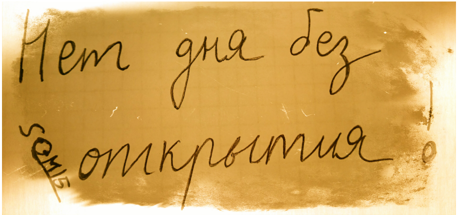
Open Charm at LHC

Marlene Nahrgang
Duke University



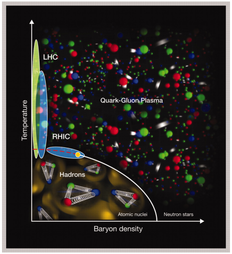
July 8th, Dubna,
Strangeness in Quark Matter
2015

Duke
UNIVERSITY

DAAD

Probes of the quark-gluon plasma

- Study of properties of strongly interacting many-body systems via ultra-relativistic heavy-ion collisions.
- Probes should not thermalize with the medium, e.g. dileptons, high-pT jets,...

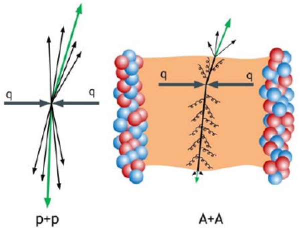


- The mass of heavy quarks (HQ) sets another scale: m_c, m_b
- HQ vacuum shower terminates much earlier: E / Q_H^2 with $Q_H = \sqrt{Q_0^2 + m_Q^2}$.
- Number of thermally excited HQ is negligibly small.
- Contributions from gluon-splitting are negligible for charm quarks at current p_T-range.
- HQ as leading parton is always tagged.

Quark-gluon plasma and its properties

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

jet quenching

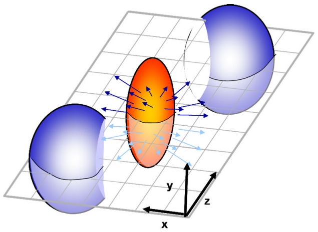


observable: nuclear modification factor

$$R_{AA}(p_T) = \frac{1}{N_{\rm coll}} \frac{\mathrm{d}N_{AA}/\mathrm{d}p_T}{\mathrm{d}N_{pp}/\mathrm{d}p_T}$$

sensitive to jet quenching parameter $\hat{q}$

collective flow



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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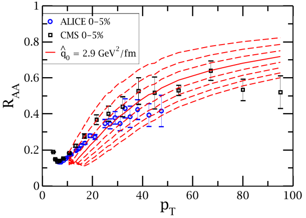

Jet Collab. PRC90 (2014)

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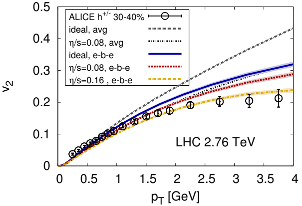

B. Schenke et al. PLB702 (2011)

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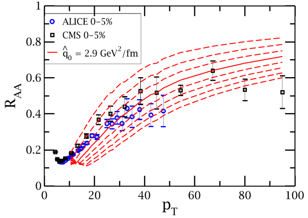

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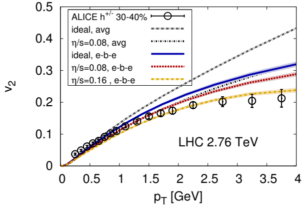

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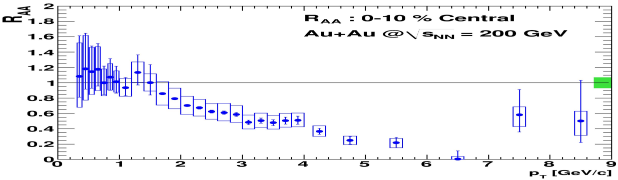
Learn from the success in the light hadron sector for heavy-flavor studies!

What to expect from heavy-quark observables?

PHENIX, PRC84 (2011)



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?

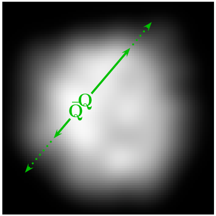
at high $p_T >> m_Q$

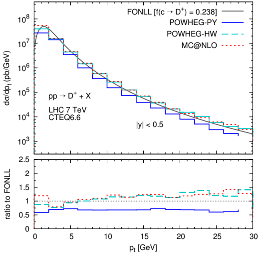
- Similar to light partons.
- Perturbative regime...
- Rare processes, probe the opacity of the matter.
- Energy loss dE/dx via collisional and radiative processes?
- Coherent energy loss $\rightarrow$ jet-quenching parameter $\hat{q}$?
- Hadronization via (medium-modified) fragmentation?

