What we know about QGP from heavy quarks and quarkonia, and what we can still learn

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Temple University – September 15, 2014

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Points to the address in the long range plan:

1. Unique physics of heavy quarks and quarkonia in media.

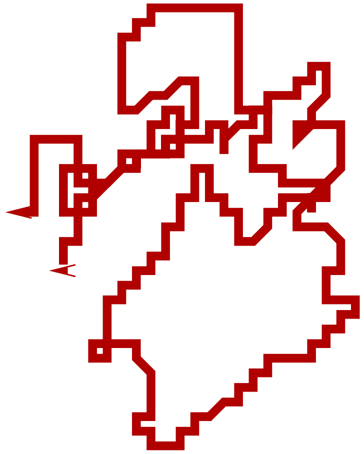
2. Current and future measurements.

3. The relative roles of RHIC and the LHC.

Talk discusses Slow Quarks, Faster Quarks, and Quarkonia

Slow Quarks

Measuring transport properties QGP with slow heavy quarks



- Brownian Motion

$$M\frac{d^2\boldsymbol{x}}{dt^2} = \underbrace{-\eta}_{\text{Drag}}\,\dot{x} + \underbrace{\xi}_{\text{Random Force}}$$

- The strength of the noise records the force-force correlation function in plasma

$$\kappa = \int dt\, \langle \xi(t)\xi(0) \rangle = \int \mathrm{d}t\, \langle F(t)F(0) \rangle$$

- Measures timelike correlations chromo-electric field correlators in plasma

$$\kappa = \int \mathrm{d}t \left\langle E_a(t) W^{ab}(t,0) E_b(0) \right\rangle$$

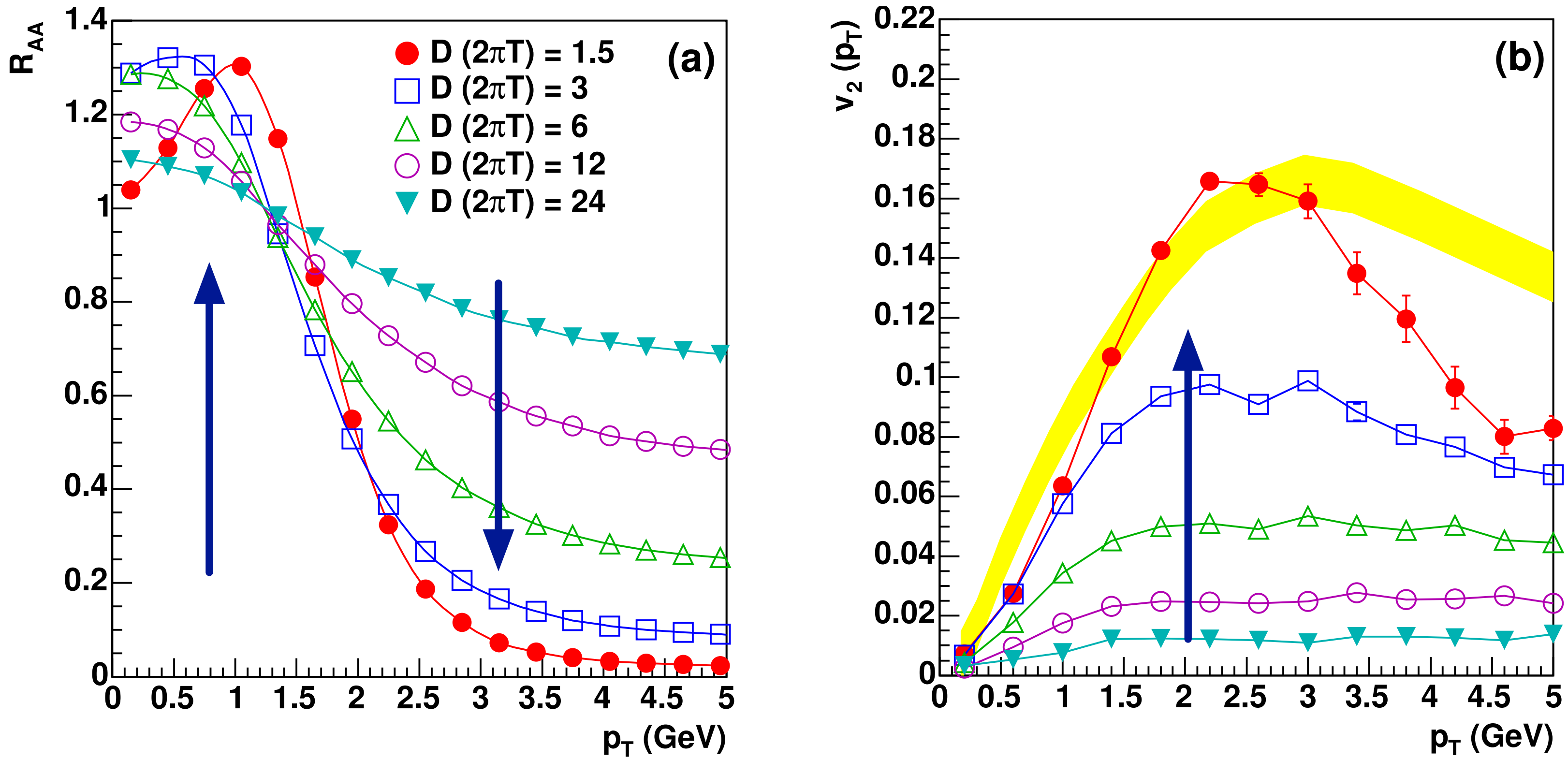
- Often expressed in terms of the diffusion coefficients of plasma

$$D = \frac{2T^2}{\kappa}$$

Independent of mass ~ 1 if strongly coupled

The old idea – extracting the diffusion coefficient:

rhic charm quark spectra modifcation and elliptic flow



- Range of diffusion coefficients is still applicable today:

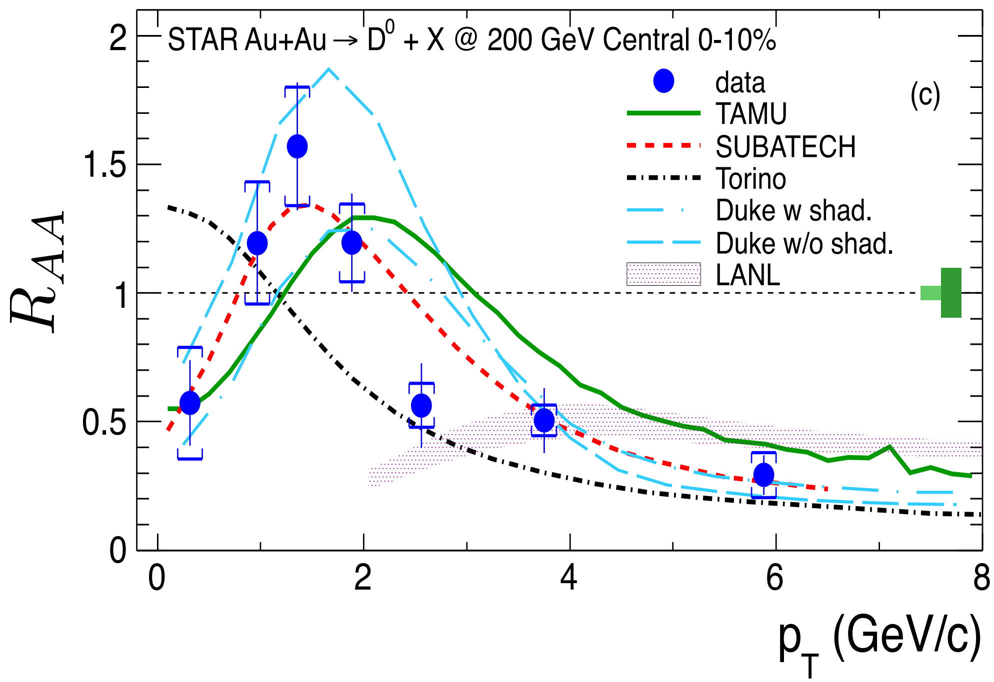
$$D \simeq (3-6)/(2\pi T)$$

- All simulations of charm have to generalize Langevin to mildly relativistic quarks

