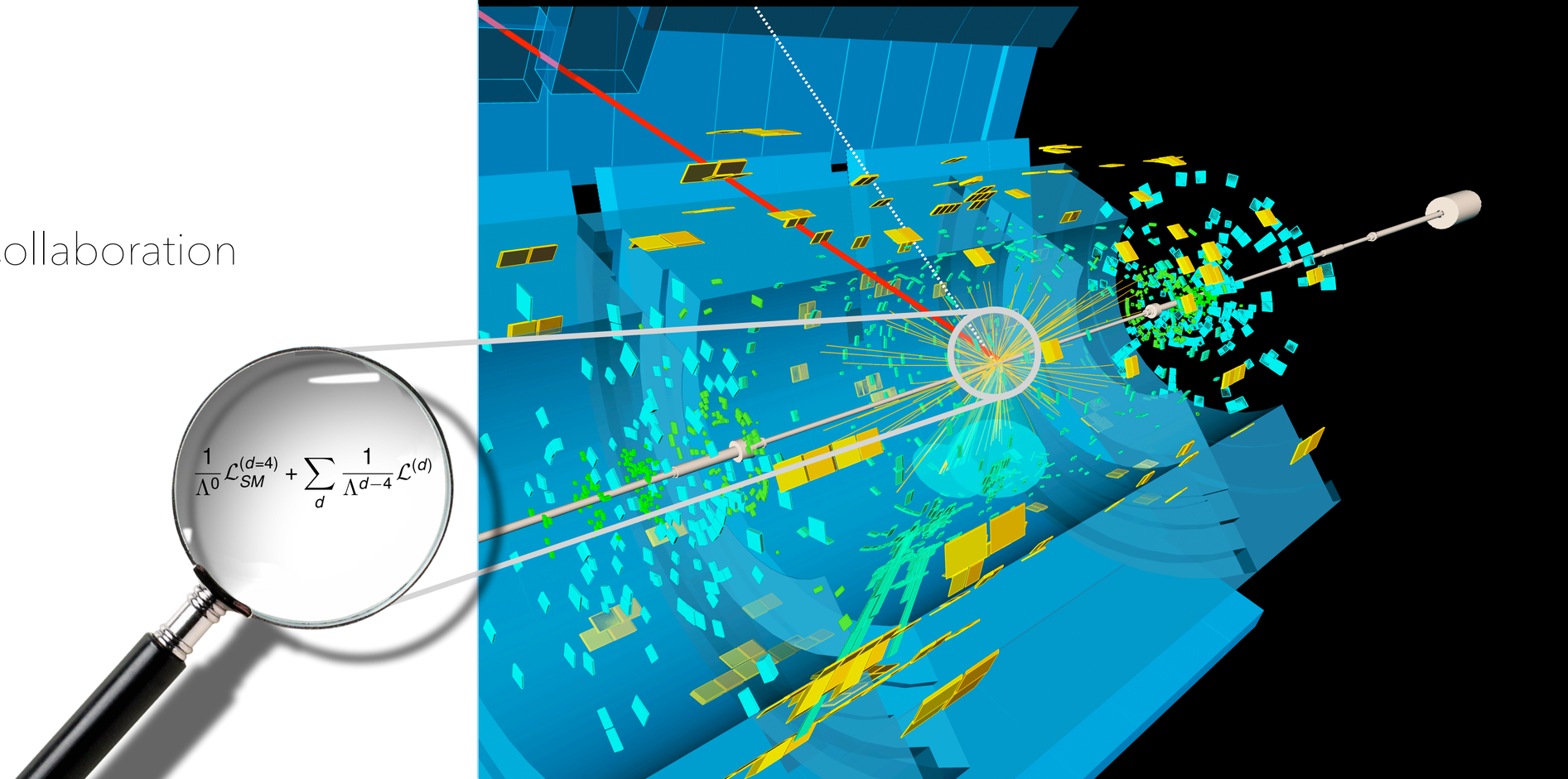
Recent EFT measurements from ATLAS

Rahul Balasubramanian
on behalf of the ATLAS Collaboration

LHC EFT Working Group
3rd General Meeting



17-11-2021

Overview

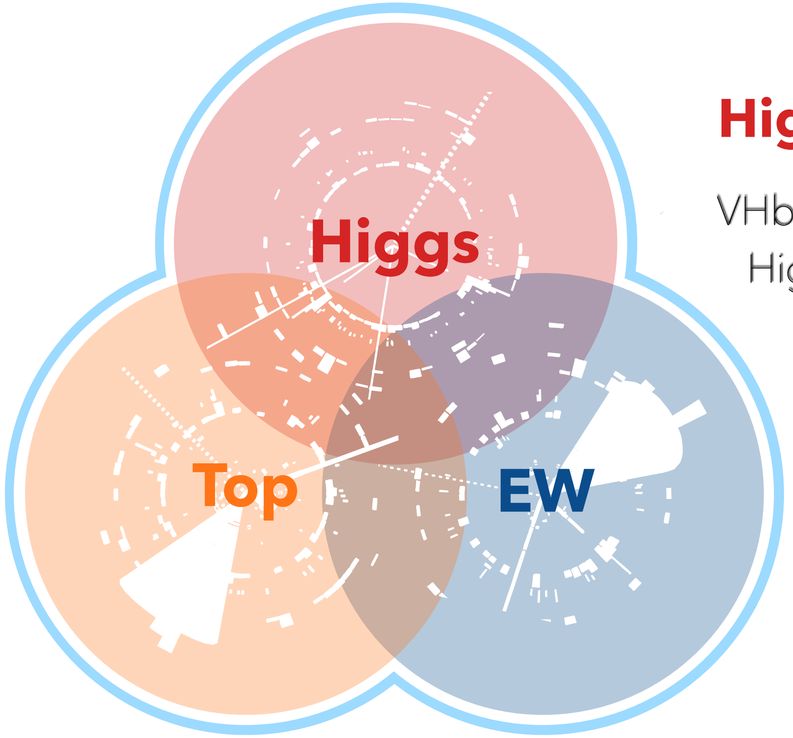
Growing effort in recent years to have EFT interpretation of ATLAS measurements across different sectors

Higgs

VHbb resolved + boosted combination
Higgs combination

Top

Energy asymmetry in $t\bar{t}j$ production
boosted $t\bar{t}$ production
angular observables
Top EFT Summary plots



Sketch inspired from Ken Mimasu

EW

WW, WZ, 4l, & Z+2jets combination

Many preliminary ATLAS EFT results across different sectors since last LHCEFTWG General Meeting

SMEFT framework

"low energy" Effective Lagrangian

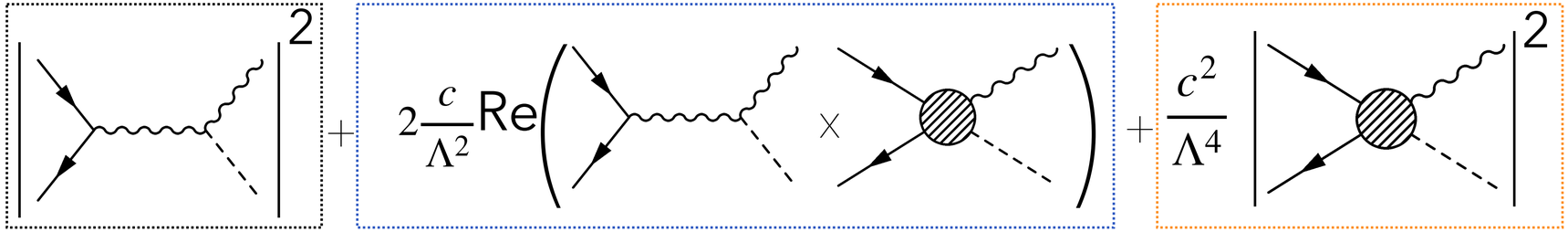
$$\mathcal{L} = \frac{1}{\Lambda^0}\mathcal{L}_{SM}^{(d=4)} + \frac{1}{\Lambda}\mathcal{L}^{(d=5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(d=6)} + \ldots = \mathcal{L}_{\mathrm{NP}} \longrightarrow$$

Lagrangian with new particles at Λ

Weinberg operator (*not relevant for processes considered*)

- All results are based on **Warsaw basis** definitions with $\mathbf{m_W}$, $\mathbf{m_Z}$, $\boldsymbol{\alpha_s}$ input parameter scheme
- $\mathcal{L}^{(d)} = \sum_i c_i \mathcal{O}_i^{(d)}$ all possible local interactions allowed by symmetries, $c_i \rightarrow$ **free parameters of model**
- 2499 operators at d=6 with **ΔL=ΔB=0**, smaller set considered with flavour assumptions
- SMEFT dependence can be parameterised as polynomials in wilson coefficients,

$\sigma_{\text{SMEFT}} \sim$



SM

Linear : SM x d=6 interference

Quadratic : (d=6)^2,
missing SM x d=8 interference

$$= \sigma_{\text{SM}}\left(1 + \sum_i \alpha_i c_i + \sum_{ij} \beta_{ij} c_i c_j\right), \quad \alpha_i, \beta_{ij} \text{ are numerical factors}$$

SM prediction from SMEFT re-scaled to best known SM prediction

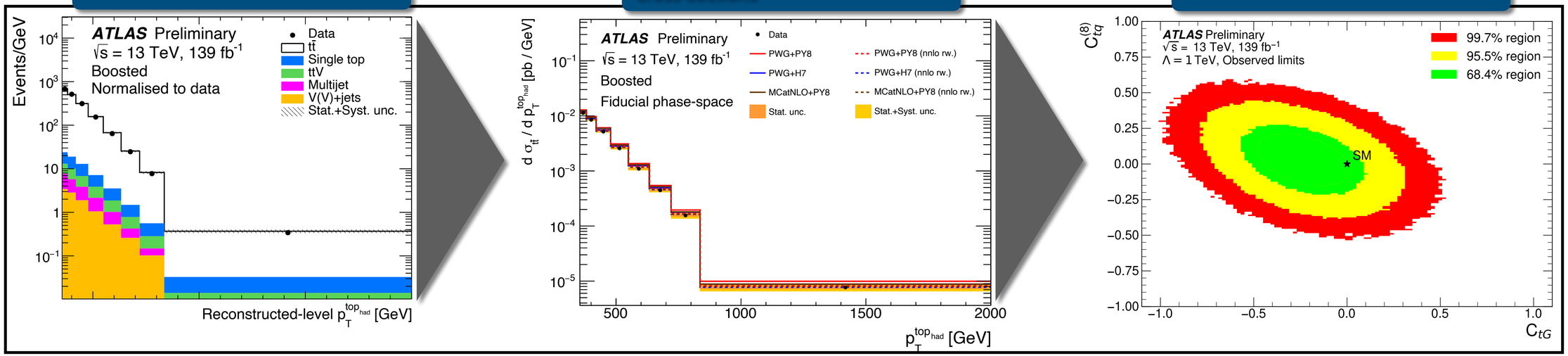
Measurements to Wilson coefficients

Wide variety of experimental observables analysed consistently in a physics framework

Reconstructed distributions
invariant mass, angles, asymmetries, transverse momenta & more

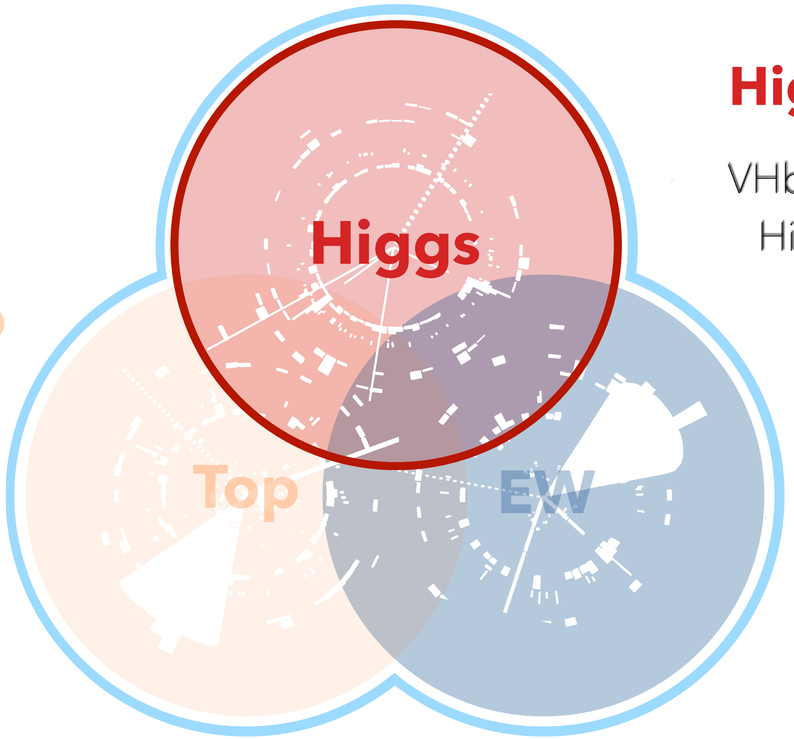
Unfolded distributions
Differential cross-sections, fiducial cross-sections

Physics Parameters
$$L_{SMEFT} = L_{SM} + \sum_{i,d>4} \frac{c_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}$$



[ATLAS-CONF-2021-031]

- Experimental acceptance on EFT contribution can be considerable for some cases
- When all wilson coefficients cannot be measured, analysis sensitivity used to measure sensitive EFT parameters
- Top processes sensitive to unique parameter set, different kinematic information crucial
- All systematic effects from experimental and theory sources included for EFT results



Higgs

VHbb resolved + boosted combination
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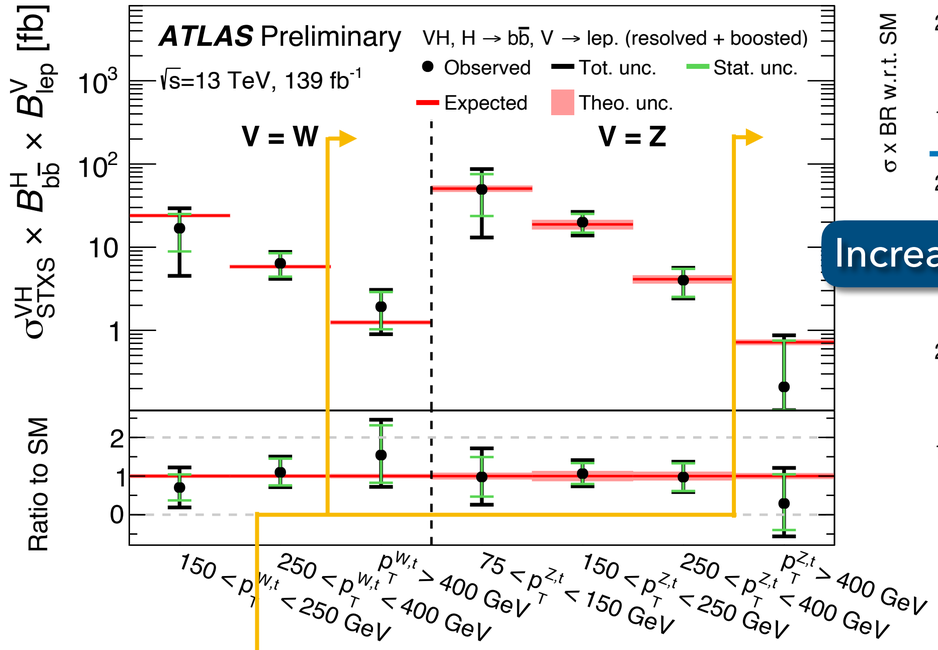
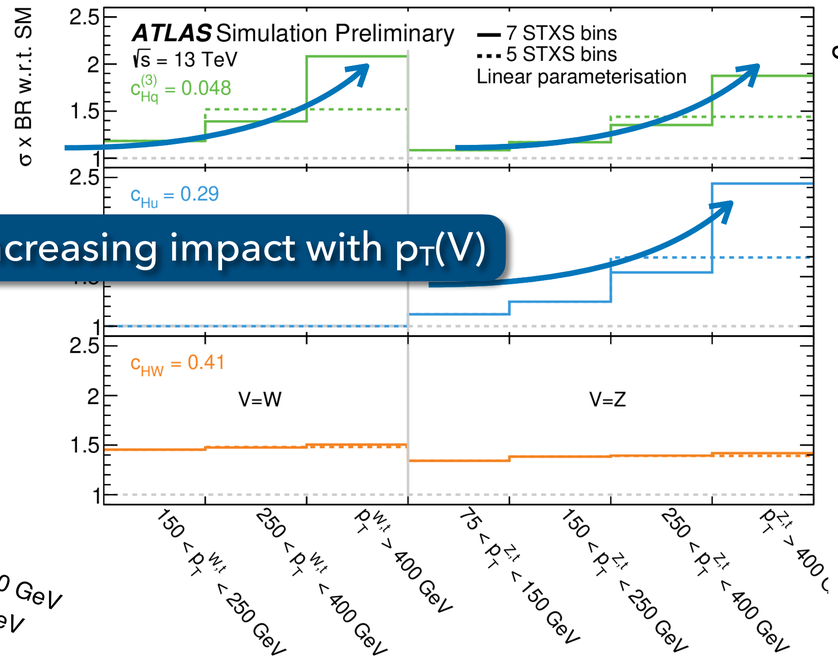
WW, WZ, 4l, & Z+2jets combination

(VH) H→bb̄ resolved + boosted

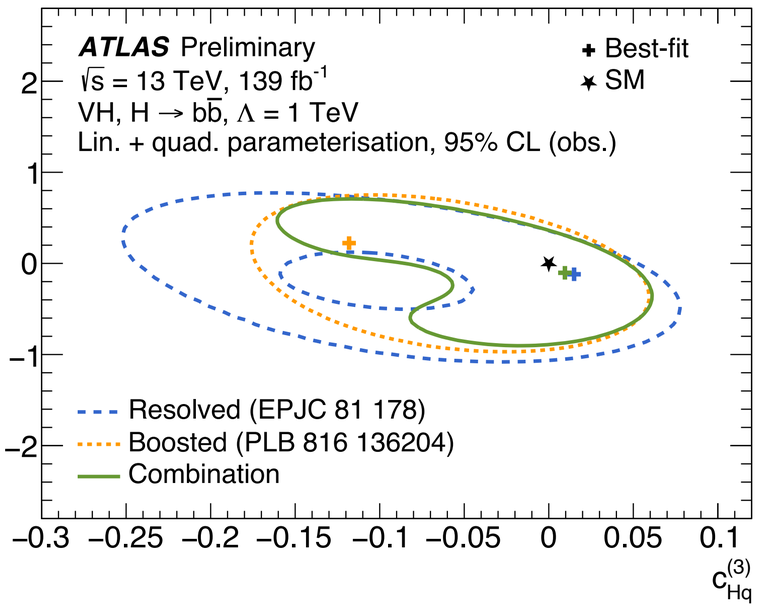
ATLAS-CONF-2021-051

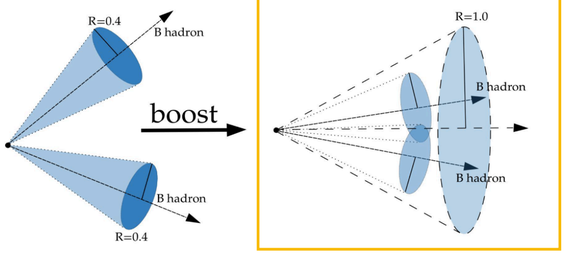


EFT Impact on STXS bins



Increasing impact with $p_T(V)$





- EFT parameterisation derived using SMEFTsim3.0 U(3)^5
- Combination of boosted with resolved analysis gives access to high p_T^V tail, going ahead EFT theory uncertainties crucial in such regimes

- Serves as key input to measuring p_T^V distribution kinematic VH production in Higgs combination

Higgs Combination

ATLAS-CONF-2021-053

- Combined Higgs results are based on a likelihood level combination built as product of individual analyses likelihood
- Negligible overlap in event selections of input analyses
- Signal modelling and related uncertainties are treated coherently across input analyses
- Nuisance Parameters : Try to full correlate between analyses where possible, if not left decorrelated, O(2000) systematic sources of uncertainties

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$	139
	$t\bar{t}H$	36.1
$H \to WW^*$	ggF, VBF	139
	$t\bar{t}H$	36.1
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139
	$t\bar{t}H$	36.1
$H \to b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H$	139
$H \to \mu\mu$	ggF, VBF, $VH, t\bar{t}H$	139
$H \to Z\gamma$	ggF, VBF, $VH, t\bar{t}H$	139
$H \to inv$	VBF	139

Updated since last round [ATLAS-CONF-2020-053]

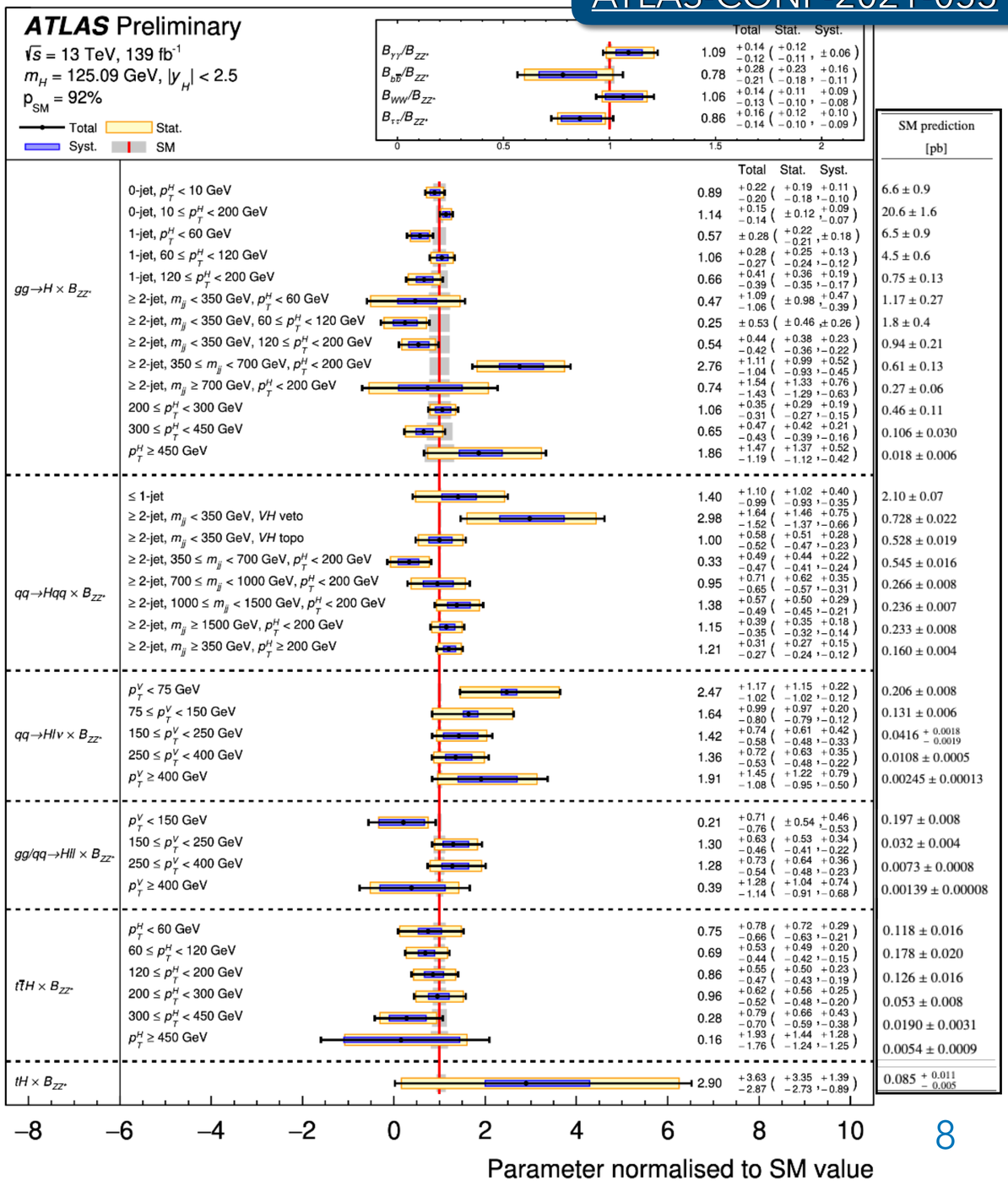
Not included for STXS & EFT

- Linear Parameterisation derived for all contributing operators with $U(3)^5$ symmetry,
  - SMEFTsim 3.0 for EFT insertions for tree-level SM process
  - SMEFTatNLO to resolve loop contributions to ggH, ggZH
  - analytical prediction for NLO-QED in **H$\gamma\gamma$** from Phys. Rev. D 98, 095005)
- Acceptance effect on EFT parameterisation relevant for 4-body Higgs decay, estimated using selections used in $H \to ZZ^*$ and $H \to WW^*$ analyses

Simplified template cross-sections

ATLAS-CONF-2021-053

- STXS regions defined to measure kinematic properties across decay channels while minimising statistical uncertainties and theory-dependence
- Kinematic regions help isolate BSM effects (typically tails of distributions)
- Measure 37 kinematic bins across 5 production modes, Probe Higgs cross-sections ranging across 4 orders of magnitude !
- Access to additional kinematic information thanks to inclusion of new analyses,
  - qq→Hqq access to higher end of mjj spectrum thanks to inclusion of HWW analysis
  - With inclusion of boosted VHbb additional split at high-pTW, pTZ (pTV = 400 GeV)
  - ttHbb analysis give access to tail of ttH pTH spectrum



EFT Impact on kinematics

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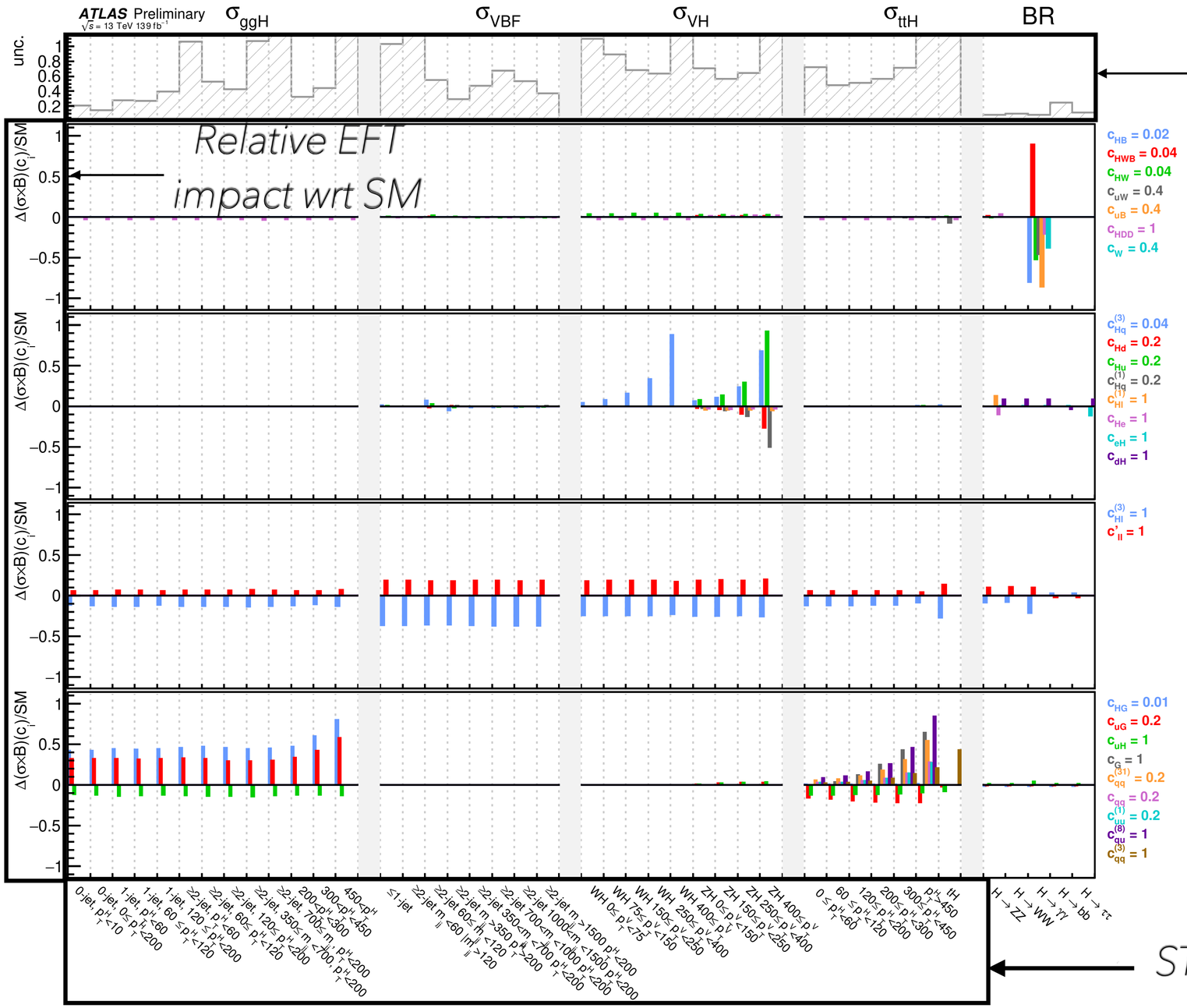

Relative EFT impact wrt SM

Uncertainty on measurements across production modes

STXS bins

EFT Impact on kinematics

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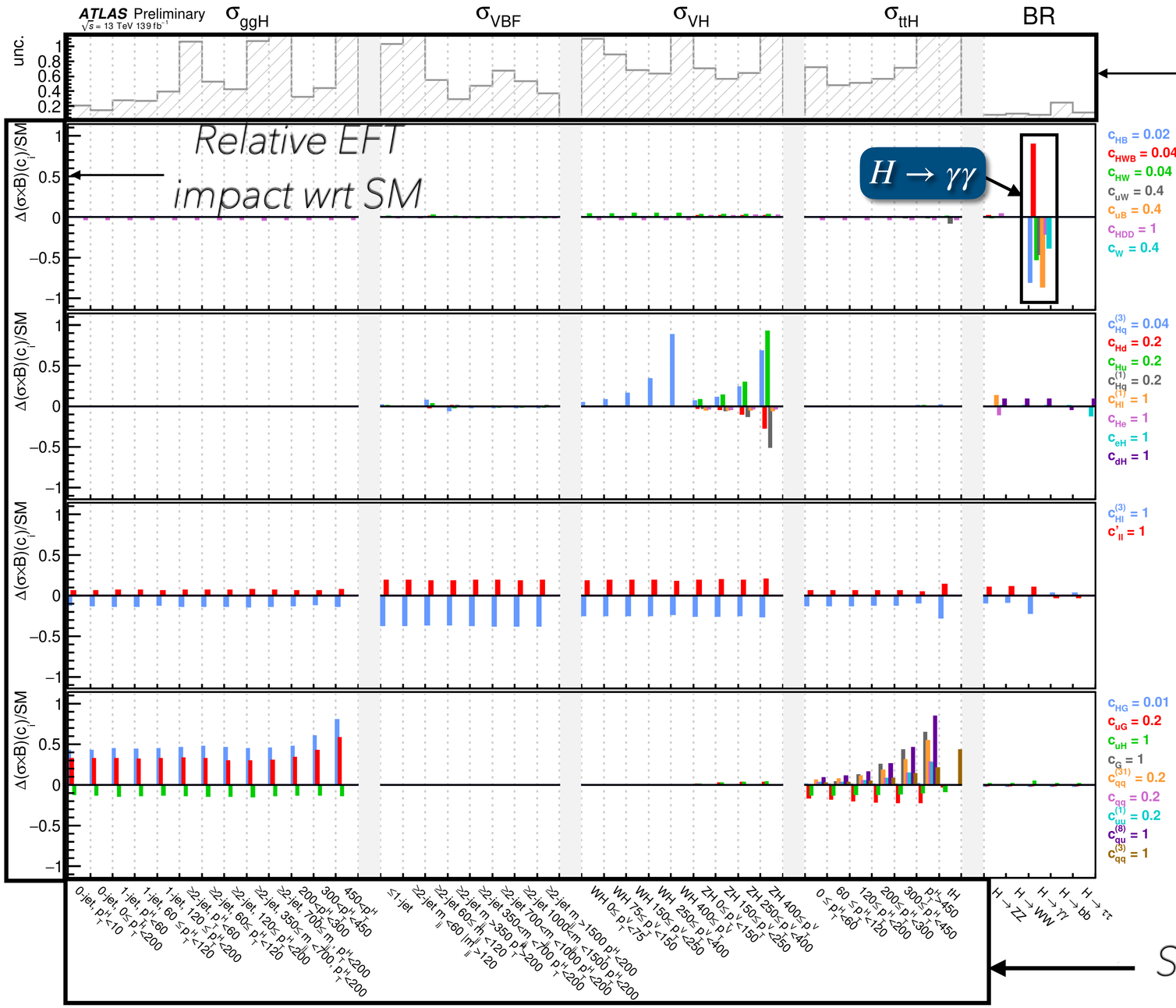
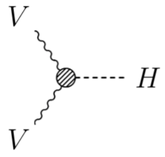


Uncertainty on measurements across production modes



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STXS bins

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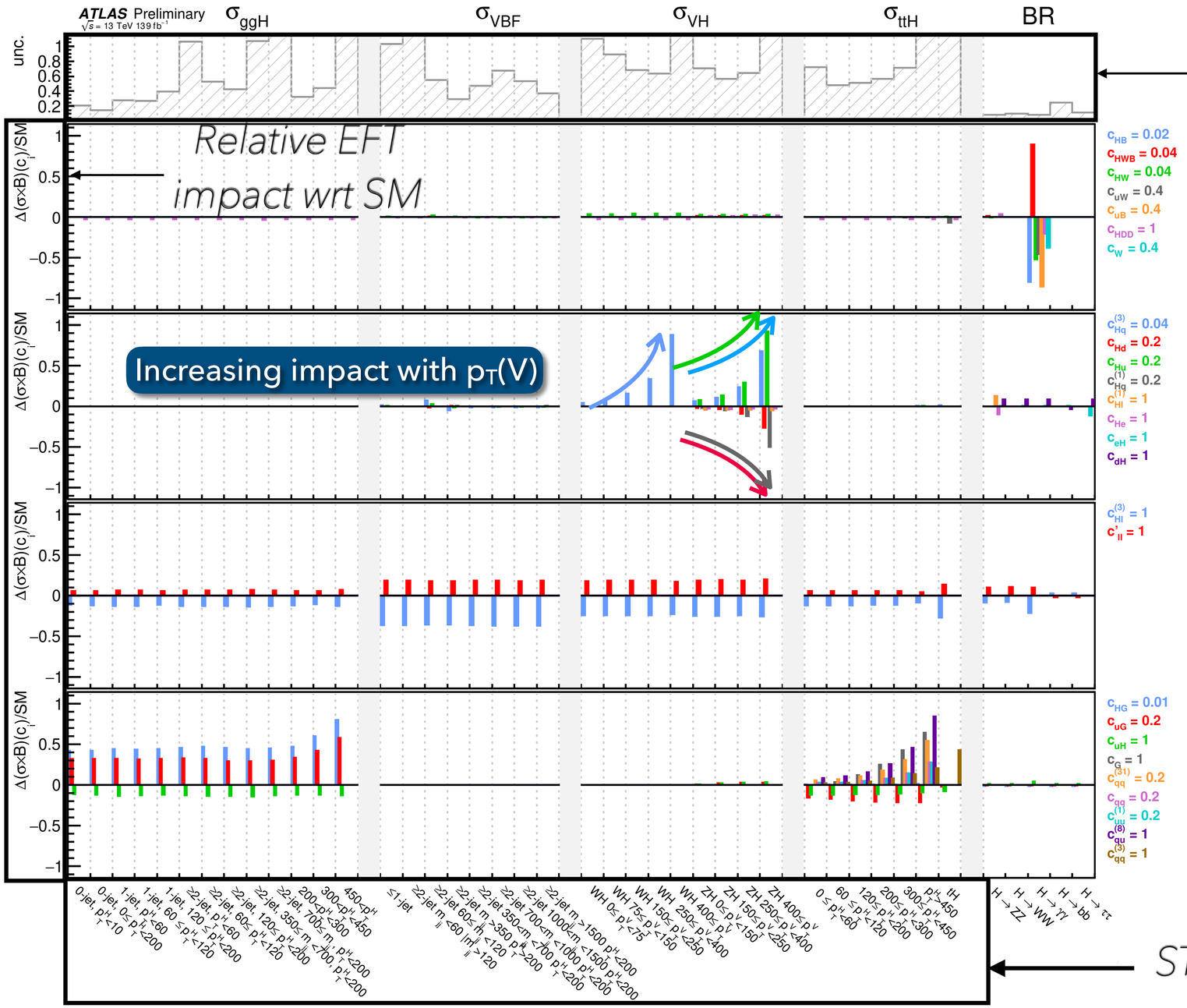
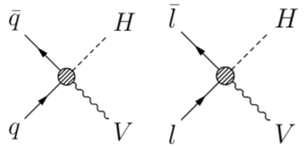
ATLAS-CONF-2021-053



Uncertainty on measurements across production modes

$\{O_{Hq}^{(3)}, O_{Hd}, O_{Hu}, O_{Hq}^{(1)}\}$



STXS bins

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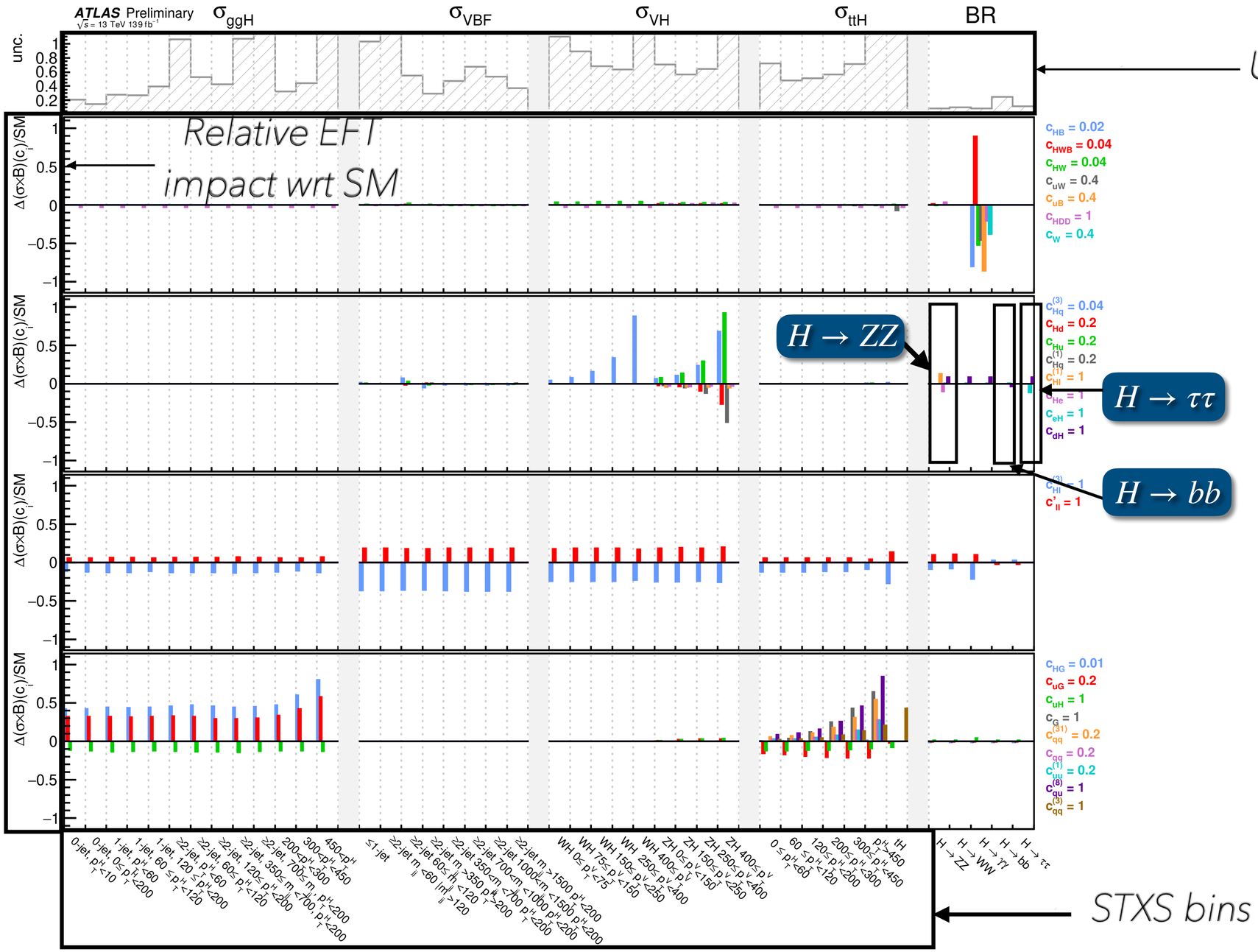
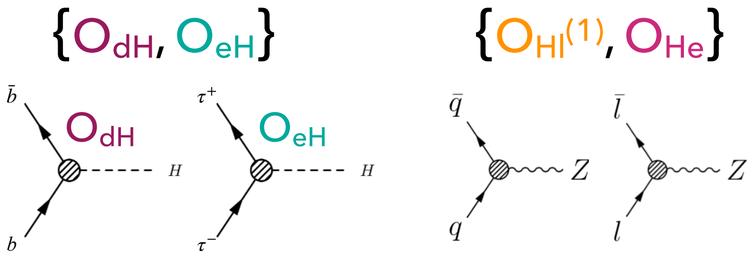


Uncertainty on measurements across production modes



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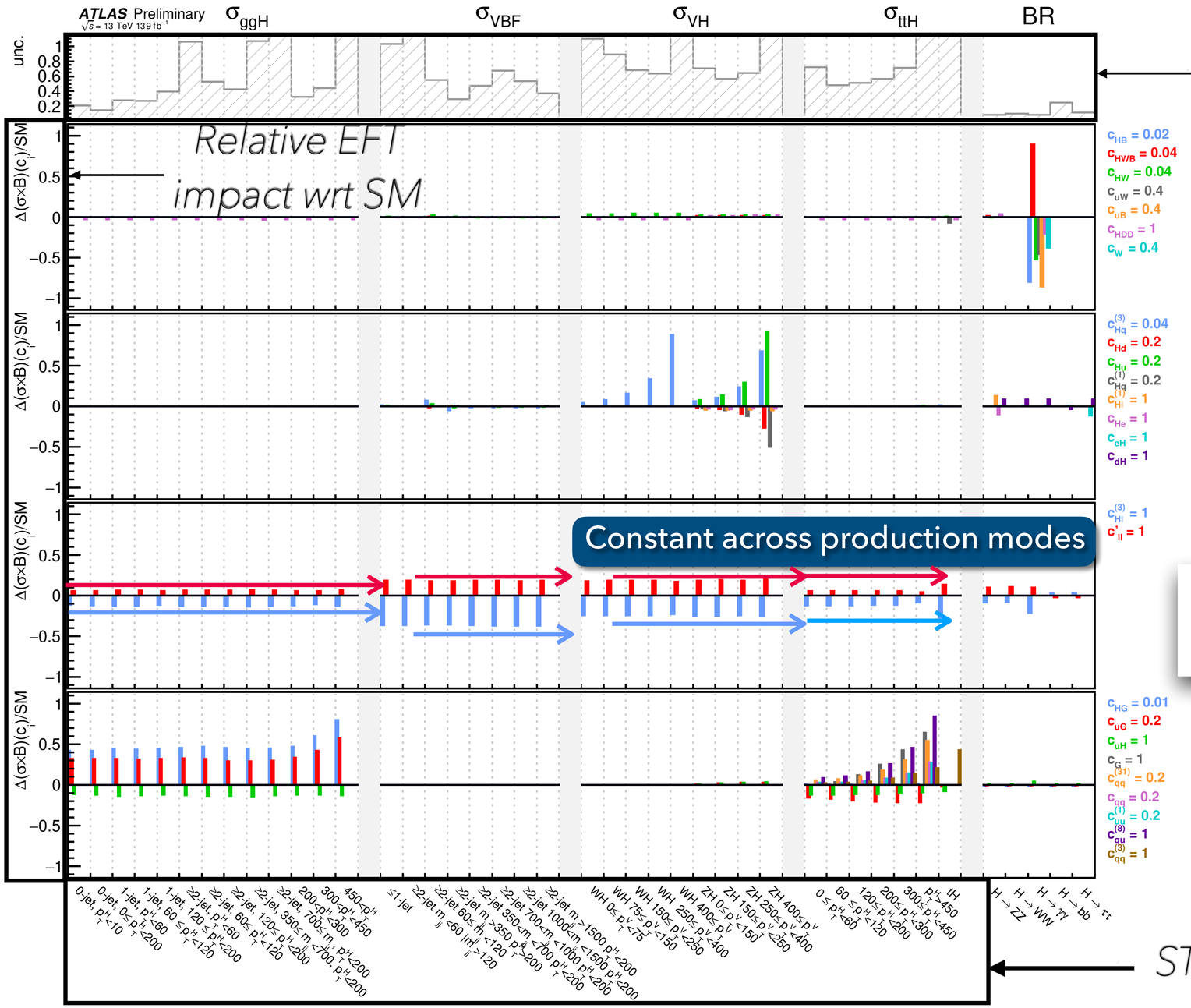


Uncertainty on measurements across production modes

STXS bins

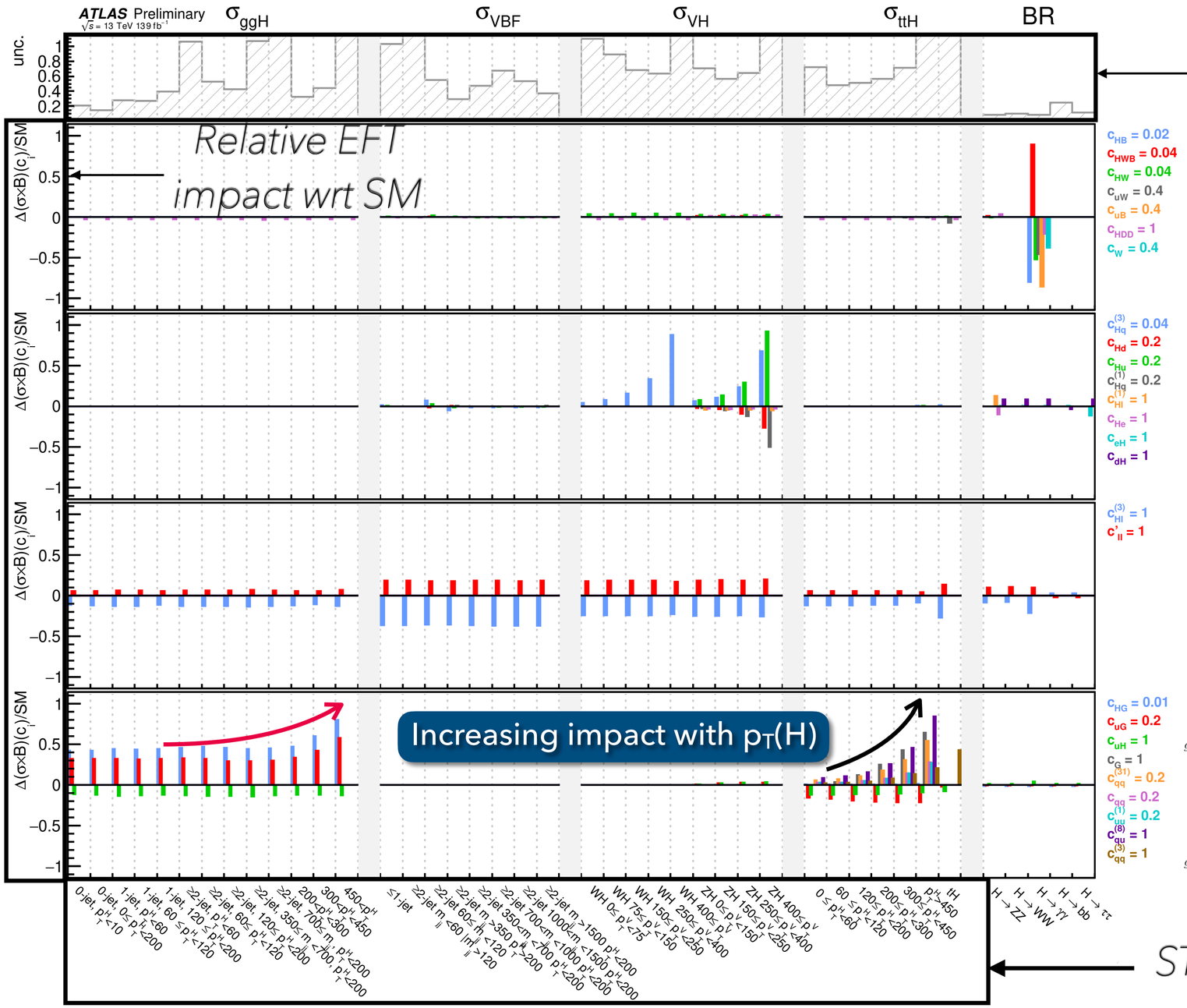
arXiv:1709.06492

extracted value of the Fermi constant in the general SMEFT is

$$-\frac{4G_F}{\sqrt{2}} = -\frac{2}{v_T^2} + \left(C_{\substack{ll\\ \mu e e \mu}} + C_{\substack{ll\\ e\mu\mu e}}\right) - 2\left(C^{(3)}_{\substack{Hl\\ ee}} + C^{(3)}_{\substack{Hl\\ \mu\mu}}\right). \qquad (10.10)$$

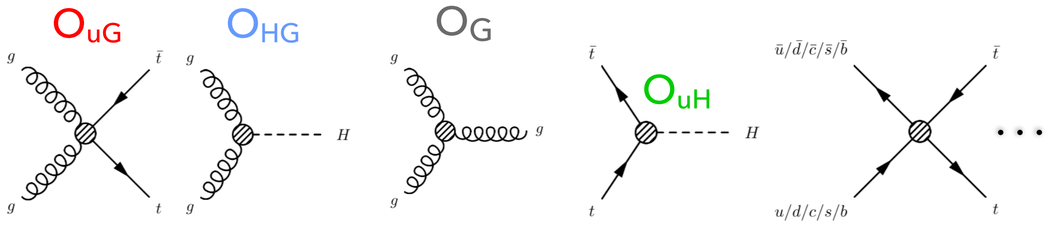
EFT Impact on kinematics

ATLAS-CONF-2021-053



Uncertainty on measurements across production modes

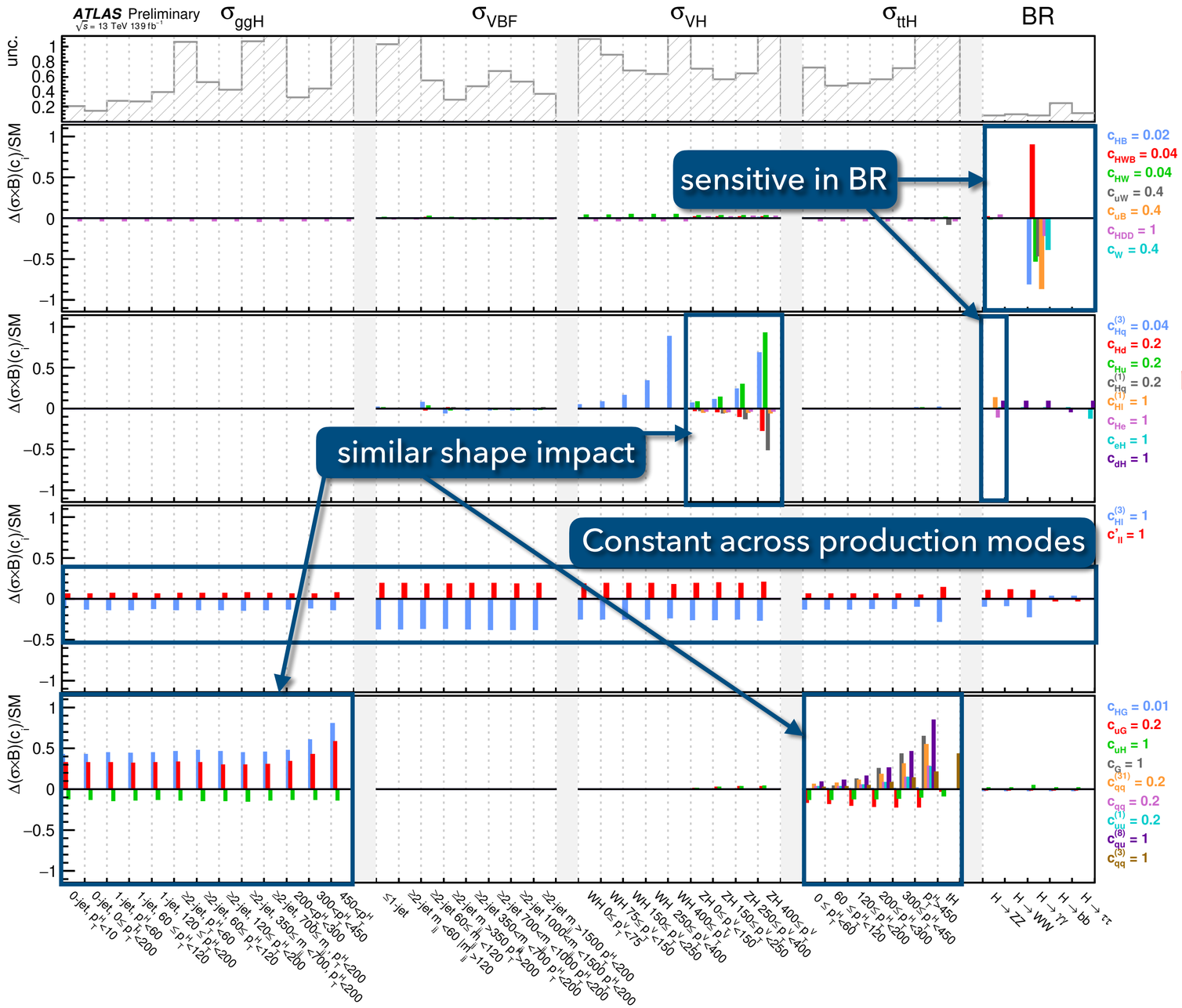
STXS bins



$\{O_{qq}^{(31)}, O_{qq}, O_{uu}^{(1)}, O_{qu}^{(8)}, O_{qq}^{(3)}\}$

EFT Impact on kinematics

ATLAS-CONF-2021-053



Groups of parameters that,

- mainly sensitive in inclusive observable
- appear as overall normalisation
- similar shape dependence across bins

Insufficient information in data to measure EFT parameters simultaneously !

Fit only sensitive directions within parameter groups using STXS covariance matrix

Principle Component Analysis of

$$C^{-1}_{EFT} = P^{T} \cdot C^{-1}_{STXS \times BR} \cdot P$$

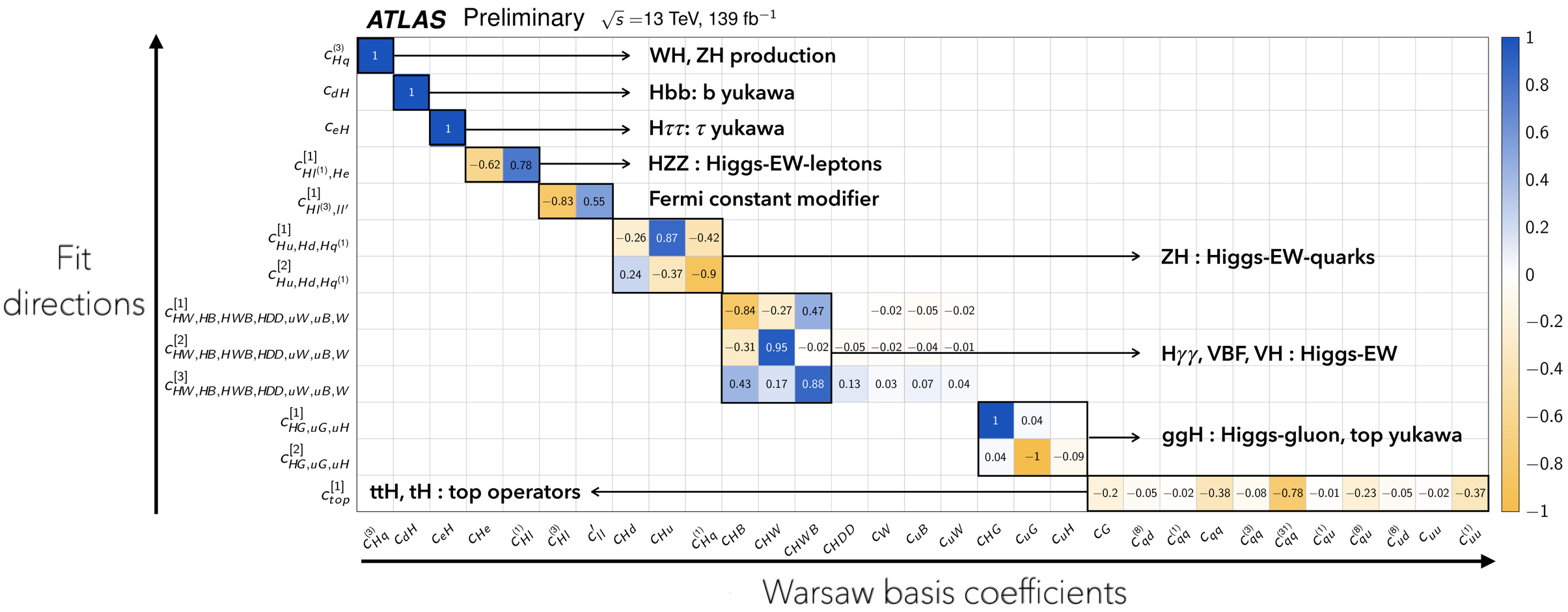
where

C → covariance matrix,

P → EFT parameterisation matrix

Fit directions

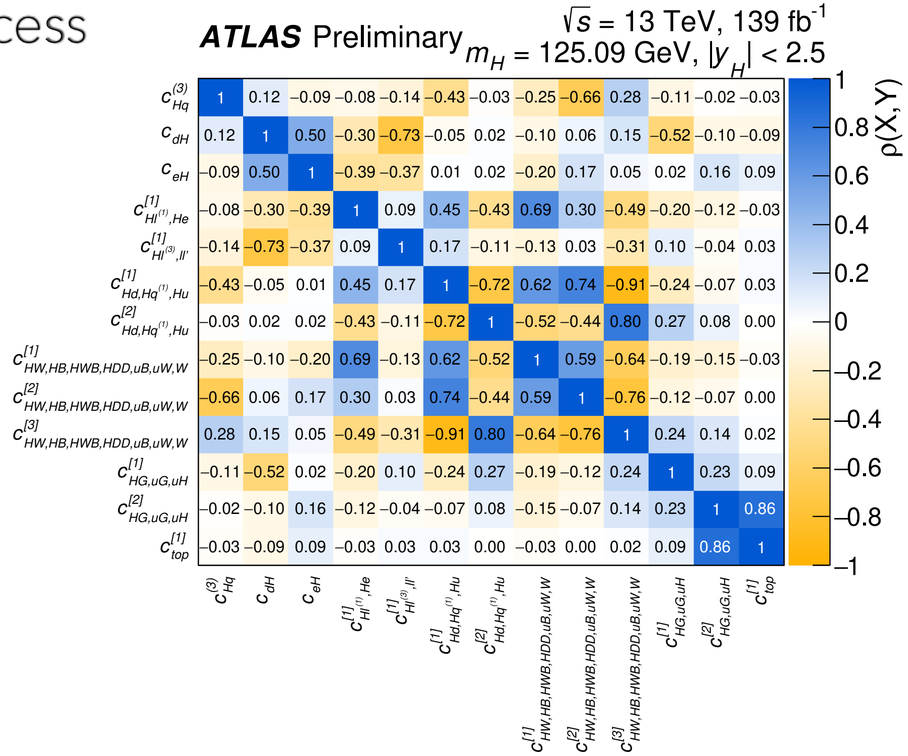
ATLAS-CONF-2021-053

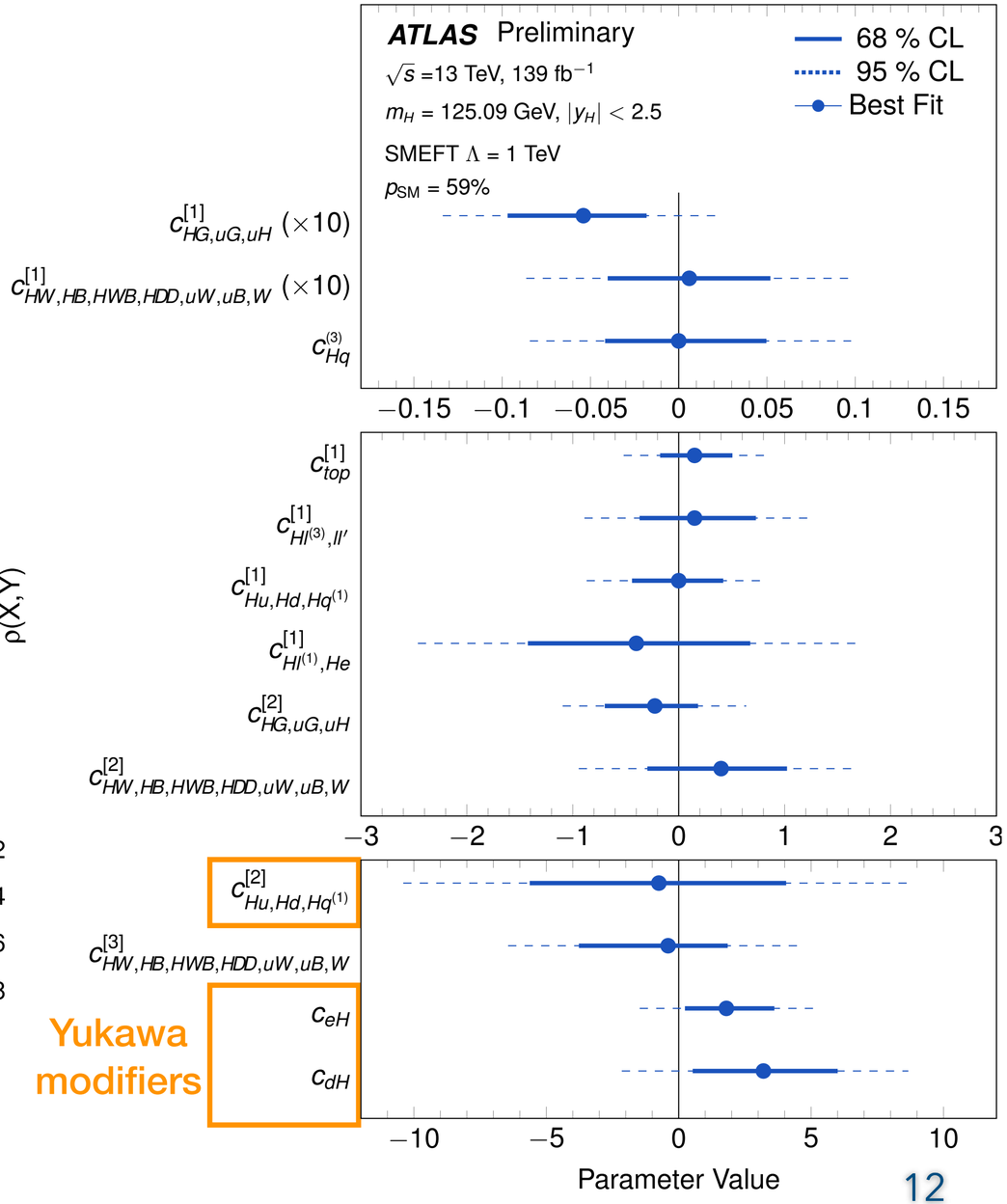


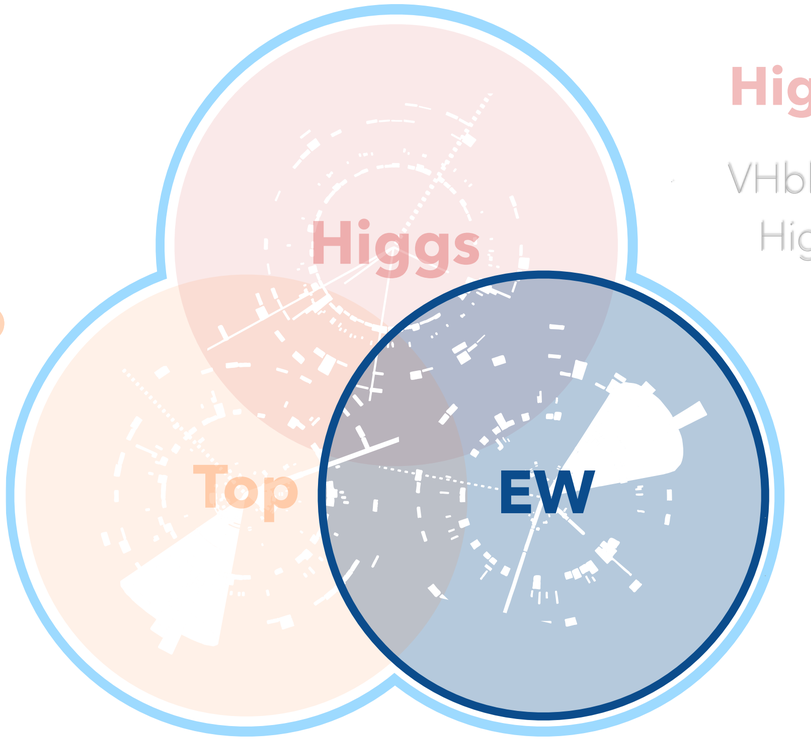
- Fit basis defined to capture maximum experimental sensitivity across Higgs measurements, can probe 13 parameters with reasonable sensitivity ($\sigma_{\text{unc.}}$ ~ 2) with manageable correlations
- Large overlap of operators that also affect top and EW sectors, combination will help improve sensitivity and relax flat directions

EFT fit results

- Only **linear** EFT parameterisation considered
- With these 13 EFT parameters, **3 new parameters** than last round (Hyy, H4l, VHbb combination)
- Up to 70 % improvement in limits compared to last round due to interplay of EFT effects across different physics process
- Residual correlations as PCA performed only with groups of operator to preserve interpretability of fit directions







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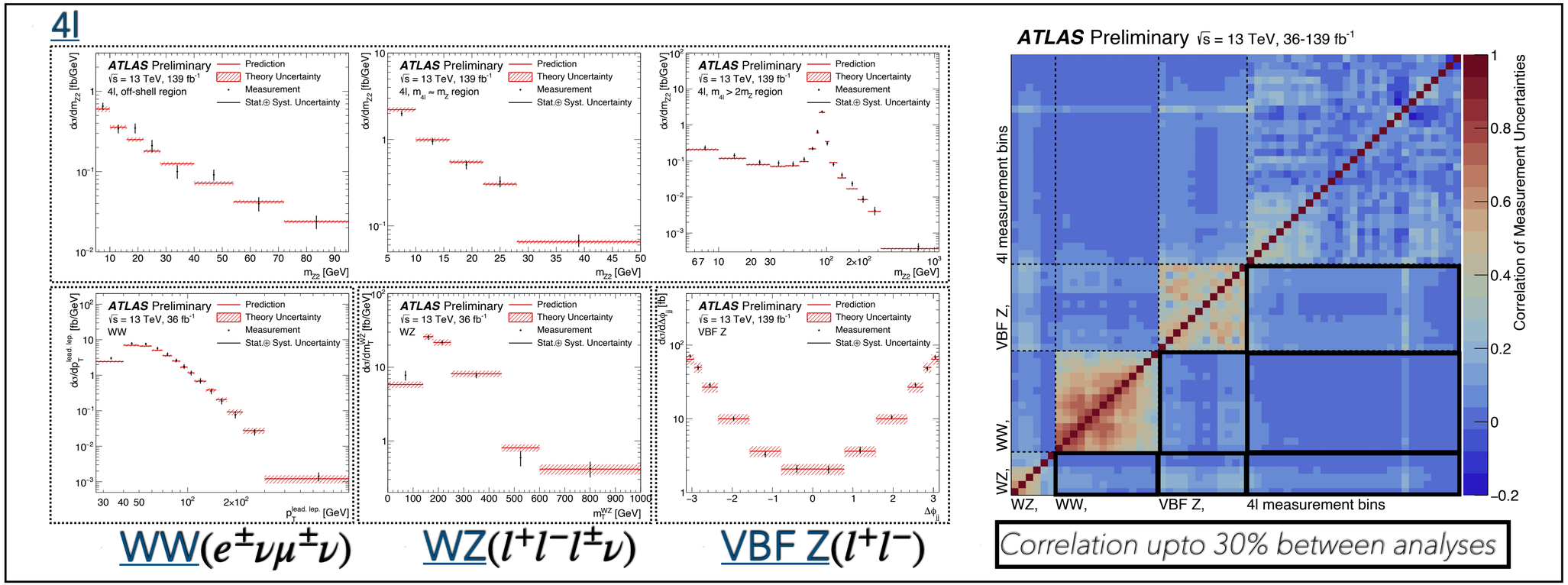
WW, WZ, 4l & Z+2jets combination

ATLAS-PHYS-PUB-2021-021

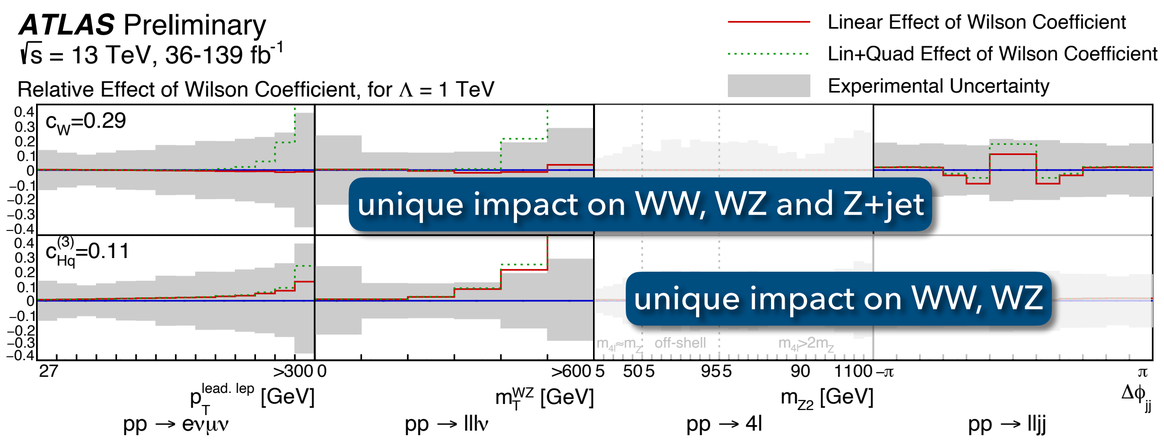
combination of unfolded differential cross-sections



- Considering one unfolded differential cross-section distribution from individual analysis of each process with consistent modelling of measurements : correlated treatment of important systematic sources and SM theory uncertainties
- SMEFTsim 3.0 used to generate linear & quadratic EFT parameterisation in topU3l symmetry

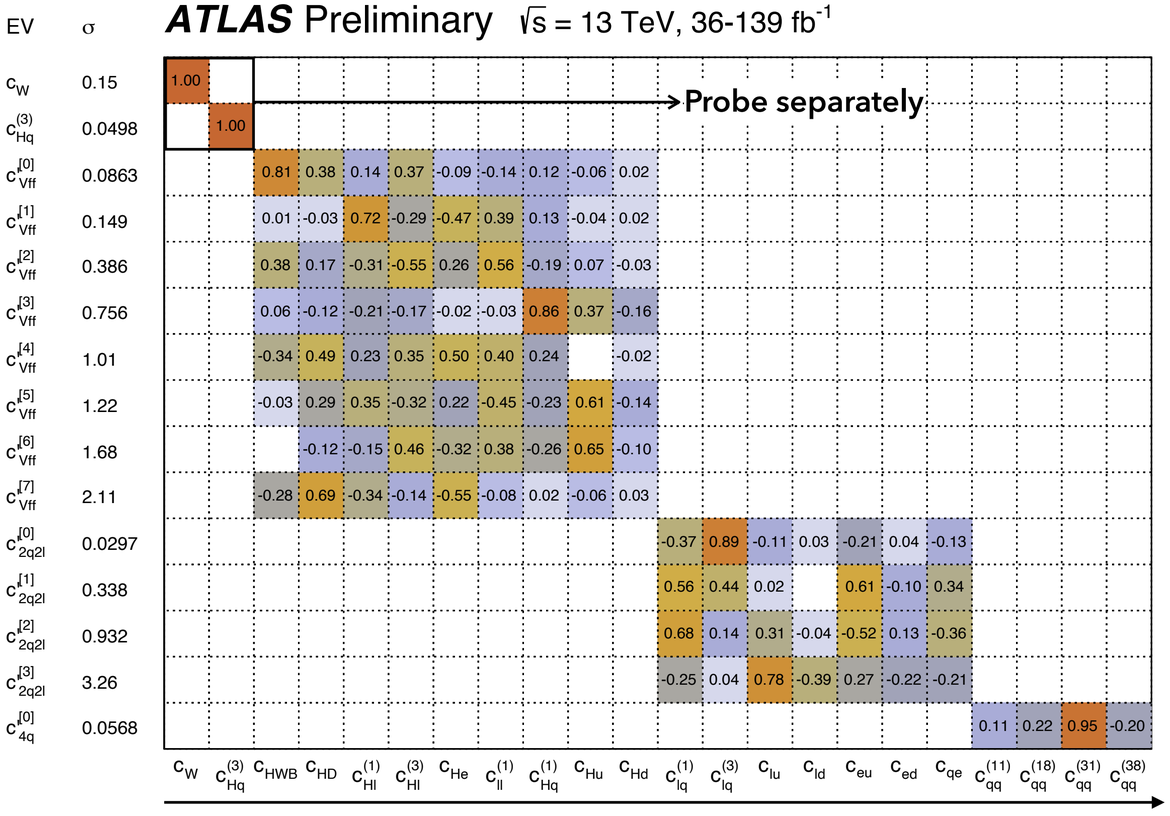
Sensitive directions

ATLAS-PHYS-PUB-2021-021



Fit directions

Fit directions determined with PCA



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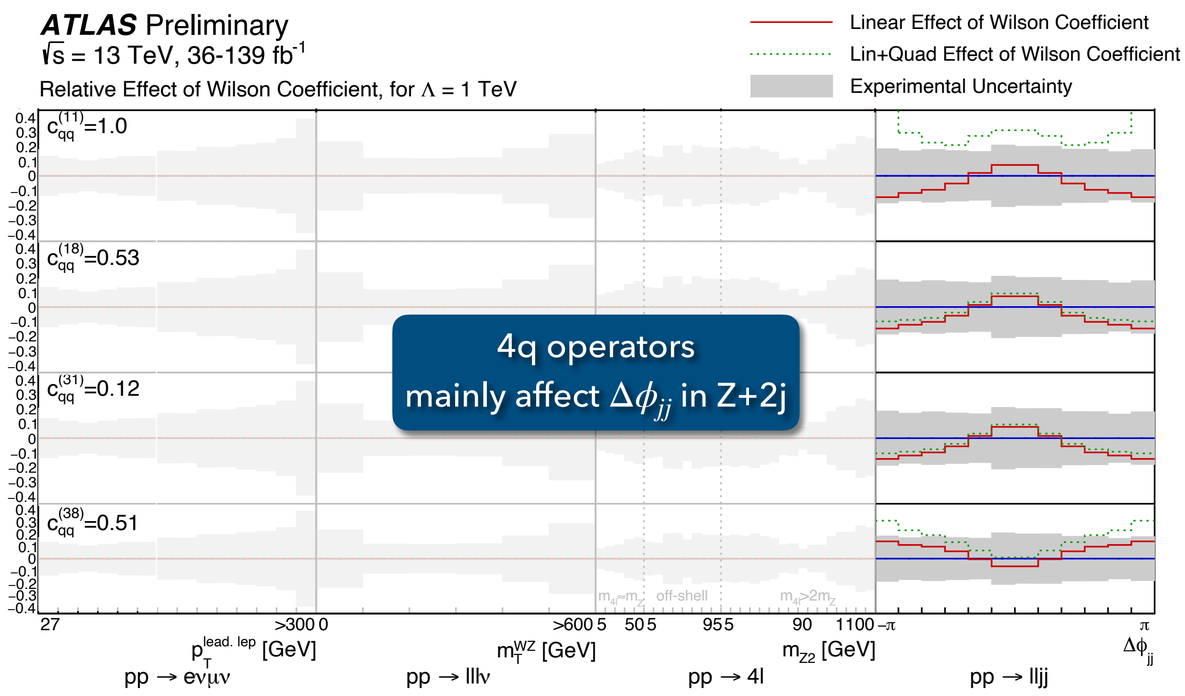
ATLAS-PHYS-PUB-2021-021



