Hot and dense matter at RHIC and LHC

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The results obtained by RHIC and LHC experiments in the study of nucleus-nucleus collisions shed light on the behaviour of the hot and dense matter produced in heavy ion interactions at high energy. The recent p-Pb run at the LHC added another piece of information, showing p-nucleus interactions provide interesting and unexpected features. The most recent results, the open questions and the perspectives will be discussed.

1 Introduction

During the last decades, high energy heavy ion physics provided impressive and outstanding results. RHIC experiments produced several fascinating discoveries: the hot and dense matter created in the nuclei collisions at a centre of mass energy $\sqrt{s_{\rm NN}}$=200 GeV behaves as a nearly viscosity-free fluid. The nuclear medium, opaque to hadrons but transparent to photons, suppresses the away-side jet in events with two back-to-back jets. Later LHC experiments showed that increasing the energy to $\sqrt{s_{\rm NN}}$=2.76 TeV gives a fireball hotter, larger and lasting longer. New phenomena manifest or become more pronounced: the suppression of the J/ψ in head-on central collisions (low impact parameter) and/or at low p_T is less pronounced compared to RHIC and this vector meson shows a non-zero elliptic flow. Charmed meson nuclear modification factor is larger than ordinary hadron one, and it looks smaller than that measured with b-quark hadrons. In addition the study of p-Pb interactions showed an unexpected collective behaviour and one cannot exclude yet the quark gluon plasma is created in this lighter system too.

Although these exciting results provided a remarkable step forward in the comprehension of this new state of matter, a precise measurement of the parameters characterizing this fluid is still missing; as an example the shear viscosity (η/s) has an uncertainty as large as a factor four and a similar uncertainty affects the jet transport parameter ($\hat{q}$) measurement. The above discoveries raised a number of compelling questions. What is the mechanism behind a so fast quark thermalization ? Does the QGP contain quasi-particle or long lived excitations are cancelled by the strong field ? What is the origin of the ridge, observed in p-p collision too ? These questions can be answered in the next years when a plenty of new data will be available: LHC will offer the opportunity to study the QGP at the highest temperatures ($\sqrt{s_{\rm NN}}$= 5.5 TeV) and RHIC will improve the beam energy scan (BES) to study the phase transition boundary and to search for the phase space critical point.

Given the available space I will not try to give a comprehensive review of heavy ion results at RHIC and LHC, but I will focus on few subjects. Jets and high p_T events will not be discussed here, since a dedicated talk on this subject was presented at this conference.

2 Global properties

The Hanbury-Brown and Twiss(HBT) [1] correlation played an important role in astrophysics in the '50s, when it was used to measure the star angular size. Years later, particle physicists relied on this method to assess the spatial scale of the emitting source size by studying identical bosons, as charged pion pairs. The two particle correlation function can be defined as the ratio of two measured distributions based on two different samples, using pion pairs from the same event and from different events, respectively. The pair three-momentum difference $\mathbf{q}$ can be decomposed into the three components (q_{out}, q_{side}, q_{long}), where the *out* axis points along the pair transverse momentum, the *side* axis is perpendicular to the transverse momentum plane and the *long* axis points along the beam. The three-dimensional correlation function is fitted to an expression accounting for the Bose-Einstein enhancement, containing a term $G(q) = e^{-q^2 R^2}$, where $R = (R_{out}, R_{long}, R_{side})$ is the HBT radius of the production region.

The ALICE results[2] give at the LHC a source volume $V \simeq 300\ fm^3$, a factor 2 larger than the volume measured at RHIC and a lifetime $\tau \simeq 10$ fm/c, a 20% larger than the one measured at RHIC. As pointed out by PHENIX [3], the fireball shines, emitting direct photon with a temperature T=221±19(sta)±19(sys) MeV [3]. ALICE measured a 30% hotter medium, obtaining T = 304±51 (sta+sys) MeV [4]. It is worth noting this is the average fireball temperature: hydro-dynamical models predict the highest temperature reached in the early stage is expected up to a factor 3 higher. The energy density can be estimated by using the Bjorken-formula approximation. At the LHC the hot and dense matter reaches ≃15 GeV/fm^3 [5], a factor 3 larger than the energy density measured at RHIC. In summary, the increase in centre of mass energy from $\sqrt{s_{\mathrm{NN}}}$=200 GeV to 2.76 TeV reflects in a fireball with a factor 2 larger volume, a factor 3 larger energy density, lasting 20% longer and with a temperature 30% hotter, equivalent to ($3{\cdot}10^{12}$K). Compared to this temperature record, the interior of the sun is an almost cold place, reaching a modest $2{\cdot}10^7$K !

3 Collectivity

The azimuthal momentum distribution of the emitted particles is usually expressed as

$$\frac{dN}{d\Phi} \propto 1 + \sum_n 2v_n \cos(2n(\Phi - \Psi_n) \tag{1}$$

where v_n is the magnitude of the $n-th$ order harmonic term relative to the angle of the plane Ψ_n.

One of the most exciting results obtained at the RHIC was the evidence that the bulk of the produced hot matter is well described by fluid-dynamics, predicting a non vanishing elliptic flow v_2. At the LHC the p_T integrated v_2 showed an increase of about 30% compared to RHIC, mainly due to the increase of the average transverse momentum of the produced particles. Recently, the ALICE collaboration, taking advantage of the detector powerful particle identification, published a paper focused on identified hadron elliptic flow [6]: a clear mass ordering was observed, with heavier particles showing a smaller v_2. This not-trivial result, predicted by fluid-dynamic models, indicates the radial flow boosts heavier particles to higher p_T, $\Delta p_T \simeq \Delta \mathrm{m}\beta$.

One of the most urgent questions to be answered is how perfect this fluid is, that is to provide a precise measurement of the shear viscosity η/s. Initial system condition, feeding the hydro models, are a very important source of uncertainty, when extracting the medium parameters from data. As pointed out in [7], the comparison of PHOBOS elliptic flow with hydro-models gives a best fit η/s ranging from 0.08 to 0.16 when applying initial conditions based on the Colour Glass Condensate or the Glauber model, respectively. Improving our knowledge on the initial conditions is therefore mandatory to reduce the uncertainties on the shear viscosity η/s. STAR studied the U-U interactions at $\sqrt{s_{\mathrm{NN}}}$= 193 GeV. The prolate shape of this nucleus, provides the possibility to study the initial condition effect on the azimuthal distributions: interactions may occur in a body-body configuration (giving large v_2 and a relatively small number of charged particles) or tip-tip (characterized by a small v_2 and a large number of charged particles). To minimize the effect due to the impact parameter, the analysis has to be restricted to events with top 0.1% centrality. Zeta Degree Calorimeters tag these two different configurations, measuring the energy of spectator nuclei. The elliptic flow was measured as a function of the normalized multiplicity(mult/<mult>): while the Glauber model predicted a too step dependence, the IP-Glasma model [8] gives a satisfactory prediction. This model provides initial conditions for systematic flow studies. It combines the IP-Sat (impact parameter saturation) model of high energy nucleon (and nuclear) wave functions with the classical SU(3) Yang-Mills (CYM) dynamics of the Glasma fields produced in a heavy-ion collision. Event by event fluctuations studied by ATLAS [9] at the LHC provide another successful test for the IP-Glasma model. The eccentricity ϵ_2, ϵ_3, ϵ_4 are expected to be proportional to v_2 ,v_3, v_4 in most hydrodynamic calculations. It is worth nothing recently few studies showed this statement hardly applies to v_4 [10]. Any deviation of the proportionality constant can be used to constrain the shear viscosity and the initial system geometry. In the ATLAS analysis, for each event, the v_2,v_3,v_4 are extracted. The v_n probability distributions are compared to the eccentricity, rescaled to match the $<v_n>$ of the data. Initial condition were provided by two different models: the Glauber model and the MC-KLN model, the latter including gluon saturation effect. Both the Glauber and the MC-KLN models predict correctly the data at low centrality, but fail for peripheral collisions [9], underestimating the probability for large v_n. On the contrary, as pointed out in ref. [11], the IP Glasma model, coupled to the MUSIC code, a 3+1 dimensional relativistic viscous hydrodinamic simulation model, predicts quite well these distributions for peripheral events too. Fluctuations are a gold mine in modern physics: as an example temperature fluctuations in the microwave background provided invaluable informations on the universe composition. Geometric nucleon position and intrinsic subnucleon scale colour charge fluctuations are quenched by the shear viscosity: their magnitude gives therefore a direct indication on how perfect this fluid is. One of the most remarkable effects of the fluctuations is the generation of harmonics of order higher than v_2(v_n,$n \geq$3). It was shown in [12] the higher orders are very sensitive to the shear viscosity. Several experiments at the LHC measured v_n in different intervals of centrality [13, 14]. In Fig. 1 the PHENIX data [15] are compared to the IP-Glasma+Music prediction for harmonics of any order. A satisfactory agreement is obtained, with η/s=0.12 as favourite parameter. Applying the fit to the ATLAS [13] or ALICE [14] results gives a nice fit too, with a preferred η/s=0.2. The above result may suggest η/s is changing from RHIC to LHC energies. An attempt to fit all the data with a η/s temperature (and hence energy) dependent was attempted. The fit at p_T > 1.5 GeV/c poorly reproduces the RHIC data(fig. 2, left panel). The η/s(T) functional

