30th Anniversary of the Rencontres du Vietnam Aug 6 – 12

ICISE

WINDOWS ON THE UNIVERSE 2023

Measurements of QCD in W/Z and multijet events in ATLAS

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30th Anniversary of Rencontres du Vietnam

09/08/2023

ATLAS EXPERIMENT

W UNIVERSITY of WASHINGTON

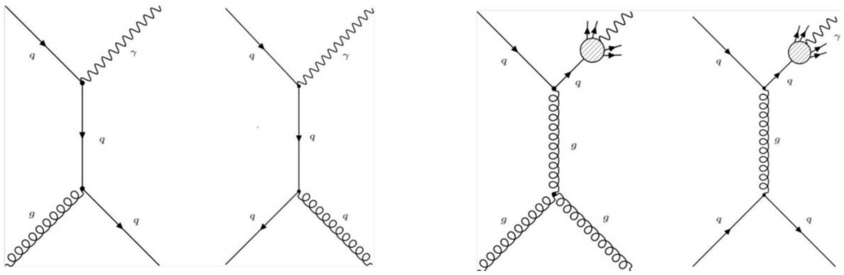
Overview

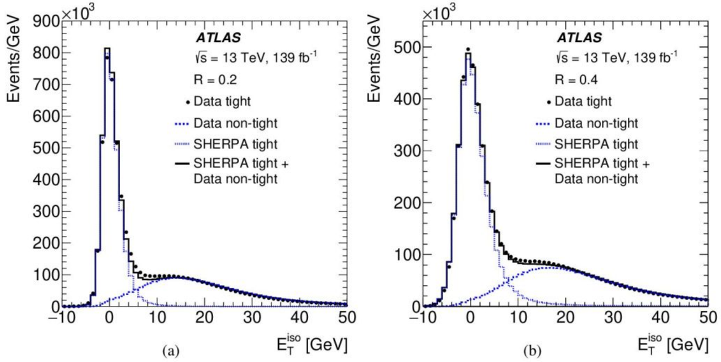
- Processes involving W/Z bosons and jets are standard candle for precision measurements and theory at LHC
  - The precise measurements of the production cross sections provide important tests of perturbative QCD
  - Measure fundamental parameters of the Standard Model (SM)
  - Improve our understanding of Parton Distribution Functions (PDFs)
- This talk will focus on the recent QCD related precise measurements in ATLAS
  - Prompt inclusive photon production at 13 TeV, JHEP07(2023)086
  - Multijet event isotropies at 13 TeV, arXIV:2305.16930
  - Z + high pT jets at 13 TeV, JHEP06(2023)080
  - W + charm hadrons at 13 TeV, arXiv:2302.00336
  - W and Z transverse momentum spectra at 5.02 and 13 TeV, ATLAS-CONF-2023-028
  - Precise determination of strong coupling constant
    - from transverse energy-energy correlations in multijets event at 13 TeV, JHEP 07 85 (2023)
    - from the recoil of Z bosons at 8 TeV, ATLAS-CONF-2023-015

Prompt inclusive photon production and its dependence on photon isolation

- Cleaner than jet production to test pQCD due to less of hadronisation effects
- Two processes contribute for prompt-photon production
  - **Direct process**: sensitive to the gluon density in the proton and can be used as input to global QCD fits to help to constrain the PDF.
- In addition to prompt photons, photons are produced copiously inside jets
  - Need isolation to study prompt photons
  - The isolation is based on the energy deposited inside a circle of radius R (0.2 and 0.4) centered on the photon in the η-φ plane
- Photon selection: $E_T^{iso} < E_{T,cut}^{iso} \equiv 4.2 \cdot 10^{-3} \cdot E_T^{\gamma} + 4.8\ \mathrm{GeV}$
  - E_T>250GeV, |η|<2.37, excluding <1.37|η|<1.56, trigger eff ~100%
  - Tight Photon ID
  - Photon isolation (R=0.2, 0.4)

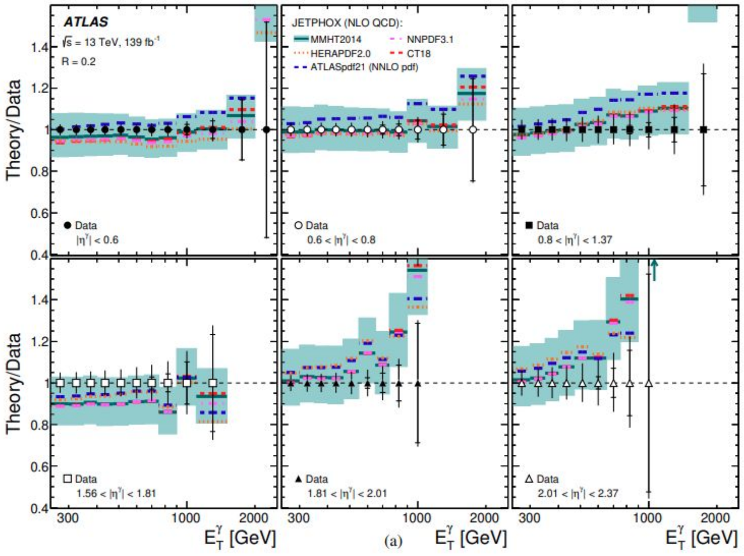
direct process | fragmentation process

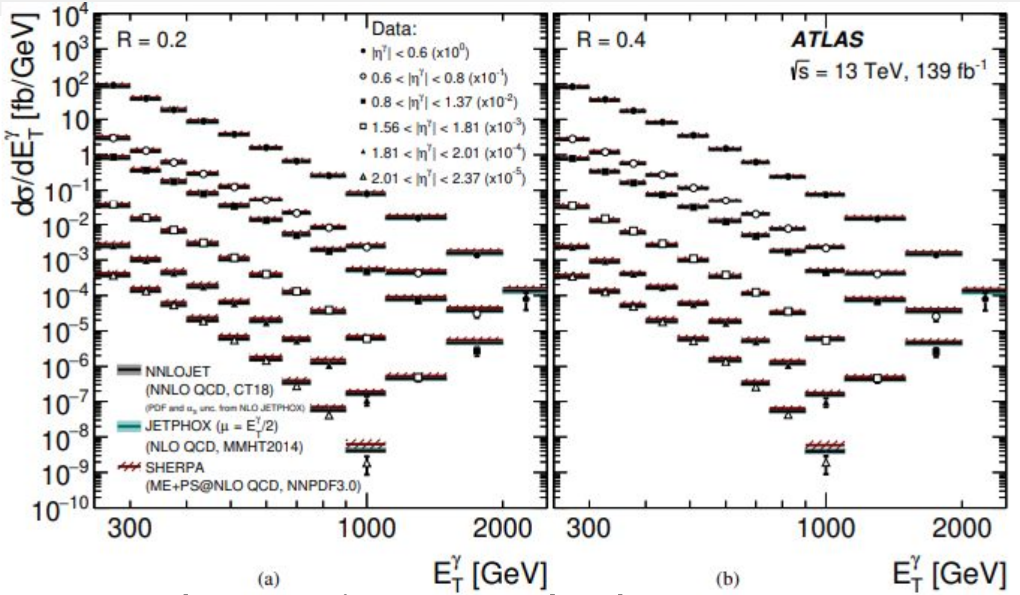




Differential cross sections

- All of the SHERPA NLO/JETPHOX/NNLOJET are consistent with measurements within uncertainties
- Systematic uncertainties dominated by the photon energy scale and luminosity.
    - Total uncertainty in the range 3% - 20%, depending on the E_T^γ and $|\eta^\gamma|$ region

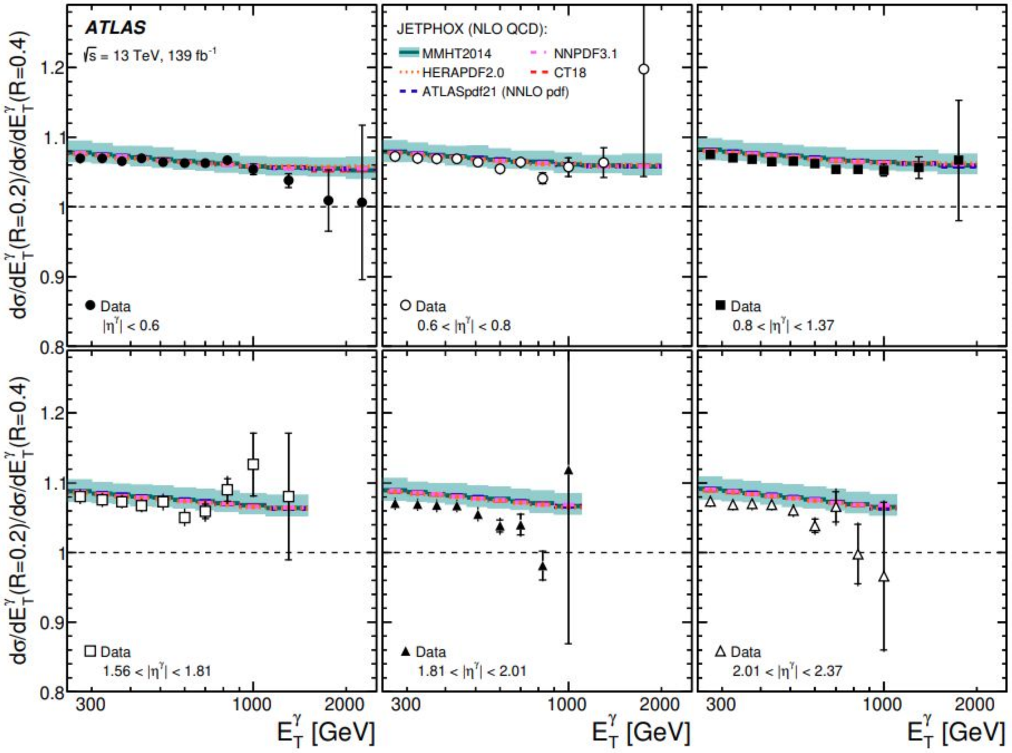




- **Measured cross sections compared to the NLO/NNLO QCD predictions** (JETPHOX/SHERPA/NNLOJET)
    - NNLO scale uncertainties reduced by more than a factor 2 w.r.t. NLO JETPHOX and SHERPA
    - For JETPHOX, several PDFs compared: MMHT2014, CT18, NNPDF3.1, HERAPDF2.0, and ATLASpdf21

R dependency of differential cross sections

- The dependence on R is studied by measuring the ratios of the differential cross sections for R=0.2 and R=0.4 as functions of E^T_γ the different $|\eta_\gamma|$ regions
- **No dependence** on the proton PDFs of the predictions of the ratio of the differential cross sections with R = 0.2 and R = 0.4 is observed.
- These measurements provide a very stringent test of pQCD with reduced experimental and theoretical uncertainties (both ~1% !)
  - Validation of the underlying pQCD theoretical description including NNLO corrections up to $\mathcal{O}(\alpha_s^2)$



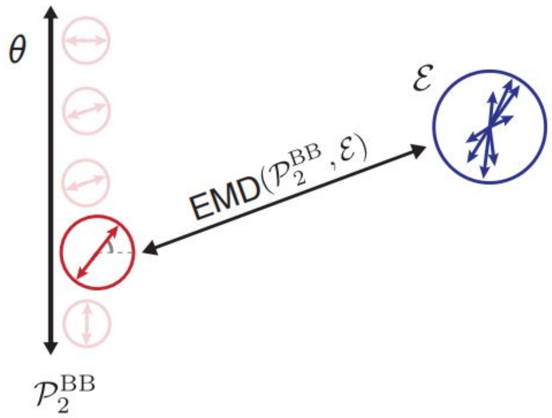
Measurements of multijet event isotropies using optimal transport

- Event shapes are used to probe fundamental properties of QCD, to tune MC, and to search for BSM
- **Event isotropies:** how far a collider event is from a symmetric radiation pattern in terms of a Wasserstein distance metric
- **Energy-Mover's Distance (EMD):** the minimum amount of 'work' necessary to transport one event ε with M particles into another ε' with M' particles, by movements of energy f_{ij} from particle i to particle j

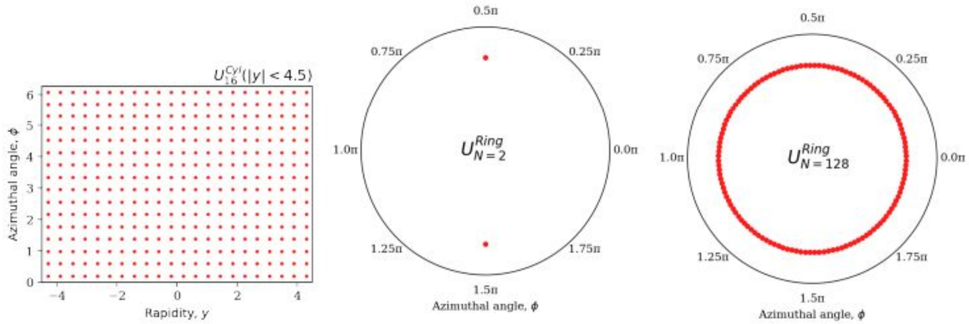
$$\mathrm{EMD}_{\beta}(\mathcal{E},\mathcal{E}') = \min_{\{f_{ij}\geq 0\}} \sum_{i=1}^{M}\sum_{j=1}^{M'} f_{ij}\theta_{ij}^{\beta},$$

θ_{ij}^{β}: ground measure between particles

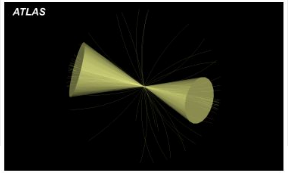
- This EMD define an optimal transport problem between energy flow in event ε and reference event ε'
- Input object for EMD calculation are jet
  - Not sensitive to non-perturebative QCD effects, i.e. hadronisation
  - Mass is not used

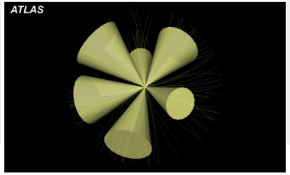


3 event shape variables are considered



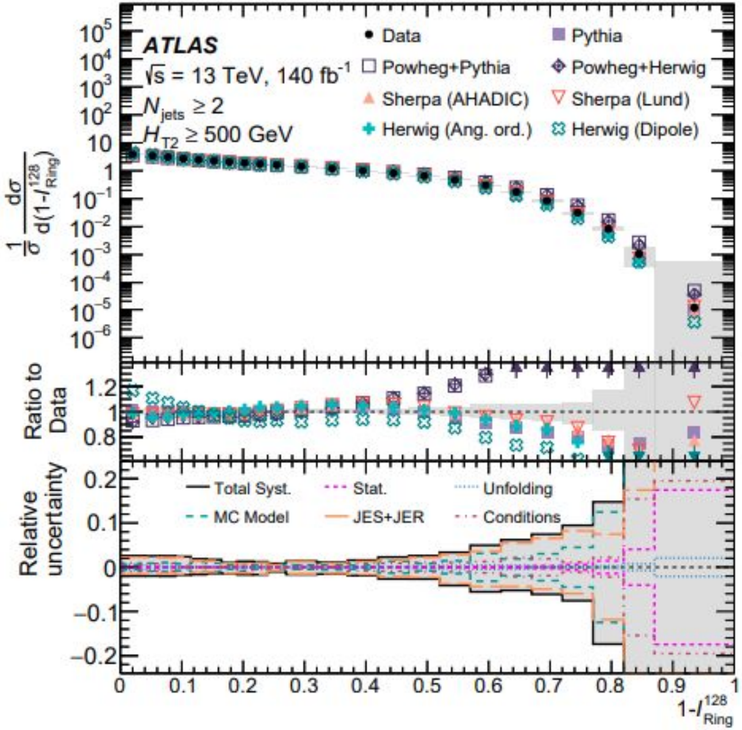
Event isotropies: $1\text{-}I^{128}_{Ring}$





back-to-back ⟷ isotropic

- **Ring-like event isotropy** (cylinder-like is in backup)
- Dijet events produce smallest value while multijet event produce the largest value
- Powheg+Pythia and Powheg+Herwig predictions are disagree with others
  - Overestimate the isotropic events
- Large difference between Herwig angle-ordered and dipole shower models
  - Dipole predicts more dijet-like events
- No notable difference between Sherpa hadronisation models
- Uncertainty of measurements is dominant by jet energy scale (JES) and jet energy resolution (JER)