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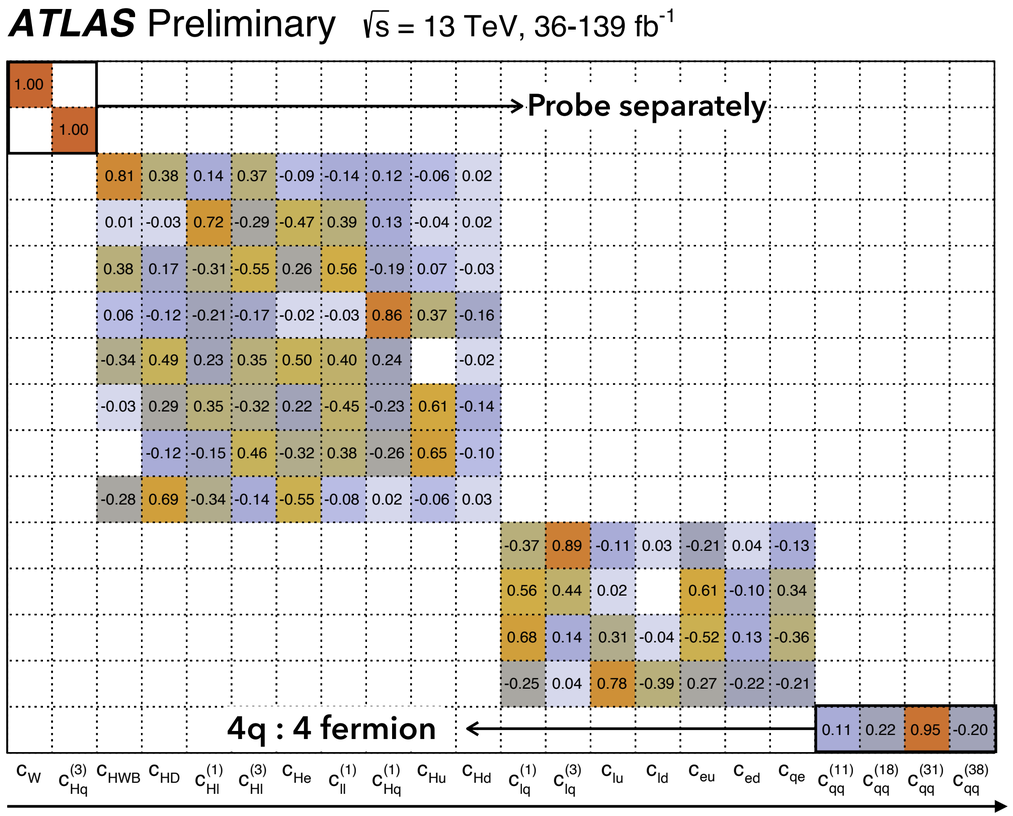

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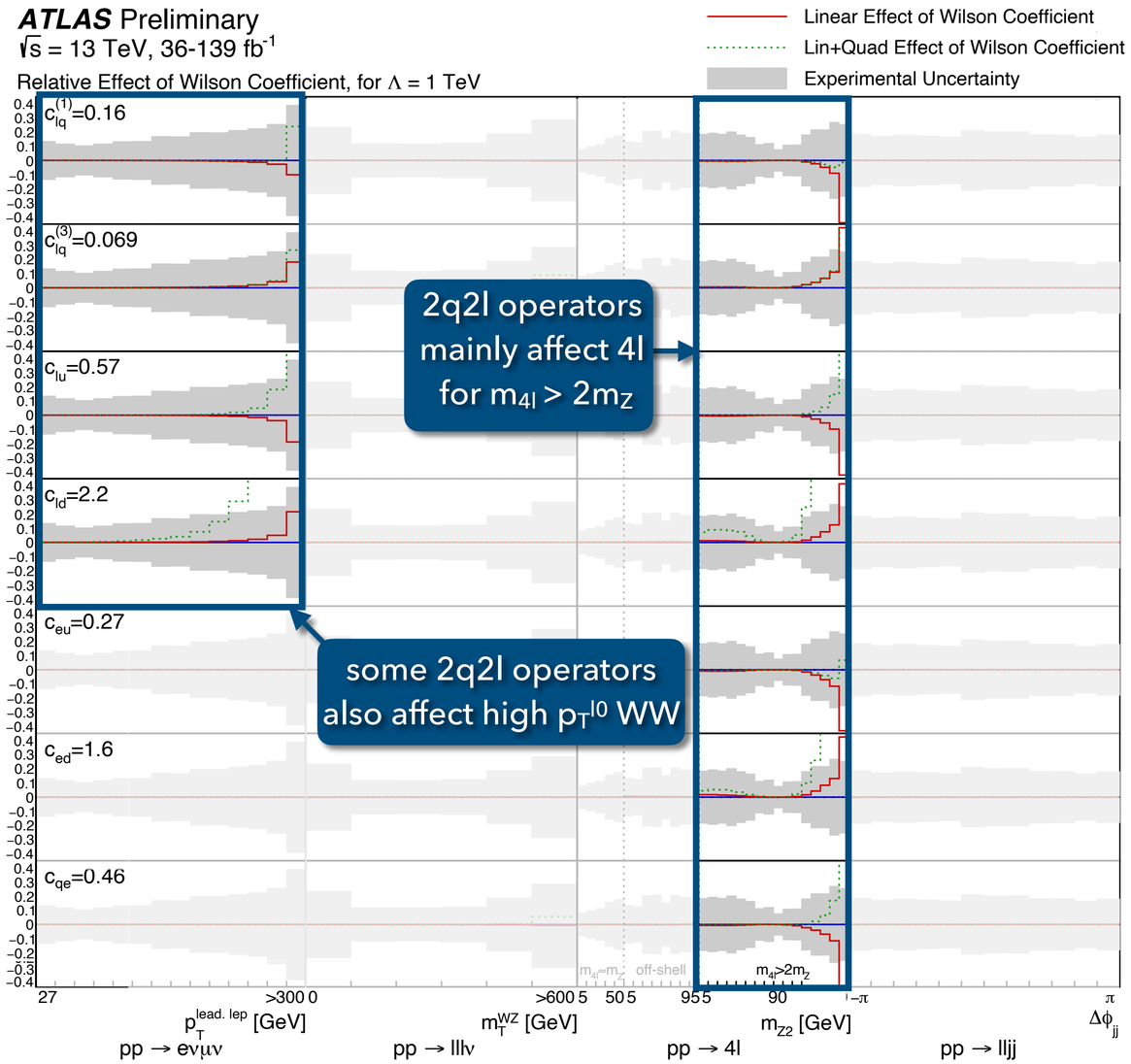

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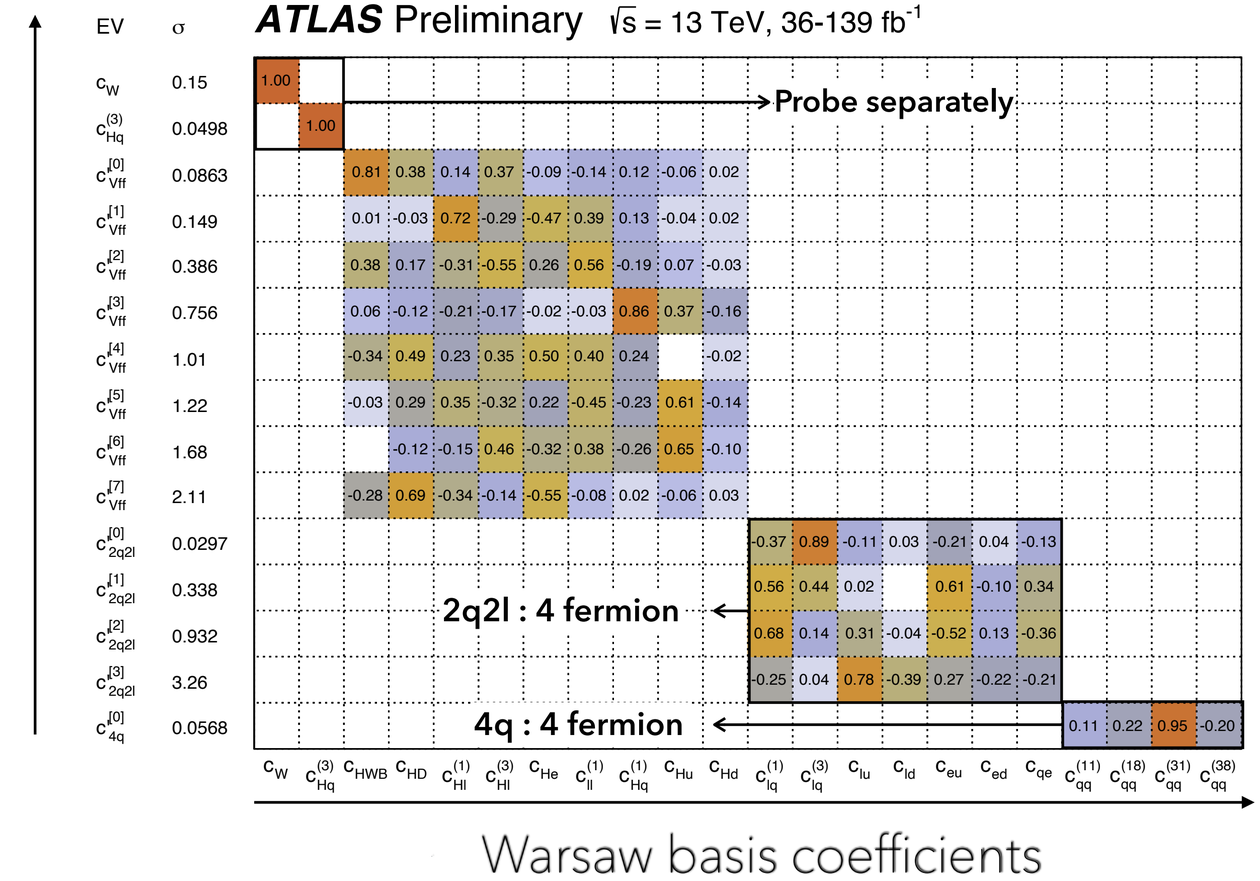

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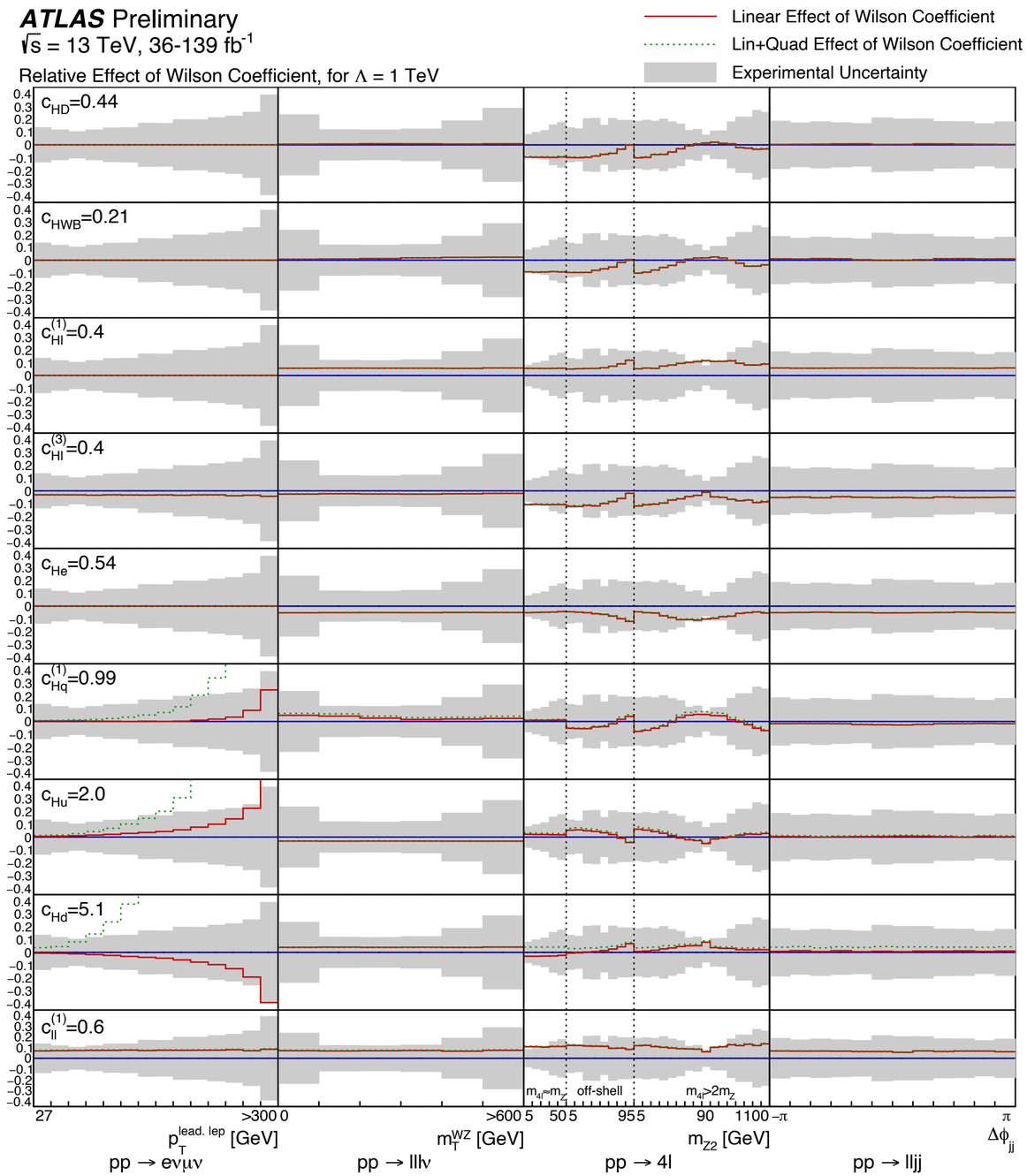

