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Relativistic Heavy Ion Physics - "Discoveries" and Future Prospects

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Abstract. Collisions of ultra-relativistic heavy nuclei at the Large Hadron Collider (LHC) at CERN and the Relativistic Heavy Ion Collider (RHIC) in the U.S. create energy densities where nuclear matter melts into a plasma of quarks and gluons. I will summarize the accomplishments of the ultra-relativistic heavy-ion program and present the "big questions" remaining to be answered. In the process I will elucidate how the answers are being pursued and our current understanding of the high density QCD matter created in these collisions. I will offer a brief perspective on the planned detector upgrades, the presently envisioned future experiments and collider facilities, and how they intend to address the remaining questions of the field.

1. Introduction

Since this conference covers a range of physics from nuclear and particle physics to astrophysics, it is prudent to distinguish the experimental approach taken in relativistic heavy-ion physics from the more commonly recognized approach of high-energy physics. This was encapsulated succinctly by T.D. Lee (Nobel Laureate) at the dawn of the field in his infamous quote [1]. "In high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions. But, in order to study the question of 'vacuum', we must turn to a different direction; we should investigate bulk phenomena by *distributing high energy over a relatively large volume*." This is a concise description of the approach of relativistic heavy-ion physics to investigate Quantum Chromodynamics (QCD) at high energy density. At sufficiently high energy density (temperature), the vacuum melts to form a Quark-Gluon Plasma (QGP).

This can be seen in any number of more recent lattice QCD calculations [2] that address the behavior of QCD at high temperature. Those calculations conclude that the QCD vacuum melts to form a QGP at temperatures $T_c \geq 160$ - 190 MeV, corresponding to energy densities $\epsilon \sim 0.3$ - 1.0 GeV/fm^3. This would also then be the temperature of the phase transition from quarks to hadrons in the expansion and cooling of the early Universe. Thus, the Standard Model predicts a QCD deconfinement phase transition at T = 160 – 190 MeV, the same quark-hadron phase transition that must have occurred in the early Universe, and could occur in the cores of dense stars or in other aspects of stellar evolution. The goal of relativistic heavy-ion physics is to create the QGP in the laboratory and to study its properties.

2. An Ambitious Mission and Big Questions

Relativistic heavy-ion physics seeks to determine and understand the properties and states of matter that exist at high temperature and density. More fundamentally, it strives to explore the phase structure of a fundamental gauge theory QCD. Might our understanding of other gauge theories (like gravity!) benefit from this? There are many questions to be addressed. Is the phase diagram of QCD featureless above T_c? What are its constituents (are there quasi-particles, exotic states, others)? Can we determine characteristics of the QGP such as its transport properties, sound attenuation length, coupling strength $\alpha_s(T)$, sheer viscosity/entropy density ratio (η/s), formation time (t_f), potential excited modes, and its equation of state? Finally, are there other new phenomena or new states of matter at high energy densities [3]? Answering these questions (and more) encompasses an extremely ambitious mission for the field of relativistic heavy-ion physics!

3. Remarkable "Discoveries"

After a start in this exploration at various fixed-target facilities, the acceleration of heavy ions at the CERN Super Proton Synchrotron (SPS) facility fostered sufficient energy to adequately lead exploration in this field. The advent and use of colliders for heavy-ion physics, namely RHIC and LHC, at significantly higher energies has led to a profound increase in our understanding of the behavior of QCD at high energy density. Results from RHIC and LHC have been summarized in detail in Ref. [4] and [5], respectively. I will focus in this presentation on what in my view are the most significant results or debatably the "discoveries" of the field.[1]

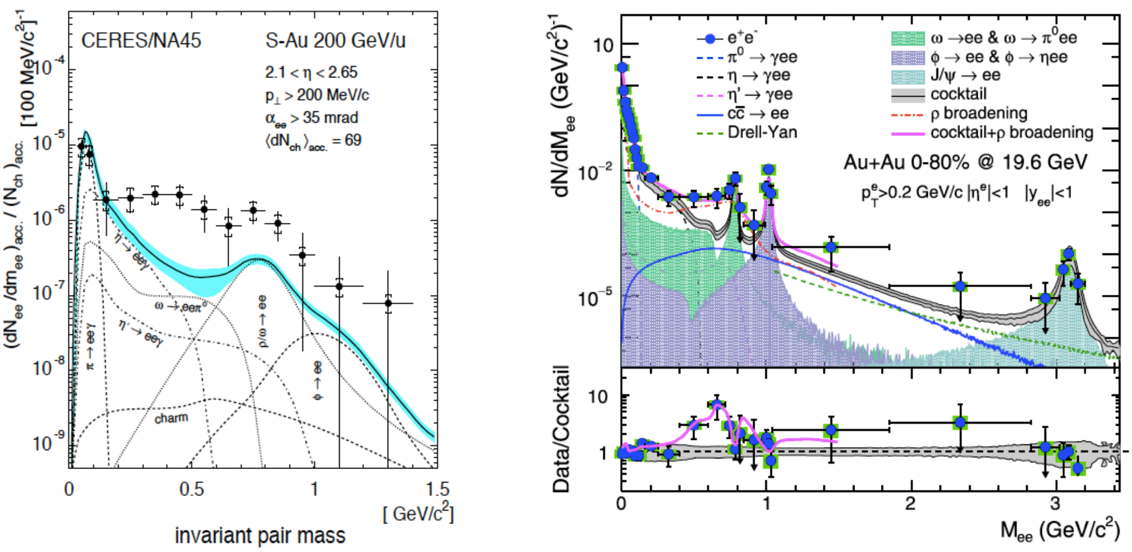

Figure 1. Dielectron invariant mass spectra. Left: $E_{lab}/n = 200$ GeV/n ($\sqrt{s_{NN}}$= 19.6 GeV) S-Au CERES data (circles), and contributions from hadron decays (as labeled) and their systematic error (shaded region).[6] Right: STAR data after efficiency correction, compared to decays of light hadrons and correlated decays of charm in Au-Au collisions at $\sqrt{s_{NN}}$= 19.6 GeV. [11] The data to hadronic cocktail ratio is shown in the bottom panel. Theoretical calculations incorporating a broadened ρ are also shown. Systematic uncertainties for data (green boxes) and the hadronic cocktail (gray band) are presented. See [11] for details and references therein for details on the theoretical calculations.

[1] I utilize this terminology with trepidation, and not scientifically justified in the literal sense, but I simply refer to its relation and relevance to the Conference title and beg your scientific indulgence!

4. Indications of Medium Modification and Possible Chiral Symmetry Restoration in Low-mass e^+e^- Measurements

Investigation of low-mass electron pairs in the S-Au system at $E_{lab}/n = 200$ GeV ($\sqrt{s_{NN}}$= 19.6 GeV) by the CERES Collaboration at the SPS [6] revealed an enhancement of pairs in the mass region (200 – 700 MeV) just below the ρ mass, compared to pairs produced from hadronic decays. This is seen in Fig. 1 (left). The enhancement has been attributed in many theoretical publications to broadening of the ρ in the nuclear medium [7] and possible chiral symmetry restoration [8]. Subsequently, CERES has measured an enhancement in low-mass di-electrons in Pb-Au collisions at $E_{lab}/n = 40$ GeV [9] and NA60 an enhancement in low-mass muon pairs in 158 GeV ($\sqrt{s_{NN}}$= 17.3 GeV) Indium-Indium collisions [10]. STAR [11] has confirmed the enhancement in Au-Au collisions at RHIC at the SPS c.m. energy, as seen in Fig. 1 (right). STAR [11] and PHENIX [12, 13] have observed enhancements of di-electrons in the same mass region in Au-Au collisions at $\sqrt{s_{NN}}$= 200 GeV.

5. Thermal Radiation from the QGP

A thermal component of direct photons has been observed in central collisions (0-20%) $\sqrt{s_{NN}}$= 200 MeV Au-Au by PHENIX [13, 14] at RHIC and $\sqrt{s_{NN}}$= 2.76 TeV Pb-Pb by ALICE [15] at the LHC. After careful scaling by the number of binary collisions in next-to-leading order perturbative QCD calculations and subtraction of the predicted direct photons (or in the PHENIX case photons measured in pp interactions), an additional component of photons is observed at momenta below $\sim$ 2.5 GeV/c. These photons represent a thermal component and can be fit with an exponential to yield an inverse slope of T $= 297 \pm 12(stat) \pm 41(syst)$ MeV at the LHC and T = 221 $\pm$ 19 (stat) $\pm$ 19 (stat) MeV at RHIC. This is a strong indication of direct thermal radiation. However, it represents an integral of the radiation over the entire evolution of the system, and thus the values of T may not be strictly due to thermal radiation. A detailed comparison of the thermal photon emission data at RHIC energy [13] with a model assuming formation of a hot system with initial temperature $T_{initial}$ ranging from 300 - 600 MeV at times 0.6 – 0.15 fm/c is in qualitative agreement with the data.

