Heavy-quark diffusion

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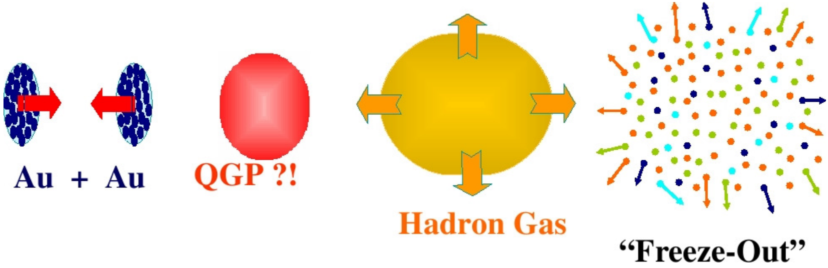
Outline

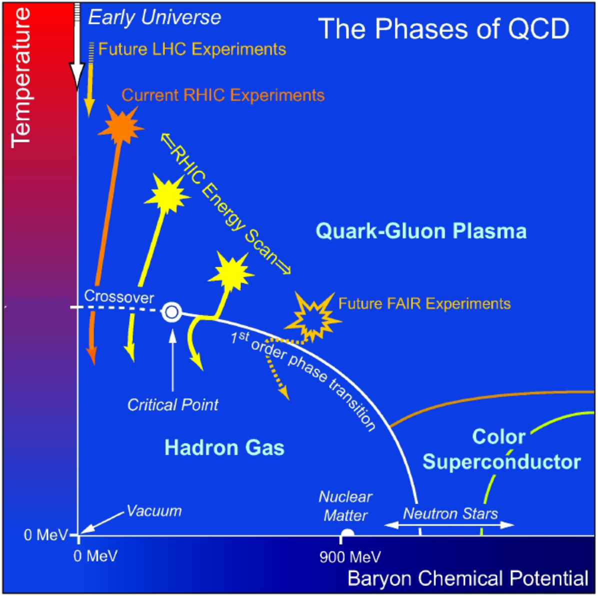
1. Introduction: QCD medium created in HICs
2. Heavy Quarks in AA collisions
3. HQ interactions in the QGP
4. Glance at small systems (pA)

Ultrarelativistic Heavy-Ion Collisions

- ultra-relativistic collisions of heavy nuclei
- creates hot and dense fireball behaving like a strongly coupled medium
- early thermalization, starting in QGP phase
- rapidly expanding and cooling
- (cross-over) transition to hadron-resonance gas ($T_{\text{pc}} \simeq 150\text{-}160\,\text{MeV}$)

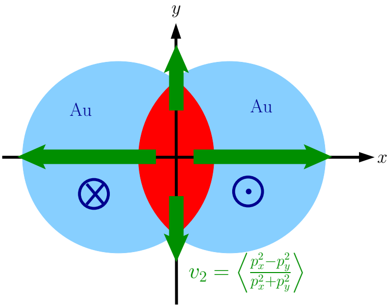


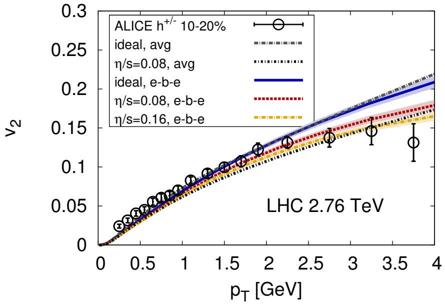
QCD Phase Diagram



Hydrodynamical Behavior

- particle spectra compatible with collective flow (hydrodynamical expansion)
- elliptic flow as signature of pressure
- (nearly) ideal hydrodynamics $\eta/s \simeq 1\text{-}2 \times 1/4\pi$





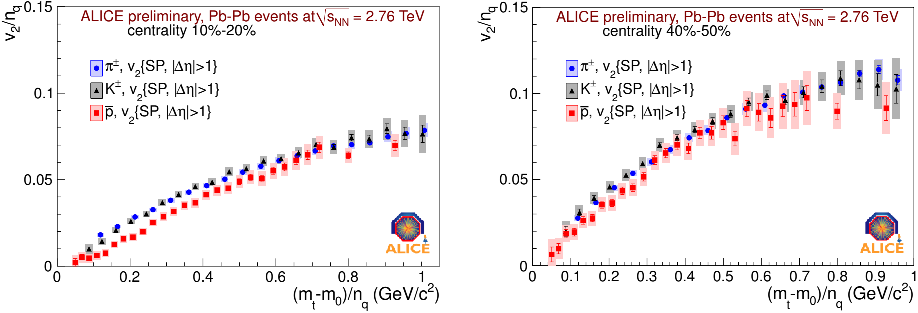
[Bjoern Schenke, Sangyong Jeon, Charles Gale, Phys. Lett.B]

