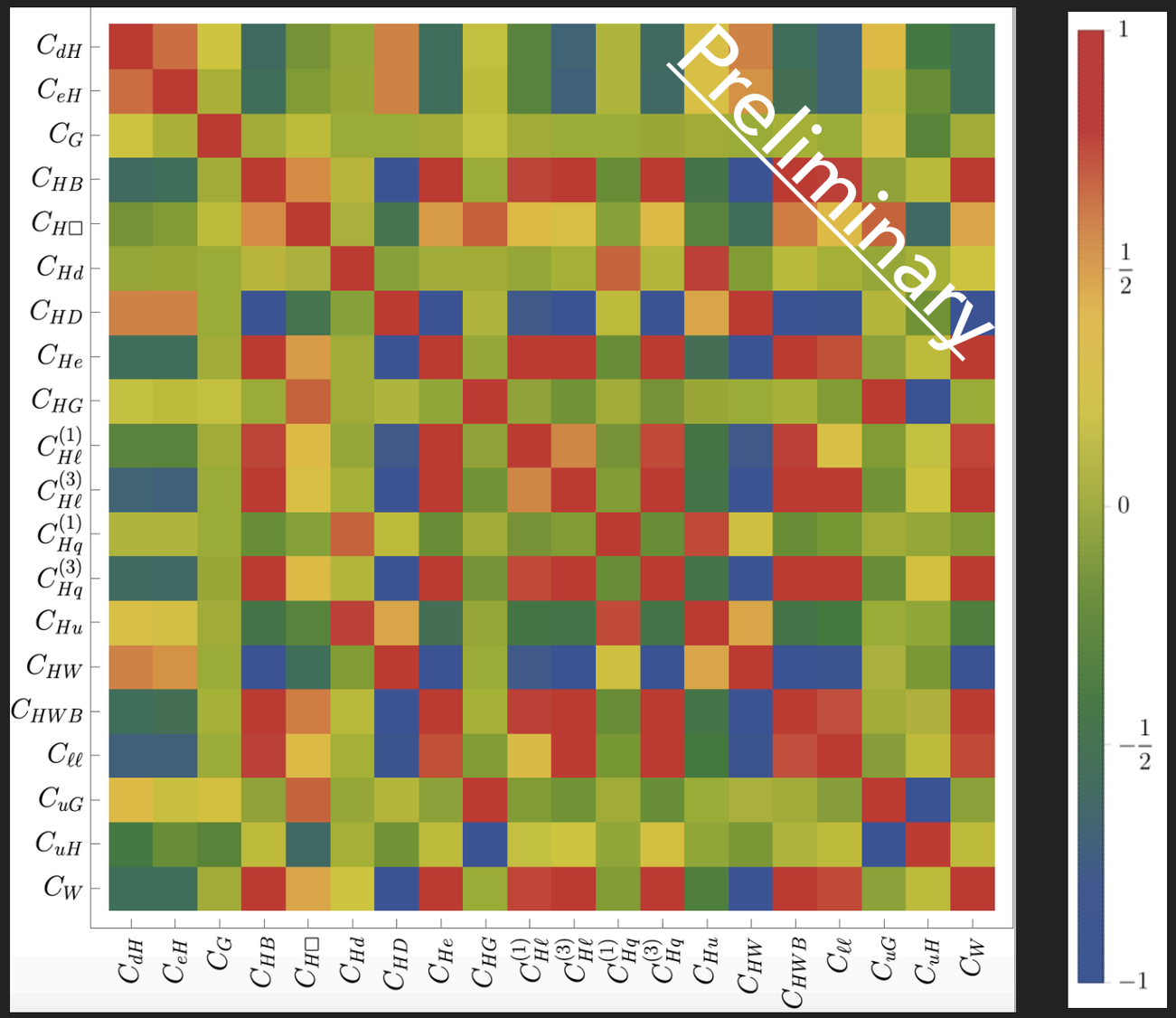
HE-LHC



CM: in progress

CORRELATIONS APPEAR IN PROJECTION

- A challenge (re)appears for theorists doing SMEFT fits
- Correlations tamed by:
  - using a finer binning for Higgs measurements (via STXS)
  - including more info for LHC diboson measurements
  - (a future linear collider would also help)

SUMMARY

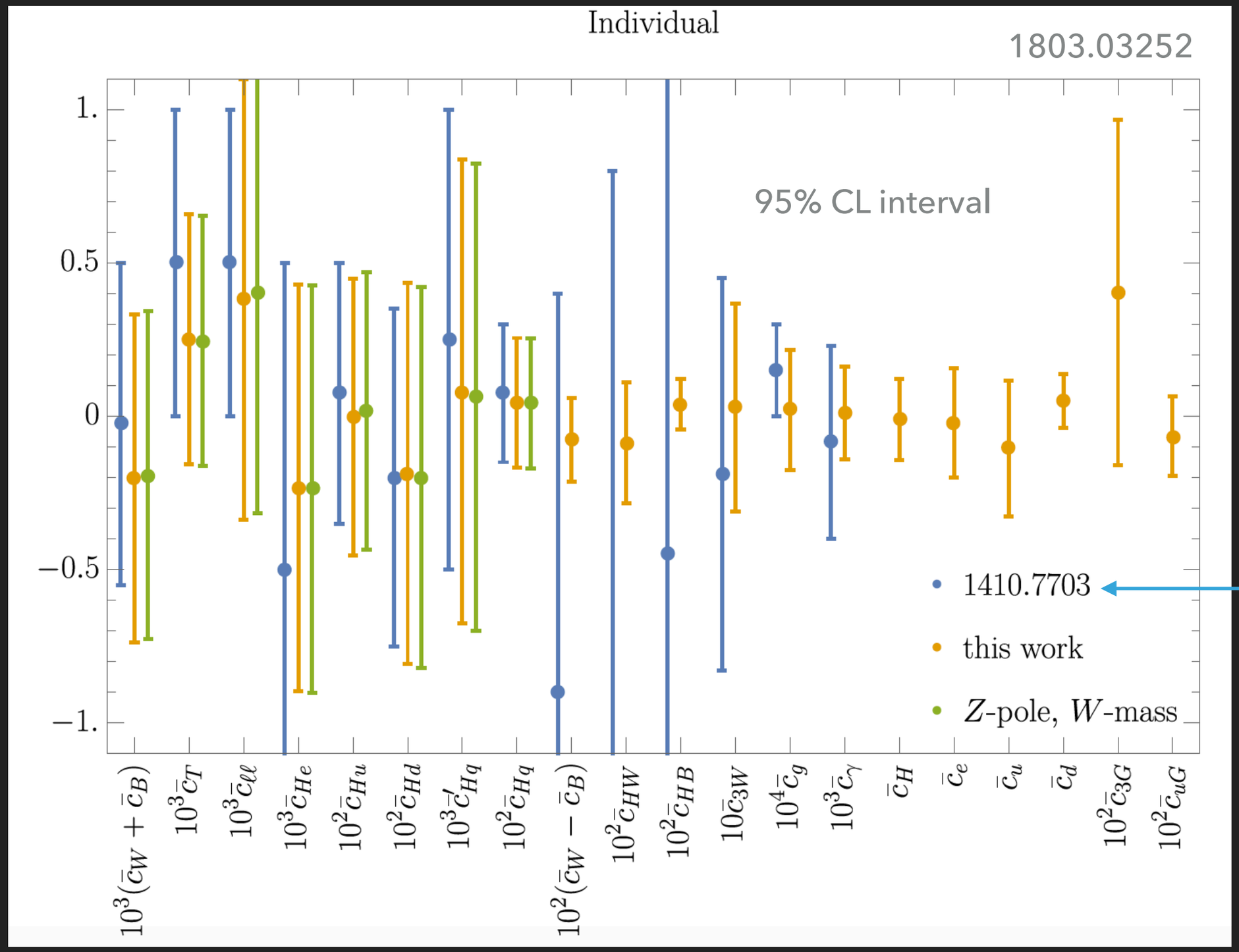
- EMSY 1803.03252 was the first combined global analysis within the SMEFT of electroweak, diboson, and Higgs data
  - Higgs/LHC measurements currently compete w/ EWPD
- HE-LHC better option for constraining SMEFT Wilson coefficients
  - but this is a win-win situation, either HL- or HE-LHC will improve existing bounds

