Theory aspects of open heavy flavor production and suppression in cold and hot nuclear matter

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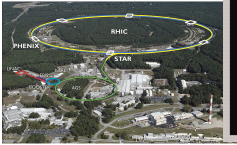
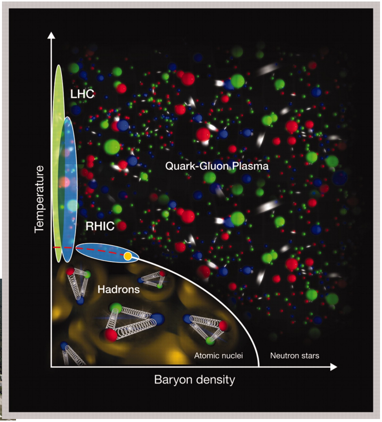
What do we want to study?

- Properties of strongly interacting many-body systems.
- Phases of hot and dense nuclear matter.
- Tool: (ultra)relativistic heavy-ion collisions.
- LHC: PbPb at $\sqrt{s_{\mathrm{NN}}} = 2.76,\ 5$ TeV
  RHIC: AuAu at $\sqrt{s_{\mathrm{NN}}} = 200 - 7.7$ GeV





Barbara V. Jacak, and Berndt Müller Science 2012;337:310-314

- How to probe the properties of the quark-gluon plasma?

Probes

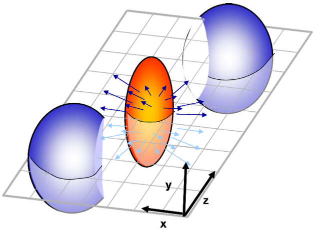
- Probes should not thermalize with the medium, e.g. dileptons, high-pT jets,...
- The mass of heavy quarks (HQ) sets another scale: m_c, m_b
  (top is too heavy to be produced abundantly and decays quickly)
- HQ vacuum shower terminates much earlier: E/Q_H^2
  with $Q_H = \sqrt{Q_0^2 + m_Q^2}$.
- The HQ mass reduces the radiation phase space:
  dead cone effect.
- Number of thermally excited HQ is negligibly small.
- HQ as leading parton is always tagged (hard radiations change energy but not identity).

Quark-gluon plasma and its properties

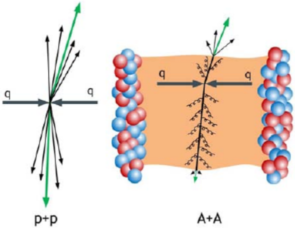
Expectation in heavy-ion collisions:

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

collective flow



jet quenching



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

observable: nuclear modification factor

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

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

Quark-gluon plasma and its properties

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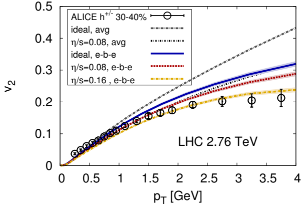

B. Schenke et al. PLB702 (2011)

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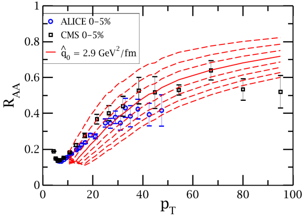

Jet Collab. PRC90 (2014)

observable: nuclear modification factor

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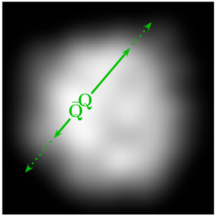
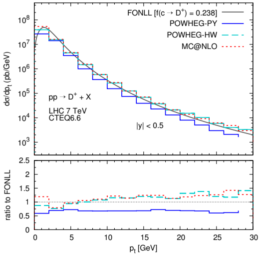
sensitive to jet quenching parameter $\hat{q}$

Modeling of heavy-quark dynamics in the QGP

production interaction with the medium hadronization





- LO pQCD $\rightarrow$ including resummation of logs: FONLL $\rightarrow$ inclusive spectra $\Rightarrow$ back-to-back initialization, no information about the 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

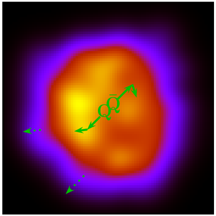
  S. Frixione et al. JHEP **0206** (2002), JHEP **0308** (2003)

- 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)

Modeling of heavy-quark dynamics in the QGP

production **interaction with the medium** hadronization

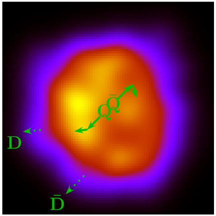


- Collisional (elastic) cross sections ⇒ $\Delta E \sim \log(E)L$
- Incoherent radiation (GB regime) ⇒ $\Delta E \sim EL/l_{\mathrm{mfp}}$
- Coherent radiation (BDMPS-Z regime) ⇒ $\Delta E \sim \sqrt{E}L$
- Dead cone effect reduces radiative energy loss for heavy quarks.
- For very energetic partons and thin media ⇒ $\Delta E \sim L^2$
- Further radiative effects: finite gluon mass and width

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); B. Kämpfer et al., PLB **477** (2000); M. Djordjevic et al., PRC **68** (2003) PLB **560** (2003); M. Bluhm et al. PRL **107** (2011); O. Fochler et al. PRD88 (2013); M. Djordjevic, PLB734 (2014); J. Aichelin et al. PRD89 (2014)

Modeling of heavy-quark dynamics in the QGP

production | interaction with the medium | **hadronization**

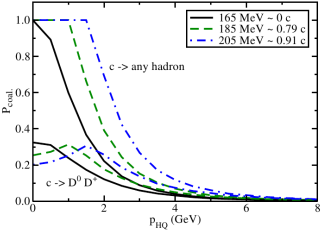


- Coalescence/Recombination – predominantly at small p_T.

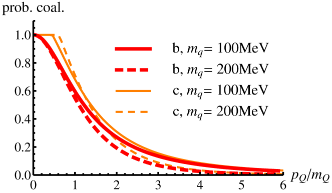
  C. B. Dover, U. W. Heinz, E. Schnedermann, J. Zimanyi PRC **44** (1991)

- Fragmentation – predominantly at large p_T.

  M. Cacciari, P. Nason, R. Vogt PRL **95** (2005)



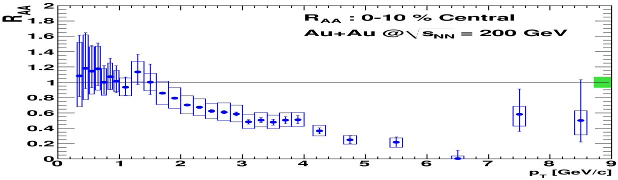
S. Cao et al. arxiv:1505.01413



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

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?

Set the stage: Transport 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):

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

Diffusion coefficient from lattice QCD

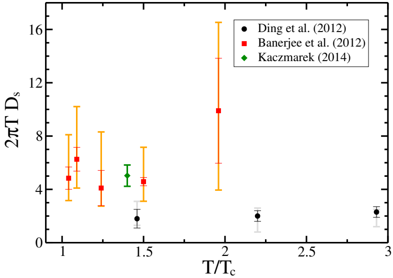
Lattice QCD at finite T is performed in Euclidean space $\Rightarrow$ notoriously difficult to calculate dynamical quantities.

Transport coefficients calculated from correlation function of conserved currents

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

momentum diffusion:

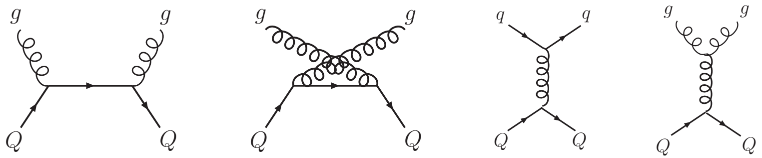
$$\frac{\kappa}{T^3} = \lim_{\omega \to 0} \frac{2T\rho_E(\omega)}{\omega}$$



$\Rightarrow$ No reliable input from lattice QCD calculations yet...

