Measurements of W/Z production at ATLAS

Nataliia Zakharchuk
on behalf of ATLAS collaboration

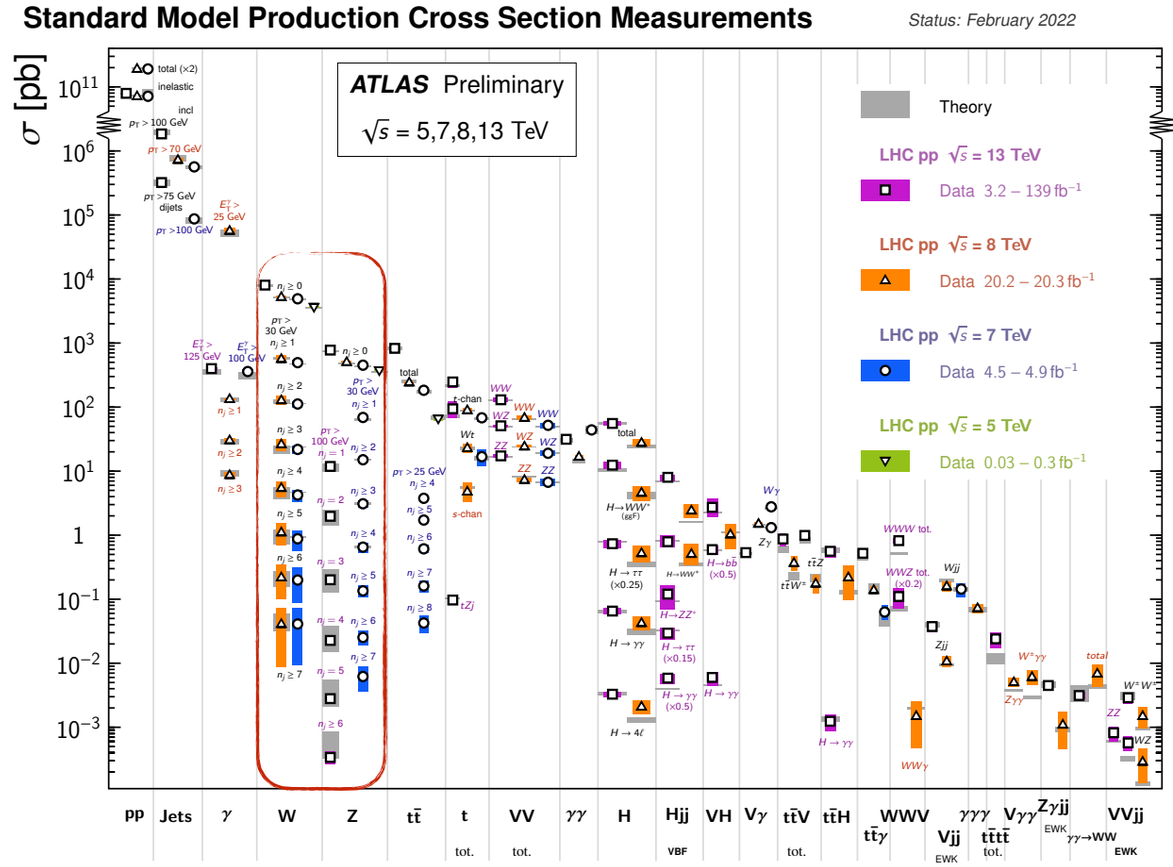
ICHEP 2022
6-13 July 2022
Bologna, Italy

Motivation

- Large production cross sections for W and Z bosons at the LHC
  - clean experimental signature
- Precision measurements of the production cross-sections of W/Z (+ jets)
  - understanding of perturbative quantum chromodynamics (pQCD) and electroweak (EW) processes
  - sensitive to parton distribution functions (PDFs) in proton
  - important background for the Standard Model processes and searches for new physics

➡ *Numerous measurements at different energies and conditions*

- Talk highlights **the latest results**:
  - ☑ Z + high-p_T jets in extreme phase-space [arXiv:2205.02597] (sub. to JHEP)
  - ☑ Z decays to a pair of leptons and photon NEW
    [ATLAS-CONF-2022-058]
  - ☐ Z + large-radius jet, flavour inclusive and with 2 b-tags [arXiv:2204.12355] → talk by Benedetto Giacobbe



Z + high-p_T jets in extreme phase-space

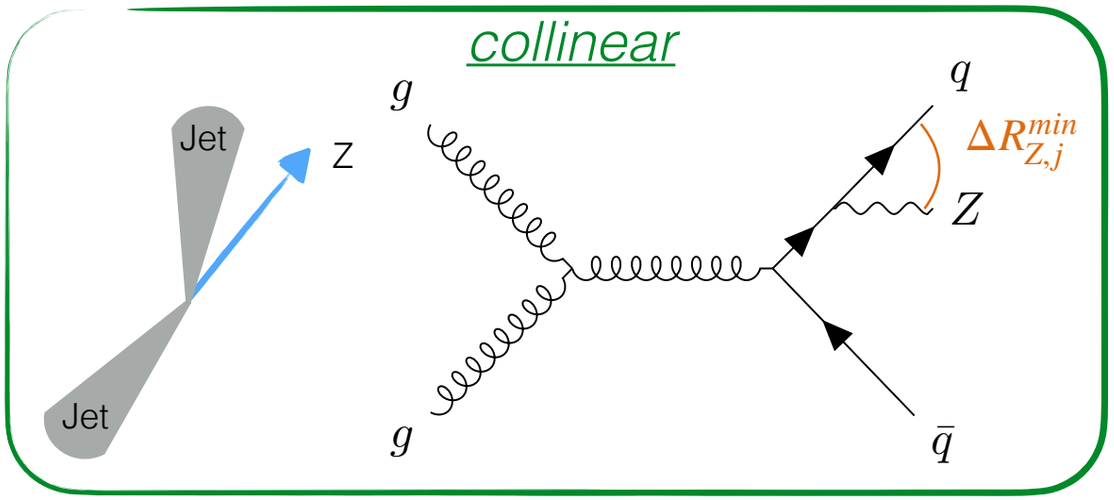
Z + high-p_T jets: event topologies

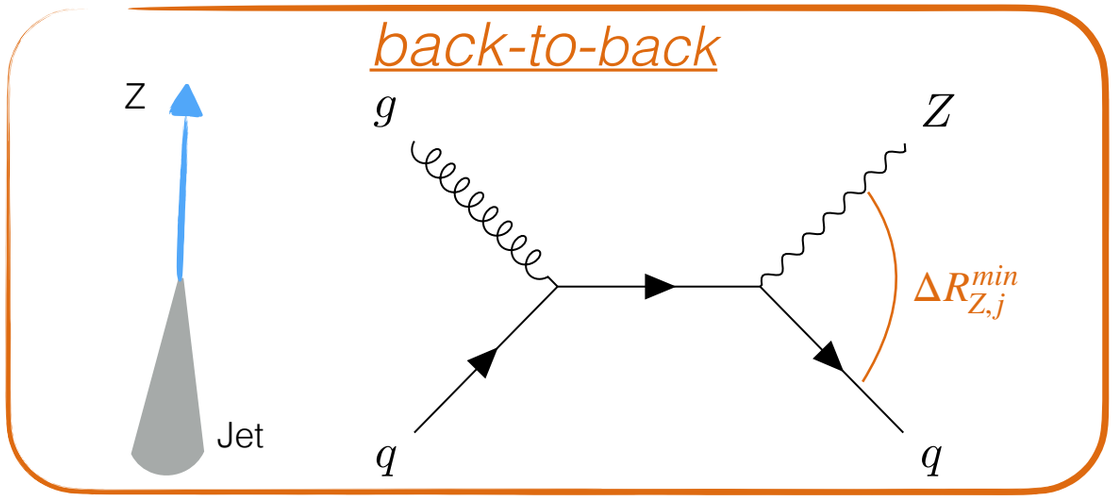
➡ *Probe state-of-the-art MC and pQCD predictions in different event topologies*

➡ *Sensitive to electroweak and pQCD corrections*

- Full Run-2 dataset at $\sqrt{s}$ = 13 TeV, L = 139 fb^{-1}
- $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ decay channels
  - plus jets with $p_T \geq 100$ GeV
- **Wide range of observables** in the different phase-space regions:
  - Inclusive
  - High-p_T: leading jet with $p_T \geq 500$ GeV
    - **collinear** emission: $\Delta R_{Z,j}^{min} \leq 1.4$
    - **back-to-back** emission: $\Delta R_{Z,j}^{min} \geq 2$
  - High-S_T: scalar sum p_T of jets, $S_T \geq 600$ GeV

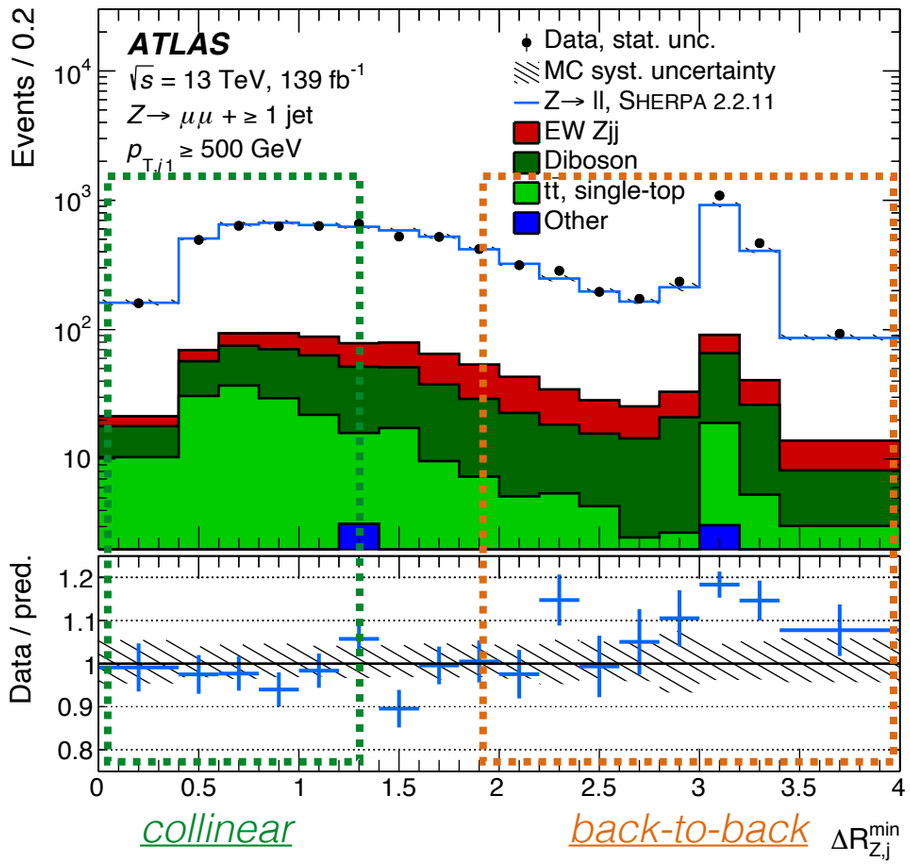
✓ **Integrated and differential fiducial cross sections** for different observables





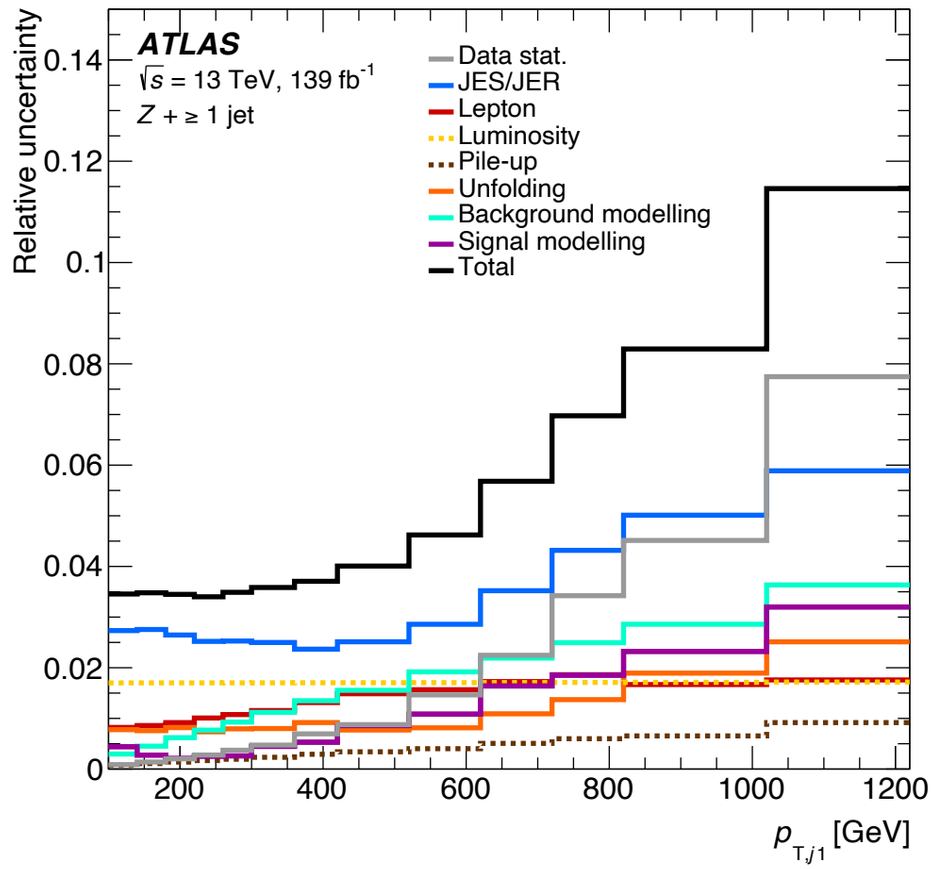
Z + high-p_T jets: Analysis overview

- **Angular distance**: key observable to characterize event topologies: $\Delta R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$



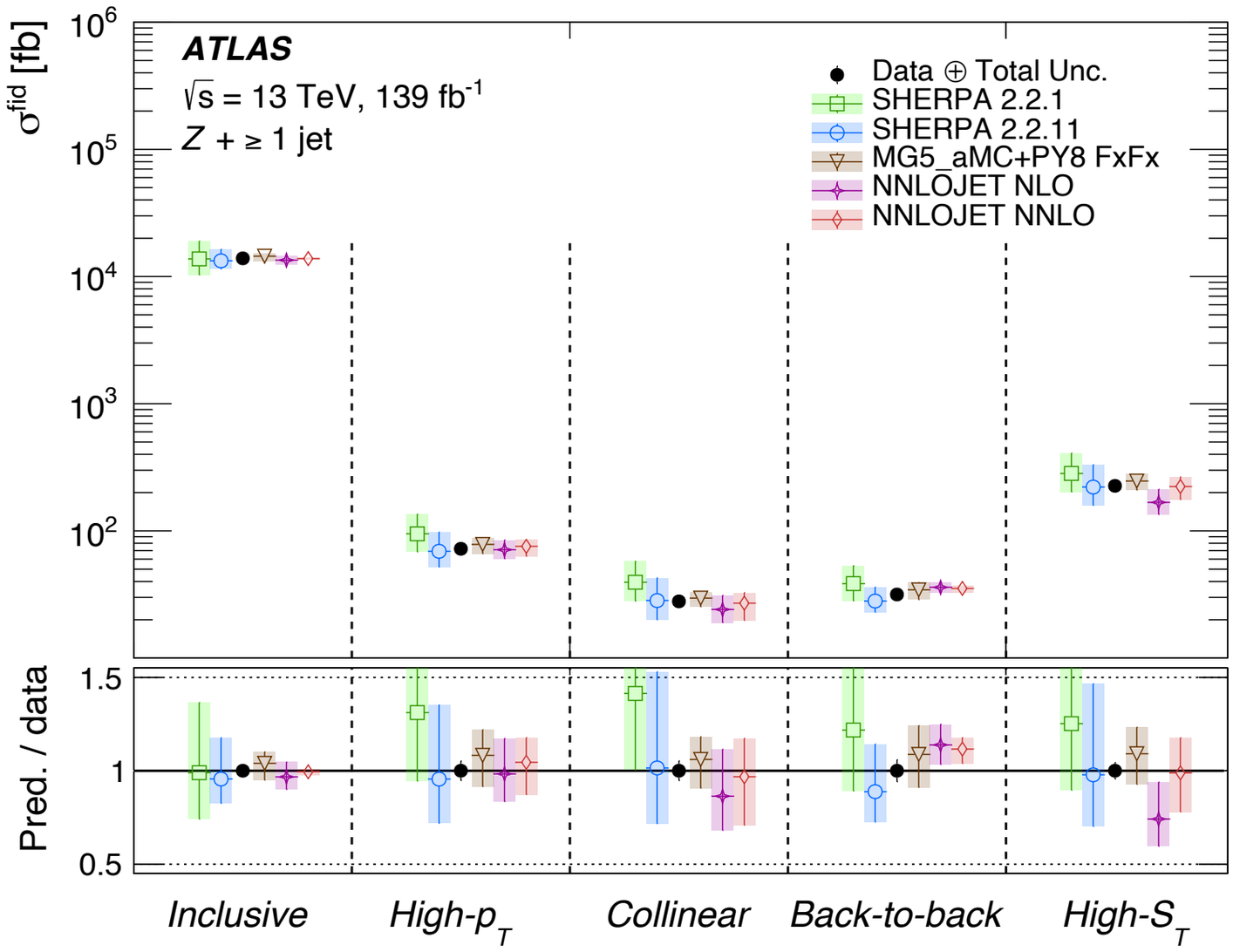
- State-of-the-art Sherpa2.2.11 used for nominal signal modelling and unfolding
- The main **background contributions**:
  - $t\bar{t}$ (data-driven): 2-5%
  - diboson: 2-6%
  - EW Zjj: 1-5%

➡ **Dominant systematics uncertainties** in the integrated cross sections



Uncertainty source [%]	*Inclusive*	*High-p_T*	*Collinear*	*Back-to-back*	*High-S_T*
JES/JER	2.6	3.2	2.8	3.6	2.8
Lepton	0.9	1.6	1.4	2.0	1.1
Luminosity	1.7	1.7	1.7	1.7	1.7
Pile-up	0.1	0.4	0.4	0.4	0.4
Unfolding	0.5	1.0	1.1	1.4	0.8
Background modelling	0.5	2.0	2.0	1.9	1.7
Signal modelling	0.5	1.2	1.1	1.1	1.1
Total syst. uncertainty	3.4	4.8	4.4	5.3	4.2
Data stat. uncertainty	0.1	2.1	2.9	2.7	1.2
Total uncertainty	3.4	5.3	5.3	5.9	4.4

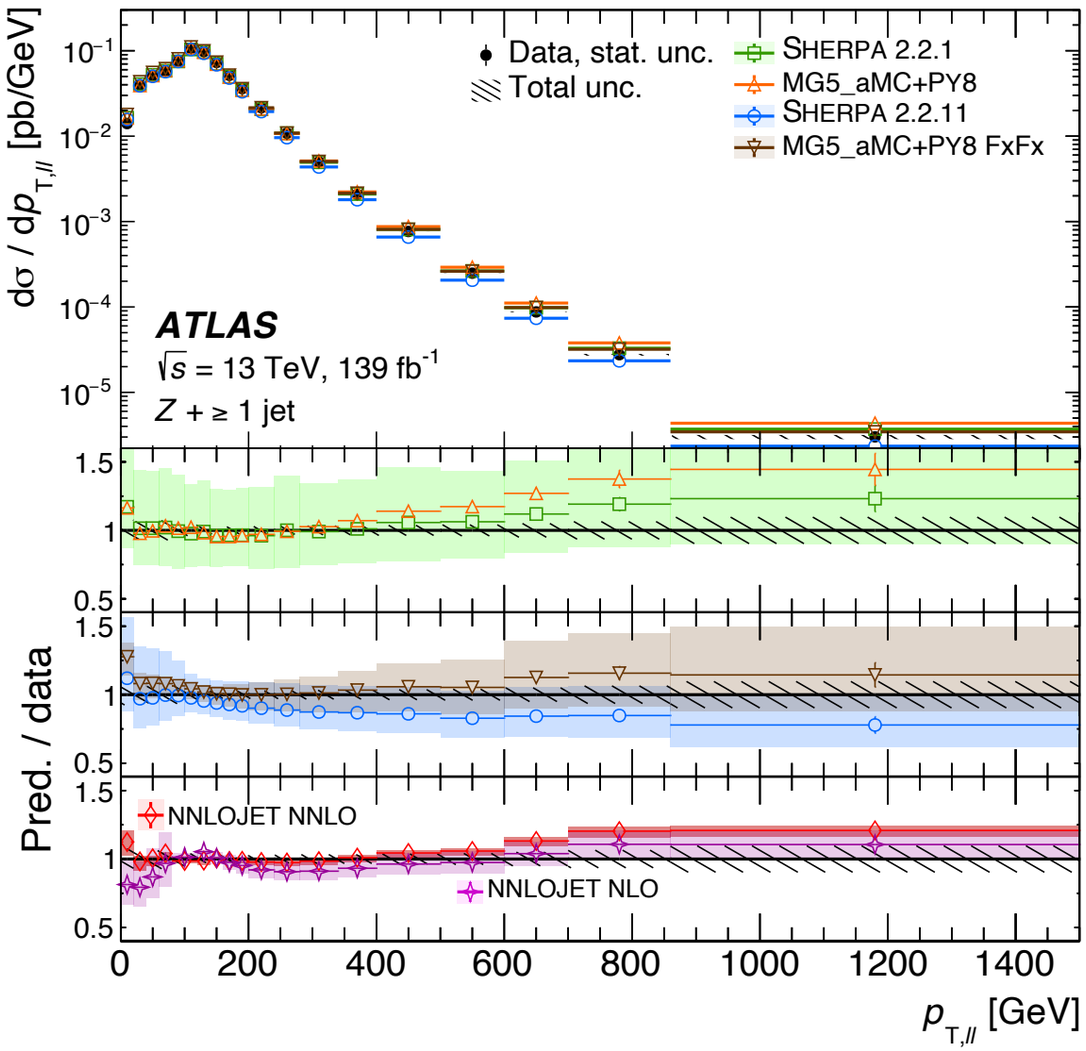
Z + high-p_T jets: Integrated cross sections

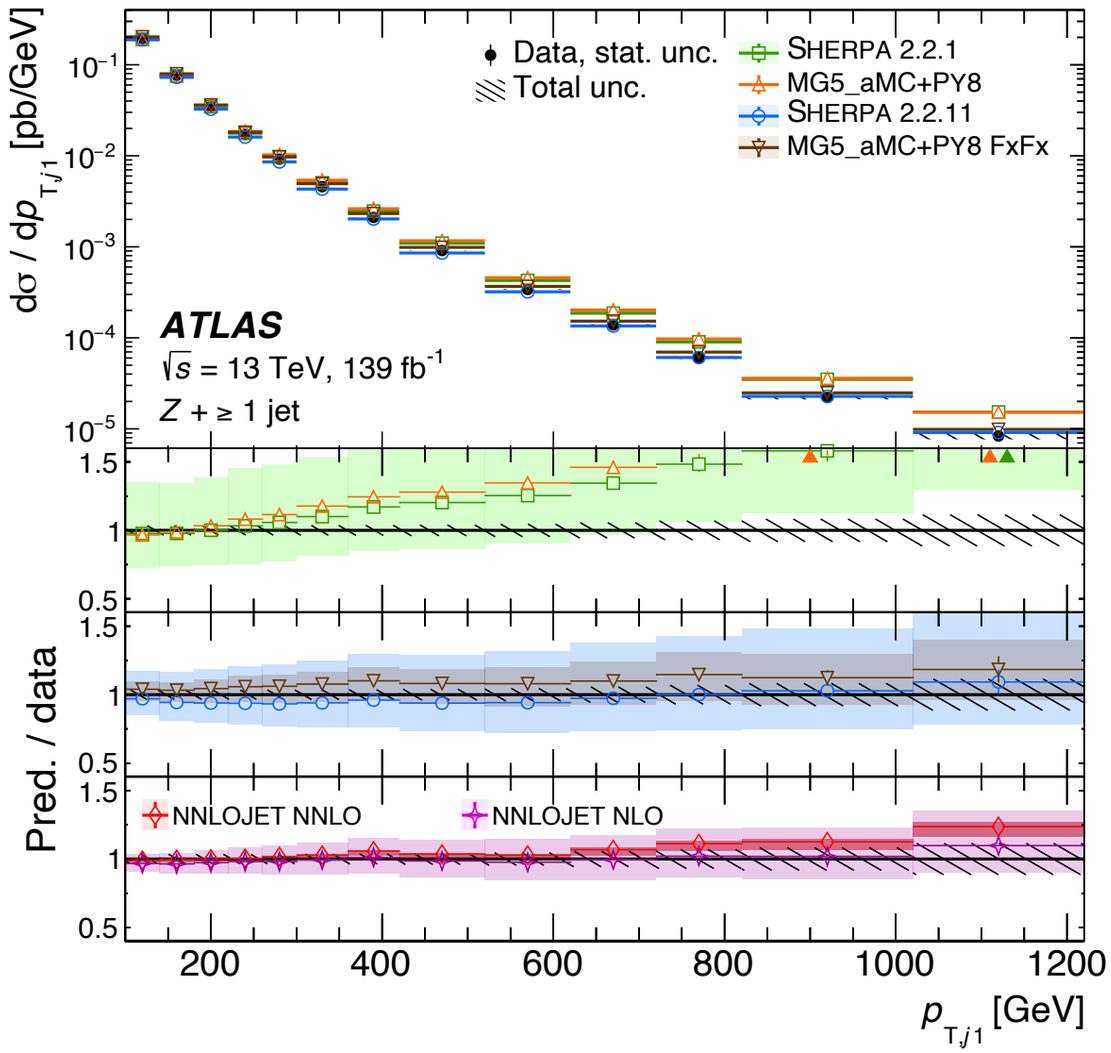


- Data measurements are more precise than the predictions
- Good agreement

- **Theoretical predictions** include ME+PS generators and pQCD in NNLO:
  - **Sherpa 2.2.11**: NLO up to 2 jets + LO up to 5 jets
    - includes NLO virtual EW corrections
  - **Sherpa 2.2.1**: NLO up to 2 jets + LO up to 4 jets
  - **MG5_aMC+PY8 FxFx**: NLO up to 3 jets
  - **NNLO$_{JET}$**: NNLO&NLO for 1 jet

Z + high-p_T jets: Inclusive phase space

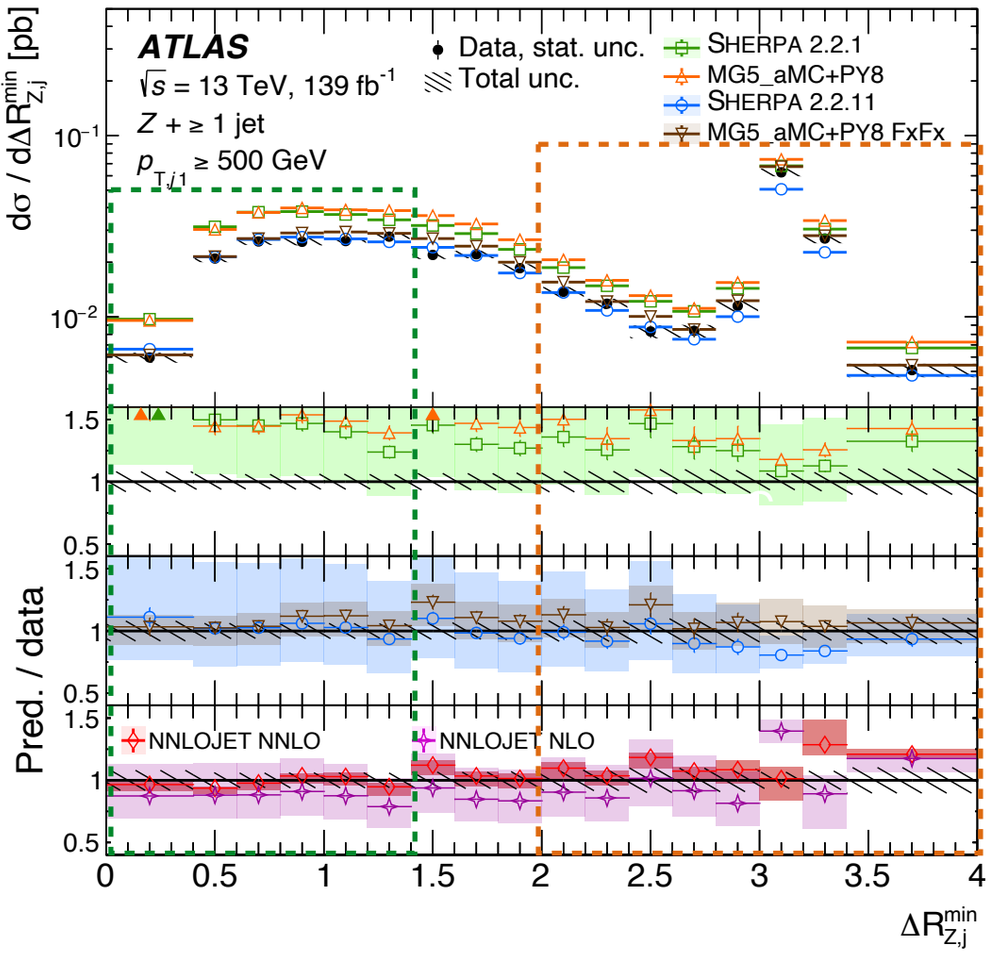




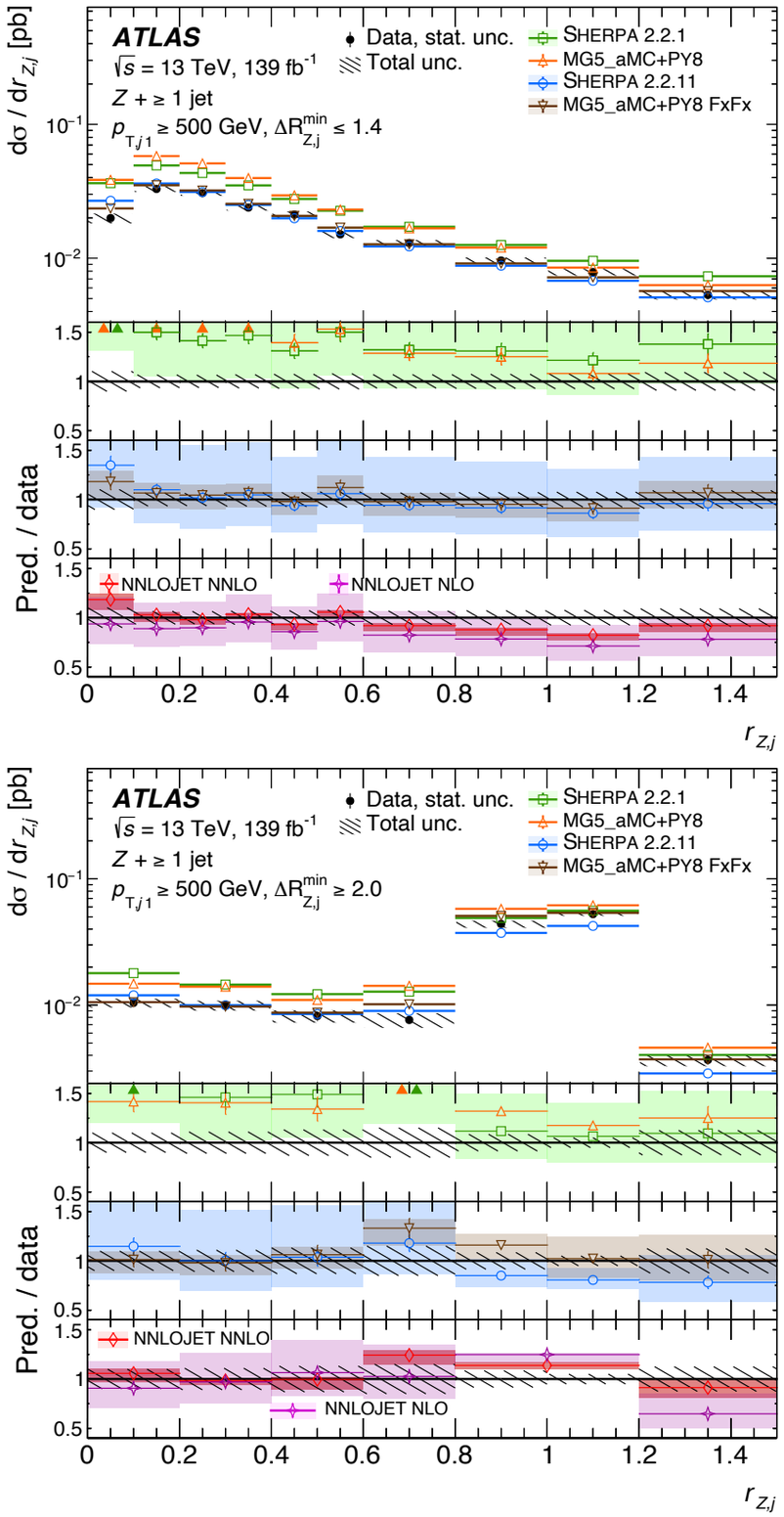
- **Sherpa 2.2.1** & **MG5_aMC+Py8 CKKWL** overestimate the cross section at high $p_{T,j1}$
- **Sherpa 2.2.11** & **MG5_aMC+Py8 FxFx** show significantly improved agreement
  - improved matching scheme in Sherpa 2.2.11, MG5_aMC+Py8 FxFx with 3 NLO partons
- **NNLO$_{JET}$@NNLO** describes the data with higher precision

➡ *uncertainties up to 50% in the predictions*

Z + high-p_T jets: High-p_T region



- Low $\Delta R_{Z,j}^{min}$ region is dominated by collinear Z emission
- $\Delta R_{Z,j}^{min} \sim \pi$ region is dominated by back-to-back topology
- State-of-the-art MC predictions are in the agreement with data within the uncertainties



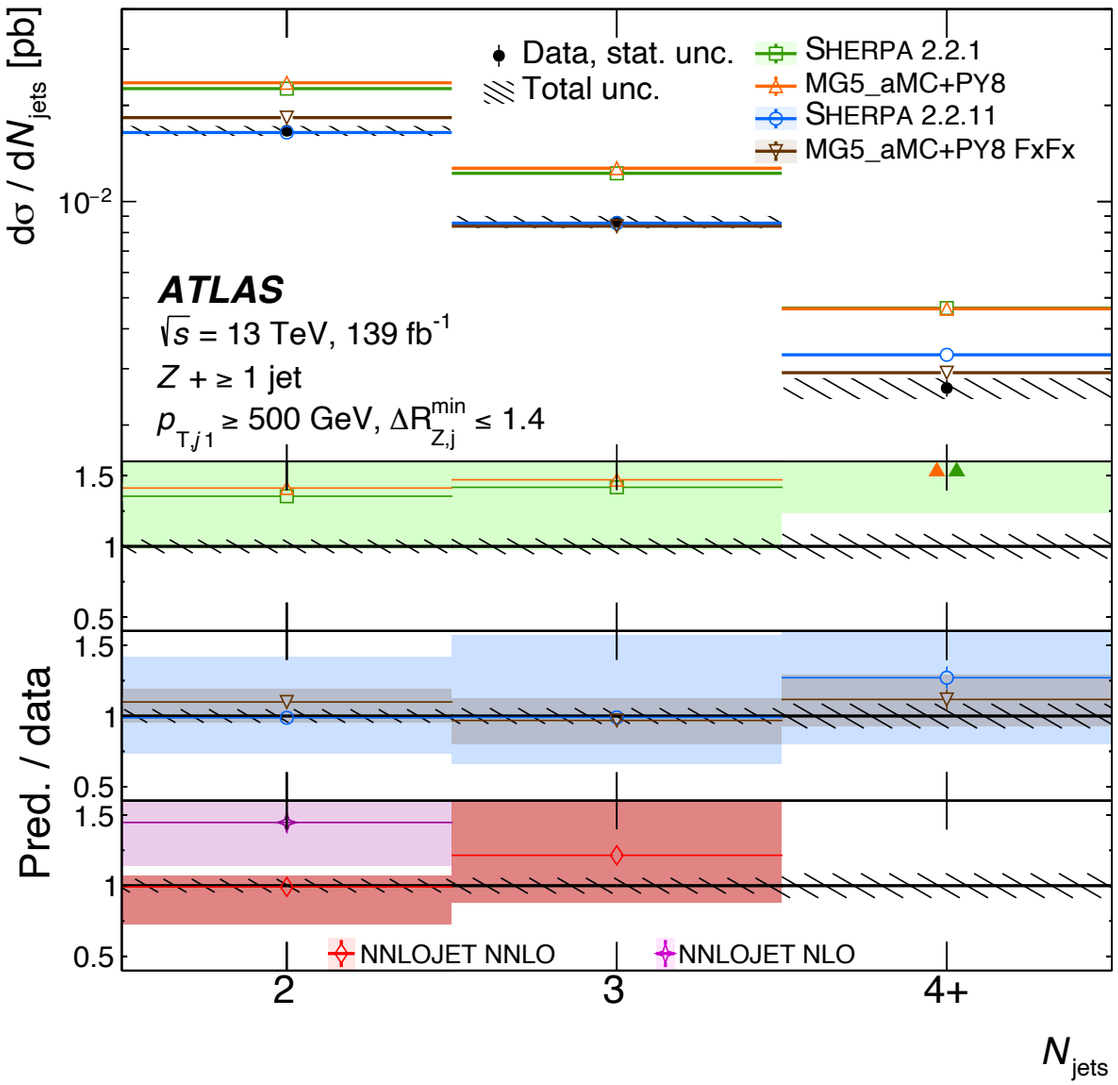
- **Collinear** region: accumulation of low $r_{Z,j}$ events

$$r_{Z,j} \equiv \frac{p_{T,ll}}{p_T(closest\ jet)}$$

- **Back-to-back** region: accumulation of events with $r_{Z,j} \sim 1$

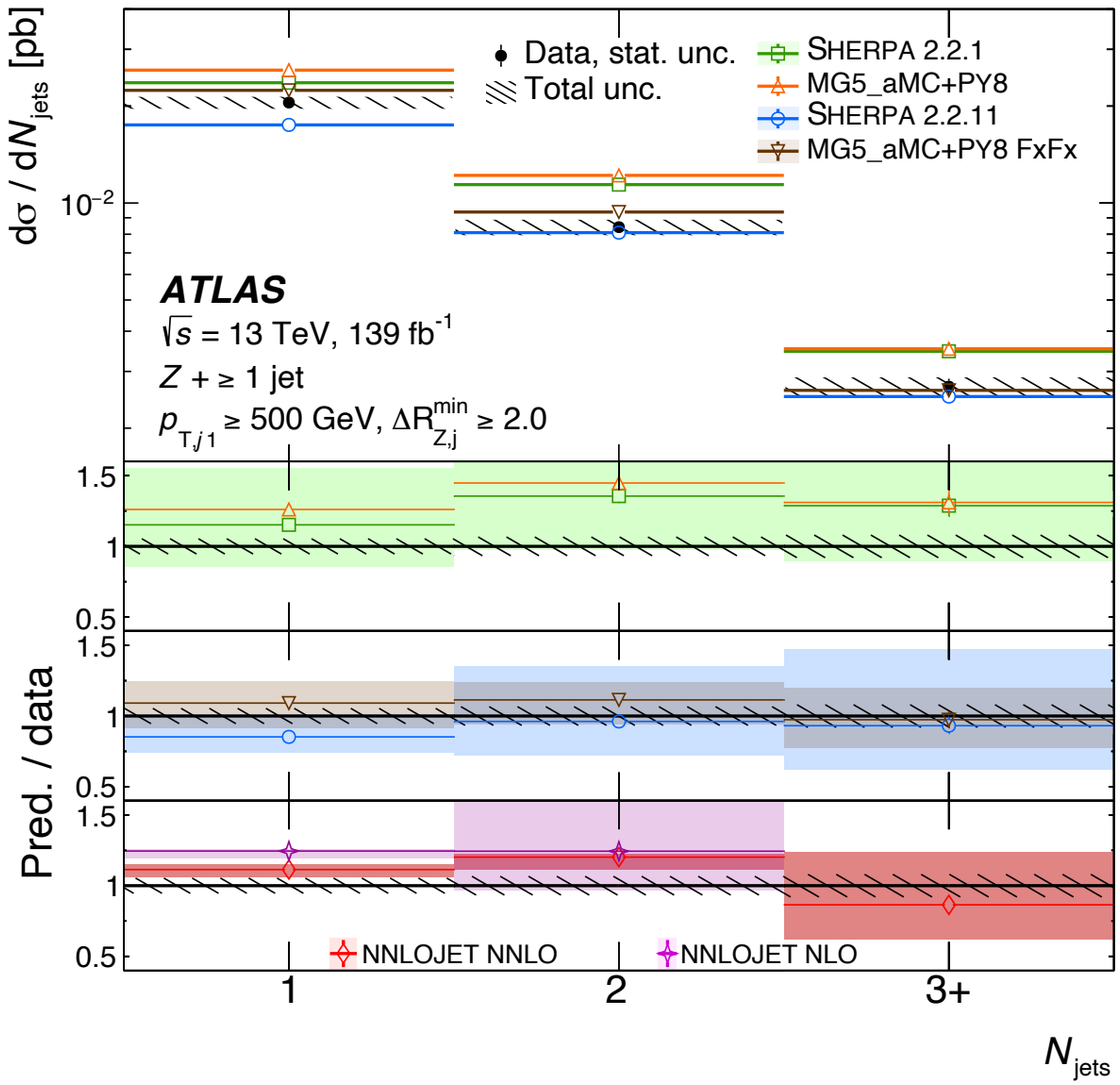
Z + high-p_T jets: high-p_T jet multiplicity

collinear region



- dominated by **Z + 2 jets** events
- **MG5_aMC+Py8 FxFx** shows good agreement with the high precision

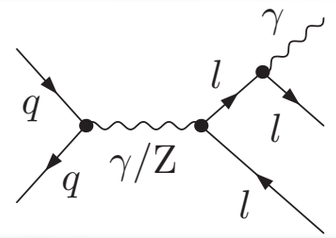
back-to-back region



- dominated by **Z + 1 jet** events
- generally well modelled by MCs

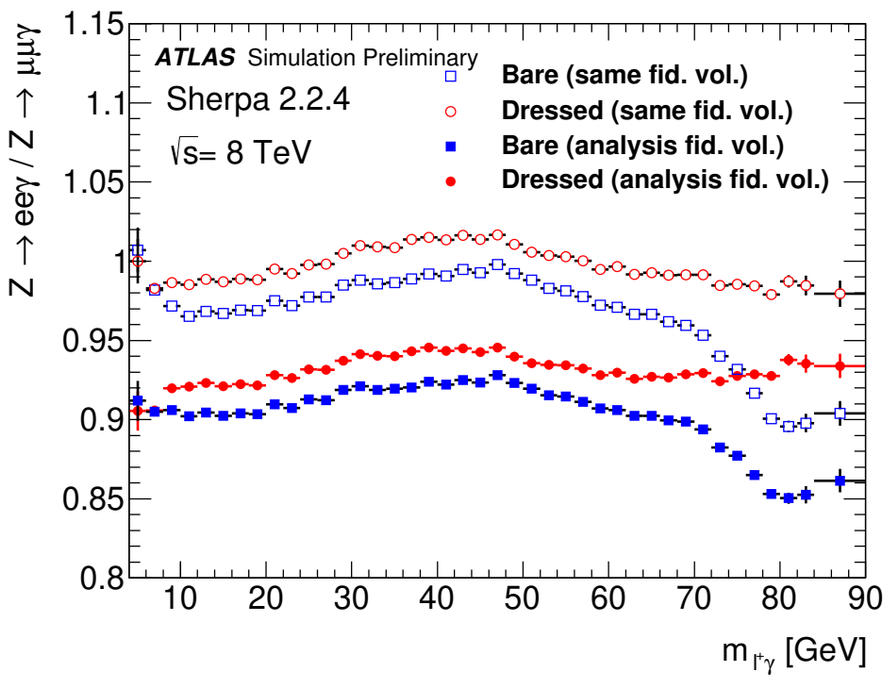
$Z \rightarrow ll\gamma$ decays at $\sqrt{s} = 8$ TeV

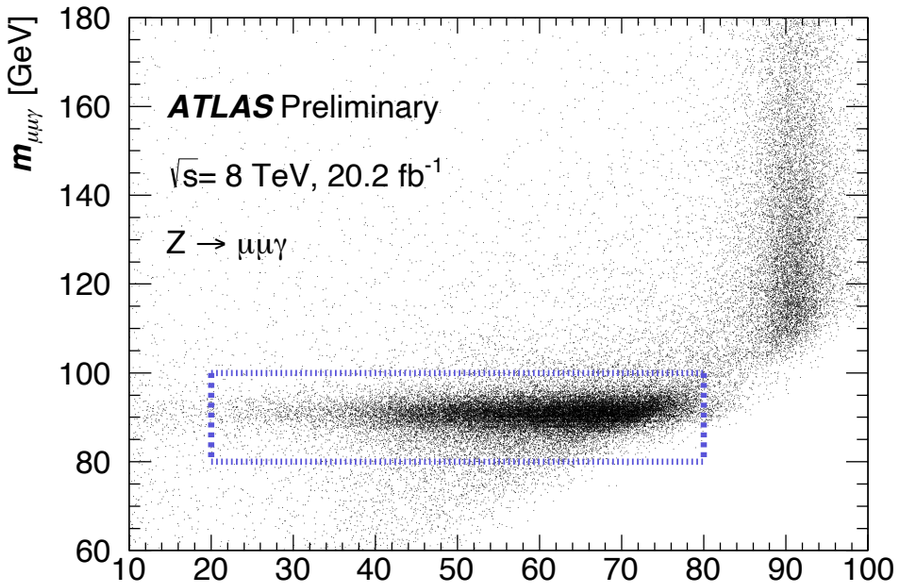
$Z \to ll\gamma$: Analysis overview



➡ *Sensitive to the kinematics of final-state QED radiation (QED FSR)*

- Using **20.2 fb^{-1}** of data at $\sqrt{s}$ = 8 TeV
- $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ decay channels
  - plus at least one photon
- Electrons and muons **radiate differently** at high orders
  - results presented separately for "bare" leptons





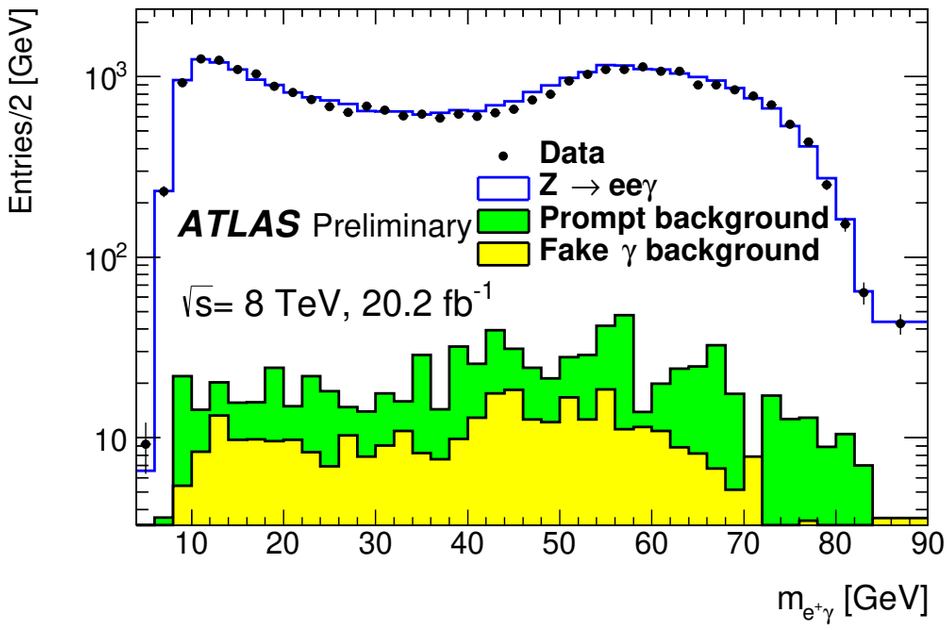
- **Fiducial phase space**:
  - $p_T^l > 25,\ 10$ GeV
  - $|\eta_\mu| < 2.7,\ |\eta_e| < 2.47;$
  - $p_T^\gamma > 15$ GeV
  - $|\eta_\gamma| < 2.37,\ 1.37 < |\eta_\gamma| < 1.52$
  - $\Delta R_{l\gamma} > 0.4$
    - $20 < m_{ll} < 80\ GeV$
    - $80 < m_{ll\gamma} < 100\ GeV$

➡ Small contributions from initial-state-radiation (QED ISR) and initial-final-state-interference (QED IFI)

✓ Integrated and normalized differential fiducial cross sections
  - $m_{l^+\gamma}$, $\Delta R_{l,\gamma}$, p_T^γ

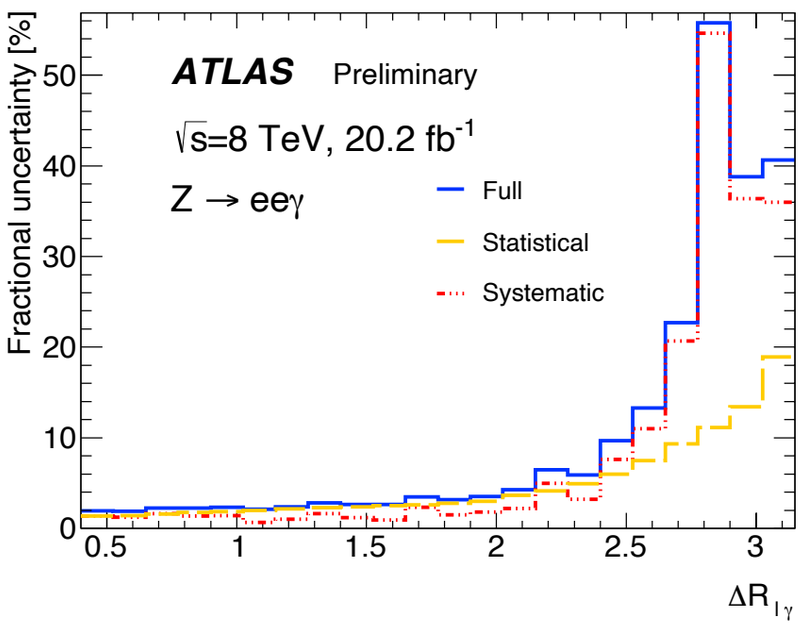
✓ The first measurement of Z → ***llγγ*** decays

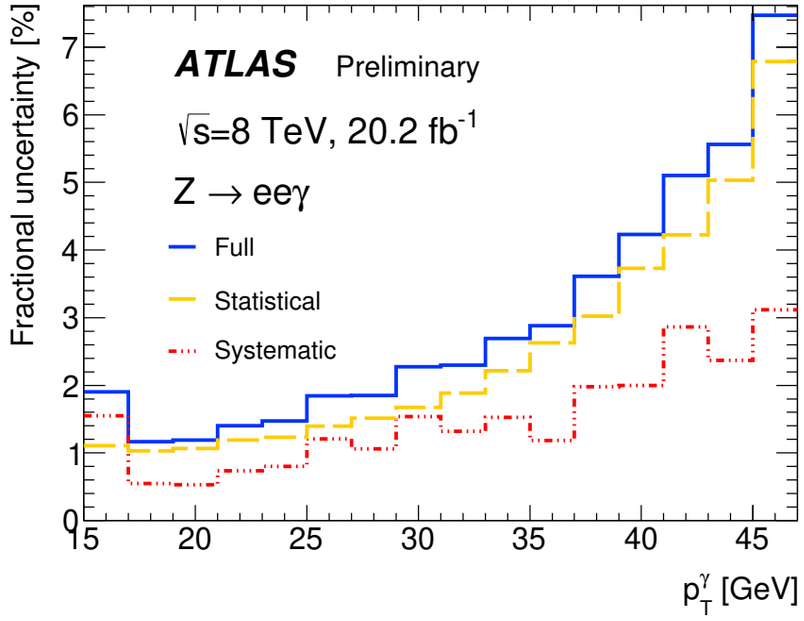
$Z \to ll\gamma$: Analysis overview



- The nominal MC sample: **Powheg+Pythia+Photos**
- Overall **small background contribution** (~2-3%):
  - dominated by $t\bar{t}$ and Z+jets
  - "prompt" (simulation)
  - "fake γ" (data-driven method)

Breakdown of uncertainties

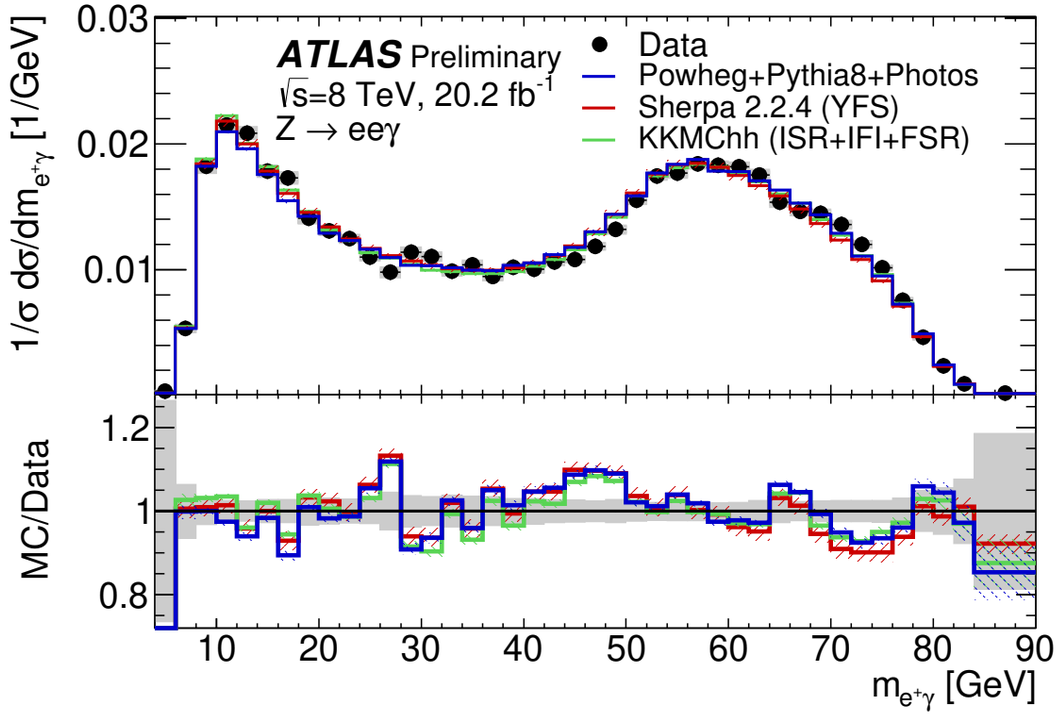


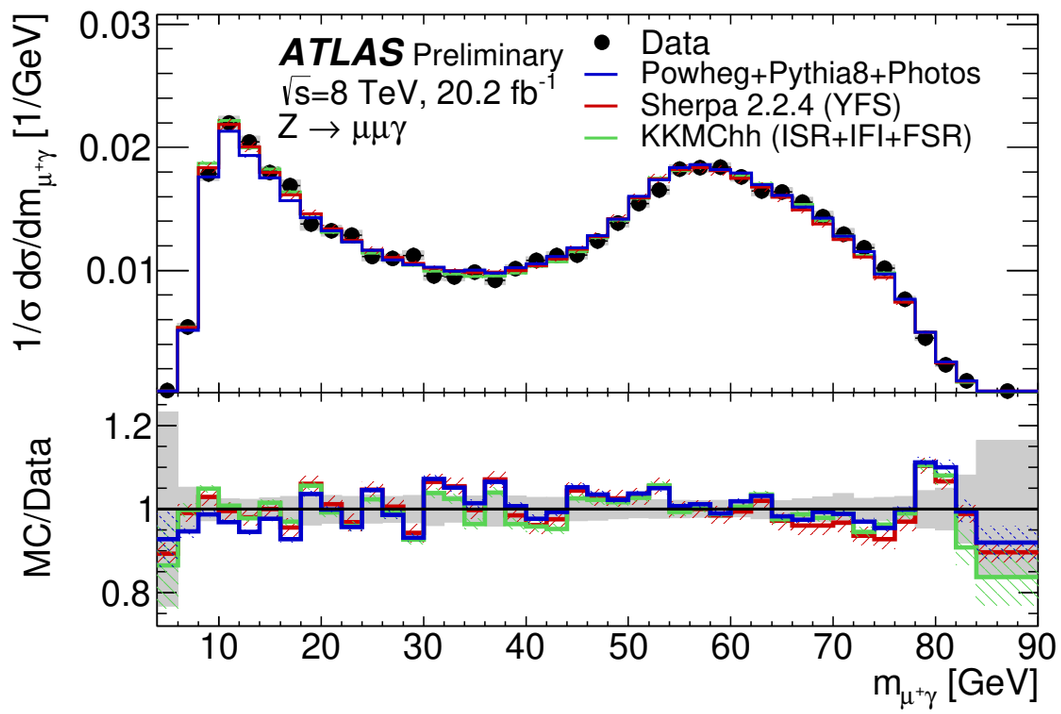


- Main contribution to the **experimental uncertainty**:
  - statistical component
  - systematics dominate at the edge of the phase space for $m_{l+\gamma}$ and $\Delta R_{l,\gamma}$
- **Theoretical uncertainties:**
  - at the per mil level

Z→*l*l*γ*: Normalized differential cross-sections

Invariant mass

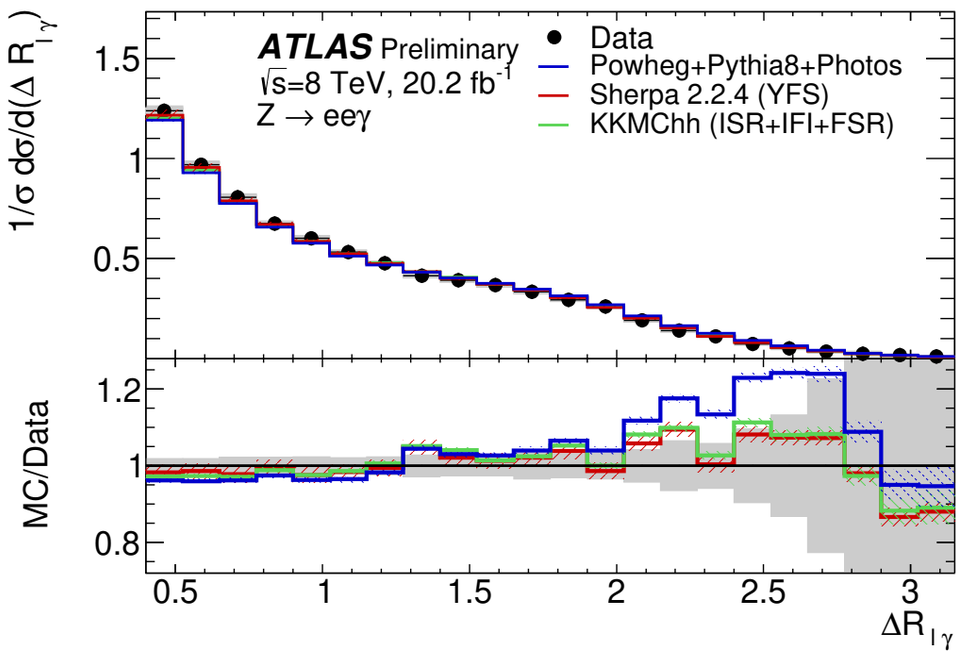


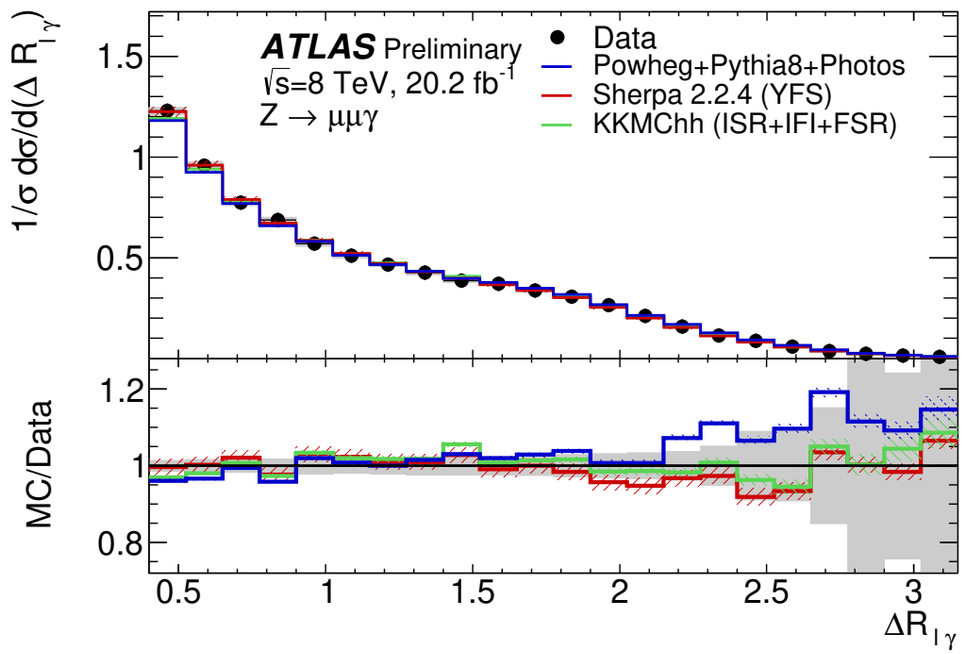


- State-of-the-art MC predictions are in a reasonable agreement with the data
  - **Powheg+Pythia8+Photos:** NLO QCD, only NNLO QED FSR (using exponentiation), includes ME correction for Z
  - **Sherpa 2.2.4 (YFS):** NLO up to 2 partons + LO up to 3 partons, includes ISR & FSR (using exponentiation)
  - **KKMChh (ISR+IFI+FSR):** LO QCD, ISR &IFI& FSR (using exponentiation) and EW corrections
- Similar agreement between predictions

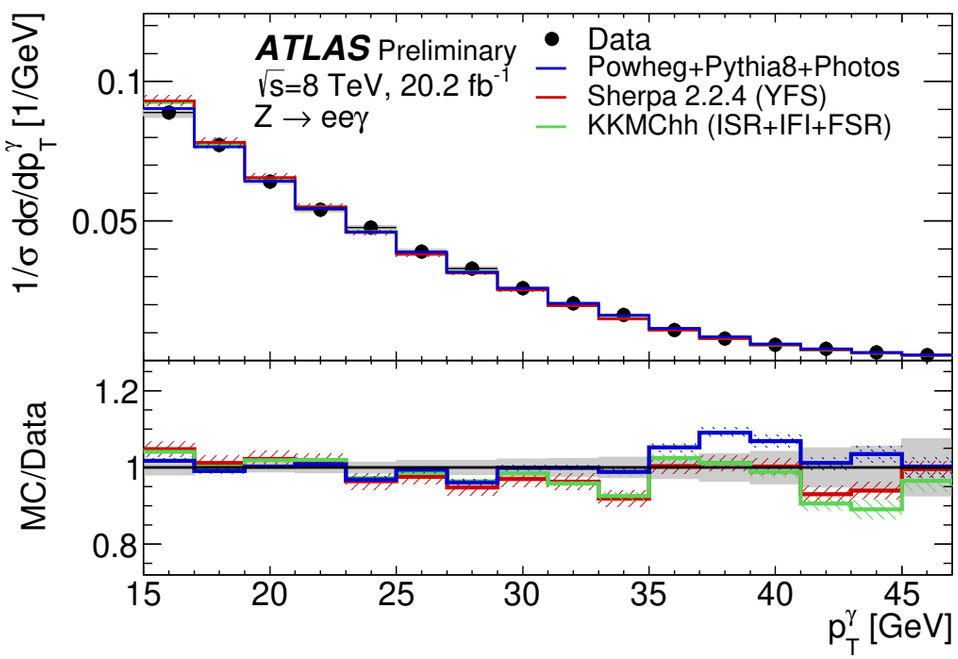
Z→*l*l*γ*: Normalized differential cross-sections

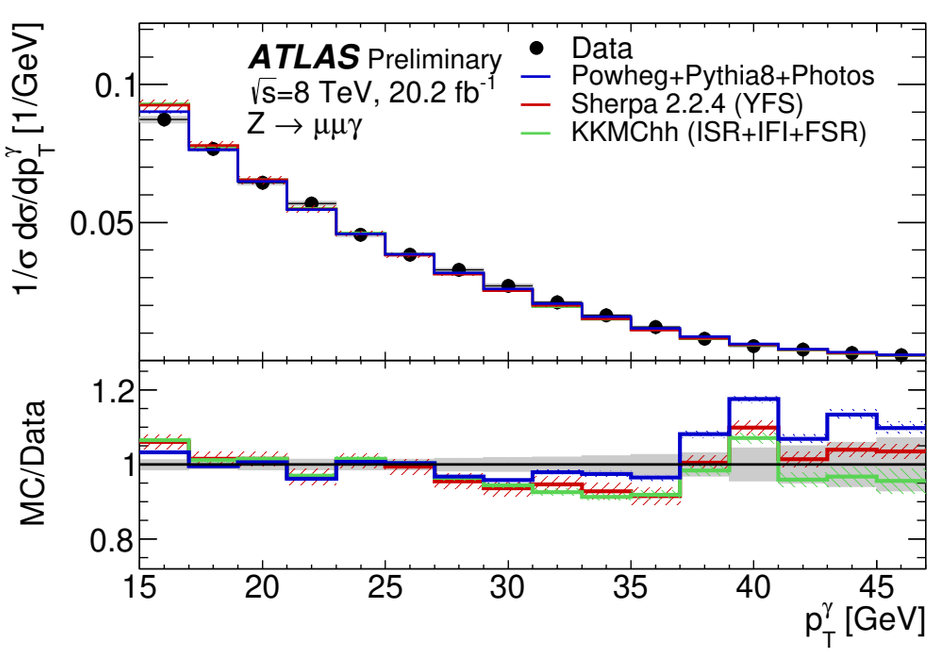
Angular distance





p_T *of photon*

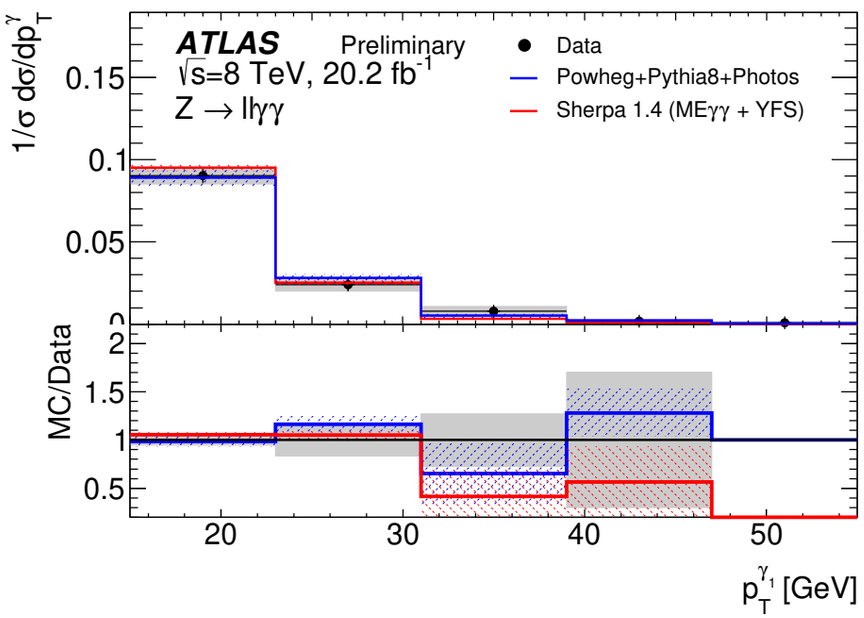


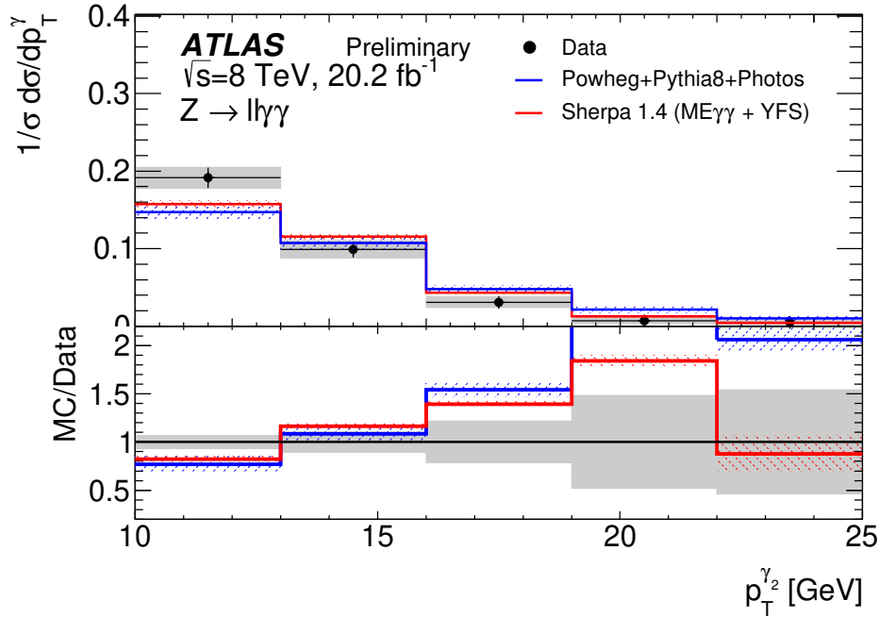


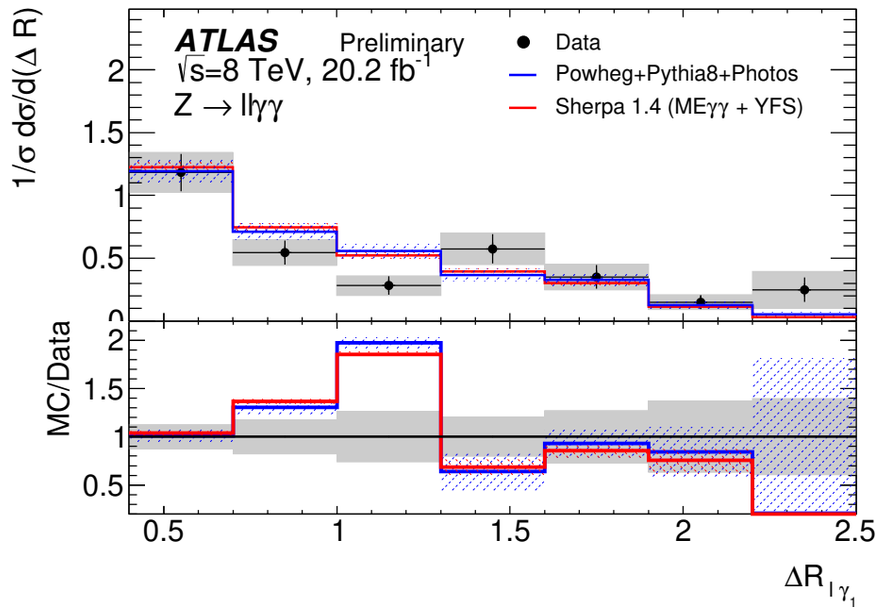
- State-of-the-art MC predictions are in a reasonable agreement with the data

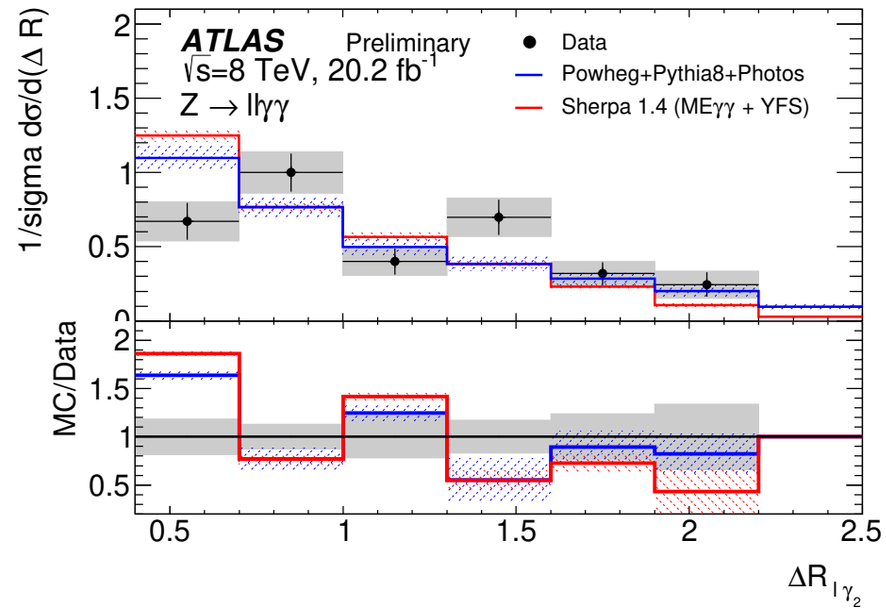
Z→*ll*γγ: Normalized differential cross-sections

- The first measurement of Z→ll$\gamma\gamma$ process at the LHC
  - dominated by the limited statistics of the dataset
  - some modifications of selection criteria with the respect to Z→llγ + specific version of Sherpa 1.4 ME$\gamma\gamma$









Conclusions

- The most recent W/Z (+ jets) production measurements presented
  - ✓ provide valuable input for a better understanding of pQCD and SM predictions

  - *Z + high-p_T jets in extreme phase-space using full Run-2 dataset*
    - first measurements in the collinear and back-to-back regions
    - Sherpa 2.2.1 and MG5_aMC+Py8 CKKWL show mismodelling in the higher jet p_T observables
    - recent state-of-the-art predictions show much better description of data
  - *Z decays to a pair of leptons and photon using data at $\sqrt{s}$ = 8 TeV*
    - measurements are in agreement with MC generators containing state-of-the-art QED FSR calculations, and with KKMChh containing QED (ISR & IFI & FSR) and EW corrections
    - the first results for the $Z \to ll\gamma\gamma$ process are in agreement with predictions (within large uncertainties)

➡ **More V+jets measurements are available at:**
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

More new measurements will follow. Stay tuned!

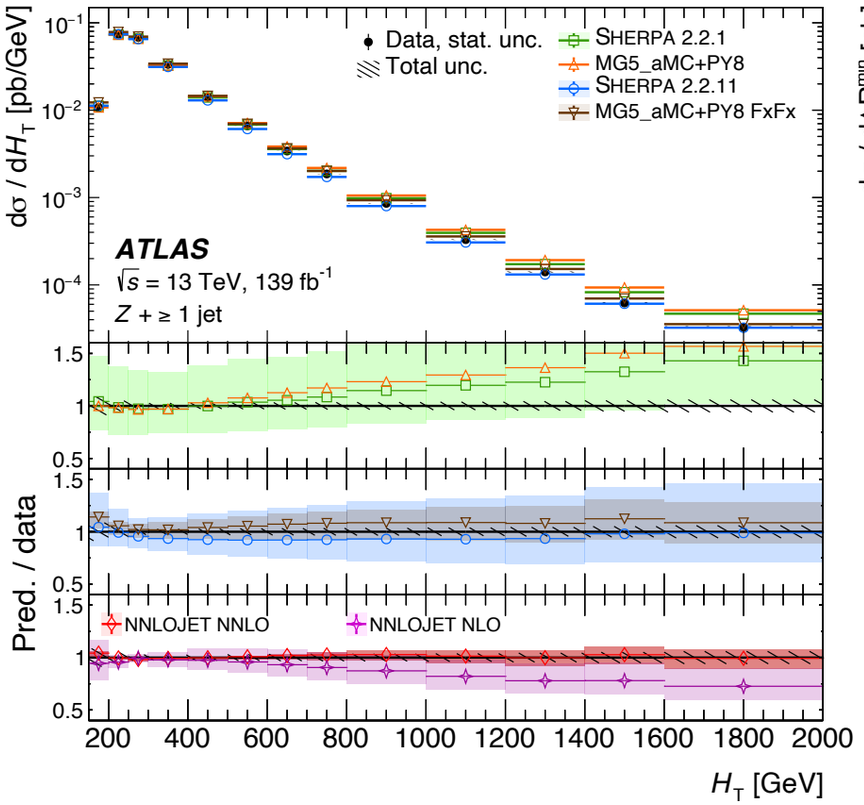
Backup

Z+high-p_T jets: MC generators and calculations

Process	Generator	Order pQCD	References
Signal			
$Z \to \ell\ell$ $(\ell = e, \mu)$	SHERPA 2.2.11	0–2p NLO, 3–5p LO	[19,32,33,34,35,36,37,38,39,40,41,42]
$Z \to \ell\ell$ $(\ell = e, \mu)$	MG5_aMC+PY8 FxFx	0–3p NLO	[20,21,43,44,45,42,19]
$Z \to \ell\ell$ $(\ell = e, \mu)$	SHERPA 2.2.1	0–2p NLO, 3–4p LO	[18,32,33,34,35,36,37,38,39,40]
$Z \to \ell\ell$ $(\ell = e, \mu)$	MG5_aMC+PY8 CKKWL	0–4p LO	[46,47,48,43]
$Z \to \ell\ell$ $(\ell = e, \mu)$	NNLOJET@NNLO	1p NNLO	[24,25]
$Z \to \ell\ell$ $(\ell = e, \mu)$	NNLOJET@NLO	1p NLO	[24,25]
Backgrounds			
EW $Zjj(\to \ell\ell$ $(\ell = e, \mu))$	HERWIG 7.1.5, VBFNLO 3.0.0	NLO	[49,50,51]
$Z \to \tau\tau$	SHERPA 2.2.1	0–2p NLO, 3–4p LO	[18,32,33,34,35,36,37,38,39,40]
$W+$jets	SHERPA 2.2.1	0–2p NLO, 3–4p LO	[18,32,33,34,35,36,37,38,39,40]
$t\bar{t}$	POWHEG BOX v2 + PYTHIA 8.230	NLO	[52,53,54,55]
Single top (t-, Wt-, s-channel)	POWHEG BOX v2 + PYTHIA 8.230	NLO	[52,53,54,55]
$Z/W(\to qq)Z(\to \ell\ell)$	SHERPA 2.2.1	0–1p NLO, 2–3p LO	[18,32,33,34,35,36,37,38,39,40]
$W(\to \ell\nu)Z(\to qq)$	SHERPA 2.2.1	0–1p NLO, 2–3p LO	[18,32,33,34,35,36,37,38,39,40]
$W^{\pm}(\to qq)W^{\mp}(\to \ell\nu)$	SHERPA 2.2.1	0–1p NLO, 2–3p LO	[18,32,33,34,35,36,37,38,39,40]
$\ell\ell\nu\nu, \ell\ell\ell\nu, \ell\ell\ell\ell$	SHERPA 2.2.2	0–1p NLO, 2–3p LO	[18,32,33,34,35,36,37,38,39,40]
$V(\to \ell\ell) + \gamma$	SHERPA 2.2.8	0–1p NLO, 2–3p LO	[18,32,33,34,35,36,37,38,39,40]

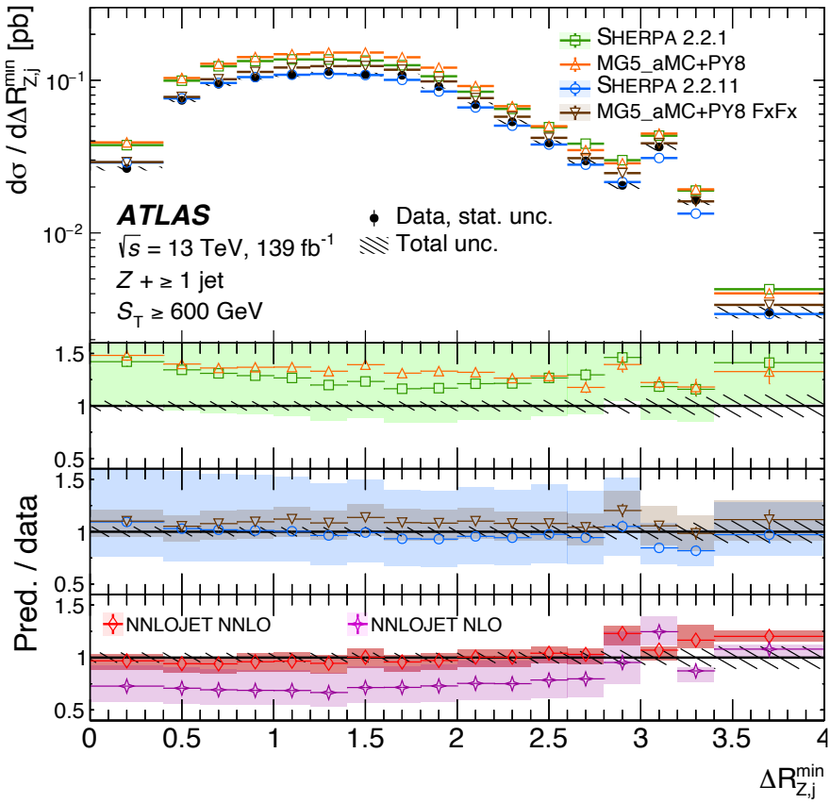
Z+high-p_T jets: Alternative high-energy region

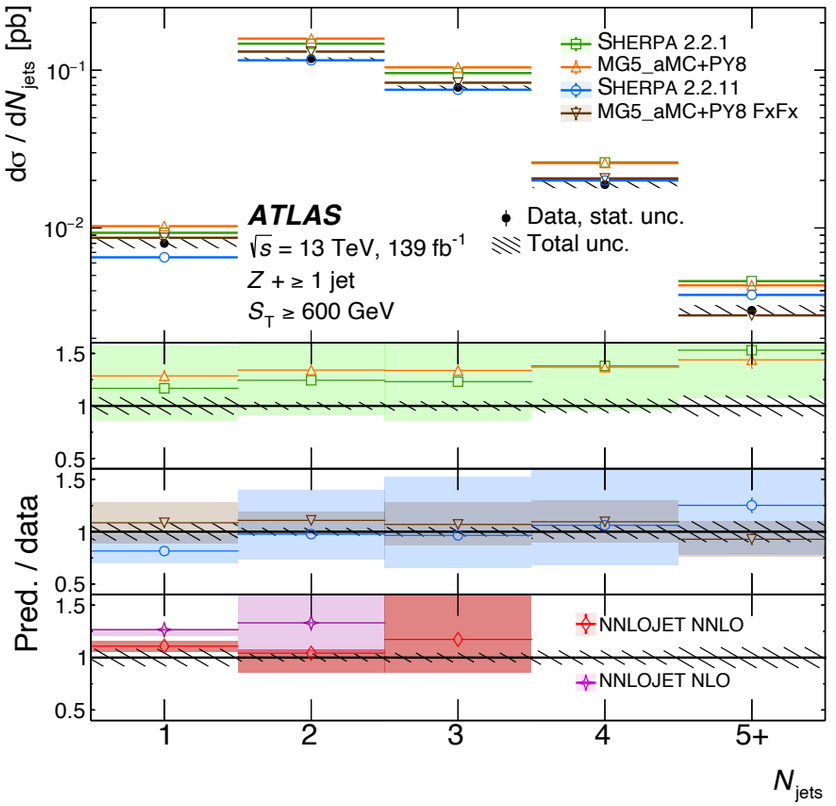
Inclusive region



scalar sum of jet p_T

High-S_T region





$Z \to l l \gamma$: Breakdown of systematic uncertainties

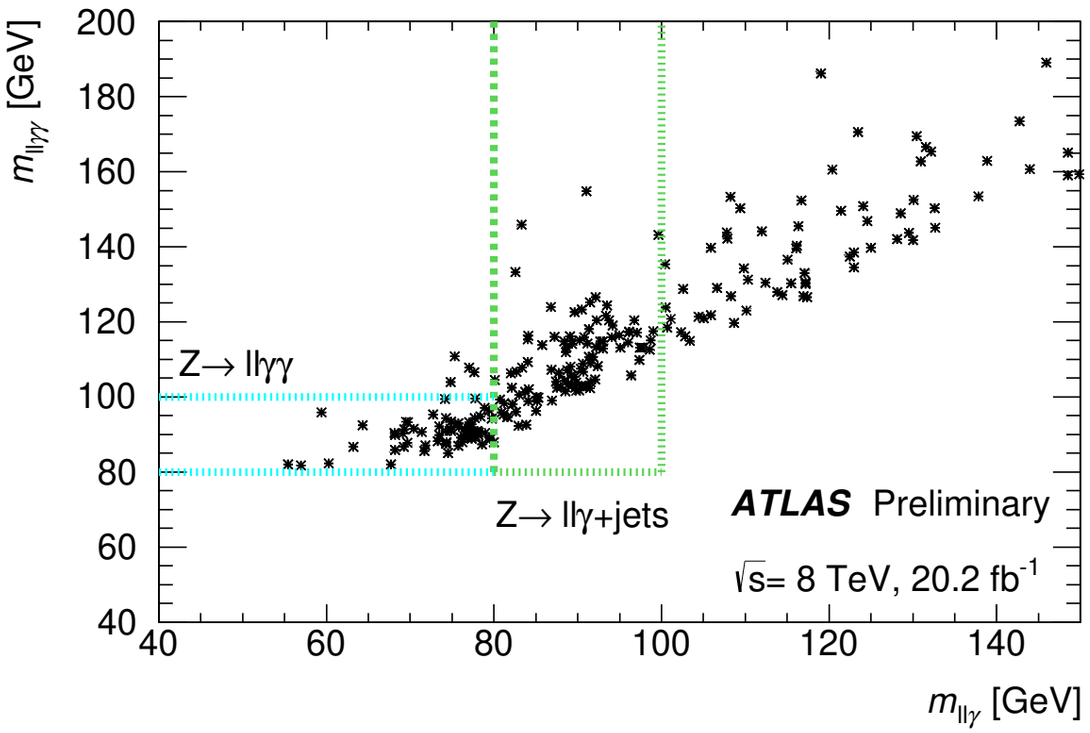
- Breakdown of systematic uncertainties for the normalized differential fiducial cross sections
  - values shown are typical over most of the kinematic range of the unfolded observables

Uncertainty source	$Z \to ee\gamma$ channel	$Z \to \mu\mu\gamma$ channel
Experimental		
Energy/momentum scale and resolution	0.2%	0.2%
Efficiency	0.3%	0.3%
Unfolding	< 0.1%	< 0.1%
Background subtraction	0.3%	0.3%
Theory		
PDF	< 0.1%	< 0.1%
QCD scale variations	0.1 %	0.1%
QCD modelling	0.3%	0.3%
Total	0.6%	0.6 %

- Breakdown of systematic uncertainties in the integrated fiducial cross-section measurements

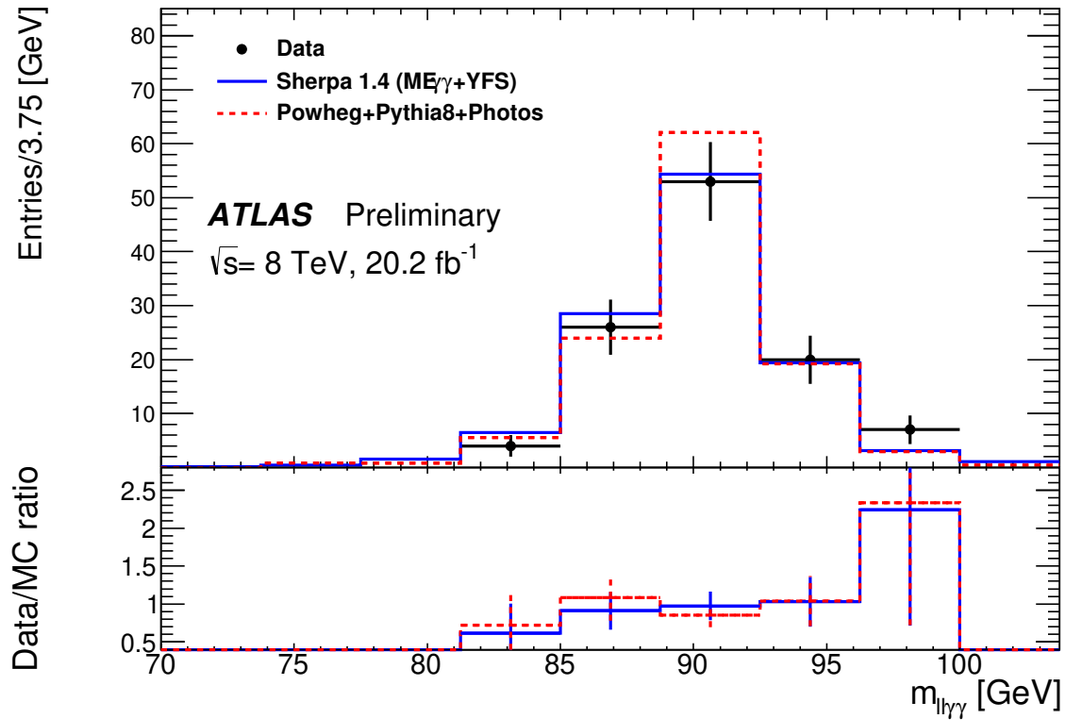
Uncertainty	$Z \to ee\gamma$	$Z \to \mu\mu\gamma$
Statistical	0.7%	0.7%
Experimental systematic	3.5%	2.3%
Luminosity	1.9%	1.9%
QCD theory	0.3%	0.3%
Total	4.1%	3.1 %

Z→llγγ: Analysis overview



- Modified selection with the respect to the Z→llγ analysis:
  - $p_T^l > 25(15)\ GeV$, $p_T^\gamma > 15(10)\ GeV$
  - $|\eta_\mu| < 2.7$, $|\eta_e| < 2.47$; $|\eta_\gamma| < 2.37$, $1.37 < |\eta_\gamma| < 1.52$
  - $\Delta R_{l\gamma} > 0.4$ for both photons
    - $m_{ll\gamma} < 80\ GeV$ for both photons

- The nominal MC sample: **Powheg+Pythia+Photos**
  - Sherpa 1.4 ME$\gamma\gamma$ (YFS): 1 photon from ME LO with up to 3 jets at ME LO, QED ISR & FSR



$Z \to ll\gamma\gamma$: Data to MC comparison