

Production of electroweak bosons in $Pb+Pb$, $p+Pb$ and pp collisions with the ATLAS detector

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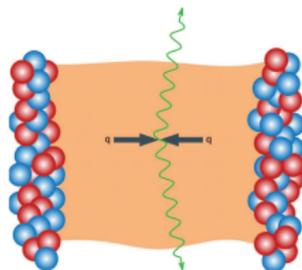


(on behalf of the ATLAS Collaboration)

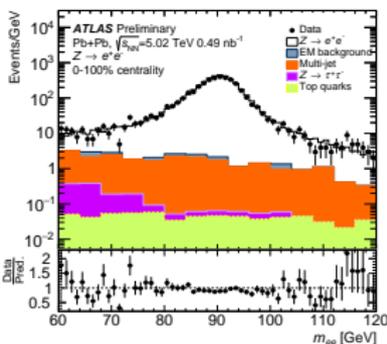


Electroweak bosons in heavy ion collisions

- ▶ Electroweak bosons and their leptonic decay products do not interact strongly. Therefore if formed in a hard parton-parton interaction at a very early stage of the Pb+Pb or p +Pb collision they carry out unmodified by the surrounding medium information about the geometry of the collision and possible nuclear modifications of PDFs in a nucleon.
- ▶ Recent ATLAS results to be reviewed in this talk:
 - Measurements of W and Z boson production in pp collisions at $\sqrt{s} = 5.02$ TeV with the ATLAS detector. [Eur. Phys. J. C 79 \(2019\) 128](#), erratum: [Eur. Phys. J. C 79 \(2019\) 374](#), [arXiv:1810.08424 \[hep-ex\]](#)
 - Measurement of W^\pm boson production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector. [to be submitted to EPJC](#)
 - Z Boson production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured by the ATLAS detector. [ATLAS-CONF-2019-024](#)
 - Measurement of prompt photon production in $\sqrt{s_{NN}} = 8.16$ TeV p +Pb collisions with ATLAS. [submitted to Phys. Lett. B](#), [arXiv:1903.02209 \[nucl-ex\]](#)
 - Measurement of photon-jet transverse momentum correlations in 5.02 TeV Pb+Pb and pp collisions with ATLAS. [Phys. Lett. B 789 \(2019\) 167](#), [arXiv:1809.07280 \[nucl-ex\]](#)
 - More details and results from the heavy ion physics program realized by ATLAS are available in <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults>



Reconstruction of Z/W bosons with the ATLAS detector



- Z/W bosons are measured in their leptonic ($\ell = e, \mu$) decay channels: $W^\pm \rightarrow \ell^\pm \bar{\nu}$ and $Z \rightarrow \ell^+ \ell^-$

- Events collected with single-lepton triggers:

$$p_T^e > 15 \text{ GeV} \text{ and } p_T^\mu > 14 \text{ GeV}$$

- High quality reconstruction and isolation (minimize hadronic activity around) requirements on the leptons.
- Final kinematic selection cuts on Z/W bosons:

$$|\eta_e| < 1.37, \quad 1.52 < |\eta_e| < 2.47, \quad |\eta_\mu| < 2.4$$

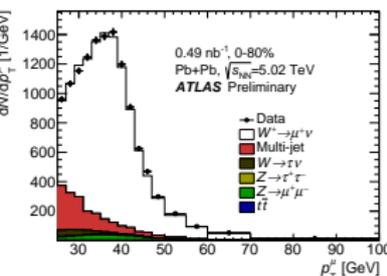
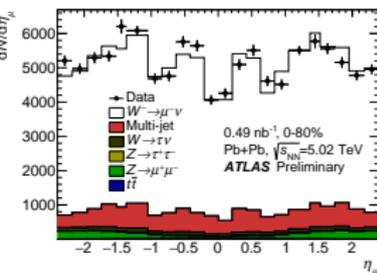
Specific cuts for Z boson selection:

- opposite charge leptons with $p_T^\ell > 20 \text{ GeV}$,
- invariant mass $66 < m_{\ell\ell} < 116 \text{ GeV}$.

Specific cuts for W^\pm boson selection:

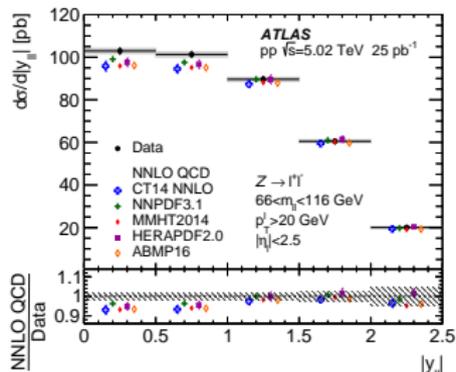
- $p_T^\ell > 25 \text{ GeV}$, $p_T^{\text{miss}} > 25 \text{ GeV}$,
- $m_T = \sqrt{2p_T^\ell p_T^{\text{miss}}(1 - \cos \Delta\phi)} > 40 \text{ GeV}$,
- veto on Z events: $m_{\ell\ell} < 66 \text{ GeV}$, with $p_{T,2}^\ell > 20 \text{ GeV}$.

- Multi-jet bkg. (semileptonic decays of HF, decays of K -s and π -s in muon channel, photon conversions, misidentified hadrons, ...) - estimated from data using template fits.



Z/W boson production in pp collisions at $\sqrt{s} = 5.02$ TeV

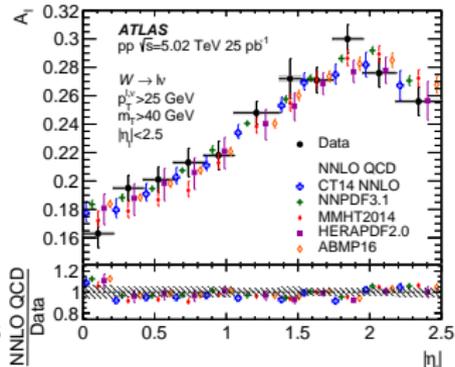
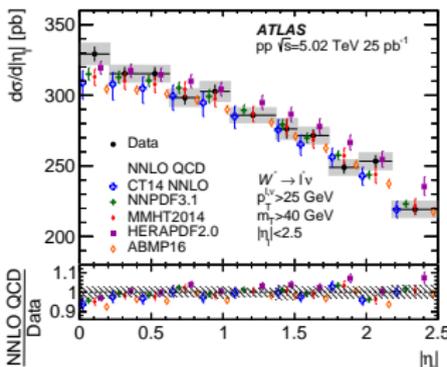
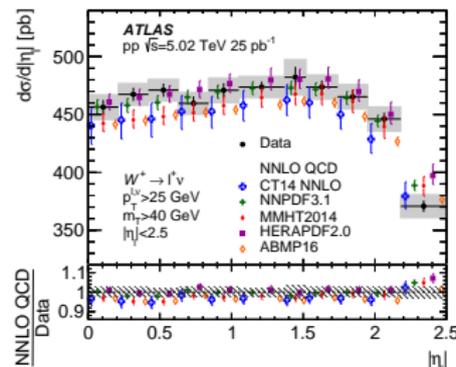
Fiducial integrated and differential cross sections measured in pp collisions serve as a reference for Pb+Pb interactions.



