Probing QCD medium effects in pPb collisions via heavy flavor productions and correlations with the CMS experiment

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Collectivity in small systems

- Positive $v_2$ of light flavor hadrons
- Mass order shows common velocity
- Similar observations to large systems

Is the origin of collectivity in pPb collisions the same as that in PbPb? – from the hot medium effects?
Heavy flavor in large systems

• QGP droplet in heavy ion collisions
  • Hot dense medium, partons interacts strongly
  • Perfect fluid, Initial geometric eccentricity hydrodynamically propagate to final states

• Heavy flavor quarks – good probes to initial condition
  • can only be created at initial stage
  • Experience the entire evolution
  • Large $v_2$ for open charm mesons and charmonia

\[
E \frac{d^3N}{d^3p} = \frac{1}{2\pi p_t dp_t dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{RF})] \right)
\]
Heavy flavor in large systems

- Nuclear modification
  - Open charm suppression, suffer energy loss
  - Charmonium suppression, Debye screening radius < binding radius
Hot medium effects in small systems?

• Possibly find similar observations in small systems if there is any hot medium effect
  • Collectivity,
    • $v_2$ for prompt $D^0$ mesons, prompt $J/\psi$ mesons, beauty quarks …
  • Nuclear modifications
    • $R_{ppb}$ for prompt $D^0$ mesons, prompt $J/\psi$ mesons …
  • ……

<table>
<thead>
<tr>
<th>Observable</th>
<th>Large system</th>
<th>Small system</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_2$ for light flavor</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$v_2$ for open charm/ charmonia</td>
<td>✓/✓</td>
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<td>✗/✓</td>
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</tbody>
</table>
Mass order at low $p_T$ -- common flow velocity

Similar to PbPb
Prompt J/$\psi(c\bar{c})$ in pPb Collisions

• Can also observe positive $v_2$ signal for prompt J/$\psi$

• Calculations based on medium effects inconsistent with data

• Caveat: medium effects may not strong enough in MB samples

$v_2$ for
Prompt J/$\psi$
Prompt D$^0$
Prompt $J/\psi(c\bar{c})$ in pPb Collisions

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- Calculations based on medium effects inconsistent with data
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![Graph showing $v_2$ vs $p_T$ for CMS and pPb 8.16TeV data.]

$185 \leq N_{\text{trk}}^{\text{offline}} < 250$

In-medium $J/\psi$ in MB pPb (Du, Rapp, JHEP 03 (2019) 015)
Prompt $J/\psi(c\bar{c})$ in pPb Collisions

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- Calculations based on medium effects inconsistent with data
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In-medium $J/\psi$ in MB pPb

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Modifications for charmonia in pPb collisions

- Modifications for prompt $J/\psi$ and prompt $\psi(2S)$ consistent with unity
- $\psi(2S)$ slightly suppressed in backward (Pb-going) compared to $J/\psi$
- A hint for final state effects

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Modifications for charmonia in pPb collisions

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- Prompt ψ(2S) slightly suppressed in backward (Pb-going) compared to prompt J/ψ
- A hint for final-state effects?
Medium effects in pPb Collisions

• Multiplicity (system size) has an impact?
An alternative scenario

- An alternative scenario based on initial state interactions – Color Glass Condensate
  - Before collisions, non-zero color electric fields exist
  - Non-geometry-related and non-hydrodynamical evolution
  - Predict large $v_2$ for $\Upsilon$ and prompt $J/\psi$
Beauty quarks in pPb Collisions

- Can we observe collectivity of even heavier quarks?
  - b quarks are very heavy and hard to thermalize
  - CGC calculations predict large $v_2$ for $\Upsilon$ comparable to prompt $J/\psi$ (PRL 122 (2019), 172302)
  - b quarks provide new opportunities to study the medium effects and CGC
Nonprompt $D^0$ in pPb Collisions

- Nonprompt $D^0$ originates from b hadron
- Distinguish prompt and nonprompt $D^0$ by DCA distribution
Nonprompt $D^0$ in pPb Collisions

- Evaluate $v_{2\Delta}$ in each integrated DCA bin with two particle correlation function
- Extrapolate signal with linear fit
- $v_2$ obtained from using charged particles as reference
Nonprompt D⁰ in pPb Collisions

- Evaluate in each integrated DCA bin with two particle correlation function
- Extrapolate with linear fit
- v² obtained from using charged particles as reference

![Graph showing v² vs. DCA for pure prompt and nonprompt D⁰](image)

CMS Preliminary

- Data total D⁰
- Combination

pPb 186 nb⁻¹ (8.16 TeV)

- 2 < p_T < 5 GeV
- |y_{lab}| < 1

185 ≤ N_{trk}^{ offline} < 250

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Nonprompt $D^0$ in pPb Collisions

- Evaluate $v_2$ obtained from $v_{signal}^{2\Delta}$ using charged particles as reference in each integrated DCA bin with two particle correlation function
- Extrapolate with linear fit
- $v_2$ obtained from $v_{signal}^{2\Delta}$ using charged particles as reference

$\text{CMS Preliminary}$

$\text{PbPb 186 nb}^{-1}$ (8.16 TeV)

- Data total $D^0$
- Combination
- $D^0$ from b hadrons
- Prompt $D^0$

$2 < p_T < 5$ GeV

$|y_{lab}| < 1$

CMS-PAS-HIN-19-009

$185 \leq N_{\text{trk}}^\text{offline} < 250$

$3 < p_T < 4$ GeV

$|y_{lab}| < 1$

CMS-PAS-HIN-19-009
• First measurement of $b$ flow in pPb collisions

• Indication of flavor hierarchy between charm and beauty at low $p_T$

• Comparison between CGC calculations and data
Nonprompt $D^0$ in pPb Collisions

- First measurement of b flow in pPb collisions
- Indication of flavor hierarchy between charm and beauty at low $p_T$
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First measurement of b flow in pPb collisions

Indication of flavor hierarchy between charm and beauty at low $p_T$

Comparison between CGC calculations and data
Summary and future

- A comprehensive study of heavy flavor collectivity in small systems
  - Observation of strong charm collectivity
  - First measurement of bottom collectivity in pPb collisions, which is much smaller
  - Hint of charmonia suppression for $\psi(2S)$ via final-state effects
  - Medium effects or CGC still on debate

- Future
  - Modifications for heavy flavors
  - Correlations between heavy flavors
  - ... ...
Backup
Prompt $D^0$ in pPb Collisions

- $D^0 (c\bar{u})$ reconstruction
Prompt $D^0$ in pPb Collisions

- $D^0$ reconstruction

- Two particle correlation techniques

\[
\frac{1}{N_{D^0}} \frac{dN^{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi} \left[ 1 + \sum_{n=1}^{3} 2V_{n\Delta}\cos(n\Delta\phi) \right]
\]

\[
v_n(D^0) = V_{n\Delta}(D^0, \text{ref}) / \sqrt{V_{n\Delta}(\text{ref}, \text{ref})}
\]
Prompt $D^0$ in pPb Collisions

- $D^0$ reconstruction
- Two particle correlation techniques
- Signal extraction

\[ v_{2}^{S+B}(m_{inv}) = \alpha(m_{inv}) v_{2}^{S} + [1 - \alpha(m_{inv})] v_{2}^{B}(m_{inv}) \]
Backup

Backup System size and Collectivity

- Positive $v_2$ is observed in high multiplicity events
- $v_2$ of prompt $D^0$ in pp collisions is comparable to that in pPb collisions with similar multiplicity under large uncertainty
- Non-zero $v_2$ of prompt $D^0$ mesons diminish towards low-multiplicity regimes
Backup nonflow

\[ V_{n\Delta}^{\text{sub}} = V_{n\Delta} - V_{n\Delta}(N_{\text{trk}}^{\text{offline}} < 35) \times \frac{N_{\text{assoc}}(N_{\text{trk}}^{\text{offline}} < 35)}{N_{\text{assoc}}} \times \frac{Y_{\text{jet}}}{Y_{\text{jet}}(N_{\text{trk}}^{\text{offline}} < 35)}. \]
Backup

Large nuclei

Small nucleon, low temperature (energy density)

Small nucleon, high T

Smaller system size

Ridge in high multiplicity events

No ridge in low multiplicity events