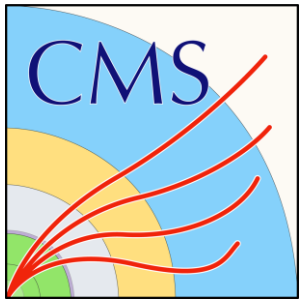
VH(bb) CP analyses

Ricardo Barrué, on behalf of the ATLAS and CMS Collaborations

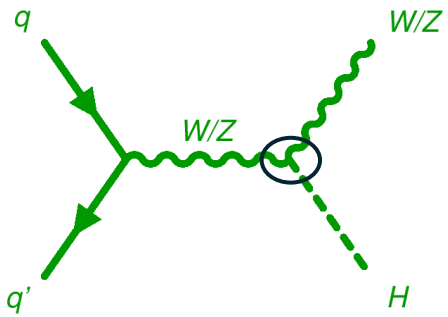


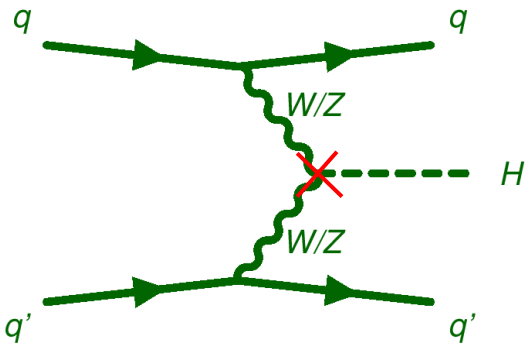
Motivation

BSM sources of CP violation required to explain baryonic asymmetry

VH production can probe HWW and HZZ interactions separately

- Not possible in VBF





H → $b\bar{b}$ decay has largest branching ratio

V → leptons allows efficient triggering and removal of QCD background

Theoretical formalism

SMEFT, Warsaw basis, 3 dimension-6 CP-odd operators:

- $O_{\widetilde{HW}} = H^\dagger H\, W_{\mu\nu}\, \widetilde{W}^{\mu\nu}$ (HWW, HZZ)
- $O_{\widetilde{HB}} = H^\dagger H\, B_{\mu\nu}\, \tilde{B}^{\mu\nu}$ (HZZ)
- $O_{\widetilde{HWB}} = H^\dagger \sigma^a H\, W^a_{\mu\nu} \tilde{B}^{\mu\nu}$ (HZZ)

$$|M|^2 = \underbrace{|M|^2_{SM}}_{\text{CP-even}} + \underbrace{\sum \frac{\tilde{c}_i}{\Lambda^2} 2\,\Re\left(M^*_{\tilde{O}_i}\, M_{SM}\right)}_{\textbf{CP-odd}} + \underbrace{\sum \frac{\tilde{c}_i^2}{\Lambda^4} |M|^2_{\tilde{O}_i} + \sum \frac{\tilde{c}_i\, \tilde{c}_j}{\Lambda^4} 2\,\Re\left(M^*_{\tilde{O}_i}\, M_{\tilde{O}_j}\right)}_{\text{CP-even}}$$

Challenge: CP-odd components do not change total or p_T^V-differential cross-sections

- Require CP-odd (angular) observables

Outline

ATLAS: ATL-PHYS-PUB-2025-022

- WH/$O_{\widetilde{HW}}$ only
- STXS-like categorization in CP-odd angular observable and p_T^W
- Interpretation of STXS signal strengths as function of $c_{\widetilde{HW}}$, linear-only

CMS: JHEP03(2025)114

- WH+ZH
- Multivariate optimal observable from simulation-based inference techniques
- Reconstruction-level fit to coefficients of CP-odd **and** CP-even operators

ATLAS WH(bb) CP measurement

ATLAS analysis overview

Spin-off of ATLAS VH(bb+cc) analysis (JHEP04(2025)075) targetting WH(bb) events:

- One isolated electron or muon + missing transverse energy
- Resolved regime ($p_T^W < 400$ GeV) with 2 *b*-tagged R=0.4 jets
- Boosted regime ($p_T^W > 400$ GeV) with R=1.0 jet with two *b*-tagged subjets

Resolved regime categorized in bins of p_T^W and #jets (reconstruction-level)

- Higher S/B in 2-jet events and for higher p_T^W

Several control regions defined in the resolved and boosted regimes

- Control $t\bar{t}$ and W+jets backgrounds

CP-odd observable

CP-odd observable: $\cos\delta^+$ (JHEP 04 (2015) 103)

$$\cos\delta^+ = \frac{\vec{p}_\ell^{(W)} \cdot (\vec{p}_H \times \vec{p}_W)}{\left|\vec{p}_\ell^{(W)}\right| |\vec{p}_H \times \vec{p}_W|}$$

$\vec{p}_\ell^{(W)}$: momentum of lepton in W boson rest frame

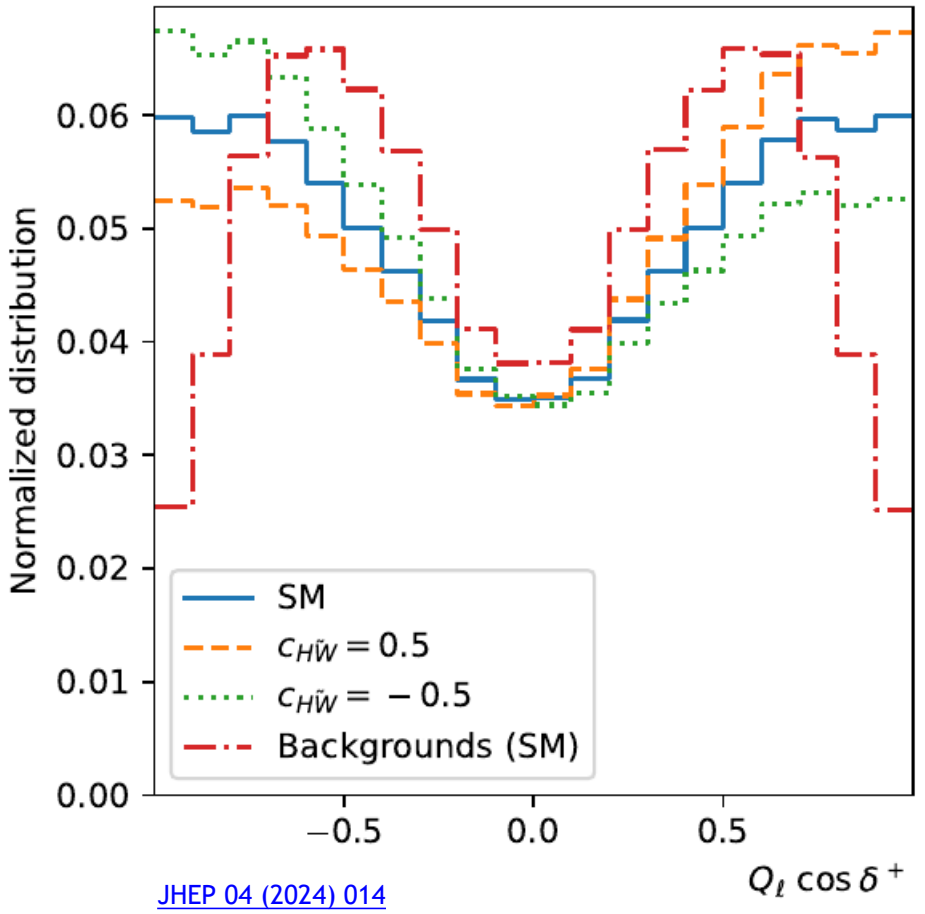
Multiplying by lepton charge, $Q_\ell \cos\delta^+$,

increases sensitivity (JHEP 04 (2024) 014)

Neutrino p_z reconstructed from W mass constraint

- Selecting solution that minimizes $|\beta_z^W - \beta_z^H|$

  (β_z: longitudinal boost)

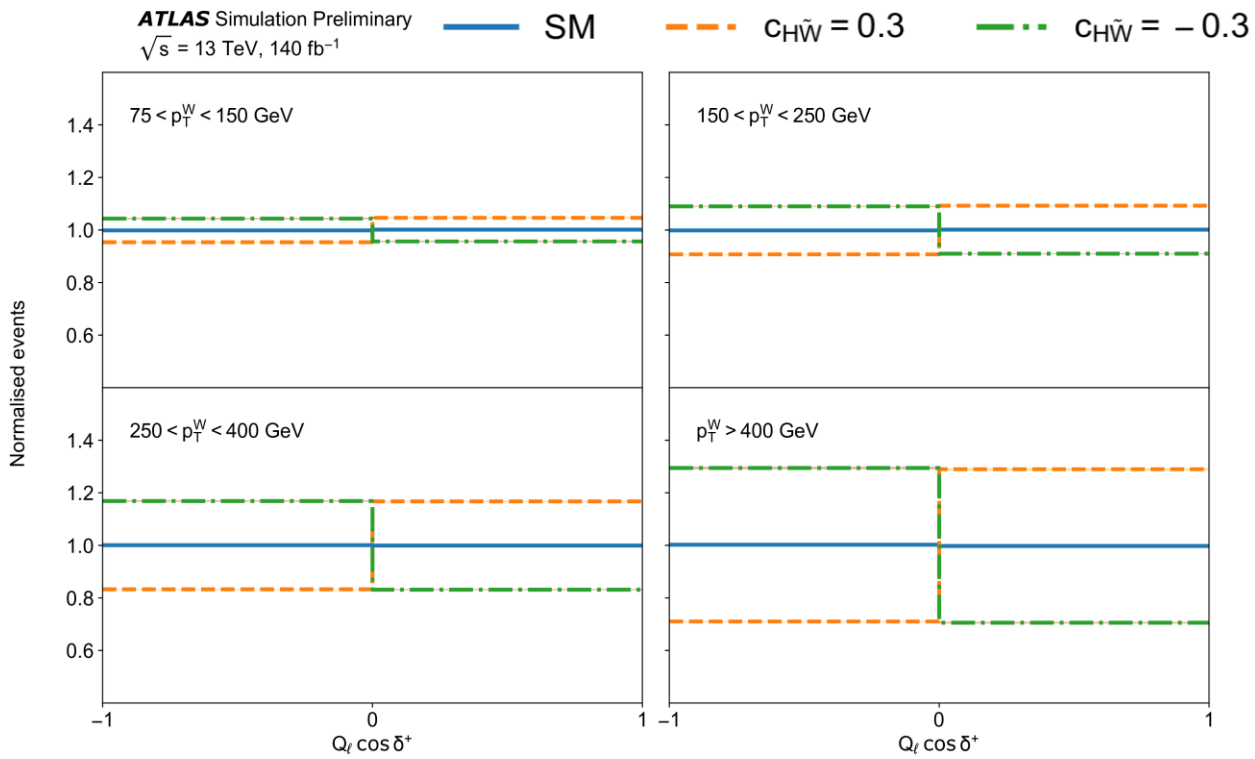


JHEP 04 (2024) 014

Analysis overview - II

Reconstruction-level signal regions split into $Q_\ell \cos\delta^+ \leq 0$ and $Q_\ell \cos\delta^+ > 0$

