Energy Loss as a Probe of Quark-Gluon Plasma Formation Across Collision System Size

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Abstract. The quark-gluon plasma (QGP) forms when protons and neutrons melt at temperatures over 100,000 times hotter than the Sun's core—conditions achieved in high-energy heavy-ion collisions, such as those involving lead or gold nuclei at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC). More recent observations suggest that small droplets of QGP may also form in rare, high-multiplicity proton-proton and proton-lead collisions. One way to probe the QGP is by measuring the suppression of high-momentum particles, which lose energy to the medium as they traverse it. If QGP forms in these small systems, non-negligible suppression is expected; however, no conclusive evidence of energy loss in such systems has been measured. Oxygen-oxygen collisions conducted at the LHC in July 2025 offer a new opportunity to test QGP formation in smaller systems. In this work, we use a statistically driven analysis of R_{AA} data from large collision systems to constrain an energy loss model that incorporates small-system-size corrections. We then make novel predictions for small systems including $p/d + A$ and $\mathrm{O} + \mathrm{O}$ collisions. Our results show that high-momentum particle suppression in central $p/d + A$ collisions agrees with central photon-normalized $d + \mathrm{Au}$ data from RHIC but deviates significantly from central Glauber-normalized LHC $p + \mathrm{Pb}$ results. We argue that this discrepancy likely arises from event selection biases. Upcoming minimum bias $\mathrm{O} + \mathrm{O}$ measurements will provide key insights into the system size dependence of energy loss and QGP formation in an environment free from selection biases.

1 Introduction

The quark-gluon plasma (QGP) is a state of deconfined quarks and gluons formed at extreme temperatures in the ultra-relativistic collision of heavy ions [1]. While there is overwhelming evidence for QGP formation in large systems like $\mathrm{Au} + \mathrm{Au}$ and $\mathrm{Pb} + \mathrm{Pb}$ collisions, a key question in the field is whether QGP can form in smaller systems such as $p/d/^{3}\mathrm{He} + \mathrm{Au}$. Surprisingly, signatures of collective behaviour, such as multi-particle correlations, appear to turn on smoothly as a function of particle multiplicity, irrespective of system size, suggesting the formation of tiny QGP droplets even in high-multiplicity $p + \mathrm{Pb}$ and $p + p$ collisions [2]. However, another key QGP signature, the suppression of high-transverse-momentum (p_{T}) particles due to partonic energy loss [3], presents a puzzle. While this suppression is unambiguously observed in central A+A collisions [4, 5], measurements in small systems are contradictory: RHIC has observed suppression in central d+Au collisions [6], whereas LHC measurements in $p + \mathrm{Pb}$ collisions show an enhancement [7, 8]. This tension motivates a quantitative theoretical investigation.

This work aims to better understand the theoretical expectation for energy loss in small systems based on matching experimental data in large systems. We employ a perturbative quantum chromodynamics (pQCD) based energy loss model that includes both collisional [9, 10] and radiative [11] energy loss channels, and importantly,

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incorporates small-system-size corrections to both the collisional [10, 12] and radiative energy loss [13, 14]. To make robust predictions, we first constrain our model's single free parameter, the effective strong coupling $\alpha_s^{\text{eff.}}$, through a rigorous χ^2 statistical analysis against a wide array of high-p_{T} hadron suppression data from central heavy-ion collisions at RHIC and the LHC. This procedure allows us to establish a well-calibrated baseline from which to make zero-parameter extrapolations to smaller systems.

Our extrapolations to small systems show good agreement with the photon-normalized $R_{d\text{Au}}$ data from PHENIX [6], which minimizes sensitivity to event selection biases. In contrast, our predictions disagree with Glauber-model-normalized $R_{p\text{Pb}}$ data from the LHC [7, 8], which are known to be more sensitive to such biases [8]. We argue that this discrepancy likely reflects experimental biases rather than a failure of the energy loss paradigm. A promising way to clarify this issue is to study oxygen-oxygen collisions, where the no-energy-loss baseline is under better theoretical control and the system is large enough to expect suppression even in minimum bias events [15]. In July 2025, O + O collisions at $\sqrt{s_{NN}} = 5.36$ TeV were conducted at the LHC; however, experiments have not yet reported data. In this work, we present novel predictions for minimum bias O + O collisions using our model constrained entirely by large-system data.

2 Theoretical Framework

Our theoretical framework is described in detail in our previous works [12, 14, 16] and is based on the Wicks-Horowitz-Djordjevic-Gyulassy (WHDG) model [17]. The model computes energy loss via two primary mechanisms: gluon radiation (radiative energy loss) and elastic scattering (collisional energy loss). To make realistic predictions, we utilize fluctuating, initial conditions provided by IP-Glasma [18] to determine the distribution of event-by-event path lengths and temperatures. Realistic parton production and fragmentation is also included in the model, and energy loss is calculated on a path-by-path basis.

The radiative energy loss is calculated using the DGLV opacity expansion formalism [11] to first order in opacity. A key feature of our model is the inclusion of a short path length correction (SPLC), which allows for the more rigorous extrapolation of the large-system results to small systems, where the standard assumption of a large, static medium breaks down [13]. We previously showed [14] that the naive inclusion of the SPLC violates the large formation time (LFT) approximation [13] that is made in the DGLV formalism. To remedy this, we introduced a novel kinematic cutoff on the radiated gluon's transverse momentum, which enforces the self-consistency of the calculation across all system sizes [16]. The exact value of this cutoff, along with the transition between hard thermal loop (HTL) and vacuum propagators in the collisional energy loss calculation [9, 10], constitutes the main theoretical uncertainties in our model. We quantify these uncertainties by performing our analysis with the cutoff varied up and down by factors of two, and for two different collisional energy loss models: Braaten and Thoma (BT) [9] and HTL-only [10].

The central observable of interest in this work is the *leading hadron nuclear modification factor* defined as

$$R^h_{AB}(p_T) \equiv \frac{\mathrm{d}N^{AB\to h+X}/\mathrm{d}p_T}{\langle N_{\text{coll}}\rangle \mathrm{d}N^{pp\to h+X}/\mathrm{d}p_T}, \tag{1}$$

for the collision $A + B$ and final state hadron h, where $dN^{AB(pp)\to h+X}$ is the differential number of measured hadrons h in the collision $A+B$ ($p+p$) and N_{coll} is the number of binary nucleon-nucleon collisions. The quantity R_{AB} is normalized such that suppression of the final state in $A+B$ collision leads to $R_{AB} < 1$ and no modification of the final state spectrum leads to $R_{AB} = 1$.

3 Statistical Analysis

To make zero-parameter predictions for small systems, we first constrain our model's sole free parameter: the effective strong coupling $\alpha_s^{\text{eff.}}$. The χ^2 is defined as:

$$\chi^2(\alpha_{\text{s}}^{\text{eff}}) = \sum_{i,j} [y_i - \mu_i(\alpha_{\text{s}}^{\text{eff}})](C^{-1})_{ij}[y_j - \mu_j(\alpha_{\text{s}}^{\text{eff}})], \tag{2}$$

where $\vec{y}$ is the vector of experimental data points, $\vec{\mu}(\alpha_{\text{s}}^{\text{eff}})$ is the vector of corresponding theory predictions, and C is the covariance matrix that accounts for statistical, systematic, and normalization uncertainties and their correlations. As a function of p_T, statistical uncertainties are uncorrelated, normalization uncertainties are fully correlated, and systematic uncertainties are modelled as "length-correlated", which allows points closer together in p_T to be correlated while points further apart are uncorrelated [19]. To extract $\alpha_s^{\text{eff.}}$, we minimize the χ^2 against all available R_{AB} data for charged hadrons, π^0 mesons, D mesons, and B mesons at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 200$ GeV with 8 GeV $\leq p_T \leq 50$ GeV and a centrality of 0–50%. These requirements resulted in 197 data points from LHC and 98 data points from RHIC being included in our analysis.

4 Results and Discussion

Figure 1 shows a representative sample of the experimental data (markers) that was used in our extraction of $\alpha_s^{\text{eff.}}$ and the equivalent post-extraction model result (red bands). The global fit to central and semi-central heavy-ion data yields a good description of all available measurements, with best-fit values of $\alpha_{\text{s}}^{\text{eff}} = 0.41^{+0.14}_{-0.10}$ at RHIC and $\alpha_{\text{s}}^{\text{eff}} = 0.37^{+0.11}_{-0.08}$ at the LHC. The uncertainties are dominated by the theoretical model variations and **not** statistical uncertainties associated with the extraction. The ability for our model to reproduce experimental data across a wide range of centralities and flavours gives us confidence to extrapolate our results to small systems.

