EXPERIMENTAL ACHIEVEMENTS AT THE DAWN OF LHC ERA*

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A summary on experimental achievements in the study of nucleus–nucleus collisions is presented, on the basis of the new results reported at Strangeness in Quark Matter 2011 by the GSI–SIS18, RHIC, and LHC experiments. Ultra-relativistic heavy-ion physics entered the new era with the first LHC Pb–Pb operations.

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1. Introduction

This contribution summarizes the experimental presentations at the SQM 2011 Conference. Most of the material is taken from the original contributions, however, all the mistakes, errors, and omissions are mine. Moreover, the choice of the topics described here, as well as my comments, are unavoidably subjective and may well be biased. In view of the wide range of subjects covered at the conference, this summary is organized as follows: low-energy experiments (GSI), beam-energy scan (RHIC), various topics at high energies, and future facilities. The high-energy topics include: event characterization, identified hadrons, strangeness production, azimuthal flow, heavy-flavour production, quarkonia, high-p_{t} and jets. They describe data both from RHIC and the LHC, understandably, however, they are focused on the new flavour-physics LHC results.

The picture most often shown at this conference (I counted close to twenty occurrences), taken from [1], is reproduced in Fig. 1. The problem with this phase diagram of QCD is the label in the upper-left corner saying "Future LHC Experiments". On one occasion this text was covered by the

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more proper label "LHC Experiments". In fact, after some stammering during the LHC commissioning and start-up, the future came so fast that many did not recognize it. The future is now! A similar conclusion was reached independently by Stephans [2].

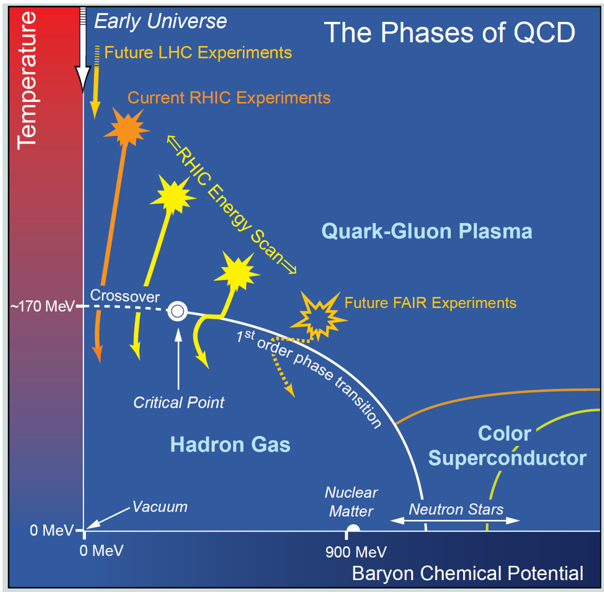

Fig. 1. The picture most often shown at this conference, taken from [1]. It still mentions in the upper-left corner "Future LHC Experiments".

2. Low-energy experiments

Two experiments based at GSI, Darmstadt, utilizing beams from SIS18, reported their results at the conference. The HADES Collaboration presented [3] their measurement of Ξ^--cascade yield in Ar(1.76 A GeV)–KCl collisions published in [4]. They observe Ξ^- production at this deeply subthreshold energy that is an order of magnitude above the predictions (statistical model, UrQMD). The possible production mechanism has to involve multi-step strangeness-exchange reactions. Comparing the yields of other detected particles to the statistical model calculations [5] the second troublemaker is the η meson, whose measured yield is significantly higher than that from the model.

The FOPI Collaboration presented results on charged-kaon and ϕ-meson production in Al–Al and Ni–Ni collisions. The threshold energy for K^- created in nucleon–nucleon collision is significantly lower than that for K^+, therefore the FOPI measurement of the K^-/K^+ ration [6] at an energy in between the two thresholds is very sensitive to in-medium kaon-mass modification or kaon effective potentials. To describe the observed energy and rapidity dependencies of this ratio, the models need to include in-medium effects. The measurement of the ϕ yield implies that 15–22% of observed K^- mesons originate from ϕ decays [7].

