Charm hadrons from parton coalescence

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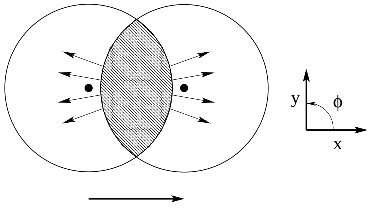
- **references:** Z.W. Lin & D.M. - nucl-th/0304045
  D.M. & S.A. Voloshin - nucl-th/0302014
  D.M. & M. Gyulassy - NPA 697, 495

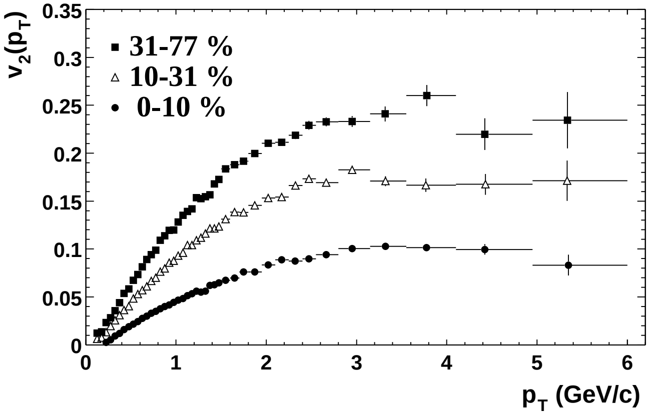
Why do we need parton coalescence?

Elliptic flow puzzle

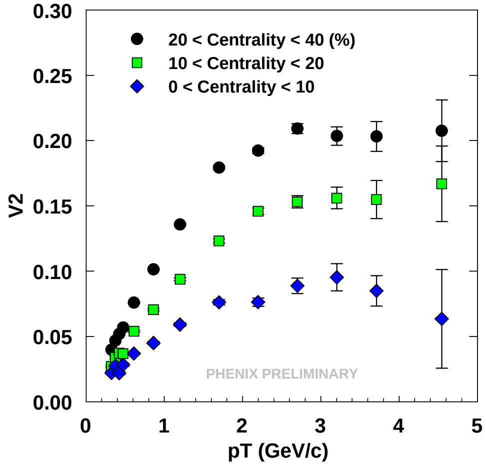


Experimental data vs. Theoretical expectations

STAR, PRL 90, 032301 ('03)



PHENIX, nucl-ex/0210007 ('03)

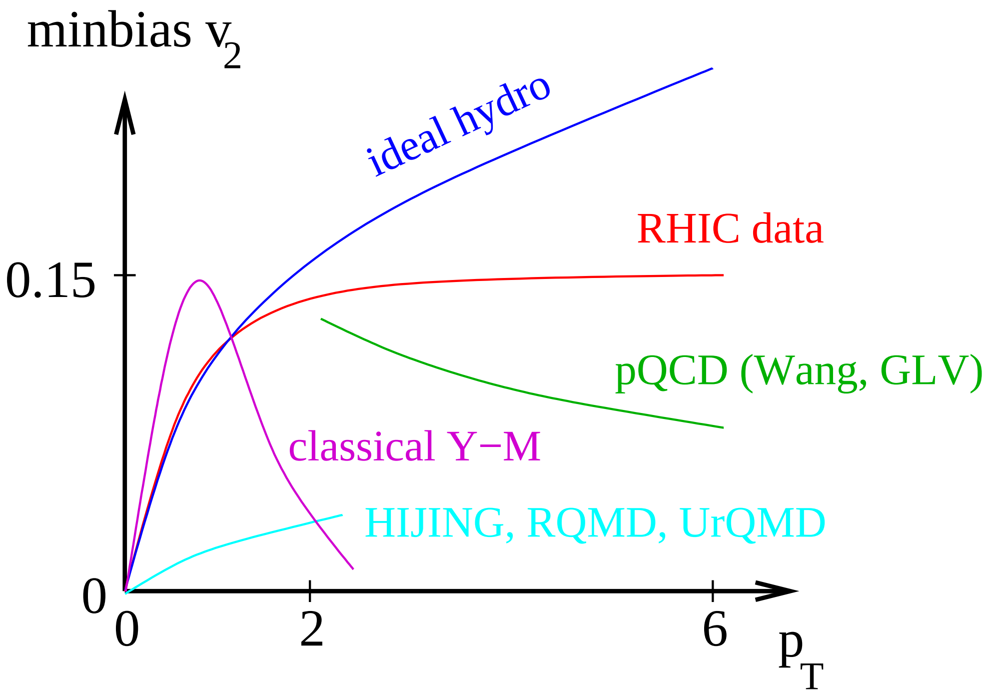


[Heinz, Kolb, Huovinen et al;

Gyulassy, Vitev, Wang et al;

Sorge et al; Bleicher, Stöcker et al;

Krashnitz, Venugopalan et al]

