Precision measurements of W- and Z-boson transverse momentum spectra at ATLAS

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For the *International School of Subnuclear Physics*
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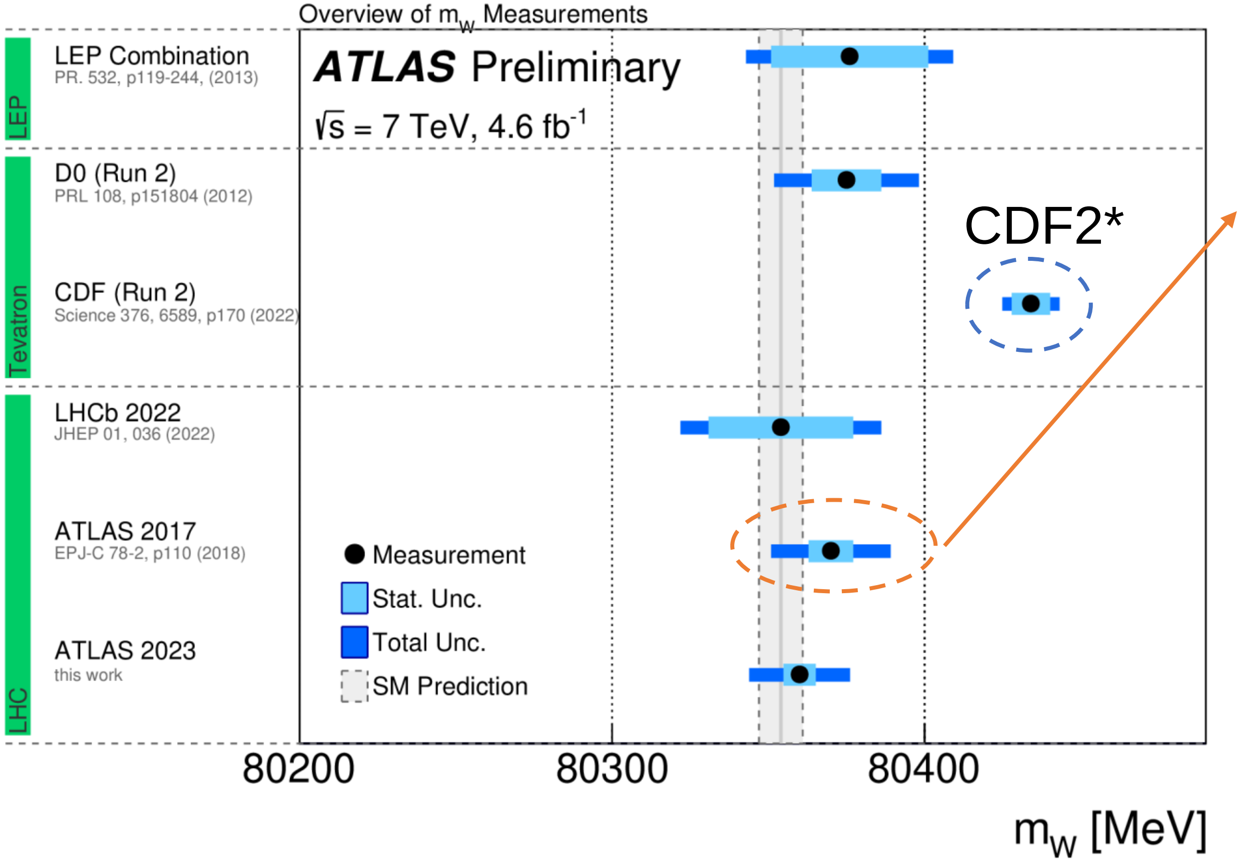
The motivation of p_T^W and p_T^Z measurements

Reduce the p_T^W modelling uncertainty in the m_W measurement.



*doi: 10.1126/science.abk1781

- ATLAS 7 TeV m_W analysis:

6 MeV p_T^W modelling uncertainty due to the p_T^Z-> p_T^W extrapolation.

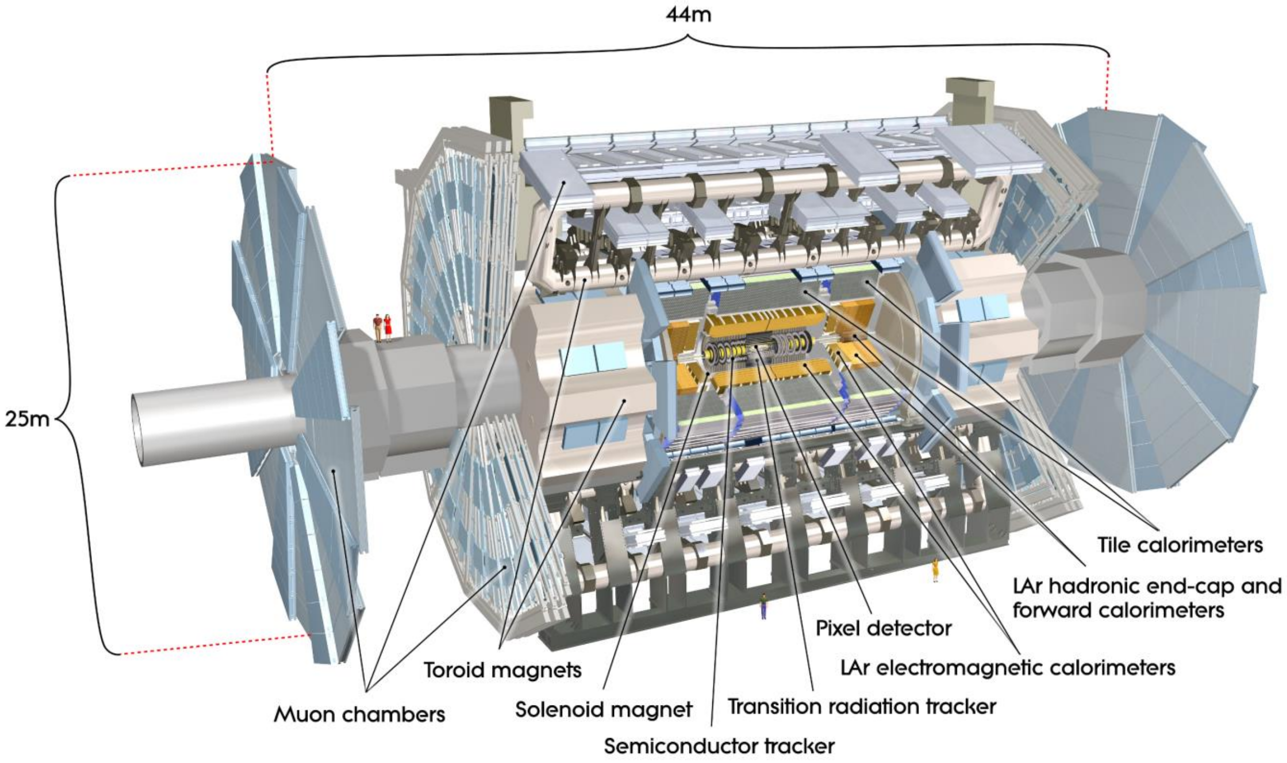
- Solution: **Direct p_T^W measurement.**
- Measuring both p_T^W and p_T^Z tests the underlying QCD predictions.