"When you come to the fork in the road, take it" - Yogi Berra

SILH BASIS

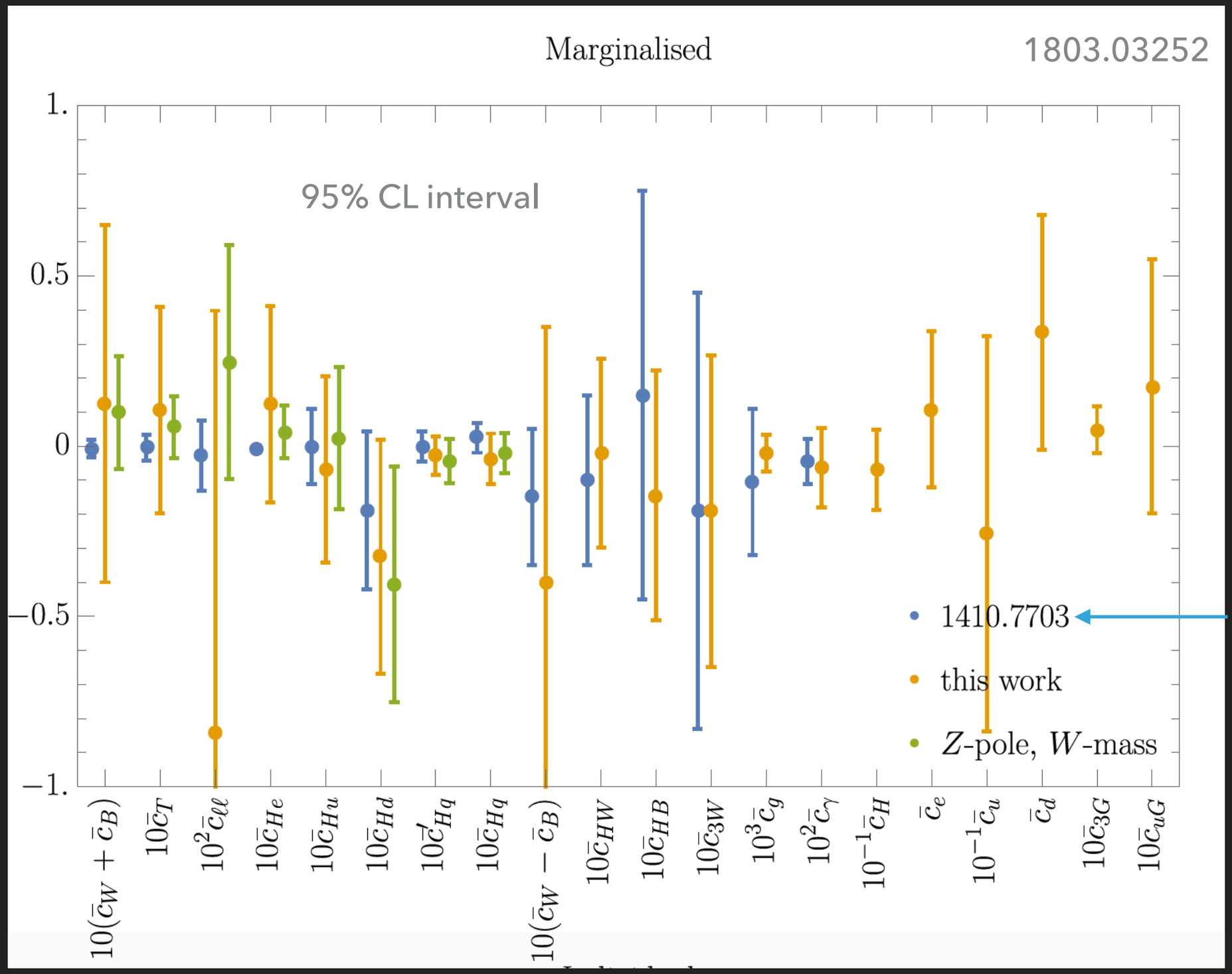
$$
\begin{aligned}
\mathcal{L}_{\rm SMEFT}^{\rm SILH} \supset\ & \frac{\bar c_W}{m_W^2}\frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu} + \frac{\bar c_B}{m_W^2}\frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu} + \frac{\bar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

GLOBAL FITS IN THE SILH BASIS



previous work by JE, VS, TY

GLOBAL FITS IN THE SILH BASIS



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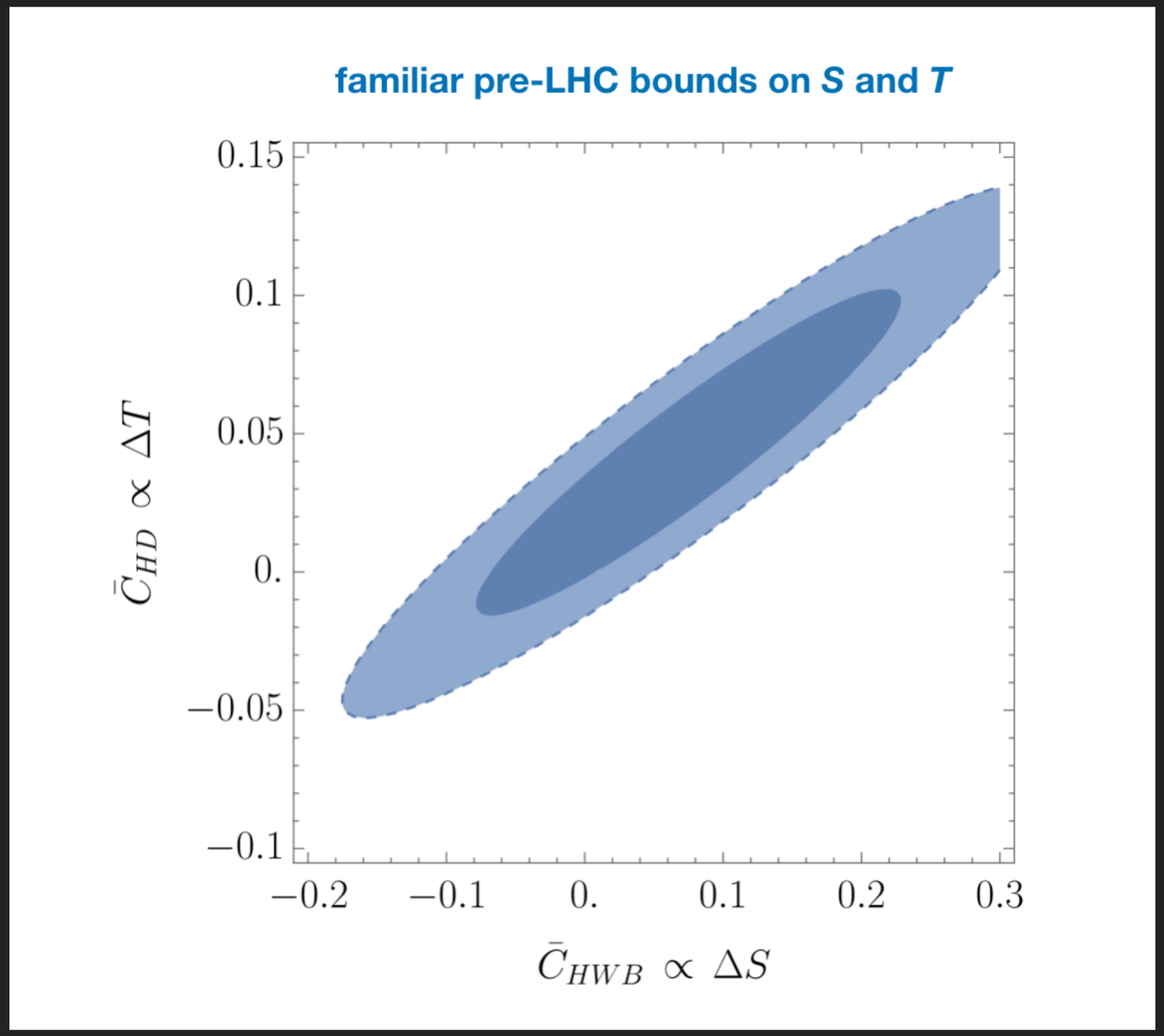
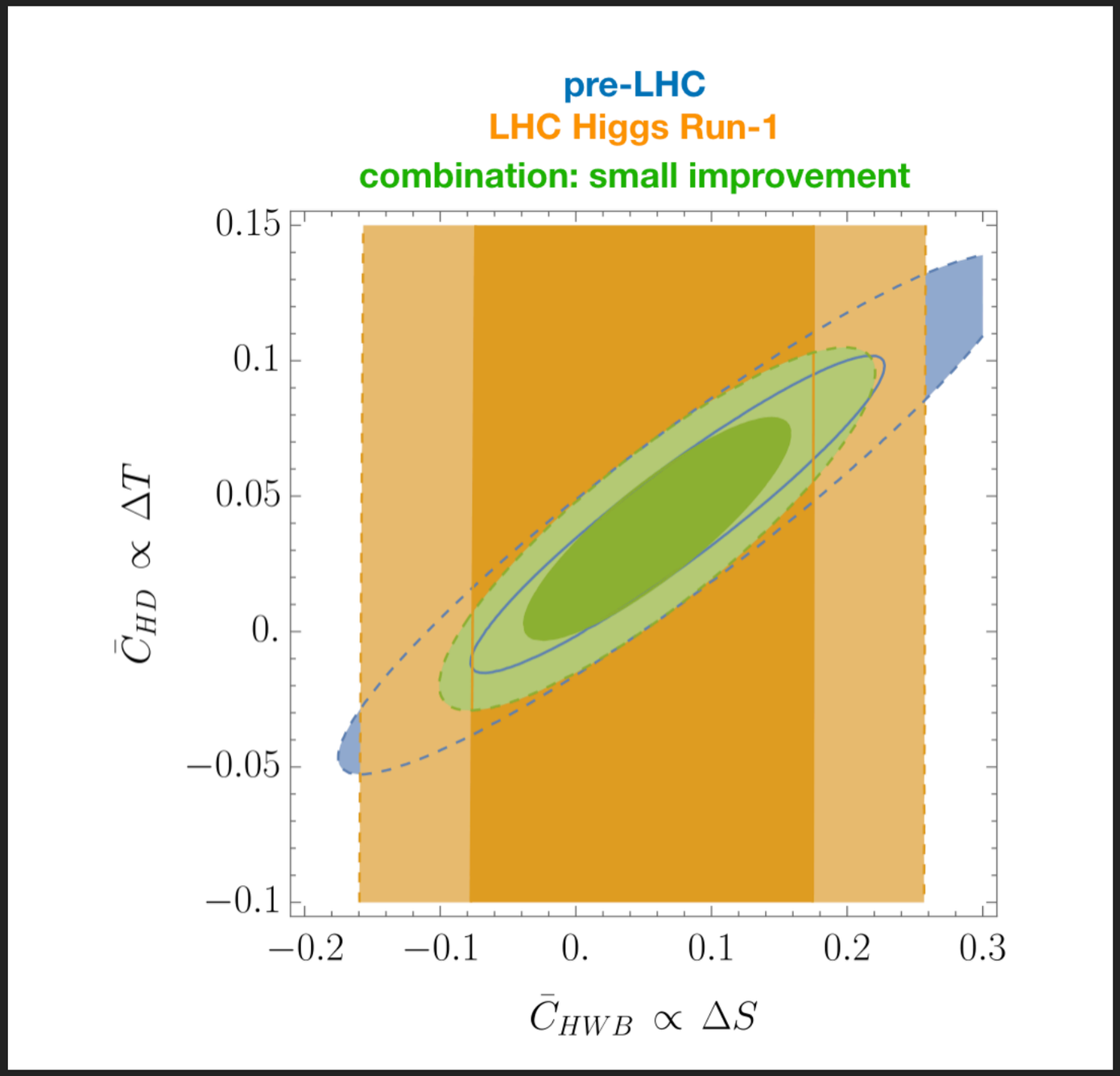
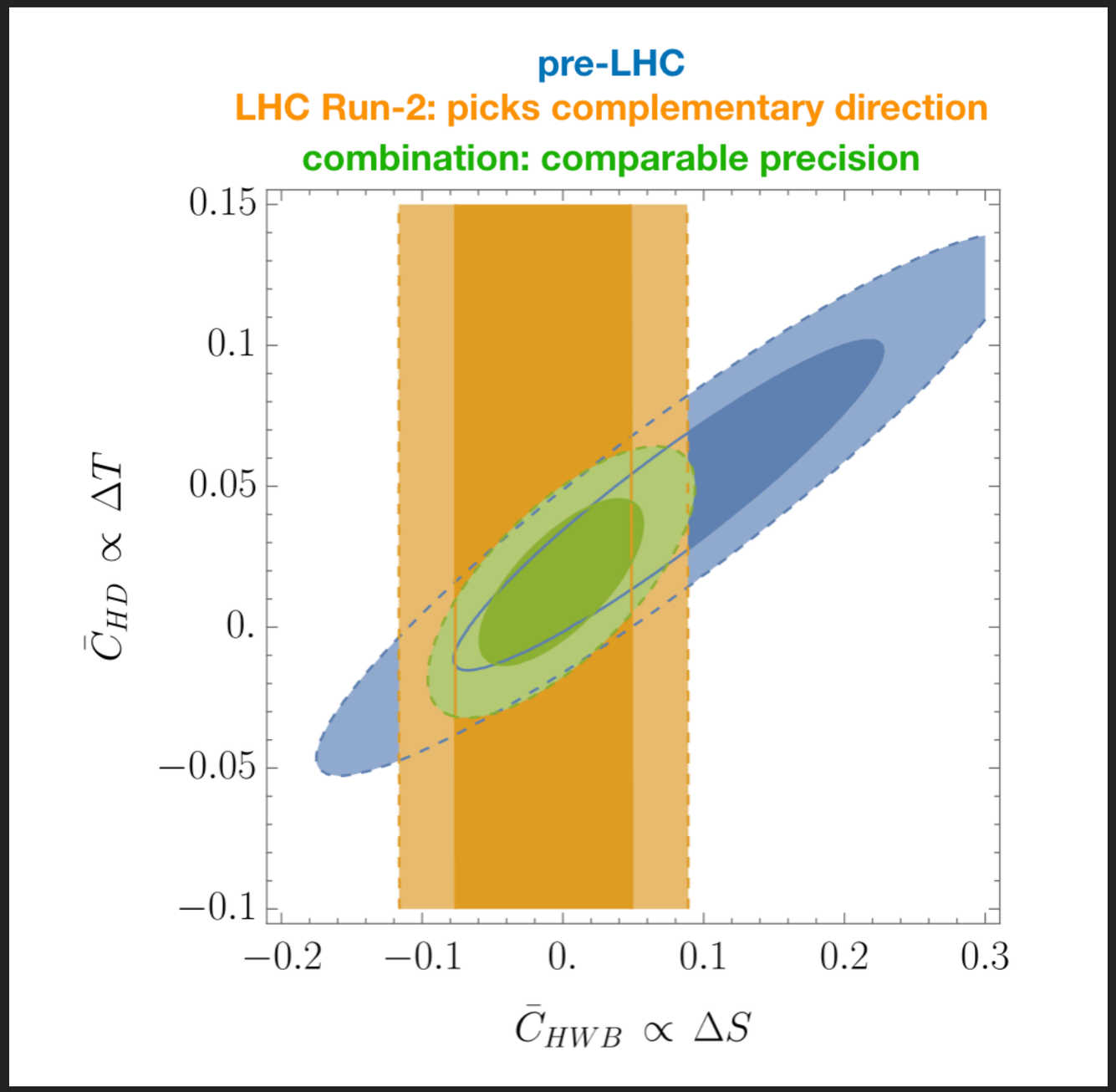


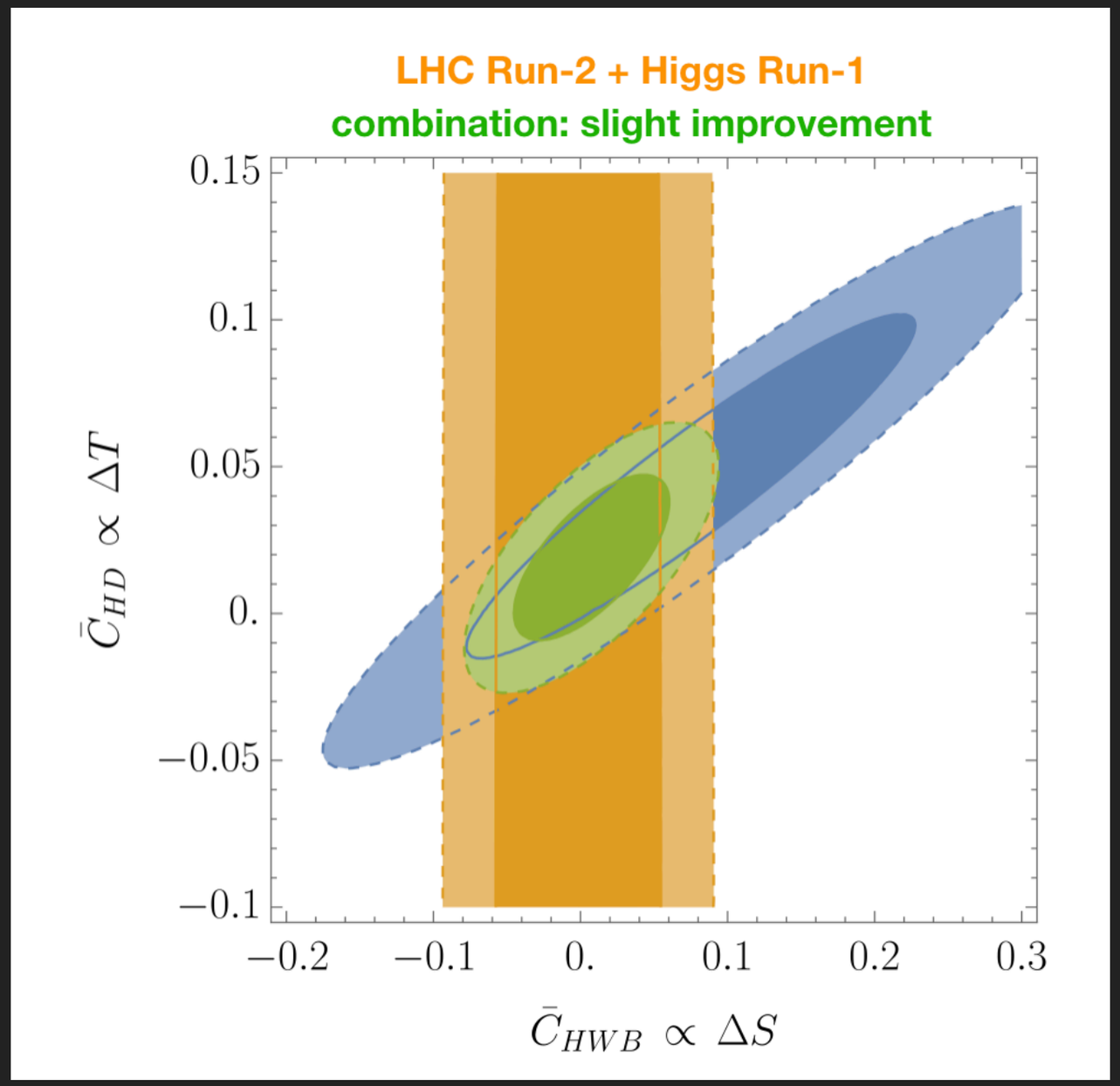
based on Ellis, CM, Sanz, You: 1803.03252



