PROCEEDINGS OF SCIENCE

Initial state in heavy-ion collisions at colliders: experimental summary

Émilien Chapon[*]
CERN, Geneva, Switzerland
E-mail: `emilien.chapon@cern.ch`

An accurate understanding of the initial state of nuclei accelerated at TeV energies is crucial for the interpretation of all measurements carried out in heavy-ion collisions at the LHC. The initial state geometry, including the spatial distribution of nucleons and their fluctuations, is most often modeled using the Glauber model, which can be tested using two-particle correlations or electroweak boson measurements. The parton distribution functions, encoding information about their longitudinal momentum, are still poorly constrained, though LHC data provide new stringent inputs. Future impact from planned experimental upgrades and new facilities are also discussed.

International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions
30 September - 5 October 2018
Aix-Les-Bains, Savoie, France

PoS(HardProbes2018)009

---

[*] Speaker.

An accurate description of a heavy-ion collision and of the underlying particle production mechanisms requires good knowledge of many ingredients. Among them, it is crucial to characterise correctly the initial state of the collision. In particular, the average spatial position of the nucleons (or partons) in the nucleus, and more importantly their fluctuations, is needed for a proper normalisation of heavy-ion yields and for an experimental determination of the collision centrality, as well as to properly interpret observables related to azimuthal anisotropies and correlations. The Glauber model, the simplest approach to describe the (transverse) geometrical distribution of nucleons inside the colliding nuclei, is widely used, but other models exist with a description at parton level (such as IP-Glasma or MC-KLN), which will not be discussed here.

The (longitudinal) momentum distribution of the partons inside the nucleus is also needed for the description of partonic processes. They are described by parton distribution functions (PDFs), but are modified inside the nucleus with respect to their free proton equivalent. Uncertainties are large, due to the relatively small data samples of nuclear deep-inelastic collisions available in the kinematic range relevant to RHIC or LHC. Several global fits of nuclear PDFs exist, such as nCTEQ15 [1] and EPPS16 [2], and are being updated as LHC results start bringing significant constraints.

In this document, we will review recent experimental results presented at the Hard Probes 2018 conference, constraining the initial state geometry or the initial momentum distributions of the partons in the nucleus. We will also discuss planned experimental upgrades and new facilities relevant to initial state studies.

1. Initial state geometry

One of surprising results at the LHC is the large azimuthal anisotropies (in particular elliptical ones, quantified by the v_2 parameter) of hadron production observed in high multiplicity proton-proton (pp) collisions. Their origin, and the role of initial- and final-state interactions, is still not clear, and more studies are needed to better understand these phenomena. The ATLAS Collaboration has reported new results for v_2 in Z-tagged pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ [3]. With the requirement of a Z boson, the motivation for this study is to select events with a high energy scale Q^2, thereby selecting more central impact parameters b or the second order eccentricity ε_2 of the events analysed. In addition, the presence of the Z boson helps triggering and allows to perform the measurement of two-particle correlations in a large sample ($19.4\,\mathrm{fb}^{-1}$) of high pileup data. Mitigation of pileup effects needs to be done with care, and the corresponding correction amounts to up to 20%. The v_2 in Z-tagged events shows no dependence on multiplicity, similarly to what had been found in inclusive high-multiplicity results at 5 TeV or 8 TeV, but is larger by $(8 \pm 6)\%$ than inclusive 13 TeV pp [4] as can be seen in Fig. 1. Though not significant, this difference could be due the different p_T spectrum of the tracks in the events, because of the presence of the Z boson.

Electroweak bosons can be used in a more direct way to constrain the initial state geometry, by studying their production in heavy ion collisions as a function of centrality. They are produced early in the collision and do not interact strongly, neither do their decay products in the leptonic channels. They are then direct probes of the initial state geometry, that do not interact with the quark gluon plasma (QGP) and are expected to directly scale with the number of binary collisions, as if the heavy ion collision was a simple superposition of independent nucleon-nucleon collisions.

