Extraction of heavy quark transport coefficients

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Strangeness in Quark Matter 2019, Bari, Italy June 13, 2019

SUBATECH, IMT Atlantique, Nantes, France

Heavy quarks as probes of the quark gluon plasma

The heavy-quark mass is parametrically large compared to the scales of the QGP:

$$m_{HQ} \gg T_{\rm pc}$$

$\Rightarrow$ promising tool for QGP tomography, because:

- well controlled production in initial hard processes,
- at low p_T well-defined transport coefficient for spatial diffusion D_s,
- at high p_T, scale separation $T \ll m_{HQ} \ll E$, probe $\hat{q} \sim m_D^2/\lambda$,
- thermalization time is enhanced by $\sim m_{HQ}/T$, preserve memory,
- HQ keep their identity during gluon emission/hadronization.

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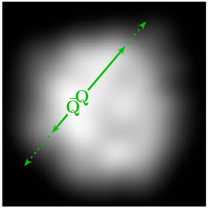
Theoretical/phenomenological modeling is a highly complex problem!

Theoretical and phenomenological modeling - in practice

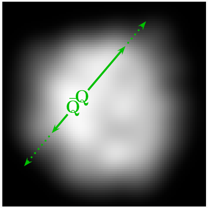
production



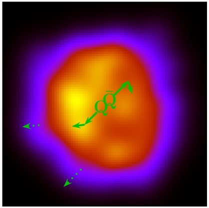
- LO pQCD, e.g. FONLL $\rightarrow$ inclusive spectra, no azimuthal $Q\bar{Q}$ correlations
  M. Cacciari et al. PRL95 (2005), JHEP 1210 (2012)
- NLO pQCD matrix elements plus parton shower, e.g. POWHEG or MC@NLO $\Rightarrow$ exclusive spectra, like $Q\bar{Q}$ correlations S. Frixione et al. JHEP 0206 (2002), JHEP 0308 (2003)
- Cold nuclear matter effects, i.e. shadowing, p_T broadening, Cronin effect, etc.
  K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP 0904 (2009)
- Consistent initialization of HF and LF sectors!

Theoretical and phenomenological modeling - in practice

production

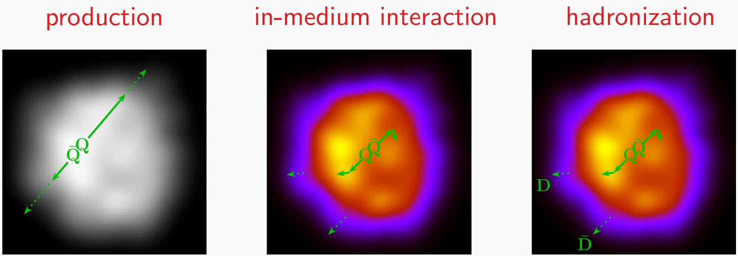


in-medium interaction



- Scattering off light QGP constituents, sampled from fluid dynamics (or given within microscopic transport).
- Interaction strength needs to be modeled as a function of T and HQ p_T:
    - perturbative vs non-perturbative
    - collisional vs radiative (coherent/incoherent)
    - nature of the light QGP constituents
- Proper modeling of the QGP evolution is important! Should be well tested in the light hadron sector!

Theoretical and phenomenological modeling - in practice



- Coalescence/Recombination – predominantly at small p_T. Parameter-dependent!

  C. B. Dover et al., PRC 44 (1991); R. Fries et al. PRL 90 (2003); V. Greco et al. PRC 68 (2003)

- Fragmentation – predominantly at large p_T. Medium-modification?

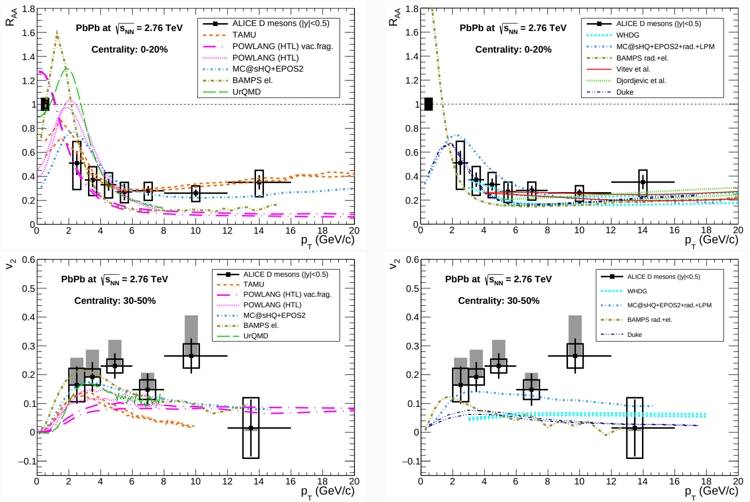
  e.g. M. Cacciari et al., PRL 95 (2005)

- After hadronization: final hadronic interactions of D mesons.

  M. He et al. PLB701 (2012); L. Tolos et al., PRD88 (2013); J. Torres-Rincon et al., PRD89 (2014)

Model-to-data comparison 2016

purely elastic scatterings



elastic scatterings + radiation

SaporeGravis Network, EPJC76 (2016) 1506.03981

Model-to-data comparison 2016

purely elastic scatterings

elastic scatterings + radiation

Conclusions

- Many approaches achieve qualitative/semi-quantitative description of (some of) the available experimental observables.
- No single approach can reproduce all of the existing data.
- Approaches have vastely different ingredients... How to move forward toward (precision) extraction of transport coefficients?
- Large community efforts (theory) to compare their models:
    - **R. Rapp et al. NPA979 (2018), arxiv:1803.03824, (EMMI-RRTF)**
    - **S. Cao et al. PRC99 (2019), arxiv:1809.07894, (JET Collaboration)**
    - **Y. Xu et al. PRC99 (2019), arxiv:1809.10734, (Duke-Frankfurt-...)**

Throughout this talk: for references to models please go to these reviews!

At low momentum: diffusive "Brownian motion"

Fokker-Planck dynamics: D. Walton et al., PRL84 (2000); G. Moore et al., PRC71 (2005)

$$\frac{\partial}{\partial t} f_Q(t,\vec{p}) = \frac{\partial}{\partial p^i}\left(A^i(\vec{p}) f_Q(t,\vec{p}) + \frac{\partial}{\partial p^j}\left[B^{ij}(\vec{p}) f_Q(t,\vec{p}) \right] \right)$$

The friction (drag) and momentum diffusion coefficients depend on the HQ momentum and the medium temperature.

Recast to **Langevin equation** $\frac{\mathrm{d}}{\mathrm{d}t}\vec{p} = -\eta_D(p)\vec{p} + \vec{\xi}$ and $\langle \xi^i(t)\xi^j(t')\rangle = \kappa \delta^{ij}\delta(t-t')$

Transport coefficients connected by **fluctuation-dissipation theorem** (Einstein relation):

$\eta_D = \frac{\kappa}{2 m_Q T}$ $\qquad$ $D_s = \frac{T}{m_Q \eta_D}$ $\qquad$ spatial diffusion coefficient

Fokker-Planck equation is second moment approximation of the **Boltzmann equation**:

$$\frac{\mathrm{d}}{\mathrm{d}t} f_Q(t,\vec{x},\vec{p}) = \mathcal{C}[f_Q] \quad \text{with} \quad \mathcal{C}[f_Q] = \int \mathrm{d}\vec{k}[\underbrace{w(\vec{p}+\vec{k},\vec{k}) f_Q(\vec{p}+\vec{k})}_{\text{gain term}} - \underbrace{w(\vec{p},\vec{k}) f_Q(\vec{p})}_{\text{loss term}}]$$

Diffusion coefficient from lattice QCD calculations

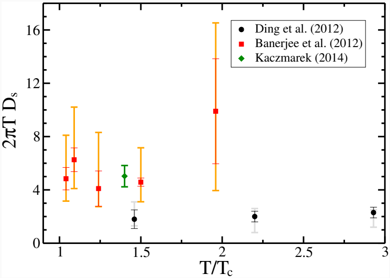
- The diffusion coefficient can be defined via the spectral function $\sigma(\omega, \vec{p})$ corresponding to the current-current correlator of heavy quarks:

$$D_s = \lim_{\omega \to 0} \frac{\sigma(\omega, \vec{p} = 0)}{\omega \chi_q \pi}$$

- Lattice QCD at finite T is performed in Euclidean space $\Rightarrow$ notoriously difficult to calculate dynamical quantities.
- Relate the current-current correlators (calculated on the lattice) to spectral functions

$$G(\tau; T) = \int_0^\infty \frac{\mathrm{d}\omega}{2\pi} \sigma(\omega; T) K(\tau, \omega; T)$$

Approximations/limitations:
quenched QCD, heavy quark vs. charm quark, (no) continuum extrapolation, ...



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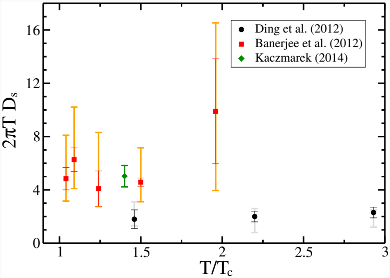
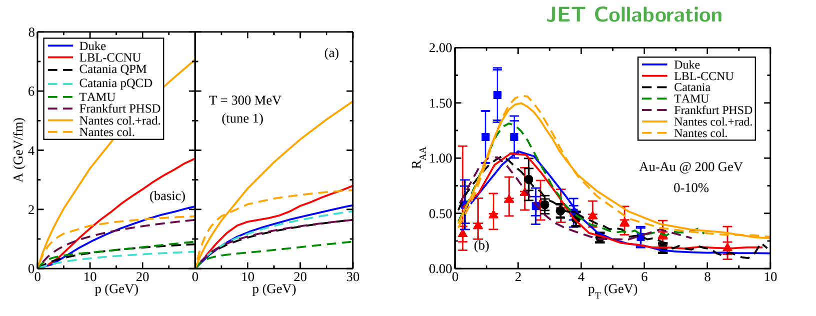
$D_s \sim 2 - 7(2\pi T)$



Comparison of interaction strengths - model approaches

- Most model approaches achieve a qualitative/semi-quantitative agreement with the available data - **for very different interaction strengths and concepts!**



- basic: no parameter tuning
- tune 1: tuning to data

- After tuning to data, the quantitative differences in the drag coefficient become smaller but there is still no convergence.

Tuning to the data?

- Every model relies on some explicit or implicit tuning/choice of parameters.
- There is no common strategy on how to do this...
- Values of χ^2/dof from model to data comparison:

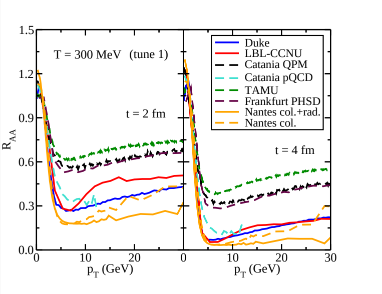
JET Collaboration

Models	2.76 ATeV Pb-Pb	200 AGeV Au-Au
Duke	0.769	2.819
CCNU-LBNL	0.132	1.49
Catania	0.113	1.01
TAMU	0.178	2.40
Frankfurt PHSD	0.637	1.59
Nantes col. + rad.	0.629	17.3
Nantes col. only	0.524	17.9

- Need to adjust parameters systematically to the experimental data!

Heavy quark evolution in a static QGP

- If very different transport coefficients can describe the same experimental data sufficiently well - other ingredients must balance the discrepancy: initial spectra, medium evolution, hadronization...



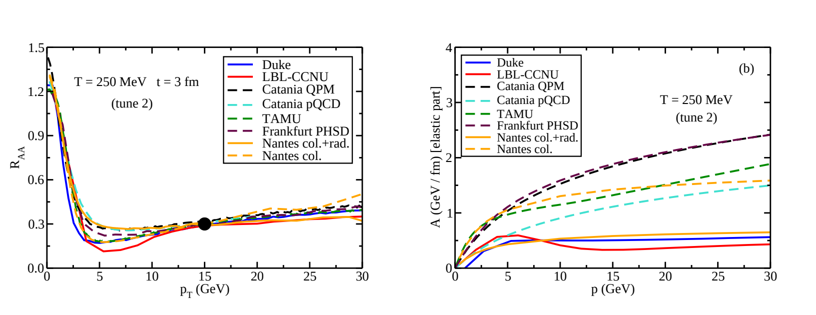
- Take them out by looking at HQ propagation through a static QGP medium at $T = 300$ MeV.
- Use a common parametrized initial spectra.

JET Collaboration

- Large differences in the R_{AA} observed if only in-medium interaction is compared!

Heavy quark evolution in a static QGP - new tune

- New tune proposed: fixed value of $R_{\mathrm{AA}} = 0.3$ at $p_T = 15$ GeV and $t = 3$ fm.



Three groups of models emerge approaches including **JET Collaboration**

1. elastic and inelastic processes
2. pQCD-based elastic scattering of partons with small quasi-particle masses and TAMU
3. elastic scatterings driven by quasi-particle models (large thermal masses in the transition region)

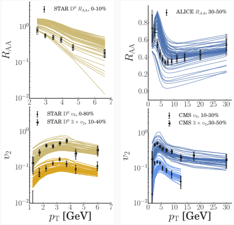
Bayesian model-to-data statistical analysis

- HQ Langevin dynamics + 2+1d fluid dynamics + UrQMD

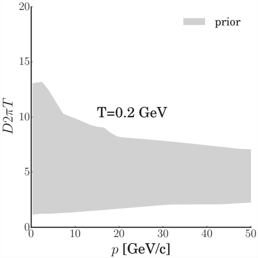
($\eta/s(T)$, $\zeta/s(T)$ constraint by bulk observables via Bayesian analysis)

J. Bernhard, J. Moreland, S. Bass, J.Liu and U. Heinz, PRC94 (2015)

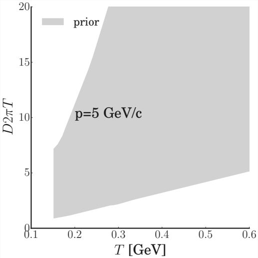
exprimental data



momentum



temperature



assume parametrization:

$$D_s(T,p) = \frac{1}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\rm lin}(T;\alpha,\beta) + \frac{(\gamma^2 p)^2}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\rm pQCD}(T,p)$$

know the probability distributions of all parameters and correlations

⇒ **momentum and temperature dependence of charm quark diffusion coefficient!**

Y. Xu, J. Bernhard, S. Bass, MN, S. Cao, PRC97 (2018)

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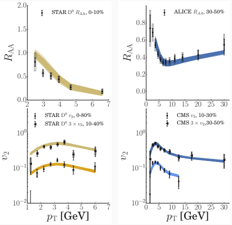

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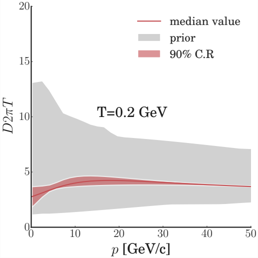
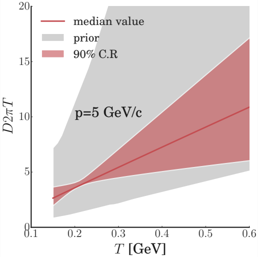


temperature



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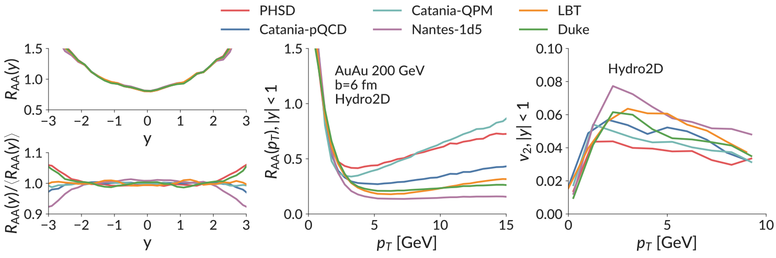
Effect of transport coefficients

- Next step in the comparison: common transport equation and common model of the QGP evolution, here the $2+1$D OSU hydro code with PHSD initial conditions.

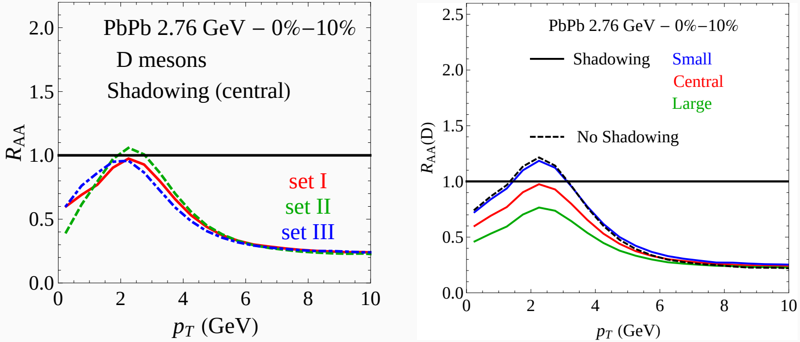


Duke-Frankfurt

- Notable differences appear for $p_t \gtrsim 2$ GeV in the charm quark R_{AA} and v_2.
- QPmodels (PHSD, Catania) and LBT/Duke (same radiative eloss) group together.

- Test different parameter sets of FONLL initial HQ spectra and different degrees of shadowing in the Nantes model.

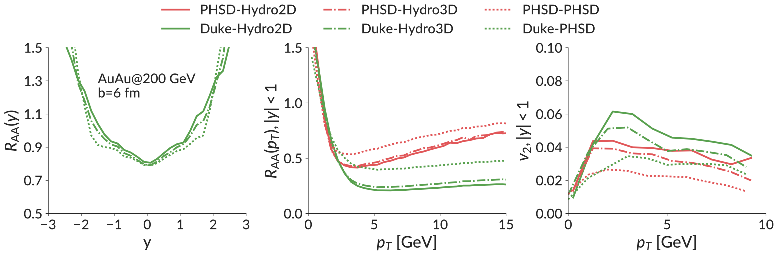
EMMI-RRTF



- Effect from uncertainties in the initial *pp* reference spectra relatively small.
- Large uncertainty from error bands in shadowing descriptions (here EPS09) at $p_T < 4$ GeV, negligible for $p_T > 6$ GeV.

