News from ATLAS
New Standard Model measurements with sensitivity to PDFs

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on behalf of the ATLAS Collaboration

PDF4LHC meeting
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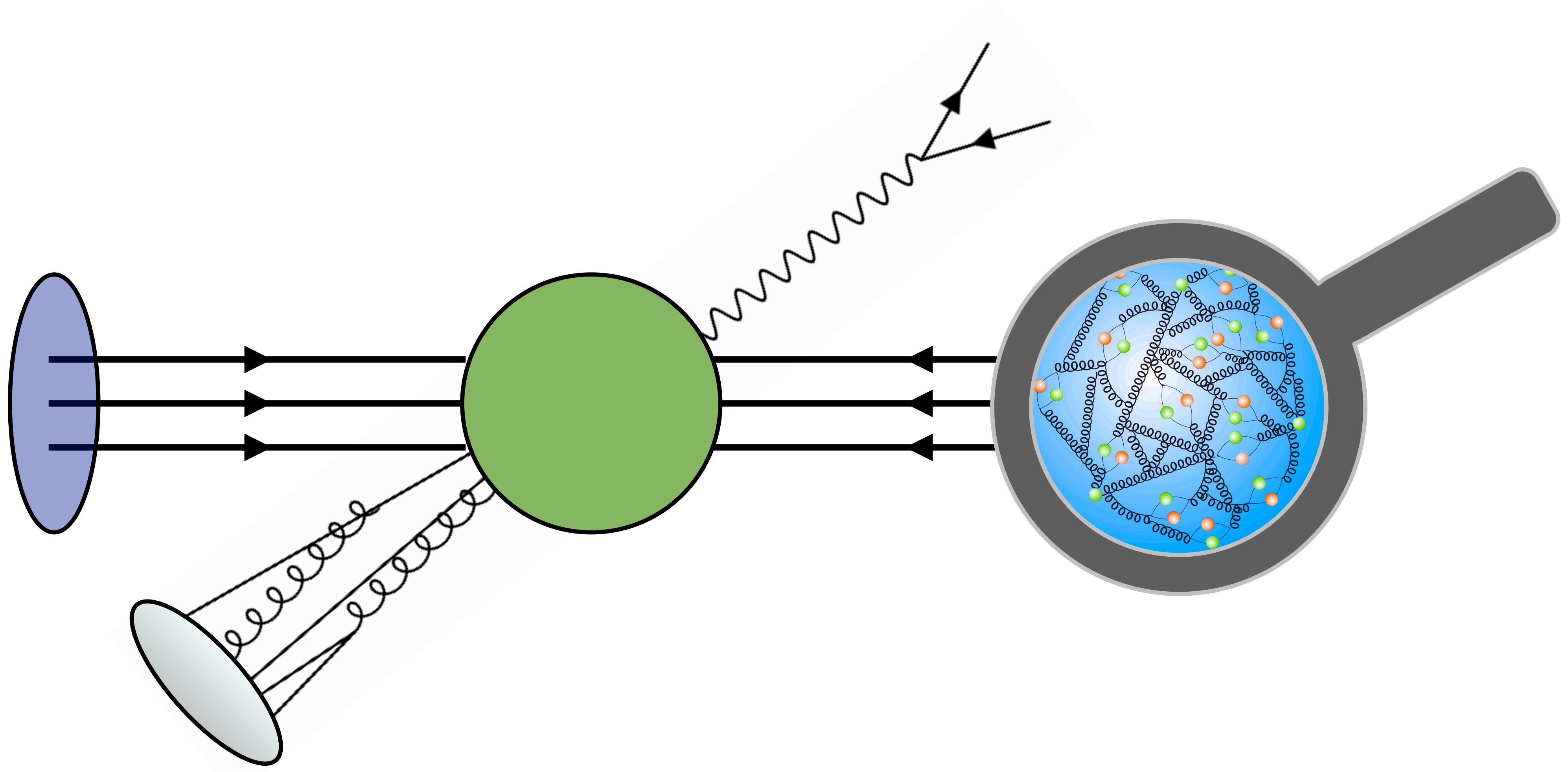
ATLAS EXPERIMENT
"YOU ARE WELCOME HERE!"

- Many new Standard Model precision measurements released by ATLAS in the last year
  - See the ATLAS SM public page for a complete list (about 30 since November 2022)
  - Great understanding of the Run 2 dataset with precision calibrations and **<1% luminosity uncertainty**

- Today will focus on **new results that can be used to constrain PDFs**:
  - $W+D^{(*)\pm}$ cross section at 13 TeV: Phys. Rev. D 108 (2023) 032012
  - Inclusive photon production at 13 TeV: JHEP 07 (2023) 086
  - $p_T(Z)$ and $y(Z)$ at 8 TeV in the full decay phase space: STDM-2018-05 (submitted to JHEP)
  - $p_T(Z)$ and $p_T(W)$ from low mu data (5.02 and 13 TeV): ATLAS-CONF-2023-028
  - ttbar/Z cross section ratio at 13.6 TeV (Run 3 data): TOPQ-2023-21 (submitted to PLB)

- Maarten's talk will discuss the impact of PDFs on SM precision measurements (m_W, $\alpha_S(m_Z)$, $\sin^2\theta_W$)
  - https://indico.cern.ch/event/1311146/#12-precision-measurements-of-s

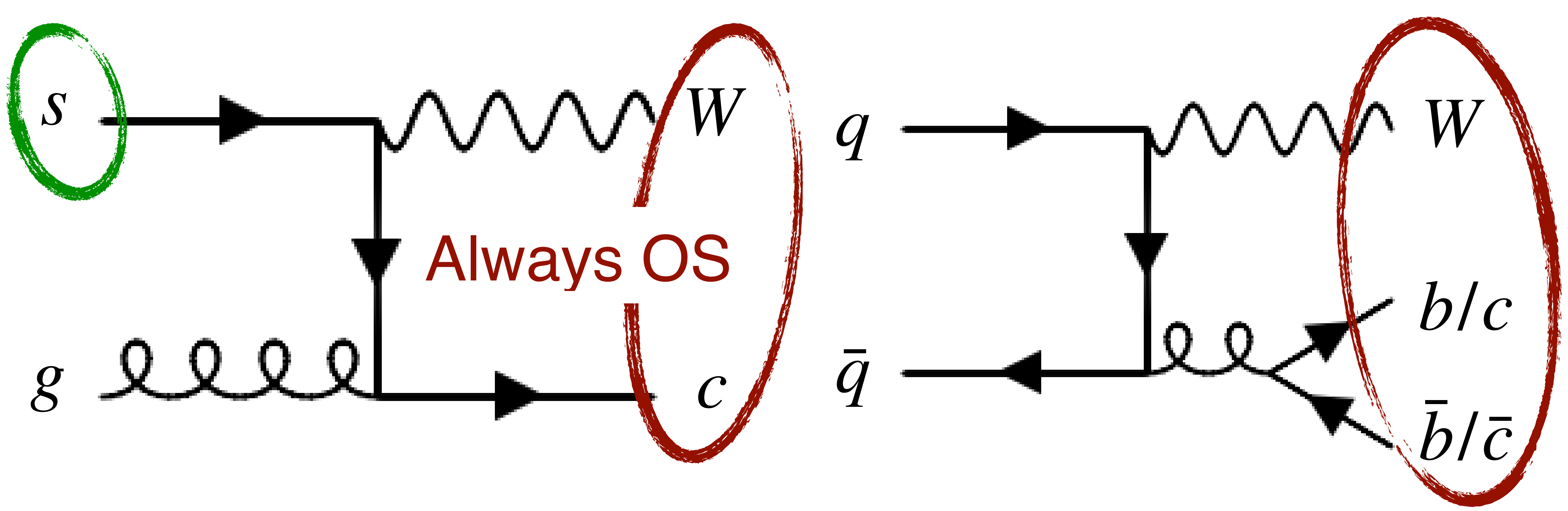


W+D(*)± cross section measurement at 13 TeV

W+D(*)± cross section measurement at 13 TeV

- The main goal is to measure the sg → W+c process and thus gain sensitivity to the **s-quark PDF**
  - Relies on the charge correlation to remove the gluon splitting component of pp → W+cc
- The "**OS-SS subtraction**" performed both at the **truth** and **detector level**:
  - Statistically removes the W+cc component (verified up to NNLO[1]); not sensitive to PDFs
  - Removes most of the combinatorial backgrounds from other sources

- Crucial to identify c-quarks and determine their electric charge
- Perform **Secondary Vertex fit** using Inner Detector tracks to reconstruct two D-meson decay chains:
  - $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ and $D^{*\pm} \to D^{0}\pi^{\pm} \to (K^{\mp}\pi^{\pm})\pi^{\pm}$ — excellent p_T resolution and charge determination



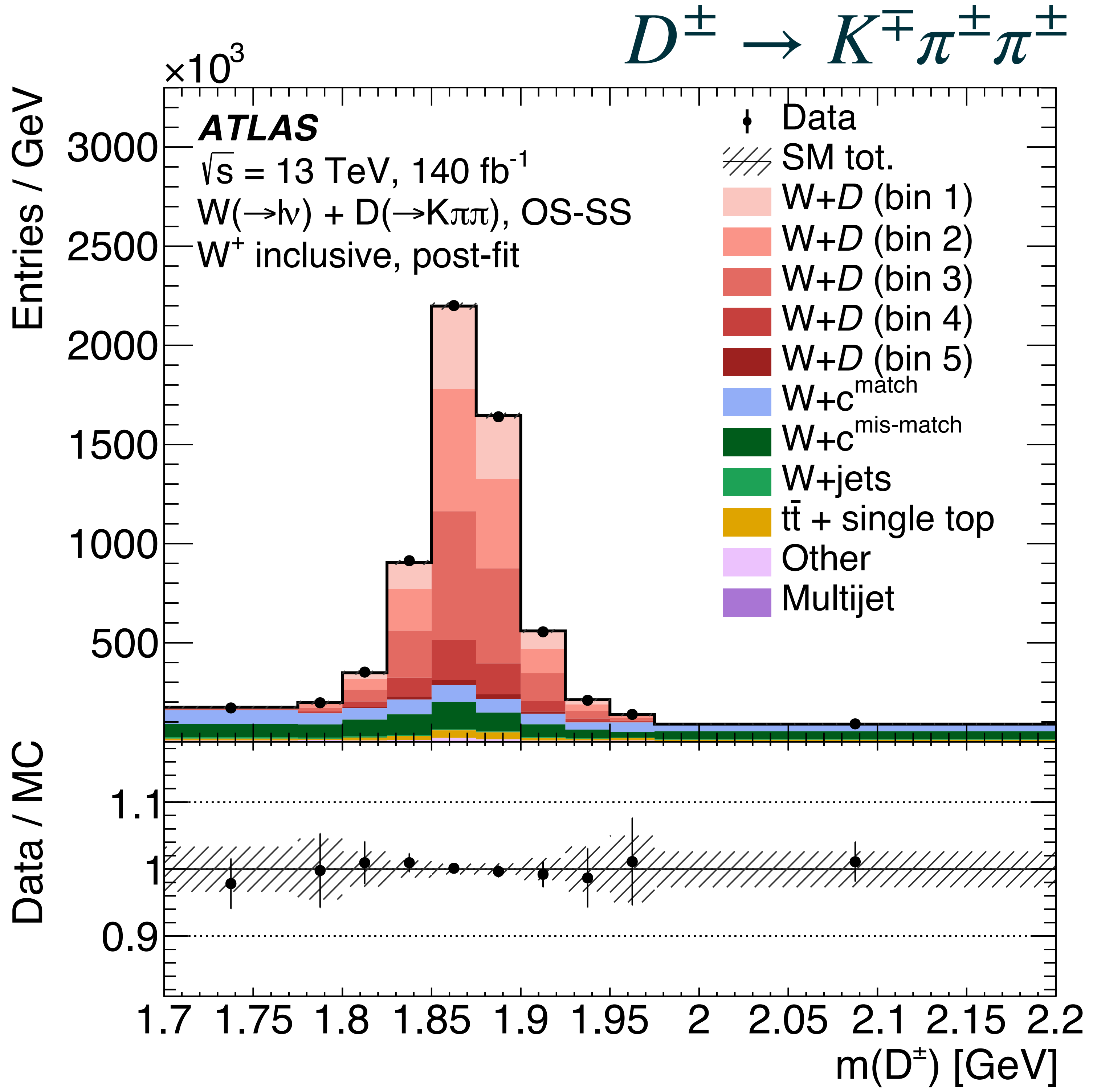
Detector-level selection			Truth fiducial selection	
Requirement	W+$D^{(*)}$ SR	Top CR	Requirement	W+$D^{(*)}$
$N(b\text{-jet})$	0	≥ 1	$N(b\text{-jet})$	—
E_T^{miss}	> 30 GeV		E_T^{miss}	—
m_T	> 60 GeV		m_T	—
Lepton p_T	> 30 GeV		Lepton p_T	> 30 GeV
Lepton $\lvert\eta\rvert$	< 2.5		Lepton $\lvert\eta\rvert$	< 2.5
$N(D^{(*)})$	≥ 1		$N(D^{(*)})$	≥ 1
$D^{(*)}$ p_T	> 8 GeV and < 150 GeV		$D^{(*)}$ p_T	> 8 GeV
$D^{(*)}$ $\lvert\eta\rvert$	< 2.2		$D^{(*)}$ $\lvert\eta\rvert$	< 2.2

