Measurements of electroweak diboson production in association with two jets in ATLAS

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For ATLAS collaboration

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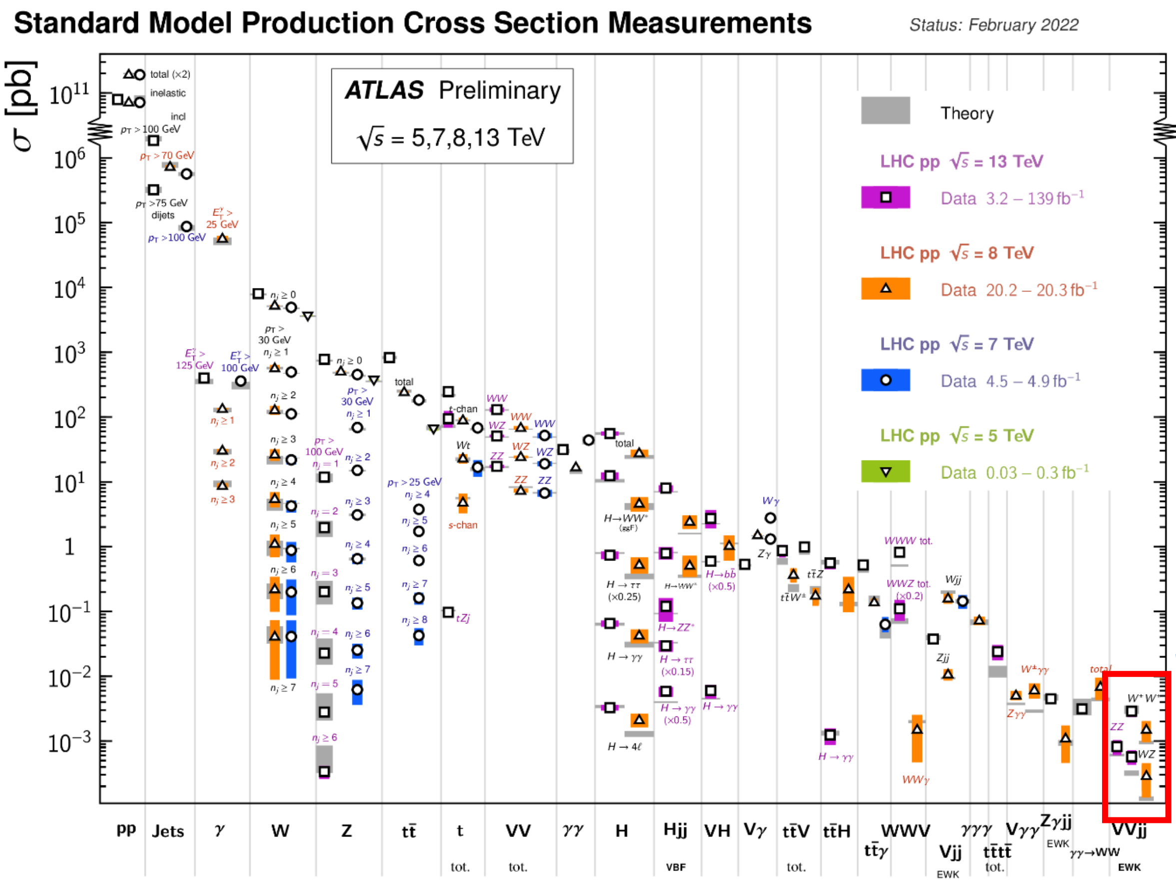
Overview

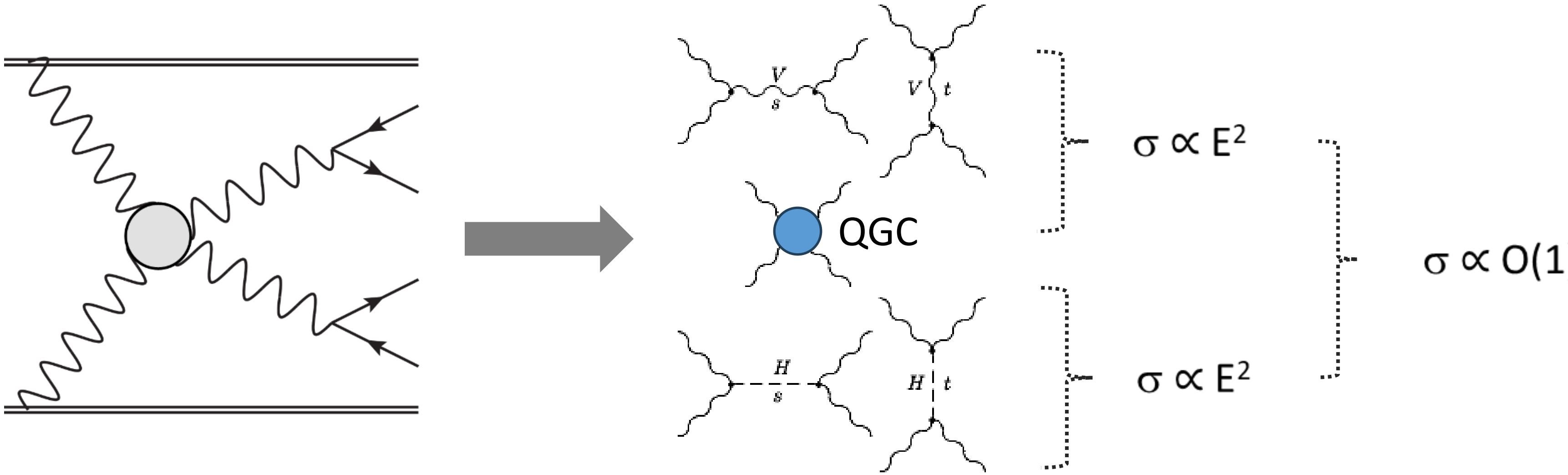
- ❑ Precise measurements of **SM processes** at the LHC
  - ✓ ***Unprecedented scrutiny of the SM***, model parameters, particle properties, Gauge structures, **rare processes**, differential phase spaces, and QCD effects (PDF etc.)
  - ✓ ***Close interplay with Higgs physics***, ***Sensitivity to new physics***



One of rarest SM processes to probe is the electroweak production of diboson with two jets (**EW VVjj process**)

Cross-section at O(fb)

EW VVjj Production



Involving Vector boson scattering

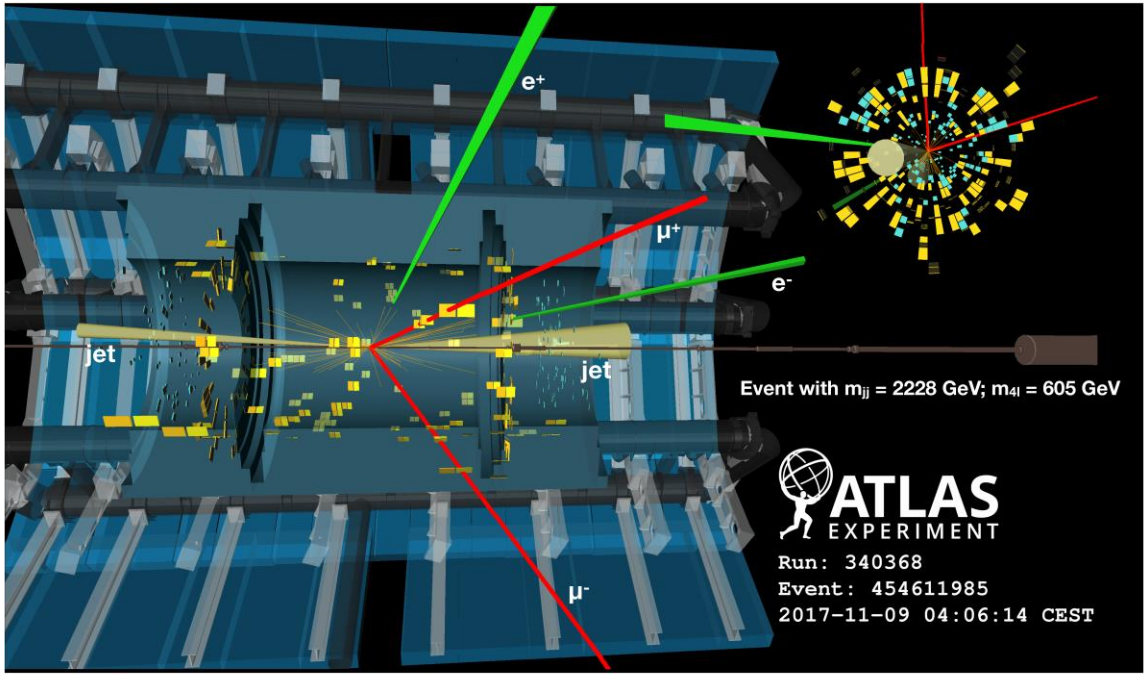
⇒ *Probe of EWSB dynamics and sensitive to new physics in EWSB sector*

