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Initial state in heavy ion collisions

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Abstract

We briefly review advances in understanding the initial stages of a heavy ion collision. In particular the focus is on moving from parametrizing the initial state to calculating its properties from QCD, consistently with the description of hard probes and dilute-dense scattering experiments. Modeling the event-by-event fluctuating nuclear geometry in initial state calculations has significantly improved in recent years. We also discuss prospects of directly seeing effects of particle correlations created in the initial state in the experimental observables.

Keywords: Heavy Ion Collisions, Quark Gluon Plasma, Quantum Chromodynamics

1. Introduction

For a practitioner of hydrodynamic modeling of heavy ion collisions, the question of initial conditions often boils down to an acronym soup of models. One tries out a suitable subset of these (“Glauber”, KLN, [mc]KLN, mcrcBK, EPOS, EKRT, IPglasma etc.) as an input to a fluid dynamics calculation and compares to experimental data. The purpose here is very different, namely to discuss the physics ingredients in these calculations and concentrate more on their common aspects than on their differences. This is done with the caveat that we are concentrating exclusively on a weak coupling partonic description of the degrees of freedom involved. We will start with a very brief introduction to the physics picture in the weak coupling approach. We then discuss dilute-dense control experiments that can be used to more directly probe the degrees of freedom in the initial state of a heavy ion collision. The most recent dynamical initial state models will then be discussed in comparison to Monte Carlo Glauber parametrizations. Finally we will describe recent calculations of long range correlations originating from the initial state. A remaining challenge is to discriminate between initial state and of collective flow effects in these correlations.

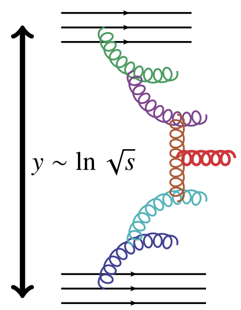

Figure 1: Gluon cascade leading to particle production in the central rapidity region.

2. Initial state at weak coupling

The weak coupling picture of particle production at central rapidities in very high energy hadronic collisions is depicted in Fig. 1. The gluons that are mainly responsible for particle production result from a cascade of multiple splittings from the initial valence quarks. The emission probability for one splitting is $\alpha_s\, dx/x$, where x is the fraction of the longitudinal momentum of the incoming hadron and α_s is the QCD coupling. This form is constant as a function of rapidity, and thus leads naturally to a rapidity plateau, i.e. a multiplicity dN/dy

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approximately independent of y for scales $\Delta y \lesssim 1/\alpha_s$. While at RHIC the total collision energy is still so low that the y-dependence is dominated by large-x physics, at the LHC this plateau has become prominently visible in the experimental data. At high enough energy there is phase space for many gluon emissions in the cascade, each additional one suppressed by a factor α_s but enhanced by a phase space volume $\Delta y \sim \ln \sqrt{s}$. With a factor $1/n!$ from the rapidity ordering of n gluons one could in fact very roughly expect

$$\frac{\mathrm{d}N_g}{\mathrm{d}y} \sim \sum_n \frac{1}{n!}\left(\alpha_s \ln \sqrt{s}\right)^n \sim \sqrt{s}^{\alpha_s} \tag{1}$$

gluons. Again, the experimental energy dependence of multiplicities in pp ($\sim \sqrt{s}^{0.2}$) and AA ($\sim \sqrt{s}^{0.3}$) collisions fits in very nicely with this very crude weak coupling, small angle scattering estimate. This could be contrasted with a strong coupling picture, which would generically lead to complete baryon stopping [1] and a stronger growth of the multiplicity with $\sqrt{s}$.

Eventually the gluons in this cascade will overlap and gluon mergings will start to compete with splittings. This increase in the gluon density corresponds to the Yang-Mills theory becoming completely nonperturbative. This happens when the two terms of the covariant derivative $-iD_\mu = -i\partial_\mu + gA_\mu = p_\mu + gA_\mu$ become of the same order. The (transverse) momentum scale at which this happens is referred to as the saturation scale $p_T \sim gA_\perp \sim Q_s$. When the energy is high enough, $Q_s \gg \Lambda_{QCD}$ and the coupling is still weak. What results is a picture that has a weak coupling g but is still nonperturbative due to the large gluon field strengths $A_\mu \sim 1/g$. Since the occupation numbers of gluonic states $f(k) \sim A_\mu A_\mu \sim 1/\alpha_s$ are large, the gluon field is, to leading order in the coupling, a classical field.

Our understanding of how exactly such a system of strong (but very anisotropic) gluon fields thermalizes (or slightly more modestly isotropizes) has seen significant progress in the recent years (for a review see [2]). Pursuing this question in any depth is out of scope here, but as a rough outline the process must behave in the following way. The initial classical fields, with with occupation numbers $f(k) \sim \frac{1}{\alpha_s} \gg 1$ are very anisotropic due to the longitudinal expansion of the system. As gluons start to scatter off the transverse plane and occupy a larger volume in phase space, the occupation number decreases. When $f(k) \ll \frac{1}{\alpha_s}$ one can switch to a kinetic theory description and follow the system towards local equilibrium. Close to isotropy kinetic theory matches smoothly into a 2$^{\text{nd}}$ order viscous hydrodynamical description. A recent weak coupling calculation using an

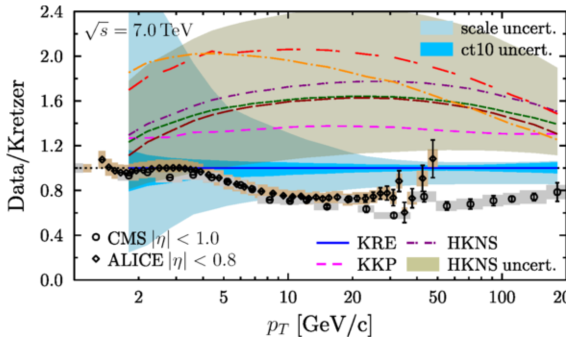

Figure 2: Different fragmentation functions in NLO pQCD compared to CMS data for charged particle spectra in proton-proton collisions, from [9].

effective kinetic theory for QCD [3] arrives, when extrapolating to realistic values of α_s, to times as short as 1 fm/c for a matching to viscous hydrodynamics.

3. Dilute-dense control measurements

The quintessential experiment for measuring the partonic content of a hadron or nucleus is deep inelastic scattering (DIS). A good description of the initial state of a heavy ion collision should be consistent with the precise measurements of quarks and gluons in a proton at HERA and with the available electron-nucleus cross section data. It should also be able to give quantitative predictions for future measurements at an EIC. This is naturally true for calculations whose starting point are nuclear pdfs (e.g. EPS09 [4]). It also applies to more recent Color Glass Condensate (CGC) calculations using e.g. the IPSat or bCGC parametrizations [5, 6] or the running coupling Balitsky-Kovchegov equation (rcBK) [7, 8]. In the classical field CGC picture the initial color fields in a heavy collision are calculated in terms of Wilson lines, whose correlator determines the total DIS cross section.

Another check of QCD descriptions is provided by hadronic dilute-dense, i.e. proton-nucleus, collisions. The most straightforward observables here are ratios of particle spectra in proton-nucleus collisions to those in proton-proton ones, normalized with the number of nucleons, known as R_{pA}. At high p_T these ratios would be expected to approach unity for many particle species. This is particularly important when moving from minimum bias proton-nucleus collisions to separate centrality classes, where hard prticle production serves as an important consistency check of the Glauber modeling [10] needed for the centrality determination. If the normalization of R_{pA} is under control, its small-p_T be-