Potentials - Challenges - Directions: Heavy-Flavor Theory

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Hard Probes 2016, Wuhan

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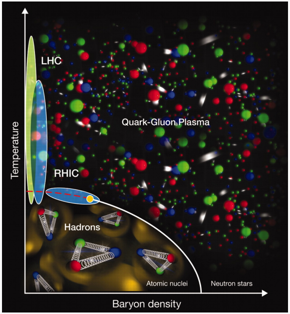
What can we learn from heavy-flavor observables?



potentials

What are the challenges to reach a quantitative level?

challenges

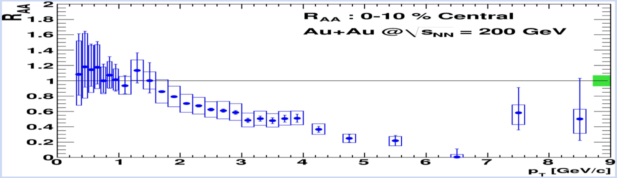
Which directions to go to make progress?

directions

potentials

Heavy quarks as probes of the QGP

- 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.
- HQ as leading parton is always tagged.



PHENIX, PRC84 (2011)

potentials

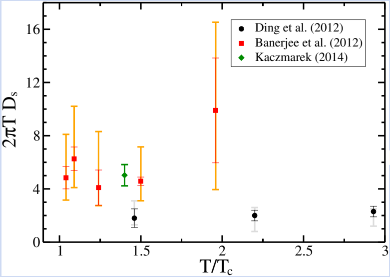
probe the entire momentum range from

low $p_T \sim m_Q$ to high $p_T >> m_Q$ dynamics

Diffusion coefficient from lattice QCD

- Lattice QCD at finite T is performed in Euclidean space $\Rightarrow$ notoriously difficult to calculate dynamical quantities.
- Relate the current-current correlations (calculated on the lattice) to spectral functions by the inversion of the spectral respresentation by an initial assumption for the spectral function, Maximal Entropy Method, etc.
- Obtain transport coefficients from the slope of spectral function ρ_E at $\omega = 0$ (Kubo formula).

Talk by O. Kaczmarek



momentum diffusion:

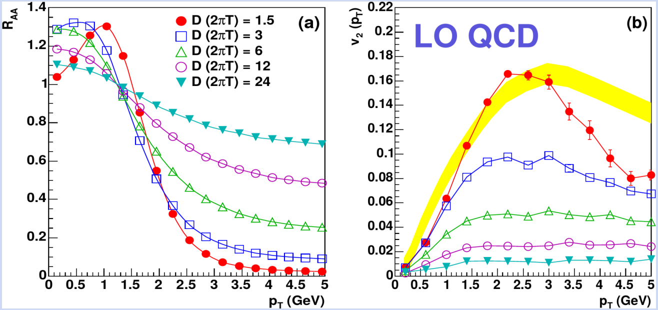
$$\frac{\kappa}{T^3} = \lim_{\omega \to 0} \frac{2T\rho_E(\omega)}{\omega}$$

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

Approximations/limitations: quenched QCD, heavy quark vs. charm quark, continuum extrapolation, ...

Current lattice QCD estimates are between $D_s \sim 2 - 7$...

Sensitivity to the diffusion coefficient



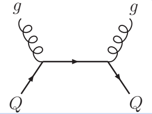
G. Moore and D. Teaney PRC71 (2005)

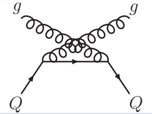
The observables R_{AA} and v_2 reflect the dependence of the in-medium energy loss and “partial“ thermalization on the heavy-quark diffusion coefficient!

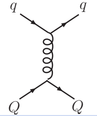
potentials

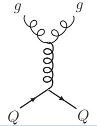
Collisional (elastic) energy loss - pQCD inspired

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



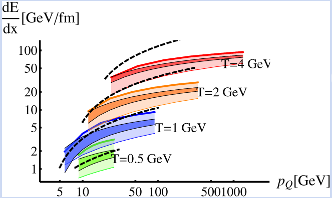






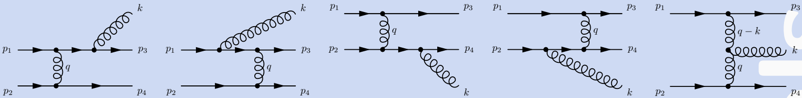
- t-channel IR singularity, regulated by the Debye screening mass m_D
- HTL energy loss: resummed propagator for $|t| \ll t^*$, bare propagator $|t| \gg t^*$
- Relevant separation of scales $g^2 T^2 \ll T^2$ probably not fullfilled at RHIC/LHC.