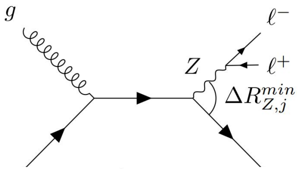
Z+high pT jets

- High-pT jet and Z phase spaces sensitive to NNLO QCD and higher order EW corrections
- First ever Z + high-pT jets measurement using the full Run-2 dataset
- Measurements unfolded to fiducial phase space
  - Two leptons with pT≥25 GeV & |η|<2.5
  - 71 ≤$m_{\ell\ell}$≤ 111 GeV
  - ≥1 jet with pT≥100GeV & |y|<2.5
- Using $\Delta R^{min}_{Z,jet} = \sqrt{\Delta y^2 + \Delta\phi^2}$ to study enhanced topologies

The cross sections predicted by the three generators (Sherpa, MG5_aMC@NLO+PY8 and NNLOJET) and the NNLOjet predictions agree with the measured values within the theory uncertainties.

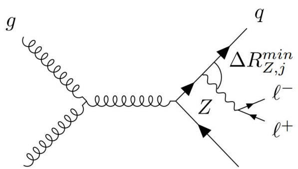
- The first two include PS but are NLO, while the third one provide only fixed-order calculations at both NLO and NNLO
- NLO virtual EW corrections have 10% - 20% impact on events with P_T≥ 500 GeV.
- QCD scale uncertainties very large: several 10s of %.

Back-to-back Z+1jet

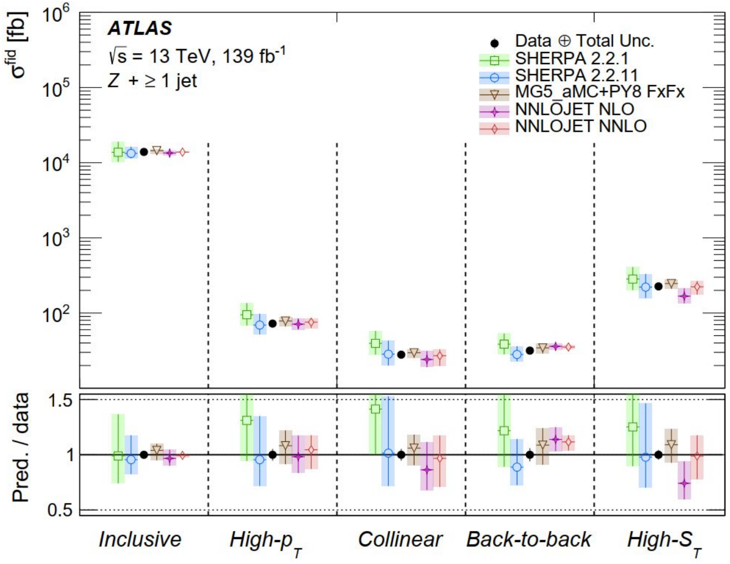


$\Delta R^{min}_{Z,jet} \geq 2.0$

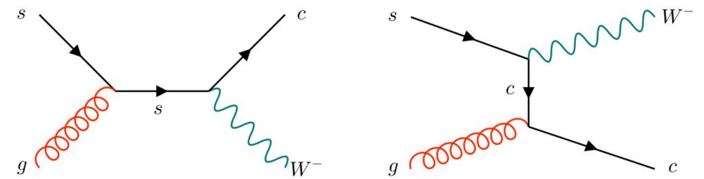
Collinear Z+2jets



$\Delta R^{min}_{Z,jet} \leq 1.4$



W + charm hadrons

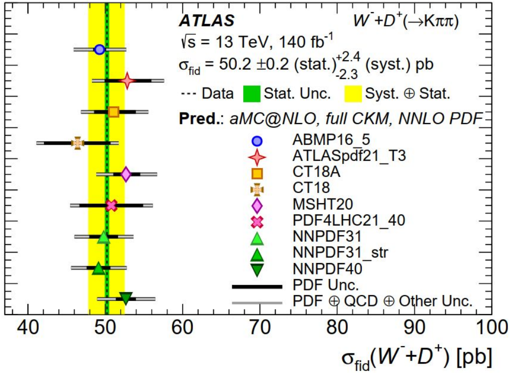


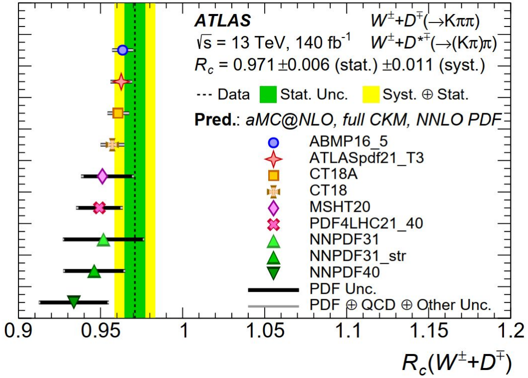
- W + c production is dominant by $gs \rightarrow W^{-}c$
  - Sensitive to the s-quark PDF
- Strategy: identify c-jet via charmed hadron reconstruction
- W + c signal extracted through profile likelihood fit
  - D+: reconstructed secondary-vertex mass distribution
  - D*+: mass difference $m(D{*}{+}\text{-}D0)$
- Fiducial cross-sections
  - Fiducial region:
    - pT(ℓ)>30 GeV, |η(ℓ)|<2.5 for W
    - pT($D^{(*)}$)>30 GeV, |η($D^{(*)}$)|<2.5 for $D^{(*)}$
  - Data-theory agreement for all PDFs
  - Precision (syst. dominated) comparable to the PDF uncertainties
- **R_c measurement**
  - Systematics in the “+” and ”-” channels mostly cancel out
  - PDFs which assume (s-$\bar{s}$) asymmetry in worse agreement with ATLAS data --> asymmetry is small in the region probed by this analysis