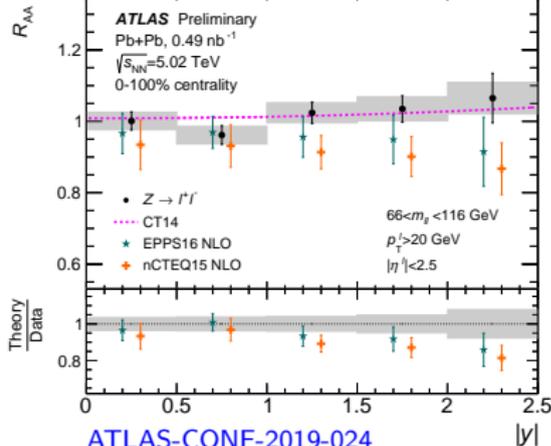
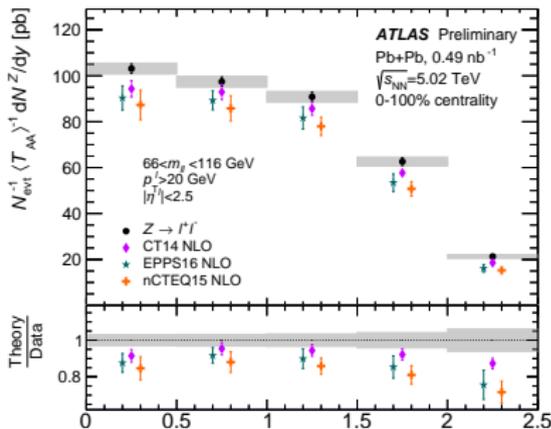
EPJC (2019) 79:128

- Separate measurements in e and μ decay channels.
- Combined integrated fiducial cross sections:
 - W^+ : 2266 ± 9 (stat) ± 29 (sys) ± 43 (lumi) pb
 - W^- : 1401 ± 7 (stat) ± 18 (sys) ± 27 (lumi) pb
 - Z : 374.5 ± 3.4 (stat) ± 3.6 (sys) ± 7.0 (lumi) pb
- Overall good agreement with NNLO pQCD calculations.

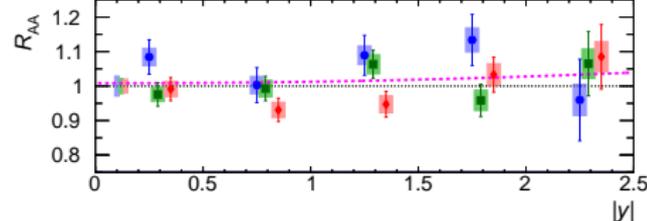
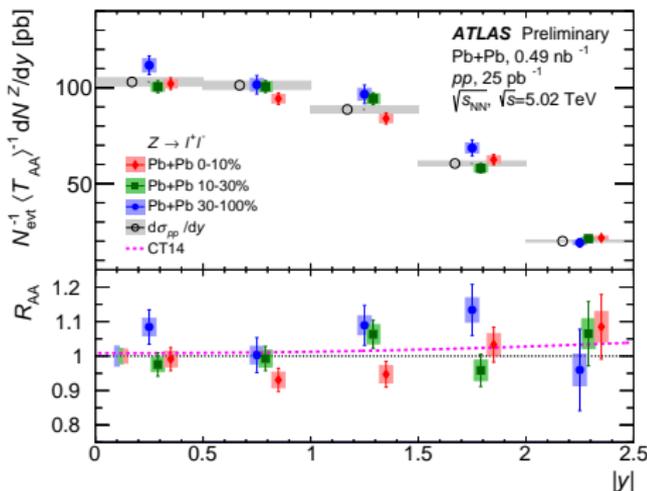
$$A_e = \frac{dN_{W^+ \rightarrow e^+ \nu_e} / d\eta_e - dN_{W^- \rightarrow e^- \bar{\nu}_e} / d\eta_e}{dN_{W^+ \rightarrow e^+ \nu_e} / d\eta_e + dN_{W^- \rightarrow e^- \bar{\nu}_e} / d\eta_e}$$



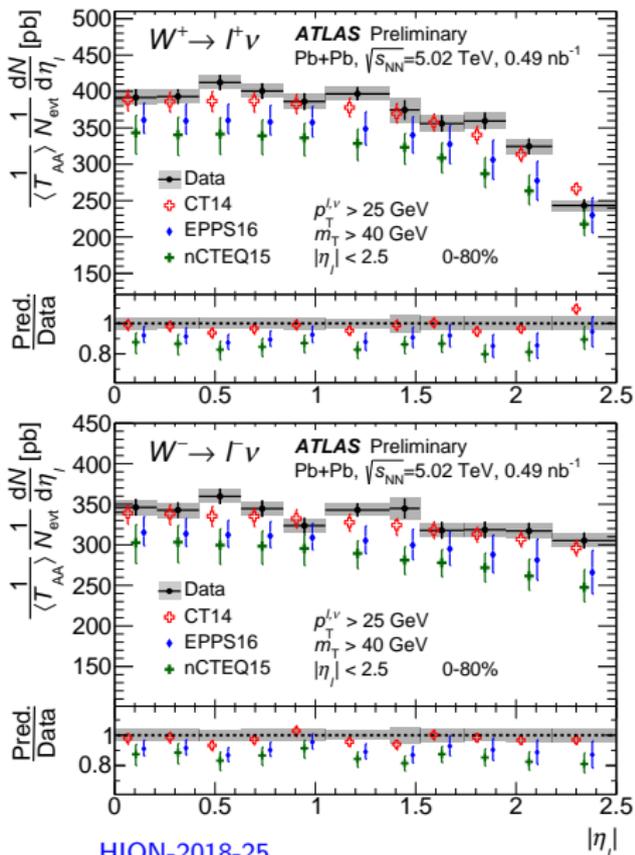
Z boson yields in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



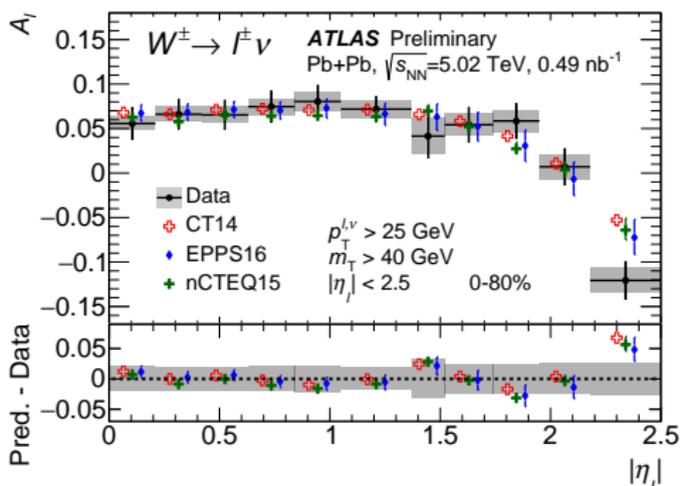
- Normalized Z boson yields as function of rapidity, integrated over centrality, are in better agreement with free proton PDF (+isospin) than with nPDFs.
- $R_{AA} = \frac{N_{AA}^Z / N_{evt}}{\langle T_{AA} \rangle \times \sigma_{pp}^Z}$ is consistent with the isospin effect expected only from the different valence quark content of p and n in the Pb nucleus.
- No significant difference in rapidity distribution between different centrality classes.