With the model constrained, we make predictions for small systems with no additional tuning. Figure 2 compares our predictions to central $d+\text{Au}$ data at RHIC and central $p+\text{Pb}$ data at the LHC. The $d+\text{Au}$ data measured by PHENIX uses direct-photons to provide a model-independent normalization for the R_{AB} while the $p+\text{Pb}$ data are measured by ALICE and ATLAS and uses the Glauber model to calculate the normalization. We observe that a non-negligible suppression of $R_{AB} \sim 0.75$ is measured in $d+\text{Au}$ collisions, in good agreement with our model predictions. In contrast, the LHC data shows enhancement of $R_{AB} \simeq 0.9$–1.2 in stark disagreement with our model predictions.

We argue that the striking discrepancy at the LHC is not a failure of the energy loss paradigm but is instead due to significant event selection biases (*centrality bias*) in the experimental analyses [8]. Centrality bias refers to a non-trivial correlation between the production of high-p_T particles and the total multiplicity, which is used to determine the centrality. There is evidence [8] that such biases, and additionally model dependencies related to the assumptions made in various Glauber-style models [26], may significantly affect the normalization of the centrality-cut R_{AB}.

An interesting proposal is to avoid centrality bias by considering only minimum bias collisions [15]. In particular, $\text{O}+\text{O}$ is an ideal system: small enough to probe the onset of QGP, yet large enough to expect measurable suppression even without centrality selection [15]. In anticipation of the experimental measurements of R_{AB} from