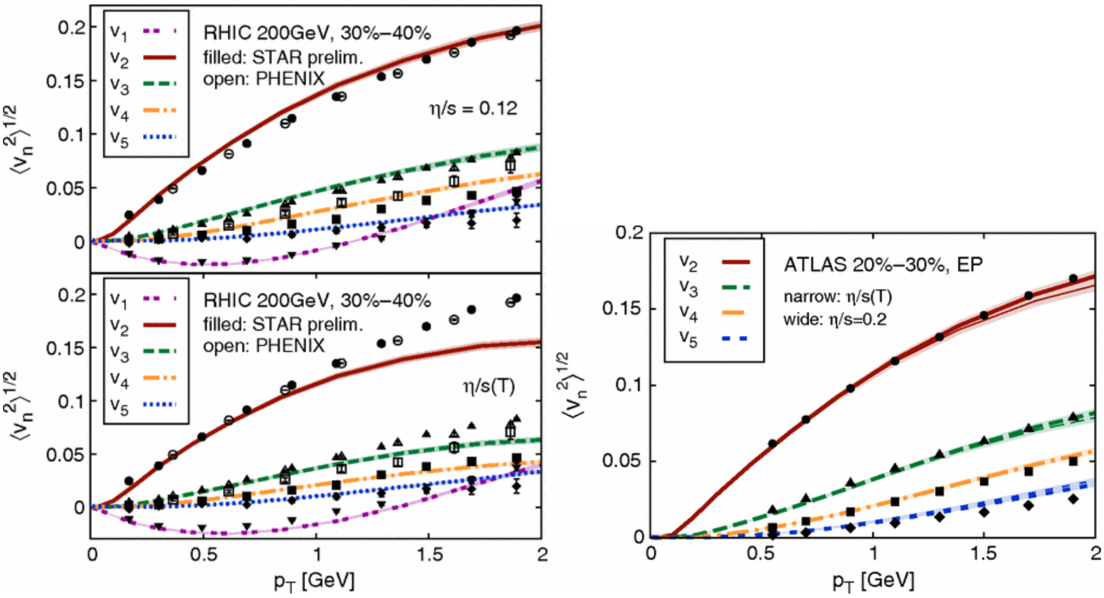

Figure 1: Comparison of $v_n(p_T)$ at RHIC (left) using constant η/s=0.12 and a temperature dependent (η/s)(T), and at the LHC(right) using constant η/s=0.20 and a temperature dependent (η/s)(T)

form should be improved and more data at different energies, as those coming from RHIC BES, are required. Ultra central collisions are marginally dependent on initial conditions: Luzum and Ollitreatus showed [16] the root mean square of the harmonic eccentricity decreases with centrality. In addition the predictions obtained by using several different models get closer. The shear viscosity can be extracted comparing the ATLAS p_t integrated v_n data [17] to different model predictions. As a result a shear viscosity $0.07 \leq \eta/\text{s} \leq 0.43$ was obtained. The large allowed interval (factor 6) is mostly due to a tension between the v_2 and the v_3 constrain. G. Denicol et al. [18] included in the simulation the repulsive effect of nucleon-nucleon correlation, playing a non negligible role for the most central events. The fit of the IP-Glasma+Music model to the ATLAS v_n data, improves the v_2 and v_3 predictions, reduce their mutual tension and gives a preferred value of η/s=0.21. Further improvements may came from the recent data published by CMS, studying v_n at centrality as small as 0-0.2% [19].

4 Nuclear modification factor

The energy loss of scattered partons traversing the hot and dense medium can be quantified using the nuclear modification factor R_{AA}, defined as

$$R_{AA}(p_T) = \frac{Yield_{AA}(p_T)}{< N_{coll} >_{AA} \; Yield_{pp}(p_T)}, \tag{2}$$

where $Yield_{AA}$ is the yield obtained in nucleus-nucleus collisions, $Yield_{pp}$ is the yield obtained in pp collisions and $< N_{coll} >_{AA}$ is the average number of nucleon-nucleon collisions in A-A events.

A nuclear modification factor close to unit indicate that nucleus-nucleus collisions are equivalent to the superposition of nucleon-nucleon collisions, properly normalized. Partons are expected to lose energy in the hot and dense medium via gluon radiation and elastic collisions, leading to $R_{AA} < 1$. The QCD picture of parton energy loss in high energy heavy ion interactions predicts a gluon energy loss higher than the quark energy loss. In addition heavy quarks are expected to lose less energy compared to ligher quarks, due to the lack of gluon radiation in a forward cone (Casimir cone), whose angle θ=M_q/E_q. Hints for a charged mesons (D^0, D^+, D^-) R_{AA} larger than that of charged particles has been reported by the ALICE experiment [20]. CMS showed the nuclear modification factor for non prompt J/Ψ(coming from b decay) is larger than D meson R_{AA}. These are clear indications the energy loss in the hot and dense matter follows the expected quark hierarchy.

The beam energy scan performed at RHIC is a nice opportunity to study the parton energy loss at different temperatures. At $\sqrt{s_{\rm NN}}$=200 GeV PHENIX found[21] a strong suppression for heavy flavour electrons compared to pp interactions (R_{AA} <1), while at $\sqrt{s_{\rm NN}}$=62 GeV the nuclear modification factor is compatible or larger than unit [22]. Although an higher statistics and a pp run at the same energy is required, this result indicates a change in the competition between the Cronin enhancement, that is prevalent in lower energy collisions, and the suppressing effects of the hot medium, that dominates at high energies. Another remarkable result obtained during the RHIC BES comes from STAR, measuring [23] the central-to-peripheral nuclear modification factor R_{CP} as a function of the centre of mass energy, where R_{CP} is defined as

$$R_{CP}(p_T) = \frac{< N_{Coll} >^{60-80\%}}{< N_{Coll} >^{0-5\%}} \frac{Yield_{AA}^{0-5\%}(p_T)}{Yield_{AA}^{60-80\%}(p_T)} \tag{3}$$

where $< N_{Coll} >^{60-80\%}$ is the average number of nucleon-nucleon collisions in events with centrality 60-80%, $< N_{Coll} >^{0-5\%}$ is the average number of nucleon-nucleon collisions in events with centrality 0-5%. While at $\sqrt{s_{\rm NN}}$=200 GeV $R_{CP} < 1$, as expected for partonic energy loss, at $\sqrt{s_{\rm NN}}$=7.7 GeV it exceeds 5 at p_T= 3 GeV/c. These two opposite trends show a smooth transition, with $R_{CP} \simeq$1 reached between $\sqrt{s_{\rm NN}}$=27 GeV and $\sqrt{s_{\rm NN}}$=39 GeV: is the phase transition boundary within this energy interval ?

5 Quarkonia

The evidence for J/ψ suppression was a smoking gun of QGP formation at CERN-SPS experiments. Years later the RHIC experiments showed an unexpected result: the amount of suppression at $\sqrt{s_{\rm NN}}$=200 GeV was almost unchanged with respect to the SPS energies. The J/ψ suppression measured by ALICE at the LHC, was less pronounced at small centrality compared to RICH, both at forward and mid-rapidity. A possible explanation is provided by the recombination mechanism, playing an important role in J/ψ formation in heavy ion collisions at high energy. On average 70-80 $c\bar{c}$ pairs/events are expected at the LHC, to be compared to $\simeq$10 pairs at RHIC. J/ψ from $c\bar{c}$ recombination are expected to show a softer p_T spectrum and hence the J/ψ suppression should be stronger at higher p_T. Indeed ALICE results confirms this interpretation, as shown in Fig. 2(left panel). Moreover, in contrast to primordial J/ψ, the J/ψs from recombination are expected to inherit from c and $\bar{c}$ quarks their elliptic flow, due to the c quark thermalization. At RHIC a J/ψ elliptic flow consistent with zero was reported [24], while at the LHC ALICE [25] and CMS showed [26] a non zero v_2, with a $\simeq 4\sigma$ significance.

