Heavy quark diffusion in a hydrodynamically expanding medium

A Langevin dynamical calculation

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with thanks to

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Heavy quarks in the QGP

A well-calibrated probe of the medium

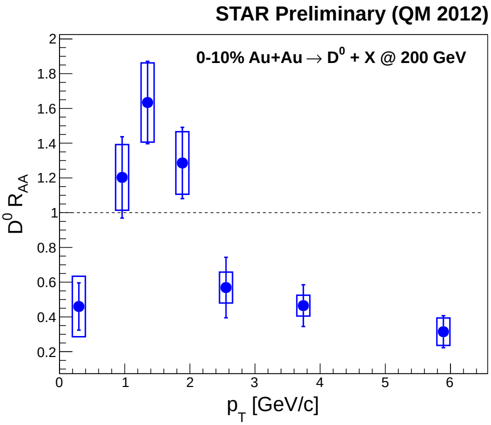
- They are distinct
  - c, b are conserved quantum numbers
  - Identifiable from final-state products
- They are around at the beginning
  - But they thermalize slowly:
    $\tau \approx M/T \approx 6\times$ longer than for light quarks
  - Well-defined initial conditions (hard processes)
- They suffer collisional energy loss
  - c vs b energy loss an important constraint
  - Diffusion
  - Drag

D^0 modification experimentally established

Not a weak effect!

Initial naive thinking (large mass ⇒ small modification) is unsupported.

STAR D^0s in Au+Au



- Features in data:
  - Strong low-p_T suppression
  - Large enhancement around 1-2 GeV
  - 2-3× suppression for $p_T > 2$ GeV

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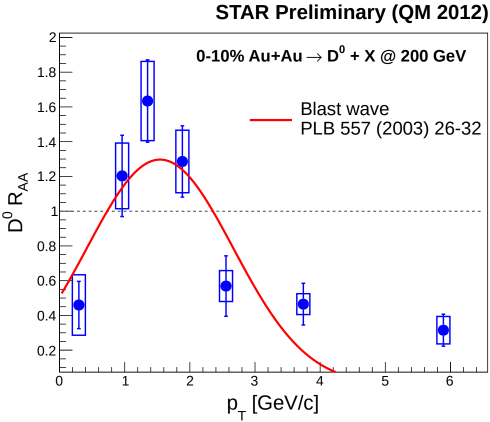

- Blast-wave fit (Batsouli, Kelly, Gyulassy, Nagle) describes low-p_T data well
- **But** with boosted thermal particles only, the high-p_T behavior is not matched.

The radial velocity

$$\beta_T = \beta_{\max} \frac{r}{R}$$

has a linear boost profile, with uniform initial density.

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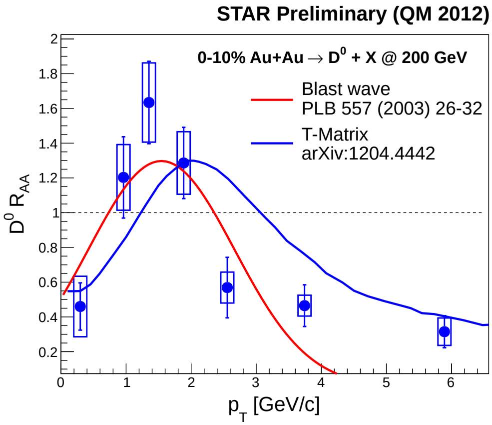
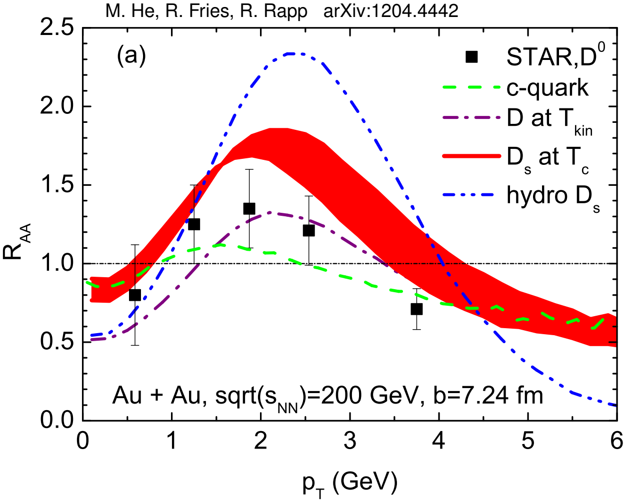


- T-matrix interactions + coalescence (M. He, R. Fries, R. Rapp) roughly captures R_{AA} features over full p_T range.
- Model includes a non-thermal component.
- How much of this shape comes from hadronization?

