Heavy flavor collectivity in small systems

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Collectivity in small systems?

- Detailed flow measurements in pp/pPb indicate that
  - centrality/event activity and \( p_T \) dependence qualitatively similar to that in AA
  - identified particle and multiparticle correlation techniques support a collective origin of \( v_n \)
    - encompassed by hydrodynamical models, but not a unique description

- We start answering whether a collective component in \( v_n \) exists by studying
  - the role of the initial conditions
  - the impact of hard-scattering processes and energy loss
  - alternative systems, e.g., ultraperipheral collisions (UPC)

![Graph showing \( v_2 \) measurements in various collision conditions](image)
Key features of heavy flavor measurements

- Variety of meson/baryon states with different flavors in a broad kinematic range
  - techniques to separate heavy from light flavor decays

- We gain insight on
  - whether heavy quarks flow with the bulk
  - parton interactions in the QGP (thermalization, energy loss,...)
  - QGP properties (transport coeff)
  - pQCD predictions, parton shower modeling, hadronization mechanisms

PRL 126 (2021) 162001

PRL 124 (2020) 082301

PLB 813 (2021) 136036
Measuring HF particle flow in PbPb

Heavy-flavor hadrons and their decay products are effective probes of QGP

- a series of measurements with, e.g., $D^0$, $J/\psi$, $\Upsilon(nS)$, and heavy-flavor decay leptons

- extension to studies of EM fields effects, e.g., no rapidity dependence of $\Delta v_2$ ($D^0-\bar{D}^0$)

- The harmonics for $c$ mesons are comparable to the light-flavor hadrons

- Closer to zero anisotropy observed for nonprompt $D^0$, $\Upsilon(nS)$ or beauty decay electrons/muons

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PRL 126 (2021) 162001

PLB 819 (2021) 136385

PLB 807 (2020) 135595
Observation of c flow

- the number-of-constituent-quark ($n_q$) scaling holds for $K E_T/n_q < 1 \text{ GeV}$
- model with final-state interactions underestimates the $v_2$ signal

First measurements of b flow

- indication of flavor hierarchy between light, charm, and beauty at low $p_T$
- qualitative agreement with CGC calculations and data → an important role for initial-state effects?

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**PLB 791 (2019) 172**

**PLB 813 (2021) 136036**
First measurements of c and b flow

- no dependency on track multiplicity
- charm \( v_2 > 0 \) decreasing with \( p_T \) (similar to charged hadrons)
- bottom \( v_2 - 0 \)

No calculation yet available in the smallest systems

- in PbPb we can describe the larger \( v_2 \) for D than B mesons at \( p_T < 10 \) GeV while being similar above

\[ \text{PRL 124 (2020) 082301} \]
Comparing HF particle flow in all systems

There is charm anisotropy... everywhere

- apparent ordering: \( v_2 \) (PbPb) > \( v_2 \) (pPb) > \( v_2 \) (pp)
  - so system size should play a role?

For open bottom hadrons: \( v_2 \) (PbPb) > 0 but \( v_2 \) (pPb) - \( v_2 \) (pp) - 0

- do we hit some threshold between charm and beauty processes?

Novel input to the description of heavy-quark transport and energy loss in small systems

C. Mironov (HP2020)
New measurements of $\Lambda_c^+$ cross section **down to** $p_T = 0$

- significant difference wrt to pp in $\Lambda_c^+/D^0 \to$ radial flow or multiplicity dependence of hadronization?
  - challenging further the universality of hadronization process
- $R_{pPb} > 1$ for $4 < p_T < 8$ GeV → radial flow or hadronization?
  - similarities with the strange sector
- significant suppression for $p_T < 2$ GeV/c
  - precision of $\Lambda_c^+/D^0$ and $R_{pPb}$ measurements **improved** thanks to the pPb (2016) and pp ref samples
Long-range angular correlations in heavy ion as well as high-multiplicity pPb&pp collisions identified particle and multiparticle correlation techniques support a collective origin of $v_n$

Comprehensive studies of heavy flavor collectivity in all systems

- $c$ quark flow is comparable to light quark whereas that of $b$ quarks closer to 0 in PbPb
- charm $v_2$ in pPb&pp is significant, but lower than in PbPb
- $b$ flows in PbPb, but seems not in pPb or pp

