Quark Matter 2011
Annecy, France, May 23, 2011

Quark Recombination and Heavy Quark Diffusion

Rainer Fries

Texas A&M University & RIKEN BNL

with Min He and Ralf Rapp

Overview

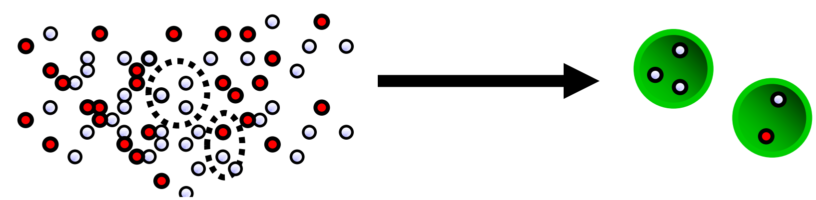
- The case for a microscopic hadronization model
- Instantaneous and resonance recombination
- Recombination in equilibrium
- Heavy quarks in a strongly interacting medium: resonance scattering and resonance recombination
- Summary

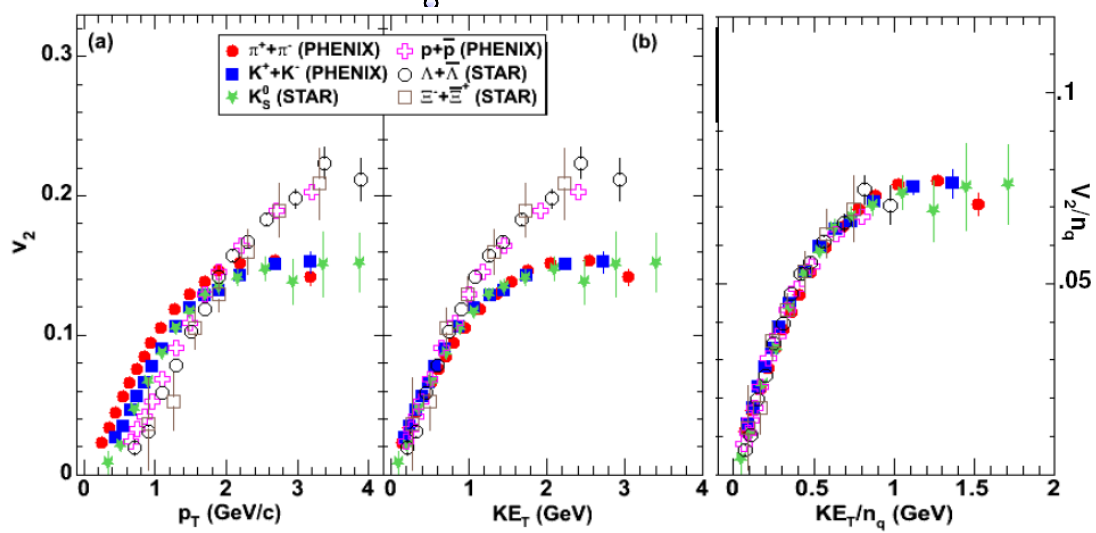
[He, RJF & Rapp, PRC 82, 034907 (2010)]
[He, RJF & Rapp, to appear (2011)]
[He. RJF & Rapp, arxiv:1103.6279]

Recombination: A Microscopic Hadronization Model

Hadronization

- Bulk QGP: equation of state in hydrodynamics
  - Local equilibrium assumption, no microscopic information.
- At high-P_T: in-vacuum fragmentation for single partons.
  - Based on QCD factorization, little microscopic information.
- Recombination of quarks: a simple *microscopic* hadronization model.
  - Useful for partons in a medium.
- Experimental evidence:
  - Large baryon R_{AA} at intermediate P_T.
  - Large baryon/meson ratios
  - Elliptic flow scaling in KE_T and quark number n_q.

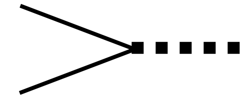




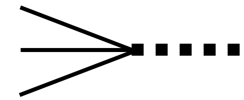
Resonance Recombination

- Early recombination models:

$$N_M = \int \frac{d^3P}{(2\pi)^3} \langle M;P|\rho|M;P\rangle$$

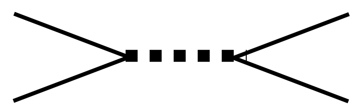


  - Instantaneous projection of states
  - $2 \to 1$ & $3 \to 1$ processes: no energy conservation



- Resonance recombination:
  - Mesons appear as resonances of quark-antiquark scattering
  - Described by Boltzmann equation, start with ensemble of quarks/antiquarks

$$\frac{\partial}{\partial t} f_M(t,\vec{p}) = -\frac{\Gamma}{\gamma_p} f_M(t,\vec{p}) + g(\vec{p})$$



