CHRIS MURPHY

GLOBAL FITS IN THE SMEFT

CM 1710.02008

J. Ellis, CM, V. Sanz, T. You 1803.03252

HEP SCORE CARD

- origin of EWSB: Higgs discovery! (incomplete)
- something unexpected: inconclusive
- dark matter: no
- EW baryogenesis: no
- neutrino masses: no
- naturalness: no

HOW SHOULD WE INTERPRET THESE MEASUREMENTS?

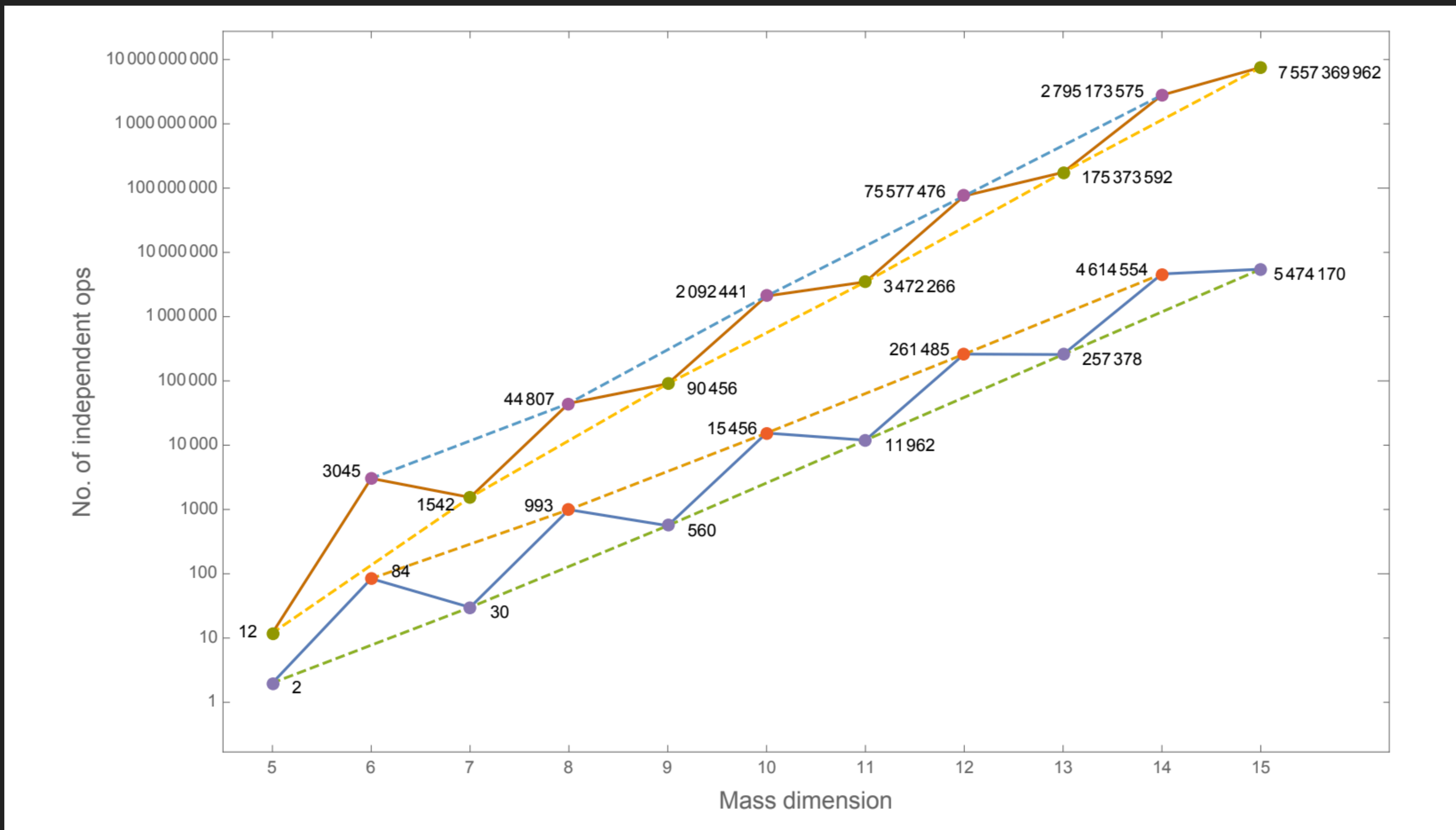
- No evidence of other new particles
  - implies a separation of scales, $v < \Lambda$
- Use effective field theory approach

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \ldots$$

$$\mathcal{L}^{(n)} = \sum_i \frac{c_i^{(n)}}{\Lambda^{n-4}} O_i^{(n)}$$

PART 1 – STATISTICAL APPROACH TO HIGGS COUPLINGS

A LARGE NUMBER OF PARAMETERS



Henning, Lu, Melia, Murayama 1512.03433

2,499 *B#* conserving at dimension-6: Alonso, Jenkins, Manohar, Trott 1312.2014

WHAT TO DO ABOUT LARGE NUMBER OF PARAMETERS

- Impose symmetries
- Add more (classes of) measurements to the fit
  - more on this later
- Regularize the fit…

REVIEW OF LEAST SQUARES

- chi-squared function $$\chi^2(\mathbf{c}) = (\mathbf{y} - \boldsymbol{\mu}(\mathbf{c}))^\top V^{-1} (\mathbf{y} - \boldsymbol{\mu}(\mathbf{c}))$$
- predicted values linear functions of parameters $\mu_i = H_{ij} c_j$
- estimators for central values $$\hat{\mathbf{c}} = \left(H^\top V^{-1} H\right)^{-1} H^\top V^{-1} \mathbf{y}$$
- covariance matrix for estimators $$U = \left(H^\top V^{-1} H\right)^{-1}$$

- U exists if
  - # measurements > # parameters
  - H_i sufficiently unique

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

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

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

MEASUREMENTS USED

- Higgs Results:
  - 22 Run-1 signal strengths (mostly ATLAS+CMS combined)
  - 33 Run-2 signal strengths
  - no differential/boosted measurements
- no EWPD or diboson couplings

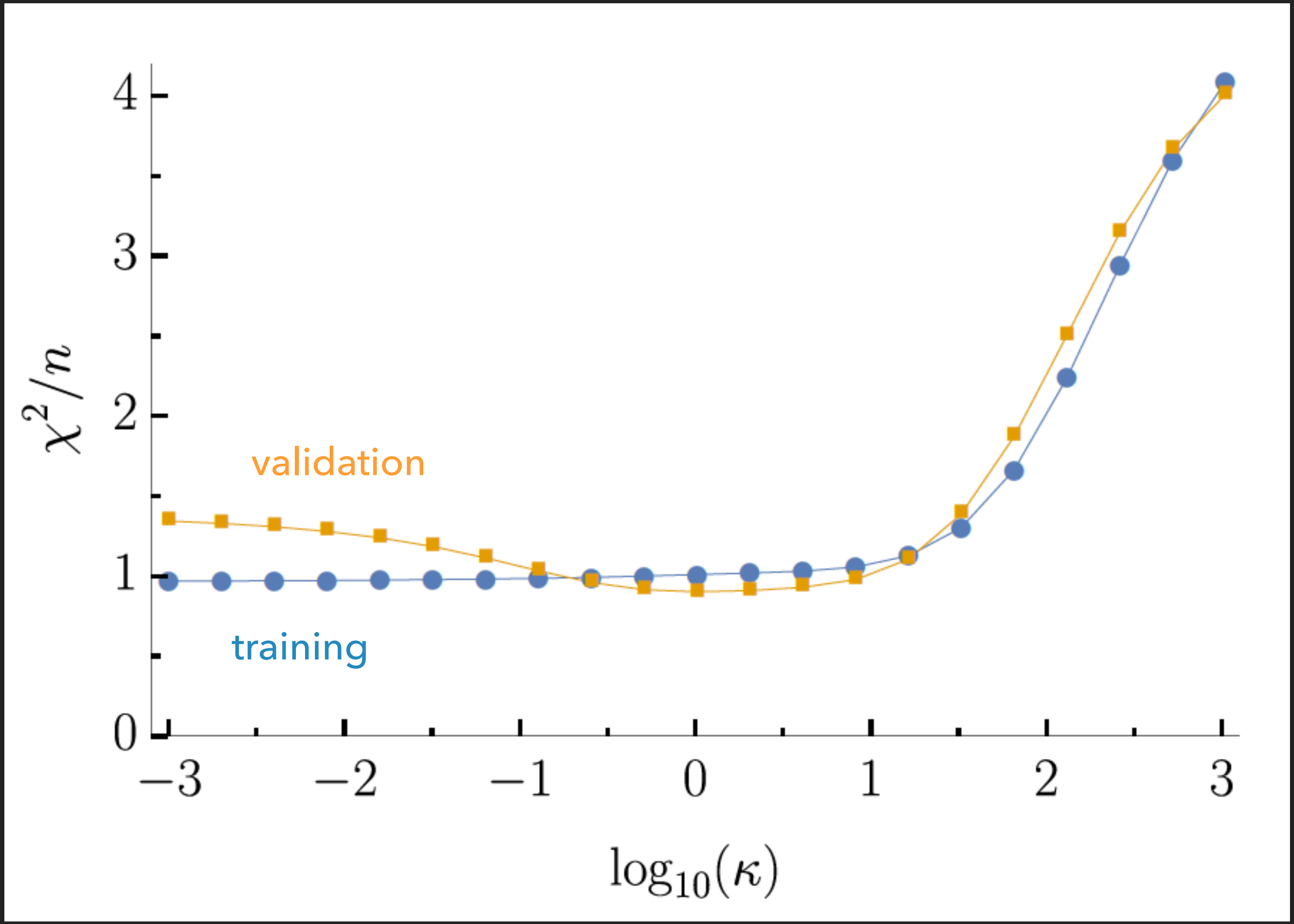
HIGGS SIGNAL STRENGTHS

- Probe 10 directions in SMEFT space
- Proof of principle: include 12 operators in the fit
  - Explicit expressions will be shown later

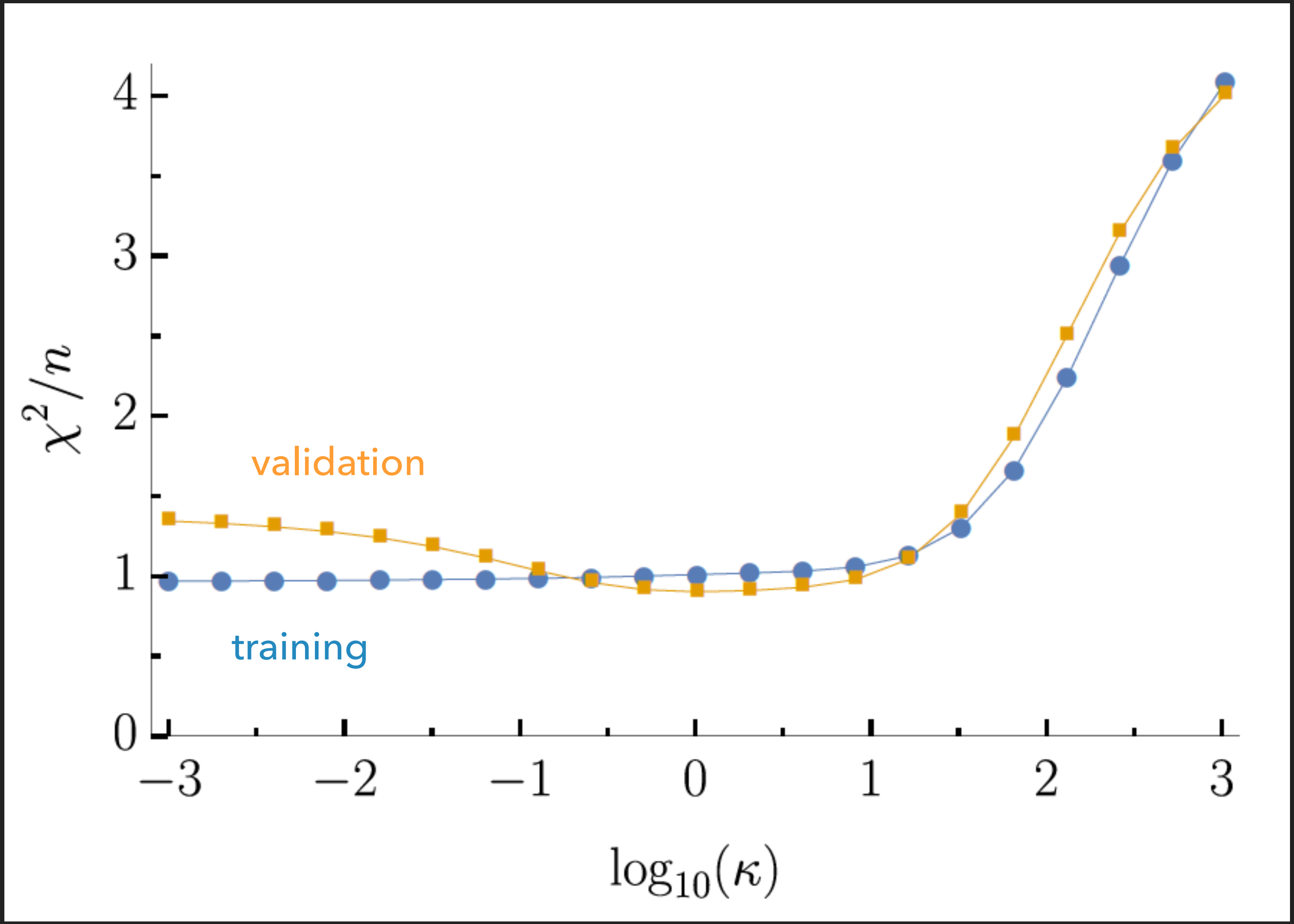
CROSS-VALIDATION

- Split data into training and validation sets
- Optimize parameters using training data w/ regularized linear regression
- Compute χ^2 w/ optimized parameters w/o regularization
- Optimal regularization parameter minimizes this χ^2 / n

