Correlations from transport theory

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- covariant transport theory
- correlations at RHIC - results & what we learn

  1) - elliptic flow
  2) - space-momentum correlations (relevant for quark coalescence)
  3) - jet correlations
  [4) - HBT]

Heavy-ion double challenge

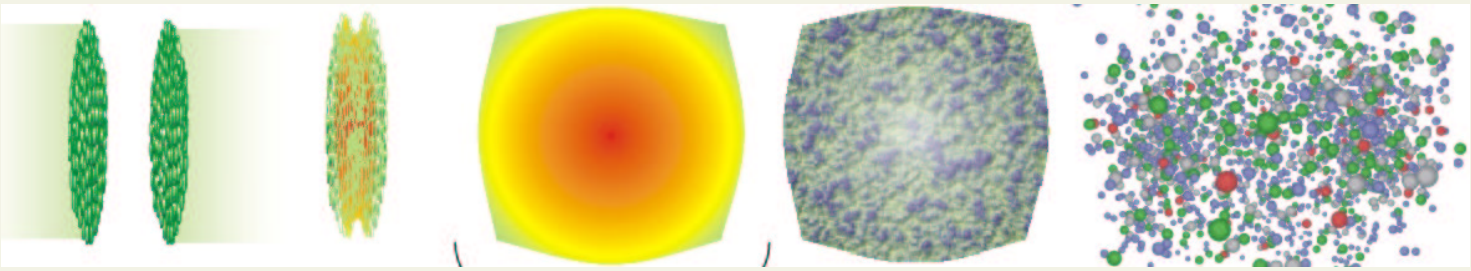
- **partonic condensed matter physics** Kajantie '96

many-body system $\gg \sum$ constituents

- **collision dynamics ($\sim$ plasma physics, nonlinear systems)**

evolving system $\gg$ system in a box

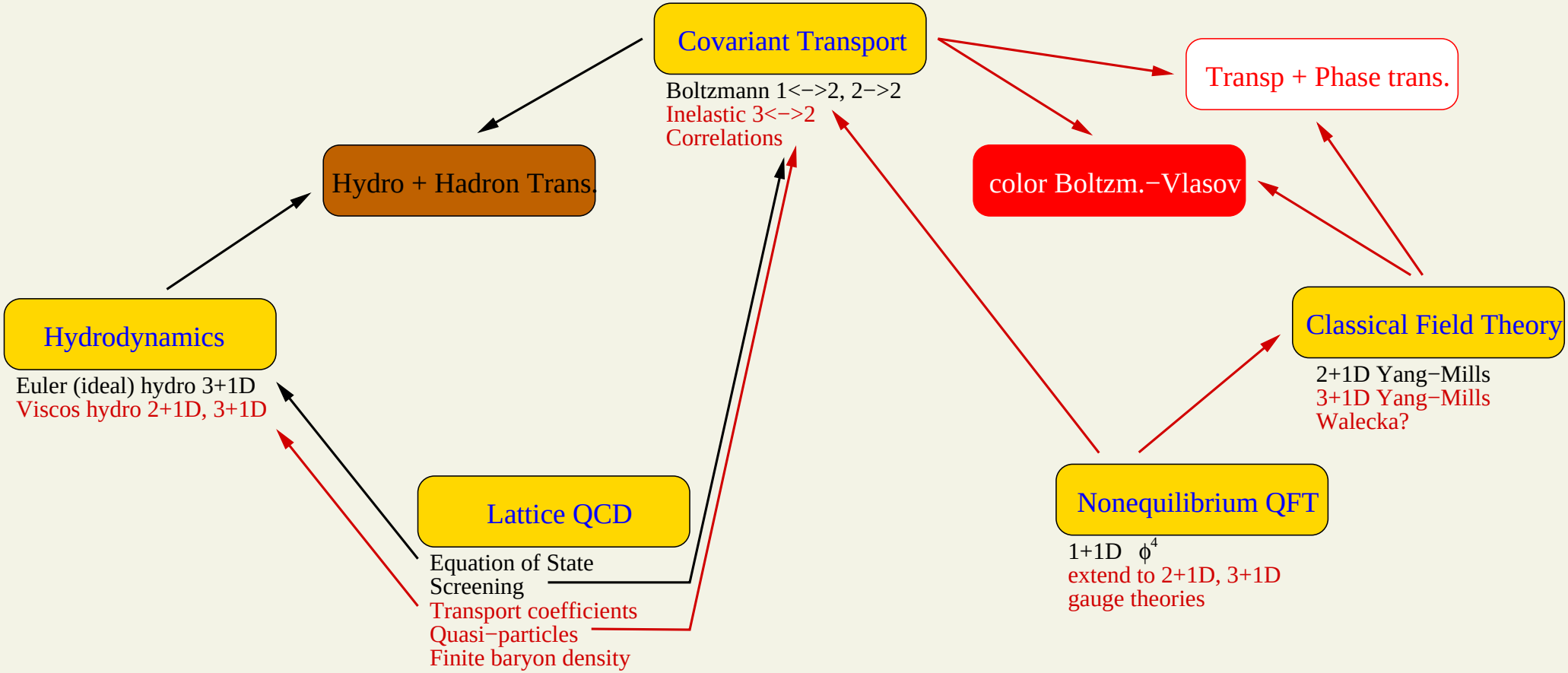
initial nuclei parton plasma hadronization hadron gas



$\sim 10^{-14}$ **m**
= 10 fermis

<—— $\sim 10^{-23}$ **sec = 10 yocto(!)-secs** ——>

Dynamical frameworks



lots of progress - still many open questions

several transport models: RQMD, UrQMD, ZPC, AMPT, MPC, ...

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

→ common ingredient: - kinetic theory

Quark-gluon kinetic theory

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

Incoherent, particle limit of underlying quantum theory (QCD) . Nonequilibrium approach.

local mean free path:

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

Transport opacity: most relevant parameter [DM & Gyulassy NPA 697 ('02)]

$$\chi \equiv \langle n_{coll} \rangle \langle \sin^2 \theta_{CM} \rangle \quad \sim \# \text{ of collisions} \times \text{deflection weight}$$

$$\searrow \sigma^{-1} \int d\Omega \frac{d\sigma}{d\Omega} \sin^2 \theta \equiv \sigma_{tr}/\sigma \rightarrow \textbf{2/3 for isotropic}$$

Boltzmann transport eqn: f_i **- quark/gluon phase space distributions**

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

highly relativistic case $\rightarrow$ only a few covariant algorithms: ZPC, MPC, Bjorken-τ, ...

Molnar's Parton Cascade (MPC)

Elementary processes: elastic $2 \to 2$ **processes** + $gg \leftrightarrow q\bar{q}$, $q\bar{q} \to q'\bar{q}'$ + $ggg \leftrightarrow gg$

Equation for $f^i(x,\vec{p})$**:** $\quad i = \{g, d, \bar{d}, u, \bar{u}, ...\}$

$$
\begin{aligned}
p_1^\mu \partial_\mu \tilde{f}^i(x,\vec{p}_1) \quad = \quad & \frac{\pi^4}{2} \sum_{jkl} \iiint_{2\,3\,4} \left(\tilde{f}^k_3 \tilde{f}^l_4 - \tilde{f}^i_1 \tilde{f}^j_2 \right) \left| \bar{\mathcal{M}}^{i+j\to k+l}_{12\to 34} \right|^2 \delta^4(12-34) \qquad 2 \to 2 \\
& + \frac{\pi^4}{12} \iiiint_{2\,3\,4\,5} \left(\frac{\tilde{f}^i_3 \tilde{f}^i_4 \tilde{f}^i_5}{g_i} - \tilde{f}^i_1 \tilde{f}^i_2 \right) \left| \bar{\mathcal{M}}^{i+i\to i+i+i}_{12\to 345} \right|^2 \delta^4(12-345) \qquad 2 \leftrightarrow 3 \\
& + \frac{\pi^4}{8} \iiiint_{2\,3\,4\,5} \left(\tilde{f}^i_4 \tilde{f}^i_5 - \frac{\tilde{f}^i_1 \tilde{f}^i_2 \tilde{f}^i_3}{g_i} \right) \left| \bar{\mathcal{M}}^{i+i\to i+i+i}_{45\to 123} \right|^2 \delta^4(123-45) \qquad 3 \leftrightarrow 2 \\
& + \tilde{S}^i(x,\vec{p}_1) \quad \leftarrow \textbf{initial conditions}
\end{aligned}
$$

with shorthands:

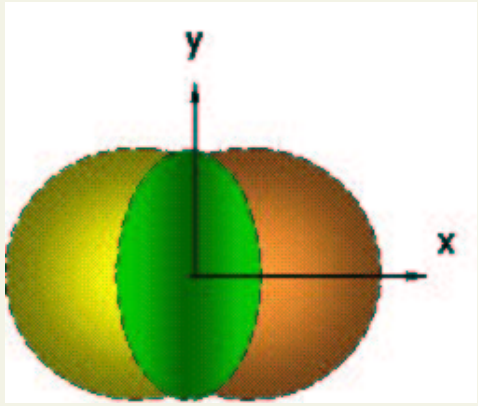
$$\tilde{f}^q_i \equiv (2\pi)^3 f_q(x,\vec{p}_i), \quad \int_i \equiv \int \frac{d^3p_i}{(2\pi)^3 E_i}, \quad \delta^4(p_1+p_2-p_3-p_4) \equiv \delta^4(12-34)$$

I. Elliptic flow

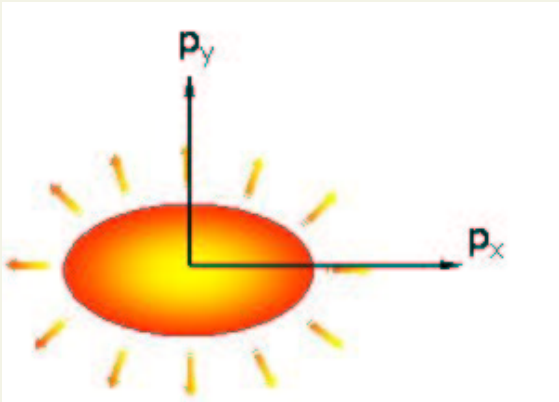
Elliptic flow (v_2)

spatial anisotropy $\longrightarrow$ final azimuthal momentum anisotropy

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



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

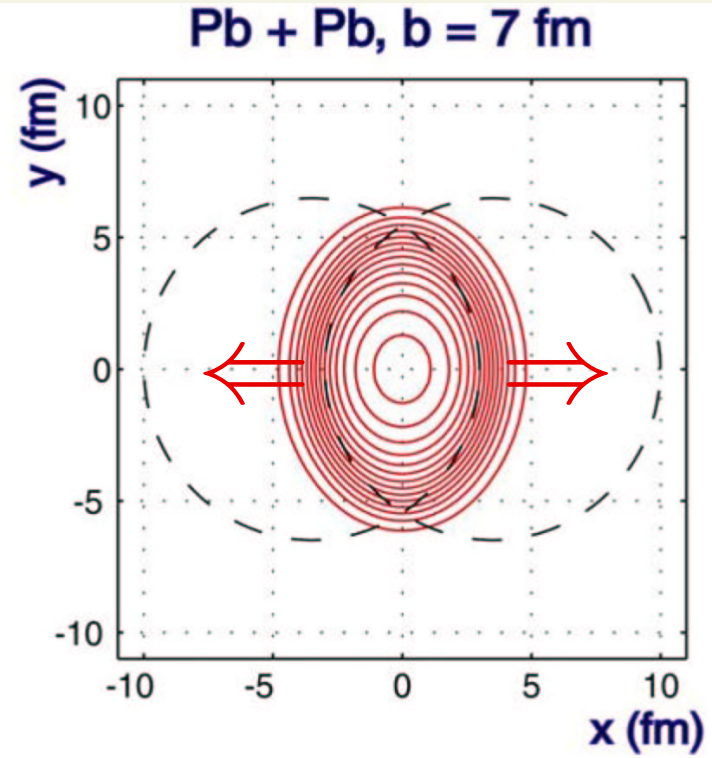


- **measures strength of interactions**
- **self-quenching, develops at early times**

