Effective Field Theory interpretations of ATLAS measurements

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on behalf of the ATLAS Collaboration

Higgs 2021, October 19th, 3pm EST

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Introduction

- The LHC has not found any new physics beyond SM + Higgs boson
- Direct searches for SUSY or exotics continue, but focus on indirect exploration increases
  - independent of specific model of new physics
  - applicable to wide range of analyses
- Interpretation in context of **Effective Field Theories** complementing (or superseding) other interpretations
  - interim κ-framework (Higgs)
  - anomalous couplings (SM, Top)
  - polarization measurements (SM, Top)
- Plethora of ATLAS results contain interpretations in terms of EFT
  - limited time for individual results, provide references instead of details
  - focus on **interpretation methodology** and **new developments**

Standard Model Effective Field Theory

- Introduce new effective operators with free coefficients to capture new physics appearing beyond scale Λ (typically chosen as 1 TeV)

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathcal{O}_i^{(6)} + \frac{1}{\Lambda^4}\sum_i c_i^{(8)}\mathcal{O}_i^{(8)} + \ldots$$

- New heavy internal particles are integrated out and are represented as vertices in the new effective theory
- Most common: **Warsaw-basis** (59+h.c. dim-6 operators)

SMEFT in a nutshell

- $\mathscr{L}_{\text{SM}}$ is dim-4, high orders only valid in the low-energy regime $E \ll \Lambda$
- terms with odd dimensionality violate $B - L$ symmetry and are usually not considered for LHC physics
- Wilson coefficients $c \equiv 0$ for SM, deviations might indicate new physics

Parametrization

- Analyses primarily measure cross-sections (or signal strengths) with likelihood fit

$$L(\boldsymbol{\mu}, \boldsymbol{\theta}) = \prod_{i}^{\text{bins}} P\left(n_i^{\text{obs}} \mid \mu_i n_i^{\text{sig}}(\boldsymbol{\theta}) + n_i^{\text{bkg}}(\boldsymbol{\theta})\right) \cdot \prod_{j}^{\text{nuis}} G(\theta_j)$$

- For **direct** interpretation, replace $\mu n_i^{\text{sig}}(\boldsymbol{\theta}) \rightarrow n_i^{\text{sig}}(\boldsymbol{c}, \boldsymbol{\theta})$ for the Wilson coefficients c

$$n^{\text{sig}}(\boldsymbol{c}) \cdot \mathcal{L}^{-1} = \sigma_{\text{SM}} + \overbrace{\sum_j \frac{c_j}{\Lambda^2} \int \left|\mathcal{M}_{\text{SM}}^{d-1} \mathcal{O}_j^{(6)}\right| d\Omega}^{\text{“linear”}} + \overbrace{\sum_{jk} \frac{c_j c_k}{\Lambda^4} \int \left|\mathcal{M}_{\text{SM}}^{d-2} \mathcal{O}_j^{(6)} \mathcal{O}_k^{(6)}\right| d\Omega}^{\text{“quadratic”}} + \ldots$$

- For **indirect** (re)interpretation perform the same procedure on the cross-sections in the rewritten likelihood based on published, unfolded result with data bin correlation matrix C

$$L(\boldsymbol{\Delta\sigma}) = \frac{1}{\sqrt{(2\pi)^{n_{\text{bins}}} \det C}} \exp\left(-\frac{1}{2} \boldsymbol{\Delta\sigma}^T C^{-1} \boldsymbol{\Delta\sigma}\right) \qquad \text{with } \Delta\sigma = \sigma^{\text{obs}} - \sigma^{\text{sig}}$$

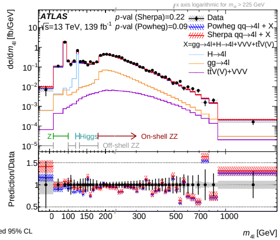
Considerations: Quadratic terms

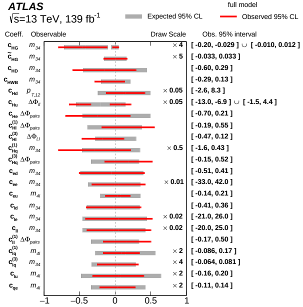
- same order as linear dim-8 terms – not possible to interpret at fixed order in EFT
- often only included as an estimate for higher order corrections
- for some processes, linear terms are suppressed – here quadratic terms drive sensitivity!