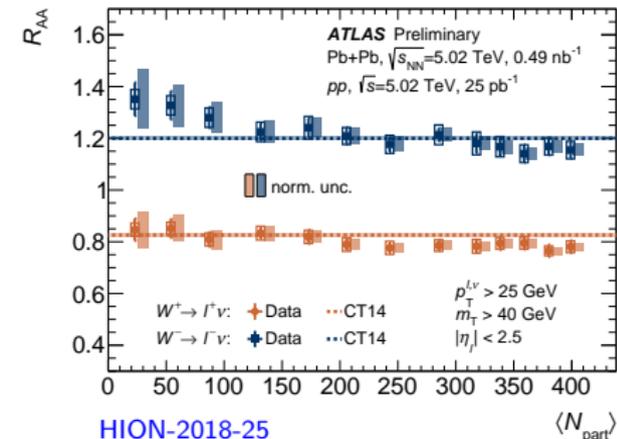
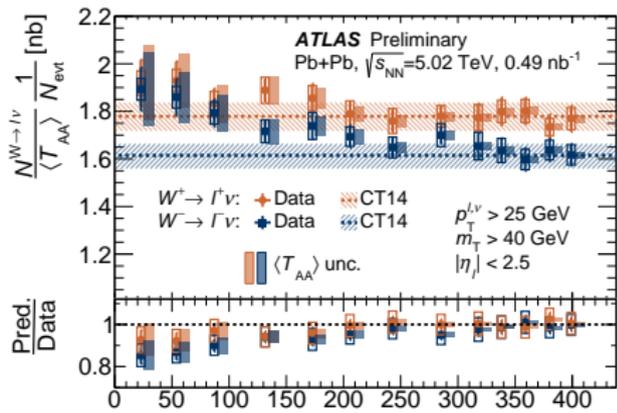
W^\pm boson yields in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



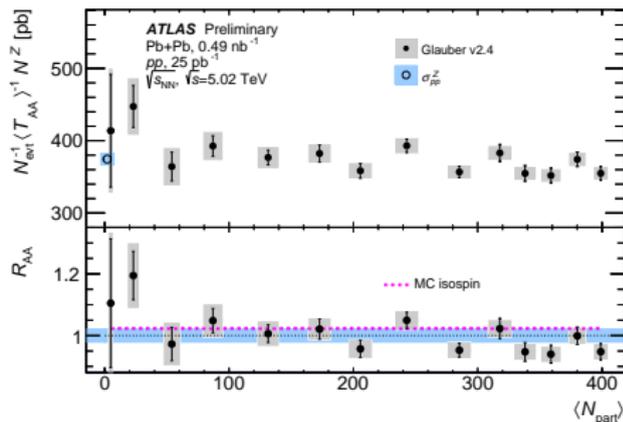
- Normalized W^\pm boson yields as function of $|\eta_l|$, integrated over centrality, are in better agreement with free proton PDF (+isospin) than with nPDFs.
- Lepton charge asymmetry A_ℓ is equally well described by both free proton PDF (+isospin) and the nPDFs. Disagreement on the level of 1-2 σ is observed in highest η_ℓ bin.



Z/W boson yields in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



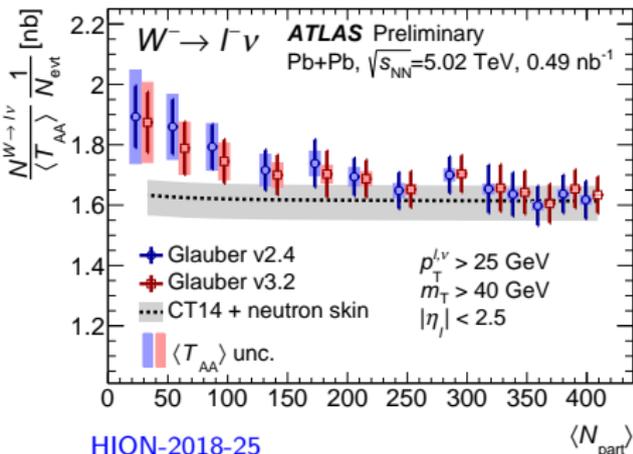
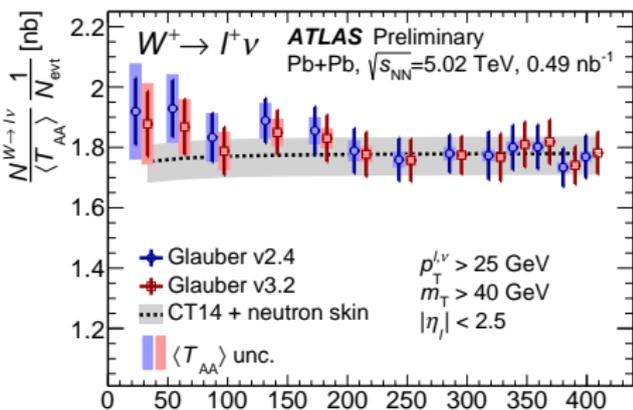
- Normalized W^\pm boson yields as function of $\langle N_{part} \rangle$ are in good agreement with theory predictions for $\langle N_{part} \rangle > 200$, but a slight excess of the data over predictions in more peripheral collisions is observed.
- Normalized Z boson yields consistent with the pp cross-section at all centralities and show only weak dependence on $\langle N_{part} \rangle$.
- These are also reflected in R_{AA} behaviour.



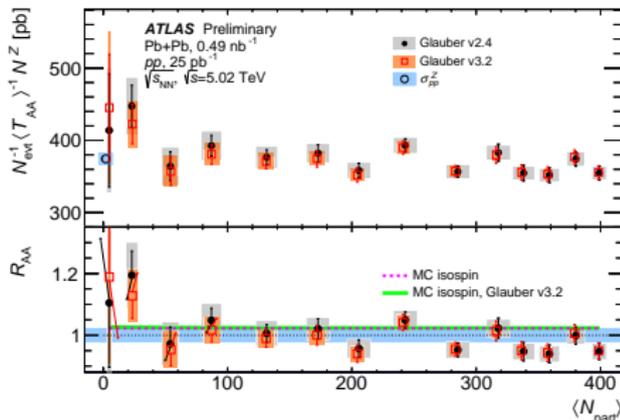
ATLAS-CONF-2019-024

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Binary scaling - Glauber MC comparison



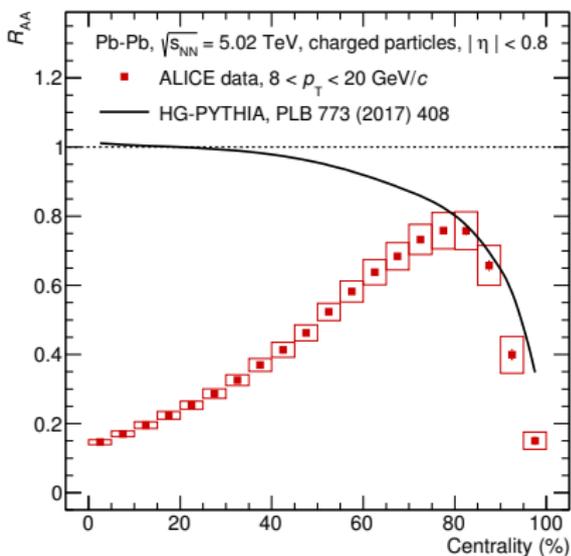
- Comparison of Glauber MC v2.4 and v3.2 (includes different radial distributions of p and n in nuclei, which results in an evolution of the effective p/n ratio with centrality).
- No significant change of the measured yields.
- Theory curves obtained using the CT14 NLO PDF set include the neutron skin effect included in Glauber MC v3.2.
- Slopes of Z boson R_{AA} vs. $\langle N_{part} \rangle$:
 Glauber v2.4: $(10 \pm 7)\%$; v3.2: $(5 \pm 6)\%$



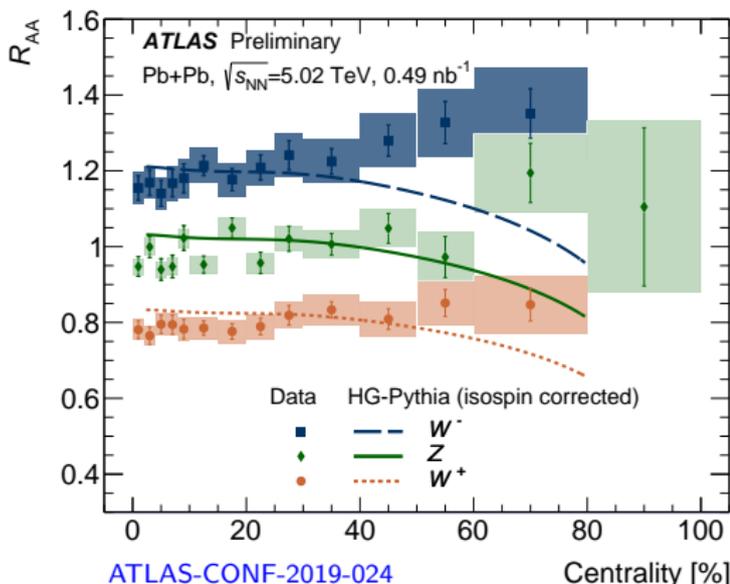
ATLAS-CONF-2019-024

Comparison with HG-Pythia predictions

- Peripheral decrease in production yield predicted by HG-PYTHIA (PLB773 (2017) 408)
- In qualitative agreement with charged hadrons R_{AA} suppression observed by ALICE.
- Opposite trends observed by ATLAS in Z and W boson yields.
- Theoretical predictions are calculated with the CT14 NLO PDF set multiplied by the R_{AA} obtained from HG-PYTHIA.



