SMEFT interpretation within the SMEFiT toolbox

Luca Mantani

In collaboration with:
J. Ethier, F. Maltoni, E. Nocera, J. Rojo, E. Slade, E. Vryonidou and C. Cen

UCLouvain

Slide from Juan Rojo's talk at LHCEFTWG

Building upon extensive **expertise in global PDF determinations**, SMEFiT was designed as a **flexible EFT analysis framework** with the built-in capabilities for producing a **global EFT interpretation of particle physics data** (including non-LHC constraints)

SMEFiT

Publications based on SMEFiT:

- ***A Monte Carlo global analysis of the Standard Model Effective Field Theory: the top quark sector,*** Hartland, Maltoni, Nocera, JR, Slade, Vryodinou, Zhang, JHEP 04 (2019) 100, arXiv:1901.05965 [hep-ph]
- ***Constraining the SMEFT with Bayesian reweighting,*** van Beek, Nocera, JR, Slade, SciPost Phys. 7 (2019) 5, 070, arXiv:1906.05296 [hep-ph]
- ***SMEFT analysis of vector boson scattering and diboson data from the LHC Run II,*** Ethier, Gomez-Ambrosio, Magni, JR, arXiv:2101.03180 [hep-ph] — See G. Magni talk
- ***Combined EFT interpretation of Higgs, electroweak, and top quark measurements at the LHC,*** Ethier, Maltoni, Luca Mantani, Nocera, JR, Slade, Vryonidou, Zhang, in preparation

representative results show in this talk

6

Theory

(N)NLO QCD + NLO EW SM XS

NLO-QCD, linear and quadratic, EFT (**SMEFT@NLO**)

PDFs, avoid redundancy (no top)

Data

Higgs data (inclusive, diff, STXS)

Top quark data

Diboson production (LEP + LHC)

SMEFiT

Output

Validation statistical toolbox: **Fisher information, PCA, closure tests**

Posterior probabilities in EFT parameter space**, CL intervals**

Methodology

Two independent fitting methods: **MCfit** and **Nested Sampling**

Modular structure: easy to add new theory predictions and data

MCnet

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{1}{\Lambda}\mathcal{O}_i^5 + \sum_i \frac{1}{\Lambda^2}\mathcal{O}_i^6 + \ldots$$

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Dim 6: Large number of operators and therefore degrees of freedom

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Many observables and final states → **Break degeneracies in parameter space**

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Many observables and final states → **Break degeneracies in parameter space**

$$\mathcal{O} = \mathcal{O}_{SM} + \frac{C_i}{\Lambda^2}\,\mathcal{O}_i^{INT} + \frac{C_i\,C_j}{\Lambda^4}\,\mathcal{O}_{ij}^{SQ}$$

NLO-QCD with SMEFT@NLO

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Linear contribution: leading correction

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NLO-QCD with SMEFT@NLO

Linear contribution: leading correction

Quadratic contribution: useful information in many instances

EWPO

$$\frac{1}{4}g_1^2\left(-2c_{\varphi l_1}^{(3)}-2c_{\varphi l_2}^{(3)}+c_{ll}\right)-\frac{c_{\varphi D}g_w^2}{4}-g_1g_wc_{\varphi WB},$$

$$c_{\varphi l_i}^{(3)}-f\left(-\frac{1}{2},-1\right)+f\left(\frac{1}{2},0\right)\qquad i=1,2,3,$$

$$f\left(-\frac{1}{2},-1\right)-\frac{c_{\varphi l_i}^{(3)}}{2}-\frac{c_{\varphi l_i}^{(1)}}{2}\qquad i=1,2,3,$$

$$f(0,-1)-\frac{c_{\varphi e}}{2},\qquad f(0,-1)-\frac{c_{\varphi\mu}}{2},\qquad f(0,-1)-\frac{c_{\varphi\tau}}{2},$$

$$f\left(\frac{1}{2},\frac{2}{3}\right)-\frac{c_{\varphi q}^{(-)}}{2},\qquad f\left(-\frac{1}{2},-\frac{1}{3}\right)-\frac{c_{\varphi q}^{(-)}}{2}-c_{\varphi q}^{(3)}$$

$$f\left(0,\frac{2}{3}\right)-\frac{c_{\varphi u}}{2},\qquad f\left(0,-\frac{1}{3}\right)-\frac{c_{\varphi d}}{2},$$

where the function f is given by:

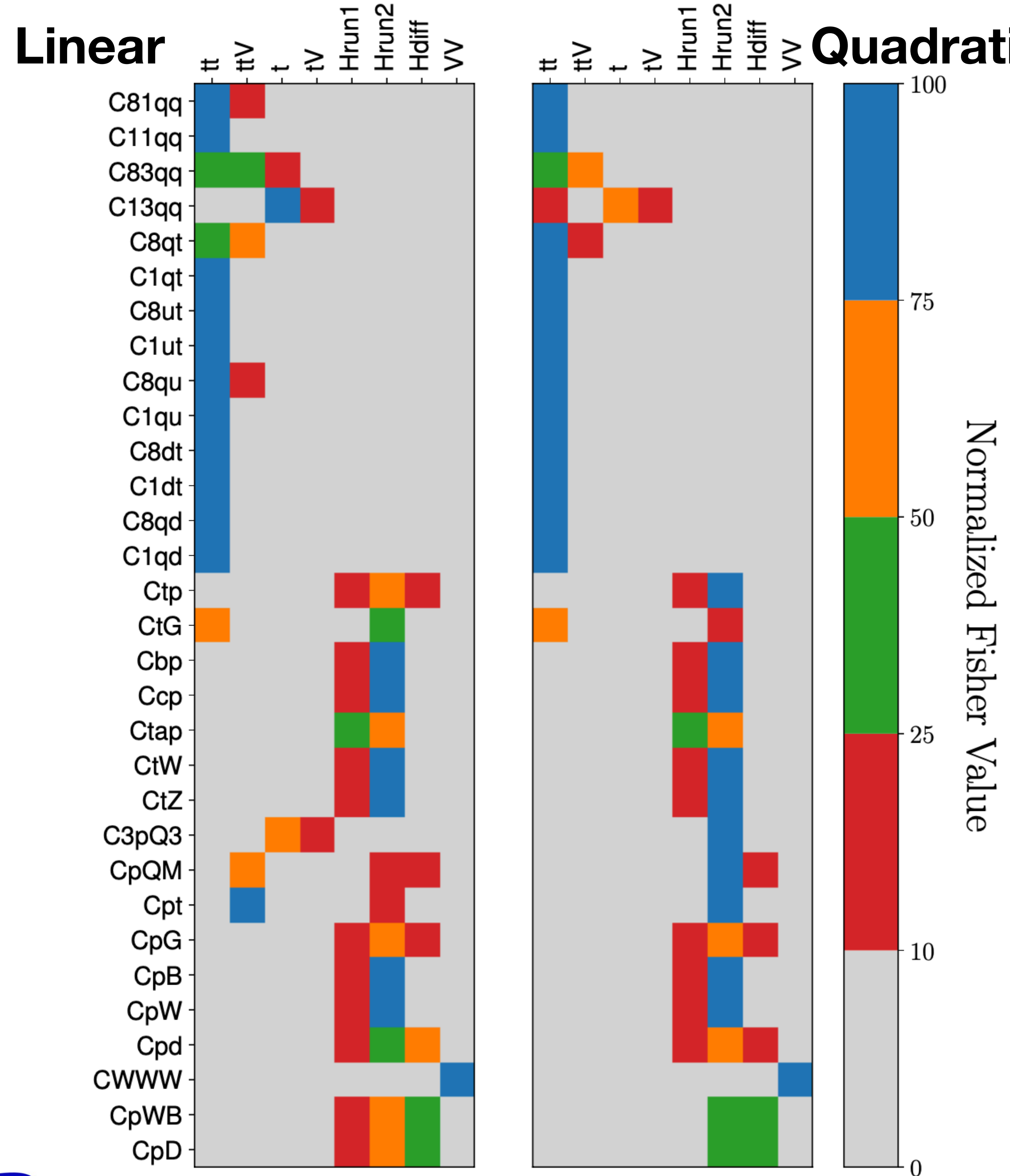
$$f(T_3,Q)=\left(-\frac{c_{\varphi l_1}^{(3)}}{2}-\frac{c_{\varphi l_2}^{(3)}}{2}+\frac{c_{ll}}{4}-\frac{c_{\varphi D}}{4}\right)\left(\frac{g_1^2Q}{g_w^2-g_1^2}+T_3\right)-c_{\varphi WB}\frac{Qg_1g_w}{g_w^2-g_1^2},$$

Class	$N_{\rm dof}$	Independent DOFs	DoF in EWPOs
four-quark (two-light-two-heavy)	14	$c_{Qq}^{1,8}, c_{Qq}^{1,1}, c_{Qq}^{3,8}$, $c_{Qq}^{3,1}, c_{tq}^{8}, c_{tq}^{1}$, $c_{tu}^{8}, c_{tu}^{1}, c_{Qu}^{8}$, $c_{Qu}^{1}, c_{td}^{8}, c_{td}^{1}$, c_{Qd}^{8}, c_{Qd}^{1}	
four-quark (four-heavy)	5	$c_{QQ}^{1}, c_{QQ}^{8}, c_{Qt}^{1}$, c_{Qt}^{8}, c_{tt}^{1}	
four-lepton	1		c_{ll}
two-fermion (+ bosonic fields)	23	$c_{t\varphi}, c_{tG}, c_{b\varphi}$, $c_{c\varphi}, c_{\tau\varphi}, c_{tW}$, $c_{tZ}, c_{\varphi Q}^{(3)}, c_{\varphi Q}^{(-)}$, $c_{\varphi t}$	$c_{\varphi l_1}^{(1)}, c_{\varphi l_1}^{(3)}, c_{\varphi l_2}^{(1)}$, $c_{\varphi l_2}^{(3)}, c_{\varphi l_3}^{(1)}, c_{\varphi l_3}^{(3)}$, $c_{\varphi e}, c_{\varphi\mu}, c_{\varphi\tau}$, $c_{\varphi q}^{(3)}, c_{\varphi q}^{(-)}$, $c_{\varphi u}, c_{\varphi d}$
Purely bosonic	7	$c_{\varphi G}, c_{\varphi B}, c_{\varphi W}$, $c_{\varphi d}, c_{WWW}$	$c_{\varphi WB}, c_{\varphi D}$
Total	50 (36 independent)	34	16 (2 independent)

Category	Processes	n_{dat}
Top quark production	$t\bar{t}$ (inclusive)	94
	$t\bar{t}Z$, $t\bar{t}W$	14
	single top (inclusive)	27
	tZ, tW	9
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6
	Total	**150**
Higgs production and decay	Run I signal strengths	22
	Run II signal strengths	40
	Run II, differential distributions & STXS	35
	Total	**97**
Diboson production	LEP-2	40
	LHC	30
	Total	**70**
Baseline dataset	**Total**	**317**

Useful to gain insight from Information Geometry

$$I_{ij}(\boldsymbol{c}) = -\mathrm{E}\left[\frac{\partial^2 \ln f\left(\boldsymbol{\sigma}_{\exp} \mid \boldsymbol{c}\right)}{\partial c_i \partial c_j}\right]$$