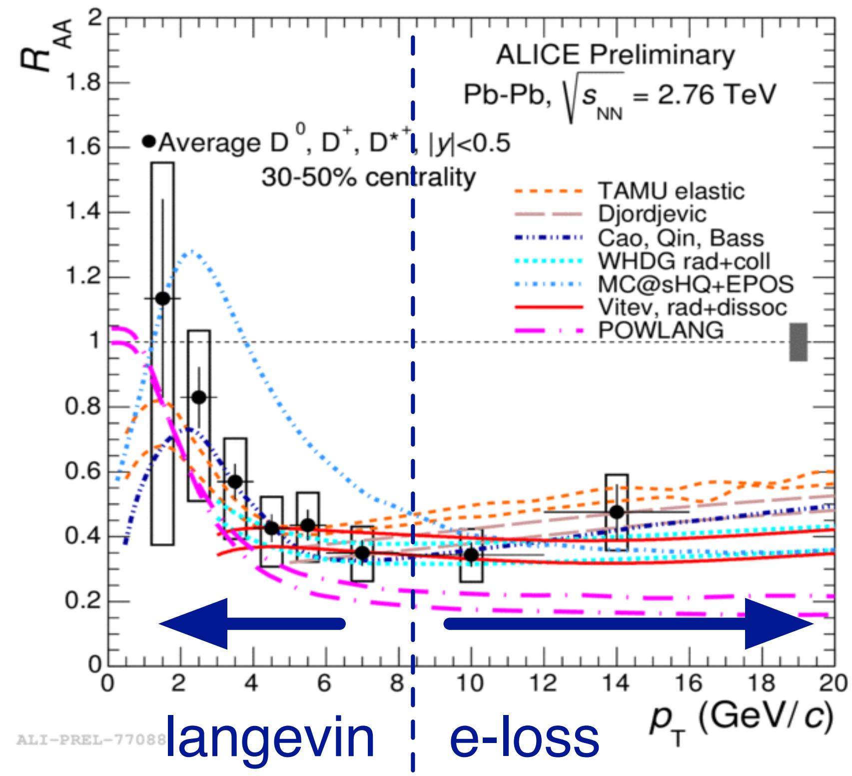
Current implementation compared to low p_T measurements at RHIC and LHC

- Measure reconstructed $D \to K\pi$ at low p_T
- (Subatech, Duke, TAMU, Torino, POWLANG) are Langevin based $0 < p_T \lesssim 6$

RHIC



LHC

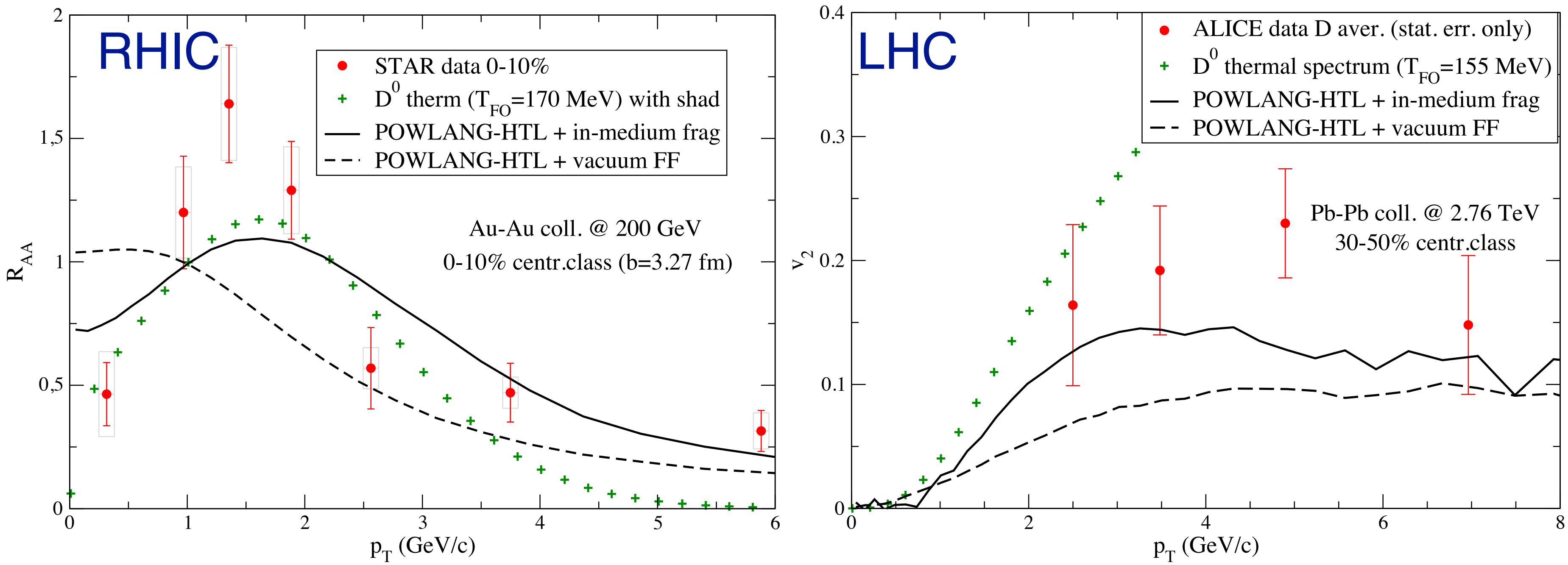


For diffusion, want to measure at low p_T.

Well developed codes exist.

Discussion of low p_T results

(Torino – Beraudo et al)



1. The extracted diffusion coefficient:

$$D \simeq \frac{(3.5 - 4.5)}{2\pi T}$$

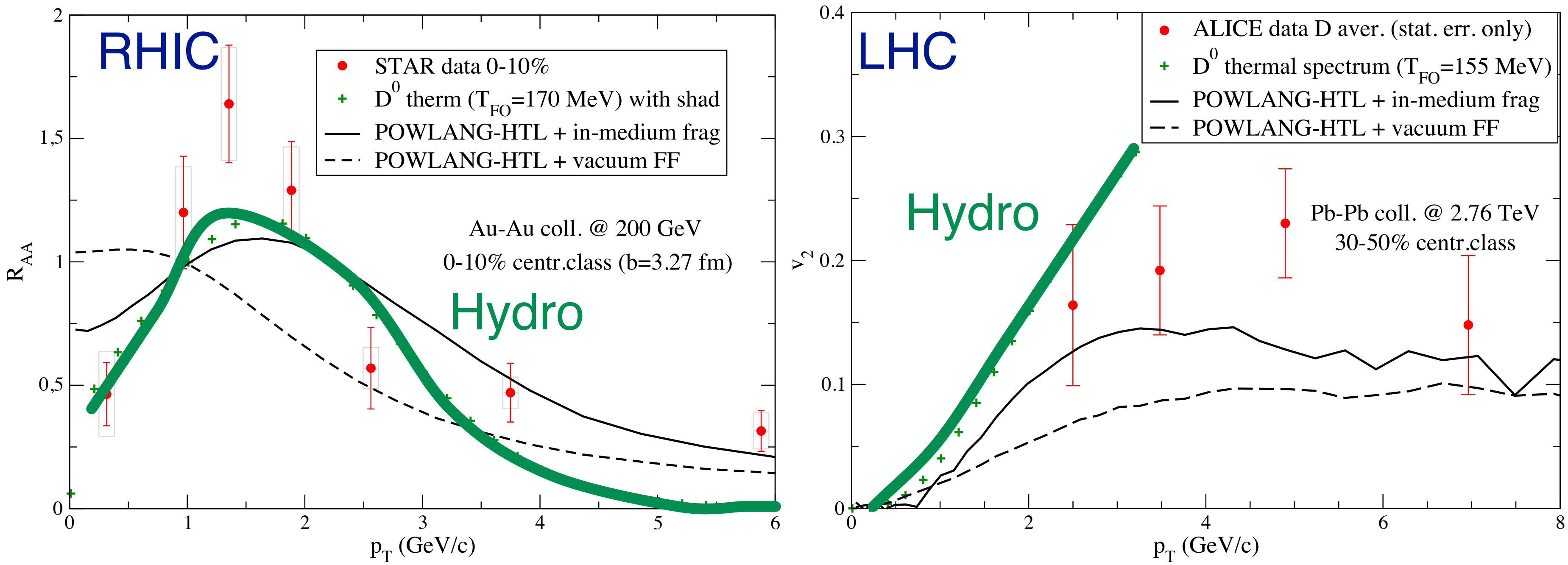
$\Longleftarrow$ error estimate from comparison of TAMU/Torino results

2. Approaching the hydrodynamic limit

3. Medium kick during hadronization process

Hees,Greco,Rapp

Discussion of low p_T results (Torino – Beraudo et al)



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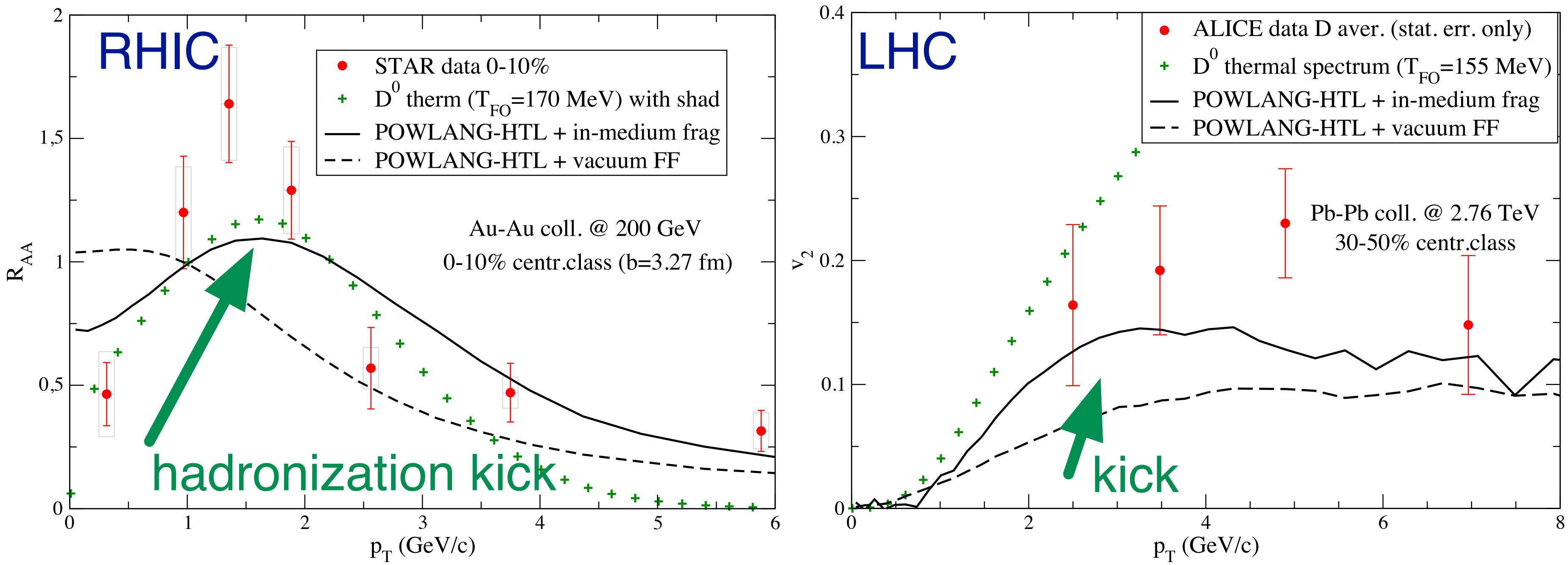

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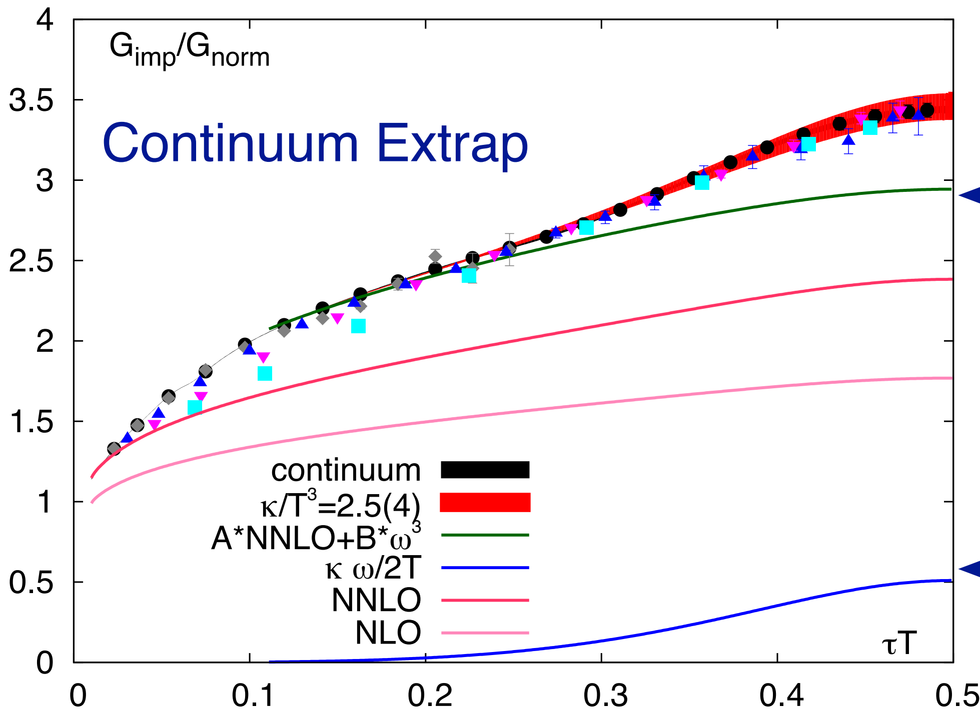
Lattice estimate of diffusion from electric field correlators:

Francis, Laine, Kaczmarek, Muller, Neuhaus, Ohno

$$\underbrace{G(\tau)}_{\text{Lattice correlator}} = \int_0^\infty \frac{d\omega}{2\pi} \underbrace{\rho_{EE}(\omega)}_{\text{our force-force correlator}} \frac{\cosh(\omega(\tau-\beta/2))}{\sinh(\omega\beta/2)}$$



Informed model for high frequency

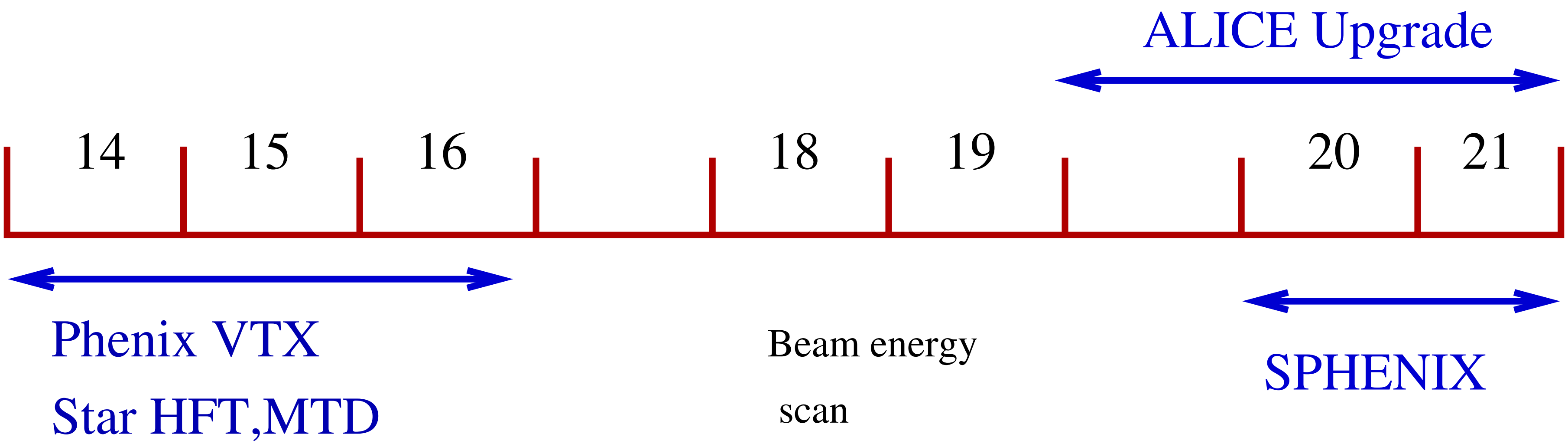
transport at low frequency

euclid time

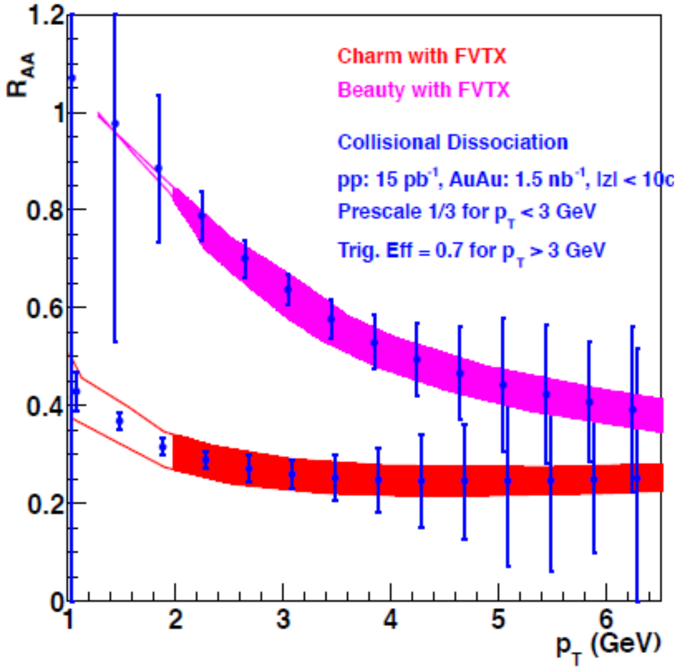
Clearly visible low frequency contribution in euclidean correlator:

$$D = \frac{2T^2}{\kappa} = (5 \pm 1)\,\frac{1}{(2\pi T)}$$

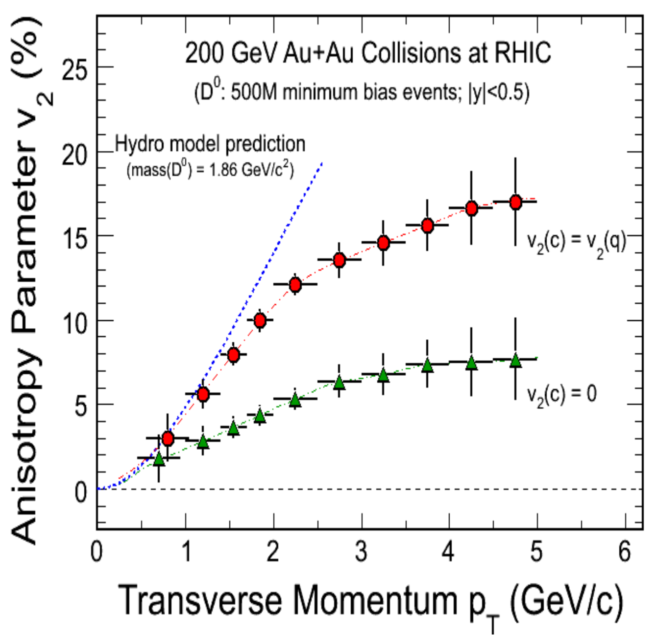
Important upcoming Heavy Flavor Measurements & Quarkonia



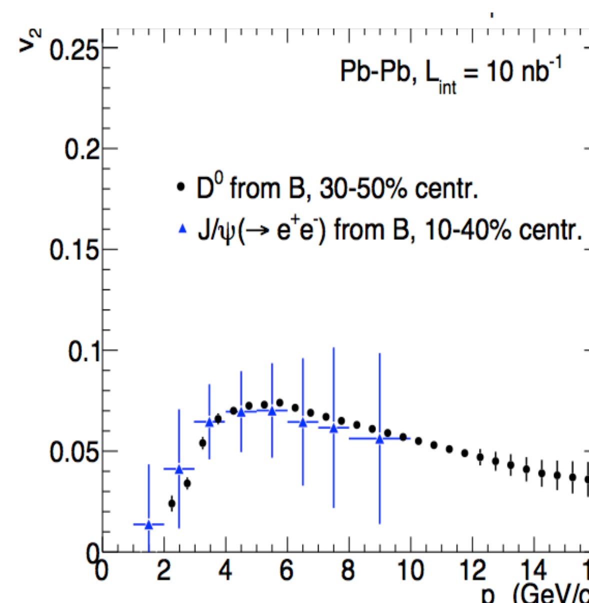
PHENIX-14 RAA



STAR-16 flow



ALICE-20 flow



Why are these upgrades are important?

- Test energy loss and the Langevin process giving confidence in theory error bar
  - System size
  - Mass dependence
- What is the charm v_2, v_3, v_4 and the light hadron v_2, v_3, v_4 vs. centrality
  - Diffusion damps the higher harmonics in a characteristic way, determining

$$D_{HQ} \qquad vs. \qquad \eta/(e+P)$$

Have complete theoretical codes predicting full phase space for these diffusion rates

Faster Quarks

Heavy quarks at higher momenta:

- Heavy flavor is a tool to test QCD energy loss models:
  1. Color charge
  2. Relative roles of collisional and radiative loss
  3. Mass dependence changes the formation time, providing a unique fingerprint of Landau-Pomeranchuk-Migdal radiative loss

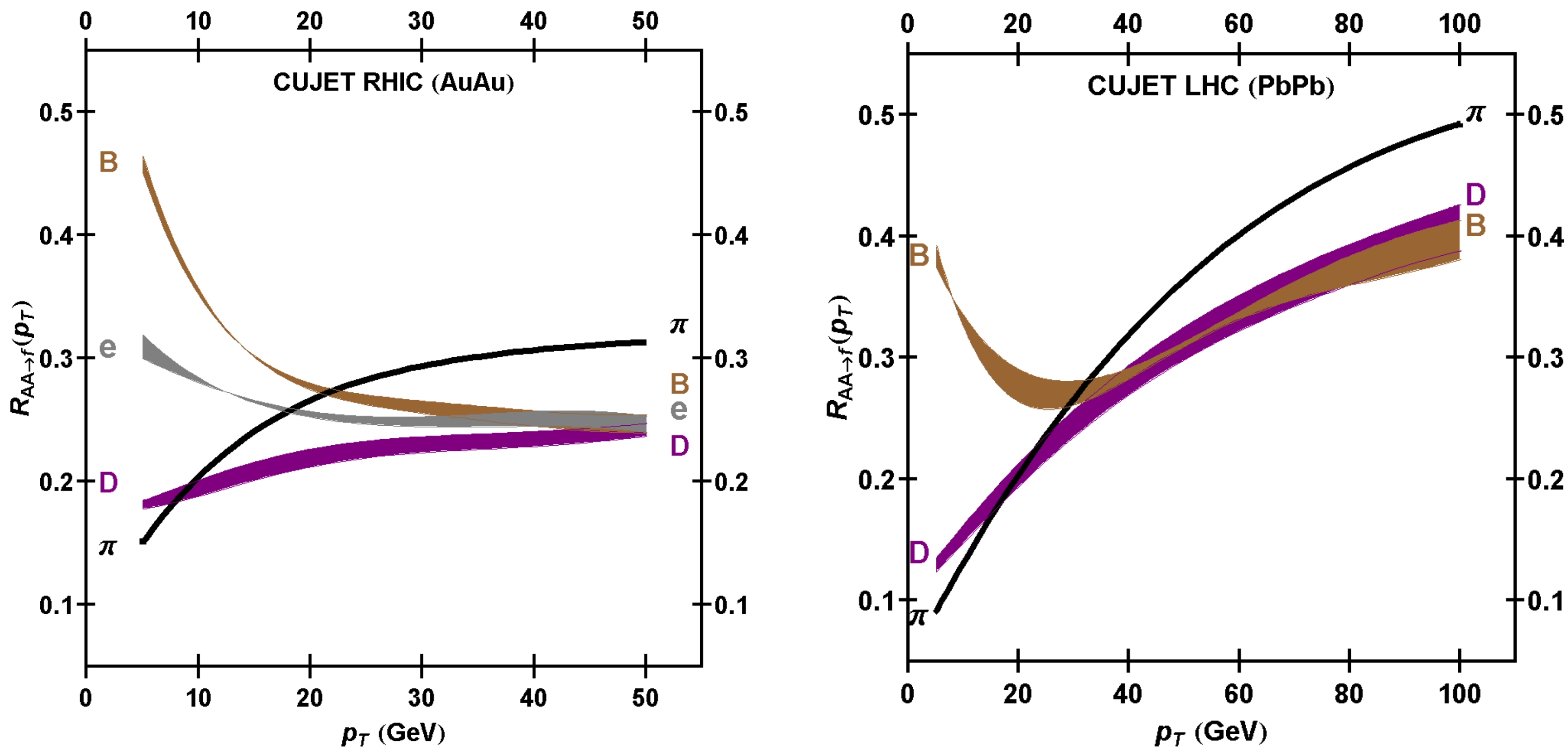
$$\tau_{\rm form} \equiv \frac{1}{\omega(1-\beta\cos\theta)}$$

- Want to measure the transition from low to high momentum correlators:

$$\underbrace{\kappa = \int dt\, \langle F(t)F(0)\rangle}_{\text{Low momentum}} \qquad vs. \qquad \underbrace{\hat{q} = \int dx^+ \, \big\langle F(x^+)F(0)\big\rangle}_{\text{High momentum}}$$

Predictions from complete energy loss computer codes (e.g. CUJET 2.0)

- Viscous hydrodynamics, estimates for running coupling, light and heavy flavors, estimates for not-exactly collinear emissions, and collisional loss.



Very rich set of model predictions for D vs. B vs π suppression, and B tagged jets versus centrality at LHC (CMS) and sPHENIX

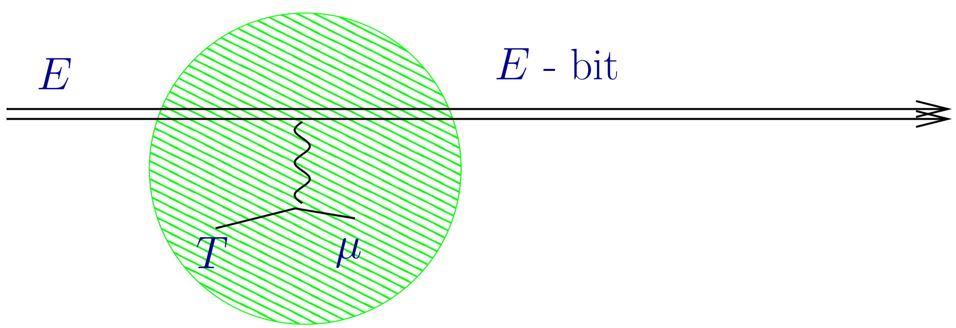
Many open issues in heavy quark energy loss:

1. The choices made for HQ energy loss in CUJET are good ones, well motivated by weakly coupled plasmas.

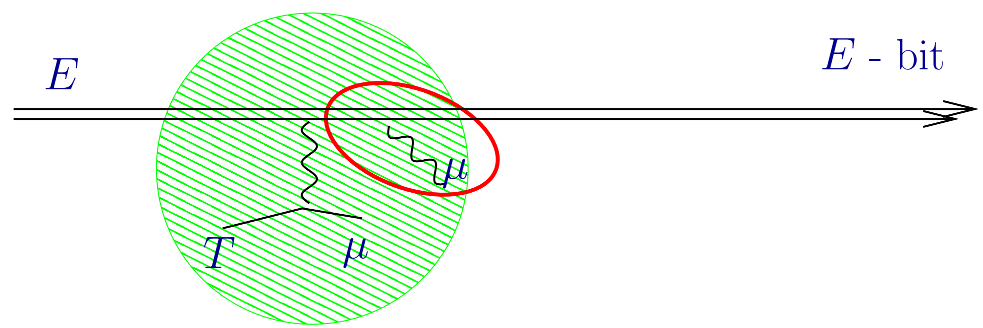
   - Extend SCET energy loss analysis to heavy quarks.

2. Want to be careful to separate medium and jet scales when combining radiative and collisional loss.

Collisional Energy Loss: $\frac{dp^{LO}_{\rm coll}}{dt}(\mu)$



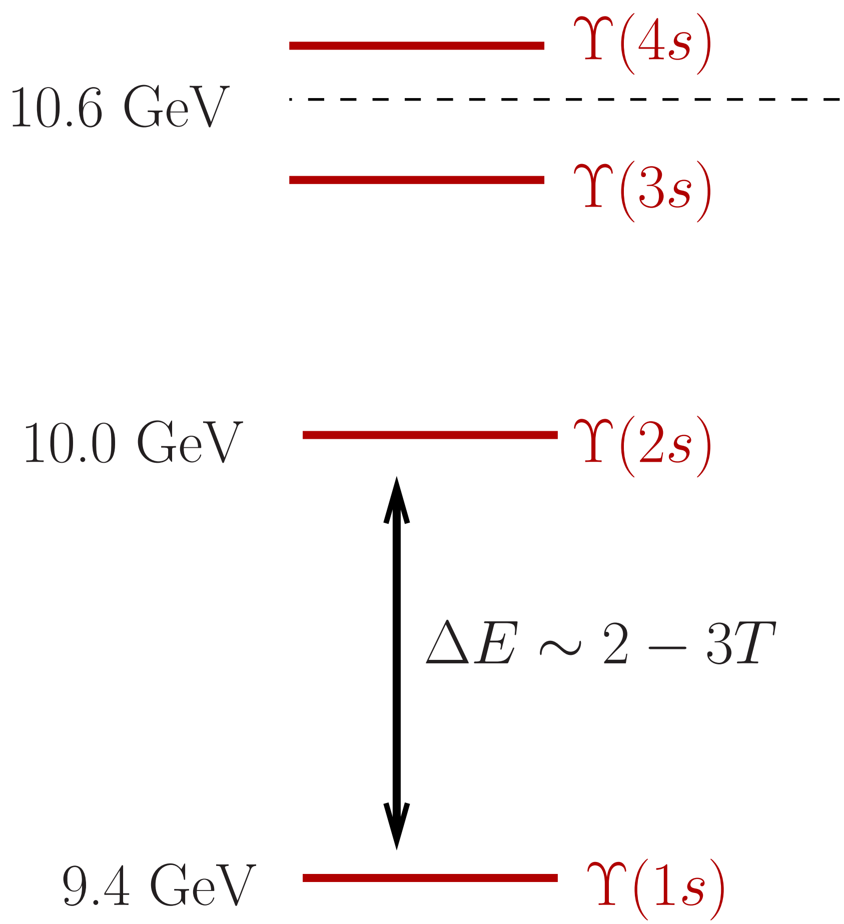
Soft Radiative Loss: $\frac{dp^{NLO}_{\rm coll}}{dt}(\mu)$



3. Want the collisional component to smoothly connect with the lattice computation of the diffusion coefficient (or not?)

Quarkonia:

Quarkonia:



- The $Q\bar{Q}$ system comes with scales:

$$M,\ Mv,\ Mv^2 \,\mathrm{etc}$$

- Medium comes with its own scales:

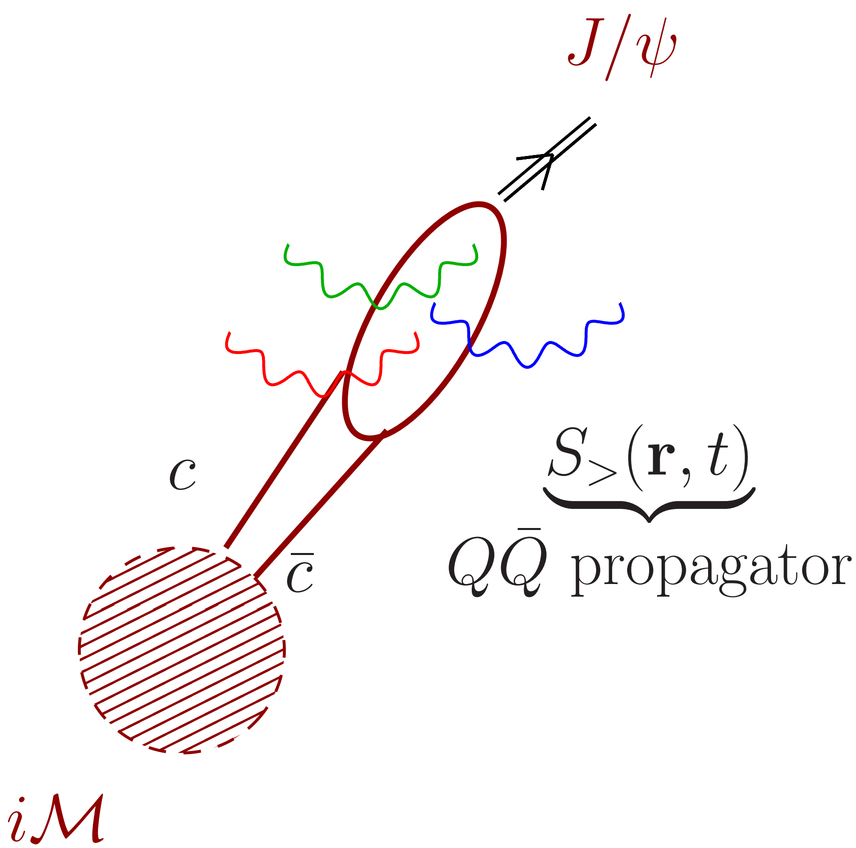
$$\sqrt{MT},\ T,\ m_D,\ \mathrm{etc}$$

Want to use the scales to probe the gauge field dynamics near T_c. A useful diagonistic

$$\underbrace{T \gtrsim Mv^2}_{J/\psi} \qquad vs. \qquad \underbrace{T \lesssim Mv^2}_{\Upsilon}$$

