High Energy Physics and Instrumentation Center at USP

Heavy-flavor R_{AA} and event-by-event v_n correlations in heavy ion collisions

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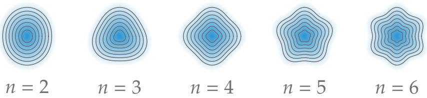
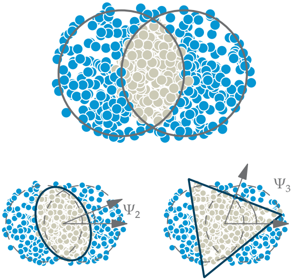
Quark Matter 2017

Chicago-US — February 5–11, 2017

Observables

- Nuclear modification factor;
- Collective flow;
  - Higher order coefficients: v_3 for heavy flavor!
- Multiparticle cumulants:
  - Unambiguous measurement;
  - Account for event-by-event flow fluctuations;





Multiparticle cumulants

- Event-plane method is obsolete:

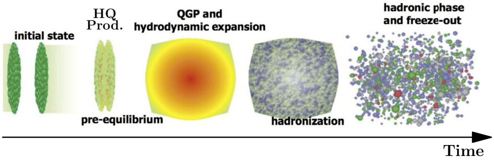
  Luzum M. and Ollitrault J.Y. PRC **87**, 044907 (2013).

  - Ambiguous results;
  - $v_n\{2\}$ and $v_n\{4\}$ already have all information contained in $v_n\{EP\}$.
- Using Q-Cumulants method define $v_n\{m\}$:

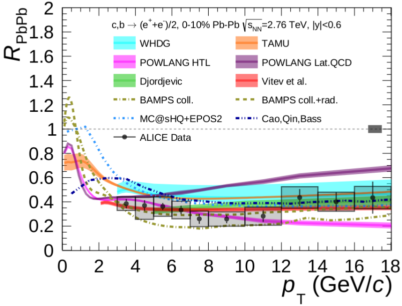
  Bilandzic A. *et al*, PRC **83** 044913 (2011), PRC **89** 064904 (2014)

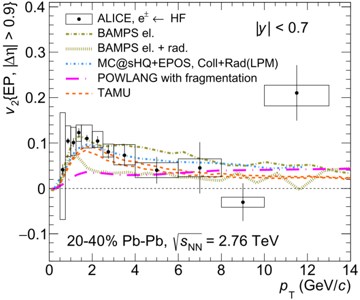
  - $v_n\{2\}(p_T) = \dfrac{d_n\{2\}(p_T)}{\left(c_n\{2\}\right)^{1/2}}$
  - $v_n\{6\}(p_T) = \dfrac{d_n\{6\}(p_T)}{\left[4(c_n\{6\})^5\right]^{1/6}}$
  - $v_n\{4\}(p_T) = \dfrac{-d_n\{4\}(p_T)}{\left(-c_n\{4\}\right)^{3/4}}$
  - $v_n\{8\}(p_T) = \dfrac{-d_n\{8\}(p_T)}{\left[33(-c_n\{8\})^7\right]^{1/8}}$
- Reference m-particle cumulants:
  - $c_n\{2\} = \langle\langle 2\rangle\rangle$
  - $c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2$
  - $c_n\{6\} = \langle\langle 6\rangle\rangle - 9\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\langle\langle 2\rangle\rangle^3$
  - $c_n\{8\} = \langle\langle 8\rangle\rangle - 16\langle\langle 6\rangle\rangle\langle\langle 2\rangle\rangle - 18\langle\langle 4\rangle\rangle^2 + 144\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle^2 - 144\langle\langle 2\rangle\rangle^4$
- Correct wide centrality bins with multiplicity weighting.

Current Picture



- Hard in general to get both observables right;
- Try new observables in order to distinguish models.





arXiv:1609.07104 [nucl-ex] (2016)

JHEP **09**, 028 (2016)

Open questions in heavy flavor

- What happens with the higher flow harmonics?
- How does the collision energy affects these observables?
- Is there collectivity in the heavy flavor sector?
- How do fluctuations in an event-by-event approach affect these observables?

