QUARK MATTER 2015

The XXVth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions

AGH

Vector boson production in p+Pb and Pb+Pb collisions measured with ATLAS at the LHC

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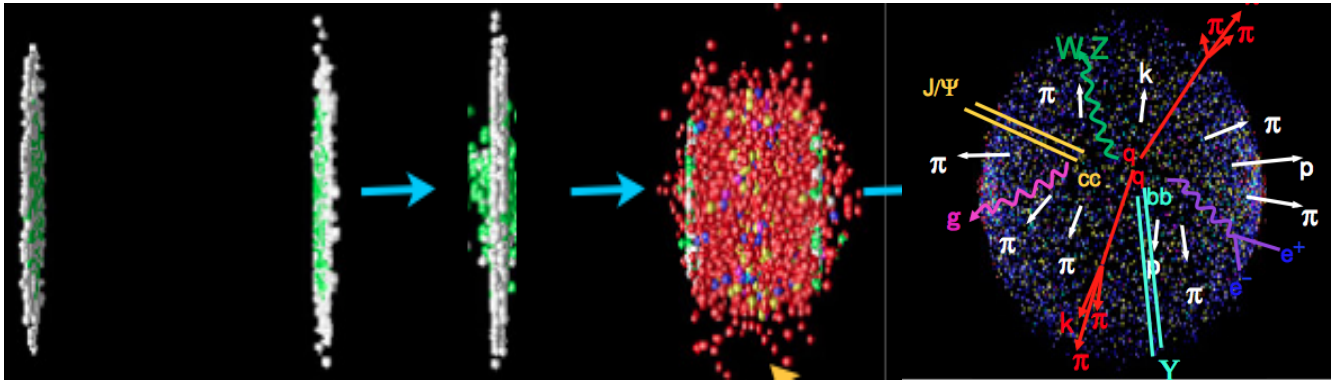
on behalf of the ATLAS Collaboration
Kobe, Japan, Sept 30th, 2015

Outline

- Introduction
  - Physics motivation
  - ATLAS experiment
- Overview of measurements on vector bosons
  - Photons
    - Inclusive photons in Pb+Pb (arxiv:1506.08552)
    - γ+jet momentum imbalance in Pb+Pb (ATLAS-CONF-2012-121)
  - Z bosons
    - Z bosons in Pb+Pb (Phys.Rev.Lett 110 (2013) 022301)
    - Z+jet momentum imbalance (ATLAS-CONF-2012-119)
    - Z boson production in p+Pb (arxiv:1507.06232)
  - W bosons
    - W bosons in Pb+Pb (Eur. Phys. J. C75 (2015) 23, 1-30)
    - W bosons in p+Pb (ATLAS-CONF-2015-056)
- Summary

Old measurements
New/final measurements

Physics motivation

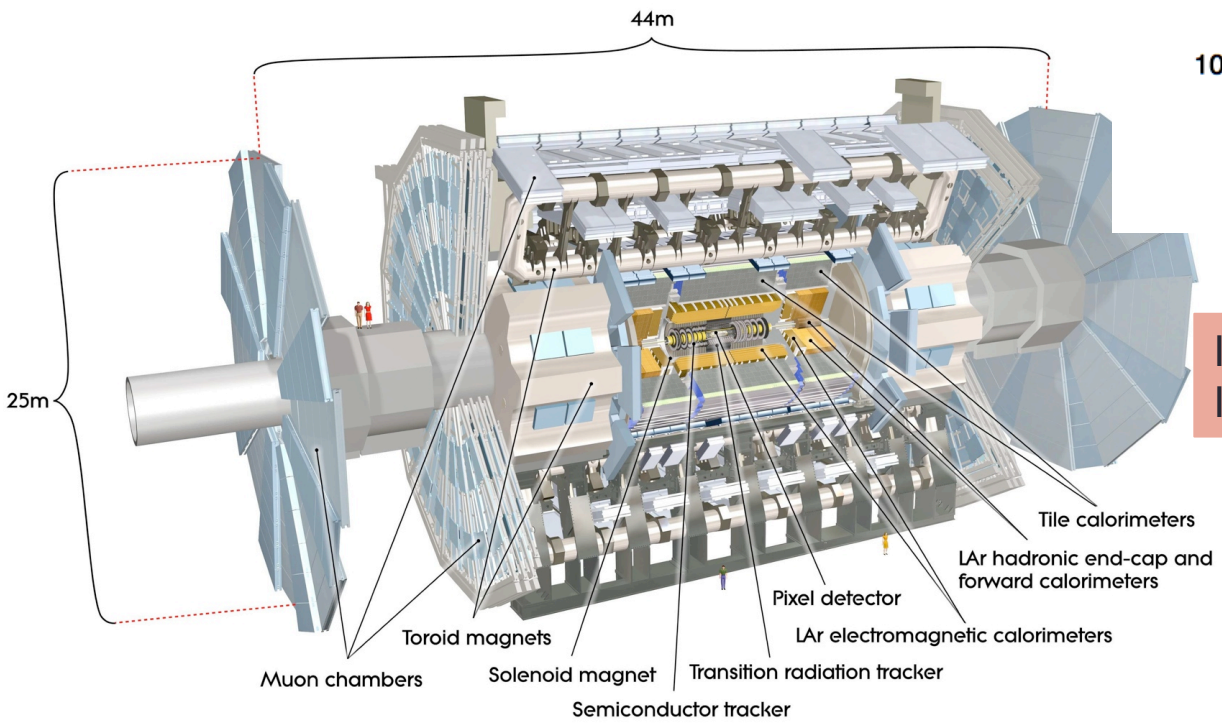


One of the main goals of heavy-ion physics is to study the QGP

- *Electroweak (EW) bosons* are produced in hard processes before the quark-gluon plasma (QGP) is formed
- They are colorless probes which are supposed not to interact with the QGP
  - Leptons (decay products) are colorless as well → the QGP should be transparent to them
- One can explore *jet quenching* in EW+jet events using EW bosons as a calibration tool
- In addition, the EW boson production mechanism (e.g. via qq-bar annihilation) makes them sensitive to *parton distribution functions* (PDFs)
  - One can investigate nuclear modifications to PDFs (nPDFs)
  - Proton-lead (p+Pb) collisions are a perfect tool to disentangle initial- from final-state effects

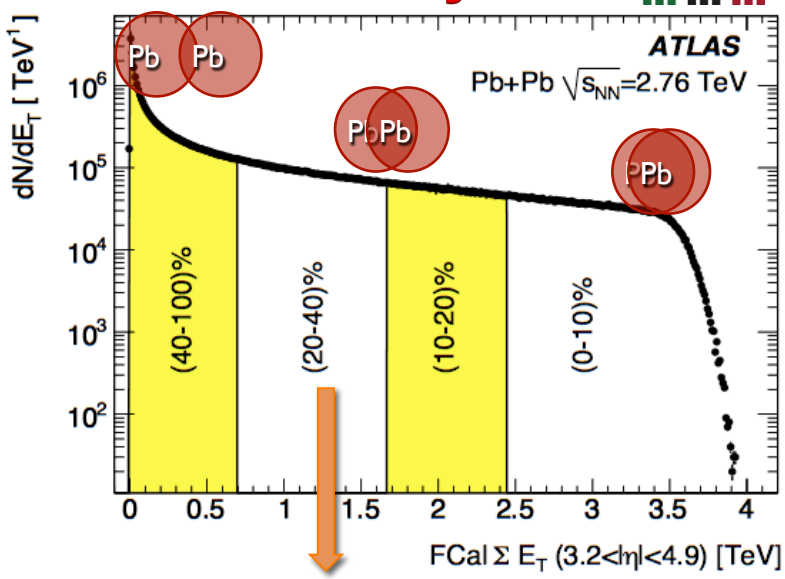
ATLAS detector

Three main components: inner tracker, electromagnetic (EM) and hadronic (HAD) calorimeters, and muon system



Full azimuthal acceptance

Centrality

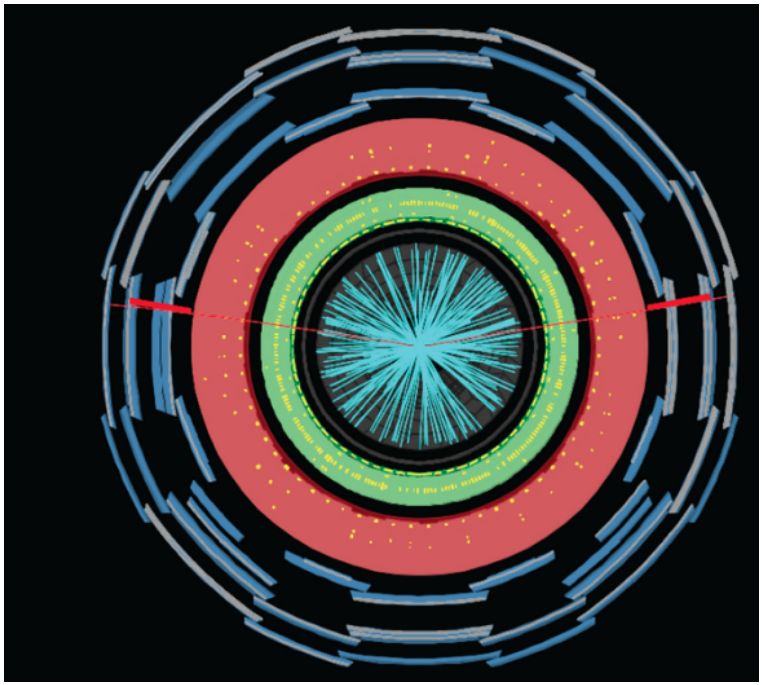


FCal E_T→centrality→$N_{part}N_{coll}$

In Pb+Pb: total FCal E_T
In p+Pb: FCal E_T on Pb-going side

Sub-detectors	|η| coverage
Inner Tracker	<2.5
Muon Spectrometer	< 2.7
EM Calorimeter	<3.2
HAD Calorimeter	<4.9

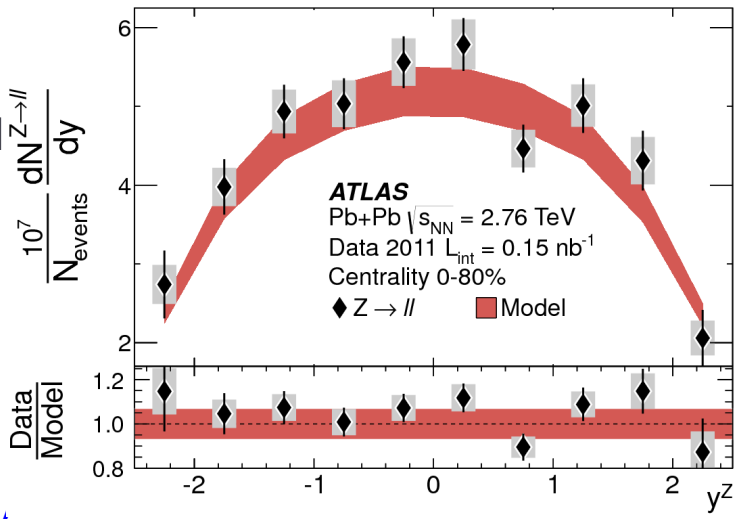
Pb+Pb system



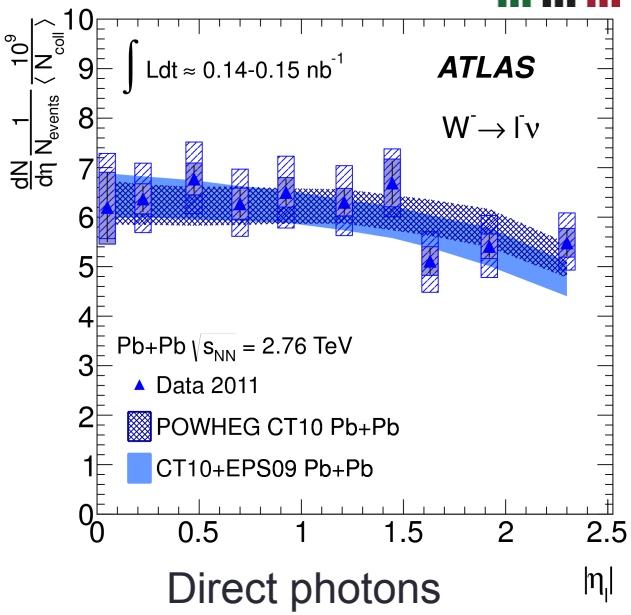
Yields of EW bosons

- Direct photons
  - Kinematics: $22<p_T<280$ GeV and $|\eta|<1.37$ (**central**) and $1.52<|\eta|<2.37$ (**forward**)
  - Predictions: JETPHOX
- Z bosons
  - Kinematics: $|\eta^Z|<2.5$ and $66<m_Z<116$ GeV
  - Predictions: NNLO +CT10
- W bosons
  - Kinematics: $p_T^l>25$ GeV, $p_T^\nu>25$ GeV, $m_T>40$ GeV and $|\eta|<2.5$
  - Predictions: NLO +CT10

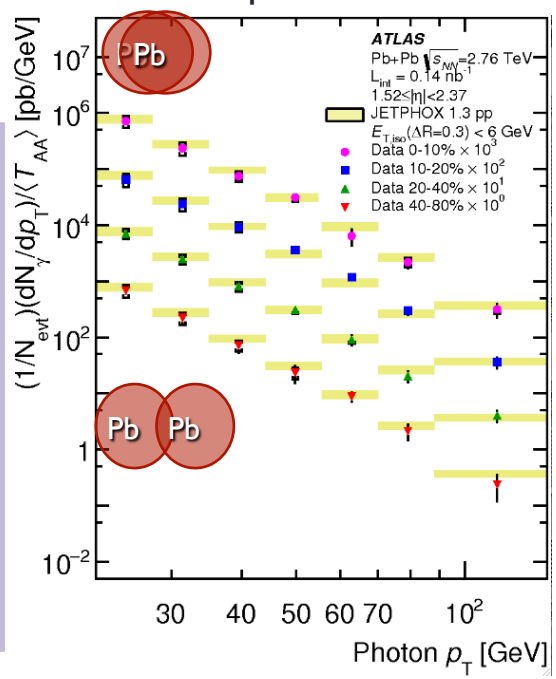
Z bosons



W- bosons



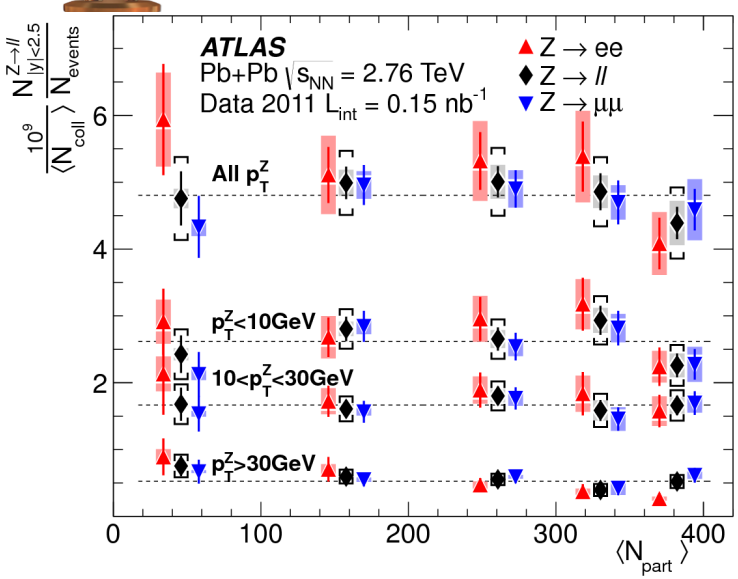
Direct photons



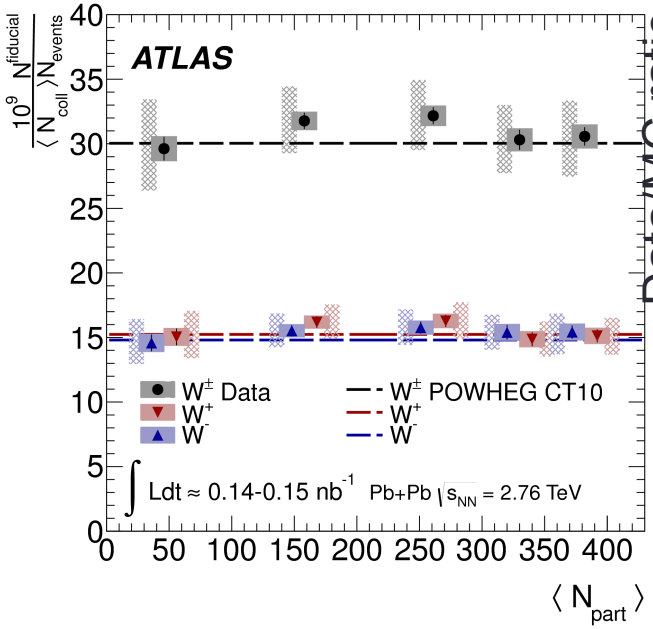
- → EW boson production yields measured in a broad kinematic range
- → NLO or NNLO pQCD predictions describe data pretty well in shape and normalization over many orders of magnitude
- → Need to include the isospin effect necessary to describe W boson yields

