Conference Summary - The Quest Continues: Details, Details, Details

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Abstract. At this Quark Matter conference, once again, a wealth of the data and ideas have been presented via 262 oral presentations and over 300 posters. It is impossible to summarize such a deluge of results, instead I try to highlight those results that settled a long standing questions, unexpectedly raised new ones, or triggered the most discussions in the corridors.

Introduction

This year's Quark Matter shirts reminded us that this 30^{th} edition of the series brought us together to report recent advances in our quest to understand the nature of nuclear matter. I have therefore organized this summary report to highlight our progress in six sub-quests; each probes a different key question in our field.

The Quest to Understand the QCD Phase Diagram and the EOS

There were many updates from theory on the potential location of the QCD Critical Point and possible signatures of its existence. Significant progress has been made in performing Lattice calculations at both zero chemical potential and finite μ_B [1]. The results indicate that a location of $\mu_B/T < 3$ is strongly disfavored, in fact they suggest T= 90-100 MeV and $\mu_B = 500 - 600$ MeV [2, 3] as the preferred range. This means experimentally we should be looking in the vicinity of $\sqrt{s_{\mathrm{NN}}}$= 3-5 GeV, i.e. the low end of the RHIC BES-II campaign, and where future data from CBM will be recorded [4]. However, it should be noted that not everyone agrees that a Critical Point even exists in the QCD phase diagram. For more details see these plenary talks and the references therein [5, 6]. Meanwhile, the combination of astrophysics, nuclear theory, and particle theory is enabling the study of the very low T, high μ_B region of the phase diagram. There is now significant thermodynamic evidence for a transition to deconfined cold quark matter within massive neutron stars [7].

Experimentally, cumulant ratios measured in the BES-II data were shown to have a falling trend with rising order for $\sqrt{s_{\mathrm{NN}}}$= 7.7- 200 GeV, as expected from Lattice calculations. However at $\sqrt{s_{\mathrm{NN}}}$= 3 GeV the trend reverses, and is now in agreement with UrQMD [8]. In addition, NCQ scaling of v_2, which holds at $\sqrt{s_{\mathrm{NN}}}$= 14.6 GeV and above, is shown to fail at 3.2 GeV [9]. Both these results suggest that hadronic matter effects dominate the measurements at $\sqrt{s_{\mathrm{NN}}}$< 3.2 GeV.

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At HADES, dileptons with a mass above that of the pion were shown to have a v_2 consistent with zero, in agreement with expectations that they are penetrating probes with no collective boost [10]. This reinforces the use of dilepton spectra in the intermediate-high mass regions to access the early temperatures in the medium [11]. However such spectra are hard to extract, especially at low $\sqrt{s_{\mathrm{NN}}}$. The field needs to continue to discuss other ways to access the early temperatures, which is critical if we want to determine the initial location of the created medium in the QCD phase diagram.

The larger acceptance of STAR's upgraded TPC and high statistics from the BES-II are enabling extraction of the T_{ch} and μ_B in rapidity slices at fixed $\sqrt{s_{\mathrm{NN}}}$. Preliminary results suggest that while T_{ch} remains constant when varying the rapidity window, μ_B increases as you move to forward rapidities [12]. This suggests an interesting future study; namely to compare bulk properties at mid-rapidity low- $\sqrt{s_{\mathrm{NN}}}$ to those from high-rapidity high- $\sqrt{s_{\mathrm{NN}}}$ events with a comparable μ_B. The initial conditions of these two samples will be different and it will be informative to see how/if these differences are imprinted in other experimental measurements. Meanwhile similar statistical model fits to the increasingly higher precision charm yields reported by ALICE indicate that while charm is statistically distributed, charm hadrons potentially freeze-out earlier than lighter hadrons containing light or strange quarks [13].

CMS revealed impressive agreement between the extracted speed of sound in the medium in Pb–Pb data at 5.02 TeV to that predicted by Lattice calculations [14]. By focusing on ultra-central events they aim to avoid geometrical fluctuations, allowing measurement of the medium's rate of change of temperature with respect to its entropy. The temperature being accessed experimentally via the mean p_{T}, and the entropy determined from the charge particle multiplicity. More time is needed to digest this simple but elegant preliminary analysis. How does the particle composition affect the results? Can we get a better handle on the temperature this measurement is made at? Do we get consistent results from other systems?

The Quest to Detect the Initial EM Field

It is expected that a sizable late stage magnetic field will cause a splitting in the measured Λ and $\bar{\Lambda}$ baryon polarizations. High precision data from STAR showed that at a 95% confidence level the late stage magnetic field is $<9.4\times10^{12}$ T and $<1.4\times10^{13}$ T at $\sqrt{s_{\mathrm{NN}}}$ = 19.6 and 27 GeV respectively [15]. Since a sizeable initial magnetic field is expected to be generated in these collisions, these results suggest it dies away too rapidly to cause a polarization difference.

However, ALICE has potentially identified a different approach which utilizes the centrality dependence of the net-proton fluctuations. Their Pb–Pb studies at $\sqrt{s_{\mathrm{NN}}}$= 5.02 TeV show a rise in $\kappa_2(p-\bar{p})/\langle p-\bar{p}\rangle$ with decreasing centrality for intermediate momentum ($1.5 < p < 2.8$ GeV/c) protons [16]. More peripheral events are expected to result in larger initial magnetic fields, and Lattice calculations have shown the net-proton fluctuations should rise with increasing magnetic field [17]. While this result is consistent with the Lattice, more discussion and experimental studies are needed, especially on the p_{T} range dependence. It will be particularly interesting to see the *pp* results where the multiplicity is similar to peripheral Pb–Pb data but no initial magnetic field is expected.

The Quest to Understand Small Systems

The large LHC *pp* datasets allowed ALICE to conduct an impressive multi-dimensional analysis of strangeness production that is stress testing MC models [18]. PYTHIA with ropes approximately explains the rate of multiple strange baryon production in a given event as a function of mid-rapidity multiplicity. This model also best reproduces the trend that the Λ/K_s^0 ratio is flat as a function of multiplicity when only one Λ and K_s^0 are produced, but increases when there are multiple strange particles in the event. This type of study is important for disentangling strangeness versus baryon production in small systems.

In pPb data at LHC energies a mass ordering of v_2 is observed at low p_{T}, with a transition to NCQ scaling at intermediate p_{T} [19], consistent with trends seen in A–A data and attributed there to QGP fluid-like properties. The first measurements on far forward flow from LHCb at 5 TeV will provide valuable input to models; AMPT was shown to get the trend correct, but miss the magnitude [20]. First results from O–O collisions at RHIC were presented and revealed that v_2(O–O)< v_2(dAu)~v_2(He^3Au) while v_3(O–O)~ v_3(dAu)~ v_3(He^3Au) [21].

Meanwhile theoretical advances in performing 3+1D hydrodynamical calculations showed that the differences in the STAR and PHENIX small system v_n data can be largely explained as due to the medium not being boost invariant [22]. However, as we edge towards a deeper understanding in some areas, other new perplexing results have emerged. ATLAS reported measurements of strong v_2 signals in the underlying event (UE) of both pp and pPb collisions whether or not the event contained a jet. However, the v_2 determined from jet constituent-UE particle correlations is zero [23]. What therefore is driving the previously reported high p_{T} v_2 in these high multiplicity pp events? [24] Mini-jets? Different sensitivities due to subtle differences in the analyses? Adding to this interesting puzzle were data from CMS probing the v_2 of constituent particles in jets with p_{T}> 550 GeV in pp collisions at 13 TeV. Clear signals are observed that decrease in magnitude as the number of constituents in the jet increases [25]. PYTHIA and SHERPA give a reasonable description of the data up to N_{Const}~80. However, for larger number of constituents the data reveal a dramatic uptick, while the MC models continue their smooth decrease. Do these results suggest that for these extreme cases the number density becomes sufficiently high for partonic or hadronic scatterings to generate collective motion during the jet's fragmentation? Or is it rather that the models have just not been sufficiently tuned in this specific corner of jet fragmentation phase space? It was noted that some tunes of PYTHIA could reproduce some of this uptick, but that the parameters needed do not reproduce other, more common, measurements.

Finally, the question of whether high-multiplicity small system collisions, that reveal clear evidence of v_n signals, also indicate "jet quenching" of hard scattered probes was much discussed. CMS dijet studies revealed no signs of quenching in pPbevents [26]. The decreasing log-linear dependence on x_p of the dijet R_{CP} in pPb events reported by ATLAS suggests the proton configuration in the initial state rather than final-state effects is the underlying cause [27].

