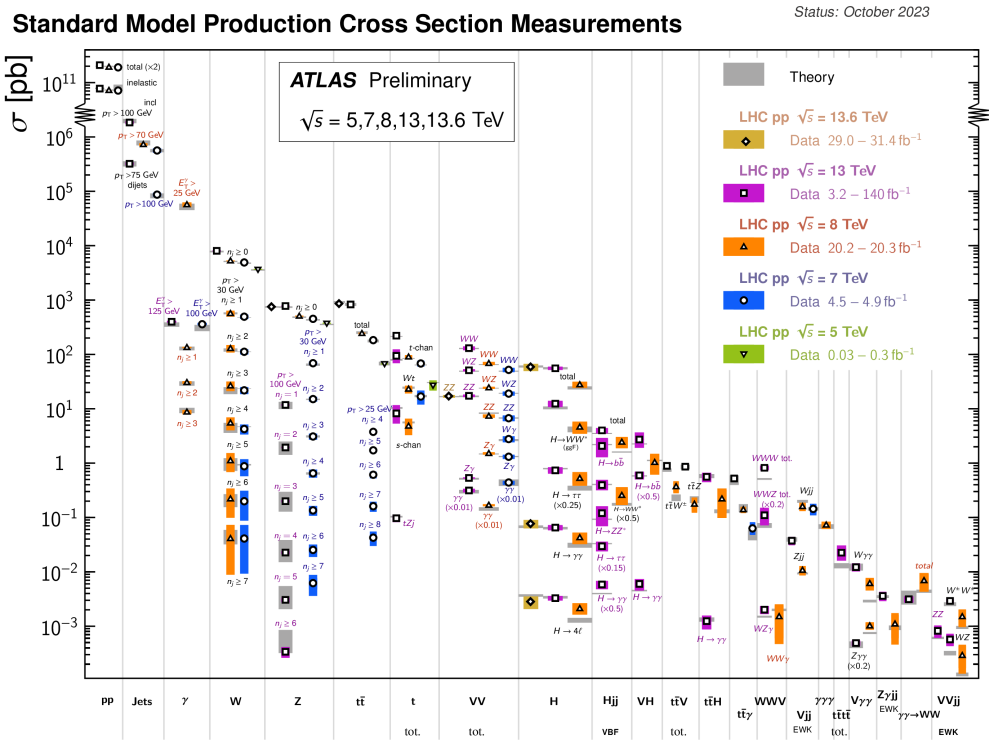
Measurement of $4\ell jj$ production using 140 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector

Matteo D'Uffizi for the ATLAS Collaboration

Standard Model at the LHC 2024

Introduction and motivations

- Wide community interest in studying **VBS-like (vector boson scattering) topologies**
  - Understanding VBS-background modelling is of paramount importance if we are to squeeze the most physics out of VBS in the LHC Run 3
  - Measurement of $4\ell jj$ **production** can improve our understanding of **EW and Strong interactions**
  - Sensitive to 3 and **4-weak boson self-interactions**
  - Differential cross-sections can probe New Physics (aTGC, aQGC)
- Electroweak (EW) $ZZjj$ production is a **very rare** process
- Previous observation by ATLAS [1] and evidence by CMS [2]