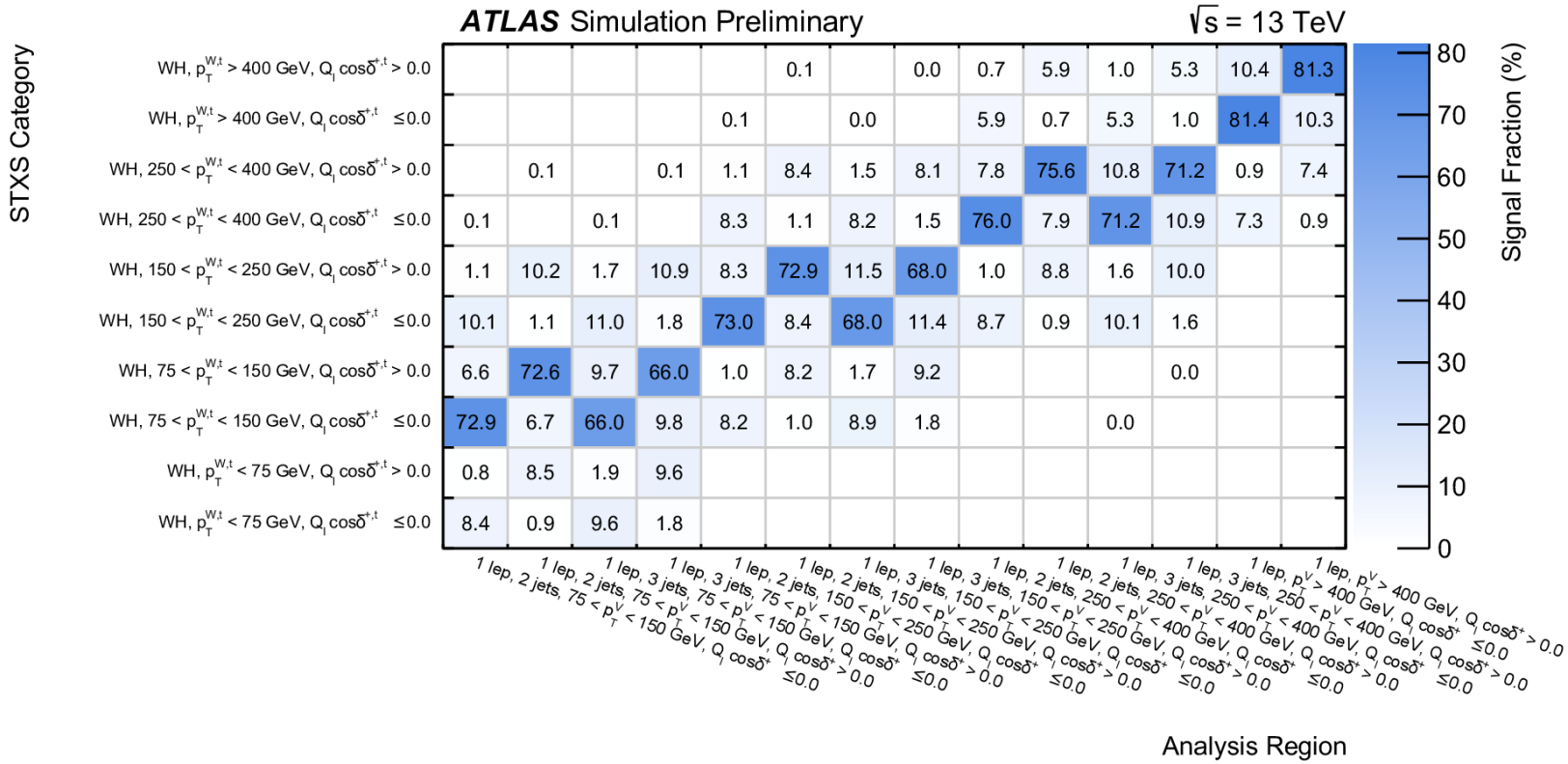
- Impact of CP-odd term, $\propto c_{H\widetilde{W}}$, increases with p_T^W (see e.g. JHEP07(2020)075)



STXS categorization

Splitting the events into STXS-style templates in $Q_\ell \cos\delta^+ \times p_T^W$