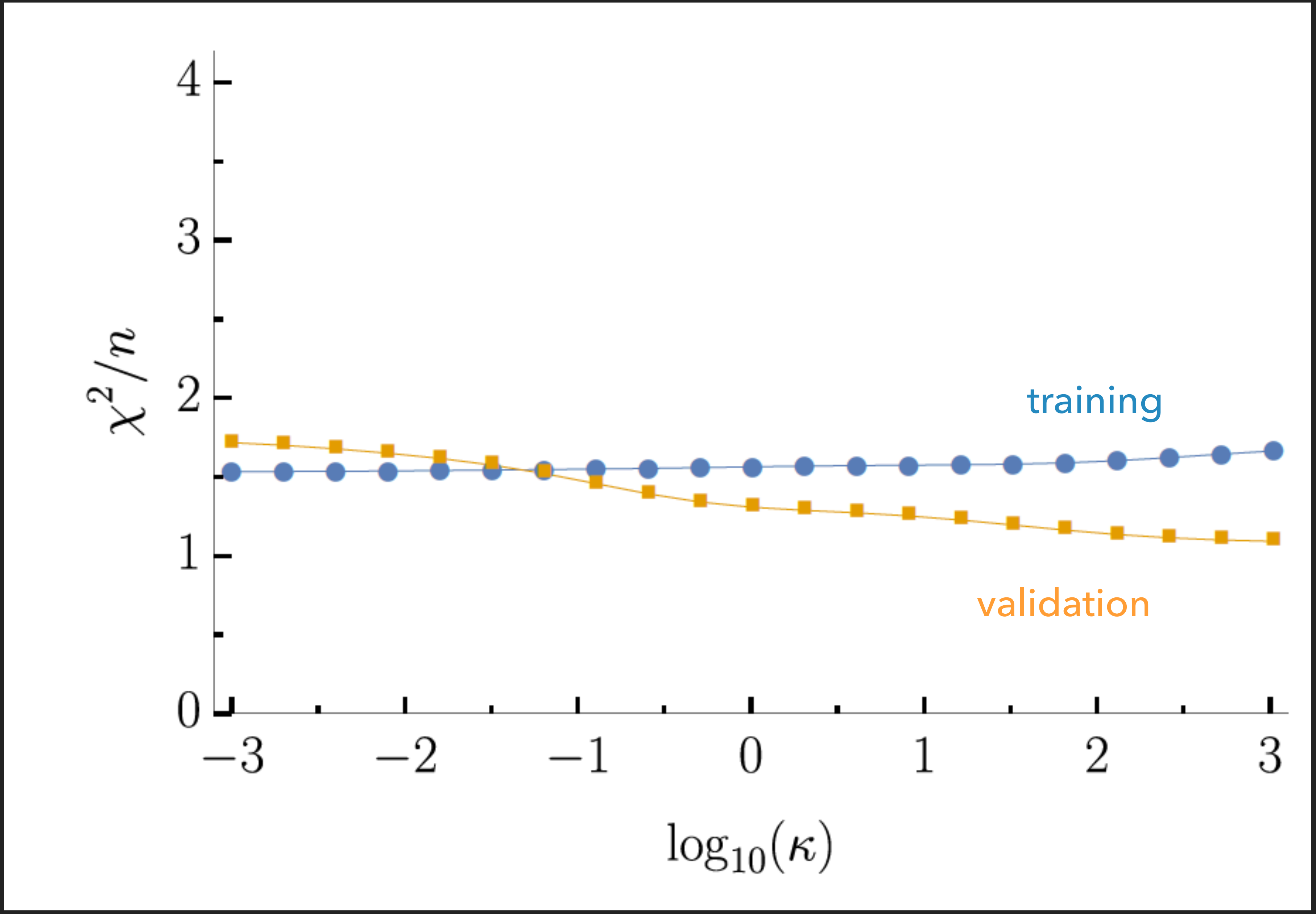
CROSS-VALIDATION…



CROSS-VALIDATION W/ ARTIFICIAL BSM SIGNAL



CROSS-VALIDATION W/ ACTUAL DATA



UTILITY OF κ ?

- $\kappa < 1$: enforce experimental upper limit (*pp*→*hh*; *h*→*Zγ*)
- $\kappa \geq 1$: set lowest BSM scale of $\Lambda_{min} \sim v\sqrt{\kappa}$

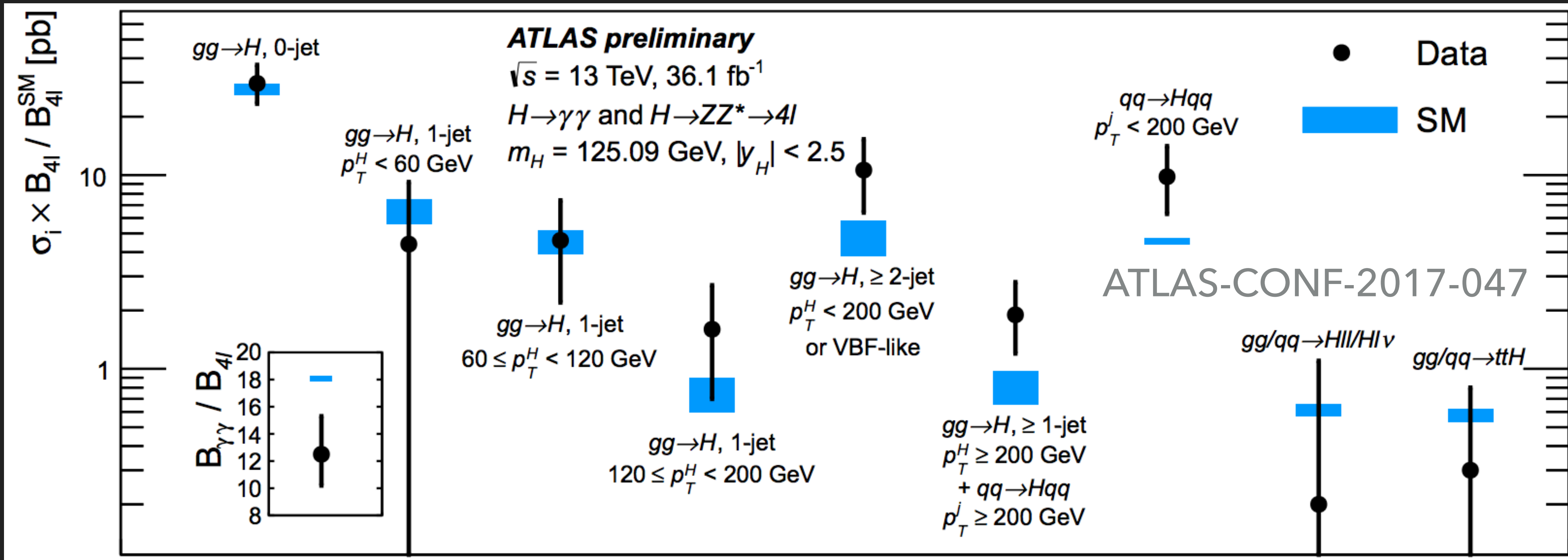
$$\Delta c_i \lesssim \frac{1}{\sqrt{\kappa}}$$

  - normalization dependent
- Regularization matrix in general not proportional to identity
  - e.g. if strongly coupled theory assumed, relate entries of κ_{ij} to size of coefficients expected from NDA?

PART 2 – UPDATED GLOBAL SMEFT FIT

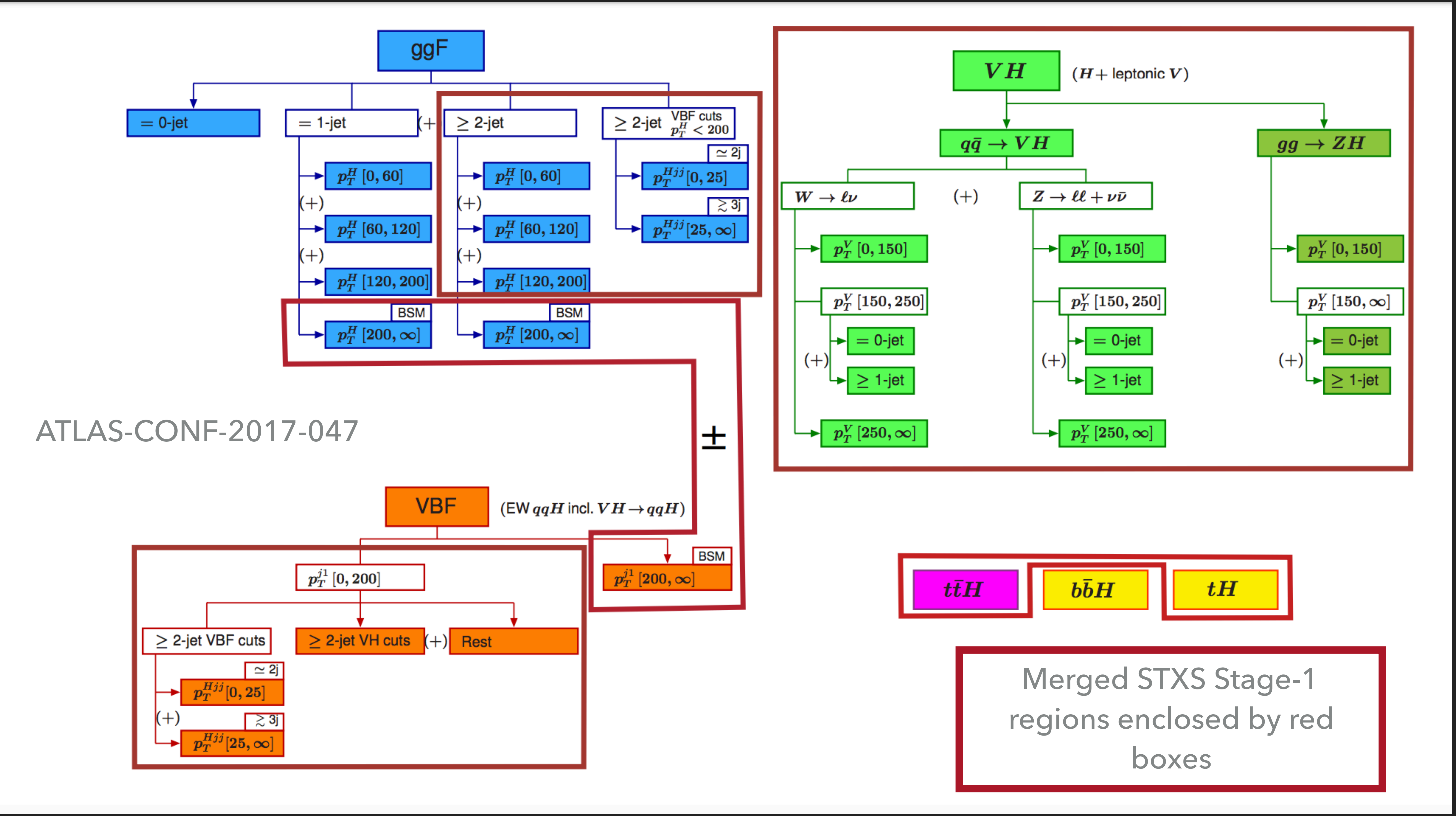
NEXT-GENERATION ANALYSIS

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



ATLAS-CONF-2017-047

SIMPLIFIED TEMPLATE CROSS SECTIONS



see next talk by Zemaityte

ANALYSIS FRAMEWORK

- Focus on leading dimension-6 operators

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

- Work to linear order in Wilson coefficients
- Impose $U(3)^5$ flavor symmetry for fermionic operators
- Use $\alpha_{\rm EM}$, G_F, M_Z, as input parameters

DIMENSION-6 OPERATORS IN WARSAW BASIS

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

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

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

results of EMSY 1803.03252 expressed in both SILH and Warsaw bases

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

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

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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

