



online

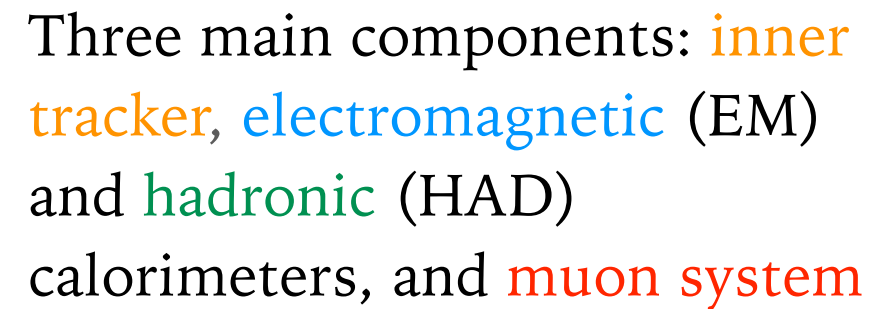
Electroweak probes in heavy-ion collisions with ATLAS

*Iwona Grabowska-Bold (AGH UST, Kraków)
for the ATLAS Collaboration*

*10th International Conference on Hard and Electromagnetic
Probes of High-Energy Nuclear Collisions
Online, June 1st, 2020*



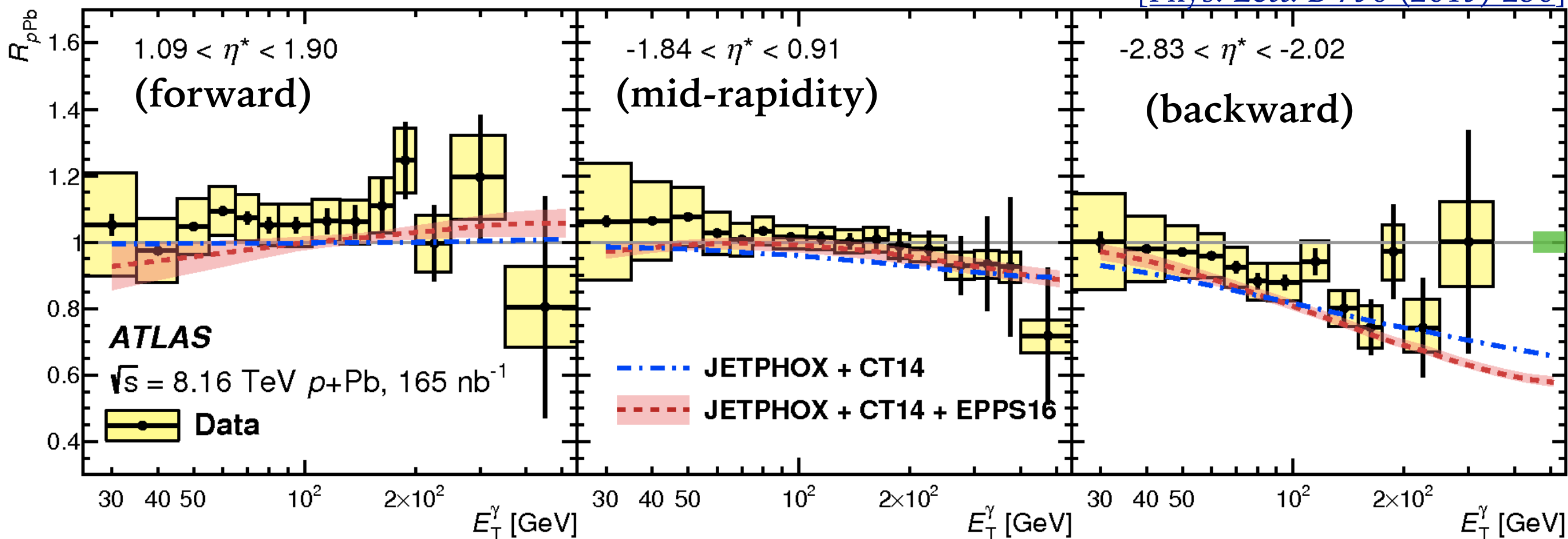
- **Electroweak (EW) bosons** are important probes of Quark Gluon-Plasma (QGP)
 - Produced in heavy-ion collisions (HIC) before the QGP is formed
 - Production rates scale with **collision geometry**
 - Production mechanism sensitive to initial state i.e. **parton distribution functions** (PDF)
 - Since partons are bound in nuclei, they can provide input on **nuclear PDF** (nPDF)
 - They **do not carry colour charges**, thus, the QGP is **transparent** to them
 - Measured yields of EW bosons or their leptonic decay products should be unaffected by the medium (**standard candles** of HIC)
 - Provide **calibration** for **jet energy loss** in the QGP (photon-jet, Z-jet)
- **Final results on photons, Z and W^\pm from ATLAS** are discussed:
 - Inclusive photons in p+Pb at 8.16 TeV [[Phys. Lett. B 796 \(2019\) 230](#)]
 - Z and W^\pm bosons in pp at 5.02 TeV [[Eur. Phys. J. C 79 \(2019\) 128](#)]
 - Z bosons in Pb+Pb at 5.02 TeV [[Phys. Lett. B 802 \(2020\) 135262](#)]
 - W^\pm bosons in Pb+Pb at 5.02 TeV [[Eur. Phys. J. C 79 \(2019\) 935](#)]
- **New** result on light-by-light (LbyL) scattering:
 - Rare $\gamma\gamma \rightarrow \gamma\gamma$ process and search for $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$: [[ATLAS-CONF-2020-010](#)]


$$p_{\text{T}}^{\mu} > 20 \text{ (25) GeV for } Z \text{ (} W^{\pm} \text{)}$$


NUCLEAR MODIFICATION FACTORS FOR PHOTONS

4

[Phys. Lett. B 796 (2019) 230]

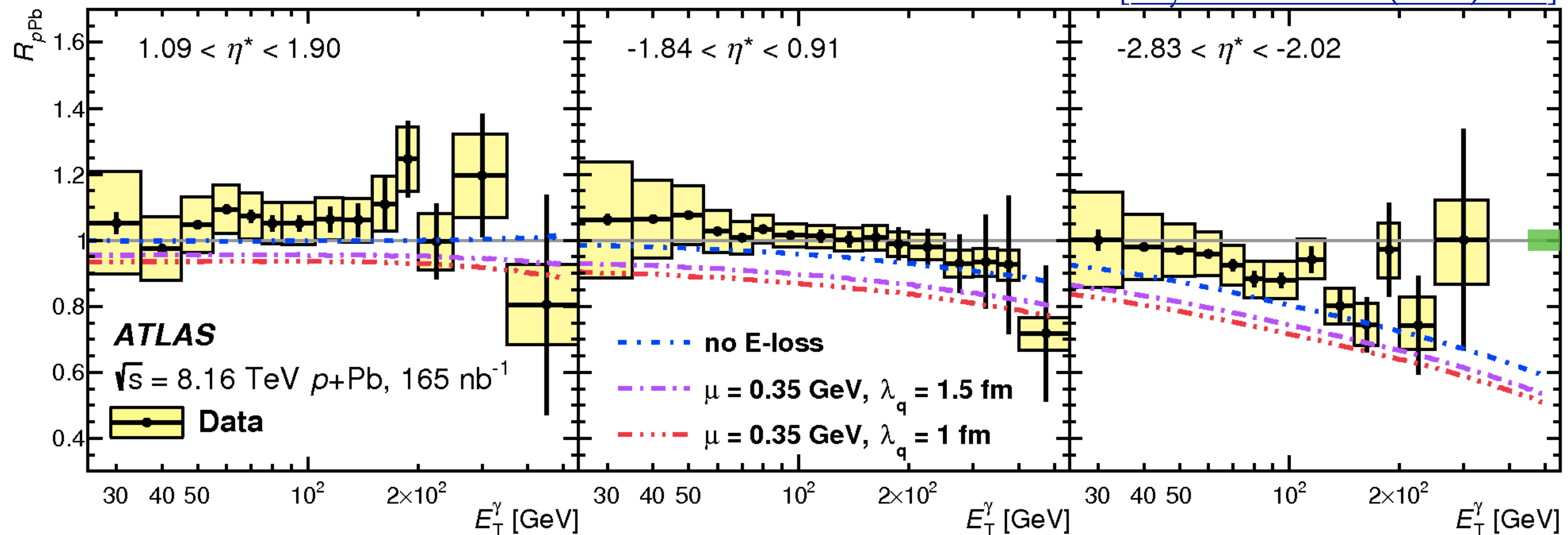


- $R_{p\text{Pb}}$ sensitive to $3 \times 10^{-3} < x_A < 4 \times 10^{-1}$ shadowing, $0.4 < x_A < 0.1$, anti-shadowing $0.1 < x_A < 0.3$ and EMC $0.3 < x_A < 0.7$
- $R_{p\text{Pb}}$ measured as a function of E_T^γ and η^*
 - $R_{p\text{Pb}}$ consistent with unity: in the forward, and at mid-rapidity and low E_T
 - $R_{p\text{Pb}}$ tends to drop below unity: at mid-rapidity and high E_T , and in the backward
 - Sensitive to different composition of u- and d-quarks in p+Pb wrt pp (isospin effect)
 - Data is consistent with both CT14 and EPPS16 within the present uncertainties
 - Similar conclusions for nCTEQ15

$$R_{p\text{Pb}} = \frac{\frac{d\sigma^{p\text{Pb}}}{dE_T^\gamma}}{A \frac{d\sigma^{pp}}{dE_T^\gamma}}$$

INITIAL ENERGY LOSS FOR PHOTONS

5

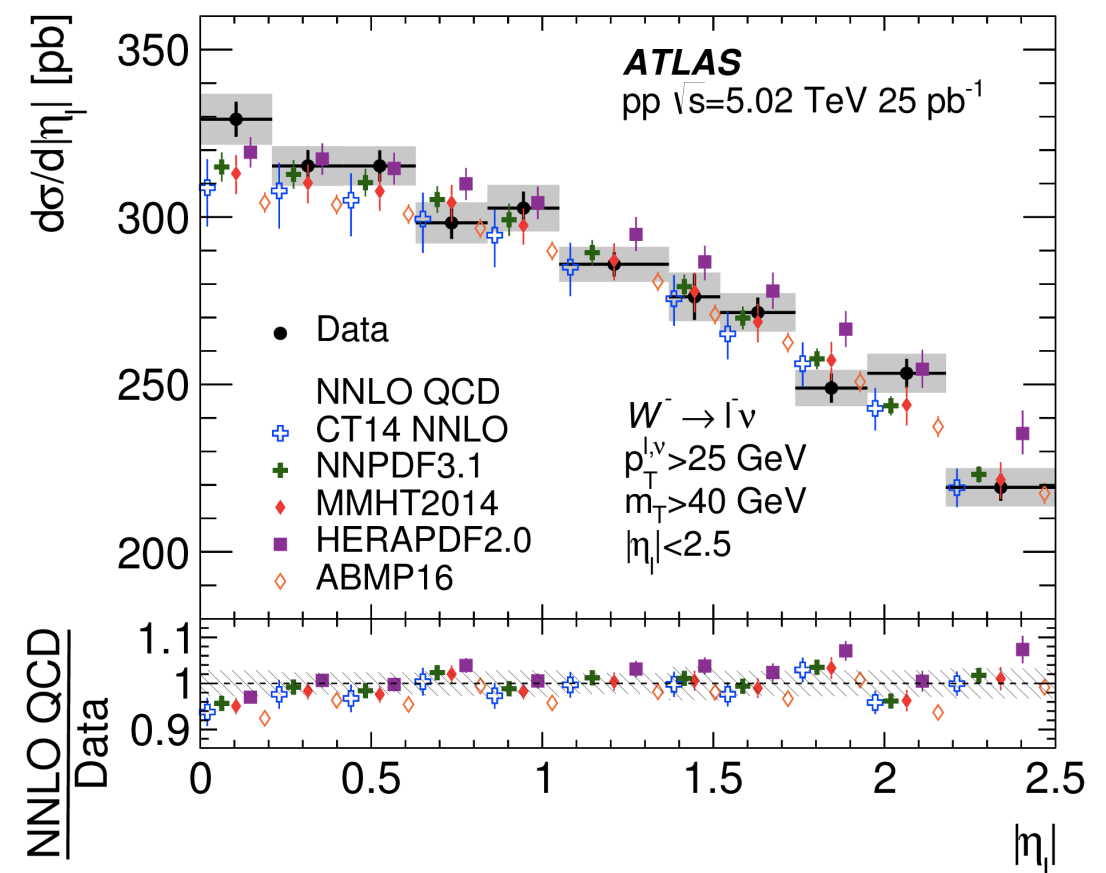
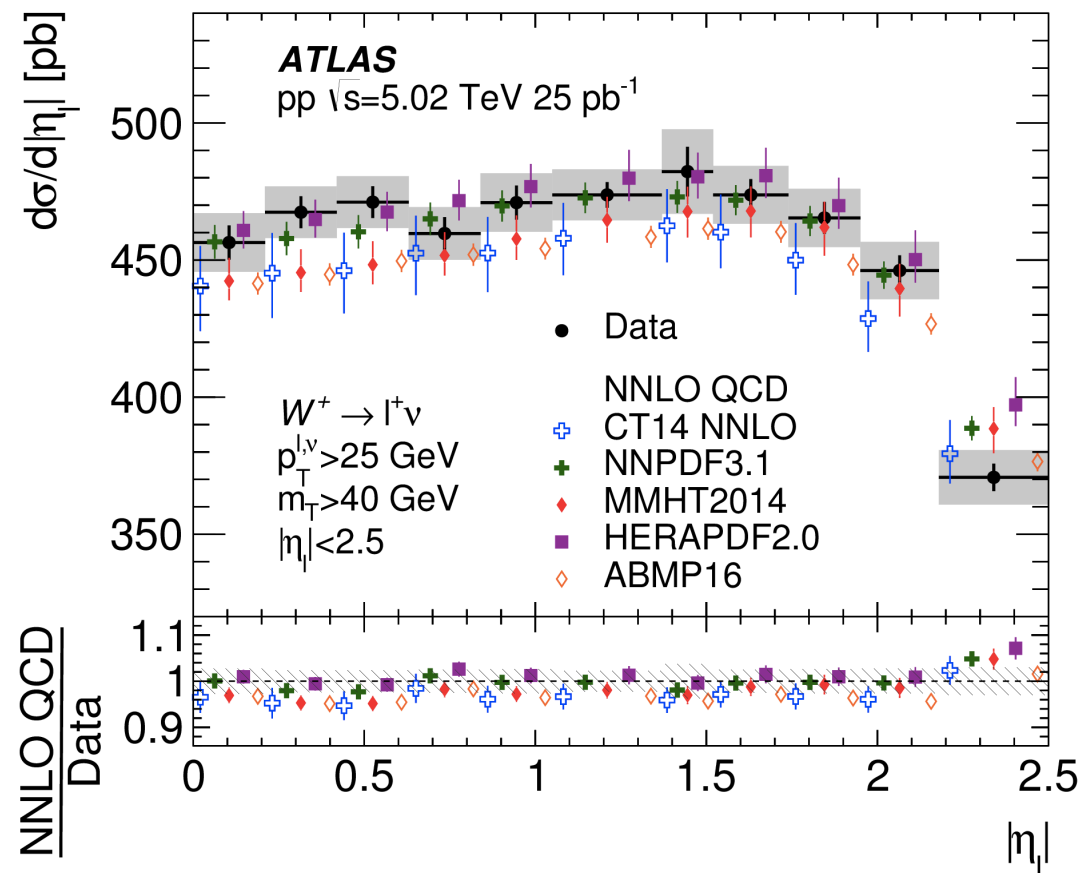
[\[Phys. Lett. B 796 \(2019\) 230\]](#)

- Initial-state energy-loss prediction from I. Vitev et al [[Phys. Lett. B 669 \(2008\) 337](#), [Phys. Rev. C 92 \(2015\) 054911](#)]
 - Energetic partons undergo multiple scattering in the cold nuclear medium and lose energy due to medium-induced gluon bremsstrahlung, before the hard collision
 - Parameters: μ - parton-gluon momentum transfer and λ_q - mean free path for quarks
 - Data disfavors a large suppression of R_{pPb} from initial-state energy-loss effects

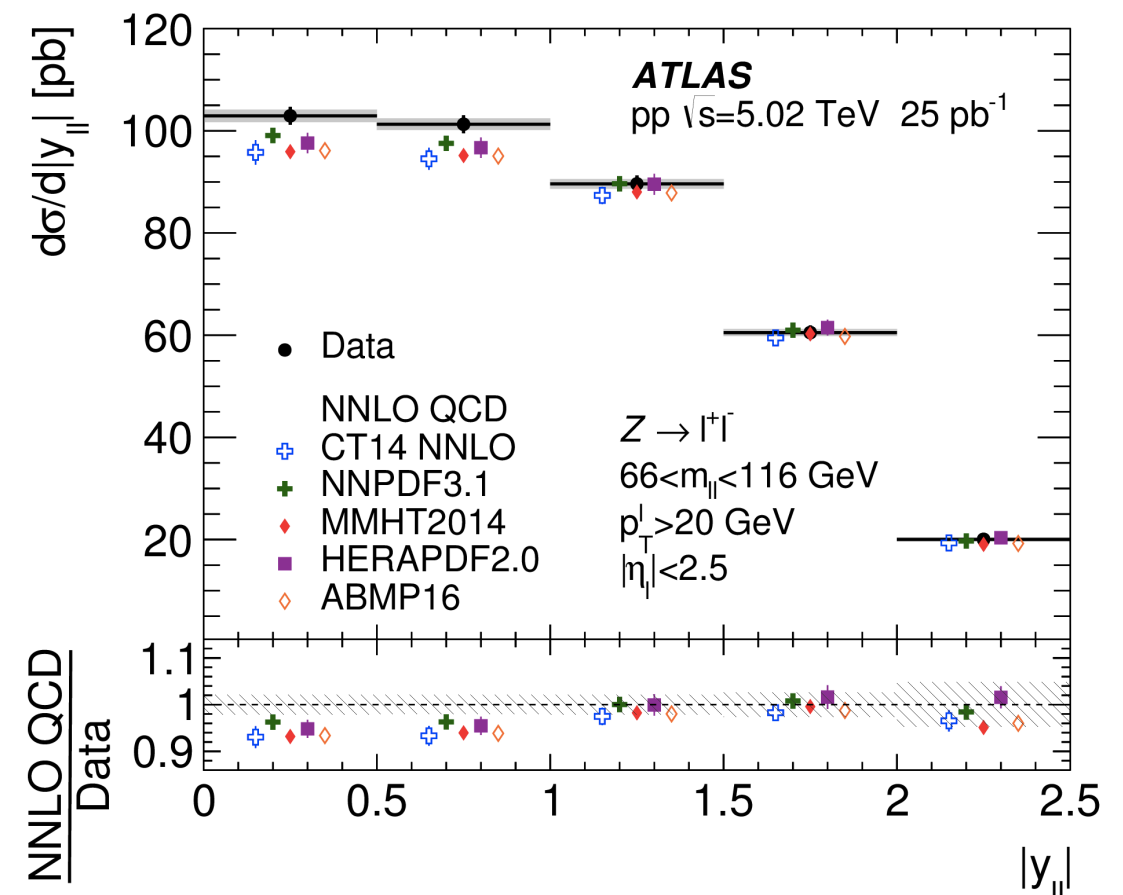
Z AND W BOSONS IN PP COLLISIONS

[Eur. Phys. J. C 79 (2019) 128]

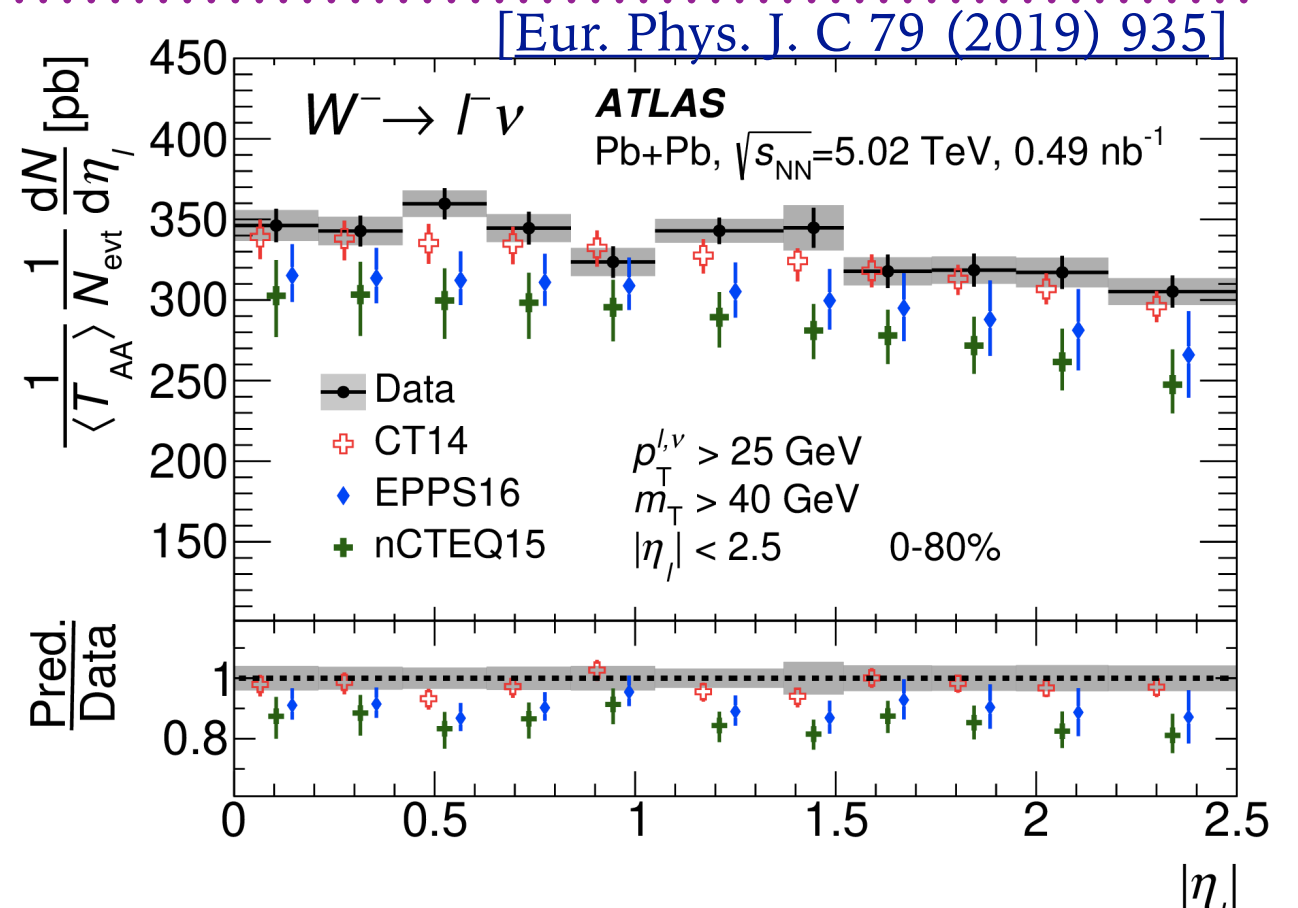
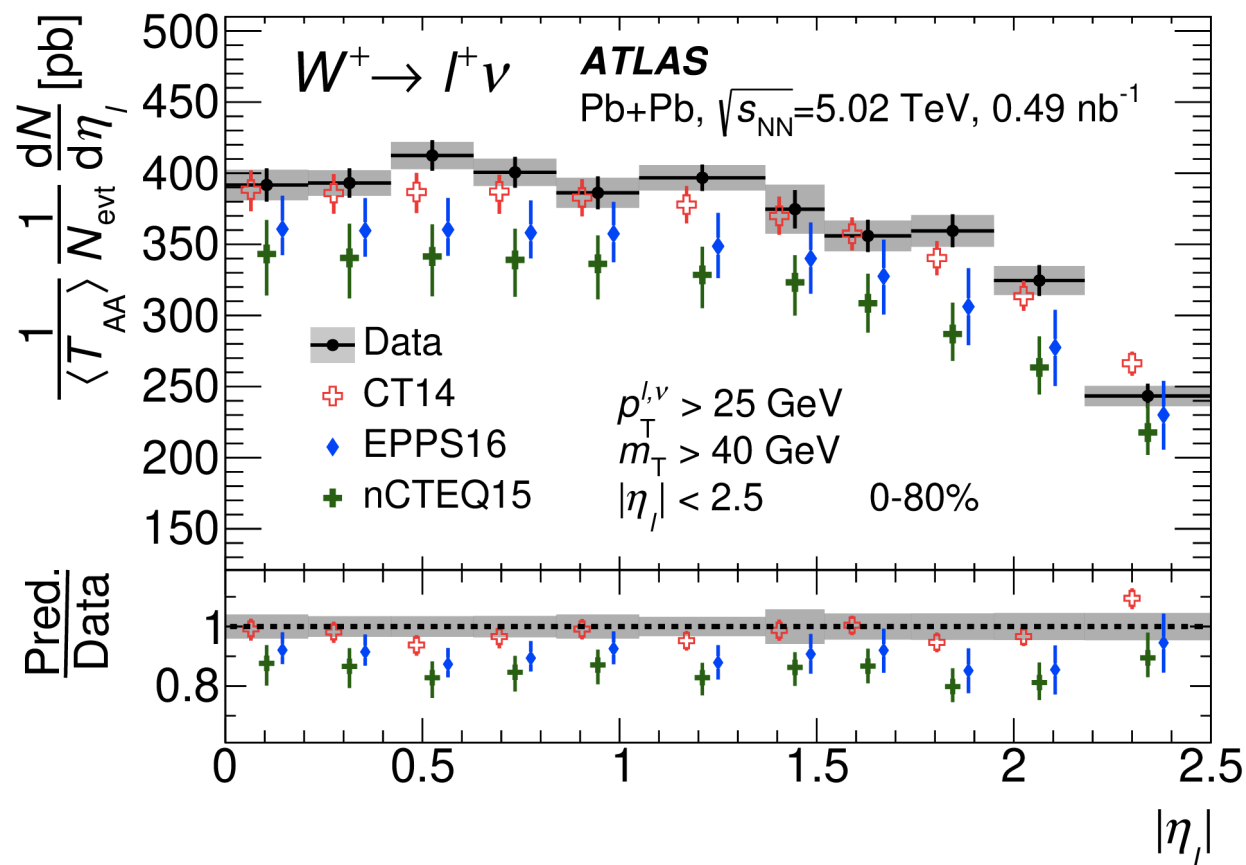
6



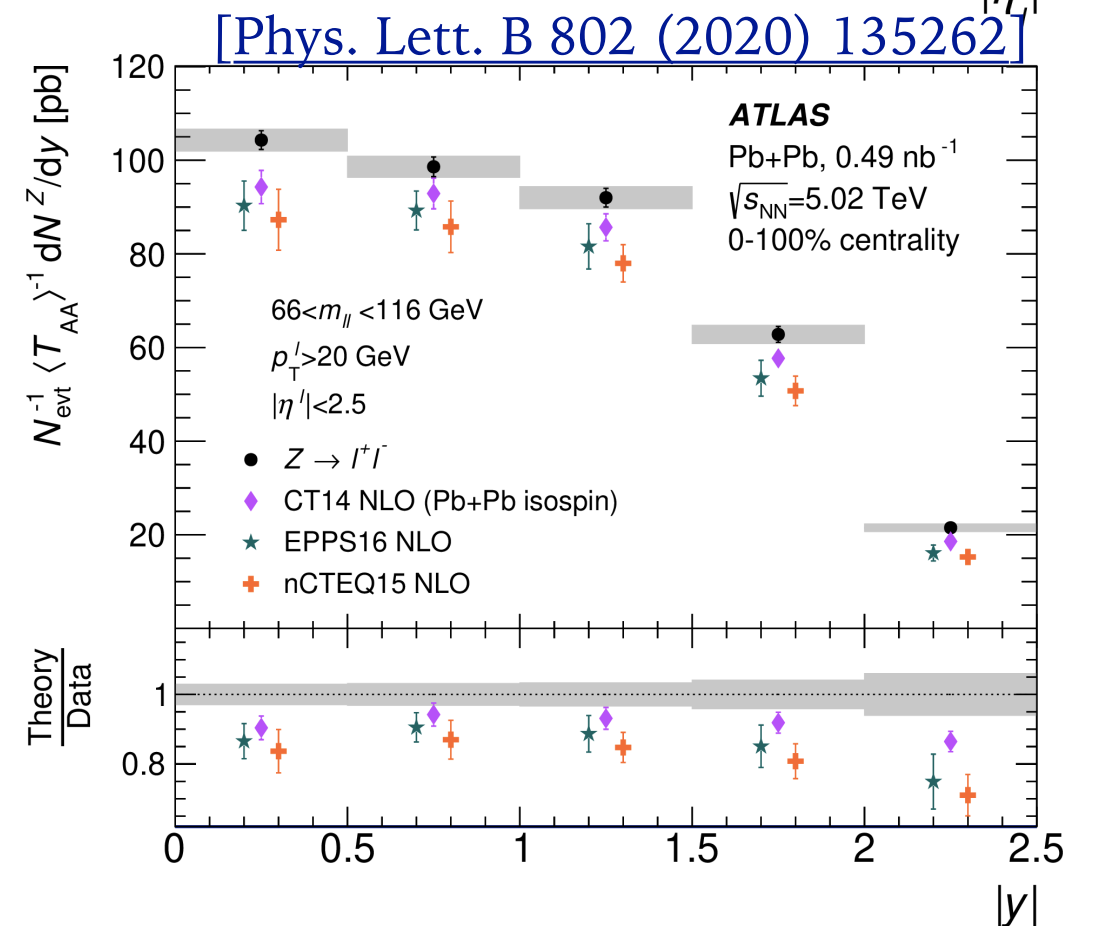
- W^+ , W^- and Z bosons measured in combined muon and electron channels in 5.02 TeV pp collisions
 - Reference data for EW bosons in Pb+Pb collisions
- Fiducial cross sections measured to within 1.2-1.7%
- Data compared to NNLO QCD predictions using various PDFs
- NNPDF3.1 in good agreement with data
- Other predictions exhibit 1–2 σ deviations