DAB-MOD — A modular simulation

Prado *et al*, arXiv:1611.02962 [nucl-th] (2016)

- Monte Carlo simulation (C++ with ROOT and Pythia8);
- Modules:
  - Energy loss model;
  - Hadronization;
  - Meson decay.
- Different models can be freely plugged in/out;
- Possible to run the simulation on top of any hydrodynamics code;
- Heavy quarks (bottom and charm) are probes:
  - Sampled at the beginning of simulation;
  - Evolved with the medium;
  - We currently neglect any effect of the probes on the medium.
- Currently no coalescence is implemented (future work).

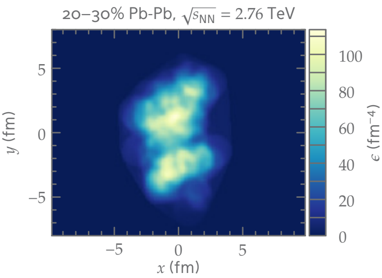
Initial Conditions

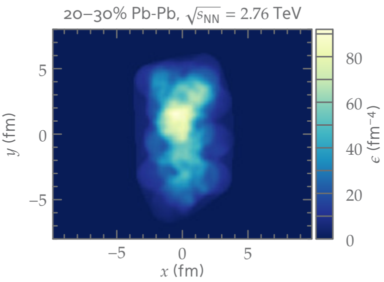
Noronha-Hostler *et al*, PRL **116**, 252301 (2016), PRC **90**, 034907 (2014), PRC **88** 044916 (2013)

- MCKLN initial conditions + v-USPhydro;
- 2D profiles:
  - Energy density;
  - Temperature;
  - Transverse velocity.

- Heavy quarks initial state:
  - Position: number of binary collisions;
  - Momentum: FONLL;
  - Direction: random.

Cacciari *et al*, JHEP **1210**, 137 (2012)





Prado *et al*, arXiv:1611.02962 [nucl-th] (2016)

Energy Loss and Hadronization

- Energy loss parametrization: $\frac{\mathrm{d}E}{\mathrm{d}x}(T,v) = \alpha\Gamma_{\mathrm{flow}}$.

  Das *et al*, PLB **747** 260–264 (2015)

  - Simple model; can be replaced anytime for more realistic ones;
- Flow factor: $\Gamma_{\mathrm{flow}} = \gamma\left[1 - v\cos(\varphi_{\mathrm{quark}} - \varphi_{\mathrm{flow}})\right]$.

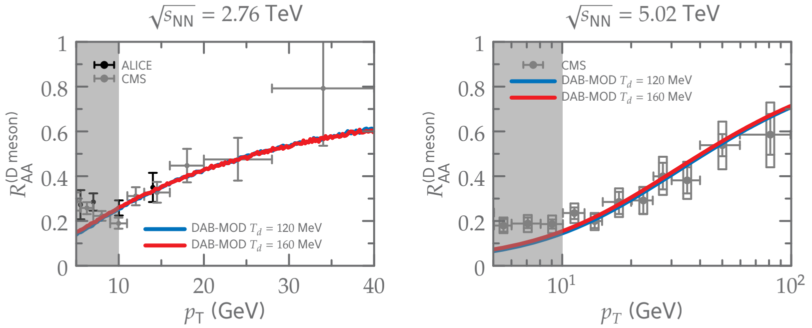
  Armesto *et al*, PRC **72** 064910 (2005); Noronha-Hostler *et al*, PRL **116**, 252301 (2016)

  - Couples differences in path length in the medium to energy loss experienced by partons.
- Free parameter α fit:
  1. Fit α_{charm} using D meson R_{AA} data;
  2. Fit α_{bottom} using B meson or electron R_{AA} data;

Nuclear modification factor

- Collision energies: 2.76 TeV and 5.02 TeV;
- After fitting α, temperature has little influence on R_{AA} results.