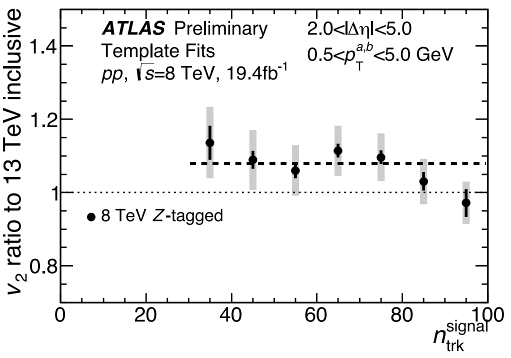

Figure 1: Ratio of the v_2 values measured by ATLAS in Z-tagged events pp collisions at $\sqrt{s} = 8\,\text{TeV}$ to those measured at 13 TeV, as a function of track multiplicity [3].

Some additional nuclear modifications do need to be taken into account, including the isospin effect (especially strong for W bosons), due to the superposition of proton-proton, proton-neutron and neutron-neutron collisions, and other nuclear PDF (nPDF) effects, which will be discussed in the next section. The latter are nevertheless found to be small for W and Z boson production in lead-lead (PbPb) at the LHC, in the kinematic range covered by the ATLAS and CMS experiments.

The W and Z boson measurements can then be used to test the initial state geometry and the Glauber model. Their corrected yields, scaled by the nuclear overlap function T_{AA} obtained from the Glauber model, are expected to be independent of centrality. Results from the ATLAS experiment, for both W [5] and Z [6] bosons (shown in Fig. 2, left) in lead-lead (PbPb) collisions at $\sqrt{s_{\text{NN}}} = 5.02\,\text{TeV}$, confirm this binary scaling, except for a small hint for an excess in peripheral collisions in both cases. Interestingly, measurement uncertainties are found to be smaller than the normalisation ones on T_{AA}, for peripheral events. This suggests that one could define a new observable, $Z_{\text{AA}} = \frac{N^X_{\text{AA}} \cdot \sigma^Z_{\text{pp}}}{N^X_{\text{pp}} \cdot \sigma^Z_{\text{AA}}}$, replacing the usual nuclear modification factor R_{AA} for the comparison of some process X between AA and pp : scaling with T_{AA} of the yields for X in pp and AA, N^X_{pp} and N^X_{AA}, would be replaced with a scaling directly from the Z boson cross section measurements in pp and AA, σ^Z_{pp} and σ^Z_{AA}. Such scaling will become even more interesting with the new 2018 PbPb dataset, more than three times larger than the 2015 one used in Refs. [5, 6]. The measurement of Z bosons in PbPb collisions in the forward direction by the ALICE experiment [7] leads to the same conclusions, albeit with larger uncertainties and being more sensitive to nPDF effects.

Electroweak bosons can also be used to study centrality in proton-lead (pPb) collisions, where the small size of the system makes it difficult to control the estimation of the centrality of the collisions. The ALICE Collaboration has studied W bosons in pPb collisions as a function of centrality [8], as a way to test the Glauber model in this system. The centrality and the average number of binary collisions $\langle N_{\text{coll}} \rangle$ have been estimated using the neutron zero degree calorimeters (ZN), in combination with an "hybrid method" assuming that the charged particle multiplicity measured at mid-rapidity is proportional to the average number of nucleons participating in the interaction, $\langle N_{\text{part}} \rangle$. This method uses Glauber Monte Carlo to relate the centrality classes determined from the ZN to $\langle N_{\text{part}} \rangle$. W boson production is found to be consistent with the expectation from geometric scaling, as shown in Fig. 2 (right).