What v_2 measures

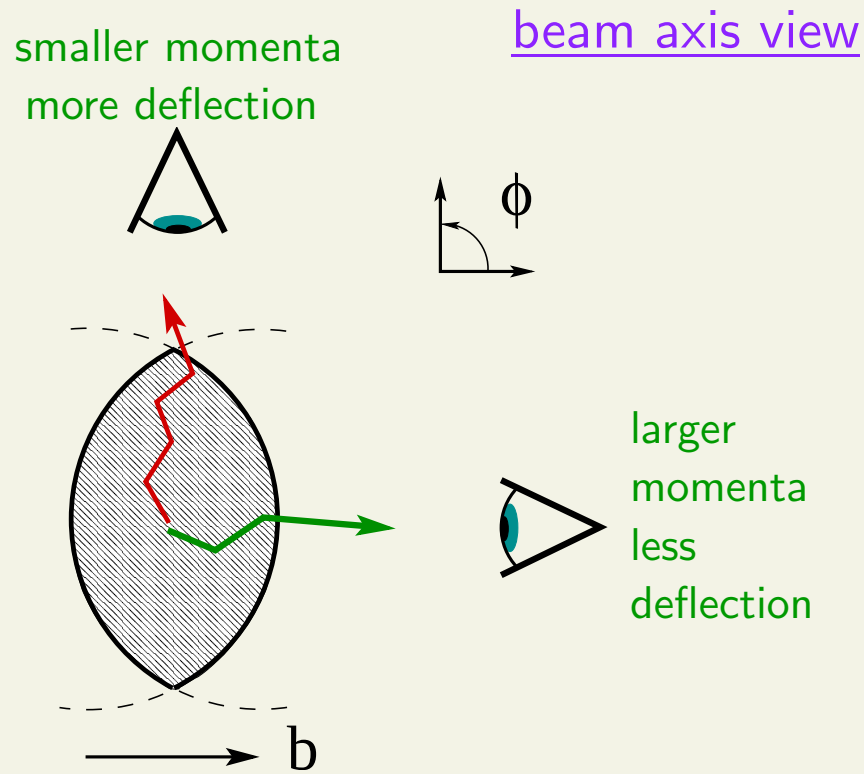
macroscopically: pressure gradients

$$\Delta\vec{F}/\Delta V = -\vec{\nabla}p$$



$\Rightarrow$ **larger acceleration in impact parameter direction**

microscopically: transport opacity



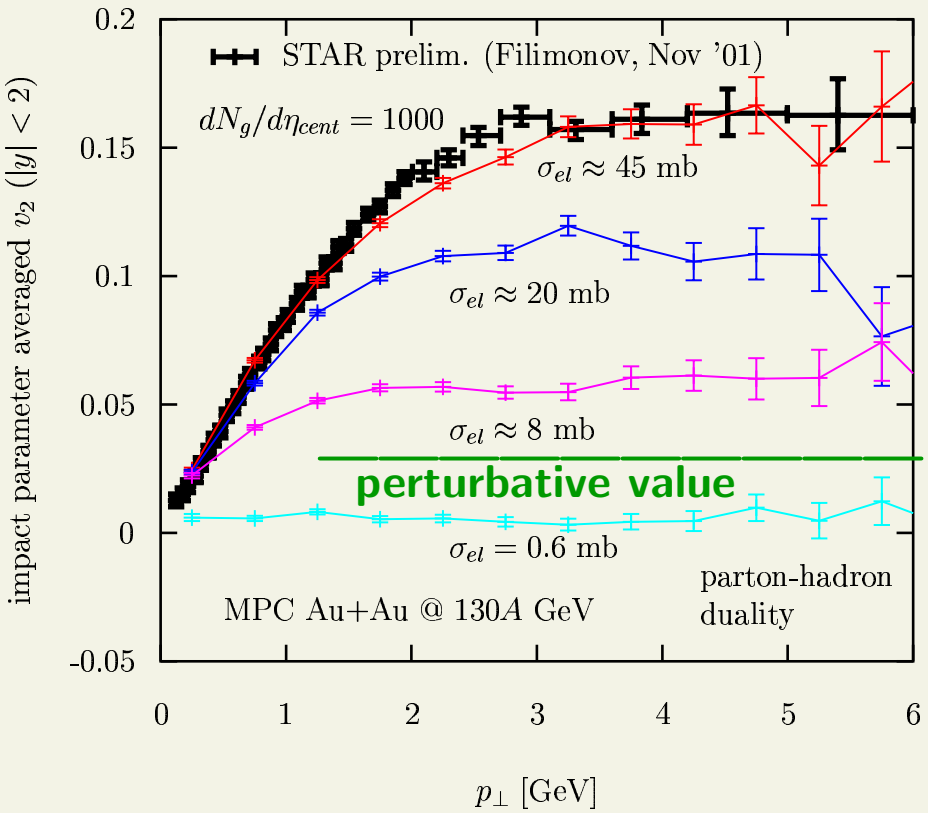
variation in pathlength

$\Rightarrow$ **momentum anisotropy** v_2

Need strong interactions at RHIC

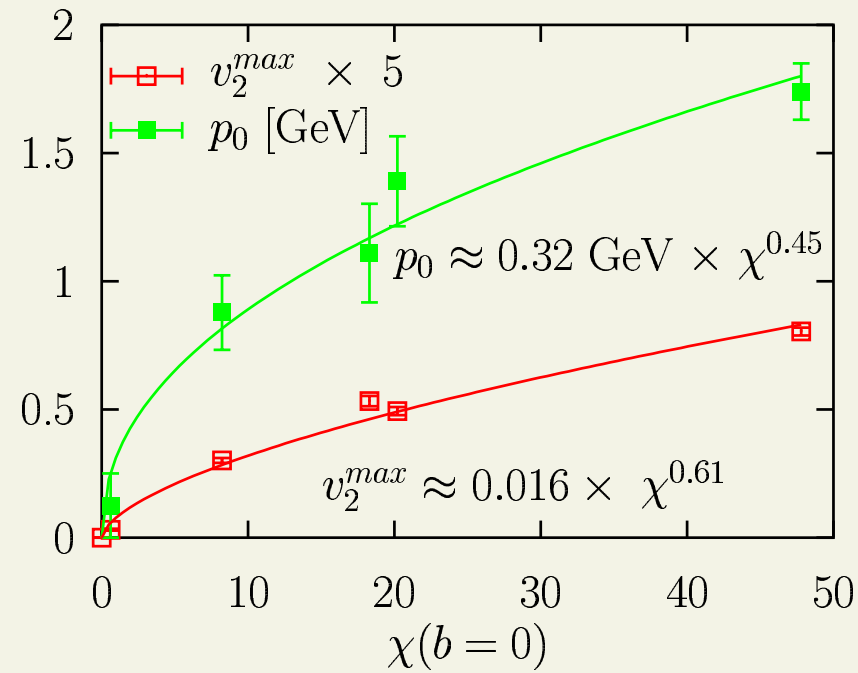
Au+Au @ 130 GeV, $b = 8$ fm from covariant transport

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



nonlinear opacity dependence

$$v_2(p_T, \chi) \approx v_2^{max}(\chi) \tanh(p_T/p_0(\chi))$$



super-opaque plasma - $15\times$ perturbative opacities, $N_{coll}(b{=}0) \sim 70$, $\lambda_{MFP} \sim 0.1$fm

(saturated gluon $\frac{dN^{cent}}{d\eta} = 1000$, $T_{eff} \approx 0.7$GeV, $\tau_0 = 0.1$fm, 1 parton $\rightarrow$ 1 π hadr.)

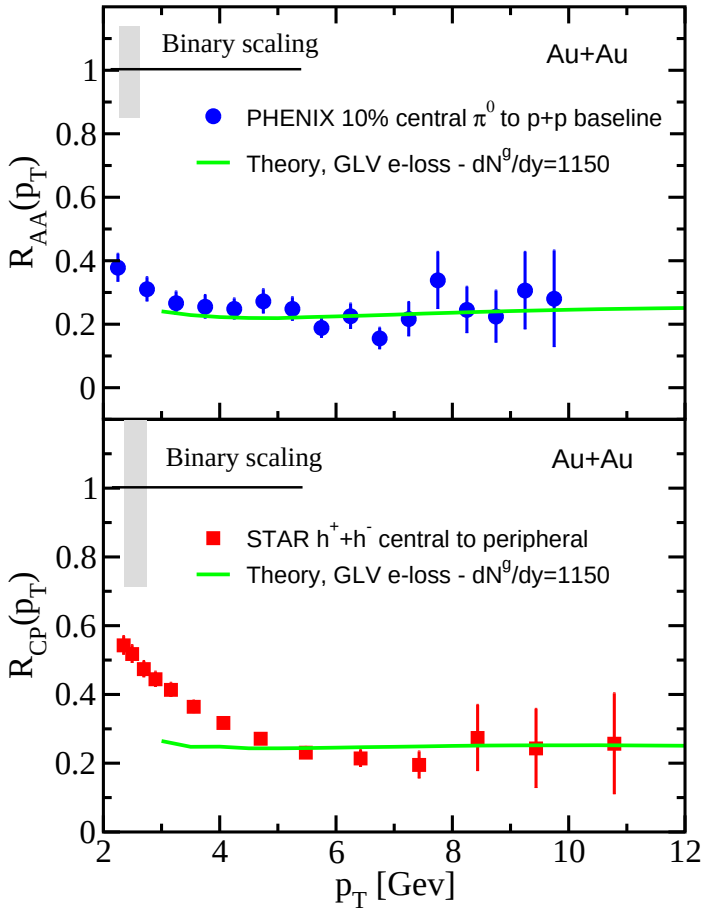
Alternative: Eikonal dynamics

Gyulassy, Vitev, Wang et al, Dokshitzer et al, Wiedemann, Salgado et al ...

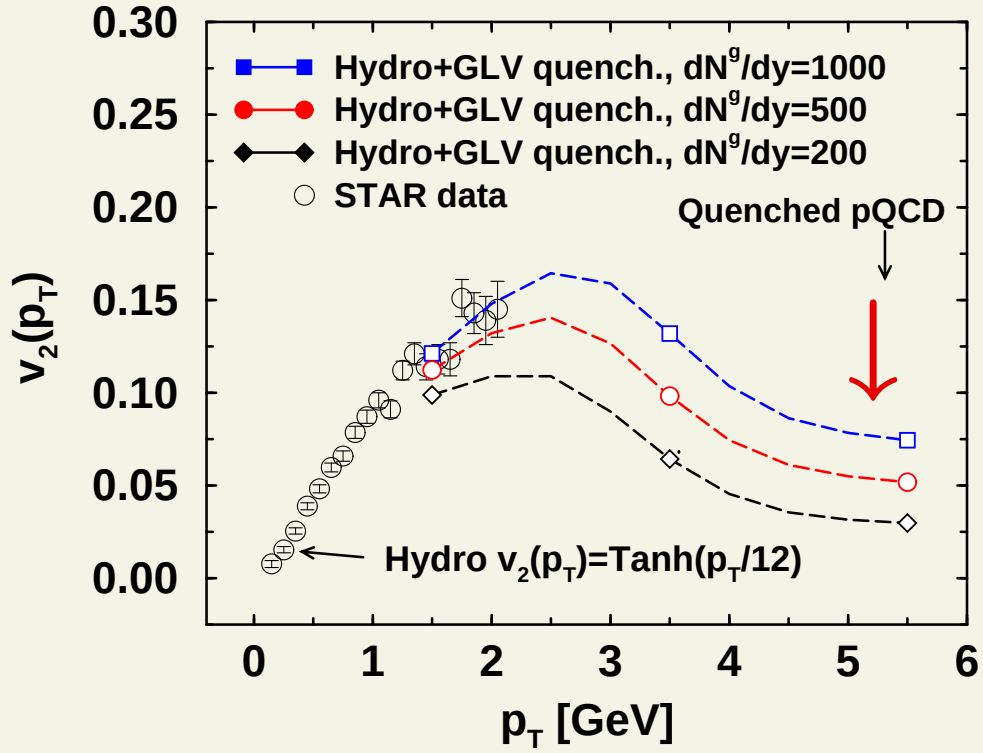
modest opacities, coherent inelastic interactions, $N_{coll}(b{=}0) \sim 5$, $\lambda_{MFP} \sim 1$**fm**

- $dN^{glue}/d\eta \sim 1100$, **perturbative cross sections**

Vitev, QM2004: GLV approach



Gyulassy, Vitev, PRL86 '01:



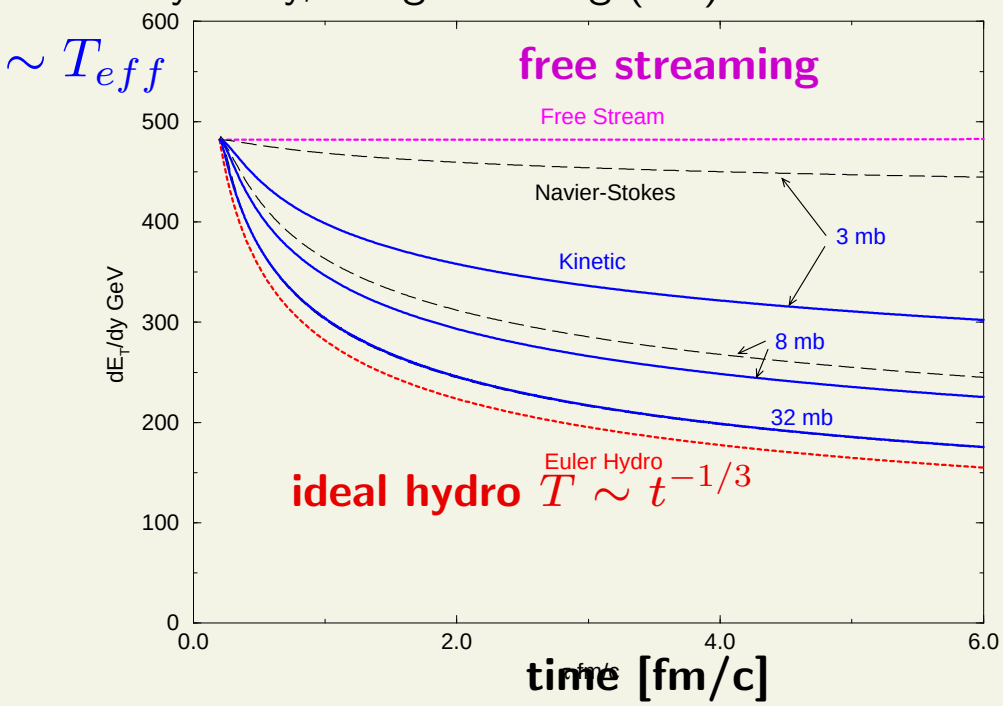
reality probably lies between coherent and incoherent limits

Still not ideal fluid(!)

Even $\sigma_{gg\to gg} \sim 50$ mb is insufficient for ideal hydro (perturbative QGP: ~ 3 mb)

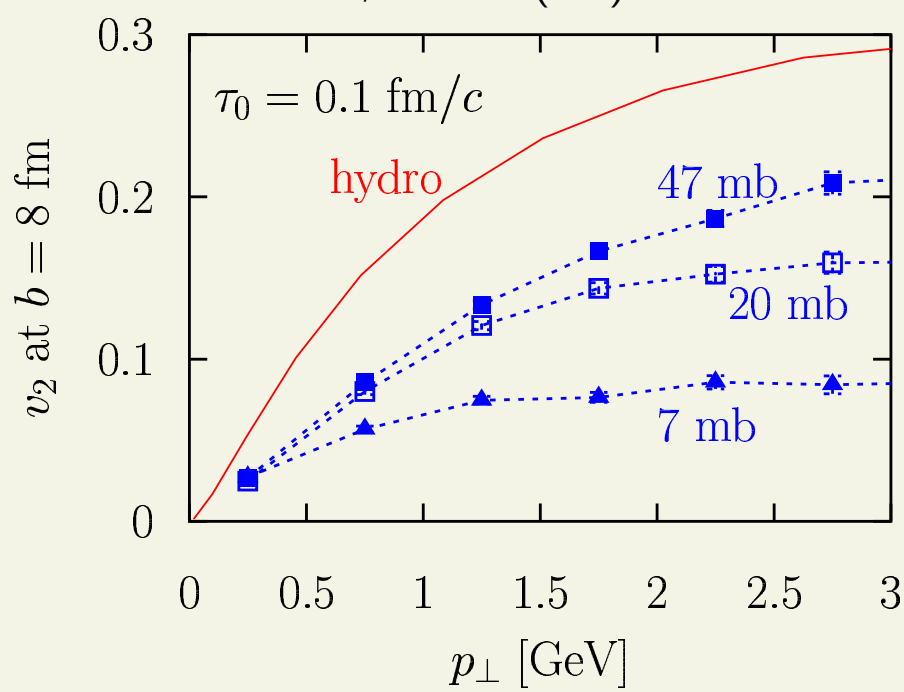
- **less pdV work, slower cooling**

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



- **dissipation reduces v_2 by $30-50$%**

DM & Huovinen, PRL94 ('05): 3+1D



$\rightarrow$ **dense, strongly-interacting system, but dissipative**

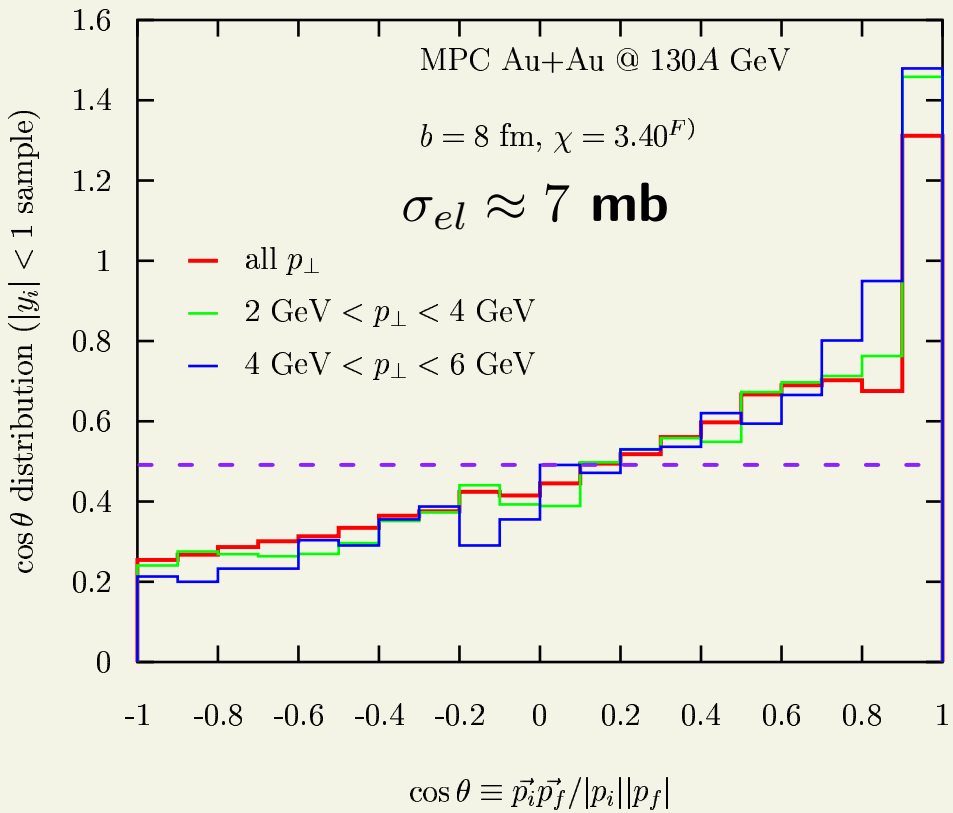
very short mean free path $\lambda \sim 0.1$ fm - close to uncertainty bound $\lambda T \gtrsim 1/5$