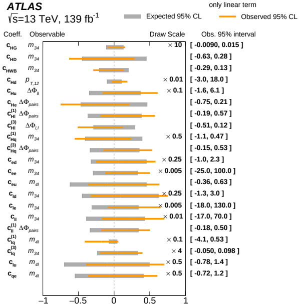
$pp \to 4\ell$

JHEP 07 (2021) 005

- 4ℓ events with isolated same-flavour (SF), opposite-charge (OC) pairs ($4e$, 4μ, $2e2\mu$)
  - construct lepton pairs by proximity to Z-mass (smallest $|m_{2\ell} - m_Z|$)
  - define 4 regions by $m_{4\ell}$: single-Z, on-shell ZZ, off-shell ZZ, and $H \to 4\ell$
  - pre-unfolding efficiency correction reduce assumptions on signal modelling
  - subtract background from misidentified leptons
  - unfold differential fiducial cross-section in m_{12}, m_{34}, $m_{4\ell}$, p^T_{34}, $p^T_{4\ell}$, $\Delta\Phi_{\ell\ell}$, $\Delta Y_{\ell\ell}$ using Iterative Bayesian Unfolding







- reparametrize unfolded result (**indirect**) with Wilson coefficients
- fit rewritten LH to unfolded data, one coefficient at a time
- use most sensitive observable each

Other SM differential measurements

more involved analyses with similar interpretation strategies

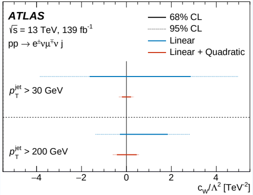
Z+dijet with 139 fb^{-1} — Eur. Phys. J. C 81 (2021) 163

- SF OC lepton pair $|m_{\ell\ell} - m_Z| < 10\,\text{GeV}$
- two VBF/VBS-like jets ($m_{jj} > 1\,\text{TeV}$, $\Delta y_{jj} > 2$)
- Z within (+ balanced against) dijet system
- data-driven estimate for QCD $Z + jj$ bkg.
- Iterative Bayesian Unfolding to 4 obs.
- reparametrize $\Delta\Phi_{jj}$ to infer Wilson coeff.
- p-values derived with 1000 toys

Wilson coefficient	Includes $\vert\mathcal{M}_{d6}\vert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	$[-0.30,\ 0.30]$	$[-0.19,\ 0.41]$	45.9%
	yes	$[-0.31,\ 0.29]$	$[-0.19,\ 0.41]$	43.2%
$\tilde{c}_W/\Lambda^2$	no	$[-0.12,\ 0.12]$	$[-0.11,\ 0.14]$	82.0%
	yes	$[-0.12,\ 0.12]$	$[-0.11,\ 0.14]$	81.8%
c_{HWB}/Λ^2	no	$[-2.45,\ 2.45]$	$[-3.78,\ 1.13]$	29.0%
	yes	$[-3.11,\ 2.10]$	$[-6.31,\ 1.01]$	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	$[-1.06,\ 1.06]$	$[0.23,\ 2.34]$	1.7%
	yes	$[-1.06,\ 1.06]$	$[0.23,\ 2.35]$	1.6%

WW+$\geq$ 1jet with 139 fb^{-1} — JHEP 06 (2021) 003

- one DF OC lepton pair with $m_{e\mu} > 85\,\text{GeV}$
- ≥ 1 central jet with $p_T > 30\,\text{GeV}$, no b-jets
- additional signal region with $p_T^{\text{jet}} > 200\,\text{GeV}$ to reduce helicity-suppression of dim-6 interference term
- Iterative Bayesian Unfolding to 12 obs.
- use $m_{e\mu}$ to infer limits on c_W
- strongest limits from quadratic term



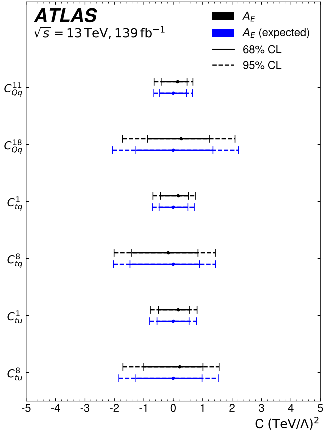
Energy asymmetry in $t\bar{t}j$ production

arXiv:2110.05453

- semileptonic top: isolated ℓ + b-jet + E_T^{miss}
- hadronic top: large-R-jet ($p_T > 350\,\text{GeV}$)
- boosted: +1 hard jet ($p_T > 100\,\text{GeV}$)
- non-prompt bkg.: data-driven matrix method
- Fully Bayesian Unfolding of jet scattering angle and energy asymmetry

$$\Delta E = E_t - E_{\bar{t}}$$

$$N^{\text{opt}}(\theta_j) = N(\theta_j | y_{t\bar{t}j} > 0) - N(\pi - \theta_j | y_{t\bar{t}j} < 0)$$



