Measurements of the production cross section for the collinear emission of a Z boson from a jet in pp collisions at 13 TeV with the ATLAS detector

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Outline

- ▷ **The ATLAS experiment**
- ▷ **Z bosons & jets**
- ▷ **Collinear *Z* boson production**
- ▷ **Analysis & Results**

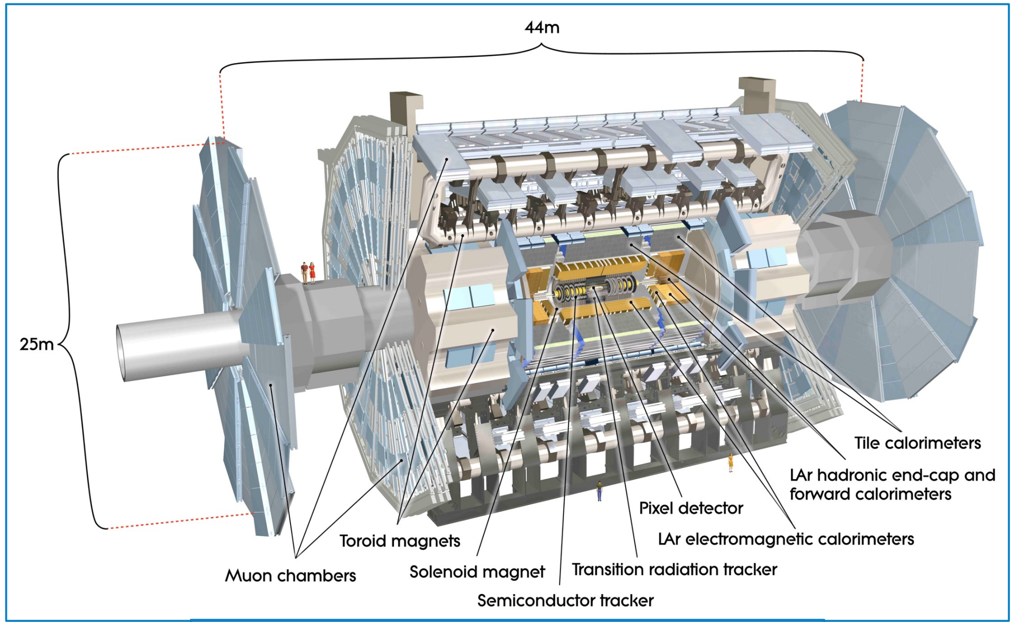
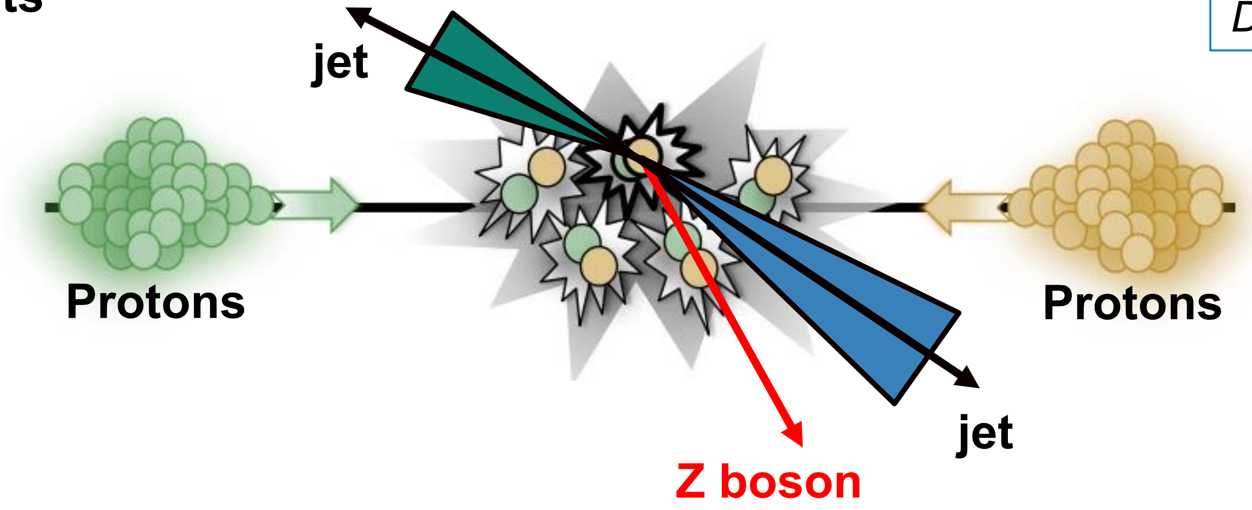
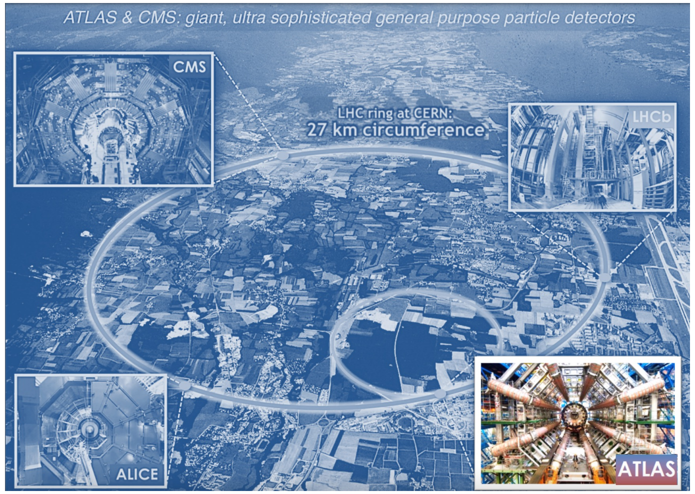


Diagram of the ATLAS detector

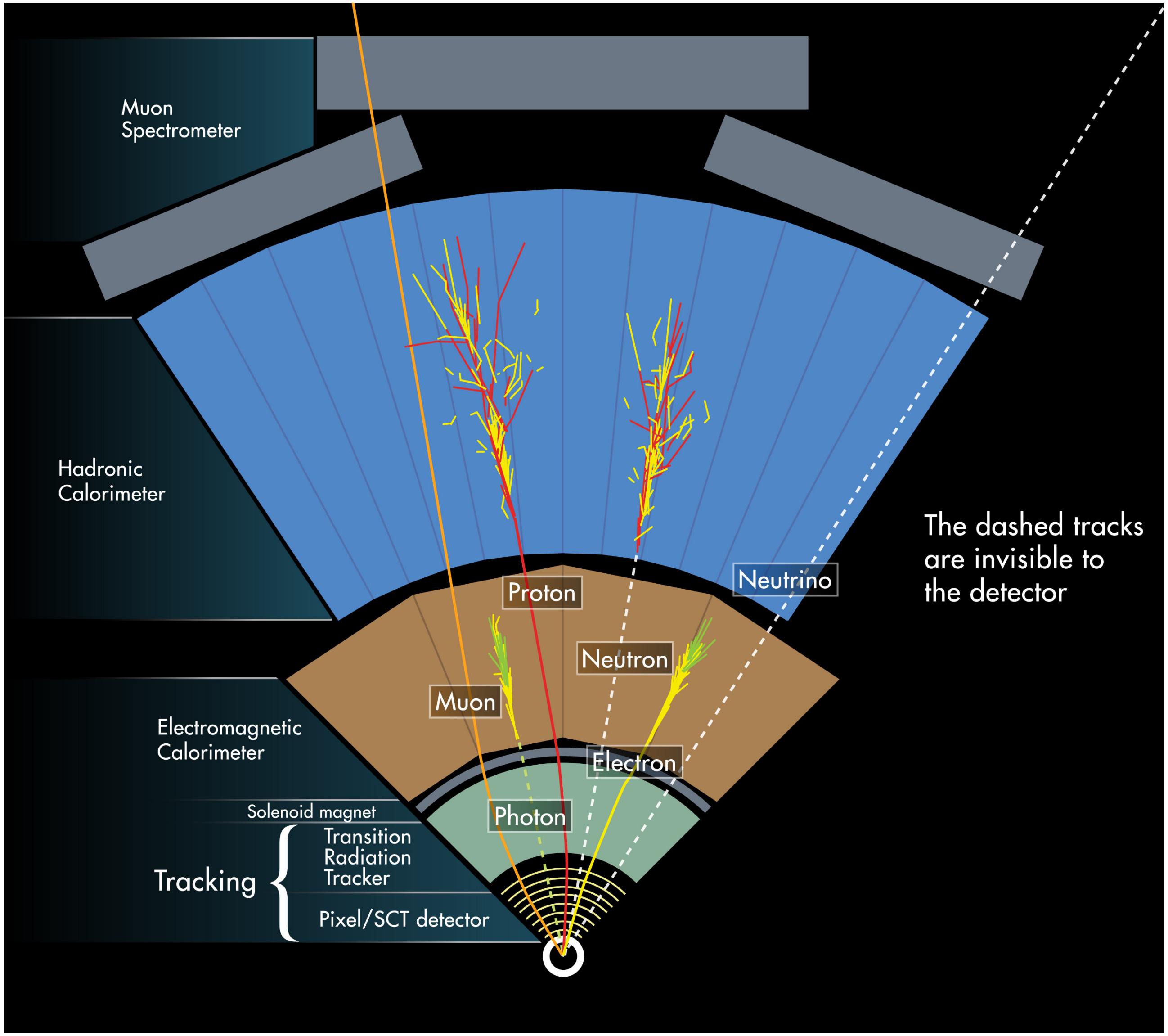


Collinear Emission of a Z boson

The ATLAS Experiment



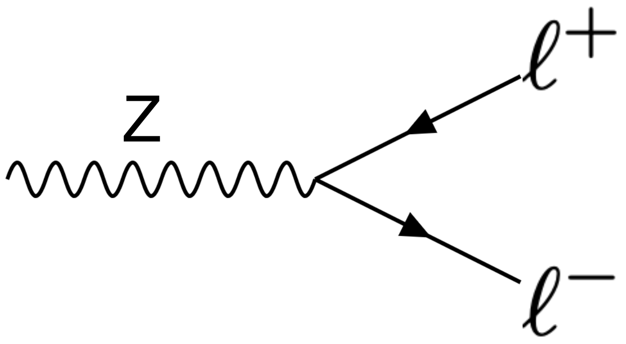
- One of four main experiments at the Large Hadron Collider (LHC).
- LHC is the world's largest and most powerful particle collider.
- ATLAS is a general-purpose detector.
  → Measures large range of physics.
- Measures the products of proton-proton collisions.



Z Bosons and Jets

Z Bosons

- One of the 4 particles mediating the electroweak force.
- Electrical charge of zero.
- 10% of decays into charged leptons.
- Clean and precise signatures of electron and muon decays.



Clean and easy to measure!

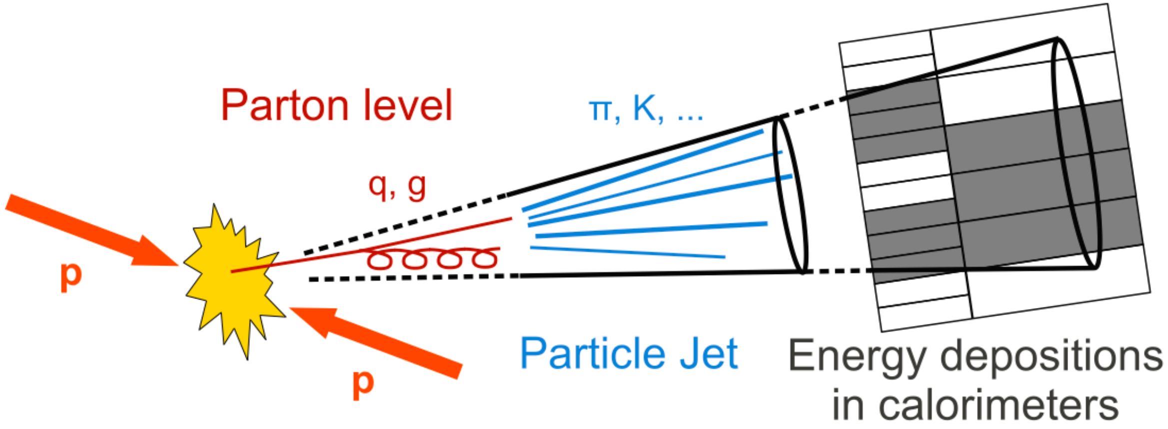
$$Z \to e^+e^-$$
$$Z \to \mu^+\mu^-$$

$$Z \to \tau^+\tau^-$$

Exhibits a different signature. We'll ignore this one for now.

Jets

- Streams of particles produced when a quark or gluon is an outgoing particle of collision.
- Quarks and gluons hadronize and create a series of different mesons.
- Are measured in the general shape of a cone called jets.



Collinear Z + Jets Analysis

Cross-section measurements for the production of a Z boson in association with high-transverse-momentum jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

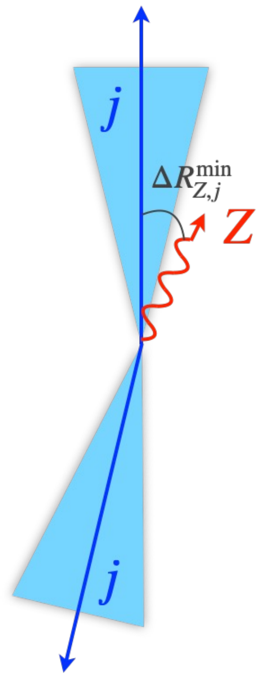
The ATLAS Collaboration

arXiv:2205.02597

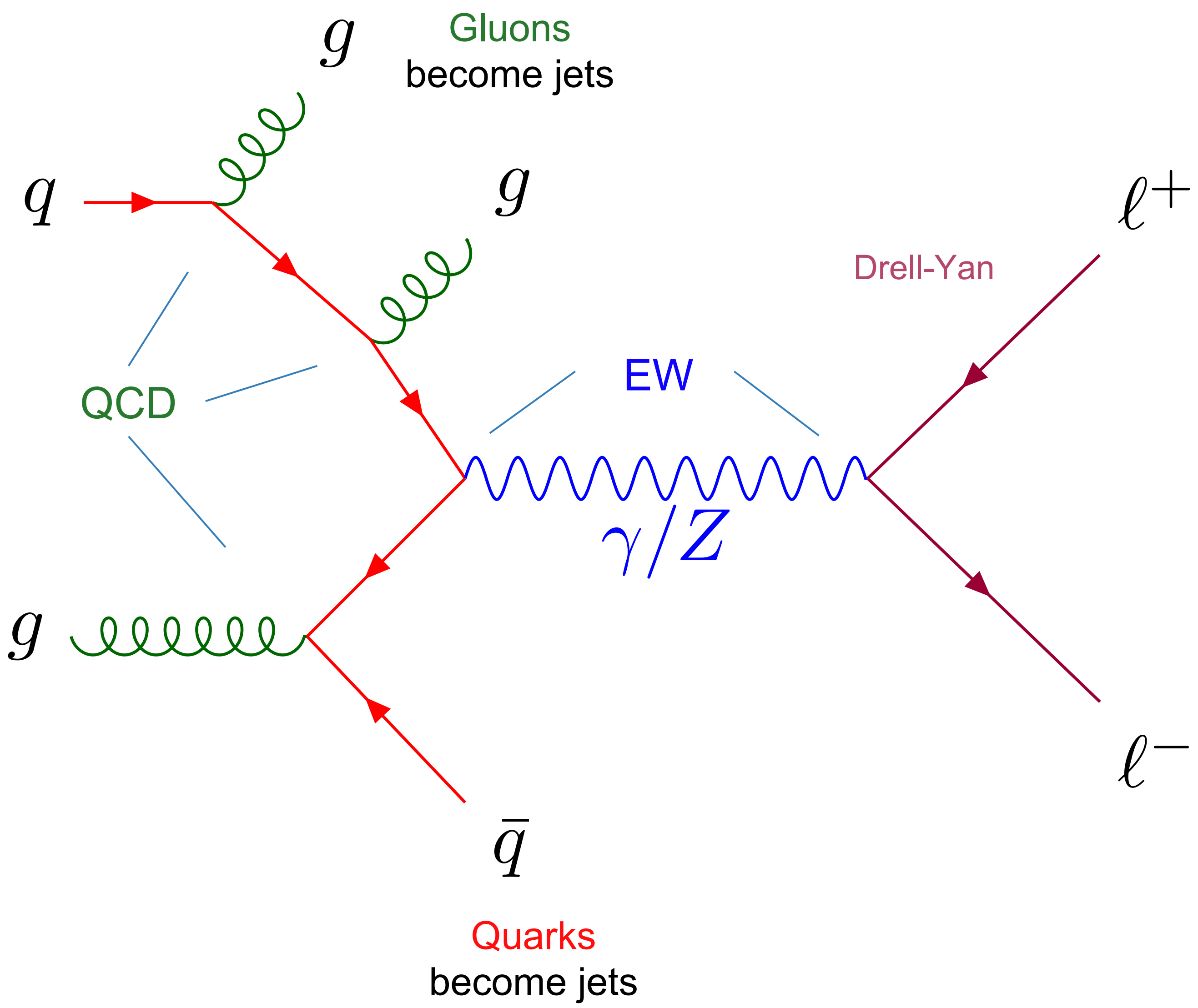
STDM-2018-49

- Analysis of the full Run 2 ATLAS dataset at $\sqrt{s} = 13$ TeV.
  → Proton-proton collisions collected in 2015-2018.
- Measure events with Z boson and high transverse-momentum (p_{T}) jets.
  → Z decaying to $e^{+}e^{-}$ or $\mu^{+}\mu^{-}$ pairs.
  → $p_{\mathrm{T}}(jet) \geq 100$ GeV.
  → ATLAS analyses often consider jets with $p_{\mathrm{T}}(jet) \geq 20 - 60$ GeV.
- Focus on extreme selection where most energetic jet has $p_{\mathrm{T}}(jet) \geq 500$ GeV.
  → Enhances collinear emission of Z boson from a jet.
  → Collinear Z boson emission is extreme phase space and poorly understood.
- Focus on measuring kinematics between Z boson and closest jet.
- Measure differential cross-section distributions for 13 observables.
- Measure production cross section of Z + high transverse-momentum jets.

Collinear

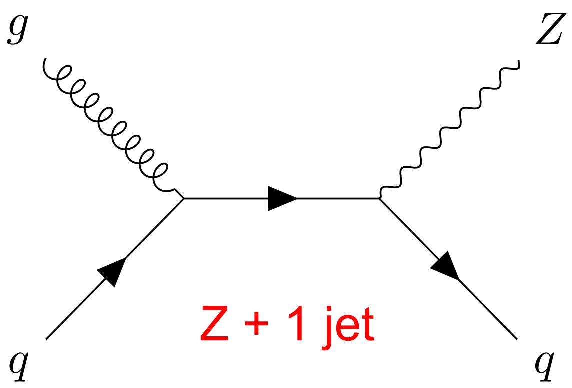


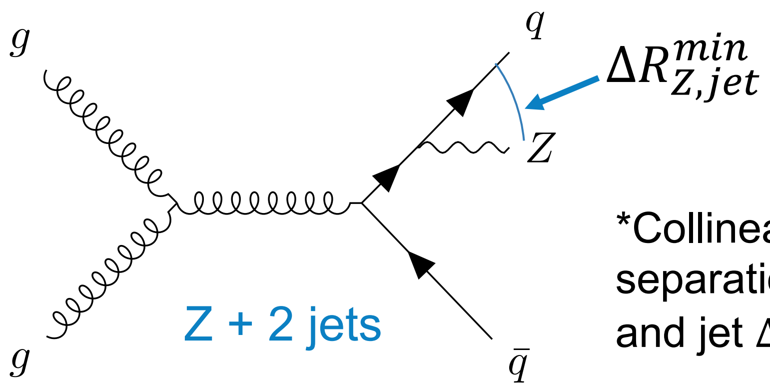
Z Bosons in Association with Jets



- LHC is the largest Z + jets factory in the world.
  → Produced about 7-8 billion Z bosons in **Run 2**.
- Perfect experimental conditions to test quantum chromodynamics (QCD) and electroweak (EW) interactions.
- Encompasses wide family of different physics.
- Significant backgrounds to many processes.
- Sensitive to high order effects at high energies.

High Transverse Momentum Jets





*Collinear: Small angular separation between *Z* boson and jet $\Delta R_{Z,jet}^{min}$.

- **Z + 2 jet** process suppressed by an extra order of α_s but …
- Ratio of **Z + 2 jets** to **Z + 1 jet** goes as $\alpha_s \ln^2 \frac{p_{\mathrm{T}}(jet)}{M_Z}$ in collinear *Z* boson emissions.

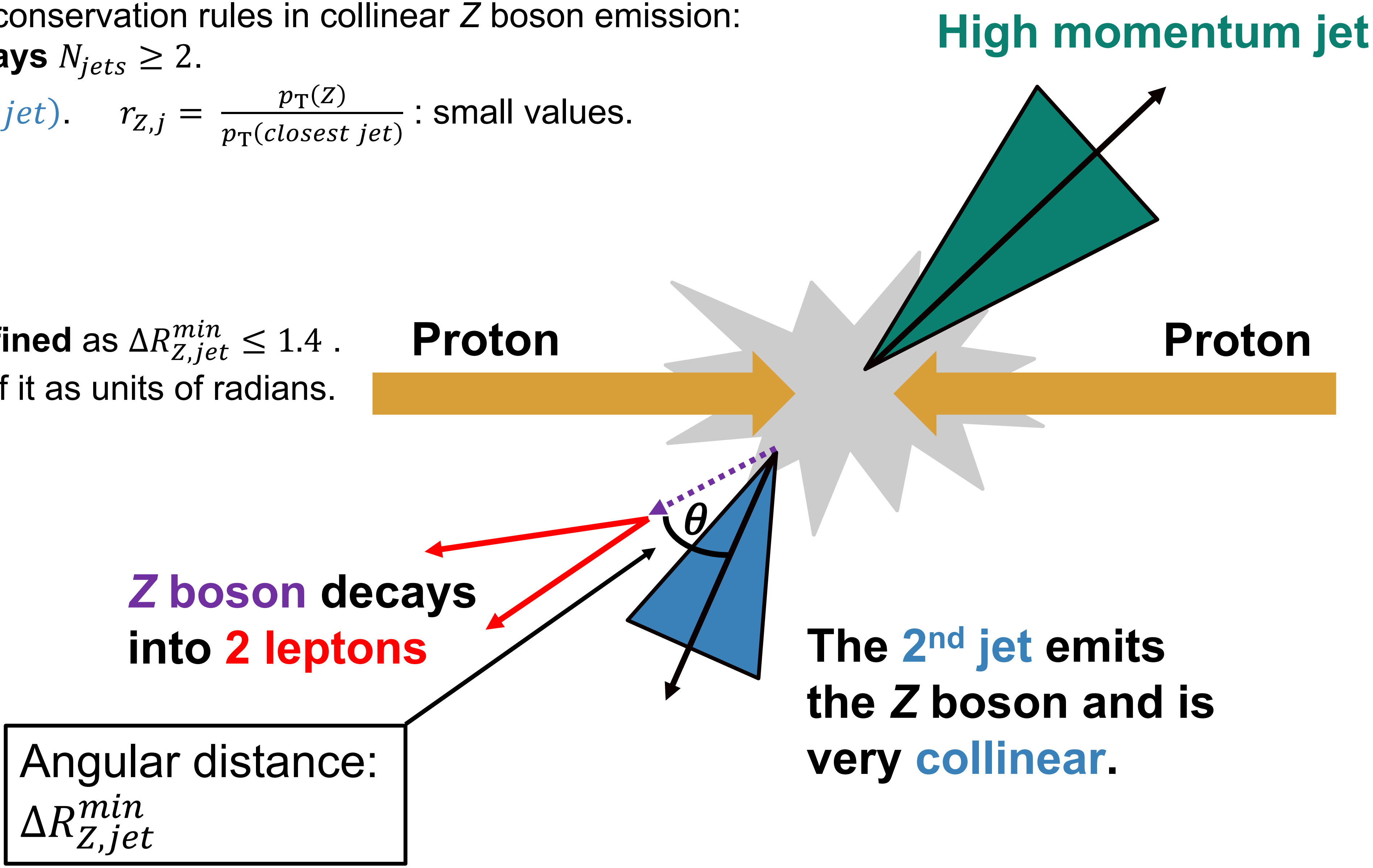
- With large $p_{\mathrm{T}}(jet)$, **Z + 2 jets** no longer suppressed vs **Z + 1 jet** .
- Focus on very high $p_{\mathrm{T}}(jet)$ events to study the collinear emissions.
  → $p_{\mathrm{T}}(leading\ jet) \geq 500\ \mathrm{GeV}$.

- **Z + 2 jets** offer unique event kinematics (**collinear Z boson emission**) which we can study!
  → No longer suppressed with high jet transverse momenta.

Collinear Z + Jets Signatures

- Energy & momentum conservation rules in collinear Z boson emission:
  → Number of jets **always** $N_{jets} \geq 2$.
  → $p_{\mathrm{T}}(Z) \ll p_{\mathrm{T}}(closest\ jet)$. $r_{Z,j} = \frac{p_{\mathrm{T}}(Z)}{p_{\mathrm{T}}(closest\ jet)}$: small values.
  → $\Delta R^{min}_{Z,jet}$ small.

- Collinear emission **defined** as $\Delta R^{min}_{Z,jet} \leq 1.4$.
  → Can broadly think of it as units of radians.



Measuring Cross Sections

▷ In the i-th bin of a given observable, the fiducial cross section is:

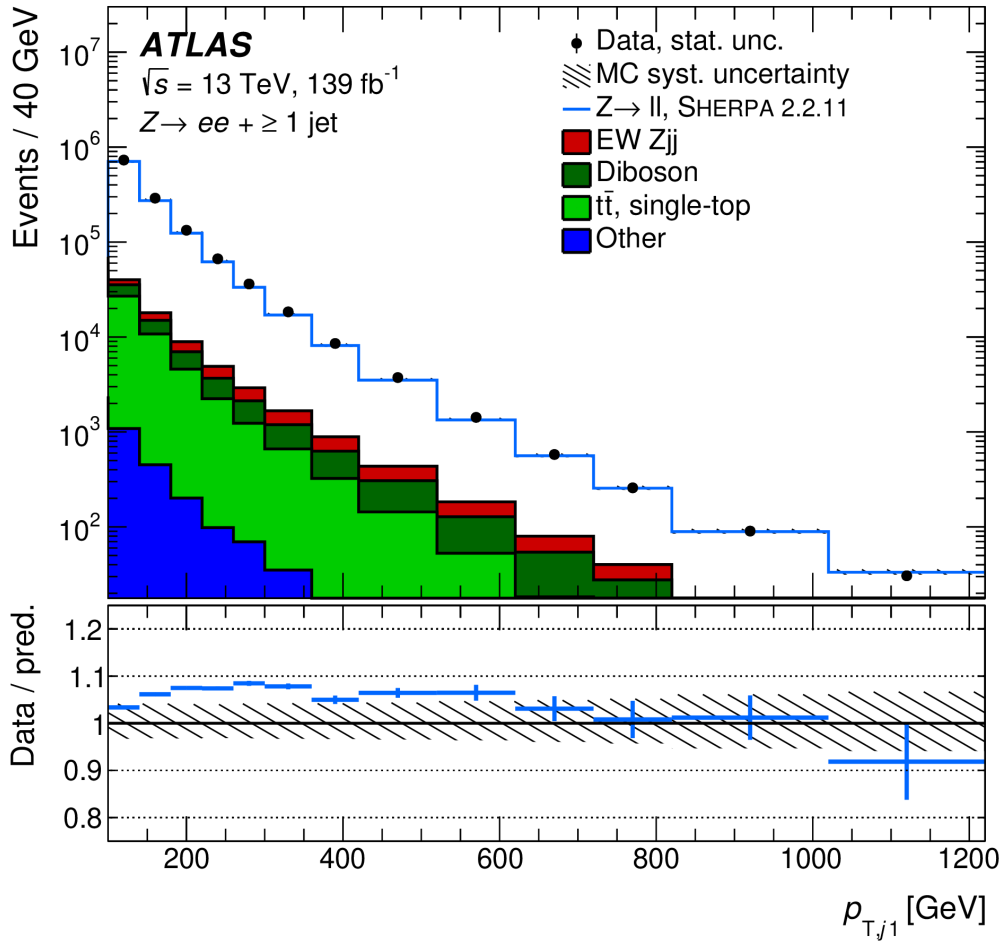
$$\sigma_i = \frac{N_i^{observed} - N_i^{background}}{C_i \mathcal{L}}$$

