

Opportunities for Heavy Ion Physics at the Large Hadron Collider LHC

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Abstract. This talk discusses extrapolations to the LHC of several, apparently universal trends, seen in the data on relativistic nucleus-nucleus collisions up to RHIC energies. In the soft physics sector, such extrapolations to the LHC are typically at odds with LHC predictions of the dynamical models, advocated to underlie multi-particle production up to RHIC energies. I argue that due to this, LHC is likely to be a discovery machine not only in the hard, but also in the soft physics sector.

1. Introduction

Heavy ion physics is an integral part of the baseline program at the CERN Large Hadron Collider LHC [1], which will start operation within the next year. In lead-lead collisions, the LHC will reach a center-of-mass energy of $\sqrt{s_{NN}} = 5.5$ TeV, a factor 27 higher than the maximal energy explored at the Relativistic Heavy Ion Collider RHIC so far. This is an even larger increase in center of mass energy than the factor 10 in going from the CERN SPS to RHIC. It leads to a significant extension of the kinematic range in transverse momentum p_T and in Bjorken- x , experimentally accessible for the study of hot and dense QCD matter. Rather than elaborating the often discussed novel questions, which we can address in the logarithmically wide *terra incognita* at high- p_T , this talk will focus on the most direct manifestation of QCD matter produced in heavy ion collisions: soft physics.

2. LHC is a discovery machine for soft physics

Soft multi-particle production has been studied extensively in the collisions of hadrons and nuclei, but despite insight from model-dependent approaches, it is lacking a fundamental understanding.‡ In nucleus-nucleus collisions, soft multi-particle

‡ This is so in p-p, as well as in A-A collisions. For instance, uncertainties in model extrapolations of the charged particle multiplicity per unit rapidity dN_{ch}/dy over an order of magnitude in $\sqrt{s_{NN}}$ are of similar size in nucleus-nucleus and hadron-hadron collisions. Models successful for hadron-hadron collisions up to the Tevatron energy ($\sqrt{s_{NN}} = 1.8$ TeV) vary by up to a factor 2 if extrapolated to p-p collisions at the LHC [2].

production shows imprints of collective dynamics, such as elliptic flow, and of kinematic and hadrochemical equilibration [3]. This makes soft multi-particle production a testing ground for the central question of how collective phenomena, involving many degrees of freedom, can emerge from the fundamental laws of elementary particle physics.

2.1. Example 1: multiplicity distributions

To illustrate the discovery potential of LHC for this class of questions, we contrast here model predictions for heavy ion collisions at the LHC with extrapolations of generic trends. As repeatedly emphasized e.g. by Wit Busza [4], soft multi-particle production displays characteristic and apparently universal trends over many orders of magnitude in center of mass energy. For pseudo-rapidity distributions, these generic trends are i) extended longitudinal scaling and ii) the factorization of the $\sqrt{s_{NN}}$ - and the centrality/ A -dependence in pseudo-rapidity distributions. Here, extended longitudinal scaling refers to the observation that pseudo-rapidity distributions, plotted in the rest frame of one of the colliding hadrons, fall on a universal, energy-independent limiting curve in the projectile fragmentation region. The region within which this limiting fragmentation accounts for the data, increases with center of mass energy, see Fig. 1.

Such generic trends can serve as a basis for agnostic extrapolations to the LHC. As seen in Fig. 1, requiring that both limiting fragmentation and the trapezoidal shape of the pseudo-rapidity distribution persist at the LHC, one expects $dN_{PbPb}^{ch}/d\eta \simeq 1100$ at $\eta = 0$. On the other hand, if one requires solely that the limiting fragmentation curve specifies the maximally allowed distribution at all rapidities, one concludes $dN_{PbPb}^{ch}/d\eta \simeq 1700$ at $\eta = 0$. In general, since the baseline of the trapezoid in Fig. 1 increases $\propto \log \sqrt{s_{NN}}$, limiting fragmentation implies that the multiplicity at central rapidity increases at most logarithmically.

