(Hot and) heavy quarks at RHIC from parton transport theory

Denes Molnar

Purdue University & RIKEN/BNL Research Center

Quarks
Hot~~test~~ Υ Workshop

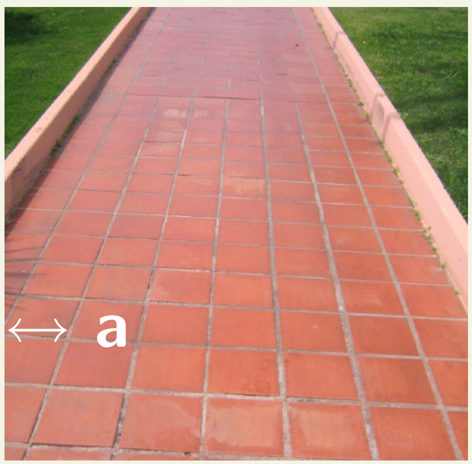
May 15-20, 2006, Villasimius, Italy

Ways to explore

hydrodynamics

transport theory

classical field theory (a.k.a. "color glass")



lattice QCD

nonequilibrium quantum field theory ("Holy Grail")

Parton transport theory

Pang, Zhang, Gyulassy, DM, Vance, Csizmadia, Pratt, Cheng, ...

Covariant, nonequilibrium approach - formulated in terms of local rates.

mean free path: **characterizes local conditions**

$$\lambda(x) \equiv \frac{1}{\text{cross section} \times \text{density}(\mathbf{x})} \qquad \begin{cases} \lambda \to 0 & - \text{ideal hydrodynamics} \\ \lambda \to \infty & - \text{free streaming} \end{cases}$$

near equilibrium: related to transport coefficients (e.g., viscosity $\eta \sim \lambda T^4$)

Transport eqn: $f_i(\vec{x}, \vec{p}, t)$ - **quark/gluon phase space distributions**

$$p^\mu \partial_\mu f_i(\vec{x}, \vec{p}, t) = \overbrace{S_i(\vec{x}, \vec{p}, t)}^{\text{source}} + \overbrace{C_i^{el.}[f](\vec{x}, \vec{p}, t)}^{2 \to 2\ (\text{ZPC}, \text{GCP}, \ldots)} + \overbrace{C_i^{inel.}[f](\vec{x}, \vec{p}, t)}^{2 \leftrightarrow 3\ (\text{MPC}, \text{Xu}-\text{Greiner})} + \ldots$$

HERE: utilize MPC model/algorithm DM, NPA 697 ('02)

available from OSCAR code repository @ http://nt3.phys.columbia.edu/OSCAR

Observations at RHIC

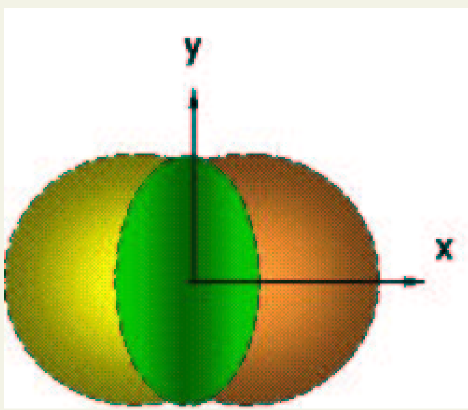
strong attenuation of energetic particles **"jet quenching"** (R_{AA})

large "elliptic flow" (v_2) **collectivity**

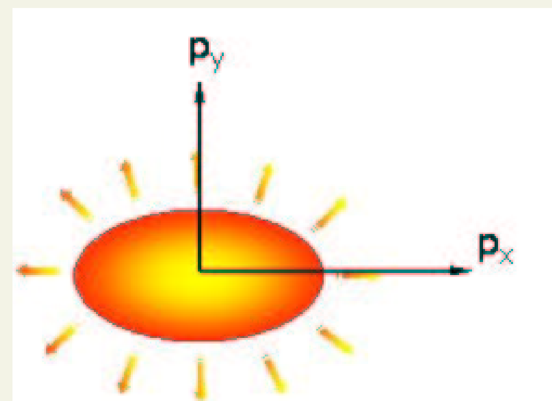
beam axis view:

spatial anisotropy $\longrightarrow$ **final azimuthal momentum anisotropy**

$$\varepsilon \equiv \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$$

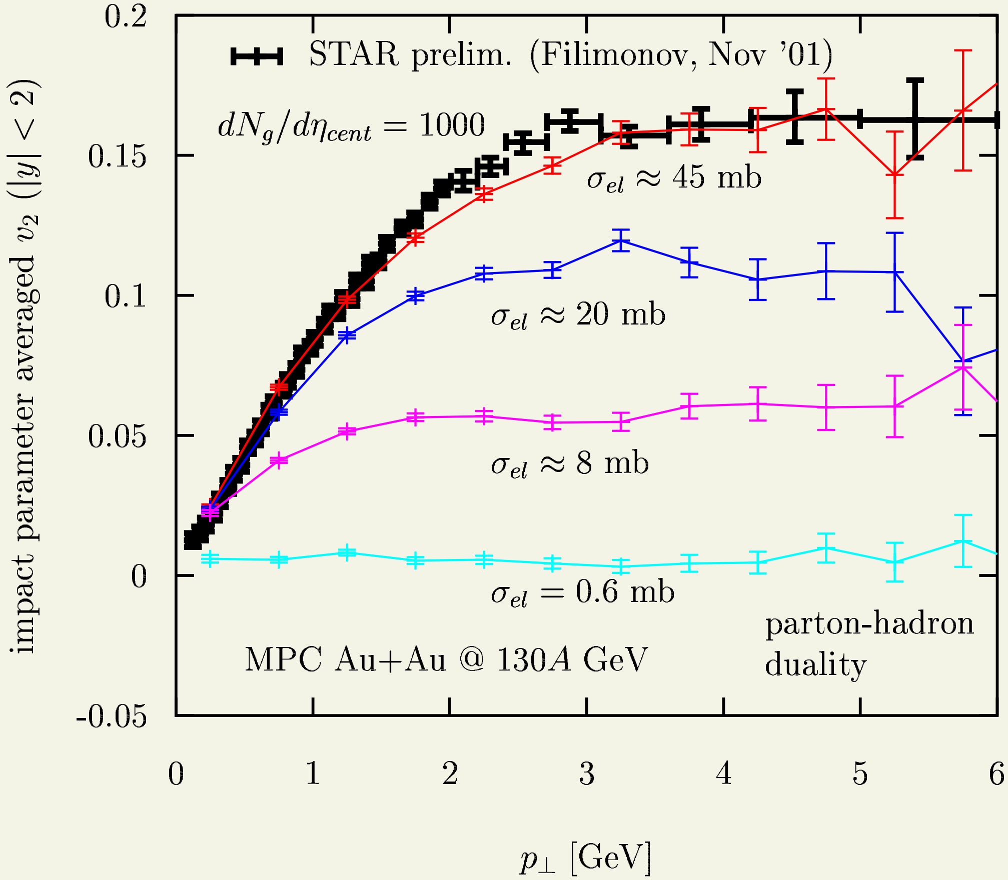


$$\longrightarrow \quad v_2 \equiv \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$



RHIC - $2:1$ **anisotropy**

DM & Gyulassy, NPA 697 ('02): $v_2(p_T, \chi)$



parton transport model MPC

$2 \to 2$ **only**

Au+Au @ 130 GeV, $b = 8$ fm

- minijet initconds
- 1 parton $\longrightarrow$ 1 π hadronization

- v_2 at RHIC requires $15\times$ **perturbative** $2 \to 2$ **rates**

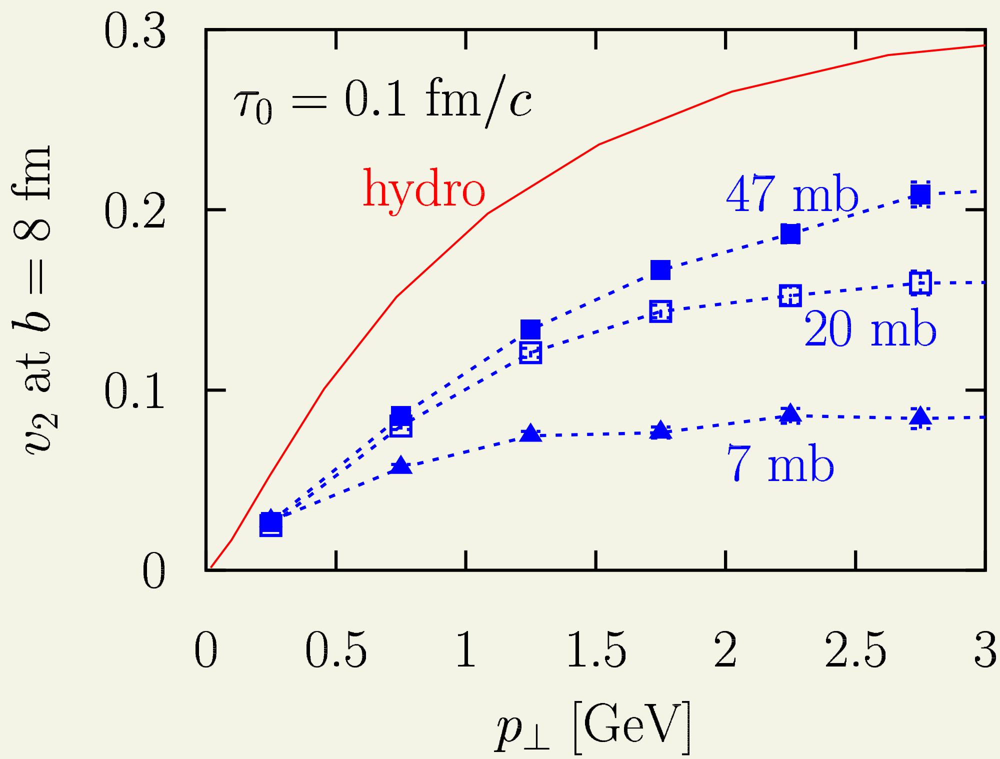
  $\sigma_{el} \times dN_g/d\eta \approx 45$ **mb** $\times 1000$ $\gg$ **perturbative QCD plasma (**3 **mb** $\times 1000$**)**

note: inelastic channels, e.g., $3 \leftrightarrow 2$ **can help by factor** $2 - 4$

Maybe "perfect" fluid, but not ideal

very opaque system but still dissipative even for $\sigma_{gg} \sim 50$ **mb** (**$\lambda \sim 0.1$ fm**)

DM & Huovinen, PRL94 ('05): **final** $v_2(p_T)$

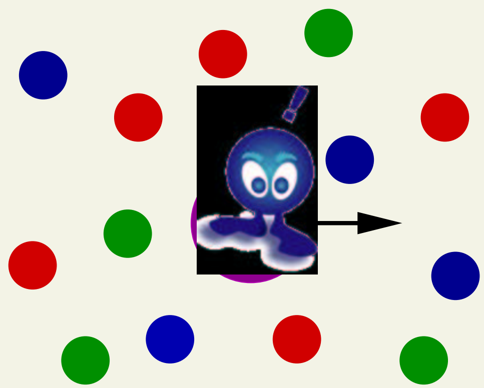


quantum mechanics: $\lambda > 1/3T \leftrightarrow$ **"minimal viscosity"** $\eta/s \approx 1/15$

$\Rightarrow \sigma_{gg} \sim 50$ **mb "as good as it gets"** $\rightarrow$ **troublesome for ideal hydro @ RHIC**

Cross-check: heavy quarks

slower thermalization - mass matters for "Brownian motion" in plasma



$m_g, m_{u,d}, m_s \sim T$

$m_c \sim 1.2$ **GeV** $\gg T$

$v \sim \sqrt{T/m}$

$p \sim \sqrt{m \cdot T}$

$N_{coll} \sim p/\Delta q \sim \sqrt{m/T}$

heavy quarks $\Rightarrow$ need more collisions to randomize/thermalize

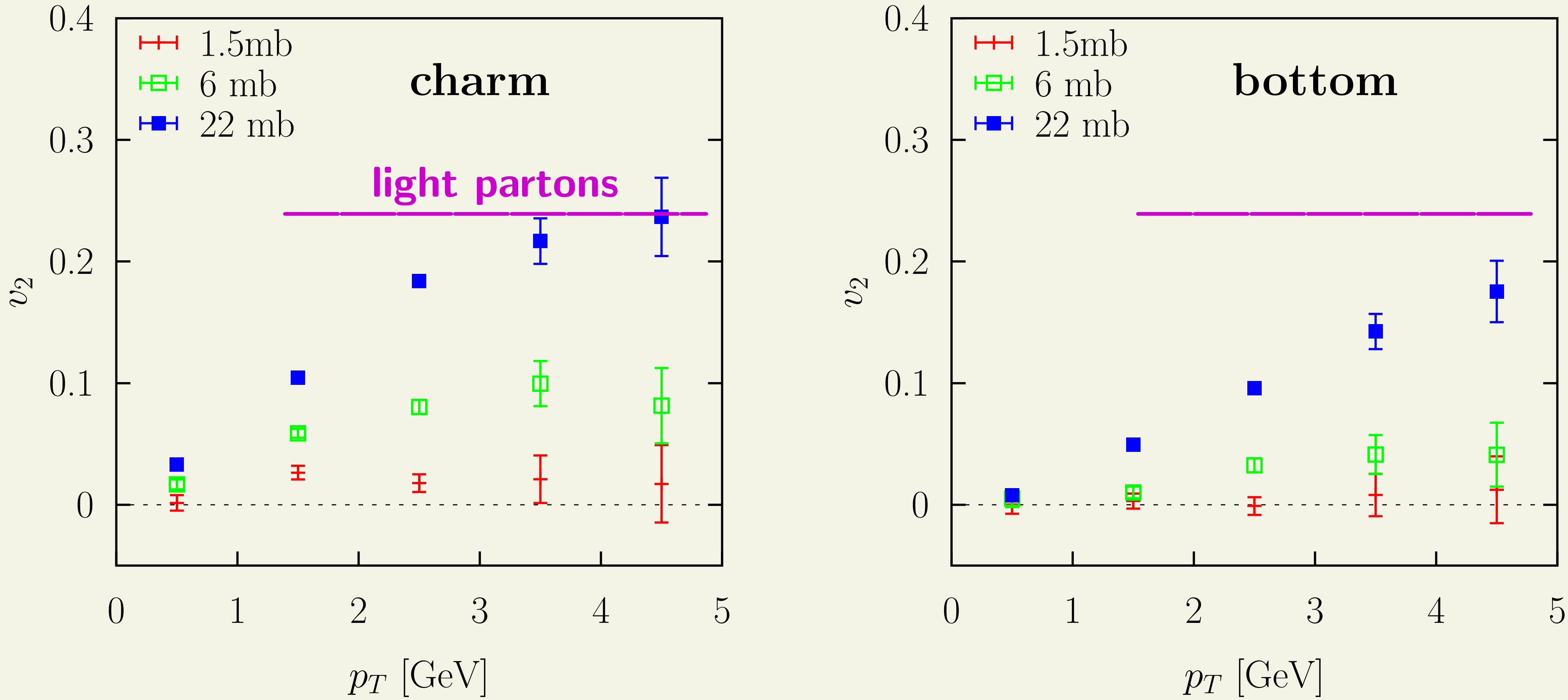
note: perturbatively $\sigma_{quark-gluon} = 4\sigma_{glue-glue}/9 \sim 1.5$ **mb at RHIC**

(also, suppressed radiative energy loss - "dead-cone" effect)

Dokshitzer, Kharzeev, Gyulassy, Djordjevic, Wiedemann, Salgado, ...

Heavy quark elliptic flow (v_2)

DM '06, using MPC 1.8.4:

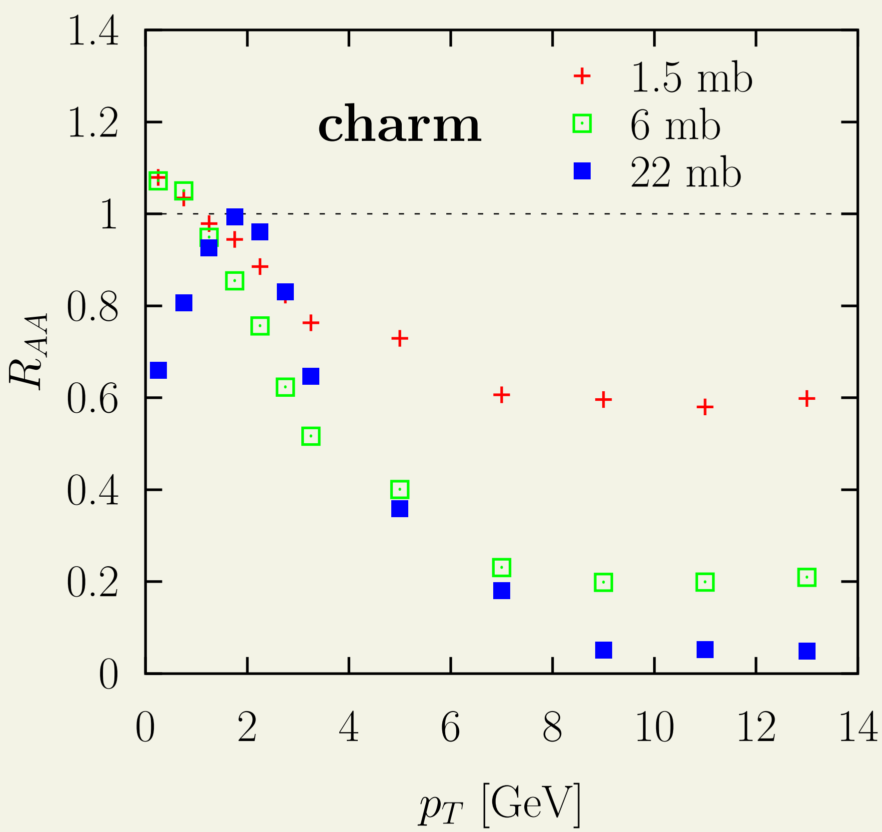


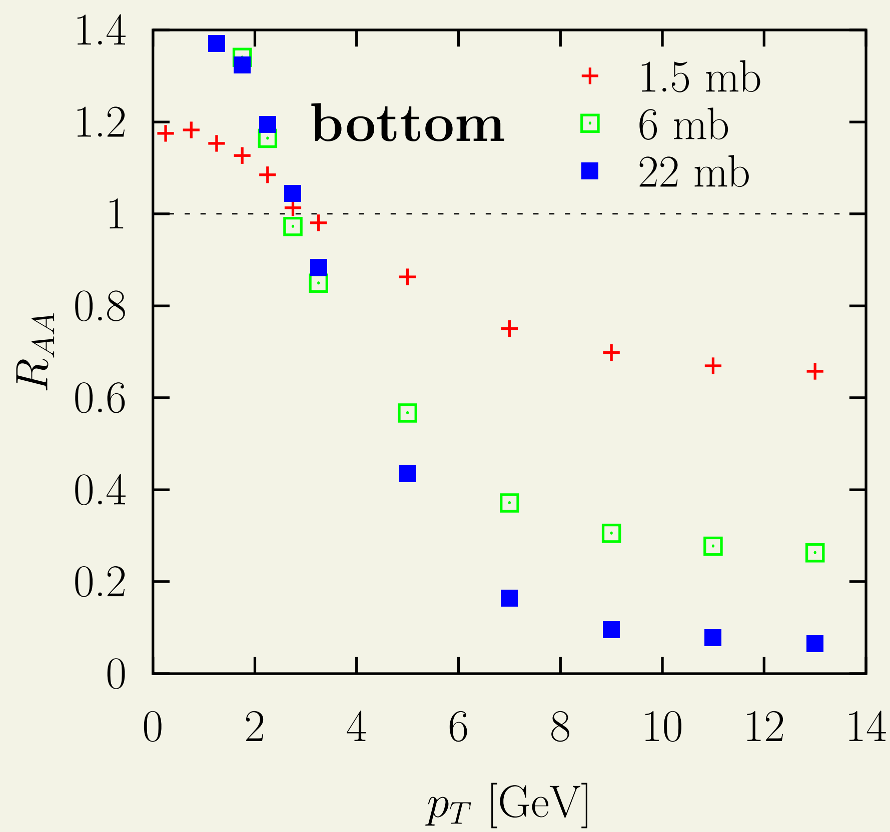
mass suppresses v_2 **at low** p_T**:** $v_2^{light} > v_2^{charm} > v_2^{bottom}$

appreciable heavy quark $v_2 \sim 0.1$ **requires** $\sigma_{qg} \sim 5 - 10$ **mb**

$$R_{AA}(p_T) \equiv \frac{measured\ yield\ in\ A+A}{expectation\ for\ indep.\ N+N scatterings}$$

DM '06, using MPC 1.8.4:





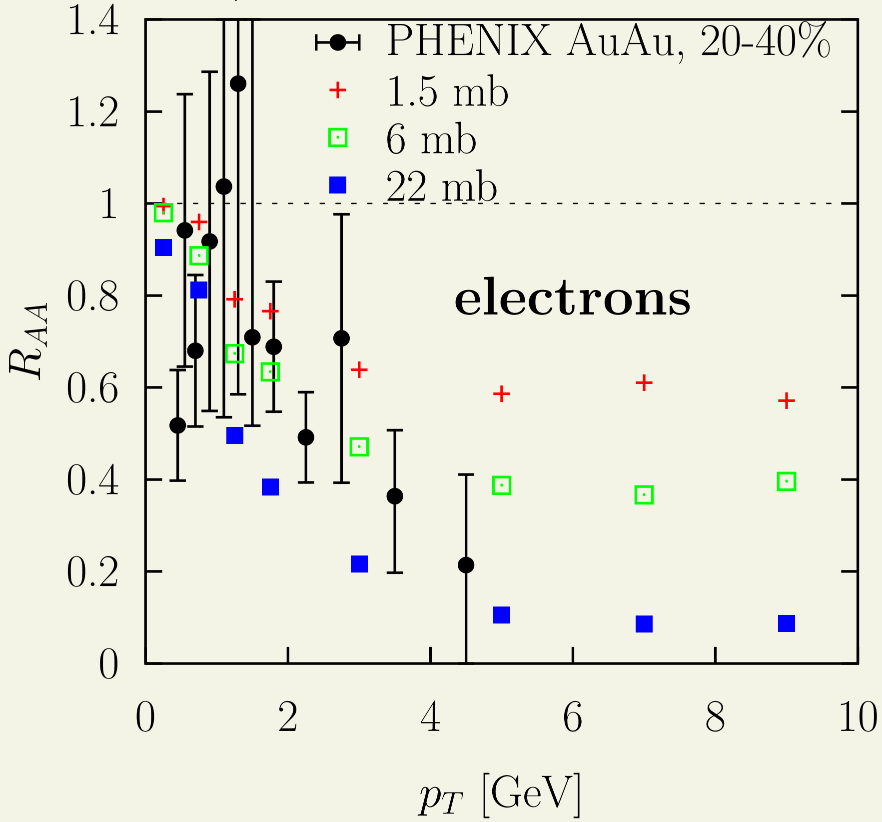
charm is more suppressed than bottom, especially at low p_T

even a small, perturbative $\sigma_{cg} \sim 1.5$ mb generates $R_{AA} \sim 0.6$ at high p_T

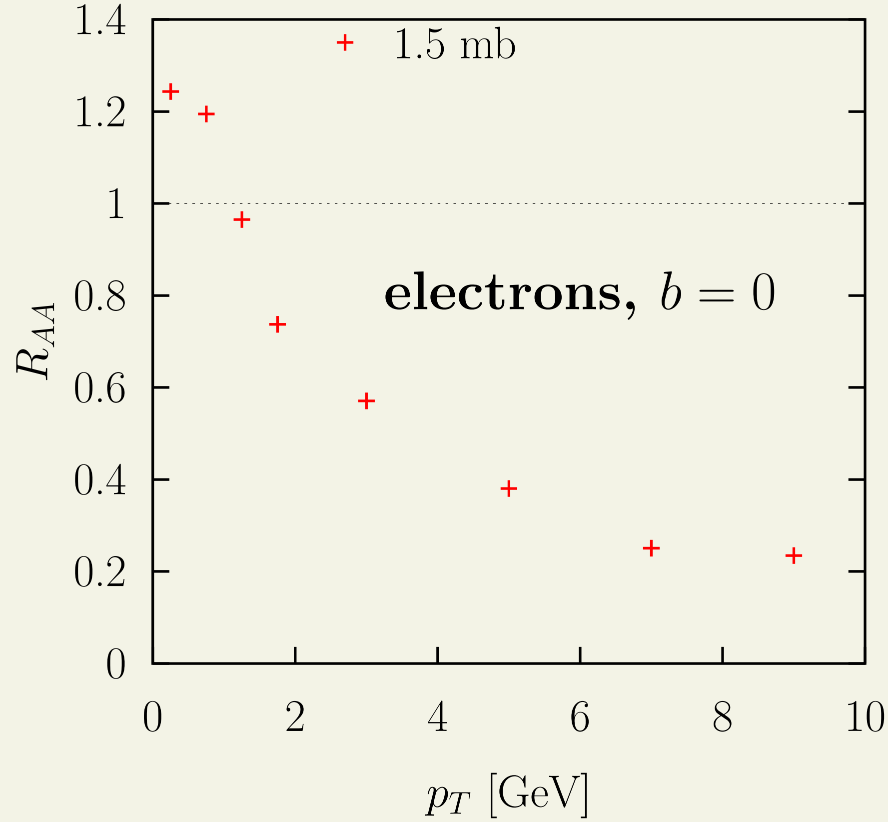
Electron R_{AA}

RHIC: indirect measurement via decay electrons $c\,(D) \to e^{\pm}$**,** $b\,(B) \to e^{\pm}$