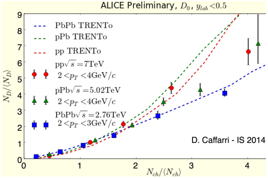
Modeling of heavy-quark dynamics in the QGP

production interaction with the medium hadronization

Remember talk by C.Y. Wong Tue 15h40!







W. Ke et al., Duke, in prep.

- LO pQCD, e.g. FONLL $\rightarrow$ inclusive spectra, no azimuthal $Q\bar{Q}$ correlations
  M. Cacciari et al. PRL**95** (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)
- Consistent initialization of HF and LF sectors!
- Cold nuclear matter effects, i.e. shadowing, p_T broadening aka Cronin effect, etc.
  K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP **0904** (2009)

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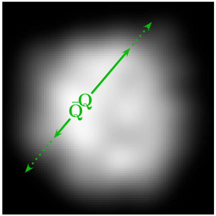

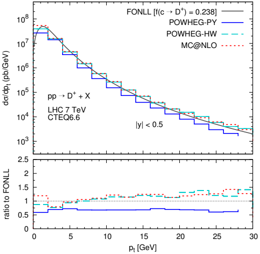

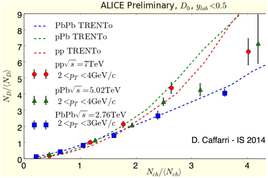

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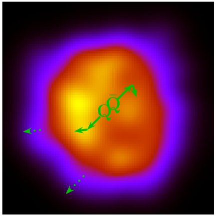
$\Delta\phi$ $D\bar{D}$ distributions in pp collisions need to be better understood!

Modeling of heavy-quark dynamics in the QGP

production **interaction with the medium** hadronization

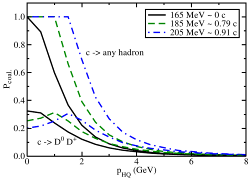


J. D. Bjorken (1982); E. Braaten et al, PRD **44** (1991), PRD **44** (1991); A. Peshier, PRL **97** (2006); S. Peigne et al., PRD **77** (2008) 114017; M. Gyulassy et al, NPB **420** (1994); BDMPS PLB **345** (1995); NPB **483** (1997); ibid. **484** (1997); B. G. Zakharov, JETP Lett. **63** (1996) 952; ibid. **64** (1996) 781; ibid. **65** (1997) 615; ibid. **73** (2001) 49; ibid. **78** (2003) 759; M. Gyulassy et al, PRL **85** (2000); NPB **571** (2000) 197; ibid. **594** (2001); Y. L. Dokshitzer et al., PLB **519** (2001); P. B. Arnold et al., JHEP 0011 (2000), 0305 (2003); N. Armesto et al., PRD **69**(2004); PRCC **72** (2005); B.-W. Zhang et al., PRL **93** (2004); NPA783 (2007); S. Wicks et al., NPA783 (2007); W. Horowitz et al., PLB666 (2008); P. Chesler et al. JHEP1310 (2013); B. Kämpfer et al., PLB **477** (2000); M. Djordjevic et al., PRC **68** (2003); PLB560 (2003); NPA733 (2004); PRC **77** (2008); PLB734 (2014); M. Bluhm et al. PRL **107** (2011); O. Fochler et al. PRD88 (2013); J. Aichelin et al. PRD89 (2014), A. Majumder 1506.08648

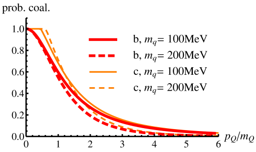
Remember talk by B. Blagojevic Tue 17h40!

Modeling of heavy-quark dynamics in the QGP

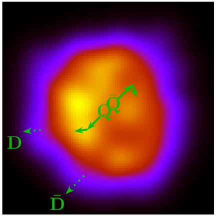
production   interaction with the medium   **hadronization**



S. Cao et al. arxiv:1505.01413



Gossiaux et al. PRC **78** (2008)



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

  e.g. C. B. Dover et al., PRC **44** (1991)

- 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.

