Measurements of Z-boson Production in Association with Jets at ATLAS

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Introduction: Theory and Experiment Background

V+jets Measurements in ATLAS

- To accurately and precisely describe V+jets processes at the LHC, every aspects of QCD have to be well-understood over a large range of scales.
  - PDF, Higher-order Matrix Element calculation, parton shower, matching or merging, factorization/renormalization, hadronization.

- ATLAS performed a large set of such measurements so far (Run-1 and Run-2) providing information to the theory community that results in much improved predictions.
  - Z+jets, W+jets, Met+jets, and their ratio
  - W+jets where the jets are collinear to the W
  - V+HF (b,c) and gluon splitting in bb
  - kT-splitting

Two New Measurements

- Exploiting conditional probabilities by probing various phase space regions features different sensitivities to the various effects, helping disentangling some of them
  - New observables
  - More exclusive events selections
  - A combination of both

- Today's presentation focuses on two narrower phase space regions of Z+jets processes to improve QCD predictions.
  - Z plus a large-jets, w/o 2-b-tagged smaller jets
  - Z plus a high-pT jet

ATLAS measurements: Z+large-jets:

arXiv:2204.12355 [hep-ex]

*All results can be found in:
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-37/

Z+Large-jet: Motivation

- Boosted-jet topology through large-R-jet reconstruction is sensitive to new very heavy resonances

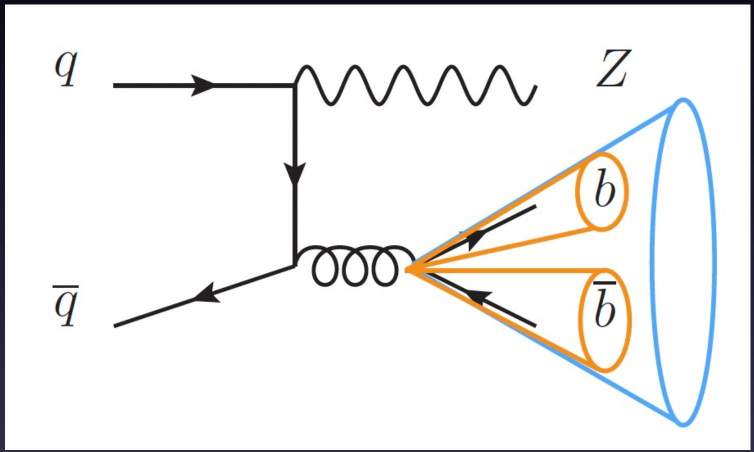
- Requires a good understanding of hard collinear parton splitting in pQCD at high-p_T.
  - How valid is the gluon splitting into heavy quarks from parton showers

- Ambiguity in the description of initial-state HF quarks isolated in the cross section or encoded in the PDF
  - 5 Flavor Scheme (5FS): Resummed, massless and longitudinal splitting
  - 4 Flavor Scheme (4FS): Explicit gluon-splitting in ME,with p_T exchange

- Different from resolved, non-boosted Z+bb topologies

Z+Large-jet: What is Measured?

- Probe two different phase space regions
  - Inclusive large-R trimmed jet recoiling the Z-boson
  - Boosted 2-b-jets, within the above large-R jet



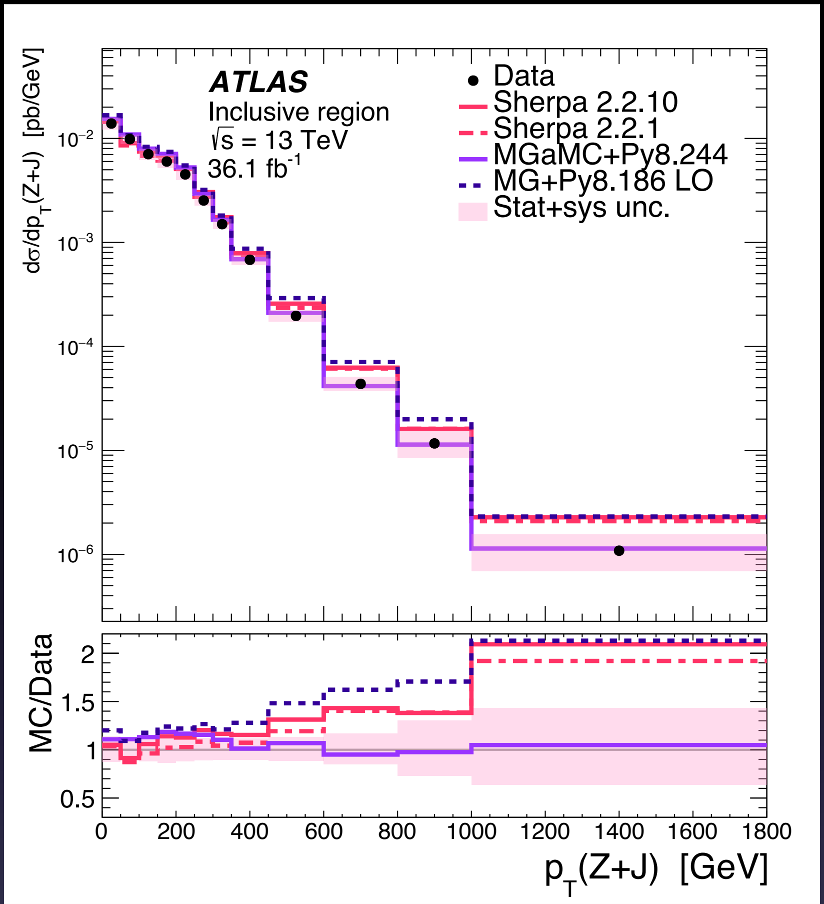
- Measurement performed on 36 fb-1 of 13 TeV ATLAS data, and results are fully unfolded to fiducial phase space region

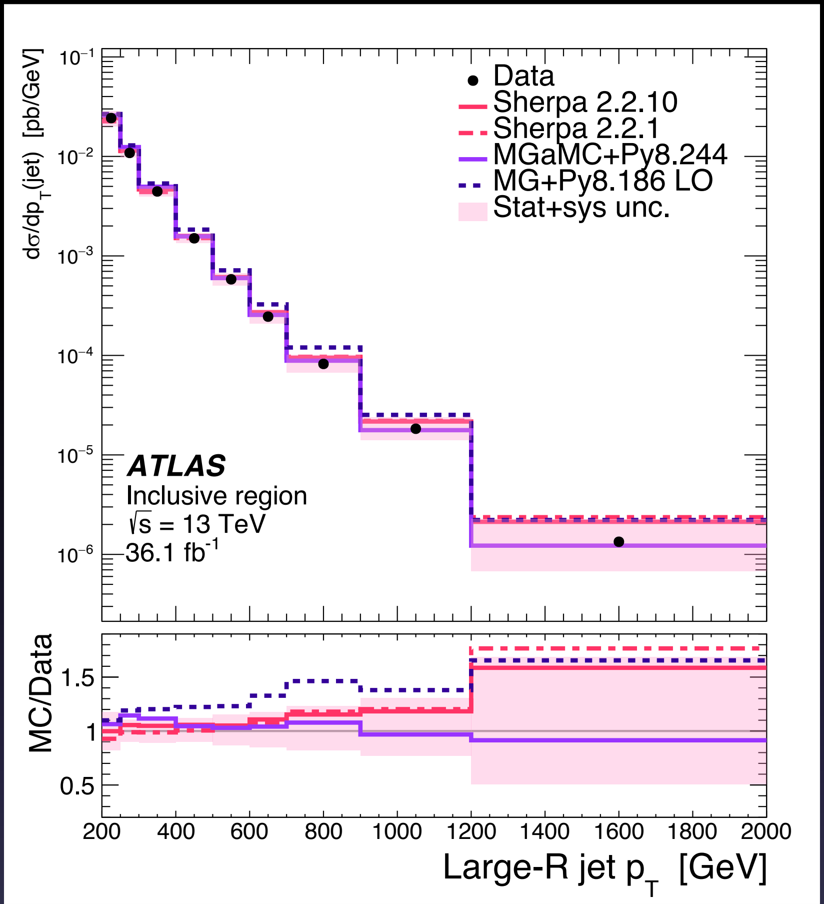
Z+Large-jet : Total Cross Sections

Cross sections	Measured	Sherpa 2.2.10	Sherpa 2.2.1	NLO MG+P8	LO MG+P8
$\sigma^{inc}(Z+R_1\text{-jet})$ [pb]	2.37±0.28	2.53±1.25	2.37	2.68±0.67	2.84
$\sigma^{2\text{-}tag}(Z+R_1\text{-jet})$[fb]	14.6±4.6	9.4±3.1 (4FS) 14.9±4.2 (5FS) 14.3±4.8 (fused)	9.1	4.4±1.1. (4FS) 14.4±1.9. (5FS)	
$\sigma^{2\text{-}tag}/\sigma^{inc}$ [%]	0.62±0.12	0.59±0.39	0.42	0.54±0.21	0.38

- Consistent, although slightly high, inclusive NLO predictions
  - NLO required
- The 5FS and the fused predictions are much more accurate at describing boosted heavy-flavor pair production
- The better precision on the ratio measurement, accounting for suppression of shared uncertainties, offers new discriminative power for high-p_T heavy-flavor production rate.

