

ATLAS+CMS SMEFT Fitting Exercise

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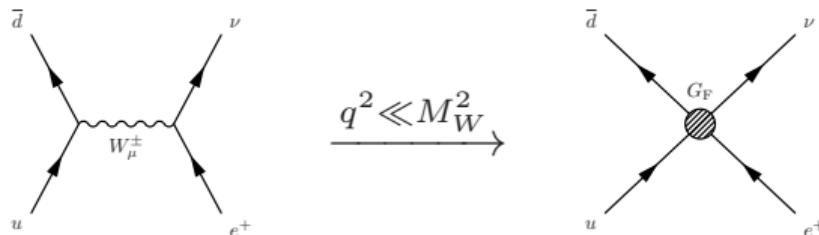


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The Standard Model Effective Field Theory (SMEFT)

- Well known example of an Effective Field Theory: Fermi theory describes the weak charged currents in the limit $q^2 \ll M_W^2$ as an effective four-fermion interaction $\sim G_F$
→ non-renormalizable mass dimension 6 operator, suppressed by M_W^{-2}

$$\mathcal{L}_{\text{Fermi}} = \frac{4G_F}{\sqrt{2}} (\bar{e}_L \gamma^\mu \nu_L) (\bar{u}_L \gamma_\mu d_L) + \text{h.c.} \quad \text{with} \quad \frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8M_W^2}$$



- In analogy: Assume BSM physics involves heavy particles beyond LHC energy reach
→ Could still appear off-shell as mediators of interactions of light SM fields
→ SM can be interpreted as low energy limit of unknown theory

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}}^{(d \leq 4)} + \frac{1}{\Lambda} \sum_i c_i \mathcal{Q}_i^{(5)} + \frac{1}{\Lambda^2} \sum_j c_j \mathcal{Q}_j^{(6)} + \dots$$

Dimension-6 operators in the SMEFT

(table from Grzadkowski et al, arXiv:1008.4884)

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\square}$	$(\varphi^\dagger \varphi) \square (\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\star (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \widetilde{W}}$	$\varphi^\dagger \varphi \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \widetilde{WB}}$	$\varphi^\dagger \tau^I \varphi \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

ATLAS+CMS SMEFT Fitting Exercise

- LHC EFT Working Group, CMS+ATLAS SMEFT Fitting exercise: Work towards a combined EFT interpretation of ATLAS and CMS data
 - EFT reinterpretation of differential cross section measurements
- 1) Parameterise cross sections in terms of Wilson coefficients, using Monte Carlo event generators and Rivet routines

$$\sigma_i(\mathbf{c}) = \sigma_i^{\text{SM}} + \underbrace{\sigma_i^{\text{int}}(\mathbf{c})}_{\sim \Lambda^{-2}} + \underbrace{\sigma_i^{\text{BSM}}(\mathbf{c})}_{\sim \Lambda^{-4}} = \sigma_i^{\text{SM}} \left(1 + \sum_j A_j c_j + \sum_{j,k} B_{jk} c_j c_k \right)$$

- 2) Construct likelihood based on multivariate Gaussian pdf

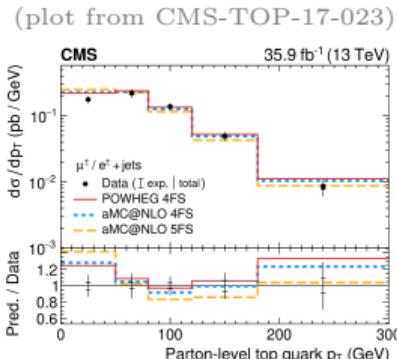
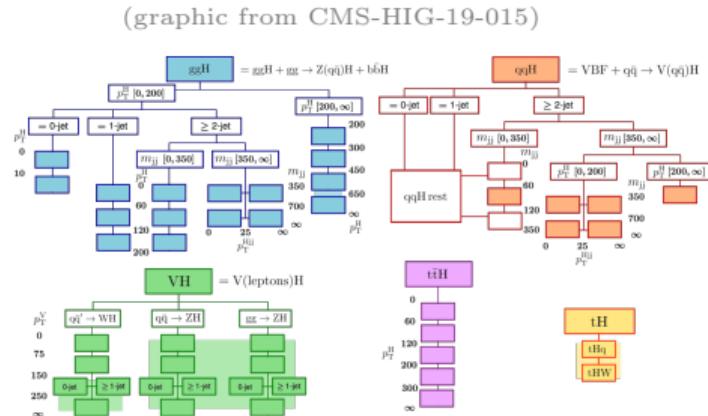
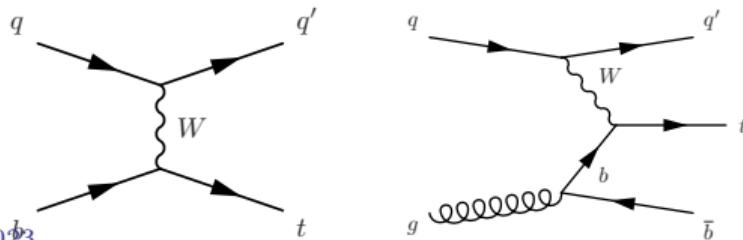
$$f(\mathbf{c}) = \exp \left[(\boldsymbol{\sigma}(\mathbf{c}) - \hat{\boldsymbol{\sigma}})^T V_{\text{xs}}^{-1} (\boldsymbol{\sigma}(\mathbf{c}) - \hat{\boldsymbol{\sigma}}) \right]$$

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

- 3) Derive constraints on Wilson coefficients c_i

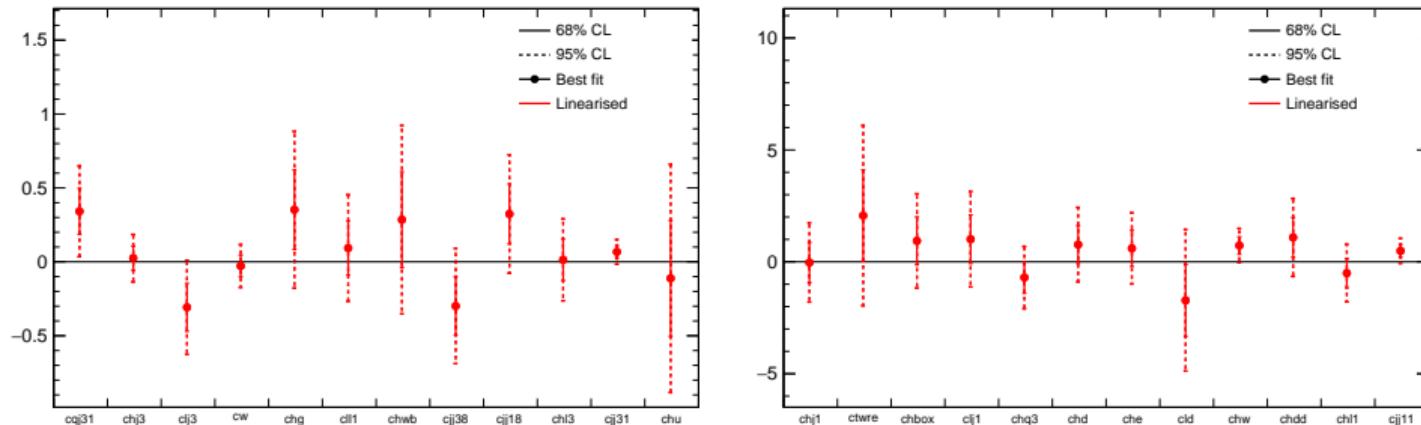
Input Measurements

- Higgs sector: CMS-HIG-19-015 (STXS $H \rightarrow \gamma\gamma$)
 - Simplified Template Cross Section (STXS) measurement
 - Binning based on Higgs production mode
 - Gluon-gluon fusion bins not yet included
- Electroweak sector:
 - CMS-SMP-20-005 ($W\gamma$)
 - ATLAS-STDM-2017-24 (WW)
 - ATLAS-STDM-2017-27 (Zjj)
- Top sector: CMS-TOP-17-023 (single top, t -channel)
 - taking measurement in p_T^t as input



Constraints on Wilson coefficients from individual scans

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



Principal Component Analysis (PCA)

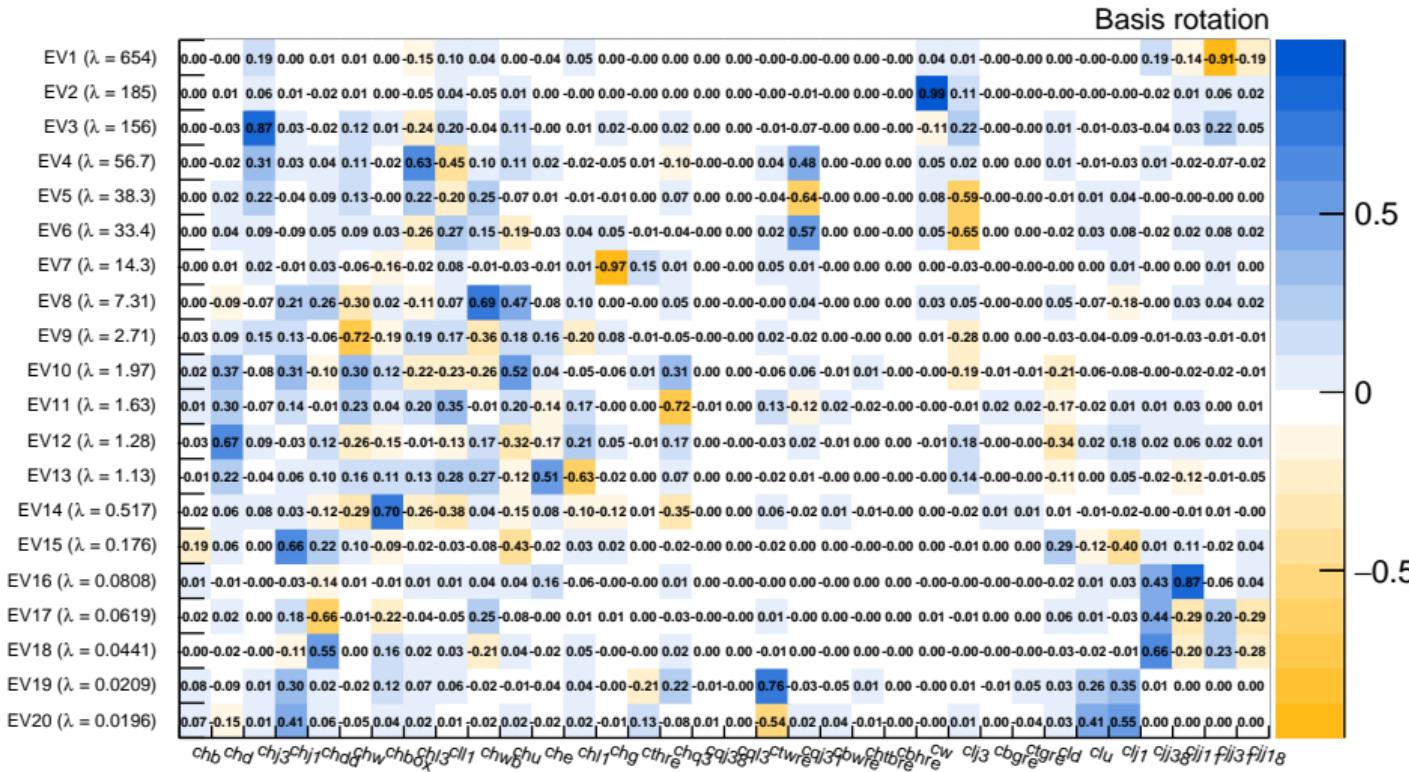
- Insufficient information to constrain all Wilson coefficients in a simultaneous fit
 - Principal Component Analysis is a tool to identify the combinations of degrees of freedom with largest and smallest variability in a linear algebra problem
 - Use it to find linear combinations of Wilson coefficients that can be constrained
- 1) Rotate Hessian matrix to EFT basis using matrix of linear scaling parameters A_i