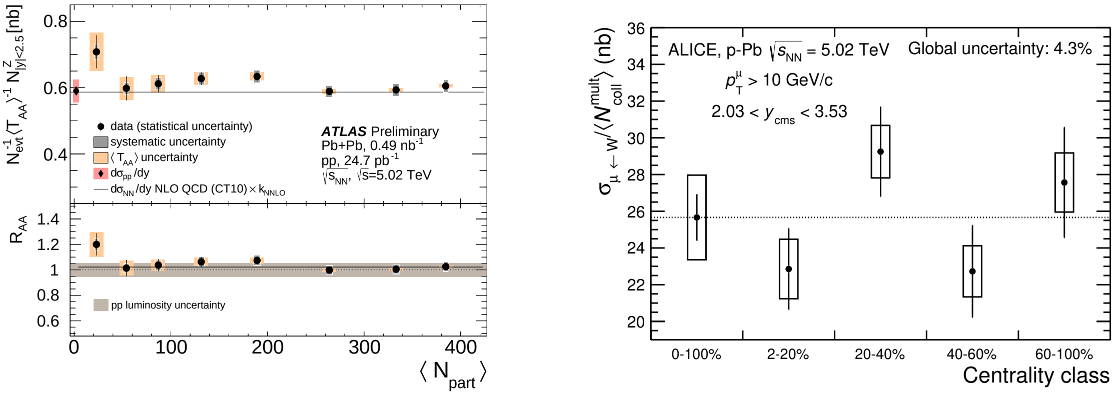

Figure 2: Left: Corrected Z boson yields measured by ATLAS in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, normalised by T_{AA} and as a function of the number of participants. The nuclear modification factor is also shown in the bottom panel [6]. Right: Cross section for W boson production in the muon channel from ALICE, in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, divided by the number of binary collisions, in several centrality classes defined using the zero degree calorimeters. [8].

2. Nuclear PDF

Nuclear PDFs are needed for almost any cross section or nuclear modification factor theoretical prediction. Several regions in the longitudinal momentum fraction x in the nucleus can be identified: a region of suppression at low x, called shadowing, an enhancement at intermediate x in the anti-shadowing region, and again a suppression at higher x, known as the EMC effect. At the LHC, they are best extracted from pPb measurements: in this case, only one interacting parton is coming from a bound nucleon in the lead nucleus, while the other one is coming from the free proton. This also means that there is a direct correlation between the pseudorapidity of the produced object and the x_{Pb} value in the Pb, according to $x_{\mathrm{Pb}} \approx \left(\sqrt{p_{\mathrm{T}}^2 + M^2}/\sqrt{s_{\mathrm{NN}}}\right)\exp(-\eta)$. In the case of dijet production, higher p_{T} jets also probe higher x_{Pb} values. Further information can be gained from AA measurements however, especially at forward rapidity, where the effects of the EMC and shadowing regions can be combined.

The "golden" probes of valence and sea quark nuclear PDFs at the LHC are W and Z bosons. In a new measurement [9], the CMS Collaboration reports the W^+ and W^- boson cross sections as a function of the decay muon pseudorapidity in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$. The data are compared to predictions using either one of the two most recent nPDF sets, EPPS16 [2] and nCTEQ15 [1], or CT14 [10], a free proton PDF. As shown in Fig. 3 (left), results are found to be inconsistent with the calculations using CT14, while a good agreement is found with both EPPS16 and nCTEQ15, though the former is slightly favoured, in particular in the shadowing region where nCTEQ15 tends to over-estimate the amount of suppression compared to a free proton PDF. In addition, experimental uncertainties are smaller than the nPDF ones: significant constraints are expected on future nPDF fits using these data.

The ALICE experiment has also reported measurements of W and Z boson production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [8], probing an x range complementary to that of ATLAS and CMS. Though experimental uncertainties are still large, calculations with nPDF effects are found to better describe the data.