Targeted p_T^W precision:

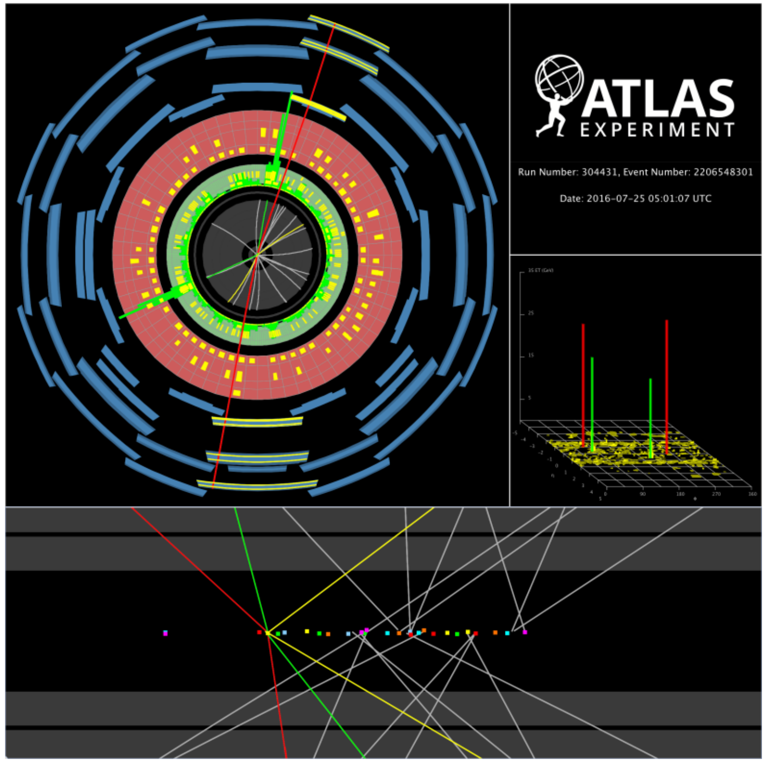
- A granularity of 6~7 GeV.
- 1~2% uncertainty for p_T^W<25 GeV where the fixed-order perturbative prediction fails.

The ATLAS experiment

ATLAS detector: one of the general purpose detectors at LHC



Cut-away view of ATLAS



ATLAS detects the final state particles of proton-proton collisions.

e.g. pp -> H -> eeμμ event display

Event topology: leptonic decay of W/Z

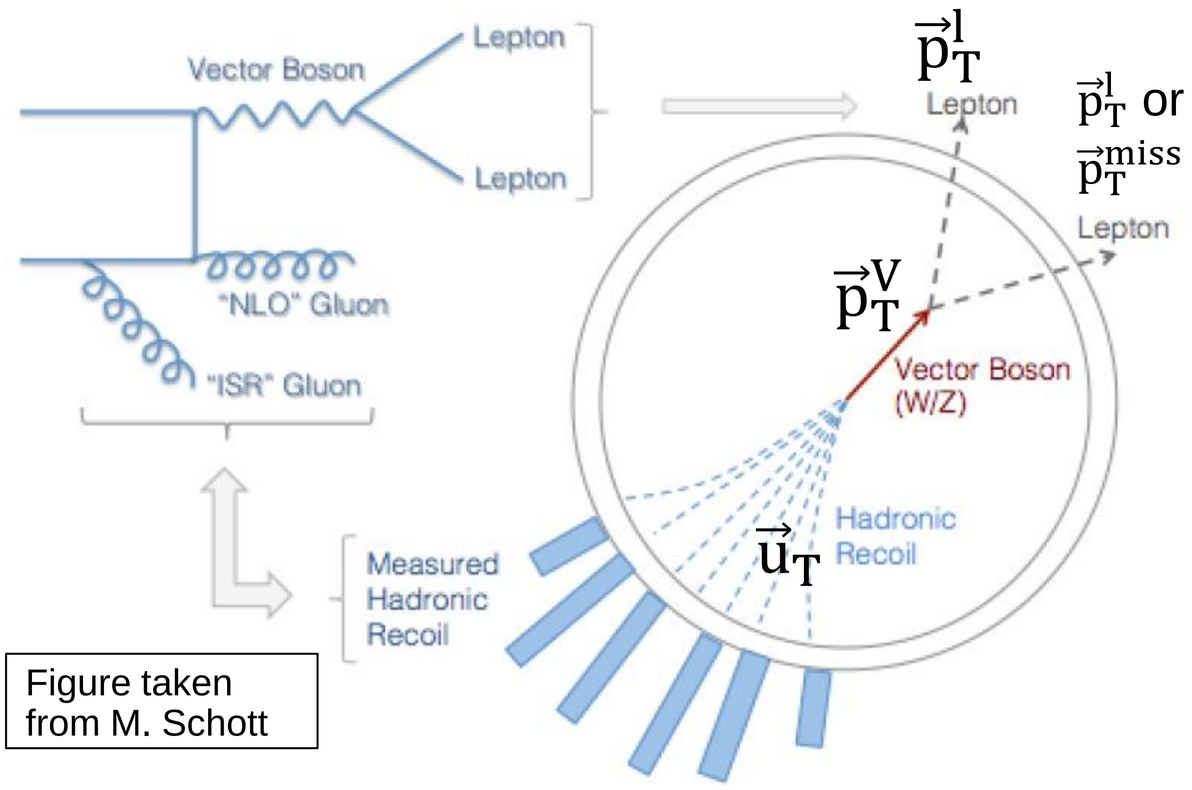


Figure taken from M. Schott

- Only **two objects** to measure:

(1) The charged lepton

(2) Hadronic recoil $\vec{\mathrm{u}}_{\mathrm{T}} = \Sigma\vec{\mathrm{p}}_{\mathrm{T}}^{\mathrm{ISR}\ q,g} = -\vec{\mathrm{p}}_{\mathrm{T}}^{\mathrm{V}}$

W events: u_{T} -> $\mathrm{p}_{\mathrm{T}}^{\mathrm{W}}$
Z events: $\mathrm{p}_{\mathrm{T}}^{ll}$ -> $\mathrm{p}_{\mathrm{T}}^{\mathrm{Z}}$ or u_{T} -> $\mathrm{p}_{\mathrm{T}}^{\mathrm{Z}}$

- Detector calibrations are needed for lepton and recoil.
- Detector resolution of u_{T} is affected by underlying event and pile-up.