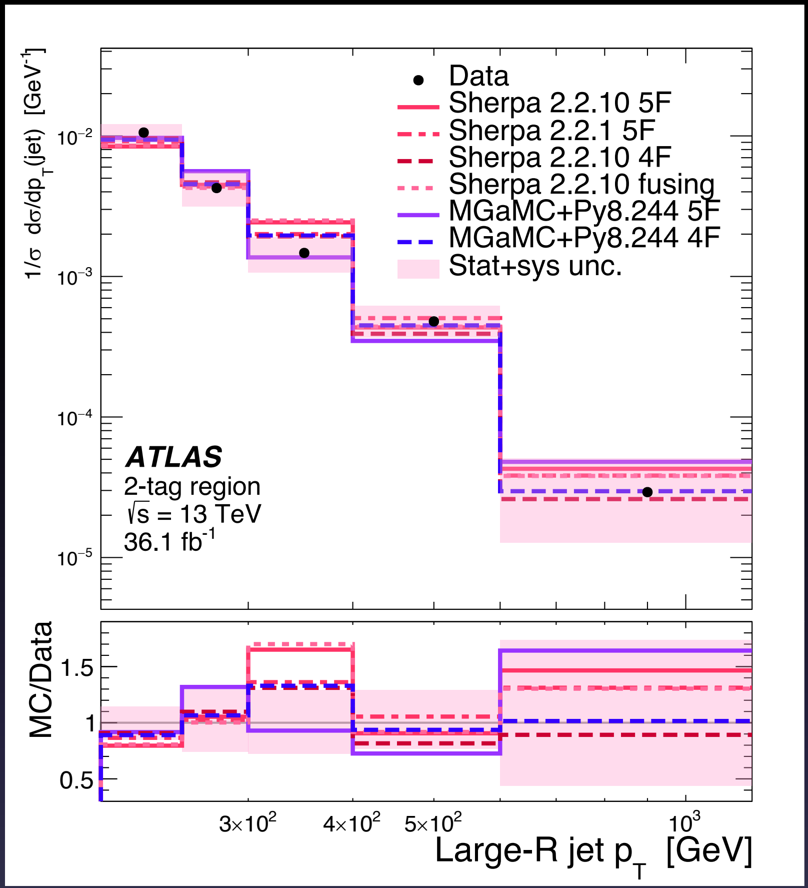
Z+Large-jet: : Inclusive Flavor Results

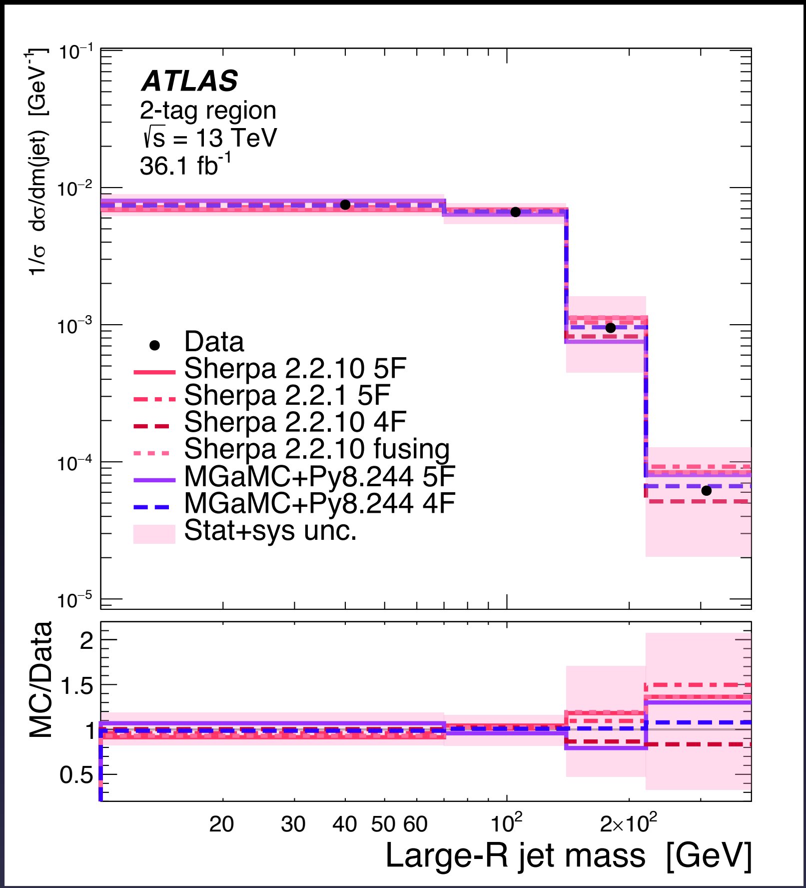




Too large p_T of the Z+J system, as well as too large p_T of the large-R jet in the Sherpa and LO MG predictions indicate a serious mismodeling of recoiling radiations. This is however not an issue for the NLO MG prediction.

Z+Large-jet: bb-boosted Results





Similar discrepancies are not observed in the 2-b-tagged phase space region, mostly either because the uncertainty is larger than potential theoretical discrepancies, or that the observable is not sensitive to variations in the predictions on this region of the phase space.

ATLAS measurements: Z+high-p_T jets :

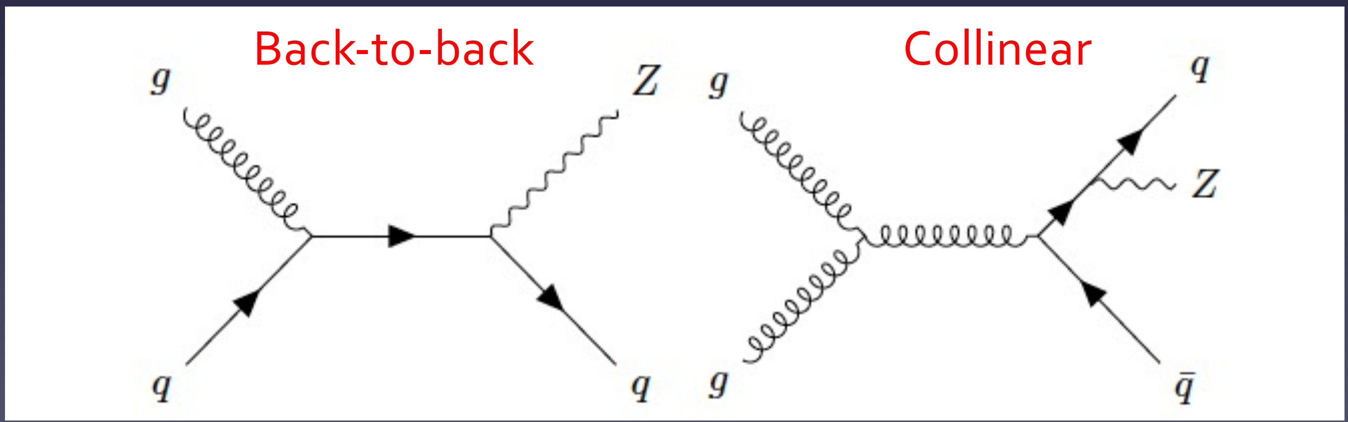
[arXiv:2205.02597 [hep-ex]](arXiv:2205.02597)

*All results can be found in:
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-37/

Z+high-p_T jets: Motivation

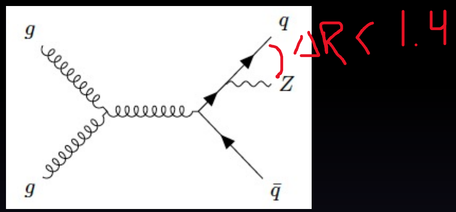
- Provide a more precise and complete characterization of the interplay between higher-order QCD and EWK corrections

- These effects play different roles in different phase space regions.
  - Z collinear to a jet: real EWK correction to dijet, enhanced by $\alpha_s \ln^2(p_T^j/m_Z)$, vs real QCD corrections to Z+jets
  - Z back-to-back to a jet: large virtual corrections at high-p_T.

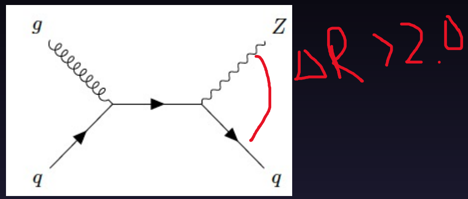


Z+high-p_T jets: What is Measured?

