LHCP In The Virtual World

Multiboson Measurements @ATLAS

(not photon-induced)

Introduction and Motivation

- Tests of Electroweak and QCD Theories
- Electroweak Boson self-interactions
- Background to Higgs and BSM signatures
- Fiducial and differential cross sections corrected for detector effects, useful for tuning Monte Carlos
- Look for evidence of coupling modifications of gauge bosons, Higgs in tails of distributions
- Search for new interactions: e.g. 4 fermion interactions, MSSM, models with additional gauge bosons, Higgses
- Publish full set of correlated uncertainties such that measurements can easily provide constraints on new physics models.

Related Talks:

1. Multiboson Measurements - Wed., June 9 plenary
2. Experimental EFT Results - Wed., June 9 EFT Interpretations parallel
3. Rare Decay Search - Thurs., June 10 EWK precision parallel

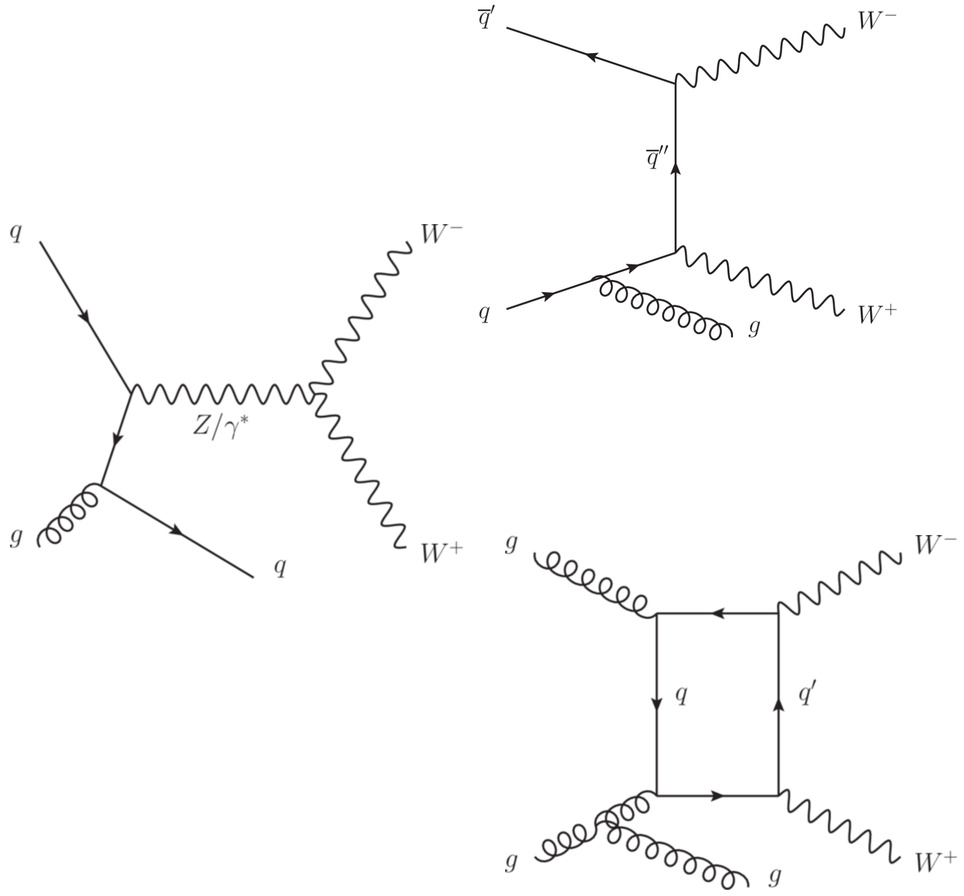
Measurements of W^+W^- + ≥1 jet production

Accepted by JHEP

arXiv: 2103.01918

WW + 1 jet inclusive measurement

- Integrated and differential fiducial cross section measurements
- First differential measurements in this final state at the LHC
- Sensitivity to triple gauge coupling vertex
- One jet topologies contain increased interference (over WW inclusive) between SM amplitude and anomalous amplitude by allowing different helicity configurations, increasing sensitivity to aTGCs



WW+1jet event selection

- eμ channel only
- kinematic cuts designed to match fiducial region
- large top background suppressed with b-jet veto
- $m_{e\mu}$ > 85 GeV suppresses resonant H->WW and Drell-Yan backgrounds
- correct for detector effects using iterative Bayesian unfolding

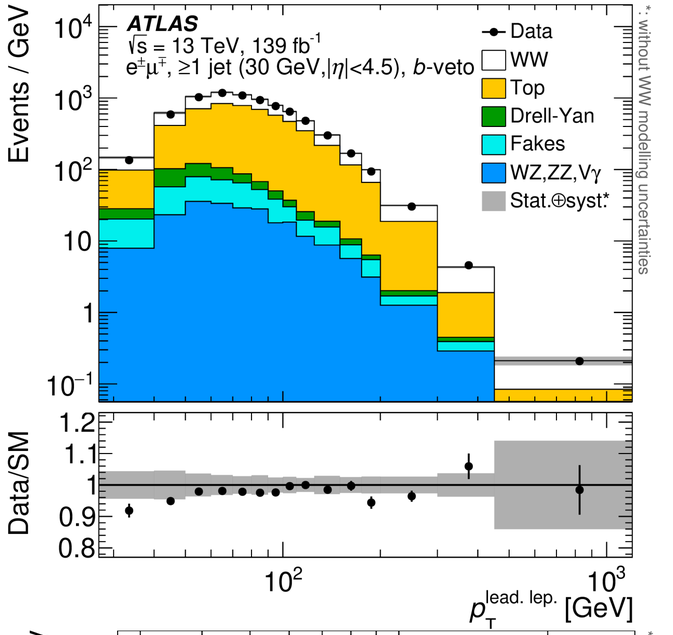
Selection	Criteria	
Lepton p_{T}	> 27 GeV	
Lepton η	$\lvert\eta\rvert < 2.47$ and not $1.37 < \lvert\eta\rvert < 1.52$ (electron) $\lvert\eta\rvert < 2.5$ (muon)	
Lepton identification	`TightLH` (electron), `Medium` (muon)	
Lepton isolation	`Gradient` (electron), `Tight_FixedRad` (muon)	
Lepton impact parameter	$\lvert d_0/\sigma_{d_0}\rvert < 5, 3$ (electron, muon) $\lvert z_0 \cdot \sin\theta\rvert < 0.5$ mm	
Jet selection	$p_{\mathrm{T}} > 30$ GeV, $\lvert\eta\rvert < 4.5$	
b-jet selection	$p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 2.5$, DL1r (85% eff. WP)	
Lepton selection	1 electron and 1 muon of opposite charge, no additional lepton with $p_{\mathrm{T}} > 10$ GeV, `Loose` isolation, and `LooseLH` (electron) / `Loose` (muon) identification	
Number of jets	≥ 1	
Number of b-jets	0	
$m_{e\mu}$	> 85 GeV	
High $p_{\mathrm{T}}^{\text{lead. jet}}$ selection	$p_{\mathrm{T}}^{\text{lead. jet}} > 200$ GeV	*for anomalous coupling limits, testing for H.O. EWK corrections*

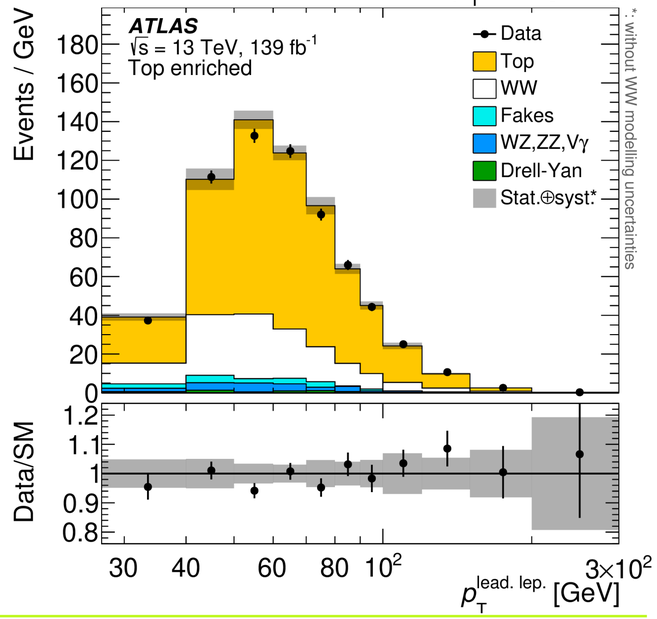
Background Estimations

- Backgrounds are top dominated
  - $t\bar{t}$ is estimated with data-driven technique[1]
  - two control regions: =1 btag and =2btags
  - reduction in background uncertainty relative to using simulation is factor ~5.
  - estimation is validated in top enriched subset of signal region with additional requirements $m_{\ell j} < 140$ GeV and $\Delta\phi(e, \mu) < \pi/2$

$$N_{1b}^{t\bar{t}} = N_{1b} - N_{1b}^{\text{others}} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot 2\varepsilon_b (1 - C_b\varepsilon_b)$$
$$N_{2b}^{t\bar{t}} = N_{2b} - N_{2b}^{\text{others}} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot C_b\varepsilon_b^2 ,$$
$$N_{0b}^{t\bar{t}} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot \left(1 - 2\varepsilon_b + C_b\varepsilon_b^2\right) ,$$

- Drell-Yan (mostly Z->$\tau\tau$) is estimated with simulation
- Fake leptons (mainly from W+jets) estimated using data-driven technique[2]
- Single top and diboson backgrounds simulated with Sherpa

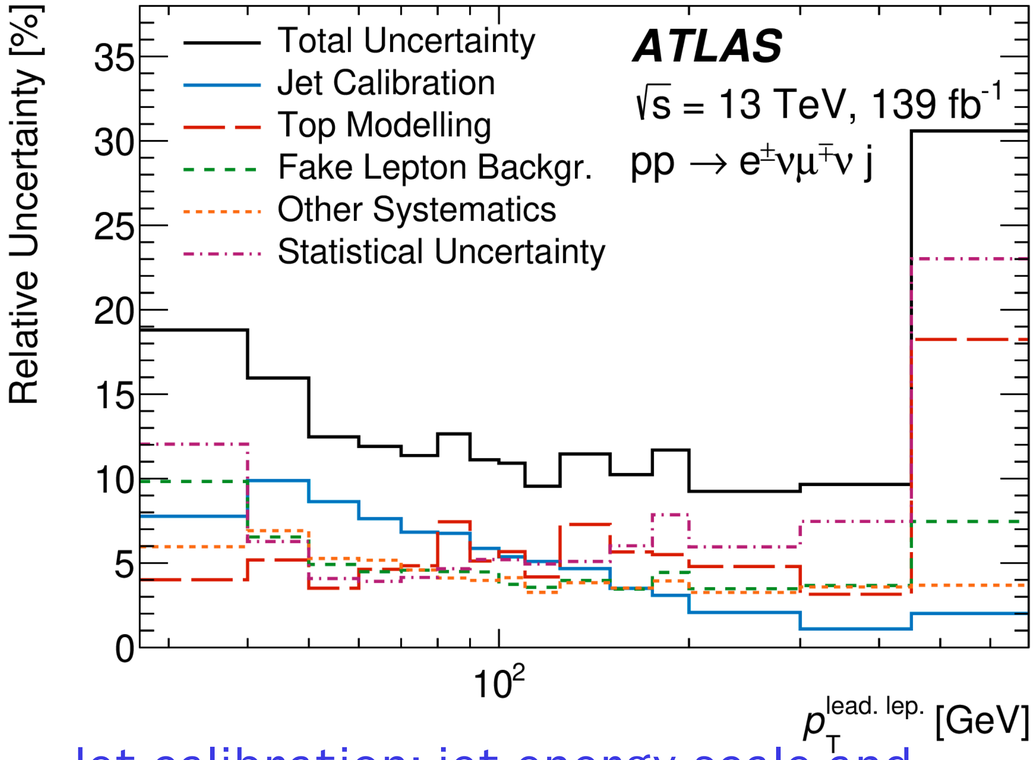




1. adapted from tt cross section measurement http://dx.doi.org/10.1140/epjc/s10052-020-7907-9
2. adapted from http://dx.doi.org/10.1103/PhysRevLett.123.161801

Systematic Uncertainties

Uncertainty source	Relative effect
Total uncertainty	10%
Signal region statistical uncertainty	1.1%
Data-driven background and MC statistics	1.2%
Jet calibration	6.3%
Top modelling	4.5%
Fake-lepton background	4.3%
Signal modelling	2.7%
Other background	2.3%
Flavour tagging	2.3%
Luminosity	1.9%
Other systematic uncertainties	0.6%



Jet calibration: jet energy scale and resolution

Top modeling: uncertainties in ME calculation, scale choices, parton shower modeling, ISR/FSR, interference

Fiducial Cross Section

- Measurement:

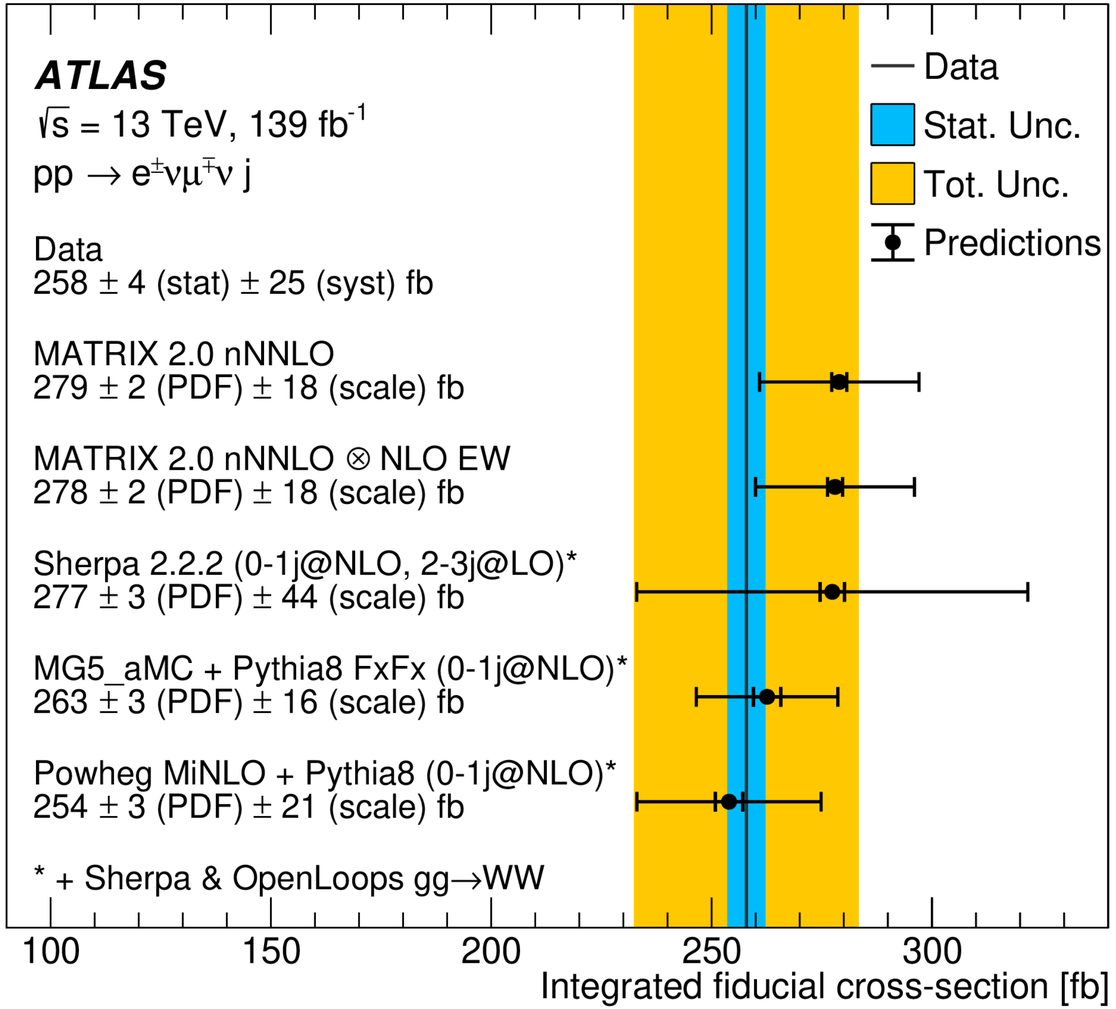
$$\sigma_{\text{fid}} = 258 \pm 4\ (\text{stat.}) \pm 25\ (\text{syst.})\ \text{fb}$$

10% uncertainty!

- Predictions from fixed-order NLO predictions (MATRIX) and MEPS programs (Sherpa, MG5, Powheg) in good agreement with measurement

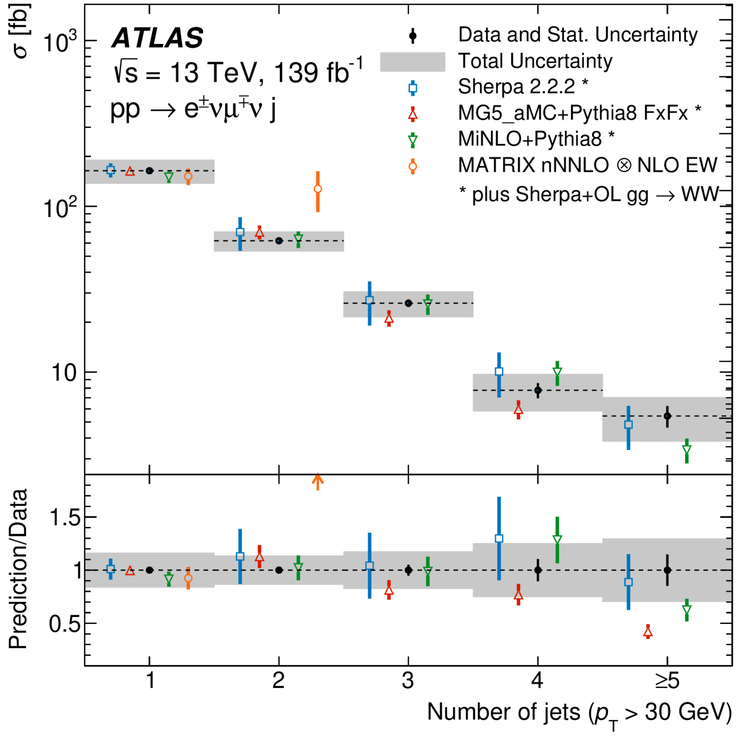
Fiducial selection requirements		
p_{T}^{ℓ}	>	27 GeV
$\lvert\eta^{\ell}\rvert$	<	2.5
$m_{e\mu}$	>	85 GeV
p_{T}^{j}	>	30 GeV
$\lvert y^{j}\rvert$	<	4.5

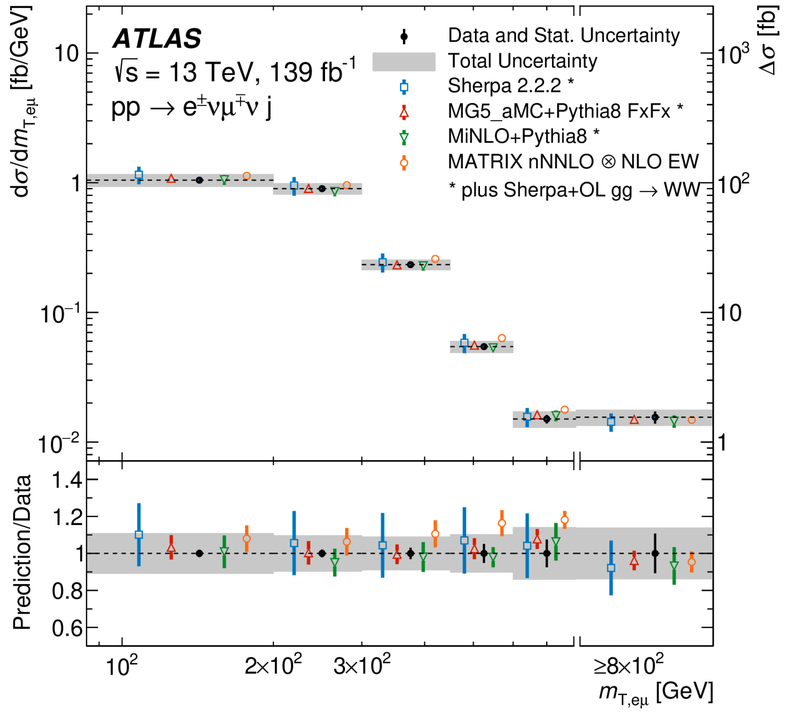
Results with fiducial b-veto available on HEPDATA

