Experimental overview of p(d)–A physics

Roberto Preghenella
European Organisation for Nuclear Research (CERN), Geneva, Switzerland
Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Bologna, Italy
E-mail: preghenella@bo.infn.it

Abstract. This document reports on the main topics discussed in the experimental overview talk on p(d)–A results given at the Hot Quarks 2014 Workshop. Recent measurements of the production of high transverse momentum hadrons and jets, inclusive identified particles and their correlations, quarkonia and vector bosons are presented. They represent a small set of the currently available results, which provide a deeper understanding of the hot QCD matter produced in A–A collisions and reveal the presence of unexpected phenomena in small systems.

1. Introduction
A wealth of physics results are reported by RHIC and LHC experiments, providing further understanding of the dynamics of the hot QCD matter produced in nucleus-nucleus (A–A) reactions and exciting insight for genuine proton(deuteron)-nucleus (p–A, d–A) physics. Measurements of the production of high transverse momentum hadrons and jets allow to conclude that the suppression observed in A–A collisions is not due to an initial-state effect, but it is rather the fingerprint of jet quenching in hot QCD matter. The study of inclusive identified particle spectra and their correlations revealed unexpected phenomena that promptly suggested the presence of collective behaviour in small systems and triggered further investigations. Results on quarkonia production also show that cold nuclear matter effects are important for the interpretation of heavy-ion results and the study of the production of the excited quarkonium states reveals sizeable and intriguing final-state effects as well. Electroweak boson production provide significant constraints to the nuclear modifications of parton distribution functions. These are the main topics discussed in the following sections of these proceedings, which report on a limited selection of experimental results. Given the large amount of new results, many other interesting topics related to p(d)–A physics, like centrality determination, detailed study of the production of jets and their modifications, strangeness and nuclei production and open heavy-flavour observables could not be discussed here.

2. Understanding initial-state and cold nuclear matter effects
High transverse momentum hadrons, arising from the fragmentation of partons scattered with large momentum transfer, provide an excellent probe of the high energy-density matter created in relativistic heavy-ion collisions. In the absence of medium effects, hard scattering yields should scale with the average number of inelastic nucleon-nucleon collisions (binary scaling). One of the main observations in central A–A collisions was a large suppression of high-\(p_T\) hadron yields with respect to binary-scaled pp results [1–3]. It is therefore of paramount interest to determine experimentally the modification of high-\(p_T\) hadron yields due to initial-state nuclear effects.
Measurements by RHIC experiments reported on the absence of suppression of high-$p_T$ hadrons in d–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [4,5]. The results were based on measurements of the inclusive hadron production and two-particle azimuthal distributions at high $p_T$ and provided evidence that the suppression phenomena seen in central Au–Au collisions at RHIC are due to final-state interactions with the dense system generated in the collision. Measurements of the charged-particle $p_T$ spectra and the nuclear modification in inelastic p–Pb collisions at the $\sqrt{s_{NN}} = 5.02$ TeV [6] show a nuclear modification factor consistent with unity at high momenta, indicating that also at the LHC the strong suppression of hadron production in Pb–Pb collisions is not due to initial-state effects, but it is rather the fingerprint of jet quenching in hot QCD matter.

Thanks to the wide coverage and high performance of the calorimetric systems installed in LHC experiments, it was possible to directly observe jet quenching phenomena by studying the centrality dependence of dijet production, in particular the dijet asymmetry in Pb–Pb collisions. The first observation of an enhancement of events with such large dijet asymmetries, not observed in proton-proton collisions, has been reported [7,8]. Results on dijet asymmetry in $\sqrt{s_{NN}} = 2.76$ TeV Pb–Pb collisions are shown in several centrality bins and compared to $\sqrt{s} = 7$ TeV pp collisions in Figure 1 (left). Dijet production has also been measured in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [9] and the results are shown in Figure 1 (right): in contrast to what is seen in Pb–Pb collisions, no significant dijet transverse momentum imbalance is observed in p–Pb data. This further confirms that the imbalance observed in Pb–Pb collisions is not originating from initial-state effects.

It is worth mentioning that the surprising observation reported in recent measurements of inclusive charged hadron nuclear modification in minimum bias p–Pb collisions at the $\sqrt{s_{NN}} = 5.02$ TeV. An excess compared to binary-scaled pp data is observed at high $p_T > 30$ GeV/c by ATLAS and CMS [10,11]. The excess is larger than expected from the EPS09 [12] nuclear parton distribution functions and it is even more surprisingly not observed in jet measurements [13,14]. ALICE data [15] do not show such enhancement, though the $p_T$ reach is limited. Statistical and systematic uncertainties are large and in particular there are substantial uncertainties in the pp reference, which had to be interpolated from higher and lower energy results. It is therefore of greatest importance to improve the precision and establish the excess with proton-proton reference data measured at the same energy in the next LHC run.

**Figure 1.** (left) Dijet asymmetry ratio for 7 TeV pp collisions and 2.76 TeV Pb–Pb collisions in several centrality bins [8]. (right) Dijet transverse momentum ratio distributions in p–Pb events without any selection on the HF transverse energy and for different classes [9].
Figure 2. (left) Anisotropic flow $v_2$ results obtained from multi-particle cumulants and LYZ method in Pb–Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV (left) and p–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [30]. (right) Anisotropic flow $v_2$ results for hadrons, pions, kaons and protons in p–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV obtained in the 0–20% multiplicity class after subtraction of the correlation from the 60–100% [26].

3. Similarities to A–A and hints for collectivity

The measurements of inclusive charged-hadron nuclear modification in minimum bias p–Pb collisions [15] show a weak indication of a Cronin-like enhancement at intermediate $p_T$, where a stronger enhancement is seen at lower energies [4, 5, 16]. Traditional explanations of the Cronin enhancement involve multiple soft scatterings in the initial state, prior to the hard scattering, and subsequent fragmentation of the hard scattered parton [17]. This process on the other hand does not account for the observed particle species dependence [18] that suggests final state effects. A strong baryon-to-meson enhancement is observed both at RHIC and LHC [15, 19, 20] with a clear evolution with multiplicity. This is similar to the pattern observed in high-energy heavy-ion collisions [21], where the effect is usually attributed to collective radial expansion. In contrast to the inclusive distribution, the ratio within jets in high-multiplicity p–Pb collisions does not exhibit such baryon enhancement [22].

Measurements at the LHC in high-multiplicity pp and p–Pb collisions have revealed a near-side long-range “ridge” structure in the two-particle correlation functions [23–25]. The observation of an unexpected “double-ridge” structure in the two-particle correlations in high-multiplicity p–Pb collisions has also been reported [26–29]. In A–A collisions, long-range correlations are interpreted as a consequence of the collective hydrodynamic expansion of the produced medium from the initial geometry: the presence of a ridge structure in p–A collisions promptly suggested collective behaviour and triggered further investigations.

The azimuthal particle distributions are characterised by their Fourier components. Of particular importance are the elliptic and triangular flow, namely the second and third Fourier coefficients. They most directly reflect the medium response to the initial collision geometry and fluctuations, allowing to shed light on the transport properties of the medium. Measurements of the second-order azimuthal anisotropy Fourier harmonic $v_2$ [30, 31] using multi-particle correlations are shown in Figure 2 (left). Significant multi-particle correlation signals are observed in both p–Pb and Pb–Pb collisions, which show in addition a remarkable agreement between the results derived from the four- or more particle-correlation methods. This strongly supports the collective nature of the observed signals.

Angular correlations between unidentified charged trigger particles and identified associated particles (pions, kaons, protons, $K^0_S$ and $\Lambda$) are also measured in p(d)–A collisions [32–34]. The results show an elliptic-flow pattern qualitatively similar to the one observed in heavy-ion collisions [35]. The results for pion, kaon and proton $v_2$ are shown in Figure 2 (right). A mass
ordering effect at low transverse momenta is consistent with expectations from hydrodynamic model calculations [36] assuming a collectively expanding system.

4. Quarkonia: further hints for final state effects

A clear suppression of $J/\psi$ production with respect to binary-scaled pp collisions is observed in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the forward region, corresponding to the proton direction [37, 38]. No suppression is present in the backward region. The nuclear modification factor has been determined separately for prompt $J/\psi$ mesons and $J/\psi$ from $b$-hadron decays and is compared with results for $\Upsilon(1S)$ [39] in Figure 3 (left). The suppression of the production of $J/\psi$ from $b$-hadron decays and of $\Upsilon(1S)$ is found to be smaller than in the case of prompt $J/\psi$ mesons. Theoretical predictions based on nuclear shadowing, as well as on models including, in addition, a contribution from partonic energy loss, are in fair agreement with the experimental results [40, 41]. The measurements show that cold nuclear matter effects are important for interpretations of quarkonium-related quark-gluon plasma signatures in heavy-ion collisions.