1: M. Czakon, A. Mitov, M. Pellen, and R. Poncelet: 2011.01011

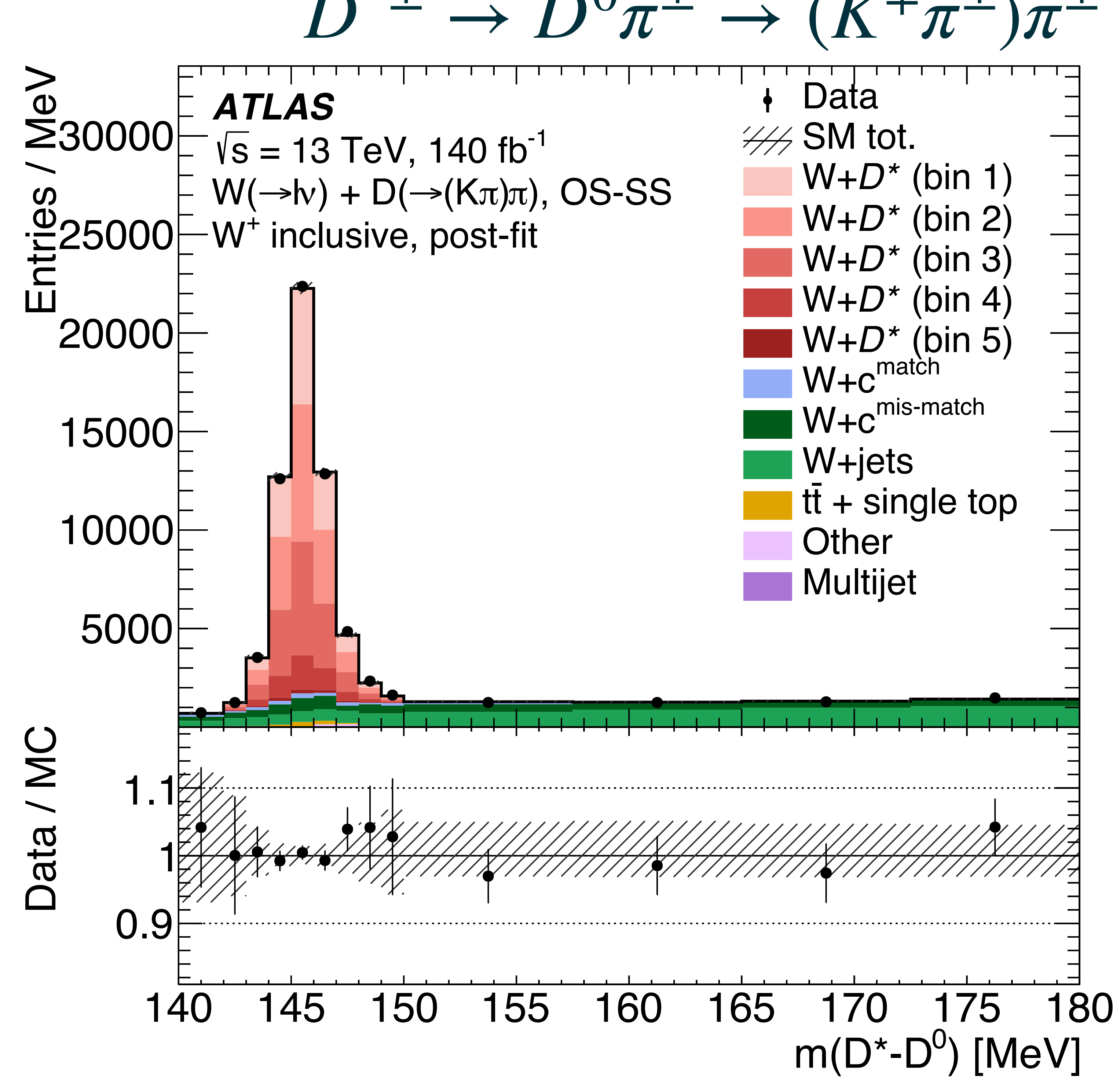
Cross section extraction and unfolding

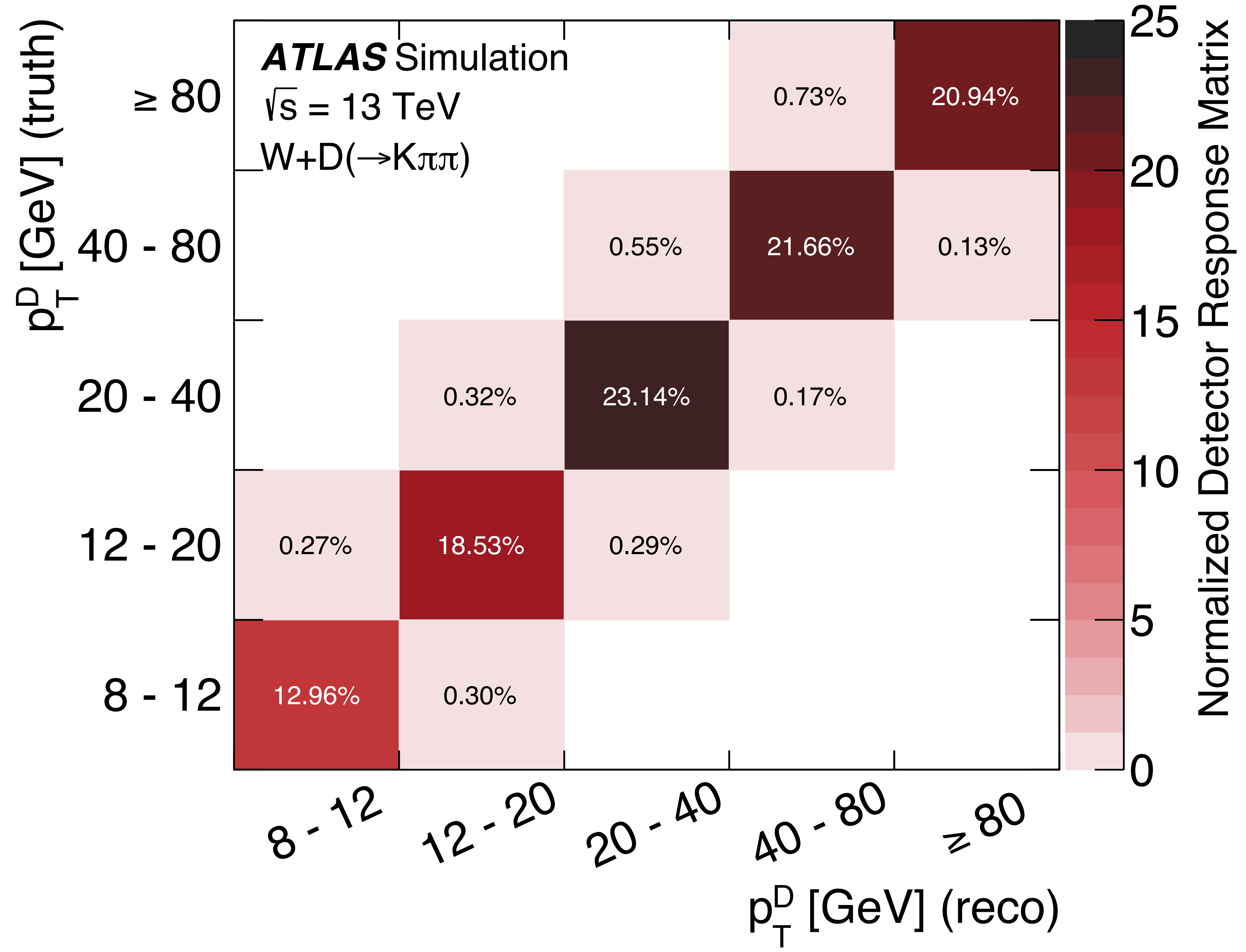
- The invariant *D*-meson mass is fitted in each differential bin simultaneously
  - With the available statistics up to five bins per observable— split into W+ and W- (2×5 bins)
- Measured observables:
  - $d\sigma/dX$ for $X = p_T(D)$ or $|\eta(\ell)|$
  - Rc = σ(W+D-) / σ(W-D+)— potentially sensitive to s-sbar asymmetry
- Achieved better than 5% precision on absolute cross section
  - 1-3% precision on normalized differential cross sections and percent-level on Rc

$D^{\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$



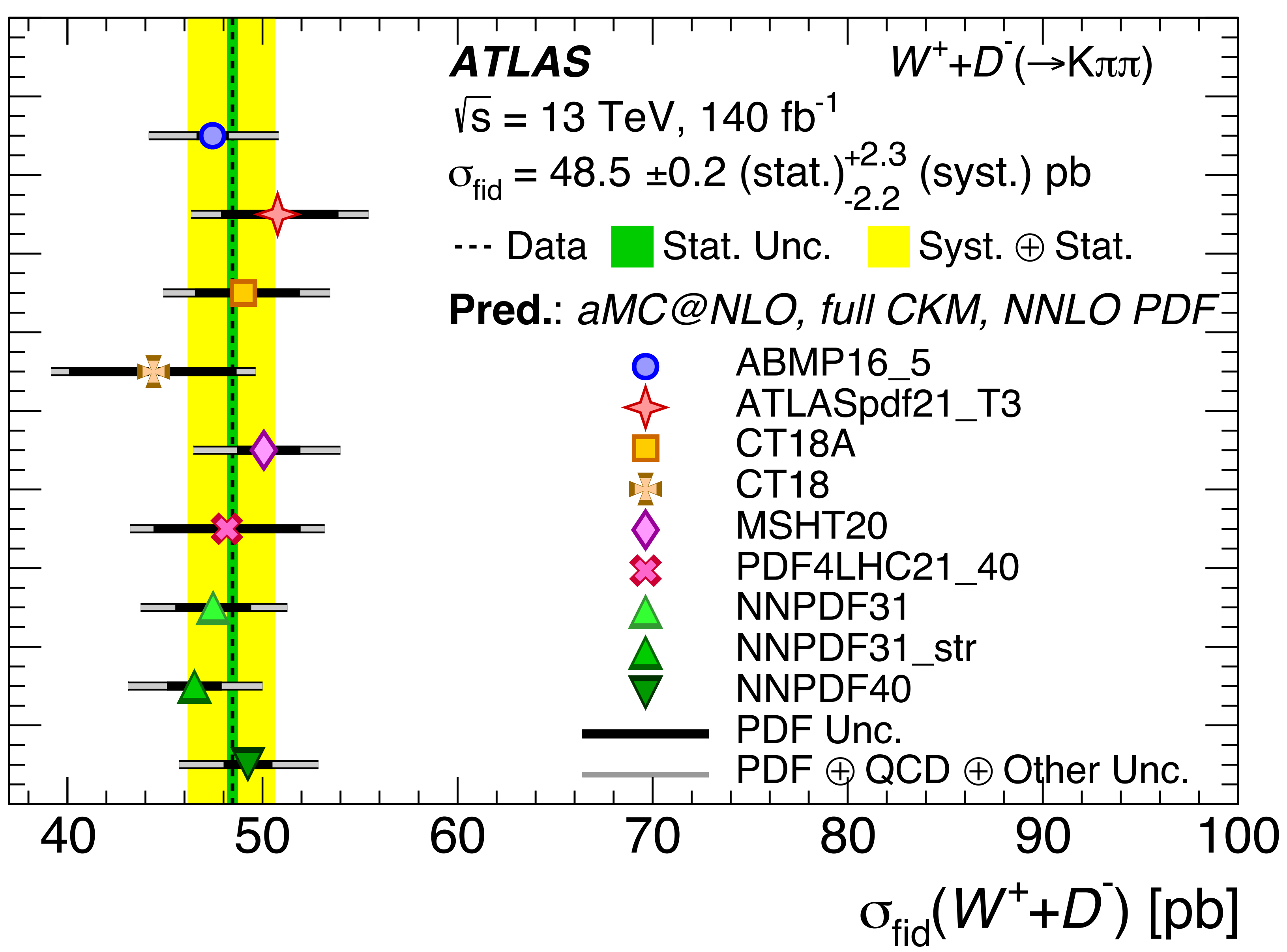
$D^{*\pm} \rightarrow D^{0}\pi^{\pm} \rightarrow (K^{\mp}\pi^{\pm})\pi^{\pm}$



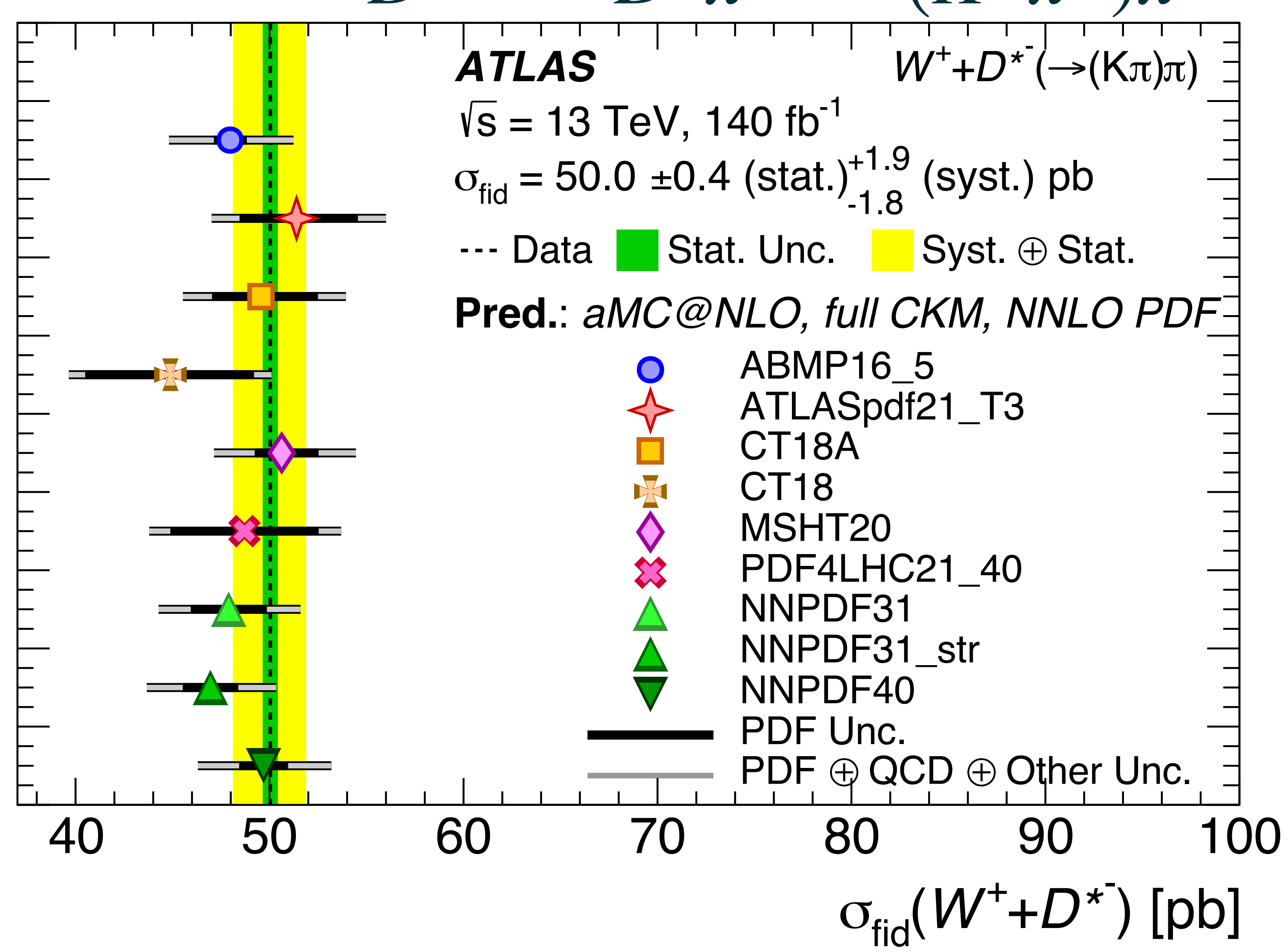


- Predictions calculated with NLO **aMC@NLO+Pythia8** with finite m_c = 1.55 GeV and full CKM matrix
  - Latest state-of-the-art PDFs used— nominally NNLO PDFs but also checked NLO PDFs
- **Systematic uncertainties** considered in predictions:
  - Scale, PDF, and α_S uncertainties
  - Charm hadron production fractions
  - Shower uncertainty— compare Pythia8 vs Herwig7 and A14 vs Monash tune in Pythia8
  - Matching uncertainty— compare aMC@NLO vs PowHel [G. Bevilacqua, M.V. Garzelli, A. Kardos, L.Toth: 2106.11261]
- Uncertainty in predictions generally about 2× larger than the measurement precision for absolute x-sec

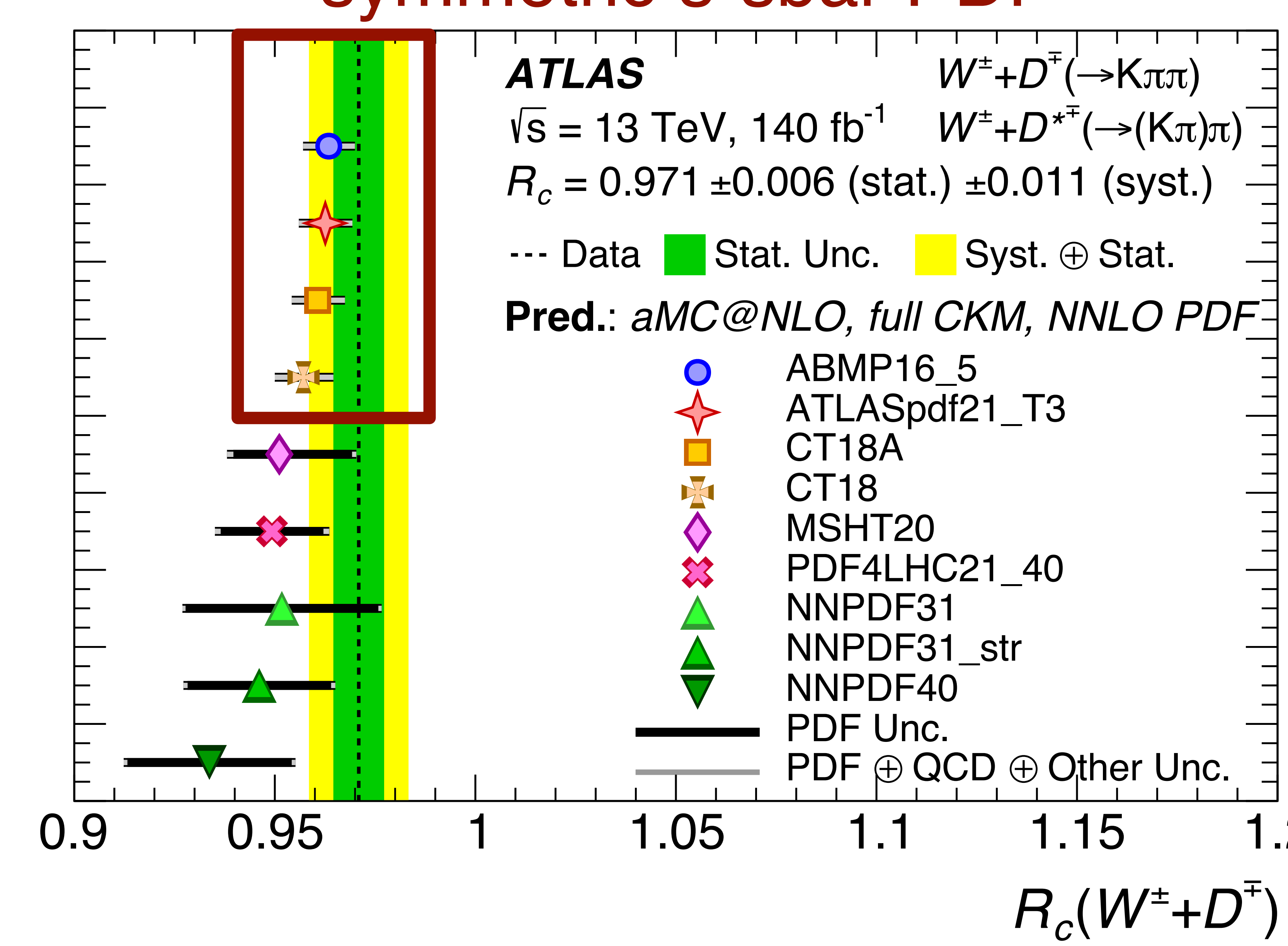
$D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$