DM '06, MPC 1.8.4 vs PHENIX 20-40%: $b = 8$ **fm**



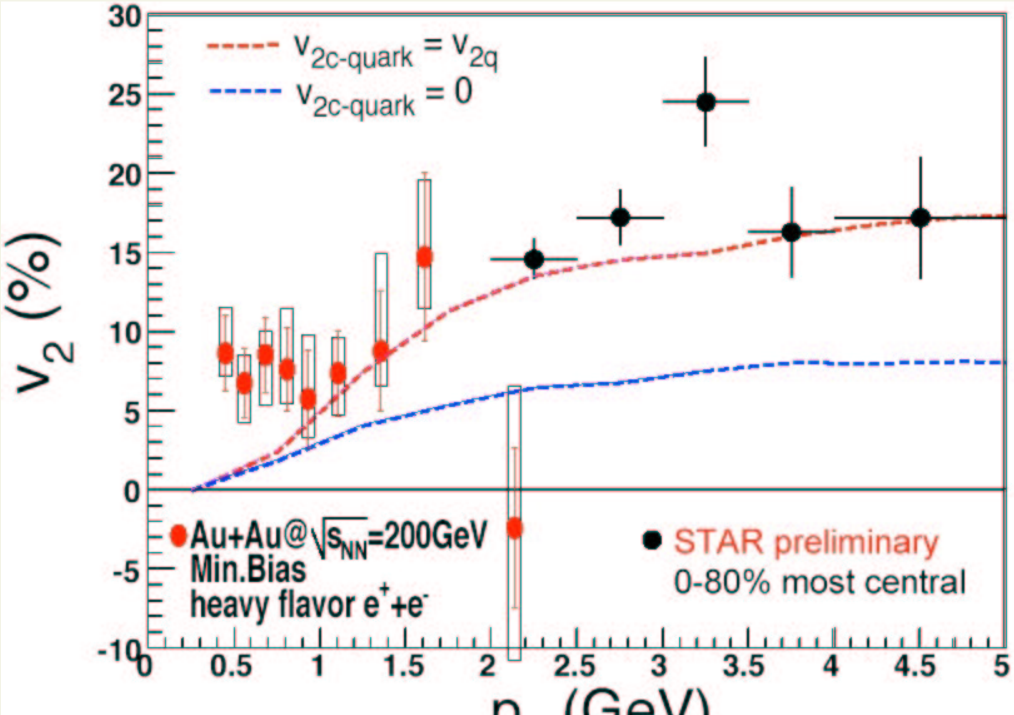
$b = 0$



$\sigma_{cg} \sim 6 - 10$ **mb is most consistent with PHENIX** R_{AA}

$\to$ **up to** $7\times$ **perturbative estimate**

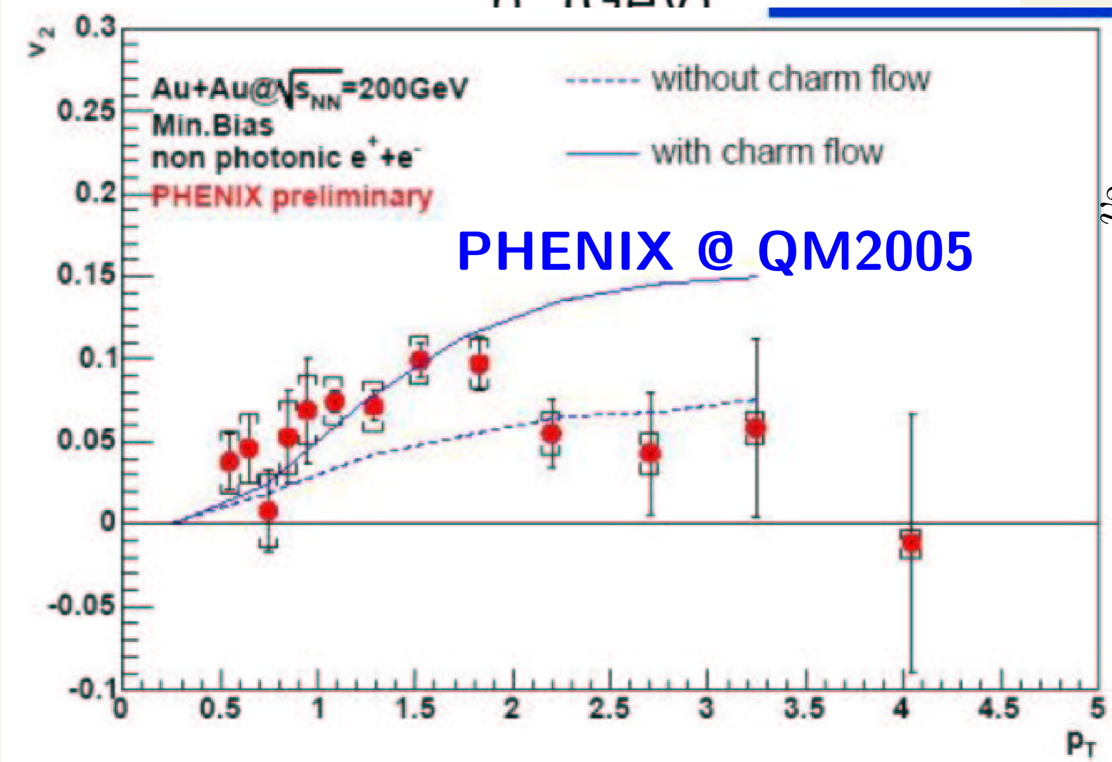
STAR @ QM2005



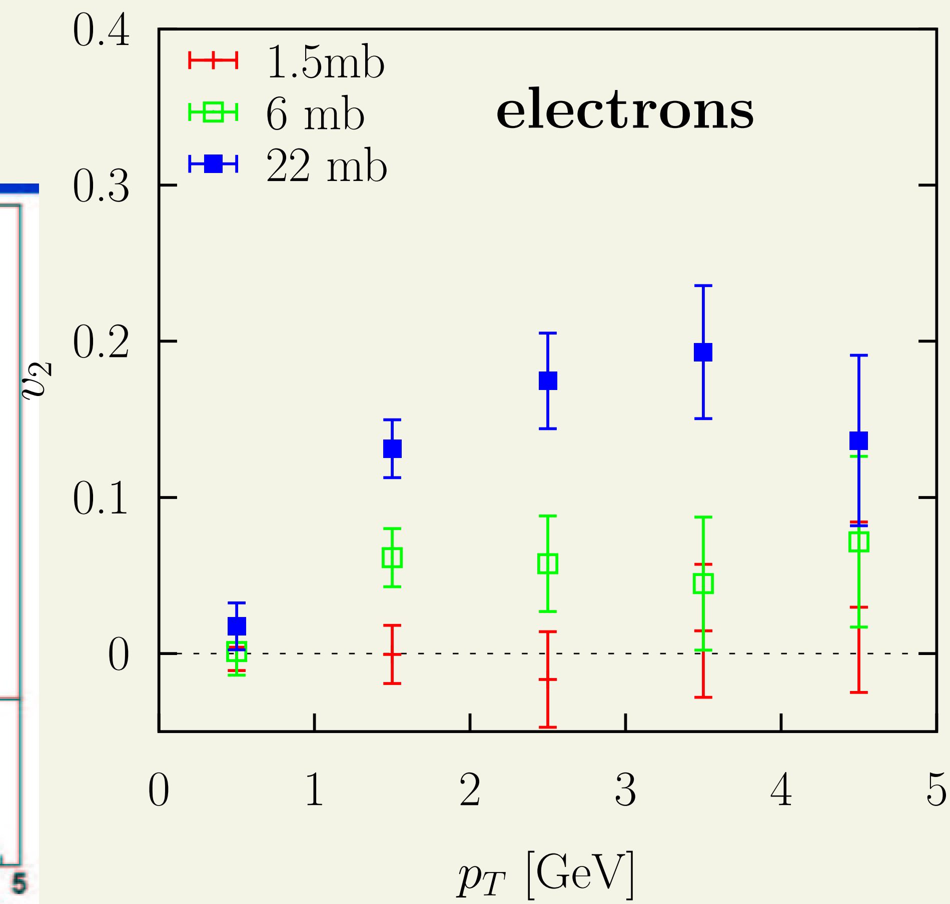
v_2 measurement is tough

STAR: $v_2 \sim 15$%, PHENIX: $v_2 \sim 5$%

transport R^e_{AA} results would be consistent with $v^e_2 \sim 10$ %

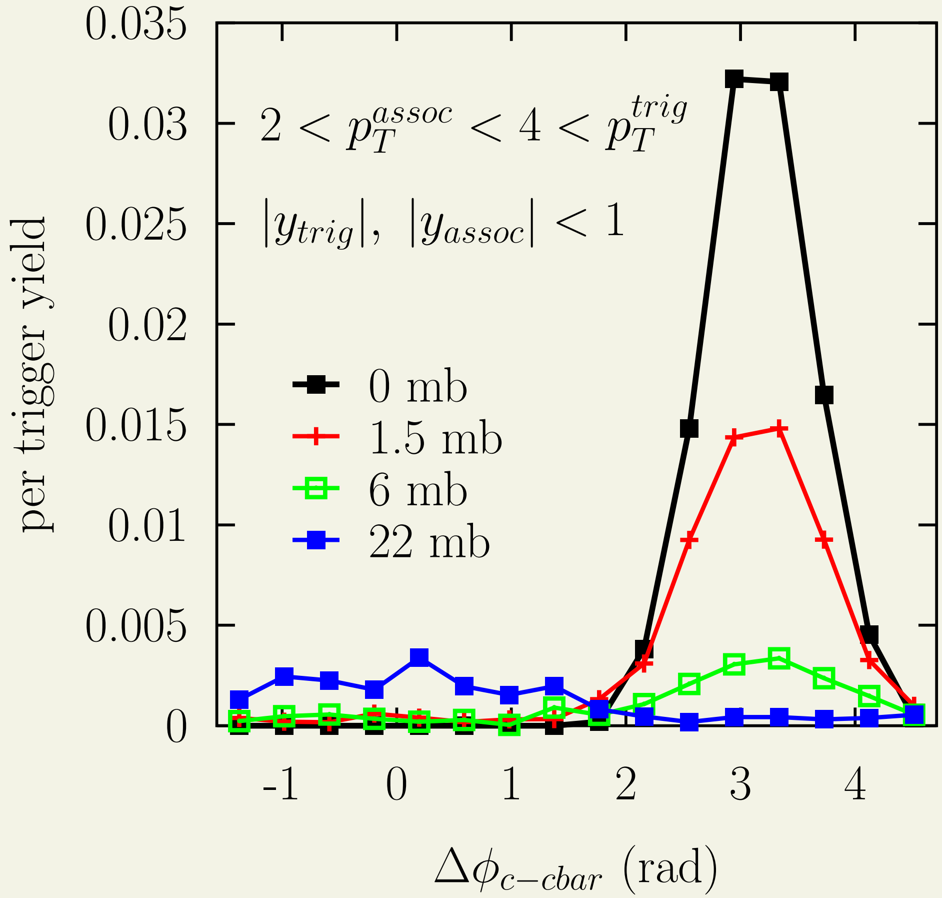


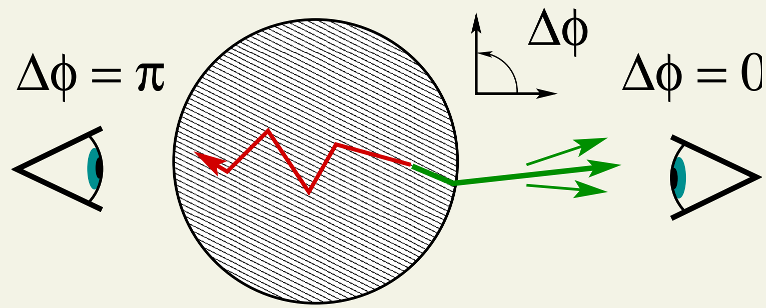
PHENIX @ QM2005



c-cbar azimuthal correlations

DM '06: $b = 8$ **fm @ 200 GeV**





predict $2\times$ **smaller away-side correlation, even for perturbative** $\sigma_{qg} \approx 1.5$ **mb**

Summary

Parton transport theory provides a covariant, nonequilibrium framework to infer the properties of the parton system created at RHIC