Lower pile-up in the dataset
-> More precise measurement of $\mathrm{p}_{\mathrm{T}}^{\mathrm{W}}$

ATLAS Run 2 low pile-up data

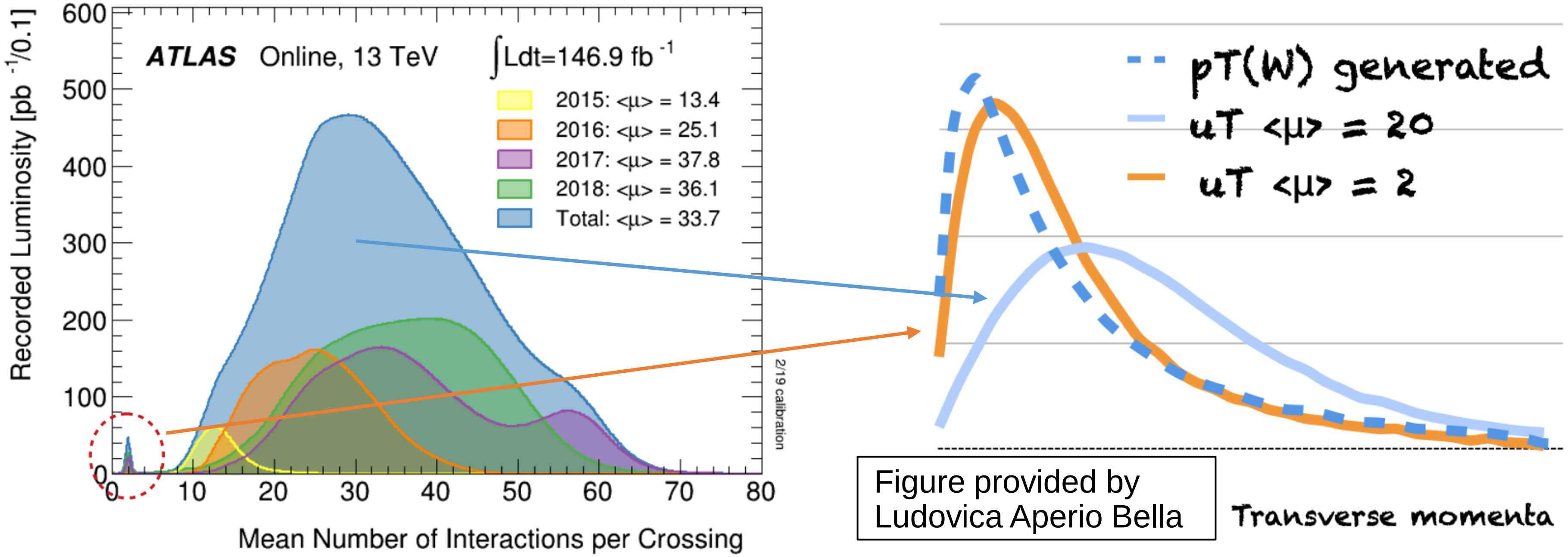


Figure provided by
Ludovica Aperio Bella

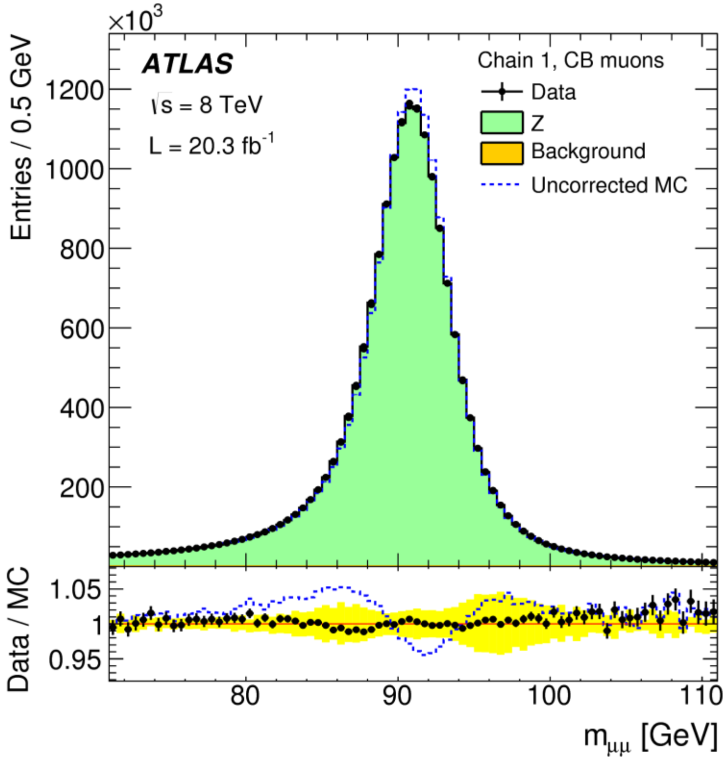
Probes of perturbative and non-perturbative QCD in W events, as well as in Z events at 5.02 TeV.

	2017, $\sqrt{s}$=5.02 TeV	2017+2018, $\sqrt{s}$=13 TeV
Luminosity (pb^{-1})	255	338
Total W events after selection	1.45M	4.36M
Total Z events after selection	122K	379K

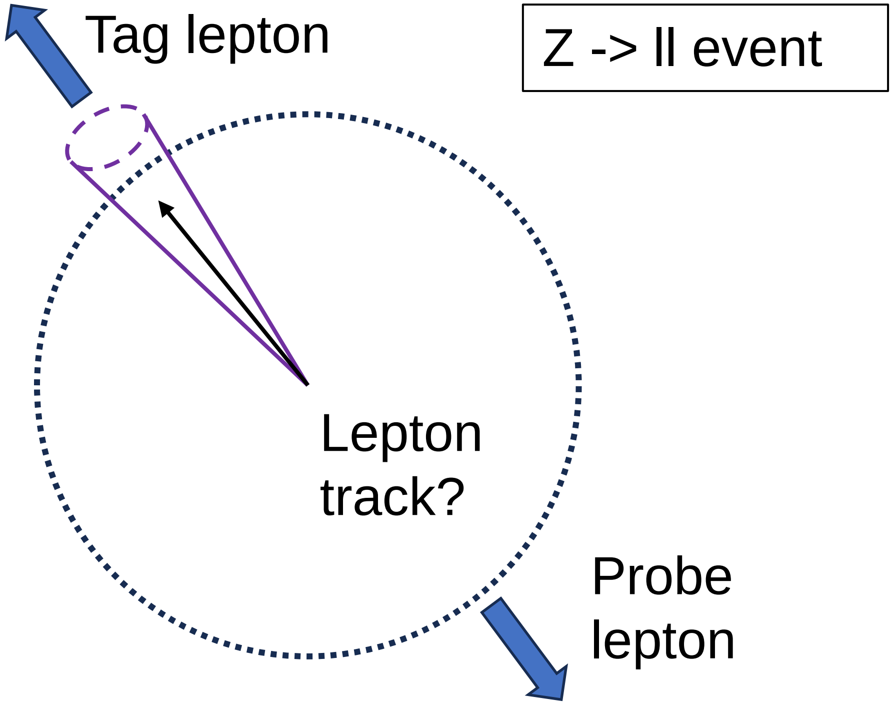
MC simulations matching the low pile-up condition in data:

- W & Z, top-related background and di-boson background.

Detector calibration



- The lepton momentum in the simulation is corrected to reproduce the resonance of Z-boson in data.
- Recoil calibration: use p_T^{ll} to constrain the detector response of recoil ($p_T^Z = p_T^{ll}$ and $\vec{u}_T + \vec{p}_T^V = 0$)



Tag lepton

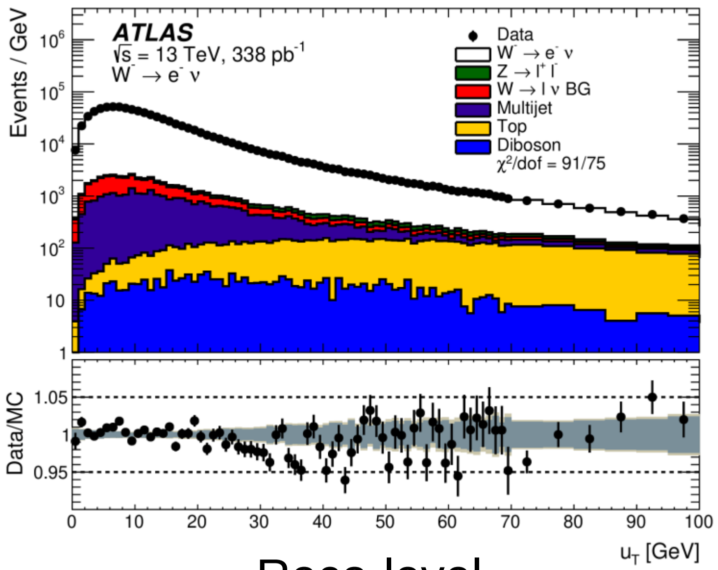
Z -> ll event

Lepton track?

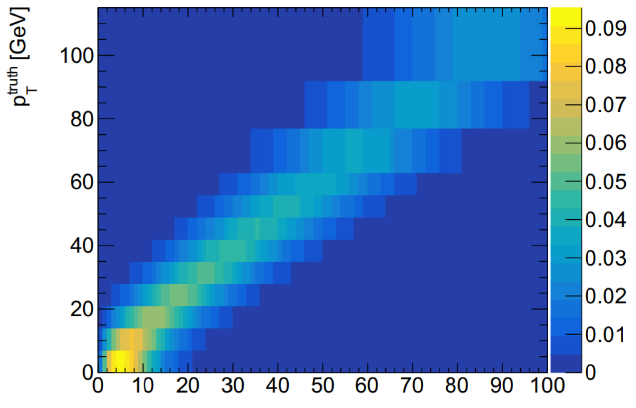
Probe lepton

Efficiency measured in Z->ll events with “tag & probe”.

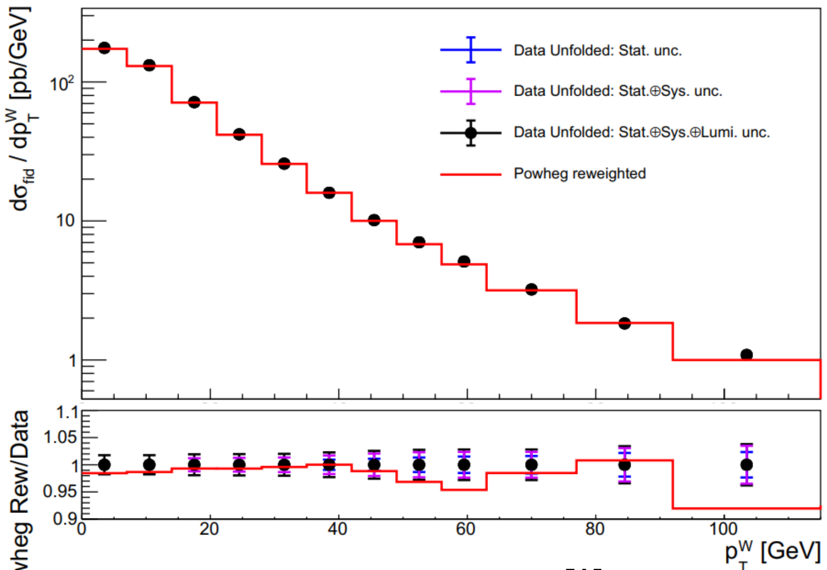
Unfolding



Reco-level u_T



IBU using the migration matrix



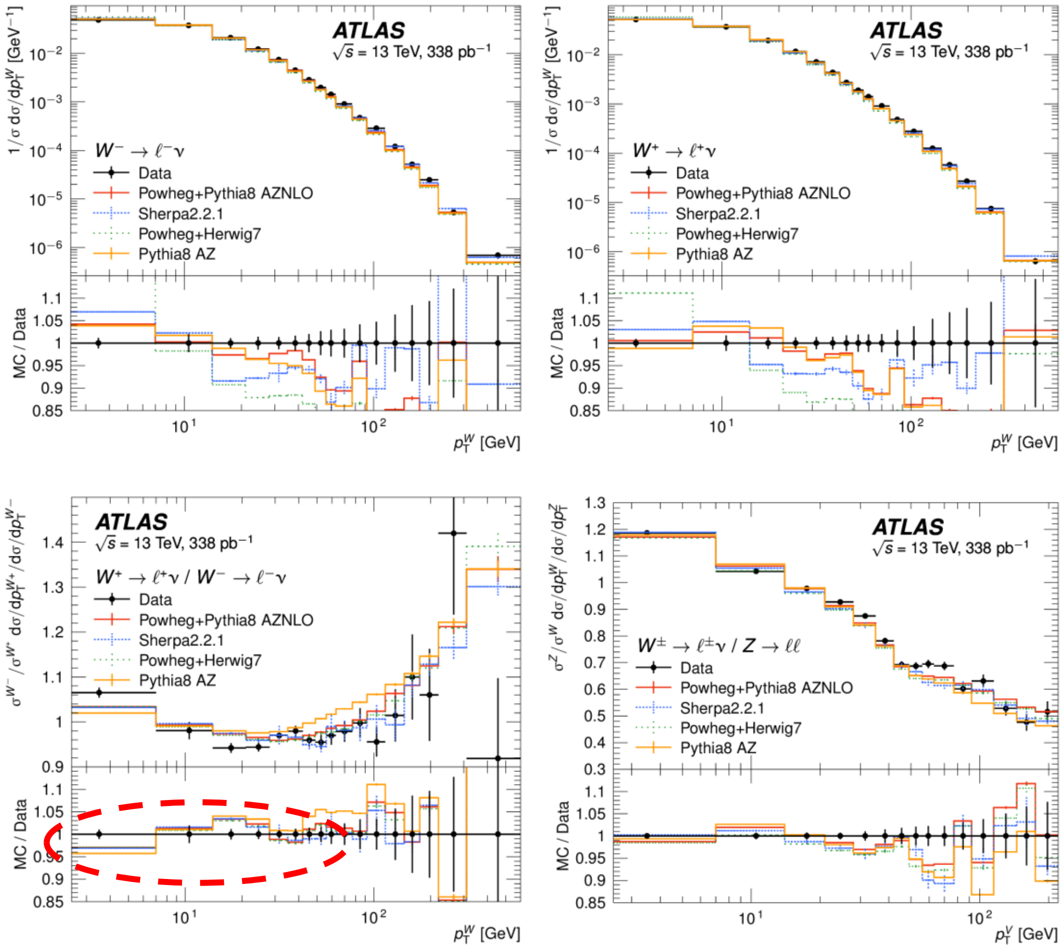
Unfolded p_T^W

- Iterative Bayesian unfolding (IBU) for p_T^W: $\vec{u}_T = \Sigma \vec{p}_T^{\,ISR\ q,g} = -\vec{p}_T^{\,V}$
- p_T^Z spectrum can be obtained by unfolding u_T and p_T^{ll}.

-> Compatibility test of the unfolding

Results of the measurements

Differential cross-section @ 13 TeV



Integrated fiducial cross-section

Process	$\sigma_{\text{fid}}(\sqrt{s} = 5.02\text{ TeV})$ [pb]	$\sigma_{\text{fid}}(\sqrt{s} = 13\text{ TeV})$ [pb]
$W^- \to \ell^- \nu$	1384 ± 2 (stat.) ± 5 (syst.) ± 15 (lumi.)	3486 ± 3 (stat.) ± 18 (syst.) ± 34 (lumi.)
$W^+ \to \ell^+ \nu$	2228 ± 3 (stat.) ± 8 (syst.) ± 23 (lumi.)	4571 ± 3 (stat.) ± 21 (syst.) ± 44 (lumi.)
$Z \to \ell\ell$	333.0 ± 1.2 (stat.) ± 2.2 (syst.) ± 3.3 (lumi.)	780.3 ± 2.6 (stat.) ± 7.1 (syst.) ± 7.1 (lumi.)

Integrated cross-section ratios

Processes	Cross-section ratio at $\sqrt{s} = 5.02$ TeV	Cross-section ratio at $\sqrt{s} = 13$ TeV
W^+/W^-	1.609 ± 0.003 (stat.) ± 0.004 (syst.)	1.308 ± 0.003 (stat.) ± 0.004 (syst.)
W^-/Z	4.16 ± 0.02 (stat.) ± 0.03 (syst.)	4.46 ± 0.02 (stat.) ± 0.05 (syst.)
W^+/Z	6.69 ± 0.02 (stat.) ± 0.05 (syst.)	5.84 ± 0.02 (stat.) ± 0.06 (syst.)
$W^\pm/Z$	10.85 ± 0.04 (stat.) ± 0.07 (syst.)	10.30 ± 0.04 (stat.) ± 0.10 (syst.)

Paper submitted to EPJC (arXiv:2404.06204)

The p_T^W uncertainties are propagated to the m_W fit for the preliminary result.

Summary

- The p_T^W measurement in ATLAS using special low pile-up data achieves remarkable precision (1-2% total uncertainty and a granularity of 7 GeV) and provides valuable input to the m_W measurement.
- The production of the Z-boson is compared with that of the W-boson at two well-separated center-of-mass energies.
- In addition to electro-weak precision measurements, I was also involved in the detector production for the upgrade of the ATLAS muon system* and the development of statistics method for high energy physics experiments**.

- Nowadays, I'm focusing on Higgs self-coupling and flavour tagging in ATLAS, as well as the detector simulation for FCC.