Constituent-quark-number scaling of v_2

- v_2 scales with number of constituent quarks

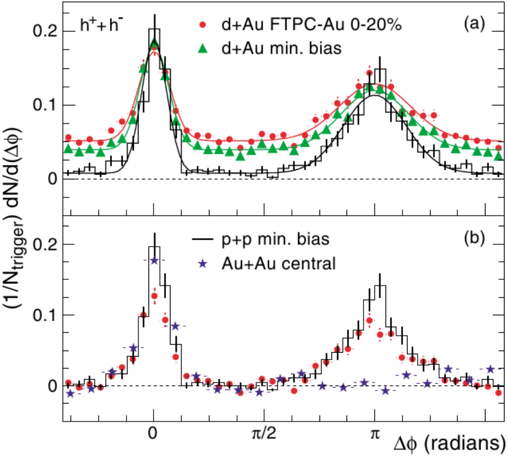
$$v_2^{(\text{had})}(p_T^{(\text{had})}) = n_q v_2^{(q)}(p_T^{(\text{had})}/n_q)$$

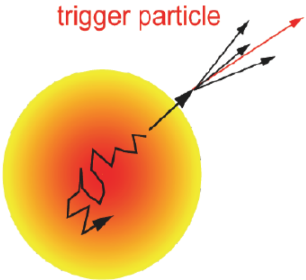
- indicates recombination of quarks in medium around T_{pc}
- "coalescence" of partonic degrees of freedom!



[M.Krzewicki (ALICE Collaboration) arXiv:1107.0080v1 [nucl-ex]]

Jet Quenching





- high p_T: jets going through medium suppressed
- high-density medium $\Rightarrow \rho > \rho_{\text{krit}}$
- energy loss due to elastic scattering and gluon bremsstrahlung

Heavy Quarks as Probes of the Medium

- "heavy" quark: $m_{\mathrm{Q}} \gg \Lambda_{\mathrm{QCD}}$, $m_{\mathrm{Q}} \gg T_{\mathrm{medium}}$
- production in primordial hard collisions ($\tau_{\mathrm{form}} \simeq 0.1\,\mathrm{fm}/c$)
- at low p_{T} dynamics in medium describable as diffusion process
- characterized by drag and diffusion coefficients (Fokker-Planck equation)

$$\partial_t f_Q = \vec{\nabla}_p \cdot (\vec{p} A f_Q) + \partial_{p_i} \partial_{p_j} B_{ij} f_Q$$

- $\tau_{\mathrm{therm}}^{(\mathrm{HQ})} \sim \tau_{\mathrm{therm}}^{(\mathrm{light})} \cdot m_{\mathrm{Q}}/T$
  $\Rightarrow$ degree of HQ thermalization $\Leftrightarrow$ insight in QGP transport properties!

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- sensitivity to: bulk-medium evolution, hadronization mechanism ("recombination" vs. "fragmentation")

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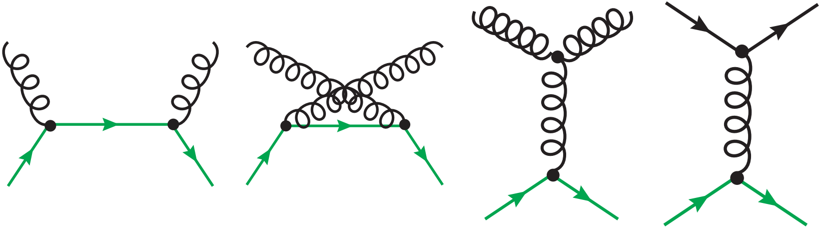
- sensitivity to: bulk-medium evolution, hadronization mechanism ("recombination" vs. "fragmentation")
- high p_T: energy loss $\Leftrightarrow$ elastic vs. gluo-radiative
- large m_Q: "dead-cone effect" for radiative energy loss
- "mass hierarchy" in jet quenching (b vs. c quarks) at high p_T

[X. Dong, Y-J. Lee, R. Rapp, Annu. Rev. of Nucl. and Part. Sci. **69**, 417 (2019)]

