

EFT tools and global fits

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SMEFT global analyses

This talk: **SMEFT $d = 6$**

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \frac{1}{\Lambda^3} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \dots$$

Idea probe **indirect signals** of new physics in an **agnostic & systematic** way

- allow *all* possible deviations, let data tell us where NP is
- “model-independent”

caveats!! ↵ Tim Cohen, Ian Banta's talks

Two steps:

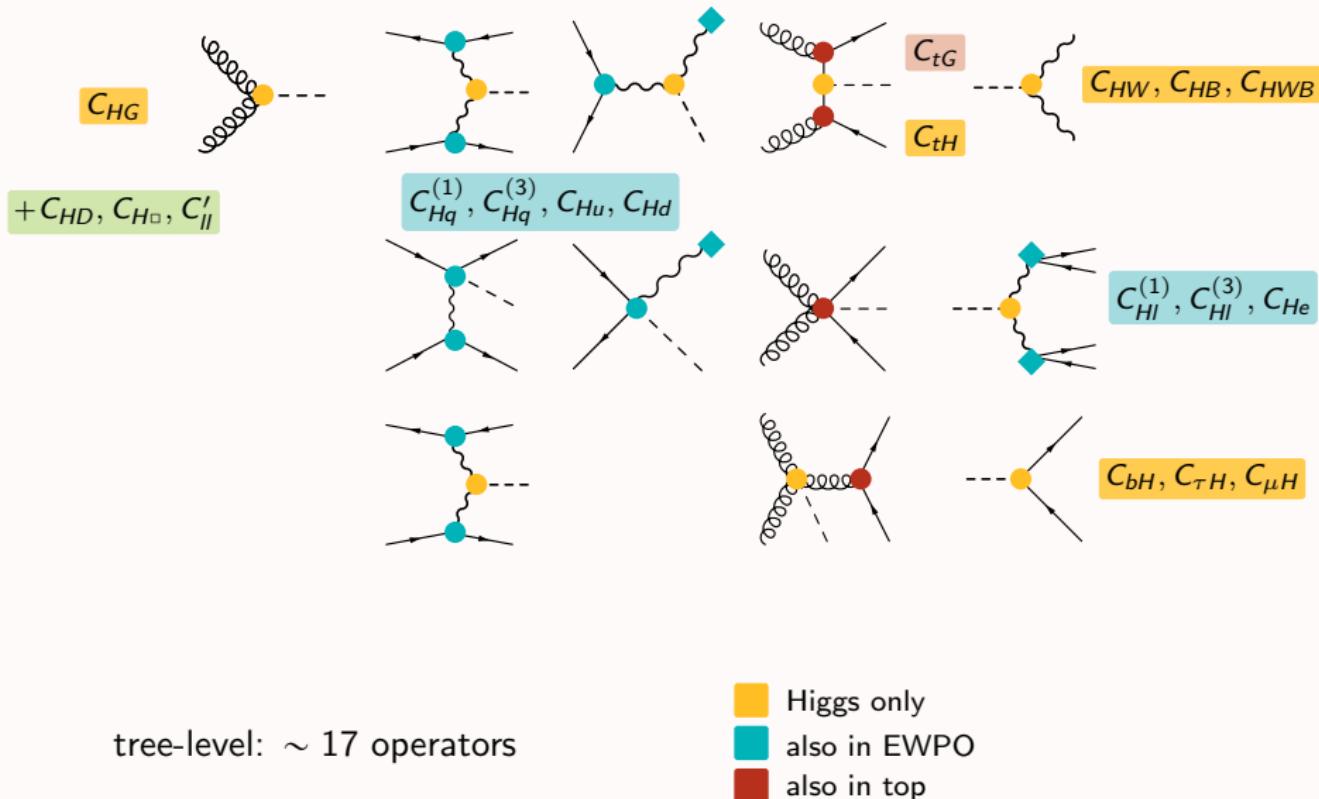
1. being **sensitive** to indirect BSM effects *(some $C_i \neq 0$)*
→ evidence for NP