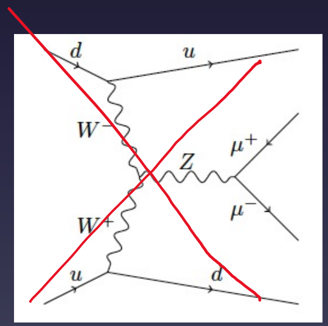
- Measured observables in various kinematic regions:
  - inclusive Z+jets region with jets defined by p_T>100 GeV and $|\eta|$<2.5
  - high-p_T region (p_T^{j1}>500 GeV) split as:



    - $\Delta R^{min}_{Z,j} < 1.4$: Soft radiation of a Z from dijet

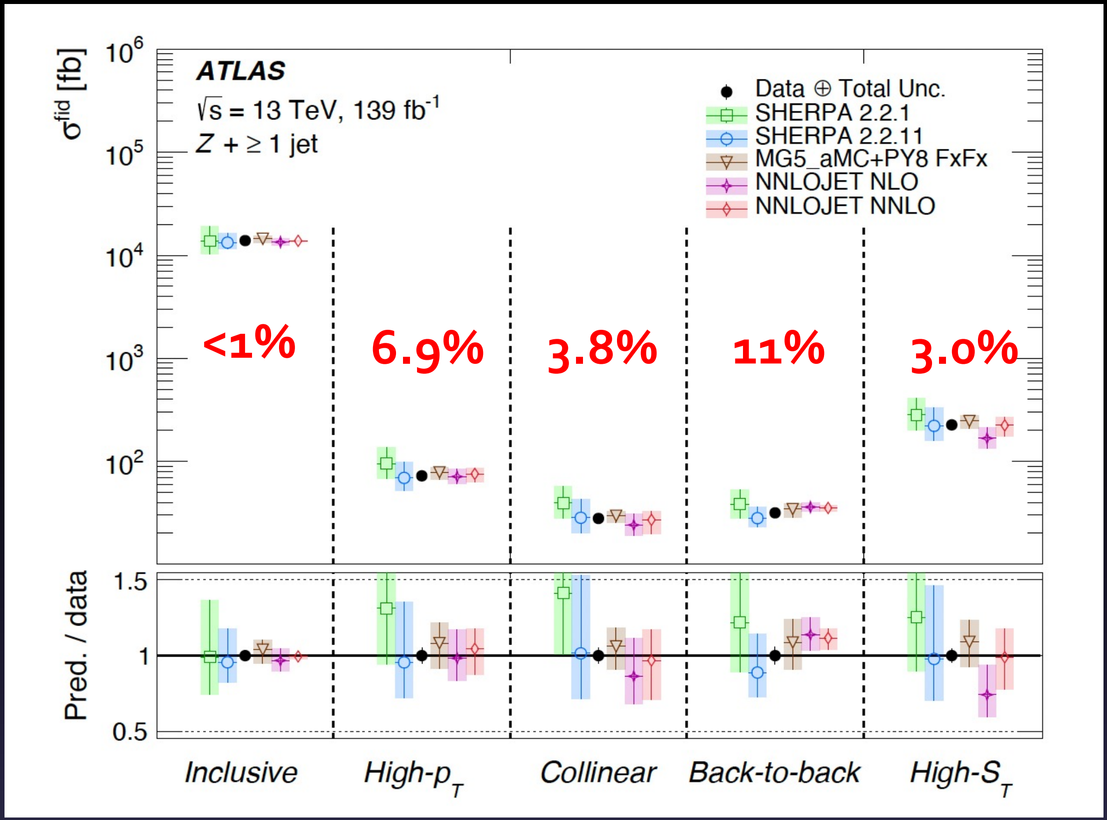


    - $\Delta R^{min}_{Z,j} > 2.0$: Hard scatter of a Z against a jet
    - Soft Z emission indicated by low value of $r_{Z,j} = p_T^{ll}/p_T^{j(closest)}$



- Fully EWK Z+2-jets production treated as background
- Measurement performed on 139 fb-1 of 13 TeV ATLAS data, and results are fully unfolded to fiducial phase space region

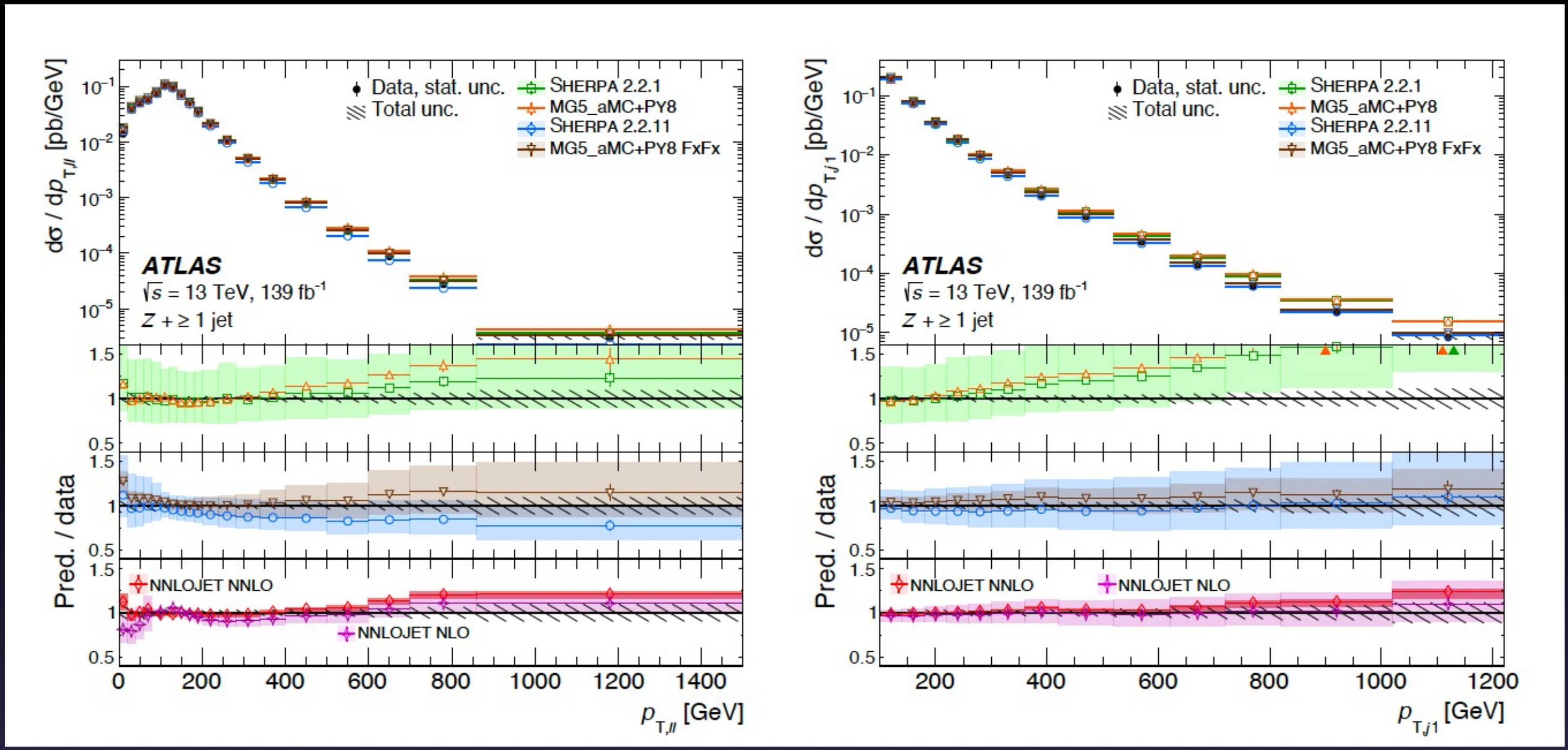
Z+high-p_T jets: Fiducial Cross



Impact of EWK virtual (neg.) corrections:

- Precision much higher for the measurements than all predictions
- All predictions accurately describe data in various phase spaces
  - Sherpa 2.2.11 is the only prediction with EWK virtual corrections, and no real emission correction included in any prediction.
  - QCD uncertainty in the predictions still too large compared to the size of the virtual electroweak corrections