⇒ *Delicate cancellation needed to unitarize at TeV scale*

⇒ *Historically, one of main motivations for a Higgs boson!*

⇒ *Quartic gauge boson couplings (QGC) offer unique probe of SM gauge structures and sensitive to new physics modifications*

Features of EW VVjj Production



A typical event display (EW ZZjj)

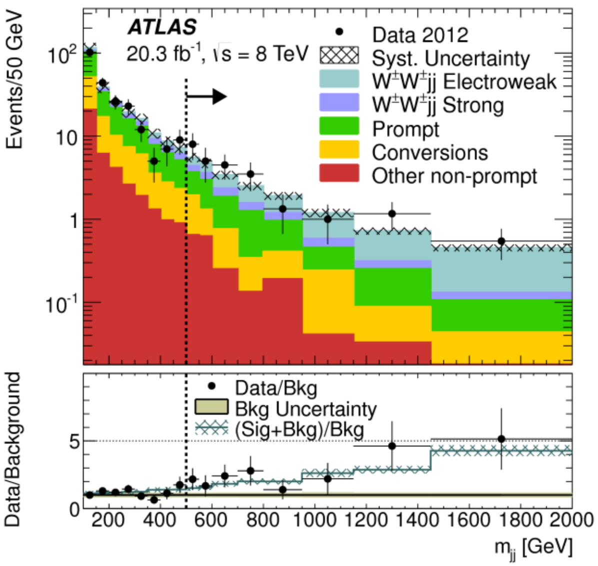
- Signature involves no color flow between scattering partons
  - two QCD jets relatively forward, with large mjj and rapidity separation
  - often define centrality variable to indicate EW production contained in rapidity gap of jets

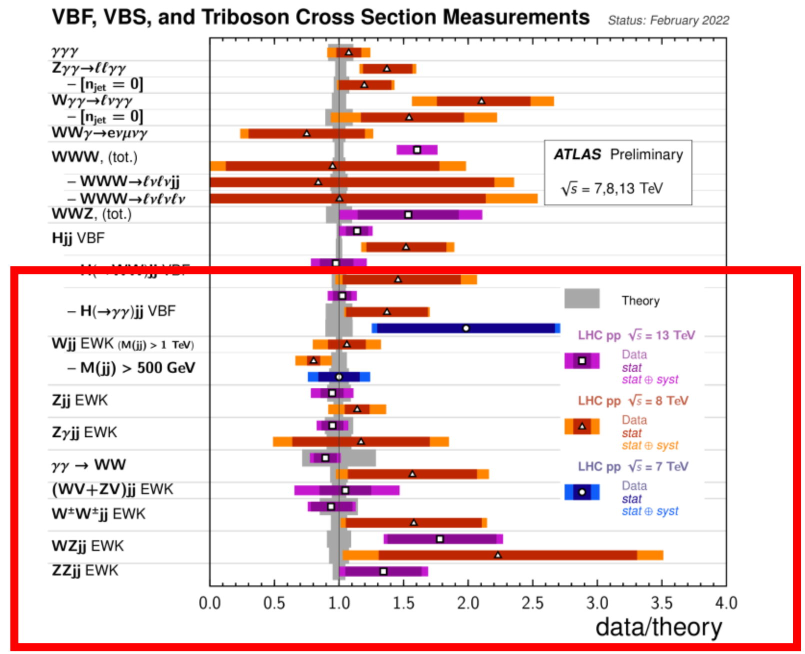
e.g. $$\zeta = \frac{(y_{4\ell} - 0.5(y_{j_1} + y_{j_2}))}{\Delta y_{jj}}$$

- Irreducible background from QCD production of VVjj

Past → Now

PRL 113 (2014) 141803



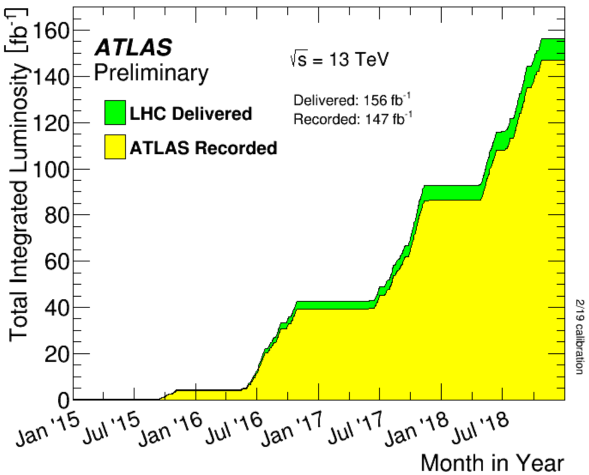


Almost **ten years ago**, started with **same-sign WW pairs + jj** with a handful of signal events

All EW VVjj modes have been observed by now, start to study the differential distributions and constrain anomalous QGCs (aQGCs)

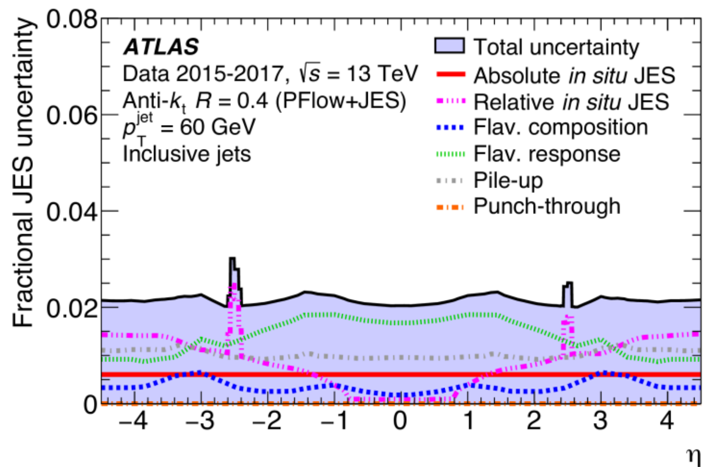
This talk focus on recent results with ATLAS Run-2 13 TeV data on:
EW Zγjj [arXiv:2305.19142, JHEP 06 (2023) 082],
EW WWjj (same-sign) [ATLAS-CONF-2023-023], **EW ZZjj** [ATLAS-CONF-2023-024],
aQGC combination from EW WZjj and WWjj (early Run-2 data) [ATL-PHYS-PUB-2023-002]

Data and processing

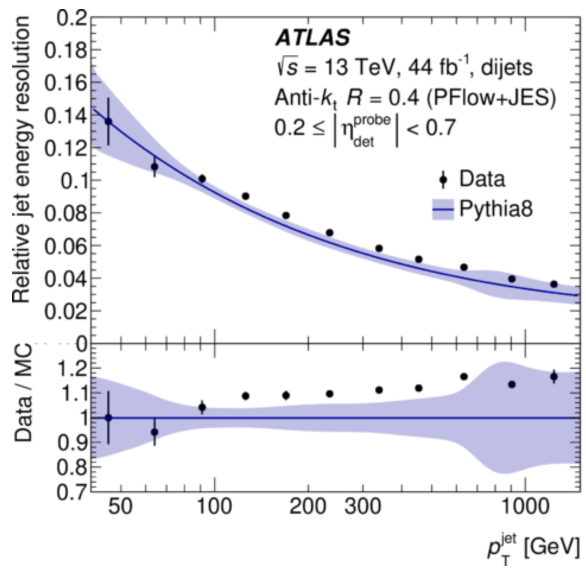


Thanks to the smooth operation of LHC and ATLAS, effective luminosity increase x10 comparing to initial studies back in Run-1