6. Particles Are Formed at the Universal Hadronization Temperature

The yields of produced hadrons have been measured extensively at mid-rapidity at RHIC and LHC. The yields of the various types of hadrons have been compared to statistical hadronization (thermal) model [16] calculations, which are successful at reproducing the relative abundances of the observed hadrons. The model assumes rapid freeze-out, with typical implementations utilizing as parameters only temperature T, baryochemical potential μ_B and volume V. Shown in Fig. 2 (left) are results from the three RHIC experiments [17] and in Fig. 2 (right) those from ALICE [18] at LHC. Global thermal model fits to data are represented as a horizontal line for each ratio with the parameters T and μ_B presented in each figure. It is of interest to note that the temperatures are similar for the two c.m. energies and near that predicted by Lattice QCD as the deconfinement phase transition temperature and the quark-hadron phase transition in the early Universe.

7. High Transverse Momentum (p_T) Hadrons Are Suppressed

The products of the scattering of partons (fast quarks and gluons) in the colliding nuclei serve as probes with which to study properties of the hot QCD medium, since they are calculable in perturbative QCD. As partons traverse the medium, they lose energy through interactions or radiation leading to parton energy loss that alters the final distribution of high p_T particles, jets, and particles that contain heavy quarks.

Shown in Fig. 3 is the nuclear modification factor R_{AA} for central collisions of heavy ions for charged hadrons and pions at SPS, RHIC and LHC energies. R_{AA} is the ratio of the spectrum

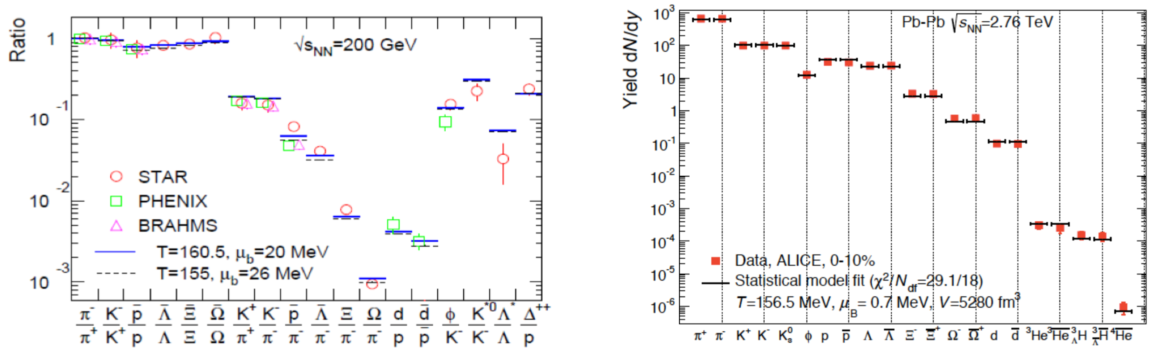

Figure 2. Left: Measured ratios (ordinate) of various hadrons (abscissa) at mid-rapidity for Au-Au central collisions by the three RHIC experiments (denoted by the different symbols in the legend).[17] Right: Measured yields per unit rapidity at mid-rapidity in central Pb-Pb collisions. A horizontal line for each ratio represents the result of a global thermal model fit to the hadron yields in each figure with parameters in each legend.[18]

of particles at high p_T in heavy-ion collisions compared to that in pp collisions, scaled by the number of binary nucleon-nucleon collisions in the nucleus-nucleus geometry and given by

$$R^i_{AA}(p_T) = \frac{d^2N^i_{AA}/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma^i_{NN}/dp_T d\eta}$$

where N^i_{AA} is the yield for particle type i in nucleus-nucleus collisions and σ^i_{NN} is the cross section for particle i in nucleon-nucleon collisions. $\langle T_{AA}\rangle$ is the ratio of the number of binary nucleon-nucleon collisions (typically calculated in the Glauber or Glauber-Gribov model) to the inelastic nucleon-nucleon cross section. R_{AA} is expected to be unity in the case where the nucleus-nucleus collisions are simply a superposition of nucleon-nucleon collisions in the absence of nuclear effects such as parton-energy loss or color screening.

