QCD in W/Z/γ boson + jets events

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ATLAS EXPERIMENT

QCD&LHC 2019
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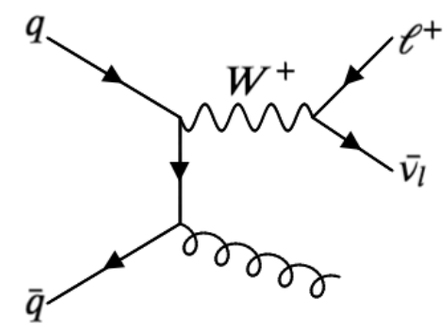
Buffalo, NY, USA

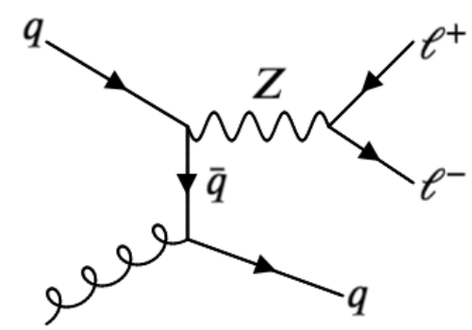
CMS

Motivation

- Vector boson production associated with jets:
  - precise tests of perturbative quantum chromodynamics (pQCD)
  - sensitive to parton distribution functions (PDFs) in proton: gluon and sea-quarks PDF
    - presence of jets increases parton momentum fraction (x) and energy scale (Q^2) ranges
    - potential to improve the understanding of PDFs
  - important background for the Standard Model processes and for searches of new physics

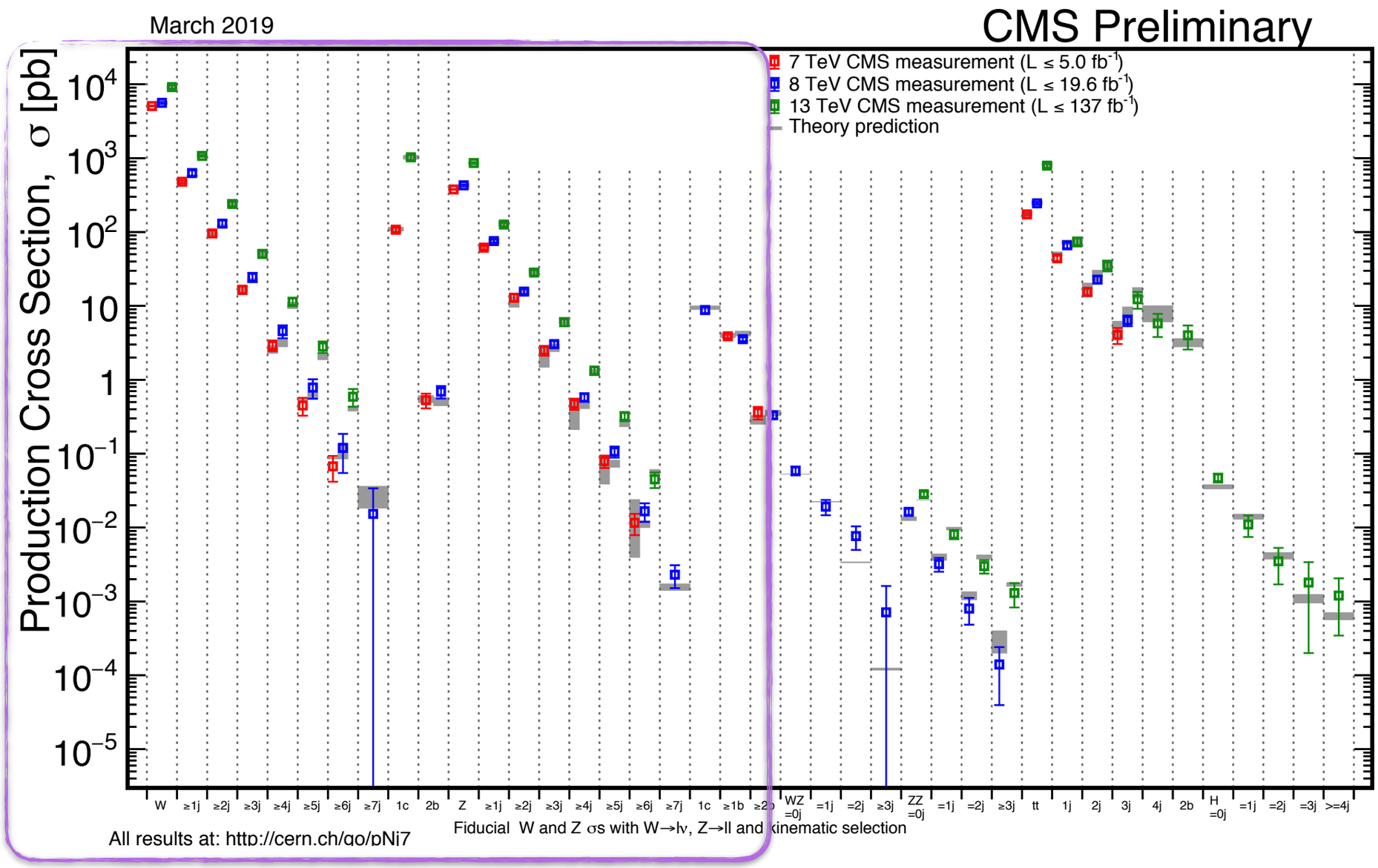


$q\bar{q} \rightarrow Vg$



dominant: $qg \rightarrow Vq$

Analyses overview

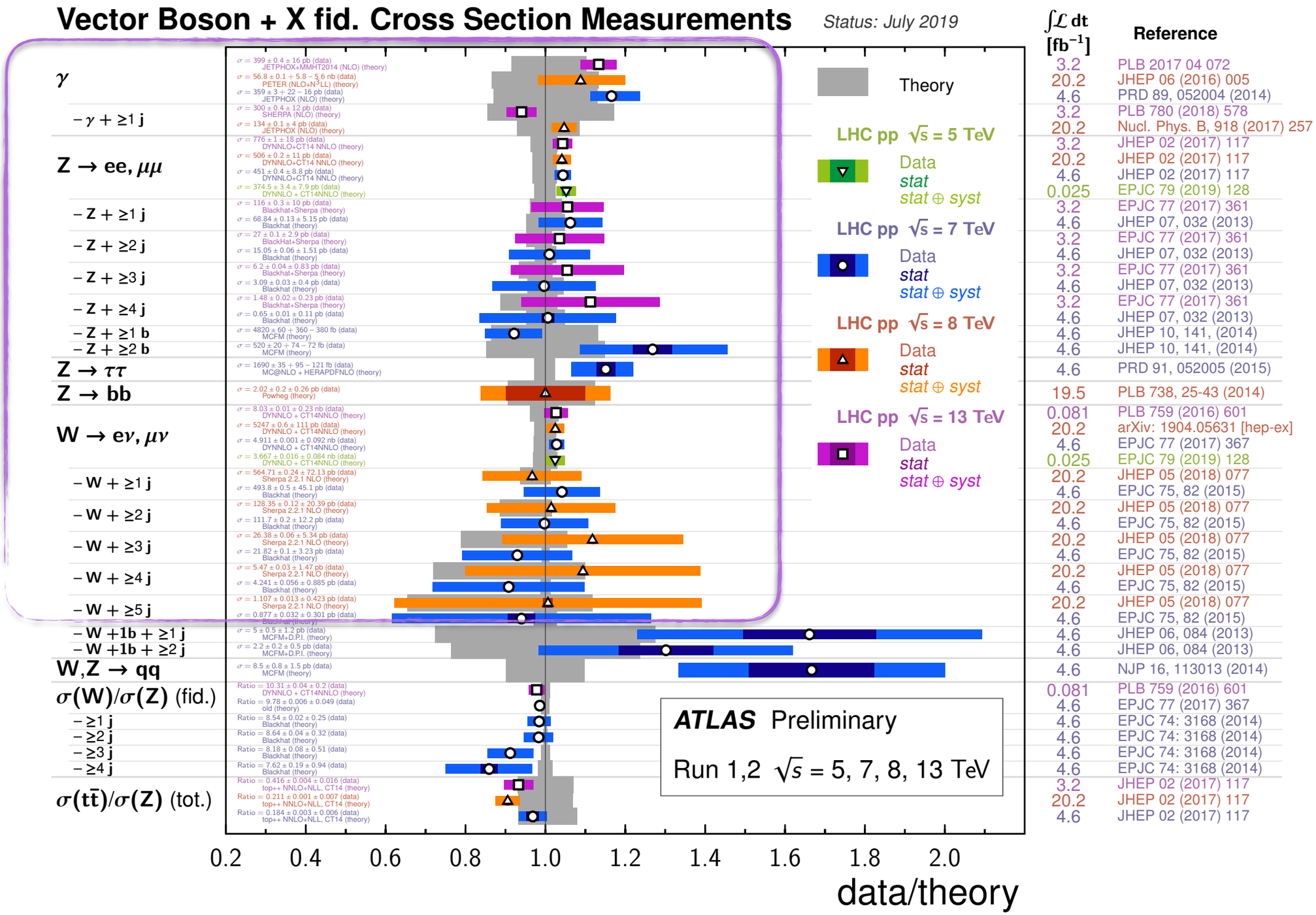


- Large production cross sections for vector boson
- Numerous measurements at different energies and conditions by ATLAS and CMS

Today in the talk:

- **ATLAS**
  - ✓ W+jets at √s=8 TeV
    JHEP 05 (2018) 077
  - ✓ Z+jets at √s=8 TeV **new**
    arXiv:1907.06728
- **CMS**
  - ✓ W+jet at √s=13 TeV
    PRD 96 (2017) 072005
  - ✓ Z+jets at √s=13 TeV
    Eur. Phys. J. C 78 (2018) 965
  - ✓ γ+jets at √s=13TeV
    Eur. Phys. J. C 79 (2019) 20

Analyses overview



✓ **Good agreement between data and predictions**

2012, 20.2 fb^{-1}

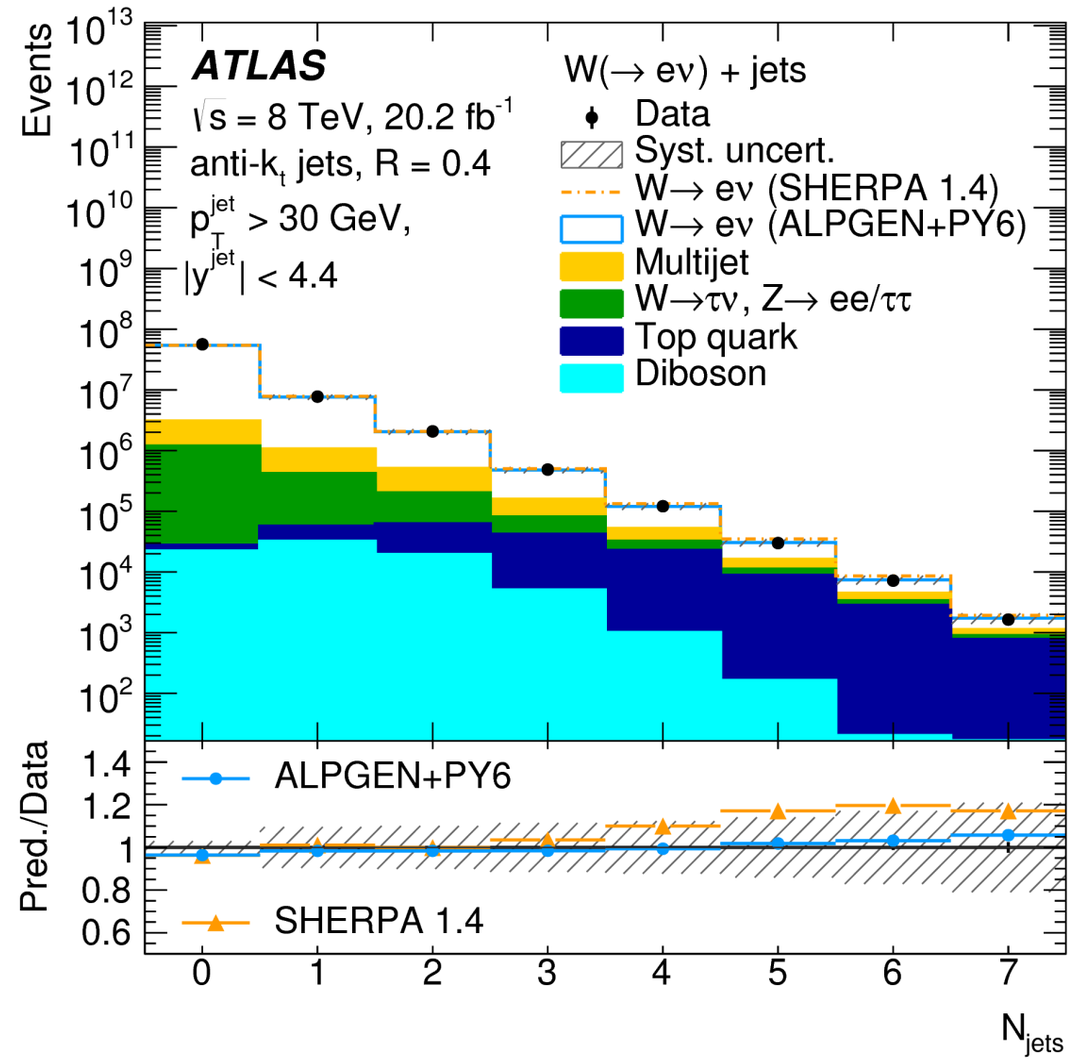
W+jets at 8 TeV

JHEP 05 (2018) 077

Analysis overview

- Main backgrounds:
  - Z+jets and multijet for $N_{jets} \leq 2$ jets
  - $t\bar{t}$ at high jet multiplicities
- Dominant systematic uncertainties:
  - jet energy scale (8% to 55% for $N_{jets} \geq 1$ to $N_{jets} \geq 7$)
  - jet energy resolution (9% to 20% for $N_{jets} \geq 1$ to $N_{jets} \geq 7$)

- **Theoretical predictions:**
  - **Multi-parton MC LO or NLO** (Alpgen, Sherpa)
  - **NLO**: BlackHat+Sherpa (BH+S) up to 5 jets, CT10 NLO PDF set
  - **NLO**: Sherpa 2.2.1 up to 2 jets + LO for 3rd jet, CT10 PDF set
  - **NNLO**: N-jettiness subtraction technique (N_{jetti}), CT14 NNLO PDF set



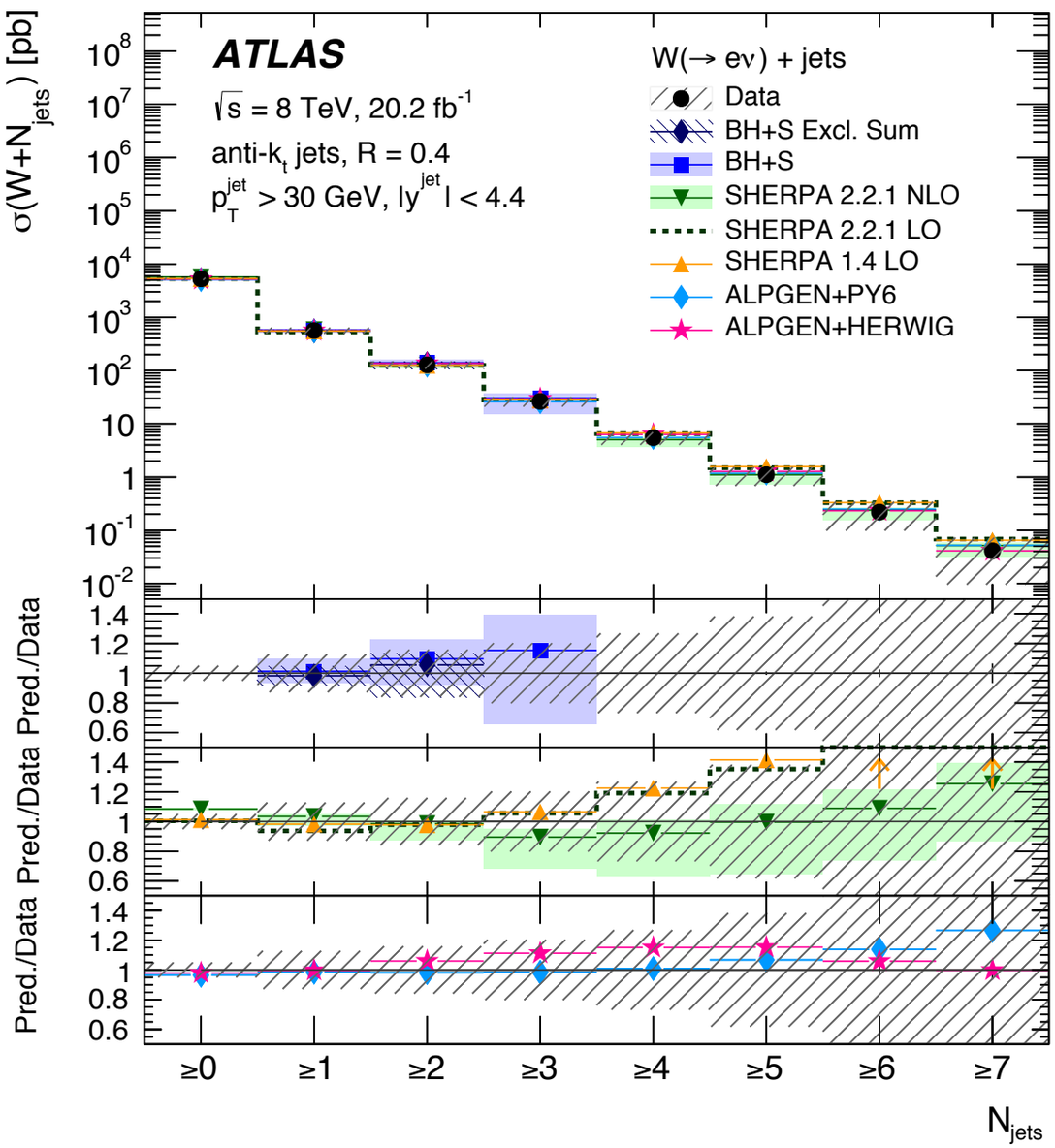
✓ Differential cross sections for W production with one or two jets

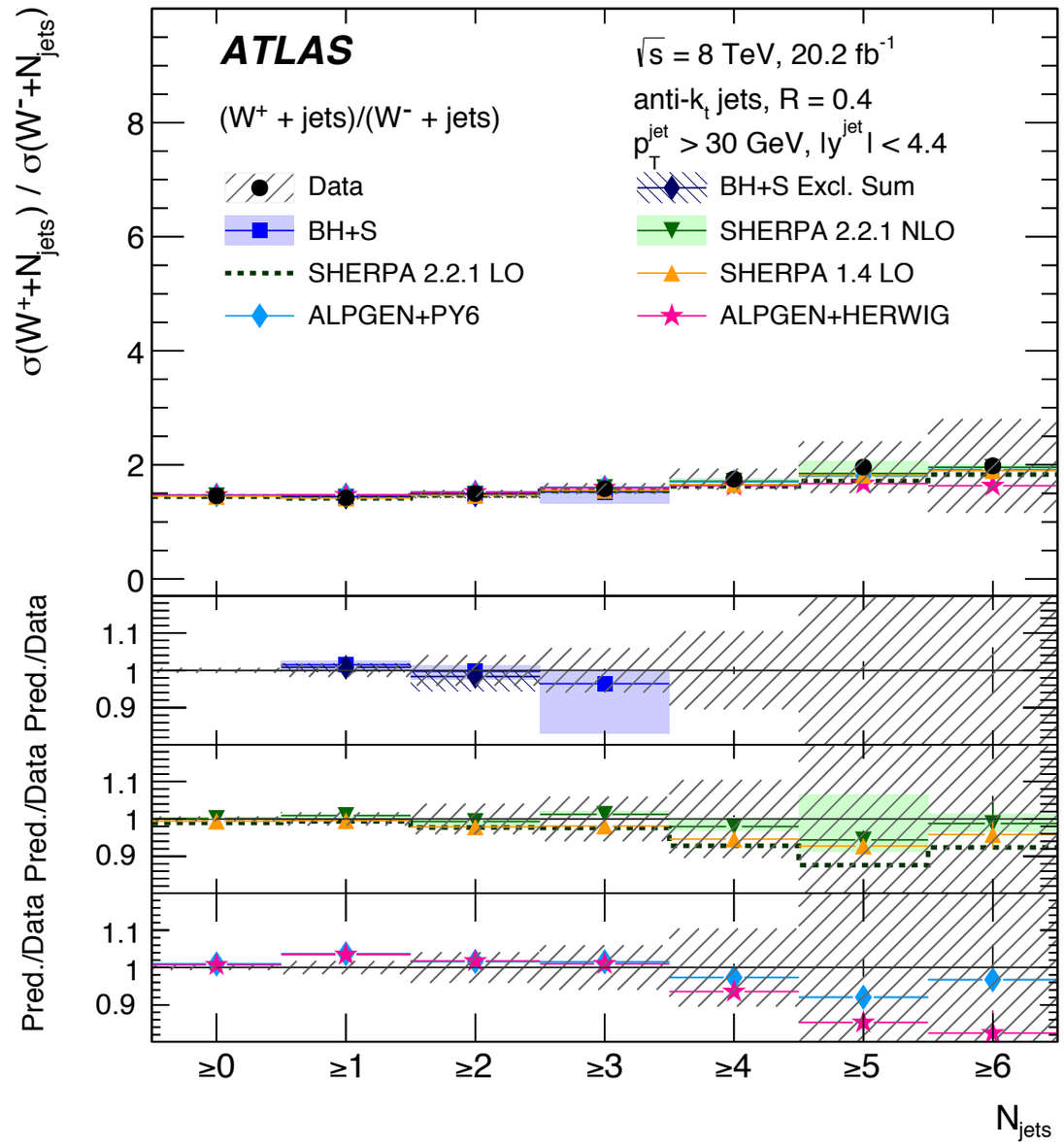
✓ Cross-section ratios of W^+/W^-

Many observables are measured!

Jet multiplicity and ratio

- Comparison to the various theoretical predictions



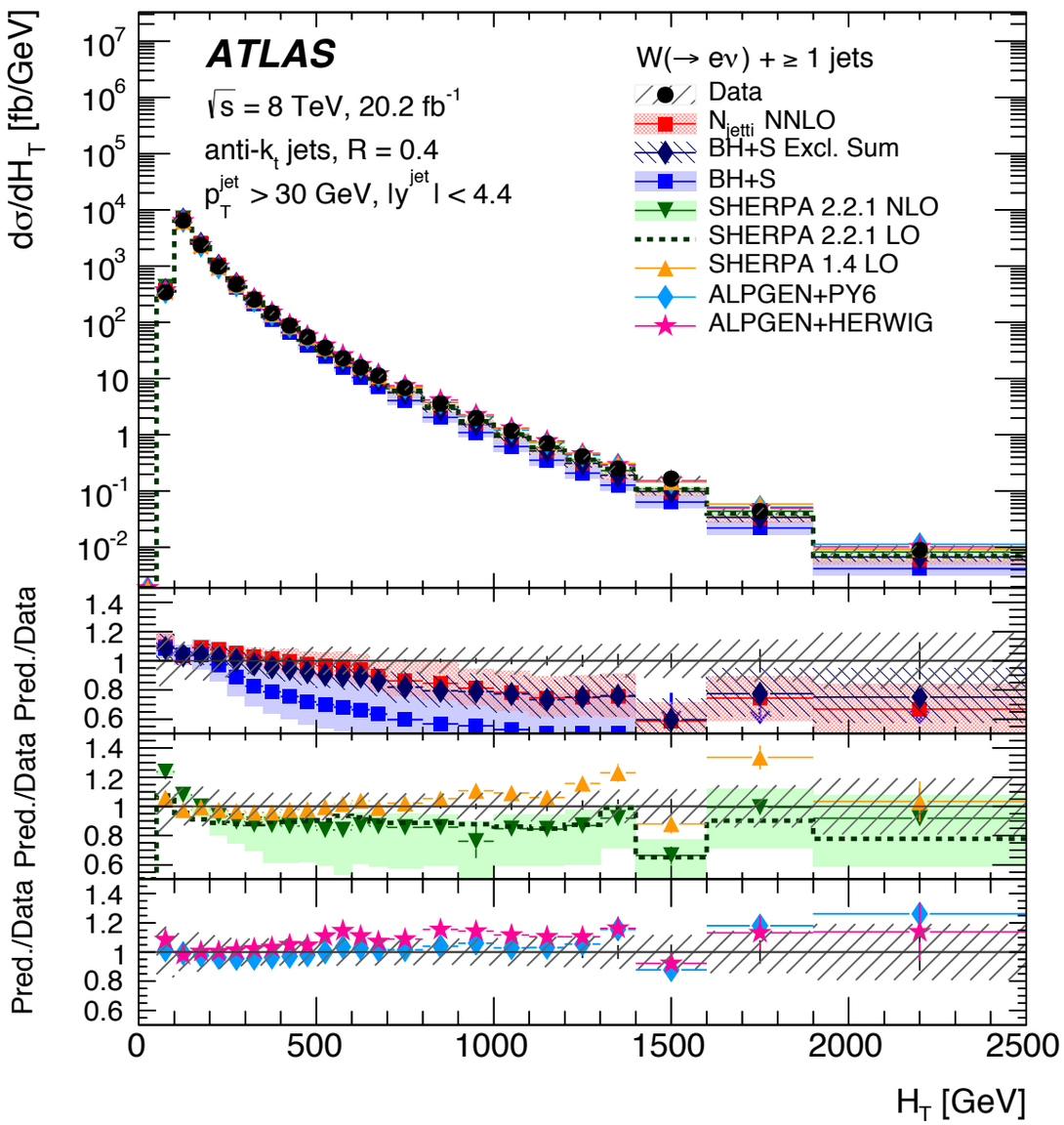


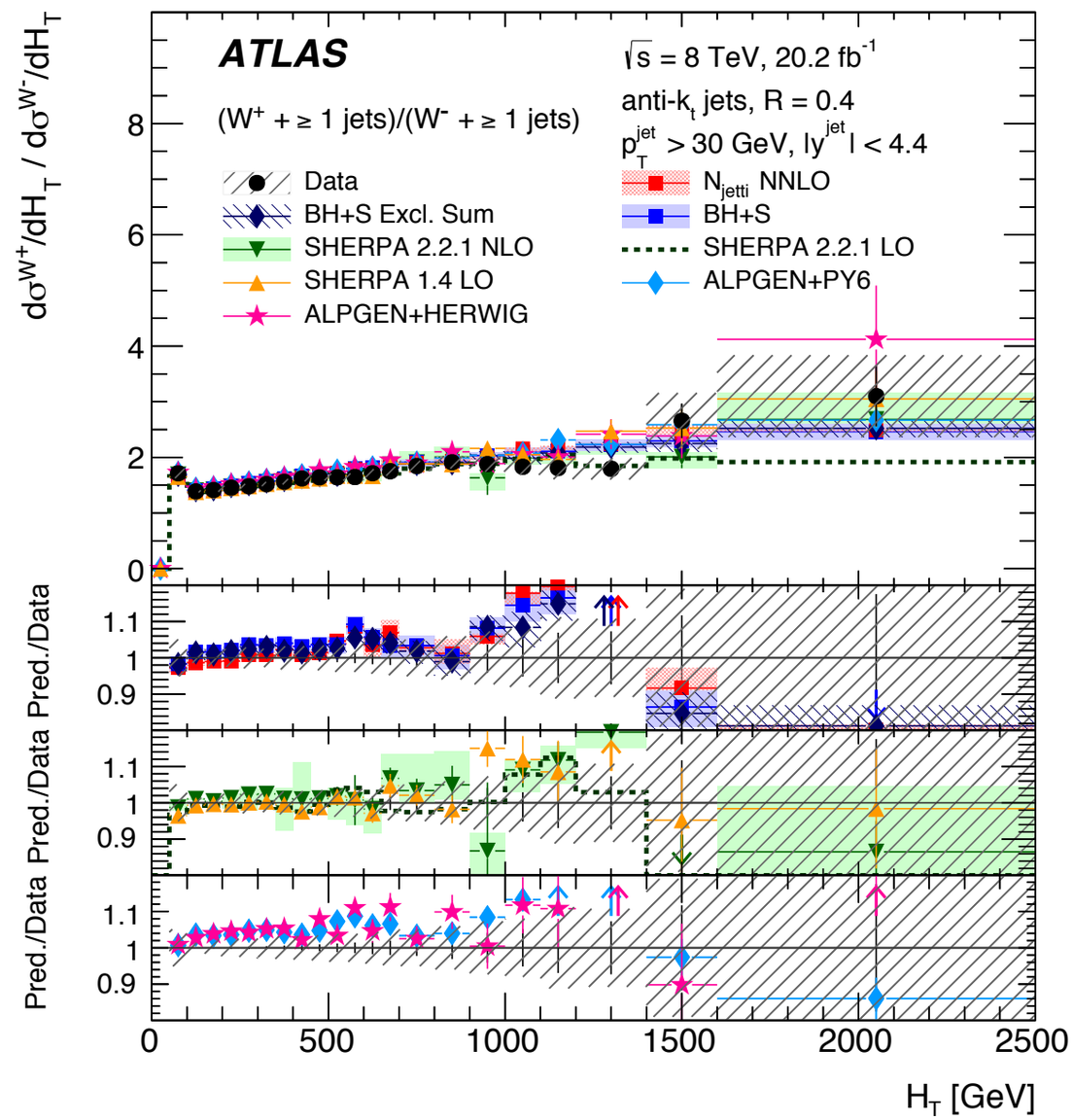
- agree with the predictions within the experimental uncertainties

- agreement improved for the ratio
- mismodelling related to jet emission cancels out

Differential cross section and ratio: $N_{jets} \geq 1$

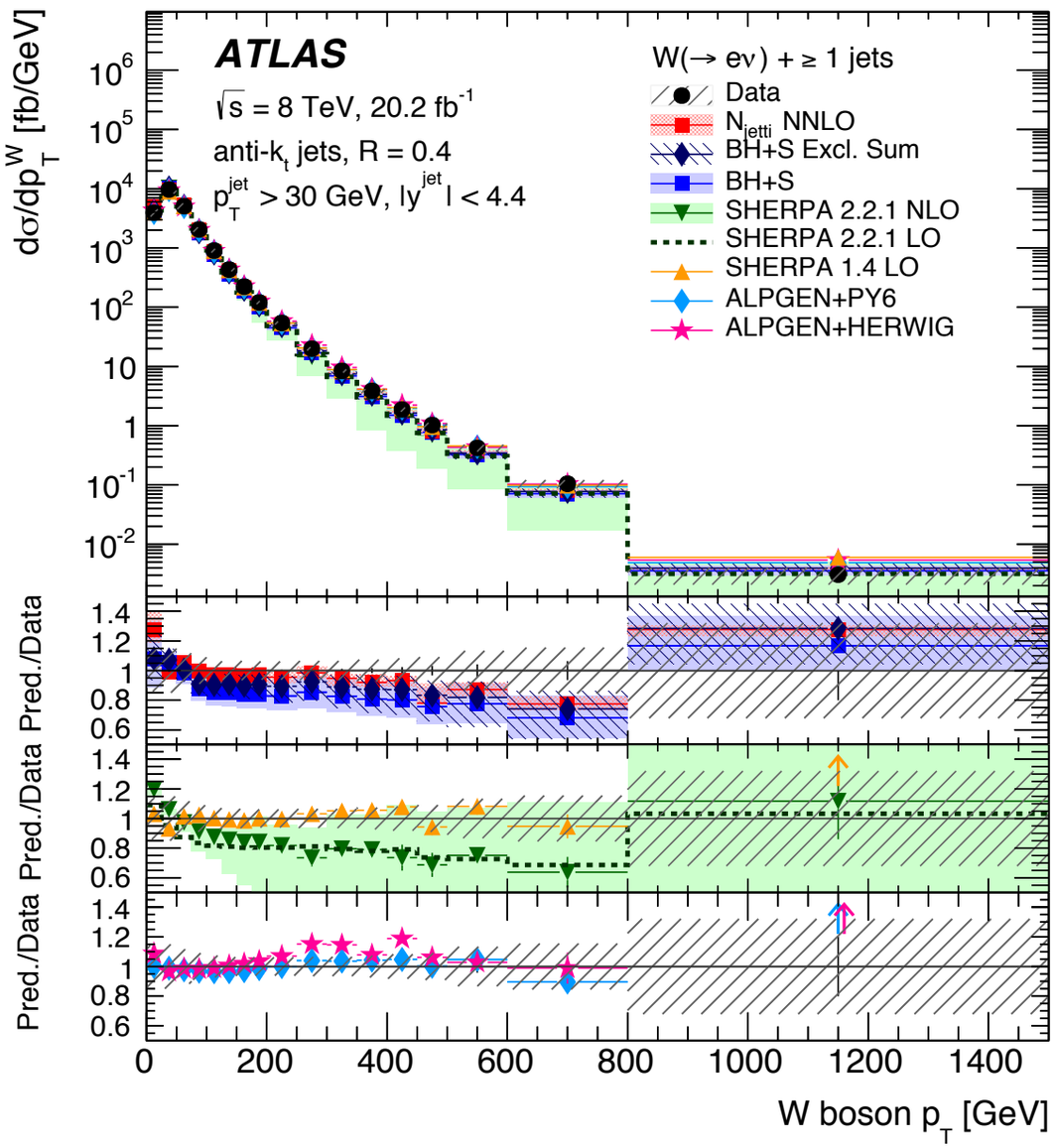
- H_T: scalar sum of the jet, lepton p_T's
  - higher values are sensitive to the higher jet multiplicities and topologies as qq→qq'W

