18 December 2016

Second China LHC Physics Workshop

KARRI FOLAN DIPETRILLO

Z+JETS @ 13 TEV IN ATLAS

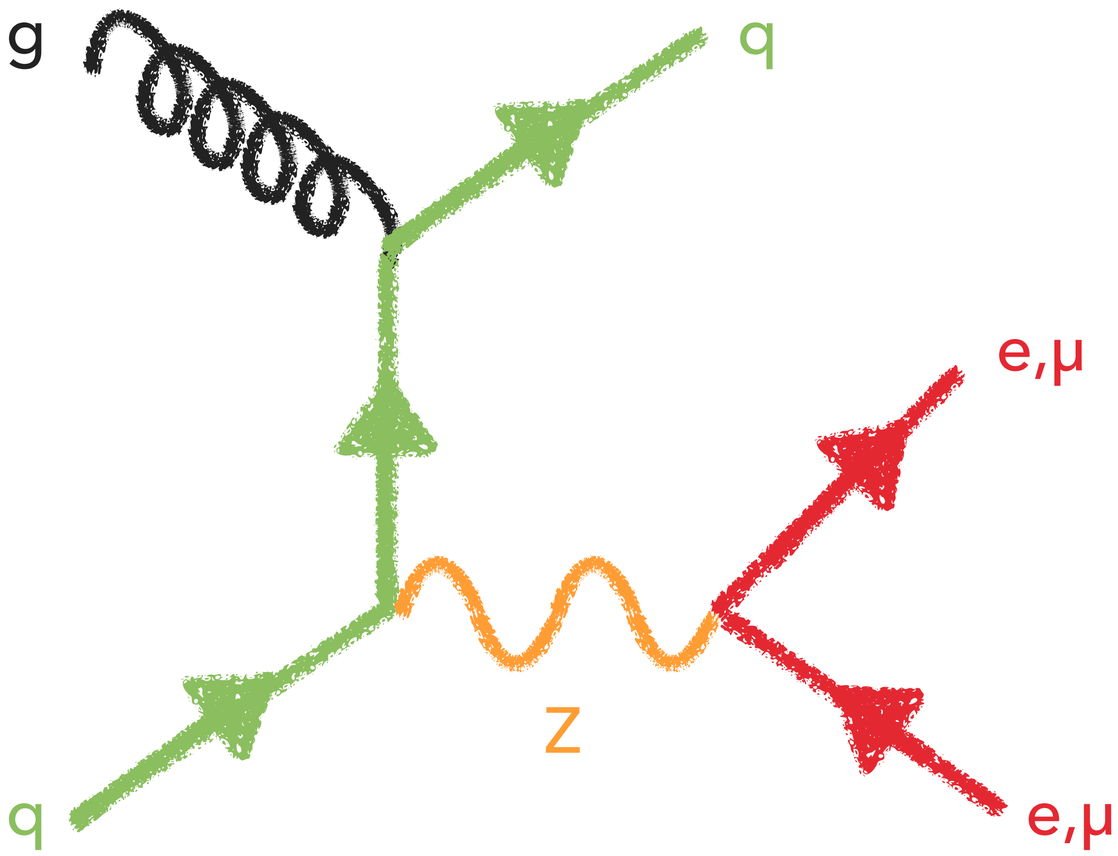
Institute of High Energy Physics
Chinese Academy of Sciences

Motivation

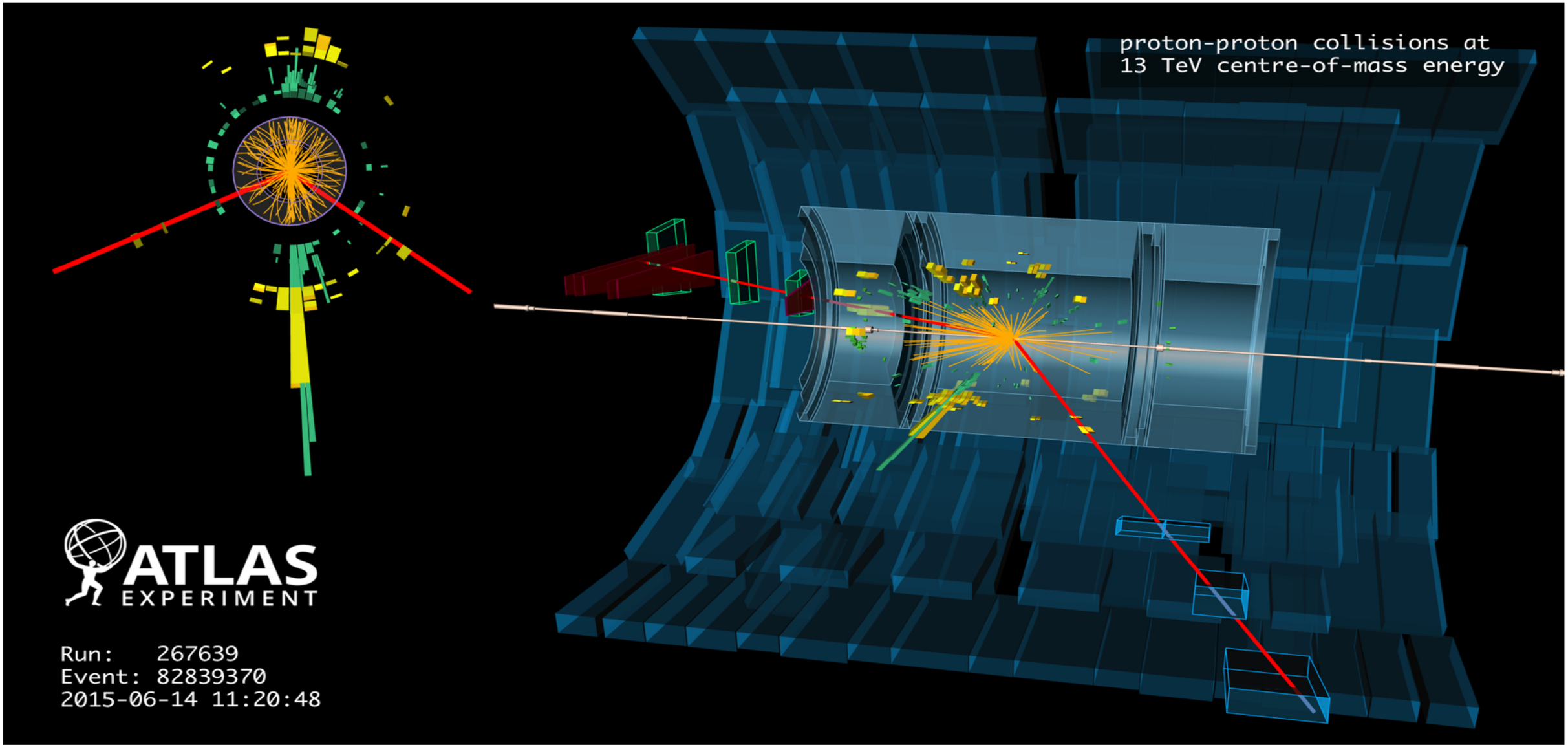
- Powerful test of perturbative QCD
- Important background for SM Higgs production & BSM searches
- Clean experimental signature & high cross sections make for precise measurement

Scope of the analysis

- $Z \rightarrow ll$ + jets @ 13 TeV in ATLAS, 3.16 fb^{-1}
- Inclusive & exclusive jet multiplicities
- Ratios of inclusive jet multiplicities
- p_T (leading jet) for Z + 1 jet events
- p_T (leading jet) for Z + ≥ 1-4 jets & Z + 1 jet
- Leading jet rapidity for Z + ≥ 1 jet events
- H_T for Z + ≥ 1 jet events
- $\Delta\phi_{jj}$ for Z + ≥ 2 jet events
- m_{jj} for Z + ≥ 2 jet events
- Comparisons made to state of the art generators and fixed order predictions
- ATLAS-CONF-2016-046



$Z \rightarrow \mu\mu$ + jets



INITIAL SELECTION:

Data quality cuts and hard scatter vertex

TRIGGER:

Single electron/muon triggers

LEPTON SELECTION:

pt > 25 GeV
electrons: $|\eta| < 1.37 \,||\, 1.52 < |\eta| < 2.47$
muons: $|\eta| < 2.4$
medium quality, isolated, vertex cuts

JETS:

anti-kT R=0.4
pT > 30 GeV
$|y| < 2.4$

Z BOSON:

2 opposite sign leptons, same flavor
$71 < m_{ll} < 111$ GeV

Monte Carlo Generators

Normalized to NNLO predictions
Flat 5% theoretical uncertainty

Fixed Order Predictions

PDF and scale uncertainties
QED FSR & parton-to-hadron corrections

LO

ALPGEN:
5 partons LO
CTEQ6L1
Pythia 6

MADGRAPH AMC@NLO + CKKWL:
4 partons LO
NNPDF23NLO
Pythia 8
CKKW-L Merging

BLACKHAT + SHERPA:
Z+≥ 1-4 jets NLO
CT14
scale ~ $H_T/2$

NLO

SHERPA 2.1;
2 partons NLO, 4 LO
CT10
Sherpa Parton Shower
ME+PS@NLO Merging

MADGRAPH AMC@NLO + FXFX:
2 partons NLO
NNPDF23NLO
Pythia 8
FxFx Merging

New!!!

