UNIVERSITY OF OXFORD

ATLAS EXPERIMENT

QCD Measurements with ATLAS

18/06/24

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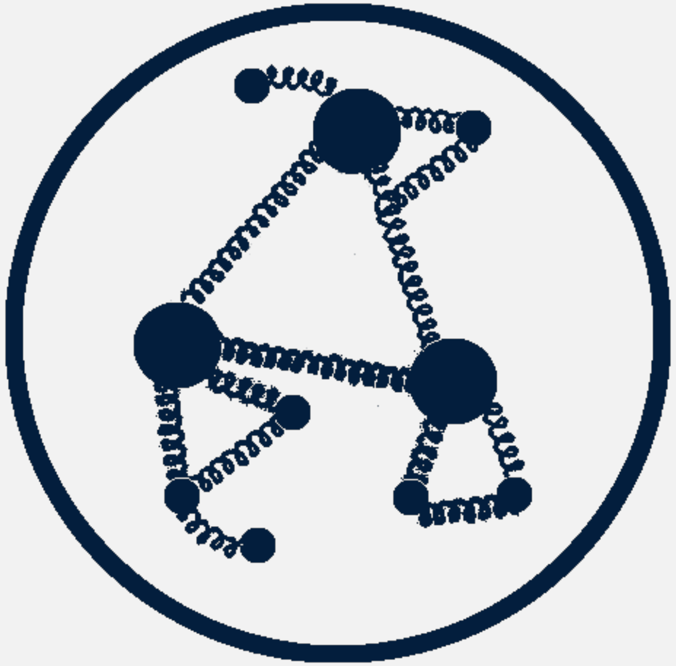
QCD@Work 2024

Introduction

- ATLAS: General purpose LHC experiment, with the power to precisely measure a broad range of physics processes
- Many recent QCD-sensitive measurements…
- … in several different **topologies**
  - Jets (inlusive, dijet, multijet)
  - Z boson
  - Lund plane/jet substructure
  - and more!
- … with a range of different **aims**
  - PDF fitting
  - α_s extraction
  - Theory benchmarking



ATLASpdf21 Fit

Eur. Phys. J. C 82 (2022) 438

Analysis strategy

ATLAS datasets also routinely included by global PDF fitters

Q^2_{min} = 10 GeV^2 cut placed on HERA data to avoid regions requiring additional treatment e.g. small-x resummation

Simultaneously fitting as many useful ATLAS datasets as possible

- **LHC:** Medium-high x, Q^2, quark flavour separation, direct sensitivity to gluon at high x
- **HERA:** Wide x, Q^2 range

Data set	$\sqrt{s}$ [TeV]
Inclusive $W, Z/\gamma^*$	7
$t\bar{t}$	8
$W^\pm$ + jets	8
Z + jets	8
Inclusive Z/γ^*	8
Inclusive W	8
Inclusive isolated γ	8, 13
$t\bar{t}$	13
Inclusive jets	8

NNLO QCD analysis performed in xFitter, independently cross-checked

- Parameterisation:

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2+Fx^3)$$ (extra gluon term: $-A'_g x^{B'_g}(1-x)^{C'_g}$)

if needed

- Constraints → Sum rules
  - Number sum rule
  - Momentum sum rule

- Using starting scale $\mathbf{Q_0^2 = 1.9\ GeV^2}$ and $\boldsymbol{\alpha_s(m_Z) = 0.118}$ we fit six parton distributions using 21 free parameters

Previous ATLAS fits: 15/16

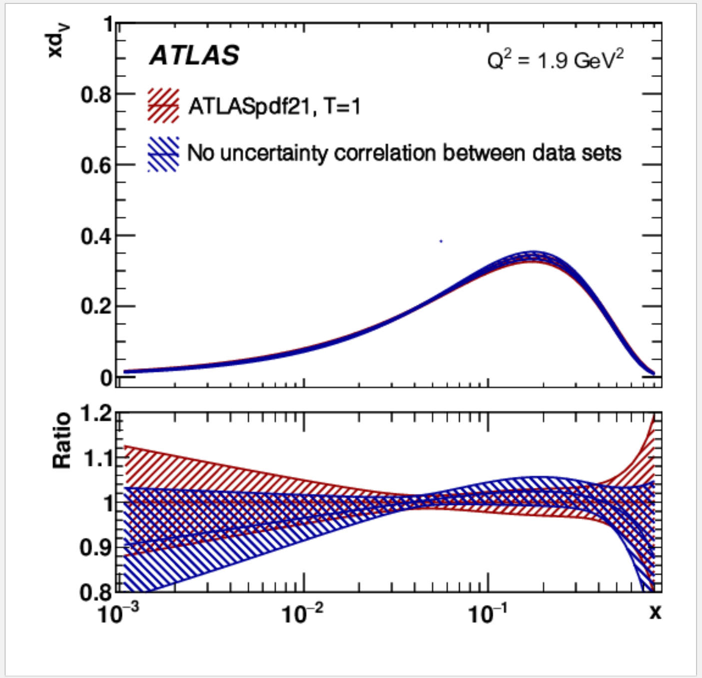
Analysis highlights

Careful consideration also made of scale uncertainties and treatment of jet data

Don't want to fit away BSM effects at high scale

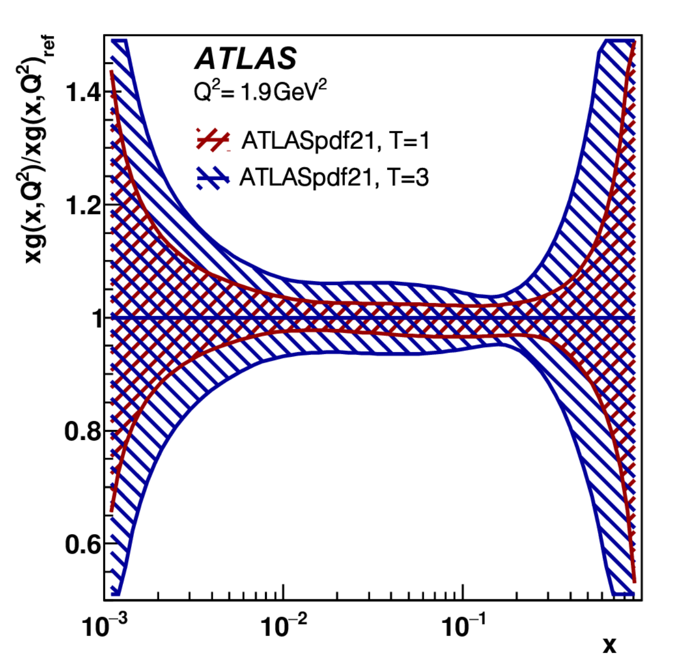
Many datasets → Possible tensions

Accounting for correlations



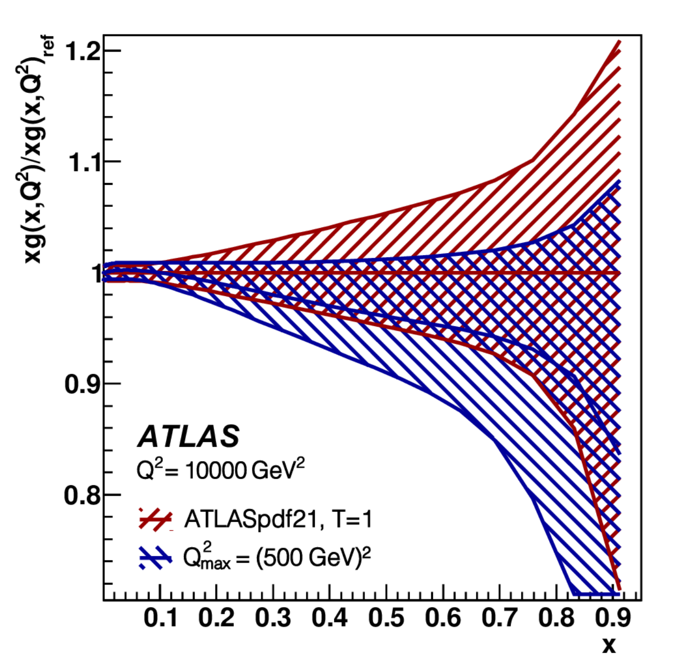
Not accounting for systematic correlations → PDFs varying up to 20% (especially d-type)

Enhanced χ^2 tolerance



Enhanced tolerance from T=1 to T=3 (MSHT dynamic tolerance procedure)

Possible BSM effects



High Q^2 cut on input data has little impact on shape & uncertainties

Resulting PDFs

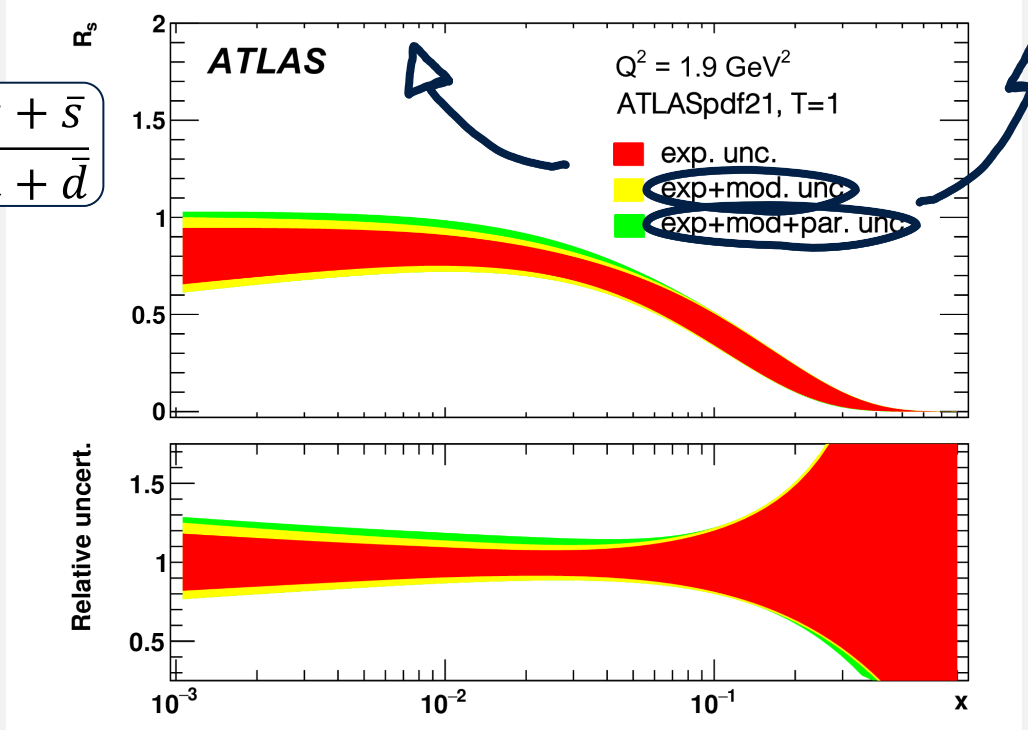
ATLASpdf21 fit global χ^2

total χ^2/NDF	2010/1620 (1.24)

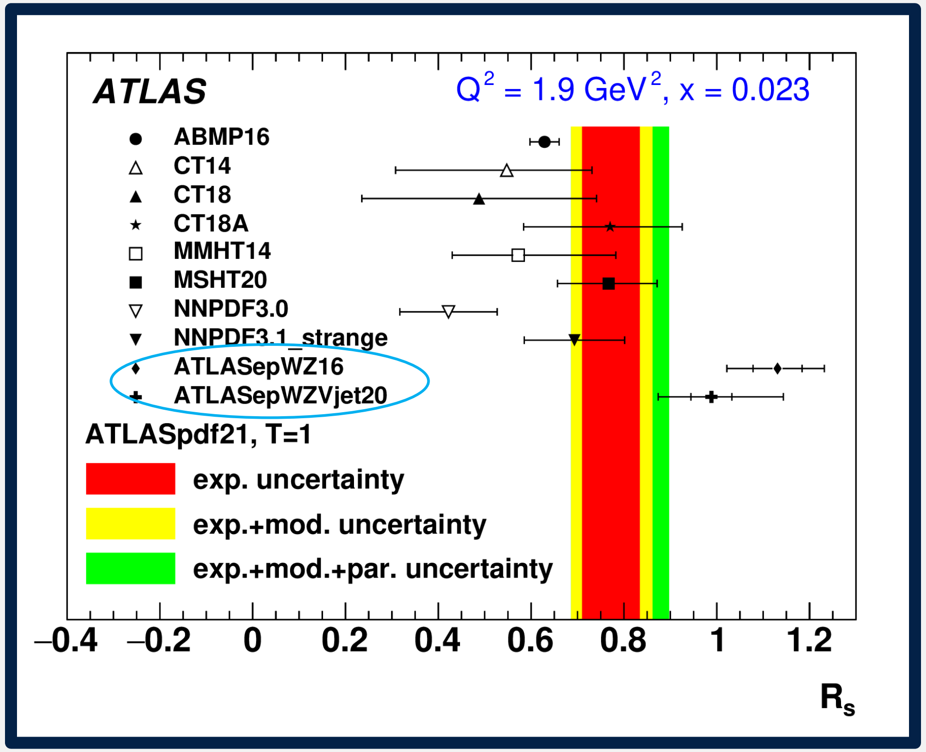
Vary theoretical assumptions: Q^2_{min}, Q^2_0, heavy quark masses etc.

Add extra D, E, F parameters (low-x sea)

$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$$



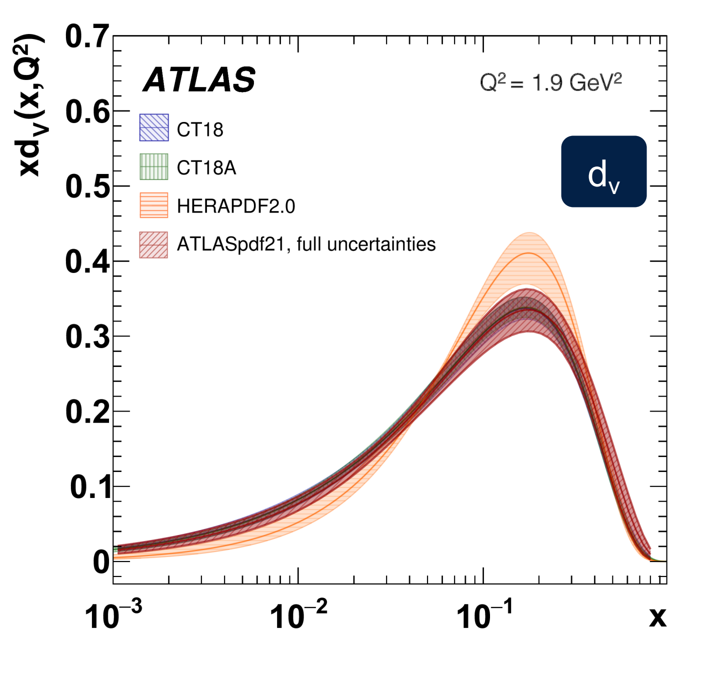
R_s still unsuppressed at low-x but less tension with global fitters than previous ATLAS fits

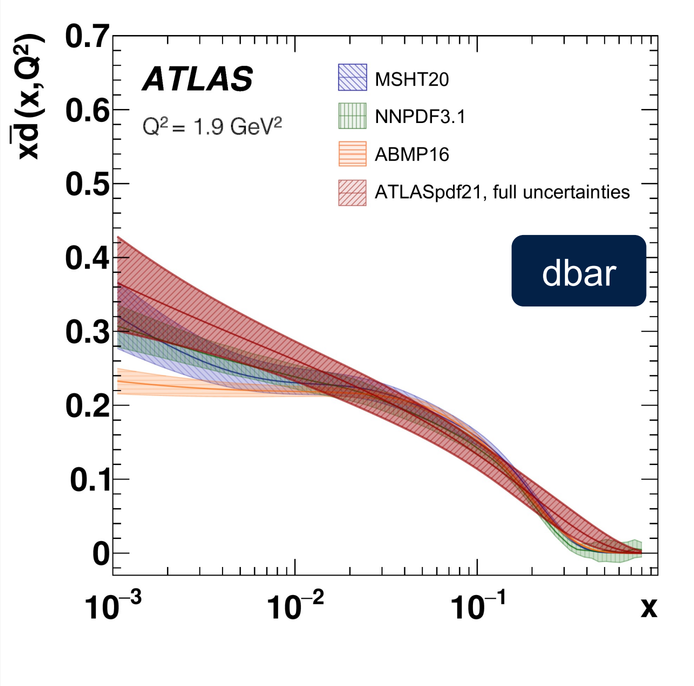


CT18A, MSHT20, NNPDF3.1_strange i.e. the global fits which include ATLAS 7 TeV W,Z data which leads to the unsuppressed strange, are most consistent with our fit

Comparison with global PDFs

ATLASpdf21 agrees as well with the global fits as they do with each other





d_v, dbar distributions brought more in line with global fitters (which include Tevatron and fixed target DIS, DY data) than to HERAPDF.