based on Ellis, CM, Sanz, You: 1803.03252

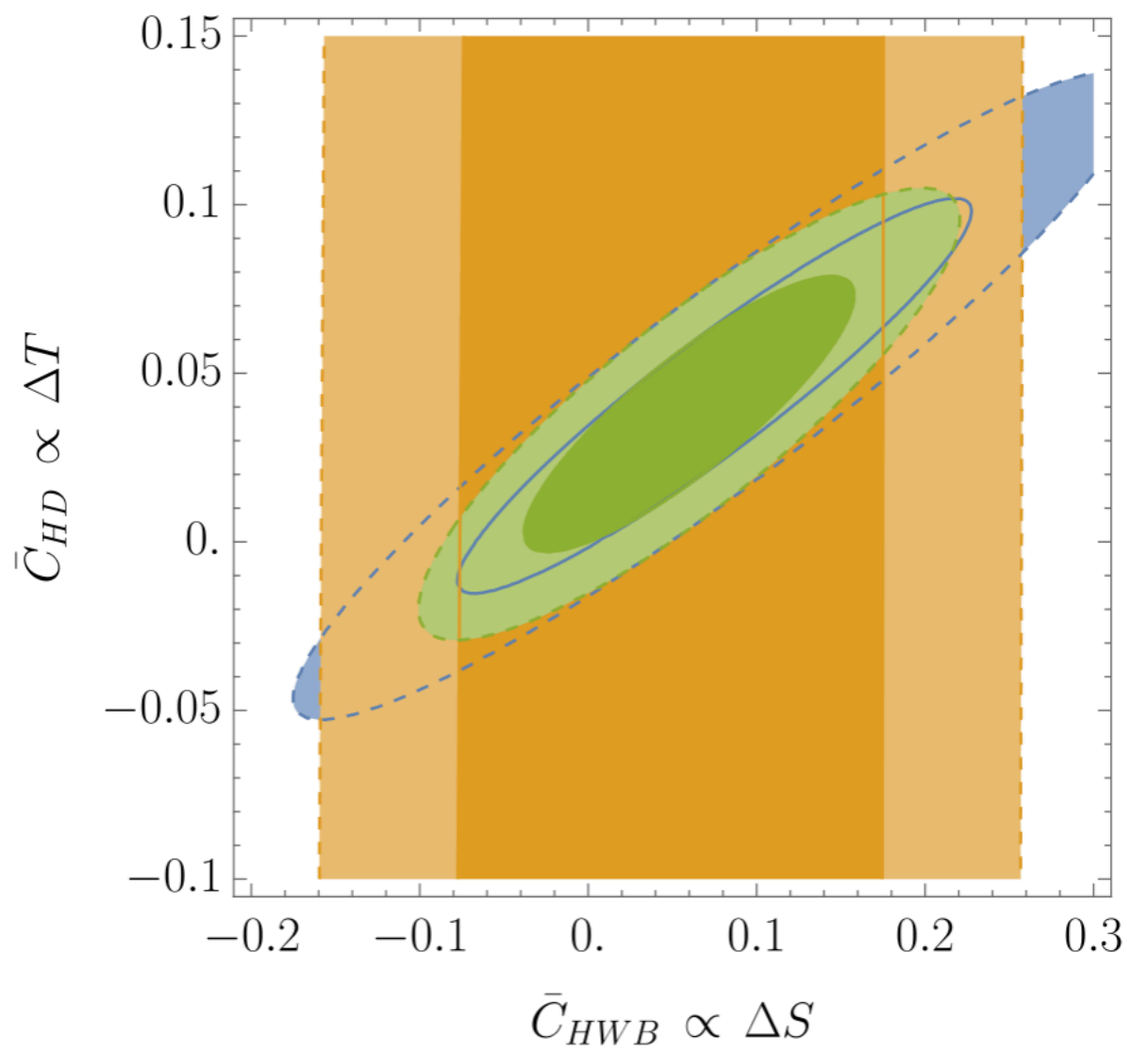


based on Ellis, CM, Sanz, You: 1803.03252

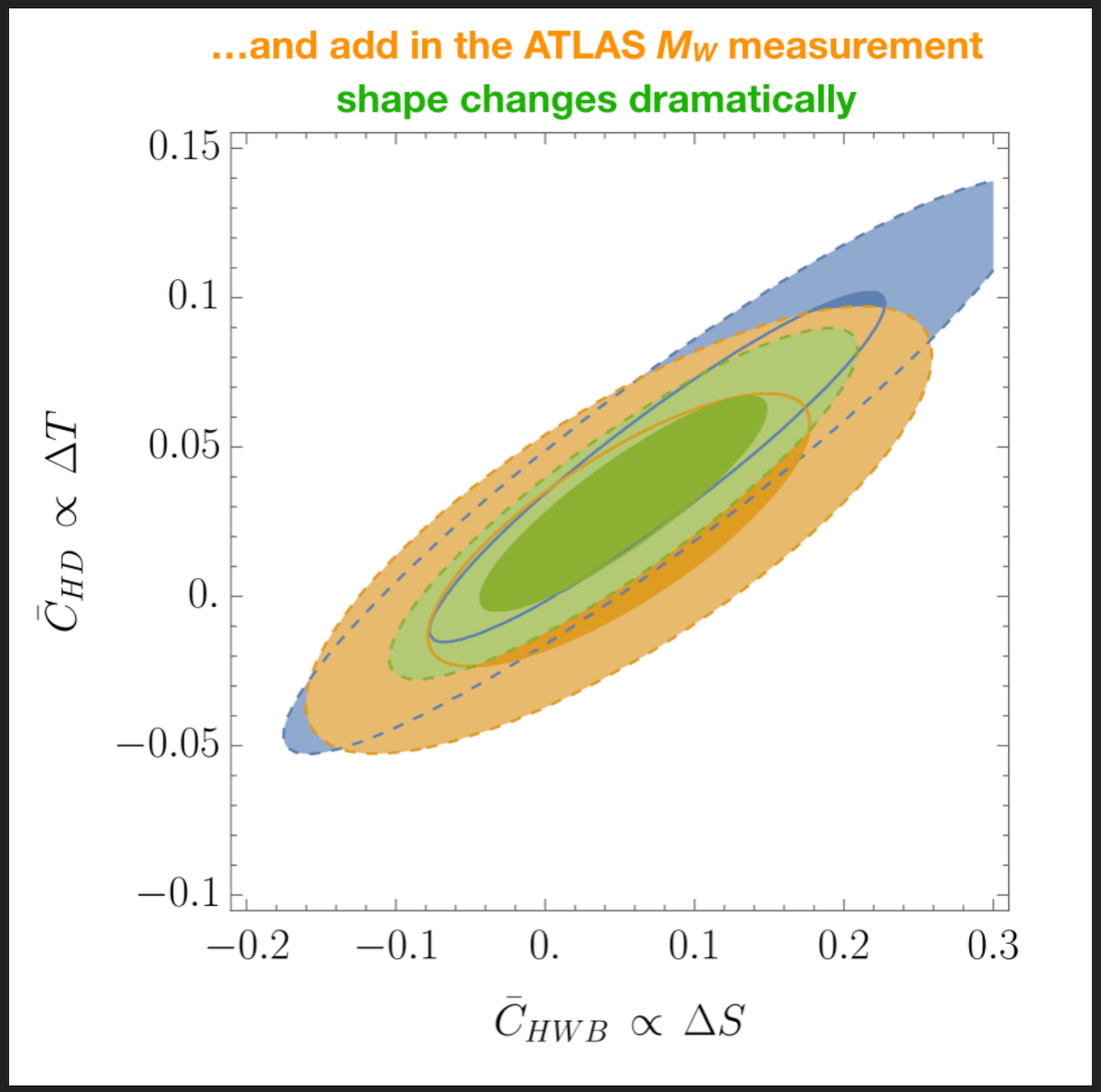


based on Ellis, CM, Sanz, You: 1803.03252

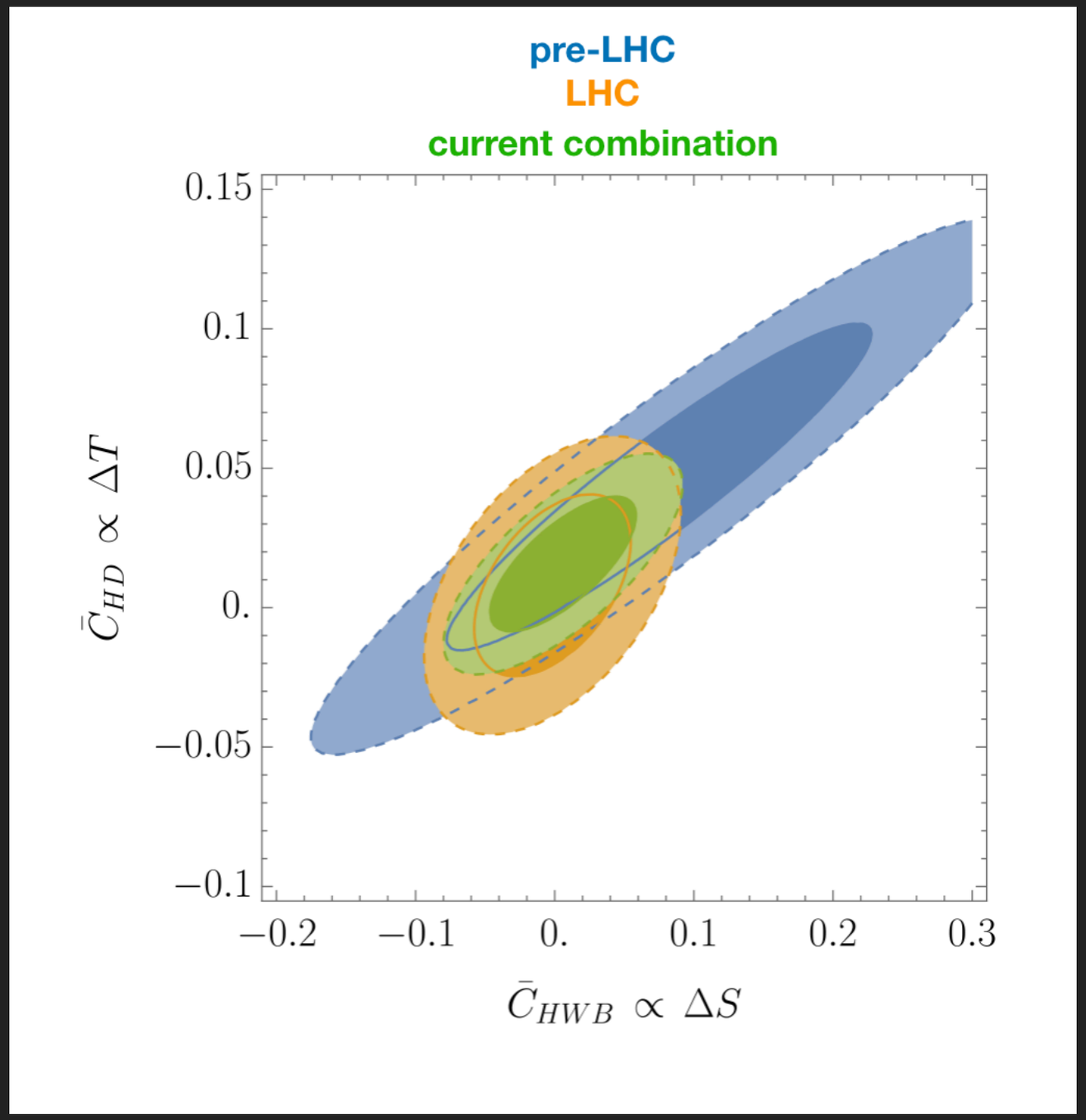
let's go back to just Higgs Run-1…



based on Ellis, CM, Sanz, You: 1803.03252

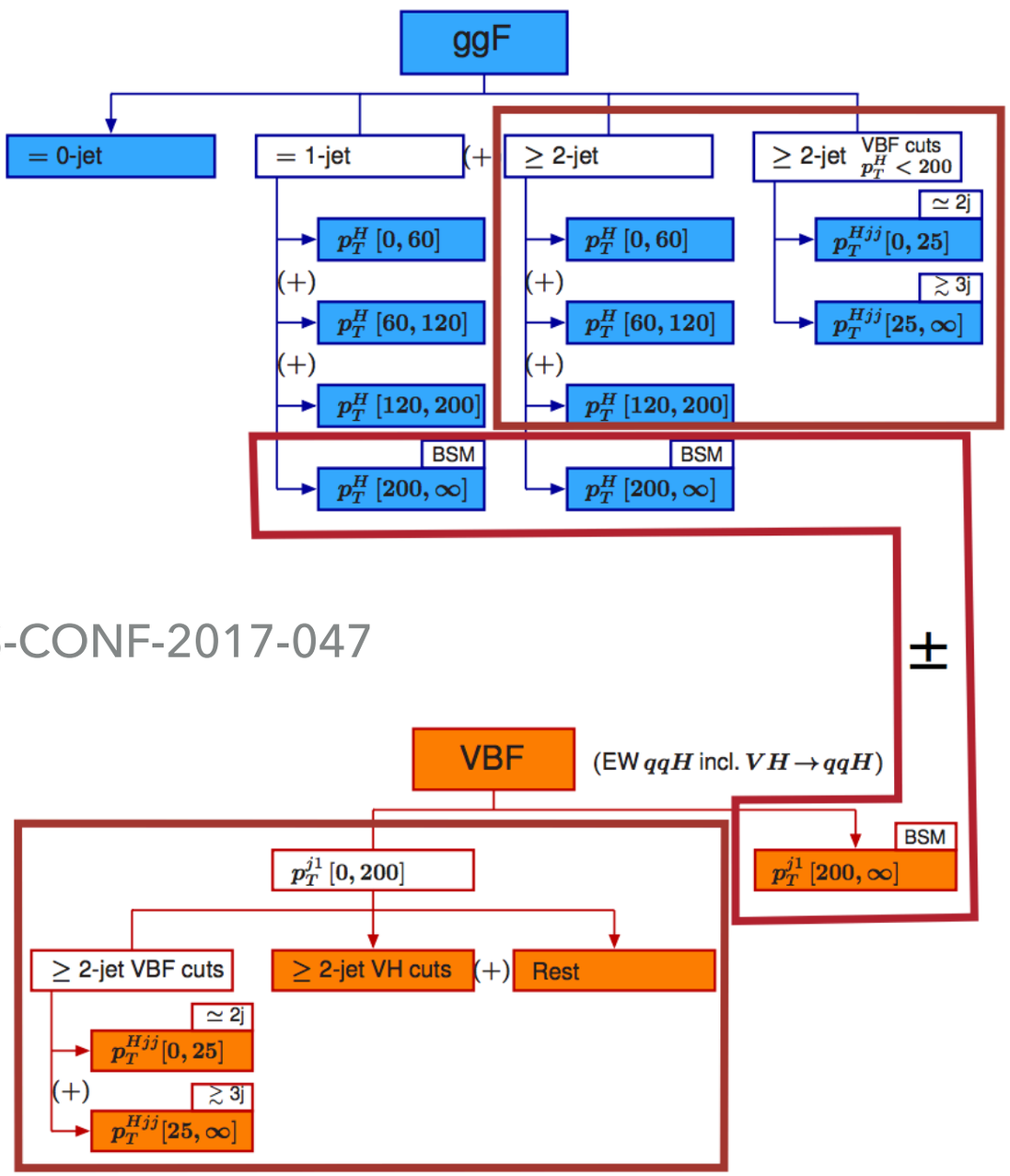


based on Ellis, CM, Sanz, You: 1803.03252

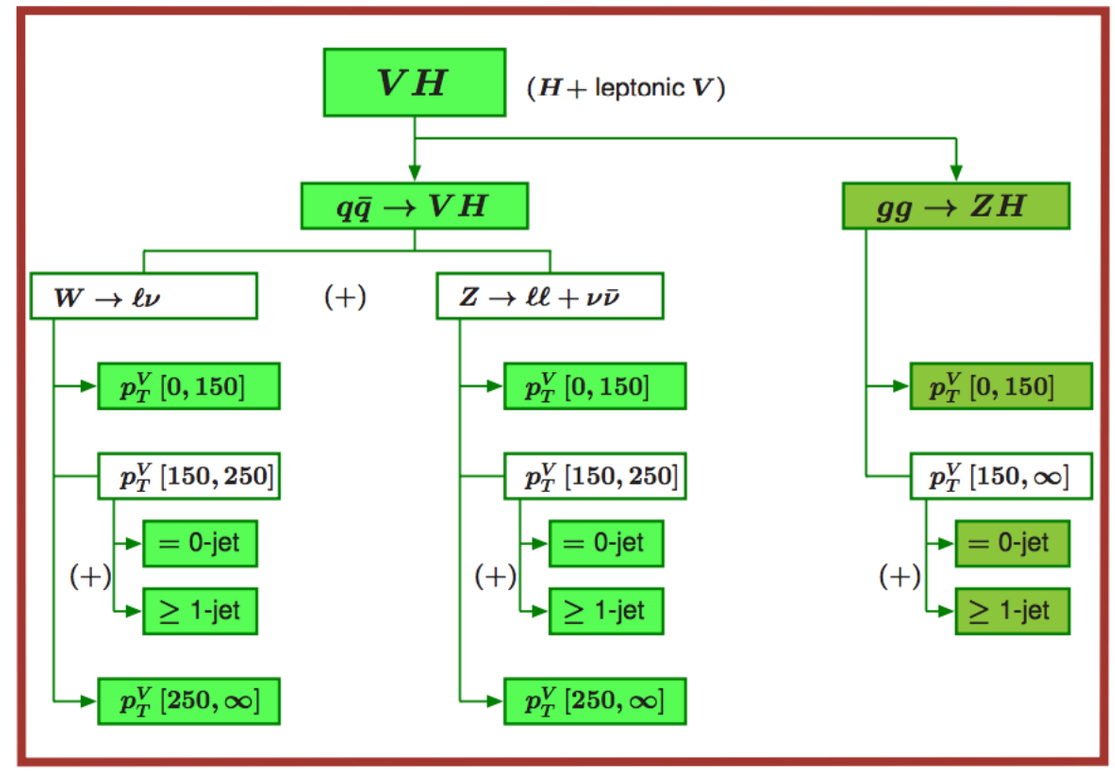


based on Ellis, CM, Sanz, You: 1803.03252

SIMPLIFIED TEMPLATE CROSS SECTIONS



ATLAS-CONF-2017-047



Merged STXS Stage-1 regions enclosed by red boxes

FIT METHODOLOGY

- Method of least squares

$$\chi^2(\mathbf{c}) = (\mathbf{y} - \boldsymbol{\mu}(\mathbf{c}))^\top \mathbf{V}^{-1} (\mathbf{y} - \boldsymbol{\mu}(\mathbf{c}))$$

- Working to linear order in Wilson coefficients

$$\boldsymbol{\mu} = \boldsymbol{\mu}_{SM} + \mathbf{H} \cdot \mathbf{c}$$

- Analytic solution

$$\hat{\mathbf{c}} = \left(\mathbf{H}^\top \mathbf{V}^{-1} \mathbf{H}\right)^{-1} \mathbf{H}^\top \mathbf{V}^{-1} (\mathbf{y} - \boldsymbol{\mu}_{SM})$$

$$\mathbf{U} = \left(\mathbf{H}^\top \mathbf{V}^{-1} \mathbf{H}\right)^{-1}$$

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…
  - add in top-quark measurements

REGULARIZED LEAST SQUARES

- Augment standard chi-squared function w/ positive definite regulation term

$$\chi^2(\mathbf{c}) = (\mathbf{y} - \boldsymbol{\mu}(\mathbf{c}))^\top V^{-1} (\mathbf{y} - \boldsymbol{\mu}(\mathbf{c})) + \mathbf{c}^\top \kappa \, \mathbf{c}$$

take $\kappa_{ij} = \kappa \delta_{ij}$

$$\hat{\mathbf{c}} = \left(H^\top V^{-1} H + \kappa \mathbb{1}\right)^{-1} H^\top V^{-1} \mathbf{y}$$