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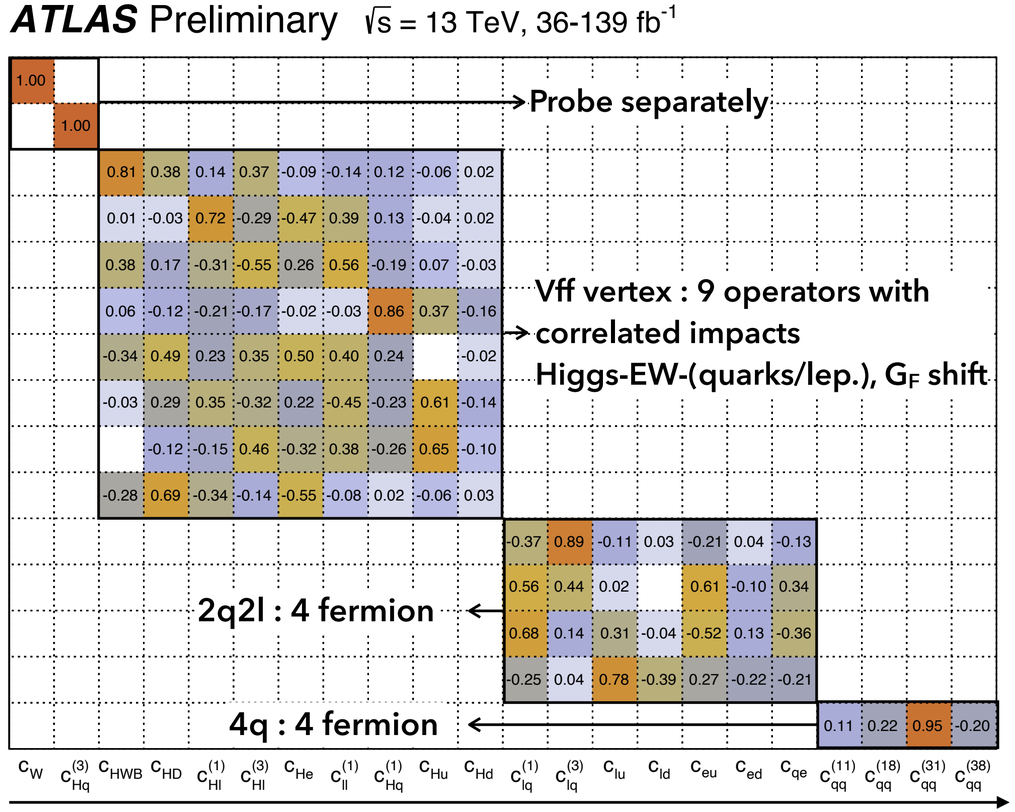
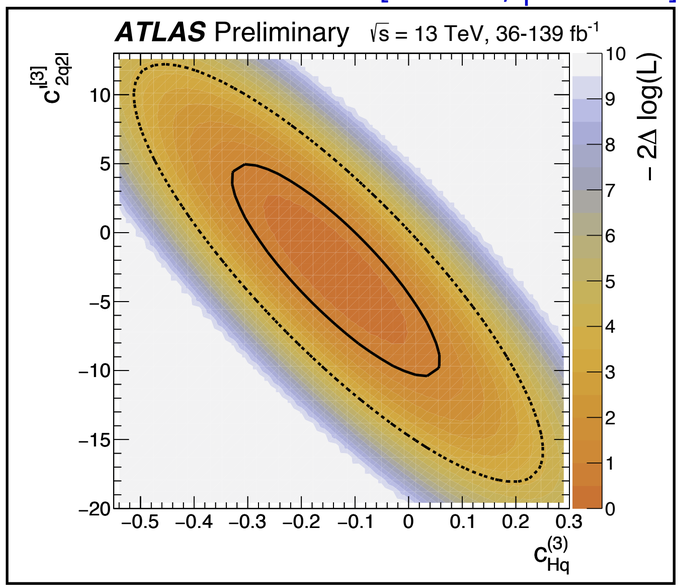


Results for sensitive parameters

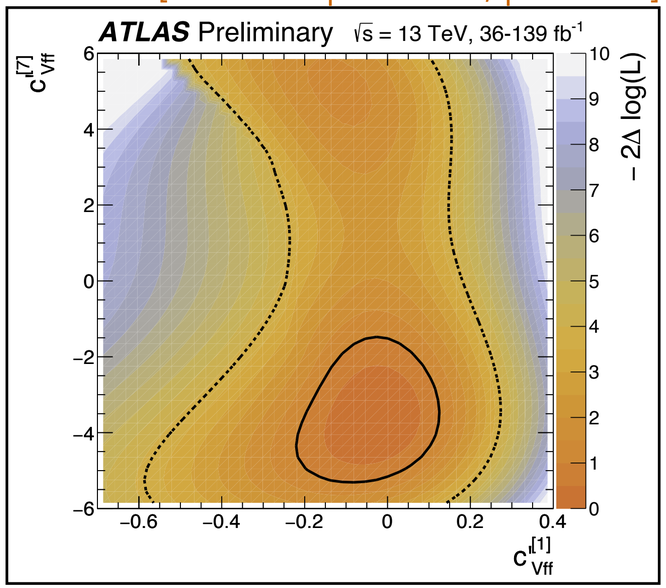
- Measure 15 EFT parameters simultaneously with combination of four EW analyses

- Results derived for both profiled and one-at-a-time, differences indicative of correlation of parameter

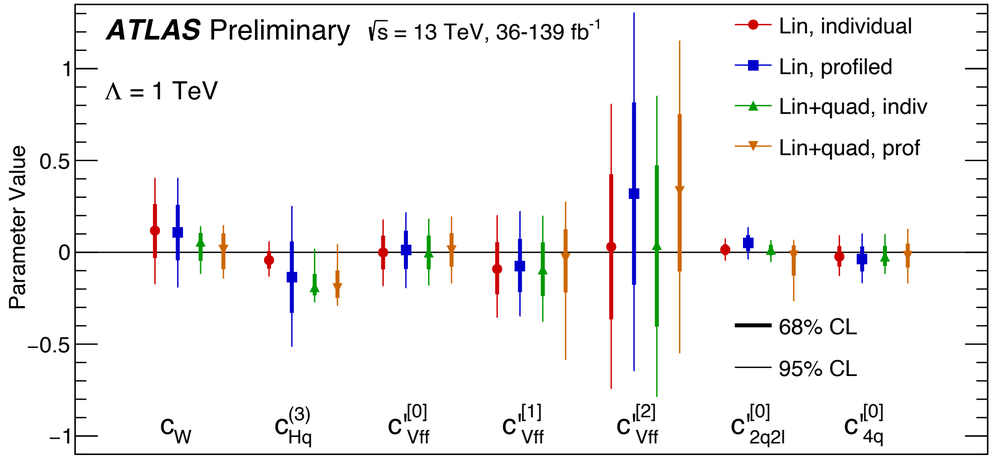
[Linear, profiled]

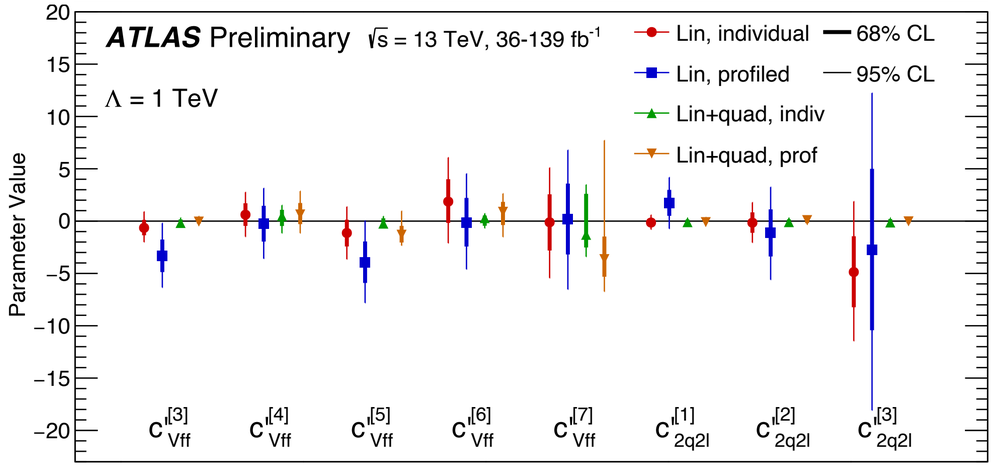


[Linear+quadratic, profiled]



- Probe coefficients from to ~5 to ~0.1 corresponding to energy scale $\left(\frac{\Lambda}{\sqrt{c}}\right)$ of ~0.45 TeV to ~3 TeV





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

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

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

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

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

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

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

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

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

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

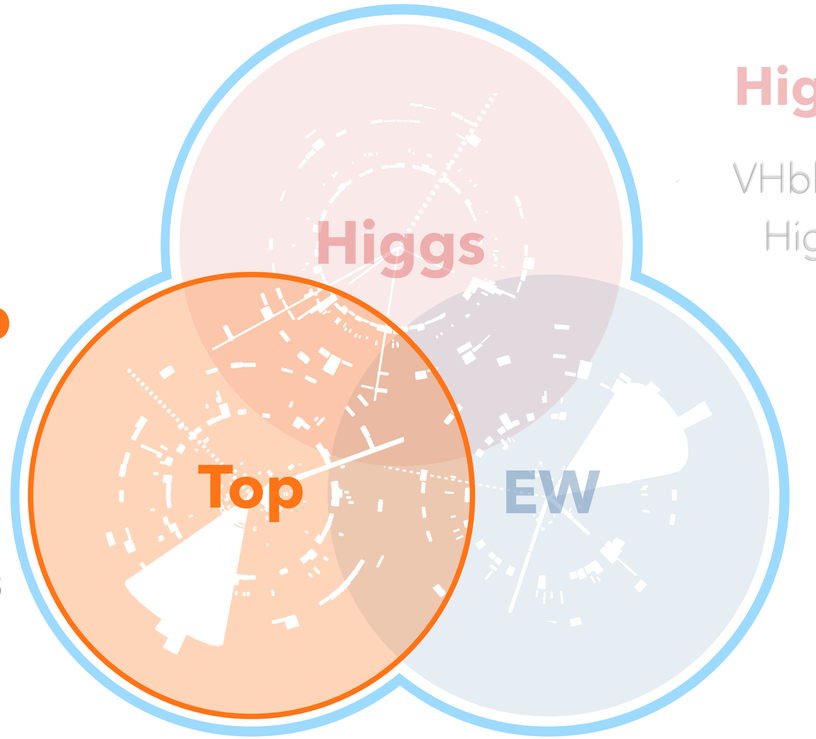
$$c^{[3]}_{2q2l} \approx -0.27c^{(1)}_{lq} + 0.79c_{lu} - 0.39c_{ld} + 0.26c_{eu} - 0.22c_{ed} - 0.16c_{qe}$$

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

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

Top

Energy asymmetry in $t\bar{t}j$ production
boosted $t\bar{t}$ production
angular observables
Top EFT Summary plots



Higgs

VHbb resolved + boosted combination
Higgs combination

EW

WW, WZ, 4l, & Z+2jets combination

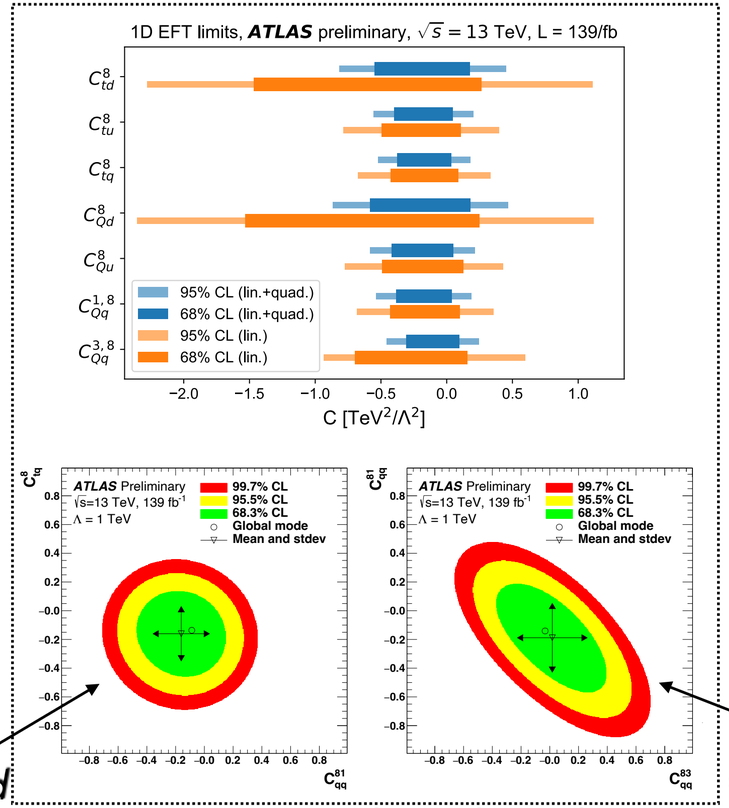
boosted $t\bar{t}$ production

Differential cross-section measured as a function of $p_T^{t,1}$ most sensitive to EFT effects, used for reinterpretation

ATLAS-CONF-2021-050

$t\bar{t}$ all-hadronic

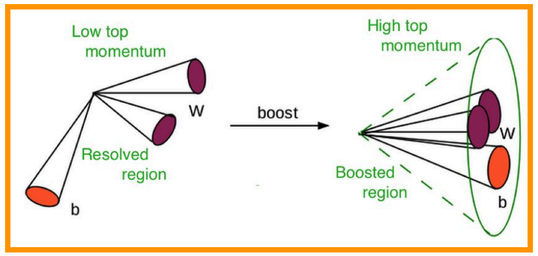
Sensitivity to 4-fermion operators



directions de-correlated

directions correlated

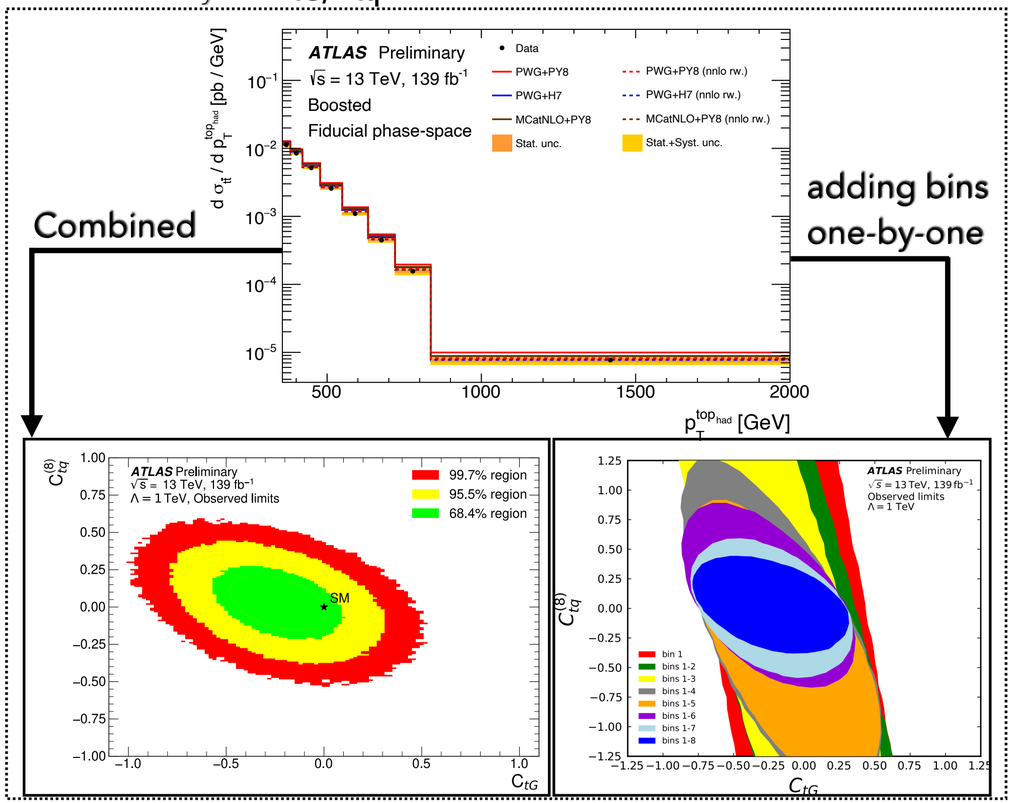
based on dim6top



ATLAS-CONF-2021-031

$t\bar{t}$ + jets

Sensitivity to c_{tG}, c_{tq}^8



based on SMEFTatNLO

- boosted topologies to access top quarks with high p_T^t
- One-at-a-time limits for several 4-fermion (2-light-quark 2-heavy quark) operators
- Constraints are also placed for two parameters simultaneously, ({c_{tG}, $c_{Qq}^{3,8}$}, {$c_{Qq}^{1,8}$, $c_{Qq}^{3,8}$}, {$c_{Qq}^{1,8}$, c_{tq}^8})