→ ATLAS data replicates features of these data instead

Lower χ^2 for these data than the global fitters

ATLASpdf21	CT18	CT18A	MSHT20	HERAPDF2.0	NNPDF3.1
2010/1641 (1.22)	2135/1641 (1.30)	2133/1641 (1.30)	2218/1641 (1.35)	2262/1641 (1.37)	2109/1641 (1.29)

α_s from multijet TEEC at 13 TeV

JHEP 07 (2023) 85

α_s measurements

Beneficial to have several measurements with different sensitive observables and theory predictions

- α_s → least precisely determined coupling of a fundamental interaction
  - Orders of magnitude!
  - This needs to be better → Cross-section calculations for LHC, key observables for e^+e^-
- How?
  1. Lattice QCD analysis of hadron spectroscopy (most precise)
  2. Hadronic τ decays
  3. Global fits of EW observables
  4. Hadron-hadron collisions (jets, ttbar, W, Z…)
- Two major theory limitations:
  - Accuracy of the perturbative predictions
  - Size of non-perturbative effects

Transverse energy–energy correlations

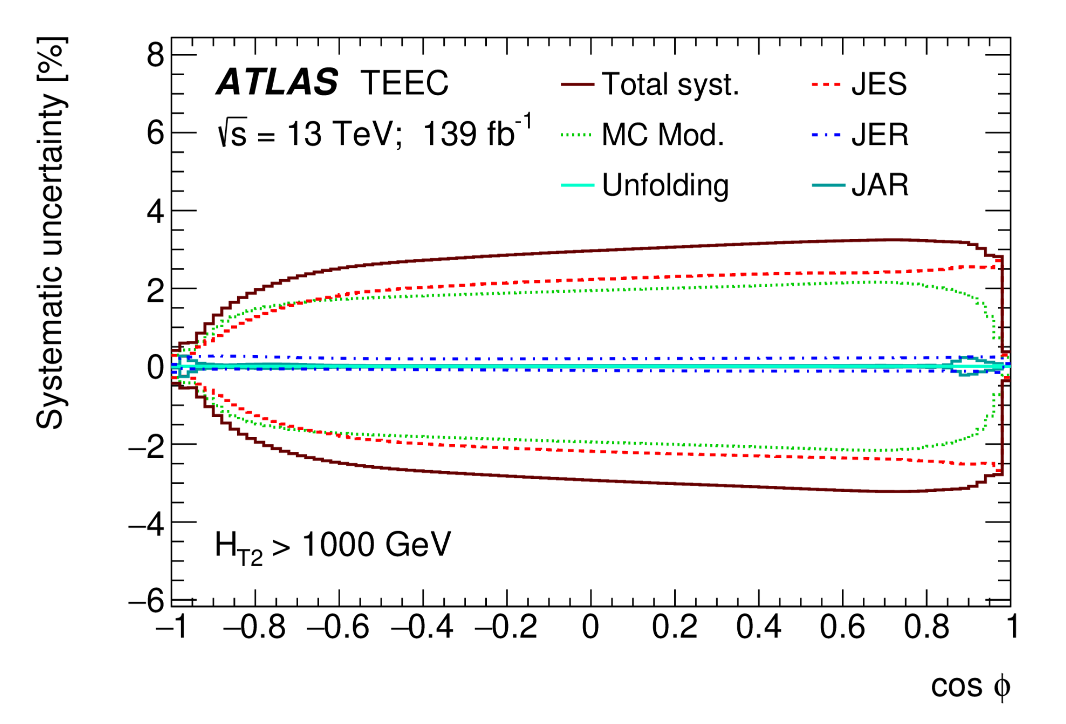
- **Event shapes:** Category of observables which characterise hadronic energy flow
  - Precisely test pQCD calculations and extract α_s
  - e.g. Energy-energy-correlations (EEC) → IRC safe, modest $O(\alpha_s^2)$ corrections
- Require generalisation for hadronic colliders:
  - **Transverse EECs** (TEEC)
    - Transverse-energy-weighted distribution of azimuthal differences between final-state jet pairs
  - Associated **Azimuthal TEECs** (ATTEC)
    - Difference between forward and backward part of TEEC
  - Sensitive to gluon radiation, clear dependence on α_s
- Previously measured by ATLAS at 7 & 8 TeV

Experimental Measurement

Jets:
anti-k_T, R=0.4, p_T > 60 GeV, |η| < 2.4

Event:
$N_{jets} \geq 2$, H_{T2} > 1 TeV

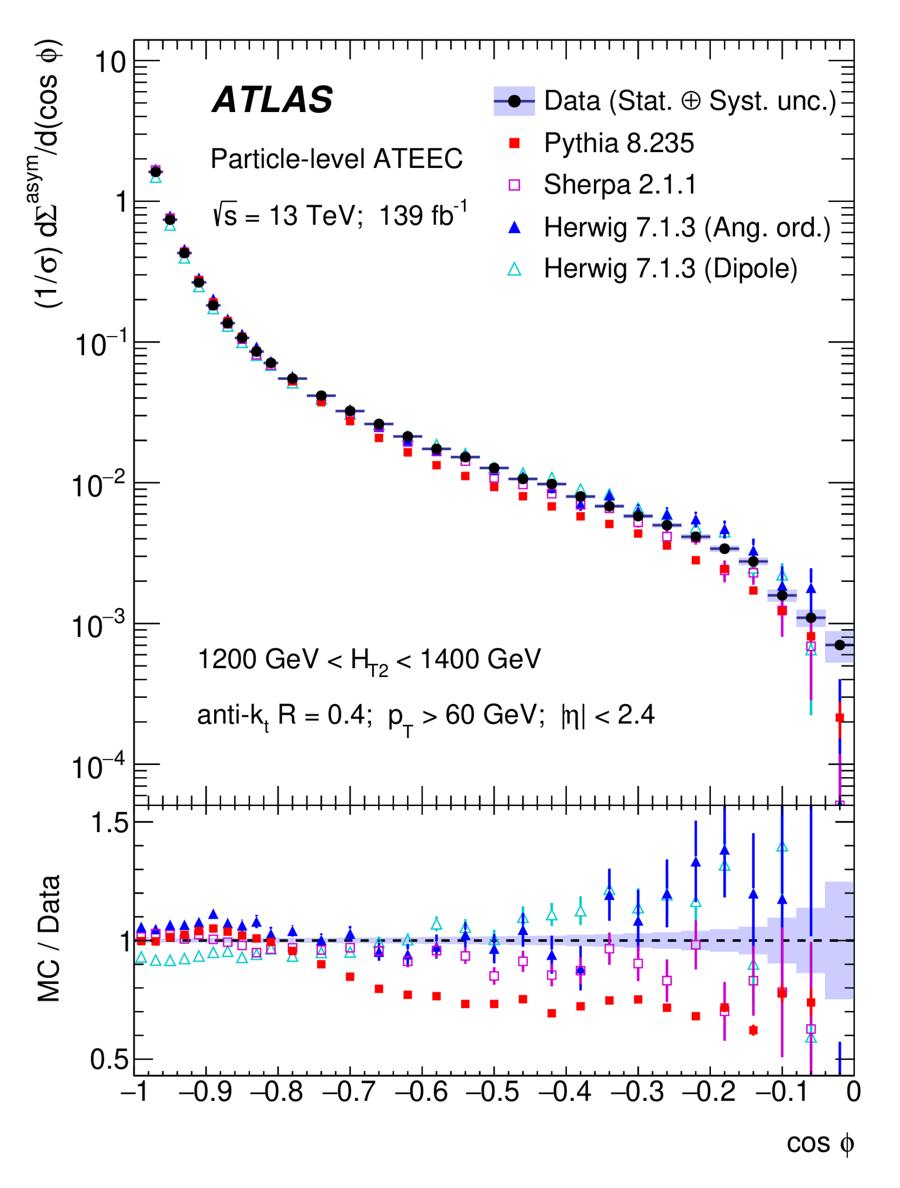
- Full ATLAS Run 2 13 TeV pp data
- Observables: TEEC, ATEEC vs H_{T2}
- Unfolded:
  - Iterative Bayesian, separately in each H_{T2} considering only cos(ϕ) dependence
- Uncertainties:
  - ~2% for TEECs, ~1% for ATEEC
  - Dominated by JES and unfolding model



