Quark Recombination and Heavy Quarks

Rainer Fries

Texas A&M University & RIKEN BNL

6th Workshop on High-P_T Physics at LHC

Utrecht NL, April 6, 2011

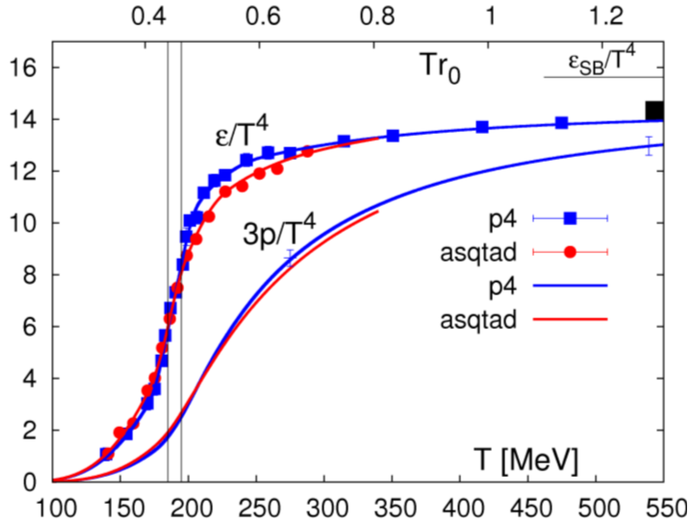
Overview

- The Case for a Microscopic Hadronization Model
- Instantaneous and Resonance Recombination
- Recombination and Hydro
  [with Min He and Ralf Rapp]
- Recombination in the Kinetic Regime: Heavy Quarks
  [with Min He and Ralf Rapp]
- Summary

The Case For a Microscopic Hadronization Model

How Does QGP Hadronize?

- Bulk description via hydrodynamics:
  - local equilibrium assumption + equation of state
  - No microscopic information on the underlying process

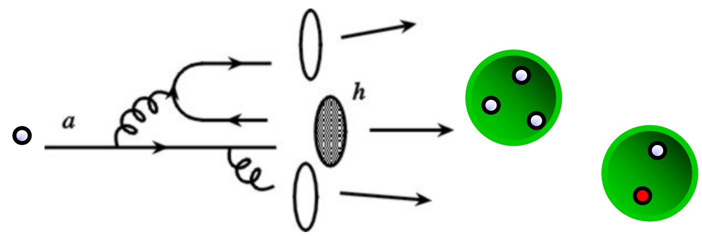


- Can we construct quark recombination models that preserve local equilibrium?
  - "Traditional" recombination models fail
  - Equilibrium → extra features like quark number scaling should not be visible!

How Does QGP Hadronize?

- Fragmentation at high-P_T: vacuum process for single partons

$$D_{u\to h} \sim \langle 0 | \bar{u} | h \rangle \gamma^{+} \langle h | u | 0 \rangle \qquad \sigma_h = \sum_a \sigma_a \otimes D_{a\to h}$$

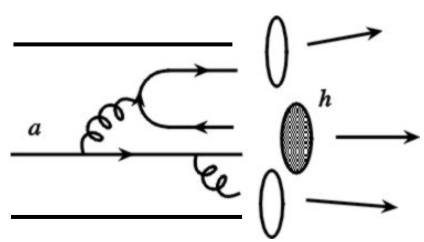


  - True for asymptotically large P_T.

[Collins and Soper, NPB 194 (1982)]

  - D can be approximated by gluon shower + parton-hadron duality
- QCD factorization: applicable to partons emerging directly from hard processes:
  - Need hard scale Q to suppress multi-parton processes by $1/Q^n$.
  - Questionable for partons travelling through an extended medium.

$$\frac{1}{Q^n}$$

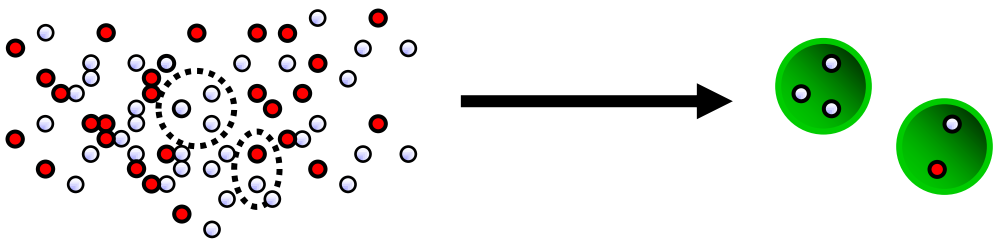


How Does QGP Hadronize?

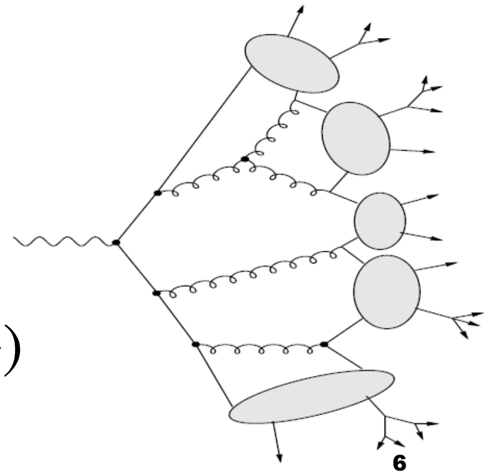
- Recombination/coalescence of quarks: a simple microscopic hadronization model.
  - Coalescence of valence quarks into mesons and baryons

$$q\bar{q} \rightarrow M \qquad\qquad qqq \rightarrow B$$

  - Quarks are dressed (constituent quarks), gluons have been split into quark-antiquark pairs.
- Developed as the "dense" limit of hadronization, as opposed to single parton fragmentation: phase space filled with partons at a critical density



- Not unlike cluster hadronization models (e.g. HERWIG)



Experiment: Leading Particle Effect

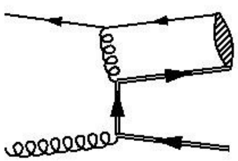
- Recombination at very forward rapidity
  - No hard scale
  - Recombine beam remanants/spectators.

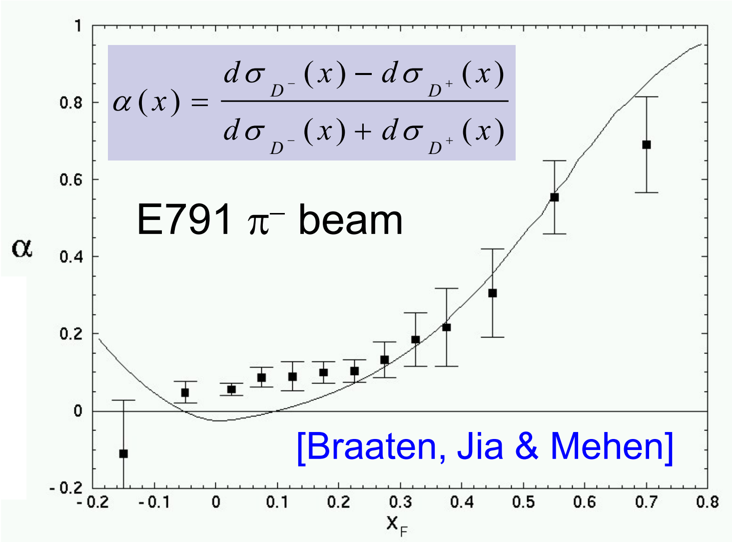
$$d\sigma_M(x) = \int \frac{dx_1 dx_2}{x_1 x_2} F(x_1, x_2) R_M(x_1, x_2, x)$$

[K.P. Das & R.C. Hwa: Phys. Lett. B68, 459 (1977): *Quark-Antiquark Recombination in the Fragmentation Region*]

- Leading Particle Effect (forward rapidities)
  - D^+/D^- asymmetries clearly not described by pQCD + fragmentation.
  - Explained by recombination with beam remnants

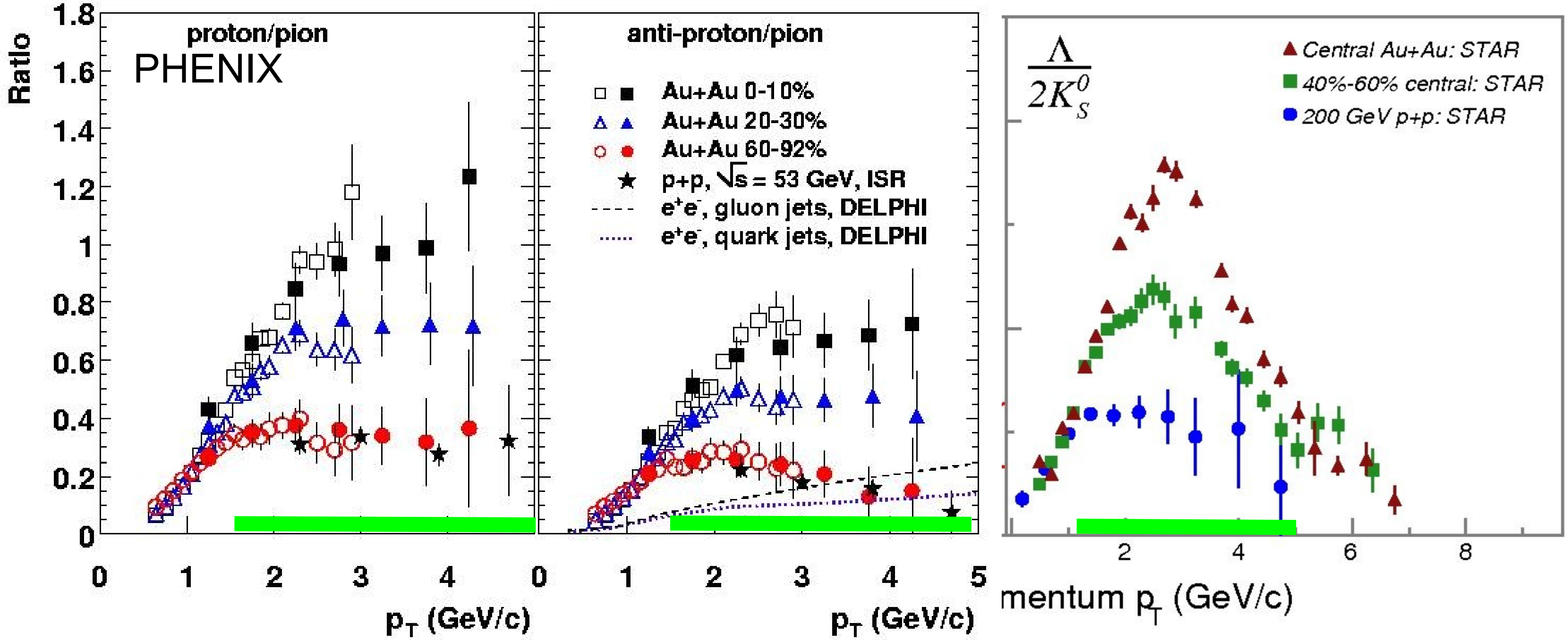
E791 π^- beam: hard $c\bar{c}$ production; recombine $\bar{c}$ with d valence quark from π^- > reco of c with $\bar{d}$