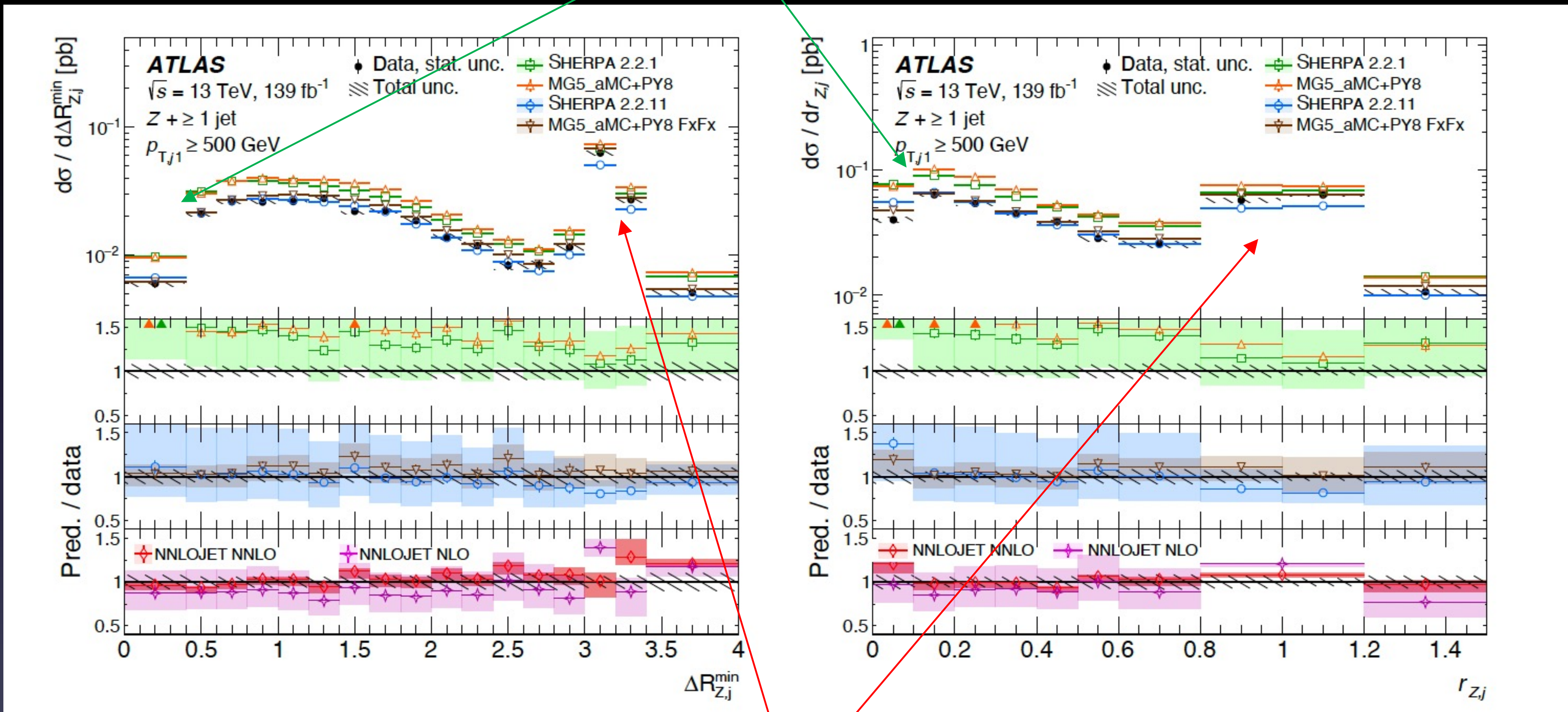
Z+high-p_T jets: Inclusive Phase Space



- Negative virtual EWK corrections included in Sherpa 2.2.11 is likely not the explanation to the improved agreement:
  - New matching in Sherpa 2.2.11 reduce cross section in the tail over 2.2.1.
  - MGaMC FxFx, the only prediction with 3 NLO partons, is in good agreement with data

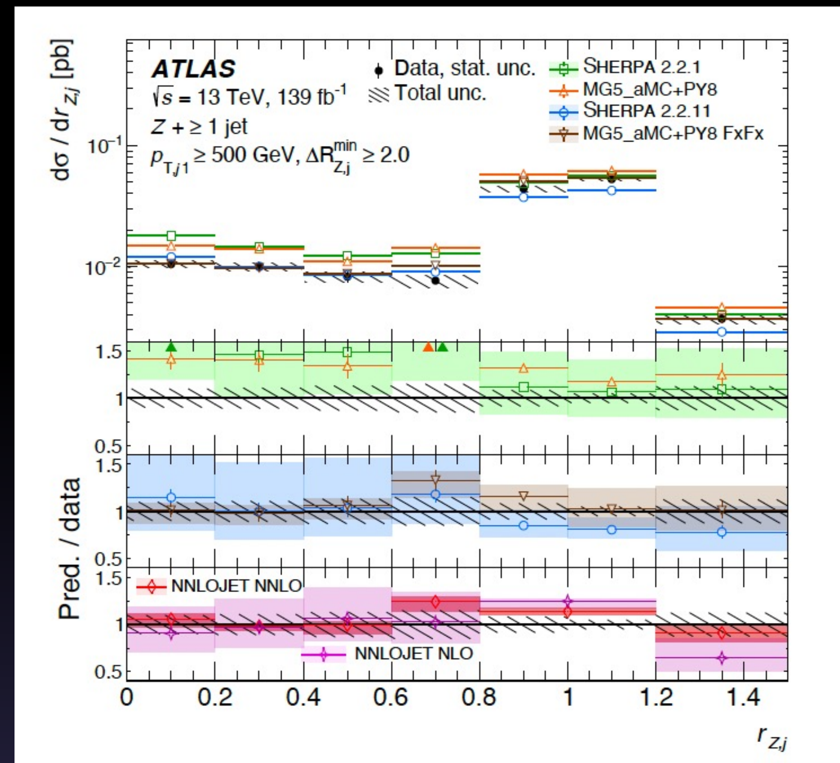
Z+high-p_T jets: : Collinear and Soft?

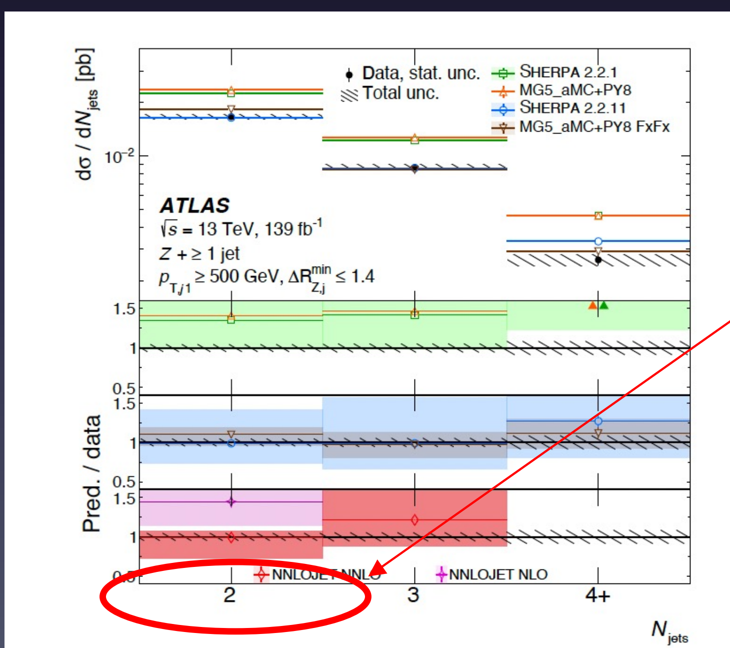
Large collinear contribution where NLO EWK real emission are important



Large back-to-back contribution where NLO EWK virtual corrections are important

- Suppressing low $\Delta R^{min}{}_{Zj}$ events suppresses low r_{Zj} events
  - A large contribution of collinear events comes from soft Z emission.





- The collinear region is domined by Z+2-jets events while the back-to-back region mainly consists in Z+1-jet events.

Conclusion

- ATLAS performed comprehensive studies of various pQCD effects in various exclusive jet production final states

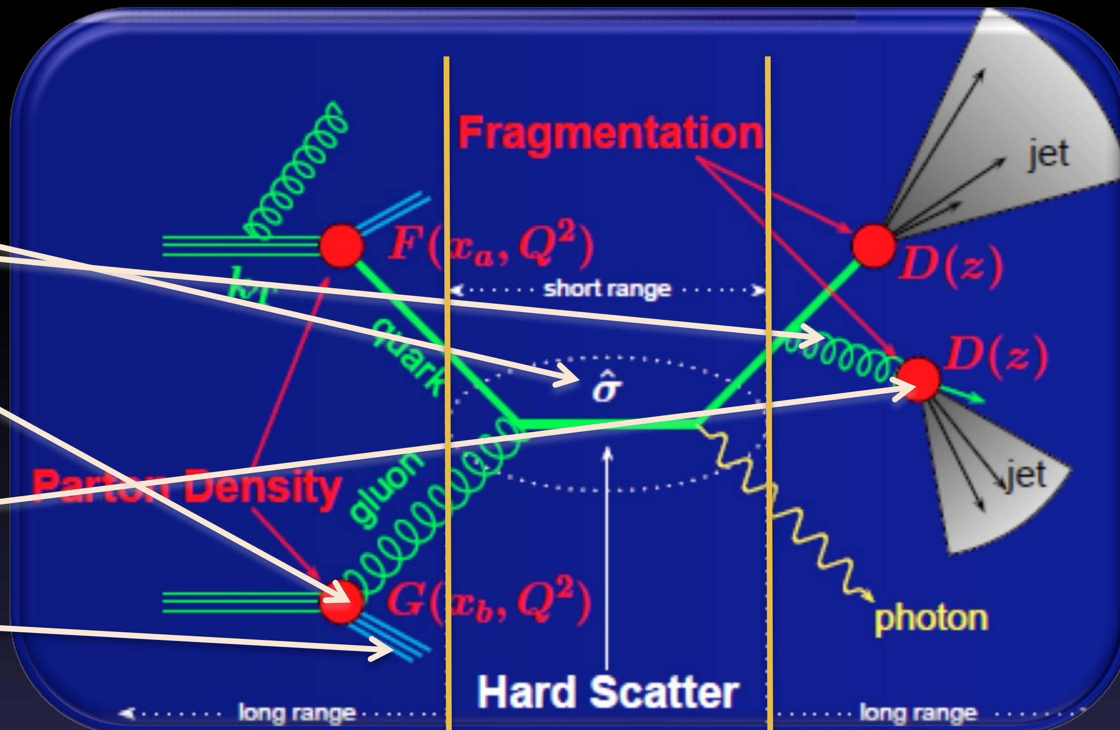
- Two very new Run-2 data Z+jets measurements are presented
  - A large-R jet w/o 2-btagged substructure testing heavy-flavor modeling in boosted jet topologies
  - A high-p_T jet, collinear or back-to-back to a Z, testing QCD modeling in phase space regions sensitive to EWK NLO real/virtual corrections