* doi : 10.1016/j.nima.2021.166143

** doi : 10.1140/epjc/s10052-024-12877-5

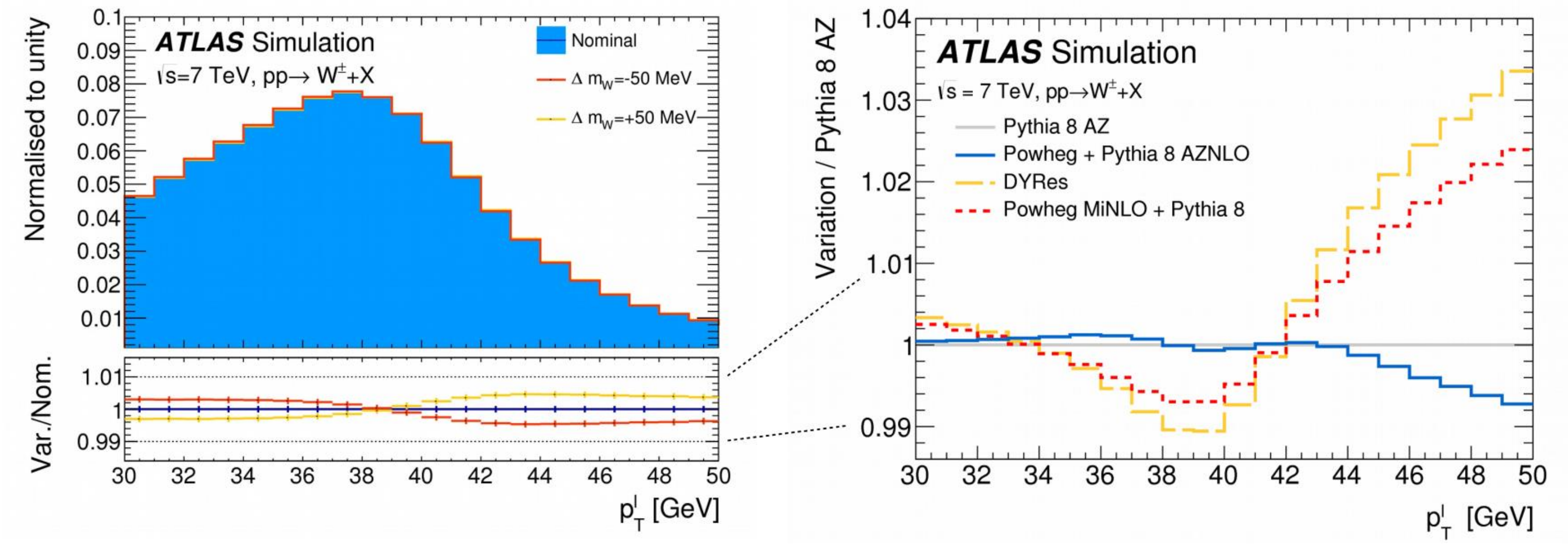
Thank you!

Backup

Motivation of the measurement

- In the m_W measurement, the lepton p_T spectrum requires a modelling of p_T^W < ~1% in the low values of p_T^W where the fixed-order perturbative prediction fails.

- Direct measurement of p_T^W, instead of modelling p_T^W based on measured p_T^Z, avoids the uncertainty due to the extrapolation.



- p_T^Z is also measured: Measuring both p_T^W and p_T^Z tests the differences in W and Z production processes. The measurement at 5.02 TeV is the input to the PDF fit.

Physics modelling

The “master formula” of differential cross-section for the Drell-Yan process

$$\frac{d\sigma}{dp_1 dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\left.\frac{d\sigma(p_T)}{dp_T}\right|_y \frac{d\sigma(y)}{dy}^{-1}\right] \times \left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y, m)P_i(\cos\theta, \phi)\right]$$

For the leptonic decay of W/Z bosons, the kinematics of the decay product can be described by a factorization of differential cross-sections.

- $\frac{d\sigma(m)}{dm}$: The resonance peak of the vector boson -> Breit Wigner distribution.
- $\frac{d\sigma(y)}{dy}$: Boson rapidity
- $\frac{d\sigma(p_T)}{dp_T}\ |_y \left(\frac{d\sigma(y)}{dy}\right)^{-1}$: Boson transverse momentum at given rapidity.
- A_i: Angular coefficients describe the polarization of the vector boson.

MC samples and event selection

In order to match the low pile-up condition in data:

- W & Z, top-related background and di-boson background: MC simulations.
- Multijet background: Heavy flavor quark decays and pions faking electrons are hard to simulate accurately.

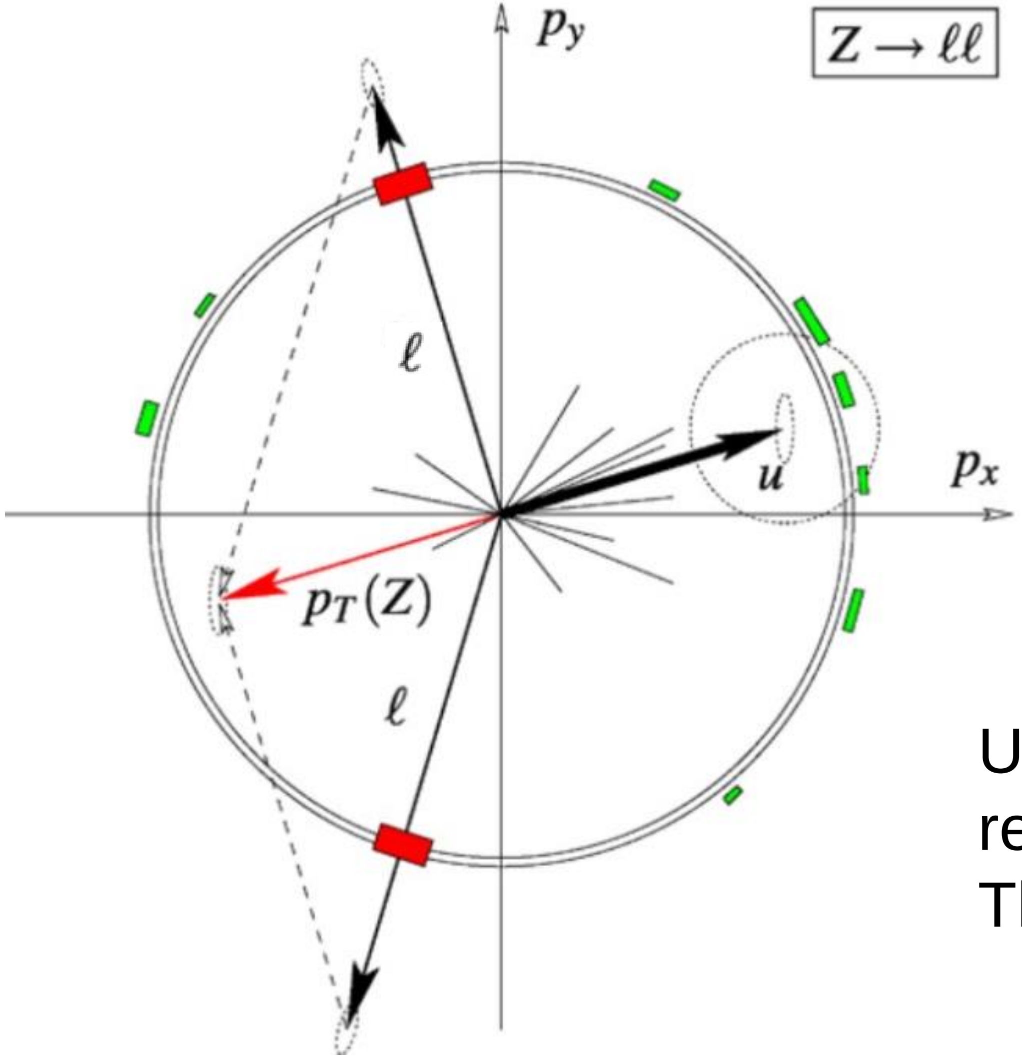
-> Data-driven estimation of the multijet yield and shape.

