Heavy flavour dynamics in event-by-event viscous hydrodynamic backgrounds

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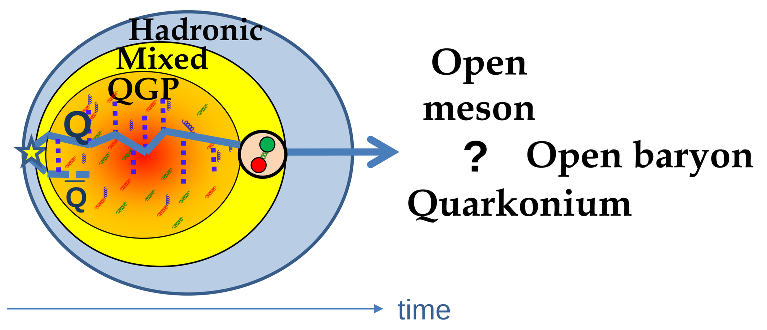
Abstract: Heavy flavour probes provide important information about the in-medium properties of the quark gluon plasma produced in heavy-ion collisions. In this work, we investigate the effects of (2+1)d event-by-event fluctuating hydrodynamic backgrounds on the nuclear suppression factor and momentum anisotropies of heavy flavour mesons and non-photonic electrons [1]. Using the state-of-the-art D and B mesons modular simulation code (the so-called "DAB-Mod"), we perform a systematic comparison of different transport equations, including a few energy loss models - with and without energy loss fluctuations - and a relativistic Langevin model with different drag parametrizations.
We present the resulting D and B mesons R_{AA}, v_2, v_3 and v_4 as well as their multiparticle cumulants, in Au-Au collisions at 200 GeV and Pb-Pb collisions at 5.02 TeV, and compare them to the latest experimental data. We also study the linearity of the resulting heavy meson and soft hadron flow correlations, as new experimental observables that could provide greater insight into flow fluctuations, and compare for the first time our predictions with ALICE preliminary measurements of D meson v2 vs q2 in Pb-Pb collisions at 5.02 TeV.
[1] C. Prado, J. Noronha-Hostler, R. Katz, A. Suaide, J. Noronha and M. Munhoz, Nucl. Phys. A 967 (2017) 664-667 [arXiv:1704.04654]; Phys. Rev. C 96 (2017) 064903 [arXiv:1611.02965]

1. Motivations

- Develop a simulation (the so called "DAB-Mod") to study the production of open heavy mesons in heavy ion collisions.
- Explain simultaneously the nuclear modification factor R_{AA} and the elliptical azimuthal anisotropy v_2. Compare different transport models with the same background.
- Study the heavy flavour azimuthal anisotropies through the more rigorous cumulant method (unambiguous measurement and remove non-flow contributions; see arXiv:1209.2323).
- Explore new related observables, such as the correlations of soft hadron and heavy meson flows, which might help to distinguish between the different models.



2. The DAB-Mod simulation

Heavy flavor dynamics …

➢ Initial conditions:
- Large oversampling of the heavy quarks for each hydro. event (~10^7 per event – necessary for the statistics) distributed spatially following initial QGP energy density.
- Transverse momentum distribution given by FONLL spectra and with random azimuthal direction.
- No shadowing or cold nuclear matter effects considered.

➢ Transport equations: heavy quark interactions with the moving medium

Energy loss « E_{loss} » parametric model

$$\frac{dE}{dx} = -f(T,p,x)\,\zeta\,\Gamma_{\text{flow}}$$

where the chosen parametrizations

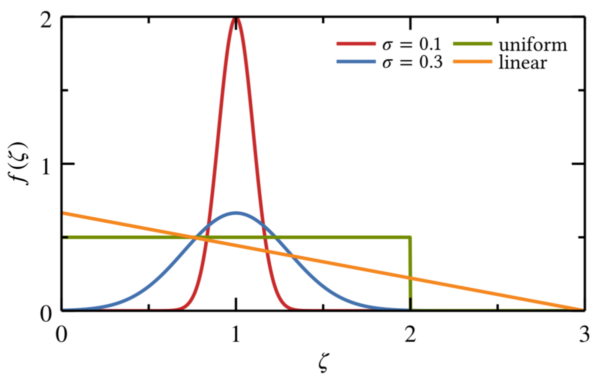
$f(T,p,x) = \alpha$ and $f(T,p,x) = \xi T^2$