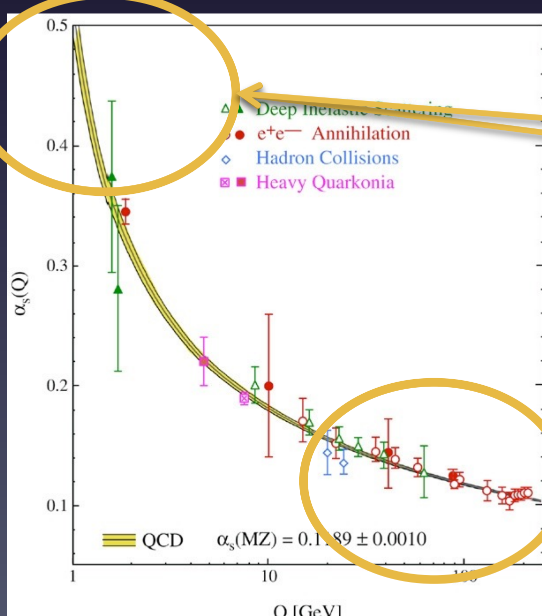
- From measurement, we learned :
  - Boosted-jet events are not particularly well-described except for the MG FxFX predictions, but the 2-tag selection is less sensitive to mismodeling when predictions are done in the 5FS or the fused scheme.
  - The state-of-the-art QCD calculation in phase space regions sensitive to EWK Z+jets processes (collinear and back-to-back) provide an excellent description of the observed data, treating EWK processes as background.

Back-up slides

The strong interaction intervenes in various ways and at various scales in every single event at the LHC

- Matrix element of interest $(\hat{\sigma})$
- Gluon emission (ISR/FSR)
- Proton structure (F,G)
- Fragmentation and hadronization (D(z))
- Underlying event





Long distance physics

Short distance physics

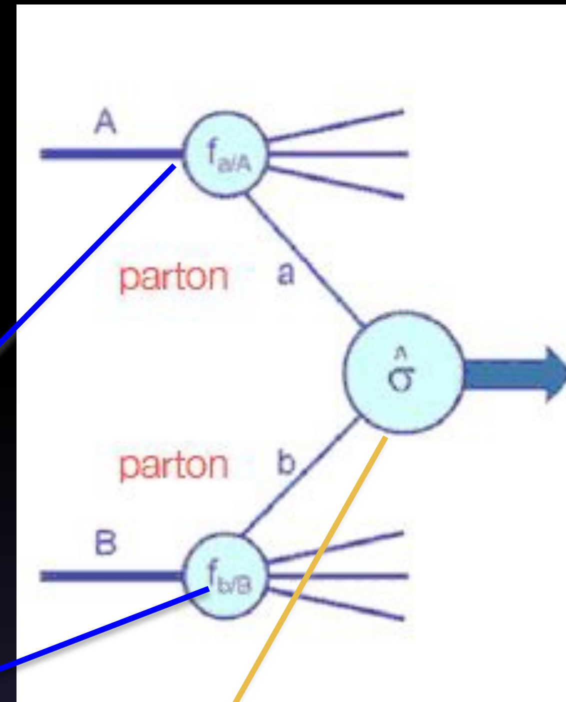
Long distance physics

We can make predictions from 1st principles

Require a mix of theoretical parameterization and data measurements to model these effects

Factorization theorem:

The probabilities for short-distance and long-distance processes factorize

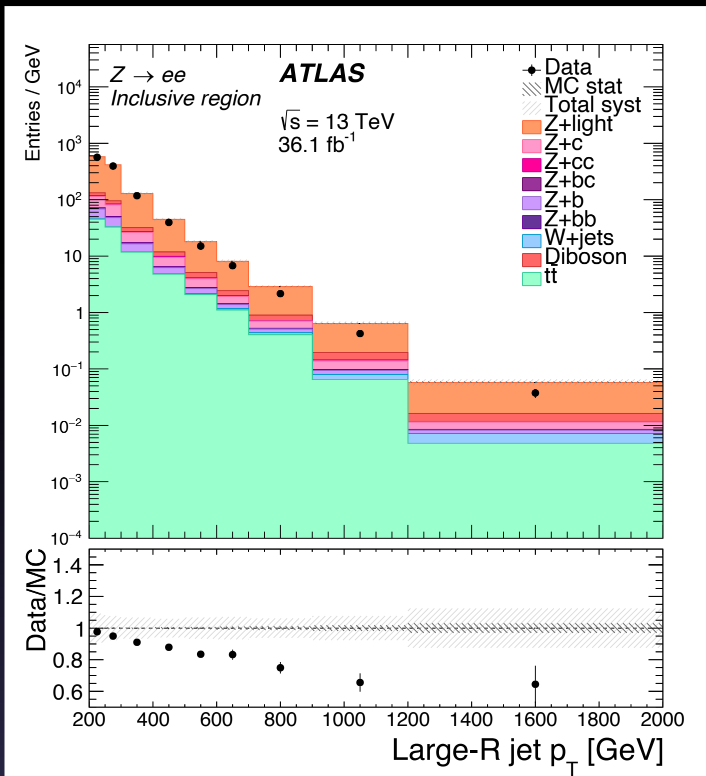


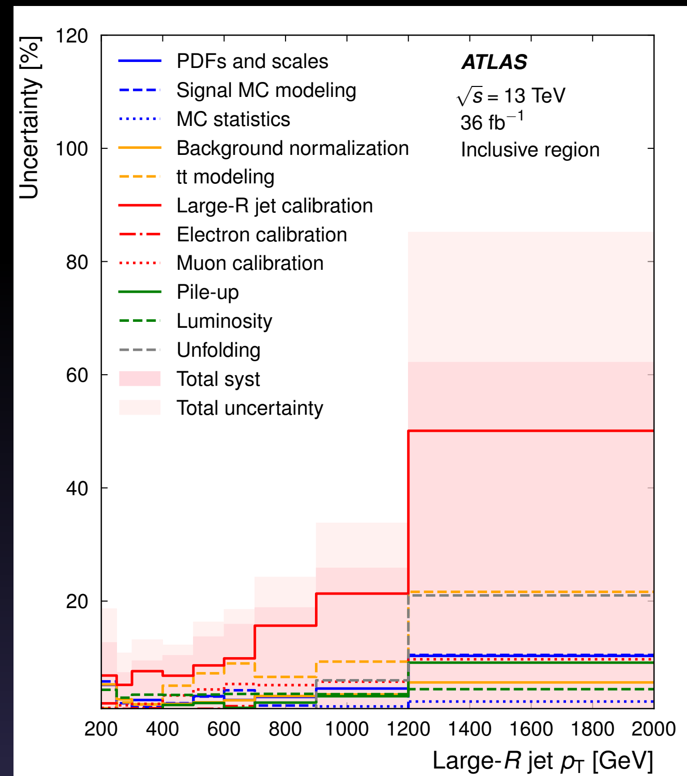
The long-distance factors are universal and can be empirically obtained from ancillary measurements. **Idea behind PDF "industry"**

$$d\sigma(P_1,P_2) = \sum_{i,j,k} \int dx_1\, dx_2\, dz\, f_i(x_1,\mu_F) f_j(x_2,\mu_F) D_{k\to H}(z,\mu_F)$$
$$\times\, d\tilde{\sigma}_{ij\to k+X}(p_1 = x_1 P_1, p_2 = x_2 P_2, p_k = P/z, \alpha_S(\mu_R), Q^2, \mu_R, \mu_F)$$

Evolution equations (e.g. DGLAP), analogous to β-functions for α_S, account for transition from one scale to the other

