Heavy-quark dynamics in a hydrodynamically evolving medium

Marlene Nahrgang

Strangeness in Quark Matter 2017, Utrecht, Netherlands July 11, 2017

SUBATECH, IMT Atlantique, Nantes, France

Light versus heavy flavor

light/soft flavor

heavy flavor

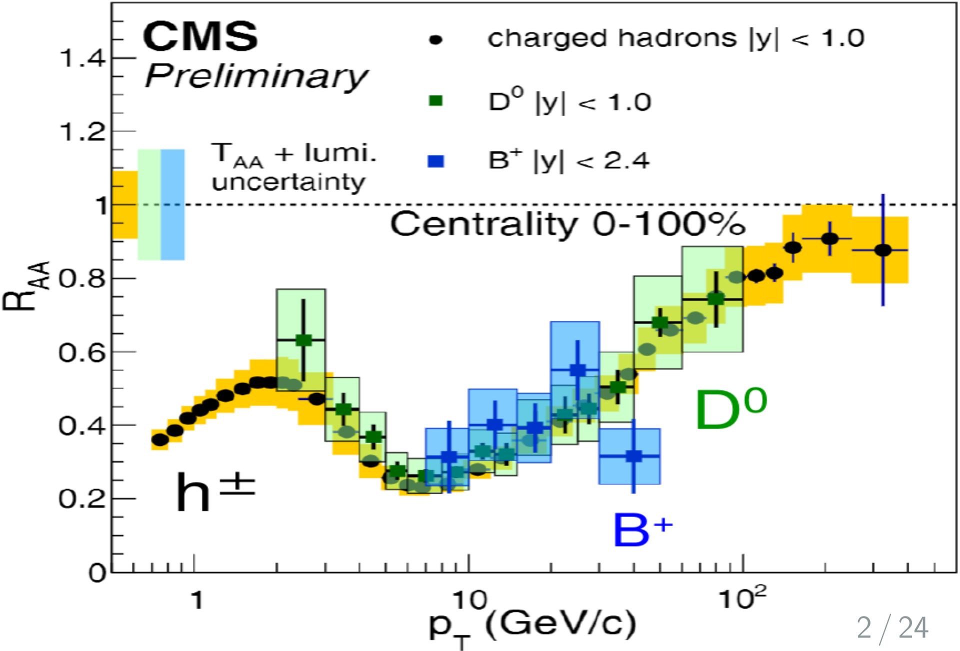
- local equilibration during preequilibrium phase ⇒ formation of the QGP!
- loss of memory/information of microscopic interactions

⇒ study collective phenomena on the hydro hypersurface!

- initial production in hard processes ⇒ not equilibrated with the QGP at τ_0
- keep some memory of the interaction with the QGP

⇒ study as probes of the underlying QCD force!

Low versus high momentum



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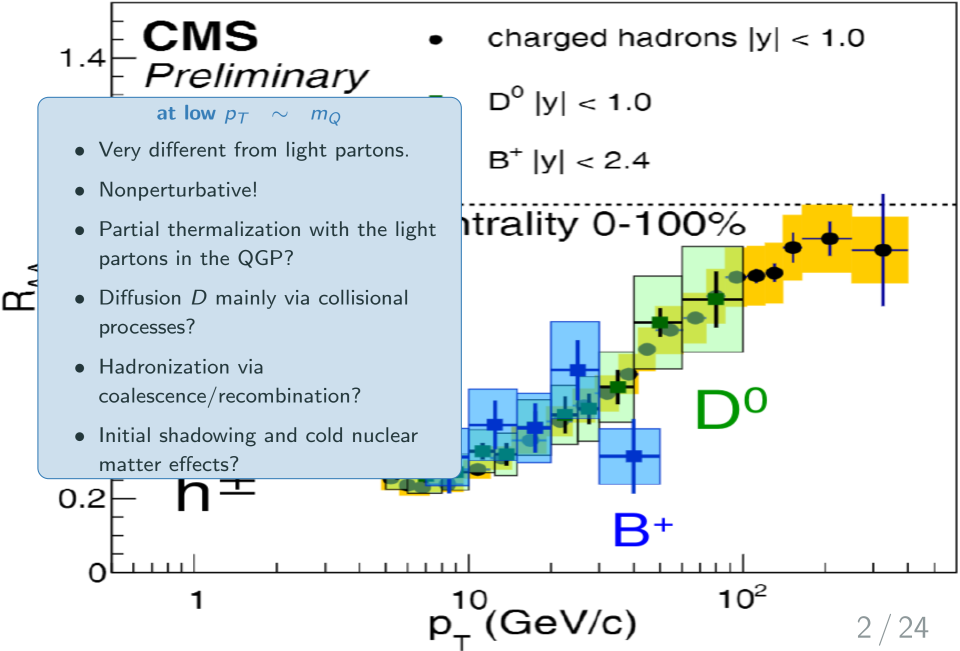

at low $p_T \sim m_Q$

- 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?

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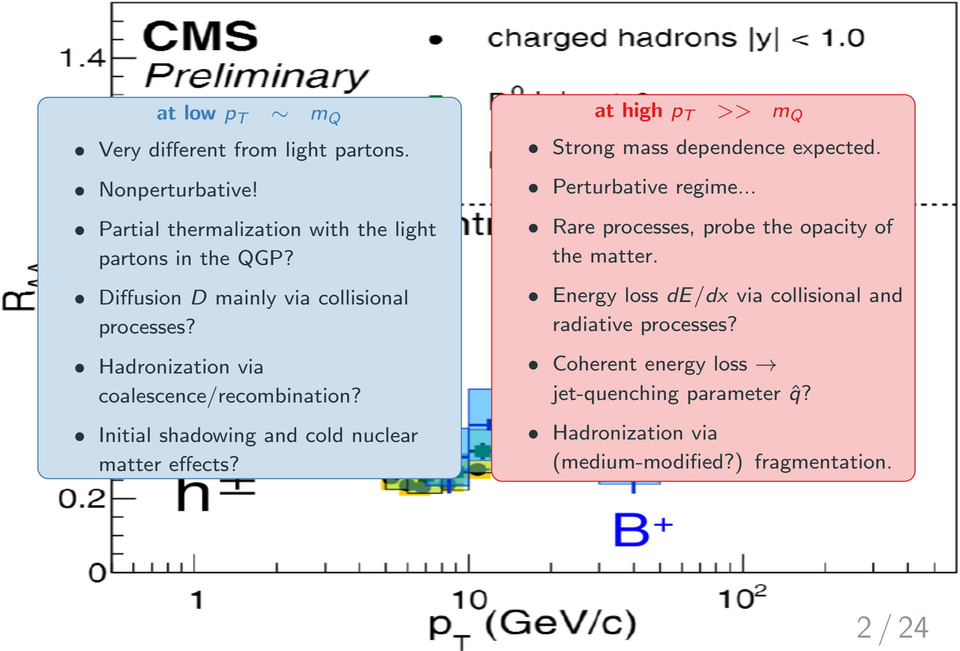

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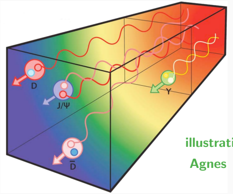
at high $p_T >> m_Q$

- 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 $\rightarrow$ 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 ⇒ **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 ⇒ **formation/temperature of QGP**

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

← dissociation

regeneration →

Fluid dynamical description and heavy quarks

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

energy-momentum conservation

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

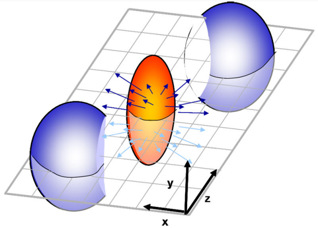
for conserved charge densities

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

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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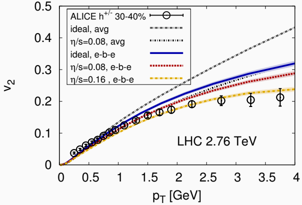

B. Schenke et al. PLB702 (2011)

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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):

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

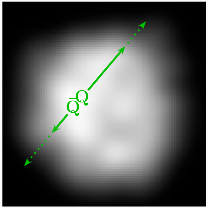
Fokker-Planck equation is second moment approximation of the **Boltzmann equation**:

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

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)

Coupling of the HQ to fluid dynamical QGP - in practice

production



- LO pQCD, e.g. FONLL → 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 ⇒ 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)

  next talk, R. Vogt!
- Consistent initialization of HF and LF sectors!

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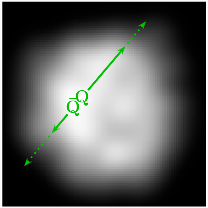
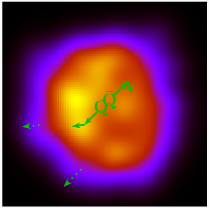
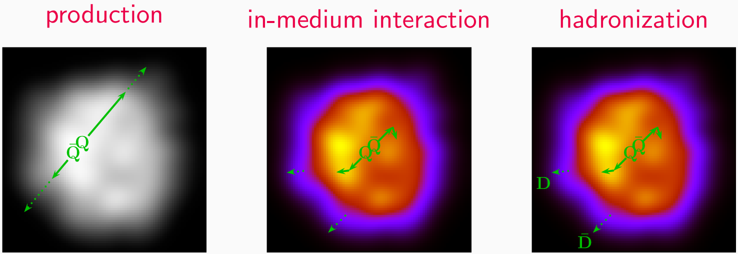


in-medium interaction



- Scattering off light QGP constituents, sampled from fluid dynamics (or given within microscopic transport).
- Any model with $P(\Delta E)$ produces the generic p_T shape of R_{AA}, magnitude depends strongly on the bulk evolution model! T. Renk, PRC85 (2012)
- Proper modeling of the QGP evolution is important! Should be well tested in the light hadron sector!
- Does the equation of state match the representation of the medium (quasiparticles)? MN et al. PRC93 (2016)