- 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)

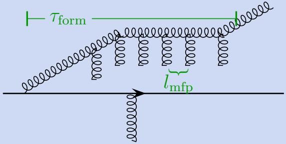
Radiative energy loss - pQCD inspired



- 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)



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

  K. Zapp et al. PRL103 (2009), JHEP 1107 (2011)

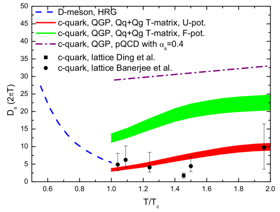
- heavy vs light probes different regions of coherence

potentials

... and nonperturbative approaches!

Resonance scattering (TAMU): **Talk by M. He**

- 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

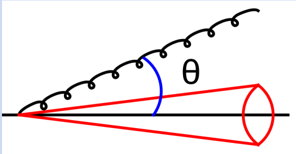
Strong coupling:

- In AdS/CFT a heavy quark is represented by a string connected to a D7 brane.
  C. Herzog et al. JHEP2006; S. Gubser PRD74 (2006)
- 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)

potentials

Mass dependence: light vs heavy flavor

$$R_{\mathrm{AA}}(g) < R_{\mathrm{AA}}(u,d,s) < R_{\mathrm{AA}}(c) < R_{\mathrm{AA}}(b) < R_{\mathrm{AA}}(t?)?$$

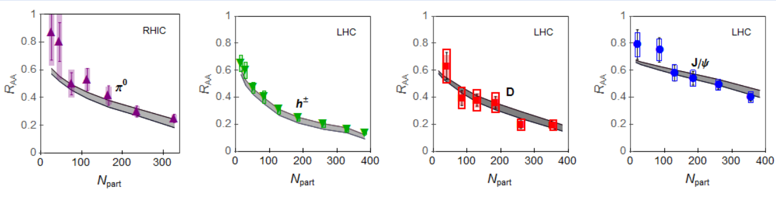


Dead cone effect: Dokshitzer et al., PLB 519 (2001)

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

M. Djodjevic and M. Gyulassy PLB560 (2003); N. Armesto, C. Salgado and U. Wiedemann, PRD69 (2004)

When the hard scattering assumption is relaxed, emission at low $k_\perp$ is significantly less suppressed. J. Aichelin et al. PRD89 (2014)

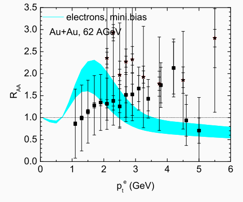


M. Djordjevic et al. PLB737 (2014)

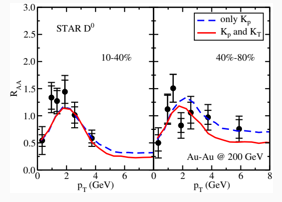
potentials

Temperature dependence: from $\sqrt{s} = 0.062$ to 5 TeV

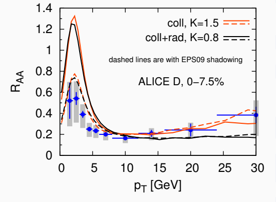
TAMU



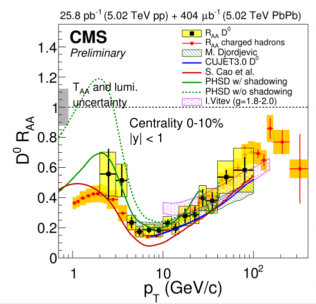
LBL



MC@sHQ+EPOS2



- QGP becomes hotter from $\sqrt{s} = 62$GeV to $\sqrt{s} = 5$TeV.
- Temperatures in the space-time evolution have more weight on the probed transport coefficient.
- Better handle on the temperature dependence of the diffusion coefficient!



HQ as probes of the magnetic field

- strong initial magnetic field in heavy-ion collisions $\approx \mathcal{O}(10^{19})$ Gauss $\approx 10 m_\pi^2$
- fast decay of the magnetic field within the first 0.1 fm

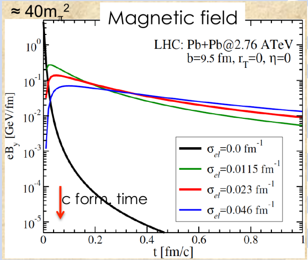
Talk by V. Greco: sizable effect on heavy quark v_1 due to the Lorentz force

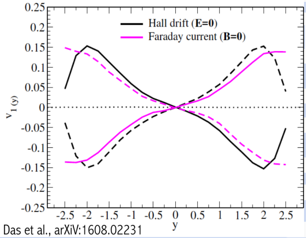
S. Das et al. 1608.02231

- short formation time of heavy quarks!
- long equilibration times!

