Highlights of SM measurements including Top with the ATLAS experiment at the LHC

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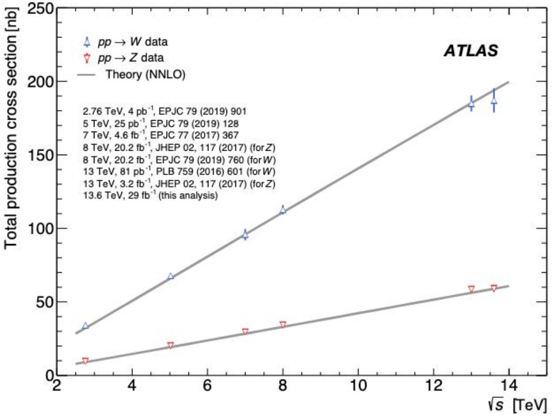
Introduction

- Recent highlights from ATLAS Standard Model and Top quark physics program
  - W/Z (+jets) production measurements
  - Multiboson measurements
  - Measurements of jet observables and measurements sensitive to UE
  - Top quark (+jet) measurements

W/Z Boson Production Measurements

Measurement of W/Z production Cross sections at 13.6 TeV

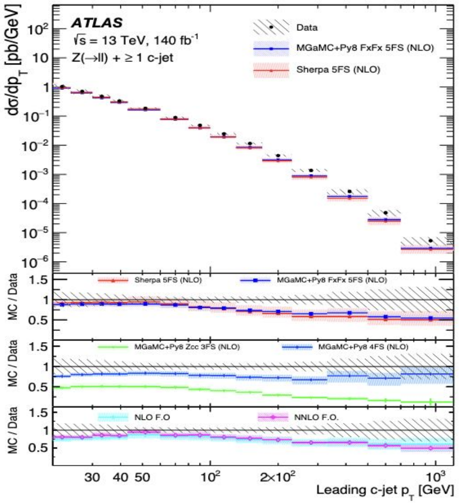
- $W^+ \rightarrow \ell^+\nu$, $W^- \rightarrow \ell^-\bar{\nu}$, and $Z\rightarrow\ell^+\ell^-$ ($\ell = e, \mu$) production XS 4250 ± 150 pb, 3310 ± 120 pb, and 744 ± 20 pb
- Standard-Model predictions calculated at NNLO in α_s and NLO in α_{EW}



Phys. Lett. B 854 (2024) 138725

Measurement of Z production in association with b or c jets at 13 TeV

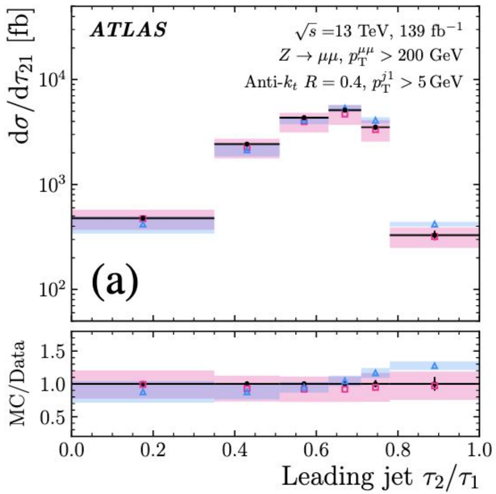
- First ATLAS measurement of Z+charm production
- Generators underestimate Z+c jet cross section



Eur. Phys. J. C 84 (2024) 984

Simultaneous unbinned differential cross section measurement of twenty-four Z+jets kinematic observables

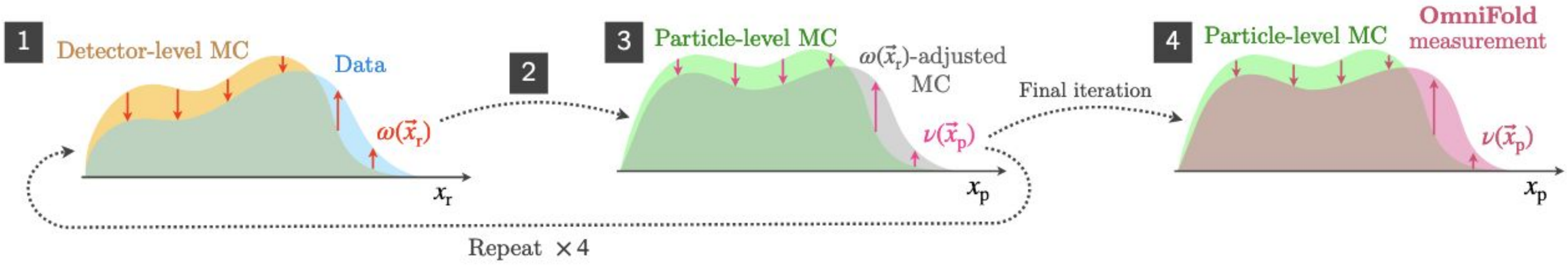
- MULTIFOLD used to produce simultaneous measurements
- Result is presented unbinned as a dataset of particle-level events



CERN-EP-2024-132

Particle Level Unbinned Z+jets differential distributions

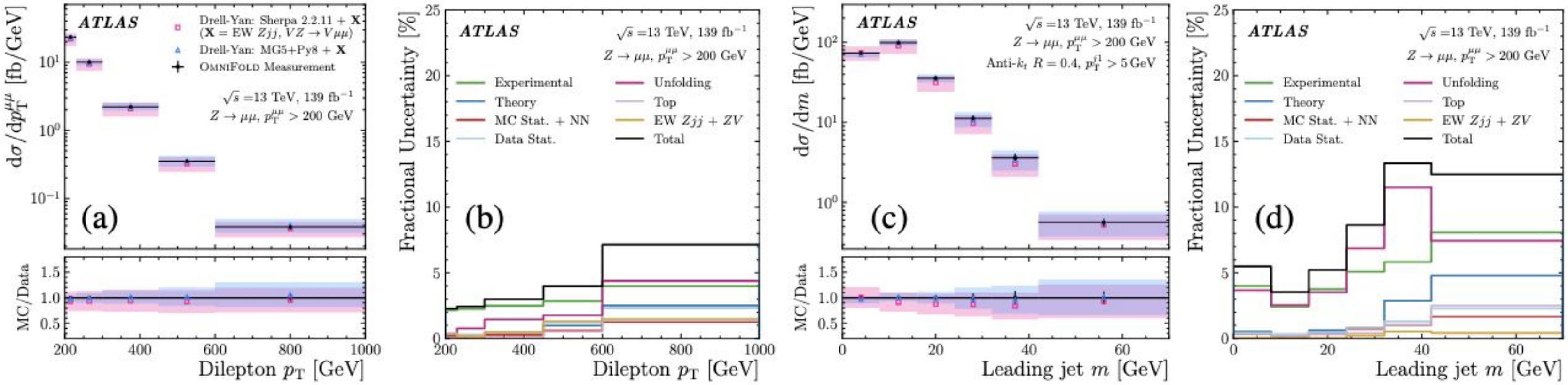
- MULTIFOLD algorithm is used to simultaneously unfold 24 observables
  - Smooth weighting function learned by NN correcting reconstructed level MC to data
  - Weights are propagated to particle level
  - New reweighting learned correcting particle level to corrected particle level
  - Weighting propagated back to detector level
  - Done for pre-defined number of iterations



- Larger uncertainties than Iterative Bayesian unfolding
- Allows for re-analyzing results at particle level: constructing new observables from 24 input observables, applying selections to different kinematic regions and adjusting binning.
- Usage recommendations provided.

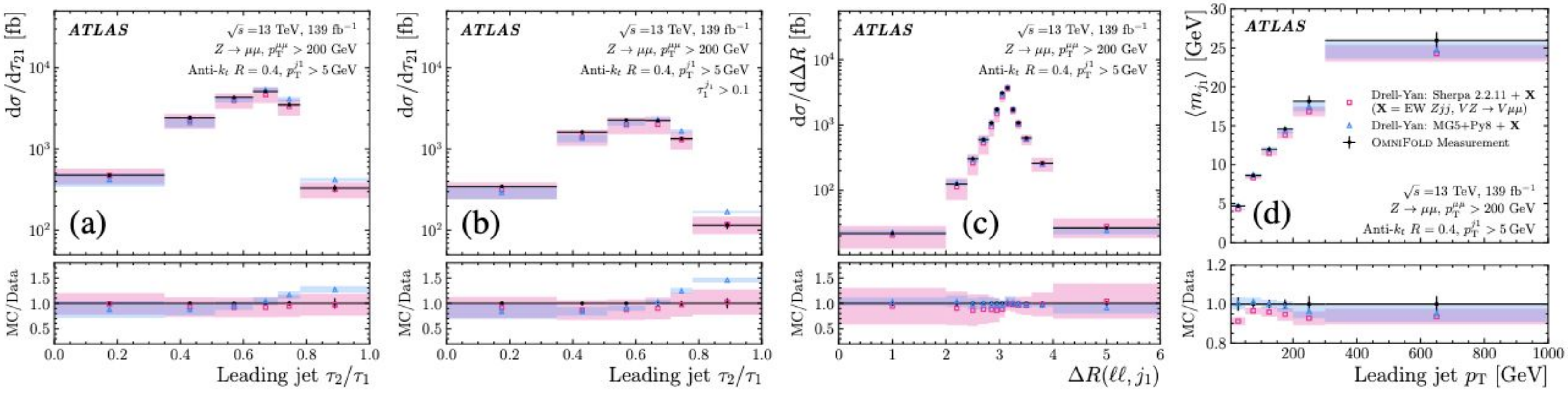
Particle Level Unbinned Z+jets differential distributions

- 24 input variables unfolded
  - p^T and rapidity of di-muon system
  - p^T, η, ϕ of two muons
  - p^T, rapidity of two leading charged particle jets
  - Masses, charged particle multiplicities and N-subjettiness ratios of 2 leading jets



Particle Level Unbinned Z+jets differential distributions

- Additional “derived” variables that were not directly unfolded

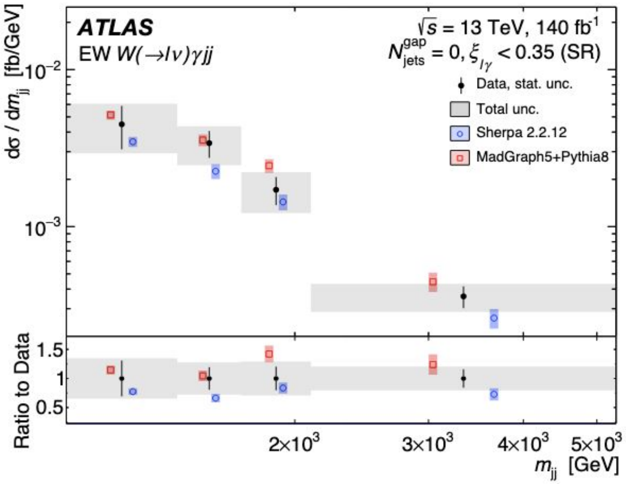


- τ_2/τ_1 is a useful observable for hadronic W/Z identification
- $\Delta R(\ell\ell, j_1)$ sensitive to higher order effects
- Potential use case is event generator tunes improving modelling of parton showers, hadronization and the underlying event

Multiboson Measurements

Fiducial and differential cross-section measurements of electroweak Wɣjj production

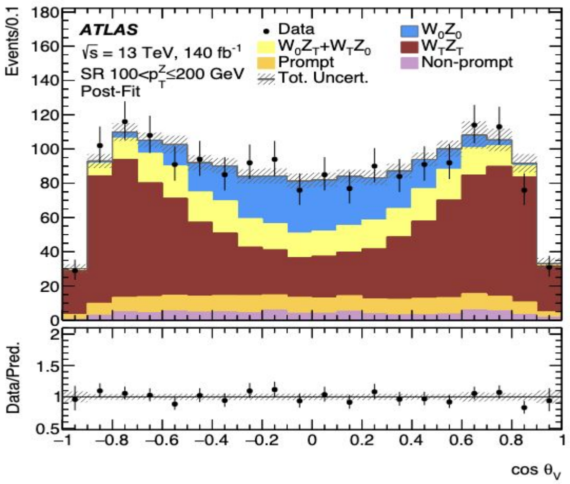
- Observation of electroweak process with a neural network
- Measurement in 6 kinematic observables
- aQGC constraints



Eur. Phys. J. C 84 (2024) 1064

Measurement of Polarization Fractions and RAZ effect in WZ Production

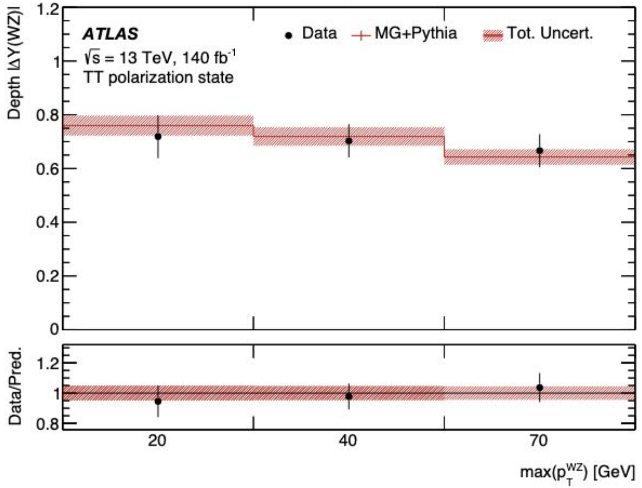
- Energy-dependence of diboson polarization fractions in $WZ \to \ell\nu\ell'\ell'$ ($\ell, \ell' = e, \mu$) production
- Radiation Amplitude Zero effect
- Unfolded $\Delta Y(\ell_W Z)$ and $\Delta Y(WZ)$



Phys. Rev. Lett. 133 (2024) 101802

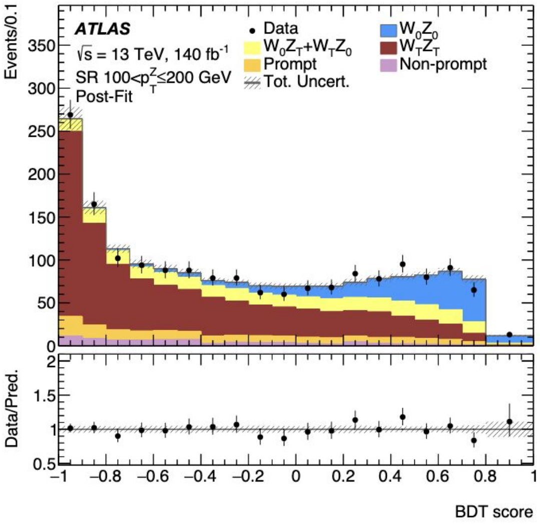
Measurement of Polarization Fractions and RAZ effect in WZ Production

