ATLAS+CMS EFT Fitting Exercise

5th General Meeting of the LHC EFT Working Group

Fabian Stäger on behalf of the
ATLAS and CMS EFT combination teams

University of Zurich UZH

CMS Compact Muon Solenoid

ATLAS EXPERIMENT

2 December 2022

Introduction, 1/3

- LHC EFT WG Area 4, CMS+ATLAS EFT Fitting exercise: Work towards EFT combination with input measurements from top, Higgs, and electroweak sector
- Agreed on SMEFT conventions:
  - → Single insertion of dimension 6 operators in Warsaw basis
  - → $(G_{\mathrm{F}}, m_W, m_Z)$ input parameter scheme
  - → `topU3l` flavour symmetry: (q_p, u_p, d_p) with $p = 1, 2$ and (Q, t, b)
- Git repositories:
  - → CMS: https://github.com/ajgilbert/eft-exercise-cms
  - → ATLAS: https://gitlab.cern.ch/nberger/smeft-combination-exercise
- Additional information in talks from earlier this year:
  - → Andrew Gilbert's talk at Area 4 meeting (February)
  - → Rahul Balasubramanian's talk at 4th LHC EFT WG General Meeting (May)

Introduction, 2/3

- EFT reinterpretation of existing differential cross section measurements

1) Parameterise cross sections using `MG5_aMC@NLO + SMEFTsim3` → `Pythia` → `Rivet`

$$\sigma(\boldsymbol{c}) = \sigma_{\text{SM}}\left(1 + \sum_i A_i c_i + \sum_{i,j} B_{ij} c_i c_j\right)$$

2) Construct multivariate Gaussian PDF

$$f(\boldsymbol{c}) = \exp\left[\left(\boldsymbol{\sigma}(\boldsymbol{c}) - \hat{\boldsymbol{\sigma}}\right)^{\text{T}} V_{\text{xs}}^{-1} \left(\boldsymbol{\sigma}(\boldsymbol{c}) - \hat{\boldsymbol{\sigma}}\right)\right]$$

→ $\boldsymbol{\sigma}(\boldsymbol{c})$ and $\hat{\boldsymbol{\sigma}}$: predicted and measured cross sections
→ V_{xs}: covariance matrix of measurements

3) Derive constraints on Wilson coefficients c_i

Introduction, 3/3

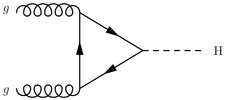
- Outline of this talk
  - → Analyses entering the Combination
  - → Reproducibility of EFT parameterisations
  - → Linear and Linear+Quadratic fit with Principal Component Analysis
  - → Topics that can be studied with this exercise

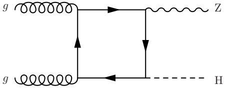
Input Measurements, 1/3

- Analyses entering the combination:
  - → Higgs sector:
    - CMS-HIG-19-015 (STXS $H \to \gamma\gamma$)
    - ATLAS-CONF-2020-053 (STXS $H \to \gamma\gamma + H \to 4\ell$)
  - → Top sector:
    - CMS-TOP-17-023 (single top, t-channel)
  - → Electroweak sector:
    - CMS-SMP-20-005 ($W\gamma$)
    - ATLAS-STDM-2017-24 (WW)
    - ATLAS-STDM-2018-03 (WZ)
    - ATLAS-STDM-2017-27 (Zjj)
    - arXiv:hep-ex/0509008 (Z-pole data from LEP and SLAC)
- Can always be extended, looking for more inputs (Differential cross section measurements with covariance matrix and Rivet routine)

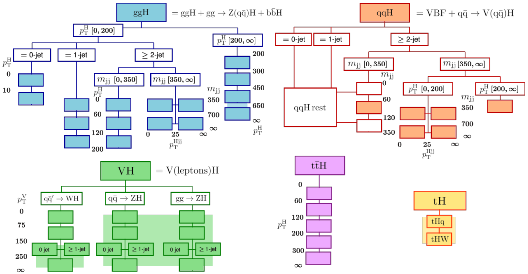
Input Measurements, 2/3

- Higgs sector: CMS-HIG-19-015 (STXS $H \to \gamma\gamma$)
  - → Simplified Template Cross Section (STXS) measurement
  - → Binning based on Higgs production mode
  - → Gluon-gluon fusion bins not yet included

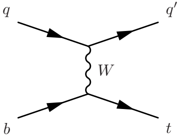


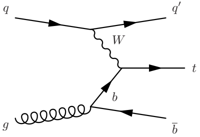


(graphic from CMS-HIG-19-015)

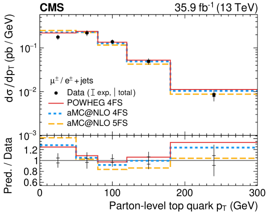


- Top sector: CMS-TOP-17-023 (single top, t-channel)
  - → taking measurement in p_T^t as input



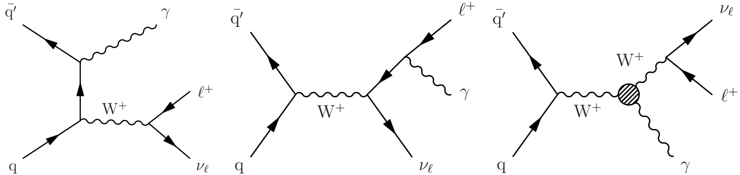


(plot from CMS-TOP-17-023)



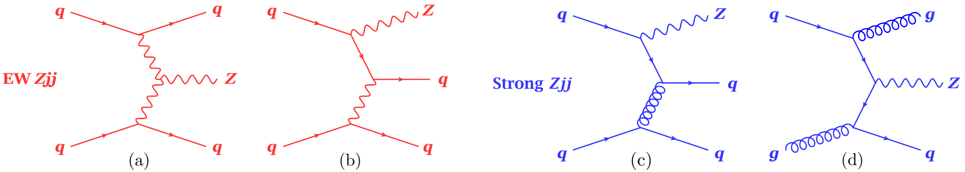
Input Measurements, 3/3

- Electroweak Sector
  - → CMS-SMP-20-005: Wγ production, double differential cross section in $p_T^\gamma \times |\Delta\phi_f|$



(diagrams from CMS-SMP-20-005)

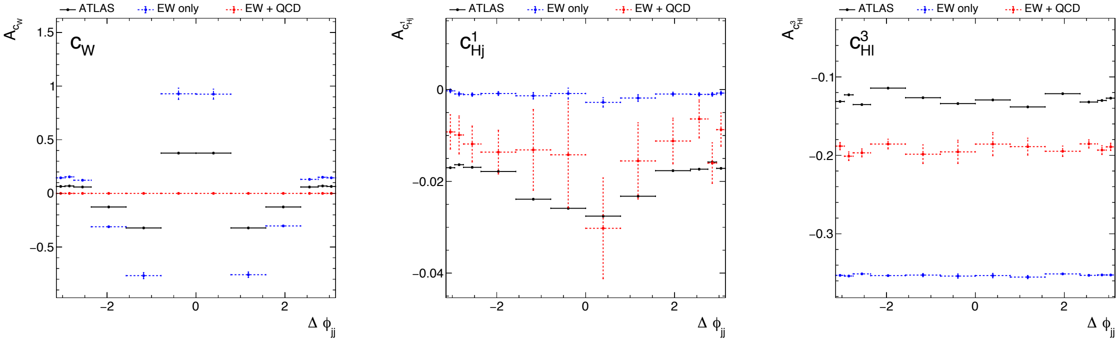
  - → ATLAS-STDM-2017-24: WW production, lepton p_T
  - → ATLAS-STDM-2017-27: Z + two jets, $\Delta\phi_{jj}$



(diagrams from ATLAS-STDM-2017-27)

EFT Parameterisation: example Z+jj

- Reproducing EFT parameterisation can be challenging and depends on several choices
  - → Process definition (e.g. number of QCD and EW vertices)
  - → Use of propagator corrections
  - → Reweighting vs. dedicated samples
  - → Inclusive or separate SM, interference, and quadratic terms

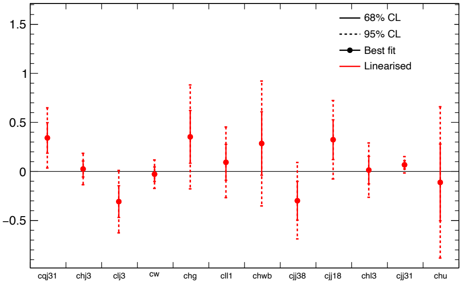


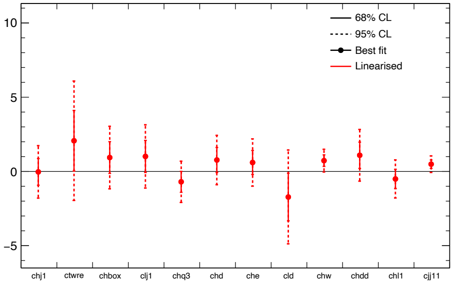
EFT Parameterisation: Different approaches to discuss

- Different approaches to event generation for calculating EFT scaling terms
  - → Generate events with $c_i = 0$ and use reweighting module
  - → Dedicated samples for each Wilson coefficient
- Separate SM, interference, and quadratic contributions?
  - → `NP<=1:` $\sigma = \sigma_{\text{SM}} + \sum c_i \sigma_i + \sum c_i c_j \sigma_{ij}$
  - → `NP=0:` $\sigma = \sigma_{\text{SM}}$
  - → `NP^2==1:` $\sigma = \sum c_i \sigma_i$
  - → `NP==1:` $\sigma = \sum c_i c_j \sigma_{ij}$
- Propagator corrections?
- Study the differences and discuss which is the best approach for this project

Constraints on Wilson coefficients from individual scans

- Combining STXS H $\rightarrow \gamma\gamma$, single top, Wγ (all CMS), WW, and Z+jj (ATLAS)
  - $\rightarrow$ Remember: parameterisations preliminary
- Due to correlations can not do full fit with all Wilson coefficients floating
  - $\rightarrow$ Get constraints from 1-by-1 scans with all other coefficients fixed to zero





Principal Component Analysis (PCA)

1) Rotate Hessian matrix to EFT basis using matrix of linear scaling parameters A_i

$$V_{\mathrm{EFT}}^{-1} = P^{\mathrm{T}} V_{\mathrm{xs}}^{-1} P \,, \qquad \text{with } P = \begin{pmatrix} A_{c_1}^{\text{bin 1}} & A_{c_2}^{\text{bin 1}} & \dots \\ A_{c_1}^{\text{bin 2}} & A_{c_2}^{\text{bin 2}} & \dots \\ \vdots & \vdots & \end{pmatrix}$$

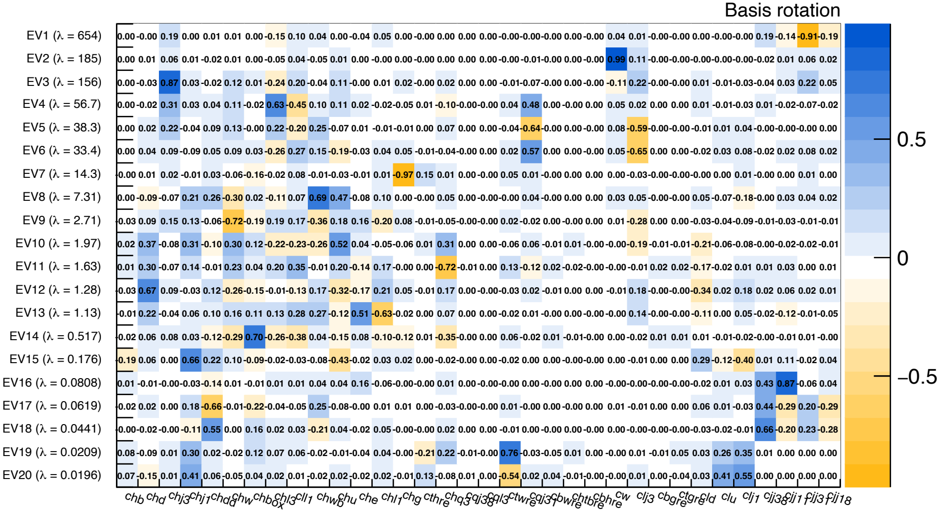
2) Eigendecomposition of $V_{\mathrm{EFT}}^{-1} \longrightarrow$ Eigenvectors $\boldsymbol{x}_i$ and eigenvalues λ_i

3) Obtain set of orthogonal directions in Wilson coefficient space: $\mathrm{PC}_i = \sum_k x_i^k c_k$

$\rightarrow$ Expected uncertainty on measurement of PC_i is $1/\sqrt{\lambda_i}$

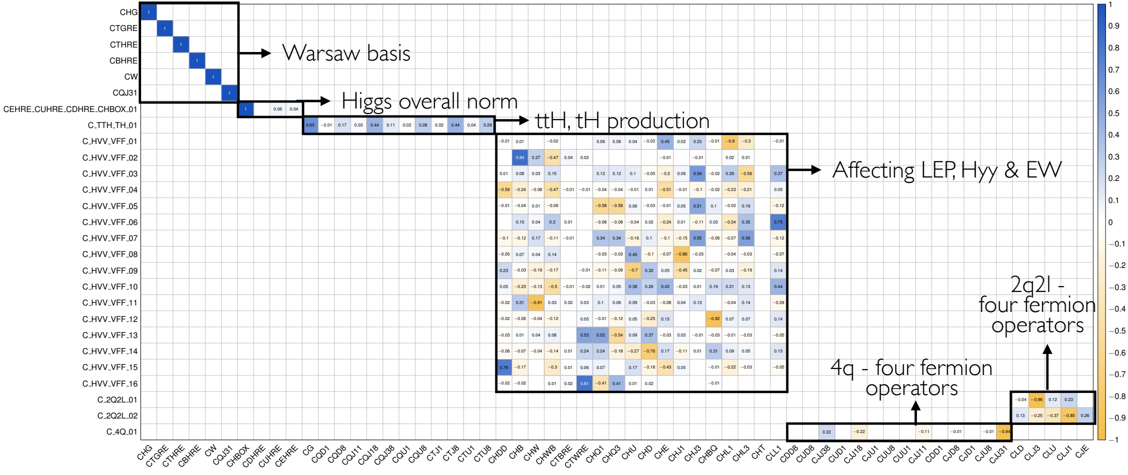
Basis rotation (CMS side)

- Result of PCA, rotation matrix $(\boldsymbol{x}_1, \boldsymbol{x}_2, \ldots)^T$:



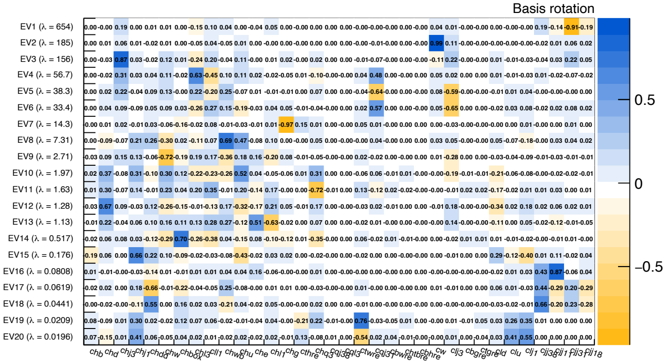
Basis rotation (ATLAS side)

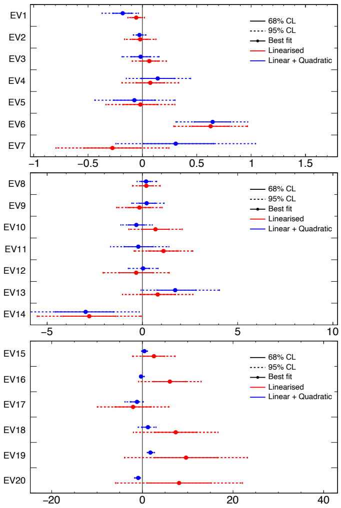
- ATLAS: Principal Component Analysis within subgroups of operators
  → https://indico.cern.ch/event/1136803/contributions/4849627/attachments/2449246/4197140/20220523_lhceftwg.pdf



Fit in rotated basis (CMS side): 1/2

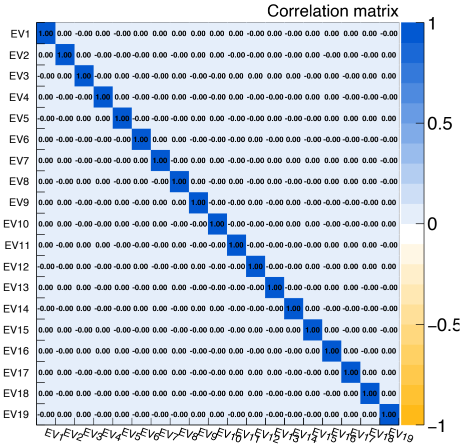
- Flat directions (eigenvectors with small λ) fixed to zero
- Can now do full fit with all POI floating



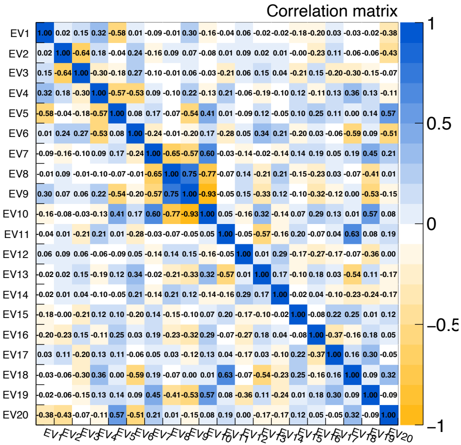


Fit in rotated basis (CMS side): 2/2

- As expected, the principal components are uncorrelated when doing a linear only fit
  - → By adding quadratic terms we reintroduce correlations



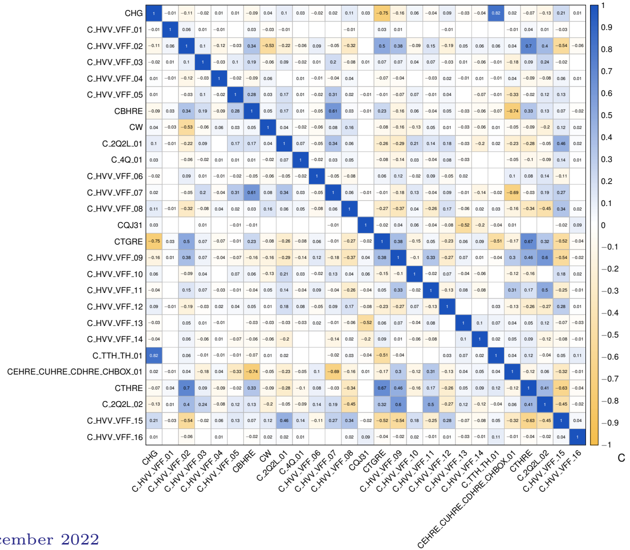
linear only fit

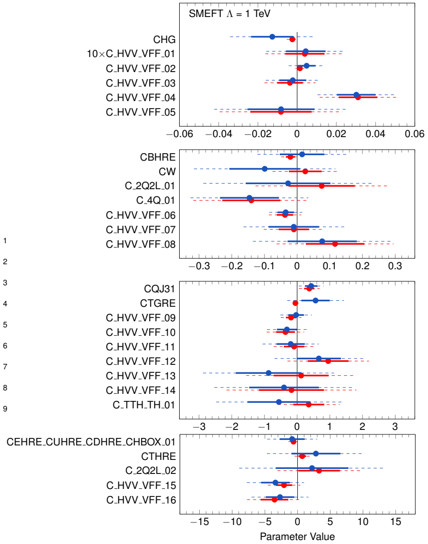


linear+quadratic fit

Fit in rotated basis (ATLAS side)

- Combination includes more analyses than on CMS side
  - → https://indico.cern.ch/event/1136803/contributions/4849627/attachments/2449246/4197140/20220523_lhceftwg.pdf





Topics that could be studied with this exercise

- Truncation studies:
  - → Study effects of data and MC «clipping» (not always clear which variable to cut on)
- Validation of Linear+Quadratic fits:
  - → Can global likelihood minima be identified
  - → Validity of confidence intervals
- Uncertainties on EFT parameterisation
- Flavour symmetry:
  - → Rederive EFT parameterisation under different flavour assumptions, compare number of sensitive directions
- Matching to UV models

Summary and Outlook

- LHC EFT WG combination exercise, ATLAS and CMS teams working in parallel
- EFT reinterpretation of differential cross section measurements (covariances, Rivet)
- So far three CMS and four (two) ATLAS analyses included, but looking to add more
- Discuss how to do event generation to calculate scaling terms
  - → Use reweighting module or dedicated samples?
  - → Separate SM, interference, and quadratic contributions?
- Using PCA to determine uncorrelated linear combinations of Wilson coefficients
- Many things that can be studied with this exercise:
  - → EFT truncation effects, flavour assumptions, UV matching, ...