Probing QGP medium in large and small systems using light and heavy quarks

Zhenyu Chen (Rice University)

For the CMS Collaboration

Santa Fe Jets and Heavy Flavor Workshop 2018
Jet quenching

Jet quenching in PbPb collisions firmly established
- Examined in detail with inclusive jet studies
- Initial energy of quenched partons can’t be precisely determined for inclusive jet

Leading Jet

Subleading Jet

\[ X_j = \frac{p_T^{\text{sub lead}}}{p_T^{\text{lead}}} \]
Photon tagged jets

Photon in $\gamma$-jet events do not interact with the medium

- Clean tag of the initial parton energy
- Better handle on quark/gluon jet ratio
  - High $p_T$ $\gamma$-jet dominated by quark-jet (for $p_T^{\gamma} > 30$ GeV/c)

![Diagram of photon and jets](image)
Photon tagged jets

Photon in $\gamma$-jet events do not interact with the medium

- Clean tag of the initial parton energy
- Better handle on quark/gluon jet ratio
  - High $p_T$ $\gamma$-jet dominated by quark-jet

For the analyses:

Photon required to pass isolation cuts

- Suppress neutral hadron decays mimicking prompt photon signal

Jet cuts

- Anti-$k_T$, $R = 0.3$
- $p_T^{\text{jet}} > 30$ GeV
- $\Delta\phi(\gamma, \text{jet}) > 7\pi/8$
γ-jet pT imbalance

- Strong shift in $X_{j\gamma}$ observed in 0-30% PbPb relative to pp
\textbf{γ-jet pT imbalance}

- Strong shift in $X_{jγ}$ observed in 0-30% PbPb relative to pp
- Weaker quenching seen in 30-100%

\texttt{arxiv.1711.09738}
• Lower $<X_{j\gamma}>$ in 0-30% PbPb relative to pp

• Compatible $<X_{j\gamma}>$ to pp in peripheral events
**γ-jet \( <X_{j\gamma}> \) & \( R_{j\gamma} \)**

- Lower \( <X_{j\gamma}> \) in 0-30% PbPb relative to pp
- Compatible \( <X_{j\gamma}> \) to pp in peripheral events
- \( R_{j\gamma} \) – average number of jets with \( p_T > 30 \text{ GeV}/c \) and recoiling from \( γ \)
- \((0-30\%) < (30-100\%) < \text{pp}\)
**γ-jet fragmentation function**

- Constrain how the parton lose energy to the medium
- Per-jet yield of charged particles vs two variables:

\[
\zeta_{\text{jet}} = \ln \frac{|p^\text{jet}|^2}{p^\text{trk} \cdot p^\text{jet}}
\]

\[
p^\text{jet} : 3\text{-momentum vector of the jet}
\]

\[
p^\text{trk} : 3\text{-momentum vector of the track}
\]

\[
\zeta_T = \ln \frac{-|p_T^\gamma|^2}{p_T^\text{trk} \cdot p_T^\gamma}
\]

\[
p_T^\gamma : \text{transverse momentum vector of the photon}
\]

\[
p_T^\text{trk} : \text{transverse momentum vector of the track}
\]

\[
p_T^\text{trk} \text{ projected to } p_T^\gamma
\]

\[
-p_T^\gamma \text{ projected to } -p_T^\text{trk}
\]
Probing novel long-range correlations in PbPb (collisions with identified particles at CMS) for the CMS Collaboration. Zhenyu Chen (Rice University) at the Hot Quarks Workshop 2014.

$\sqrt{s_{NN}} = 5.02$ TeV, PbPb 404 $\mu$b$^{-1}$, pp 27.4 pb$^{-1}$

- $p_T^\gamma > 60$ GeV/c, $|\eta^\gamma| < 1.44$, $\Delta\phi^\gamma > \frac{7\pi}{8}$
- anti-$k_T$ jet $R = 0.3$, $p_T^{\text{jet}} > 30$ GeV/c, $|\eta^{\text{jet}}| < 1.6$
- $p_T^{\text{trk}} > 1$ GeV/c

$1/N^{\text{jet}}$ vs $dN^{\text{trk}}/d\xi^{\text{jet}}$

- 0-10% (+1)
- 10-30% (+2)
- 30-50% (+4)
- 50-100% (+6)

- Enhancement of low $p_T$ particles for central events

arxiv.1801.04895
γ-jet fragmentation function

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV}, \text{ PbPb} 404 \ \mu b^{-1}, \text{ pp} 27.4 \ \text{pb}^{-1} \]