Quark vs. hadron R_{AA}

Coalescence is an important effect!



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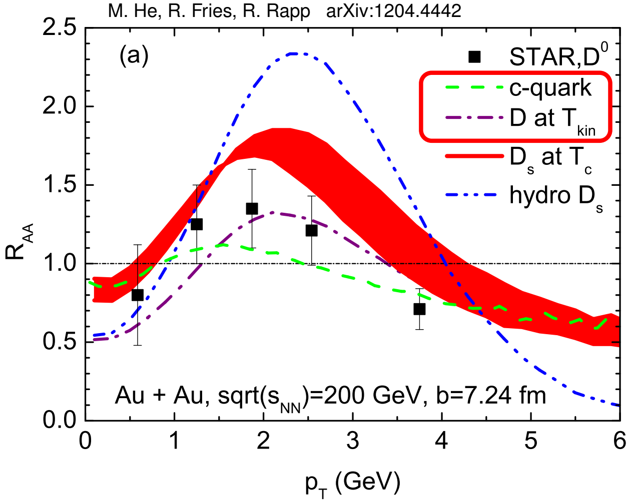

Compare c-quark and D-meson:

Far stronger low-p_T suppression and intermediate-p_T enhancement in hadronization stage

Modeling heavy quark diffusion

Checking further into things

Since heavy quark modification is so informative, modeling in-medium interactions is valuable.

Many groups have produced interesting calculations. We throw our hat into the ring as well.

We used a Langevin MC model embedded in 2+1D viscous hydro by P. Romatschke.

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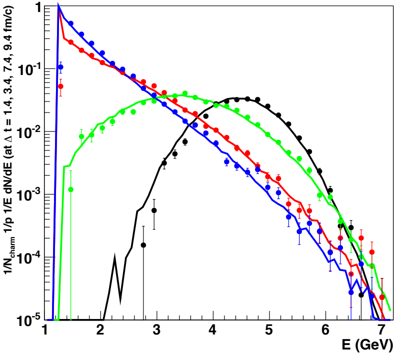

Phys. Rev. C 84, 064902 (2011)

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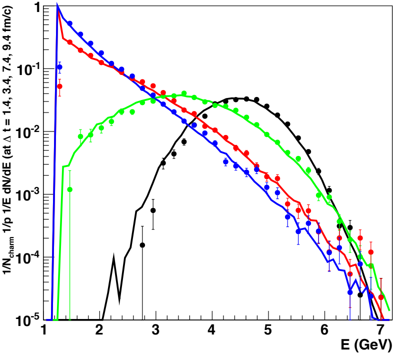

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Now for some details about the calculation…

Langevin dynamics

Brownian motion in a thermal bath

The **Langevin equation:**

$$\frac{d\mathbf{p}^i(t)}{dt} = -\eta_D^{ij}\mathbf{p}^j(t) + \xi^i(t)$$

- Viscous drag force η_D^{ij} describes large-scale average motion.
- ξ^i describes stochastic fluctuations about the average motion

$$\langle \xi^i(t)\xi^j(t')\rangle = 4TE\eta_D^{ij}\delta(t-t'), \qquad \langle \xi^i(t)\rangle = 0.$$

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Time discretization

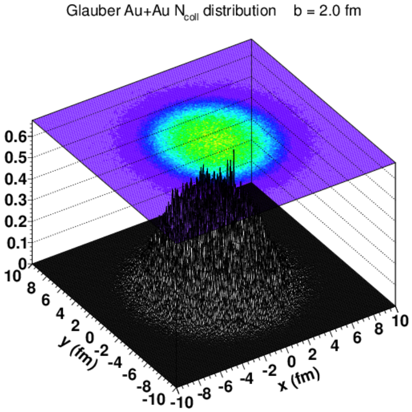
In each step Δt, the quark suffers a normally-distributed random deflection: $\sigma = \sqrt{2T^2/(D\Delta t)}$, where D is the diffusion parameter.

