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

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for the ATLAS Collaboration

Strangeness in Quark Matter 2016
UC Berkeley

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# Electroweak Bosons $\gamma$,W,Z in Heavy Ions: PHYSICS

The electroweak bosons can only interact with gluons at one loop and beyond, thus enabling:

- Estimation of effective *parton distribution functions* in collisions involving heavy ions
- Study of the *binary scaling* assumptions made in modeling ion-ion collisions
- Tool for validation of *centrality modeling*
- Approximate calibration of initial *jet energies* in boson-jet events

# ATLAS Results for EW Bosons

Pb+Pb collisions:

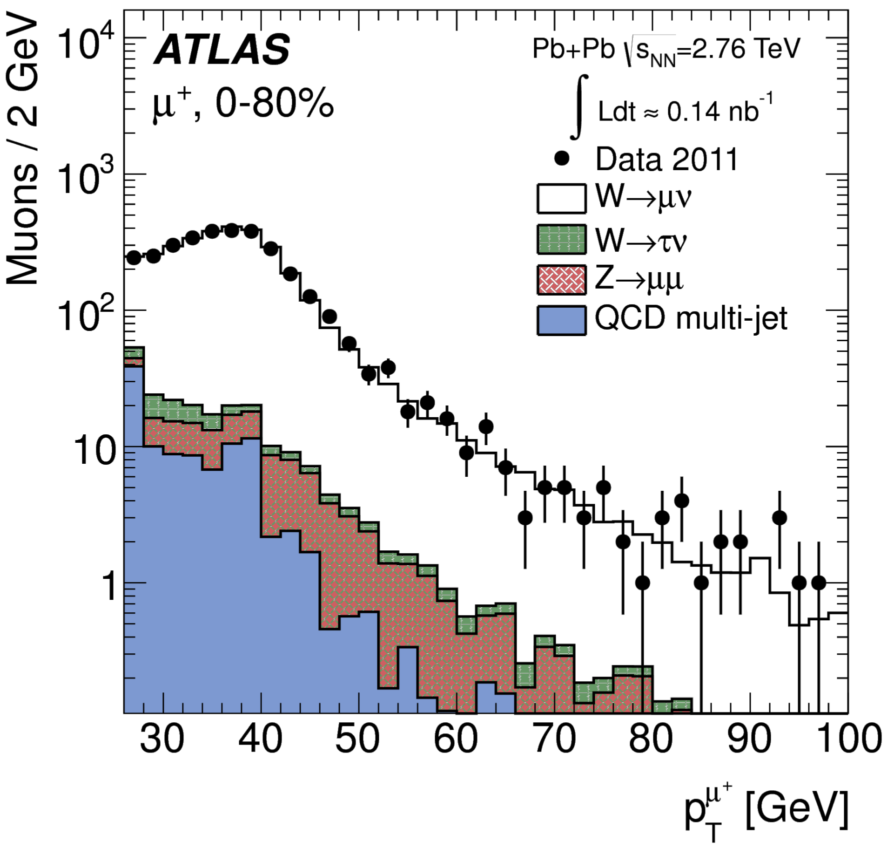
- W bosons in Pb+Pb, Eur. Phys. J. C75 (2015) 23, 1-30
- Z bosons in Pb+Pb, PRL 110 (2013) 022301
- Inclusive photons in Pb+Pb, PRC 93, 034914 (2016)
- γ+jet momentum imbalance in Pb+Pb, ATLAS-CONF-2012-121
- Z+jet momentum imbalance, ATLAS-CONF-2012-119

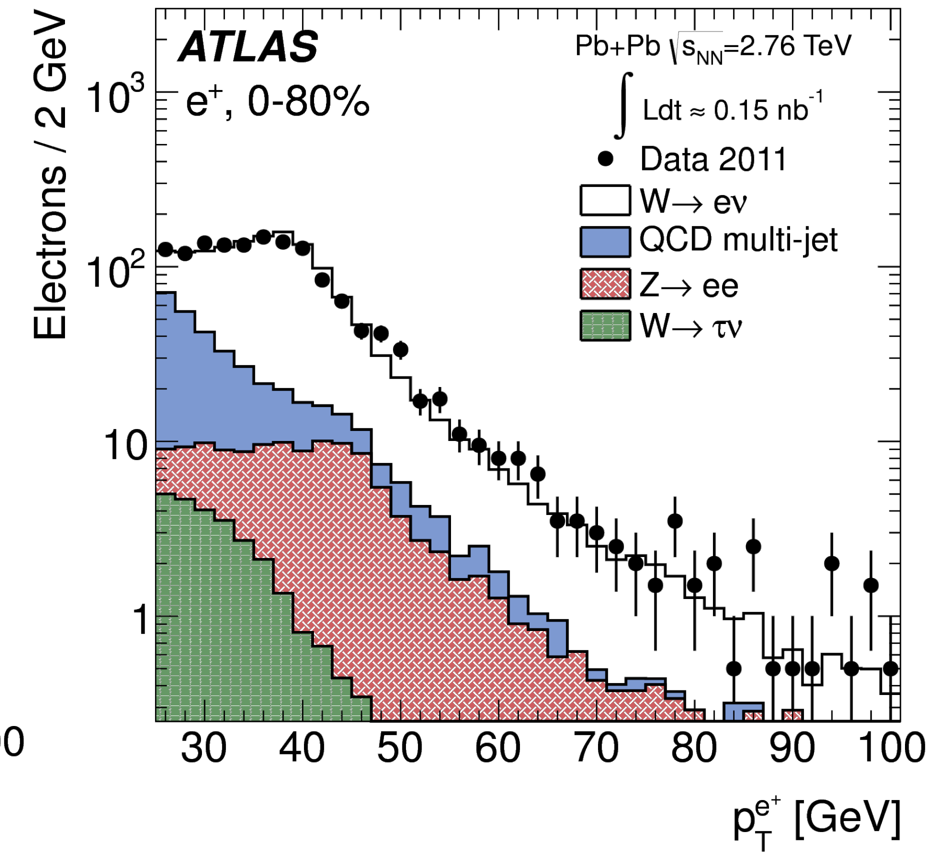
p+Pb collisions:

- Z bosons in p+Pb, PRC 92, 044915 (2015)
- W bosons in p+Pb, ATLAS-CONF-2015-056

# W bosons in lead-lead collisions

[Eur. Phys. J. C75 (2015) 23, 1-30]

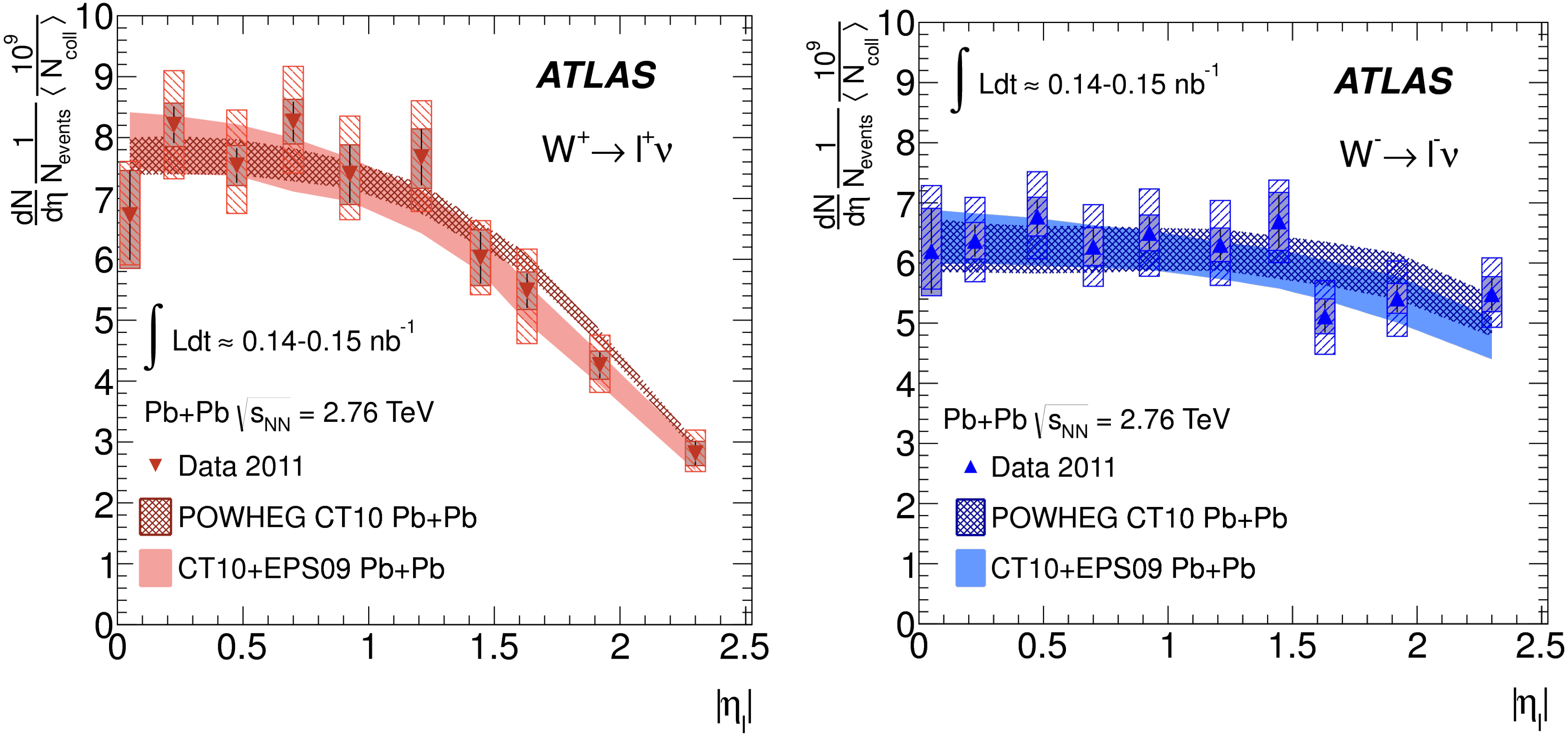



- Combined signal from $e^-/e^+$ and $\mu^+/\mu^-$, measured with different ATLAS systems.
- Isolation cuts.
- Analysis constrained by missing $p_T$ and transverse mass.

# Parton distribution functions: W in lead-lead collisions

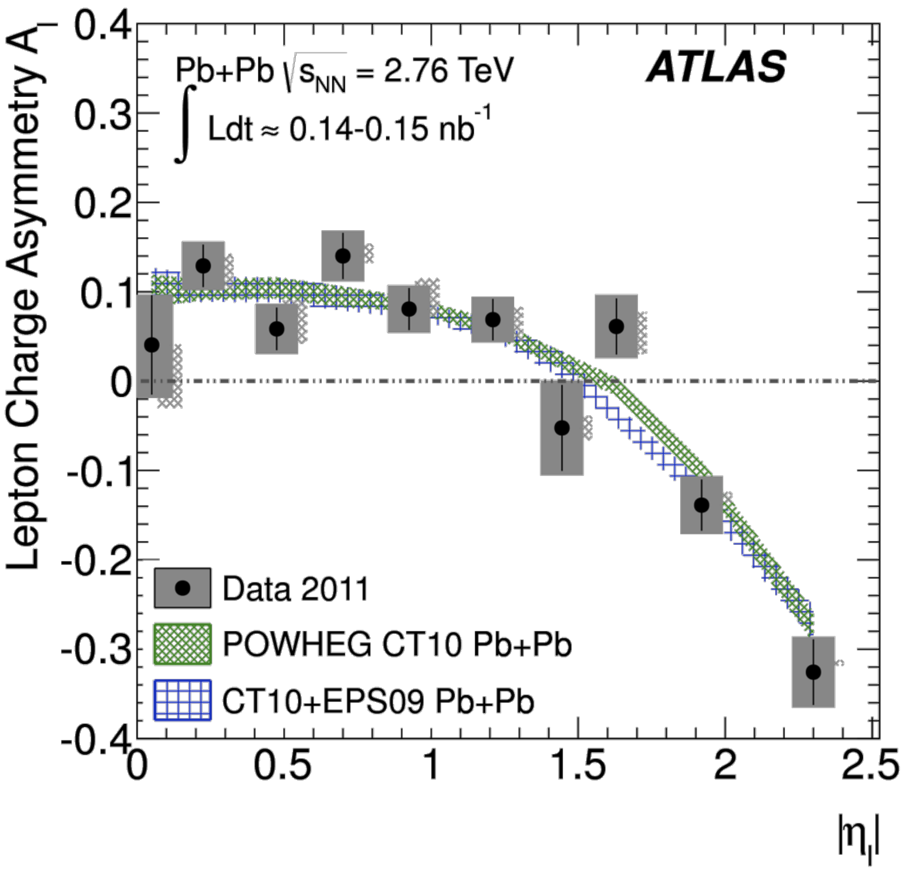
Eur. Phys. J. C75 (2015) 23, 1-30




- POWHEG with CT10 PDF set
- EPS09 corrections: (anti)shadowing, EMC, Fermi [JHEP03:071 (2011)]
- Within the existing uncertainties, no visible PDF modifications