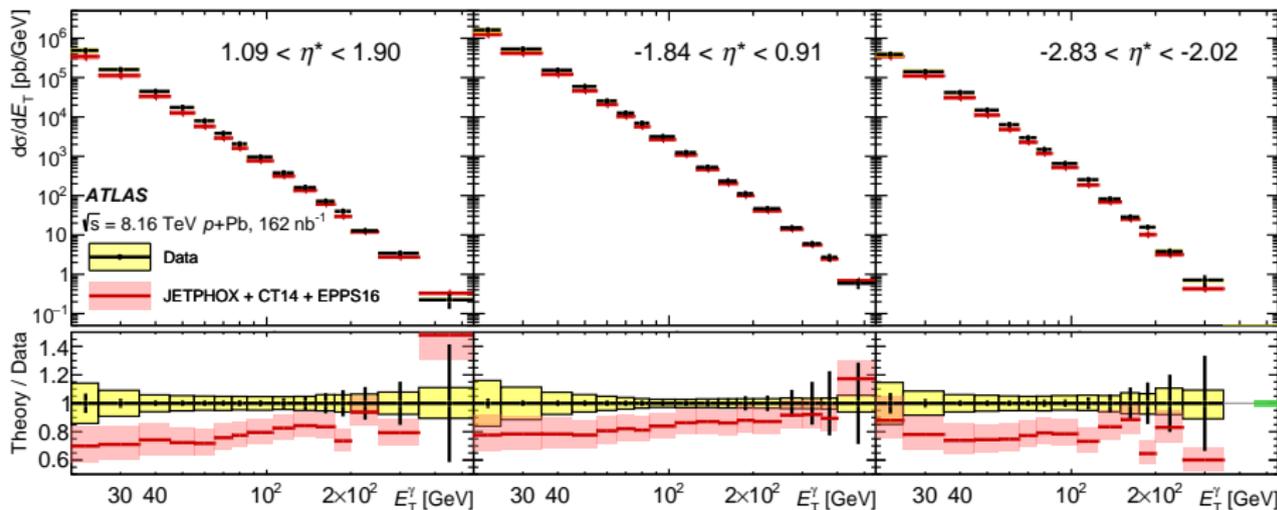
PLB 793 (2019) 420



ATLAS-CONF-2019-024

Prompt photons in $p+Pb$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV

- Sources of prompt photons: quark-gluon Compton scattering $qg \rightarrow q\gamma$ and production of hard photons during parton fragmentation $\bar{q}q \rightarrow g\gamma$ (distinguishable only at LO).
- Prompt photons being colourless are unaffected by the subsequent evolution of the QGP and probe the very initial stages of the collision i.e. nuclear modifications to PDF.
- Kinematical range covered by this measurement gives access also to nuclear gluons.
- Differential cross section for the production of isolated ($E_T^{iso} < 4.8 + 4.2 \cdot 10^{-3} E_T^\gamma$ [GeV]) prompt photons as a function of E_T^γ in three intervals of η^* ($= \eta - 0.465$) in data is underestimated by JETPHOX (NNLO pQCD including nPDF effects).



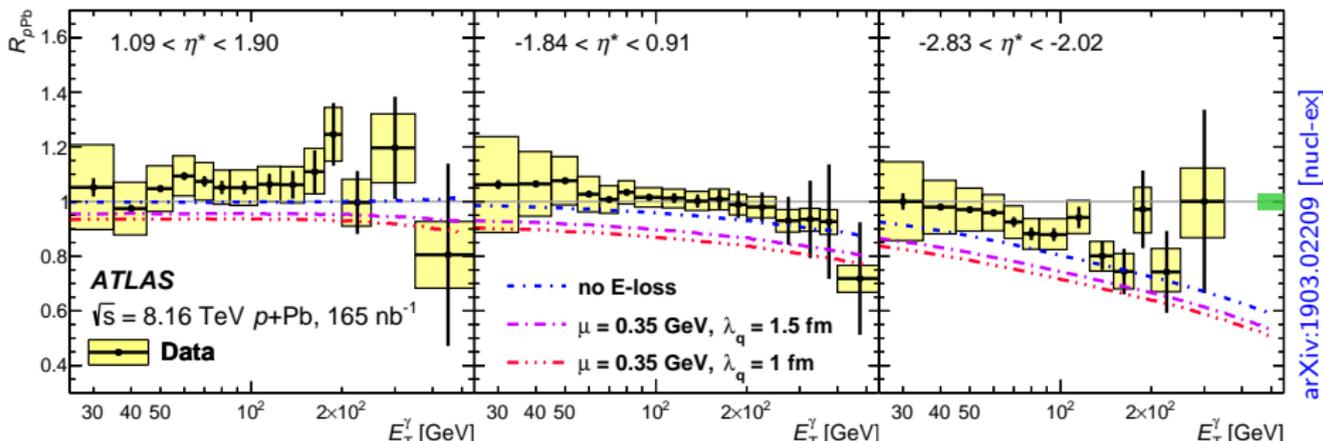
arXiv:1903.02209 [nucl-ex]

Prompt photons in $p+\text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$

- Using pp data at 8 TeV extrapolated to 8.16 TeV to obtain nuclear modification factor

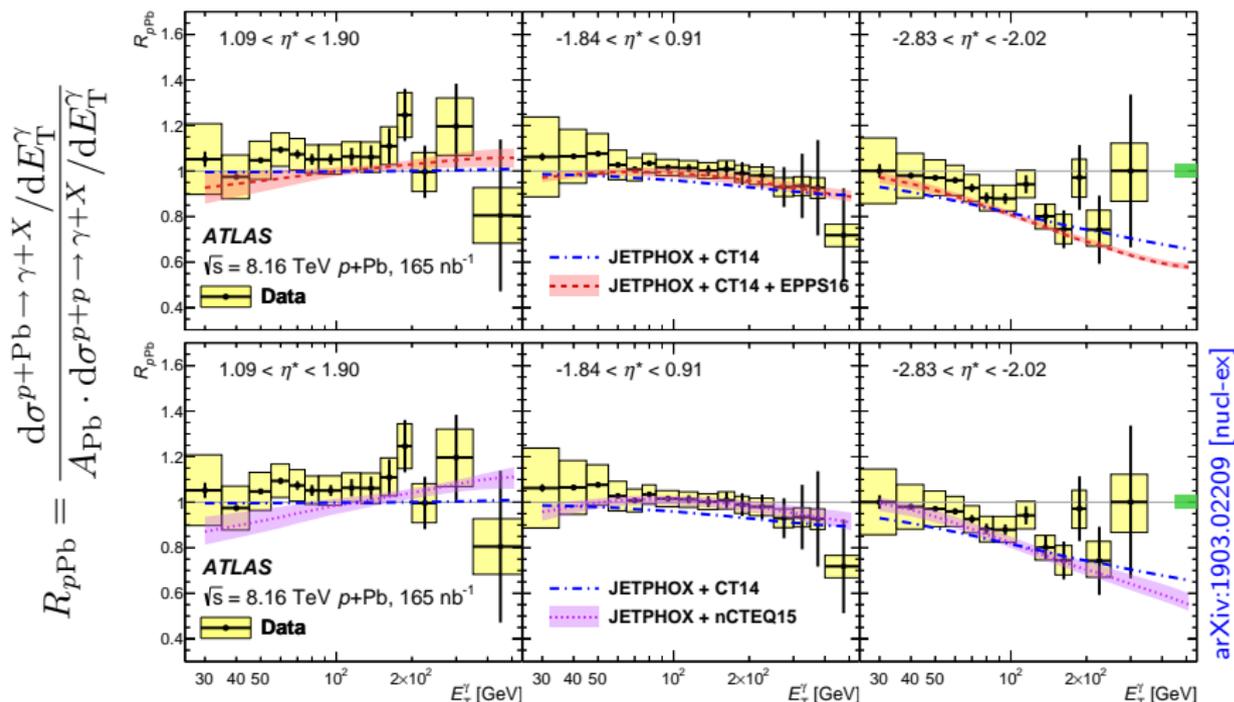
$$R_{p\text{Pb}} = \frac{d\sigma^{p+\text{Pb} \rightarrow \gamma+X} / dE_T^\gamma}{A_{\text{Pb}} \cdot d\sigma^{p+p \rightarrow \gamma+X} / dE_T^\gamma}$$