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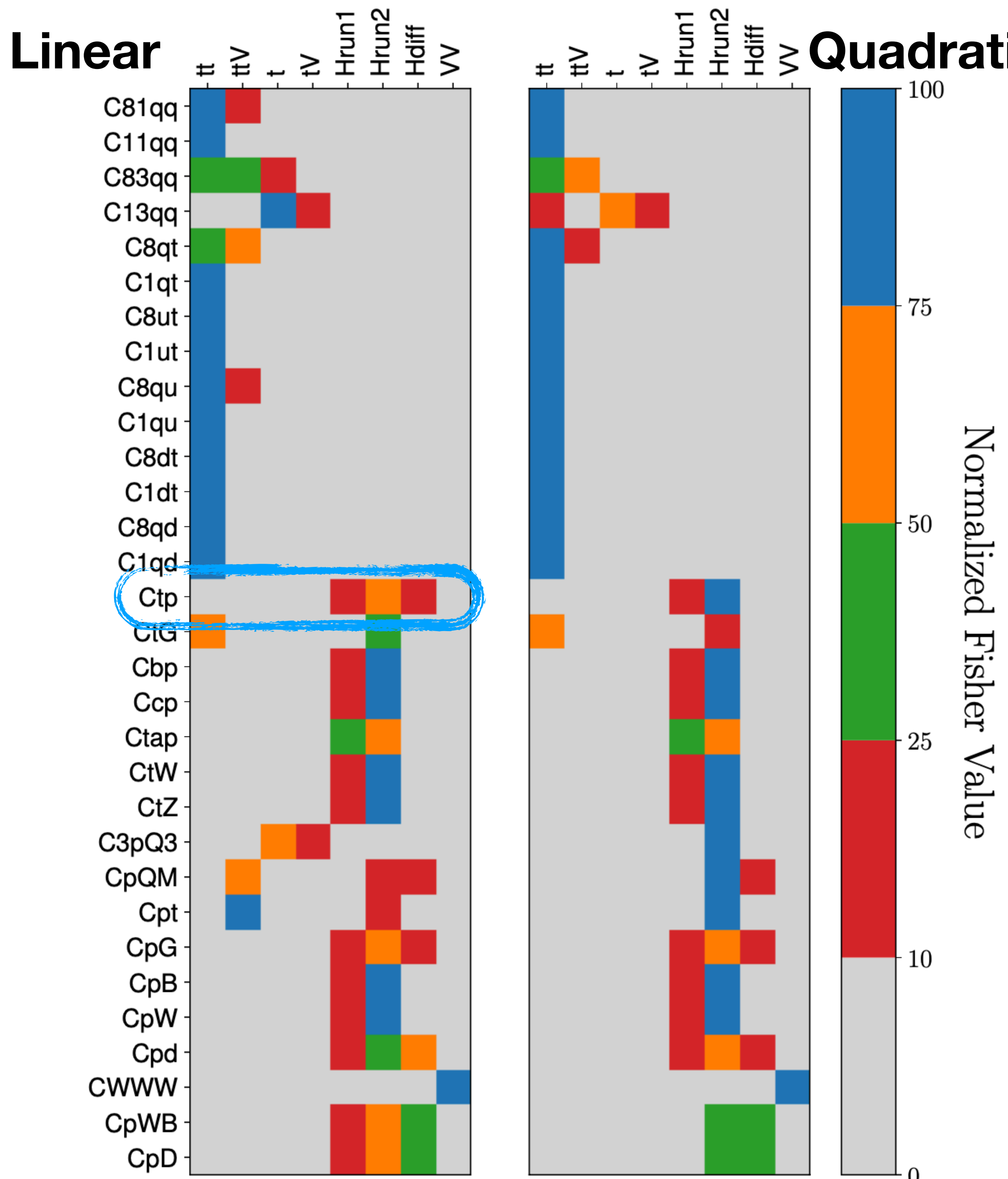

Top Yukawa

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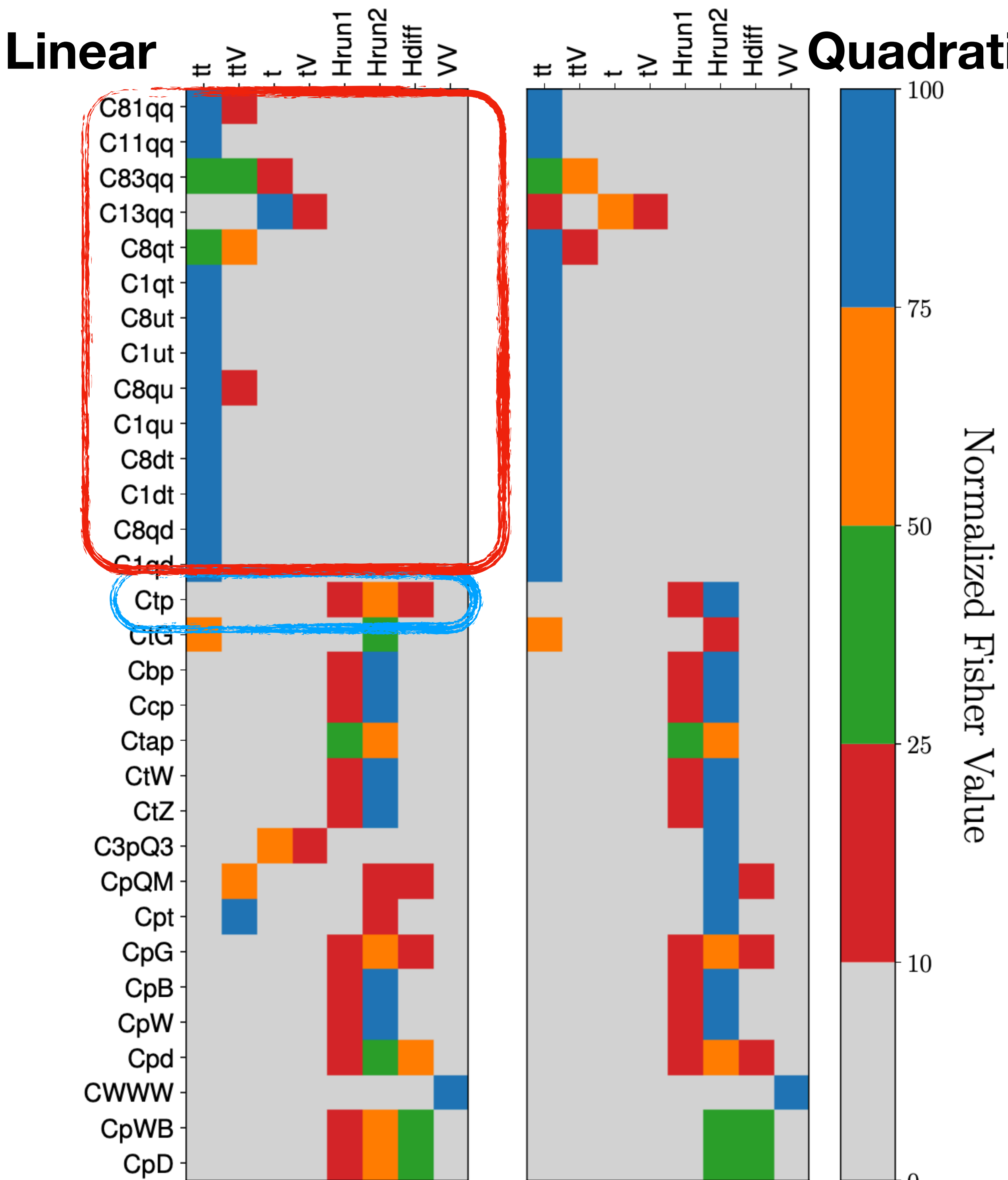

Top Yukawa

Four fermion operators

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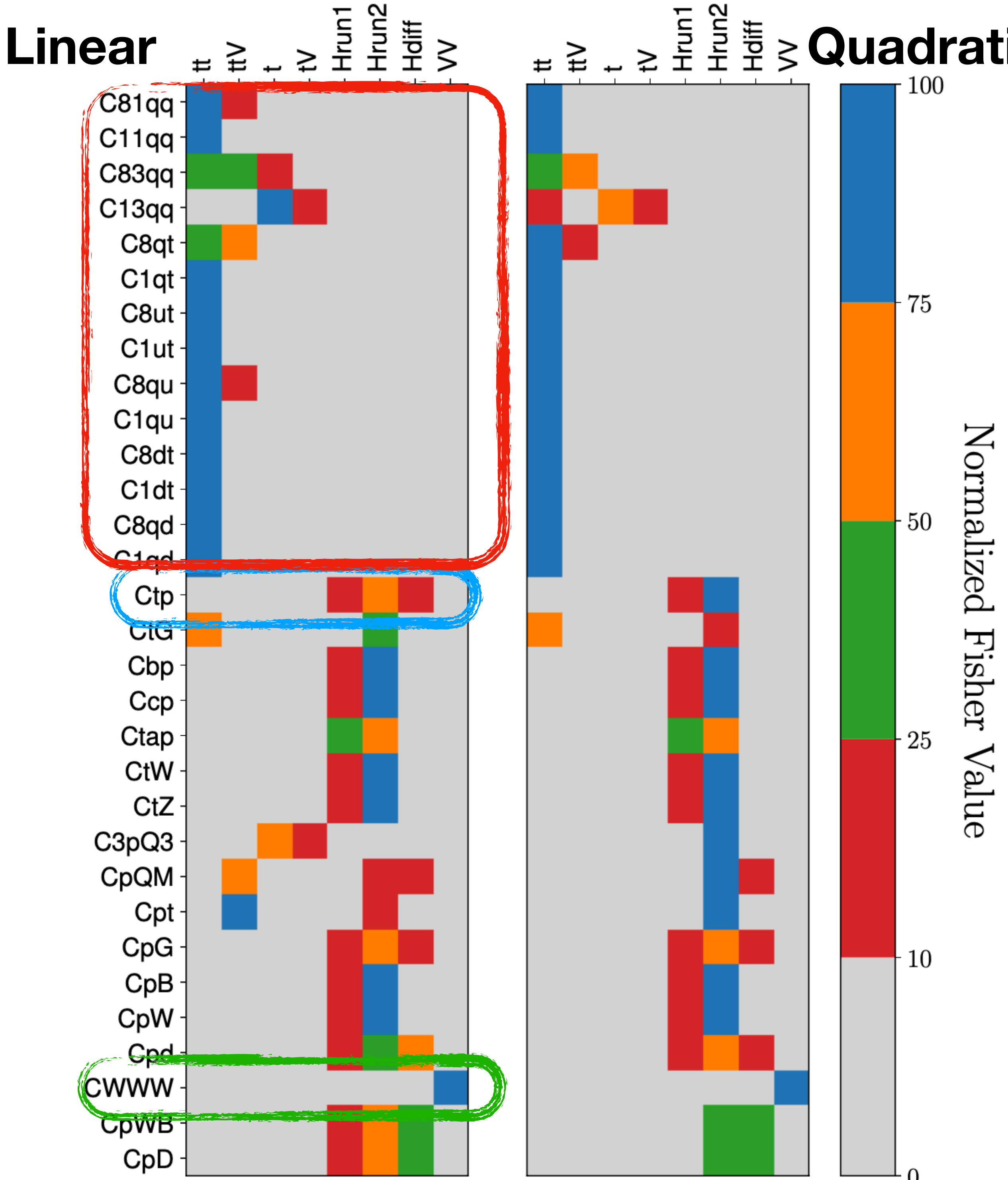

Top Yukawa

Four fermion operators

TGC operator

Useful to gain insight from Information Geometry

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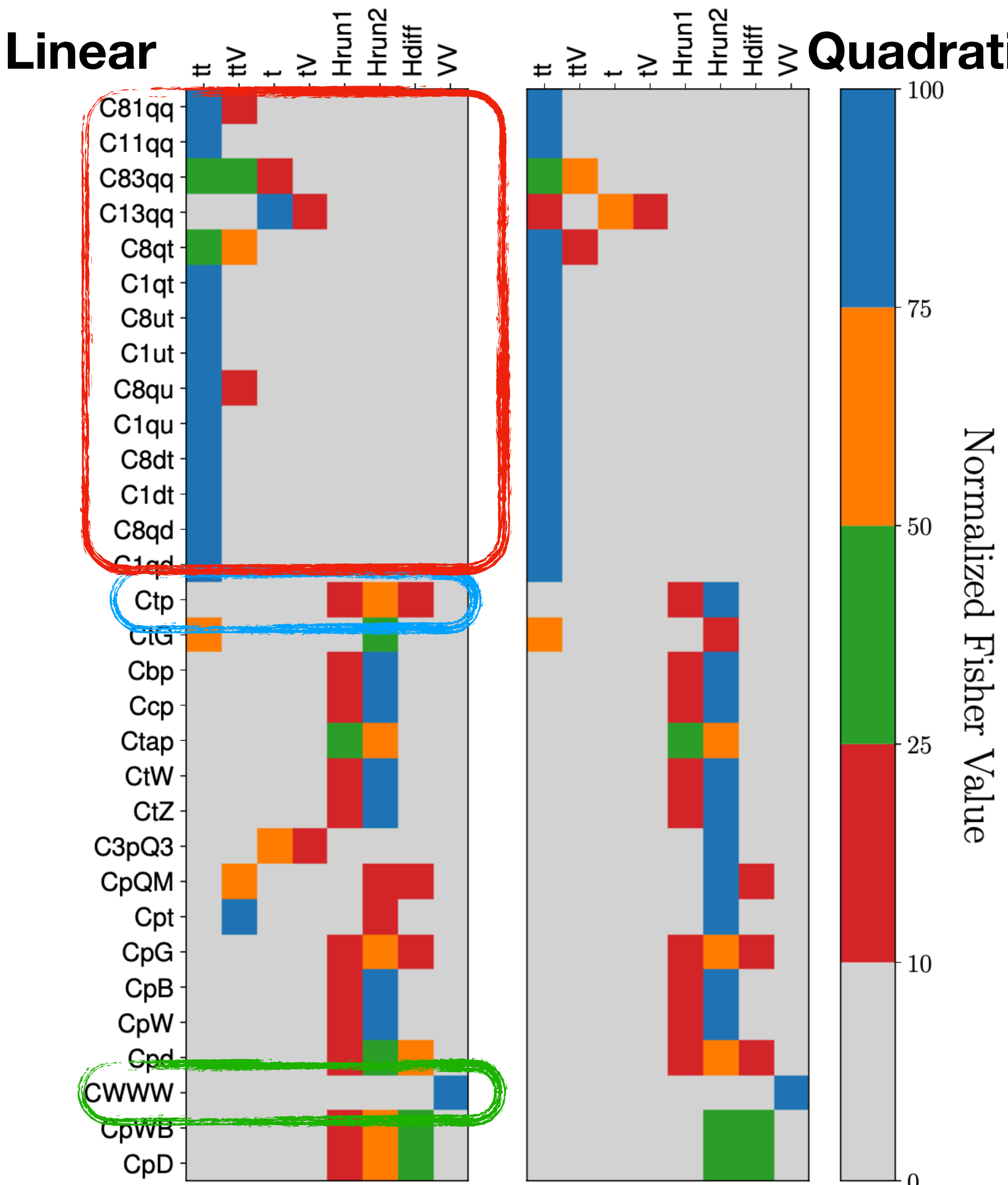