superopaque but still dissipative medium at RHIC, even for minimal viscosity)

electron R_{AA} and v_2 data are consistent with effective heavy quark cross sections that are $\sim 4-7\times$ the elastic perturbative values

prediction for c-cbar azimuthal correlations

- Further tests:
  - J/ψ suppression & v_2 calculation (in progress)
  - centrality and collision energy dependence
  - radiative energy loss

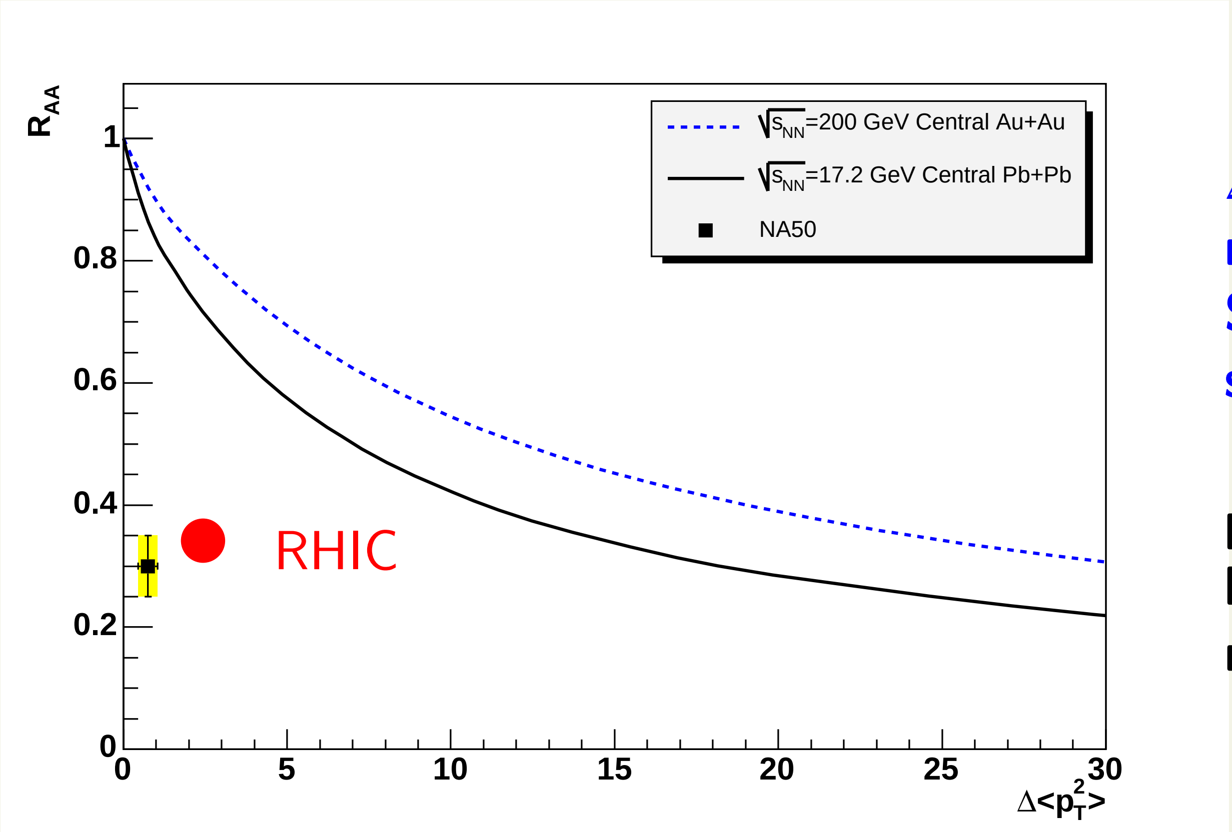
Backup slides

J/Psi suppression

cold nucl. matter ($d+Au$): multiple interactions, $\Delta p_i^2 \sim N_{coll}$ "random walk"

this increases $c\bar{c}$ pair relative momentum $\Rightarrow J/\psi$ suppressed Qiu, Vary, Zhang '98

in addition, $\langle \Delta p_T^2 \rangle \sim N_{coll}$ increases as well Glenn, Nagle, DM, nucl-th/0602068:



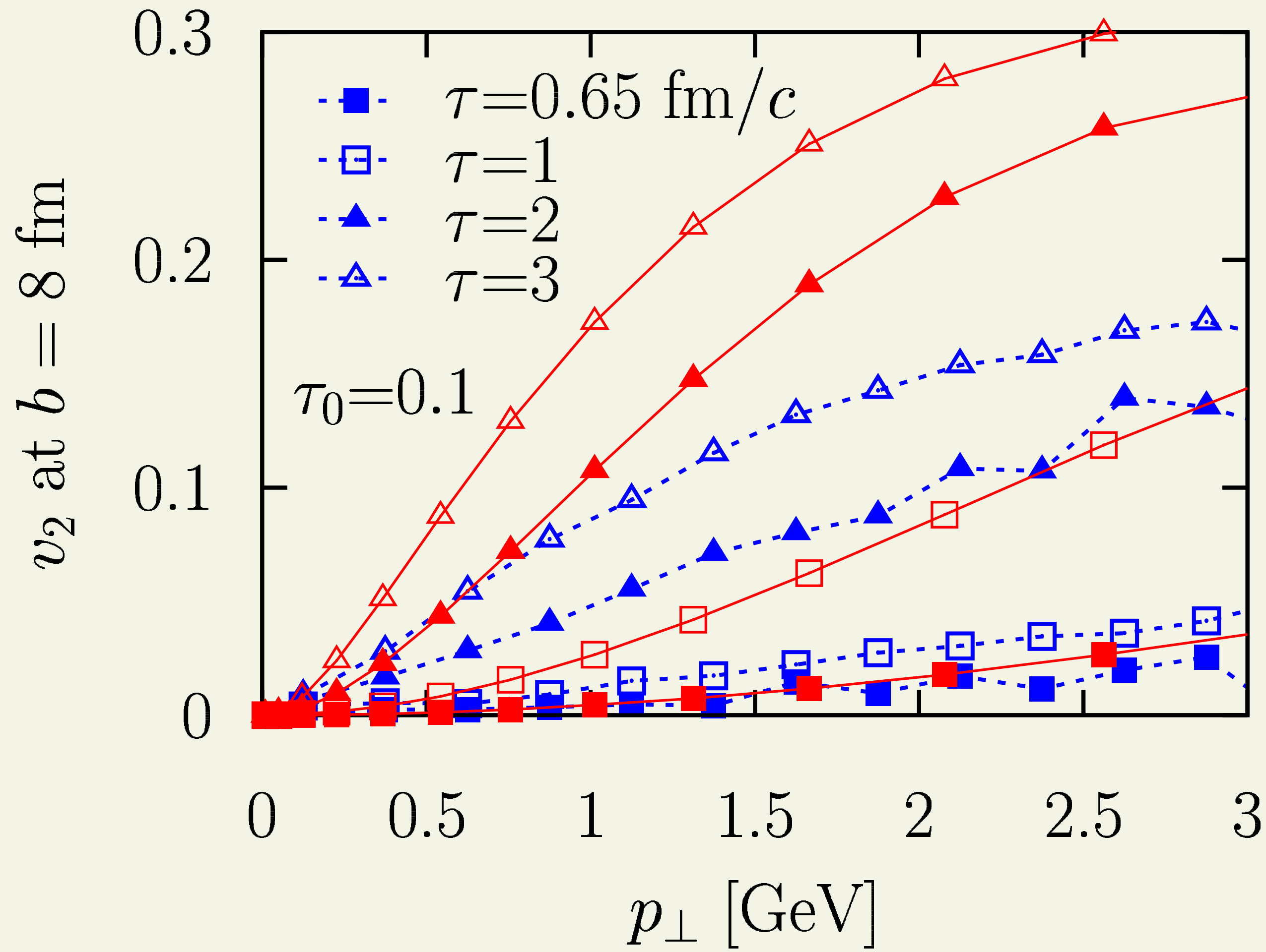
$\Delta p_T^2 - R_{AA}$ correlation prevents reproduction of $A+A$ data at SPS or RHIC for any "collision strength"

provided collective flow, energy loss, and regeneration can neglected

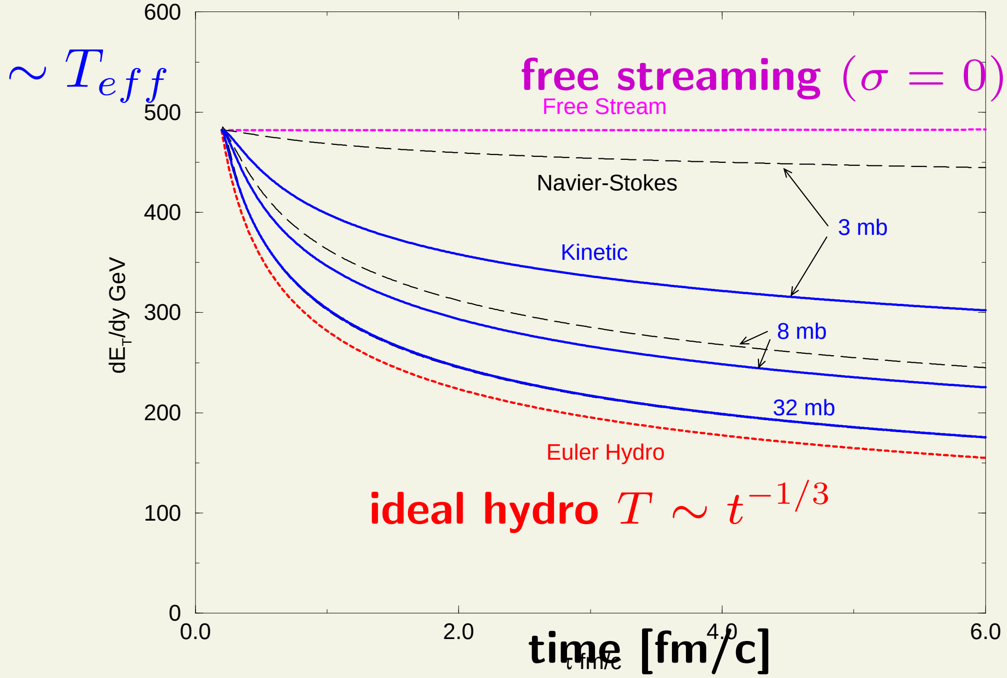
in dense medium all these are important $\rightarrow$ MPC study in progress

Hydro vs transport - v_2 evolution

DM & Huovinen, PRL94 ('05): $v_2(\tau, p_T)$

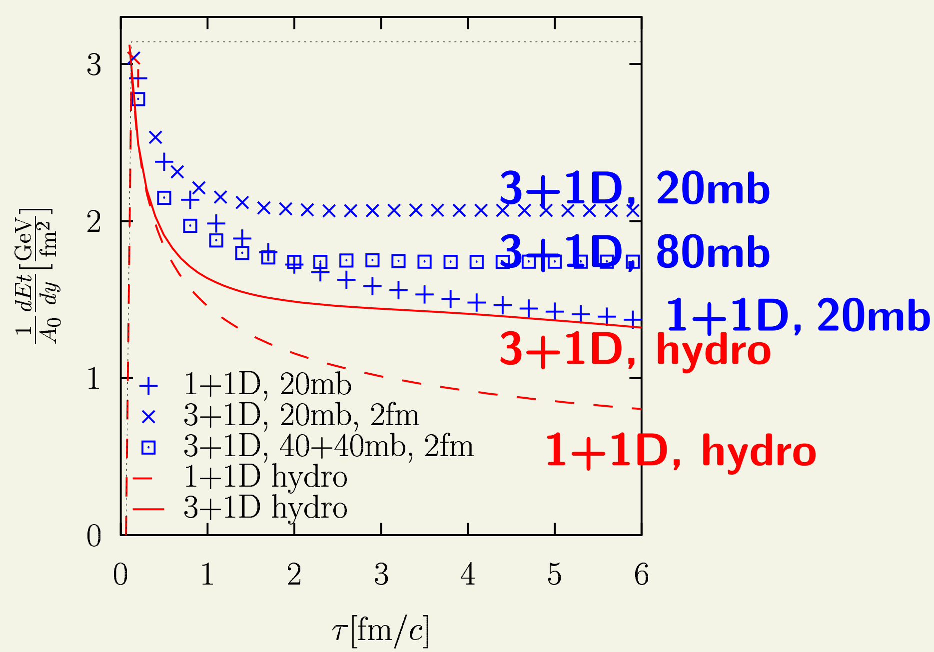


Gyulassy, Pang, Zhang ('97): 1+1D kinetic

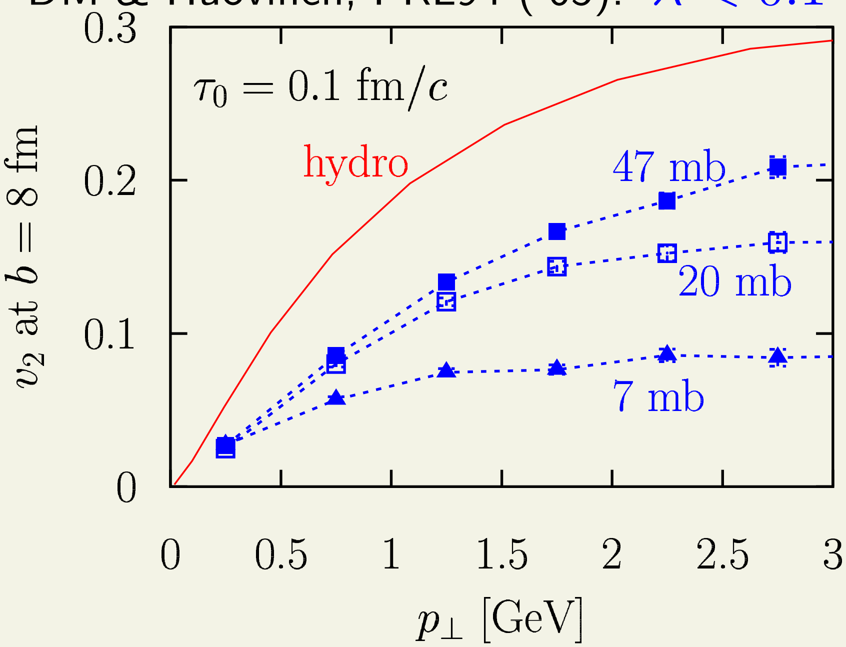


DM & Gyulassy ('00): 3+1D kinetic theory

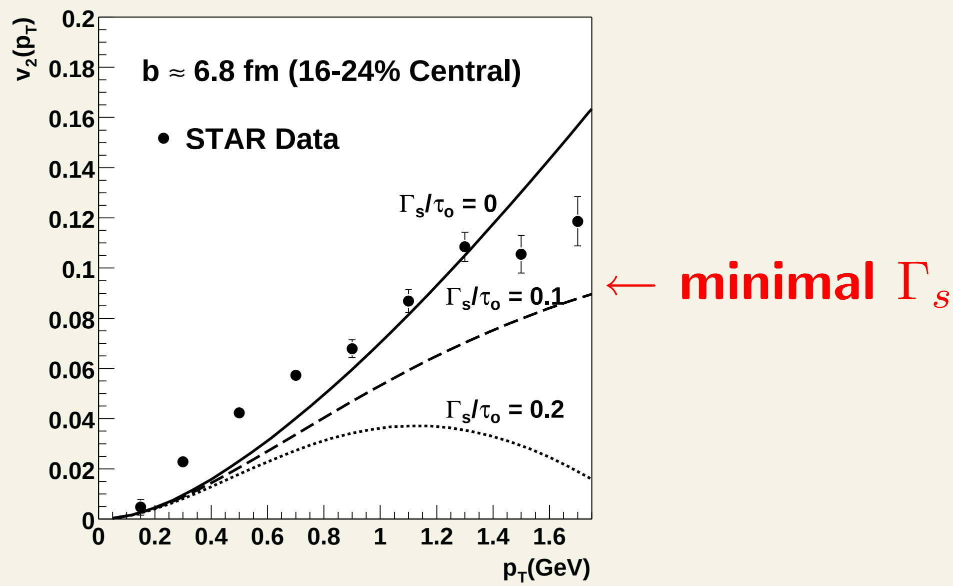
MPC vs hydro (1+1D and 3+1D)



DM & Huovinen, PRL94 ('05): $\lambda < 0.1$ fm



Teaney ('04): $\Gamma_s \equiv 4(\eta/s)/3T$



"Minimal" viscosity

$\sigma_{gg} \sim 50$ **mb** $\Rightarrow \lambda_{MFP}$ **is very short**

quantum mechanics: $\Delta E \cdot \Delta t \geq \hbar/2$

$\Rightarrow$ **kinetic theory:** $T \cdot \lambda_{MFP} \geq \hbar/3$ Gyulassy & Danielewicz '85

viscosity: $\eta = s\frac{\lambda T}{5}$ $\Rightarrow$ **minimal viscosity** $\eta/s \geq 1/15$

"universal" conjecture: $\eta/s \geq 1/4\pi$ Son et al ('02), ('04) - $\mathcal{N} = 4$ SYM

very short MFP at RHIC $\rightarrow$ **most ideal fluid possible? ("perfect fluid")**

Viscous hydro (Navier-Stokes)

zero baryon density limit: $\partial_\mu T^{\mu\nu} = 0$ **with**

$$T^{\mu\nu} = (\varepsilon + p) u^\mu u^\nu - p g^{\mu\nu} + \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \tfrac{2}{3}\Delta^{\mu\nu}\nabla_\alpha u^\alpha) + \zeta \Delta^{\mu\nu}\nabla_\alpha u^\alpha,$$

$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$
$\nabla^\mu = \Delta^{\mu\nu}\partial_\nu$

η, ζ - **shear and bulk viscosities**

sound attenuation: $\omega(k) = c_s k - \frac{i}{2}\frac{1}{\varepsilon+p}\left(\zeta + \frac{4}{3}\eta\right)k^2 = c_s k - \frac{i}{2}k^2\Gamma_s \qquad \left(c_s^2 \equiv \frac{\partial\varepsilon}{\partial p}\right)$

slower cooling in 1D Hubble flow: $\frac{d\varepsilon}{d\tau} = -\frac{\varepsilon+p}{\tau}\left(1 - \frac{\Gamma_s}{\tau}\right)$ Gyulassy & Danielewicz '85

in heavy ion collisions, large gradients $\Rightarrow$ even a small viscosity can matter

DM @ RHIC/AGS Users' Mtg (June 2005):

estimate effect of "minimal" viscosity $\eta/s \equiv \kappa = 1/(4\pi)$: DM '05

for 1D Bjorken expansion, ideal gas $\epsilon = 3p \propto T^4$, $\partial_i u_j \neq 0$ ($i, j \in \{0, z\}$)

$$\frac{d\epsilon}{d\tau} + \frac{\epsilon + p}{\tau} = \frac{4}{3}\frac{\eta}{\tau^2} \approx \frac{4}{3}\kappa\frac{\epsilon + p}{T\tau^2}$$

$$\Rightarrow \frac{T(\tau)}{T_0} = \left(\frac{\tau_0}{\tau}\right)^{1/3}\left[1 + \frac{2\kappa}{3\tau_0 T_0}\left(1 - \left(\frac{\tau_0}{\tau}\right)^{2/3}\right)\right]$$

entropy production already relevant during QGP phase at RHIC

$$\frac{\tau s}{\tau_0 s_0} = \frac{\tau T^3}{\tau_0 T_0^3} \approx 1.1 - 1.2$$

($\tau_0 = 0.6$ fm/c, $T_0 \sim 300$ MeV, $\tau_{QGP} \sim 3 - 5$ fm/c, $\kappa = 1/4\pi$)

even more in realistic case (not uniform 1D, also mixed phase)

challenge: naive Navier-Stokes formulation is severely acausal

causal formulation: viscosities AND microscopic relaxation times Israel & Stewart

$$e.g. \quad \dot{\pi}_{ij}(x) = -\frac{\pi_{ij}(x) - \pi_{ij}^{naive}(x)}{\tau_{rel}}$$

$\Rightarrow$ these could be inferred from heavy-ion data

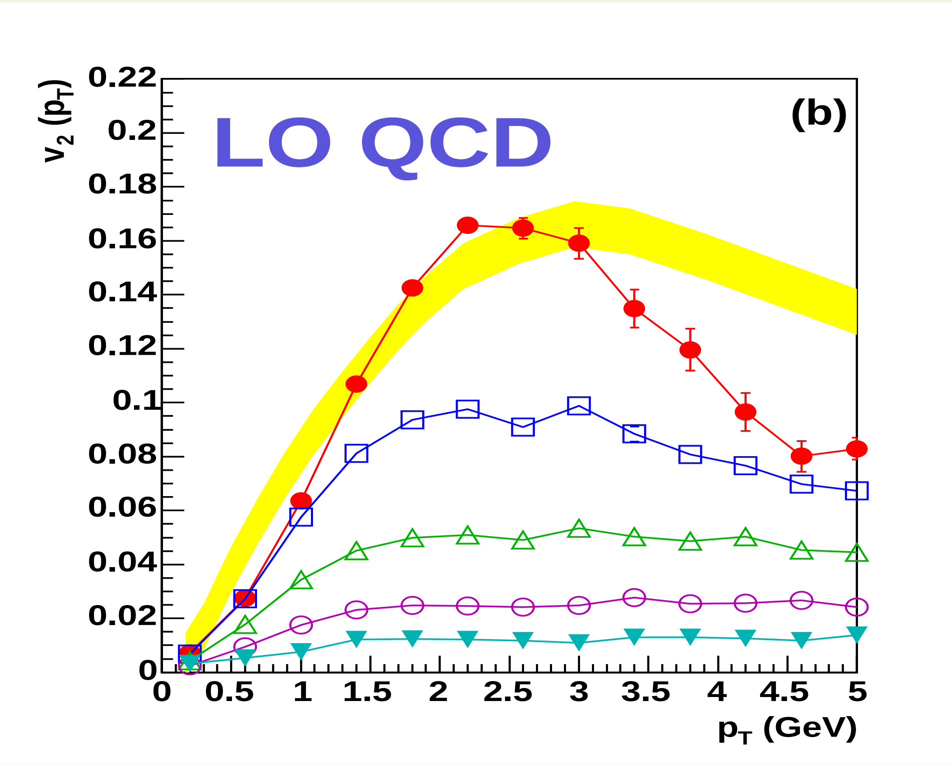
2+1D algorithms are being developed ... Muronga, Teaney, Chaudhuri, Heinz ...

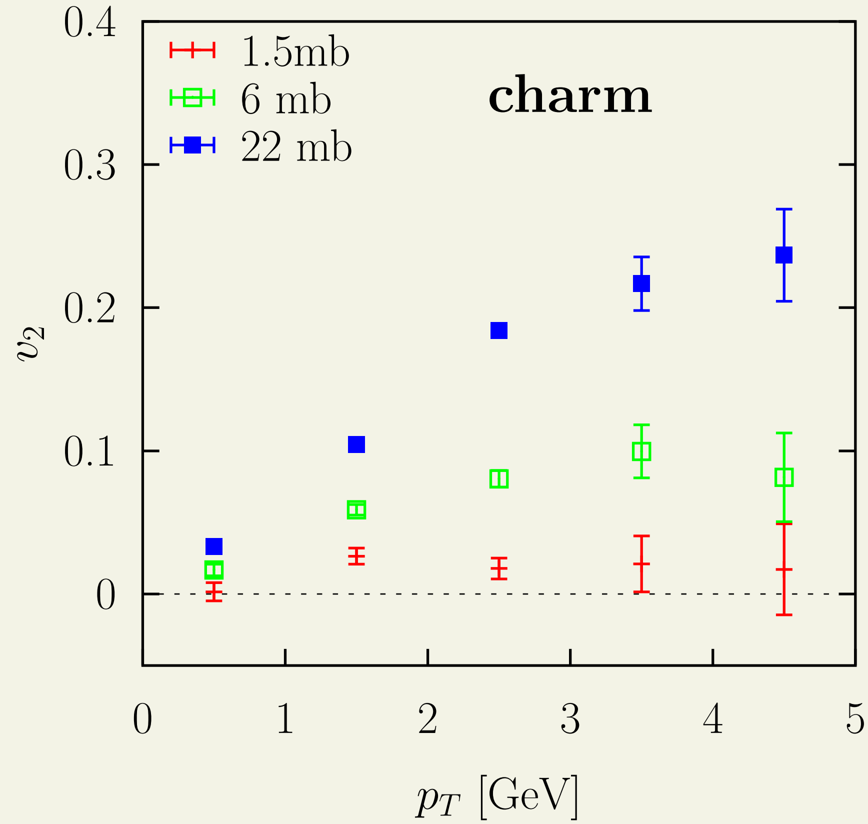
heavy-ion collisions: even viscous version breaks down eventually
$\rightarrow$ decoupling problem

$\rightarrow$ opaque transport gives in fact Navier-Stokes + self-consistent decoupling

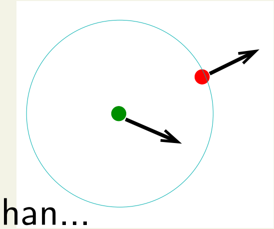
Moore & Teaney ('05): **Fokker-Planck limit (drag + diffusion)**

charm v_2





Lorentz covariance violation

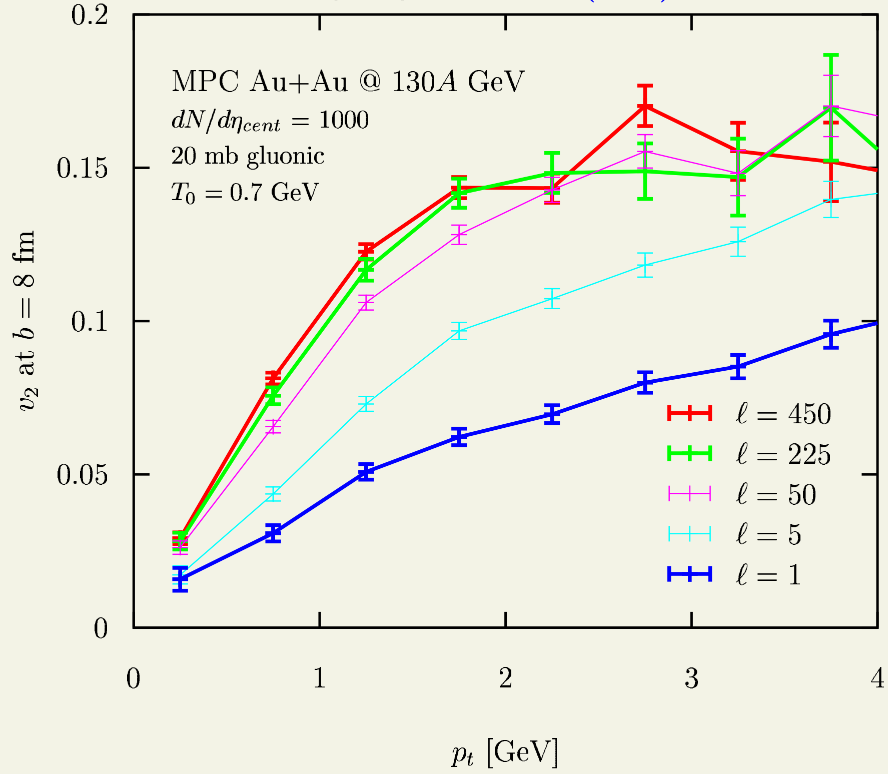


Naive $2 \to 2$ cascade nonlocal - action at distance $d < \sqrt{\frac{\sigma}{\pi}}$

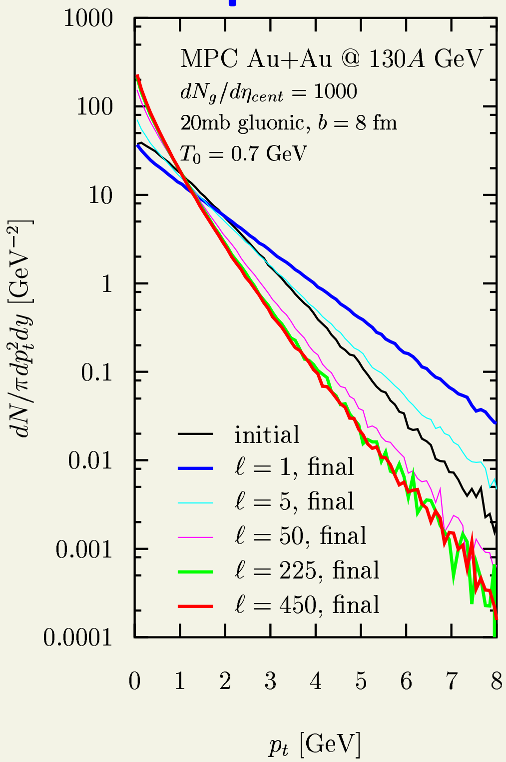
recall - NO-GO theorems in relativistic Hamilton dynamics Currie, Jordan, Sudarshan...

subdivision: rescale $f \to f \cdot \ell$, $\sigma \to \sigma/\ell$ $\Rightarrow$ $d \propto \ell^{-1/2}$ local as $\ell \to \infty$

DM & Gyulassy ('02): $v_2(p_T)$



spectra



RHIC (b=8 fm): need subdivision $\ell \sim 200$ to eliminate $2 \to 2$ artifacts