Centrality scaling

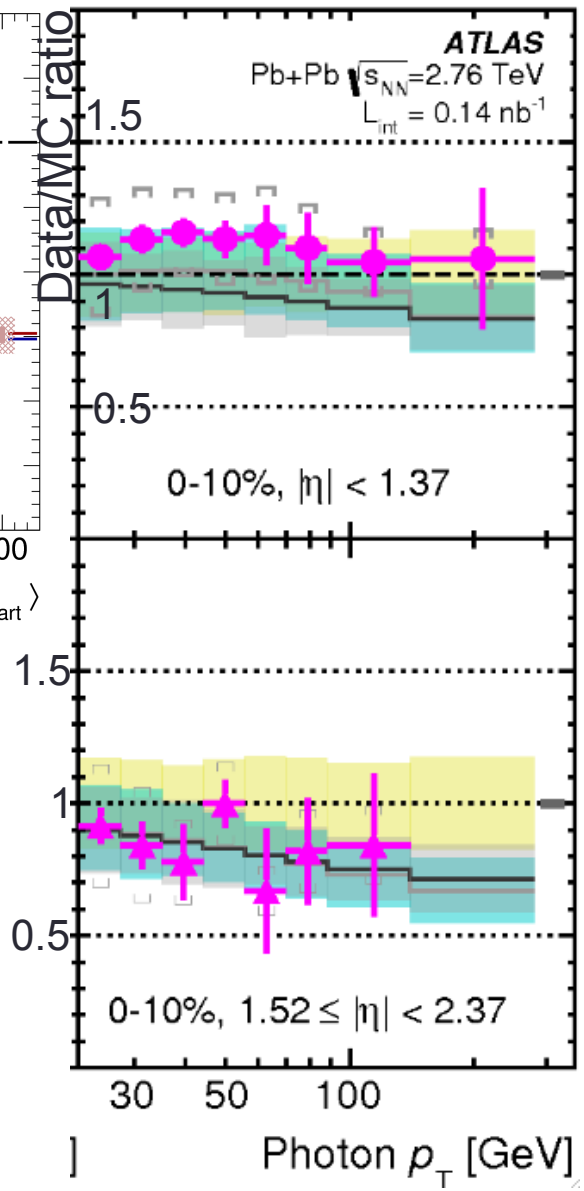
Z bosons



W bosons



Direct photons

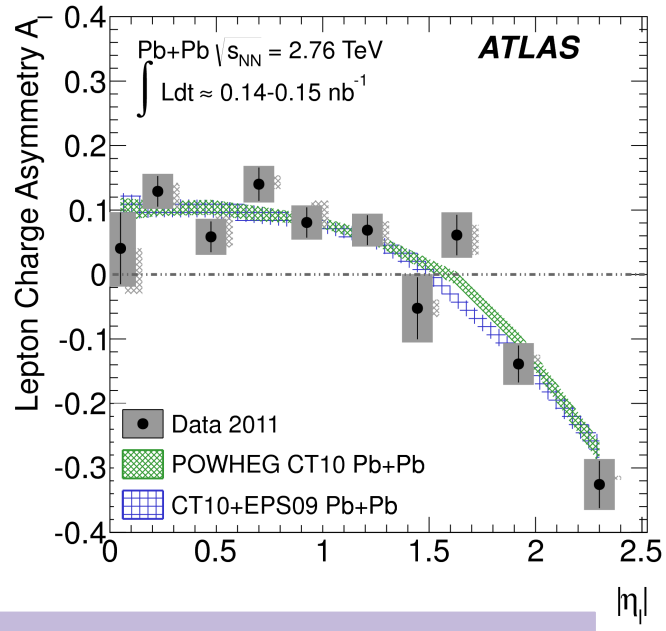


→EW boson yields per binary collision have been measured
→They show no centrality dependence
- → Neither EW boson nor they decay products interact with the QGP
- → EW bosons can be used as a calibration tool to investigate the energy loss of color objects in the QGP

→EW boson production is consistent with NLO/NNLO pQCD predictions

Initial state (PDF/nPDF)

W bosons



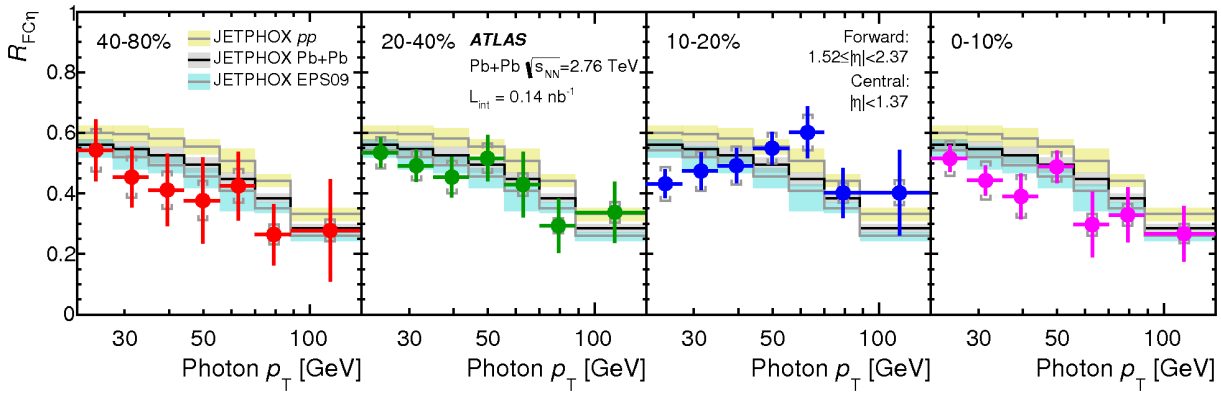
$$A_\ell = \frac{N_{W^+} - N_{W^-}}{N_{W^+} + N_{W^-}}$$

- Many correlated systematics cancel out in the ratio

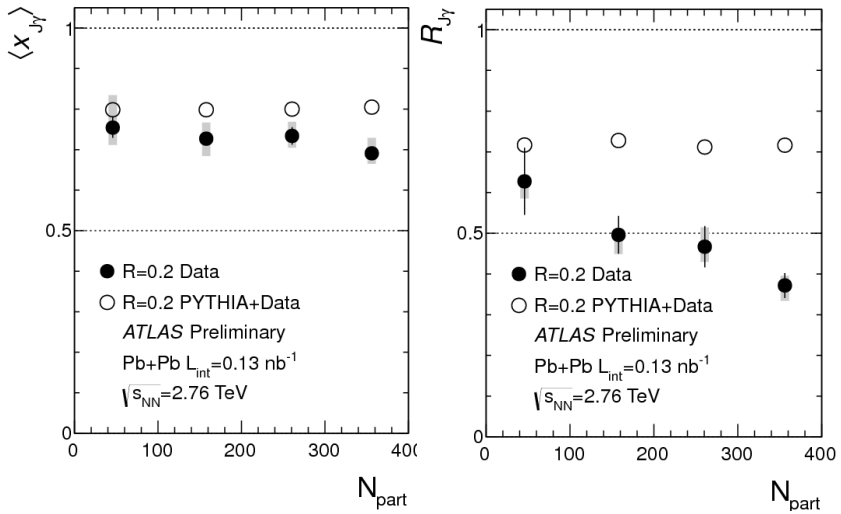
→A_l sensitive to nuclear modifications of PDF + spin conservation in W boson production
→Each theoretical prediction:
NLO + CT10 (PDF in vacuum)
NLO + CT10 + EPS09 (nPDF)
describes data well
→Nuclear modifications remain unclear within the experimental precision of Run-1 Pb+Pb data

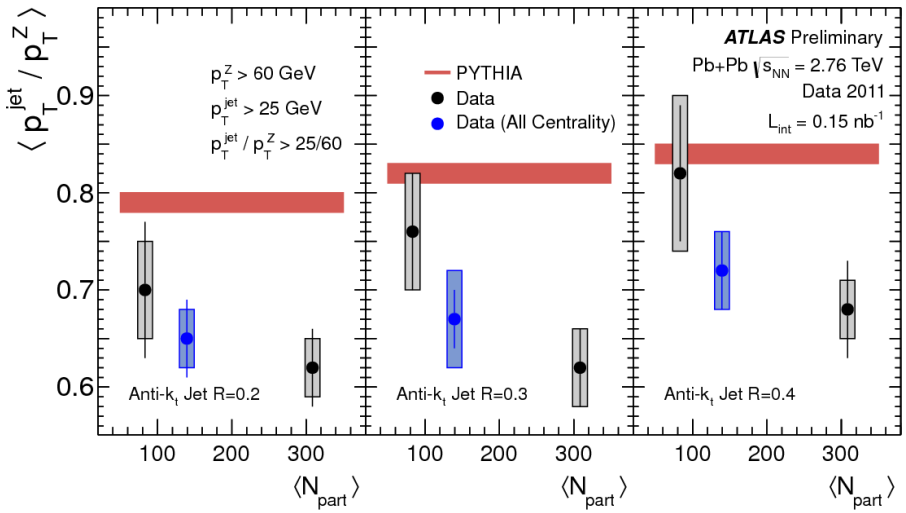
→ $R_{FC\eta}$ – measured for three scenarios:
NLO p+p
NLO Pb+Pb
NLO Pb+Pb with EPS09
→ $R_{FC\eta}$ indicates a slight preference for isospin effects
→ Better precision expected in Run-2 data

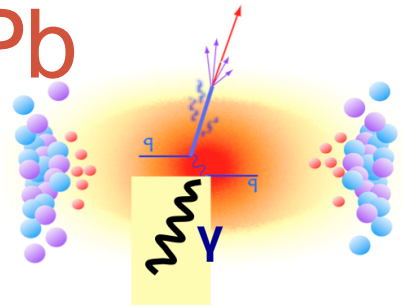
$R_{FC\eta}$ – forward-to-central production ratio of direct photons