Top Yukawa

Four fermion operators

TGC operator

In the quadratic case the picture does not change much

$$\chi^2(\boldsymbol{c}) \equiv \frac{1}{n_{\rm dat}} \sum_{i,j=1}^{n_{\rm dat}} \left(\sigma_i^{(\rm th)}(\boldsymbol{c}) - \sigma_i^{(\rm exp)}\right) \left(\text{cov}^{-1}\right)_{ij} \left(\sigma_j^{(\rm th)}(\boldsymbol{c}) - \sigma_j^{(\rm exp)}\right)$$

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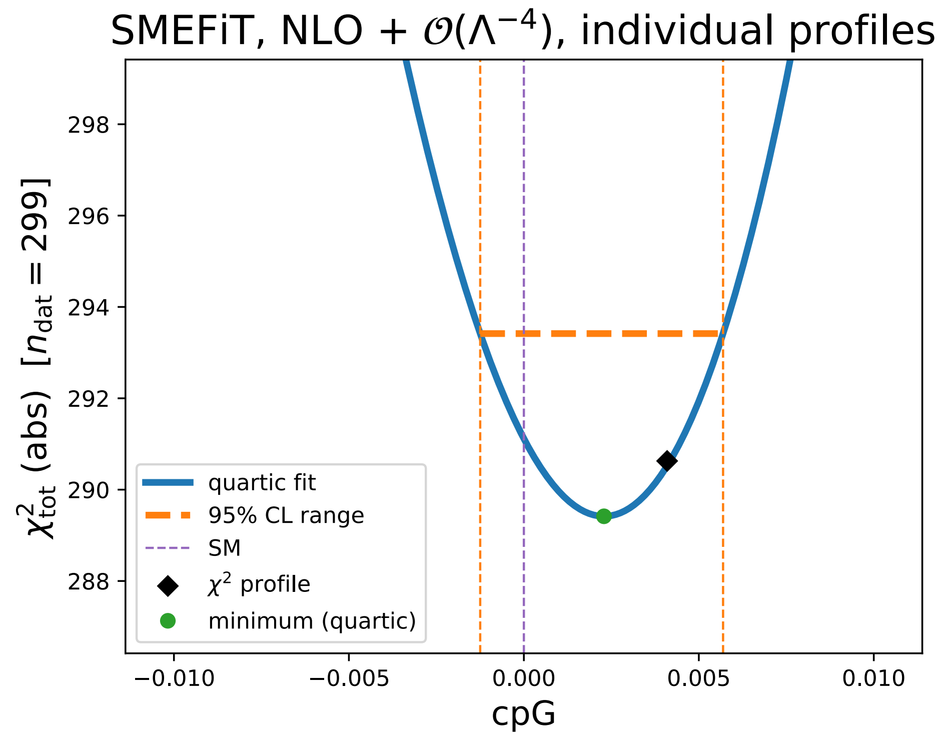

Gaussian profile

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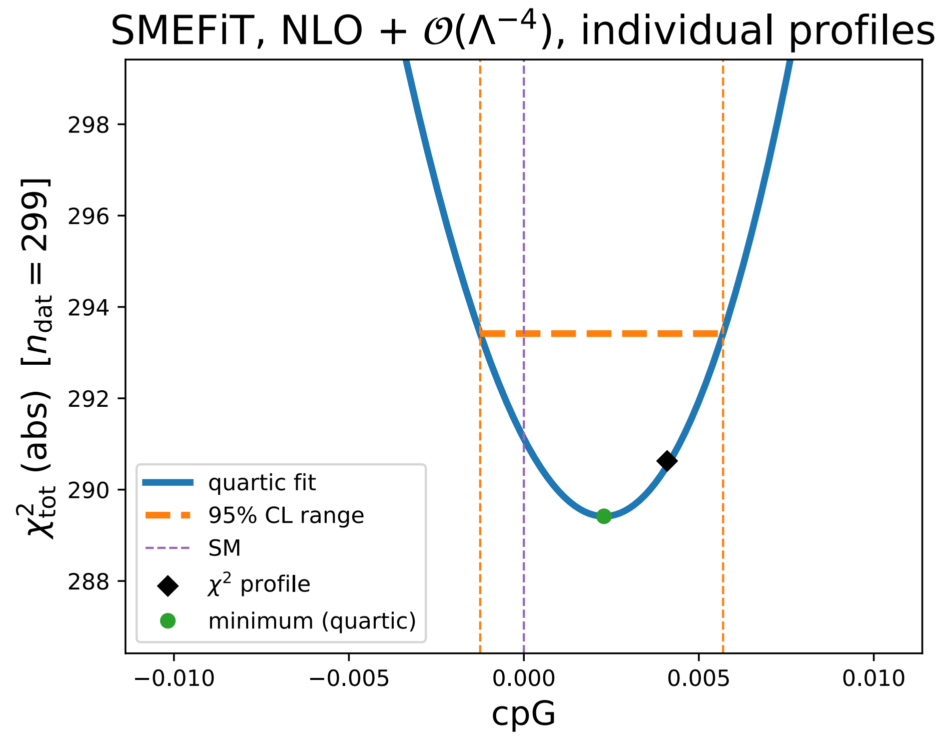
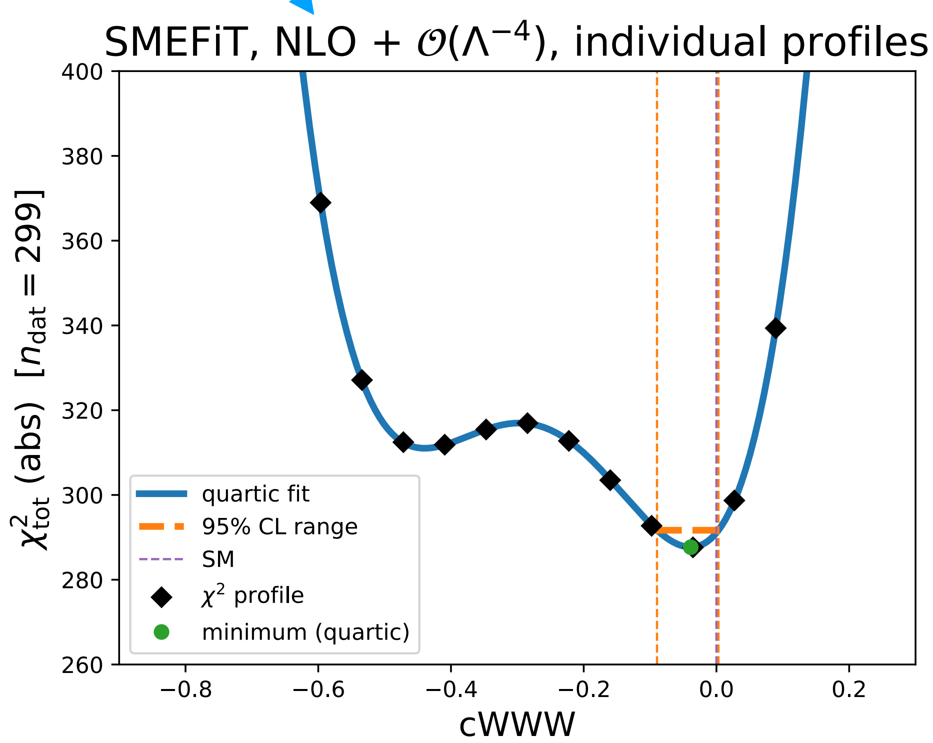


Gaussian profile

Non gaussian global minimum



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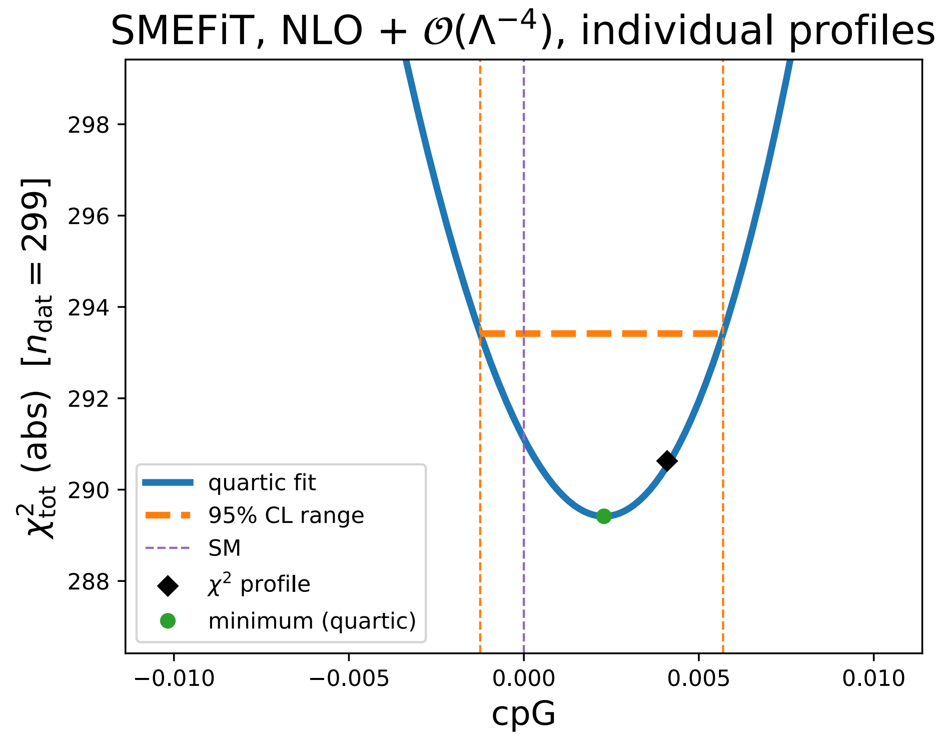
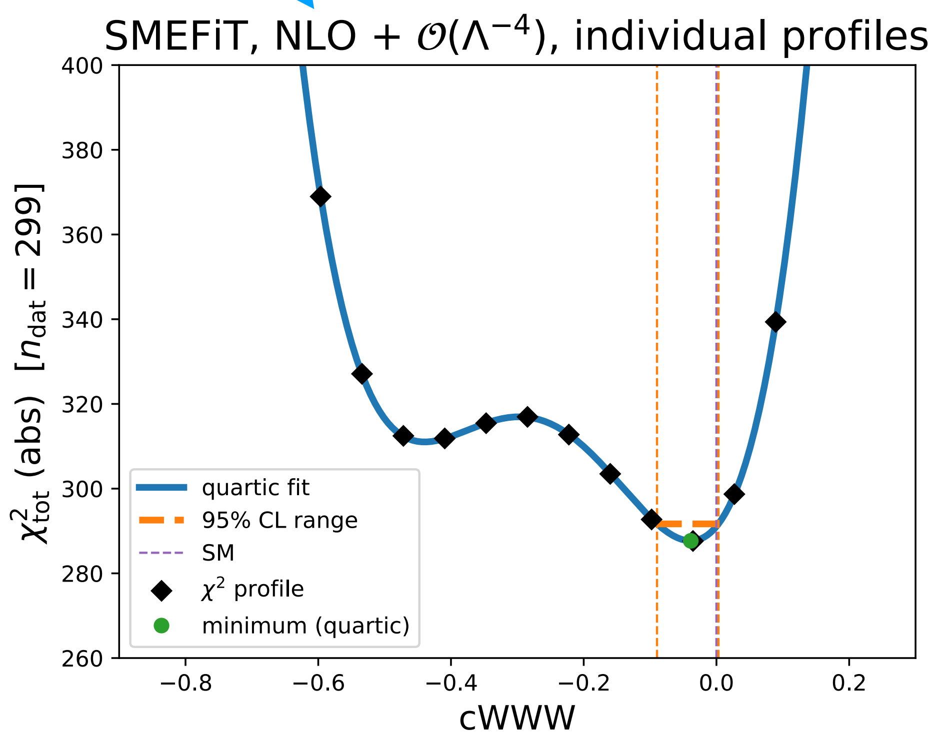
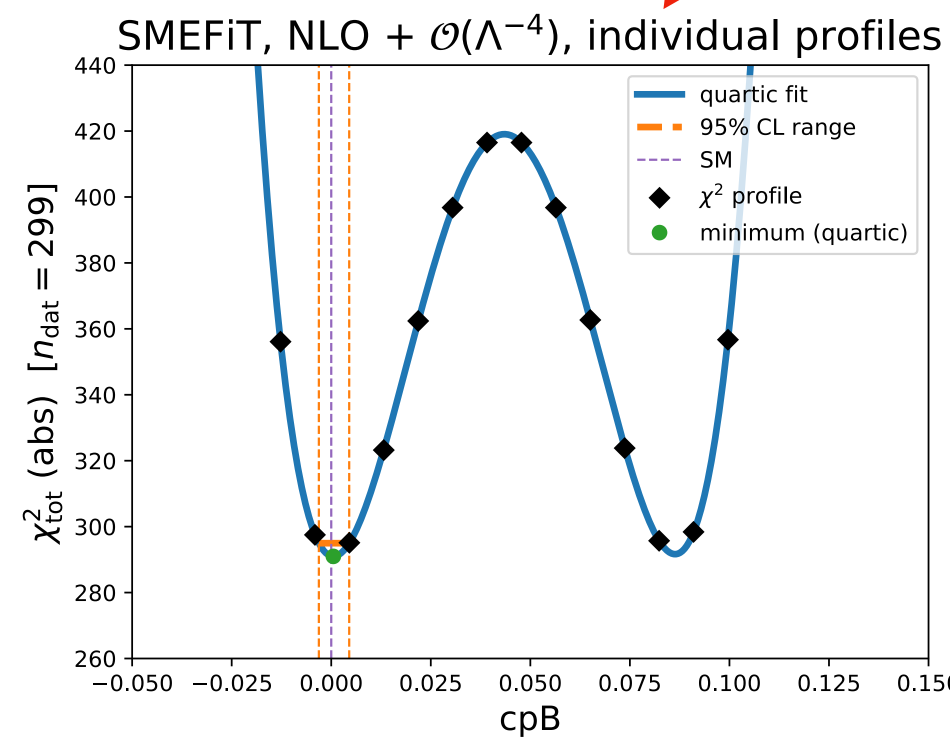


