Parton Production Spectra and Energy Loss in High-Energy $O + O$-Collisions

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Abstract. We outline a framework for computing parton production spectra for high-momentum light quarks and gluons in high-energy oxygen–oxygen (O+O) collisions at LHC Run-3 energies. These spectra are a crucial input for modelling parton energy loss in small collision systems, which in turn enables phenomenological investigations into the possible formation of a quark-gluon plasma (QGP) under such conditions. We describe the theoretical ingredients involved and motivate the need for updated spectra at previously uncalculated collision energies. This work lays the groundwork for future quantitative studies of energy loss in O+O collisions and contributes to the broader effort to probe QGP formation in small systems.

1 Introduction

The quest to understand the fundamental constituents of matter has been one of the central goals of modern physics. Quantum field theories have proven remarkably successful in this endeavour, culminating in the development of the Standard Model of Particle Physics [1], which encapsulates our current understanding of elementary particles and their interactions. Within this framework, the strong nuclear force—responsible for binding quarks into hadrons—is described by the theory of quantum chromodynamics (QCD).

Despite its success, the high-energy behaviour of QCD remains incompletely understood. At high energies and densities, such as those achieved in heavy-ion collisions, QCD predicts the formation of exotic states of matter like the quark-gluon plasma (QGP), where quarks and gluons are no longer confined within hadrons. Studying such regimes is crucial for probing the non-linear and collective dynamics of QCD.

Experimental investigations of QCD in these extreme conditions are carried out at large-scale facilities such as the Large Hadron Collider (LHC) at CERN and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. Broadly speaking, these experiments can be categorized into two types, analogous to different ways of examining a watermelon[1]: one can either smash it open to see what it's made of, or slice it carefully to inspect its internal structure. The former corresponds to high-energy hadronic or nuclear collisions—such as those performed at the LHC and RHIC—where the goal is to study the emergent properties of QCD matter under extreme conditions. The latter corresponds to deep-inelastic scattering (DIS), where an electron scatters off a nucleon or nucleus, probing its internal partonic structure.

This work focuses on the first of these approaches, particularly on parton production and energy loss in high-energy heavy-ion collisions. In light of the recent Run-3 data at the LHC, we investigate parton production spectra and energy loss mechanisms in high-energy oxygen–oxygen (O+O) collisions—a novel collision system providing new opportunities to explore QCD dynamics in small systems at high energy.

[1]Analogy adapted from Asmita Mukherjee's seminar available at: https://www.youtube.com/watch?v=r8zRBCigWTw.

2 Quark Gluon Plasma

The quark-gluon plasma (QGP), a deconfined state of quarks and gluons, is believed to be formed in relativistic heavy-ion (A+A) collisions at sufficiently high energy densities [2, 3, 4]. Experimental signatures from RHIC and the LHC have confirmed the existence of the QGP in such systems, where the medium behaves like a nearly perfect fluid with low shear viscosity.

In recent years, attention has turned to the possibility that a QGP may also be formed in smaller collision systems, such as proton–nucleus (p+A) and even proton–proton (p+p) interactions. While the smaller size and shorter lifetime of these systems complicate the interpretation of experimental results, collective behaviour and QGP-like signatures have been observed, motivating further investigation into the dynamics of energy loss in such environments [5, 6, 7].

One of the key tools in probing the QGP is the energy loss experienced by high-momentum partons as they traverse the medium. These energetic quarks and gluons, produced early in the collision, act as microscopic probes—functioning as a type of *femtoscope*—that can reveal properties of the medium through the modification of their spectra. By studying how these partonic probes lose energy via interactions with the QGP, one can gain insights into its density, temperature, and transport coefficients.

This work contributes to that effort by computing the parton production spectra and estimating the energy loss of high-momentum quarks in high-energy oxygen–oxygen (O+O) collisions. Such small collision systems, studied during Run-3 at the LHC, provide a unique environment to explore the onset of QGP formation and to test the limits of energy-loss models typically applied to larger systems.

3 Parton Production Spectra

A key ingredient in modelling energy loss in high-energy collisions is the initial production spectra of partons. These spectra quantify the number of high-momentum partons—primarily light quarks and gluons—produced in the early stages of the collision. Since energy loss calculations require knowledge of the initial parton population, accurate predictions of these spectra are crucial.

The production spectra can be obtained from the inclusive cross-section for the process $AB \to f + X$, where A and B are the incoming hadrons or nuclei (in our case, oxygen nuclei), and f denotes a final-state parton of a specific flavour. For a parton of flavour f, the differential cross-section with respect to transverse momentum p_T and rapidity y_f is given by [8, 9]:

$$\begin{aligned}\frac{d\sigma^{AB\to f+X}}{dp_T^2 dy_f} &= \int dy_2 \sum_{\langle ij\rangle\langle kl\rangle} \frac{1}{1+\delta_{kl}}\frac{1}{1+\delta_{ij}} \Bigg\{ x_1 f_{i/A}(x_1,Q^2)\, x_2 f_{j/B}(x_2,Q^2) \\ &\times \left[\frac{d\hat{\sigma}}{d\hat{t}}^{ij\to kl}(\hat{s},\hat{t},\hat{u})\delta_{fk} + \frac{d\hat{\sigma}}{d\hat{t}}^{ij\to kl}(\hat{s},\hat{u},\hat{t})\delta_{fl} \right] \\ &+ x_1 f_{j/A}(x_1,Q^2)\, x_2 f_{i/B}(x_2,Q^2) \left[\frac{d\hat{\sigma}}{d\hat{t}}^{ij\to kl}(\hat{s},\hat{u},\hat{t})\delta_{fk} + \frac{d\hat{\sigma}}{d\hat{t}}^{ij\to kl}(\hat{s},\hat{t},\hat{u})\delta_{fl} \right] \Bigg\} \end{aligned} \tag{1}$$

The sum runs over parton channels $\langle ij\rangle, \langle kl\rangle \in \{gg, gq, g\bar{q}, qq, q\bar{q}, \bar{q}\bar{q}\}$, where $q \in \{u, d, s, \dots\}$. The parton distribution functions (PDFs) $f_{i/A}(x, Q^2)$ describe the probability of finding parton i inside hadron A carrying momentum fraction x at scale Q. The variables x_1 and x_2 are given by [9]:

$$x_1 = \frac{p_T}{\sqrt{s}}\left(e^{y_f} + e^{y_2}\right), \quad x_2 = \frac{p_T}{\sqrt{s}}\left(e^{-y_f} + e^{-y_2}\right), \tag{2}$$

and the rapidity integration range is constrained by:

$$-\log\left(\frac{\sqrt{s}}{p_T} - e^{-y_f}\right) \le y_2 \le \log\left(\frac{\sqrt{s}}{p_T} - e^{y_f}\right). \tag{3}$$

The partonic differential cross-sections $d\hat{\sigma}/d\hat{t}^{ij\to kl}$ are computed from perturbative QCD and depend on the Mandelstam variables $\hat{s}, \hat{t}, \hat{u}$. These matrix elements scale as $\alpha_s^2(\mu^2)$, where α_s is the strong coupling evaluated at the renormalisation scale μ, which is typically set to $\mu \sim Q \sim p_T$ [8].

While reference plots of production spectra for various collision systems and energies exist in the literature—such as those provided by Eskola and Honkanen [8]—these are often limited to earlier LHC energies and heavier systems like Pb+Pb. We aim to extend such computations to include oxygen–oxygen (O+O) collisions at LHC Run-3 energies, which remain relatively unexplored, in further studies. These small systems offer a unique opportunity to probe QCD phenomena such as the possible formation of a QGP in minimal-volume environments.