→ N_i^{observed} is the number of observed events,
→ $N_i^{\text{background}}$ is the estimated number of background events,
→ $\mathcal{L}$ the luminosity and
→ C_i a transfer function which corrects for detector effects to get the true (fiducial) cross section.

▷ C_i is a complicated function of event kinematics and detector performance, estimated with Monte Carlo (MC) simulation.

▷ Leading backgrounds are from $t\bar{t}$ and diboson processes, estimated with MC and data-driven methods.

arXiv:2205.02597



Detector level event yields for leading jet p_T. The Z+jets prediction (blue line) is stacked with the backgrounds (filled colors). Corresponds to N_i^{observed}.

Key Results

- Data is compared against 6 different predictions.
  → Green and Orange: Default ATLAS MC (~5 years old).
  → Blue and Brown: State-of-the-art MC (2022).
  → Red and Purple: Fixed order calculations. NNLO can only predict Z + up to 3 jets, while NLO only Z + up to 2 jets.

- Green and Orange overestimate data.
  → 50% modelling uncertainties!

- Very good central predictions from state-of-the-art MC. Brown **very** precise.
  → **Incredible improvements** over previous generation!

- NNLO prediction is most precise and often most accurate.

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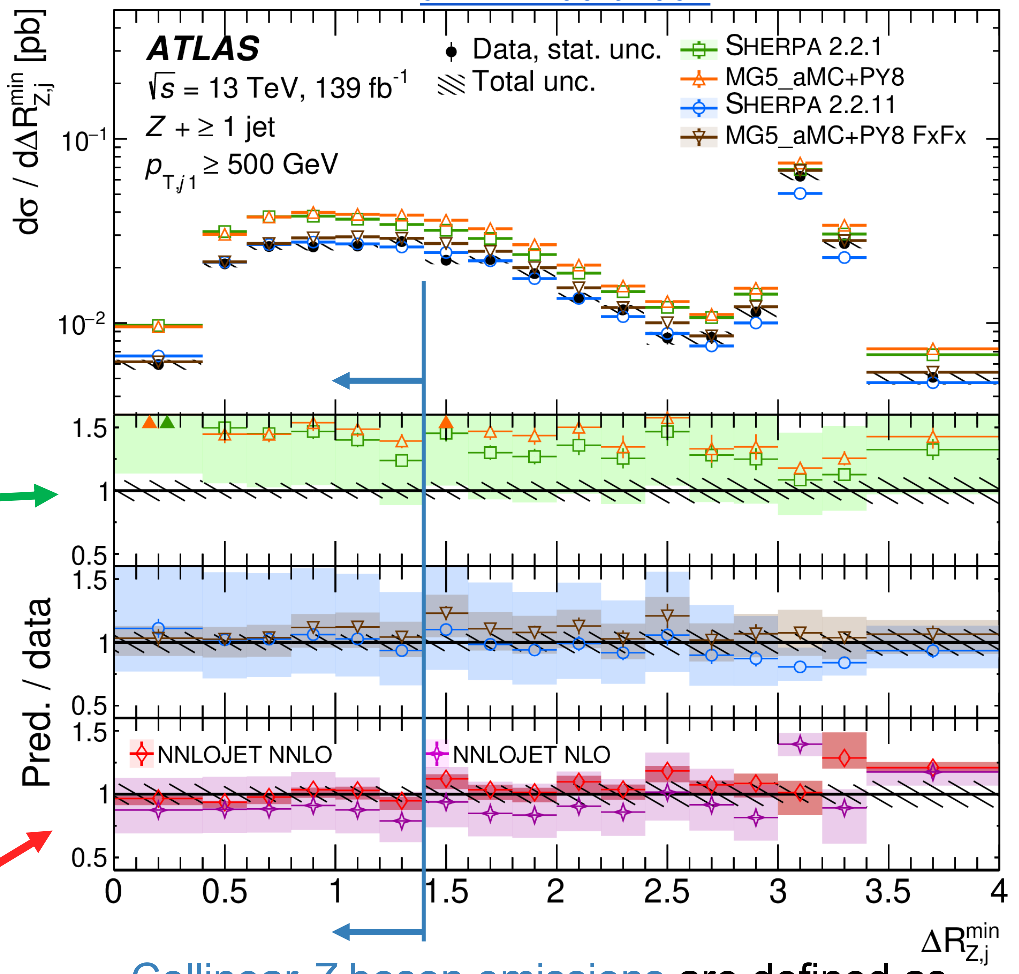


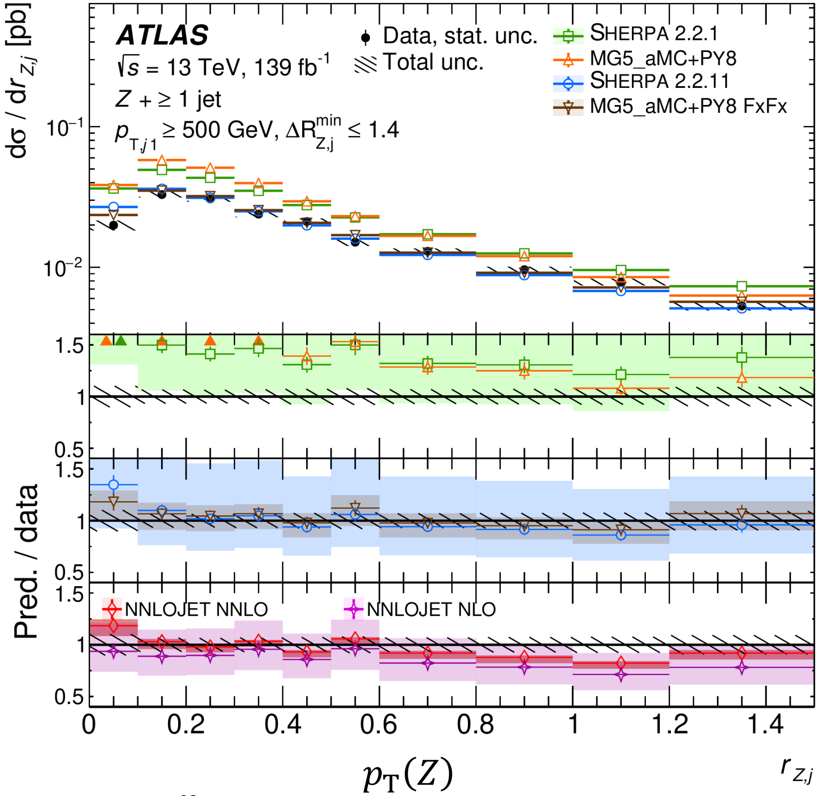
Collinear Z boson emissions are defined as $\Delta R_{Z,jet}^{min} \leq 1.4$

- **Data measurements are more precise than the predictions.**
- **Data uncertainty about 5%.**
  → Statistical uncertainty leading at 3%.