Comparison with Theory

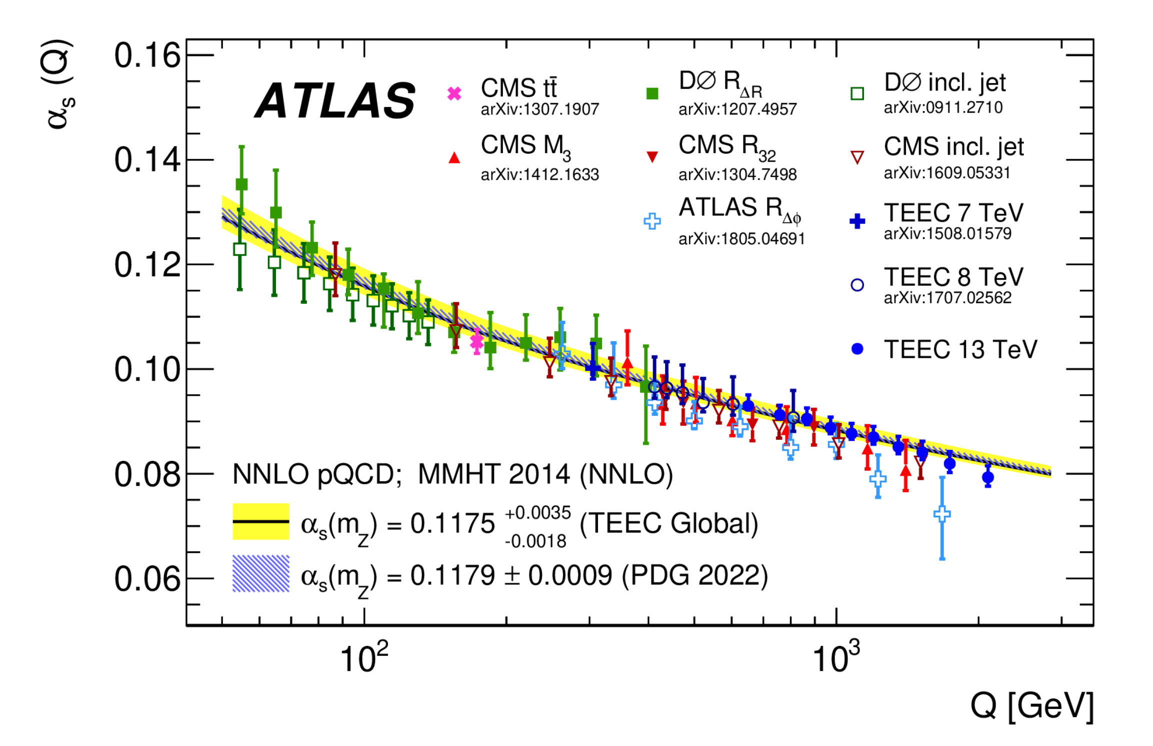
- Compared to MC predictions
  - Pythia8, Sherpa, Herwig7 angle-ordered & dipole PS

- Compared to pQCD predictions for α_s extraction
  - At $O(\alpha_s^5)$, TEEC calculation involves 2→3 at NNLO (first time), 2→4 at NLO and 2→5 at LO
    - $\mu_r = \mu_f = \hat{H}_T = \sum_i p_{T,i}$
    - NP corrections from ratio $\frac{\text{MC with hadronisation \& UE}}{\text{MC without hadronisation \& UE}}$
  - Uncertainties dominated by scale
    - ~2%, reduced 3x by NNLO corrections
  - Excellent agreement between data and theory



Extracting α_s

- $\alpha_s(M_Z)$ via χ^2 minimisation to TEEC & ATEEC distributions:
  - $\alpha_s(M_Z) = 0.1175 \pm 0.0006 \text{ (exp.) } {}^{+0.0034}_{-0.0017} \text{ (th.) (TEEC)}$
  - $\alpha_s(M_Z) = 0.1185 \pm 0.0009 \text{ (exp.) } {}^{+0.0025}_{-0.0012} \text{ (th.) (ATEEC)}$
- $\alpha_s(Q)$ extracted by evolving fitted $\alpha_s(M_Z)$ using NNLO solutions to the RGE
  - Test asymptotic behaviour of QCD
  - Good agreement RGE predictions and previous measurements up to high energy scales

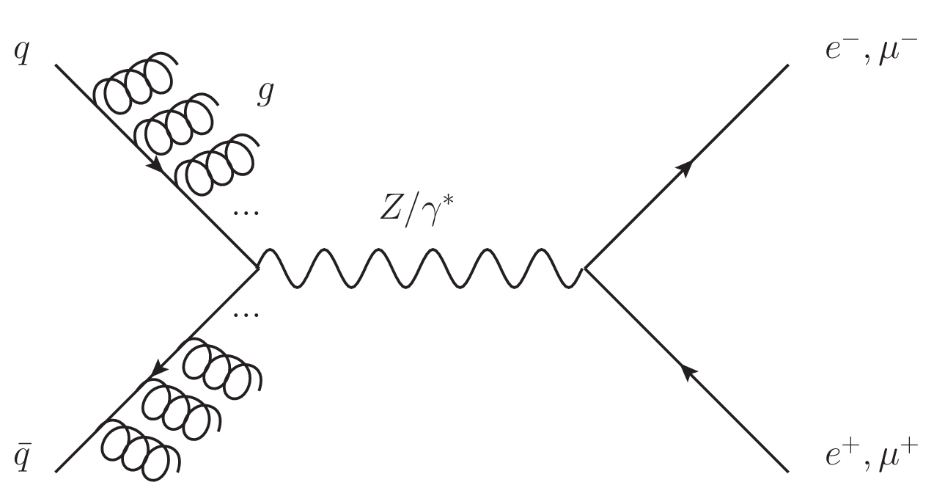


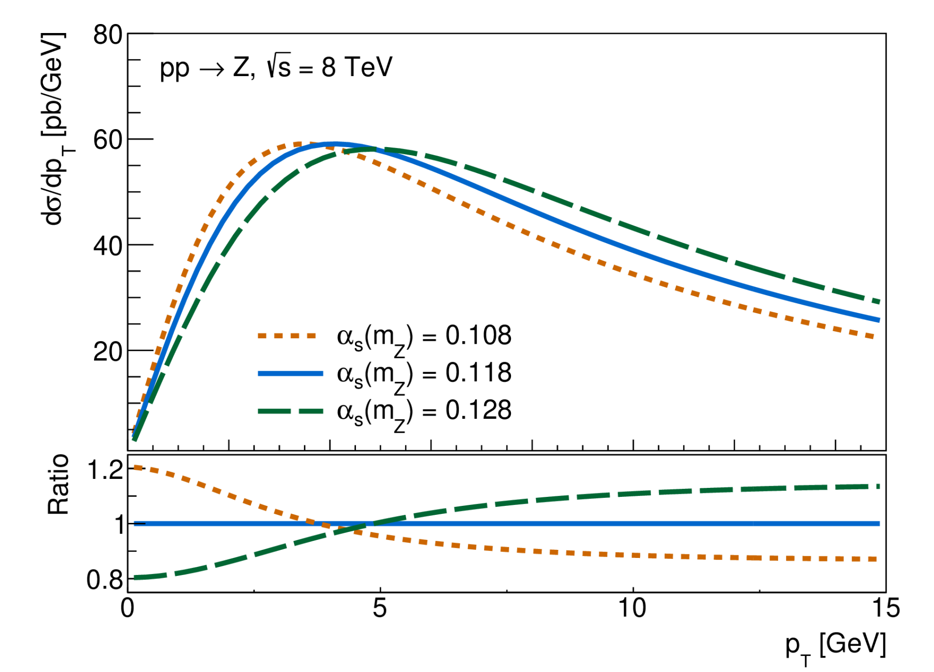
α_s from p_T^Z

arXiv:2309.12986 [hep-ex]

$\alpha_s(M_Z)$ from p_T^Z

- Measure Drell-Yan p_T^Z in low-momentum 'Sudakov region'
  - Many soft gluon emissions in the initial state
  - Strong force responsible for ISR and subsequent Z recoil
- $\alpha_s(M_z)$ determined by hardness of the p_T^Z spectrum
  - Measure of boson recoil, $\propto \alpha_s(M_z)$
- Advantages:
  - Less common to measure α_s using ISR objects
  - DY → final state objects do not experience strong force
    - Reduce theoretical complexity
  - Sudakov region not usually used in PDF fits (correlations)
  - Scale fixed at Z mass
  - Clear signature and low backgrounds