Coupling of the HQ to fluid dynamical QGP - 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)

Now we need the interaction...

a) from lattice QCD calculations

b) from models

c) from experimental data

Diffusion coefficient from lattice QCD calculations

- 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

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

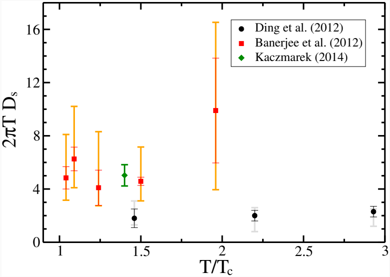
- Obtain transport coefficients from the slope of spectral function ρ_E at $\omega = 0$ (Kubo formula).

momentum diffusion:

$$\frac{\kappa}{T^3} = \lim_{\omega \to 0} \frac{2T\rho_E(\omega; T)}{\omega}$$

spatial diffusion: $D_s = \frac{2T^2}{\kappa}$

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



Now we need the interaction...

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   Current lattice QCD estimates are between $D_s \sim 2 - 7(2\pi T)$ ...

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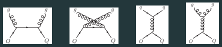
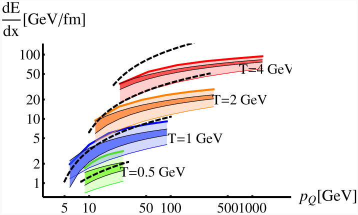
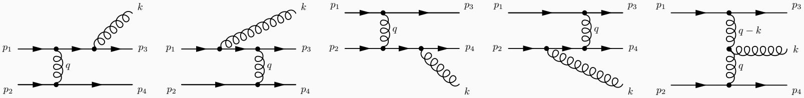
pQCD inspired models - 

- 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 $\Rightarrow$ distribution of induced gluon radiation ($E_{\rm rad}^{\rm loss} \propto E\,L$):

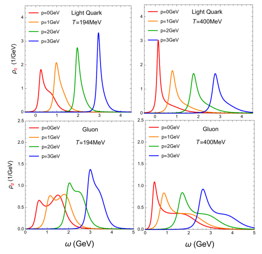
$$P_g(x, \vec{k_\perp}, \vec{q_\perp}, m_Q) = \frac{3\alpha_s}{\pi^2}\frac{1-x}{x}\left(\frac{\vec{k_\perp}}{\vec{k_\perp}^{\,2} + x^2 m_Q^2} - \frac{\vec{k_\perp} - \vec{q_\perp}}{(\vec{k_\perp} - \vec{q_\perp})^2 + x^2 m_Q^2}\right)^2$$

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

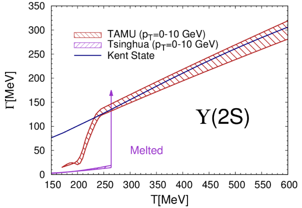
- Implemented in MC@sHQ + EPOS2, Subatech, MN, J. Aichelin, PB. Gossiaux, K. Werner, PRC 89 (2014), PRC 90 (2014), PRC 91 (2015), PRC 93 (2016)

T-matrix approach - TAMU

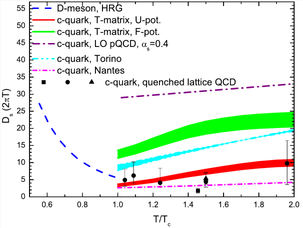
- Thermodynamic T-matrix approach, $T = V + VGT$, given by a two-body driving kernel V, estimated from the lQCD internal/free energy for a static $Q\bar{Q}$ pair.
  D. Cabrera, R. Rapp PRD 76 (2007); H. van Hees, M. Mannarelli, V. Greco, R. Rapp PRL 100 (2008)
- Comprehensive sQGP approach for the EoS, 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 $\Upsilon(2S)$

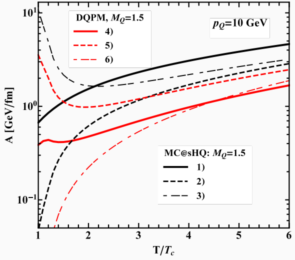


charm spatial diffusion coefficient

Quasiparticles or AdS/CFT

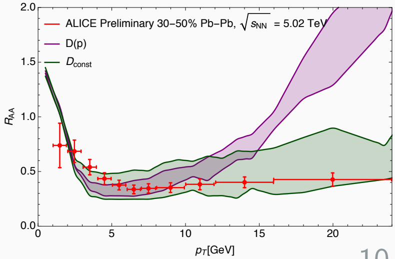
Quasiparticles:

- 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 ⇒ string falling onto the BH horizon, D_{const}. R. Moerman, W. Horowitz, arxiv:1605.09285



Now we need the interaction...

a) from lattice QCD calculations
   Current lattice QCD estimates are between $D_s \sim 2 - 7(2\pi T)$**...**
b) from models
   different approaches, different answers, different D_s**...**
c) from experimental data