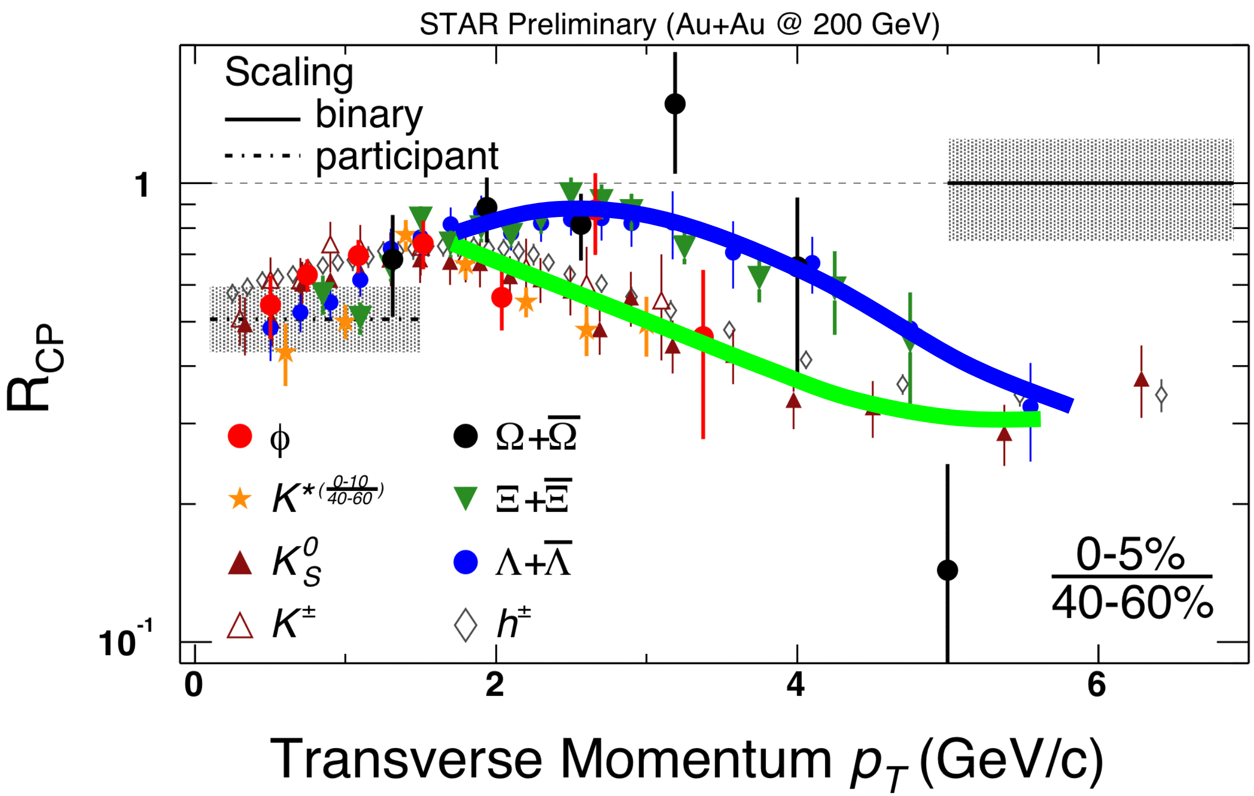
Experiment: Baryon Puzzle @ RHIC

- Proton/pion ratio > 1 at P_T ~ 4 GeV in Au+Au collisions.
- Expectation from parton fragmentation: p/π ~ 0.1 … 0.3
  - As measured in p+p and e^++e^-



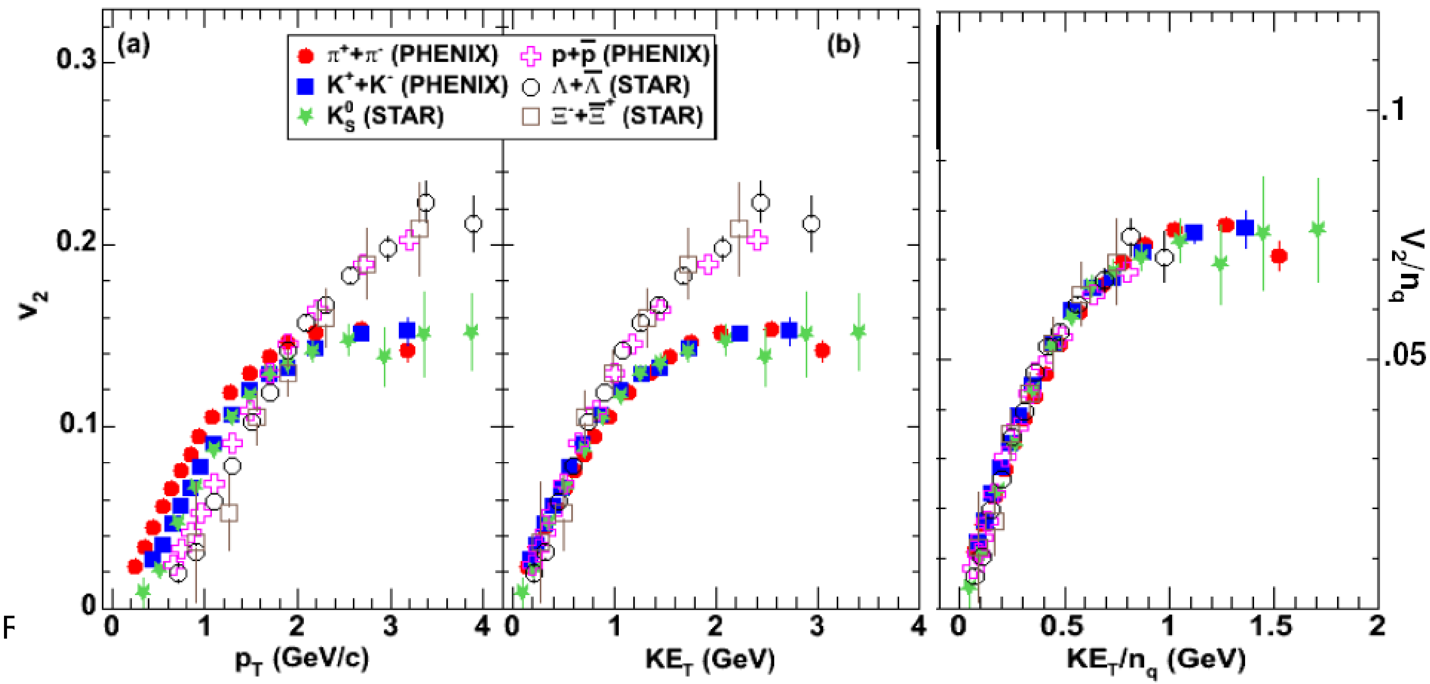
Experiment: Baryon vs Meson in HI

- General baryon/meson pattern: p, Λ, Ξ, Ω versus K, π, ϕ, K*, η
- Incompatible with hydro and fragmentation.



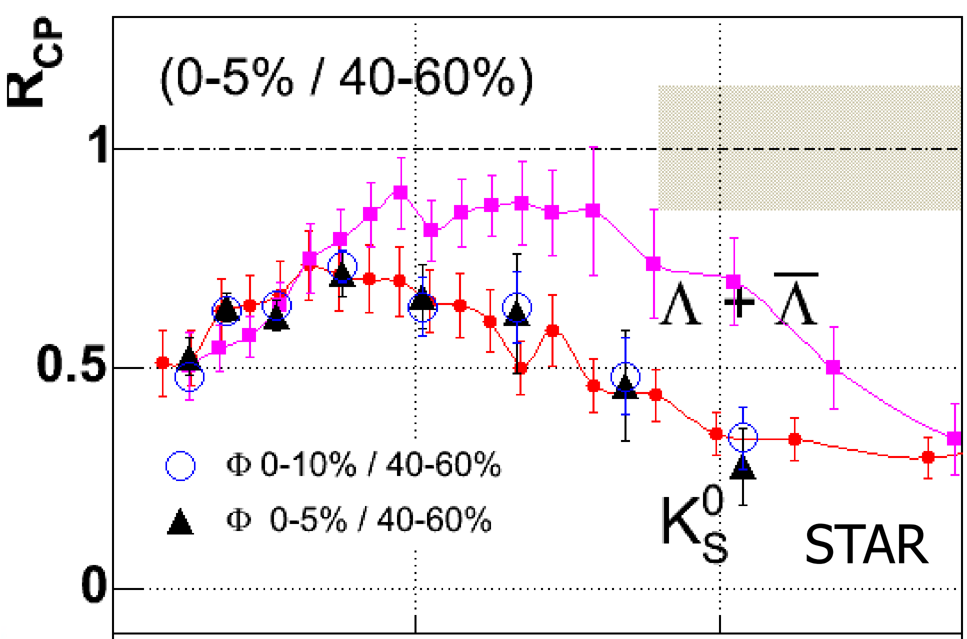
Elliptic Flow Scaling(s) in HI

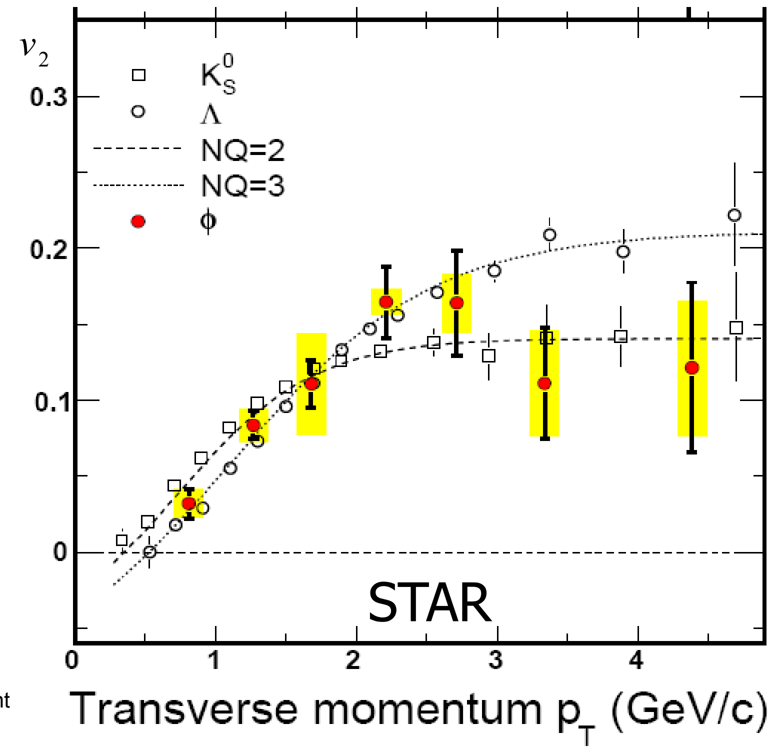
- Quark number scaling first found experimentally at RHIC
  - *n* = number of valence quarks
  - Very much unlike (ideal) hydrodynamics
- In addition at low P_T: scaling with kinetic energy
  - Hydrodynamic feature?
- Scaling of both KE_T and *n* close to perfect up to KE_T/n ~ 1.0 GeV