Z AND W BOSONS IN PB+PB



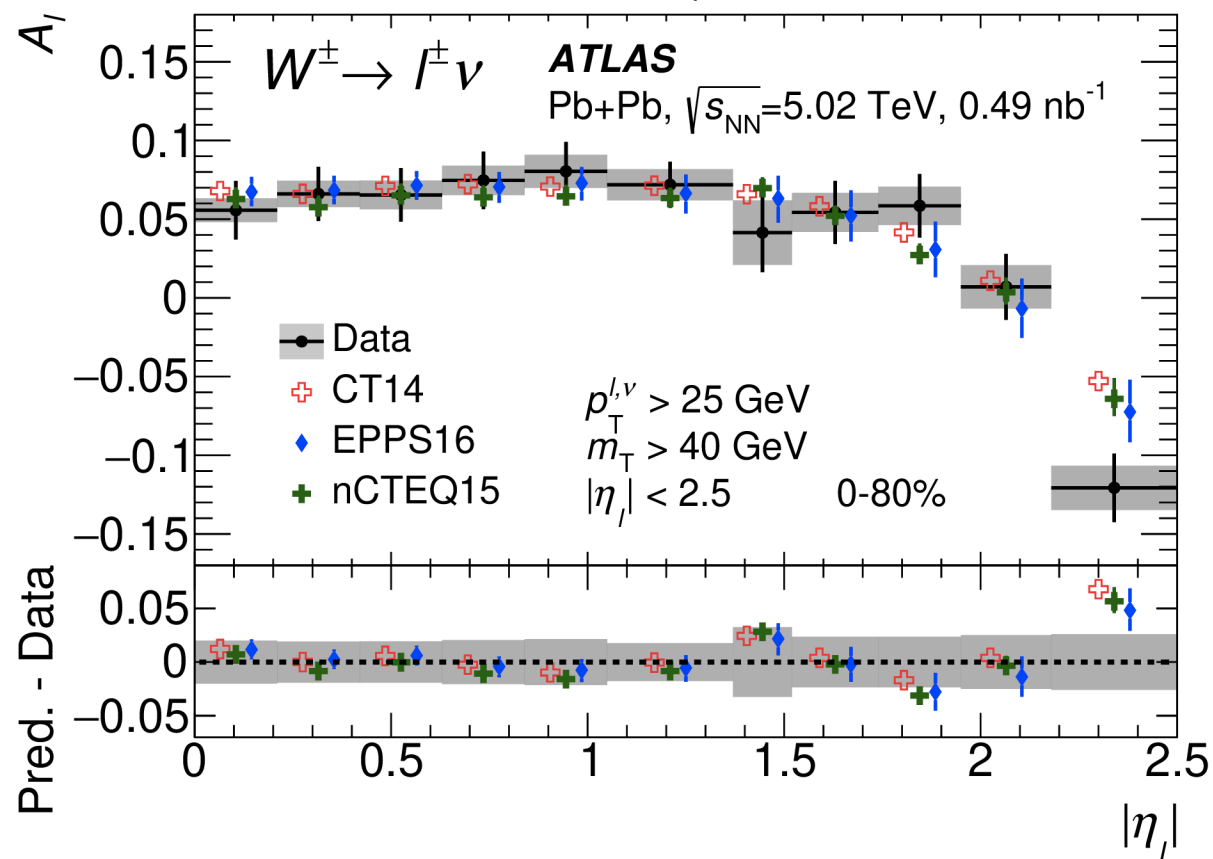
- Normalised W[±] and Z boson production yields measured in $|\eta_\ell|$ or $|y|$ in 5.02 TeV Pb+Pb
 - Combined muon and electron channels
- Data compared to NLO pQCD predictions (MCFM) using free PDF CT14 or nPDFs: EPPS16 and nCTEQ15
 - All predictions account for the **isospin effect**
 - All predictions describe shape well, while **normalisation is underestimated by 2-3% (CT14) and 10-20% (nPDFs)**



CHARGE ASYMMETRY

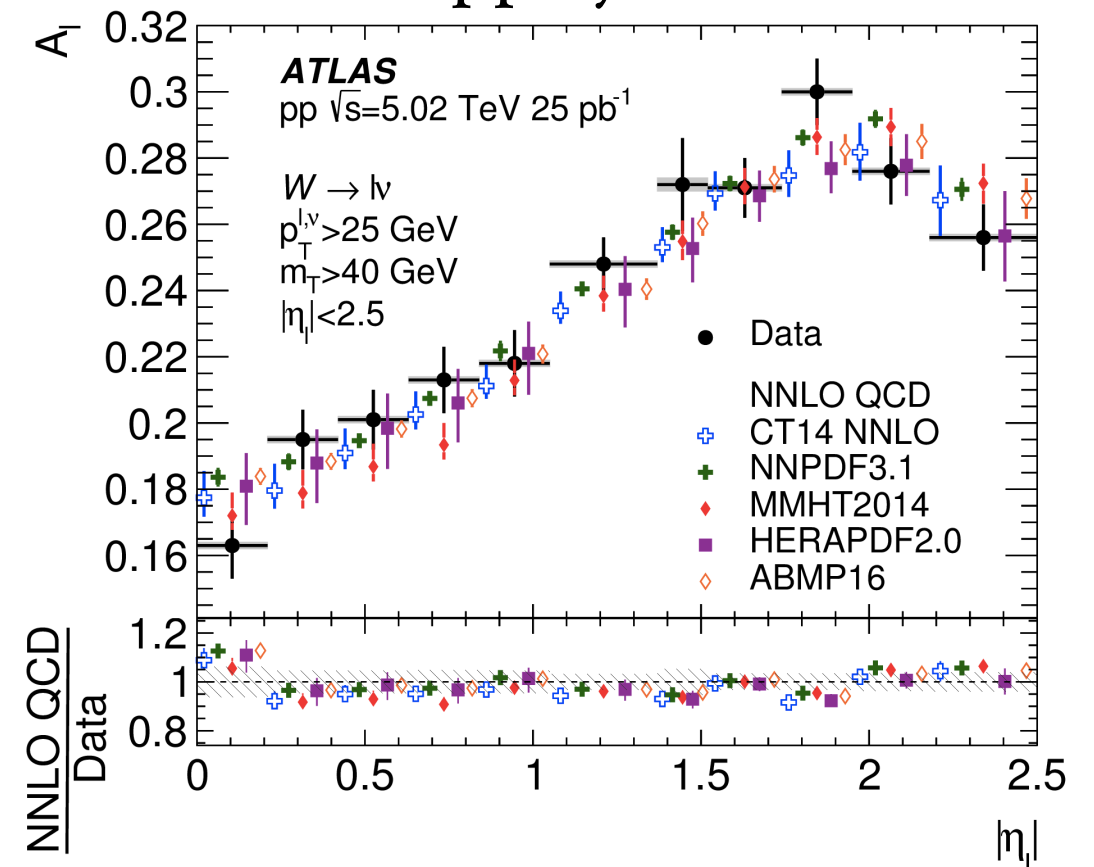
8

Pb+Pb system



[Eur. Phys. J. C 79 (2019) 935]

pp system



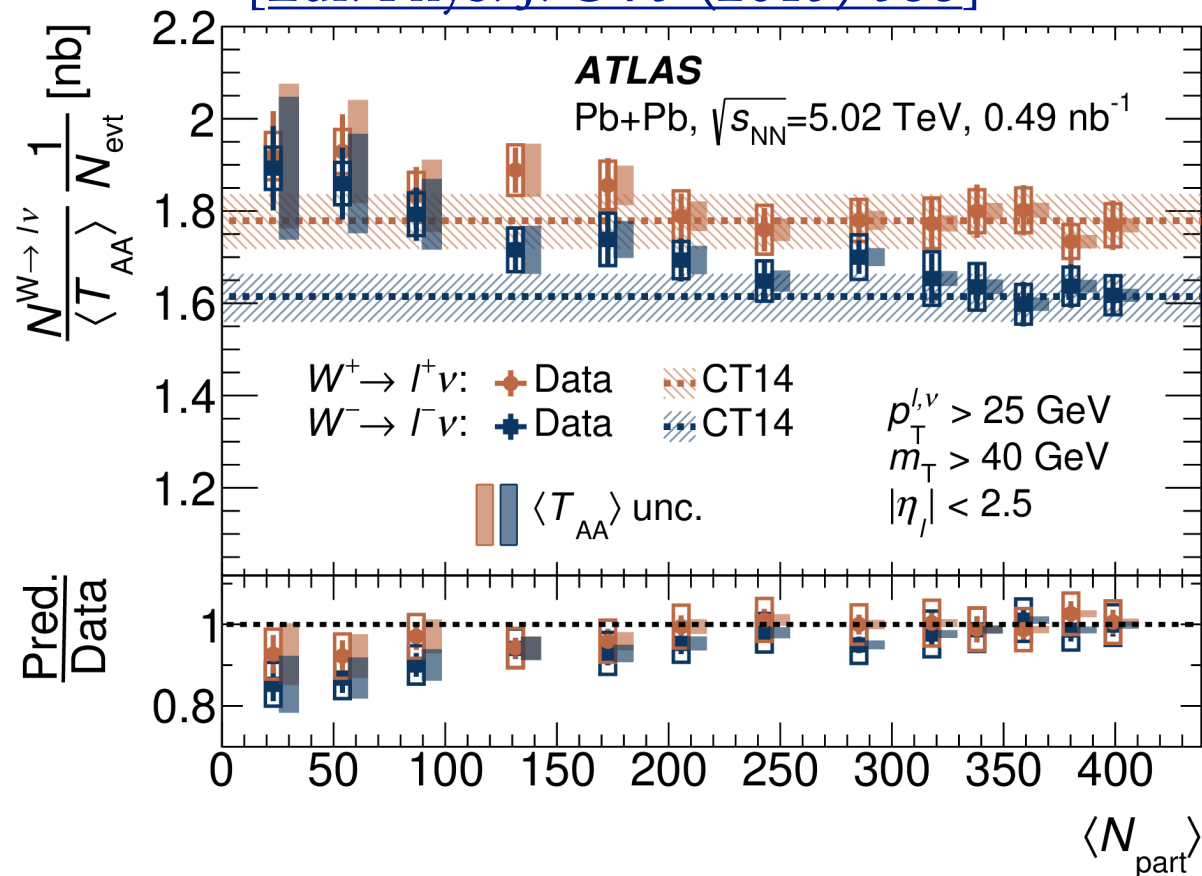
[Eur. Phys. J. C 79 (2019) 128]

$$A_{\ell}(|\eta_{\ell}|) = \frac{N^{W^+} - N^{W^-}}{N^{W^+} + N^{W^-}}$$

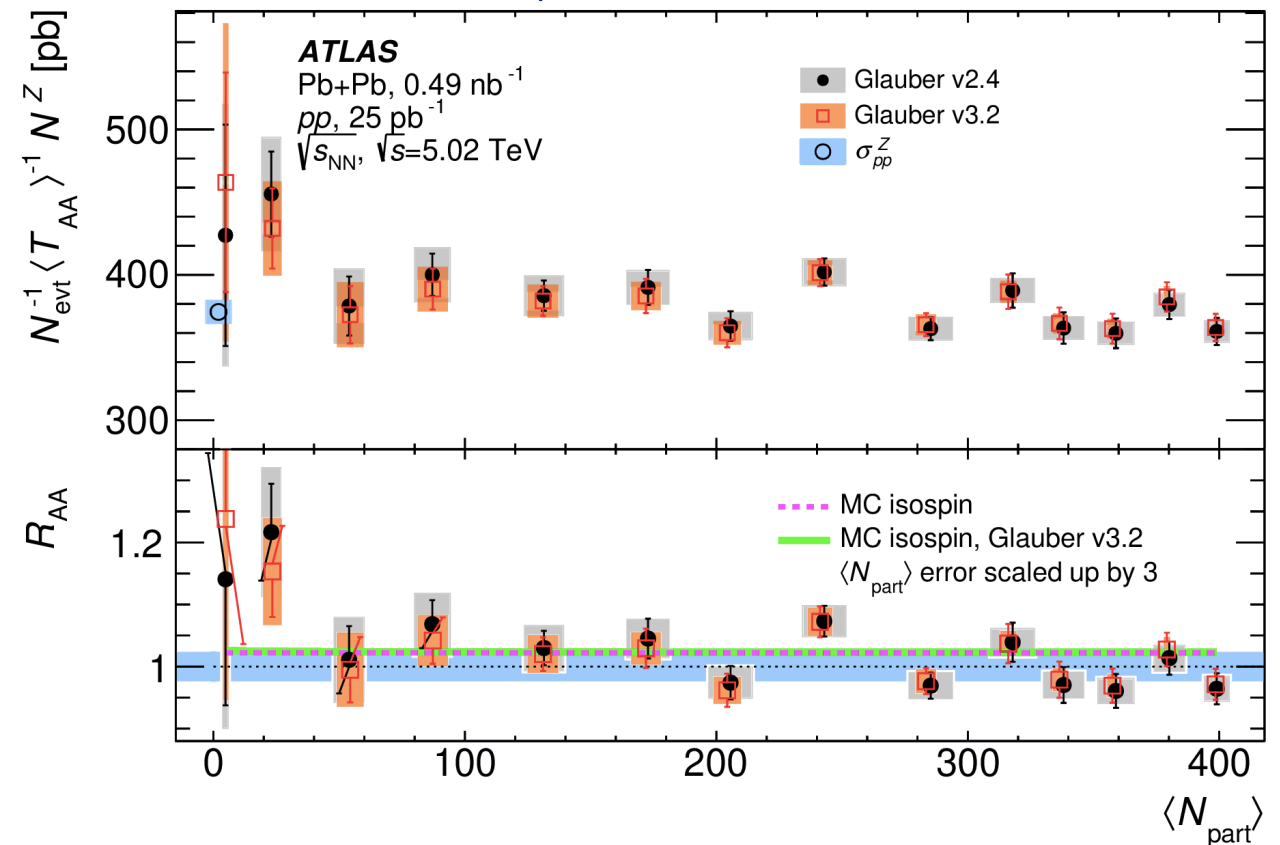
- **Charged-lepton asymmetry** of W^{\pm} measured in **Pb+Pb** (left) and **pp** (right) collisions at 5.02 TeV
 - Systematic uncertainties largely reduced in the ratio
 - A_{ℓ} sensitive to the quark content of projectiles
- Different shapes and absolute values of A_{ℓ} in the two systems
 - In Pb+Pb, A_{ℓ} becomes negative due to a larger number of W^- over W^+ in the most forward bin
- **Good description** of the data by predictions with various PDF and nPDF sets

W/Z SCALING WITH CENTRALITY

[Eur. Phys. J. C 79 (2019) 935]

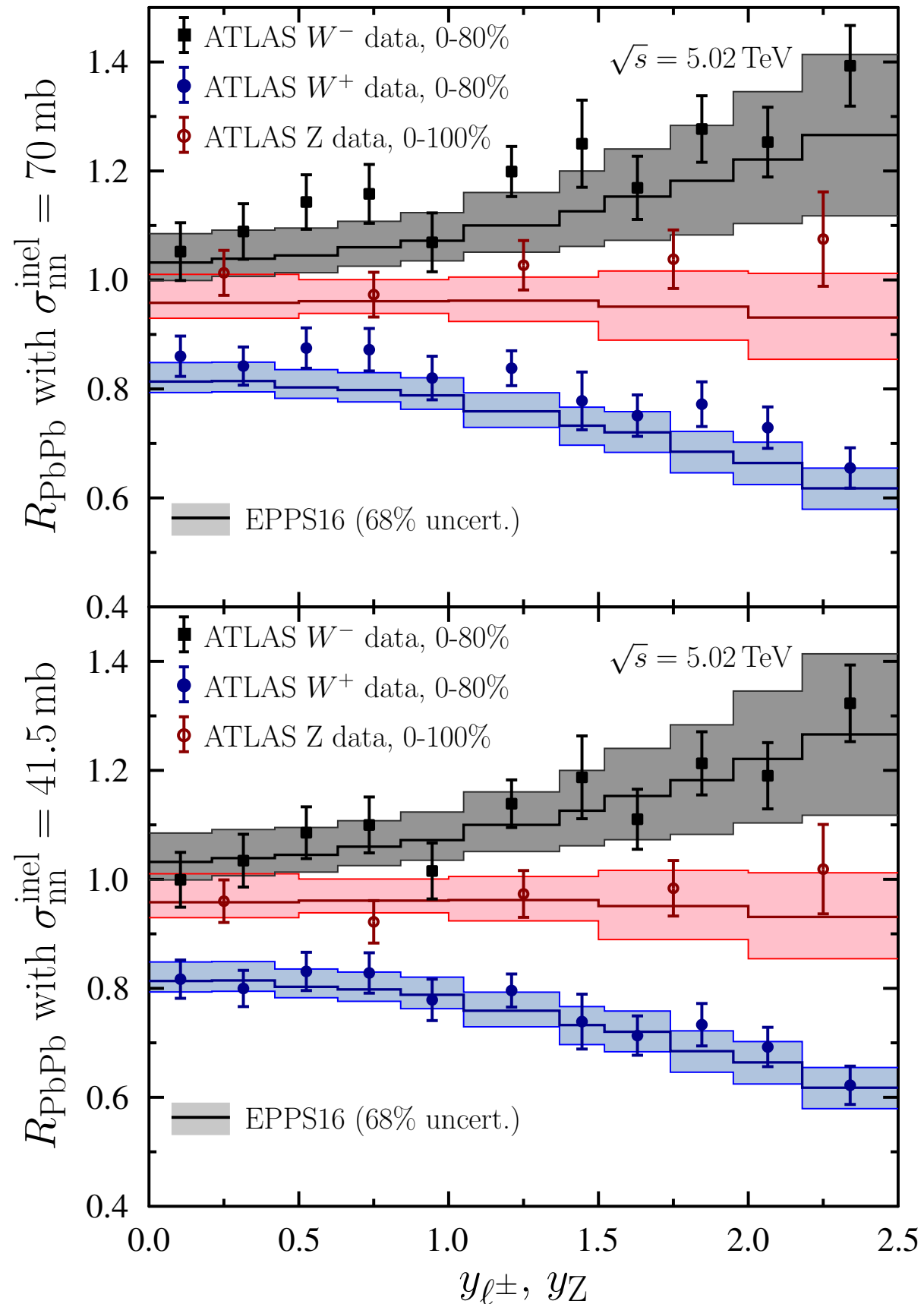


[Phys. Lett. B 802 (2020) 135262]

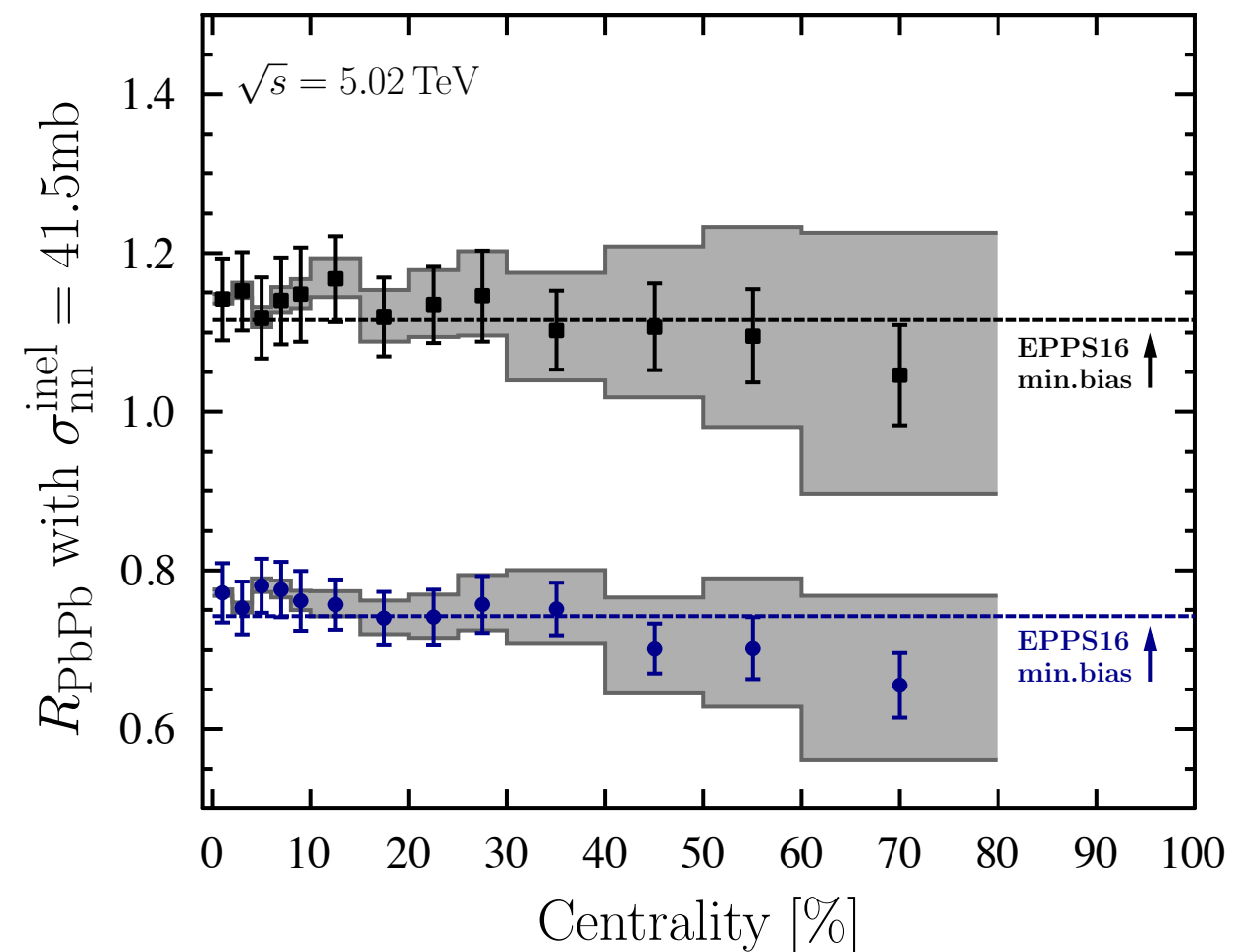


- **Normalised Z/W $^\pm$ boson production yields** as a function of centrality $\langle N_{\text{part}} \rangle$ test scaling with nuclear thickness function $\langle T_{AA} \rangle = \langle N_{\text{coll}} \rangle / \sigma_{NN}^{\text{inel}}$ from MCGlauber v2.4
- W $^\pm$ bosons: normalised yields of W $^+$ bosons are about 10% higher than W $^-$
- Z bosons: normalised yields **are consistent** with σ_{pp}^Z
- Data is compared to NLO CT14 predictions
 - **Good agreement** for Z bosons and for W $^\pm$ bosons at mid-central and central events
 - W $^\pm$ bosons: for $\langle N_{\text{part}} \rangle < 200$ (peripheral) **the excess** of W $^+$ (W $^-$) up to 0.8 (1.7) σ is observed
 - Minor difference between MCGlauber v2.4 and v3.2

SHADOWING IN INELASTIC NN CROSS SECTION

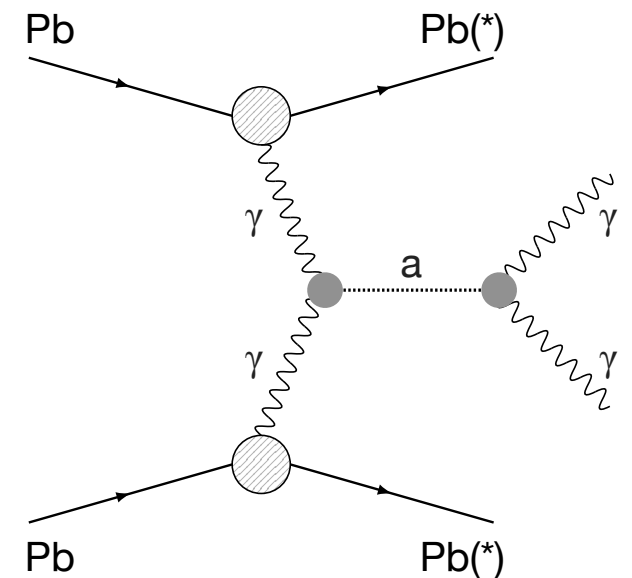
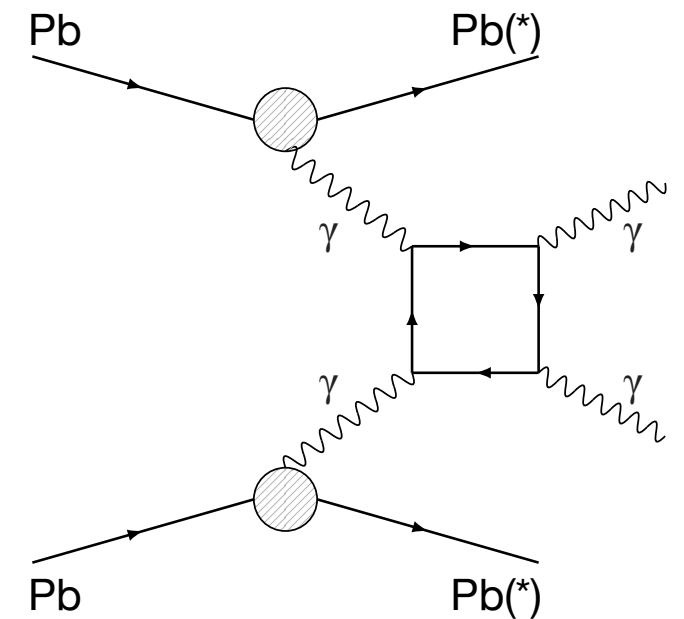


- In the paper by K.Eskola et al [\[arXiv:2003.11856\]](https://arxiv.org/abs/2003.11856)
 - Traditionally $\sigma_{\text{NN}}^{\text{inel}} = 70 \text{ mb}$ used as input to MCGlauber
 - What about if $\sigma_{\text{NN}}^{\text{inel}}$ is modified at high energy in HIC? (gluon shadowing, saturation phenomena)
 - From the fit to η, y -dependent normalised yields:
 $\sigma_{\text{NN}}^{\text{inel}} = 41.5^{+16.2}_{-12.0} \text{ mb}$
 - Very good agreement in R_{PbPb} for Z and W bosons
 - Conclusion: Standard paradigm of using $\sigma_{\text{NN}}^{\text{inel}} = 70 \text{ mb}$ may lead to a misinterpretation of the experimental data