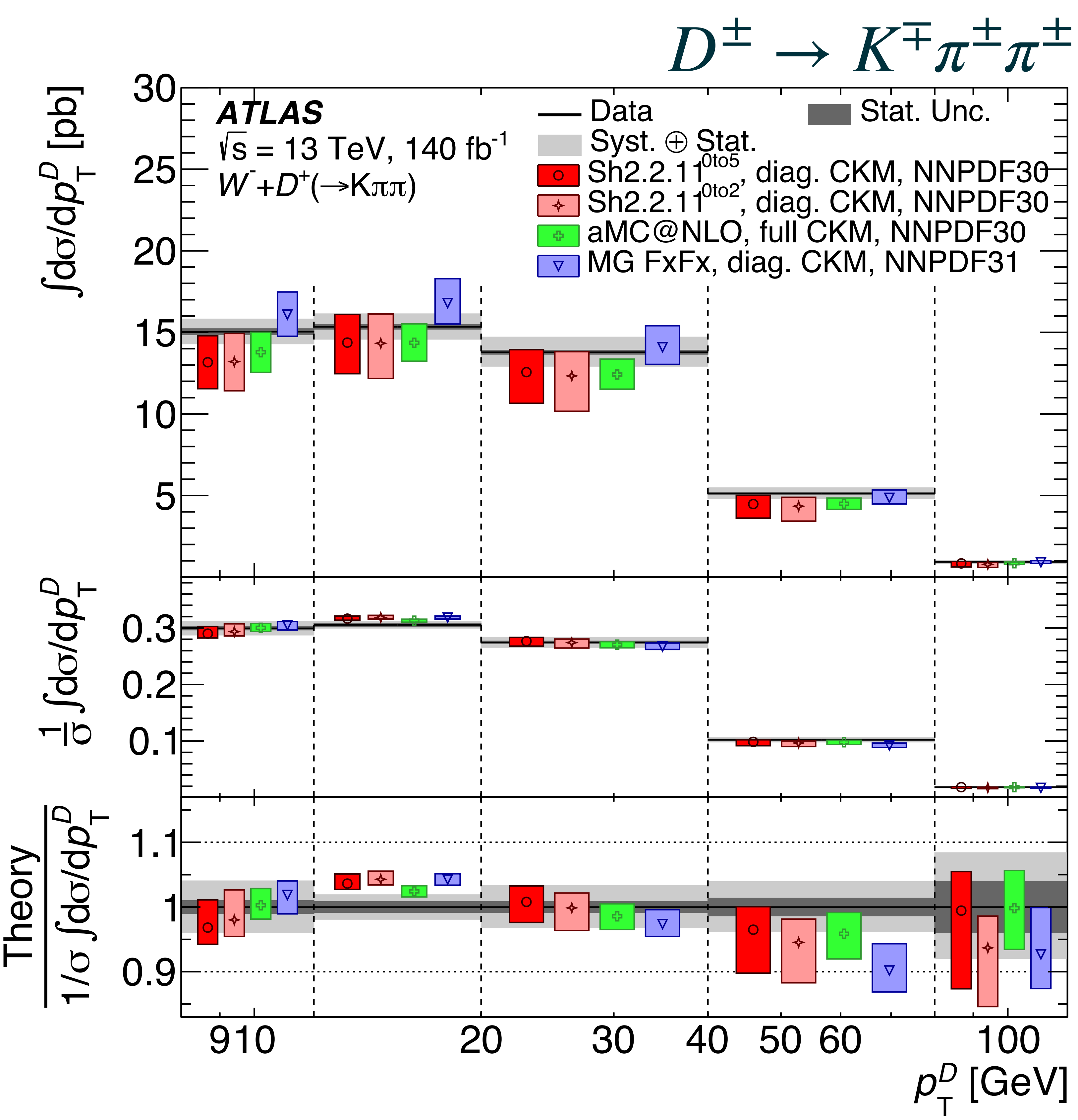
$D^{*\pm} \to D^{0}\pi^{\pm} \to (K^{\mp}\pi^{\pm})\pi^{\pm}$

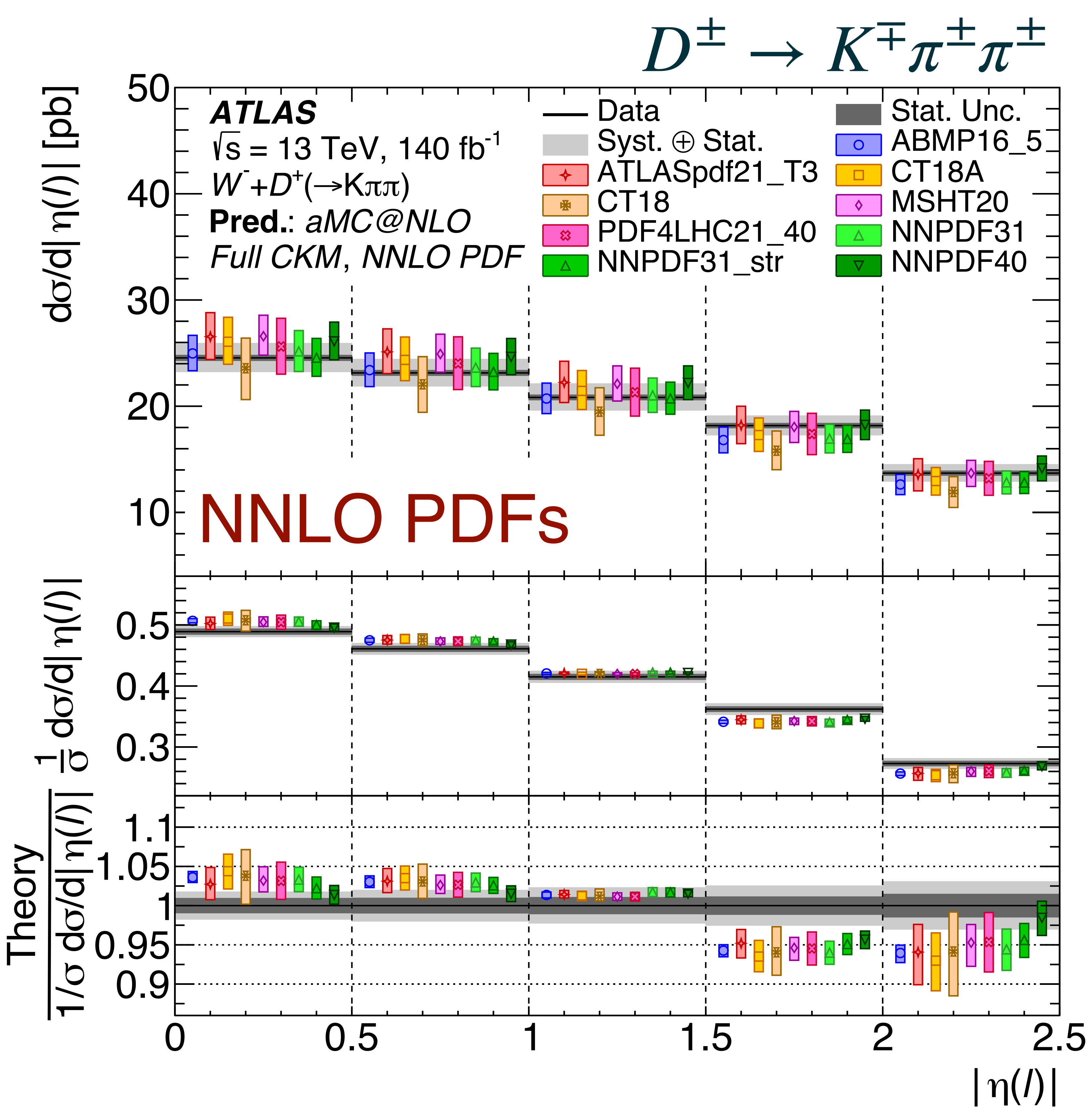


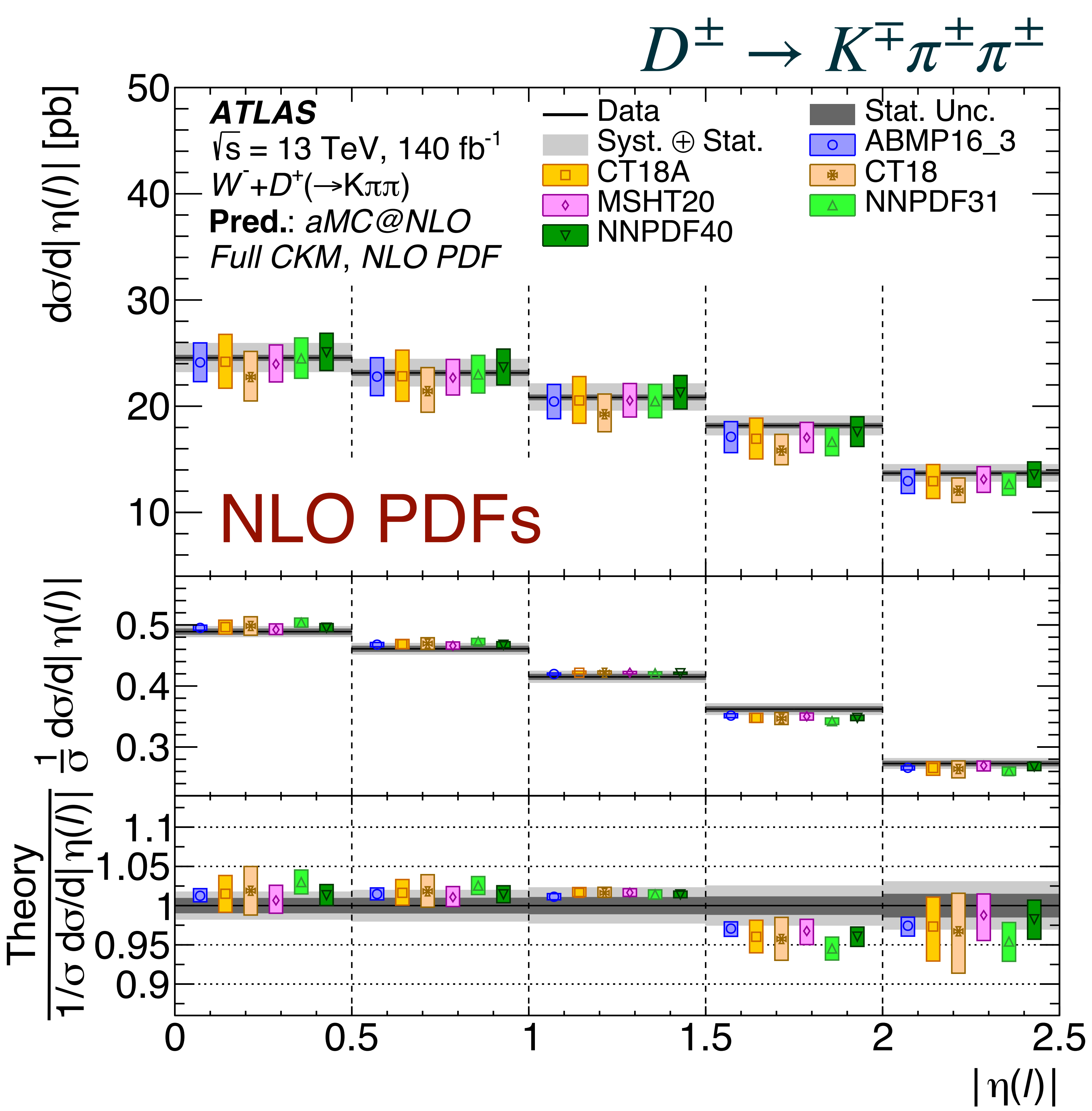
symmetric s-sbar PDF



- Differential $p_T(D)$ cross section useful for **MC tuning**
  - Generally a trend seen in all predictions (Sherpa2.2.11, NLO MG, MG+Py8 (FxFx))
- Differential $|\eta(\ell)|$ cross section potentially useful for constraining the **s-quark PDF**
  - All NNLO PDFs overshoot the data in the central region and undershoot in the forward region
  - NLO PDFs generally better match the $|\eta(\ell)|$ cross sections
  - Covered well by the PDF systematic uncertainty (*p*-values on next page)







W+D(*)$^{\pm}$ summary and conclusions

- Most precise W+D(*)$^{\pm}$ measurement so far using the exclusive *D*-meson reconstruction
- Generally the predictions describe the data well within the PDF uncertainties
  - Central values are typically outside the experimental error bands
  - About 2x smaller uncertainty in the data— expect to constrain s-quark PDFs with the |η(ℓ)|
- **Outstanding issue** with parton-level and particle-level matching for W+c
  - For PDF fits likely need a NLO / NNLO particle-level calculation including charm hadronization
  - Encouraging development for *B*-hadron production in ttbar: [M. Czakon, et. al.: 2102.08267]
  - **How far away from actually including W+c measurements in PDF fits?**
    (without parton-level / particle-level smearing or approximations)

$D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ NNLO PDFs

Channel	D^{+} $\lvert\eta(\ell)\rvert$			
p-value for PDF [%]	Exp. Only	⊕ QCD Scale	⊕ Had. and Matching	⊕ PDF
ABMP16_5_nnlo	7.1	11.8	12.9	19.8
ATLASpdf21_T3	9.0	9.7	11.5	84.7
CT18ANNLO	0.7	1.0	1.1	76.0
CT18NNLO	1.4	6.1	6.3	87.6
MSHT20nnlo_as118	2.7	2.9	3.3	45.6
PDF4LHC21_40	3.9	5.3	5.6	75.8
NNPDF31_nnlo_as_0118_hessian	1.5	2.6	2.8	50.7
NNPDF31_nnlo_as_0118_strange	9.1	14.7	15.2	59.9
NNPDF40_nnlo_as_01180_hessian	9.9	10.2	10.2	43.7

$D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ NLO PDFs

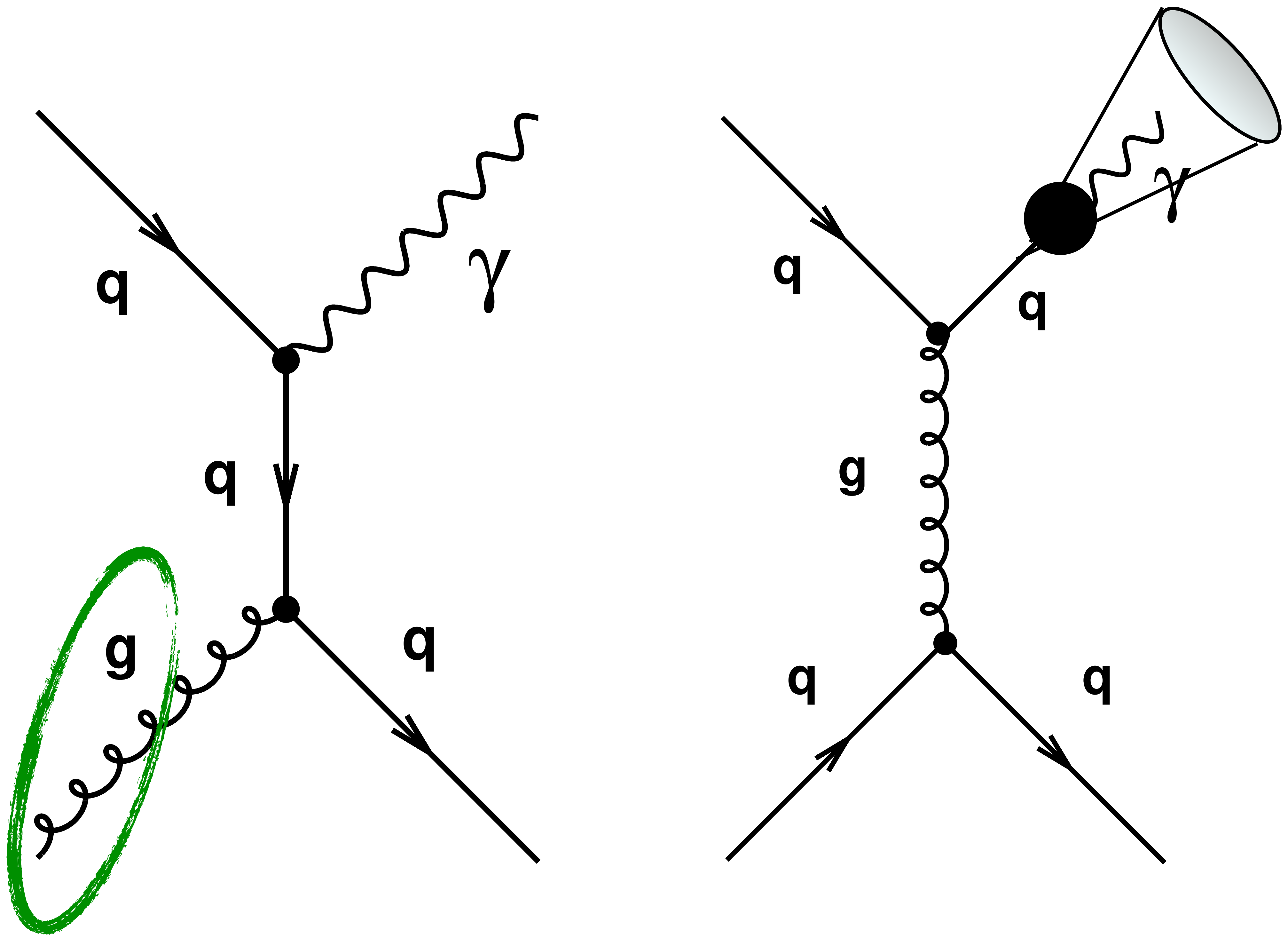
Channel	D^{+} $\lvert\eta(\ell)\rvert$			
p-value for PDF [%]	Exp. Only	⊕ QCD Scale	⊕ Had. and Matching	⊕ PDF
ABMP16_3_nlo	91.7	97.7	97.9	98.3
CT18ANLO	67.8	82.9	83.4	98.2
CT18NLO	19.0	53.5	53.6	88.9
MSHT20nlo_as118	75.4	87.8	87.9	96.8
NNPDF31_nlo_as_0118_hessian	1.0	2.4	2.5	38.9
NNPDF40_nlo_as_01180	8.3	10.7	10.7	46.3

Inclusive photon production at 13 TeV

- Main objective is to measure the production of high-p_T prompt photons
  - Testing ground for pQCD with a hard colorless process
  - Sensitive to the **gluon density in the proton** (via qg → qγ) and input for global QCD fits
- The main **experimental challenges**:
  - Precise photon identification and energy scale calibrations (percent-level precision needed)
  - Separate prompt photons from photons originating form neutral hadron decays
- Prompt photons selected by applying isolation requirements in a cone around the photon
  - Measurement provided for two different cone sizes (R = 0.2 and 0.4) to study dependencies

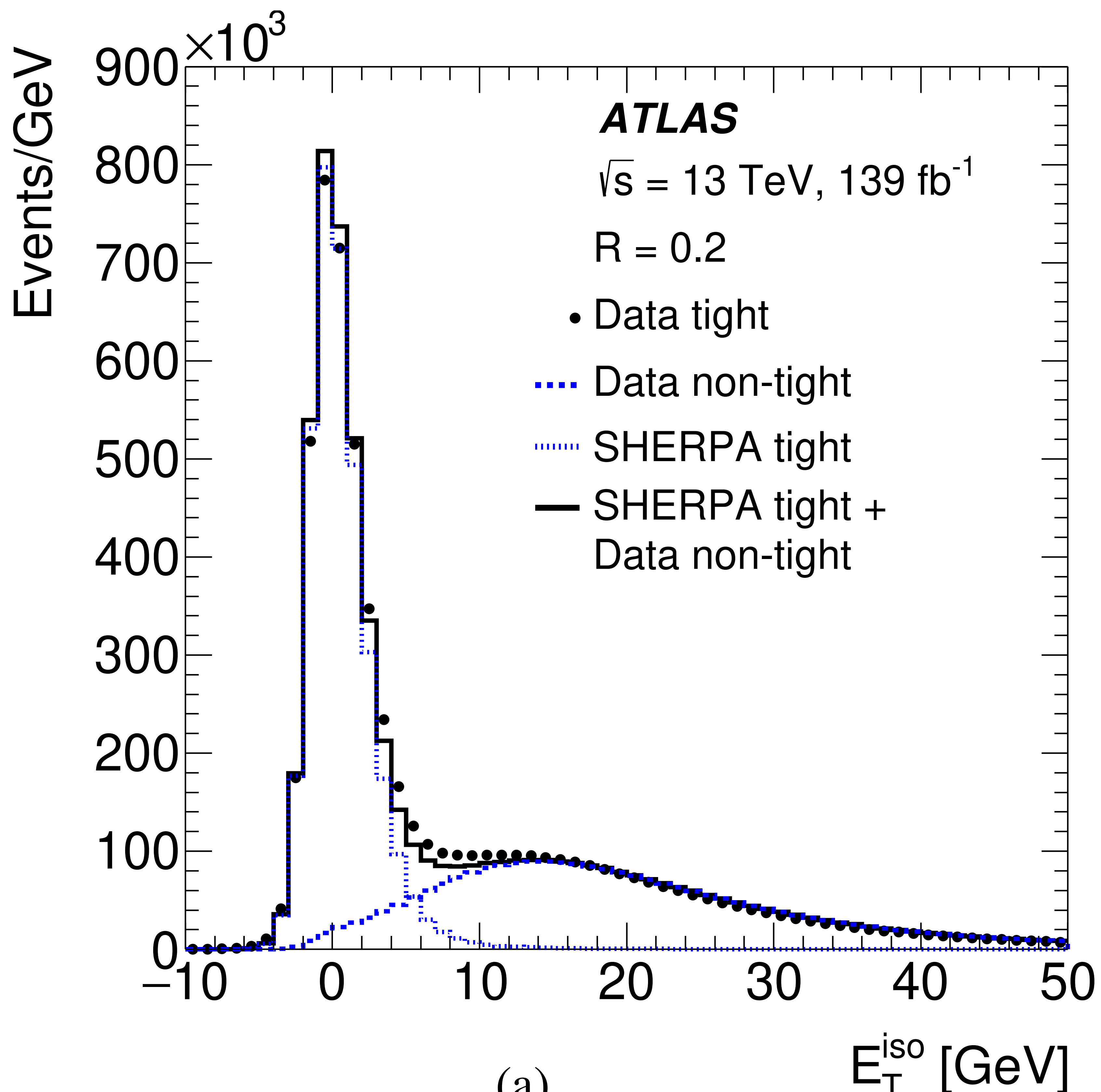
Truth fiducial phase space (including particle-level isolation)

Requirement	Phase-space region					
E_T^{γ}	$E_T^{\gamma} > 250$ GeV					
Isolation	$E_T^{iso} < 4.2 \cdot 10^{-3} \cdot E_T^{\gamma} + 4.8$ GeV					
η^{γ}	$\lvert\eta^{\gamma}\rvert < 0.6$	$0.6 < \lvert\eta^{\gamma}\rvert < 0.8$	$0.8 < \lvert\eta^{\gamma}\rvert < 1.37$	$1.56 < \lvert\eta^{\gamma}\rvert < 1.81$	$1.81 < \lvert\eta^{\gamma}\rvert < 2.01$	$2.01 < \lvert\eta^{\gamma}\rvert < 2.37$

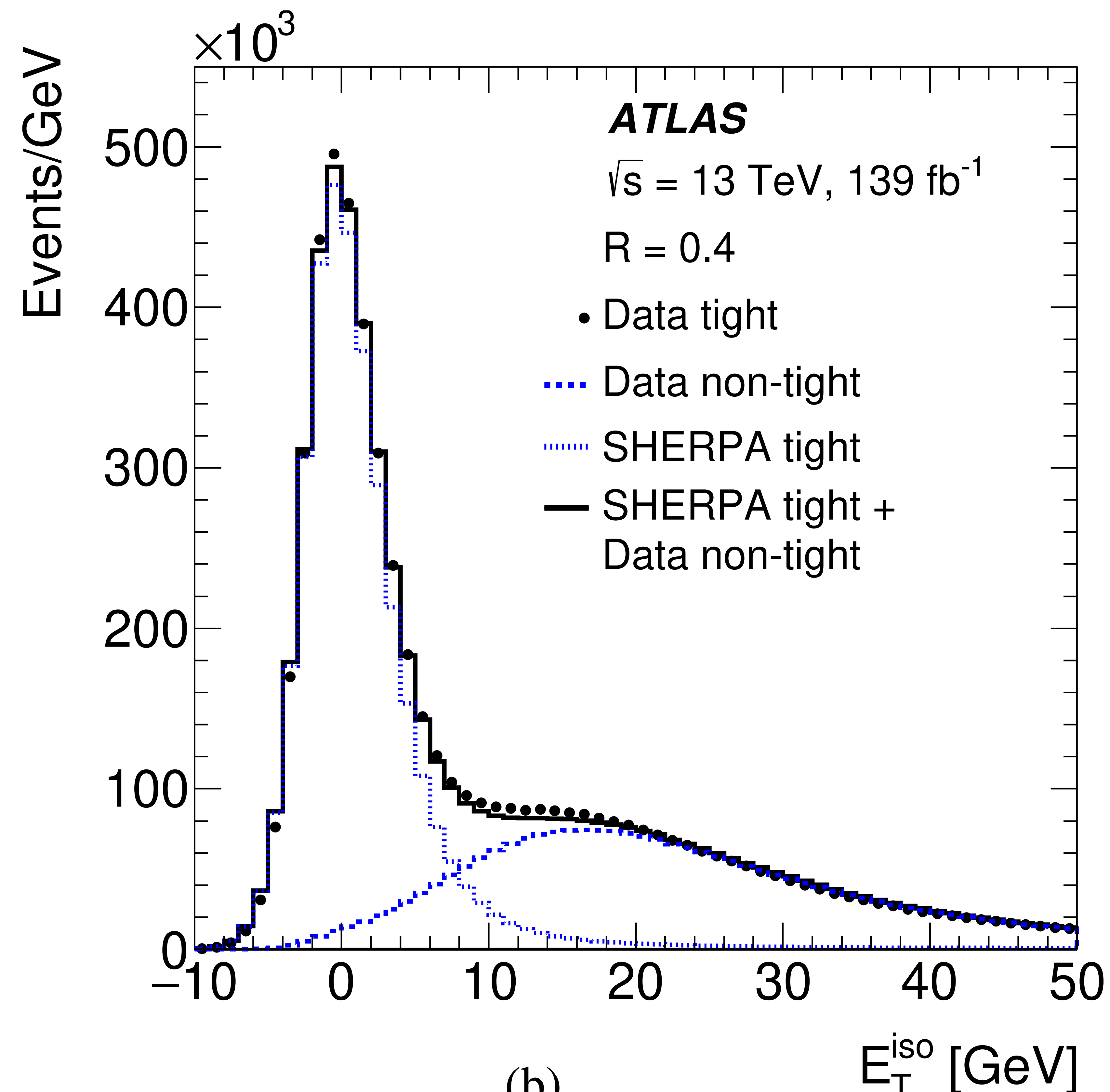


- In each pseudo-rapidity (η) bin the multijet background is subtracted using the ABCD method
- ABCD regions constructed with photon ID and isolation
  - Assumed no correlation ($R^{bg} = 1$)
  - Leakage factors (f_X) estimated with MC and systematic uncertainty applied to cover the difference between Sherpa and Pythia8

$$N_A^{sig} = N_A - R^{bg} \cdot \frac{\left(N_B - f_B N_A^{sig}\right) \cdot \left(N_C - f_C N_A^{sig}\right)}{\left(N_D - f_D N_A^{sig}\right)}$$

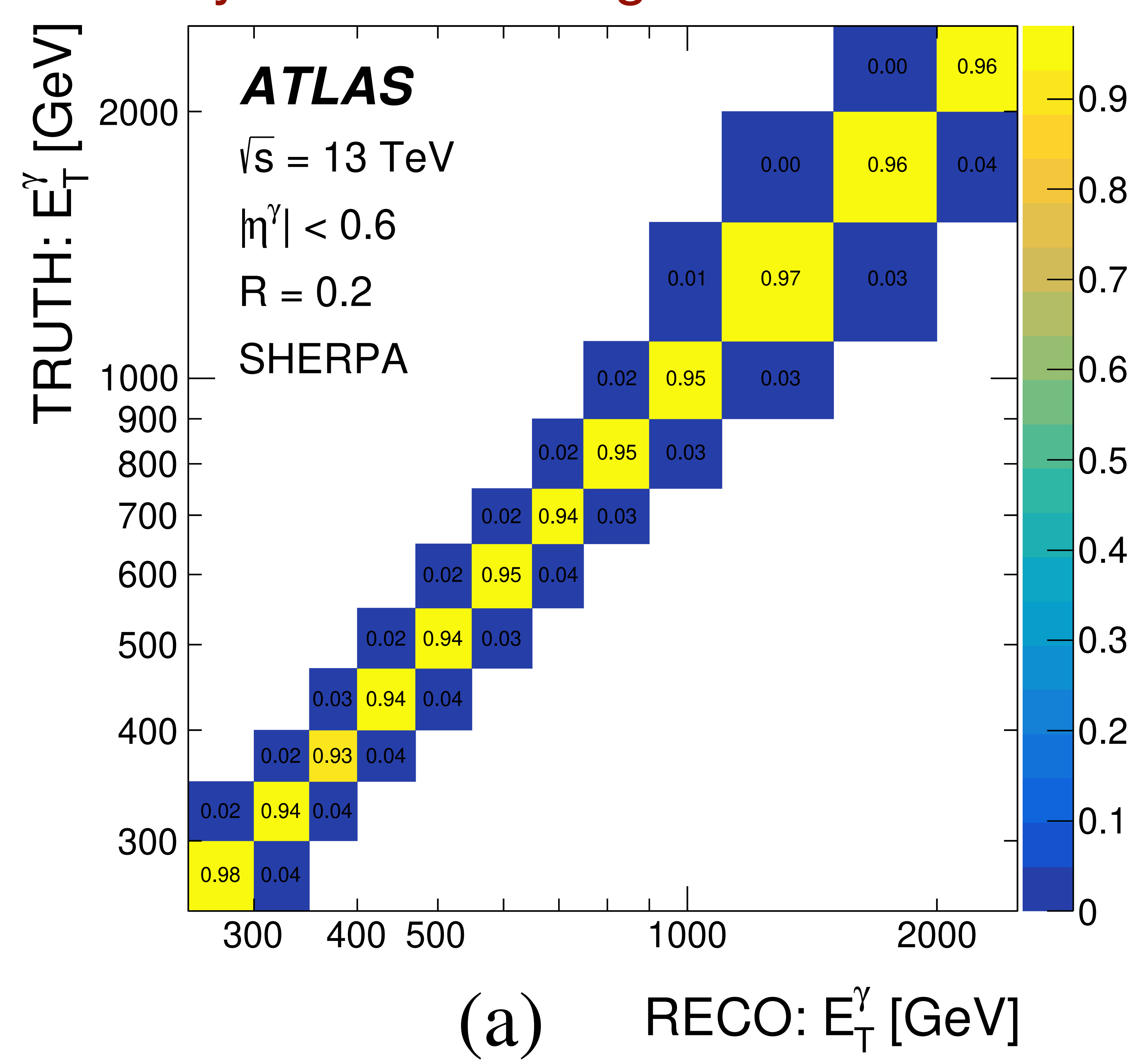


(a)



(b)

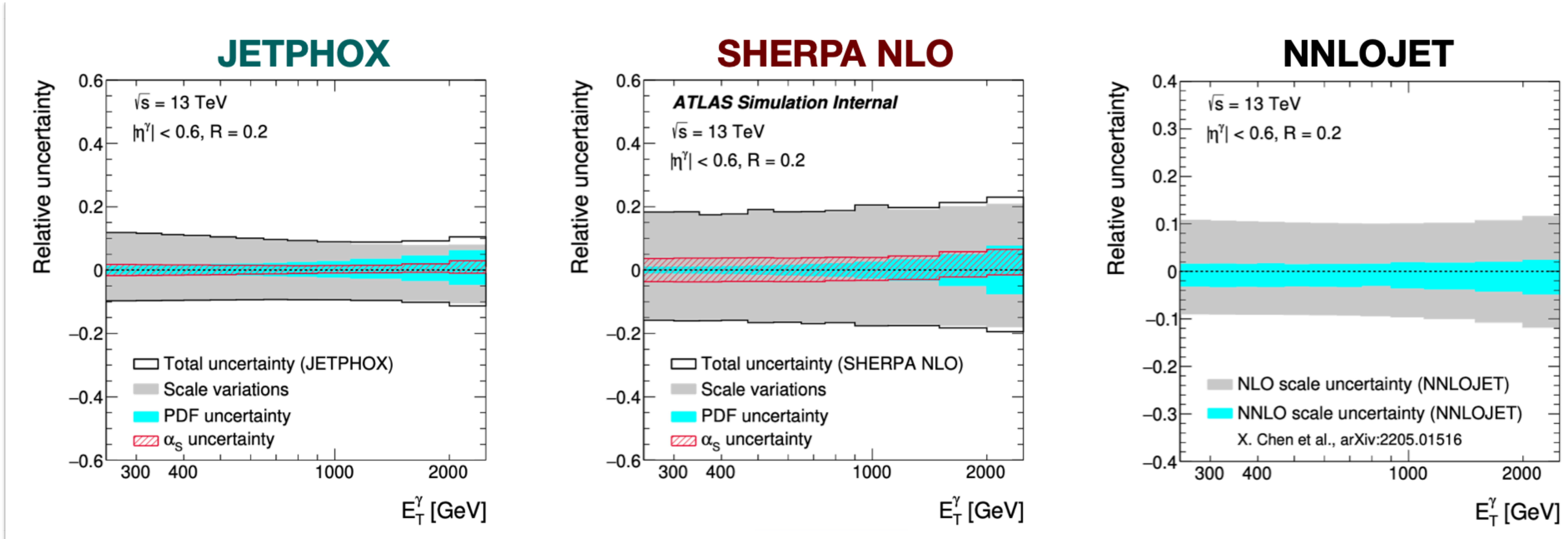
Bayesian unfolding with RooUnfold



(a)