However, it is far from clear that a consistent picture is emerging when one takes into consideration the recently reported PHENIX results on π^0 nuclear modification factors in high event-activity dAu collisions. In this analysis instead of using Glauber calculations to determine N_{coll} they use the value that forces their photon R_{dAu} to unity. The π^0 R_{dAu} determined using this new technique equals unity for low activity events, but results in a 20% suppression in those with the largest activity [28]. Discussions continue as to whether this is the first evidence of "hot-matter" effects in small system collisions, initial-state effects or remaining "biases" in the calculation of N_{coll}. For example, does the fact that a π^0 with the same p_{T} as a direct photon comes from a higher Q^2 scattering on average need to be taken into account in this new N_{coll} calculation? Possible support for the "hot matter" interpretation in small system data from RHIC comes from the preliminary reports of sizeable jet v_2 in O–O collisions at RHIC from STAR [29]. The event-plane is determined via their EPD ($2.1<|\eta|<5.2$) to try to ensure a sufficient η gap to prevent recoil jets biasing the event-plane angle determination. However, dijets with large η swings are not impossible, so detailed studies are needed to see if they occur with sufficient frequency to generate a fake signal of the magnitude seen.

The Quest to Understand Nuclear and Hadronic Structure

The substructure of the $f_0(980)$ has been a long standing question. Both CMS and ALICE weighed in on this topic. CMS measured the elliptic flow of the $f_0(980)$, and the K_S^0, Λ, Ξ and Ω in pPb events at 8.16 TeV. Clear evidence of NCQ scaling is seen for the strange baryons and mesons. The flow of $f_0(980)$ also NCQ scales when $n_q = 2$ [30]. $n_q= 4$, valid for the tetra-quark state or $K\bar{K}$ molecular hypotheses, is excluded at the 7.7σ level, and $n_q=$ 3, for the $q\bar{q}g$ hybrid state, with 3.5σ. Measurements of the $f_0(980)/K^{*0}$ ratio as a function of multiplicity from ALICE in pPb data at 5.02 TeV suggest that if it is a di-quark, the quark content is $(u\bar{u} + d\bar{d})/2$ not $s\bar{s}$ [31]. However other experimental searches, for example [32], have suggested it to be tetraquark, so I suspect the debate is far from settled.

Turning to nuclei, STAR is using measurements of $v_2\{4\}/v_2\{2\}$ to probe the substructure of the oxygen nucleus. Since $v_2\{2\}$ is sensitive to fluctuations and $v_2\{4\}$ less so, the ratio is sensitive to α clustering of the nucleons in the nucleus. Comparisons of ultra-central data to models strongly favor those including α clusters [21].

The Quest to Understand the Nature of Energy Loss to the QGP

Use of a mixed event technique to remove background allowed direct comparison of the inclusive jet R_{AA} from RHIC [33] and the LHC [34] for the first time. While the measured suppression values are comparable, one should keep in mind that R_{AA} results are the combination of jet quenching, parton composition and the initial spectral shapes. LHC spectra are hard, and gluon dominated, whereas quarks dominate the significantly softer RHIC spectra. Hence similar R_{AA} actually indicate more energy loss for partons traversing the QGP at the LHC. The clear differences in the R_{AA} for photon-tagged jets compared to that of inclusive jets at 5.02 TeV seen by ATLAS [35] at first glance is an indication that quarks and gluons loose different amounts of energy. However, once again these jet populations have different slopes in the pp data, and that alone can create an ~10% difference.

To assist in the interpretation of these measurements several collaborations are also studying the shift in p_{T} needed to match the A–A spectra to that of the binary scaled pp. This Δp_{T} measure is largely insensitive to different p_{T} slopes. Such analyses show that at LHC energies Δp_{T}(q dominated) < Δp_{T}(g dominated) and Δp_{T}(RHIC)< Δp_{T}(LHC) [35, 36]. How to “unfold" these, and other upcoming, Δp_{T} measurements to determine the true energy loss of gluons and light and heavy quarks remains an open question, as does the question of how large the fluctuations are around these mean losses. Interestingly, if you take the existing wide range of charged particle R_{AA} from RHIC and the LHC a near linear dependence of Δp_{T} on the initial energy density is observed from peripheral Cu–Cu collisions at 200 GeV to central Pb–Pb events at 5.02 TeV [37]. The initial energy density is approximated via the hadron multiplicity and Glauber estimates of the initial overlap area (as laid out in [38]). However, this deserves deeper exploration, as the link between entropy and charged particle density is very sensitive to viscosity [39].

JETSCAPE extended its Bayesian Inference studies on $\hat{q}$ to include hadron and jet inclusive yield suppression data, and jet substructure data. A consistent picture emerges of $\hat{q}/T^3$~5-6 when the jet R_{AA} and substructure are considered. However some tension appears when the hadron nuclear modification factors are also included with the analysis now preferring slightly higher values [40]. This suggests either some missing physics in the JETSCAPE calculations, an underestimation of the measurement uncertainties, and their correlations, or the need to better understand the theoretical uncertainties, or potentially all of the above.

Several presentations discussed techniques and new results on probing energy flow in jets. As predicted the range of the perturbative region grows with jet p_{T}, and when scaled by p_{T} the correlators of light flavor jet display a universal transition point [41, 42]. The transition point of HF tagged jets are predicted to be slightly shifted due to the deadcone effect [43, 44]. The behaviors of the ratio of 3-to-2 point correlators are consistent with the running of α_s [45]. These results clearly showed that energy correlators are well understood in vacuum, and while much work remains, first theoretical studies predict that they should display significant modification by the QGP [46], but more realistic modeling of the medium is needed.

As hard-scattered partons pass through the medium it is predicted that they might create diffusion wakes and/or undergo elastic Moliere scattering. ATLAS studies in photon-jet events determined that any wake results in a $< 0.8\%$ perturbation of the bulk matter at the 95% CL [35]. However, ALICE's studies of jets recoiling off high p_{T}-trigger hadrons are best reproduced by models that incorporate a wake, while being unaffected by modeling of Moliere scattering effects [47]. The apparent discrepancy in these results might be explained by differing sensitivities of the different analyses. Groomed substructure measurements were proposed as better probes for teasing out these small effects [48]. However, it remains unclear how to fully disentangle wake effects from soft gluon emission.

A deeper understanding of the observed dependence of R_{AA} on the groomed jet radius [49] is potentially emerging; selection biases seem to play a significant role [50]. Using photon-tagged jets CMS was able to select events based on the measured x_j. When no selection in x_j is made no R_{AA} dependence on R_g is observed. However, when x_j is required to be balanced (i.e. the recoil jet looses no energy) wide R_g jets become disfavored. At a fixed p_{T} inclusive jets, such as those used for the ATLAS publication, are biased towards jets with less E_{loss}, since those with high E_{loss} are now at lower p_{T} resulting in narrower jets being favored.

Moving to quarkonia LHCb reported the first measurement of $\Xi_c \rightarrow J/\Psi$ in pPb events. This is a crucial first step in studying final state effects on charmonia [51]. Meanwhile CMS extracted the first $\Upsilon(3S)$ signal in heavy-ion events, conclusively showing that quarkonia suppression follows the binding energy of the particle [52]. We eagerly await sufficient statistics from sPHENIX to repeat this measurement at RHIC [53].

A similar suppression of hadrons opposite charm quarks compared to hadrons recoiling off of light quarks was reported by ALICE [54]. While the correlations of back-to-back heavy-quark pairs measured by ATLAS via di-muons show no broadening due to E_{loss}[55].

The Quest to Search For New Physics Via UPCs

There has been an explosion of UPC results over the past few years and new studies continued to be reported at this conference. Both CMS and ATLAS reported on their measurements of a_τ, the anomalous magnetic moment of the τ [56, 57]. These were first uses of hadron collider data to test electro-magnetic properties of the τ. Recent measurements of a_μ have challenged standard model predictions and if this is due to new physics involving massive particles the τ should be more sensitive. Both experiments report values consistent with zero, but importantly these results are competitive with existing lepton-collider constraints.

Hints of gluon saturation from both the LHC and RHIC were shown. The shape of the J/Ψ coherent photo-production cross-section across a wide range of W is not predicted by models, suggesting that the gluon saturation or black-disk region is being reached [58, 59]. However, while di-pion correlations from pp, pAl, and pAu data from STAR show the predicted A dependence of gluon saturation, no broadening is seen [60]. In light of these results it is critical that we make every effort to record more pA data at RHIC before it shuts down. The newly installed STAR forward upgrades provide unique opportunities for deeper insights in this area prior to the EIC [61].

Summary

A wealth of high quality data across $\sqrt{s_{\rm NN}}$, species, and centralities were shown at this conference, I only briefly presented a small fraction here. The large statistics and breadth of results are enabling more detailed studies and comparisons to theory that were not previously possible. The precision era is truly being reached, answering some long standing questions while revealing features that were previously hidden behind uncertainties.

The future looks bright and the quest continues unabated. Next QM we expect to see first results from sPHENIX, STAR's forward upgrades, and much more from the LHC Run-3 A–A data. Then looking far into the future, the next-to-next-to-next-to-next QM promises data from the EIC, ALICE3, and CBM.

Finally, three notes of appreciation to the LoC. First for once again providing childcare for the duration of the conference, second for working so hard to ensure this conference was open and enjoyable for all, and third for making this the first QM where 25% of the speakers were female; representation on the stage matters.

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