Probing quark gluon plasma in pA collisions

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Abstract. We present novel predictions for the suppression of high momentum particles in high multiplicity proton-nucleus (pA) collisions at LHC. Shocking recent data from LHC demonstrates that high multiplicity pA collisions show signatures of the formation of a quark-gluon plasma (QGP), thought previously to only result from nucleus-nucleus collisions. Our work provides a new test of this QGP creation hypothesis.

We generate our predictions by first computing the initial spectrum of high momentum quarks and gluons using leading order (LO) perturbative quantum chromodynamics (pQCD). These LO pQCD predictions use both the usual parton distribution functions (PDFs) and nuclear PDFs, which encapsulate the modifications of the usual PDFs by the presence of multiple nucleons in a nucleus. We find that our results consistently describe the $p\bar{p}$ data at Fermilab, across multiple orders of magnitude in centre of mass energy $\sqrt{s}$, and over many orders of magnitude in transverse momentum. Next we implement state-of-the-art LO pQCD energy loss including radiative and collisional modes through a dynamical QGP medium. Finally, the particles are fragmented into hadrons and compared to the spectrum of high momentum particles in minimum bias pp collisions for future comparison with experimental data.

1. Introduction
Experiments from RHIC[1] and Cern[2] reveal a new state of matter that allow us to probe quantum chromo-dynamics (QCD). This state of matter is the quark-gluon-plasma (QGP). It occurred micro-seconds after the big-bang[3] and arises due to the emergent, many-body physics of QCD[4]. Successfully predicting and understanding QGP will give us an insight into these precesses.

The primary mechanism by which we will investigate QGP is that of parton pair production on near the edge of the QGP medium[5]. When partons are pair-produced, by conservation of momentum, they scatter back-to-back. One parton escapes escapes the QGP quickly and forms a jet largely unmitigated by the presence of a medium. The second parton has to travel through medium, where it undergoes radiative[6] and collisional[7] energy loss via interactions with the medium, eventually forming a jet with much lower energy than the first. These two jets may be compared, where the energy loss between the two may be used to deduce properties of the medium.

There are two prerequisites to performing energy-loss calculations. The first is that any and all non-energy-loss effects need to be under good theoretical control in order to not conflate between disparate effects. In particular, since there is strong evidence of QGP in nucleus nucleus collisions[8], the nuclear effects of interacting partons that arise from nuclei need to be taken
into account. To the end of setting up this good theoretical control, careful analysis of proton
anti-proton and proton nucleus collisions are presented.

The second prerequisite is that energy-loss calculations can only be performed for partons
with known momenta. Therefore it is critical to obtain the spectra for the outgoing partons
in these collisions. These spectra are also known as the partonic contributions to the total
cross-section.

In this work we satisfy these two conditions, laying the groundwork for exploration into
energy-loss, not only in nucleus nucleus collisions, but proton nucleus and proton proton
collisions as well.

2. Leading Order pQCD Calculations

Using formulae derived from perturbative QCD (pQCD), we intend to calculate the inclusive
spectra of charged hadron production from proton anti-proton and proton nucleus collisions.
We also intend to lay the groundwork for energy-loss calculations that can be used to determine
the presence of QGP in collider experiments.

This is done by calculating the differential cross-section of charged hadron production from
these collisions, which has the following structure

\[
\text{cross-section} = \text{PDF} \times \text{partonic cross-section} \times \text{energy-loss} \times \text{fragmentation}
\]

where the terms on the right-hand side each describe a phase in the collision. The PDF (parton
distribution function) describes partons incoming from their respective hadrons. The partonic
cross-section describes the probability of them interacting in a particular way, e.g. the likely-
bhood of two gluons scattering into a quark anti-quark pair. After the parton scattering, the
outgoing partons may then lose energy in the presence of a medium and it is this aspect of
collisions by which we aim to probe the QGP. Finally, the outgoing partons fragment into
hadrons.

It is vital to get the PDF and partonic cross-section correct in isolation, because they feed
directly into the energy-loss and fragmentation. In other words, it would be impossible to discern
effects due to energy-loss in isolation until we have a comprehensive understanding of all the
non-energy-loss effects present in these heavy-ion collisions. To that end, we need to study
collisions where we do not expect energy-loss or the presence of a medium. Proton anti-proton
collisions serve this purpose. We also need to study nuclear effects, the difference in behaviour
of partons that come from nuclei as opposed to single protons. The study of proton nucleus
collisions serve this.

More details of each constituent to the cross-section are given in the next section.

2.1. \( p\bar{p} \) collisions

Using Mathematica, we calculate the inclusive differential cross-section for production of a
charged hadron \( h \) at a rapidity \( y \) from an proton anti-proton (\( p\bar{p} \)) collision. The expression
for this cross-section, derived using pQCD, is given in (1)

\[
\frac{d\sigma^{AB\rightarrow h+X}}{dq_T^2 dy} = K(\sqrt{s}) J(m_T, y) \int \frac{dz}{z^2} \int dy_2 \sum_{<ij><kl>} \frac{1}{1 + \delta_{kl}} \frac{1}{1 + \delta_{ij}} \times
\]

\[
\times \left\{ x_1 f_{i/A}(x_1, Q^2) x_2 f_{j/B}(x_2, Q^2) \left[ \frac{d\hat{\sigma}^{ij\rightarrow kl}}{dt}(\hat{u}, \hat{t}) D_{k\rightarrow h}(z, \mu_F^2) + \frac{d\hat{\sigma}^{ij\rightarrow kl}}{dt}(\hat{u}, \hat{t}) D_{l\rightarrow h}(z, \mu_F^2) \right] \right\}
\]

(1)

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where $y_1$ and $y_2$ are the rapidities of the final-state partons, $k$ and $l$. The momentum fractions of the incoming partons are given by $x_1 = \frac{p_T}{\sqrt{s}} (e^{y_f} + e^{y_2})$ and $x_2 = \frac{p_T}{\sqrt{s}} (e^{-y_f} + e^{-y_2})$. $z$ is a parameter equal to the ratio of the energy of the quark, $f$, to hadron $h$. $\sqrt{s}$ is the root center of mass energy, the energy in the rest frame of the interaction. Present are the differential cross-sections of parton interactions, $d\sigma$ and the Mandelstam variables, $t, \hat{t}$. Also present are the parton distribution functions[10][11], $f$ and fragmentation functions[12][13], $D$. $J$ is the Jacobian of the change between pseudo-rapidity and rapidity, given by

$$J(m_{T},y) = \left(1 - \frac{m^2}{m_{T}^2 \cosh^2 y}\right)^{-1/2}$$

where $m$ is the mass of the outgoing hadron and $m_{T}$ is the transverse mass of the outgoing hadron. The sum over $i, j, k, l$ is a sum over every possible interaction, where $i, j, k, l$ stand for labels of the different partons (quarks, anti-quarks and gluons). The constant, $K$, is the ratio of the experimental cross-section to the leading order cross-section. It was found by Eskola and Honkanen[9] that $K$ was a function only of $\sqrt{s}$ and encapsulates the next-to-leading order contributions.

Intuitively, what is being described by this integral, is that the probability of $h$ being formed at momentum $q_T$, is equal to the sum over every possible interaction that could form $h$ with momentum $q_T$.

2.2. $pA$ collisions
Using Mathematica, we calculate the differential cross-section for the production of charged hadrons for proton-nucleus ($pA$) collisions. We use the same calculation as for $p\bar{p}$ collisions, except one of the parton distribution functions of eq[1] are replaced with the nuclear parton distribution function[14] to indicate that the associated parton forms part of a larger nucleus, rather than a mere proton. These nuclear parton distribution functions encapsulate the nuclear effects that arise from involving nuclei in the collision.

2.3. Modification to extract partonic contributions
We now modify our calculation so that we can calculate the individual contribution to the total cross-section from each parton to serve as an input into future energy-loss calculations. The modification is quite simple. Examining eq[1], we eliminate the fragmentation functions, since these are used to tell us about the formation of hadrons. This leaves us with a calculation concerning the production of partons.

The second modification is that, rather than summing over all the partons, we record the contribution due to each parton separately. Our calculation then looks like

$$\frac{d\sigma^{AB\rightarrow k+X}}{dq_T^2 dy_f} = \int d y_2 \sum_{ijkl} \frac{1}{\frac{1}{1+\delta_{kl}} + \delta_{ij}} \times$$

$$\times x_1 f_i/A(x_1, Q^2) x_2 f_j/B(x_2, Q^2) \left[ \frac{d\hat{\sigma}^{ij\rightarrow kl}}{dt} (i, \hat{t}) \right]$$

where, once again, $i, j, k, l$ represent each of the participating partons where we now save the result for the $k$ outgoing partons individually.

3. Results
3.1. $pp$ cross-section
In order verify that eq[1] is valid, we compute the cross-section at $\sqrt{s} = 630$ GeV and compare to data.
3.2. \( pA \) cross-section

In order to verify our understanding of the nuclear effects in scattering cross-section we calculate the differential cross-section of \( pA \) collision at \( \sqrt{s} = 5.02 \text{ TeV} \) and compare with data from ALICE\[15].

Figure 2. (Top) Plotted is the minimum bias inclusive differential cross-section of charged hadron production. The red line is our calculation, the blue points are data from ALICE. (Bottom) A ratio of our calculation to the data with systematic and statistical uncertainties.

We find that our calculation agrees with the data to within 40 percent. This is a strong agreement for a QCD calculation.
3.3. Partonic contribution
To serve as a critical input into energy loss calculations we find it useful to extract the partonic contributions from the above calculated cross-sections as calculated in eq\[3\]. As an example, we calculate the partonic contribution of a $p\bar{p}$ collision at $\sqrt{s} = 5.02$ TeV.

![Figure 3. Spectra of each parton and their contribution to the total differential cross-section](image)

4. Discussion
The goal of this work was to establish good theoretical control over the non-energy loss processes that occur in collisions. Figure 1 shows that we can accurately predict the result of $p\bar{p}$ collisions. This demonstrates an understanding of the partonic processes, the interaction between partons in these collisions, as well as the fragmentation process into hadrons. Figure 2 shows that we are able to predict the result of $pA$ collisions. Since the only effects we included into our calculation that differ from the $p\bar{p}$ calculation are the nuclear effects and the fact that we have such strong agreement with data, indicate that we have good theoretical control over the nuclear effects.

We have also demonstrated the ability to extract the partonic contribution to the cross-section. We have confidence in this result because, in the absence of energy-loss (such as in $p\bar{p}$ collisions), the partonic contribution serves as a direct input into the fragmentation process, which gives the total differential cross-section of fig 1.

5. Outlook
The techniques of pQCD have shown to be apt when it comes to the prediction of differential cross-sections of charged hadron production. We have confidence that non-energy-loss effects are under good control. The stage is set to perform energy-loss calculation to probe the presence of a QGP. The most obvious avenue to do this is for $AA$ collisions, but recent research suggests that high-multiplicity cuts of $pp$ and $pA$ collisions show characteristics of possessing a medium [10]. This presents the perfect opportunity to apply energy-loss calculations to $pp$ and $pA$ collisions, where the presence of QGP has not been confirmed, but could serve as a new probe into this medium.

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References


