# Overview of recent EFT interpretations from ATLAS

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# Outline

- Introduction
- Latest EFT results from ATLAS
  - Electroweak
  - Higgs
  - Top
- Future plans
- Summary

# Introduction

- EFT interpretation: increasingly important physics program in ATLAS
  - Complementary to precision measurements in the EWK, Higgs and Top sector
  - Probe new physics with minimal model dependence, in a coherent way
- Recent EFT results from ATLAS

**EWK**
- ✸ WW+jets (arXiv:2103.10319)
- ✸ Inclusive 4l (arXiv:2103.01918)
- ✸ VBF Zjj (*EPJC81(2021)163*)
- WW+0jet (*EPJC 79 (2019) 884*)

**Higgs**
- ✸ HWW VBF (ATLAS-CONF-2020-055)
- ✸ VH(bb) boosted STXS(*PLB816(2021)136204*)
- ✸ VH(bb) resolved STXS(*EPJC81(2021)178*)
- H4l STXS (EPJC 80(2020)957)
- H$\gamma\gamma$ differential(ATLAS-CONF-2019-029)

✸ New resutls since HEFT 2020

**Combination**
- ✸ HWW* + SM WW (ATL-PHYS-PUB-2021-010)
- ✸ Higgs STXS combination(ATLAS-CONF-2020-053)

**Top**
- ✸ W polarization in top-quark decays (*JHEP08(2020)51*)
- Charge asymmetry in $t\bar{t}$ (ATLAS-CONF-2019-026)
- ttW+ttZ (*PRD99(2019)072009*)
- FCNC tq$\gamma$ (*PLB800(2020)135082*)
- FCNC tqZ (*JHEP07(2018)176*)

# Overview

- EFT interpretations in ATLAS are quite complicated in methodology

$$\sigma = \sigma_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\sigma_i^{\text{dim-6, lin.}} + \sum_{i,j} \frac{c_i c_j}{\Lambda^4}\sigma_{ij}^{\text{dim-6, quad.}} + \sum_i \frac{c_i}{\Lambda^4}\sigma_i^{\text{dim-8, lin.}} + \ldots$$

- Experimental observables
  - Detector level or unfolded?
  - Fiducial or differential cross-sections?
- EFT formalism
  - Dim-6: Warsaw basis, Higgs basis or SILH basis?
  - Linear only or linear + quadratic terms?
  - How to deal with dim-8 operators?
  - Simulation tools and flavor assumptions?
- Statistical analysis
  - Treatment of flat directions?
  - Systematic uncertainties on EFT predictions?

So far interpretations have been tailored for individual analyses

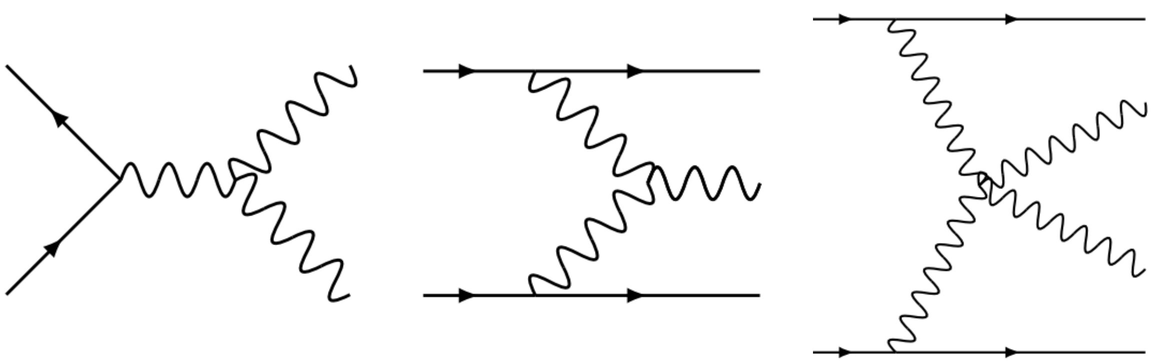
Now the collaboration is moving towards a more coherent approach using the acquired expertise

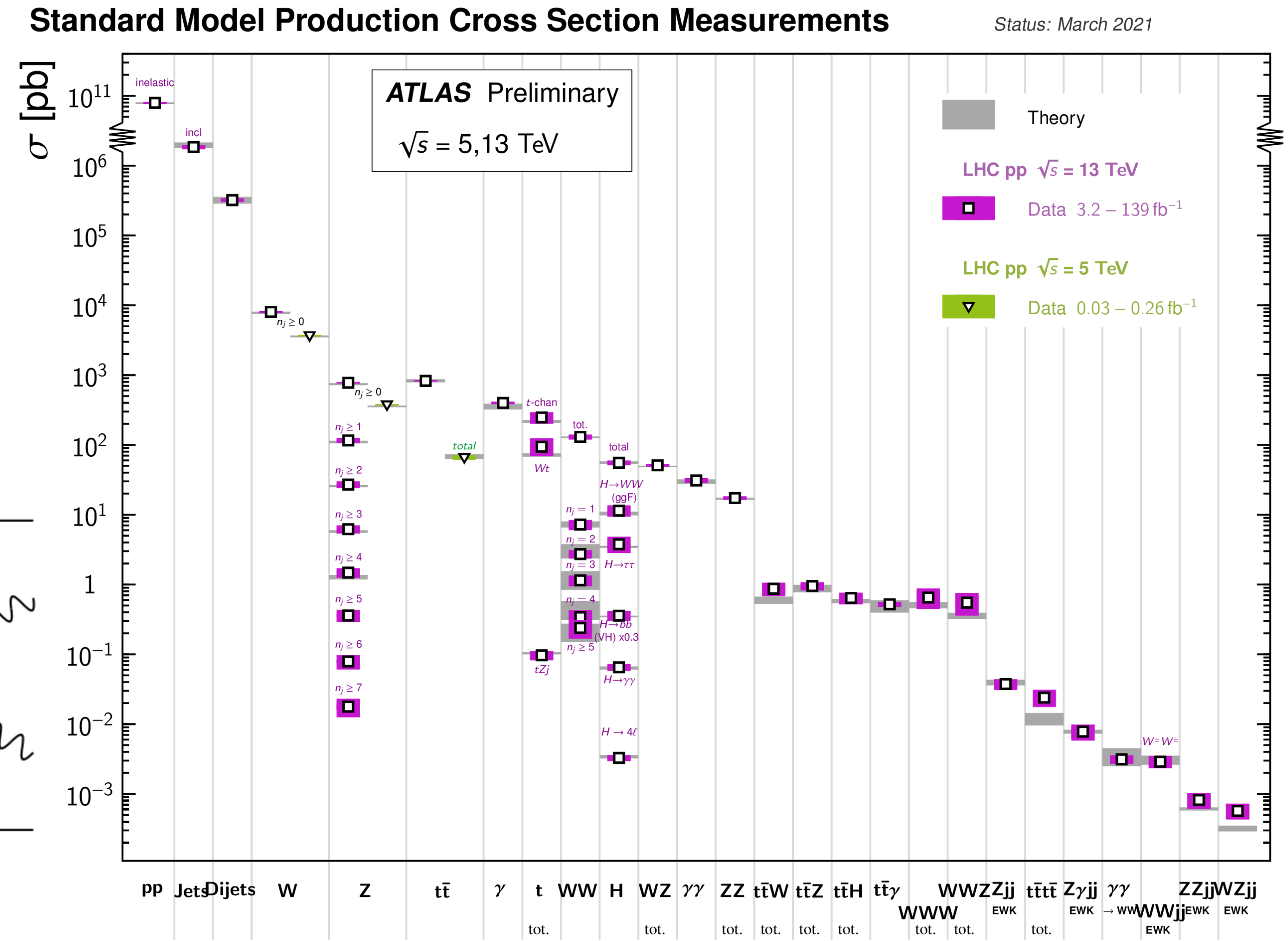
# EFT interpretation in the EWK sector

# EWK precision measurements

- Wide range of phase spaces being measured
- Offers great opportunities to probe anomalous gauge couplings
  - **aTGC**: WV (V=W,Z, γ) and VBF Zjj, Wjj
  - **nTGC**: ZZ, Zγ
  - **aQGC**: VVV, VBS VVjj, exclusive WW

ATL-PHYS-PUB-2021-005

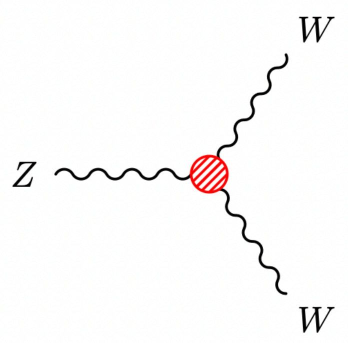




# From anomalous couplings to EFT

- Traditionally BSM effects are presented in the form of effective Lagrangian or Vertices
  - e.g. Charged TGC, CP conserving, with LEP parametrization: $\Delta g_1^Z, \Delta\kappa_Z, \lambda_Z$
- Limitations of the effective Lagrangian/Vertices approach
  - Only at tree level
  - Need ad hoc form factors to avoid unitarity violation

$$c \to \frac{c}{(1+\frac{\hat{s}}{\Lambda_{FF}^2})^n}$$




- **aTGC** in EFT
  - At dim-6 in the **HISZ** basis, two CP odd operators, and three CP conserving ones

$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_\rho^\mu]$$
$$\mathcal{O}_{\tilde{W}} = (D_\mu\Phi)^\dagger\tilde{W}^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^\mu]$$
$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

Céline Degrande, Cen Zhang et al, arXiv:1205.4231

  - Translation of relevant parameters

aTGC → HISZ

$$\Delta g_1^Z = \frac{g^2+g'2}{8}c_W\frac{v^2}{\Lambda^2}$$
$$\Delta\kappa_\lambda = \frac{g^2}{8}(c_W+c_B)\frac{v^2}{\Lambda^2}$$
$$\lambda_Z = \frac{3g^4}{8}c_{WWW}\frac{v^2}{\Lambda^2}$$

aTGC → Warsaw

$$\Delta g_1^Z = -\frac{v^2}{\Lambda^2}\frac{g_L^2+g_Y^2}{4(g_L^2-g_Y^2)}(4\frac{g_Y}{g_L}c_{HWB}+c_{HD}-...)$$
$$\Delta\kappa_\lambda = \frac{v^2}{\Lambda^2}\frac{g_Y}{g_L}c_{HWB}$$
$$\lambda_Z = -\frac{v^2}{\Lambda^2}\frac{3}{2}g_L c_W$$

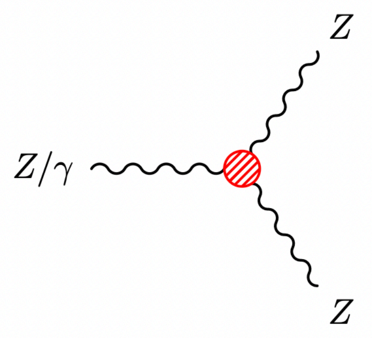
Adam Falkowski et al, arXiv:1609.06312

# From anomalous couplings to EFT

- **nTGC** in EFT: only appears at dim-8

$$\mathcal{O}_{\widetilde{B}W} = i\, H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H,$$

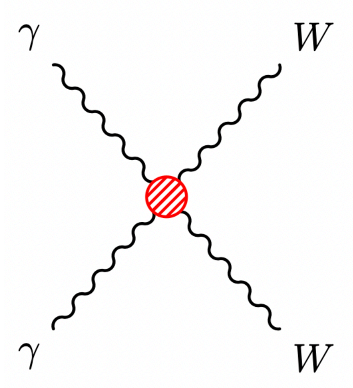
$$\begin{aligned} \mathcal{O}_{BW} &= i\, H^\dagger B_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H, \\ \mathcal{O}_{WW} &= i\, H^\dagger W_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H, \\ \mathcal{O}_{BB} &= i\, H^\dagger B_{\mu\nu} B^{\mu\rho} \{D_\rho, D^\nu\} H. \end{aligned}$$




Celine Degrande, arXiv:1308.6323

- **aQGC** in EFT: dim-8

| | WWWW | WWZZ | ZZZZ | WWAZ | WWAA | ZZZA | ZZAA | ZAAA | AAAA |
|---|---|---|---|---|---|---|---|---|---|
| $\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$ | X | X | X | O | O | O | O | O | O |
| $\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$,$\mathcal{L}_{M,6}$ ,$\mathcal{L}_{M,7}$ | X | X | X | X | X | X | X | O | O |
| $\mathcal{L}_{M,2}$ ,$\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$ ,$\mathcal{L}_{M,5}$ | O | X | X | X | X | X | X | O | O |
| $\mathcal{L}_{T,0}$ ,$\mathcal{L}_{T,1}$ ,$\mathcal{L}_{T,2}$ | X | X | X | X | X | X | X | X | X |
| $\mathcal{L}_{T,5}$ ,$\mathcal{L}_{T,6}$ ,$\mathcal{L}_{T,7}$ | O | X | X | X | X | X | X | X | X |
| $\mathcal{L}_{T,9}$ ,$\mathcal{L}_{T,9}$ | O | O | X | O | O | X | X | X | X |




Eboli, Gonzalez-Garcia, arXiv:1604.03555

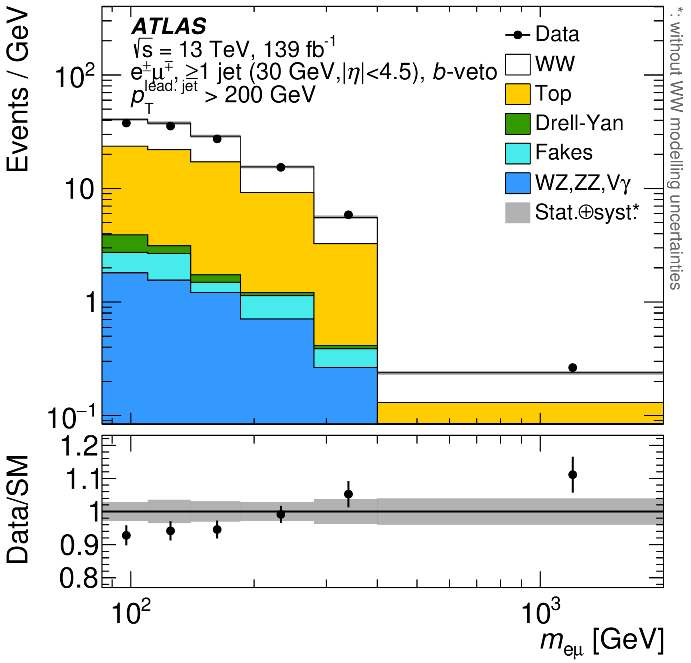
*This talk is focused on dim-6 EFT interpretations*

# WW+jets

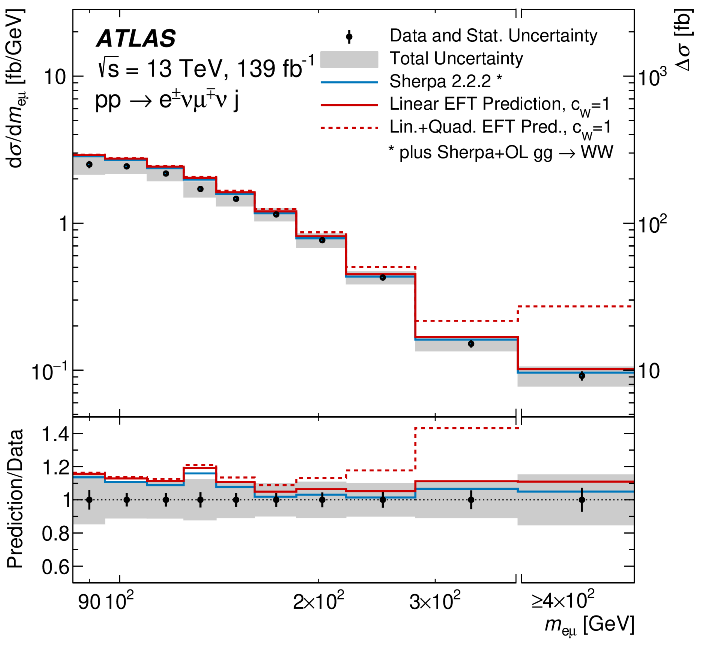
arXiv:2103.10319

- Fiducial and differential cross-section measurements with full Run-2 data
  - First jet-inclusive measurement of WW production at the LHC
  - One-jet topology enhances the interference with aTGC (A. Azatov et al arXiv:1707.08060 )
- EFT interpretation using unfolded $m_{e\mu}$ distributions

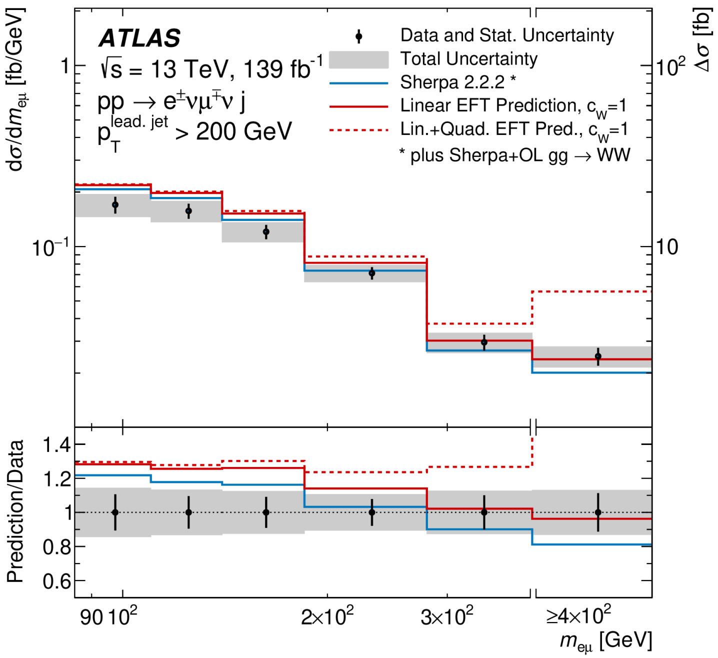
Detector level




Unfolded ($p_T$(jets) > 30 GeV)




Unfolded with $p_T$(leading jet) > 200 GeV



# WW+jets

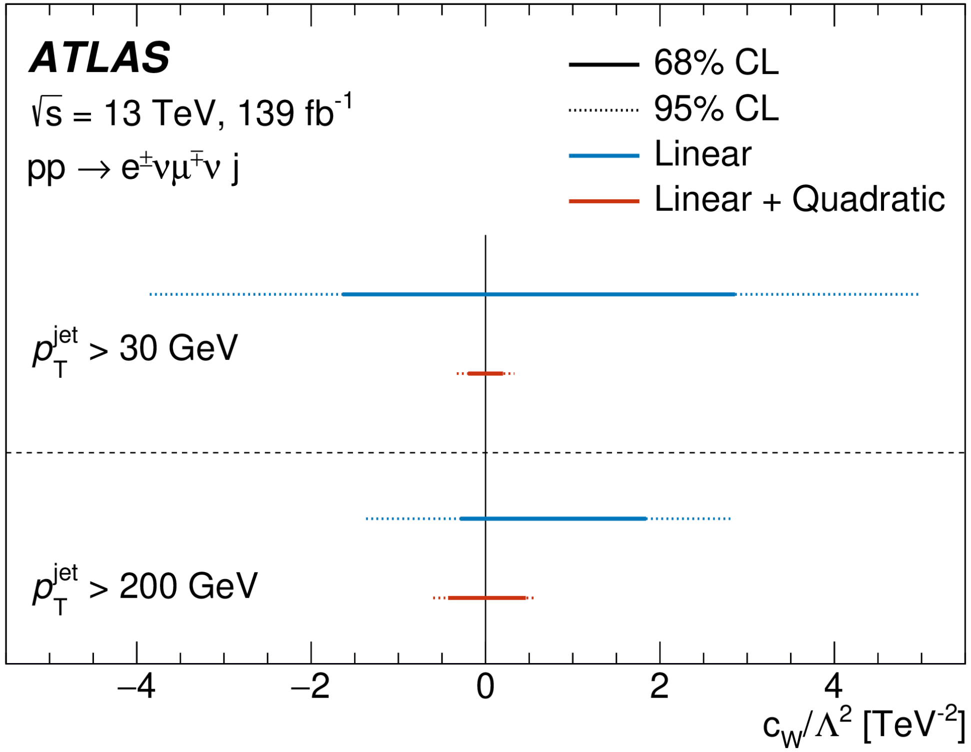
arXiv:2103.10319

- EFT interpretation
  - Based on **SMEFTsim** with the **Warsaw** basis, only $\mathbf{c_W}$ considered

$$Q_W = \epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$

$$\mathcal{L}(\vec{\mu}, \vec{\theta}) = \frac{1}{\sqrt{(2\pi)^k |C|}} exp(-\frac{1}{2}(\vec{\sigma}_{\rm data} - \vec{\sigma}_{\rm pred}(\vec{\mu}, \vec{\theta}))^T C^{-1} (\vec{\sigma}_{\rm data} - \vec{\sigma}_{\rm pred}(\vec{\mu}, \vec{\theta}))) \mathcal{G}(\vec{\theta})$$

$$\vec{\sigma}_{\rm pred}(\vec{\mu}, \vec{\theta}) = \sigma_{\rm SM} + \sum_i \mu_i \sigma_i^{\text{dim-6, lin.}} + \sum_{i,j} \mu_i \mu_j \sigma_{ij}^{\text{dim-6, quad.}}$$




Four scenarios:
[linear only, linear + quadratic] x [$p_T$(jet) > 30 GeV, > 200 GeV]

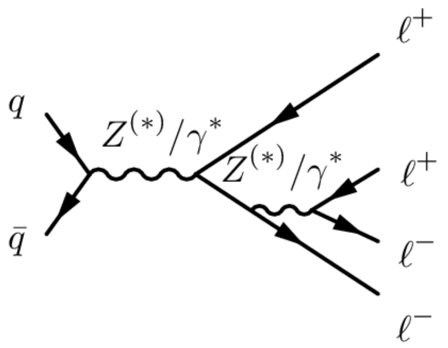
The 200 GeV jet requirement indeed increases sensitivity in fit of terms linear in $\mathbf{c_W}$