Fate of Hydro + Jet Models

- Assume hydro valid up to 3-6 GeV/c at RHIC, interpolate with jet spectra.
- Spoiler: ϕ behaves like a pion ($m_\phi \approx m_p$, $m_\phi \gg m_\pi$) [Hirano + Nara (2004)]
- Baryon vs meson universality classes seem to be incompatible with hydro.
- Intermediate P_T: non-standard (hydro, fragmentation) hadronization features?





Two Recombination Models

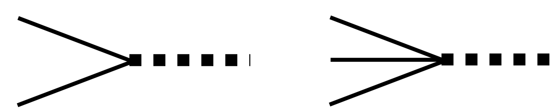
Instantaneous Coalescence Model

- Simplest realization of a recombination model
  - Recombine valence quarks of hadrons

$$q\bar{q} \rightarrow M \qquad\qquad qqq \rightarrow B$$

  - Dressed quarks, no gluons
- Instantaneous projection of quark states (density matrix ρ) on hadronic states with momentum P:

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



- Effectively: $2 \rightarrow 1$, $3 \rightarrow 1$ processes
  - Big caveat: projection conserves only 3 components of 4-momentum.

Instantaneous Coalescence

- Hadron spectra can be written as a convolution of Wigner functions W, Φ
  - Replace Wigner function by classical phase space distribution

$$W_{ab} \rightarrow f_{ab} \approx f_a f_b \left(1 + C_{ab} + \ldots\right)$$

Production hypersurface

Meson Wigner function

$$E\frac{d^3N_M}{d^3P} = \sum_{a,b}\int_\sigma \frac{d\sigma\cdot P}{(2\pi)^3}\left(W_{ab}\otimes\Phi_M\right)$$

Quark Wigner function

- "Master formula" for all classical instantaneous reco models

[Greco, Ko & Levai]
[RJF, Müller, Nonaka & Bass]
[Hwa & Yang]
[Rapp & Shuryak]

- One further approximation: collinear limit
  - Similar to light cone formalism with $k_T \gg P$

Can be modeled with hard exclusive light cone wave functions

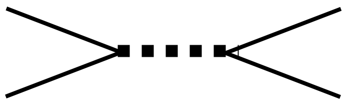
$$E\frac{d^3N_M}{d^3P} = C_M\int_\sigma \frac{d\sigma\cdot P}{(2\pi)^3}\int dx\, f_a(R;xP)\, f_b(R;(1-x)P)\left|\phi_M(x)\right|^2$$

$$E\frac{d^3N_B}{d^3P} = C_B\int_\sigma \frac{d\sigma\cdot P}{(2\pi)^3}\int dx_1 dx_2\, f_a(R;x_aP)\, f_b(R;x_bP)\, f_c(R;(1-x_a-x_b)P)\left|\phi_B(x_1,x_2)\right|^2$$

Transport Approach (RRM)

- Boltzmann approach applied to ensemble of quarks and antiquarks
- Mesons = resonances created through quark-antiquark scattering

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



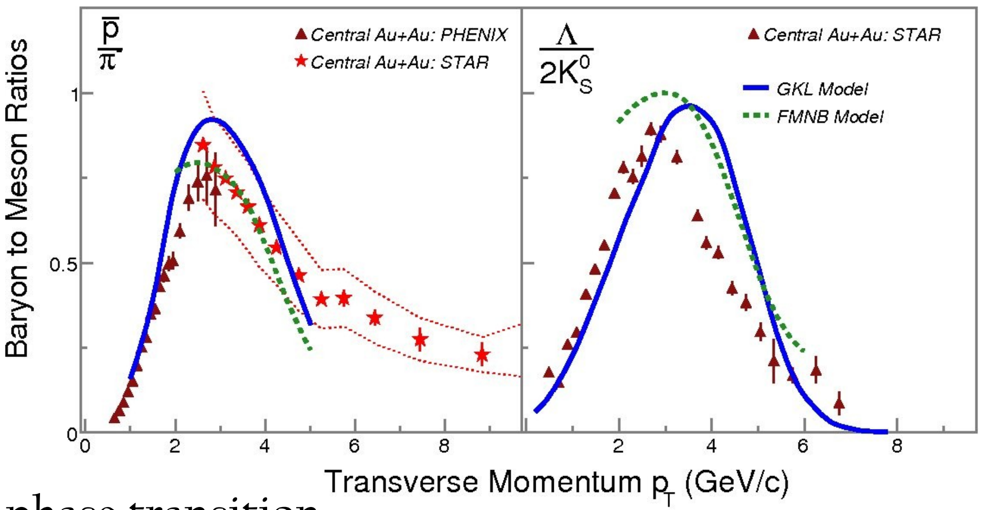
  - Breit-Wigner cross sections: $\sigma(s) = C_M \frac{4\pi}{k^2} \frac{(\Gamma m)^2}{(s-m^2)^2 + (\Gamma m)^2}$
  - Resonance Recombination
- In the long-time limit:

$$E\frac{dN_M}{d^3P} = \frac{E\gamma}{8(2\pi)^3\Gamma} \int \frac{d^3x d^3p_{rel}}{(2\pi)^3} f_a(x,p_1) f_a(x,p_2) \sigma(s) v_{rel}(P,p_{rel})$$

- Properties:
  - Conserves energy <u>and</u> momentum, leads to finite hadronization times
  - Baryons: coming, need to implement diquarks.
  - No confinement: no quark loss terms

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

Instantaneous Recombinaton



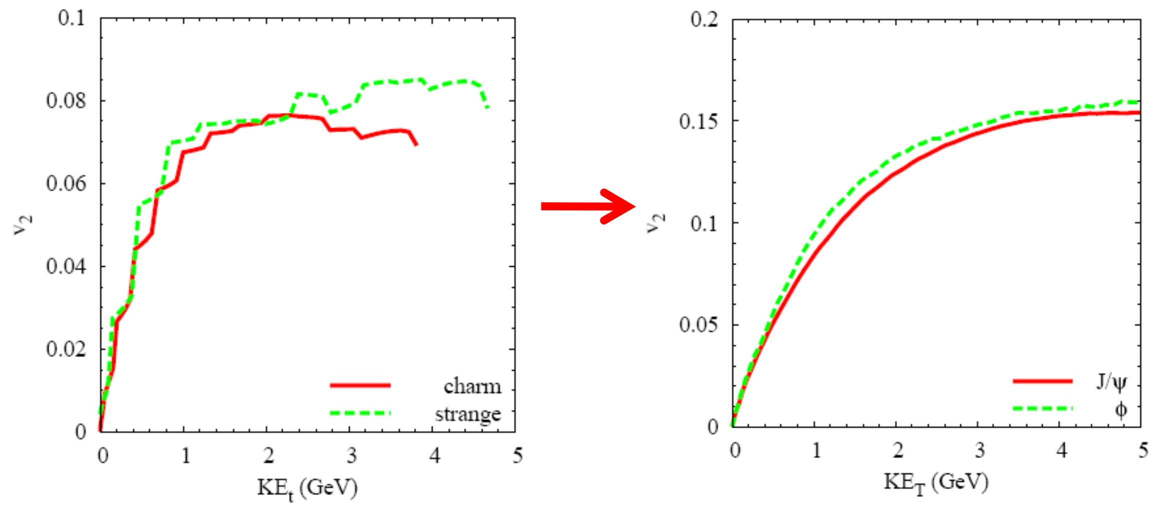
- Describe essential features of RHIC data at int. P_T.
  - [Greco, Ko & Levai, (2003)]
  - [RJF, Müller, Nonaka & Bass, (2003)]
- Elliptic flow:
  - Assume universal elliptic flow v_2^p of the partons before the phase transition
  - Recombination prediction (factorization of momentum and position space!)

$$v_2^M(p_t) = 2v_2^p\left(\frac{p_t}{2}\right) \quad \text{and} \quad v_2^B(p_t) = 3v_2^p\left(\frac{p_t}{3}\right)$$

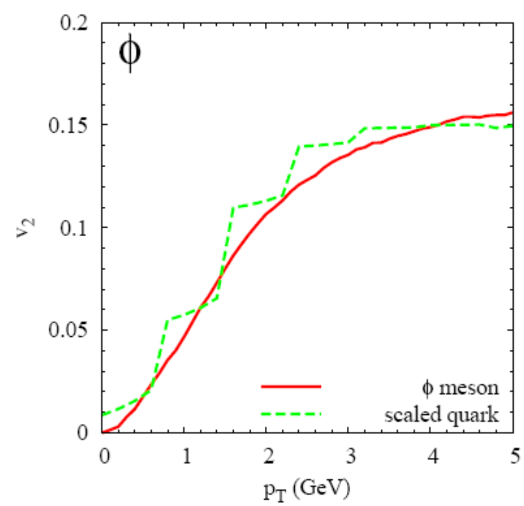
  - Recover scaling law for infinitely narrow wave functions
  - Scaling holds numerically also for less special choices.
- Uses very special flow field, maybe fragile prediction?
  - [Pratt & Pal, NPA 749 (2005)]
  - [Molnar, nucl-th/0408044]

Resonance Recombination

- Kinetic energy scaling for quarks is preserved going from the quark to the hadron phase.



- Quark number scaling holds between mesons and quarks
  - Confirmation with baryons still missing.