Gaussian profile

Non gaussian global minimum

Degenerate minima





MCfit: generate MC replicas to construct **probability distribution** in experimental data space.
Determine EFT coefficients **replica by replica.**

$$E(\{c_l^{(k)}\}) \equiv \frac{1}{N_{\rm dat}} \sum_{i,j=1}^{N_{\rm dat}} \left(\mathcal{O}_i^{(\rm th)} \left(\{c_n^{(k)}\} \right) - \mathcal{O}_i^{(\rm art)(k)} \right) ({\rm cov}^{-1})_{ij} \left(\mathcal{O}_j^{(\rm th)} \left(\{c_n^{(k)}\} \right) - \mathcal{O}_j^{(\rm art)(k)} \right)$$

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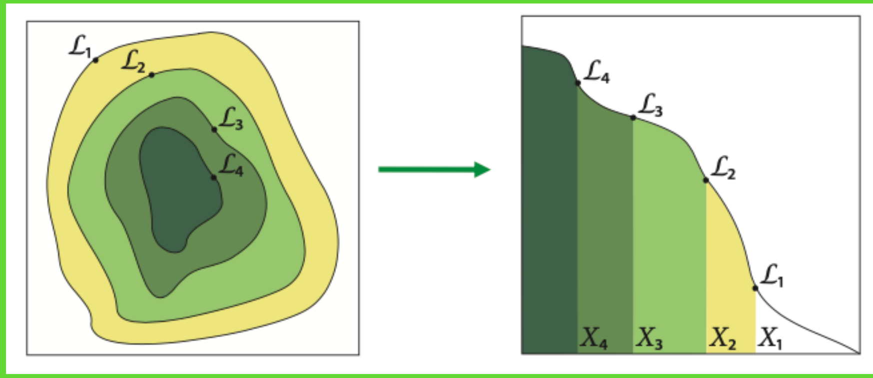
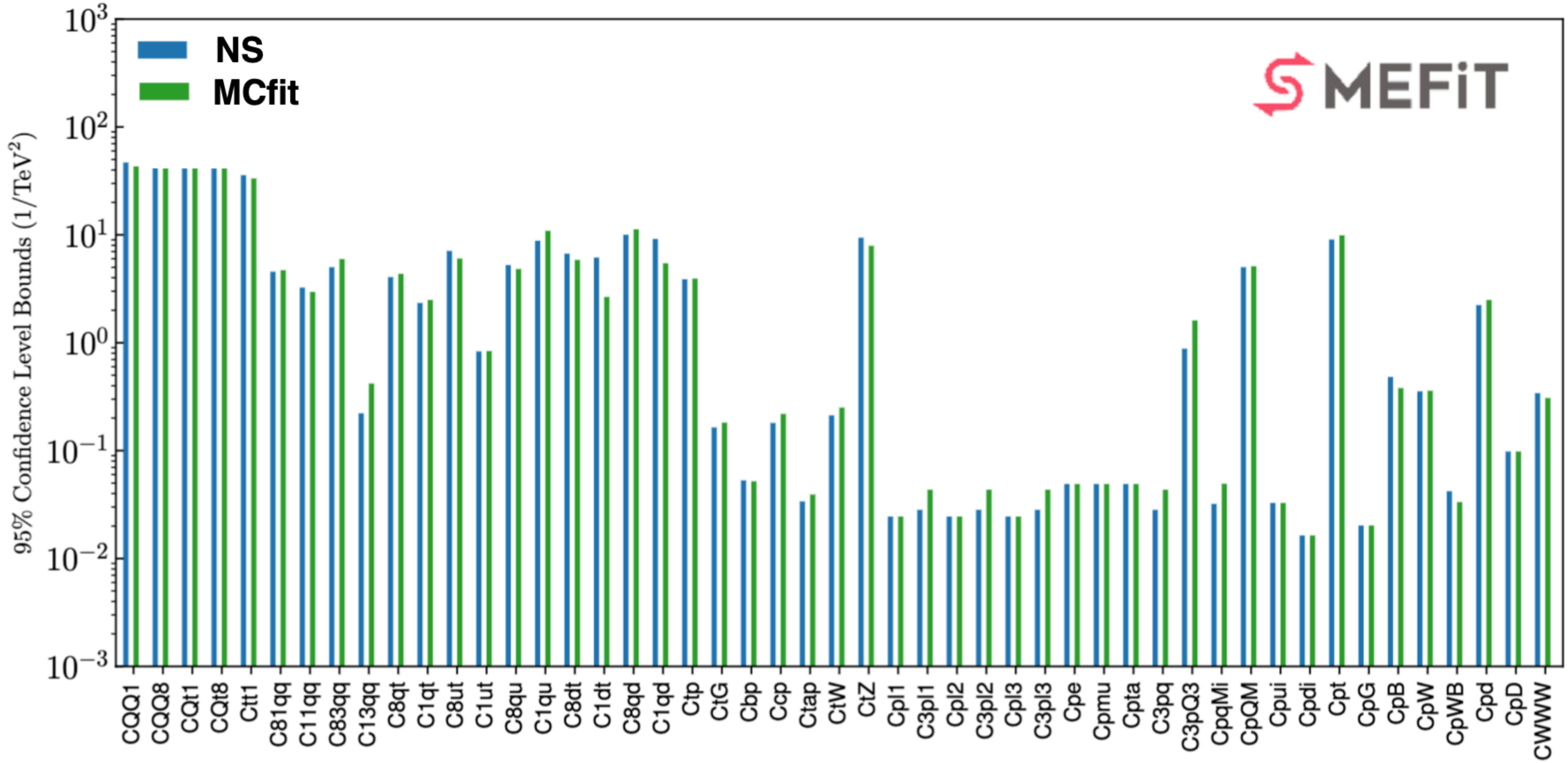
Nested Sampling: statistical mapping of the likelihood**.**

$$Z = \int d^N c \mathscr{L}\left(\text{data} \,|\, \vec{c}\right) \pi(\vec{c}) = \int_0^1 dX \mathscr{L}(X)$$



Samples from prior space to locate maximum.
No need for optimisers.
Construct posterior distribution.

MCfit: generate MC replicas to construct **probability distribution** in



Construct posterior distribution.

Chi2 values: slight improvement (dataset dependent)

Dataset	$n_{\rm dat}$	$\chi^2_{\rm SM}/n_{\rm dat}$	$\chi^2_{\rm EFT}/n_{\rm dat}$ (Λ^{-2})	$\chi^2_{\rm EFT}/n_{\rm dat}$ (Λ^{-4})
$t\bar{t}$ inclusive	94	1.36	1.14	1.23
$t\bar{t}+V$	14	0.65	0.60	0.68
single-top inclusive	27	0.43	0.45	0.43
single-top $+V$	9	0.71	0.71	0.61
$t\bar{t}b\bar{b}$ & $t\bar{t}t\bar{t}$	6	1.68	1.05	1.91
Higgs signal strenghts (Run I)	22	0.86	0.84	0.89
Higgs signal strenghts (Run II)	40	0.68	0.65	0.62
Higgs differential & STXS	35	0.88	0.84	0.83
Diboson (LEP+LHC)	70	1.31	1.31	1.32
Total	**317**	**1.05**	**0.96**	**1.01**

