

Three Predictions for Partonic Energy Loss from Light to Heavy Ion Collisions

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In July 2025 the Large Hadron Collider collided $^{16}\text{O}^{16}\text{O}$ and $^{20}\text{Ne}^{20}\text{Ne}$ isotopes in a quest to understand the physics of ultrarelativistic light ion collisions. One of the key motivations for this run was to discover partonic energy loss in systems with a small quark-gluon plasma. In this Letter we combine a Baier-Dokshitzer-Mueller-Peigné-Schiff and Zakharov based model, a weighted path based energy loss prescription, and JEWEL together with two realistic geometries of the ^{16}O and ^{20}Ne isotopes. The different sizes of the ions affect the energy loss in characteristically different ways depending on the model.

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Introduction—Ultrarelativistic light-ion collisions at the Large Hadron Collider (LHC) are bringing the collider into a new experimental phase that will enhance the discovery potential of the heavy-ion program [1,2] and broaden the impact of particle and collider physics as a whole. In this context there has been an effort recently from the nuclear structure community to understand the shapes of the isotopes ^{16}O and ^{20}Ne precisely, which is both interesting and necessary to understand the upcoming collisions [3–6]. The collisions will have an impact on cosmic-ray physics [7] [Sec. 11.3] as well as synergy with the same collisions performed at Relativistic Heavy Ion Collider at a lower collision energy [8,9].

The light-ion run will enhance our understanding of relativistic hydrodynamics at its limits (as demonstrated by the first low- p_T results from $^{16}\text{O}^{16}\text{O}$ runs at the Relativistic Heavy Ion Collider and LHC that appeared after the first release of this Letter [10–13]), as well as jet-medium interactions in small droplets of quark-gluon plasma (QGP) [14]. A particular hope for the light-ion run at the LHC is that it will shed light on what is the smallest droplet of deconfined quark matter. That question lingers since in (high multiplicity) proton-proton and proton-lead collisions several telltale signs such as collectivity, strangeness

enhancement, and J/ψ melting have been seen [15–19] and studied [20–22], but it has not been possible to observe in-medium parton energy loss [23]. Crucially, nonzero energy loss is expected in such small systems from a variety of theoretical approaches that successfully describe energy loss in large systems [24].

Part of the difficulty with observing the modification of hard partons due to the presence of the medium, often called jet quenching, is that any quenching must necessarily be small, since the quenching is expected to depend on the distance traveled by a hard parton through the medium. The measurement of such a small signal is hampered by the need to select events with large event activity, which correlates with the production of such partons and hence results in large systematic uncertainties [25–27].

Excitingly, many of these experimental difficulties can be avoided entirely in minimum-bias light-ion collisions. A further theoretical and experimental reduction of the uncertainties is possible when taking ratios of observables in different but similar colliding systems, such as will now be possible with $^{16}\text{O}^{16}\text{O}$ and $^{20}\text{Ne}^{20}\text{Ne}$ [3,10–12]. Freed from the experimental burden of attempting to select relevant events in which a medium with small initial spatial extent is created, the theoretical modeling of jet quenching in small systems is more easily aligned with experimental measurements.

The charged hadron nuclear modification factor has long been the gold-standard observable for jet quenching, enjoying success in a variety of large collision systems, and highlighting precisely the absence of such in small systems [28–31]. In this Letter we present three models that compute the charged hadron nuclear modification factor for

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^{16}O and ^{20}Ne collisions at the LHC. The first is the simple model based on the Baier-Dokshitzer-Mueller-Peigné-Schiff and Zakharov (BDMPS-Z) model in the multiple soft limit with the harmonic oscillator approximation. Second, we use a phenomenological model extrapolating experimental results for PbPb (central) collisions to other heavy and light ion collisions. Finally, we use the interface of the Trajectum hydrodynamic medium with the Monte Carlo jet evolution code JEWEL.