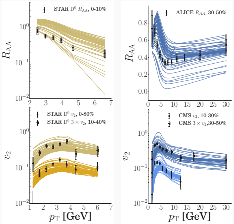
Bayesian model-to-data statistical analysis

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

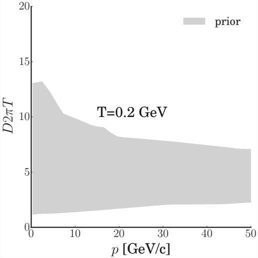
  ($\eta/s(T)$, $\zeta/s(T)$ constraint by bulk observables via Bayesian analysis)

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

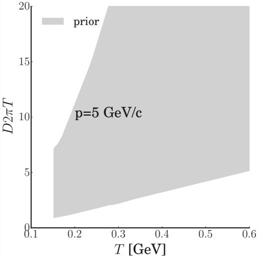
exprimental data



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, MN, J. Bernhard, S. Cao, S. Bass, in preparation

Talk by Yingru Xu, Thu 9:00

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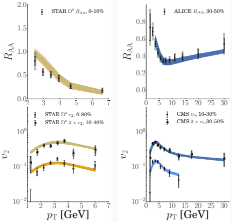

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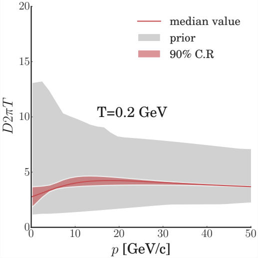

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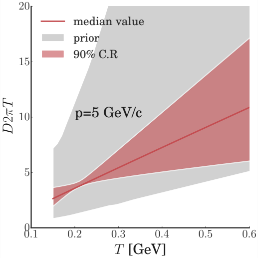

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a) from lattice QCD calculations
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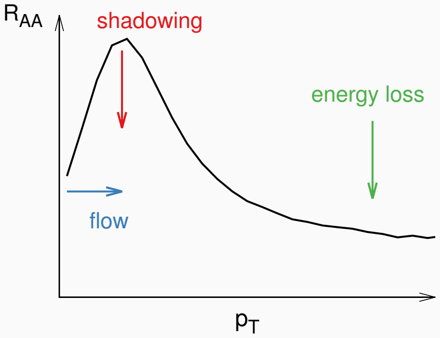
b) from models
different approaches, different answers, different D_s...

c) from experimental data
rigorous parameter determination, depends on parametrization and model, $D_s \sim 2 - 7(2\pi T)$

What can we learn from the R_{AA}?



flow bump: due to

- (radial) flow of the medium
- recombination with light quarks

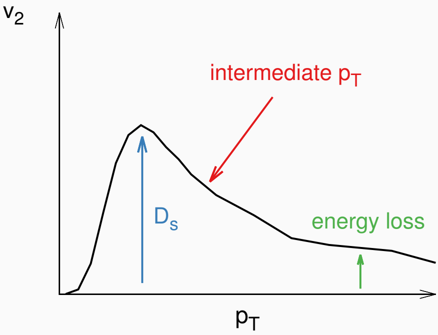
shadowing: due to

- initial state nuclear effects

energy loss: due to

- elastic and inelastic scatterings
- coherence important at larger p_T

What can we learn from the v_2?



spatial diffusion:

- height of v_2 at low p_T sensitive to the spatial diffusion coefficient

energy loss:

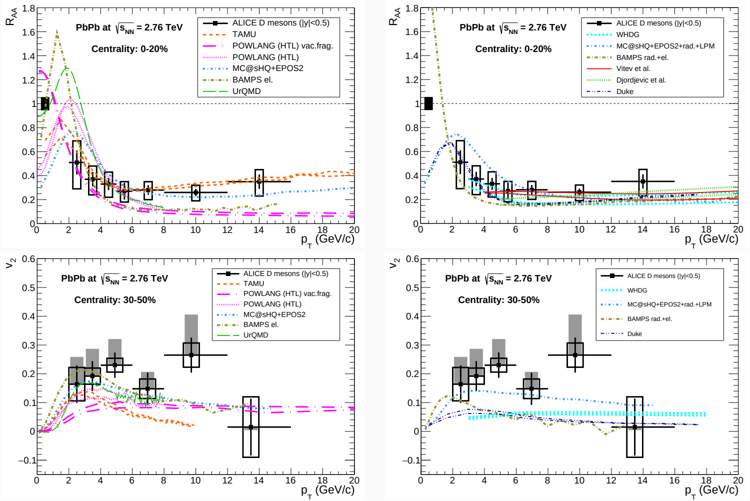
- at high p_T leads to non-zero v_2 due to the initial geometry.

intermediate p_T:

- onset and offset of many competing effects.