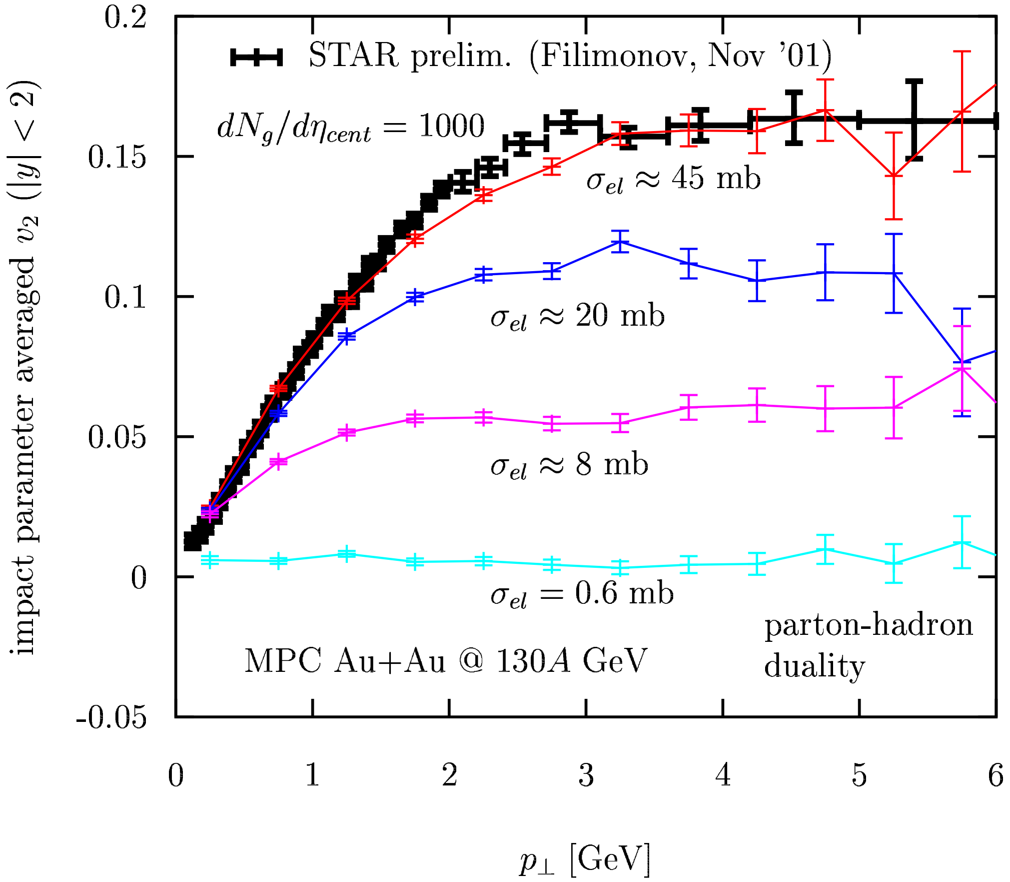


- **large and saturating anisotropy $v_2(p_\perp)$**

- **difficult to explain**

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

D.M. & Gyulassy, NPA 697 ('02):



parton transport **MPC 1.6.0**

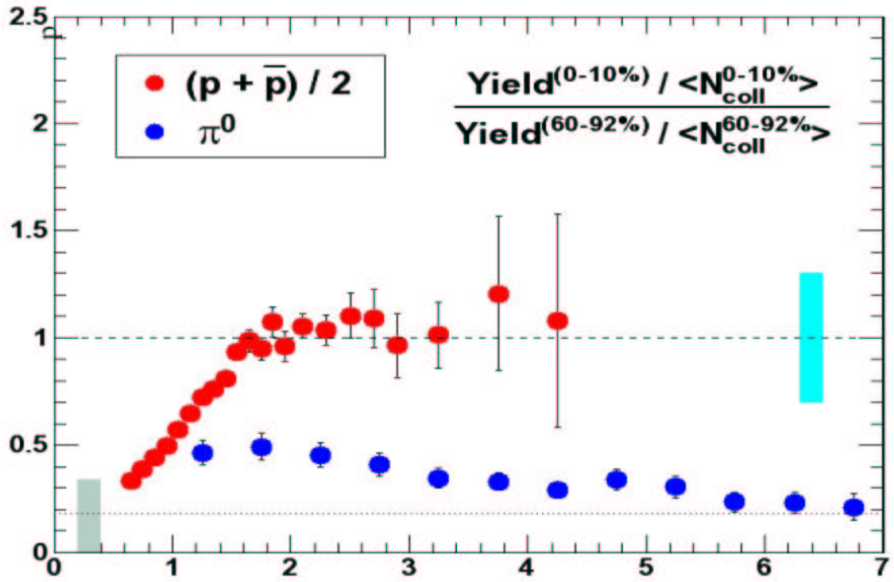
$$p^\mu \partial_\mu f_i = S_i + C_i^{2\to2}[f] + \ldots$$

- $15\times$ **larger opacities required** **to reproduce saturation pattern**

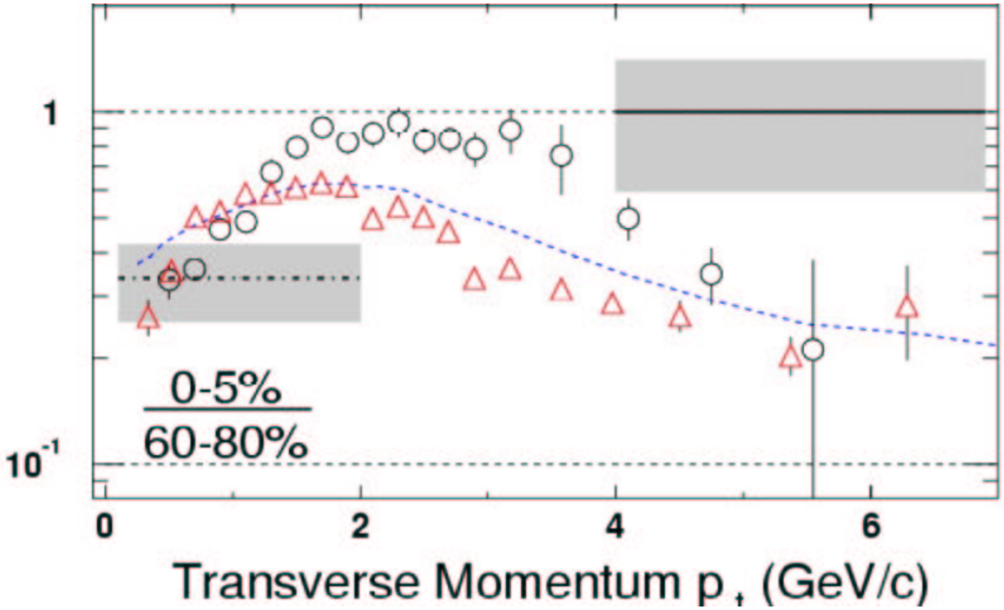
$\sigma_{el} \times dN_g/d\eta \approx 45000$ **mb** $\gg$ **pQCD** (3 **mb** $\times 1000$)

Baryon (non)suppression puzzle

d'Enterria (PHENIX) - INT, June '03: p, π^0



Sorensen (STAR) - SQM2003: K_S^0, Λ



- $p_\perp > 2$ **GeV, pQCD jet quenching works well for pions, kaons (see talks by Wang, Jacobs & Bathe on Wednesday)**

but does not for baryons?

Good news: coalescence helps explain both puzzles

Ok, but what is coalescence?

Coalescence

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

  Sato & Yazaki, PLB98 ('81)
  Dover, Heinz, Schedemann & Zimányi PDR44 ('91)
  Scheibl & Heinz, PRC59 ('99)
  ...

- **recently applied to hadronization in heavy ion collisions**

  hadron yields: Biró et al PLB347 ('95); Csizmadia & Lévai JPG28 ('02)

  elliptic flow ordering: Ko & Lin, PRL89 ('02)

  proton/pion ratio: Hwa & Yang, PRC65 ('02); Greco et al & Fries et al, PRL90 ('03)

  flow amplification and elliptic flow ordering: D.M. & Voloshin, nucl-th/0302014

  charm hadron elliptic flow: Lin & D.M., nucl-th/0304045

Parton coalescence

An alternative to independent fragmentation

- **picture: - coalescence of massive “dressed” valence quarks**
  - no dynamical gluons

- **basic equations:** $qq \to meson$, $qqq \to baryon$

$$E\frac{dN_M(\vec{p})}{d^3p} = \int d\sigma^\mu p_\mu \int d^3q |\psi_{\vec{p}}(\vec{q})|^2 f_\alpha(\vec{p_\alpha}, x) f_\beta(\vec{p_\beta}, x)$$

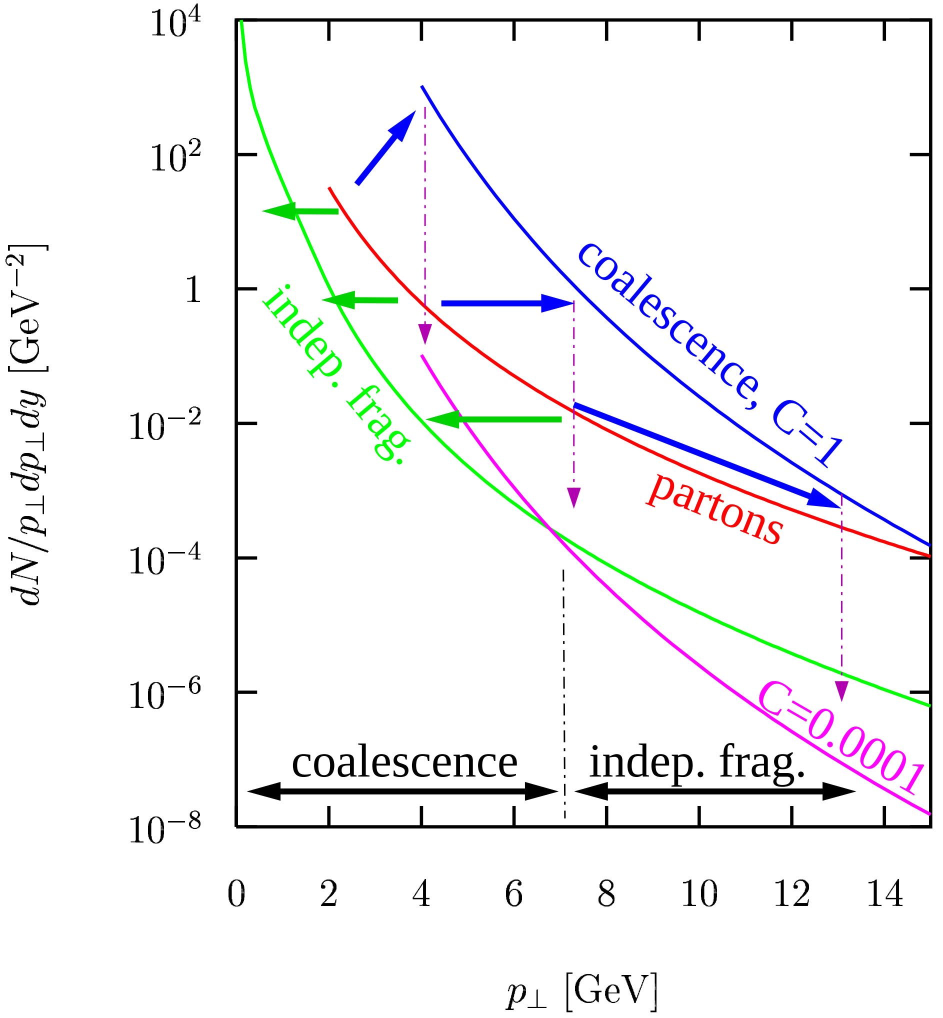
$$E\frac{dN_B(\vec{p})}{d^3p} = \int d\sigma^\mu p_\mu \int d^3q_1 d^3q_2 |\psi_{\vec{p}}(\vec{q_1}, \vec{q_2})|^2 f_\alpha(\vec{p_\alpha}, x) f_\beta(\vec{p_\beta}, x) f_\gamma(\vec{p_\gamma}, x)$$

hadron yield space-time wave-fn. quark distributions

assumes: rare process, weak binding, factorizable 2-body density matrix, smooth spacetime distributions, 3D hypersurface

Coalescence window

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



[red: central Au+Au @ 200 GeV, mesons
GRV98LO, BKK95, $K = 2$, $Q^2 = p_\perp^2$]

- **momentum shift:**

  frag: $p_\perp \longrightarrow z p_\perp \ (z < 1)$ **DOWN**

  coal: $p_\perp \longrightarrow n p_\perp \ (n = 2, 3)$ **UP**

- **phasespace density dependence:**

  frag: **linear** $dN_{had} \propto dN_{part}$

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

$$\Downarrow$$

coalescence yield drops steeper than fragmentation yield

$p_\perp^{crit}$: **decreases with incr. centrality**

may be large ~ 5 GeV

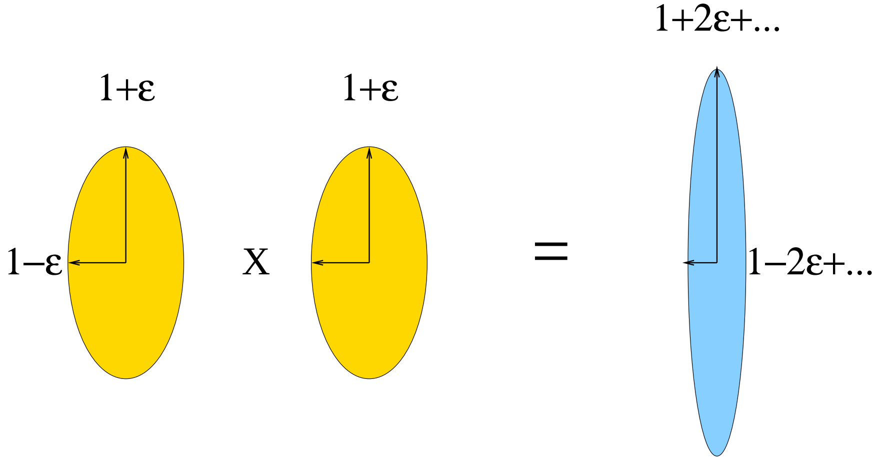
(Greco et al, Fries et al)

Amplification of elliptic flow

[D.M & Voloshin ('03)]

in narrow wave fn. limit ($\vec{q} = 0$):

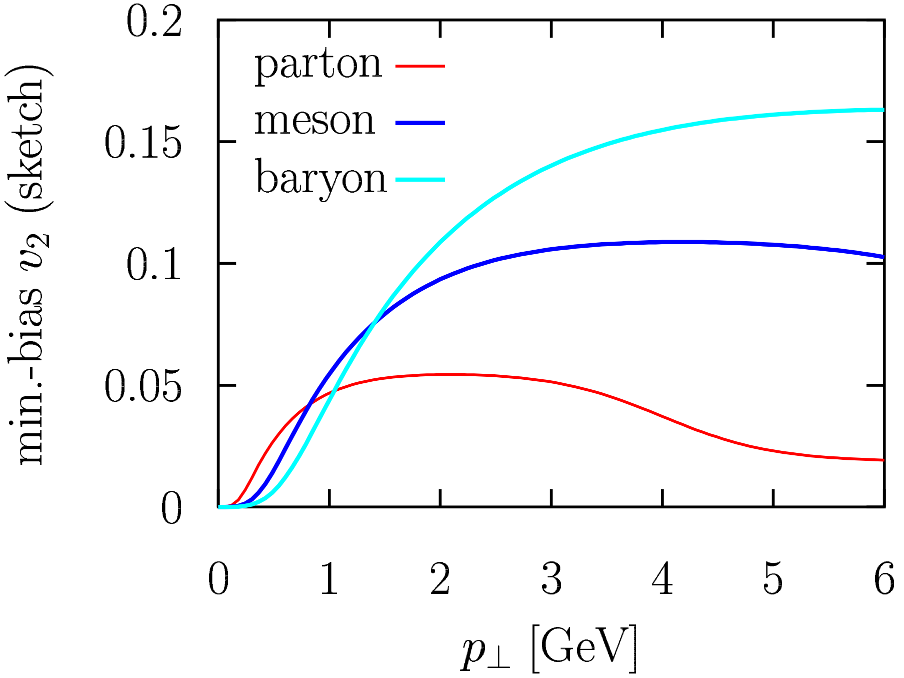
$$\begin{aligned} v_2^M(p_\perp) &\approx v_2^a\left(\frac{p_\perp}{2}\right) + v_2^{\bar{a}}\left(\frac{p_\perp}{2}\right) \\ v_2^B(p_\perp) &\approx v_2^a\left(\frac{p_\perp}{3}\right) + v_2^b\left(\frac{p_\perp}{3}\right) + v_2^c\left(\frac{p_\perp}{3}\right) \end{aligned}$$



$\Rightarrow$ hadron flow amplified at high $p_\perp$:

$3\times$ for baryons

$2\times$ for mesons

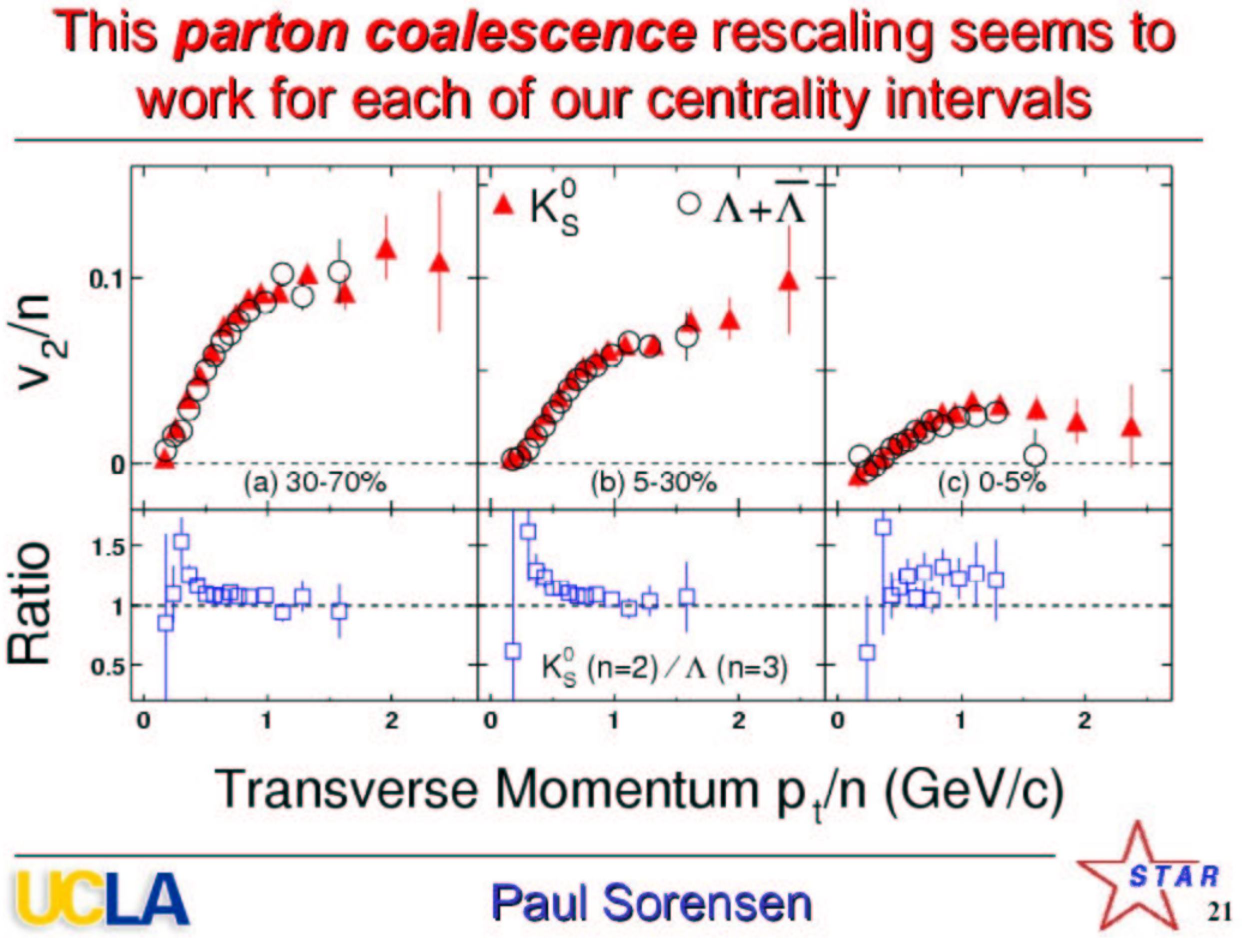


- this is the **KEY INGREDIENT** to resolve opacity puzzle (nucl-th/0302014)

Experimental test of flow scaling

STAR, SQM2003:

PHENIX, nucl-ex/0305013:


This *parton coalescence* rescaling seems to work for each of our centrality intervals

Paul Sorensen

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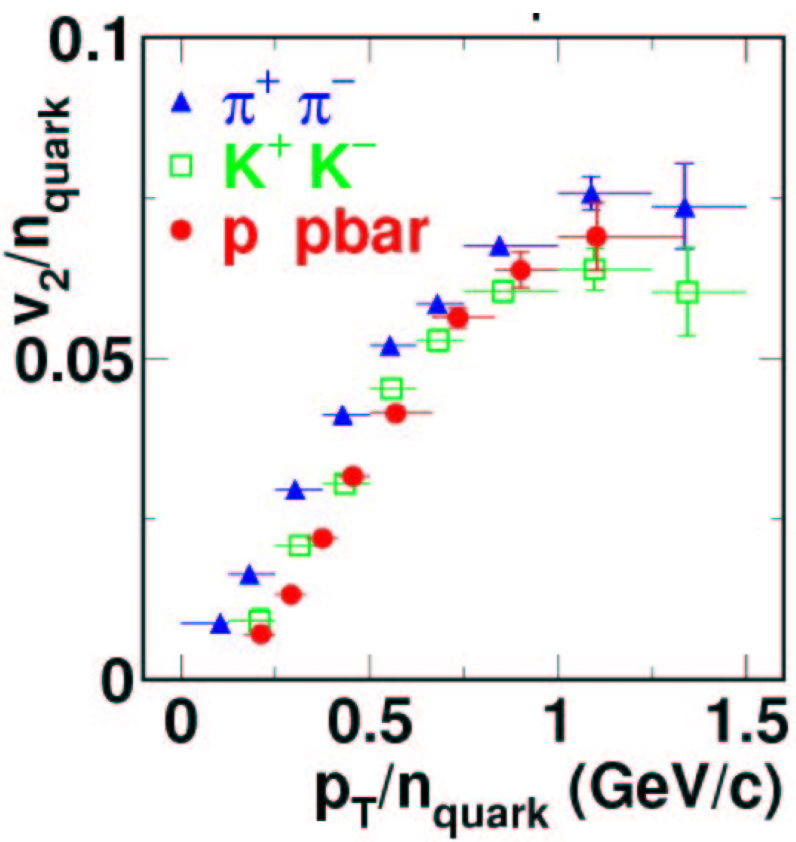


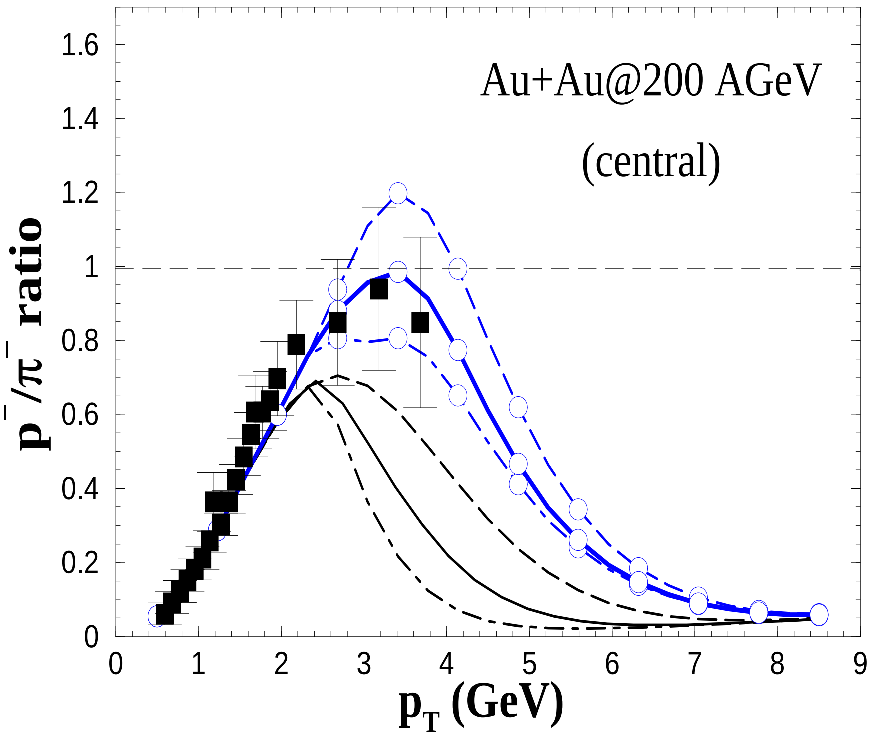
- **confirms coalescence predictions**, **indicates** $v_2^q \approx v_2^s$
- **even** Ξ **works** (talk by Castillo on Thursday), **and of course** d **(poster by Sakai)**

Baryon puzzle and coalescence

Coalescence momentum addition $p_\perp \to np_\perp$ pushes the low-$p_\perp$, close to thermal region in parton spectra out to $3\times$ larger $p_\perp$ baryons but only $2\times$ larger for mesons

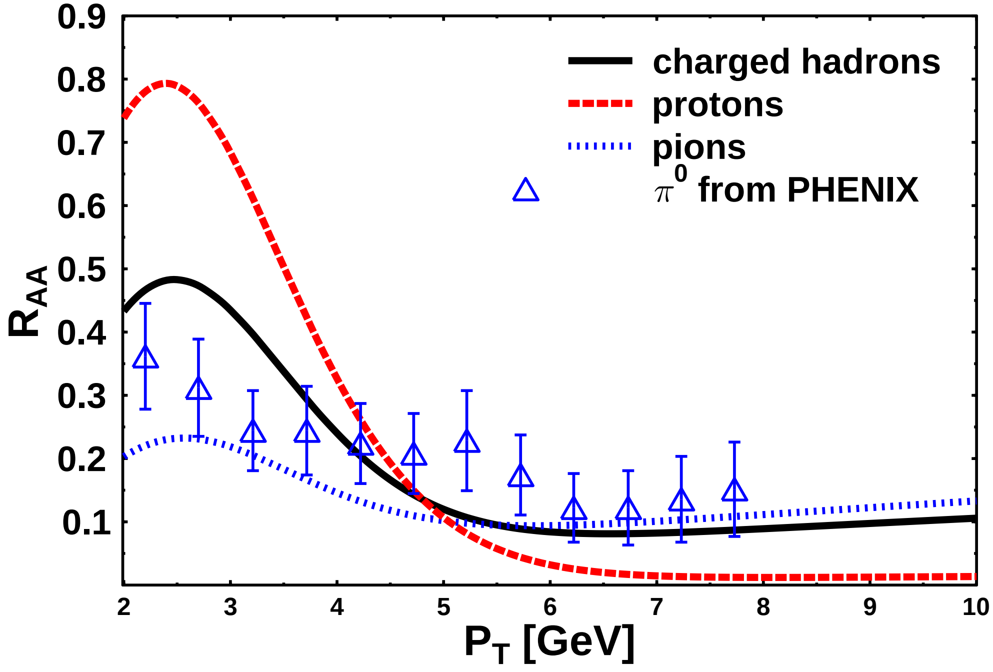
→ different from pQCD fragmentation even at $p_\perp \sim 4$ GeV

p/π ratio



[Greco, Ko, Lévai, PRL90]

R_{AA} for hadrons



[Fries, Müller, Nonaka, Bass, PRL90]

Charm hadrons

Why charm?

(Lin & D.M., nucl-th/0304045)

- test pQCD (jet propagation) & properties of parton medium
  - **are heavy quarks (not) quenched?** [Djordjevic, Gyulassy ('03), Dokshitzer, Kharzeev ('01)]
  - **do heavy quarks thermalize?** [Batsouli et al ('03)]
  - **can extract charm quark flow to help answer these questions**
- more predictions - additional tests of quark coalescence model
  - **next long RHIC run can verify/falsify these**
- coalescence is better applicable to charm
  - **binding energy is less important,** $m_h \approx \sum m_i$
  - **narrow wave fn. limit applicable because of large mass** ⇒ **can extract quark flows**
- special wave function effects due to unequal constituent mass (D, D_s, Λ_c)

Wave function

In hadron rest frame: - consider $|\vec{p}_1, \vec{p}_2\rangle = |\vec{q}/2, -\vec{q}/2\rangle$

- with $\langle|\vec{q}|\rangle \sim \Lambda_{QCD}$

For a fast (weakly bound) hadron with mom. $\vec{n}p$: - a kinematic estimate

$$p_i' \equiv \vec{p}_i{}'\vec{n} = \frac{E_i'}{m_H}p + \vec{q}_i \cdot \vec{n}\frac{\sqrt{p^2 + m_H^2}}{m_H} \approx \frac{m_i}{m_H}p + \frac{\vec{q}_i\vec{n}p}{m_H}$$

→ **with the momentum fractions** $z_i \equiv p_i'/p$

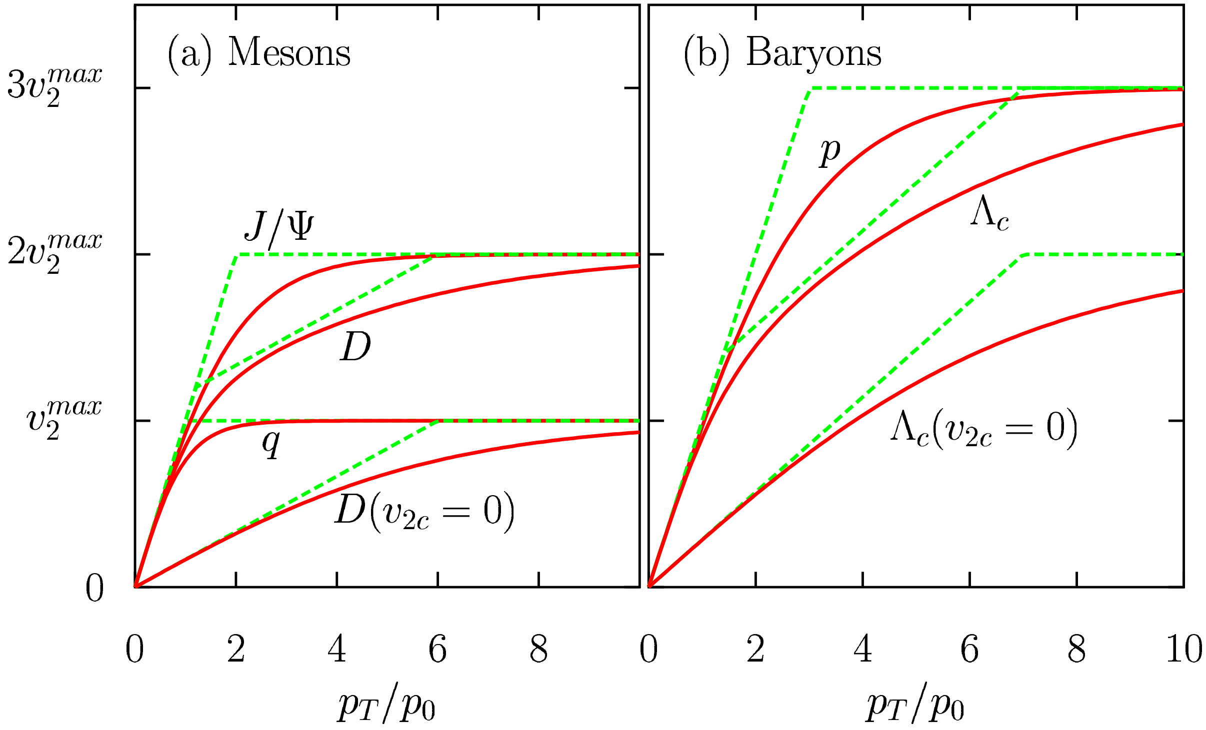
$$z_i = \bar{z}_i + \delta z_i \approx \underbrace{\frac{m_i}{m_H}}_{\text{average}} + \underbrace{\frac{\vec{q}_i\vec{n}}{m_H}}_{\text{spread}}$$

Two effects:
- **lighter quark carries smaller fraction of momentum**
  - because similar velocities (not momenta) in moving frame
- **wave function is narrower in δz for heavy quarks**

Mass effect on elliptic flow

even in $\delta z_i = 0$ limit: flow addition formula modified

$$\begin{aligned} v_{2,M}(p_\perp) &\approx v_{2,a}(\bar{z}_a p_\perp) + v_{2,\bar{a}}(\bar{z}_b p_\perp) \\ v_{2,B}(p_\perp) &\approx v_{2,a}(\bar{z}_a p_\perp) + v_{2,b}(\bar{z}_b p_\perp) + v_{2,c}(\bar{z}_c p_\perp) \end{aligned}$$



e.g.: $D - \; m_q : m_c = 1 : 5$

$v_{2,D}(p_\perp) \approx v_{2,c}(\frac{5p_\perp}{6}) + v_{2,q}(\frac{p_\perp}{6})$

green: $v_{2q}(p_\perp)$ **linear out to** $p_\perp = p_0$**, then flat**

red: more realistic $v_{2q}(p_\perp) = v_2^{max} \tanh(p_\perp/p_0)$

- **main effect:** $v_2(p_\perp)$ **rises slower, saturates later for asymmetric system**
- **easy to invert the linear relations to deduce** v_2^q, v_2^c **from hadron** $v_2(p_\perp)$**'s**

Parton spectra

sofar needed only parton $v_2(p_\perp)$ but for $\delta z \neq 0$ also need parton spectra

light quarks: - pQCD component with energy loss $\Delta p_\perp = -\sqrt{\lambda p_\perp}$
(LO, GRV98, BKK95, $K = 2.5$, $Q^2 = p_\perp^2$, $\lambda = 1$ GeV)

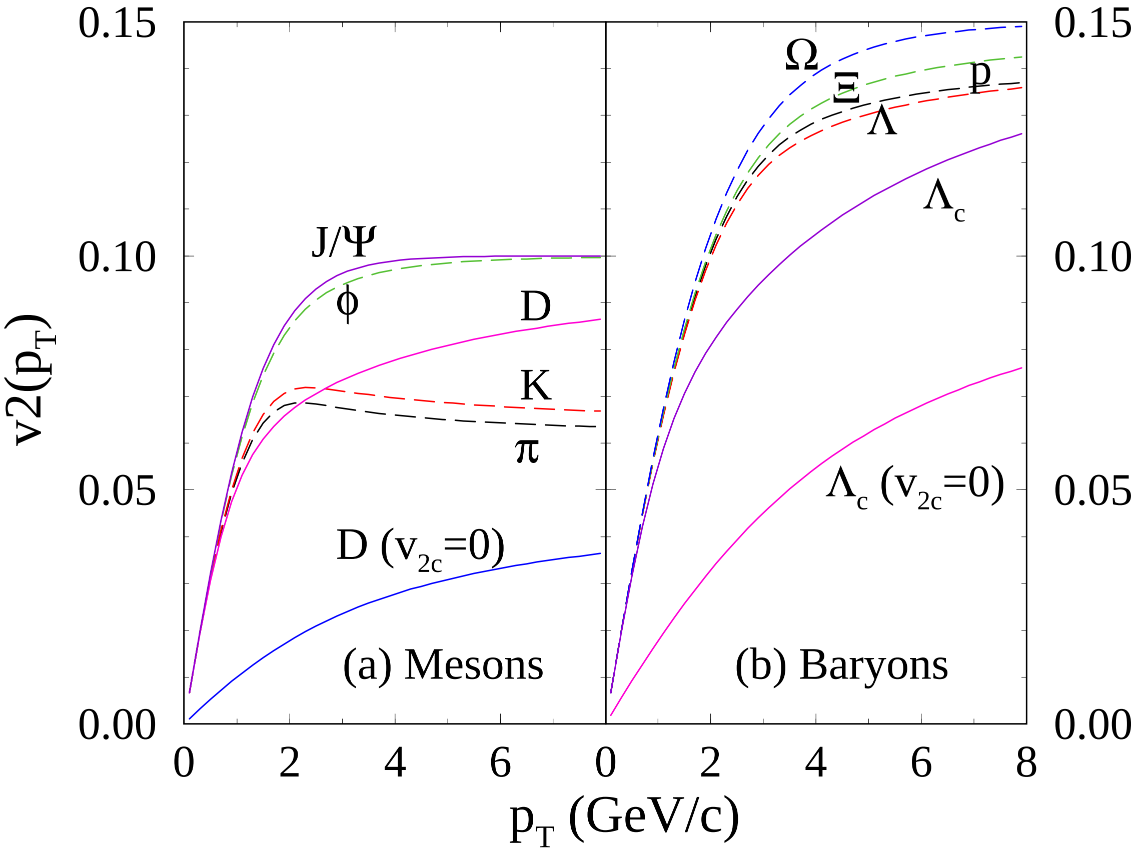
- soft component with Bjorken geometry
($V = \tau A_\perp = 1000$ fm^3, $T = 0.2$ GeV)

charm: PYTHIA 6.154, no energy loss
$dN^{c\bar{c}}/dy = 2.5$ at $y = 0$ in central Au+Au

parton $v_2(p_\perp)$: $\tanh(p_\perp/p_0)$ form as from MPC 1.6.0
$v_2^{max} = 0.05$, $p_0 = 0.75$ GeV

Effect of momentum spread

Convolution w/ wave function and spectra <u>reduces</u> v_2 $[v_2(p_\perp)$ is concave$]$



[Lin & D.M., nucl-th/0304045]

$m_u = m_d = 0.3$, $m_s = 0.5$, $m_c = 1.5$ **GeV**

wave functions: uncertainty relation + valon model [Hwa and Yang], $|\psi|^2 \sim z_\alpha^a z_\beta^b (z_\gamma^c)$

lighter systems are wider in z

- $30-40\%$ **for light systems** π, K **(for these, also binding energy problem!)**
- $< 20\%$ **for asymmetric heavy ones,** D, D_s, Λ_c
- **only few % for symmetric** $p, J/\Psi, \phi, \Omega$

Coalescence window for charm

Question: where can coalescence dominate fragmentation for charm?

good news (for D): $dN_D \propto f_c(p_{\perp,c}) \times f_q(p_{\perp,q})$

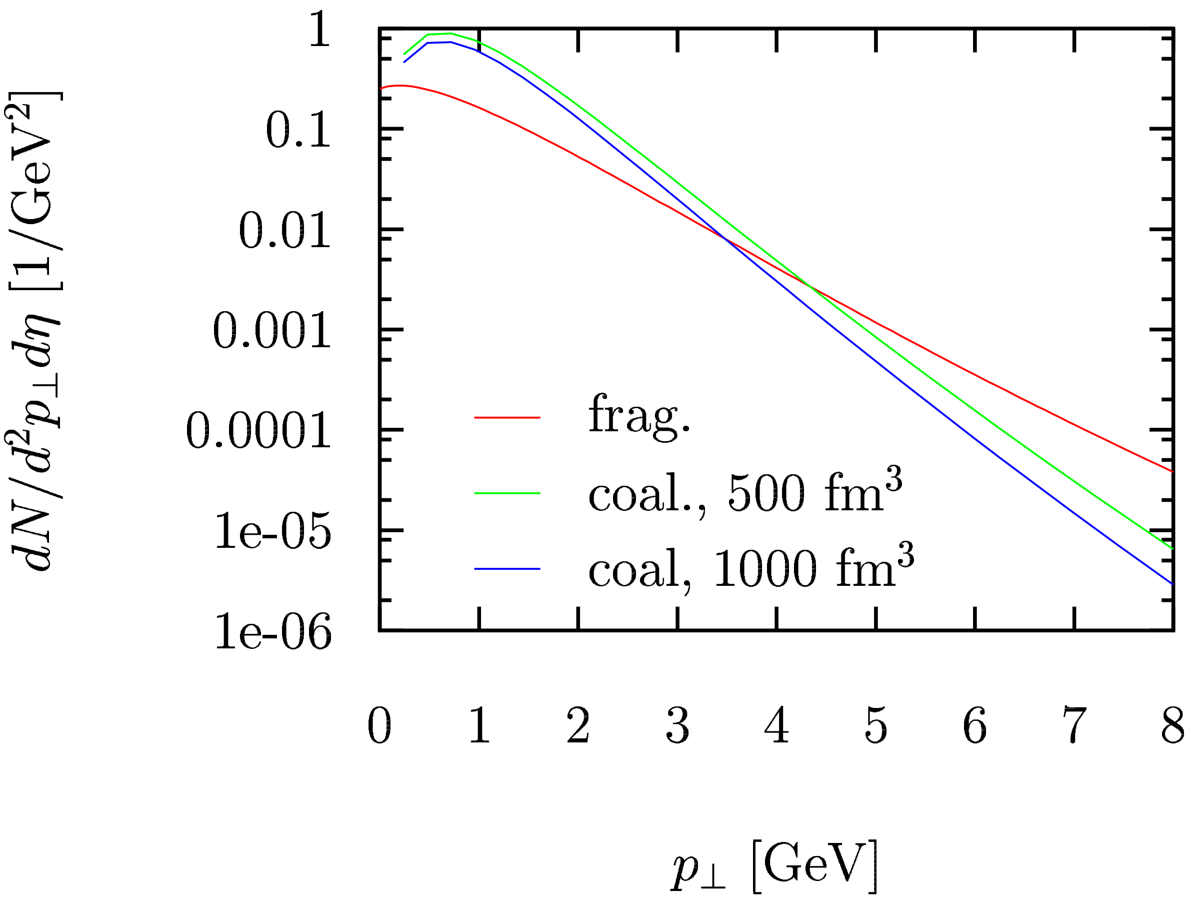
lower $p_\perp$ fraction for light quark - larger phase space density

bad news:

harder fragmentation for charm, flatter spectra

D meson spectra

Test pessimistic case: **- quench for light but not for charm, $z = 1$ fragm.**



- **simple estimate:** **coalescence dominates for D below $p_\perp < 3.5 - 4.5$ GeV**

- but sensitive to parton spectrum ansatz (V) $\Rightarrow$ better approach needed

Outlook

- coalescence dynamics (instead of sudden process on hypersurface)

  WORK IN PROGRESS

  - utilize parton cascade MPC
  - quantitative answer to coalescence/fragmentation competition

- explore other observables (e.g., HBT)

- relax theory assumptions
  - add space-momentum correlations
  - allow for multiparton correlations in phasespace
  - more realistic wave functions
  - binding energy problem for π, K - maybe only solution is resonances?

Summary

- **There is growing evidence indicating that hadronization in the moderate $p_\perp$ region ($\sim 2-6$ GeV) occurs dominantly via quark coalescence. The coalescence mechanism can provide a solution to the RHIC elliptic flow (opacity) puzzle and also explain the anomalously large baryon/meson ratios seen at RHIC.**
  Even pessimistic estimates indicate that for D mesons the coalescence window can extend to $p_\perp \sim 4$ GeV.

- **Charm hadrons provide unique information on charm v_2 and very low $p_\perp$ light quark v_2, and serve as additional testing ground for the coalescence model.**
  D, D_s and Λ_c are predicted to have a much slower rising elliptic flow as a function of $p_\perp$ than hadrons with only ligther (u, d, s) constituents. Except for the J/Ψ, in the coalescence scenario, charm hadrons show elliptic flow, even if charm quarks have zero v_2.

- **For narrow wave function one can "unfold" hadron flow and determine quark flow → crucial insights into dynamics of dense QCD matter and question of charm thermalization.**