Gyulassy, Danielewicz '85

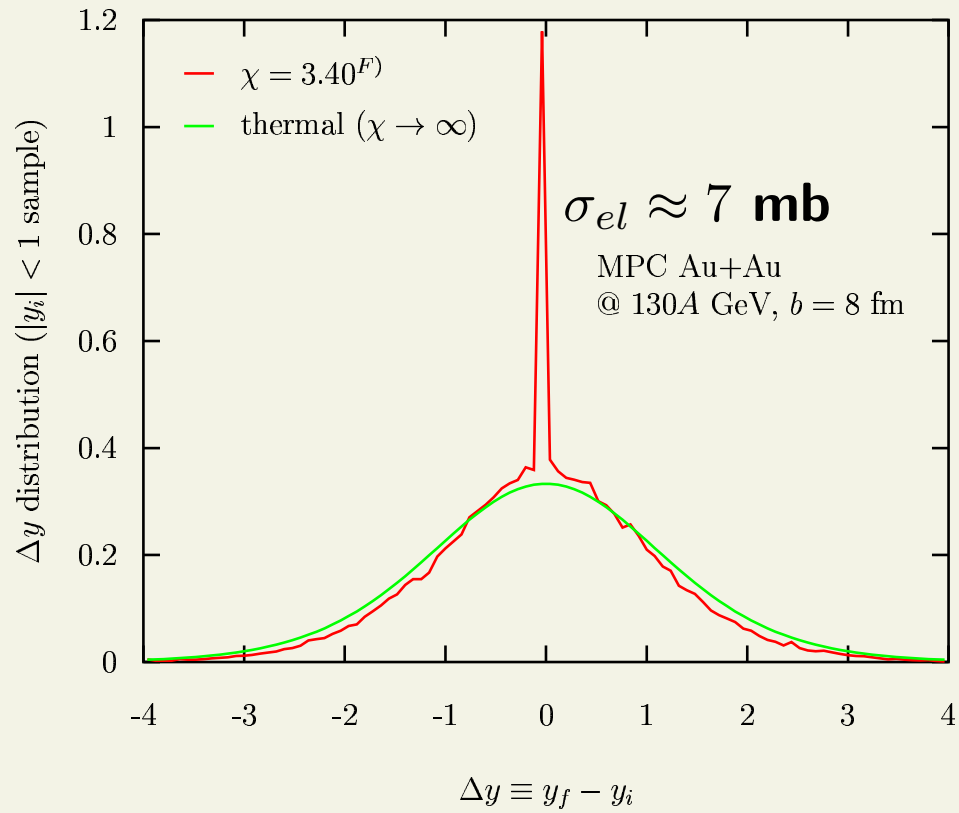
Significant randomization

DM & Gyulassy, NPA697 ('02):

a) cosine of deflection angle $\vec{p}_i \angle \vec{p}_f$



b) rapidity shift $y_f - y_i$

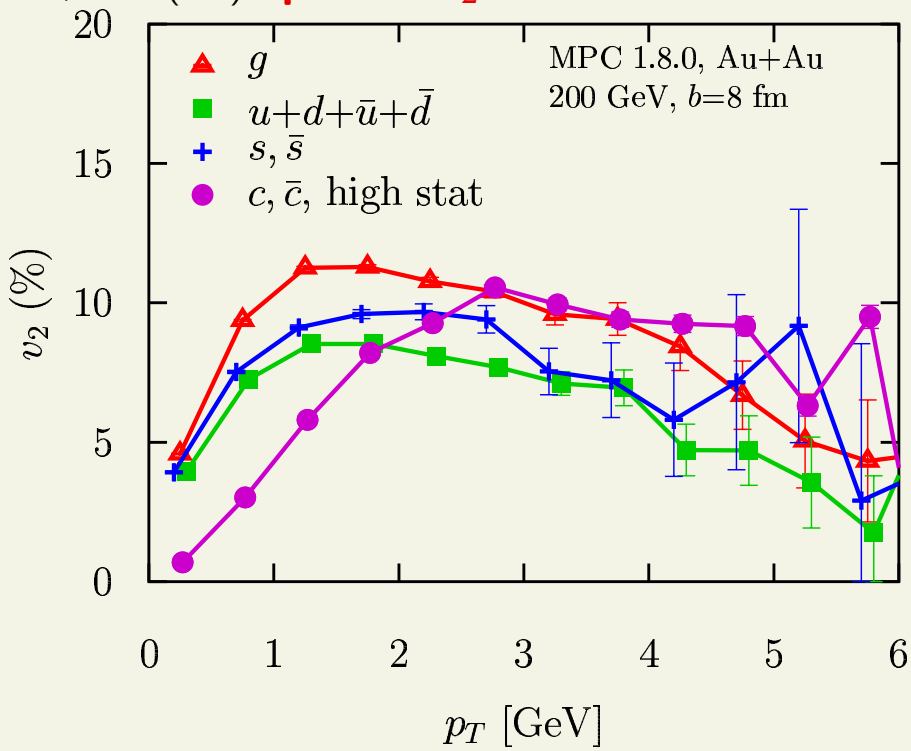


light parton momenta randomize to large degree, already for $\sigma \sim 7$ mb ($\chi \sim 7$) - very different from Eikonal

Even charm (should) flow

parton transport MPC 1.8.0 **vs** **indirect $D(qc)$ meson measurement:**

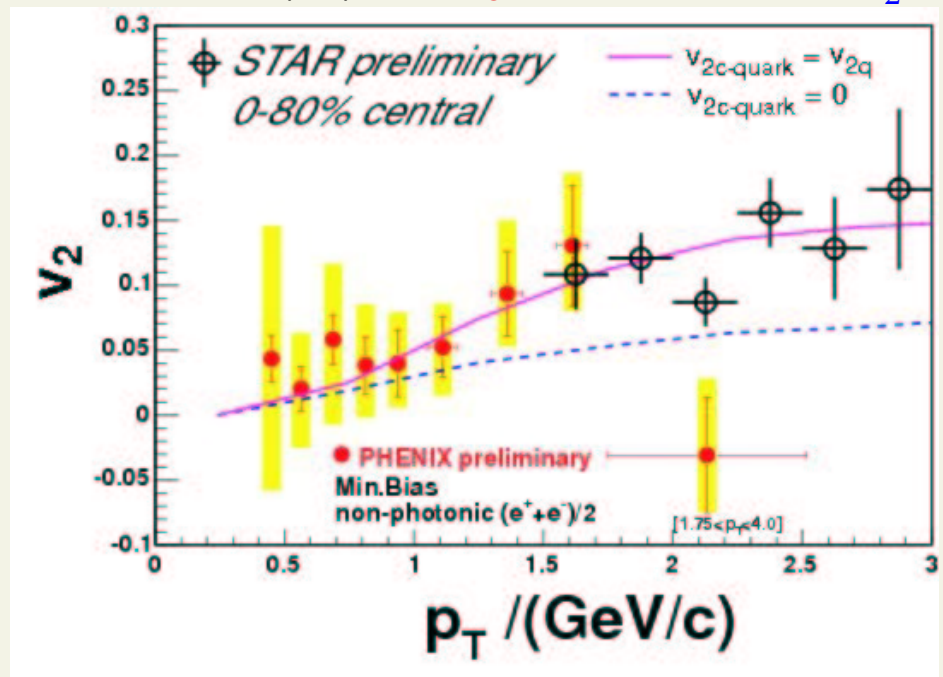
DM, JPG ('04): **parton v_2**



elastic & inel. $2 \to 2$

$6\times$ perturbative opacities

PHENIX, STAR ('04): **decay electron v_2** $\approx v_2^D$



uses decay electrons: $D \to K^{(*)}\,\nu\, e$

e's from hadron decays and γ-conversion subtracted
$\equiv$ "non-photonic"

qualitative agreement, now detailed studies needed - $v_2(b, \chi, \sqrt{s})$

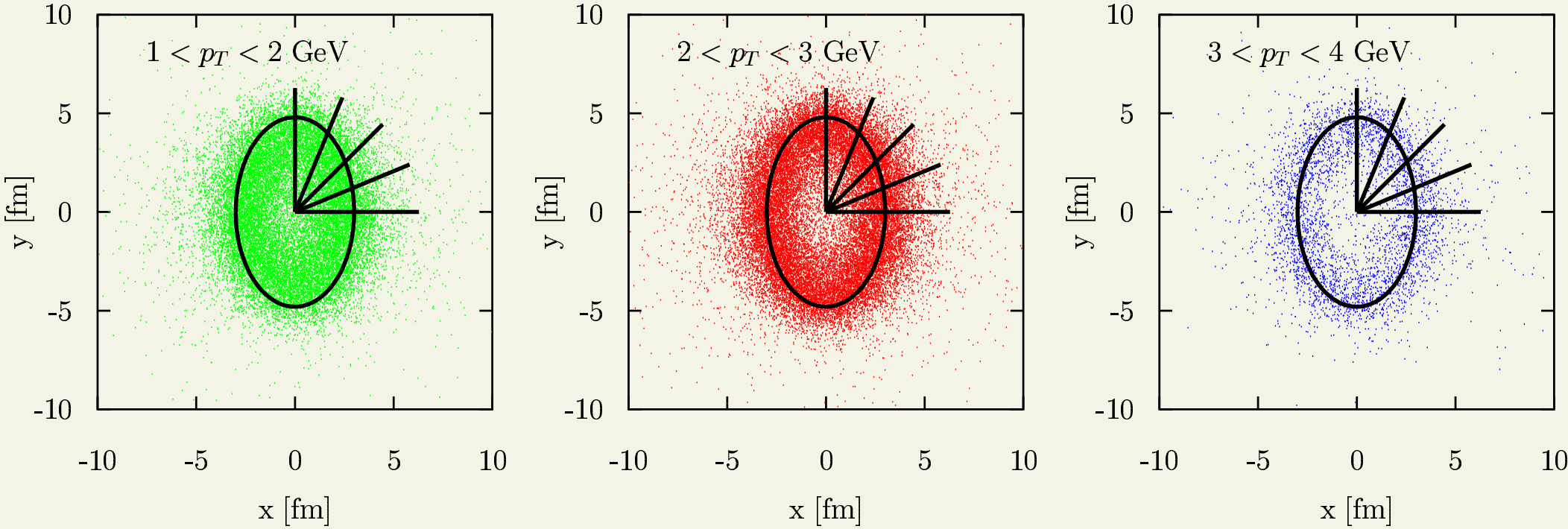
though puzzling that predicted secondary charm production not seen DM '04

II. where high-pT particle come from

- **spacetime**
- **pT history**

Transverse position

DM '04: **final transverse position distributions** $(|y_{rap}| < 2)$

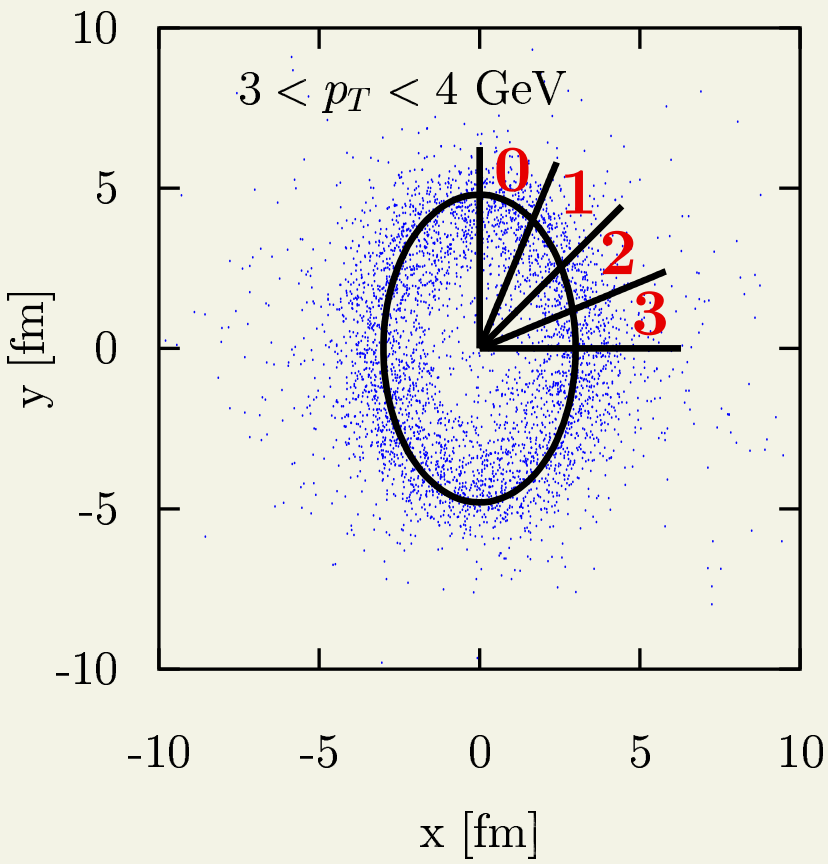


no sharp freezeout - diffuse, typical for transport DM & Gyulassy, PRC62 ('00)

