High Energy Physics and Instrumentation Center at USP

Heavy flavor R_{AA} and v_n in event-by-event viscous relativistic hydrodynamics

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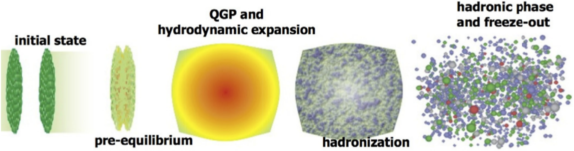
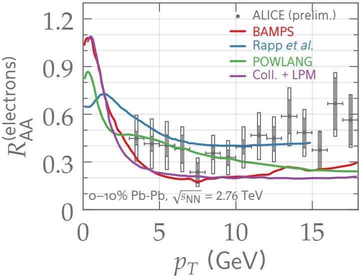
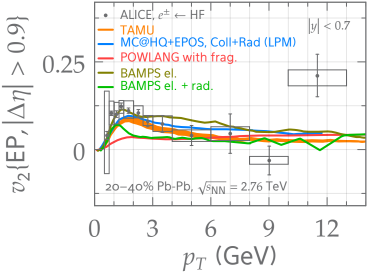
Strangeness in Quark Matter 2016

UC Berkeley — June 30, 2016

Status quo







(QM2015) AIP Conference Proceedings **1625**, 226–229 (2014)

arXiv:1606.00321

Open questions

- What happens with the higher Fourier harmonics?
- How sensitive are these observables to the energy loss model?
- Is there collectivity in the heavy flavor sector?
- How do fluctuations in an event-by-event approach affect these observables?

Observables

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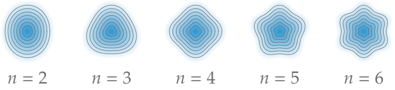
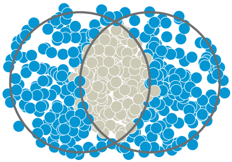
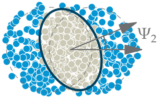
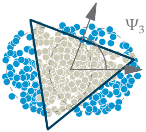
- Nuclear Modification Factor: $R_{\mathrm{AA}}(p_T, \varphi) = \dfrac{\frac{\mathrm{d}N_{\mathrm{AA}}}{\mathrm{d}p_T\,\mathrm{d}\varphi}}{N_{\mathrm{coll}}\frac{\mathrm{d}N_{\mathrm{pp}}}{\mathrm{d}p_T}}$;
- Collective flow:
$$E\frac{\mathrm{d}^3N}{\mathrm{d}p^3} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_T\,\mathrm{d}p_T\,\mathrm{d}y}\left\{1 + \sum_n 2v_n \cos\left[n\left(\varphi - \Psi_n\right)\right]\right\};$$





- Multi-particle Cumulants:
  - 2-, 4-, 6- and 8-particle.





Details of the modeling

- Develop a Monte Carlo simulation;
  - C++ programming language;
  - ROOT and Pythia8.
- Modular paradigm (QCD factorization):
  - Initial conditions (MCKLN);
  - Event-by-event hydrodynamics (v-USPhydro);
  - Energy loss model;
  - Hadronization;
  - Meson decay;
- Heavy quarks (bottom and charm) are probes:
  - What happens in the heavy-flavor sector?
  - High multiplicity experiments allow for the heavy-flavor study.
  - Sampled at the beginning of the simulation and evolved with the medium.
  - We currently neglect any effect of the probes on the medium.

Energy Loss and Hadronization

- Simple energy loss model: $\frac{\mathrm{d}E}{\mathrm{d}x}(T,v;\alpha) = \alpha\Gamma_{\text{flow}} f(T,v)$;

$$\Gamma_{\text{flow}} = \gamma\left[1 - v\cos(\varphi_{\text{quark}} - \varphi_{\text{flow}})\right].$$

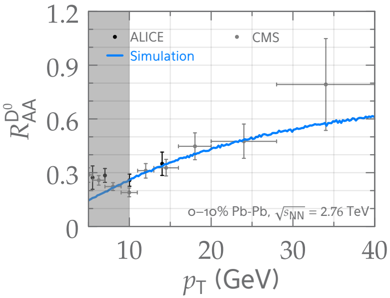
PRC **72** 064910 (2005); arXiv:1602.03788 [nucl-th].