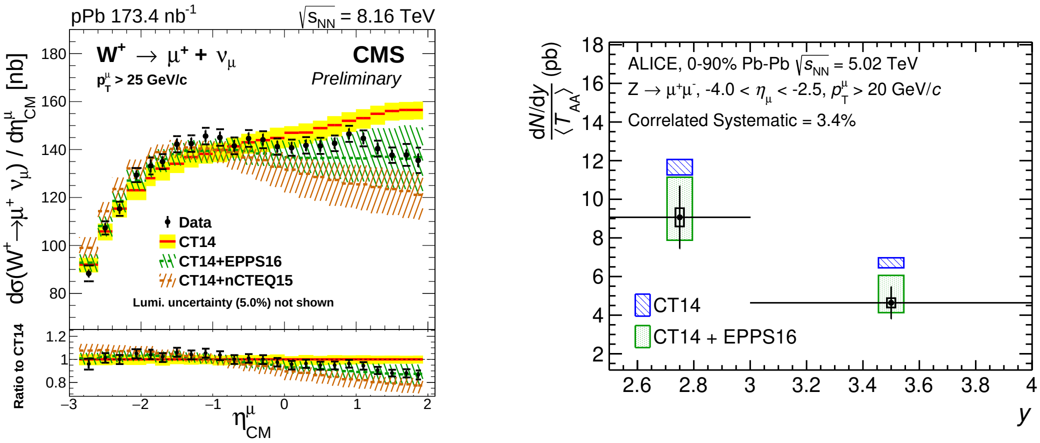

Figure 3: Left: Cross section for W^+ boson production in the muon channel in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV, as a function of the muon pseudorapidity, measured by CMS and compared to calculations using CT14, EPPS16 or nCTEQ15 [9]. Right: Corrected yields for Z boson production in the muon channel, in ALICE PbPb data at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, as a function of rapidity, compared to calculations with and without nPDF effects [7].

The PHENIX experiment has reported a measurement of the Drell-Yan process at low mass (below 14 GeV) in proton-gold collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, in the dimuon channel. This brings interesting prospects in constraining nPDFs at low scales and low x, also in a different nucleus than lead. Differential cross sections, as well as nuclear modification factors, are reported as a function of the dimuon mass and p_{T}. Within the current uncertainties, results are compatible both with no nuclear modification and with expectations from EPPS16.

As mentioned earlier, measurements of electroweak bosons in PbPb collisions are usually less precise, but are not without sensitivity to nPDF effects. The ATLAS measurements of W bosons in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [5] shows consistency of the η-differential cross sections with predictions at next-to-next-to-leading order (NNLO) from CT10. Next-to-leading order (NLO) calculations using nPDFs tend to undershoot the data, however the difference in normalisation with CT10 is expected to be due to the different order in perturbation theory. As expected, the charge asymmetry is mostly insensitive to nuclear PDF modifications, and the data are in good agreement with calculations both with CT10 or nPDFs. On the other hand, the kinematic range of the ALICE measurement of Z bosons in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [7] corresponds to sizeable nPDF effects, and the results favour EPPS16 over CT14, with experimental uncertainties already smaller in size as EPPS16 ones, as seen in Fig. 3 (right).

Yet the most sensitive LHC result to nPDFs to date is the CMS measurement of dijets in pPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [11]. It probes gluon nPDFs over a wide range of x in the lead nucleus, from the shadowing region to the anti-shadowing and EMC regions, through a measurement of cross sections as a function of the pseudorapidity of the dijet system, in several bins of the average p_T. It follows a measurement of the pPb data alone [12], already included in the EPPS16 nPDF. The direct use of pp data as a reference makes the results less sensitive to pp modelling: indeed, it has been found that the pp measurement is imperfectly described by NLO calculations. Such mismodellings mostly cancel in the pPb/pp ratio (shown in Fig. 4, left), featuring unambiguously the shadowing, anti-shadowing and EMC modifications, with a trend neither perfectly captured by EPS09 [13] nor nCTEQ15 and with higher precision than the nPDF uncertainties, triggering high interest from the nPDF fitters community.

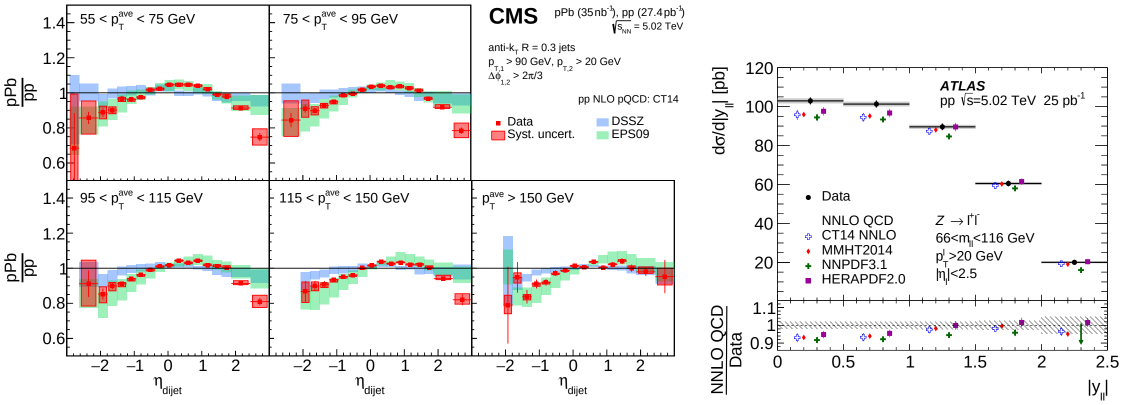

Figure 4: Left: Ratio of dijet production in pPb to pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV from CMS, as a function of dijet pseudorapidity, in different bins of the average p_T of the jets, compared to calculations using nPDFs [11]. Right: Z boson cross section in pp collisions at $\sqrt{s} = 5.02$ TeV from ATLAS, as a function of the Z boson rapidity, compared to calculations using various PDFs [14].

It is useful to further comment on the modelling of the pp reference. While free proton PDFs are more precisely known than nPDFs, calculations do not always describe all the features of the data. This was found in the CMS measurement of dijet η, where NLO perturbative QCD fails to reproduce the data, independently of the free proton PDF used. A recent measurement of the differential cross sections of W and Z bosons in pp collisions at $\sqrt{s} = 5.02$ TeV by the ATLAS Collaboration [14] also finds that most recent PDFs, with the exception of HERAPDF2.0, fail to describe the data (see Fig. 4, right). The results, very precise (including an only 1.9% luminosity uncertainty), could be used to constrain free proton PDFs, and will serve as a data-driven reference for future PbPb measurements. Interestingly, this tension between the ATLAS pp data at $\sqrt{s} = 5.02$ TeV and NNLO calculations using various PDFs is not new: it had been also seen before at $\sqrt{s} = 7$ TeV [15], but it is not found in similar measurements from CMS at $\sqrt{s} = 8$ TeV [16].

Coming back to nPDFs, photon production in pPb collisions is also expected to be sensitive to modifications of the initial state, including isospin (because of the different electric charge of up and down quarks). Measurements are available from the ALICE [17] and ATLAS [18] Collaborations, differential in photon energy, showing hints of the isospin effect, but not yet sensitive to the other expected small nPDF effects given rather large systematic uncertainties. The ALICE results are also presented in several bins of multiplicity.

Studies of ultra-peripheral collisions (UPC), when the impact parameter is larger than twice the radius of the nucleus, provide yet another class of processes sensitive to nPDFs. The heavy nuclei are used as a source of quasi-real photons, which can be used as a probe of the projectile structure. The interaction can happen between the photon (fluctuating into a vector meson state) and two gluons in a colour-single state in the "target", as in exclusive quarkonia photoproduction; or between the former and a single gluon, for instance in jet photoproduction, a process theoretically better controlled.

Exclusive vector meson production has been studied in γp collisions: exclusive J/ψ and $\psi(2S)$ in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ by the LHCb Collaboration [19], and exclusive $\Upsilon(1S)$ in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ by the CMS Collaboration [20]. Both sets of results, reported as cross sections differential in the meson rapidity, show a good agreement between the data and perturbative QCD models at NLO, implementing gluon saturation in the case of pPb. Leading order calculations tend to overshoot the data, however.

Similar studies have been performed for coherent J/ψ production in γPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, at forward rapidity by the LHCb Collaboration [21] (see Fig. 5, top right). The ALICE Collaboration has measured this process in non-UPC events, with nuclear overlap, in two centrality bins. Both measurements are presented as a function of the J/ψ rapidity, and compared to a variety of models implementing different initial state assumptions (including gluon shadowing) and different quarkonium production mechanisms.

The ATLAS Collaboration has measured dijets produced in photonuclear interactions [22], in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, selecting γPb interactions combining information from the Zero Degree Calorimeters with rapidity gap requirements. Results are compared to PYTHIA, where the photon spectrum has been reweighted to match the predictions of the STARLIGHT generator, as shown in Fig. 5 (left). Sensitivity to nuclear PDFs is expected, and such data could be included in nPDF fits in the future.