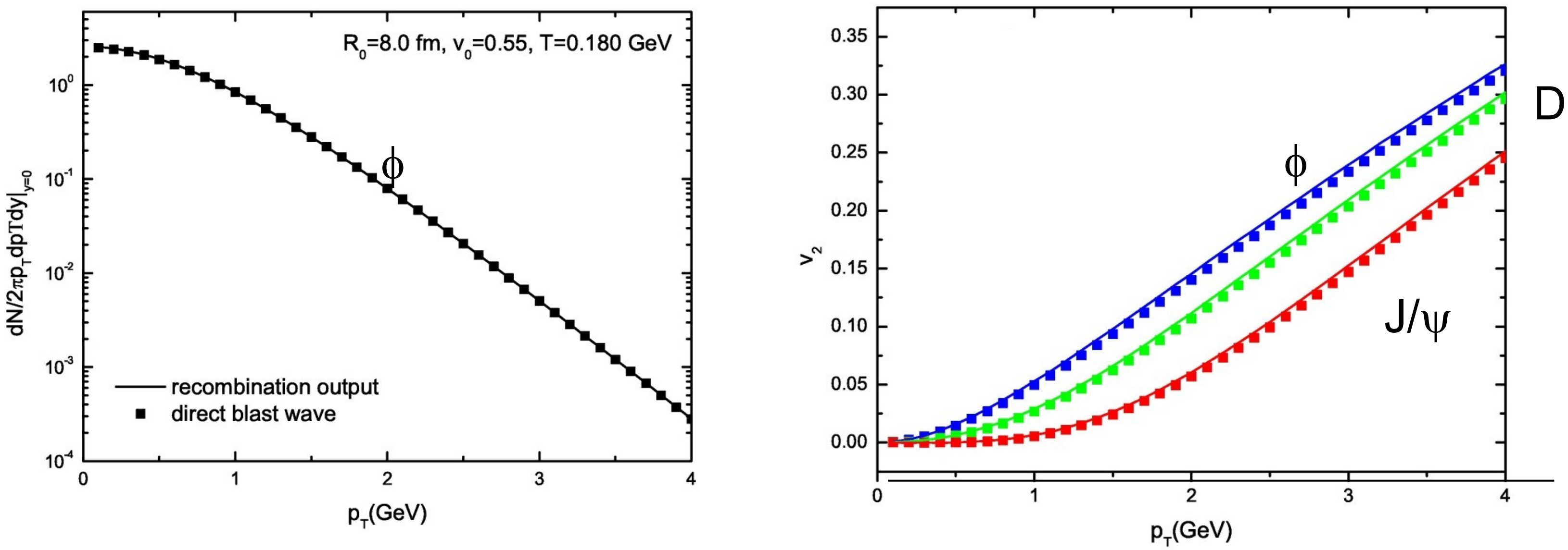
[Ravagli & Rapp PLB 655 (2007)]
[Ravagli, van Hees & Rapp, PRC 79 (2009)]

  - Breit-Wigner resonance cross sections: $\sigma(s) = C_M \frac{4\pi}{k^2} \frac{(\Gamma m)^2}{(s-m^2)^2 + (\Gamma m)^2}$
  - Long-time limit: $E\frac{dN_M}{d^3P} = \frac{E\gamma}{8(2\pi)^3\Gamma} \int \frac{d^3x d^3p_{rel}}{(2\pi)^3} f_a(x,p_1) f_a(x,p_2) \sigma(s) v_{rel}(P,p_{rel})$
  - Conserves energy and momentum, should be able to attain equilibrium.
  - Compatible with the picture of a strongly interacting medium.

Resonance Recombination in Equilibrium

RRM in Equilibrium

- Energy conservation + detailed balance + equilibrated quark input → equilibrated hadrons!
- Numerical tests: compare blast wave hadrons at T_c-ε to hadrons coalesced from quarks of the same blast wave at T_c+ε:

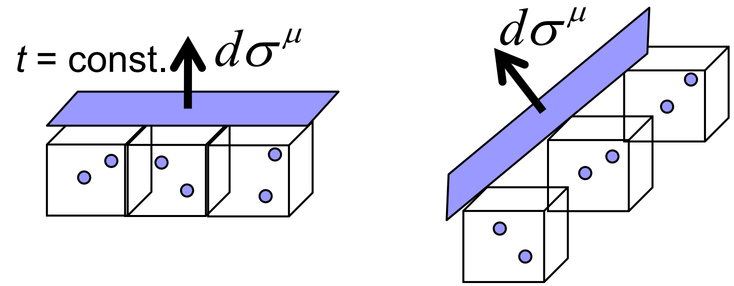


- Excellent agreement of spectra and v_2.
- Here: hadronization hypersurface at const. time

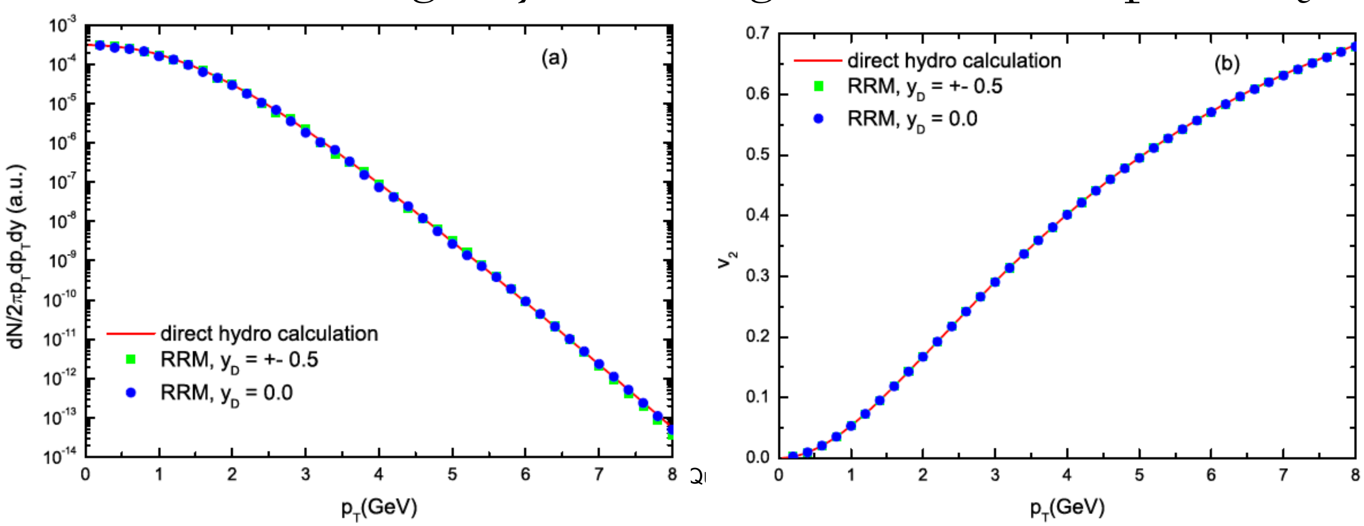
[He, RJF & Rapp, PRC 82 (2010)]

Equilibrium: Arbitrary Hypersurface

- Realistic hadronization hypersurface Σ:
  - Extract equal-time quark phase space distributions f_q along Σ from hydro or kinetic model.
  - Apply RRM locally (cell-by-cell) → meson phase space distr. f_M along Σ.
  - Compute meson current across Σ a la Cooper-Frye: $$\frac{dN}{p_T dp_T d\phi dy} = \int_\Sigma \frac{p_\mu d\sigma^\mu(\tau,x,y)}{(2\pi)^3} f_M(\tau,x,y;\mathbf{p})$$



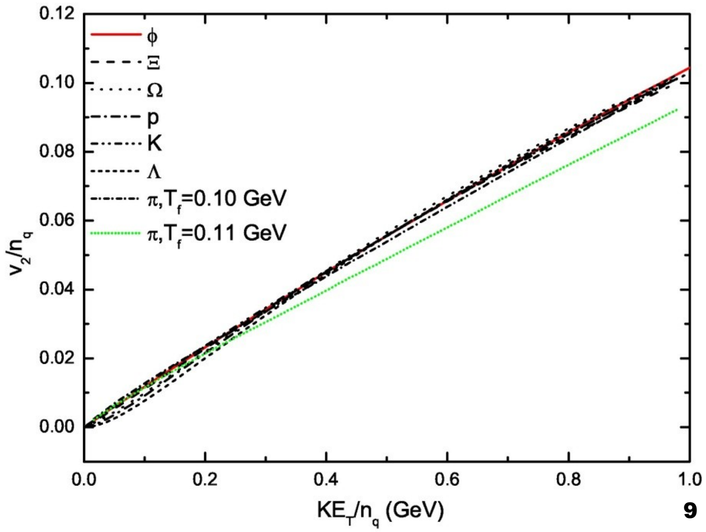
- Result for charm-light system using AZHYDRO output at T_c:



[He, RJF & Rapp, to appear (2011)]

Lessons from RRM in Equilibrium

- Resonance recombination is compatible with equilibration and hydro.
  - Will work with any hydrodynamic flow field and hadronization hypersurface.
  - Important consistency check.
  - Can extract quark spectra at T_c from spectra of hadrons freezing out just below T_c (multi-strange hadrons).
- Microscopic information lost in kinetic equilibrium: how can we understand simultaneous KE_T- and n_q-scaling at low P_T?
  - Not a manifestation of recombination (at low P_T!)
  - Approximate KE_T-scaling provided by hydrodynamic flow.
  - Further improved by sequential freeze-out from heavier to lighter hadrons.
  - Additional n_q-scaling accidental?



Application of Recombination in the Kinetic Regime: Heavy Quarks

Setup of the HQ Formalism

- Our goal: a formalism for consistent description of heavy quarks in a strongly interacting medium via resonance interactions.

- Three important ingredients:
  - Langevin simulation of heavy quarks/mesons with realistic non-perturbative transport coefficients; model approach to equilibrium
  - Relativistic Hydrodynamic background for the medium.
  - Resonance recombination appropriate for the medium, consistently augmented by fragmentation.

[See also: Moore and Teaney, van Hees and Rapp, …]

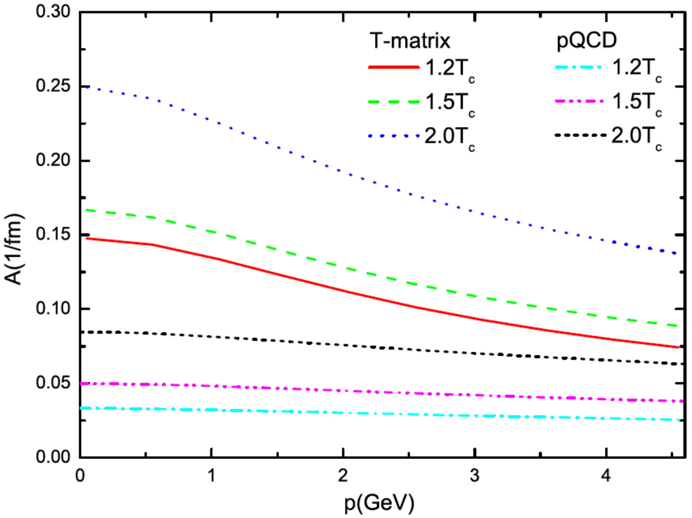
Langevin Dynamics

- Langevin Equations

$$dx = \frac{\mathbf{p}}{E}dt,$$

$$d\mathbf{p} = -\Gamma(p)\mathbf{p}dt + \sqrt{2D(\mathbf{p}+d\mathbf{p})\,dt}\rho$$

- Transport coefficients:
  - HQ relaxation rates in QGP: (T-matrix approach: resonant correlations around T_c.
    [Riek and Rapp, Phys. Rev. C 82, 035201 (2010)]
  - Hadronic phase: coming soon.