A large suppression ($R_{AA} < 1$) is observed in Fig. 3 (left) for RHIC and LHC energies at intermediate p_T (between 2-20 GeV) with a gradual rise as p_T increases beyond 20 GeV.[19] Several model calculations [20, 21, 22, 23, 24] are shown, with somewhat divergent predictions. The model predictions depend on their parton energy-loss mechanisms, e.g. scattering and/or radiation and their assumed parton density. The observed suppression is in all cases a result of parton-energy loss in the dense medium.[2]

Information on parton-energy loss mechansisms may be derived from differences in the energy loss of propagating quarks and gluons by comparing the suppression of light and heavy quarks. Shown in Fig. 3 (right) is R_{AA} for D mesons (average of D^0, D^+, $D^\pm$), π^- from ALICE [26], and non-prompt J/ψ mesons from CMS [27] as a function of centrality in Pb-Pb collisions. The suppression of D mesons is consistent with that of charged particles, indicating that the energy loss of the heavier charm quark is not very different (if at all) from that of light quarks. The B-decays are less suppressed, which may indicate the emergence of the dead-cone effect [28]. QCD predicts a dead-cone effect in which the radiation pattern of gluons from partons is dependent upon the mass of the parton emitter. For quarks with mass m and energy E, radiation is suppressed for emission angles $\theta <$ m/E, resulting in heavier quarks being less suppressed than light quarks as observed for the B-mesons.

[2] Note that an enhancement is observed at SPS energies, which is commonly attributed to the Cronin effect.[25]

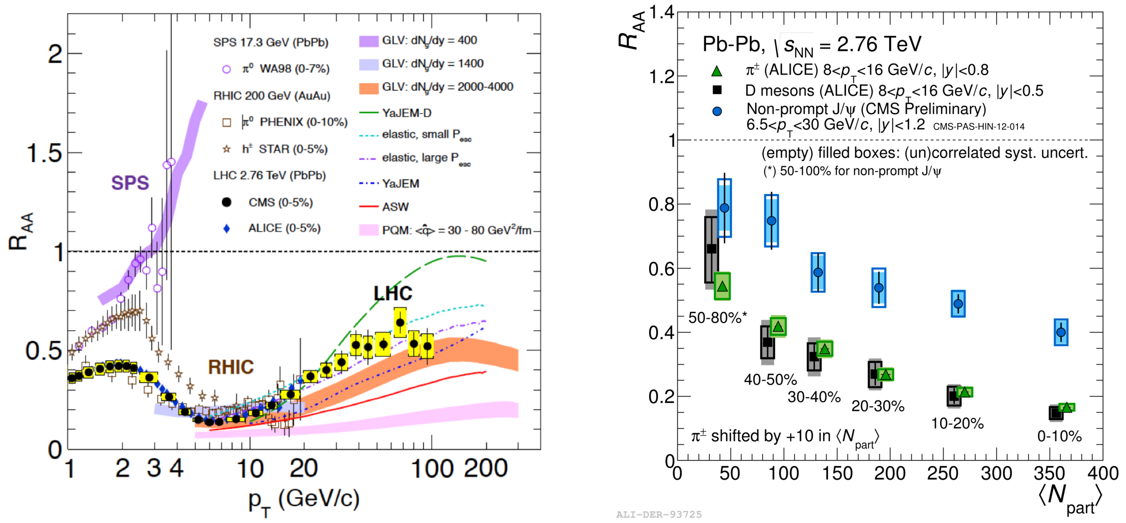

Figure 3. Left: R_{AA} as a function of p_T for central collisions of heavy ions for charged hadrons and pions at SPS, RHIC and LHC energies (see legend). Various model predictions are also shown (see text for details).[19] Right: R_{AA} for D-mesons (average D^0, D^+, $D^{\pm}$) and π^- for $8 < p_T < 16$ GeV/c from ALICE [26] and for non-prompt J/ψ mesons with $6.5 < p_T < 30$ GeV/c from CMS [27] as a function of centrality (the mean number of participant nucleons in the collision $\langle$ N_{part} $\rangle$).