(for light quarks effect is smaller U. Gursoy, K. Rajagopal, D. Kharzeev, PRC89 (2014))

Talk by K. Hattori: effects on heavy quark v_2

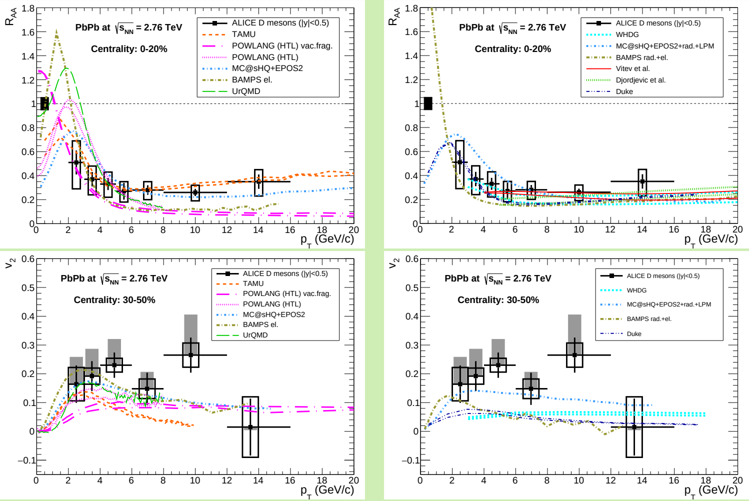




challenges

Challenge to describe R_{AA} and v_2 simultaneously "puzzle"

purely elastic scatterings



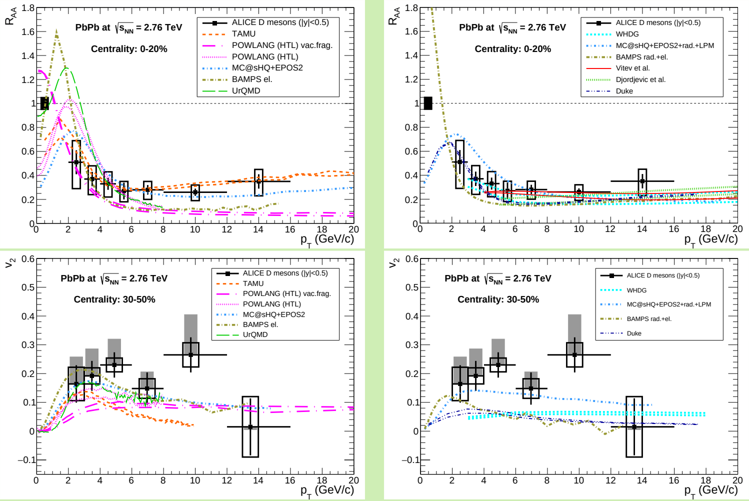
elastic scatterings + radiation

Challenges

SaporeGravis Network, EPJC76 (2016) 1506.03981

(Too) many models describe R_{AA} and v_2

purely elastic scatterings



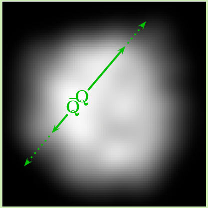
elastic scatterings + radiation

Challenges

SaporeGravis Network, EPJC76 (2016) 1506.03981

Heavy-quark dynamics in HIC

production

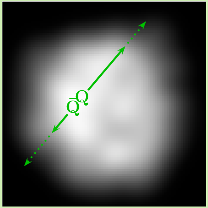


- LO pQCD, e.g. FONLL → inclusive spectra, no azimuthal $Q\bar{Q}$ correlations
  M. Cacciari et al. PRL95 (2005), JHEP 1210 (2012)
- NLO pQCD matrix elements plus parton shower, e.g. POWHEG or MC@NLO ⇒ exclusive spectra, like $Q\bar{Q}$ correlations S. Frixione et al. JHEP 0206 (2002), JHEP 0308 (2003)
- 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)
- Consistent initialization of HF and LF sectors!

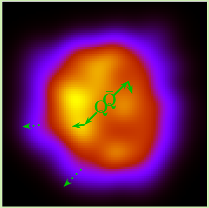
challenges

Heavy-quark dynamics in HIC

production



in-medium interaction

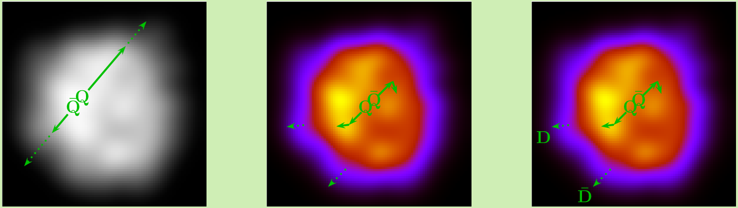


- Scattering off light QGP constituents, sampled from fluid dynamics or given within microscopic transport BAMPS J. Uphoff et al. PRL114 (2015) or PHSD T. Song et al. PRC92 (2015)
- Any model with $P(\Delta E)$ produces the generic p_T shape of R_{AA}, magnitude depends strongly on the bulk evolution model! T. Renk, PRC85 (2012)
- Proper modeling of the QGP evolution is important! Should be well tested in the light hadron sector!

challenges

Heavy-quark dynamics in HIC

production | in-medium interaction | hadronization



challenges

- 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)

Consistent coupling of the HQ to medium

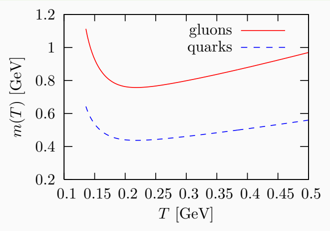
challenges

Does the EoS match the representation of the medium (quasiparticles)?