Due to the lower b$\bar{b}$ production cross section compared to the $c\bar{c}$ one, Υ is a powerful tool to study colour screening at the LHC. Nevertheless the feed-down from higher mass bottomonia, complicates data interpretation. Lattice QCD predicts a vector meson sequential suppression pattern with temperature: large uncertainties exist in the absolute calibration of this thermometer: Υ is expected to melt at a temperature 2-5 T_C, depending on the model considered, while the J/ψ melting temperature ranges from 1.5T_C to 3T_C. STAR and PHENIX at RHIC showed hints for a Υ suppression in Au-Au interactions at $\sqrt{s_{\rm NN}}$=200 GeV. This suppression is compatible with the suppression reported at the LHC by CMS [27], suggesting the measured Υ suppression is consistent, both at RHIC and at the LHC, with the $\Upsilon(2s)$, $\Upsilon(3s)$ and χ_B full melting only, suggesting the Υ(1s) melting threshold was not reached yet. CMS measured the suppression of the three excited state: the $\Upsilon(1s)$ suppression increases with the centrality and is not suppressed in very peripheral collisions. On the contrary $\Upsilon(2s)$ is suppressed in peripheral collisions too. Finally the suppression of $\Upsilon(3s)$ is quite strong: an upper limit in the $\Upsilon(3s)/\Upsilon(1s)$ ratio <0.04 was set.

The ratio of $\Upsilon(2s)/\Upsilon(1s)$ is quite similar in pp (0.26 $\pm$ 0.01(sta) $\pm$ 0.01(sys) $\pm$ 0.02(glob))) and p-Pb interactions (0.22 $\pm$ 0.01(sta)$\pm$ 0.01(sys) $\pm$ 0.01(glob)) [27]. As a consequence, the strong $\Upsilon(2s)$ suppression seen in Pb-Pb collision (0.09 $\pm$ 0.02(sta) $\pm$ 0.02(sys) $\pm$ 0.01(glob)) cannot be explained by cold matter effects.

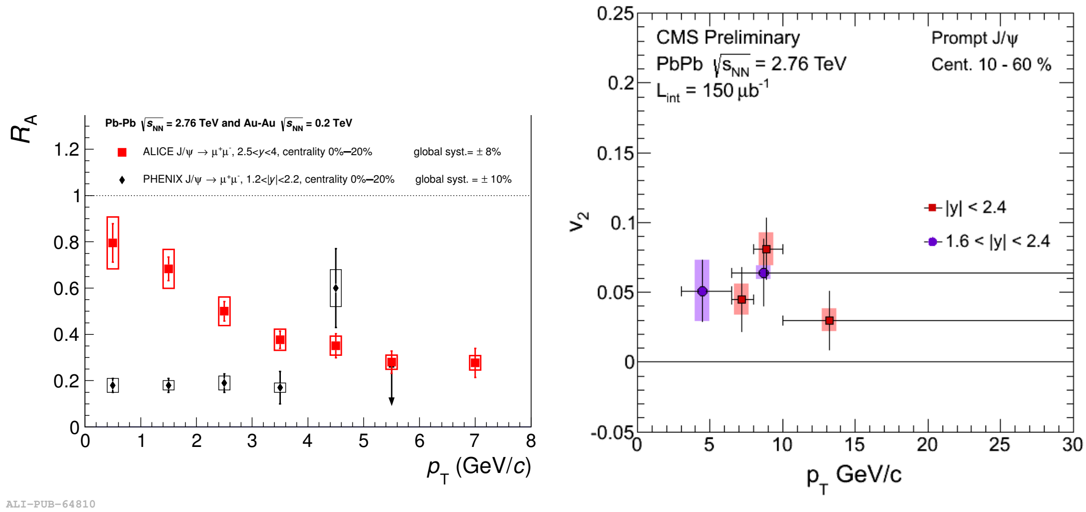

Figure 2: Left: comparison of J/ψ suppression as a function of the transverse momentum measured at the RHIC and at the LHC in the centraliy bin 0-20%. ALICE points show a less pronounced suppression at low p_T. Right: the elliptic flow measured by CMS. Both the result support a J/ψ recombination scenario.

6 The Ridge

Is Cold Nuclear Matter produced in p-Pb collisions at the LHC really cold ? Looking at electrons produced in heavy flavour decay (R_{pPb} $\simeq$1), to be compared with a much smaller nuclear modification factor obtained in Pb-Pb collisions, the answer is affirmative. A similar conclusion can be drawn considering D meson production [28] or inclusive jet production [29] in p-Pb collisions. In addition the study of J/ψ in p-Pb collisions shows a modest to zero suppression, depending on the considered rapidity region; this result can be fully explained by initial state effects, as gluon shadowing. CMS discovered a ridge-like structure in events with a large number of produced charged particles in pp collisions [30]. A similar structure was previously found in Au-Au collisions by the RHIC experiments. The p-Pb collisions showed a ridge-like structure too, very similar, at a first look, to that observed in Pb-Pb collisions. This unexpected feature triggered a large amount of experimental [31, 32, 33] and theoretical studies. The ridge-like structure in pp and p-Pb collisions is surprisings, since these systems were not expected to produce a fireball dense and hot enough to produce strong collective effects. Several methods to separate the jet and the ridge components have been used. Namely ALICE subtracted the sample with a centrality 60-100% from the most 0-20% central events. As a result a double ridge-like structure was obtained [31]. The projection in the $\Delta\Phi$ plane can be fitted to a function:

$$\frac{1}{N_{trig}}\frac{dN}{d\Delta\Phi} = a_0 + 2\sum_{n>1} a_n \cos(n\Delta\Phi), \tag{4}$$

with v_n=$\sqrt{a_n/b}$, where b is the function baseline. As a result most of the Φ dependence comes from v_2 component, but higher orders are present too. ATLAS studied the v_n harmonics (n=1,2,3,4,5) in events with high multiplicity (220≤N<260) [33]: the results are fully consistent with the CMS analysis using the same charged particle intervals [34]. The v_n harmonics (n=1,2,3,4,5) distributions show an impressive similarities to those obtained in Pb-Pb collisions with similar multiplicity (20-30% centrality) [17]. To quantify this evidence CMS used multiparticle correlation in p-Pb interactions [35]: any effect coming from a genuine cumulative dynamics should not depend on the number of particles used to compute the v_2. The v_2 coefficient was extracted from the cumulant ($v_2(4)$,$v_2(6)$,$v_2(8)$ and $v_2(LYZ)$). For a given multiplicity range in either the Pb-Pb or p-Pb system, the values of $v_2(4)$,$v_2(6)$,$v_2(8)$ and $v_2(LYZ)$ are found to be in agreement within ±10%. The data support the multiparticle nature of the observed long-range correlations in p-Pb collisions. In addition ALICE and CMS measured the elliptic flow for identified hadrons in p-Pb collisions[36]: a mass ordering was observed (softer hadrons show larger v_2), as expected by hydro models. The above results give a convincing evidence that a large collectivity exist in p-Pb data. We cannot conclude Quark Gluon Plasma is formed in p-Pb collisions too, but this system looks hotter than expected. Another interesting effect reported in p-Pb collisions is the possible enhancement of R_{pPb} reported by ATLAS and CMS at high transverse momentum, ($p_T \geq 20$ GeV/c): more data are required and a dedicated pp run at $\sqrt{s_{\mathrm{NN}}}$=5 TeV is mandatory to have a firm conclusion on this effect.

7 Conclusions

An integrated luminosity as high as $1nb^{-1}$ will be delivered at the LHC during Run 2(2015-2018) for Pb-Pb collisions. The pp centre of mass energy will reach 13 TeV ($\simeq$ 5.1 TeV in Pb-Pb collisions). During Run 3 (2019-2026) an integrated luminosity $10nb^{-1}$ will be available to perform high statistic Pb-Pb studies; major detector upgrades during the Long Shutdown 2 will allow a reduction of the systematic error and an increase of the data samples.

After a successful Au-Au run in 2014, RHIC will provide p-Au collisions in 2015. A new beam energy scan (BES II) will be performed starting from 2018, with $\sqrt{s_{\mathrm{NN}}}$≤ 20 GeV, focusing on the critical point search and on a detailed study of the phase transition. The main goal of the electron-ion collider at BNL(eRHIC) is the exploration of the nucleus structure with the precision of electromagnetic probes at high energy and with sufficient intensity to access the gluon-dominated regime. The project foresees a startup on 2025 and new experiments, as sPHENIX and eSTAR [37].

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