- \[ p_T^\gamma > 60 \ \text{GeV/c}, \ |\gamma| < 1.44, \ \Delta \phi > 7\pi/8 \]
- antik_{T} \text{ jet } R = 0.3, \ p_{T^\text{jet}} > 30 \ \text{GeV/c}, \ |\eta^\text{jet}| < 1.6
- \[ p_T^{\text{trk}} > 1 \ \text{GeV/c} \]

\[ 50-100\% (+3) \]
\[ 30-50\% (+2) \]
\[ 10-30\% (+1) \]
\[ 0-10\% \]

\[ \begin{align*}
1/N_{\text{jet}} & \frac{dN^{\text{trk}}}{d\xi_{\text{jet}}} \\
\xi_{\text{jet}} & = 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5
\end{align*} \]

- Large \( p_T^{\text{trk}} \)
- Small \( p_T^{\text{trk}} \)

- Enhancement of low pT particles for central events

arxiv.1801.04895
γ-jet fragmentation function

\[ \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, \text{ PbPb } 404 \mu \text{b}^{-1}, \text{ pp } 27.4 \text{ pb}^{-1} \]

- Larger effect for \( \xi_T^\gamma \)
- Enhancement of low \( p_T \) particles
- Depletion of high \( p_T \) particles

[Graph showing data points and descriptions]

arxiv.1801.04895
γ-jet fragmentation function

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV}, \text{ PbPb} 404 \mu\text{b}^{-1}, \text{ pp} 27.4 \text{ pb}^{-1} \]

- Larger effect for \( \xi_T^\gamma \)
- Enhancement of low \( p_T \) particles
- Depletion of high \( p_T \) particles

Strong constrain on parton energy loss mechanism

Same studies can be extended to HeavyFlavor jets
Clear evidence of interaction between Heavy Flavor and medium
- Path length dependence of energy loss
- Flavor dependence of coupling strength to the medium
Collectivity and "QGP" in small system

Collectivity discovered in high-multiplicity pp & pPb
Collectivity and “QGP” in small system

Collectivity discovered in high-multiplicity pp & pPb

Parton medium interaction in small system?

Heavy Flavor azimuthal anisotropy provide unique constrain
D⁰ reconstruction in pPb

2016 pPb data
MinimumBias: 7 Billion
HighMultiplicity: 550 Million

D⁰ -> Kπ, BR = 3.88±0.05%

D⁰ from B decay fraction less than 1-7% for 1.4 < pT < 8 GeV/c
D^0 v_2 extraction – diharon correlation

- Dihadron correlation - D0 candidates with charged particles

**N_{trk}^{offline} < 35**

**CMS Preliminary**

\( p\bar{p} 8.16 \text{ TeV}, N_{trk}^{offline} < 35 \)

\( 4.2 < p_T^D < 5 \text{ GeV} \)

\( 0.3 < p_{ref}^T < 3 \text{ GeV} \)

\[ |M_{inv} - M_{D^0}| < 0.4 \text{ GeV} \]
D⁰ v₂ extraction – diharon correlation

- Long-range (|Δη|>1) to get rid of short range correlation

- VₙΔ extracted using Fourier fit
  \[
  \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta \phi} = \frac{N_{\text{assoc}}}{2\pi} \left[ 1 + \sum_n 2V_{n\Delta} \cos(n\Delta \phi) \right]
  \]

- Single vn coefficients computed with
  \[
  v_n(p_T^{\text{trg}}) = \frac{V_{n\Delta}(p_T^{\text{trg}}, p_T^{\text{ref}})}{\sqrt{V_{n\Delta}(p_T^{\text{ref}}, p_T^{\text{ref}})}}
  \]
**D⁰ v₂ extraction – signal v₂**

**CMS Preliminary**

\[ p_{\text{Pb}} \sqrt{s_{\text{NN}}} = 8.16 \text{ TeV} \]

- \( 185 \leq N_{\text{trk}}^{\text{offline}} < 250 \)
- \( 4.2 < p_T < 5.0 \text{ GeV/c} \)
- \( |y| < 1 \)

**Formula:**

\[ \nu_n^{\text{Sig} + \text{Bkg}}(m_{\text{inv}}) = \alpha(m_{\text{inv}}) \nu_n^{\text{sig}} + (1 - \alpha(m_{\text{inv}})) \nu_n^{\text{Bkg}} \]
Prompt $D^0 v_2$ in pPb

Strange hadrons
- Mass ordering at low $p_T$
- Similar to PbPb
Prompt $D^0 v_2$ in pPb

Strange hadrons
- Mass ordering at low $p_T$
- Similar to PbPb

CMS Preliminary

$185 \leq N_{\text{offline}}^{\text{trk}} < 250$, $|y| < 1$

CMS-PAS-HIN-17-003
Prompt $D^0 v_2$ in pPb

Strange hadrons
- Mass ordering at low $p_T$
- Similar to PbPb
Prompt $D^0 v_2$ in pPb

Strange hadrons
- Mass ordering at low $p_T$
- Similar to PbPb

$D^0$ meson
- Significant $v_2$ signal
  $\rightarrow$ c quark interaction
  with "QGP"
- Follow mass ordering

CMS Preliminary

CMS-PAS-HIN-17-003
Prompt $D^0 v_2$ in pPb

- Jet contribution removed using low multiplicity subtraction
  - Significant $v_2$ for $D^0$
  - Mass ordering
Prompt $D^0 v_2$ in pPb

- Jet contribution removed using low multiplicity subtraction
  - Significant $v_2$ for $D^0$
  - Mass ordering
- Larger splitting between $D^0$ and strange hadron $v_2$ than PbPb
Number of constituent quark scaling

- NCQ scaling holds for strange hadrons

![Graph showing the relationship between \( V_2 \) and \( K_0^0 \) for different values of \( K_{ET}/n_q \) and \( |y| < 1 \).](image)
• NCQ scaling holds for strange hadrons
• $D^0$ results significantly lower -> weaker collective behavior for $c$ quark
Number of constituent quark scaling

- NCQ scaling holds for strange hadrons
- $D^0$ results significantly lower -> weaker collective behavior for c quark
- Different than observation in PbPb

CMS-PAS-HIN-17-003
What can we learn?

**Significant D⁰ v² signal in high-multiplicity pPb**
- Thermalization of charm quark in a small droplet of QGP?
- Initial state effect? E.g. CGC

**Why weaker collective flow for charm quark in pPb?**
- Much smaller system size?
- Late thermalization?

**We look forward to theoretical calculations in small systems!**

Zhenyu.Chen@cern.ch
Photon tagged jet in PbPb

- Shift of $\langle X_{j\gamma} \rangle$ to lower value
- Suppression in $R_{j\gamma}$
- Fragmentation pattern modification

Prompt D0 elliptic flow in pPb

- Significant D$^0$ $v_2$ signal
- Weaker collective flow for charm quark
Prompt $D^0$ reconstruction in pPb

$D^0 \rightarrow K\pi$, BR = 3.88+0.05%

$D^0$ candidates
- Pairing oppositely charged tracks
- Secondary vertex reconstruction

Topological selections:
- 3D decay length significance
- Pointing angle
- Secondary vertex probability

Non-prompt $D^0$ fraction less than 1-7% for $1.4 < pT < 8\text{GeV/c}$
Probing (novel long range correlation phenomena in PbPb (collisions with identified particles at CMS)

Zhenyu Chen (Rice University) for the CMS Collaboration

Hot Quarks Workshop 2014

Prompt $D^0 v_2$ in pPb

CMS Preliminary

pPb 8.16 TeV

$185 \leq N_{\text{trk}}^{\text{offline}} < 250$, $|y| < 1$

- $D^0$
- $\Lambda$
- $K_S^0$
- $\Xi^-$
- $\Omega^-$

V$_2$

$p_T$ (GeV/c)

High multiplicity

- Finite $v_2$ for $D^0$
- Mass ordering at low $p_T$

CMS Preliminary

pPb 8.16 TeV

$N_{\text{trk}}^{\text{offline}} < 35$, $|y| < 1$

- $D^0$
- $\Lambda$
- $K_S^0$
- $\Xi^-$
- $\Omega^-$

V$_2$

$p_T$ (GeV/c)

Low multiplicity

- $v_2$ from di-jet correlation
- No mass ordering

CMS-PAS-HIN-17-003
Heavy Flavor $v_2$ in AA collisions

![Diagram of anisotropy parameter $v_2$ for different particles in STAR Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, 10-40% centralities.](image)

1. For $p_T$ (GeV/c):
   - $D^0$, $\Lambda$
   - $\Xi^-$, $K_S$

2. For $(m_T - m_b) / n_q$ (GeV/c²):
   - $D^0$, $\Lambda$
   - $\Xi^-$, $K_S$
High-multiplicity pPb with CMS

Dedicated high-multiplicity trigger for 2016 pPb data taking

- High efficiency and purity
- 550M events collected for multiplicity > 185

**CMS Preliminary**

![High-Level Trigger Efficiency vs. N_{off}](image)

- \( N_{ch}^{\text{online}} > 120 \)
- \( N_{ch}^{\text{online}} > 150 \)
- \( N_{ch}^{\text{online}} > 185 \)
- \( N_{ch}^{\text{online}} > 250 \)
- \( N_{ch}^{\text{online}} > 280 \)