Precision measurements of jet and photon production at the ATLAS experiment

Jennifer Roloff, on behalf of the ATLAS collaboration

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Brookhaven National Laboratory

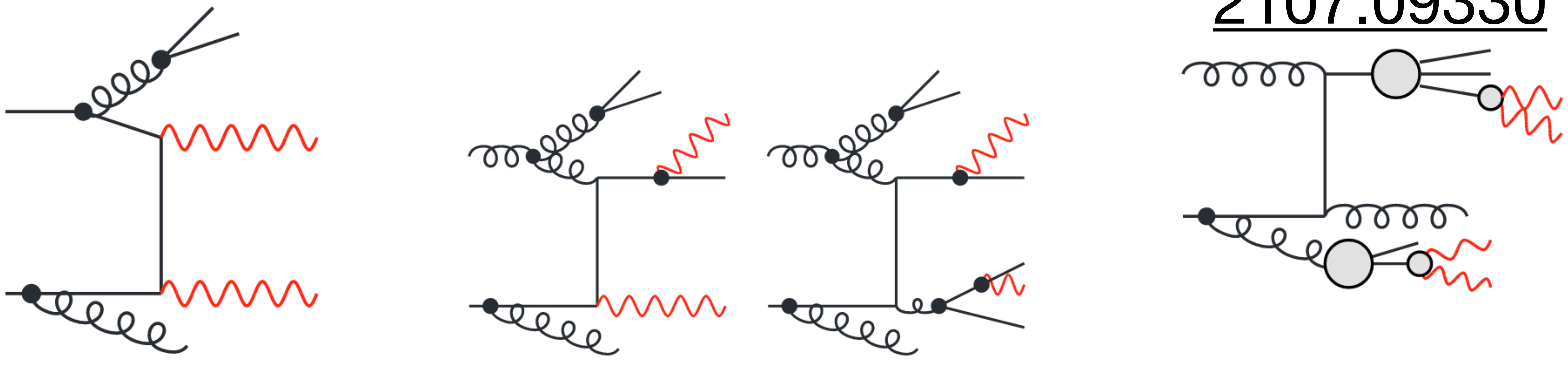
ATLAS EXPERIMENT

Precision QCD at the LHC

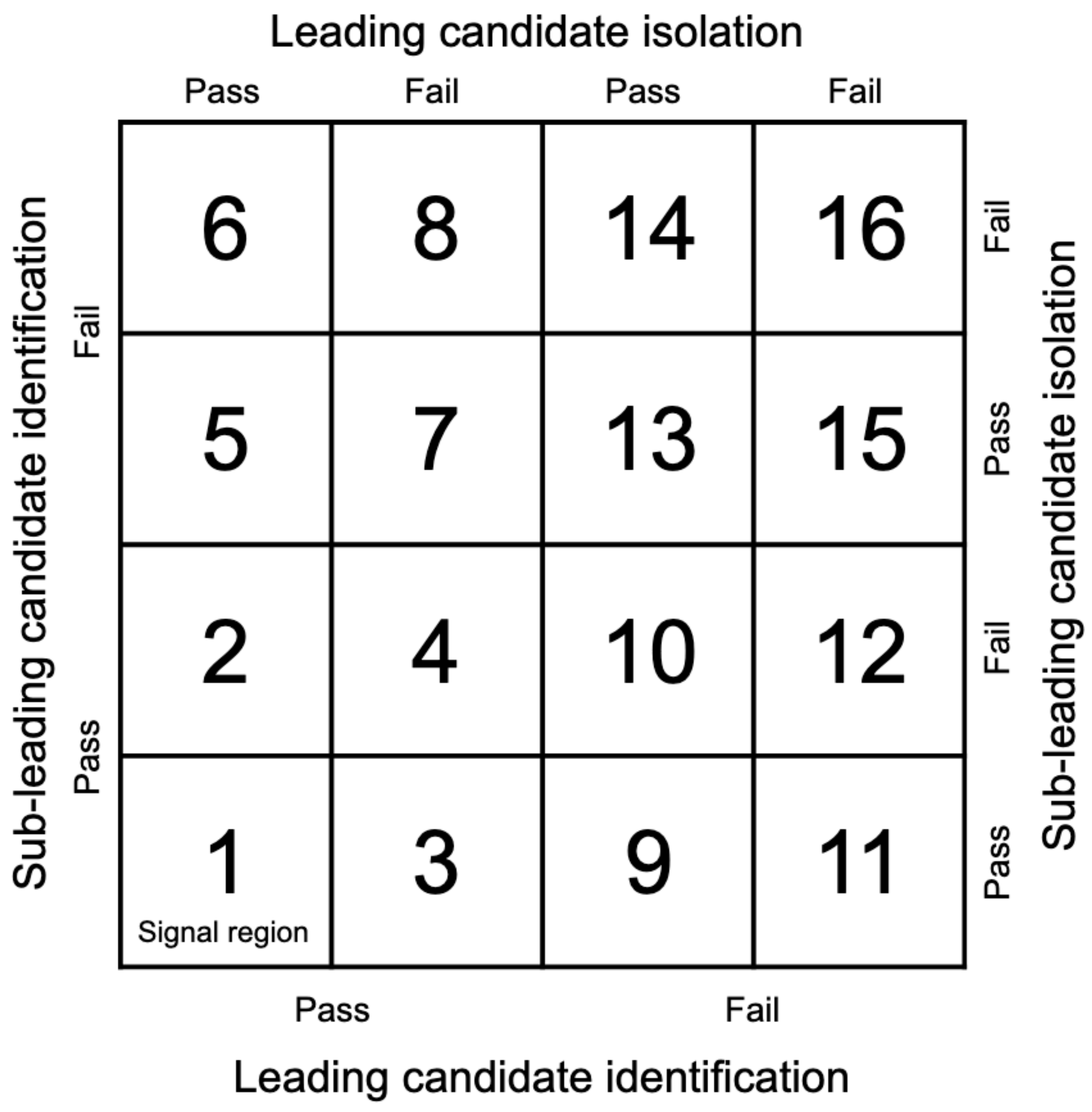
- LHC dataset enables precise tests of QCD
  - Tests of perturbative QCD predictions, especially at high scales
  - Extracting the strong coupling constant and its running
  - Studying non-perturbative parton showers and hadronization
- Huge dataset and precise object reconstruction enable increased precision and more granular measurements
- Focusing on 3 measurements today
  - *Measurement of isolated diphoton cross-section*
  - *Extraction of α_S using transverse energy-energy correlations (TEECs)*
  - *Measurement of b-quark fragmentation in jets*

Measurement of diphoton production

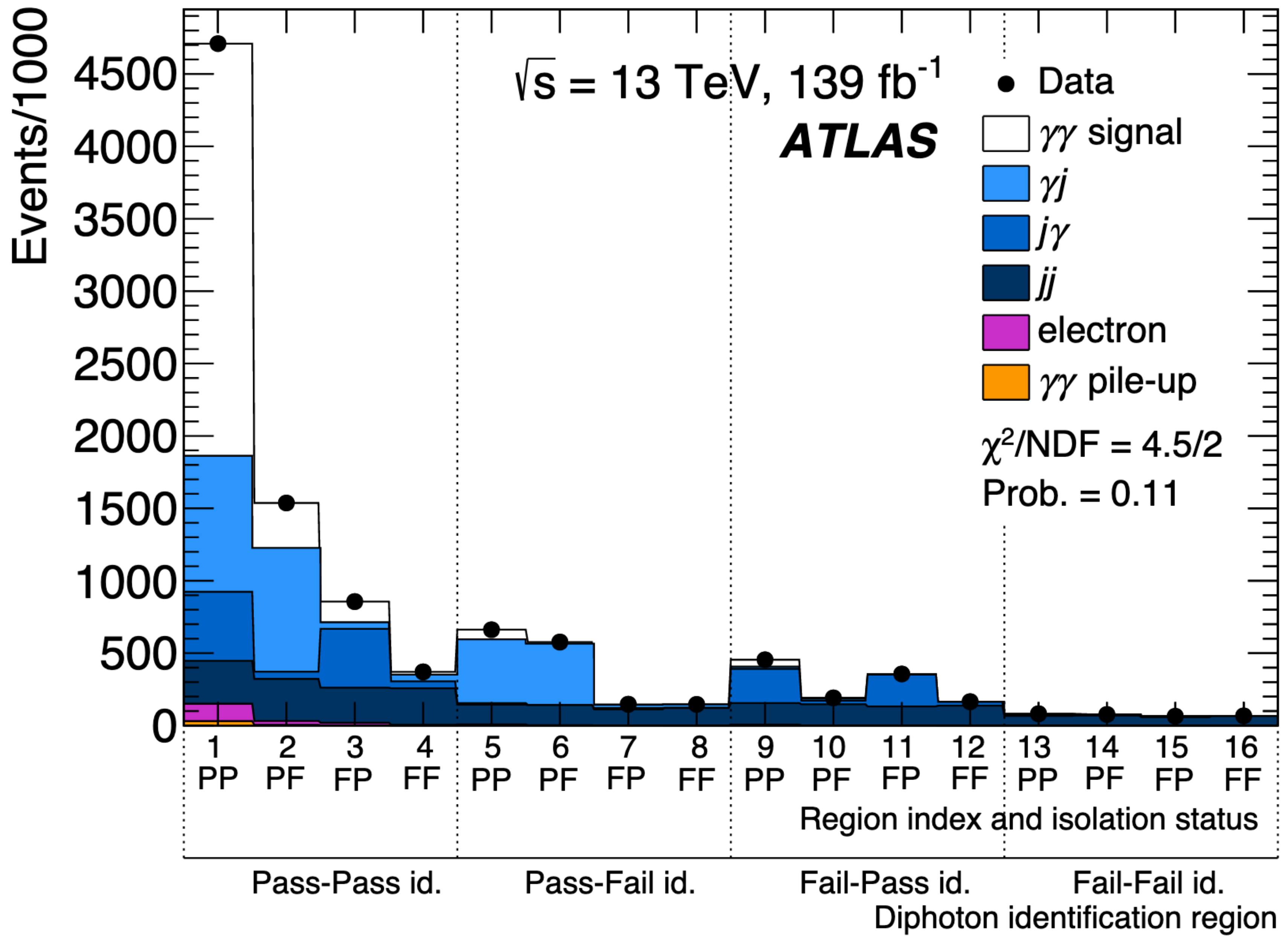
2107.09330



(a) Direct photons (b) Single- and double-fragmentation photons (c) Non-prompt photons



- Diphoton final state, but very sensitive to QCD
  - Direct and fragmentation photon processes are sensitive to different effects
- Important background for Higgs production
- Measuring the inclusive and differential diphoton cross-section
- Using isolation and photon ID to estimate the background contributions
  - Most background is from jets misidentified as photons



Measurement of diphoton production

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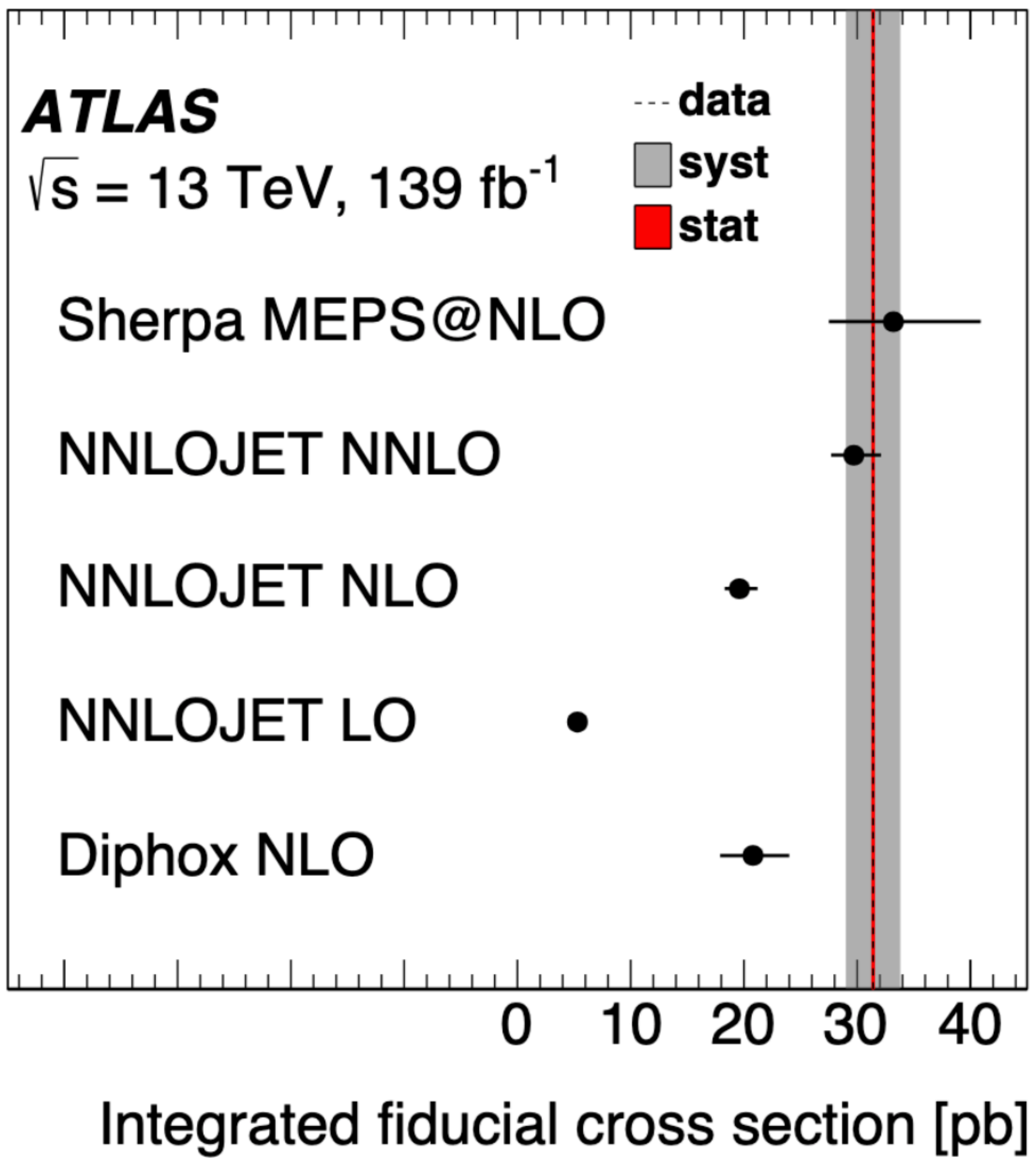
- Comparing inclusive cross-section measurement to several theoretical predictions
- Important to have high fixed-order accuracy, as well as contributions from $\gamma\gamma$+(2j, 3j)



	Fixed-order accuracy						Fragmentation		QCD	NP
	$\gamma\gamma$	$+1j$	$+2j$	$+3j$	$+\geq 4j$	$gg \to \gamma\gamma$	single	double	res.	effects
DIPHOX	NLO	LO	-	-	-	LO	NLO		–	–
NNLOJET	NNLO	NLO	LO	-	-	LO	–	–	–	–
SHERPA	NLO		LO		PS	LO	ME+PS		PS	✓

Measurement of diphoton production

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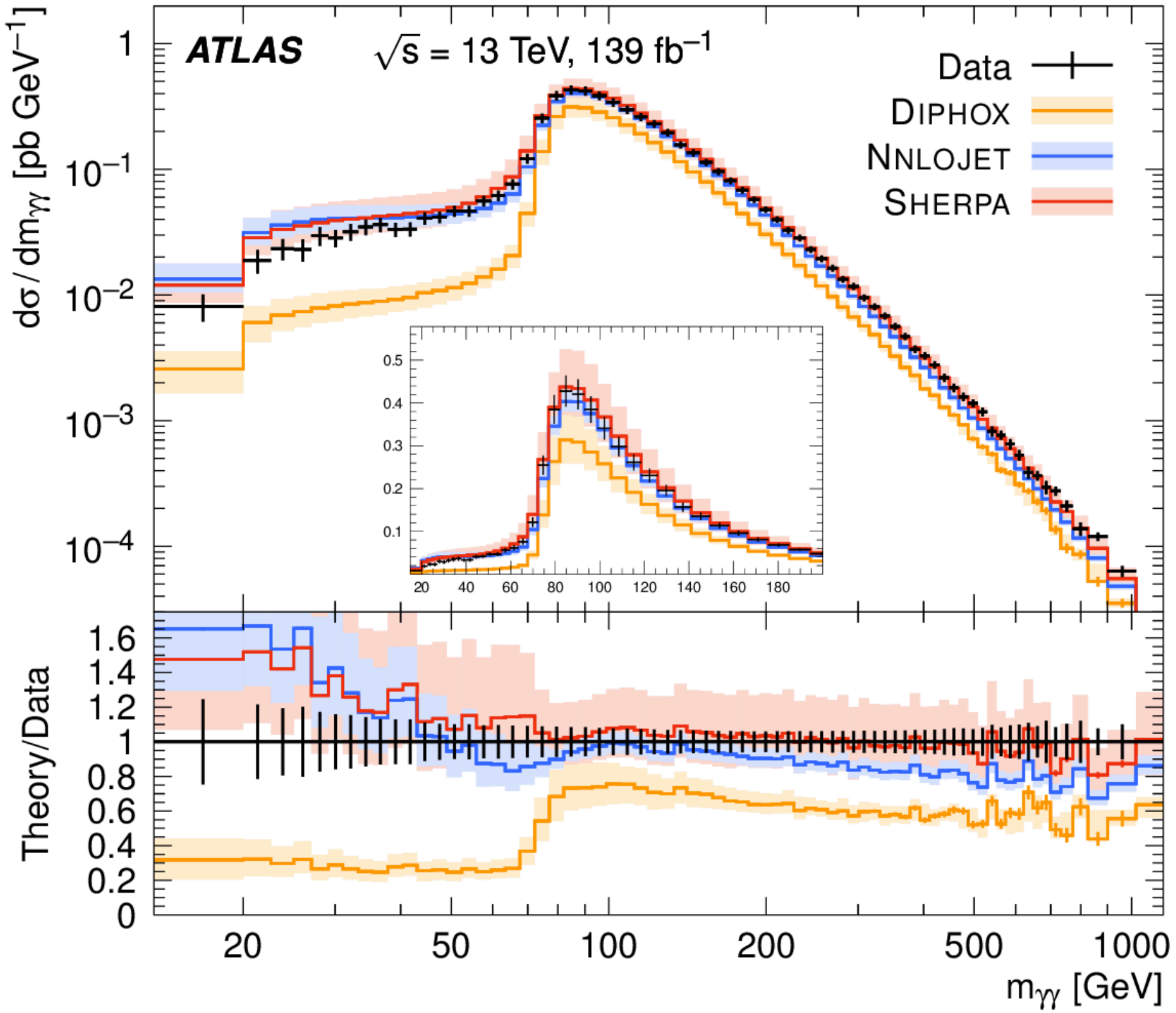
- $m_{\gamma\gamma} < p_{T1} + p_{T2}$ is suppressed
  - Only populated because of $\gamma\gamma$+multijet
  - Low-mass distribution is dependent on photon kinematic cuts
- DIPHOX doesn't model these well, but NNLOJET and Sherpa both include higher order contributions
- Slight underestimation from NNLOJET at high $m_{\gamma\gamma}$



Measurement of diphoton production

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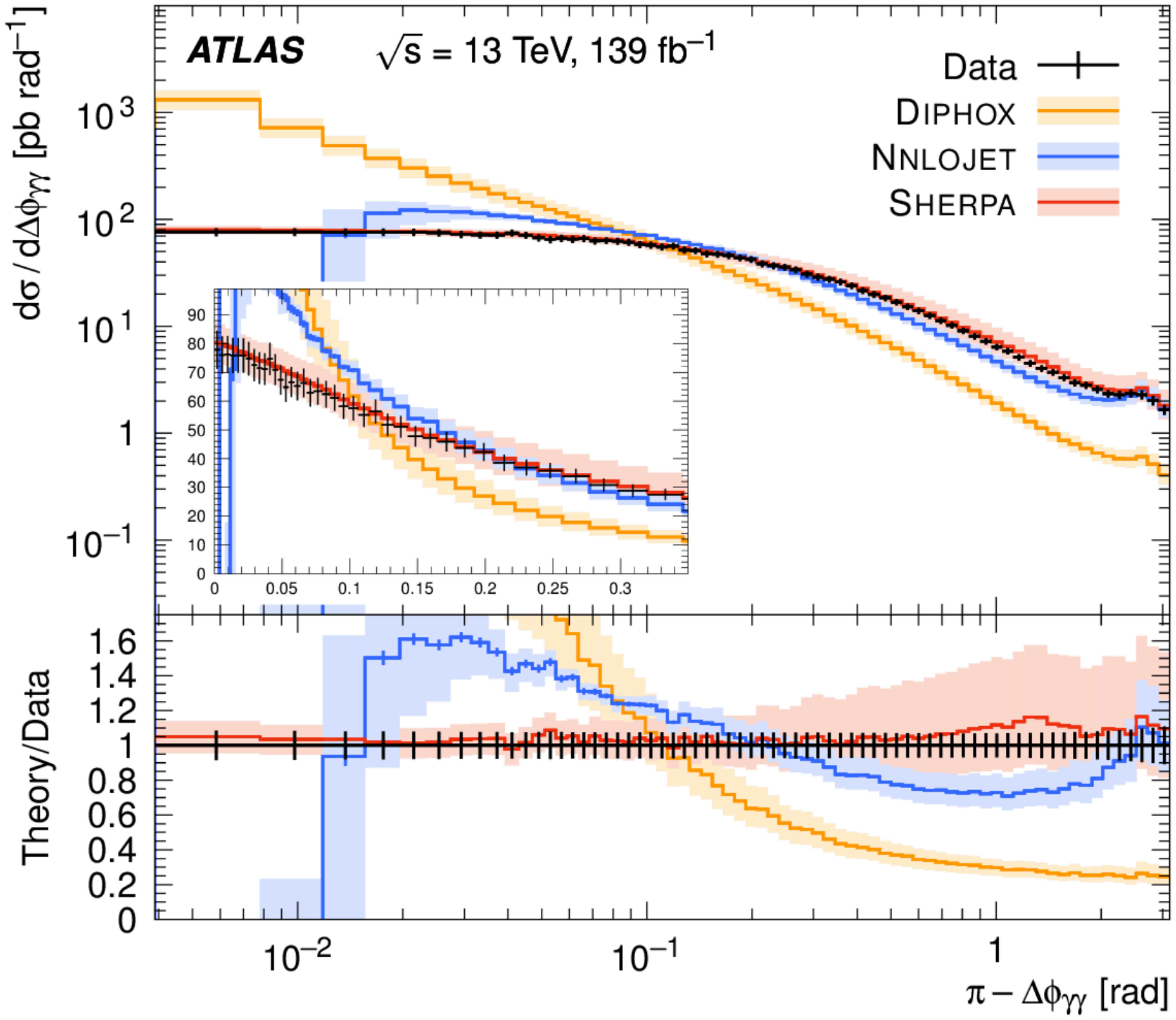
- Very small azimuthal decorrelation means very collinear → large impact from soft emissions
  - Difficult to model well, large disagreements with fixed-order predictions
- Sherpa includes resummation of these effects, and is able to model this fairly well
- Some underestimation from NNLOJET in the intermediate region
- DIPHOX does not model this well anywhere



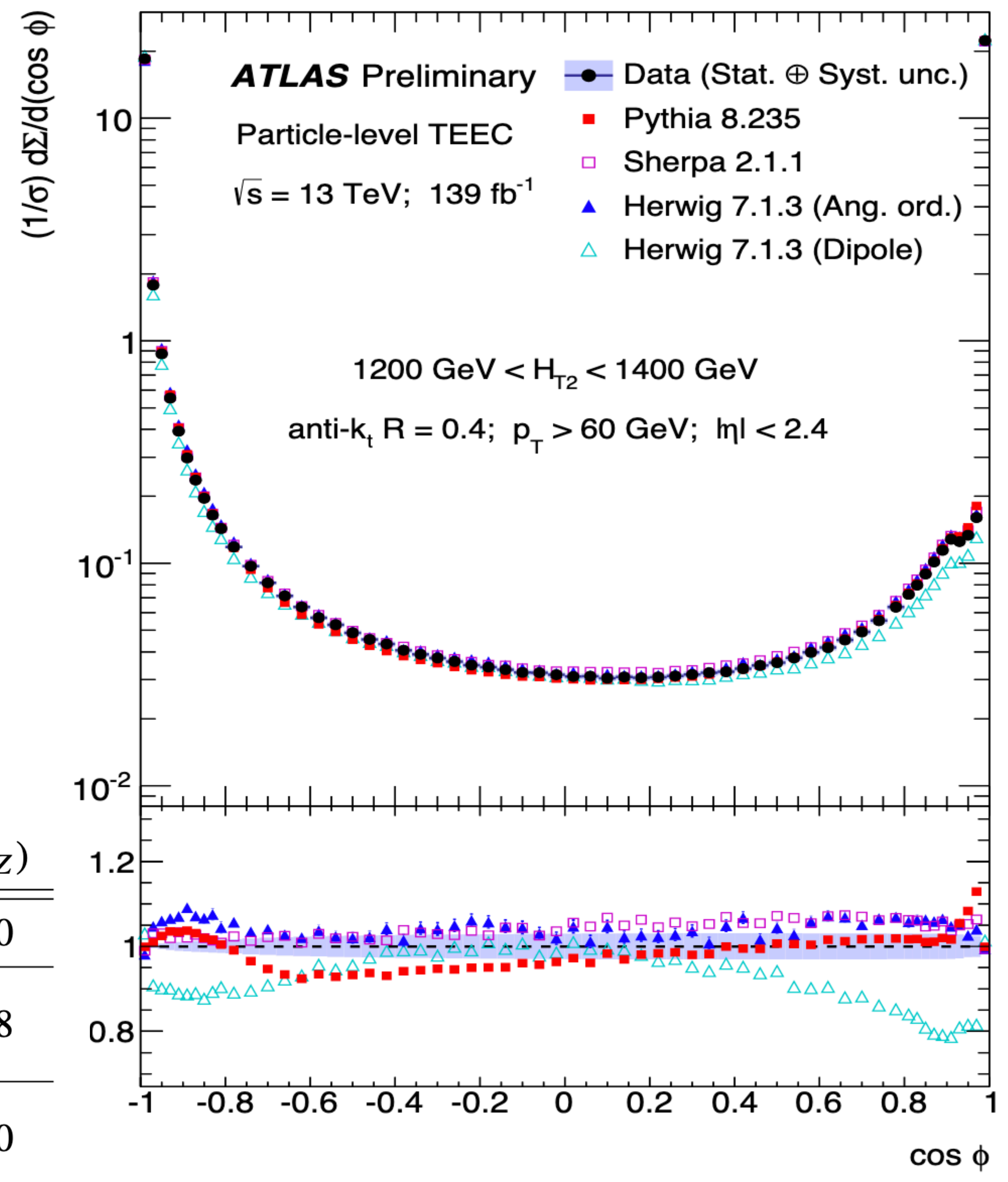
Transverse energy-energy correlations

ATLAS-CONF-2020-025

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi} \equiv \frac{1}{\sigma}\sum_{ij}\int \frac{\mathrm{d}\sigma}{\mathrm{d}x_{\mathrm{T}i}\mathrm{d}x_{\mathrm{T}j}\mathrm{d}\cos\phi} x_{\mathrm{T}i}x_{\mathrm{T}j}\mathrm{d}x_{\mathrm{T}i}\mathrm{d}x_{\mathrm{T}j} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

- E_T-weighted distribution of the Δϕ between jet pairs
- cosϕ = -1: back-to-back jets, very dijet-like
- cosϕ = 1: collinear jets, sensitive to splittings and soft effects
- Kink in the cosphi distribution around double the jet radius (0.92)

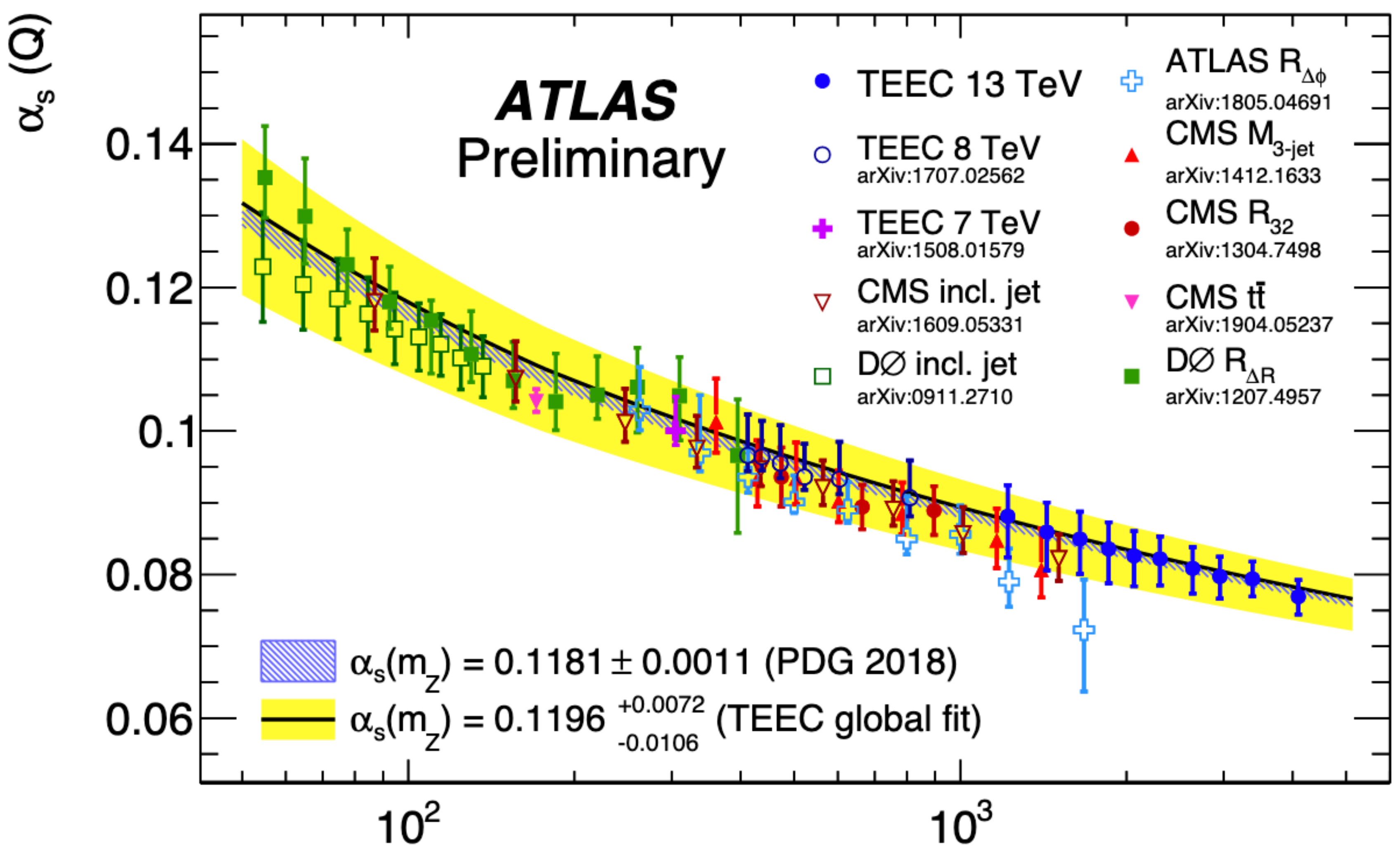
Generator	ME order	ME partons	PDF set	Parton shower	Scales μ_R, μ_F	$\alpha_s(m_Z)$
Pythia 8	LO	2	NNPDF 2.3 LO	p_T-ordered	$(m_{T3}\cdot m_{T4})^{\frac{1}{2}}$	0.140
Sherpa	LO	2,3	CT14 NNLO	CSS (dipole)	$H(s,t,u)$ [2 → 2] CMW [2 → 3]	0.118
Herwig 7	NLO	2,3	MMHT2014 NLO	Angular-ordered Dipole	$\max_i \{p_{Ti}\}_{i=1}^{N}$	0.120