Effect of medium evolution: equilibrium vs nonequilibrium

- Use a common transport equation of HQ: Duke-Langevin implementation with two sets of transport coefficients (Duke and PHSD).
- Models for medium evolution: $2+1$D OSU Hydro code, $3+1$D vHLLE Hydro code and local temperature and velocity profiles from PHSD transport.

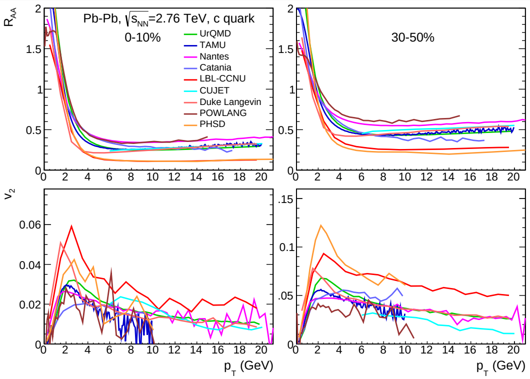


Duke-Frankfurt

- Dimensionality matters for the elliptic flow.
- For each set of transport coefficients: large deviations induced by hydro vs transport evolution!
- This deviation is more pronounced for the Duke set of transport coefficients.

Effect of medium evolution

- A common transport coefficient D_s for Langevin codes, pQCD Born cross section for Boltzmann transport codes, rescale by $K = 5$.
- Applied in the various models for medium evolution.

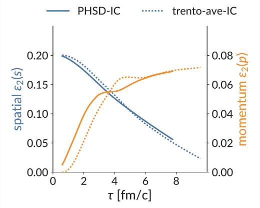


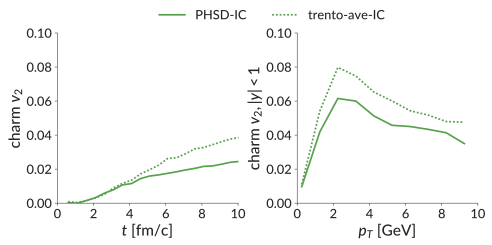
EMMI-RRTF

- Difference in the charm quark R_{AA} can be largely understood by the difference of the total entropies in the QGP evolution models.
- Outliers: LBL-CCNU Boltzmann (massless partons sampled), PHSD (implementation of pQCD cross sections via $K(T, p)$ rescaling)

Effect of medium evolution - HQ as probes of the QGP

- Different initial conditions: PHSD vs. Trento; same $2+1$D OSU Hydro code; same HQ transport model (Duke LV).
- Trento in Hydro and PHSD transport describe well the flow of light hadrons.





- HQ pick up substantially more flow for the Trento IC from $t > 4$ fm/c on.
  $\Rightarrow$ HQ are indeed a good probe of the QGP evolution history!

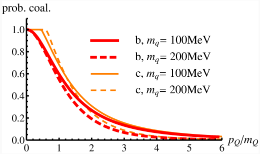
Hadronization via recombination/coalescence

$$\frac{\mathrm{d}N_M}{\mathrm{d}^3P} = g_M \int \{\mathrm{d}x\mathrm{d}p\} f_q(x_1,p_1) f_q(x_2,p_2) |\psi_M(y,P)|^2 \delta(P-p_1-p_2)$$

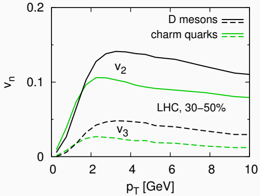
R. Fries et al. PRL 90 (2003); V. Greco et al. PRC 68 (2003)

Plenary talk by F. Prino, Wed 12:00

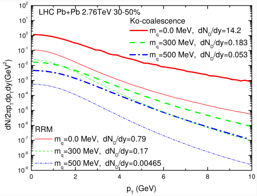
- Recombination prob. large at low p_T $\Rightarrow$ bump in R_{AA}, adds $25-50\%$ to v_n.
- What is the meson/baryon wavefunction? Dependence on parameters, like the constituent quark mass, etc... $\Rightarrow$ Λ_c/D^0 and D_s/D^0 can help constrain!
- Implementation on a fluid dynamical background not trivial. What is the probability for inhomogeneous fluid velocities, etc...?
- RRM M. He, R. Fries, R. Rapp PRC 82 (2010), PRC 86 (2012) recovers equilibrium limit for the hadron spectra and conserves energy.
- RRM gives smaller and softer D spectra than instantaneous recombination.



P.-B. Gossiaux et al. PRC 78 (2008)



MN et al. PRC91 (2015)

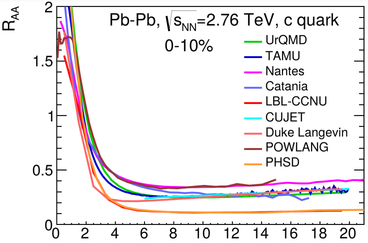


EMMI-RRTF

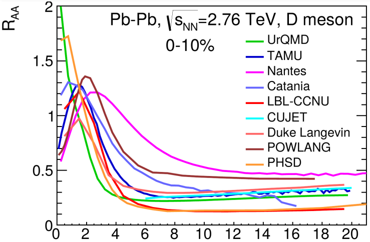
Effect of hadronization

- Take charm quark results from the common pQCD∗5 transport coefficient and hadronize into D mesons.

charm quark



D mesons



- Common fall-off region around $p_T \sim 2$ GeV gets fanned out. **EMMI-RRTF**
- No flow bump develops for UrQMD (ICM Wigner functions with $m_q > 370$ MeV) and the PHSD (ICM Wigner functions with finite times).
- Strong coalescence effect in the Nantes model also leads to an enhanced contribution to flow.

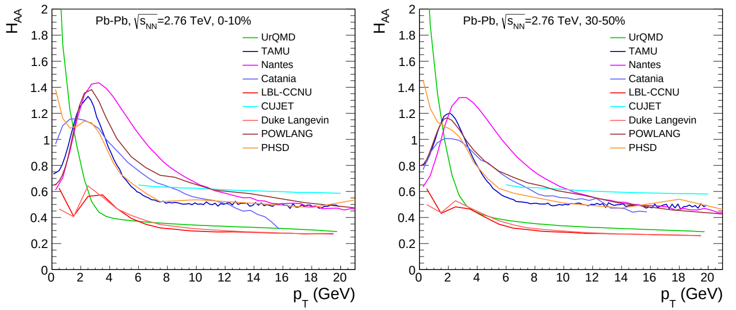
Effect of hadronization - H_{AA}

- Take the ratio of the D meson over the charm quark spectra to highlight the effect of hadronization.

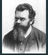
$$H_{\mathrm{AA}}(p_T, p_t = p_T) = \frac{\mathrm{d}N_D/\mathrm{d}p_T}{\mathrm{d}N_c/\mathrm{d}p_t}$$

EMMI-RRTF

central peripheral

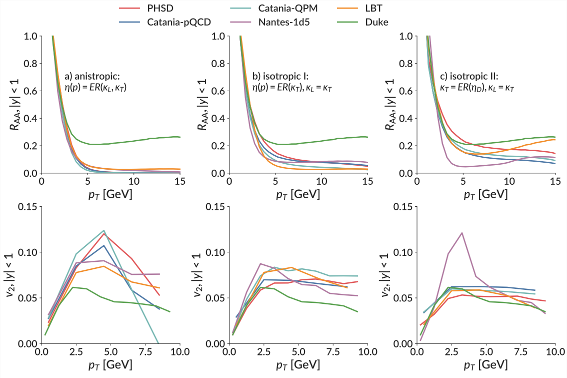


- Dominant structure: flow bump at low/intermediate p_T (TAMU, Nantes, POWLANG).
- Levels off in the high p_T region, where fragmentation is dominant.

Boltzmann  vs. Langevin 

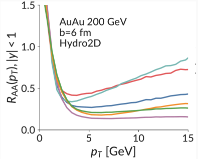
Einstein's relation (for a Boltzmann-Jüttner eq. distr.) $\eta_D = \frac{\kappa_L}{2ET} - \frac{\kappa_L - \kappa_T}{p^2} - \frac{\partial \kappa_L}{\partial p^2}$

- Calculated separately from the Boltzmann collision integral, η_D, κ_L, κ_T do not fulfill Einstein's relation ⇒ system does not equilibrate in a Langevin approach.