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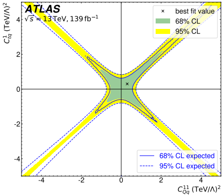
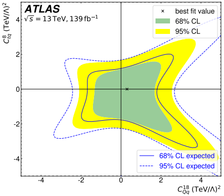
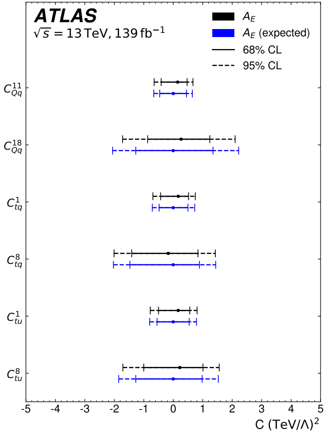






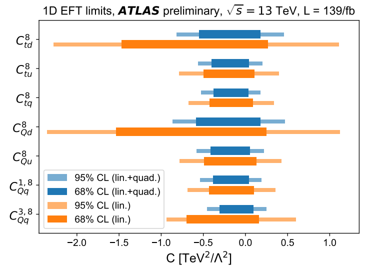
- many more contours in the paper!

Two-dimensional scans from $t\bar{t}$

highly sensitive analyses can probe several coefficients at once

boosted $t\bar{t}$ all-hadronic ATLAS-CONF-2021-050

- two large-R jets with $p_T > 500/350$ GeV
- top-tagging, masses close to the top mass, b-matching of associated small-R-jets
- Iterative Bayesian Unfolding to 13 observables (plus $12 \times 2d$, $1 \times 3d$ distribution)
- results prepared on particle-level and parton-level
- reparametrize p_T^{t1} distribution



boosted $t\bar{t}$ + jets ATLAS-CONF-2021-031

- select exactly one lepton close to a b-jet and far from a top-tagged jet, cut on E_T^{miss} & m_T^W
- Iterative Bayesian Unfolding to 18 1d and 4 2d observables
- reparametrizing $p_T^{\text{top}_{\text{had}}}$ distribution

Coeff.	Marginalised 95% intervals		Individual 95% intervals	
	Expected	Observed	Expected	Observed
C_{tG}	[-0.44, 0.44]	[-0.68, 0.21]	[-0.41, 0.42]	[-0.63, 0.20]
$C_{tq}^{(8)}$	[-0.35, 0.35]	[-0.30, 0.36]	[-0.35, 0.36]	[-0.34, 0.27]

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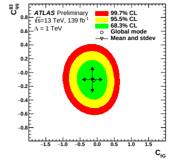
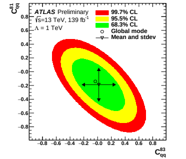
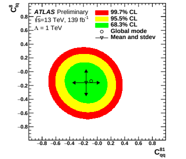
- also prepared $2d$ confidence regions!







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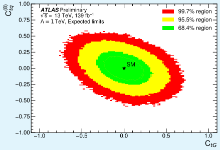
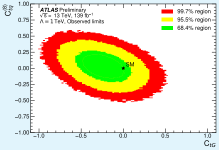




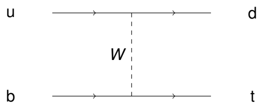
Consideration: Cross sections vs. EFT coefficients?

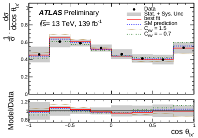
- unfolded spectra are important results in their own right
- precision measurements sensitive to wide array of coefficients
- what about measurements targeting individual coefficients?

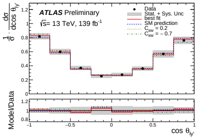
Single $t/\bar{t}$ polarization limits on tWb dipole

ATLAS-CONF-2021-027

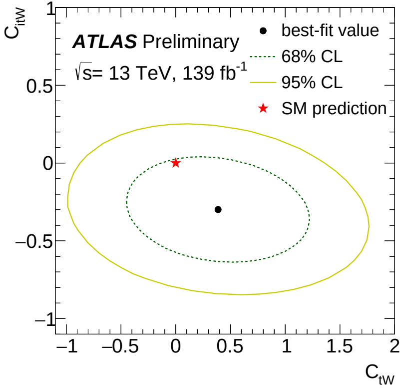
- focus on t-channel exchange of a W boson in single-top events – dominant process at the LHC
- $V-A$ structure of the tWb vertex $\Rightarrow$ top quarks spin aligned with d-quark or spectator quark
- predicted $t/\bar{t}$ polarization alongside spectator: 0.9/0.86
- Warsaw basis: only $\mathcal{O}_{tW}$ affects pol. angle (C_{tW} & C_{itW})
- rely on leptonic top decays: events with $\ell + E_T^{\text{miss}} + 2$ jets
  - one b-jet, one “specatator” jet
- specialized geometrical cuts enhance s/b
- CR for $t\bar{t}$ and W+jets, data-driven method for multijet
- split SR and CRs by lepton charge, slice SR $3d$ space of $\cos\theta_{\ell x'}$, $\cos\theta_{\ell y'}$, $\cos\theta_{\ell z'}$ into octants
- use Iterative Bayesian Unfolding to obtain angular differential distributions in $\cos\theta_{\ell x'/y'/z'}$







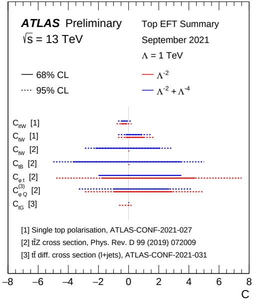
	C_{tW}		C_{itW}	
	68% CL	95% CL	68% CL	95% CL
All terms	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^4$	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^2$	[-0.2, 1.0]	[-0.7, 1.7]	[-0.5, -0.1]	[-0.8, 0.2]

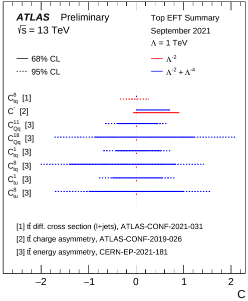


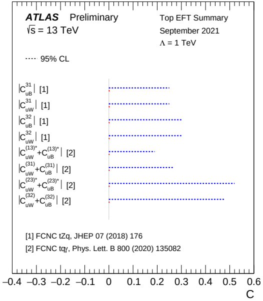
Top summary plots

ATL-PHYS-PUB-2021-036

- compilation of single-operator results
- sorted into two-fermion, four-fermion and FCNC operators







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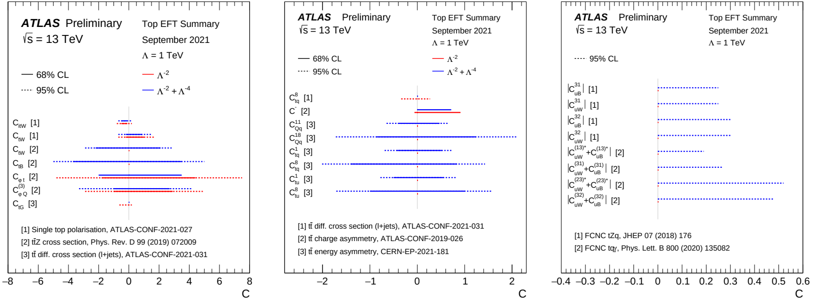


All of these results use unfolded precision measurements

- next slides explore other approaches measuring EFT coeff.

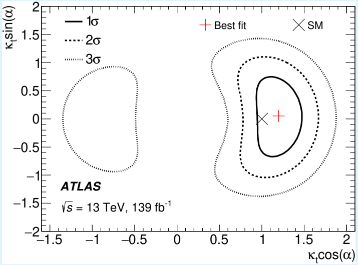
Measurements of Higgs-Top coupling *CP*

dedicated analyses of *CP*-odd and *CP*-even higgs couplings

ttH $H \to \gamma\gamma$ with 139 fb^{-1} PRL 125 061802 (2020)

- two photons + 1 *b*-tagged jet
- categorization by top decay (lep. or had.)
- different approaches to reconstructing top-quarks
- two BDTs (background-rejection / CP)
- data-driven background estimate
- use κ_g and κ_γ from the Run 2 Higgs combination

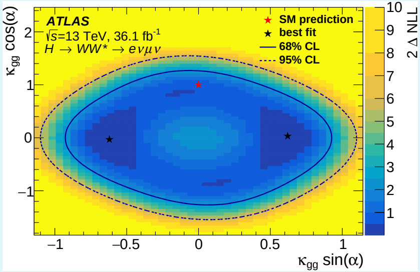
$$\mathscr{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos\alpha + i\sin\alpha\gamma_5\right]\psi_t\right\} H$$



ggF+2j $H \to WW$ with 36 fb^{-1} arXiv:2109.13808v1

- select two isolated DF OC leptons + 2 jets, various background rejection cuts
- BDT to distinguish between ggF and VBF
- signed $\Delta\Phi_{jj}$ allows to infer *CP*-nature of Top-Yukawa-Coupling

$$\mathscr{L} = -\frac{g_{Hgg}\kappa_{gg}}{4}\left(G^a_{\mu\nu}G^{a,\mu\nu}\cos\alpha + \tilde{G}^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\sin\alpha\right) H$$



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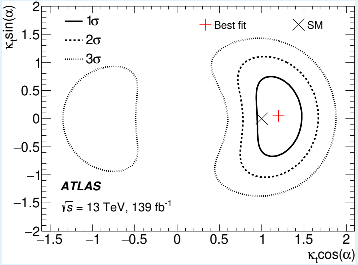

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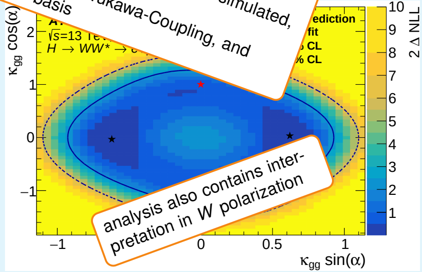
- …ed $\Delta\Phi_{jj}$ allows to infer CP-nature of … Coupling

$$\ldots + \tilde{G}^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\sin\alpha\Big) H$$



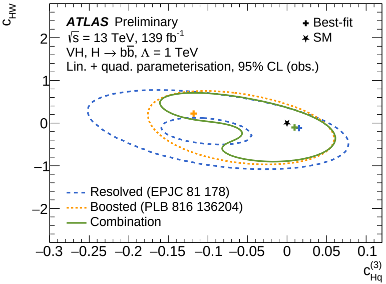
- **direct** EFT interpretation (without unfolding)
- for interpretation, EFT template samples are simulated, reconstructed and analyzed
- both analyses focus on Top-Yukawa-Coupling, and neither uses Warsaw basis

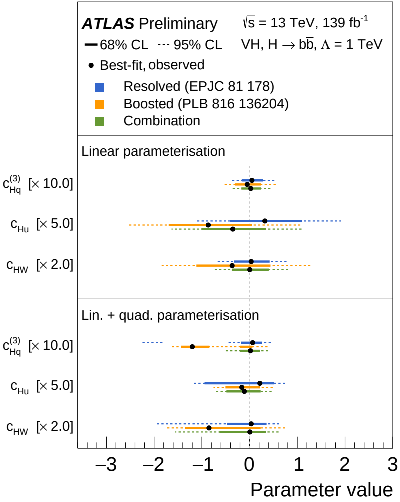
analysis also contains interpretation in W polarization

VH($\to$ bb) resolved + boosted combination

ATLAS-CONF-2021-051

- combination of two $H \to bb$ analyses
  - resolved: $p_T^V > 75\,\text{GeV}$ + two separate jets
  - boosted: $p_T^V > 250\,\text{GeV}$ + one large-R jet
- binned in lepton multiplicity, selecting E_T^{miss}
- overlap avoided through cut at p_T^V=400 GeV
- **direct** interpretation of p_T^V spectrum
- in-likelihood unfolding with simplified template cross-sections
- many pairwise contours studied





The more, the merrier

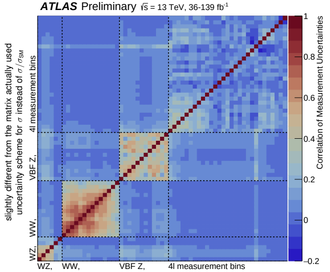
How can we move towards more comprehensive results?

- Wealth of Wilson coefficients poses a challenge
  - Many analyses are only sensitive to few
  - Constraints typically sufficient for 1*d* or 2*d* limits, rarely more
  - Can we avoid having to fix many coefficients to SM?
  - **Combine** analyses to get a more comprehensive picture!
- What can we do with coefficients that we are not sensitive to?
  - If the coefficients have no effect on the results, we can still fix them
  - With limited sensitivity, try to measure combination of coefficients
  - **Rotate** space of coefficients to a basis that allows for maximum extraction of information!