3. Beam-energy scan

In 2008 at RHIC it was proposed to proceed with a study of heavy-ion interactions at lower energies. The main motivation was to explore the region of baryon-chemical potential $160\,\mathrm{MeV} < \mu_B < 500\,\mathrm{MeV}$ in the phase diagram of QCD searching for a critical point. Operation below injection energy was successfully tested in 2009 with Au–Au collisions at the c.m.s. energy $\sqrt{s_{NN}} = 9.2\,\mathrm{GeV}$ per nucleon pair [8]. The systematic beam-energy scan programme started in 2010 with data collection at energies $\sqrt{s_{NN}} = 7.5$, 11.5, and 39 GeV, continued in 2011 at $\sqrt{s_{NN}} = 19.6$ and 27 GeV; collisions at the energies $\sqrt{s_{NN}} = 5$ and 15.5 GeV are still envisaged. The RHIC beam-energy scan results have been summarized at this conference by Odyniec [9]. The STAR Collaboration analysed the measured particle yields from data collected in 2010 in the framework of the statistical hadronization model [10] and put the resulting parameters (μ_B and chemical freeze-out temperature) in the QCD phase diagram. Thus, the RHIC results now span in μ_B from 20 to 400 MeV.

The preliminary yields of Λ, $\overline{\Lambda}$, Ξ^-, and $\overline{\Xi}^+$ at mid-rapidity measured by the STAR Collaboration [11] are consistent with the results of the NA49 experiment at similar energies obtained at the CERN SPS. At first sight, these results may resolve the tension, already with us for some time, between the yields in this energy range published by the NA49 and NA57 collaborations, especially for Λ. However, when considering the energy dependence of the Λ yield (see Fig. 2) one tends to admit that the combination of the NA57 data and the higher-energy ($\sqrt{s_{NN}} \geq 62.4\,\mathrm{GeV}$) STAR data makes more sense, than using at lower energies the NA49–STAR (consistent) data. In fact, the STAR mid-rapidity Λ yields exhibit a kind of unnatural step between the energies 39 GeV and 62.4 GeV. To clarify this energy-dependence puzzle, probably the best would be if the STAR Collaboration could review the Λ energy dependence.

The STAR results on the K^+/π^+ ratio [9] are also consistent with the energy dependence of this ratio measured originally by NA49, which shows a sharp maximum at $\sqrt{s_{NN}} \approx 8\,\mathrm{GeV}$ [12], known as Marek's horn (named after M. Gazdzicki). The new data are, however, available only at the higher-energy side of that peak and show less steepness than the NA49 results. The horn became more blunt, so to say.

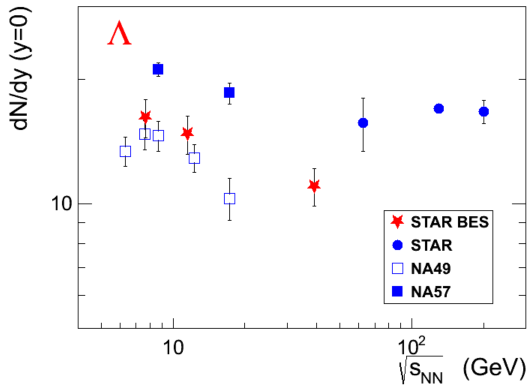

Fig. 2. Energy dependence of the Λ yield per unit of rapidity at mid-rapidity in central heavy-ion collisions measured by different experiments at the CERN SPS and RHIC.

The STAR Collaboration presented data on the energy dependence of the elliptic flow for different particle species [13]. The first observation is that while for energies $\sqrt{s_{NN}} \geq 39$ GeV the v_2 coefficients agree for a particle and its antiparticle within 10%, moving to lower energies they start differ. This effect is more pronounced for baryons, where v_2 for p and Λ is larger than the value for corresponding antiparticles. For mesons a smaller difference is seen, at lowest energy $v_2(K^+) > v_2(K^-)$, however, $v_2(\pi^+) < v_2(\pi^-)$. A possible explanation could be the absorption of particles in the hadronic matter. The second effect reported is a v_2 value for the ϕ meson lower than for the other particles at $\sqrt{s_{NN}} = 11.5$ GeV (at the lowest energy ($\sqrt{s_{NN}} = 7.7$ GeV) there is not enough statistics for this analysis). This could signal that ϕ mesons at this low energy do not come from a partonic matter.