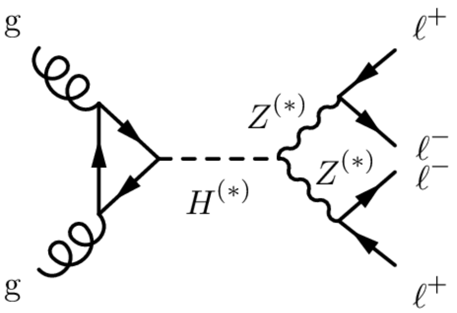
Quadratic term still dominant, comparable to the 36 $fb^{-1}$ WW+0j constraints(EPJC 79 (2019) 884)

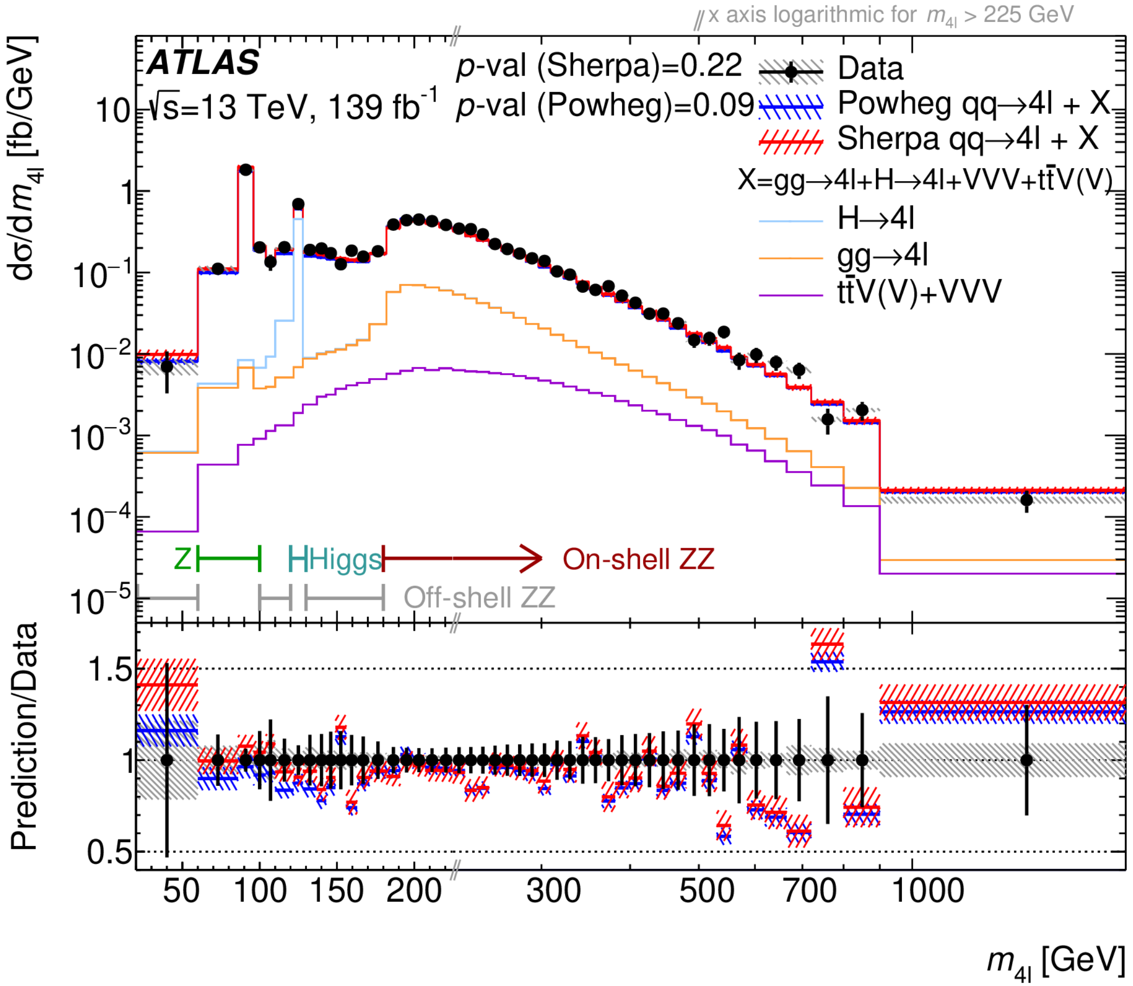
# Inclusive 4l measurements

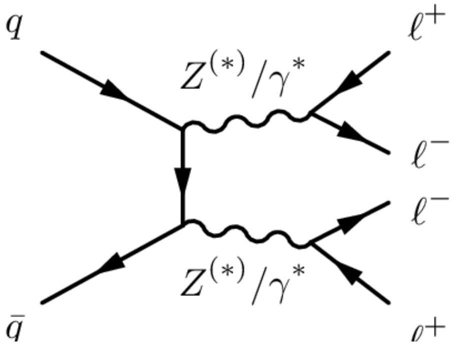
arXiv:2103.01918

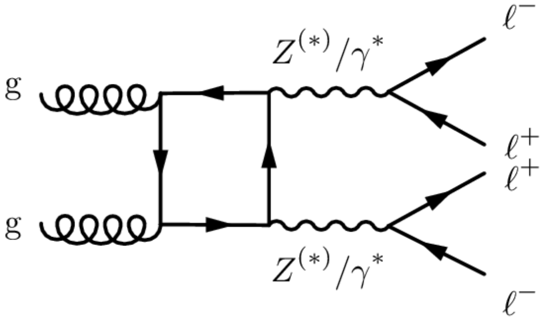
- Differential measurements of inclusive pp→4l production
  - $20 < m_{4l} < 2000$ GeV









Though nTGC is suppressed, 4l events are sensitive to dim-6 EFT due to rich contributing processes

# Inclusive 4l measurements

arXiv:2103.01918

- Various observables unfolded **in 4 slices of $\mathbf{m_{4l}}$**
  - $m_{12}$, $m_{34}$, $p_{T,12}$ ,$p_{T,34}$, cos $\theta^{*}_{12}$, cos $\theta^{*}_{34}$, $|\Delta y_{pairs}|$, $|\Delta\phi_{pairs}|$, $|\Delta\phi_{ll}|$.
  - single $Z$: (60, 100), Higgs: (120, 130), on-shell $ZZ$: (180, 2000), off-shell $ZZ$: others

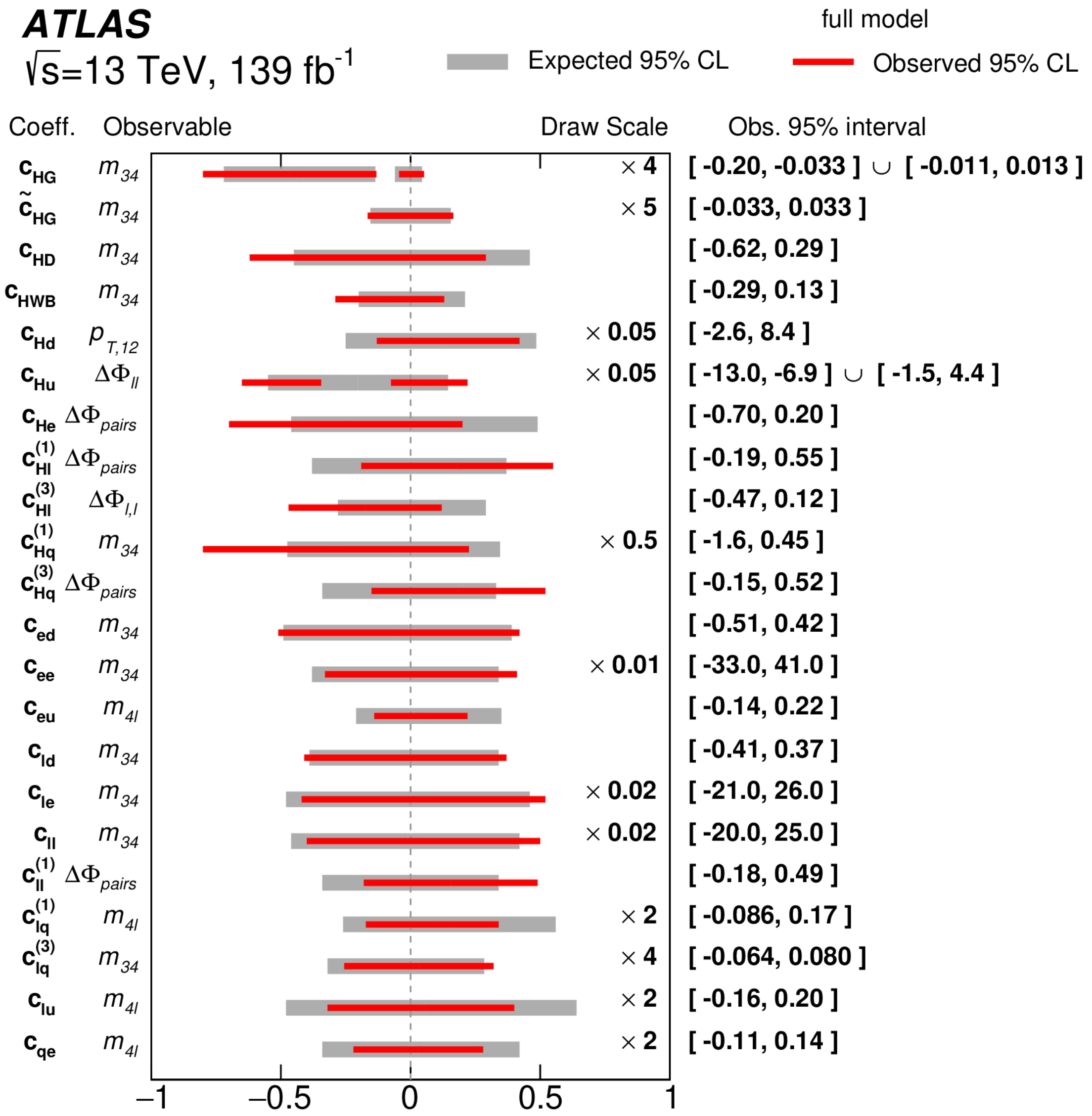
- EFT interpretation
  - Based on **SMEFsim** with the **Warsaw** basis
  - Scanned all 59 operators and found 22 coefficients that give non-negligible contribution
    - three affecting Higgs couplings: $c_{HG}$, $\tilde{c}_{HG}$, $c_{HD}$;
    - one affecting gauge boson couplings: $c_{HWB}$;
    - seven affecting the $Z\rightarrow$ll vertex: $c_{Hd}$, $c_{Hu}$, $c_{He}$, $c_{Hl}^{(1)}$, $c_{Hl}^{(3)}$, $c_{Hq}^{(1)}$, $c_{Hq}^{(3)}$
    - eleven from four-fermion interactions (contact terms): $c_{ed}$, $c_{ee}$, $c_{eu}$, $c_{ld}$, $c_{le}$, $c_{ll}$, $c_{ll}^{(1)}$, $c_{lq}^{(1)}$ , $c_{lq}^{(3)}$ ,$c_{lu}$, $c_{qe}$.
  - Fitting only one coefficient at a time

# Inclusive 4l measurements

[arXiv:2103.01918]

- EFT constraints
  - Both linear and linear + quadratic fits
  - Fit one parameter at a time

Linear + quad.



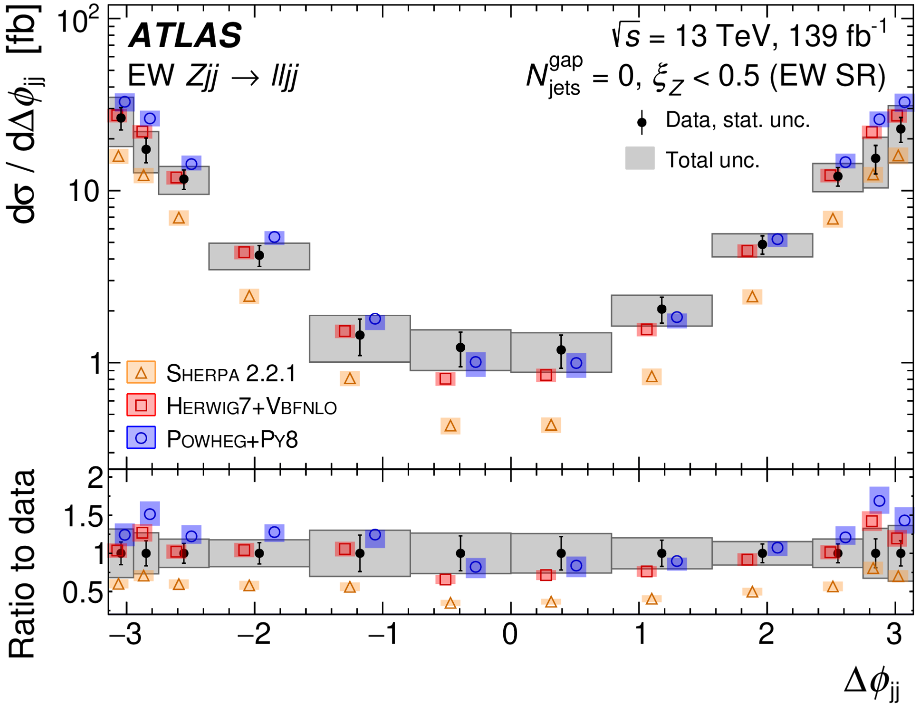

| $c_{HWB}$ [95% CL] | $m_{4l}$ [GeV] | Expected | Observed |
|---|---|---|---|
| H4l STXS [EPJC 80(2020)957] | [115, 130] | [-1.1, 1.0] | [-1.1, 1.0] |
| Inclusiv 4l | [20, 2000] | [-0.2, 0.21] | [-0.29, 0.13] |

$c_{HWB}$ affect the entire $m_{4l}$ spectrum, not just the region close to $m_H$ → The advantange of being inclusive

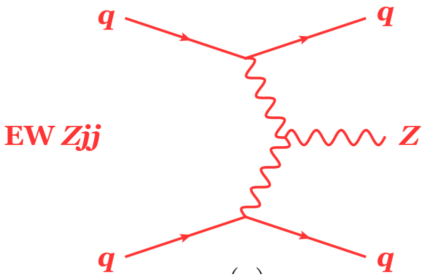
# VBF Zjj measurements

EPJC81(2021)163

- Differential measurements of EW Zjj
  - Sensitive to aTGC
  - Signed $\boldsymbol{\Delta\phi_{jj}} = \phi_f - \phi_b$, sensitive to CP-odd EFT operators



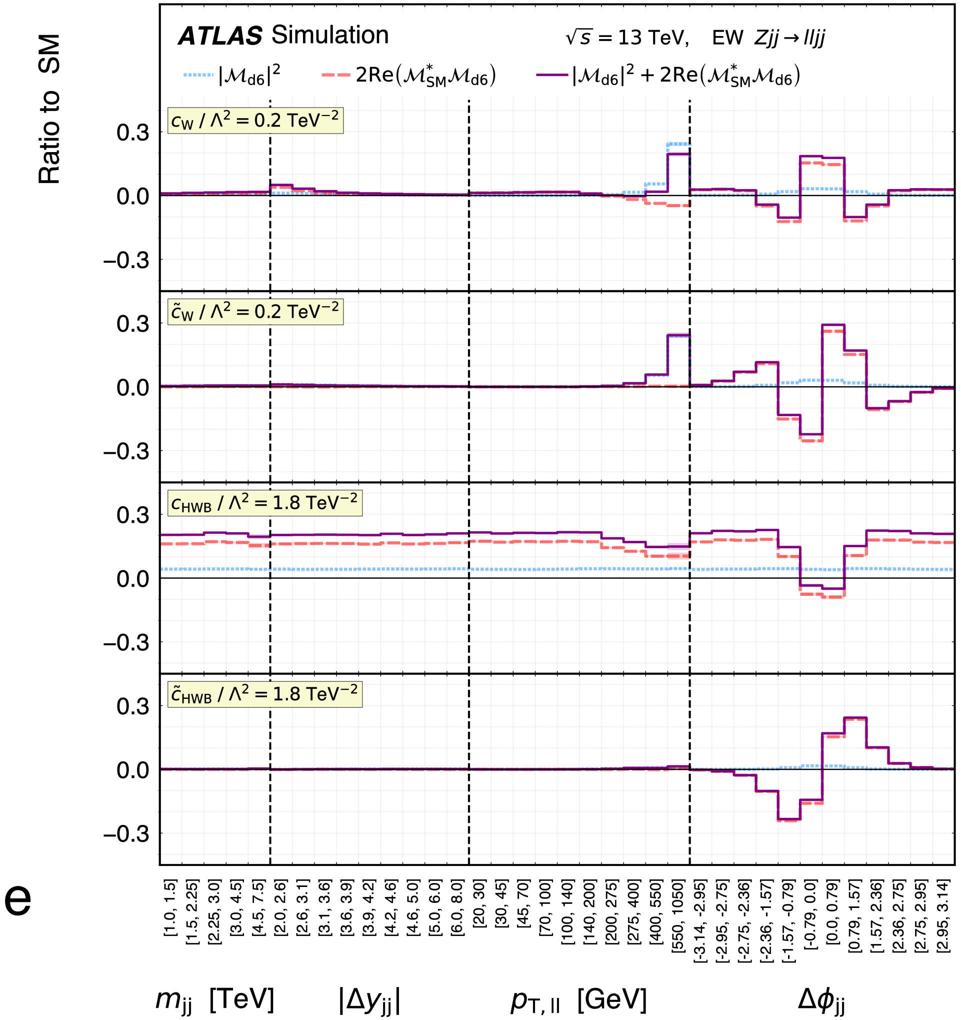

with $y_f > y_b$




Unfolded $\Delta\phi_{jj}$ is used to constrain:

CP-even: $O_W$, $O_{HWB}$
CP-odd: $\tilde{O}_W$, $\tilde{O}_{HWB}$

Based on **`SMEFsim`** with the **Warsaw** basis



# VBF Zjj measurements

EPJC81(2021)163

- EFT interpretation
  - 1-D fit results, both linear and linear + quadratic fits

| Wilson coefficient | Includes $\|\mathcal{M}_{d6}\|^2$ | 95% confidence interval [TeV$^{-2}$] Expected | Observed | $p$-value (SM) |
|---|---|---|---|---|
| $c_W/\Lambda^2$ | 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% |
| $c_{HWB}/\Lambda^2$ | 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% |

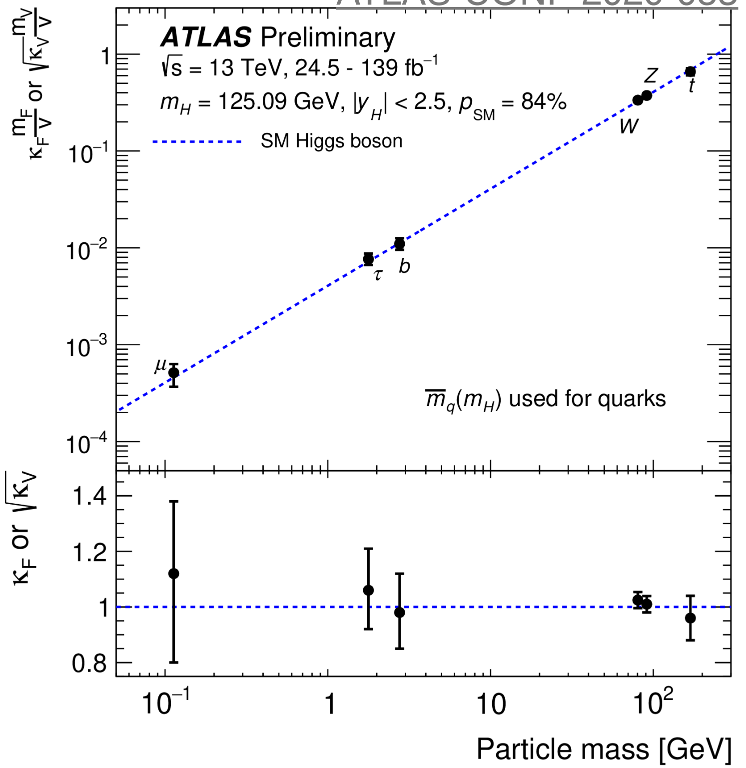
Sensitivity dominated by the linear term only, thanks to the signed $\Delta\phi_{jj}$

# EFT interpretation in the Higgs sector

# EFT interpretation in the Higgs sector

- More precise measurements of Higgs properties are coming out
  - Signal strength (μ)
  - Simplified Template Cross-sections (STXS)
  - Differential cross-sections
- … also come with constraints on BSM
  - Anomalous couplings strategy also followed in the Higgs sector
  - Moving to EFT interpretations in the meanwhile
- EFT interpretations
  - Results presented in several bases: **Warsaw, SILH, Higgs** basis
  - Mapping from one basis to another can be done (**`Rosetta`**, Ken Mimasu et al, arXiv:1508.05895 )
  - Methodology for EFT interpretation of STXS results documented in ATL-PHYS-PUB-2019-042