- Misassignment of events largely due to mismeasured p_T^W



Results - Interpretation

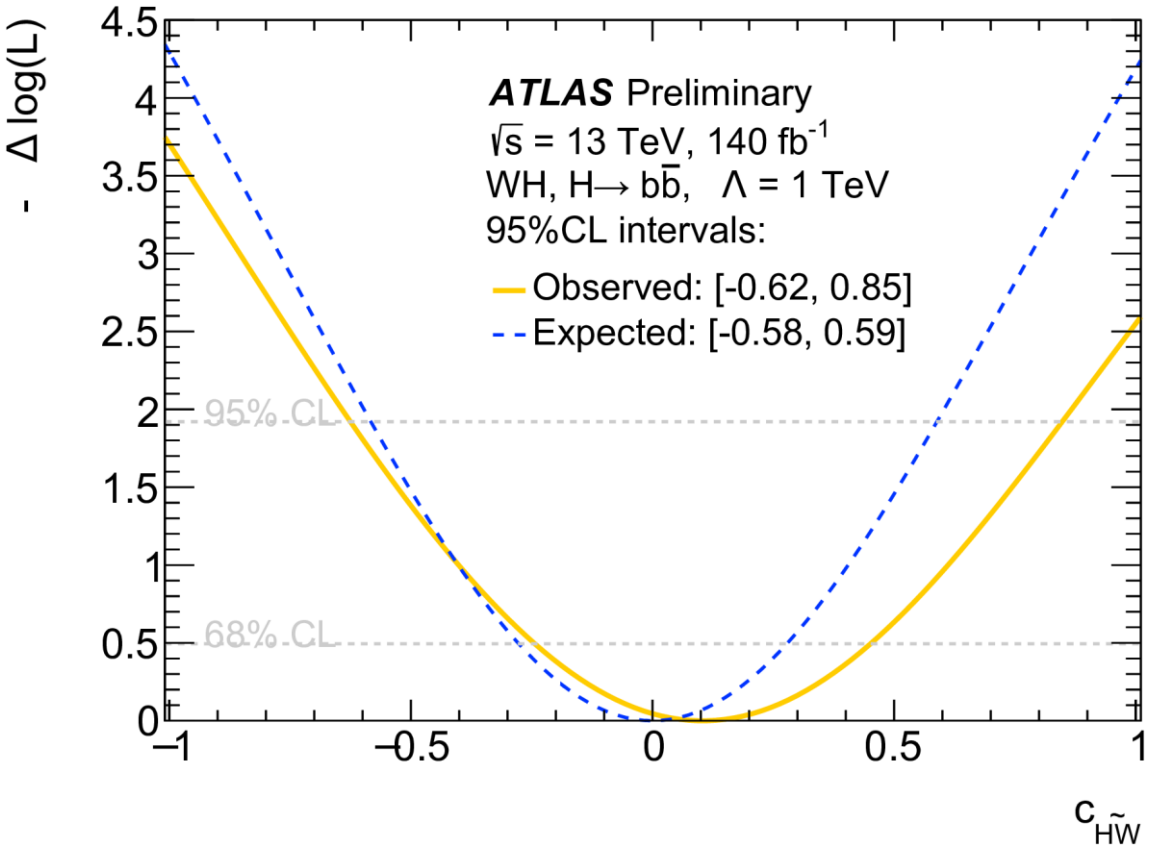
Parametrization of STXS signal strengths derived using SMEFTsim3 and Rivet.

- Neglecting terms $\propto c_{H\widetilde{W}}^2$

Additional signal strength per p_T^W category,

$$\mu = (1 \pm A c_{H\widetilde{W}}) \rightarrow \mu_{p_T^W} \times (1 \pm A c_{H\widetilde{W}})$$

- Ensure only shape effects are considered



Second best world constraints, behind ATLAS VBF $H \rightarrow \tau\tau$, $c_{H\widetilde{W}} \in [-0.41, 0.44]$ (JHEP10(2025)092)

- WH analysis provides assumption-free measurement of $c_{H\widetilde{W}}$

CMS VH(bb) EFT measurement

Analysis overview - I

Targeting VH(bb) events in the leptonic final states of the vector boson:

- $Z \to \nu\nu$ (large MET), $W \to \ell\nu$ (1 isolated lepton + MET) and $Z \to \ell\ell$ (2 isolated leptons)
- Resolved regime with 2 *b*-tagged R=0.4 jets
- Boosted regime with a R=0.8 jet, tagged using Soft Drop mass and $X \to bb$-type tagger

Several control regions defined in resolved and boosted regimes

Operators impacting HWW and HZZ vertex structure "rotated" to mass eigenstates

$$g_4^{WW} = -2\frac{v^2}{\Lambda^2} c_{\widetilde{HW}} \qquad g_4^{ZZ} = -2\frac{v^2}{\Lambda^2}(\sin^2\theta_W\, c_{\widetilde{HB}} + \cos^2\theta_W\, c_{\widetilde{HW}} + \sin\theta_W \cos\theta_W\, c_{\widetilde{HWB}})$$

Multivariate optimal observable

Likelihood ratio, q_θ, is the optimal test statistic for simple hypothesis tests

This analysis trains per-event estimators of $p(x|\theta)/p(x|\theta_0)$ to estimate q_θ (θ_0: SM)

- Boosted Information Tree (BIT), described in [arXiv:2205.12976]

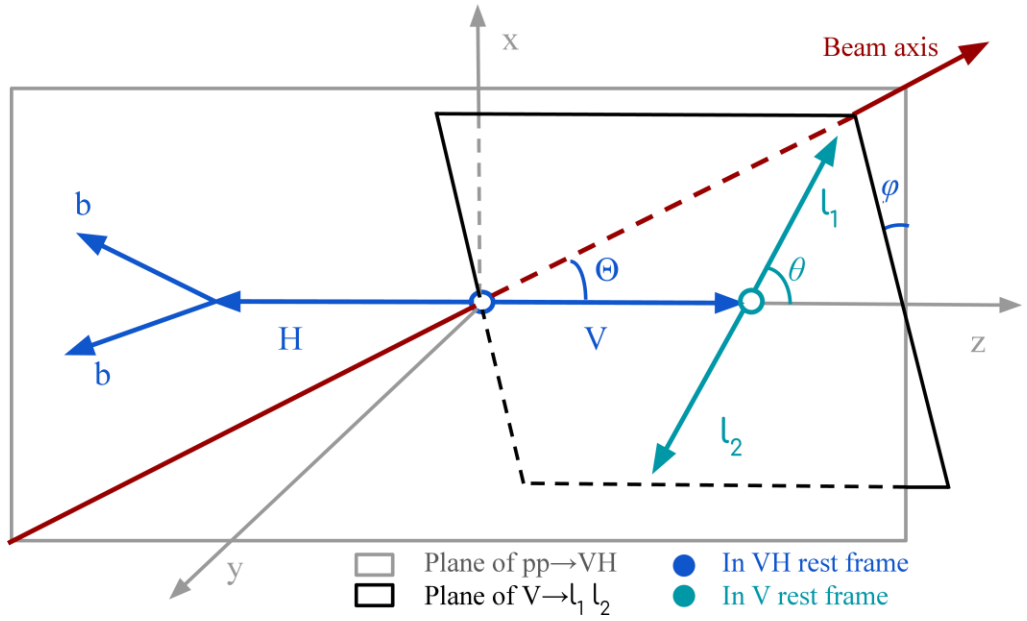
Needs to separate signal and background + be EFT-sensitive, large set of input variables:

- Higgs candidate mass
- B-tagging scores
- Vector boson and Higgs kinematics
- Large set of angular variables (see next slide)

Angular variables

Angles and angular moments defined in [JHEP09(2020)170](), used in 1- and 2-lepton events

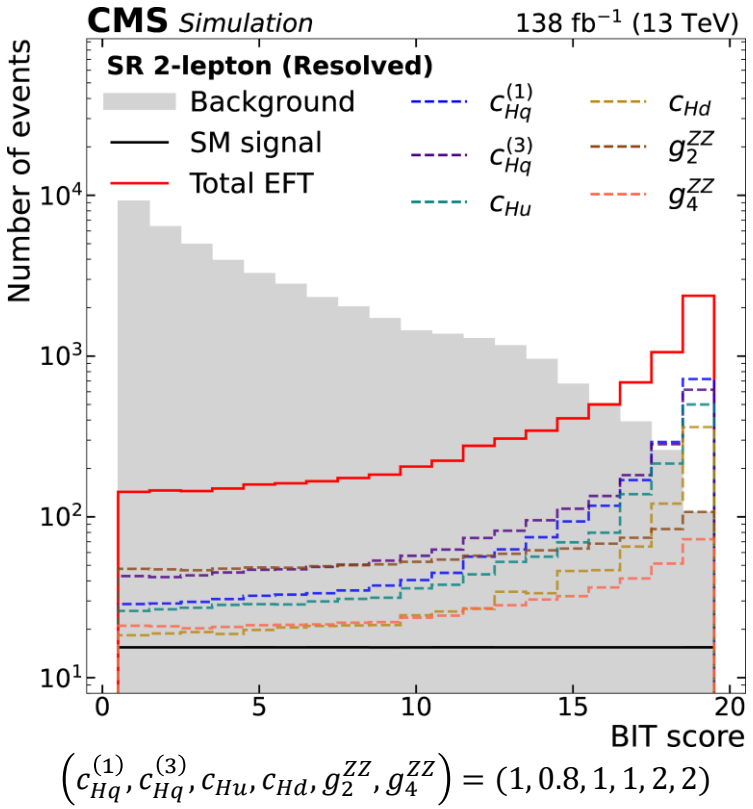
In 1-lepton events, neutrino p_z reconstructed from W boson mass constraint, both solutions used

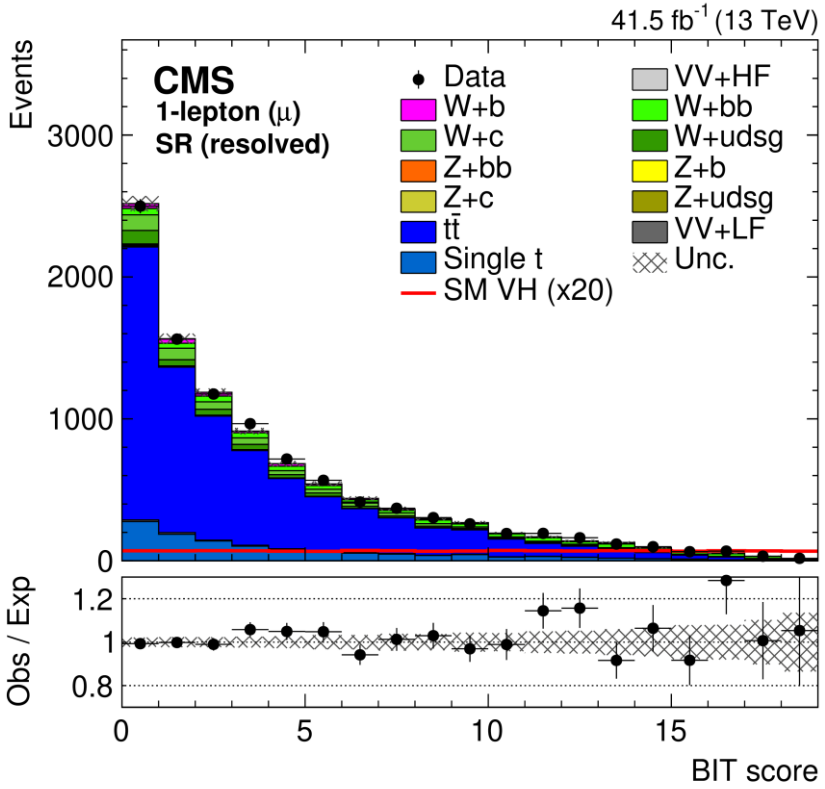


$$
\begin{aligned}
f_{LL} &= S_\Theta^2 S_\theta^2, \\
f_{TT}^1 &= C_\Theta C_\theta, \\
f_{TT}^2 &= (1+C_\Theta^2)(1+C_\theta^2), \\
f_{LT}^1 &= C_\varphi S_\Theta S_\theta, \\
f_{LT}^2 &= C_\varphi S_\Theta S_\theta C_\Theta C_\theta,
\end{aligned}
$$

$$
\begin{aligned}
\tilde{f}_{LT}^1 &= S_\varphi S_\Theta S_\theta, \\
\tilde{f}_{LT}^2 &= S_\varphi S_\Theta S_\theta C_\Theta C_\theta, \\
f_{TT'} &= C_{2\varphi} S_\Theta^2 S_\theta^2, \\
\tilde{f}_{TT'} &= S_{2\varphi} S_\Theta^2 S_\theta^2 ,
\end{aligned}
$$

Distributions of BIT score





BIT has both signal-background separation power + EFT sensitivity, well modelled in data

