New insights on heavy flavor dynamics and hadronization in the small systems with CMS

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Observations in large systems

• QGP fluid in nucleus-nucleus collisions
  • Collective motions – elliptic flow ($v_2$) and ridges
  • Coalescence process – baryon enhancement
• ...

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PRL 124 172301

arxiv:2112.08156
Observations in small systems

- Not expected at the beginning
  - Large and positive elliptic flow
  - Baryon enhancement
- …
Creation of tiny QGP?

- A small QGP droplet created – in-medium and final state effects
- Alternative explanations for collectivity:
  - Correlations established prior to collisions – initial state effects

![Diagram showing large nuclei on the left and small nucleon, low temperature (low energy density) on the right, with small nucleon, high density shown in the center.](image)
Explore the small system deeply

• If there are any in-medium effects
  • $\lambda_{m.f.p.} \ll L$
  • to test medium effects
    • Increase $\lambda_{m.f.p.}$
    • decrease $L$
Explore the small system deeply

• We need probes sensitive to
  • Initial correlations
  • Relative system size – $\lambda_{m.f.p.}/L$

• Light flavor particles (q)
  • Can be created anytime – lose the sensitivity to initial correlations
  • $\lambda_{m.f.p.}^q$ may be always small compared to system size
  • Hard to disentangle *initial and final state effects*
Explore the small system deeply

- We need probes sensitive to
  - Initial correlations
  - Relative system size – $\lambda_{m.f.p.}/L$

- Heavy flavor quarks (HF or Q)
  - Mostly created in initial stages
  - Evolve in the entire evolution of the system
  - $\lambda_{m.f.p.}^Q \gg \lambda_{m.f.p.}^q$
  - Sensitive to both initial correlations and in-medium effects!

$p$ Pb

HF

Light quark

$\text{time}$
Observables we are interested in

- HF flavor $v_2$
  - Open charm/bottom quarks, charmonia and bottomonia
- $v_2$ signal and its dependence on multiplicity (relative system size)
- Collisions geometry and dynamics, $v_2$ *driven by eccentricity*?
Open HF collectivity in pPb

- First time in pPb collisions – vanishing $v_2$ for b hadrons via non-prompt $D^0$

- Indication of flavor hierarchy between charm and bottom hadrons at low $p_T$

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Open HF collectivity in pPb

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Open HF collectivity in pPb

- Comparisons with CGC calculations – show consistency within large uncertainties

- Precision measurements in the future – HL-LHC with CMS MTD
Collectivity in even smaller system

- First measurement of prompt $D^0 v_2$ in high multiplicity pp collisions
- Indication of positive $v_2$ signal at $2 < p_T < 4$ GeV
- $v_2$ of prompt $D^0$ comparable with that of light hadrons

Multiplicity is defined in the same way as in pPb
System size dependence

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

• A new timing detector with timing resolution ~30ps
  • PID for Kaon up to 2.5 GeV
  • PID for proton up to 5 GeV
Opportunities at HL-LHC

- Uncertainties significantly reduced, from Run 2 to Run 4
  - A factor of 3 increase on luminosity, 186 nb\(^{-1}\) => 0.6 pb\(^{-1}\)
  - Better signal discriminating power, no PID => good PID
- CMS talk by Andre Govinda Stahl Leiton, 7 Apr 2022, 15:20

CMS-TP-2021-037

![CMS Phase-2](image1)

![CMS Phase-2](image2)
Opportunities in the future

- Insights from **LARGE** systems – fluctuations of elliptic flow
  - \( v_2 = \kappa \epsilon_2 \) where \( \epsilon_2 \) is the eccentricity of the collision geometry
  - *Event-by-event* fluctuations of \( \epsilon_2 \) lead to fluctuations of \( v_2 \)
  - \( \kappa \) can also fluctuate *event-by-event* if the system is *small*
  - Multi-particle correlation sensitive to fluctuations
    - \( v_2 \{4\}^2 \approx v_2^2 - \sigma^2, \quad v_2 \{2\}^2 \approx v_2^2 + \sigma^2 \)
Origin of $v_2$ fluctuations

- Insights from **LARGE** systems – fluctuations of elliptic flow
  - If fluctuations only from $\varepsilon_2$,
    \[
    \frac{v_2\{4\}(pT)}{v_2\{2\}(pT)} = \frac{v_2\{4\}}{v_2\{2\}} = \frac{\varepsilon_2\{4\}}{\varepsilon_2\{2\}}
    \]
  - If $k$ can fluctuate,
    \[
    \frac{v_2\{4\}(pT)}{v_2\{2\}(pT)} = \frac{v_2\{4\}}{v_2\{2\}} + \delta(pT)
    \]
  - Full equation for $v_2$ fluctuations, see PRC 95 (2017) 044901
  - Initial $\varepsilon_2$ fluctuations vs. final state (in-medium) $k$ fluctuations?
\( \nu_2 \) via multi-particle correlations

- **First time to measure charm \( \nu_2 \) using **multiple particle correlator**
- Correlator
  - \( \ll 2' \gg = \ll e^{i2(\phi(D_0^0)_1 - \phi^{ref}_2)} \gg \)
  - \( \ll 4' \gg = \ll e^{i2(\phi(D_0^0)_1 + \phi^{ref}_2 - \phi^{ref}_3 - \phi^{ref}_4)} \gg \)
  - \( \nu_2 \{4\} \) and \( \nu_2 \{2\} \) can be calculated from these correlator
- More info in PRC 83 (2011) 044913
Fluctuations of $v_2$

- Expected ordering between $v_2\{2\}$ and $v_2\{4\}$, $v_2\{4\} < v_2\{2\}$
Fluctuations of $v_2$

• The fluctuations of $D^0$ is comparable with charged particles – fluctuations are from $\epsilon_2$ dominately
Fluctuations across different system size

- $v_2\{4\}/v_2\{2\}$ for charm sectors are almost the same across different centrality classes – similar findings of charged particles – fluctuations almost from initial geometry
Fluctuations towards smaller systems

• Indication of splitting between charged particles and charm sectors – hint of fluctuations on energy loss towards smaller system

• Possible findings in pPb and pp collisions if medium effects are dominant?
Future opportunities via HF productions

• If there are any in-medium effects
  • Hadronization and its dependence on multiplicity – possible baryon enhancement for high multiplicity events?
Summary and outlook

• Evident charm collectivity in pPb collisions and indications of charm flow in pp collisions
• Elliptic flow signal diminishes towards lower event activity
• Hint of energy loss fluctuations in peripheral PbPb collisions
• Future opportunities with CMS-MTD
Backup
Opportunities at HL-LHC

• A new timing detector with timing resolution 30ps
  • Barrel Timing Layer: scintillating crystals and SiPM device
  • Endcap Timing Layer: Low Gain Avalanche Detector
• Both Langevin processes and the processes of radiational energy loss describe the tendency but not quantitatively – data put strong constraints on theoretical models (PRC 102 (2020) 024906)
Models

• Both Langevin processes and the processes of radiational energy loss describe the tendency but not quantitatively – data put strong constraints on theoretical models (PRC 102 (2020) 024906)
Opportunities in the future

- Zhang et al. predict large $v_2$ for $\Upsilon$ and prompt $J/\psi$ based on CGC
- Vanishing $v_2$ for $\Upsilon$ in pPb and PbPb – not expect large $v_2$ in pPb intuitively based on in-medium effects
- CMS talk by Kisoo Lee, 6 Apr 2022, 15:20