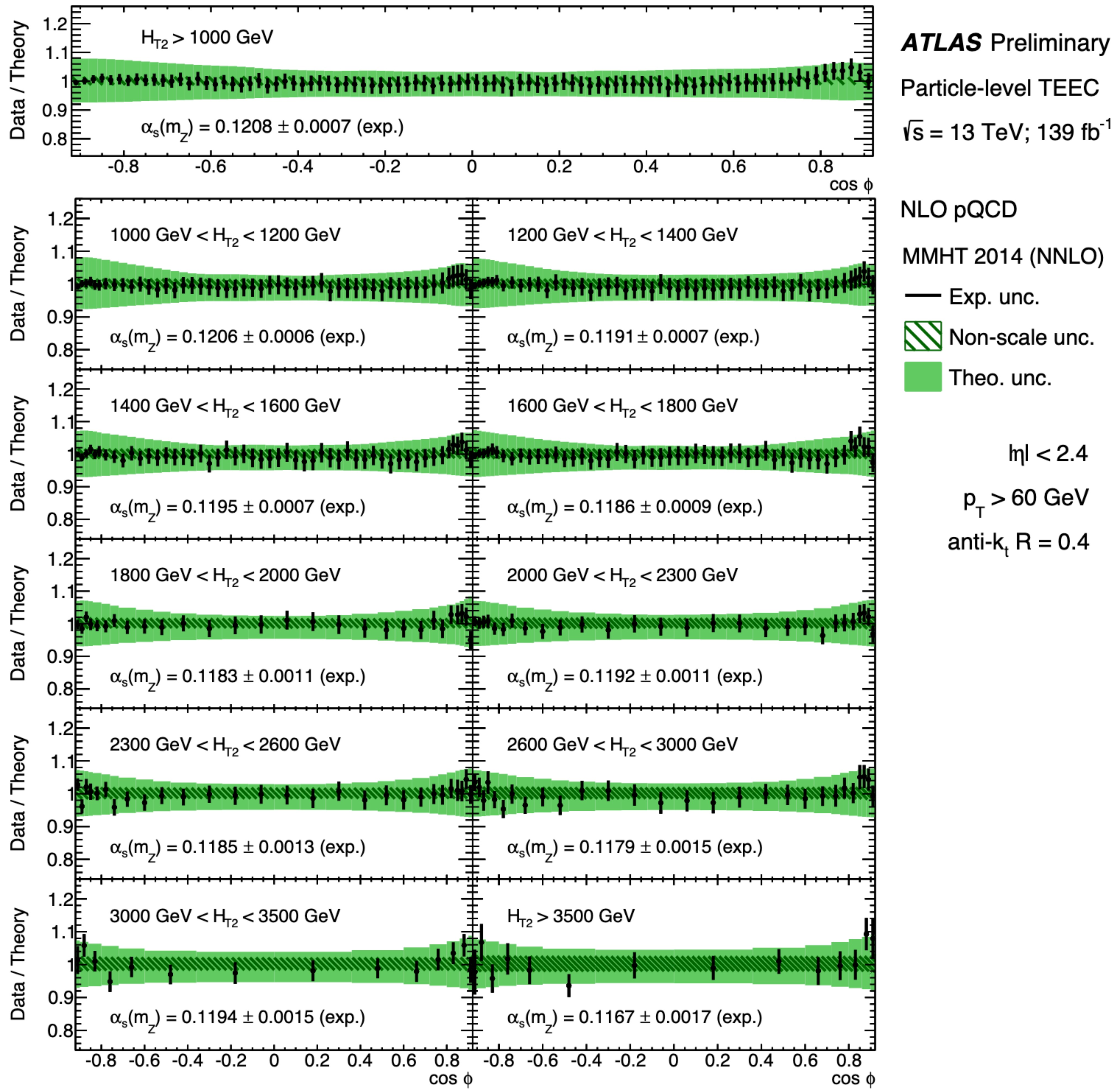


Transverse energy-energy correlations

ATLAS-CONF-2020-025

- Used NLO predictions to extract α_S and its running
  - Able to probe α_S to high Q (up to 4 TeV)
- Scale uncertainties are dominant
  - Systematic uncertainties (JES and modeling) are next-most important





$$\alpha_s(m_Z) = 0.1196 \pm 0.0001\,(\text{stat.}) \pm 0.0004\,(\text{syst.})^{+0.0071}_{-0.0104}\,(\text{scale}) \pm 0.0011\,(\text{PDF}) \pm 0.0002\,(\text{NP})$$

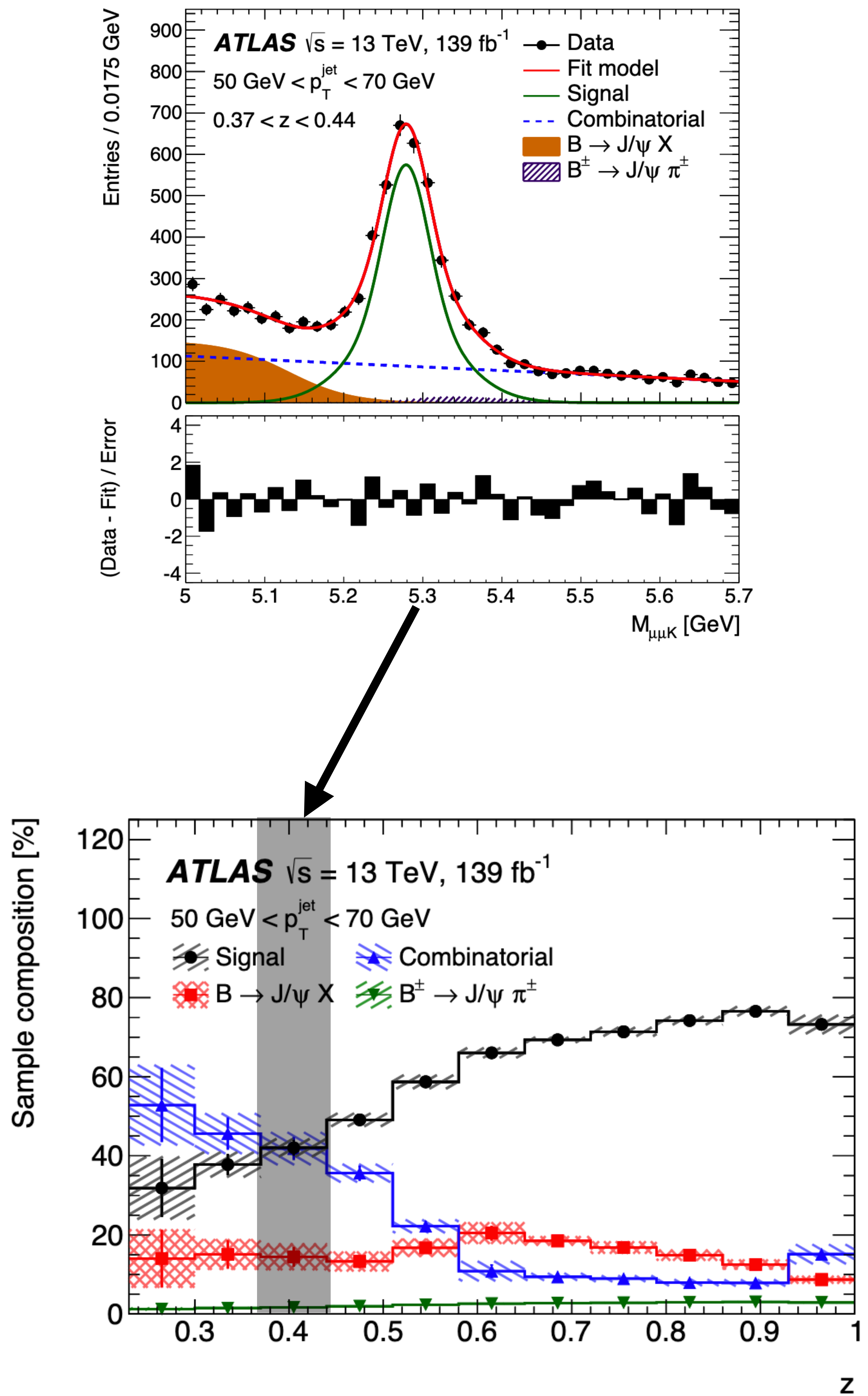
2108.11650

Exclusive B fragmentation

- Measuring b-fragmentation within jets using $B \rightarrow J/\psi K^{+/-}$
- B-fragmentation important for Higgs measurements, top mass measurements, and more
- Measuring longitudinal and transverse profiles of B-mesons over the jet momentum

$$z = \frac{\vec{p}_B \cdot \vec{p}_j}{|\vec{p}_j|^2}; \quad p_{\mathrm{T}}^{\mathrm{rel}} = \frac{|\vec{p}_B \times \vec{p}_j|}{|\vec{p}_j|},$$

- B-meson yield is extracted for each bin of the measurement using a template fit
- Sensitive to fragmentation functions and $g \rightarrow bb$ splitting



