(Multiple) Hard Parton Interactions in Heavy-Ion Collisions

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Abstract
Multiple hard interactions of partons in the same $p + p(\bar{p})$ collision are a useful concept in the description of these collisions at collider energies. In particular, they play a crucial role for the understanding of the background (the so-called underlying event) in the reconstruction of jets. In nucleus-nucleus collisions multiple hard parton interactions and the corresponding production of mini-jets are expected to contribute significantly to the total particle multiplicity. In this article a brief overview of results on particle production at high-p_{T} in proton-proton and nucleus-nucleus at RHIC will be given. Moreover, the observed centrality dependence of the charged particle multiplicity in Au+Au collisions will be discussed in light of multiple partonic interactions.

1 Introduction

In a $p + p(\bar{p})$ collision the location of a hard parton-parton scattering in which a parton with transverse momentum $p_{\mathrm{T}} \gtrsim 2\,\mathrm{GeV}/c$ is produced is well defined ($\Delta r \sim 1/p_{\mathrm{T}} \lesssim 0.1\,\mathrm{fm}$ in the plane transverse to the beam axis) and much smaller than the radius of proton ($r \approx 0.8\,\mathrm{fm}$). Thus, it is expected that multiple hard parton scatterings can contribute incoherently to the total hard scattering cross section [1, 2]. When going from p+p to nucleus-nucleus (A+A) collisions and neglecting nuclear effects the increase in the number of hard scatterings is given by the nuclear geometry expressed via the nuclear overlap function T_{AB} [3]. For a given range of the impact parameter b of the A+A collisions the yield of produced partons with a transverse momentum p_{T} can thus be calculated from the corresponding cross section in p+p collisions according to

$$\frac{1}{N_{\mathrm{inel}}^{\mathrm{A+A}}} \left.\frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}}\right|_{\mathrm{A+A}} = \frac{\int \mathrm{d}^2 b\, T_{\mathrm{AB}}(b)}{\int \mathrm{d}^2 b \left(1 - \exp\left(-T_{\mathrm{AB}} \cdot \sigma_{\mathrm{inel}}^{\mathrm{NN}}\right)\right)} \cdot \left.\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}}\right|_{\mathrm{p+p}} \tag{1}$$

where $N_{\mathrm{inel}}^{\mathrm{A+A}}$ denotes the total number of inelastic A+A collisions and $\sigma_{\mathrm{inel}}^{\mathrm{NN}}$ the inelastic nucleon-nucleon cross section. This corresponds to a scaling of the yield of produced high-p_{T} partons (and hence also of the yield of hadrons at high p_{T}) with the number of binary nucleon-nucleon collisions (N_{coll}). On the other hand, the yield of particles at low $p_{\mathrm{T}} \lesssim 1\,\mathrm{GeV}/c$ is expected to scale with the number N_{part} of nucleons that suffered at least one inelastic nucleon-nucleon collision. Based on this separation of soft and hard processes the centrality dependence of the charged particle multiplicity in nucleus-nucleus collisions can be predicted.

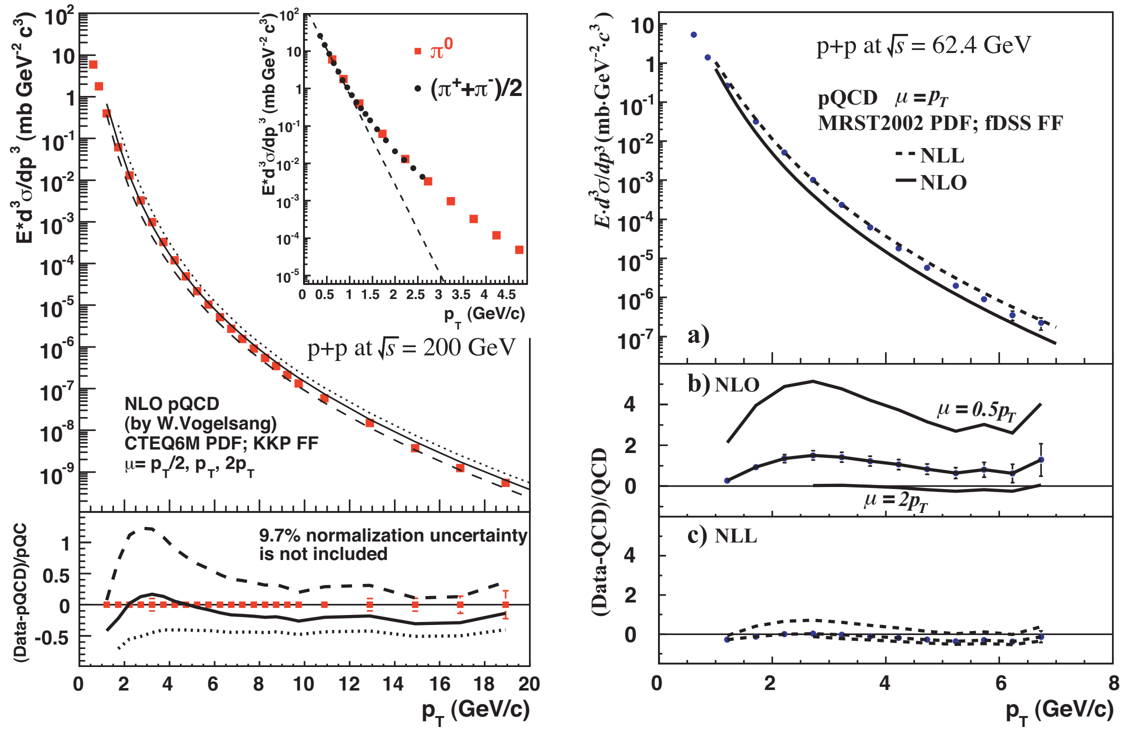

Fig. 1: Invariant cross sections for the reaction $p + p \rightarrow \pi^0 + X$ at $\sqrt{s} = 200\,\mathrm{GeV}$ (left panel) and $\sqrt{s} = 62.4\,\mathrm{GeV}$ (right panel) as measured by the PHENIX experiment at RHIC [10, 11]. The data are compared to next-to-leading-order (NLO) perturbative QCD calculations performed with equal factorization (μ_F), renormalization (μ_R), and fragmentation ($\mu_{\mathrm{F}'}$) scales. The theoretical uncertainties were estimated by choosing $\mu = \mu_\mathrm{F} = \mu_\mathrm{R} = \mu_{\mathrm{F}'} = p_\mathrm{T}, 0.5p_\mathrm{T}, 2p_\mathrm{T}$, respectively.

2 Hard Scattering at RHIC

In this article the focus is on the study of hard scattering in p+p and A+A collisions at RHIC by measuring particle yields at high transverse momentum. Further methods are the statistical analysis of 2-particle angular correlations and full jet reconstruction on an event-by-event basis [4, 5]. The latter method is challenging in heavy-ion collisions since, *e.g.*, in a central Au+Au collision with a transverse energy of $\mathrm{d}E_\mathrm{T}/\mathrm{d}\eta \approx 500\,\mathrm{GeV}$ at midrapidity the background energy from the underlying event in a cone with a radius $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.7$ is $E_\mathrm{T}^\mathrm{background} \approx 120\,\mathrm{GeV}$. For a general overview of result from the four RHIC experiments see [6–9].

Deviations from point-like scaling of hard processes in nucleus-nucleus collisions described by Eq. 1 can be quantified with the nuclear modification factor

$$R_\mathrm{AA} = \frac{1/N_\mathrm{inel}^\mathrm{A+A}\,\mathrm{d}N/\mathrm{d}p_\mathrm{T}|_\mathrm{A+A}}{\langle T_\mathrm{AB}\rangle\cdot\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T}|_\mathrm{p+p}} = \frac{1/N_\mathrm{inel}^\mathrm{A+A}\,\mathrm{d}N/\mathrm{d}p_\mathrm{T}|_\mathrm{A+A}}{\langle N_\mathrm{coll}\rangle\cdot 1/N_\mathrm{inel}^\mathrm{p+p}\,\mathrm{d}N/\mathrm{d}p_\mathrm{T}|_\mathrm{p+p}}\,. \tag{2}$$

Neutral pion p_T spectra in p+p collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ and $62.4\,\mathrm{GeV}$ used in the denominator of Eq. 2 are shown in Fig. 1. Next-to-leading-order perturbative QCD calculations describe

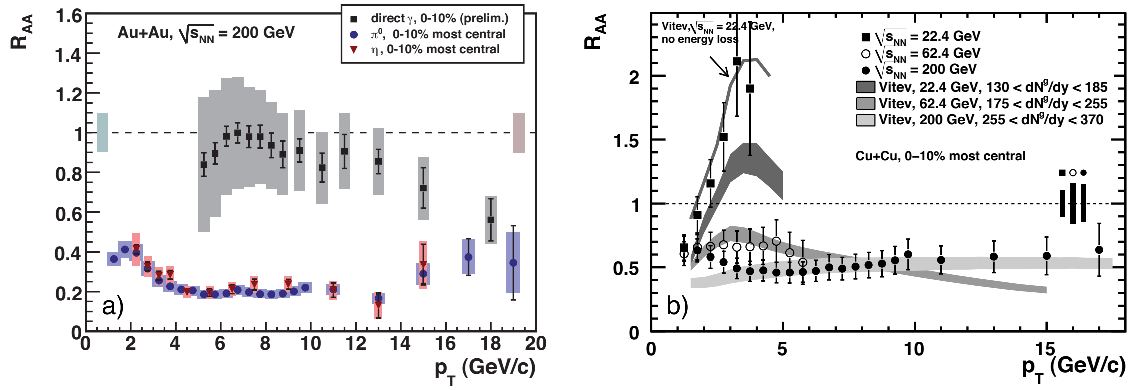

Fig. 2: a) R_{AA} for π^0's, η's, and direct photons in central Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ [14]. b) Energy ($\sqrt{s_{NN}}$) dependence of R_{AA} for π^0's in central Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4, 62.4$ and $200\,\mathrm{GeV}/c$ [12].

the data down to $p_{\mathrm{T}} \approx 1\,\mathrm{GeV}/c$ at both energies.

In Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ a dramatic deviation of π^0 and η yields at high p_{T} from point-like scaling is observed. In the sample of the 10% most central Au+Au collisions the yields are suppressed by a factor of $4-5$ (Fig. 2a). On the other hand, direct photons, measured on a statistical basis by subtracting background photons from hadron decays like $\pi^0 \to \gamma\gamma$ or $\eta \to \gamma\gamma$ from the p_{T} spectrum of all measured photons, are not suppressed for $p_{\mathrm{T}} \lesssim 12\,\mathrm{GeV}/c$. Thus, one can conclude that the hadron suppression is caused by the presence of the created hot and dense medium and is not related to properties of cold nuclear matter.

In order to search for the onset of the high-p_{T} hadron suppression Cu+Cu collisions at three different energies ($\sqrt{s_{NN}} = 22.4, 62.4, \mathrm{and}\,200\,\mathrm{GeV}$) were studied by the PHENIX experiment [12]. In central Cu+Cu collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ neutral pions at high p_{T} are suppressed by a factor ~ 2 (Fig. 2b). A similar suppression is observed at $\sqrt{s_{NN}} = 62.4\,\mathrm{GeV}$. However, at $\sqrt{s_{NN}} = 22.4\,\mathrm{GeV}$ an enhancement ($R_{\mathrm{AA}} > 1$) is found which can be explained by a broadening of the transverse momentum component of the partons in the cold nuclear medium (nuclear-k_{T} or *Cronin* enhancement). The upshot is that in Cu+Cu collisions the suppression of high-p_{T} pions sets in between $\sqrt{s_{NN}} \approx 20-60\,\mathrm{GeV}$. In very central collisions of heavier nuclei (Pb ions) the WA98 experiment at the CERN SPS found a suppression of neutral pions with $p_{\mathrm{T}} > 2\,\mathrm{GeV}/c$ already at $\sqrt{s_{\mathrm{NN}}} = 17.3\,\mathrm{GeV}$ [13].

The most likely explanation for the suppression of hadrons at high p_{T} is energy loss of partons from hard scatterings in the medium of high color-charge density produced nucleus-nucleus collisions (*jet-quenching*) [15, 16]. In this picture the absolute value of the nuclear modification factor contains information about properties of the medium such as the initial gluon density $\mathrm{d}N^{\mathrm{g}}/\mathrm{d}y$. The parton energy loss calculation shown in Fig. 2b reproduces the suppression in central Cu+Cu collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ for $255 < \mathrm{d}N^{\mathrm{g}}/\mathrm{d}y < 370$, whereas the suppression in Au+Au at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ requires a gluon density on the order of $1250 < \mathrm{d}N^{\mathrm{g}}/\mathrm{d}y < 1670$ [17].

Direct photons are not expected to be suppressed in A+A collisions since they interact only electro-magnetically with the medium and thus have a much longer mean free path length. How-

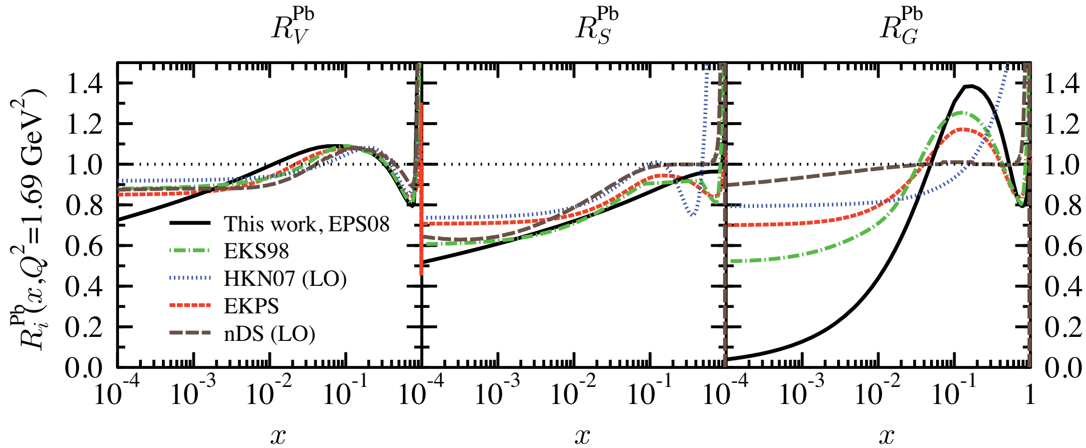

Fig. 3: Different results from leading-order (LO) QCD analyses for the ratio of the parton distribution in the lead nucleus and in the proton for valence quarks (left panel), sea quark (middle panel), and gluons (right panel) [20].

ever, preliminary data from the PHENIX experiment indicate a suppression in central Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ also for direct photons with $p_\mathrm{T} \gtrsim 12\,\mathrm{GeV}$ (Fig. 2a). This suppression can partly be explained by the different quark content of the proton and the neutron (isospin effect) which is not taken into account in the definition of R_AA [18]. A further contribution might come from the suppression of direct photons which are not produced in initial parton scatterings but in the fragmentation of quark and gluon jets (fragmentation photons) [18].

The modification of the parton distribution functions (PDF's) in the nucleus with respect to the proton PDF's are also not taken into account in the nuclear modification factor R_AA. Roughly speaking, features of nuclear PDF's as compared to proton PDF's are a reduced parton density for $x \lesssim 0.1$ (shadowing), an enhancement for $0.1 \lesssim x \lesssim 0.3$ (anti-shadowing) followed again by a suppression for $0.3 \lesssim x \lesssim 0.7$ (EMC-effect) [19]. For $x \to 1$ the parton densities are enhanced due to the Fermi motion of the nucleons inside the nucleus. In Fig. 3 different parameterizations of the ratio $R(x, Q^2) = f_i^\mathrm{A}(x, Q^2)/f_i^\mathrm{p}(x, Q^2)$ of the parton distribution for a lead nucleus and for the proton are shown for valence quarks, sea quarks, and gluons [20]. It is obvious from this comparison that the gluon distribution in the lead nucleus is not well constrained by lepton-nucleus deep inelastic scattering data at low x ($x \lesssim 10^{-2}$). This leads to a large uncertainty of the gluon PDF as determined in a systematic error analysis [21].

The gluon distribution is of special interest for the understanding of direct-photon production since quark-gluon Compton scattering $q + g \to q + \gamma$ significantly contributes to the total direct-photon yield. In Fig. 2a $p_\mathrm{T} \approx 10\,\mathrm{GeV}/c$ where $R_\mathrm{AA}^{\mathrm{direct}\,\gamma} \approx 1$ and $p_\mathrm{T} \approx 20\,\mathrm{GeV}/c$ where $R_\mathrm{AA}^{\mathrm{direct}\,\gamma} \approx 0.6$ roughly correspond to $x \approx 0.1$ and $x \approx 0.2$, respectively, according to $x \approx 2p_\mathrm{T}/\sqrt{s}$. From the ratio R_G^Pb in this x range (Fig. 3) there is no indication that the suppression of direct photons at high p_T in central Au+Au collisions is related to the gluon distribution in heavy nuclei. This is in line with the calculation presented in [18].

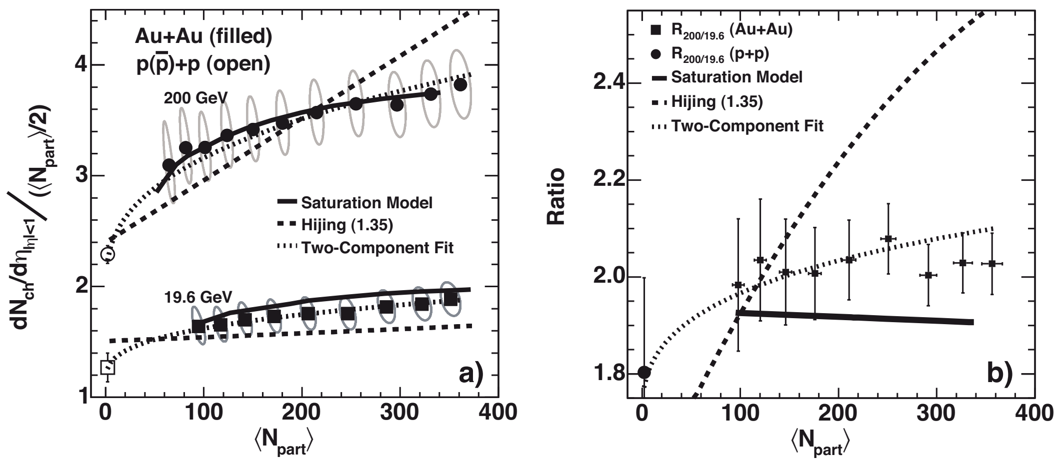

Fig. 4: a) Centrality dependence of the charged particle multiplicity in Au+Au collisions at $\sqrt{s_{\rm NN}} = 19.4\,\mathrm{GeV}$ and $200\,\mathrm{GeV}$ measured by the Phobos experiment [7]. b) Ratio of the two data sets of Figure a) [7].

3 Charged Particle Multiplicity: Hard and Soft Component

Multiple hard partonic interaction in $p + p(\bar{p})$ collisions explain many observed features of these collisions including the rise of the total inelastic $p + p(\bar{p})$ cross section with $\sqrt{s}$, the increase of $\langle p_{\rm T} \rangle$ with the charged particle multiplicity $N_{\rm ch}$, the increase of $\langle p_{\rm T} \rangle$ with $\sqrt{s}$, the increase of $\mathrm{d}N_{\rm ch}/\mathrm{d}\eta$ with $\sqrt{s}$, and the violation of KNO scaling at large $\sqrt{s}$. In such mini-jet models a $p + p(\bar{p})$ collision is classified either as a purely soft collision or a collision with one or more hard parton interactions depending on a cut-off transverse momentum $p_{\rm T,min}$ (see e.g. [22]). The cross section $\sigma_{\rm soft}$ for a soft interaction is considered as a non-calculable parameter. The energy dependence of the charged particle multiplicity in $p + p(\bar{p})$ collisions can then be described by

$$\left.\frac{\mathrm{d}N_{ch}}{\mathrm{d}\eta}\right|_{p+p} = \langle n_{\rm soft} \rangle + \langle n_{\rm hard} \rangle \cdot \frac{\sigma_{\rm jet}(\sqrt{s})}{\sigma_{\rm inel}(\sqrt{s})} \ . \tag{3}$$

This can be extrapolated to nucleus-nucleus collisions by assuming that the soft component scales with the number of participating nucleons $N_{\rm part}$ whereas the mini-jet component scales with the number of nucleon-nucleon collisions $N_{\rm coll}$:

$$\left.\frac{\mathrm{d}N_{ch}}{\mathrm{d}\eta}\right|_{A+A} = \frac{1}{2}\langle N_{\rm part} \rangle \cdot \langle n_{\rm soft} \rangle + \langle N_{\rm coll} \rangle \cdot \langle n_{\rm hard} \rangle \cdot \frac{\sigma_{\rm jet}(\sqrt{s})}{\sigma_{\rm inel}(\sqrt{s})} \ . \tag{4}$$

Here $\langle n_{\rm soft} \rangle$ and $\langle n_{\rm hard} \rangle$ are fixed parameters determined from $p + p(\bar{p})$ collisions.

The centrality dependence of the charged particle multiplicity measured in Au+Au collisions at $\sqrt{s_{\rm NN}} = 19.4\,\mathrm{GeV}$ and $200\,\mathrm{GeV}$ is shown in Fig. 4a. Interestingly, the relative increase of the multiplicity per participant from $\langle N_{\rm part} \rangle \approx 100$ to $\langle N_{\rm part} \rangle \approx 350$ is identical for the two energies. This can be described within the experimental uncertainties with a saturation model [23] (Fig. 4, solid line) and a two-component fit which extrapolates from p+p to A+A as in Eq. 4 but leaves the relative fraction of the soft and the hard component in p+p (Eq. 3) as a free parameter [24] (Fig. 4, dotted line). However, this behavior cannot be reproduced with the two-component mini-jet model implemented in the Monte Carlo event generator Hijing 1.35 (Fig. 4, dashed line). This does not necessarily mean that the two-component picture is not valid in nucleus-nucleus collisions as pointed out in [22]. With the two-component mini-jet model of ref. [22] the experimentally observed centrality dependence can be reproduced if a strong shadowing of the gluon distribution in the gold nucleus is assumed. However, the used gluon distribution deviates from the parameterizations in Fig. 3 and it is stated in [22] that with a gluon distribution that exhibits a strong anti-shadowing as the distributions in Fig. 3 the data cannot be reproduced. Thus, the question whether the two-component mini-jet picture is a useful concept in nucleus-nucleus collisions hinges on the knowledge about the gluon PDF and can only be answered if the uncertainties of the gluon distribution in nuclei can be significantly reduced.

4 Summary

The interest in hard scattering of partons in nucleus-nucleus collisions is twofold: First, QCD predictions for the energy loss of highly-energetic partons in a medium of high color-charge density can be tested experimentally. Second, the observed hadron suppression in conjunction with parton energy loss models renders the possibility to characterize the medium created in ultra-relativistic nucleus-nucleus collisions. The assumption that indeed the created medium causes the suppression was confirmed by the observation that direct photons at high p_{T} which result from hard parton-parton scatterings are not suppressed (at least for $p_{\mathrm{T}} \lesssim 12\,\mathrm{GeV}/c$ in Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$). It remains to be understood how the apparent suppression of direct photons with $p_{\mathrm{T}} \gtrsim 12\,\mathrm{GeV}/c$ fits into this picture. It was argued that it is unlikely that this direct-photon suppression is related to the gluon distribution function in the gold nucleus.

A natural extension of the successful concept of multiple partonic interactions in $p + p(\bar{p})$ collisions to nucleus-nucleus collisions is the two-component mini-jet model for the centrality (N_{part}) dependence of the charged particle multiplicity. As shown in [22] such a model can indeed describe the experimental data, but only if a relatively strong suppression of the gluon distribution in a gold nucleus is assumed. The gluon distribution in this model appears to be only barely consistent with recent parameterizations such as EPS09LO [21] so that it remains to be seen whether the two-component mini-jet model is a useful concept in nucleus-nucleus collisions.

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