The inclusive production of $\psi(2S)$ has also been measured [42] and its nuclear modification factor is compared to the measurement of the same quantity for $J/\psi$ and to theoretical models in Figure 3 (right). The results show a significantly larger suppression of the $\psi(2S)$ compared to that measured for $J/\psi$ and to models, both in the forward and in the backward region. A stronger suppression of $\psi(2S)$ relative to $J/\psi$ was observed in previous fixed-target experiments at central rapidity, while at forward rapidity no difference was found within uncertainties [43,44]. This feature was interpreted in terms of pair break-up: at central and backward rapidity the time spent by the $c\bar{c}$ state in the nuclear medium (crossing time) is typically larger than the formation time of the resonances, so that the loosely bound $\psi(2S)$ can be more easily dissociated than the $J/\psi$. Conversely, in forward production the crossing time is smaller than the formation time and the influence of the nucleus on the pre-hadronic state is the same, independent of the particular resonance being produced. No break-up effects depending on the final charmonium state should be expected at forward rapidity. As a consequence, the strong difference observed between $\psi(2S)$ and $J/\psi$ suppression in the forward region represents a clear indication for sizeable final-state effects in $\psi(2S)$ production. In addition, the ratios of the excited-to-ground state cross sections $\psi(2S)/J/\psi$ and $\Upsilon(nS)/\Upsilon(1S)$ are found to decrease with the charged-particle multiplicity [45, 46]. Other final state effects should be considered to describe these features,
Figure 4. (left) Forward-backward ratio of Z boson cross section in p–Pb collisions as a function of rapidity compared to predictions [47]. (right) W boson lepton-charge asymmetry in p–Pb collisions computed as a function of the lepton pseudorapidity in the laboratory frame [49].

including the interaction of the $c\bar{c}$ pair with the final-state hadronic system created in the collision.

5. Constraints on nPDFs with vector bosons

Electroweak boson production is an important benchmark measurement that can provide constraints allowing to probe the nuclear modification of parton distribution functions in a phase-space region that was never studied before. The production of W and Z bosons in proton-nucleus collisions at the LHC has been reported [47–50]. Results on forward-backward ratio of Z boson cross section and of W boson lepton-charge asymmetry are shown in Figure 4. At large rapidity, the Z forward-backward ratio deviates from unity by an amount which is compatible with nuclear PDF (nPDF) modifications, though due to the large uncertainties, these measurements are not able to distinguish between different nuclear PDF sets. Nonetheless, these measurement provide significant input to nPDF fits with a significant constraining power in a previously unexplored region of the phase space. The W lepton-charge asymmetry, a sensitive probe of the down to up quark PDF, deviates from calculations for $\eta < -1$, suggesting that different nuclear modifications can occur for up and down quark PDFs.

6. Summary

In summary, p(d)–A collision results both at RHIC and LHC show no indication of quenching of high-$p_T$ hadrons and jets, confirming that the strong suppression in A–A is a final-state hot QCD matter effect. However, a still unexplained enhancement of high-$p_T$ hadrons is observed by CMS and ATLAS. Bulk identified-particle production reveals features that are reminiscent of A–A phenomena, triggering studies on genuine collective effects in small systems. This is strongly supported by the observation of non-zero elliptic flow from multi-particle correlations and by the mass-dependence of $p_T$ spectra and $v_2$. The measurement of quarkonia production and of the suppression of quarkonia ground states is in line with the predictions from nuclear parton shadowing and/or initial-state energy-loss. The observation of a stronger suppression of quarkonia excited states provides a clear evidence for exotic final-state $c\bar{c}$ pair break-up phenomena. Furthermore, the measurement of vector boson production provides significant constraints for nPDF fits.
Acknowledgements
Thanks to the Hot Quarks 2014 organisers for the invitation to such a delightful and constructive Workshop, to the CERN ALICE group for financial support and advices, to the LHC and RHIC Collaborations for the large amount of high-quality results and to Maria Valentina Carlucci for proofreading this report.