$$\text{in bulk } \sim \frac{v^2}{\Lambda^2} \rightarrow 1.5\%$$

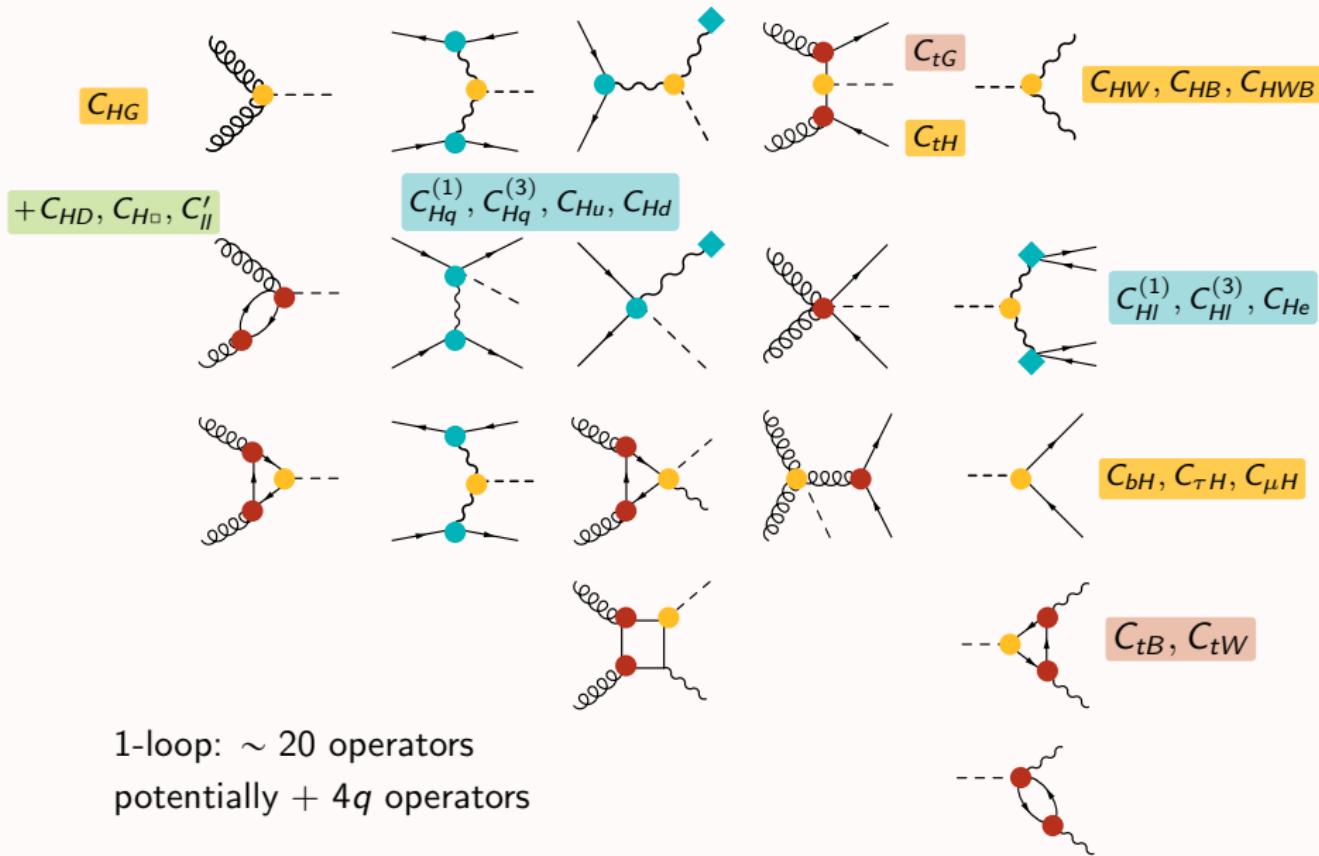
$$\text{on tails } \sim \frac{E^2}{\Lambda^2} \rightarrow 10\%$$

2. making sure that, if we observe one, we **interpret it correctly** *(which C_i ?)*
→ hints about NP nature

SMEFT in the Higgs sector



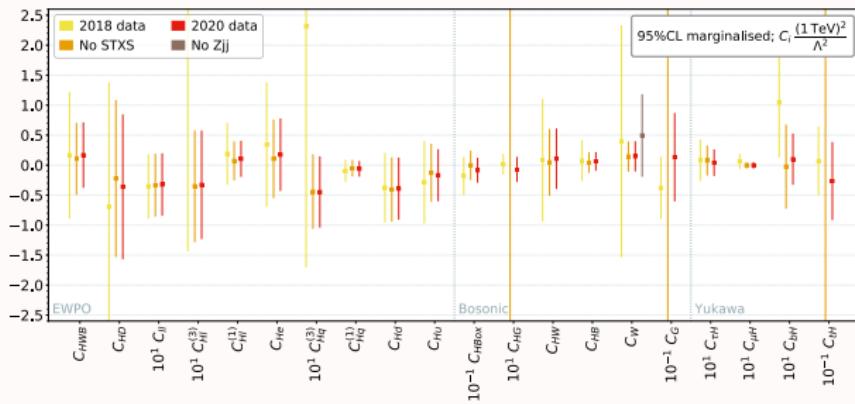
SMEFT in the Higgs sector



SMEFT global analyses of the Higgs (+EW) sector

Theory: performed for a long time, combined with **EWPO** and **diboson**

... Ellis et al 1803.03252
da Silva Almeida et al 1812.01009
Biekötter et al 1812.07587
de Blas et al 1910.14012
Falkowski, Straub 1911.07866
Dawson, Homiller, Lane
2007.01296
...



H + EW + top

Ellis, Madigan, Mimasu, Sanz, You 2012.02779

Ethier, Magni, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou, Zhang 2105.00006

~~ Ken Mimasu, Giacomo Magni's talks

Experiment: combined EFT analyses recently published

$H \rightarrow \gamma\gamma$, $H \rightarrow 4\ell$ ATL-PHYS-PUB-2017-018, CMS-HIG-19-009

Higgs STXS CMS-PAS-HIG-19-005, ATLAS-CONF-2021-053

HW + WW ATL-PHYS-PUB-2021-010

~~ Carsten D. Burgard, Marco Battaglia's talks

SMEFT global analyses: what does it take?

- ▶ EXP input: precise measurements, known uncertainties & correlations
- ▶ precise SM predictions → small TH error
- ▶ SMEFT predictions → how do the observables depend on C_i ?
- ▶ statistics framework (fitting tool)
- ▶ look at results from many directions
→ understand fit space
- ▶ bonus: a (simplified) UV model to apply this to



SMEFT predictions

$$A_{SMEFT} = A_{SM} + \sum_i \left(C_i^{(6)} / \Lambda^2 \right) A_i$$



$$|A_{SMEFT}|^2 = |A_{SM}|^2 + \sum_i \frac{C_i^{(6)}}{\Lambda^2} 2\text{Re} \left(A_{SM} A_i^\dagger \right) + \sum_{i,j} \frac{C_i^{(6)} C_j^{(6)}}{\Lambda^4} |A_i A_j^\dagger|$$

interference/linear

quadratics

$\times (\text{SM } K\text{-factor})$

- ▶ A_{SMEFT} computed up to 1-loop in QCD / EW
- ▶ always polynomial in $C_i^{(6)}$ → **morphing** techniques
- ▶ quadratics → incomplete Λ^{-4}
 - introduce dependence on more EFT parameters
 - generally improve fit convergence (ensure $\sigma > 0$)
 - included for EFT validity check

ATL-PHYS-PUB-2015-047

Monte Carlo generators: most used

▶ MG5_aMC@NLO + UFO models

→ automated for arbitrary processes up to NLO QCD

→ interaction orders syntax for morphing

→ reweighting module

Gainer et al. 1404.7129, Mattelaer 1607.00763

- re-use event samples → faster

- smaller stat. uncertainties in ratios/sums/diffs of SM(EFT) components

▶ POWHEG-BOX

processes available at NLO QCD in SMEFT:

- EW Higgs production

Mimasu,Sanz,Williams 1512.02572

- diboson

Baglio,Dawson,(Homiller,Lewis) 1812.00214, 1909.11576

- $\ell\ell$ Drell Yan up to dim 8

Alioli,Dekens,Girard,Mereghetti 1804.07407

Alioli,Bouhezal,Mereghetti,Petriello 2003.11615

▶ JHUGen

H production + $H \rightarrow 4\ell, \tau\tau$, on- and off-shell

Gritsan,Roskes,Sarica,Schulze,Xiao,Zhou 2002.09888
Davis,Gritsan,Guerra,Kyriacou,Schulze 2109.13363

↔ Savvas Kyriacou's talk

SMEFT UFO models



Brivio,Jiang,Trott 1709.06492
Brivio 2012.11343

- ▶ only LO → most used for **EW Higgs, diboson...**
- ▶ full Warsaw basis. CP even + odd, includes all m_f and y_f
- ▶ 5 flavor structures × 2 EW input schemes
- ▶ includes $hgg(g)$, $h\gamma\gamma$, $hZ\gamma$ SM interactions in $m_t \rightarrow \infty$ limit
- ▶ includes *linear* SMEFT corrections in propagators (δm , $\delta\Gamma$) of top, Higgs and EW bosons

SMEFT@NLO

Degrade,Durieux,Maltoni,
Mimasu,Vryonisou 2008.11743

- ▶ allows NLO QCD → most used for **top, ggF...**
- ▶ CP even, 5 flavor scheme (only $m_t, y_t \neq 0$)
- ▶ flavor structure: $U(3)_d \times U(2)_u \times U(2)_q \times U(1)_{l+e}^3$
- ▶ EW inputs: $\{G_F, m_Z, m_W\}$

others: **HEL** Alloul,Fuks,Sanz 1310.5150 , **BSMC** Fuks,Matawari , **dim6top** Durieux,Zhang 1802.07237 . . .

Analytical predictions in SMEFT

- ▶ Required for NLO EW predictions in SMEFT

available for Higgs:

| | |
|------------------------------|--|
| $h \rightarrow \gamma\gamma$ | Hartmann,Trott 1505.02646,1507.03568, Passarino et al 1505.03706, Dedes et al 1805.00302, Dawson, Giardino 1807.11504 |
| $h \rightarrow Z\gamma$ | Dedes,Suxho,Trifyllis 1903.12046,1801.01136 |
| $h \rightarrow WW, ZZ$ | Dawson, Giardino 1807.11504,1801.01136 |
| $h \rightarrow \bar{f}f$ | (Cullen,Gauld),Pecjak,Scott 1512.02508,1904.06358,2007.15238 |

→ R_ξ gauge, Ward identities, BFM Dedes et al 1704.03888, Quadri 2102.10656,
Trott et al 1803.08001,1909.08470,2010.08451

→ automated Feynman rules in R_ξ gauge (+BFM) Dedes et al 1704.03888,1904.03204,
Corbett 2010.15852

- ▶ Convenient for inclusive observables , calculated once and for all
e.g. $\Gamma_{H \rightarrow f}$, Γ_H^{tot} , ubiquitous in STXS