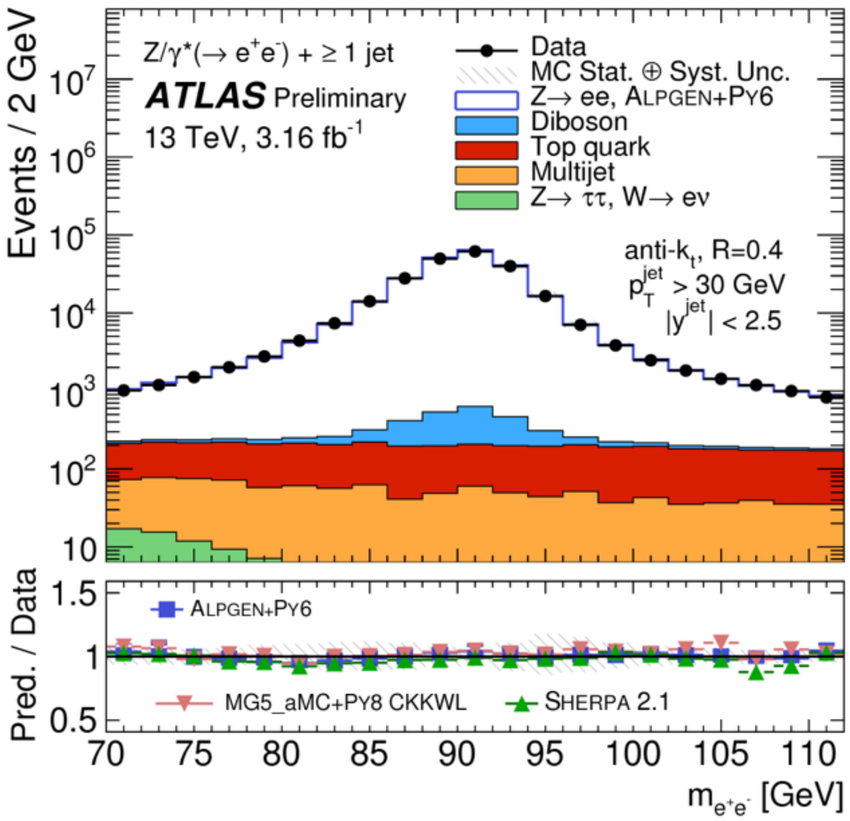
N JETTI:
Z+≥1jet NNLO
CT14
scale ~ sqrt [$m^2_{ll} + \Sigma (p_T^{jet})^2$ }]

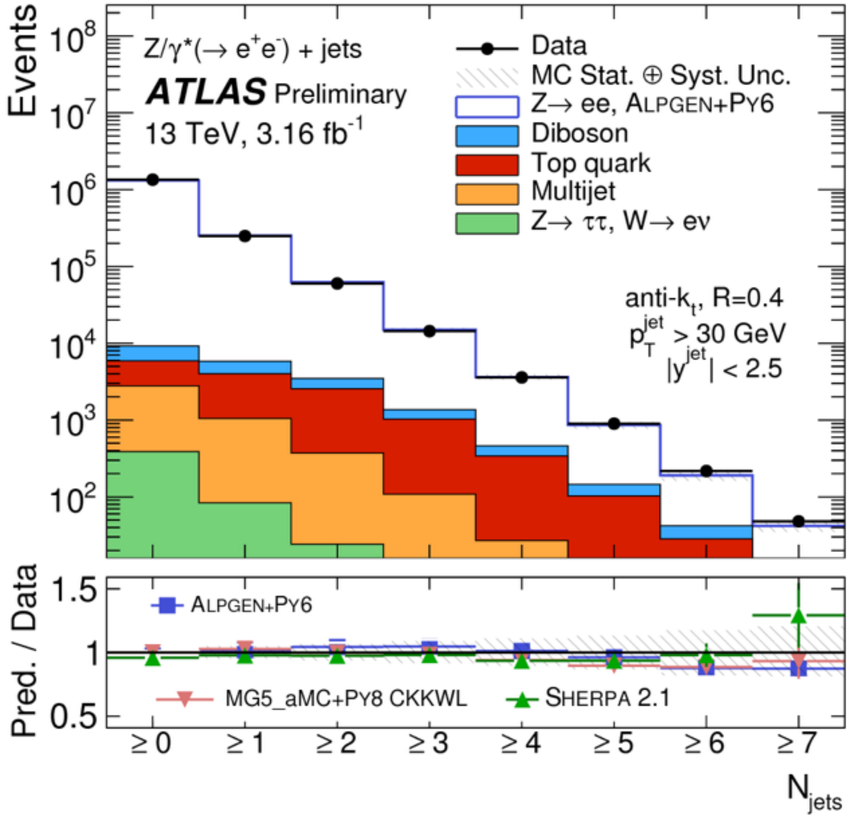
Diboson:
Sherpa 2.1.1

Single Top and tt-bar:
Powheg + Pythia6

Multijet
data driven estimate

W→lν & Z→ττ:
MadGraph 5 + Pythia8





- Detector level electron channel di-lepton invariant mass and inclusive N_{jets} (above)
  - Top and diboson co-dominant backgrounds contribute ~1% for Z+≥1 jet to 10% for Z+≥7 jets
  - Multijet background fraction 0.4 % for Z+≥1 jet to 1-2% for Z+≥7 jets
  - W and Z backgrounds < 0.01%

- Iterative Bayesian Unfolding
  - Use signal MC to "invert" detector effects (acceptance, resolution, etc) on background subtracted data
  - Using Alpgen+Pythia 6 to unfold to particle level
  - Fiducial Volume
    - p_T lepton > 25 GeV, $|\eta(\text{lep})| < 2.5$
    - p_T jet > 30 GeV, $|y(\text{jet})| < 2.5$
    - $\Delta R(l,\text{jet}) < 0.4$
    - 71 GeV < mll < 111 GeV

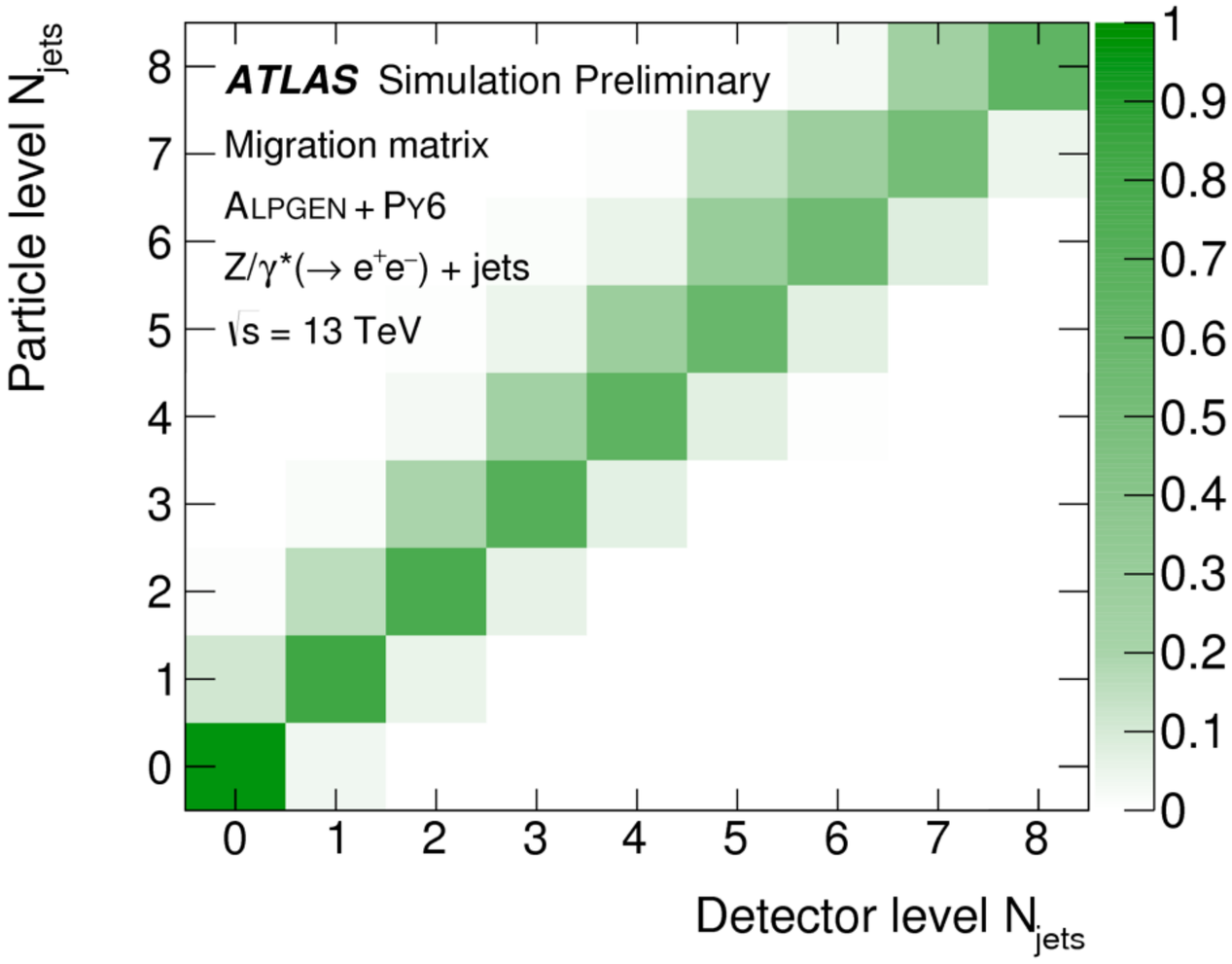
LUMINOSITY

NUMBER OF OBSERVED EVENTS

$$\frac{d\sigma}{dX_i} = \frac{1}{\Delta X_i \cdot \mathcal{L} \cdot \epsilon_i^m} \sum_m \sum_j (\mathcal{M}_{ij}^{-1})^m (N_j^{\text{obs},m} - N_j^{\text{bkg},m})$$

