Challenges towards the global EFT fit

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Introduction

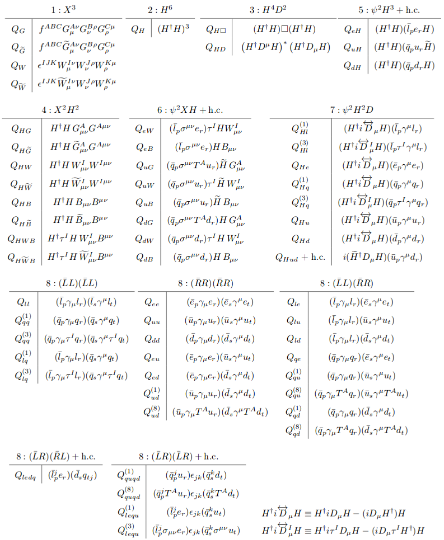
- Will discuss challenges towards global EFT interpretations in ATLAS+CMS
- Using 2022 ATLAS global combination as main example
  (no CMS or ATLAS+CMS combination published so far)
- Will highlight certain challenges with examples from CMS
- Will also discuss steps towards ATLAS+CMS combinations in LHC EFT WG

Global EFT fits

- SMEFT describes possible *patterns of deviations* introduced by new physics
- Constrain deviations predicted by SMEFT ⇒ constrain UV theories
  - (UV-SMEFT matching overview: CERN-LHCEFTWG-2022-002)
- Global fits allow us to
  - Use a theoretically consistent framework for many measurements
  - Enhance our sensitivity (possibly combine small deviations to strong signal)
  - Improve coverage of parameter space (reduce blind directions)
  - Take into account measurement correlation
- Global fits exist from theory collaborations (e.g., SMEFiT, "fitmaker")
- Experimental combinations using different assumptions, different strengths
  - More accurate treatment of uncertainties
  - Direct feedback to measurements
  - Can feed into external, more comprehensive fits

Challenge #1: So many degrees of freedom! (part 1)

- Focused on leading effects: dimension-six operators
- Large number of dimension six operators, >2000 degrees of freedom!
- Need to make symmetry assumptions, ATLAS choice
  - Flavour symmetric but t and b separate $U(2)_q^3 \times U(3)_\ell^2$
  - CP-even operators only
  - → O(100) d.o.f.
- Include many measurements to constrain degrees of freedom



1 : X^3	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

2 : H^6	
Q_H	$(H^\dagger H)^3$

3 : $H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$

5 : $\psi^2 H^3$ + h.c.	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

4 : $X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

6 : $\psi^2 X H$ + h.c.	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

7 : $\psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

8 : $(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

8 : $(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

8 : $(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

8 : $(\bar{L}R)(\bar{R}L)$ + h.c.	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

8 : $(\bar{L}R)(\bar{L}R)$ + h.c.	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \epsilon_{jk} (\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \epsilon_{jk} (\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \epsilon_{jk} (\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$

$H^\dagger i \overleftrightarrow{D}_\mu H \equiv H^\dagger i D_\mu H - (i D_\mu H^\dagger) H$

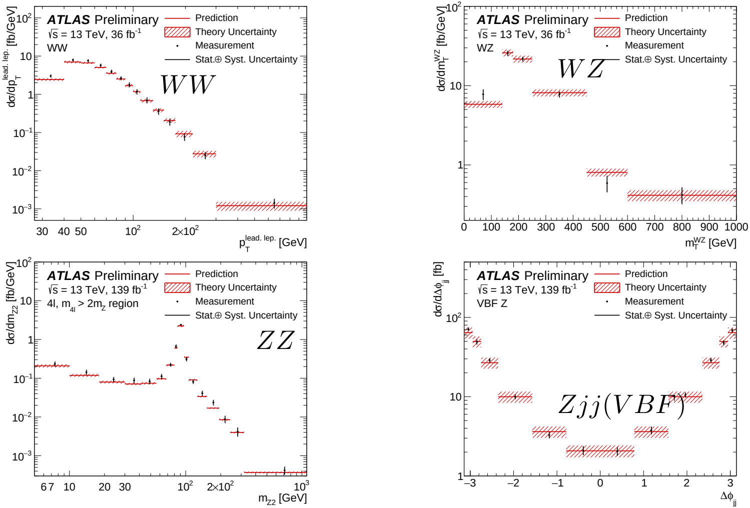
$H^\dagger i \overleftrightarrow{D}_\mu^I H \equiv H^\dagger i \tau^I D_\mu H - (i D_\mu \tau^I H^\dagger) H$