CMS				ATLAS			
	Production	Decay	Sig. Stren.		Production	Decay	Sig. Stren.
[100]	1-jet, $p_T > 450$	$b\bar{b}$	$2.3^{+1.8}_{-1.6}$	[109]	pp	$\mu\mu$	-0.1 ± 1.5
[101]	Zh	$b\bar{b}$	0.9 ± 0.5	[110]	Zh	$b\bar{b}$	$0.69^{+0.35}_{-0.31}$
[101]	Wh	$b\bar{b}$	1.7 ± 0.7	[110]	Wh	$b\bar{b}$	$1.21^{+0.45}_{-0.42}$
[102]	$t\bar{t}h$	$b\bar{b}$	$-0.19^{+0.80}_{-0.81}$	[111]	$t\bar{t}h$	$b\bar{b}$	$0.84^{+0.64}_{-0.61}$
[103]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-1.20^{+1.50}_{-1.47}$	[112]	$t\bar{t}h$	$2\ell os + 1\tau_h$	$1.7^{+2.1}_{-1.9}$
[103]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$0.86^{+0.79}_{-0.66}$	[112]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-0.6^{+1.6}_{-1.5}$
[103]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.22^{+1.34}_{-1.00}$	[112]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.6^{+1.8}_{-1.3}$
[104]	$t\bar{t}h$	$2\ell ss$	$1.7^{+0.6}_{-0.5}$	[112]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$3.5^{+1.7}_{-1.3}$
[104]	$t\bar{t}h$	3ℓ	$1.0^{+0.8}_{-0.7}$	[112]	$t\bar{t}h$	3ℓ	$1.8^{+0.9}_{-0.7}$
[104]	$t\bar{t}h$	4ℓ	$0.9^{+2.3}_{-1.6}$	[112]	$t\bar{t}h$	$2\ell ss$	$1.5^{+0.7}_{-0.6}$
[105]	0-jet	WW	$0.9^{+0.4}_{-0.3}$	[113]	VBF	WW	$1.7^{+1.1}_{-0.9}$
[105]	1-jet	WW	1.1 ± 0.4	[113]	Wh	WW	$3.2^{+4.4}_{-4.2}$
[105]	2-jet	WW	1.3 ± 1.0	[114]	$B(h \to \gamma\gamma)/\ B(h \to 4\ell)$		$0.69^{+0.15}_{-0.13}$
[105]	VBF 2-jet	WW	1.4 ± 0.8	[114]	0-jet	4ℓ	$1.07^{+0.27}_{-0.25}$
[105]	Vh 2-jet	WW	$2.1^{+2.3}_{-2.2}$	[114]	1-jet, $p_T < 60$	4ℓ	$0.67^{+0.72}_{-0.68}$
[105]	Wh 3-lep	WW	-1.4 ± 1.5	[114]	1-jet, $p_T \in (60, 120)$	4ℓ	$1.00^{+0.63}_{-0.55}$
[106]	ggF	$\gamma\gamma$	$1.11^{+0.19}_{-0.18}$	[114]	1-jet, $p_T \in (120, 200)$	4ℓ	$2.1^{+1.5}_{-1.3}$
[106]	VBF	$\gamma\gamma$	$0.5^{+0.6}_{-0.5}$	[114]	2-jet	4ℓ	$2.2^{+1.1}_{-1.0}$
[106]	$t\bar{t}h$	$\gamma\gamma$	2.2 ± 0.9	[114]	"BSM-like"	4ℓ	$2.3^{+1.2}_{-1.0}$
[106]	Vh	$\gamma\gamma$	$2.3^{+1.1}_{-1.0}$	[114]	VBF, $p_T < 200$	4ℓ	$2.14^{+0.94}_{-0.77}$
[107]	ggF	4ℓ	$1.20^{+0.22}_{-0.21}$	[114]	Vh lep	4ℓ	$0.3^{+1.3}_{-1.2}$
[108]	0-jet	$\tau\tau$	0.84 ± 0.89	[114]	$t\bar{t}h$	4ℓ	$0.51^{+0.86}_{-0.70}$
[108]	boosted	$\tau\tau$	$1.17^{+0.47}_{-0.40}$				
[108]	VBF	$\tau\tau$	$1.11^{+0.34}_{-0.35}$				

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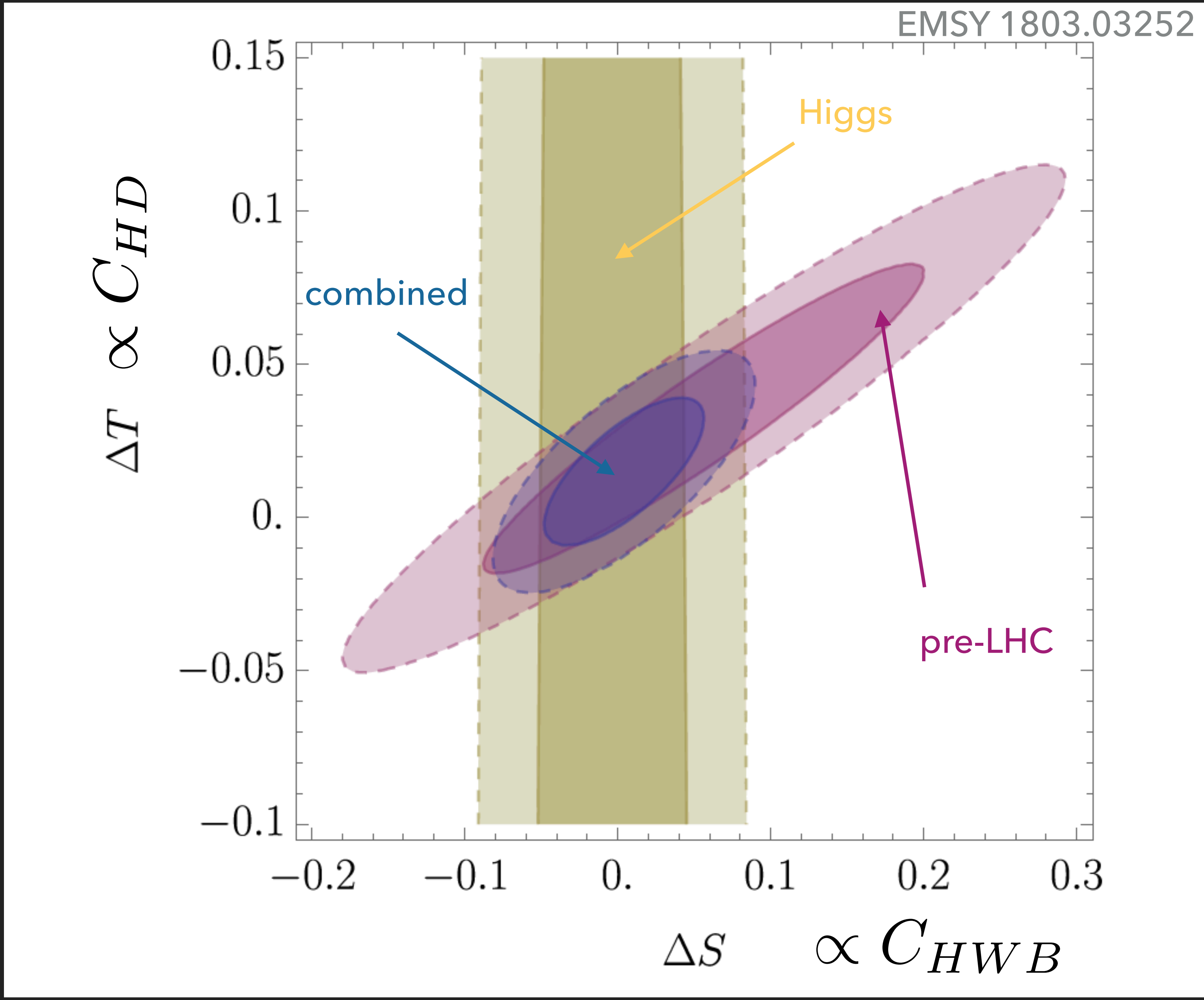
SMEFT PREDICTIONS

- pre-LHC
  - Berthier, Bjorn, Trott 1606.06693; Brivio, Trott 1706.08945
- LHC
  - SMEFTsim: Brivio, Jiang, Trott 1709.06492

CONSTRAINTS ON OBLIQUE PARAMETERS



GLOBAL FIT RESULTS

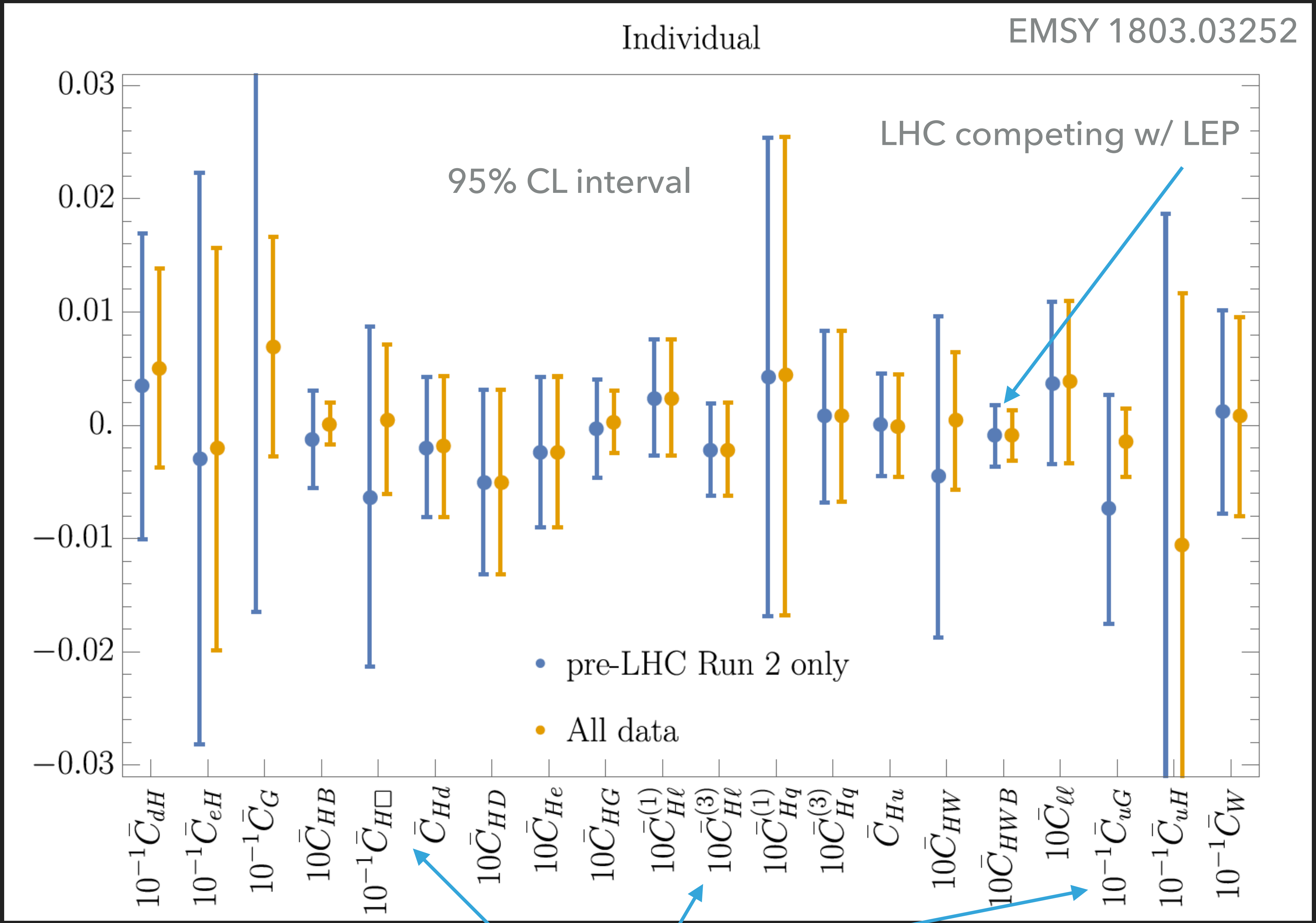
Theory	χ^2	χ^2/n_{d}	p-value
SM	153	0.972	0.585
SMEFT	133	0.973	0.572
SMEFT*	139	0.963	0.609

20 coefficients → SMEFT

13 coefficients → SMEFT*

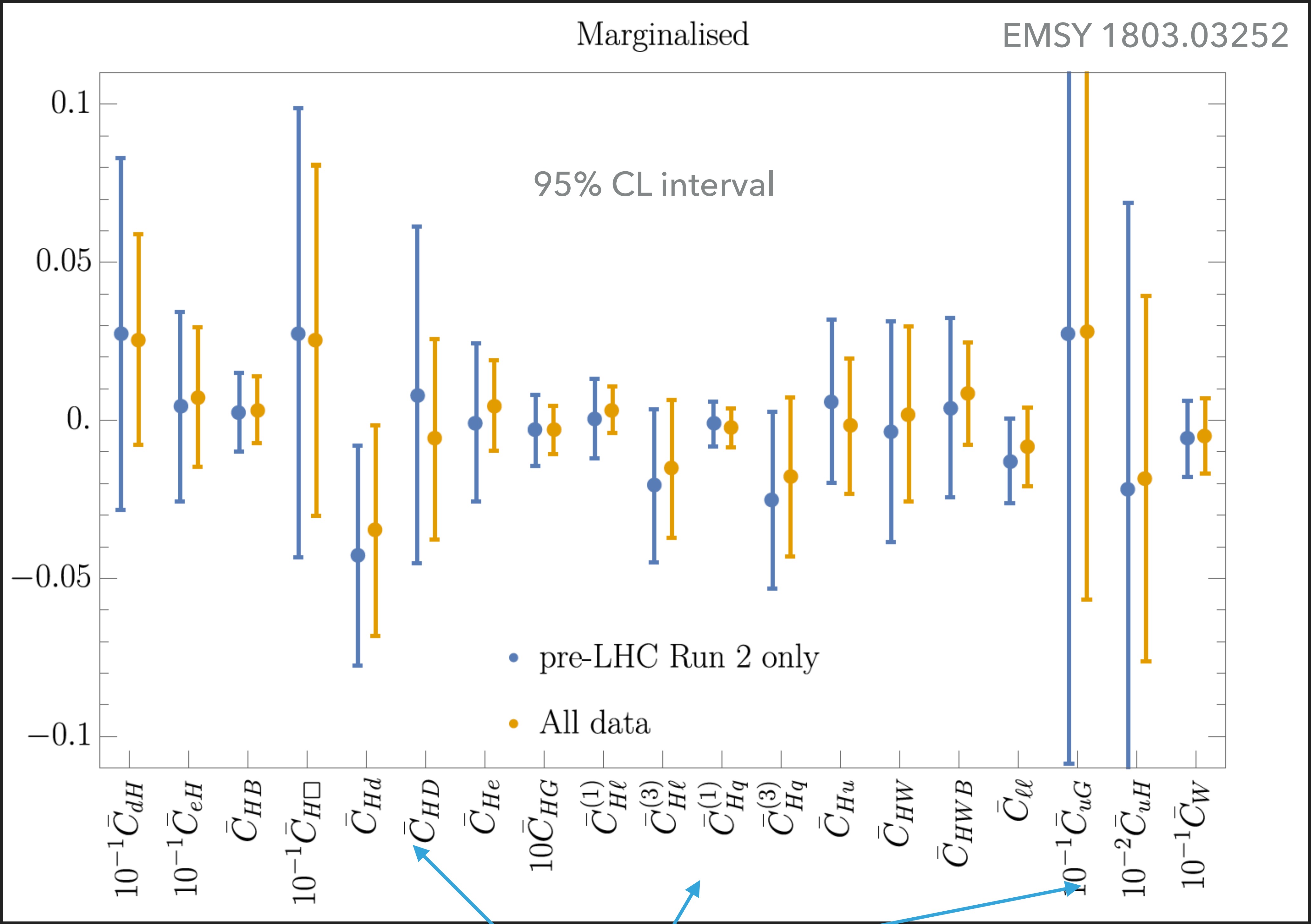
*assumes SMEFT is UV-completed by a renormalizable, weakly-coupled theory