Z+large-jet: Background and Systematics

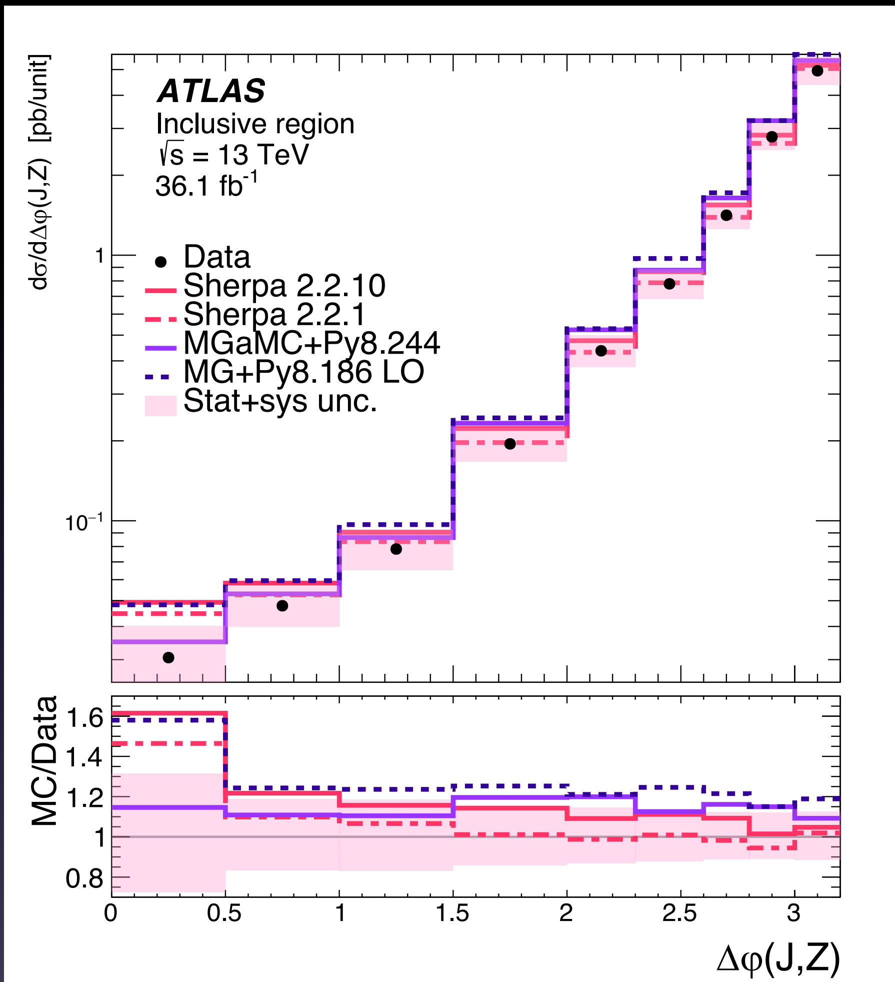


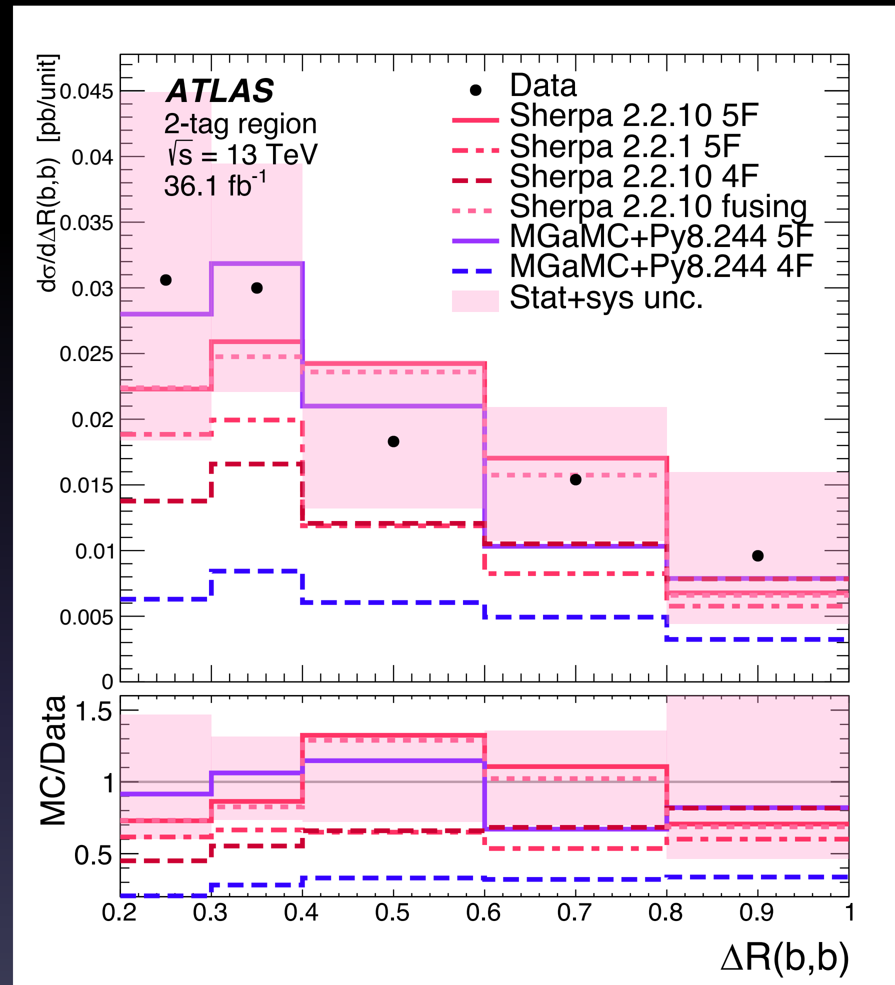


	Inclusive		2-tag	
	ee	$\mu\mu$	ee	$\mu\mu$
Z+$b\bar{b}$	324 ± 4	305 ± 4	163.8 ± 2.6	157.2 ± 2.5
Z+$c\bar{c}$	536 ± 10	530 ± 9	12.3 ± 1.8	19.3 ± 2.0
Z+bc	89 ± 2	81 ± 2	14.6 ± 1.2	12.1 ± 0.9
Z+b	2588 ± 13	2423 ± 12	14.8 ± 1.1	12.4 ± 1.3
Z+c	5073 ± 32	4862 ± 39	5.5 ± 1.3	6.9 ± 1.7
Z+light	$53\,808 \pm 164$	$51\,206 \pm 145$	9.4 ± 1.1	11.1 ± 1.5
$t\bar{t}$	5960 ± 46	5204 ± 43	82.7 ± 5.3	75.4 ± 5.6
W+jets	73 ± 4	7 ± 1	0.4 ± 0.1	< 0.1
Diboson	2042 ± 17	1834 ± 16	21.5 ± 1.4	20.7 ± 1.4
MC total	$70\,493 \pm 175$	$66\,452 \pm 158$	324.9 ± 6.8	315.1 ± 7.2
Data	66 481	65 034	391	384

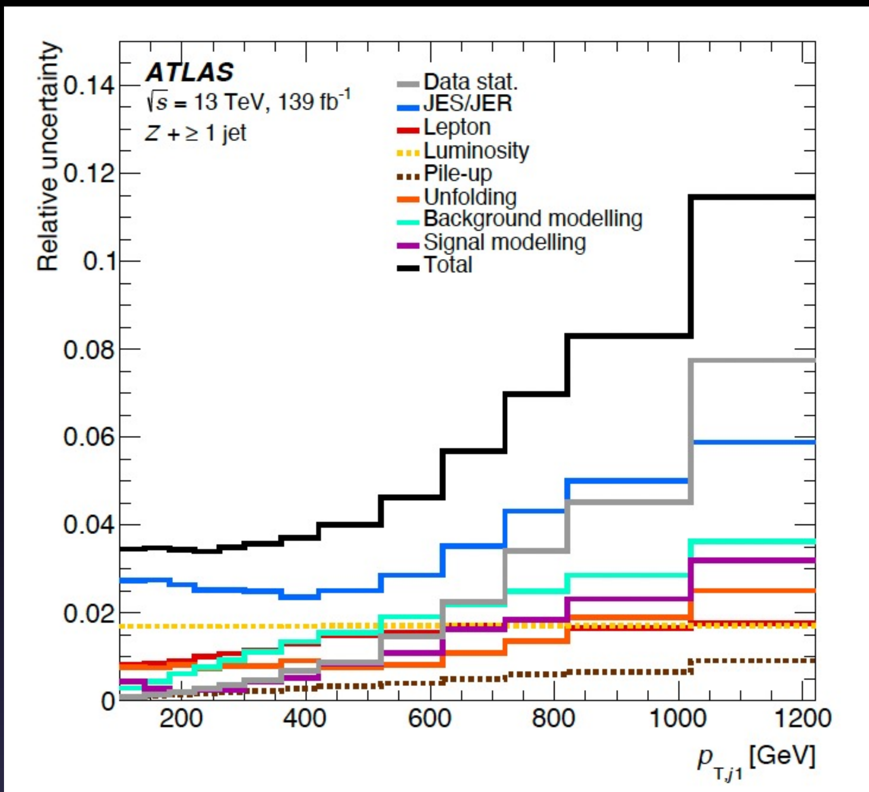
	Inclusive				2-tag		
	p_T^J	m_J	p_T^{Z+J}	$\Delta\phi(Z,J)$	p_T^J	m_J	$\Delta R(b,\bar{b})$
Scales & PDFs	0 – 10 %	3 – 7 %	2 – 9 %	1 – 4 %	2 – 9 %	3 – 9 %	2 – 14 %
MC modeling	1 – 11 %	0 – 12 %	1 – 6 %	1 – 6 %	0 – 15 %	4 – 9 %	2 – 9 %
MC statistics	0 – 2 %	3 – 10 %	0 – 5 %	0 – 1 %	4 – 12 %	3 – 11 %	2 – 4 %
Bkg normalization	2 – 6 %	4 – 7 %	3 – 6 %	2 – 7 %	9 – 37 %	11 – 23 %	11 – 26 %
$t\bar{t}$ modeling	1 – 22 %	3 – 13 %	2 – 13 %	2 – 11 %	4 – 23 %	11 – 29 %	3 – 24 %
Jet reco.	5 – 50 %	6 – 11 %	5 – 21 %	7 – 22 %	9 – 33 %	15 – 24 %	11 – 21 %
b-tagging					5 – 33 %	6 – 12 %	7 – 11 %
Electron reco.	0 – 2 %	1 – 7 %	2 – 7 %	1 – 3 %	4 – 8 %	0 – 9 %	1 – 3 %
Muon reco.	1 – 10 %	2 – 9 %	0 – 2 %	1 – 5 %	1 – 3 %	1 – 7 %	0 – 2 %
Pile-up	0 – 9 %	0 – 3 %	0 – 2 %	0 – 1 %	1 – 16 %	0 – 7 %	1 – 4 %
Luminosity	3 – 4 %	0 – 7 %	3 – 7 %	4 – 5 %	5 – 7 %	3 – 7 %	4 – 6 %
Unfolding closure	0 – 21 %	0 – 0 %	0 – 18 %	0 – 0 %	0 – 0 %	0 – 0 %	0 – 0 %
Total syst.	7 – 62 %	11 – 27 %	10 – 33 %	9 – 27 %	23 – 66 %	24 – 45 %	22 – 41 %

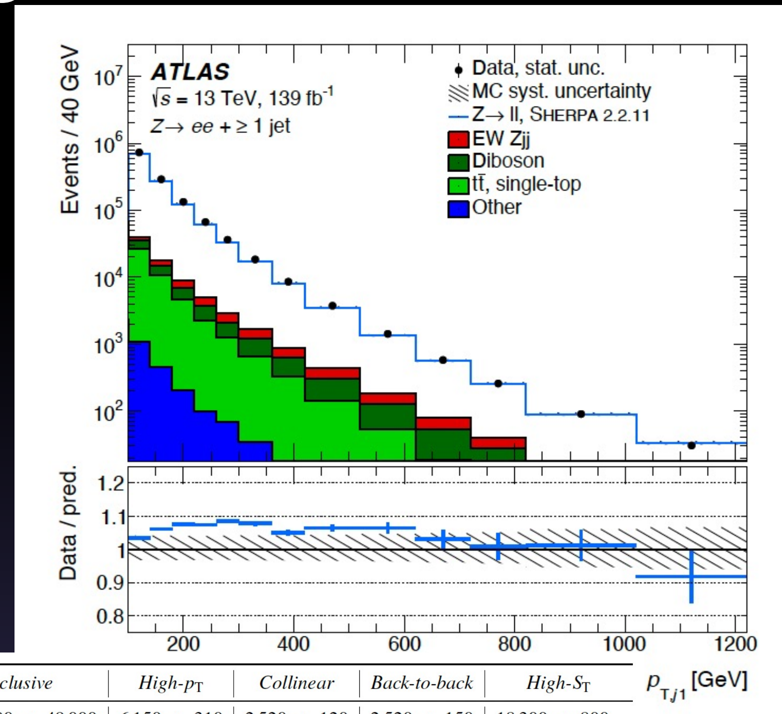
Z+large-jet: Angular Separations





Collinear Z+jets: Background and Systematics



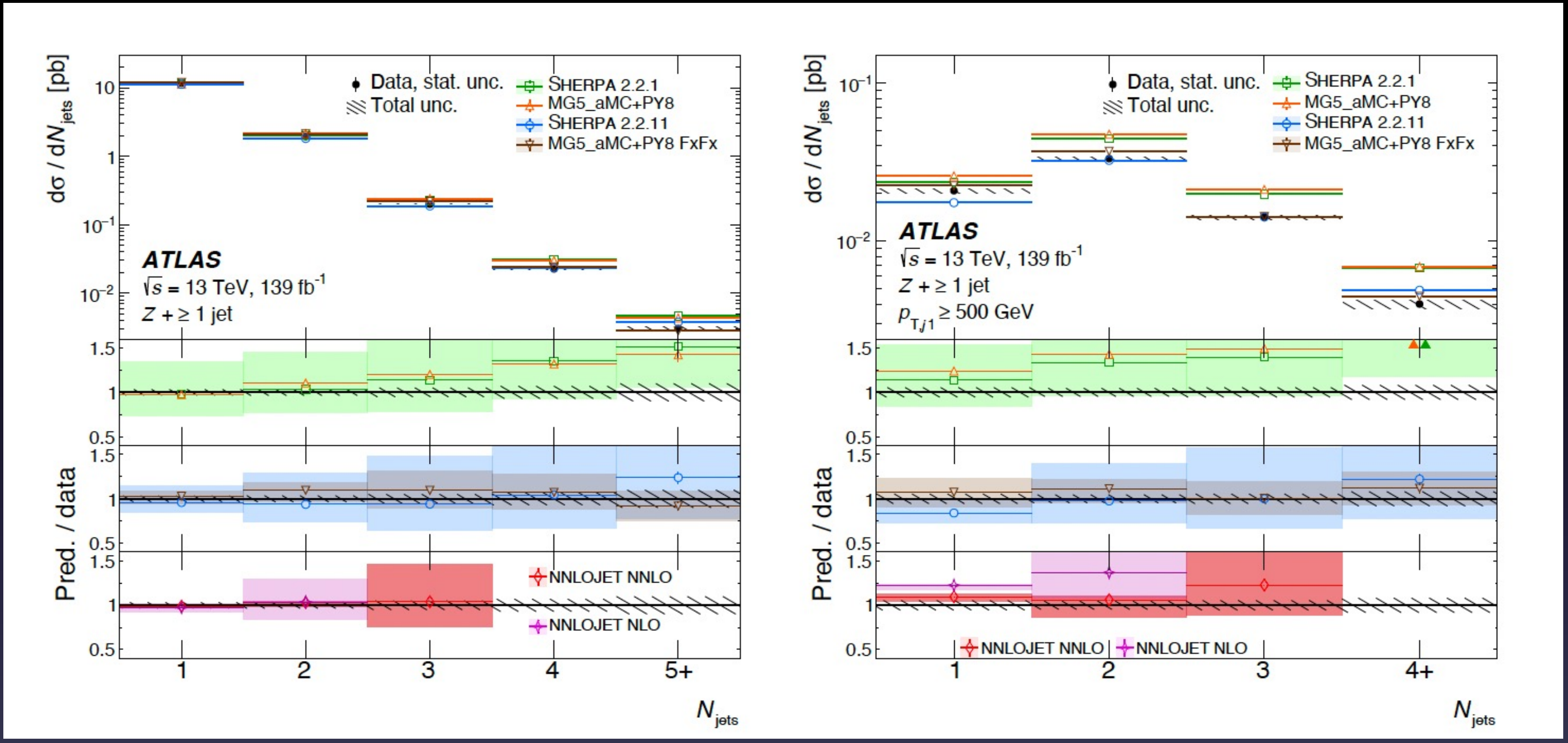


Uncertainty source [%]	*Inclusive*	*High-p_T*	*Collinear*	*Back-to-back*	*High-S_T*
JES/JER	2.6	3.2	2.8	3.6	2.8
Lepton	0.9	1.6	1.4	2.0	1.1
Luminosity	1.7	1.7	1.7	1.7	1.7
Pile-up	0.1	0.4	0.4	0.4	0.4
Unfolding	0.5	1.0	1.1	1.4	0.8
Background modelling	0.5	2.0	2.0	1.9	1.7
Signal modelling	0.5	1.2	1.1	1.1	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

$Z \to e^+e^-$	*Inclusive*	*High-p_T*	*Collinear*	*Back-to-back*	*High-S_T*
Z + jets	1 171 000 ± 49 000	6 150 ± 310	2 520 ± 120	2 520 ± 150	18 300 ± 800
$t\bar{t}$	43 400 ± 1 300	209 ± 16	136 ± 13	47.2 ± 7.5	917 ± 41
Diboson	19 530 ± 750	428 ± 29	183 ± 16	167 ± 16	1 008 ± 53
EW Zjj	13 270 ± 500	312 ± 23	102 ± 11	135 ± 14	789 ± 43
Single-top	2 430 ± 160	27.9 ± 5.5	14.0 ± 3.8	9.8 ± 3.2	54.2 ± 8.2
$Z \to \tau\tau$	515 ± 37	4.6 ± 4.2	1.6 ± 2.1	2.2 ± 1.7	10.6 ± 6.2
W + jets	93 ± 16	3.4 ± 1.9	0.3 ± 0.6	2.9 ± 1.7	3.4 ± 1.9
$V + \gamma$	1 413 ± 83	14.2 ± 4.3	6.5 ± 2.6	5.1 ± 2.3	34.1 ± 7.3
Total predicted	1 252 000 ± 51 000	7 150 ± 350	2 970 ± 130	2 890 ± 170	21 100 ± 880
Data	1 312 145	7 539	2 955	3 231	21 746

