Elliptic flow at high p_T from parton coalescence

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Outline

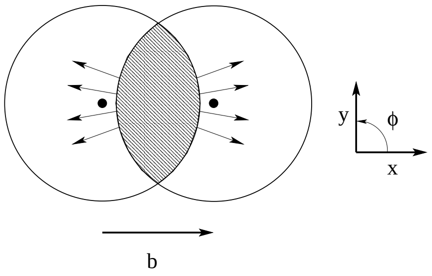
- **Elliptic flow puzzle** - data vs. theory, large parton opacities?
- **Parton coalescence** - why/how it helps resolve opacity problem
- **Implications** - elliptic flow ordering at high $p_\perp$, baryon/meson ratios
- **Conclusions**, next steps

References: - nucl-th/0302014
- NPA 697, 495 ('02) [nucl-th/0104073]

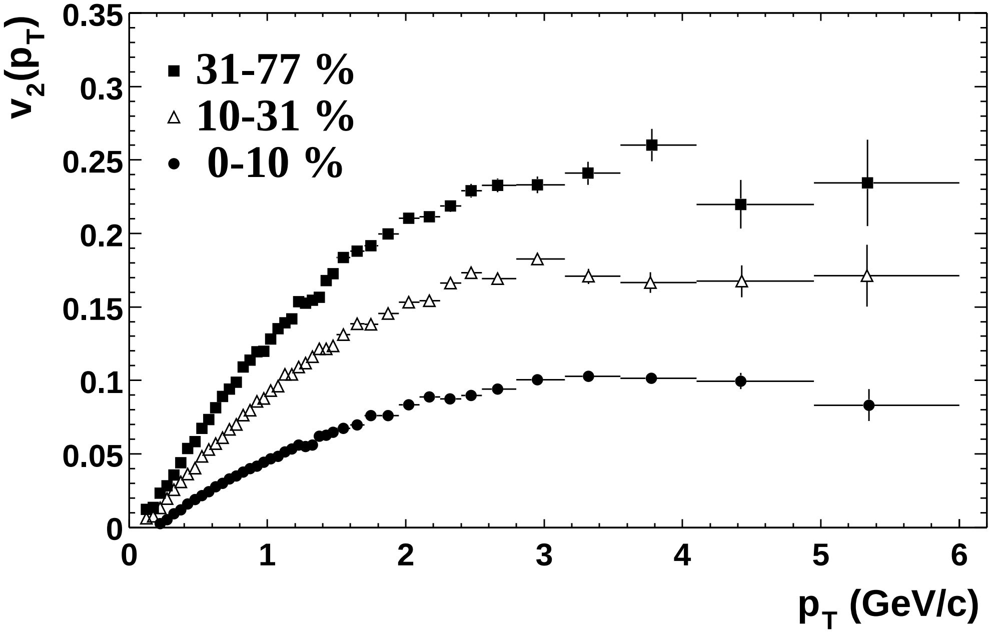
Saturation of elliptic flow at RHIC

- **coordinate-space → momentum-space anisotropy**

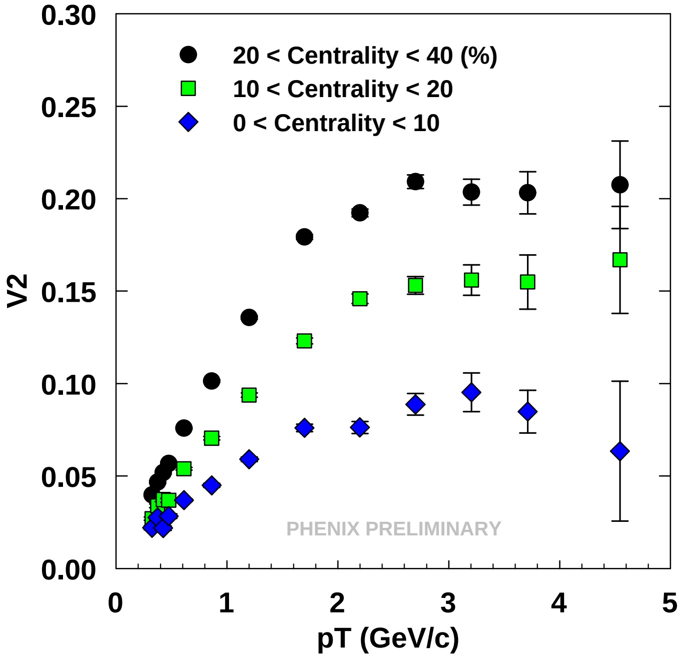
$$\frac{dN}{d\phi dX} \equiv \frac{1}{2\pi}\frac{dN}{dX}[1 + 2\sum_{n=1} v_n(X)\cos(n\phi)]$$



STAR, PRL 90, 032301 ('03):