Details on improvements in Sherpa2.2.11 and MadGraph FxFx. arXiv:2112.09588

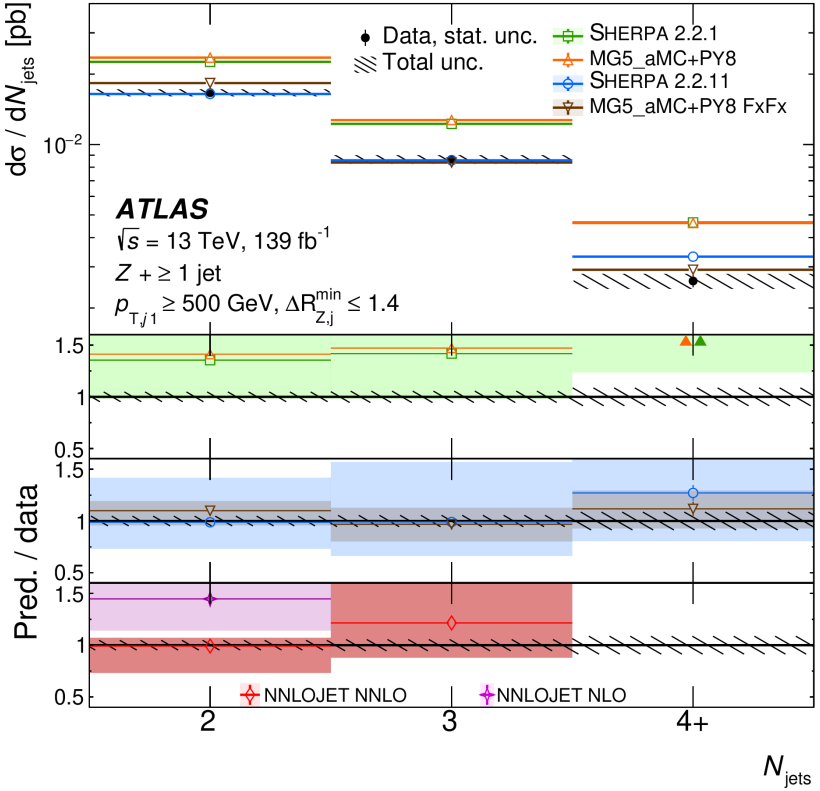
Collinear *Z* emission Results

arXiv:2205.02597



$$r_{Z,j} = \frac{p_{\mathrm{T}}(Z)}{p_{\mathrm{T}}(closest\ jet)}$$

$r_{Z,j}$ in the *Collinear* region. Collinear *Z* boson emissions are expected with $r_{Z,j}$ << 1.



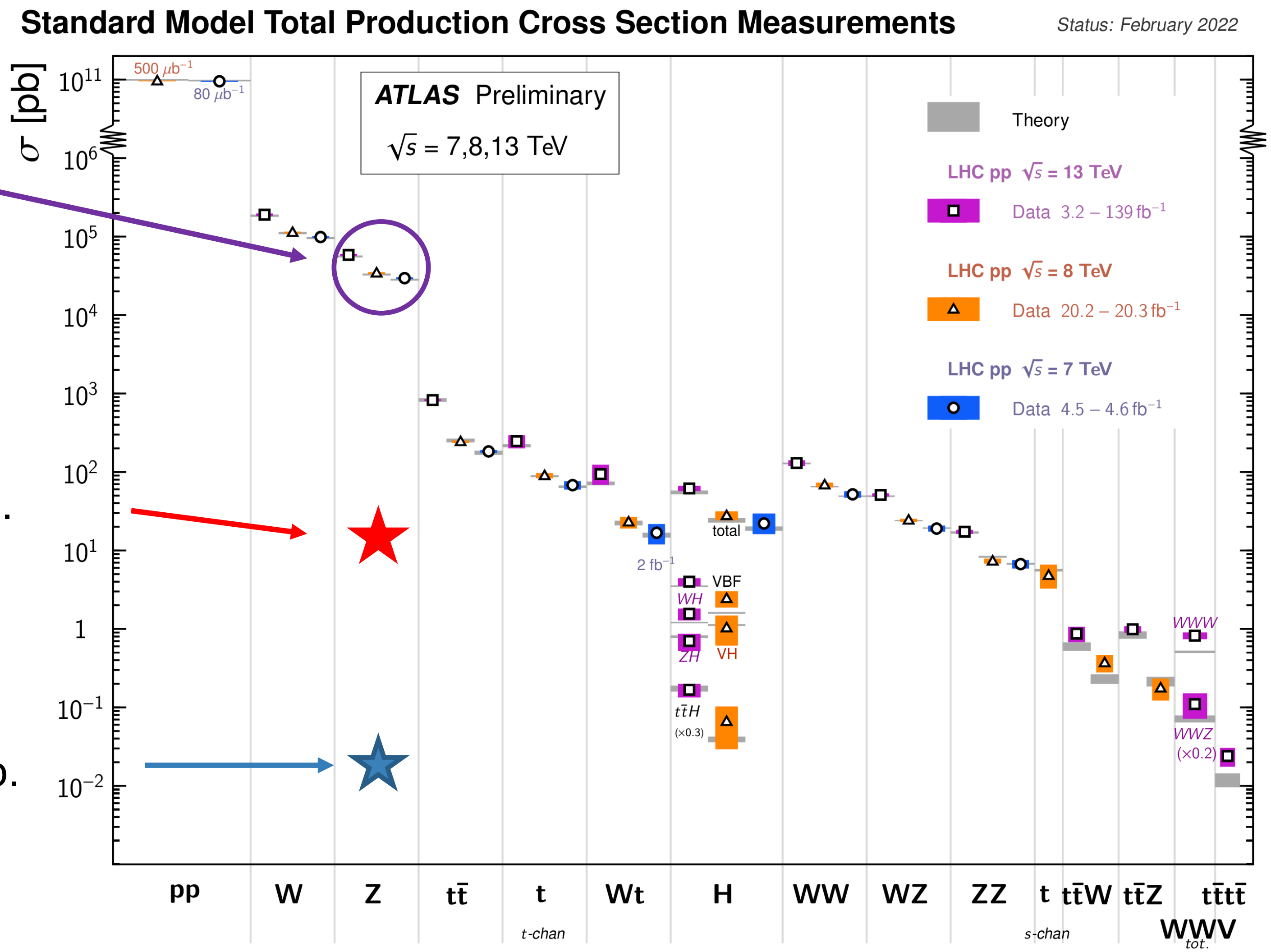
Jet multiplicity in the *Collinear* region. Collinear *Z* boson emissions are expected to always have $N_{jets} \geq 2$.

- Both distributions confirm expected kinematics of collinear *Z* boson emission from a jet!
- No collinear data events measured with exactly 1 jet.
- State-of-the-art MC Sherpa2.2.11 & MadGraph FxFx model collinear emissions, MadGraph FxFx with high precision.

Total Production Cross Sections

- ATLAS has many Standard Model measurements under its belt.
- *Z* boson production cross section is large! → 7-8 billion produced in Run 2.
- ***Z* + high transverse momentum jets**: ~14 pb.
- **Collinear *Z* boson emission**: $\sim 2.8 * 10^{-2}$ pb.

ATL-PHYS-PUB-2022-009



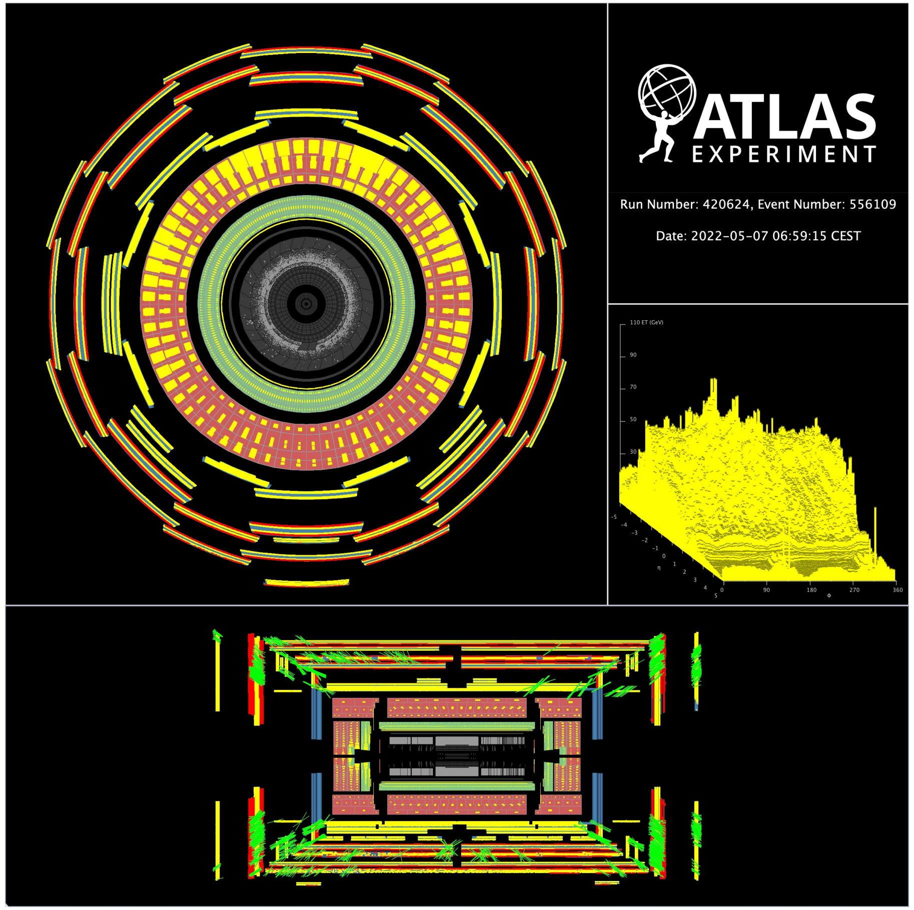
Conclusion

- The **first** measurement with the full Run 2 dataset measuring:
  → high transverse momentum jets and
  → collinear emission of a *Z* boson from a jet.

- Results show large mismodelling from previous-gen predictions.
- State-of-the-art predictions in agreement with data. **Very exciting!**
  → Important for future Run 3 analyses to use these.

- State-of-the-art predictions exhibit large modelling uncertainties.
  → This data will help to improve future predictions of *Z* + jets processes and increase the precision of analyses: other *Z* + jets, Higgs, new physics…

- LHC Run 3 and High-Luminosity phase will open the way for much higher statistics.
  → Further push the precision of these measurement.
  → Explore more and more extreme phase spaces.



ATLAS Run 3 preparation beam splash event display of May 7th 2022. The start of exciting times with Run 3.

Backup


AHH! IT'S 5:00PM AND I HAVEN'T DONE ANYTHING TODAY!
WHY!? WHY DID I WASTE THE WHOLE DAY DOING STUPID THINGS THAT DON'T MATTER!??
JORGE CHAM © 2007
MUST... DO... SOMETHING... ANYTHING...
reads one paragraph of paper
PHEW..!
ANOTHER DAY IN GRAD SCHOOL.
WWW.PHDCOMICS.COM

Uncertainties

- Considered over 70 different sources of uncertainties.
  → Mix of experimental, theoretical and statistical.

- For collinear *Z* boson emission, statistical uncertainty is largest.
  → Good precision with 5% total uncertainty.

- Data uncertainties smaller than those of predictions.
  → Can use data to help improve predictions!

Uncertainty source [%]	*Collinear*
JES/JER	2.8
Lepton	1.4
Luminosity	1.7
Pile-up	0.4
Unfolding	1.1
Background modelling	2.0
Signal modelling	1.1
Total syst. uncertainty	4.4
Data stat. uncertainty	2.9
Total uncertainty	5.3

$$\sigma_i = \frac{N_i^{observed} - N_i^{background}}{C_i \mathcal{L}}$$

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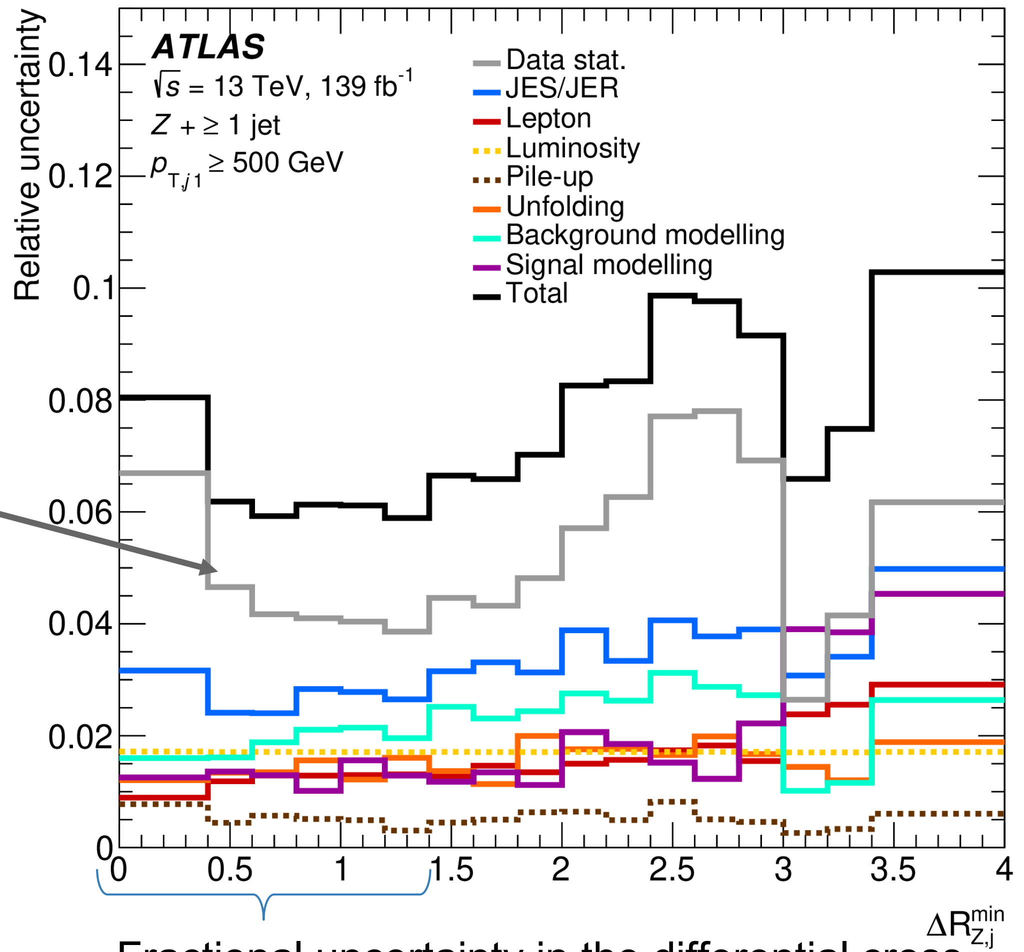
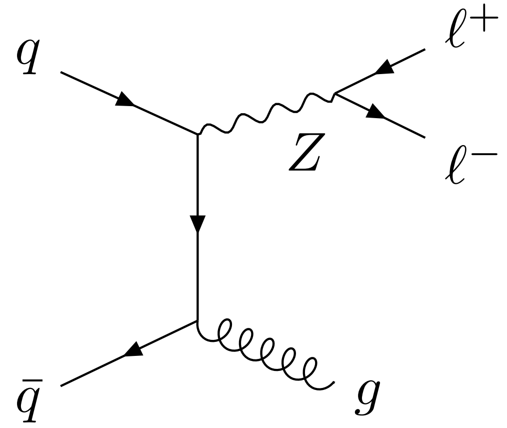


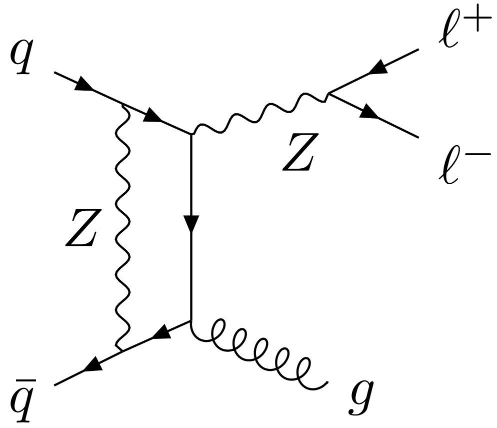
Fractional uncertainty in the differential cross-sections of angular distance between the *Z* boson and the closest jet. Collinear *Z* boson emissions are defined as $\Delta R_{Z,jet}^{min} \leq 1.4$

Virtual Electroweak Corrections

- Sherpa2.2.11 includes NLO virtual EW corrections to the cross sections.



Leading Order Z + 1 jet production.



Next-to-leading order virtual correction to Z + 1 jet production.

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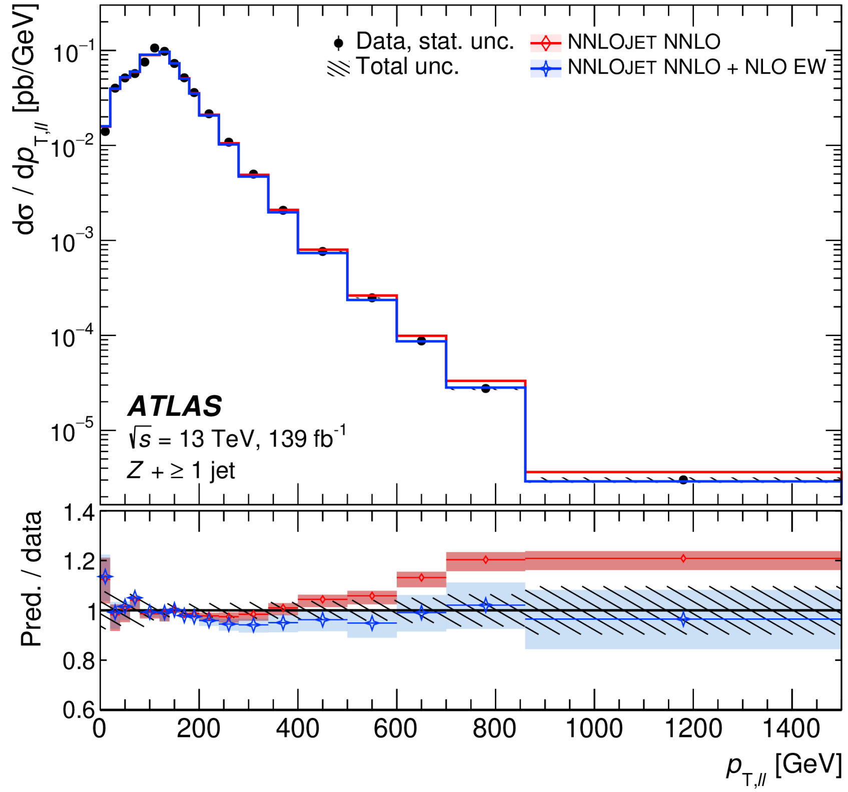
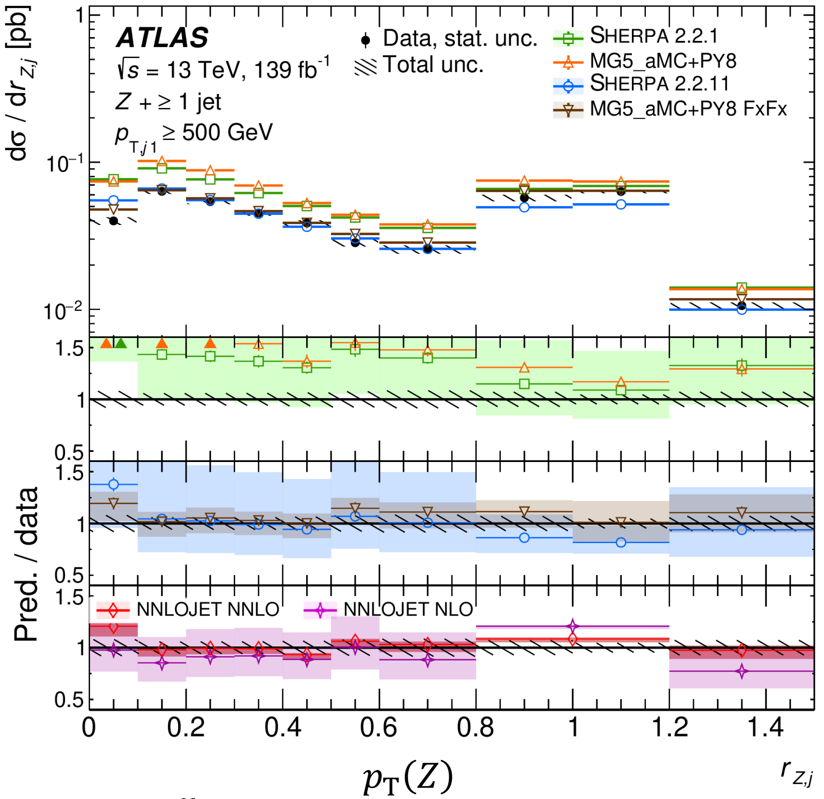


- Effect grows as Q^2.
  → Negative contribution.
  → Largest contribution in very energetic *Z* + 1 jet events.
  → Correction can reach ~20% in high $p_{\mathrm{T}}(jet)$ and $p_{\mathrm{T}}(Z)$ regions.
- Uncertainty is usually only few %.

- Only NNLOJet @ NNLO is precise enough to be sensitive to these NLO EW corrections.

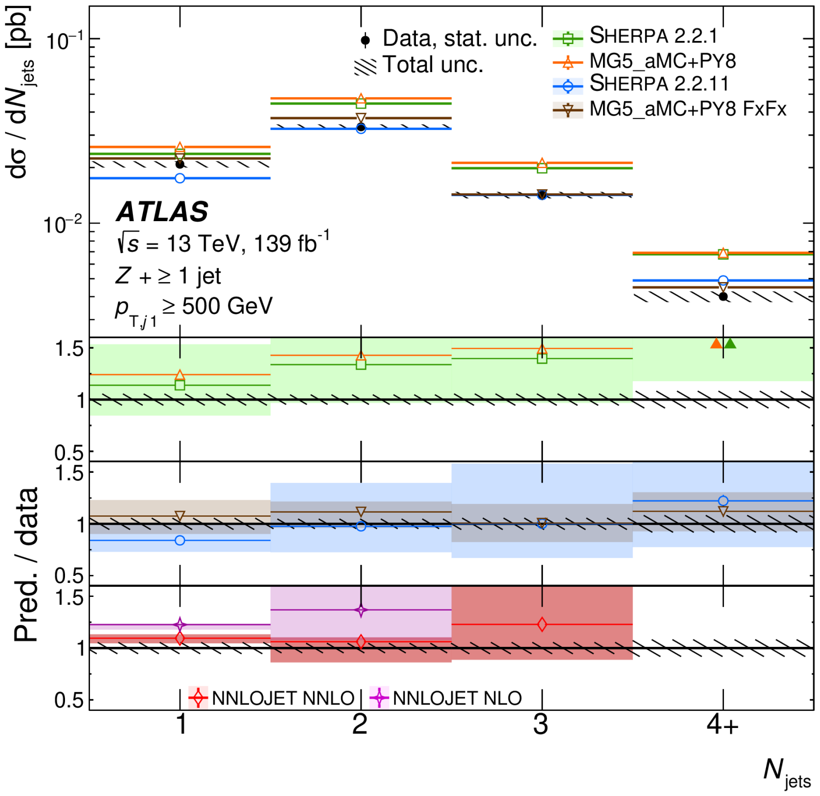
Z + high p_T jets Results

arXiv:2205.02597



$$r_{Z,j} = \frac{p_T(Z)}{p_T(closest\ jet)}$$

Differential cross section as a function of $r_{Z,j}$ in the *high*- p_T region. Large (collinear) population at low values and peak of *Z*+1 jet events around 1.



Differential cross section as a function of jet multiplicity in the *high*- p_T region. Mostly populated by 1 and 2 jet events.

- Combination of *collinear* and *back-to-back* *Z*+1 jet events.

Details on improvements in Sherpa2.2.11 and MadGraph FxFx in respect to their previous versions. arXiv:2112.09588

Improvements in the MC

arXiv:2112.09588

- Improvements in Sherpa2.2.11 mostly due to improvements in parton showering.

Configuration	Sherpa 2.2.1	Sherpa 2.2.11
Generator version	Sherpa 2.2.1	Sherpa 2.2.11
PDF set	NNPDF3.0nnlo	NNPDF3.0nnlo
EW input scheme	Effective	$\sin^2\theta_{\text{eff}}$
QCD accuracy	0–2j@NLO+3,4j@LO	0–2j@NLO+3,4,5j@LO
NLO EW_{virt} corrections	No	Yes
Subtraction scheme	Default	Modified Catani–Seymour
Unordered histories allowed	Yes	No
Scale for H-events	STRICT_METS	H'_{T}
Gluon colour/spin exact matching	Yes	No
Core process for K-factor	$2\to 4$	$2\to 2$
Phase-space strategy	Sliced in $\max(H_{\text{T}}, p_{\text{T}}^{V})$	Analytic enhancement

Biggest change at high pT(jet) and pT(Z)

- **MadGraph** comparisons like apple to oranges.
- MadGraph is LO prediction normalized to inclusive cross sections.
- New MadGraph FxFx uses FxFx matching + merging scheme, up to 3partons at NLO

Process	Generator	Order pQCD
Signal		
$Z\to\ell\ell$ $(\ell=e,\mu)$	Sherpa 2.2.11	0–2p NLO, 3–5p LO
$Z\to\ell\ell$ $(\ell=e,\mu)$	MG5_aMC+Py8 FxFx	0–3p NLO
$Z\to\ell\ell$ $(\ell=e,\mu)$	Sherpa 2.2.1	0–2p NLO, 3–4p LO
$Z\to\ell\ell$ $(\ell=e,\mu)$	MG5_aMC+Py8 CKKWL	0–4p LO

arXiv:2205.02597

Measured Event Yields

arXiv:2205.02597

$Z \to e^+e^-$	*Inclusive*	*High-p_T*	*Collinear*	*Back-to-back*	*High-S_T*
Z + jets	1 171 000 ± 49 000	6150 ± 310	2520 ± 120	2520 ± 150	18 300 ± 800
$t\bar{t}$	43 400 ± 1300	209 ± 16	136 ± 13	47.2 ± 7.5	917 ± 41
Diboson	19 530 ± 750	428 ± 29	183 ± 16	167 ± 16	1008 ± 53
EW Zjj	13 270 ± 500	312 ± 23	102 ± 11	135 ± 14	789 ± 43
Single-top	2430 ± 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
$V+\gamma$	1413 ± 83	14.2 ± 4.3	6.5 ± 2.6	5.1 ± 2.3	34.1 ± 7.3
Total predicted	1 252 000 ± 51 000	7150 ± 350	2970 ± 130	2890 ± 170	21 100 ± 880
Data	1 312 145	7539	2955	3231	21 746

$Z \to \mu^+\mu^-$	*Inclusive*	*High-p_T*	*Collinear*	*Back-to-back*	*High-S_T*
Z + jets	1 537 000 ± 63 000	6700 ± 300	2950 ± 130	2420 ± 120	23 110 ± 920
$t\bar{t}$	55 400 ± 1300	209 ± 16	142 ± 12	39.1 ± 6.6	1058 ± 41
Diboson	24 160 ± 870	438 ± 27	198 ± 16	157 ± 14	1149 ± 55
EW Zjj	17 020 ± 580	328 ± 22	113 ± 12	134 ± 13	915 ± 45
Single-top	3110 ± 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
$V+\gamma$	1273 ± 90	2.5 ± 2.4	0.0 ± 0.7	2.2 ± 1.5	22.4 ± 5.5
Total predicted	1 638 000 ± 64 000	7710 ± 330	3420 ± 140	2770 ± 140	26 300 ± 1000
Data	1 673 057	7896	3372	3059	26 567