$$U = \left(H^\top V^{-1} H + \kappa \mathbb{1}\right)^{-1}$$

CM: 1710.02008

REGULARIZED LEAST SQUARES

- Fit an arbitrary number of coefficients

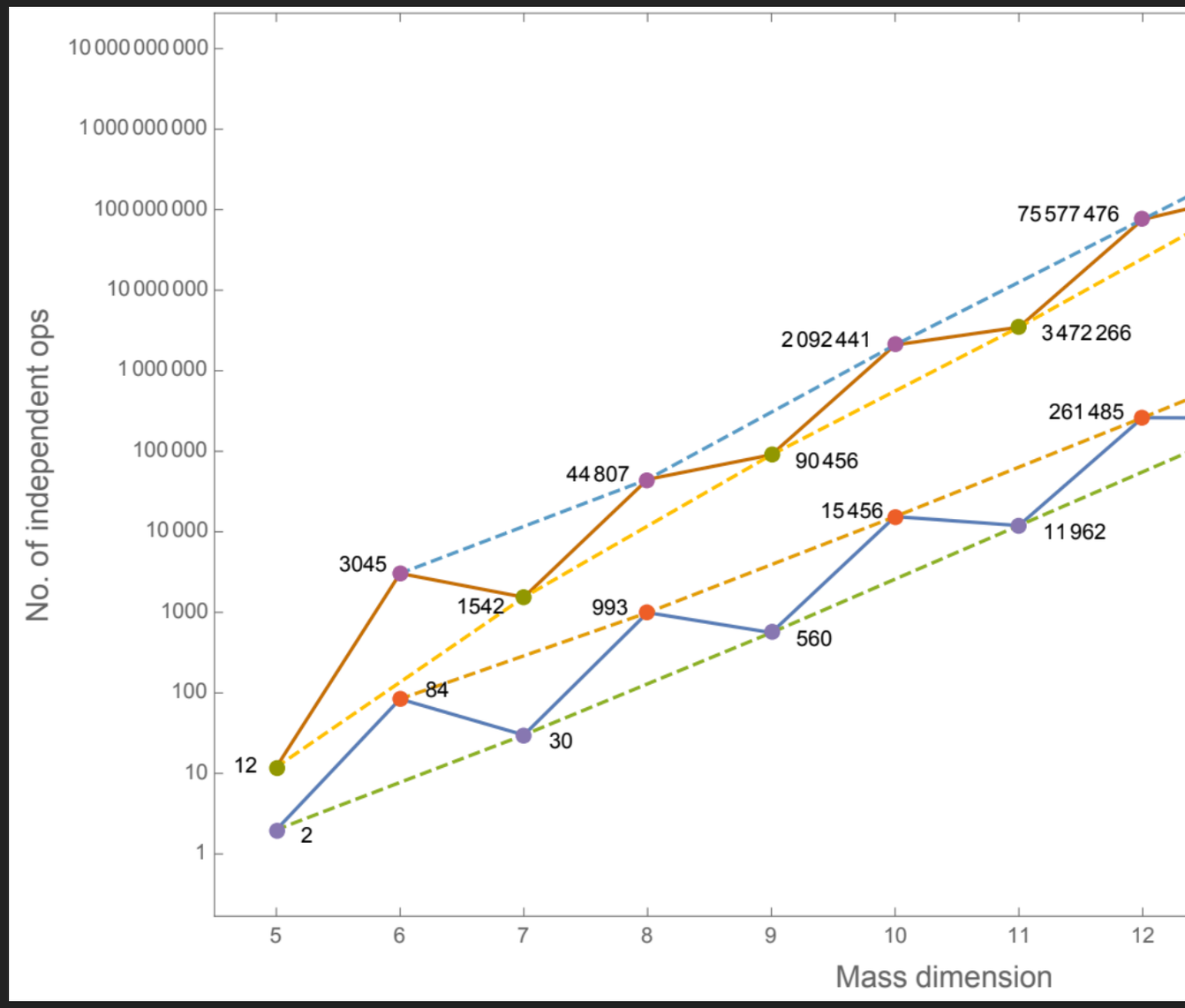
$$\chi^2(\mathbf{c}) = (\mathbf{y} - \boldsymbol{\mu}(\mathbf{c}))^\top V^{-1} (\mathbf{y} - \boldsymbol{\mu}(\mathbf{c})) + \mathbf{c}^\top \kappa \mathbf{c}$$

$$\kappa_{ij} = \kappa \delta_{ij}$$

$$\hat{\mathbf{c}} = \left(H^\top V^{-1} H + \kappa \mathbb{1}\right)^{-1} H^\top V^{-1} \mathbf{y}$$

$$U = \left(H^\top V^{-1} H + \kappa \mathbb{1}\right)^{-1}$$

CM: 1710.02008



Henning, Lu, Melia, Murayama: 1512.03433

GLOBAL FIT RESULTS

Theory	χ^2	$\chi^2/n_{\rm d}$	p-value
SM	157	0.987	0.532
SMEFT	137	0.987	0.528
SMEFT*	143	0.977	0.564

20 coefficients

13 coefficients

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

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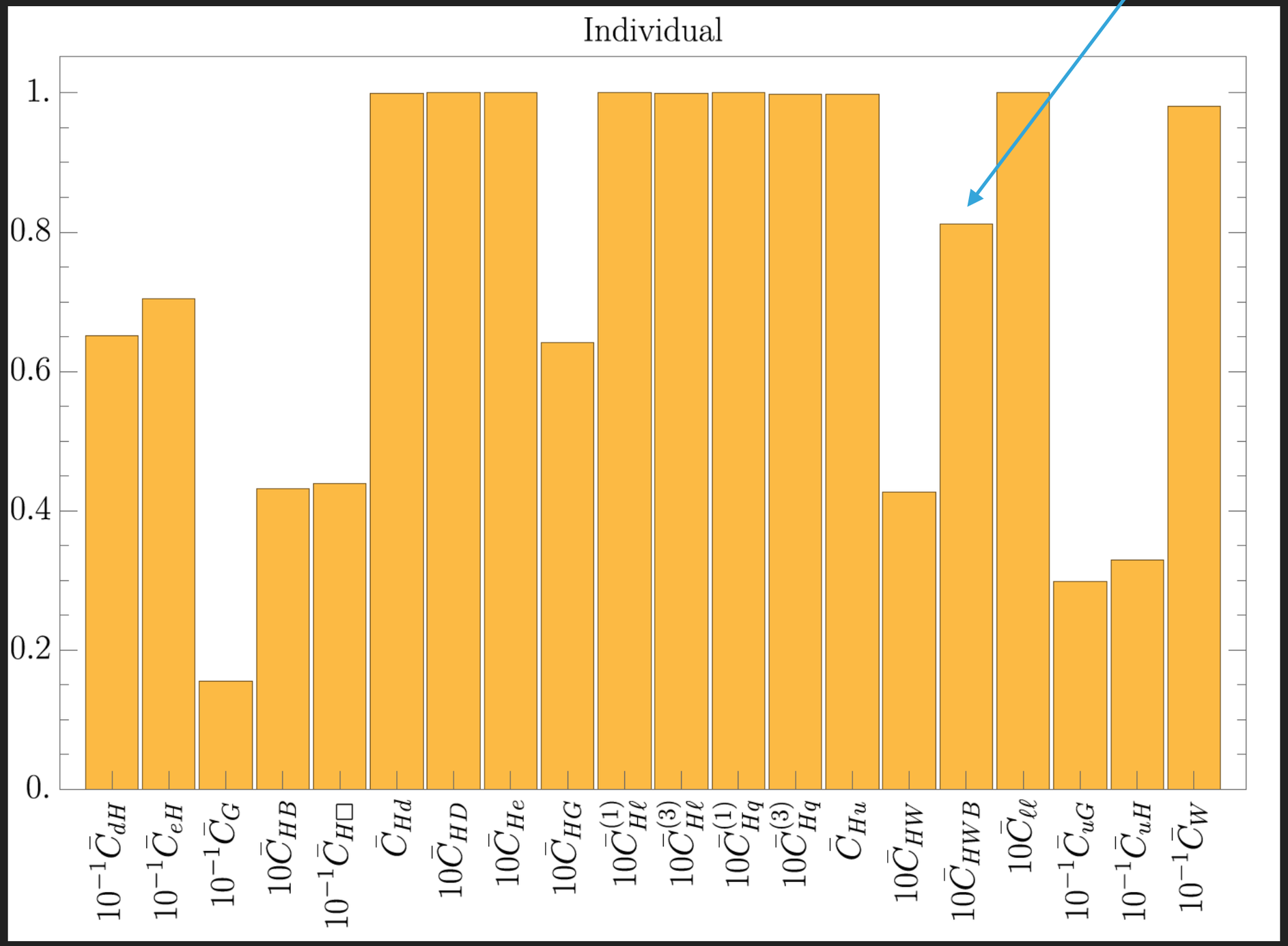
GLOBAL FITS IN THE WARSAW BASIS

LHC competing w/ LEP



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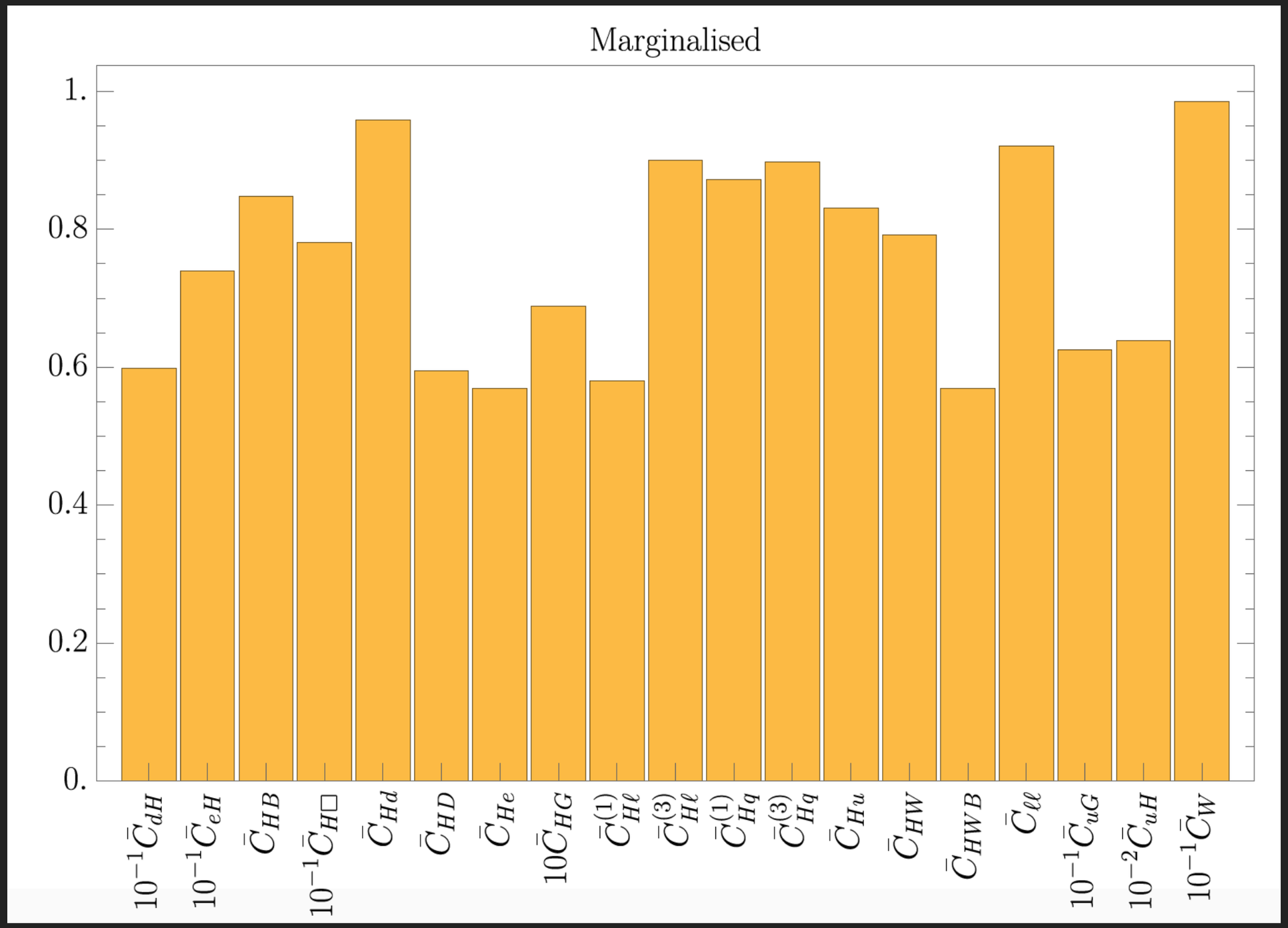
GLOBAL FITS IN THE WARSAW BASIS