$$\Gamma(p) = A(p) + \mathcal{O}(T/m_Q)$$

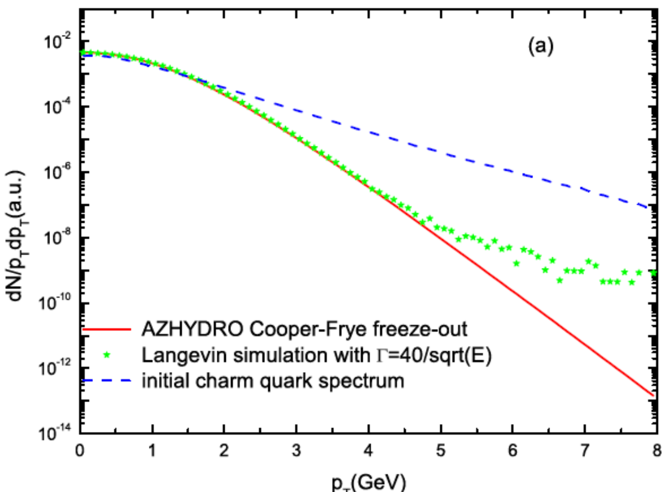
$$D(p) = \Gamma(p)E(p)T$$

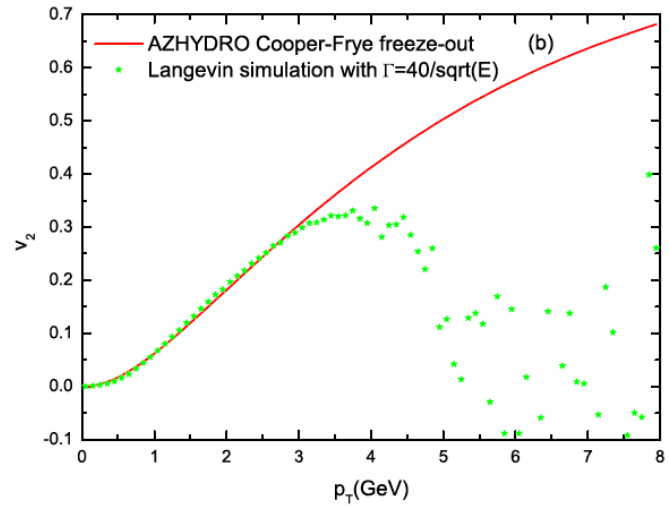
- Initial distribution: binary collision density ⊗ pQCD spectrum.

- Running Langevin in AZHYDRO background.
  - Test particles in lab frame → boost to fluid rest frame for Langevin step.
  - Stop at hydro hadronization hypersurface, extract phase space distributions.

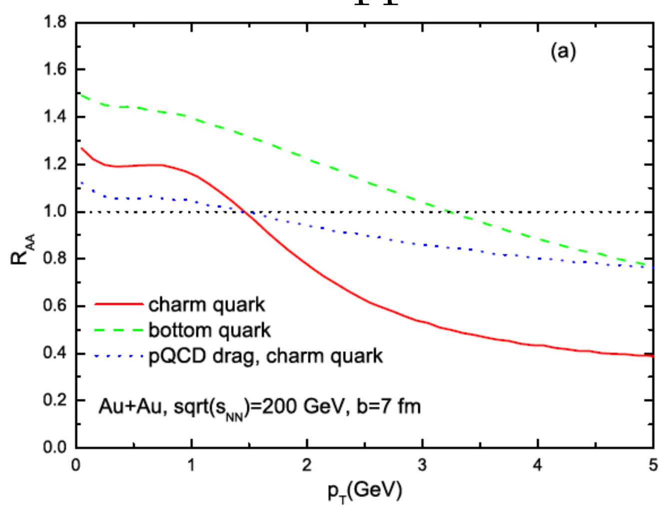
Heavy Quarks: Results

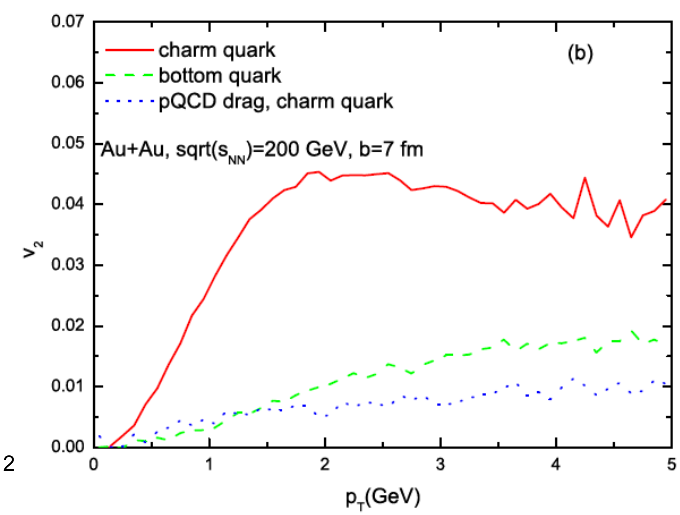
- Equilibrium check (artificially large relaxation rates)





- Realistic Riek-Rapp coefficients



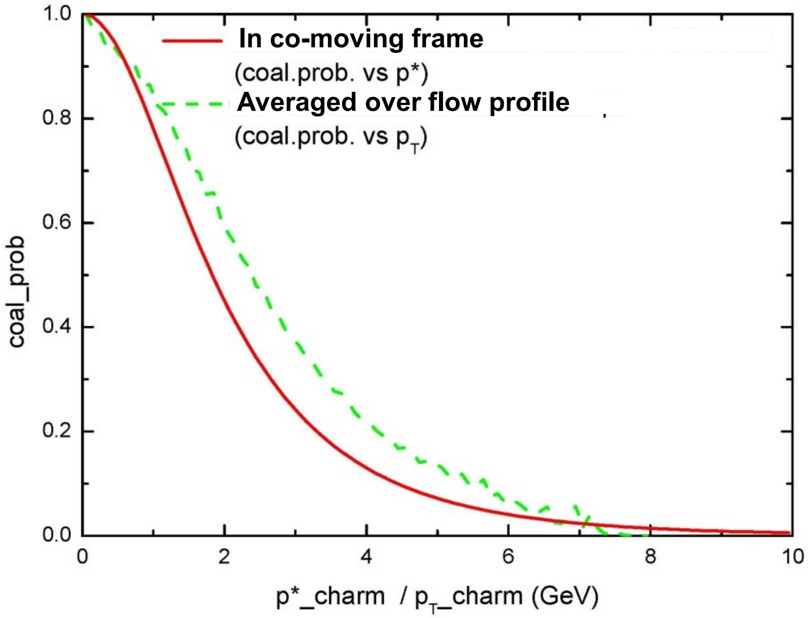


Hadronization of Heavy Quarks

- Calculate recombination probability $P_{coal}(p)$ of heavy quarks for given heavy quark momentum using RRM in local fluid rest frame.
  - Assume RRM probability $\rightarrow$ 1 for perfectly co-moving partners.