Collisional (elastic) energy loss

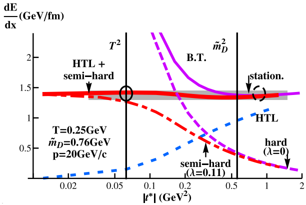
LO Feynmann diagrams for perturbative heavy quark scattering off a light parton

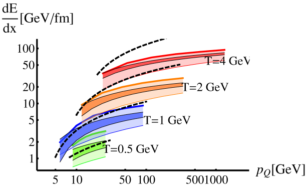


- Dominant contribution from the t-channel
- Well-known IR singularity, regulated by the Debye screening mass m_D
- Gluon propagator: $G(t) = \frac{\alpha_s}{t} \to \frac{\alpha_s}{t - m_D^2}$ with $m_D \sim \mathcal{O}(gT)$
- Use the Hard-Thermal Loop (HTL) resummed gluon propagator for small $|t| \ll t^*$ and the bare gluon propagator $|t| \gg t^*$ to calculate energy loss.
- For well-separated scales $g^2 T^2 \ll T^2$ results are independent of the intermediate scale t^*.

Nantes model

- Relevant separation of scales $g^2T^2 \ll T^2$ probably not fullfilled in RHIC and LHC experiments.
- Idea: introduce a reduced IR regulator λm_D^2 in the hard part: HTL+semi hard $\Rightarrow$ by tuning λ achieve independence from t^*.
- Calibrate pQCD Born matrix elements with $G(t) = \frac{\alpha_s}{t - \lambda m_D^2}$ to HTL+semi hard energy loss
- Use a running coupling at the scale of the specific process $\alpha_{\text{eff}}(t)$.
- Self-consistently determine the Debye-mass from $m_D^2 = (1 + 6n_f)4\pi\alpha_s(m_D^2)T^2$

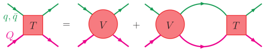




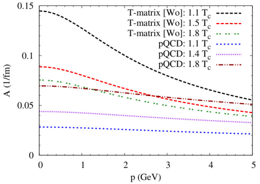
A. Peshier, hep-ph/0601119, PRL **97** (2006); P. B. Gossiaux et al. PRC78 (2008), NPA **830** (2009)

Non-perturbative resonance scattering

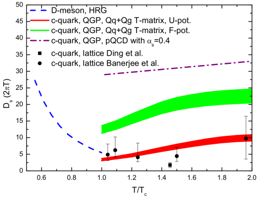
- Basic assumption: two-body interactions $\rightarrow$ potential $V(t)$ with $t \simeq -\vec{q}^{\,2}$ (c, b quarks; $T \lesssim 3T_c$)



- $\mathcal{T}$-matrix follows from Lippmann-Schwinger equation: $\mathcal{T} = V + \int d^3k V\, G_2\, \mathcal{T} \rightarrow$ HQ transport coefficients, e.g. $A_Q(\vec{p}) \sim |\mathcal{T}|^2$



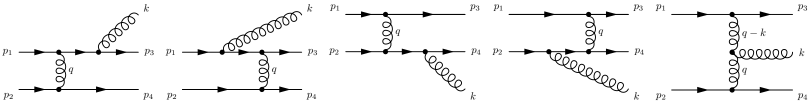
- Medium-modified HQ potential from lQCD free/internal energy:
  - Stronger interaction from internal energy based V
  - Enhanced ΔE_{loss} than in pQCD due to resonant HQ-meson and di-quark states in scattering channels



- 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

Radiative energy loss



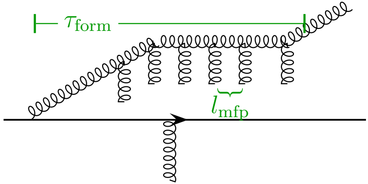
- LO pQCD matrix element for $2 \to 3$ process Kunszt et al. PRD21 (1980)
- Gunion-Bertsch approximation derived in the high-energy limit, where the radiated gluon $k_\perp$ and the momentum transfer $q_\perp$ are soft $\ll \sqrt{s}$.
- Incoherent radiation off a massless parton, mid-rapidity
- Extention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