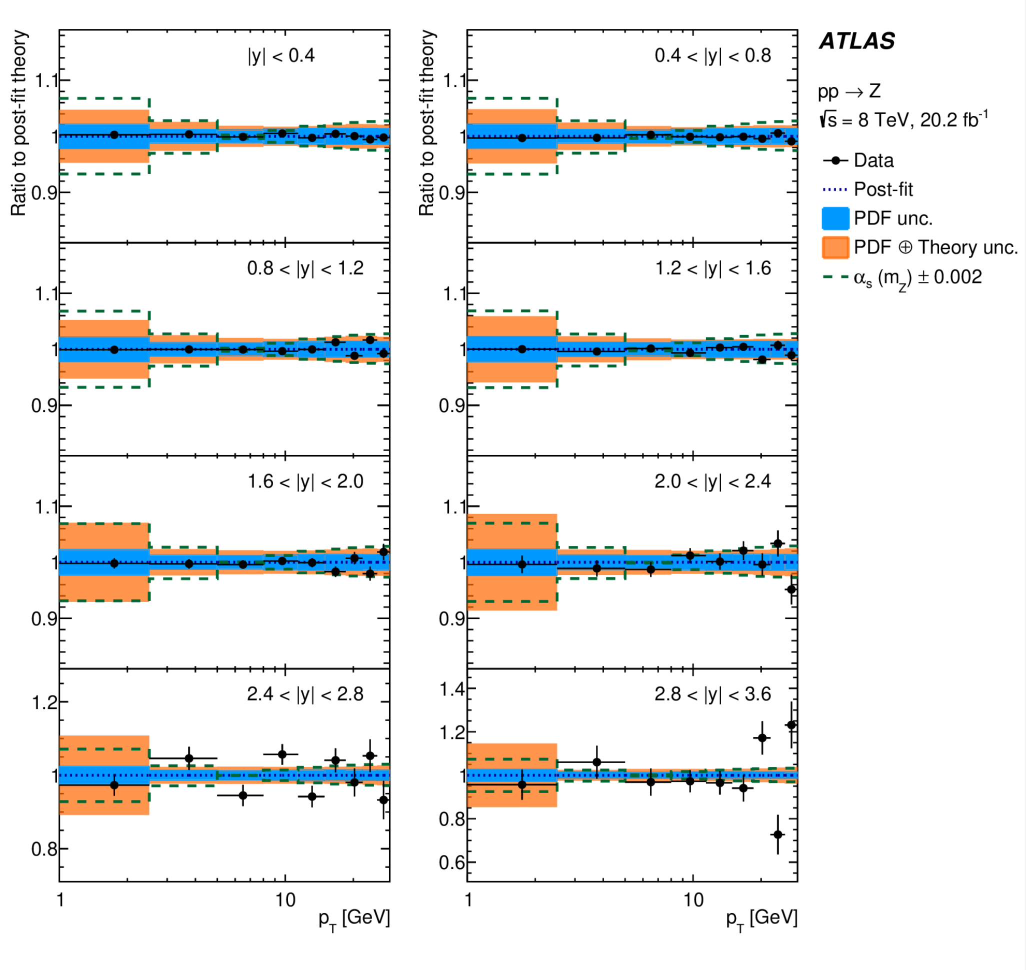




Experimental measurement

Z boson:
80 GeV < m_{ll} < 100 GeV
Leptons:
Central/ forward, p_T > 20/25 GeV

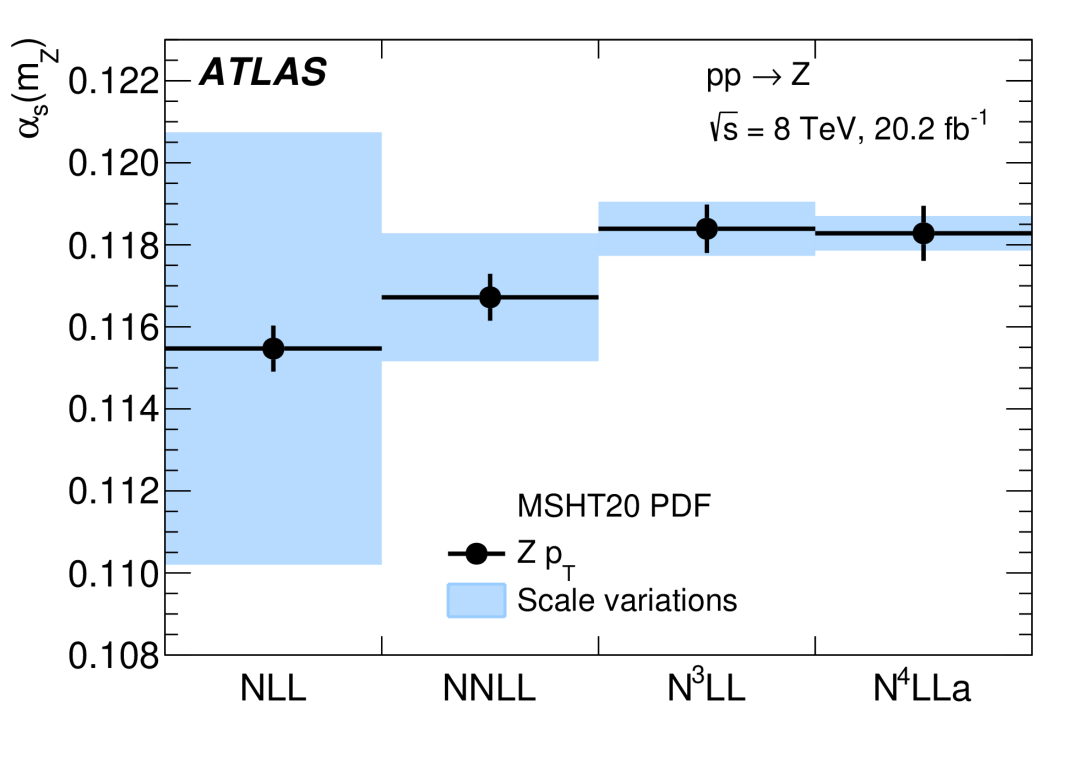
- Measure 20.2 fb^{-1} of 8 TeV events in electron & muon channels
- **Observables:** Double-differential $\sigma(p_T^Z, y^Z)$ in Z pole region
  - $p_T^Z < 29$
  - Eight rapidity regions in $|y| < 3.6$
- Extended to full lepton phase space by fitting spherical harmonic templates in Collins–Soper frame to $\cos(\theta^l)$, Φ^l in data
  - No longer need to model polarisation and decay of the Z
- QCD+EW backgrounds → 0.3-1.1%
- Data stat uncertainties dominate
  - Lumi uncertainty (1.8%)
  - Otherwise, total uncertainties <1-10%(central vs forward y)