B fragmentation

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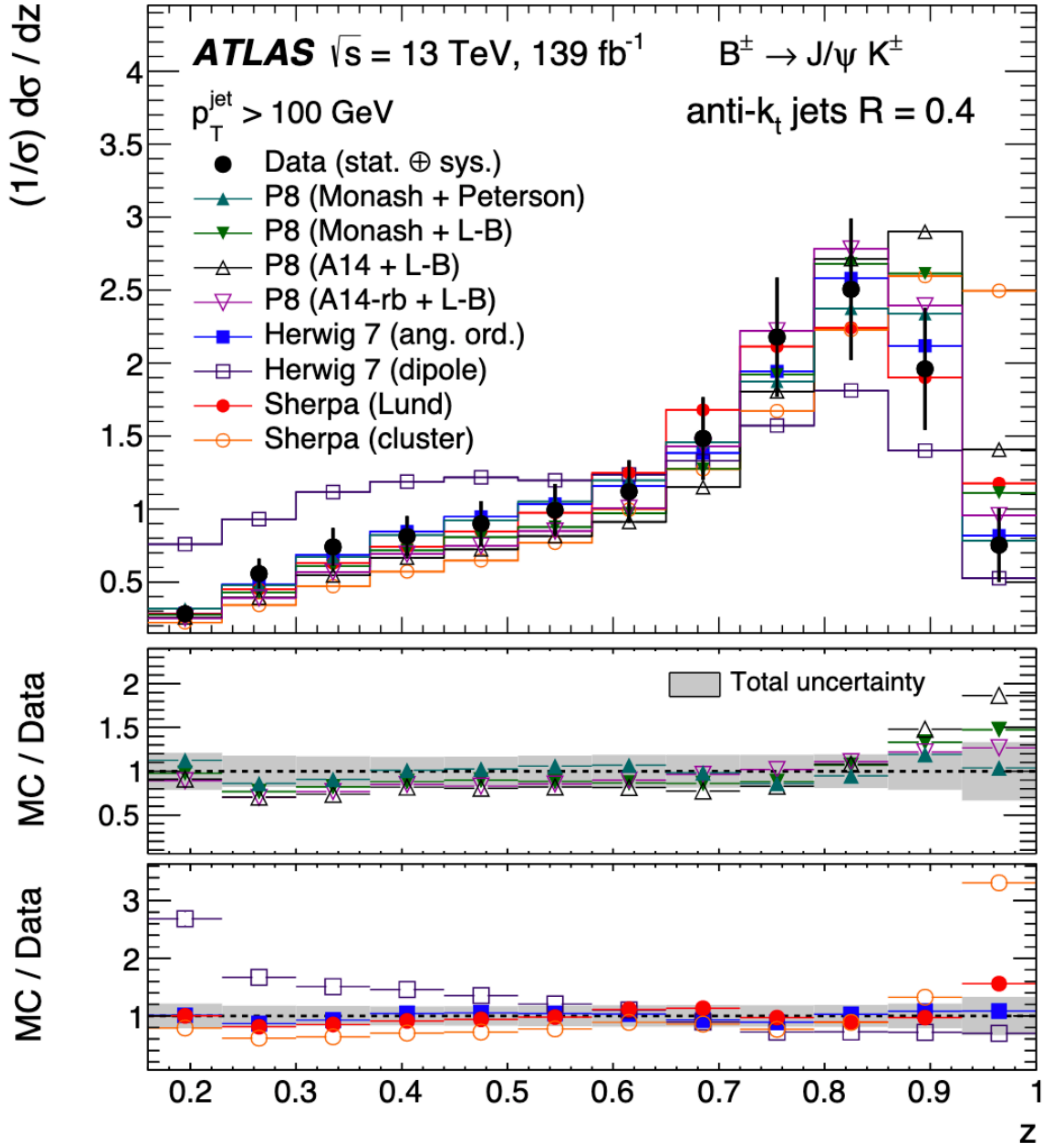
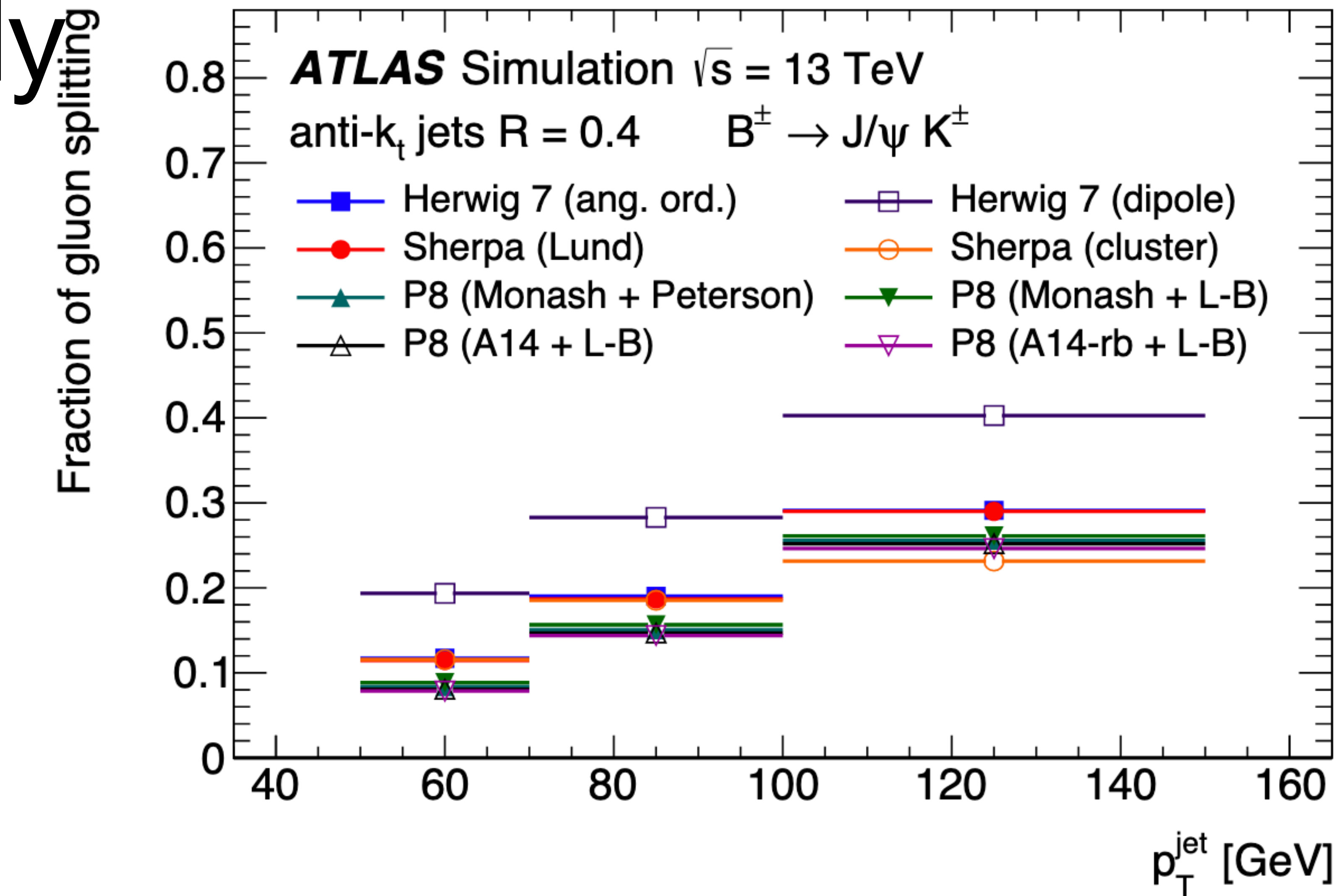
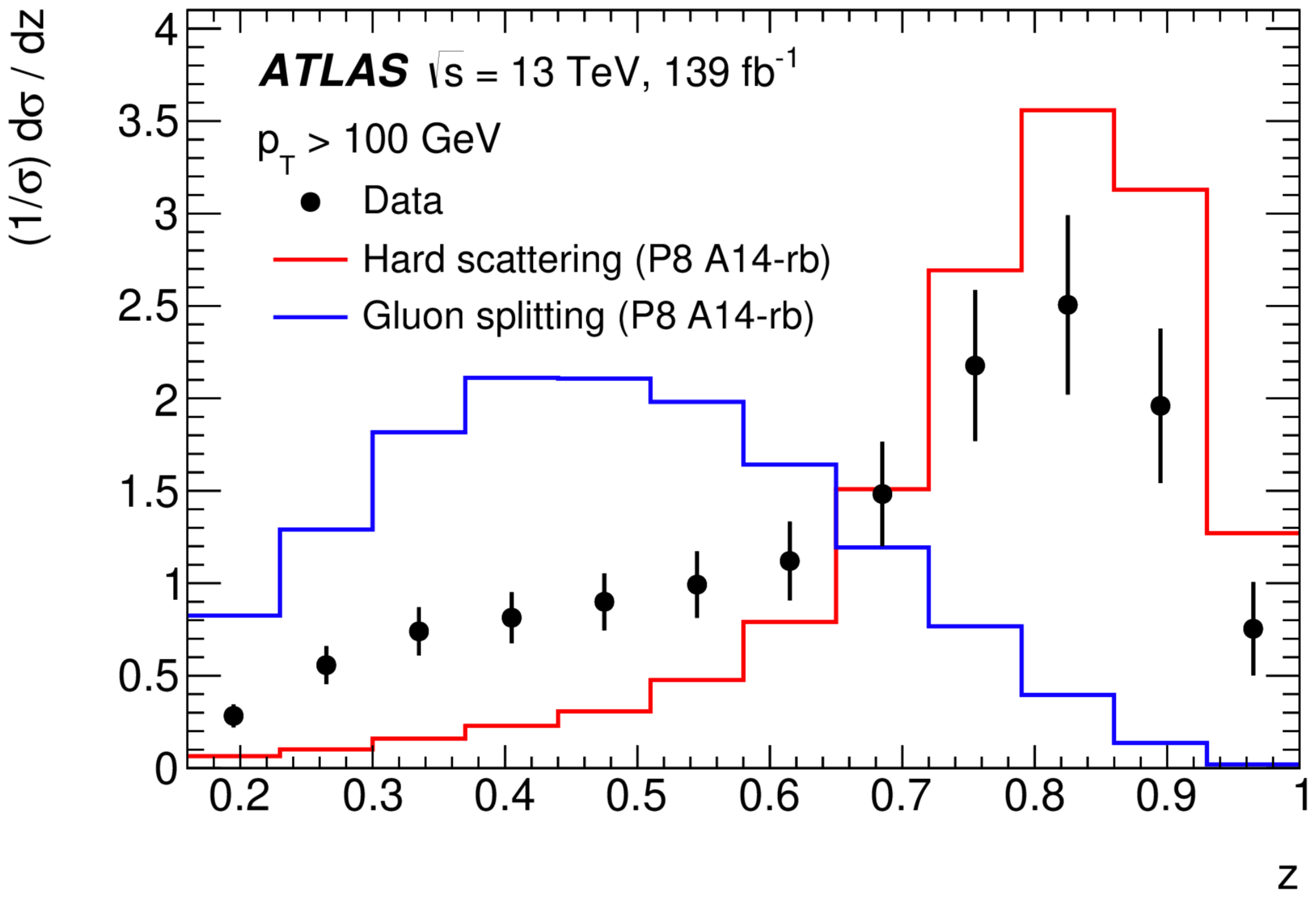


- Z-distribution from hard scattering and gluon splitting are very distinct
- Herwig7 angle-ordered shower very similar to both Sherpa predictions
- Both Sherpa predictions are similar, except at very high z
  - Little impact from hadronization
- Herwig7 dipole significantly overestimates g → bb
- Pythia Monash has a higher α_S than Pythia A14, so more g → bb splitting





Summary

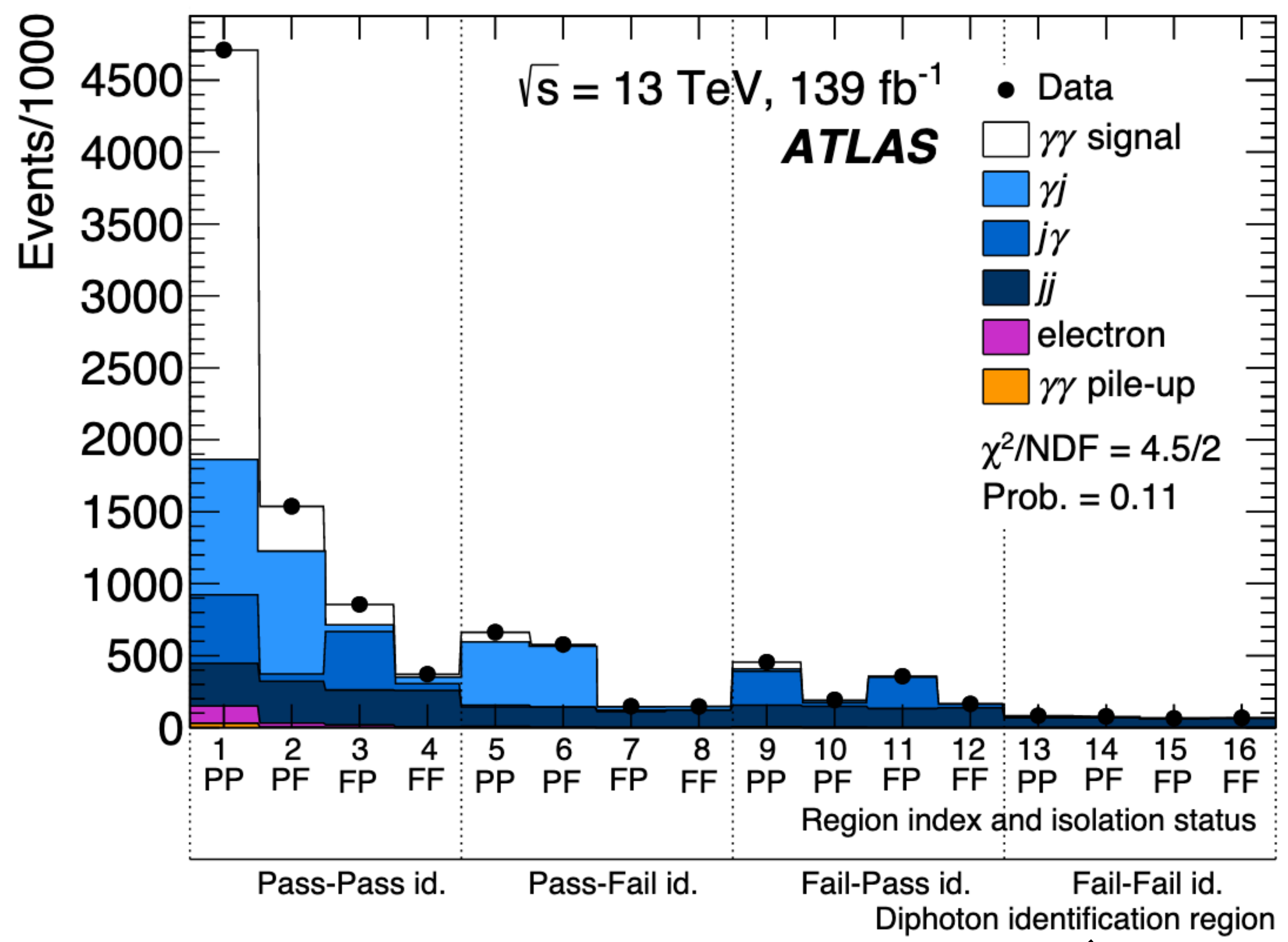
- LHC provides a rich playground for studying QCD
  - Able to study to high scales not tested by other experiments
  - Large dataset enables precise measurements
- Advances in theoretical predictions enable studying a wide range of effects
  - Measurement of diphotons provides strong tests of higher-order QCD corrections
  - Measurement of TEECs enables extraction of the running of aS at NLO for scales up to 4 TeV
  - Measurement of b-fragmentation improves understanding of heavy quark fragmentation