FIT TO EACH OPERATOR INDIVIDUALLY



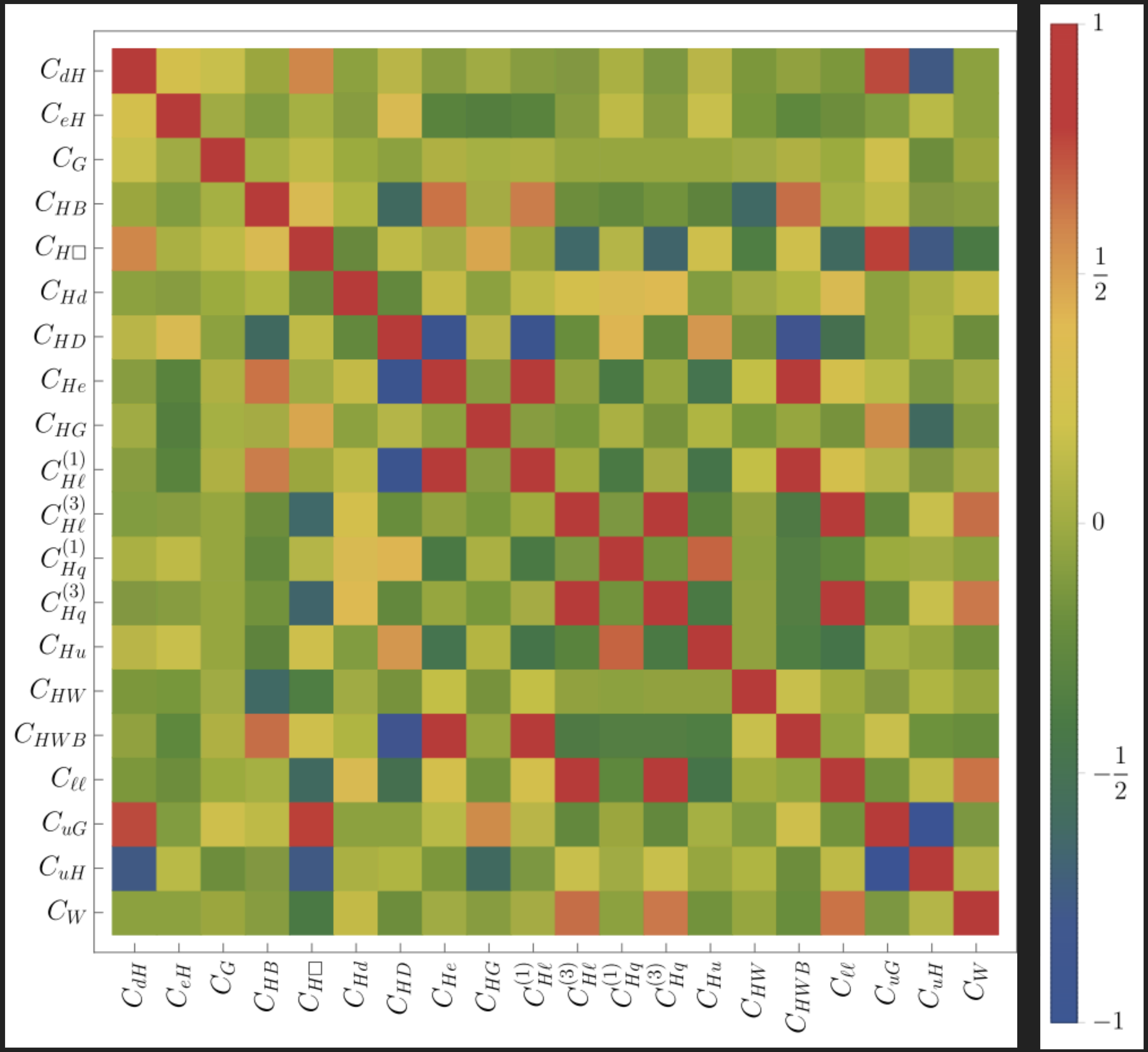
different powers of 10

FIT TO ALL OPERATORS SIMULTANEOUSLY



different powers of 10

CORRELATION MATRIX



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

Group	Model	χ^2	χ^2/n_d	Coupling	Mass / TeV
	SM	152.6	0.972	-	-
improve χ^2 & χ^2/n_d	$\mathcal{S}_1$	151	0.971	$\lvert y_{\mathcal{S}_1}\rvert^2 = (6.3 \pm 5.9)\cdot 10^{-3}$	$M_{\mathcal{S}_1} = (9.1,\ 53)$
	Ξ	151	0.968	$\lvert\kappa_\Xi\rvert^2 = (4.1 \pm 3.4)\cdot 10^{-3}$	$M_\Xi = (12,\ 36)$
	N	150	0.963	$\lvert\lambda_N\rvert^2 = (1.8 \pm 1.2)\cdot 10^{-2}$	$M_N = (5.8,\ 13)$
	$\mathcal{W}_1$	151	0.968	$\left\lvert\hat{g}^{\phi}_{\mathcal{W}_1}\right\rvert^2 = (3.3 \pm 2.7)\cdot 10^{-3}$	$M_{\mathcal{W}_1} = (4.1,\ 13)$
only improve χ^2	φ, Type I (2HDM)	152	0.976	$Z_6 \cdot \cos\beta = -0.41 \pm 0.66$	$M_\varphi = (1.0,\ \infty)$
	E	152.5	0.978	$\lvert\lambda_E\rvert^2 = (2.0 \pm 9.7)\cdot 10^{-3}$	$M_E = (9.2,\ \infty)$
	Δ_3	152	0.975	$\lvert\lambda_{\Delta_3}\rvert^2 = (0.8 \pm 1.1)\cdot 10^{-2}$	$M_{\Delta_3} = (7.3,\ \infty)$
	Σ	152	0.977	$\lvert\lambda_\Sigma\rvert^2 = (0.9 \pm 2.0)\cdot 10^{-2}$	$M_\Sigma = (5.9,\ \infty)$
	Q_5	152	0.975	$\lvert\lambda_{Q_5}\rvert^2 = 0.07 \pm 0.10$	$M_{Q_5} = (2.4,\ \infty)$
	T_2	152	0.977	$\lvert\lambda_{T_2}\rvert^2 = (1.8 \pm 5.1)\cdot 10^{-2}$	$M_{T_2} = (3.8,\ \infty)$
improve neither	$\mathcal{S}$	152.6	0.978	$\lvert y_\mathcal{S}\rvert^2 < 0.47$	$M_\mathcal{S} > 1.5$
	Δ_1	152.6	0.978	$\lvert\lambda_{\Delta_1}\rvert^2 < 5.7\cdot 10^{-3}$	$M_{\Delta_1} > 13$
	Σ_1	152.6	0.978	$\lvert\lambda_{\Sigma_1}\rvert^2 < 7.3\cdot 10^{-3}$	$M_{\Sigma_1} > 12$
	U	152.6	0.978	$\lvert\lambda_U\rvert^2 < 3.1\cdot 10^{-2}$	$M_U > 5.7$
	D	152.6	0.978	$\lvert\lambda_D\rvert^2 < 1.5\cdot 10^{-2}$	$M_D > 8.2$
	Q_7	152.6	0.978	$\lvert\lambda_{Q_7}\rvert^2 < 7.2\cdot 10^{-2}$	$M_{Q_7} > 3.7$
	T_1	152.6	0.978	$\lvert\lambda_{T_1}\rvert^2 < 0.11$	$M_{T_1} > 3.0$
	$\mathcal{B}_1$	152.6	0.978	$\left\lvert\hat{g}^{\phi}_{\mathcal{B}_1}\right\rvert^2 < 2.4\cdot 10^{-3}$	$M_{\mathcal{B}_1} > 20$

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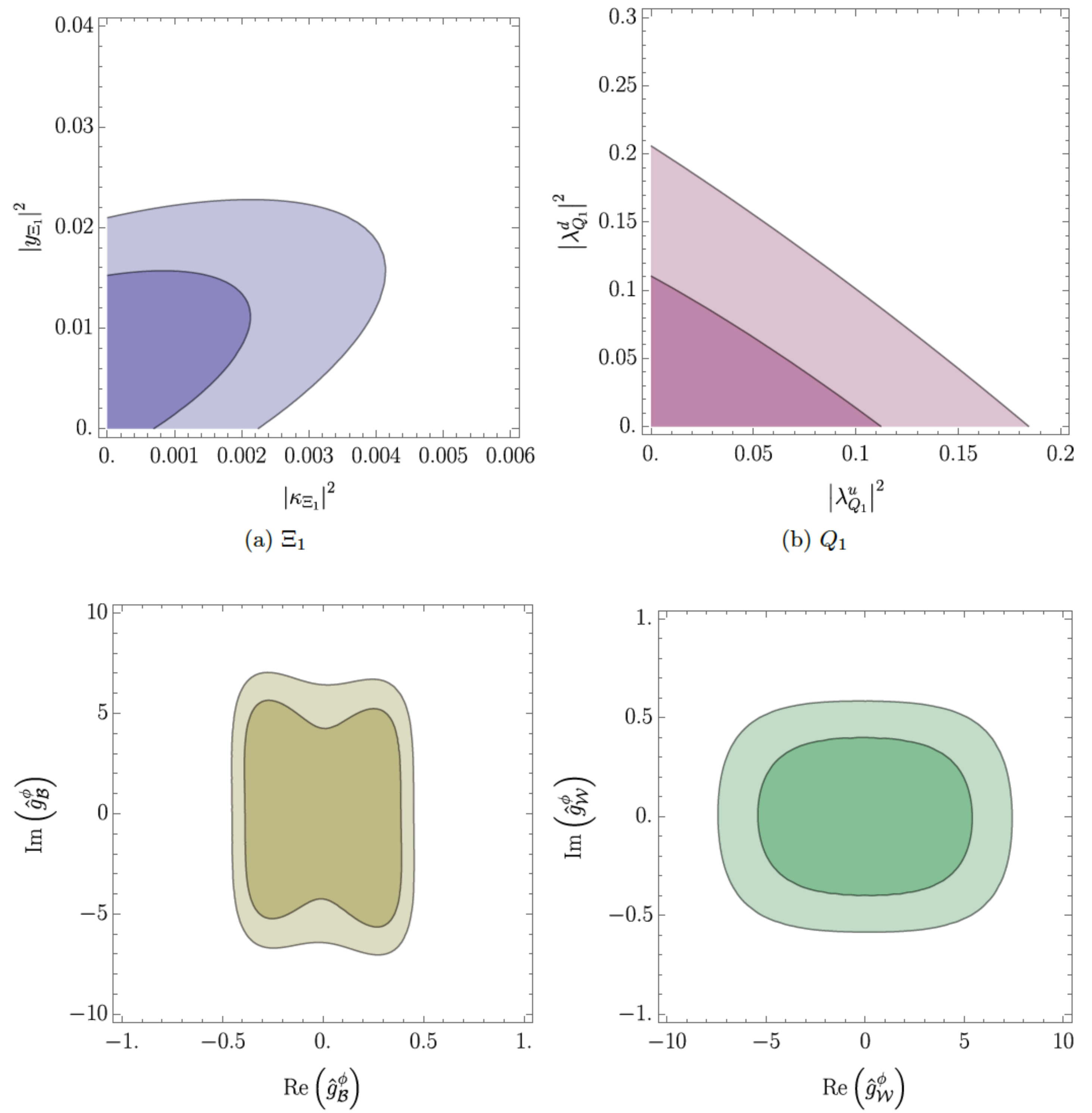
CONSTRAINTS ON SM EXTENSIONS



(a) Ξ_1 (b) Q_1

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

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NON-RENORMALIZABLE MODELS

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

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

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

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

see e.g. Jenkins, Manohar, Trott 1305.0017

NON-RENORMALIZABLE MODELS

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

- $E^{(5)}$: $C^{(1)}_{H\ell} = C^{(3)}_{H\ell}$.

$$\begin{pmatrix} \bar{C}_{eH} \\ \bar{C}^{(3)}_{H\ell} \end{pmatrix} = \begin{pmatrix} (-1.9 \pm 8.9) \cdot 10^{-2} \\ (-0.3 \pm 1.5) \cdot 10^{-4} \end{pmatrix}$$

- $\Delta^{(5)}_{1,3}$:

$$\begin{pmatrix} \bar{C}_{eH} \\ \bar{C}_{He} \end{pmatrix} = \begin{pmatrix} (-1.9 \pm 8.9) \cdot 10^{-2} \\ (-2.3 \pm 3.3) \cdot 10^{-4} \end{pmatrix}$$

- $\Sigma^{(5)}_1$: $C^{(1)}_{H\ell} = -3C^{(3)}_{H\ell}$.

$$\begin{pmatrix} \bar{C}_{eH} \\ \bar{C}^{(3)}_{H\ell} \end{pmatrix} = \begin{pmatrix} (-1.9 \pm 8.9) \cdot 10^{-2} \\ (-1.2 \pm 0.9) \cdot 10^{-4} \end{pmatrix}$$

EMSY 1803.03252

NON-RENORMALIZABLE MODELS

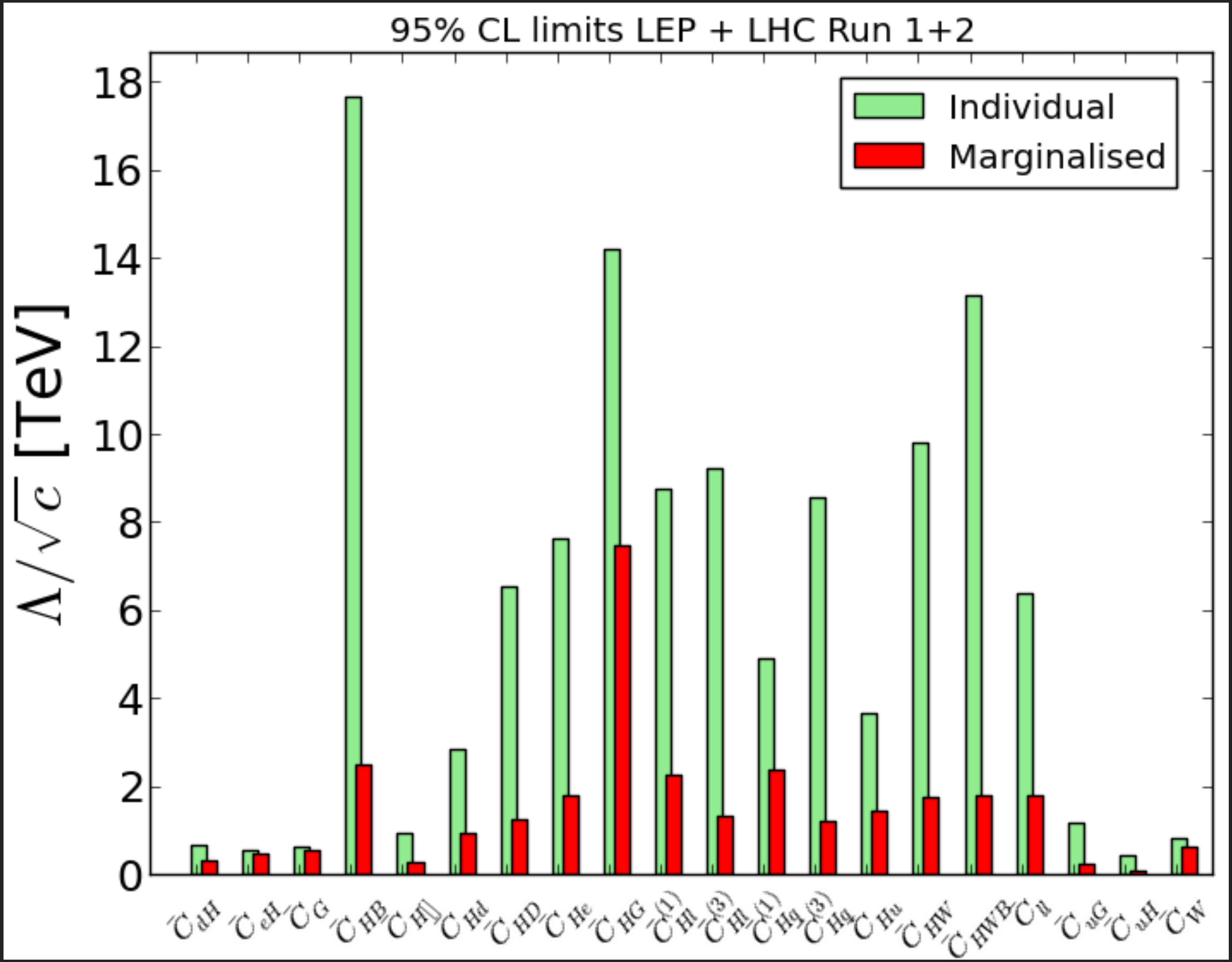
- Heavy scalar singlet

- $\mathcal{S}^{(5)}$: Pull = 1.4.

$$
\begin{pmatrix}
0.46\bar{C}_{H\Box} - 0.04\bar{C}_{HW} + 0.01\bar{C}_{HB} + 0.18\bar{C}_{eH} + 0.84\bar{C}_{uH} + 0.21\bar{C}_{dH} \\
-0.27\bar{C}_{H\Box} + 0.02\bar{C}_{HW} + 0.66\bar{C}_{eH} - 0.16\bar{C}_{uH} + 0.68\bar{C}_{dH} \\
0.55\bar{C}_{H\Box} - 0.05\bar{C}_{HW} + 0.02\bar{C}_{HB} + 0.62\bar{C}_{eH} - 0.32\bar{C}_{uH} - 0.45\bar{C}_{dH} \\
0.63\bar{C}_{H\Box} - 0.06\bar{C}_{HW} + 0.02\bar{C}_{HB} - 0.39\bar{C}_{eH} - 0.40\bar{C}_{uH} + 0.54\bar{C}_{dH} \\
0.10\bar{C}_{H\Box} + 0.95\bar{C}_{HW} - 0.29\bar{C}_{HB} \\
0.93\bar{C}_{HG} + 0.11\bar{C}_{HW} + 0.35\bar{C}_{HB} \\
-0.36\bar{C}_{HG} + 0.27\bar{C}_{HW} + 0.89\bar{C}_{HB}
\end{pmatrix}
=
\begin{pmatrix}
-0.02 \pm 0.19 \\
0.21 \pm 0.12 \\
(-3.8 \pm 8.3) \cdot 10^{-2} \\
(7.7 \pm 6.2) \cdot 10^{-2} \\
(-3.8 \pm 9.2) \cdot 10^{-3} \\
(0.5 \pm 1.6) \cdot 10^{-4} \\
(0.3 \pm 8.4) \cdot 10^{-5}
\end{pmatrix}
\quad (18)
$$

EMSY 1803.03252

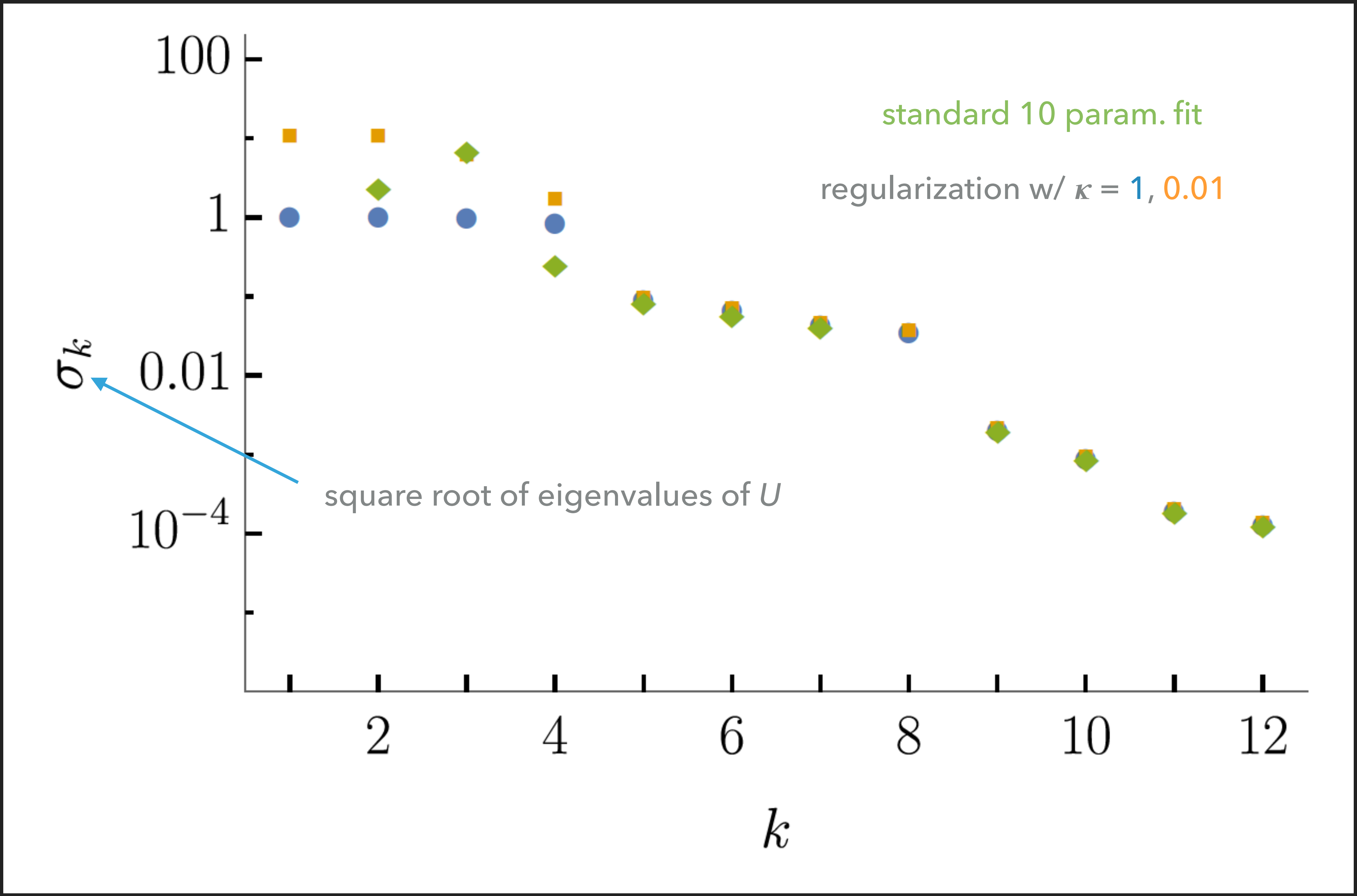
SUMMARY


95% CL limits LEP + LHC Run 1+2
Individual
Marginalised
$\Lambda/\sqrt{c}$ [TeV]
0
2
4
6
8
10
12
14
16
18

SUMMARY

- SMEFT: model-independent way to search for heavy, new physics
- Regularized linear regression prevents a fit from falling into an overfit solution
- Higgs measurements currently compete w/ EWPD

ONE SIGMA LIMITS ON EIGENVECTORS



EIGENVECTOR COMPOSITION

$$W_1 \simeq 0.99c_B + 0.09c_{HW} + 0.09c_T - 0.08c_W + 0.05c_{HB}, \quad \text{(B1)}$$

$$W_2 \simeq 0.67c_{HW} - 0.56c_W - 0.36c_B + 0.33c_{HB} - 0.02c_T,$$

$$W_3 \simeq 0.99c_6 - 0.13c_t + 0.05c_W + 0.03c_{HW} + 0.02c_{HB} - 0.01c_H,$$

$$W_4 \simeq 0.67c_W + 0.45c_{HW} + 0.38c_H - 0.38c_t + 0.24c_{HB} - 0.09c_6,$$

$$W_5 \simeq 0.76c_t + 0.40c_W - 0.32c_H + 0.24c_{HW} + 0.22c_T + 0.20c_{HB} + 0.06c_6 - 0.02c_B,$$

$$W_6 \simeq 0.78c_H + 0.51c_t - 0.32c_T - 0.10c_W + 0.08c_6 - 0.07c_{HB} - 0.05c_{HW} + 0.03c_b + 0.03c_B,$$

$$W_7 \simeq 0.87c_{HB} - 0.48c_{HW} + 0.09c_H + 0.09c_T - 0.06c_W - 0.03c_t + 0.01c_b,$$

$$W_8 \simeq 0.91c_T + 0.34c_H - 0.16c_{HB} - 0.11c_W - 0.08c_B - 0.03c_{HW} + 0.03c_b + 0.01c_6,$$

$$W_9 \simeq 0.97c_b + 0.24c_\tau - 0.07c_g + 0.04c_\gamma - 0.03c_H + 0.02c_W + 0.01c_{HW} - 0.01c_t - 0.01c_T,$$

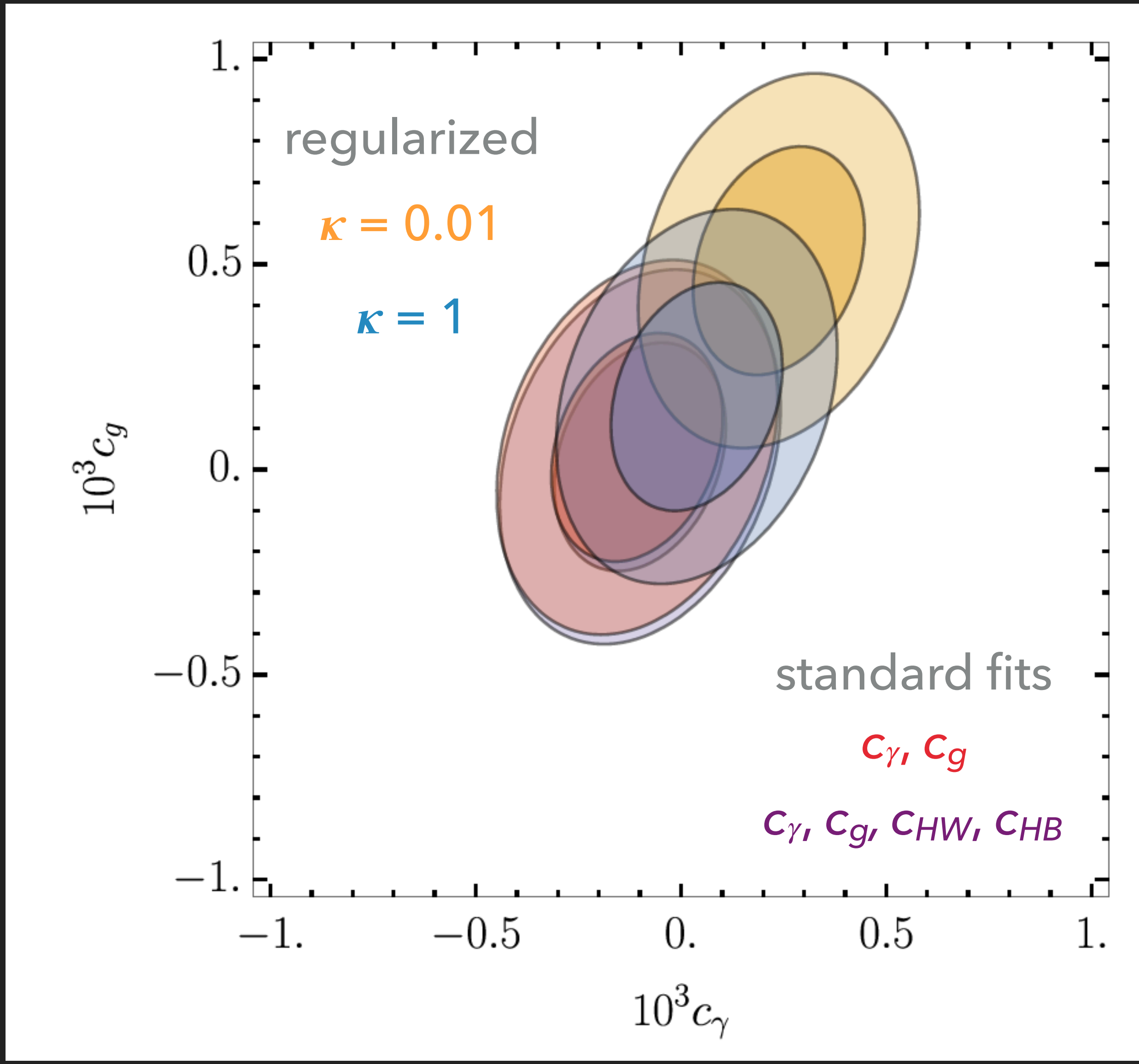
$$W_{10} \simeq 0.97c_\tau - 0.24c_b + 0.05c_g,$$