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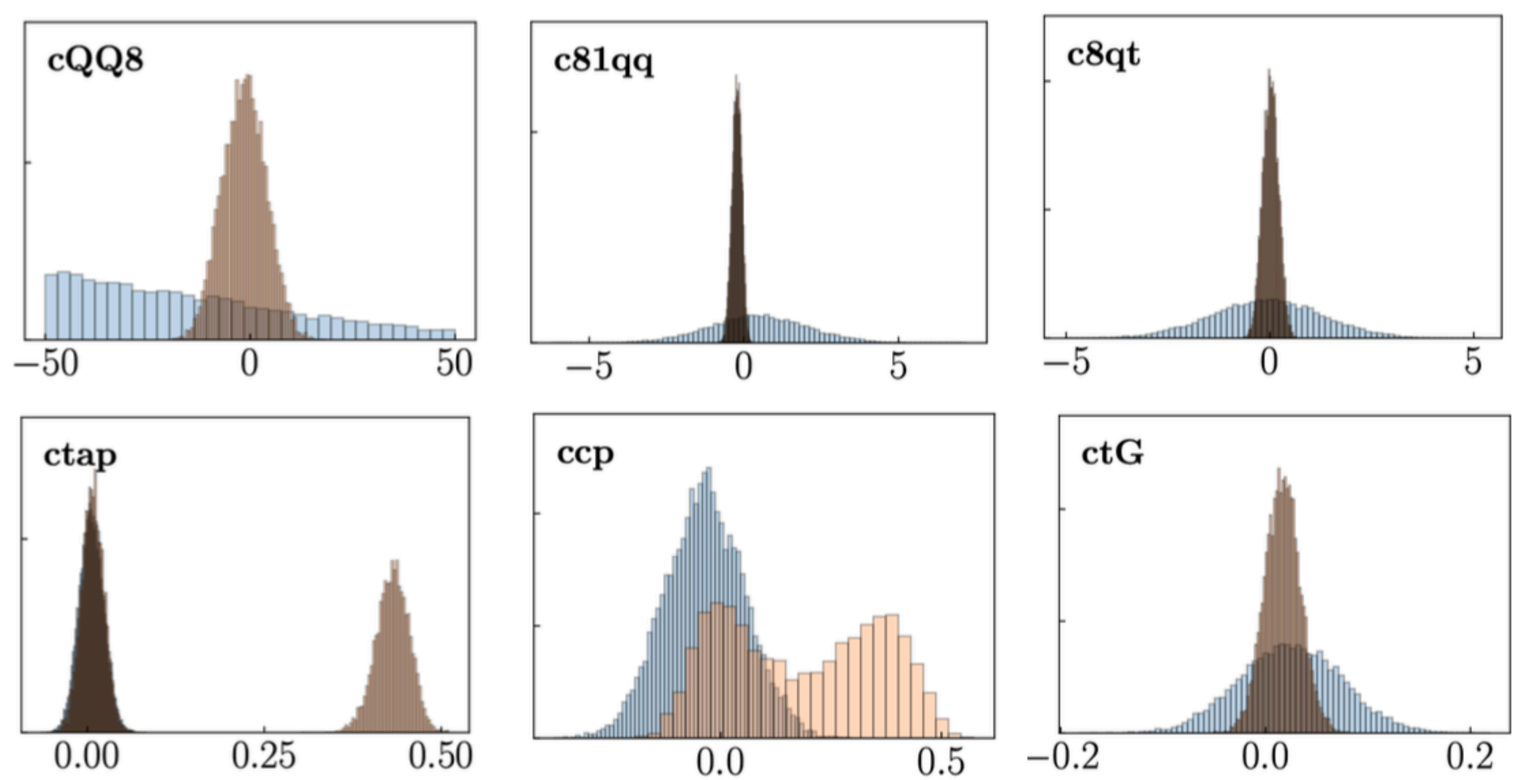
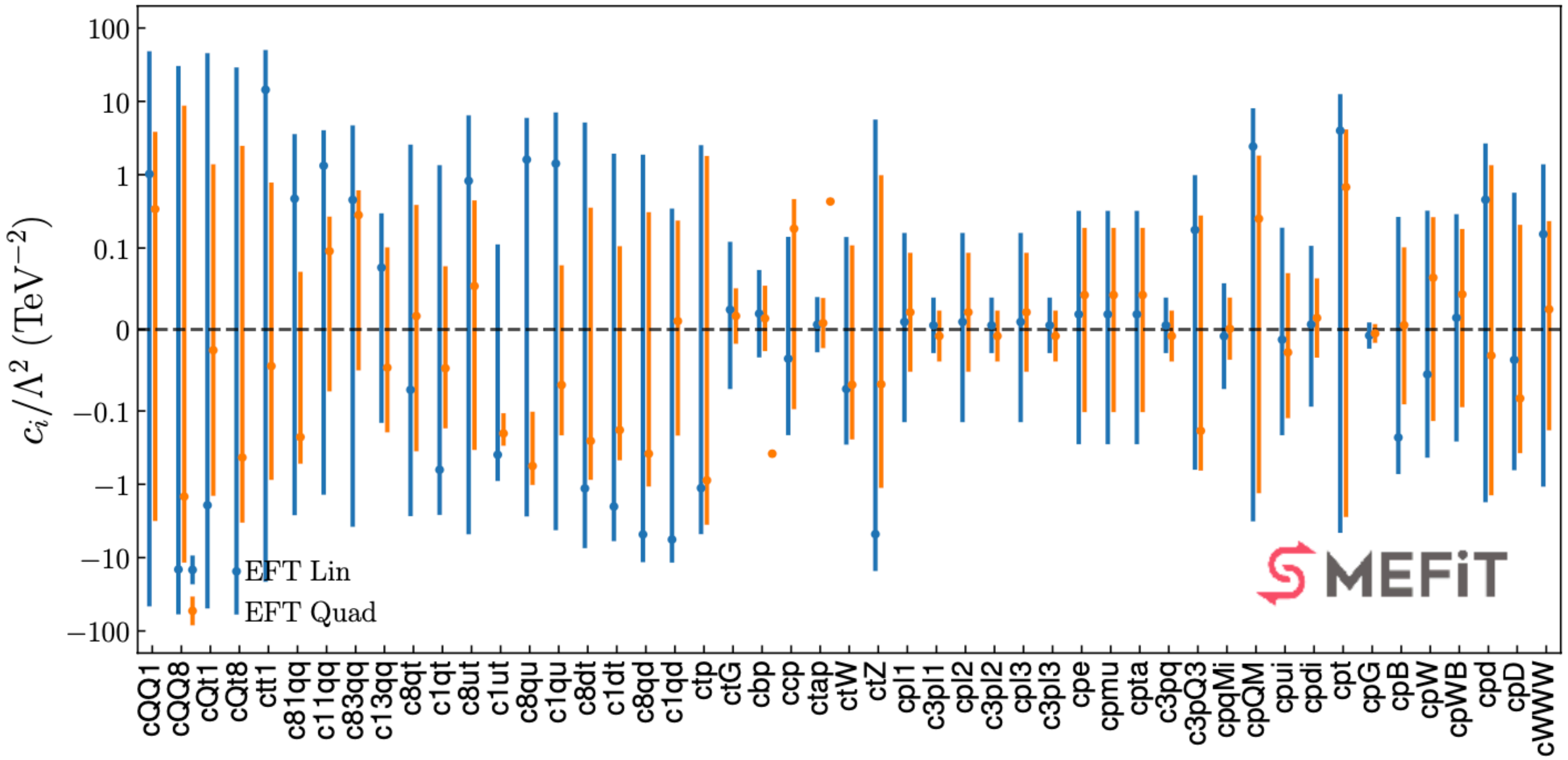
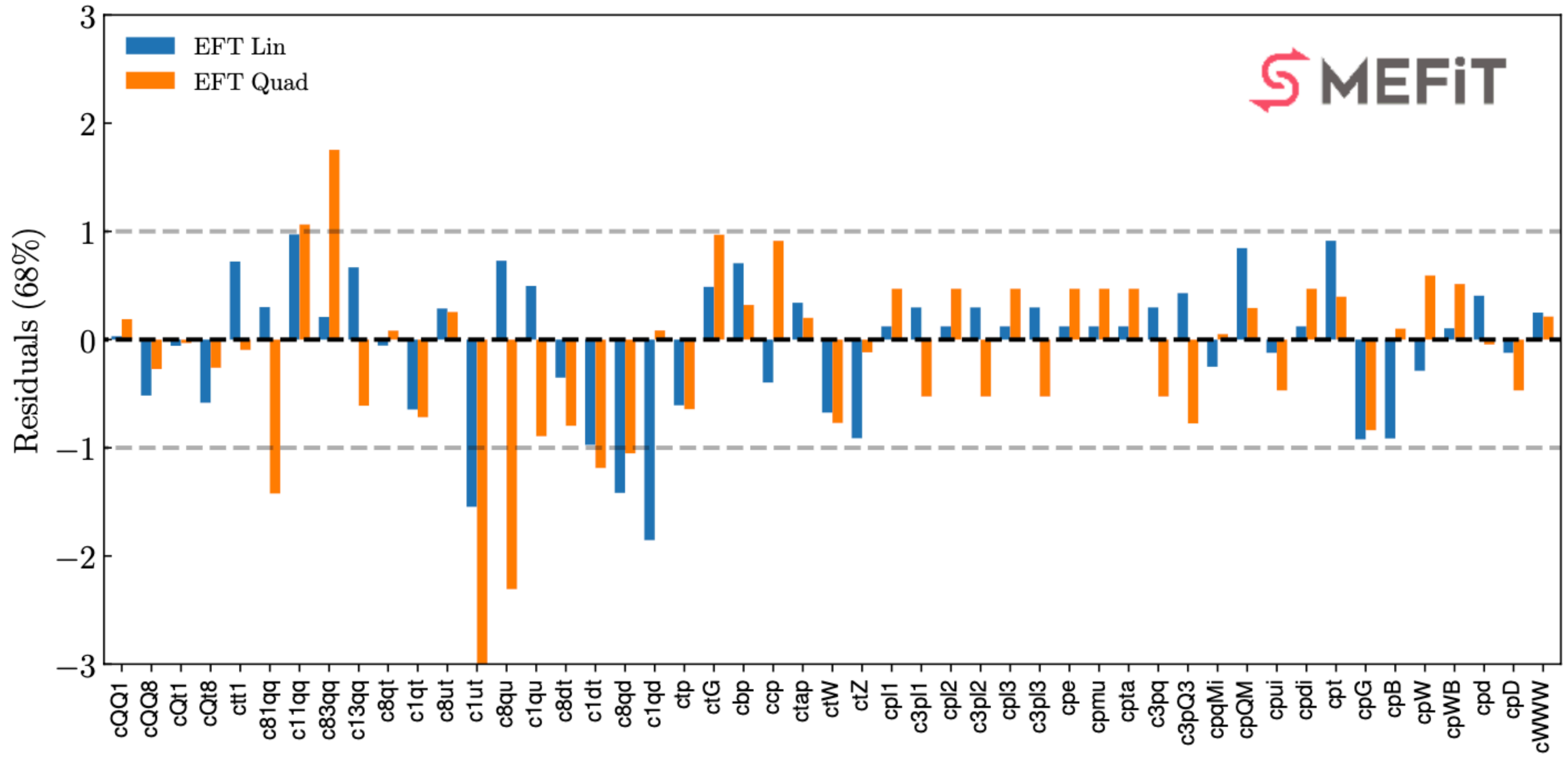
Effects of quadratic corrections can be drastic

Linear Quadratic

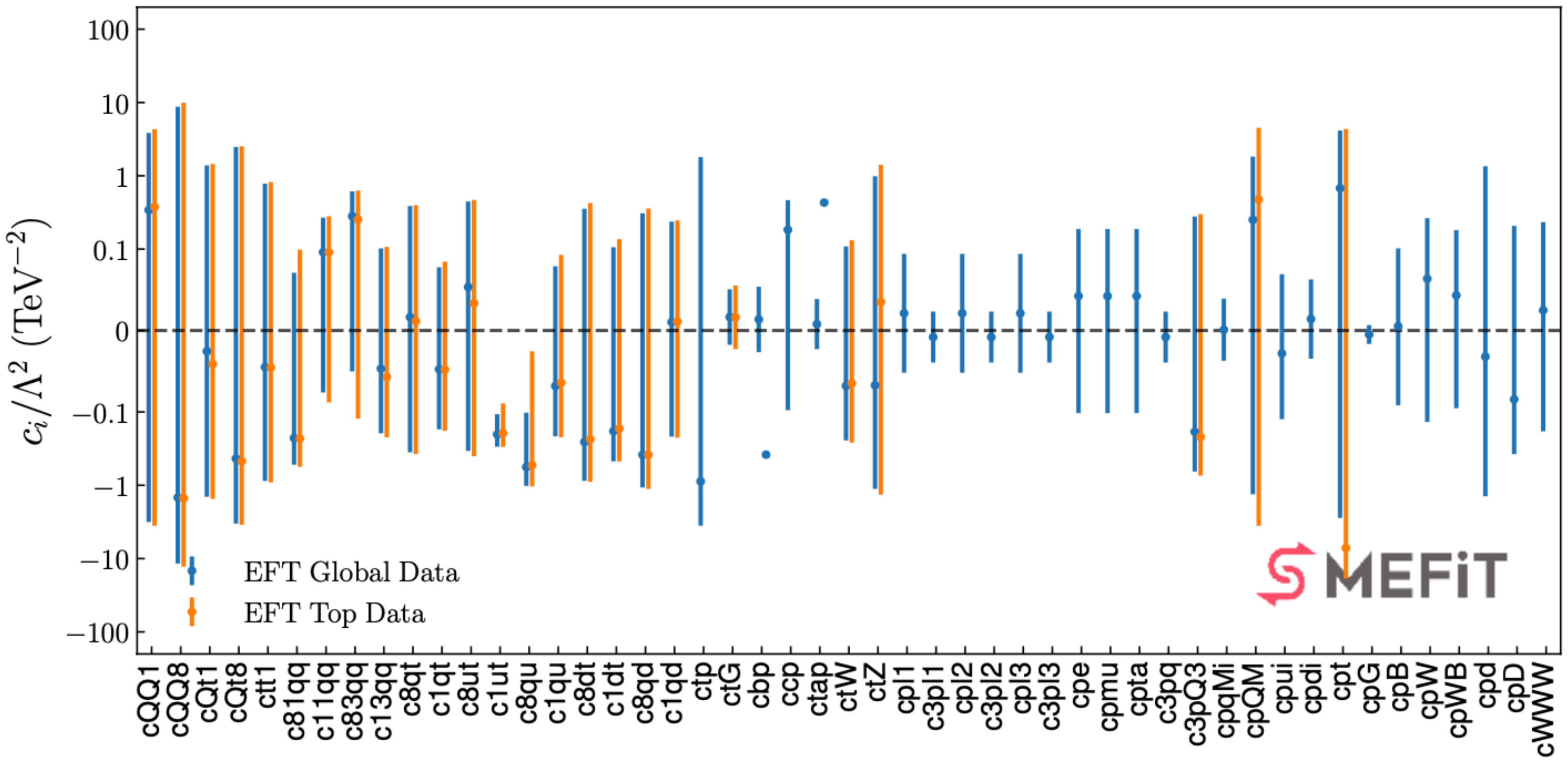




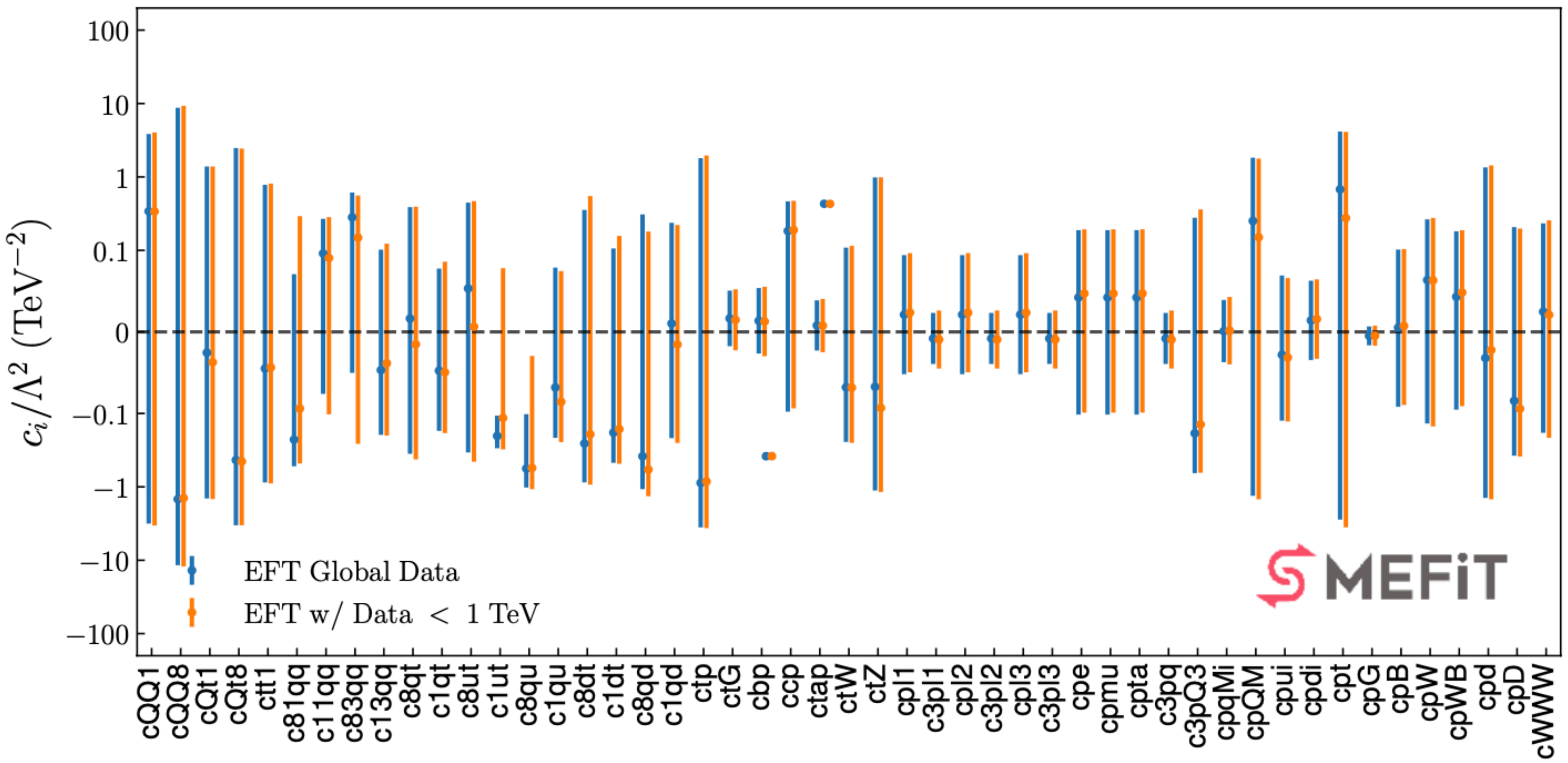
c_i/Λ^2 (TeV^{-2})
EFT Lin
EFT Quad
MEFiT
cQQ1 cQQ8 cQt1 cQt8 ctt1 c81qq c11qq c83qq c13qq c8qt c1qt c8ut c1ut c8qu c1qu c8dt c1dt c8qd c1qd ctp ctG cbp ccp ctap ctW ctZ cpl1 c3pl1 cpl2 c3pl2 cpl3 c3pl3 cpe cpmu cpta c3pq c3pQ3 cpqMi cpQM cpui cpdi cpt cpG cpB cpW cpWB cpd cpD cWWW



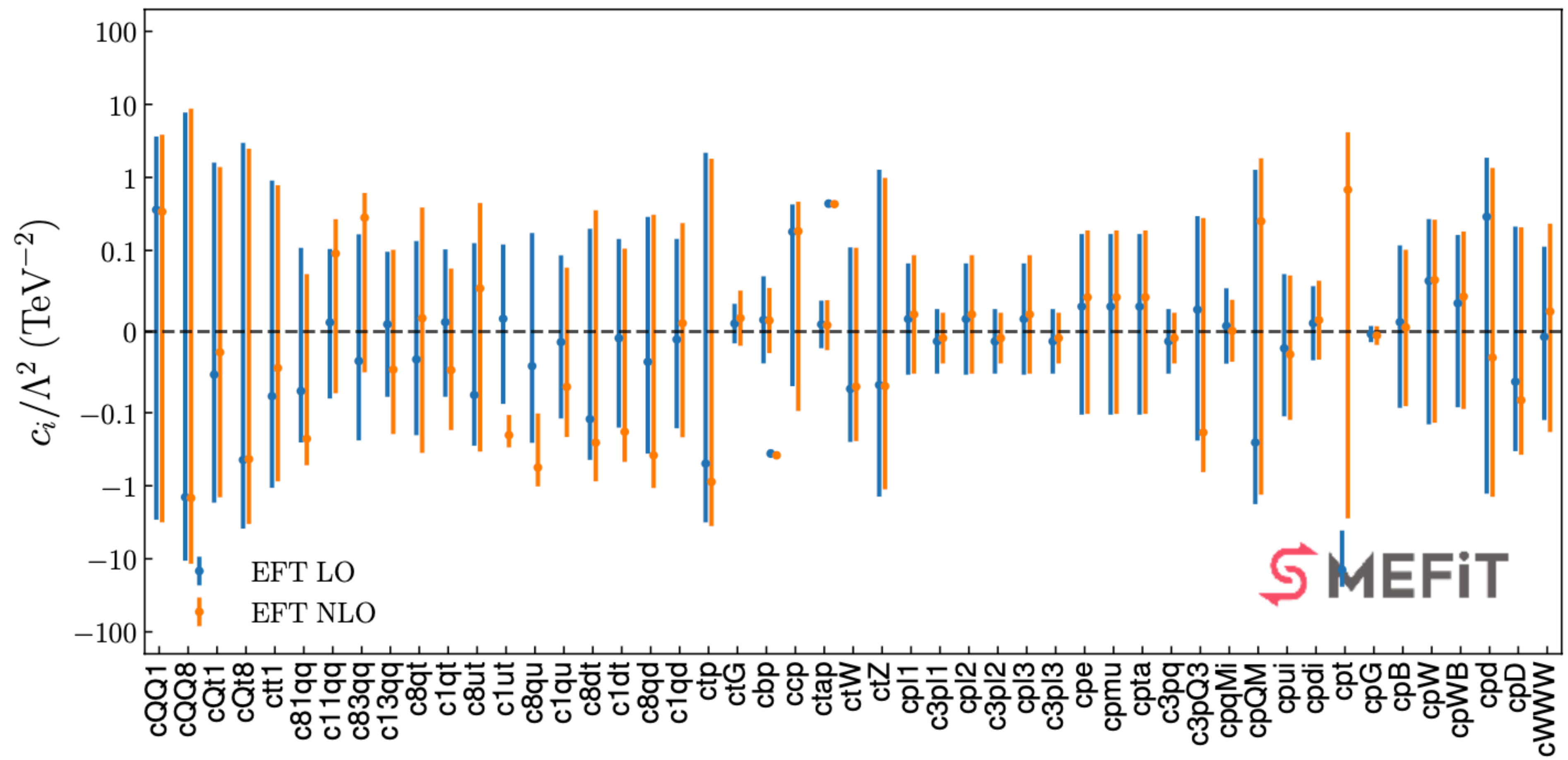
Residuals (68%)
EFT Lin
EFT Quad
MEFiT
cQQ1 cQQ8 cQt1 cQt8 ctt1 c81qq c11qq c83qq c13qq c8qt c1qt c8ut c1ut c8qu c1qu c8dt c1dt c8qd c1qd ctp ctG cbp ccp ctap ctW ctZ cpl1 c3pl1 cpl2 c3pl2 cpl3 c3pl3 cpe cpmu cpta c3pq c3pQ3 cpqMi cpQM cpui cpdi cpt cpG cpB cpW cpWB cpd cpD cWWW

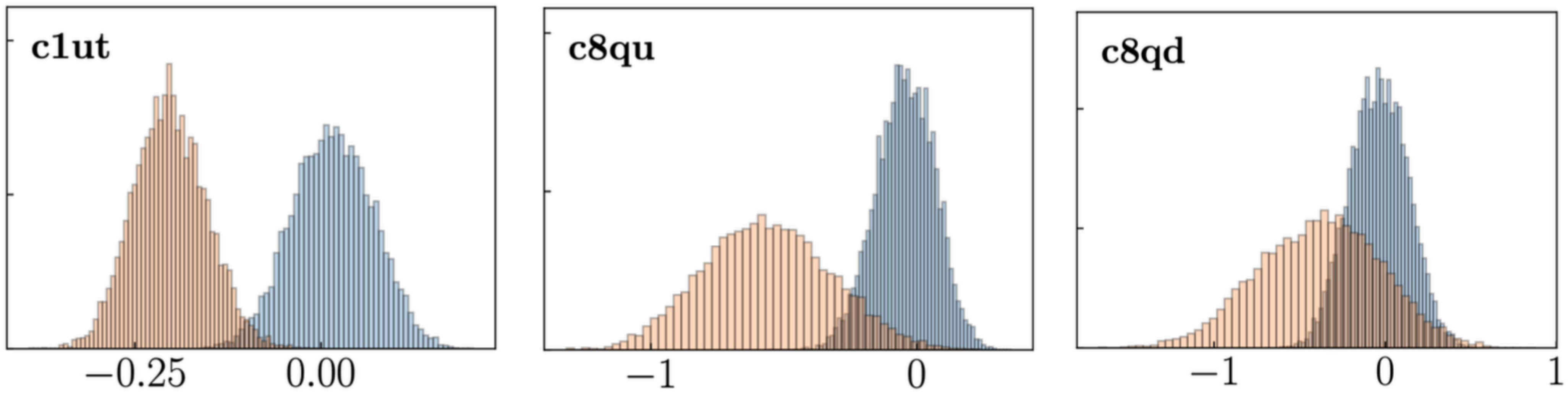


100
10
1
0.1
0
−0.1
−1
−10
−100
c_i/Λ^2 (TeV^{-2})
EFT Global Data
EFT Top Data
SMEFiT
cQQ1 cQQ8 cQt1 cQt8 ctt1 c81qq c11qq c83qq c13qq c8qt c1qt c8ut c1ut c8qu c1qu c8dt c1dt c8qd c1qd ctp ctG cbp ccp ctap ctW ctZ cpl1 c3pl1 cpl2 c3pl2 cpl3 c3pl3 cpe cpmu cpta c3pq c3pQ3 cpqMi cpQM cpui cpdi cpt cpG cpB cpW cpWB cpd cpD cWWW



100
10
1
0.1
0
−0.1
−1
−10
−100
c_i/Λ^2 (TeV^{-2})
EFT Global Data
EFT w/ Data < 1 TeV
SMEFiT
cQQ1 cQQ8 cQt1 cQt8 ctt1 c81qq c11qq c83qq c13qq c8qt c1qt c8ut c1ut c8qu c1qu c8dt c1dt c8qd c1qd ctp ctG cbp ccp ctap ctW ctZ cpl1 c3pl1 cpl2 c3pl2 cpl3 c3pl3 cpe cpmu cpta c3pq c3pQ3 cpqMi cpQM cpui cpdi cpt cpG cpB cpW cpWB cpd cpD cWWW


c_i/Λ^2 (TeV^{-2})
100
10
1
0.1
0
−0.1
−1
−10
−100
EFT LO
EFT NLO
MEFiT
cQQ1 cQQ8 cQt1 cQt8 ctt1 c81qq c11qq c83qq c13qq c8qt c1qt c8ut c1ut c8qu c1qu c8dt c1dt c8qd c1qd ctp ctG cbp ccp ctap ctW ctZ cpl1 c3pl1 cpl2 c3pl2 cpl3 c3pl3 cpe cpmu cpta c3pq c3pQ3 cpqMi cpQM cpui cpdi cpt cpG cpB cpW cpWB cpd cpD cWWW


c1ut
−0.25
0.00
c8qu
−1
0
c8qd
−1
0
1

- ❖ **SMEFiT** is a **novel and flexible framework** for global EFT interpretations.
- ❖ **Already successfully employed for Top, Higgs and diboson data.**
- ❖ Several functionalities to **cross-check** and **validate** results**.**

New steps:

- ❖ **Add new data** (VBS, Tevatron, recent LHC results, …)
- ❖ **Improve theory** (RGEs, NLO-QCD and EW in EFT, etc)
- ❖ **Improve fit methodology** (higher number of operators require better efficiency)

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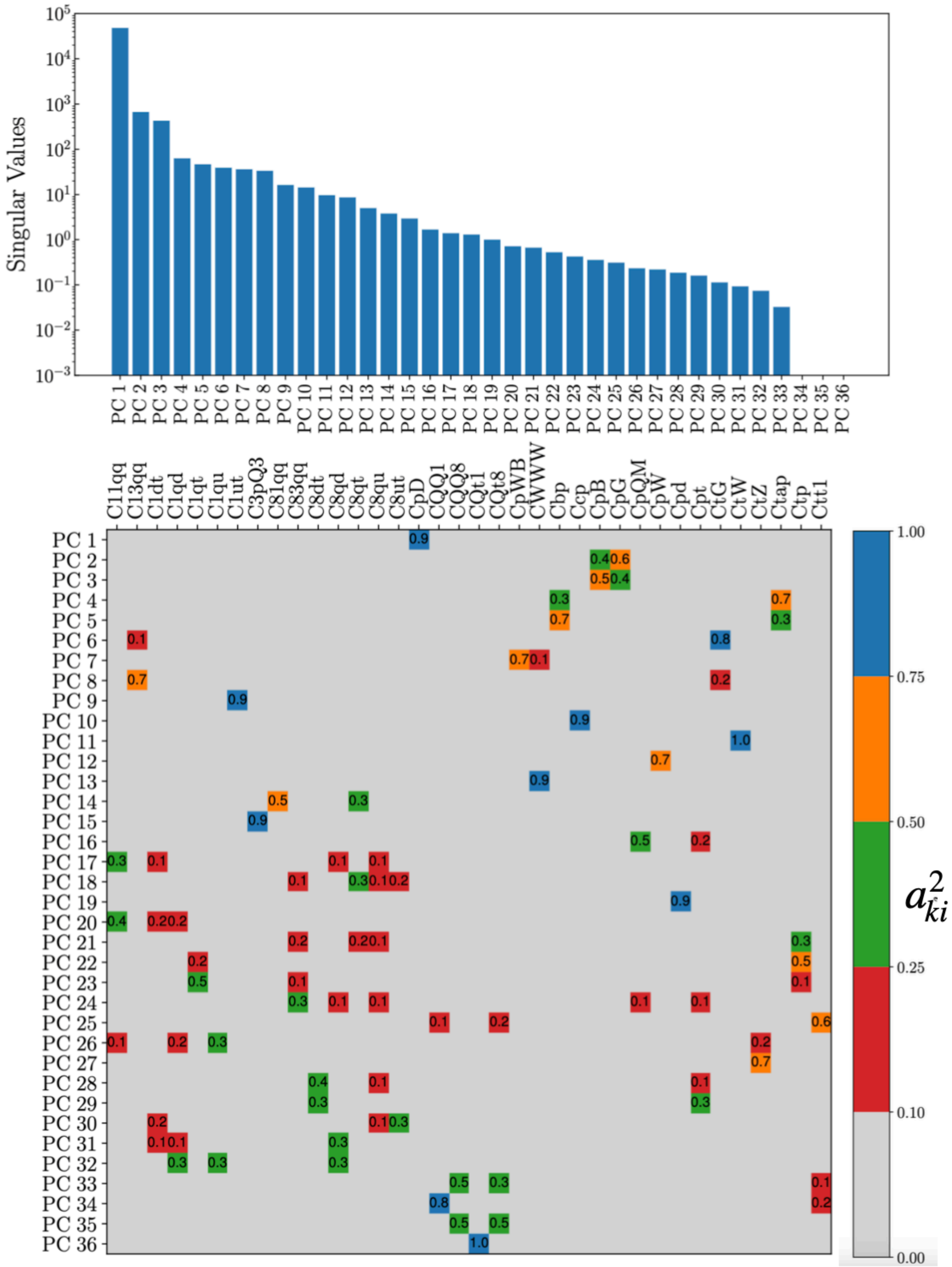
Thanks!

Backup



$$\mathrm{PC}_k = \sum_{i=1}^{n_{\mathrm{op}}} a_{ki} c_i, \quad k = 1, \ldots, n_{\mathrm{op}} \quad \left(\sum_{i=1}^{n_{\mathrm{op}}} a_{ki}^2 = 1 \forall k \right)$$

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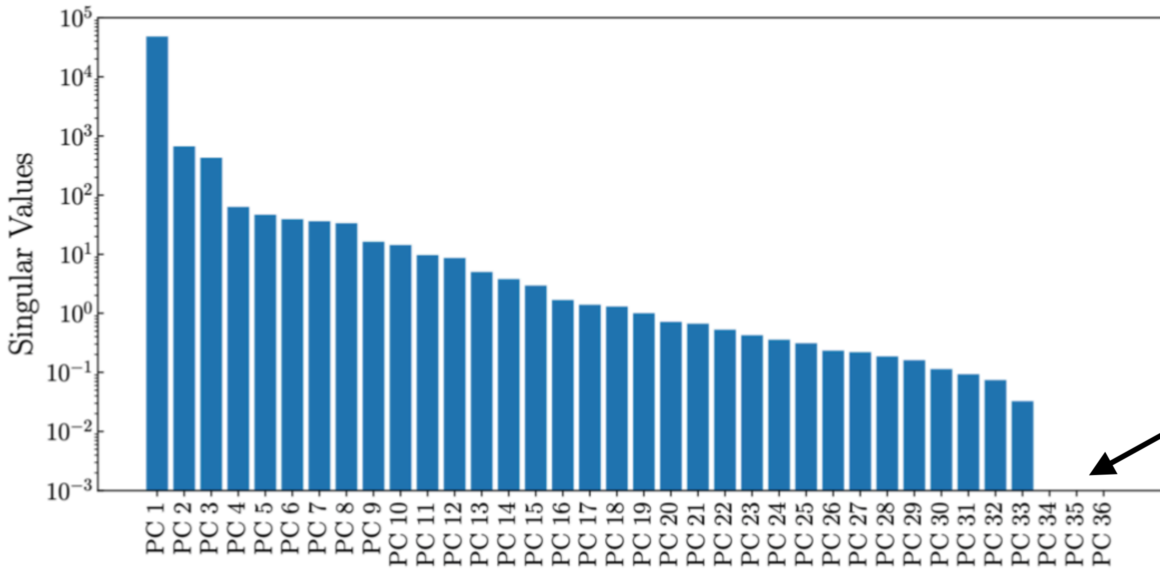
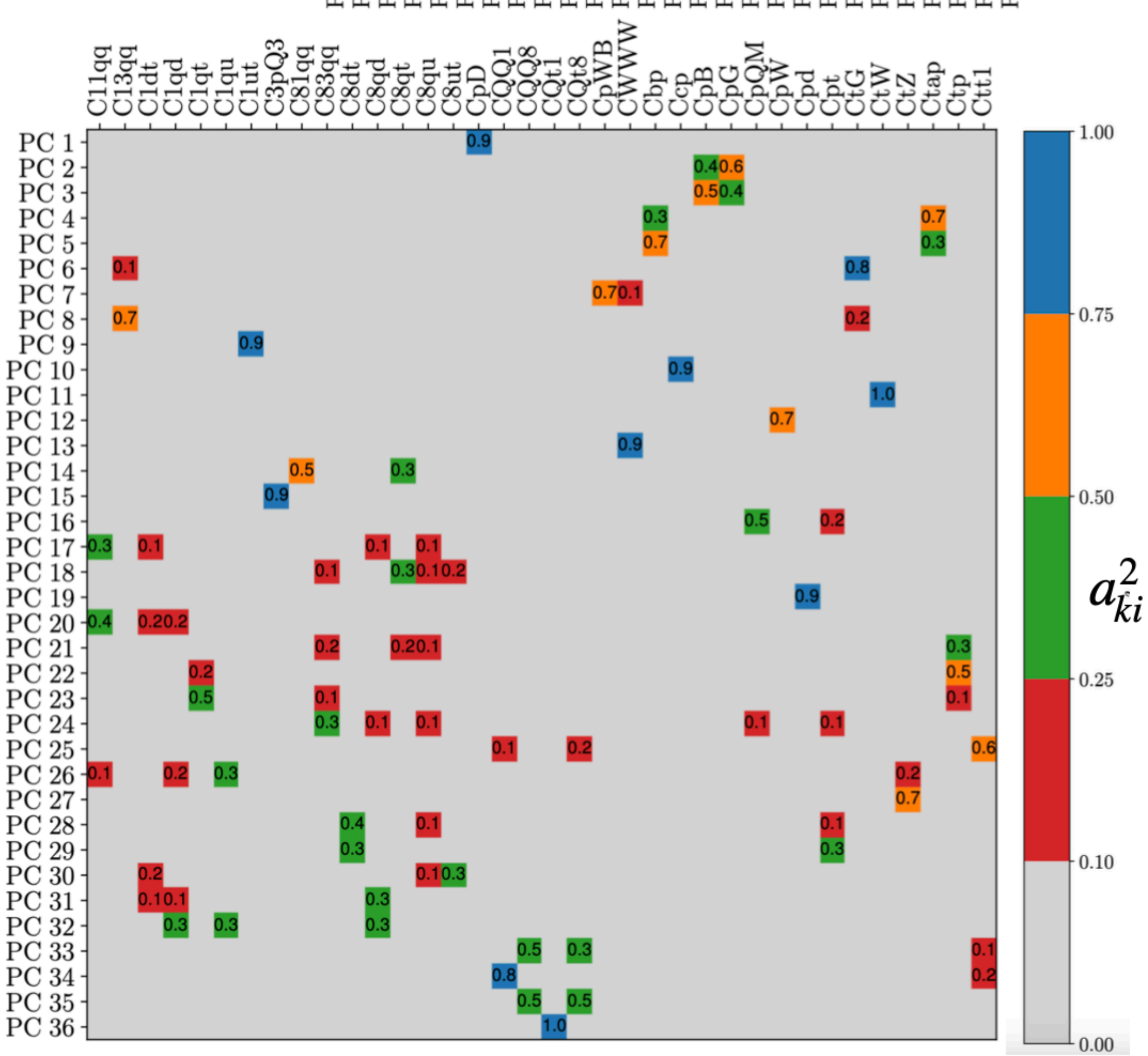
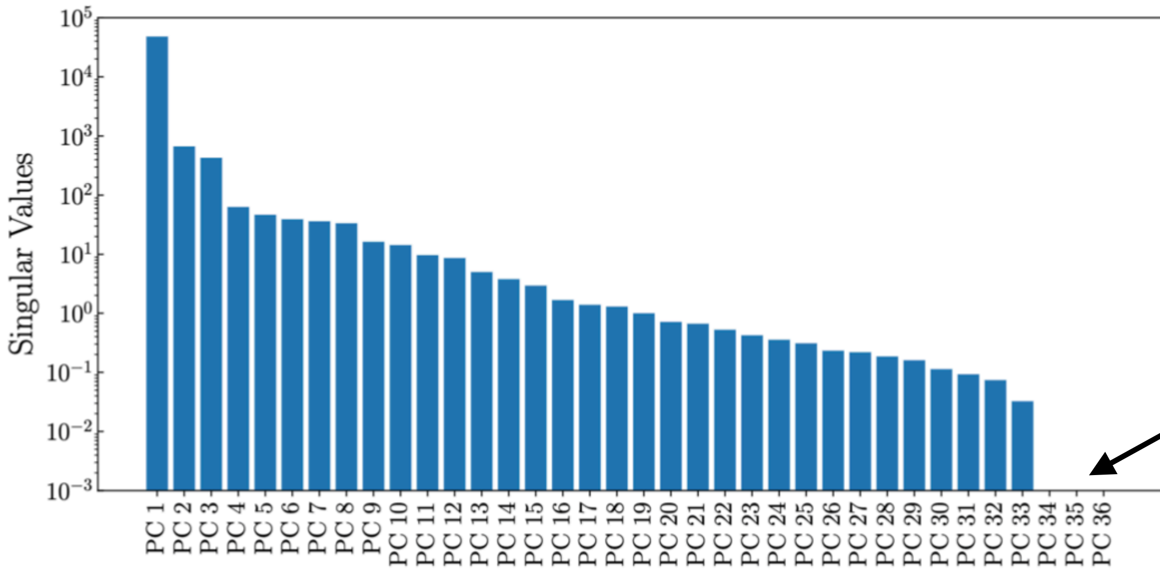