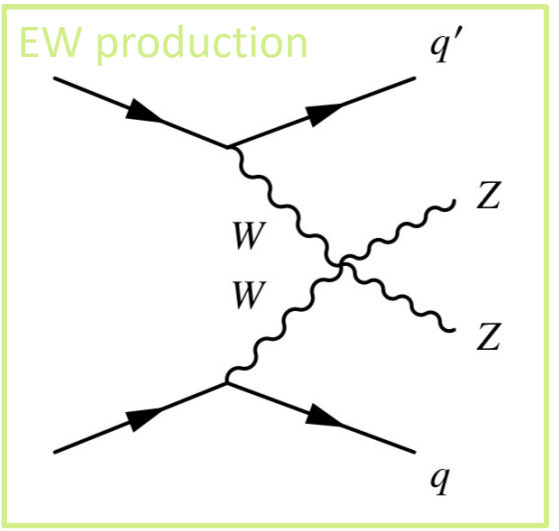


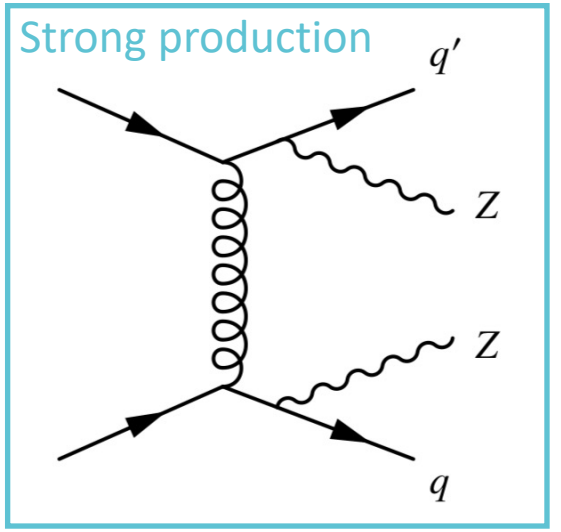
Plot from [3]

[1] Nature Phys. 19 (2023) 237
[2] Phys. Lett. B 812 (2020) 135992
[3] ATL-PHYS-PUB-2023-039

Measurement overview

- This measurement **recently published by ATLAS** [4] exploits the full 140 fb^{-1} **Run 2** dataset to provide
  - **unfolded differential cross-sections** of $\mathrm{pp} \to \ell^+\ell^-\ell'^+\ell'^- jj$ with $\ell, \ell' = e, \mu$
  - **EFT interpretations** of dim-8 operators
- **Signal**
  - "EW $4\ell jj$" production (VBS)
  - "Strong $4\ell jj$" production (jets arising from strong interactions)
- **Backgrounds**
  - Events with four prompt leptons ($t\bar{t}Z$ and VVV) estimated from MC
  - Events with $\geq$1 non-prompt leptons ($WZjj$ and $t\bar{t}$) estimated with a data-driven technique





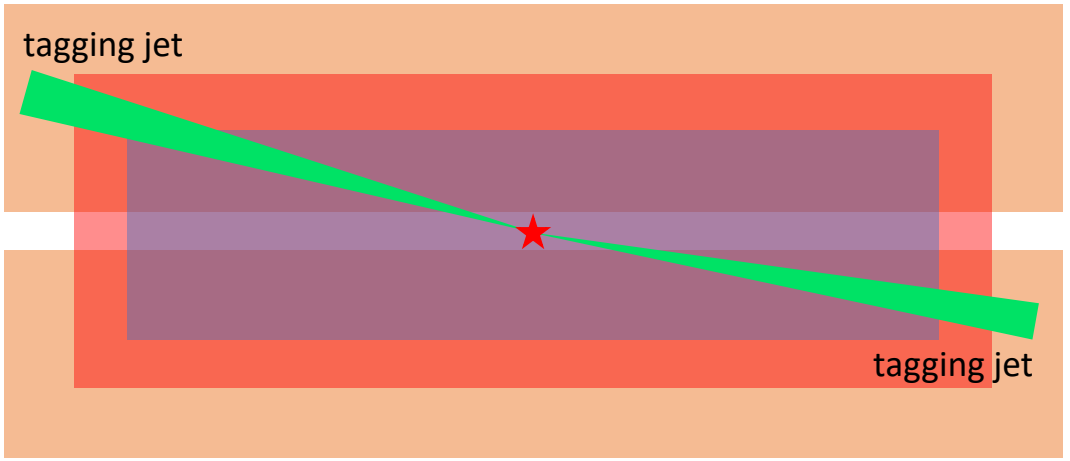
[4] JHEP 01 (2024) 004

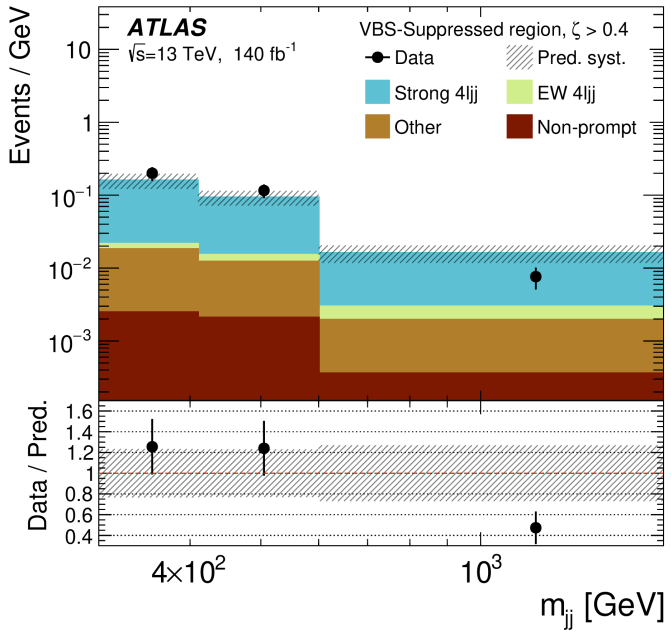
Selection and region definition

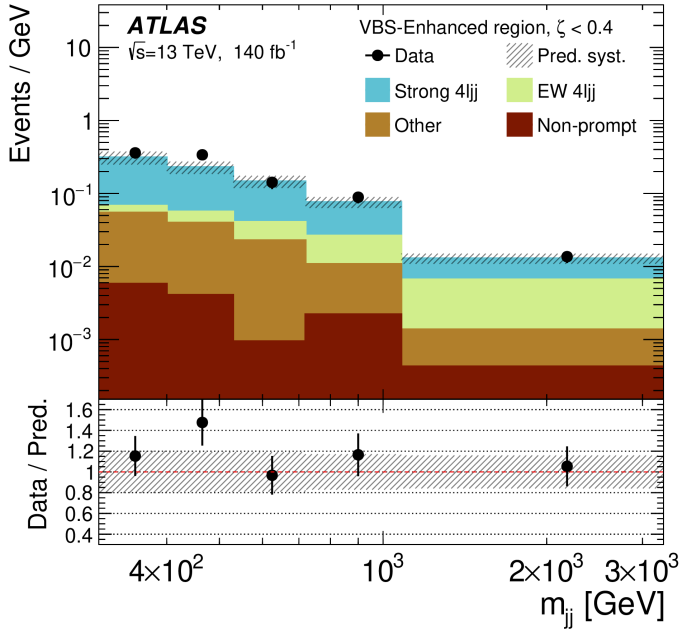
- Completely reconstructible final state (selection details in backup)
- 2 Same-Flavour Opposite-Sign lepton pairs (e, μ)
- **Dijet** system with VBS-like topology
  - High **invariant mass** ($m_{jj} > 300$ GeV)
  - Large **rapidity** separation ($|\Delta y_{jj}| > 2$)
- Events from EW production tend to have a low **centrality** value

$$\zeta_{4\ell jj} = \left| \frac{y_{4\ell} - 0.5(y_{j1} + y_{j2})}{\Delta y_{jj}} \right|$$

- **VBS-Enhanced** and **VBS-Suppressed** signal regions defined with $\zeta_{4\ell jj}$

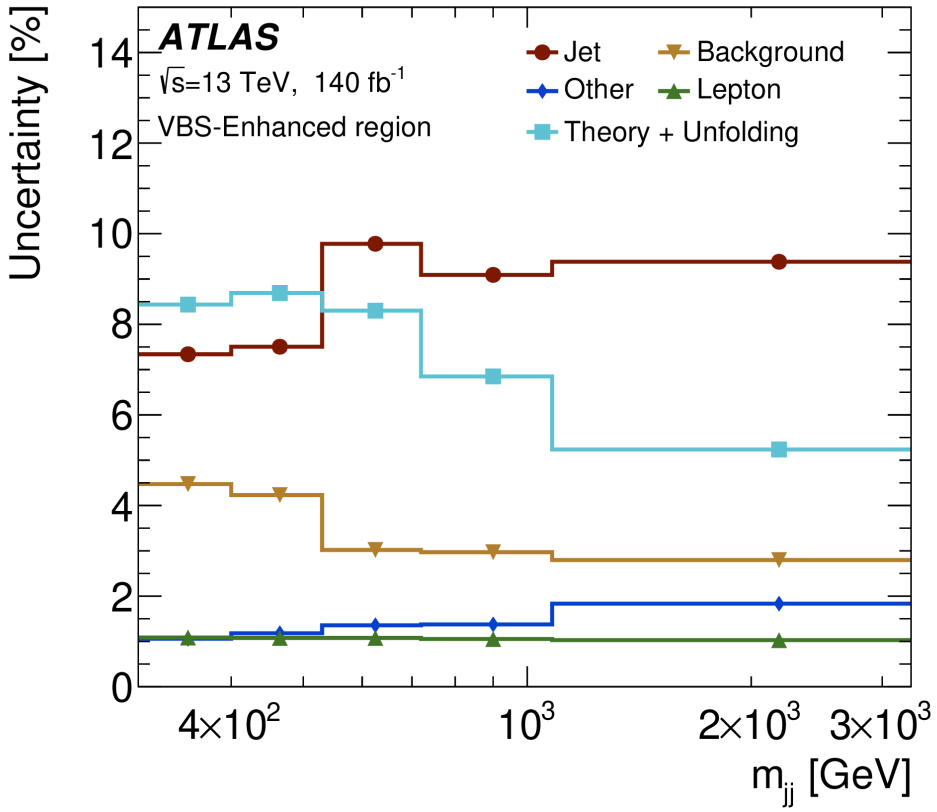






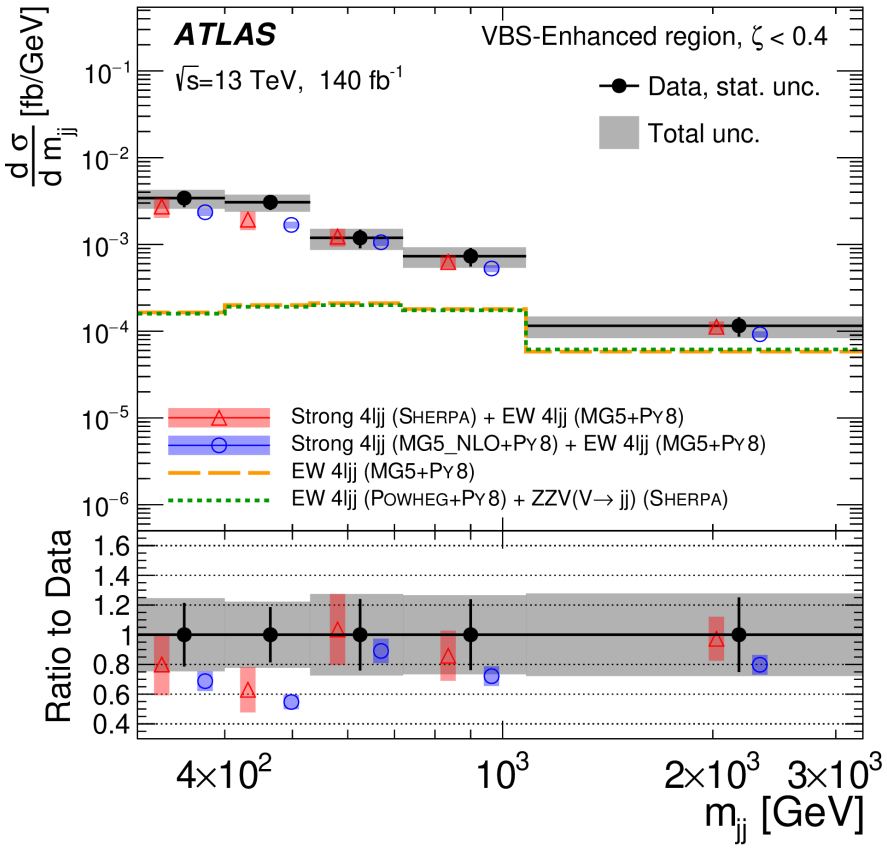
Unfolding and uncertainties

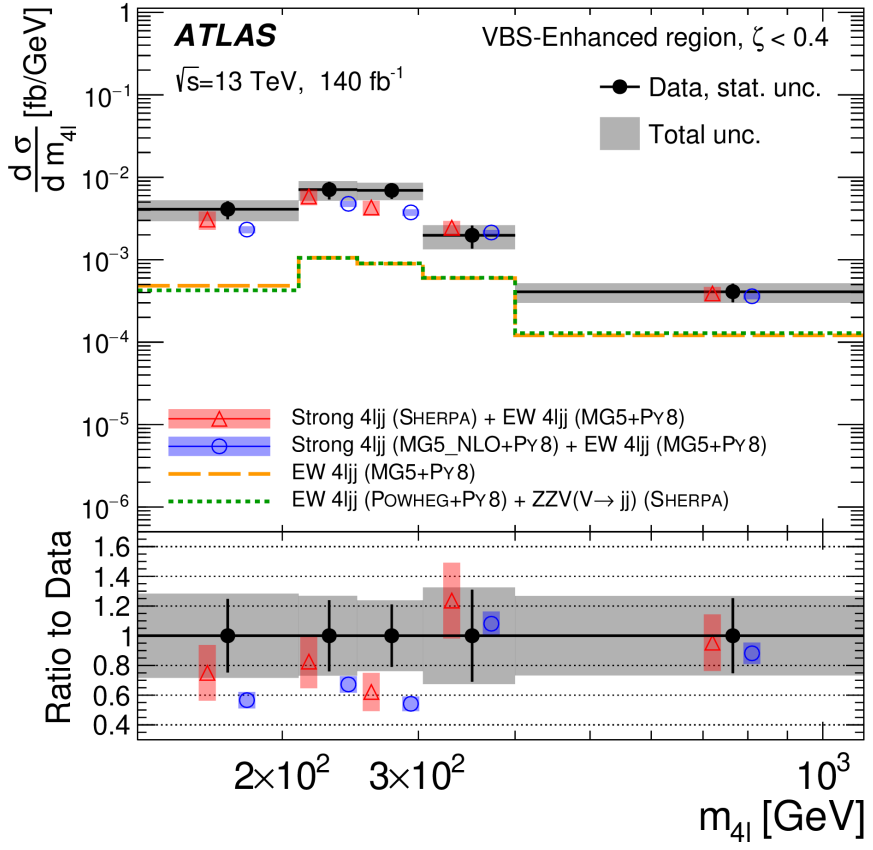
- **Iterative Bayesian unfolding** to correct for detector effects
  - Important to preserve the results
  - Allows for direct comparison with theory predictions
- **Binning** chosen to have a sensible statistical uncertainty and low migrations
- **Number of iterations** optimised to minimise the total unfolding and statistical uncertainty
- **Systematic uncertainties** are propagated through the unfolding procedure
  - Leading sources from **jet reconstruction**, **theory** predictions and **unfolding bias**



Unfolded differential cross-sections

- Unfolded cross-sections in agreement with predictions (some underestimation from MG5+PY8 strong production)





- "Strong $4\ell jj$" Sherpa and MG have similar accuracy for the 2-jet final state
- Different modelling for additional emissions
  - Sherpa is LO up to 3 jets
  - MG relies on parton shower

EFT interpretations

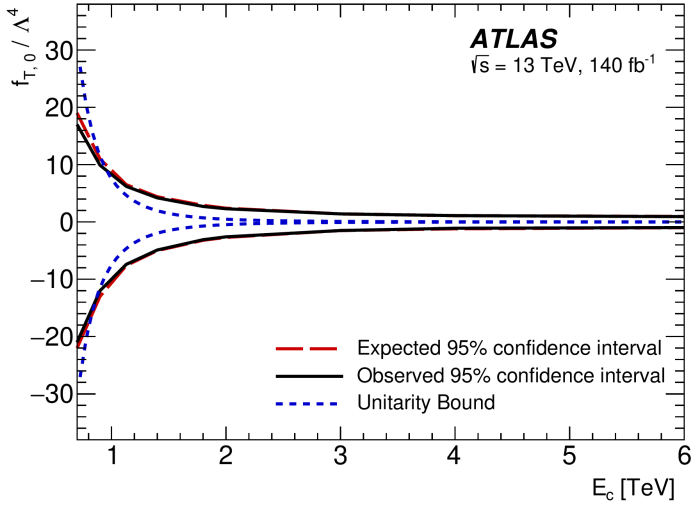
- The EFT Lagrangian extends the SM with higher-order operators

$$\mathcal{L}^{(d8)} = \mathcal{L}_{SM} + \sum_i \frac{f_{T,i}}{\Lambda^4} \mathcal{O}_{T,i}$$

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

- Dimension-8 operators can induce **anomalous** weak-boson self-interactions
- Can only be tested in VBS or VVV production
- **Limits** to dim-8 operators obtained from a **combined fit** to m_{jj} and $m_{4\ell}$ in the VBS-Enhanced region (**profile-likelihood** test statistic)

Wilson coefficient	$\lvert\mathcal{M}_{d8}\rvert^2$ Included	95% confidence interval [TeV^{-4}] Expected	Observed
$f_{T,0}/\Lambda^4$	yes	[-1.00, 0.97]	[-0.98, 0.93]
	no	[-19, 19]	[-23, 17]
$f_{T,1}/\Lambda^4$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-140, 140]	[-160, 120]
$f_{T,2}/\Lambda^4$	yes	[-2.6, 2.5]	[-2.5, 2.4]
	no	[-63, 62]	[-74, 56]
$f_{T,5}/\Lambda^4$	yes	[-2.6, 2.5]	[-2.5, 2.4]
	no	[-68, 67]	[-79, 60]
$f_{T,6}/\Lambda^4$	yes	[-4.1, 4.1]	[-3.9, 3.9]
	no	[-550, 540]	[-640, 480]
$f_{T,7}/\Lambda^4$	yes	[-8.8, 8.4]	[-8.5, 8.1]
	no	[-220, 220]	[-260, 200]
$f_{T,8}/\Lambda^4$	yes	[-2.2, 2.2]	[-2.1, 2.1]
	no	[-3.9, 3.8]$\times 10^4$	[-4.6, 3.1]$\times 10^4$
$f_{T,9}/\Lambda^4$	yes	[-4.7, 4.7]	[-4.5, 4.5]
	no	[-6.4, 6.3]$\times 10^4$	[-7.5, 5.5]$\times 10^4$



Summary

- **VBS processes** provide an exciting opportunity to deepen our knowledge of the SM **EW sector** and probe for **New Physics**
- Improving the modelling of **strong production** in such extreme phase-spaces can be very helpful for future analyses
- **Differential cross-section** of $4\ell jj$ production were measured in a VBS-Enhanced and Suppressed region, characterising different kinematic observables
- m_{jj} and $m_{4\ell}$ cross-sections were used to set **constraints on dimension-8 EFT operators**
- **No significant deviations** from the SM have been observed
- The measurement is limited by the rarity of the process and the Run2 luminosity
- Room for improvement with additional data from LHC **Run3** and beyond

Backup

Event selection

- Lepton quadruplet
  - $p_{T,\ell} > 20$ GeV for the two leading leptons
  - Two $\ell^+\ell^-$ pairs with $m_{\ell\ell} > 5$ GeV and $\Delta R_{\ell_1,\ell_2} > 0.05$
  - Select the two pairs with smallest $\left|m_{\ell_1,\ell_2} - m_Z\right| + \left|m_{\ell_3,\ell_4} - m_Z\right|$
  - $m_{4\ell} > 130$ GeV
  - Pair ordering based on smallest $\left|y_{\ell_i\ell_j}\right|$
- Dijet system
  - $p_{T,j_1} > 40$ GeV and $p_{T,j_2} > 30$ GeV
  - $\eta_{j_1} \cdot \eta_{j_2} < 0$ and $\left|\Delta y_{jj}\right| > 2$
  - $m_{jj} > 300$ GeV