- Hard time isolating impact of CP-odd component

Results - linear-only

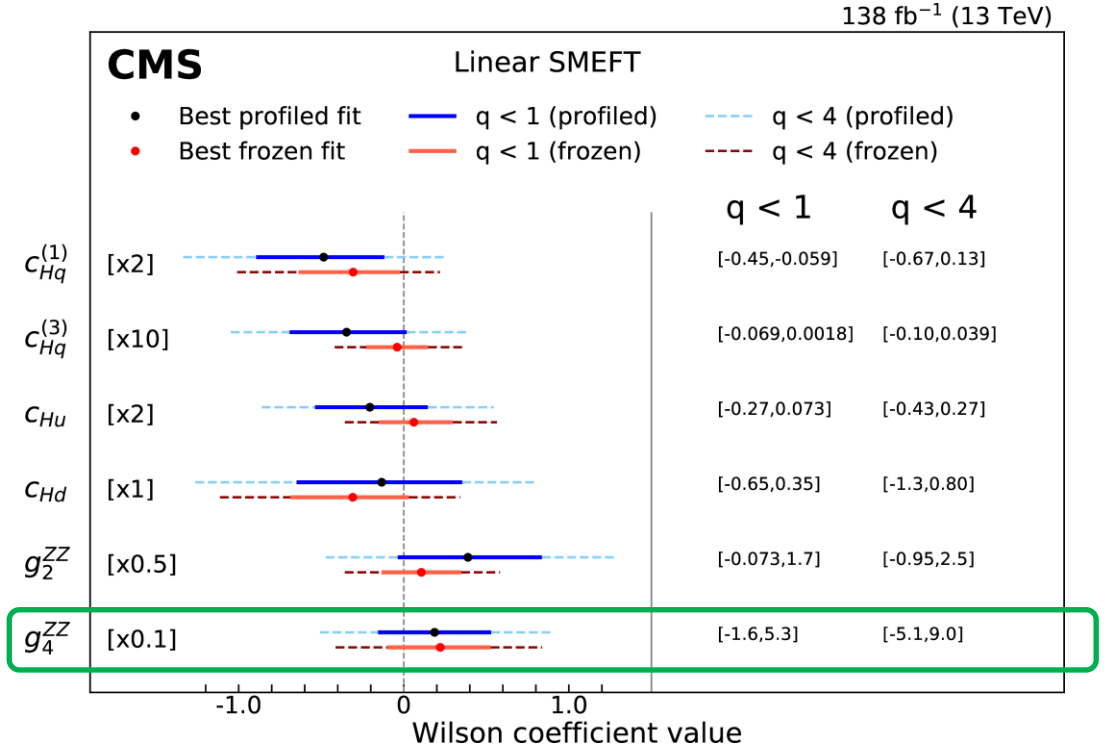
CP-odd operator constraints done as a function of g_4^{ZZ}

$q < 1$ and $q < 4$ are equivalent to 68% and 95% CL

- not the case for linear+quadratic (arXiv:2207.01350)

Sensitivity to linear terms of CP-odd operators much smaller than that for CP-even operators

- Expected from distributions seen in last slide



Multiplication factor applies to the intervals on the left

Confidence intervals on the right correspond to profiled results.

Comparison to ATLAS analysis

For an apples-to-apples comparison, one should compare:

- ATLAS 95% CL: $c_{\widetilde{HW}} \in [-0.62, 0.85]$
- CMS $q < 4$ linear-only g_4^{ZZ}-only (frozen) constraint: $g_4^{ZZ} \in [-5, 9]$

Translating between $c_{\widetilde{HW}}$ and g_4^{ZZ} not well defined, since g_4^{ZZ} also includes $c_{\widetilde{HB}}$ and $c_{\widetilde{HWB}}$

- Neglecting $c_{\widetilde{HB}}$ and $c_{\widetilde{HWB}}$, one gets $g_4^{ZZ} \approx -2\frac{v^2}{\Lambda^2}\cos^2\theta_W\, c_{\widetilde{HW}}$

Taking $\Lambda = 1$ TeV, the equivalent g_4^{ZZ} result from ATLAS would be $g_4^{ZZ} \in [-0.85, 0.47]$

Reduced sensitivity of CMS analysis likely due to the fact it targets extraction of multiple Wilson coefficients simultaneously **by design.**

Conclusions and a glimpse into the future

Presented first ever measurements of CP-odd components in VH production.

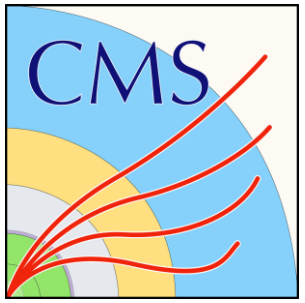
Two distinct yet complementary approaches:

- STXS measurement + analytical interpretation
- Reconstruction-level measurement using simulation-based inference

Several avenues of progress (personal opinion):

- Inclusion of NLO CP-odd SMEFT effects (arXiv:2409.00168)
- Extending STXS measurement to ZH production + additional angles and CP-even operators
- Using ML-based CP-odd observables (PLB.2022.137246) (JHEP04(2024)014)
- Fully unbinned likelihood ratio estimation using simulation-based inference (arXiv:2509.03307)

Thank you!

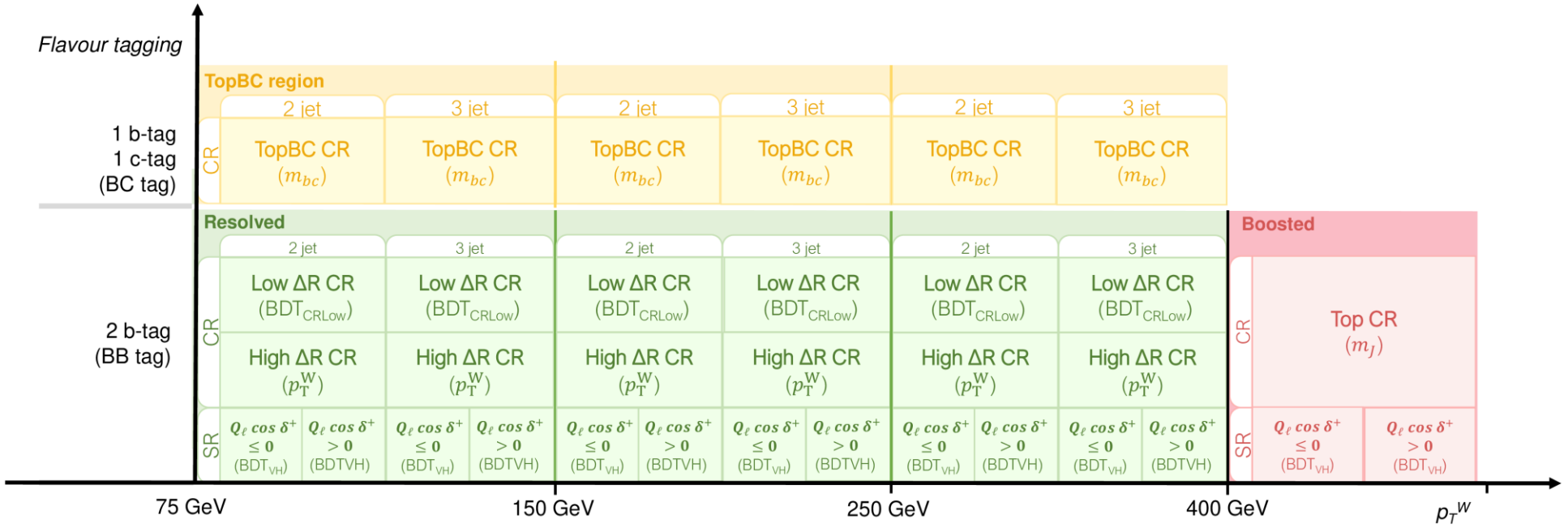


MBI Marietta-Blau-Institut für Teilchenphysik

ÖAW Austrian Academy of Sciences

Backup

ATLAS - Regions



Category	Signal region threshold
Two-jet	$\Delta R(j_1, j_2) < 0.787 + e^{1.387 - 0.007 \times p_T^V}$
Three-jet	$\Delta R(j_1, j_2) < 0.684 + e^{1.204 - 0.006 \times p_T^V}$

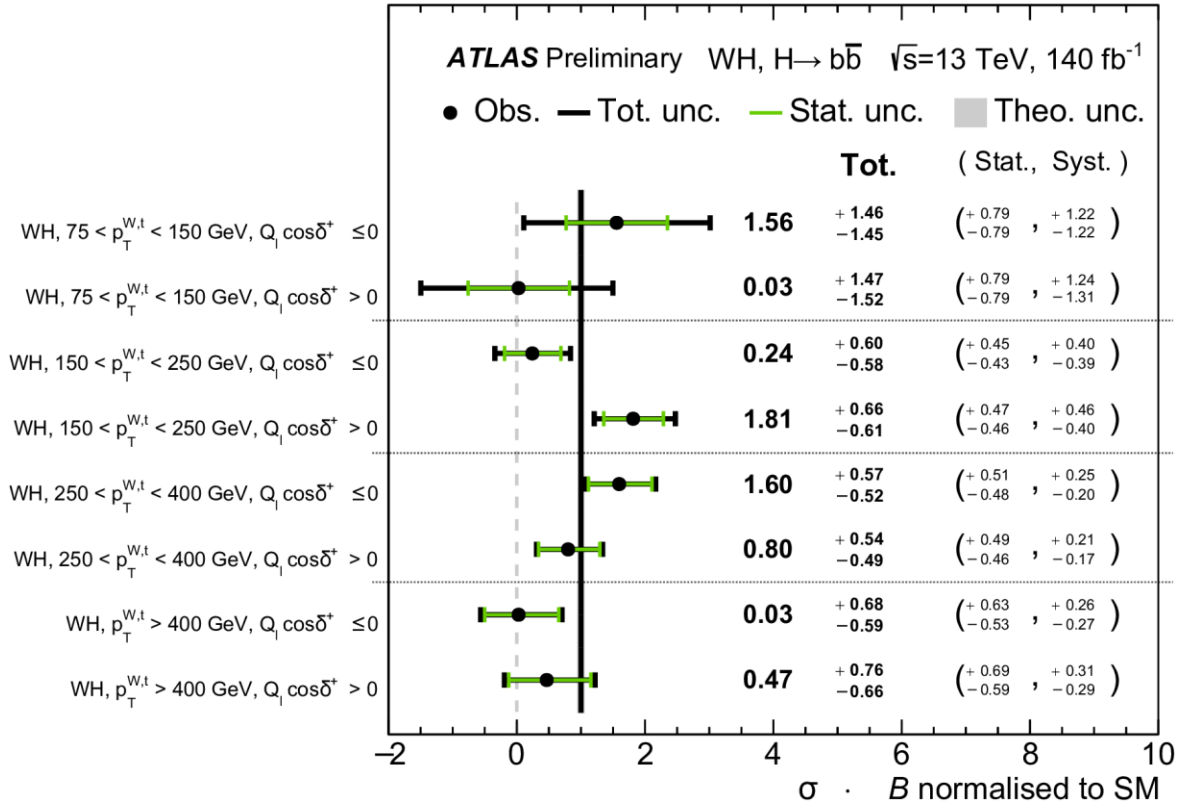
Category	Low-ΔR-CR threshold
Two-jet	$\Delta R(j_1, j_2) < 0.41 + e^{0.818 - 0.01056 \times p_T^V}$
Three-jet	$\Delta R(j_1, j_2) < 0.43 + e^{0.399 - 0.000931 \times p_T^V}$

ATLAS - Results - STXS fit

Large set of uncertainties, including migration between $Q_\ell \cos\delta^+$ categories for main backgrounds

Fitting S vs. B BDT in each region

STXS results consistent with SM within 2σ



CMS results - linear+quadratic

$q < 1$ and $q < 4$ are **not** equivalent to 68% and 95% CL

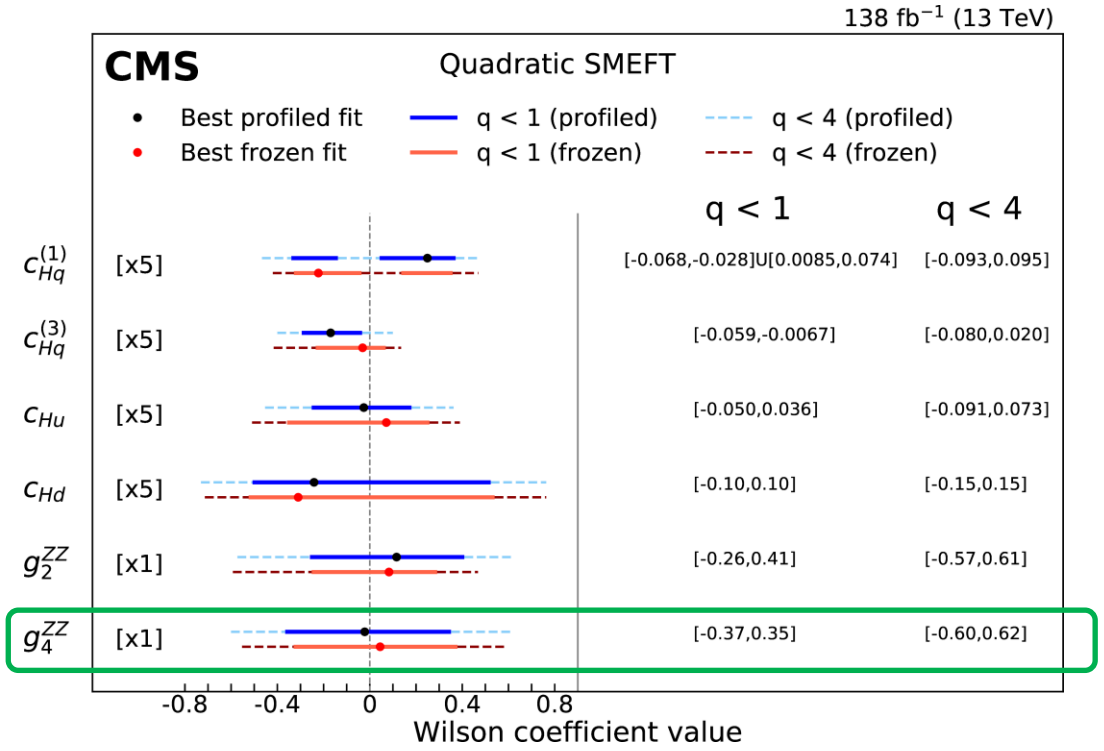
- Wilks' theorem violated (arXiv:2207.01350)

Constraints on CP-odd operators are **much tighter** when quadratic terms are included

- Seems that trained BITs have quite a lot of sensitivity to energy-dependent effects

BIT can distinguish between quadratic effects of CP-even and CP-odd operators

ATLAS linear+quadratic results not available.



Multiplication factor applies to the intervals on the left-hand side.

Intervals on the right-hand side correspond to profiled constraints.

CMS - Multivariate observable

Likelihood ratio is the optimal test statistic for test between two simple hypothesis, $\boldsymbol{\theta}$ and $\boldsymbol{\theta_0}$ (e.g. SM)

$$q_\theta = L\big(\sigma(\boldsymbol{\theta}) - \sigma(\boldsymbol{\theta}_0)\big) - \sum \log R(\boldsymbol{x_i}|\boldsymbol{\theta}, \boldsymbol{\theta_0}), \qquad i = 1, \dots, N_{events}$$

$$R(\boldsymbol{x}|\boldsymbol{\theta}, \boldsymbol{\theta_0}) = \frac{\sigma(\boldsymbol{\theta})\, p(\boldsymbol{x}|\boldsymbol{\theta})}{\sigma(\boldsymbol{\theta_0})\, p(\boldsymbol{x}|\boldsymbol{\theta_0})}$$

Issue: calculating $R(\boldsymbol{x}|\boldsymbol{\theta}, \boldsymbol{\theta_0})$ from the full kinematic information in each event is **not possible**

- Usually estimated from histograms of a small number of kinematic variables

BIT uses BDTs with generator-level weights and their derivatives around $\boldsymbol{\theta_0}$ as targets to estimate R

CMS - Histogram template choice

$R(\boldsymbol{x}|\boldsymbol{\theta}, \mathbf{0})$ is the optimal test statistic (observable) to separate hypothesis $\boldsymbol{\theta}$ from the SM

- it is **not** the optimal test statistic for separating $\boldsymbol{\theta}'$ from the SM

$R(\boldsymbol{x}|\boldsymbol{\theta}', \mathbf{0})$ can be obtained using the polynomial EFT structure **but**

- histograms for systematic variations would need to be constructed for each $\boldsymbol{\theta}'$

To choose a value of $\boldsymbol{\theta}$ to build the histogram templates, Bayesian optimization was used:

- Find the value of $\boldsymbol{\theta}$ that minimizes product of fully profiled 95% CI (without systematics)
  - Different subset of Wilson coefficients per channel: for 1L, $c_{Hq}^{(3)}, g_2^{WW}, g_4^{WW}$