  L. Tolos et al., PRD88 (2013); J. Torres-Rincon et al., PRD89 (2014) **See talk J. Torres-Rincon Thu 17h40!**

Set the stage: Transport equations & coefficients

Boltzmann equation for HQ phase-space distribution

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

expanding $\mathcal{C}$ for small momentum transfer $k \ll p$ (in the medium $k \sim \mathcal{O}(gT)$) and keeping lowest 2 terms $\Rightarrow$ Fokker-Planck equation

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

friction (drag) momentum diffusion

Recast to Langevin equation (probably good for bottom, but for charm?)

$$\frac{\mathrm{d}}{\mathrm{d}t} \vec{p} = -\eta_D(p) \vec{p} + \vec{\xi} \quad \text{with} \quad \langle \xi^i(t) \xi^j(t') \rangle = \kappa \delta^{ij} \delta(t - t')$$

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

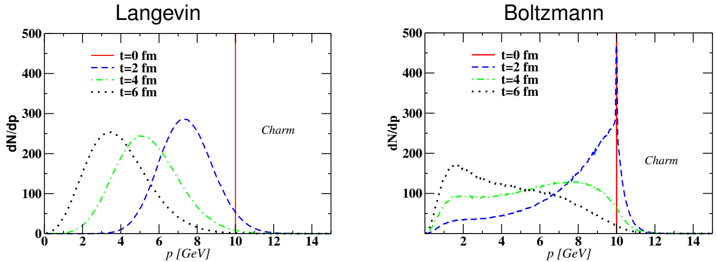
$$\eta_D = \frac{\kappa}{2 m_Q T}, \qquad D_s = \frac{T}{m_Q \eta_D} \quad \text{spatial diffusion}$$

D. Walton et al., PRL84 (2000); G. Moore et al., PRC71 (2005)

Boltzmann vs Langevin dynamics

- 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.
- Langevin leads to Gaussian momentum distribution, Boltzmann very different.

Remember talk by S. Das Tue 16h20!



S. Das et al, PRC90 (2014)

Boltzmann equation assumes independent scatterings (dilute medium) - is this a correct assumption?

Diffusion coefficient from lattice QCD

Lattice QCD at finite T is performed in Euclidean space $\Rightarrow$ notoriously difficult to calculate dynamical quantities.

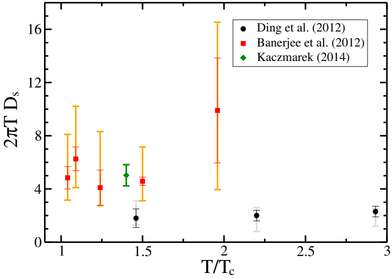
Transport coefficients calculated from correlation function of conserved currents

via slope of spectral function ρ_E at $\omega = 0$ (Kubo formula)

momentum diffusion:

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

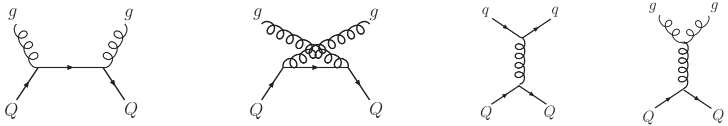
spatial diffusion: $D_s = \frac{2T^2}{\kappa}$



No reliable input from lattice QCD calculations yet...

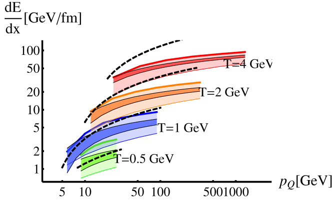
Collisional (elastic) energy loss

LO Feynmann diagrams for perturbative heavy quark scattering off a light parton



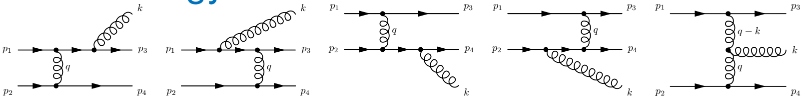
- t-channel IR singularity, regulated by the Debye screening mass m_D
- HTL energy loss: resummed propagator for $|t| \ll t^*$, bare propagator $|t| \gg t^*$
- Relevant separation of scales $g^2 T^2 \ll T^2$ probably not fullfilled at RHIC/LHC.