HQ interactions in the QGP: pQCD (HTL)

- leading-order diagrams for elastic scattering of heavy quarks with gluons and light quarks



- last two diagrams with t-channel-gluon exchange most important
- lead to IR-divergent cross sections in naive perturbation theory!
- in the medium: Debye screening $\mu_{\mathrm{D}} \simeq g\,T$

Hard-thermal loop resummed pQCD interactions

- more detailed calculation of gluon self-energy at finite temperature

$$\Pi_T(\omega,\boldsymbol{q}) = \mu_D^2 \left\{ \frac{\omega^2}{2\boldsymbol{q}^2} + \frac{\omega(\boldsymbol{q}^2-\omega^2)}{4q^3} \left[\ln\left(\frac{q+\omega}{q-\omega}\right) - \mathrm{i}\pi \right] \right\},$$

$$\Pi_{00}(\omega,\boldsymbol{q}) = \mu_D^2 \left\{ 1 - \frac{\omega}{2q} \left[\ln\left(\frac{q+\omega}{q-\omega}\right) - \mathrm{i}\pi \right] \right\}.$$

- leads to gluon propagator

$$G_{\mu\nu}(\omega,q) = -\frac{\delta_{\mu 0}\delta_{\nu 0}}{q^2+\Pi_{00}} + \frac{\delta_{ij} - q_i q_j/q^2}{q^2-\omega^2+\Pi_T}$$

Interactions with running coupling

- with small $\alpha_s \lesssim 0.4$ + "naive Debye-screening" $\mu_D \simeq g T$
  not enough drag
- ansatz for effective Gluon propagator

$$G_r(t) \propto \frac{1}{t - r\mu_D^2}$$

- determining r such that the HQ energy loss in LO-pQCD matches with result where for $|t| < |t^*|$ the HTL propgator and for $|t| > |t^*|$ the perturbative propagator is used
- scale: $|t^*| \in [g^2 T^2, T^2]$
  - in QCD results depends on $|t^*|$ (not for QED)
  - solved by IR regulator mass in hard part of gluon-t-channel diagrams such that dependence on $|t^*| < T$ weak
  - leads to $r \simeq 0.1$-0.2
  - $r = 0.15$ enhances A only by factor of 2
  - reason: forward-scattering nature of pQCD (t-channel) scattering

[A. Peshier, arXiv: 0801.0595 [hep-ph]; P. B. Gossiaux, J. Aichelin, PRC 78, 014904 (2008)]

Interactions with running coupling

- self-consistent determination of m_D
  - start from running α_s:

$$\alpha_{\text{eff}}(Q^2) = \frac{4\pi}{\beta_0} \begin{cases} L_-^{-1} & \text{for } Q^2 \leq 0 \\ 1/2 - \pi^{-1} \arctan(L_+/\pi) & \text{for } Q^2 > 0, \end{cases}$$

$$\text{with} \quad \beta_0 = 11 - 2N_f/3, \quad L_\pm = \ln(\pm Q^2/\Lambda^2)$$

  - gluon propagator in t-channel diagrams

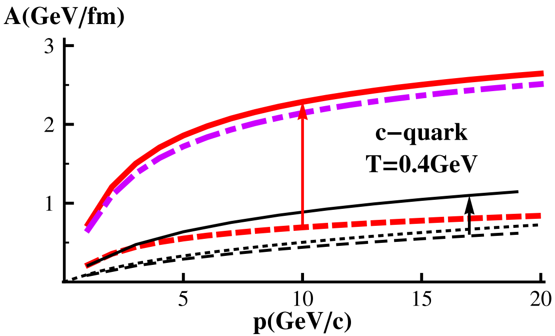
$$G_{\text{eff}}(t) \simeq \frac{\alpha_{\text{eff}}(t)}{t - \tilde{\mu}^2}$$

  - regulator mass $\tilde{\mu}^2 \in [1/2, 2]\tilde{\mu}_D^2$ determined by same matching procedure as for r-parameter approach
  - Debye-screening mass determined self-consistently

$$\tilde{\mu}_D^2 = \left(\frac{N_c}{3} + \frac{N_f}{6}\right) 4\pi\alpha(-\tilde{\mu}_D^2) T^2$$

[S. Peigné, A. Peshier, PRD **77**, 114017 (2008); A. Peshier, arXiv: 0801.0595 [hep-ph]; P. B. Gossiaux, J. Aichelin, PRC **78**, 014904 (2008)]