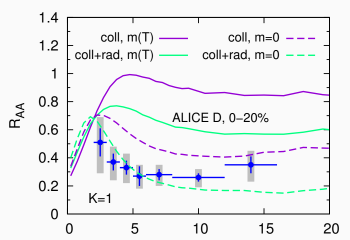
- HQ scatter off (thermal) QP in the medium
- Inconsistent: Massless partons or $m(T)$ from pQCD DO NOT reproduce the lattice EoS!

MN et al. PRC93 (2016) 1602.03544;

H. Berrehrah et al. 1604.02343

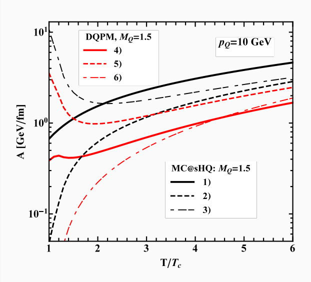


$m(T)$ and $\alpha_s(q)$



MC@sHQ+EPOS2

$m(T)$ and $\alpha_s(q, T)$



Transport equations

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

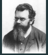
Recast to Langevin equation (probably good for bottom, but for charm?)

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

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

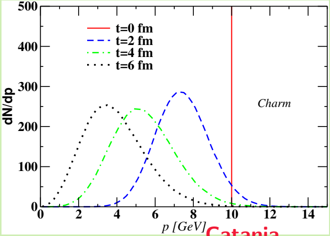
$$\eta_D = \frac{\kappa}{2 m_Q T}, \qquad D_s = \frac{T}{m_Q \eta_D} \quad \text{spatial diffusion}$$

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

 vs. 

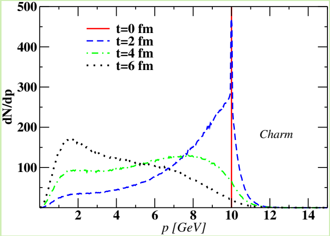
- Under which conditions should Brownian motion be a valid approximation for relativistic particles?
- Calculations of transport coefficients from the underlying theory do not necessarily fulfil FDT.
- Langevin leads to Gaussian momentum distribution, Boltzmann very different.

Langevin



Catania

Boltzmann

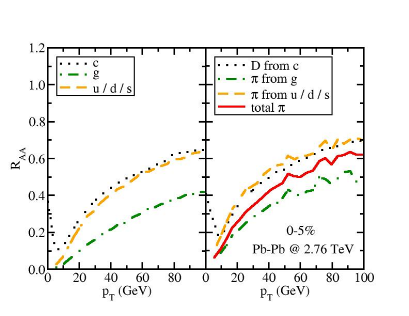


S. Das et al, PRC90 (2014)

challenges

Mass dependence: light vs heavy flavor

Delicate interplay between energy loss and fragmentation can lead to similar R_{AA} of light hadrons and D mesons: **M. Djordjevic et al. PRL112 (2014)**



Talk by Shanshan Cao

- Similar effects seen in LBL-Boltzmann transport with (scaled) LO pQCD cross sections and radiative energy loss according to higher-twist formulation.

  S. Cao, T. Luo, G.Y. Qin, X.N. Wang PRC94 (2016); X.F. Guo, X.N. Wang (2000), A. Majumder (2012); B.W. Zhang, E. Wang and X.N. Wang (2004)

- Currently no well accepted theoretical description gives $R^D_{\mathrm{AA}} \sim R^B_{\mathrm{AA}}$...

Challenges

directions

Complete models and theoretical improvements

Continuous improvement on the theory side is needed, many ingredients contribute, eg. for the pQCD-based description by M. Djordjevic:

- dynamical scattering centers,
- finite size QCD medium,
- radiative and collisional energy loss,
- finite magnetic mass,
- running coupling,
- ...

M. Djordjevic et al. PRC68 (2003), PRC80 (2009), PRL101 (2008), PRC74 (2006), PLB709 (2012), PLB734 (2014)

How to connect

- high-p_T jet shower evolution to leading-parton energy loss to low-p_T diffusion?
- perturbative and nonperturbative regimes?
- weak- and strong-coupling scenarios?
- coherent and incoherent radiation pattern?