- Radiation Amplitude Zero effect: WZ production suppressed
  - Dominant helicity amplitude with two transversely polarized is 0
  - Experimental signature is a dip at 0 in $\Delta Y\,(W\,Z)$ and $\Delta Y\,(\ell_W\,Z)$
- Hard to measure with NLO QCD corrections: reduce jet activity by cutting on p_T^{WZ}
- Quantify presence of dip using
  $D = 1 - 2(N_{central}/N_{sides})$
  where
  $N_{central}$ is N events with $|\Delta Y\,(W\,Z)| < 0.5$
  N_{sides} is N events with $(0.5 < |\Delta Y\,(W\,Z)| < 1.5)$



Measurement of Polarization Fractions and RAZ effect in WZ Production

- BDT is trained to separate 00 and other polarization states.
- Binned MLE fit performed on BDT distributions
- 5.2 (4.3)σ for f_{00} in 100 < p_T^Z ≤ 200 GeV

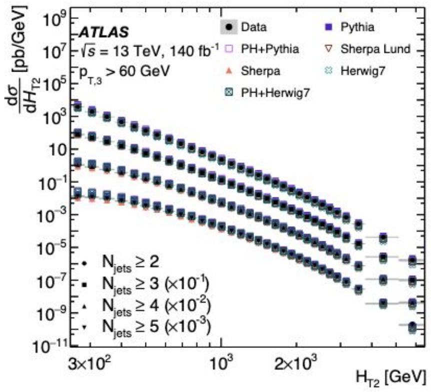


	Measurement		Prediction		
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV		$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.19 \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13 \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23 \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (syst)	f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{TT}	$0.63 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.04}_{0.04}$ (syst)	$0.64 \pm^{0.12}_{0.12}$ (stat) $\pm^{0.06}_{0.06}$ (syst)	f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ	f_{TT}	0.619 ± 0.007	0.646 ± 0.008

Standard Model Measurements with Jets

Measurement of Jet Cross-Section Ratios

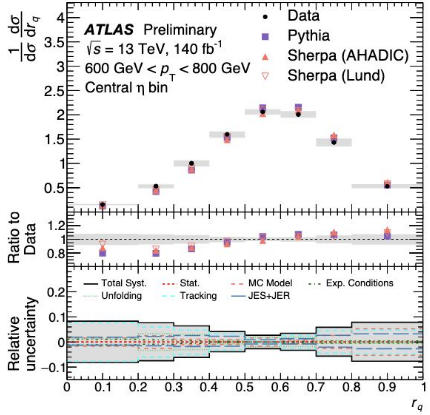
- Observables sensitive to JES, angular distribution of radiation due to QCD measured double differentially in bins of jet multiplicity
- Precision benefits from improvements in modelling of JES uncertainties



Phys. Rev. D 110, 072019 (2024)

Measurement of Jet Track Functions

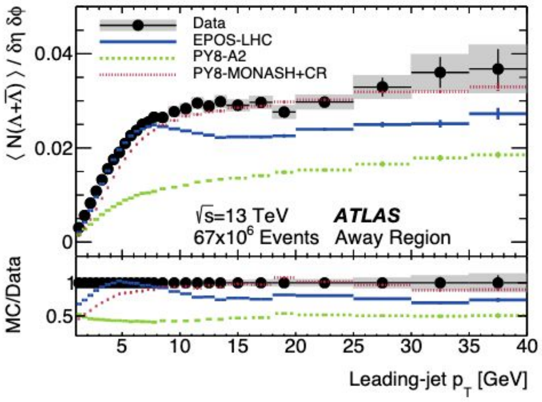
- Measurement of $r_q = p^T_{tracks}/p^T_{jet}$
- Measurement of r_q enables determination of universal track functions.
- Important input to theoretical models of jet formation



ATLAS-CONF-2024-012

Study of Underlying Events with Strange Hadrons

- K_S^0 and Λ production ratios measured and compared to different generators
- Hadronisation and UE models considered cannot describe the data over the full kinematic range considered



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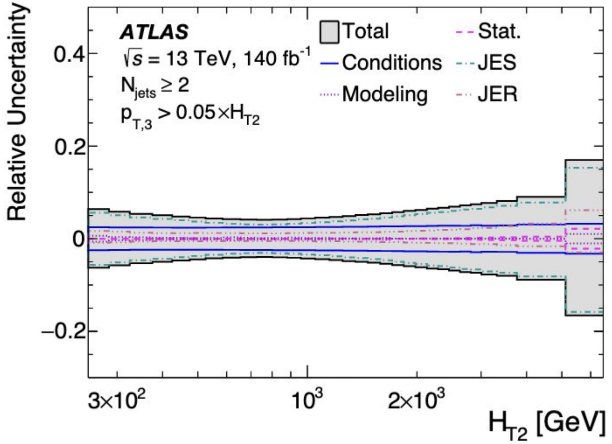
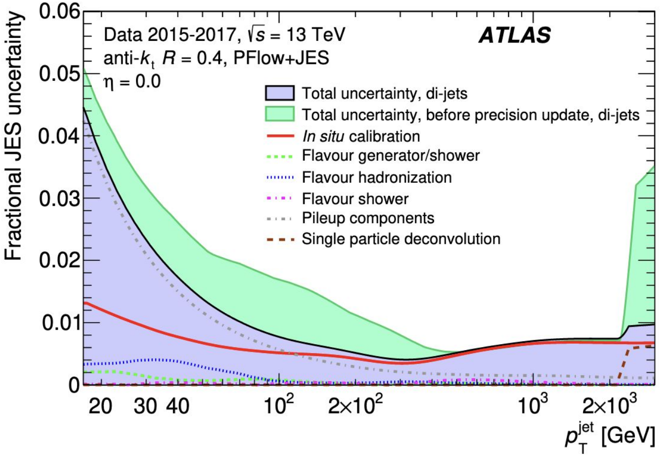
Improved JES in Measurement of Jet Cross Section Ratios