LIGHT-BY-LIGHT SCATTERING AND AXIONS

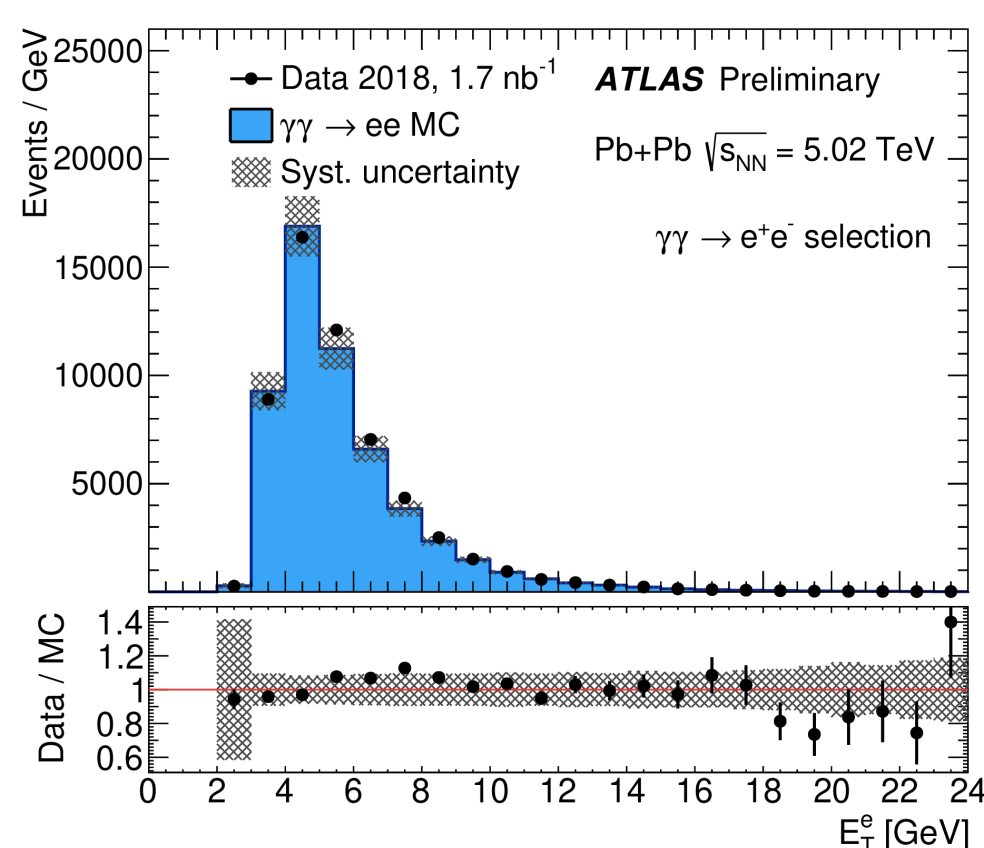
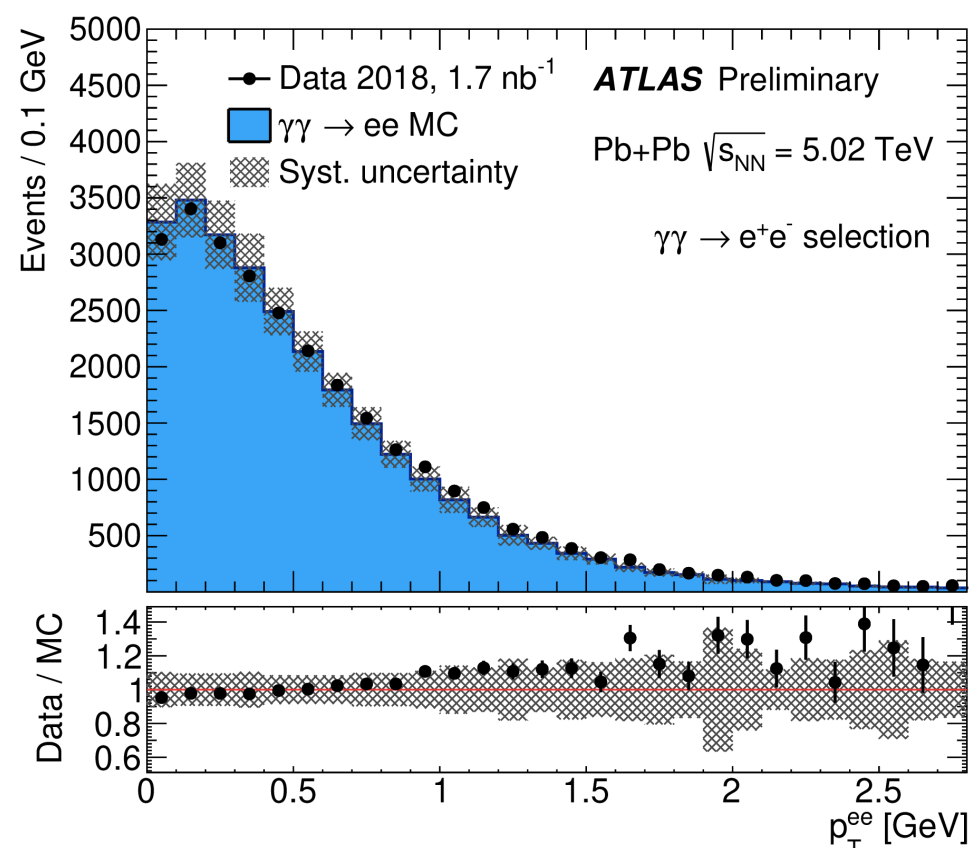
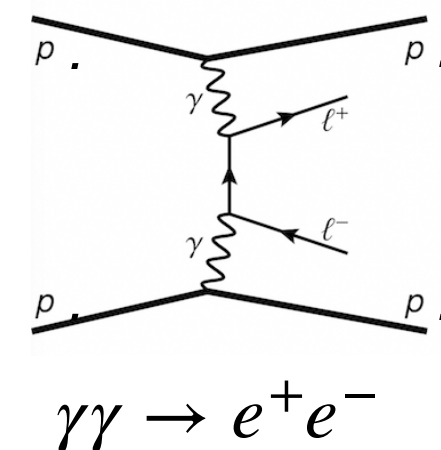
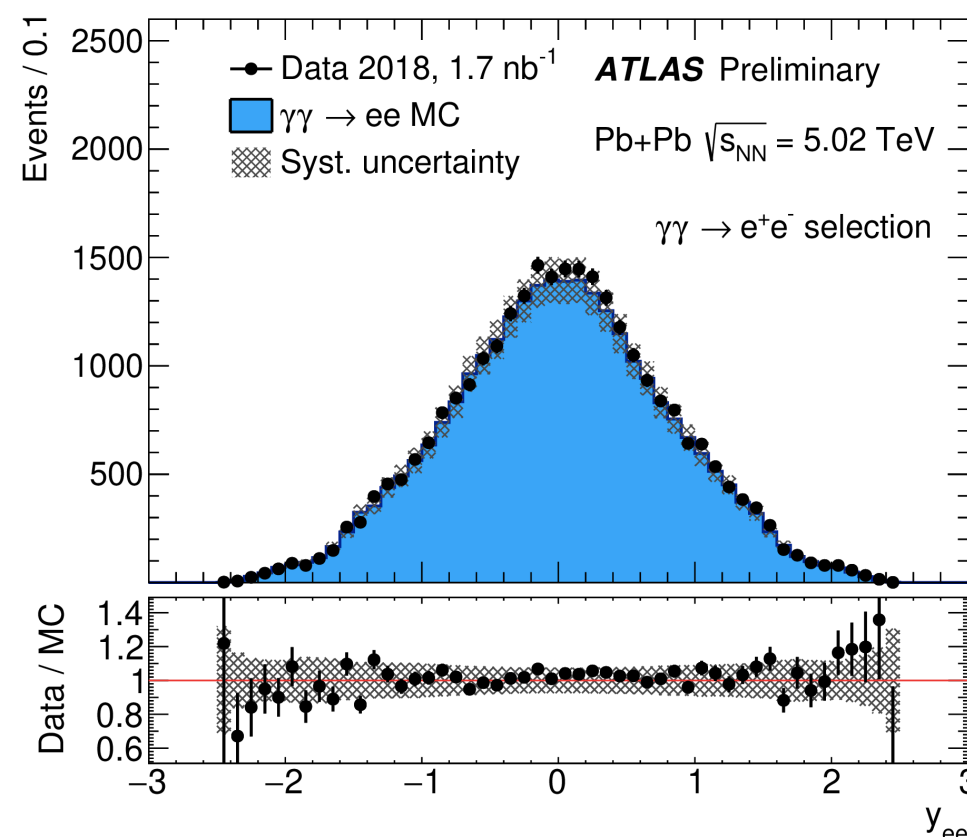
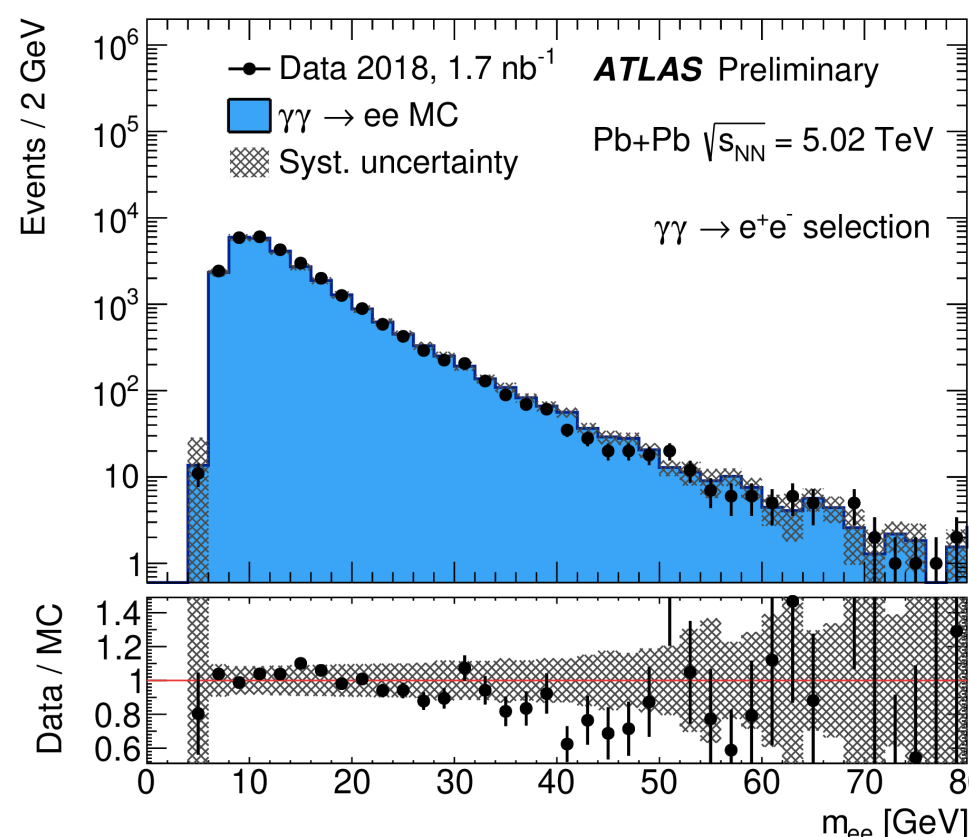
- **NEW** result on **LbyL scattering** ($\gamma\gamma \rightarrow \gamma\gamma$) from ATLAS
 - **Fundamental QED** process with a **tiny cross section**
 - Prior to the LHC, tested indirectly (anomalous magnet moment of the electron and muon)
 - **Sensitive to new physics**
 - Possible contributions from new particles beyond SM
 - Anomalous gauge couplings
- Earlier results at the LHC:
 - **Evidence** with **2015** data: ATLAS and CMS [[Nat. Phys. 13 \(2017\) 852–858](#), [Phys. Lett. B 797 \(2019\) 134826](#)]
 - **Observation** with **2018** data: ATLAS [[Phys. Rev. Lett. 123 \(2019\) 052001](#)]
- Several improvements introduced in **the NEW result**:
 - All Run-2 Pb+Pb data (2015+2018): **2.2 nb⁻¹**
 - **Improved luminosity** calibration: 3.2% uncertainty
 - **Lower photon E_T threshold** ($E_T > 2.5$ GeV)
 - **Differential cross sections**
 - **Search for axion-like particles (ALP)**



CONTROL PLOTS FOR EXCLUSIVE DIELECTRONS

New 12

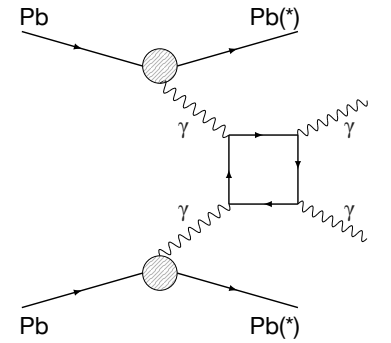
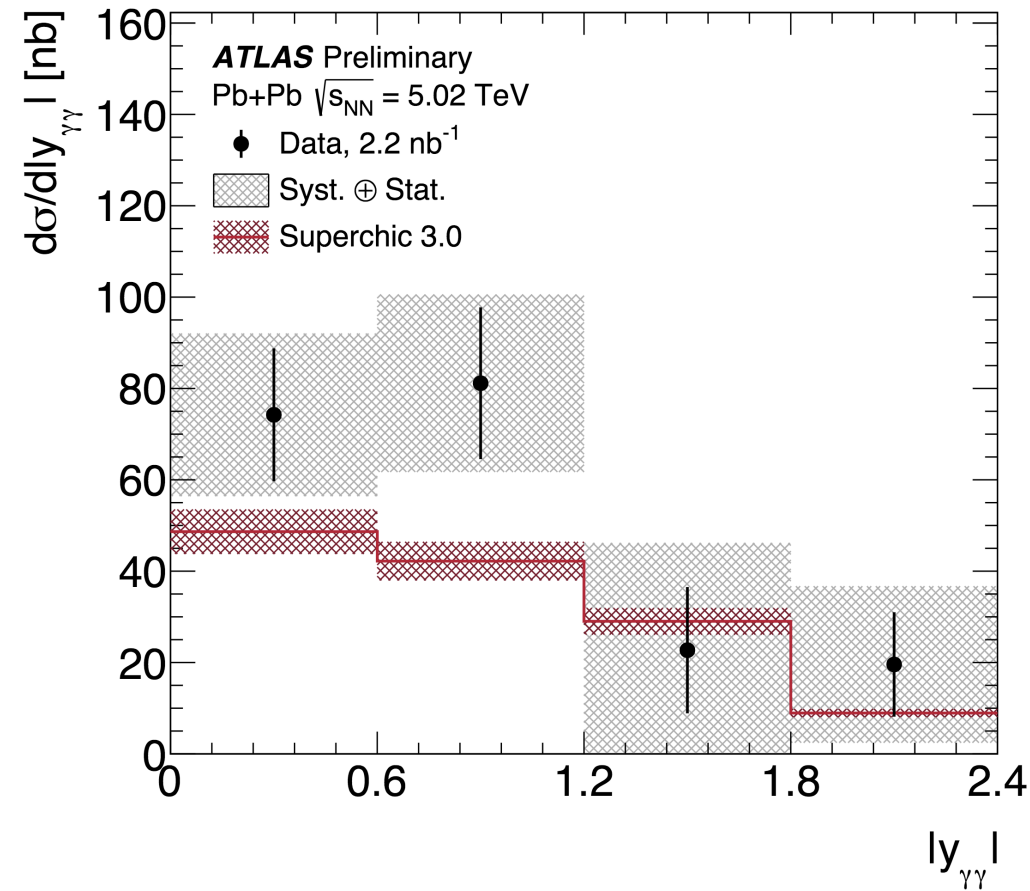
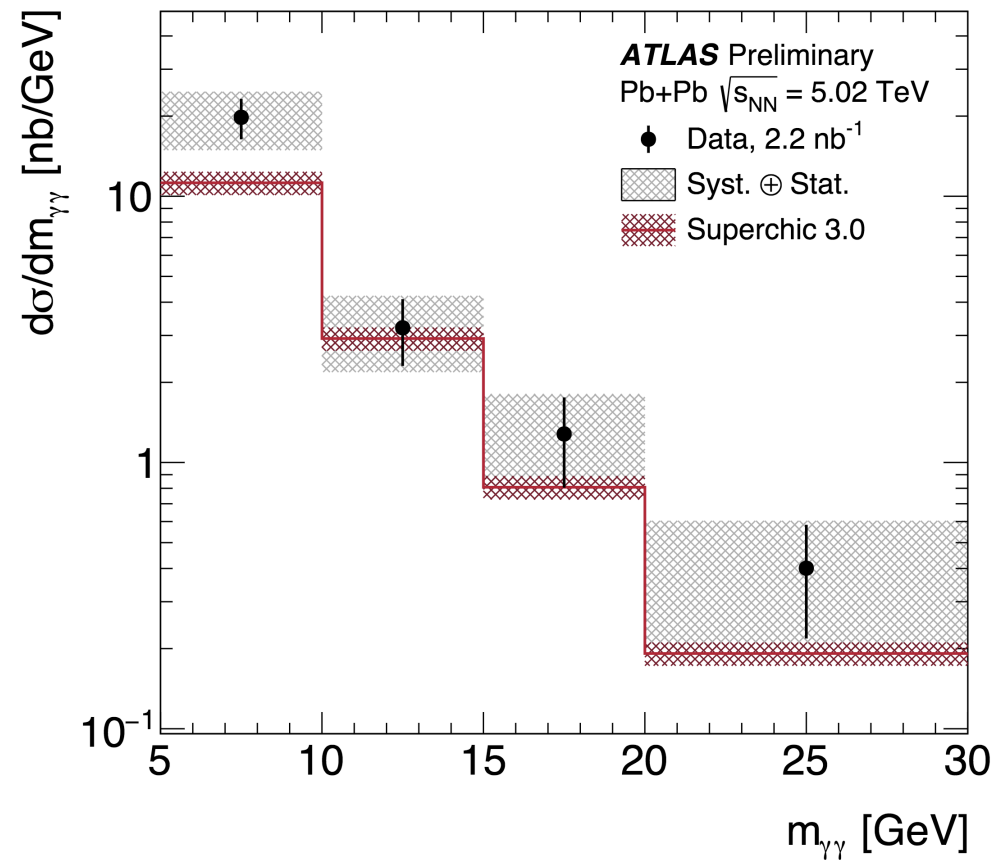
[ATLAS-CONF-2020-010]



► Very good agreement between 2018 data and MC simulation (STARLight)

LIGHT-BY-LIGHT CROSS SECTIONS

New [ATLAS-CONF-2020-010]



- Cross section in the fiducial region $E_T^\gamma > 2.5$ GeV, $m_{\gamma\gamma} > 5$ GeV, $|\eta^\gamma| < 2.4$, $p_T^{\gamma\gamma} < 1$ GeV

$$\sigma_{\text{fid}}^{\text{meas}} = 120 \pm 17 \text{ (stat.)} \pm 13 \text{ (syst.)} \pm 4 \text{ (lumi.) nb}$$