arXiv:2110.05453

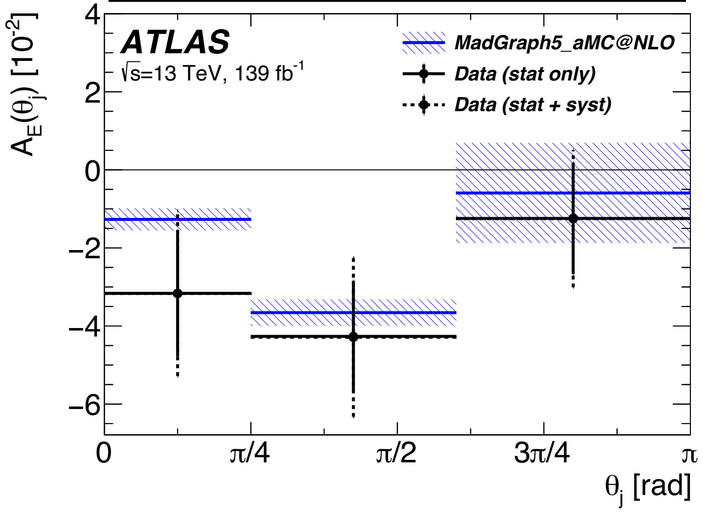
Angular Observables

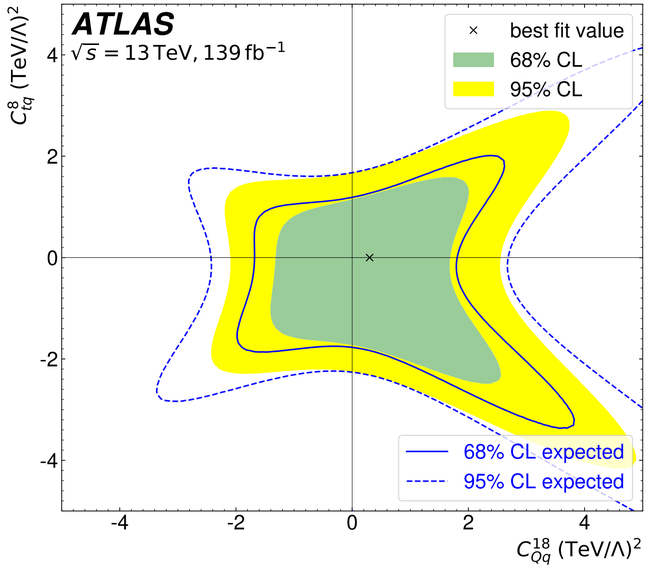
ATLAS-CONF-2021-027

Energy Asymmetry

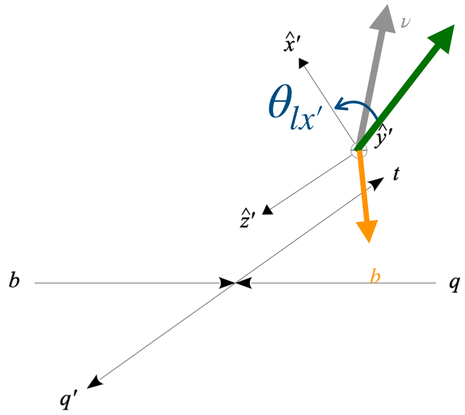
$$A_E(\theta_j) \equiv \frac{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) - \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) + \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)} \equiv \frac{\sigma_A(\theta_j)}{\sigma_S(\theta_j)}$$

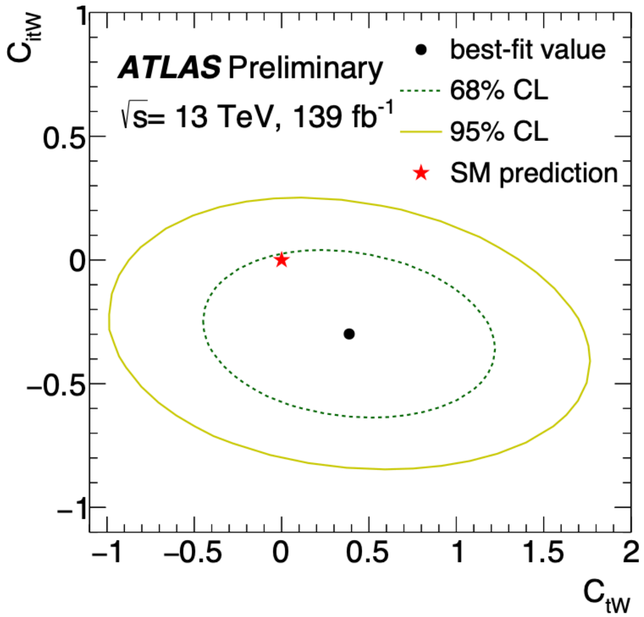
θ_j: Jet scattering angle wrt. incoming parton
ΔE and θ_j are defined in the $t\bar{t}j$ rest system





- First ATLAS measurement of top - anti top-quark energy asymmetry !
- reconstruct boosted hadronic top decay to single lepton+jets
- Sensitive operators : LL, RR = $\{c_{Qq}^{11}, c_{Qq}^{18}, c_{tu}^{8}, c_{tu}^{1}\}$, RL = $\{c_{tq}^{8}, c_{tq}^{1}\}$
- One-at-a-time and two-at-time limit for these four fermion operators

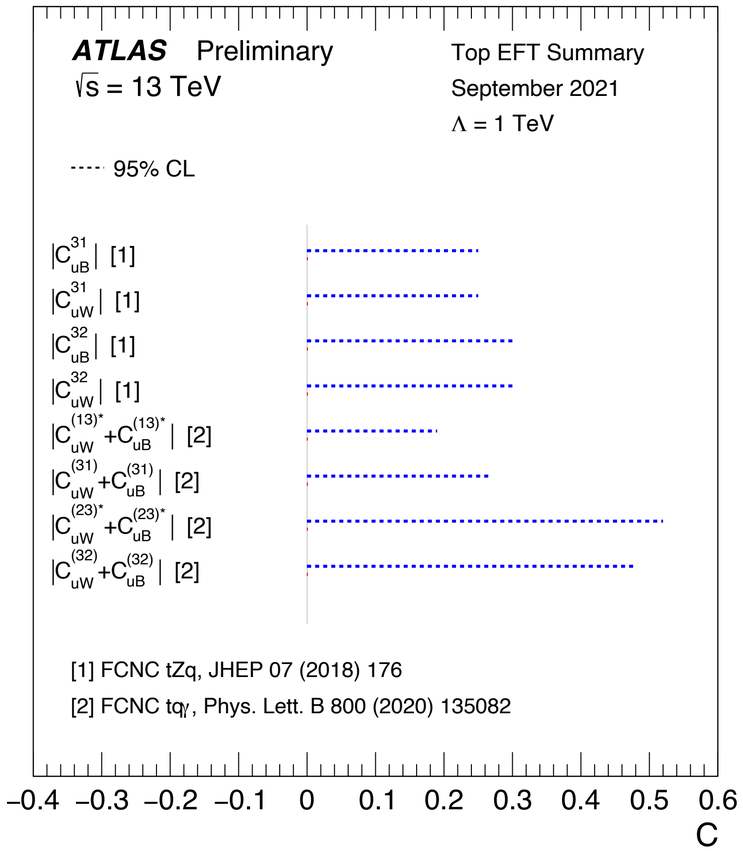


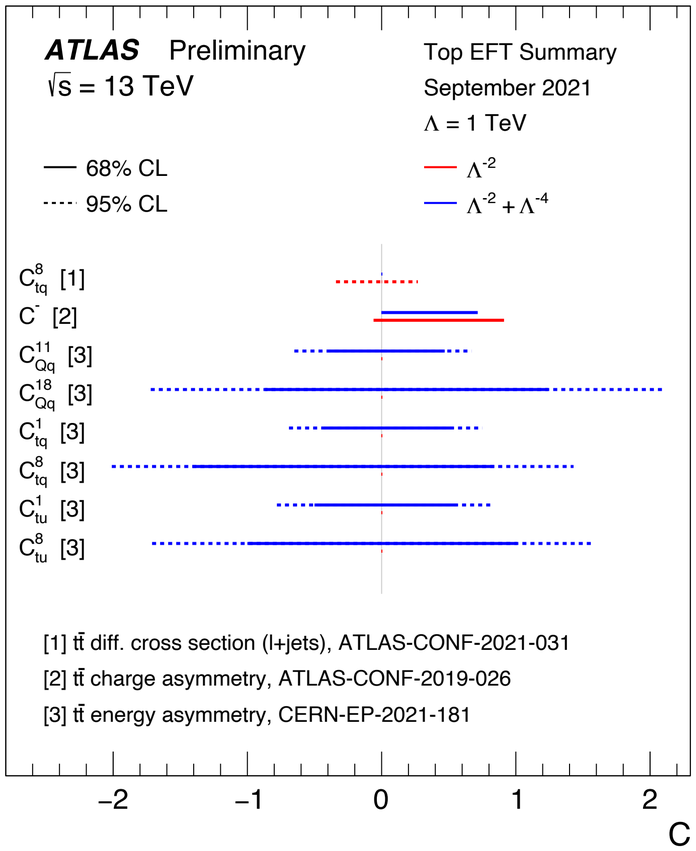


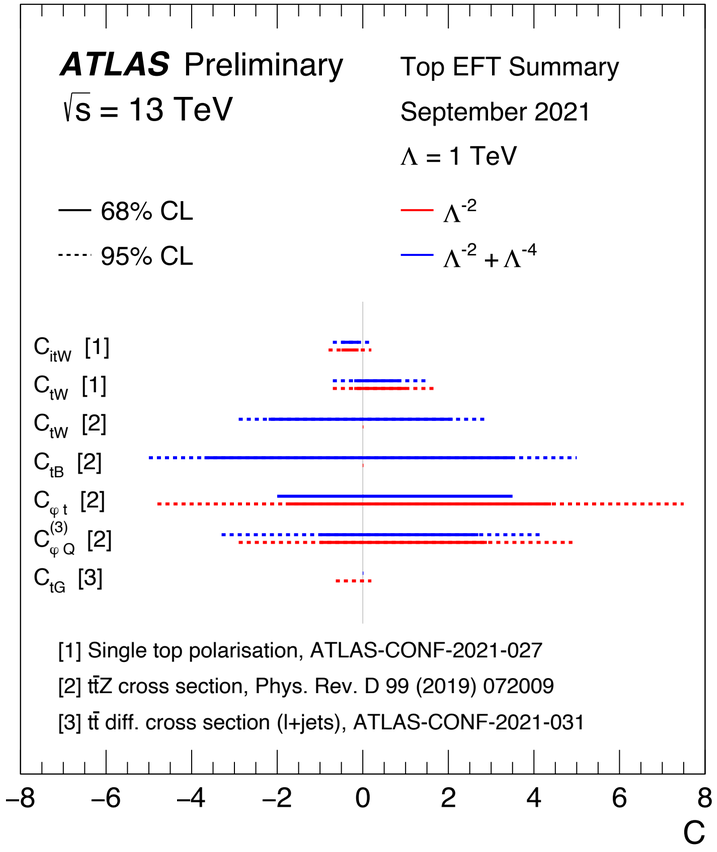
- Highly polarised top quarks due to V-A nature, decay preserve spin information !
- Polarisation in t-channel single top production
- Unfolded differential distribution of $\cos\theta_{lx'}$ & $\cos\theta_{ly'}$, correlation estimated using statistical bootstrap
- Sensitive to c_{tW} and c_{itW} respectively

Top EFT Summary Plots

ATL-PHYS-PUB-2021-036





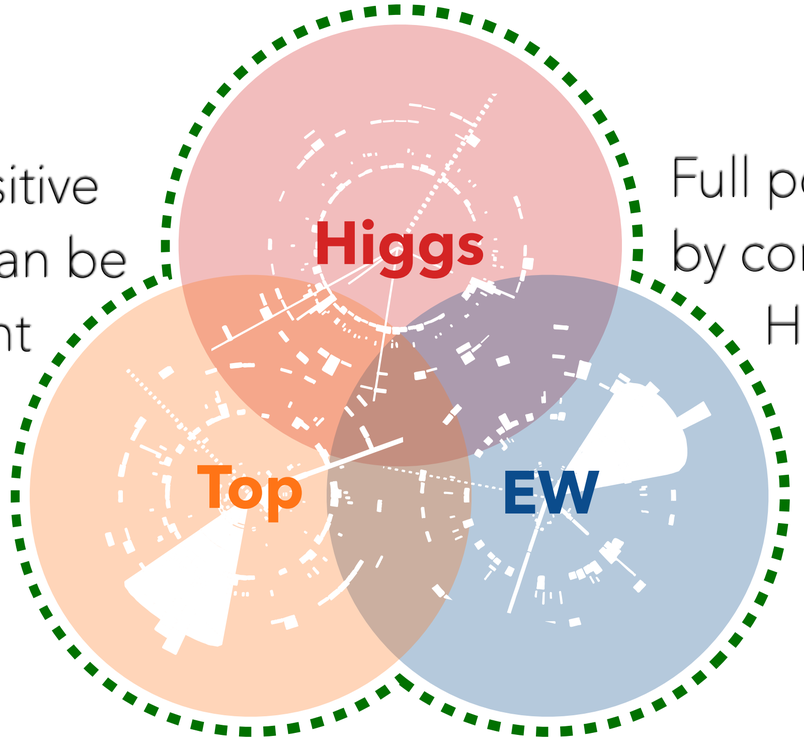


- Summary plots showing sensitivity of different top measurements ($t\bar{t}$, $t\bar{t}$ + X, single top) to wilson coefficients
- Linear term negligible for FCNC, constraints reported for d=6 operators contributions at $O(\Lambda^{-4})$
- Single top polarisation probes c_{itW} and c_{tW} simultaneously, rest of the limits are obtained for one-at-a-time where all other parameters are set to SM

Conclusions

- SMEFT interpretations across different sectors and processes with ATLAS data evolving well !

Top processes uniquely sensitive to a large set of operators, can be probed by using different kinematic measurements



Full power of SMEFT captured by combining different processes !
Higgs(13 parameters)
EW (15 parameters)

- Moving towards a harmonised SMEFT framework to interpret different measurements in **global fit**
- Theory and experimental considerations evolving for a lot of items,
  (*d=8 operators, EFT uncertainties, EFT validity, matching to UV models, ….*)

Exciting Times Ahead !