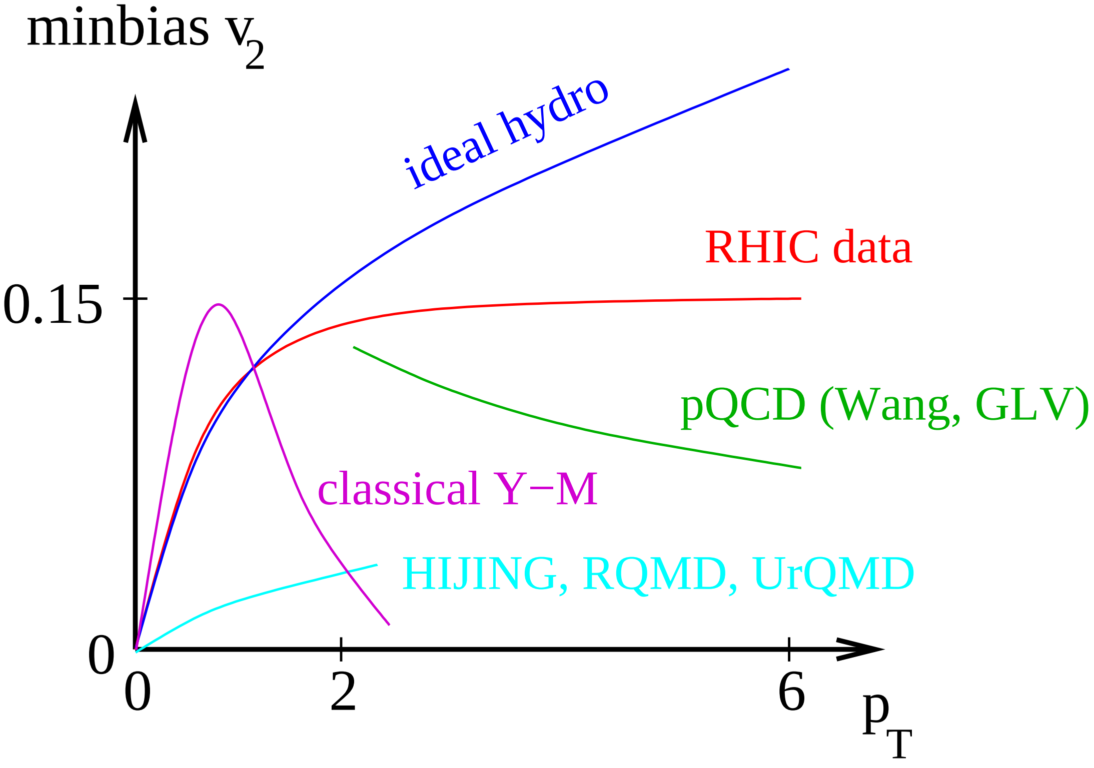
PHENIX, nucl-ex/0210007:



- $v_2 \approx 0.15 \Rightarrow$ **large** $2:1$ **asymmetry, which saturates for** $p_\perp > 2$ **GeV**
- **same pattern for all centralities, all particle species**

Puzzle for theory

Various theoretical expectations: [Heinz, Kolb, Huovinen et al; Gyulassy, Vitev, Wang et al; Sorge et al; Bleicher, Stöcker et al; Krashnitz, Venugopalan et al]



- **cannot make $v_2(p_\perp)$ flat**

$$\Downarrow$$

explore what it takes to make it flat

Try covariant parton transport theory

Pang, Zhang, Gyulassy, D.M., Vance, Csizmadia, Pratt, Cheng , ...

Simplest Lorentz-cov. nonequil. theory (next step beyond hydrodynamics)

- **dynamics governed by the mean free path:** $\lambda(s,x) = 1/\sigma(s)n(x)$
  - **- interpolates between ideal hydro $\lambda = 0$ and free streaming $\lambda = \infty$**
- **natural decoupling,** $\lambda(t \to \infty) \to \infty$ ↔ **unlike Cooper-Frye in hydro**

Nonlinear transport equation, in classical limit:

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

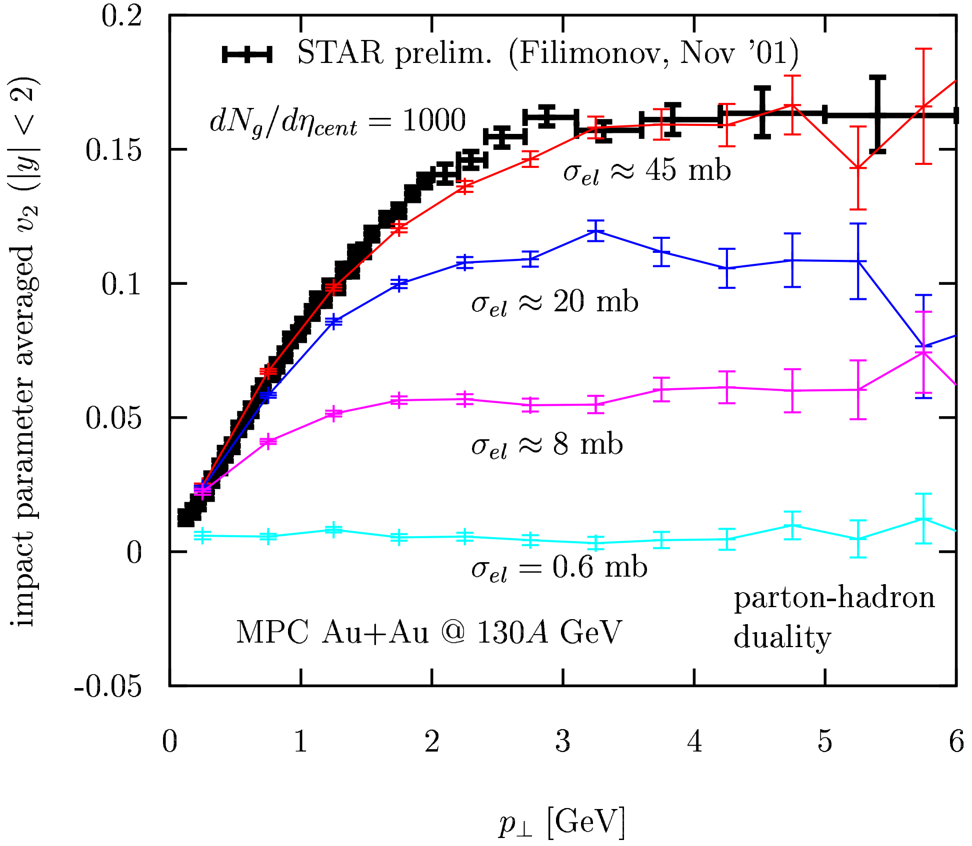
solvable numerically → only a handful of covariant algorithms: ZPC, MPC, ...

Real dynamical parameter: transport opacity

[see NPA 697, 495 ('02)]

$$\chi \equiv \langle n_{coll} \rangle \sigma_{tr} / \sigma_{el} \quad \propto \quad \sigma_{tr} \times dN/d\eta$$

$\mathbf{v_2(p_T)}$ at RHIC from parton transport



$$v_2 \equiv \langle \cos 2(\phi - \phi_0) \rangle$$

minijet initial conditions

$1g \to 1\pi$ hadronization

- **saturation pattern can be reproduced with elastic $2 \to 2$ interactions,**
  requires large transport opacities $\chi_0 \approx 45 \Leftrightarrow \sigma_{el} \times dN_g/d\eta \approx 45000$ mb
  - **pion HBT data (R_O, R_L) also suggest large opacities** [nucl-th/0211017]

Off by factor 15 - checkmate?

Need $\sigma_{el} \times dN_g/d\eta \approx 45000$ mb $\gg$ optimistic pQCD estimates 3 mb $\times$ 1000
(EKRT)

- **can cross sections be larger? - only few times**
  - **large Q^2: no room, pQCD works (verified against pp, $p\bar{p}$)**
  - **small Q^2: some uncertainties - e.g., in Debye screening mass μ**
    but soft scatterings do little for transport (though $\sigma_{tot} \propto 1/\mu^2$)
  - **multiple scatterings: only incoherent $2 \to 2$ implemented**
    - overestimate: missing interference effects (LPM)
    - underestimate: missing inelastic channels, e.g., $2 \leftrightarrow 3$
    likely to give a factor two only [NPA 661 ('99) 236]

- **what about the parton density?**
  - **large p_T: initial jet production is fixed by pQCD**
  - **low p_T: large uncertanties - could assume $dN/d\eta \sim 15000$**
    but $dN_{had}/d\eta \approx 1000$ only $\Rightarrow$ novel "many $\to$ 1" hadronization?

Solution: parton coalescence

(Voloshin, D.M., nucl-th/0302014)

- **Coalescence:** $q\bar{q} \to meson$, $qqq \to baryon$

$$\frac{dN_h}{p_\perp dp_\perp d\Phi}(p_\perp) = C_h \left[\frac{dN_p}{p_\perp dp_\perp d\Phi}(p_\perp/n)\right]^n \quad , \qquad (n = 2,3)$$

  - **valid if coalescence is rare, i.e., phase space densities are not large**
  - **otherwise linear relation**

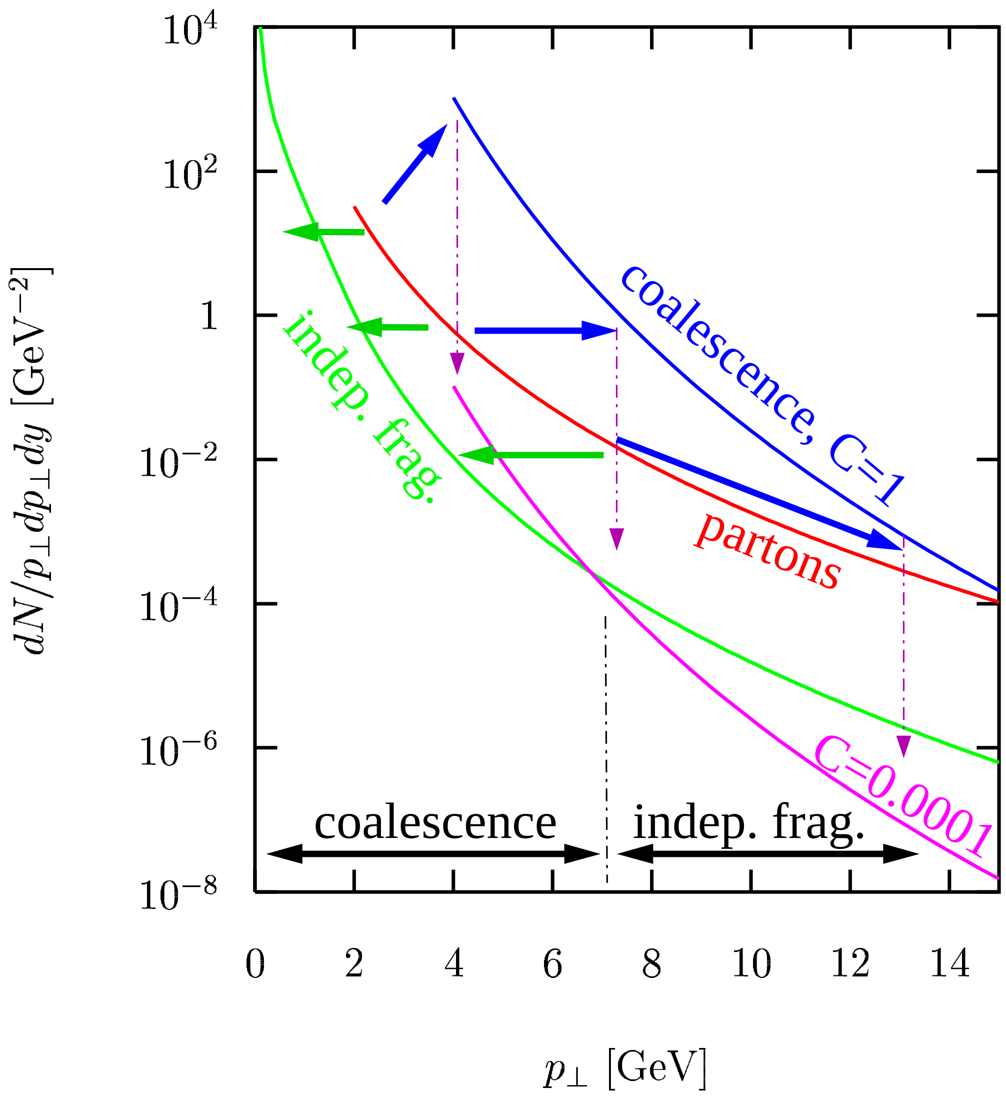
- **Coalescence helps because**
  - **requires larger parton densities**

$$\frac{dN_p}{d\eta} = n \ \times \ \frac{dN_{had}}{d\eta} \ \sim \ 2000 - 3000$$

  - **enhances hadron elliptic flow → much smaller opacities are enough**

$$v_{2,had}^{max} \approx n \times v_{2,p}^{max}$$

Coalescence vs. fragmentation



[central Au+Au @ 200 GeV, mesons]

- **momenta:**

  frag: $p_\perp \rightarrow z p_\perp \; (z < 1)$
  coal: $p_\perp \rightarrow n p_\perp \; (n = 2, 3)$

- **parton spectrum dependence:**

  frag: **linear** $dN_{had} \propto dN_{part}$
  coal: **nonlinear** $dN_{had} \propto [dN_{part}]^n$

$$\Downarrow$$

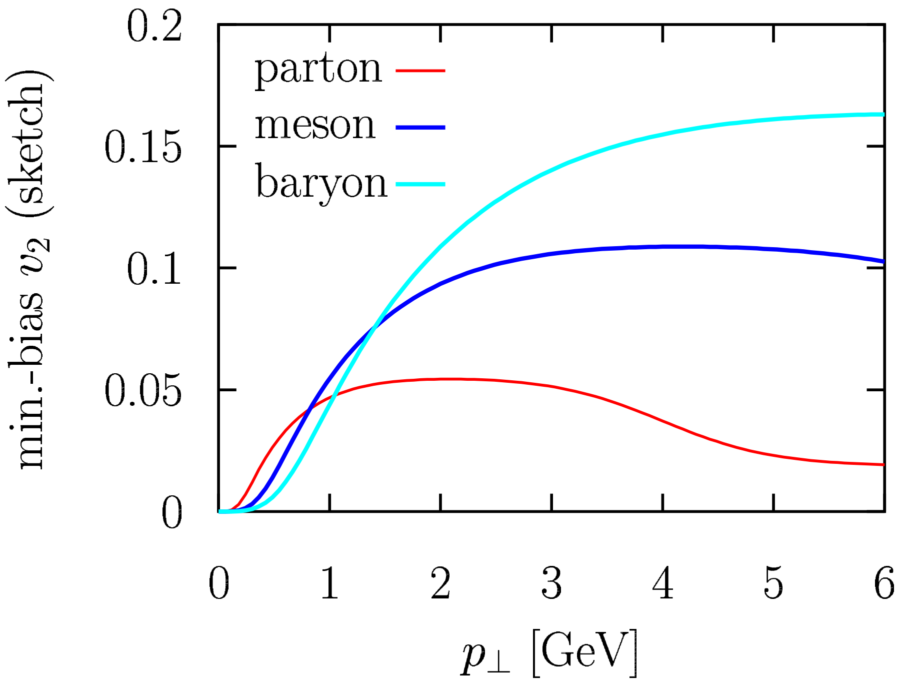
$p_\perp > p_\perp^{crit}$: **fragmentation region**
$p_\perp < p_\perp^{crit}$: **coalescence dominates**

$p_\perp^{crit}$: **decreases with incr. centrality**
depends on C_h
may be large > 5 **GeV**

Amplification of elliptic flow

Easy to work out that $dN_{had} = C_h[dN_{part}]^n$ implies [nucl-th/0302014]

$$\begin{aligned} v_{k,M}(p_\perp) &\approx v_{k,a}(p_\perp/2) + v_{k,\bar{a}}(p_\perp/2) \\ v_{k,B}(p_\perp) &\approx v_{k,a}(p_\perp/3) + v_{k,b}(p_\perp/3) + v_{k,c}(p_\perp/3)\ , \quad (k = 1, 2, \ldots) \end{aligned}$$



- **behavior depends on $v_{k,p}(p_\perp)$:**

  faster than linear: $v_{k,p} > v_{k,M} > v_{k,B}$

  weaker than linear: $v_{k,p} < v_{k,M} < v_{k,B}$

  ENHANCEMENT

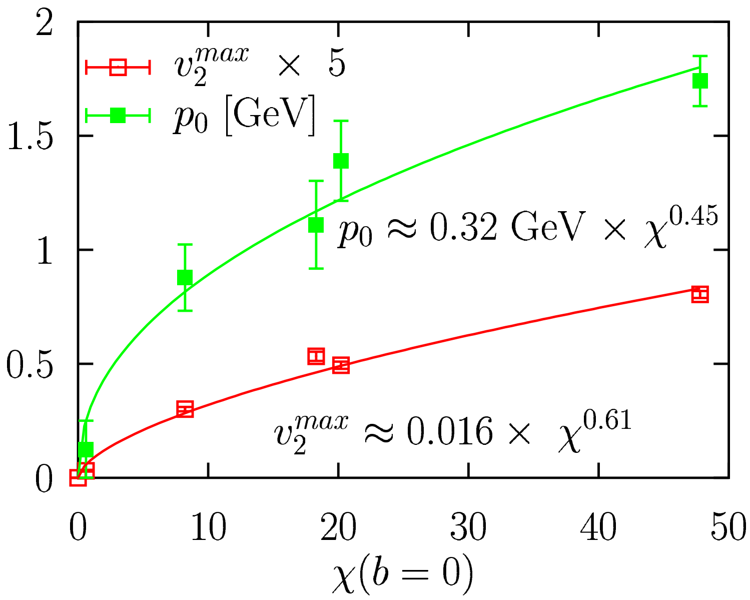
  flat: $v_{k,B} \approx 3v_{k,p}$; $v_{k,M} \approx 2v_{k,B}$

- **baryons saturate at higher value and at higher $p_\perp$ than mesons**

- **any drop in parton v_2 is pushed out to higher $p_\perp$ for hadrons**

Putting the pieces together

- **larger parton density → factor $2-3$ in opacity** $[\chi \propto \sigma_{el} \times dN/d\eta]$
- **amplification of elliptic flow → $2-3\times$ in v_2 → $3-6\times$ in opacity**



WHY? - parton transport solutions show
v_2 depends nonlinearly on opacity

$$v_2^{parton}(p_\perp, \chi) \approx v_2^{max}(\chi) \tanh(p_\perp / p_0(\chi))$$

where $\underline{v_2^{max}(\chi) \propto \chi^{0.61}}$

[NPA 697, 495 ('02)]

- **nonflow correlations in first v_2 data → extra 25% opacity reduction**

⇒ $\boxed{\textbf{total } 7.5-23\times \textbf{ reduction in opacity}}$ → back to reality (needed 15)

note: lower value assumes purely mesons, upper one purely baryons

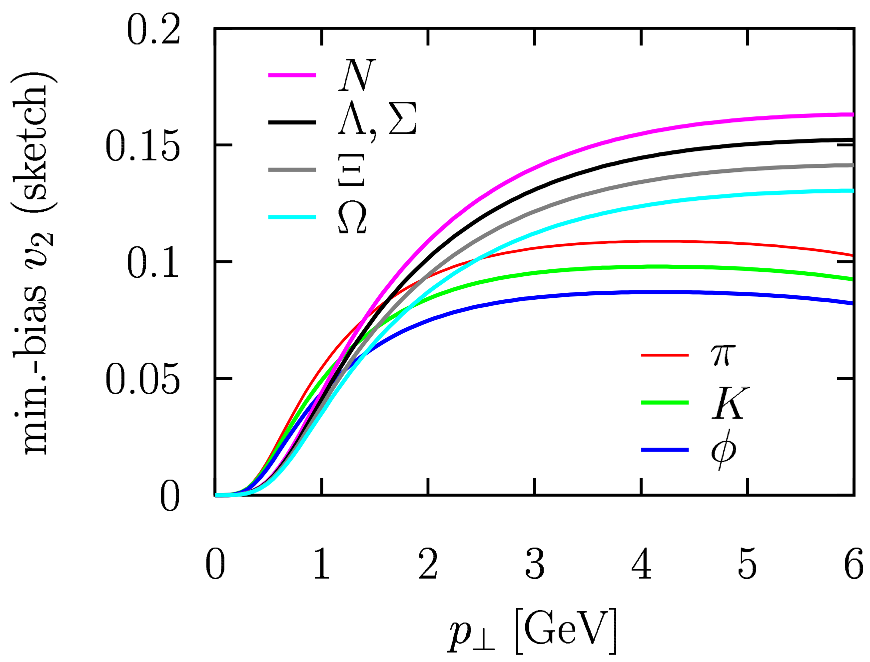
Elliptic flow ordering at high $p_\perp$

In the saturation region: $v_{2,B} \approx v_{2,a} + v_{2,b} + v_{2,c}$; $v_{2,M} \approx v_{2,a} + v_{2,\bar{a}}$

$\Rightarrow$ **if all $v_{2,p}$ are same: baryons have $\approx 50\%$ larger flow than mesons**

however: - **high $p_\perp$: quark energy loss depends on quark mass**
- **low $p_\perp$: hydrodynamic flow depends on mass**

$\Rightarrow$ $v_{2,s} < v_{2,light}$**: leads to richer v_2 ordering at high $p_\perp$**



- $p > \Lambda \approx \Sigma > \pi > K > \phi$
- $\Lambda, \Sigma > \Xi > K$
- $\Xi > \Omega > \phi$

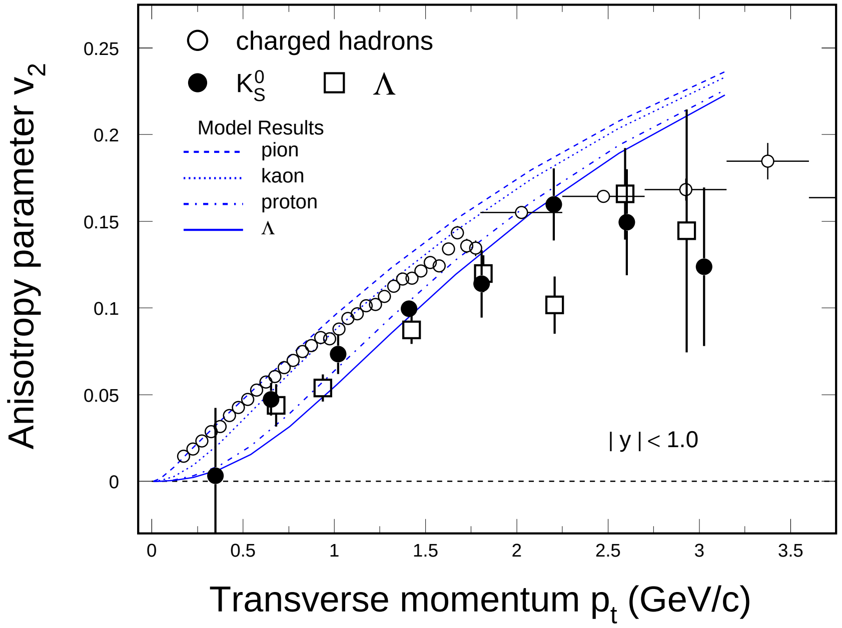
very different from that of Lin & Ko
$p = \pi > \Lambda, \Sigma > K > \Xi > \Omega = \phi$

reason: they assume coalescence of a high-$p_\perp$ quark and low-$p_\perp$ quark(s) - for the latter $v_2 \approx 0$ [PRL 89, 202302 ('02)]

Experimental evidence

Sorensen [STAR], JPG 28 ('02) 2089:

$$\Lambda > K_{0,S}$$

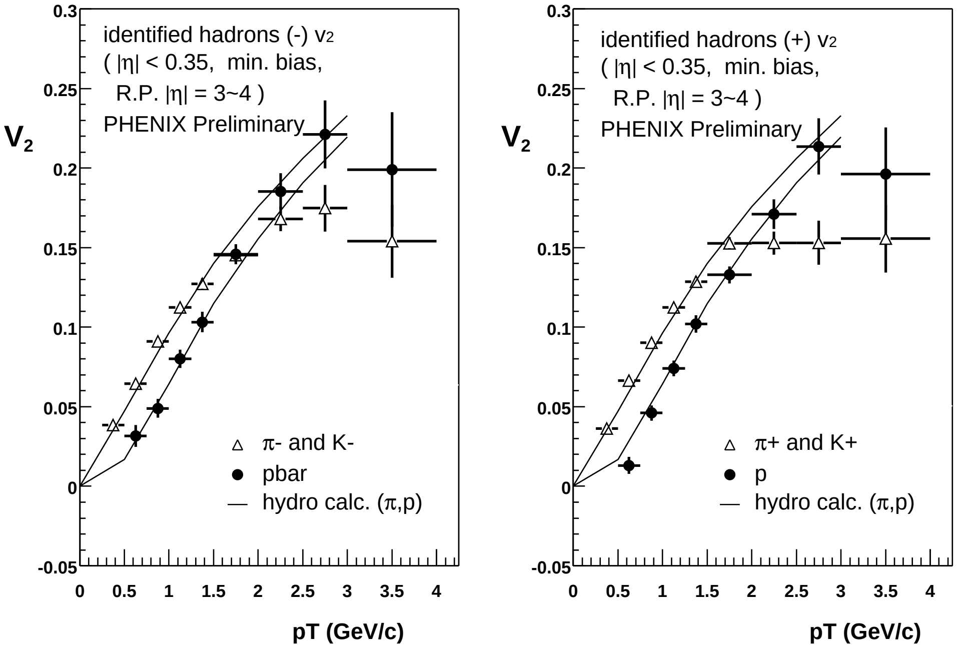


↑

by now better statistics (INT WS., Dec '02)
showing clearly $\Lambda > K_{0,S}$

Esumi [PHENIX], nucl-ex/0210012:

$$p > \pi + K$$



↑

also, indication of $p > \pi, K$ (not shown)

- **confirms expectations qualitatively - quant. comparison soon possible**

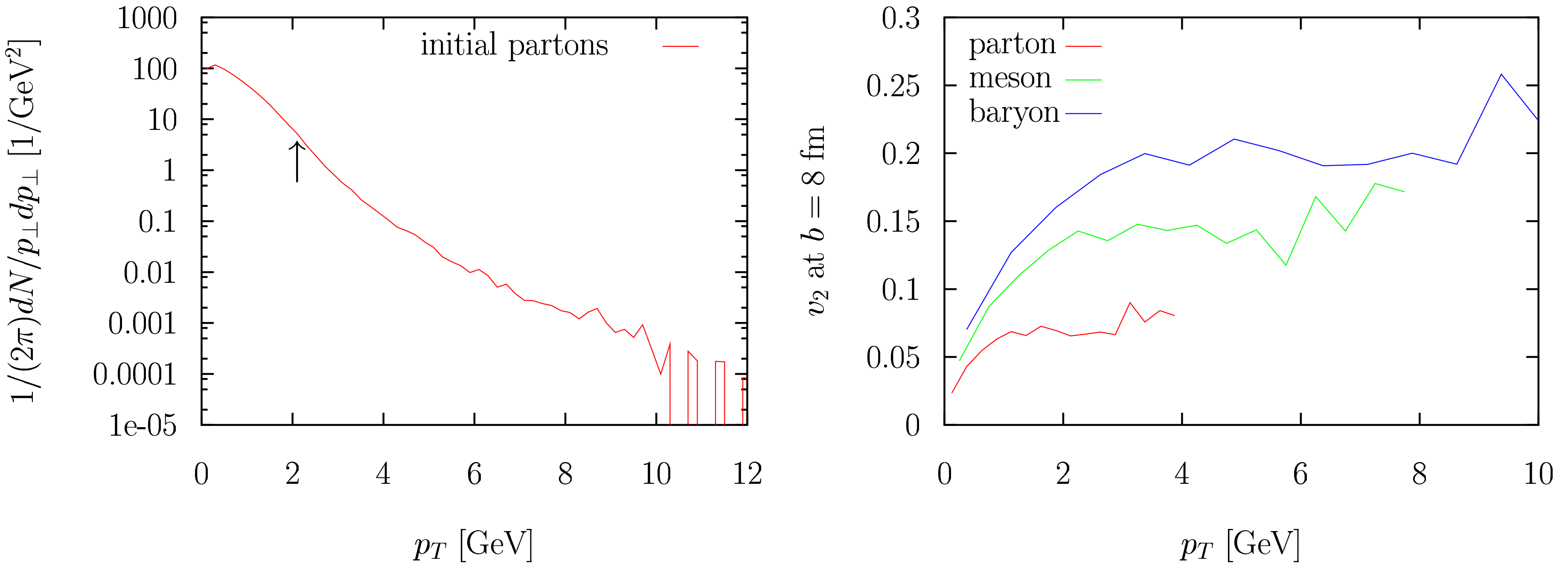
Flow ordering from parton transport

PRELIMINARY

goal: **quantitative results for Au+Au @ 200 GeV, at first only $b = 8$ fm**

- **cross sections:** **3mb for $gg \to gg$;** $qg \to qg$, $qq \to qq$ **reduced by** $4/9$, $(4/9)^2$
- **parton spectra:** - $p_\perp > 2$ **GeV: use LO pQCD (GRV98LO, BKK95, K=2,** $Q^2 = p_\perp^2$**)**

  - $p_\perp < 2$ **GeV: continue spectra smoothly s.t.** $dN/d\eta(b{=}0) = 2000$



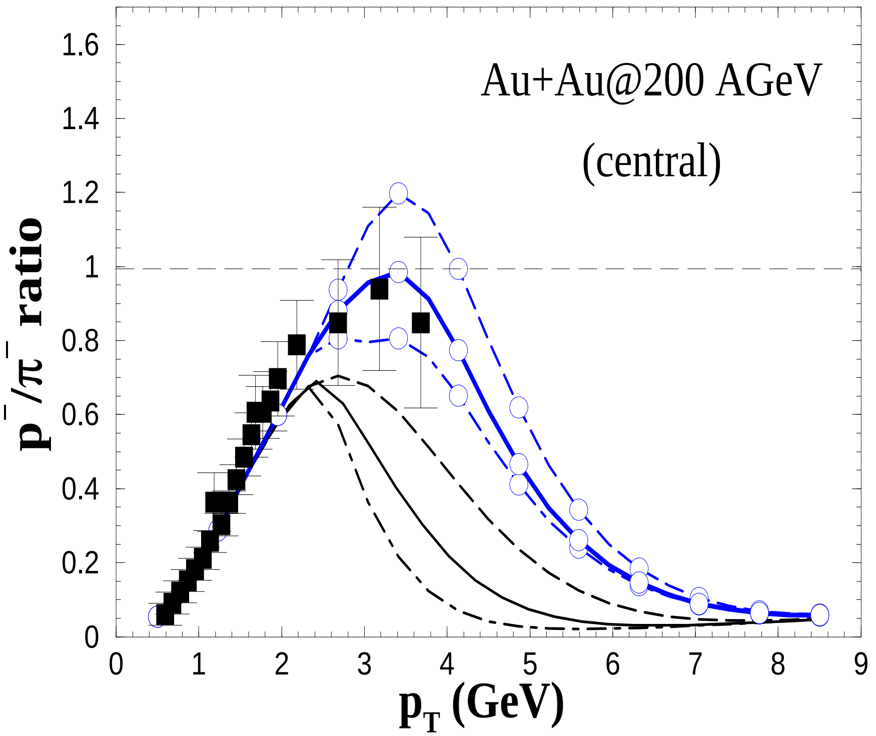
- **confirms simple estimates → full scale study with MPC in progress**

Other observables

Idea: **coalescence $p_\perp \to np_\perp$ pushes the low-$p_\perp$, close to thermal region in spectra out further for baryons than for mesons**

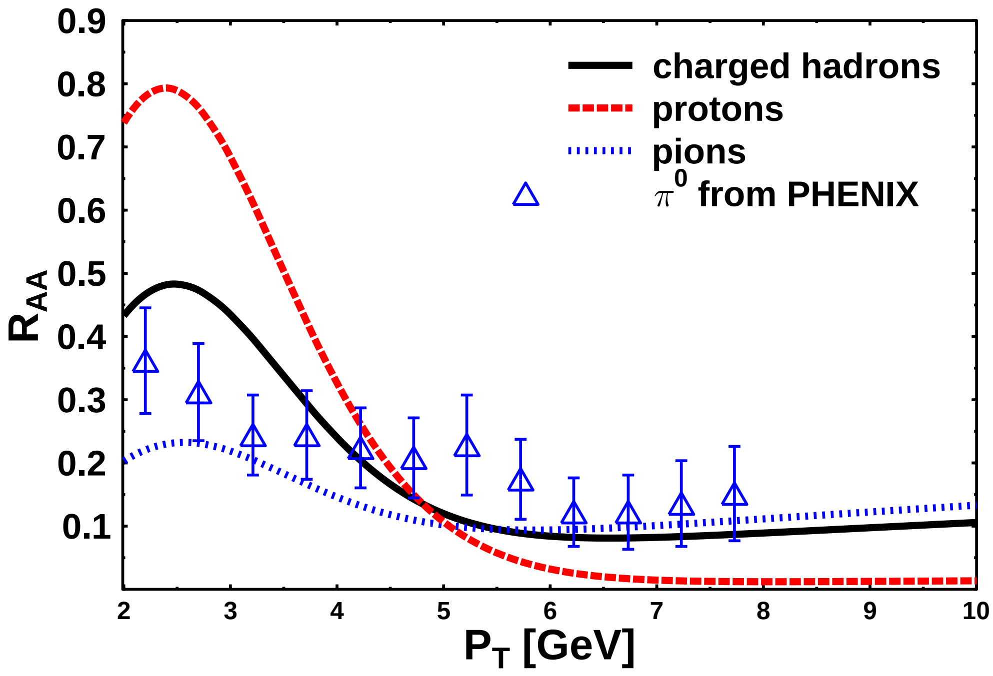
$\to$ different from pQCD fragmentation even at $p_\perp \sim$ several GeV

p/π ratio



[Greco, Ko, Lévai, nucl-th/0301093]

R_{AA} for hadrons



[Fries, Müller, Nonaka, Bass, nucl-th/0301087]

Coalescence factor

Much of the theory is based on deuteron formation "$pn \to d$"

- **consider momentum space:**

- **this talk:** **equal parton momenta, e.g.,** $(p_\perp/2, p_\perp/2) \to p_\perp$
assumes negligible momentum spread $\Delta p \approx 0$

- **in principle:** **momentum spread is allowed**
Δp **distribution depends on hadron wave fn.**

Fries et al: $dN_M(p) \sim \int d\sigma(r) \int dq \; |\psi^M_{ab}(q)|^2 \; f_a(p - q/2, r) f_b(p + q/2, r)$

Greco et al: $dN_M(p) \sim \int dr_1 dp_1 dr_2 dp_2 \; f_a(r_1, p_1) f_b(r_2, p_2) \; f_M(x_1 - x_2, p_1 - p_2)$

- **Lin & Ko:** **assume any Δp is equally probable**
→ **coalescence controlled by shape of constituent spectra**

None of the approaches consider the large hadronic binding energies, or at least exact energy-momentum conservation. [These were not an issue in the deuteron case where $E_{binding} \ll m_N$]

Summary

- the large saturating elliptic flow at observed RHIC can be explained via parton coalescence, with "conventional", i.e., moderate initial parton densities and cross sections

- the reasons are that coalescence
  - requires $2-3\times$ larger parton densities $dN_g/d\eta \sim 2000-3000$
  - also leads to a 2-to-3-fold amplification of hadron elliptic flow

- observable effects, predictions:
  - baryon v_2 saturating ≈ 50% above that of mesons
  - unique elliptic flow ordering at high $p_\perp$
    $p{>}\Lambda \approx \Sigma > \pi > K > \phi$, $\Lambda, \Sigma > \Xi > K$, $\Xi > \Omega > \phi$ (if $v_{2,s} < v_{2,q}$)
  - enhanced baryon/meson ratios at moderately large $p_\perp$

Open problems

- refined/extended calculations (centrality dependence, ...)
- explore effects on other observables (spectra, HBT, ...)
- detailed space-time dynamics of coalescence mechanism

This talk is on the WWW at http://nt3.phys.columbia.edu/people/molnard