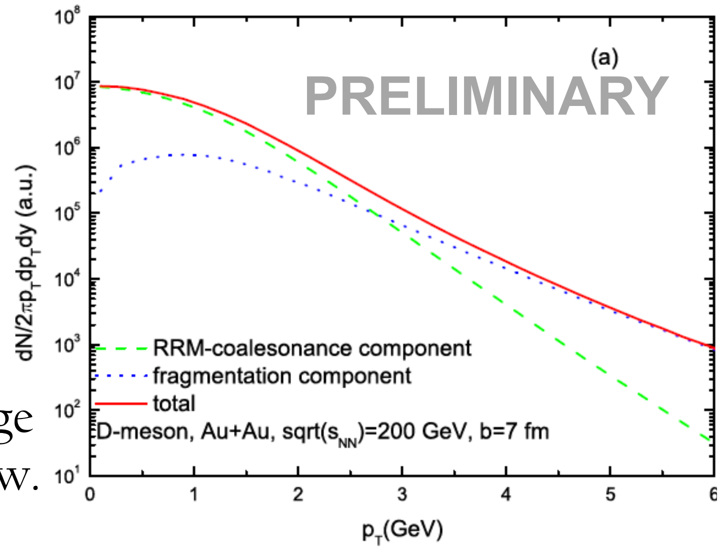
- We see a consistent picture:
  - Low/thermal HQ momenta (in co-moving frame) = RRM dominated.
  - High momenta (not co-moving) = fragmentation dominated.

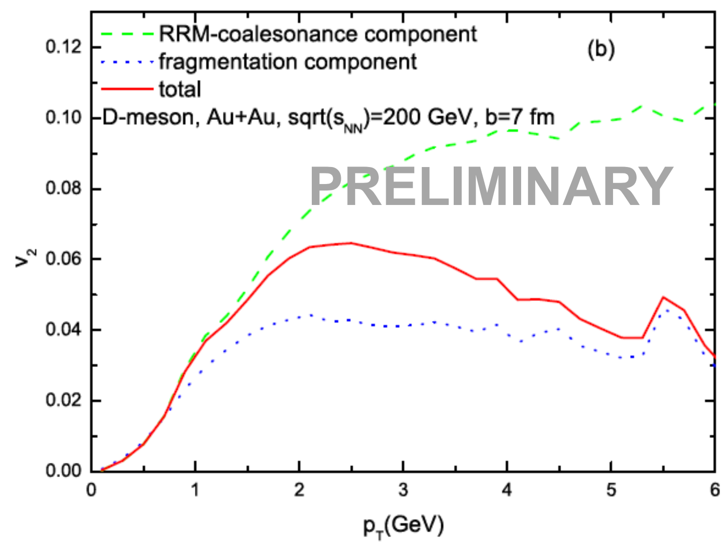
- $P(p)$ decides whether to recombine or fragment a given heavy quark.
  - Apply fragmentation with probability $1-P(p)$.



Heavy Mesons: Preliminary Results

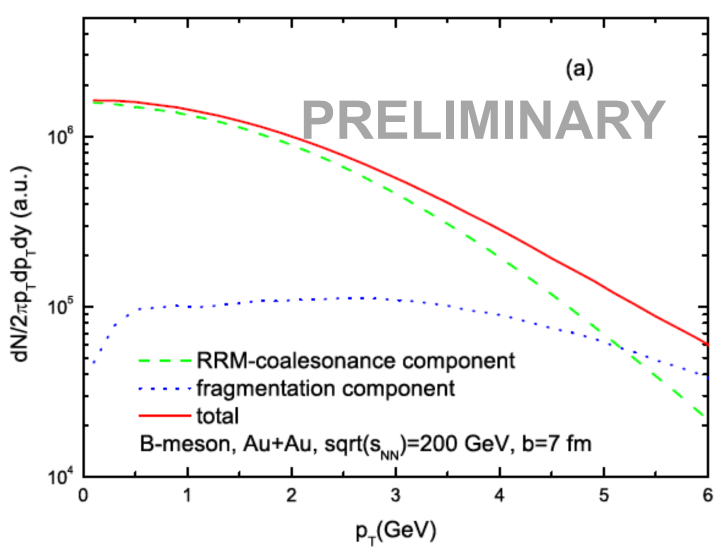
- Charm (D)

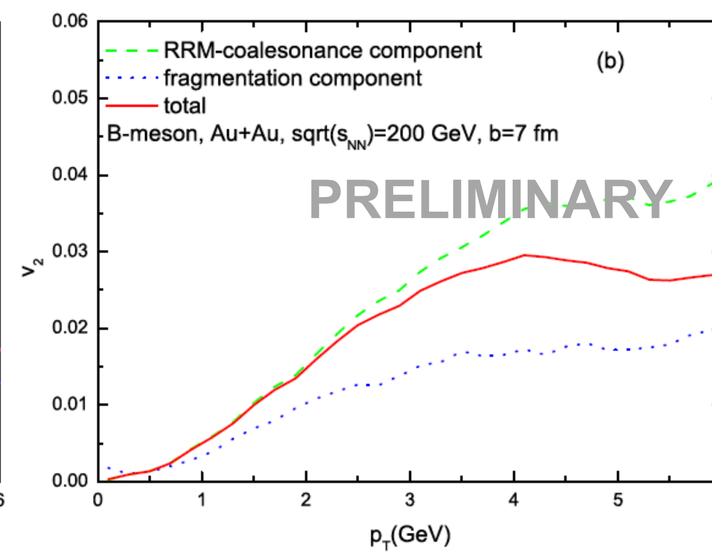




Recombination: large effect on elliptic flow.