Important to have precise understanding of e, μ, E_T^{miss}, and in particular **jets**



EPJC 81 (2021) 689

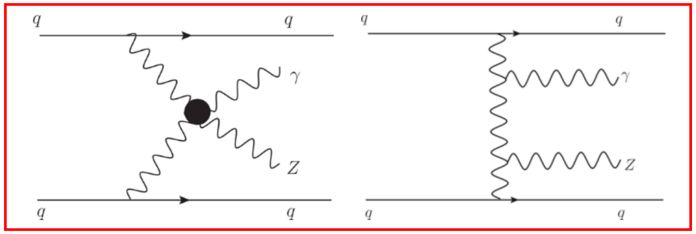


Calibration of jet energy scale to 2% at forward, 100 GeV regime
good modelling of jet energy resolution
is a key to study
EW VVjj topology

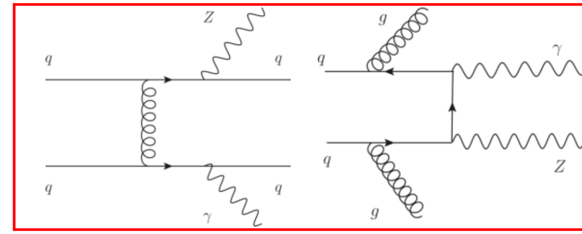
EW Zγjj

arXiv:2305.19142

Utilization of Z→ dilepton decays yields a clean final state

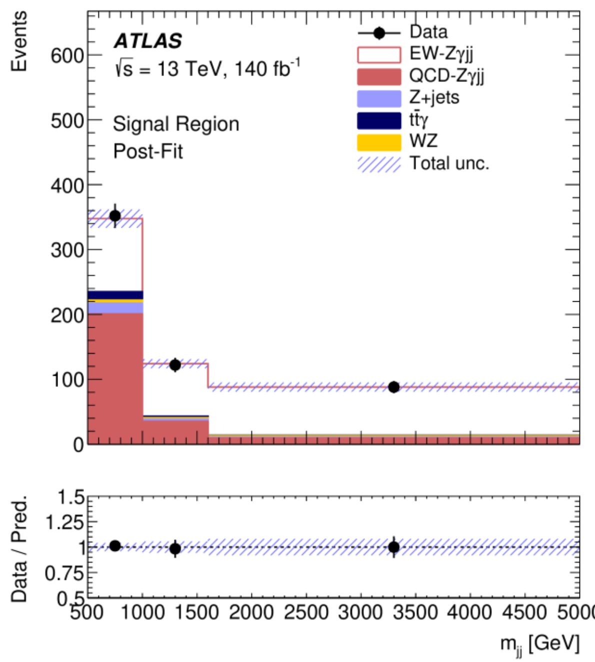


EW Zγjj

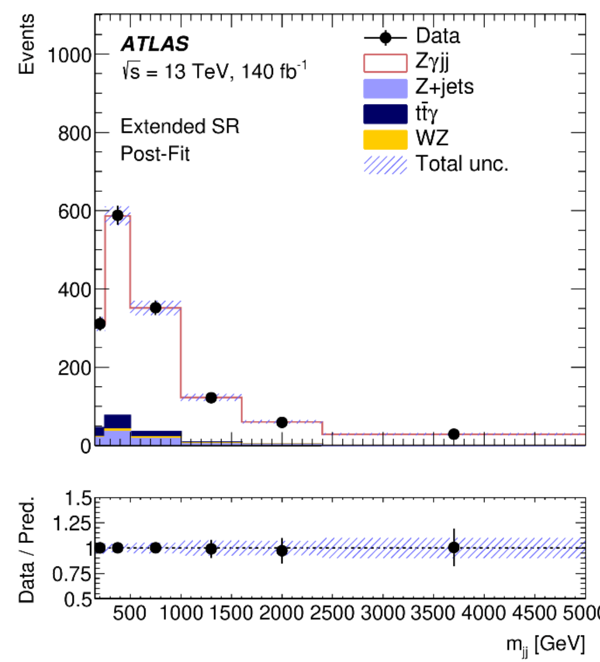


QCD Zγjj

- High pT leptons and photon, high m(jj) and topological cuts for EW production
- Small backgrounds from Z+jets, ttγ, WZ



Signal region with high m(jj) to measure EW process



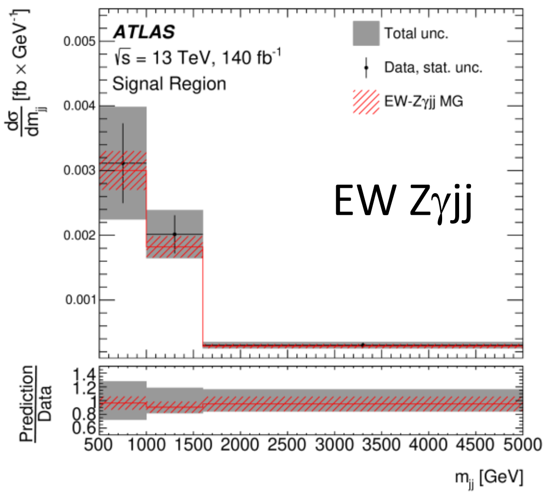
Relaxed region to measure inclusive EW+QCD process

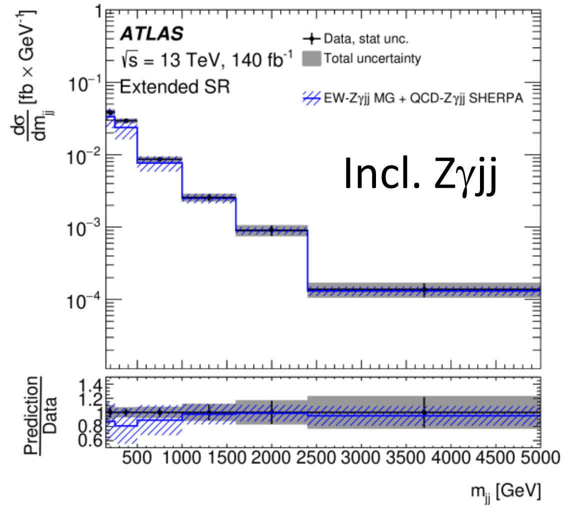
EW Zγjj

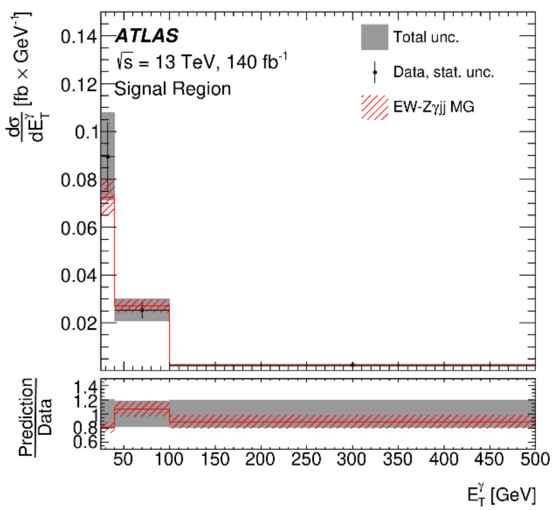
arXiv:2305.19142

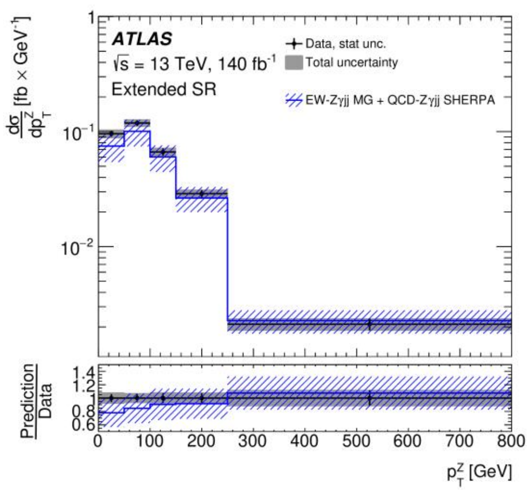
Measured differential σ

In fiducial regions defined close to detector selections









LO Madgraph gives reasonable modelling of EW process

Measurement precision is already constraining models in the inclusive case

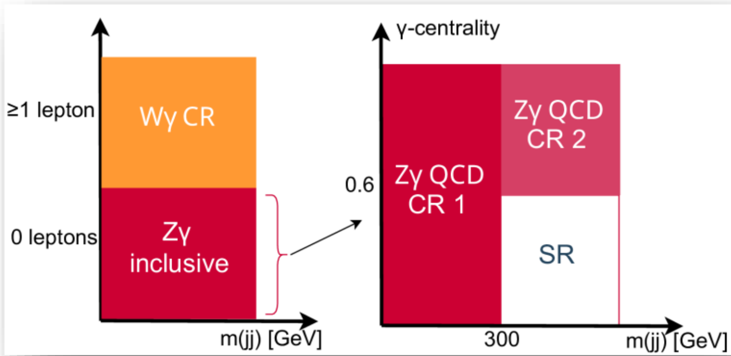
Statistical unc. dominates with modelling unc. being important

EW Zγjj

JHEP 06 (2023) 082

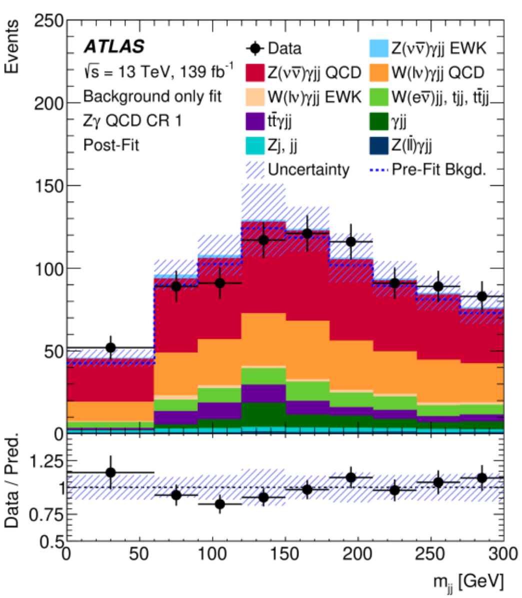
Z→νν decay is more challenging,
- independent cross-check
- sensitivity to aQGCs

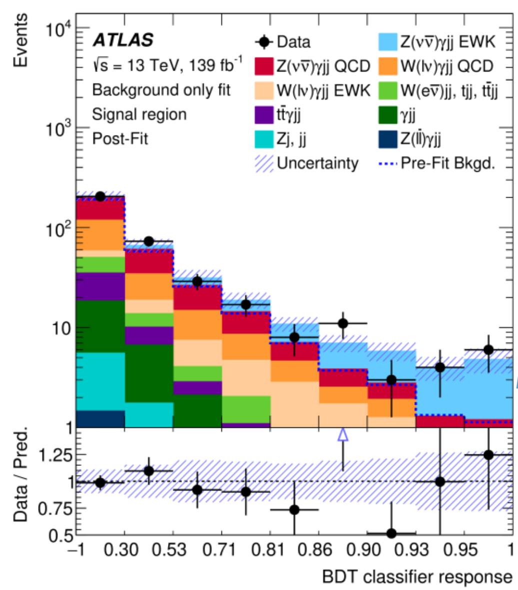
Used harsher cuts on photon E_T and p_T^{miss} to suppress backgrounds



Multiple regions defined to improve background modelling

MVA to improve signal significance in the SR





Simultaneous fits of SR and CRs are used to extra signal yields

A close-by, cut-based fiducial region is defined to measure

$$\sigma_{Z\gamma \mathrm{EWK}} = 0.77^{+0.34}_{-0.30}\ \mathrm{fb}$$

- Stat. unc. compatible to syst. unc. (mainly modelling)
- 3.2 σ evidence for high pT EW Zγjj measurement

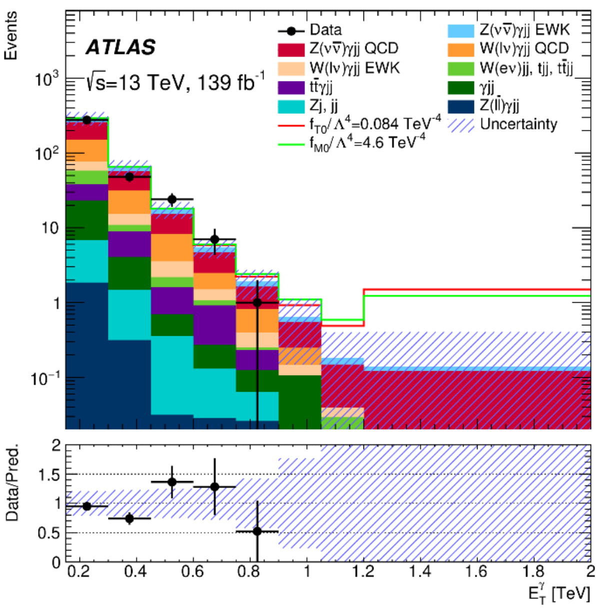
EW Zγjj

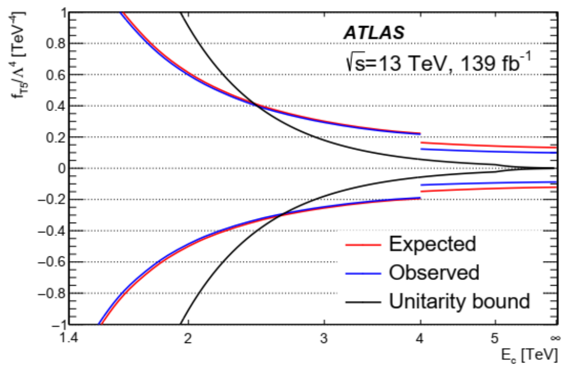
Detector distributions fitted to explore the modification from aQGCs (in the Effective Field Theory framework)

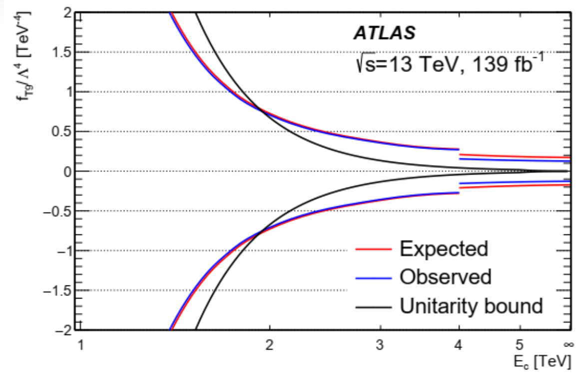
$$\mathcal{L} = \mathcal{L}^{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_j \frac{f_j}{\Lambda^4} O_j$$

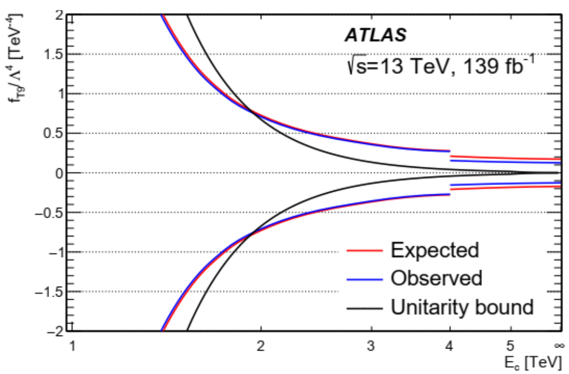
Sensitive to dim-8 Wilson coefficients, in particular those relating to neutral couplings

f_{M0}/Λ^4, f_{M1}/Λ^4, f_{M2}/Λ^4 f_{T0}/Λ^4, f_{T5}/Λ^4, f_{T8}/Λ^4 and f_{T9}/Λ^4









