A Snapshot of our Experimental Knowledge Circa Winter 2012-13

Helen Caines

Physics Dept., Yale University, New Haven, CT 06511, U.S.A

E-mail: helen.caines@yale.edu

Abstract. I present a snapshot of some experimental results from the LHC and RHIC experiments as of Winter 2012-13. This sets the scene for the new data that will be presented at this conference.

Introduction

By presenting edited highlights of the recent experimental results from RHIC and the LHC, I aim to describe where our field is standing prior to the new data that will be presented at this conference. This includes results from proton-proton, proton-Pb, deuteron-Au and heavy-ion collisions over a wide range in collision energies. The RHIC collaborations have been focused on the new Beam Energy Scan (BES) data, collected to search for evidence of a "turn-off" of the QGP, a Critical Point in the QCD phase diagram or evidence of a first order phase transition. Meanwhile at the LHC the Pb-Pb results indicate that the medium created at $\sqrt{s_{NN}}$= 2.76 TeV is hotter, denser, and longer lived than that created via collisions at RHIC. There are also remarkable first results emerging from the p-A run at the LHC, which was designed as a control dataset with which to explore cold nuclear matter effects and search for possible evidence for the Color Glass Condensate (CGC).

Pb-Pb collisions - a more extreme QGP

The temperature formed in the collision can be probed using direct photons. In the range $p_T \leq 4$ GeV/c thermal photons emitted during the early stages of the collision are believed to dominate the measured photon spectrum. Once the contributions from NLO pQCD processes have been subtracted the resulting distribution can be fit with an exponential and an estimate of the temperature extracted. Preliminary analysis by ALICE of the 0-40% Pb-Pb data indicate that T_{init} = 304 ± 51 MeV more than twice the critical temperature, T_c, required to form a QGP (Fig. 1) [1] and significantly above that reported by PHENIX of T_{init} = 221 ± 19 ± 19 MeV for Au-Au collisions at $\sqrt{s_{NN}}$=200 GeV [3]. Interpretation of this result is however complex since the photon spectrum, while expected to be dominated by early times, is actually an integration over the whole lifetime of the medium.

An alternative approach, first suggested nearly three decades ago [4], is to access the initial temperature via measurements of quarkonia suppression (J/Ψ, $\Psi^{'}$, Υ states etc). These heavy quark-anti-quark states are loosely bound and therefore expected to disassociate in the QGP due

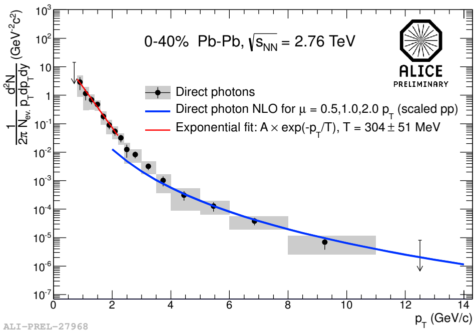

Figure 1. Direct photon p_T distribution for 0-40% Pb-Pb events at $\sqrt{s_{NN}}$=2.76 TeV. Blue curve: scaled pp NLO calculation. Red curve: exponential fit to the data. Figure from [1].

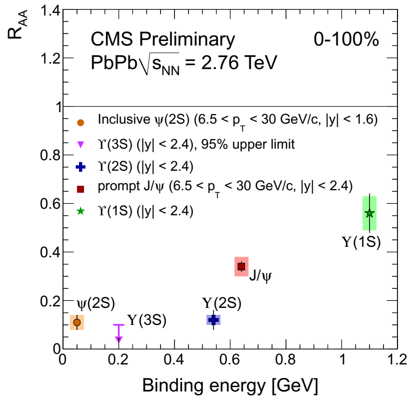

Figure 2. Minimum R_{AA} as a function of binding energy for quarkonia in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV. Figure from [2].

to color screening. The temperature at which each quarkonium "melts" depends on its binding energy. Therefore measurements of various quarkonia yields in A-A collisions relative to the binary collision scaled rates in pp should act as a QGP thermometer. Figure 2 shows one such set of measurements by CMS in $\sqrt{s_{NN}}$=2.76 TeV Pb-Pb collisions [2]. The expected dependence of the suppression on binding energy is observed. Although it should be noted that the p_T and rapidity ranges are not the same for all the measurements shown, these results suggest that T_{init} is well above T_c, in agreement with the temperature deduced from direct photons [5].