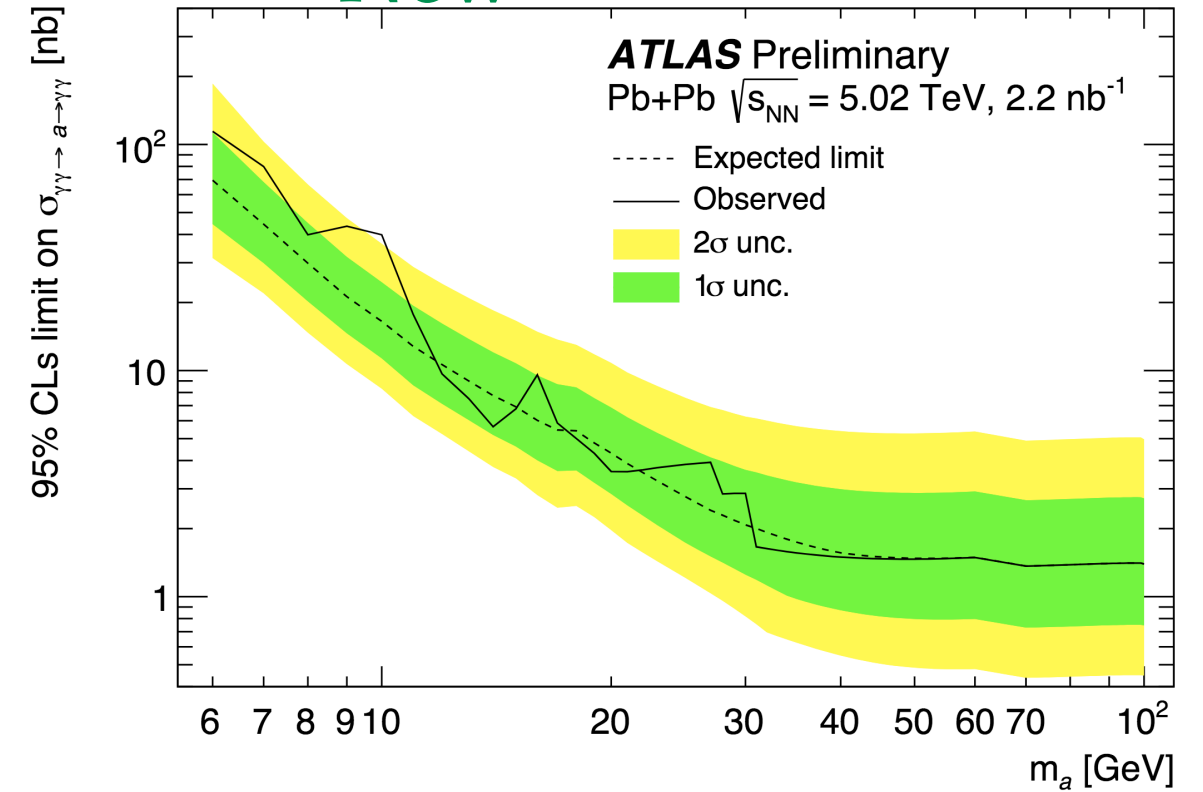
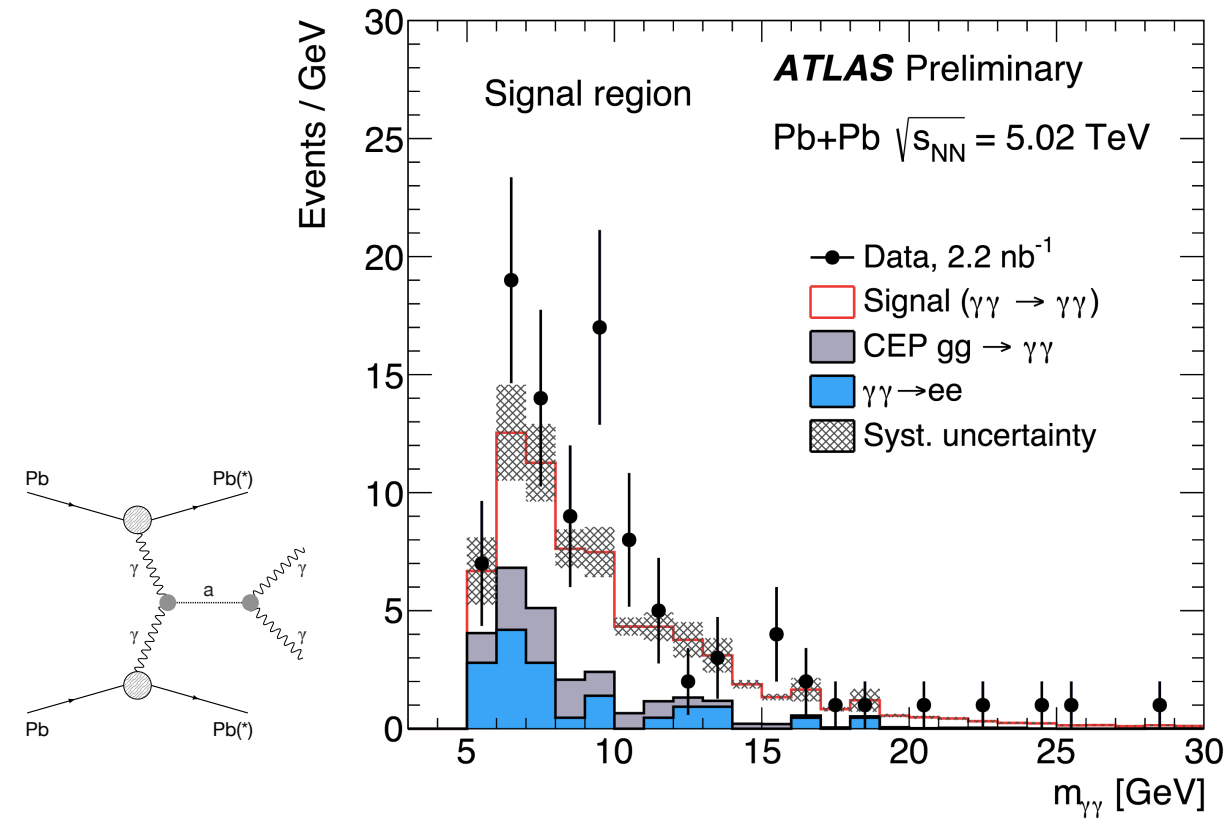
- Comparison to theory predictions

$$\sigma_{\text{fid}}^{\text{theory1}} = 80 \pm 8 \text{ nb by M.Klusek-Gawenda et al. [Phys. Rev. C 93 (2016) 044907]}$$

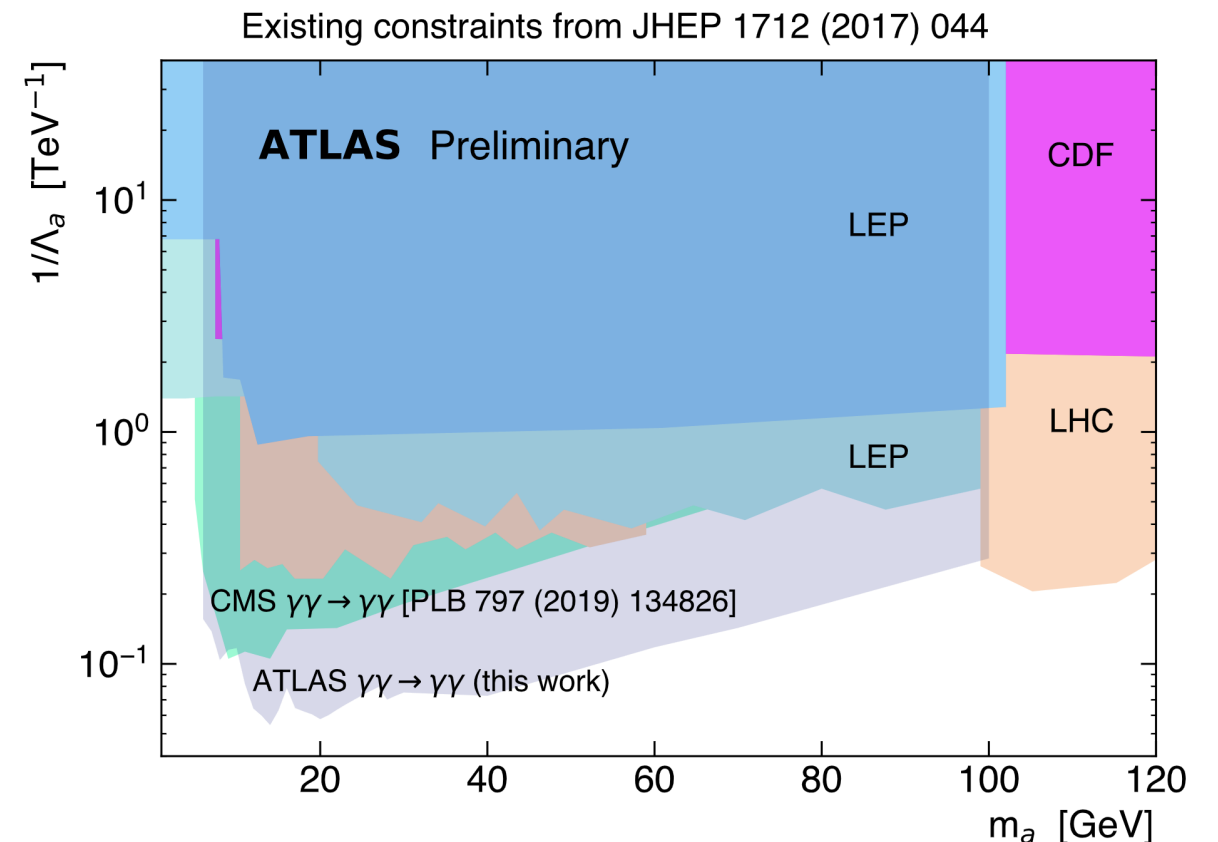
$$\sigma_{\text{fid}}^{\text{theory2}} = 78 \pm 8 \text{ nb from SuperChic 3.0 [Eur. Phys. J. C 79 (2019) 39]}$$

- Theory about 50% below data
- Differential cross sections measured in four variables: $m_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, $|\cos \theta^*|$, $(p_T^{\gamma 1} + p_T^{\gamma 2})/2$
 - Good agreement in shape, differences in the normalisation

New [ATLAS-CONF-2020-010]



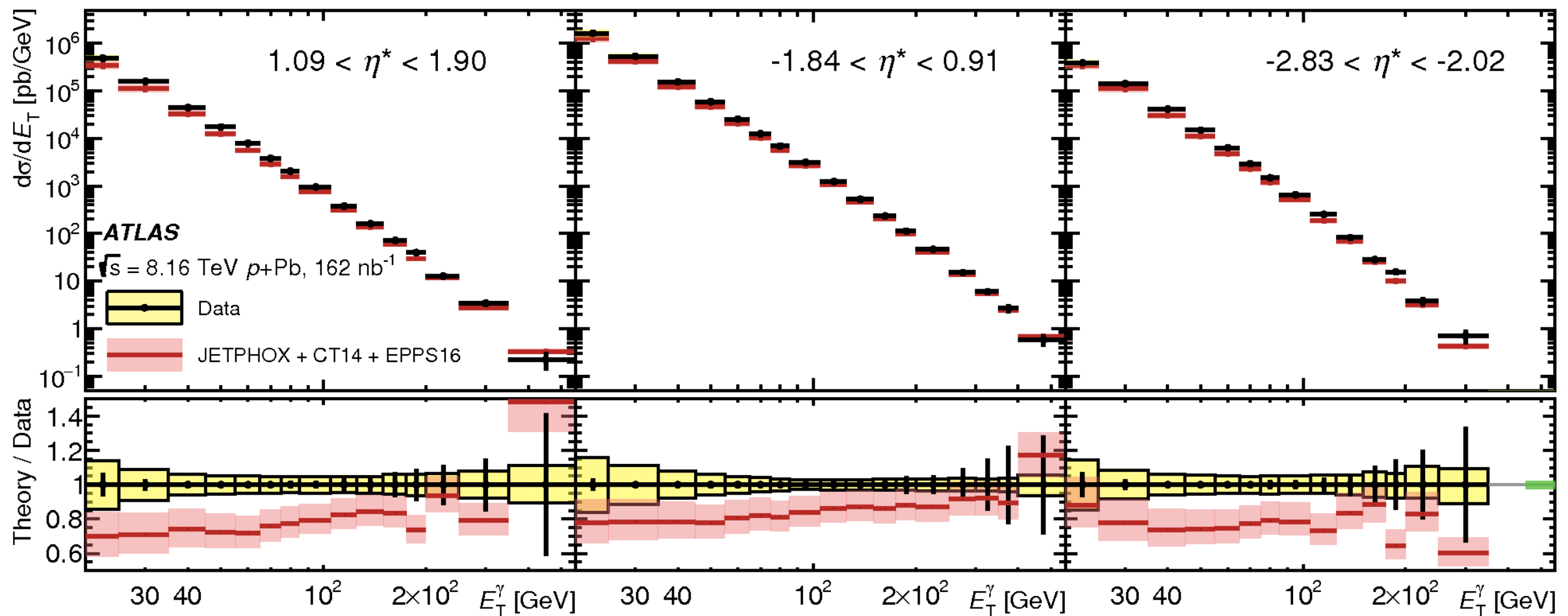
- Distribution of $m_{\gamma\gamma}$ used to search for ALP in $6 < m_{\gamma\gamma} < 100$ GeV range using a cut-and-count method
 - Signal: $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$, $\text{BR}(a \rightarrow \gamma\gamma) = 100\%$
 - Background: LbyL, $\gamma\gamma \rightarrow e^+e^-$, central exclusive production of $gg \rightarrow \gamma\gamma$
- 95% CL limits on σ and coupling $1/\Lambda_a$
 - Largest deviation of 2.1σ at $m_{\gamma\gamma} \sim 10$ GeV
 - **The most stringent limit** established for ALP masses between 6-100 GeV



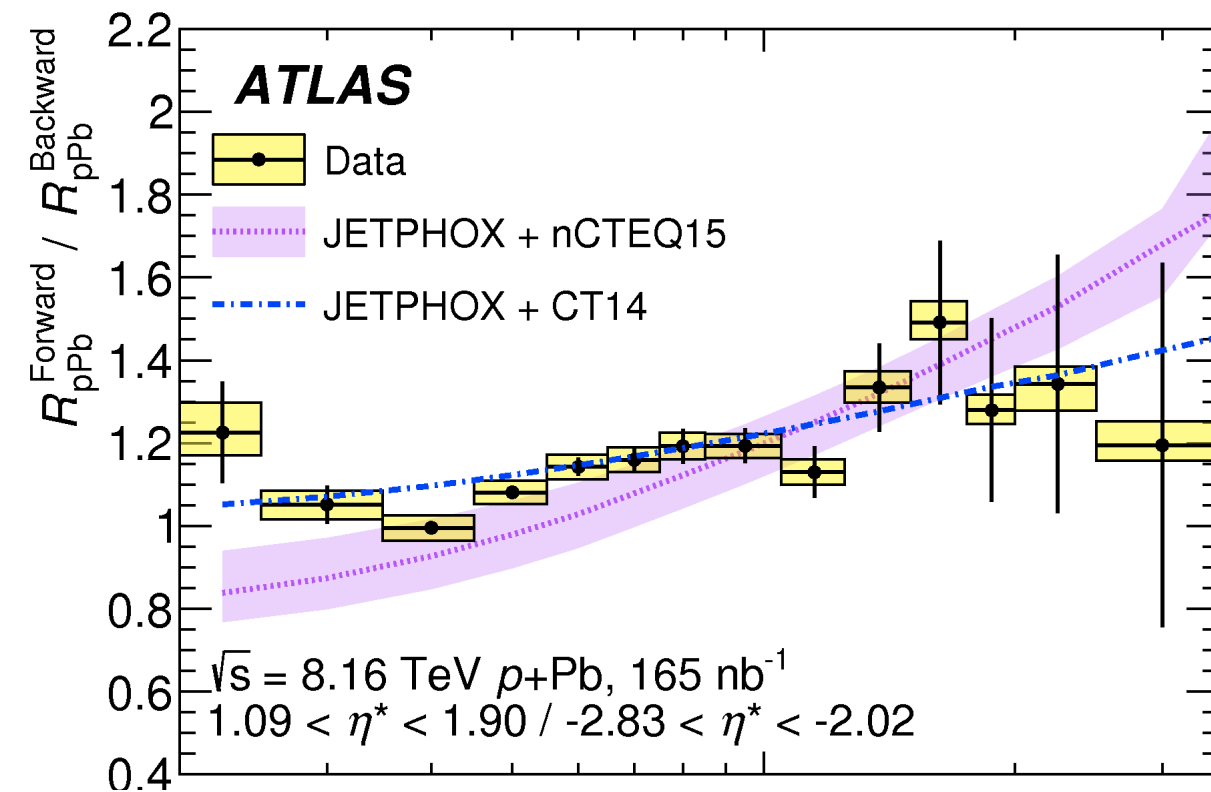
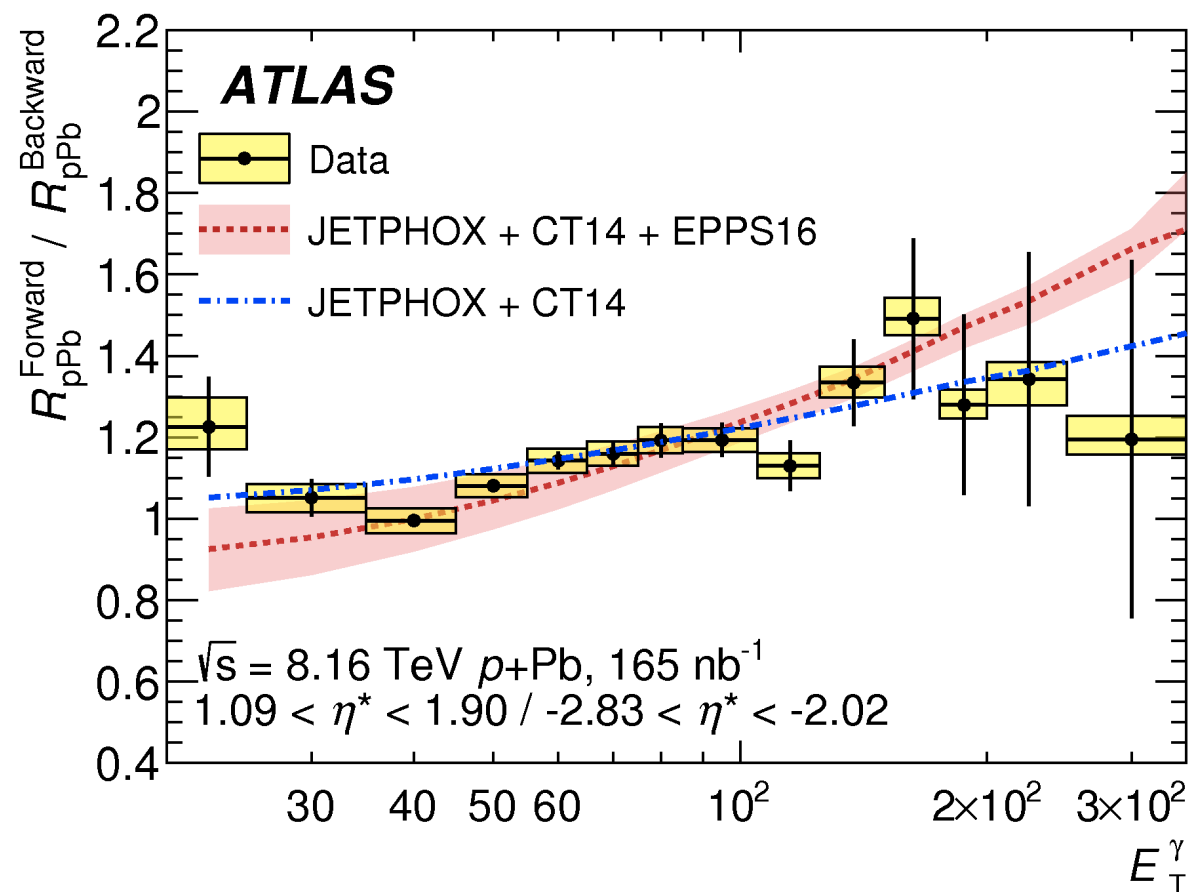
SUMMARY