D meson R_{AA}; 0–10% Pb-Pb



JHEP **03**, 081 (2016) (ALICE)

CMS-PAS-HIN-16-001 (2016)

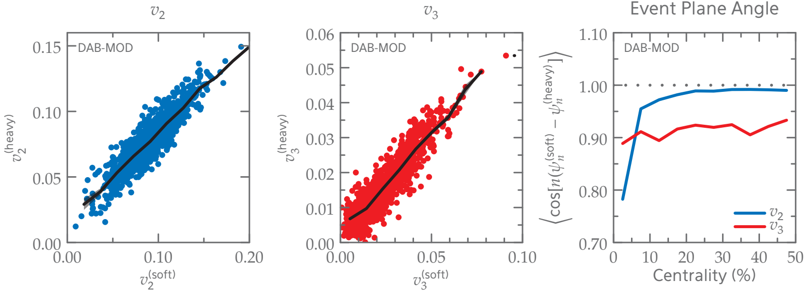
CMS-PAS-HIN-15-005 (CMS)

*Gray area: where coalescence may be important.

Flow Harmonics

- 2-particle correlation: $v_n\{2\}(p_T) = \frac{\left\langle v_n^{(\text{heavy})}(p_T) v_n^{(\text{soft})} \cos\left[n\left(\psi_n^{(\text{heavy})}(p_T) - \psi_n^{(\text{soft})}\right)\right]\right\rangle}{\sqrt{\left\langle \left(v_n^{(\text{soft})}\right)^2 \right\rangle}}.$
  - This formula maximizes v_n.
  - Heavy and soft sectors have the medium as the same underlying cause for flow;

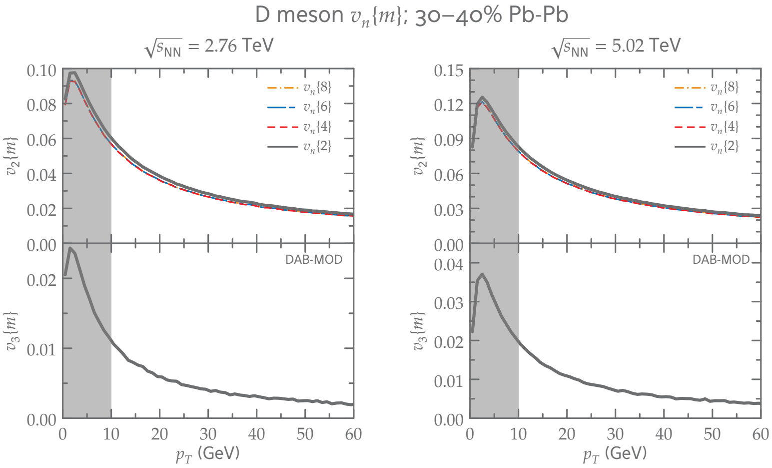
D meson; 30–40% Pb-Pb, $\sqrt{s_{\text{NN}}} = 5.02$ TeV



Noronha-Hostler *et al*, PRL **116**, 252301 (2016) Nahrgang *et al*, PRC **91**, 014904 (2015)

Cumulants

- 2, 4, 6 and 8-particle correlations for v_2 and $v_3\{2\}$.



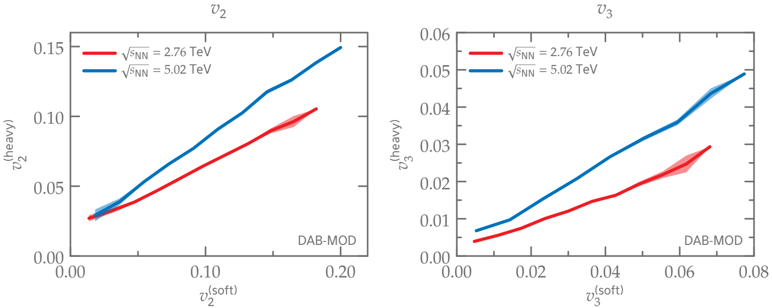
*Gray area: where coalescence may be important.