Comparison to predictions

- Results compared to three predictions: Sherpa2.2.2 and two fixed-order predictions (Jetphox / NNLOJET)

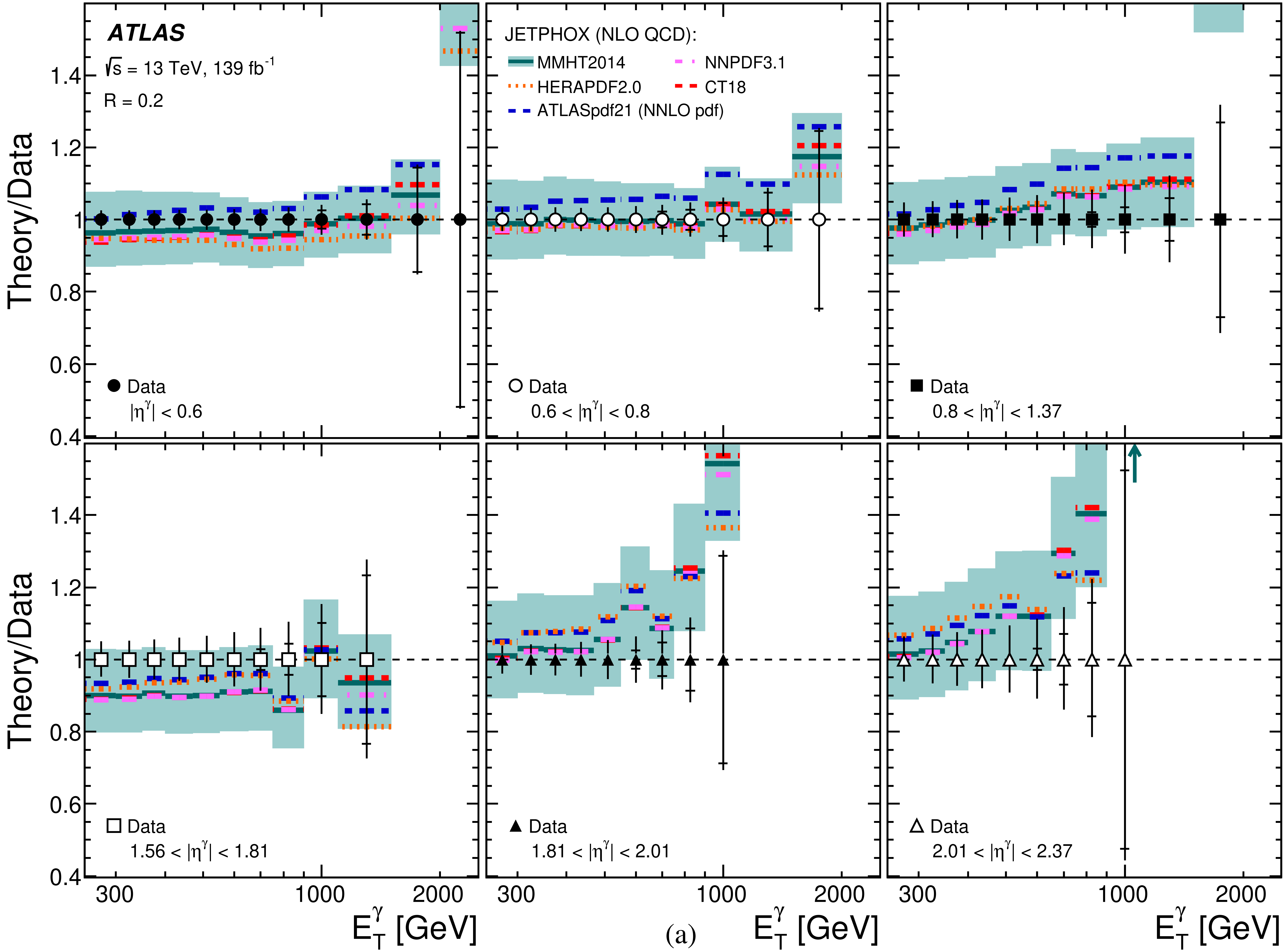


Largest scale uncertainty in Sherpa. NNLOJET about a factor of two smaller scale uncertainty.

Program	Order in α_s	Fragmentation	Parton shower	Isolation method	PDF	Particle level
JETPHOX	NLO	yes	no	fixed cone	– MMHT2014 – CT18 – NNPDF3.1 – HERAPDF2.0 – ATLASpdf21	no
SHERPA 2.2.2	NLO for γ + (1, 2)-jet LO for γ + (3, 4)-jet	no	yes	hybrid	NNPDF3.0	yes
NNLOJET	(N)NLO	yes	no	fixed cone	CT18NNLO	no

Focus of this talk

Multiple NLO and NNLO PDFs tested with Jetphox and NNLOJET.

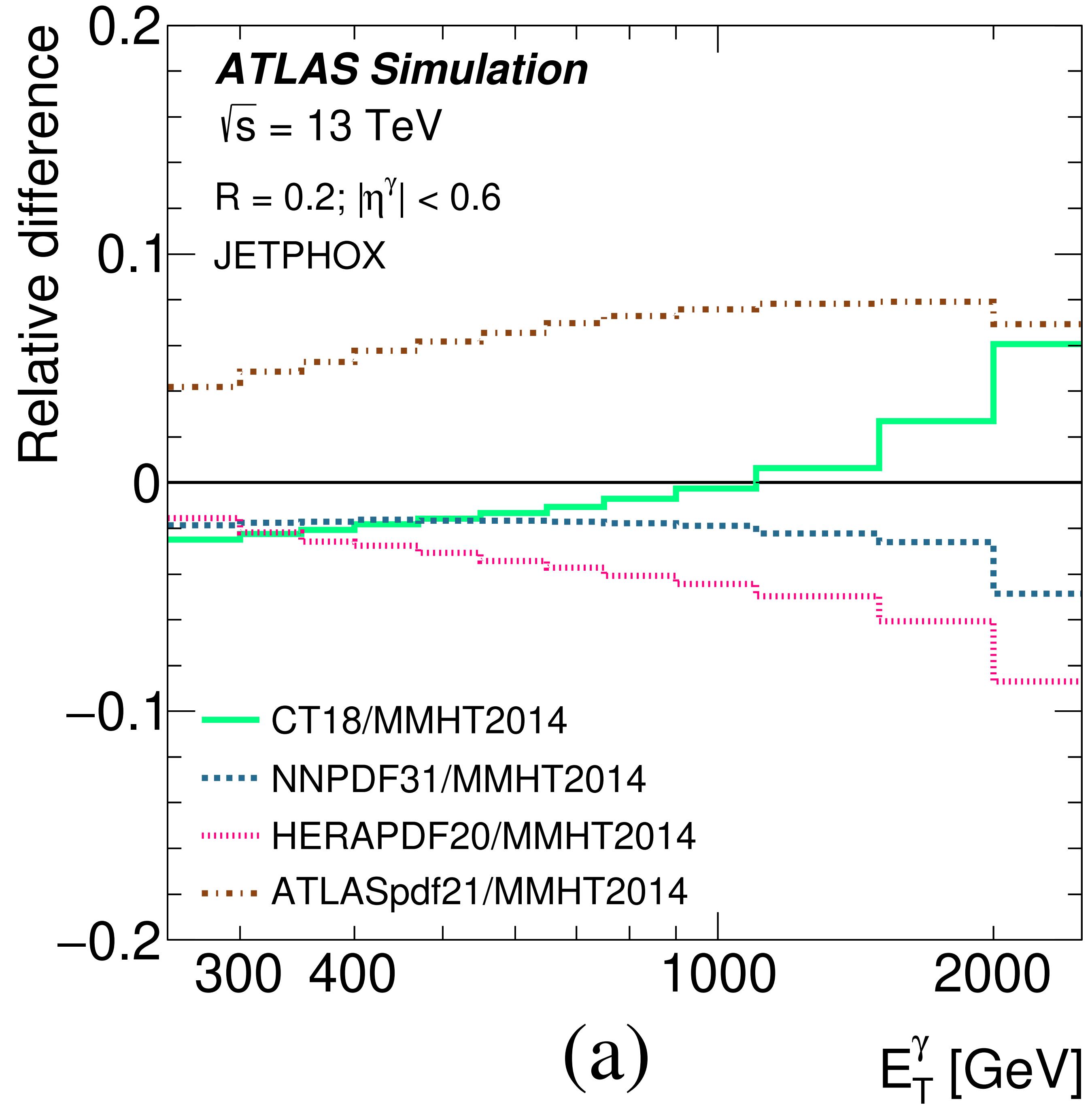


(a)

Adequate description of the data within the experimental and theoretical uncertainties.

Central values up to 50% away at large energies.

Relatively large difference between the PDFs!

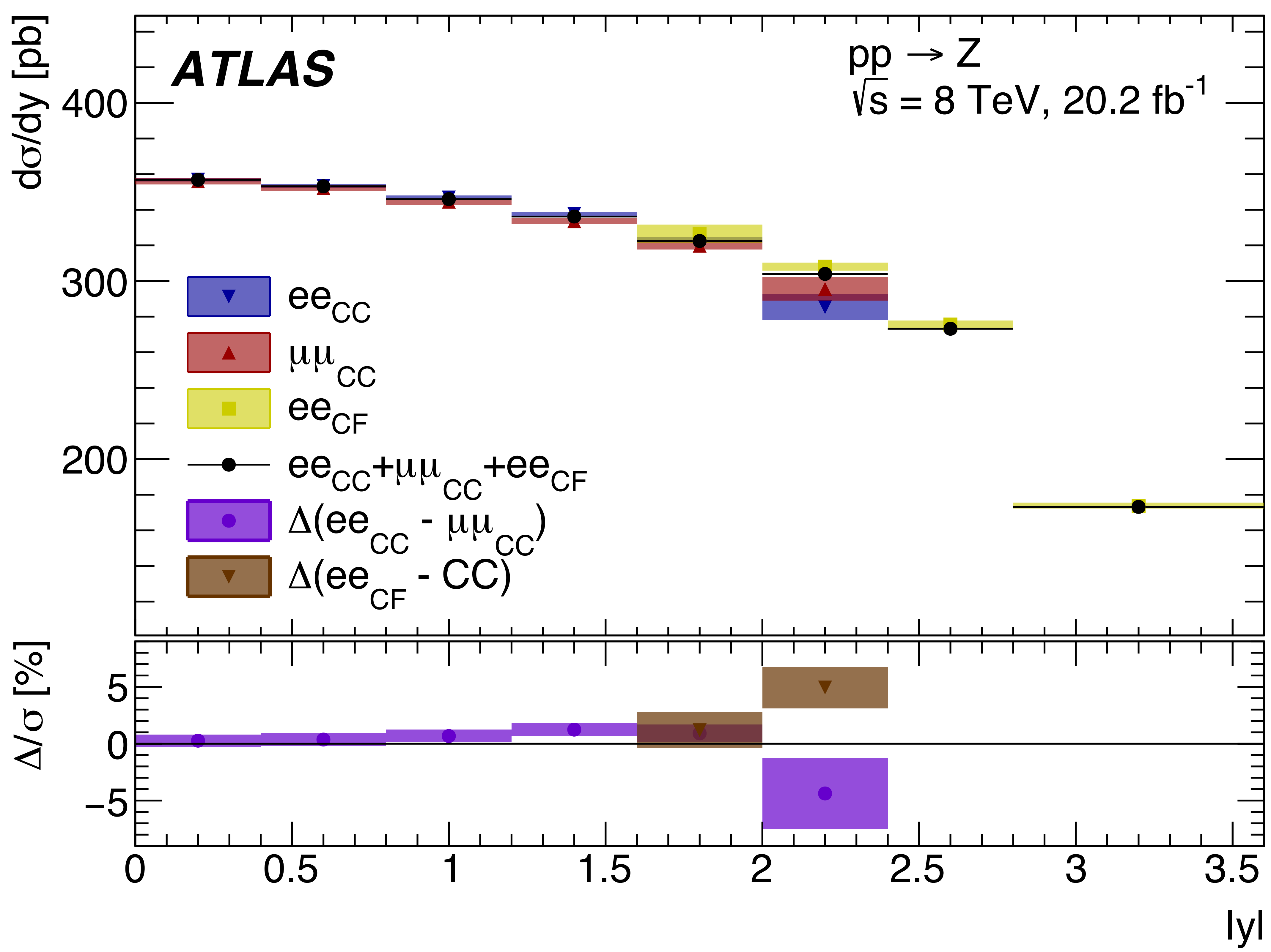


(a)

$p_T(Z)$ and $y(Z)$ at 8 TeV in the full decay phase space

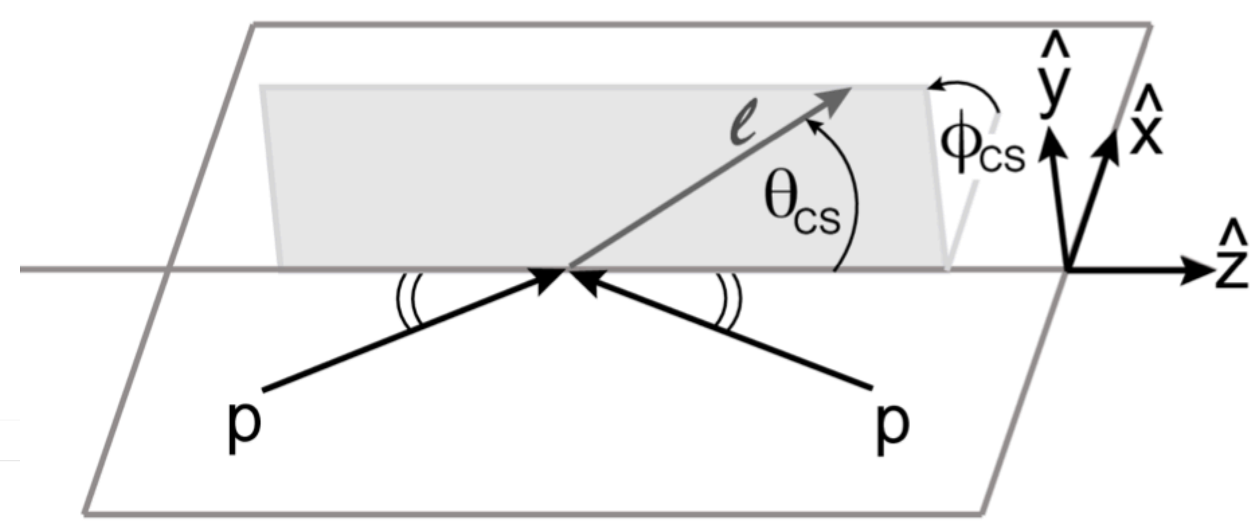
pT(Z) and y(Z) at 8 TeV in the full decay phase space

- 22,528 4D detector-level bins in ($p_T(Z)$, $y(Z)$, $\cos\theta$, ϕ)
- Extrapolated to full decay phase space by measuring the angular coefficients and $d^2\sigma/(dp_T dy)$
- Provides a framework for clean interpretations of rapidity and p_T cross sections
  - No polarization and decay efficiency uncertainties, at the cost of larger statistical uncertainty
- **Heroic experimental effort**— Run 1 forward electron calibration needed to be re-done due to slight tension with the central calibration.



Template likelihood fit with POIs
- 352 |y| and p_T cross sections
- 8 angular coefficients (Ai)

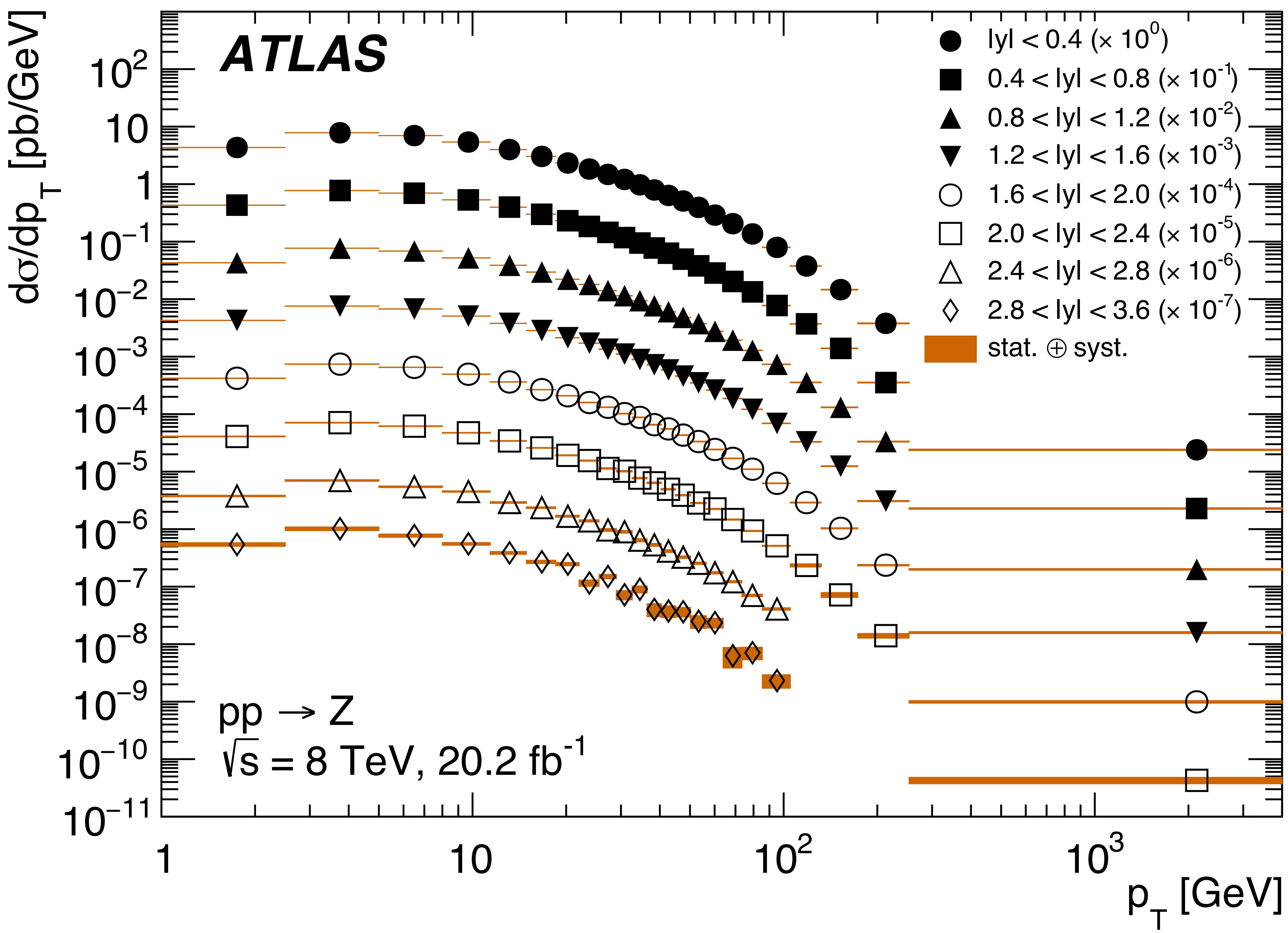
Collins-Soper frame



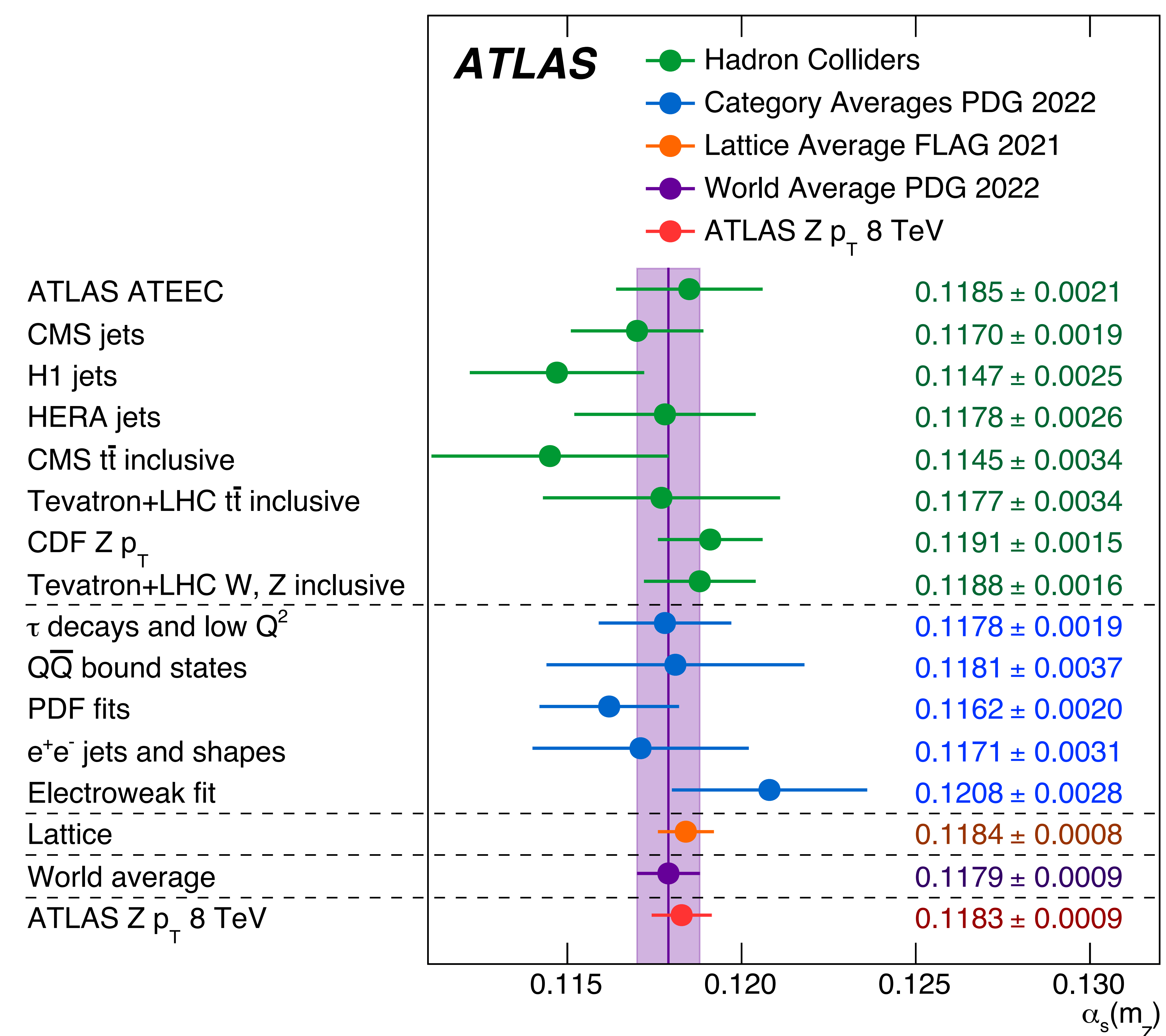
Analytic formula for decay in the full phase space

$$\frac{d\sigma}{dp_T\, dy\, dm\, d\cos\theta\, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T\, dy\, dm} \Big\{(1+\cos^2\theta) + \frac{1}{2} A_0 (1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2} A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi\Big\}.$$

- Results can be interpreted / used in various ways:
  - Integrate over |y| to get a precise $p_T(Z)$ differential cross section— was used to extract $\alpha_S(m_Z)$
  - Integrate over $p_T(Z)$ to get a precise |y| distribution— sensitive to PDFs!



More about $\alpha_S(m_Z)$ extraction in Maarten's talk



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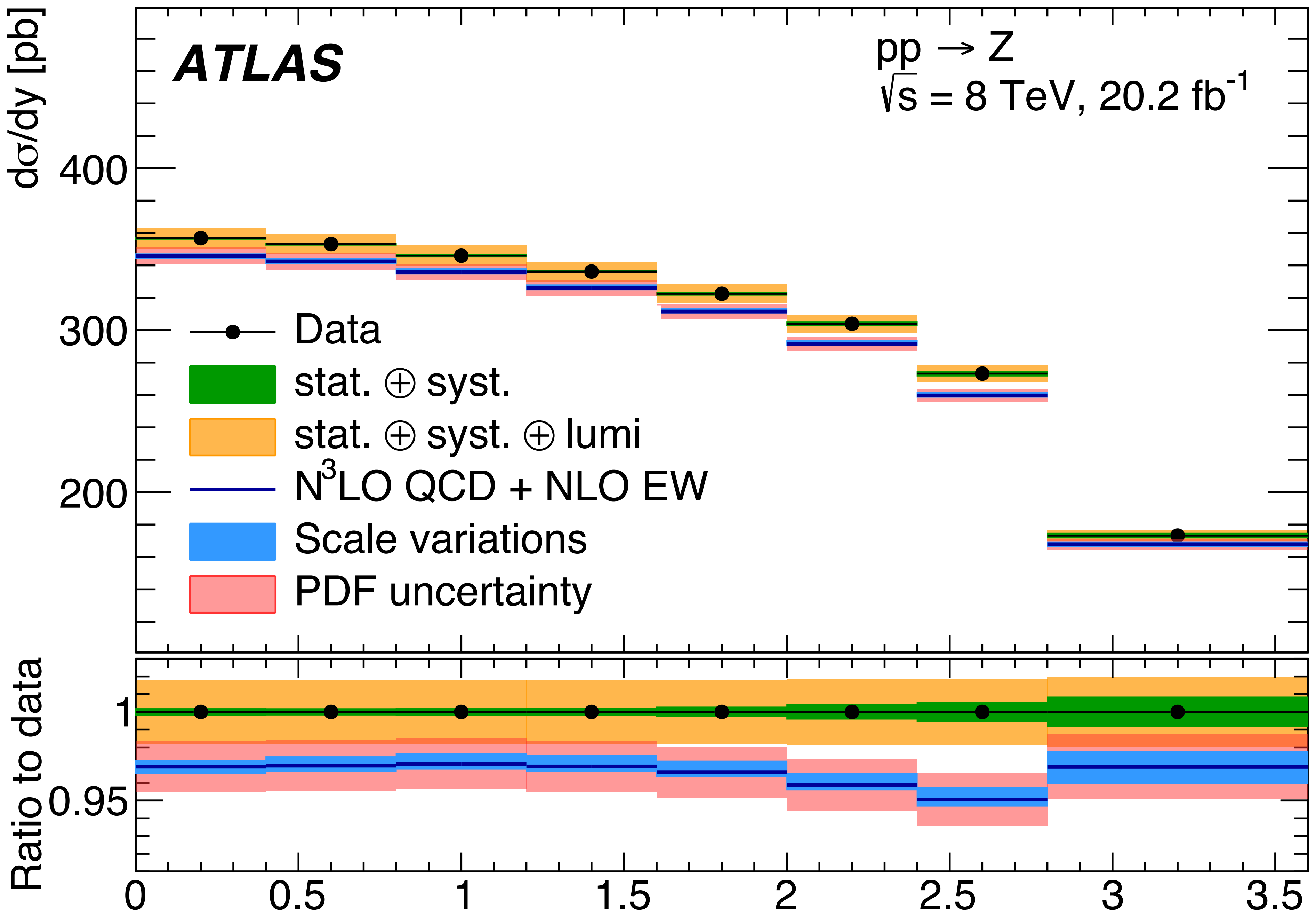
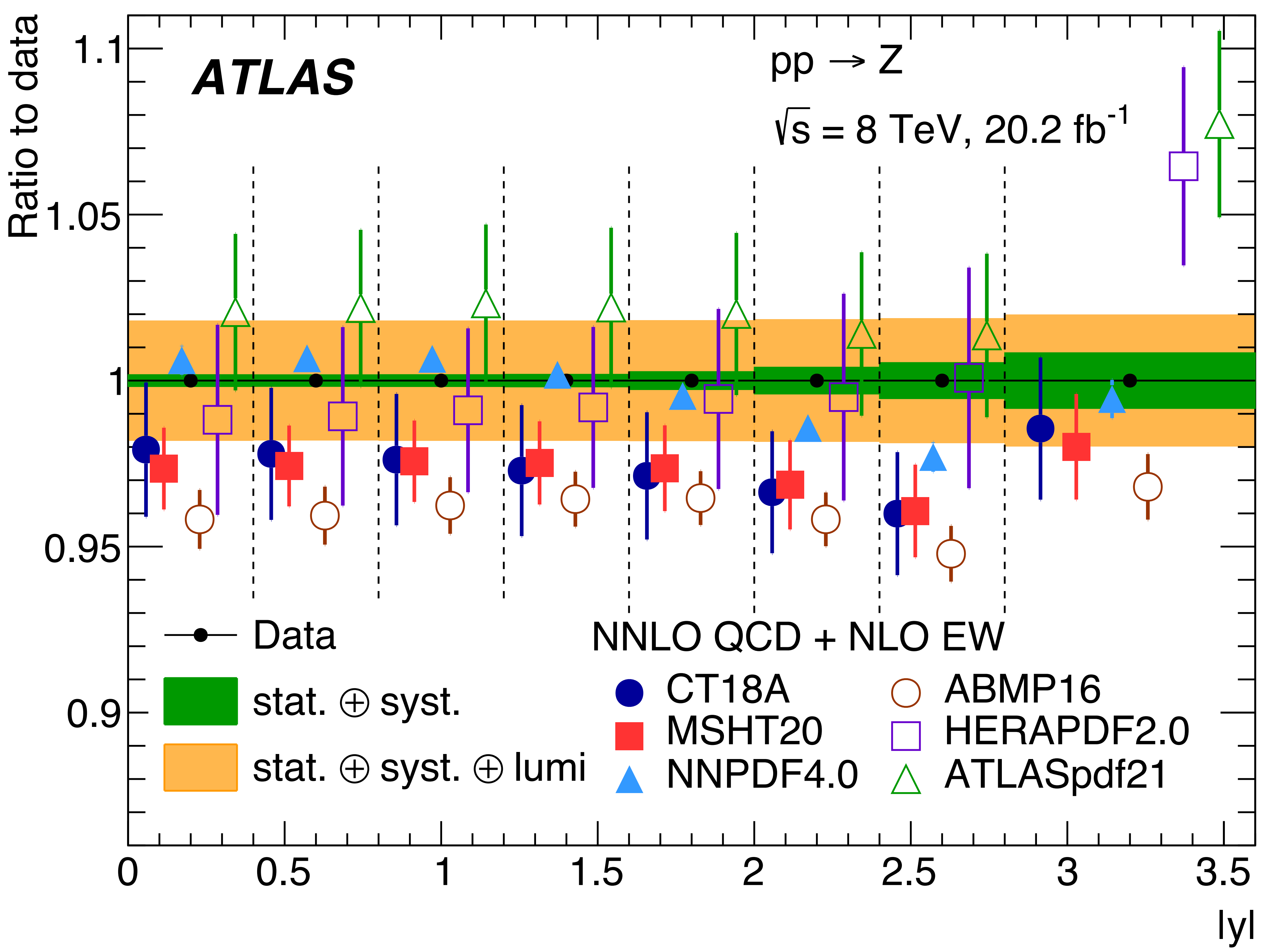




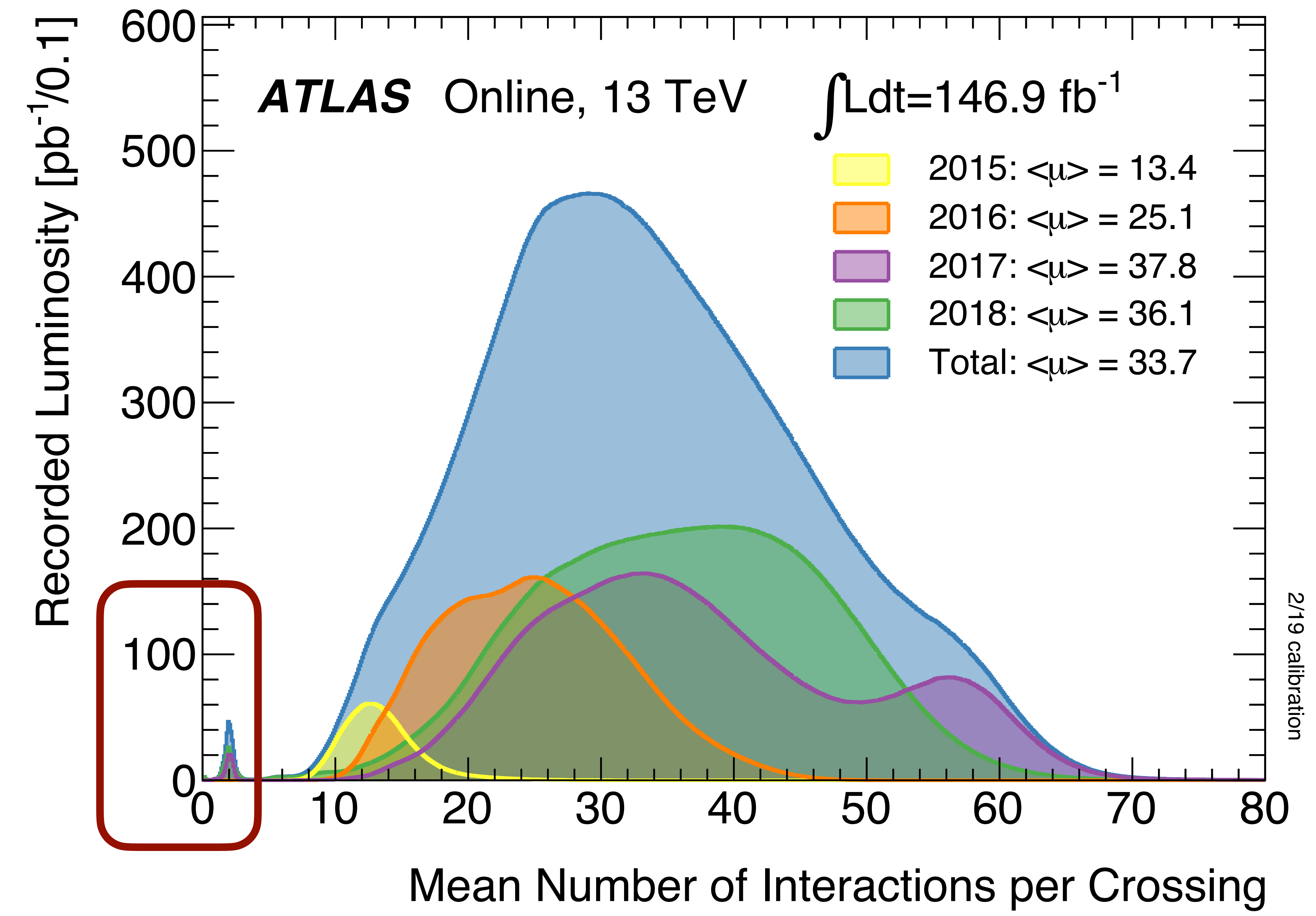
- Excluding luminosity uncertainty (correlated across bins), permille-level precision in the central region, sub-percent uncertainties up to $|y| < 3.6$
- First comparison to N3LO QCD predictions
  - DYTurbo with the aN3LO MSHT20 PDF set
- Comparisons with NNLO PDFs:
  - NNLO QCD + NLO EW DYTurbo calculation
- **NNPDF4.0** mostly within the luminosity uncertainty, but poor p-value due to small PDF uncertainty and the discrepancy in the $|y|$ cross section shape

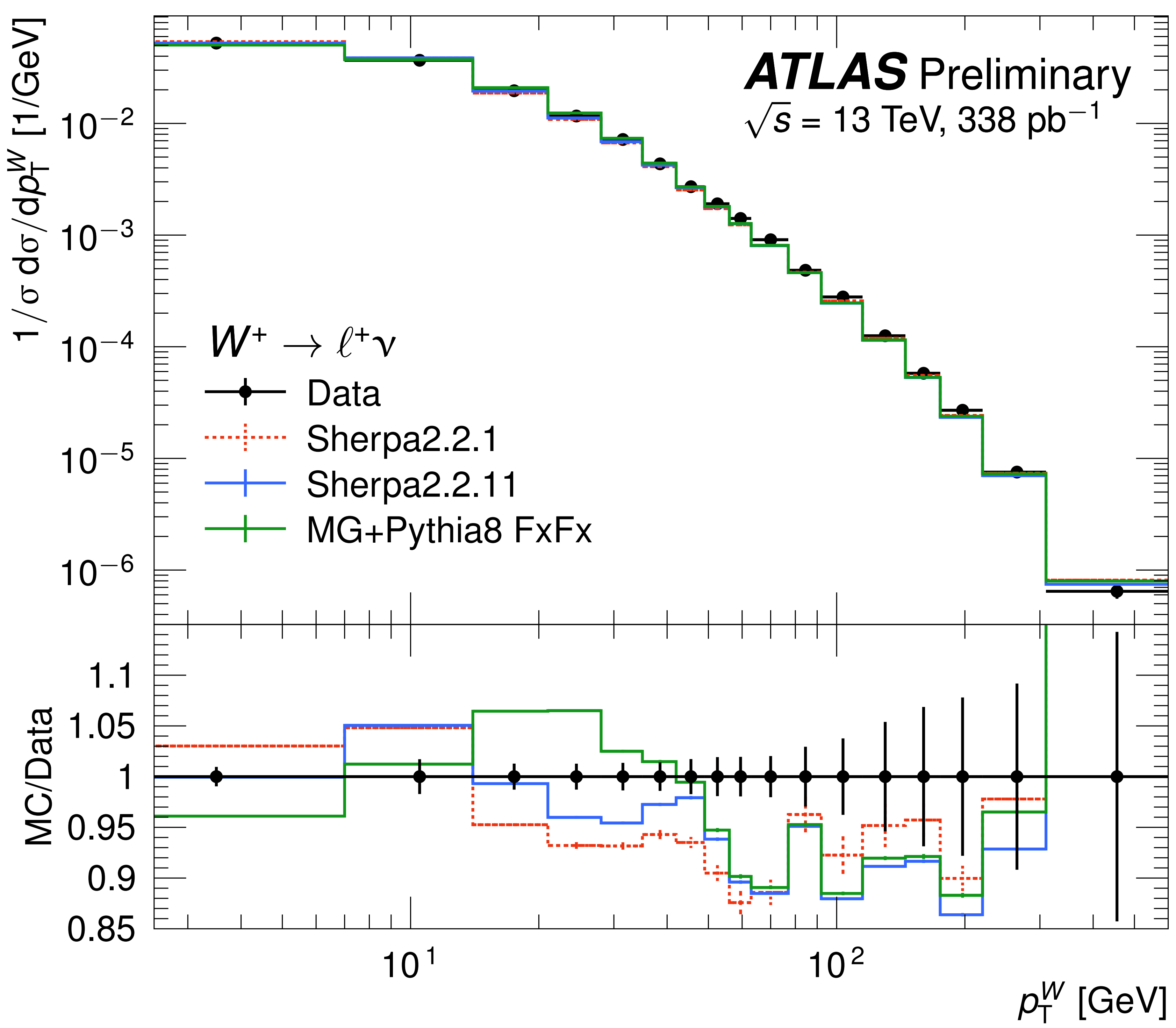
PDF set	Total χ^2 / d.o.f.	χ^2 p-value	Pull on luminosity
MSHT20aN^{3}LO [58]	13/8	0.11	1.2 ± 0.6
CT18A [59]	12/8	0.17	0.9 ± 0.7
MSHT20 [60]	10/8	0.26	0.9 ± 0.6
NNPDF4.0 [61]	30/8	0.0002	0.0 ± 0.2
ABMP16 [62, 63]	30/8	0.0002	1.8 ± 0.4
HERAPDF2.0 [64]	22/8	0.005	−1.3 ± 0.8
ATLASpdf21 [65]	20/8	0.01	−1.1 ± 0.8

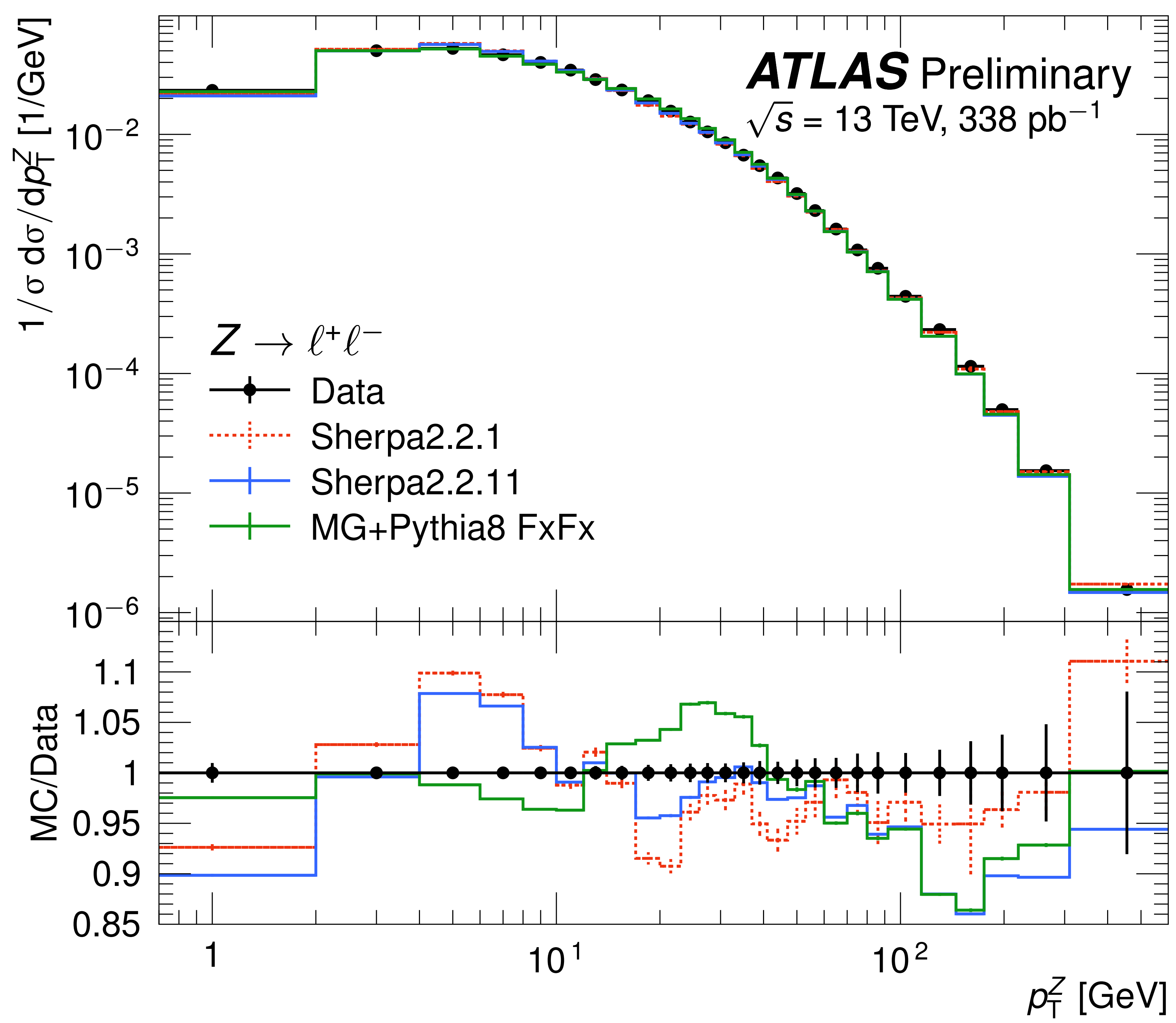
pT(Z) and pT(W) from low mu data (5.02 and 13 TeV)

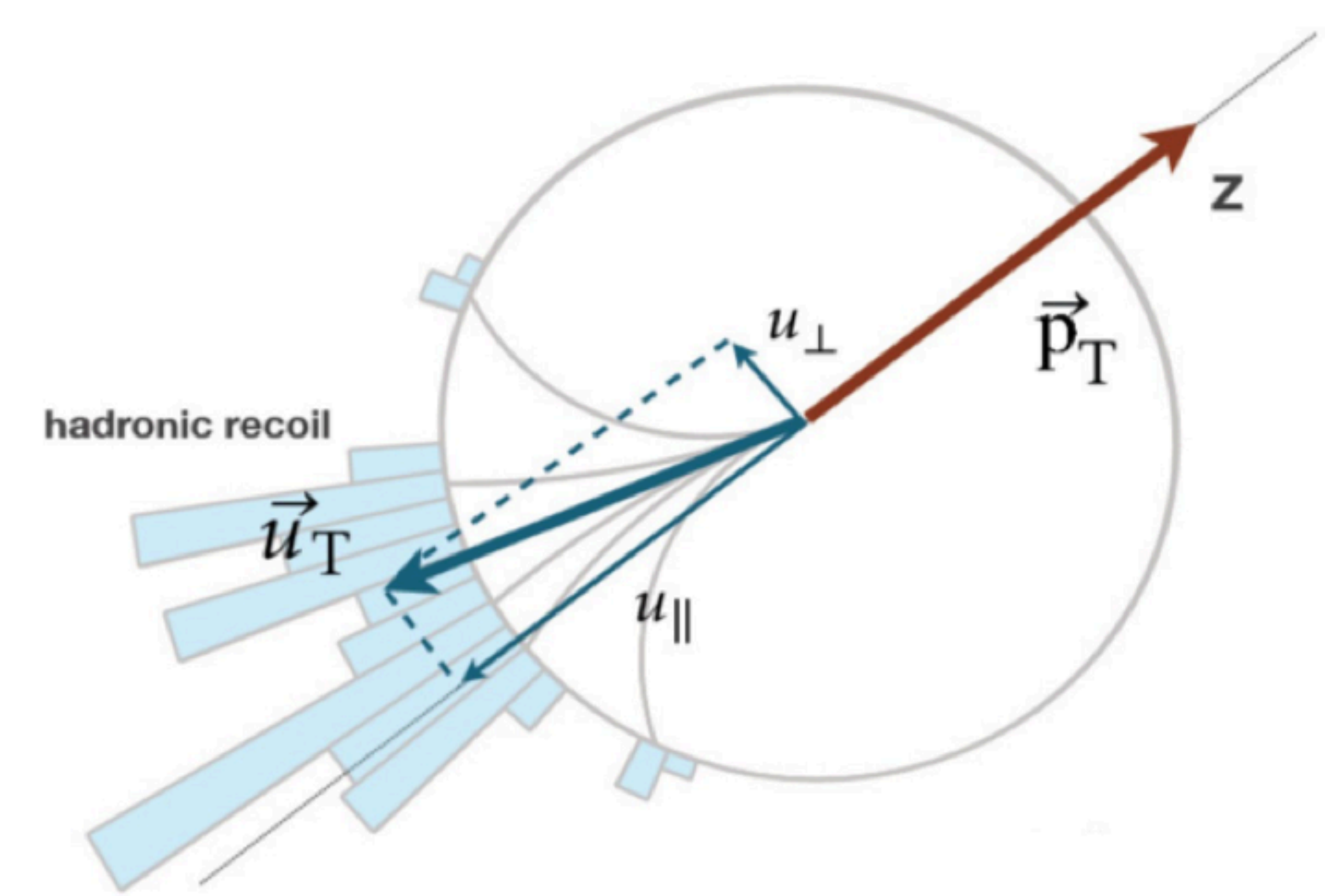
$p_T(Z)$ and $p_T(W)$ from low mu data (5.02 and 13 TeV)

- Using the **low-pileup data** with <μ> ~ 2 taken in 2017 and 2018
  - 255 pb^{-1} at 5.02 TeV and 338 pb^{-1} at 13.0 TeV
  - About 1.5M *Z* and 120k *W*-bosons after selection
- Uses the **hadronic recoil** to access $p_T(W)$
  - Calibrated with $p_T(Z)$— $p_T(\ell\ell)$ vs hadronic recoil
- Reduce the modeling uncertainty and theory assumptions in the m(W) measurements— also insight into PDFs
- Dedicated electron / muon calibrations for Run 2 low-pileup!









PDF sensitivity

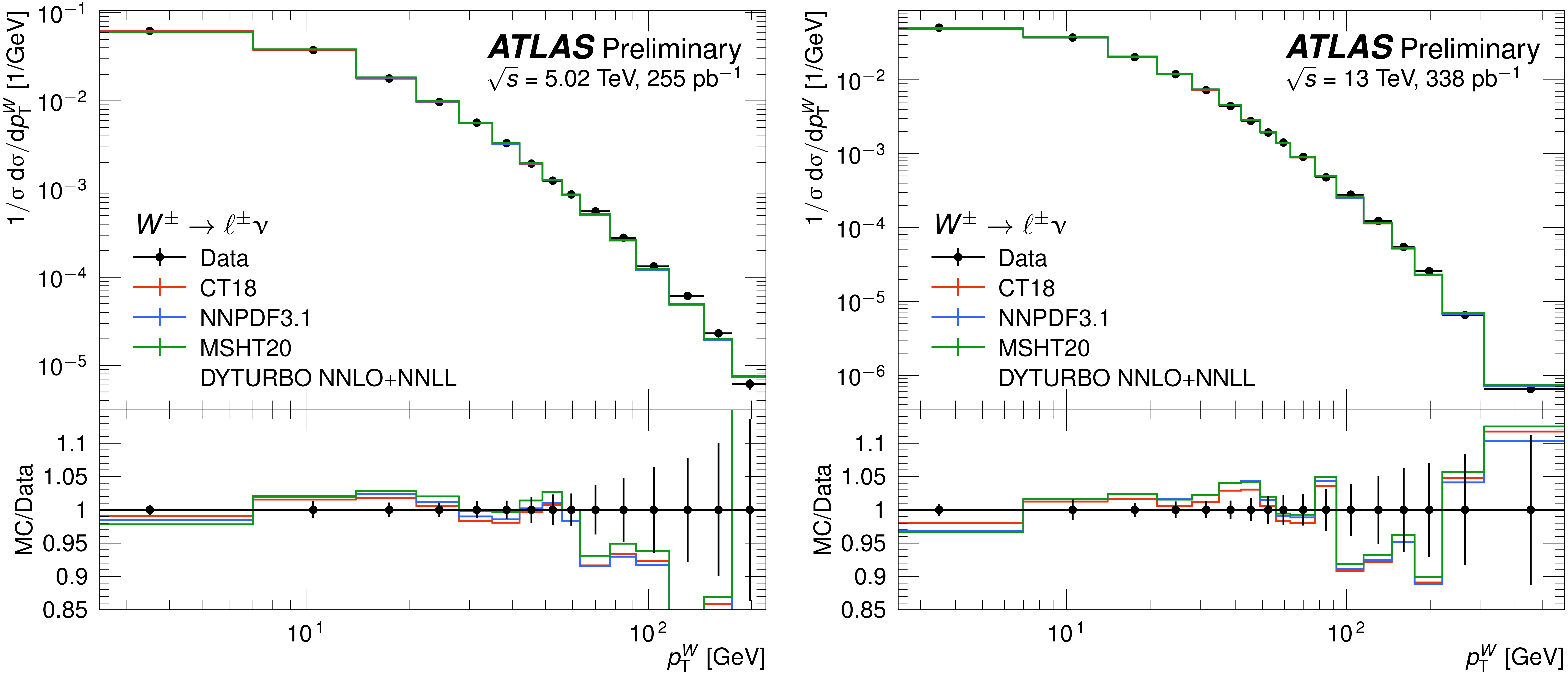
- Predictions calculated with DYTurbo at NNLO + NNLL accuracy using NNLO PDF sets
- Central values of tested PDFs generally undershoot the cross section by 1-2σ experimental error
- Sizable difference (compared to exp. error) between the PDF sets (NNPDF3.1 vs others)
- Cross section ratios however, are spot-on within the percent-level precision
- Expected to have constraining power

PDF set	$W^- \to \ell\nu$	$W^+ \to \ell\nu$	$Z \to \ell\ell$
Cross-section at 5.02 TeV [pb]			
CT18	1364 -1.25σ	2199 -1.16σ	320.9 -2.95σ
MSHT20	1351 -2.06σ	2185 -2.69σ	324.3 -2.12σ
NNPDF3.1	1381 -0.19σ	2232 +0.16σ	329.8 -0.78σ
Data	1384 ± 16	2228 ± 25	333.0 ± 4.1
Cross-section at 13 TeV [pb]			
CT18	3410 -2.00σ	4462 -2.22σ	749.8 -2.93σ
MSHT20	3397 -2.34σ	4457 -2.33σ	766.1 -1.37σ
NNPDF3.1	3452 -0.89σ	4513 -1.18σ	771.4 -0.86σ
Data	3486 ± 38	4571 ± 49	780.3 ± 10.4

PDF set	$W^- \to \ell\nu$	$W^+ \to \ell\nu$	$Z \to \ell\ell$
Ratio $\sigma_{\text{fid}}(13\,\text{TeV})/\sigma_{\text{fid}}(5.02\,\text{TeV})$			
CT18	2.499	2.029	2.337
MSHT20	2.515	2.040	2.362
NNPDF3.1	2.500	2.022	2.339
Data	2.517 ± 0.038	2.047 ± 0.031	2.340 ± 0.036

PDF set	W^+/W^-	W^-/Z	W^+/Z	$W^\pm/Z$
Cross-section ratios at 5.02 TeV				
CT18	1.612	4.25	6.85	11.10
MSHT20	1.618	4.16	6.74	10.90
NNPDF3.1	1.616	4.19	6.77	10.95
Data	1.611 ± 0.005	4.16 ± 0.05	6.69 ± 0.08	10.85 ± 0.12
Cross-section ratios at 13 TeV				
CT18	1.309	4.55	5.95	10.50
MSHT20	1.312	4.43	5.82	10.25
NNPDF3.1	1.307	4.48	5.85	10.33
Data	1.312 ± 0.003	4.46 ± 0.07	5.84 ± 0.09	10.31 ± 0.15

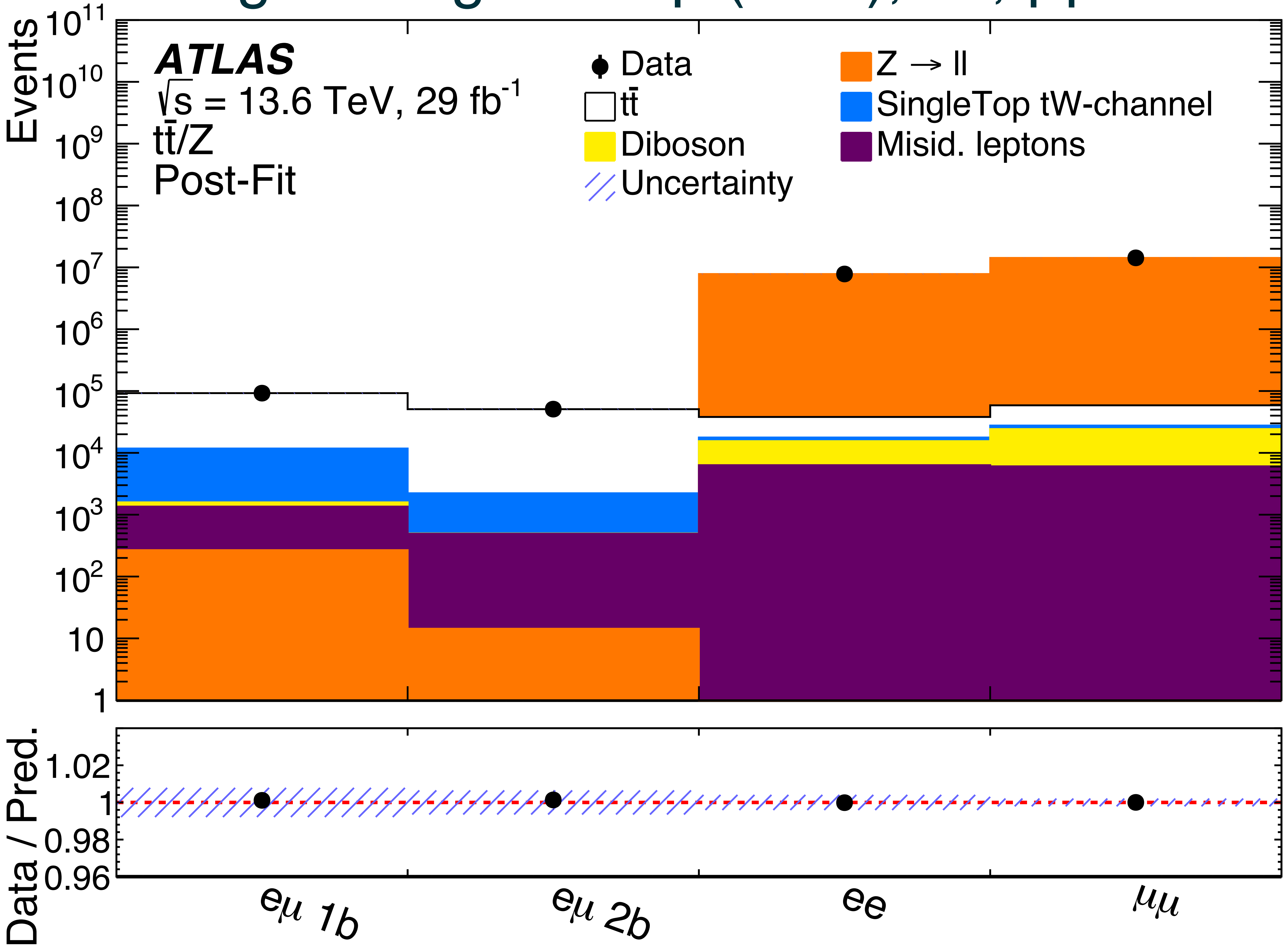
- Only a small difference in the normalized cross section between the tested PDF sets
  - Do we expect to be able to constrain PDFs from the $p_T(W)$ shape?
  - Would be interesting to see the PDF errors / eigenvectors

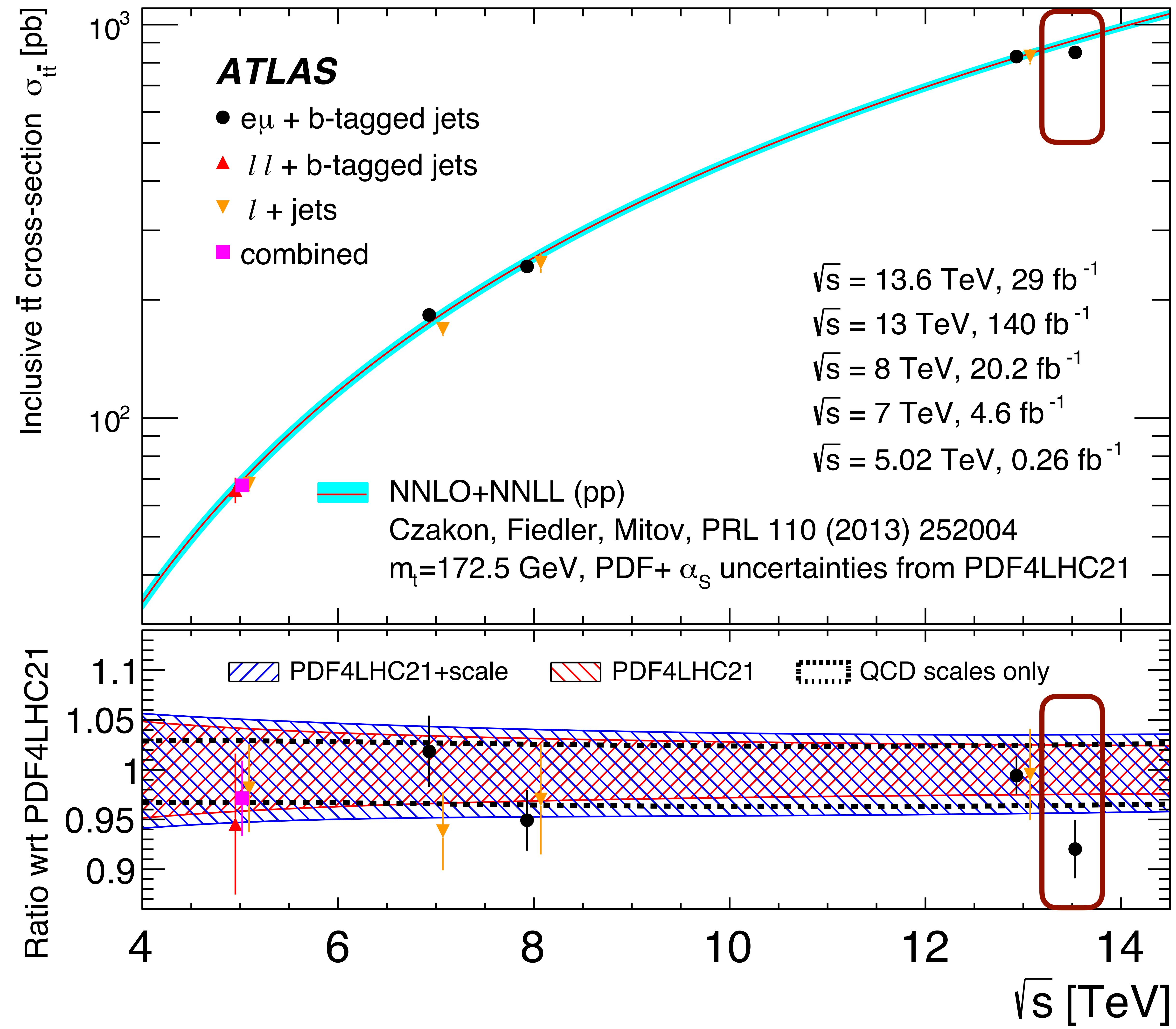


ttbar/Z cross section ratio at 13.6 TeV (Run 3 data)

- Cross section measurements with initial early Run 3 data limited by luminosity uncertainty
  - Mostly cancels out in a cross section ratio— measure σ(ttbar) / σ(Z)!
- Results given both for separate cross sections and the cross section ratio

4 Signal Regions: eμ (1/2b), ee, μμ



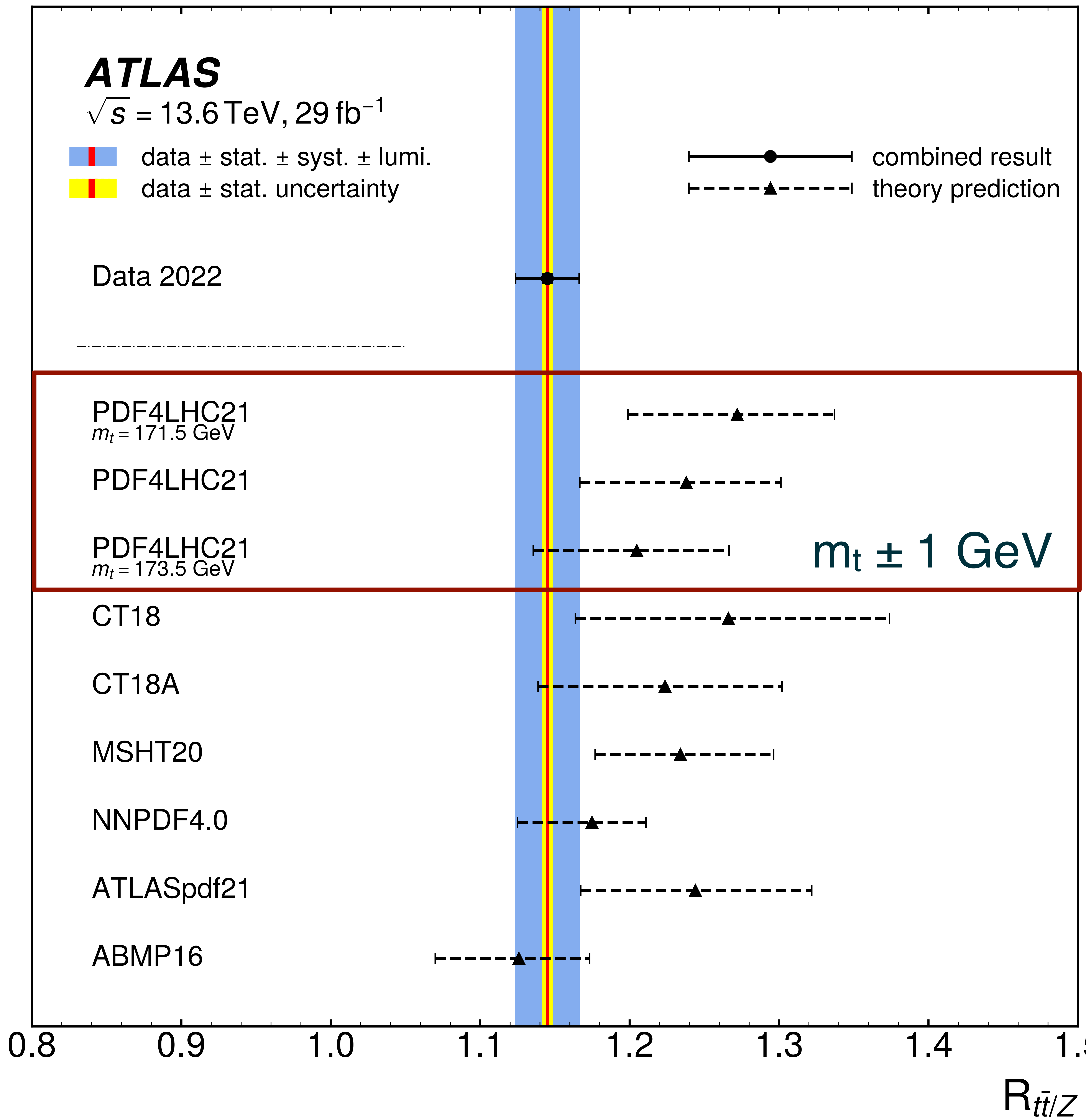


Comparison to PDF sets

- Ratio calculated in a fiducial phase space
  - $p_T(\ell) > 27$ GeV, $|\eta(\ell)| < 2.5$
  - Invariant mass 66 GeV < $m(\ell\ell)$ < 116 GeV

- ttbar x-sec prediction: NNLO + NNLL
- Z x-sec prediction: NNLO QCD + NLO EW
- Scale uncertainty in predictions fully **uncorrelated** between ttbar and Z x-sec
- PDF uncertainty assumed fully **correlated**

- Predictions agree with the data within the uncertainties
- Relatively large spread of central values with different PDF sets
  - Up to 10% relative difference
  - About 2% experimental precision



Summary

- Many new SM measurements in the last year and several of them **important for PDF interpretation**:
  - $W+D^{(*)\pm}$ cross section at 13 TeV: Phys. Rev. D 108 (2023) 032012
  - Inclusive photon production at 13 TeV: JHEP 07 (2023) 086
  - $p_T(Z)$ and $y(Z)$ at 8 TeV in the full decay phase space: STDM-2018-05 (submitted to JHEP)
  - $p_T(Z)$ and $p_T(W)$ from low mu data (5.02 and 13 TeV): ATLAS-CONF-2023-028
  - ttbar/Z cross section ratio at 13.6 TeV (Run 3 data): TOPQ-2023-21 (submitted to PLB)

- Open question regarding the inclusion of W+c datasets in PDF fits
- Most results accompanied with **HEPData** and **Rivet** routines— feedback from theory community welcome!
- How can we maximally exploit this new data to reduce the PDF uncertainties?

Backup