Cut	Description
One charged lepton	Exactly one electron or muon
Lepton trigger	• 1 electron, $E_T > 15$ GeV, loose ID. • Or 1 muon, $E_T > 14$ GeV.
Isolation	Ptcone20 / Min(p_T^l, 50GeV) < 0.1
Kinematics	$p_T^l > 25$ GeV
	$E_T^{miss} > 25$ GeV
	$m_T > 50$ GeV

Analysis cuts for W signal selection

ptconeXX: The sum of p_T of tracks in the given cone around the interested object.

Detector calibration: hadronic recoil



- In Z->ll events, the transverse momentum of the di-lepton pair ($\mathrm{p_T^{ll}}$) is well-measured.
- $\mathrm{p_T^{ll}}$ corresponds to the transverse momentum of Z-boson ($\mathrm{p_T^Z = p_T^{ll}}$).

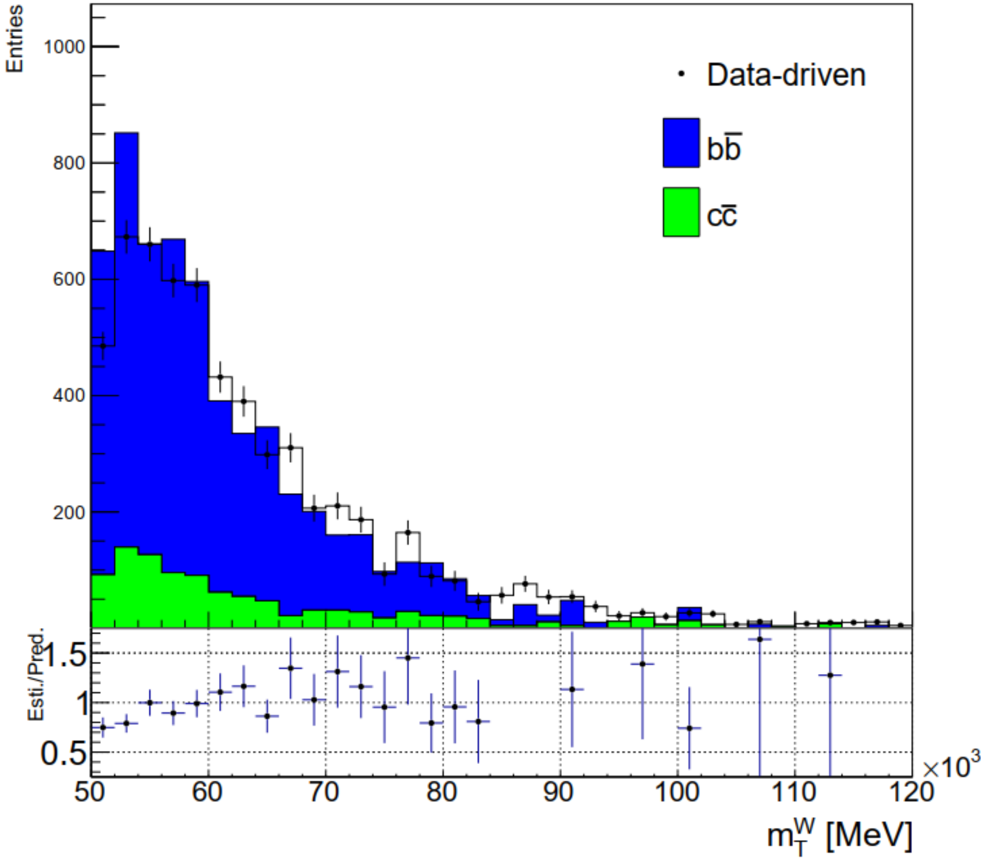
Use the $\mathrm{p_T^{ll}}$ constraint to calibrate the response and resolution of $\mathrm{u_T}$ in Z->ll events. Then extrapolate the results to W events.

Multijet background

In W events:

$$m_T = \sqrt{2p_T^l p_T^{miss}\left(1 - \cos\left(\phi_l - \phi_{p_T^{miss}}\right)\right)}$$

$\vec{p}_T^{miss} = -\left(\vec{p}_T^l + \vec{u}_T\right)$ for the neutrino



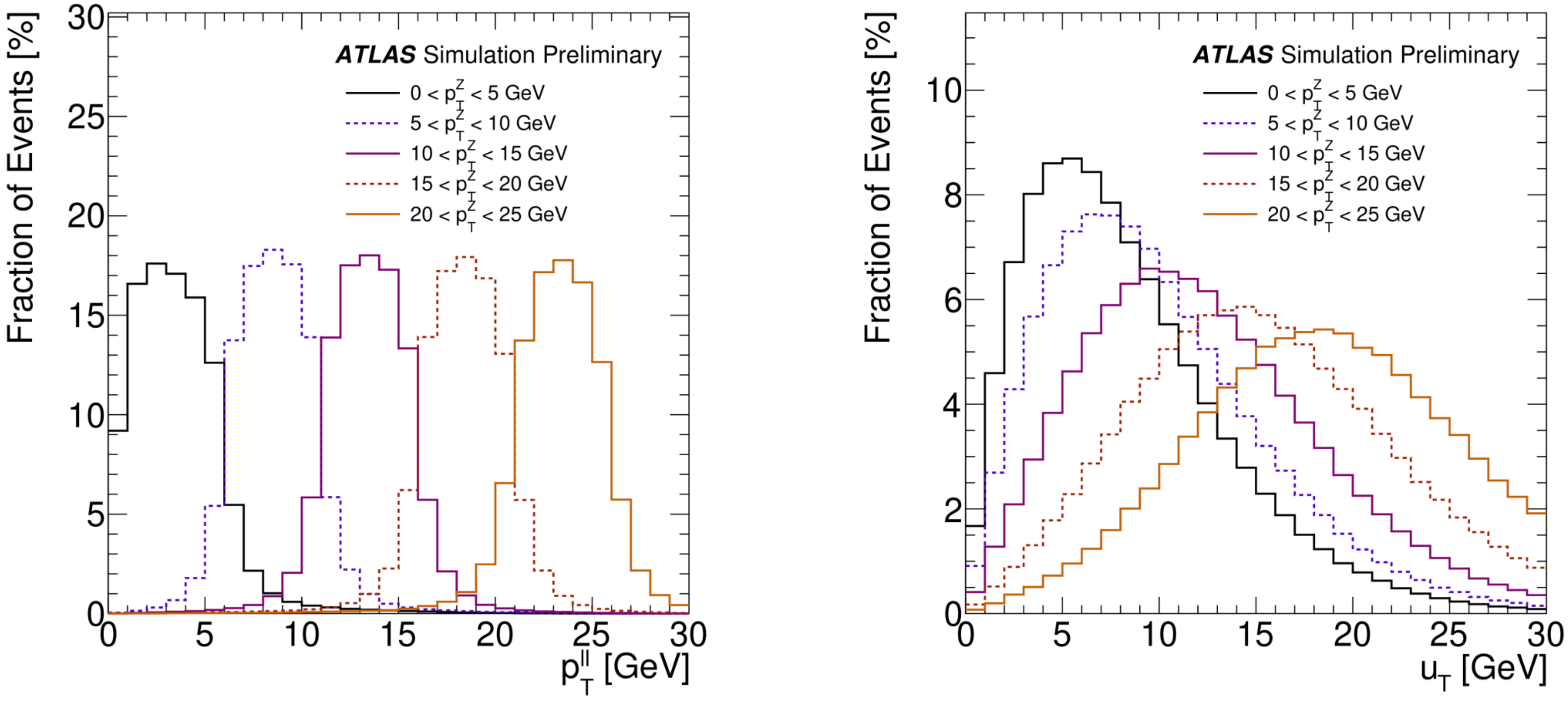
The main contribution of multijet background in muon channels: $b\bar{b}$, $c\bar{c}$ decay. MC simulation normalized to the data-driven estimation.