EFFICIENCY

NUMBER OF BACKGROUND EVENTS



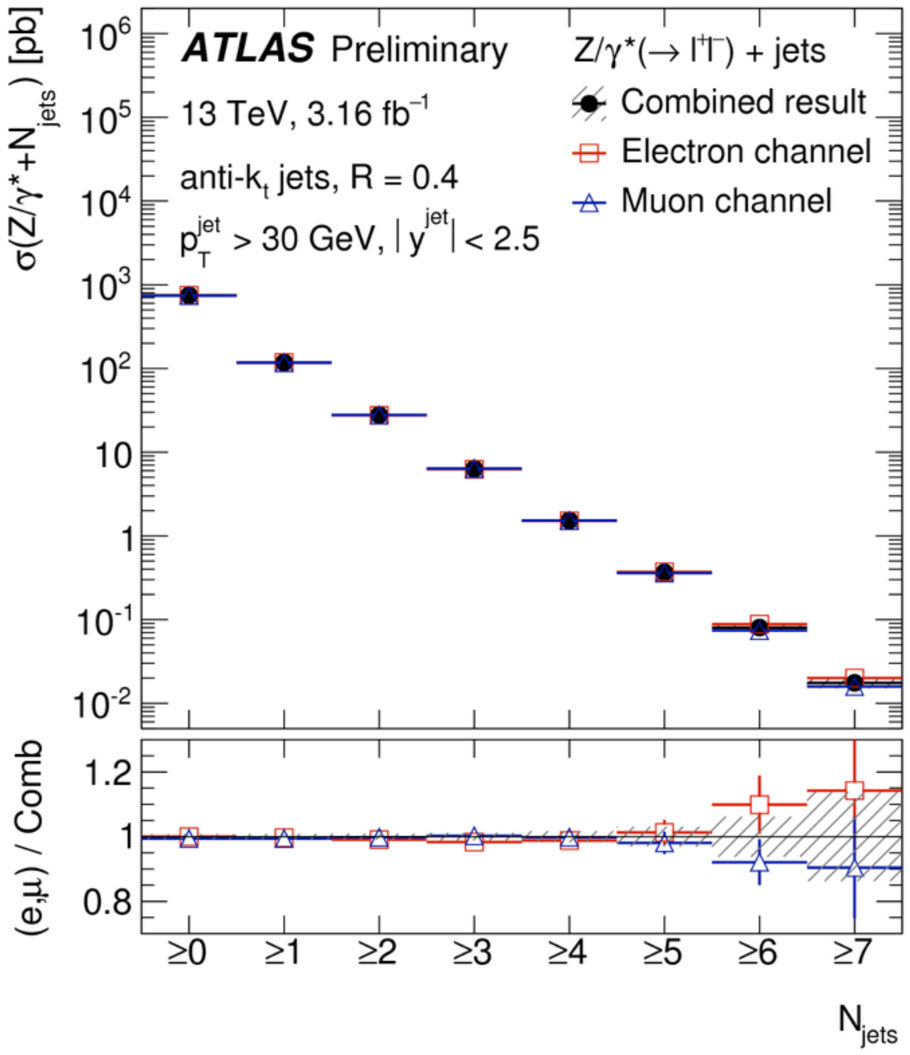
- Systematic uncertainties are propagated through the unfolding
- Relative systematic and statistical uncertainties (in %) on electron and muon inclusive N_{jet} cross sections

Relative uncertainty on $\sigma(Z(\to \ell^+\ell^-)+\geq N_{jets})$ (%)								
	$Z \to e^+e^-$							
Systematic source	+ $\geq$ 0 jet	+ $\geq$ 1 jet	+ $\geq$ 2 jets	+ $\geq$ 3 jets	+ $\geq$ 4 jets	+ $\geq$ 5 jets	+ $\geq$ 6 jets	+ $\geq$ 7 jets
Electron Trigger	0.1	0.1	0.1	0.1	0.2	0.3	0.4	0.8
Electron Selection	1.2	1.6	1.8	2.0	2.2	2.7	2.9	4.1
JES	< 0.1	6.1	8.0	10.3	12.8	15.0	21.7	23.7
JER	< 0.1	3.1	3.0	3.6	4.5	5.5	4.7	2.4
JVT	< 0.1	1.3	2.0	2.7	3.3	3.8	5.4	6.5
Pile-up	0.4	< 0.1	< 0.1	0.2	0.3	0.7	0.3	1.5
Luminosity	2.1	2.2	2.2	2.3	2.4	2.5	2.6	2.8
Unfolding	2.0	2.0	2.0	2.1	2.0	2.0	2.1	2.6
Background	0.1	0.3	0.5	1.0	1.5	3.2	6.0	12.5
Syst. uncertainty	3.2	7.8	9.4	11.9	14.6	17.3	24.0	28.3
Stat. uncertainty	0.1	0.2	0.5	1.0	1.9	3.9	8.2	17.7
	$Z \to \mu^+\mu^-$							
Systematic source	+ $\geq$ 0 jet	+ $\geq$ 1 jet	+ $\geq$ 2 jets	+ $\geq$ 3 jets	+ $\geq$ 4 jets	+ $\geq$ 5 jets	+ $\geq$ 6 jets	+ $\geq$ 7 jets
Muon Trigger	0.4	0.4	0.4	0.5	0.5	0.4	0.8	3.3
Muon Selection	0.8	0.9	1.0	1.1	1.1	1.6	2.3	3.7
JES	< 0.1	6.3	8.2	10.2	12.2	15.3	19.2	21.7
JER	< 0.1	3.1	3.1	3.6	4.2	4.5	5.1	3.2
JVT	< 0.1	1.3	2.1	2.7	3.4	4.1	5.0	4.7
Pile-up	0.4	0.1	0.1	0.2	0.2	0.7	0.4	2.6
Luminosity	2.1	2.2	2.2	2.3	2.4	2.5	2.6	2.7
Unfolding	2.0	2.0	2.0	2.1	2.0	2.1	2.8	4.7
Background	0.2	0.4	0.6	0.9	1.6	4.0	7.4	13.7
Syst. uncertainty	3.1	7.8	9.5	11.7	13.9	17.4	22.3	27.8
Stat. uncertainty	0.1	0.2	0.4	0.9	1.8	3.5	7.7	17.3

JET ENERGY SCALE:
Dominant source of uncertainty!

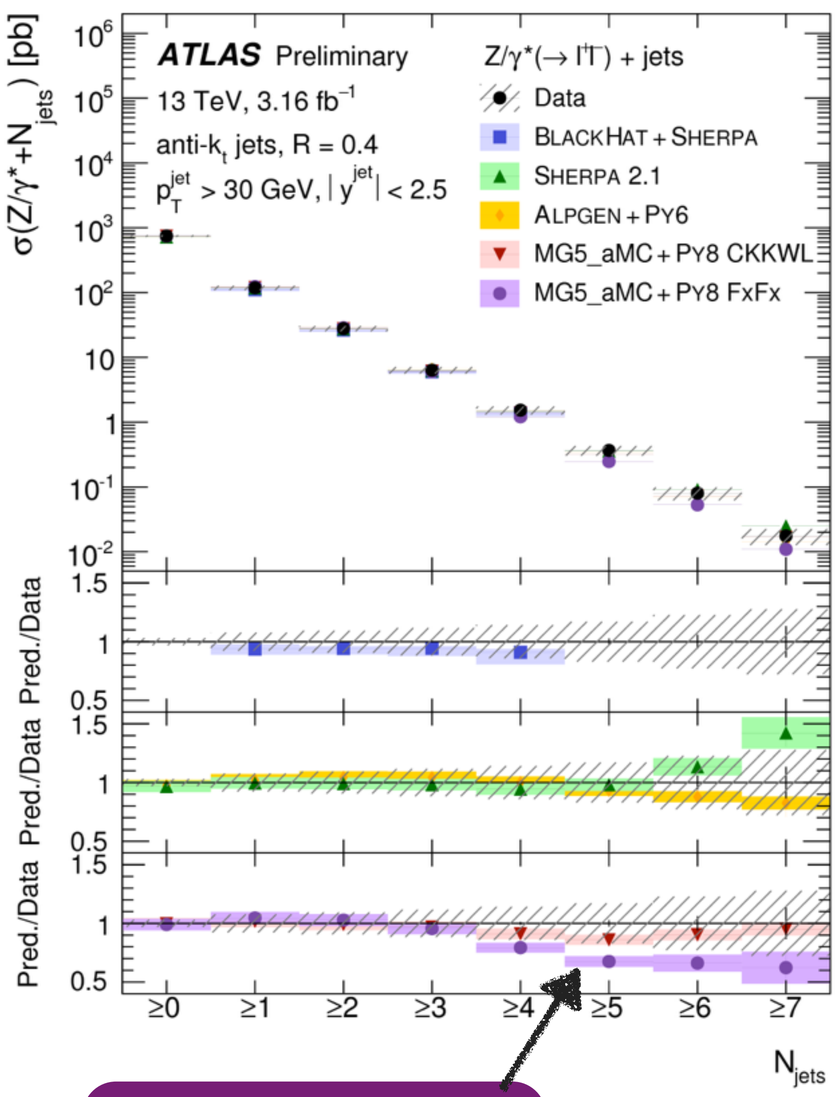
- Combination done using χ^2 minimization, treating correlated systematics as nuisance parameters
  - Central Value:
    - bin-to-bin uncorrelated uncertainties (statistical)
    - bin-to-bin correlated uncertainties but independent of e/μ datasets (lepton systematics)
  - Remaining uncertainties (jet, luminosity, pileup systematics) are averaged after combination

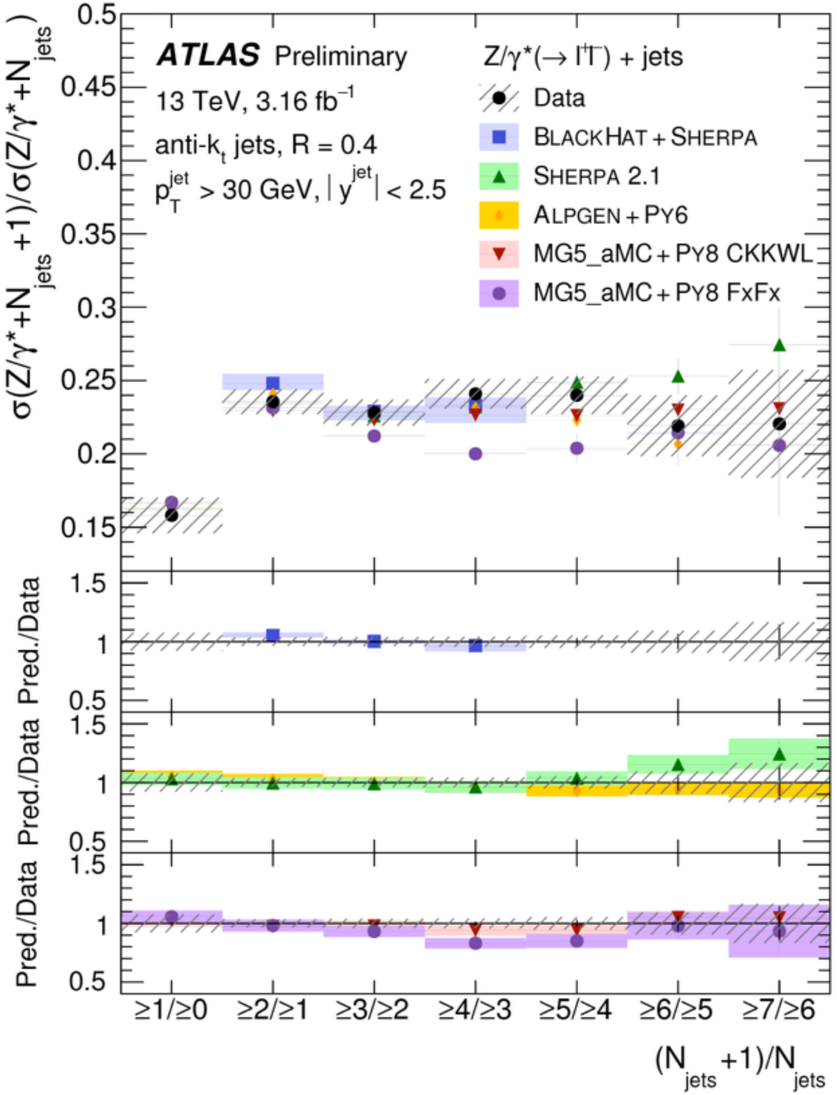
Jet multiplicity	Measured cross section ± (stat.) ± (syst.) ± (lumi.) [pb]							
	$Z \to ee$				$Z \to \mu\mu$			
≥ 0 jets	747 ±	1 ±	18 ±	16	743 ±	1 ±	17 ±	16
≥ 1 jets	117.7 ±	0.3 ±	8.8 ±	2.5	117.4 ±	0.2 ±	8.8 ±	2.5
≥ 2 jets	27.6 ±	0.1 ±	2.5 ±	0.6	27.8 ±	0.1 ±	2.6 ±	0.6
≥ 3 jets	6.24 ±	0.06 ±	0.73 ±	0.15	6.37 ±	0.06 ±	0.73 ±	0.15
≥ 4 jets	1.51 ±	0.03 ±	0.22 ±	0.04	1.53 ±	0.03 ±	0.21 ±	0.04
≥ 5 jets	0.371 ±	0.014 ±	0.063 ±	0.009	0.359 ±	0.013 ±	0.062 ±	0.009
≥ 6 jets	0.088 ±	0.007 ±	0.021 ±	0.002	0.074 ±	0.006 ±	0.016 ±	0.002
≥ 7 jets	0.0200 ±	0.0036 ±	0.0056 ±	0.0006	0.0159 ±	0.0027 ±	0.0044 ±	0.0004



- Cross Sections
  - Discrepancies at high jet multiplicities where generators rely on parton shower
  - Disagreement in MadGraph FxFx, because Matrix Elements are only provided for Z+≥2jets
  - Precision ranging from 3 to 27%
- Ratios
  - partial cancellation of systematics

Jet multiplicity	Measured cross section $\pm$ (stat.) $\pm$ (syst.) $\pm$ (lumi.) [pb]
	$Z \to \ell\ell$
≥ 0 jets	$747 \pm 1 \pm 16 \pm 16$
≥ 1 jets	$118.1 \pm 0.2 \pm 8.7 \pm 2.5$
≥ 2 jets	$27.8 \pm 0.1 \pm 2.5 \pm 0.6$
≥ 3 jets	$6.35 \pm 0.04 \pm 0.72 \pm 0.15$
≥ 4 jets	$1.53 \pm 0.02 \pm 0.21 \pm 0.04$
≥ 5 jets	$0.37 \pm 0.01 \pm 0.06 \pm 0.01$
≥ 6 jets	$0.080 \pm 0.005 \pm 0.018 \pm 0.002$
≥ 7 jets	$0.0176 \pm 0.0024 \pm 0.0042 \pm 0.0005$



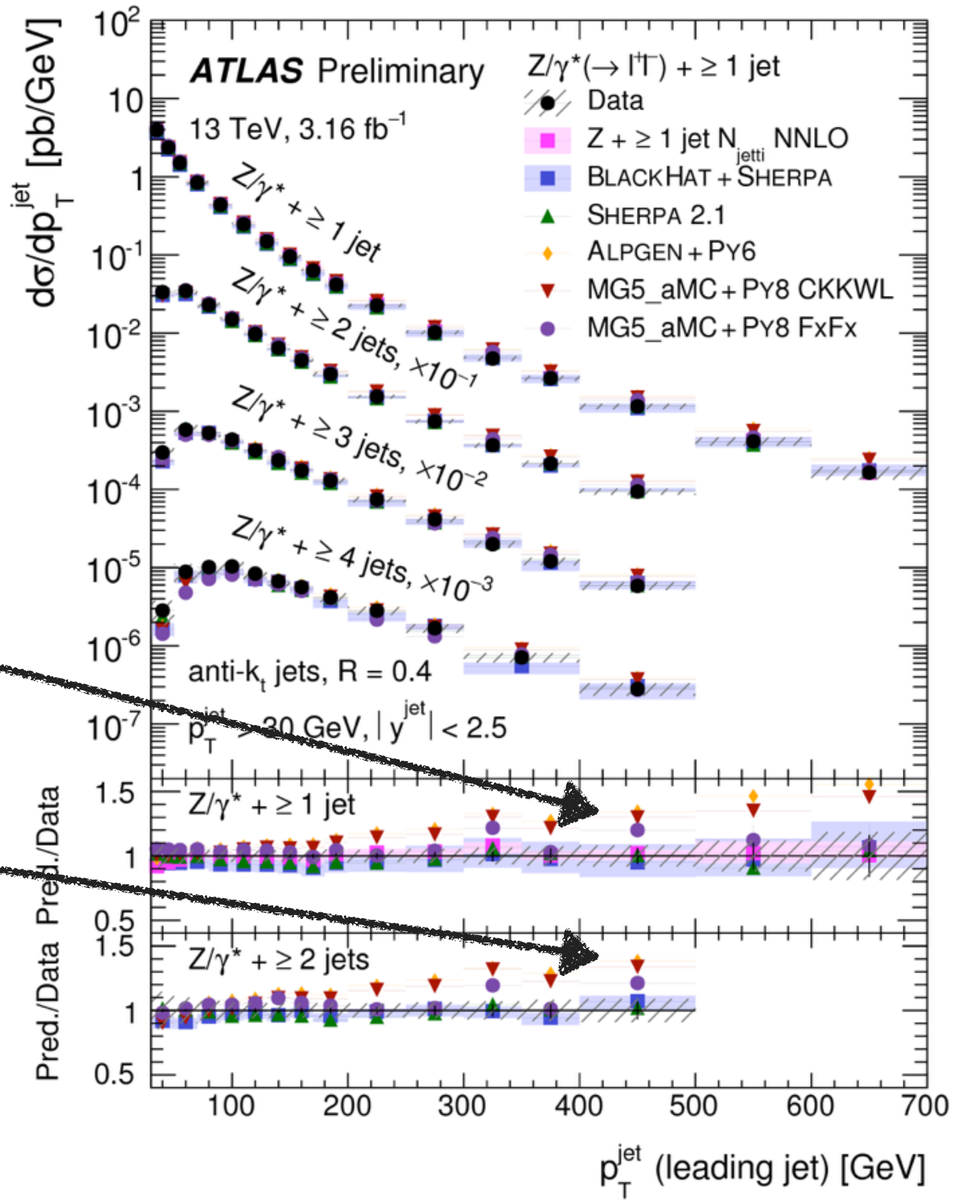


MadGraph FxFx low!

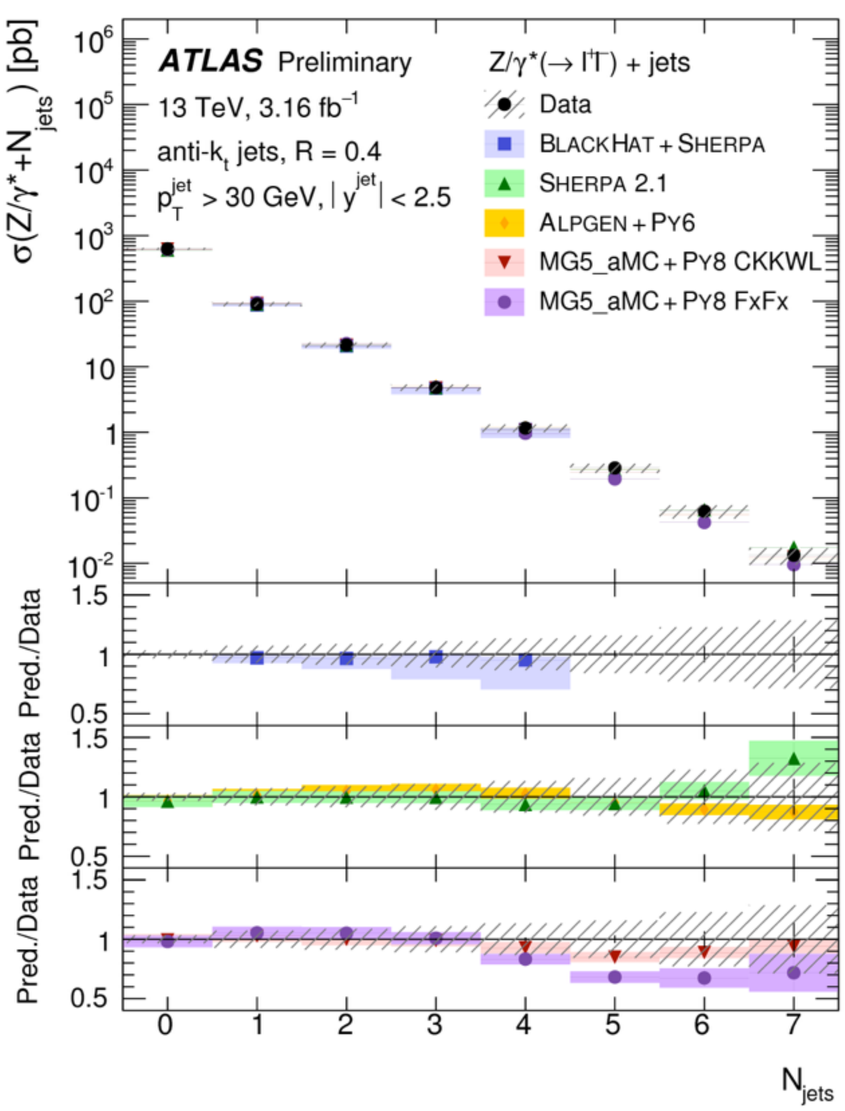
- Fundamental observable for Z+jets process
  - probes pQCD at a large range of scales
  - LO: Alpgen+Pythia6and MadGraph+CKKWL model the leading jet p_T too hard
  - NLO: Sherpa, MadGraph FxFx, and BlackHat are in good agreement over the full p_T range
  - NNLO: N_{jetti} models Z+≥1 jet p_T spectrum very well