Future data with improved precision will provide crucial insights

- for example $\Lambda_c^+/D^0$ and $\Lambda_c^+ R_{pPb}$ measurements improved thanks to the pPb (2016) and pp ref samples
Long-range ($2 < |\Delta \eta| < 4$), near-side ($\Delta \phi \approx 0$) angular correlations are seen at LHC at various $\sqrt{s}$ in

- heavy ion (XeXe and PbPb), and
- “small systems”, i.e., high-multiplicity pPb and pp collisions

Signs reminiscent of collective behavior of a quark-gluon plasma (QGP)

JHEP 09 (2010) 091 (also in [1])
PLB 718 (2013) 795 (also in [2])
JHEP 07 (2011) 076 (also in [3])
Understanding collectivity in small systems

- Correlation between $v_n$ and the event mean $p_T$ (radial flow) sensitive to initial conditions
  - $v_2 - [p_T]$ in pPb favors a more compact initial state $\rightarrow$ stronger flow and prominent ridge
- Process-dependent $v_n$ can distinguish complementary particle production mechanisms
  - $v_{2,3}$ similarity (ordering) in MB vs jet-triggered pPb events indicative of flow (soft+hard admixture)
  - $v_{2-4}$ largely independent of whether measured in jet enriched/depleted pp events [8]
- Photonuclear collisions in UPC offer an alternative dynamics of small systems
  - competing explanations can be tested in cases one of the “beams” has a simpler initial state
  - both ATLAS and CMS see significant $v_2$ in UPC PbPb [9] and pPb collisions, respectively

Schenke et al, PRC 102 (2020) 034905

EPJ C 80 (2020) 73

CMS-PAS-HIN-18-008
Flow harmonics in heavy ion collisions

- Detailed measurements of up to $v_7$ ($v_6$) in PbPb (XeXe [4, 5]) collisions
  - found positive with their magnitude dependent on the particle species and method of calculation
    - heavier particles “flow more”; level of nonflow suppression and flow fluctuations impact $v_n$
  - centrality dependence – $v_n$ are the largest in the 20-50% central events
    - $v_{n>3}$ show a weaker dependence
  - $p_T$ dependence – an increase up to 3 GeV, depending on centrality, and then gradually decreasing
  - empirical scaling behaviors seen
    - for fixed $n$ same scaled shape as a function of scaled $p_T$ across centrality
    - the ratio $(v_n/v_m)^{n/m}$ for two harmonics $m$ and $n$ is independent of $p_T$ in a given centrality

EPJ C 78 (2018) 997 (also in [6])
**Prompt D⁰ v₂ in pp and Υ(nS) v₂ in PbPb**

- **First** measurement with high-multiplicity events in pp
  - v₂ ≠ 0; close to the v₂ of light flavors

- Flow of bottomonia in PbPb
  - Precise Υ(1S) v₂ consistent with 0
  - **First** Υ(2S) v₂ measurement consistent with 0 too
    - in contrast to larger J/ψ v₂
Prompt $D^0$ $v_2$ and $v_3$ in PbPb

- Multidifferential in $p_T$, $|y|$, and centrality
  - $v_2$, $v_3$ as expected from collision geometry
- Search for strong EM fields effects
  - **no** sign of rapidity dependence of $\Delta v_2 (D^0-\bar{D}^0)$

(accepted by PLB)
Flow harmonics in XeXe collisions

- Detailed measurements of $v_2$-$v_6$
  - $p_T$ dependence similar to that in PbPb
  - Centrality dependence – $v_2$ higher (lower) than PbPb in most central ( peripheral) events
    - Weaker dependence with higher $n$
    - Qualitatively consistent with theoretical predictions
  - Scaling behaviors from PbPb observed to hold in XeXe too
  - XeXe $v_n$ and the cross-system comparisons an opportunity to improve the current modeling

![Graph showing $v_n$ vs. centrality for XeXe and PbPb collisions](image)
Reconstruction of muons from c and b hadron decays separated from π/K bkg using

- the momentum imbalance $\rho = (p_{\text{ID}} - p_{\text{MS}})/p_{\text{ID}}$
- between the inner detector and muon spectrometer
- real muons have a $\rho$ distribution peaked around zero
- π/K bkg a broader $\rho$ shifted towards higher values
- the transverse impact parameter $d_0$
- different $d_0$ due to c and b hadrons’ decay lengths