EW+ jet correlations in Pb+Pb





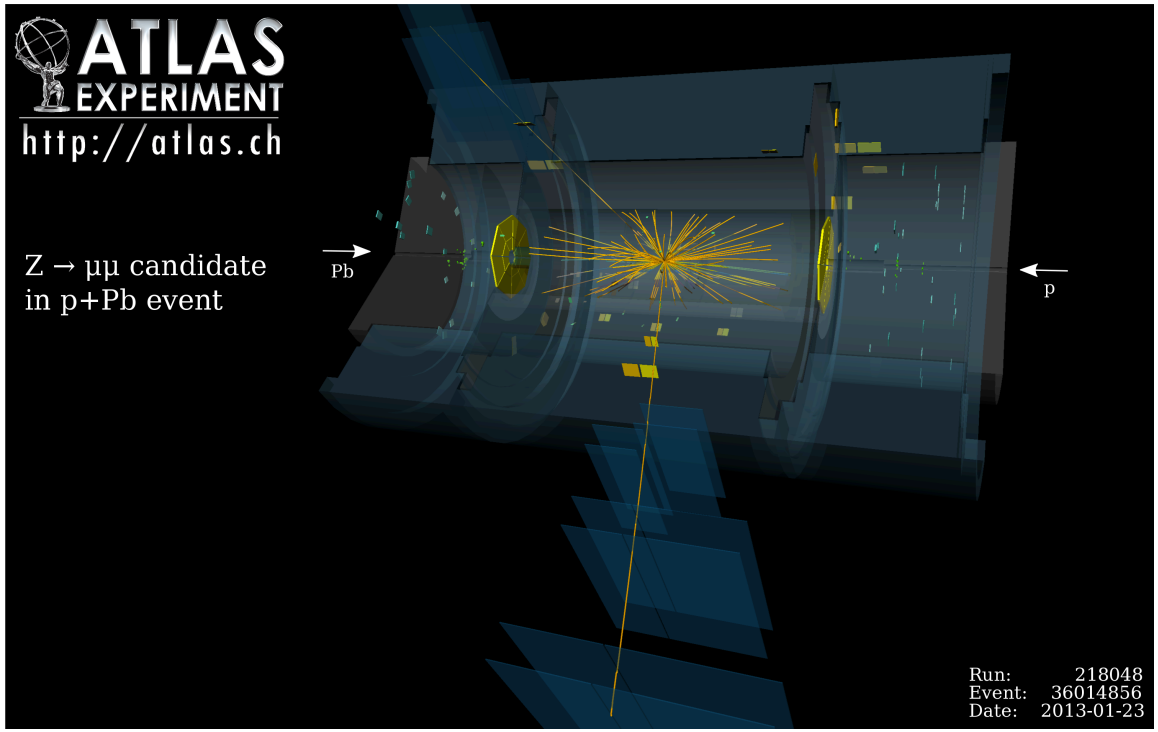


$$x_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

In events with photon/Z + jet measure: 1) energy fraction, 2) azimuthal angle separation and 3) $R_{J\gamma}$ - fraction of jet-gamma pairs to the total number of photons

→$x_{J\gamma}$ diminishes with centrality while two objects remain back-to-back
→Significant change in $R_{J\gamma}$ in central events, which is inconsistent with the PYTHIA-based model
→Similar observations in Z+jet events however, the measurement limited by statistical precision

p+Pb system


ATLAS
EXPERIMENT
http://atlas.ch
Z → μμ candidate
in p+Pb event
Pb
p
Run: 218048
Event: 36014856
Date: 2013-01-23

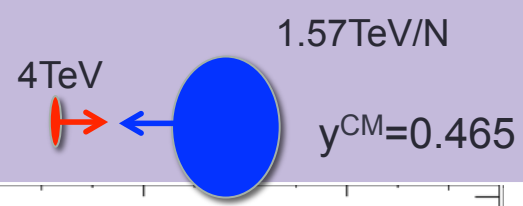
Z boson production

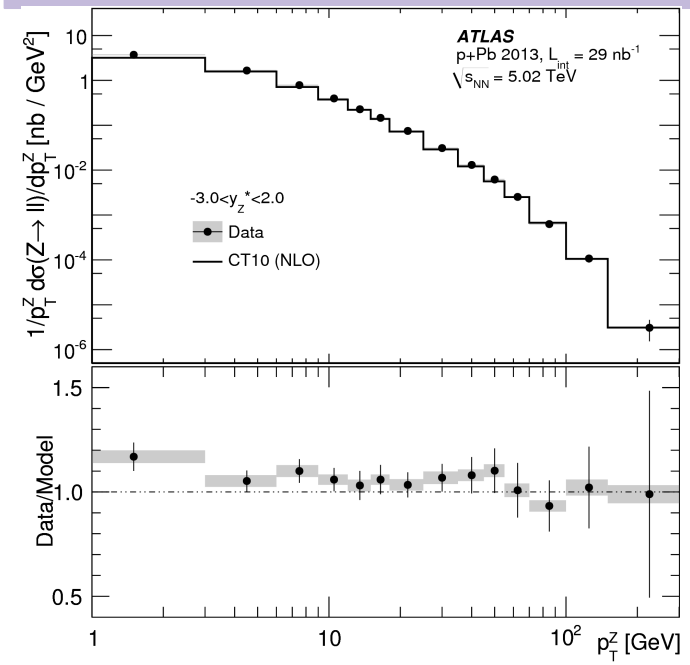
→ Total cross-sections for muon and electron channels

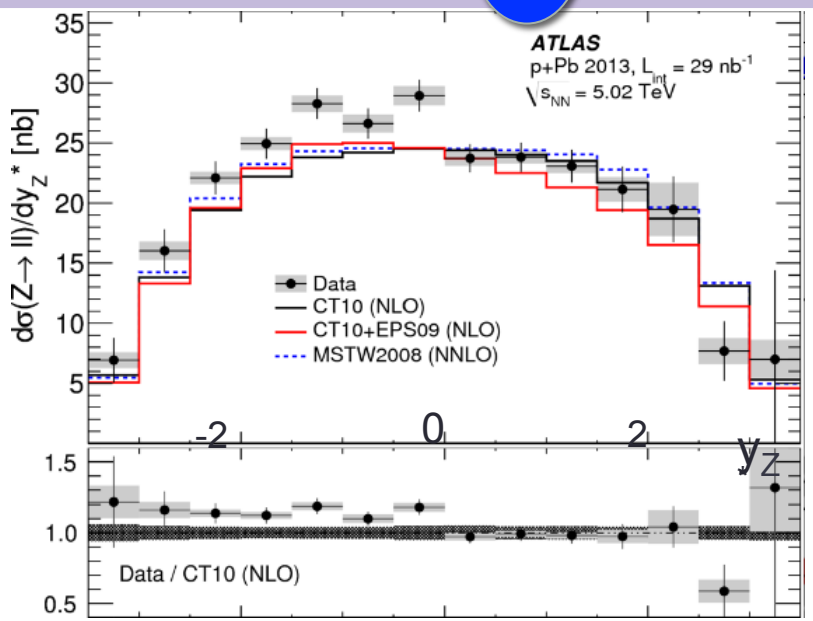
y_Z^*	[−2, 0]	[0, 2]
$Z \to \mu\mu$	54.2 ± 1.6 ± 1.3	45.3 ± 2.1 ± 0.9
$Z \to ee$	55.1 ± 1.8 ± 5.9	46.5 ± 2.2 ± 5.0
$Z \to \ell\ell$	54.4 ± 1.3 ± 1.4	45.9 ± 1.4 ± 1.4
CT10 (NLO)	47.4 ± 0.9	46.8 ± 0.9
CT10+EPS09 (NLO)	48.7 ± 1.0	43.5 ± 1.1
MSTW2008 (NNLO)	$48.3^{+1.2}_{-0.9}$	$47.9^{+1.2}_{-0.9}$

Good agreement for $y_Z^*>0$
Excess of the data for $y_Z^*<0$

→ Differential cross-sections in p_T^Z and y^Z are compared to NLO predictions with CT10 PDFs
- → Good shape description by the model in p_T^Z
- → Data reveals asymmetry in y^Z about $y_Z^*=0$
- → p-value favors the CT10+EPS09 prediction