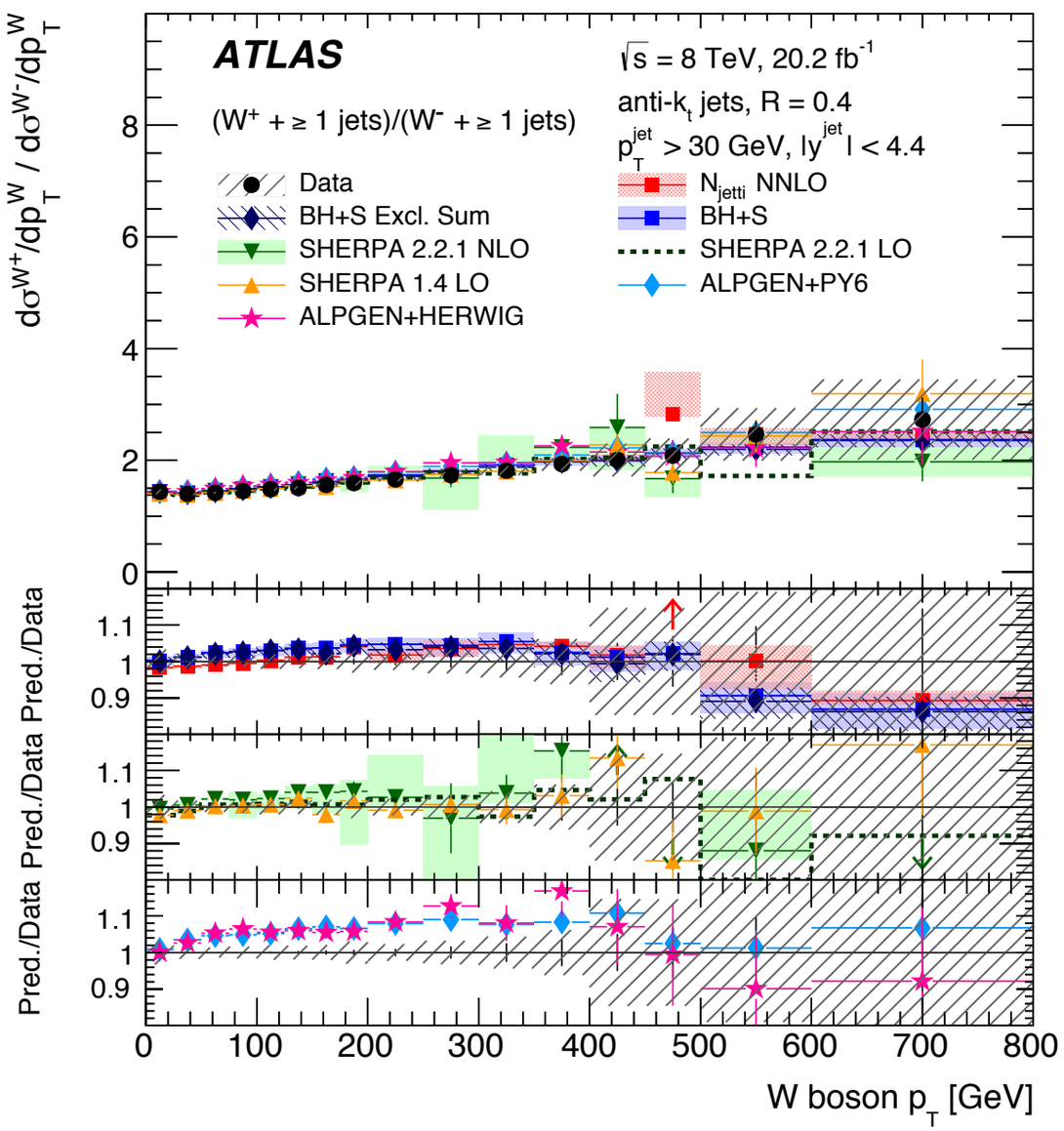




- best agreement with Sherpa and Alpgen (LO) predictions

Differential cross section and ratio: $N_{jets} \geq 1$





- good agreement between the data and most LO predictions and NNLO
- NLO and LO Sherpa 2.2.1 predictions perform worse than LO Sherpa 1.4

- improved experimental precision
- most predictions (except N_{jetti} NNLO and Sherpa 1.4) overestimate the data

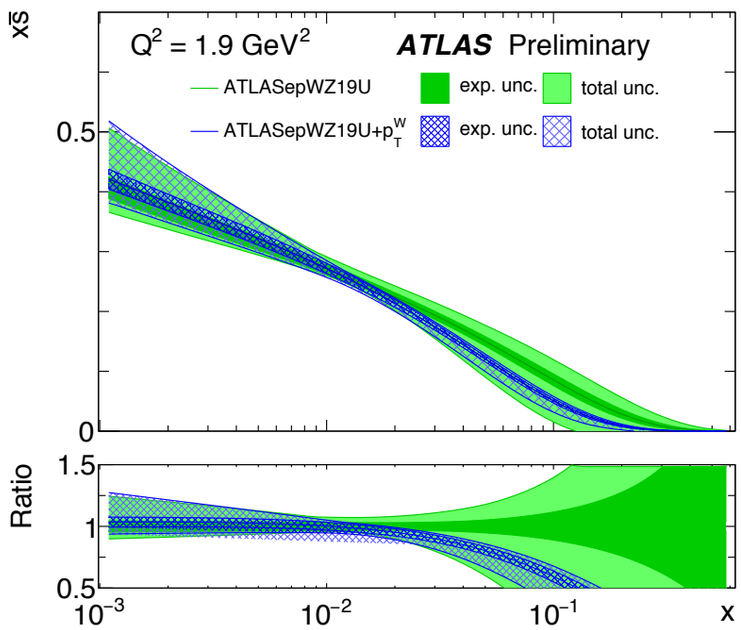
QCD analysis of W+jets data

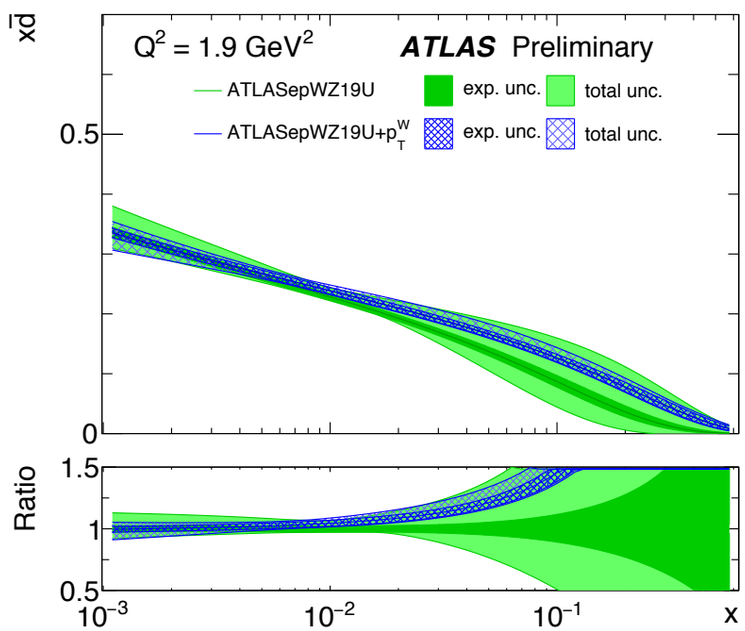
ATL-PHYS-PUB-2019-016

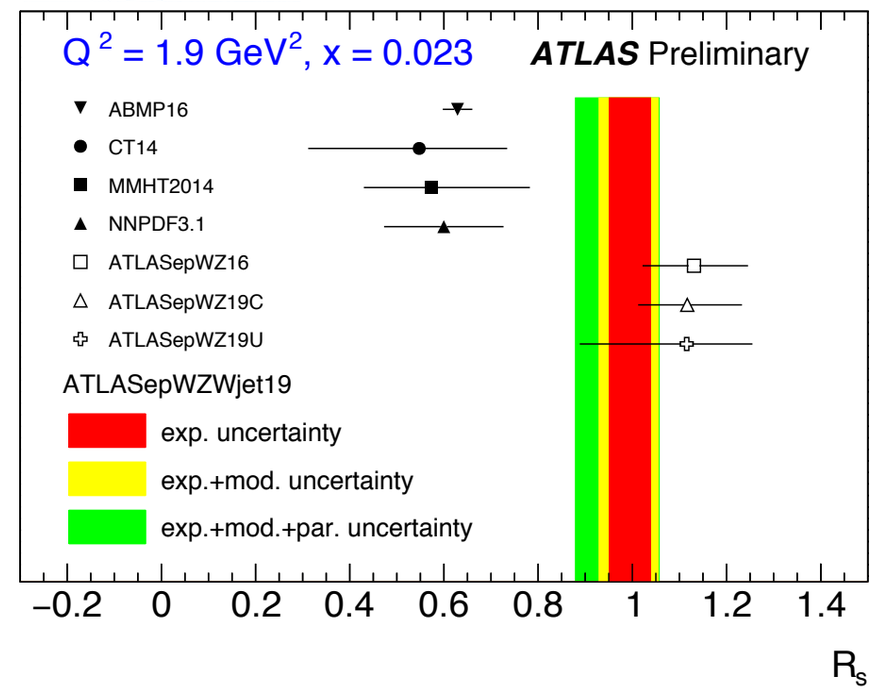
- W+jets probes higher x of partons than W and Z data
  - new input to PDF fits
- W^- and W^+ data (8 TeV) are fitted with datasets used for the previous ATLASepWZ16 fit
- **New PDF set:** ATLASepWZWjets19 (using p^W_T spectrum)

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

strange-quark density







- PDFs obtained for sea quarks
  - improved determination of the high-x sea-quark densities

➡Claire Gwenlan's talk

- confirming the unsuppressed strange-quark density at low $x \lesssim 0.02$
- consistent with previous ATLAS fits

2015, 2.2 fb^{-1}

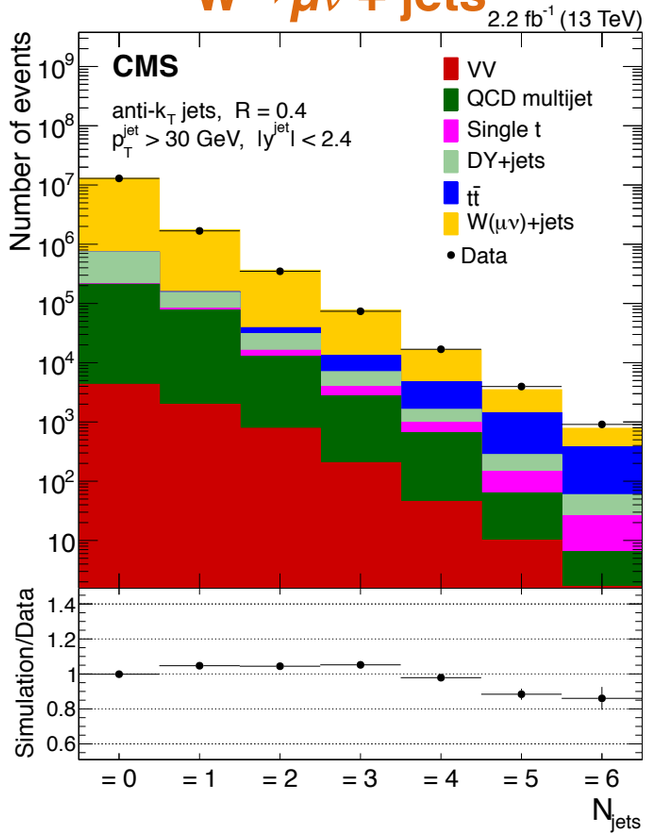
W/Z+jets at 13 TeV

PRD 96 (2017) 072005

Eur. Phys. J. C 78 (2018) 965

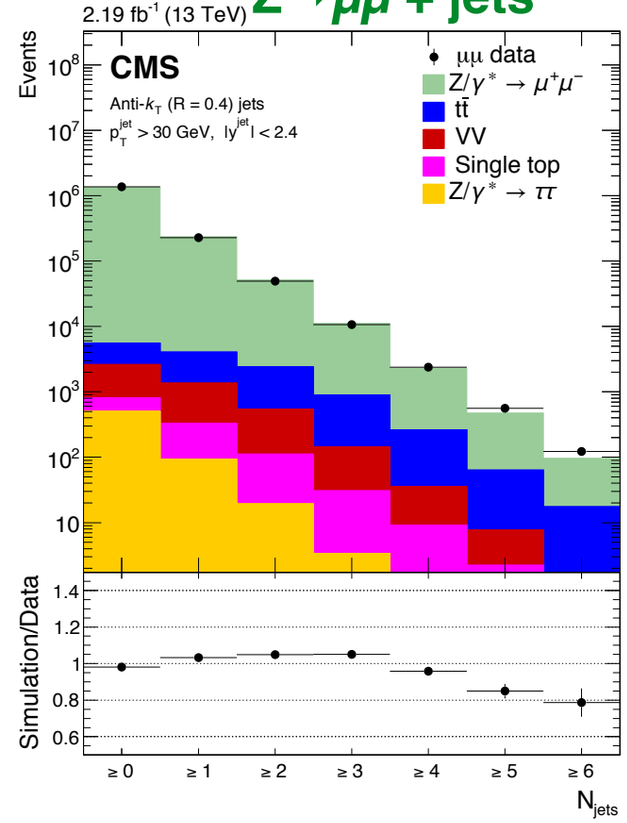
Analyses overview

W→μν + jets



- muon channel
- main background: $t\bar{t}$
- dominant systematic uncertainties:
  - jet energy scale (1–25% for N=1-6) and resolution (1%)
  - measured efficiency (1.2%)

Z→μμ + jets



- electron and muon channels (combined)
- main background: $t\bar{t}$
- dominant systematic uncertainties:
  - jet energy scale (~5% for N=1) and resolution (1%)
  - measured efficiency (2%–4%)

- **Differential cross sections (up to 4 jets)**
  - **p_T, |y|** of the leading jet
  - **$\Delta\phi(\mu,j)$:** azimuthal correlation between the muon and the leading jet
  - **ΔR(μ, closest jet):** angular distance between the muon and the closest jet
  - **H_T**: the scalar p_T sum of the jets

- **Differential cross sections**
  - **jet multiplicity** (up to 6 jets)
  - **p_T of Z**
  - jet kinematics: **p_T**, **y**, **H_T** (up to 3 jets)
  - **p_T^{bal}:** balance between the Z boson and jet transverse momenta
  - **JZB**: jet-Z balance

Theoretical predictions for W/Z+jets

- **MC multileg LO ME+PS**: MadGraph5_aMC@NLO generator
  - k_T- MLM merging scheme
  - interfaced with PYTHIA8 using NNPDF2.3 (LO) and NNPDF3 (LO) PDFs
  - up to N = 0..4 jets in the final state

LOMG_aMC

- **MC multileg NLO ME+PS**: MadGraph5_aMC@NLO generator
  - FXFX jet merging scheme
  - interfaced with PYTHIA8 using NNPDF2.3 (LO) and NNPDF3 (NLO) PDFs
  - NLO accuracy for N = 0,1,2 partons and LO accuracy for N = 3, 4

NLOMG_aMCFxFx

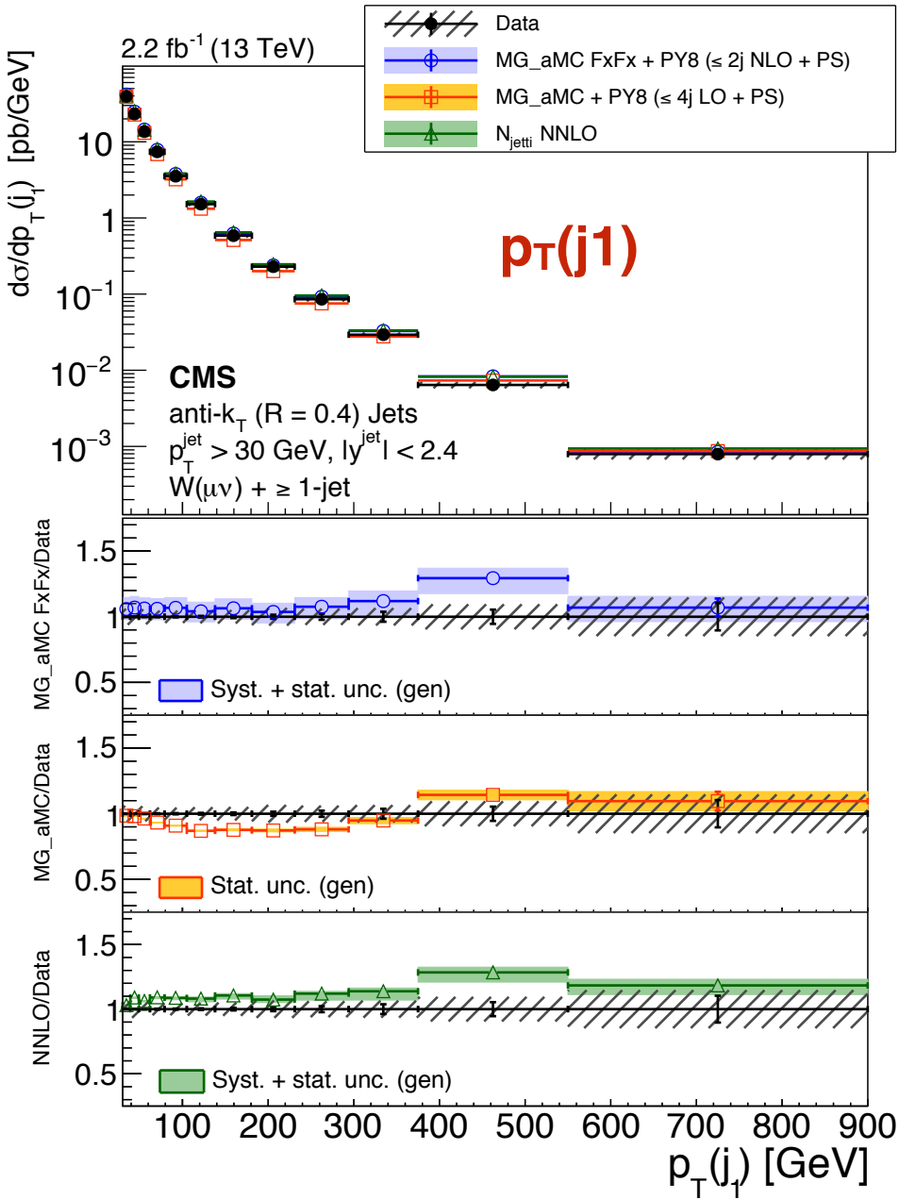
- **NNLO+NNLL**: Geneva1.0-RC2 MC using PDF4LHC15 (**for Z**)
  - combined with parton showering and hadronization provided by PYTHIA8

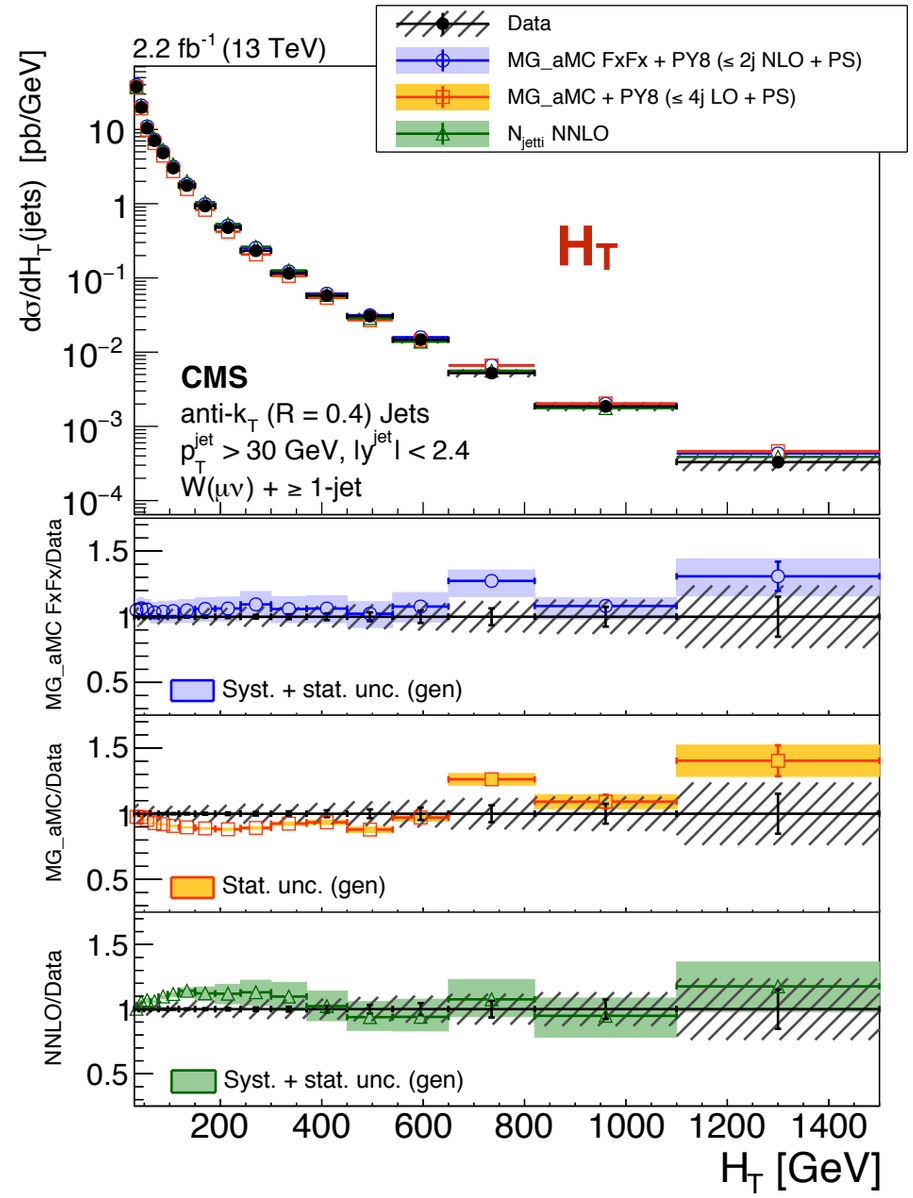
GE

- **Fixed-order NNLO** calculations for V+1jet
  - N-jettiness subtraction scheme using CT14
    - non perturbative correction from MadGraph5_aMC@NLO+ PYTHIA8

N_{jetti} NNLO

W+jets at 13 TeV

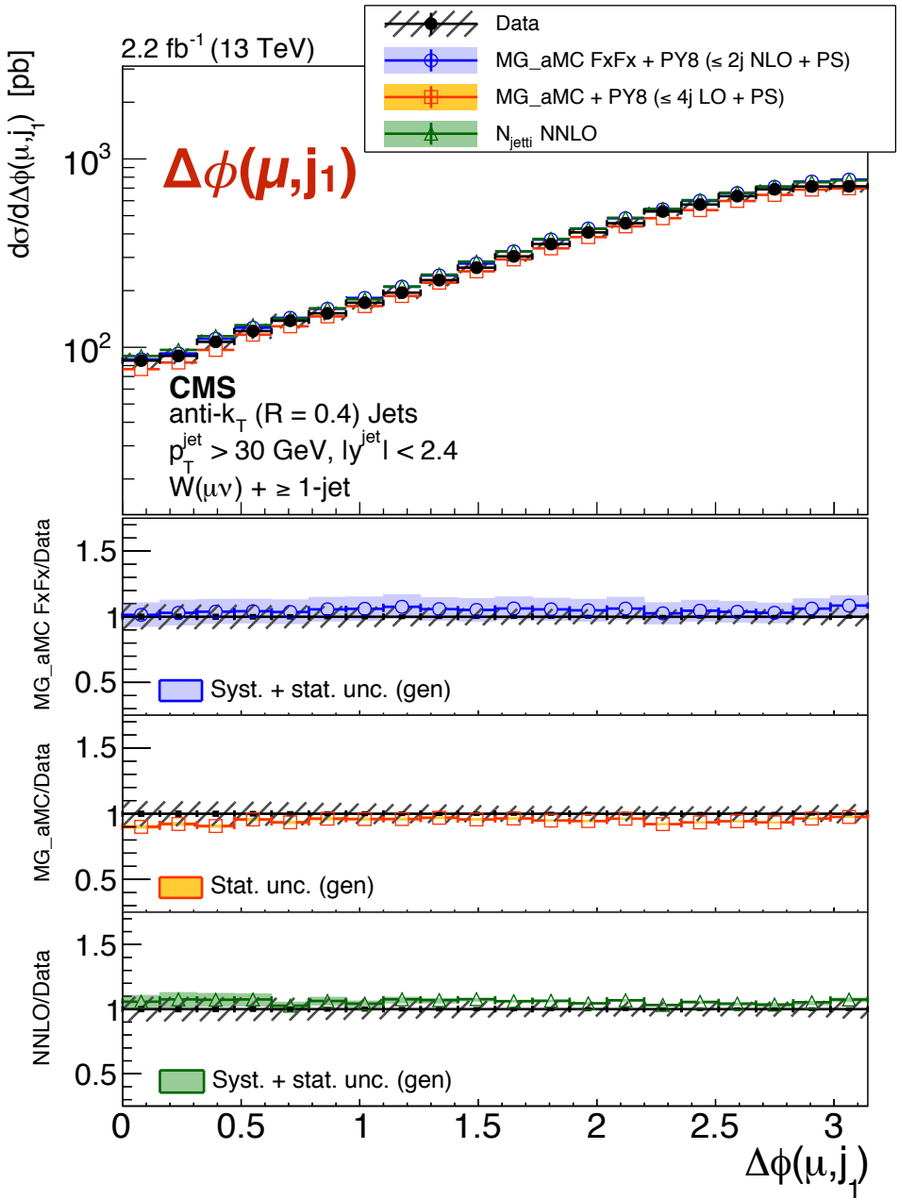


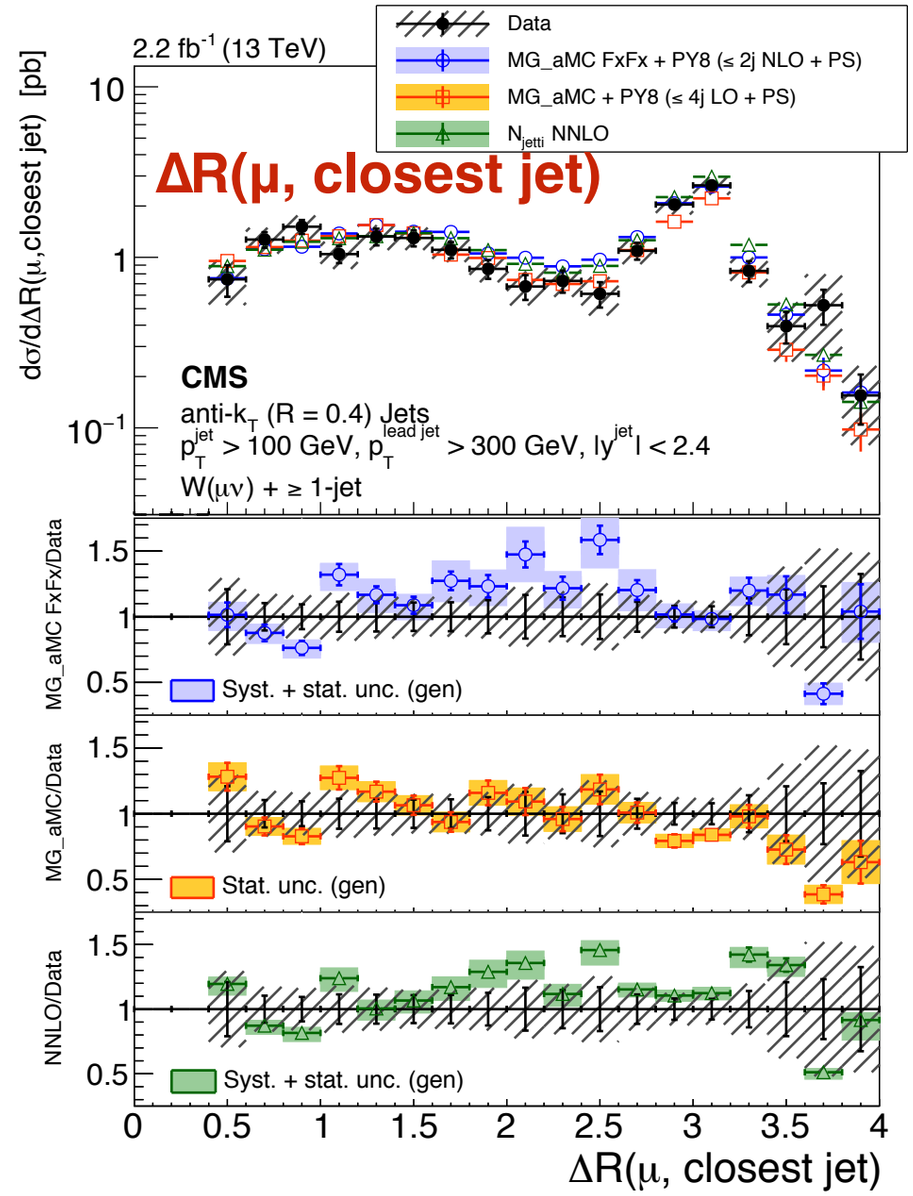


- **NLO MG_aMC FxFx:** good agreement
- **Njetti NNLO:** best agreement for W ≥1jet
- **LO MG_aMC:** underestimates the data at low jet p_T

- predictions are in good agreement with data
  - exception: underestimation at low p_T by **LO MG_aMC**

W+jets at 13 TeV

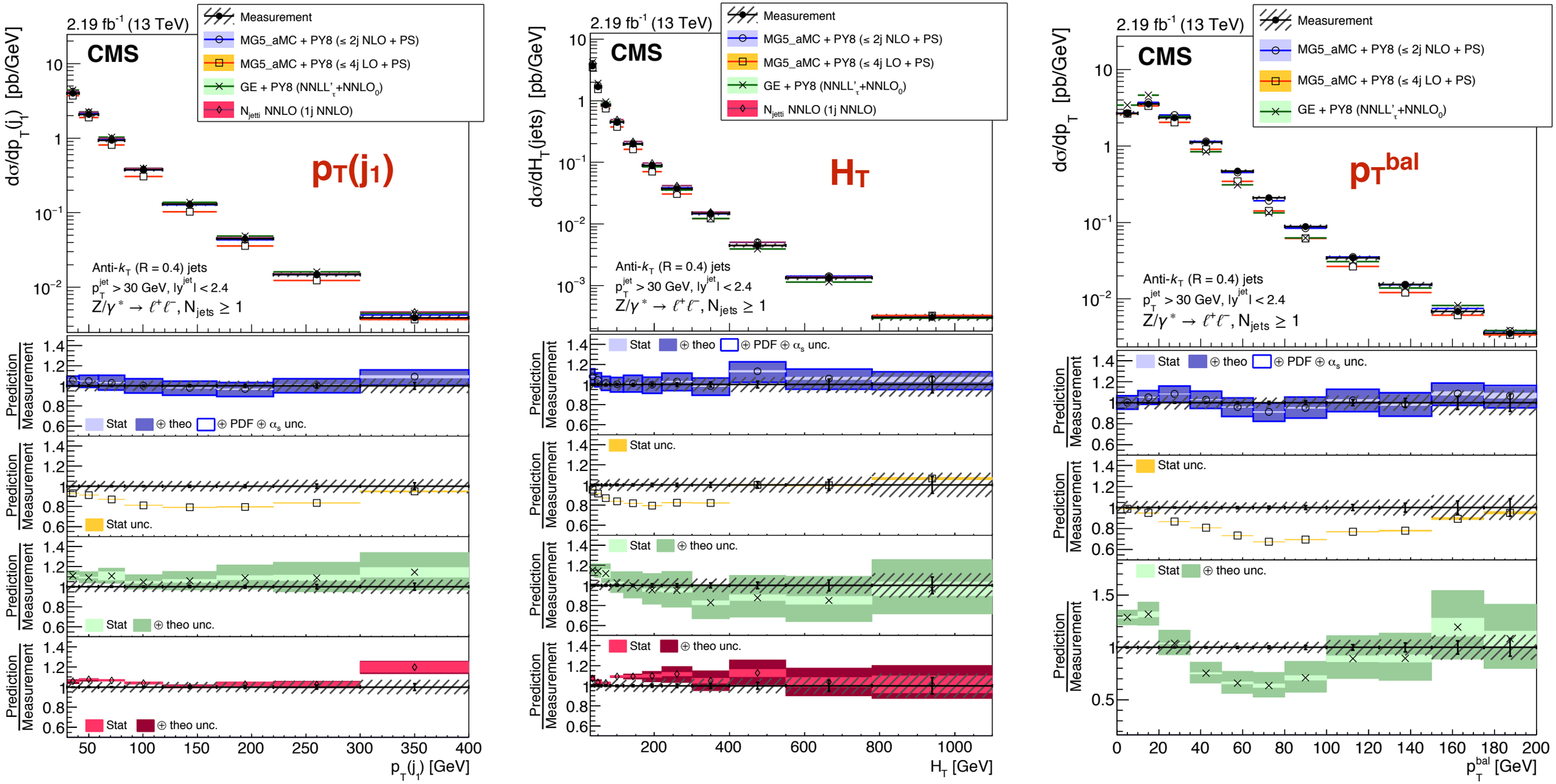




- predictions describe data within uncertainties

- fairly good agreement with data
  - within the uncertainties
- **LO MG_aMC**: underestimates the data in the high-ΔR region

Z+jets at 13 TeV



- **NLO MG5_aMC** and **NNLO**: the best description
- **GENEVA**: good agreement for the 1st jet
- **LO MG5_aMC**: not describing well

2012, 19.9 fb^{-1}

Z+jets at 8 TeV

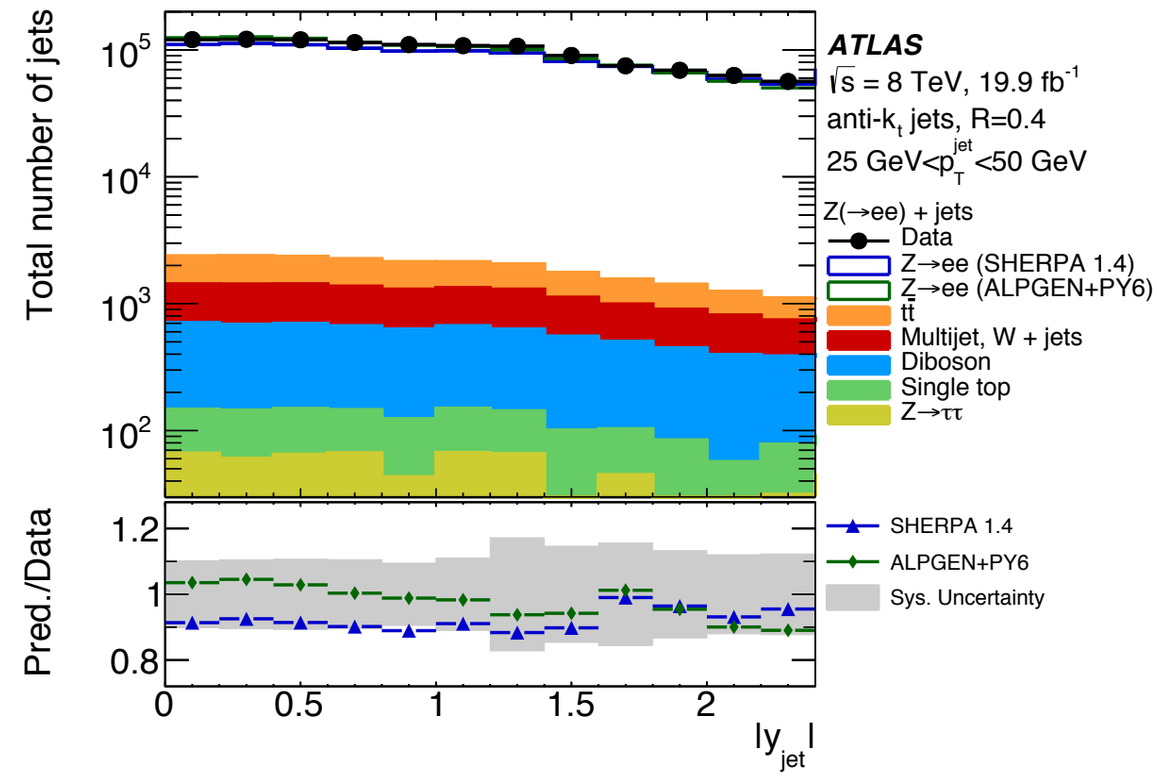
arXiv:1907.06728

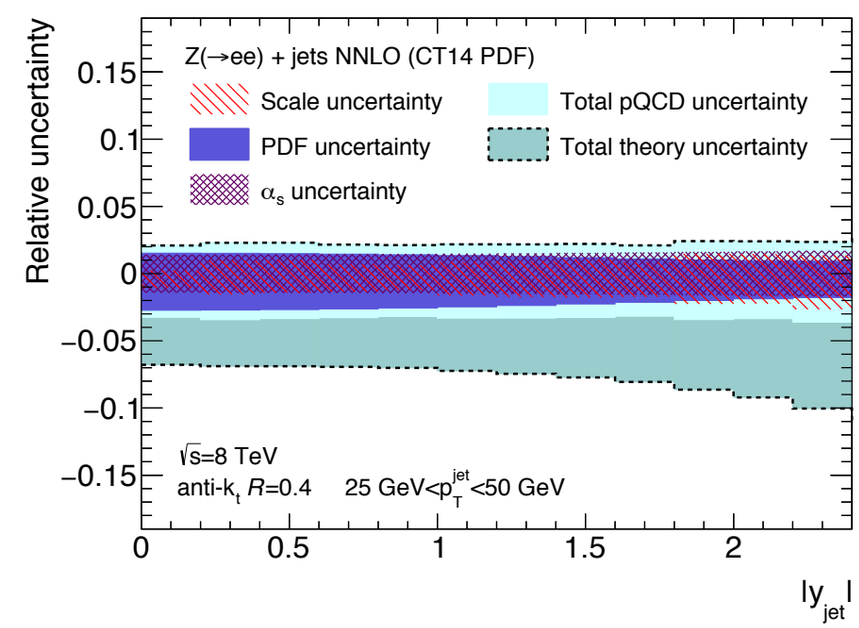
NEW

Analysis overview

- Based on the electron channel
- Main background: $t\bar{t}$ (within 3%)
- Dominant systematic uncertainties:
  - jet energy scale: 3–10% in the first bin of p_T and reduces to 0.5–3% in larger bins
  - jet energy resolution in the first bin: ~6%
  - unfolding uncertainty: 2–5% in p_T^{jet} < 100 GeV

- **Fixed order predictions:**
  - **NLO**: calculated using MCFM interfaced to APPLgrid
    - different PDF sets
    - total uncertainty: 8–10%
  - **NNLO**: provided by A. Gehrmann-De Ridder et al.
    - total uncertainty: 2–5%.
  - QED radiation and non-perturbative corrections
  - total uncertainty includes: scale, PDF, α_S, unc. from the non-perturbative and QED radiation effects

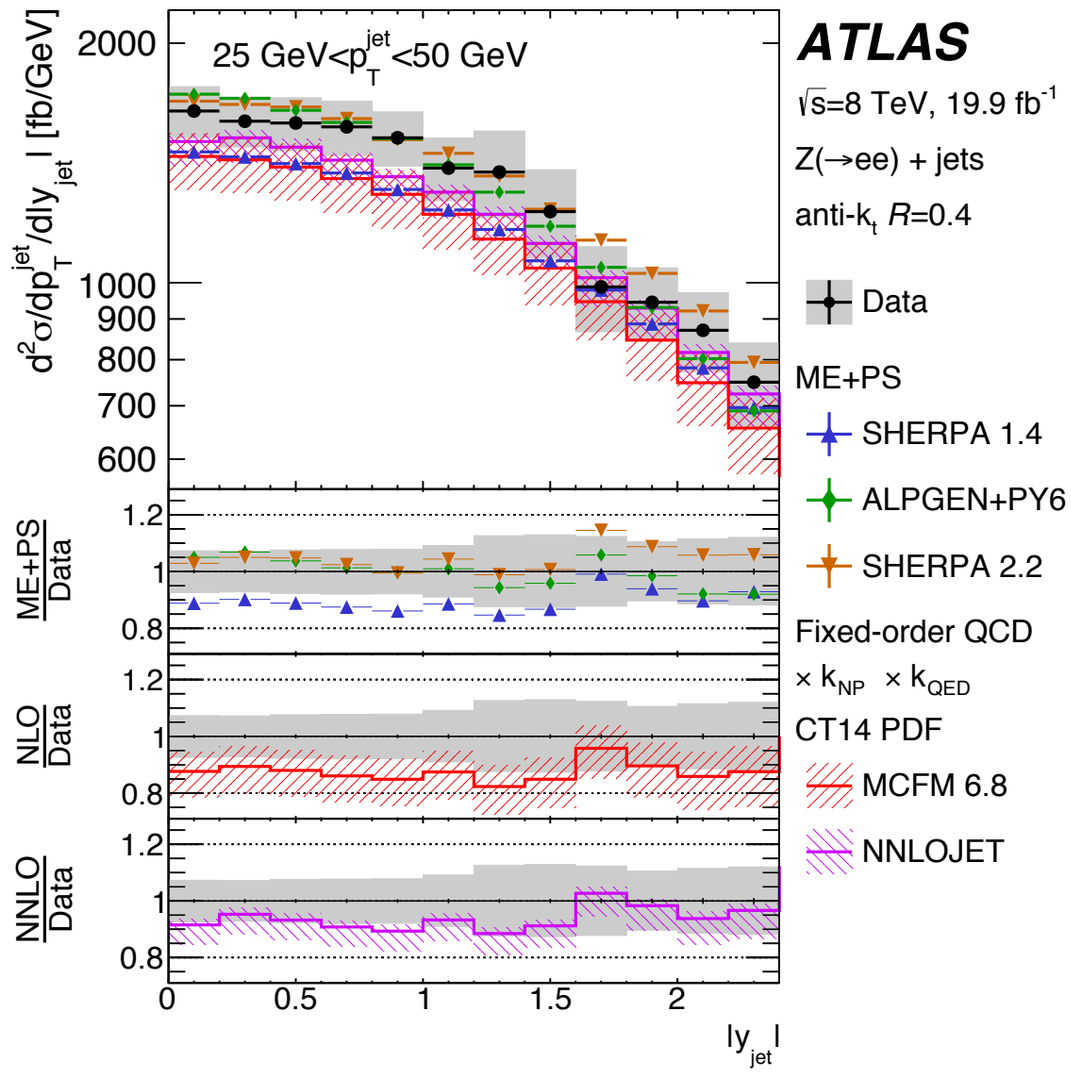


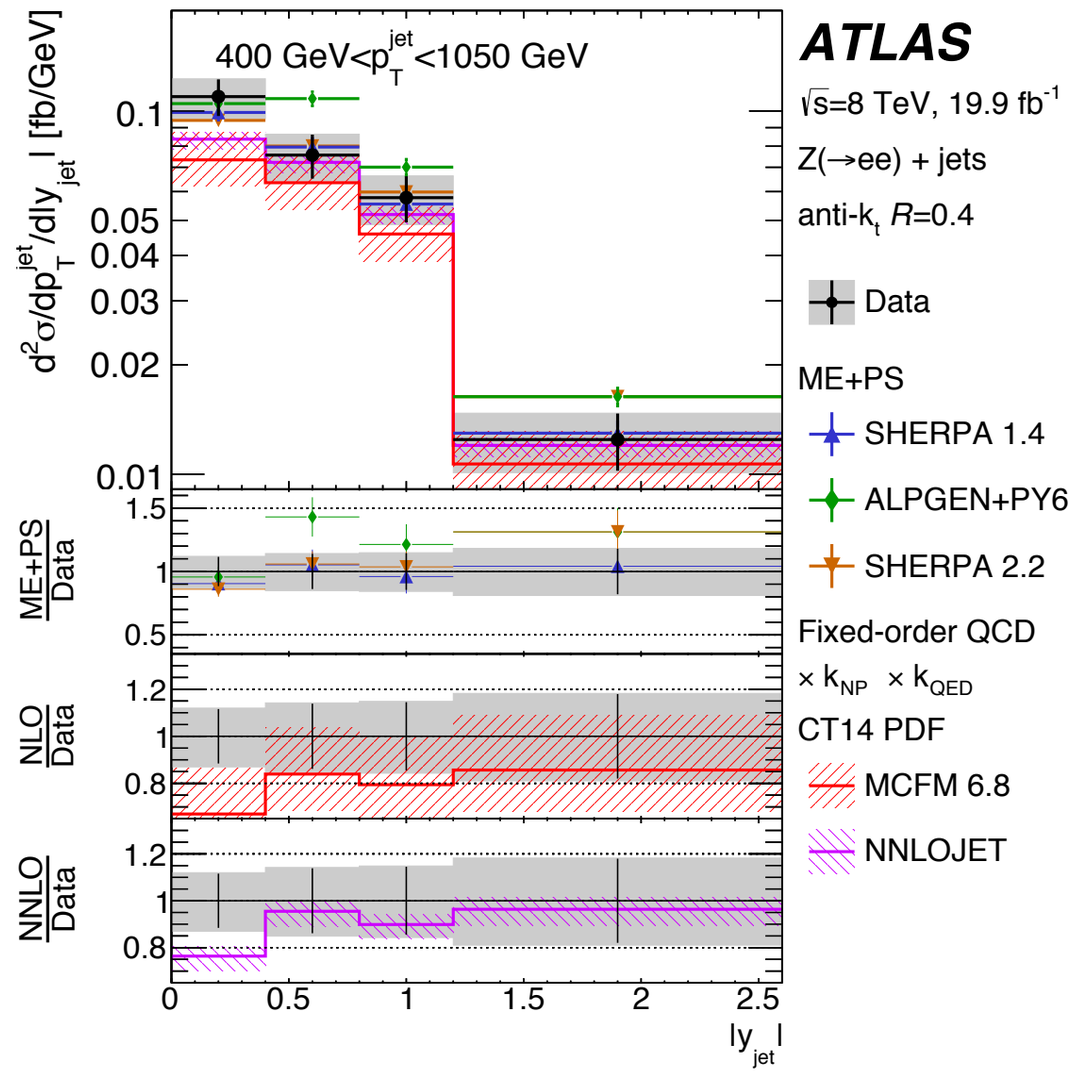


✓Double differential cross sections:

✓as function of $|y_{jet}|$, p_T^{jet}

Differential cross sections

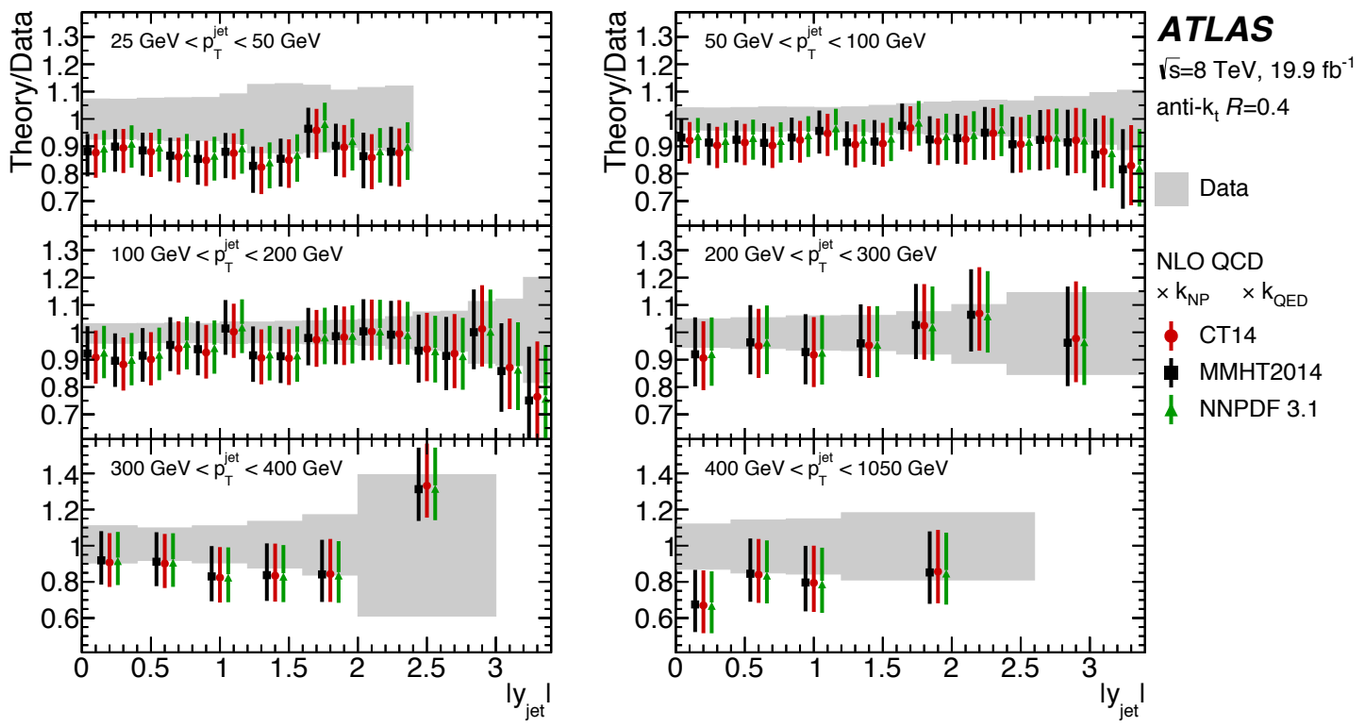


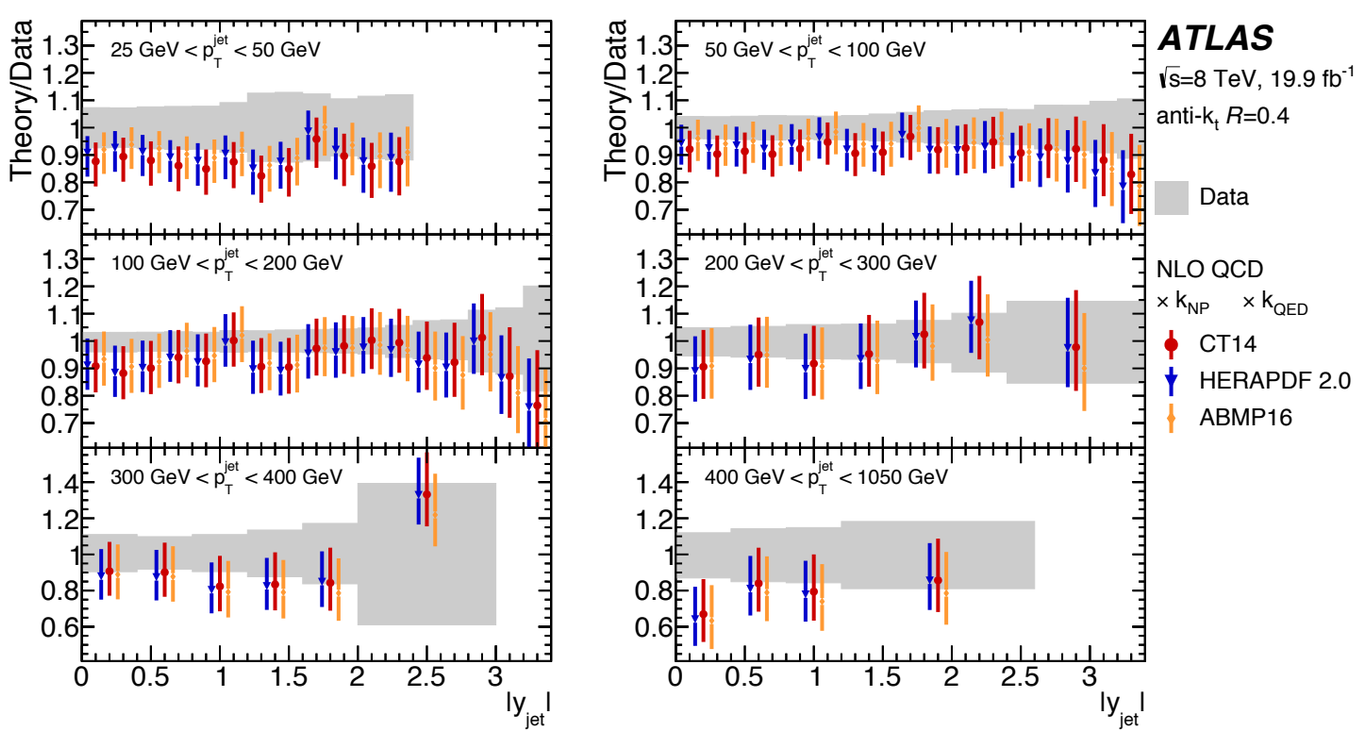


- **NLO** predictions: lower than data by ~5–10%
  - difference covered by the uncertainties
- **NNLO** predictions: better agreement
- **Sherpa 1.4**: lower than data by about 10% in the low region and few % in the high region

- **Alpgen+Pythia:** agree with data up to p_T^{jet} =100 GeV
  - the biggest difference in the largest p_T^{jet} bin: ~20%

Comparison between different PDF sets





NLO predictions with different PDFs:

- **MMHT2014 & NNPDF3.1:**
  - 1–2% larger cross-sections in comparison to those using the CT14 PDF.

- **ABMP16 & HERAPDF2.0:**
  - 3–5% are larger in the $|y_{jet}| < 2.0$ and $p_T^{jet} < 100$ GeV
  - up to 5% lower in other bins with respect to CT14

- Differences between the cross-sections calculated at NLO accuracy with various PDF sets:
  - covered by the theoretical uncertainties

2015, 2.26 fb^{-1}

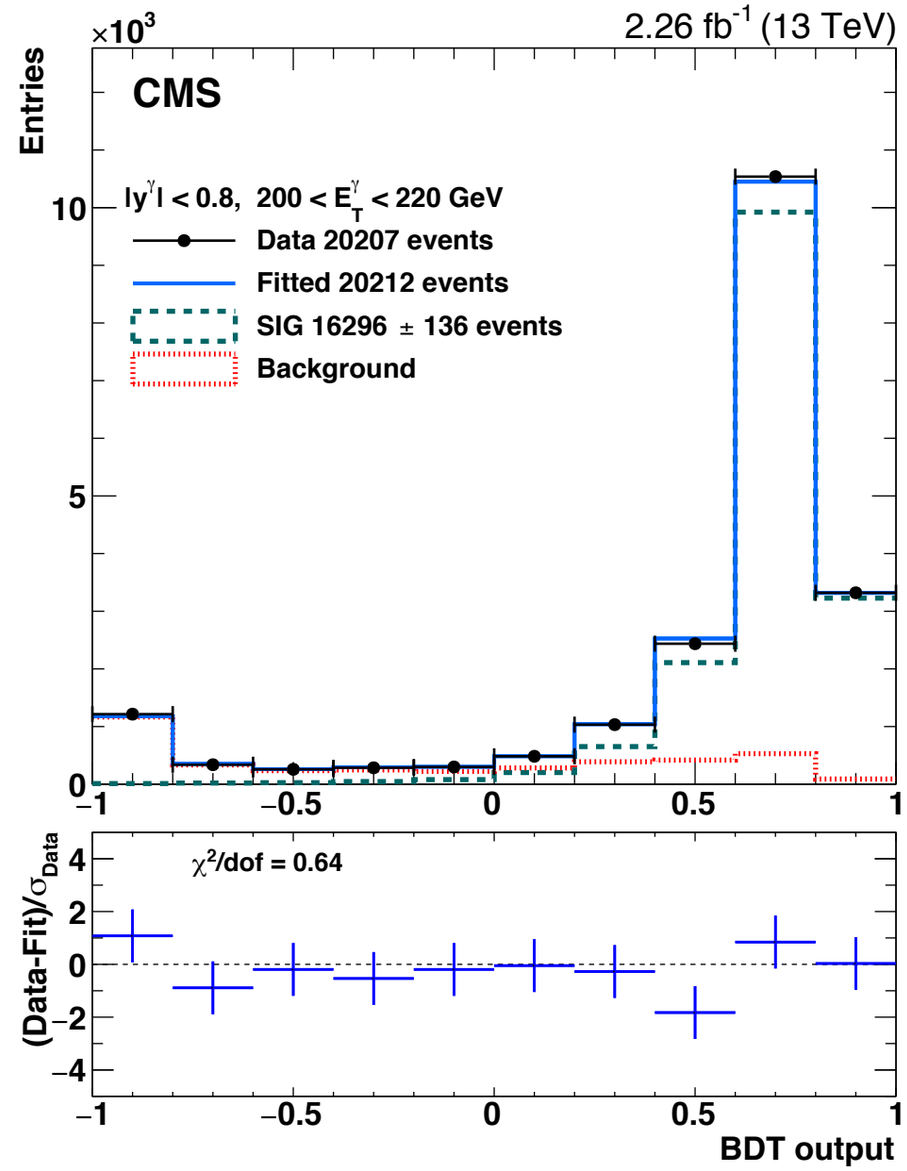
γ+jets at 13 TeV

Eur. Phys. J. C 79 (2019) 20

γ+jets production at 13TeV

- **Signal extraction:**
  - BDT based on photon (kinematic + shower shape) variables
  - signal BDT template: γ+jets MC (Pythia8), validated with Z→ee, Z→μμ

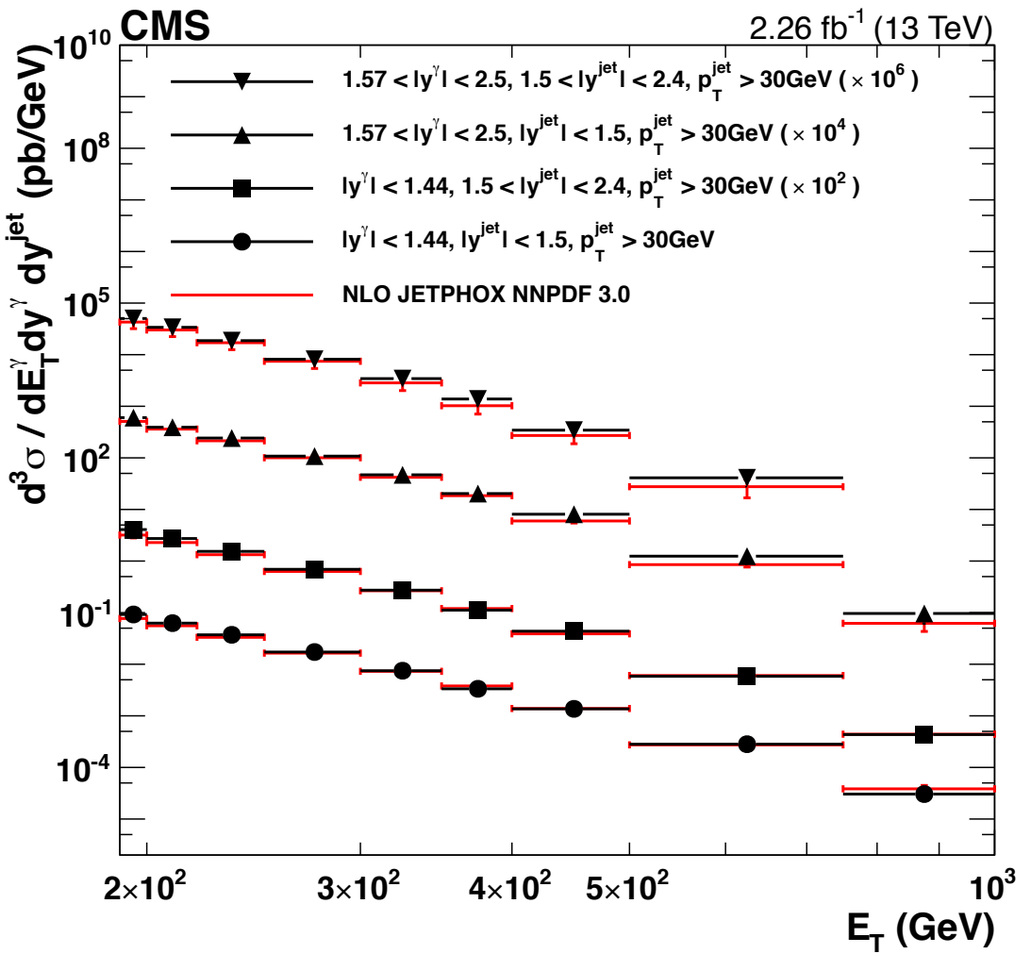
- **Theoretical predictions:**
  - NLO: JETPHOX 1.3.1 generator, NNPDF3.0 PDFs and the Bourhis-Fontannaz-Guillet (BFG) set II parton fragmentation functions
  - photon E_T used as the scale
  - total uncertainty includes:
    - the scale, PDF, α_S, and underlying event and parton shower uncertainties

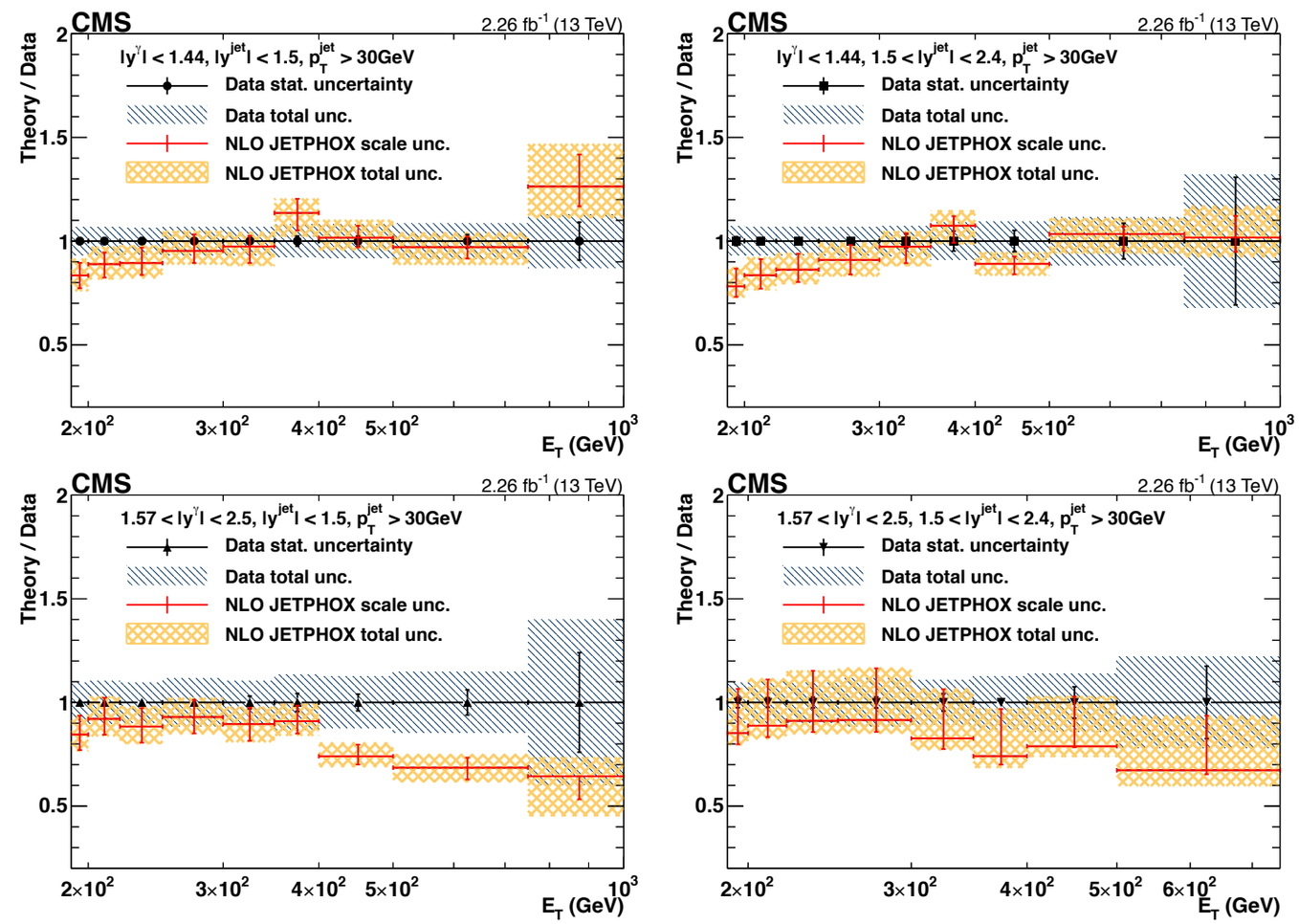


✓ Differential cross sections as a function of the photon E_T

➡Hugues LATTAUD's talk

γ+jets production at 13TeV





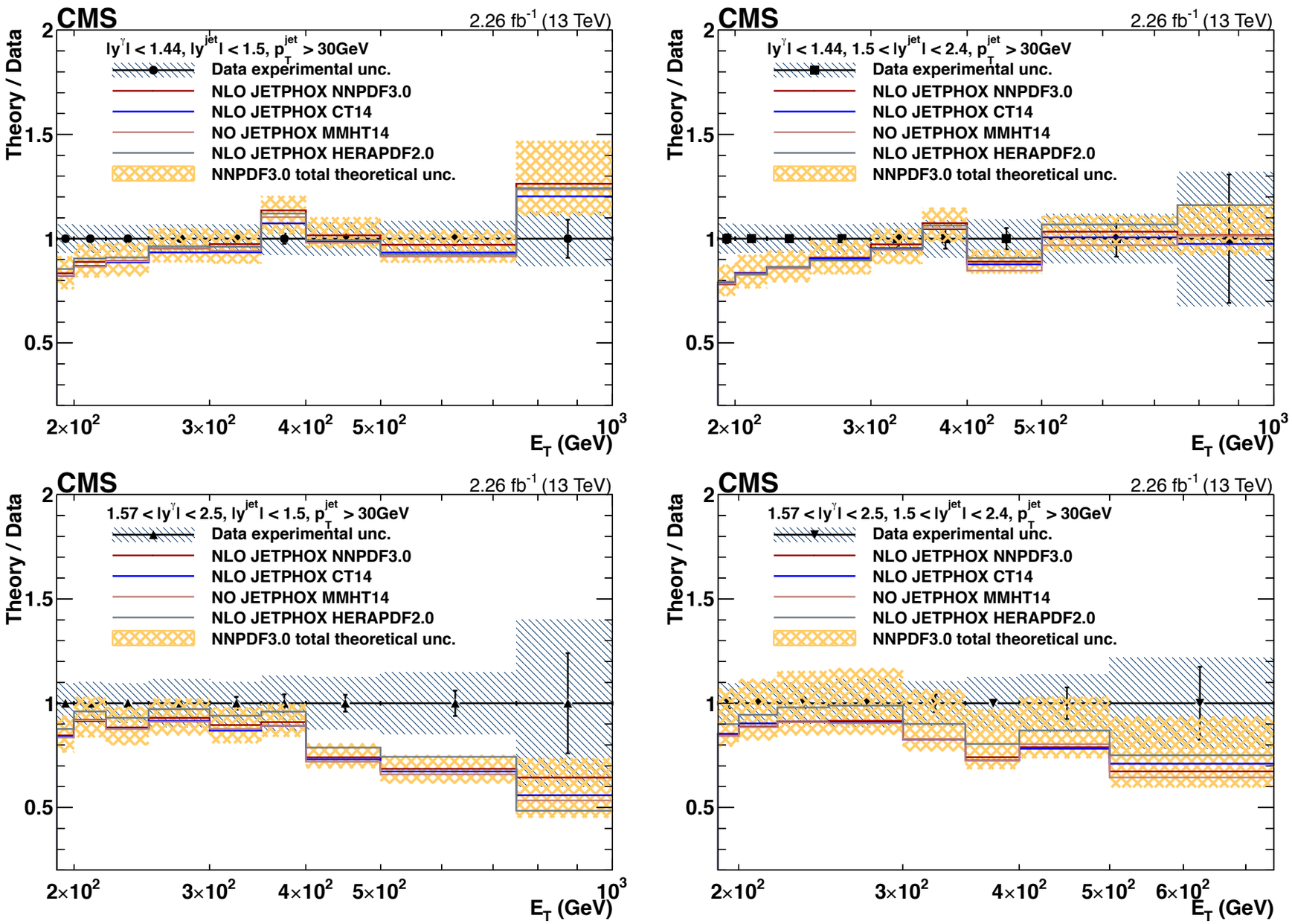
- Comparison between the cross sections and NLO pQCD calculations
  - in two photon rapidity and two jet rapidity bins
  - extended the photon E_T range up to 1 TeV

- The ratio of the theoretical predictions to data
  - agreement within statistical and systematic uncertainties
  - low to middle range in photon E_T: the experimental uncertainties are smaller or comparable to theoretical uncertainties

✓ **Experimental input to improve gluon PDF**

γ+jets production at 13TeV

- Comparison between data and predictions using different PDF sets:



- The ratio of the theoretical predictions to data:
  - differences are small
  - within the theoretical uncertainties estimated with NNPDF3.0

Summary

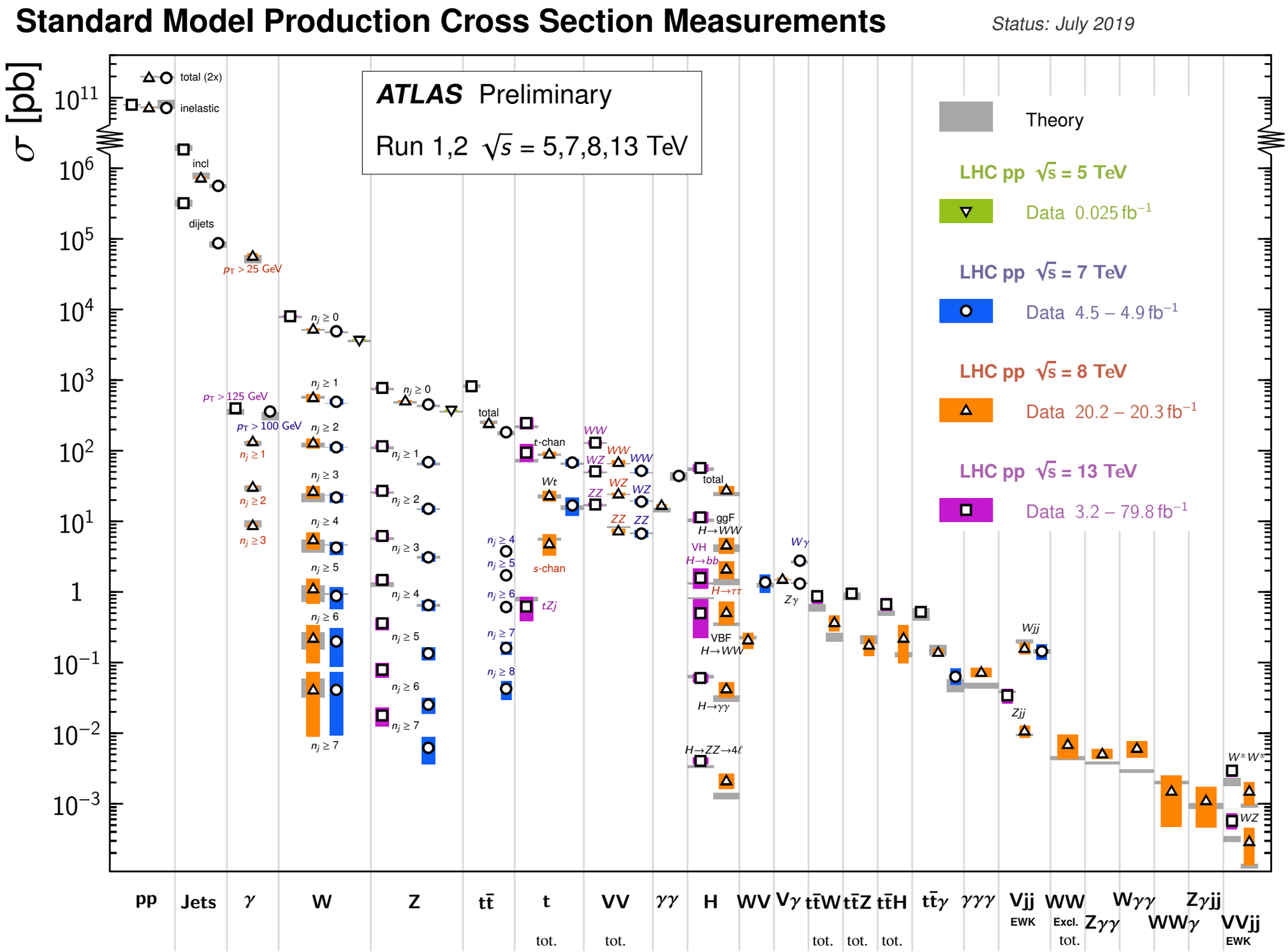
- Plenty of measurements of differential cross sections provided by ATLAS and CMS collaborations
  - covering different centre-of-mass energies
  - many observables are studied
  - compared to the theoretical predictions
- Theoretical calculations reached (NNLO) QCD precision for V+1jet and (NLO) for four and five jets
  - overall good agreement between predictions and data (NLO and NNLO)
- Measurements provide valuable input for a better understanding of
  - perturbative QCD
  - SM predictions
  - PDFs of the proton
- Cross section ratios bring the high precision of the measurements

➡ **More V+jets measurements are available at:**

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
- http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

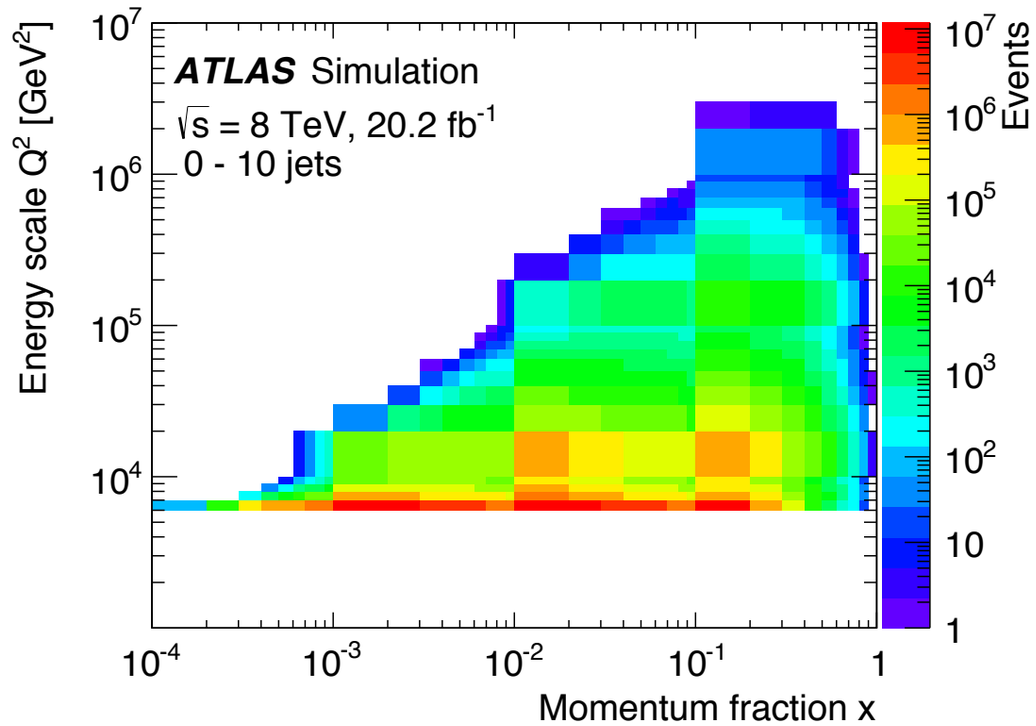
Backup

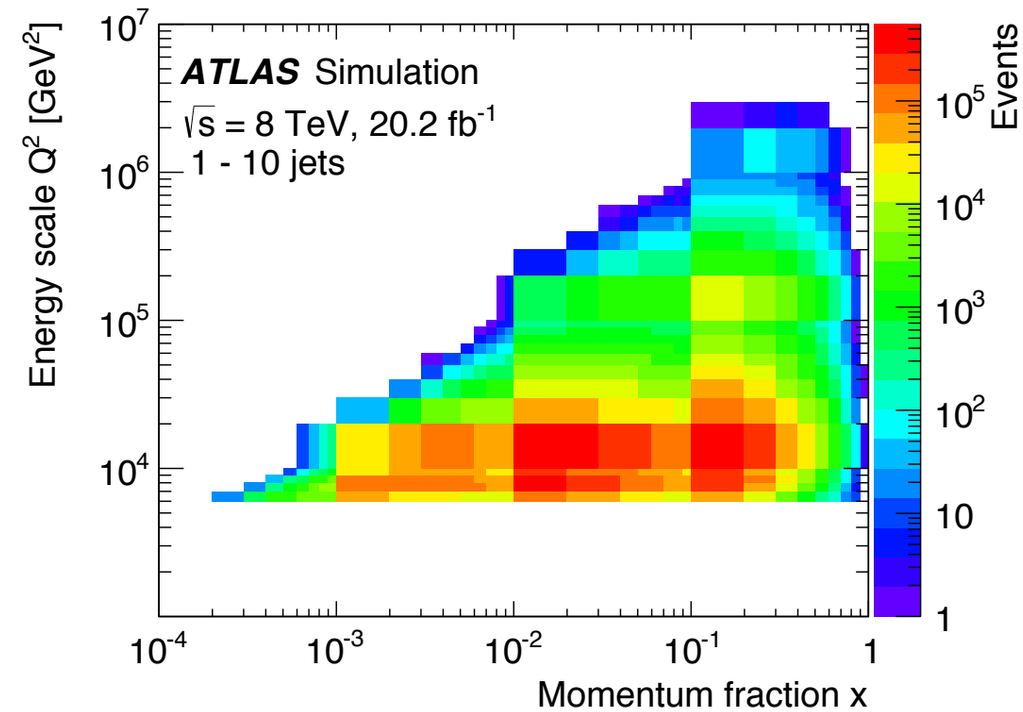
ATLAS Result Summary

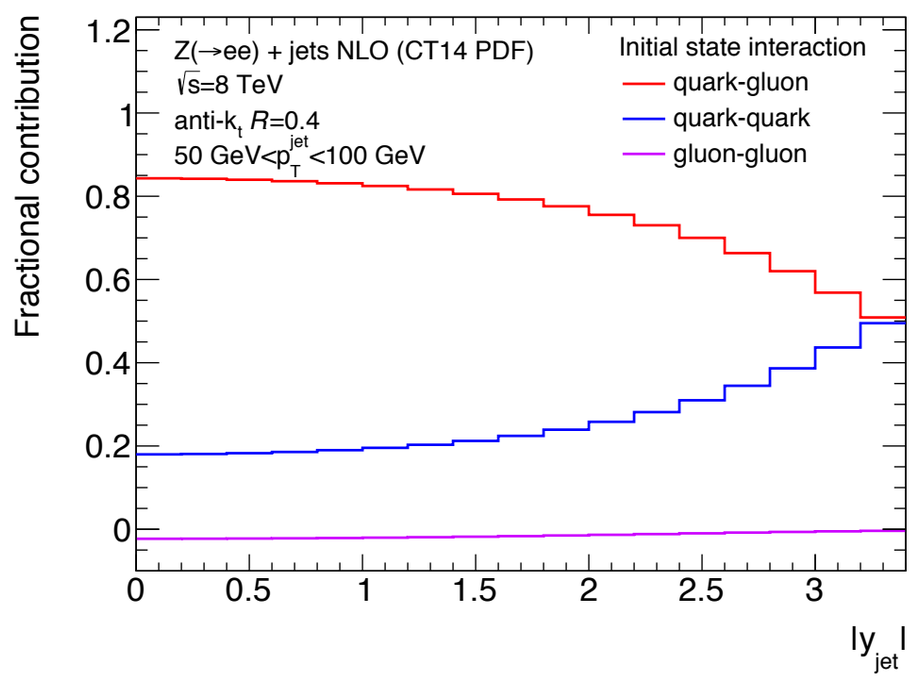


PFD sensitivity

- Including jet increases sensitivity at higher x and Q^2





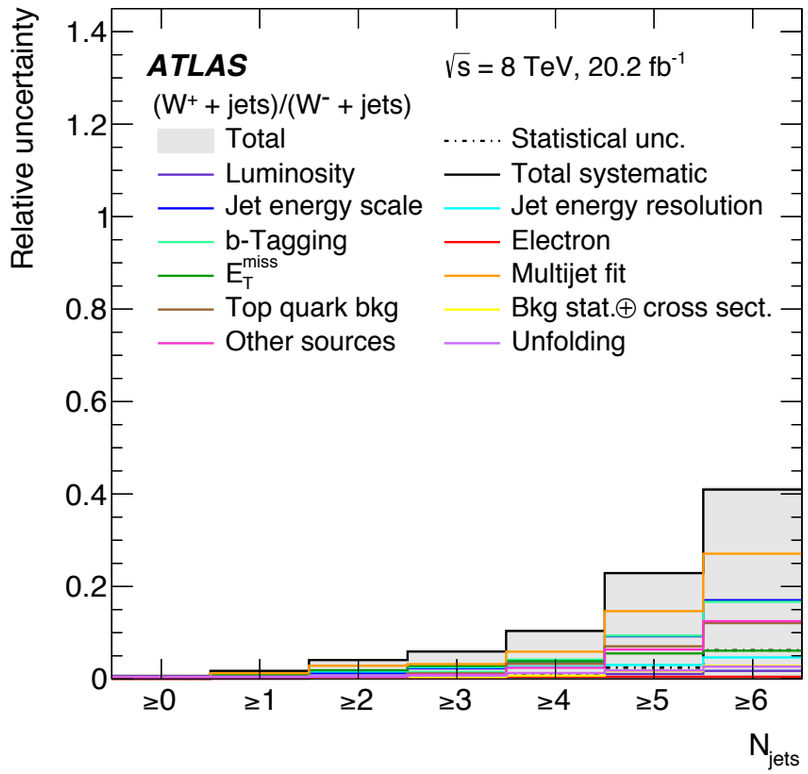


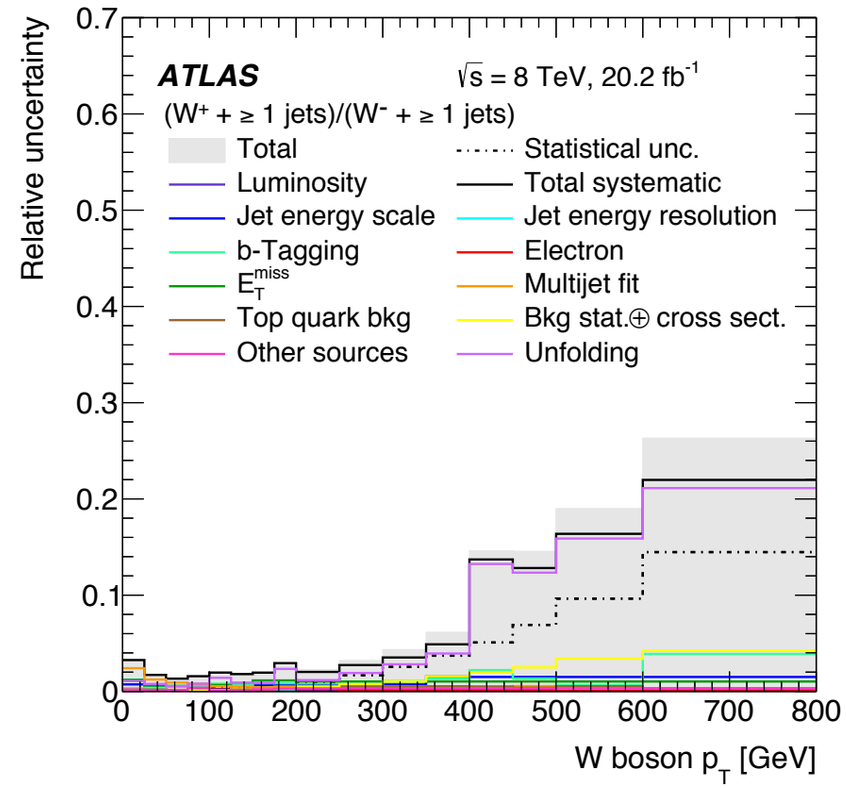
- Initial-state dominated by quark-gluon