Brivio,Corbett,Trott 1906.06949



Statistical analysis

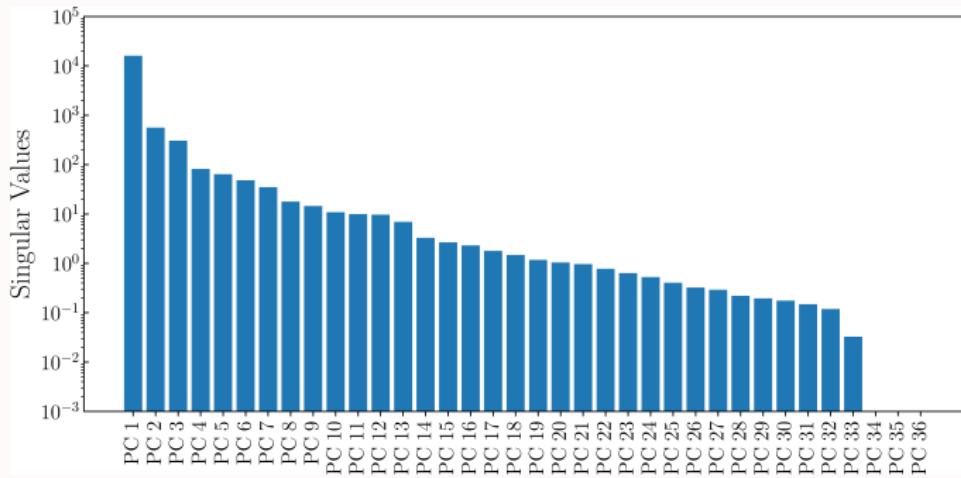
Main features of SMEFT fits

- ▶ many **dimensions**: state-of-the-art 30–35 LHC target (EW+H+top) ~ 50

Statistical analysis

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- ▶ large **hierarchies** between constraints (easily 2 – 5 orders of magnitude)

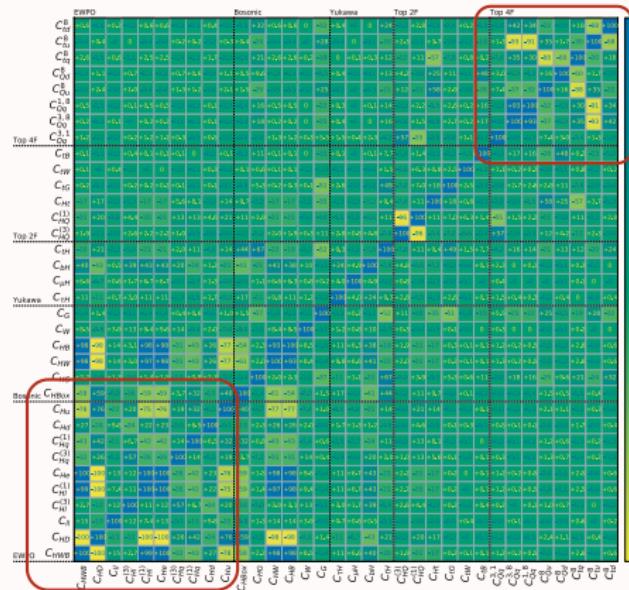


Ethier et al 2105.00006

Statistical analysis

Main features of SMEFT fits

- ▶ many **dimensions**: state-of-the-art 30–35 LHC target (EW+H+top) ~ 50
 - ▶ large **hierarchies** between constraints (easily 2 – 5 orders of magnitude)
 - ▶ weakly broken flat directions → highly **correlated** sub-spaces

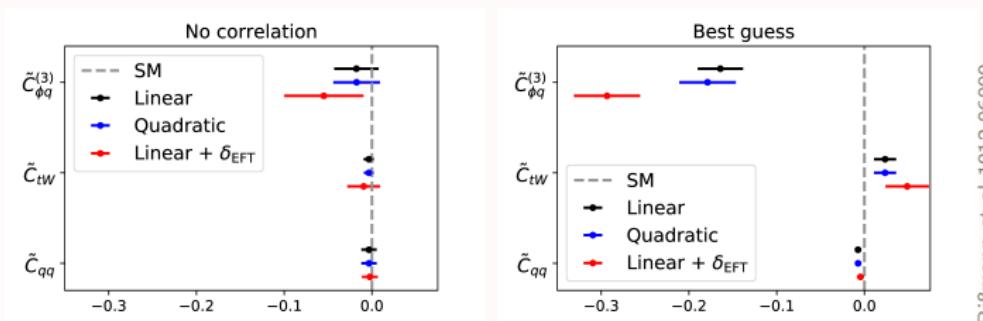


Ellis, Madigan, Mimasu, Sanz, You 2012.02779

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Bißmann et al 1912.06090

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Many fitting codes: EFTfitter, Fitmaker, HEPfit, SFitter, SMEFiT...