ATLAS-CONF-2020-053



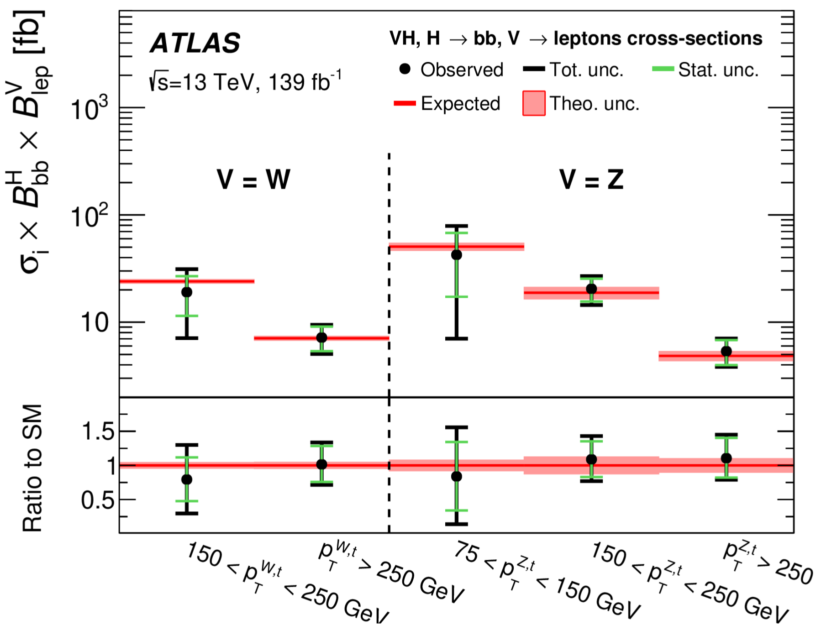

*See more details by Philipp Windischhofer* (Thu. Afternoon)

# VH(H→bb) resolved

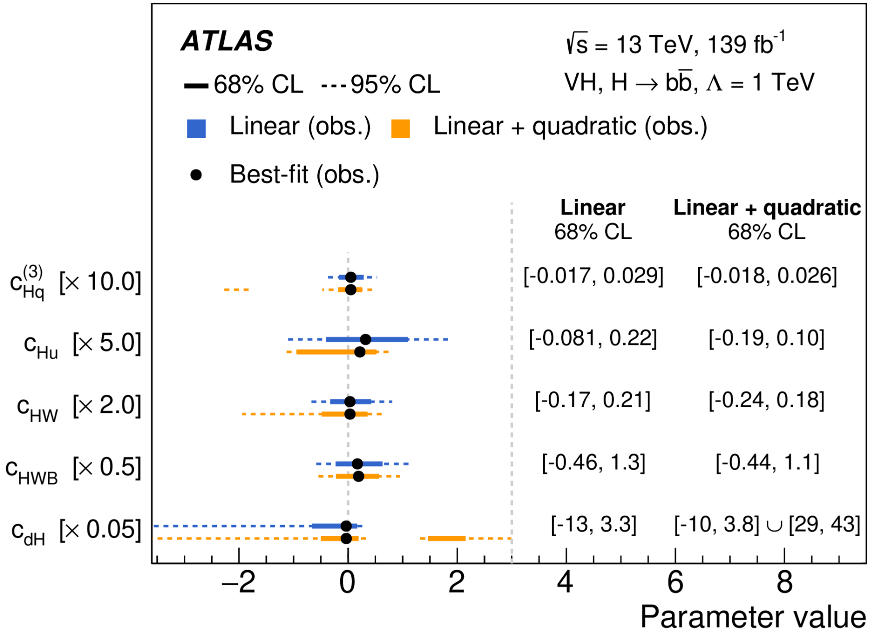
EPJC81(2021)178

- STXS results are used to constrain Wilson coefficients of the Warsaw basis
  - 1-D results by fitting one parameter at a time (with others fixed at 0)
  - 5-D fits using most sensitive directions of the measurement
    - **eigenvectors**, an orthogonal set of linear combinations of the Wilson coefficients

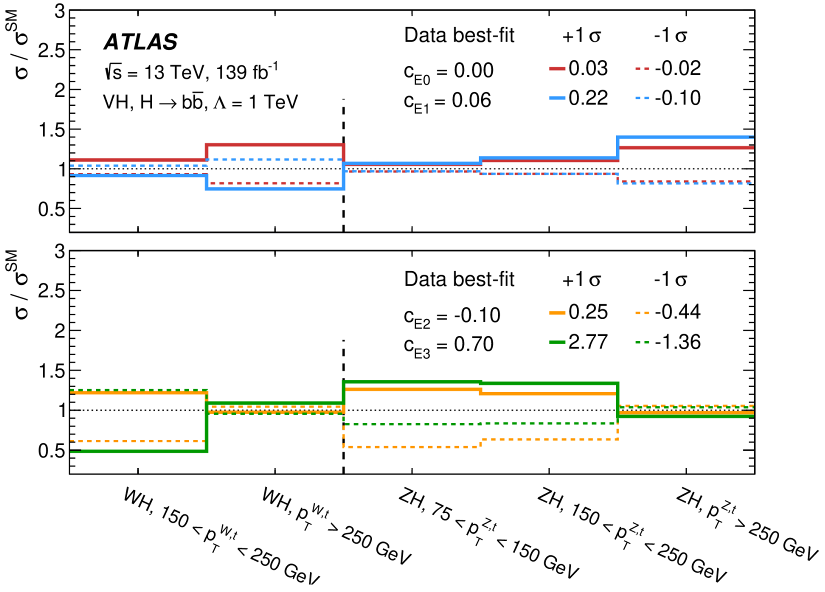
STXS




1-D results




5-D results



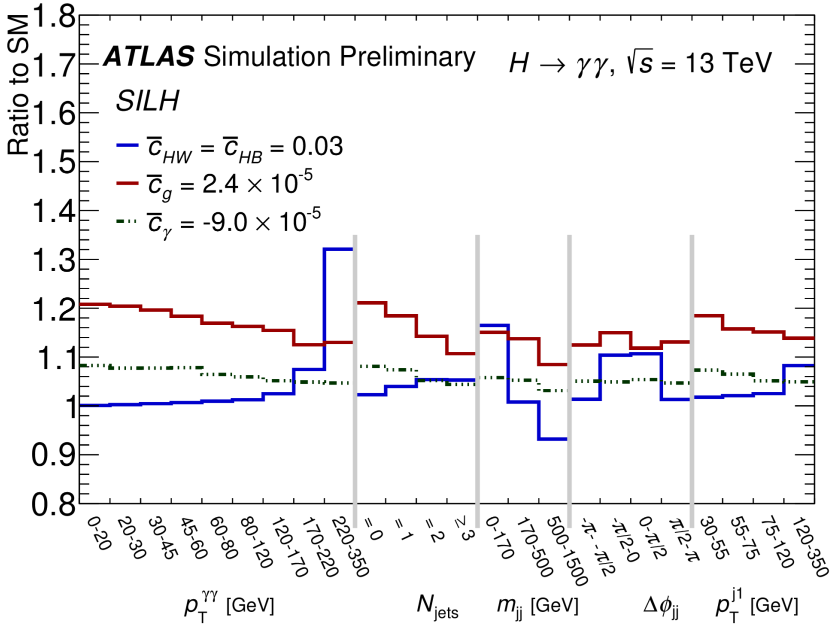

$$c_{E0} = 0.98 \cdot c_{Hq}^{(3)}$$

$$c_{E1} = 0.85 \cdot c_{Hu} - 0.39 \cdot c_{Hq}^{(1)} - 0.27 \cdot c_{Hd}$$

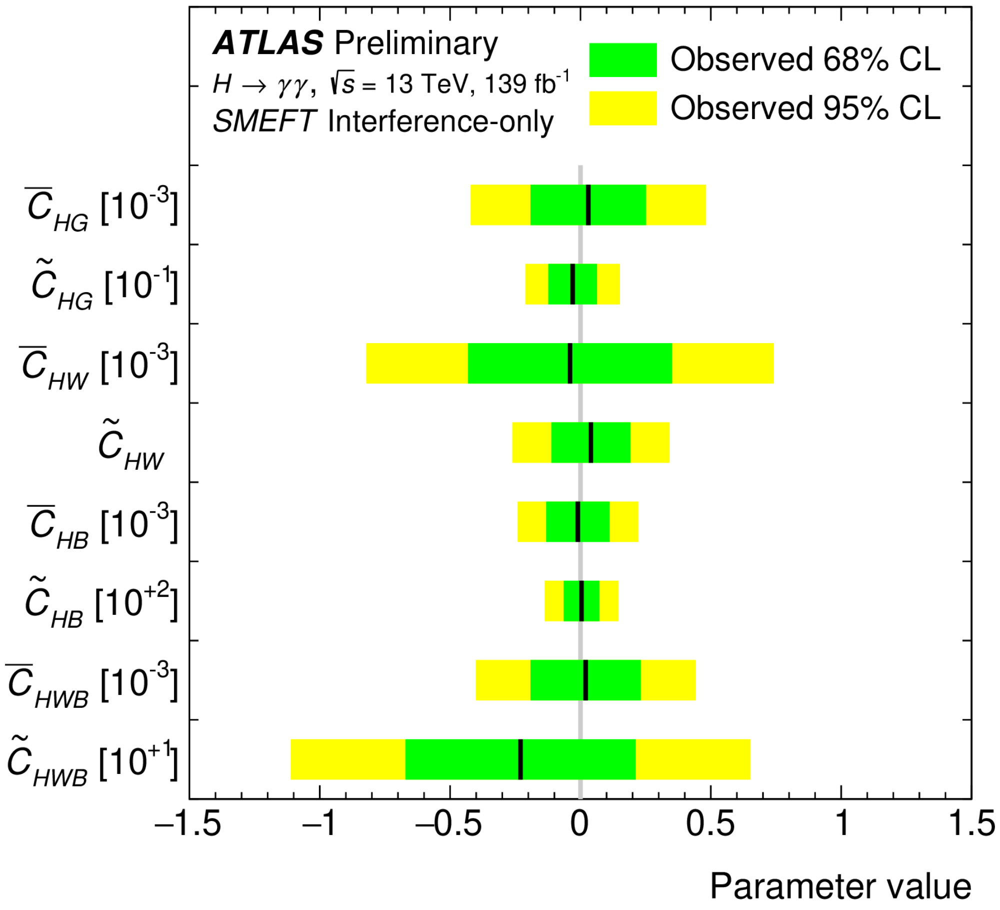
# H→$\gamma\gamma$ differential

ATLAS-CONF-2019-029

- EFT interpretation from differential cross-sections using **Warsaw** and **SILH** bases
  - 1-D fit results using **five** differential distributions




Warsaw basis




SILH basis

| Coefficient | Observed 95% CL limit | Expected 95% CL limit |
|---|---|---|
| $\bar{c}_g$ | $[-0.26, 0.26] \times 10^{-4}$ | $[-0.25, 0.25] \cup [-4.7, -4.3] \times 10^{-4}$ |
| $\tilde{c}_g$ | $[-1.3, 1.1] \times 10^{-4}$ | $[-1.1, 1.1] \times 10^{-4}$ |
| $\bar{c}_{HW}$ | $[-2.5, 2.2] \times 10^{-2}$ | $[-3.0, 3.0] \times 10^{-2}$ |
| $\tilde{c}_{HW}$ | $[-6.5, 6.3] \times 10^{-2}$ | $[-7.0, 7.0] \times 10^{-2}$ |
| $\bar{c}_\gamma$ | $[-1.1, 1.1] \times 10^{-4}$ | $[-1.0, 1.2] \times 10^{-4}$ |
| $\tilde{c}_\gamma$ | $[-2.8, 4.3] \times 10^{-4}$ | $[-2.9, 3.8] \times 10^{-4}$ |

# EFT interpretation in the Top sector

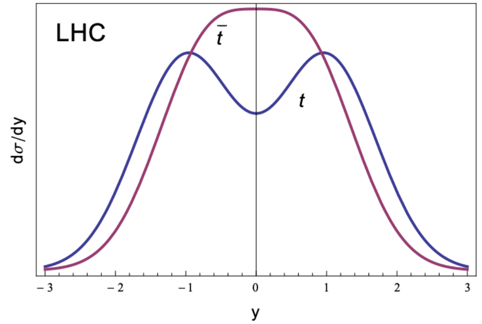
# EFT interpretation in the Top sector

- Measurements in the top-quark sector offer an unique window to BSM
  - Largest top Yukawa coupling → interplay with the Higgs sector
  - Two complementary approaches
    - Direct searches: Flavor-changing neutral currents (FCNC)
    - Precision measurements: differential cross-sections and other top-quark properties
- EFT interpretation
  - Distinguish from the EW and Higgs sector due to the flavor assumption
    - **$U(3)^5$** flavor assumption used for EW and Higgs EFT interpretations
  - Agreement in the top-quark community for common standards for EFT interpretation (LHC TopWG note arXiv:1802.07237)
    - Dim-6 SMEFT, **Warsaw** basis
    - 3 different flavor assumptions, baseline is **$U(2)_q \times U(2)_u \times U(2)_d$**
    - FCNC is treated separately (breaks the $U(2)_q \times U(2)_u \times U(2)_d$ symmetry)
    - Identify the linear combinations of Warsaw-basis operators to reduce the number of relevant parameters

# Charge asymmetry in $t\bar{t}$

ATLAS-CONF-2019-026

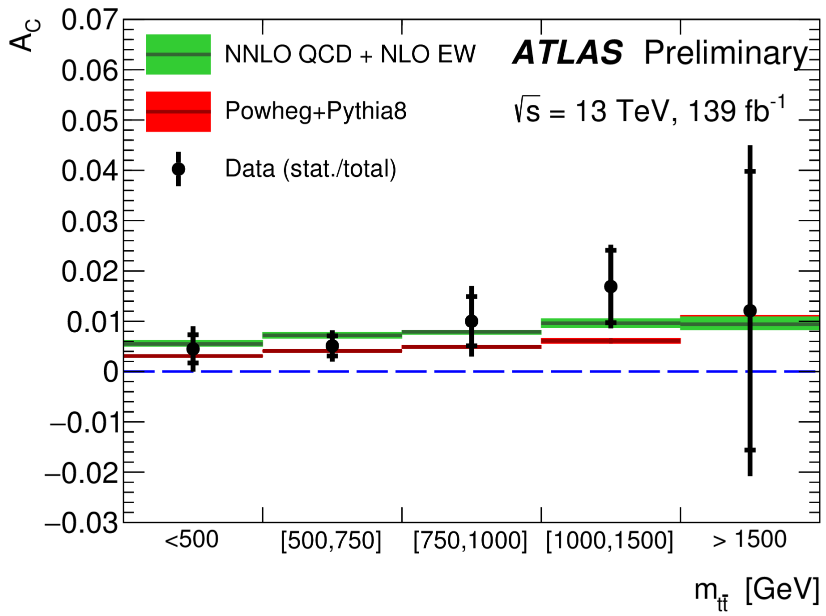
- Charge asymmetry $A_c$:
  - At the LHC top-quarks produced more forward than anti-top quarks
  - Extremely challenging to measure (<1% effect)
  - Sensitive to BSM (eg, anomalous vector or axial couplings)
  - Extracted from unfolded Δ|y| distributions, in the single-lepton channel




$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)},$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

- EFT interpretation
  - $A_C$ is sensitive to 7 four-fermion operators in the Warsaw basis
    - Reduced to 4 by using a flavor-specific linear combination
  - EFT predictions simulated with `dim6top` UFO




$$C_u^1 = C_{qq}^{(8,1)} + C_{qq}^{(8,3)} + C_{ut}^{(8)}$$
$$C_u^2 = C_{qu}^{(1)} + C_{qt}^{(1)}$$
$$C_d^1 = C_{qq}^{(8,1)} - C_{qq}^{(8,3)} + C_{dt}^{(8)}$$
$$C_d^2 = C_{qd}^{(1)} + C_{qt}^{(1)}$$

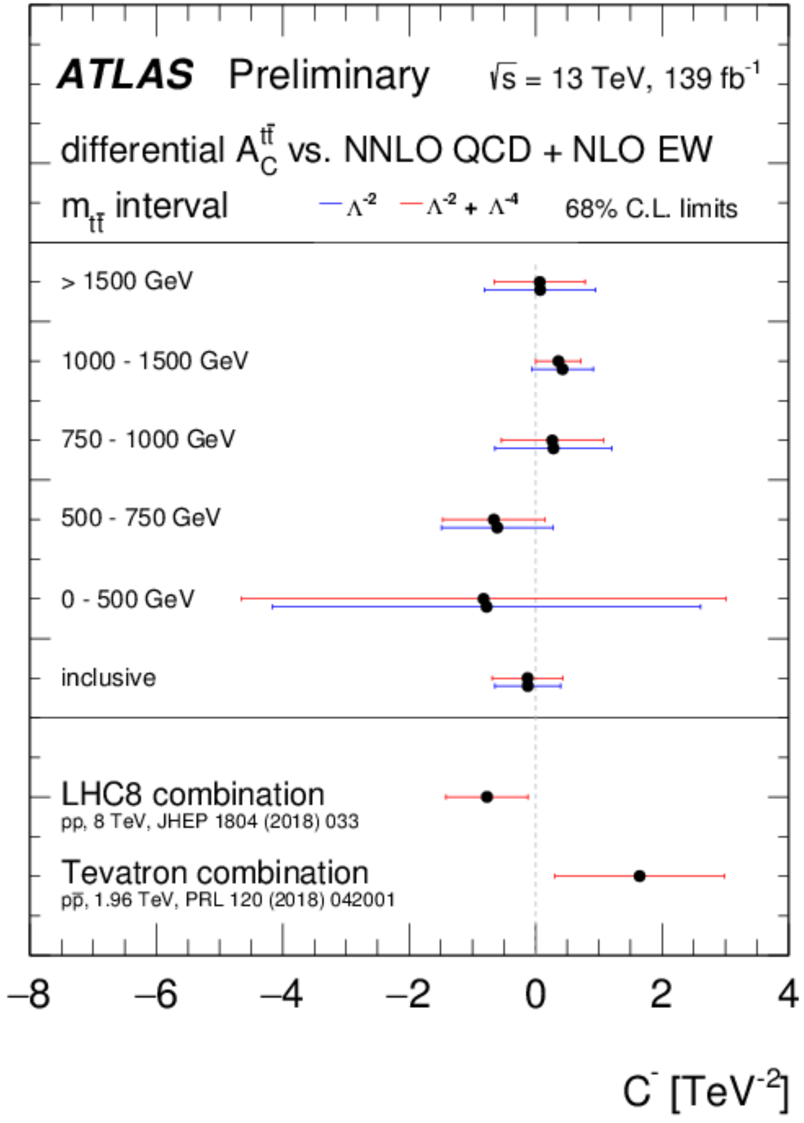
Further assume equal couplings to up- and down-type quarks

⇒
$$C_u^1 = C_d^1 = C^1$$
$$C_u^2 = C_d^2 = C^2$$
⇒
$$C^+ = C^1 + C^2$$
$$C^- = C^1 - C^2$$

# Charge asymmetry in $t\bar{t}$

ATLAS-CONF-2019-026

- EFT results derived from the measured $A_c$
  - Both the inclusive measurement, and each differential $m_{t\bar{t}}$ bins
  - Two scenarios: linear vs linear + quadratic

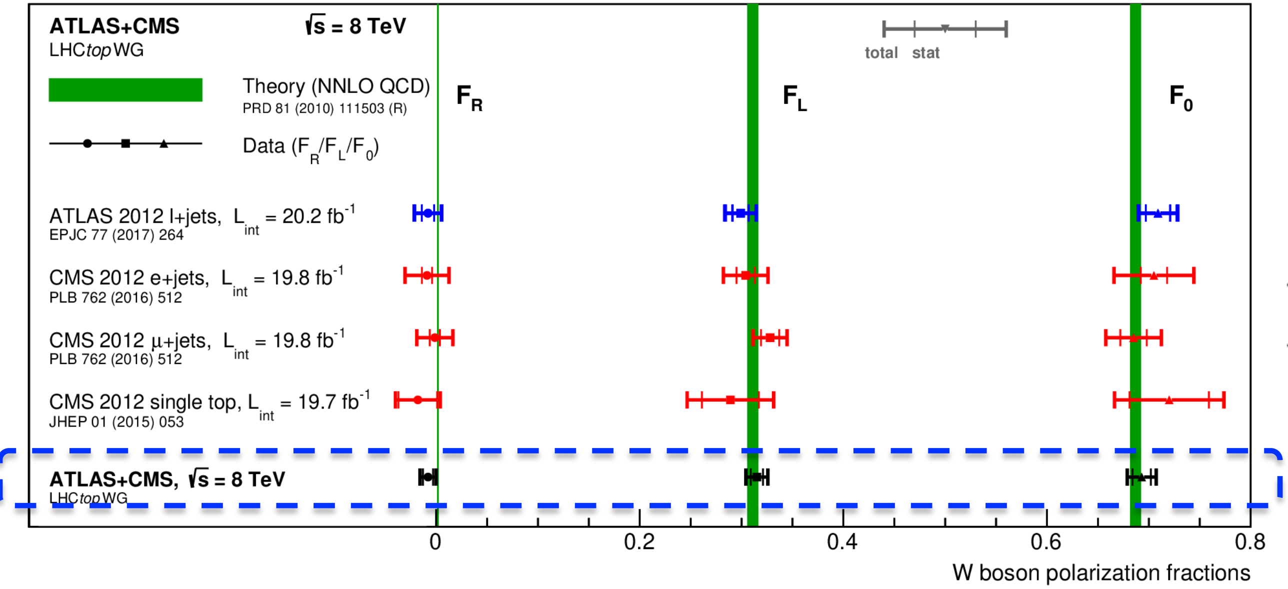



Small dependence on quadratic terms:
→ dim-6 approach is stable and appropriate.

# W polarization in top decays

JHEP08(2020)51

- ATLAS+CMS combined measurements of W polarization (8 TeV)
  - Sensitive to the **V-A structure** of the weak interaction
  - Polarization fractions (**$F_L$, $F_R$, $F_0$**) fit from $\cos\theta^*$ distributions at the detector level
- EFT interpretation
  - Combined polarization resutls are used to constrain dim-6 operators that modify effective tWb couplings in the **Warsaw** basis




$$O_{\phi\phi} = \mathrm{i}(\tilde{\phi}^\dagger D_\mu \phi)(\bar{\mathrm{t}}_\mathrm{R}\gamma^\mu \mathrm{b}_\mathrm{R}),$$
$$O_{\mathrm{tW}} = (\bar{\mathrm{q}}_\mathrm{L}\sigma^{\mu\nu}\tau^I \mathrm{t}_\mathrm{R})\tilde{\phi}W^I_{\mu\nu},$$
$$O_{\mathrm{bW}} = (\bar{\mathrm{q}}_\mathrm{L}\sigma^{\mu\nu}\tau^I \mathrm{b}_\mathrm{R})\phi W^I_{\mu\nu},$$

J. A. Aguilar-Saavedra, arXiv:0811.3842

| | 95% CL interval | | |
|---|---|---|---|
| Coefficient | ATLAS | CMS | ATLAS+CMS |
| $C^*_{\phi\phi}$ | $[-5.64, 7.68]$ | $[-3.84, 4.92]$ | $[-3.48, 5.16]$ |
| $C^*_{\mathrm{bW}}$ | $[-1.30, 0.96]$ | $[-1.06, 0.72]$ | $[-0.96, 0.67]$ |
| $C_{\mathrm{tW}}$ | $[-0.34, 0.67]$ | $[-0.62, 0.19]$ | $[-0.48, 0.29]$ |

# Combined EFT results

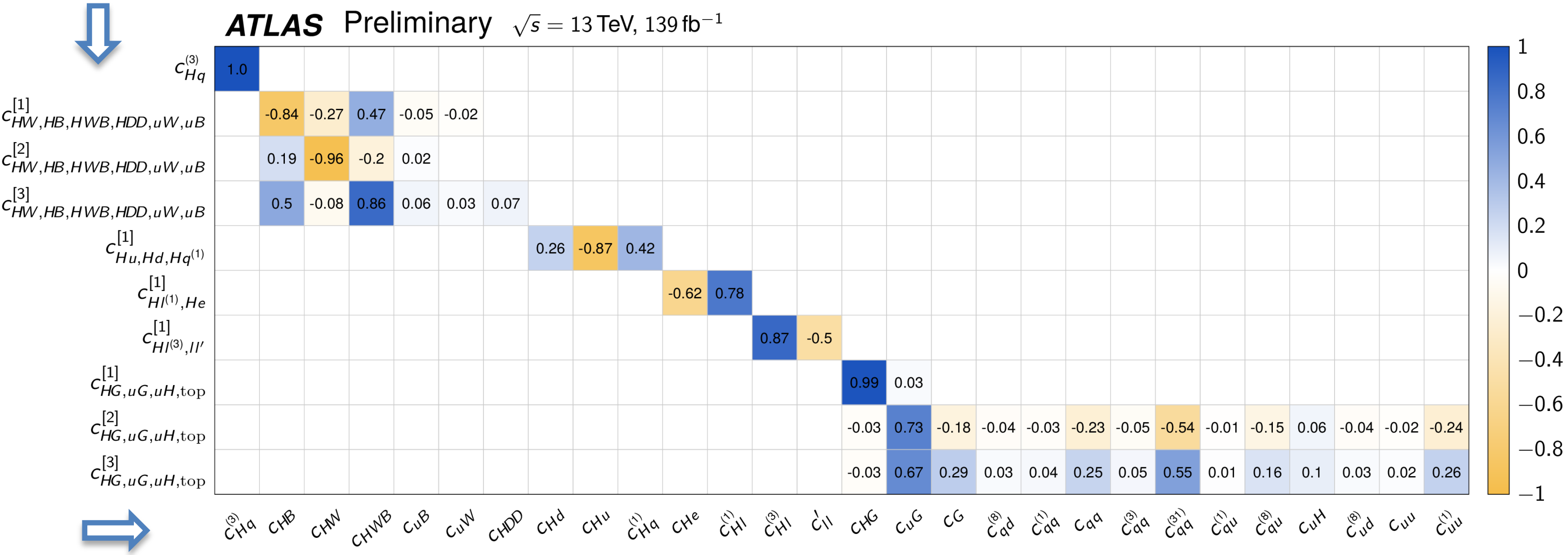
*See more details by Philipp Windischhofer* (Thu. Afternoon)

# Combined Higgs STXS

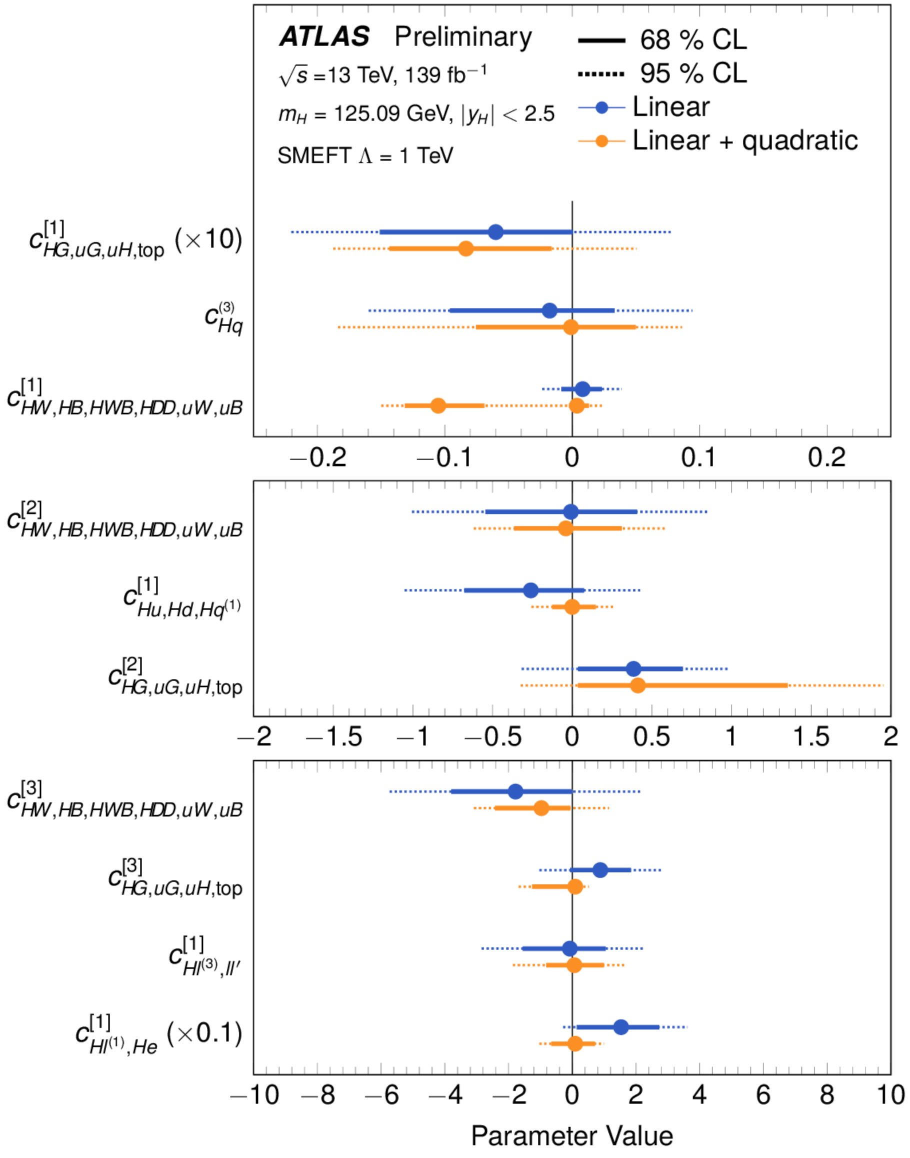
ATLAS-CONF-2020-053

- Combination of STXS from H→4l, H→$\gamma\gamma$ and VH(bb)
  - SMEFT in **Warsaw** basis
  - An eigenvalue decomposition approach used to avoid flat directions
  - Two scenarios: linear vs linear + quadratic
    - With all coefficients profiled simultaneously

Eigenvectors




Composition of Wilson coefficients

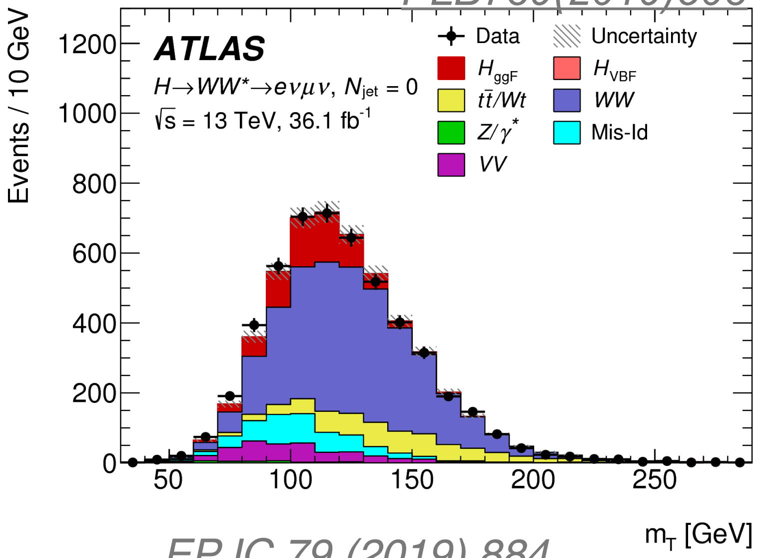


# HWW* + SM WW combination

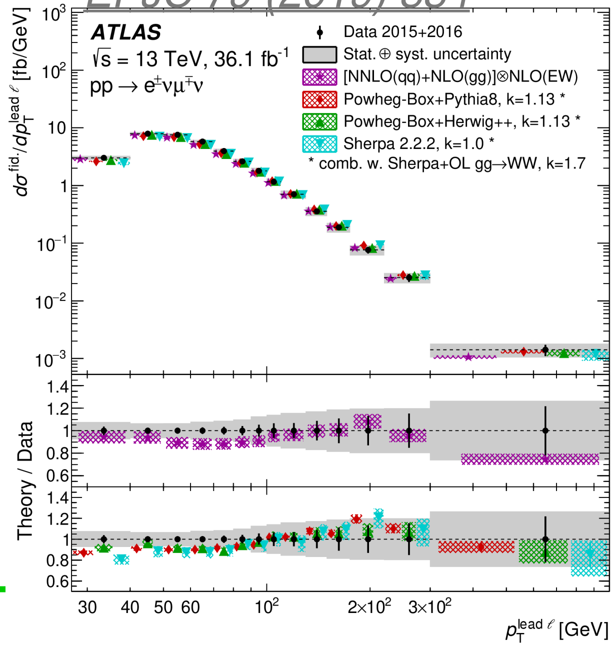
ATL-PHYS-PUB-2021-010

- H→WW* measurements: *PLB 789 (2019) 508*
  - Signal strength measurements in ggF,VBF production modes
- SM WW measurements: *EPJC 79 (2019) 884*
  - 36 $fb^{-1}$ WW+0j differential cross-sections, leading lepton $p_T$
- EFT combination
  - SMEFT in **Warsaw** basis, 22 CP-even operators
  - Eigenvalue decomposition approach
- Instructional test case towards future global EFT combination
  - Correlation of systematic uncertainties is taken into account carefully
  - EFT effects on the WW "background" in the HWW* signal regions are also taken into account
  - We try to avoid setting parameters to zero as much as possible

PLB789(2019)508




EPJC 79 (2019) 884



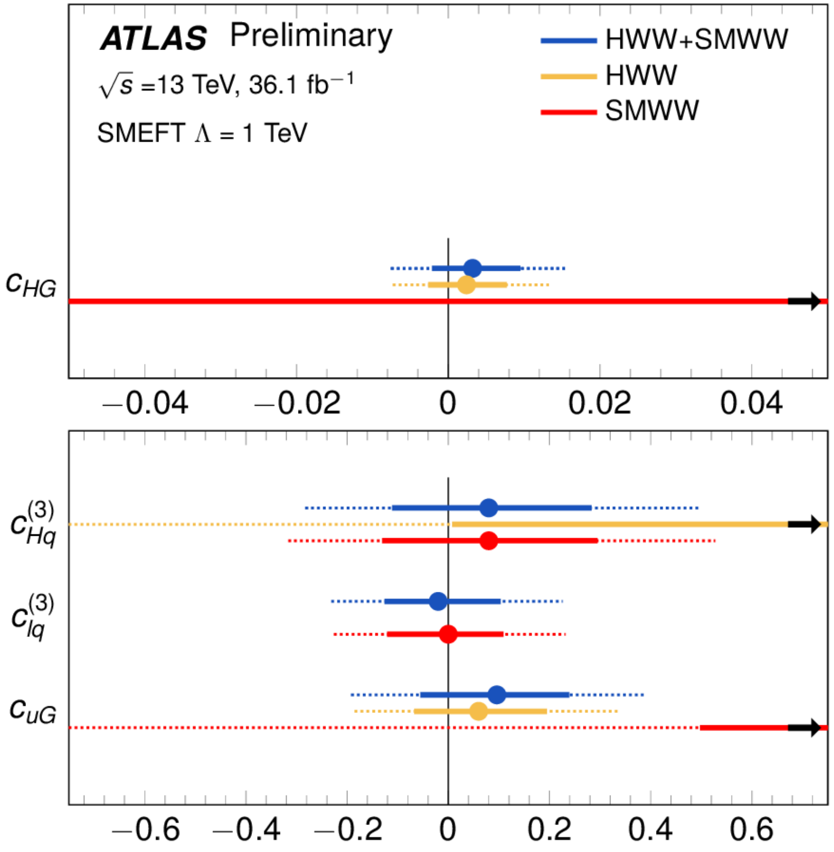
# HWW + SM WW combination

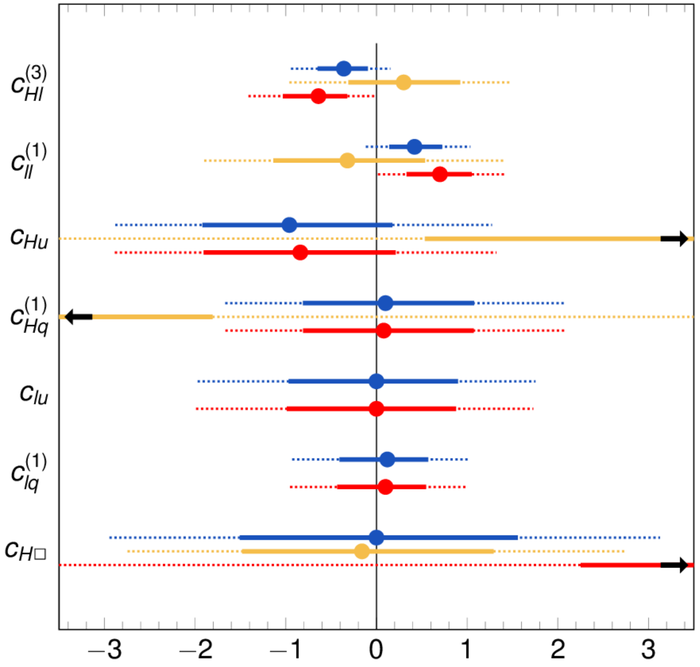
ATL-PHYS-PUB-2021-010

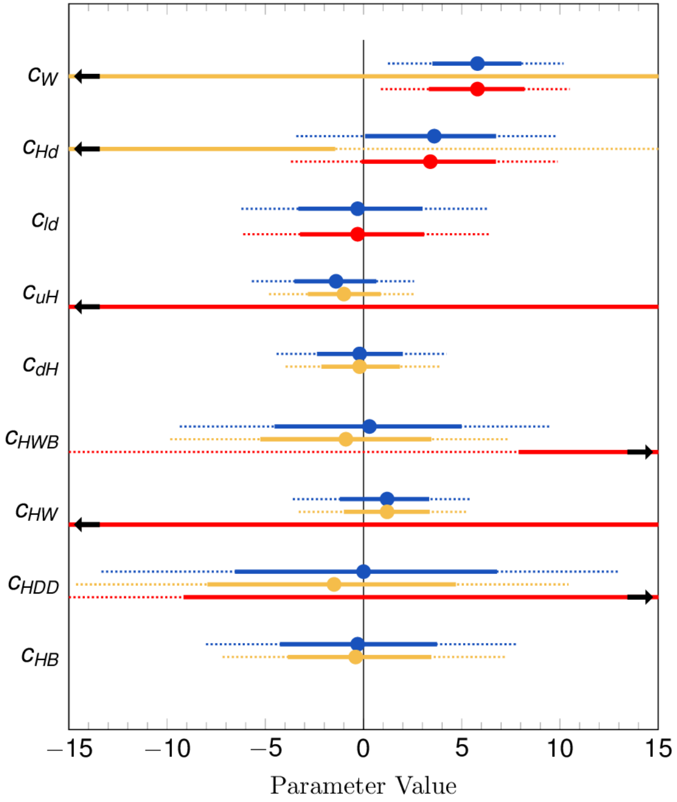
- Combined EFT constraints
  - 1-D fit results shown below
  - 8-D simultaneous fit of eigenvectors are also provided

HWW+SMWW
HWW
SMWW

Stronger together!



# Towards ATLAS EFT combination

# ATLAS EFT combination

- Complementary constraints from different sectors
  - Need wide combination to fully leverage EFT
  - Also the original idea behind the EFT theory development
- To include some of the most relevant existing **H + EW + top + non-ATLAS** constraints
  - **Higgs** : STXS combination
  - **EW**: WW + WZ + 4l + VBF Z (Gaussian model with NPs)
    - One distribution from each to avoid correlation issues (eg. $p_T^{lep}$, $m_{WZ}$, $m_{34}$ vs. $m_{4l}$, $\Delta\phi_{jj}$)
  - **Top** : possible observables are ttV, $t\bar{t}$ differential cross-section, $t\bar{t}$ charge asymmetries, 4t
  - **Non-ATLAS** constraints:
    - Z-pole (LEP-1/SLC) and diboson (LEP-2) data, others?
    - Not strictly needed but simplifies treatment of flat combinations
    - Implemented as a multivariate Gaussian term in the likelihood

Not a finalized blueprint
Feedback and discussion welcome!

See also
Sandra Kortner, LHC EFT WG meeting, Oct 2020
Nicolas Berger, Area 3&4 meeting, Feb 2021

# EFT framework

I. Brivio, Y. Jiang and M. Trott, arXiv:1709.06492
I. Brivio, arXiv:2012.11343

- SMEFT Model
  - Basis: Dim-6 Warsaw basis, $\Lambda$ = 1 TeV
  - Focus on CP-even operators for now
  - Flavor structure:
    - Investigate the "**topU3l**" structure ($U(2)_q \times U(2)_u \times U(2)_d$, $U(3)_l \times U(3)_e$) in SMEFTsim3.0
    - → Well-suited to top measurements
    - Also consider the simpler $U(3)^5$
- SMEFT Predictions
  - Use ($m_W$, $m_Z$ , $G_F$) scheme, consider ($\alpha$, $m_Z$ , $G_F$) as alternate
  - Use LO predictions
    - Except for loop effects ($gg \to H$, $gg \to ZH$, $H \to \gamma\gamma$), which are calculated with SMEFT@NLO
  - Use **SMEFTsim** and **SMEFT@NLO** to simulate SMEFT impact

SMEFT@NLO, Gauthier Durieux et al, arXiv:2008.11743

# EFT parametrization

- SMEFT Predictions (cont.) :
  - Linear EFT expansion (terms up to $1/\Lambda^2$ ) as a baseline
    - Inclusion of all dim-8 operators impractical
  - Also report results with linear + quadratic terms
    - This can be used as an estimate of EFT convergence
  - Rescale predictions to best SM computations

$$\vec{\sigma}(c) = \vec{\sigma}^{\mathrm{SM,best}} \cdot \frac{\vec{\sigma}^{\mathrm{EFT}}(c)}{\vec{\sigma}^{\mathrm{EFT}}(c=0)}$$

- SMEFT uncertainties
  - How to define uncertainties on the EFT predictions?
    - Missing terms in EFT expansion?
    - Higher order QCD/EW corrections?

# Summary

- Growing number of EFT measurements in ATLAS
  - New results coming out with full Run-2 data
  - Individual measurements across the SM/Higgs/Top sectors
  - And also small-scope combined results:
    - Higgs STXS combination, H→WW* + SM WW combination

- Plans for an ATLAS-wide combination
  - Aim for a (Higgs + EW + Top + EWPD) scope
    - A first attempt to pave the road and to gain experience
    - Possibly leaving for later the optimal treatment of some of the more difficult issues
  - Common ground (theory framework) is largely in place
  - Still many challenges to meet
  - Feedback welcome

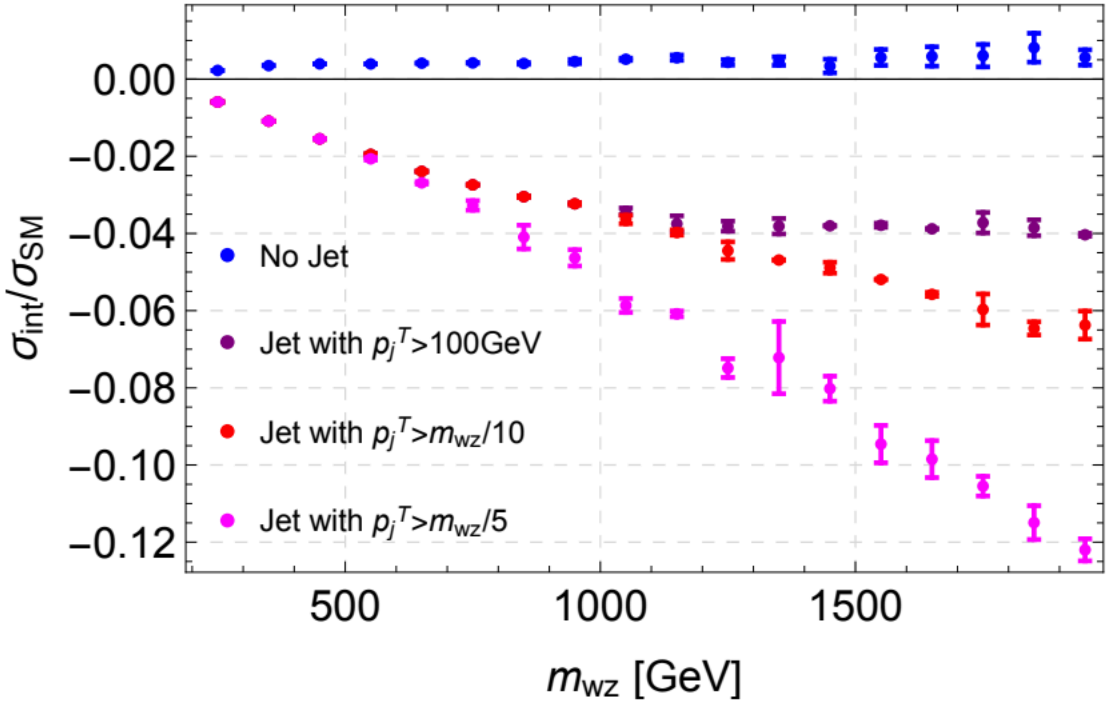
# Backup

# Summary of ATLAS EFT results

| | EW | Higgs | Top | Combination |
|---|---|---|---|---|
| Meas. | WW+jets, 140 $fb^{-1}$ | VH(bb) boosted STXS, 140$fb^{-1}$ | W polarization in top-quark decays (8 TeV) | Higgs STXS combination, 140 $fb^{-1}$ |
| | Inclusive 4l, 140 $fb^{-1}$ | VH(bb) resolved STXS, 140$fb^{-1}$ | ttZ signal strength, 36 $fb^{-1}$ | H→WW* and SM WW combination, 36 $fb^{-1}$ |
| | VBF Zjj, 140 $fb^{-1}$ | H4l STXS, 140$fb^{-1}$ | $t\bar{t}$ charge asymmetry, differential, 36 $fb^{-1}$ | |
| | WW+0j, 36 $fb^{-1}$ | H→$\gamma\gamma$ differential, 140$fb^{-1}$ | FCNC tq$\gamma$, 81 $fb^{-1}$ | |
| | | | FCNC tq$Z$, 36 $fb^{-1}$ | |
| EFT framework | Warsaw and HISZ basis `SMEFTsim` and `EWdim6` | SILH and Warsaw basis `SMEFTsim` and `SMEFT@NLO` | Warsaw bais `topFCNC, dim6top` | Warsaw basis `SMEFTsim` and `SMEFT@NLO` |
| Wilson coefficients in the fit | 1-D fit | Simultaenous fit, 1-D fit | 1-D fit | Simultaenous fit, 1-D fit |

- Both detector and particle level measurements are used
- **U(3)$^5$** flavor assumption is used in Higgs & EW EFT interpretations, while **U(2)$_q$ × U(2)$_u$ × U(2)$_d$** for Top
- Usually EFT results reported for both linear and linear+quadratic fits

# WW+jets




A. Azatov et al arXiv:1707.08060

**Figure 4:** $\sigma_{\rm int}/\sigma_{\rm SM}$ as a function of $m_{WZ}$ for the process $pp \to WZ$ (blue) and the process $pp \to VW + j$, with $p_j^T > m_{WZ}/5$ (pink), $p_j^T > m_{WZ}/10$ (red), and $p_j^T > 100$ GeV (purple).

# EFT in WW

- Some details

$$\mathcal{L}(\vec{\mu},\vec{\theta}) = \frac{1}{\sqrt{(2\pi)^k|C|}} exp(-\frac{1}{2}(\vec{\sigma}_{\rm data} - \vec{\sigma}_{\rm pred}(\vec{\mu},\vec{\theta}))^T C^{-1}(\vec{\sigma}_{\rm data} - \vec{\sigma}_{\rm pred}(\vec{\mu},\vec{\theta})))\mathcal{G}(\vec{\theta})$$

$$\vec{\sigma}_{\rm pred}(\vec{\mu},\vec{\theta}) = \vec{\sigma}_{\rm SM} + \sum_i \mu_i \vec{\sigma}_i^{\text{dim-6, lin.}} + \sum_{i,j} \mu_i \mu_j \vec{\sigma}_{ij}^{\text{dim-6, quad.}}$$

High-order corrections:

$$\vec{\sigma}_{\rm pred} = \vec{\sigma}_{\rm SM} \times (1 + c_i \cdot \frac{\vec{\sigma}_i^{\rm dim-6,lin.}}{\vec{\sigma}_{\rm LO,SM}} + c_i^2 \cdot \frac{\vec{\sigma}_i^{\rm dim-6,quad.}}{\vec{\sigma}_{\rm LO,SM}})$$

WW+jets, 140/fb, arXiv:2103.10319, SMEFT Warsaw basis

| Jet $p_{\rm T}$ | Linear only | 68% CI obs. | 95% CI obs. | 68% CI exp. | 95% CI exp. |
|---|---|---|---|---|---|
| > 30 GeV | yes | [–1.64, 2.86] | [–3.85, 4.97] | [–2.30, 2.27] | [–4.53, 4.41] |
| > 30 GeV | no | [–0.20, 0.20] | [–0.33, 0.33] | [–0.28, 0.27] | [–0.39, 0.38] |
| > 200 GeV | yes | [–0.29, 1.84] | [–1.37, 2.81] | [–1.12, 1.09] | [–2.24, 2.10] |
| > 200 GeV | no | [–0.43, 0.46] | [–0.60, 0.58] | [–0.38, 0.33] | [–0.53, 0.48] |

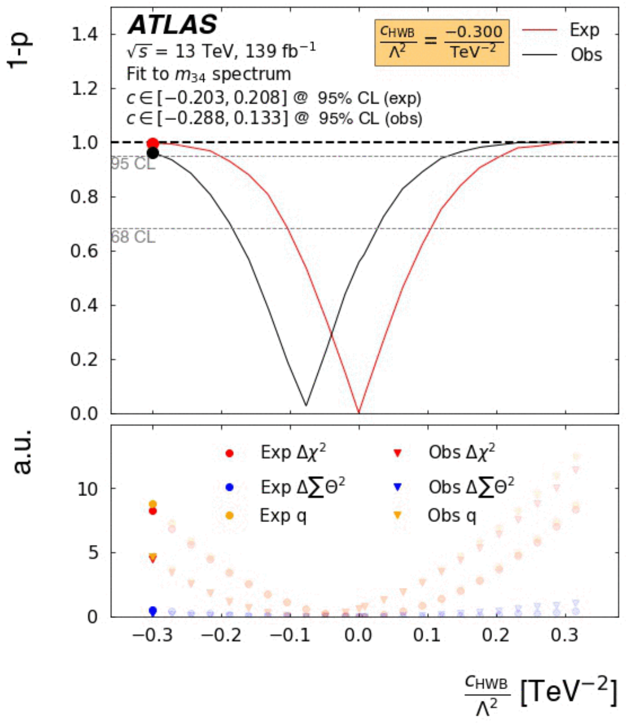
Compared to the results from 36/fb WW 0j (arXiv:1905.04242)
HISZ basis, EWdim6

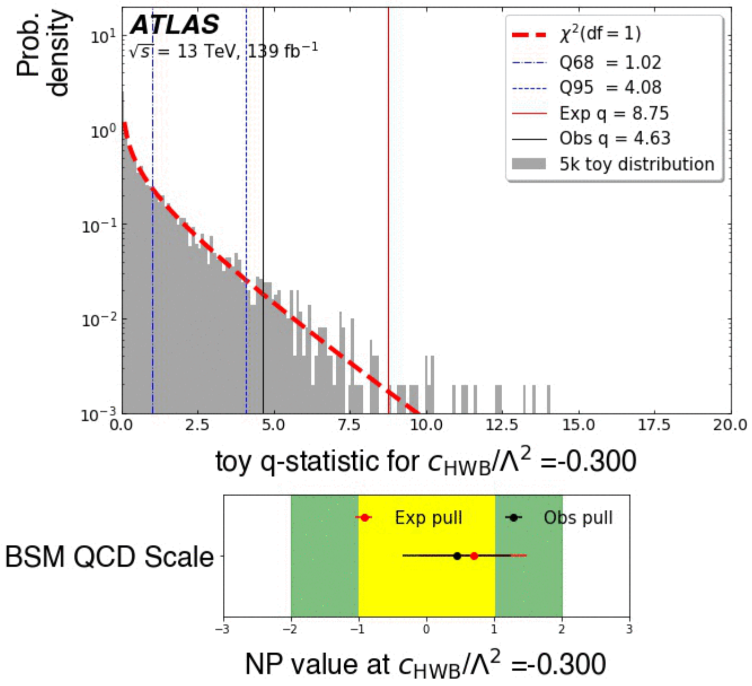
| Operator | 95% CL (linear and quadratic terms) | 95% CL (linear terms only) |
|---|---|---|
| $c_{WWW}/\Lambda^2$ | $[-3.4\ \text{TeV}^{-2}, 3.3\ \text{TeV}^{-2}]$ | $[-179\ \text{TeV}^{-2}, -17\ \text{TeV}^{-2}]$ |
| $c_W/\Lambda^2$ | $[-7.4\ \text{TeV}^{-2}, 4.1\ \text{TeV}^{-2}]$ | $[-13.1\ \text{TeV}^{-2}, 7.1\ \text{TeV}^{-2}]$ |
| $c_B/\Lambda^2$ | $[-21\ \text{TeV}^{-2}, 18\ \text{TeV}^{-2}]$ | $[-104\ \text{TeV}^{-2}, 101\ \text{TeV}^{-2}]$ |

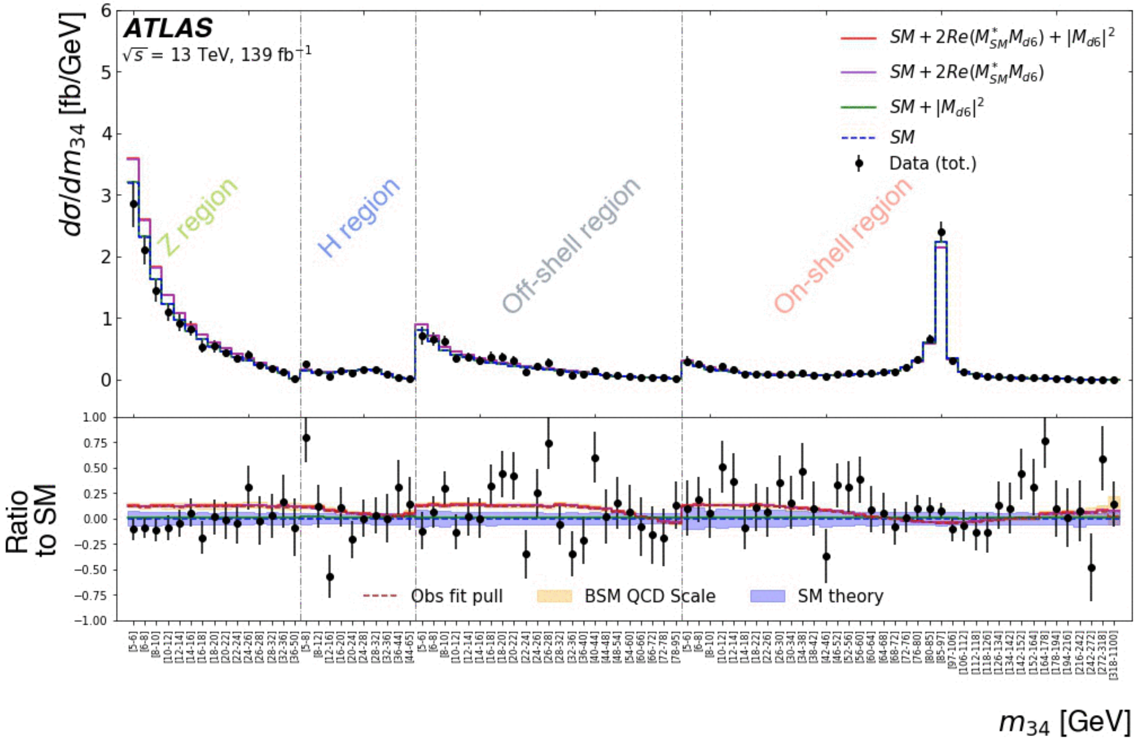
# Inclusive 4l measurements

arXiv:2103.01918

- Example: how $c_{HWB}$ affects the $m_{34}$ prediction



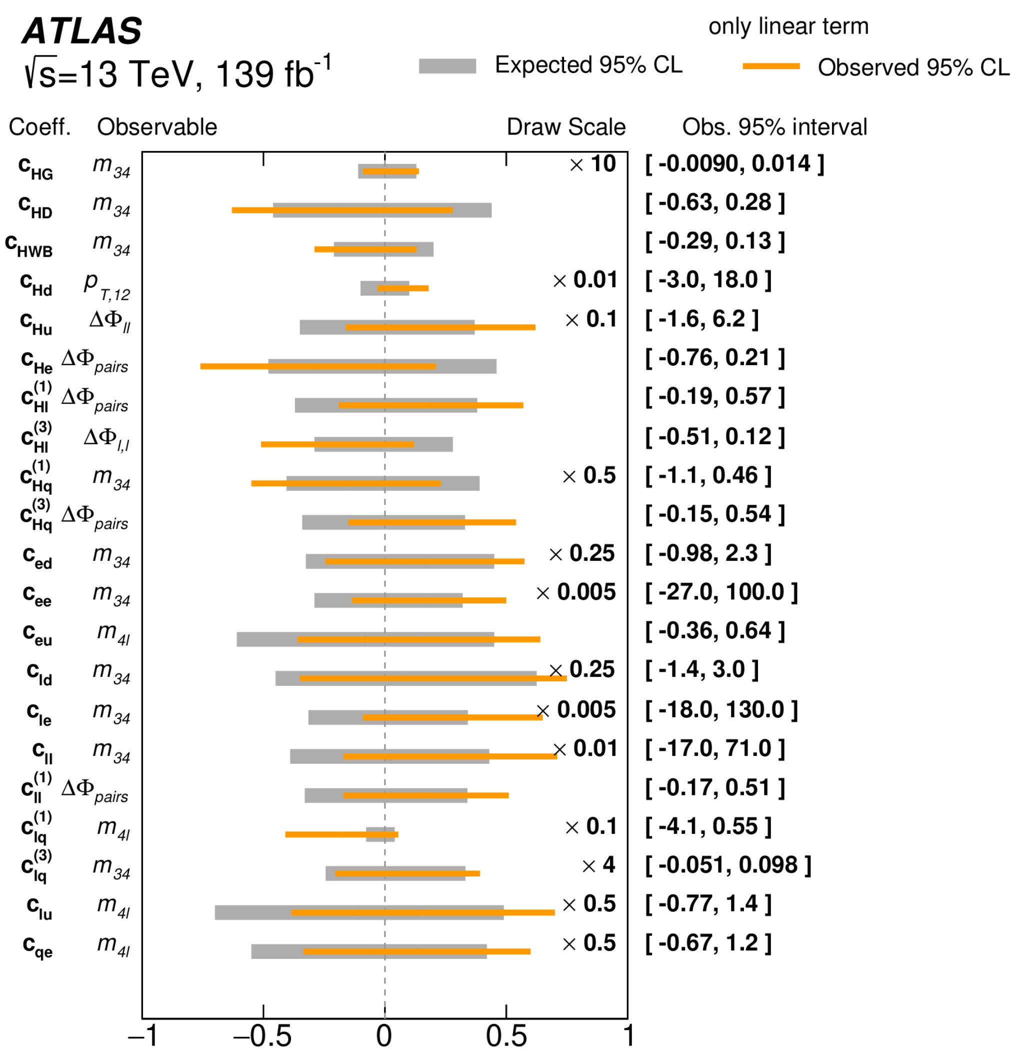



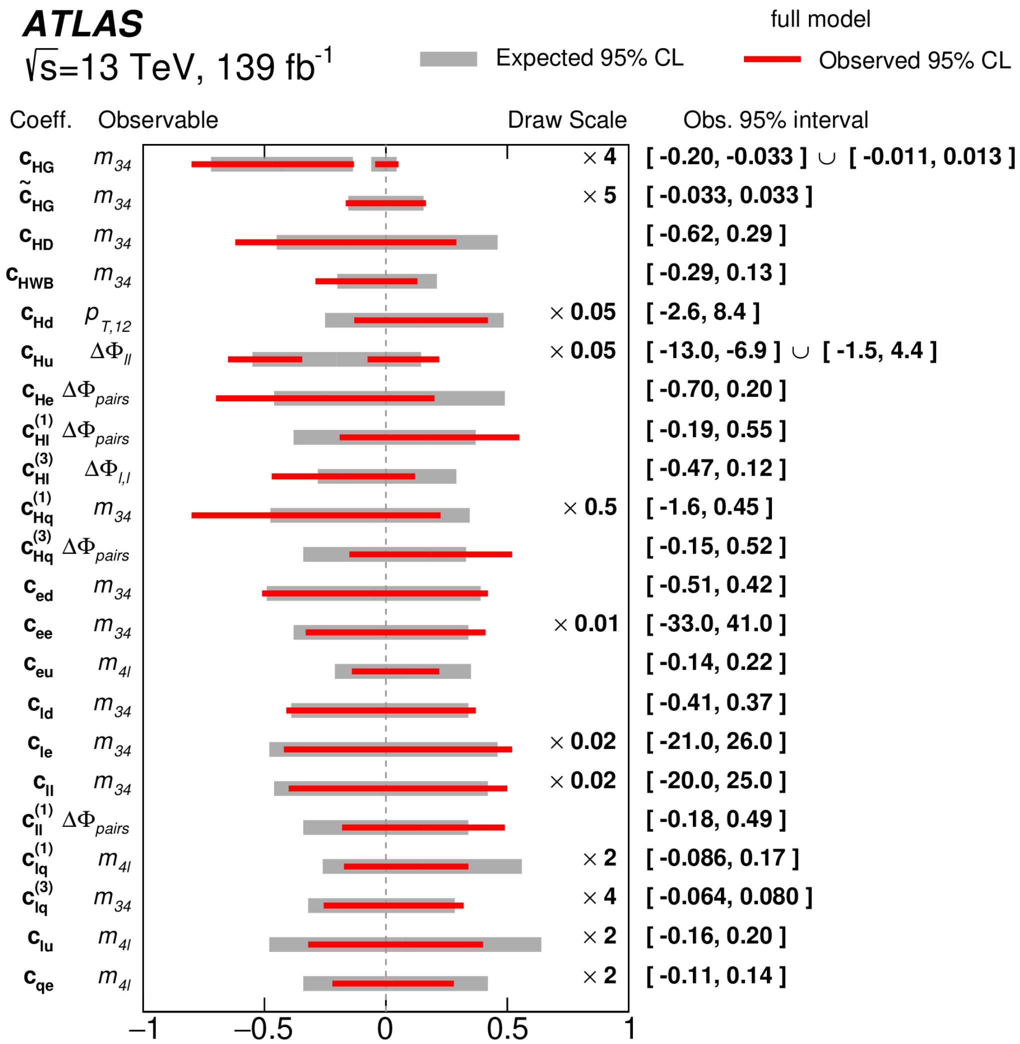



# Inclusive 4l measurements

arXiv:2103.01918

- EFT results with linear fit only vs linear + quadratic fit

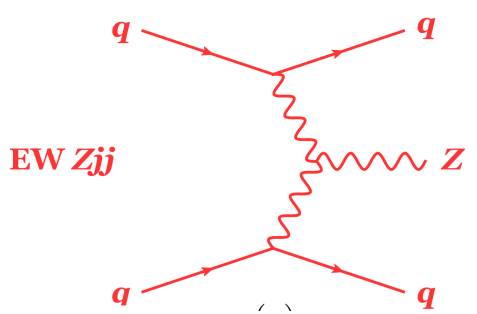


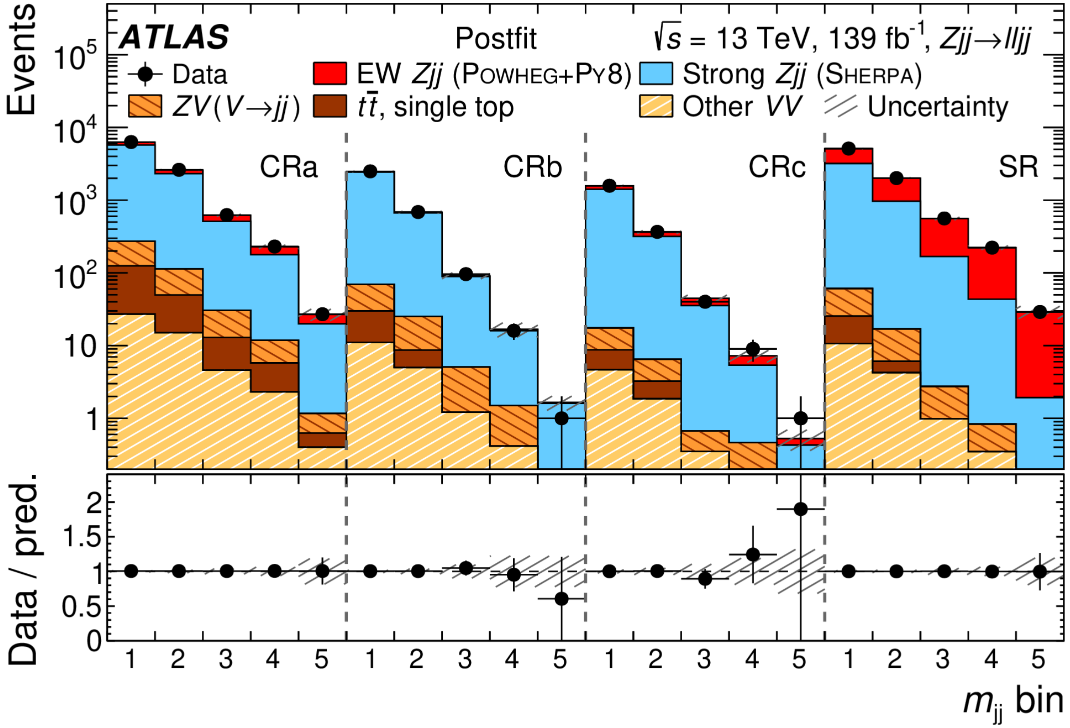



# VBF Zjj measurements

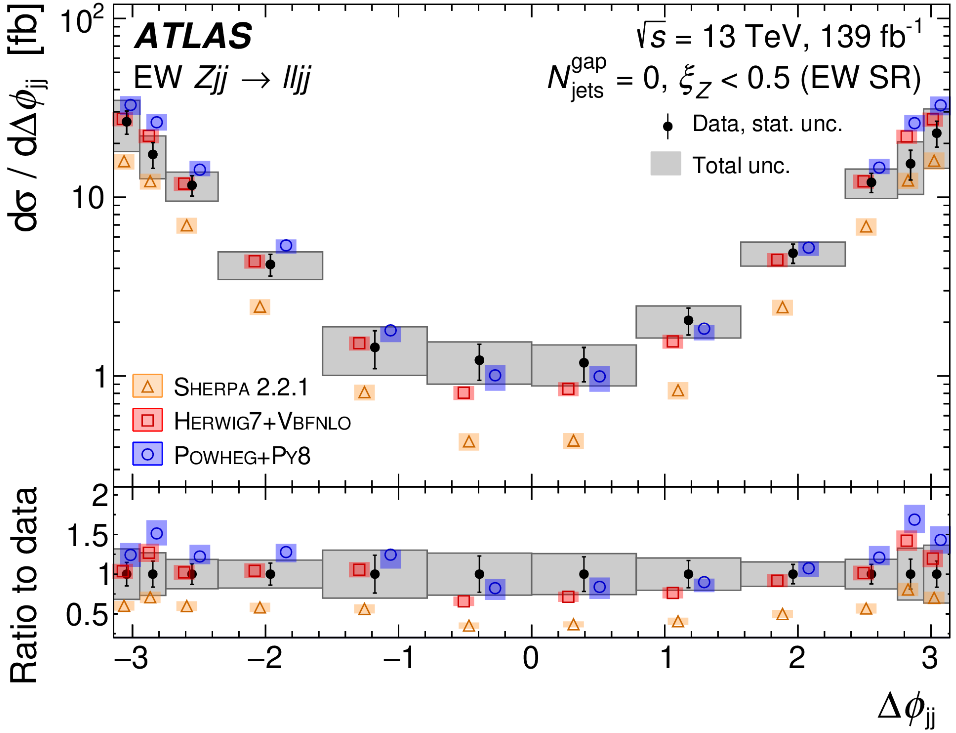
EPJC81(2021)163

- Differential measurements of EW Zjj
  - Sensitive to aTGC
  - Large background contribution from QCD Zjj subtracted




Dedicated data control regions are used to constrain the modelling of QCD Zjj

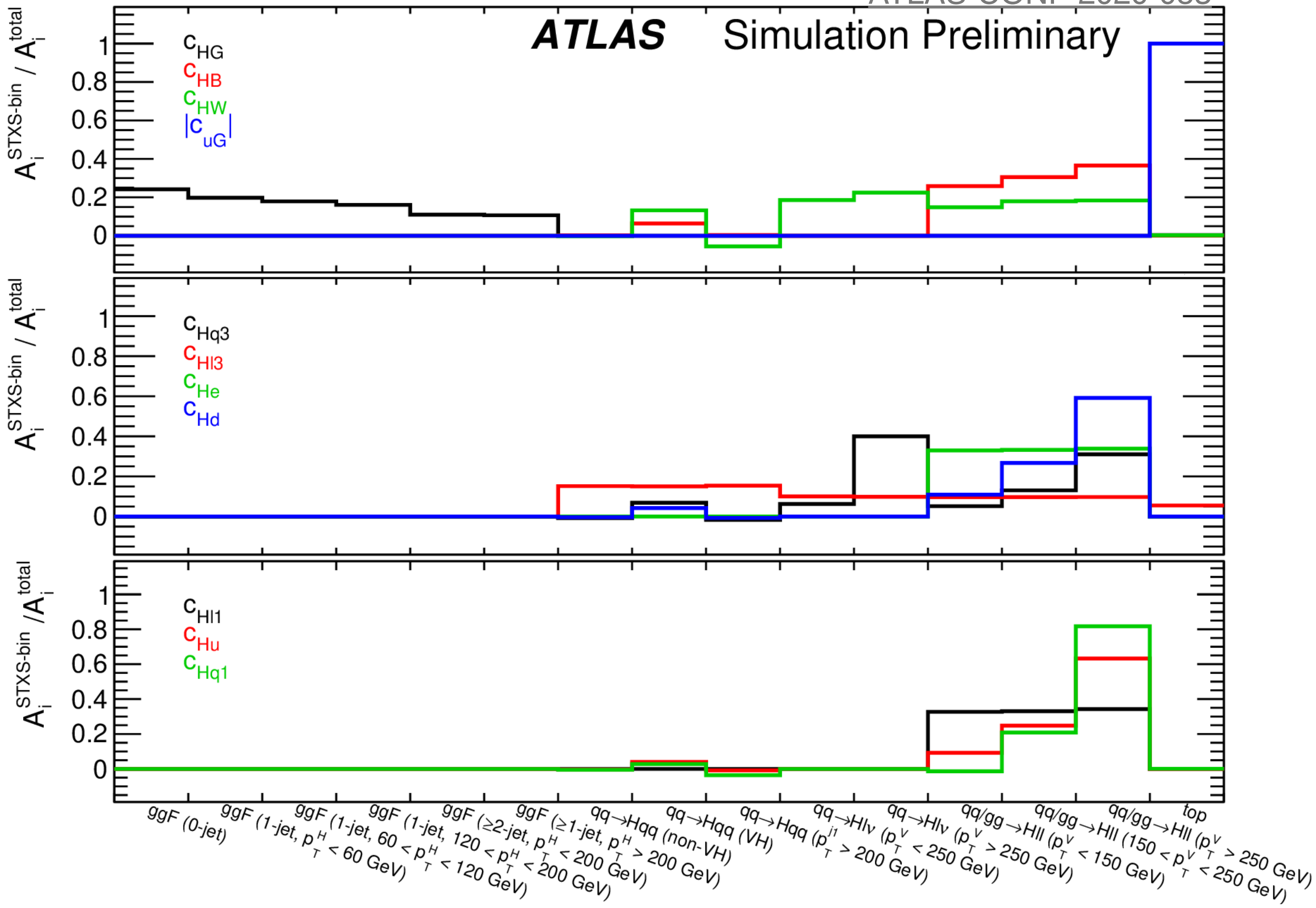



Signed $\Delta\phi_{jj} = \phi_f - \phi_b$, with $y > y_b$, sensitive to CP-odd EFT operators

# EFT interpretation in the Higgs sector

- Relative impact of selected SMEFT operators on STXS
  - Warsaw basis

ATLAS-CONF-2020-053



# VH(H→bb) resolved

EPJC81(2021)178

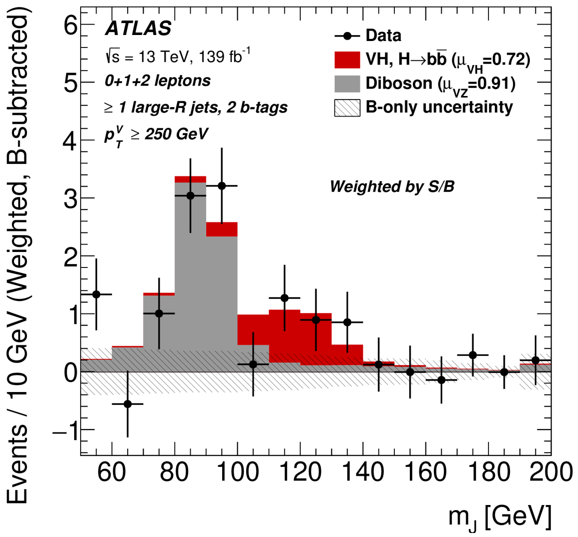
- Eigenvectors

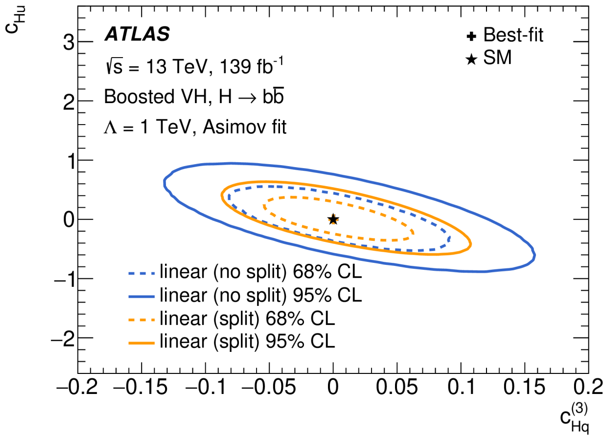
| Wilson coefficient | Eigenvalue | Eigenvector |
|---|---|---|
| $c_{E0}$ | 2000 | $0.98 \cdot c_{Hq}^{(3)}$ |
| $c_{E1}$ | 38 | $0.85 \cdot c_{Hu} - 0.39 \cdot c_{Hq}^{(1)} - 0.27 \cdot c_{Hd}$ |
| $c_{E2}$ | 8.3 | $0.70 \cdot \Delta\mathrm{BR}/\mathrm{BR}_{\mathrm{SM}} + 0.62 \cdot c_{HW}$ |
| $c_{E3}$ | 0.2 | $0.74 \cdot c_{HWB} + 0.53 \cdot c_{Hq}^{(1)} - 0.32 \cdot c_{HW}$ |
| $c_{E4}$ | $6.4 \cdot 10^{-3}$ | $0.65 \cdot c_{HW} - 0.60 \cdot \Delta\mathrm{BR}/\mathrm{BR}_{\mathrm{SM}} + 0.35 \cdot c_{Hq}^{(1)}$ |

# VH(H→bb) boosted

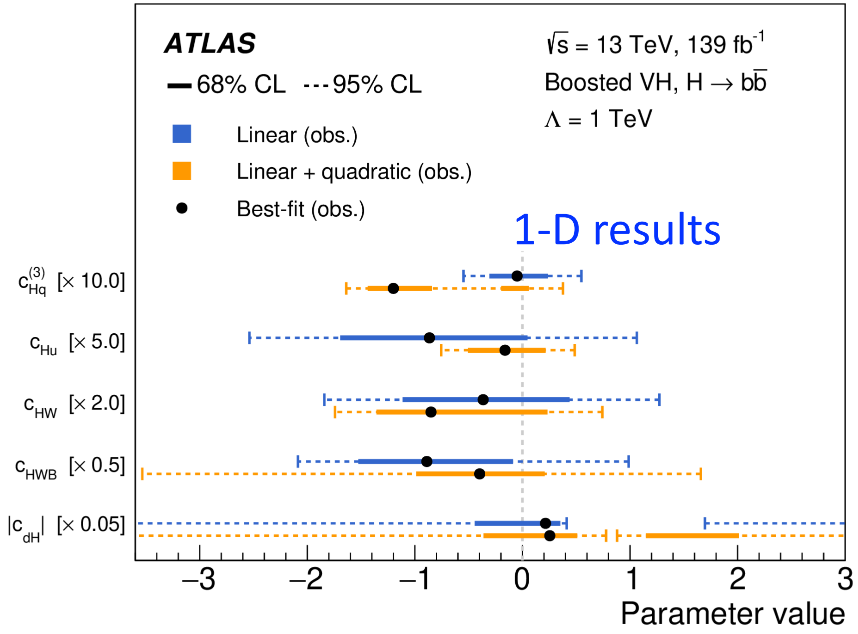
EPJC81(2021)178

- Similar strategy as in the resolved analysis
- Expected better sensitivity to EFT at higher $p_T$

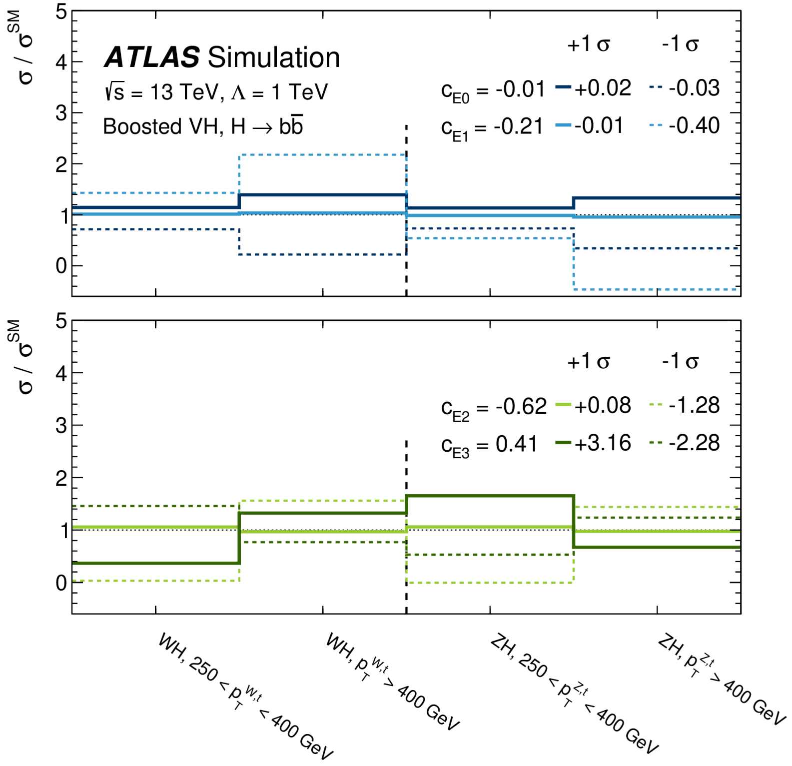



1-D results




5-D results

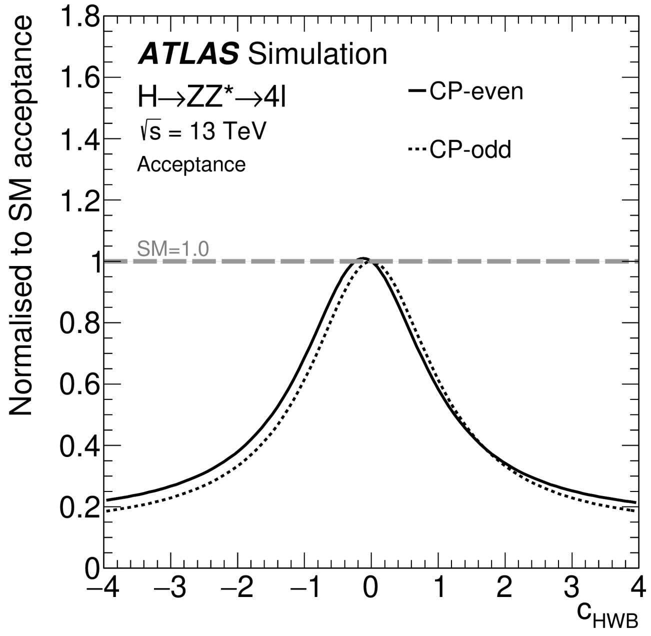


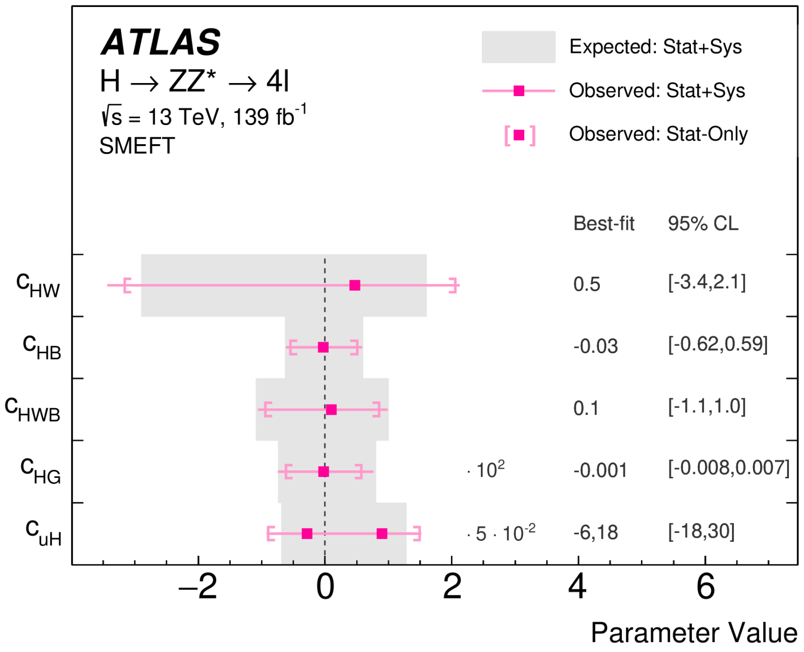

Expected sensitivity with two $p_T^V$ bins (blue lines) and using a single bin of $p_T^V$>250 GeV (orange lines)

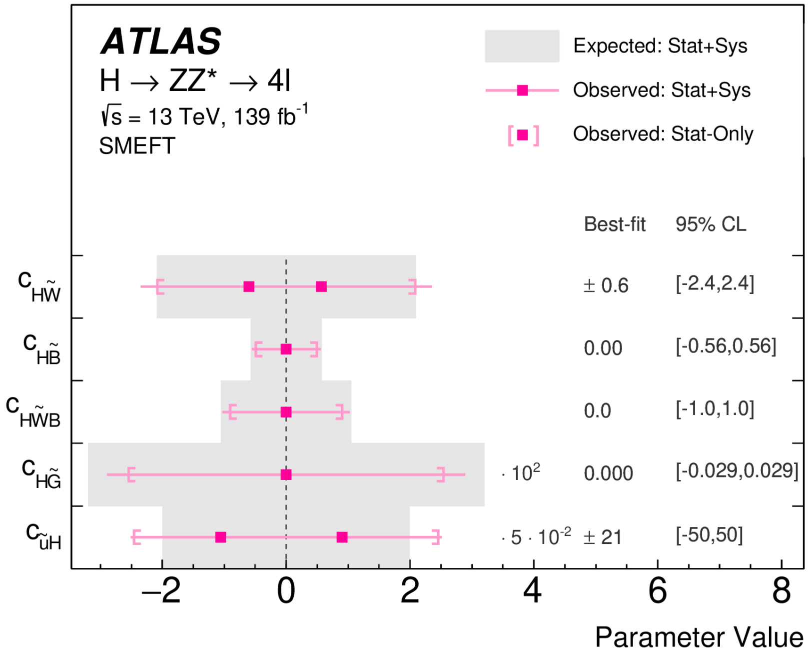
# H→4l STXS

EPJC 80(2020)957

- STXS results are used to constrain 5 CP-even and 5 CP-odd operators
  - Acceptance effects taken into account
  - 1-D fit results (2-D results also provided)



# HWW + SM WW combination

- Statistical model
  - HWW: Poisson
  - SM WW: a multivariate Gaussian

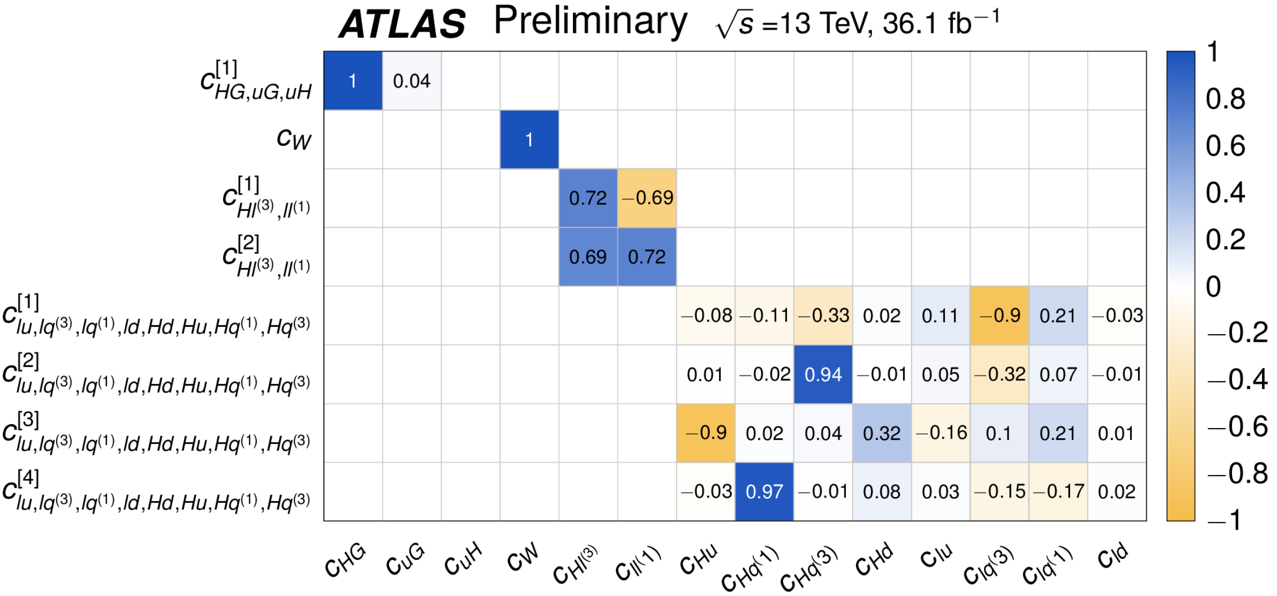
$$L^{\text{comb}}\left(\boldsymbol{N},\boldsymbol{x}\middle|\boldsymbol{c},\boldsymbol{\theta}^{\text{comb}}\right)=\prod_{b\notin\text{WW-CR}}^{n_{\text{bins}}^{\text{SR+CR}}}\text{Poisson}\left(N_b\middle|\sum_p \mu_p\left(\boldsymbol{c}\right)S_p\left(\boldsymbol{\theta}^{HWW}\right)+B\left(\boldsymbol{c},\boldsymbol{\theta}^{HWW}\right)\right)$$
$$\times\frac{1}{\sqrt{(2\pi)^{n_{\text{bins}}^{WW}}\det\left(C\right)}}\exp\left(-\frac{1}{2}\Delta\boldsymbol{x}\left(\boldsymbol{c},\boldsymbol{\theta}^{WW}\right)^{\mathsf{T}}C^{-1}\Delta\boldsymbol{x}\left(\boldsymbol{c},\boldsymbol{\theta}^{WW}\right)\right)$$
$$\times\prod_{i}^{n_{\text{syst}}^{\text{comb}}}f_i\left(\theta_i^{\text{comb}}\right).$$

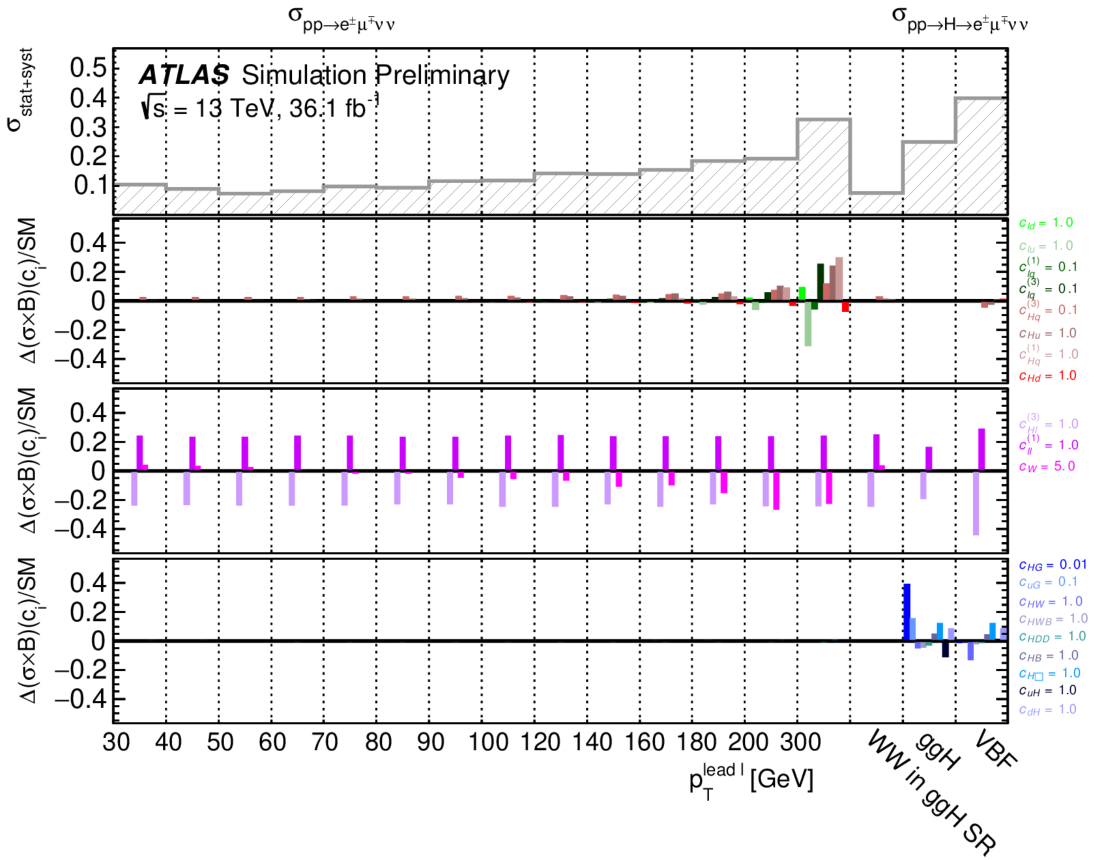
- Overlap of the two measurements:
  - These control regions of the HWW analysis are removed and the signal region of the WW measurement is used instead
  - Uncertainties on this extrapolation are implicitly taken into account by the statistical model
    - Uncertainties affecting WW production are treated as fully correlated between the two

# HWW* + SM WW combination

ATL-PHYS-PUB-2021-010

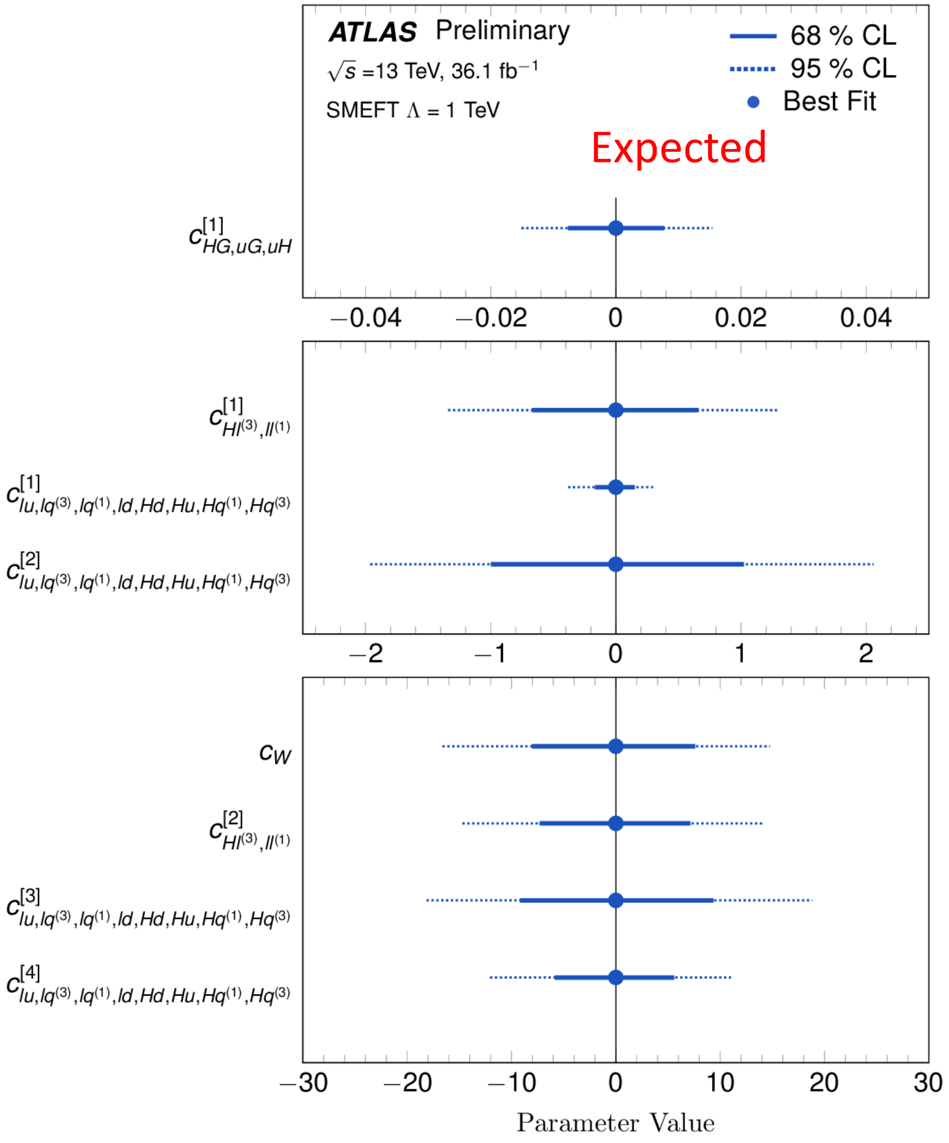
- EFT combination
  - SMEFT in Warsaw basis, 22 CP-even operators
  - Eigenvalue decomposition approach

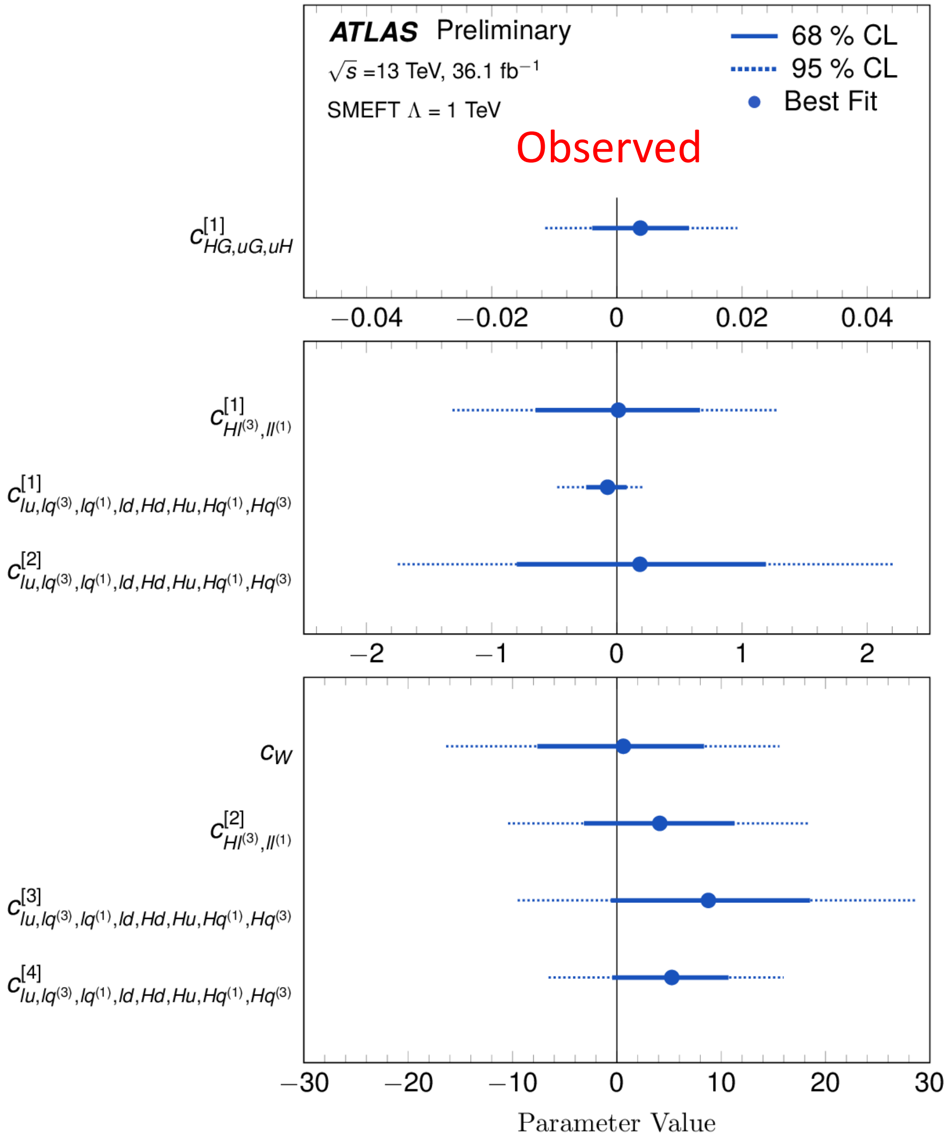


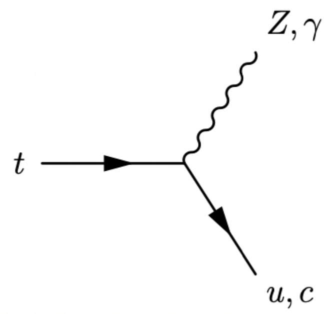
# HWW + SM WW combination

- 8-D results

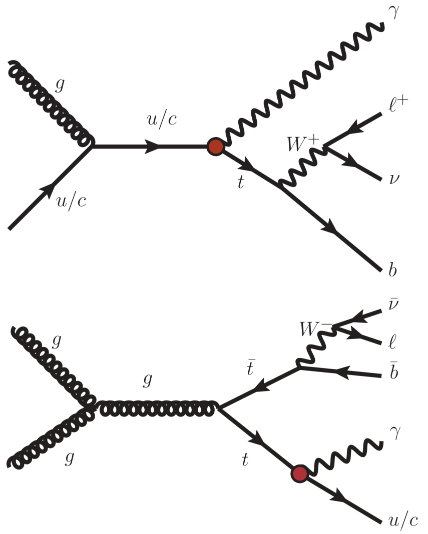


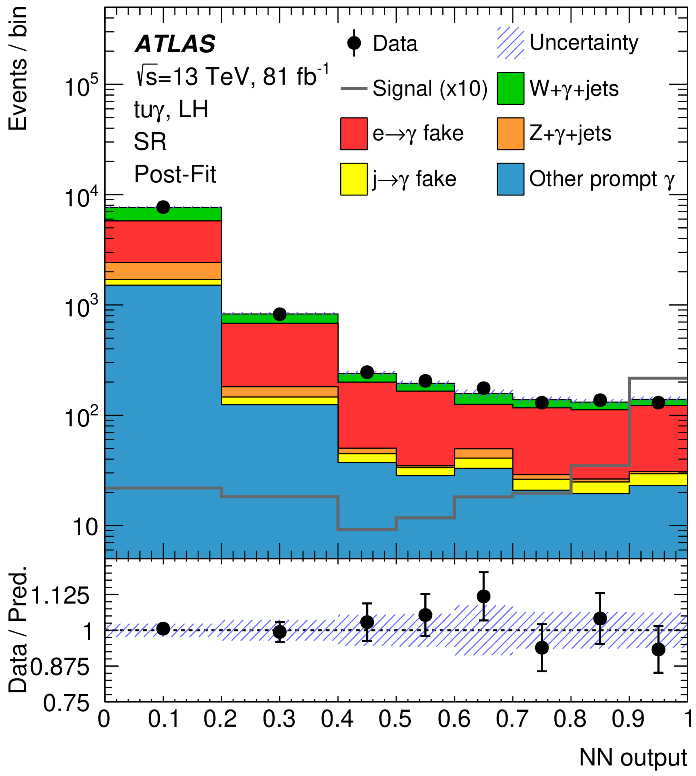



# FCNC tq$\gamma$




- Direct searches using detector level observables
  - A neural network discriminant used
  - EFT samples simulated with the TopFCNC UFO






| Observable | Vertex | Coupling | Obs. | Exp. |
|---|---|---|---|---|
| $\lvert C_{\mathrm{uW}}^{(13)*} + C_{\mathrm{uB}}^{(13)*}\rvert$ | $tu\gamma$ | LH | 0.19 | $0.22^{+0.04}_{-0.03}$ |
| $\lvert C_{\mathrm{uW}}^{(31)} + C_{\mathrm{uB}}^{(31)}\rvert$ | $tu\gamma$ | RH | 0.27 | $0.27^{+0.05}_{-0.04}$ |
| $\lvert C_{\mathrm{uW}}^{(23)*} + C_{\mathrm{uB}}^{(23)*}\rvert$ | $tc\gamma$ | LH | 0.52 | $0.57^{+0.11}_{-0.09}$ |
| $\lvert C_{\mathrm{uW}}^{(32)} + C_{\mathrm{uB}}^{(32)}\rvert$ | $tc\gamma$ | RH | 0.48 | $0.59^{+0.12}_{-0.09}$ |

Complementary to limits on the single operators from the ATLAS FCNC tqZ search JHEP 07 (2018) 176

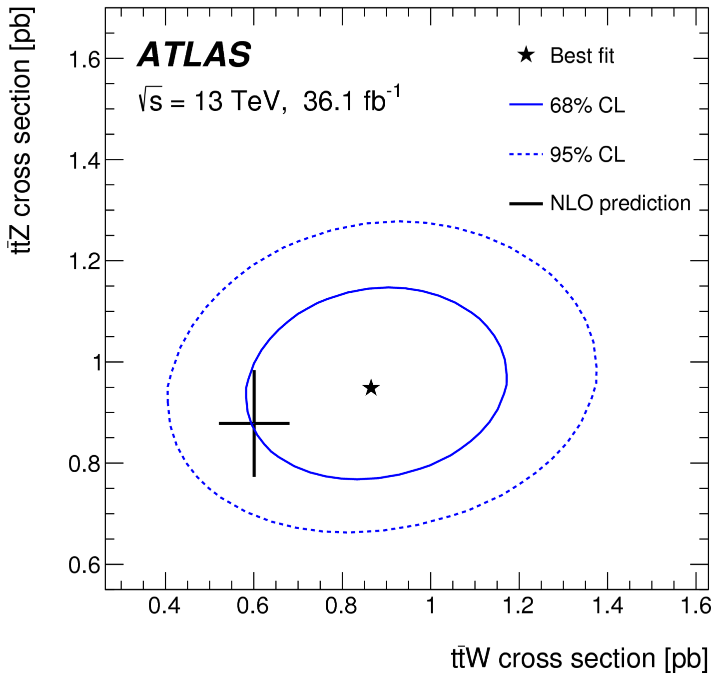
# ttW, ttZ measurements

PRD99(2019)072009

- Direct probe of the weak couplings of the top quark
  - Signal strength measurements at the detector level $\mu_{ttW}$, $\mu_{ttZ}$
- EFT interpretation
  - Using $\sigma_{ttZ}$ measurement only
  - EFT predictions simulated with dim6top UFO

| Process | $t\bar{t}$ decay | Boson decay | Channel |
|---|---|---|---|
| $t\bar{t}W$ | $(\ell^{\pm}\nu b)(q\bar{q}b)$ | $\ell^{\pm}\nu$ | SS dilepton |
| | $(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$ | $\ell^{\pm}\nu$ | Trilepton |
| $t\bar{t}Z$ | $(q\bar{q}b)(q\bar{q}b)$ | $\ell^{+}\ell^{-}$ | OS dilepton |
| | $(\ell^{\pm}\nu b)(q\bar{q}b)$ | $\ell^{+}\ell^{-}$ | Trilepton |
| | $(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$ | $\ell^{+}\ell^{-}$ | Tetralepton |

| Coefficients | $\mathcal{C}^{(3)}_{\phi Q}/\Lambda^2$ | $\mathcal{C}_{\phi t}/\Lambda^2$ | $\mathcal{C}_{tB}/\Lambda^2$ | $\mathcal{C}_{tW}/\Lambda^2$ |
|---|---|---|---|---|
| Previous indirect constraints at 68% CL | [–4.7, 0.7] | [–0.1, 3.7] | [–0.5, 10] | [–1.6, 0.8] |
| Previous direct constraints at 95% CL | [–1.3, 1.3] | [–9.7, 8.3] | [–6.9, 4.6] | [–0.2, 0.7] |
| Expected limit at 68% CL | [–2.1, 1.9] | [–3.8, 2.7] | [–2.9, 3.0] | [–1.8, 1.9] |
| Expected limit at 95% CL | [–4.5, 3.6] | [–23, 4.9] | [–4.2, 4.3] | [–2.6, 2.6] |
| Observed limit at 68% CL | [–1.0, 2.7] | [–2.0, 3.5] | [–3.7, 3.5] | [–2.2, 2.1] |
| Observed limit at 95% CL | [–3.3, 4.2] | [–25, 5.5] | [–5.0, 5.0] | [–2.9, 2.9] |
| Expected limit at 68% CL (linear) | [–1.9, 2.0] | [–3.0, 3.2] | – | – |
| Expected limit at 95% CL (linear) | [–3.7, 4.0] | [–5.8, 6.3] | – | – |
| Observed limit at 68% CL (linear) | [–1.0, 2.9] | [–1.8, 4.4] | – | – |
| Observed limit at 95% CL (linear) | [–2.9, 4.9] | [–4.8, 7.5] | – | – |



# Operators in the Warsaw basis

Sandra Kortner

Only CP-even operators

| Coefficient | Operator | Vertex | Higgs production and decay modes | SM processes |
|---|---|---|---|---|
| $c_{HG}$ | $H^\dagger H G^A_{\mu\nu} G^{A\mu\nu}$ | $Hgg$ | $ggH, ttH, \Gamma_H$ | $(WW), ZZ, (VBFZ)$ |
| $c_{Hbox}$ | $(H^\dagger H)\Box(H^\dagger H)$ | $HVV$ | $VBFH, VH, ttH, 4\ell, WW, \tau\tau, bb, \Gamma_H$ | $WW, ZZ$ |
| $c_{HDD}$ | $(H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$ | $VVV, HVV, \delta$ | $VBFH, VH, ttH, 4\ell, WW, \tau\tau, bb, \Gamma_H$ | $WW, WZ, ZZ, VBFZ$ |
| $c_{HW}$ | $H^\dagger H W^I_{\mu\nu} W^{I\mu\nu}$ | $HVV$ | $VBFH, VH, ttH, \gamma\gamma, 4\ell, WW, \Gamma_H$ | $(WW), ZZ$ |
| $c_{HB}$ | $H^\dagger H B_{\mu\nu} B^{\mu\nu}$ | $HVV$ | $VBFH, VH, ttH, \gamma\gamma, 4\ell, , \Gamma_H$ | $ZZ$ |
| $c_{HWB}$ | $H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$ | $VVV, HVV, \delta$ | $VBFH, VH, ttH, \gamma\gamma, 4\ell, WW, \Gamma_H$ | $WW, WZ, ZZ, VBFZ$ |
| $c_W$ | $\epsilon^{ijk} W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$ | $VVV$ | | $WW, WZ, VBFZ$ |
| $c_{Hq1}$ | $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$ | $Vqq, HVqq$ | $VBFH, VH$ | $WW, WZ, ZZ, VBFZ$ |
| $c_{Hq3}$ | $(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$ | $Vqq, HVqq$ | $VBFH, VH, ttH, \Gamma_H$ | $WW, WZ, ZZ, VBFZ$ |
| $c_{Hu}$ | $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$ | $Vqq, HVqq$ | $VBFH, VH$ | $WW, ZZ, VBFZ$ |
| $c_{Hd}$ | $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$ | $Vqq, HVqq$ | $VBFH, VH$ | $WW, ZZ, VBFZ$ |
| $c_{He}$ | $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$ | $Vll, HVll$ | $VH, 4\ell, WW$ | $WZ, ZZ, VBFZ$ |
| $c_{Hl1}$ | $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$ | $Vll, HVll$ | $VH, 4\ell$ | $WW, WZ, ZZ, VBFZ$ |
| $c_{Hl3}$ | $(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$ | $Vll, HVll, VVV, HVV, \delta$ | $VBFH, VH, ttH, 4\ell, WW, \tau\tau, bb, \Gamma_H$ | $WW, WZ, ZZ, VBFZ$ |
| $c_{ll1}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$ | $llll$ | $VBFH, VH, ttH, 4\ell, WW, \tau\tau, bb, \Gamma_H$ | |
| $c_{lq1}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$ | $qqll$ | | $WW, WZ$ |
| ... | | | | |
| $\lvert c_{uG} \rvert$ | $(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\tilde{H} G^A_{\mu\nu}$ | $gttH$ | $ttH$ | |
| ... | | | | |

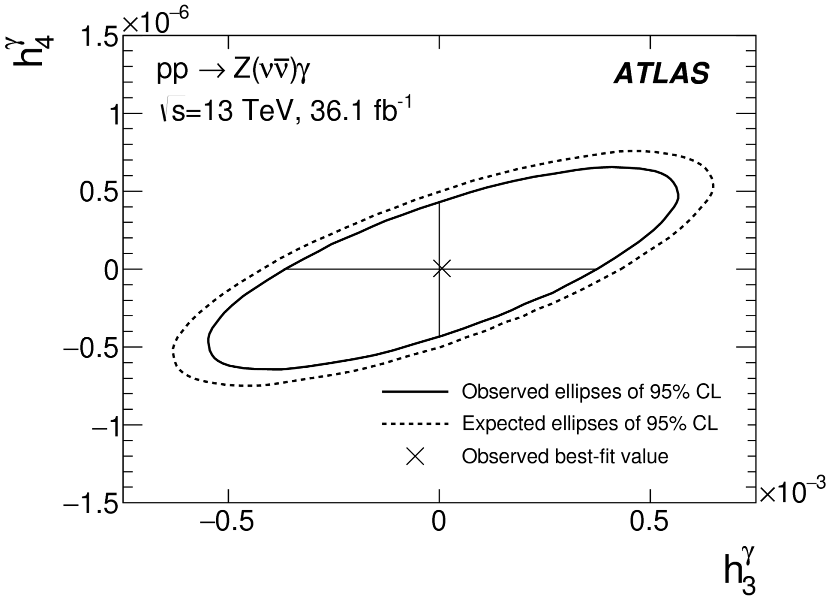
# Fit inputs and statistical analysis

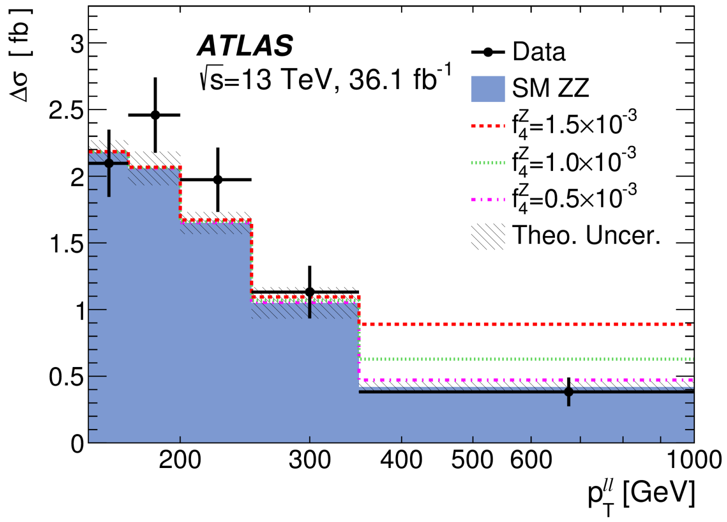
- Input measurements:
  - Higgs STXS should include (A × ε) changes where relevant
    - H→4l for now, H→WW* being investigated
  - Unfolded measurements: “uninterested” processes usually subtracted
    - The impact of SMEFT on those “background” processes missing, eg VBF Zjj, VH(bb)
  - Analysis overlaps should be removed
    - e.g. HWW* and SM WW, H→4l and SM inclusive 4l
- Statistical analysis:
  - Use principal component analysis (PCA) to identify and remove flat directions
    - Define measurement eigenvectors in the remaining parameter space
  - Combined likelihood:
    - Poisson for detector level measurements
    - Multi-Gaussian for unfolded
    - Use common Gaussian nuisance parameters to describe correlated exp/ and the. Uncertainties
  - Report confidence intervals with all parameters floating simultaneously (profiled)

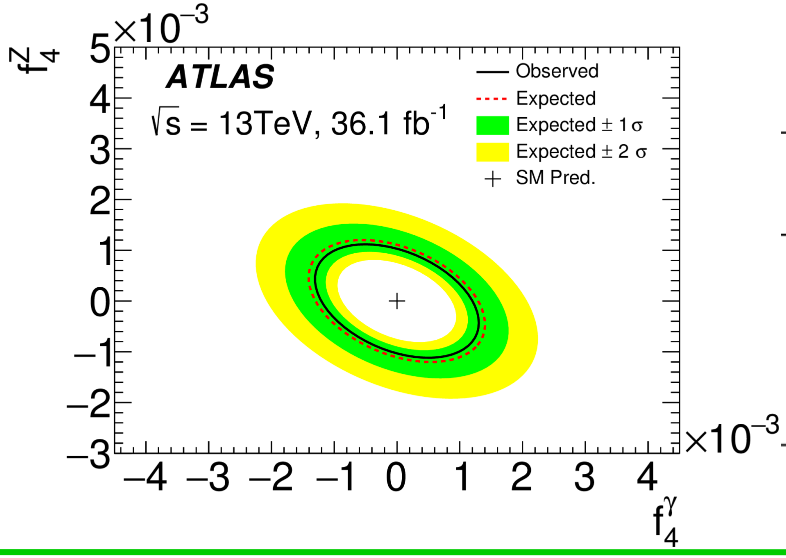
# ZZ→2l2v and Z(vv)γ measurements

- ZZ→2l2v *JHEP 10 (2019) 127*
  - Unfolded $p_T^{ll}$ fiducial cross section used for limit extraction *JHEP 12 (2018) 010*
- Z(vv) γ
  - The yields of Zγ events with high $E_T^{\gamma}$(>600 GeV) from the exclusive (zero-jet) selection are used to set limits on

$$N_{Z\gamma}^{\text{aTGC}}(h_3^V, h_4^V) = \sigma_{Z\gamma}^{\text{aTGC}}(h_3^V, h_4^V) \cdot C_{Z\gamma} \cdot A_{Z\gamma} \cdot C^{*(\text{parton}\to\text{particle})} \cdot \int L\, dt.$$

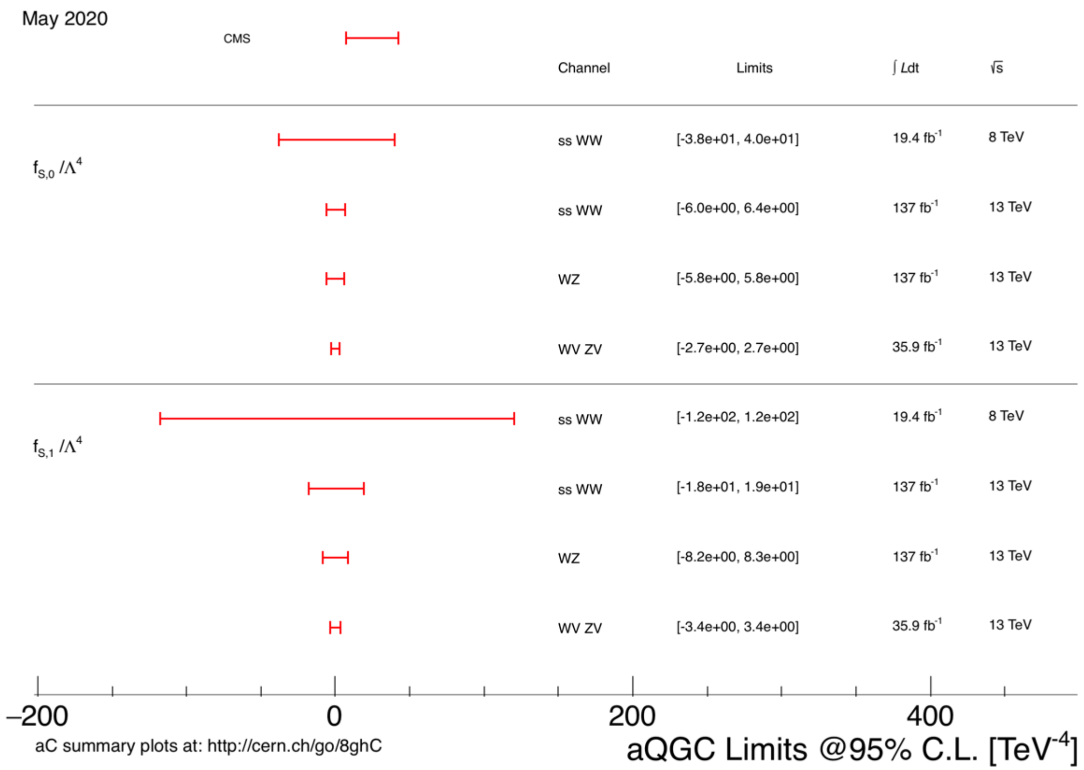


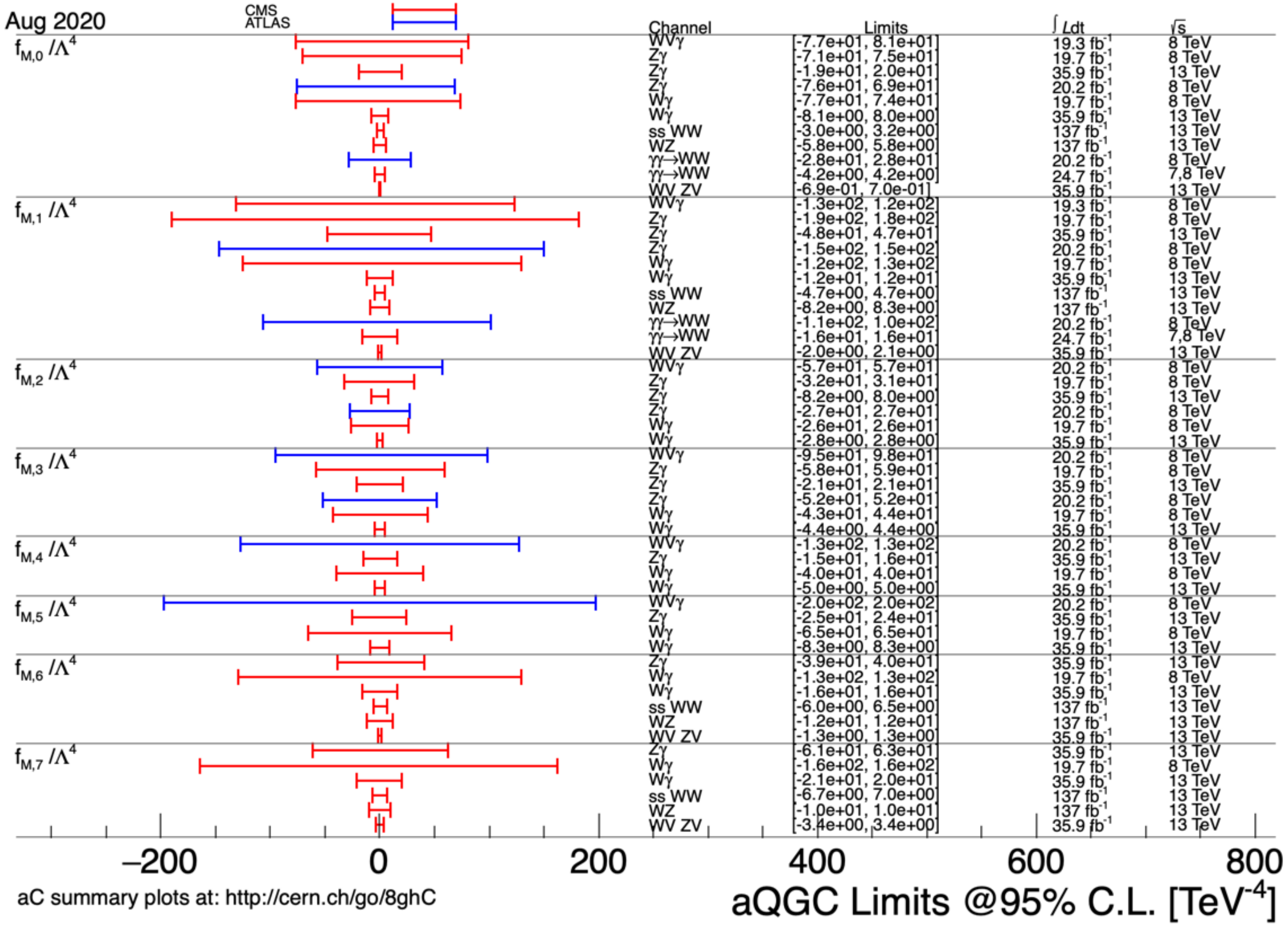




| Parameter | Limit 95% CL | |
|---|---|---|
| | Measured [TeV$^{-4}$] | Expected [TeV$^{-4}$] |
| $C_{\widetilde{B}W}/\Lambda^4$ | (−1.1, 1.1) | (−1.3, 1.3) |
| $C_{BW}/\Lambda^4$ | (−0.65, 0.64) | (−0.74, 0.74) |
| $C_{WW}/\Lambda^4$ | (−2.3, 2.3) | (−2.7, 2.7) |
| $C_{BB}/\Lambda^4$ | (−0.24, 0.24) | (−0.28, 0.27) |

# Summary of aQGC constraints

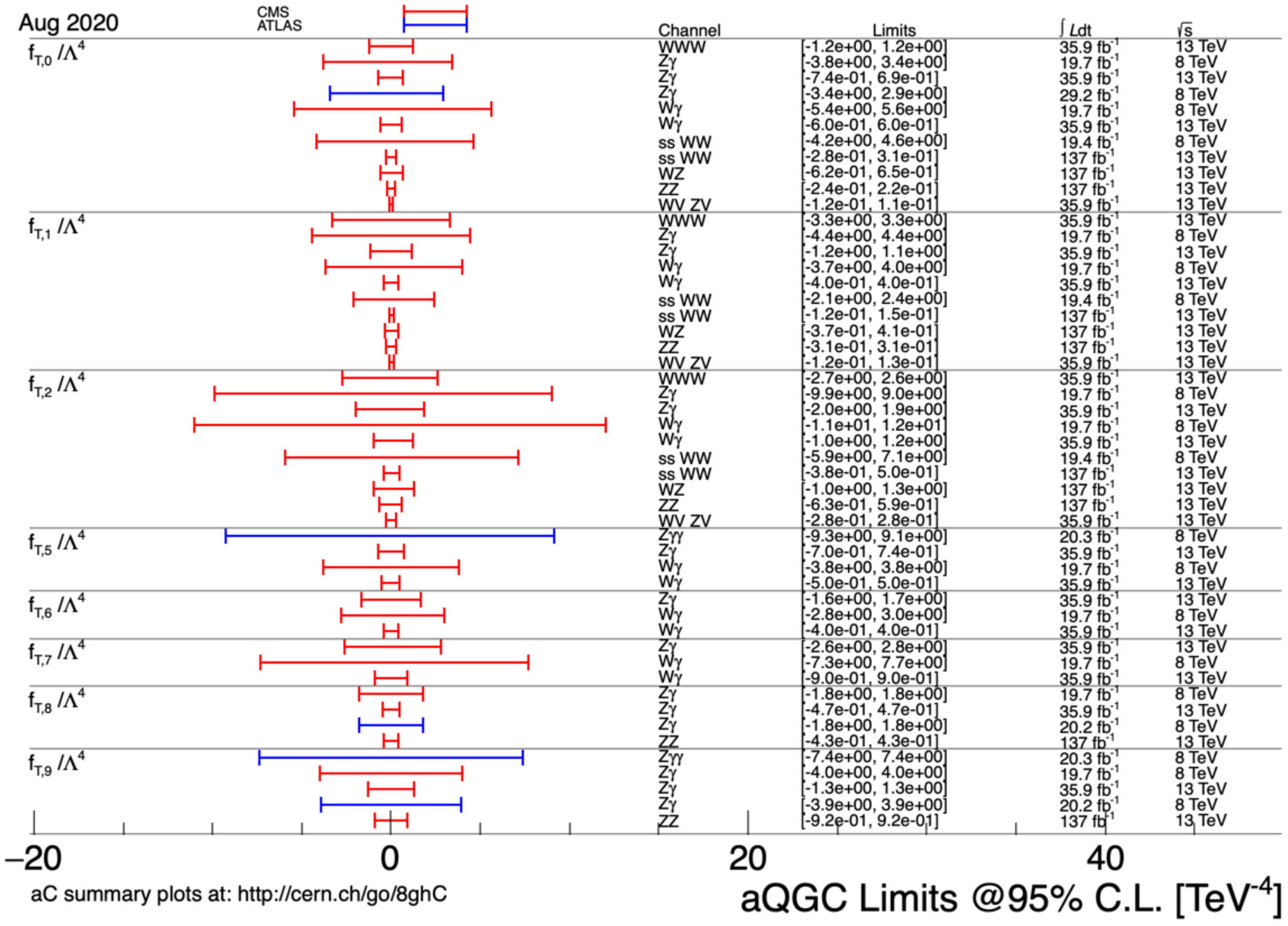



Link



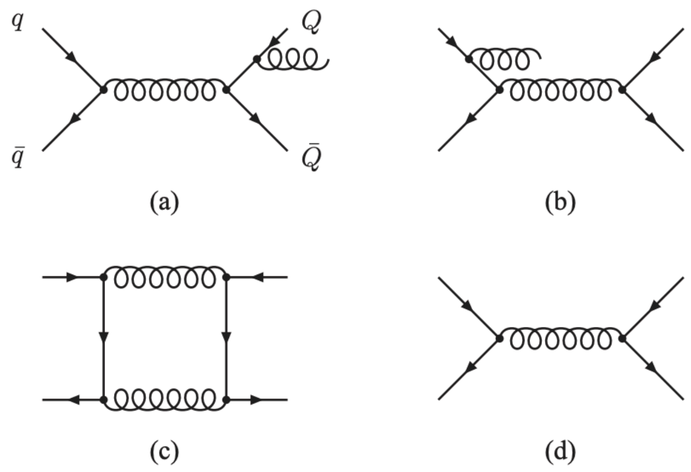
# Summary of aQGC constraints

Link



# Charge asymmetry in $t\bar{t}$

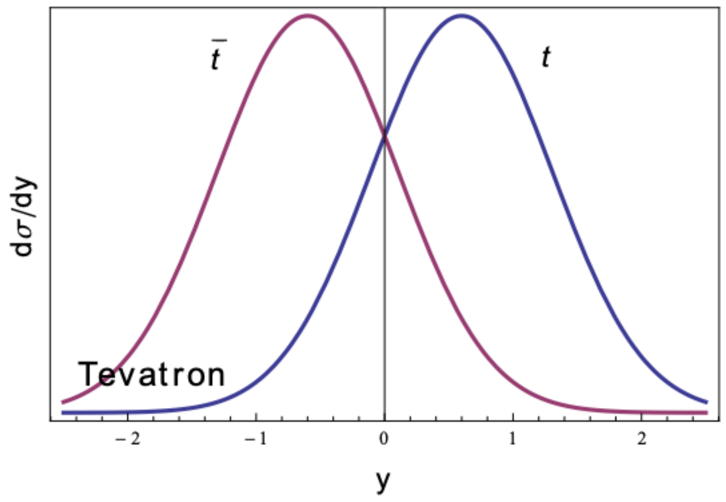
- Interference between $q\bar{q}$ Born and Box diagrams

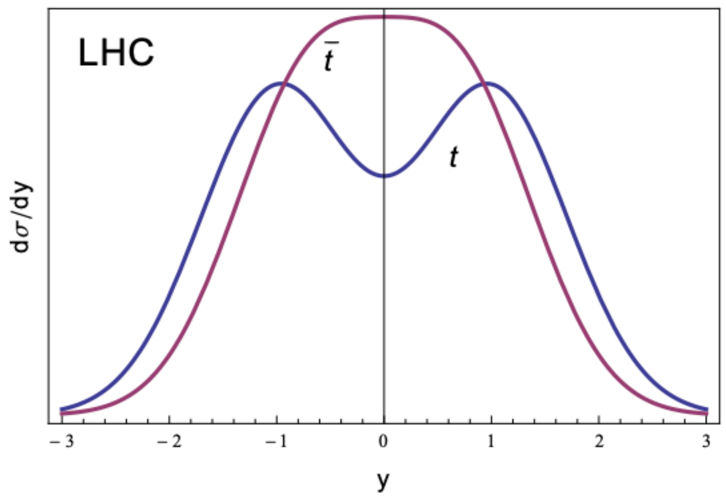



German Rodrigo, arXiv:1207.0331

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)},$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



# Effective Wtb vertices

- Effective Lagrangian by adding dim-6 anomalous couplings

$$\mathcal{L}_{\mathrm{tWb}} = -\frac{g}{\sqrt{2}}\bar{\mathrm{b}}\,\gamma^{\mu}\left(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}}\right)\mathrm{t}\,\mathrm{W}_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\,\frac{i\sigma^{\mu\nu}\mathrm{q}_{\nu}}{m_{\mathrm{W}}}\left(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}}\right)\mathrm{t}\,\mathrm{W}_{\mu}^{-} + \mathrm{h.c.},$$

$V_{L,R}$ and $g_{L,R}$ are left- and right-handed vector and tensor couplings, respectively
$_{PL,R}$ refers to the left- and right-handed chirality projection operators

In the SM, VL is given by the CKM matrix element Vtb, with a measured value of ≈ 1, $V_R = g_L = g_R = 0$ at the tree level

The polarization fractions can be translated into the couplings $V_L$ , $V_R$, $g_L$ , and $g_R$

- From anomalous couplings to Dim-6 EFT

$$\delta V_L = C_{\phi q}^{(3,33)*}\frac{v^2}{\Lambda^2}, \qquad \delta g_L = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2},$$

$$\delta V_R = \frac{1}{2}C_{\phi\phi}^{33}\frac{v^2}{\Lambda^2}, \qquad \delta g_R = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}.$$