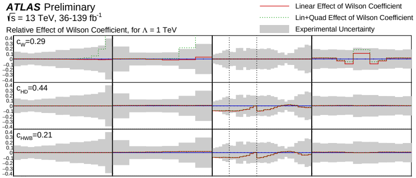
Combination of *WW*, *WZ*, 4*l*, and *Z*+2j

ATL-PHYS-PUB-2021-022

> exp. covariances of XS



> EFT parametrization



⋮

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ATL-PHYS-PUB-2021-022

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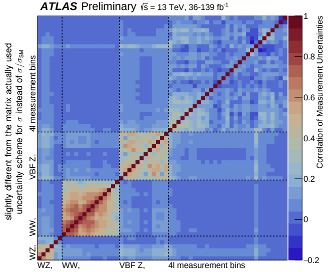
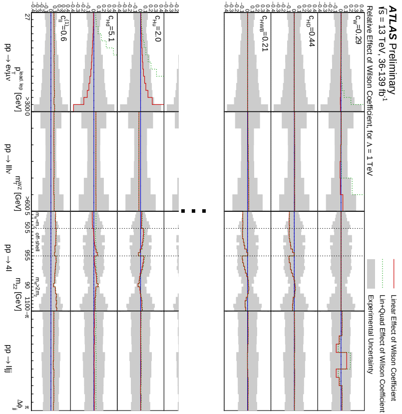


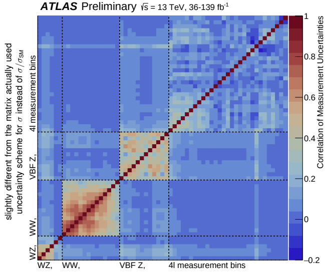
> EFT parametrization



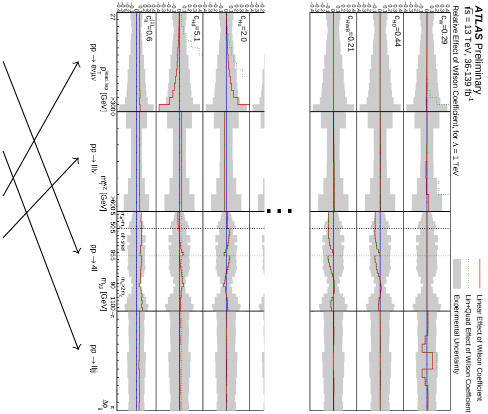
Combination of *WW*, *WZ*, 4*l*, and *Z*+2j

ATL-PHYS-PUB-2021-022

> exp. covariances of XS



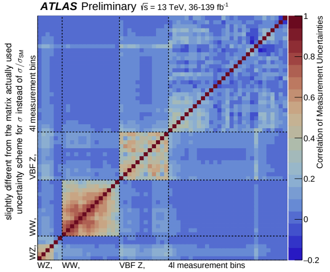
> EFT parametrization



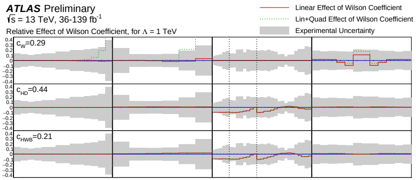
Combination of *WW*, *WZ*, 4*l*, and *Z*+2j

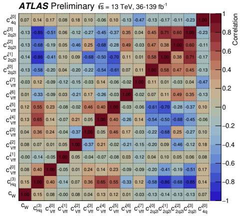
ATL-PHYS-PUB-2021-022

> exp. covariances of XS



> EFT parametrization



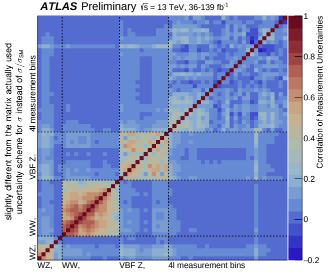


> (estimated) EFT covariance matrix

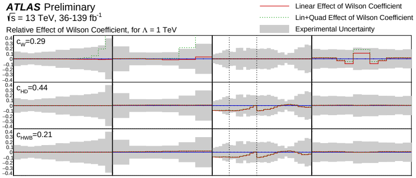
Combination of *WW*, *WZ*, 4*l*, and *Z*+2j

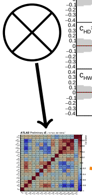
ATL-PHYS-PUB-2021-022

> exp. covariances of XS



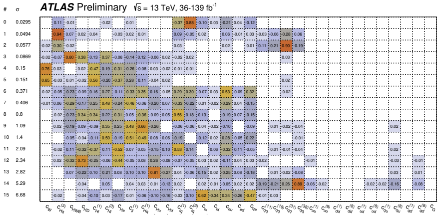
> EFT parametrization





⋮

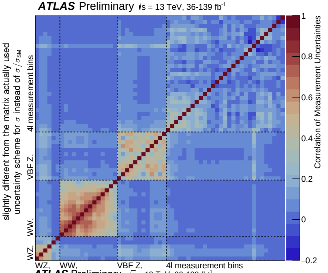
principal component analysis



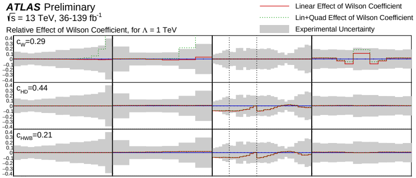
Combination of *WW*, *WZ*, 4*l*, and *Z*+2j