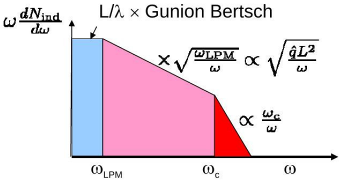
$$P_g(x, \vec{k}_\perp, \vec{q}_\perp, m_Q) = \frac{3\alpha_s}{\pi^2} \frac{1-x}{x} \left(\frac{\vec{k}_\perp}{\vec{k}_\perp^{\,2} + x^2 m_Q^2} - \frac{\vec{k}_\perp - \vec{q}_\perp}{(\vec{k}_\perp - \vec{q}_\perp)^2 + x^2 m_Q^2} \right)^2$$

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

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

Coherent emission - LPM





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

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

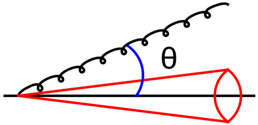
Baier et al. PLB **345** (1995); NPB **483** (1997); ibid. **484** (1997); B. G. Zakharov, JETP Lett. **63** (1996) 952

Dead cone effect

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

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

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



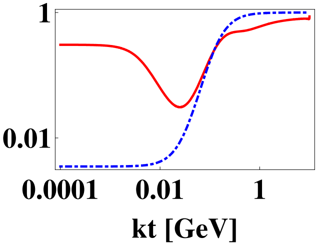
- Suppresses gluon emission in the dead cone $\theta_D = M_Q/E_Q$
- Introduces a mass hierarchy in the radiative energy loss.
- But: assumes hard scatterings!

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

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

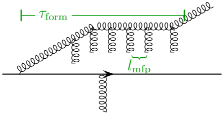
hard-scattering approximation

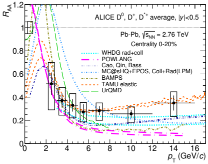
all scatterings



J. Aichelin et al. PRD89 (2014)

From theoretical input to dynamical modeling

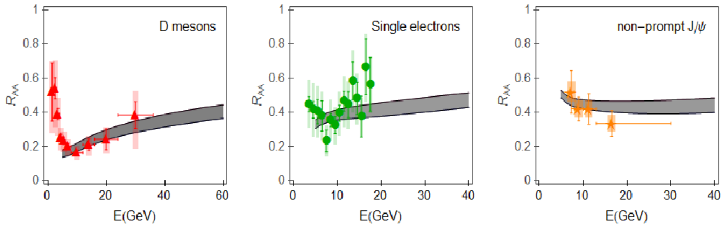




- No reliable input for the HQ diffusion coefficient from lattice QCD calculations.
- pQCD and pQCD inspired models of collisional and radiative processes.
- In a fully dynamical system processes on many scales involved, simple approximations are prone to fail at intermediate p_T.
- Due to uncertainties 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!

And finally some results...

pQCD at high momenta

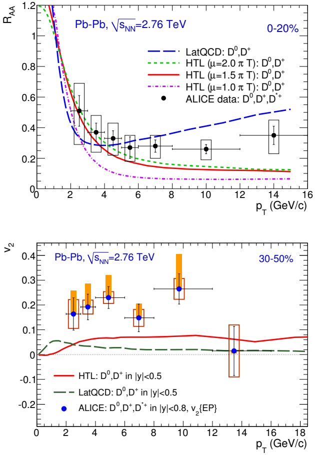


- Collisional and radiative pQCD energy loss implemented, only applicable at high p_T
- Good simultaneous description of D mesons, light hadrons and J/psi.
- While D meson suppression = charm quark suppression, the fragmentation into light hadron distorts the picture ⇒ light hadron suppression dominated by light quark suppression.
- No dynamical QGP description, only parametrized temperatures.