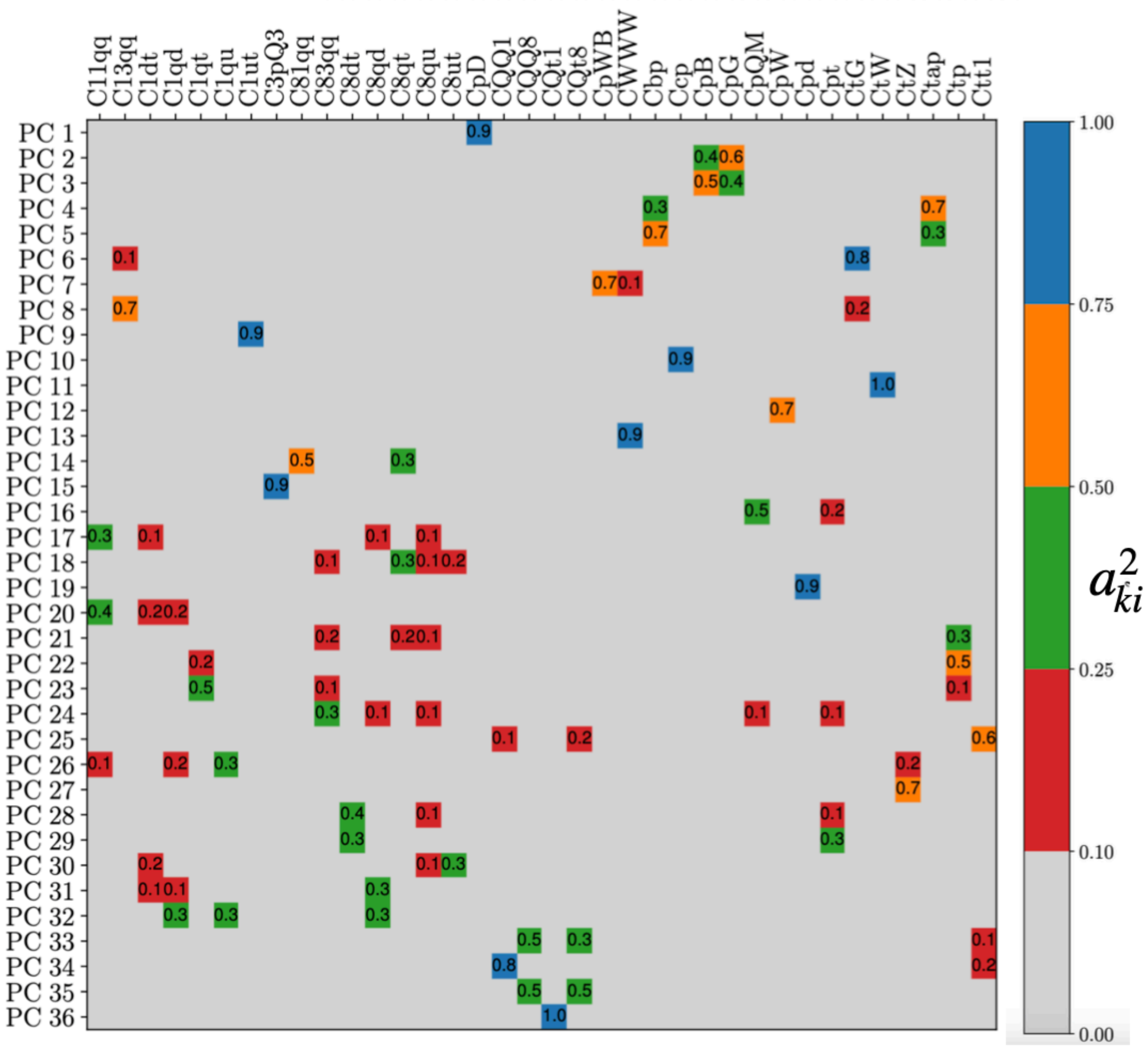
Flat directions



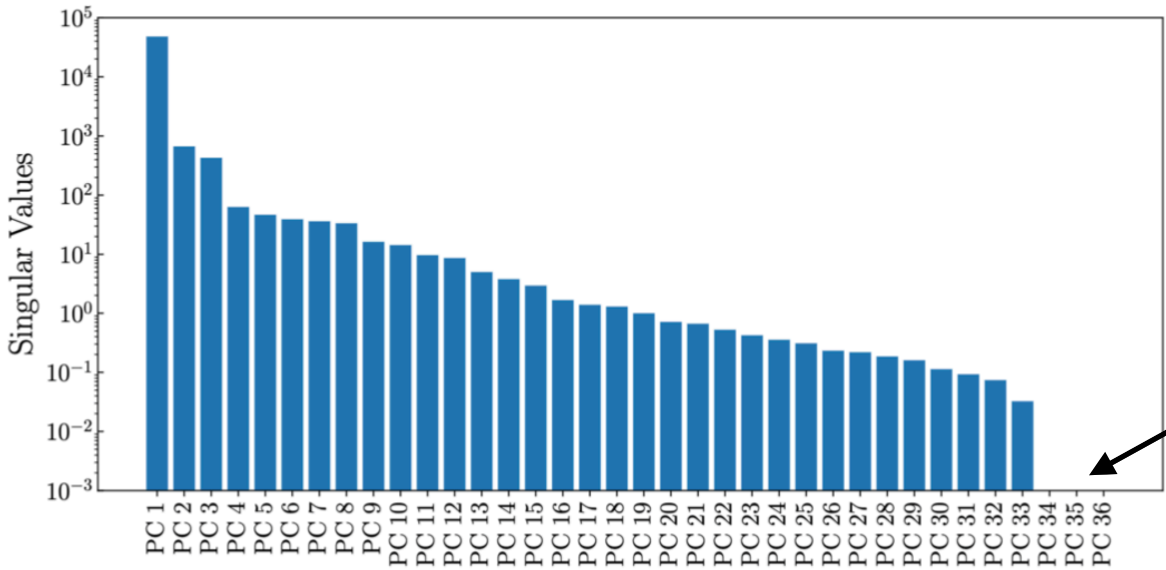


$$\mathrm{PC}_k = \sum_{i=1}^{n_{\mathrm{op}}} a_{ki} c_i, \quad k = 1, \ldots, n_{\mathrm{op}} \qquad \left(\sum_{i=1}^{n_{\mathrm{op}}} a_{ki}^2 = 1 \forall k \right)$$

Flat directions

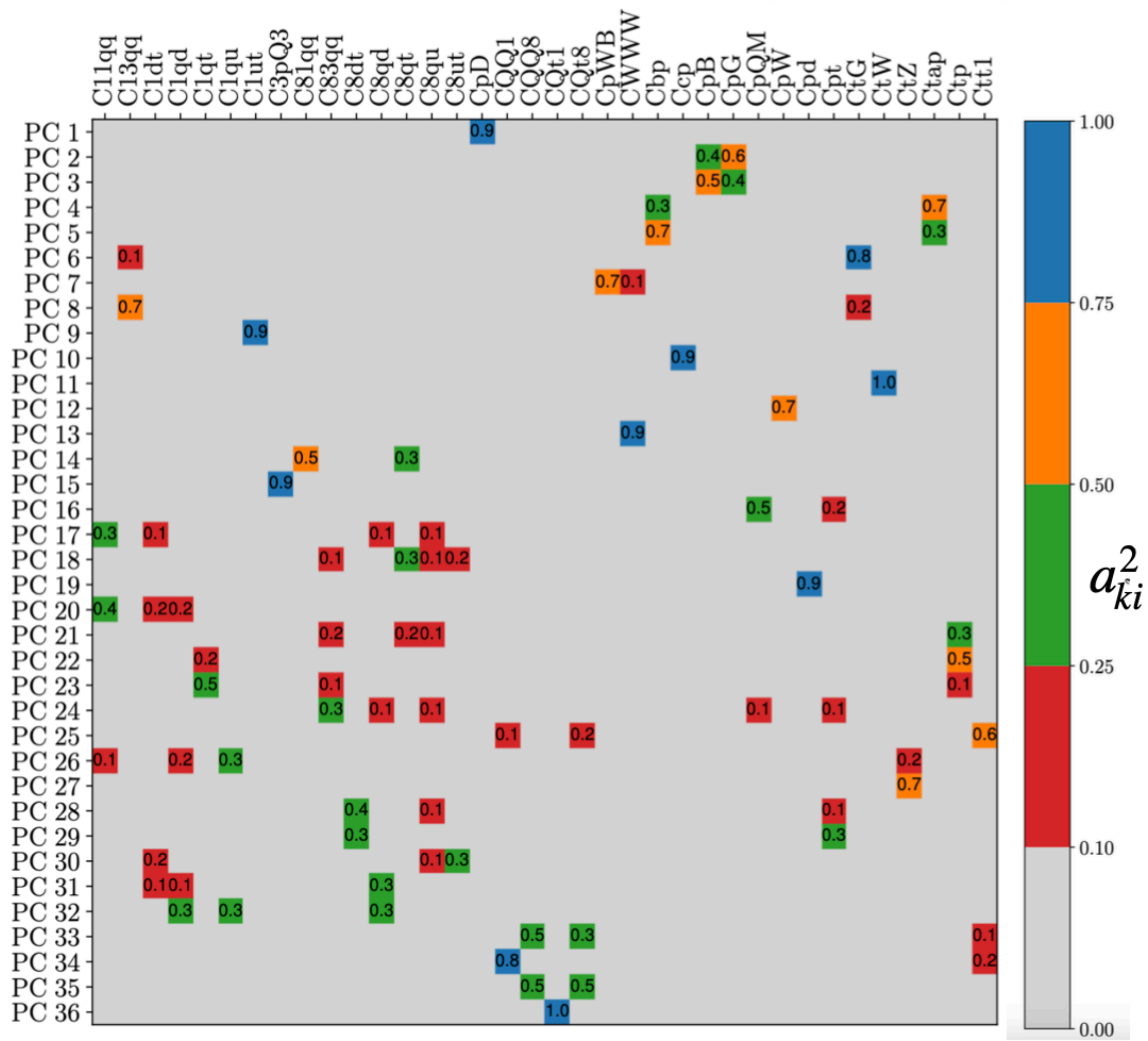


Diagnostic tool: is the basis used good for the dimensionality?



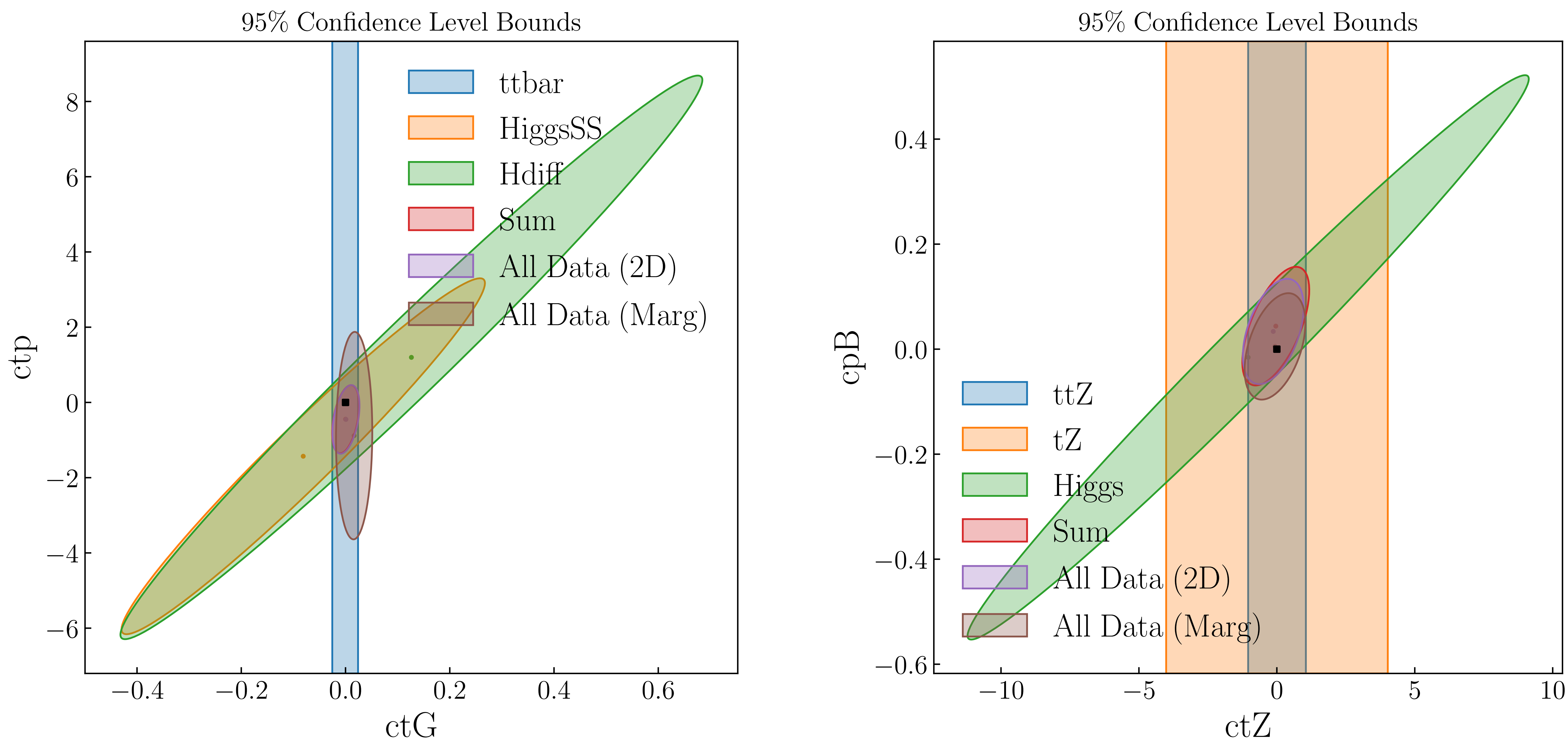
$$\mathrm{PC}_k = \sum_{i=1}^{n_{\rm op}} a_{ki} c_i, \quad k = 1, \ldots, n_{\rm op} \qquad \left(\sum_{i=1}^{n_{\rm op}} a_{ki}^2 = 1 \forall k \right)$$

Flat directions



Diagnostic tool: is the basis used good for the dimensionality?

Eventually one can fit in the PC basis (not done in the present fit)


95% Confidence Level Bounds
ttbar
HiggsSS
Hdiff
Sum
All Data (2D)
All Data (Marg)
ctp
ctG
8
6
4
2
0
−2
−4
−6
−0.4
−0.2
0.0
0.2
0.4
0.6
95% Confidence Level Bounds
ttZ
tZ
Higgs
Sum
All Data (2D)
All Data (Marg)
cpB
ctZ
0.4
0.2
0.0
−0.2
−0.4
−0.6
−10
−5
0
5
10