Interactions with running coupling

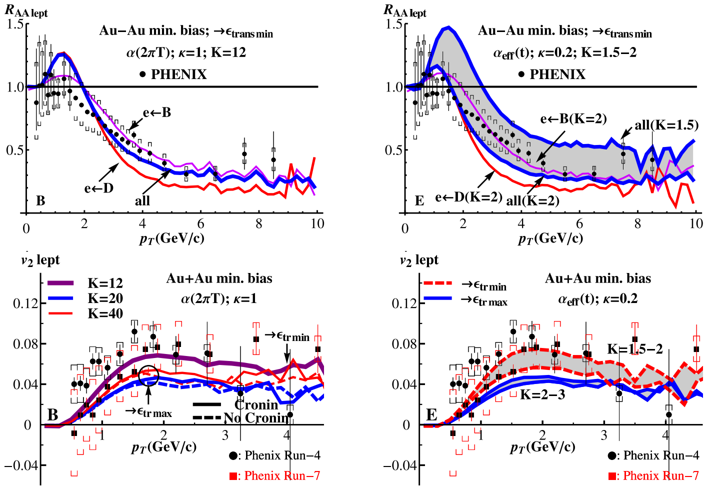


	α_S	μ^2	line form	figure color
A	0.3	m_D^2	dotted thin	black
B	$\alpha_S(2\pi T)$	m_D^2	dashed thin	black
C	$\alpha_S(2\pi T)$	$0.15 \times m_D^2$	full thin	black
D	running (Eq. (29))	$\tilde{m}_D^2$	dashed bold	red
E	running (Eq. (29))	$0.2 \times \tilde{m}_D^2$	full bold	red
F	running (Eq. (29))	$0.11 \times 6\pi\, \alpha_{\text{eff}}(t)\, T^2$	dashed dotted bold	purple

[P. B. Gossiaux, J. Aichelin, PRC 78, 014904 (2008)]

Interactions with running coupling

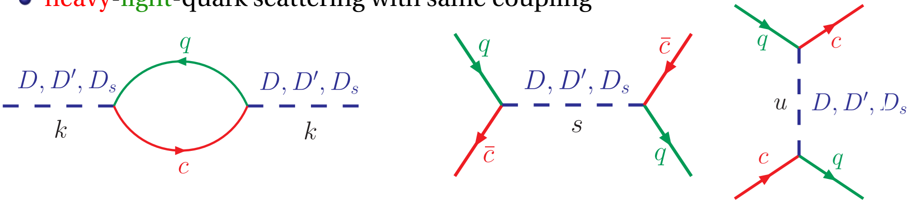
- Boltzmann-transport model and running-coupling model
- checked also with Fokker-Planck approach ⇒ good agreement!

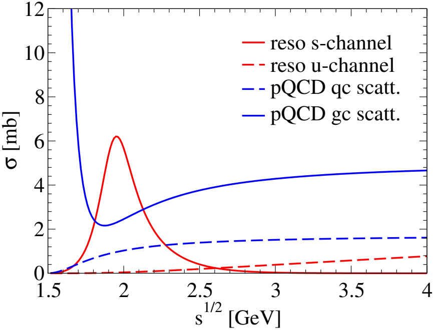


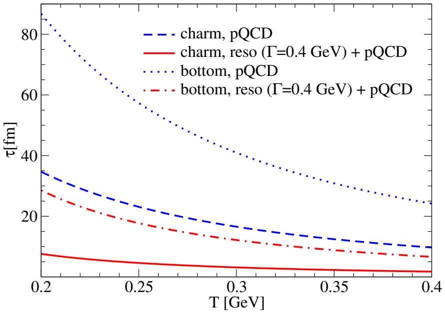
[P. B. Gossiaux, J. Aichelin, PRC 78, 014904 (2008)]

Resonance-scattering model

- width of D/B-like resonances via one-loop self energy
- heavy-light-quark scattering with same coupling

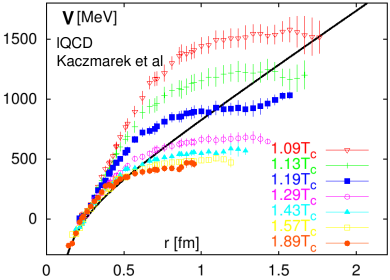






[HvH, R. Rapp, PRC **71**, 034907 (2005)]

Microscopic model: Static potentials from lattice QCD



- color-singlet free energy from lattice
- use internal energy

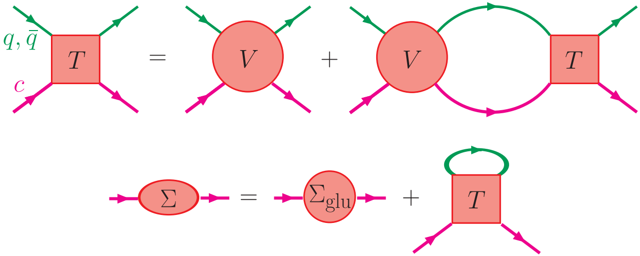
$$U_1(r,T) = F_1(r,T) - T\frac{\partial F_1(r,T)}{\partial T},$$
$$V_1(r,T) = U_1(r,T) - U_1(r \to \infty, T)$$

- Casimir scaling for other color channels [Nakamura et al 05; Döring et al 07]

$$V_{\bar{3}} = \frac{1}{2}V_1, \quad V_6 = -\frac{1}{4}V_1, \quad V_8 = -\frac{1}{8}V_1$$

[HvH, M. Mannarelli, V. Greco, R. Rapp, PRL **100**, 192301 (2008); HvH, M. Mannarelli, R. Rapp, EJC **61**, 799 (2009)]

- Brueckner many-body approach for elastic Qq, $Q\bar{q}$ scattering

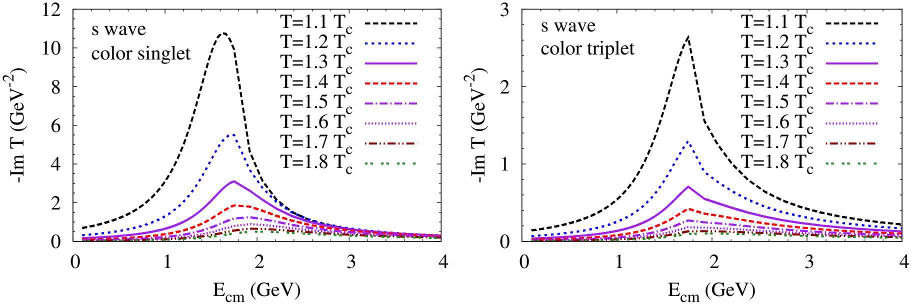


- reduction scheme: 4D Bethe-Salpeter → 3D Lipmann-Schwinger
- S- and P waves
- same scheme for light quarks (self consistent!)
- Relation to invariant matrix elements

$$\sum |\mathcal{M}(s)|^2 \propto \sum_q d_a \left(|T_{a,l=0}(s)|^2 + 3 |T_{a,l=1}(s)|^2 \cos\theta_{\text{cm}} \right)$$

[HvH, M. Mannarelli, V. Greco, R. Rapp, PRL **100**, 192301 (2008); HvH, M. Mannarelli, R. Rapp, EJC **61**, 799 (2009)]

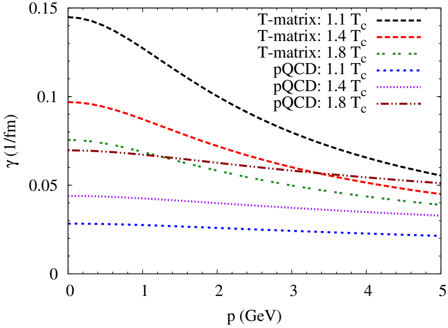
T-matrix

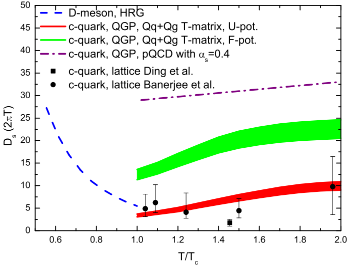


- resonance formation at lower temperatures $T \simeq T_c$
- melting of resonances at higher T! $\Rightarrow$ sQGP
- P wave smaller
- resonances near T_c: natural connection to quark coalescence

  [Ravagli, Rapp 07; Ravagli, HvH, Rapp 08]
- model-independent assessment of elastic Qq, $Q\bar{q}$ scattering
- problems: uncertainties in extracting potential from lQCD
- in-medium potential U vs. F?