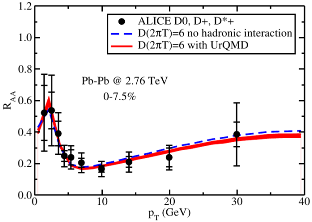
M. Djordjevic, PLB734 (2014)

Langevin at the LHC

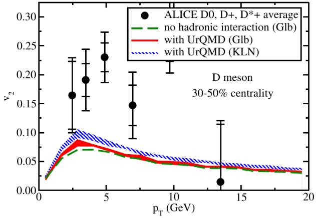
Alberico et al. (Torino)



Cao et al. (Duke)



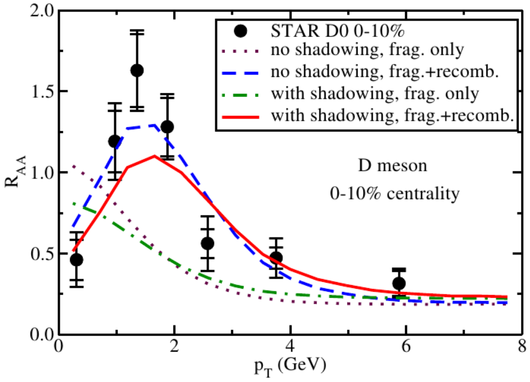
D tuned to fit the R_{AA}



- Langevin models have problems describing both the R_{AA} and the v_2.

Alberico et al. EPJC73 (2013); Cao et al. arxiv:1505.01413

Importance of recombination - RHIC

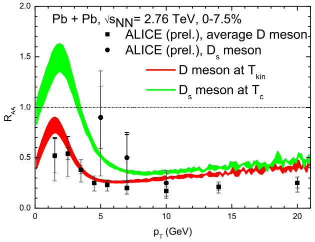


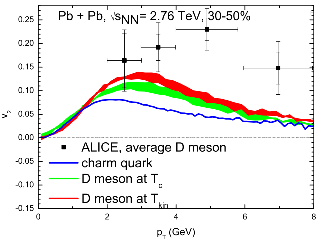
- Recombination needs to be included in order to describe the R_{AA} at lower p_T.

Cao et al. arxiv:1505.01413

Nonperturbative diffusion at the LHC

- Transport coefficients from $\mathcal{T}$-matrix approach, Langevin dynamics and $2+1$d ideal fluid dynamical QGP evolution.





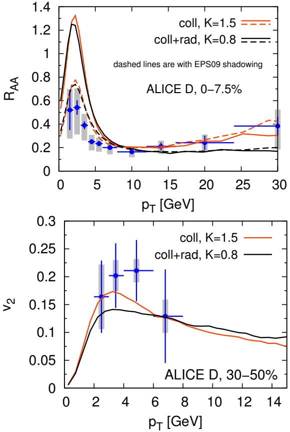
- Rather good description of R_{AA} but v_2 underestimated.
- Strangeness enhancement as signal of the QGP (thermal production) $\Rightarrow$ enhancement of D_s compared to D mesons.

H. Min et al. PLB735 (2014)

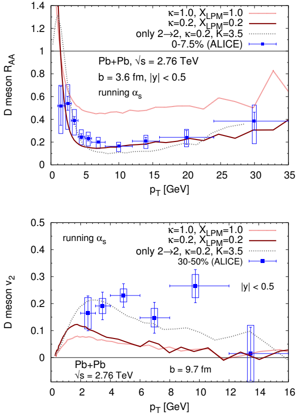
pQCD Boltzmann transport

- pQCD-inspired Boltzmann transport in $3+1$d 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)

Initial shadowing - cold nuclear matter effects

How much of the observed suppression really comes from the hot QGP? Look at reference systems, like p+Pb collisions.

- The parton distribution function (pdf) is different for a proton in a nucleus than for a free proton: shadowing (ie. a depletion) at small x and possibly antishadowing (ie. enhancement) at intermediate x. $\rightarrow$ effect is parametrized in sets of npdf
- Parton saturation at small x: large parton densities in the nucleus. E.g. Color Glass Condensate formalism (JIMWLK non-linear evolution equations).
- multiple scattering of partons in the cold nucleus before & after the hard scattering $\Rightarrow$ transverse momentum broadening, Cronin effect
- If high-multiplicity pA collisions produce a QGP hot medium effects will also contribute (work in progress by groups in Duke, Nantes,...)

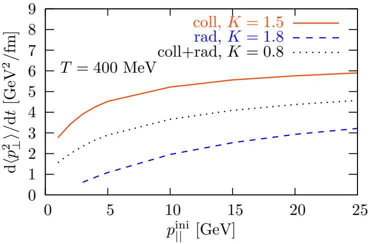
For much more, see talk by R. Vogt this afternoon!

Beyond traditional observables...

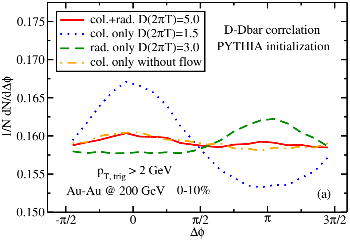
Conclusion: too many models can (more or less) well describe the available data.

$\Rightarrow$ Need new observables with high discriminating power between purely collisional and collisional+radiative approaches: eg. azimuthal correlations of $Q\bar{Q}$ pairs.

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



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



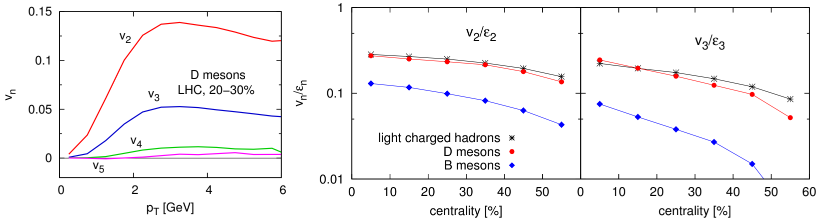
- Advantages: sensitive to the interaction mechanism: purely coll or coll+rad
- Difficulties: already the $c\bar{c}$ proton-proton baseline is not well understood theoretically, contributions from final hadronic interactions, experimental feasibility...

MN et al. PRC90 (2014)

Cao et al., arxiv:1505.01869

Beyond traditional observables...

- What can we learn from comparison to data from flow measurements?
- Most models give a τ_{relax} for charm quarks much longer than the evolution of the QGP, but HF v_2 is very similar to ligth hadron v_2.
- Further contributions from coalescence and energy loss.
- What about higher-order Fourier coefficients?



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

MN et al. PRC91 (2015)

Summary

- HQ probe partial thermalization at low p_T and energy loss at high p_T in the QGP.
- Mass ordering is seen in collisional and radiative interaction mechanisms from light hadrons $\rightarrow$ charm $\rightarrow$ bottom.
- 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.
- In order to compare to experiment theory of energy loss needs to be coupled to a dynamical evolution of the QGP (better to use a model which is well tested in the light hadron sector!)
- R_{AA} and v_2 are described well by (too?) many models.
- Need for further observables, like $Q\bar{Q}$ correlations and higher-order flow coefficients, for veri/falsi-fication of models!

backup

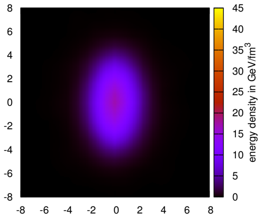
Modeling of heavy-quark dynamics in the **QGP**

production interaction with the medium hadronization

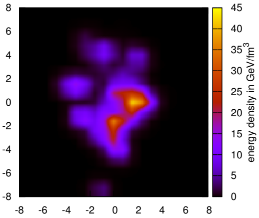
medium description coupling medium - HF sector