One parameter controls essential physics (scattering, drag, boosts)

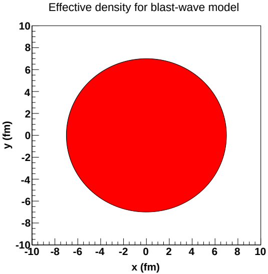
Langevin + Hydro inputs

Initial conditions

Initial quark positions distributed according to MC Glauber N_{coll} distribution



Contrast with linear boost profile of blast-wave:



Many particles at large radii
⇒ high sensitivity to late-stage expansion

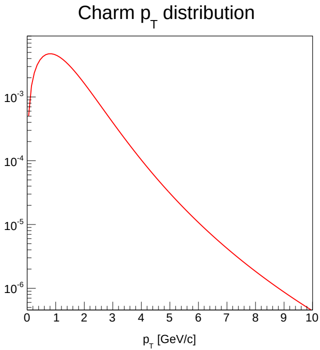
Langevin + Hydro inputs

Quark momentum distributions

Charm quark momentum distributions are given this shape:

$$\frac{1}{p_T}\frac{dn}{dp_T} \propto \frac{1}{(p_T^2 + \Lambda^2)^\alpha}$$

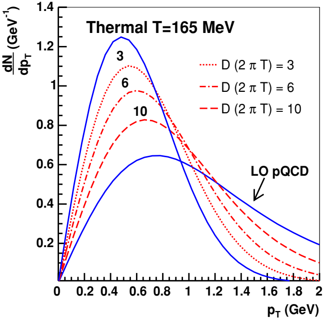
where $\alpha = 3.9, \Lambda = 2.1$, following Cao, Qin, & Bass (arXiv:1205.2396v1)



Charm p_T distribution

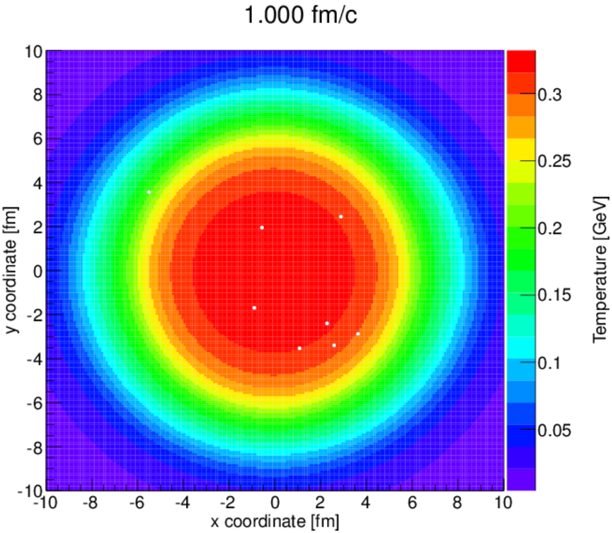
This form also used by Moore & Teaney (labeled “LO pQCD”):

PHYSICAL REVIEW C **71**, 064904 (2005)