$D^{+} \rightarrow K^{-}\pi^{+}\pi^{+}$ and

$D^{*+} \rightarrow D^{0}\pi^{+} \rightarrow (K^{-}\pi^{+})\pi^{+}.$

$$\begin{aligned}
\sigma_{\text{fid}}^{\text{OS-SS}}(W^{-}+D^{+}) &= 50.2 \pm 0.2\,(\text{stat.})\,^{+2.4}_{-2.3}\,(\text{syst.})\text{ pb}\\
\sigma_{\text{fid}}^{\text{OS-SS}}(W^{+}+D^{-}) &= 48.5 \pm 0.2\,(\text{stat.})\,^{+2.3}_{-2.2}\,(\text{syst.})\text{ pb}\\
\sigma_{\text{fid}}^{\text{OS-SS}}(W^{-}+D^{*+}) &= 51.1 \pm 0.4\,(\text{stat.})\,^{+1.9}_{-1.8}\,(\text{syst.})\text{ pb}\\
\sigma_{\text{fid}}^{\text{OS-SS}}(W^{+}+D^{*-}) &= 50.0 \pm 0.4\,(\text{stat.})\,^{+1.9}_{-1.8}\,(\text{syst.})\text{ pb}\\
R_c^{\pm}(D^{(*)}) &= 0.971 \pm 0.006\,(\text{stat.}) \pm 0.011\,(\text{syst.})
\end{aligned}$$





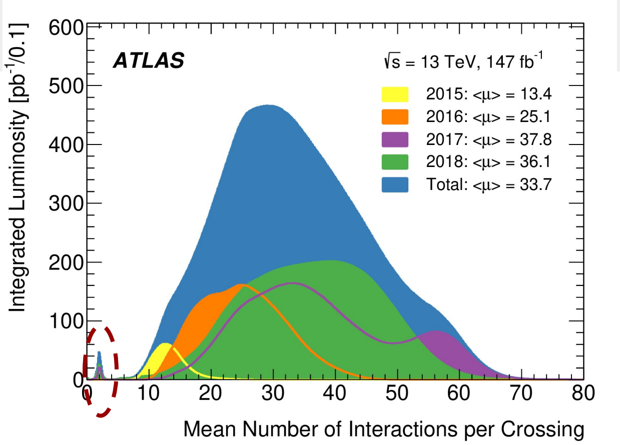
W/Z pT at 5.02 and 13 TeV

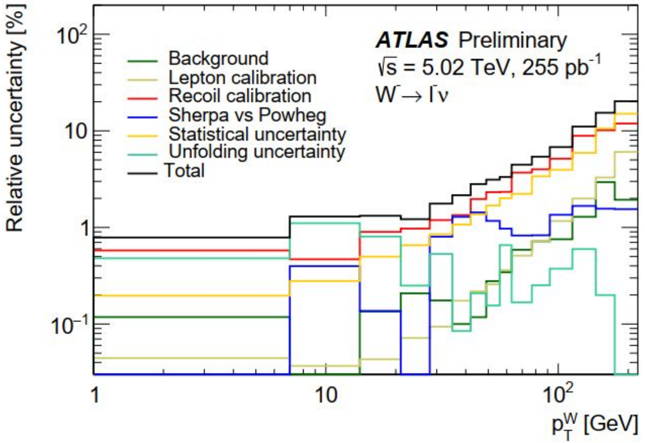
- Precise measurement of the W pT is important in reducing the modeling uncertainty in the W mass measurements
- **Hadronic recoil** is the main limitation of the pT W measurements
  - Pile-up events add energy to the recoil and hinder the experimental extraction of W pT
  - Calibration of recoil (u_T) is carried out in-situ using Z events
    - Modeling of underlying activity
    - Response and resolution corrections, azimuthal angle
  - Dominant uncertainty
- Dedicated low-pileup runs with **<μ> of about 2** taken in 2017 and 2018
  - 255 pb^{-1} at 5.02 TeV and 338 pb^{-1} at 13 TeV
- Fiducial volume

$$W \to \ell\nu : p_T^\ell > 25 \text{ GeV}, |\eta^\ell| < 2.5, p_T^\nu > 25 \text{ GeV, and } m_T > 50 \text{ GeV}$$

$$Z \to \ell\ell : p_T^\ell > 25 \text{ GeV}, |\eta^\ell| < 2.5, \text{ and } 66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$$

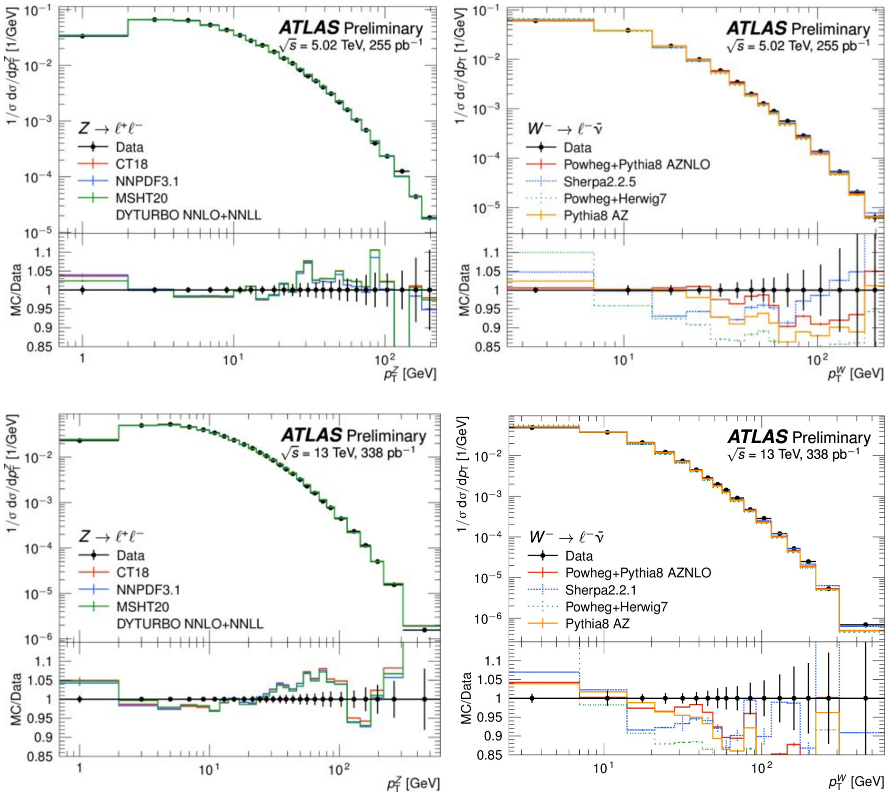
- Bayesian unfolding of u_T for W and pT(ℓℓ) for Z





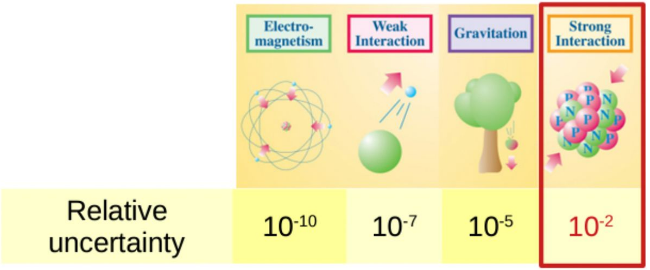
W/Z pT differential cross sections

- Precise measurements of the spectra at low pT are particularly interesting for future W mass study
- Predictions using the ATLAS tune (used for the W mass measurement on 7 TeV data) describe data reasonably at low pT especially at √s=5.02 TeV
  - Failed to describe data at 13 TeV
    - Better for Z cross section
- Better performance from Sherpa 2.2.5 and 2.2.1 at high pT
- The DYTURBO predictions (NNLO in QCD) show the best agreement and generally match the data at percent level
  - Small difference in different PDF sets
- Beneficial for future W mass measurement



Determination of strong coupling constants - α_s

- Strong coupling constant is the least well known in nature
- Dominant uncertainties to precision measurements of Higgs coupling at LHC or EW precision observables at lepton colliders



Recent two studies in ATLAS:
Extract the strong coupling constants from:

- Transverse energy-energy correlations at 13 TeV
- Z pT measurements at 8 TeV

Strong coupling constants from transverse energy-energy correlations

- In addition to event shape measurement, the multijet events can be used to precisely extract the strong coupling α_s
- **TEEC**: transverse energy weighted distribution of the azimuthal differences between jet pairs
  - Essentially an energy-weighted ratio of three-jet to two-jet cross sections

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{Ti}E^A_{Tj}}{\left(\sum_k E^A_{Tk}\right)^2}\delta\left(\cos\phi - \cos\varphi_{ij}\right)$$

- **ATEEC**: difference between the forward (cos ϕ >0) and backward (cos ϕ <0) part of TEEC

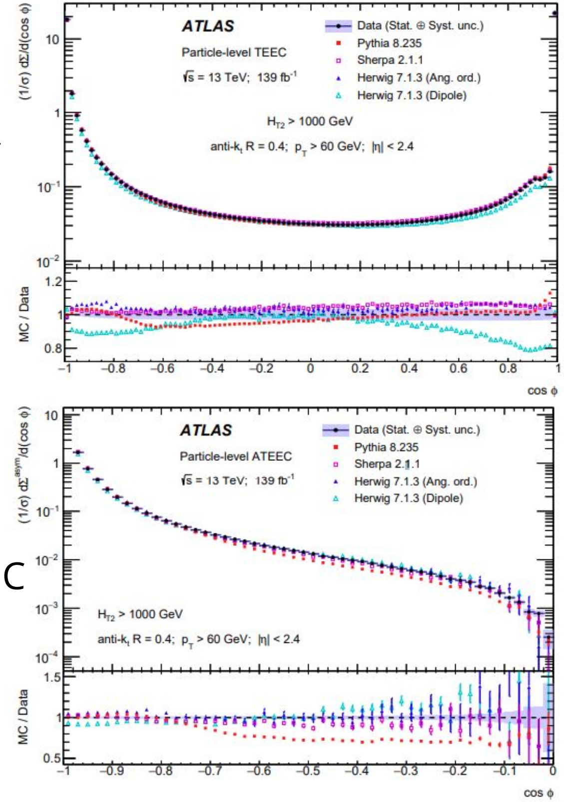
$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}.$$