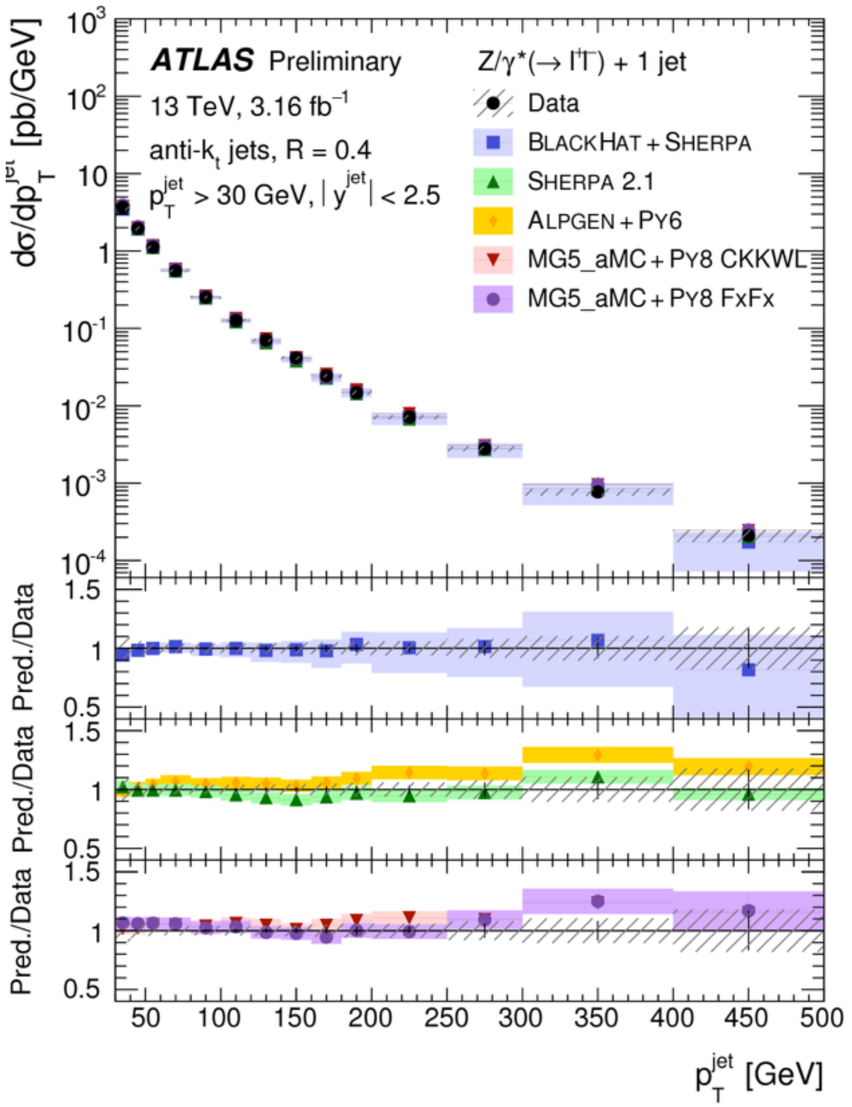
Alpgen overestimates high p_T cross section

MadGraph CKKWL overestimates high p_T jets



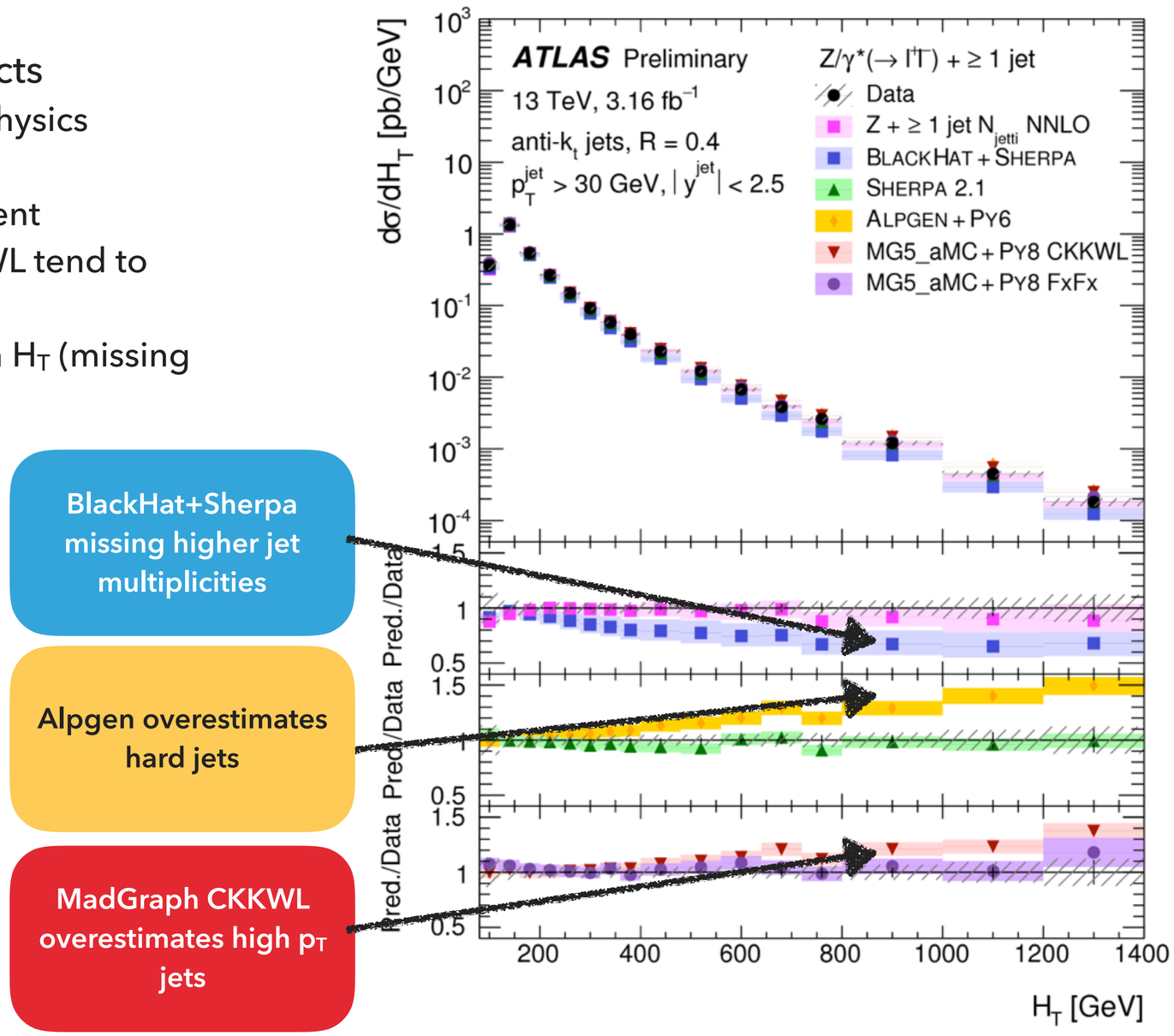
- Exclusive N_{jet} Cross sections
  - MC discrepancies when depending only on Parton Shower
- For Z+1 jet events, p_T (jet)
  - probes validity of predictions at high QCD scales, even though veto is at a constant low scale (30 GeV)