- **Final results on prompt photons in 8.16 TeV p+Pb collisions** provide insight into initial-state physics
 - Important role of the **isospin effect** in the backward direction
 - With the current precision both w/o and w/ nuclear PDFs are supported
- **Final results on Z and W^\pm bosons in pp and Pb+Pb collisions at 5.02 TeV from 2015**
 - Most precise results from the LHC at the moment
 - **Isospin effect** very important to describe W^\pm bosons
 - **Standard candles** of HIC
- **New preliminary result on light-by-light scattering and search of axion-like particles with full Run-2 Pb+Pb data**
 - Measurement of total fiducial and differential cross sections
 - Most stringent limits on ALP production for $6 < m_a < 100$ GeV established
 - Poster by **Klaudia Maj** on June 2nd at 7:30am
- About **3 times** more data from the **2018 Pb+Pb** run at 5.02 TeV available
 - Results on **γ -jet and Z-jet correlations** presented by **Jeff Ouellette** on June 4th at 1:30PM
- All results from ATLAS available at
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults>

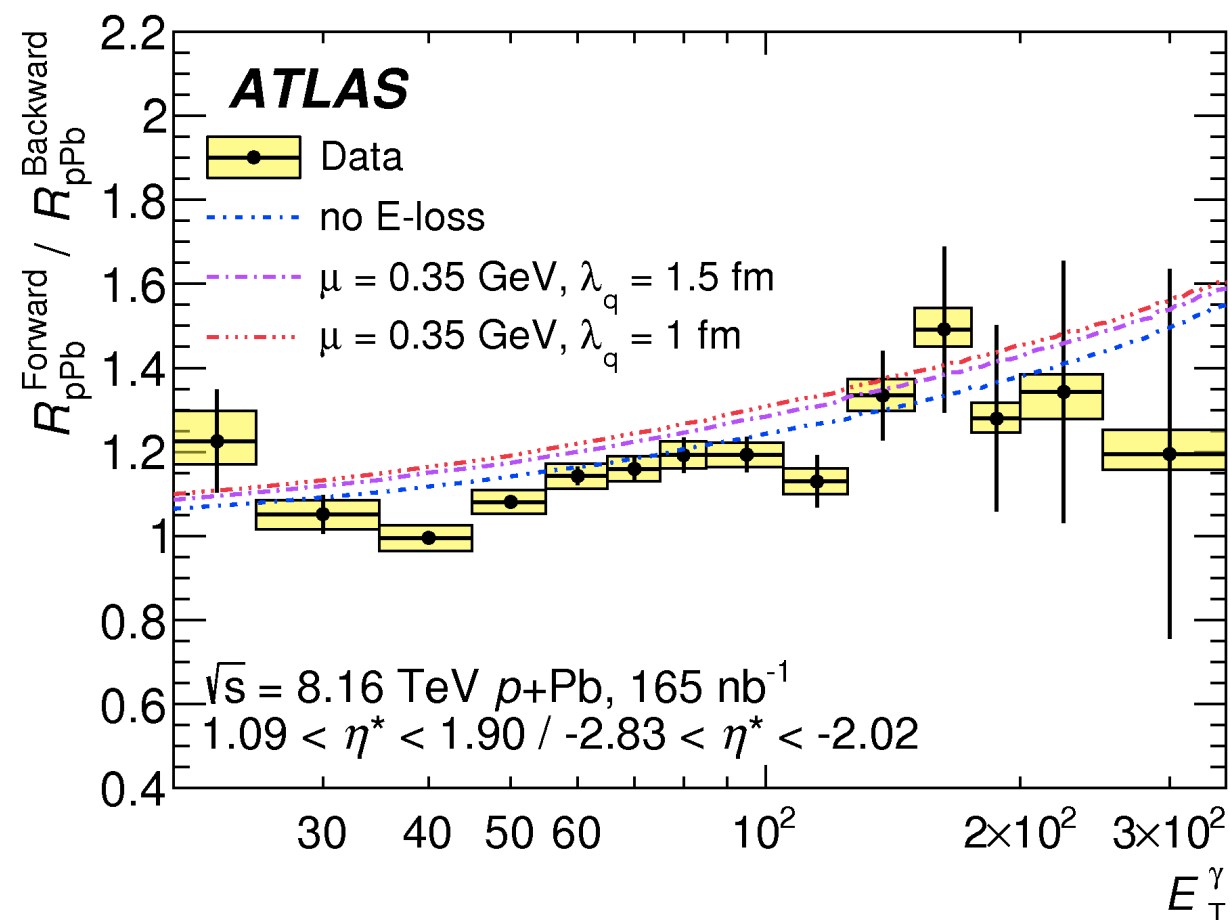
BACK-UP SLIDES

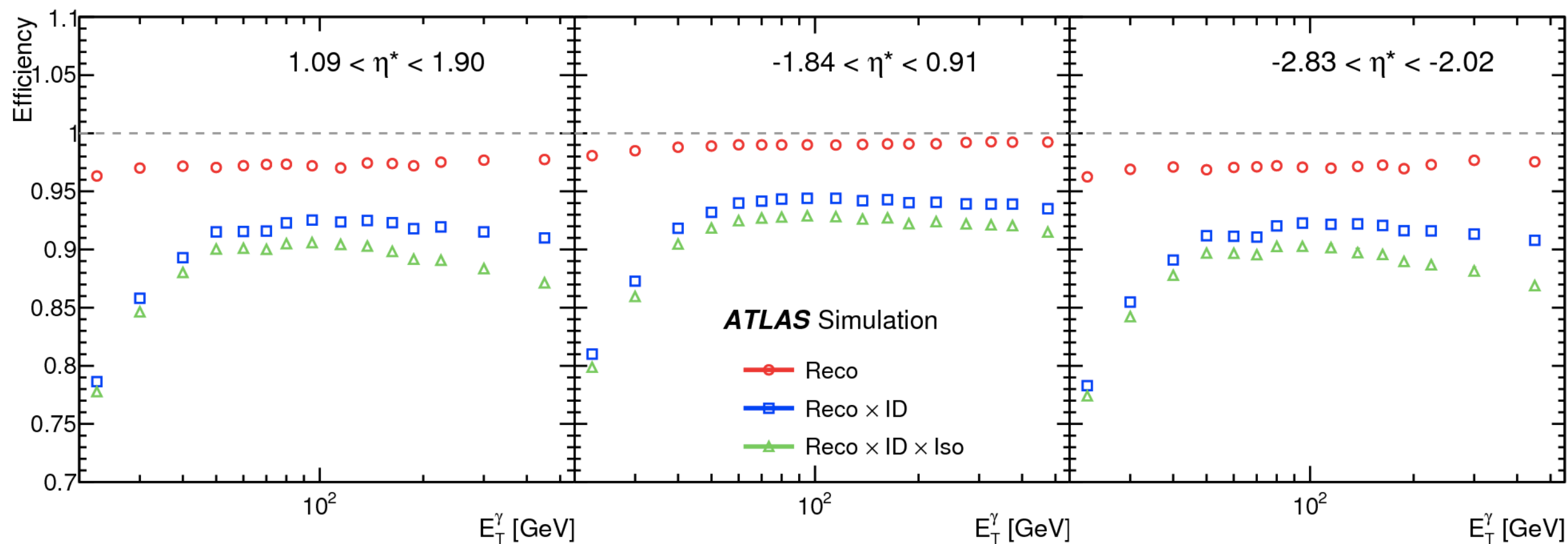


- Photon production cross sections in photon E_T measured in 20-500 GeV in three centre-of-mass η^* slices in 8.16 TeV p+Pb collisions
- Measurement sensitive to $3 \times 10^{-3} < x_A < 4 \times 10^{-1}$ (shadowing $x_A < 0.1$, anti-shadowing $0.1 < x_A < 0.3$ and EMC $0.3 < x_A < 0.7$)
- Data compared with NLO pQCD calculation from JETPHOX (direct+fragmentation contributions)+CT14+EPPS16
 - Prediction is systematically lower than the data by up to 20% at low E_T and closer to the data at high E_T
 - Observation consistent with measurements in pp collisions

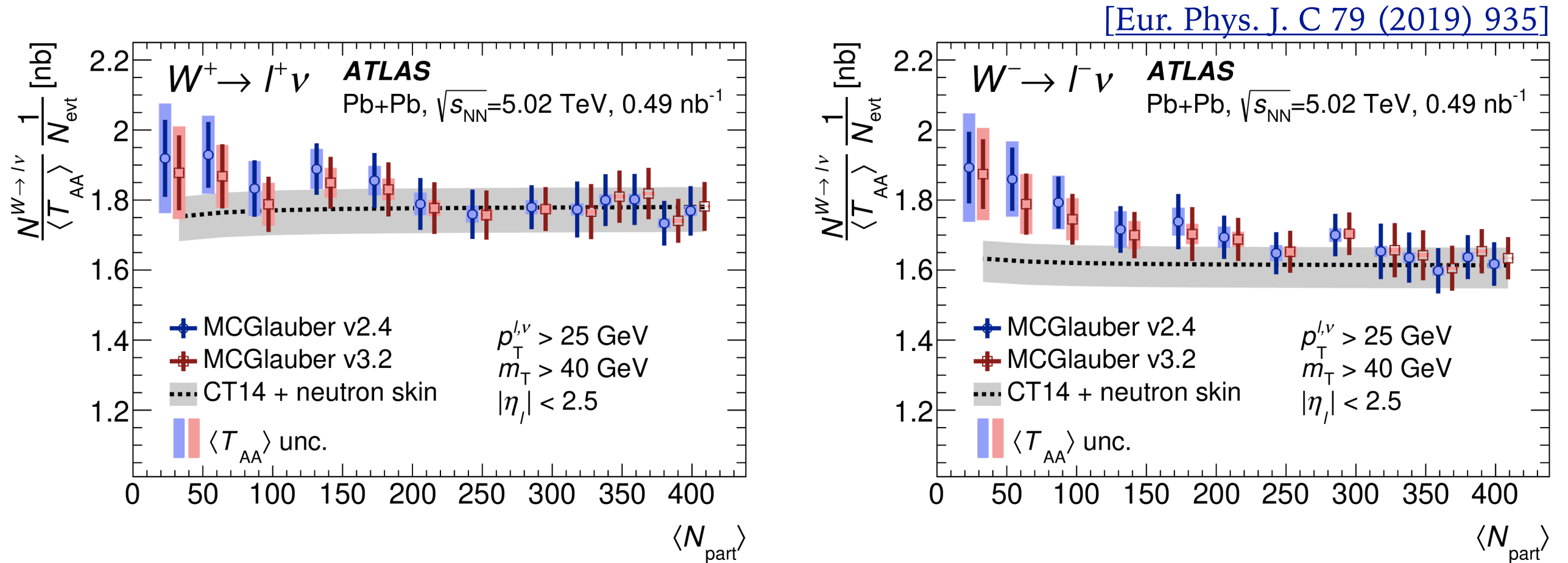


- Conclusions similar to those for R_{pPb}





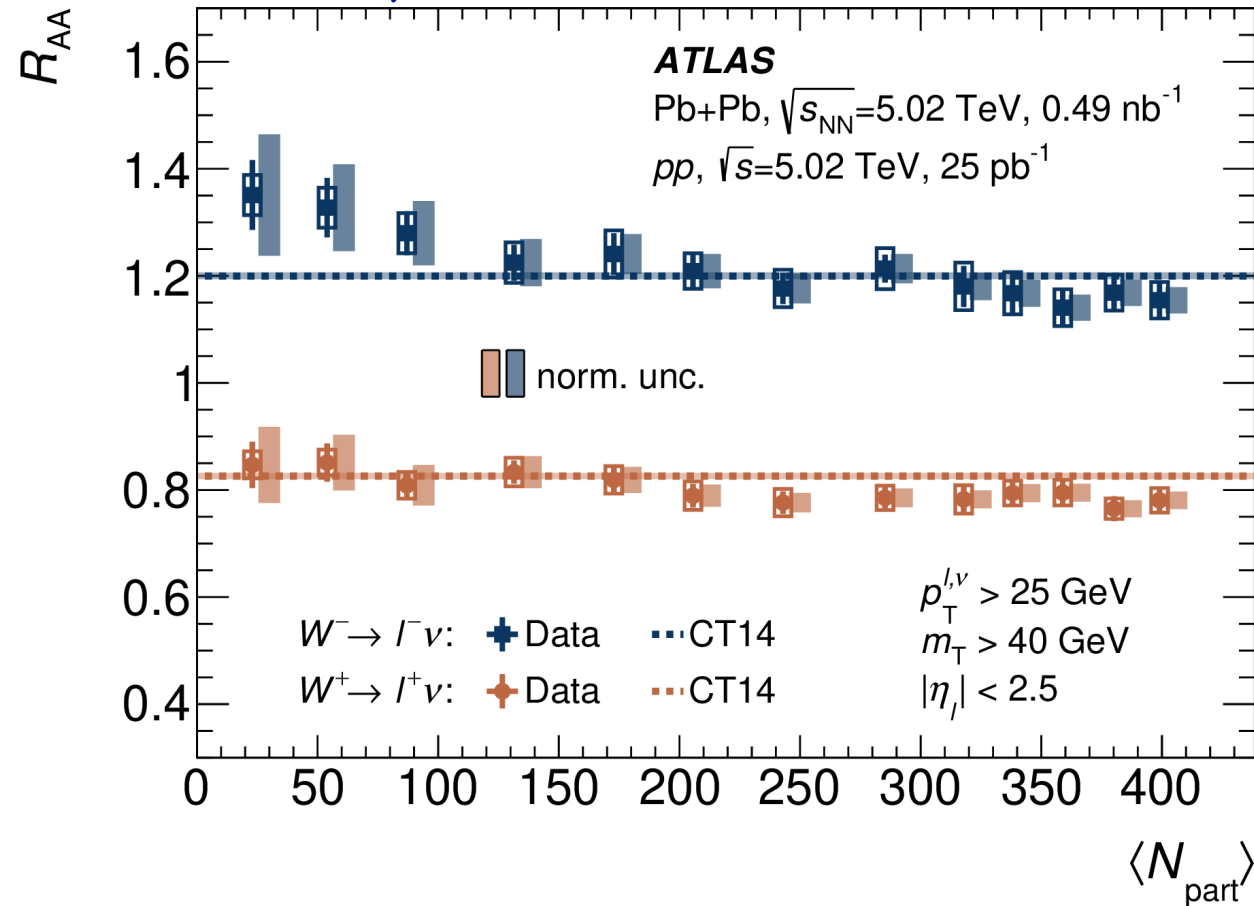
- Efficiency split into three parts: reconstruction (Reco), identification (ID), and isolation (Iso)