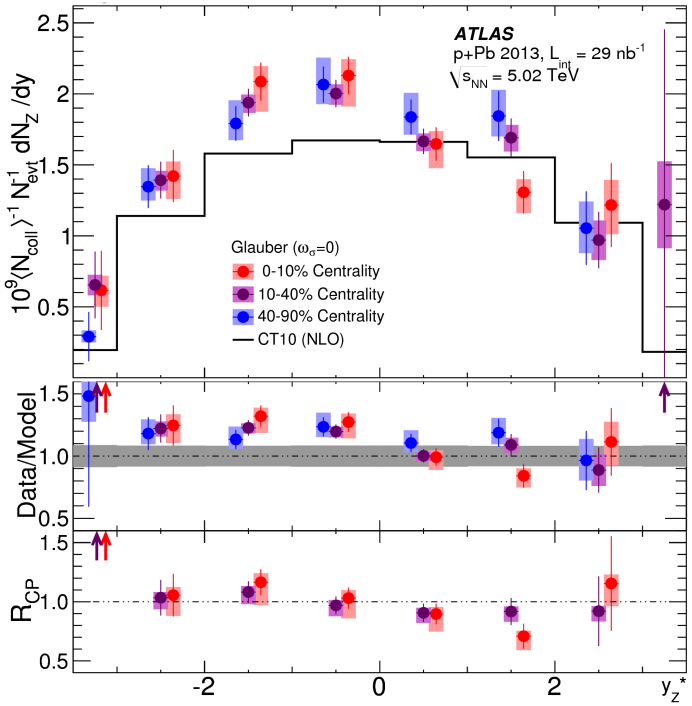


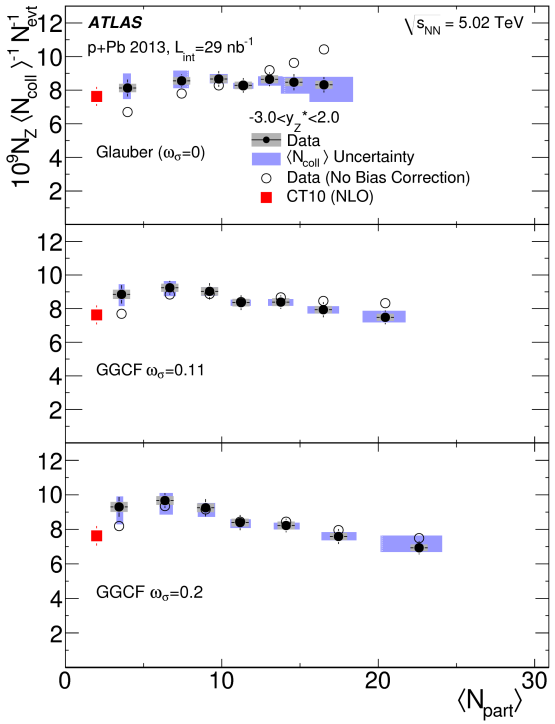




Centrality dependence of Z bosons

- Measurement of cross-section dependence on y_Z^* in centrality classes





Z boson production yields per minimum bias event divided by $\langle N_{coll}\rangle = \langle N_{part}\rangle - 1$

- Various models explored for collision geometry: standard Glauber (ω=0), Glauber-Gribov (GGCF:ω=0.11, ω=0.2)

→ Larger differences between data and model in the most central collisions

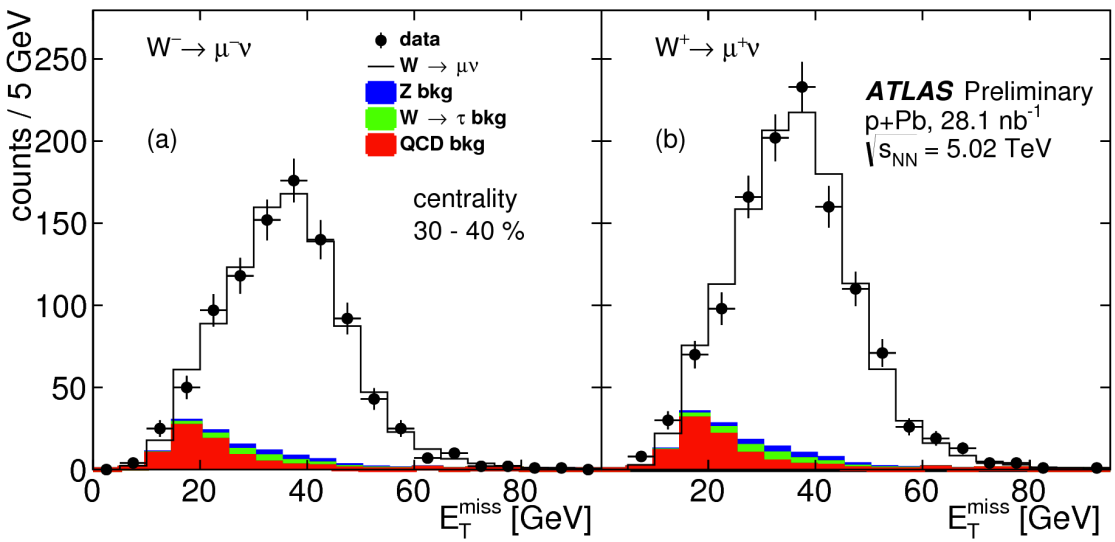
→ R_{cp}= Yield^{central}/Yield$^{40\text{-}90\%}$ reveals departure from unity

→Z boson production scaling with centrality holds in the standard Glauber model after centrality-bias correction

→GGCF extensions shows some dependence on N_{part}

W boson production

NEW



Fiducial volume:

$$0.1 < |\eta^{\mu}_{lab}| < 2.4$$
$$p^{\mu}_{T} > 25\ GeV$$
$$p^{\nu}_{T} > 25\ GeV$$
$$m_{T} > 40\ GeV$$

- W bosons measured via muon decays in the entire p+Pb data sample (28.1 nb^{-1})
- Background contributions estimated from the template fit to the E_T^{miss} distribution
  - From heavy flavor (QCD bkg), Z boson, $W \rightarrow \tau\nu_\tau$
  - Good signal-to-background ratio
- Cross sections or yields measured in the fiducial volume in bins of centrality and muon pseudorapidity

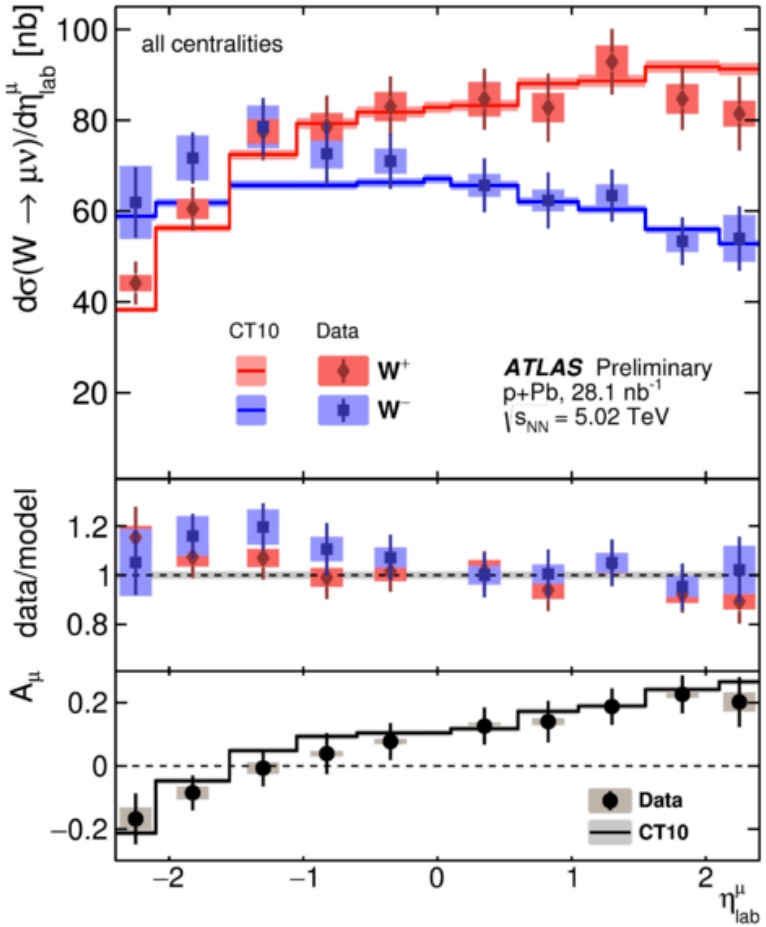
W boson cross section

NEW

- W^+ and W^- production cross sections integrated over all centralities have been measured
- Lepton-charge asymmetry (A_μ) also extracted

$$A_\mu = \frac{N_{W^+} - N_{W^-}}{N_{W^+} + N_{W^-}}$$

→ Differences in positive and negative η_{lab} due to isospin effects and center-of-mass shift
→ Data reasonably well described by the NLO CT10 + isospin calculations
→ A_μ is consistent with the predictions except for W^- production in negative η_{lab}