Total Production Cross Sections

- Measured Z boson production with higher transverse momentum jets in 5 different kinematic regions.
- **Z + high transverse momentum jets**: ~14 pb.
- **Collinear Z boson emission**: ~ $2.8 * 10^{-2}$ pb.
- Data uncertainty is much smaller than the predictions.

arXiv:2205.02597

Inclusive $Z+$jets					
Data	13.90	$\pm$ 0.01 (stat)	$\pm$ 0.47 (syst)		pb
Sherpa 2.2.11	13.3	$^{+0.2}_{-0.2}$ (PDF)	$^{+3.1}_{-1.8}$ (Scale)	$\pm \leq 0.1$ (EW)	pb
MG5_aMC+Py8 FxFx	14.5	$^{+0.1}_{-0.1}$ (PDF)	$^{+0.8}_{-1.2}$ (Scale)		pb
Sherpa 2.2.1	13.8	$^{+0.5}_{-0.5}$ (PDF)	$^{+5.2}_{-3.4}$ (Scale)		pb
NNLOjet@NNLO	13.83		$^{+0.18}_{-0.27}$ (Scale)		pb
NNLOjet@NLO	13.5		$^{+1.1}_{-0.9}$ (Scale)		pb
High-p_T: $p_{T,j1} \geq 500$ GeV					
Data	72.3	$\pm$ 1.5 (stat)	$\pm$ 3.5 (syst)		fb
Sherpa 2.2.11	69	$^{+2}_{-1}$ (PDF)	$^{+28}_{-17}$ (Scale)	$^{+2}_{-2}$ (EW)	fb
MG5_aMC+Py8 FxFx	78	$^{+4}_{-1}$ (PDF)	$^{+9}_{-12}$ (Scale)		fb
Sherpa 2.2.1	95	$^{+4}_{-3}$ (PDF)	$^{+40}_{-26}$ (Scale)		fb
NNLOjet@NNLO	76		$^{+10}_{-12}$ (Scale)		fb
NNLOjet@NLO	71		$^{+14}_{-11}$ (Scale)		fb
Collinear: *High-p_T* and $\Delta R^{min}_{Z,j} \leq 1.4$					
Data	27.9	$\pm$ 0.8 (stat)	$\pm$ 1.2 (syst)		fb
Sherpa 2.2.11	28	$^{+1}_{-1}$ (PDF)	$^{+14}_{-8}$ (Scale)	$\pm \leq 1$ (EW)	fb
MG5_aMC+Py8 FxFx	29.6	$^{+1.3}_{-0.3}$ (PDF)	$^{+3.1}_{-4.3}$ (Scale)		fb
Sherpa 2.2.1	39	$^{+2}_{-1}$ (PDF)	$^{+18}_{-11}$ (Scale)		fb
NNLOjet@NNLO	27.0		$^{+5.7}_{-7.2}$ (Scale)		fb
NNLOjet@NLO	24.1		$^{+7.0}_{-5.1}$ (Scale)		fb
Back-to-back: *High-p_T* and $\Delta R^{min}_{Z,j} \geq 2.0$					
Data	31.6	$\pm$ 0.8 (stat)	$\pm$ 1.7 (syst)		fb
Sherpa 2.2.11	28.1	$^{+0.6}_{-0.3}$ (PDF)	$^{+7.9}_{-4.9}$ (Scale)	$^{+1.4}_{-1.4}$ (EW)	fb
MG5_aMC+Py8 FxFx	34.4	$^{+1.6}_{-0.3}$ (PDF)	$^{+4.6}_{-5.6}$ (Scale)		fb
Sherpa 2.2.1	38	$^{+2}_{-1}$ (PDF)	$^{+15}_{-10}$ (Scale)		fb
NNLOjet@NNLO	35.3		$^{+1.9}_{-2.4}$ (Scale)		fb
NNLOjet@NLO	36.0		$^{+3.5}_{-3.3}$ (Scale)		fb
High-S_T: $S_T \geq 600$ GeV					
Data	226.0	$\pm$ 2.6 (stat)	$\pm$ 9.5 (syst)		fb
Sherpa 2.2.11	220	$^{+10}_{-10}$ (PDF)	$^{+110}_{-60}$ (Scale)	$\pm \leq 10$ (EW)	fb
MG5_aMC+Py8 FxFx	247	$^{+10}_{-2}$ (PDF)	$^{+30}_{-37}$ (Scale)		fb
Sherpa 2.2.1	280	$^{+10}_{-10}$ (PDF)	$^{+130}_{-80}$ (Scale)		fb
NNLOjet@NNLO	223		$^{+43}_{-47}$ (Scale)		fb
NNLOjet@NLO	168		$^{+45}_{-33}$ (Scale)		fb

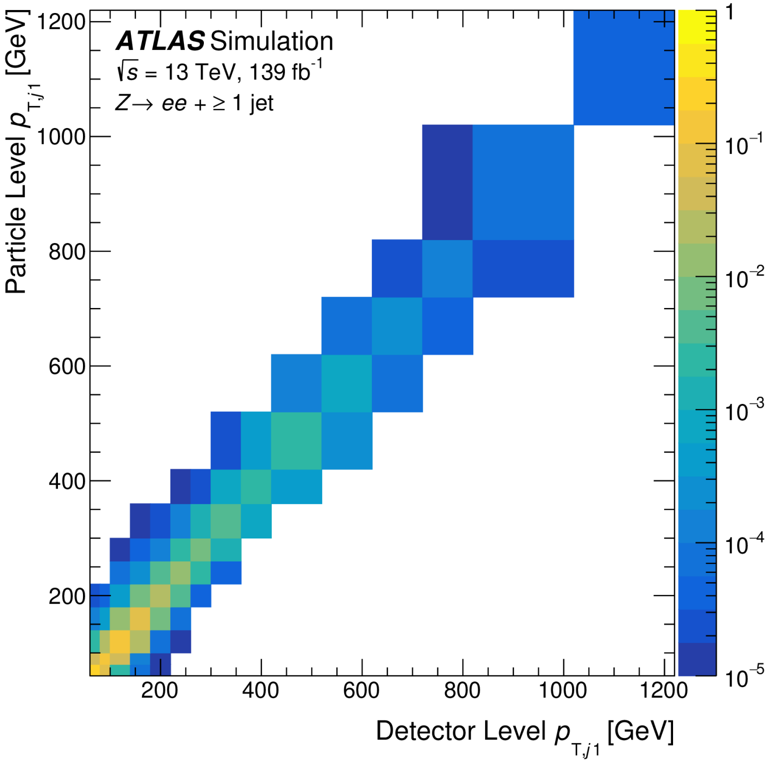
Unfolding: Response Matrices

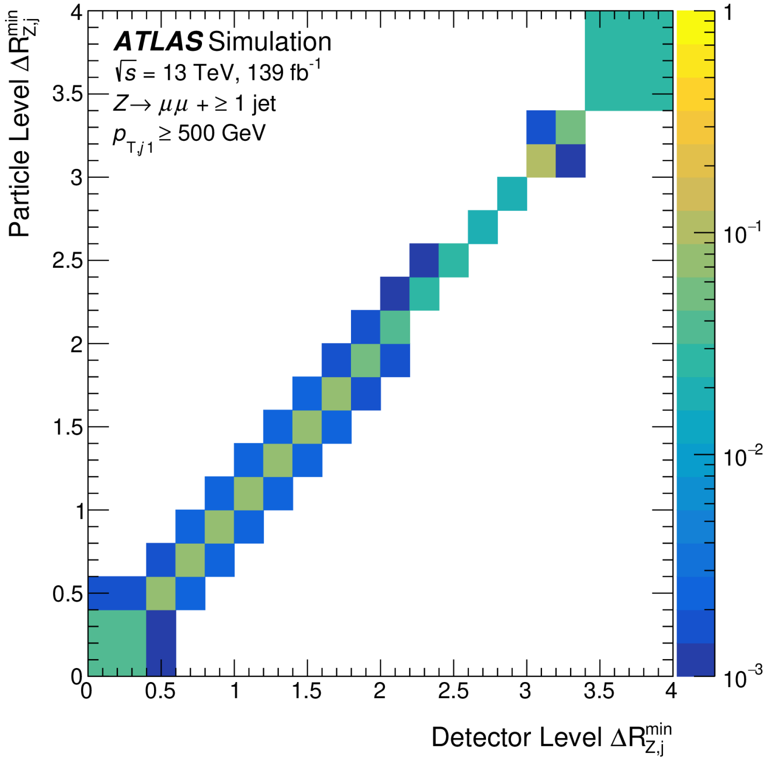
- Response matrices are used during unfolding to erase detector effects and produce fiducial cross sections.
- Significant aspect of the transfer function C_i in the cross section:

$$\sigma_i = \frac{N_i^{observed} - N_i^{background}}{C_i \mathcal{L}}$$

- Diagonal distributions are good and mean that the detector measures an event in the same bin as the truth.

STDM-2018-49





Unfolding: Efficiencies

- The efficiency of the detector of measuring events with certain kinematic properties.
- Significant aspect of the transfer function C_i in the cross section:

$$\sigma_i = \frac{N_i^{observed} - N_i^{background}}{C_i \mathcal{L}}$$

- Usually want the distributions to be flat with high efficiencies.