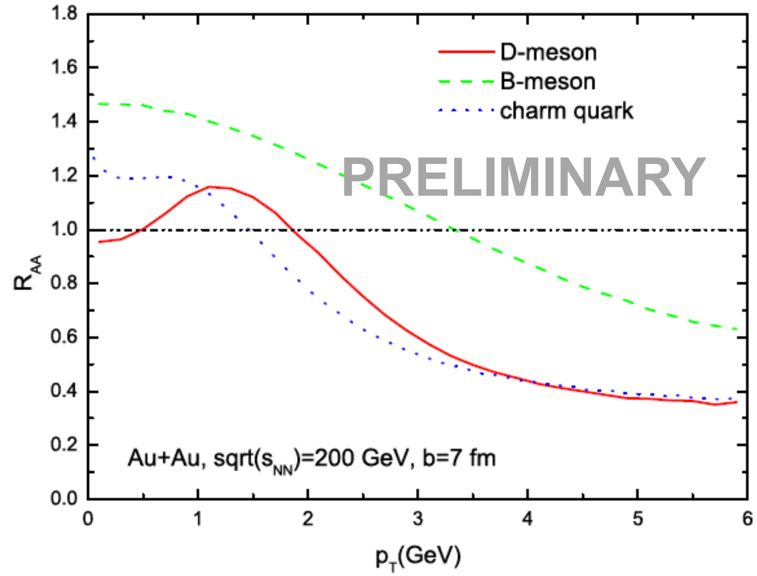
- Bottom (B)





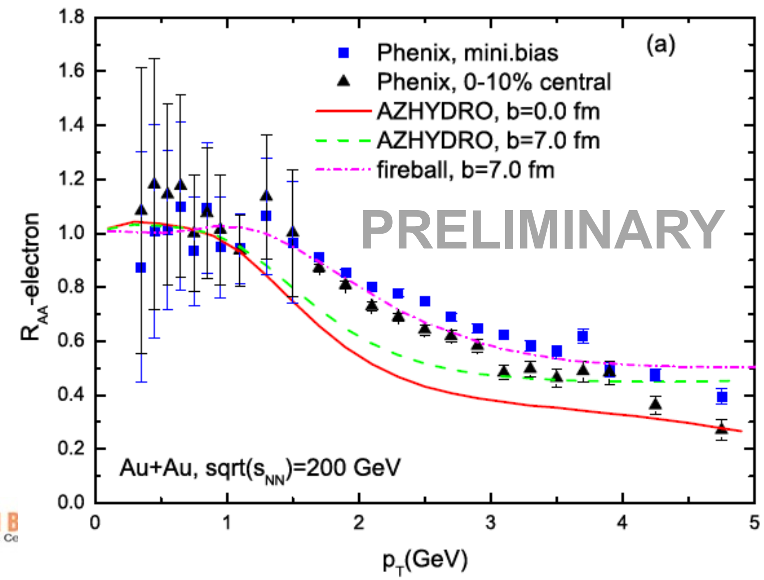
Semi-Leptonic Decays and Data

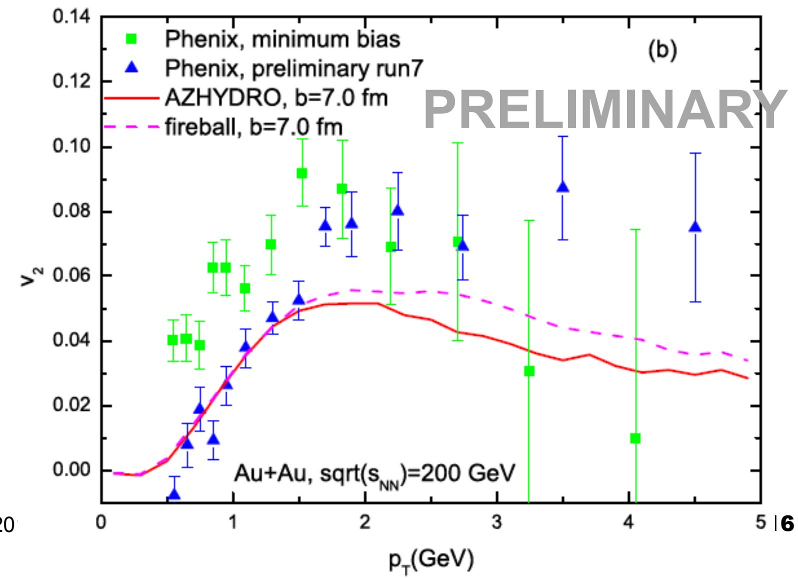
- R_{AA}



[He, RJF & Rapp, to appear (2011)]

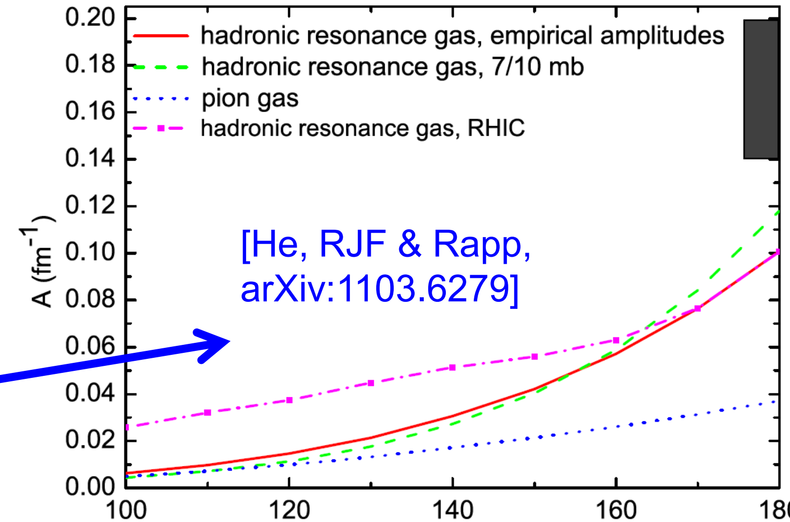
- Electrons





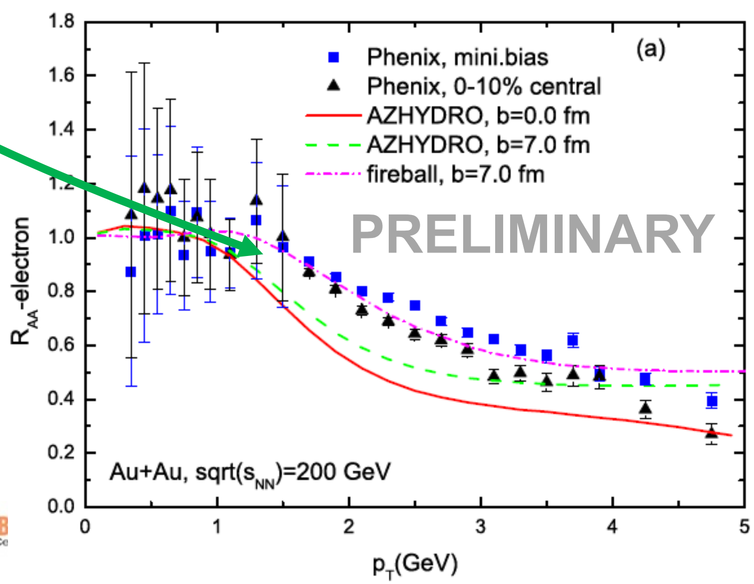
Semi-Leptonic Decays and Data

- What's missing?
- RRM not yet completely implemented.
- Flow!
  - Have to tune hydro; currently gravely underestimate flow at T_c.
- Diffusion in the hadronic phase.
  - Just published transport coefficient for hadronic charm.



[He, RJF & Rapp, arXiv:1103.6279]

[See also:
Laine (2011),
Ghosh et al. (2011),
Abreu et al. (2011)]



Summary

- Resonance Recombination is a microscopic hadronization model compatible with kinetic equilibrium.

- KE_T and quark number scaling compatible with recombination in the equilibrium regime (but not a consequence of it).

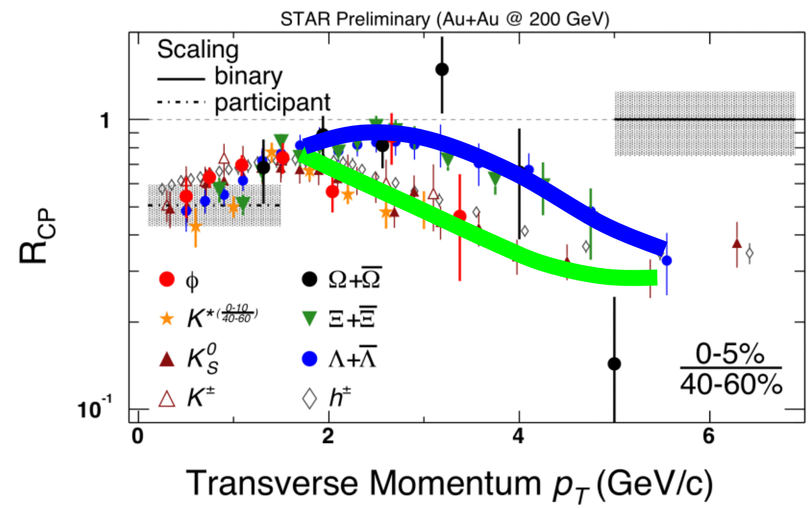
- Formalism for heavy quarks in strongly interacting medium based on resonance interactions:
  - Setup complete with Langevin dynamics, hydro background.
  - Consistent blend of recombination and fragmentation.
  - Preliminary results available
  - To do: tuning of (equilibrium) flow, hadronic diffusion.

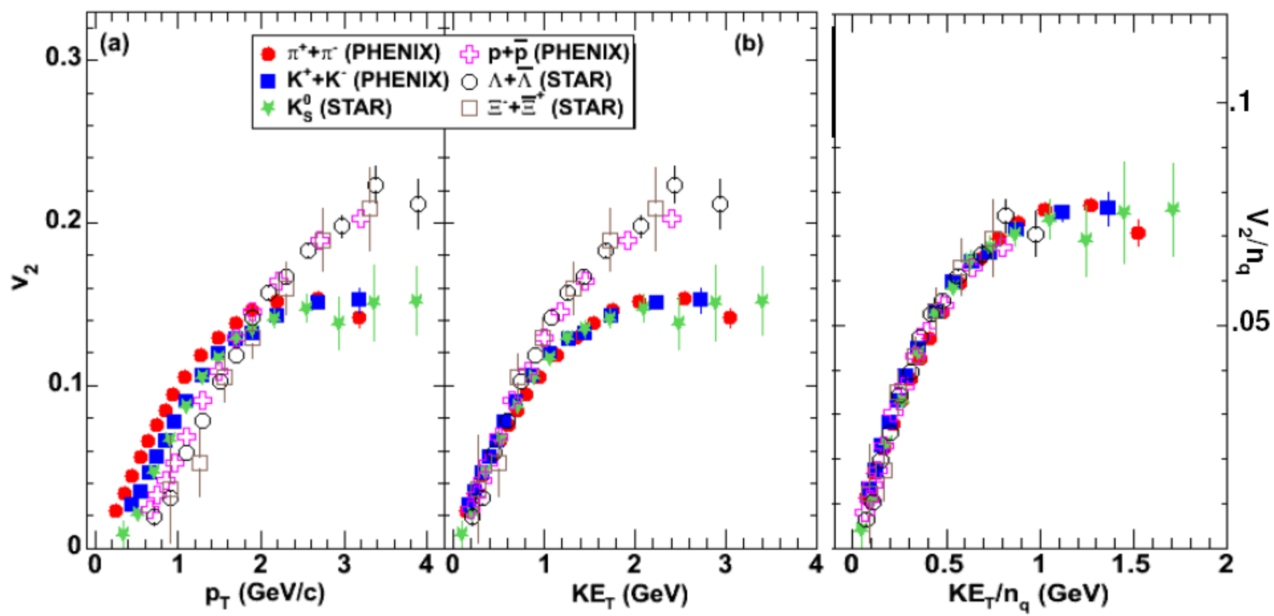
- To do: resonance recombination for baryons: check n_q scaling at intermediate P_T.

Backup Slides

Exp. Evidence and Challenges

- Leading Particle Effect (forward rapidities
  - Charm quark recombination with beam remnants.
- Large baryon/meson ratios and large baryo R_{AA}, R_{CP} at intermediate P_T.
  - Failure of “hydro+jet” models.
- Elliptic flow scaling in KE_T and quark number n_q.
  - Signs of quark recombination?



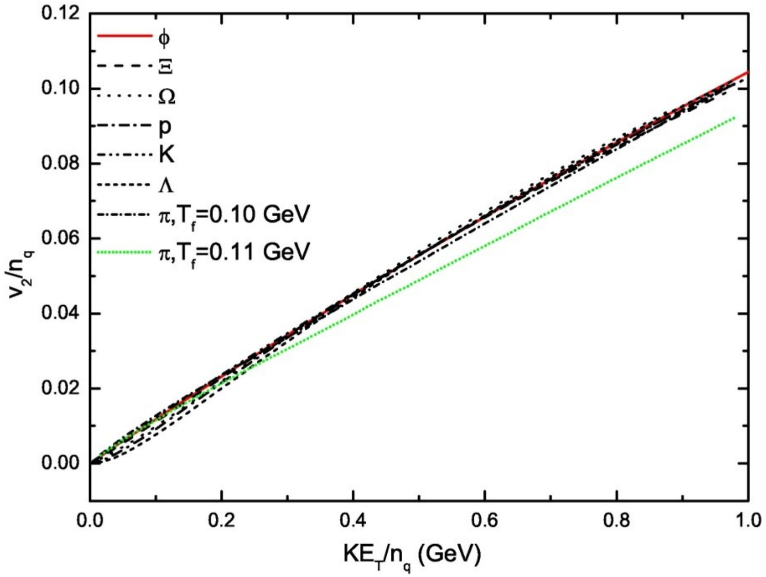


KE_T-Scaling (Low P_T)

- Blastwave + two-stage freeze-out works within exp. uncertainties.
  - Group I: multi-strange particles freeze-out at T_c.
  - Group II: all others including pions freeze-out at ~ 110 MeV.
  - Can extract quark distributions at T_c from data on multi-strange hadrons.

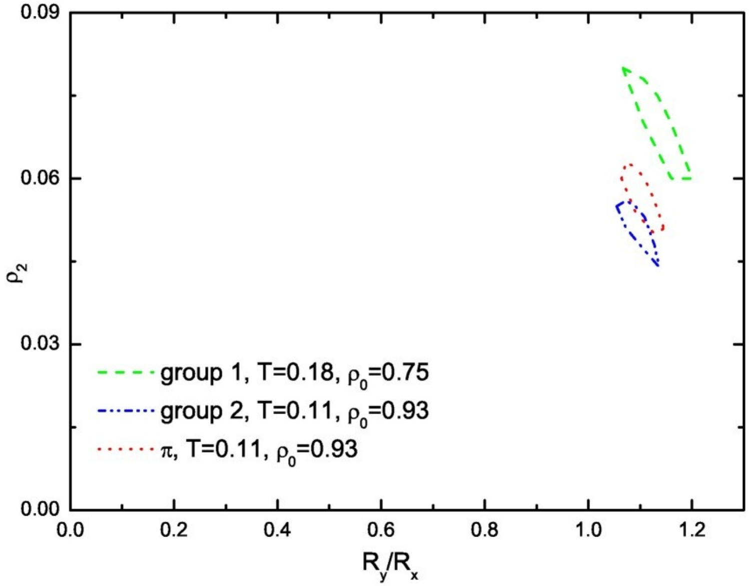
- $v_2(KE_T)$ tends to be straight line for the parameters at RHIC → additional quark number scaling becomes trivial.

- Expectations:
  - KE_T scaling fairly robust (at low P_T!)
  - KE_T+n_q scaling maybe accidental



KE_T-Scaling (Low P_T)

- Easy to find reasonable parameters in the Retiere and Lisa blast wave to achieve KE_T- and n_q-scaling within 10% accuracy.
- Contours in space of flow asymmetry and fireball eccentricity.
- Pions prefer slightly lower freeze-out temperatures but are compatible with group II within the 10% accuracy (not changed by resonance decays!).
- This behavior should qualitatively also hold for a full hydro simulation.



[He, Fries & Rapp, PRC (2010)]

Hadronic Diffusion

- Charm relaxation in hadronic medium.
- Use parameterization of existing D+h amplitudes from the literature.
- h = π, K, ρ, η, ω, N, Δ
- Lots of channels, partial waves missing: lower bound!
- Relaxation rates at T_c comparable to non-perturbative QGP estimates.
- Minimum of Ds at T_c?

[He, RJF & Rapp, arXiv:1103.6279]