

SQM2016: Theory Summary

Vincenzo Greco

Department of Physics and Astronomy, University of Catania, Via S. Sofia 64, I-95125
Catania, IT

E-mail: greco@lns.infn.it

Abstract. This is an overview of the main theoretical developments presented at SQM2016 held in Berkeley, California (USA) in June 2015.

1. Introduction

During the "*Strangeness in Quark Matter 2016*" (SQM2016) conference, more than 50 talks were presented about the theoretical effort to understand the many facets of the heavy-ion collisions and the properties of the hot QCD matter. Here in a few pages we overview the main aspects that have been subject of intense discussion focusing on the theoretical plenary talks.

2. Collectivity in Small Systems

The study of several observables and their critical assessment impinges on the understanding of the initial state space-momentum distribution and correlations. At this conference it was presented a main advancement showing that strong eccentric initial fluctuations of the proton shape, once coupled to viscous hydrodynamics, can account for the v_2 observed at $p + Pb$ collision at LHC [1]. A main novelty is that proton shape fluctuations can be constrained by exclusive vector meson production in lepton-proton scatterings at HERA lepton-proton scattering, creating a nice link with high-energy hadronic physics. It remains the issue of the validity of hydrodynamics for a system with large initial Kundsens number. Although the system may undergo "hydrodynamization" in a short time scale as indicated by AdS/CFT approaches [2], it would be important to see if kinetic theory also leads to a similar conclusions. However still such an approach has to be contrasted with the relevance of local initial momentum correlations (on a $1/Q_s$ scale) that lead also to final anisotropies, but not directly related to the space eccentricities [3].

3. Sub-threshold Strangeness and Charm production

The large ϕ/K^- and Ξ^-/Λ ratios reported by HADES and FOPI [4, 5] at subthreshold energy have not been correctly predicted by microscopic transport model and the thermal fits are also not convincing. It has been shown, employing uRQMD augmented by $N^* \rightarrow \phi, \Xi^-$ decays, that the Fermi motion plus secondary interaction are a fast way to generate collisions pairs with invariant mass that goes above the threshold. Such a mechanism appears to correctly reproduce the low $\sqrt{s_{NN}}$ enhancement measured experimentally [7], predicting a peak at $\sqrt{s_{NN}} = 1.25$ GeV. The quantitative prediction is reasonably regulated by the ANKE pp data for the ϕ production in the 2.5 – 3 GeV energy range [6]. A similar study for subthreshold charm production has also

been presented, showing that J/Ψ , Λ_c , \bar{D} may have the chance to be abundant already at SIS100 energy range, $E_{lab} = 5 - 11$ AGeV. Finally it is becoming clear that fast resonance excitation and decays allow for an effective thermalization of hadron yields in a time scale comparable with the nuclei passing time, thanks to the large density of states [8].

4. Thermal model, freeze-out, susceptibilities and phase diagram

The statistical thermal hadronization model (SHM) is able to correctly predict the hadronic yields, and surprisingly recently also light nuclei like 3He , ${}^3He_\Lambda$ and their anti-nuclei. Considering that this involves a span of about 9 orders of magnitude and is valid at least over the entire range of collisions from SPS to LHC energy [10], this result constitutes one of the bulk achievements of the field that easily at a glance shows that a matter hadronizing with a temperature $T \simeq 155 - 165$ MeV has been created [9]. At first glance it always appears quite surprising that the hadronic system can achieve a nearly full equilibrium in a short time. At this conference it has been shown that a microscopic mechanism like the Hagedorn state decays, at the energy densities relevant for QCD transition, can lead to a system nearly born in chemical equilibrium [11].