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

- 2) Eigendecomposition of V_{EFT}^{-1} → Eigenvectors \mathbf{x}_i and eigenvalues λ_i
- 3) Obtain set of orthogonal directions in Wilson coefficient space: $\text{PC}_i = \sum_k x_i^k c_k$
→ Expected uncertainty on measurement of PC_i is $1/\sqrt{\lambda_i}$

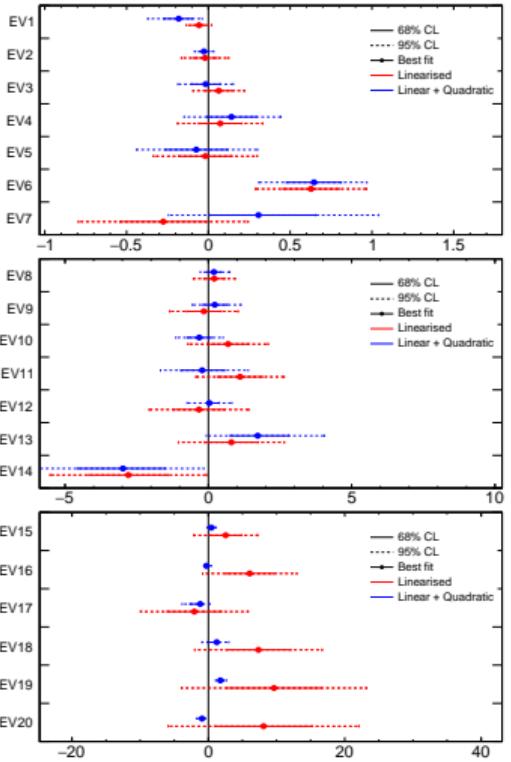
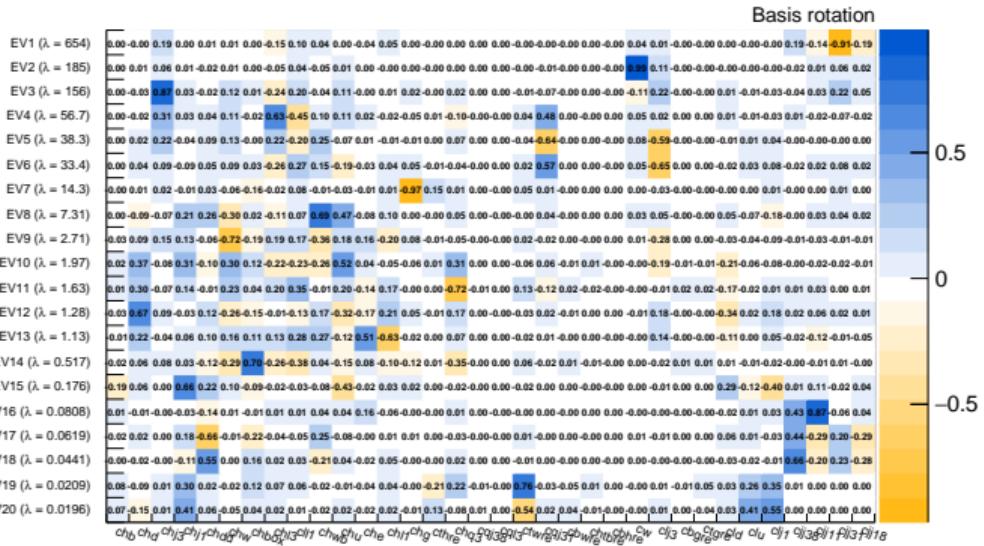
Principal Component Analysis (PCA)