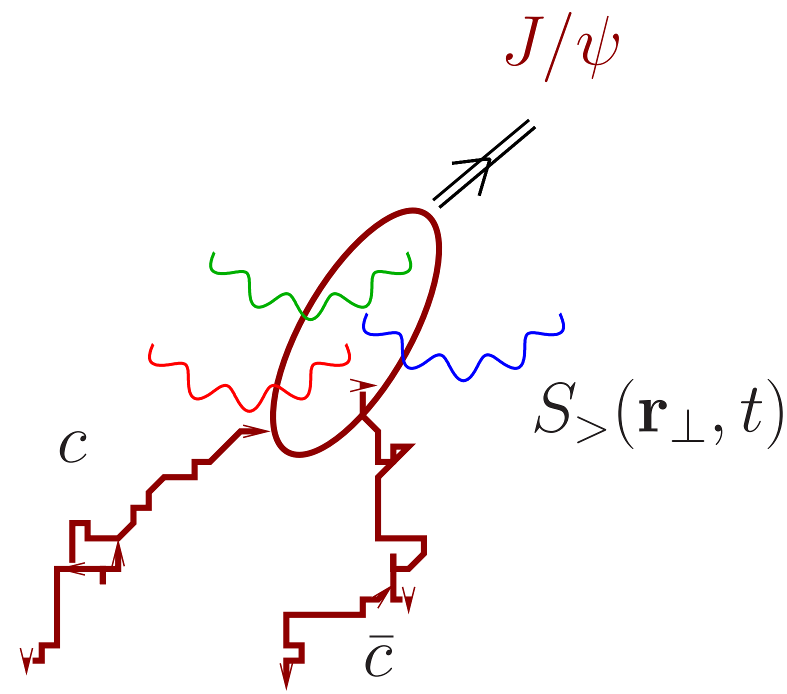
Direct production vs. Regeneration:

Direct production:



1. A correction in central LHC
2. Dominant at RHIC

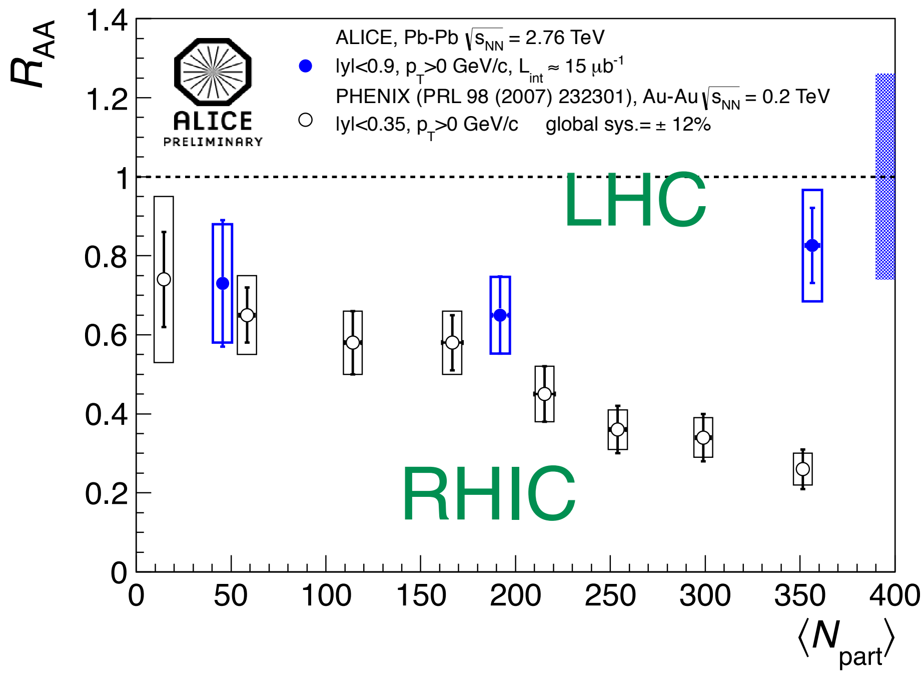
Regeneration:

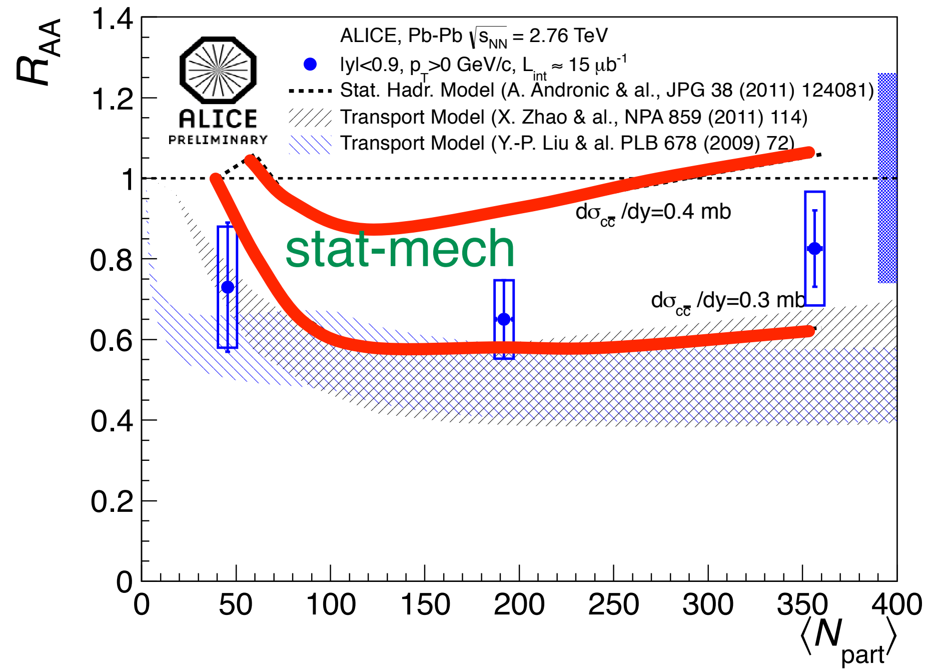


1. Dominant at LHC
2. A correction at RHIC

An important limit – thermal charm:

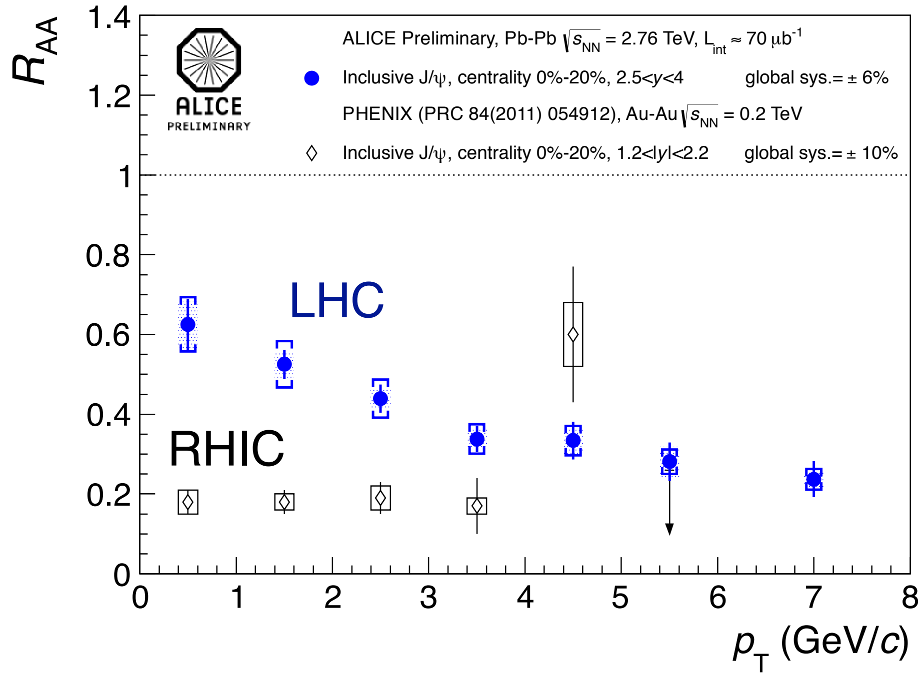
1. Assume charm is thermalized and abundant (LHC).
2. Then, independent of details of J/ψ medium interactions, find the statistical mechanical result:





- The total cross section (ALICE upgrade) is an input to the stat-mech prediction
- Charm spectra are not completely thermalized (Langevin)

Experimental evidence for decreasing regeneration at high p_T



1. Transport and potential models have basic scales correct: (Zhao; Young et al.)

    - binding energy, number of pairs, c-quark phase space dist, etc

Transport - potential models reproduce the p_T dependence of the suppression

Can we do better?

Recent theoretical progress in quarkonia:

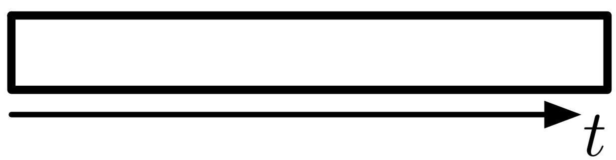
- Formulate a complex potential propagation of quarkonia. (Laine, Romatschke, et al)

$$i\partial_t S_>(\mathbf{r},t) = \left(-\frac{\nabla^2}{M_Q} + V_s(\mathbf{r})\right) S_>(\mathbf{r},t)$$

  where the singlet potential arises from a Wilson loop:

wilson loop

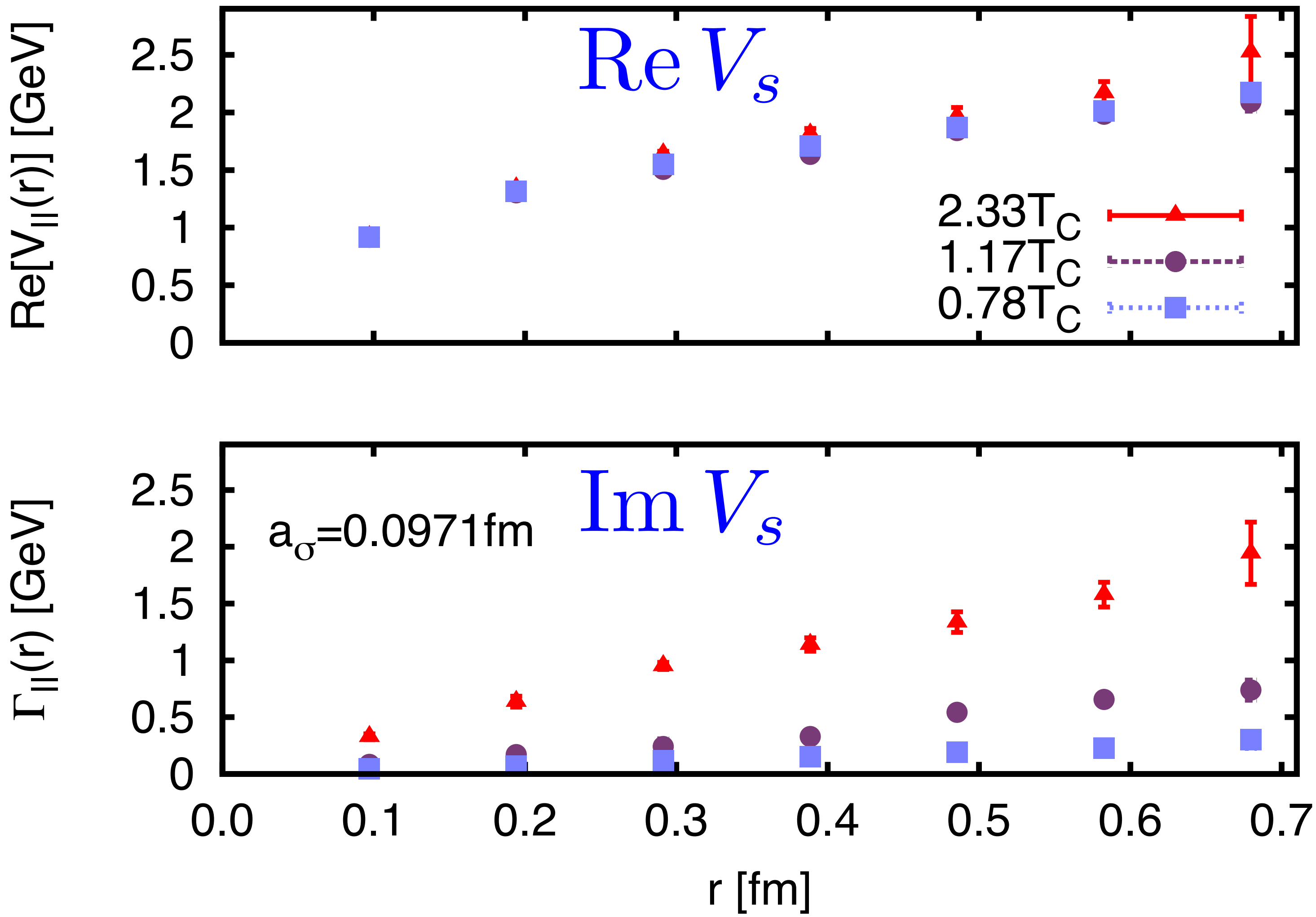
$W(\mathbf{r},t) =$



$= \exp(-i\int^t V(\mathbf{r}))$

- These results can be rederived using an EFT – thermal pNRQCD. (Ghiglieri, et al)
  - The imaginary part arises from from medium induced singlet-octet transitions.
- Calculate a Euclidean version of the $W(\mathbf{r},\tau)$ on the lattice (Rothkopf, Hatsuda, Sasaki)
  - Adopt a MEM strategy to extract a $V(\mathbf{r})$ from Euclidean points (Burnier, Rothkopf)

First lattice results for potential vs temperature: (Rothkopf, Hatsuda, Sasaki)



This work needs to inform the phenomenology of Υ "suppression" at the LHC (currently CMS) and at a future sPHENIX

Points to the address in the long range plan:

1. Unique physics of heavy quarks and quarkonia in media.
   (a) Extracting diffusion rates and corroborating strongly coupled picture
   (b) An invaluable test of radiative loss and the transition to strong coupling
   (c) A sensitive probe of multiple scales in plasma.
2. Current and future measurements.
3. The relative roles of RHIC and the LHC.
   (a) We used the comparison between RHIC and LHC to reach all conclusions
   (b) Want to systematically change the system size . . . flow in pA?
   (c) A comparison of RHIC and LHC can indicate changes in transport rates