8. Jets Are Quenched and Dijet Energies Modified

Additional insight into the kinematics of the initial binary parton-parton scattering and the parton energy loss is gained by measuring jets, dijets and γ-jet correlations in heavy-ion collisions and comparing to results in pp and p-A collisions. Shown in Fig. 4 (left) are the R_{AA} from particles and jets [29] (see [5] and references therein) measured in central Pb-Pb collisions. The electromagnetic probes (Z, W, γ) do not interact strongly and are thus unaffected by the medium ($R_{AA} = 1$). Charged particles are suppressed, although non-prompt J/ψ mesons are less suppressed at p_T< 20 GeV, as discussed above. B-jet suppression generally appears of similar magnitude to that of inclusive jets indicating a lack of flavor dependence in the quenching mechanism at large jet energies.

ATLAS [30] and CMS [31] have observed an energy imbalance of dijet pairs. The ATLAS results for the dijet energy asymmetry A_J are shown in Fig. 4 (right) for $\sqrt{s_{NN}}$= 2.76 TeV Pb-Pb central collisions compared to 7 TeV pp data and Monte Carlo simulations using Pythia dijets embedded in Hijing events, where A_J = (E_{T_1} - E_{T_2}) / (E_{T_1} + E_{T_2}). T_1 is defined as the highest transverse energy jet with transverse energy E_{T_1} > 100 GeV and T_2 the highest transverse energy jet in the opposite hemisphere with E_{T_2} > 25 GeV. The Pb-Pb events exhibit a large asymmetry A_J with the away-side jet having lost considerable energy compared to that observed in the pp data and Hijing + Pythia simulations. This is a clear indication of jet quenching in Pb-Pb collisions at the LHC. It is interesting to note (although not shown here) that the same measurements exhibit a peak at $\Delta\phi = \pi$ in the azimuthal angular correlation between the leading and the away-side jet with little difference in the $\Delta\phi$ widths between the Pb-Pb data and the pp data and Hijing + Pythia simulations. This latter result will require further investigation with higher statistics. Clearly a better understanding of the fragmentation and its modification in-medium and fragmentation of large energy heavy-flavor jets is necessary and the subject of further studies.

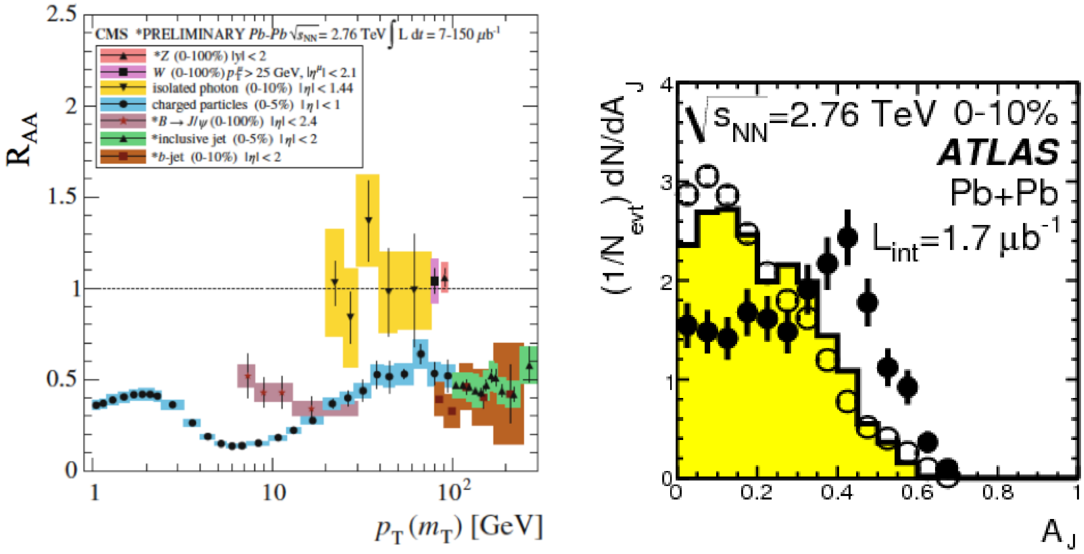

Figure 4. Left: R_{AA} for charged particles, B-meson decays to J/ψ, electromagnetic probes (Z, W, γ) and jets [29] measured in central Pb-Pb collisions (from [26] and [27]). Right: Transverse energy asymmetry of dijets (defined in text) in central Pb-Pb data (solid circles) compared to that observed in pp data (open circles) and Hijing + Pythia simulations (histogram).

9. Quarkonia - J/ψ and Υ Are Suppressed

Quarkonia, charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$), were predicted early-on [32] to be sensitive to deconfinement in the medium via the color analogue of Debye screening. The color screening of J/ψ was observed at the SPS, RHIC and LHC. Suppression of the Υ states in Pb-Pb compared to pp at LHC, seen in Fig. 5 (left), provides strong evidence of effects of the colored medium on the quarkonia [33]. The Υ(2S) and Υ(3S) states are observed to be more suppressed than the Υ ground state in the Pb-Pb data.

Theoretically, a sequential melting scheme evolved for the various quarkonium states [34], since the screening length in a deconfined medium depends on its temperature. The less tightly-bound states dissociate at lower temperatures than those that are more tightly-bound, thus producing a characteristic suppression pattern based on the binding energies of the quarkonia and the temperature of the medium. Such a pattern is observed in Fig. 5 (right), which provides a compilation of the measured suppression of the various J/ψ and Υ states as a function of their binding energies [33]. This supports the predicted color screening picture. Lattice QCD calculations are able to relate the degree of quarkonium screening to the temperature although this is complicated by the time evolution and regeneration of bound states in the medium (see [35]).

10. Collective Flow Indicative of a Strongly-Coupled Medium with Ultra-low η/s (shear viscosity/entropy density)

A clear signature of collective flow was discovered in A–A collisions as early as the 1980s at the BEVALAC [36] and later on at SPS, RHIC and LHC. The multi-particle azimuthal distributions are analyzed typically utilizing Fourier-decomposition techniques. A substantial second-order coefficient (v_2), called elliptic flow and investigated thoroughly at RHIC and LHC, is described well in a hydrodynamic description of a hot expanding fluid with a small shear viscosity to entropy density (η/s) ratio. Presented in Fig. 6 (left) and Fig. 6 (right) are results from RHIC and LHC, respectively, compared to a relativistic viscous hydrodynamic model with

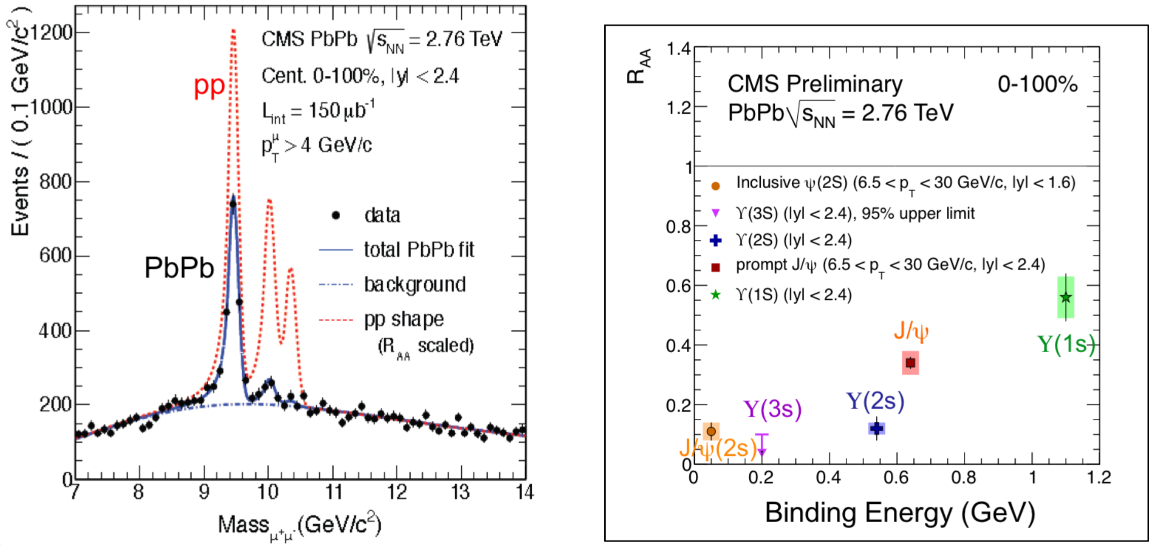

Figure 5. Left: Comparison of di-muon mass spectra measured in pp (dashed red) and Pb-Pb (solid black) collisions. Right: Suppression of Quarkonium states as a function of binding energy. (adapted from [33])

IP-GLASMA initial conditions and an evolution of matter through the quark-gluon plasma and hadron gas phases [37, 38]. Various values of η/s are shown with $\eta/s = 0.08$ matching the RHIC data from STAR and $0.08 < \eta/s < 0.16$ being closer to the LHC data from ALICE. These values are near the conjectured minimum value for an infinitely strongly-coupled theory [39, 40].

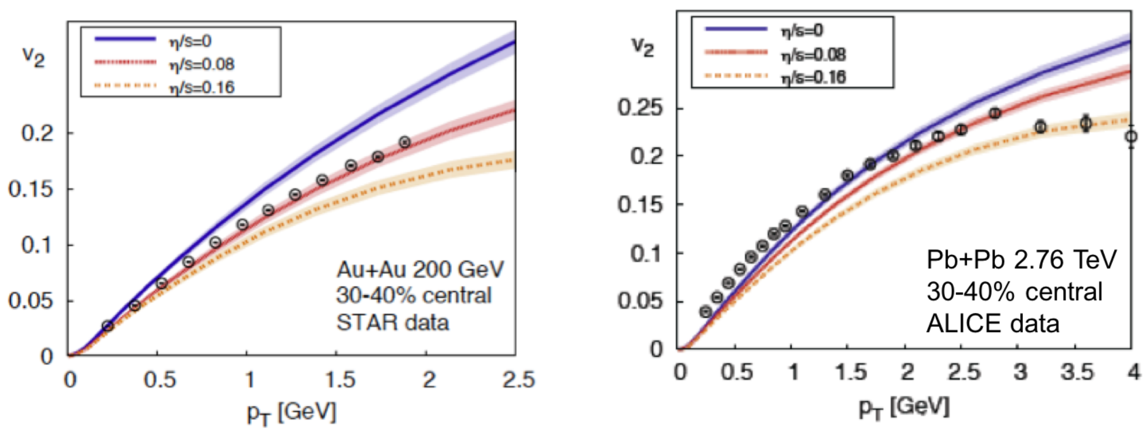

Figure 6. v_2 as a function of p_T. Left: from RHIC (STAR). Right: from LHC (ALICE). Data are compared to a relativistic viscous hydrodynamic model with various values of η/s as shown. [37, 38]

The transverse-momentum distributions of hadrons at low and high p_T are sensitive to properties of the different phases of a nuclear collision. At low p_T production of hadrons is governed by soft processes and the momentum distributions reflect properties of the medium at kinetic freeze-out. The spectra of identified hadrons (primarily pions, kaons and protons) exhibit a clear mass hierarchy where the inverse slope of the p_T distributions increases with increasing hadron mass. This is observed at RHIC and LHC energies and has been described in terms of the emission of hadrons from a thermal system that is expanding radially at a common velocity.

[41] In this scenario, heavier hadrons have larger momenta than lighter ones due to the common radial flow velocity. At p_T (> a few GeV) hadrons originate primarily from jet fragmentation in hard scattering processes that occur in the initial phase of the collision.

11. Effects in Small Systems (p-A, high multiplicity pp)

Proton-proton (pp) and proton-nucleus (p-A) collisions have been investigated in order to better understand phenomena observed in nucleus-nucleus (A-A) collisions. It is essential to identify and separate experimentally and theoretically, to the extent possible, initial-state and final-state effects. The p-A measurements can help to understand the initial state by establishing the extent of gluon saturation and the possible existence of a color-glass condensate at low-x in nuclei. Furthermore, the extent and impact of cold nuclear matter effects on the A-A data and their interpretation, for example in terms of color screening and jet quenching, are critical in understanding effects observed in the A-A data.

The results of measurements in small systems is the topic of another presentation[3] and thus only a summary is presented here. In measurements utilizing hard probes, no suppression of particles at high p_T nor quenching of jets is observed in p-A collisions. Neither are quarkonia observed to be suppressed in p-A, whereas cold nuclear matter effects may be expected to induce suppression. These measurements in p-A systems confirm that the quenching and suppression in A-A collisions are final state effects that can be interpreted from theory to result from parton energy loss and deconfinement in a high energy density environment.

One marked difference from the above conclusions that is observed in the p-A data is that the low p_T spectra and particle correlations in p-A exhibit similar effects as in A-A with regard to the spectral mass ordering of hadrons attributed to collective (radial flow) in A-A systems (see [41]). Furthermore, there are similar though weaker trends in the flow harmonic decomposition of the particle correlations in p-A and in high multiplicity pp data. This has generated significant interest and investigation to determine the smallest size and energy density of a droplet of QCD matter that behaves like a liquid.

12. Remaining Questions for the Field

As we investigate high density QCD phenomena in collisions of various (large and small) systems, there are still many questions to be answered! We seek to identify and separate the initial state from the final state by comparing p-p, p-A, A-A results to answer questions like the following. To what extent is there saturation in the initial state? Can nuclear parton distribution functions be extended from our current knowledge to describe the initial state? Does it consist of a color-glass condensate? What is the effect of cold nuclear matter on the final state observables that are being measured? How does the system evolve and thermalize from its initial state?

We seek to identify the underlying dynamical properties of the QGP that describe mechanisms of equilibration, transport and particle production (e.g. hadronization and fragmentation) and the equation of state. Can we accurately determine η/s, the coupling $\alpha_s(T)$, the formation time (t_f), sound attenuation length, the q-hat parameter (energy loss per unit length) for parton energy loss and its underlying mechanisms as a function of temperature?

Investigation of the QCD phase diagram and its understanding is fundamentally important to the field. Are there excited modes of the high energy density QCD medium, and if so what are they? What are its constituents (are there quasi-particles, exotic states, others)? Is there a critical point in the QCD phase diagram, and if so can we locate it? Is the QCD Phase Diagram featureless above T_c?

We seek to better understand quarkonium melting (suppression) at the microscopic level. What role and to what extent does quark recombination play and impact the suppression? What

[3] "Small systems in p-Pb collisions," Markert C, Proceedings of this Conference

are the effects of cold nuclear matter on the observed suppression? Is the melting/suppression sequence as a function of temperature consistent with Lattice QCD calculations as they evolve?

By identifying the dependence on the system size, multiplicity and c.m. energy of observables that can be measured in pp, p-A and A-A collisions, we may be able to discriminate various mechanisms and models. To make progress clearly requires close cooperation between experiment and theory. Can there be new developments in theory (lattice, hydrodynamics, parton energy loss, string theory, others) and an understanding across fields, with possibly a combination of approaches where appropriate?

13. Future

In the near-term the RHIC Beam Energy Scan 2 is scheduled for 2018-2019.[4] Its goal is to investigate the QCD phase diagram by conducting a detailed scan at low c.m. energy in a search for a critical point. It will also study fluctuation phenomena and properties of the collisions that may shed light on the location of the critical point and properties of the medium.

A new detector sPHENIX[5] is being constructed for high statistics jet and quarkonium measurements at RHIC starting in 2022. These measurements seek to understand how the properties of the QGP emerge from the underlying quark and gluon interactions, including its temperature dependence and coupling strength. Precision jet and upsilon measurements will be undertaken to probe the different length scales of the QGP to better determine and understand its properties.

In Europe NICA[6] and FAIR[7] are expected to come online in the next several years. NICA is expected to be commissioned around 2020, and will collide heavy ions at c.m. energies from 4 - 11 GeV per nucleon pair in order to investigate the QGP phase transition and critical point. FAIR is on a similar timeline with an extremely diverse experimental program. In heavy ion physics FAIR will investigate very baryon-rich matter at high densities, study in-medium modification of hadrons and search for the critical point, to name a few goals.

A detector upgrade at LHC[8] in 2018-2020 will increase capabilities allowing higher rate heavy-ion operation in Run-3 starting in 2021. Along with detector upgrades, this will allow detailed investigation of heavy flavor jets, jet substructure, high p_T particles and heavy flavors, and event-by-event correlations of hard and soft processes.

In the longer term, an Electron Ion Collider (EIC) has been designated by the U.S. Nuclear Physics Community [42] as the next construction project for nuclear physics in the U.S. for operation in the post-2025 timeframe. The EIC will allow an in-depth investigation of the gluon-dominated low-x region of QCD. Goals are to investigate the position and momentum distributions of quarks, gluons and their spins in the nucleon; to determine and investigate the existence of gluon saturation and a possible color glass condensate; and to study the response of the nuclear medium to traversing color charge.

Together these new capabilities should provide a strong and exciting physics program internationally to investigate the questions raised by the field of heavy-ion physics and further illuminate the properties of high energy density QCD.

Acknowledgments
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