- By default $\langle T_{AA} \rangle$ is evaluated using **MC Glauber v2.4**
- Comparison to new **MC Glauber v3.2** with improvements to geometric modelling
 - Updated $\sigma_{NN}^{\text{tot,inel}}$, separate radial distributions for protons and neutrons in Pb, neutron-skin effect
 - Overall only **tiny improvement** wrt MC Glauber v2.4

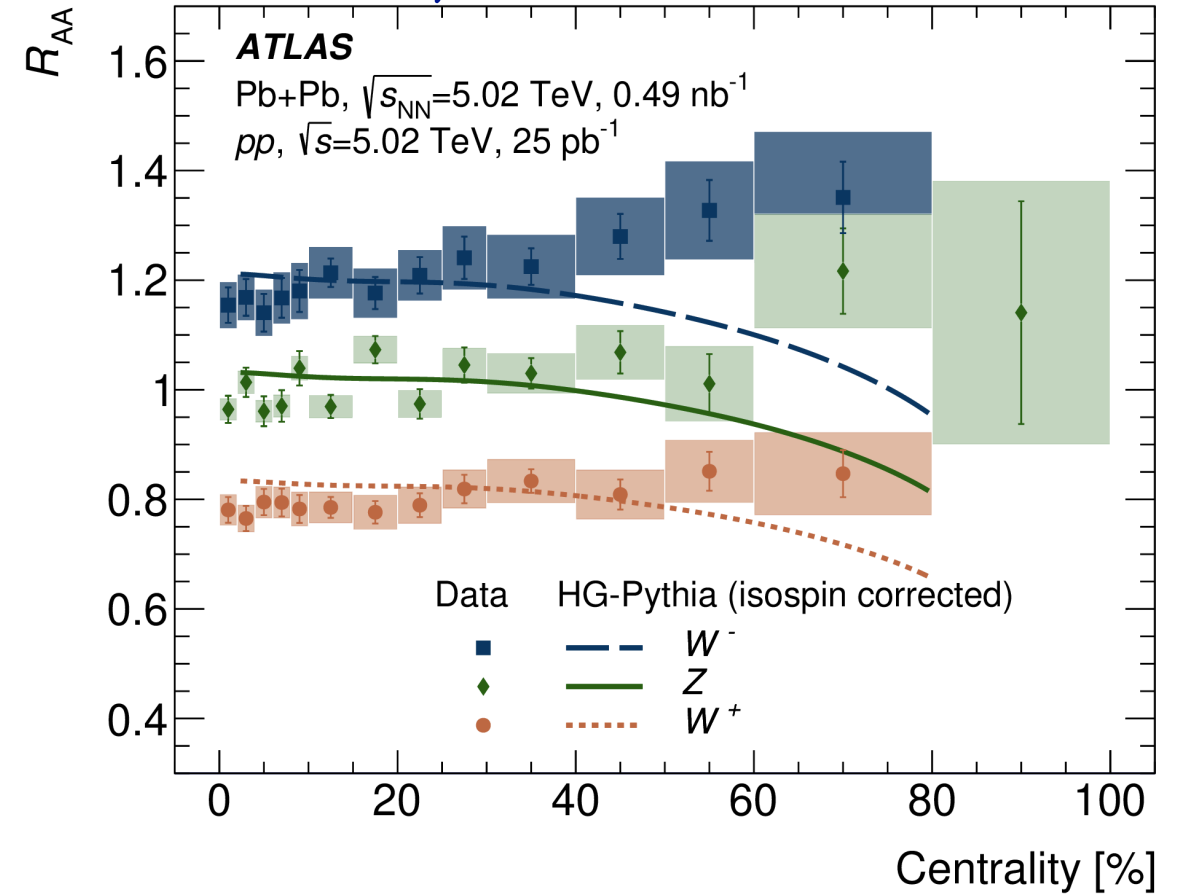
NUCLEAR MODIFICATION FACTOR

[Eur. Phys. J. C 79 (2019) 935]



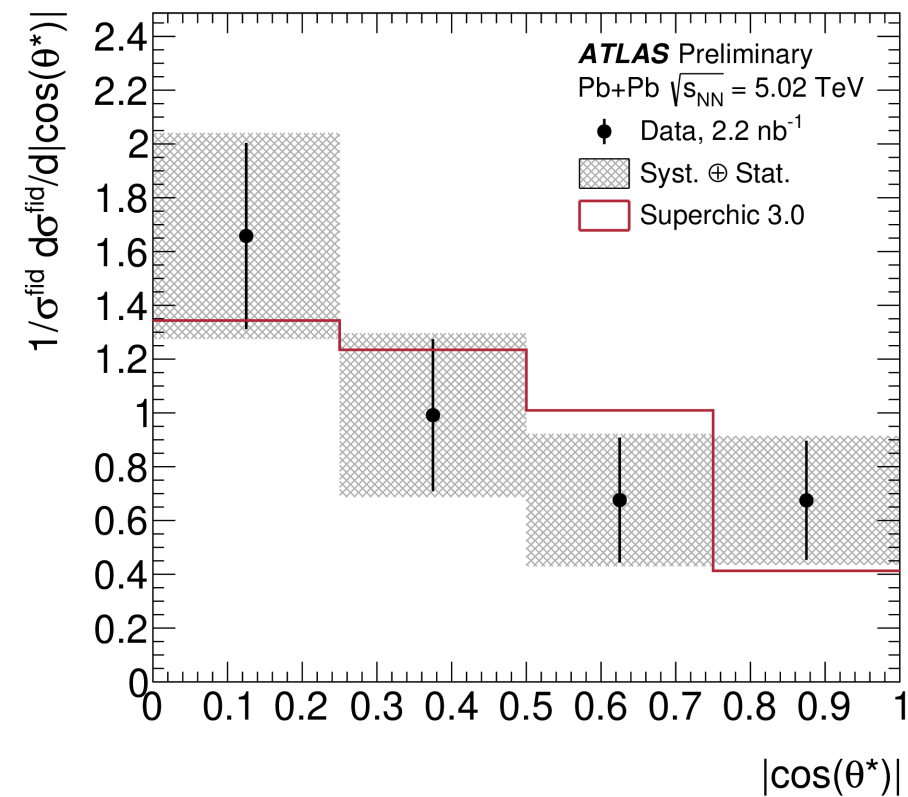
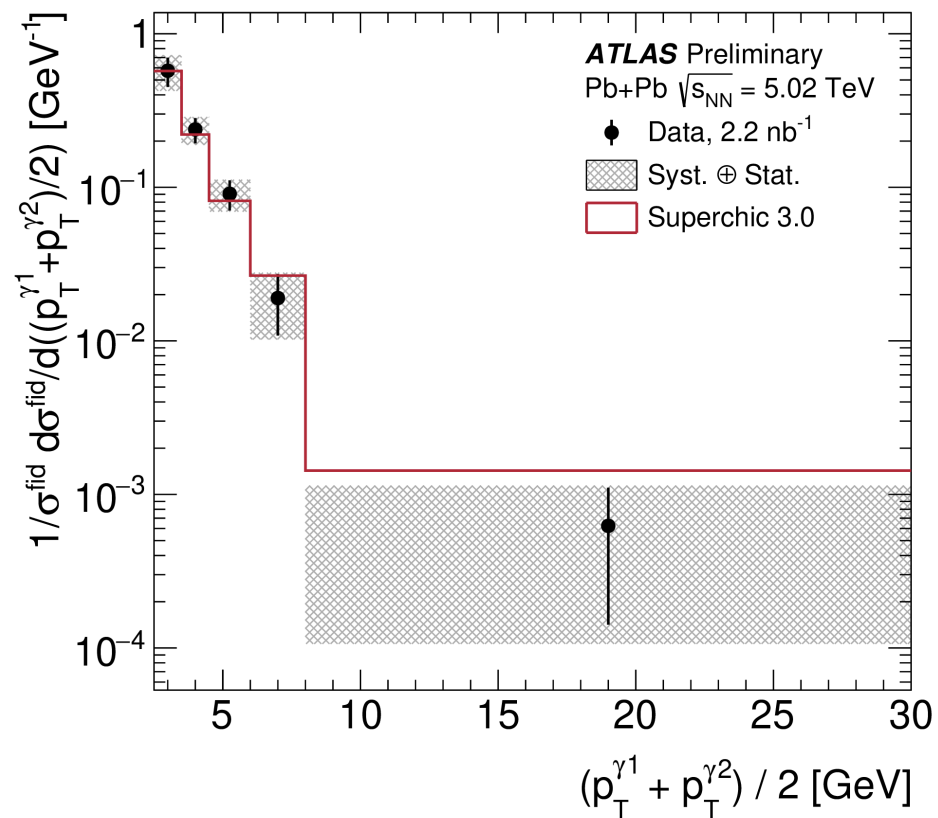
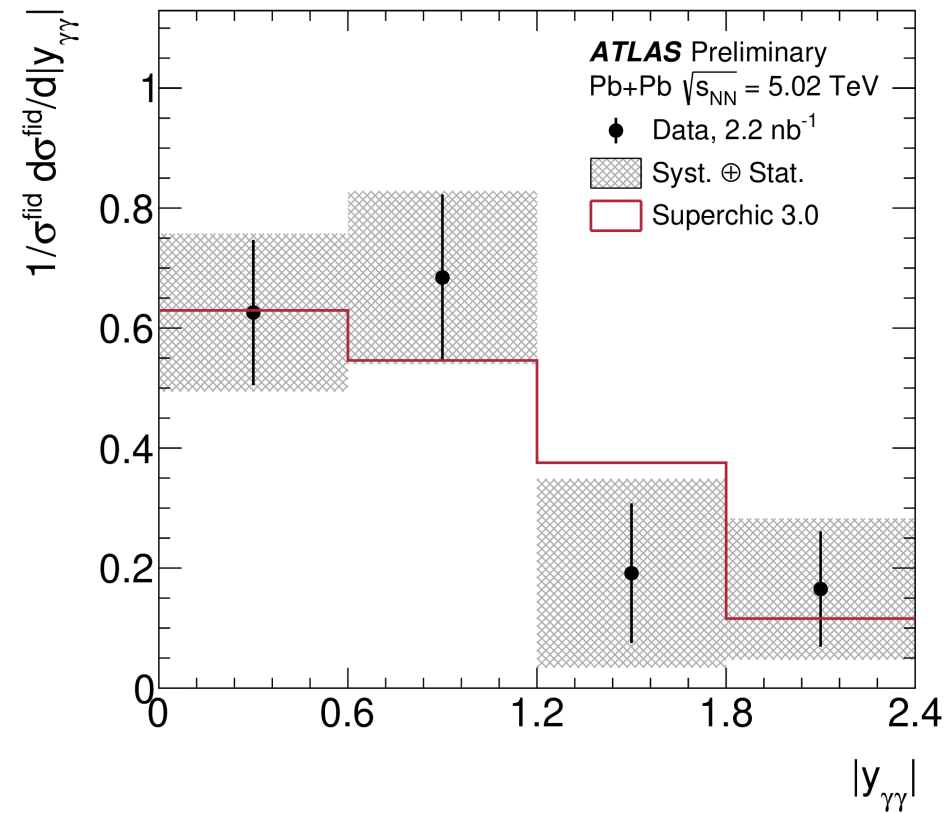
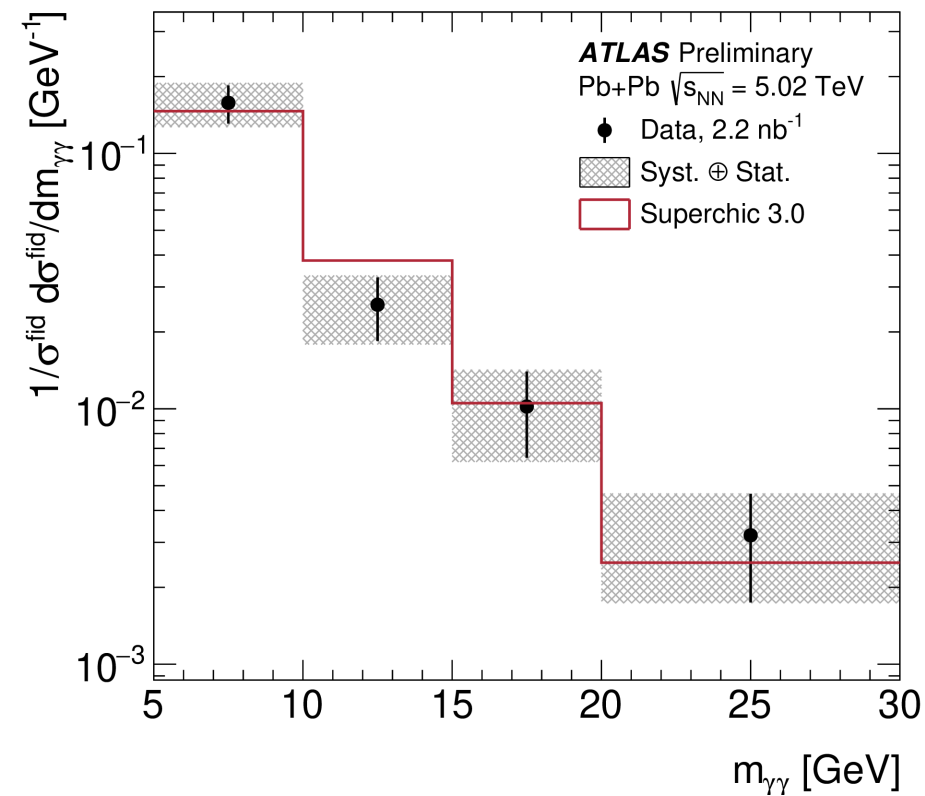
- R_{AA} for W^- and W^+ is **different** from **unity** due to the **isospin effect**
 - More **valence-d** quarks in Pb: enhancement of W^- and suppression of W^+ relative to the pp system
 - Data compared to CT14 NLO predictions which do not fully describe R_{AA}

[Phys. Lett. B 802 (2020) 135262]



- R_{AA} for W^- , Z , W^+ bosons using the HG-PYTHIA model [Phys. Lett. B 793 (2019) 420]
 - Centrality bias in peripheral collisions
 - Proved to describe charged-hadron R_{AA} from ALICE
 - W^- , Z , W^+ boson data goes in the opposite direction

NORMALISED CROSS SECTIONS FOR LBYL



➤ Good agreement between measured and predicted $1/\sigma^{\text{fid}} d\sigma^{\text{fid}}/dX$

