Discovering partonic rescattering in light nucleus collisions

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Two mutually exclusive descriptions of hadronic collisions:

- min-bias pp: no parton rescattering $\Rightarrow$ ideal gas
  \textit{PYTHIA, Herwig, ...}
- central AA: Many rescattering $\Rightarrow$ perfect fluid
  \textit{(viscous) hydrodynamics}

Observation of collectivity in small systems challenges both paradigms

Big question: How does one interpolate between these two extremes?
Complication: Only some of the signs of collectivity are seen in small systems
  - Collective flow, $v_n$’s
  - Strangeness enhancement
  - ... but no parton energy loss?

Assuming that collectivity arises from parton rescattering, some amount of parton energy loss must be present also in small systems

Is energy loss avoiding detection because
  - it is a small?
  - it is not there $\Rightarrow$ different mechanism of collectivity
Hadron (jet) nuclear modification factor

- Compares yield in AA to an equivalent number of pp collisions:
  \[ \langle N_{\text{coll}} \rangle = \sigma_{pp}^{\text{inel}} \langle T_{AA} \rangle \]

  \[ R_{AA}^{h,j}(p_T, y) = \frac{1}{\langle T_{AA} \rangle} \frac{(1/N_{\text{ev}}) dN_{AA}^{h,j}/dp_T dy}{d\sigma_{pp}^{h,j}/dp_T dy} \]

- System-size dependence studied in terms of centrality dependence of \( R_{AA} \)

- Nuclear overlap function \( \langle T_{AA} \rangle \) from model calculations

\[ \Rightarrow \text{high-}p_T \text{ observable depends on soft physics assumptions} \]
Is there energy loss at $\langle N_{\text{part}} \rangle \approx 10$?
Are the different collision systems in agreement?

▶ Systematic uncertainty (boxes) dominated by $\langle T_{AA} \rangle$

$\Rightarrow$ Need hard observable independent of soft modelling
Inclusive nuclear modification factor

Replace $\langle T_{AA} \rangle$ with \textbf{experimentally measurable} beam luminosity

$$R_{AA,\text{minbias}}^{h,j}(p_T, y) = \frac{1}{A^2} \frac{d\sigma_{AA}^{h,j}/dp_T dy}{d\sigma_{pp}^{h,j}/dp_T dy}$$

- No dependence on soft modelling
- Only applicable to min bias measurements
- but system size can be controlled by changing $A$

For small systems, need to collide light nuclei
Proposed OO collisions probe the physically interesting region.
In order to detect a small signal of parton rescattering the **null hypothesis** (= no energy loss) must be known accurately.

In absence of parton rescattering the $R_{AA,\text{minbias}}$ can be computed in a systematically improvable way in QCD factorization:

$$
P_T \gg \Lambda_{QCD}
$$

$$
\sigma(p + p \rightarrow j + X) = \text{PDFs} \otimes \sigma_{a+b\rightarrow c+d}
$$

$$
\sigma(^{16}O + ^{16}O \rightarrow j + X) = \text{nPDFs} \otimes \sigma_{a+b\rightarrow c+d}
$$
The null hypothesis

The state-of-art-calculation of the null hypothesis:

- **NLO** inclusive $R_{AA,\text{minbias}}$ **without parton rescattering**

![Graph showing deviation from null hypothesis](image)

**EPPS16** nPDFs

Deviation form null hypothesis $\Rightarrow$ discovery of energy loss
The null hypothesis

- Under perturbative control
- nPDFs dominate uncertainty
- nPDF errors systematically improvable with new data
  - reweighting with additional di-jet data further reduces uncertainty

Illustration of the statistical uncertainties with 0.5nb⁻¹

few hours with 'moderately optimistic' scenario 1812.06772

CMS 1805.04736, Eskola et al. 1903.09832
Model predictions for light-ion collisions

- Model calculations give an estimate on the signal size and inform about feasibility of detection.

- None of the available Monte-Carlo tools for heavy-ion collisions are tuned for small systems (JetScape, JEWEL, etc).

- Simple modular energy-loss model:
  - Standard methods developed for heavy-ion collisions extrapolated to OObaier et al. hep-ph/0106347
  - Restricted to hadron $R_{AA}^h$ for simplicity.
  - Model agnostic approach, vary model assumptions for a conservative estimate of model uncertainty.
Model predictions for light-ion collisions

- **Background** $T(\tau, r)$-profile:
  - From Hydro-like to free streaming
  - with and w/o freeze-out
  - conformal EoS vs. lattice EoS
  - dynamical geometry vs. Bjorken $\tau^{-1/3}$
  - isotropic geometry vs. azimuthal anisotropy $\epsilon_2$.

- **Energy-loss models**:
  - BDMPS-Z vs. AdS/CFT inspired
  - $dE/dL \sim L^{0.4}T^{1.2}$
  - vs. $dE/dL \sim LT^3$
  - Varying starting time of energy loss $\tau_0 = 0.05 - 0.5\text{fm/c}$
  - With or without nPDFs and FFs
For each of the models: fit model parameter $\hat{q}$ at single point $R_{PbPb}^h(p_T = 54.4\text{GeV})$

System-size, and $p_T$-dependence are then predictions
Validation of the simple model by comparing to centrality and $p_T$-dependence in PbPb (and similarly for XeXe)

- Good agreement for central to mid-central data
Model predictions for light-ion collisions

- Dramatic variation of model assumptions quantifies modelling uncertainty
Improved accuracy of the baseline allows to separate most of the models from null hypothesis for 

\[ 20 \text{GeV} < p_T < 50 \text{GeV} \]
Conclusions

- Interpretation of collectivity in small systems as a sign of parton rescattering demands that some amount of parton energy loss is present.

- Irreducible model uncertainties in centrality selected $R_{AA}$ make it difficult to separate the signal from background.

- Improved accuracy of min-bias $R_{AA}$ allows to use an OO run to either:
  - discover partonic rescattering in small system
  - exclude a wide range of energy loss models, challenging the picture of collectivity in small systems as a result of parton rescattering.