  - Fit the α parameter:
    1. Fit α_{charm} using D^0 R_{AA} data;
    2. With fixed α_{charm}, fit α_{bottom} using electron R_{AA} data;
  - The energy loss model can be changed at will.
- Hadronization using Peterson fragmentation function:
  - Occurs after heavy-quarks have crossed T_{frag} isothermal;
  - Currently not implementing coalescence;
- Decays performed by Pythia8.

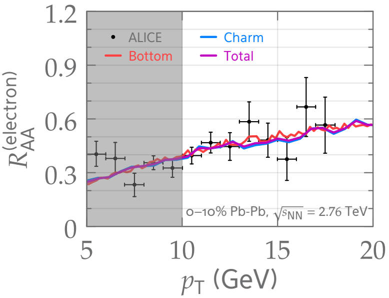
Nuclear modification factor

- $\frac{\mathrm{d}E}{\mathrm{d}x} = \alpha\Gamma_{\text{flow}}$ $\qquad T_{\text{frag}} = 140$ MeV. PLB **747** 260–264 (2015)

D^0 R_{AA}



Electron R_{AA}

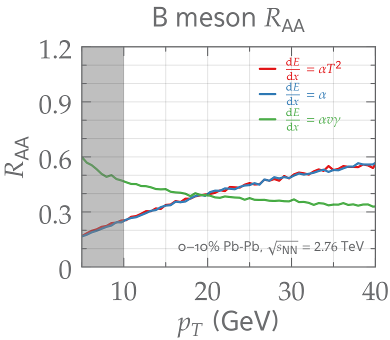


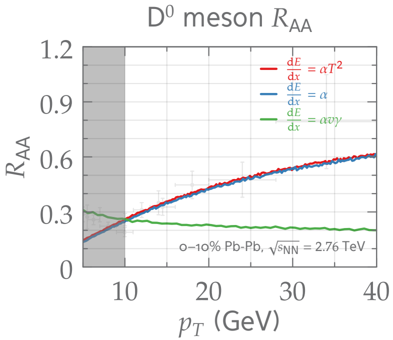
*Gray area: where coalescence should be important.

QM2015 (ALICE); CMS-PAS-HIN-15-005 (CMS) (QM2015) AIP Conference Proceedings **1625**, 226–229 (2014)

Nuclear modification factor

- R_{AA} is highly affected by the energy loss model!
- $T_{frag} = 140$ MeV.





Multi-particle cumulants

First calculation of cumulants event-by-event for heavy-quarks!!!

- $c_n\{4\} = \langle\langle 4\rangle\rangle - 2\,\langle\langle 2\rangle\rangle^2$

$$v_n\{4\}(p_T) = \frac{-d_n\{4\}}{\left(-c_n\{4\}\right)^{3/4}};$$

- $c_n\{6\} = \langle\langle 6\rangle\rangle - 9\,\langle\langle 4\rangle\rangle\,\langle\langle 2\rangle\rangle + 12\,\langle\langle 2\rangle\rangle^3$

$$v_n\{6\}(p_T) = \frac{d_n\{6\}}{\left[4(c_n\{6\})^5\right]^{1/6}};$$

- $c_n\{8\} = \langle\langle 8\rangle\rangle - 16\,\langle\langle 6\rangle\rangle\,\langle\langle 2\rangle\rangle - 18\,\langle\langle 4\rangle\rangle^2 + 144\,\langle\langle 4\rangle\rangle\,\langle\langle 2\rangle\rangle^2 - 144\,\langle\langle 2\rangle\rangle^4$