In marked contrast, a power-law increase of multiplicity distributions with $\sqrt{s_{NN}}$ is a generic consequence of perturbative particle production mechanisms, which may be expected to become relevant with increasing $\sqrt{s_{NN}}$. Arguably, the main lesson learnt from the lower than predicted event multiplicities measured at RHIC [3] is, that the power-law dependence of (the simplest) perturbative multiplicity-enhancing mechanisms, such as minijet production, is too strong to be reconciled with data. On the other hand, saturation models offer a fundamental reason for the very weak $\sqrt{s_{NN}}$ -dependence of event multiplicities, namely the taming of the perturbative rise due to density-dependent non-linear parton evolution. They are based on the assumption that multiplicity distributions at ultra-relativistic energies are calculable within perturbation theory, since they are governed by a perturbatively high, $\sqrt{s_{NN}}$ - and A -dependent momentum (saturation) scale $Q_{sat,A}^2 \propto \sqrt{s_{NN}}^\lambda$. In saturation models, multiplicities at mid-rapidity rise essentially $\propto Q_{sat,A}^2$ times transverse area. This also accounts naturally for the experimentally observed factorization of $\sqrt{s_{NN}}$ - and centrality-dependence. The exponent λ is not a free fit parameter, but is taken to be constrained by data on $e - A$ collisions and by studies of non-linear small- x evolution. Depending on details

Au-Au collisions 0-6% centrality

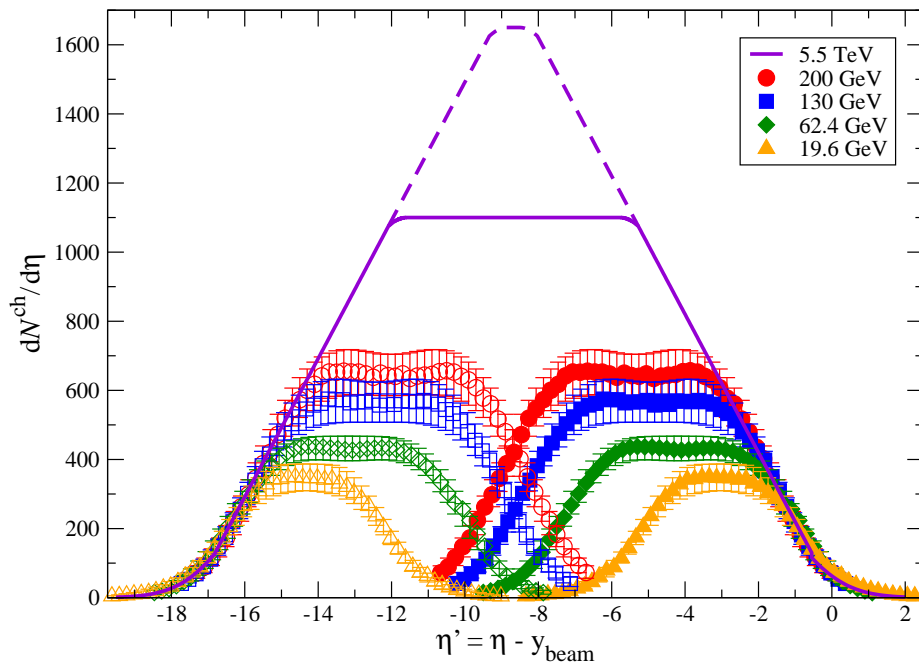


Figure 1. Pseudorapidity distribution of charged particle production in Au-Au collisions at different center of mass energy. Data are plotted in the rest frame of one of the colliding nuclei (full symbols), and mirrored at LHC mid-rapidity (open symbols). Agnostic extrapolations to the LHC are based on assuming i) that limiting fragmentation persists up to mid-rapidity (dashed line), or ii) that multiplicity distributions show limiting fragmentation and a self-similar trapezoidal shape (solid line). Data from [5,6]. Figure taken from [7].

of the modeling of this idea, one arrives at estimates between $dN_{\text{PbPb}}^{\text{ch}}/d\eta \simeq 1700$ [8] and $dN_{\text{PbPb}}^{\text{ch}}/d\eta \simeq 1800 - 2100$ [9]. Similar values are also obtained by invoking other mechanisms to tame the perturbative growth [10]. They are significantly higher than extrapolations of the apparently universal trends shown in Fig. 1.

To sum up this first argument: While the factor 30 increase in $\sqrt{s_{\text{NN}}}$ from RHIC to LHC will not be sufficient to discriminate a logarithmic increase from an arbitrarily tamed power-law increase, it is sufficient to discriminate $\log \sqrt{s_{\text{NN}}}$ from the factor $\sqrt{s_{\text{NN}}}^\lambda$, where λ is constrained by our current understanding of saturated QCD. So, we observe that the apparently universal trends seen in multiplicity distributions can be accounted for by saturation models up to RHIC energies. However, the logarithmic extrapolation of these trends to the LHC is not consistent with the power-law dependence of the dynamical models advocated to underly multi-particle production at RHIC. In this sense, LHC will be a discovery machine for soft physics, starting from day 1 of its operation. Either, it will find characteristic violations of the apparently universal trends, seen up to RHIC data - thus providing qualitatively novel support for a specific microscopic collision dynamics. Or, LHC will confirm these generic trends

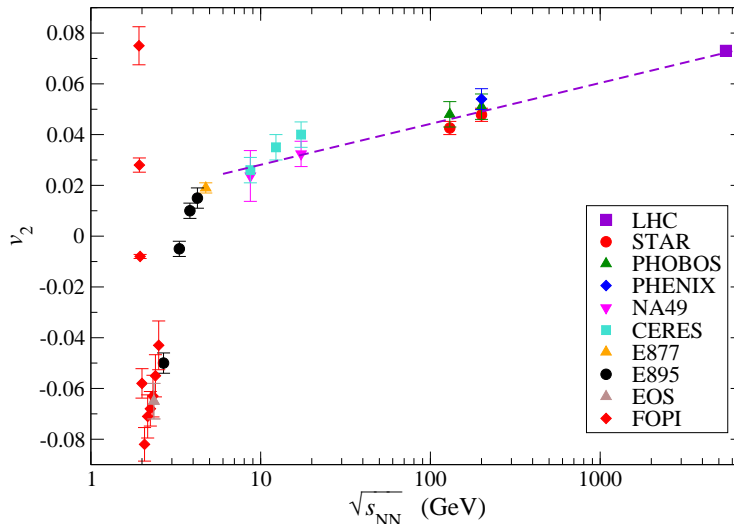


Figure 2. $\sqrt{s_{NN}}$ -excitation function of $v_2(y=0)$ in mid-central collisions. Data are taken from the compilation in Ref. [14]. The point at LHC energy is obtained by agnostic linear extrapolation of the pseudo-rapidity dependence $v_2(\eta)$ from RHIC. Figure taken from [7].

- thereby prompting us to revisit the central dynamical ideas currently proposed for the tamed growth of event multiplicities up to RHIC energies. In both cases, the day 1 measurement of multiplicity distributions at the LHC is likely to have profound consequences for our understanding of the matter produced in nucleus-nucleus collisions at the LHC *and* at RHIC.

2.2. Example 2: elliptic flow

The above line of argument can be adopted to other characteristic features of soft multi-particle production in heavy ion collisions. As a second illustration, we mention here the azimuthal asymmetry of hadron production commonly referred to as 'elliptic flow' v_2 . The observable v_2 is constructed such that it is an unambiguous signature of collective dynamics in the collision. At lower energies, the p_T -integrated elliptic flow shows characteristic changes of sign, indicative of significant changes in the collision dynamics. At SPS energies and above, one finds that the pseudo-rapidity distribution $v_2(\eta)$ of p_T -integrated elliptic flow changes smoothly and shows extended longitudinal scaling [11]. The shape of $v_2(\eta)$ is triangular, and extrapolation to the LHC yields $v_2(\eta=0) \simeq 0.075$.

At RHIC energies, ideal fluid dynamic simulations of the collective dynamics arrive at a fair description of elliptic flow at mid-rapidity [3, 12, 13]. They account for the absolute size of v_2 , its p_T -dependence up to $p_T \leq 1.5 - 2$ GeV, some aspects of the centrality dependence and qualitative features of the particle-species dependence [3, 12, 13]. However, neither the approximately linear increase of $v_2(\eta=0)$ with $\log \sqrt{s_{NN}}$, nor the triangular shape of the pseudo-rapidity distribution of v_2 emerge as natural

consequences of these dynamical models. Even more restrictively, the energy dependence of detailed characteristics of elliptic flow, such as PID-, p_T - and A - dependence, has not been employed fully to test and refine fluid dynamic models, simply because one argues that an ideal liquid is produced solely in sufficiently central collisions at the highest RHIC energies. Thus, beyond the statement that RHIC may have seen the onset of ideal fluid behavior, the main consequence of this claim is arguably the prediction that this behavior will persist in heavy ion collisions above RHIC energies. Irrespective of whether LHC will finally be the confirmation or falsification machine for this ideal fluid dynamic picture, it is clear that the factor 30 increase in $\sqrt{s_{NN}}$ turns LHC into the discovery machine, needed to adequately support such a strong claim. LHC is well-positioned to provide critical tests for the ideal fluid paradigm.

The last argument may be questioned. It is true that ideal fluid simulations of heavy ion collisions at the LHC favor significantly lower elliptic flow values of $v_2(\eta = 0) \simeq 0.055 - 0.06$ for $dN_{ch}/d\eta \simeq 1100$, than the results of the extrapolation shown in Fig. 2. However, changes in the transverse spatial profile of the initial conditions, which are difficult to constrain, have been found to affect the final v_2 -signal significantly [15]. One may suspect that such model-dependent uncertainties in the initial conditions (or in implementing dissipative corrections and in simulating the freeze-out process [16]) are too significant to turn LHC measurements into decisive tests which go qualitatively beyond what has been achieved at RHIC. In my view, improving the accuracy of model simulations responds only partially to such concerns. In addition, one should require that a 'good' dynamical interpretation does not discard as mere numerical coincidences trends which persist over wide kinematic ranges, but that it can account for them as natural consequences of the underlying dynamic picture. The fact that LHC extends for the first time by a factor 30 the $\sqrt{s_{NN}}$ -range within which ideal fluid dynamics applies (if it applies at RHIC), will give access to the detailed study of such generic trends which must emerge from a valid dynamic explanation. To what extent does the $\sqrt{s_{NN}}$ -dependence of p_T -integrated v_2 arise from the increase of the rms transverse momentum $\langle\sqrt{p_T^2}\rangle$ with $\sqrt{s_{NN}}$ in elementary nucleon-nucleon collisions (which is not directly invoked in ideal fluid dynamics) rather than from an increase of $v_2(p_T)$ at fixed p_T with $\sqrt{s_{NN}}$? How does v_2 at RHIC mid-rapidity differ from v_2 at an LHC rapidity which has the same $dN_{ch}/d\eta$ as RHIC at $\eta = 0$? How does the breaking point in $v_2(p_T)$ and the PID composition of v_2 change as a function of $\sqrt{s_{NN}}$? The interest in these and other systematic dependencies is clearly motivated by RHIC measurements. But LHC will be the first machine to address these systematic dependencies in a kinematic regime in which ideal fluid dynamics is argued to apply. In this sense, the physics opportunities at the LHC for critically testing the ideal fluid paradigm go significantly beyond the obviously novel measurements, such as extending with the help of the azimuthal dependence of D -, B -meson and quarkonium spectra our understanding of mass-ordering at small p_T and of constituent quark counting rules of v_2 at intermediate p_T .

2.3. How do the properties of hot and/or dense QCD matter evolve?

The heavy ion programs at RHIC and at the LHC are complementary for the understanding of collective soft physics phenomena in ultra-relativistic heavy ion collisions. The arguments presented above support this view by emphasizing that the $\sqrt{s_{\text{NN}}}$ -systematics provided by LHC measurements is indispensable for providing compelling experimental support of the main tentative physics conclusions reached at RHIC energies: the onset of saturation phenomena and the onset of ideal liquid behavior [3]. More generally, with a combined analysis of data from RHIC and the LHC, the question will come into experimental reach of how the fundamental properties of QCD matter, produced in ultra-relativistic heavy ion collisions, change with center of mass energy. A combined analysis of RHIC and LHC is of particular interest, since no abrupt change of physics is expected to occur in between the two collider energies.

Here, we use the discussion of the $\sqrt{s_{\text{NN}}}$ - and Y -dependence of the Cronin effect to illustrate the novel opportunities. The nuclear-modification factor for d-Au collisions, measured at RHIC, shows at intermediate transverse momentum a characteristic Cronin-type enhancement at mid-rapidity, which is typically attributed to initial state p_T -broadening. Towards forward rapidity, this enhancement disappears and one finds, compared to the yield in proton-proton collisions, a suppression which grows rapidly stronger with increasing rapidity Y [3]. Models invoking non-linear small- x evolution of parton distributions arrive at a semi-quantitative description of this phenomenon. These models illustrate the fact that extended longitudinal scaling, a precursor of QCD saturation at transverse momenta above the saturation scale Q_s , can account for a significant reduction of partonic yields at intermediate p_T [17]. However, one may imagine other mechanisms at work in the rapidity-dependence of $R_{dAu}(p_T, Y)$. In particular, any inelastic process which is enhanced due to multiple initial state scattering, has the potential to shift particle yield from forward rapidity towards mid-rapidity. Since parton distributions are steeply falling towards projectile rapidity, this may introduce a significant rapidity dependence of $R_{dAu}(p_T, Y)$. In the context of RHIC data, there has been some discussion on how to disentangle such confounding factors from signals of non-linear QCD evolution, e.g. by studying isospin effects and the particle species dependence of $R_{dAu}(p_T, Y)$. However, the best discriminatory tool is arguably provided by the LHC: In models of saturation physics, there is a one-to-one correspondence between effects of the rapidity dependence and the $\sqrt{s_{\text{NN}}}$ -dependence, simply because a parton distribution boosted to higher rapidity Y is a distribution looked at in a process at higher $\sqrt{s_{\text{NN}}}$. As a consequence, the saturation physics explanation of the Y -dependent disappearance of the Cronin peak at RHIC also implies the replacement of this peak by a significant suppression at LHC mid-rapidity. In contrast, the confounding mechanisms alluded to above are expected to result in a small but visible Cronin-peak in p -Pb collisions at LHC mid-rapidity.

In general, comparing the Y - and $\sqrt{s_{\text{NN}}}$ -dependence of measurements is a powerful tool for identifying the manifestations of (non-linear) small- x evolution, not only in

h-A but also in A-A collisions. One may go one step further and argue that it is of fundamental interest to study how intrinsic properties of the produced matter, such as its dissipative characteristics (e.g. shear viscosity, but not only shear viscosity), or its jet quenching parameter \hat{q} depend on $\sqrt{s_{\text{NN}}}$, and whether they depend on $\sqrt{s_{\text{NN}}}$ solely via $dN_{\text{ch}}/d\eta$. This is so, since it is mainly the scale evolution, rather than predictions at a fixed scale, which provides tests of the fundamental QCD dynamics. § It is an exciting thought that the ability of comparing the $\sqrt{s_{\text{NN}}}$ - and Y - dependence of measurements over logarithmically wide ranges, well beyond providing a novel tool for discriminating different physics effects, may be the basis for a new line of fundamental scientific investigation into medium-dependent QCD evolution.

3. LHC is a discovery machine for hard physics

On purpose, I have put the emphasis of this article on soft physics at the LHC. There is a risk that these opportunities are overlooked or ranked second, simply because the *terra incognita* of hard probes, opening up at the LHC, is so striking. Novel opportunities for hard probes at the LHC have been emphasized repeatedly [19] (for my own detailed view, see Ref. [18]). Here, I characterize them crudely by recalling the following facts: First, high- p_T hadron suppression at RHIC persists unattenuated up to the highest transverse momenta (a factor 5 suppression in central collisions up to $p_T \sim 15 - 20$ GeV) tested so far [3]. This makes it likely that strong medium-effects will persist in heavy ion collisions at the LHC up to very high transverse momenta in all aspects of hadron and multi-hadron production. Second, high- p_T hadron production in the multi-10 to 100 GeV transverse momentum regime is a hard, but abundant probe at the LHC. It is the size of the expected medium-dependent signal, which facilitates its unambiguous attribution to a specific dynamic attenuation mechanism despite the obvious experimental uncertainties in a high-multiplicity environment, and despite the well-known uncertainties of performing QCD calculations for this situation. And it is the abundance of the expected medium-dependent signal, which will allow us to constrain details of the proposed dynamics against sufficiently differential measurements. In short, the combination of a large signal and an abundant yield is the basis for a detailed characterization of hot and dense QCD matter with hard probes.

Beyond this improved precision due to the wider kinematic range and higher yield, can we identify qualitatively novel aspects of QCD, which come into experimental reach at the LHC? Arguably, measurements of heavy ion collisions at the LHC will study for the first time a logarithmically wide transverse momentum range at perturbatively high p_T . Since internal jet structures (i.e. intra-jet multiplicity and energy distributions, as well as jet-like particle correlations) are known to be characterized by QCD evolution, this may provide a unique possibility to test the medium-dependence of the QCD scale

§ We note that there has been some progress recently on calculating *at fixed scale* and at strong coupling fundamental quantities accessible in heavy ion collisions, such as \hat{q} or the shear viscosity. For an overview of related results based on string theory techniques, see Ref. [20]

evolution. Also, the potential to discriminate from the underlying event entire jet structures is significantly improved with increasing $\sqrt{s_{\text{NN}}}$.

There is at least one alternative line of thought which links the analysis of the microscopic mechanisms underlying jet quenching to a novel fundamental question of hot and dense QCD: Jet quenching studies address the issue of how and to what extent equilibration processes occur in heavy ion collisions. What could be further away from thermal equilibrium initially than a more than 100 GeV parent parton? And how could we hope for a clearer picture of how partons equilibrate, than by assessing in detail how this parent parton approaches kinetic and hadrochemical equilibrium as a function of the external parameters of the cauldron which we can regulate, such as in-medium pathlength or event multiplicity? Here, enhanced precision and enhanced kinematic range are likely to further novel connections between the phenomenology of heavy ion physics and the fundamental questions of hot and dense QCD.

I am indebted to many friends and colleagues for arriving at some of the thoughts expressed here. I would like to single out the collaboration with Nicolas Borghini on Ref. [7], which has shaped part of the present line of argument.

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