- Both are sensitive to gluon radiation and strong coupling
- Full Run2 dataset
  - pT > 60 GeV, |η|<2.4, $H_{T2}=pT_1+pT_2$ > 1 TeV
  - 57.5M events after selections
  - unfolded to particle level
- NNLO pQCD calculations applied for the first time in gg->jjj process [PRL.127.152001]
  - Significant reduction of theoretical uncertainty
    - A factor of 3 in cross sections for both TEEC and ATEEC and in α_s

back-to-back ⟷ collinear

TEEC

ATEEC



Determination of the strong coupling $\alpha_s(Q)$

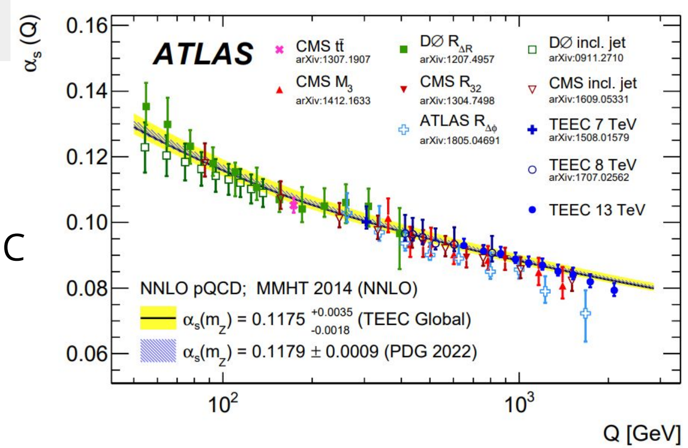
- Determination of $\alpha_s(Q)$ from the (A)TEEC in 10 intervals at NNLO accuracy in pQCD
    - obtained for both the inclusive and 10 exclusive bins in H_{T2}
    - Running scale Q as half averaged HT of all final-state partons in each H_{T2} bin

- TEEC with better experimental precision, ATEEC with better theoretical precision
- Uncertainty dominated by the jet energy scale and the model used to correct for detector effects
- Good agreement with other measurements and RGE prediction

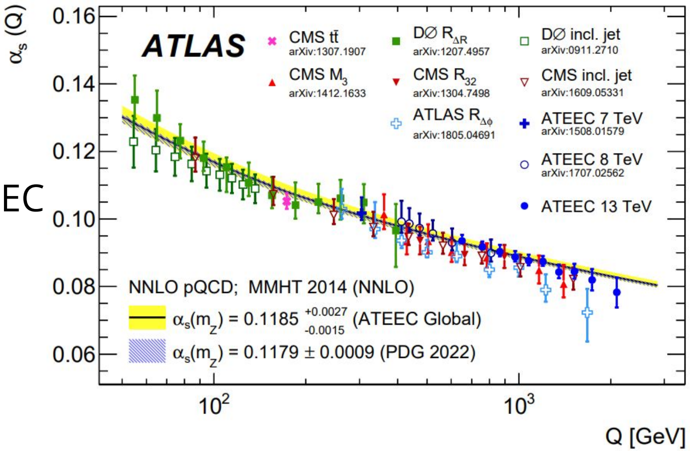
$$\alpha_s(m_Z) = 0.1175 \pm 0.0006\,(\text{exp.})^{+0.0034}_{-0.0017}\,(\text{theo.})\text{ and}$$
$$\alpha_s(m_Z) = 0.1185 \pm 0.0009\,(\text{exp.})^{+0.0025}_{-0.0012}\,(\text{theo.}).$$