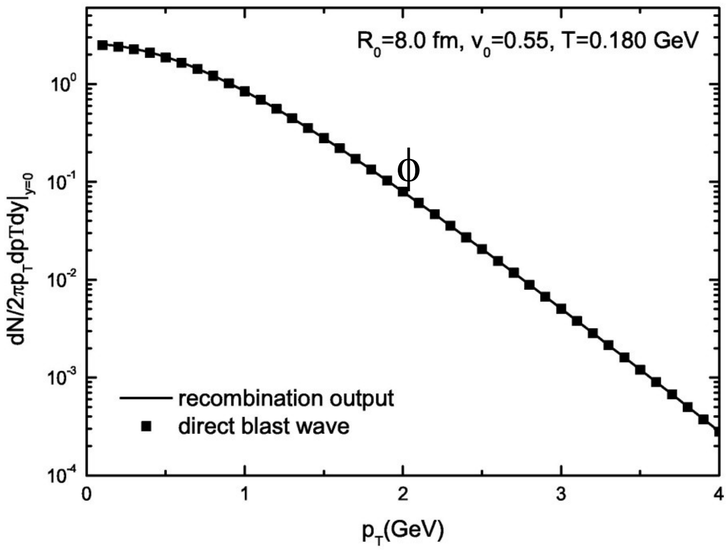
[Ravagli, van Hees, Rapp, PRC 79 (2009)]

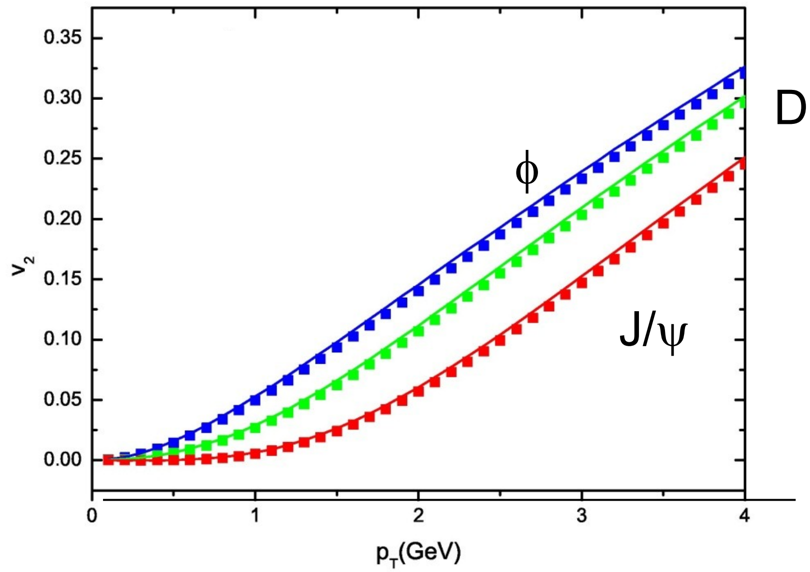
Recombination and Hydro

[Work with Min He and Ralf Rapp]

Recombination in Equilibrium

- Boltzmann implementation: energy conservation + detailed balance + equilibrated quark input should lead to 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:



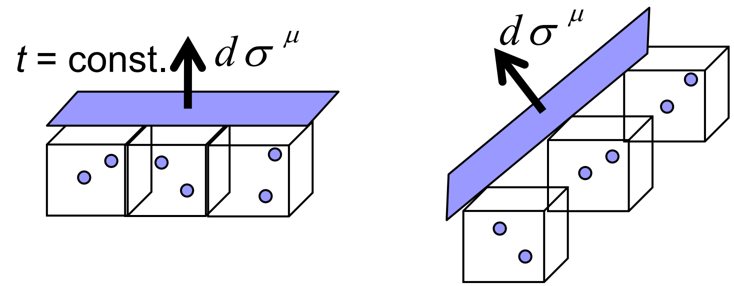


- Excellent agreement of spectra and v_2.
- Hadronization hypersurface: equal time

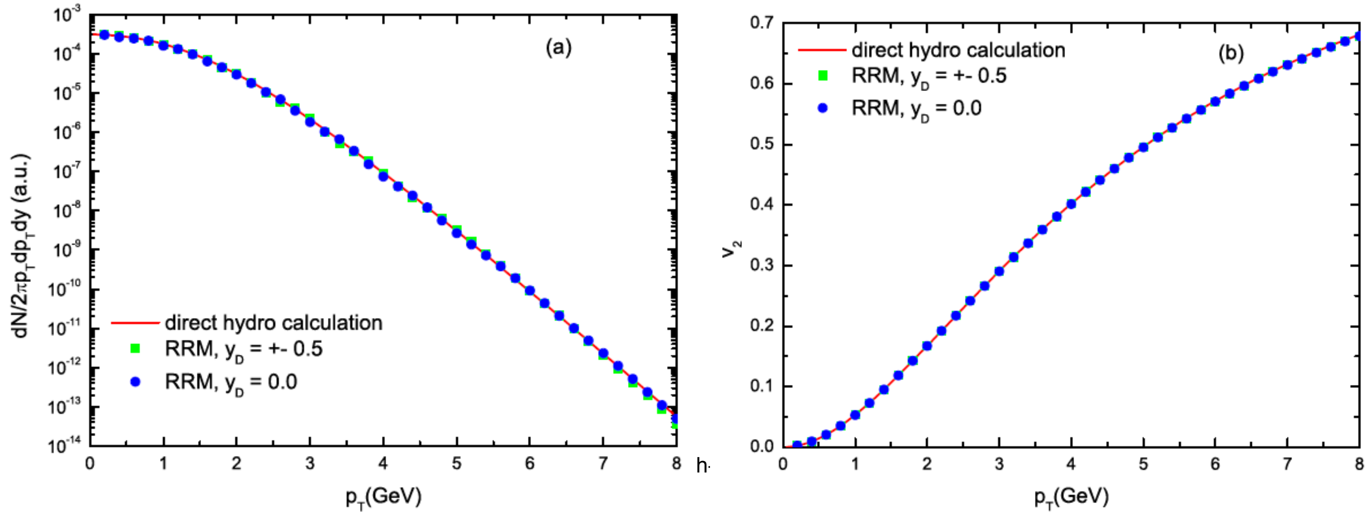
[He, RJF & Rapp, PRC (2010)]

Recombination in Equilibrium

- Realistic hadronization hypersurface Σ:
  - Extract equal-time quark phase space distributions f_q along Σ from hydro or kinetic model.
  - Cell-by-cell apply RRM $\rightarrow$ meson phase space distribution 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:



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

Recombination in Equilibrium

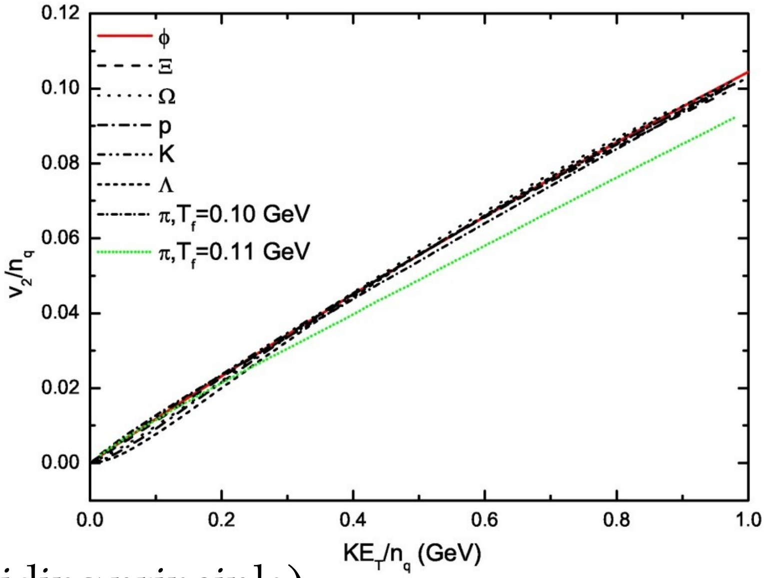
- The resonance recombination model is compatible with equilibration and hydrodynamics.
  - Even can get negative J/ψ v_2 from positive charm quark v_2.
  - Will work with any hydrodynamic flow field and hadronization hypersurface.

- However, universal hydrodynamic behavior leads to a demise of the predictive power of recombination as a microscopic model in that regime.

- How can we understand simultaneous KE_T- and n_q-scaling at low P_T?
- KE_T-scaling almost provided by simple hydrodynamic flow:
  - Strong mass dependence vs P_T, weak mass dependence vs KE_T.
  - Can be reduced further by sequential freeze-out from heavier to lighter hadrons.

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 robust
  - KE_T+n_q scaling maybe accidental (no guiding principle)



Recombination in the Kinetic Regime: Heavy Quarks

[Work with Min He and Ralf Rapp]

RRM at Intermediate P_T

- Need:
  - Realistic quark phase-space distributions away from equilibrium
  - Baryons (for quark number scaling)

- Scenarios:
  - Boltzmann (parton cascade)
  - Langevin (for heavy quarks)
  - Viscous hydro (??)

- Here: Langevin for heavy quarks in hydrodynamic background.