led to relevant R_{AA} results,

where the effect of the moving medium on energy loss is given by:

$$\Gamma_{\text{flow}} = \gamma\,[1 - v_{\text{flow}}\cos(\varphi_{\text{quark}} - \varphi_{\text{flow}})]$$

and where ζ gives the energy loss fluctuations (only added to $f(T,p,x)=\alpha$ here), described by a uniform, linear or gaussian distribution:



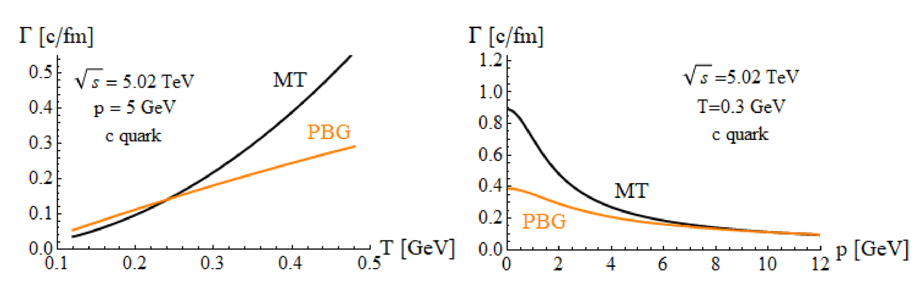
Refs: arXiv:1404.6378, arXiv:1609.05171

OR

Relativistic Langevin equation

$$dx_i = \frac{p_i}{E}dt,$$
$$dp_i = -\Gamma(\vec{p})p_i dt + \sqrt{dt}\sqrt{\kappa}\rho_i$$

with the necessary boosts between global and fluid frames and with the classic fluctuation-dissipation relation for the diffusion coefficients: $\kappa = 2E\Gamma T = 2T^2/D$
Here 2 different parametrizations:
- « MT »: From Moore and Teaney, pQCD +HTL microscopic model: $D \propto 1/(2\pi T)$
- « PBG »: From Gossiaux and Aichelin, pQCD+HTL collisional model with running coupling constant and optimized gluon propagator.



Refs: arXiv:0412346, arXiv:0802.2525

The values of the coefficients of proportionality (α, ξ, for D...) are fixed to obtain the best fits to the D^0 meson R_{AA} for the centrality range 0-10% for Td=120 and 160 MeV.

➢ Hadronisation and decay:
- *Fragmentation*: with the Peterson frag. function $f(z) \propto [z(1-1/z-\epsilon_Q/(1-z))]^{-1}$ to obtain the fraction z of the heavy quark E_Q+p_Q taken by the hadron E_H+p_H. Parameters chosen such as to reproduce D^0/B^0 FONLL spectra in pp collisions.
- *Light-heavy quark coalescence* à la Dover et al. (implementation in progress): instantaneous projection of parton states onto hadron states on the freeze-out hypersurface to obtain coalescence probabilities for different local flow values.
- Freeze-out/Decoupling temperature: large chosen range 120 < T_d < 160 MeV to encode the large uncertainties regarding hadronization.
- No re-scattering considered in the final hadronic phase.
- Decay performed with Pythia 8. Focus on semi-leptonic decays.