Comparison with Theory

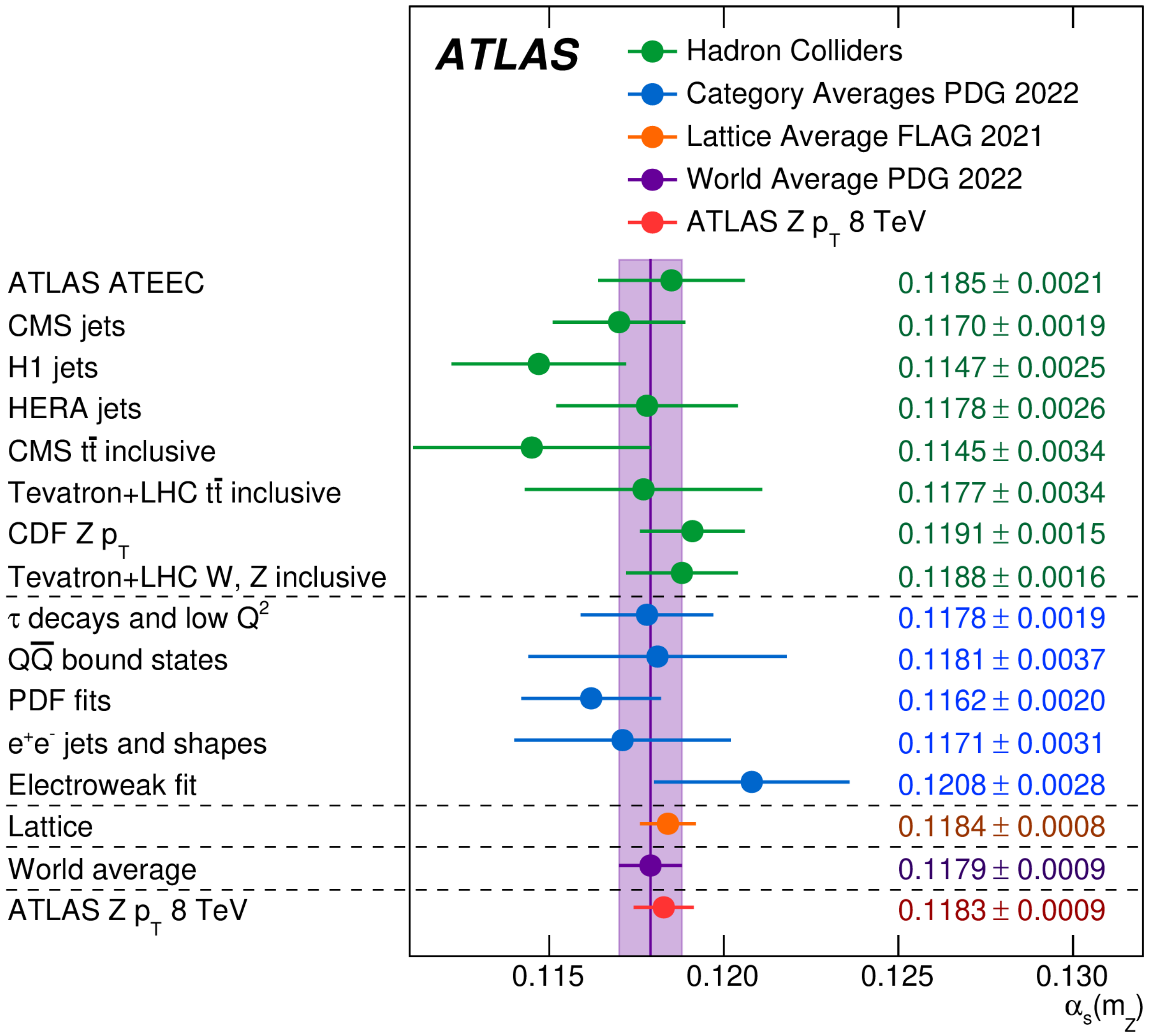
χ^2 = 82/72 NDF

- Predictions computed with DY Turbo:
  - Hard-collinear contributions at N3LO matched to fixed order N3LO
  - Resum low-p_T logs at N4LLa accuracy
- $\mu_r = \mu_f = Q = m_{ll}^2 + (p_T^Z)^2$
- PDF: MSHT20 at aN3LO
- IS photons' impact on p_T^Z estimated at LL with Pythia8.
  - Higher QED order effects considered at NLO
- Statistical analysis done with xFitter via χ^2 minimisation
  - Uncertainties (except PDF) included as nuisance parameters
  - Account for correlations between PDFs and α_s using α_s -series PDF sets



Results

- $\alpha_s(M_Z)$ **= 0.1183 ± 0.0009**
  - Most precise experimental determination of $\alpha_s(M_Z)$
  - First based in N4LLa+N3LO pQCD predictions
- Also performed simultaneous PDF fit determination of α_s
  - HERA combination + ATLAS p_T^Z
  - $\alpha_s(M_Z) = 0.11866 \pm 0.00064$



Jet cross-section ratios at 13 TeV

arXiv:2405.20206 [hep-ex] (submitted to PRD)

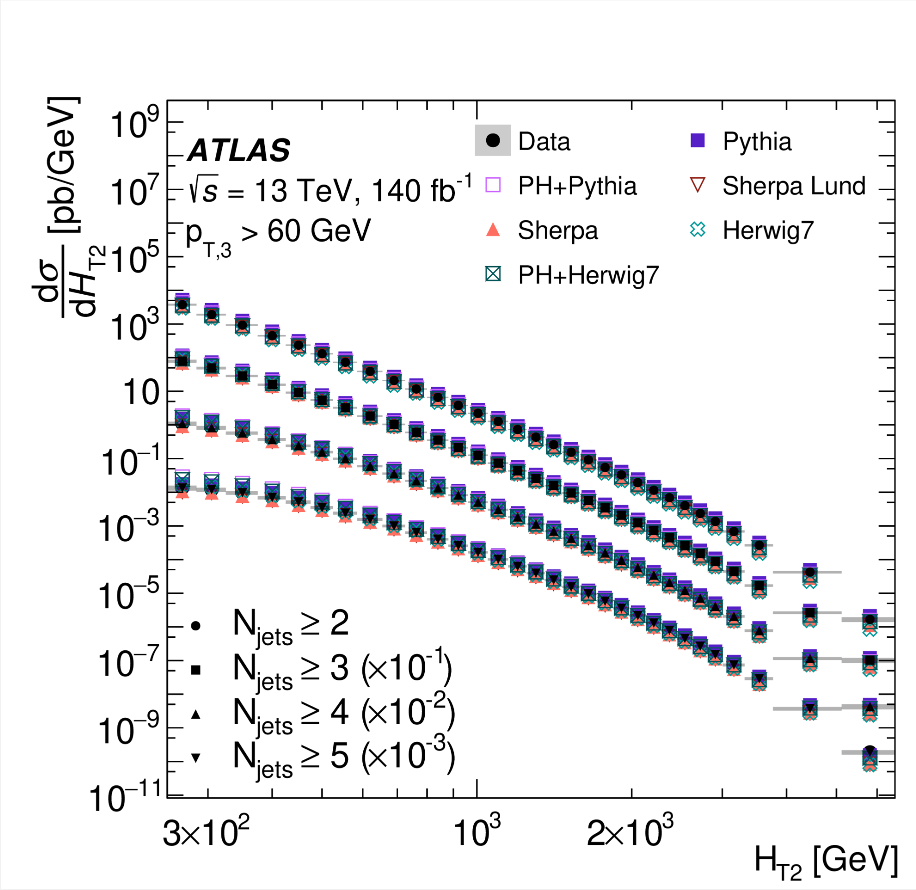
Jet cross-section ratios at 13 TeV

- Differential σ's in multiple observables
  - Target different facets of QCD
    - e.g. hard-scatter energy scale, fixed-order ME, FS energy flow
- First measurement of R_{32} in 13 TeV pp
  - $R_{32} \rightarrow \frac{\sigma_{3\ jets}}{\sigma_{2\ jets}}$
  - Reduces sensitivity to systematic uncertainties & PDFs
- Compare with NNLO fixed order predictions
- R_{43}, R_{42}, R_{54} also measured
  - Precision predictions not yet available
  - Reference for future developments

Experimental Measurement

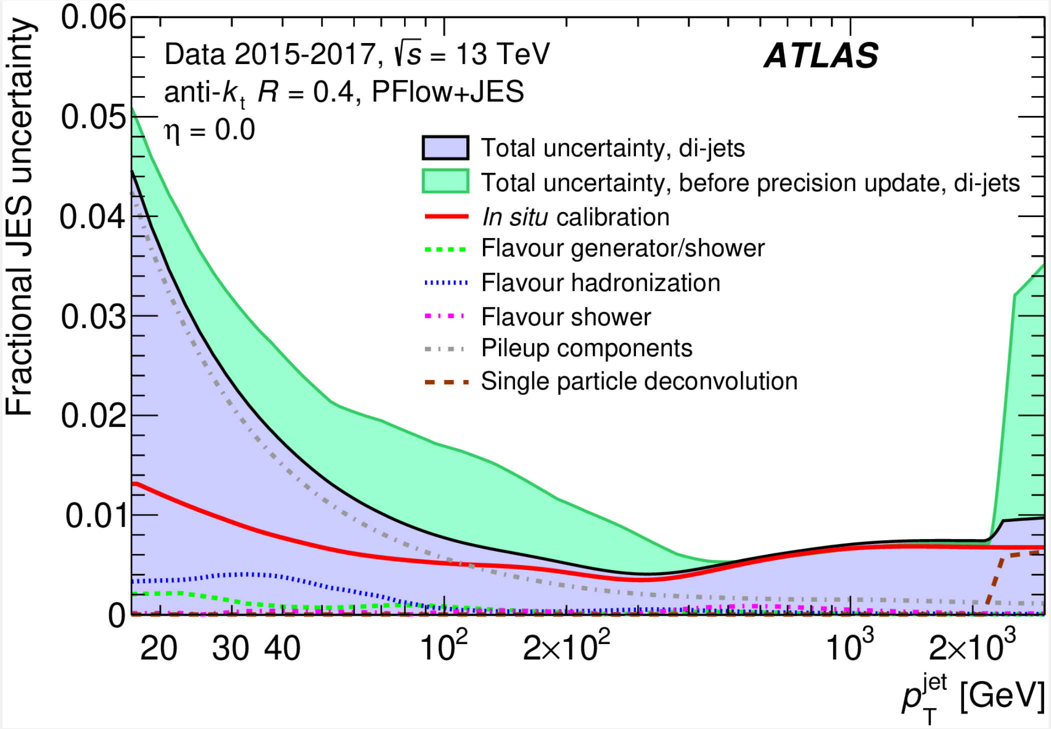
Jets:
anti-k_T, R=0.4, pT > 60 GeV, |y| < 4.5
Event:
$N_{jets} \geq 2$, H_{T2} > 250 GeV

- Measure dijet events in 140 fb^{-1} of 13 TeV data
- Observables:
  - $d\sigma/(dN_{jets}\, dH_{T2}\, dp_{T,3})$ vs H_{T2}, p_T^{Nincl}
    - *And ratios*
    - H_{T2}: Proxy for hard-scatter energy scale
    - $p_{T,3}$: Determines sensitivity to resummation effects
  - R_{32} vs m_{jj}, Δy_{jj}
    - Target arge logarithmic corrections
- Unfolding:
  - Iterative Bayesian, double/triple differentially