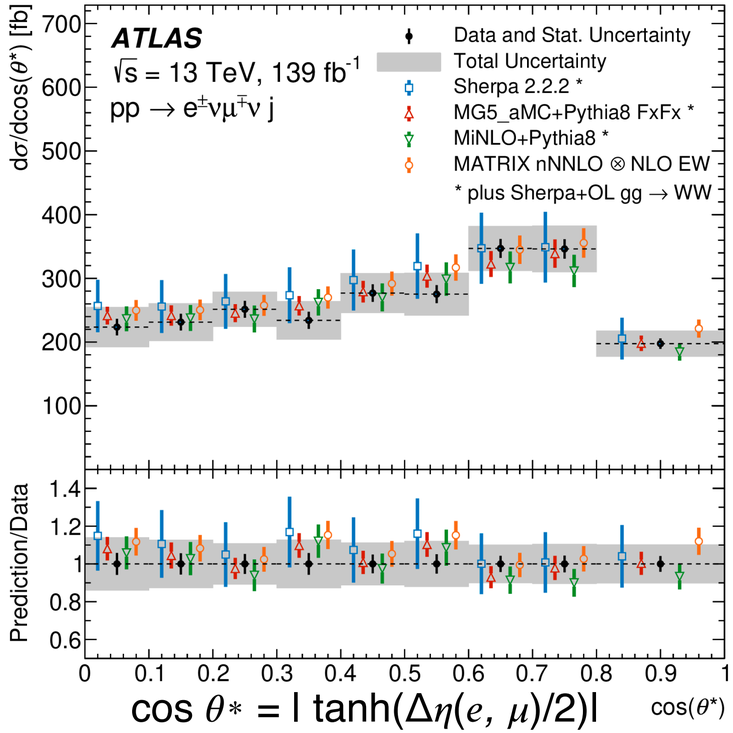


Differential cross sections

Very good agreement between measurements and predictions in hadronic and leptonic variables

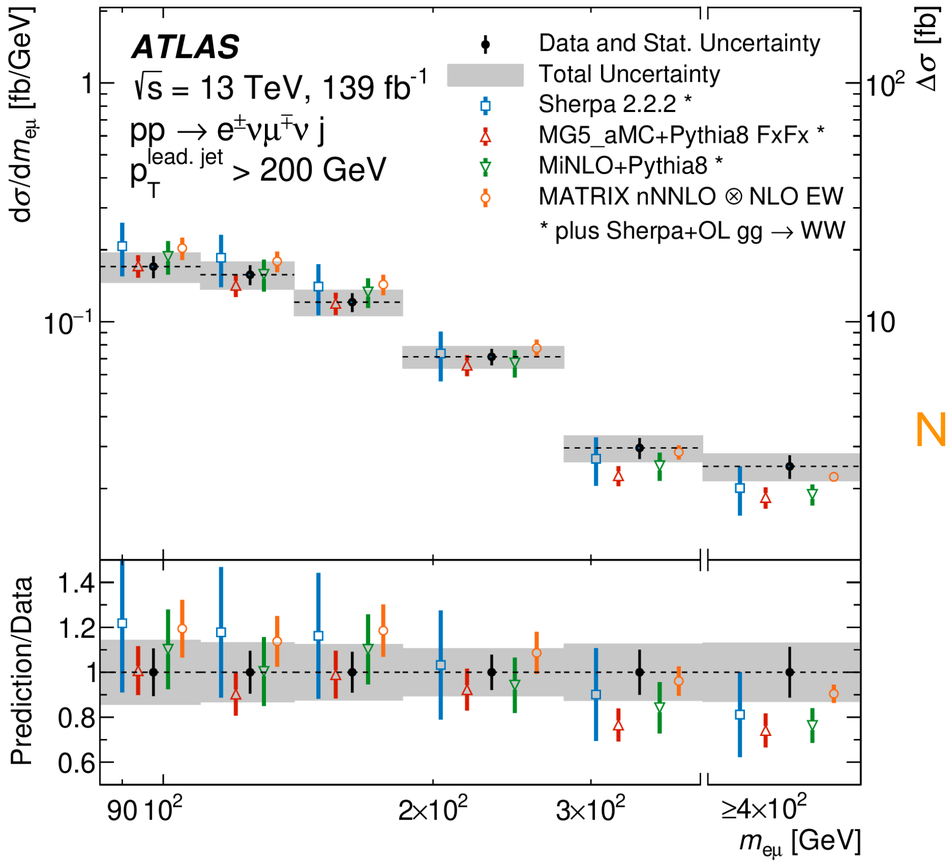






(sensitive to the spin structure of the W-boson pair)

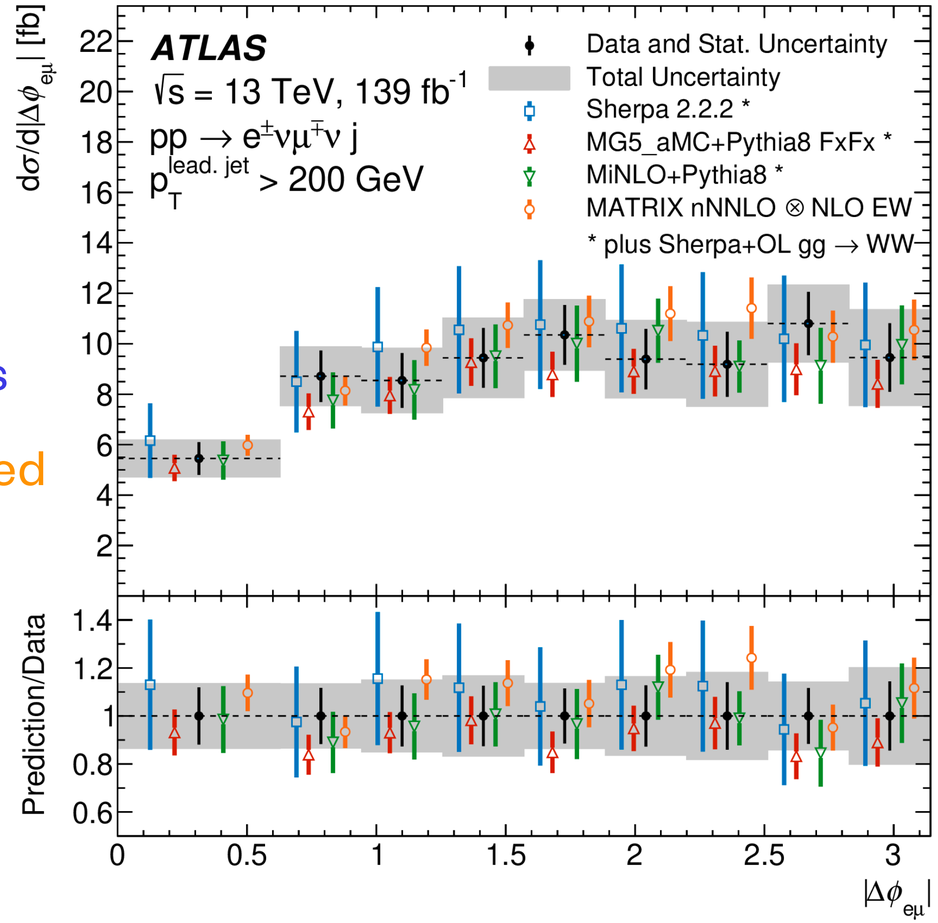
Differential cross sections: high p_T



leading jet p_T > 200 GeV

higher sensitivity to aTGCs

NLO EW corrections expected to be non-negligible



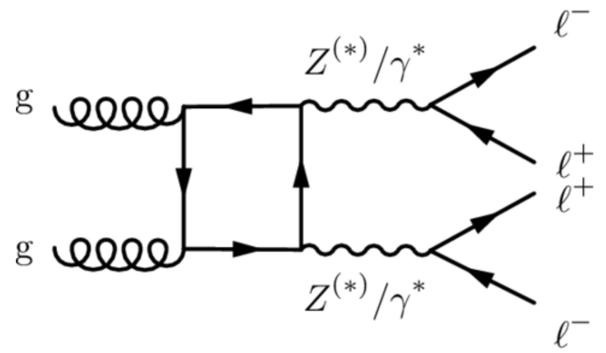
All theory predictions in agreement with data
MATRIX predictions (with NLO EW corr. from Sherpa+OpenLoops) most precise

Differential cross sections in 4-lepton events

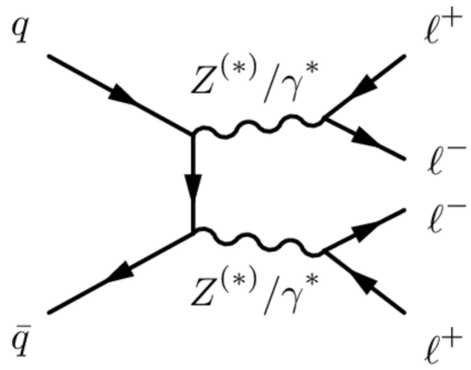
Accepted by JHEP

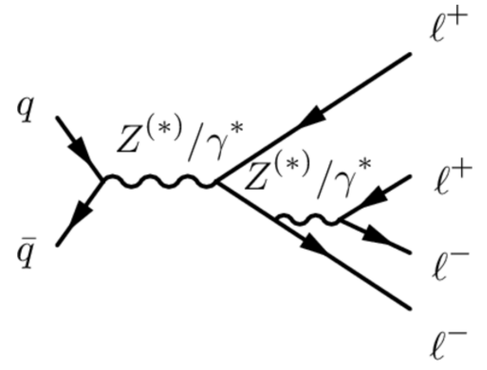
arXiv: 2103.01918

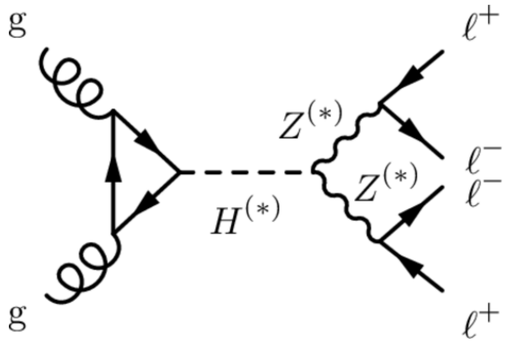
4 lepton processes



- Integrated and differential fiducial cross sections of processes:
  - t-channel qq->4l
  - gluon induced gg->4l via quark loop
  - internal conversion of Z boson decays
  - Higgs boson mediated s-channel production



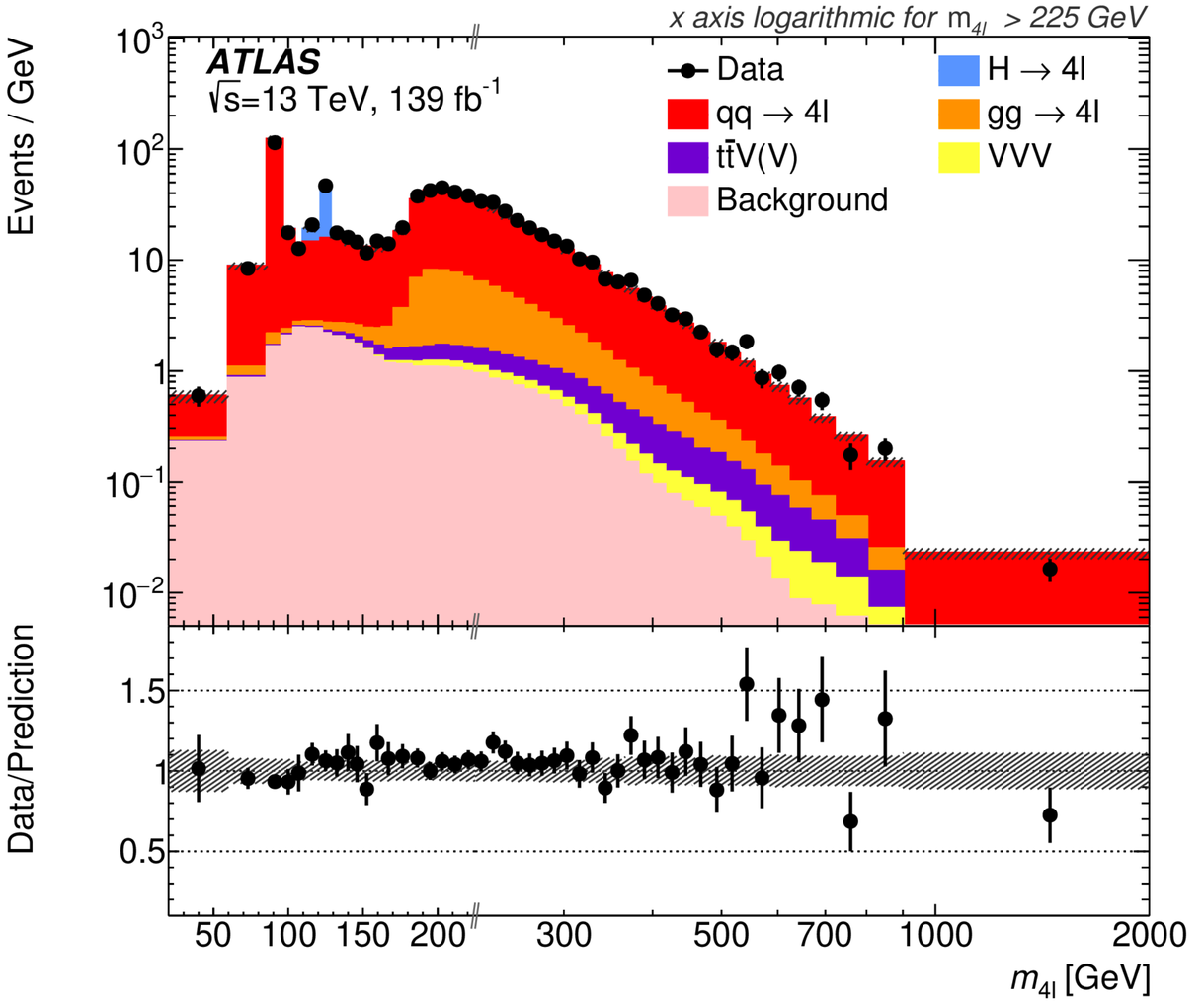




- Extraction of Z->4l branching fraction (shown Thursday)
- Measurements can be used to set limits on variety of BSM models.

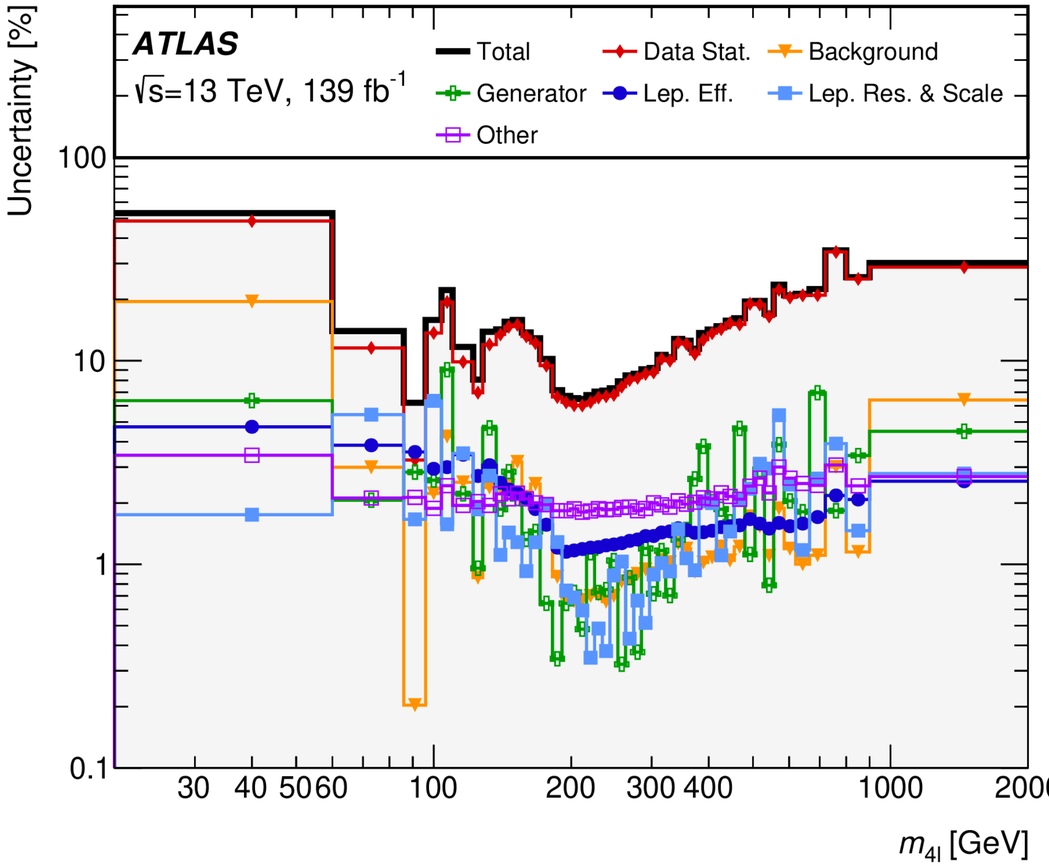
Fiducial region and Event Selection

- Fiducial selection
  - leading lepton pT>20 GeV
  - sub-leading lepton pT > 10 GeV
  - mll > 5 GeV for any same-flavor, opposite-charge lepton pair
  - ΔR > 0.05 for any pair of leptons
- 4-lepton quadruplet chosen based on best match of lepton pairs to Z-boson mass
- Detector selection driven by trigger
  - kinematic cuts mimic fiducial ones (minimizes extrapolation uncertainties)
  - additional cleaning cuts suppress hadronic backgrounds
- Events contain on-shell and off-shell ZZ produced through quark or gluon initiated processes, Higgs->ZZ, background in which at least one lepton is not prompt, and small contributions from top and triple-boson production.



Signal, Background Estimations and Uncertainties

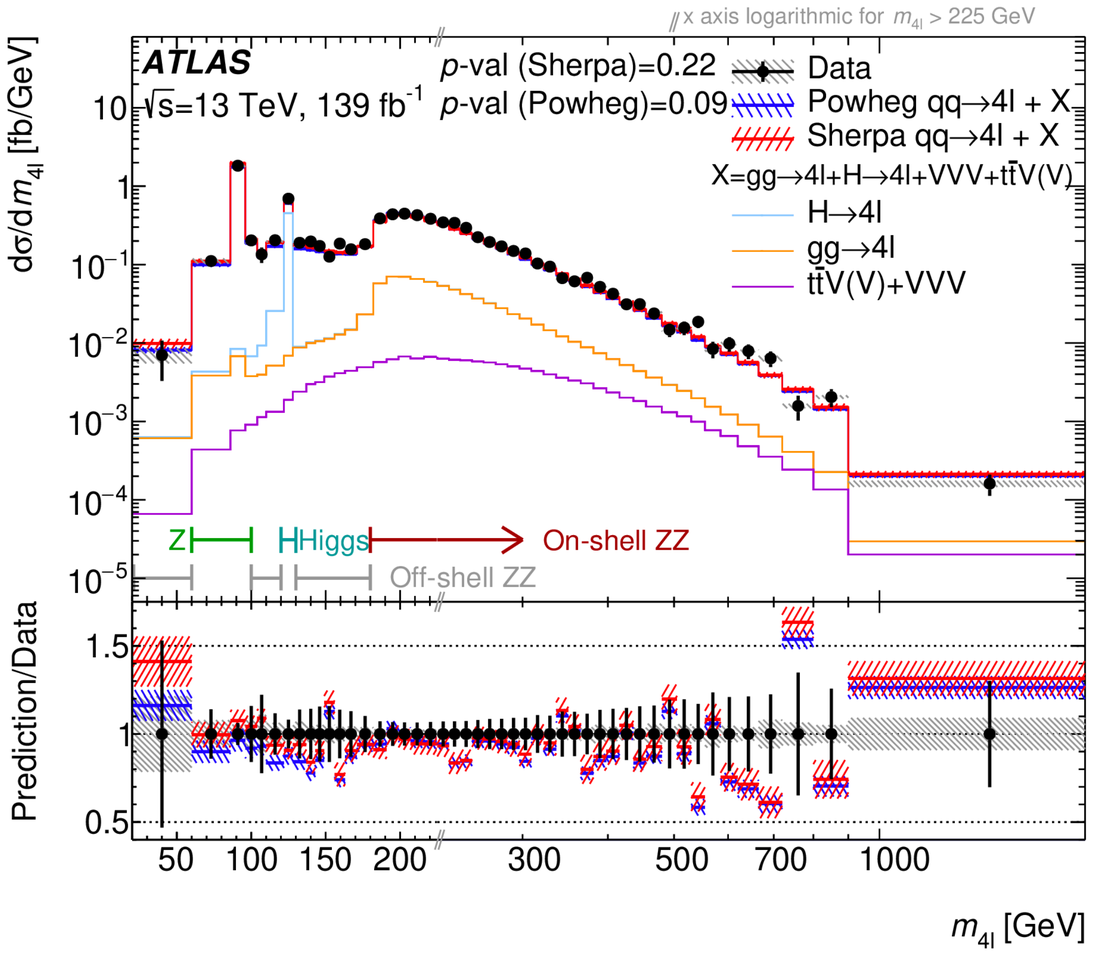
- Signal processes are simulated
  - qq->4l (NLO), gg->4l (LO) with Sherpa 2.2.2
  - gg->H->4l with Powheg NNLOPS, VBF, VH with Powheg+Pythia
- Non-prompt lepton backgrounds estimated with data driven fake-factor method
- Other smaller backgrounds simulated
- Statistical uncertainty dominates
- Relatively small systematic uncertainties arise from generator modeling differences, lepton efficiency, resolution and scale and statistics of the control samples used to determine backgrounds
- Covariance matrices for statistical and systematic uncertainties available in HEPData for every distribution