JHEP 12 (2017) 070

Observables

- Experimental input of the ATLAS global fit ATL-PHYS-PUB-2021-022
  - SM input parameters: m_W, m_Z, and G_μ (Recommendations of CERN-LHCEFTWG-2021-001)
  - LEP&SLD measurements on Z resonance (pseudo observables): Γ_Z, σ_{had}, R_ℓ, R_b, R_c, $A^0_{\text{FB},\ell}$, $A^0_{\text{FB},b}$, $A^0_{\text{FB},c}$
  - Four ATLAS multiboson measurements (unfolded differential cross-sections)
  - ATLAS Higgs measurements (simplified template cross-sections, “STXS”)
- Similar to theory collaboration fits but fewer measurements, no top quark measurements
- See also a review of different observables and measurements in CERN-LHCEFTWG-2022-001

ATLAS global fit: electroweak measurements



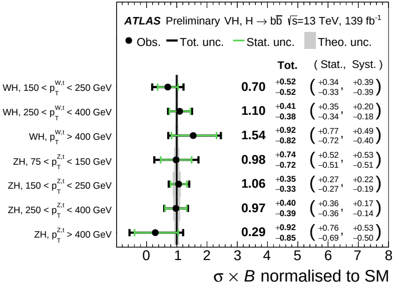
- Interpretation of fiducial differential cross-sections ATL-PHYS-PUB-2021-022

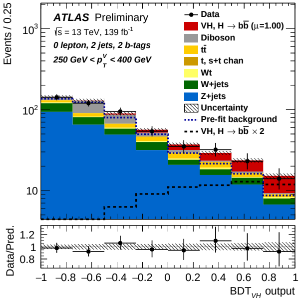
ATLAS global fit: Higgs STXS

- Considering 22 combinations of production and decay
- Split into regions based on kinematics (70 STXS×BR)

Decay channel	Target Production Modes
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$
$H \to WW^*$	ggF, VBF
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{\mathrm{had}}\tau_{\mathrm{had}})$
$H \to b\bar{b}$	WH, ZH
	VBF
	$t\bar{t}H$

ATLAS-CONF-2021-053





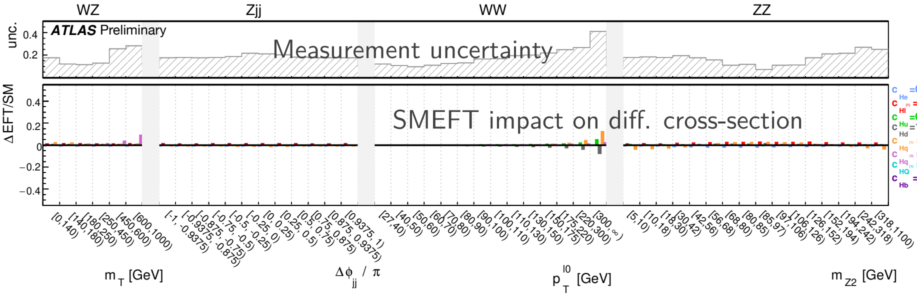
ATLAS-CONF-2021-051

- Example $VH(b\bar{b})$ and one region only (250 GeV $< p_T^V <$ 400 GeV)