The multijet background (MJ) due to the heavy flavor quark decays and pions faking electrons is hard to be accurately simulated by MC
-> Derive from the data-driven estimation method.

Two elements to be estimated:

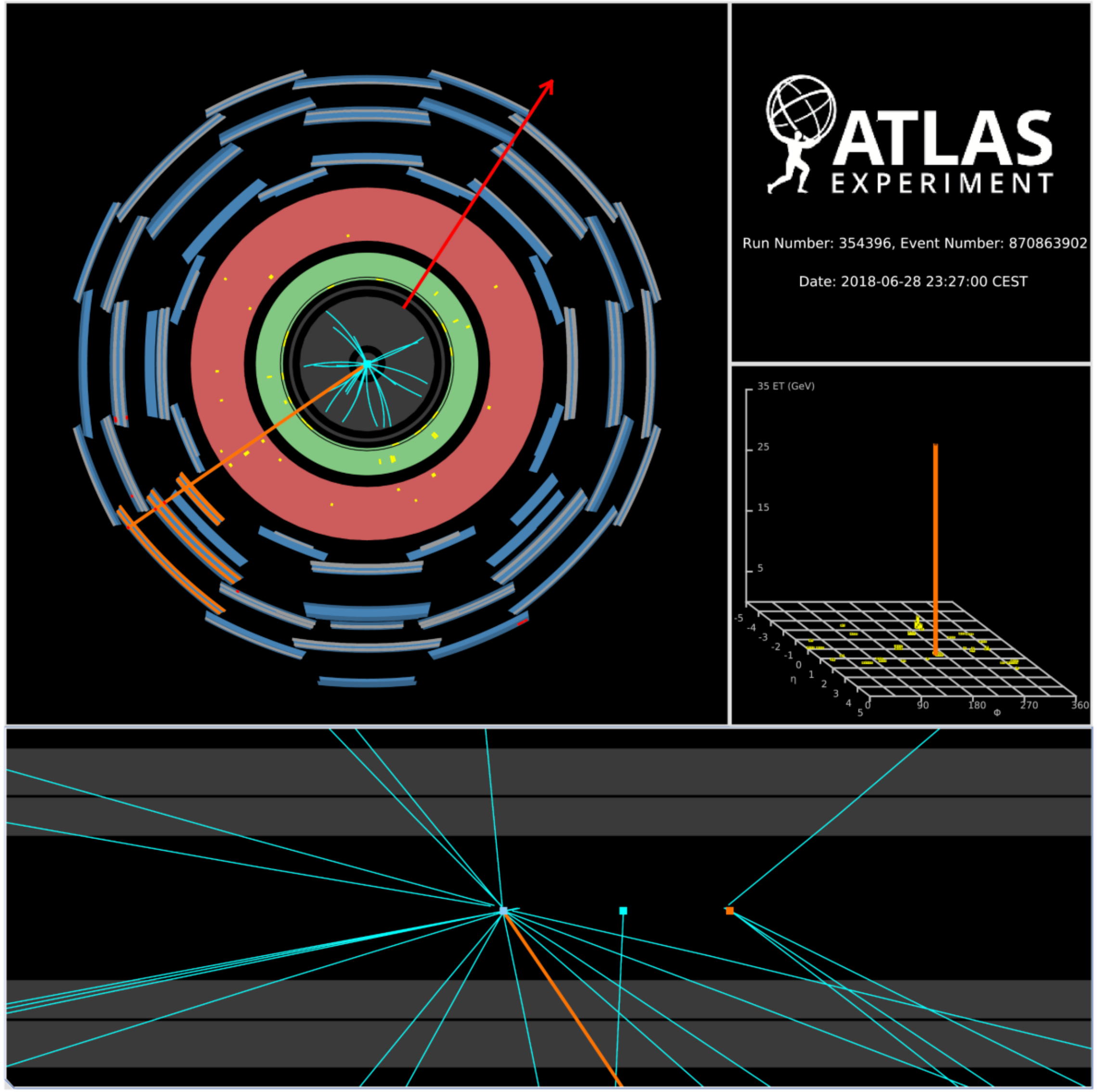
- MJ yield in the signal region.
- MJ shape in the signal region.

Unfolding



ATLAS Simulation Preliminary
$0 < p_T^Z < 5$ GeV
$5 < p_T^Z < 10$ GeV
$10 < p_T^Z < 15$ GeV
$15 < p_T^Z < 20$ GeV
$20 < p_T^Z < 25$ GeV
Fraction of Events [%]
0
5
10
15
20
25
30
p_T^{ll} [GeV]
ATLAS Simulation Preliminary
$0 < p_T^Z < 5$ GeV
$5 < p_T^Z < 10$ GeV
$10 < p_T^Z < 15$ GeV
$15 < p_T^Z < 20$ GeV
$20 < p_T^Z < 25$ GeV
Fraction of Events [%]
0
2
4
6
8
10
0
5
10
15
20
25
30
u_T [GeV]

Event display of the low pile-up data



The event display of a W^{-} boson candidate at 13 TeV.

- Orange line: muon
- Red arrow: missing transverse momentum

Event kinematics:

- p_T^{μ}=35 GeV
- Reconstructed p_T^{W} = 16 GeV
- m_T=77 GeV
- p_T^{miss}=49 GeV.