Soft-Heavy Event Engineering

ATLAS Coll., PRC **92**, 034903 (2015)

- Heavy-soft correlation is affected by the collision energy;
- Only possible to compute in event-by-event analysis;

D meson v_n; 30–40% Pb-Pb



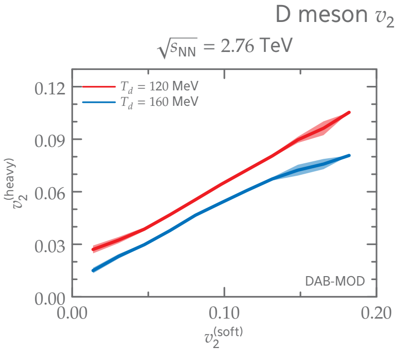
...see also Dobrin's talk: Tue 2pm

Soft-Heavy Event Engineering

HEPIC USP

ATLAS Coll., PRC **92**, 034903 (2015)

- Heavy-soft correlation is also affected by T_d;
- With higher T_d quarks lifetime within the plasma is shortened leading to smaller v_n.

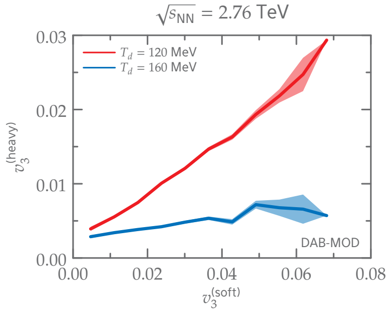


Soft-Heavy Event Engineering

ATLAS Coll., PRC **92**, 034903 (2015)

- v_3 is heavily affected by the change of temperature!

D meson v_3; 30–40% Pb-Pb

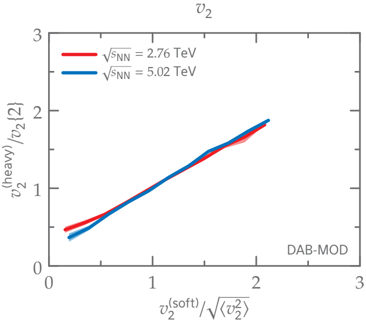


Soft-Heavy Event Engineering

- By normalizing the axes all the correlation curves superpose;
- This is a direct consequence of the linear response between v_2 and ε_2 both in the heavy and the soft sector.

Prado *et al*, arXiv:1611.02962 [nucl-th] (2016); Noronha-Hostler *et al*, arXiv:1609.05171 (2016)

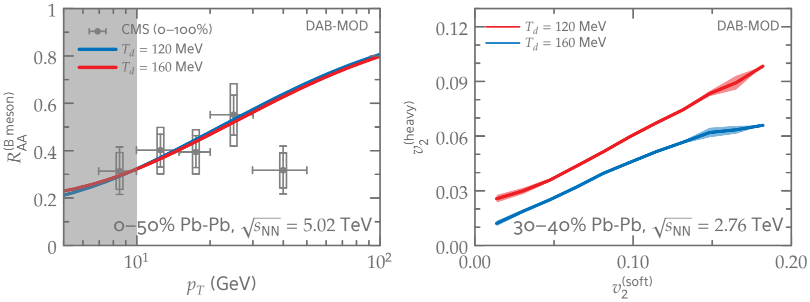
D meson v_n; 30–40% Pb-Pb



Quick look at B meson

- Preliminary results for B meson.

B meson R_{AA} and v_2



CMS-PAS-HIN-16-011 (2016)

*Gray area: where coalescence may be important.

Conclusions and outlook

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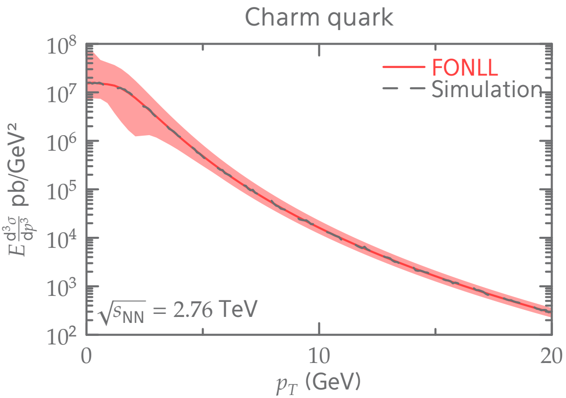
- DAB-MOD (D and B mesons MODular code): A new framework to study heavy probes in an event-by-event hydrodynamics expanding QGP;
- Soft-heavy engineering:
    - One can compute the event-by-event correlations between soft and heavy sectors;
    - Leads to a new observable which can provide a novel signature of collectivity in the heavy flavor sector;
    - Needs experimental data for confirmation.
- Future work:
    - Improvement in the low-p_T sector;
    - Correlations between v_n in the heavy-flavor sector;
    - Check the influence of a T dependent shear and bulk viscosities;

Backup

Heavy-flavor production

- Quark initial momentum: pQCD (FONLL).
- Quark initial direction (φ): random;



Cacciari *et al*, JHEP **1210**, 137 (2012)

Hadronization and Decays

- Hadronization:
  - Heavy quarks hadronize after crossing the T_{d} isothermal.
  - We use Peterson fragmentation function:

$$D(z) \propto \frac{1}{z\left(1 - \frac{1}{z} - \frac{\varepsilon}{1-z}\right)^2};$$

  - The parameter ε is fitted to reproduce FONLL calculations;
  - Neglect coalescence: focus on the intermediate regime ($p_T > 10$ GeV).
- Decays:
  - Performed using Pythia8;
  - Only semi-leptonic channels selected;

Hydrodynamics

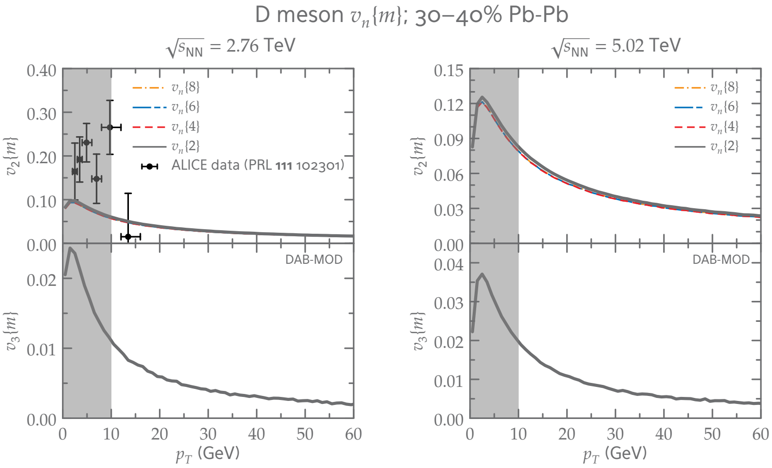
- Viscous event-by-event 2D+1 hydrodynamics:

  Noronha-Hostler *et al*, PRL **116**, 252301 (2016), PRC **90**, 034907 (2014), PRC **88** 044916 (2013)

  - v-USPhydro code;
  - MCKLN initial conditions;
  - Fast computational time;
  - Well tested code that fits data for soft flow harmonics!
- Freeze-out: Cooper-Frye prescription:
  - Includes viscous corrections;
  - Decoupling temperature $T_\mathrm{d} = 120$ MeV.

Cumulants

- 2, 4, 6 and 8-particle correlations for v_2 and $v_3\{2\}$.



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Noronha-Hostler *et al*, PRC **93**, 014909 (2016)

D meson v_n; 30–40% Pb-Pb $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV