**Bottom line up front**

**Predictions of QGP signals in small systems**

- Include dynamical CNM effects to better understand the baseline.
- QGP-modified splitting functions from SCET\(_G\) + modified DGLAP evolution.
- HTL collisional energy loss (more important in small systems).

Based on W. Ke, I. Vitev arXiv:2204.00634

**Onset of light & heavy meson quenching in small systems**

Weiyao Ke and Ivan Vitev, Los Alamos National Laboratory
Challenges of identifying QGP signals in small systems with high-$p_T$ hadrons

- Potential cold nuclear matter (CNM) effects distort the baseline
  **This work** → dynamical calculations of CNM modifications [1].

- Nuclear geometry / centrality definition:
  **This work** → study both $p$-Pb, $d$-Au and light-ion systems O-O.

- Is there a QGP? How it evolves in small systems?
  **This work** → test two extremes:
  - No QGP formation, color density=0 (or, the medium scattering centers).
  - QGP formation with maximum color density $\propto T^3$, given by hydrodynamic simulation [2] \(\nabla\).

### Max. $T$ of QGP using lattice EoS [3]

<table>
<thead>
<tr>
<th>Systems</th>
<th>$p$-Pb 5 TeV</th>
<th>O-O 7 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1%</td>
<td>0.315</td>
<td>0.325</td>
</tr>
<tr>
<td>60-90%</td>
<td>0.174</td>
<td></td>
</tr>
<tr>
<td>0-10%</td>
<td>0.325</td>
<td></td>
</tr>
<tr>
<td>30-50%</td>
<td>0.263</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{max}}$ [GeV]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing $N_{ch}$, $E_{T}$ vs centrality for different systems](image)
Dynamical cold nuclear matter (CNM) effects

- Cronin (broadening) effect: $\Delta k_{\perp}^2 \propto \mu^2 A^{1/3}$; dynamical shadowing: $\delta x_a / x_a \propto \frac{\mu^2 B^{1/3}}{- u}$ [4]
- Cold nuclear matter energy loss from collision-induced soft gluon emission [5]

$$\frac{\Delta x_a}{x_a} \approx \frac{\alpha_s C_R}{\pi^2} \frac{L_B}{\lambda_g} \int_0^{\mu_B^+} \frac{d^2 q_{\perp}}{2\pi} \frac{\mu^2}{(q_{\perp}^2 + \mu^2)^2} \left[ \frac{q_{\perp}^2}{k_{\perp}^2 (k_{\perp} - q_{\perp})^2} - \frac{2(q_{\perp}^2 - q_{\perp} \cdot k_{\perp})}{k_{\perp}^2 (k_{\perp} - q_{\perp})^2} \sin \frac{k_{\perp}^2 L_B}{xp^+} \right]$$

Quark + antiquark

\begin{align*}
\Delta \frac{d^2 \sigma}{d^2 k_{\perp}} & \quad 10^0 \\
10^{-1} & \quad 10^0 \quad 10^1 \\
p_T \ [\text{GeV}] & \quad (n)NNPDF \\
& \quad \text{Cronin} \quad \text{Cronin+eloss} \\
\end{align*}

Multiple collision broadening and power corrections

\(\Delta\) Dynamical approach compared to nNNPDF [6]
QGP effects in large and small systems

- HTL collisional energy loss of hard parton [7]:
  \[
  \frac{dE_{el}}{d\Delta z} = \frac{C_R}{4} \alpha_s (ET) m_D^2 \ln \left( \frac{ET}{m_D^2} \right) \left( \frac{1}{v} - \frac{1-v^2}{2v^2} \ln \frac{1+v}{1-v} \right)
  \]

- QGP-modified fragmentation functions:
  \[
  \frac{\partial D_{h/i}}{\partial \ln Q^2} = [P_{ji}^{\text{vac}} + \Delta P_{ji}^{\text{med}} (E - \Delta E_{el})] \otimes D_{h/j}
  \]
  obtained in SCET_G [8]

In small systems:

- Collisional energy loss becomes more important. For example \( T^3 \propto \tau^{-\alpha} \): \( \Delta E_{rad} \propto L^{2-\alpha} \) v.s. \( \Delta E_{el} \propto L^{1-\frac{2}{3}\alpha} \)

- Use heavy flavor to further suppress radiation to study collisional process.
Results

**Scenario I: no QGP formation, only cold nuclear matter effects**

- **O-O 7.0 TeV**
- **p-Pb 5.02 TeV**
- **d-Au 0.2 TeV**

- **R_{AB, h^+}**
- **R_{AB, D^-}**
- **R_{AB, B^+}**

- *d-Au* data: PHENIX [9]; *p-Pb* data: ATLAS [10] (with $\langle T_{pA} \rangle$ from the Glauber-Gribov model)

- Compare to *d-Au* & *p-Pb*, CNM effects in O-O are small → ideal to searching for QGP.

- QGP effects in *d-Au* at RHIC energy is small.

- In *p-Pb* at LHC energy, QGP effects with color density $\propto T^3$ is inconsistent with data.

**Scenario II: QGP formed with a local-thermal color charged density**

- **O-O 7.0 TeV**
- **p-Pb 5.02 TeV**
- **d-Au 0.2 TeV**

- *d-Au* data: PHENIX [9]; *p-Pb* data: ATLAS [10] (with $\langle T_{pA} \rangle$ from the Glauber-Gribov model)

- Compare to *d-Au* & *p-Pb*, CNM effects in O-O are small → ideal to searching for QGP.

- QGP effects in *d-Au* at RHIC energy is small.

- In *p-Pb* at LHC energy, QGP effects with color density $\propto T^3$ is inconsistent with data.
Conclusion & references

CNM effects

- are strong in small asymmetry systems such as $p$-Pb and $d$-Au;
- are much weaker in light-ion system O-O;
- can introduce centrality-dependent suppression at large $p_T$ due to CNM energy loss.

QGP effects?

- QGP effects with color-source density given by hydrodynamics ($\propto T^3$) is inconsistent with $R_{AA}^h$ in $p$-Pb.
- $\Delta E_{el}/\Delta E_{rad}$ increases in small systems: a change in the flavor separation of $R_{AA}$.
- Future scenario III: jet quenching with non-equilibrium color charged density.

References: