Parton coalescence and flow

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Outline

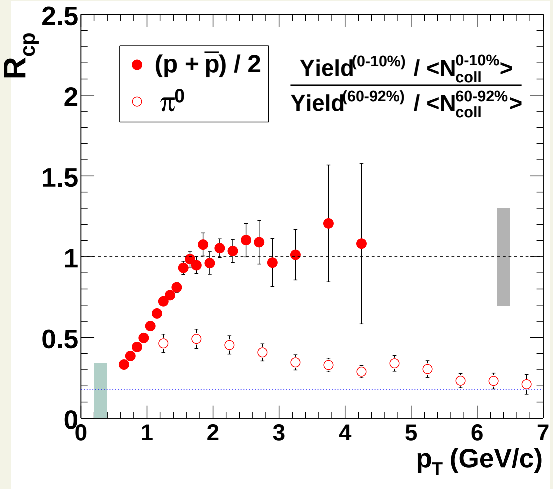
- **Introduction**
  - motivation, what coalescence is
  - simple parton coalescence formula
- **Spectra from coalescence (radial flow)**
  - coalescence window at RHIC
  - baryon enhancement
- **Azimuthal anisotropy**
  - anisotropy amplification from coalescence
  - elliptic flow scaling with quark number, mesons vs baryons
  - charm hadron elliptic flow
- **Open issues and next steps**
  - current and recent challenges
  - coalescence dynamics
- **Summary**

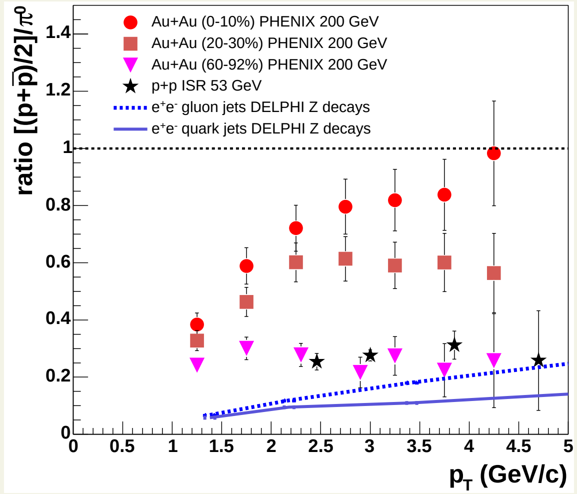
Introduction

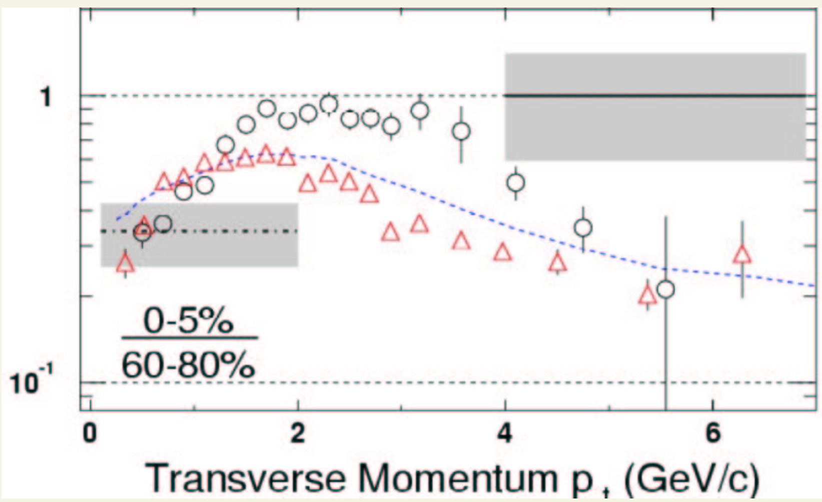
Two surprises at RHIC

baryon non-suppression, $p/\pi \sim 1$ — **elliptic flow saturates higher for baryons**

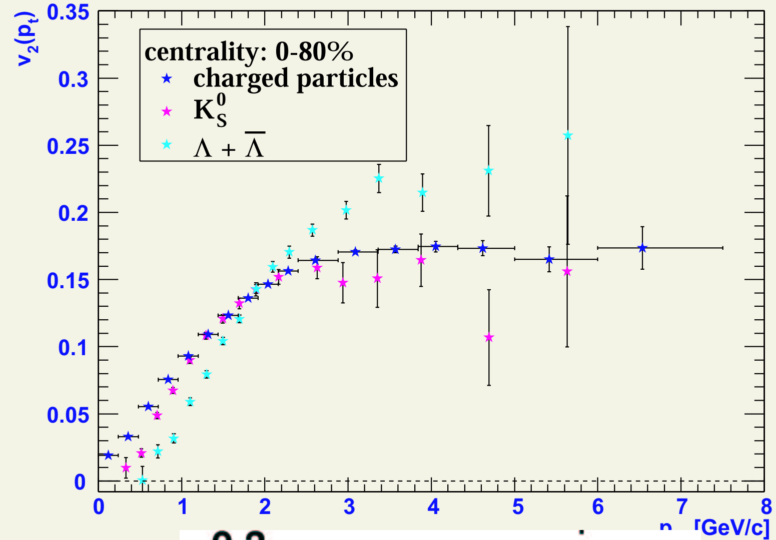
d'Enterria [PHENIX], Sorensen [STAR]:

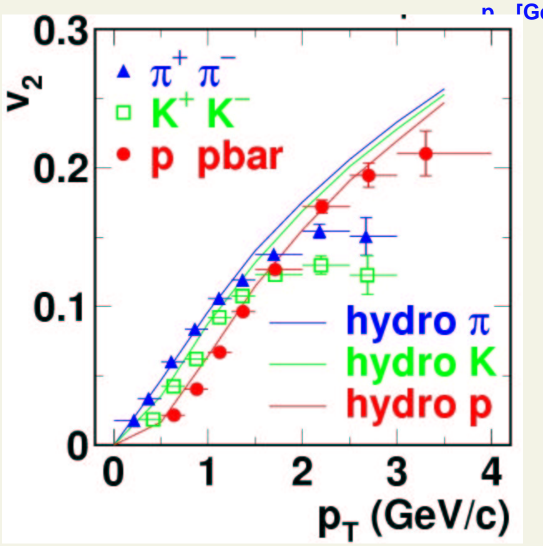






Sorensen [STAR], Esumi [PHENIX]:



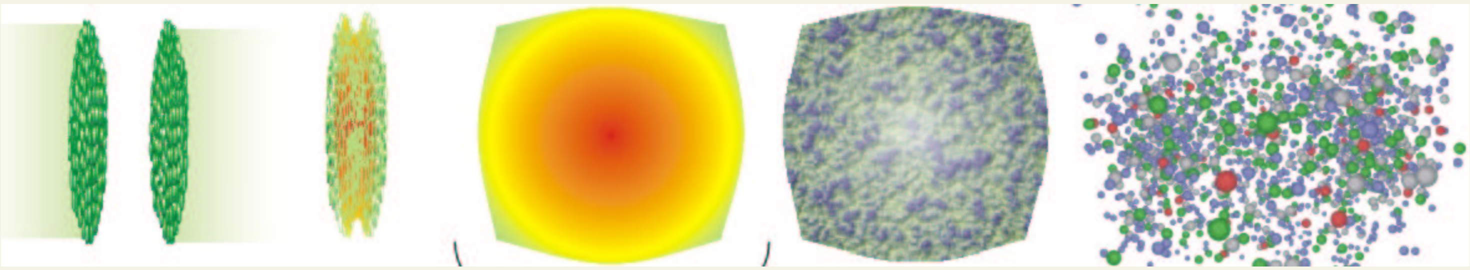


$\longrightarrow$ parton coalescence provides an explanation $\longleftarrow$

Hadronization problem

- **heavy-ion collision stages**

initial state **parton evol.** **hadronization** **hadronic evolution**



- **hadronization:** **least understood part**
  - nonperturbative
  - confinement

better knowledge is essential in order to learn about partonic stage from observed hadrons

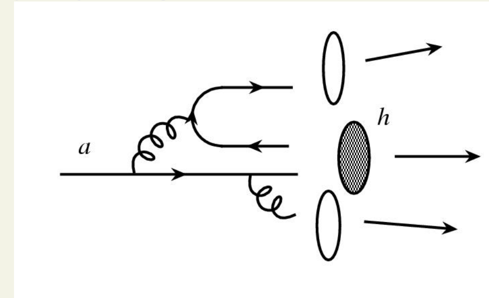
Independent fragmentation

factorized pQCD: $dN_h = f_i \otimes f_j \otimes d\sigma_{ij \to aX} \otimes D_{a \to h}$

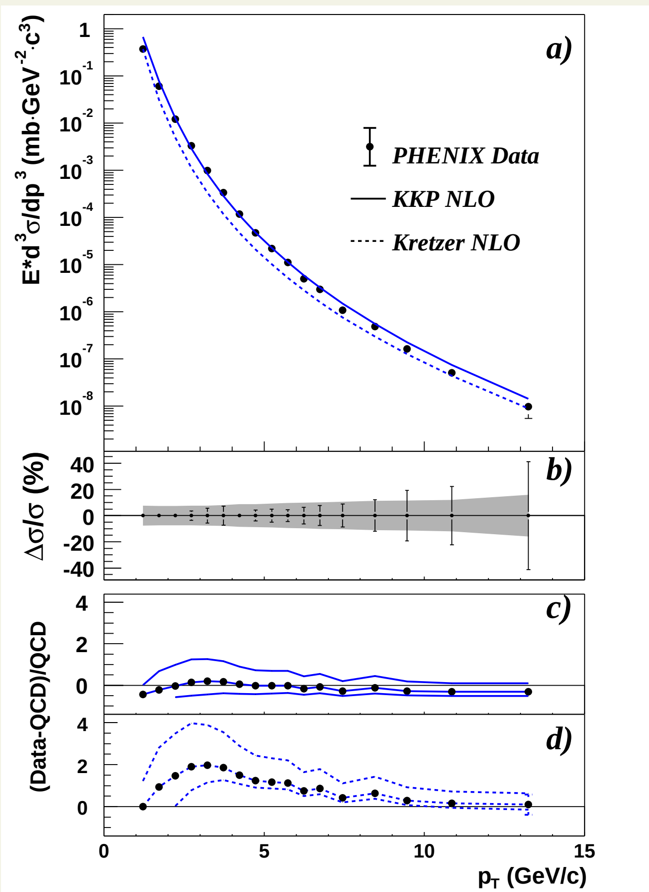
[applicable at large p_T]

fragmentation function

- **universal, measured** **(nonperturbative)**



$p + p$: works

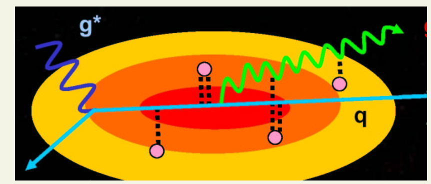


$A + A$: works for pions, but fails for baryons

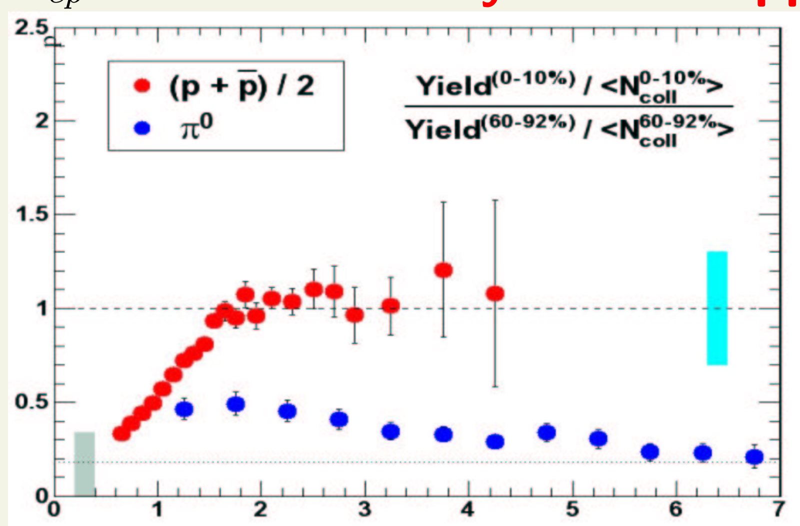
$$dN_h = f_{A,i} \otimes f_{A,j} \otimes d\sigma_{ij \to aX} \otimes E_{loss} \otimes D_{a \to h}$$

Wang, Gyulassy, Dokshitzer, Mueller, Levai,

Vitev, Wiedemann, Guo, Salgado, Djordevic, ...



R_{cp} from PHENIX: **baryon non-suppression**



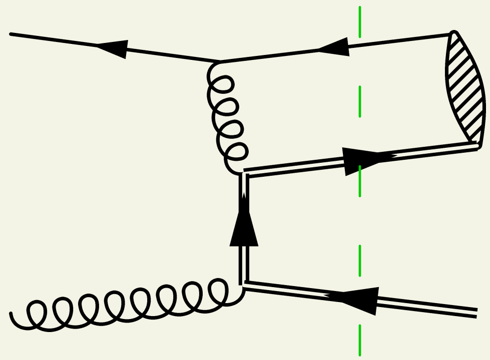
Multi-parton hadronization

leading particle effect: $\pi^-(u\bar{d}) + A \to D + X$ (E791 - $E_{lab} = 500$GeV)

$\alpha[D^+(c\bar{d})] \equiv \frac{\sigma[D^+]-\sigma[D^-]}{\sigma[D^+]+\sigma[D^-]} \sim 0.2 - 0.7$ - **large asymmetry**

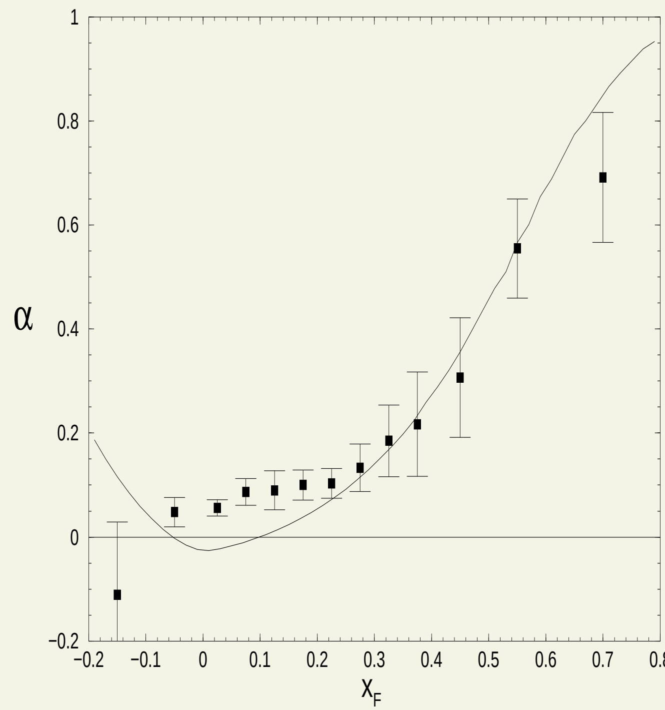
- **LO pQCD:** $\alpha = 0$, **NLO still too small** $\rightarrow$ **power corrections large**

- **need** $\bar{d} + g \to (c\bar{d}) + \bar{c} \to D^+ + \bar{c}\ (+X)$



[Braaten & Jia, PRL89 ('02)]

reproduces E791:



D^+ favored because valence $\bar{d}$ is already there

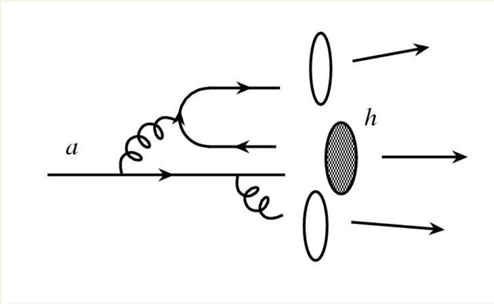
- **beam-drag effect (natural in string models)**

Parton coalescence

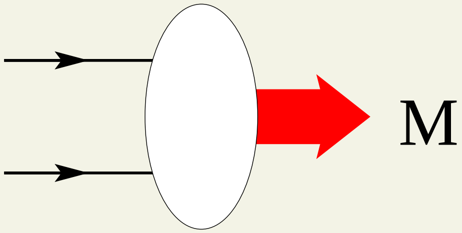
Hwa, Yang, Biró, Zimányi, Lévai, Csizmadia, Ko, Lin, Voloshin, D.M., Greco, Fries, Müller, Nonaka, Bass, ...

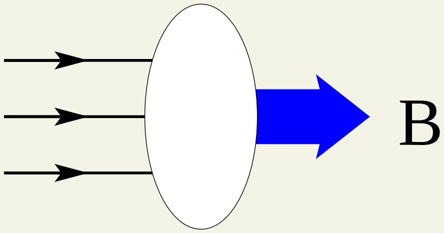
- **heavy-ion collisions: large parton density $\Rightarrow$ multi-parton processes probable**

besides jet fragmentation



additional hadronization channels via parton coalescence/recombination





- **consider lowest-order $q\bar{q} \to M$, $qqq \to B$ (valence quarks only)**

Applications

hadron multiplicity: Das & Hwa, PLB68 ('77)
Biró et al, PLB347 ('95) - ALCOR
Csizmadia & Lévai, JPG28 ('02) - MICOR

baryon/meson ratio: Hwa & Yang, PRC65 ('02)
Greco, Ko, Levai, PRL90 ('03); PRC68 ('03)
Fries, Müller, Nonaka, Bass, PRL90 ('03); PRC68 ('03)
Hwa, Yang, PRC67 ('03)
Fries, Müller, Nonaka, Bass, JPG30 ('04)
Hwa & Yang, nucl-th/0401001

resonances: Nonaka, Müller, Asakawa, Bass, Fries, PRC69 ('04),
Zimányi & Lévai, nucl-th/0404060

elliptic flow: Ko & Lin, PRL89 ('02)
Voloshin, NPA715 ('02)
D.M. & Voloshin, PRL91 ('03)
Nonaka, Fries, Bass, PLB583 ('04)
D.M., JPG30 ('04)
Greco, Ko, nucl-th/0404020
D.M., nucl-th/0404065

charm hadron elliptic flow: Lin & D.M., PRC68 ('03)
Greco, Ko, Rapp, nucl-th/0312100

Formalism

Traditional coalescence

- **original problem:** $n + p \to d$

  Butler & Pearson, PR129 ('63)
  Schwarzschild & Zupancic, PR129 ('63)
  Sato & Yazaki, PLB98 ('81)
  Gyulassy, Frankel & Remler, NPA402 ('86)
  Dover, Heinz, Schnedermann & Zimányi PRC44 ('91)
  Nagle, Kumar, Kusnezov, Sorge & Mattiello, PRC53 ('96)
  Kahana, Kahana, Pang, Baltz, Dover, Schnedermann & Schlagel, PRC54 ('96)
  Scheibl & Heinz, PRC59 ('99)
  ...

Simple coalescence formula

- **basic equations:** $q\bar{q} \to meson$, qqq (or $\bar{q}\bar{q}\bar{q}$) $\to baryon$

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

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

hadron yield   space-time   wave-fn.   quark distributions

assumes: - **weak binding**
- **no 2-body or 3-body correlations**
- **rare process - otherwise violates unitarity (need low phasespace density)**
- **3D hypersurface (e.g., equal time - sudden approximation)**

comes from the QM projection theorem: $P_\phi(t) = |\langle \phi | \Psi(t) \rangle|^2$

- **need** f_q, $f_{\bar{q}}$, **hypersurface, and hadron wave functions**

Applying the formulas

- f_q, $f_{\bar{q}}$, and hypersurface can in principle be obtained from a dynamical calculation

- however, most common approach:

  educated guess for distributions, with a few parameters fitted to a subset of data
  [analogous to: hydro $\leftrightarrow$ blastwave; hydro, transport HBT $\leftrightarrow$ HBT source parameterizations]

  - thermal constituent spectra + radial flow
  - uniform temperature & density, fixed proper time

  yield from fragmentation included additively

$$dN_h = dN_h^{coal}(f_q \otimes f_{\bar{q}} \otimes W_h, \text{hypersurface}) + dN_h^{frag}(d\sigma \otimes E_{loss} \otimes \text{FFs})$$

- useful simplifications:

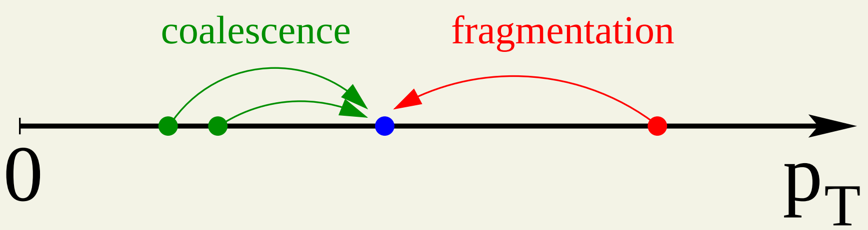
  slowly varying spatial distributions: - $W_M(\Delta\vec{p}, \Delta\vec{x}) \to \tilde{W}_M(\Delta\vec{p})\delta^3(\Delta\vec{x})$, ...

  if also narrow wave fn: - $W_M(\Delta\vec{p}, \Delta\vec{x}) \to (2\pi)^3\delta^3(\Delta\vec{p})\delta^3(\Delta\vec{x})$, ...

Spectra (radial flow)

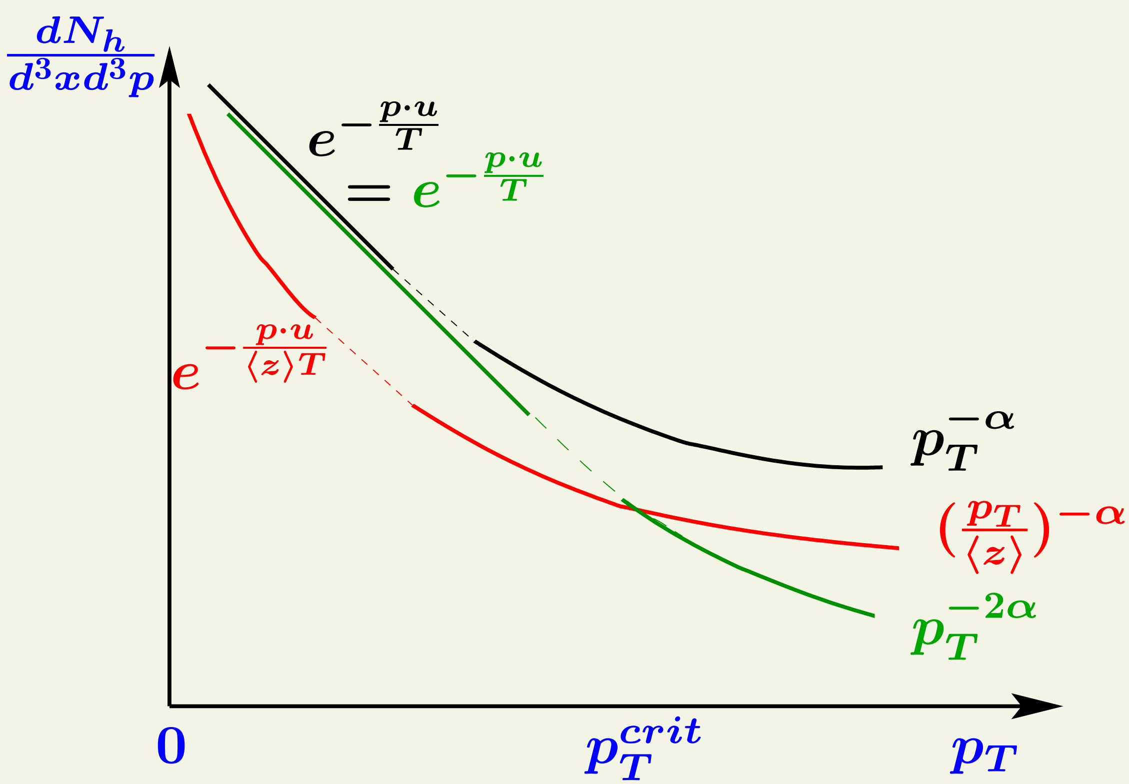
Coalescence window

Coalescence competes with fragmentation and wins below $p_\perp < p_\perp^{crit}$



coal: $p_T \to \approx n\, p_T$, $n = 2, 3$

frag: $p_T \to z\, p_T$, $z < 1$



- for exponential, coal wins
- for power-law, frag wins

$\Downarrow$

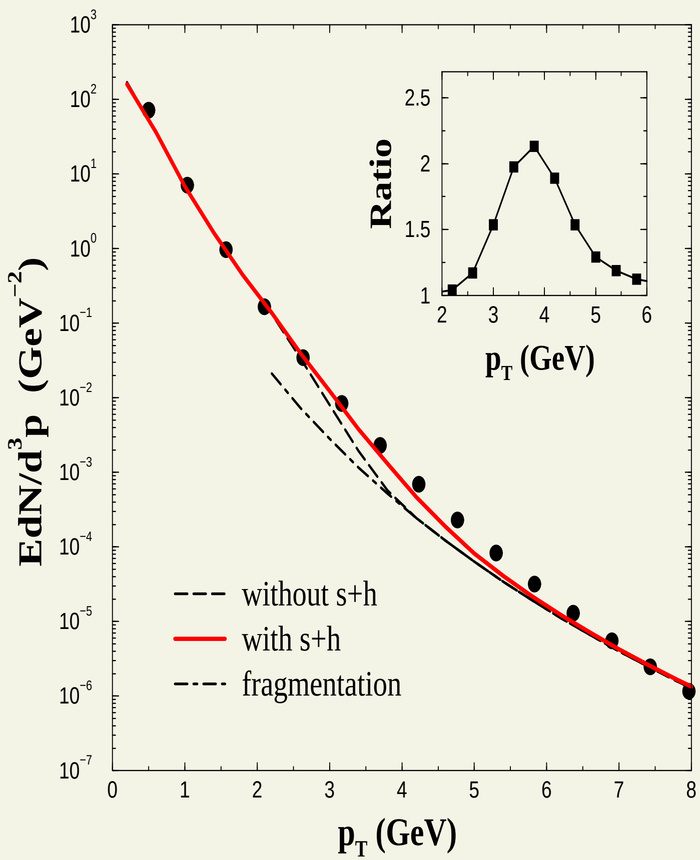
coalescence yield drops steeper than fragmentation yield

p_T^{crit}: decreases with incr. centrality

Parametrized soft component

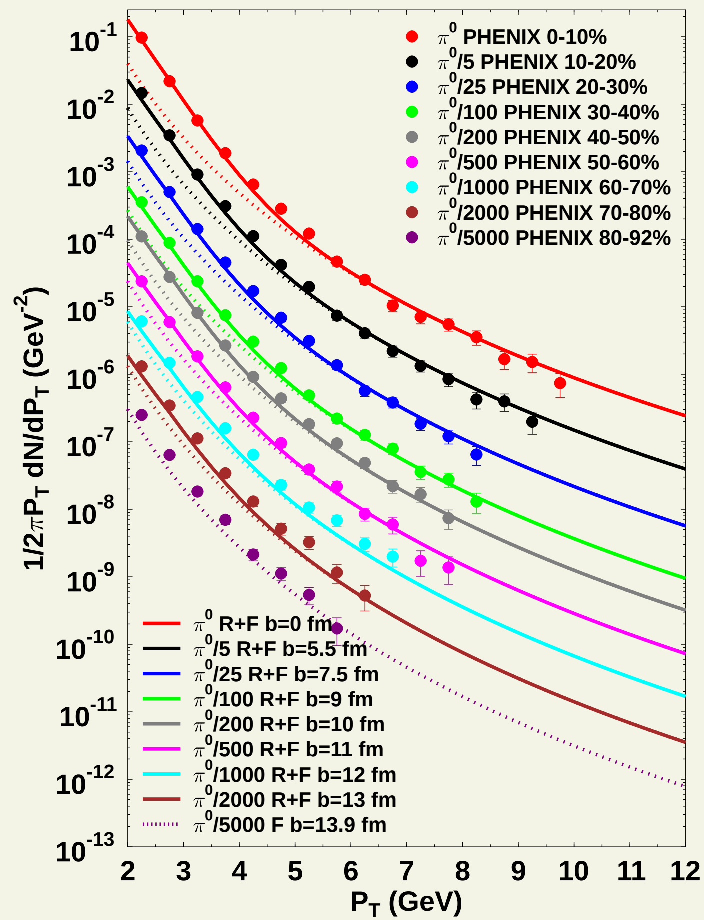
(!) a quark-antiquark "plasma", thermalized at $T \approx T_c$, w/ strong radial flow works

Greco, Ko, Levai ('03): T_q=170 **MeV**, v_T^{max}=0.5



[A_T=225 fm^2, τ=4 fm, $L/\lambda = 3.5$]

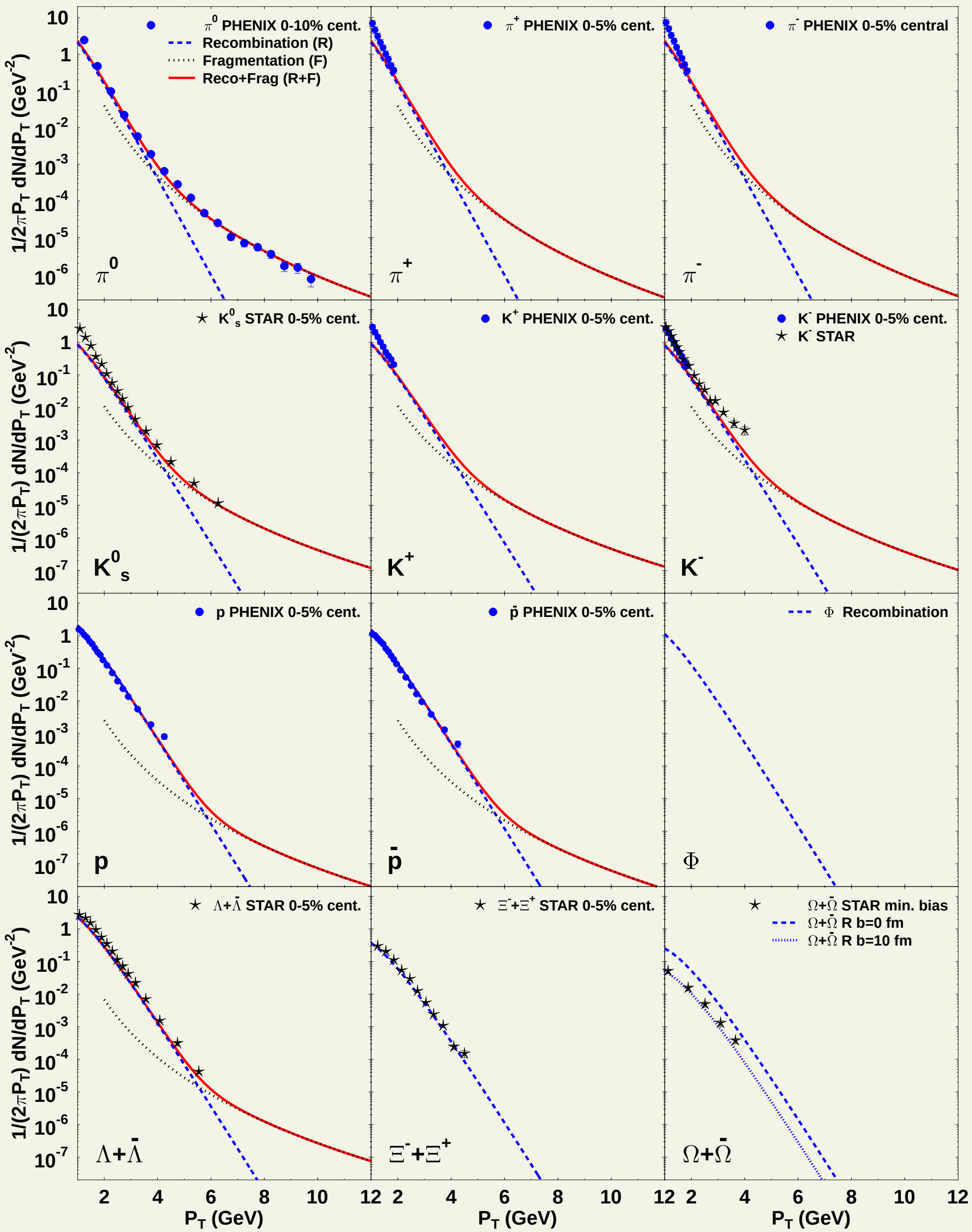
Fries et al ('03): T_q=175 **MeV**, v_T^{max}=0.55



[A_T = 155 fm^2, τ=5 fm, $\lambda = 0.67$]

- **coal. dominates meson production out to $p_T \sim 4$ GeV (~ 6 GeV for baryons)**

Fries et al ('03):



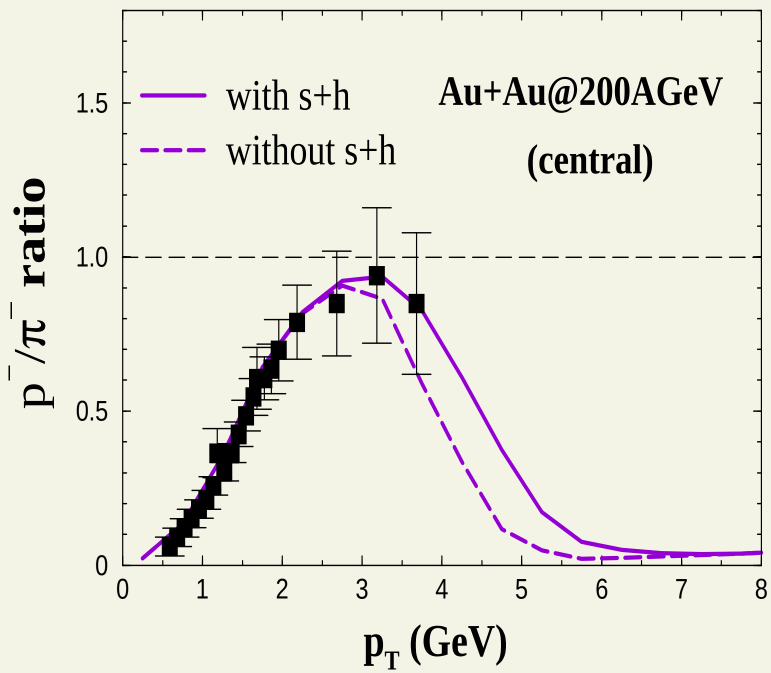
30-50% typical accuracy

Baryon enhancement

Thermal $p_\perp <\sim 2$ GeV partons contribute, via recombination, out to $2\times \sim 2$ GeV for mesons, while $3\times \sim 2$ GeV for baryons

$\Rightarrow$ **thermal tails extend into the intermediate p_T regime $\to$ fixes p/π**

Greco, Ko, Levai ('03):



[A_T=225 fm^2, τ=4 fm, $L/\lambda = 3.5$]

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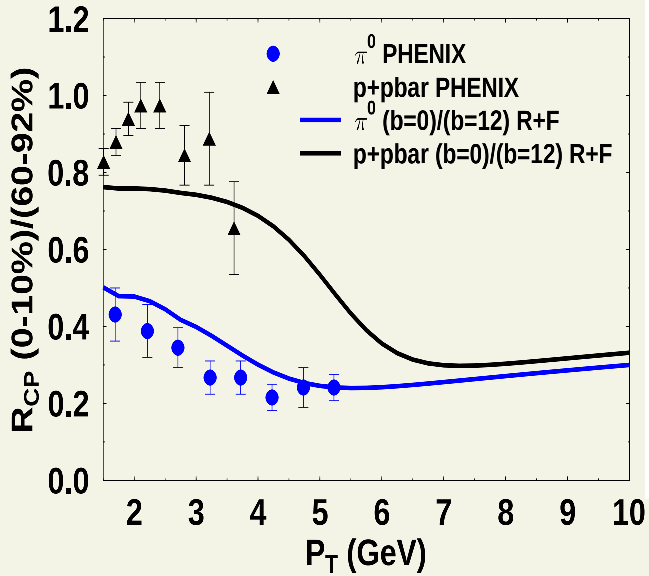
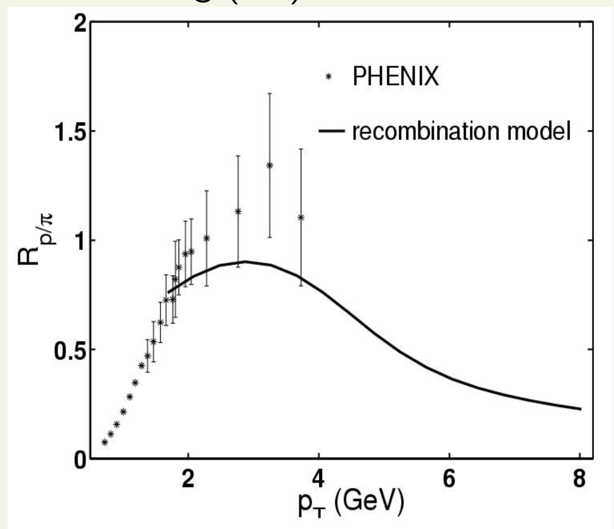


[$A_T = 155$ fm^2, τ=5 fm, $\lambda = 0.67$]

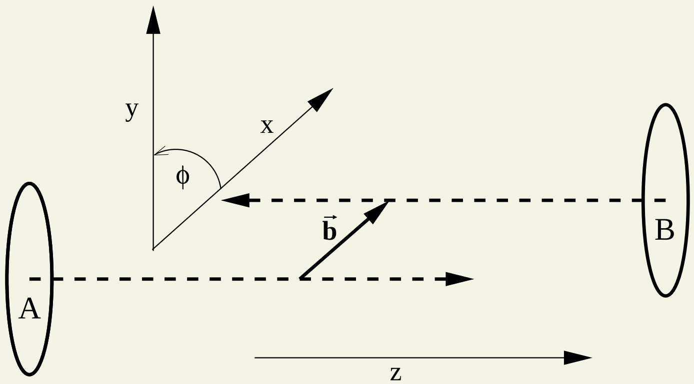
Hwa & Yang ('04):

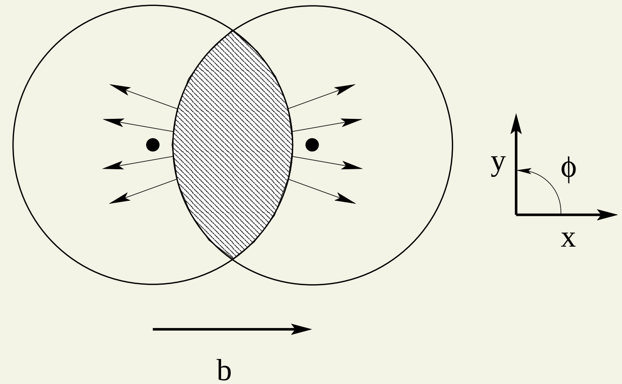


Azimuthal anisotropy

Azimuthal anisotropy

- **momentum-space anisotropy of particle production in A+A collisions**





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

directed flow: $v_1(X) \equiv \langle \cos\phi \rangle_X$
elliptic flow: $v_2(X) \equiv \langle \cos 2\phi \rangle_X$
...

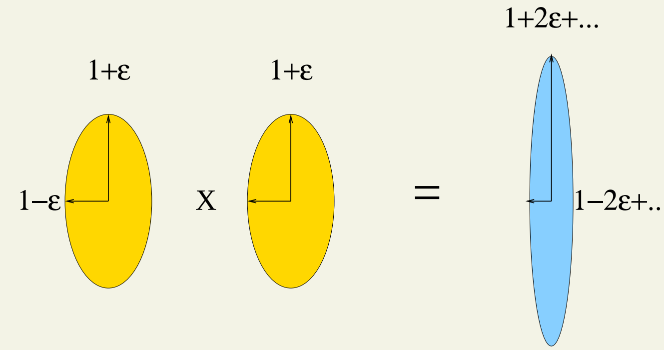
X : **event and particle selection, e.g., centrality, transverse momentum**

Anisotropy amplification

[Voloshin & D.M. ('03)]

narrow wave fn.: $(2\times\frac{\vec{p}}{2})\to\vec{p}$, $(3\times\frac{\vec{p}}{3})\to\vec{p}$ $\quad \frac{dN_M}{d\phi} \propto \left(\frac{dN_q}{d\phi}\right)^2$, $\frac{dN_B}{d\phi} \propto \left(\frac{dN_q}{d\phi}\right)^3$

$$v_k^M(p_\perp) = v_k^a(\frac{p_\perp}{2}) + v_k^{\bar{b}}(\frac{p_\perp}{2}) + \mathcal{O}(v^3), \quad k = 1, 2, \ldots$$
$$v_k^B(p_\perp) = v_k^a(\frac{p_\perp}{3}) + v_k^b(\frac{p_\perp}{3}) + v_k^c(\frac{p_\perp}{3}) + \mathcal{O}(v^3)$$

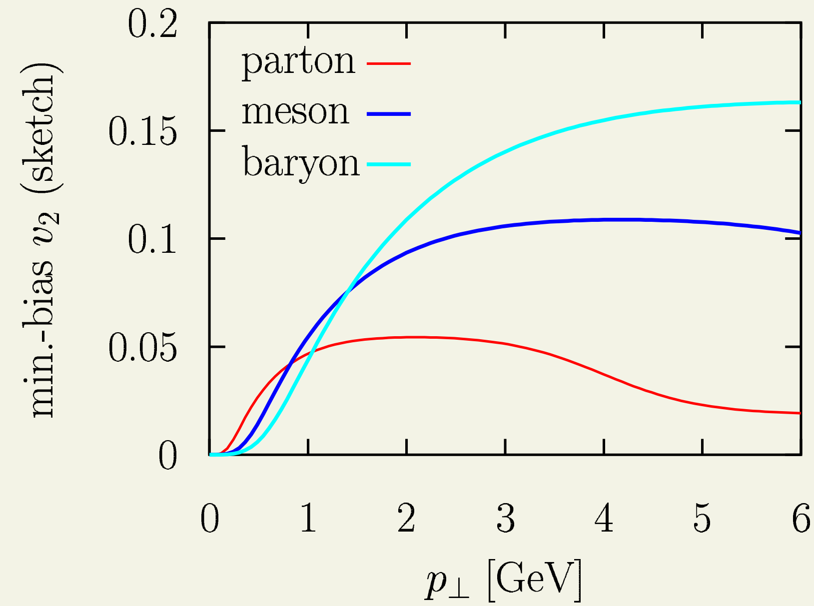


$\Rightarrow$ **hadron v_2 amplified at high $p_\perp$**
if all quarks have same v_2:

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

" $v_2^h(p_\perp) \approx n \times v_2^q(p_\perp/n)$ "

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



- **if v_2 depends on quark flavor, further differentiation by flavor content**

Determination of parton v_2

Via measuring $v_2(p_\perp)$ for various hadrons, one can extract quark flows AND test consistency of coalescence model

Consider, e.g., $v_2^q \neq v_2^s$ (light vs. strange)

$$
\begin{aligned}
v_2^\pi(p_\perp) &\approx 2v_2^q(\frac{p_\perp}{2}) \\
v_2^K(p_\perp) &\approx v_2^q(\frac{p_\perp}{2}) + v_2^s(\frac{p_\perp}{2}) \\
v_2^\phi(p_\perp) &\approx 2v_2^s(\frac{p_\perp}{2})
\end{aligned}
$$

$$
\begin{aligned}
v_2^p(p_\perp) &\approx 3v_2^q(\frac{p_\perp}{3}) \\
v_2^{\Lambda,\Sigma}(p_\perp) &\approx 2v_2^q(\frac{p_\perp}{3}) + v_2^s(\frac{p_\perp}{3}) \\
v_2^\Xi(p_\perp) &\approx v_2^q(\frac{p_\perp}{3}) + 2v_2^s(\frac{p_\perp}{3}) \\
v_2^\Omega(p_\perp) &\approx 3v_2^s(\frac{p_\perp}{3})
\end{aligned}
$$

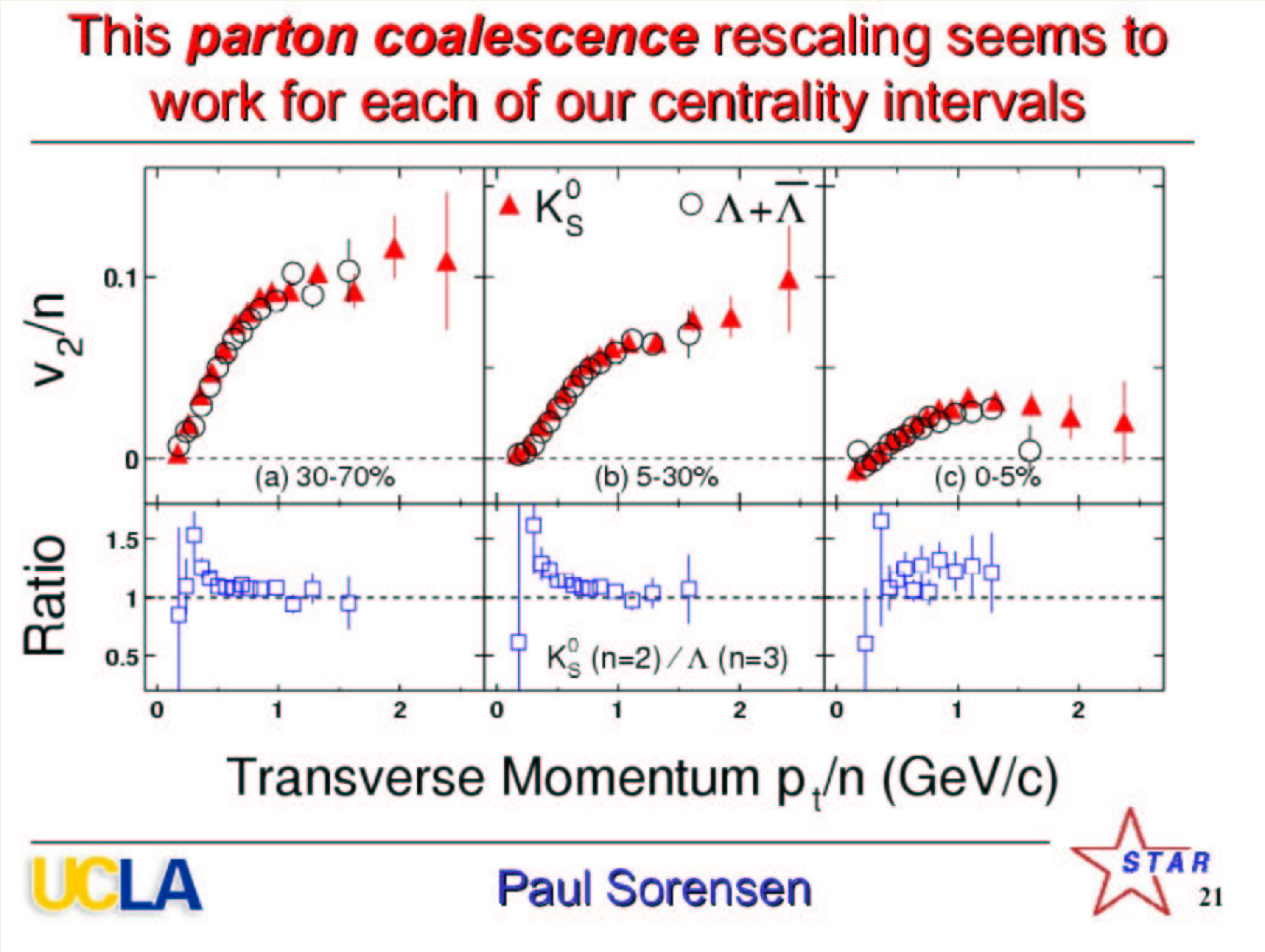
2 unknowns, 7 equations $\Rightarrow$ e.g.,

$$
\begin{aligned}
v_2^q(p_\perp) &= v_2^\pi(2p_\perp)/2 = v_2^p(3p_\perp)/3 = v_2^\Lambda(3p_\perp) - 2v_2^p(3p_\perp)/3 \\
v_2^s(p_\perp) &= v_2^\phi(2p_\perp)/2 = v_2^\Omega(3p_\perp)/3 = v_2^K(2p_\perp) - v_2^\pi(2p_\perp)/2
\end{aligned}
$$

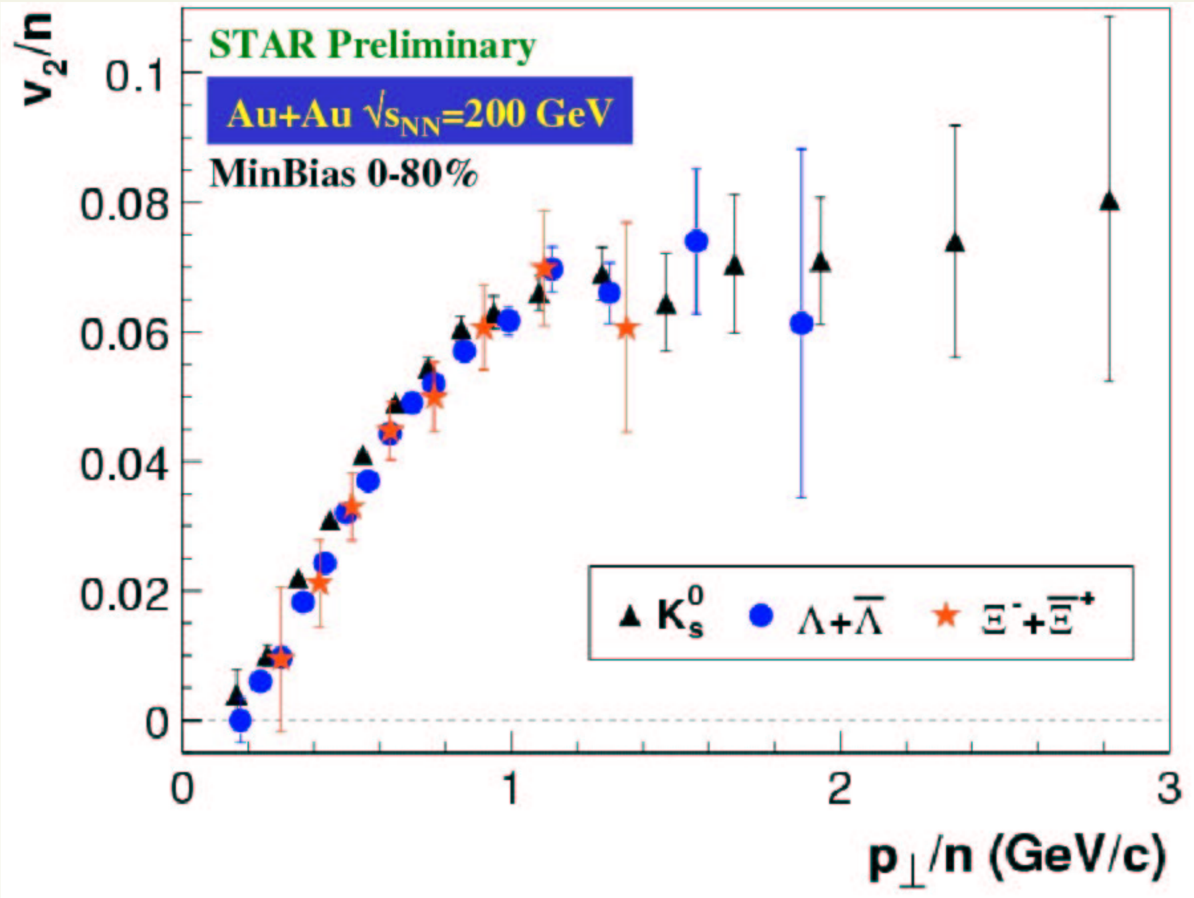
Simplest $v_2^q = v_2^s$ case: $v_2^{hadron}(np_\perp)/n$ universal fn. ($n = 2, 3$ for meson,baryon)

Experimental test of v_2 scaling

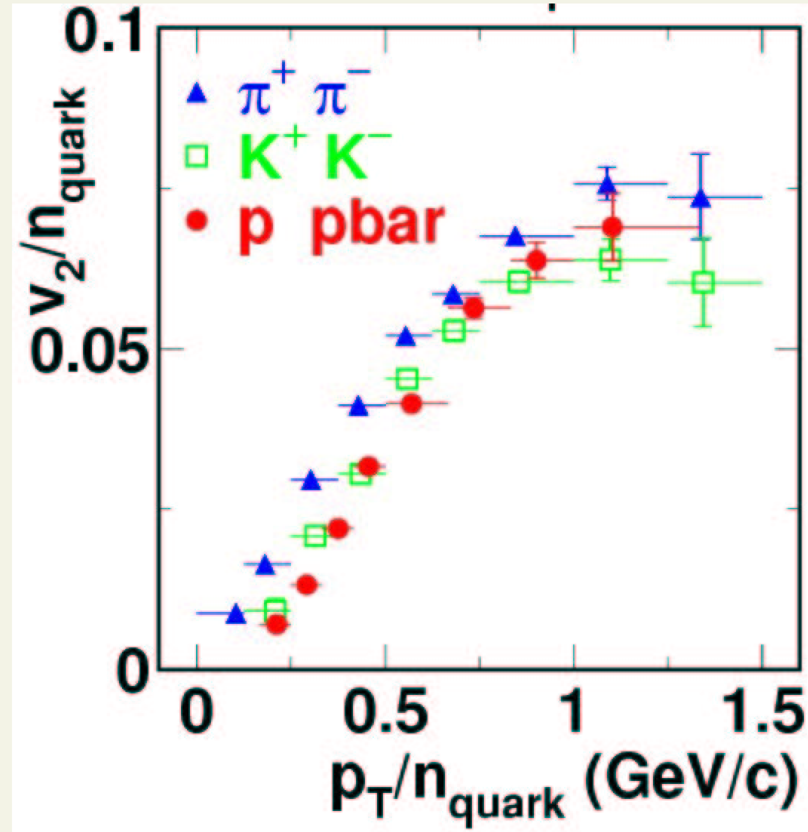
first good news - STAR, SQM2003: K^S_0, Λ



Castillo [STAR], HIC03: Ξ flow



PHENIX, PRL91 ('03): π, K, p



- **coalescence predictions confirmed for $\pi, K, K_0, p, \Lambda, \Xi$ - also for Ω, ϕ (poor statistics)**

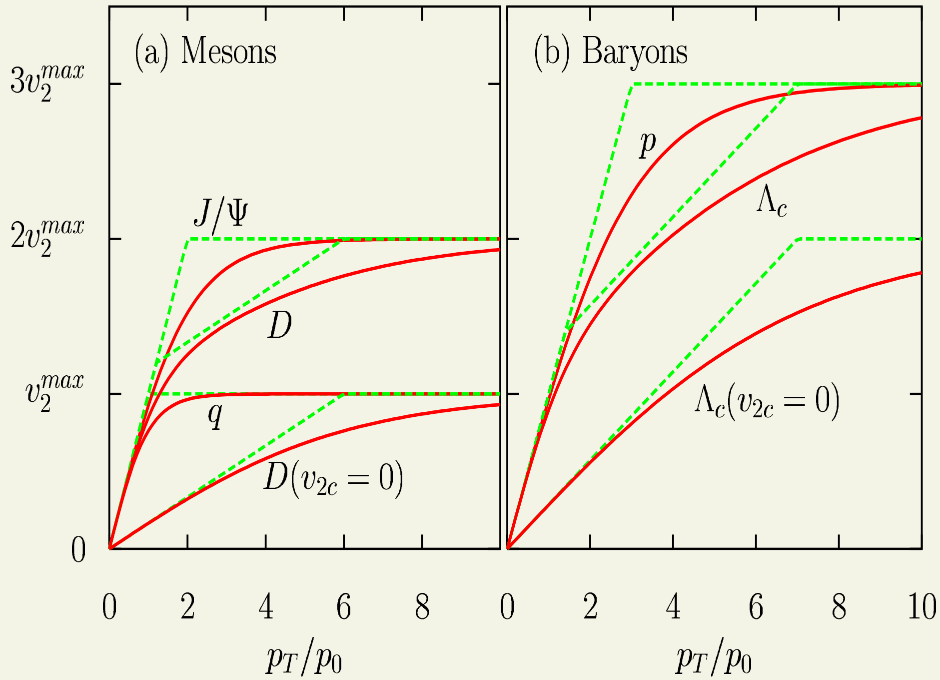
  - pions are little off the curve, likely due to resonance decays [Greco & Ko]

- **surprisingly, RHIC data indicate $v_2^q \approx v_2^s$**

Elliptic flow for charm

generic expectations:

Lin & D.M. ('03)



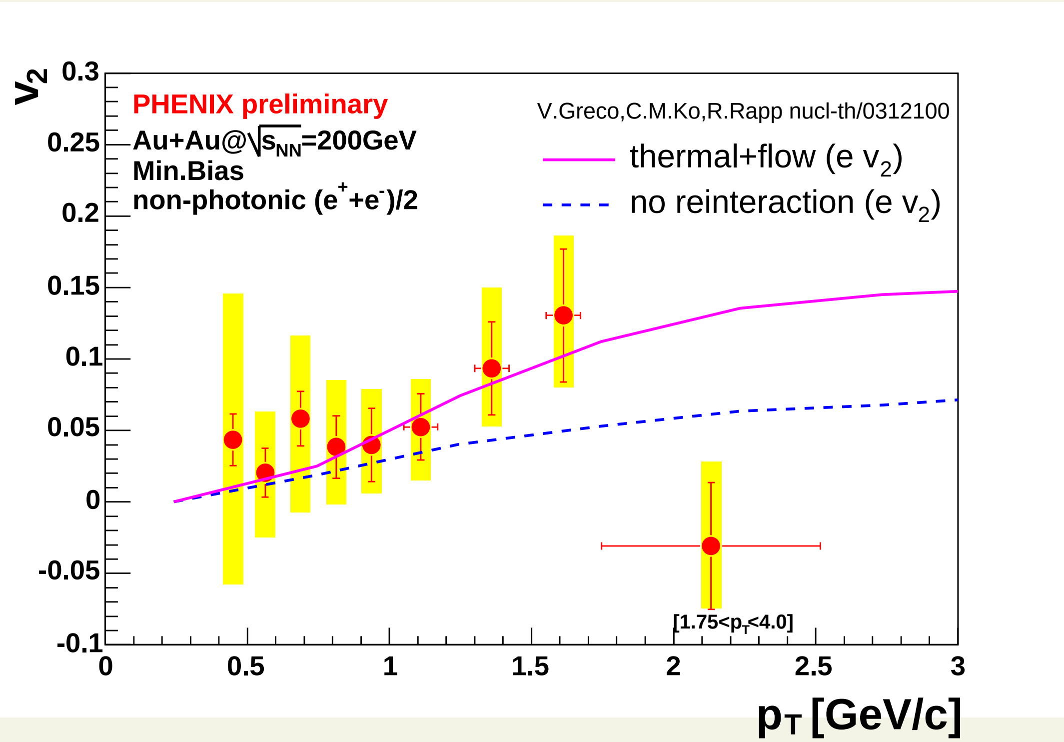
simplistic (linear & flat); more realistic (based on parton cascade MPC)

- **$v_2(p_\perp)$ rises slower, saturates later for asymmetric systems (D, D_s, Λ_c)**
  - **heavy quark carries most of the hadron momentum**

    (momentum proportional to constituent mass)
- **nonzero v_2 for D, D_s, Λ_c even for zero charm v_2 (no thermalization)**

decay electron v_2: $D \to K\,\nu\,e$, $D \to K^*\,\nu\,e$

Kaneta, nucl-ex/0404014; Greco & Ko, nucl-th/0312100:



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

- **need better data to discriminate between scenarios with or without charm flow**

Open issues and next steps

A few recent issues

- **entropy:** $2 \to 1$, $3 \to 1$??
  - globally, problem is cured by resonance decays and larger s/n for massive particles
  - locally, the issue is still interesting (but less of a worry)

- **binding energy:** only relevant for Goldstones π & K
  - likely a small correction because resonance channels $K^* \to K$; $\rho, \omega, \Delta, \ldots \to \pi$ dominate production

- **extend to low-p_T regime:** simple formula not applicable (unitarity)
  - does coal w/ unitarity still reduce to statistical models/hydrodynamics?

- **constituents vs partons:** so far - two, mostly independent components
  - Hwa & Yang: hadrons made of constituents, which in turn consist of partons limited to momentum space $\to$ need extension to 6D phasespace

- **hadron correlations:** coal dilutes jetlike correlations??
  - not necessarily: constituent correlations possible $\Rightarrow$ map uniquely to hadron correlations
  - a correlation source: parton showers [Hwa & Yang, nucl-th/0401001]

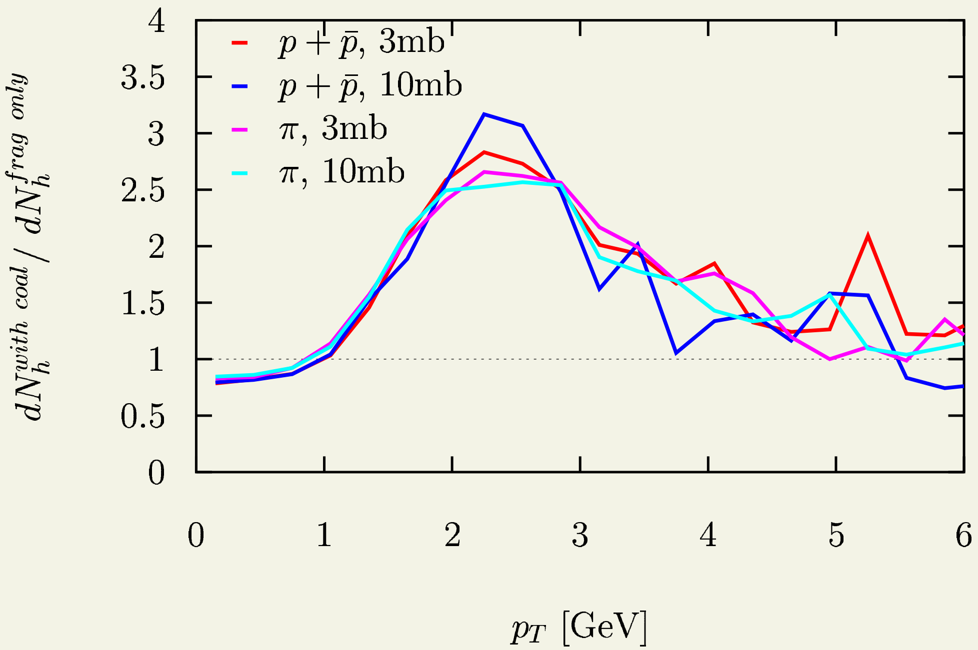
Coalescence dynamics - puzzle

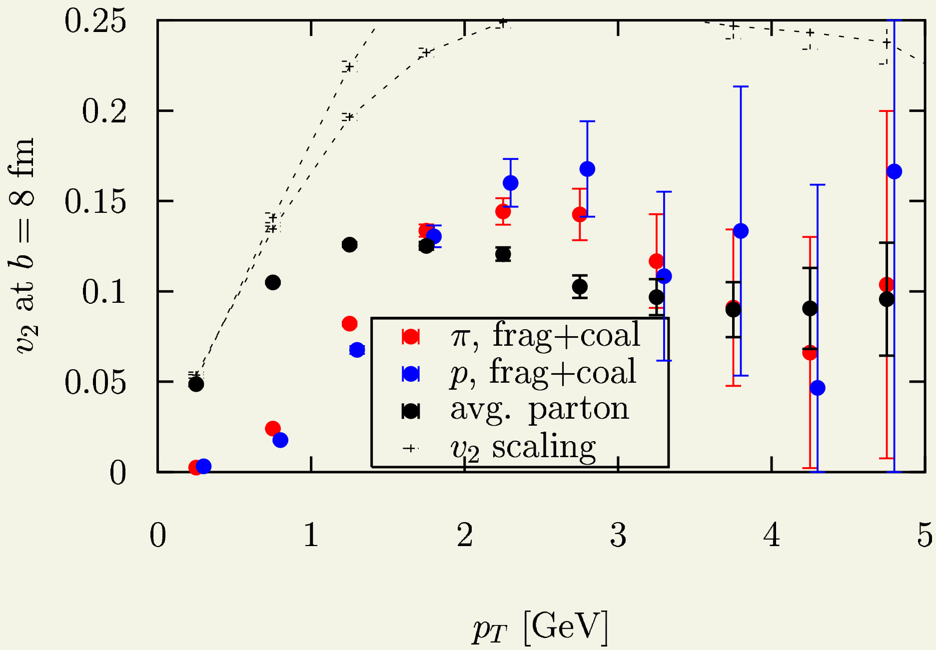
parton transport + coalescence (e.g., MPC, AMPT, VNI/BMS)

hadronization: - partons nearby in phasespace coalesce, those without a partner fragment
- weakly-bound hadrons

Au+Au @ 200 GeV, b=8 fm - **hadron enhancement** **elliptic flow**

D.M. ('04):





- $2-3\times$ **enhancement over fragmentation for** $1.5 < p_T < 4$ **GeV**

but same for protons as pions $\Rightarrow p/\pi$ **stays low**
$\rightarrow$ **baryons have more constituents** $\Rightarrow$ **are more "fragile"**

- **flow amplification negated**
  $\rightarrow$ **25-30% frag contribution, reduces flow**
  $\rightarrow$ **dynamical correlations,** $f(\vec{x},\vec{p}) \neq F(\vec{x})g(\vec{p})$
  imperfect scaling
- **baryon-meson splitting disappeared**

Summary

- hadronization via quark coalescence is important at RHIC, dominates hadroproduction at intermediate $1.5 < p_\perp < 4 - 6$ GeV

- both the observed large baryon/meson ratios and elliptic flow scaling with quark number (baryon flow enhancement) follow from the simple coalescence formulas - predictions for ϕ, Ω, and charm hadron flow are yet to be tested

  $\Rightarrow$ strong indication for quark degrees of freedom at hadronization

  for narrow wave functions, elliptic flow of quarks can be extracted from that of hadrons via simple relations

- spacetime dynamics ($x-p$ correlations, "diffuse" freezeout) can significantly influence both the flow scaling and baryon/meson ratio enhancement

  for weakly-bound hadrons, baryon production is reduced because baryons are more fragile than mesons (except for the "sudden" hadronization scenario)

$\Rightarrow$ further studies required to find a dynamical approach that preserves features of the simple models