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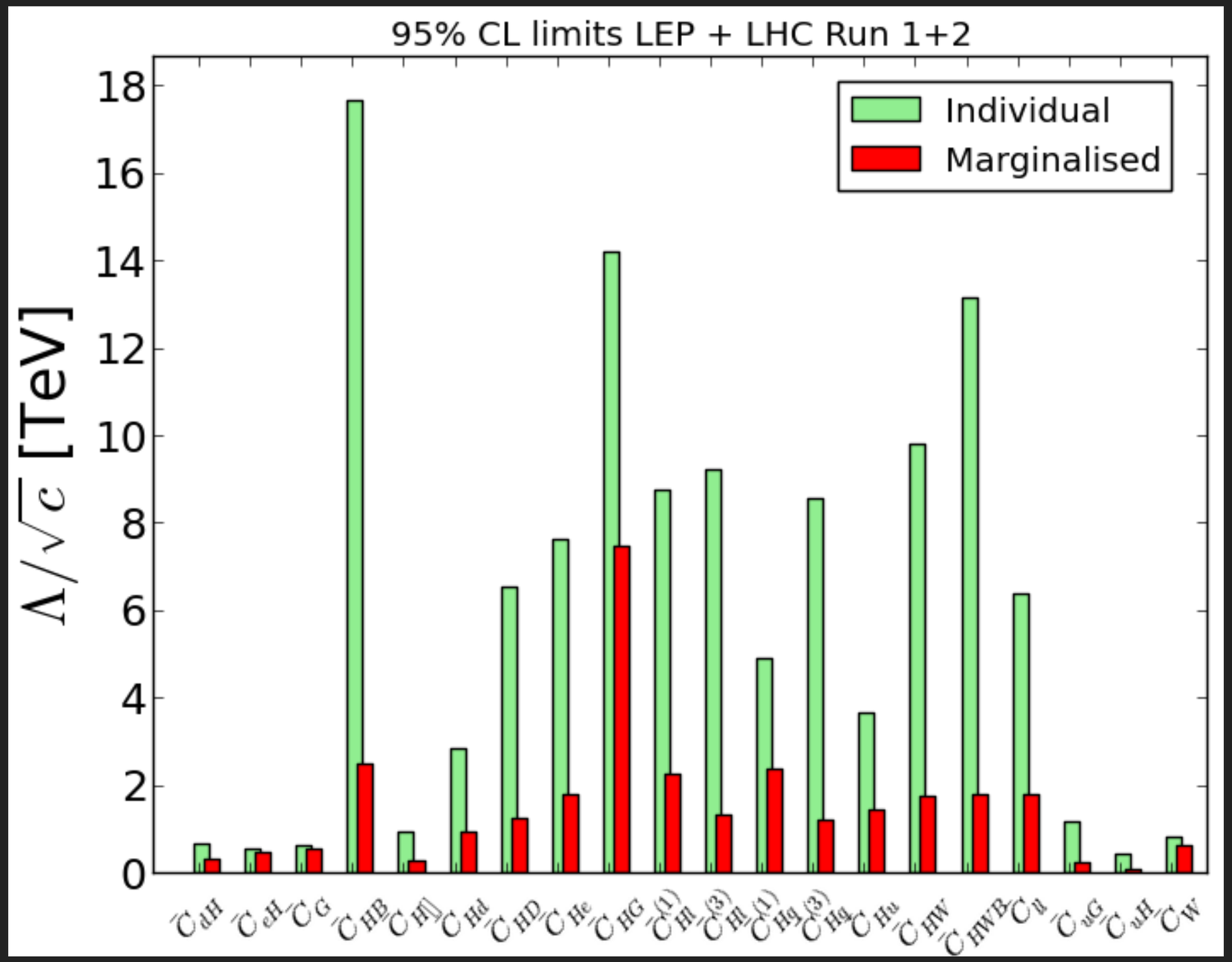
FIT SUMMARY



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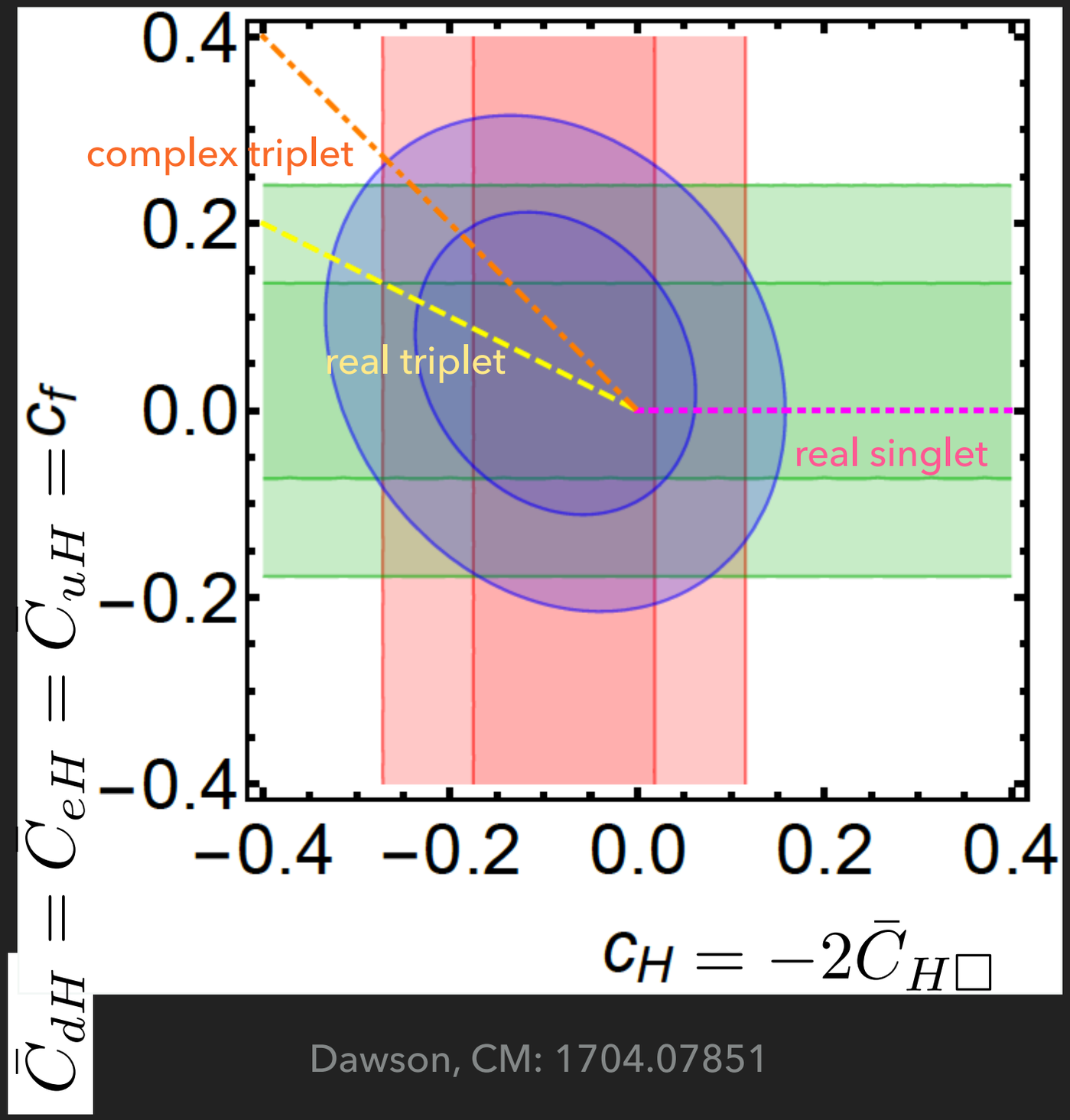
WHAT DO WE LEARN FROM THE FIT?