Statistical model fits to the central Pb-Pb particle ratios reported ALICE show some tension when trying to fit the central data. While the measured K/π ratio is in agreement with calculations from thermal models, the p/π ratio is a factor of 1.5 lower [6]. Discussions of interpretations of this result are still underway as this conference begins. However, one possible explanation is that hadronic re-scatterings after chemical freeze-out drive the system out of chemical equilibrium. If the protons are not included in the fits the extracted temperature is $T_{ch} \sim 164$ MeV with a baryon chemical potential of $\mu_b = 1$ MeV. Spectral analyses of identified protons, kaons, and pions show that the medium is expanding more explosively than at RHIC, $\langle\beta_T\rangle = 0.65c$, but that the temperature at kinetic freeze-out stays approximately the same at $T_{kin} \sim$ 80-95 MeV [6]. Femtoscopic radii have been utilized to extract information about the volume and lifetime of the medium at kinetic freeze-out [7]. Results from ALICE show that in central events with a volume of ~5000 fm^3 and a lifetime of ~11 fm/c at freeze-out the medium made at the LHC has twice the volume of that made at RHIC and lives 40% longer.

Measurements of photons, W bosons, and Z bosons by CMS exhibit binary scaling of the central Pb-Pb data, as expected for colorless objects, Fig. 3. However, the nuclear modification factor for charged particles and b quarks, inferred from displaced J/Ψ measurements, are highly suppressed in the same centrality class [8]. These hadrons have similar R_{AA} values to those of fully reconstructed jets with a resolution parameter of R=0.2 [8,10,11]. Both ATLAS and CMS report that jets continue to be highly suppressed out to $p_T \sim 300$ GeV/c in central events, even for R=0.4-0.5. These results indicate that (heavy) quarks and gluons remain strongly coupled to the medium at the LHC, and that the lost energy appears at large angles with respect to the jet axis.

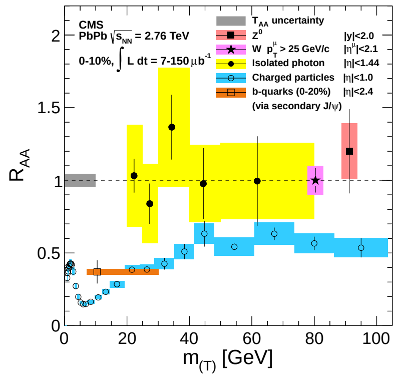

Figure 3. W, Z, b quarks, photon, and charged particle Pb-Pb R_{AA} for $\sqrt{s_{NN}}$=2.76 TeV. Figure from [8].

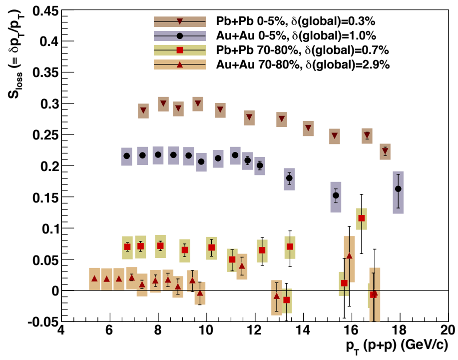

Figure 4. $\delta p_T/p_T$ as a function of pp p_T for central and peripheral A-A collisions at the LHC and RHIC energies. Figure from [9].

In a new analysis from PHENIX the fractional shift in p_T required to match the yield in a given A-A bin to that in pp, $\delta p_T/p_T$, is calculated instead of R_{AA} [9]. Figure 4 shows this energy loss estimate for central and peripheral data at both RHIC and the LHC. These results indicate that $\delta p_T/p_T$ is $\sim$ 1.3 times larger for a given centrality and p_T bin at the LHC than at RHIC, but that at both facilities $\delta p_T/p_T$ decreases at high p_T. It should be noted that at the same time dN/dy is $\sim$ 2.2 times that at RHIC, suggesting that the coupling to the QGP is smaller at the LHC. Much of this lost energy re-emerges as numerous low momentum particles at large angles to, but still correlated with, the jet axis. This has been demonstrated both at RHIC using jet-hadron [12] and gamma-hadron correlations [13] and at the LHC by measuring, for example, fragmentation functions down to low p_T [14]. Such a measurement from ATLAS is illustrated in Fig. 5. The central to peripheral ratio of the unfolded fragmentation functions for R=0.3 jets with $p_T > 92$ GeV in Pb-Pb events is shown, and a clear enhancement of low p_T hadrons is observed. highly suppressed R_{AA}s can be reconciled with the notion of enhanced soft particle production during the jet's fragmentation by noting that the jet R_{AA} results are for R=0.4. While there is increased low p_T production within this radius, the majority of the soft particles are emitted at larger angles. This causes significantly less of the initial parton's energy to be recovered within a cone radius of R=0.4 in Pb-Pb collisions than for the same R in the pp data; which in turn results in a jet and hadron R_{AA} that is less than unity.