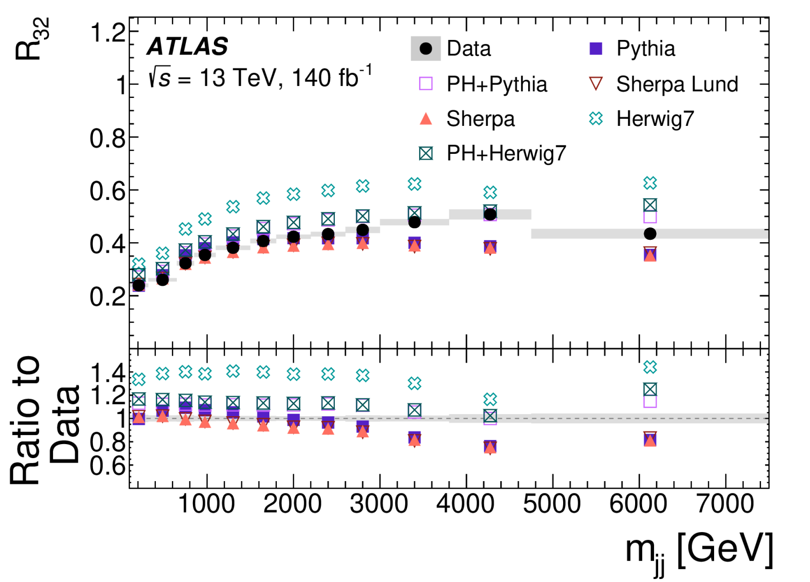
Improvements to experimental uncertainties

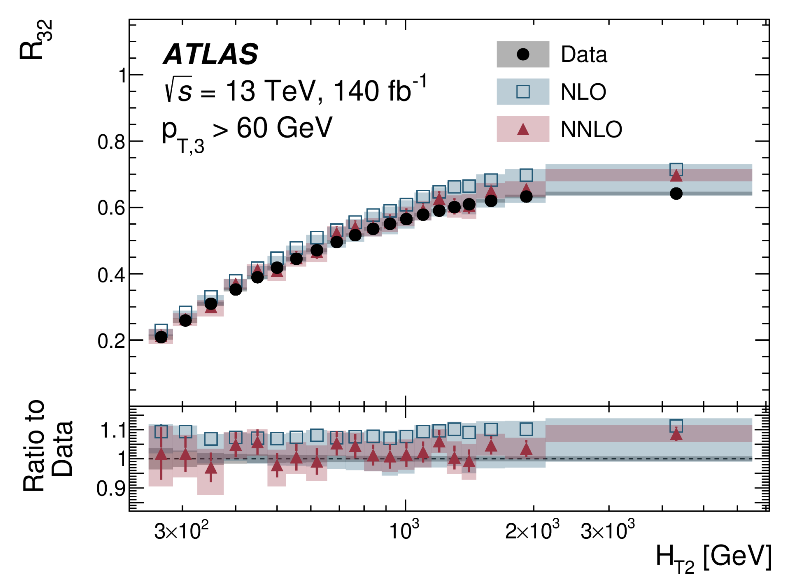
- Jet Energy Scale (JES) calibration → Leading source of experimental uncertainty
  - Updated JES prescriptions…
- Jet Flavour Response
  - Impact of initial parton flavour
  - Previously estimated from two-point MC comparison
  - Factorised → components targeting specific flavour/factorisation/hadronisation effects
  - **2x reduction, p_T^{jet} > 100 GeV**
- 'Single particle deconvolution':
  - High-p_T component of JES,
    - From extrapolation of single-particle response
  - Several inputs updated
    - EM showers, high-p_T pion response, detector simulation
  - **3x reduction p_T^{jet} > 2 TeV**



Results

- High-precision: Uncertainties O(<10%)
- Compared to:
  - MC generators:
    - Pythia 8.230, Sherpa2.2.5, 2.2.11, Herwig7.1.6, Powheg2+Pythia8, Powheg2+Herwig7
  - Fixed-order predictions: NLO, NNLO
    - $\mu_r = \mu_f = \hat{H}_T = \sum_i p_{T,i}$
    - NP corrections from ratio $\frac{\text{hadron-level, with MPI}}{\text{parton-level, no MPI}}$
  - High Energy Jet: Resummed LL corrections
    - e.g. VBS/VBF
- **MC:** Significant differences at large m_{jj}, Δy_{jj}
- **NNLO:** H_{T2} modelled well across all $p_{T,3}$ bins
- **HEJ:** Good description of ratios in regions where log terms contribute



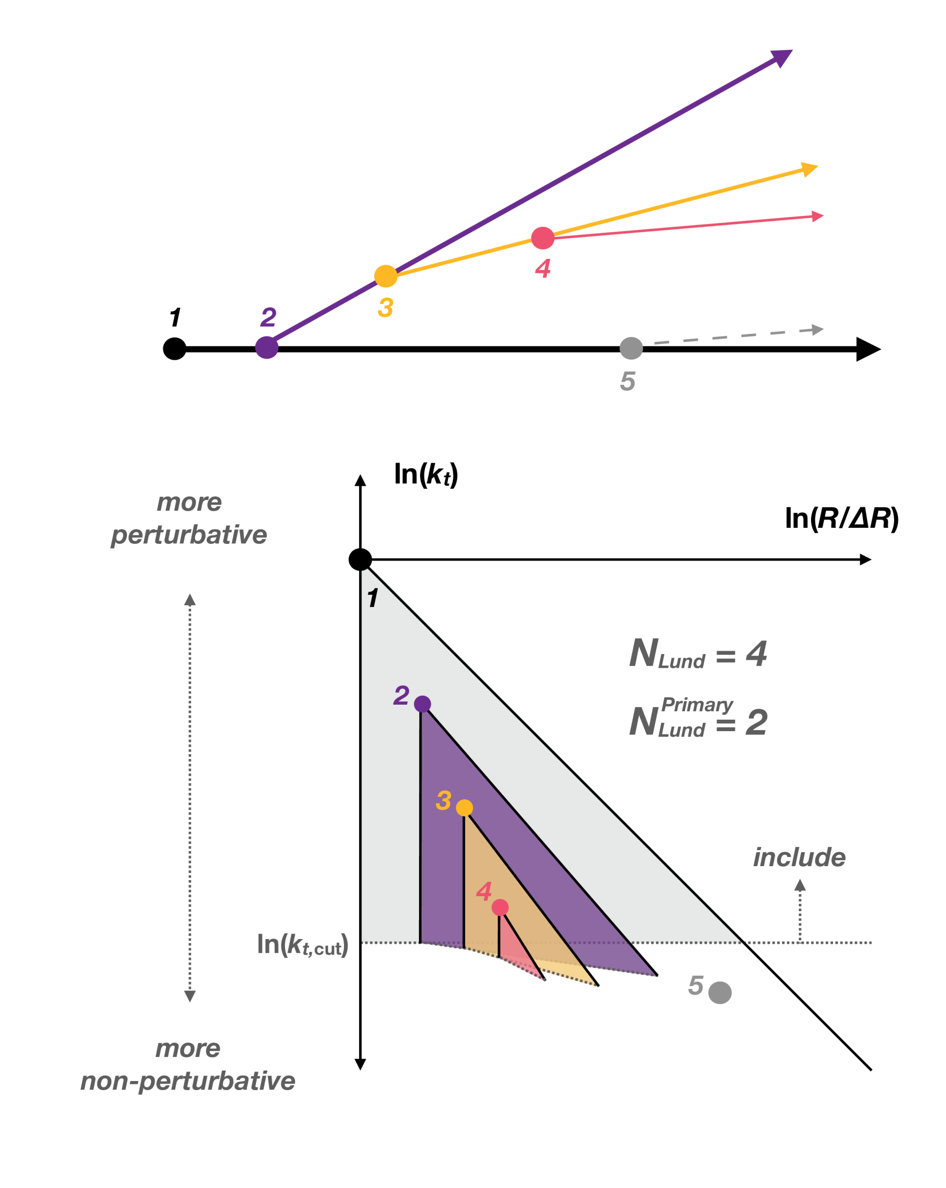


Lund Subjet Multiplicities

arXiv:2402.13052 [hep-ex] (submitted to Phys. Lett. B)

Lund Subjet Multiplicities

- **Jet substructure (JSS):** Setting for colinear limit QCD tests involving wide range of energy scales e.g. PS algorithms
- Lund multiplicity → JSS observable
  - Tests for inclusion of double-soft splittings
  - Calculated with analytical resummation at NNDL in QCD
- Count $N_{subjet} > k_T^{thresh}$ in jet's angle-ordered clustering history via reclustering with C/A algorithm
  - Measure N_{Lund} and/or $N_{Lund}^{Primary}$
- **Goals:** Precision measurement, test higher-order effects in QCD predictions, input to parton shower developments