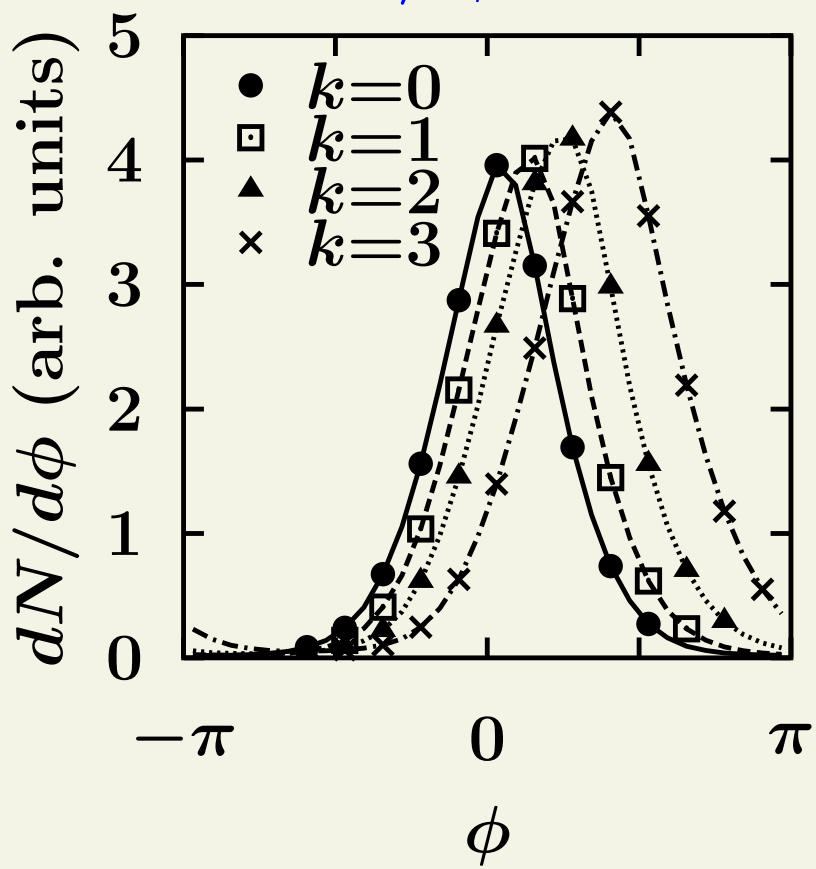
still, partons tend to come from edges of system, especially at high pT

Surface emission

transverse position



momentum $dN/d\phi$ in each wedge



surface emission at high p_T $\Rightarrow v_2(x, p_T)$ - $k = 0$ **region:** $v_2 < 0$, $k = 3$**:** $v_2 > 0$

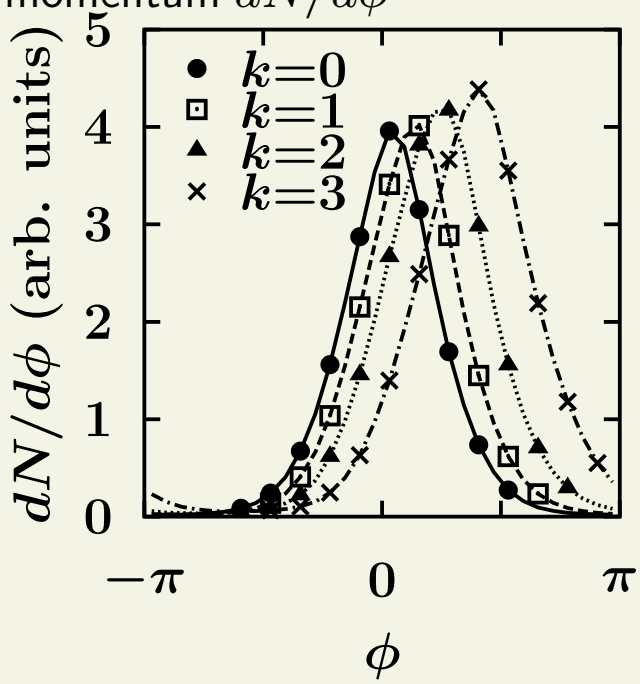
similar result expected from hydrodynamics (boosted thermal sources)

Novel flow scaling w/ quark number

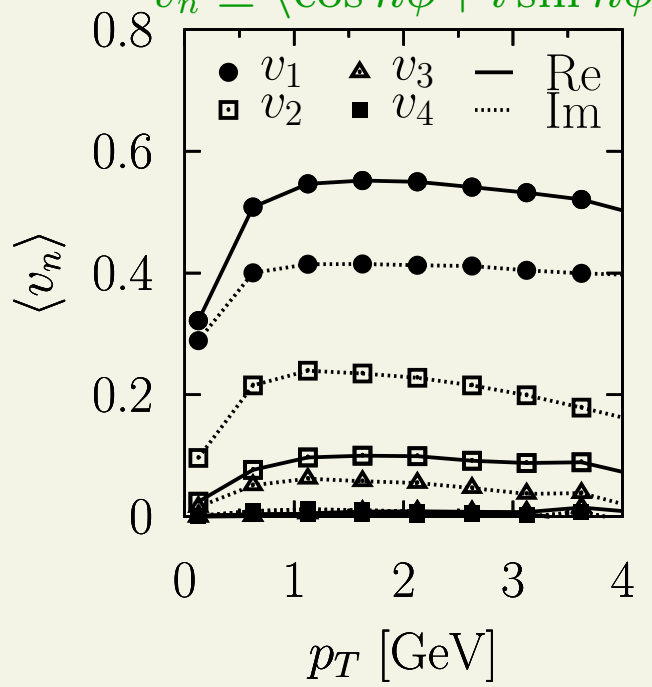
DM, nucl-th/0408044

narrow, almost Gaussian peaks - $dN/d\phi \sim \exp[-(\phi - \phi_0(x))^2/(2\sigma(x)^2)]$

momentum $dN/d\phi$



$v_n \equiv \langle \cos n\phi + i \sin n\phi \rangle$ over 4 spatial wedges



$\Rightarrow \langle \cos(n\phi_{quark}) \rangle \approx \cos(n\phi_0(x)) \cdot \exp[-n^2/(2\sigma(x)^2)] \rightarrow$ **varies with x(!)**

coalescence gives nonlinear scaling w/ quark number:

$$v_k^{hadron}(p_T, x) \simeq v_k^{quark}(\frac{p_T}{n_q}, x)^{1/n_q} \quad \neq \quad n_q v_k^{quark}(\frac{p_T}{n_q}, x) \qquad (\phi_0 = 0)$$

Origin in pT (soft tails)

partons can end up with some final parton momentum (p_T, y) in three ways:

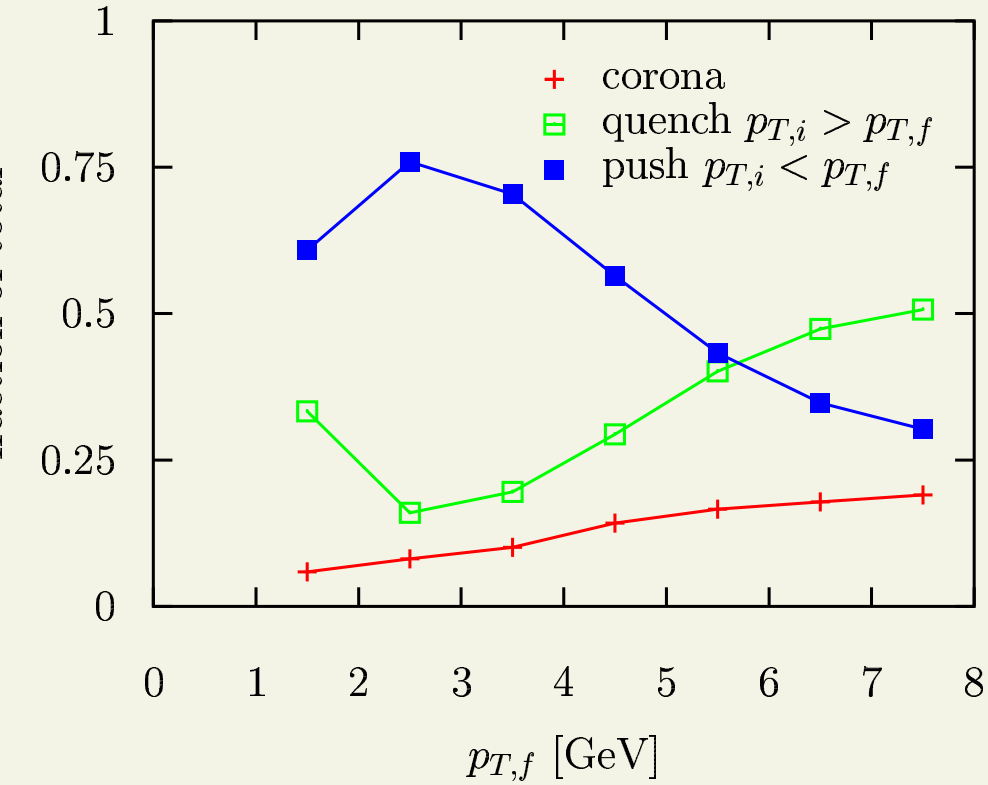
- **escape with no interaction - corona**
- **interact and lose energy - quench**
- **3rd possibility: interact and gain energy - "push"**

in opaque plasma, gain component can be relevant at surprisingly high p_T, pushing "pure" hard physics out to $p_T \gtrsim 10$ GeV

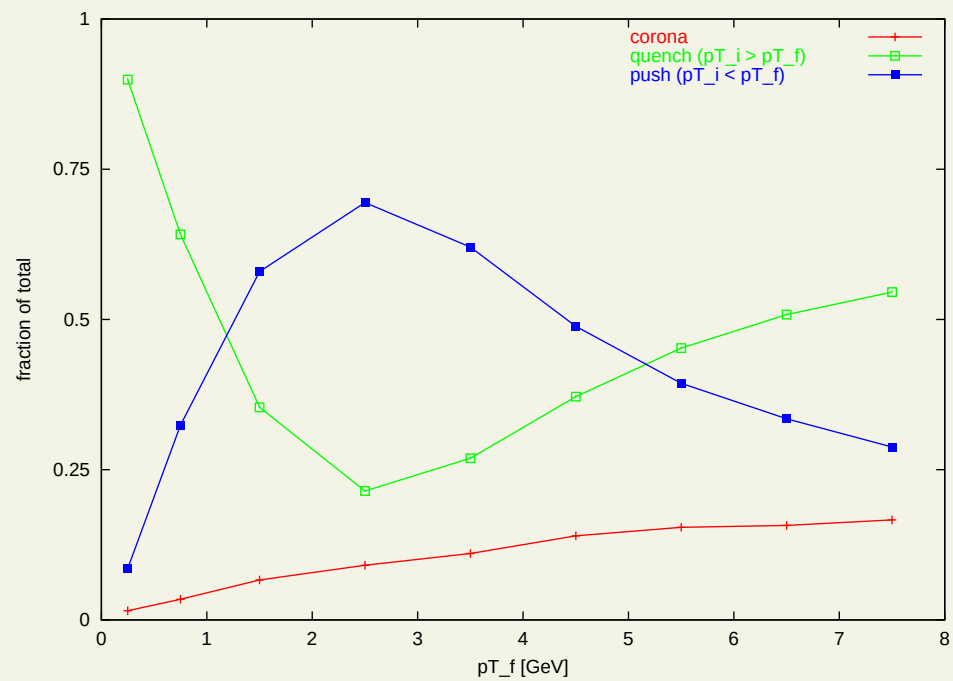
study using MPC 1.8.0 w/ elastic and inelastic $2 \to 2$, $dN^{cent}/d\eta = 2000$

fractions from corona, quench, push vs pT, $(|y_f| < 1)$

DM, nucl-th/0503051: $\sigma_{gg} = 10$ **mb**



$\sigma_{gg} = 5$ **mb**



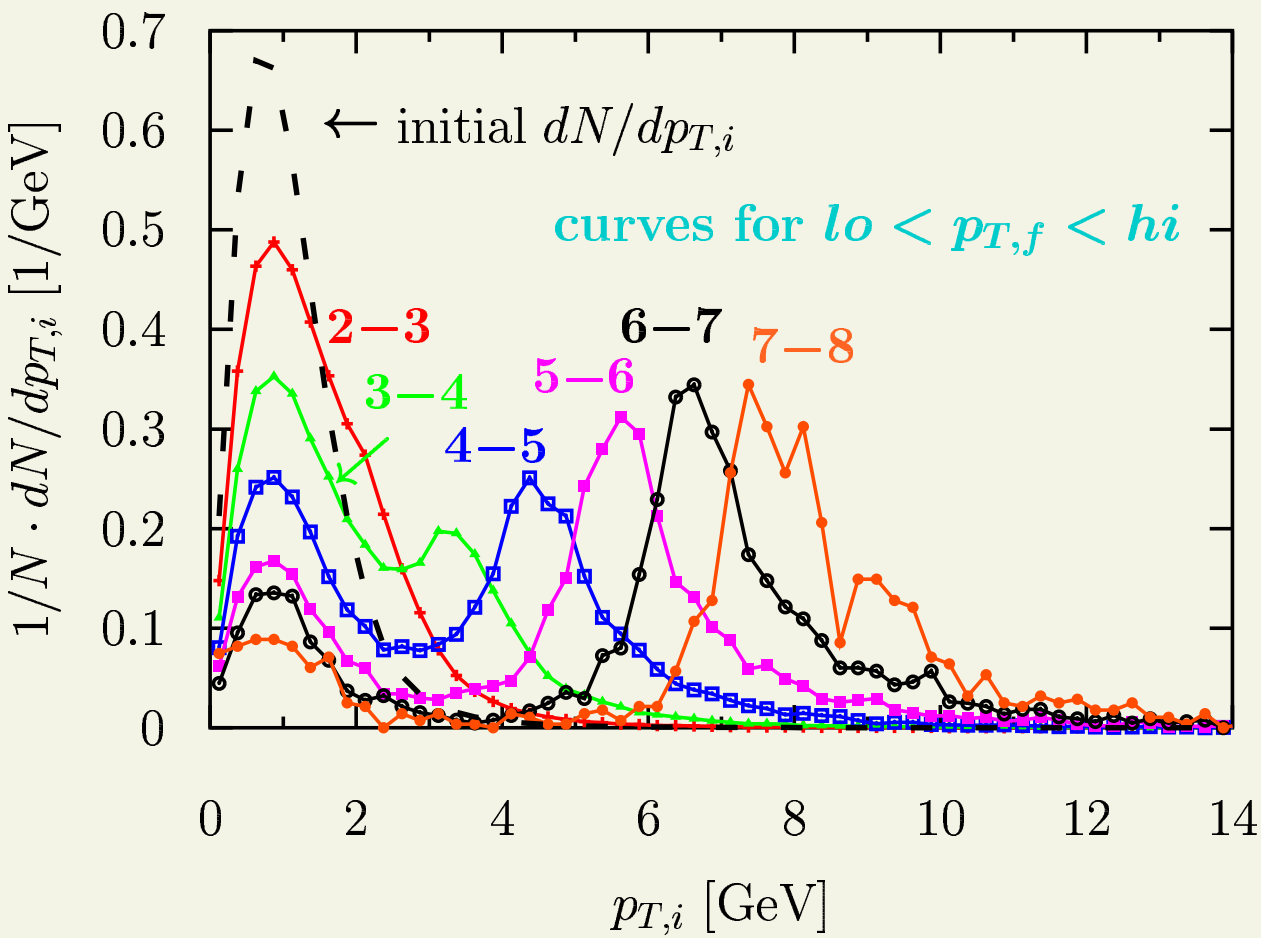
corona and "push" are significant even at $p_{T,parton} \sim 8$ GeV

fractions show surprisingly weak opacity dependence

distribution of initial momenta for fixed final momentum bins, $|y_{fin}| < 1$

(only quench + "push" plotted, normalized)