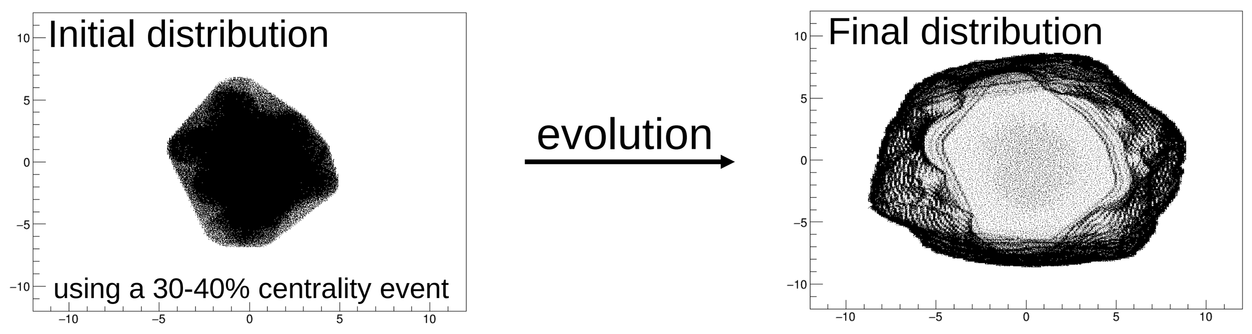
… on the top of a 2D viscous event-by-event QGP

- The transport equations requires hydrodynamical profiles to provide the temperature and flow fields at each time step for each event.
- We use Monte Carlo Kharzeev-Levin-Nardi (MCKLN) initial conditions which include initial fluctuations.
- Evolution with the v-USPhydro code: a 2D+1 event-by-event relativistic viscous hydrodynamical model. Viscosity is set to η/s = 0.05 and initial time to 0.6 fm/c.
- This model describes experimental data in the soft sector, such that all the hydrodynamic parameters are fixed. We use ~1000-2000 events per centrality range.

Refs: arXiv:1305.1981, arXiv:1508.02455, arXiv:1307.6130, arXiv:0707.0249

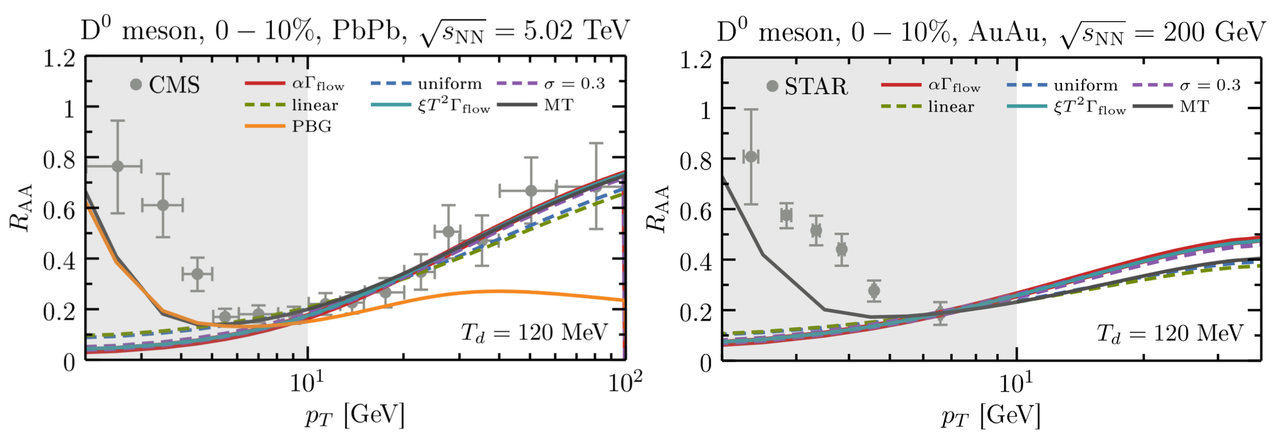
3. Results

Example of charm quark position distributions:



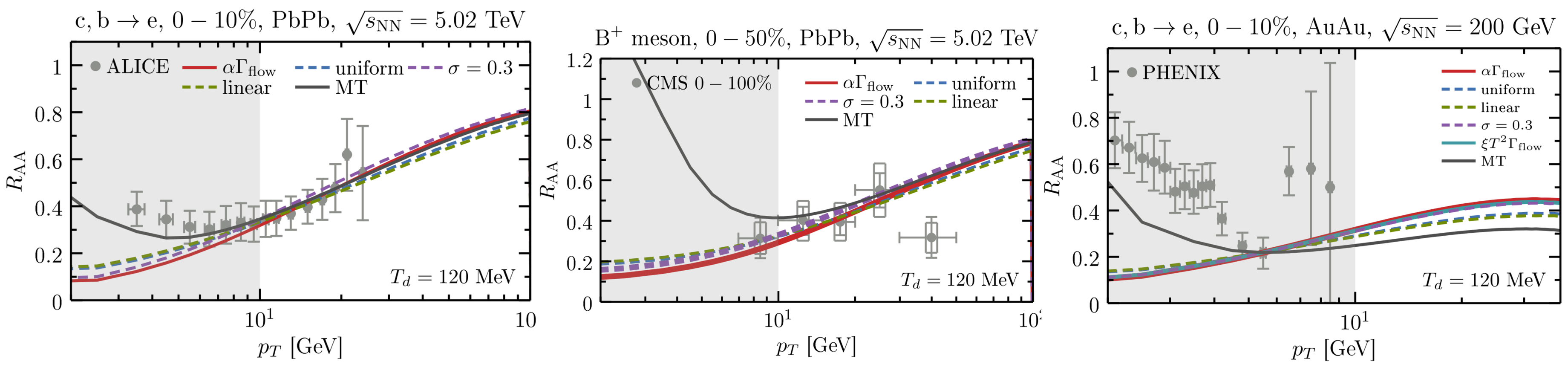
Gray areas for p_T < 10GeV below: where coalescence and cold nuclear matter effects could be important.

Nuclear modification factor R_{AA}



- Chosen E_{loss} models: good behaviour at high p_T
- E_{loss} fluctuations: lead to similar behaviour
- Langevin: better at low p_T; MT also good at high pT

Refs: arXiv:1708.04962, arXiv:1601.00695, ALI−PREL−133360, arXiv:1705.04727, PHENIX: Nagashima QM 2017 prel.



Flow anisotropies with the cumulants

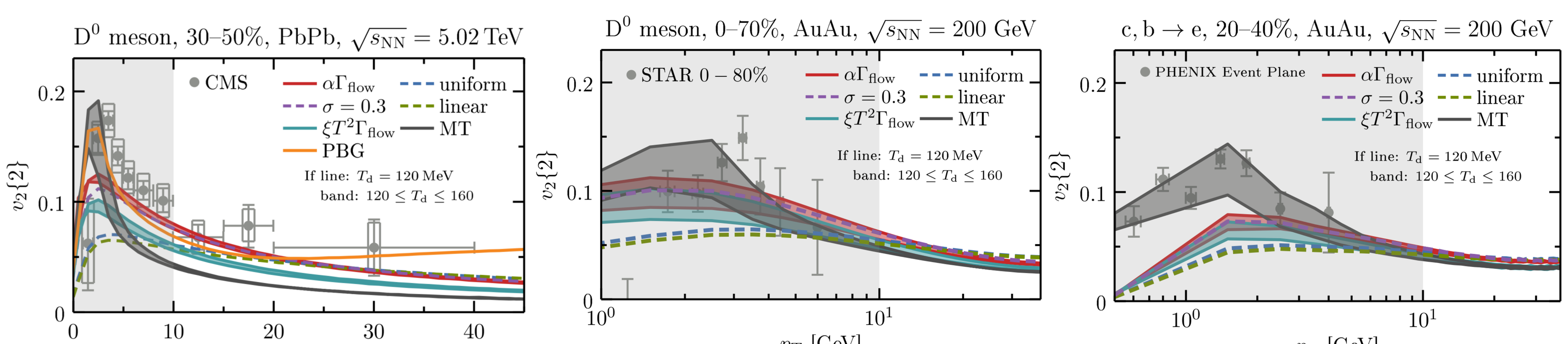
We use the scalar product method; e.g. for the 2nd cumulant:

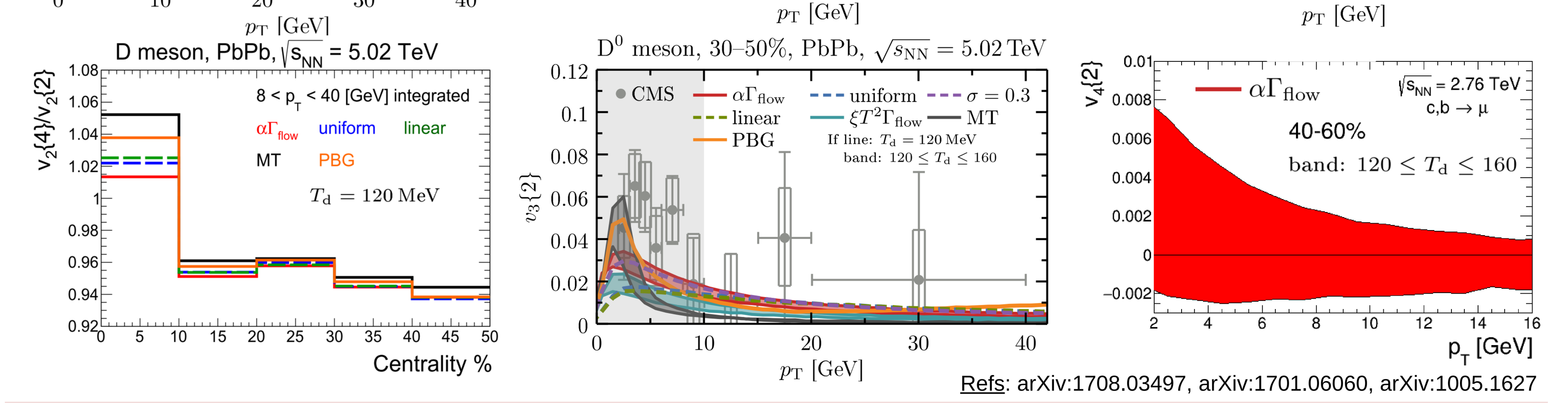
$$v_n\{2\}(p_T) = \frac{\langle v_n^{\text{soft}} v_n^{\text{heavy}}(p_T)\cos(n[\psi_n^{\text{soft}} - \psi_n^{\text{heavy}}(p_T)])\rangle}{\sqrt{\langle (v_n^{\text{soft}})^2\rangle}}$$

+ some multplicity weighting and where

$$v_n^{\text{heavy}}(p_T) = \frac{\frac{1}{2\pi}\int_0^{2\pi} d\phi\, \cos[n(\phi - \psi_n^{\text{heavy}}(p_T))]\, R_{AA}^{\text{heavy}}(p_T,\phi)}{R_{AA}^{\text{heavy}}(p_T)},$$

$$\psi_n^{\text{heavy}}(p_T) = \frac{1}{n}\tan^{-1}\left[\frac{\int_0^{2\pi} d\phi\, \sin(n\phi)\, R_{AA}^{\text{heavy}}(p_T,\phi)}{\int_0^{2\pi} d\phi\, \cos(n\phi)\, R_{AA}^{\text{heavy}}(p_T,\phi)}\right].$$

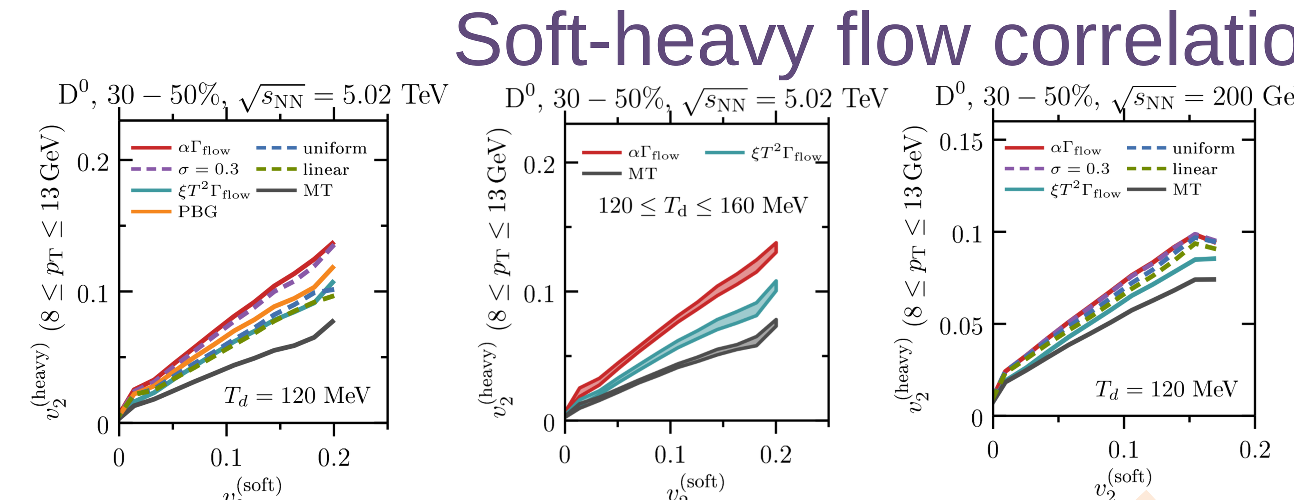




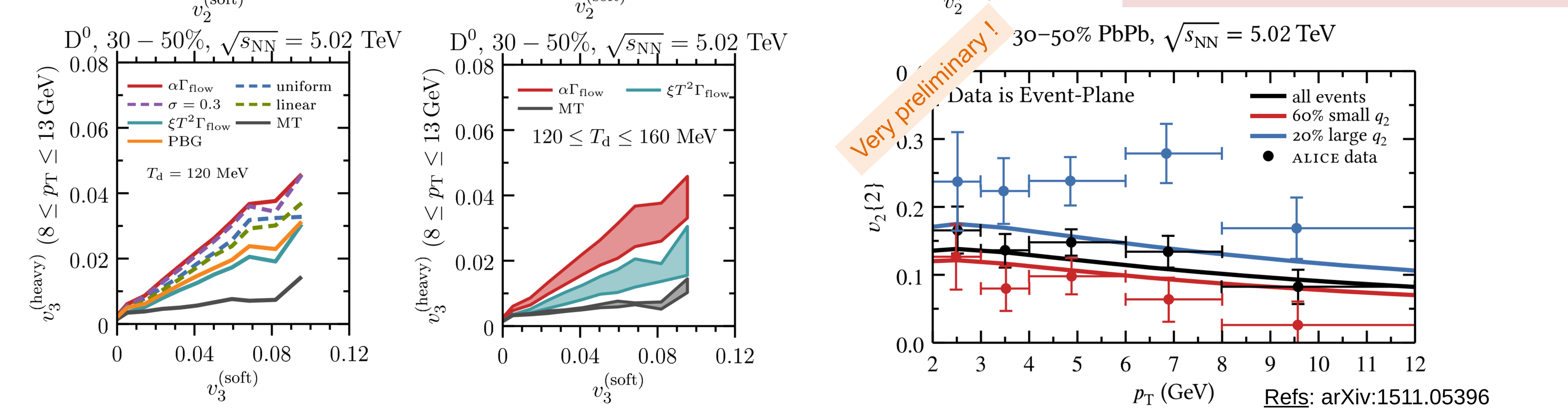
Refs: arXiv:1708.03497, arXiv:1701.06060, arXiv:1005.1627

- LHC: we underestimate a bit the data; RHIC: better agreement
- MT and ξT^2: not good at high p_T
- Langevin: good at very low p_T
- E_{loss} fluctuations: tends to lower the v_n at low p_T
- v_4 < 0 for heavy flavor leptons at T_d=160 MeV (due to an anti-correlation of ψ_4^{heavy} and ψ_4^{soft})
- Ratio $v_2\{4\}/v_2\{2\}$: almost independent of centrality (for >10%), T_d, transport models, flavor and statistics

Soft-heavy flow correlations



- Clear linear correlations between heavy quark and all charged particles elliptical and triangular flows whatever is the transport model
- Average correlations: not more differentiative than cumulants



Refs: arXiv:1511.05396

Conclusion:
- Energy loss and Langevin: quite different results at low p_T, often close at high p_T
- Energy loss fluctuations: lower the v_n at low pT; linear and uniform leads to similar results
- Clear linear correlations between soft and heavy elliptic and triangular flows.
- $v_2\{4\}/v_2\{2\}$ ratio: almost independent of the variables and models
- Negative HF leptons v_4 for most centralities when T_d = 160 MeV

Future: Coalescence, other colliding systems (pPb, XeXe), 3D...