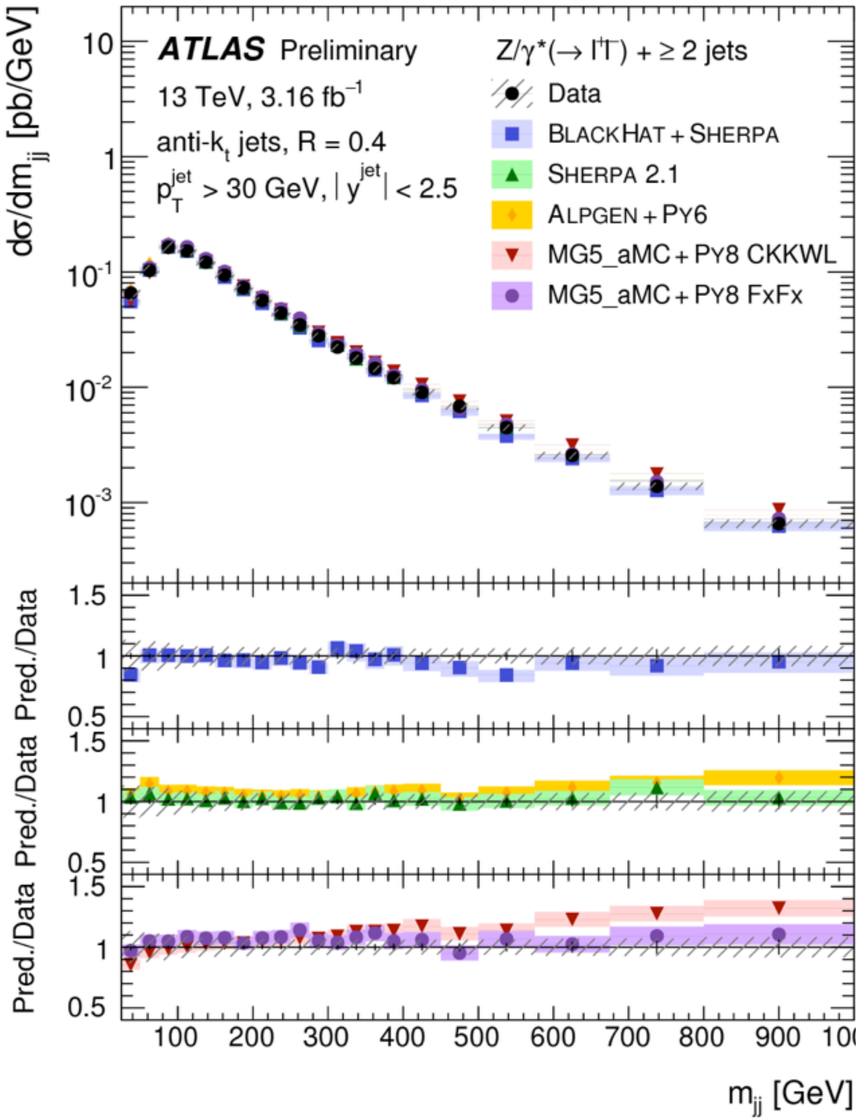
A TEST OF SCALE: H_T

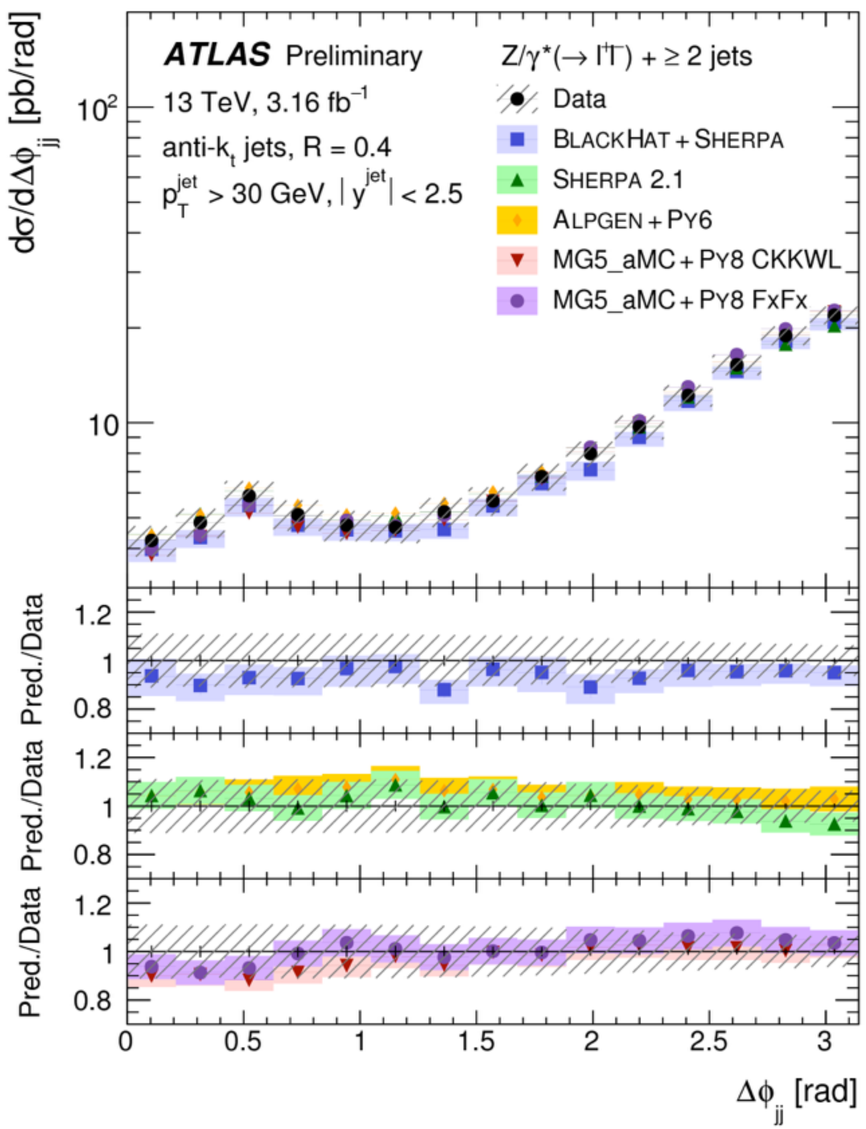
- H_T Scalar sum of the pT of all visible objects
  - Common search variable to separate heavy physics
  - Often used as scale variable in pQCD
  - Sherpa and MadGraph FxFx in good agreement
  - LO predictions, Alpgen and MadGraph CKKWL tend to overestimate hard jets
  - BlackHat underestimates cross section at high H_T (missing contributions from higher jet multiplicities)
  - Njetti recovers agreement by going to NNLO



COMMON SEARCH VARIABLES: m_{JJ} AND $\Delta\phi_{JJ}$

- m_{JJ} partial cancellation of systematics
  - often used to separate BSM physics from Z+jets
  - MadGraph CKKWL models m_{JJ} too hard
- Angular distribution, $\Delta\phi_{JJ}$
  - correlated with mJJ
  - preference for back-to-back jets well modeled by all predictions

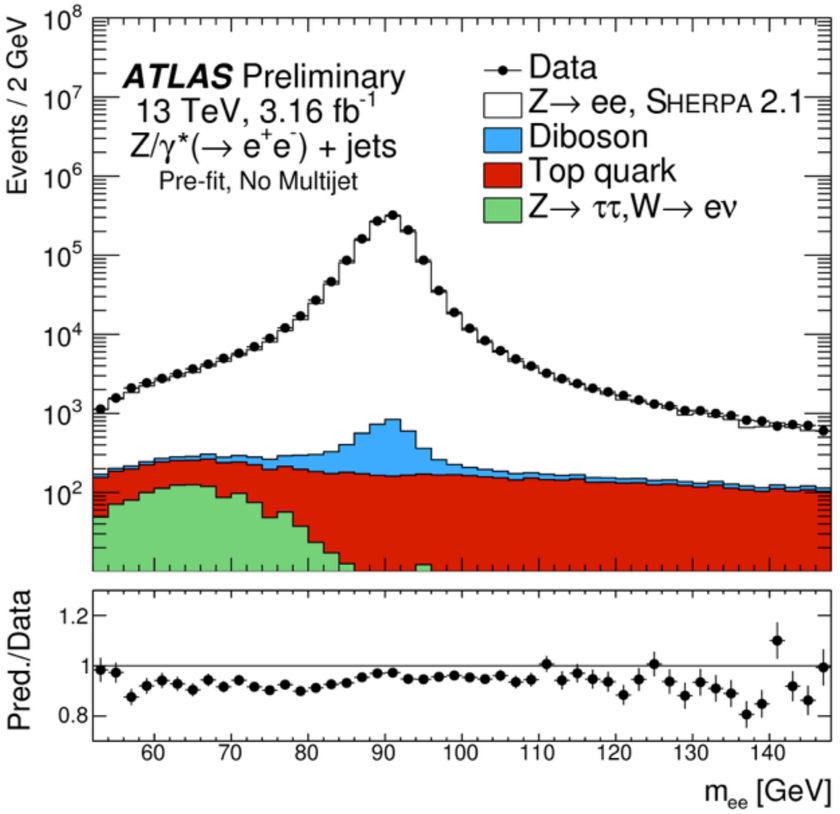


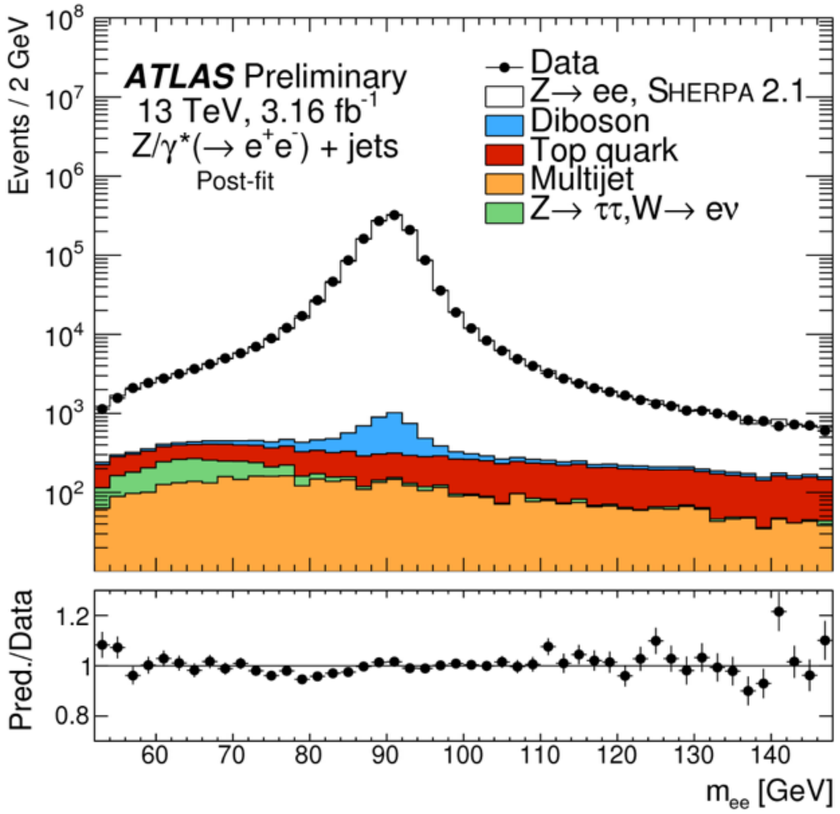


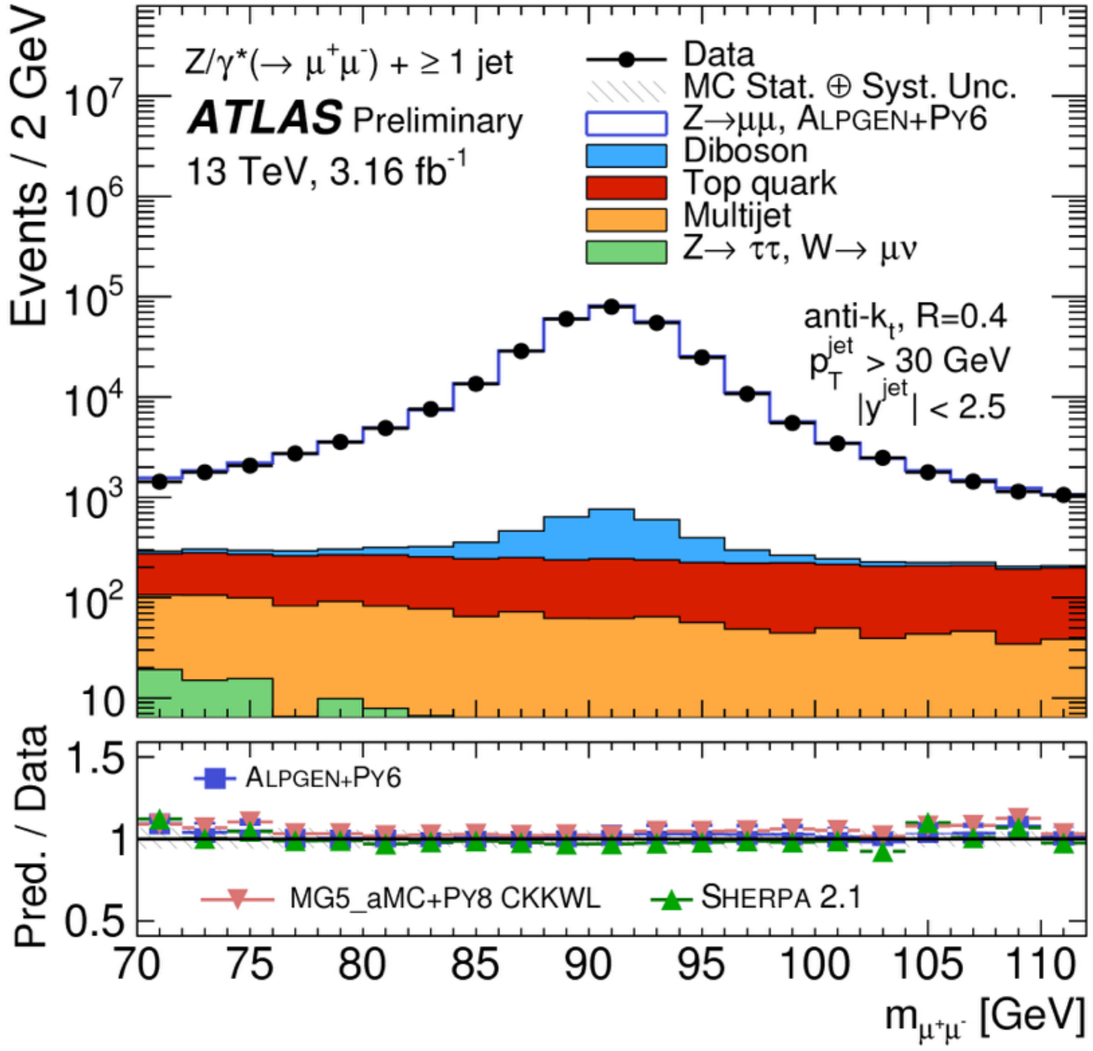
- First measurement of Z+jets inclusive and differential cross sections with 3.2 fb^{-1} of 13 TeV data
  - Measurement extends up to Z+≥7 jets!
  - Precision ranging from 3% to 27%!
- Assessed modeling of state of the art generators
  - LO: Alpgen and MadGraph CKKWL overestimate contributions from high p_T jets
  - NLO: Sherpa 2.1 and MadGraph FxFx in overall agreement with data
- Comparisons to fixed order predictions
  - BlackHat+Sherpa for Z+≥1-4jets (NLO)
  - NEW: NNLO Njetti for Z+≥1 jet
- IHEP Contributions
  - Karri Folan DiPetrillo, Lianyou Shan, Joao Guimaraes da Costa
- Future Work
  - paper to be submitted in January
  - w/ more statistics can probe statistically limited regions of phase space: eg. boosted Zs, VBF, pdfs

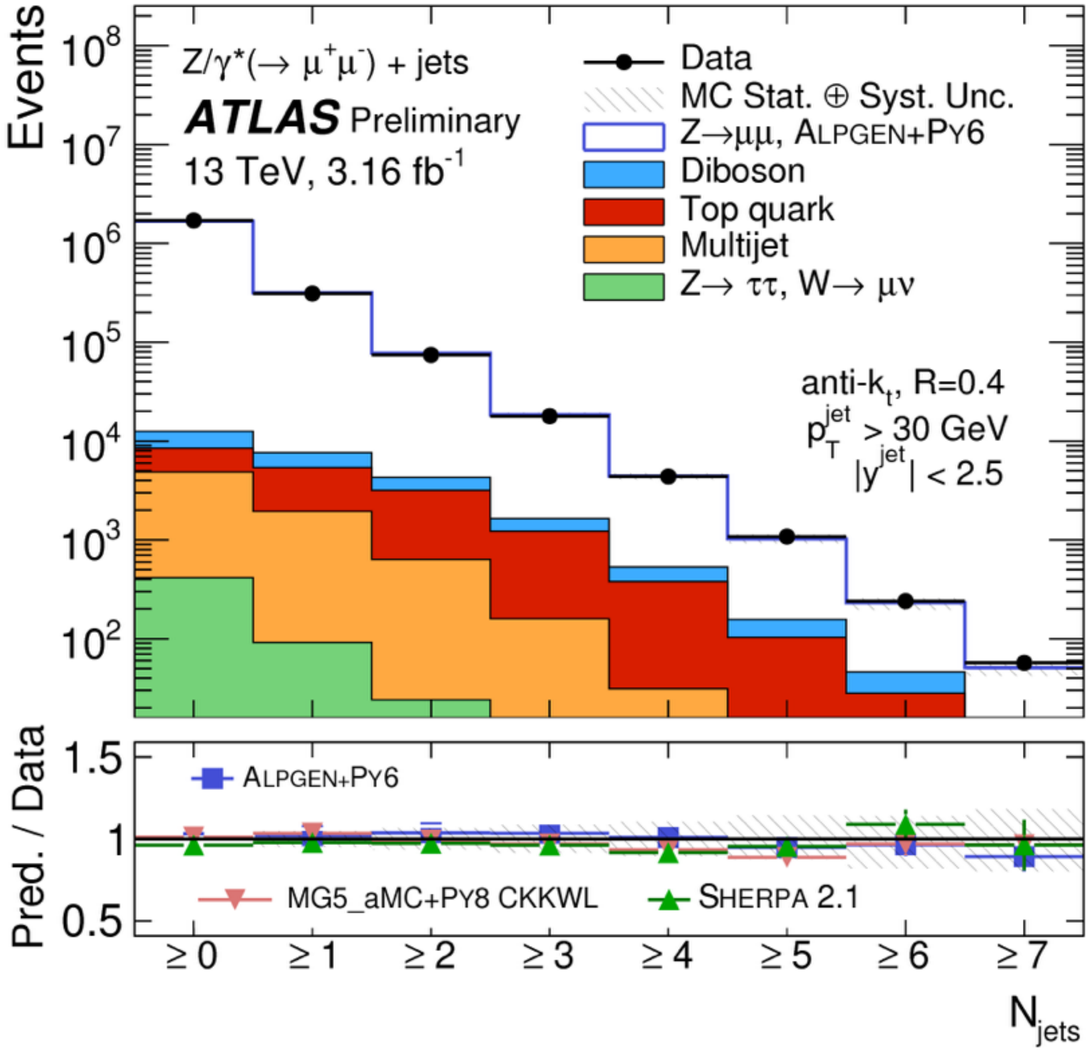
- Multijet Template:
  - Invert electron ID
  - Drop electron isolation requirement
  - Select two same sign electrons
  - Subtract non-multijet processes

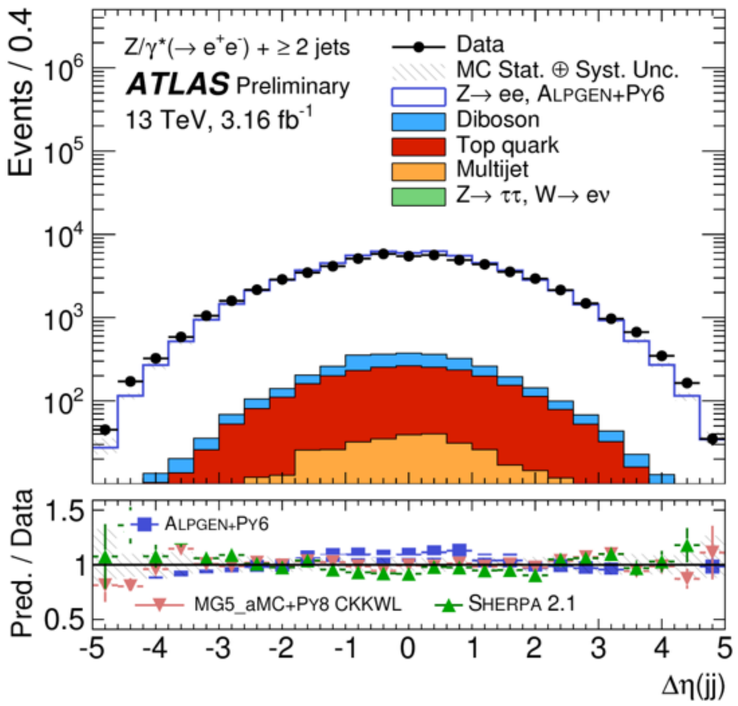
- Estimating contribution in Signal Region
  - fit multijet template and non multi-jet processes in di-electron invariant mass window
  - pre & post-fit distributions at right