Langevin Dynamics

- Langevin Equations

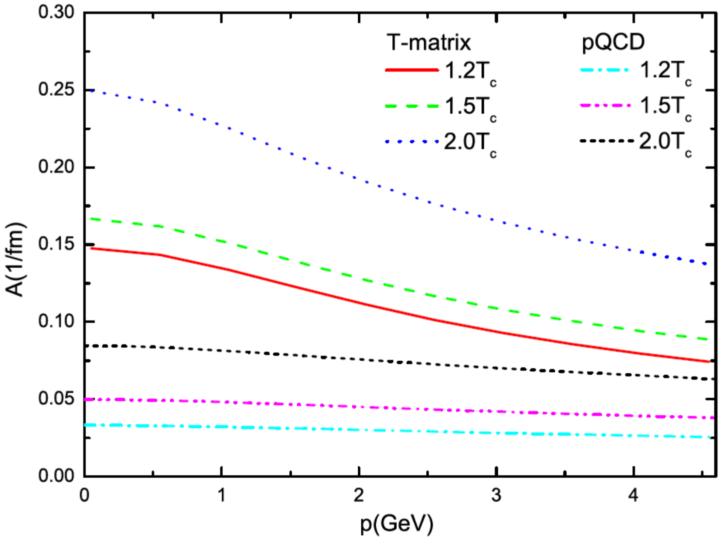
$$d\mathbf{x} = \frac{\mathbf{p}}{E} dt,$$

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

- Transport coefficients:
  - HQ relaxation rates in T-matrix approach

[Riek and Rapp, Phys. Rev. C 82, 035201 (2010)]

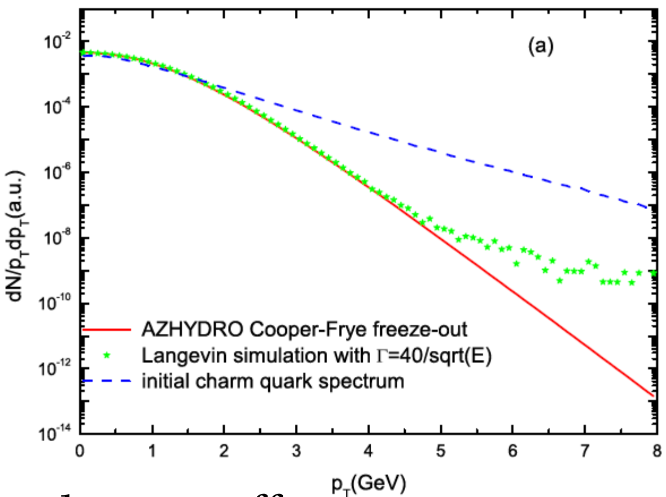
$$\Gamma(p) = A(p) + \mathcal{O}(T/m_Q) \qquad D(p) = \Gamma(p)E(p)T$$

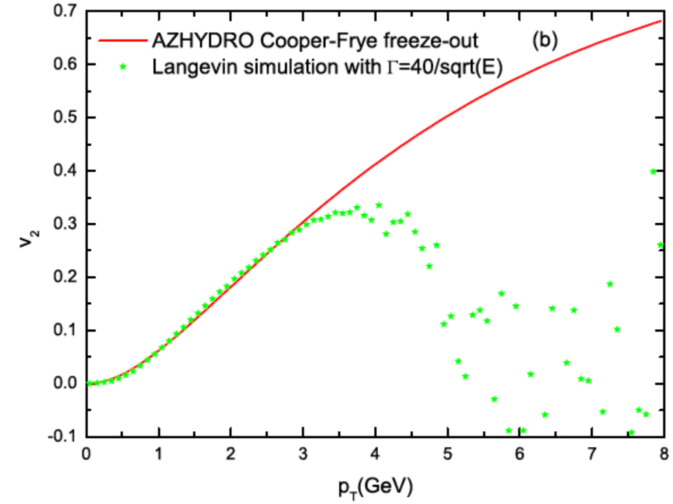


- Run Langevin in AZHYDRO background.
  - Test particles in lab frame → boost to fluid rest frame → Langevin step → boost back to lab frame.
  - Stop at AZHYDRO hadronization hypersurface.
  - Initial distribution: binary collision density ⊗ pQCD spectrum.

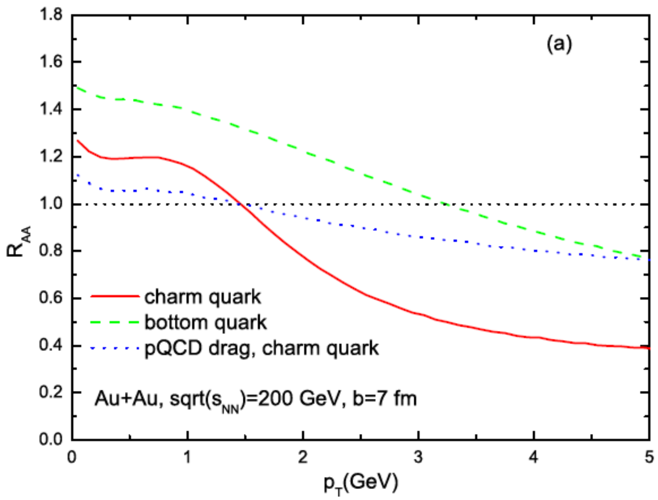
Langevin Dynamics

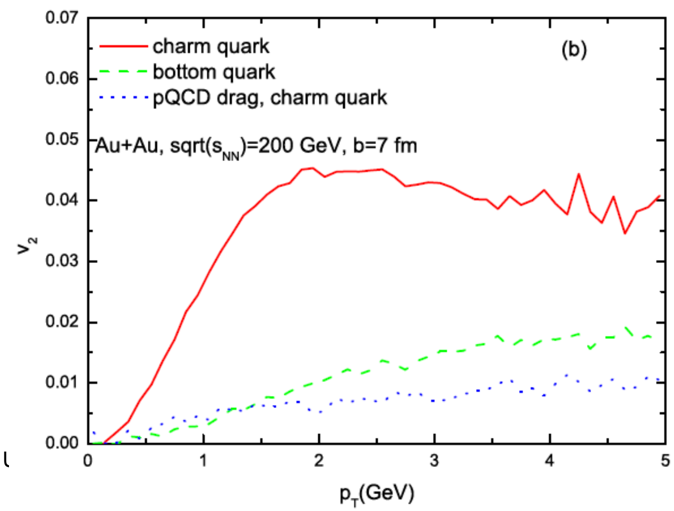
- Equilibrium check (artificially large relaxation times)





- Realistic coefficients



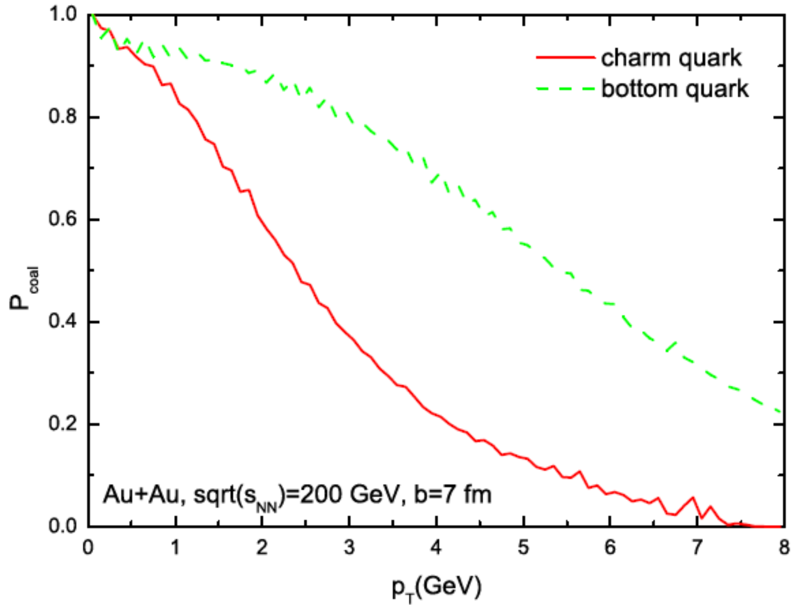


Hadronization of Heavy Quarks

- Calculate recombination probability $P(p_T)$ of heavy quarks for given p_T.
  - Light quarks from hydro.
  - Low momentum heavy quarks spend a long time in the QGP → relaxed and close to mass shell → fix $P(p_T)$ to be unity at $p_T = 0$.

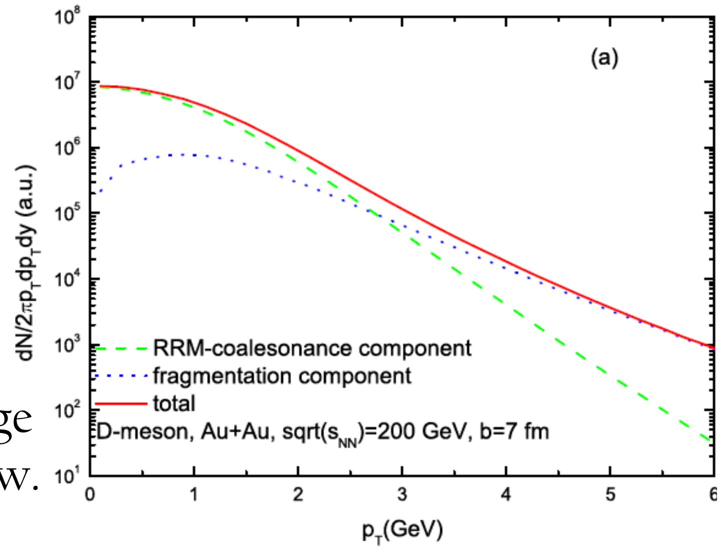
- Apply RRM across Σ for fraction $P(p_T)$ of test particles.

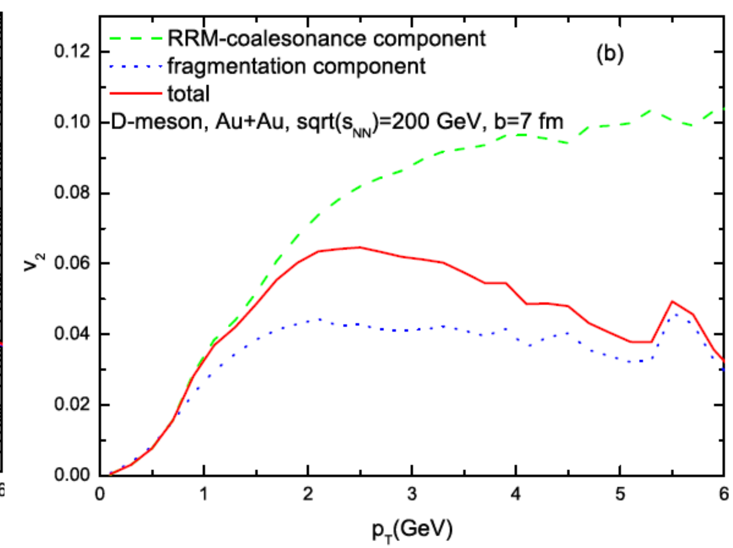
- Apply fragmentation for fraction $1-P(p_T)$ of test particles.



Heavy Mesons

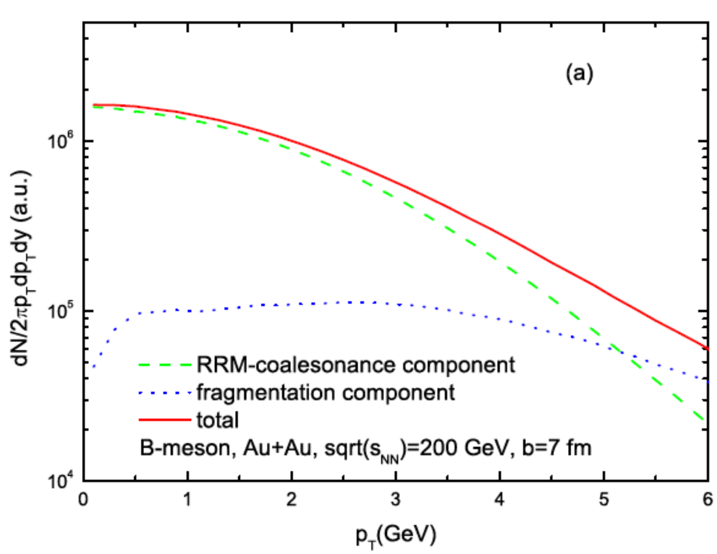
- Charm (D)

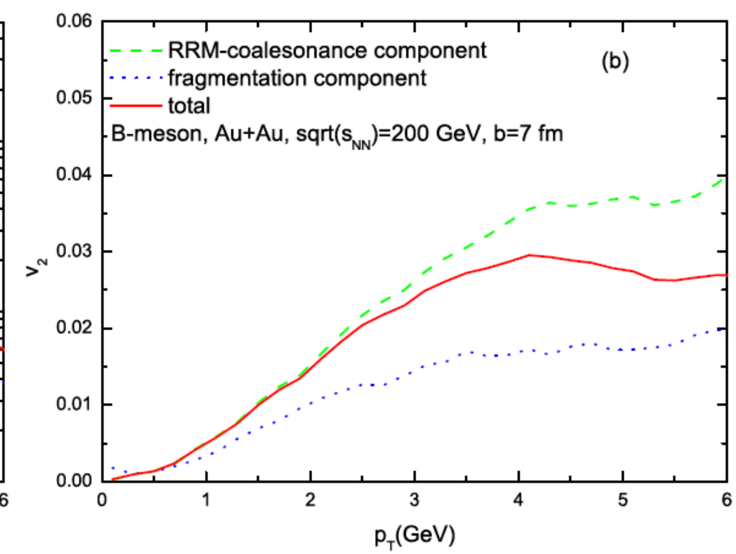




Recombination: huge effect on elliptic flow.

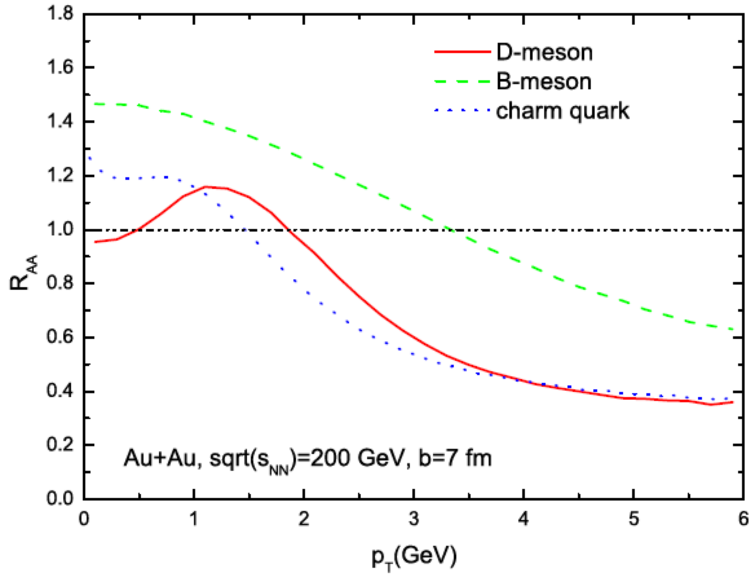
- Bottom (B)





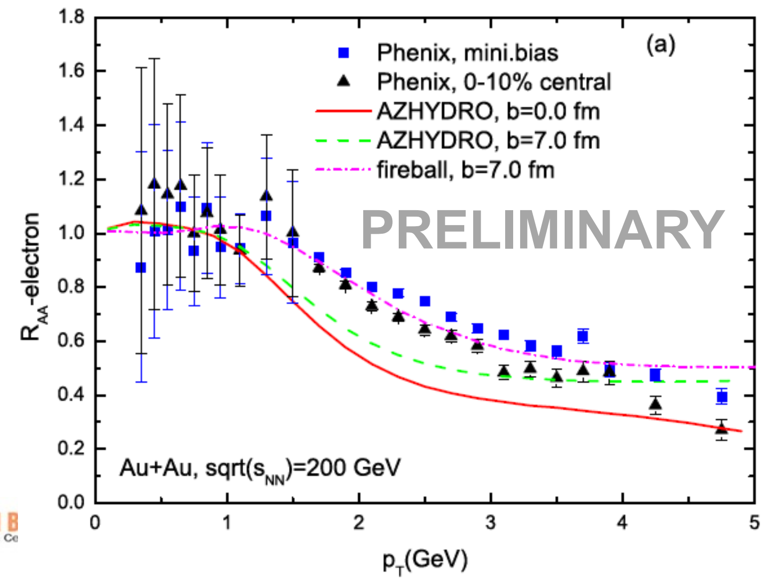
Semi-Leptonic Decays and Data

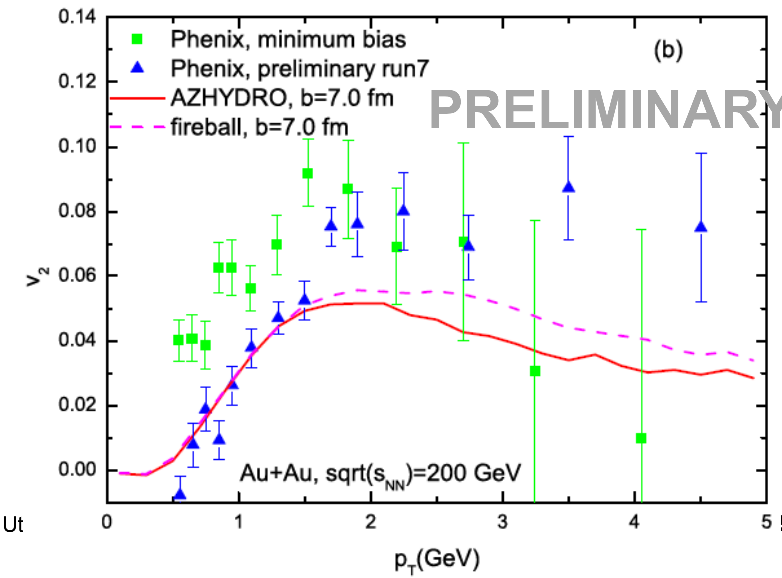
- R_{AA}



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

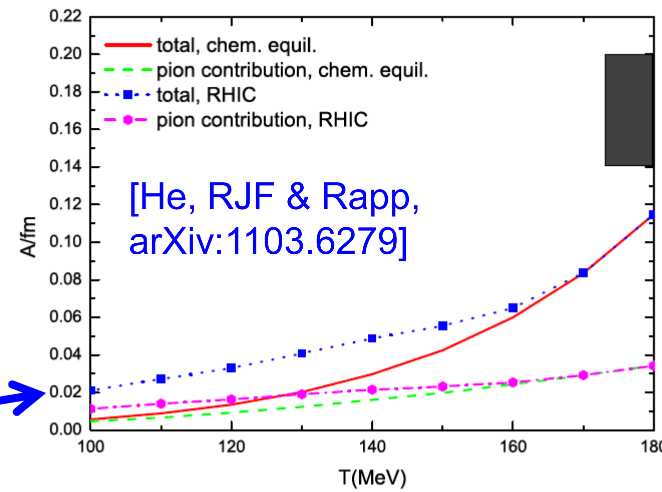
- Electrons

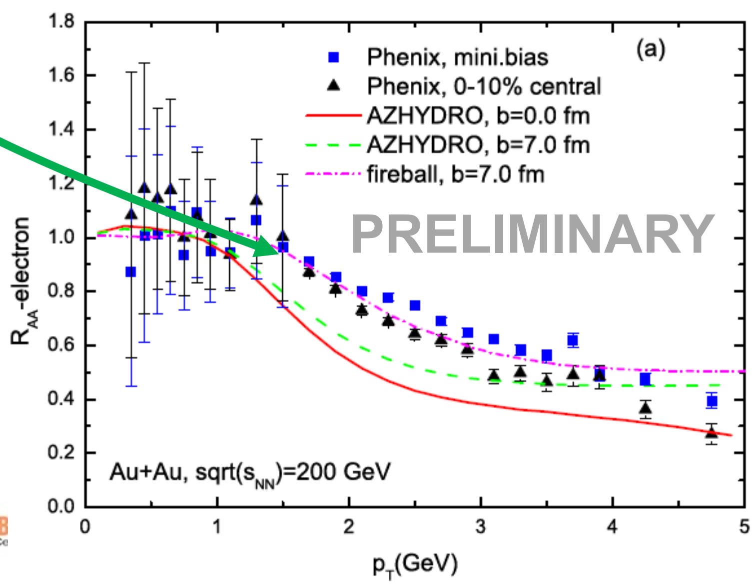


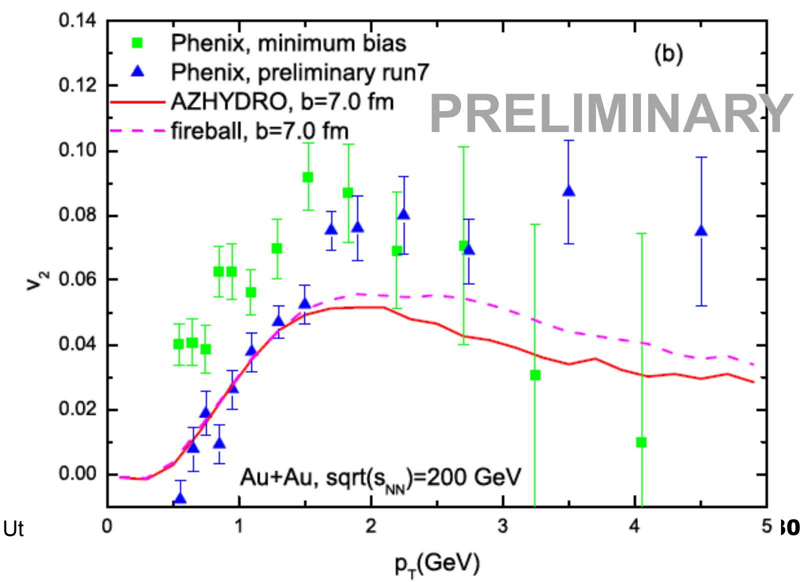


Semi-Leptonic Decays and Data

- What's missing?
- Flow!
  - Have to tune hydro; underestimates flow at T_c.
- Diffusion in the hadronic phase.
  - Transport coefficient for D:







Summary

- There is need for a microscopic hadronization model in some situations
  - Hadron production in nuclear collisions at intermediate momenta.
  - Should be consistent with hydro (soft) hadron production and high P_T fragmentation.
  - Candidate: resonance recombination via Boltzmann dynamics
- Low momentum (equilibrated region):
  - Capable of producing equilibrium hadrons.
  - KE_T and quark number scaling compatible with recombination but not a consequence of it.
  - Recombination does not add any new predictive power to hydrodynamics regime.
- Intermediate P_T:
  - True testing ground for recombination models.
  - Meson-quark v_2 scaling for realistic flow fields: baryons to come.

Summary II

- Application to heavy quark ensemble prepared with Langevin dynamics, hydro background, recombination + fragmentation.
  - Data needs tuning of (equilibrium) flow, maybe hadronic diffusion.
  - Full heavy quark calculation coming soon.
- Quark number scaling at intermediate P_T with realistic phase space distributions:
  - Works for mesons vs quarks
  - Need check with baryons

Backup: Recombination at High P_T

Recombination at High P_T

- Recombination for jets?
- E.g. shower recombination + mixed processes (soft-hard or soft-shower recombination). [Hwa, Yang]

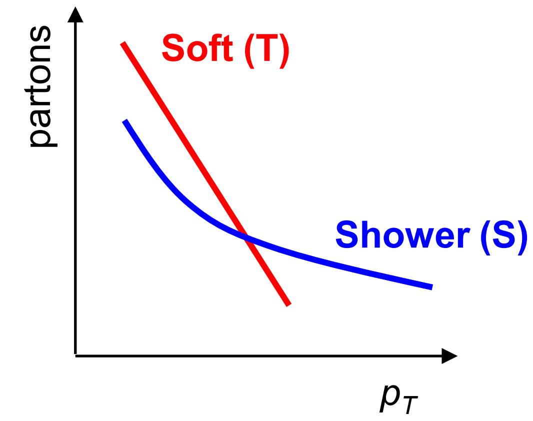
soft-soft

Partons from 1 jets

$$w_{q\bar{q}} = TT + TS + (SS) + SS'$$

soft-shower

Partons from 2 jets



- Modifications to fragmentation functions.

  [Majumdar, Wang & Wang (2005)]

Hadronization Module for JET

- Topical Collaboration on Jet and Electromagnetic Tomography.
- Recombination module for jet-shower simulations in preparation.
- Goals:
  - Reproduce vacuum fragmentation.
  - Add medium partons.

[Fries, Ko et al., work in progress]

Backup Slides

Fate of the Gluons?

- We should not be surprised that valence quarks are the dominant degrees of freedom.
- Is there any room to accommodate higher Fock states (gluons or sea quarks)?

$$\left| M \right\rangle = \alpha_0 \left| a\bar{b} \right\rangle + \alpha_{1i} \left| a\bar{b}\, q_i \bar{q}_i \right\rangle + \alpha_{2ij} \left| a\bar{b}\, q_i \bar{q}_i q_j \bar{q}_j \right\rangle + \ldots$$

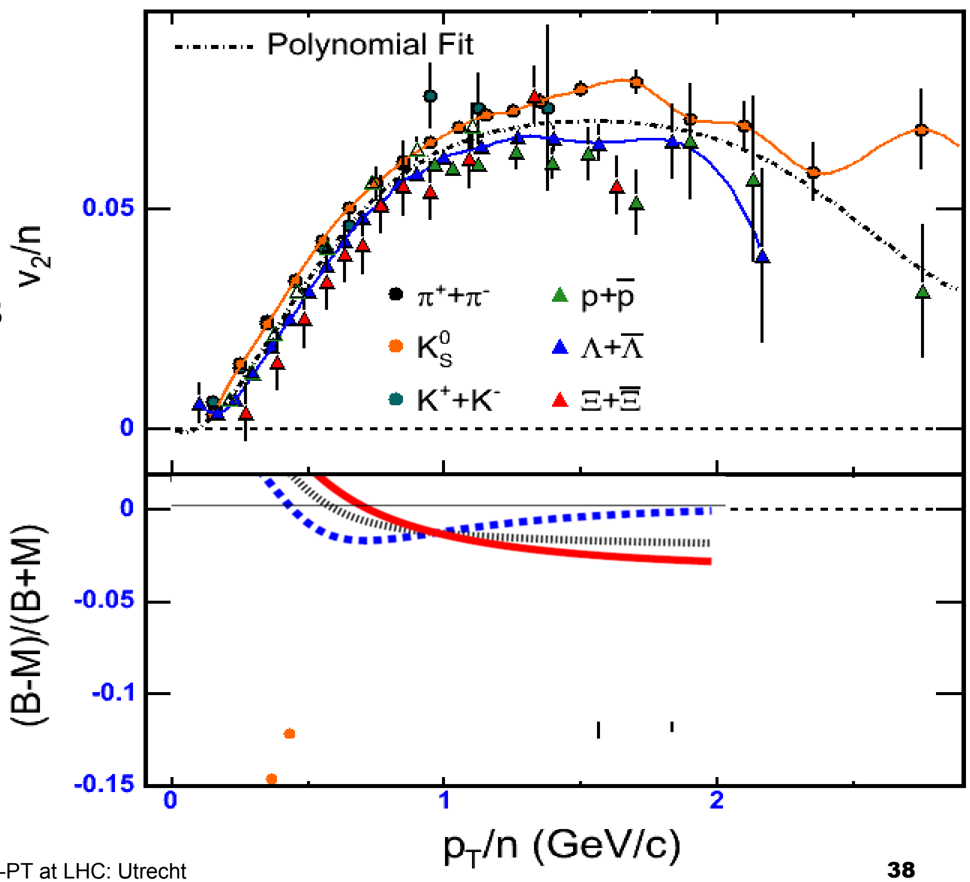
- Maybe: no effect on particle yields for thermal spectra!

$$\sum_i \left| \alpha_i \right|^2 \prod_{\kappa=1}^{n_i} e^{-x_i P/T} = \sum_i \left| \alpha_i \right|^2 e^{-P/T} = e^{-P/T}$$

- Elliptic flow for hadrons does not obey analytic scaling law anymore
  - For equally shared momenta: $v_2^M(P_T) = \left|\alpha_0\right|^2 2 v_2^p(P_T/2) + \sum_i \left|\alpha_{1i}\right|^2 4 v_2^p(P_T/4) + \ldots$
  - But numerically it can still be close to scaling .
  - Systematic difference between baryons and mesons introduced.

Uncertainties on the Scaling Law

- Scaling law potentially receives uncertainties from:
  - Hadron wave function (higher Fock states, shape)
  - Non-trivial space-momentum correlations
  - Resonance decays, hadronic phase (pions!)
- Experimentally: small deviations confirmed



Instant. Reco: The Thermal Case

- Thermal parton spectra yield thermal hadron spectra.
  - For instant. recombination (collinear case):

$$w \sim e^{-p/T} \Rightarrow \begin{cases} N_M \sim w_\alpha w_\beta \sim e^{-xP/T} e^{-(1-x)P/T} = e^{-P/T} \\ N_B \sim w_\alpha w_\beta w_\gamma \sim e^{-x_\alpha P/T} e^{-x_\beta P/T} e^{-(1-x_\alpha - x_\beta)P/T} = e^{-P/T} \end{cases}$$

  - Should also hold in the transport approach.
  - Automatically delivers $N_B \sim N_M$ if mass effects are suppressed

- Details of hadron structure do not seem to be relevant for thermal recombination at intermediate and high momentum.
  - Wave function can be integrated out.
  - Important for elliptic flow scaling.
  - Also seen numerically in full 6-D phase space coalescence.

Instant. Reco: Exp & Power Laws

- Comparison of different scenarios
- Power law parton spectrum
  - Recombination is suppressed
  - Good: QCD factorization should hold at least for asymptotically large momentum
- Exponential parton spectrum
  - Recombination more effective
  - Even larger effect for baryons

Power law: $w \sim p_T^{-\alpha}$

$$N_{frag} \sim P_T^{-\alpha-\delta}$$

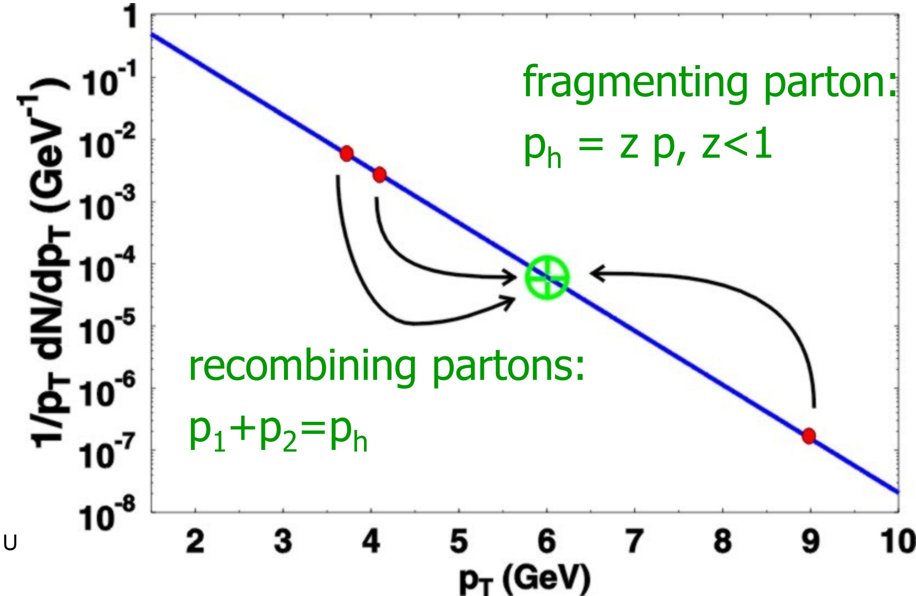
$$N_{reco} \sim P_T^{-2\alpha}$$

for mesons

Exponential: $w \sim Ae^{-p_T/T}$

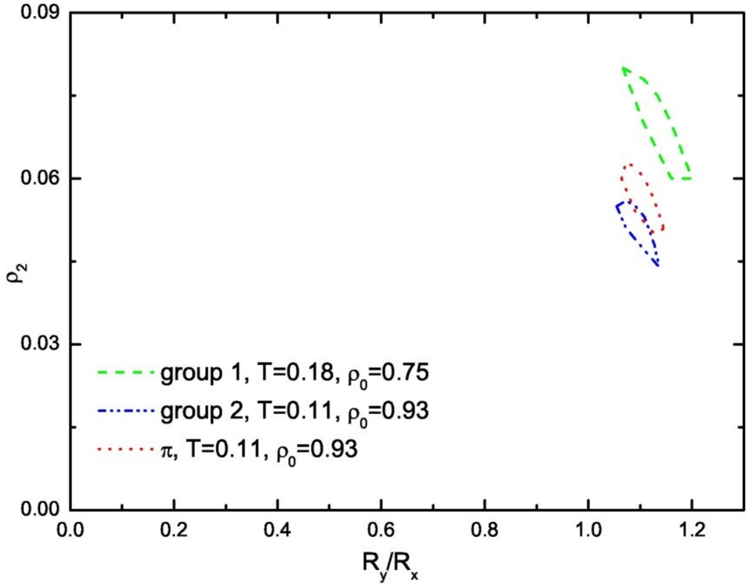
$$N_{frag} = w \otimes D \sim Ae^{-P_T/\langle z \rangle T} \langle D \rangle$$

$$N_{reco} = w \otimes \Phi \otimes w \sim A^2 e^{-P_T/T}$$



KE_T-Scaling (Low P_T)