Challenge #2: Predictions

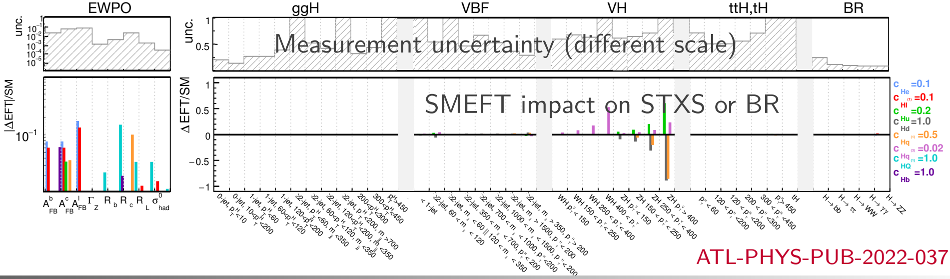
- For each observable and bin: parametrize rate
$\sigma_{\text{SMEFT}} = \sigma_{\text{SM}}^{\text{best}} \frac{\sigma_{\text{SMEFT}}^{\text{LO}}}{\sigma_{\text{SM}}^{\text{LO}}} = \sigma_{\text{SM}}^{\text{best}} (1 + \sum_i A_i \frac{c_i}{\Lambda^2} + \sum_{i,j} B_{ij} \frac{c_i c_j}{\Lambda^4})$
- Assumes higher-order corrections factorize → not always good assumption
- Searching for small deviations requires precise SM predictions and uncertainty estimates
- Huge number of SMEFT degrees of freedom to simulate → reweighting
- For ATLAS global fit: parametrization on particle level, SMEFT samples not propagated through detector simulation (faster turnaround)
- Will focus on leading linear term $\sum_i A_i \frac{c_i}{\Lambda^2}$ (due to BSM-SM interference) first

SMEFT impact example



Measurement uncertainty

SMEFT impact on diff. cross-section

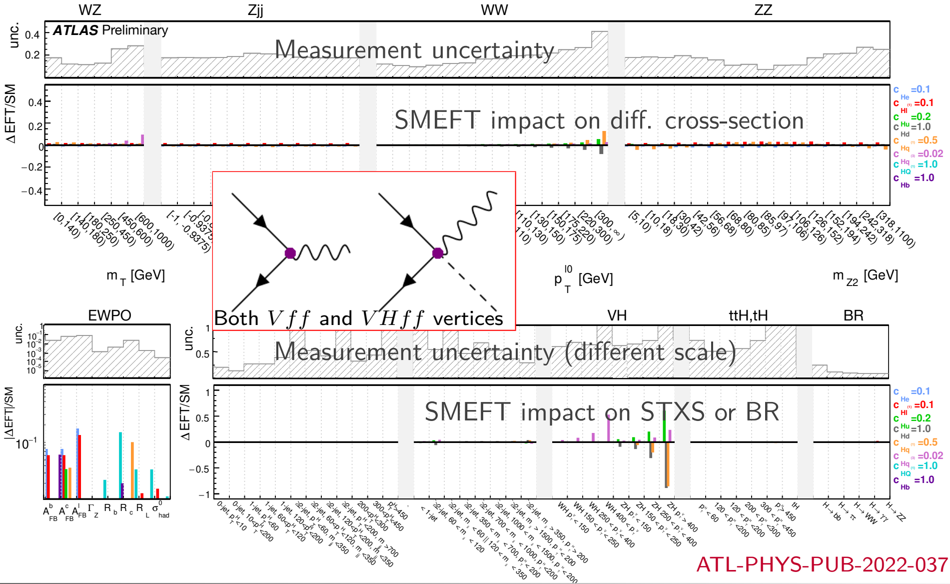


Measurement uncertainty (different scale)

SMEFT impact on STXS or BR

ATL-PHYS-PUB-2022-037

SMEFT impact example



Measurement uncertainty

SMEFT impact on diff. cross-section

Both $V f f$ and $V H f f$ vertices

Measurement uncertainty (different scale)

SMEFT impact on STXS or BR

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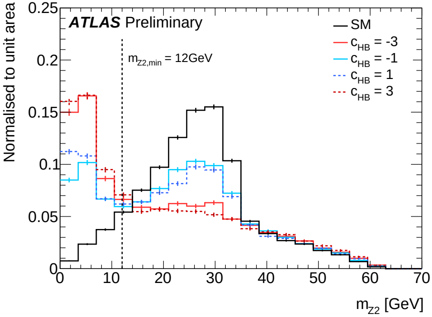
Challenge #3: Validity of SM assumption

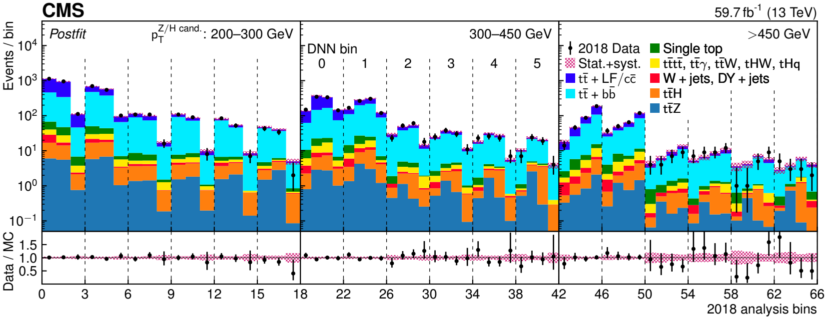
- Reparametrization on particle level assumes SM efficiency
- Only small differences in efficiency for fully differential cross-section measurements
- STXS defined in full phase space for decay → need to model acceptance (important for 4ℓ)



ATL-PHYS-PUB-2022-037

- Effects on backgrounds typically not considered
  - Often estimated from data in control regions
  - Otherwise assumed to be subdominant
- Most correct and most powerful: dedicated measurements...

Adding dedicated SMEFT measurements?



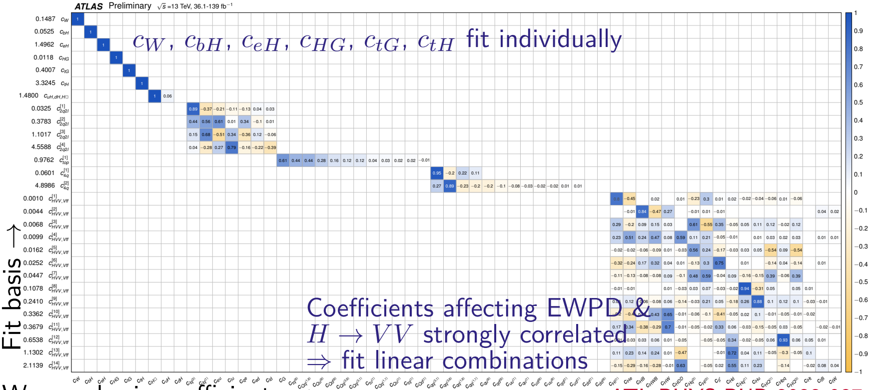
arXiv: 2208.12837

- Example CMS $t\bar{t}H(b\bar{b})+t\bar{t}Z(b\bar{b})$ EFT interpretation (see also top+leptons measurement CMS PAS TOP-22-006 and Kelci's talk)
  - SMEFT effects simulated for $t\bar{t}H$, $t\bar{t}Z$, and $t\bar{t}b\bar{b}$ background
  - SMEFT samples propagated through detector simulation
- Dedicated measurements can maximize sensitivity (e.g. machine learning)
- So far not included in global fit as post-hoc harmonization of assumptions (e.g. operators considered) challenging