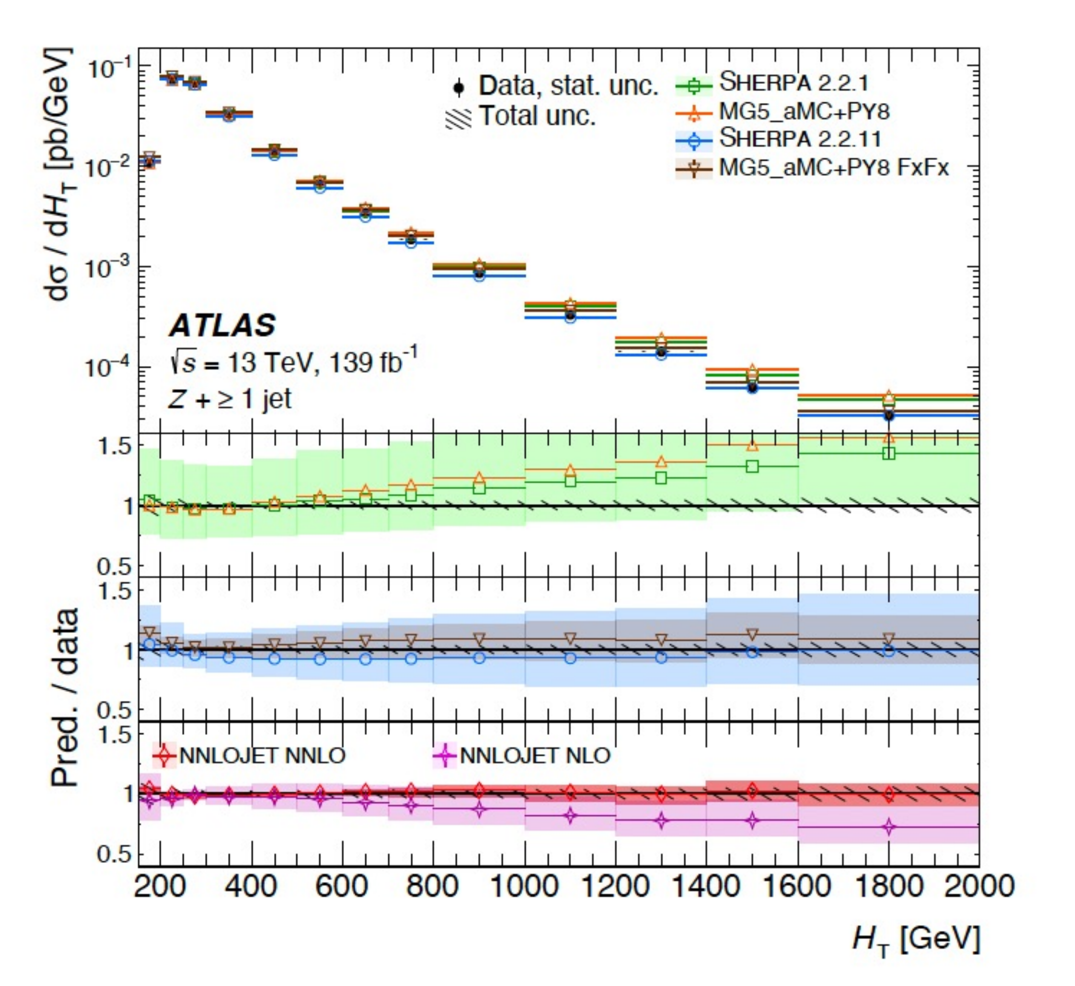
$Z \to \mu^+\mu^-$	*Inclusive*	*High-p_T*	*Collinear*	*Back-to-back*	*High-S_T*
Z + jets	1 537 000 ± 63 000	6 700 ± 300	2 950 ± 130	2 420 ± 120	23 110 ± 920
$t\bar{t}$	55 400 ± 1 300	209 ± 16	142 ± 12	39.1 ± 6.6	1 058 ± 41
Diboson	24 160 ± 870	438 ± 27	198 ± 16	157 ± 14	1 149 ± 55
EW Zjj	17 020 ± 580	328 ± 22	113 ± 12	134 ± 13	915 ± 45
Single-top	3 110 ± 190	29.1 ± 5.5	13.6 ± 3.8	11.2 ± 3.5	70.0 ± 9.2
$Z \to \tau\tau$	460 ± 33	3.5 ± 4.0	1.1 ± 2.3	1.8 ± 1.5	8.8 ± 5.4
W + jets	128 ± 14	1.9 ± 1.4	0.3 ± 0.5	1.5 ± 1.3	2.7 ± 2.0
$V + \gamma$	1 273 ± 90	2.5 ± 2.4	0.0 ± 0.7	2.2 ± 1.5	22.4 ± 5.5
Total predicted	1 638 000 ± 64 000	7 710 ± 330	3 420 ± 140	2 770 ± 140	26 300 ± 1 000
Data	1 673 057	7 896	3 372	3 059	26 567

Collinear Z+jets: Jet Multiplicity



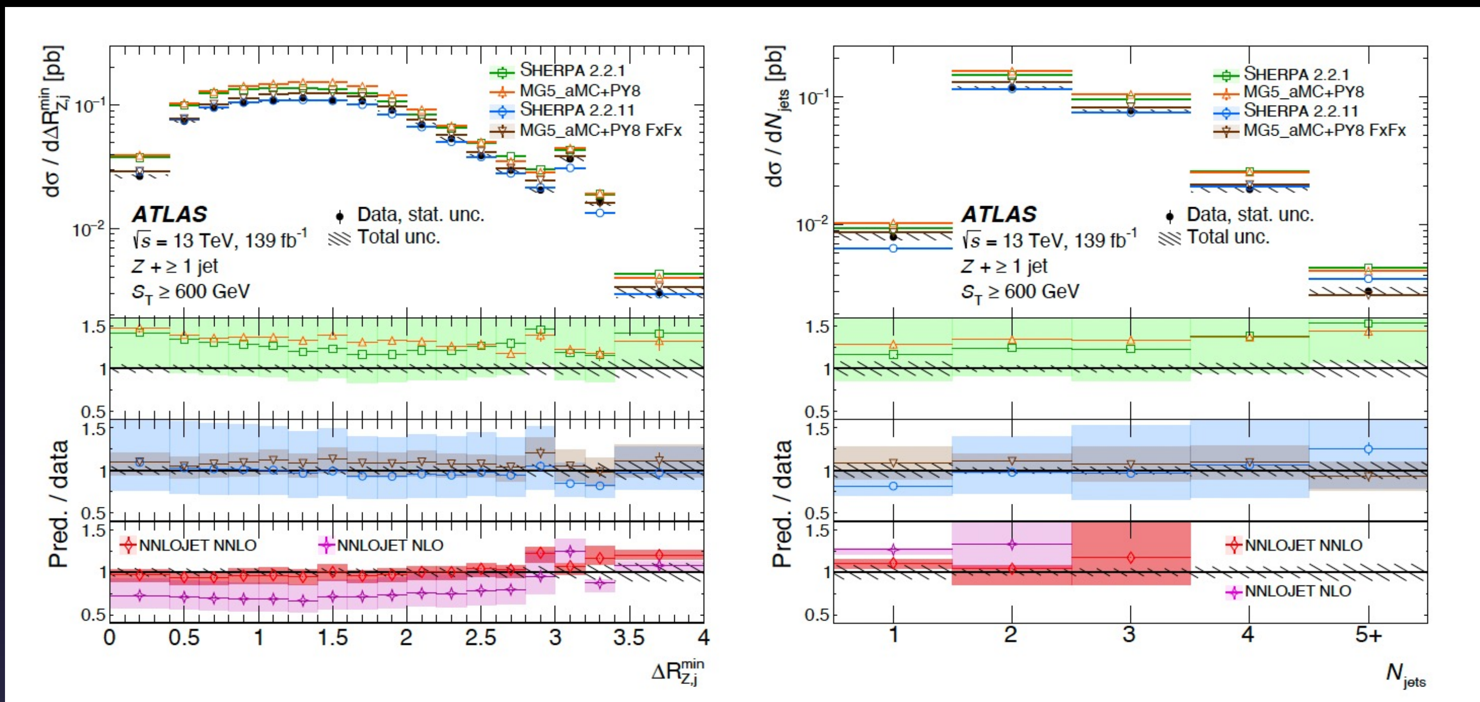
Jet multiplicity: inclusive vs high-p_T regions

Collinear Z+jets: H_T



H_T: inclusive regions

Collinear Z+jets: high-S_T Events Results



$$S_T = \sum_{jet} p_T^{jet}$$

- Jet multiplicity is enhanced in this high-S_T region, and the back-to-back peak of the $\Delta R^{min}{}_{Zj}$ distribution is suppressed.
- The state-of-the-art predictions accurately describe this phase space region, as well as the more exclusive ones.