Coefficients constraints w.r.t. cut-off scale (with unitarity bound displayed)

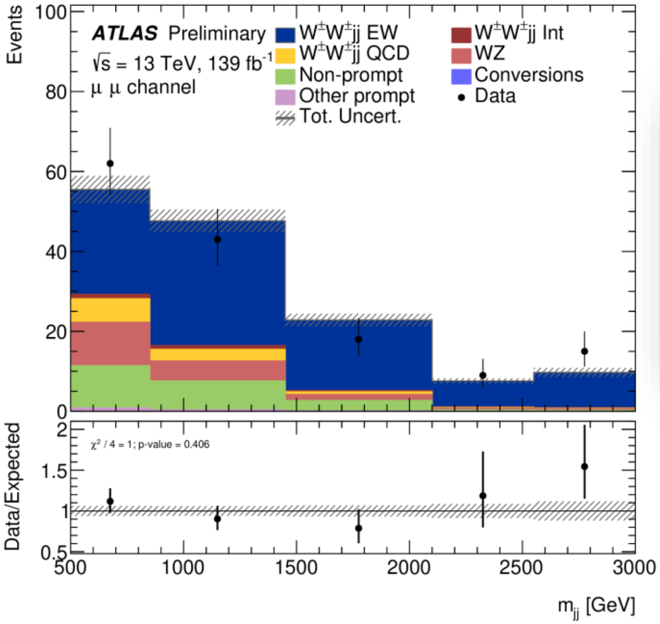
Best limits so far on T5-9 coefficients O(0.1) TeV^{-4}

Same-sign EW WWjj

ATLAS-CONF-2023-023

High S/B ratio channel due to requirement of same-sign W pairs
➔ same-sign dilepton + E_T^{miss} + jets

Likelihood fits used to extract cross-sections,
- QCD WWjj, WZjj normalization floating
- non-prompt, charge conversion background estimated with data



Fiducial σ fitted with m(jj)

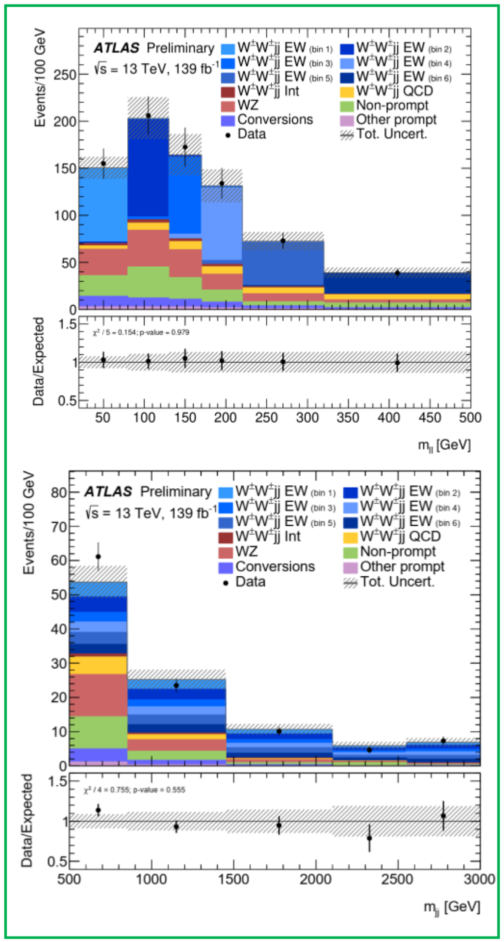
Description	$\sigma_{\text{fid}}^{\text{EW}}$, fb	$\sigma_{\text{fid}}^{\text{EW+Int+QCD}}$, fb
Measured cross section	2.88 ± 0.21 (stat.) ± 0.19 (syst.)	3.35 ± 0.22 (stat.) ± 0.20 (syst.)
MG_aMC@NLO+Herwig	2.53 ± 0.04 (PDF) $\pm^{0.22}_{0.19}$ (scale)	2.93 ± 0.05 (PDF) $\pm^{0.34}_{0.27}$ (scale)
MG_aMC@NLO+Pythia	2.55 ± 0.04 (PDF) $\pm^{0.22}_{0.19}$ (scale)	2.94 ± 0.05 (PDF) $\pm^{0.33}_{0.27}$ (scale)
Sherpa	2.44 ± 0.03 (PDF) $\pm^{0.40}_{0.27}$ (scale)	2.80 ± 0.03 (PDF) $\pm^{0.53}_{0.36}$ (scale)
Powheg Box +Pythia	2.67	–

- Consistency with a variety of predictions
  - ✓ Madgraph at LO QCD; SHERPA, Powheg with approximate NLO accuracies
- **10% overall unc. achieved!**
  - ✓ stat. unc. compatible with syst. unc.

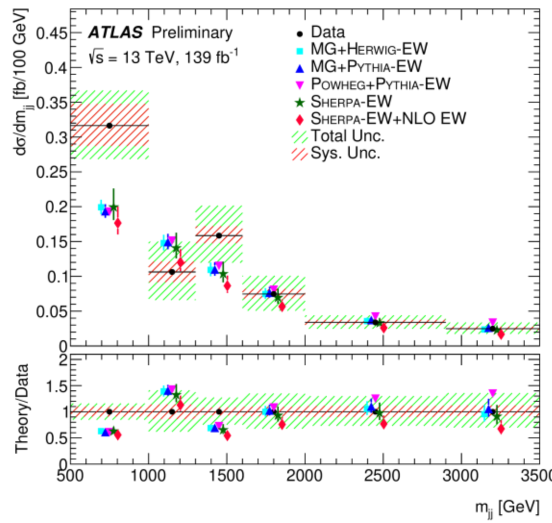
Same-sign EW WWjj

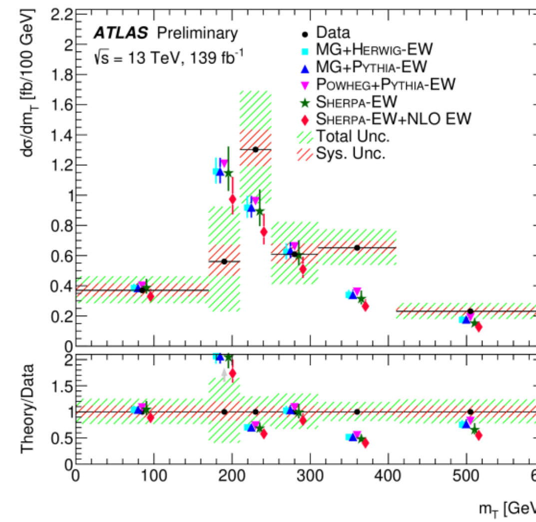
Differential σ measured by fits to 2D distributions with cross-sections per bin as POIs

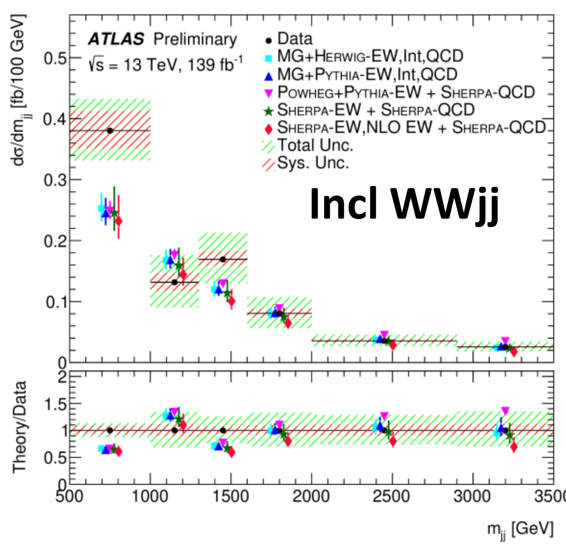
Example: 2D post fit of m(ll) and m(jj) to measured $\sigma_{m(ll)}$