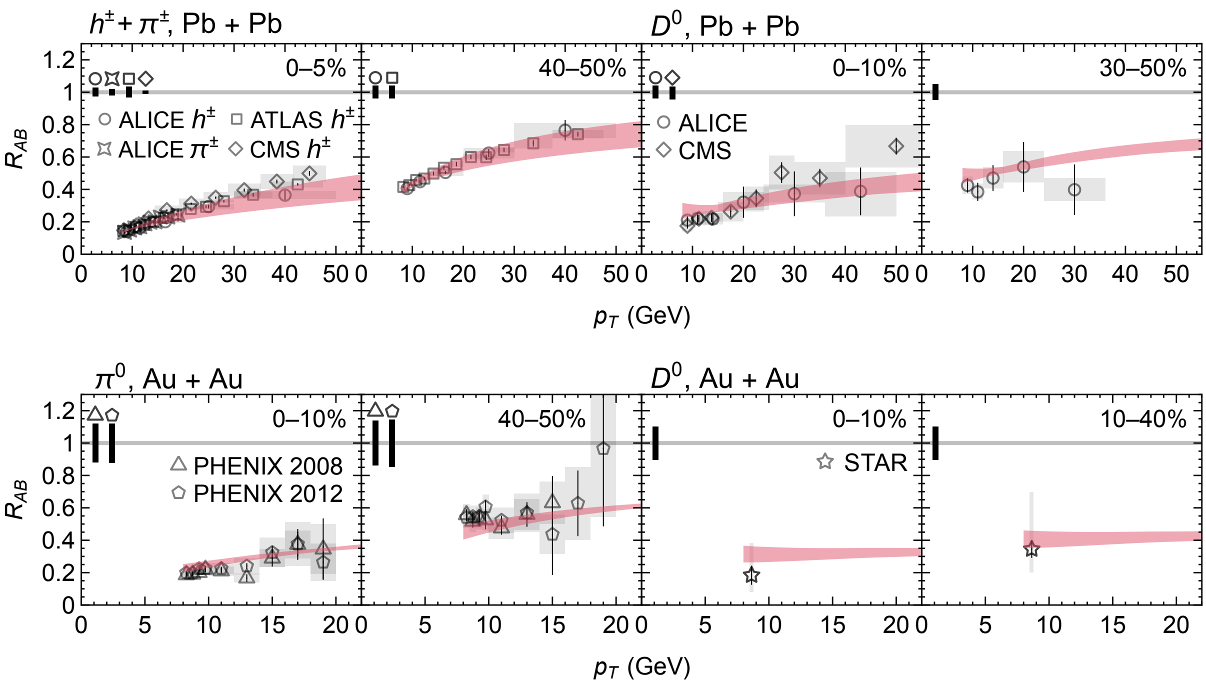

Figure 1: R_{AB} as a function of p_T for a representative sample of the experimental data that is used in our global extraction of $\alpha_s^{\text{eff.}}$. Experimental data is shown with open markers and our constrained model results are shown as a red band. Panels from left-to-right and top-to-bottom results show $h^{\pm}$ and $\pi^{\pm}$ mesons produced in 0–5% and 40–50% centrality $\sqrt{s_{NN}} = 5.02$ TeV $\text{Pb}+\text{Pb}$ collisions [5, 7, 20, 21], D^0 mesons produced in 0–10% and 30–50% centrality $\sqrt{s_{NN}} = 5.02$ TeV $\text{Pb}+\text{Pb}$ collisions [22, 23], π^0 mesons produced in 0–10% and 40–50% centrality $\sqrt{s_{NN}} = 0.2$ TeV Au+Au collisions [4, 24], and D^0 mesons produced in 0–10% and 10–40% centrality $\sqrt{s_{NN}} = 0.2$ TeV $\text{Au}+\text{Au}$ collisions [25]. Statistical experimental uncertainties are represented by error bars, systematic uncertainties by shaded boxes, and global normalization uncertainties by bars at unity. The width of the model bands corresponds to the theoretical model uncertainty.

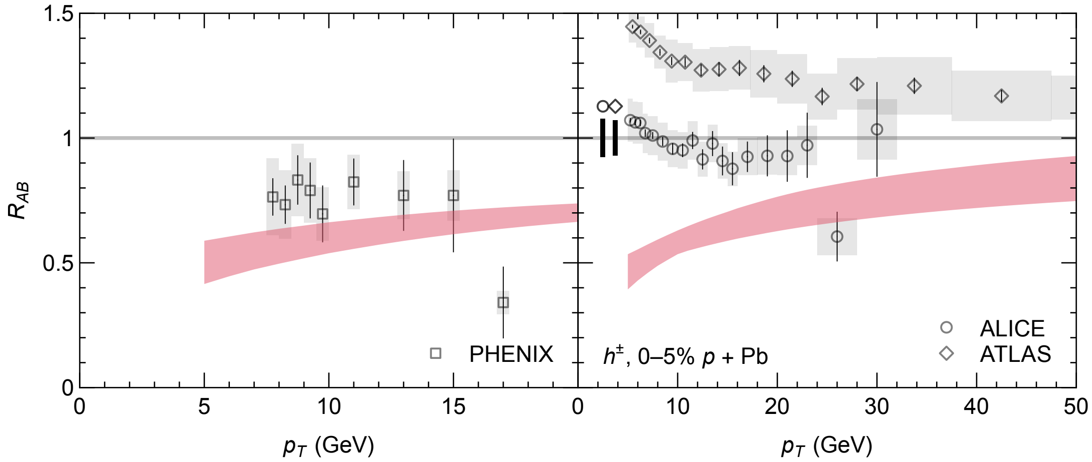

Figure 2: Predicted and measured R_{AA} for central small systems. Left: π^0 suppression in 0–5% $\sqrt{s_{NN}} =$ 200 GeV $d+\mathrm{Au}$ collisions at RHIC, with photon-normalized data from PHENIX [6]. Right: $h^{\pm}$ suppression in 0–5% $\sqrt{s_{NN}} = 5.02$ TeV $p + \mathrm{Pb}$ collisions at the LHC. Band width indicates the theoretical uncertainty.

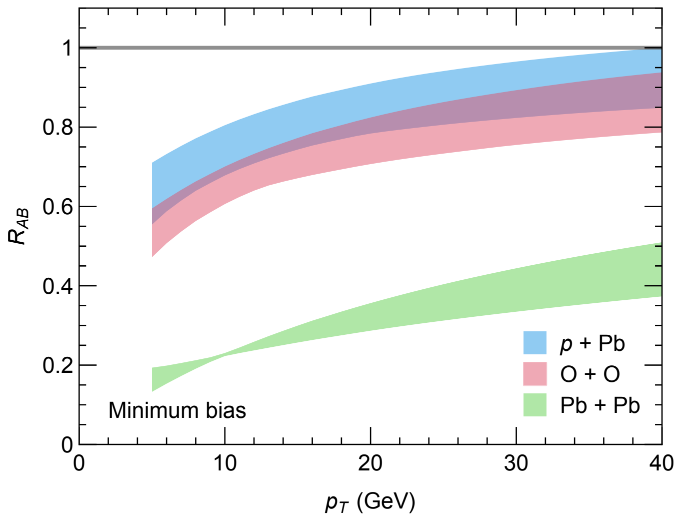

Figure 3: Model predictions for π^0 production in minimum bias $\sqrt{s_{NN}} = 5.02$ TeV $p + \mathrm{Pb}$ (blue), $\sqrt{s_{NN}} =$ 5.36 TeV $\mathrm{O}+\mathrm{O}$ (red), and $\sqrt{s_{NN}} = 5.02$ TeV $\mathrm{Pb}+\mathrm{Pb}$ (green) collisions, ordered least to most suppressed. The band width indicates the theoretical uncertainty.

the short run of oxygen-oxygen collisions at $\sqrt{s_{NN}} = 5.36$ TeV that was conducted at the LHC in July of 2025, we now present novel predictions from our model for $\mathrm{O}+\mathrm{O}$ collisions. Figure 3 plots the minimum bias (0–100% centrality) predictions from our model for $p+\mathrm{Pb}$ collisions (blue), $\mathrm{O}+\mathrm{O}$ collisions (red), and $\mathrm{Pb}+\mathrm{Pb}$ collisions (green). We observe that for the p_T range of 5–30 GeV there is R_{AB} of 0.6–0.8 predicted by our model for $\mathrm{O}+\mathrm{O}$ collisions. This fairly significant suppression suggests that the upcoming $\mathrm{O}+\mathrm{O}$ data may reveal measurable QGP-induced energy loss, offering a clean test that could help reconcile the tension between low- and high-p_T observables in small systems.

5 Conclusions and outlook

We have performed a comprehensive statistical analysis of high-p_{T} hadron suppression using a pQCD-based energy loss model that includes small-system-size corrections. Our energy loss model include event-by-event fluctuations in the initial state, distributions of path lengths, realistic hadronization and production spectra, and a quantitative estimate of various important theoretical uncertainties. By constraining the model's single parameter,

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$\alpha_s^{\text{eff.}}$, on a wide array of data from heavy-ion collisions, we generated zero-parameter predictions for small systems. After constraining our model, we found good agreement with R_{AB} measured in $\mathrm{Pb} + \mathrm{Pb}$ and $\mathrm{Au} + \mathrm{Au}$ collisions across a wide range of final state hadrons, centralities, and p_T.

We then applied our large-system-constrained model to small collision systems. Our predictions agree well with the central d+Au R_{AB} measured data by PHENIX [6], which does not rely on the Glauber model to normalize the R_{AB}. However, we find strong tension with p+Pb results from the LHC, which show slight enhancement rather than suppression. We argue that this discrepancy is likely due to event selection biases and model dependencies, which are known to be important in small systems [8, 26]. The consistency between our model and the RHIC data, combined with the expected theoretical biases in LHC measurements, supports the interpretation that QGP-induced energy loss in high-multiplicity small systems remains a strong possibility. Interestingly, simple energy loss models also predict similar suppression in peripheral large systems and central small systems [27], suggesting that in order to accurately describe peripheral large system data one *requires* non-negligible suppression in small systems.

To further clarify the system size dependence of partonic energy loss, we presented new model predictions for O+O collisions at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV. We predict a clear suppression signal in minimum bias events, with $R_{\mathrm{AA}} \sim$ 0.6–0.8 for $5 \leq p_T \leq 30$ GeV. Since centrality selection is not expected to be necessary in O + O to observe suppression [15], forthcoming measurements will hopefully provide a cleaner and less ambiguous test of energy loss and QGP formation in small systems. Such data will be crucial for understanding how QGP formation and energy loss depends on system size. Looking forward, progress in understanding energy loss in small systems will require theoretical control over correlations between jet production and soft multiplicity, improved computation of early-time energy loss [28, 29], and the derivation of small system size corrections to the equation of state [30, 31] and subsequent hydrodynamic evolution.

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