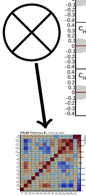
ATL-PHYS-PUB-2021-022

> exp. covariances of XS



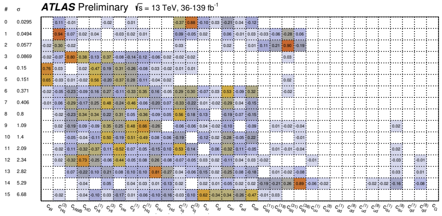
> EFT parametrization



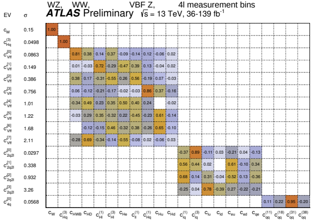


⋮

principal component analysis



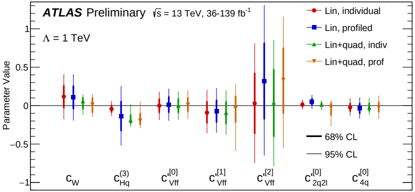
group



Combination of *WW*, *WZ*, 4*l*, and *Z*+2j

ATL-PHYS-PUB-2021-022

- combine four EW SM analyses
- correlated treatment of systematic uncertainties
- unfolded fiducial spectra, reinterpreted with Gaussian likelihood (**indirect**)
- simultaneous fit of 15 coeff.
- 2*d* profile likelihood contours



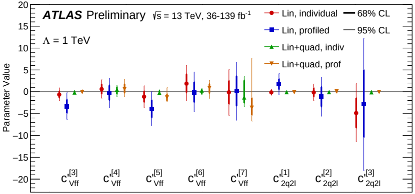
$c'^{[0]}_{Vff} \simeq 0.81c_{HWB} + 0.38c_{HD} + 0.13c^{(1)}_{Hl} + 0.37c^{(3)}_{Hl} - 0.14c^{(1)}_{ll} + 0.12c^{(1)}_{Hq}$

$c'^{[1]}_{Vff} \simeq 0.73c^{(1)}_{Hl} - 0.28c^{(3)}_{Hl} - 0.48c_{He} + 0.38c^{(1)}_{ll} + 0.13c^{(1)}_{Hq}$

$c'^{[2]}_{Vff} \simeq 0.37c_{HWB} + 0.17c_{HD} - 0.31c^{(1)}_{Hl} - 0.53c^{(3)}_{Hl} + 0.25c_{He} + 0.59c^{(1)}_{ll} - 0.21c^{(1)}_{Hq}$

$c'^{[0]}_{2q2l} \simeq -0.37c^{(1)}_{lq} + 0.89c^{(3)}_{lq} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$

$c'^{[0]}_{4q} \simeq 0.11c^{(11)}_{qq} + 0.22c^{(18)}_{qq} + 0.95c^{(31)}_{qq} - 0.2c^{(38)}_{qq}$



$c'^{[3]}_{Vff} \simeq -0.19c^{(1)}_{Hl} - 0.14c^{(3)}_{Hl} + 0.86c^{(1)}_{Hq} + 0.41c_{Hu} - 0.17c_{Hd}$

$c'^{[4]}_{Vff} \simeq -0.35c_{HWB} + 0.49c_{HD} + 0.26c^{(1)}_{Hl} + 0.35c^{(3)}_{Hl} + 0.51c_{He} + 0.38c^{(1)}_{ll} + 0.18c^{(1)}_{Hq}$

$c'^{[5]}_{Vff} \simeq 0.25c_{HD} + 0.33c^{(1)}_{Hl} - 0.22c^{(3)}_{Hl} + 0.18c_{He} - 0.35c^{(1)}_{ll} - 0.3c^{(1)}_{Hq} + 0.71c_{Hu} - 0.16c_{Hd}$

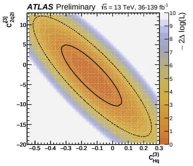
$c'^{[6]}_{Vff} \simeq -0.22c^{(1)}_{Hl} + 0.52c^{(3)}_{Hl} - 0.39c_{He} + 0.44c^{(1)}_{ll} - 0.22c^{(1)}_{Hq} + 0.52c_{Hu}$