# Lepton Charge Asymmetry: W in lead-lead collisions

[Eur. Phys. J. C75 (2015) 23, 1-30]




The lepton charge asymmetry agrees well with theoretical predictions using QCD at NLO with CT10 PDF sets with and without EPS09 nuclear corrections

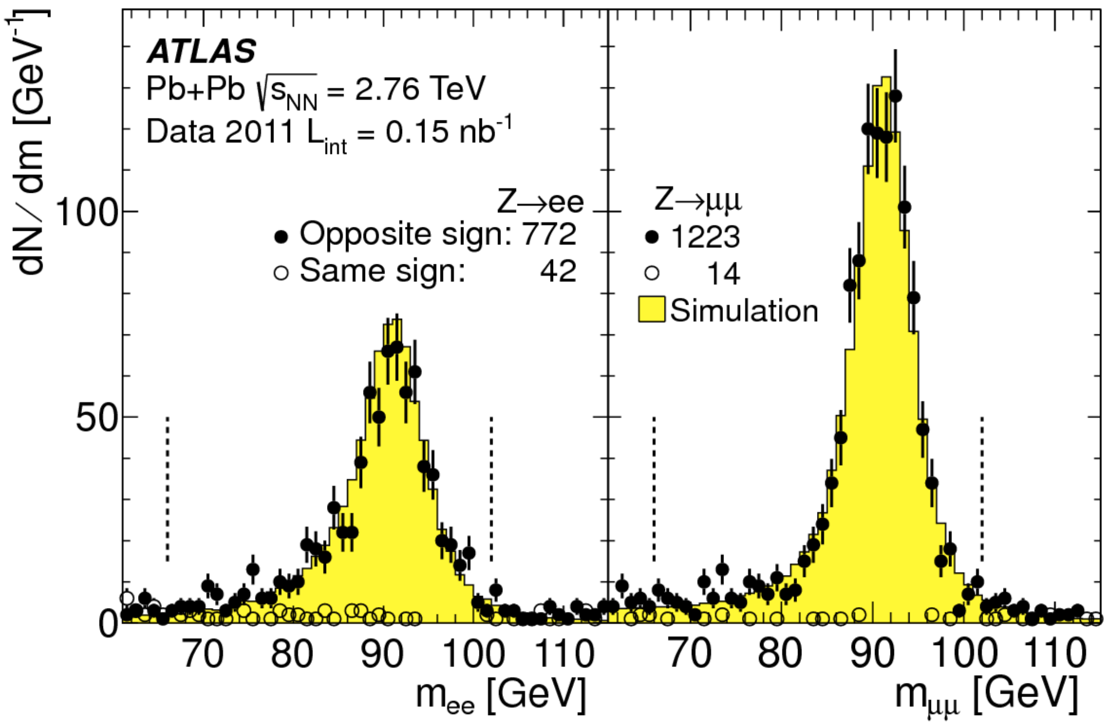
corrected ± stat. ± syst.

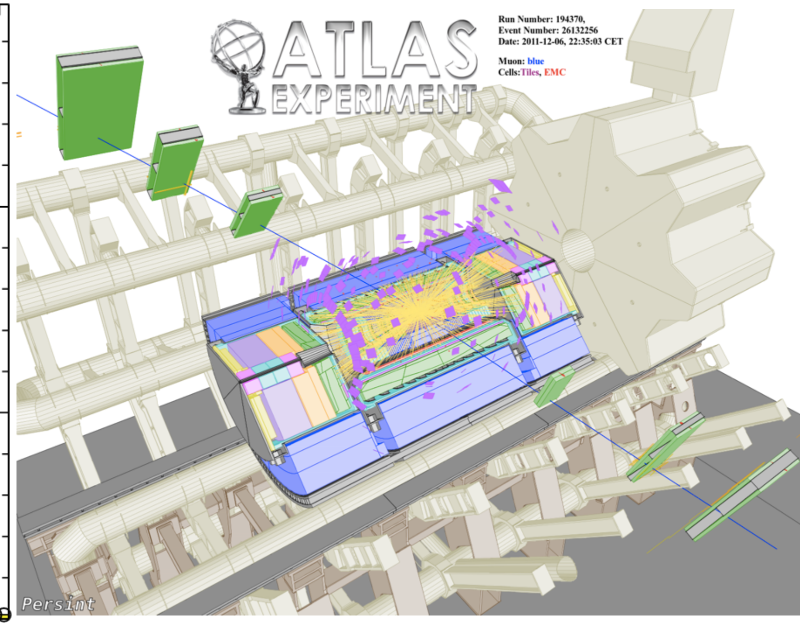
| | $W \longrightarrow \mu\nu_\mu$ | $W \longrightarrow e\nu_e$ |
|---|---|---|
| $W^+ \longrightarrow l^+ \nu$ | 5870 ± 100 ± 90 | 5760 ± 150 ± 90 |
| $W^- \longrightarrow l^- \nu$ | 5680 ± 100 ± 80 | 5650 ± 150 ± 110 |
| $W^+/W^-$ | 1.03 ± .03 ± .02 | 1.02 ± .04 ± .01 |

μ and e give consistent results

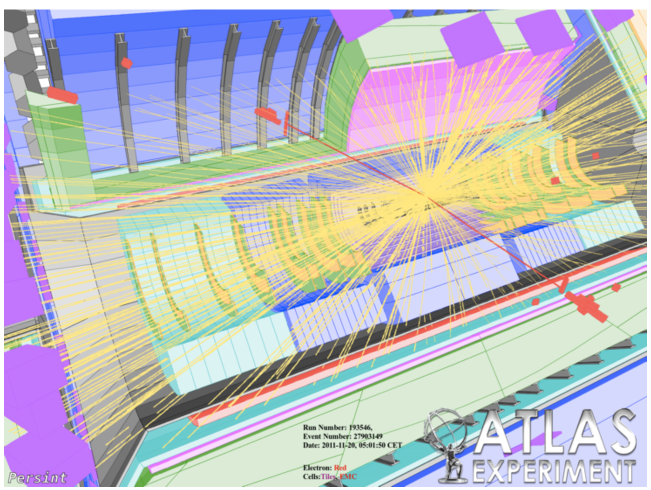
The basic asymmetry pattern in pp is understood based on the nature of the interaction.

# Z boson in lead-lead collisions




PRL 110 (2013) 022301

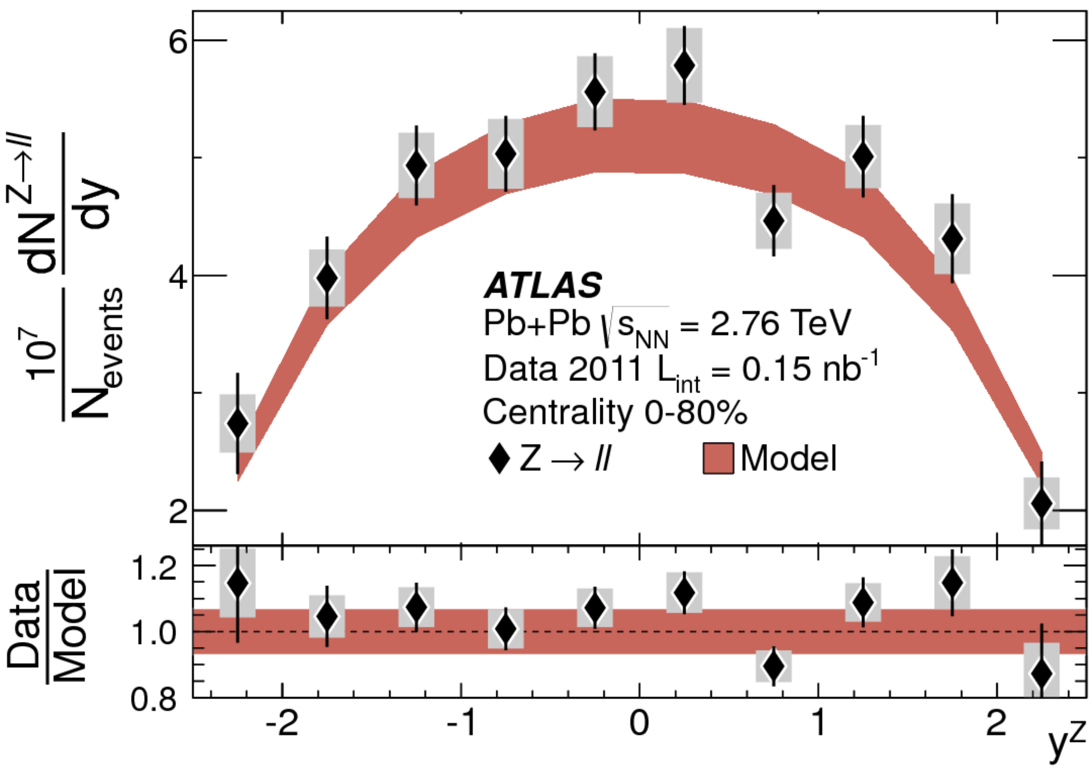


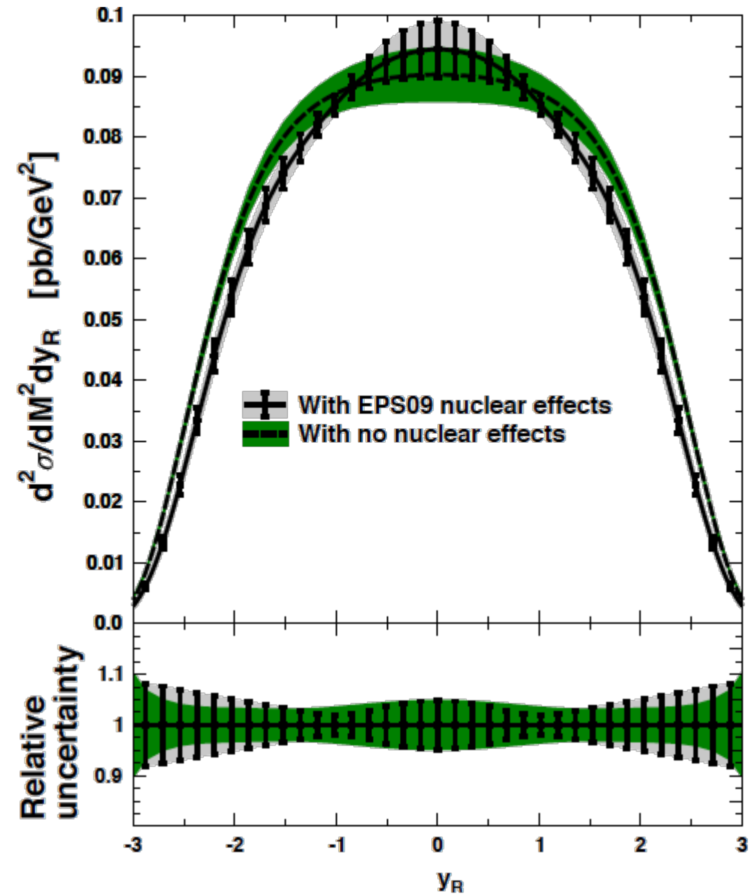

Combined signal from e⁻/e⁺ and μ⁺/μ⁻, measured with different ATLAS systems.

Lineshape, distributions well reproduced in simulation.

# Parton distribution functions: Z in lead-lead collisions

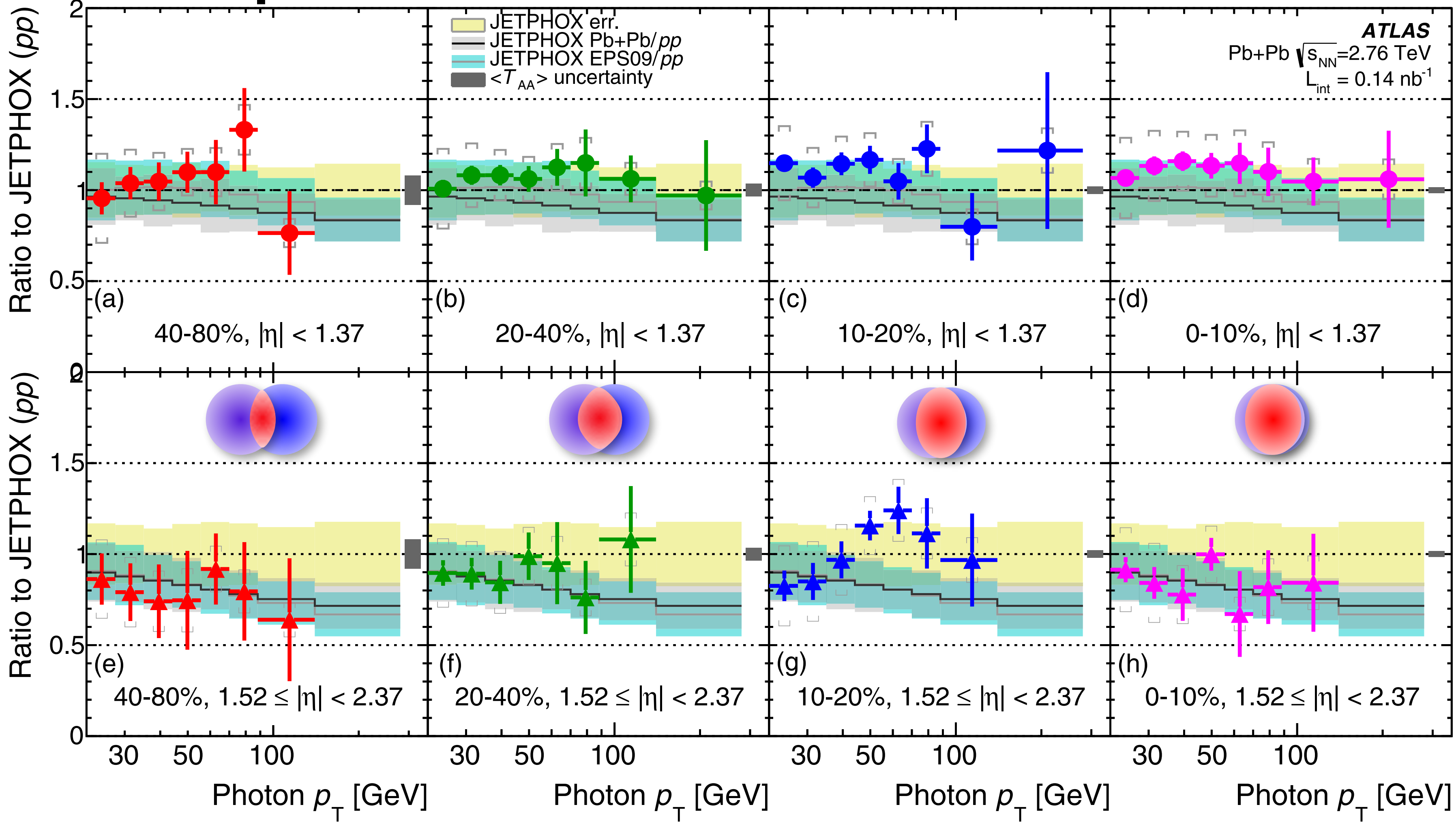
PRL 110 (2013) 022301 H. Paukkunen, C. Salgado JHEP03:071 (2011)




Model: PYTHIA per-event yields using NNLO p+p calculations scaled by $\langle T_{AA}\rangle = \langle N_{Coll}\rangle/\sigma_{pp}$. Including p+n and n+n would increase the cross section by 3%.

# Parton distribution functions: direct photons in lead-lead collisions

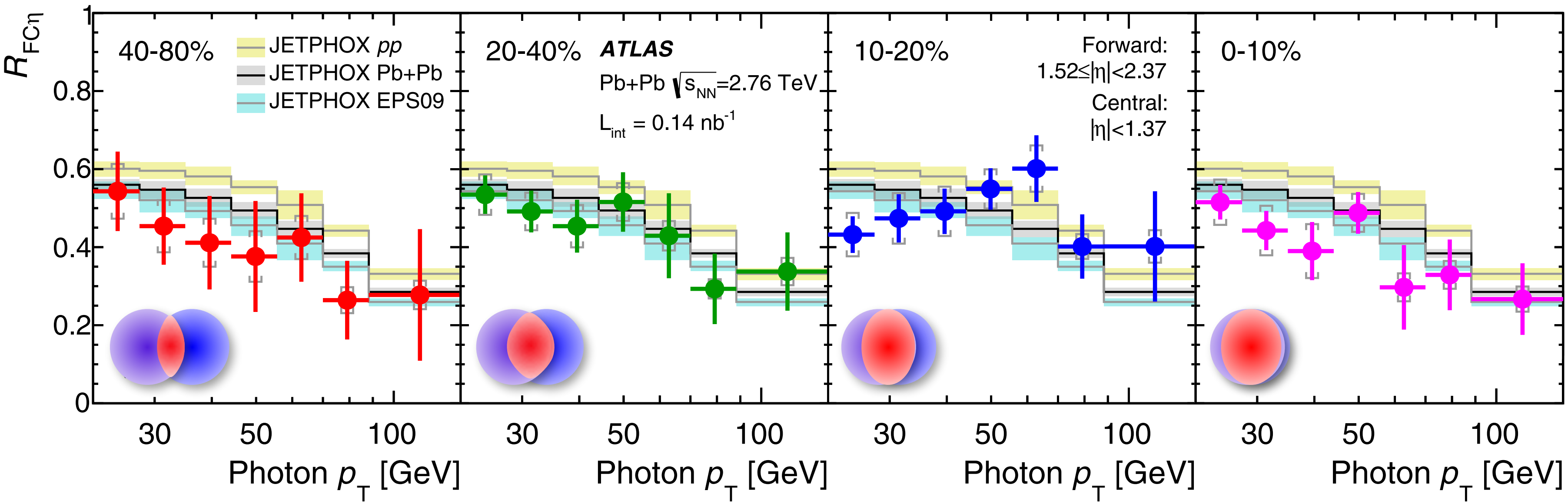



JETPHOX (NLO pQCD), CTEQ 6.6 pdfs, u/d quark reweighting
JETPHOX + EPS09 [JHEP 0904 (2009)] PRC 93, 034914 (2016)

# Forward-central ratio
# Direct photons in lead-lead collisions

$$\frac{1.52<|\eta|<2.37}{|\eta|<1.37}$$

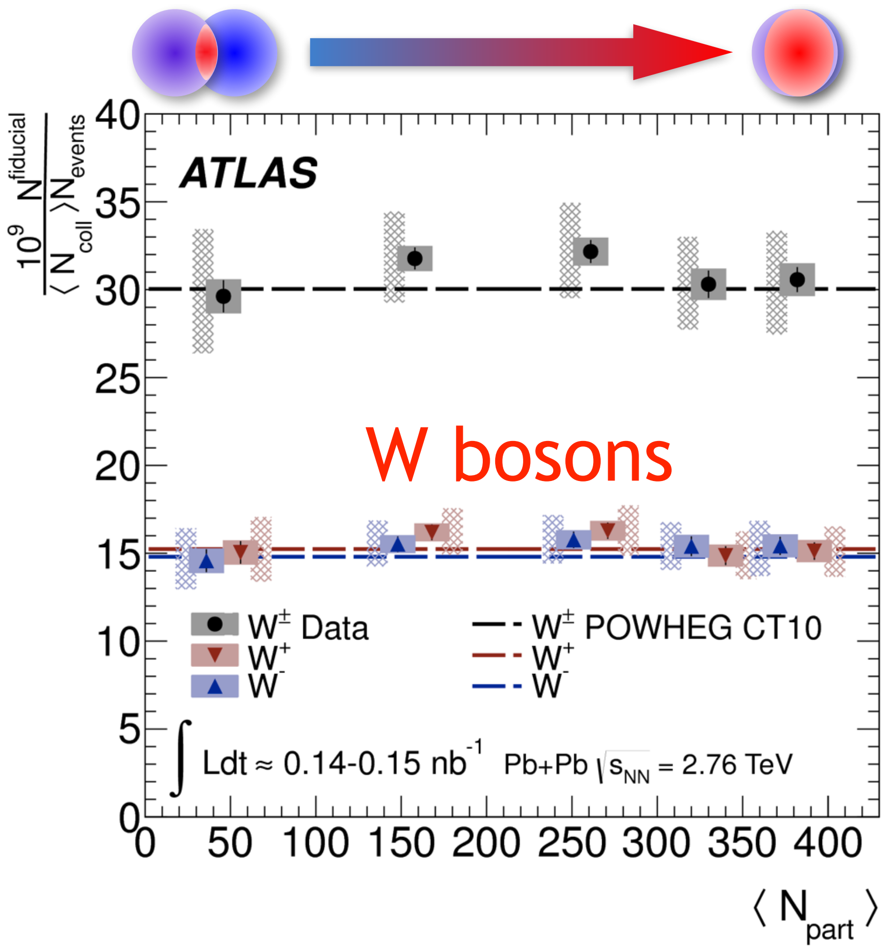
PRC 93, 034914 (2016)

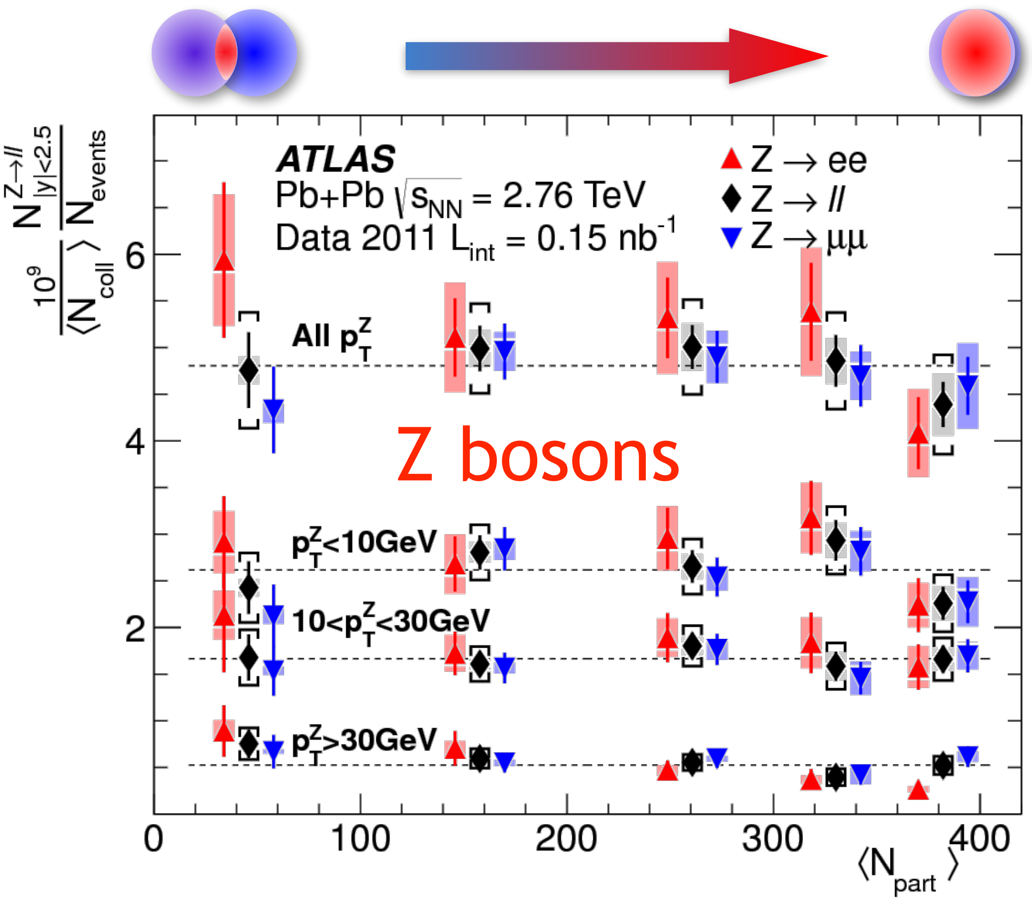



Reduction of several experimental uncertainties in this ratio.
Isospin effects visible, particularly for central events.

# $<N_{Coll}>$ scaling in lead-lead collisions

[Eur. Phys. J. C75 (2015) 23, 1-30] [PRL 110 (2013) 022301]