It is however known that there is a tension in the data on p , \bar{p} , Λ production at LHC. This is certainly very interesting and according to some of the talks may signal hadronic chemical re-interaction [12, 13] that shifts the apparent temperature. While this could be a quite natural explanation, an important warning comes from the most recent lattice QCD results on susceptibilities, which has been an hot topic of the conference. From IQCD study of the susceptibilities, involving the strange quantum number and in particular the Koch' ratio [14], it appears clear that the Hadron Resonance Gas (HRG) model, underlying the SHM, from the PDG is not able to reproduce the Koch's ratio, χ_{11}^{BS}/χ_2^S , as evaluated from IQCD for $T \geq 160$ MeV. A new result presented also shows that even a HRG based on Quark Model that appears to be in a quite good agreement with several IQCD calculations, misses for example the χ_4^S/χ_2^S already at $T > 140$ MeV, probably because of lack of $s = 1$ meson states [15, 16].

A fundamental part of the phase diagram is certainly the Equation of State (EoS) at finite μ_B/T . The Wuppertal-Budapest Collaboration has shown to be able to evaluate it up to $\mu_B/T < 2.5$ and up to term of the $(\mu_B/T)^6$ order [15].

A key part of the relativistic HIC program is certainly the search for the QCD critical point. It has been shown that kurtosis $\kappa\sigma^2$ of net protons measured by STAR and χ_4/χ_2 in IQCD appear to be in good agreement within the present uncertainties in the region $\sqrt{s_{NN}} > 19$ GeV corresponding to $\mu_B/T < 2$, where IQCD results are reliable [14]. It has to be mentioned that in this region IQCD does not see a critical point. Dynamical studies of critical fluctuations and of resonance decay impact have been presented, assuming a critical point. They show a robust remnant of critical fluctuations [17], but further advancements are needed before a reliable comparison can be done. Soon the entire range accessible with BES-I and II at RHIC will be accessible through Taylor expansion in IQCD. A proposal to face the search for the critical point by looking the high energy collisions versus the rapidity has been presented in a parallel session[18].

5. Heavy Flavor

The heavy flavor attracted quite some interest already more than a decade ago because of the large suppression observed with a call for large non-perturbative effects at least for charm quarks with $p_T \leq 10$ GeV. A main difference from the physics of the bulk QGP matter comes from the fact that the initial p_T distribution can be evaluated in a pQCD scheme and in particular the FONLL has been show to be in agreement with the experimental data within the inherent uncertainties. Furthermore one expects marginal thermal production, which is confirmed, within current error bars, also by the observed N_{coll} scaling. A main challenge, currently, is the

simultaneous description of both the $R_{AA}(p_T)$ and the $v_2(p_T)$. It has been pointed out that several ingredients contribute to this, but the main impact can come from the T dependence of the transport coefficient. In particular a constant drag coefficient γ leads to a more efficient building-up of v_2 especially in the low-intermediate $p_T \leq 4$ GeV. There a weak dependence of the drag as predicted by Quasi-Particle models [20, 19] or by T-matrix approach [21] leads to v_2 about a factor 2-3 larger w.r.t. the T^2 dependence as in pQCD ($\alpha_s = const.$) or AdS/CFT. A similar trend is observed also for v_3 for heavy quarks at intermediate-high p_T , as discussed in [22].

Another source of uncertainty comes from the microscopic heavy quark dynamics. A real heavy quark would undergo a Brownian motion well described by Langevin transport equations. A charm quark can be envisaged to be marginally heavy, if one considers that while for the thermal production m_c has to be compared with T , for the scatterings other scales enters the problem, gT and/or πT , that are comparable to the charm mass at temperatures $T \sim 300-400$ MeV, reached in particular at LHC energy. A direct comparison between Langevin and Boltzmann dynamics shows non sizeable differences for bottom quarks, while for charm it can lead to differences that range between 10–30% in the intermediate p_T region for spectra and elliptic flow, depending on the specific model for the in-medium scatterings considered [23]. The effect is predicted to be larger for $c - \bar{c}$ angular correlations. In the low p_T limit the differences between the two approaches become marginal for the predictions on the charm spectra (or R_{AA}) that especially at LHC energy appear to reach thermalization when a thermal model is able to correctly describe $R_{AA}(p_T)$ for $p_T < 2$ GeV.

The comparison to data favours a space-diffusion coefficient $2\pi T D_s$ that rises with temperature T in agreement with lQCD calculation, although such a statement suffers from the systematic errors in both lQCD and the phenomenological models. In the latter the main sources of difference may come from the background bulk expansion and from details in the hadronization mechanism. However, in general, it appears that models including quark coalescence are able to provide predictions closer to the experimental data at both RHIC and LHC energy.

An important advancement presented has been the Linearized Boltzmann Transport (LBT), from the LBL-CCNU Collaboration, that is able to treat in the same framework both the light and heavy hadrons suppression [24], confirming in the heavy quark sector the necessity to have a modification of the the diffusion coefficient w.r.t. the T^2 dependence, as pointed out in [19]. It is interesting to notice that a similar dependence for the diffusions coefficient appears to be necessary also for the $R_{AA} - v_2$ for high p_T minijets as pointed out by the CUJET approach [25]. In the latter the microscopic mechanism of a minimum in $2\pi T D_s$ would be driven by the presence of monopoles in the bulk medium, while for heavy quarks in the low p_T region it would be consistent with the dynamics implied by the remnants of confinement according to TAMU T-matrix approach [26, 27].

A novel aspect of the heavy quarks physics that has been started to be investigated is the impact of the strong initial magnetic field on their dynamical evolution. Some first work shows a modification of the parallel and transverse HQ diffusion coefficient that becomes significant for value of the magnetic field $eB > T^2$ [28, 29], which however may marginally occur in HIC at current energy.

On the other hand it has been shown initial B entails a sizeable directed flow (v_1) of charm quarks (CQs) much larger than light quarks due to a combination of several favorable conditions for CQs, mainly: (i) unlike light quarks formation time scale of CQs, $\tau_f \simeq 0.1\text{fm}/c$ is comparable to the time scale when B is around its maximum value and (ii) the kinetic relaxation time of CQs is similar to the QGP lifetime [30]. The effect is also odd under charge exchange allowing to distinguish it from the vorticity of the bulk matter due to the initial angular momentum conservation.

6. Quarkonia

The medium modification of the quarkonia production is certainly a key probe of the deconfined matter. During the years and going to collisions at increasing energies it has become clear that for charmonia more than the suppression it is the regeneration that plays a key role for the understanding of its production especially at top LHC energy. The large amount of data collected as a function of rapidity and centralities clearly show this. The theoretical approaches based on a transport evolution including both regeneration and dissociation are able to predict the J/Ψ production fairly well [31, 32, 33]. However the impact of the uncertainties in the charm cross section still leaves open a key question: is charmonia yield consistent with a regeneration at the chemical freeze-out temperature as for light hadron production? or it is necessary to have a dynamical description of suppression and regeneration to understand the production in the QGP matter? From the point of view of the SHM a clear prediction would be a strong reduction of the ratio $\Psi(2S)/J/\Psi$ with respect to pp and pA [34]. From the point of view of the dynamical regeneration approach a signature of the dynamical nature of the production is the anomalous regeneration of $\Psi(2S)$ observed in central $Pb+Pb$ collisions at high $p_T > 3$ GeV, a behavior that is predicted in such a picture due to the delayed recombination into $\Psi(2S)$ w.r.t. J/Ψ and a larger inherited radial flow [35]. This implies a quite different behavior of $R_{AA}(p_T)$ for the J/Ψ w.r.t. $\Psi(2S)$ with the latter showing a peak at $p_T \simeq 4$ GeV. Upcoming experimental data at low p_T will allow to clarify this issue. Certainly it remains important to measure the v_2 of the J/Ψ with significantly reduced static and systematic errors. This would allow, independently of the measurement of the charm cross section, the dynamics of the J/Ψ production to be clarified, as anticipated in [36].

An important theoretical development toward a quantum treatment of the quarkonia suppression has been presented. In fact most of the approaches treat the several quarkonia states as independent states by means of decays width, while they are different excited quantum states of the same system. In the framework of a Schroedinger-Langevin equation that encodes decoherence dynamics [37]. A first comparison show a reasonable agreement with data on bottomonia suppression except for most central collisions. However before full realistic calculation, the impact of realistic 3D potential extracted from lQCD and the impact of the assumptions for the initial quantum states of quarkonia as well as the relation to lQCD spectral functions, still have to be investigated [38].

7. Chiral Anomaly

The Chiral Magnetic Effect (CME) is a remarkable phenomenon emerging from a highly nontrivial interplay of QCD chiral symmetry, axial anomaly, and gluonic topology. The heavy ion collisions supply a hot chiral-symmetric QGP under a strong magnetic field, hence gluonic topological fluctuations could generate a chirality imbalance observable experimentally as a charge separation along the direction of the magnetic field. Experimentally a signal of such a separation has been measured especially in the energy range of BES-RHIC at $\sqrt{s_{NN}} = 7.7 - 62.4$ GeV [39], although currently it seems that models with magnetic field-independent flow backgrounds can also be tuned to reproduce the current measurements.

Indeed on the theoretical side a transport theory that includes the dynamics of chiral currents and the associated anomaly, is needed. This is leading to the development of a chiral viscous hydrodynamics and some attempts to develop a chiral kinetic transport theory; the latter would allow studying the pre-thermal glasma stage that is likely to be the most pertinent one given the short life-time of the magnetic field. Such efforts will supply the necessary theoretical tools to predict the size and the evolution of the CME with energy and centrality. Also it can allow us to study in a self-consistent way several observables related to CME and to see if from the experimental data a coherent picture for a fundamental effect emerges, which however till now is associated to a weak signal over a large background. Nicely, a first attempt to describe the

centrality dependence of the charge separation within chiral hydro appears to be consistent with the dynamics implied by the CME [40].

8. Global Polarization

An aspect of relativistic HIC that has been mostly overlooked is that in non-central collisions due to the large orbital momentum one is likely to create a system with a huge vorticity. One can envisage that particles emerging from such a highly vorticious fluid are globally polarized with their spins on average pointing along the system angular momentum. To study such a dynamics the development of a self-consistent theory that treat vorticity in a relativistic framework is needed. This has been recently investigated in the context of the QGP physics assuming a thermal fluid deriving a general formula that relates the vorticity of a fluid to its polarization for particles of spin 1/2 [41]. This has allowed embedding the polarization dynamics into the ECHO-QGP viscous hydro code for RHIC's studying in particular the Λ polarization that is accessible experimentally [42, 43]. Distinctive feature of thermodynamic polarization would be a C-even effect, that particle and antiparticle have the same polarization, unlike e.m. induced polarization. The predictions appear to follow a similar increase of the polarization with decreasing beam energy. Interestingly in experiments the polarization of the order of a few percent appears to be even larger than the prediction [43]. However the effect of resonance decays, hadronic rescattering, impact of the Pauli Blocking [44] have to be investigated. Certainly the developments of such studies has opened a new direction and can allow us to have an insight on the vorticity of the matter created in the early stage of the collision, adding a new dimension in the HIC phase space.

9. Summary

In Summary, there is a clear progress in the understanding of the QCD matter at high temperature created in relativistic heavy-ion collisions. Certainly in the last decade an understanding of the main features of the collision dynamics and its collective expansion has been achieved, and the surprising behavior of several observables in pA from strangeness production to anisotropic flows will at the end allow us to have deeper understanding of the matter created in such collisions and the properties of hot QCD. At the some time one should appreciate that many questions were not even conceivable a decade ago, but are now under active investigation thanks to the progress that the field has achieved in the understanding of the bulk properties of the matter created.

10. Acknowledgments

V.G. is supported under QGPDyn ERC Grant no. 259684.

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