World average (PDG) $\alpha_s(m_Z)$ = 0.1179 ±0.0009

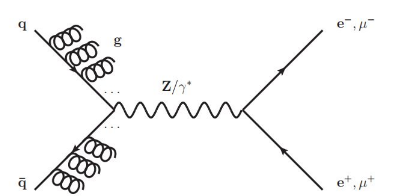
TEEC



ATEEC

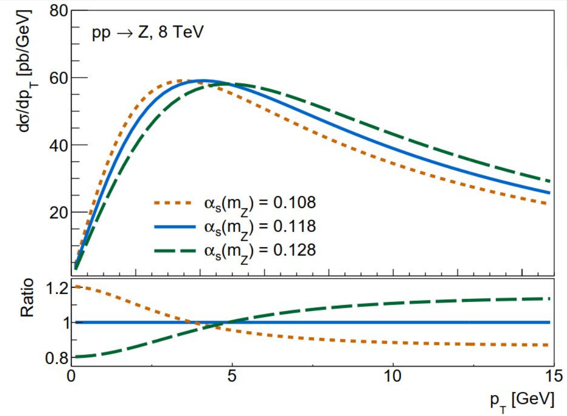


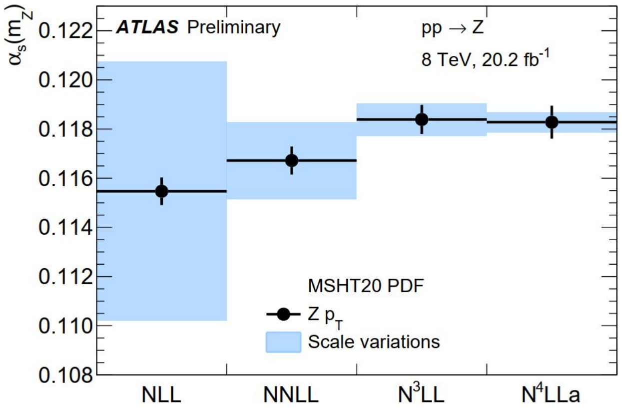
Extraction of α_s from Z pT at 8 TeV



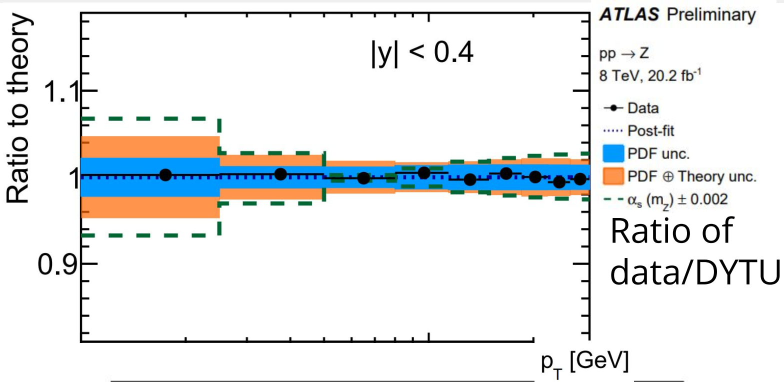
- Further measurement of $\alpha_s(m_Z)$ is limited by two theoretical uncertainties:
  - The accuracy of the perturbative predictions
  - The non-perturbative effects.
- State of art prediction:
  - DYTURBO: aN^4LL resummation + N^3LO perturbative with aN^3LO MSHT20 PDF
- Peak position of Z pT is sensitive to $\alpha_s(m_Z)$
  - QCD initial state radiation (ISR)
  - Can be measurement precisely
- Extraction from fitting the double differential pT-y cross section in full lepton phase space
  - extracted through a χ2 scan for α_s variations
  - Fit range: Z pT is < 29 GeV (vary the range to study systematic uncertainty)
  - χ2 /ndf = 82/72
  - an float nuisance parameter for the non-perturbative form factor affecting the Z pT < 5 GeV region

$$\chi^2(\beta_{\mathrm{exp}}, \beta_{\mathrm{th}}) = \sum_{i=1}^{N_{\mathrm{data}}} \frac{\left(\sigma_i^{\mathrm{exp}} + \sum_j \Gamma_{ij}^{\mathrm{exp}} \beta_{j,\mathrm{exp}} - \sigma_i^{\mathrm{th}} - \sum_k \Gamma_{ik}^{\mathrm{th}} \beta_{k,\mathrm{th}}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\mathrm{exp}}^2 + \sum_k \beta_{k,\mathrm{th}}^2 .$$





Most precise experimental result

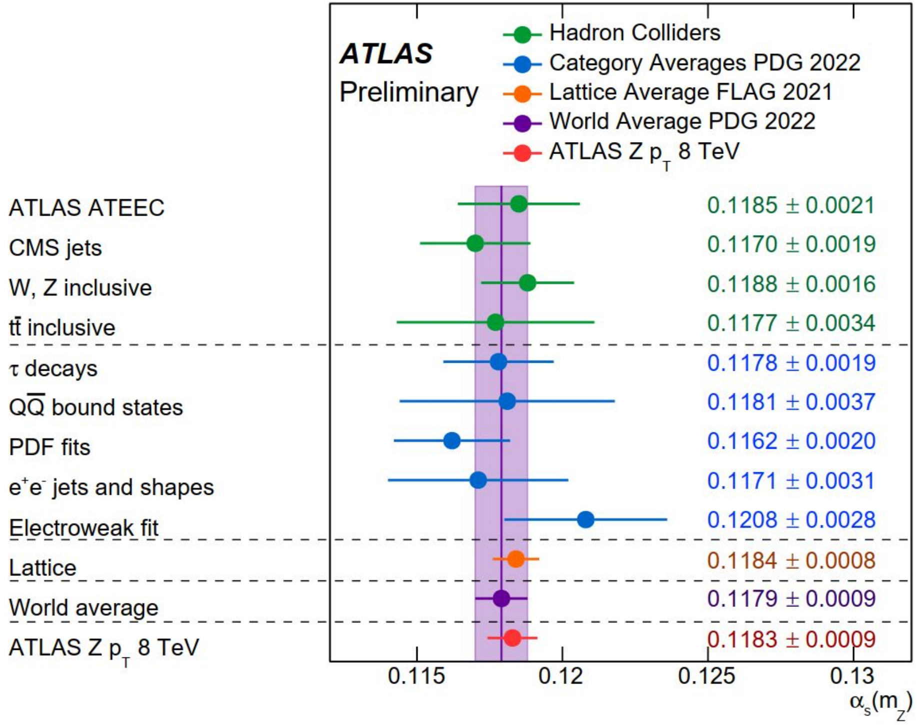


Ratio of data/DYTURBO

Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088

Precision similar to world average and lattice calculation

$$\alpha_s = 0.11828 + 0.00084 - 0.00088$$



Summary

- Wealth of precise measurements with multijet and W/Z events at ATLAS
  - Differential cross section for inclusive photon, Z + high pT jets, W + charm, W/Z pT spectra
    - compared to state-of-the-art NLO and NNLO prediction
  - Event shape variables
    - No MC can describe all the isotropies
  - Strong coupling constants
    - Two measurements with different approach, consistent with each other and with predictions
    - Most precise result and first determination using $aN^4LL + N^3LO$ prediction from Z pT study
  - Beneficial for the improvement of MC generator modelling, perturbative and non-perturbative effects, and W mass measurement ...
- Run3 is on-going
  - Experimental & theoretical physicists need to collaborate and improve our understanding
  - Many more results still to come.