W+jets at 8 TeV: theoretical predictions

Program	Order in α_S	$N_{\text{partons}}^{\text{max}}$ at highest order	PDF set	NPC	PS
N_{jetti}	NNLO	1	CT14	✓	
BlackHat+Sherpa	NLO	1, 2 or 3	CT10	✓	
MCFM 6.8	NLO	1	CT10 + 3 more	✓	
Powheg+Pythia 8	NLO	1	CT14		✓
Sherpa 2.2.1	NLO	2	CT10		✓
Sherpa 2.2.1	LO	2 (3)	NNPDF 3.0		✓
Alpgen+Pythia 6	LO	5	CTEQ6L1 (LO)		✓
Alpgen+Herwig	LO	5	CTEQ6L1 (LO)		✓
Sherpa 1.4.1	LO	4	CT10		✓

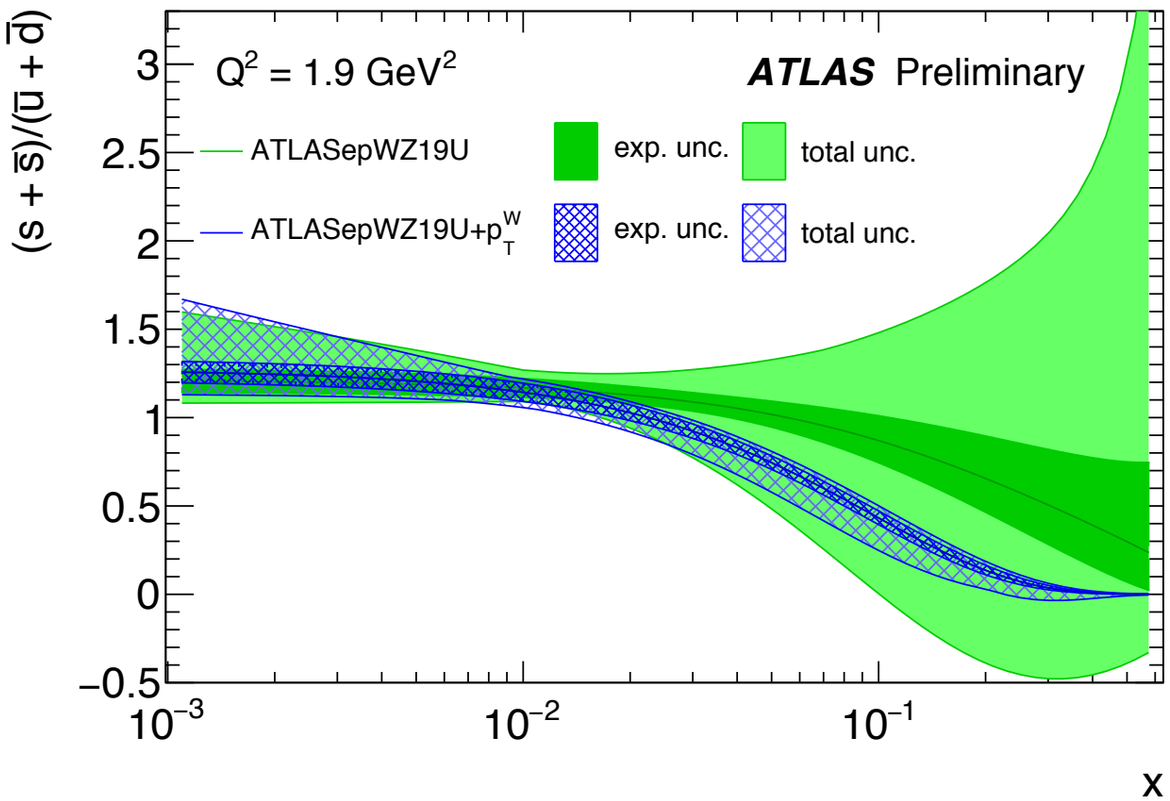
W+jets at 8 TeV: uncertainties

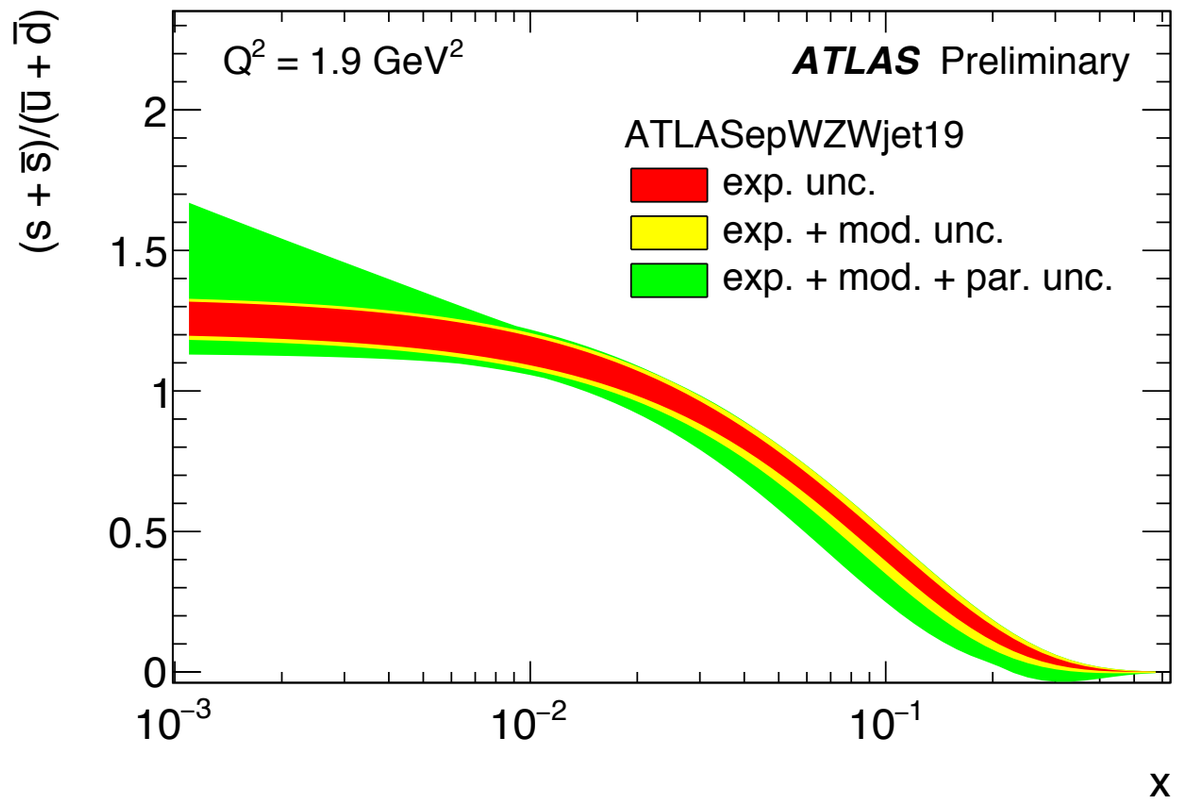




	Inclusive	≥ 1 jet	≥ 2 jets	≥ 3 jets	≥ 4 jets	≥ 5 jets	≥ 6 jets	≥ 7 jets
Jet energy scale	0.1	7.5	10	14	18	27	38	55
Jet energy resolution	0.5	8.8	9.9	12	14	15	18	20
b-tagging	0.1	0.5	1.5	3.8	8.3	15	23	33
Electron	1.1	1.4	1.4	1.5	1.8	2.1	2.1	2.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	1.1	2.6	4.2	5.5	7.1	8.8	12	14
Multijet background	0.5	1.3	2.1	2.6	2.5	4.7	8.8	12
Top quark background	<0.1	0.2	0.8	2.5	5.7	10	16	22
Other backgrounds	<0.1	0.1	0.2	0.3	0.5	1.0	1.7	2.6
Unfolding	4.7	4.1	4.9	4.4	4.0	4.7	6.9	7.2
Other	0.3	0.8	1.0	2.1	4.6	8.7	14	21
Luminosity	0.1	0.2	0.4	0.7	1.2	2.0	2.9	4.2
Total systematic uncert.	5.0	13	16	20	27	38	55	76

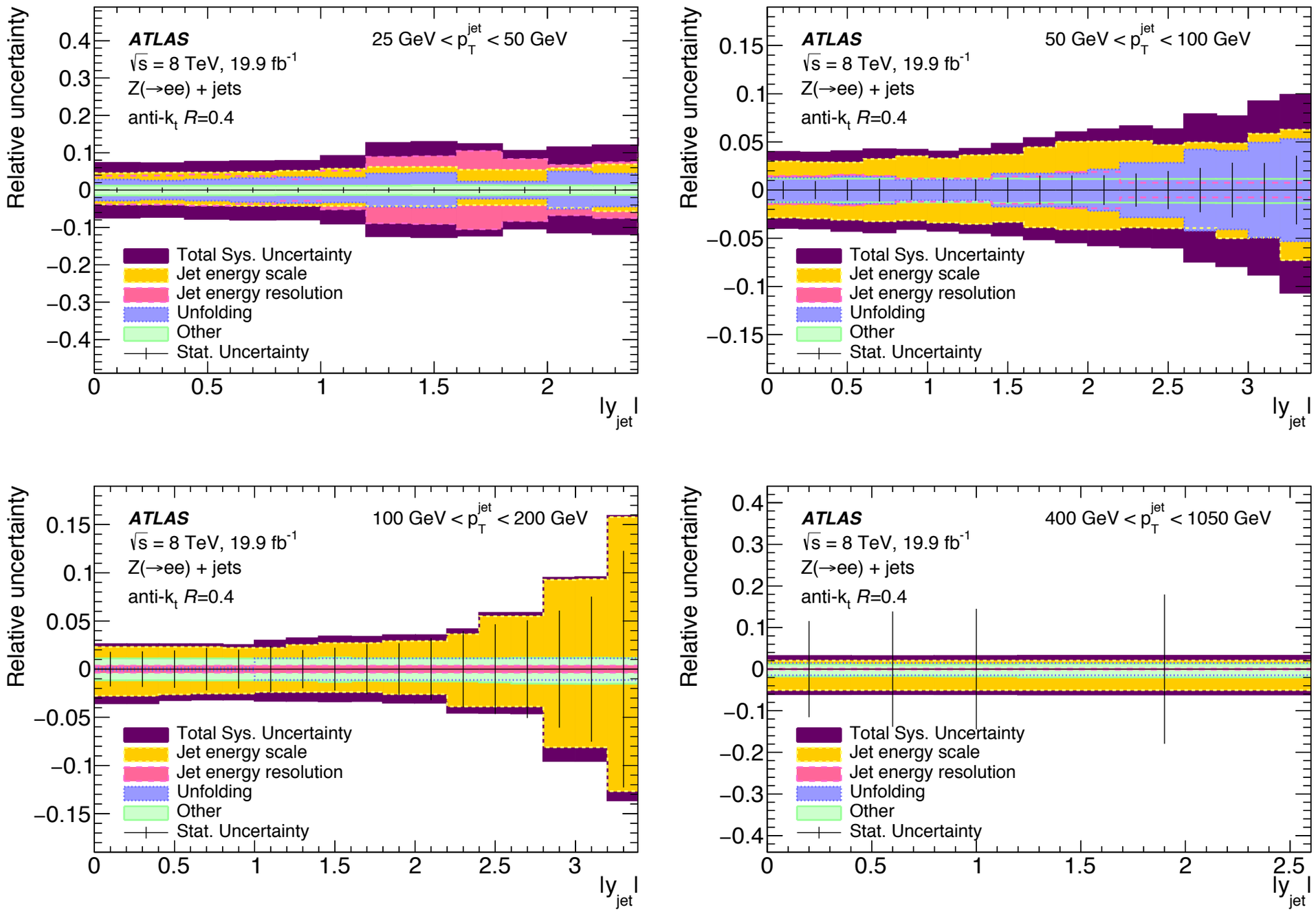
QCD analysis: R_s distribution



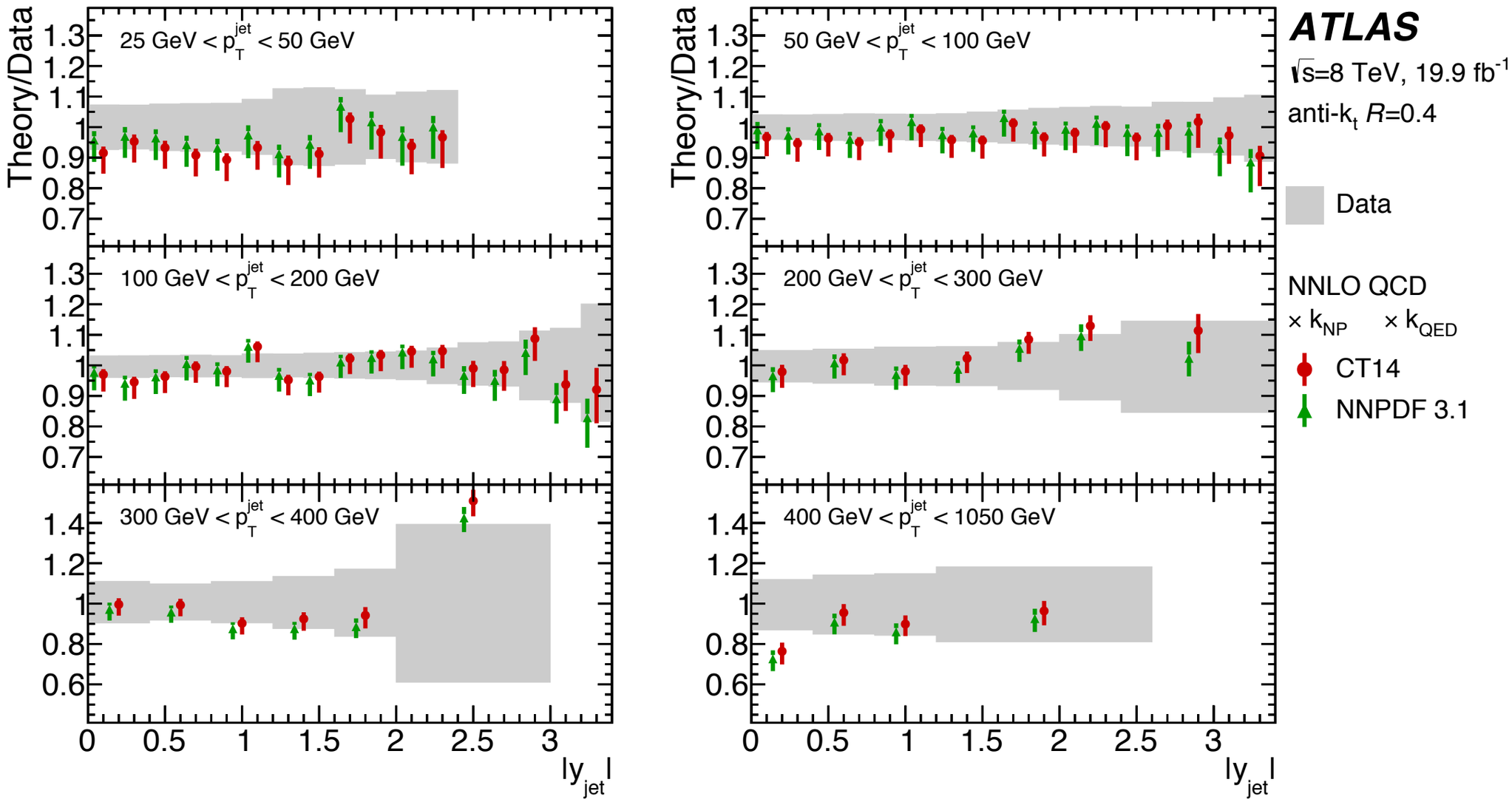


- fitting the W+jets data as a function of p_TW in comparison to the similar fit without W+jets data
- obtained **ATLASepWZWjet19** fit corresponding to the fit with W+jets data in the p_TW spectrum

Z+jets at 8 TeV



Z+jets at 8 TeV



- Difference between CT14 PDF and NNPDF3.1: 2%–5%
  - comparable to the size of the theoretical uncertainties

γ+jets production at 13TeV

- Systematics uncertainties on cross section
  - excluding the highest photon E_T bin in each y range: ~5–8%

Source	$\lvert y^\gamma \rvert < 0.8$	$0.8 < \lvert y^\gamma \rvert < 1.44$	$1.57 < \lvert y^\gamma \rvert < 2.1$	$2.1 < \lvert y^\gamma \rvert < 2.5$
Trigger efficiency	0.7–8.5	0.2–13.4	0.6–20.5	0.3–7.8
Selection efficiency	0.1–1.3	0.1–1.3	0.1–5.3	0.1–1.1
Data-to-MC scale factor	3.7	3.7	7.1	7.1
Template shape	0.6–5.0	0.1–10.2	0.5–4.9	0.6–16.2
Event migration	3.8–5.5	1.2–4.1	2.0–8.5	2.3–10.3
Total w/o luminosity	5.4–12.0	5.9–18.2	8.2–26.9	8.6–21.7
Integrated luminosity	2.3			