$$W_{11} \simeq 0.93c_g + 0.35c_\gamma + 0.06c_b - 0.03c_\tau,$$

$$W_{12} \simeq 0.93c_\gamma - 0.35c_g - 0.07c_b.$$

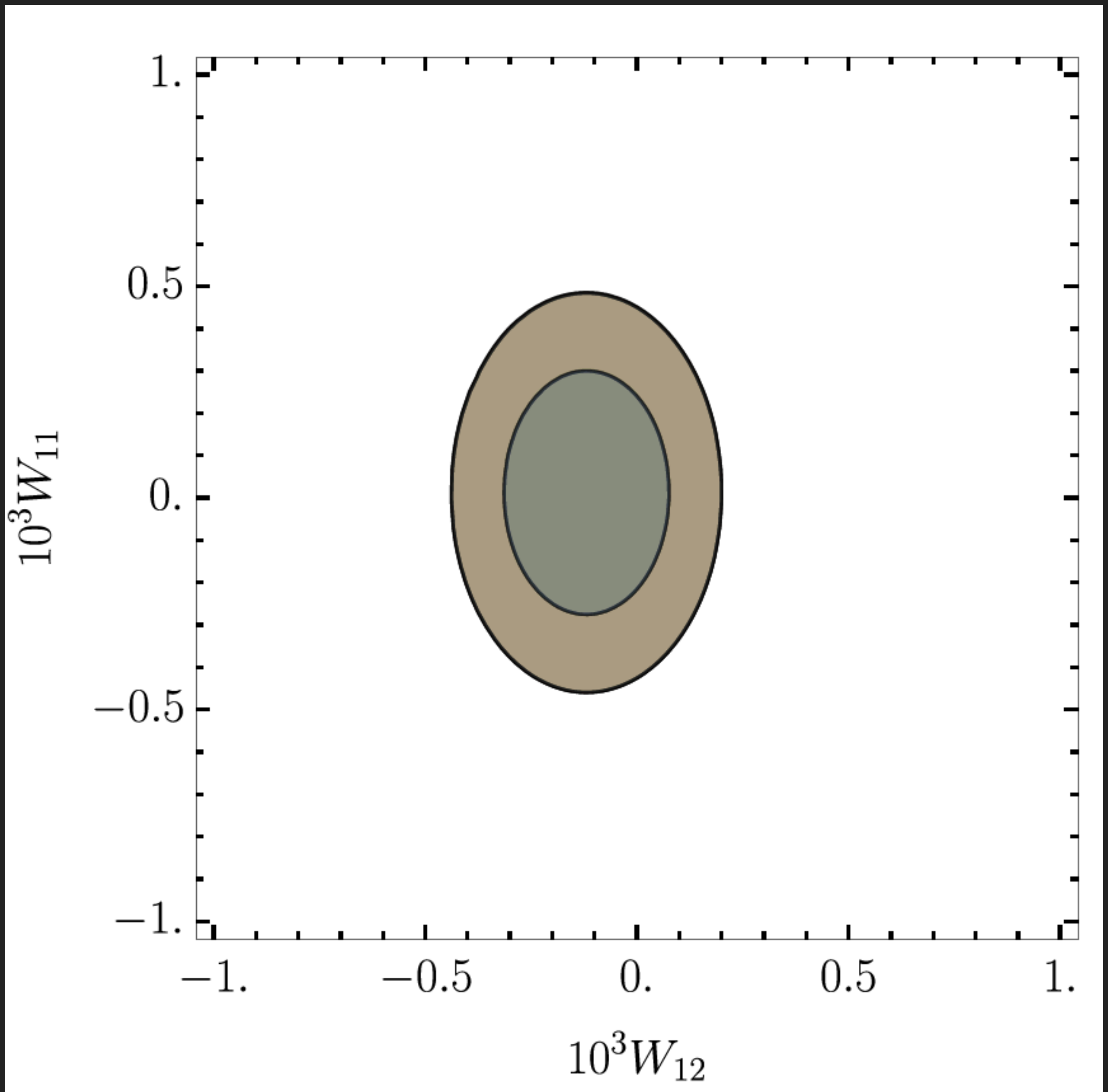
TWO-DIMENSIONAL PROFILES

- variances, correlation agree
- central values differ



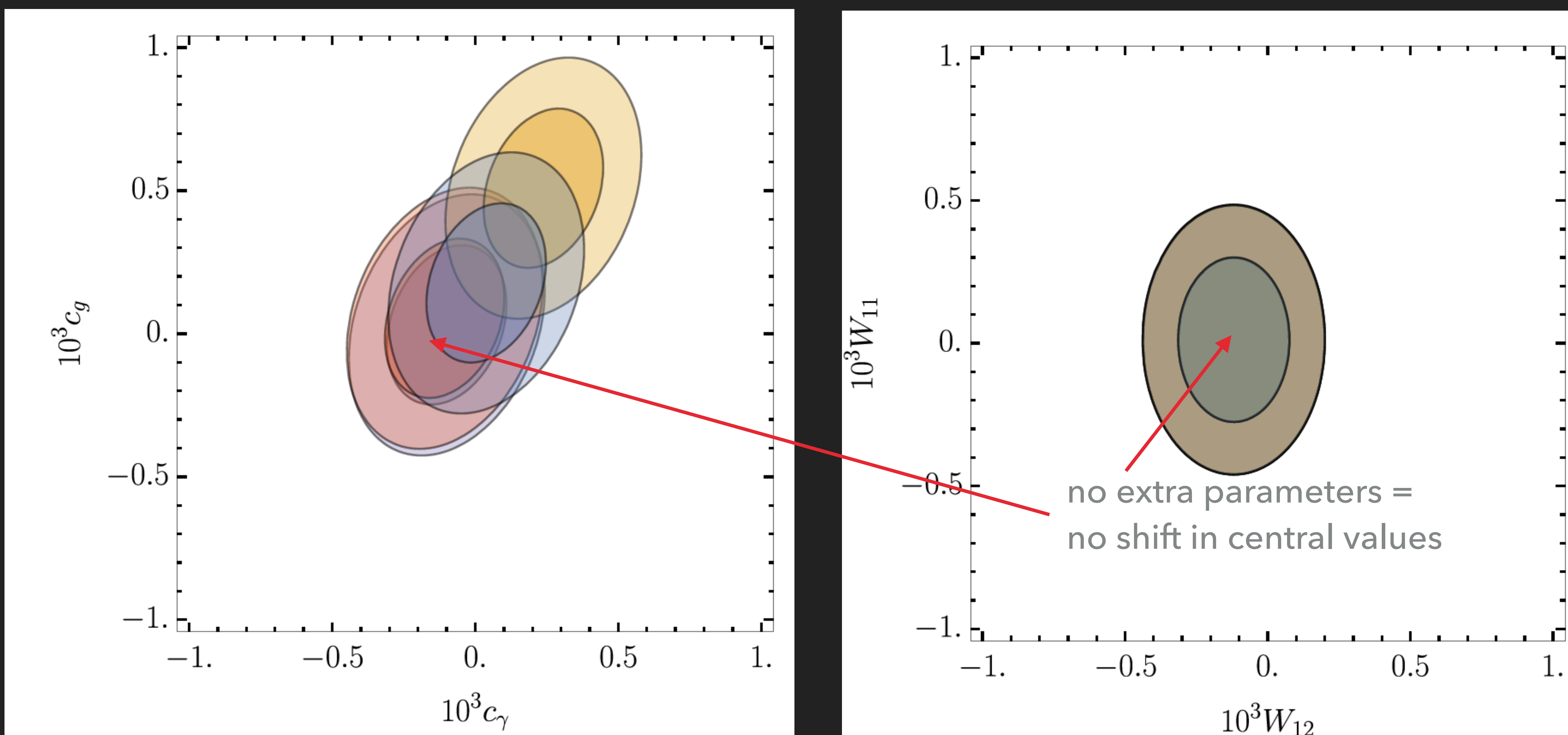
TWO-DIMENSIONAL PROFILES

- All scenarios agree perfectly
- Largely model-independent



TWO-DIMENSIONAL PROFILES

- Presence of extra parameters shifts central values of c_γ, c_g, from central values of W_{11}, W_{12}



PREDICTIONS

- Total width of Higgs boson

$$\frac{\Gamma_{SMEFT,h}}{\Gamma_{SM,h}} \simeq 0.5 \pm 0.4 \quad \text{(Run-1)}$$

$$\frac{\Gamma_{SMEFT,h}}{\Gamma_{SM,h}} \simeq 0.9 \pm 0.3 \quad \text{(Run-1+Run-2)}$$

PREDICTIONS

- Double Higgs boson production
  - CMS upper limit 19x SM rate (ATLAS 29x)
  - In most general case SMEFT bounds not competitive
  - Particular scenarios can be highly restricted, *e.g.* $c_6 = 0$:

$$\sigma_{SMEFT}(gg \to hh)/\sigma_{SM}(gg \to hh) \simeq 1.4 \pm 0.4$$

IMPLICATIONS FOR EW BARYOGENESIS IN SMEFT

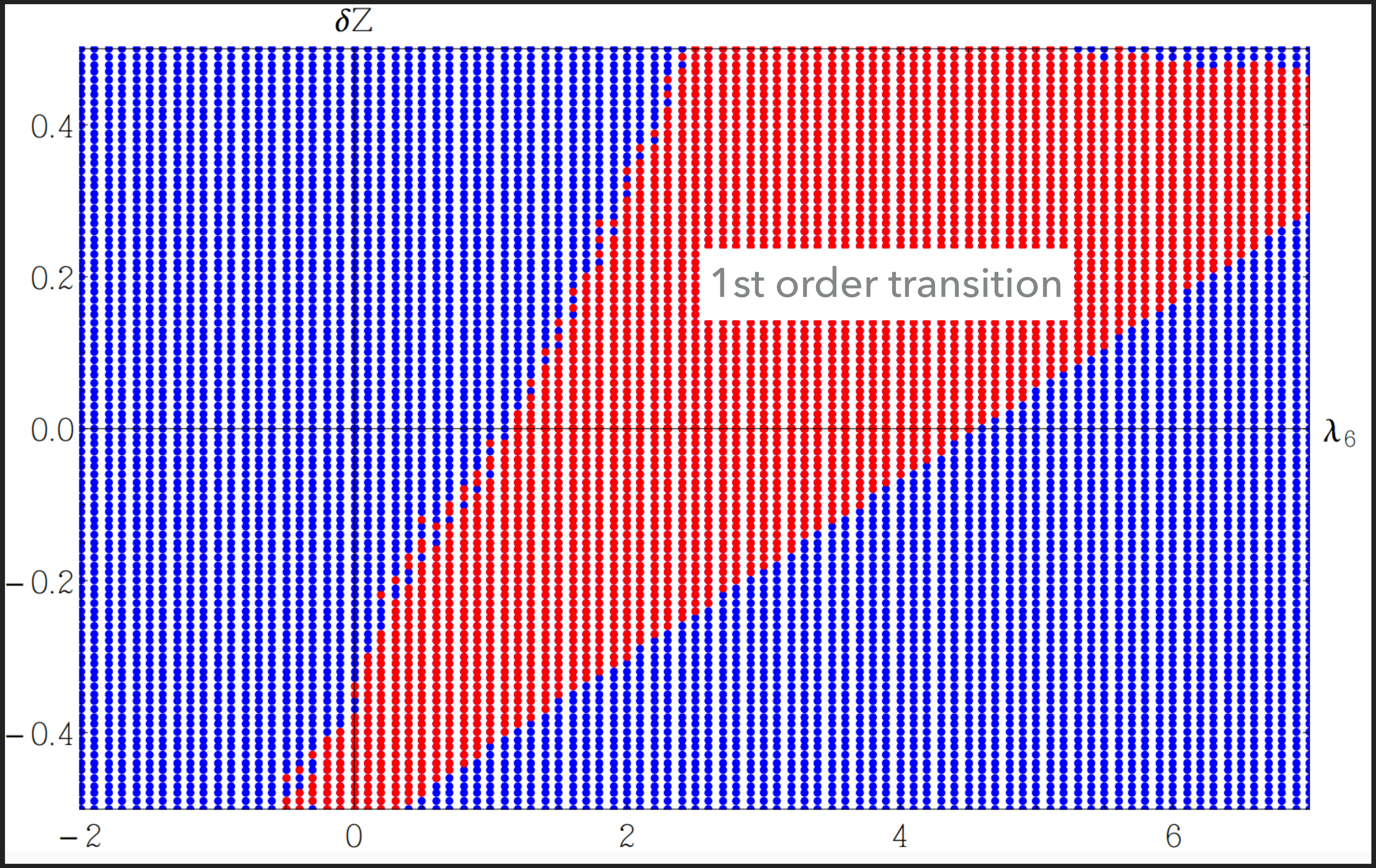
- assuming temperature dependence only in Higgs mass parameter
- 1st order transition if $\frac{2}{3} < \bar{c}_6 < 2$

$$c_H = \frac{1}{2}\bar{c}_H, \quad c_6 = -\frac{m_h^2}{2v^2}\bar{c}_6$$

hep-ph/0407019, 1512.00068, 1512.08922, 1709.03232

IMPLICATIONS FOR EW BARYOGENESIS IN SMEFT

$\propto \bar{c}_H$

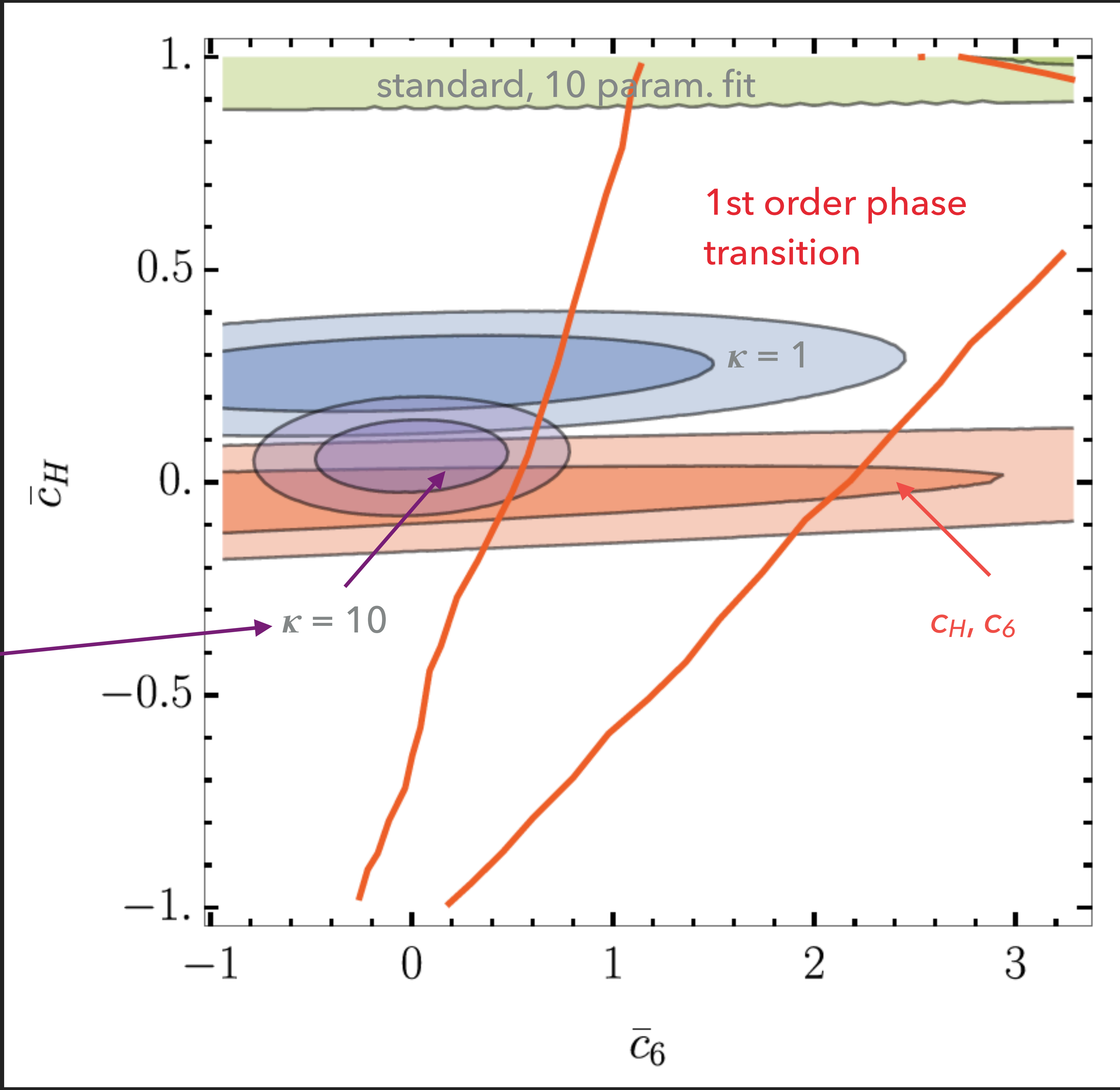


$\propto \bar{c}_6$

1512.01963

IMPLICATIONS FOR EW BARYOGENESIS IN SMEFT

effective scale ~800 GeV – need lower scale BSM



GUIDANCE FOR FUTURE MEASUREMENTS

- Which measurements would improve the global constraints the most?
- Quantify using the global determinant parameter - 1704.02333

$$\mathrm{GDP} = \left(\prod_k \sigma_k^2\right)^{\frac{1}{k}}$$

- ratios of GDPs normalization independent

GUIDANCE FOR FUTURE MEASUREMENTS

- Add one hypothetical signal strength of 1.0 ± 0.1 to the global fit
- Compute GDP ratio with/without additional measurement

Observable	GDP ratio	Observable	GDP ratio
$gg \to hh$	0.37	$Wh,\ h \to ZZ^*$	0.96
$h \to Z\gamma$	0.71	VBF, $h \to b\bar{b}$	0.98
$h \to c\bar{c}$	0.80	Γ_h	0.98
$h \to \mu^+\mu^-$	0.80	$Zh,\ h \to \tau^+\tau^-$	0.99
$tth,\ h \to ZZ^*$	0.93	$tth,\ h \to b\bar{b}$	0.99
$Zh,\ h \to ZZ^*$	0.94	ggF, $h \to b\bar{b}$	0.99

SIMPLIFIED TEMPLATE CROSS SECTIONS

- Tool to use information on kinematics
- Known dependences on operator coefficients

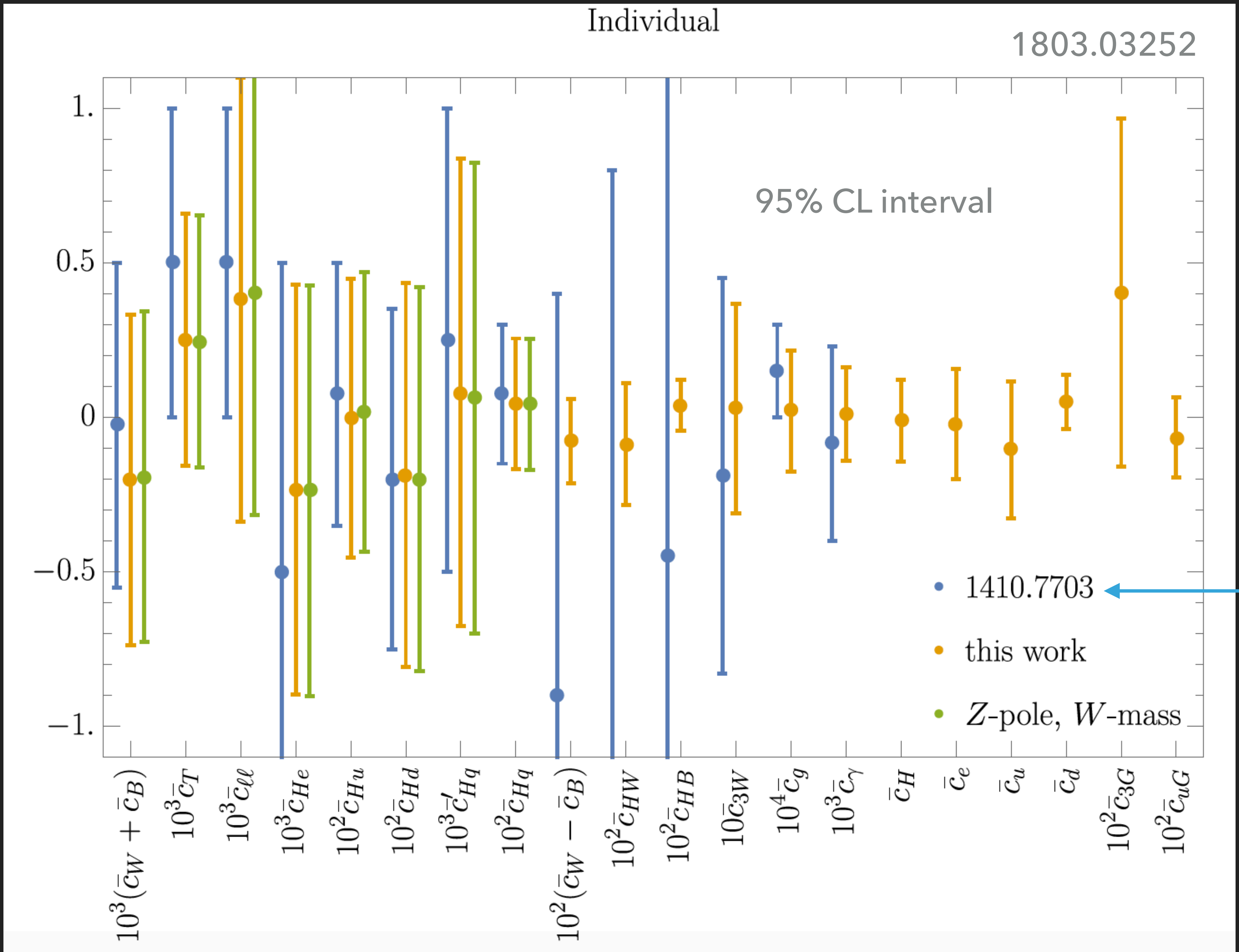
Cross-section region	$\sum_i A_i c_i$
$gg \to H$ (0-jet)	
$gg \to H$ (1-jet, $p_T^H < 60$ GeV)	$56c'_g$
$gg \to H$ (1-jet, $60 \leq p_T^H < 120$ GeV)	
$gg \to H$ (1-jet, $120 \leq p_T^H < 200$ GeV)	$56c'_g + 18\mathtt{c3G} + 11\mathtt{c2G}$
$gg \to H$ (1-jet, $p_T^H \geq 200$ GeV)	$56c'_g + 52\mathtt{c3G} + 34\mathtt{c2G}$
$gg \to H$ ($\geq$ 2-jet, $p_T^H < 60$ GeV)	$56c'_g$
$gg \to H$ ($\geq$ 2-jet, $60 \leq p_T^H < 120$ GeV)	$56c'_g + 8\mathtt{c3G} + 7\mathtt{c2G}$
$gg \to H$ ($\geq$ 2-jet, $120 \leq p_T^H < 200$ GeV)	$56c'_g + 23\mathtt{c3G} + 18\mathtt{c2G}$
$gg \to H$ ($\geq$ 2-jet, $p_T^H \geq 200$ GeV)	$56c'_g + 90\mathtt{c3G} + 68\mathtt{c2G}$
$gg \to H$ ($\geq$ 2-jet VBF-like, $p_T^{j_3} < 25$ GeV)	$56c'_g$
$gg \to H$ ($\geq$ 2-jet VBF-like, $p_T^{j_3} \geq 25$ 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, $p_T^{j_3} \geq 25$ GeV)	$-1.0\mathtt{cH} - 1.1\mathtt{cT} + 1.2\mathtt{cWW} - 0.027\mathtt{cB} - 5.8\mathtt{cHW}$
	$-0.41\mathtt{cHB} + 0.13\mathtt{cHQ} - 6.9\mathtt{cpHQ} - 0.45\mathtt{cHu} + 0.15\mathtt{cHd}$
$qq \to Hqq$ ($p_T^j \geq 200$ GeV)	$-1.0\mathtt{cH} - 0.95\mathtt{cT} + 1.5\mathtt{cWW} - 0.025\mathtt{cB} - 3.6\mathtt{cHW}$
	$-0.24\mathtt{cHB} + 0.084\mathtt{cHQ} - 4.5\mathtt{cpHQ} - 0.25\mathtt{cHu} + 0.1\mathtt{cHd}$
$qq \to Hqq$ ($60 \leq m_{jj} < 120$ 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

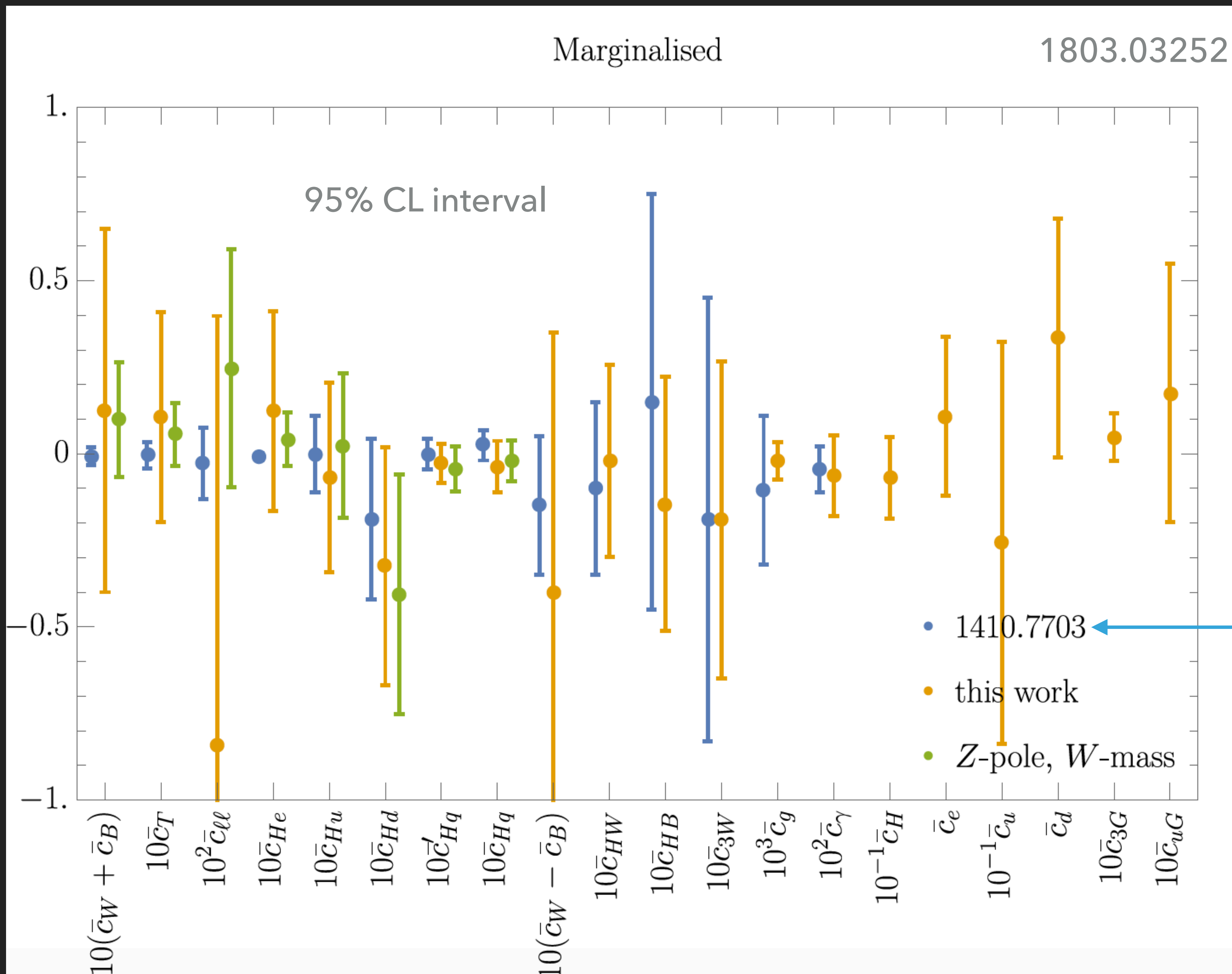
SILH BASIS

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

GLOBAL FITS IN THE SILH BASIS



GLOBAL FITS IN THE SILH BASIS



previous work by JE, VS, TY

PROJECTIONS FOR HL- AND HE-LHC

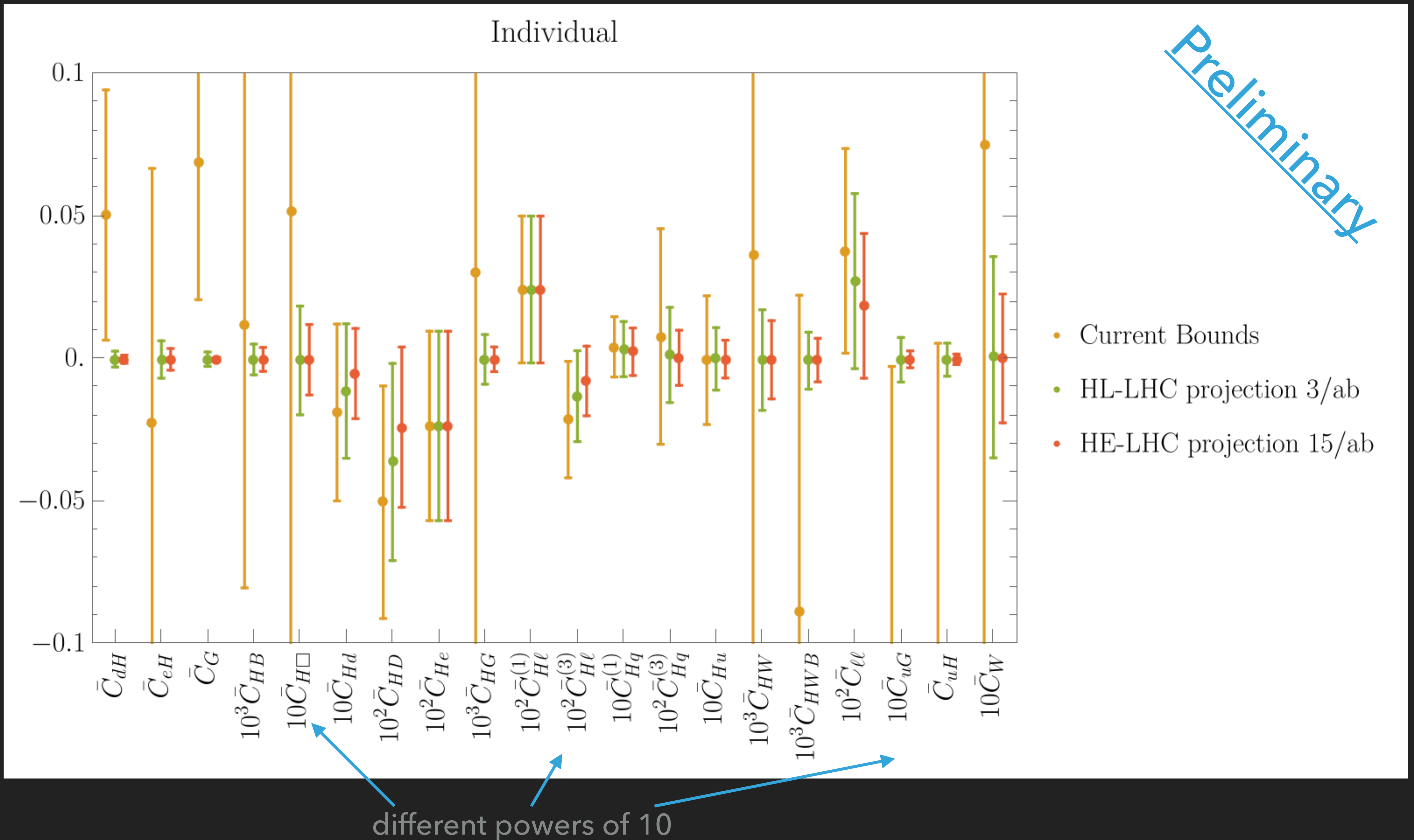
- Study ongoing looking at LHC 13/14 TeV vs. 27 TeV
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop
- "It's difficult to make predictions, especially about the future" - Yogi Berra

PROJECTION STRATEGY

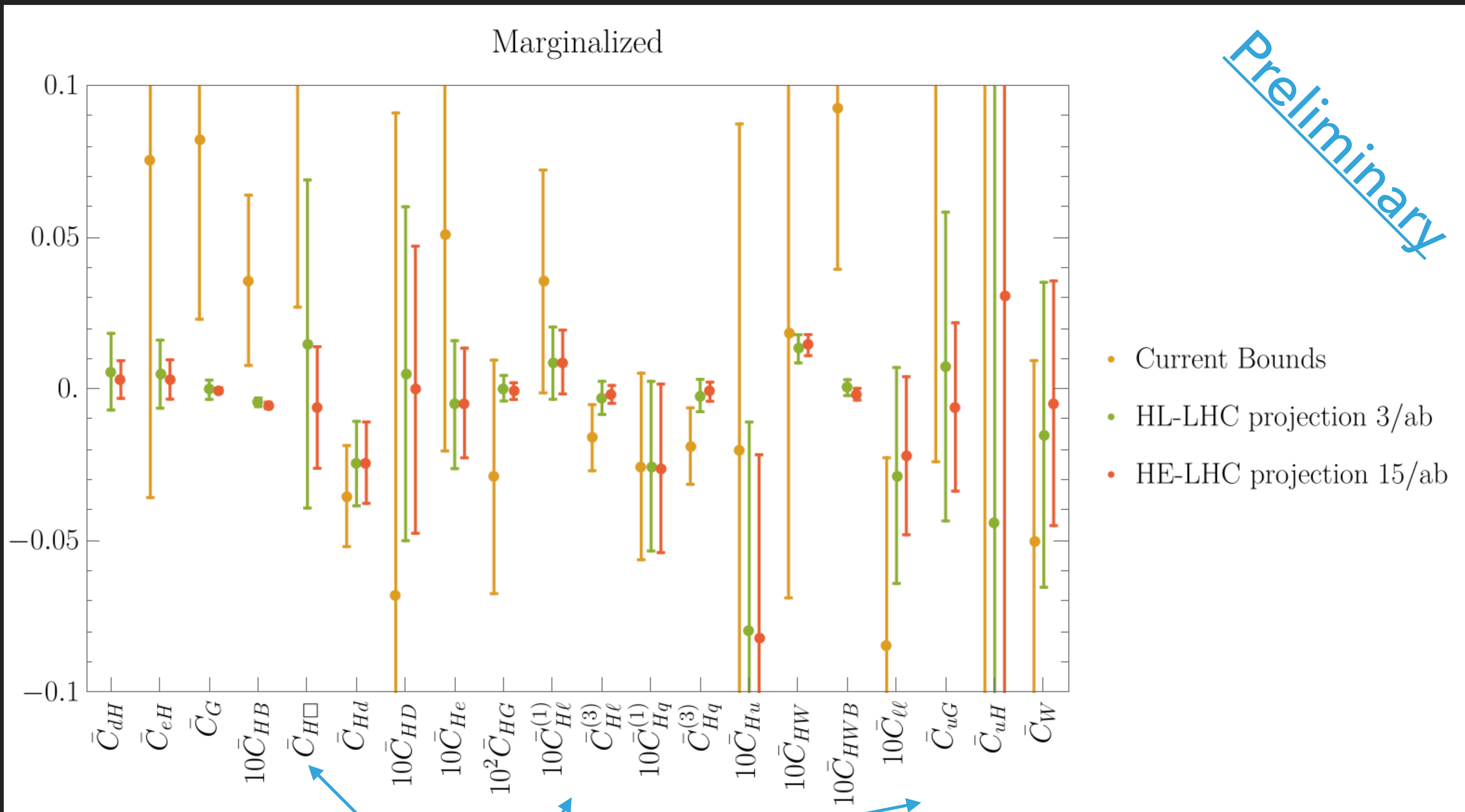
- For each LHC Run-2 measurement used in the fit of 1803.03252
  - Set central value to SM prediction
  - Scale all uncertainties for the *i*th measurement by…
    - HL-LHC: $\sqrt{\frac{L_i}{3/\mathrm{ab}}}$
    - HE-LHC: $\sqrt{\frac{\sigma_{13,i}}{\sigma_{27,i}}\frac{L_i}{15/\mathrm{ab}}}$

    most measurements currently have L_i ~ 36/fb
  - Leave correlations unchanged

PROJECTION: ONE COEFFICIENT AT A TIME



PROJECTION: ALL COEFFICIENTS SIMULTANEOUSLY



different powers of 10

ASSOCIATED PRODUCTION

- Probes many (, many) coefficients
- Generally good sensitivity already in inclusive rates

$\sqrt{s} = 27$ TeV	$\sigma_{SMEFT}/\sigma_{SM}$
Wh	$1 + 2.0\bar{C}_{H\Box} - 2.8\bar{C}_{HD} + 15\bar{C}_{HW} - 5.3\bar{C}_{HWB} - 7.0\bar{C}^{(3)}_{H\ell} + 35\bar{C}^{(3)}_{Hq} + 3.2\bar{C}_{\ell\ell}$
Zh	$1 + 2.0\bar{C}_{H\Box} - 0.24\bar{C}_{HD} + 12\bar{C}_{HW} + 1.7\bar{C}_{HB} + 3.7\bar{C}_{HWB}$ $-5.0\bar{C}^{(3)}_{H\ell} - 1.5\bar{C}^{(1)}_{Hq} + 33\bar{C}^{(3)}_{Hq} + 8.5\bar{C}_{Hu} - 3.1\bar{C}_{Hd} + 2.5\bar{C}_{\ell\ell}$
$t\bar{t}h$	$1 + 2.4\bar{C}_{G} + 1.9\bar{C}_{H\Box} - 0.48\bar{C}_{HD} + 8.7\bar{C}_{HG} - 2.4\bar{C}_{uH}$ $-15\bar{C}_{uG} - 0.49\bar{C}^{(1)}_{Hq} - 0.44\bar{C}^{(3)}_{Hq} - 0.48\bar{C}_{Hu} + 0.49\bar{C}_{\ell\ell} + \ldots$

plus additional dipole & 4-fermion operators

ASSOCIATED PRODUCTION

- Enhancements of certain coefficients at high-p_T
- Similar to high-p_T diboson production at LHC

$\sqrt{s} = 27$ TeV	$\sigma_{SM,LO}$	$\sigma_{SMEFT}/\sigma_{SM}$
Wh, $p_T^h > 250$ GeV	85 fb	$1 + 2.0\bar{C}_{H\Box} - 2.8\bar{C}_{HD} + 18\bar{C}_{HW}$ $-5.2\bar{C}_{HWB} - 7.0\bar{C}^{(3)}_{H\ell} + 2.3 \cdot 10^2\bar{C}^{(3)}_{Hq} + 3.2\bar{C}_{\ell\ell}$
Zh, $p_T^h > 250$ GeV	46 fb	$1 + 2.0\bar{C}_{H\Box} - 0.24\bar{C}_{HD} + 14\bar{C}_{HW} + 2.6\bar{C}_{HB} + 5.2\bar{C}_{HWB}$ $-5.0\bar{C}^{(3)}_{H\ell} - 17\bar{C}^{(1)}_{Hq} + 2.1 \cdot 10^2\bar{C}^{(3)}_{Hq} + 55\bar{C}_{Hu} - 18\bar{C}_{Hd} + 2.5\bar{C}_{\ell\ell}$