Nuclear PDFs modify the production of open heavy flavour mesons in proton-nucleus with respect to pp collisions. Many precise measurements have been reported at the conference, regarding D^0 mesons (from ATLAS, ALICE, LHCb — see Fig. 5, bottom right), Λ_c^+ (from ALICE, LHCb), J/ψ from b hadrons (CMS, LHCb). They are being considered for constraining nPDFs, because of their usually high experimental precision, sometimes better than nPDF uncertainties, and their access to low x, lower than using electroweak bosons or dijets because of their low mass. On the other hand, the inclusion of such measurements in nPDF fits poses theoretical challenges, in particular in the treatment of the production and scale uncertainties. The same comments apply to quarkonium results (J/ψ, $\psi(2S)$, $\Upsilon(1S)$, ...), reported also from different experiments (the four LHC experiments, but also STAR): measurements are very precise, but not necessarily trivial to include in nPDF fits for the same reasons (theoretical treatment of the production, possibility of other non-nPDF effects: see the difference between J/ψ and $\psi(2S)$, for instance).

Another PDF-related topic discussed at the conference is the possibility of intrinsic charm in the proton or the nucleus. Such contribution would be visible in heavy flavour production when one of the partons is at very high x. This regime can be probed by the LHCb experiment in fixed-target mode, using the System Measuring the Overlap with Gas (SMOG) which allows to inject gas in the interaction region and record fixed-target proton-nucleus collisions. There seems to be no signal of an intrinsic charm contribution in the LHCb D^0 results in proton-helium collisions [23], calculations without intrinsic charm already over-shooting the data.

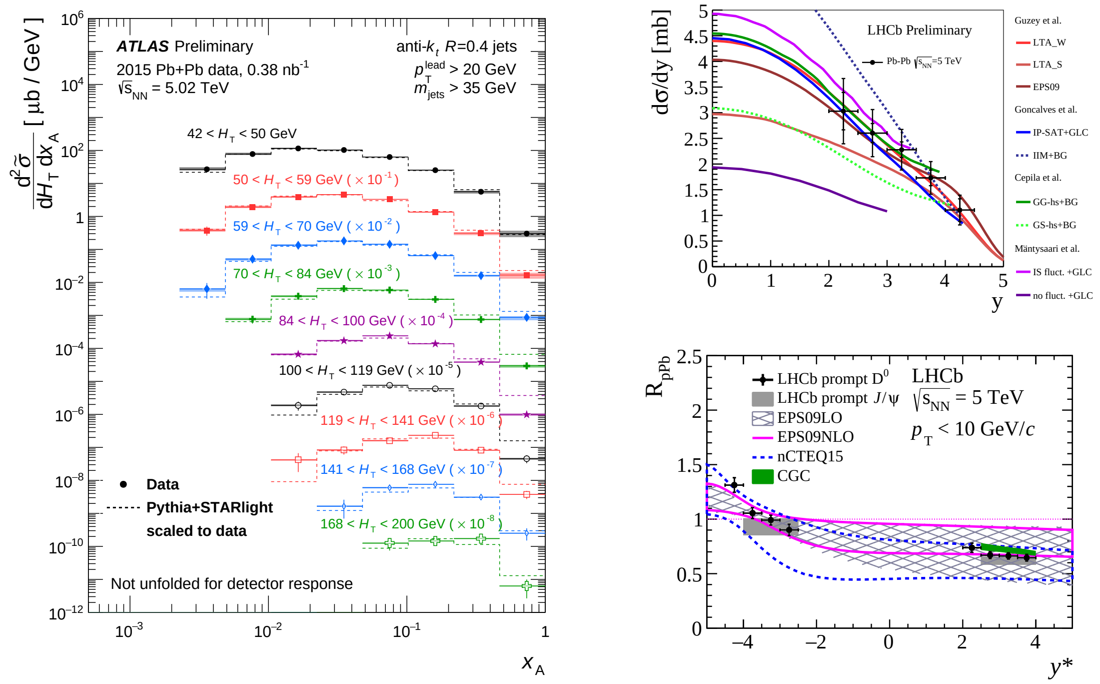

Figure 5: Left: Cross section for photonuclear dijet production in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV from ATLAS, as a function of x_A (the ratio of the energy of the struck parton in the nucleus to the per-nucleon energy of the beam), in several bins of the sum of p_T of the jets [22]. Top right: Coherent J/ψ production in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV from LHCb, as a function of rapidity, compared to various models [21]. Bottom right: Ratio of prompt D^0 and J/ψ production in pPb to pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV from LHCb, compared to several models [24].