The precision vertexing capabilities at all the LHC experiments has produced a wealth of detailed heavy flavor measurements. In the charm sector ALICE reports that the D mesons have similar R_{AA} to that of light quark mesons [15] and that v_2 remains significant for Ds at high p_T; both these results indicate significant energy loss of the c quark that is comparable to that of light quarks and gluons [16]. However the non-prompt J/Ψ results, Fig. 3, suggest that b quarks loose less energy at an equivalent initial p_T.

The J/Ψ results from ALICE at high p_T also indicate a suppression when compared to scaled pp data [18]. However, the value of R_{AA} is closer to unity than that reported by PHENIX [19], this suggests that there is significant regeneration of the J/Ψ at $\sqrt{s_{NN}}$= 2.76 TeV, which is possible due to the copious production of charm quarks at these energies. The fact that the J/Ψ also has a significant v_2 [20] supports the regeneration hypotheses, as the v_2 could then be due to the "bulk" thermalized charm rather than intrinsic flow of the original quarkonium.

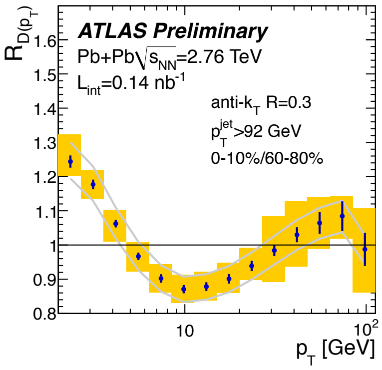

Figure 5. Ratio of 0-10% to 60-80% Pb-Pb unfolded fragmentation functions. Figure from [14].

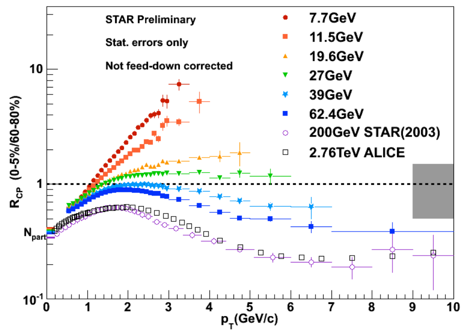

Figure 6. R_{CP} for charged hadrons for $\sqrt{s_{NN}}$=7.7-2760 GeV. Figure from [17].

Beam Energy Scan - exploring the phase diagram

The chemical potential and freeze-out temperature as extracted from particle ratios by STAR [21] show the expected trends as a function of beam energy; falling along the $\langle E \rangle$/N $\sim$1 boundary predicted by Cleymans et al. [22]. However, a recent paper from Beccattini et al. [23] suggests that the quality of such fits can be improved at the lower collision energies by taking into account hadronic re-scattering. These scatterings cause the system to fall out of equilibrium and reduce the apparent T_{ch}. Once this hadronic phase is taken into account the hadronization temperature is at, or close to, that of the phase transition boundary predicted by lattice QCD calculations. It will be interesting to see such an analysis applied to the recent RHIC BES data. Additional indications that a transition to the QGP possibly occurs down to the lowest RHIC collision energies comes from estimates of the Bjorken energy density which remain above critical values for central events even at $\sqrt{s_{NN}}$= 7.7 GeV if the formation time is less than $\sim$2 fm/c [24].

As discussed above, the suppression of high p_T particle production when compared to that in scaled pp events is used to probe partonic energy loss to the QGP. Measurements of the nuclear modification factor, R_{CP}, where peripheral events are used as a proxy for pp data have been made by STAR in the BES [17]. The results, including data from ALICE are shown in Fig. 6. A clear transition from suppression to enhancement is revealed with decreasing beam energy, with the ratio crossing unity around $\sqrt{s_{NN}}$=27 GeV. However, care must be taken when interpreting these results since the absence of suppression does not necessarily imply an absence of jet quenching. This is because a low beam energies a phenomenon known as the “Cronin Effect”, which results in enhanced particle production at intermediate p_T, has been previously observed in asymmetric collisions [25]. While the sizes of cold nuclear matter (CNM) effects such as this are known to vary with beam energy and particle species, the exact causes and magnitudes are currently not understood. It is therefore not yet possible to state at what beam energy, if any recorded so far, jet quenching “turns off” and further studies are clearly required.