Dawson, CM: 1704.07851

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	$\frac{2}{3}$

table from EMSY 1803.03252

full dictionary: de Blas, Criado, Perez-Victoria, Santiago: 1711.10391

NUMERICAL CONSTRAINTS ON EXTENSIONS

improve χ^2 & χ^2/n_d

only improve χ^2

improve neither

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	$\left\lvert\hat{g}^\phi_{\mathcal{B}_1}\right\rvert^2 < 2.4 \cdot 10^{-3}$	$M_{\mathcal{B}_1} > 21$

2HDM

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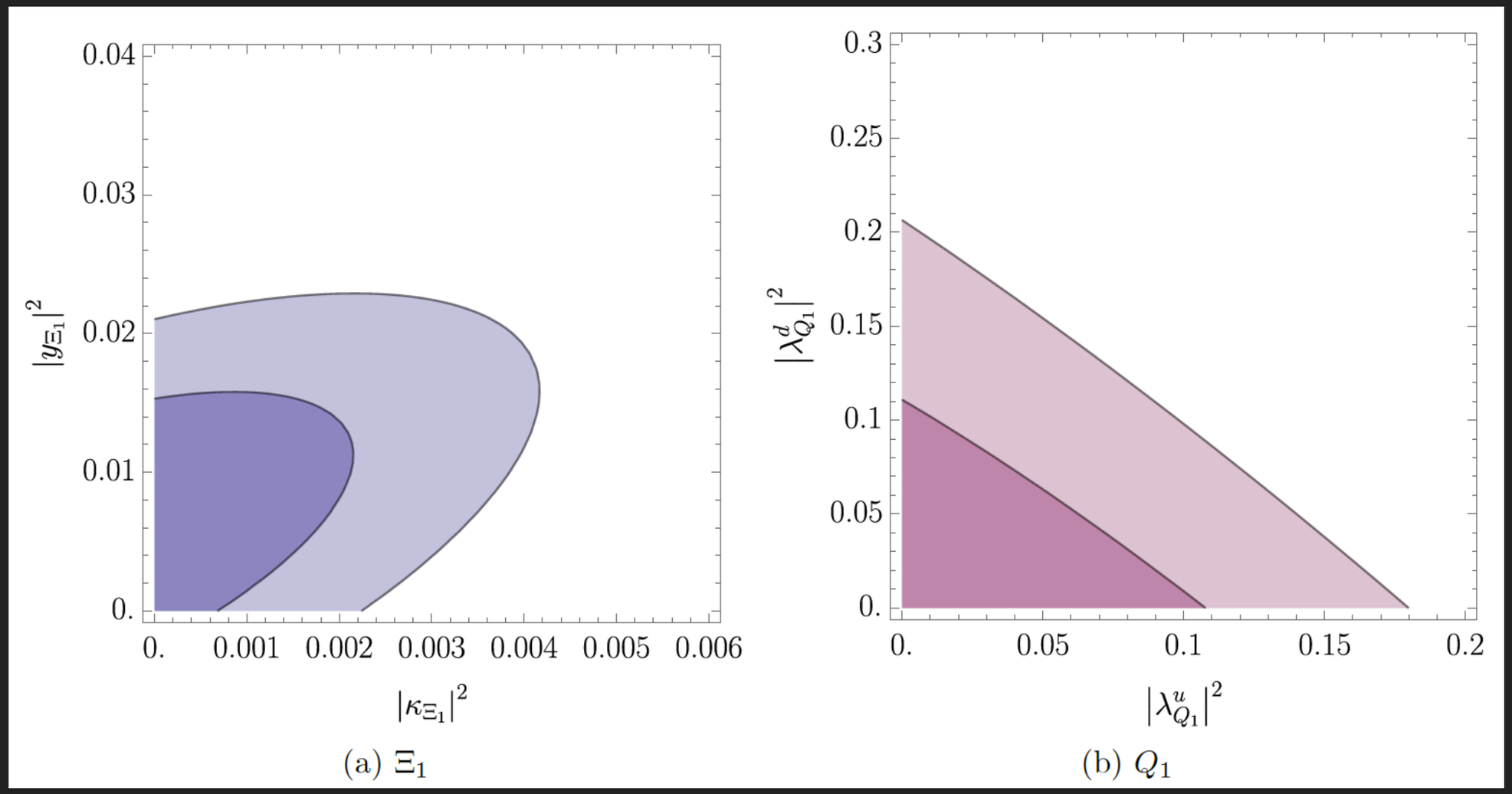
CONSTRAINTS ON SM EXTENSIONS

Complex Scalar Triplet

VLQ w/ quantum #s of SM Q_L



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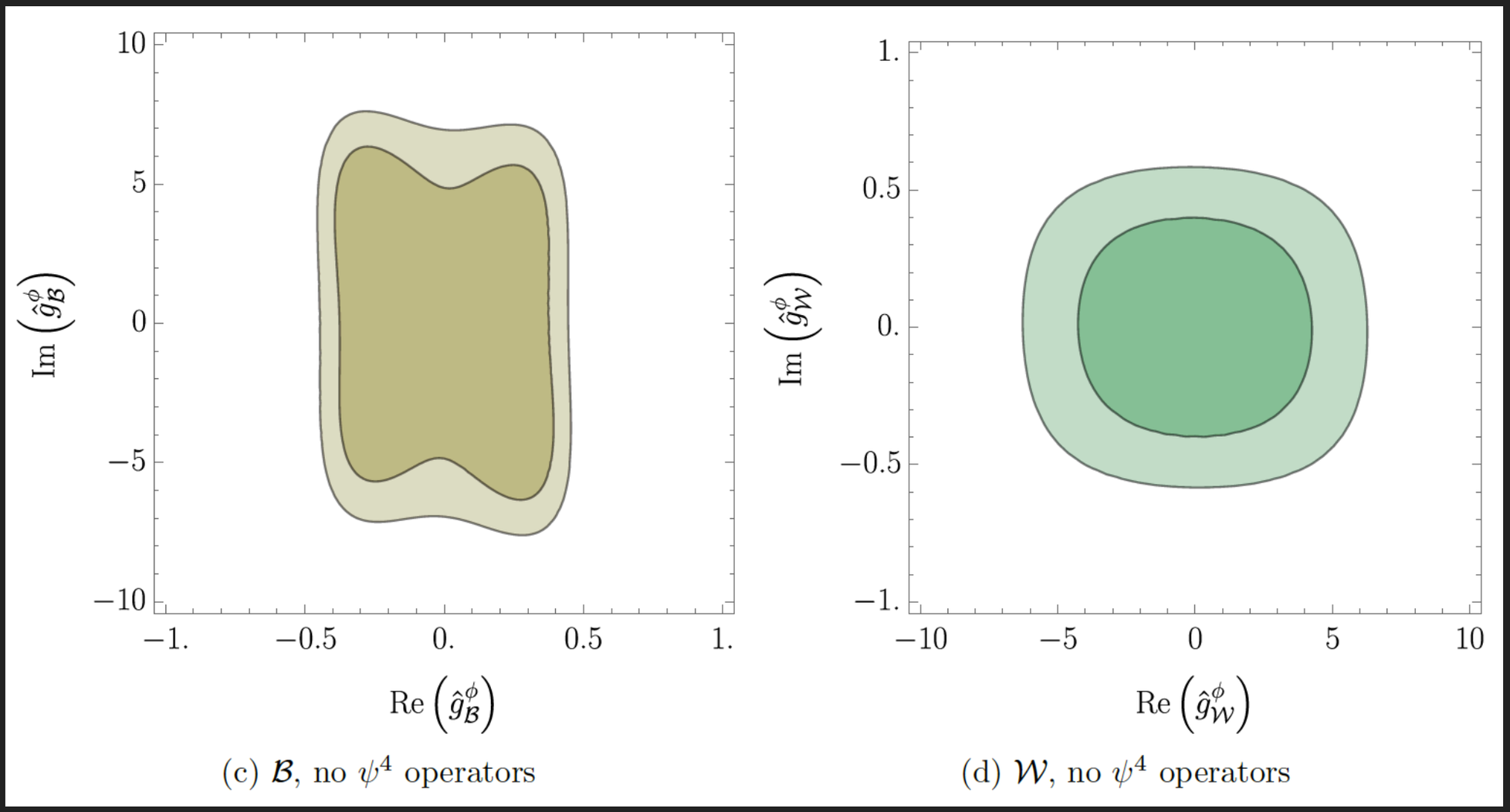
CONSTRAINTS ON SM EXTENSIONS

Z prime

Spin-One Triplet



(c) $\mathcal{B}$, no ψ^4 operators

(d) $\mathcal{W}$, no ψ^4 operators

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NON-RENORMALIZABLE MODELS

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

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

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

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

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

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

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

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NON-RENORMALIZABLE MODELS

- Heavy scalar singlet

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

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

EMSY 1803.03252

FISHER INFORMATION PER MEASUREMENT

Wilson Coefficient	Z-pole + W-mass	WW scattering at LEP2	Higgs LHC Run 1	Higgs LHC Run 2	LHC WW Scattering pt>120	All Measurements
CdH	0.	0.	10.01	8.14243	0.	3.84312
CeH	0.	0.	2.85368	1.33051	0.	0.796513
CG	0.	0.	0.465982	9.10946	0.	2.8145
CHB	0.	0.	988733.	1.96619×10^6	0.	730371.
CHbox	0.	0.	8.07586	15.1235	0.101185	5.68363
CHd	7419.93	0.	2.03053	1.48132	9.83302	654.118
CHD	429534.	51.2855	4.55967	4.48307	552.583	37850.
CHe	647991.	13.6306	0.01108	0.0366124	0.	57062.1
CHG	0.	0.	977989.	863054.	14565.6	395955.
CHl1	1.07732×10^6	51.3672	0.010927	0.036107	0.00459586	94882.5
CHl3	1.70566×10^6	1326.12	50.7988	48.8456	3531.13	150845.
CHq1	63926.9	0.	2.29327	0.961103	36.7852	5629.62
CHq3	492528.	905.433	593.469	328.133	5037.19	44001.5
CHu	13946.1	0.	18.2604	12.3092	83.0208	1234.72
CHW	0.	0.	90573.1	184318.	0.00704223	68175.4
CHWB	3.34554×10^6	185.072	301202.	571154.	2212.43	508776.
Cll	553169.	334.612	16.3139	21.4481	603.	48875.
CuG	0.	0.	17.8723	96.8722	0.	31.7173
CuH	0.	0.	0.402675	1.76306	0.	0.58796
CW	0.	6.71968	0.	0.	19.3954	3.24938

LHC diboson measurements more powerful than LEP2

Ellis, CM, Sanz, You: unpublished