Challenge #4: Correlations and overlap

- Estimating correlation of systematic uncertainties challenging even within experimental collaboration
- Overlapping event selections also lead to correlation
  - Remove overlapping events or assess correlation, e.g., with bootstrapping
  - Important for top measurements (e.g. $t\bar{t}Z$ and tZq, or various aspects of $t\bar{t}$)
- ATLAS global combination currently
  - $\mathcal{O}(1000)$ nuisance parameters
  - (Partially) correlates: luminosity, pile-up, jet energy scale and resolution, WW modelling systematics between Higgs and other EW measurements
  - Removes WW CR of $H \rightarrow WW^*$ due to overlap with WW measurement
- Note that (SM) theory uncertainties can be sizable, too – and correlation notoriously tricky

Challenge #1, part 2: So many degrees of freedom!



c_W, c_{bH}, c_{eH}, c_{HG}, c_{tG}, c_{tH} fit individually

Coefficients affecting EWPD &
$H \to VV$ strongly correlated
⇒ fit linear combinations

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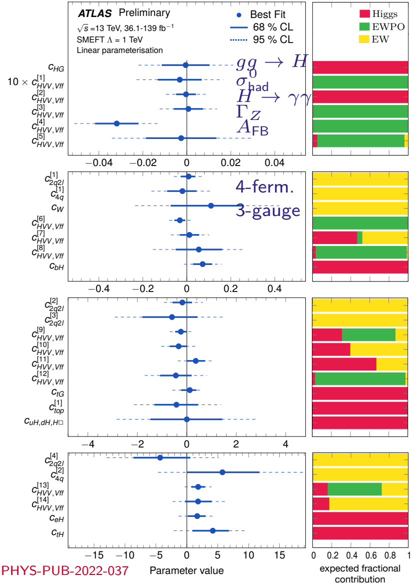
- Identify sensitive directions using simplified model of likelihood
- Decorrelated in groups – for better interpretability
- Remove EV with expected limits $c/\Lambda > 5/\mathrm{TeV}^2$
  (unlikely small Λ or extremely strongly coupled NP)

ATLAS global fit: linearized fit



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- Constraints range from $< 0.01/\text{TeV}^2$ (possibly constraining multi-TeV new physics) to $\approx 10/\text{TeV}^2$
- Tightest constraints from EWPD: σ^0_{had}, Γ_Z, A_{FB}
- Tight constraints also from $H \to \gamma\gamma$ and $gg \to H$
- Electroweak measurements constrain four-fermion and triple-gauge operators
- LHC (esp. VH and WZ) beginning to complement Z-coupling measurements

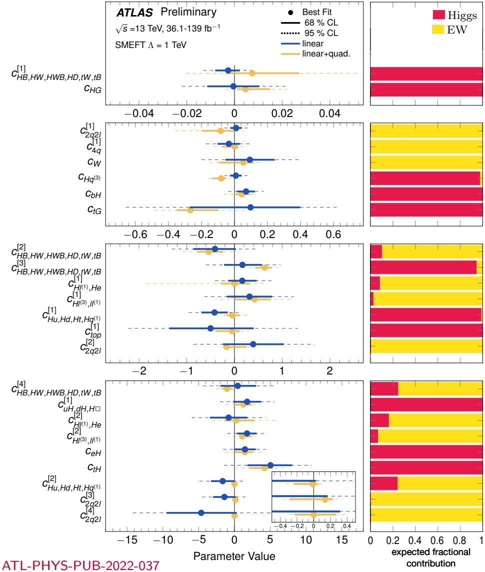
Challenge #5: Validity of SMEFT

- So far only considered effects linear in Wilson coefficients
- Calculation of cross section from SMEFT amplitude:

$$\begin{aligned}\sigma &= |\mathcal{A}_{\text{SM}} + \mathcal{A}_{\text{dim6}} + \mathcal{A}_{\text{dim8}} + \ldots|^2 \\ &= |\mathcal{A}_{\text{SM}}|^2 + \underbrace{2\text{Re}\{\mathcal{A}^*_{\text{SM}}\mathcal{A}_{\text{dim6}}\}}_{\propto \frac{c_{\text{dim6}}}{\Lambda^2}} + \underbrace{|\mathcal{A}_{\text{dim6}}|^2}_{\propto \frac{c^2_{\text{dim6}}}{\Lambda^4}} + \underbrace{2\text{Re}\{\mathcal{A}^*_{\text{SM}}\mathcal{A}_{\text{dim8}}\}}_{\propto \frac{c_{\text{dim8}}}{\Lambda^4}\text{(usually unknown)}} + \underbrace{\ldots}_{\text{add. unkown } \propto \frac{1}{\Lambda^4}}\end{aligned}$$

- Terms quadratic in c_{dim6}
  - Suppressed by Λ^{-4}, expect it to be smaller than linear term
  - Stronger energy growth than Λ^{-2} terms ⇒ often relevant at LHC
- Comparing "linear" and "quadratic" fits at dim-6 can give feeling for missing dim-8 contribution – but not an uncertainty estimate

ATLAS global fit: quadratic terms



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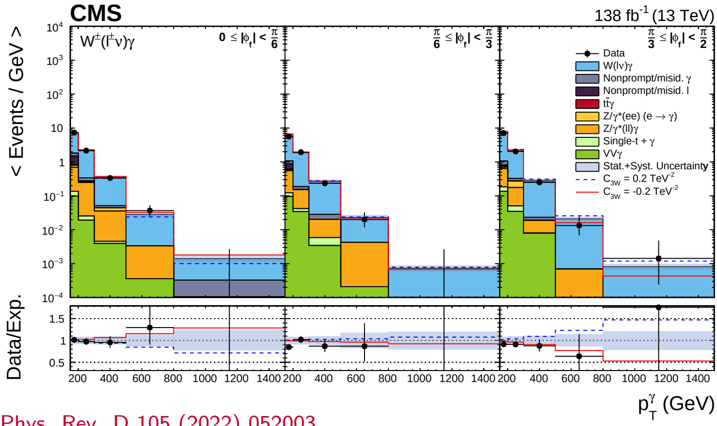
- Comparing linear and linear+quadratic (no EWPO) fit
- Results can differ significantly
- Need better estimate of truncation uncertainty, two possible approaches discussed in CERN-LHCEFTWG-2021-002:
    - Including uncertainties for missing $O(\Lambda^{-4})$ contributions in fit – hard to implement and competing recipes how to estimate these
    - Fits with varying high-mass cut-off of event selection – difficult to coordinate mass cuts in global fit

CMS Wγ: addressing validity questions

- Diboson production plagued by small interference of SM and BSM $\Rightarrow$ small linear SMEFT impact, validity questions due to dominant quadratic terms
- CMS $W\gamma$ uses 2D binning sensitive to ϕ modulation due to interference



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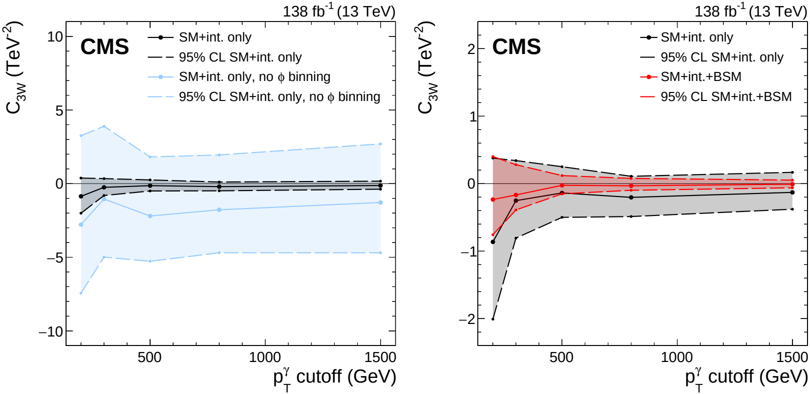
CMS Wγ: addressing validity questions