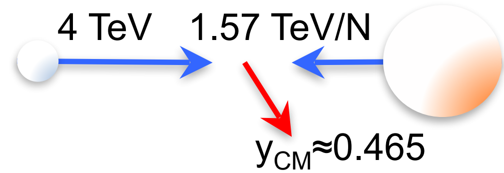


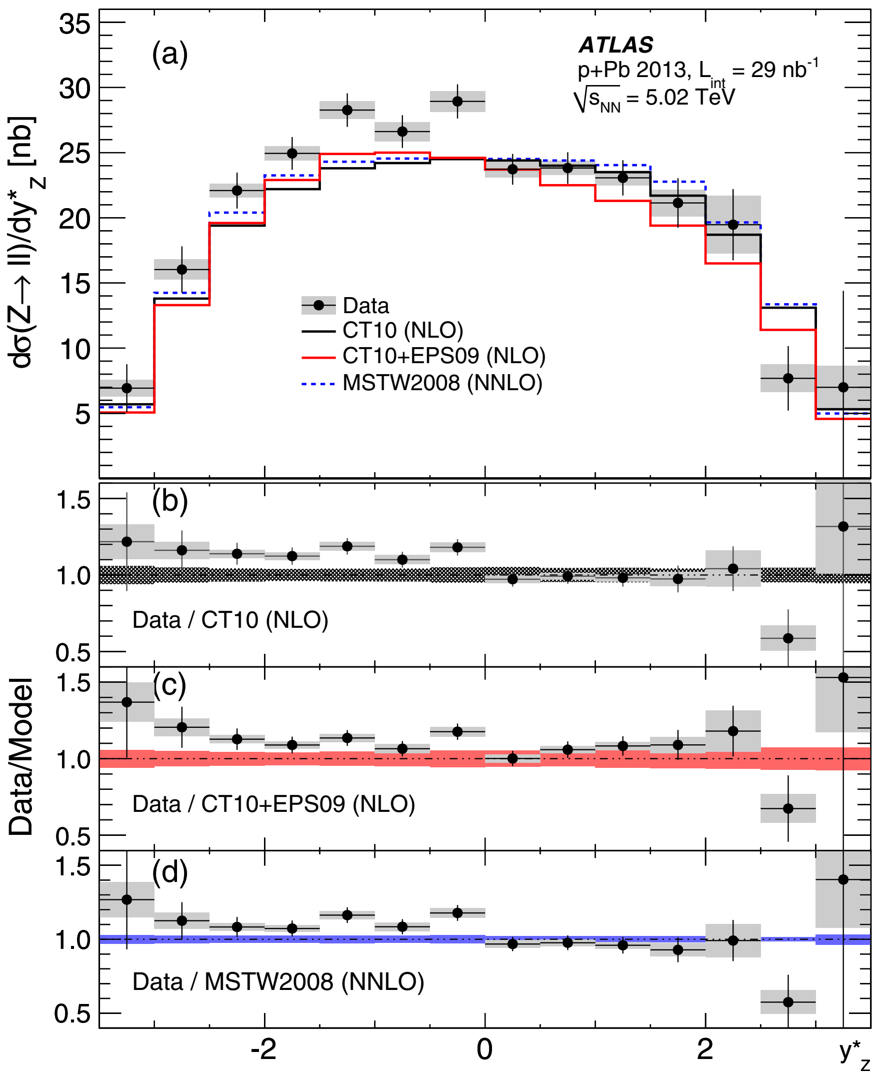

Boson yields in PbPb scale with $<N_{coll}>$

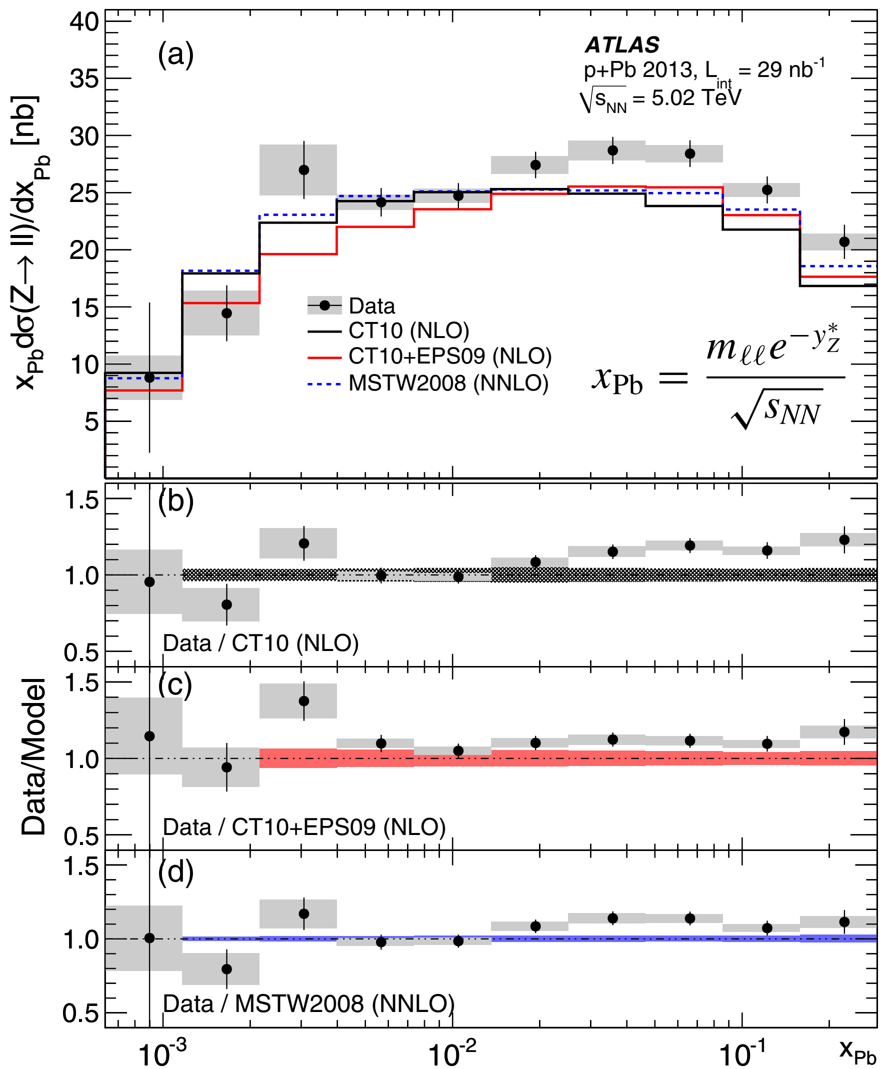
Direct photons show similarly consistent behavior.

# Z boson in p+Pb collisions




PRC 92, 044915 (2015)

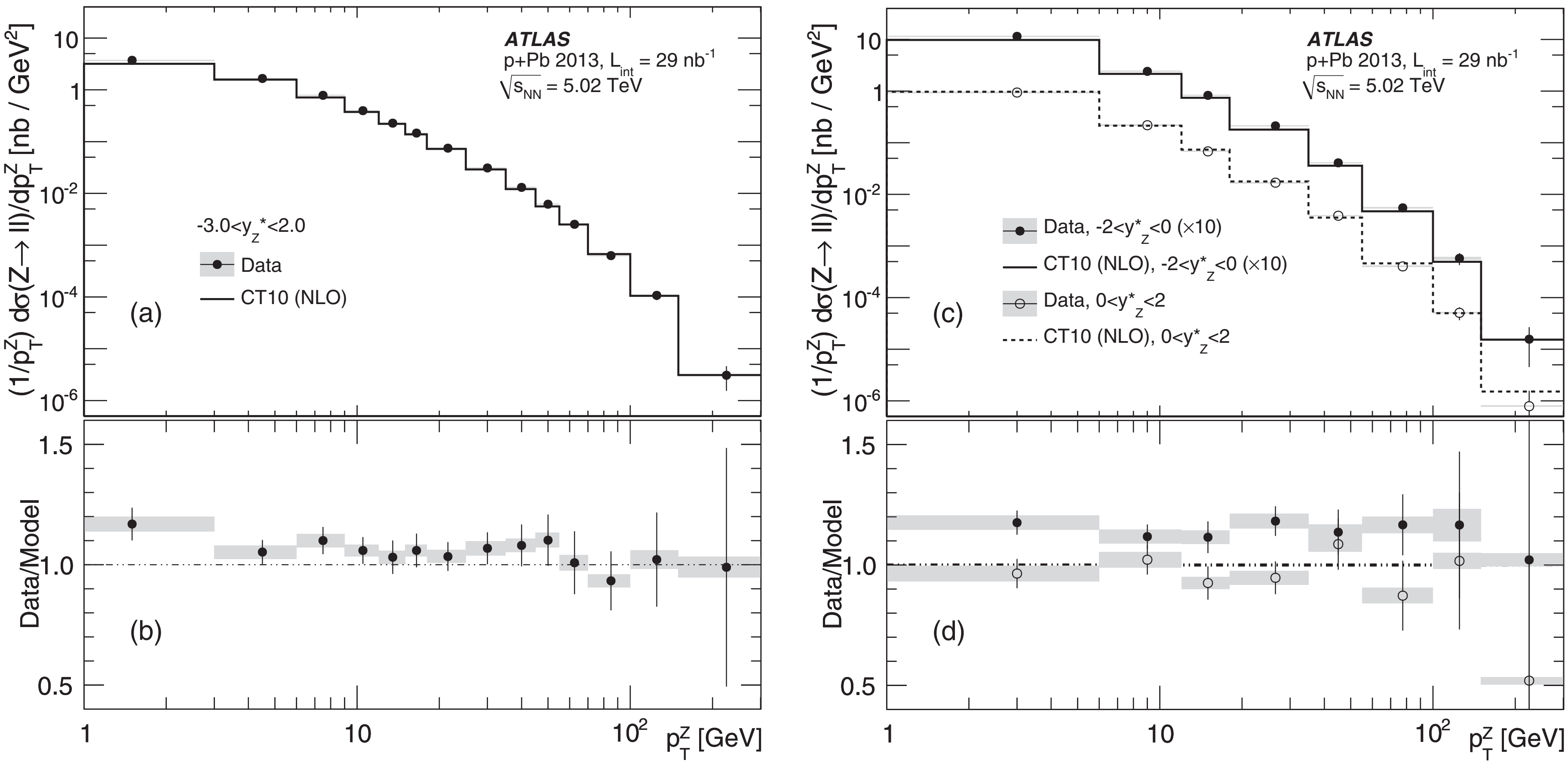



**Some tension between current model descriptions and data**

# Z boson in p+Pb collisions - $p_T$ dependence

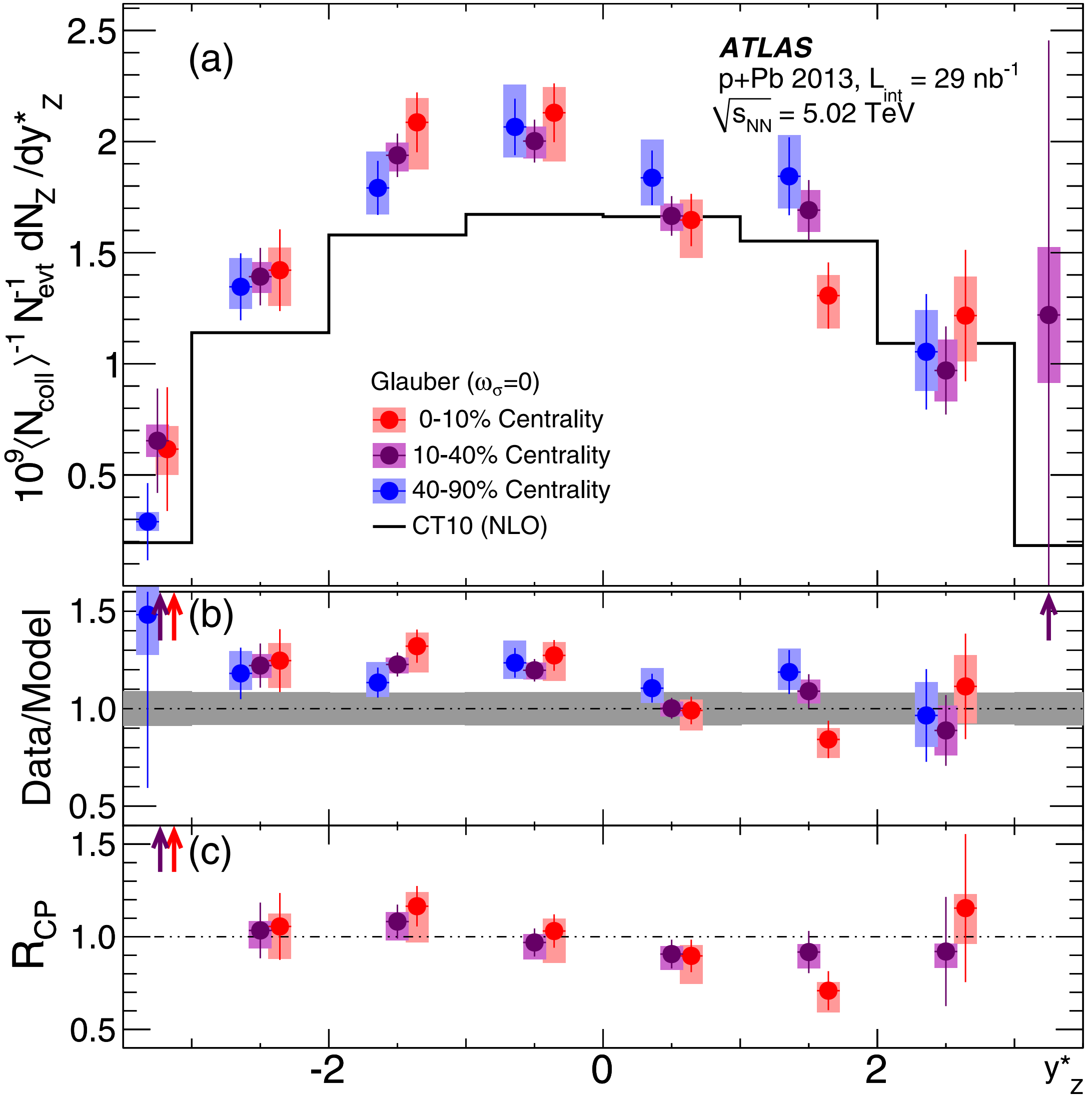
PRC 92, 044915 (2015)




Reasonable agreement between the experimental measurement and the MC simulation shape.

# Z boson in p+Pb collisions - rapidity

PRC 92, 044915 (2015)

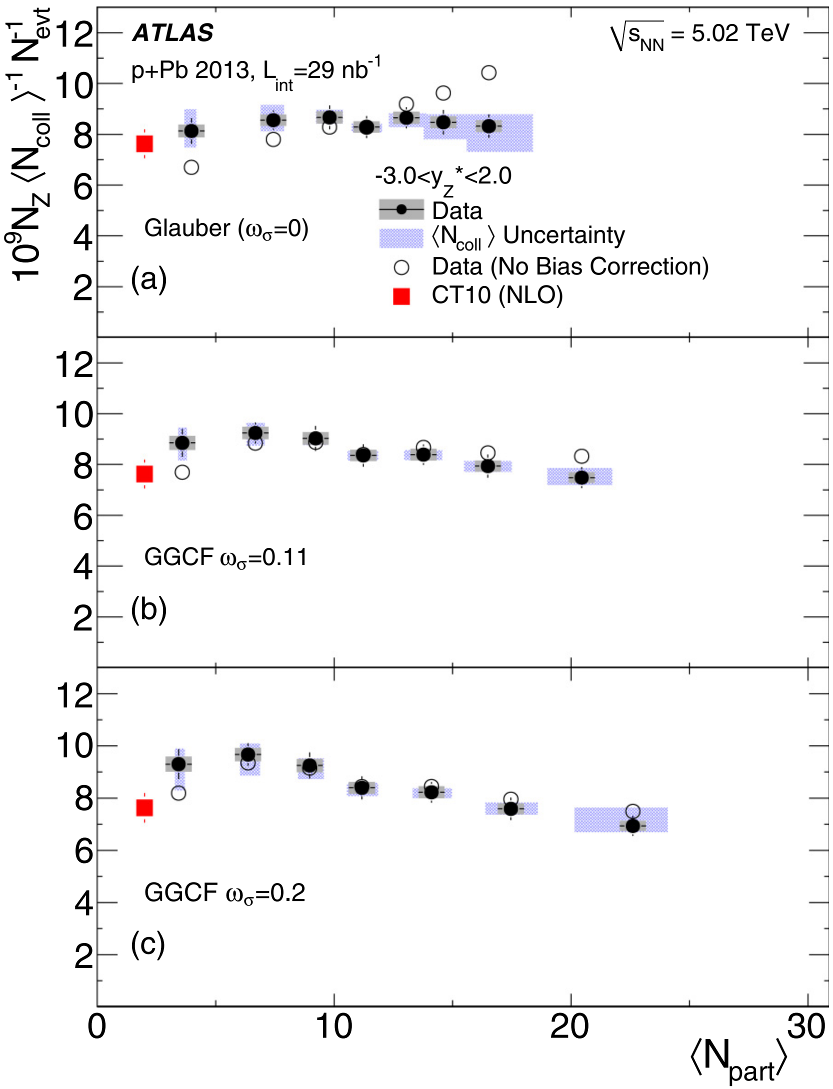


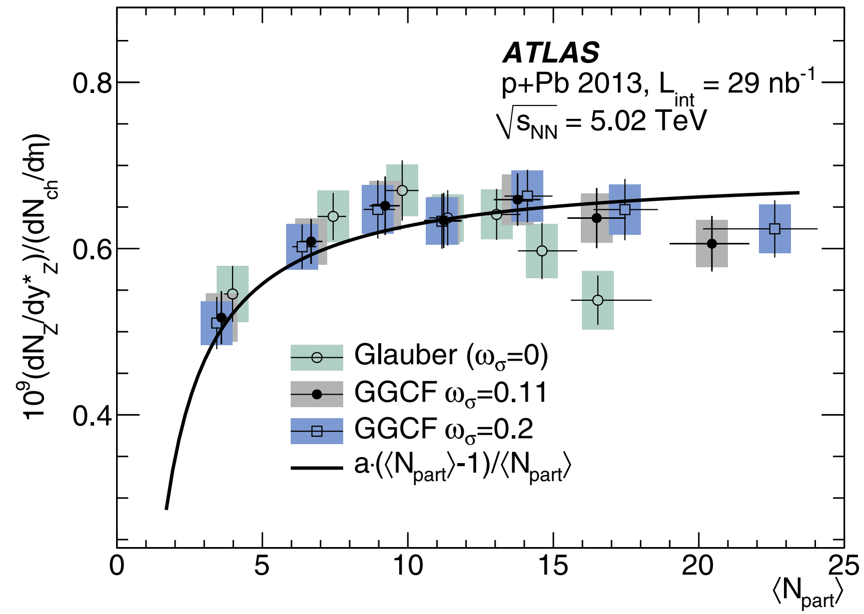

Per-event yield is generally independent of centrality after all corrections

Systematic shape difference in lead-going direction relative to CT10 (NLO)

# Z boson in p+Pb collisions - centrality

[PRC 92, 044915 (2015)](#)

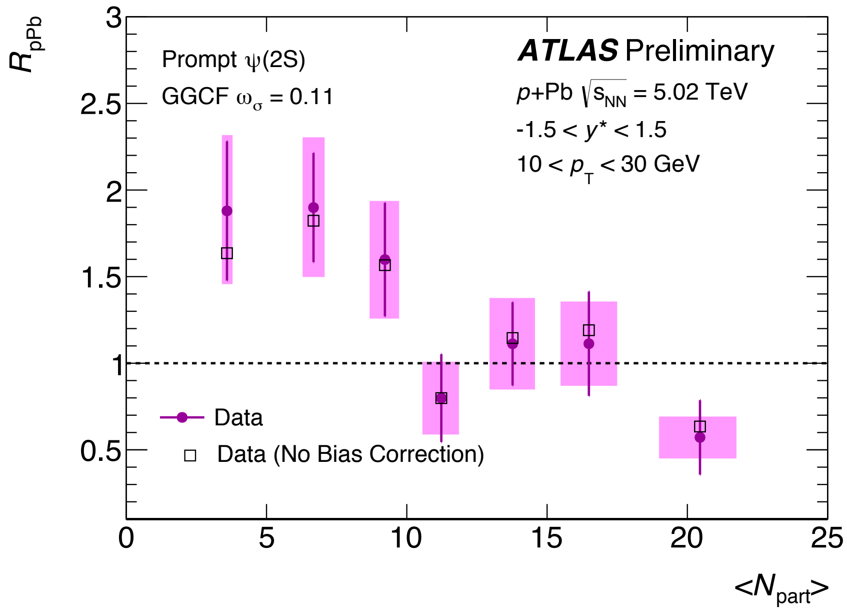



Reasonable consistency with binary scaling, after bias correction, for three models.

Fairly good consistency with charged particle multiplicity

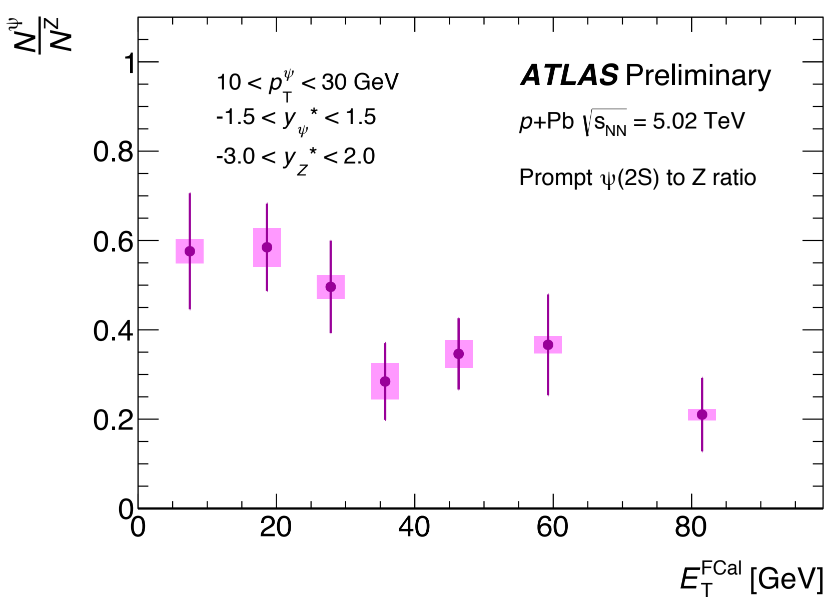
# $\psi$(2S) normalized to Z and J/$\psi$

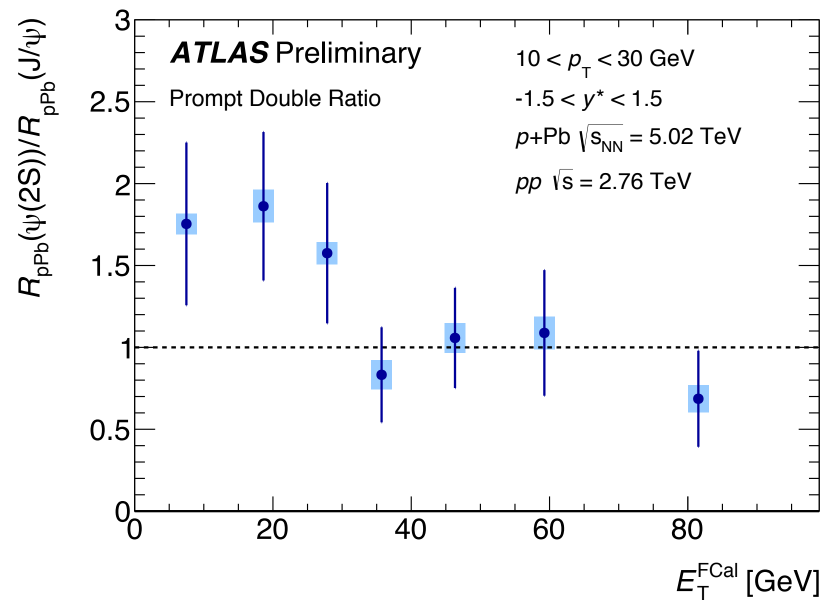



- Enhancement at low centrality seen in $R_{pPb}$
- Same pattern obtained if normalized to Z and J/$\psi$!

See Qipeng Hu talk Monday morning

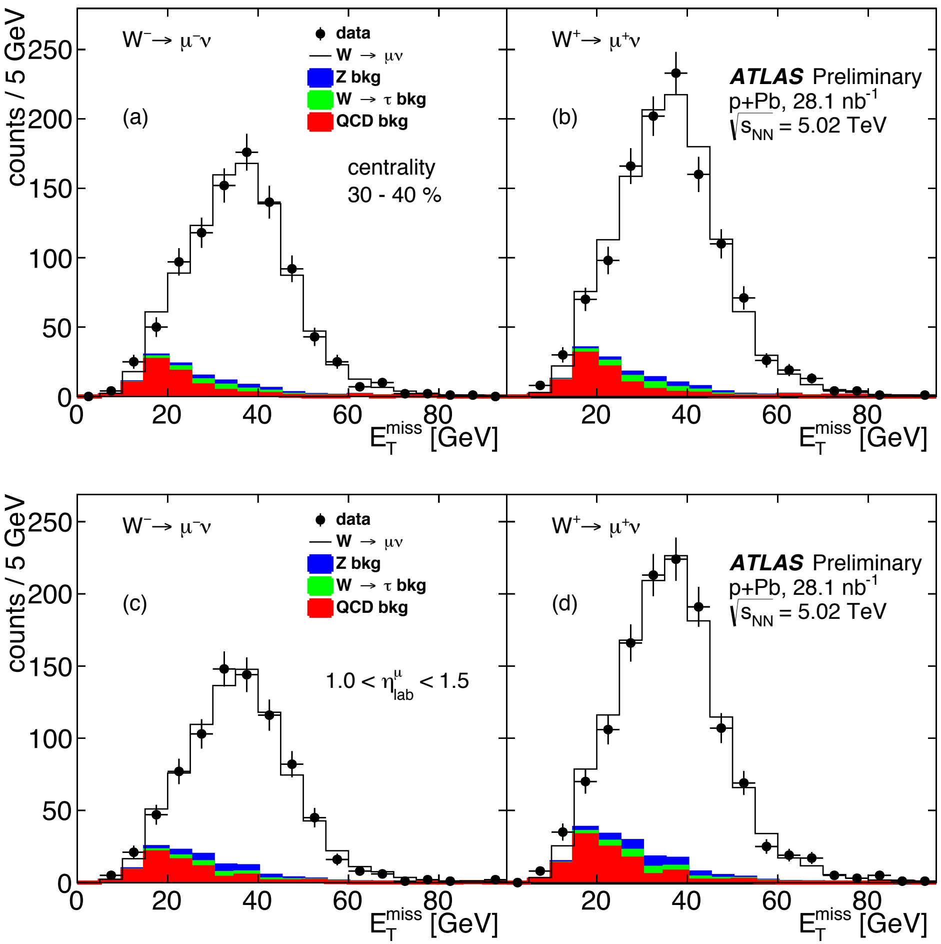
ATLAS-CONF-2015-023

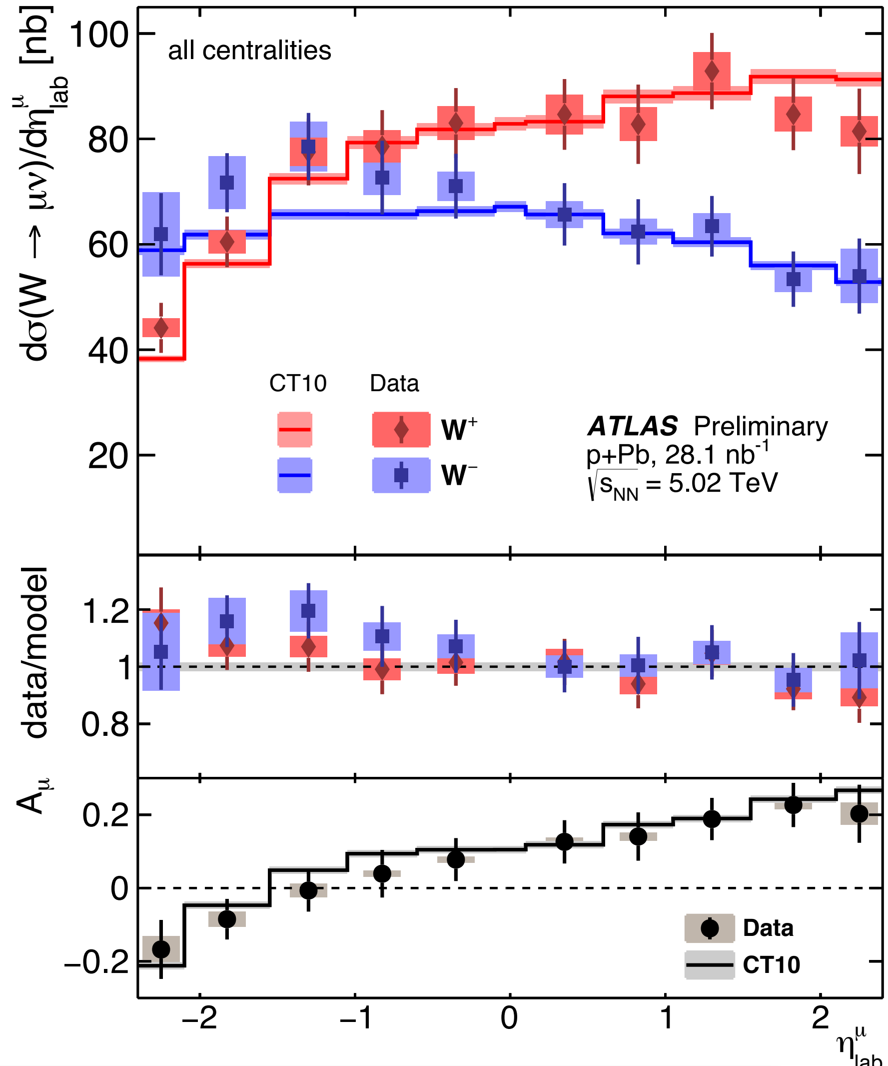


# W in p+Pb

ATLAS-CONF-2015-56

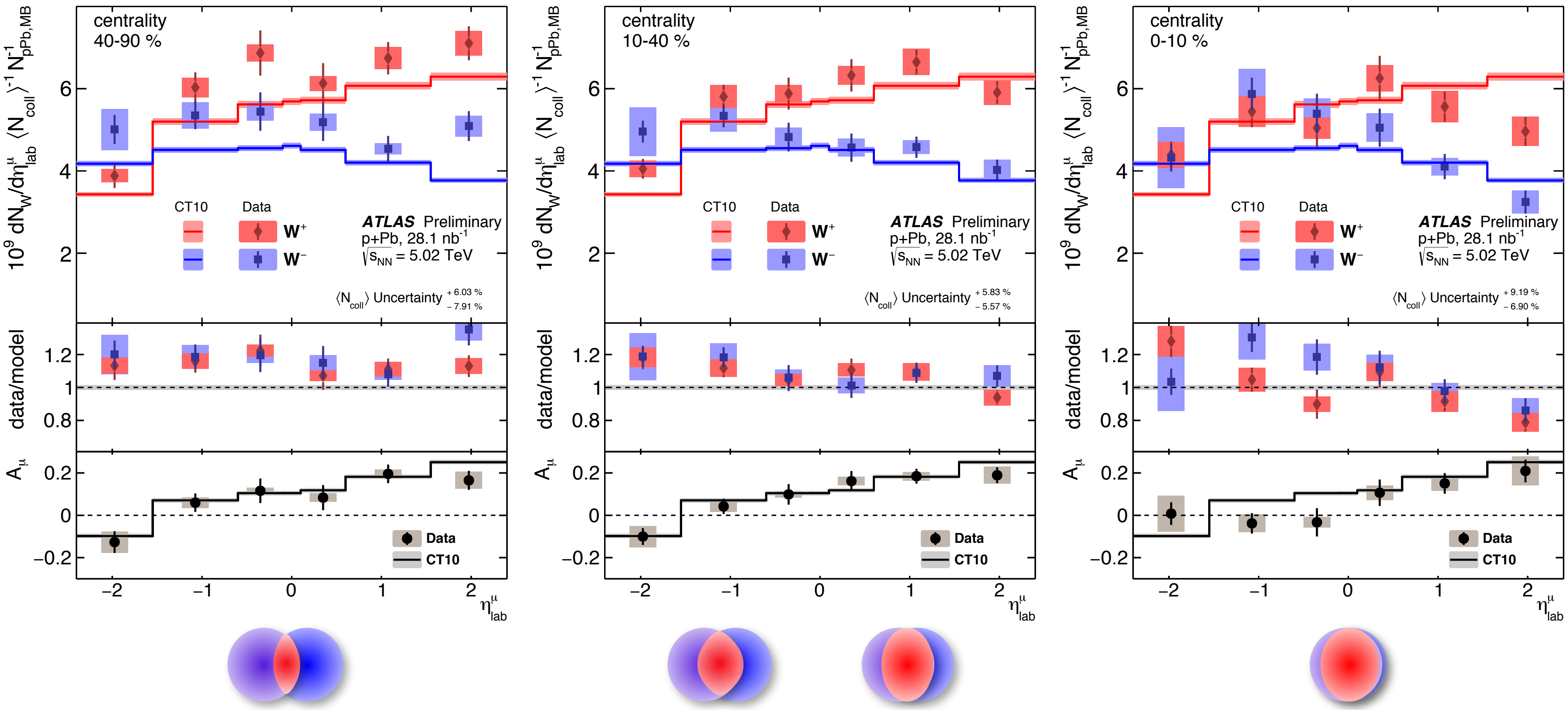



Very little background!
Fairly good agreement with CT10, centrality integrated

# W in p+Pb: Dependence on $\eta$

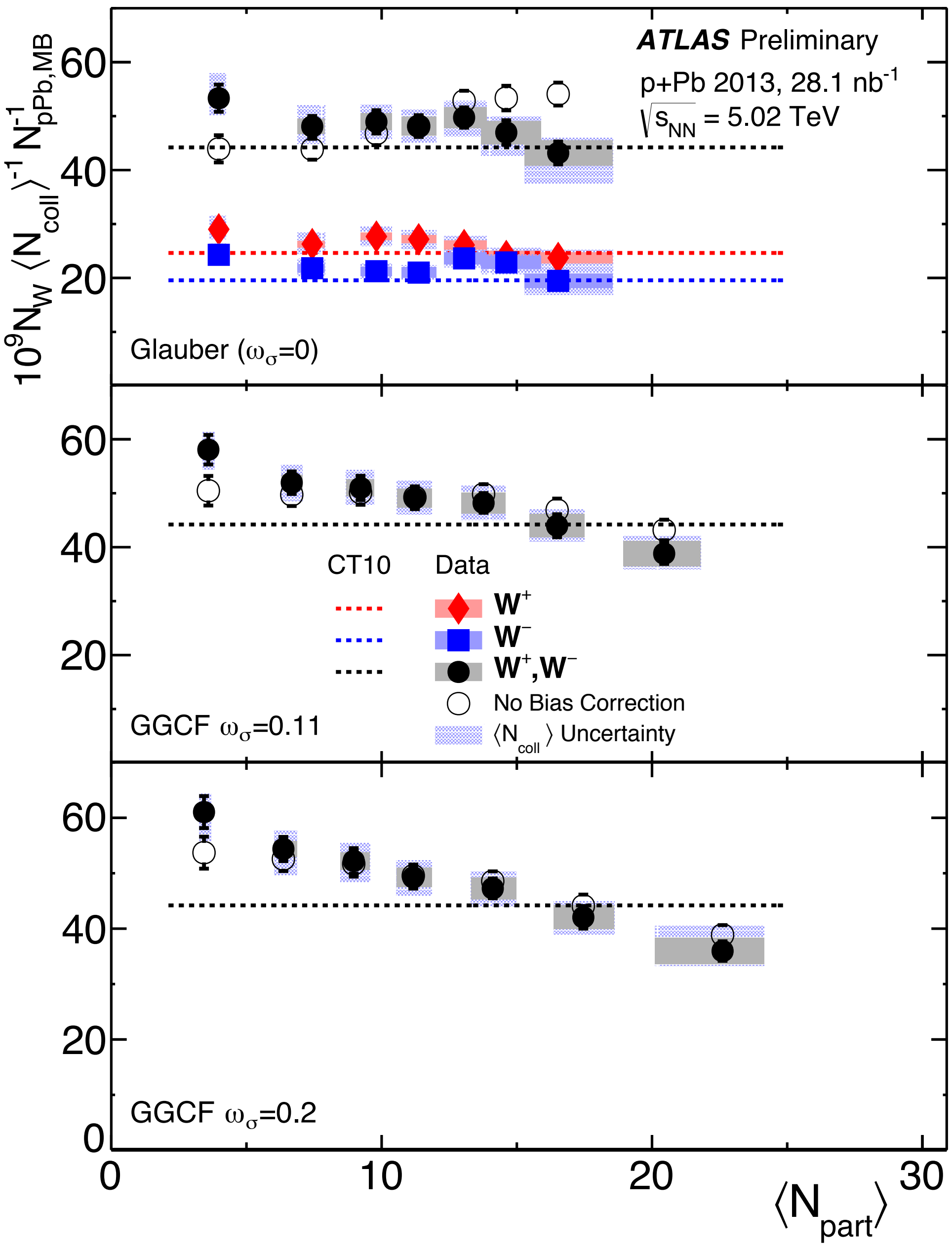
ATLAS-CONF-2015-56




Basic agreement with CT10, less so for peripheral

# W in p+Pb: Centrality

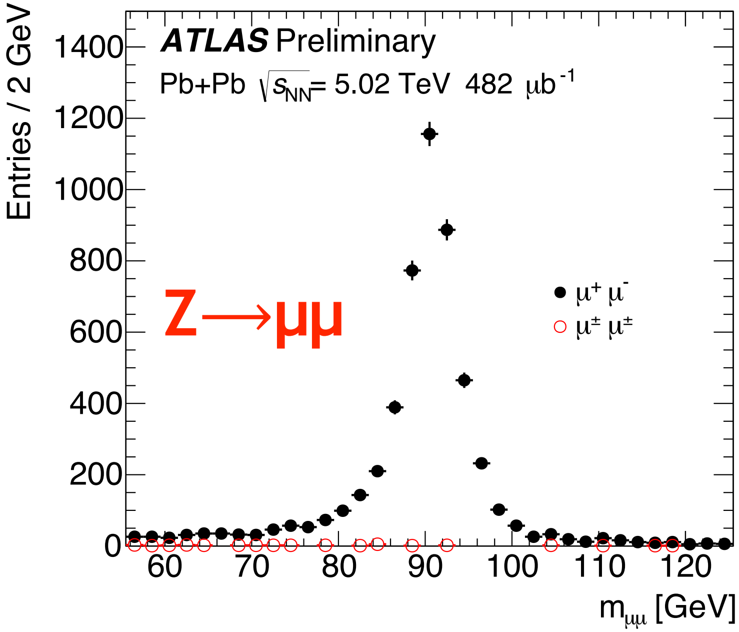
ATLAS-CONF-2015-56

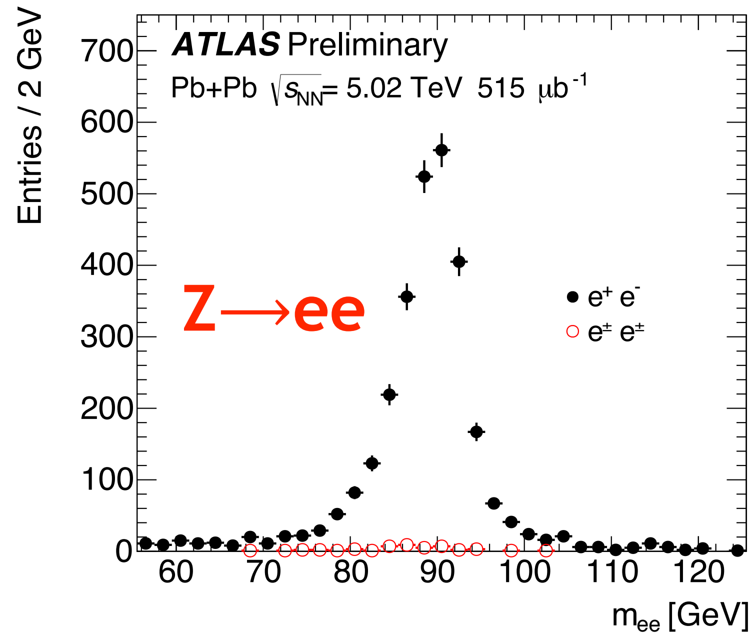


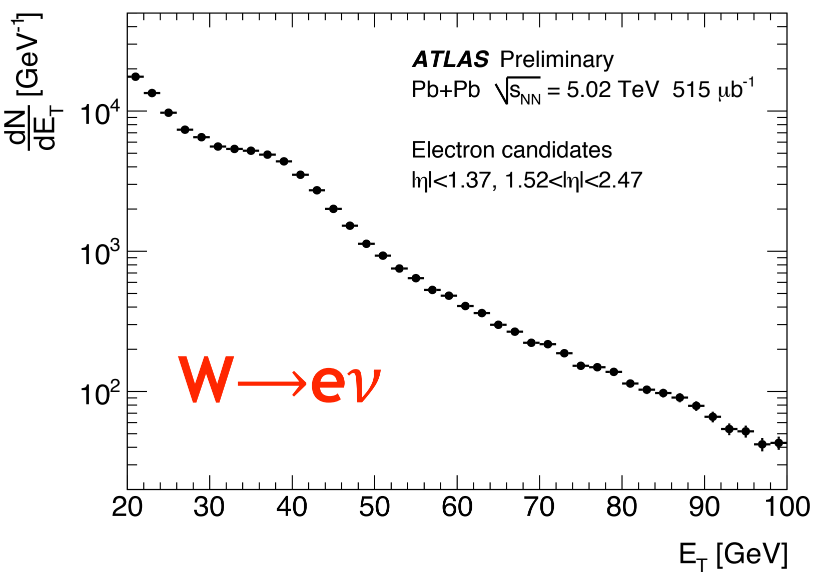

Best model description is given by Glauber + centrality bias correction, assuming binary scaling

ATLAS-CONF-2015-023

# 5 TeV Pb+Pb data preview



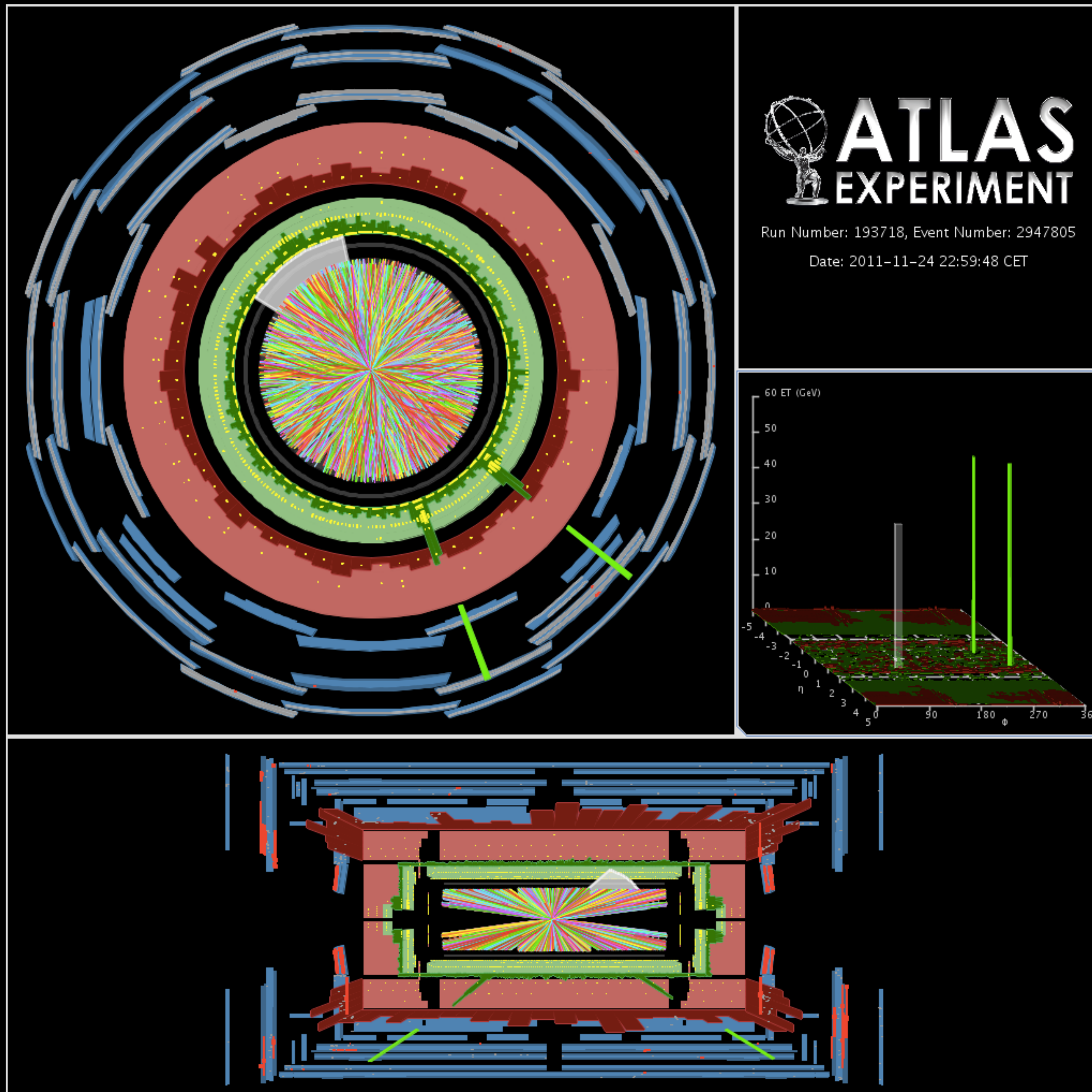




Anticipation of much better precision for 5 TeV Pb+Pb EW bosons!

# Conclusions

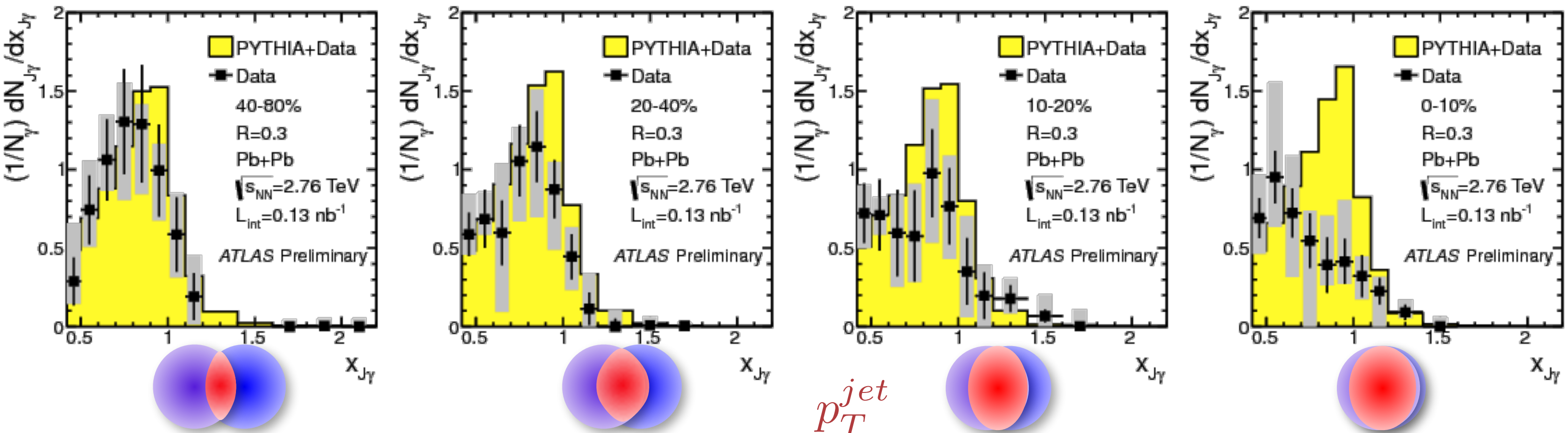
- ATLAS measurements clearly support binary scaling in Pb +Pb collisions.
- Binary scaling is also supported in p+Pb collisions, but with some questions remaining
- Several hints of nuclear effects in p+Pb collisions, especially in Pb-going direction, perhaps beyond EPS09
- New use of Z yield to validate centrality estimations
- With LHC Run 2 Pb+Pb data, we will approach measurement precision for quantitative tests of nuclear models with photons and with Z-bosons

# Boson - Jet Correlations



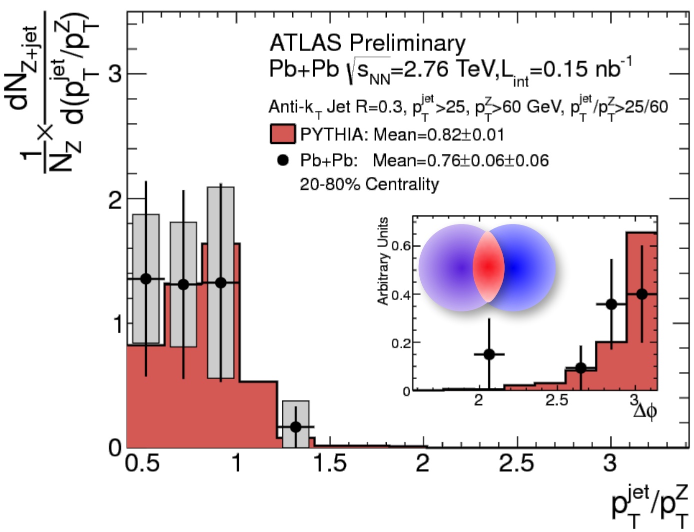
# Boson-jet correlations in Pb+Pb collisions

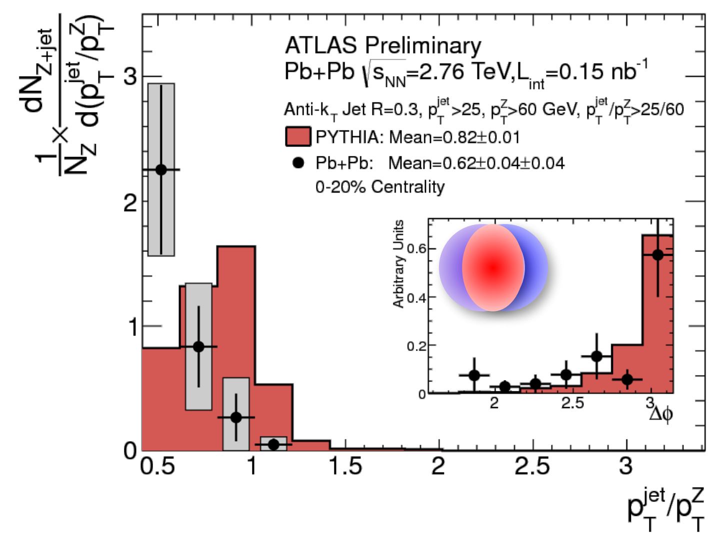
ATLAS-CONF-2012-121




$\gamma$-jet

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



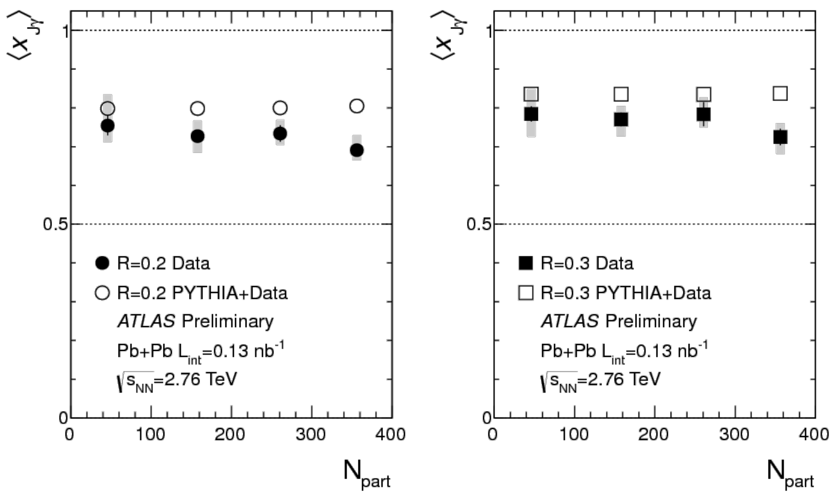

Z-jet

Clear centrality dependence measured with direct photons.
Proof of principle using Z-jet events (36 events).