Experimental Measurement

- Measure dijet events in 140 fb^{-1} of 13 TeV data
- Observables: N_{Lund} and $N_{Lund}^{Primary}$, differentially in:
  - Jet p_T (300-4500 GeV) and…
  - …relative rapidity, with…
  - …8 different emission k_T requirements
- **Procedure:**
  1. Recluster ID tracks within ΔR=0.4 of a ΔR=0.4 anti-k_T jet using CA
  2. Iteratively decluster reclustered jet
  3. Rescale emmission k_T → account for neutral particles
- Unfolded → Correct $N_{Lund}^{(Primary)}$ from detector to charged-particle level
  - Regularized migration matrix inversion

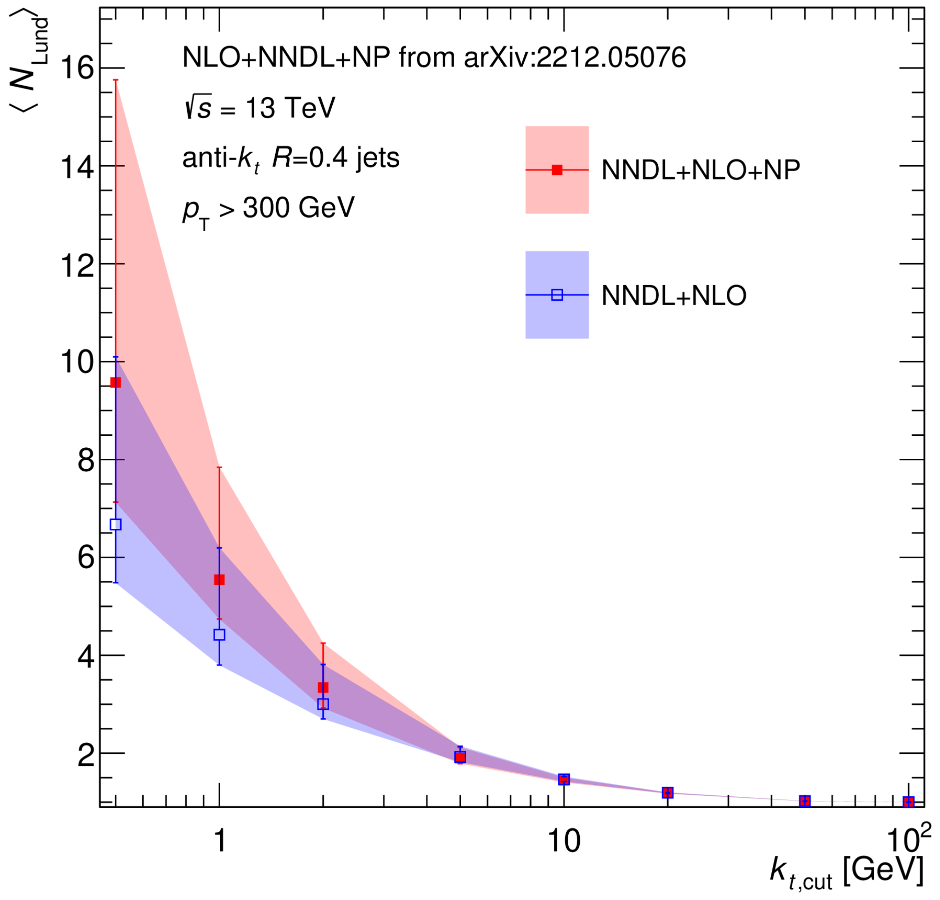
Tracks:
p_T > 500 MeV, matched to PV

Jets:
Both > 120 GeV, central, dijet balancing

Uncertainty	~Size
Jet Energy Scale	2-4%
Tracking	2%
Unfolding non-closure	< 2%
Stat	<1 %
Others	Negligible

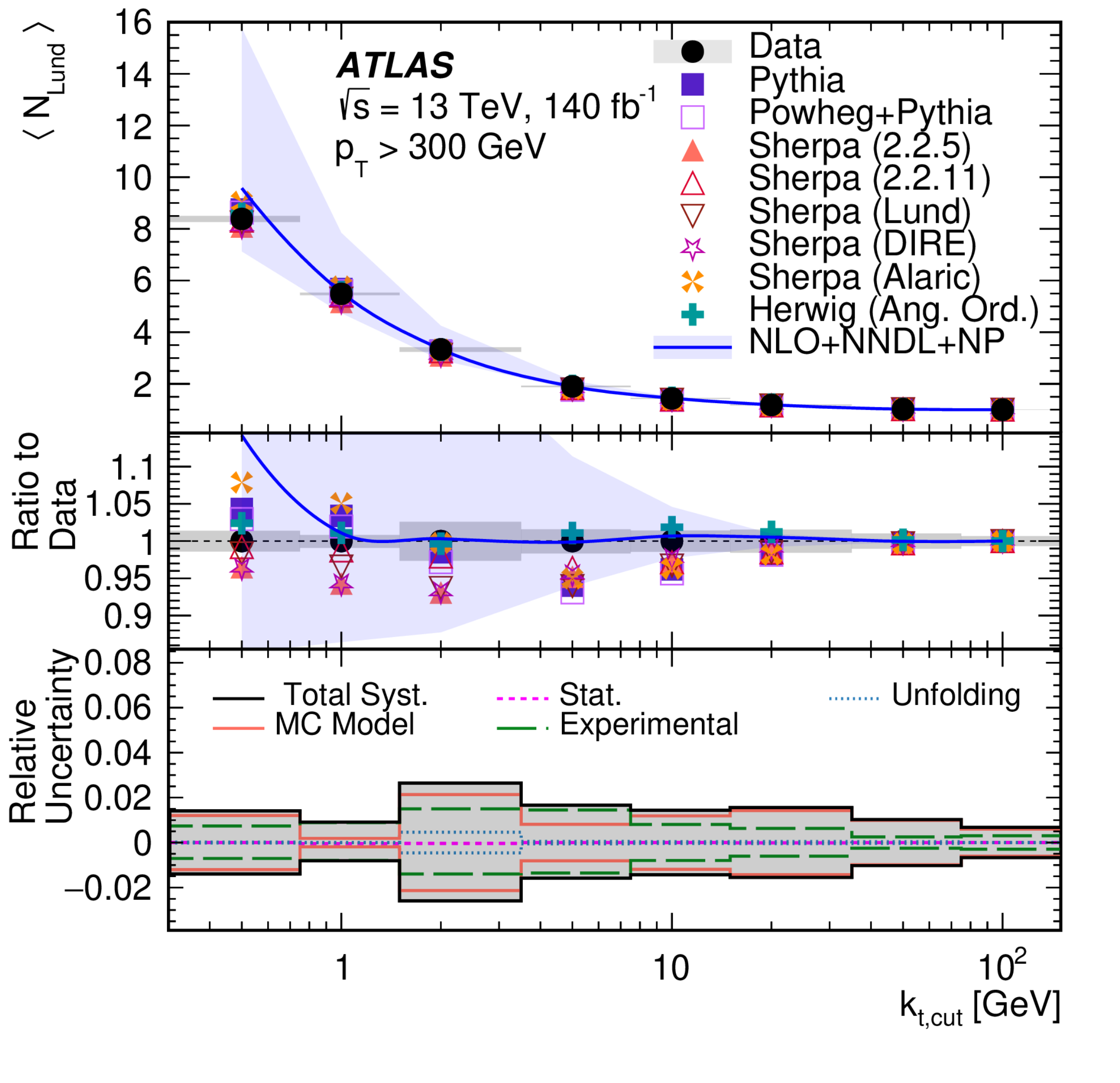
Comparison with theory

- Unfolded $\langle N_{Lund} \rangle$ and $\langle N_{Lund}^{Primary} \rangle$ compared to MC with state-of-the-art parton scatter
  - Pythia8, Powheg Box+Pythia8, Sherpa2.2.5, Sherpa2.2.11, Sherpa2.2.11 (Lund hadronisation), Sherpa2.2.11 (DIRE PS), Sherpa3 (ALARIC PS), Herwig7.1.3 (angle-ordered PS)
- $\langle N_{Lund} \rangle$ also compared to analytic NLO+NNDL+NP prediction
  - NLO matched to NNDL resummation + NP corrections
    - NP corrections from ratio $\frac{\text{hadron−level, with MPI}}{\text{parton−level, no MPI}}$



Results

- Most predictions fail to accurately describe the data, particularly at jet p_T ⬆️
- **Herwig angle-ordered PS:**
  - Best overall description of both observables
- **Recent Sherpa setups**:
  - Best when more non-perturbative (k_T < 2 GeV) emissions allowed
- **Resummed analytic prediction:**
  - Good agreement with data in the perturbative (k_T > 2 GeV) region, matching best PS MC
  - Jet p_T ⬆️ → performance ⬇️
- Highlights importance of JSS measurements at the LHC



Conclusion

- ATLAS, both historically and presently, has a strong track record of producing precision datasets and world-leading QCD measurements

- LHC Run 3 is underway! Wealth of new data to analyse → many more exciting results in the future!

Questions?