Transport coefficients





[M. He, R. J. Fries, and R. Rapp, Phys. Rev. Lett. **110**, 112301 (2013)]

- from non-pert. interactions reach $A_{\text{non-pert}} \simeq 1/(7\,\text{fm}/c) \simeq 4 A_{\text{pQCD}}$
- A decreases with higher temperature
- higher density (over)compensated by melting of resonances!
- spatial diffusion coefficient

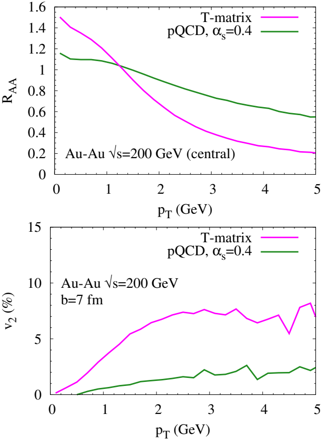
$$D_s = \frac{T}{mA}$$

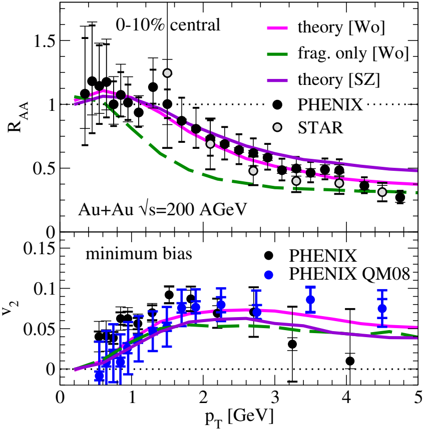
increases (decreases) with temperature above (below) T_{pc}

- typical behavior of transport coefficients: minimum at phase transitions!

Non-photonic electrons at RHIC

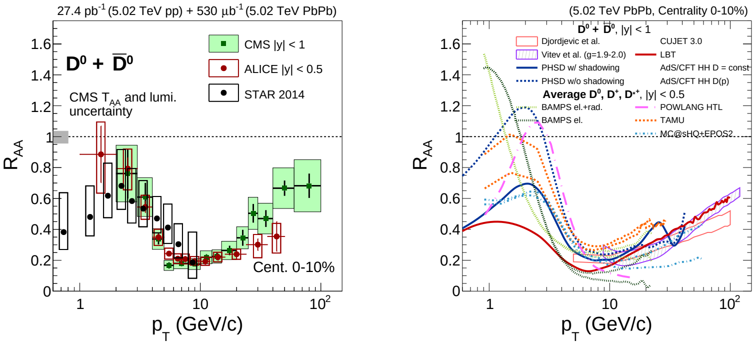
- same model for bottom
- quark coalescence+fragmentation $\rightarrow D/B \rightarrow e + X$





- coalescence crucial for description of data
- increases both, R_{AA} and $v_2 \Leftrightarrow$ “momentum kick” from light quarks!
- “resonance formation” towards $T_c \Rightarrow$ coalescence natural [Ravagli, Rapp 07]

Model comparison to recent LHC data

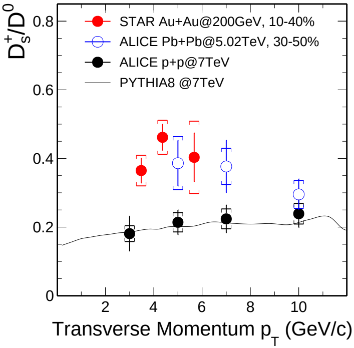


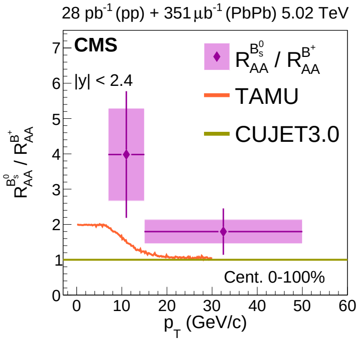
[X. Dong, Y-J. Lee, R. Rapp, Annu. Rev. of Nucl. and Part. Sci. **69**, 417 (2019)]

- remarkable: LHC and RHIC data similar!
- low p_T: pronounced flow bump ⇒ significant collectivity of c-quarks/D-mesons
- sensitive also to details of bulk evolution (and cold-nuclear-matter effects: shadowing)
- high p_T: radiative energy loss; running coupling

Hadrochemistry (HF mesons)

- D_s/D^0 ratio enhanced in pA and AA collisions
- compatible with statistical hadronization model (commmon chemical freezeout $T_{cp} \simeq 155$ MeV)
- kinetic recombination models: consistent for $p_T \lesssim 4$-5 GeV; too low at high p_T
- better understanding of close-to-equilibrium vs. fragmentation region