- One-gluon exchange model: reduced IR regulator λm_D^2 in the hard propagator
- Running coupling $\alpha_{\text{eff}}(t)$ 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)

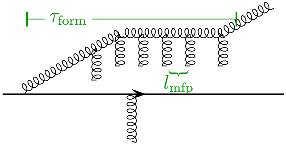
Radiative energy loss

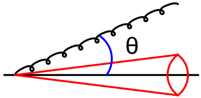


- Extention of Gunion-Bertsch approximation beyond mid-rapidity and to finite mass m_Q (heavy quarks!) ⇒ distribution of induced gluon radiation ($E_{\mathrm{rad}}^{\mathrm{loss}} \propto E\,L$):

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

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





- coherent (LPM) emission if $\tau_{\mathrm{form}} = \sqrt{\frac{\omega}{\hat{q}}} > l_{\mathrm{mfp}}$
- $E_{\mathrm{rad}}^{\mathrm{loss}} \propto \sqrt{E}\,L$, if $\tau_{\mathrm{form}} > L$ then $E_{\mathrm{rad}}^{\mathrm{loss}} \propto L^2$
- Dynamical realization challenging

  K. Zapp et al. PRL103 (2009), JHEP 1107 (2011)
- Dead cone effect: Dokshitzer et al., PLB **519** (2001)

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

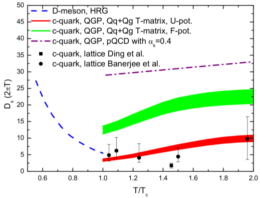
- When the hard scattering assumption is relaxed, emission at low $k_\perp$ is significantly less suppressed.

  J. Aichelin et al. PRD89 (2014)

Non-perturbative approaches

Resonance scattering:

- Basic assumption: for $T \lesssim 3T_c$ two-body interactions $\rightarrow$ potential $V(t)$
- Spatial diffusion coefficient comparable to quenched lQCD.
- smooth transition to hadronic medium with minimum close to T_c



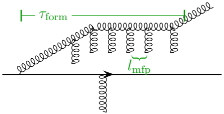
H. v. Hees, PRC73 (2006); H. v. Hees, PRL100 (2008); R. Rapp arxiv:0903.1096

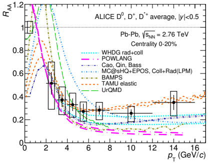
Strong coupling:

- In AdS/CFT a heavy quark is represented by a string connected to a D7 brane.
- Leading-order drag coefficients were excluded by comparison to data.
- Momentum-kicks are multiplicative and grow with the HQ velocity $\rightarrow$ important toward higher p_T!
- At larger momenta HQ in strong-coupling reach a speed limit $\rightarrow$ expected to work in an intermediate p_T regime! W. Horowitz, PRD (2015)

See talk by W. Horowitz, Fr 16h!

From theoretical input to dynamical modeling



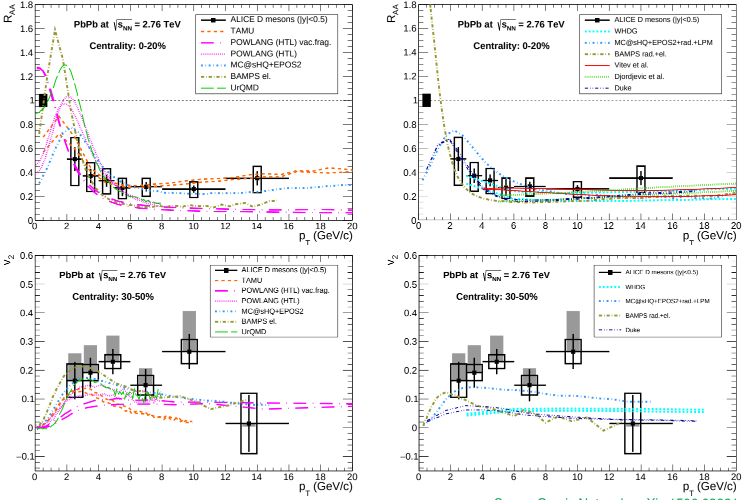


- Simple approximations are prone to fail in some kinematic region, mostly at intermediate p_T.
- Due to uncertainties all models when compared to data contain (implicit or explicit) parameter tuning.
- Proper modeling of the QGP evolution is important! Should be well tested in the light hadron sector!
- Does the equation of state match the representation of the medium quasiparticles?
- Effects of viscosity, initial state fluctations, preequilibirum dynamics?