We show all three of these predictions using nuclear structure input as computed from the framework of nuclear lattice effective field theory (NLEFT, [32–34]) simulations as well as the *ab initio* projected generator coordinate method (PGCM, [35–40]) for ^{16}O and ^{20}Ne . For ^{208}Pb we take neutron skin parameters from [1] (with neutron skin thickness $a_n = 0.66$) and for ^{129}Xe the standard elliptic deformation of $\beta_2 = 0.202$ (without any triaxiality for this study). The path-length and JEWEL implementations additionally make use of the hydrodynamic framework Trajectum [41,42]. Trajectum is a state-of-the-art heavy-ion simulation framework that combines models of the initial conditions, preequilibrium evolution, viscous hydrodynamics, and hadronic transport. Its parameters are constrained through Bayesian analyses of a wide set of experimental observables in lead-lead collisions, ensuring a quantitatively reliable description of the medium produced in heavy-ion collisions. See also Ref. [43] for a table summarizing the systematic effects taken into account.

We will first detail the three models and then end with a discussion of the results. A preprint of this Letter appeared before light-ion measurements were done and hence are true predictions. At the final submission the data is now available [45] and we will make a brief comment in the discussion.

The simple model—Despite its name, the simple model is not all that simple. In practice it uses the so-called simple formula due to Peter Arnold [46], which solves the full BDMPS-Z [47,48] emission equations in the harmonic oscillator approximation for a dynamic medium. It moreover includes realistic quark and gluon spectra, realistic fragmentation functions and, in this work, EPPS16 nuclear parton distribution functions (PDFs) [49]. The geometry is relatively simple and boost invariant, but matches Trento [50] calculations in anisotropy and in size both for the plasma as well as for the locations of the binary collisions.

Crucially, the model contains only one free parameter ($\hat{q}$) that is fitted to minimum bias charged hadron R_{AA} at 54 GeV in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (black data point in top panel of Fig. 1). Both the transverse momentum (p_T) and the centrality dependence are then a prediction of the model.

One major omission in [51] is the absence of ^{20}Ne as a light ion system. Therefore we took this opportunity to redo the calculation, but now for updated Trento profiles for both

^{16}O and ^{20}Ne , both from PGCM and NLEFT. The results of this exercise can be seen in Fig. 1.

Perhaps unsurprisingly the difference between both ^{16}O and ^{20}Ne , as well as the two structure calculations, is within the uncertainty (which, as in [51], is taken to be only the uncertainty propagated to $\hat{q}$ from the CMS data point). Nevertheless, in the ratio this uncertainty cancels almost completely, and we see both a higher energy loss in ^{20}Ne as well as a clear difference between PGCM and NLEFT. We will come back to this difference in the discussion section below.

A temperature-weighted path approach—In this section, we estimate the nuclear modification factor (R_{AA}) by assuming a power-law spectrum ($\sigma_{pp} \propto p_T^{-6}$) and a p_T -dependent energy loss [$\delta e(p_T)$] that depends on the temperature-weighted integral $\mathcal{I}$ according to [2]

$$R_{AA} = \sigma_{pp}[p_T + \delta e(p_T)] / \sigma_{pp}(p_T),$$

$$\delta e(p_T) = \kappa(p_T)\mathcal{I}, \quad \mathcal{I} \equiv \int T^3 u_\mu dL^\mu, \quad (1)$$

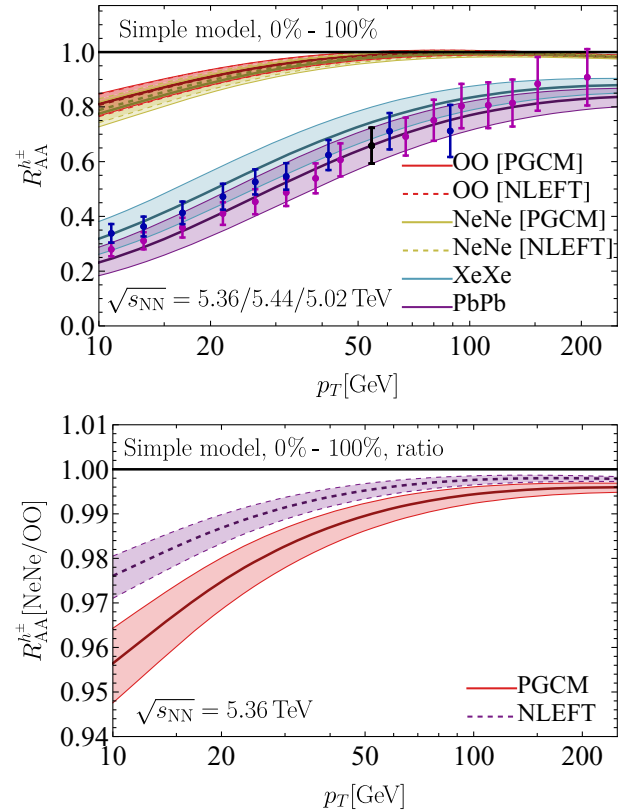


FIG. 1. Top: minimum-bias charged hadron nuclear modification factor as a function of p_T for all ion species collided at the LHC as predicted by the simple model [51] compared to data from CMS [29]. Bottom: ratio of charged hadron nuclear modification factor for ^{20}Ne over that for ^{16}O for both PGCM and NLEFT nuclear structure profiles.

where we assume that the proportionality constant $\kappa(p_T)$ depends only on p_T . Within this setup, we fix $\kappa(p_T)$ from an experimental $R_{AA}^{\text{ref}}(p_T)$ [29] and path $\mathcal{I}^{\text{ref}}$ in a reference centrality class (propagating its total uncertainty). We can determine any $R_{AA}(p_T)$ when given the temperature-weighted path $\mathcal{I}$ [52]. In this Letter we choose the 0%–5% centrality class, since this gives the most accurate value. Nevertheless, in the region of interest ($p_T > 5$ GeV) any centrality class would have given almost identical results (albeit with a larger uncertainty). Secondly, we take 10 different parameter settings from the posterior in Trajectum [2] and treat the spread as a second systematic uncertainty [53].

It is interesting that, since we fix $\kappa(p_T)$ from the experimental R_{AA}^{ref} , our results are rather insensitive to the assumed $\sigma_{pp}(p_T)$. Indeed, expanding in the power p gives

$$R_{AA} = (R_{AA}^{\text{ref}})^{\mathcal{I}/\mathcal{I}^{\text{ref}}} \left(1 + \frac{\mathcal{I}(\mathcal{I} - \mathcal{I}^{\text{ref}}) \log(R_{AA}^{\text{ref}})^2}{2(\mathcal{I}^{\text{ref}})^2 p} + \mathcal{O}(p^2) \right). \quad (2)$$

We now see that for any $\mathcal{I}/\mathcal{I}^{\text{ref}} \in [0, 1]$ and $R_{AA}^{\text{ref}} > 0.25$ the subleading term is smaller than 4%, which explains the insensitivity to the pp spectrum.

For the purposes of validation, in Fig. 2 we present the nuclear modification factor for the five different centrality classes. We deliberately also show the p_T range below 5 GeV, where Eq. (1) is not expected to apply since this starts to enter the hydrodynamic regime. Above this range the centrality and p_T dependence is captured remarkably well. The spread in the curves is the combination of experimental uncertainty and the spread due to the Trajectum posterior uncertainty.

Now that we have validated our rather basic model, we show in Fig. 3 predictions for $^{16}\text{O}^{16}\text{O}$ and $^{20}\text{Ne}^{20}\text{Ne}$ collisions (top), together with the $^{20}\text{Ne}^{20}\text{Ne}$ over $^{16}\text{O}^{16}\text{O}$

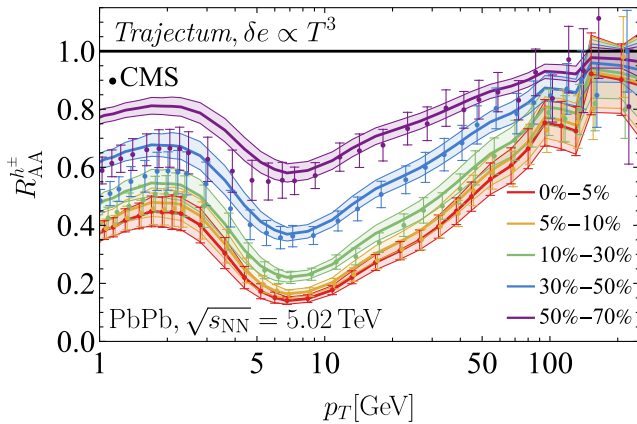


FIG. 2. PbPb charged hadron nuclear modification factor as a function of p_T and centrality. The combination of the other centralities provides the basis to postdict a given centrality according to Eq. (1).

ratio (bottom), again for both PGCM and NLEFT nuclear structure predictions. In the main plot the uncertainties make it difficult to distinguish ^{16}O from ^{20}Ne or PGCM from NLEFT, but looking more carefully at the ratio, it can be seen that partons in ^{20}Ne collisions have significantly more suppression, and again that this effect is stronger in PGCM than in NLEFT. The cancellation of the uncertainties is impressive, but an important point that is made clear in the bottom panel of Fig. 3, is that the difference between PGCM and NLEFT is a systematic uncertainty in and of itself. The fact that NLEFT has a smaller difference in size between the two nuclei (see also Ref. [3]), which in turn implies a smaller difference in the initial QGP temperature. It turns out that the temperature-weighted paths differ more for PGCM than for NLEFT [see also Supplemental Material (SM) [43]]. In anticipation of future measurements we present the 0%–10% centrality path-length approach in SM.

JEWEL and Trajectum [54]—JEWEL (Jet Evolution With Energy Loss) [55–57] is a Monte Carlo event generator

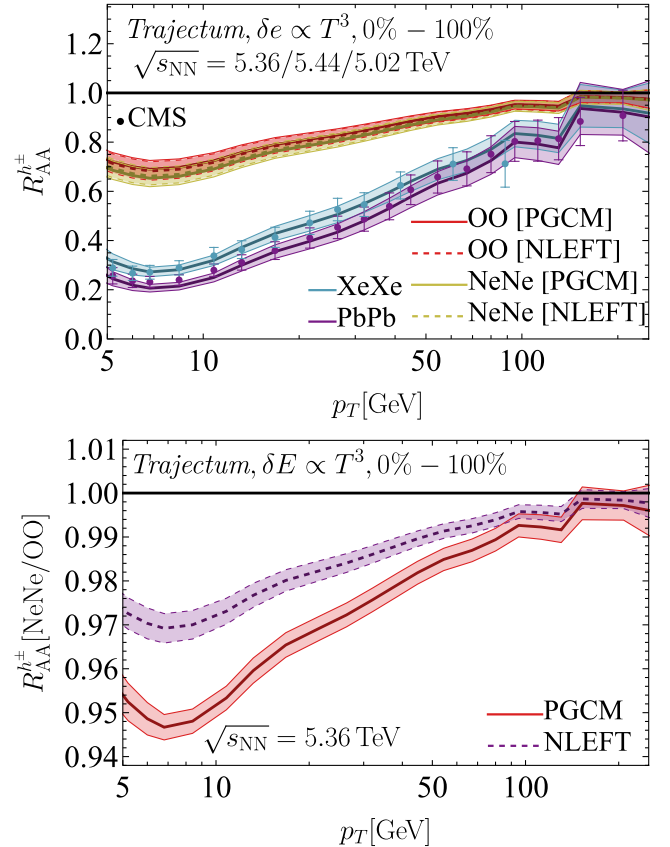


FIG. 3. Top: minimum-bias path-length approach to the charged hadron nuclear modification factor as a function of p_T for all ion species collided at the LHC. Bottom: ratio of charged hadron nuclear modification factor for ^{20}Ne over that for ^{16}O for both PGCM and NLEFT nuclear structure profiles.

designed to model parton showers in the presence of a QCD medium. It incorporates both elastic and inelastic interactions between the jet and medium constituents, and includes a treatment of medium recoil, allowing for studies of the backreaction of the plasma and jet-medium correlations. In its standard configuration, JEWEL is coupled to a simplified, boost-invariant medium model in which overlapping nuclear density distributions are used in conjunction with the equation of state for an ideal gas of quarks and gluons and longitudinal expansion.

A publicly available interface for JEWEL [54] connects JEWEL to medium profiles generated by Trajectum. The output of Trajectum can consist of event-by-event hydrodynamic profiles of energy density, temperature, and flow, which can be used as realistic backgrounds for hard probes. Instead of relying on the built-in medium model, hard partons can now evolve through dynamically expanding, event-by-event fluctuating backgrounds with spatially resolved temperature and flow fields. This allows a consistent treatment of parton-medium interactions across different collision systems, including light-ion collisions where fluctuations in the medium are expected to be dominant. The interface does not change any of the core JEWEL code, separating the medium modeling entirely from the partonic evolution and sampling only temperature and velocity values. By embedding hard partons from JEWEL in these realistic environments, the interface extends JEWEL's applicability to a broader range of systems and observables, enabling systematic studies of energy loss in evolving media.

We present the charged hadron nuclear modification factor in Fig. 4. The results presented here are untuned in the sense that default parameters were used wherever possible. For Trajectum these are from [1]. JEWEL version 2.4.0 was used with default values for all the parameters in the core JEWEL code, except for using EPPS21 nuclear parton distribution functions (nPDFs) [58]. We used the same ^{16}O nPDF set for both ^{16}O and ^{20}Ne since no dedicated ^{20}Ne set is available. The nPDFs (and their uncertainties) pose a limit on accuracy that is universal across energy-loss computations in ^{16}O and ^{20}Ne as they are not well-known.

JEWEL underpredicts the energy loss for hadrons, with a noteworthy rise above unity. For the most part, this feature is the result of a kinematical effect in which the elastic scatterings convert longitudinal momentum into transverse momentum. At the same time, the energy-loss effect disappears at high p_T . As a result, the p_T spectrum is hardened, as was already found in [59] (see Fig. 1.33) and [55]. In jets, the effect is somewhat mitigated because much of this transverse momentum is carried outside of the jet cone. In SM we present the same JEWEL results, but for the $R = 0.4$ anti- k_T jet nuclear modification, compared to ATLAS [60] and central ALICE [61] data. For ATLAS, JEWEL overpredicts the energy loss while there is good

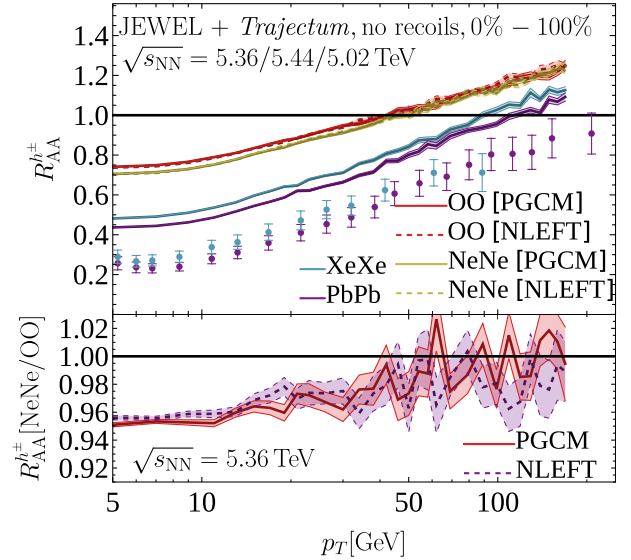


FIG. 4. The charged hadron nuclear modification factor as a function of p_T for all ion species collided at the LHC as computed with the JEWEL-Trajectum interface (uncertainties are statistical only).

agreement with central ALICE data. This makes it unlikely that we can fully tune JEWEL even for Xe and Pb collisions. Nevertheless, quite pleasingly, we see that, although the p_T dependence is different from the other models, the ion-size dependence is qualitatively similar, with the $^{20}\text{Ne}^{20}\text{Ne}/^{16}\text{O}^{16}\text{O}$ ratio even quantitatively so.

Curiously, as opposed to Fig. 3, JEWEL finds almost no difference between PGCM and NLEFT in the ratio in Fig. 4, even when using the same hydrodynamic profiles as discussed above. It is important to stress that JEWEL is considerably richer than the path-based approach and, in particular, contains fluctuations in the jet fragmentation that is known to be crucial in, e.g., the dijet asymmetry [62]. These fluctuations dominate or interplay in a nontrivial way with the temperature and plasma size such that, in the end, the PGCM and NLEFT ratios turn out to be almost identical.

Discussion—The most interesting result of this Letter is that the bands of the ^{16}O and ^{20}Ne nuclear modification factors for the path-length approach discussed above are significantly lower than those of the simple model despite the fact that both are fitted to the same lead data. At least in hindsight this should not be surprising. In the multiple soft scattering approximation, energy loss starts much slower due to coherence effects (see for instance the harmonic oscillator approximation in Fig. 2 of [63] for a clarifying explanation). Since both approaches fit the minimum-bias nuclear modification factor, it should be expected that, for small systems, energy loss is estimated to be smaller in a BDMPS-Z based approach than in a path-length approach that does not include such coherence (in Fig. 2 of [63] it would be closer to Arnold-Moore-Yaffe). The fact that the 50%–70% centrality bin (similar in size as 0%–10% light

ion collisions) is better-estimated by the path-length approach than by the simple model (compare Fig. 2 with Fig. 8 in [51]) suggests that the experimental measurement could be closer to the path-length approach. The JEWEL results are more difficult to interpret as they do not fit the lead data for charged hadrons. The fit to jet data is better (see SM). Nevertheless, it is clear that even the JEWEL charged hadron result exhibits the expected system-size dependence.

A second interesting outcome is that the $^{20}\text{Ne}/^{16}\text{O}$ ratio is significantly different for PGCM and NLEFT by about a factor of 2 when looking at $(R_{AA} - 1)$ in the path-based approach. In hindsight, this too could have been anticipated by the mean transverse momentum, as presented in [3], where the PGCM and NLEFT also differ by an amount much larger than the systematic uncertainty. The mean transverse momentum is directly related to the size of the initial QGP and indeed the $^{20}\text{Ne}/^{16}\text{O}$ ratio of the size could explain this difference (see also the SM). When comparing to the (accurately known) charge radii of ^{16}O and ^{20}Ne it turned out that both PGCM and NLEFT were off by about the same (but opposite sign) amount [3], such that it is likely that the true ratio of the R_{AA} ratio will lie somewhere in the middle [64].

Arguably, our study is not complete. Our temperature-weighted path approach only includes uncertainty from the experimental data and the systematic uncertainty from Trajectum. Our discussion of the simple model, on the other hand, only includes the uncertainty of the single data point that the model is gauged to. The nPDF uncertainties further complicate the predictions significantly and are, for example, not included at all in the temperature-weighted path approach section. In the ratio NeNe/OO those uncertainties likely largely cancel, but it is not even known if nPDF modification is monotonic with nucleus size (in fact, one could argue that ^{20}Ne is more like an ^{16}O plus ^4He and might inherit nPDFs a bit from both). As such, we did not attempt to include such effects or, even more challenging, their (correlated) uncertainties (see, however, Refs. [65,66]).

Our results are nicely summarized in Fig. 5. There, we show, for several values of p_T , how the hadron R_{AA} depends on the ion species for the three models considered. The nontrivial path-length dependence of all these models can clearly be seen, especially for the simple model. For the path-length model we also computed the $R_{AA}^{h\pm}$ for $A = 4$ ($^4\text{He}/^4\text{He}$). Even for $p_T = 10$ GeV the energy loss is small and will be challenging (though exciting) to probe given the nPDF uncertainties.

All in all there are exciting times ahead. Not only to see parton energy loss in small systems, but also to distinguish between simple and advanced models that can teach us more about the path-length dependence of energy loss. It is interesting how much these high p_T results are linked to the

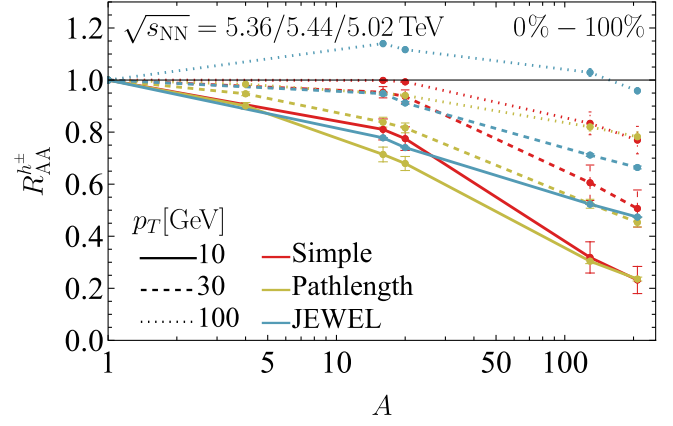


FIG. 5. Minimum-bias charged hadron nuclear modification factor as a function of ion number for several p_T values and the three models studied in this Letter.

soft sector and our understanding of the shape of the ions or the resulting QGP.

At the final submission, the experimental light-ion data is now available [45], which gives an excellent match to the path-length approach (see Fig. 3 in [45]). Both the simple model and JEWEL underpredict the energy loss. In hindsight, this could perhaps be expected for the simple model, since this model also underpredicts the energy loss in the 50%–70% centrality class for PbPb (see Fig. 8 in [51]). This could indicate that BDMPS-Z energy loss (which scales as L^2 for small lengths) has too little energy loss for small droplets of QGP.

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Data availability—The data that support the findings of this article are publicly available [67].

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