- At forward (p -going) and central rapidities $R_{p\text{Pb}}$ is consistent with unity - indicating that nuclear effects are small (probing mainly gluons at $x_A \approx 10^{-2}$).
- At backward rapidities, the $R_{p\text{Pb}}$ decreases with increasing E_T^γ - larger relative d -quark density in Pb nucleus at $x_A \approx 0.2$ decreases the photon yield.
- Data disfavour a large suppression of the cross section from initial-state energy-loss effects due to possible multiple scattering of energetic partons in the cold nuclear medium before the hard collision.



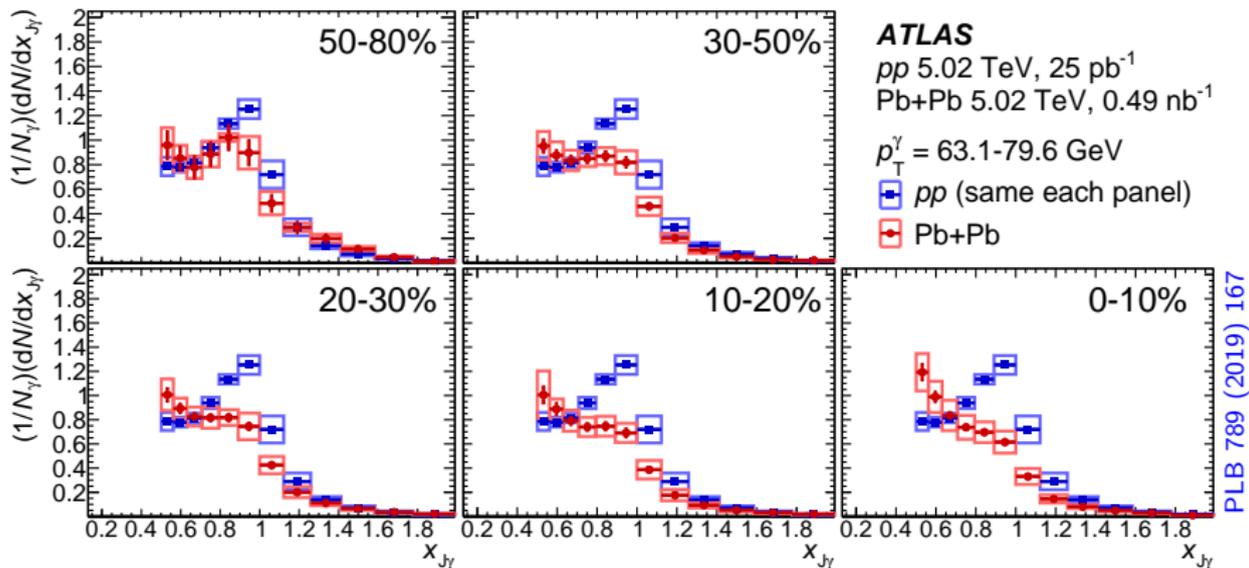
Prompt photons in $p+\text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

- Nuclear modification factor $R_{p\text{Pb}}$ for isolated, prompt photons as a function of E_T^γ .
- Data are compared to two different nuclear PDF sets: EPPS16 and nCTEQ15.
- Behaviour of nPDFs reflects the different relative d/u quark composition in the Pb nuclei than in the proton.



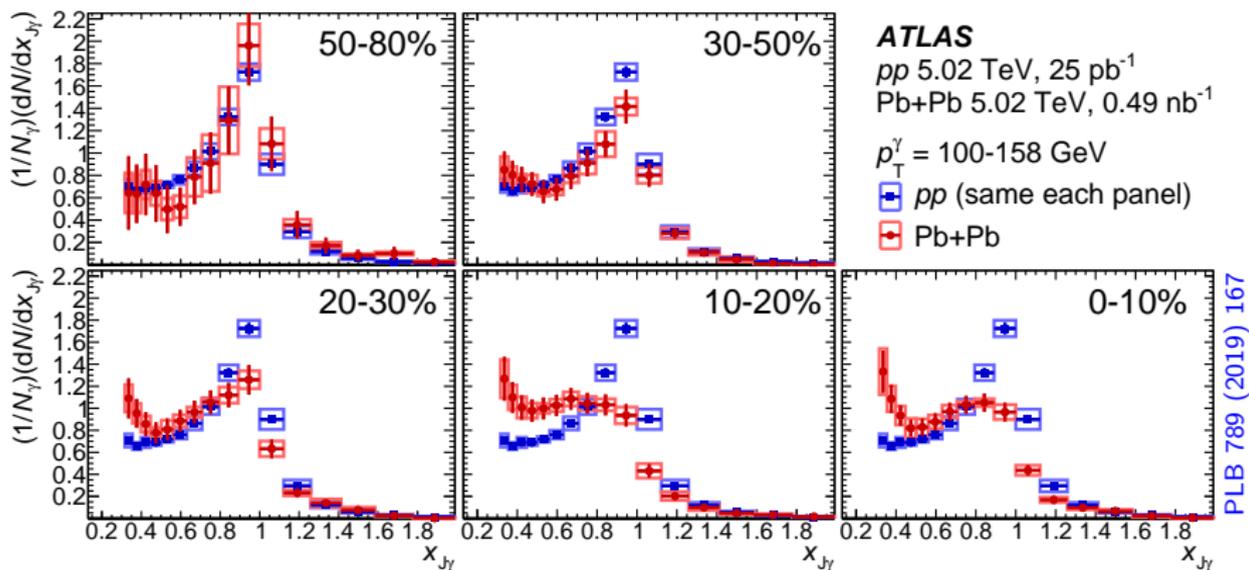
Photon-jet p_T correlations in Pb+Pb at $\sqrt{s_{NN}} = 5.02$ TeV

- Comparison of per-photon yields of photon-jet events in Pb+Pb and pp collisions as a function of transverse momentum ratio, $x_{J\gamma} = p_T^{\text{jet}}/p_T^\gamma$, for different centrality intervals and different photon transverse momenta, p_T^γ , ranges.
- The $x_{J\gamma}$ distributions in Pb+Pb evolve smoothly with centrality.
- In peripheral collisions (50 – 80%) they are similar to those measured in pp collisions.
- In central collisions (0 – 10%) for lower p_T^γ the distributions decrease monotonically, however, for $p_T^\gamma > 100$ GeV they retain a peak even in the most central collisions.



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Summary

ATLAS has provided recently several new results on electroweak bosons production in pp , $p+Pb$ and $Pb+Pb$ collisions:

- Precise measurements of Z/W boson yields in pp collisions at $\sqrt{s} = 5.02$ TeV serve as a reference for the measurements in $Pb+Pb$ and $p+Pb$. Good agreement with NNLO theory predictions using NNPDF3.1 and HERAPDF2.0 PDFs.
- Z/W boson yields in $Pb+Pb$ are in best agreement with the free proton PDF including the isospin effect. Predictions from nPDFs underestimate the measured yields by 1-3 σ .
- R_{AA} for Z/W production do not depend significantly on centrality, however, there is an indication of an excess at the level of 1-2 σ in peripheral collisions in case of W yields.
- No suppression of Z/W yields predicted by HG-Pythia is observed in peripheral collisions.
- Prompt photon production yields in $p+Pb$ collisions are in agreement with free proton PDF, however small nuclear modifications are not excluded.
- No large initial parton energy losses are observed in $p+Pb$ collisions in events with prompt photons.
- New measurement of photon-jet transverse momentum correlations in $Pb+Pb$ and pp collisions provide information on how energy loss in the strongly coupled medium varies with the initial parton p_T .

Thank you for your attention!

Backup slides

▶ A+A collisions:

- **Pb+Pb @ 2.76 TeV** (2011), $L_{\text{int}} = 0.14 \text{ nb}^{-1}$
- **Pb+Pb @ 5.02 TeV** (2015), $L_{\text{int}} = 0.49 \text{ nb}^{-1}$
- **Xe+Xe @ 5.44 TeV** (2017), $L_{\text{int}} = 3 \text{ } \mu\text{b}^{-1}$

▶ $p + A$ collisions:

- **p +Pb @ 5.02 TeV** (2013), $L_{\text{int}} = 29 \text{ nb}^{-1}$
- **p +Pb @ 5.02 TeV** (2016), $L_{\text{int}} = 0.5 \text{ nb}^{-1}$
- **p +Pb @ 8.16 TeV** (2016), $L_{\text{int}} = 0.16 \text{ pb}^{-1}$

▶ Reference pp samples:

- **pp @ 8 TeV** (2012), $L_{\text{int}} = 19.4 \text{ fb}^{-1}$
- **pp @ 2.76 TeV** (2013), $L_{\text{int}} = 4 \text{ pb}^{-1}$
- **pp @ 5.02 TeV** (2015), $L_{\text{int}} = 28 \text{ pb}^{-1}$
- **pp @ 5.02 TeV** (2017), $L_{\text{int}} = 270 \text{ pb}^{-1}$

The ATLAS detector

Detector coverage:

Inner Detector (ID):

$$|\eta| < 2.5$$

Calorimeter (CAL):

$$|\eta| < 3.2 \text{ (EM)}$$

$$|\eta| < 4.9 \text{ (HAD)}$$

$$3.2 < |\eta| < 4.9 \text{ (FCal)}$$

Muon Spectrometer (MS):

$$|\eta| < 2.7$$

Zero Degree Cal. (ZDC):

$$|\eta| > 8.3 \quad @z = \pm 140 \text{ m}$$

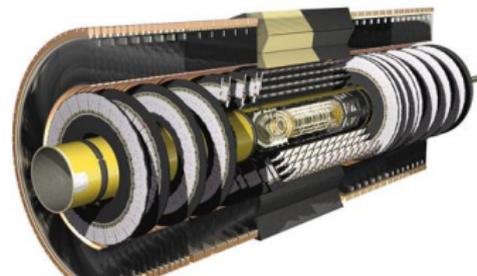
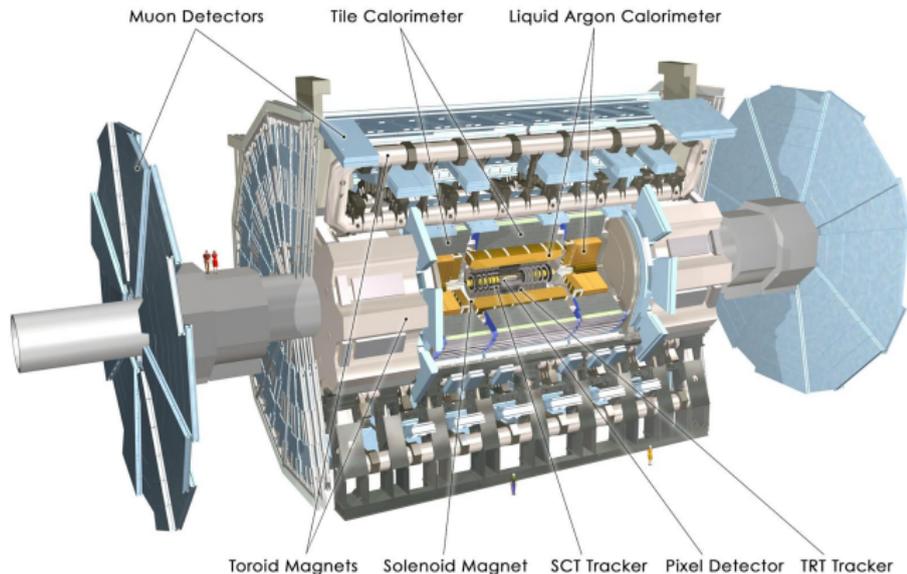
MB Trig. Scint. (MBTS):

$$2.1 < |\eta| < 3.9$$

Magnetic fields:

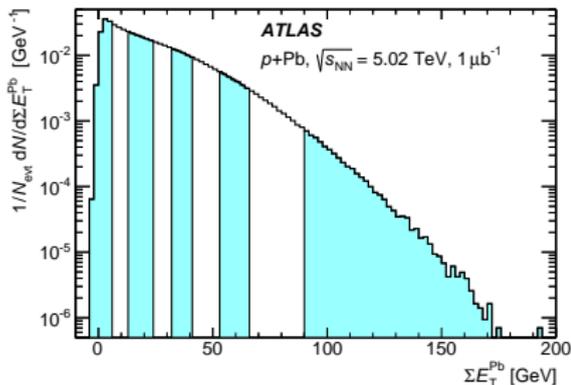
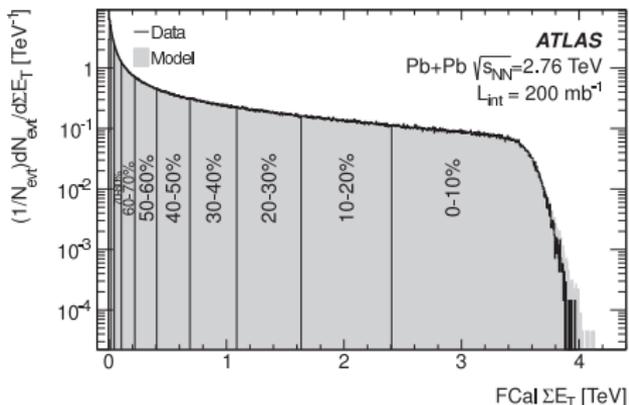
- 2T solenoid field in ID
- Toroidal field in MS

Identification of minimum-bias p +Pb and Pb+Pb collision
measurement of spectator neutrons in ZDC and charged
particle tracks (pulse height and arrival times) in MBTS.

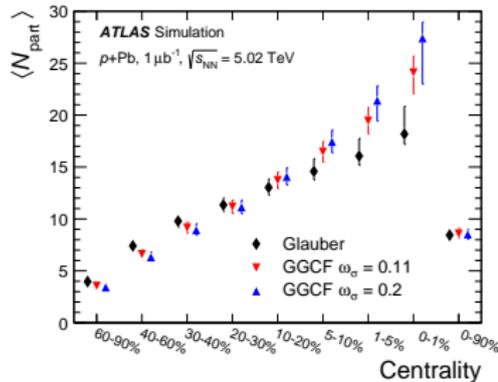


Centrality determination in Pb+Pb and p +Pb

- Centrality is measured using forward calorimeters ($3.2 < |\eta| < 4.9$):

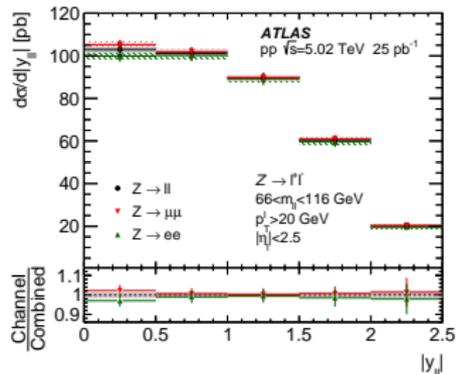


- in Pb+Pb use sum of E_T on both sides,
- in p +Pb use sum of E_T on Pb-going side only,
- for Pb+Pb use Glauber MC for geometry,
- for p +Pb use both Glauber and Glauber-Gribov color fluctuation model (PLB 633: 245 (2006)).
- Average number of participants (N_{part}) for each centrality bin resulting from fits to the measured E_T distribution for p +Pb.