How to get access to fundamental QGP properties from theory to data comparison?

D meson R_{AA} and v_2 in AA at LHC

purely elastic scatterings



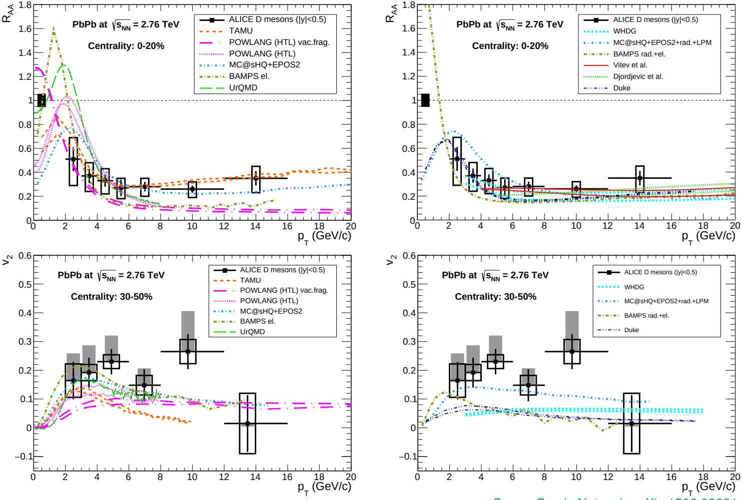
elastic scatterings + radiation

SaporeGravis Network, arXiv:1506.03981

- The simultaneous description of R_{AA} and v_2 is challenging.

D meson R_{AA} and v_2 in AA at LHC

purely elastic scatterings



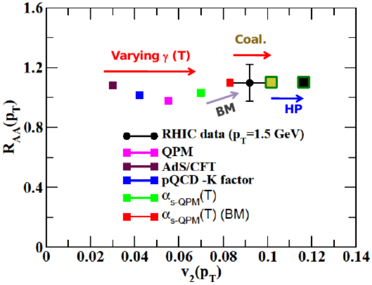
elastic scatterings + radiation

SaporeGravis Network, arXiv:1506.03981

- The simultaneous description of R_{AA} and v_2 is challenging.

(Too?) many models reproduce the R_{AA} and/or the v_2 well.

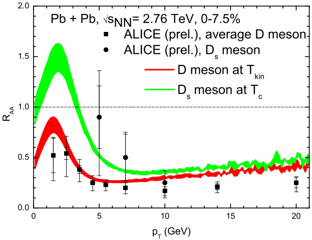
D meson R_{AA} and v_2 - miscellaneous



plot by S. Das, Catania

- R_{AA} robust, but v_2 changes significantly:
- affected by interaction details, Langevin vs Boltzmann, coalescence, hadronic final interactions...

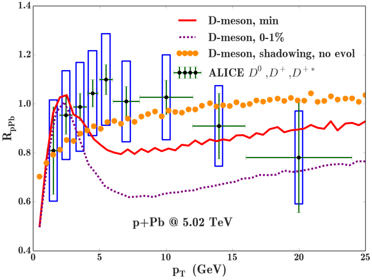
- Enhancement of strangeness in the QGP can lead to an enhancement of D_s mesons by coalescence.

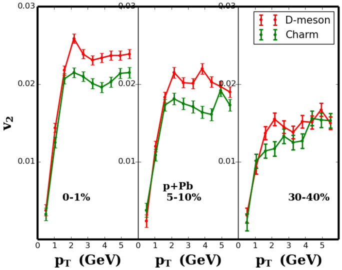


H. Min et al. PLB735 (2014)

Charm production (and diffusion?) in pPb collisions

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





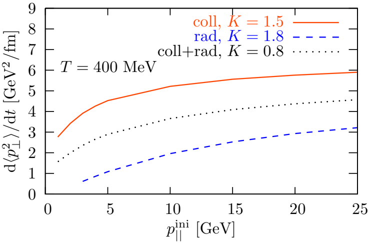
- Centrality dependence of R_{pPb} expected due to energy loss.
  (Note, that experimentally Q_{pPb}!)
- Indications that v_2 of D mesons decouples from medium flow - unlike in AA collisions - and decreases with centrality.
- Can HF measurements in pPb help answering the question of initial vs final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

Y. Xu et al, Duke University, in preparation

Beyond traditional observables...

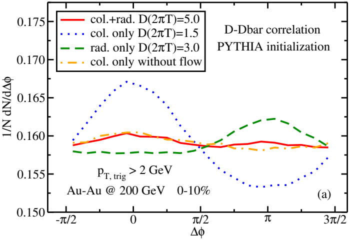
- Observables with high discriminating power between different interaction mechanisms: e.g. azimuthal correlations of $Q\bar{Q}$ pairs.

$\langle p_\perp \rangle$ from MC@sHQ+EPOS2:



MN et al. PRC90 (2014)

$D\bar{D}$ correlation plot from Duke model



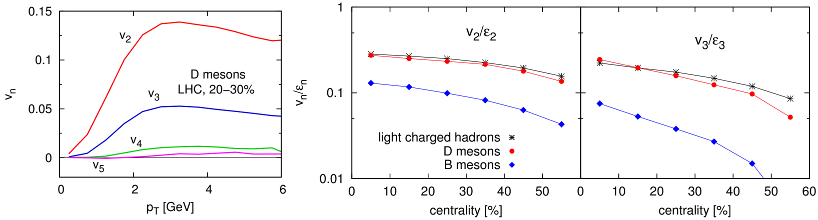
Cao et al., arxiv:1505.01869

- Difficulties: already the $c\bar{c}$ proton-proton baseline is not well understood theoretically and experimental feasibility...

For possible e(HF)-h or D-h correlations models need to couple HF-LF sectors consistently!

Beyond traditional observables...

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



- Expectation: v_3 and higher-order coefficients show the incomplete coupling of HQ to the medium.

MN et al. PRC91 (2015)

Looking forward to experimental data for v_3 from LHC and RHIC!

Summary

- HQ probe partial thermalization at low p_T and energy loss at high p_T in the QGP.
- Many effects important at intermediate p_T: onset of coherent gluon emission, gluon thermal mass, finite path length, nonperturbative scatterings,...
- Transport coefficients/scattering cross sections in Langevin or Boltzmann transport.
- Coupling to a dynamical evolution of the QGP (should be well tested in the light hadron sector!)
- R_{AA} and v_2 are described well by (too?) many models.
- Learn from the success in the the light-flavor sector!
- Study further observables, like $Q\bar{Q}$ correlations and higher-order flow coefficients, for veri/falsi-fication of models!
- Need to identify most dominant features of HQ-medium interaction: connect data to fundamental properties of QCD!

Don't miss plenary talks (theory) by M. Djordjevic, A. Beraudo, this session, E. Bratkovskaya Thu 12h30!

Thanks to J. Aichelin, S. Bass, S. Cao, P.B. Gossiaux, K. Werner, Y. Xu for fruitful collaborations and discussions!

backup

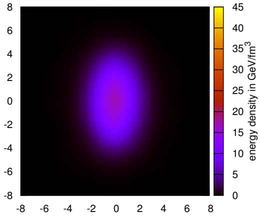
Modeling of heavy-quark dynamics in the **QGP**

production interaction with the medium hadronization

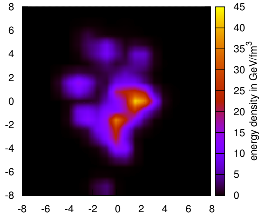
medium description coupling medium - HF sector

- 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!

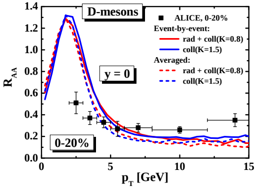
smooth initial conditions



fluctuating initial conditions



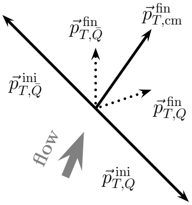
MN, J. Aichelin, P. B. Gossiaux, K. Werner NPA932 (2014)



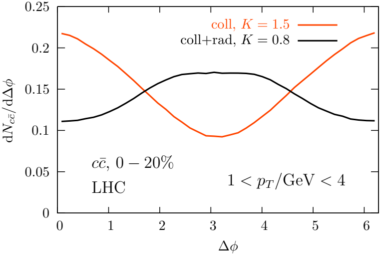
plot by V. Ozvenchuk, Nantes

“Partonic wind” effect

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

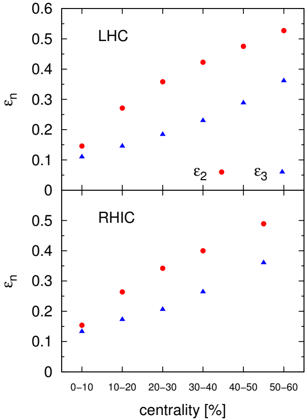


- Due to the radial flow of the matter low-p_T $c\bar{c}$-pairs are pushed into the same direction.
- Initial correlations at $\Delta\phi \sim \pi$ are washed out but additional correlations at small opening angles appear.
- This happens only in the purely collisional interaction mechanism!
- No “partonic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



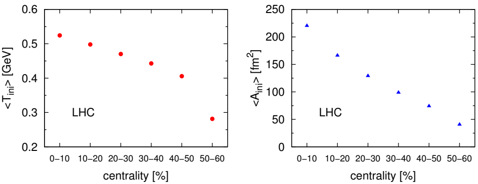
MN et al. PRC90 (2014)

QGP: initial state and bulk flow (2)



MN et al. PRC91 (2015)

average temperature and overlap area

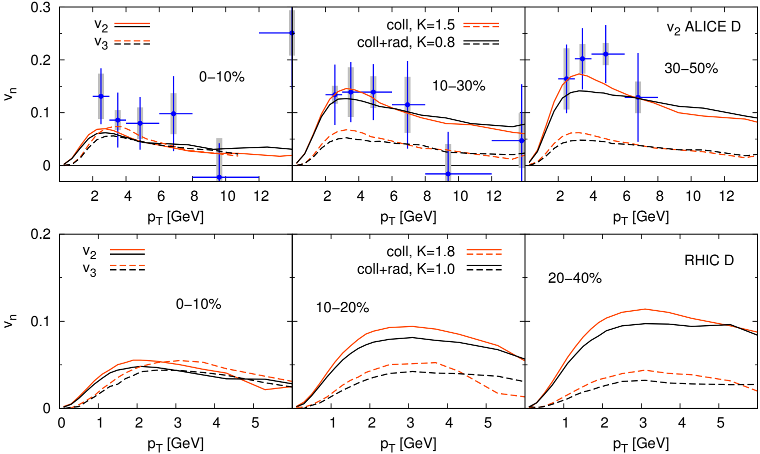


centrality dependence:

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

⇒ 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

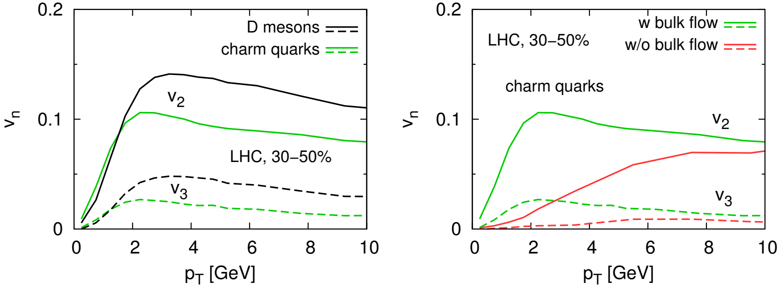


- At small p_T: relative enhancement of flow in purely collisional scenario over **collisional+radiative(+LPM)** larger for v_3 than for v_2

MN et al. PRC91 (2015)

Charm flow: hadronization and energy loss

collisional+radiative(+LPM), 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)

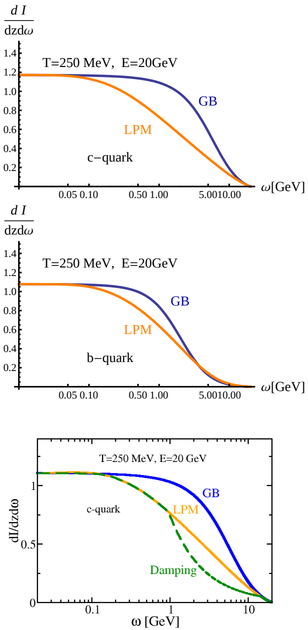
Radiative energy loss

- Incoherent radiation: Gunion-Bertsch spectrum extended to finite quark mass.

  J. Aichelin et al., PRD**89** (2014), arXiv:1307.5270

- Inclusion of an effective suppression of the spectra in the coherent radiation regime (LPM effect)
- Influence of gluon damping (not in this talk)

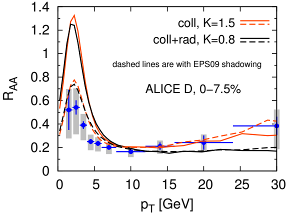
  M. Bluhm et al., PRL **107** (2011), arXiv:1204.2469

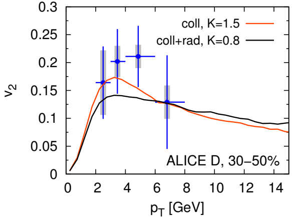


pQCD Boltzmann transport

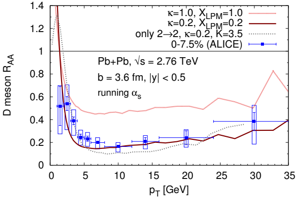
- pQCD-inspired Boltzmann transport in 3 + 1d ideal fluid dynamics (EPOS) or in partonic transport (BAMPS).

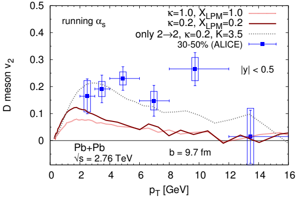
MN et al. (Nantes) - MC@sHQ+EPOS2





Uphoff et al. (BAMPS)

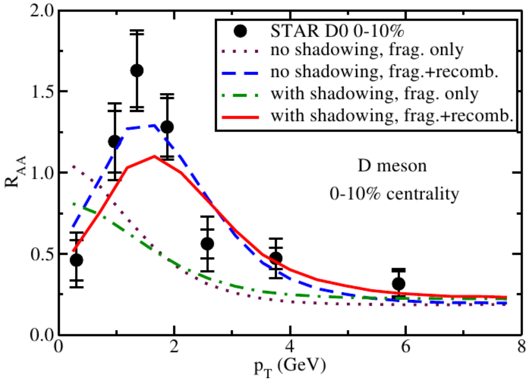




- Rather good description of the R_{AA} and the v_2.
- Slight preference for purely collisional energy loss in MC@sHQ+EPOS2.

MN et al. PRC **89** (2014); K. Werner et al. PRC **85** (2012); J. Uphoff et al. arxiv:1408.2964 (2014)

Importance of recombination - RHIC

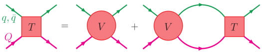


- Recombination needs to be included in order to describe the R_{AA} at lower p_T.

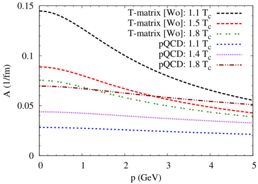
Cao et al. arxiv:1505.01413

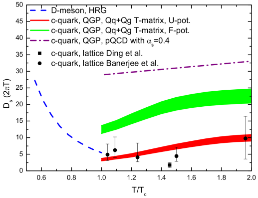
Non-perturbative resonance scattering

- Basic assumption: two-body interactions $\rightarrow$ potential $V(t)$ with $t \simeq -\vec{q}^2$ (c, b quarks; $T \lesssim 3T_c$)



- $\mathcal{T}$-matrix follows from Lippmann-Schwinger equation: $\mathcal{T} = V + \int d^3k V\, G_2\, \mathcal{T} \rightarrow$ HQ transport coefficients, e.g. $A_Q(\vec{p}) \sim |\mathcal{T}|^2$
- Medium-modified HQ potential from lQCD free/internal energy:
  - Stronger interaction from internal energy based V
  - Enhanced ΔE_{loss} than in pQCD due to resonant HQ-meson and di-quark states in scattering channels
- Spatial diffusion coefficient $D_s = 2\pi T^2 / m_Q A_Q$:
  - comparable to quenched lQCD
  - smooth transition to hadronic medium with minimum close to T_c





H. v. Hees, PRC73 (2006); H. v. Hees, PRL100 (2008); R. Rapp arxiv:0903.1096