What models make of the R_{AA} and v_2:

purely elastic scatterings



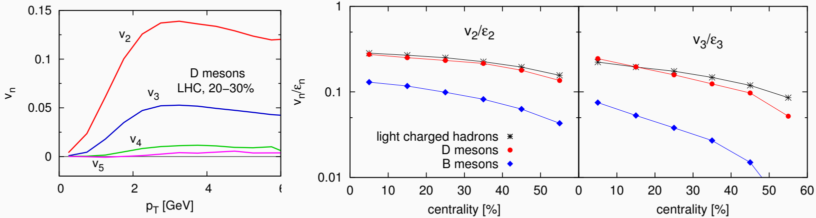
elastic scatterings + radiation

SaporeGravis Network, EPJC76 (2016) 1506.03981

What can we learn from the v3?

see also talk by F. Scardina, Fri 16:05

- Most models give a $\tau_{\rm relax}$ for charm quarks much longer than the evolution of the QGP, but $v_2(\rm HF) \lesssim v_2(\rm LF) \rightarrow$ 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

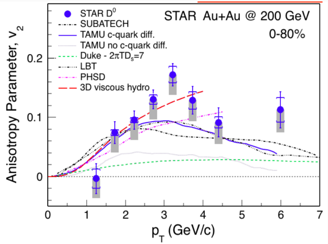
- Could heavy-flavor flow, v_2 and v_3, have a different origin? Escape mechanism?

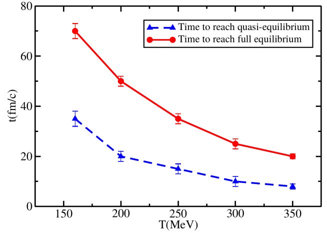
  Z.W. Lin NPA956 (2016) **talk by Z.W. Lin, Thu 11:30**

Partial thermalization of heavy quarks with the medium

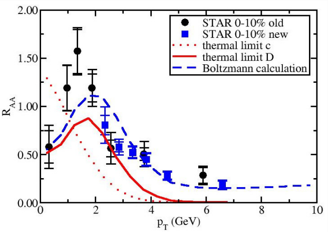
Need a good quantitative measure - or at least some common understanding - of what we mean by "(partial) thermalization"!

- HQ seem to pick up almost all of the anisotropy of the medium.
- But equilibration times are much larger, $\tau_{\mathrm{relax}} \sim \tau_{\mathrm{QGP}}$.
- 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

Hadronization via recombination/coalescence

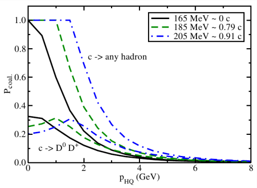
$$Q(\bar{Q}) + \bar{q}(q) \to \text{mesons}$$

and similarly for baryons!

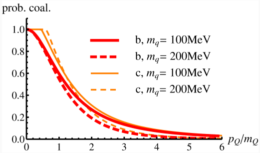
$$\frac{\mathrm{d}N_M}{\mathrm{d}^3P} = g_M \int \{\mathrm{d}x\mathrm{d}p\} f_q(x_1, p_1) f_q(x_2, p_2) |\psi_M(y, P)|^2 \delta(P - p_1 - p_2)$$

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

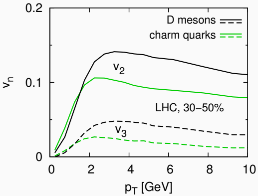
- Recombination/coalescence probability large at low p_T.
- Strongly affects low p_T observables: bump in R_{AA}, contributes 25 – 50% to v_n.
- What is the meson/baryon wavefunction? Dependence on parameters, like the constituent quark mass, etc... $\Rightarrow$ Λ_c/D^0 and D_s/D^0 can help constrain!
- Implementation on a fluid dynamical background not trivial. What is the probability for spatially varying fluid velocities, etc...?



S. Cao et al. arxiv:1505.01413



Gossiaux et al. PRC 78 (2008)



MN et al. PRC91 (2015)

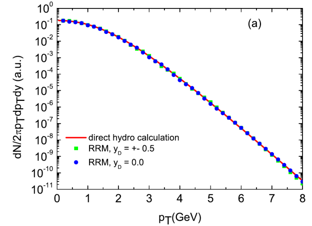
Resonance recombination model (RRM) - D_s enhancement

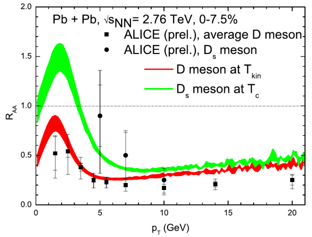
- Resonance correlations in the T-matrix naturally lead to recombination (resonance recombination model) near T_c from the same underlying interactions! **M. He, R. Fries, R. Rapp PRC 82 (2010), PRC 86 (2012)**
- RRM reproduces long-time limit of thermal equilibration as given by a fluid dynamical calculation.
- 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_{AA} over non-strange D R_{AA}!

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



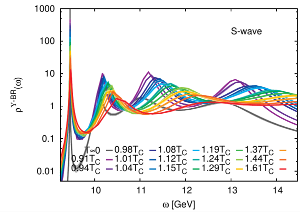


Help from hidden heavy flavor?