References
[1] Adler C et al. (STAR Collaboration) 2002 Phys.Rev.Lett. 89 202301 (Preprint nucl-ex/0206011)
[2] Adcox K et al. (PHENIX Collaboration) 2002 Phys.Rev.Lett. 88 022301 (Preprint nucl-ex/0109003)
[3] Abelev B et al. (ALICE Collaboration) 2013 Phys.Lett. B720 52-62 (Preprint 1208.2711)
[4] Adams J et al. (STAR Collaboration) 2003 Phys.Rev.Lett. 91 072304 (Preprint nucl-ex/0306024)
[5] Adler S et al. (PHENIX Collaboration) 2003 Phys.Rev.Lett. 91 072303 (Preprint nucl-ex/0306021)
[6] Abelev B et al. (ALICE Collaboration) 2013 Phys.Rev.Lett. 110 082302 (Preprint 1210.4520)
[7] Aad G et al. (ATLAS Collaboration) 2010 Phys.Rev.Lett. 105 252303 (Preprint 1011.6182)
[8] Chatrchyan S et al. (CMS Collaboration) 2011 Phys.Rev. C84 024906 (Preprint 1102.1957)
[9] Chatrchyan S et al. (CMS Collaboration) 2014 Eur.Phys.J. C74 2951 (Preprint 1401.4433)
[10] ATLAS Collaboration 2014 ATLAS-CONF-2014-029
[11] CMS Collaboration 2013 CMS-PAS-HIN-12-017
[12] Eskola K, Paukkunen H and Salgado C 2009 JHEP 0904 065 (Preprint 0902.4154)
[13] ATLAS Collaboration 2014 ATLAS-CONF-2014-024
[14] CMS Collaboration 2014 CMS-PAS-HIN-14-001
[15] Abelev B B et al. (ALICE Collaboration) 2014 Eur.Phys.J. C74 3054 (Preprint 1405.2737)
[16] Cronin J, Frisch H J, Shoehet M, Boymond J, Mermod R et al. 1975 Phys.Rev. D11 3105
[17] Accardi A 2002 (Preprint hep-ph/0212148)
[18] Adare A et al. (PHENIX Collaboration) 2013 Phys.Rev. C88 024906 (Preprint 1304.3410)
[19] Abelev B B et al. (ALICE Collaboration) 2014 Phys.Lett. B728 25-38 (Preprint 1307.6796)
[20] Chatrchyan S et al. (CMS Collaboration) 2014 Eur.Phys.J. C74 2847 (Preprint 1307.3442)
[21] Abelev B et al. (ALICE Collaboration) 2013 Phys.Rev. C88 044910 (Preprint 1303.0737)
[22] Zhang X (ALICE Collaboration) 2014 (Preprint 1408.2672)
[23] Khachatryan V et al. (CMS Collaboration) 2010 JHEP 1009 091 (Preprint 1009.4122)
[24] Chatrchyan S et al. (CMS Collaboration) 2013 Phys.Lett. B718 795-814 (Preprint 1210.5482)
[25] Abelev B et al. (STAR Collaboration) 2009 Phys.Rev. C80 064912 (Preprint 0909.0191)
[26] Abelev B et al. (ALICE Collaboration) 2013 Phys.Rev. B719 29-41 (Preprint 1212.2001)
[27] Aad G et al. (ATLAS Collaboration) 2013 Phys.Rev.Lett. 110 182302 (Preprint 1212.5198)
[28] Aad G et al. (ATLAS Collaboration) 2013 Phys.Lett. B725 60-78 (Preprint 1303.2084)
[29] Chatrchyan S et al. (CMS Collaboration) 2013 Phys.Lett. B724 213-240 (Preprint 1305.0609)
[30] CMS Collaboration 2014 CMS-PAS-HIN-14-006
[31] Aad G et al. (ATLAS Collaboration) 2014 CERN-PH-EP-2014-201 (Preprint 1409.1792)
[32] Abelev B B et al. (ALICE Collaboration) 2013 Phys.Lett. B726 164-177 (Preprint 1307.3237)
[33] Khachatryan V et al. (CMS Collaboration) 2014 CMS-HIN-14-002 (Preprint 1409.3392)
[34] Adare A et al. (PHENIX Collaboration) 2014 (Preprint 1404.7461)
[35] Abelev B B et al. (ALICE Collaboration) 2014 (Preprint 1405.4632)
[36] Bozek P, Broniowski W and Torrieri G 2013 Phys.Rev.Lett. 111 172303 (Preprint 1307.5060)
[37] Aaij R et al. (LHCb Collaboration) 2014 JHEP 1402 072 (Preprint 1308.6729)
[38] Abelev B B et al. (ALICE Collaboration) 2014 JHEP 1402 073 (Preprint 1308.6726)
[39] Aaij R et al. (LHCb Collaboration) 2014 JHEP 1407 094 (Preprint 1405.5152)
[40] Albacete J o 2013 Int.J.Mod.Phys. E22 1330007 (Preprint 1301.3395)
[41] Arleo F and Peigne S 2013 JHEP 1303 122 (Preprint 1212.0434)
[42] Abelev B B et al. (ALICE Collaboration) 2014 (Preprint 1405.3796)
[43] Leitch M et al. (NuSea Collaboration) 2000 Phys.Rev.Lett. 84 3256–3260 (Preprint nucl-ex/9909007)
[44] Abt I et al. (HERA-B Collaboration) 2007 Eur.Phys.J. C49 545–558 (Preprint hep-ex/0607046)
[45] Adare A et al. (PHENIX Collaboration) 2013 Phys.Rev.Lett. 111 202301 (Preprint 1305.5516)
[46] Chatrchyan S et al. (CMS Collaboration) 2014 JHEP 1404 103 (Preprint 1312.6500)
[47] CMS Collaboration 2014 CMS-PAS-HIN-14-003
[48] Aaij R et al. (LHCb Collaboration) 2014 JHEP 1409 030 (Preprint 1406.2885)
[49] CMS Collaboration 2014 CMS-PAS-HIN-13-007
[50] ATLAS Collaboration 2014 ATLAS-CONF-2014-020