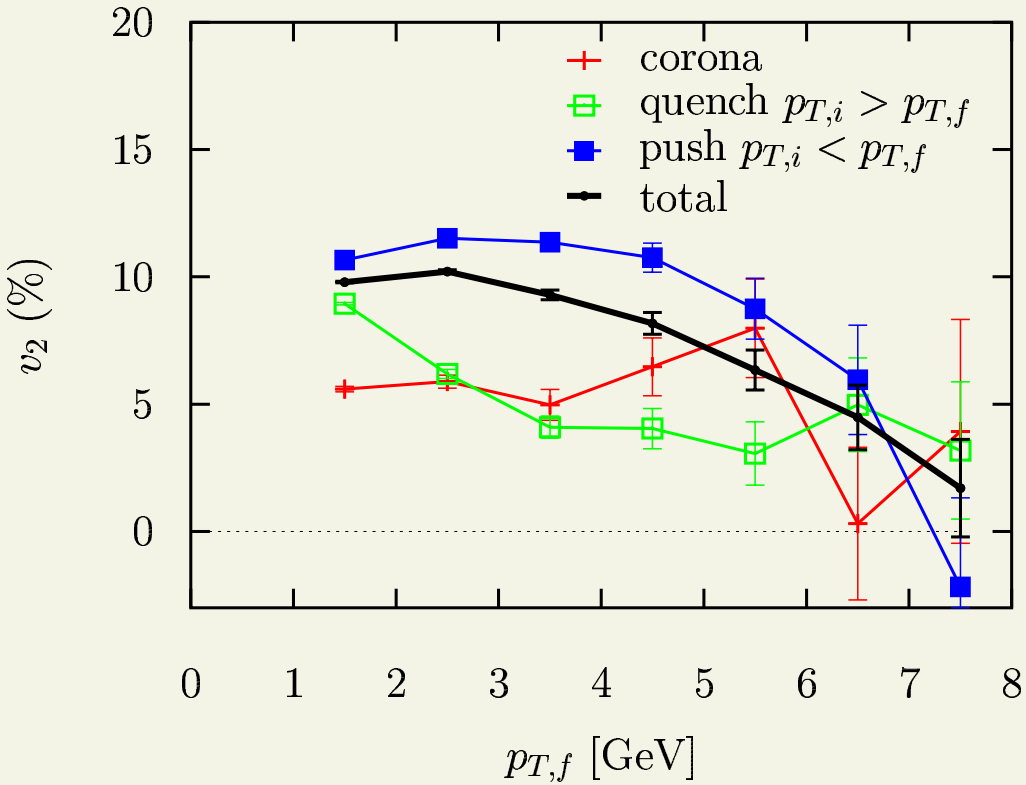
DM, nucl-th/0503051: $\sigma_{gg} = 10$ **mb**



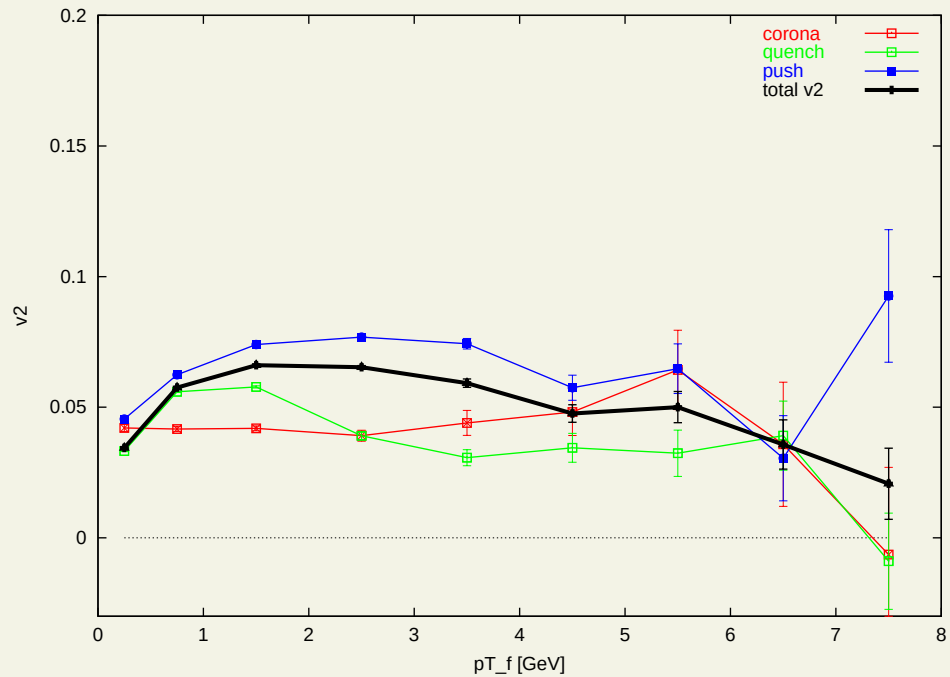
"lucky" $p_{T,i} \sim 1$ **GeV soft partons can end up at** $p_T \sim 5 - 6 - 7$ **GeV**

elliptic flow contributions vs pT

DM, nucl-th/0503051: $\sigma_{gg} = 10$ **mb**



$\sigma_{gg} = 5$ **mb**



rapid v_2 drop from quench at high p_T is compensated by large v_2 of "pushed-up" partons

combined $v_2(p_T)$ decreases more slowly at high p_T and can exceed "geometric" (extreme absorption) bounds Shuryak ('04), Voloshin ('04)

III. high-pT azimuthal correlations

advantage of transport approach :

bulk dynamics (v_2) **and jets in same framework**

HERE: study jet correlations on parton level (before hadronization)

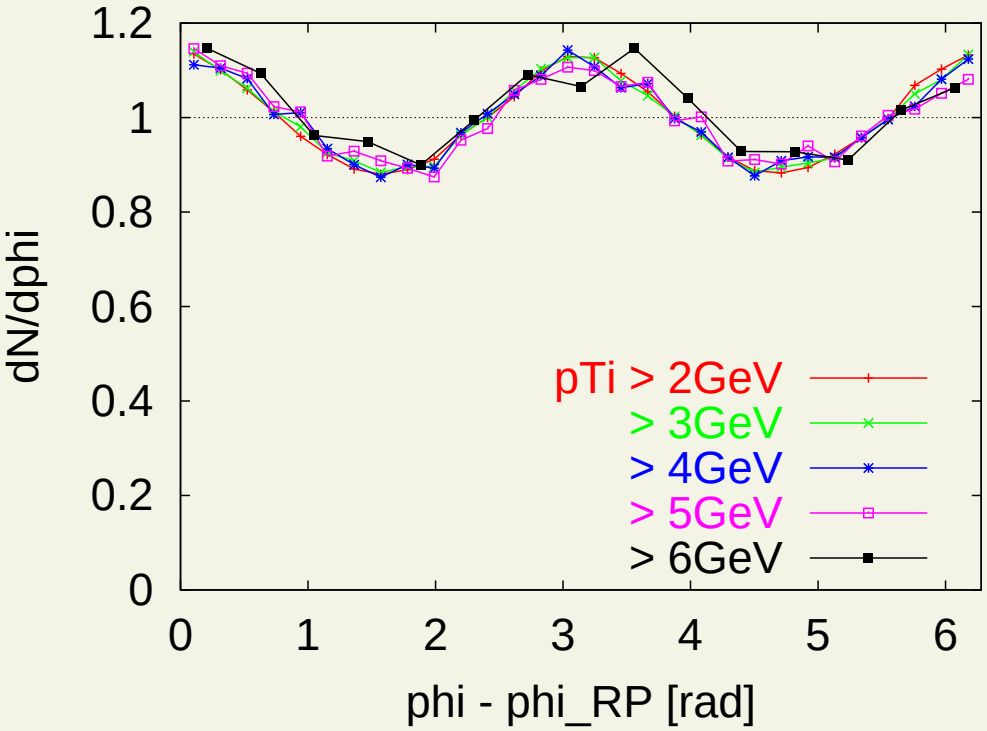
initial conditions: **back-to-back dijets above** $p_T > 2$ **GeV**
uncorrelated soft partons below $p_T < 2$ **GeV**

Au+Au @ 200 GeV, $b = 8$ fm - same as for charm study DM '04

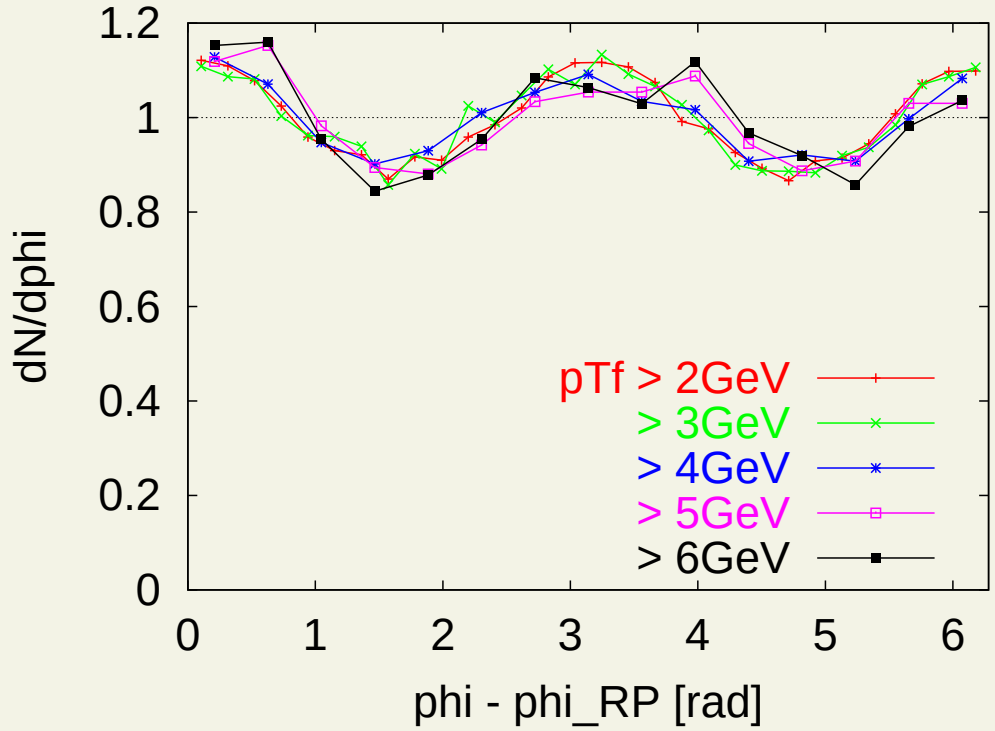
Angular dist. w.r.t. reaction plane

$dN/d\phi$ **distributions normalized to unity, only jet partons considered**

cut on initial parton p_T



cut on final parton p_T, $|y_{fin}| < 1$



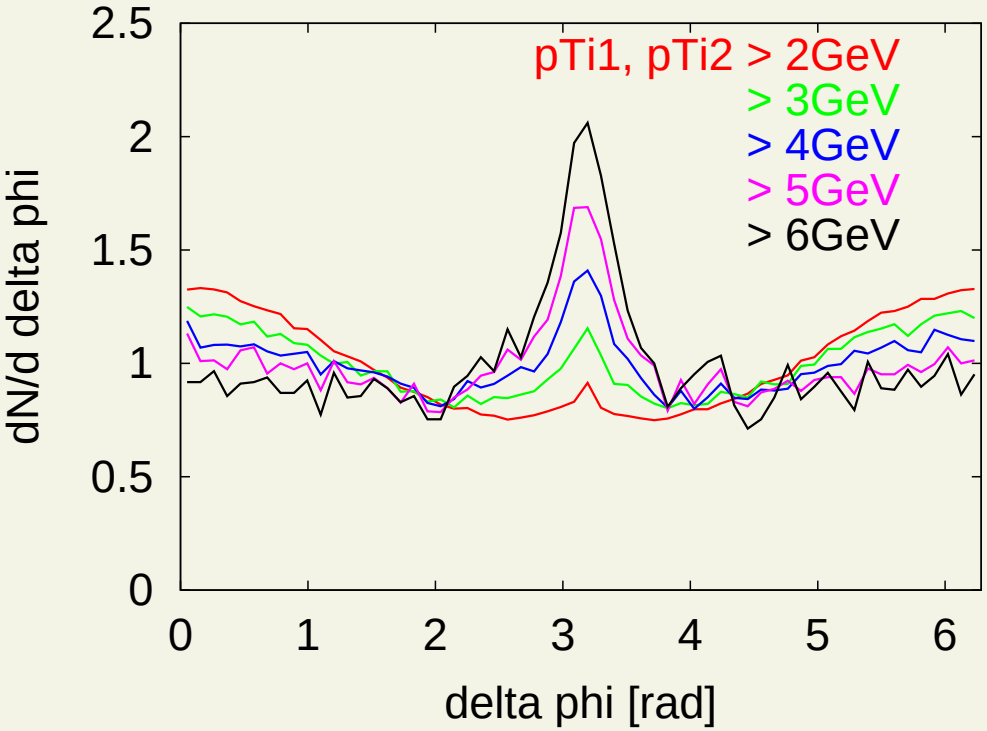
nice harmonic v_2 modulations, perhaps finer structures (need better statistics)

no sign of jet correlations...

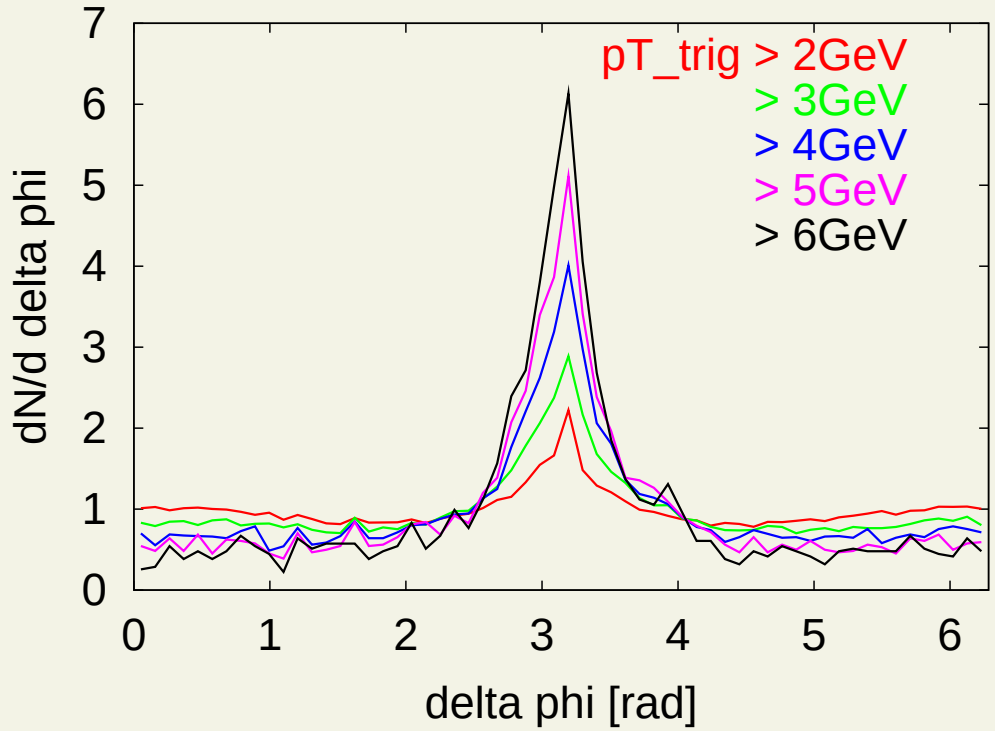
Dijet correlation in azimuth

$dN/d\Delta\phi$ **distributions normalized to unity, only dijet partons considered**

cut on initial parton p_T



cut on final $p_T^{trig}(> p_T^{partner})$, $|y_{fin}| < 1$



clear away-side peak, becomes stronger at higher pT

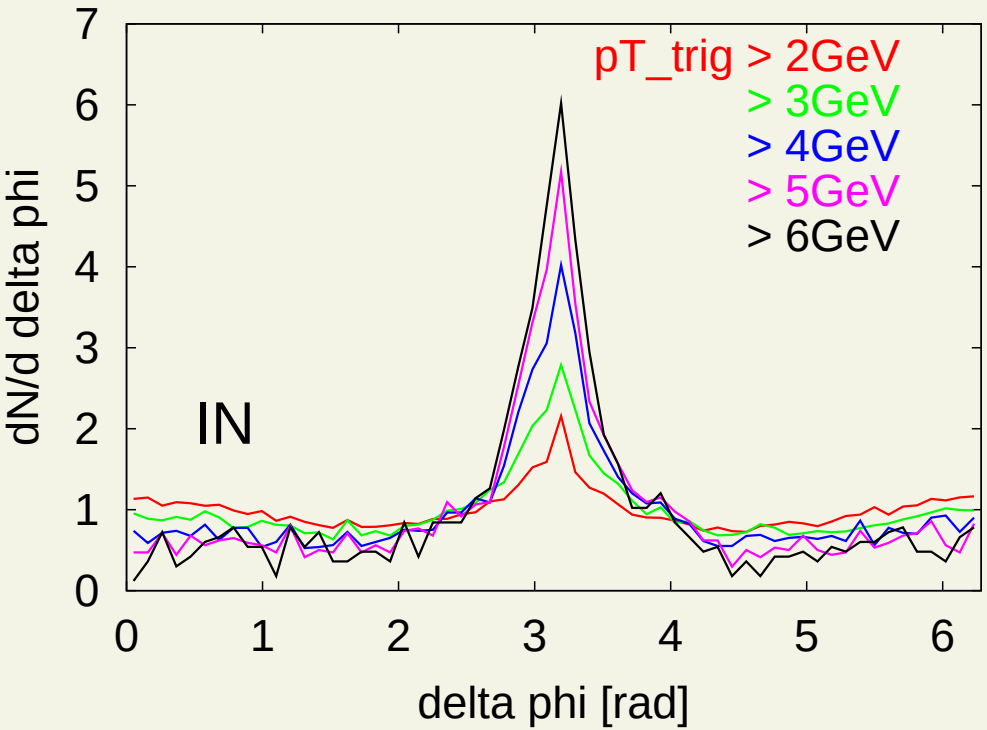
small enhancement at nearside, probably due to collective "flow"

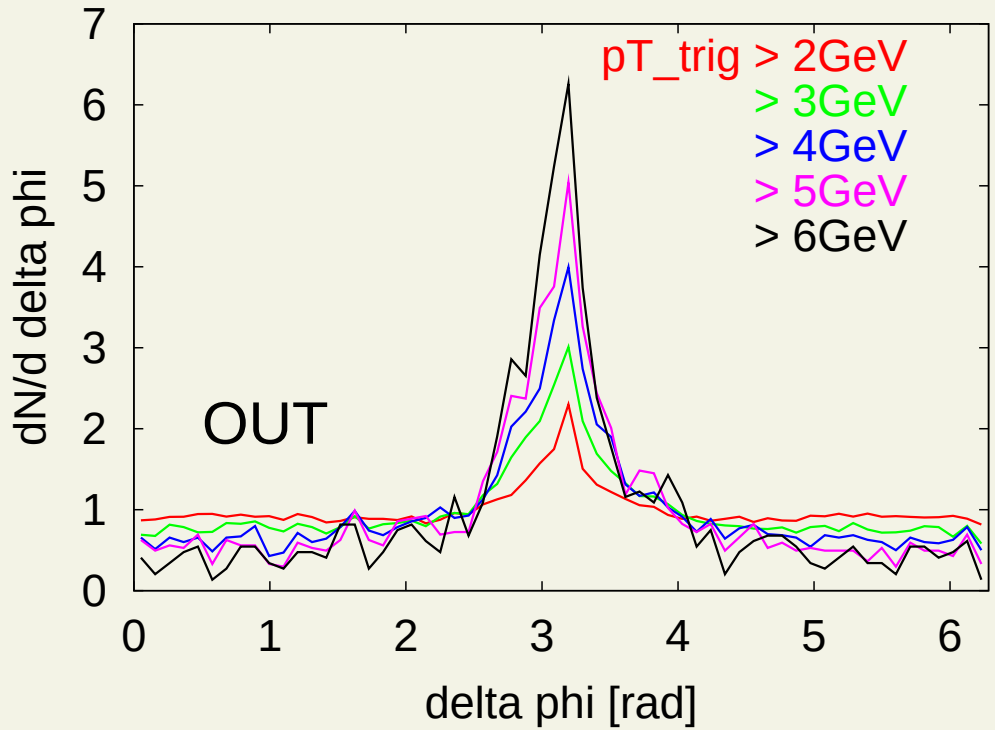
In- vs out-of-plane correlation

$dN/d\Delta\phi$ **distributions normalized to unity, only dijet partons considered**

IN: ϕ^{trig} **in-plane** ($\pm 45^o$), **OUT:** ϕ^{trig} **out-of-plane**

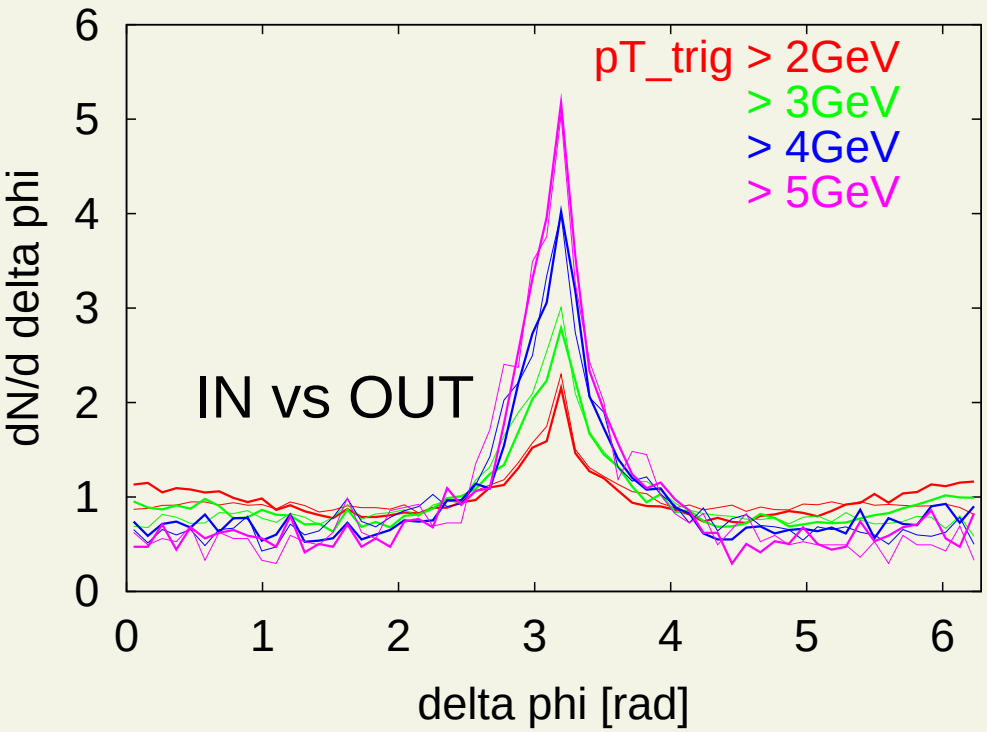
for final parton $p_T^{trig} > p_T^{threshold} > p_T^{partner}$, $|y_{fin}| < 1$

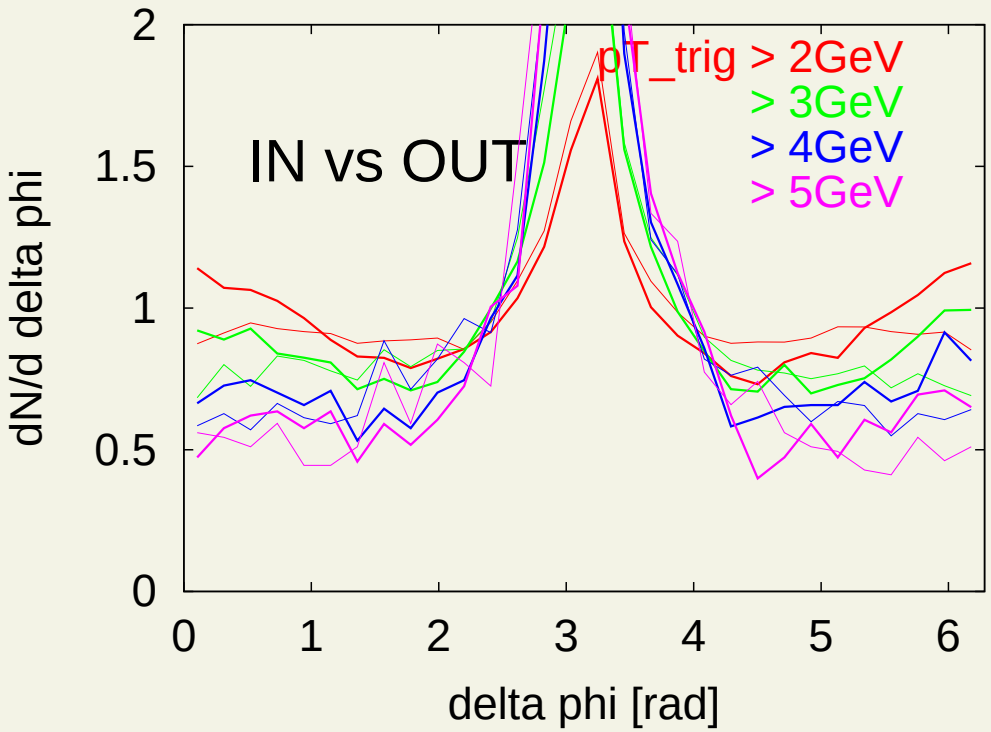




not much visible opacity effect (difference)

comparison plot - IN (thin) vs OUT (thick)





for OUT: tiny reduction of away-side peak - weak length dep. w/ elastic E-loss

main effect is stronger "collectivity" on near-side and around 90°

clearly, this study is only the first step ...

Summary

- **Based on covariant transport theory, the RHIC data indicate a very opaque, largely randomized, but still dissipative, parton system.**

- **Such opaque conditions**

  i) are predicted to generate significant charm hadron v_2,

  ii) lead to strong surface emission at high pT that makes it highly nontrivial to obtain the observed quark number scaling of elliptic flow from coalescence,

  iii) may generate soft physics tails up to rather high pT and push the "perturbative" regime above pT $>\sim$ 10 GeV.

- **This is the first study of jet correlations that treats the bulk sector and jets in the same framework. The results are encouraging but need several improvements:**
  - **add soft partons ("push" effect will contribute)**
  - **study centrality, particle type dependence (higher statistics)**
  - **include hadronization (coalescence, fragmentation)**
  - **extend to radiative processes, coherence**
  - **could also study other correlations, e.g., Mach cone ...**

assume: all $2 \to 2$ processes are enhanced by same factor in opaque plasma

based on Combridge NPB 151 ('79) 429:

$$\sigma_{gg\to q\bar{q}} = \frac{2\,r}{27}\frac{1+r}{1+2r}\ln(1+\frac{1}{r})\,\sigma_{gg\to gg} \quad , \quad \sigma_{q_i\bar{q}_i\to q_j\bar{q}_j} = \frac{16\,r}{243}\,\sigma_{gg\to gg}$$

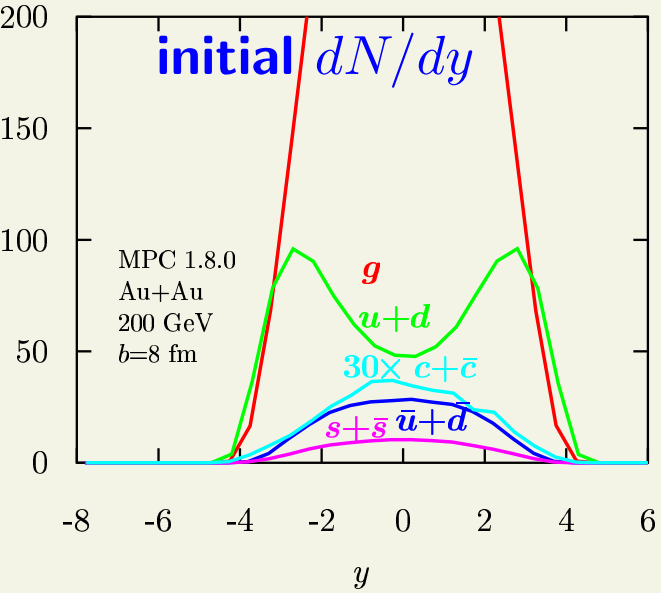
$$\sigma_{gg\to c\bar{c}} = \frac{2\,r}{27}\Theta(1-4R)\left[(1+4R+R^2)\ln\frac{1+\sqrt{1-4R}}{1-\sqrt{1-4R}} - (7+3R)\frac{\sqrt{1-4R}}{4}\right]\sigma_{gg\to gg}$$

$$\sigma_{q\bar{q}\to c\bar{c}} = \frac{16\,r}{243}\Theta(1-4R)(1+2R)\sqrt{1-4R}\,\sigma_{gg\to gg}$$

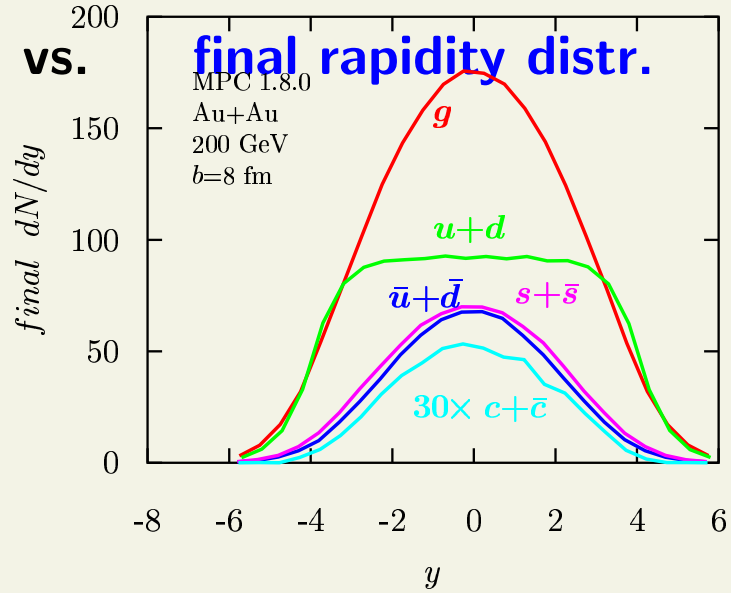
where $r \equiv \mu_D^2/s$, $R \equiv M_c^2/s$

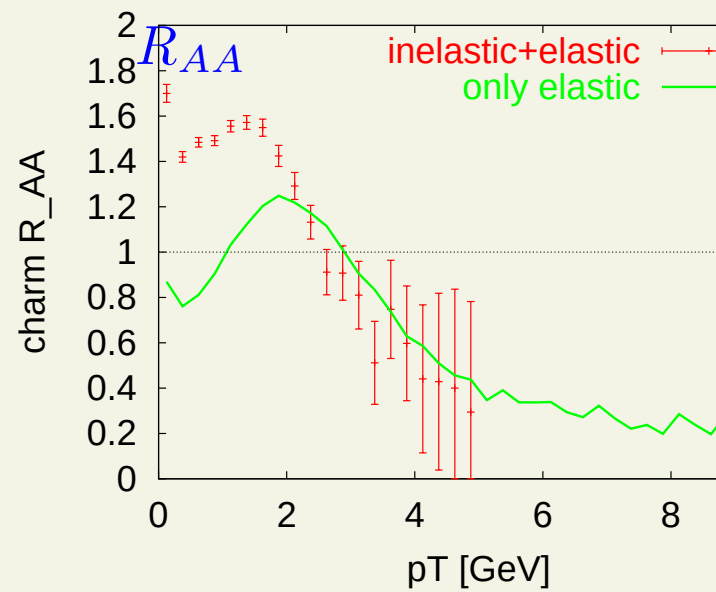
take $\mu_D = 0.7$ **GeV,** $M_c = 1.2$ **GeV**

DM, JPG ('04): **significant secondary charm production**



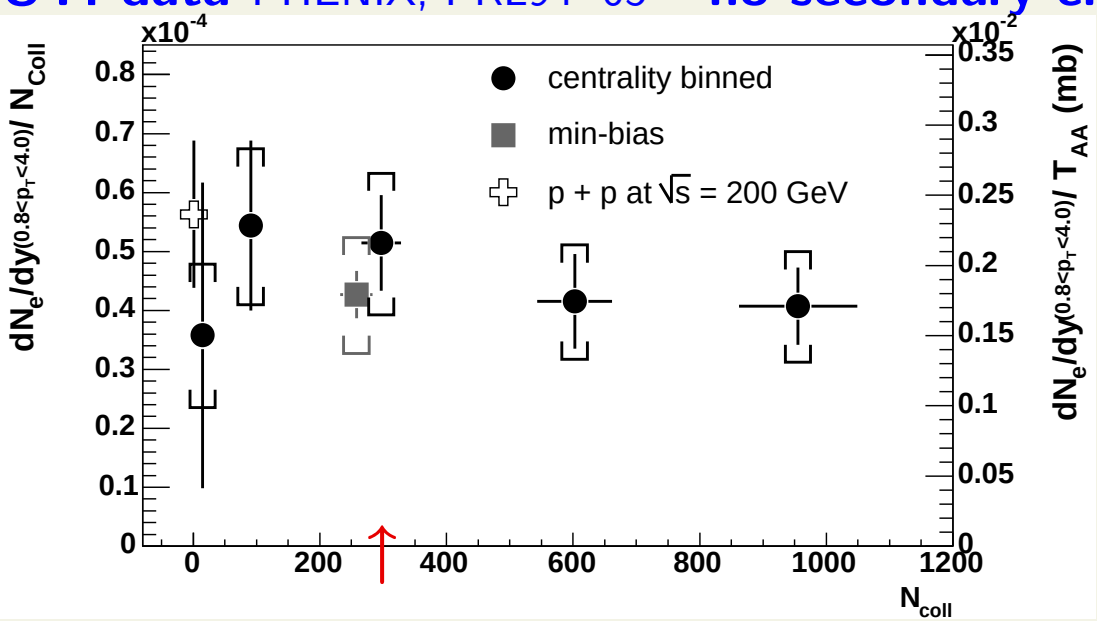
vs.





half the glue fuse to $q\bar{q}$, strangeness up $5\times$, also extra $40-50$% charm yield

BUT: data PHENIX, PRL94 '05 **- no secondary charm (collision scaling)**



Quark coalescence

Ko, Lin, Voloshin, DM, Greco, Levai, Mueller, Fries, Bass, Nonaka, Asakawa ...

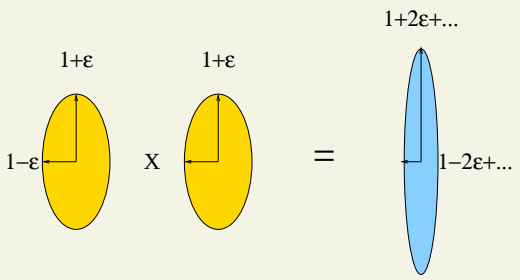
coalescence of comoving quarks: $q\bar{q} \Longrightarrow M$ $\quad 3q \Longrightarrow B$

DM & Voloshin, PRL91 ('03)

analog of $n + p \to d$

$$\frac{dN_M(p_T)}{d\phi} \propto \left[\frac{dN_q(p_T/2)}{d\phi}\right]^2$$

$$\frac{dN_B(p_T)}{d\phi} \propto \left[\frac{dN_q(p_T/3)}{d\phi}\right]^3$$

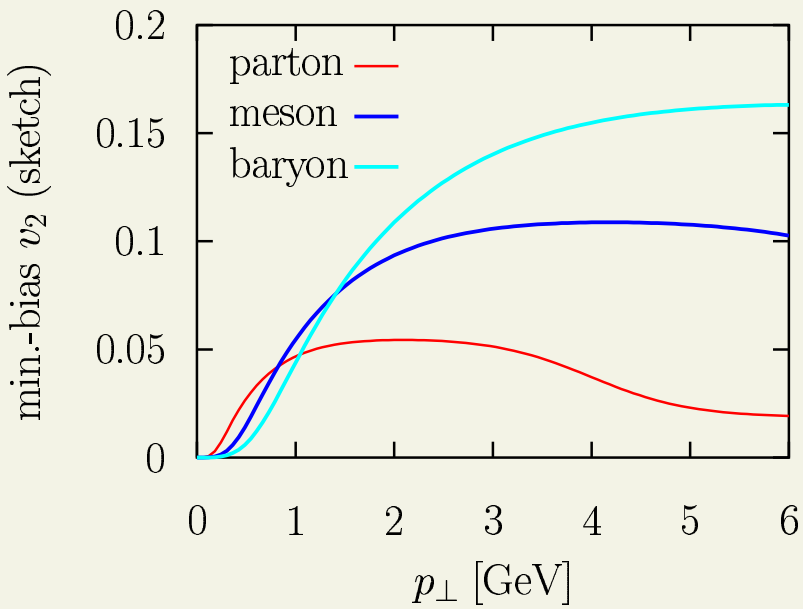


squared/cubed probability $\to$ **amplified** v_2

$$v_2^{hadron}(p_\perp) \approx n \times v_2^{quark}(p_\perp/n)$$

$3\times$ **for baryons**
$2\times$ **for mesons**
} **50% larger** v_2 **for baryons**

$\to 5\times$ **for pentaquark,** $6\times$ **for deuteron**



amplification greatly reduces opacities needed to reproduce v_2 **data**

only partons near in phasespace can fuse - "coalescence formula":

$$\frac{dN_M(\vec{p})}{d^3p} = g_M \int (\prod_{i=1,2} d^3x_i d^3p_i) W_M(x_1 - x_2, \vec{p}_1 - \vec{p}_2) f_\alpha(\vec{p}_1, x_1) f_\beta(\vec{p}_2, x_2) \delta^3(\vec{p} - \vec{p}_1 - \vec{p}_2)$$

$$\frac{dN_B(\vec{p})}{d^3p} = g_B \int (\prod_{i=1,2,3} d^3x_i d^3p_i) W_B(x_{12}, x_{13}, \vec{p}_{12}, \vec{p}_{13}) f_\alpha(\vec{p}_1, x_1) f_\beta(\vec{p}_2, x_2) f_\gamma(\vec{p}_3, x_3) \delta^3(\vec{p} - \sum \vec{p}_i)$$

hadron yield space-time hadron wave-fn. quark distributions

gives v_2 scaling trivially <u>if</u>:

1. **no other hadronization channels play a role**
2. **narrow hadron wave functions** $W \sim \delta^3(\Delta x)\delta^3(\Delta p)$ **- or small phasespace variations**
3. **only small local harmonic modulations** $|v_2(x)| \ll 1$, $|v_n(x)| \ll 1$

$$v_2^{Meson}(p_T) = \frac{2 \langle f_q^2(x, p_T/2)\, v_{2,q}(x, p_T) \rangle_x}{\langle f_q^2(x, p_T/2) \rangle_x}$$

$$v_2^{Baryon}(p_T) = \frac{3 \langle f_q^3(x, p_T/3)\, v_{2,q}(x, p_T) \rangle_x}{\langle f_q^3(x, p_T/3) \rangle_x}$$

4. **spatial dependence can be ignored (factorizes out)** $\Rightarrow v_2^{hadron}(p_T) = n v_2^{quark}(p_T/n)$
   - for example, global $v_2(x, p_T) \equiv v_2(p_T)$**, or constant FO phasespace density**

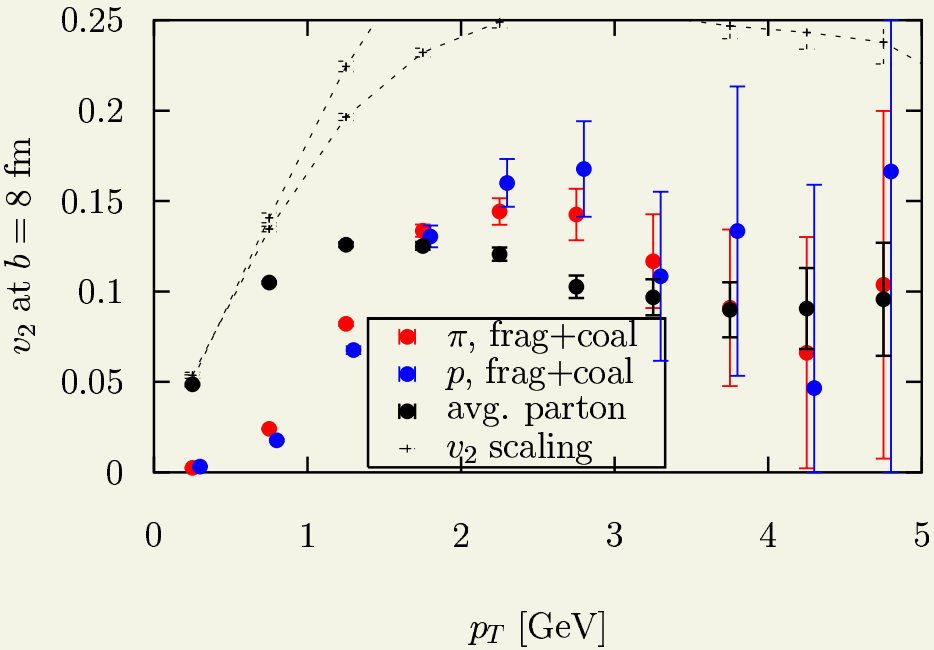
none of these satisfied in transport or hydro, contrary to parameterizations

Quark number scaling is truly puzzling for dynamics

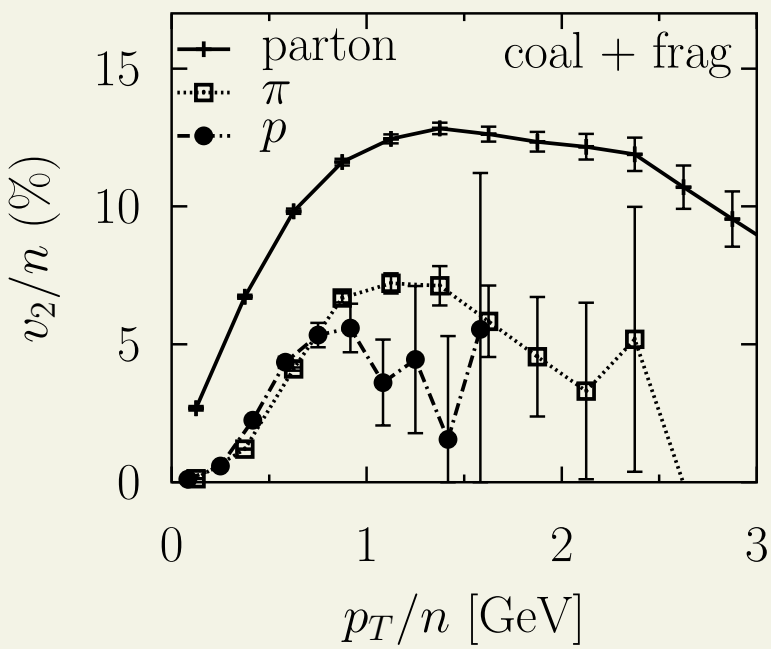
- significant fragmentation contributions
- strong space-momentum correlations (spatial anisotropies)
- surface emission, strongly peaked angular distributions

parton transport + dynamical 4D coalescence - Gyulassy, Frankel, Remler '83
and indep fragmentation -JETSET for partons without coal partner

DM ('04): $v_2(p_T)$ - π, p, q



scaled v_2



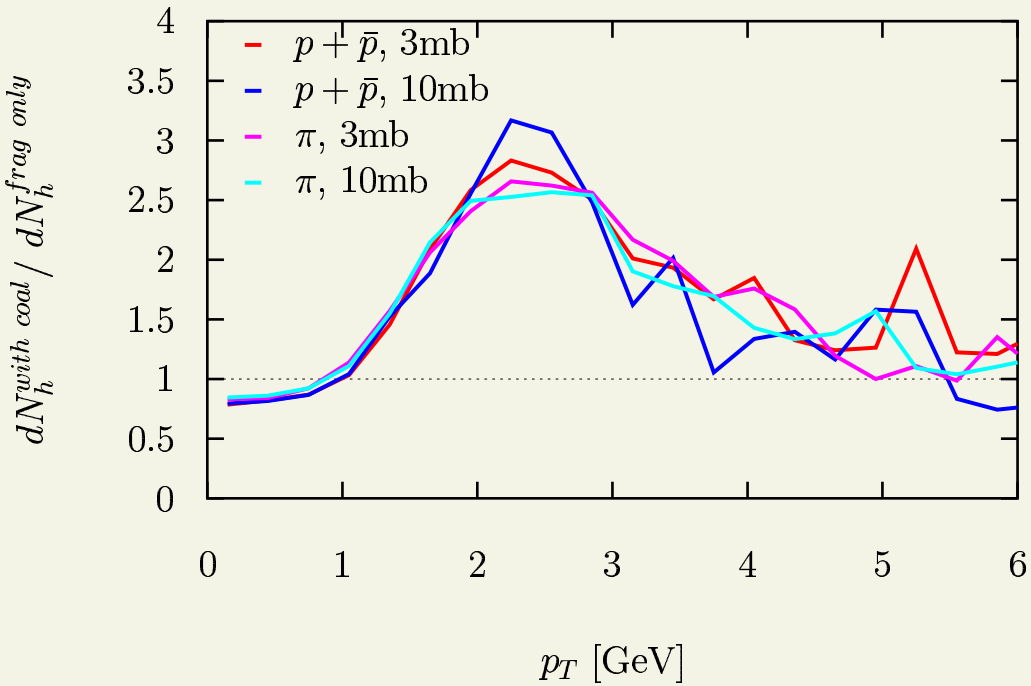
flow amplification greatly reduced, baryon-meson splitting mostly gone

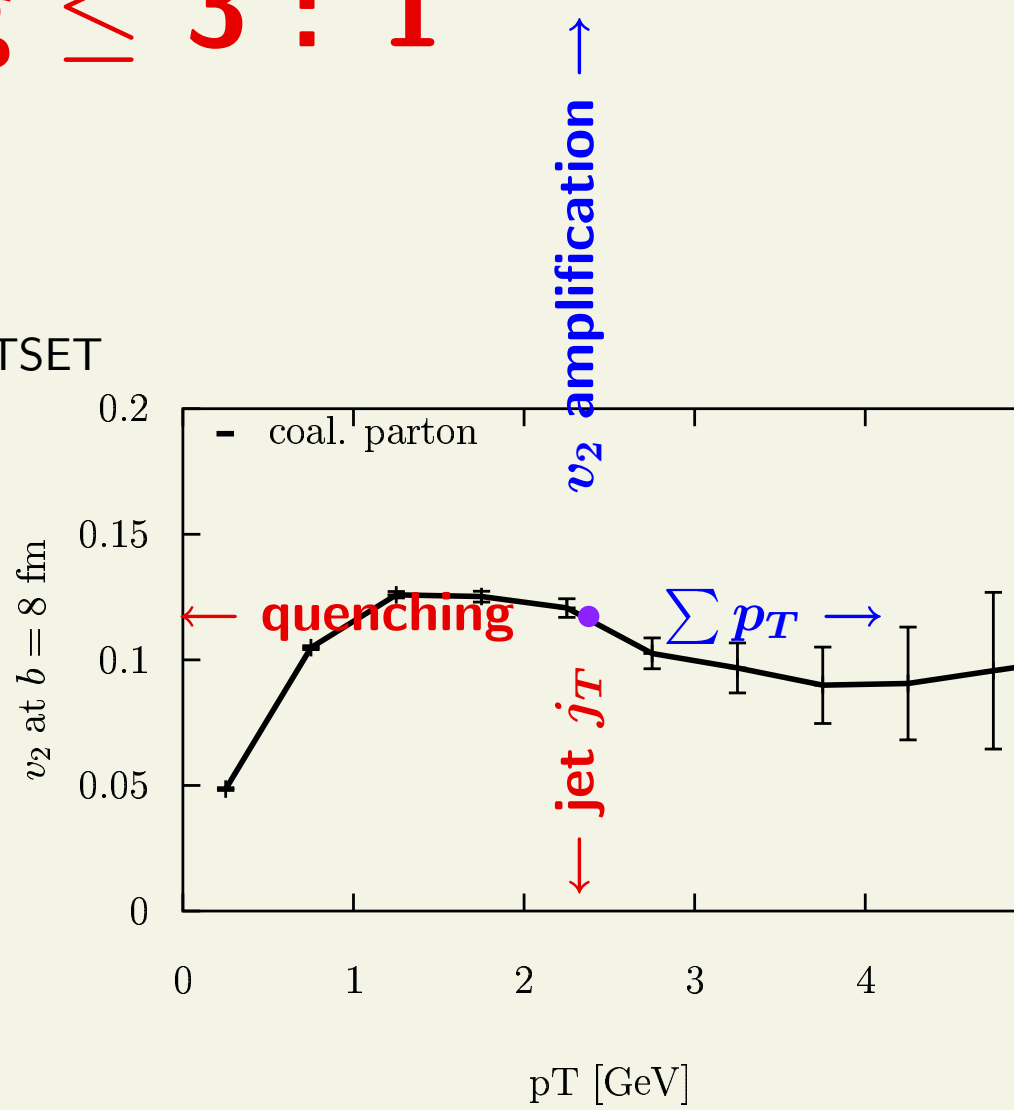
may still scale approximately $\sim$ 15% err but scaled v_2 is NOT the quark v_2

Coal : Frag $\leq$ 3 : 1

coal+frag yield / frag only yield

DM ('04): dynamical calculation MPC + coal/JETSET





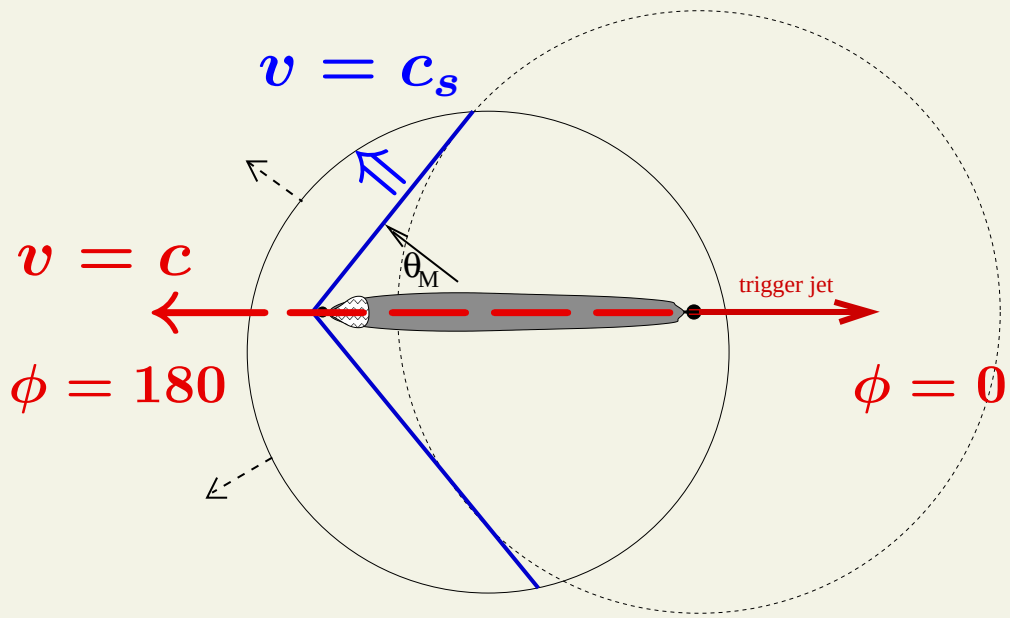
v_2 **from** $\sim 30\%$ **fragmentation contribution does not amplify** $\rightarrow$ **scaling spoiled**

also, about same enhancement for protons and pions $\rightarrow$ p/π **not enhanced**

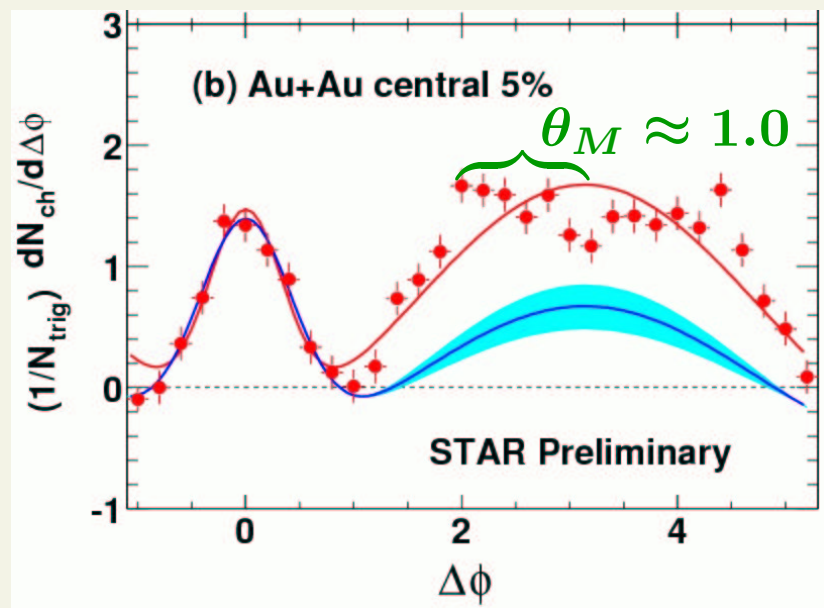
Collective excitations?

Short-wavelength probe could generate collective hydrodynamic response
- hotly debated possibility $\longrightarrow$ **main issues: rapidity averaging, dissipation**

"sonic boom" Stöcker '04, Casselderey-Solana et al



azimuthal correlations F. Wang [STAR] '04

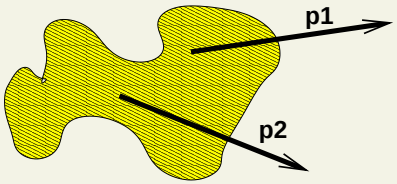


Mach cone: $\cos\theta_M = c_s/c$ $\Rightarrow$ $c_s^2 \approx 0.25 - 0.3 \cdot c^2$ **...**

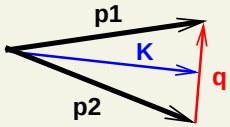
ideal parton gas: $c_s^2 = c^2/3$

HBT essentials

Momentum correlations: **reflect spacetime freezeout**



$$C(\vec{q},\vec{K}) \equiv \frac{N(\vec{p}_1,\vec{p}_2)}{N(\vec{p}_1)N(\vec{p}_2)} \approx 1 + \frac{\left|\int d^4x\ f_{FO}(x,\vec{K})\ e^{iq^\mu x_\mu}\right|^2}{\left[\int d^4x\ f_{FO}(x,\vec{K})\right]^2}$$



[e.g., Pratt, Csörgő & Zimányi, PRC 42, 2646 ('90)]

$\boldsymbol{f_{FO}(x,\vec{p}) \equiv dN/d^4x\ d^3p}$**: 7D distribution of last interaction vertices**

Out-side-long coordinates: **special choice of frame**

$$K^\mu \equiv (\tilde{K}^0, K_\perp, 0, 0), \qquad x^\mu \equiv (\tilde{t}, x_O, x_S, x_L) \qquad (\tilde{K}^0 \approx \sqrt{m^2 + K_\perp^2})$$

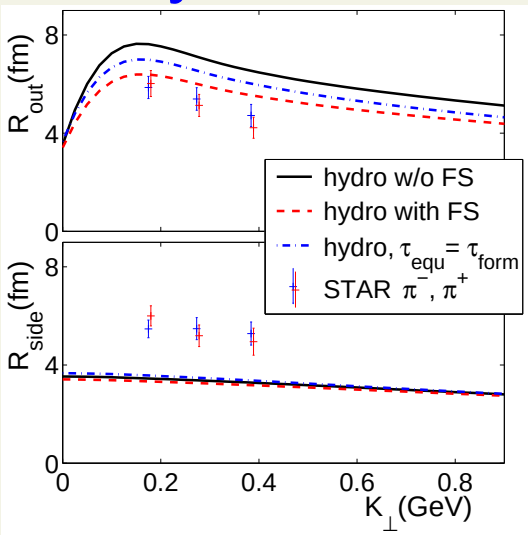
HBT radii:

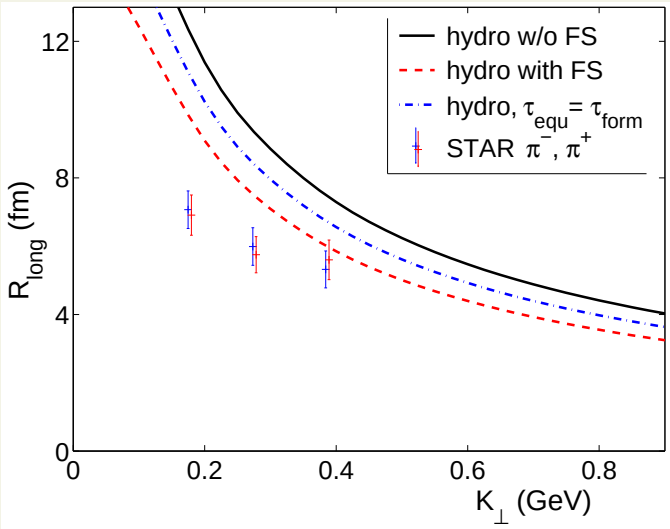
$$R_O^2 = \langle \Delta x_O^2 \rangle_K + v_\perp^2 \langle \Delta \tilde{t}^2 \rangle_K - 2 v_\perp \langle \Delta x_O \Delta \tilde{t} \rangle_K$$
$$R_S^2 = \langle \Delta x_S^2 \rangle_K, \qquad R_L^2 = \langle \Delta x_L^2 \rangle_K$$

exact for Gaussian source without final-state interactions

Small R_{side} → PUZZLE

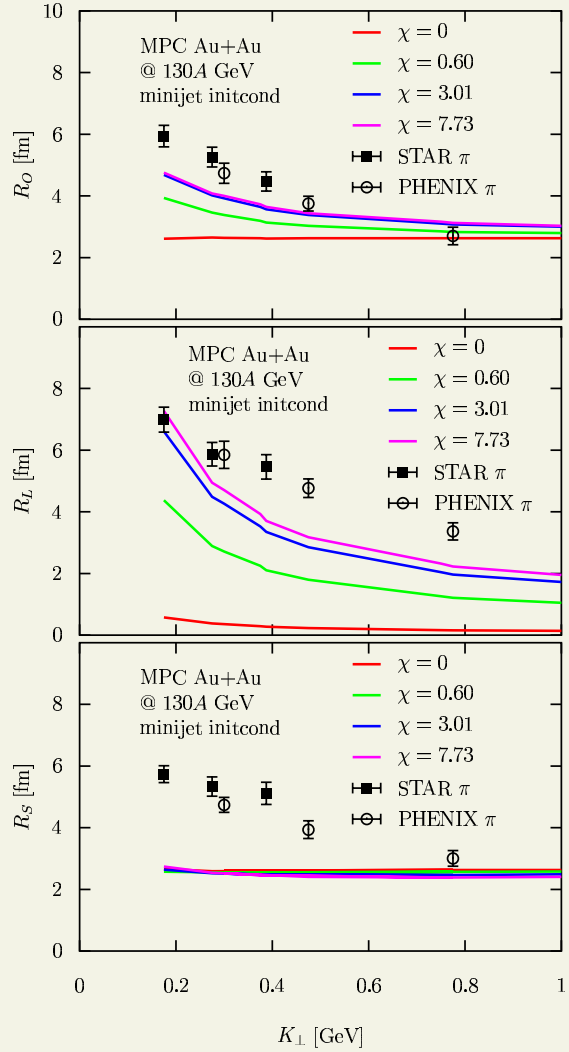
ideal hydro Heinz & Kolb ('02)





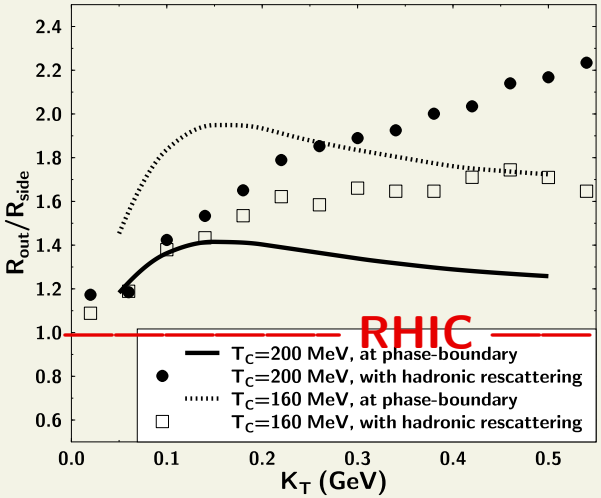
overshoots R_O & R_L
while $R_S \approx 4$ fm only

cov. transport DM & Gyulassy ('02)



R_O & R_L increase with opacity
but $R_S \approx 3.5$ fm stays flat

hydro+transport
Dumitru, Soff ('01)



R_{out}/R_{side} shoots above data

⇒ late-stage hadronic decoupling not understood

wrong spacetime evolution, or too simple HBT formula? maybe resonances?