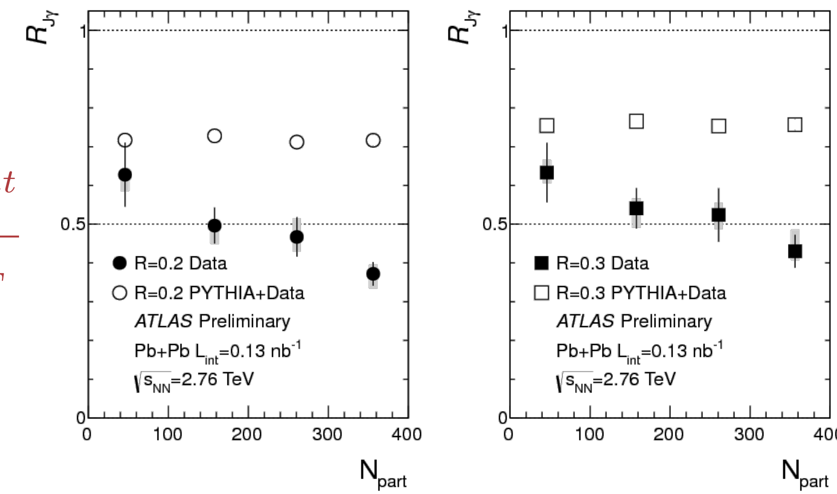
ATLAS-CONF-2012-119

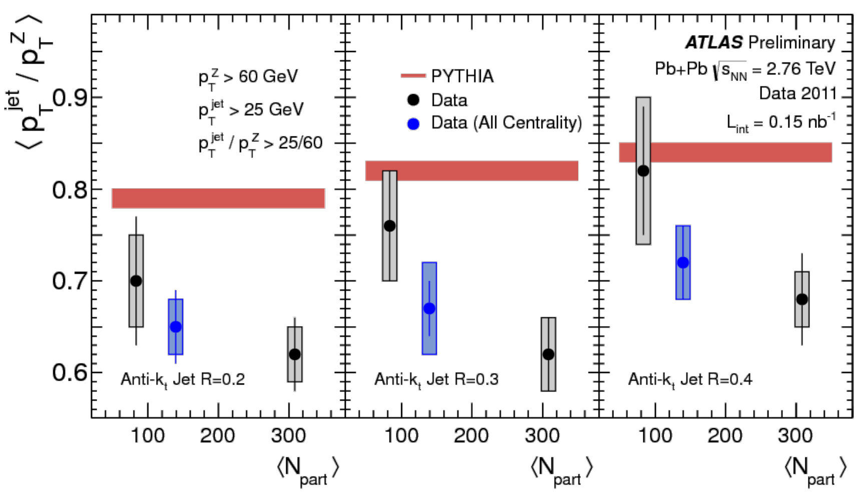
# Boson-jet correlations in Pb+Pb collisions

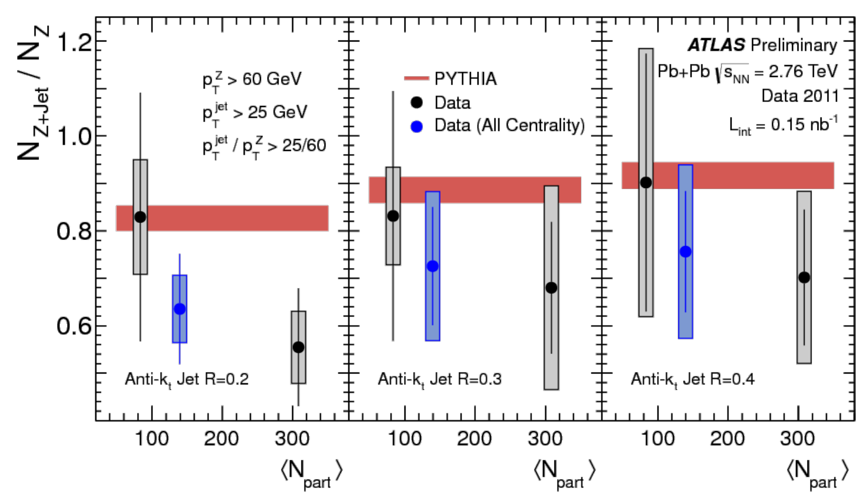
ATLAS-CONF-2012-121




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

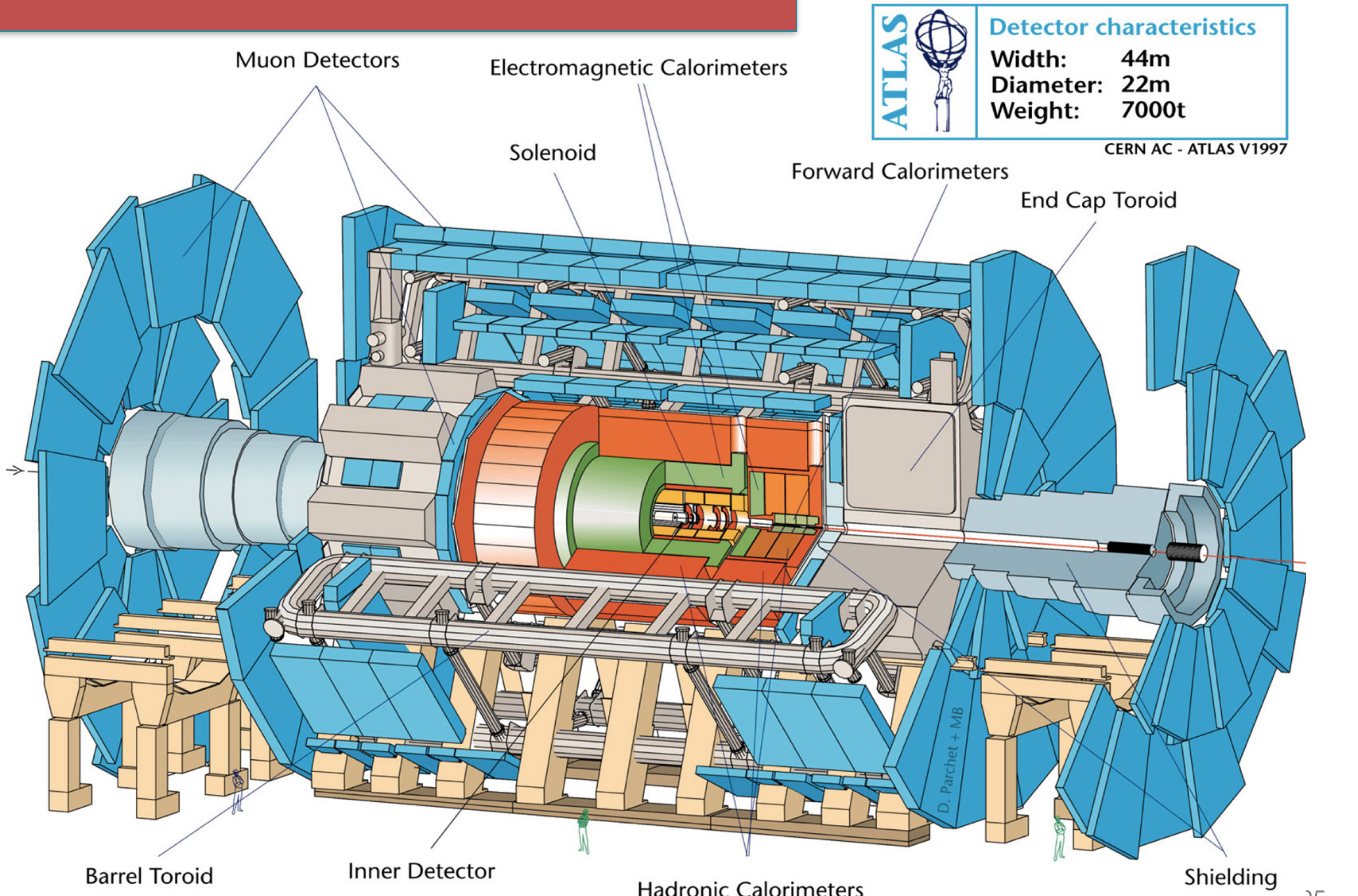


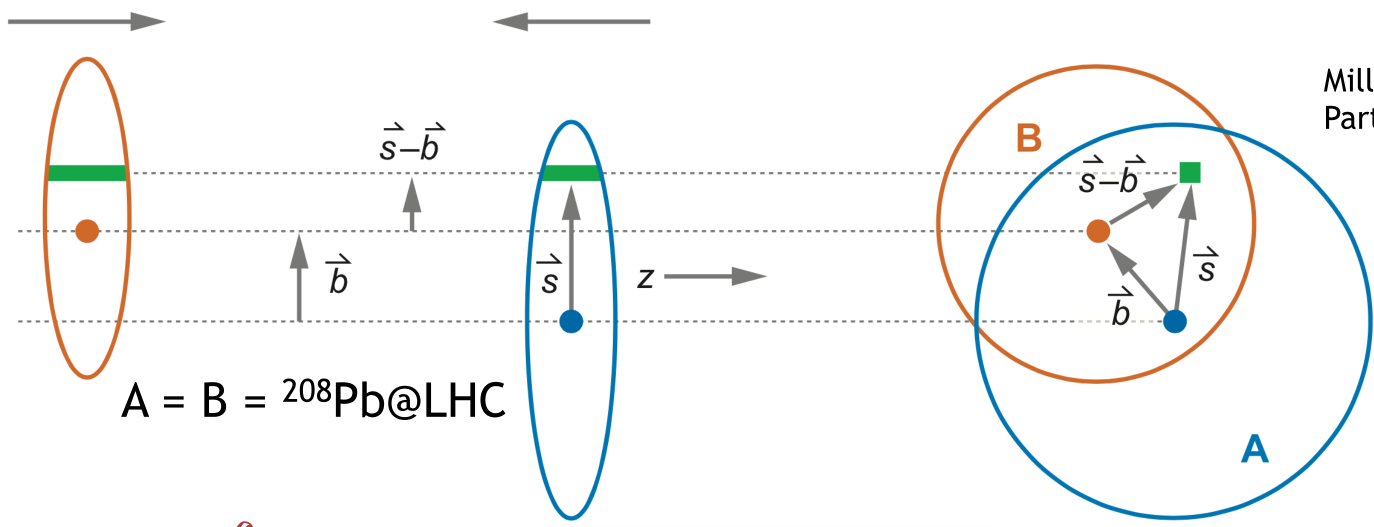




The momentum balance and the production rates change with centrality for direct photons; similar indication with Z – jet correlation.

# ATLAS at the CERN LHC



# Reminder: geometric considerations




Miller et al., Annu. Rev. Nucl. Part. Sci. 2007. 57:205-43

$$T_A(\mathbf{s}) = \int \rho_A(\mathbf{s}, z_A) dz_A$$

probability/area of nucleon at **s**

$$T_{AA}(\mathbf{b}) = \int T_A(\mathbf{s}) T_A(\mathbf{s}-\mathbf{b}) d^2 s$$

Density overlap as a function of impact parameter **b**

$$N_{Coll}(b) \sim T_{AA}(b) \cdot \sigma_{inel}^{NN}$$

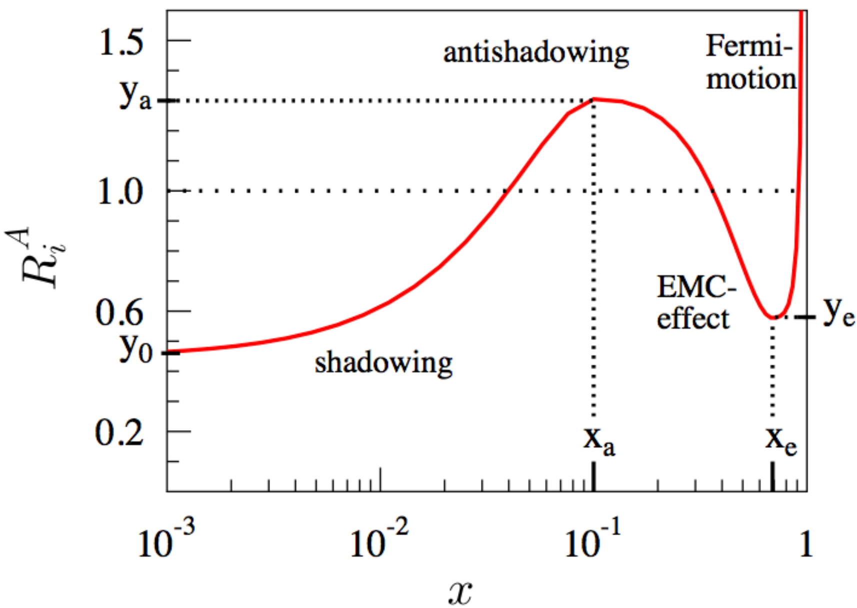
Number of binary collisions as a function of impact parameter **b**

$N_{Coll}$ can be estimated from experimental data via the "Glauber model"
Number of participants in the collision, $N_{Part}$, ranges from 2 to 416.

# Potential partonic in-medium effects

- Gluon saturation
- Gluon shadowing
- Partonic energy loss
- Modified parton distributions and fragmentation functions

Example reference: "EPS09" - Eskola, Paukkunen, Salgado(JHEP0904:065,2009)
- medium-modified PDFs
- NLO, constrained by DIS on nuclei, Drell-Yan in p+A, and inclusive pion production in d+Au and p+p




Their fits constrain nuclear modifications $R_i$ for parton flavor *i* to the free proton PDF from the CTEQ6.1M set.

$$f_i^A(x,Q^2) \equiv R_i^A(x,Q^2) f_i^{\mathrm{CTEQ6.1M}}(x,Q^2)$$

# Kinematic requirements

**Direct photons**

- $22<p_T<280$ GeV
- $|\eta|<1.37$ (central) and $1.52<|\eta|<2.37$ (forward)

**Z bosons**

- $|\eta_Z|<2.5$ and $66<m_Z<116$ GeV

**W bosons**

- lepton $p_T>25$ GeV, missing $p_T>25$ GeV, $m_T>40$ GeV and $0.1<|\eta|<2.5$ (excluding $1.37<|\eta_e|<1.52$)