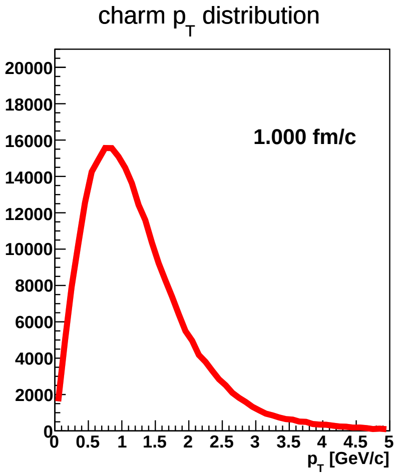
Langevin MC simulation

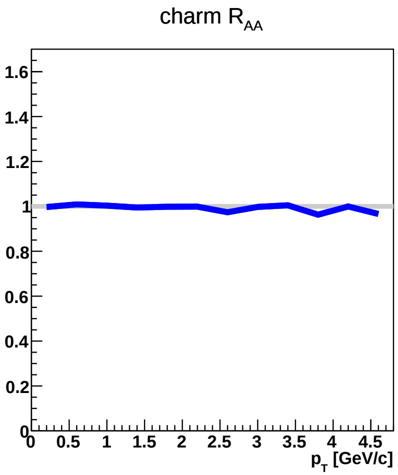
8 $c\bar{c}$ pairs shown



Langevin MC simulation

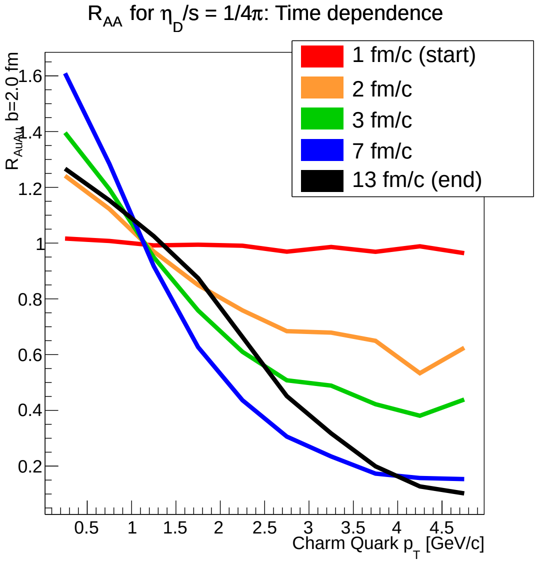
D parameter corresponding to $\eta/s = 1/4\pi$





R_{AA}: time dependence

subtitle



Increasing high-p_T suppression with time...

but $R_{AA} < 1$.

Late hydro push ($t > 7$ fm/c) decreases low-p_T contribution, but not enough to make $R_{AA} < 1$.

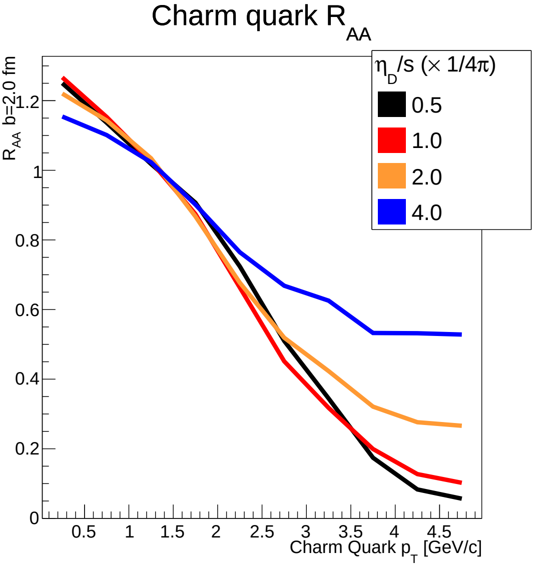
R_{AA}: varying the effective coupling

Smaller $\eta/s \Leftrightarrow$ larger diffusion

Even after varying the diffusion by an order of magnitude, the **low-p_T R_{AA} changes weakly**.

$R_{AA} > 1$, no matter the D value.

Cancellation over time:
Drag at early times + boost at late times



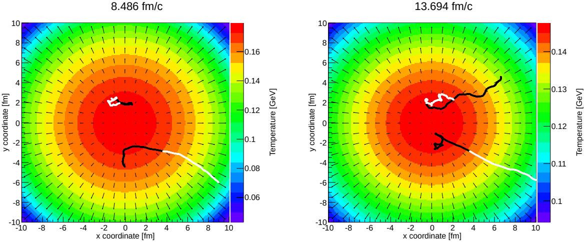
Azimuthal $q\bar{q}$ correlations

Seeking a more sensitive measure of early-time dynamics

Initial $q\bar{q}$ pairs given equal and opposite p_T

Strong effective coupling (small D): expect small-angle correlations from late-stage boosts