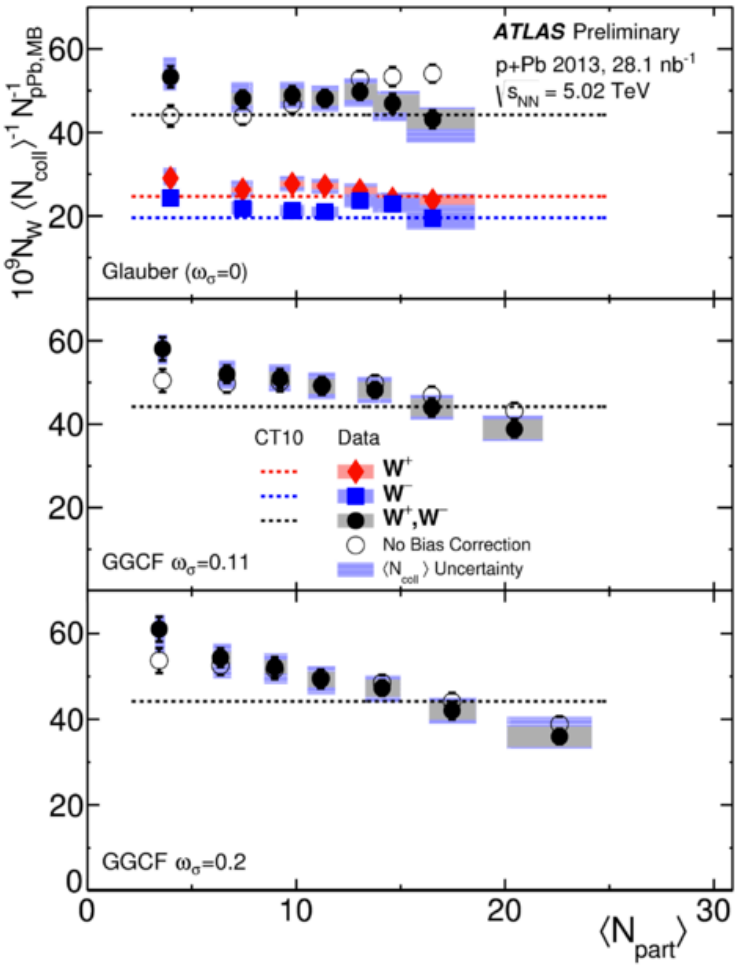


Centrality dependence

NEW

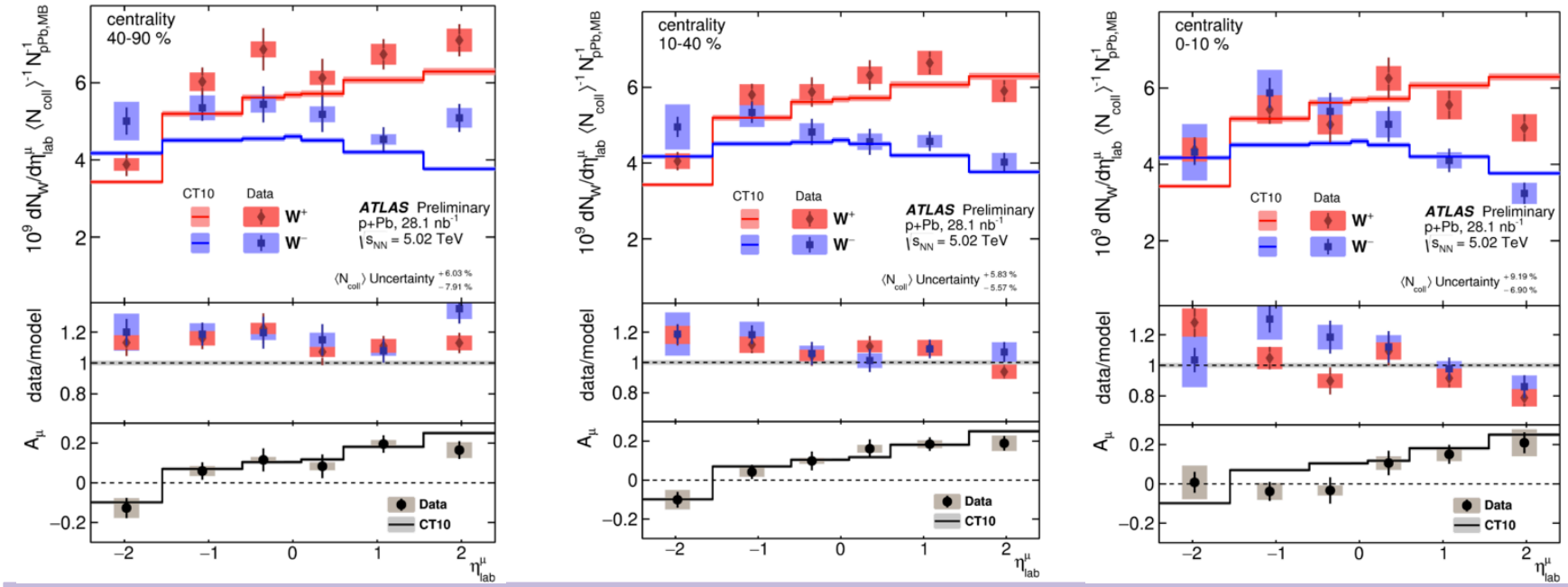
- Centrality dependence of W boson production measured for the first time
  - w/ and w/o underlying-event correction (arXiv:1412.0976)
- Three scenarios considered for geometry description:
  - Standard Glauber (ω=0)
  - GGCF with ω=0.11
  - GGCF with ω=0.2

→ W boson yields per $\langle N_{coll} \rangle$ tend to be constant with centrality only in the standard Glauber model
→ Yields consistent with NLO CT10 only in the upper panel
→ GGCF approach introduces a non-constant behavior
→ Trends are consistent with those observed in Z boson production



NEW

Centrality dependence in pseudorapidity



→ W^+ and W^- boson yields per nucleon-nucleon collision as a function of muon pseudorapidity in three centrality bins

→ Data is compared with NLO+CT10 predictions

- → In peripheral bin (40-90%), the theory underestimates the data, shape is well described
- → In central bin (0-10%), the shape is not modeled well

→ Muon charge asymmetry agrees between the data and predictions except in 0-10% centrality and negative pseudorapidity

Summary

- ATLAS experiment has a variety of measurements with vector boson production in heavy-ion collisions based on Run-1 data
  - Photons, Z and W bosons in Pb+Pb and p+Pb systems
  - New measurement of W boson production in muon decay mode in the p+Pb system has been presented

→Linear scaling of EW boson production yields with centrality ($<N_{part}>$) has been established in the Pb+Pb collisions

→Followed by no suppression of leptonic decay products in the QGP

→NLO/NNLO pQCD predictions describe data very well both in shape and normalization

→Some departure from the predictions in the p+Pb system observed

→Sensitivity to the isospin effect and nPDFs has been tested

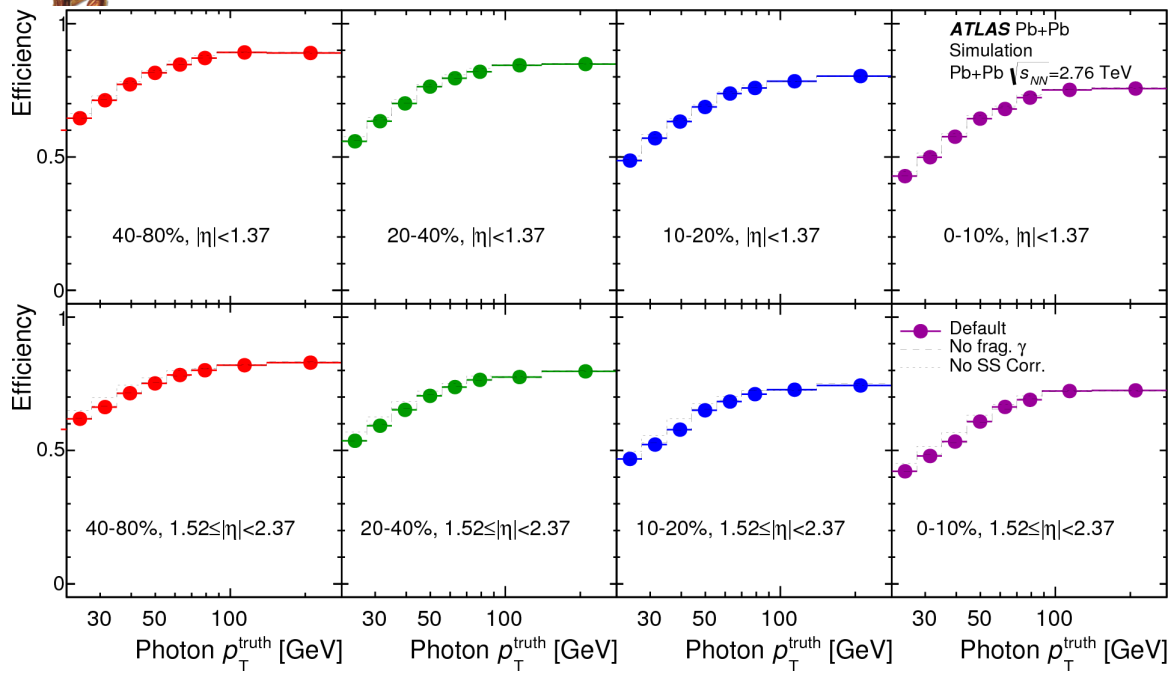
→W boson yields in |η| can be only described taking into account the isospin effect

→No much sensitivity to nuclear modifications to PDFs within the current experimental precision in Pb+Pb collisions, data exhibits departure from the in-vacuum predictions in the p+Pb system

→Looking forward to Run-2 data to constrain more nuclear PDFs and perform jet calibration with EW probes

Back-up slides

Inclusive direct photons

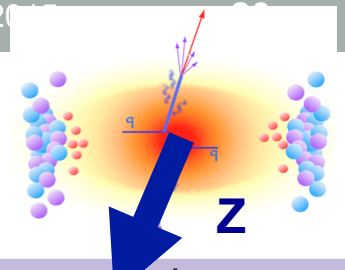


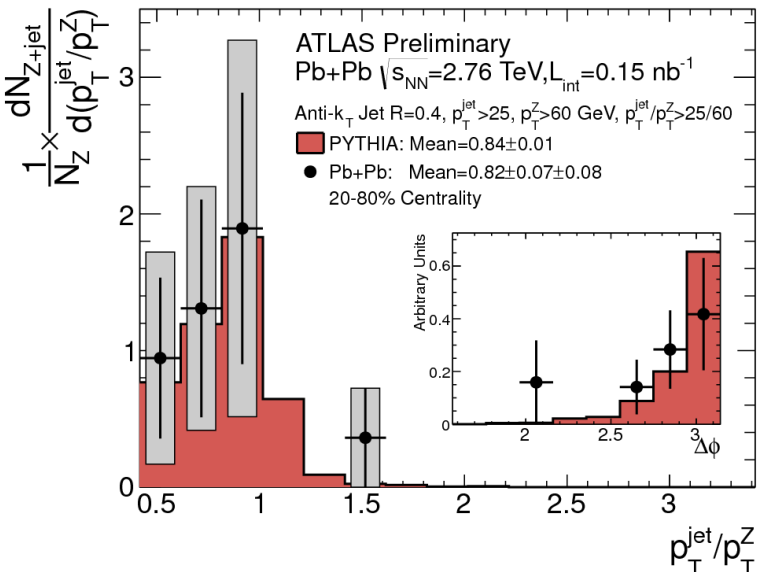
Photon efficiency as a function of p_T and centrality

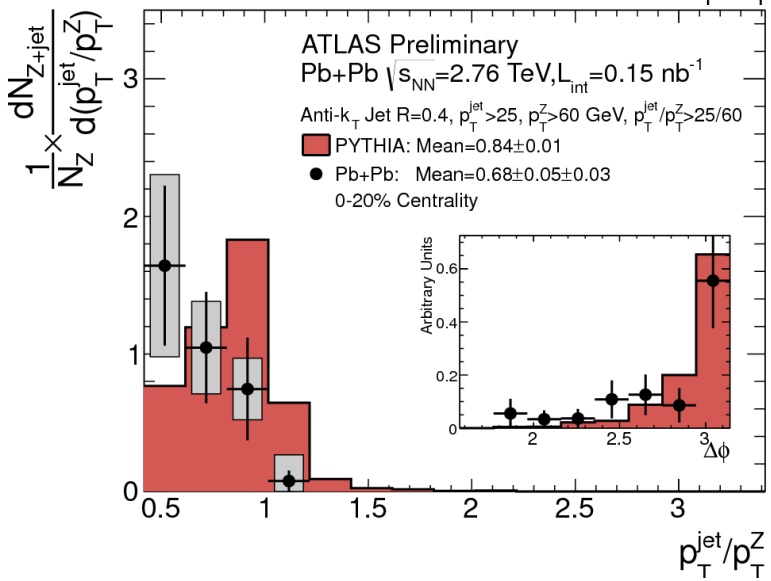
Systematic uncertainties in percentages on the ratio of photon yields

Centrality	40–80%		0–10%	
p_T [GeV]	22–28	55.6–70	22–28	70–88.2
$\gamma \to e$ leakage	1	1	1	1
Shower shape corr.	3	0	4	0
Isolation	9	9	4	4
Frag. photons	1	0	1	1
Nontight criteria	3	3	4	4
Leakage factors	2	2	2	4
R_{bkg}	1	4	2	6
Energy scale	7	7	7	7
W/Z contamination	0	1	0	1
Cent. weight	1	0	4	1
η leakage	2	1	2	2
Total [%]	13	13	11	11

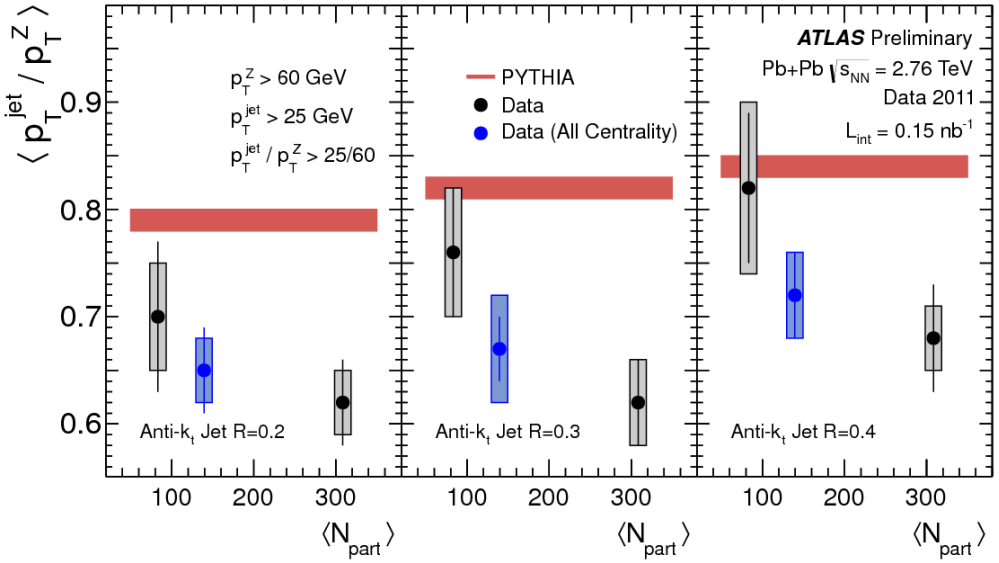
p_T imbalance of Z+jet in Pb+Pb



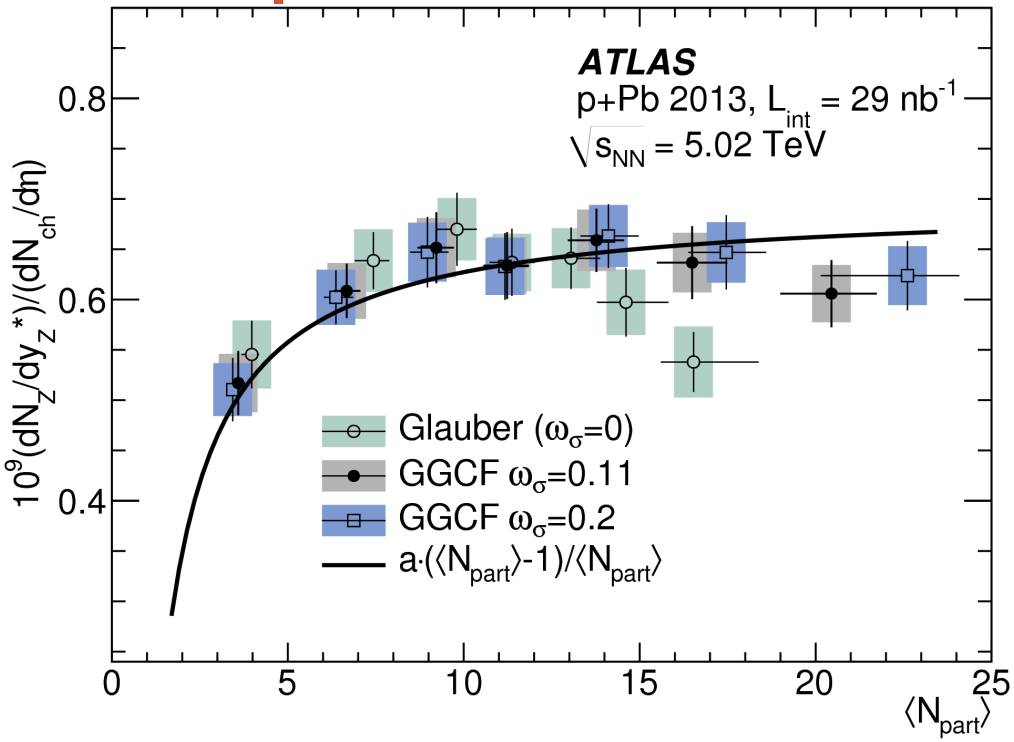




- Only 36 events satisfy the analysis criteria in the entire Pb+Pb data sample
  - Unfolded and efficiency corrected ratio p^{jet}_T/p^Z_T
  - Statistical uncertainty dominates
- Three jet sizes: 0.2, 0.3, 0.4
- Data compared to the PYTHIA-based model which contains no energy loss mechanism – significant deviation from the model
  - Both normalized by a number of Z bosons with p^Z_T>60GeV
- Expect improvement in Run-2 data



Z bosons in p+Pb



- Ratio of Z boson multiplicity to inclusive hadron multiplicity as a function of N_{part}
- Ratio is consistent with the fit of $a(\langle N_{part}\rangle-1)/\langle N_{part}\rangle$ for the GGCF scenarios
  - For the standard Glauber the description is not that good

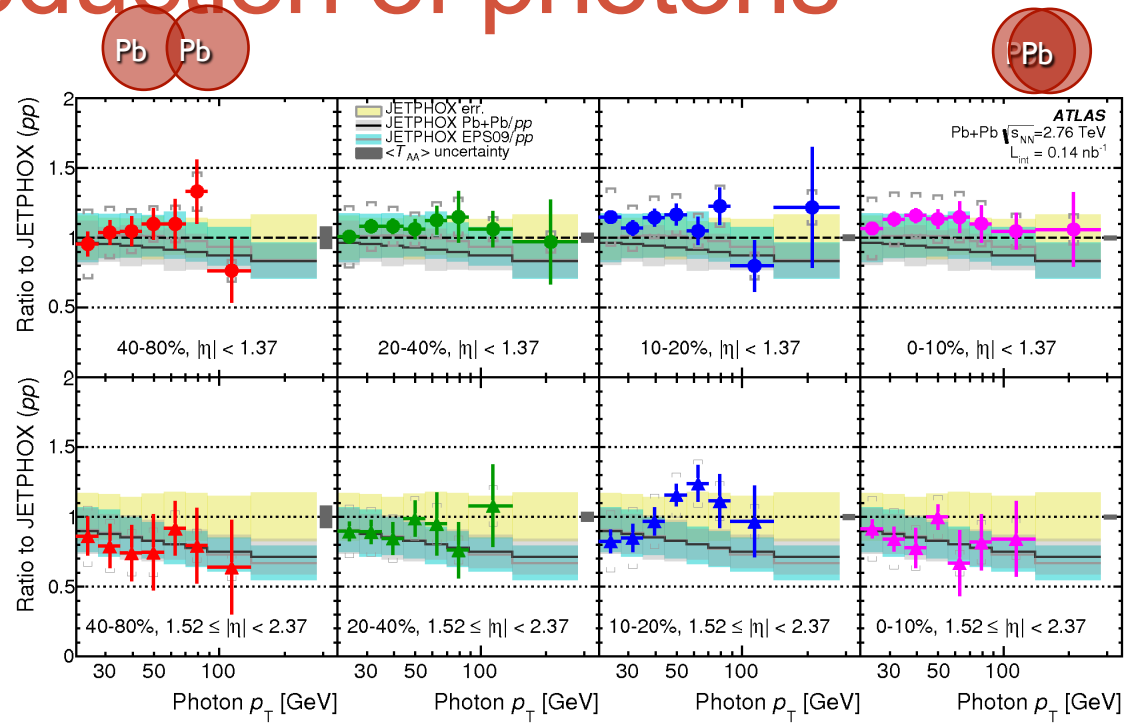
Relative production of photons

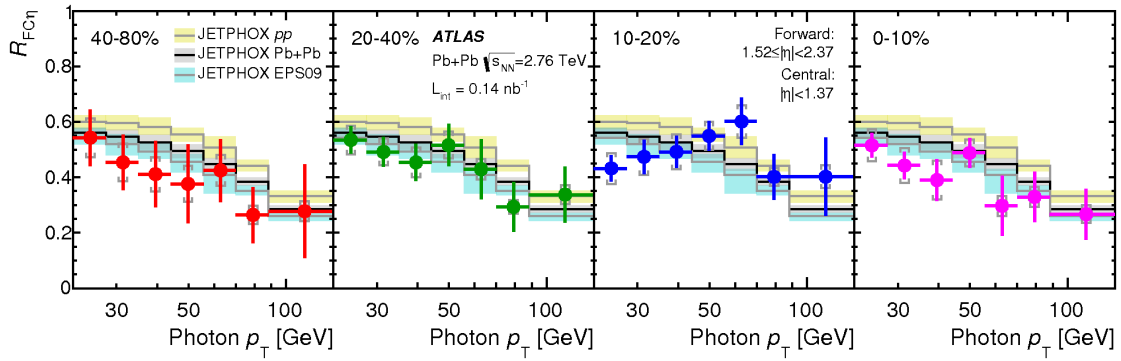
- Data-to-MC ratio is compared to three models:
  - NLO p+p
  - NLO Pb+Pb
  - NLO Pb+Pb with EPS09

→ At present, the data is unable to distinguish between three scenarios

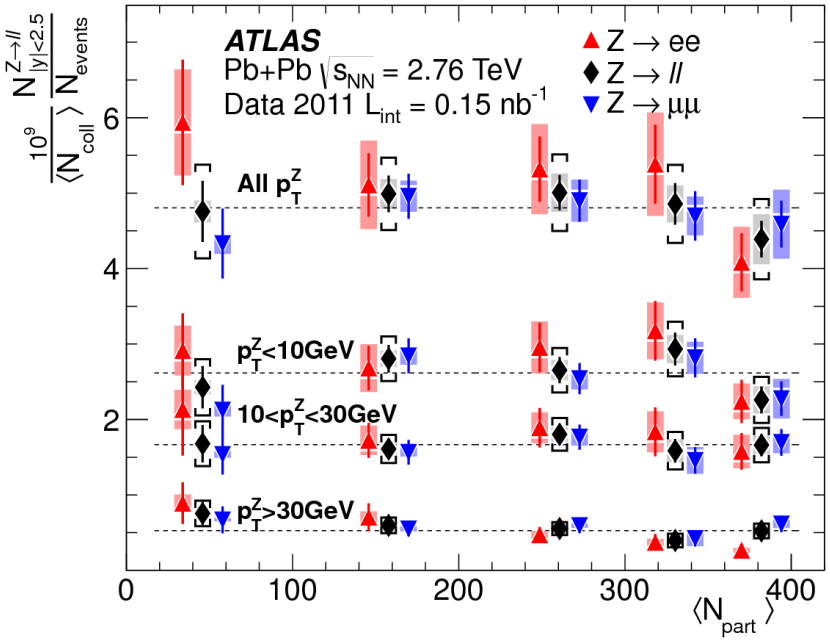
→ $R_{FC\eta}$ – forward to central production ratio indicates a slight preference for isospin effects

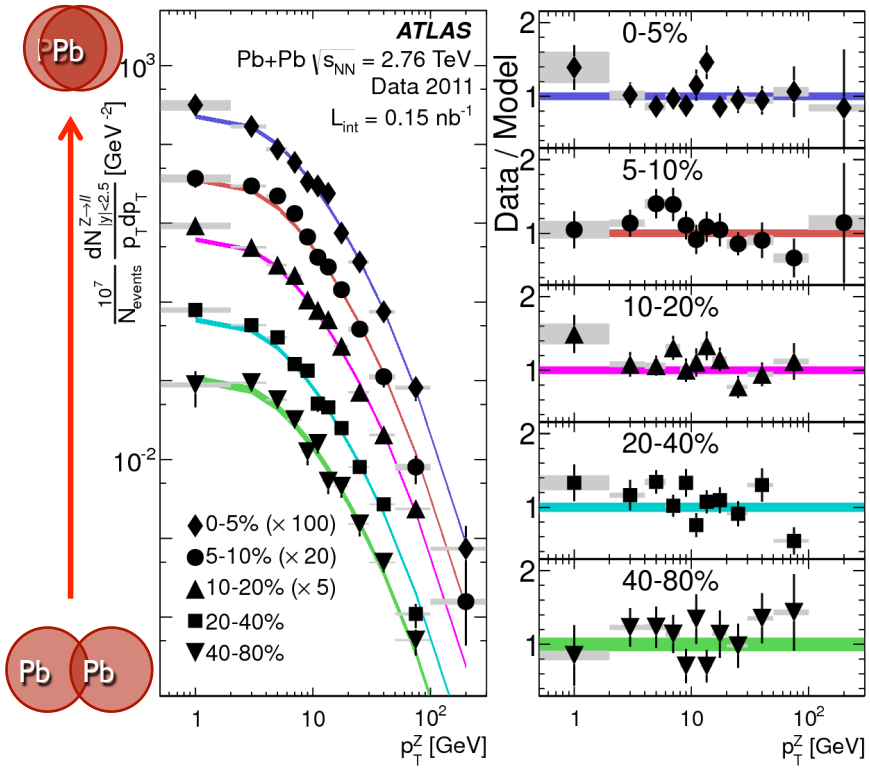
→ Expected better precision in Run-2 data



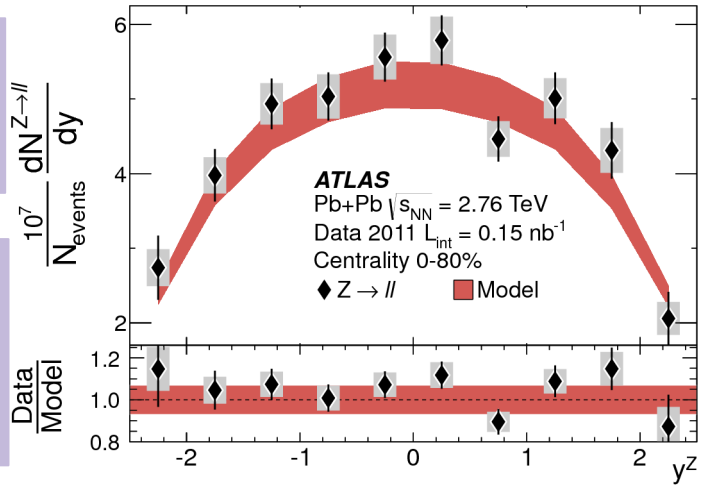


Z boson yields in Pb+Pb





→ Electron and muon channels are consistent
→ Binary collision scaling appears to hold true
→ no interaction with the QGP



→PYTHIA normalized to the Z→l+l- cross section in p+p from NNLO calculations and scaled by $\langle T_{AA} \rangle$ – agrees well
→No centrality dependence of this shape is observed

Centrality dependence of W boson production in Pb+Pb

- Measured via muon and electron channels
- Yields extracted in the fiducial volume: p_T^l>25 GeV, p_T^ν>25 GeV, m_T>40 GeV and |η|<2.5
- Two channels agree, thus they have been combined

→Yields are consistent with binary scaling for $W^\pm$, W^+ and W^-
→W^+ and W^- yields are almost identical
→W boson production is consistent with NLO predictions