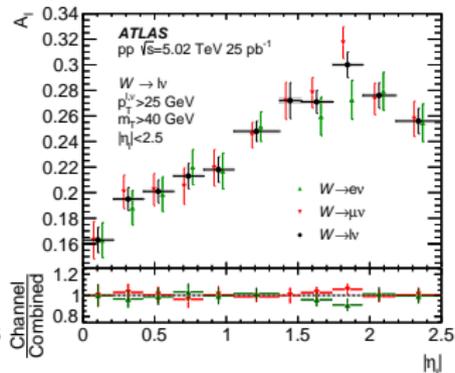
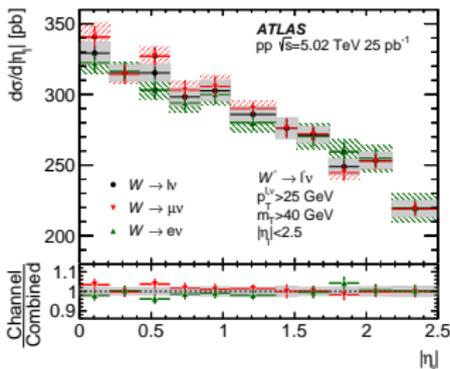
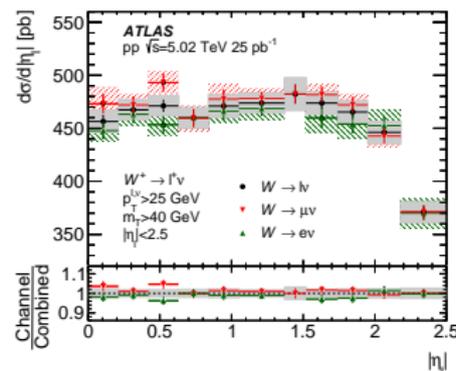
Z/W boson production in pp collisions at $\sqrt{s} = 5.02$ TeV

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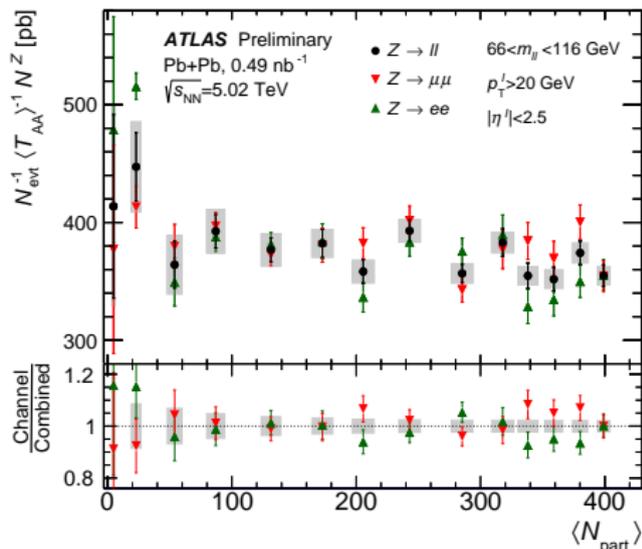
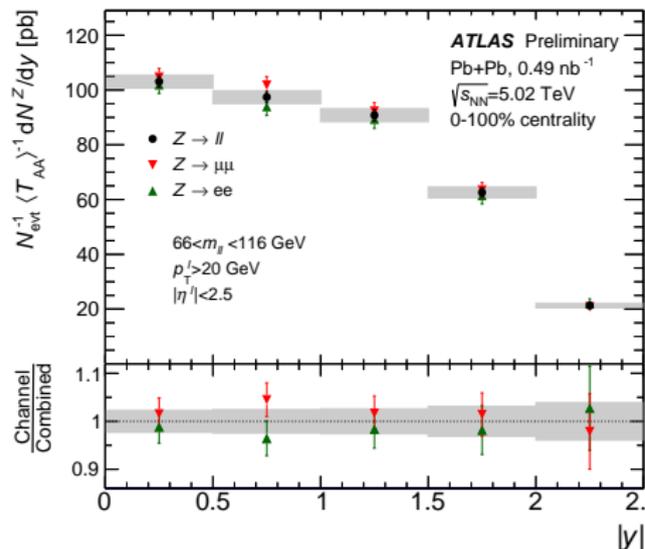
- Separate and combined measurements for electron and muon decay channels.

Eur. Phys. J. C (2019) 79:128



Z boson production in Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV

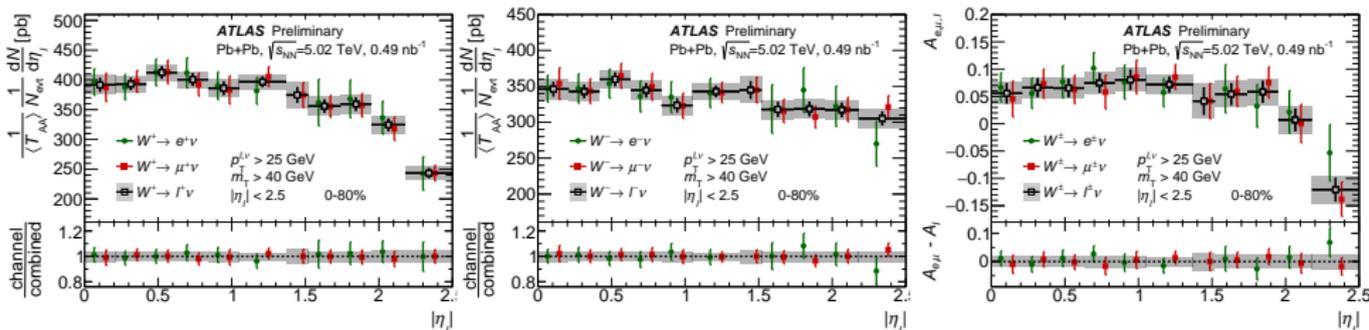
- Normalized production yields for Z boson as a function of rapidity and $\langle N_{\text{part}} \rangle$ in the electron and muon decay channels and their combination.



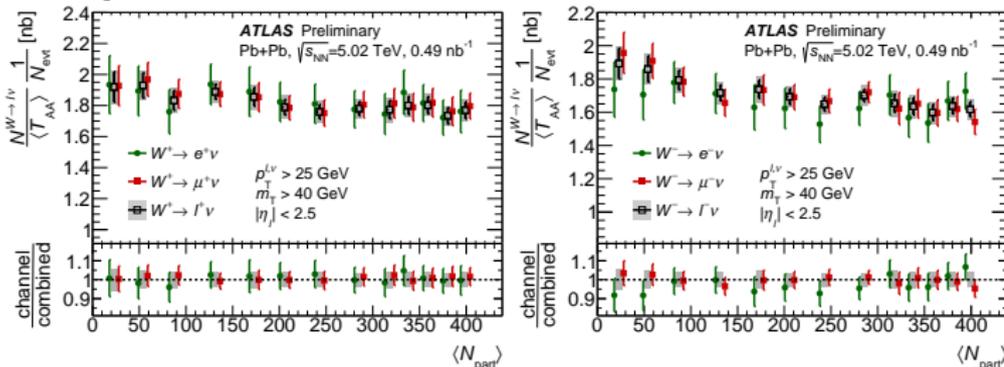
ATLAS-CONF-2019-024

W boson production in Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV

- Differential normalized production yields and lepton charge asymmetry for W^\pm as a function of pseudorapidity of the charged lepton separately for their electron and muon decay channels and their combination.