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- Cut-off in p_T^γ similar to high-mass cut-off discussed in LHC EFT WG
- Binning in ϕ "resurrects" (Phys.Lett.B 776 (2018) 473-480) interference (left)
- Quadratic/BSM effects still important, especially at high p_T^γ (right)

Challenge #6: ATLAS+CMS combination

- ATLAS+CMS combination can increase precision, improve coverage
- Two combination excersizes ongoing in Area 4 of LHC EFT WG

EW+Higgs+top

- Combination based on public data, Gaussian model
- More complex models planned
- Common infrastructure & cross checks of parametrization
- Common STXS parametrization being developed
- Combined fit can be sandbox to study LHC EFT WG proposals (e.g. on validity) in simplified fit

$t\bar{t}Z+t\bar{t}\gamma$

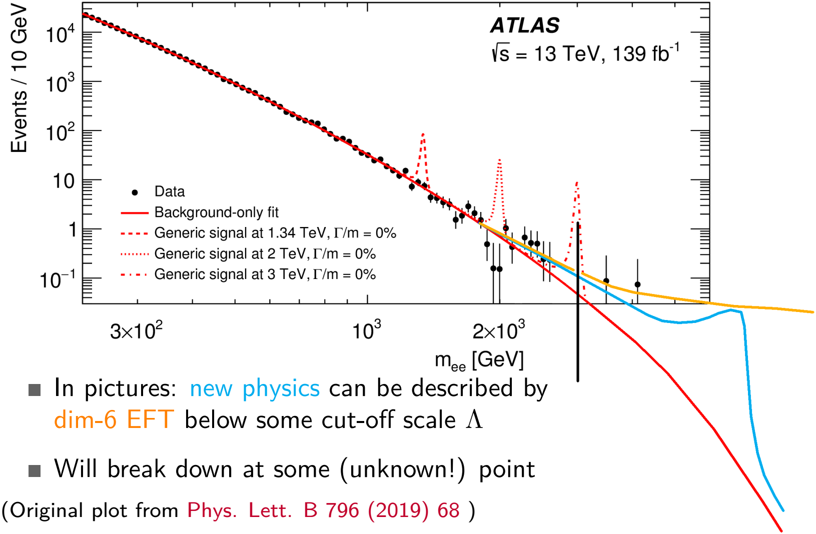
- Top combination partially under LHC top WG umbrella
- Common ttbar samples useful for SM baseline
- Complex "reconstruction level" combination of ATLAS $t\bar{t}Z$ [Eur. Phys. J. C 81 (2021) 737] CMS $t\bar{t}\gamma$ [JHEP 05 (2022) 091] studied
- Only two measurement but try to achieve perfect agreement in ATLAS and CMS fit models

Conclusion

- Presented EFT combination programme of ATLAS, CMS, and LHC EFT WG
- Mainly discussed first ATLAS global (EWPO+EW+Higgs) combination
- Highlighted six main challenges
  1. Number of degrees of freedom → requires effort but (surprisingly) manageable
  2. Precise predictions → needed for SM and SMEFT
  3. SM assumption of interpreted measurements → requires ad-hoc fixes or dedicated SMEFT measurements
  4. Overlap and correlations → so far moderate impact but sometimes difficult to assess even within collaboration
  5. Validity → possibly most serious challenge, competing proposals, difficult to implement for large combination
  6. ATLAS+CMS combination → still in infancy, requires coordination and harmonization

Backup

Motivation of cut-off



- In pictures: new physics can be described by dim-6 EFT below some cut-off scale Λ
- Will break down at some (unknown!) point

(Original plot from Phys. Lett. B 796 (2019) 68)

Sensitive directions

- Identify sensitive directions (using a simplified model)
  $\Rightarrow$ fit eigenvectors corresponding to (uncorrelated) sensitive direction, fix weakly constrained directions to zero