Typical behavior for strong effective coupling ($\eta_D/s = 0.5 \times 1/4\pi$):



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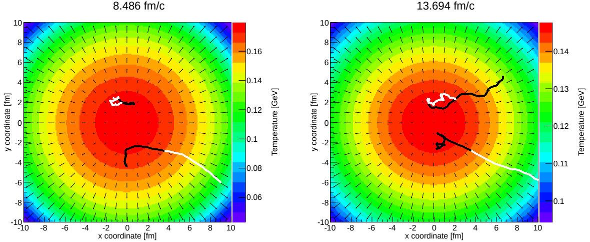
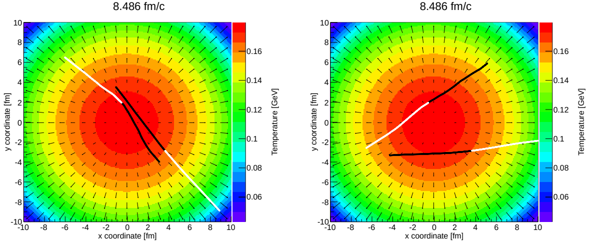


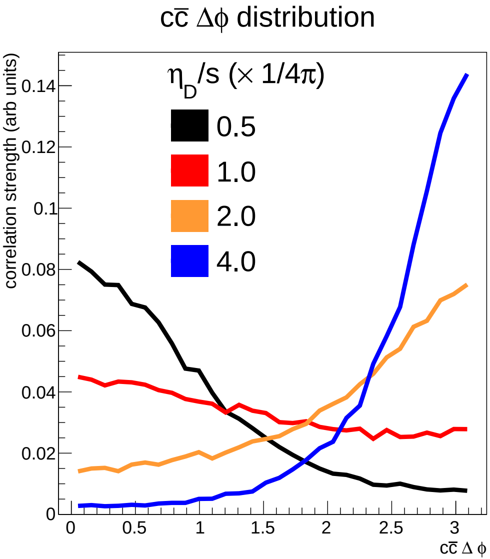
Large D: back-to-back correlation is preserved

Typical behavior for weak effective coupling ($\eta_D/s = 4 \times 1/4\pi$):



How does $\Delta\phi$ depend on effective coupling?

$\Delta\phi$ distribution for $p_T > 1$ GeV/c



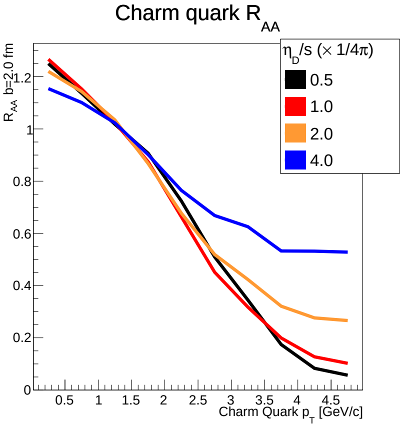
Strong coupling (small *D*) enhances same-side correlations

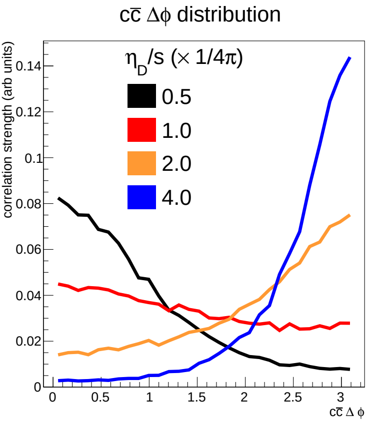
Weak coupling (large *D*) corresponds to less deflection, preserving back-to-back production.

R_{AA} and $\Delta\phi$ vs diffusion strength

Comparison of “observables”

R_{AA} is fairly insensitive to varying D near expected values.





But the $c\bar{c}$ correlation function changes dramatically from same-side → opposite-side dominance.

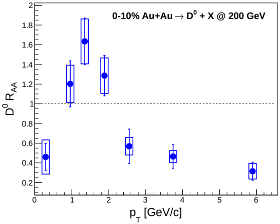
Understanding the shape of R_{AA}

Especially, low-p_T suppression

Despite large range of coupling parameters tried, we could not get $R_{AA} < 1$ below ≈ 1 GeV/c.

- Perhaps the low p_T effect is all coalescence?
- Or perhaps there is something to make the physics for $t < 7$ fm/c weaker, while preserving the strong coupling for $t > 7$ fm/c.

STAR Preliminary (QM 2012)



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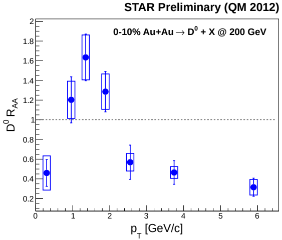


To check this, we investigate a temperature-dependent coupling.

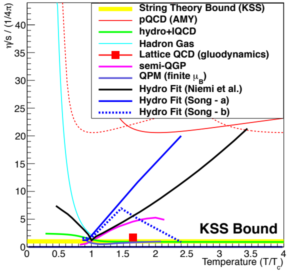
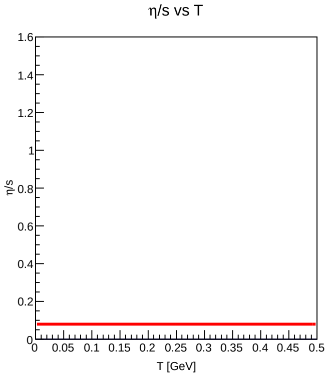


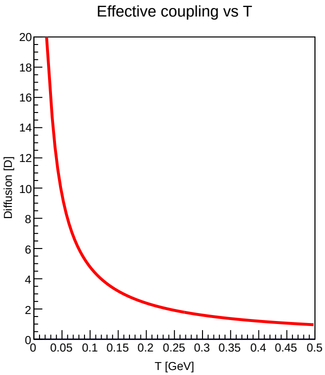
Figure from sPHENIX proposal arXiv:1207.6378

Temperature-dependent η/s

and the corresponding effective coupling D(T)

For constant $\eta/s = 1/4\pi$, the diffusion parameter is $D = 3/2\pi T$.





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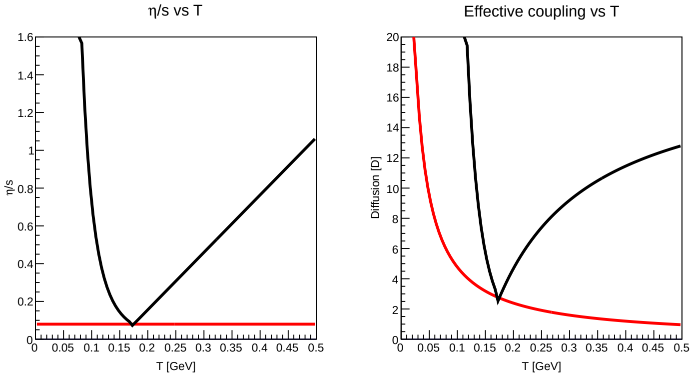
Based on many models, η/s grows sharply away from T_c
$\Rightarrow$ D much larger at high T / early time.



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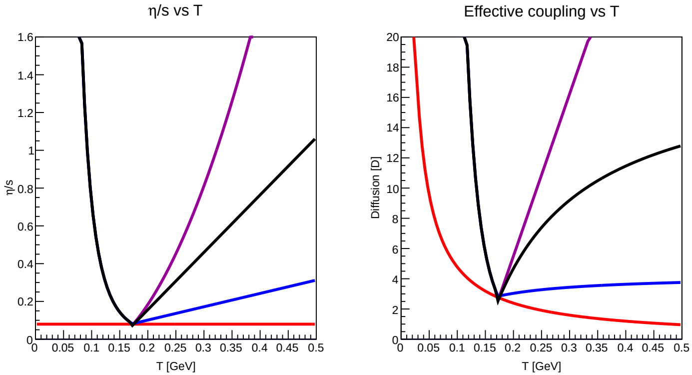
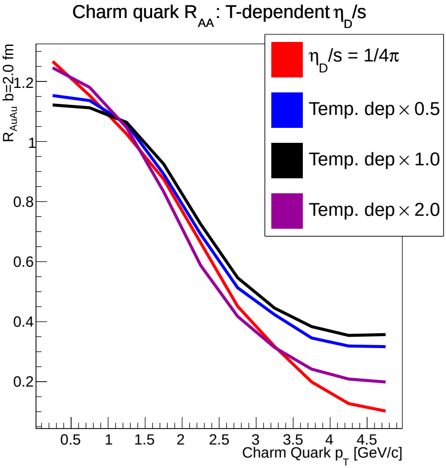