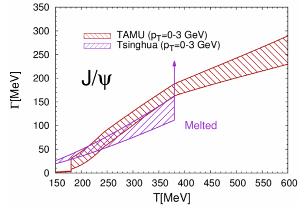
- Consistent picture of quarkonium suppression and regeneration in the QGP.
- Spectral functions contain information about masses, binding energies, reaction rates of the $Q\bar{Q}$.
- Interpretation of melting peaks in the spectral function via modeling of $Q\bar{Q}$ dynamics in HIC.
- SHM describes $N^{\rm eq}_{Q\bar{Q}}(T,\gamma)$ 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

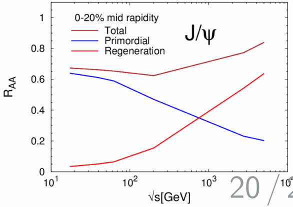
$$\mathrm{d}N_{Q\bar{Q}}/\mathrm{d}\tau = -\Gamma[N_{Q\bar{Q}} - N^{\rm eq}_{Q\bar{Q}}]$$

  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

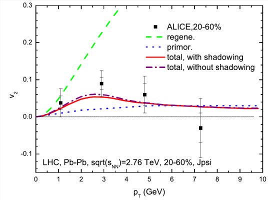


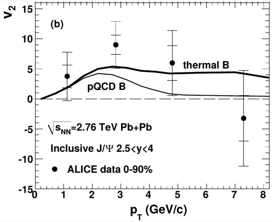


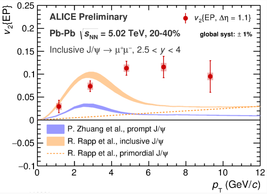
R. Rapp, arxiv:1704.07923

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

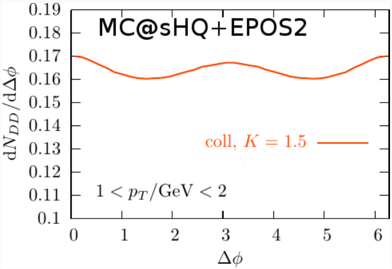
- Reasonable theoretical description at low p_T, additional effects at intermediate p_T for $\sqrt{s} = 5.02$ TeV!
- Need to address open heavy-flavor dynamics and quarkonium regeneration within the same dynamical framework!

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

New observables?

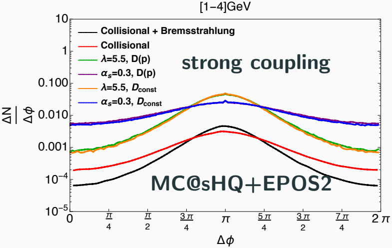
- High sensitivity of **heavy-quark correlations** to collisional vs. radiative energy loss. MN, J. Aichelin, P.B. Gossiaux, K. Werner, PRC90 (2014), 1305.3823

different view on HQ flow coefficients:



MN et al., SQM2013

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



Talk by R. Hambrock, Thu 9:20

- 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?

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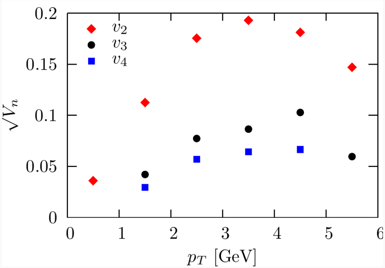

MN et al., SQM2013

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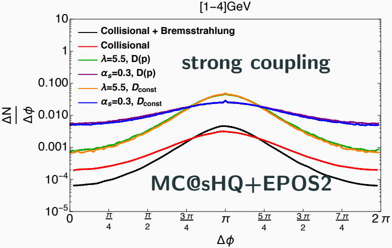

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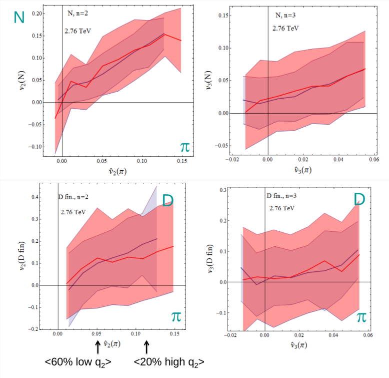
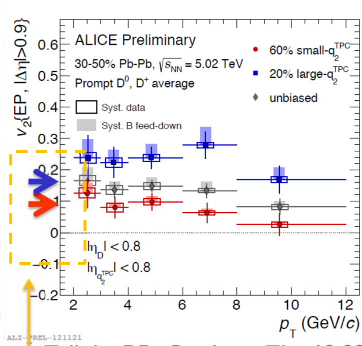
Fluctuations - event engineering?

- 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.





Talk by PB. Gossiaux, Thu 10:00

Own predictions (@2.76 TeV)

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

Conclusions

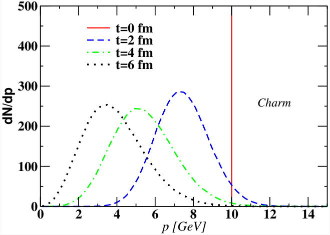
- Coupling of heavy flavor via Fokker-Planck/Boltzmann/rate equation to QPG - described fluid dynamically (or microscopically).
- Intriguing at low p_T: Do charm quarks thermalize? (and what do we mean by this question?)
- Intriguing at low p_T: How does coalescence work? Can we constrain it?
- Great potential in **new observables**, like higher-order flow, azimuthal and momentum correlations, heavy-light correlations, to explore theoretically and experimentally!
- Put open and hidden heavy flavor in a **coherent dynamical framework**! Which p_T range for similar D meson vs J/ψ flow?
- Theory collaborations for **systematic comparison of various model ingredients**: JET-HQ, EMMI RRTF $\Rightarrow$ results expected soon!

Thanks to J. Aichelin, S. Bass, S. Cao, P.B. Gossiaux, R. Hambrock, R. Rapp, T. Song, Y. Xu for helpful contributions to this talk!

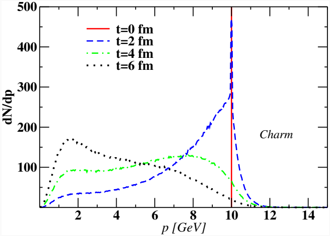
extra

- 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 $\Rightarrow$ 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

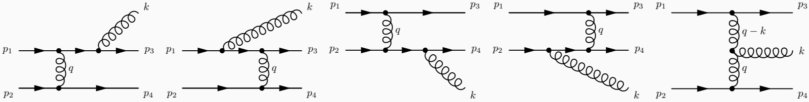


Boltzmann



S. Das et al, PRC90 (2014)

Radiative energy loss



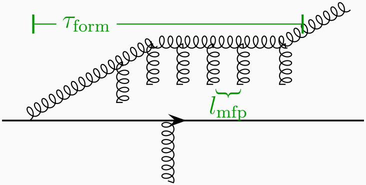
- LO pQCD matrix element for $2 \to 3$ process Kunszt et al. PRD21 (1980)
- Gunion-Bertsch approximation derived in the high-energy limit, where the radiated gluon $k_\perp$ and the momentum transfer $q_\perp$ are soft $\ll \sqrt{s}$.
- Incoherent radiation off a massless parton, mid-rapidity
- Extention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

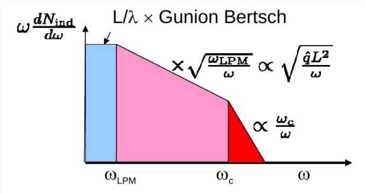
$$P_g(x, \vec{k_\perp}, \vec{q_\perp}, m_Q) = \frac{3\alpha_s}{\pi^2} \frac{1-x}{x} \left(\frac{\vec{k_\perp}}{\vec{k_\perp}^2 + x^2 m_Q^2} - \frac{\vec{k_\perp} - \vec{q_\perp}}{(\vec{k_\perp} - \vec{q_\perp})^2 + x^2 m_Q^2} \right)^2$$

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

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 $\Rightarrow$ less suppression than in QED
- At large energies in BDMPS-Z: $\Rightarrow$ $E^{\rm loss}_{\rm rad} \propto \sqrt{E}\, L$
- For very energetic partons $\tau_{\rm form} > L$, then $E^{\rm loss}_{\rm rad} \propto L^2$, estimate for the LHC ($L \sim 2fm$, $\hat{q} \sim 2$ GeV/fm $\Rightarrow \omega_c \sim 20$ GeV)

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

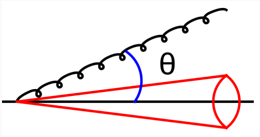
Baier et al. PLB **345** (1995); NPB **483** (1997); ibid. **484** (1997); B. G. Zakharov, JETP Lett. **63** (1996) 952

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)



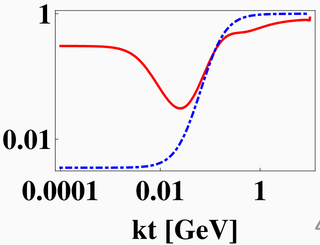
- Suppresses gluon emission in the dead cone $\theta_D = M_Q/E_Q$
- Introduces a mass hierarchy in the radiative energy loss.
- But: assumes hard scatterings!

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

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

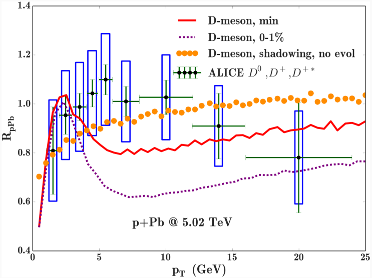
hard-scattering approximation

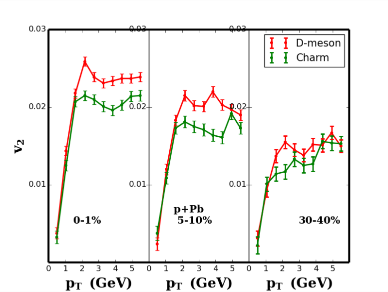
all scatterings



Charm production (and diffusion?) in pPb collisions

- 3 + 1d 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)

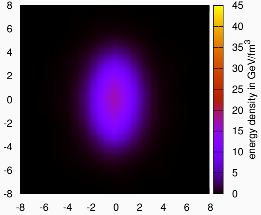
Modeling of heavy-quark dynamics in the QGP

production | interaction with the medium | hadronization

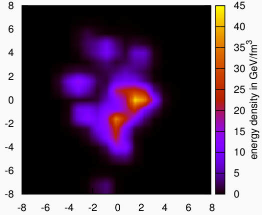
medium description | coupling medium - HF sector

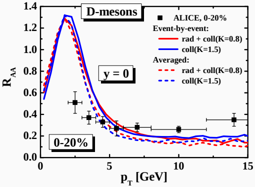
- Model the QGP: a locally thermalized medium provides the scattering partners.
- Input from a fluid dynamical description of the bulk QGP medium: temperatures and fluid velocities.
- Use a fluid dynamical description which describes well the bulk observables!

smooth initial conditions



fluctuating initial conditions

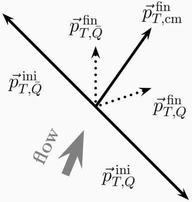




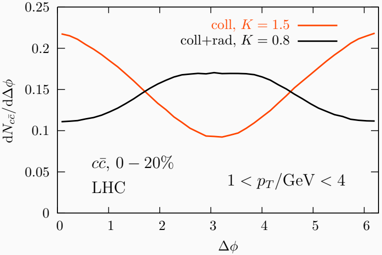
plot by V. Ozvenchuk, Nantes

"Partonic wind" effect

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

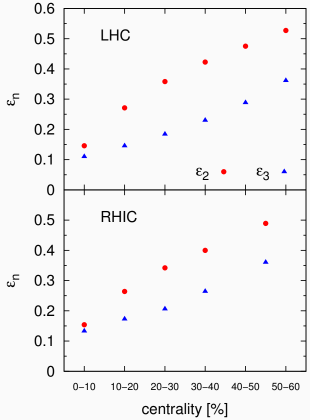


- Due to the radial flow of the matter low-p_T $c\bar{c}$-pairs are pushed into the same direction.
- Initial correlations at $\Delta\phi \sim \pi$ are washed out but additional correlations at small opening angles appear.
- This happens only in the purely collisional interaction mechanism!
- No "partonic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

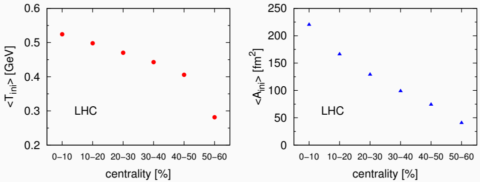


MN et al. PRC90 (2014)

QGP: initial state and bulk flow (2)



average temperature and overlap area



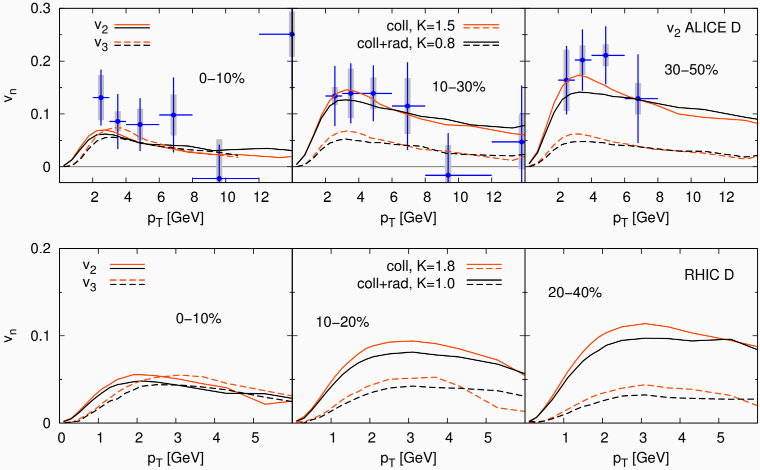
centrality dependence:

+ 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

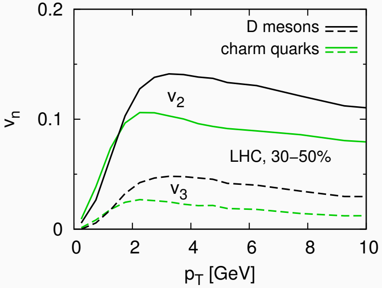
MN et al. PRC91 (2015)

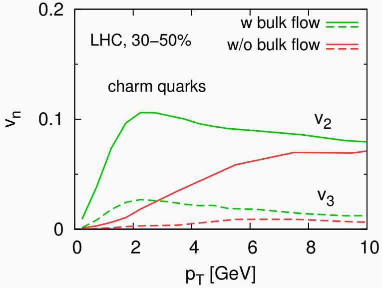
D meson v_2 and v_3 at LHC and RHIC



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

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)