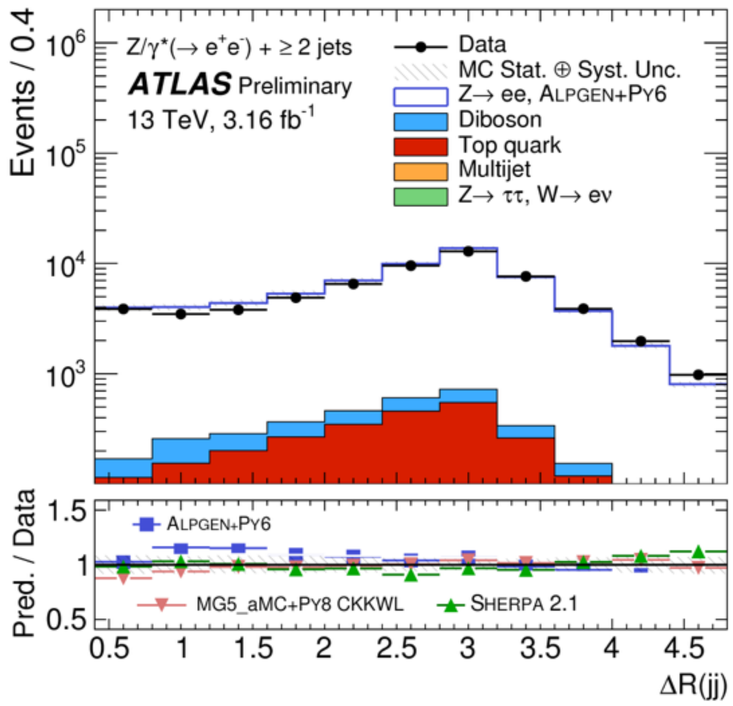


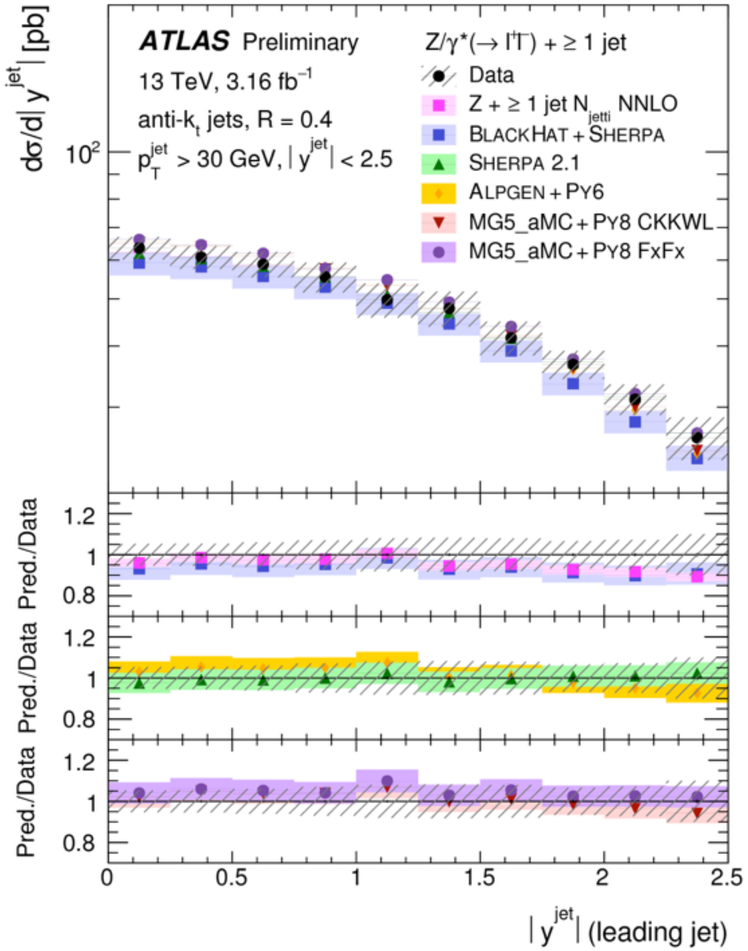



Z/γ*(→ μ+μ-) + ≥ 1 jet
ATLAS Preliminary
13 TeV, 3.16 fb-1
Data
MC Stat. ⊕ Syst. Unc.
Z→μμ, ALPGEN+PY6
Diboson
Top quark
Multijet
Z→ ττ, W→ μν
anti-kt, R=0.4
pTjet > 30 GeV
|yjet| < 2.5
Events / 2 GeV
Pred. / Data
ALPGEN+PY6
MG5_aMC+PY8 CKKWL
SHERPA 2.1
mμ+μ- [GeV]

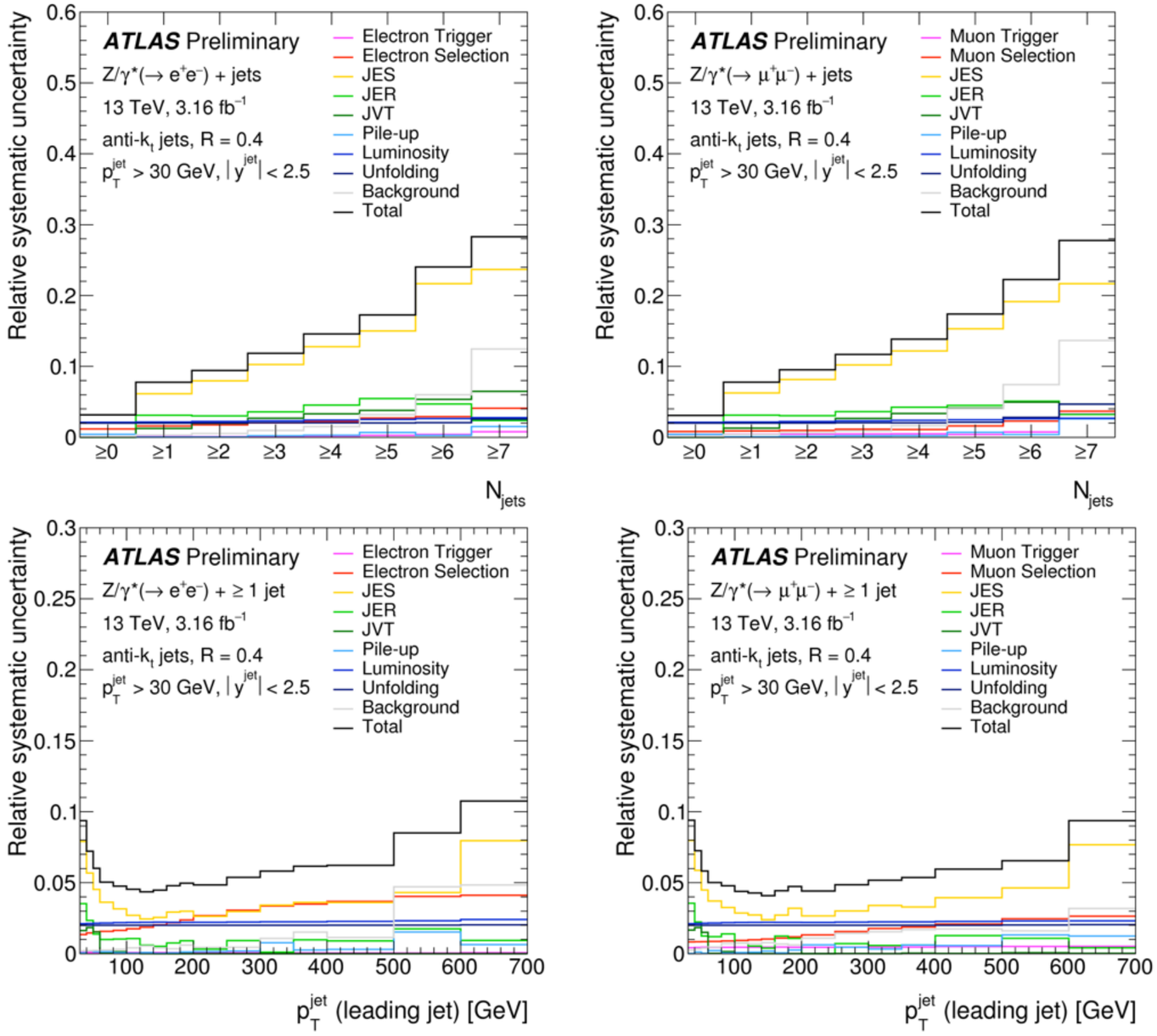

Z/γ*(→ μ+μ-) + jets
ATLAS Preliminary
13 TeV, 3.16 fb-1
Data
MC Stat. ⊕ Syst. Unc.
Z→μμ, ALPGEN+PY6
Diboson
Top quark
Multijet
Z→ ττ, W→ μν
anti-kt, R=0.4
pTjet > 30 GeV
|yjet| < 2.5
Events
Pred. / Data
ALPGEN+PY6
MG5_aMC+PY8 CKKWL
SHERPA 2.1
Njets


Z/γ*(→ e+e-) + ≥ 2 jets
ATLAS Preliminary
13 TeV, 3.16 fb-1
Data
MC Stat. ⊕ Syst. Unc.
Z→ ee, ALPGEN+PY6
Diboson
Top quark
Multijet
Z→ ττ, W→ eν
Events / 0.4
Pred. / Data
ALPGEN+PY6
MG5_aMC+PY8 CKKWL
SHERPA 2.1
Δη(jj)

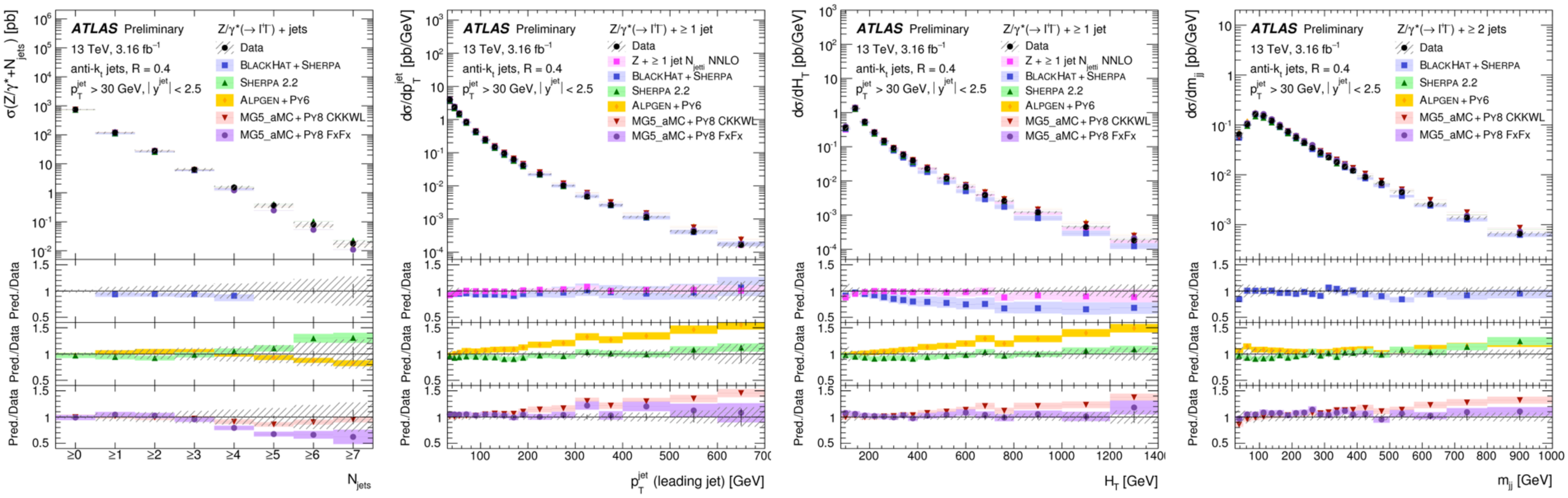

Z/γ*(→ e+e-) + ≥ 2 jets
ATLAS Preliminary
13 TeV, 3.16 fb-1
Data
MC Stat. ⊕ Syst. Unc.
Z→ ee, ALPGEN+PY6
Diboson
Top quark
Multijet
Z→ ττ, W→ eν
Events / 0.4
Pred. / Data
ALPGEN+PY6
MG5_aMC+PY8 CKKWL
SHERPA 2.1
ΔR(jj)


ATLAS Preliminary
13 TeV, 3.16 fb-1
anti-kt jets, R = 0.4
pTjet > 30 GeV, |yjet| < 2.5
Z/γ*(→ l+l-) + ≥ 1 jet
Data
Z + ≥ 1 jet Njetti NNLO
BLACKHAT + SHERPA
SHERPA 2.1
ALPGEN + PY6
MG5_aMC + PY8 CKKWL
MG5_aMC + PY8 FxFx
dσ/d|yjet| [pb]
Pred./Data
|yjet| (leading jet)

- Relative systematic uncertainties on fiducial cross sections
  - Inclusive jet multiplicity (top)
  - leading jet pT (bottom)
  - electron channel (right)
  - muon channel (left)



BACKUP: SHERPA 2.2



- The Sherpa 2.2 sample has been produced with a simplified scale setting prescription in the multi-parton matrix elements, to improve the event generation speed. A theory-based reweighting of the jet multiplicity distribution is applied at event level, derived from event generation with the strict scale prescription