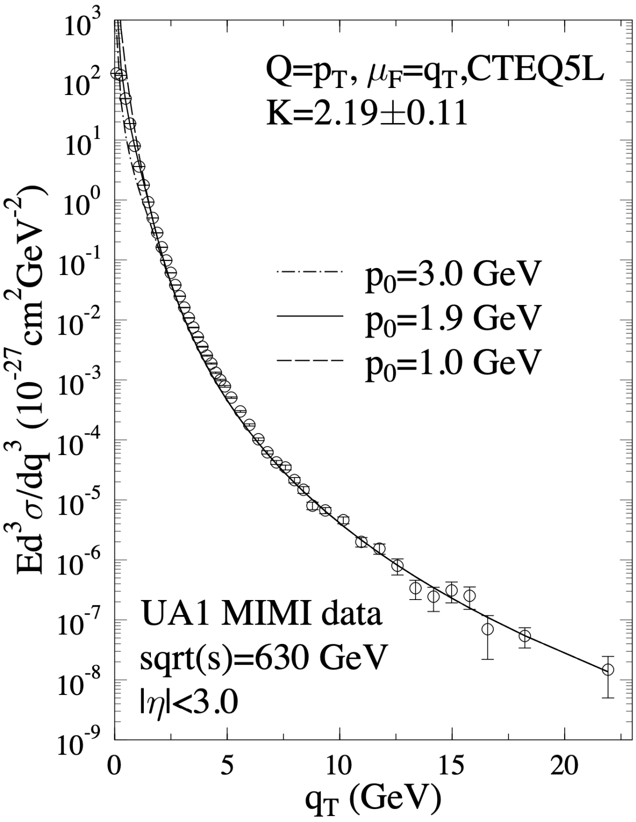

Figure 1: Example of a parton production spectrum. Adapted from [8].

4 Conclusion and Outlook

In this work, we outlined a framework for computing parton production spectra in high-energy oxygen–oxygen (O+O) collisions at the LHC. These spectra are a necessary input for studying parton energy loss in small systems, and ultimately, for investigating the formation and characteristics of the quark-gluon plasma (QGP) under such conditions.

To validate our methodology and numerical implementation, we first aim to reproduce established theoretical results in well-studied collision systems. This serves both as a consistency check and a foundation for reliable extrapolation to previously uncalculated regimes.

Our next step is to compare the computed production spectra with recent experimental data from the O+O Run-3 at the LHC, which concluded just a few weeks ago at the time of this writing. These comparisons will not only test the accuracy of our approach but also enable us to refine theoretical models of parton dynamics in small systems.

Ultimately, the calculated spectra will serve as input to quantify the energy loss of high-momentum light quarks traversing the QGP created in O+O collisions. This will allow us to make the first quantitative predictions for parton energy loss in this specific system, potentially offering new insights into the properties of QCD matter in the small-system regime. Through such studies, we hope to better characterize the transport properties and collective behaviour of the QGP, and to contribute toward understanding its emergence in systems beyond traditional heavy-ion collisions.

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References

[1] David Griffiths. *Introduction to elementary particles*. 2008.

[2] John Adams et al. Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions. *Nucl. Phys. A*, 757:102–183, 2005.

[3] K Aamodt et al. Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV. *Phys. Rev. Lett.*, 105:252302, 2010.

[4] Miklos Gyulassy and Larry McLerran. New forms of QCD matter discovered at RHIC. *Nucl. Phys. A*, 750:30–63, 2005.

[5] Vardan Khachatryan et al. Evidence for collectivity in pp collisions at the LHC. *Phys. Lett. B*, 765:193–220, 2017.

[6] James L. Nagle and William A. Zajc. Small System Collectivity in Relativistic Hadronic and Nuclear Collisions. *Ann. Rev. Nucl. Part. Sci.*, 68:211–235, 2018.

[7] Rajendra Nath Patra. Collective phenomena study in small systems using the bulk of particle production in high-multiplicity pp collisions at $\sqrt{s}$ =13 TeV with ALICE. *PoS*, EPS-HEP2023:214, 2024.

[8] K. J. Eskola and H. Honkanen. A Perturbative QCD analysis of charged particle distributions in hadronic and nuclear collisions. *Nucl. Phys. A*, 713:167–187, 2003.

[9] Alexander Huss, Aleksi Kurkela, Aleksas Mazeliauskas, Risto Paatelainen, Wilke van der Schee, and Urs Achim Wiedemann. Predicting parton energy loss in small collision systems. *Phys. Rev. C*, 103(5):054903, 2021.