4. High-energy experiments

In this section, a selection of the new results, both from RHIC higher energies and the LHC, are summarized.

4.1. Event characterization

The pseudo-rapidity charged-particle density at mid-rapidity in 5% of most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV was measured first by ALICE [14, 15]. This lead to the conclusion that the multiplicity density per participant pair in heavy-ion central interactions rises with the collision energy as $\propto s_{NN}^{0.15}$, significantly faster than in pp collisions, where a growth $\propto s_{pp}^{0.11}$ is observed. As opposed to the situation at the first RHIC measurement, this time the majority of predictions were below the observed value. The centrality dependence of charged-particle density expressed as a function of number of participants has a very similar shape as that measured at RHIC (the LHC multiplicity densities are about a factor 2.1 higher) [16, 15], and there is an excellent agreement among the three LHC experiments [17, 18].

The energy density achieved in central heavy-ion collisions at LHC is estimated from the particle density and the transverse-momentum spectra for different particle species [19]. Using the Bjorken formula, for the product of the formation time and the energy density ALICE obtained $\tau\epsilon \approx 15\,\mathrm{GeV/fm^2}$, *i.e.* 2.7 times higher than at RHIC. The size and lifetime of the emitting source is studied by identical-boson interferometry [15, 20]. For central heavy-ion collisions, from RHIC to the LHC, an increase in the size by a factor of about two, and in the lifetime by about 40% is observed.

4.2. Identified-particle production

The ALICE Collaboration presented at this conference the transverse momentum (p_{t}) spectra of charged pions, kaons and protons [15, 21, 22], for different centralities in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$. The LHC spectra are remarkably harder compared to those measured at RHIC [23, 24], the change being more pronounced for heavier particles, and this signals larger radial flow. The spectra are reasonably well described up to $p_{\mathrm{t}}\,2.5\,\mathrm{GeV}/c$ by viscous-hydrodynamic calculations (VISHNU) [25] tuned to RHIC data, except that the proton absolute yield is over-predicted. The ratio K/π at mid-rapidity [21] is only weakly centrality dependent and coincides with the RHIC measurement [24] at the same particle density. The p/π ratio is centrality independent and agrees very well with PHENIX [23] and BRAHMS [26] measurements at RHIC, but all these results are lower than the STAR value [24], which is not corrected for feed-down protons from strange-baryon decays and thus not directly comparable. The thermal hadronization model predicts [27] the K/π ratio within 6%, but gives a p/π ratio more than 50% higher. The pion, kaon, and proton spectra were simultaneously fitted with blast-wave distributions [22]. The resulting speed of radial expansion is around $0.66\,c$, about 10% faster than at RHIC.

While looking for $\mathit{\Xi}(1530)^0$ resonance in $\mathit{\Xi}^-\pi^+$ decay channel in pp collisions at $\sqrt{s} = 7$ TeV, ALICE detected no signal for $\mathit{\Phi}(1860)$ [28], a pentaquark candidate previously reported by the NA49 Collaboration [29]. The STAR Collaboration reported the first observation of the antimatter hypernuclei ${}^{3}_{\mathit{\Lambda}}\overline{H}$ [30, 31].

4.3. Strange-particle production

The ALICE Collaboration reported the transverse momentum dependence of $\mathit{\Lambda}/K^0_{\mathrm{s}}$ ratio [32]. In an intermediate p_{t} region 2–5 GeV/c this ratio increases when going from pp data to more and more central Pb–Pb collisions, reaching a value about 1.5 for the 5% of most central collisions. The magnitude of this effect also increases with the collision energy when comparing to RHIC data at higher energies. The transverse momentum at the maximum of $\Lambda/K^0_{\rm s}$ ratio also slightly increases with the energy [33]. The value of this ratio is even higher at RHIC low energies explored in the beam-energy scan [11], where baryon-number transport from incident nuclei plays a large role.

The results on multi-strange baryon production, Ξ^- and Ω^-, in both pp and Pb–Pb interactions, have been presented by ALICE. The yields of these particles are known to be very difficult to describe in the Monte Carlo event generators, like Pythia. Comparing the Ξ^- $p_{\rm t}$ spectrum in pp collisions [34], measured in the $p_{\rm t}$ range 0.8–8.5 GeV/c, to the one of the latest Pythia tunes, Perugia 2011 [35], one finds that the disagreement is concentrated at intermediate $p_{\rm t}$, where the data are a factor of two above the model. At low $p_{\rm t}$, around 0.8 GeV/c, the data approach the model calculations, and at high $p_{\rm t}$, above 6 GeV/c, the model describes the measurement very well. The ALICE spectrum is consistent with the previously published CMS Ξ^- spectrum [36], measured up to $p_{\rm t}$ of 6 GeV/c. Such a behaviour has not been fully checked for the Ω^- $p_{\rm t}$ spectrum, since it could be measured only between 1 and 5 GeV/c, due to lack of statistics.

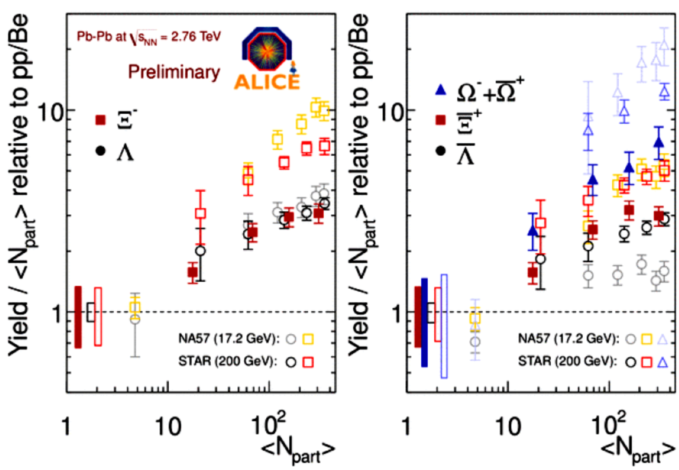

Fig. 3. Centrality dependence of strangeness enhancement in heavy-ion collisions, yield per participant normalized to that in pp (or p–Be) collisions. The results from ALICE, STAR and NA57 experiments.

The ALICE Collaboration reported the first results on multi-strange production in LHC heavy-ion collisions [15, 32, 37]. The transverse momentum spectra for different centralities have been integrated to obtain the Ξ^- and

Ω^- yields at mid-rapidity. The strangeness enhancement is measured as the yields per participant normalized to the same variable determined in pp (or p–Be) collisions. The centrality dependence of this enhancement is shown in Fig. 3 using the number of participants as the centrality measure, comparing the LHC ALICE data with RHIC STAR and the NA57 SPS results. The calculations using a thermal hadronization model [27] have been compared also to measured Ξ^- and Ω^- yields, and a good agreement was found [38]. Thus, so far only protons seem not to behave according to the thermal equilibrium, let us wait for other particles, such as Λ, ϕ, *etc.*

4.4. Anisotropic flow

The first result on anisotropic elliptic flow was published by ALICE already during the 2010 heavy-ion run [39] and reported at this conference [15]. The conclusion was that $p_{\rm t}$ integrated flow measured by v_2 coefficient is about 20% higher than that observed at RHIC, however, the $p_{\rm t}$ dependencies of v_2 are very similar between RHIC and the LHC. The measured increase is entirely due to the larger $p_{\rm t}$ of secondary particles at the LHC (*i.e.* radial flow). The ALICE Collaboration presented also the results on higher harmonic coefficients [40, 41]. The v_3 coefficient does not depend strongly on centrality and is smaller than v_2, except for very central collisions. When estimated with respect to the reaction plane the v_3 coefficient is compatible with zero. That means that v_3 has its own symmetry plane, which is uncorrelated with the v_2 symmetry plane. Appearance of this triangular flow is a consequence of fluctuations in the initial state geometry [42]. The results on anisotropic flow were presented also by the ATLAS Collaboration [43], including higher order harmonic coefficients up to v_6. Both collaborations showed that the structures observed in the azimuthal two-particle correlation, such as the long-range ridge in pseudo-rapidity and the so-called Mach cone, can be described in a coherent way with anisotropic flow coefficients up to $p_{\rm t} = 3$–4 GeV/c [15, 43].

Measurements of v_2 and v_3 for identified pions, kaons, and protons were presented by the ALICE Collaboration [44]. The hydrodynamical splitting in the v_2 $p_{\rm t}$-dependence is clearly observed. In order to describe the proton shift, measured in central collisions (10–20%), the hydrodynamical model (VISHNU) has to be supplied with an afterburner (UrQMD rescattering) [25]. Similar splitting is also observed in $K^0_{\rm s}$ and Λ transverse-momentum dependence of v_2. The v_3 $p_{\rm t}$-dependence is sensitive to the viscosity-to-entropy-density ratio and to the assumptions on initial nuclear distribution. There does not exist a calculation describing all the data on anisotropic flow yet, however, there is a strong hope that this way a v_n-iscosimeter of hot strongly-interacting matter can be constructed.

4.5. Heavy-flavour production

Both the STAR [45] and ALICE [15,46] collaborations presented results on the production of various D mesons, reconstructed using their hadronic decays. ALICE measured the charm cross section and transverse-momentum spectra in pp interactions at two energies $\sqrt{s} = 2.76$ and 7 TeV. The data are in good agreement with the QCD perturbative calculations. Also the STAR data for pp and d–p interactions are now quite close to the QCD prediction and the former STAR–PHENIX tension in the charm cross section is slowly disappearing.

ALICE also presented the heavy-flavour measurement using electrons from semi-leptonic D and B decays, both in pp and Pb–Pb collisions [47]. However, Xie in his overview talk on semi-leptonic decays [48] rightly summarized the situation about non-separated D–B measurements and model comparisons with a sentence: "Models with different or similar mechanisms can or cannot describe the data." Therefore, various groups are attempting to separate D and B contributions even in semi-leptonic decays. STAR is using correlations between non-photonic electrons and hadrons together with Pythia calculations [49,50]. ALICE presented an analysis utilizing the electron distance of closest approach to the primary vertex [47].

The ALICE results in heavy-ion collisions for D^0, D^+ and D^{*+}, reconstructed with exclusive hadronic decays, are presented as $p_{\rm t}$ dependence of the charm nuclear modification factor R_{AA} [51] in Fig. 4, together with R_{AA} for π^+-meson measured in the same experiment. D mesons are suppressed

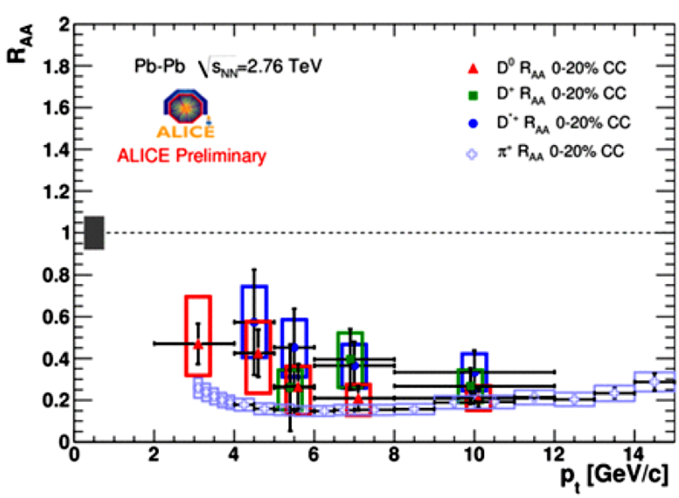

Fig. 4. Transverse-momentum dependence of nuclear modification factor R_{AA} for D mesons and for π^+ meson in 20% most central Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV.

less than pions, but still more than one would expect due to the dead-cone effect. STAR reported D meson R_{AA} values compatible with unity in a very wide centrality range 0–80% and in $p_{\rm t} = 0.5$–$4\,{\rm GeV}/c$ [45].

PHENIX presented measurement of the elliptic flow for charm, using semi-leptonic decays [52,53]. The charm v_2 at low $p_{\rm t}$ is almost as high as for light mesons, and above $1.6\,{\rm GeV}/c$ starts to drop, being insignificant above $3\,{\rm GeV}/c$. This is a hint that charm quarks at low $p_{\rm t}$ can be thermalized. The ALICE Collaboration also reported the first result on D^0 meson v_2 [54], in the $p_{\rm t}$ region 2–$12\,{\rm GeV}/c$ they measured the value around 0.1, but with large uncertainty. However, this measurements requires a significant increase in statistics.

4.6. Quarkonia

The PHENIX Collaboration reported an update of their J/ψ measurement [53, 55]. At the RHIC highest energy $\sqrt{s_{NN}} = 200\,{\rm GeV}$ J/ψ is more suppressed in the forward region than at mid-rapidity. At lower energies $\sqrt{s_{NN}} = 62$ and 39 GeV a similar $R_{\rm CP}$ is observed, albeit with very large errors at the lowest energy. The J/ψ suppression is similar to that observed at CERN SPS. STAR extended the RHIC J/ψ measurement up to $p_{\rm t}$ of $8\,{\rm GeV}/c$ [49], and the result is compatible with the PHENIX one in the overlapping region, again with substantial measurement errors. The $p_{\rm t}$ dependence of J/ψ nuclear modification factor shows a tendency towards less suppression at higher $p_{\rm t}$.

Moving to LHC, the CMS Collaboration presented an impressive plot of a dimuon mass spectrum from LHC Pb–Pb collisions with clear J/ψ, Υ, and Z signals [56], see Fig. 5. Their measurement of J/ψ at $p_{\rm t}$ above $3\,{\rm GeV}/c$ shows a trend opposite to that of the RHIC results, *i.e.* less suppression at forward rapidity compared to mid-rapidity. Furthermore, ALICE measures the J/ψ nuclear modification factor down to zero $p_{\rm t}$ [46, 57], and observes smaller suppression than CMS. This is even more pronounced when comparing to ATLAS J/ψ $R_{\rm CP}$ results for $p_{\rm t}$ above $6.5\,{\rm GeV}/c$ [17, 58]. Altogether, this would mean that at the LHC, J/ψ is less suppressed at low $p_{\rm t}$ than at high $p_{\rm t}$, which does not confirm the tendency from RHIC. The LHC observations would qualitatively support the idea about J/ψ regeneration via charm–quark recombination [59]. As already mentioned, the situation with RHIC–LHC J/ψ production is not completely clear, and the foreseen increase in the statistics at LHC will certainly bring a better understanding. In the mean time, all three LHC experiments are working on the separation of direct J/ψ from those produced in B decays. Another way to investigate charm–quark thermalization is to measure J/ψ elliptic flow. STAR extended [45] previously reported PHENIX v_2 measurement up to $p_{\rm t}$ of about $8\,{\rm GeV}/c$. The result is consistent with zero, at least for $p_{\rm t} > 2\,{\rm GeV}/c$.

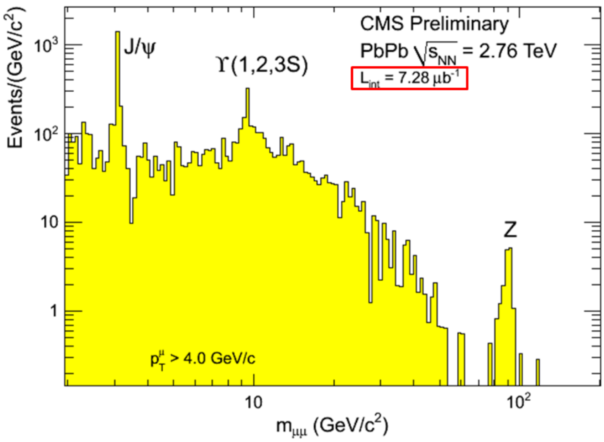

Fig. 5. Effective mass distribution of opposite-charged dimouns in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

The suppression of Υ starts to appear at conference menus. STAR reported centrality dependence of combined Υ, Υ', and Υ'' R_{AA} in Au–Au collisions at the RHIC top energy [49]. At the LHC, the CMS experiment, having an excellent dimuon-mass resolution, measured R_{AA} for Υ (1s) state separately to be about 0.6 for minimum-biased Pb–Pb collisions [56]. CMS already published the suppression of the ratio $(\Upsilon'+\Upsilon'')/\Upsilon$ observed in heavy-ion collisions with respect to *pp* [60], and this implies very strong suppression of the (2s) and (3s) states. With the forthcoming LHC heavy-ion runs the results about the Υ family suppression will improve dramatically, as the precision of these measurements are still statistics limited.