Duke-Frankfurt

no ER:

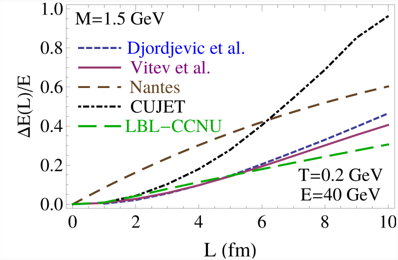


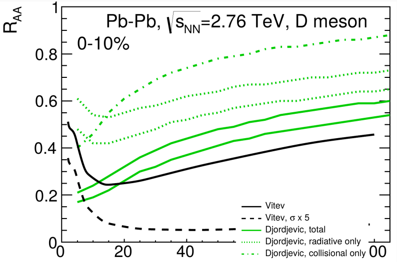
see also: S. Das et al, PRC90 (2014); W. Horowitz, PRD91 (2015); S. Li et al, PRC99 (2019)

- Charm quark R_{AA} decreases when ER is enforced.
- Large ambiguities introduced by the arbitrary choice, which transport coefficient to calculate explicitly → is LV dynamics a good choice?

And at high transverse momentum?

- Comparison of the radiative energy loss component in a static QGP: Djordjevic et al: DGLV (with dynamical scattering centers); Vitev: SCET; LBL-CCNU: HT; Nantes: GB+LPM

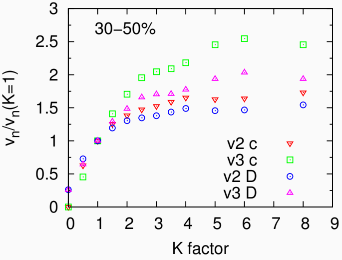




- For $L < 5$ fm relevant for HIC: DGLV, SCET and HT are consistent.
- Strongly dependent on QGP evolution! (Vitev: 1D Bjorken expansion, transverse Glauber geometry; Djordjevic: static, spherically symmetric fireball)
  Similar $\Delta E(L)$, but different R_{AA}!

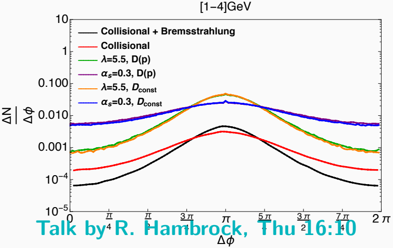
Talk by M. Djordjevic, Tue 14:00

- High sensitivity of **heavy-quark correlations** to collisional vs. radiative energy loss **MN, J. Aichelin, P.B. Gossiaux, K. Werner, PRC90 (2014), 1305.3823** or strong coupling vs. pQCD.



MN et al., SQM2017, arxiv:1804.03530

$b\bar{b}$ correlations:
strong vs. weak coupling



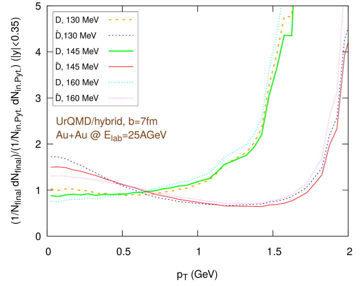
Talk by R. Hambrock, Thu 16:10

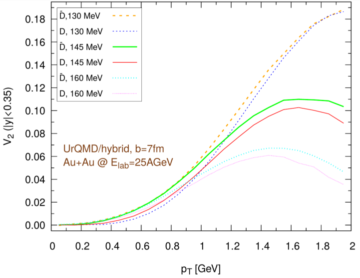
- Higher-order flow coefficients more sensitive to the transport coefficient than v_2.
- Consistent coupling from HQ and light flavor sector allows us to study correlations between the light and the heavy flavor sector → event engineering:
  MN et al, PRC91 (2015); P.-B. Gossiaux, et al. arXiv:1705.02271, C. Prado et al., PRC96 (2017)

Talks by R. Katz, Tue 14:40; S. Plumari, Tue 16:50

Charm quarks in baryon-rich matter

- Charm quarks become accessible at lower beam energies thanks to large luminosities, e.g. HADES/CBM at GSI/FAIR.
- Correlated $c\bar{c}$ pairs are an important contribution to dilepton invariant mass spectra.





G. Inghirami et al, EPJC79 (2019)

- Strong medium modification at FAIR energies due to slow medium evolution and soft initial spectra.
- Fugacity factors lead to substantial differences in D vs $\bar{D}$ meson R_{AA}.

Interesting HF physics to explore in baryon-rich matter!

Conclusions

- Many models can qualitatively/semi-quantitatively describe the HQ R_{AA} and v_2.
- A systematic effort in the theory community has revealed a couple of important ingredients:
  - A common systematic, e.g. via Bayesian analysis, tuning of parameters to the experimental data could reduce spread in the transport coefficients.
  - Uncertainties in nuclear shadowing $\rightarrow$ large uncertainties in the HQ R_{AA}.
  - Only couple HQ to medium evolution models that are well-tested in the light flavor sector!
  - HQ observables are sensitive to the medium evolution, equilibrium vs nonequilibrium, or even the IC for hydro.
  - Hadronization via recombination introduces large effects and differences between the various models. Needs more work.
- Great potential in new observables, like higher-order flow, azimuthal and momentum correlations, heavy-light correlations, to explore theoretically and experimentally, and baryon-rich matter!

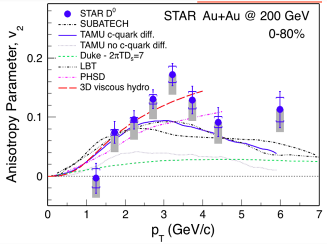
Thanks to J. Aichelin, S. Bass, E. Bratkovskaya, S. Cao, P.B. Gossiaux, T. Song, K. Werner, Y. Xu for fruitful collaborations!

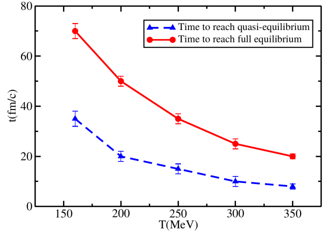
extra

Partial thermalization of heavy quarks with the medium

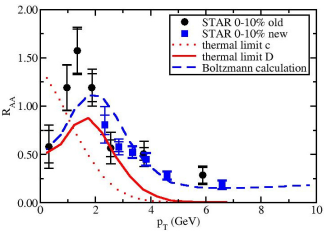
Need a good quantitative measure - or at least some common understanding - of what we mean by "(partial) thermalization"!

- HQ seem to pick up almost all of the anisotropy of the medium.
- But equilibration times are much larger, $\tau_{\text{relax}} \sim \tau_{\text{QGP}}$.
- Hydro-like flow coefficients $\neq$ thermalization/equilibration.
- Other observables do not agree with thermalized charm.

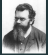




S. Cao, S. Bass PRC 84 (2011)



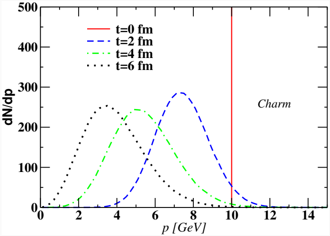
calculation by S. Cao



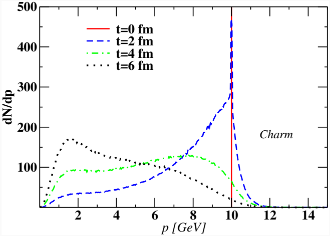
vs.

- Under which conditions should Brownian motion be a valid approximation for relativistic particles?
- Calculations of transport coefficients from the underlying theory do not necessarily fulfil FDT ⇒ calculate one and adapt the others via the FDT.
- For charm quarks: Langevin leads to Gaussian momentum distribution, Boltzmann very different.
- Does this affect the R_{AA} and the v_2 or do we need correlation observables to see a difference?

Langevin

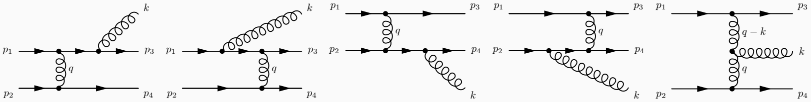


Boltzmann



S. Das et al, PRC90 (2014)

Radiative energy loss



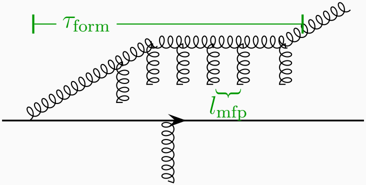
- LO pQCD matrix element for $2 \to 3$ process Kunszt et al. PRD21 (1980)
- Gunion-Bertsch approximation derived in the high-energy limit, where the radiated gluon $k_\perp$ and the momentum transfer $q_\perp$ are soft $\ll \sqrt{s}$.
- Incoherent radiation off a massless parton, mid-rapidity
- Extention beyond mid-rapidity and to finite mass m_Q (heavy quarks!)
  $\Rightarrow$ distribution of induced gluon radiation:

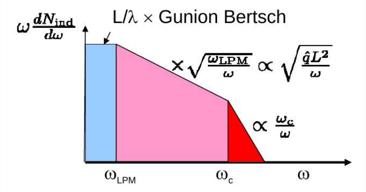
$$P_g(x, \vec{k_\perp}, \vec{q_\perp}, m_Q) = \frac{3\alpha_s}{\pi^2} \frac{1-x}{x} \left(\frac{\vec{k_\perp}}{\vec{k_\perp}^{\,2} + x^2 m_Q^2} - \frac{\vec{k_\perp} - \vec{q_\perp}}{(\vec{k_\perp} - \vec{q_\perp})^2 + x^2 m_Q^2} \right)^2$$

- $\Rightarrow E_{\mathrm{rad}}^{\mathrm{loss}} \propto E\, L$

J. Gunion, PRD25 (1982); O. Fochler et al. PRD88 (2013); J. Aichelin et al. PRD89 (2014)

Coherent emission - LPM





- coherent emission if $\tau_{\rm form} = \sqrt{\frac{\omega}{\hat{q}}} > l_{\rm mfp}$
- QCD analogon to the Landau-Pomeranchuk-Migdal (LPM) effect
- Important in QCD: rescattering of the forming gluon with medium partons ⇒ less suppression than in QED
- At large energies in BDMPS-Z: ⇒ $E_{\rm rad}^{\rm loss} \propto \sqrt{E}\, L$
- For very energetic partons $\tau_{\rm form} > L$, then $E_{\rm rad}^{\rm loss} \propto L^2$, estimate for the LHC ($L \sim 2fm$, $\hat{q} \sim 2$ GeV/fm ⇒ $\omega_c \sim 20$ GeV)

- Dynamical realization challenging K. Zapp et al. PRL103 (2009), JHEP 1107 (2011), usually implemented effectively.

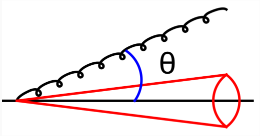
Baier et al. PLB **345** (1995); NPB **483** (1997); ibid. **484** (1997); B. G. Zakharov, JETP Lett. **63** (1996) 952

Dead cone effect

suppression of high-energetic (small angle) gluon emission by the heavy quark mass:

$$\frac{\mathrm{d}\sigma_{\mathrm{rad}}}{\theta\mathrm{d}\theta} \propto \frac{\theta^2}{\left(\theta^2 + M_Q^2/E_Q^2\right)}$$

Dokshitzer et al., PLB **519** (2001)



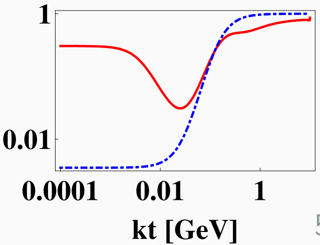
- Suppresses gluon emission in the dead cone $\theta_D = M_Q/E_Q$
- Introduces a mass hierarchy in the radiative energy loss.
- But: assumes hard scatterings!

- When the hard scattering assumption is relaxed, emission at low $k_\perp$ is significantly less suppressed:

$$\frac{P_g(x,k_\perp;M)}{P_g(x,k_\perp;0)}$$

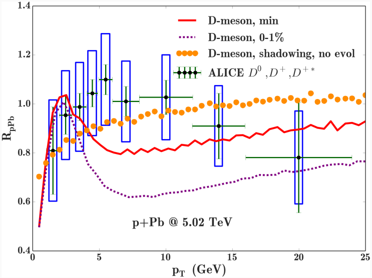
hard-scattering approximation

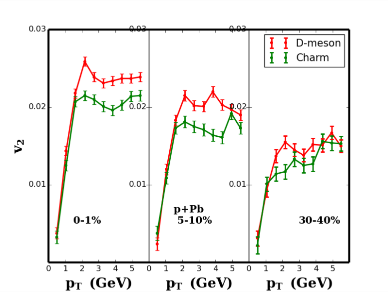
all scatterings



Charm production (and diffusion?) in pPb collisions

- $3 + 1$d fluid dynamical evolution + Langevin dynamics, initial shadowing.





- Centrality dependence of R_{pPb} expected due to energy loss.
  (Note, that experimentally Q_{pPb}!)
- Indications that v_2 of D mesons decouples from medium flow - unlike in AA collisions - and decreases with centrality.
- Can HF measurements in pPb help answering the question of initial vs final state effects?

Y. Xu et al, Duke University, in preparation

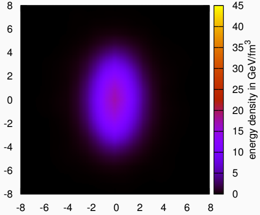
see also: A. Beraudo, JHEP1603 (2016)

production interaction with the medium hadronization

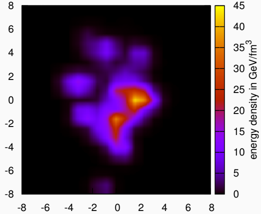
medium description coupling medium - HF sector

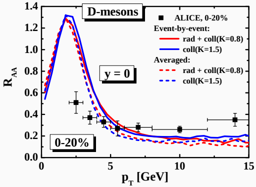
- Model the QGP: a locally thermalized medium provides the scattering partners.
- Input from a fluid dynamical description of the bulk QGP medium: temperatures and fluid velocities.
- Use a fluid dynamical description which describes well the bulk observables!

smooth initial conditions



fluctuating initial conditions





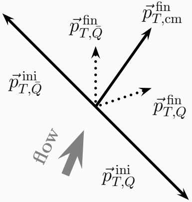
plot by V. Ozvenchuk, Nantes

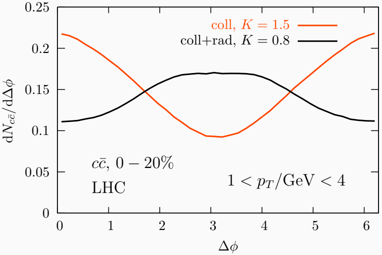
MN, J. Aichelin, P. B. Gossiaux, K. Werner, NPA932 (2014)

"Partonic wind" effect

X. Zhu, N. Xu and P. Zhuang, PRL **100** (2008)

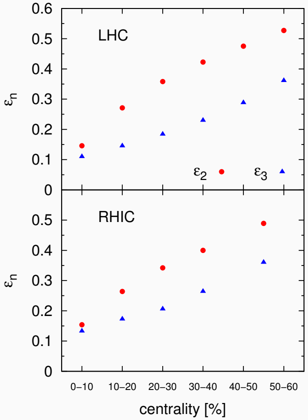
- Due to the radial flow of the matter low-p_T $c\bar{c}$-pairs are pushed into the same direction.
- Initial correlations at $\Delta\phi \sim \pi$ are washed out but additional correlations at small opening angles appear.
- This happens only in the purely collisional interaction mechanism!
- No "partonic wind" effect observed in **collisional+radiative(+LPM)** interaction mechanism!





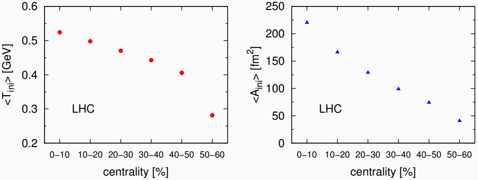
MN et al. PRC90 (2014)

QGP: initial state and bulk flow (2)



MN et al. PRC91 (2015)

average temperature and overlap area

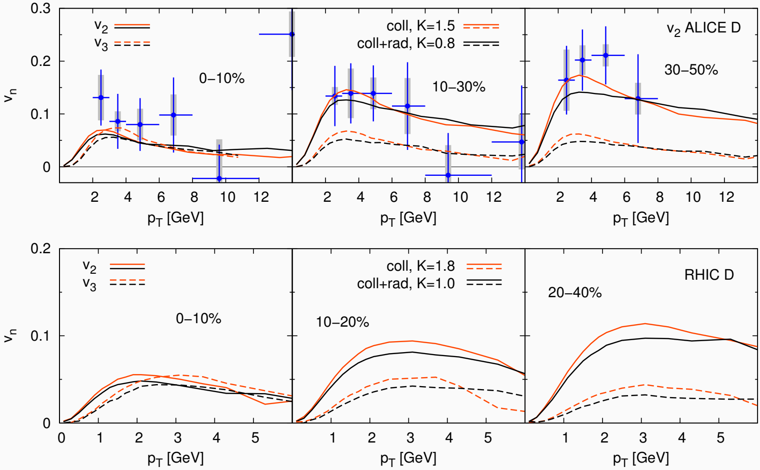


centrality dependence:

+ increase of initial eccentricities
+ decrease of interaction rate and medium size

$\Rightarrow$ expectation: heavy-flavor flow shows a weaker dependence on centrality, especially for v_3

D meson v_2 and v_3 at LHC and RHIC

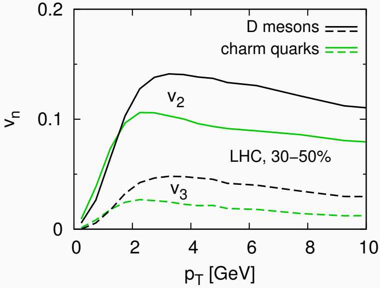


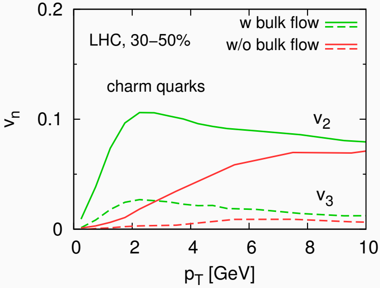
- At small p_T: relative enhancement of flow in purely collisional scenario over **collisional+radiative(+LPM)** larger for v_3 than for v_2

MN et al. PRC91 (2015)

Charm flow: hadronization and energy loss

collisional+radiative(+LPM), $\mathbf{K = 0.8}$

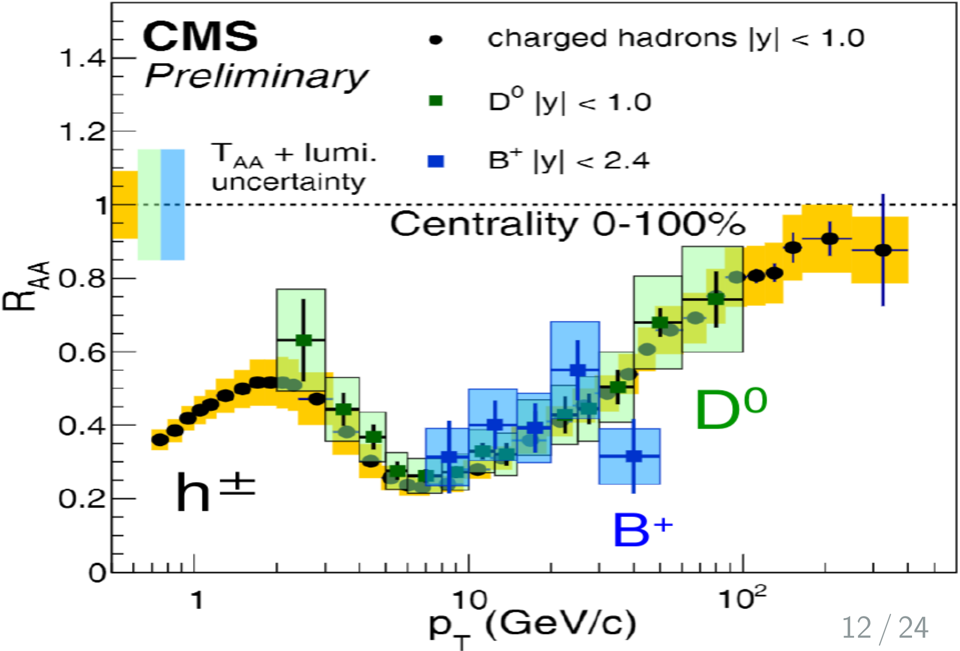




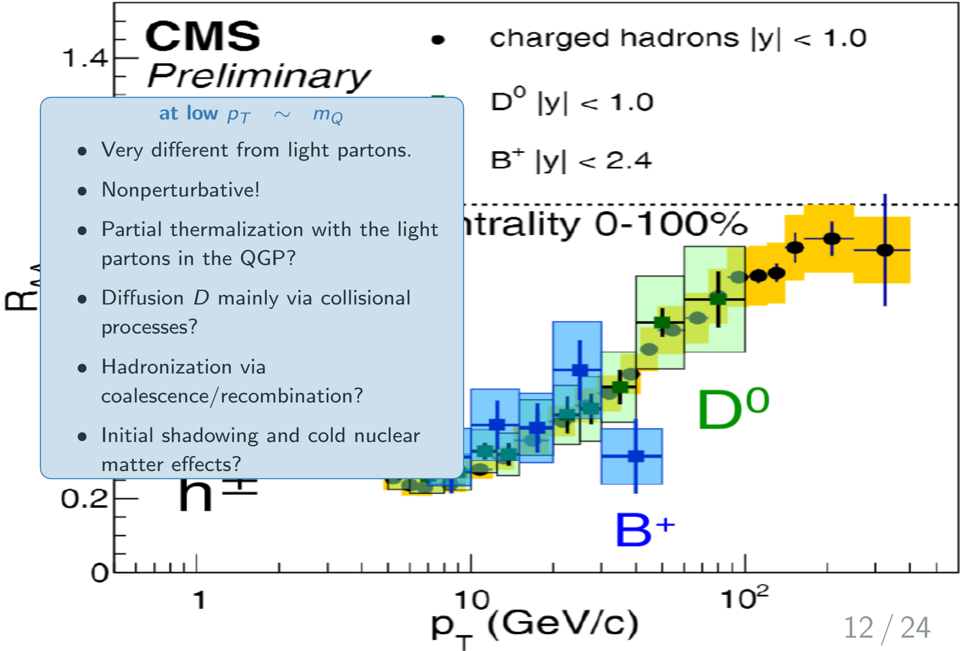
- Contribution to the flow from hadronization.
- For low p_T the charm flow is predominantly due to the flow of the bulk.

MN et al. PRC91 (2015)

Low versus high momentum



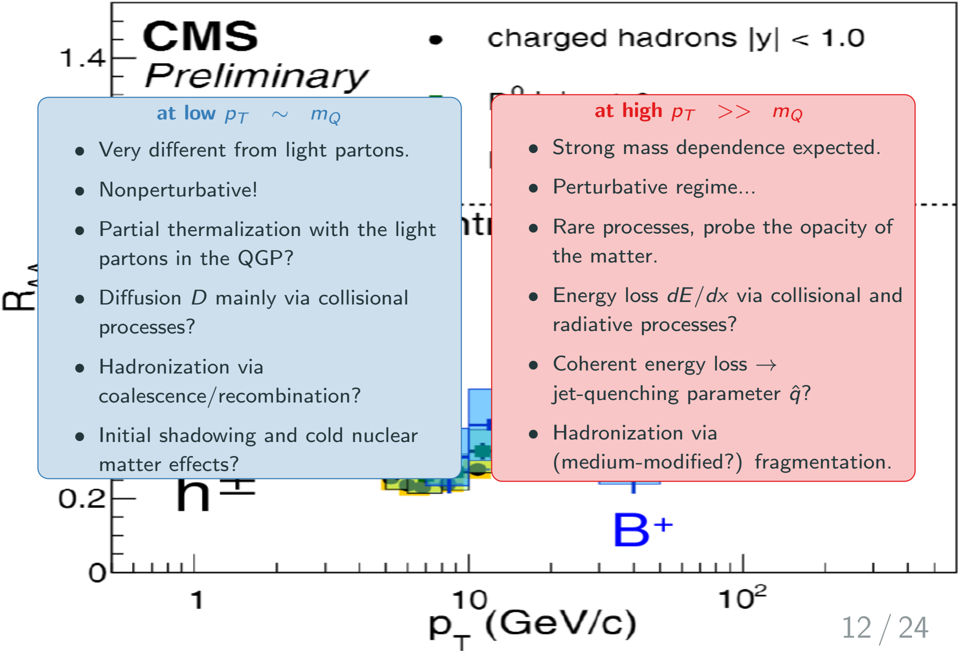
Low versus high momentum



at low $p_T \sim m_Q$

- Very different from light partons.
- Nonperturbative!
- Partial thermalization with the light partons in the QGP?
- Diffusion D mainly via collisional processes?
- Hadronization via coalescence/recombination?
- Initial shadowing and cold nuclear matter effects?

Low versus high momentum



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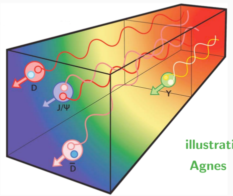
- Hadronization via coalescence/recombination?
- Initial shadowing and cold nuclear matter effects?

at high $p_T >> m_Q$

- Strong mass dependence expected.
- Perturbative regime...
- Rare processes, probe the opacity of the matter.
- Energy loss dE/dx via collisional and radiative processes?
- Coherent energy loss → jet-quenching parameter $\hat{q}$?
- Hadronization via (medium-modified?) fragmentation.

Open versus hidden heavy-flavor



open heavy flavor

hidden heavy flavor

illustration by Alex Doig;
Agnes Moscy QM 2011

- represent most of the HF production cross section
- effects in cold nuclear matter: shadowing, energy loss
- single particle
- Q is always a color charged object
- energy/momentum loss due to interactions with the medium $\Rightarrow$ **HF diffusion coefficient**

J. Bjorken, 1982

- small amount of total cross section
- effects in cold nuclear matter: shadowing, energy loss, **break-up**
- bound state with non-zero extention
- can propagate as a color-neutral bound state
- melting due to screening of $Q\bar{Q}$ potential in the medium $\Rightarrow$ **formation/temperature of QGP**

T. Matsui and H. Satz, PLB 178 (1986)

$\leftarrow$ dissociation

regeneration $\rightarrow$

Fluid dynamical description and heavy quarks

Formation of QGP, which evolves fluid dynamically as a nearly perfect fluid.

energy-momentum conservation

$$\partial_\mu T^{\mu\nu} = 0$$

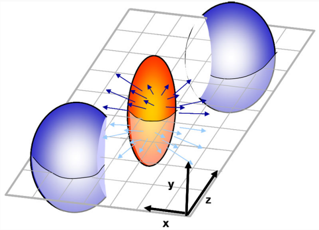
for conserved charge densities

$$\partial_\mu N^\mu = 0$$

equation of state

$$p = p(e, n) \to (T, \mu_B)$$

$\to$ Coupling heavy quarks to the medium (T and u^μ) via **Fokker-Planck dynamics**!



observable: Fourier coefficients of

$$\frac{\mathrm{d}^2 N}{\mathrm{d}p_T \mathrm{d}y} \propto \sum_n v_n \cos(n\phi)$$

sensitive to viscosity η/s

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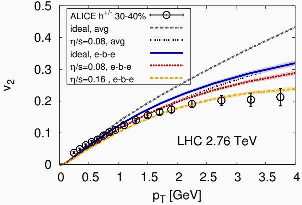


B. Schenke et al. PLB702 (2011)

observable: Fourier coefficients of

$$\frac{\mathrm{d}^2 N}{\mathrm{d}p_T \mathrm{d}y} \propto \sum_n v_n \cos(n\phi)$$

sensitive to viscosity η/s

Fokker-Planck dynamics

Assumption: scatterings in the medium are dominated by small momentum transfer
$\Rightarrow$ Description of the HQ momentum distribution f_Q as a function of time via Fokker-Planck dynamics: D. Walton et al., PRL84 (2000); G. Moore et al., PRC71 (2005)

$$\frac{\partial}{\partial t} f_Q(t,\vec{p}) = \frac{\partial}{\partial p^i}\left(A^i(\vec{p}) f_Q(t,\vec{p}) + \frac{\partial}{\partial p^j}\left[B^{ij}(\vec{p}) f_Q(t,\vec{p}) \right] \right)$$

The friction (drag) and momentum diffusion coefficients depend on the HQ momentum and the medium temperature.

Recast to **Langevin equation** $\frac{\mathrm{d}}{\mathrm{d}t}\vec{p} = -\eta_D(p)\vec{p} + \vec{\xi}$ and $\langle \xi^i(t)\xi^j(t')\rangle = \kappa\delta^{ij}\delta(t-t')$

Transport coefficients connected by **fluctuation-dissipation theorem** (Einstein relation):

$$\eta_D = \frac{\kappa}{2m_Q T} \qquad D_s = \frac{T}{m_Q \eta_D} \qquad \text{spatial diffusion coefficient}$$

Fokker-Planck equation is second moment approximation of the **Boltzmann equation**:

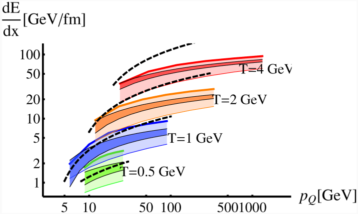
$$\frac{\mathrm{d}}{\mathrm{d}t} f_Q(t,\vec{x},\vec{p}) = \mathcal{C}[f_Q] \quad \text{with} \quad \mathcal{C}[f_Q] = \int \mathrm{d}\vec{k}[\underbrace{w(\vec{p}+\vec{k},\vec{k}) f_Q(\vec{p}+\vec{k})}_{\text{gain term}} - \underbrace{w(\vec{p},\vec{k}) f_Q(\vec{p})}_{\text{loss term}}]$$

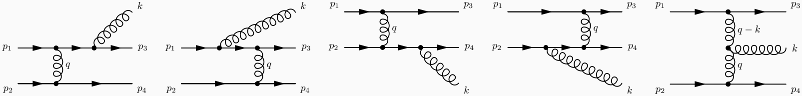
Do both dynamics lead to similar phenomenological results? Probably yes for R_{AA}, v_2, probably no for more differential observables... S. Das et al, PRC90 (2014)

pQCD inspired models - 

- One-gluon exchange model: reduced IR regulator λm_D^2 in the hard propagator
- Running coupling $\alpha_{\rm eff}(t)$ and self-consistent $m_D^2 = (1+6n_f)4\pi\alpha_s(m_D^2)T^2$

A. Peshier, hep-ph/0601119, PRL 97 (2006); P. B. Gossiaux et al. PRC78 (2008), NPA 830 (2009)





- Extention of Gunion-Bertsch approximation beyond mid-rapidity and to finite mass m_Q ⇒ distribution of induced gluon radiation ($E_{\rm rad}^{\rm loss} \propto E\,L$):

$$P_g(x, \vec{k_\perp}, \vec{q_\perp}, m_Q) = \frac{3\alpha_s}{\pi^2}\frac{1-x}{x}\left(\frac{\vec{k_\perp}}{\vec{k_\perp}^{\,2}+x^2m_Q^2} - \frac{\vec{k_\perp}-\vec{q_\perp}}{(\vec{k_\perp}-\vec{q_\perp})^2+x^2m_Q^2}\right)^2$$

J. Gunion, PRD25 (1982); B. Zakharov, JETPL 63/65 (1996/7); O. Fochler et al. PRD88 (2013); J. Aichelin et al. PRD89 (2014)

- Implemented in MC@sHQ + EPOS2, Subatech, MN, J. Aichelin, PB. Gossiaux, K. Werner, PRC 89 (2014), PRC 90 (2014), PRC 91 (2015), PRC 93 (2016)

T-matrix approach - TAMU

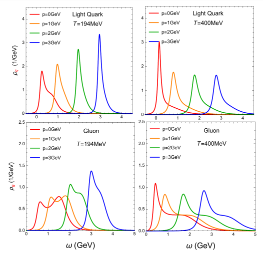
- Thermodynamic T-matrix approach, $T = V + VGT$, given by a two-body driving kernel V, estimated from the lQCD internal/free energy for a static $Q\bar{Q}$ pair.

  D. Cabrera, R. Rapp PRD 76 (2007); H. van Hees, M. Mannarelli, V. Greco, R. Rapp PRL 100 (2008)

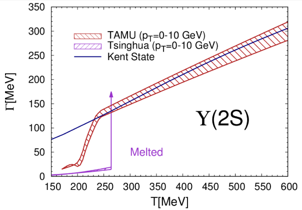
- Comprehensive sQGP approach for the EoS, light quark & gluon spectral functions, quarkonium correlators and HQ diffusion. F. Riek, R. Rapp PRC 82 (2010); S. Liu, R. Rapp arxiv:1612.09138

- Resonance correlations in the T-matrix naturally lead to recombination (resonance recombination model) near T_c from the same underlying interactions!

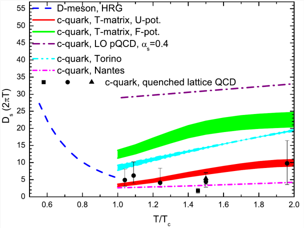
  M. He, R. Fries, R. Rapp PRC 82 (2010), PRC 86 (2012)



low-p light quarks/gluons no good quasiparticles!



inelastic reaction rates for strongly suppressed $\Upsilon(2S)$

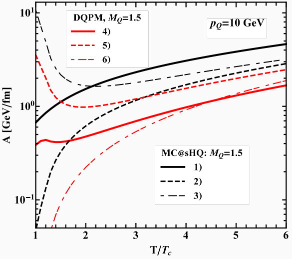


charm spatial diffusion coefficient

Quasiparticles or AdS/CFT

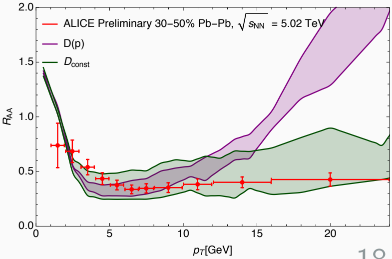
Quasiparticles:

- Nonperturbative effects near T_c are captured by $\alpha_s(T)$, leading to thermal masses/widths, determined from fits to lQCD EoS.
  A. Peshier et al. PLB 337 (1994), PRD 70 (2004); M. Bluhm et al. EPJC 49 (2007); W. Cassing et al. NPA 795 (2007)
- Implemented for HF dynamics in e.g. PHSD (full off-equilibrium transport). H. Berrehrah et al. 1604.02343, T. Song et al. PRC 92 (2015), PRC 93 (2016)



Strong coupling - AdS/CFT:

- HF string moves at constant v over BH: fluctuations grow with v, $D(p)$.
  S. Gubser NPB 790 (2008), W. Horowitz, PRD (2015)
- New derivation parametrizes between LF/HF $\Rightarrow$ string falling onto the BH horizon, $D_{\rm const}$. R. Moerman, W. Horowitz, arxiv:1605.09285

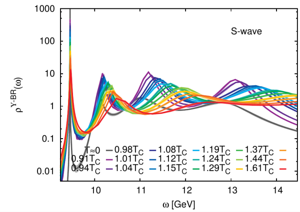


Help from hidden heavy flavor?

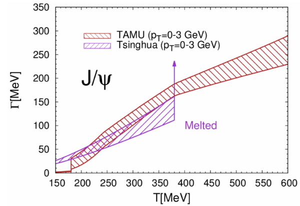
- Consistent picture of quarkonium suppression and regeneration in the QGP.
- Spectral functions contain information about masses, binding energies, reaction rates of the $Q\bar{Q}$.
- Interpretation of melting peaks in the spectral function via modeling of $Q\bar{Q}$ dynamics in HIC.
- SHM describes $N^{\text{eq}}_{Q\bar{Q}}(T,\gamma)$ based on thermal values.
  P. Braun-Munzinger et al. arxiv:0901.2500; M. Gazdzicki et al. PRL 83 (1999); A. Andronic et al. NPQ 789 (2007)
- Microscopic transport via rate equation

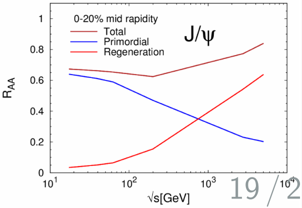
$$\mathrm{d}N_{Q\bar{Q}}/\mathrm{d}\tau = -\Gamma[N_{Q\bar{Q}} - N^{\text{eq}}_{Q\bar{Q}}]$$

  reaction rate Γ: (gluo + quasi-free dissociation) governs suppression and regeneration.
  G. Bhanot et al., NPB 156 (1979); D. Kharzeev et al. PLB 334 (1994)
  N. Brambilla et al., PRD 78 (2008); X. Zhao et al. NPA 859 (2011);
  T. Song et al. PRC 84 (2011); M. Strickland et al. NPA 879 (2012);
  E. Ferreiro, PLB 731 (2014); K. Zhou et al. PRC 89 (2014)
- Toward the inclusion of quantum effects into transport.
  JP. Blaizot et al., NPA946 (2016); PB. Gossiaux et al., arxiv:1611.06499



A. Rothkopf, arxiv:1509.03715

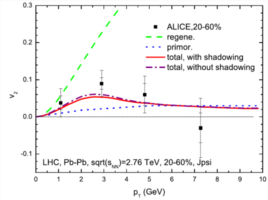


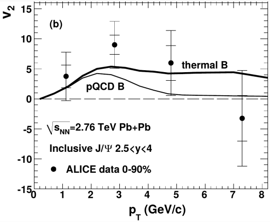


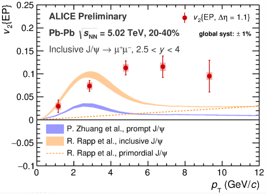
R. Rapp, arxiv:1704.07923

Help from hidden heavy flavor?

- Initially produced J/ψ, which survives the QGP phase, has little v_2 due to low elastic interaction rate.
- Charmonium regeneration concentrated at low $p_T \lesssim m_{J/\psi} \Rightarrow$ leads to a non-zero elliptic flow for J/ψ, with similar values as for D mesons.







TAMU: X. Zhao et al., NPA 904-905 (2013); Tsinghua: K. Zhou et al., PRC 89 (2014); ALICE QM2017

- Reasonable theoretical description at low p_T, additional effects at intermediate p_T for $\sqrt{s} = 5.02$ TeV!
- Need to address open heavy-flavor dynamics and quarkonium regeneration within the same dynamical framework!

$\Rightarrow$ Information about charm quark thermalization and recombination/regeneration mechanism!

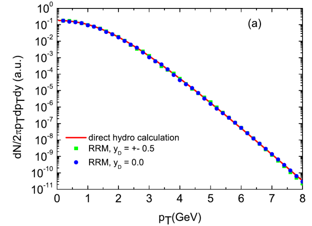
Resonance recombination model (RRM) - D_s enhancement

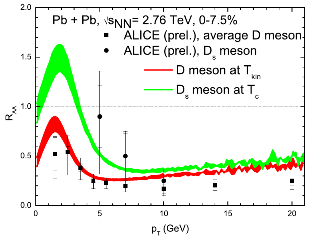
- Resonance correlations in the T-matrix naturally lead to recombination (resonance recombination model) near T_c from the same underlying interactions! **M. He, R. Fries, R. Rapp PRC 82 (2010), PRC 86 (2012)**
- RRM reproduces long-time limit of thermal equilibration as given by a fluid dynamical calculation.
- Finite recombination time window around $T_{pc} = 170$ MeV.
- Thermal weights from SHM, $\gamma_s = 0.85$

  P. Braun-Munzinger et al. nucl-th/0304013; A. Andronic et al. PLB 571 (2003)

$\Rightarrow$ Significantly enhanced D_s $R_{\rm AA}$ over non-strange D $R_{\rm AA}$!

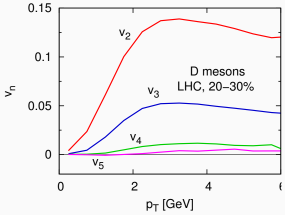
M. He, R. Fries, R. Rapp, PRL 110 (2013); PLB 735 (2014)

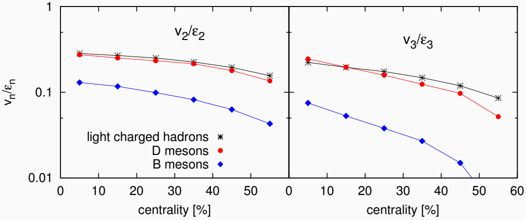




What can we learn from the v3?

- Most models give a τ_{relax} for charm quarks much longer than the evolution of the QGP, but $v_2(\mathrm{HF}) \lesssim v_2(\mathrm{LF}) \rightarrow$ indication for "partial" thermalization?
- Higher-order Fourier coefficients were important for understanding charged hadron flow $\Rightarrow$ What about heavy-flavor v_3, v_4, ...?





- Expectation: v_3 and higher-order coefficients (and centrality dependence) show the incomplete coupling of HQ to the medium!

  MN, J. Aichelin, S. Bass, P.B. Gossiaux, K. Werner, PRC91 (2015) 1410.5396

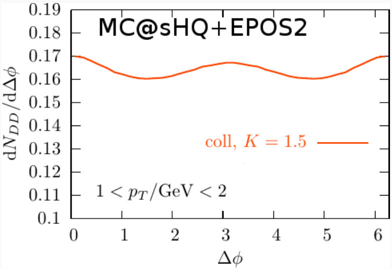
- Could heavy-flavor flow, v_2 and v_3, have a different origin? Escape mechanism?

  Z.W. Lin NPA956 (2016)

New observables?

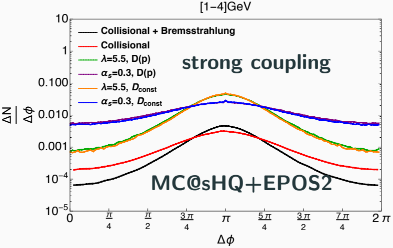
- High sensitivity of **heavy-quark correlations** to collisional vs. radiative energy loss. MN, J. Aichelin, P.B. Gossiaux, K. Werner, PRC90 (2014), 1305.3823

different view on HQ flow coefficients:



MN et al., SQM2013

$b\bar{b}$ correlations:
strong vs. weak coupling



- Flow coefficients from DD correlations agree well with v_n from event plane/participant plane.
- Low p_T pairs more likely to remain correlated for strong than for weak coupling.
- Challenge: the $c\bar{c}$ proton-proton baseline is not well understood theoretically + experimental feasibility?

New observables?

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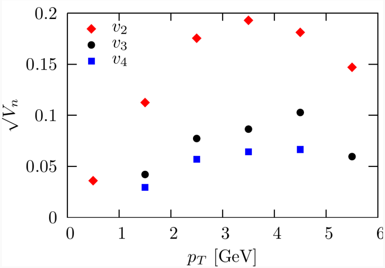
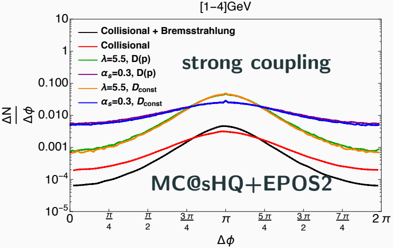


MN et al., SQM2013

$b\bar{b}$ correlations:

strong vs. weak coupling



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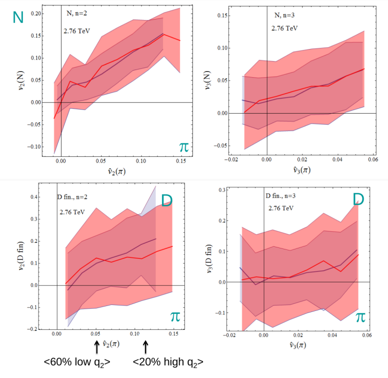
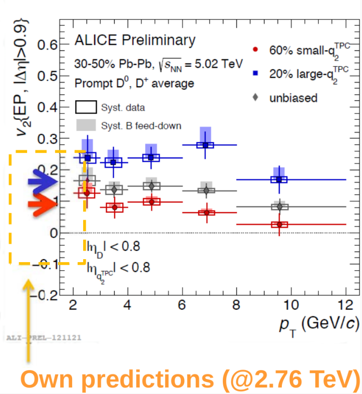
- Low p_T pairs more likely to remain correlated for strong than for weak coupling.
- Challenge: the $c\bar{c}$ proton-proton baseline is not well understood theoretically + experimental feasibility?

Fluctuations - event engineering?

- Going from MC@sHQ+EPOS2 to EPOS-HQ consistent production of charm quarks in EPOS initial conditions, viscous fluid dynamical evolution, etc. allows us to study correlations between the light and the heavy flavor sector! PB. Gossiaux, J. Aichelin, MN, V. Ozvenchuk, K. Werner, arXiv:1705.02271
- Nucleon - pion v_n correlate strongly (same production mechanism/hypersurface).
- Event-by-event D meson - pion flow is less correlated, especially v_3.





- Select light flavor events with high and low q-vector and look at heavy flavor response in these event classes!