- Result of PCA, rotation matrix $(x_1, x_2, \dots)^T$:



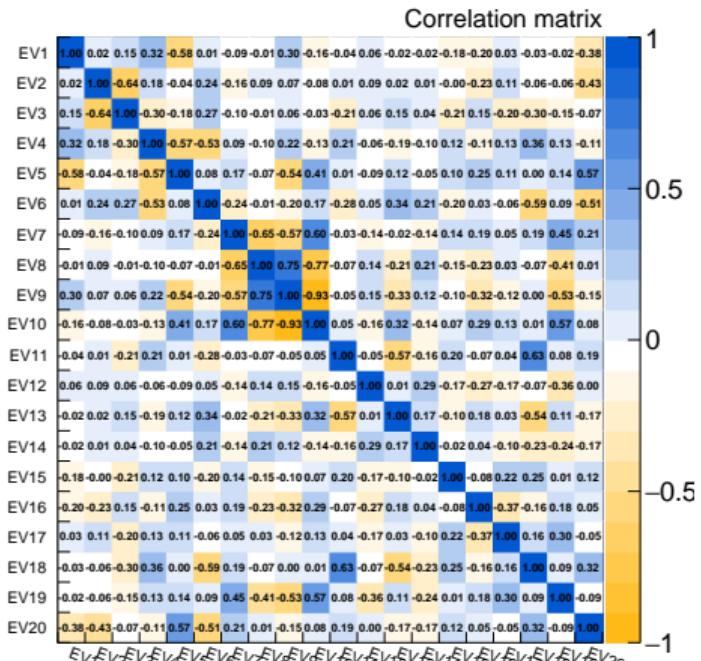
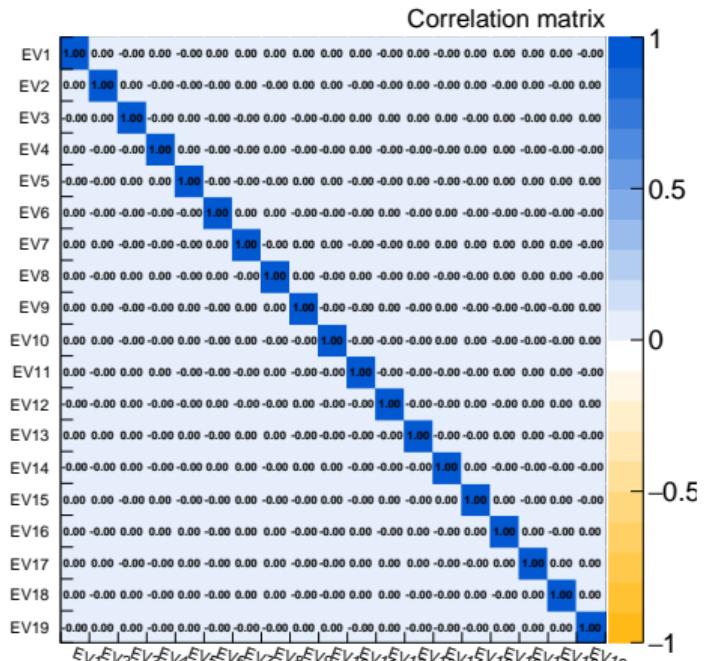
Fit in rotated basis, 1/2

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



Fit in rotated basis, 2/2

- As expected, the principal components are uncorrelated when doing a «linear only» fit
 → By taking into account quadratic terms ($\sum B_{ij} c_i c_j$), we reintroduce correlations



Summary

- EFT reinterpretation of differential cross section measurements
- So far three CMS and four (two) ATLAS analyses included
- Using PCA to determine uncorrelated linear combinations of Wilson coefficients
- A step towards a global EFT combination of ATLAS and CMS data?