Backup

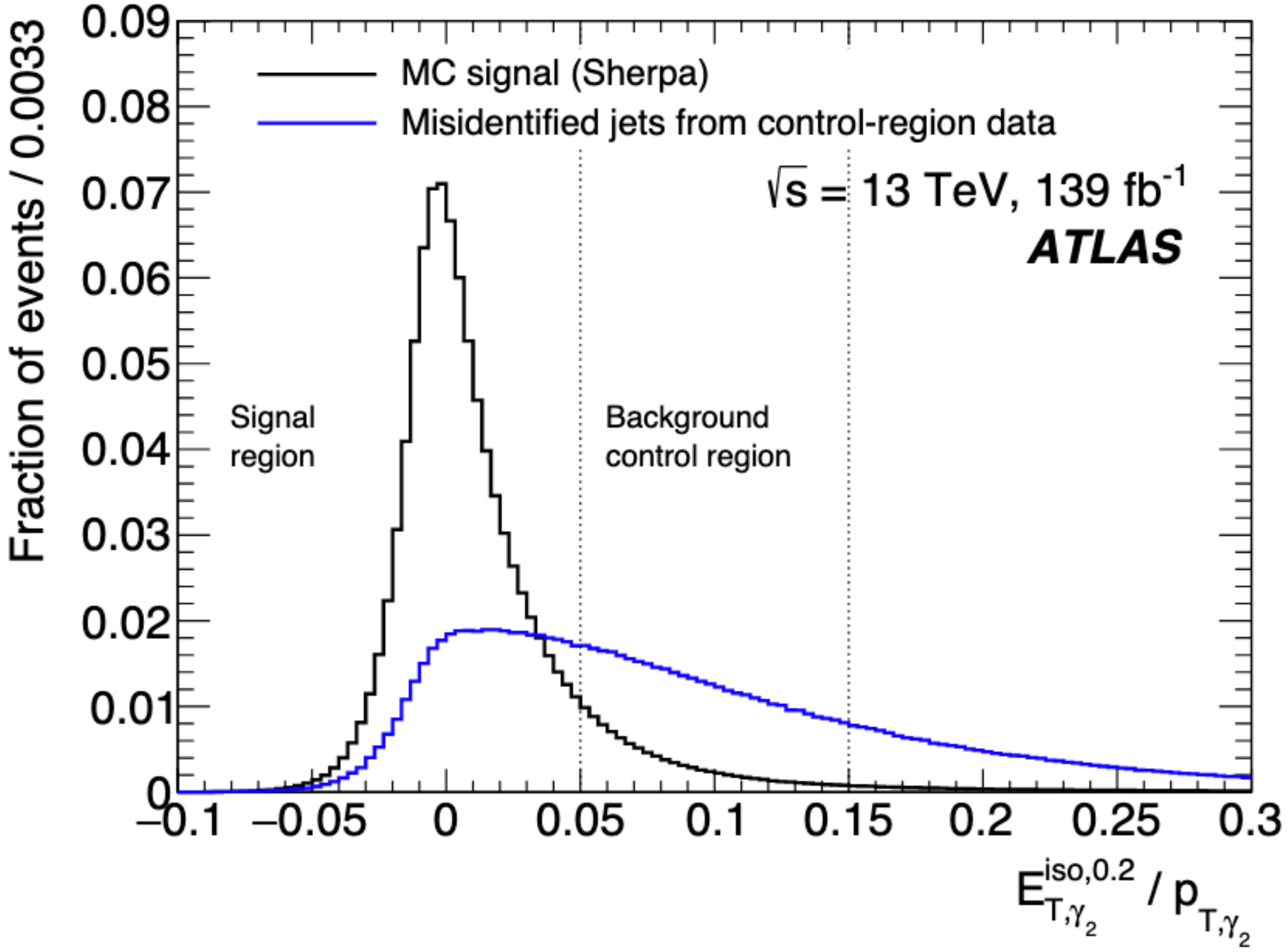
Backup

- NNLOJET:
  - NNLO predictions
  - gg→$\gamma\gamma$ at LO
  - Uses the NNPDF3.0 NNLO PDF set
  - Factorization and normalization scales of myy
  - Hybrid photon isolation to remove photon-quark configurations
  - Fragmentation component not included since these are not available at NNLO
- DIPHOX
  - NLO predictions using CT10 NLO PDFs
  - Factorization, normalization, and fragmentation scales of myy
  - Includes fragmentation component
- SHERPA
  - Includes direct and fragmentation components
  - gg→$\gamma\gamma$ at LO
  - pp→$\gamma\gamma$ + (0,1) jet at NLO, pp→$\gamma\gamma$ + (2,3) jet at LO
  - Use NNPDF3.0@NNLO

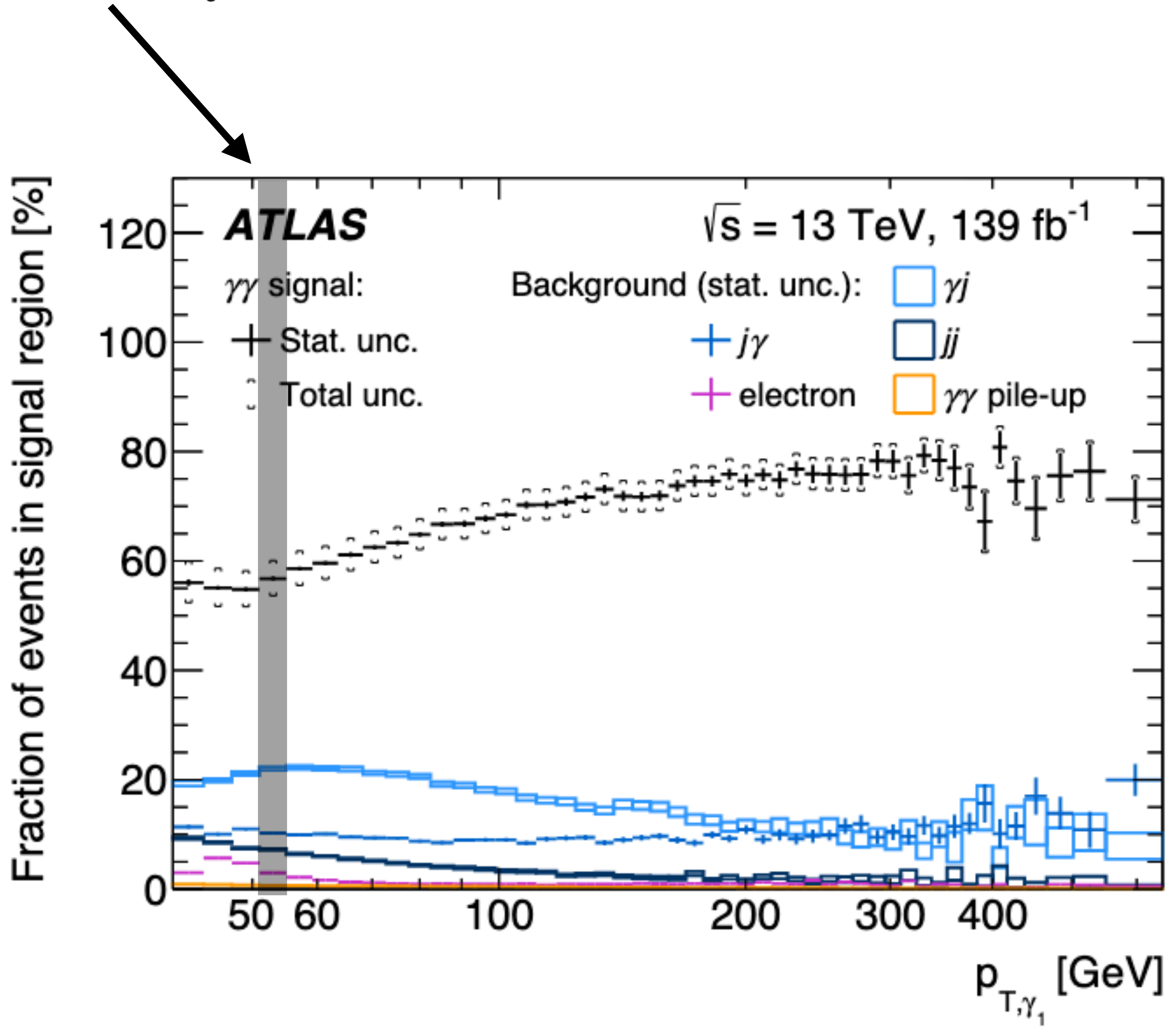
Backup



Events/1000
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
ATLAS
Data
$\gamma\gamma$ signal
γj
$j\gamma$
jj
electron
$\gamma\gamma$ pile-up
χ^2/NDF = 4.5/2
Prob. = 0.11
Region index and isolation status
Pass-Pass id.
Pass-Fail id.
Fail-Pass id.
Fail-Fail id.
Diphoton identification region



Fraction of events / 0.0033
MC signal (Sherpa)
Misidentified jets from control-region data
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
ATLAS
Signal region
Background control region
$E_{T,\gamma_2}^{iso,0.2} / p_{T,\gamma_2}$

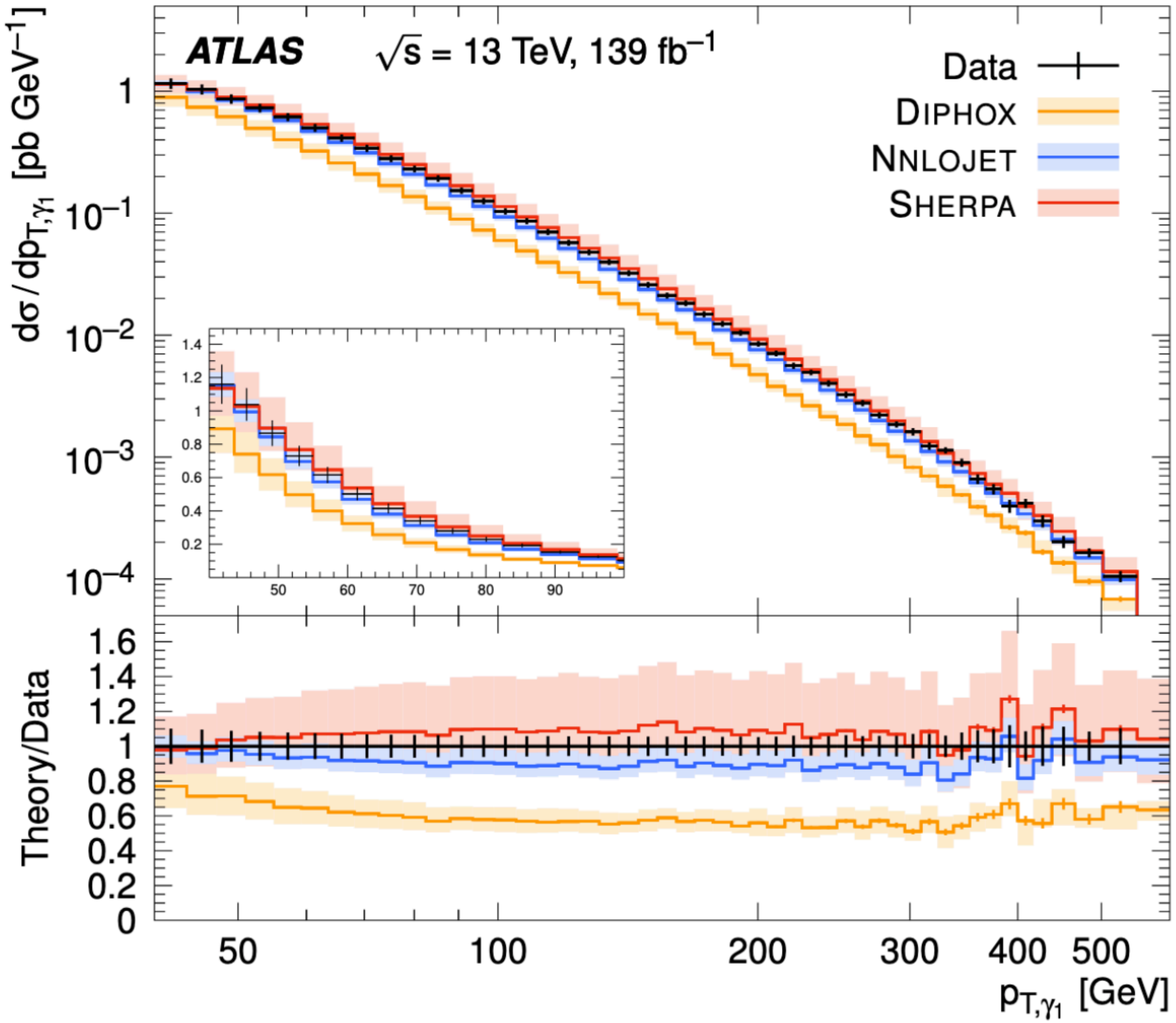


Fraction of events in signal region [%]
ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
$\gamma\gamma$ signal:
Stat. unc.
Total unc.
Background (stat. unc.):
γj
$j\gamma$
jj
electron
$\gamma\gamma$ pile-up
p_{T,γ_1} [GeV]

Measurement of diphoton production

2107.09330

- NNLOJET and DIPHOX are fixed-order (FO) predictions
  - Don't expect good agreement where multiple collinear or soft emissions are relevant
  - FO uncertainties do not cover differences with data
  - DIPHOX has different normalization, but roughly describes the shape
- Fixed order scale variations do not provide an accurate estimate of the true uncertainties
  - Typical feature of the diphoton process, where significant contributions and their uncertainties only appear at higher orders



Backup

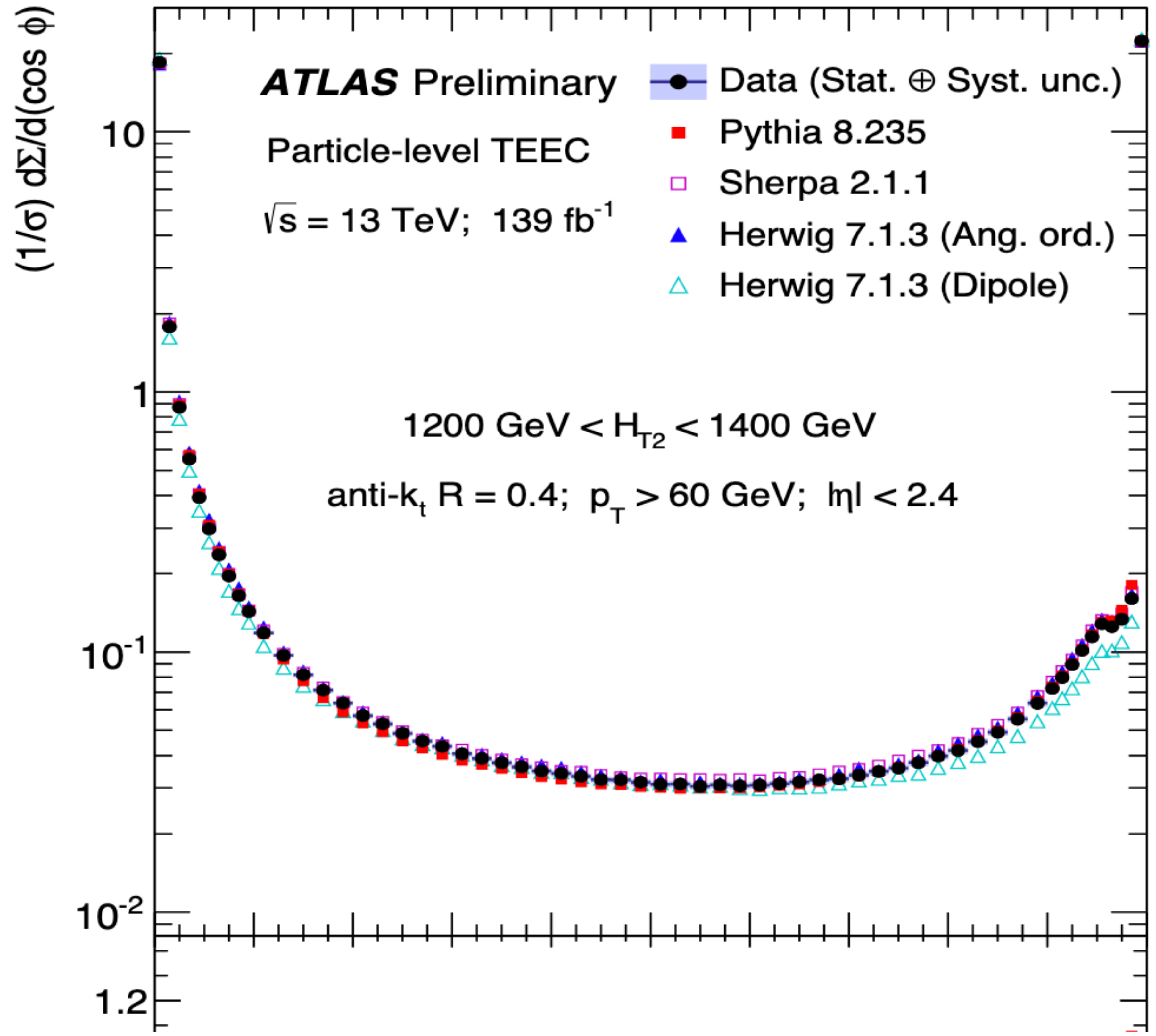
Selection	Detector level	Particle level
Photon kinematics	$p_{\mathrm{T},\gamma_{1(2)}} > 40$ (30) GeV,	$\lvert\eta_\gamma\rvert < 2.37$ excluding $1.37 < \lvert\eta_\gamma\rvert < 1.52$
Photon identification	tight	stable, not from hadron decay
Photon isolation	$E_{\mathrm{T},\gamma}^{\mathrm{iso},0.2} < 0.05 \cdot p_{\mathrm{T},\gamma}$	$E_{\mathrm{T},\gamma}^{\mathrm{iso},0.2} < 0.09 \cdot p_{\mathrm{T},\gamma}$
Diphoton topology	$N_\gamma \geq 2, \quad \Delta R_{\gamma\gamma} > 0.4$	

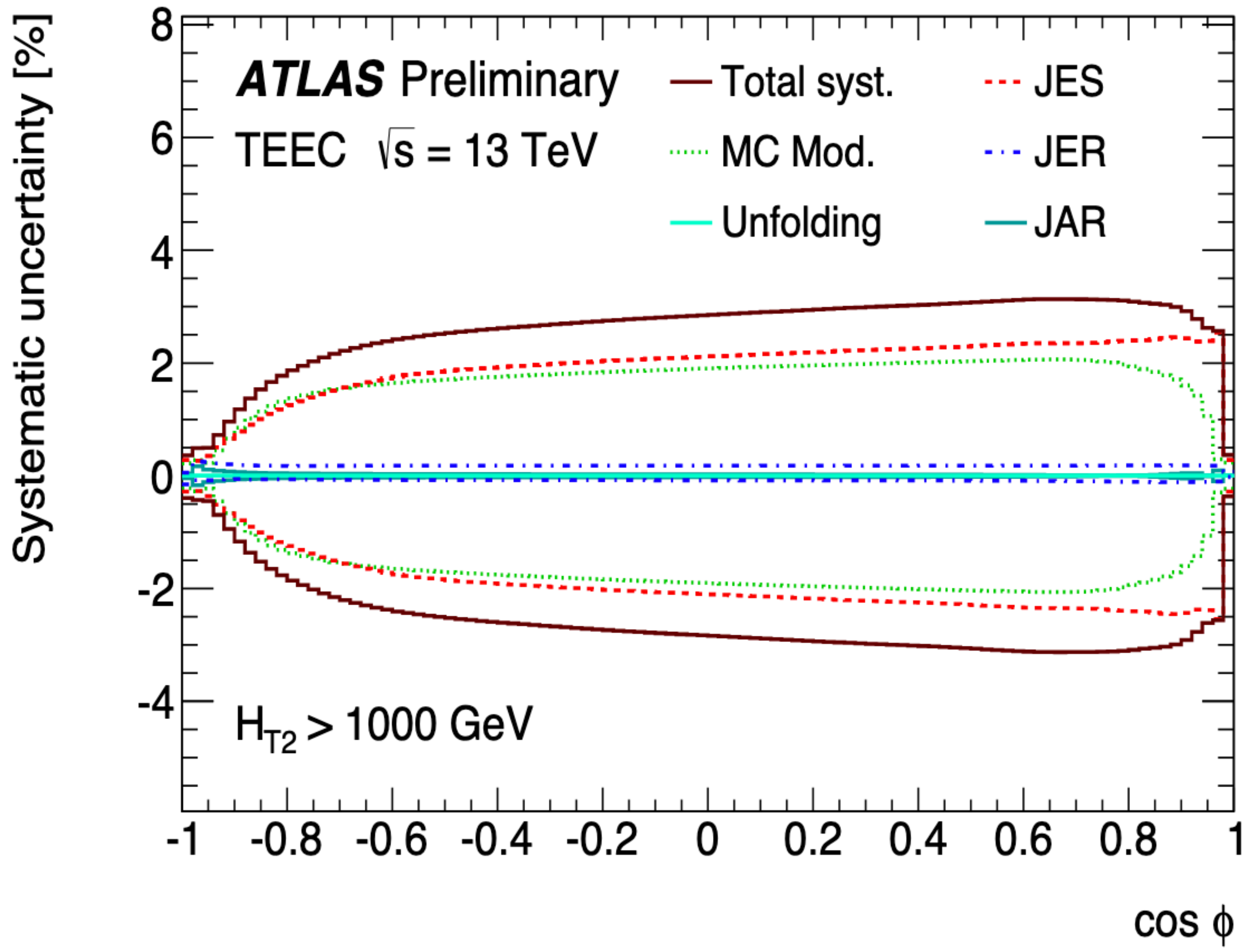
- Background estimation is typically one of the dominant uncertainties
  - Statistical uncertainties become important for large pT, myy
  -

TEECs

https://cds.cern.ch/record/2725553/

- Dominated by JES and modeling uncertainties





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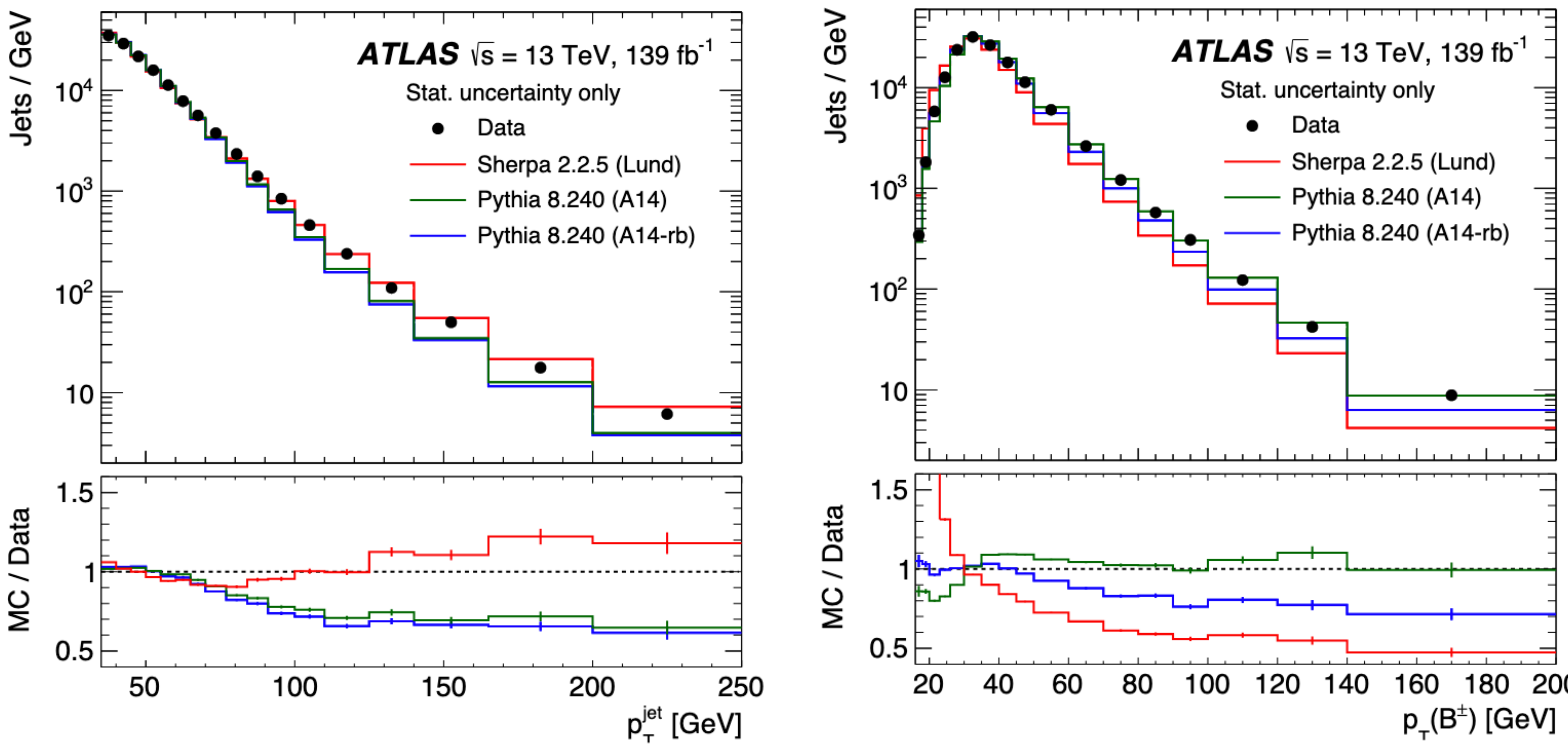
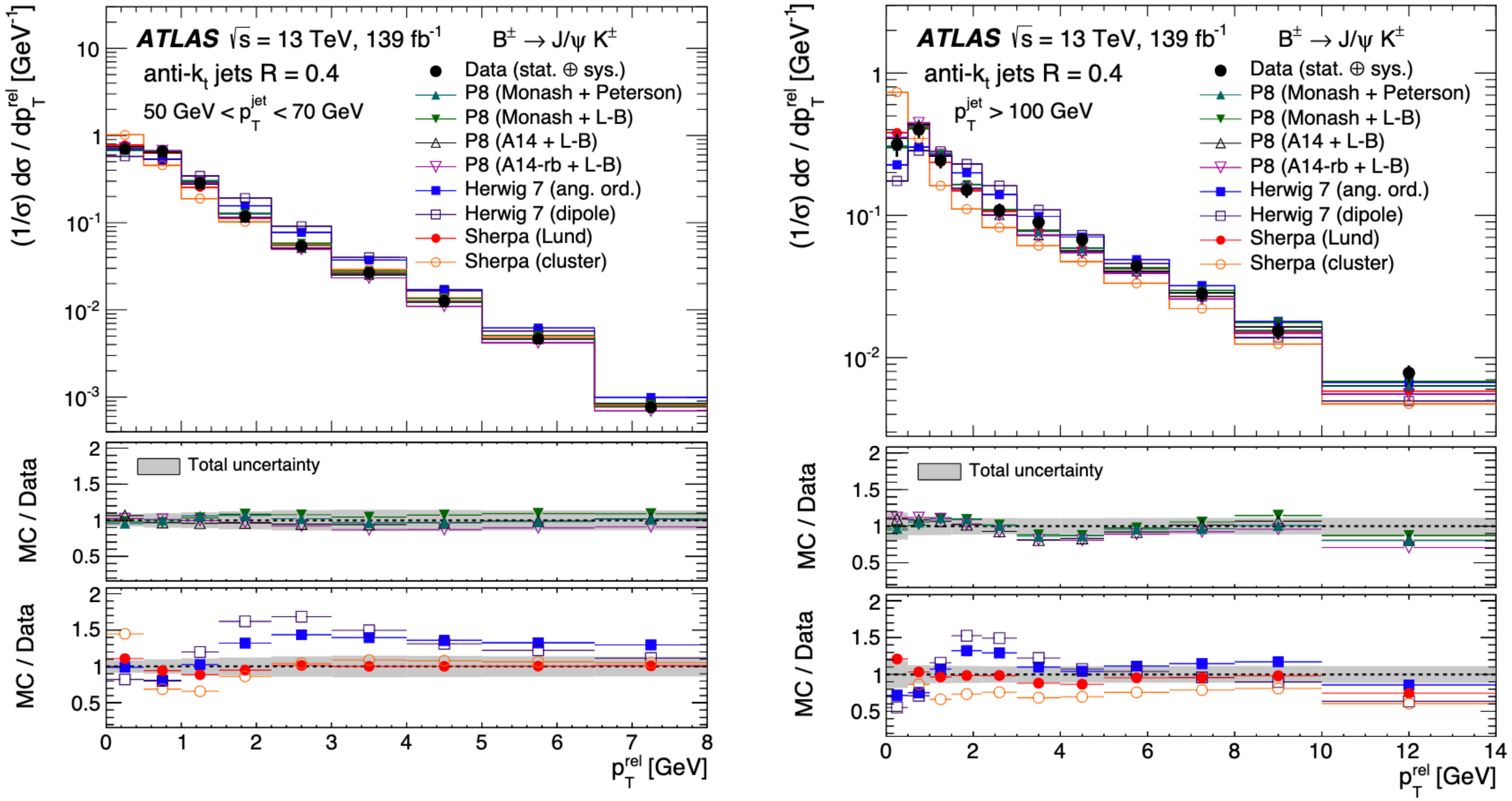
B fragmentation



Generator	ME order	Scales μ_r, μ_f	Parton shower	PDF set	Tune	Hadronisation
Pythia 8	$2 \to 2$ @ LO	$(m_{T3} \cdot m_{T4})^{\frac{1}{2}}$	p_T-ordered	CTEQ6L1	A14 A14-rb	Lund–Bowler Lund–Bowler
				NNPDF2.3	Monash	Lund–Bowler Peterson
Sherpa	$2 \to 2$ @ LO	$H(s,t,u)$	CSS (dipole)	CT14	–	Cluster model Lund string model
Herwig 7	$2 \to 2$ @ LO	$\sqrt{\frac{2stu}{s^2+t^2+u^2}}$	Angle-ordered Dipole	MMHT2014	–	Cluster model

B fragmentation



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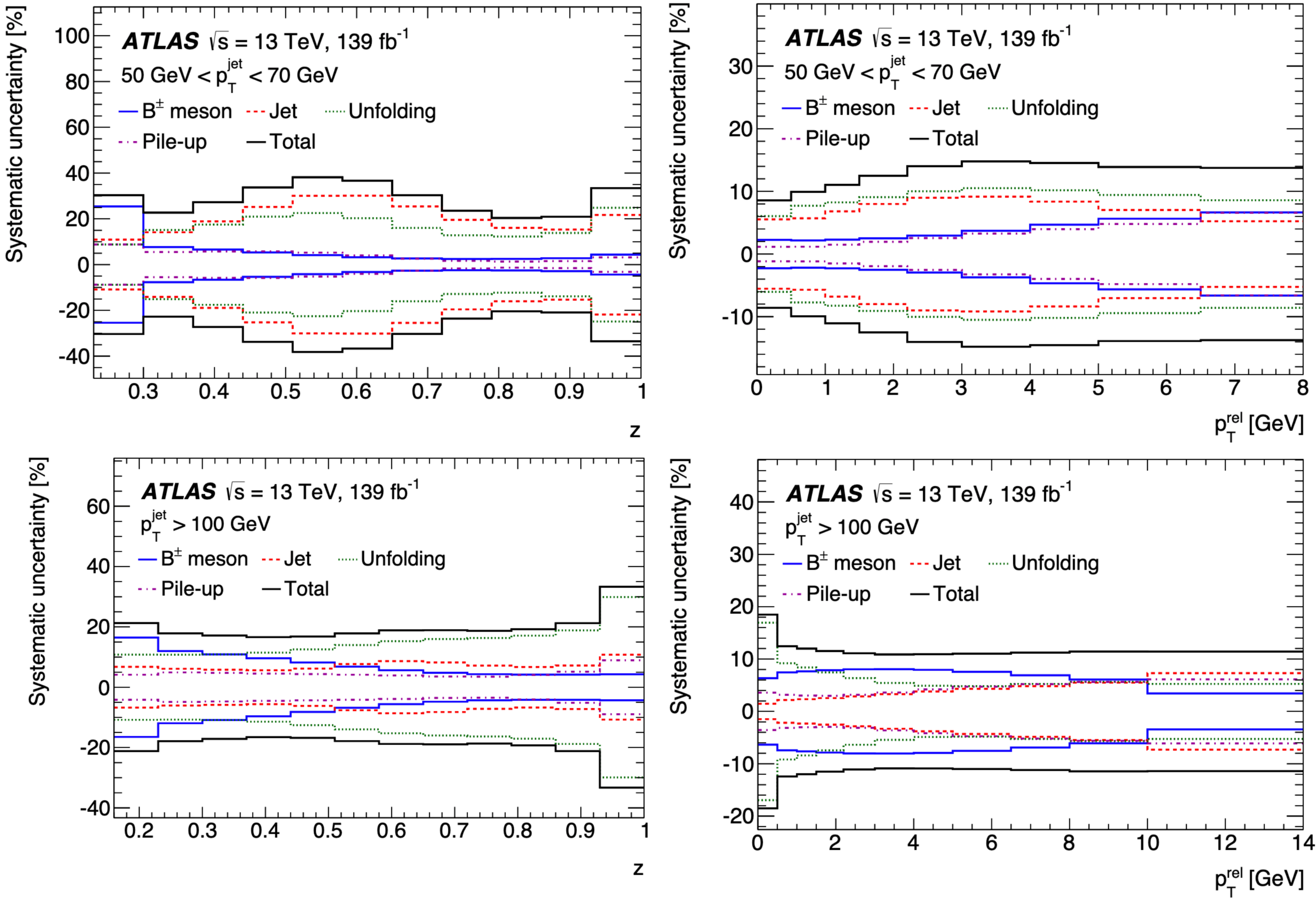

B fragmentation

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- Higher jet pt means more g → bb splitting
- Herwig7 angle-ordered shower very similar to both Sherpa predictions
- Both Sherpa predictions are similar, except at very high z
  - Little impact from hadronization
- Herwig7 dipole significantly overestimates the g → bb splitting contribution
- Pythia Monash has a higher aS than Pythia A14, so more g → bb splitting

$$z = \frac{\vec{p}_B \cdot \vec{p}_j}{|\vec{p}_j|^2}; \quad p_T^{\mathrm{rel}} = \frac{|\vec{p}_B \times \vec{p}_j|}{|\vec{p}_j|},$$