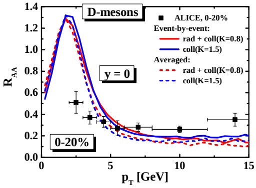
- Model the QGP: a locally thermalized medium provides the scattering partners.
- Input from a fluid dynamical description of the bulk QGP medium: temperatures and fluid velocities.
- Use a fluid dynamical description which describes well the bulk observables!

smooth initial conditions



fluctuating initial conditions

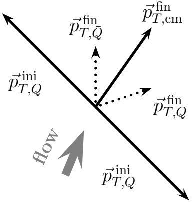


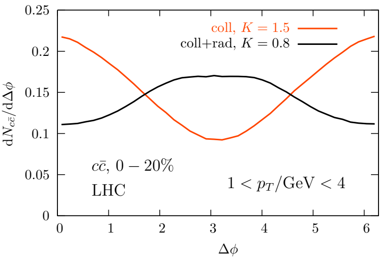


“Partonic wind” effect

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!





QGP: initial state and bulk flow (1)

- Bulk flow is driven by the initial elliptic or triangular eccentricity ϵ_2 and ϵ_3

$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

- In the light hadron sector the final $v_2 \propto \epsilon_2$ and $v_3 \propto \epsilon_3$ for not too large centralities.

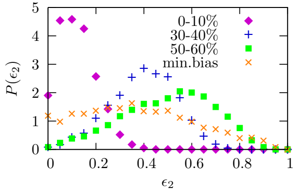
G.-Y. Qin et al., PRC**82** (2010); H. Niemi et al., PRC**87**(2013)

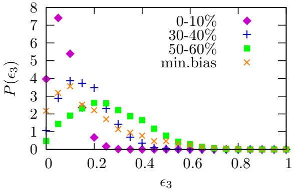
- Proportionality depends on viscosity and higher-order flow is more sensitive!

$$\frac{v_n}{\epsilon_n} = \left(\frac{v_n}{\epsilon_n}\right)_{\text{ideal}} (1 - \mathcal{O}(n^m K)) \quad m \sim 1-2$$

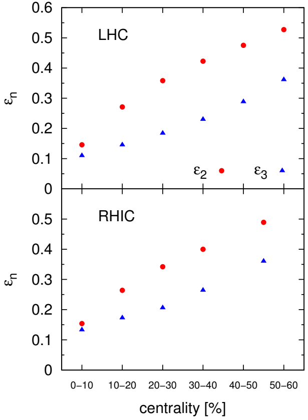
B. H. Alver et al., PRC**82**, (2010); P. Staig and E. Shuryak, PRC**84** (2011); Y. Hatta et al., arXiv:1407.5952

- Dependence on centrality already in the ideal case: FO dynamics, core-corona separation, etc.

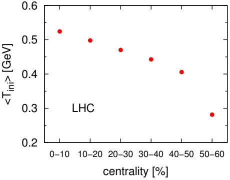


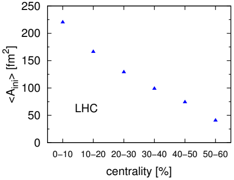


QGP: initial state and bulk flow (2)



average temperature and overlap area



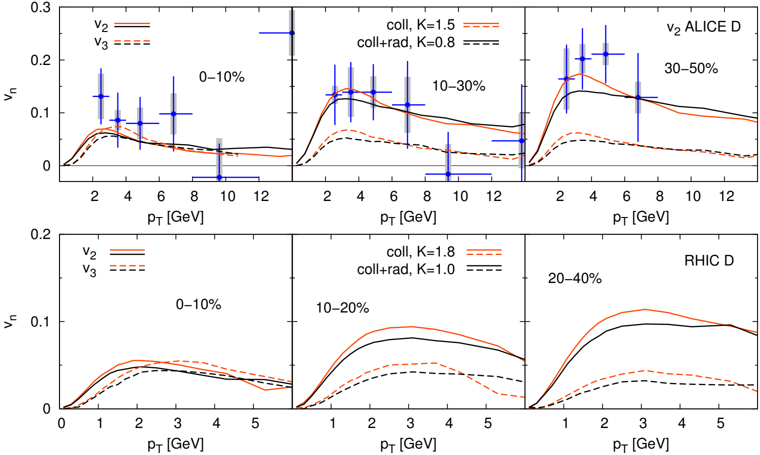


centrality dependence:

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

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

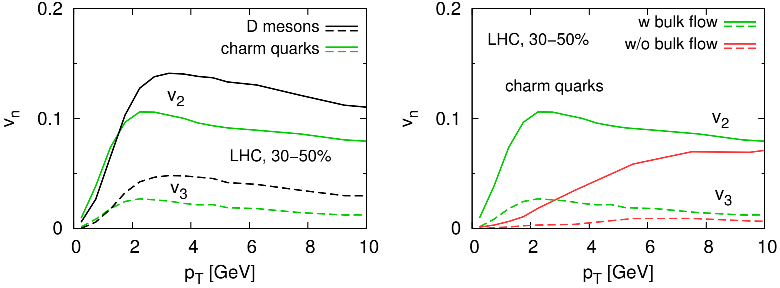
D meson v_2 and v_3 at LHC and RHIC



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

Charm flow: hadronization and energy loss

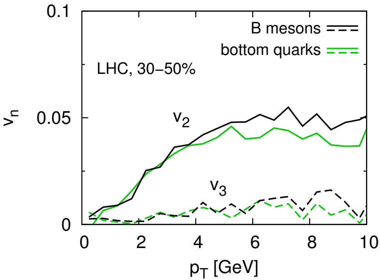
collisional+radiative(+LPM), K $= 0.8$

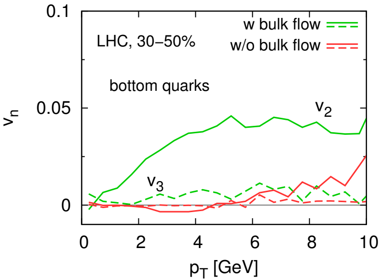


- Contribution to the flow from hadronization.
- For low p_T the charm flow is predominantly due to the flow of the bulk.

Bottom Flow: hadronization and energy loss

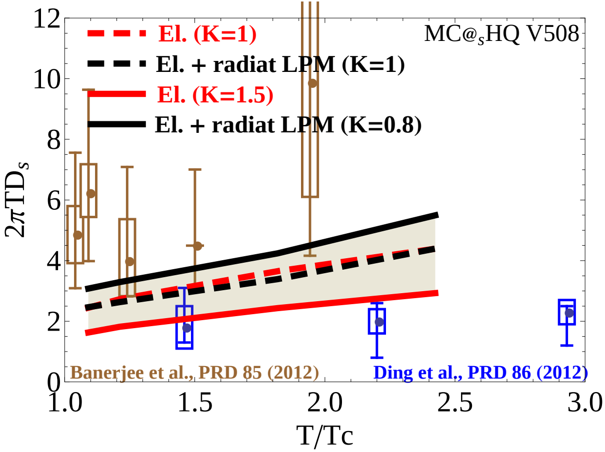
collisional+radiative(+LPM), **K** $=$ **0.8**



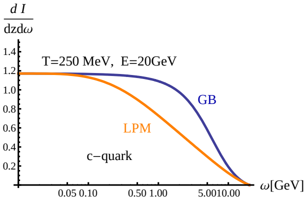


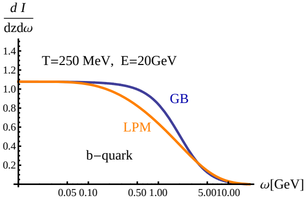
- Flow of B mesons reflects well the bottom quark flow.
- Flow of B mesons for $p_T \lesssim 6$ GeV entirely due to bulk flow.

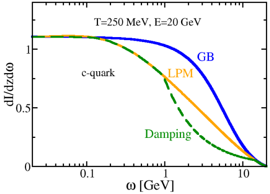
Diffusion coefficient in MC@sHQ



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