Diverse techniques employed

- ▶ frequentist/bayesian, Markov chains/Nested Sampling/replica models...
- ▶ uncertainties most often gaussian.
more sophisticated treatment → more complex likelihood structure

Looking at results from many directions

important in order to understand structure of fit space

who constrains what? what is the most stringent bound on each operator?

what is the role of NLO corrections or quadratic terms? how solid are the bounds? ...

widespread examples:

~~ Ken Mimasu, Giacomo Magni's talks

- ▶ linear \leftrightarrow linear + quadratics
- ▶ LO \leftrightarrow NLO
- ▶ individual \leftrightarrow marginalised/profiled
- ▶ comparisons between different fitting methods
- ▶ Fisher information
- ▶ Principal Component Analysis
- ▶ sub-fits to check impact of individual datasets

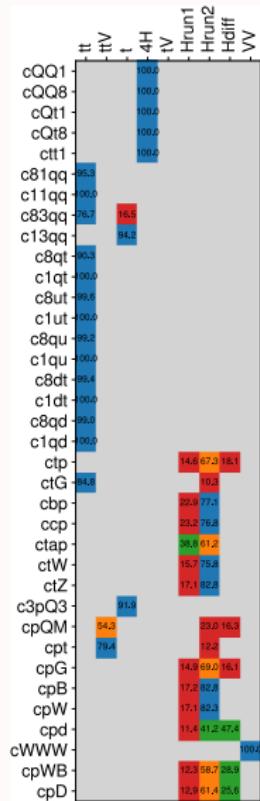
Fisher information matrix

$$I_{ij} = -E \left[\frac{\partial^2 \log \mathcal{L}_{\text{observed}}(\vec{C})}{\partial C_i \partial C_j} \right]$$

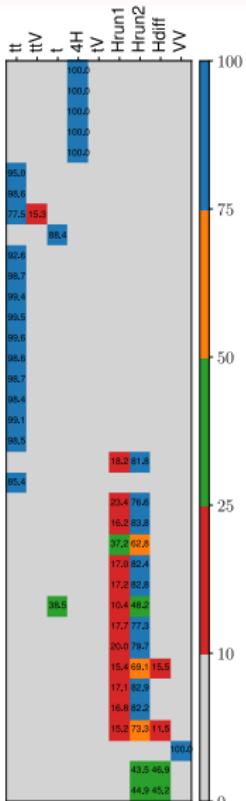
compute for sub-datasets and
normalize to 1 for each coefficient



strongest constraint on each C_i



Linear



Quadratic

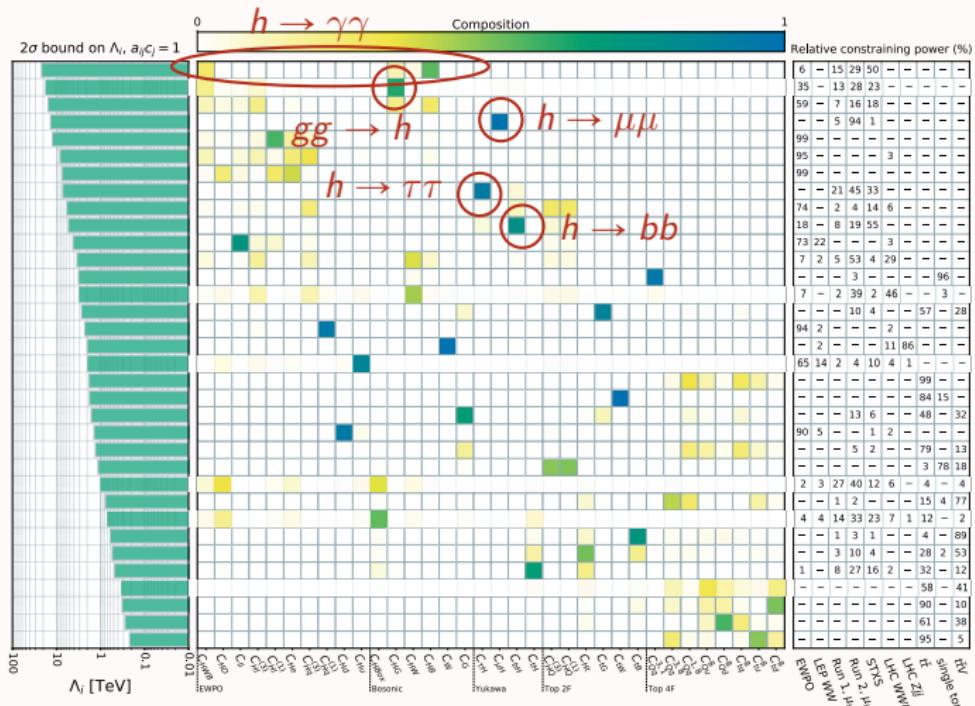
see also: Brehmer et al 1612.05261, 1712.02350, 1908.06980

Ether et al 2105.00006

Principal Component Analysis

eigensystem of the Fisher matrix

- identify the **best and worst constrained** directions in the fit space
- unconstrained directions = vectors with eigenvalue 0

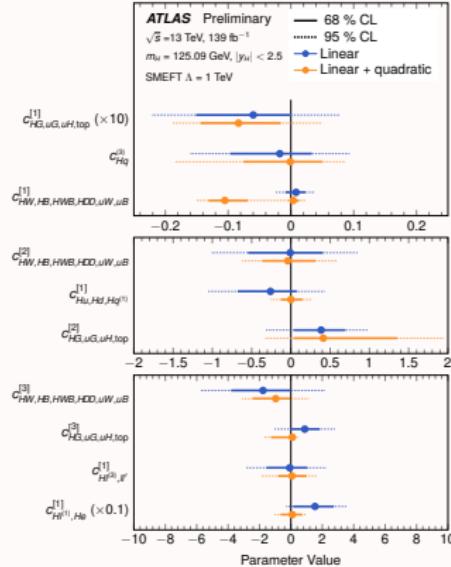


Principal Component Analysis

eigensystem of the Fisher matrix

- identify the **best and worst constrained** directions in the fit space
- unconstrained directions = vectors with eigenvalue 0

can be used to remove poorly constrained directions,
instead of setting some $C_i = 0$



| Parameter | Definition | Eigenvalue | Fit Parameter |
|---------------------------------|--|------------|---------------|
| $c_{HQ}^{(i)}$ | $c_{HQ}^{(i)}$ | 1900 | ✓ |
| $c_{HW,HB,HWB,HWD,uW,uB}^{(1)}$ | $-0.27c_{HW} - 0.84c_{HB} + 0.47c_{HWB} - 0.02c_{uW} - 0.05c_{uB}$ | 245000 | ✓ |
| 1 | $-0.96c_{HW} + 0.19c_{HB} - 0.20c_{HWB} + 0.02c_{uB}$ | 33 | ✓ |
| 2 | $-0.08c_{HW} + 0.50c_{HB} + 0.86c_{HWB} + 0.07c_{HWD} + 0.03c_{uW} + 0.06c_{uB}$ | 4 | ✓ |
| 3 | $0.03c_{HWB} - 0.85c_{HWD} + 0.32c_{uW} + 0.43c_{uB}$ | 0.017 | |
| 4 | $-0.01c_{HW} + 0.07c_{HB} + 0.05c_{HWB} - 0.44c_{HWD} - 0.86c_{uW} - 0.23c_{uB}$ | 0.0077 | |
| 5 | $-0.01c_{HW} + 0.06c_{HB} + 0.04c_{HWB} - 0.29c_{HWD} + 0.39c_{uW} - 0.87c_{uB}$ | 0.0025 | |
| 6 | $+0.99c_{HG} + 0.038c_{uG}$ | 176000 | ✓ |
| $c_{HG,uG,uH,Ag}^{(1)}$ | $-0.03c_{HG} + 0.73c_{uG} - 0.03c_{qg}^{(i)} - 0.23c_{qg} - 0.05c_{qg}^{(o)} - 0.54c_{qg}^{(m)} - 0.02c_{uu} - 0.24c_{uu}^{(i)} - 0.04c_{uu}^{(o)} - 0.01c_{qu}^{(i)} - 0.18c_{qu}^{(m)} - 0.04c_{qu}^{(o)} - 0.18c_{CG} + 0.06c_{uH}$ | 20 | ✓ |
| 1 | $-0.03c_{HG} + 0.67c_{uG} + 0.04c_{qg}^{(i)} + 0.25c_{qg} + 0.05c_{qg}^{(o)} + 0.55c_{qg}^{(m)} + 0.02c_{uu} + 0.26c_{uu}^{(i)} + 0.03c_{uu}^{(o)} + 0.01c_{qu}^{(i)} + 0.16c_{qu}^{(m)} + 0.03c_{qu}^{(o)} + 0.29c_G + 0.1c_{uH}$ | 1.3 | ✓ |
| 2 | $+0.11c_{uG} + 0.01c_{qg} - 0.018c_{qg}^{(i)} + 0.029c_{qg}^{(o)} + 0.012c_{uu}^{(i)} - 0.993c_{uH}$ | 0.14 | |
| 3 | $+0.02c_{qg} - 1.0c_{qg}^{(i)} + 0.06c_{qg}^{(o)} + 0.03c_{uu}^{(i)} + 0.02c_{qu}^{(i)} + 0.02c_{uH}$ | 0.02 | |
| 4 | $+0.07c_{uG} - 0.02c_{qg}^{(i)} + 0.07c_{qg} + 0.03c_{qg}^{(o)} + 0.32c_{qg} + 0.06c_{uu} + 0.04c_{uu}^{(i)} + 0.08c_{qu}^{(i)} + 0.04c_{qu}^{(o)} - 0.94c_G + 0.02c_{uH}$ | 0.0092 | |

From SMEFT to models

matching & running significantly streamlined in the past few years

- ▶ matching SMEFT to UV models up to 1-loop in model

→ UOLEA/CDE Henning,Lu,Murayama,delAguila,Kunszt,Santiago,Drozd,Ellis,Quevillon,You, Zhang,Fuentes-Martin,Portoles,Ruiz-Femenia,Cohen,Krämer,Summ,Voigt...

→ partially automated Criado 1710.06445, Bashki et al 1808.04403

Cohen,Lu,Zhang 2012.07851,Fuentes-Martin et al 2012.08506

- ▶ RG running of Wilson coefficients automated

Fuentes-Martin et al 1704.04504,2010.16341
Aebischer,Kumar,Straub 1804.05033

→ easier to confront SMEFT fits with models!

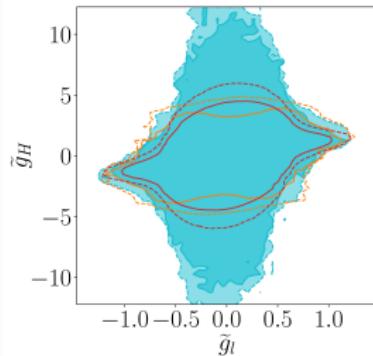
- ▶ “reduced fits” : fit SMEFT coefficients with UV relations imposed

Gorbahn,No,Sanz 1502.07352, Drozd,Ellis,Quevillon,You 1504.02409,
Ellis et al 1803.03252,2012.02779, Bakshi et al 2009.13394,
Anisha et al 2010.04088 Dawson et al 2007.01296

- ▶ fit model parameters through SMEFT : $\text{obs}(C_i(g_k))$

Brivio,Bruggisser,Geoffray,Kilian,Krämer,Luchmann,Plehn,Summ 2108.01094

↔ Emma Geoffray's talk



What's ahead?

Predictions

- ▶ more accurate SMEFT predictions
higher loop orders, account for RG running, include ~~CP~~ terms,
refine flavor structure (e.g. 3rd gen. split from rest)...
- ▶ SMEFT effects beyond matrix element : acceptances, PDFs, hadronization...
- ▶ accounting for unitarity bounds & positivity constraints

Uncertainties

- ▶ scale uncertainties in NLO SMEFT calculations (incl. matching)
- ▶ extension to $d = 8$, as uncertainty in $d = 6$ or as signal

(David), Passarino 1901.04177, 2009.00127

Trott et al 2102.02819, 2106.13794, 2107.07470, 2109.05595

Boughezal et al 2106.05537, Dawson et al 2110.06929...

we do have bases!

Li et al 2005.00008

Murphy 2005.00059

Measurements and fitting

- ▶ more processes included: $\bar{t}t\bar{t}t$, $\bar{t}t\bar{b}b$, VBS... B physics?
- ▶ more differential measurements → better discrimination
- ▶ more bayesian fits → easier for 50+ parameters