We also tried doubling and halving the high-T dependence. $\Rightarrow$ Result:

R_{AA} and $\Delta\phi$ for $D(T)$

Temperature-dependent diffusion

R_{AA} is fairly insensitive to the temperature dependence.



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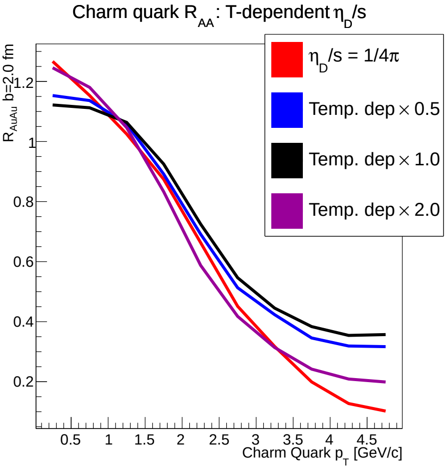
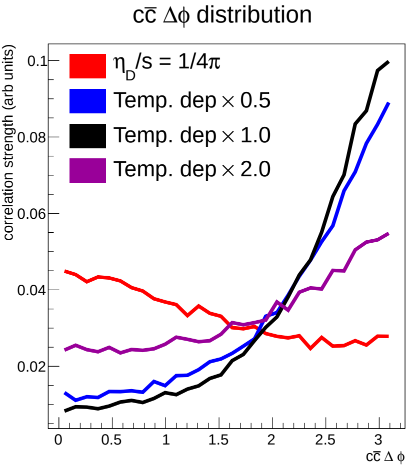




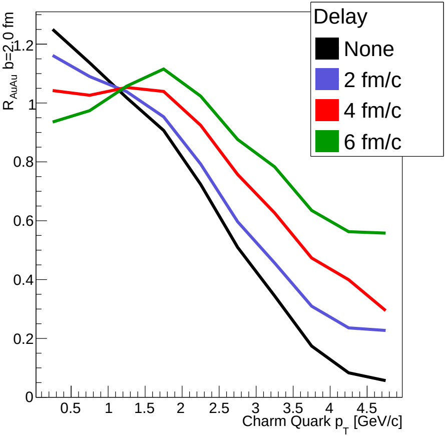
On the other hand, the pair correlation shows a strong dependence!

Delayed diffusion

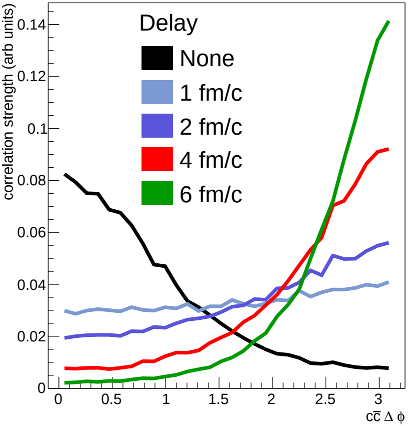
What if charm quarks don't interact at all initially?

Immediate diffusion: strong initial drag, then pairs are collinearized in late-stage boost

Charm quark R_{AA}: Start time dependence



$c\bar{c}$ $\Delta\phi$ distribution, D = $3/4\pi$



Very late diffusion: back-to-back enhancement as for large η/s case.

Summary

Lessons from this study

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- Scattering + viscous drag → high-p_T suppression
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- Whatever we tried, we could not get $R_{AA} < 1$
- With realistic initial geometry, late-stage boosts are insufficient
- What really does it is coalescence

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Thanks