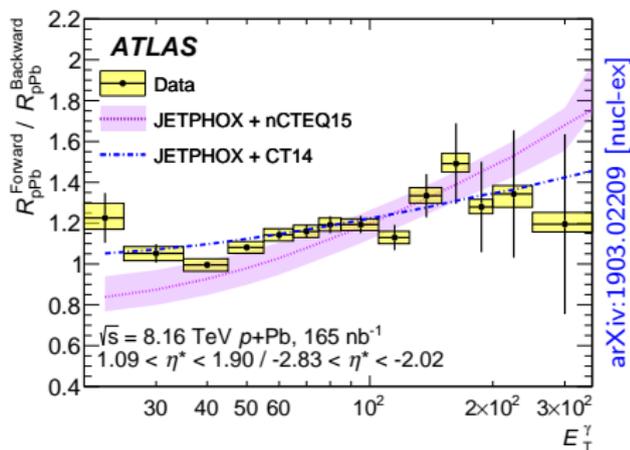
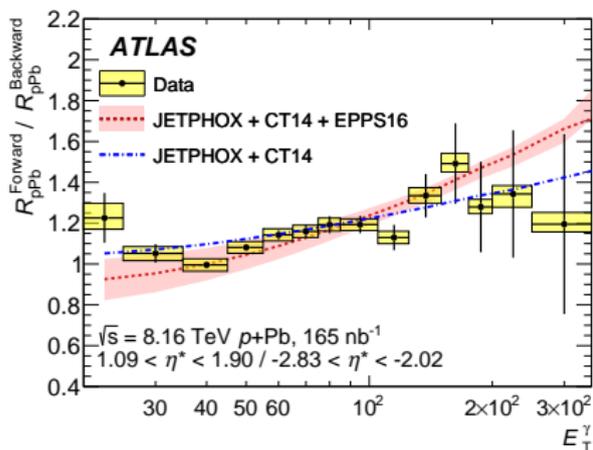
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HION-2018-25

Prompt photons in $p+Pb$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV

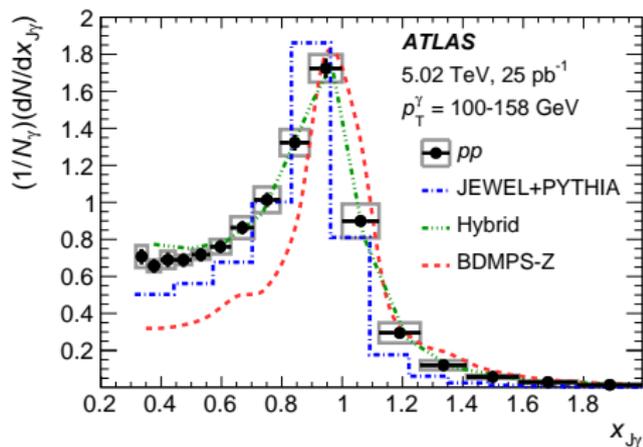
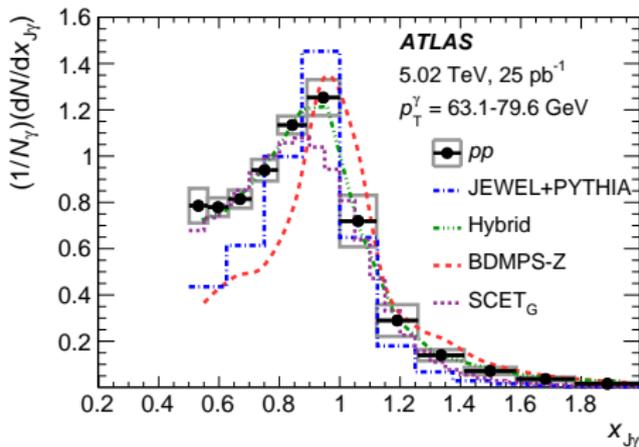
- Cancellation of many systematic uncertainties in the ratio of forward to backward R_{pPb}
- Data are consistent with the pQCD calculations before incorporating nuclear effects, except at $35 < E_T^\gamma < 45$ GeV, where the data fall below the free-proton calculation.
- Data are also compatible with small nuclear modifications represented by nPDFs in most of the considered E_T^γ range.



- Nuclear models: below $E_T^\gamma \approx 100$ GeV, the ratio corresponds to photons from gluon nuclear parton configurations in the shadowing x_A region to that from quark partons in the anti-shadowing region. This is reversed at higher E_T^γ where the numerator probes the shadowing/anti-shadowing crossover region and the denominator moves deeper into the EMC suppression region ($x_A \sim 0.2$).

Comparison of jet energy-loss with models

- Hybrid model gives a good description of pp events over broad range of $x_{J\gamma}$ and p_T^γ .

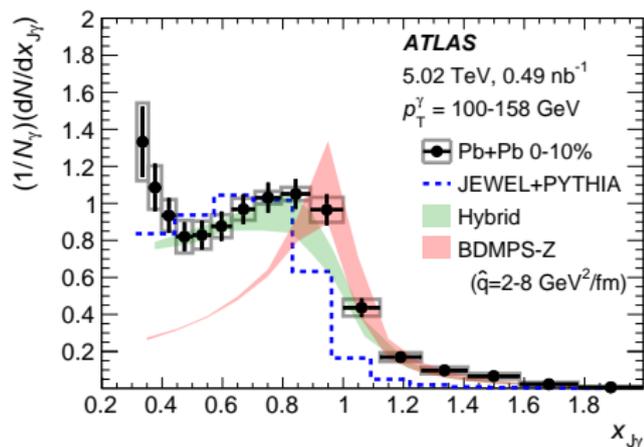
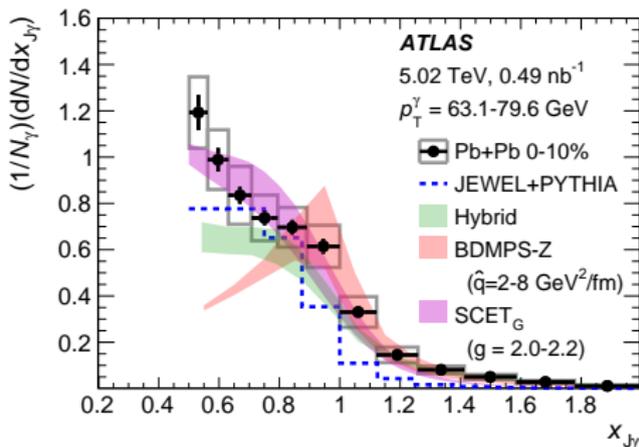


- pQCD calculation which includes energy-loss in Pb+Pb using BDMPS-Z (Nucl. Phys. B933 (2018) 306).
- perturbative calculation within framework of soft-collinear effective field theory with Glauber gluons (SCET_G) (PRC 96 (2017) 014912).
- JEWEL MC - QCD evolution in HI collisions including energy-loss effects from radiative and elastic scattering processes (EPJC 76 (2016) 695).
- Hybrid Strong/Weak Coupling model which combines initial production using Pythia with a parametrisation of energy loss derived from holographic methods (JHEP 03 (2016) 053).

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Comparison of jet energy-loss with models

- Hybrid model gives a good description of pp events over broad range of $x_{J\gamma}$ and p_T^γ .
- In Pb+Pb events at low p_T^γ all models but BDMPS-Z capture the main features of the $x_{J\gamma}$ distribution. At higher p_T^γ non of the models describe the increase of the jet yield at $x_{J\gamma} < 0.5$, however, Hybrid and JEWEL predict the reappearance of a localised peak.



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