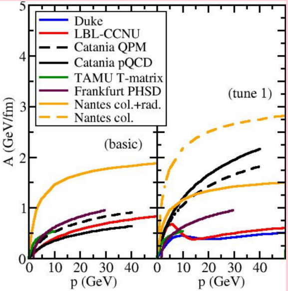
directions

Systematic comparison of model ingredients

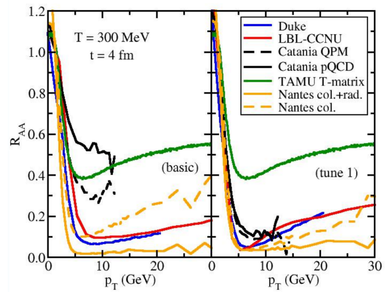
Participation of many different models brought together by JET-HQ collaboration/EMMI Task Force - more are welcome to join!

Different models in infinite static matter (aka "brick" problem)

drag coefficient



charm R_{AA}



curve compilation by S. Cao

To come next: evolution through the same background QGP evolution...

Bayesian model-to-data statistical analysis

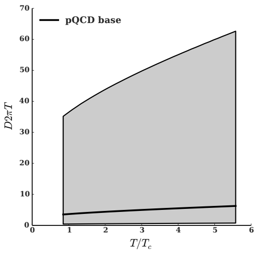
- HQ Langevin dynamics + 2+1d fluid dynamics

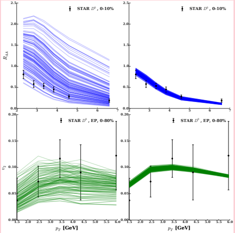
($\eta/s(T)$, $\zeta/s(T)$ constraint by bulk observables via Bayesian analysis)

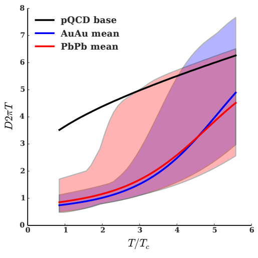
J. Bernhard, J. Moreland, S. Bass, J.Liu and U. Heinz, PRC94 (2015)

BEFORE

AFTER







assume a parametrization:

$$D_s(T) = \frac{T^2 K^{-1}}{\hat{q}_{\rm pQCD}} \left(1 + K_T \exp\left(\frac{-(T-T_c)^2}{2\sigma_T^2}\right)\right)^{-1}$$

know the probability distributions of all parameters and correlations

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

Talk by Yingru Xu

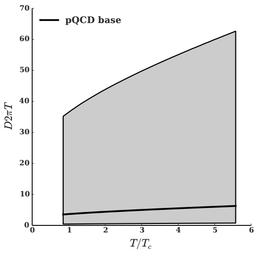
Y. Xu, S. Cao, MN, S. Bass, in preparation

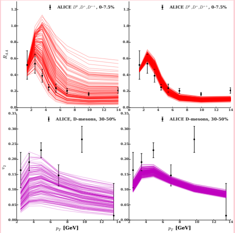
- HQ Langevin dynamics + 2+1d fluid dynamics

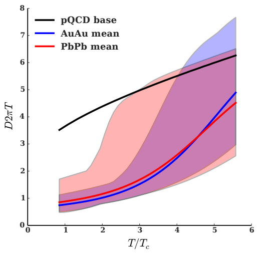
($\eta/s(T)$, $\zeta/s(T)$ constraint by bulk observables via Bayesian analysis)

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

BEFORE **AFTER**







assume a parametrization:

$$D_s(T) = \frac{T^2 K^{-1}}{\hat{q}_{\mathrm{pQCD}}} \left(1 + K_T \exp\left(\frac{-(T-T_c)^2}{2\sigma_T^2}\right)\right)^{-1}$$

know the probability distributions of all parameters and correlations

$\Rightarrow$ **temperature dependence of charm quark diffusion coefficient!**

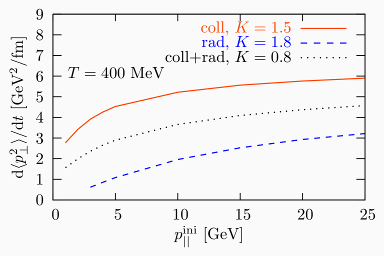
Talk by Yingru Xu

Y. Xu, S. Cao, MN, S. Bass, in preparation

Beyond traditional observables: $Q\bar{Q}$ azimuthal correlations

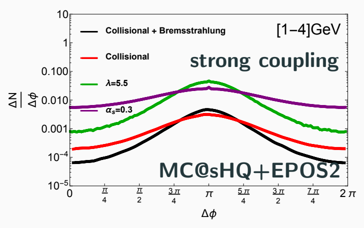
- High discriminating power between different interaction mechanisms: collisional vs. radiative energy loss.

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



MN, J. Aichelin, P.B. Gossiaux, K. Werner, PRC90 (2014), 1305.3823

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

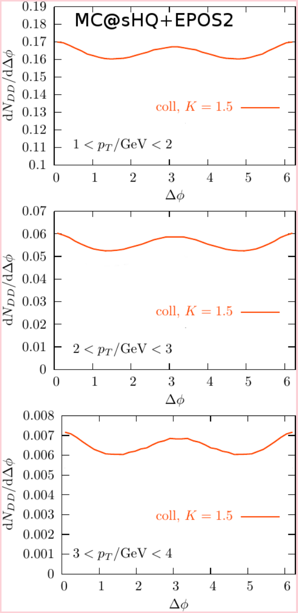


Talk by R. Hambrock

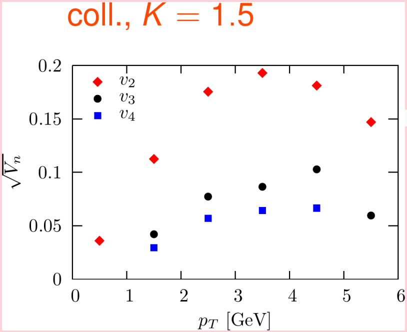
- Low p_T pairs more likely to remain correlated for strong than for weak coupling.
- Already the $c\bar{c}$ proton-proton baseline is not well understood theoretically ...

see also: S. Cao, G.Y. Qin, S. Bass, PRC92 (2015); A. Beraudo EPJC75 (2015)

directions



- Fourier transform of DD azimuthal correlations $\Rightarrow$ V_n of D mesons:

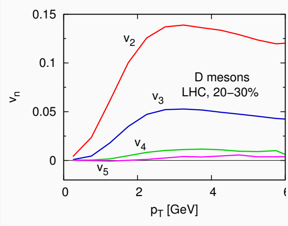


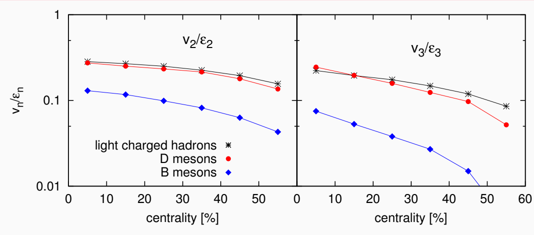
MN et al., SQM2013

First calculation of higher-order flow harmonics for heavy flavor!

Beyond traditional observables: higher-order flow harmonics

- 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!

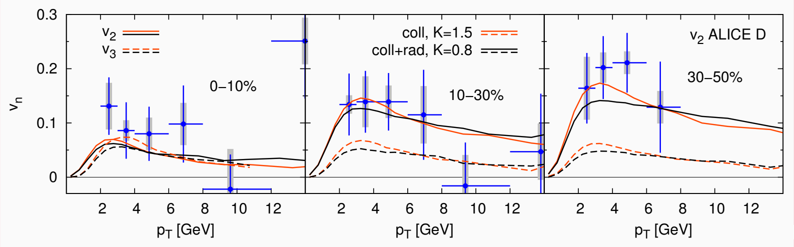
MN, J. Aichelin, S. Bass, P.B. Gossiaux, K. Werner, PRC91 (2015) 1410.5396

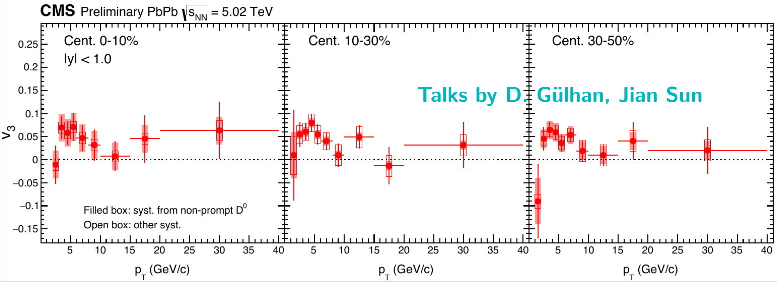
From my last talk: "Looking forward to v_3 data from LHC and RHIC!"

Beyond traditional observables: higher-order flow harmonics

(dashed lines) predictions for v_3!

MN et al. PRC91 (2015) 1410.5396

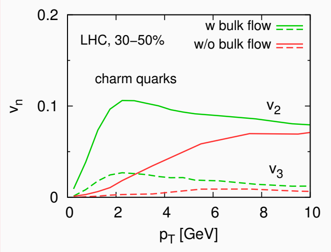




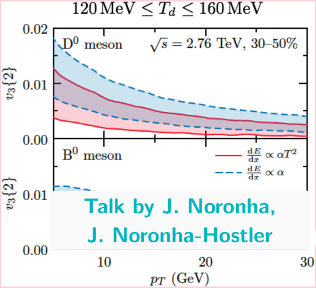
Talks by D. Gülhan, Jian Sun

directions

Beyond traditional observables: higher-order flow harmonics



MN et al. PRC91 (2015) 1410.5396



- v_3 of charm is due to the LF flow, small effect from L differences!
- EP method (≈ SP method CMS)
- sophisticated energy loss model, HF dynamics and coupling to the soft sector (medium flow)!

- flow due to L difference (no deflection due to medium flow)
- SP method (CMS)
- simple energy loss models, no HQ dynamics...

Study HF - LF correlations by consistently coupling heavy quark and medium dynamics!

(like upcoming EPOS3+HQ - successor of MC@sHQ+EPOS2 by the Subatech group Nantes → to be ready for QM17!)

directions

Conclusions

potentials

probe medium properties and the HQ-medium interaction: T, m, L, E dependence

hadronization

weak vs. strong

(in)coherent

challenges

consistent HQ-medium coupling

non-perturbative regime

model improvements

systematic comparison

model-to-data analysis

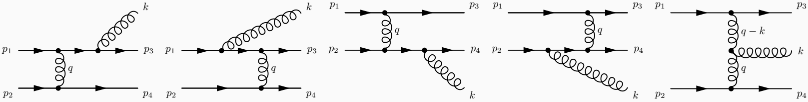
new observables

directions

Thanks to J. Aichelin, S. Bass, H. Berrehrah, E. Bratkovskaya, S. Cao, P.B. Gossiaux, V. Ozvenchuk, K. Werner, Y. Xu for fruitful collaborations & discussions!

extra

Radiative energy loss



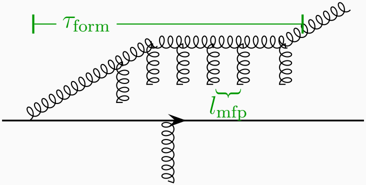
- LO pQCD matrix element for $2 \to 3$ process Kunszt et al. PRD21 (1980)
- Gunion-Bertsch approximation derived in the high-energy limit, where the radiated gluon $k_\perp$ and the momentum transfer $q_\perp$ are soft $\ll \sqrt{s}$.
- Incoherent radiation off a massless parton, mid-rapidity
- Extention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

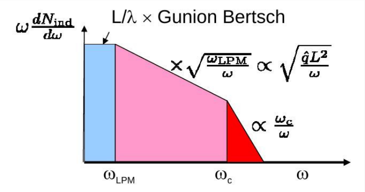
$$P_g(x, \vec{k_\perp}, \vec{q_\perp}, m_Q) = \frac{3\alpha_s}{\pi^2}\frac{1-x}{x}\left(\frac{\vec{k_\perp}}{\vec{k_\perp}^{\,2} + x^2 m_Q^2} - \frac{\vec{k_\perp} - \vec{q_\perp}}{(\vec{k_\perp} - \vec{q_\perp})^2 + x^2 m_Q^2}\right)^2$$

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

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: $\Rightarrow$ $E_{\rm rad}^{\rm loss} \propto \sqrt{E}\,L$
- 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 $\Rightarrow \omega_c \sim 20$ GeV)

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

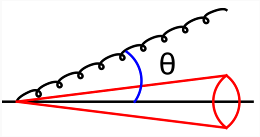
Baier et al. PLB **345** (1995); NPB **483** (1997); ibid. **484** (1997); B. G. Zakharov, JETP Lett. **63** (1996) 952

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)



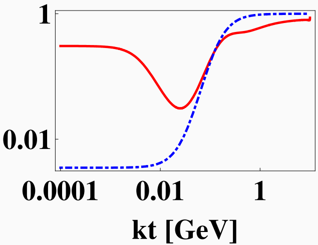
- Suppresses gluon emission in the dead cone $\theta_D = M_Q/E_Q$
- Introduces a mass hierarchy in the radiative energy loss.
- But: assumes hard scatterings!

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

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

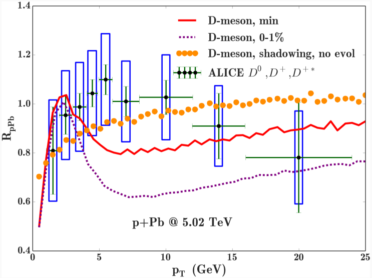
hard-scattering approximation

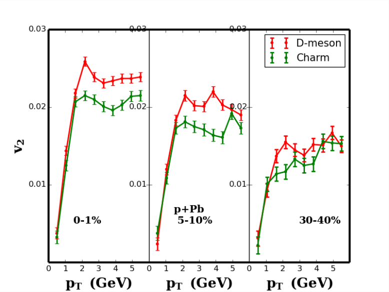
all scatterings



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)

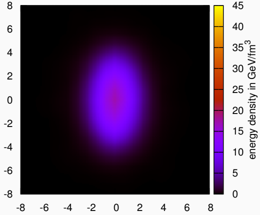
Modeling of heavy-quark dynamics in the QGP

production | interaction with the medium | hadronization

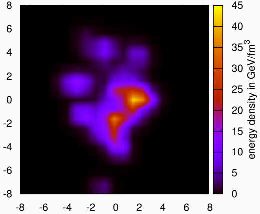
medium description | coupling medium - HF sector

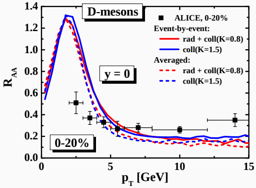
- Model the QGP: a locally thermalized medium provides the scattering partners.
- Input from a fluid dynamical description of the bulk QGP medium: temperatures and fluid velocities.
- Use a fluid dynamical description which describes well the bulk observables!

smooth initial conditions



fluctuating initial conditions



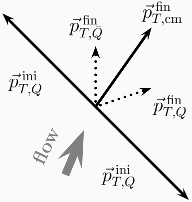


plot by V. Ozvenchuk, Nantes

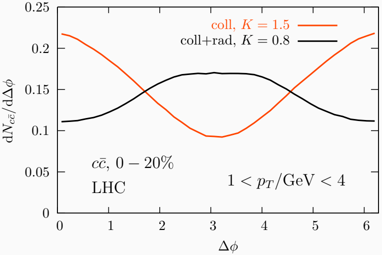
MN, J. Aichelin, P. B. Gossiaux, K. Werner, NPA932 (2014)

"Partonic wind" effect

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

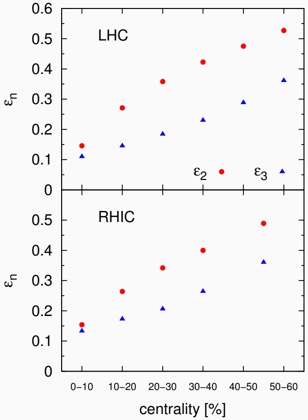


- Due to the radial flow of the matter low-p_T $c\bar{c}$-pairs are pushed into the same direction.
- Initial correlations at $\Delta\phi \sim \pi$ are washed out but additional correlations at small opening angles appear.
- This happens only in the purely collisional interaction mechanism!
- No "partonic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



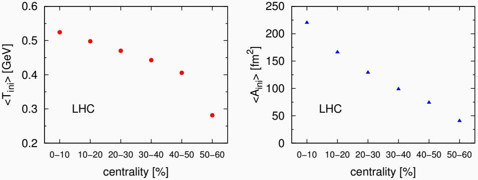
MN et al. PRC90 (2014)

QGP: initial state and bulk flow (2)



MN et al. PRC91 (2015)

average temperature and overlap area

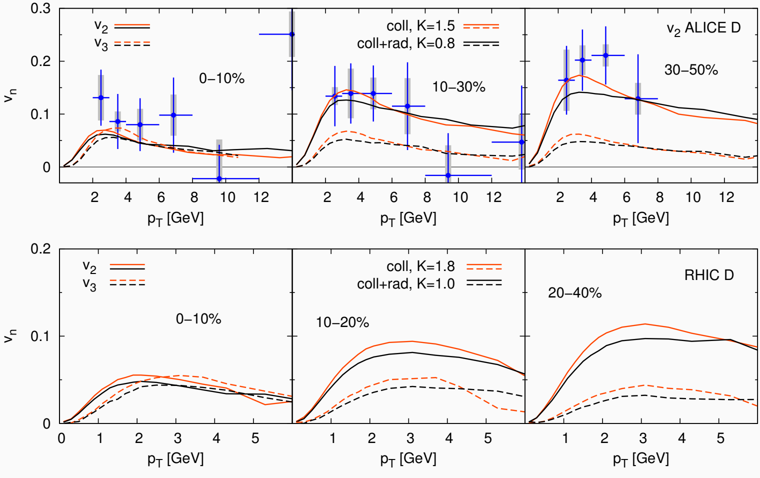


centrality dependence:

+ 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

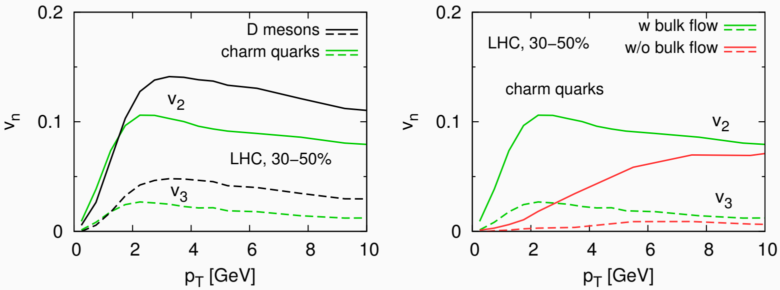
D meson v_2 and v_3 at LHC and RHIC



- 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)

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)