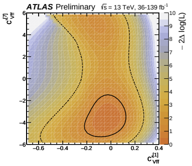
$c'^{[7]}_{Vff} \simeq -0.28c_{HWB} + 0.71c_{HD} - 0.31c^{(1)}_{Hl} - 0.21c^{(3)}_{Hl} - 0.5c_{He} - 0.14c^{(1)}_{ll}$

$c'^{[1]}_{2q2l} \simeq 0.56c^{(1)}_{lq} + 0.44c^{(3)}_{lq} + 0.61c_{eu} - 0.1c_{ed} + 0.34c_{qe}$

$c'^{[2]}_{2q2l} \simeq 0.68c^{(1)}_{lq} + 0.15c^{(3)}_{lq} + 0.33c_{lu} - 0.51c_{eu} + 0.13c_{ed} - 0.37c_{qe}$

$c'^{[3]}_{2q2l} \simeq -0.27c^{(1)}_{lq} + 0.79c_{lu} - 0.39c_{ld} + 0.26c_{eu} - 0.22c_{ed} - 0.16c_{qe}$

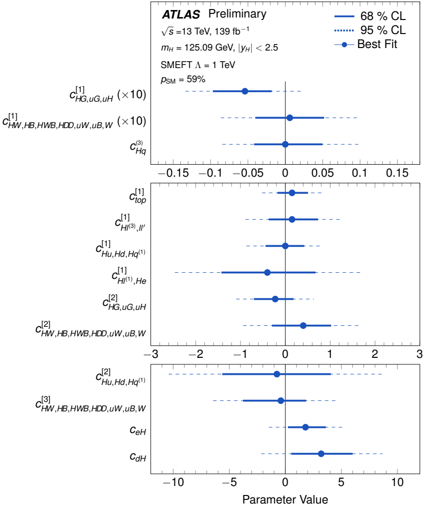


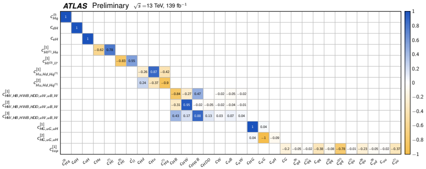


EFT interpretation of Higgs combination

ATLAS-CONF-2021-053

- comb. of $H \to \gamma\gamma / ZZ / WW / \tau\tau / bb$
- more channels without EFT interpretation in publication
- corr. treatment of systematics
- in-likelihood unfolding using simplified template cross sections
- parametrization of the full likelihood in terms of EFT (**direct**)
- simultaneous fit of 13 coefficients
  - up from 10 coeff. ($H \to \gamma\gamma / ZZ / bb$)
- rotation to sensitive basis





EFT interpretation of SM $WW + H \to WW$

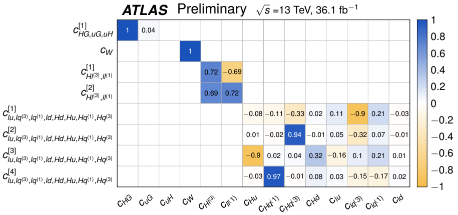
ATL-PHYS-PUB-2021-010

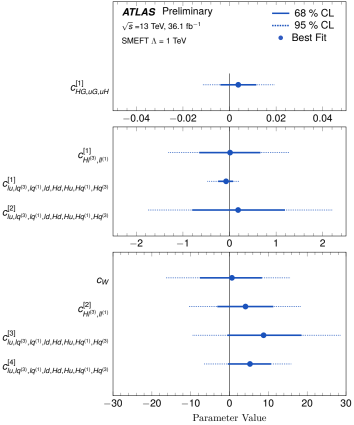
> combination of $H \to WW$ analysis with SM WW analysis
  - $H \to WW$ directly interprets μ_{ggF}/μ_{VBF}
  - SM WW interprets unfolded result (indirect, Gaussian likelihood)

> correlated treatment of systematics

> simultaneous fit of 8 coefficients

> rotation to sensitive basis





Conclusions

- Wealth of EFT results published by the ATLAS collaboration
  - Standard Model, Top and Higgs analyses
  - No significant deviations from the Standard Model observed
- Many differerent strategies
  - In many cases, EFT results interpret unfolded spectrum
  - Alternatively measure coefficients with the primary likelihood
  - Some specifically tailored to certain EFT operators
- Challenging to constrain several coefficients simultaneously
  - Currently only achievable by combinations
  - Use of basis rotation to extract maximum information
- Even possible to combine across different approaches, hope to see more interesting combined results in the future