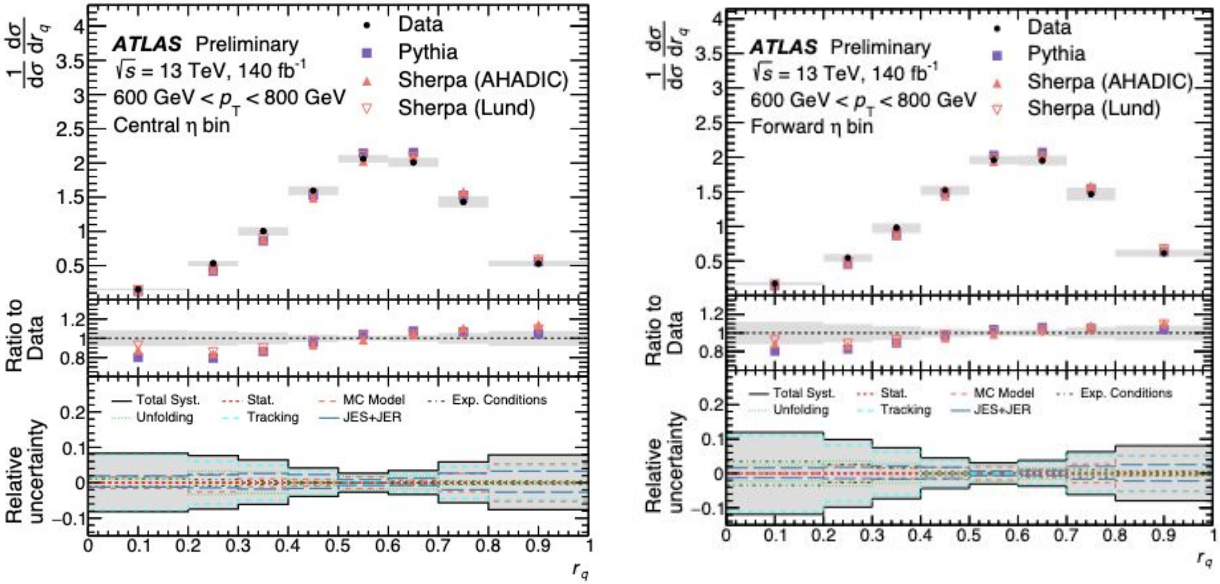
- Response of ATLAS to jets depends on underlying particle spectra
- Previously: 2 point comparison between herwig and pythia gluon jets
- Now
  - UI/MPI/Shower: Pythia vs. Sherpa lund string
  - Hadronization: Sherpa AHADIC cluster-based model and the Lund string model
  - Shower: Herwig angle ordered vs. dipole PS
- Does not consider models disfavored by data
- Derived/applied per jet flavor
- Uncertainty goes from dominant to subdominant





Measurement of Jet Track Functions

- Track functions characterize the p^T fraction r_q carried by charged hadrons from a fragmenting quark/gluon
- Non-perturbative + must be determined by experiment
- Analysis:
  - 2 leading p^T jets in multijet events (p^T_j > 240 GeV)
  - Tracks with p^T > 500 MeV
  - Measure r_q in central and forward regions
  - Use improved JES
  - MULTIFOLD used

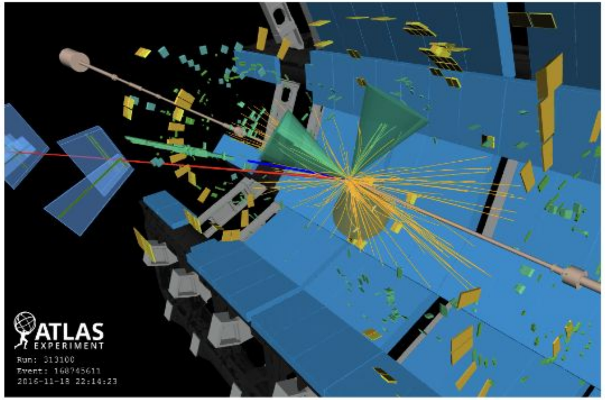


r_q underestimated at low p^T, overestimated at high p^T

Measurements with Top Quarks in p-Pb and Pb-Pb

Observation of Top Pair Production in Proton-Lead Collisions

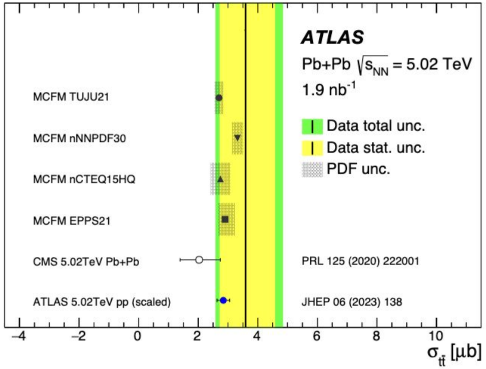
- 165 nb^{-1} of p+Pb, $\sqrt{s}$ = 8.16 TeV
- First observation of top pair production in p+Pb collision at the LHC
- Cross section and measurement of nuclear modification factor in good agreement with SM and state of the art predictions



JHEP 11 (2024) 101

Observation of Top Pair Production in Lead-Lead Collisions

- Probe nuclear PDF
- Measure cross-section in single lepton and dilepton channels
- Measurement of nuclear modification factor R_{pA}

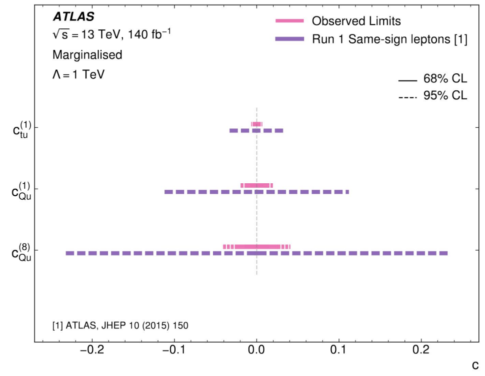


https://arxiv.org/pdf/2411.10186

Measurements with Top Quarks

Search for same charge top quark pair production

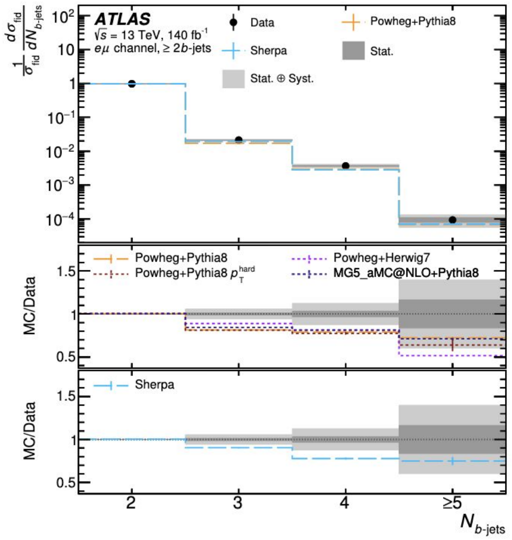
- Neural networks used to select regions sensitive to BSM couplings enhancing same sign quark pair production
- No significant excess
- Limits on total cross section and relevant SMEFT Wilson coefficients set.



CERN-EP-2024-226

Measurement of top pair production in association with b-jets

- Measurement of top pair production+b-quarks in eμ channel
- Differential cross sections measured with ~10% precision
- Fid. XS consistent with NLO prediction
- No state of the art theoretical predictions accurately describe all measured observables



CERN-EP-2024-191

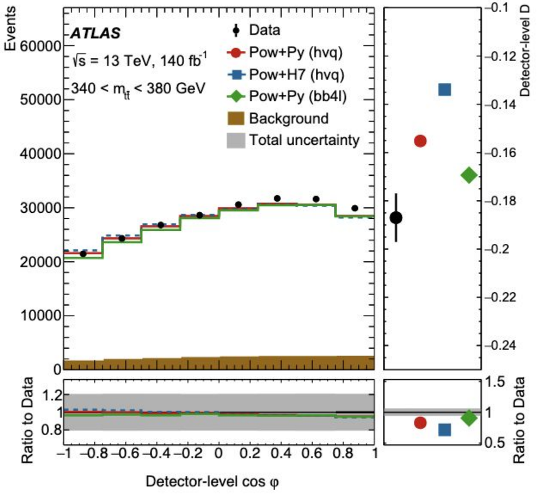
Measurement of Top Quark Pair Production in Association with Charm Quarks

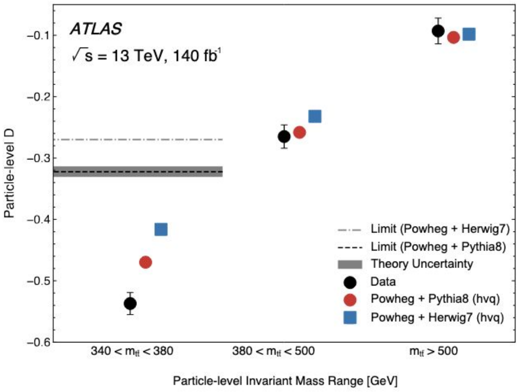
- Top quark pair production with single charm quark and ≥ 2 charm quarks measured.
- See Sergei's talk!

CERN-EP-2024-242

Observation of Quantum Entanglement with Top Quarks

- Large top mass and short lifetime: quantum numbers are transferred to its decay products
- Angular direction of leptons correlated with direction of spin of parent top quark
- Define entanglement marker as $D = -3\langle\cos\phi\rangle$
- $D < -1/3$ is sufficient criteria for existence of entangled state.
- Measurement performed near production threshold where top quark pairs are maximally entangled
- Measurement unfolded for detector effects → entanglement observed at particle level $D^{obs(exp)} = -0.537 \pm 0.002$ [stat.] ± 0.019 [syst.] (-0.470 ± 0.002 [stat.] ± 0.017 [syst.])



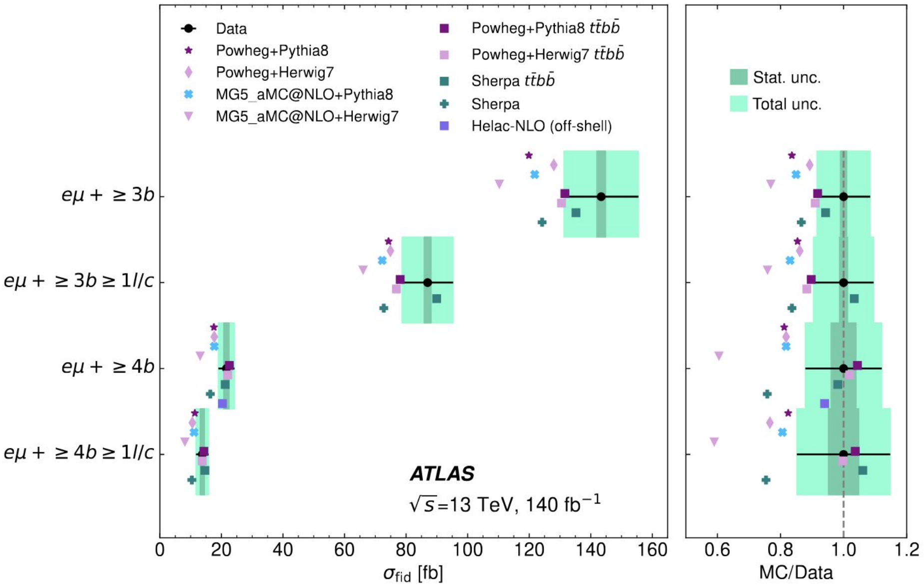


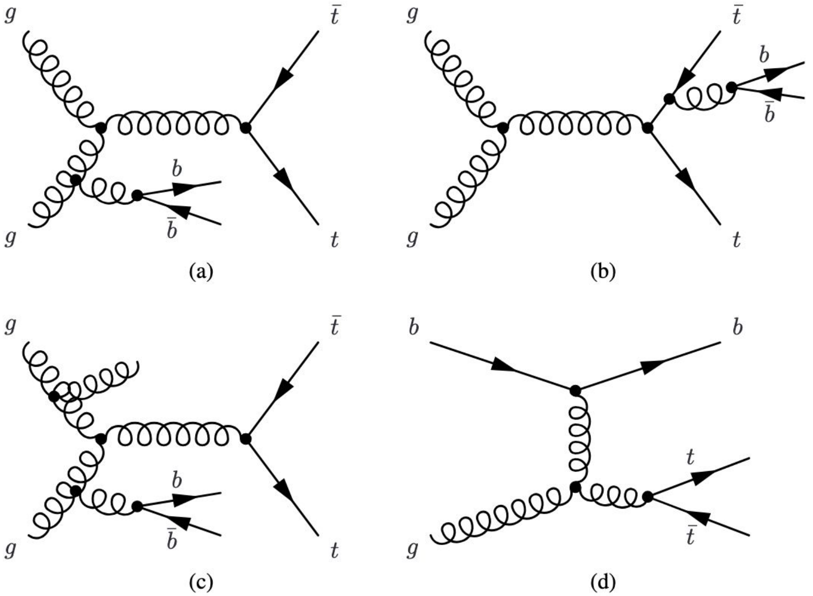
Nature 633 (2024) 542

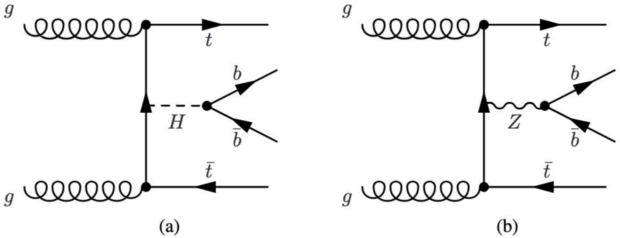
Conclusion

- The ATLAS run 2 dataset continues to provide for a rich program of Standard Model measurements
- Many new measurements and novel analysis techniques
  - Simultaneous unfolding of multiple observables with MULTIFOLD
  - WZ polarization fractions and Radiation Amplitude Zero effect
  - Jet Track Function Measurements
  - Quantum Entanglement in Top Quark Pairs
- No hints of new physics in the measurements presented
- Valuable feedback for the community as to where generators are not describing the data.
- Just getting started with run 3 results!

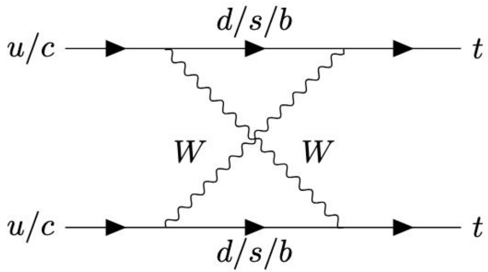
Measurement of top pair production in association with b-jets

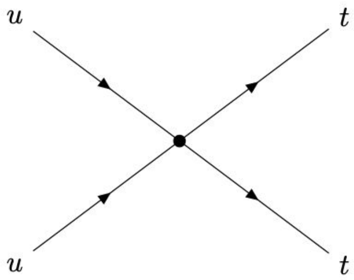


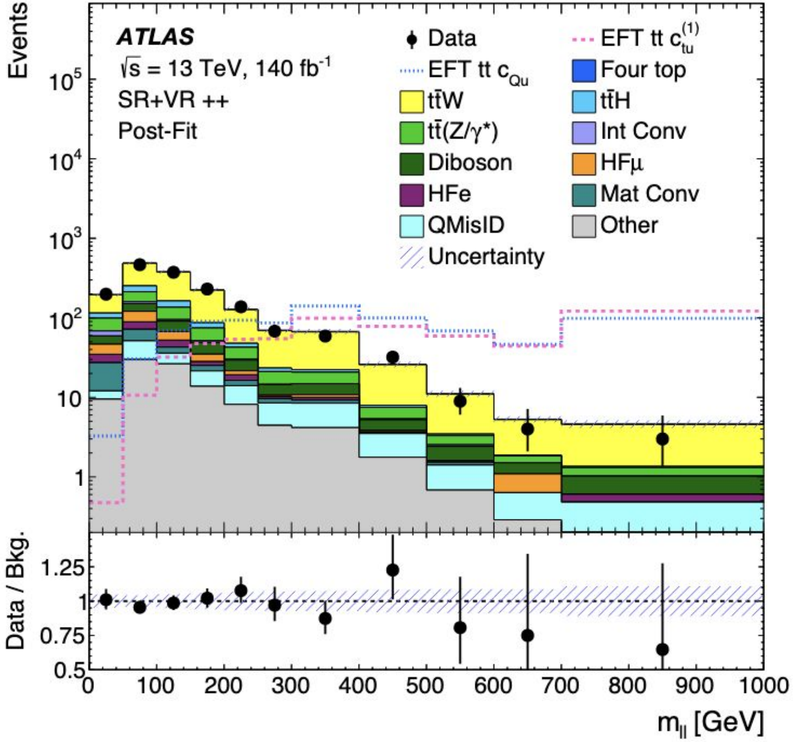




Search for same-sign top pair production

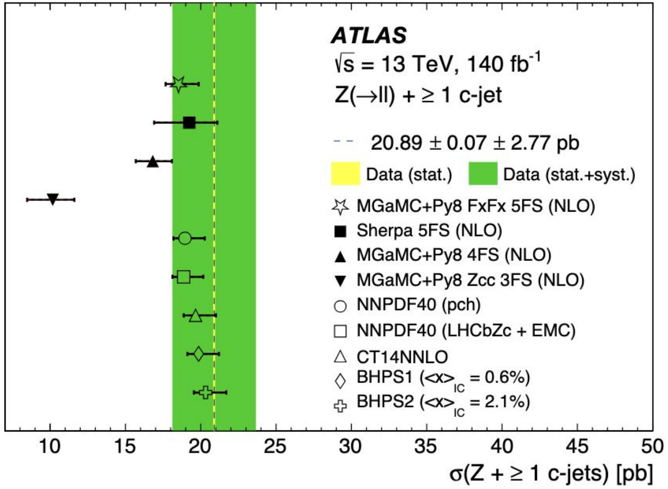


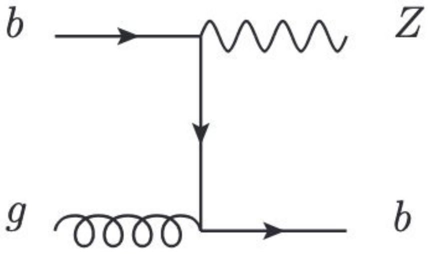


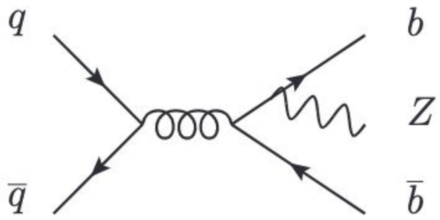


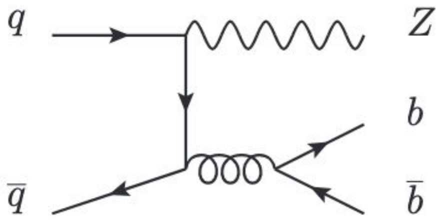
Z + heavy flavor jets

- Broad agreement of fiducial XS between different generators.
- No generator accurately describes distributions over full range









Wy + jet production

- Measurement performed in VBS enhanced region
  - 0 jets in rapidity gap between leading jets
  - Low lepton-photon centrality (<0.35)
- Modelling uncertainties dominate
  - Only LO signal prediction