$$v_n\{8\}(p_T) = \frac{-d_n\{8\}}{\left[33(-c_n\{8\})^7\right]^{1/8}}.$$

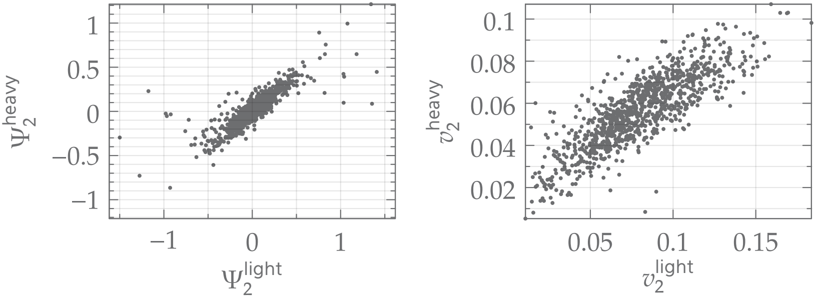
PRC **83** 044913 (2011); PRC **89** 064904 (2014); CMS-PAS-HIN-15-014 (CMS).

Elliptic flow

- Correlation between light quarks in a small p_T bin and heavy quarks:

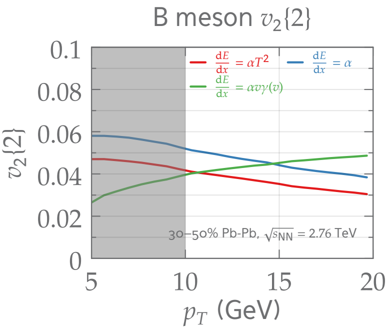
$$v_n\{2\}(p_T) = \frac{\left\langle v_n^{\text{heavy}}(p_T)v_n^{\text{light}} \cos\left[n\left(\Psi_n^{\text{heavy}}(p_T) - \Psi_n^{\text{light}}\right)\right]\right\rangle}{\sqrt{\left\langle\left(v_n^{\text{light}}\right)^2\right\rangle}}.$$

- Heavy sector inherits geometrical fluctuations of soft sector; PRL **116** 252301 (2016).



$v_2\{2\}$ — Energy loss dependence

- $T_{\text{frag}} = 140$ MeV;
- $v_2\{2\}$ depends heavily on the energy loss model.



$v_2\{2\}$ — T_{frag} dependence

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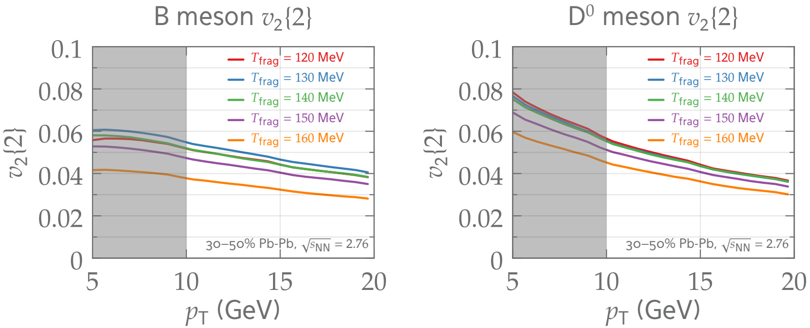
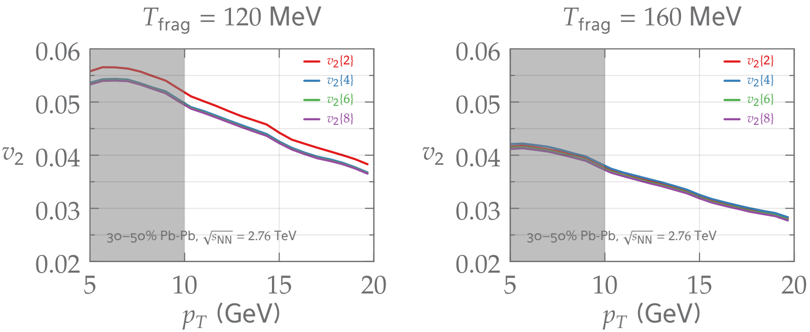
- $\frac{dE}{dx} = \alpha\Gamma_{\text{flow}}$;
- The increase of T_{frag} decreases the flow.



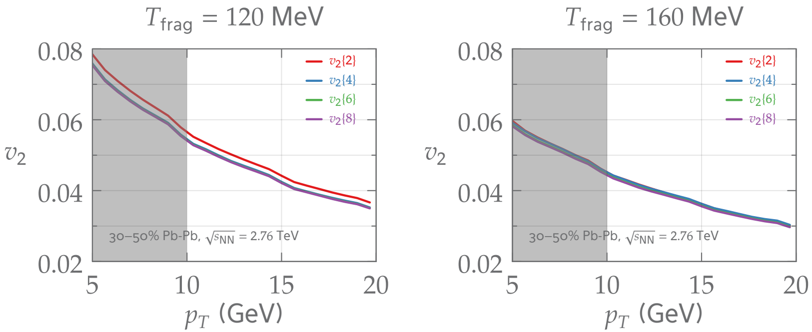
Convergence of cumulants!

- $\frac{dE}{dx} = \alpha\Gamma_{\text{flow}}$ B meson;
- Convergence may indicate collectivity in the heavy sector.



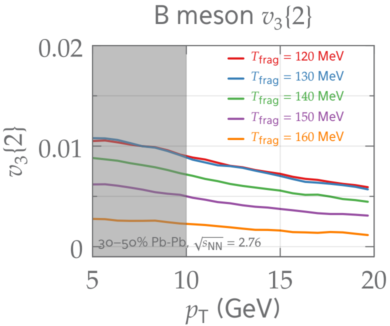
Convergence of cumulants!

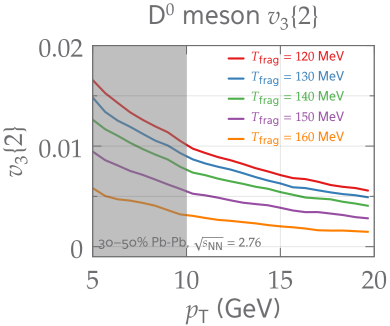
- $\frac{\mathrm{d}E}{\mathrm{d}x} = \alpha\Gamma_{\mathrm{flow}}$ D^0 meson.
- Convergence may indicate collectivity in the heavy sector.



v_3 for heavy flavor!

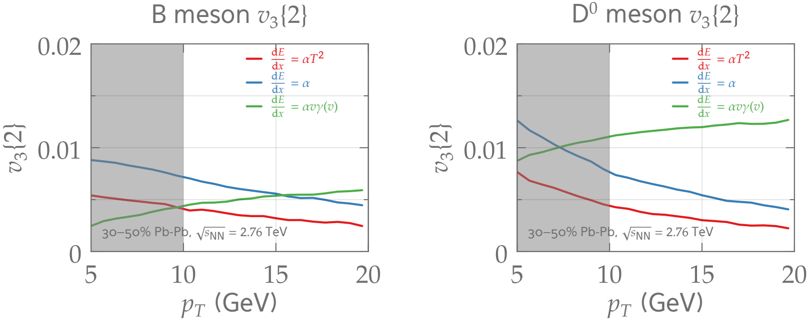
- $\frac{dE}{dx} = \alpha \Gamma_{\text{flow}}$;
- First calculation of $v_3\{2\} \neq 0$ for heavy-quark!!!
- $v_3\{2\}$ also decreases with the increase of T_{frag}.





v_3 for heavy flavor!

- $T_{\text{frag}} = 140$ MeV.
- $v_3\{2\}$ very sensitive to energy loss models;



Conclusions and outlook

- New framework to study hard probes in an event-by-event hydrodynamics expanding QGP;
- First prediction of heavy-quark cumulants:
  - Convergence of cumulants: collectivity in the heavy-flavor sector?
- First prediction of $v_3\{2\}$ for heavy-flavor;
- Future work:
  - Improvement in the low-p_T sector;
  - Correlations between v_n in the heavy-flavor sector;
  - Soft hard event engineering in the heavy-flavor sector;
  - Check the influence of a T dependent shear and bulk viscosities;
  - Check different beam energies;
  - Symmetric cumulants SC(n, m).

Backup

Initial Conditions

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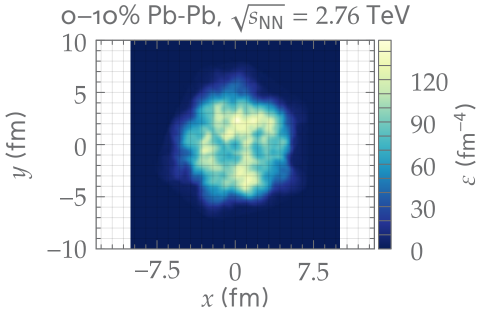
- Actual input of the program;
- 2D profiles for the hydro:
  - Energy density;
  - Temperature;
  - Transverse velocity;



- MCKLN initial conditions;
- Quarks position given by number of binary collisions;
  - Initial momentum distribution given by pQCD (FONLL).

Hydrodynamics

- Viscous event-by-event 2D+1 hydrodynamics: v-USPhydro [1]:
  - $\eta/s = 0.11$;

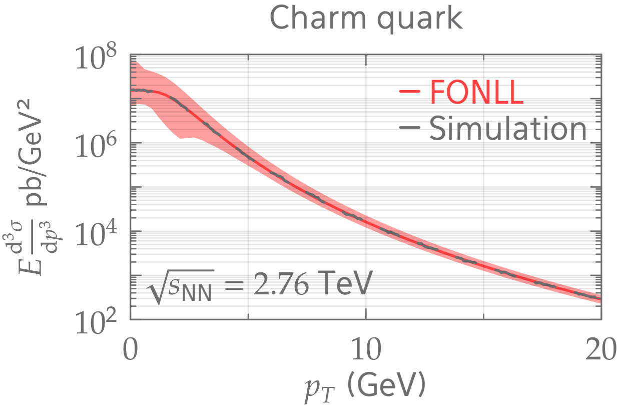
$$T^{\mu\nu} = \varepsilon u^{\nu} u^{\nu} - p\Delta^{\mu\nu} + \pi^{\mu\nu}, \qquad \partial_{\mu} T^{\mu\nu} = 0$$

- Equations of motion solved using Smoothed Particle Hydrodynamics (SPH) algorithm:
  - SPH-particles: Lagrangian method;
  - Fast computational time;
  - Well tested algorithm.
- Freeze-out: Cooper-Frye prescription including viscous corrections.
  - $T_{\mathrm{FO}} = 120$ MeV.

[1] arXiv:1602.03788 (2016), PRC **90**, 034907 (2014); PRC **88** 044916 (2013)

Heavy-flavor production

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

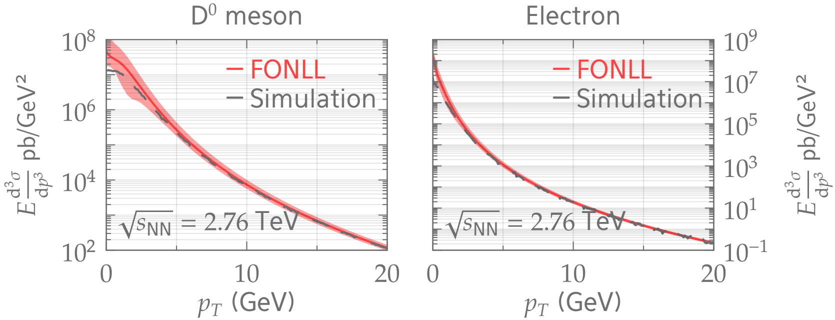


JHEP **1210**, 137 (2012)

Heavy-flavor production

Check consistency of the code:

- Turn off energy loss: get the same as FONLL predictions.



JHEP **1210**, 137 (2012)

Hadronization and Decays

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

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

  - Currently we're not implementing coalescence (future work);
- Decays:
  - Performed using Pythia8;
  - Only semi-leptonic channels selected;