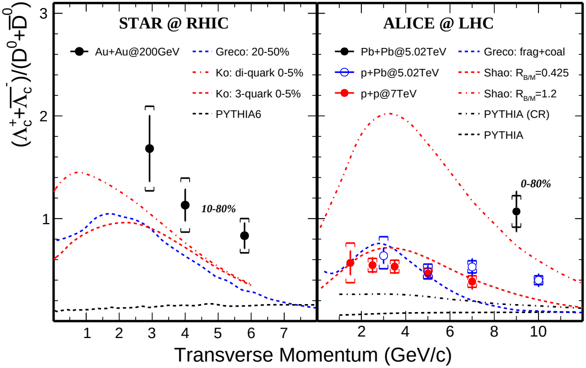




[X. Dong, Y-J. Lee, R. Rapp, Annu. Rev. of Nucl. and Part. Sci. **69**, 417 (2019)]

Hadrochemistry (HF baryons)

- Λ_c/D^0 ratio > PYTHIA baseline already in pp/pA
- in AA coalescence model only qualitative agreement with data (including diquark substructure in wavefunction)
- total charm cross section @RHIC only compatible with N_{bin} scaling of pp when enhanced Λ_c/D^0 taken into account
- more measurement of charmed baryons + mesons necessary (Λ_c at low p_T!)



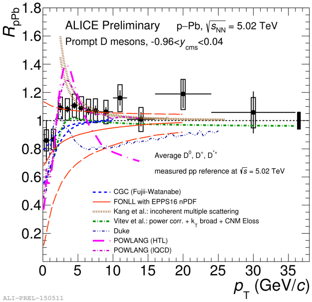
[X. Dong, Y-J. Lee, R. Rapp, Annu. Rev. of Nucl. and Part. Sci. **69**, 417 (2019)]

HF in pA collisions

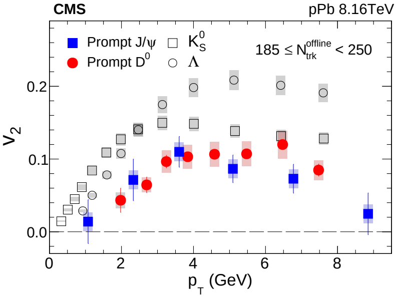
- pA measurements important as baseline for AA: cold-nuclear-matter effects
- nuclear PDFs; nuclear broadening via parton energy loss
- HF mesons show only moderate modifications (min bias)
- some suppression at low $p_{\mathrm{T}} \Rightarrow$ nuclear shadowing
- can be described by both models assuming initial-state or final-state effects

Collectivity in high-multiplicity events in pA?!?

- high-multiplicity events in pA (and even in pp!) seem to indicate some radial and elliptic flow of light hadrons
- “hot-medium effects”?
- for D-mesons: $R_{\mathrm{p}A}$ not significantly suppressed but some v_2
- more data in “ultra-central” pp and pA collisions desirable



[R. Vertesi (ALICE Collab.), arXiv:1904.06180 [nucl-ex]]



[X. Dong, Y-J. Lee, R. Rapp, Annu. Rev. of Nucl. and Part. Sci. **69**, 417 (2019)]

Conclusions

- heavy quarks in AA
  - transport properties of the medium (QGP/hadron-resonance gas) created in AA collisions
  - non-perturbative properties of strong interaction (color screening, resonance formation around T_{pc}
  - collisional vs. radiative energy loss
  - hadronization mechanisms in pp, pA, AA: coalescence/kinetic recombination, fragmentation
- heavy quarks in pA
  - important baseline for AA (cold-nuclear matter effects)
  - puzzle: $R_{\text{p}A}$ close to 1 but significant v_2
  - "collectivity" in high-multiplicity events in pA?!?
- observables
  - $R_{AA}/R_{\text{p}A}$, $v_2 \Leftrightarrow$ sensitive to transport properties/hadronization mechanisms, bulk-medium evolution
  - "hadro-chemistry": HQ mesons and baryons over all p_{T}
  - enhancement of $\text{D}_{\text{s}}/\text{D}^0$ in pA and AA
  - enhancement of $\Lambda_{\text{c}}/\text{D}$ already in pp (color reconnection/ropes, statistical hadronization?!?)
  - total charm cross section?!?