QGP tomography with direct photons and jets

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(for the ALICE collaboration)
The QCD medium

A new state of matter is produced in heavy-ion collisions at RHIC: parton degrees of freedom with hydrodynamic properties of a liquid

Several observations lead to this conclusion:

- Energy densities reached exceed the critical temperature at which LQCD predicts a phase transition
- Large elliptic flow established during the early partonic phase
- Quark scaling
- Very low viscosity
- Jet quenching
Auto-generated probes:
- hard scattered partons traversing the dense formed medium are modified → observed as reduction of high pt hadrons (jet fragments)
- direct photon traverse the medium unaffected

The measurement:
- Particle species spectra
  1. $\sigma (p_T^h)$
  2. $R_{AA} = \sigma_{AA}/(\text{Norm} \times \sigma_{pp})$

Measurement does not strongly constrain the interaction mechanism or the medium properties
jet-quenching: more exclusive measurement

**The measurement:**
- Particle species spectra
  1. $\sigma (p_T^h)$
  2. $R_{AA} = \sigma_{AA}/(\text{Norm} \times \sigma_{pp})$
- Fragmentation function
  1. $FF \left( z = p_T^h/E_{jet} \right)$
  2. $R_{FF} = FF_{AA}/(\text{Norm} \times FF_{pp})$

- Difficult to reconstruct jet in HI environment

- High $p_T$ suppression

- Low $p_T$ enhancement

$\xi = \ln\left( \frac{E_{\text{jet}}}{p_{\text{hadron}}} \right)$

$\Delta E \propto \hat{q} \cdot L^2$

$\frac{d\Delta E}{dz} \propto \hat{q} \cdot L$

$\hat{q}$

Borghini and Wiedemann, hep-ph/0506218

OPAL, $\sqrt{s} = 192–209$ GeV
- in vacuum, $E_{\text{jet}} = 100$ GeV
- in medium, $E_{\text{jet}} = 100$ GeV

TASSO, $\sqrt{s} = 14$ GeV
- in vacuum, $E_{\text{jet}} = 7$ GeV
- in medium, $E_{\text{jet}} = 7$ GeV

$p_T^{\text{hadron}} \sim 2$ GeV for $E_{\text{jet}} = 100$ GeV
**jet-quenching: even more exclusive measurement (the golden one)**

- **Direct photon - jet**
  - The photon 4-momentum remains unchanged while traversing the medium and sets the reference of the hard process
  - Balancing the hadron and the photon provides a measurement of the medium modification experienced by the jet
  - Allows to measure jets in an energy domain ($E_{\text{jet}} < 50$ GeV) where
    - The jet looses a large fraction of its energy ($\Delta E_{\text{jet}} \approx 20$ GeV)
    - The jet cannot be reconstructed in the AA environment
Toward a true tomography measurement of QCD medium in AA (X. N. Wang)

- The azimuthally misaligned back to back jets (from a 2->2 hard process) may add to $k_T$, which is a measure of qhat:

$$\langle \Delta q_T^2 \rangle = \int dy \hat{q}(y, E)$$

- Triggering $\gamma$-hadrons correlation measurement with hadrons of various $x_E$ allows to select the production point of the hard scattering:
  - large $x_E$, contributions to CF come mostly from hard scattering at the surface;
  - small $x_E$, contributions to CF are mostly from hard scattering inside the volume.

- **What can be measured with ALICE?**
ALICE: dedicated HI Experiment

EMCAL: $|\eta|<0.7$
$\Delta \phi: 110^\circ$

E $> 10 \text{ GeV} \rightarrow \Delta E/ E < 3 \%$
$\sigma_x = [3,50] \text{ mm}$

TPC: $|\eta|<0.9$
$\Delta \phi: 2\pi$

Tracking System resolution
$\Delta p/ p = 2\%$, $\alpha = 1.1^\circ$

PHOS: $|\eta|<0.125$
$\Delta \phi: 100^\circ$

E $> 10 \text{ GeV} \rightarrow \Delta E/ E < 1.5\%$
$\sigma_x = [0.5,2.5] \text{ mm}$
γ-hadron correlations in ALICE

- **Strategy (event by event):**
  - Search identified prompt photon (PHOS or EMCal) with $E_\gamma > 20$ GeV
  - Search for all charged hadrons (central tracking) or neutral $\pi^0$ (EMCal or PHOS):
    - $90^\circ < \phi_\gamma - \phi_{\text{hadron}} < 270^\circ$

- **Background:**
  - Decay photons misidentified as isolated photon
  - Soft hadrons from the underlying event (UE):
    - take the hadrons from the same side of direct photons as UE
Correlation Function (CF) and $I_{AA}$

$X_E = -\mathbf{p}_T \cdot \mathbf{p}_T\gamma / |\mathbf{p}_T\gamma|^2$

$\frac{I_{AA}}{I_{PP}} = \frac{CF_{AA}}{CF_{PP}}$

- Statistical errors correspond to one standard year of data taking with 2 PHOS modules.
- Systematic errors from decay photon contamination and hadrons from underlying events.
"$<k_T>$ in $\gamma$-jet at LHC"

- Extrapolated from existing measurements by PYTHIA tuning:

\[ k_T \text{ extrapolated from existing experiments} \]

- Intrinsic $k_T$ (PARP(91)) and ISR/FSR on $<p_T>_{\text{pair}} = <p_T>_\gamma\text{-jet}$

\[ <k_T> = <p_T>_{\text{pair}} / \sqrt{2} \]

- Fitting function:

\[ <p_T>_{\text{pair}} = A \log_{10}(B \sqrt{s}) \]

- \(A = 2.06 \pm 0.171\)
<p_T>_{\text{pair}} dependence on p_T

Reference: \( \gamma \)-parton pair:

<table>
<thead>
<tr>
<th></th>
<th>A (GeV/c)</th>
<th>B (Gev/c)^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>-----</td>
<td>3.63 ± 1.4</td>
<td>0.05 ± 0.0</td>
</tr>
</tbody>
</table>

Fitting:

\[ <p_T>_{\text{pair}} = A + B * p_T \]

Measurement: \( \gamma \)-jet pair:

<table>
<thead>
<tr>
<th>R</th>
<th>A (GeV/c)</th>
<th>B (Gev/c)^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.49 ± 3.01</td>
<td>0.04 ± 0.05</td>
</tr>
<tr>
<td>0.7</td>
<td>4.82 ± 1.91</td>
<td>0.07 ± 0.04</td>
</tr>
<tr>
<td>0.4</td>
<td>3.42 ± 1.45</td>
<td>0.10 ± 0.0</td>
</tr>
<tr>
<td>0.2</td>
<td>3.19 ± 1.19</td>
<td>0.13 ± 0.04</td>
</tr>
</tbody>
</table>
Leading particles with medium length (L) traversed

- High x leading particles come mostly from h.s. at the surface
- Low x leading particles come mostly from h.s. in the volume

However separation not very much pronounced!!
CF (differ $x_E$) dependence on L

- Ratio of quenched to unquenched scenario with $x_E$ selection on CF

$\text{CF (with UE) ratio with and without quenching}$

$p+p \rightarrow X, \text{@} 5.5\text{TeV}$

$Q = 36\text{GeV}^2/\text{fm}$

$\Delta \phi = (1.5, 4.5)$

$x_E < 0.2$

$x_E > 0.8$
Conclusion

- Medium effect could be measured by $\gamma$-hadrons correlation:
  - Modification of the photon tagged jet fragmentation function -> medium properties
  - Detailed tomography of HI collision is in "theory" possible
  - $k_T$ from pp to HI is an additional way to infer the medium property

- The measurement is challenging but worth the effort

- Let’s take a break…until LHC tell us the truth!
Acknowledgement

- To the organizers
- To Daicui Zhou, Yves Schutz, Xin-Nian Wang, Andreas Morsch, Peter Jacobs …for useful discussions
- To full Wuhan-ALICE group
- To full ALICE collaboration

THANKS FOR ALL!
Back up
What is $k_T$?

- Two partons (with hat) back to back in CM
- At an angle in lab frame due to $k_T$
- Fragment into final hadrons (no hat)
- $\langle k_T \rangle = \langle p_T \rangle_{\text{pair}} / \sqrt{2}$
Strong dependence on jet reconstruction (R) !?

Fitting:
\[ <p_T>_{\text{pair}} = A + B \times p_T \]

<table>
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<tr>
<th>R</th>
<th>A (GeV/c)</th>
<th>B (GeV/c)^{-1}</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>6.25±2.56</td>
<td>0.10±0.05</td>
</tr>
<tr>
<td>0.7</td>
<td>2.84±1.56</td>
<td>0.16±0.05</td>
</tr>
<tr>
<td>0.4</td>
<td>1.42±1.45</td>
<td>0.21±0.05</td>
</tr>
<tr>
<td>0.2</td>
<td>-</td>
<td>0.24±0.05</td>
</tr>
</tbody>
</table>

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\( \langle p_T \rangle_{\text{pair}} \) from leading-leading

Fitting:
\[ \langle p_T \rangle_{\text{pair}} = A + B \times p_T \]

<table>
<thead>
<tr>
<th>( A ) (GeV/c)</th>
<th>( B ) (GeV/c(^{-1}))</th>
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<tr>
<td>0.45 ± 0.4</td>
<td>0.07 ± 0.0</td>
</tr>
<tr>
<td>3.27 ± 1.4</td>
<td>0.07 ± 0.0</td>
</tr>
</tbody>
</table>

Delta phi between 2 leadings:

- Entries: 49753
- Mean: 14.1
- RMS: 11.08
- \( \chi^2 / \text{ndf} \): 198.2 / 27
- Constant: 1.589e04 ± 1.085e02
- MPV: 7.543 ± 0.039
- Sigma: 3.531 ± 0.025
Approach to confirm...

1) Generate $\gamma$-jet events ($E_\gamma > 20$ GeV) with PYTHIA generator with and without quenching (QPYTHIA)

2) Get the jet production point $(x_0, y_0)$ inside AA geometry from Fast Glauber model

3) Calculate the traversed medium length ($L$) based on direction of hard scattered parton using Fast Glauber

4) Search leading hadron with the highest $p_T$
Phi correlation (leading and $\gamma$)

Quenching effect:
- loss of high $x$ leading particles
- broadening of the $\Delta \Phi$ correlation at low $x$
- $x = 0.2 \rightarrow p_T \sim 4$ GeV/c

No quenching

the found $lp$ comes from the UE
No quenching

- Quenching produces more low x particles from h.s. occurring in the volume (large L)
Leading particle distribution: $x = \frac{p_T}{p}$

- Quenching will generate more low $x$ particles
- More fake leading particles from underlying events will be found due to the quenching
Medium effect for high $p_T$ leading particles

Leading particles with:
- charge only
- $x > 0.8$

- Suppression stronger for parton traversing large $L$
- But $L$ dependence is not very pronounced
Medium effect for low $p_T$ leading particles

Leading particles with:
- charge only
- $x < 0.2$

- Opposite to before: Enhancement stronger for traversing large $L$
- Again $L$ dependence is not very pronounced
Particles are generated symmetric if no quench is applied due to the L calculation approach.

High $p_T$ leading particles have higher probability to come from the surface than to the volume.
Gamma+lp triggered x distribution

- Ratio of quenched to unquenched scenario