3. Future experiments

As the LHC programme continues, planned experimental upgrades will open up new possibilities for measurements sensitive to the initial state of heavy ion collisions. The installation of new forward calorimeters for the ALICE experiment (FoCal), covering $3.3 \lesssim \eta \lesssim 5.3$, is planned for 2024–2025 [25]. They will allows the measurement of photons in the forward direction, probing nPDFs (as well as PDFs) at low x, down to about 10^{-5}, where uncertainties are very large. Such measurements will be complementary to heavy flavour studies, which are sensitive to a similar x range when done in the same rapidity range (for instance with the LHCb experiment).

Future facilities will also provide new ways to probe the initial state. The AFTER@LHC programme [26] proposes to perform fixed-target experiments at the LHC, as already demonstrated by LHCb using the SMOG system. Other implementations are proposed, including using the ALICE detector, and upgrades of the SMOG system. Such a setup is well suited for exploring the high-x frontier. On a longer timescale, several electron-ion colliders are being discussed: they will be the ideal machines to study the initial state, including nPDFs, similarly to HERA for protons. The most advanced is the eIC [27], which could be built either at BNL or at JLab. On a longer timescale, it is also proposed to transform the LHC into an electron-hadron collider [28]; it could also be one of the stages of the future circular collider (FCC) at CERN [29]. In all cases, the benefits are a very large coverage in x and Q^2, and the great precision expected from the results.

References

[1] K. Kovarik *et al.*, Phys. Rev. D **93** (2016) 085037.

[2] K. J. Eskola, P. Paakkinen, H. Paukkunen and C. A. Salgado, Eur. Phys. J. C **77** (2017) 163.

[3] ATLAS Collab., ATLAS-CONF-2017-068, `https://cds.cern.ch/record/2285806` (2017).

[4] ATLAS Collab., Phys. Rev. C **96** (2017) 024908.

[5] ATLAS Collab., ATLAS-CONF-2017-067, `https://cds.cern.ch/record/2285571` (2017).

[6] ATLAS Collab., ATLAS-CONF-2017-010, `https://cds.cern.ch/record/2244821` (2017).

[7] ALICE Collab., Phys. Lett. B **780** (2018) 372.

[8] ALICE Collab., JHEP **1702** (2017) 077.

[9] CMS Collab., CMS-PAS-HIN-17-007, `https://cds.cern.ch/record/2318138` (2018).

[10] S. Dulat *et al.*, Phys. Rev. D **93** (2016) 033006.

[11] CMS Colaboration, Phys. Rev. Lett. **121** (2018) 062002.

[12] CMS Colaboration, Eur. Phys. J. C **74** (2014) 2951.

[13] K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP **0904** (2009) 065.

[14] ATLAS Collab., arXiv:1810.08424.

[15] ATLAS Collab., Eur. Phys. J. C **77** (2017) 367.

[16] CMS Collab., Eur. Phys. J. C **76** (2016) 469.

[17] N. Schmidt [ALICE Collab.], arXiv:1812.08104 [nucl-ex].

[18] ATLAS Collab., ATLAS-CONF-2017-072, `https://cds.cern.ch/record/2285810` (2017).

[19] LHCb Collab., JHEP **10** (2018) 167.

[20] CMS Collab., arXiv:1809.11080 [hep-ex].

[21] LHCb Collab., CONF-2018-003, `https://cds.cern.ch/record/2320135` (2018).

[22] ATLAS Collab., ATLAS-CONF-2017-011, `https://cds.cern.ch/record/2244822` (2017).

[23] LHCb Collab., arXiv:1810.07907 [hep-ex].

[24] LHCb Collab., JHEP **10** (2017) 090.

[25] T. Peitzmann [ALICE Collab.], arXiv:1812.07246 [hep-ex].

[26] C. Hadjidakis *et al.*, arXiv:1807.00603 [hep-ex].

[27] A. Accardi *et al.*, Eur. Phys. J. A **52** (2016) 268.

[28] LHeC Study Group, J. L. Abelleira Fernandez *et al.*, J. Phys. G **39** 075001 (2012).

[29] A. Dainese *et al.*, CERN Yellow Report (2017) 3, 635, arXiv:1605.01389 [hep-ph].