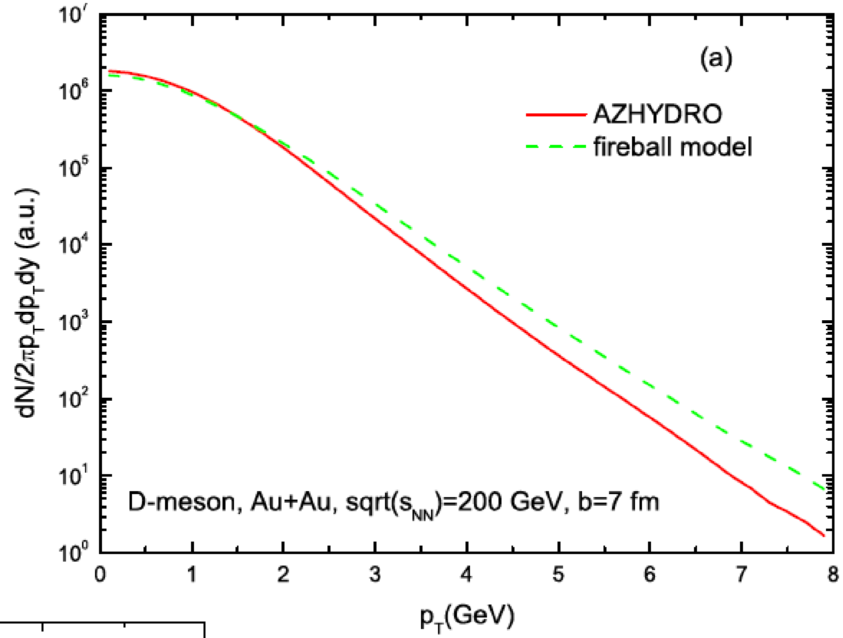
- Easy to find reasonable parameters in the Retiere and Lisa blast wave to achieve KE_T- and n_q-scaling within 10% accuracy.
- Contours in space of flow asymmetry and fireball eccentricity.
- Pions prefer slightly lower freeze-out temperatures but are compatible with group II within the 10% accuracy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



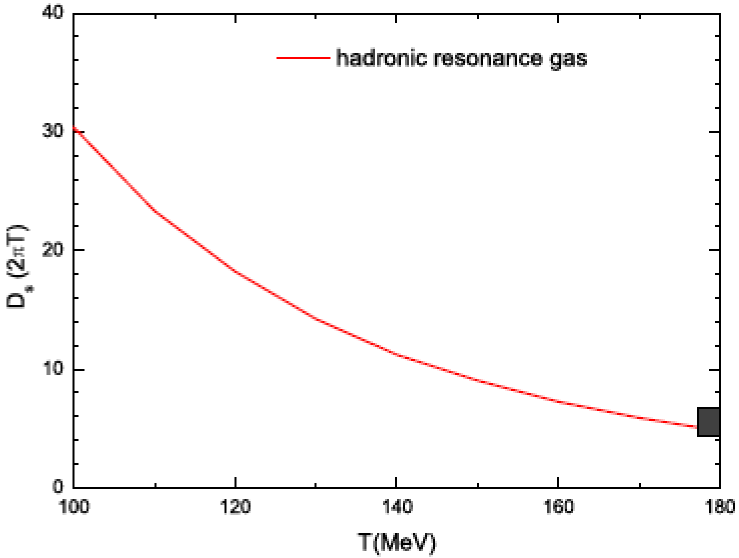
[He, Fries & Rapp, PRC (2010)]

Comparison

- Flow



- Spatial diffusion constant



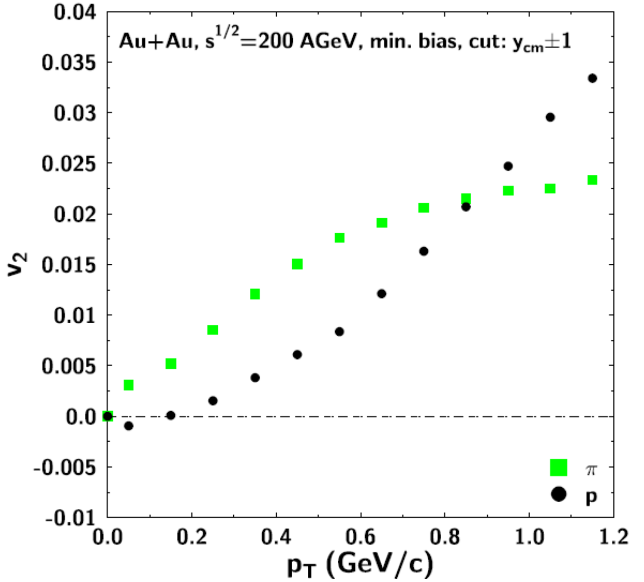
Other Suggestions for Intermed. P_T

- Prelude: valence quark scaling of hadronic cross sections can lead to v_2 scaling in URQMD.

$$\frac{\sigma(\pi N)}{\sigma(NN)} \approx \frac{2}{3}$$

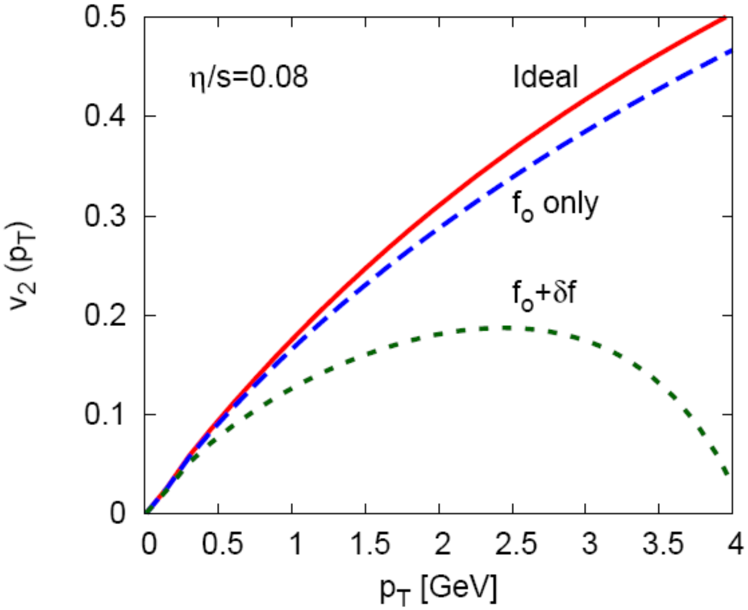
[Bleicher & Stoecker, PLB 526 (2002)]

- But absolute values are small!



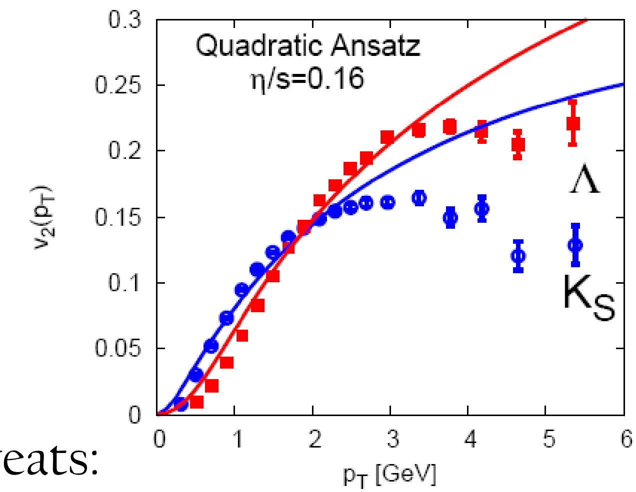
- What about hadronic phase close to but not at the hydro limit?
- 2nd order viscous hydro: large effect on v_2 from deformed freeze-out distributions.

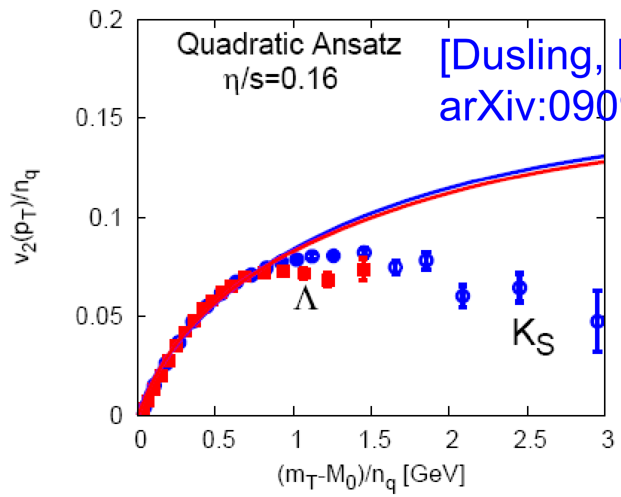
$$\delta f(\vec{p}) = -\chi(p)n(1\pm n)p^i p^j \langle \partial_i u_j \rangle$$



Viscous Hydro

- Assume different equilibration times for baryons and meson.
  - Inspired by constituent scaling of cross sections set $\frac{\chi_M}{\chi_B} \approx \frac{3}{2}$
- This yields reasonably good agreement with data
  - Intermediate p_T: meson distributions more deformed than baryons at freeze-out.





[Dusling, Moore & Teaney, arXiv:0909.0754]

- Caveats:
  - Scaling of χ is a (well-motivated) guess so far, cross sections between all measured hadrons have to scale with some accuracy.
  - Jet-like correlations at intermediate P_T?
  - Limits of applicability of viscous hydro?