New results on collectivity in small systems with CMS

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Outline

- Collectivity and quark-gluon plasma (QGP) from small systems
  - small systems: high-multiplicity pp
  - high-multiplicity pPb
  - low-multiplicity PbPb

- Collectivity of heavy quarks in small systems
  - Prompt $D^0$ $v_2$ in pPb
  - charm $v_2$ vs strange $v_2$
  - $c$ flows the same as $u$ and $d$?

- $J/\psi$ collectivity in pPb
  - $v_2$ of $D^0$: is it flow of $u$ or of $c$?
  - $J/\psi$: direct evidence for $c$ quark collectivity

- Sub-event symmetric cumulants in pPb
  - To understand collectivity in pPb down to low-multiplicity

- Conclusions
Collectivity in small systems

- Collectivity of particles (built from light $u$ and $d$ quarks) in small systems
- Do heavier quarks ($s$, $c$ …) also show collective behavior?
Heavy quarks in PbPb QGP

- c quarks flow as u and d?
- D⁰ vₙ complements Rₐₐ measurements

Scalar-product method

\[ Qₙ = \sum_{k=1}^{M} \omega_k e^{i\phi_k} \]

\[ vₙ \{SP\} = \frac{\left\langle Q_{n,D⁰} Q_{nA}^{*} \right\rangle}{\sqrt{\left\langle Q_{nA} Q_{nB}^{*} \right\rangle \left\langle Q_{nA} Q_{nC}^{*} \right\rangle}} \]

- D⁰→K+π
- No PID for K and π

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|Δη| > 3
Heavy quarks in PbPb QGP

As expected, c quarks flow. Are c quarks thermalized in PbPb?

- $p_T < 3 \text{GeV/c}$: c quark collective motion
- $p_T > 6 \text{ GeV/c}$: path length dependence of c quark energy loss
- Similarity suggests path length dependence of c quark same as for u and d
Heavy quarks in small pPb system

Extraction of $D^0$ and $J/\psi$, and their flow in pPb collisions

- $D^0 \rightarrow K^+ \pi$
- No PID for $K/\pi$

$J/\psi \rightarrow \mu^+ \mu^-$

high-multiplicity pPb events: $185 < N_{\text{trk,offline}} < 250$

Method: 2-dimensional two particle ($D^0$ or $J/\psi$ - charged particle) correlation for $v_2^{S+B}$ extraction

$|\Delta \eta| > 1$ to avoid short range correlations

$$\frac{1}{N_{D^0 or J/\psi}} \frac{dN_{\text{pair}}}{d\Delta \phi} = \frac{N_{\text{assoc}}}{2\pi} \left\{1 + 2 \sum_{n=1}^{3} V_{n\Delta} \cos(n\Delta \phi)\right\}$$
Heavy quarks in small pPb system

Extraction of $D^0$ and its flow in pPb collisions

**CMS HIN-17-003**
apXiv: 1804.09767
Submitted to PRL

high-multiplicity pPb events

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**CMS Supplementary**
apXiv:1804.09767

$pPb$ 8.16 TeV, $185 \leq N_{\text{trk}}^{\text{offline}} < 250$

$4.2 < p_T^{D^0} < 5.0$ GeV

$0.3 < p_T^{\text{ref}} < 3$ GeV

$|\Delta \eta| > 1$

1.7

1.8

1.9

2.0

Entries / (5 MeV)

10

20

30

40

$S+B$

Data

Fit

Signal

Combination

$\chi^2/\text{ndf} = 118/49$

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**CMS Supplementary**
apXiv:1804.09767

$pPb$ 8.16 TeV

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

$4.2 < p_T^{D^0} < 5.0$ GeV

$-1.46 < y_{\text{cm}} < 0.54$

$0.3 < p_T^{\text{ref}} < 3$ GeV

$|\Delta \eta| > 1$

Fourier fits

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05.06.2018

LHCP 2018, Bologna, Italy
$v_2$ of strange and charm hadron in pPb

- Potential residual back-to-back jet contribution from low-multiplicity pPb could be removed by subtraction
  
  \[ v_2^{\text{sub}} = v_2^{HM} - v_2^{LM} \frac{N_{\text{assoc}}^{LM}}{N_{\text{assoc}}^{HM}} \frac{Y^{HM}}{Y^{LM}} \]

- Significant magnitude of $v_2(D^0)$

- A clear mass ordering:
  - $p_T < 2.5$ GeV
  - $v_2(K^0_S) > v_2(\Lambda, \Xi^-, \Omega^-)$
  - $p_T > 2.5$ GeV
  - $v_2(K^0_S, D^0) < v_2(\Lambda, \Xi^-, \Omega^-)$

- At high $p_T$, $v_2(D^0)$ somewhat smaller wrt $v_2(K^0_S)$
\( v_2 \) of strange and charm hadron in \( pPb \)

- **pPb**
  - approximate \( n_q \)-scaling for lighter strange hadrons (better in \( PbPb \))
  - \( v_2(D^0) \) consistently lower: \( v_2(c) < v_2(u, d, s) \)

- less thermalization for \( c \) quarks due to much smaller system size?
Collectivity of Charmonia in small pPb system

- $v_2$ of $D^0$: is it flow of $u$ or of $c$ quarks?
- $J/\psi$: direct evidence for $c$ quark collectivity in a small pPb system
- Recombination of flowing $cc\bar{c}$ quarks?
- initial correlations from Glasma?
Heavy quarks in small pPb system

Extraction of J/ψ and its flow in pPb collisions

CMS Preliminary pPb 8.16 TeV

- 185 ≤ N_{trk}^{offline} < 250
- 6.0 < p_T < 8.0 GeV
- -2.86 < y_{cm} < -1.86 or 0.94 < y_{cm} < 1.94

χ^2/ndf = 99/81

- data
- Fit

J/ψ Signal
- Combinatorial

CMS Preliminary pPb 8.16 TeV

- 185 ≤ N_{trk}^{offline} < 250
- 6.0 < p_T < 8.0 GeV
- -2.86 < y_{cm} < -1.86 or 0.94 < y_{cm} < 1.94

χ^2/ndf = 3.0/4

- data
- Fit

CMS Preliminary pPb 8.16 TeV

- 185 ≤ N_{trk}^{offline} < 250
- 6.0 < p_T < 8.0 GeV
- 0.3 < p_{ref}^T < 3 GeV/c
- ∆η > 1

1 \frac{dN_{pair}}{d\Delta \phi} \ N_{J/ψ}

- Fourier fits

Δφ (radians)
**Prompt J/ψ meson $v_2$ in pPb**

![Graph showing $v_2$ vs $p_T$](image)

- significant $v_2$ of J/ψ – most direct evidence of c quark collectivity
- $v_2$ of J/ψ comparable with $v_2$ of D$^0$
  - low $p_T$: $v_2$ of J/ψ and $v_2$ of D$^0$ smaller wrt $v_2$ of K$^0_S$
  - high $p_T$: comparable $v_2$ of J/ψ and D$^0$, and somewhat smaller wrt K$^0_S$ mesons
Prompt J/ψ meson $v_2$ in pPb

- residual back-to-back jet contribution from low-multiplicity pPb removed by subtraction

$$v_{2}^{sub} = v_{2}^{HM} - v_{2}^{LM} \frac{N_{assoc}^{HM} Y_{jet}^{HM}}{N_{assoc}^{LM} Y_{jet}^{LM}}$$

- $n_q$-scaling shows that $v_2(D^0) \approx v_2(J/\psi) < v_2(K^0_S)$

- need stat. improvement at low $p_T$

- weaker collectivity of c quarks wrt the one of light quarks?
Sub-event symmetric cumulants in pPb

reaction plane – $\Psi_2$

Well understood in AA with hydrodynamics

Is there collectivity in small systems?

◆ Symmetric cumulants (SC) – based on 4-particle corr.
  ✦ Sensitive to initial state fluctuations and $\eta/s$

very low-multiplicity strongly affected by non-flow
  ✦ needed new method sensitive to it

◆ Sub-event symmetric cumulants (SC$_{sub}$)

$v_n$ depends on

• initial state geometry
• initial state fluctuations
• medium transport properties ($\eta/s$)

Larger suppression of non-flow contribution using more and more sub-events in $\eta$
Symmetric cumulants with sub-events in pPb

- SC with sub-events suppresses non-flow at low multiplicity
- At high multiplicity, results with and without sub-events are similar for SC(2,3)
  - Non-flow is not dominant in this region
- Reveals collectivity for \( N_{\text{trk}}^{\text{offline}} > 50 \)
- Different results between no- and sub-events at high multiplicity for SC(2,4)
  - \( SC_{\text{sub}} \) sensitive to other effects such as event-plane decorrelation – \( \Psi_2 \) dep. on \( \eta \)
SC and SC$_{\text{sub}}$ at high multiplicity

- negligible contribution from non-flow for SC(2,3)
- remaining contribution from non-flow in the no-subevents results for SC(2,4)
  - SC$_{\text{sub}}$ suppresses non-flow – differently for different number of sub-events
- there is difference among the SC$_{\text{sub}}$(2,4) results with unexpected ordering!
Again confirm small remaining contribution from non-flow for SC(2,3)

A significant contribution from non-flow in the case of SC(2,4)

★ Sensitivity to decorrelation? Or to something else?
Conclusions

- $D^0$ and $J/\psi$ flow in pPb
- Weaker collectivity wrt light quarks
- Follows a typical $n_q$-scaling
- At low $p_T$ better statistics needed

- $v_2$ vs $v_3$ and $v_2$ vs $v_4$ are studied
- $SC_{\text{sub}}$ suppresses non-flow
- To study impact of decorrelation on $SC_{\text{sub}}$
Backups
Scalar product method

**Used in PRL**120**(2018)202301**

\[
Q_n = \sum_{k=1}^{M} \sigma_k \cdot e^{i\phi_k} \quad \Rightarrow \quad v_n \{SP\} = \frac{\langle Q_n, D^0 Q_n^* \rangle}{\sqrt{\langle Q_n A \rangle^* \langle Q_n A \rangle \langle Q_n B \rangle^* \langle Q_n C \rangle^*}}
\]

\[
v_n^{S+B} (m) = \alpha (m) v_n^S + \left[ 1 - \alpha (m) \right] v_n^B (m)
\]

where

\[
\alpha (m) = \frac{S(m) + SW(m)}{S(m) + SW(m) + B(m)}
\]

- \( D^0 \rightarrow K^+\pi \)
- No PID for \( K \) and \( \pi \)

\[ |\Delta \eta| > 3 \]
Sub-event symmetric cumulants in pPb

reaction plane – $\Psi_2$

$v_n$ depends on
- initial state geometry
- initial state fluctuations
- medium transport properties ($\eta/s$)

multi-particle correlations - cumulants

$\langle \langle 2 \rangle \rangle = \langle \langle e^{in(\phi_1-\phi_2)} \rangle \rangle$
$\langle \langle 4 \rangle \rangle = \langle \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle \rangle$
$c_n \{2\} = \langle \langle 2 \rangle \rangle$
$c_n \{4\} = \langle \langle 4 \rangle \rangle - 2 \cdot \langle \langle 2 \rangle \rangle^2$
$v_n \{2\} = \sqrt{c_n \{2\}}$
$v_n \{4\} = \frac{\sqrt{\langle \langle 4 \rangle \rangle}}{\sqrt{\langle \langle 2 \rangle \rangle}}$

◆ symmetric cumulants (SC)

$SC(n,m) = \langle \langle 4 \rangle \rangle_{n,m,n,m} - \langle \langle 2 \rangle \rangle_{n,n} \langle \langle 2 \rangle \rangle_{m,m}$

◆ sub-event symmetric cumulants (SC$_{\text{sub}}$)

$SC_{2_{\text{sub}}}(n,m) = \langle \langle 4 \rangle \rangle_{n,m,n,m}^{ab\ b\ b^{*}} - \langle \langle 2 \rangle \rangle_{n,m}^{ab} \langle \langle 2 \rangle \rangle_{m,m}^{ab^{*}}$

$SC_{3_{\text{sub}}}(n,m) = \langle \langle 4 \rangle \rangle_{n,m,n,m}^{a^{*}\ b\ b\ c\ c^{*}} - \langle \langle 2 \rangle \rangle_{n,m}^{b\ b^{*}} \langle \langle 2 \rangle \rangle_{m,m}^{b\ c^{*}}$

$SC_{4_{\text{sub}}}(n,m) = \langle \langle 4 \rangle \rangle_{n,m,n,m}^{a\ b\ c\ d\ c^{*}} - \langle \langle 2 \rangle \rangle_{n,m}^{a\ c^{*}} \langle \langle 2 \rangle \rangle_{m,m}^{b\ d^{*}}$