Azimuthal HBT and directed flow, v_1, have both been predicted as sensitive to a first order phase transition or a softening of the Equation of State (EoS) [28]. The slope of the directed flow, dv_1/dy', of net-protons near mid-rapidity as a function of beam energy is shown in Fig. 7 [26] along with calculations from URQMD for 10-40% central Au-Au events. A prominent dip in the v_1 slope is observed between $\sqrt{s_{NN}}$=10-20 GeV. Such a feature is not observed in the model, which predicts a monotonic trend with beam energy. While this dip shape is consistent with the general expectations for a changing EoS, further theoretical studies are needed before conclusive

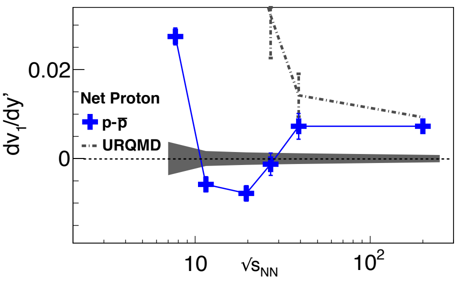

Figure 7. Net-proton directed flow as a function of beam energy compared to URQMD. Figure from [26].

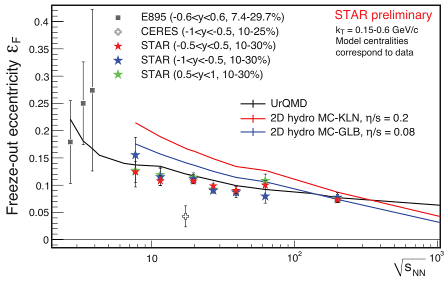

Figure 8. The kinetic freeze-out eccentricity as a function of beam energy. Figure adapted from [27].

statements can be made. The freeze-out eccentricities extracted from azimuthal HBT analyses, Fig. 8, exhibit no anomalous features in this region of $\sqrt{s_{NN}}$, instead they smoothly decrease with increasing beam energy [27]. These apparently contradictory results may be due to the fact that HBT is more sensitive to late stage hadronic interactions which wash out such early time signals. Interestingly, these HBT results demonstrate a different dependence to the modeling of the initial state, such as CGC or Glauber, and the viscosity to entropy ratio than does elliptic flow. Combining the results of spatial and momentum anisotropy analyses may therefore help us resolve ambiguities in the modeling of the initial conditions of heavy-ion collisions and the viscosity of the medium.

p-A collisions - the control dataset

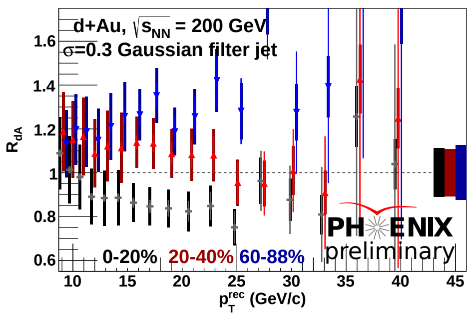

Figure 9. Jet R_{dA} for various centralities using the Gaussian filter at $\sqrt{s_{NN}}$=200 GeV. Figure from [29].

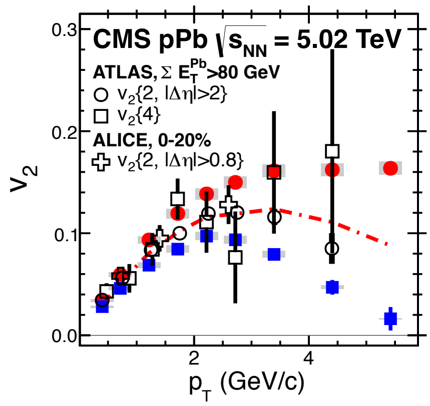

Figure 10. p-Pb $v_2\{4\}$ (filled squares) and $v_2\{2\}$ (filled circles) for 120<N_{trk}<150 compared to similar events classes in ALICE and ATLAS. Figure from [30].

In minimum-bias p-A and d-A datasets the measured nuclear modification factors are all at or slightly above unity [31–33], suggesting that cold nuclear matter effects are small for light flavor hadrons. In p-A collisions at 5.02 TeV the rapidity distribution of the data appears to favor saturation models [34]. However, at both RHIC and the LHC things get interesting when efforts are made to analyze the data in centrality or multiplicity bins. For example PHENIX report that the R_{dA} of jets for peripheral events is more enhanced than that in central d-Au events [29] (Fig. 9) and all the LHC experiments now report that long range $\Delta\eta$ correlations are seen in high multiplicity p-A collisions [35–37] with a double peak structure consistent with the events having strong v_n terms, (see for example Fig. 10) demanding the question "do p-A collisions also exhibit collective motion?"

Summary

In summary, the field is still highly active with a large number of surprising results emerging from both the LHC and RHIC in the past year. There is a wealth of experimental data now available from $\sqrt{s_{NN}}$= 7.7 to 2760 GeV and I expect to see a significant number of new results presented at this conference, along with novel theoretical explanations and predictions with which to challenge the data.

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