EW WWjj





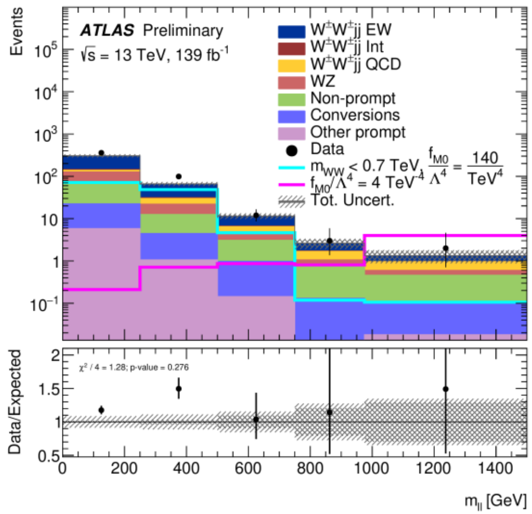


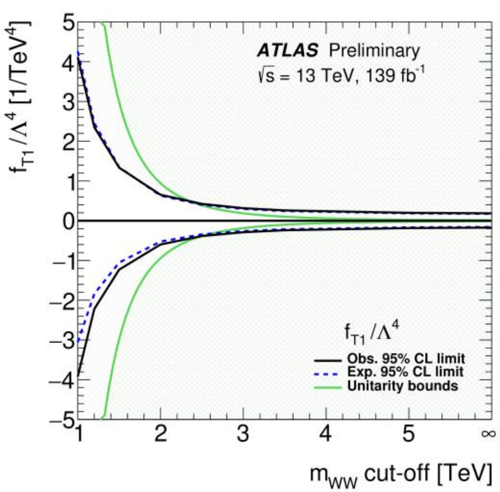
- Measurement agrees well with various predictions at high-energy regime
- A bit tension at Lower m(jj) may help to further constrain modelling

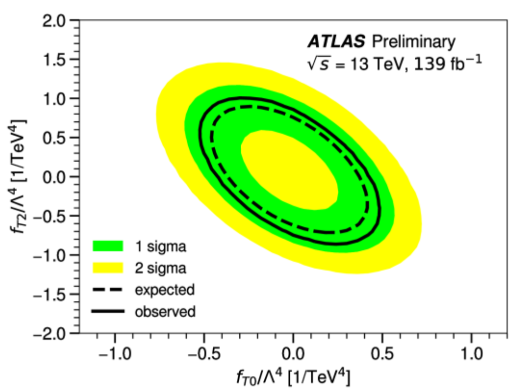
Same-sign EW WWjj

EFT constraints by fitting detector m(ll)

➔ Competitive limits on dim-8 coefficients



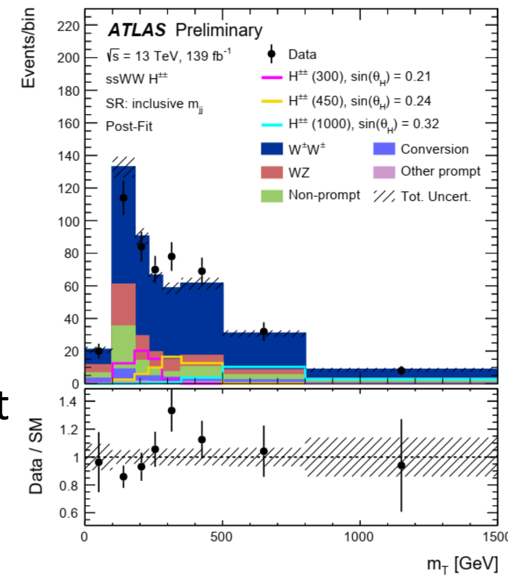


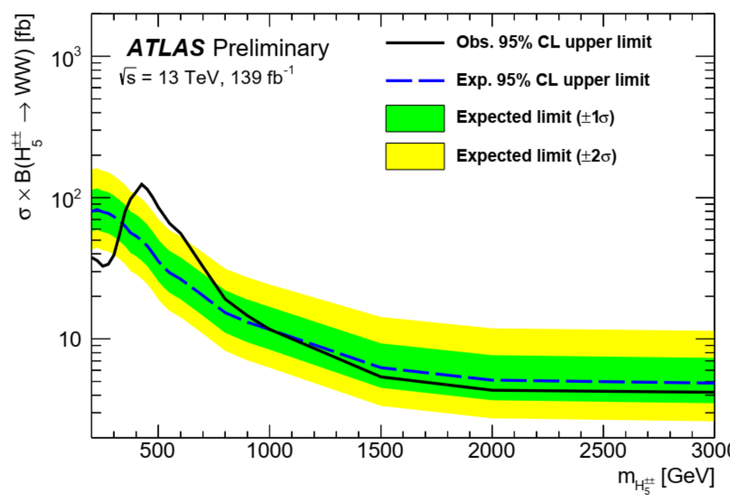


Cut-off dependence, 2D contours explored

Fit mT distribution to constrain H^{++} models

➔ Stringent limits



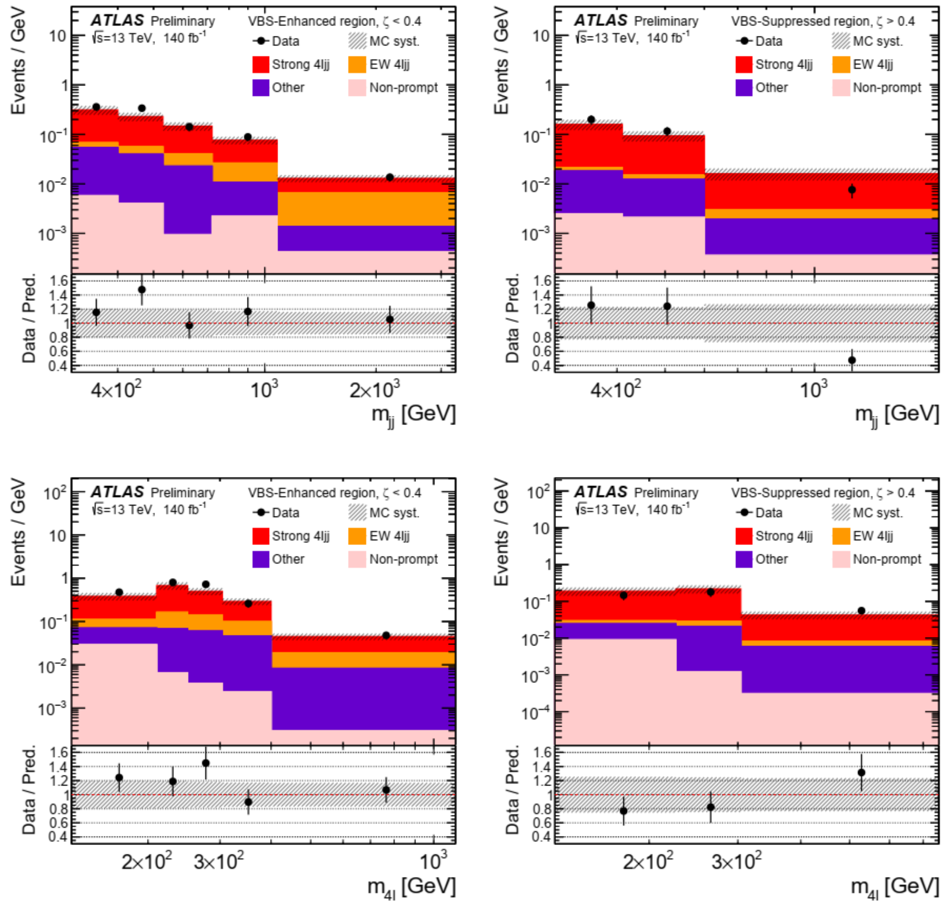


EW ZZjj

[ATLAS-CONF-2023-024]

Extend upon the previous results on EW ZZjj observation [NP 19 (2023) 237]

➔ cut-based analysis to explore differential distributions and EFT in 4-lepton channel



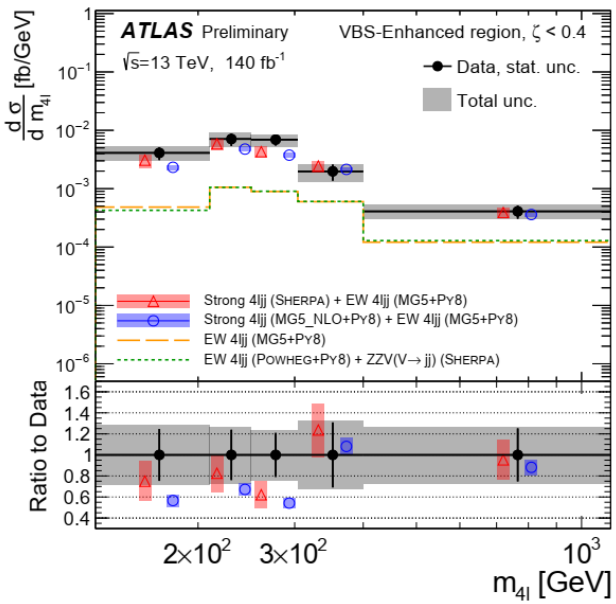
VBS enhanced   VBS suppressed

➔ Clean final state with small backgrounds

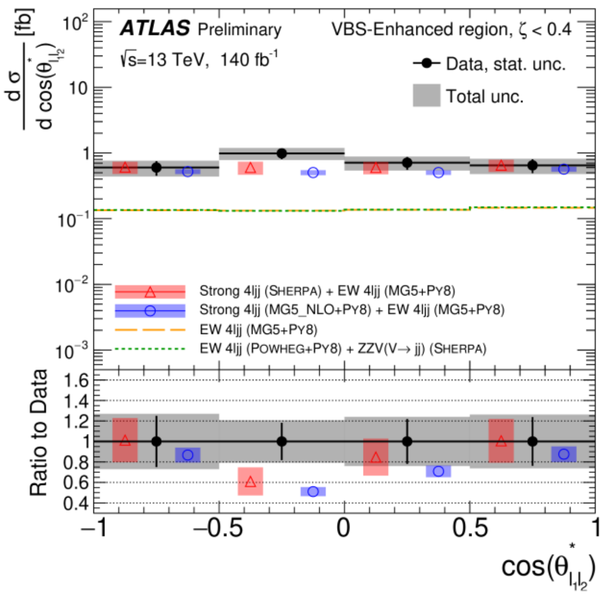
➔ Two regions one with sensitivity to EW ZZjj (small centrality), one more on inclusive ZZjj (large centrality)

EW ZZjj

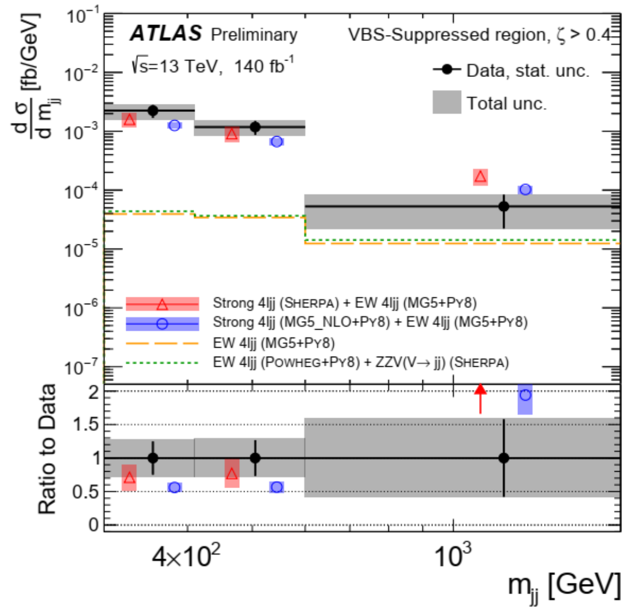
A variety of kinematic variables measured: sensitive to high-order effects, EWSB, EFT, polarization, …



Offer already probe of Higgs-related unitarization close to TeV



Angle between lepton and Z in Z rest frame sensitive to polarization, CP structures



Exposed to modelling of m(jj) from QCD and EW high-order effects

Consistent with various predictions including
NLO QCD + PS prediction for EW ZZjj from powheg

EW ZZjj

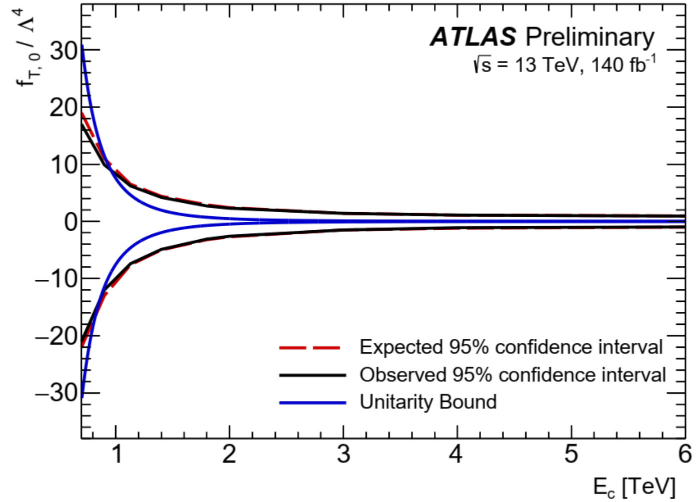
Measured differential σ as a function of m(4l) and m(jj) used constrain EFT coefficients

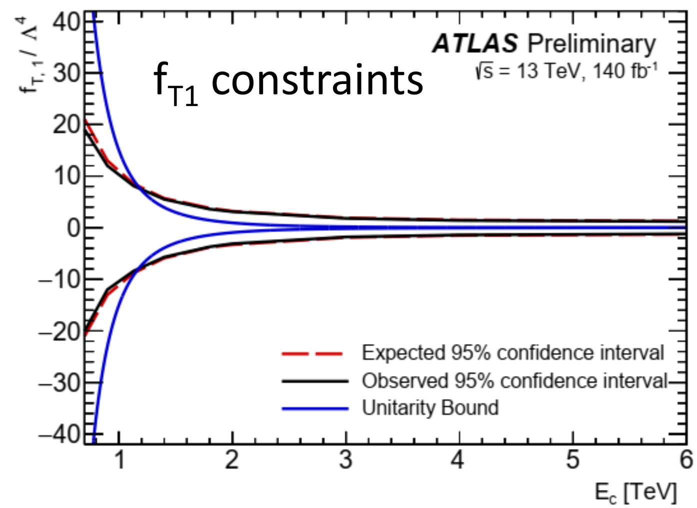
$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\,\mathrm{Re}(\mathcal{M}_{SM}{}^{*}\mathcal{M}_{d8}) + |\mathcal{M}_{d8}|^2$$

➔ Explored the constraints with and w/o dim-8 square amplitude term

Wilson coefficient	$\|\mathcal{M}_{d8}\|^2$ Included	95% confidence interval [TeV^{-4}] Expected	Observed
$f_{T,0}/\Lambda^4$	yes	[-0.98,0.93]	[-1.0,0.97]
	no	[-23, 17]	[-19, 19]
$f_{T,1}/\Lambda^4$	yes	[-1.2, 1.2]	[-1.3, 1.3]
	no	[-160, 120]	[-140, 140]
$f_{T,2}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-74, 56]	[-63, 62]
$f_{T,5}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-79, 60]	[-68, 67]
$f_{T,6}/\Lambda^4$	yes	[-3.9, 3.9]	[-4.1, 4.1]
	no	[-64, 48]	[-55, 54]
$f_{T,7}/\Lambda^4$	yes	[-8.5, 8.1]	[-8.8, 8.4]
	no	[-260, 200]	[-220, 220]
$f_{T,8}/\Lambda^4$	yes	[-2.1, 2.1]	[-2.2, 2.2]
	no	[-4.6, 3.1]×10^4	[-3.9, 3.8]×10^4
$f_{T,9}/\Lambda^4$	yes	[-4.5, 4.5]	[-4.7, 4.7]
	no	[-7.5, 5.5]×10^4	[-6.4, 6.3]×10^4

f_{T0} constraints with cut-off scale dependence





aQGC combination WZjj and WWjj

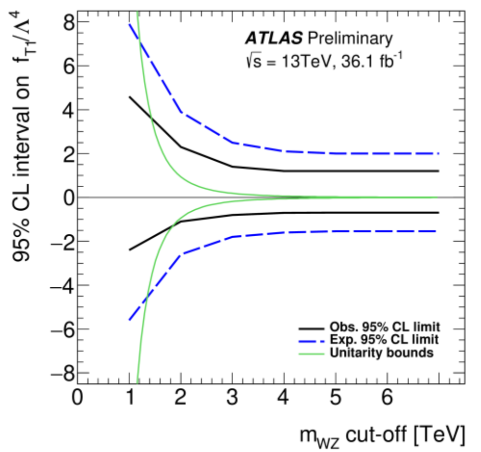
ATL-PHYS-PUB-2023-002

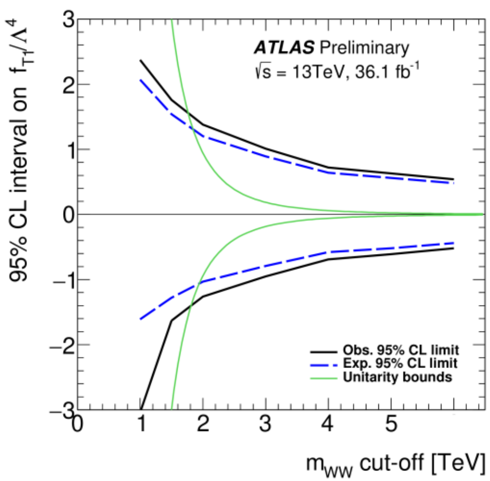
A demonstration of effects of combination to
EFT coefficient constraints from different EW VVjj channels

➔Based on partial run-2 results

➔Fit unfolded m_T(WZjj) and detector-level m(ll) in same-sign WWjj

Re-use measurement results to derive constraints over cut-off scale choices

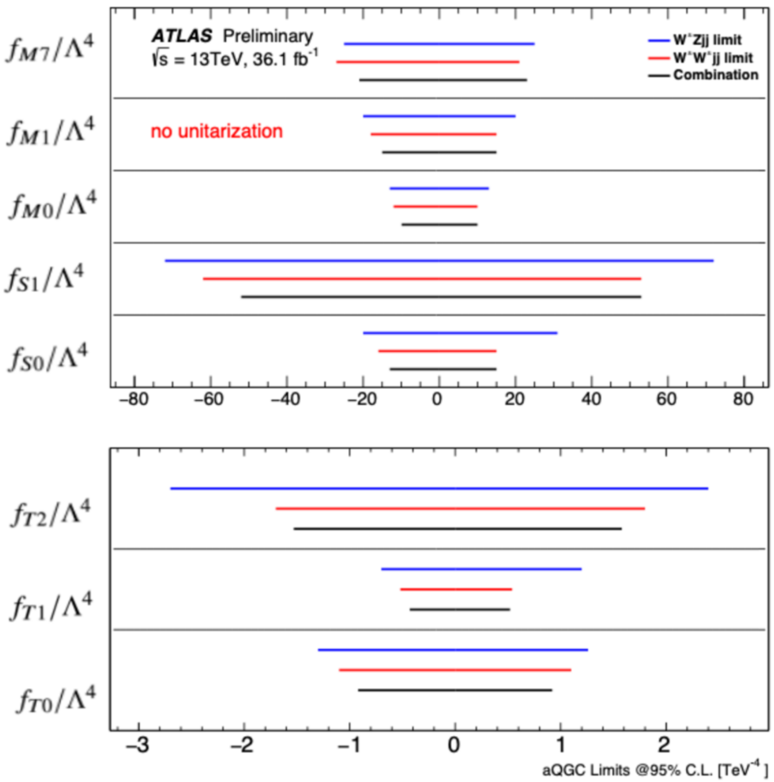


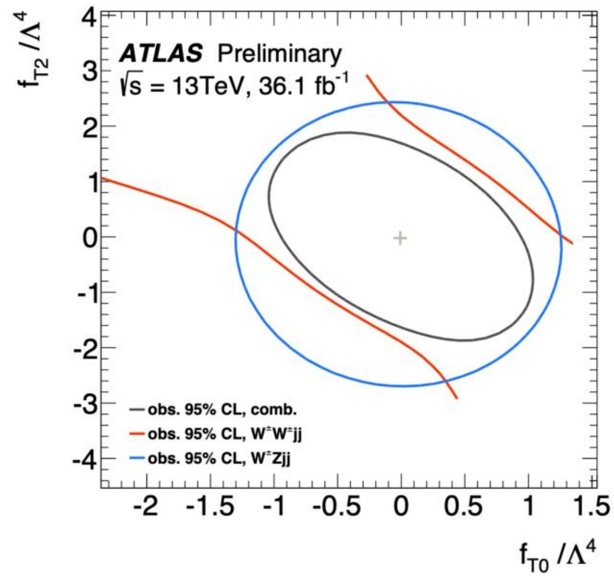


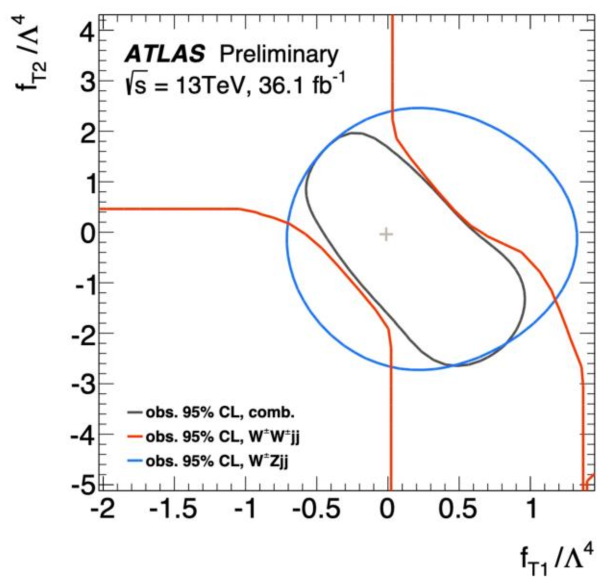
Uncertainty Source	$W^{\pm}Zjj$	$W^{\pm}W^{\pm}jj$	Combination
Luminosity	✓	✓	✓
Pile-up modelling	✓	✓	✓
Jets	✓	✓	
Electrons	✓	✓	
Muons	✓	✓	
b-tagging	✓	✓	
Misid. lepton background	✓	✓	
$W^{\pm}Zjj$ modelling	✓	✓	
Unfolding uncertainty	✓		
$W^{\pm}W^{\pm}jj$-EW modelling		✓	
EFT modelling: Scale and parton shower	✓	✓	
EFT modelling: PDF	✓	✓	✓
EFT folding uncertainty		✓	

Treat properly the experimental and theoretical uncertainty correlation for combination

aQGC combination WZjj and WWjj







Combination leads to 10-20% improvement for single parameter constraint

➔ More sizable improvement looking at multi-dimensional spaces: exploit fully potentials from different channels

Summary

- ❑ This talk reported recent ATLAS results on EW VVjj measurements
- ❑ Moving beyond first phase of making observations, differential measurements are being performed, yielding constraining power to the modelling of these rare processes at the first time
- ❑ EW VVjj processes provide sensitive probe to aQGCs: no anomalies are currently found → strong limits set in the EFT framework
- ❑ Combination of different measurements (a.k.a. global fits) can give best possible constraints, and attempts have been made
- ❑ Stay tuned for further results with LHC Run-3!

Thank you for your attention!

ATLAS Detector