Fiducial cross sections

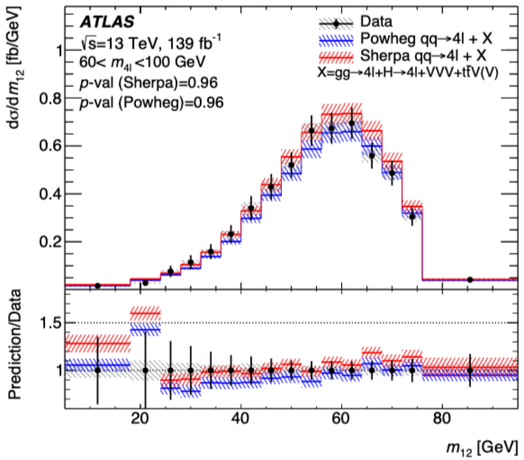
- Detector effects corrected for using Bayesian unfolding with SM prior
- 4 regions of m_{4l} defined according to process contributions
- Measurements agree well with predictions from Sherpa and Powheg in all regions

	Region				
	Full	$Z \to 4\ell$	$H \to 4\ell$	Off-shell ZZ	On-shell ZZ
Measured	88.9	22.1	4.76	12.4	49.3
fiducial	±1.1 (stat.)	±0.7 (stat.)	±0.29 (stat.)	±0.5 (stat.)	±0.8 (stat.)
cross-section	±2.3 (syst.)	±1.1 (syst.)	±0.18 (syst.)	±0.6 (syst.)	±0.8 (syst.)
[fb]	±1.5 (lumi.)	±0.4 (lumi.)	±0.08 (lumi.)	±0.2 (lumi.)	±0.8 (lumi.)
	±3.0 (total)	±1.3 (total)	±0.35 (total)	±0.8 (total)	±1.3 (total)
Sherpa	86±5	23.6±1.5	4.57±0.21	11.5±0.7	46.0±2.9
Powheg + Pythia8	83±5	21.2±1.3	4.38±0.20	10.7±0.7	46.4±3.0

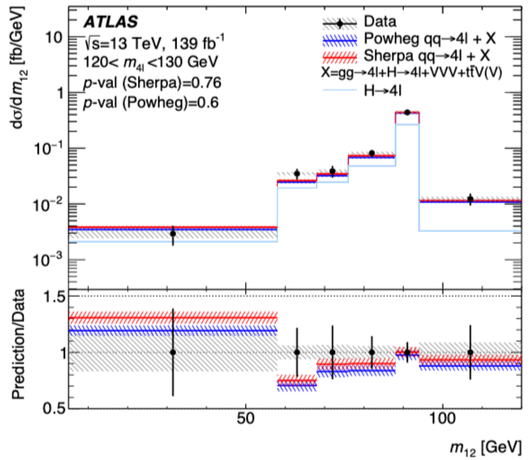


Differential cross sections

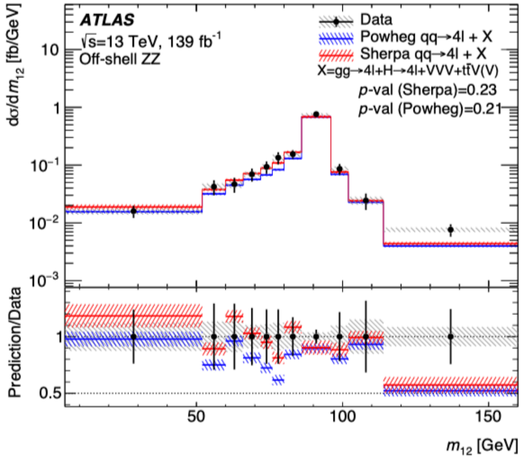
- Cross section as function of invariant mass of primary lepton pair in different m_{4l} regions
  - sensitive variable for BSM models in which lepton pairs do not originate with Z boson.
- Data are generally well-modeled by predictions from Sherpa and Powheg
- Normalization of the Powheg predictions lower than data in all regions
- On-shell ZZ region, shapes of the two predictions deviate from each other



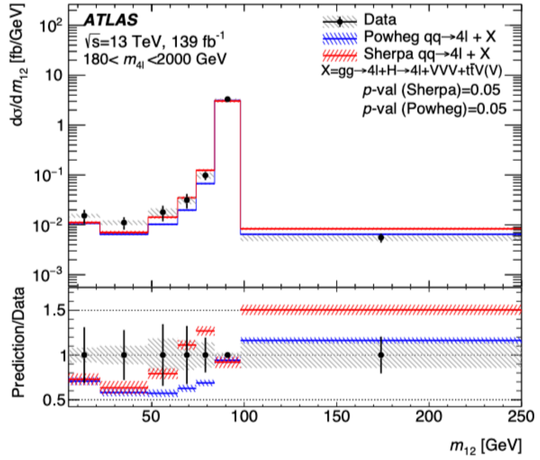
(a) $Z \to 4\ell$ region



(b) $H \to 4\ell$ region



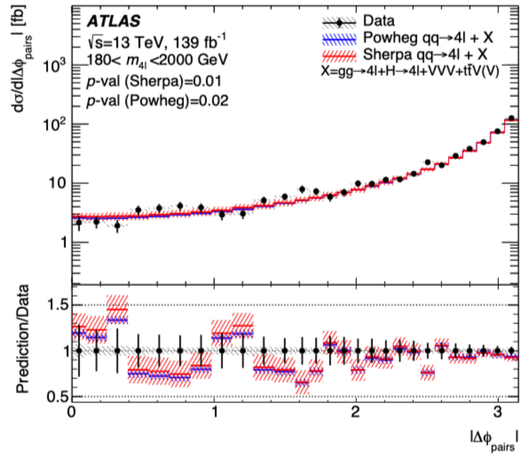
(c) Off-shell ZZ region



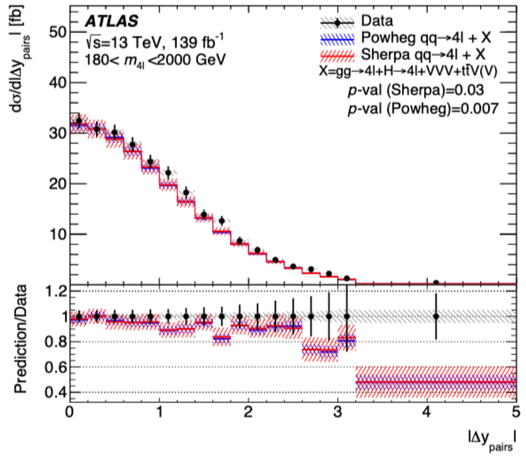
(d) On-shell ZZ region

Differential cross sections

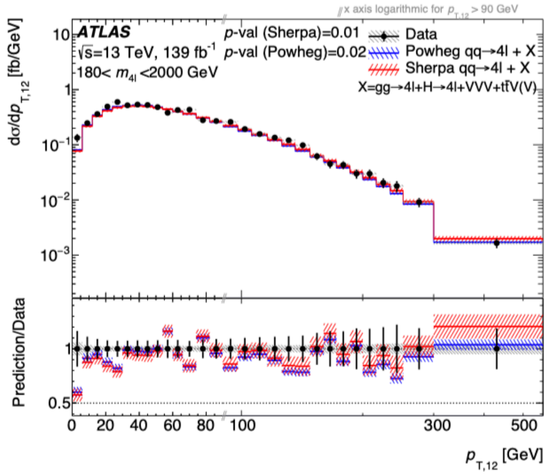
- Measurements as functions of kinematic variables of the 4-lepton quadruplets in the on-shell ZZ region (highest m_{4l})
- Predictions are able to reasonably describe most distributions, apart from $|\Delta y_{pairs}|$
  - indicates probable mis-modeling



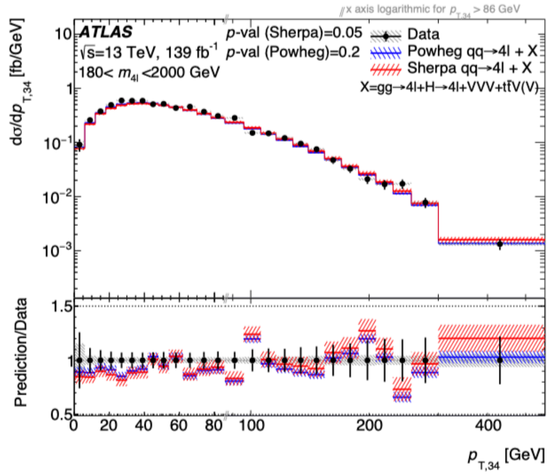
(a) $|\Delta\phi_{\text{pairs}}|$



(b) $|\Delta y_{\text{pairs}}|$



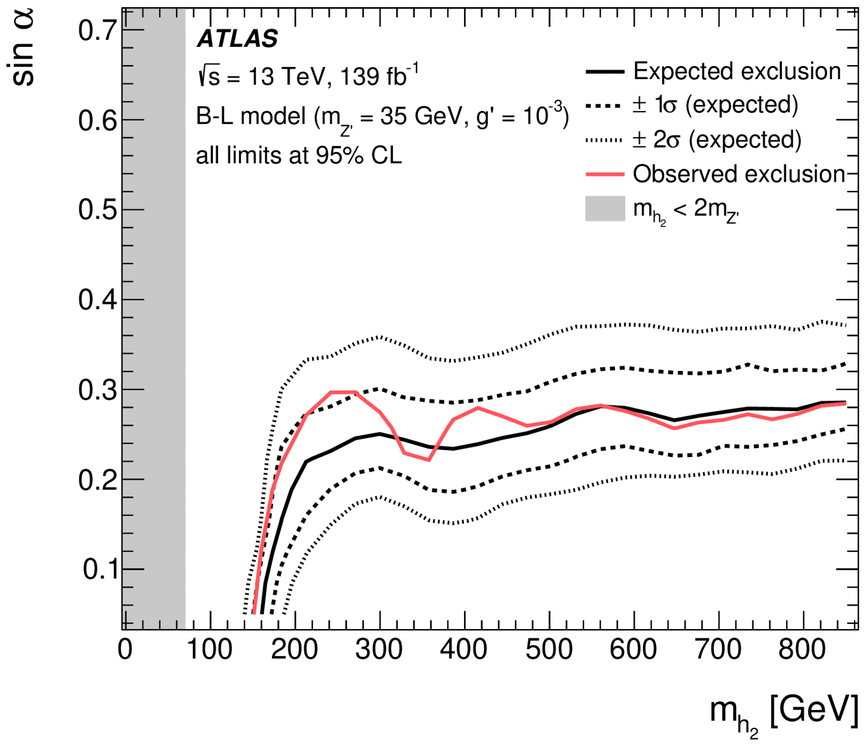
(c) $p_{\text{T},12}$

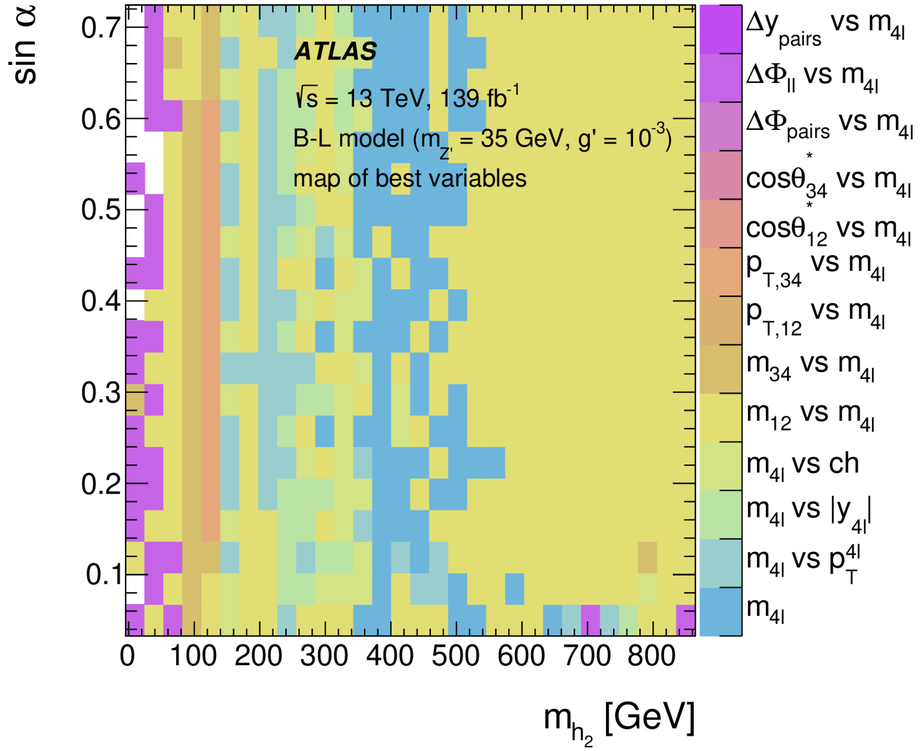


(d) $p_{\text{T},34}$

B-L Gauge model constraint

- Data are used to set limits on model in which the global baryon-number-minus-lepton-number ($B - L$) symmetry is treated as a local gauge symmetry and spontaneously broken
- Predicts Z', exotic Higgs boson h_2 which mixes with SM Higgs, mixing angle α
- 95% CL exclusion limits placed on model in sin α - m_{h2} plane using data





Observable with greatest expected sensitivity used to set limit in a given sin α - m_{h2} bin

Improvements in many bins from inclusion of m_{12} data

Improvements over previous results (Amrith et al):

- sin α > 0.28 over most of the range (from ~0.4)
- constraints on m_{h2} above ~600 GeV

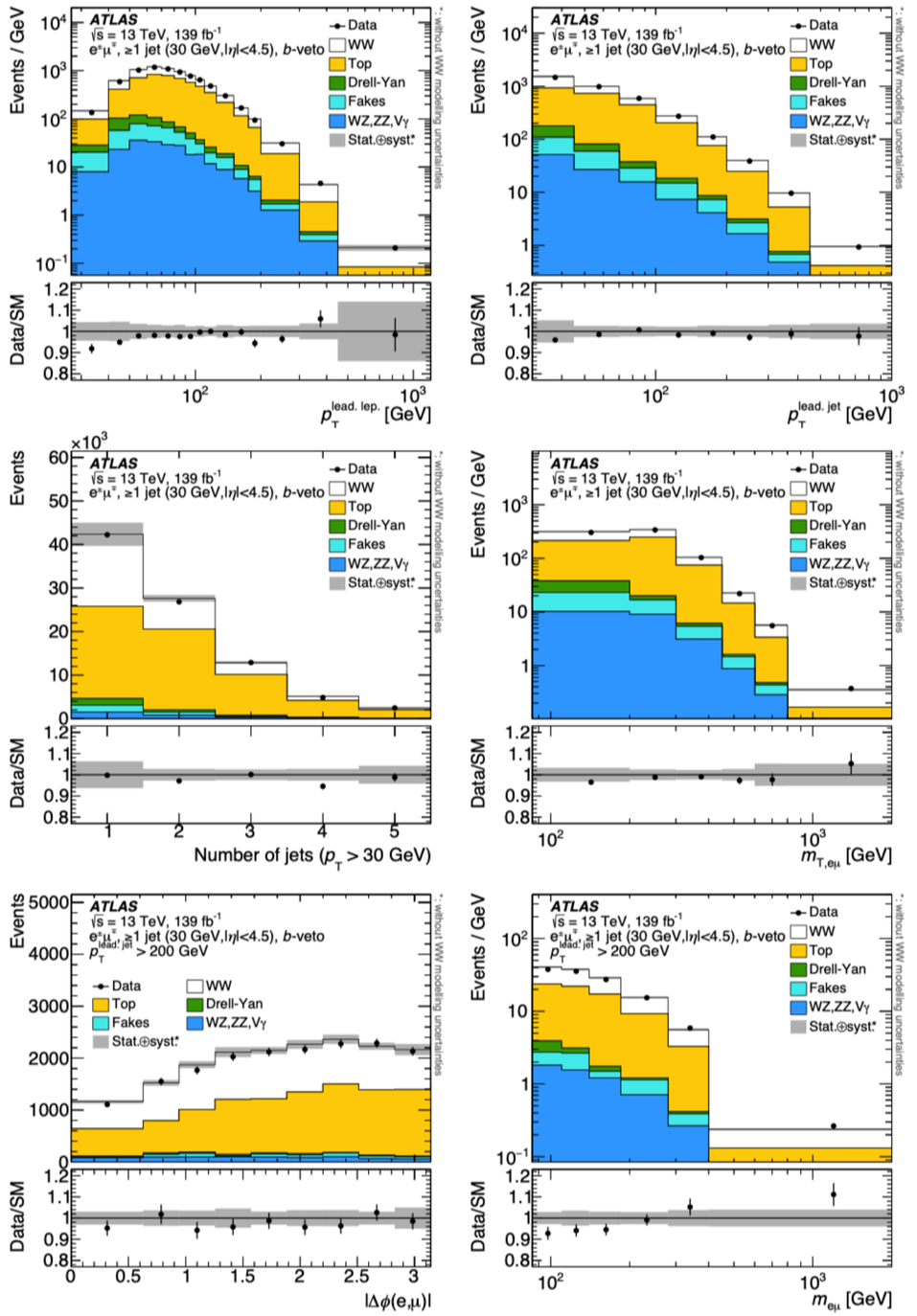
Conclusions

- Large ATLAS dataset allows for exploration of $\mathcal{O}$(fb) level processes, differentially and at high p_T
- Differential cross sections test QCD and EWK theory, models robustly
- Comprehensive publication of all results in HEPDATA
- First jet-inclusive measurement of WW production at the LHC
- Measurements of 4lepton production over large mass range

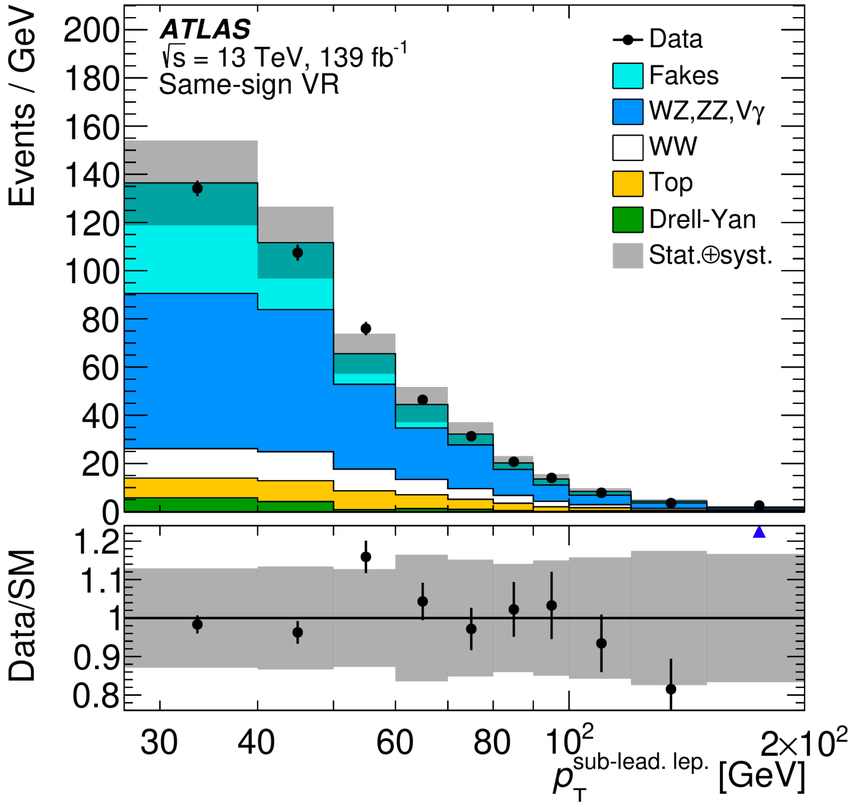
Backup

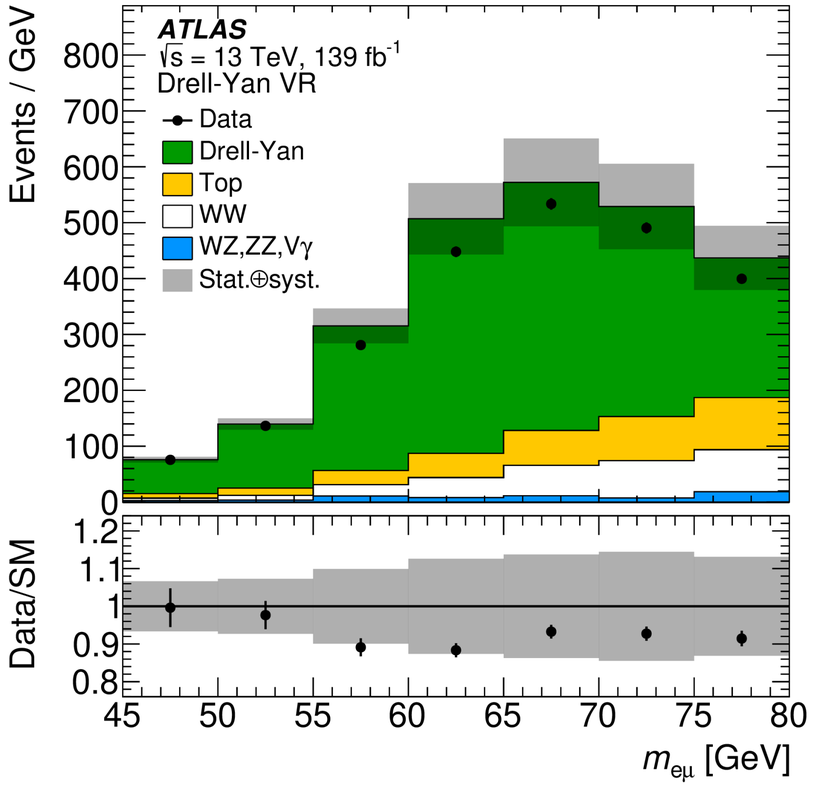
Detector distributions WW+1jet

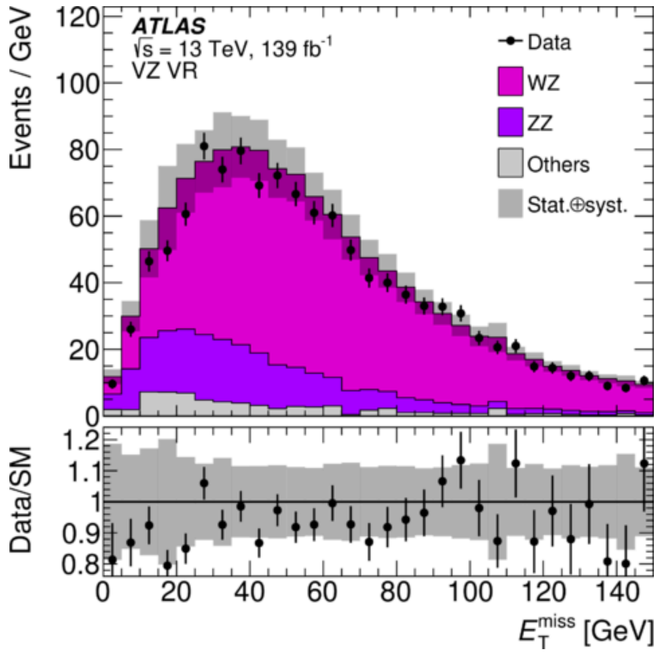
- Simulation model can generally describe the data
- Small discrepancies are covered by theory uncertainties (not shown)

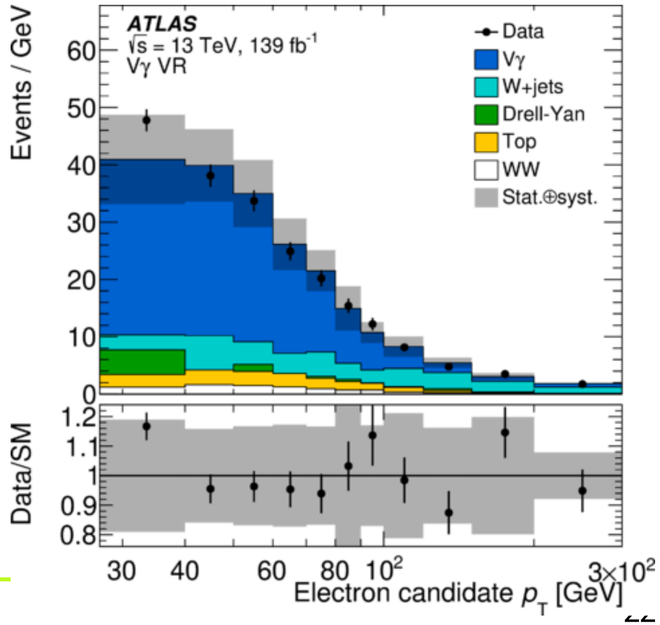


WW+1jet validation



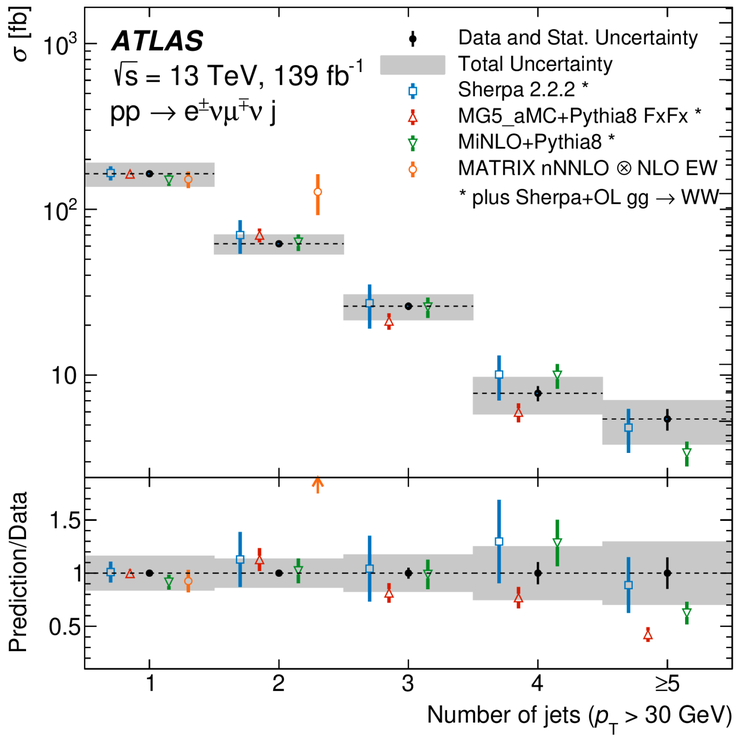


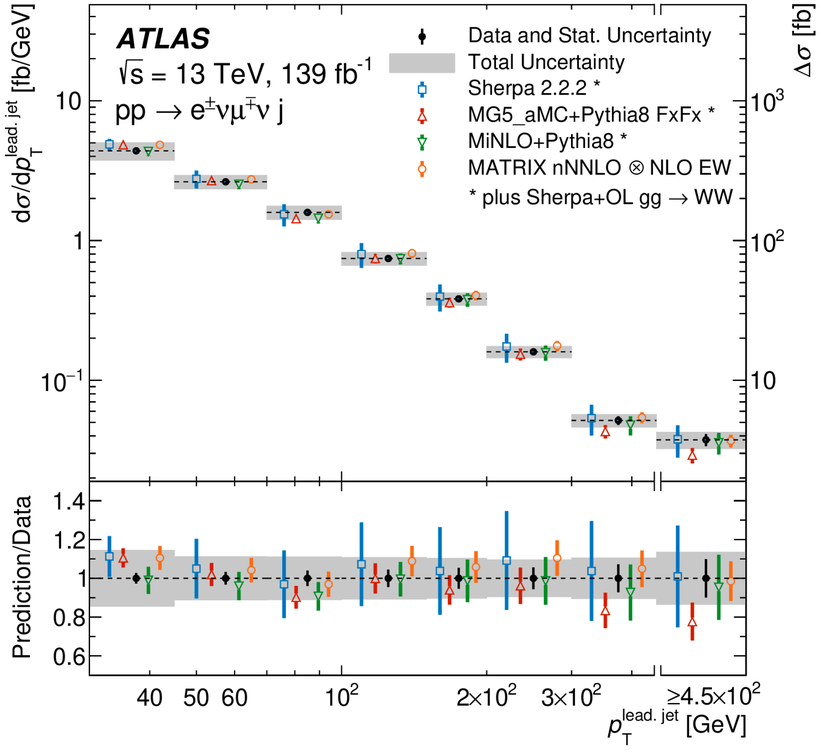


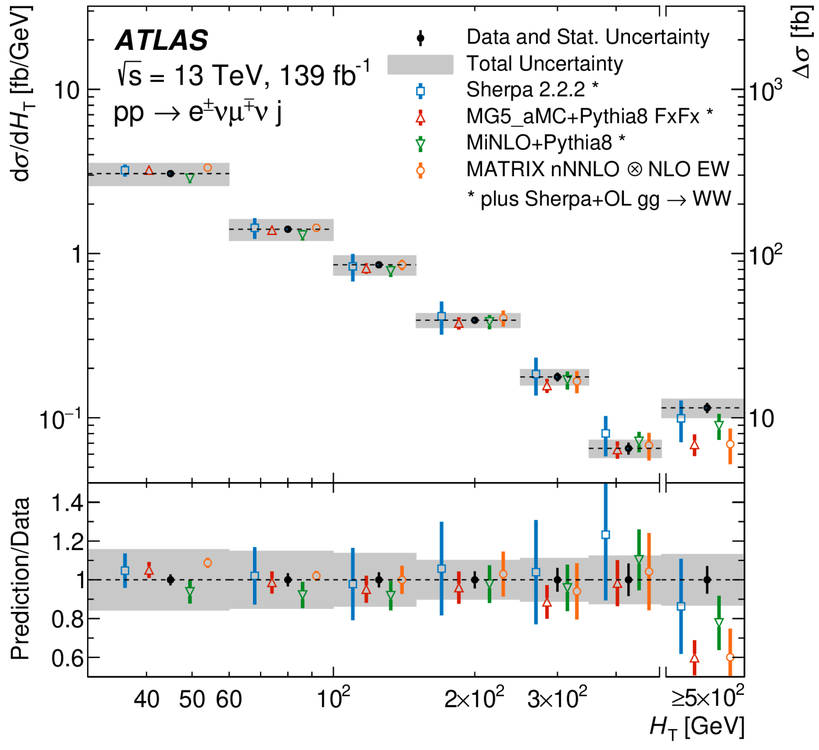


Differential cross sections WW+1jet

Very good agreement between measurements and predictions in hadronic variables



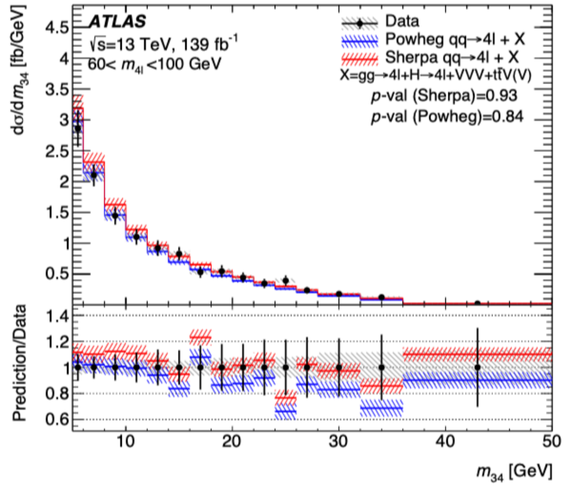




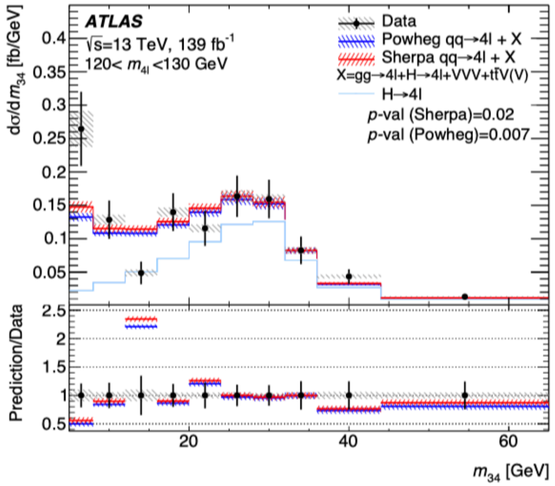
4lepton- m_{34} distributions

Differential cross-section as a function of m 34in the four m 4ℓ regions.

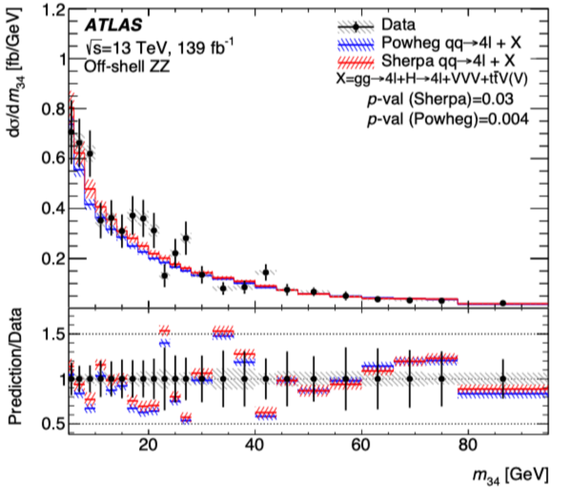
The p-value is the probability for the χ 2, with the number of degrees of freedom equal to the number of bins in the distribution, to have at least the observed value, given the SM prediction.



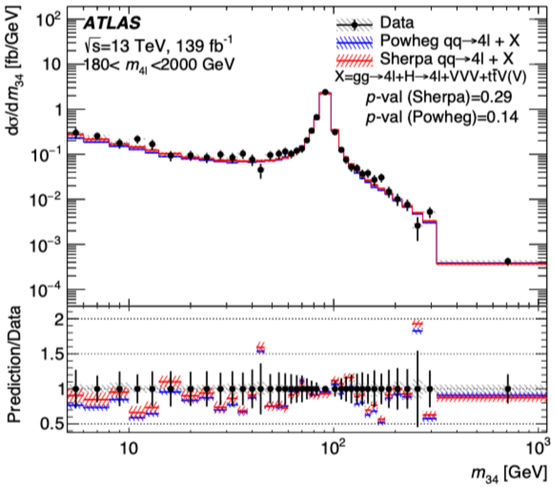
(a) $Z \to 4\ell$ region



(b) $H \to 4\ell$ region



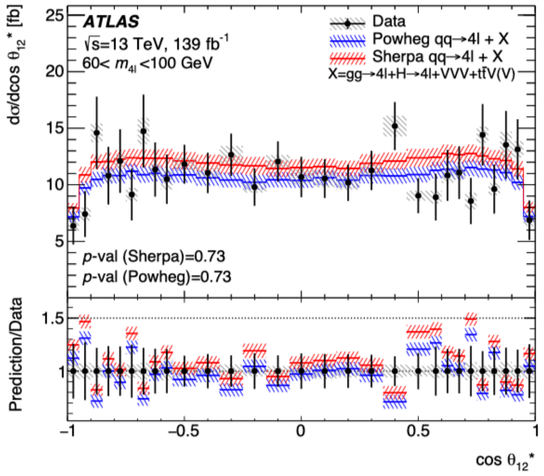
(c) Off-shell ZZ region



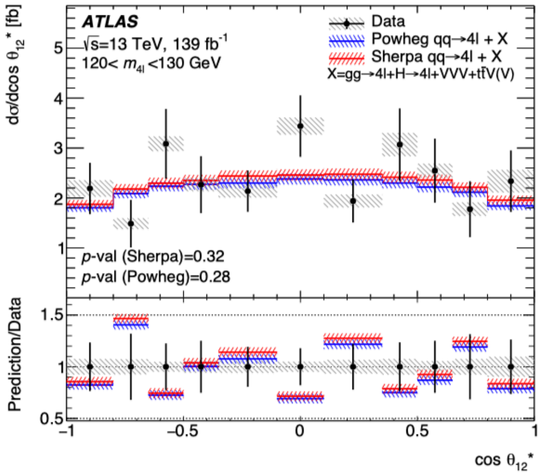
(d) On-shell ZZ region

Differential cross sections

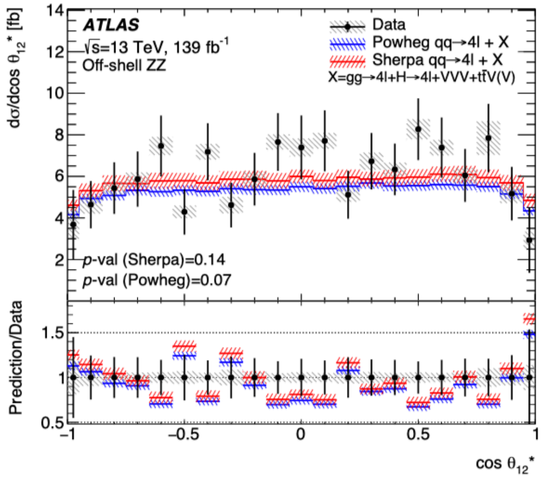
- cos θ12 (cos θ34) is the cosine of the angle between the negative lepton in the primary (secondary) dilepton rest frame, and the primary (secondary) lepton pair in the laboratory frame.
- sensitive to the polarization of the decaying particle (Z)
- data well-described



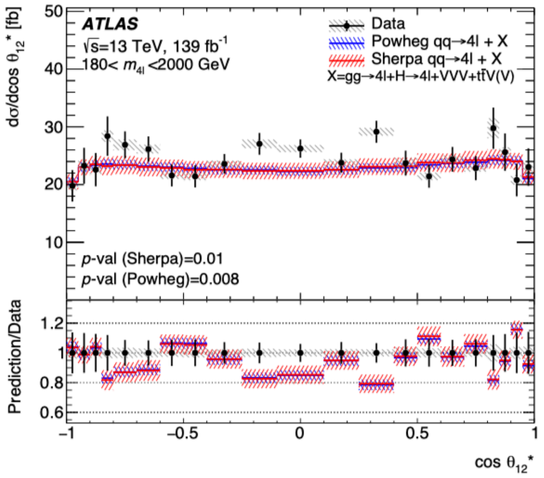
(a) $Z \to 4\ell$ region



(b) $H \to 4\ell$ region



(c) Off-shell ZZ region



(d) On-shell ZZ region