4.7. High $p_{\rm t}$ and jets

ALICE presented the transverse-momentum dependence of the nuclear modification factor R_{AA} for charged particles up to 50 GeV$/c$ [61]. For 5% of most central LHC Pb–Pb collision the particle production is suppressed down to its minimal value of about 12% at $p_{\rm t}$ around 6–7 GeV$/c$, and for higher $p_{\rm t}$ it raises again, reaching 40% above 30 GeV$/c$. A similar behaviour was reported by ATLAS Collaboration [17], this time using $R_{\rm CP}$, *i.e.* the ratio between central and peripheral collisions. The ALICE Collaboration also measured the difference in R_{AA} for particle production near the reaction plane and outside the reaction plane. Such difference might be sensitive to the in-medium length dependence of the parton quenching.

There were new results on the suppression of strange particles, $K^0_{\rm s}$ and Λ [62], reported by the ALICE Collaboration. Figure 6 summarizes the R_{AA} measurement for 20% of most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV presented by ALICE.

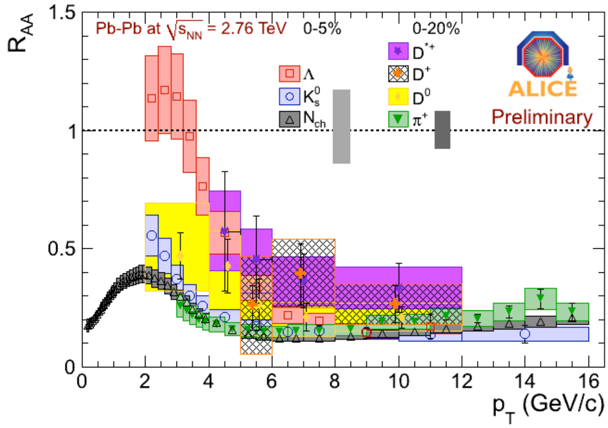

Fig. 6. Transverse-momentum dependence of nuclear modification factor R_{AA} for different identified particles in 20% most central Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76\,$TeV.

The ATLAS jet-quenching results, published during the first LHC heavy-ion run [63], were also reported at this conference [17]. They were supplemented by jet $R_{\rm CP}$ measurement, showing a suppression of the jet yield by a factor of about two in 10% of most central collisions with respect to 60–80% centrality class.

5. Future facilities

There were two presentations about future facilities at this conference. The NICA project at Dubna (Russia) [64] aims to collide heavy ions in an asymmetric collider already in 2016, reaching energy $\sqrt{s_{NN}} = 9\,$GeV and luminosity $10^{27}\,{\rm cm}^{-2}{\rm s}^{-1}$. In addition, it is planned to collide polarized protons and light nuclei. The FAIR at GSI, Darmstadt (Germany), is a fixed-target facility with heavy-ion beams at laboratory energy up to 35 $A\,$GeV and very high beam intensity [65]. However, the start of the operation is pushed till 2019. In view of this delay, there is an agreement between Dubna and GSI, Darmstadt, to prepare for the NICA collider a common detector based on the sub-detectors developed by the CBM Collaboration for FAIR.

6. Conclusion

As a conclusion, we are at the dawn of a new era. With the start of the LHC heavy-ion operations and the upcoming upgrades of the RHIC experiments, high-energy nucleus–nucleus collisions are entering an era of precision measurements that should allow us to impose tight constraints on the properties of the medium. The first LHC results confirm the basic characteristics of strongly-interacting matter observed at RHIC, there are quantitative differences, medium created in collisions is hotter, larger, and longer-lived. The outlook is brighter than ever: with a high-luminosity LHC Pb–Pb run (about 10 times the 2010 luminosity) coming up later in 2011 and possibly a p–Pb run as early as 2012, we could be in for some paradigm shifting soon.

I would like to thank my friends Federico Antinori, Emanuele Quercigh and Orlando Villalobos Baillie for their help in the preparation of this talk. This edition of Strangeness in Quark Matter conference had a privilege to host the first heavy-ion results form the LHC, therefore, condemned to the success. However, thanks to fantastic efforts of Piotr Bożek, Wojtek Broniowski, and especially Wojtek Florkowski this event will stay for a long time in our memories.

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