Particle correlations at RHIC from parton coalescence dynamics

– First results –

Dénes Molnár

The Ohio State University, Columbus, OH, USA

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Outline

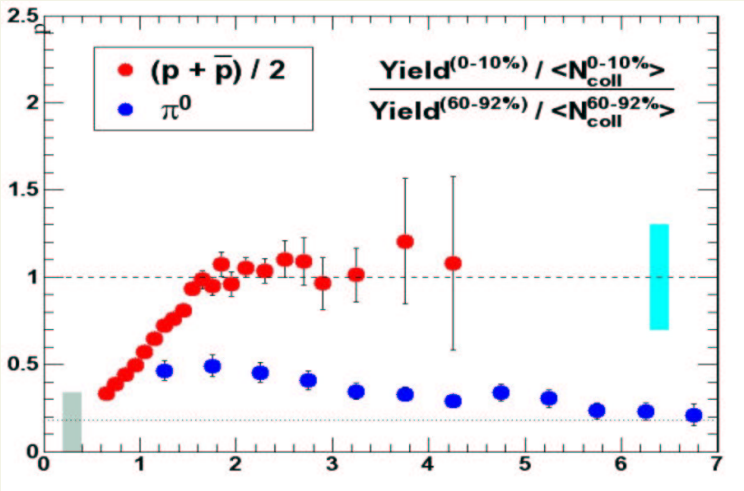
- **Motivation**
  - why parton coalescence?
- **Dynamical parton coalescence model**
  - what is new?
- **First results**
  - particle spectra
  - elliptic flow
  - angular correlations (?)

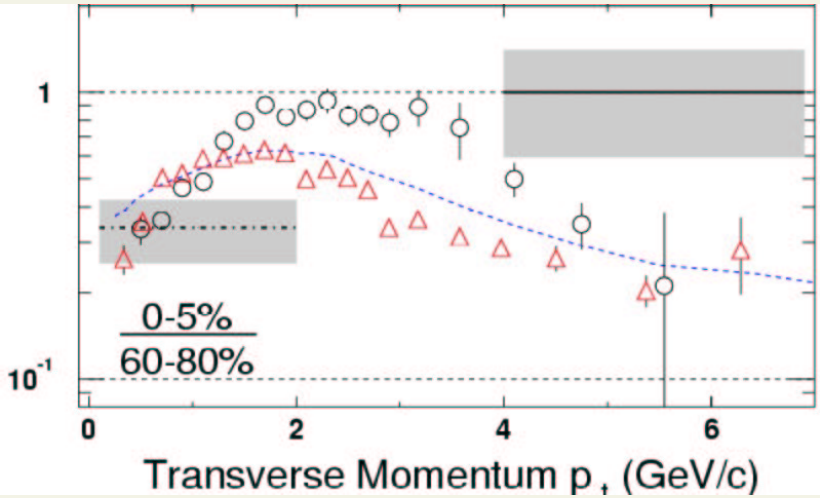
Why parton coalescence?

Two surprises at RHIC

baryon non-suppression

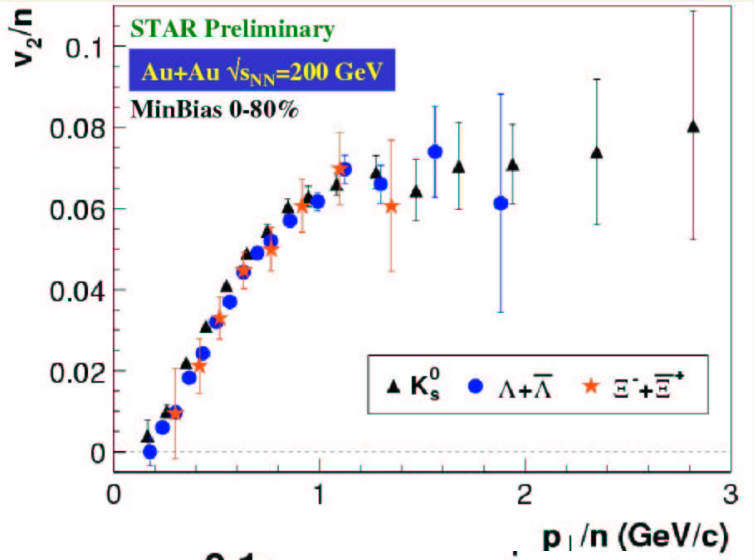
d'Enterria [PHENIX], Sorensen [STAR]:

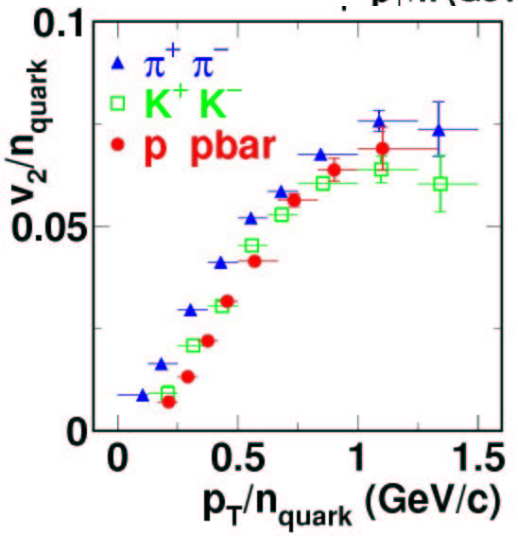




elliptic flow scaling w/ quark number

Castillo [STAR], Esumi [PHENIX]:

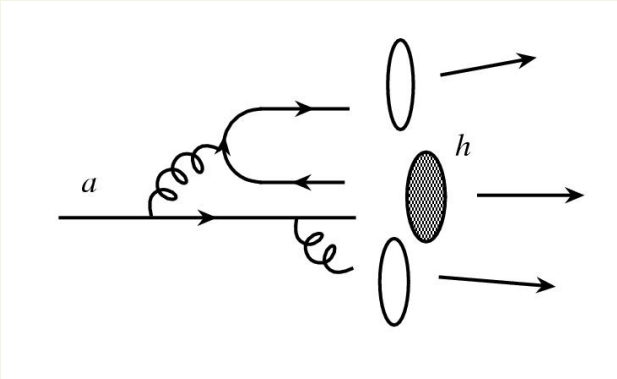




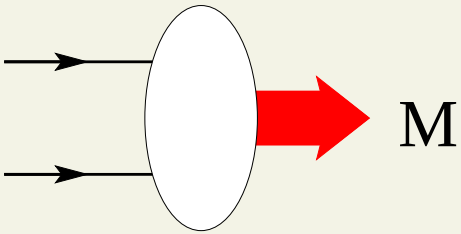
Parton coalescence

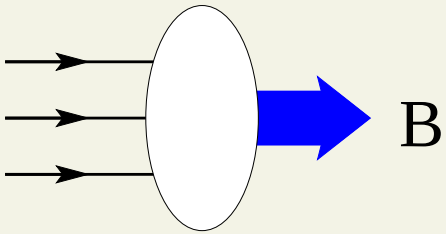
Hwa, Yang, Biró, Zimányi, Lévai, Csizmadia, Ko, Lin, Voloshin, D.M., Greco, Fries, Müller, Nonaka, Bass, ...

In addition to jet fragmentation



other hadronization channels via parton coalescence/recombination





- **simple estimates show coalescence can dominate in $AuAu$ at RHIC out to $4-6$ GeV in $p_\perp$**

Simple coalescence formula

- **developed originally for** $n + p \to d$

Butler & Pearson and Schwarzschild & Zupancic, PR129 ('63); Sato & Yazaki, PLB98 ('81); Dover, Heinz, Schnedermann & Zimányi PRC44 ('91); Scheibl & Heinz, PRC59 ('99), ...

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

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

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

hadron yield space-time wave-fn. quark distributions

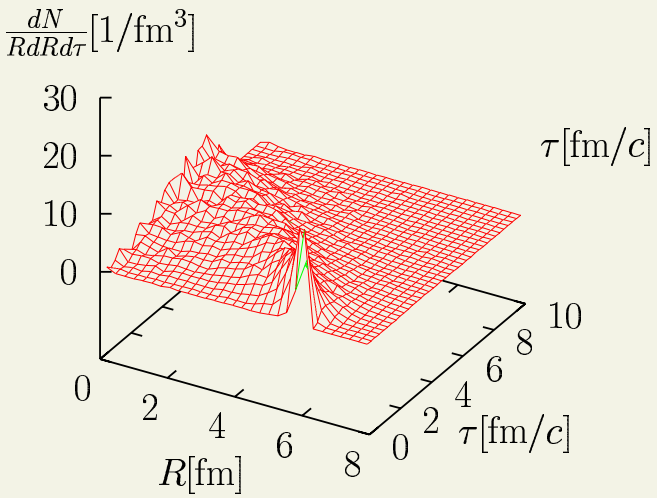
assumes: - **weak binding**
- **no 2-body or 3-body correlations**
- **rare process - otherwise violates unitarity**
- **3D hypersurface (e.g., equal time - sudden approximation)**

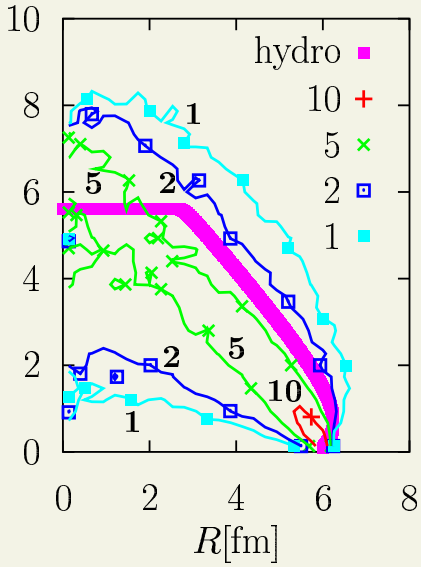
+ in studies so far, indep. fragmentation yield superimposed additively

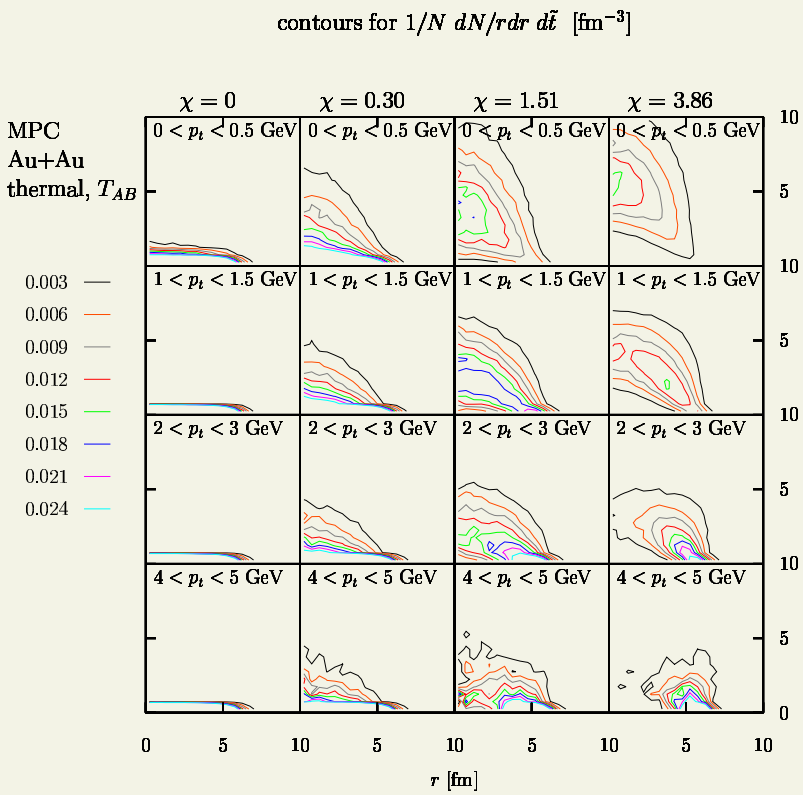
Freezeout hypersurface?

transport freezeout is never "sharp"

D.M & Gyulassy ('00), ('02)







- diffuse 4-dimensional freezeout distribution in spacetime

Coal. formalism for diffuse freezeout

Gyulassy, Frankel & Remler: [NPA 402, 596 ('83)]

- **for each constituent pair/triplet, propagate particles to the latest of freezeout times and evaluate weight $W(\Delta x, \Delta p)$ there**
- **reason (roughly): any interaction would break up a weak bound state**
- **note, relative distance changes(!), e.g., if $t_2 > t_1$:**

$$weight = W_M\left(\vec{x}_1(t_1) + (t_2 - t_1)\vec{v}_1 - \vec{x}_2(t_2), \vec{p}_1 - \vec{p}_2\right)$$

Goal:

- **study influence of freezeout dynamics in coalescence via applying the above formula to transport model freezout results**
- **naturally incorporates:**
  - **"diffuse" 4D freezeout**
  - **space-time and space-momentum correlations**
  - **solution to unitarity problem**

main question: how robust are features derived from the simple formulas?

Model ingredients

Processes: **ideally:** - $2 \to 2$ parton scatterings, showers ($1 \to 2$, $1 \to 3$), parton fusion ($2 \to 1$, $3 \to 1$), inelastic $n \to m$, parton recombination to hadrons, hadron breakup, ... etc.

here: - only $2 \to 2$ (with $g, u, d, s, \bar{u}, \bar{d}, \bar{s}$, Debye-screened $d\sigma/dt \propto 1/(t-\mu^2)^2$)
- no parton showers until freezeout
- coalescence rate computed over freezeout 4D volume via Gy-F-R
- partons with no coalescence partner fragment as in vacuum

Coalescence part: - assume easy color neutralization - no color penalty factors
- but consider spin & flavor
- channels: π, K, η, η'; ρ, K^*, ω, Φ; p, n, Σ, Λ, Ξ; Δ, Ω
- "spherical box" Wigner functions: $W_M = \Theta(p_M - |\Delta p|)\Theta(x_M - |\Delta x|)$
$W_B = \prod_{k \neq i,j} \Theta(p_B - |\Delta p_{ij}|)\Theta(x_B - |\Delta x_{ij}|)$
$x_M = x_B = 1$ fm
- convert g to a random q (extreme case of $q - \bar{q}$ splitting)
- when several coalescence final states, unbiased random choice of one

Codes: - MPC 1.6.7 for parton transport
- JETSET 7.4.10 for fragmentation & decays ("out of box")

Numerical challenge

- **parton subdivision**

  essential for (approximate) Lorentz covariance

- **high statistics**

  coalescence integral needs good sampling in 6D(!) phasespace

- **combinatorics**

  triple loop when picking out baryon candidates

  – current study corresponds to nearly 10 GHz $\times$ week –

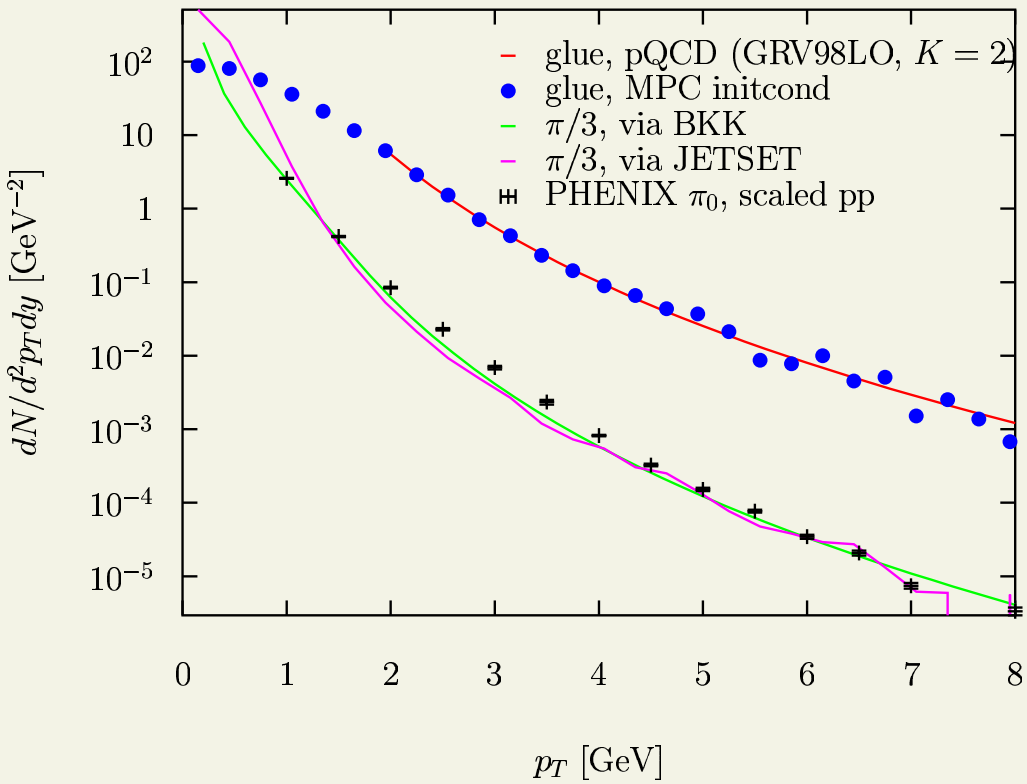
Initial conditions

- **Au+Au at RHIC with $b = 8$ fm, i.e., 30% centrality**

- $p_\perp > 2$ **GeV: minijets(dijets)**
  $p_\perp < 2$ **GeV: smoothly joined-on soft component, such that** $dN^{parton}/dy(b=0) = 2000$

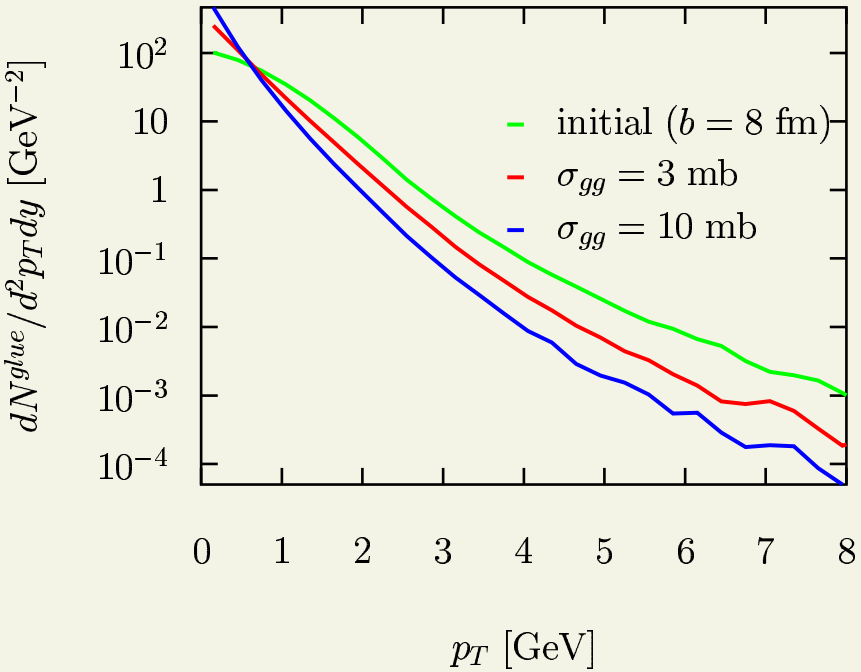
- **binary collision profile, formation time** $\tau_0 = 0.1$ **fm**$/c$

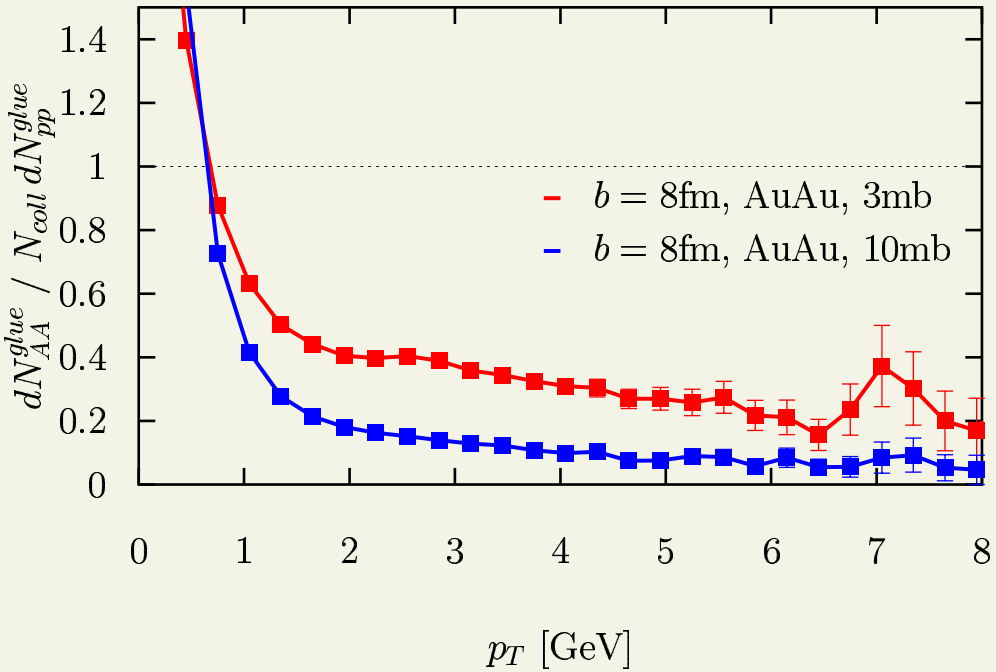
- $\sigma_{gg} = 3$ **mb,** 10 **mb** - $\sigma_{gq} = (4/9)\sigma_{gg}$, $\sigma_{qq} = (4/9)^2\sigma_{gg}$



Results – spectra

Gluon quenching during transport evolution



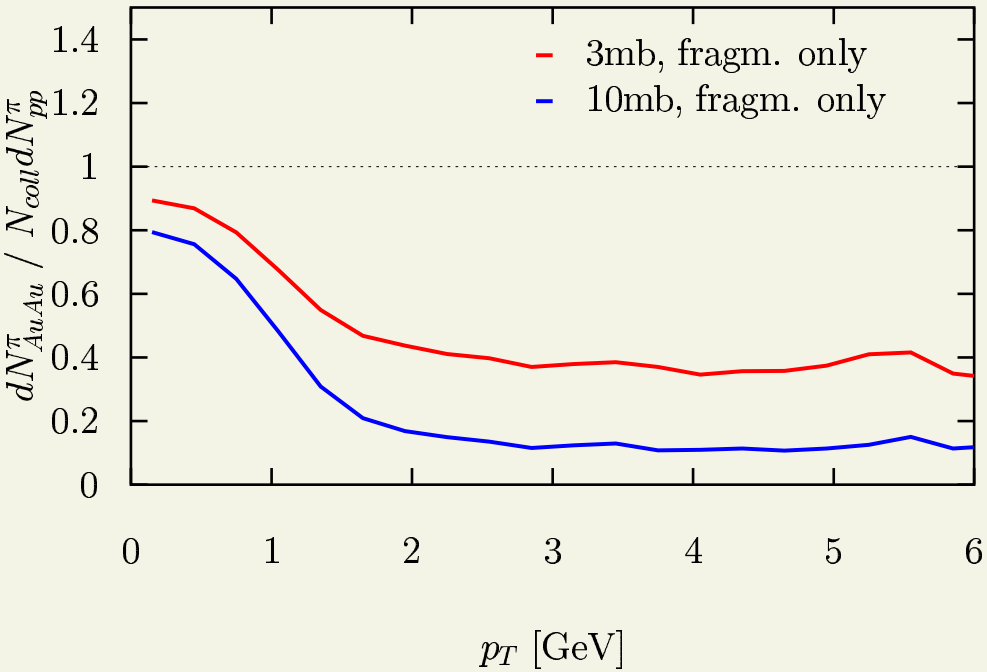


- **factor of 5-10 quenching at large p_T for $\sigma_{gg} = 3 - 10$ mb**

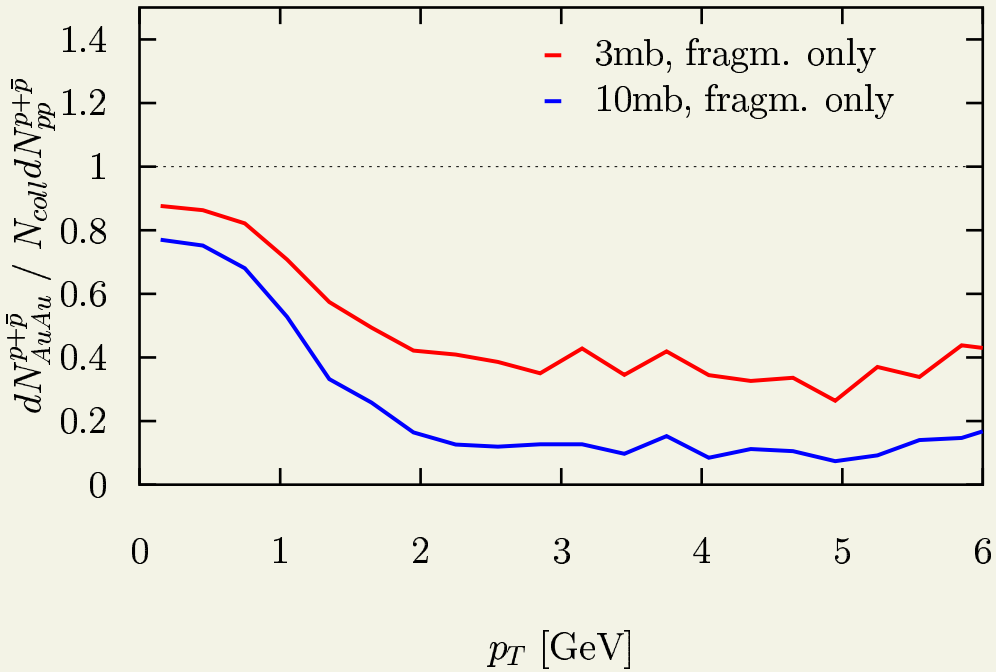
- **due to incoherent, elastic energy loss - or, in hydro language "cooling"**

Hadron suppression, fragm. only

pions



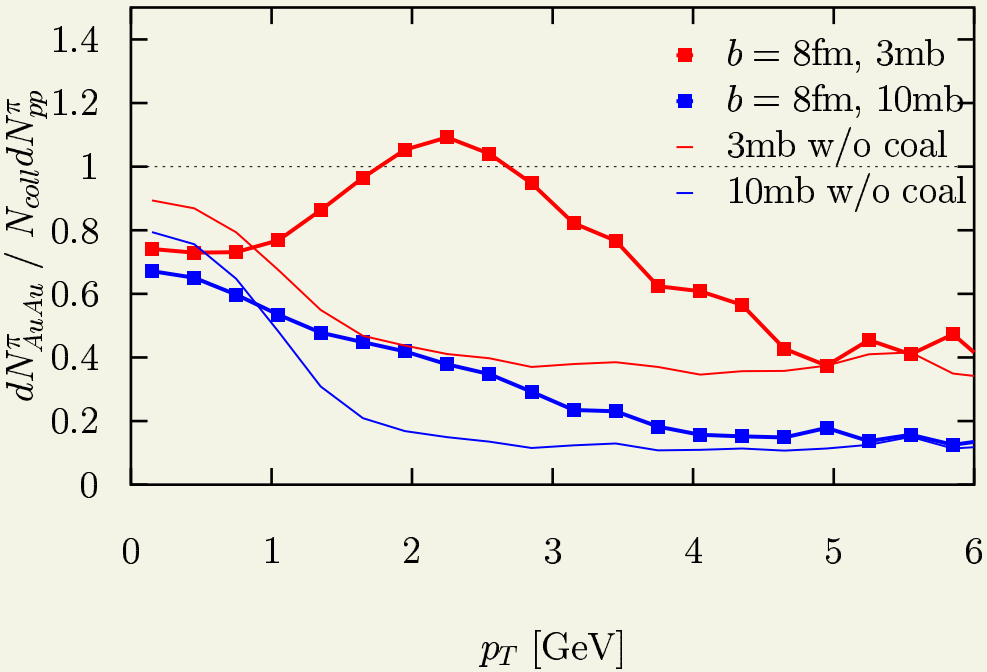
protons



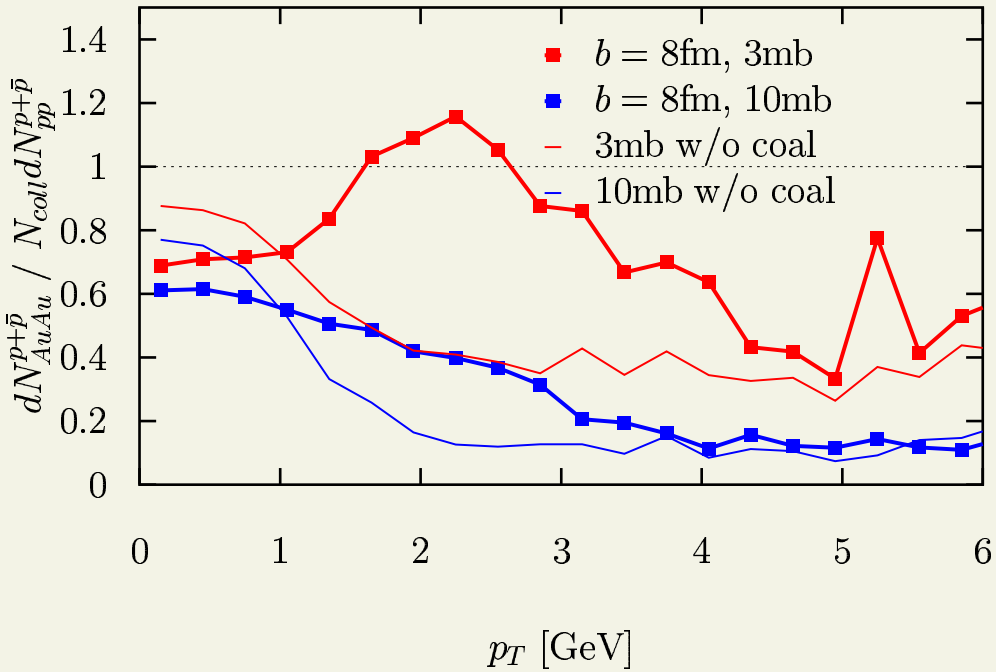
- **direct consequence of gluon quenching, similar in magnitude for π & p**

R_{AA} for coalescence + fragm.

pions



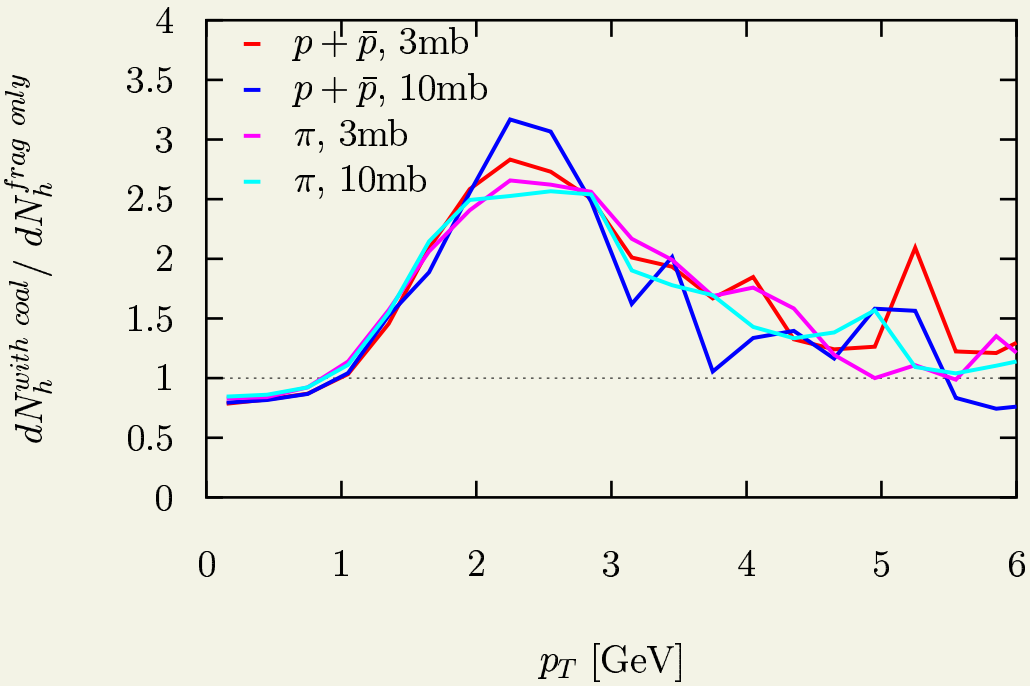
protons



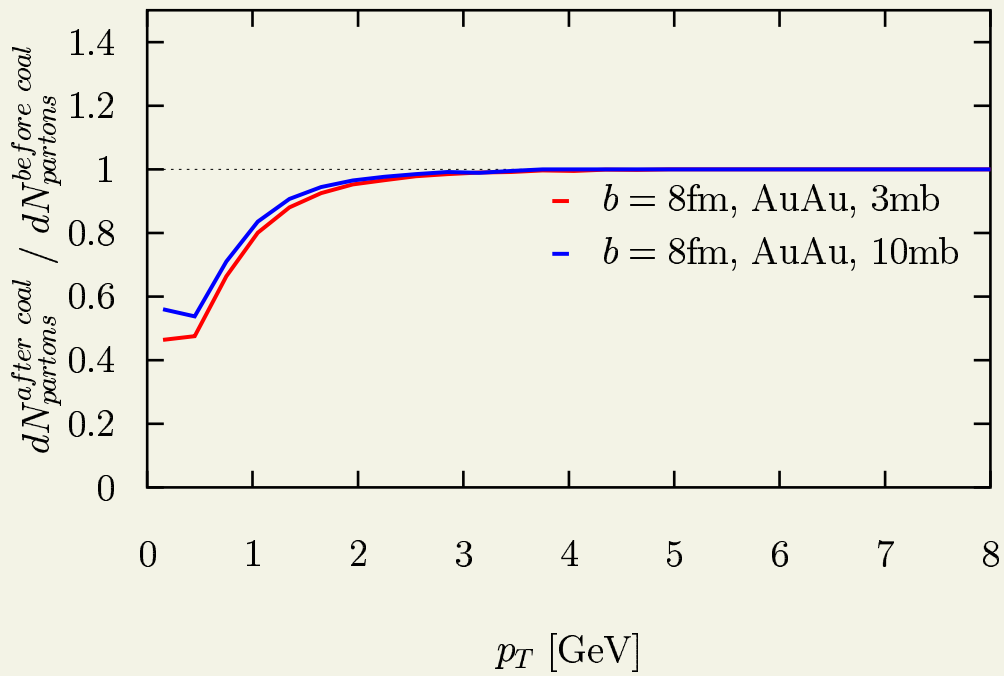
- **significant enhancement due to coalescence for** $1.5 < p_T < 4$ **GeV**

Relative enhancement due to coalescence

hadron enhancement at intermed. p_T



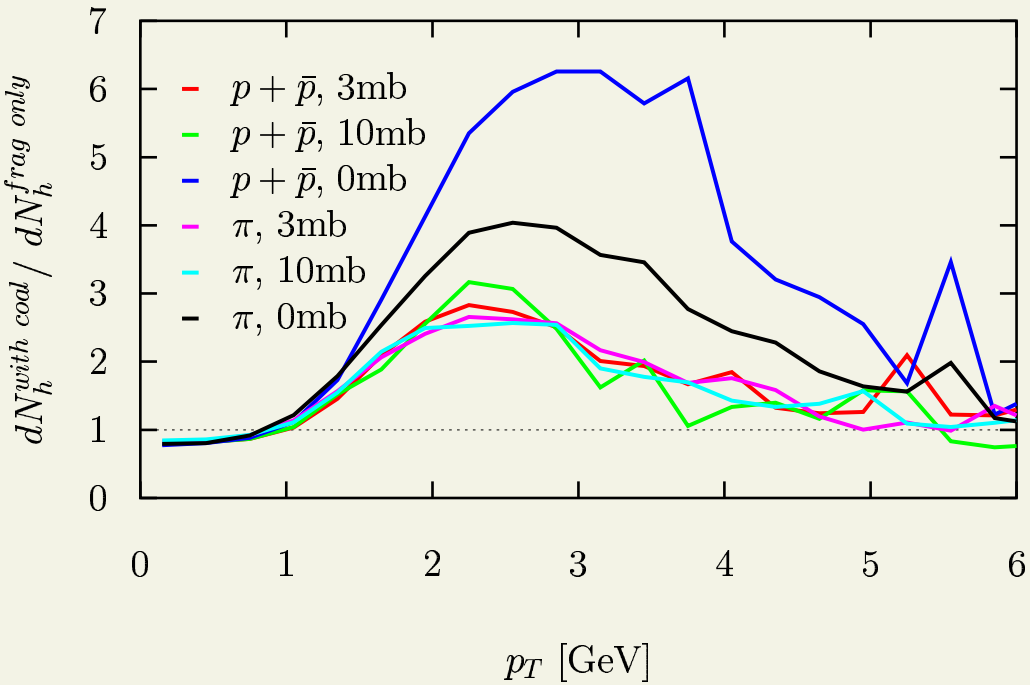
parton depletion at low p_T

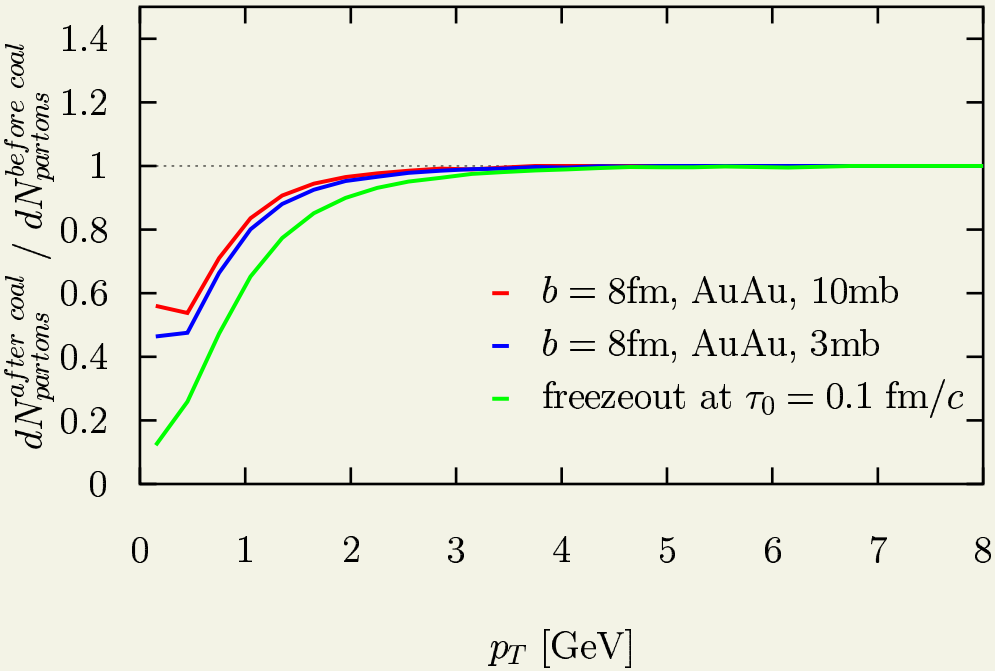


- $2-3\times$ **enhancement over pure fragmentation, at much higher** p_T **than depletion on parton level**
- **but enhancement is not more for protons than pions**
  latest FO time is larger for a triplet than for a double $\Rightarrow$ **baryons "see" lower density**

Spacetime does matter

a crazy choice - try freezeout & coalescence on formation $\tau = 0.1$ fm$/c$ hypersurface





- this particular combination did enhance baryons over mesons...

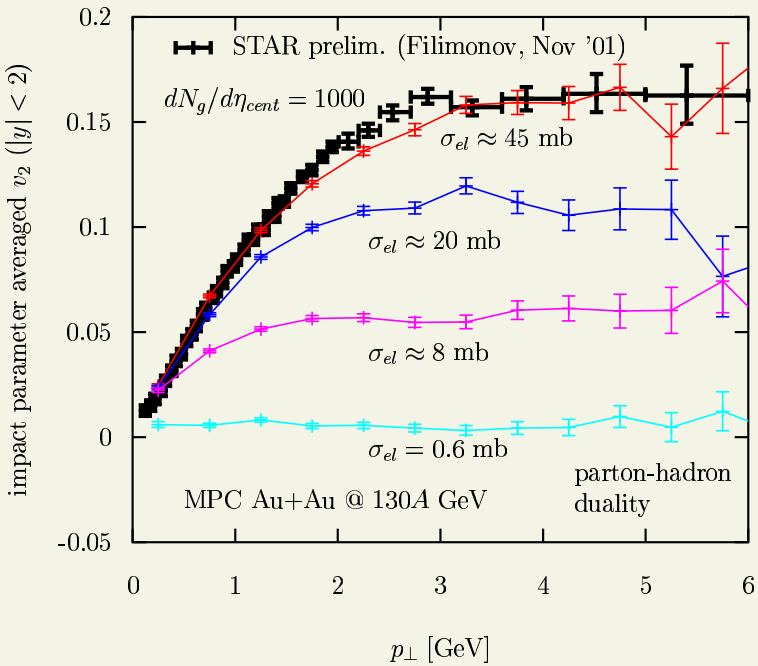
Elliptic flow results

($\sigma_{gg} = 10$ mb, $b = 8$ fm)

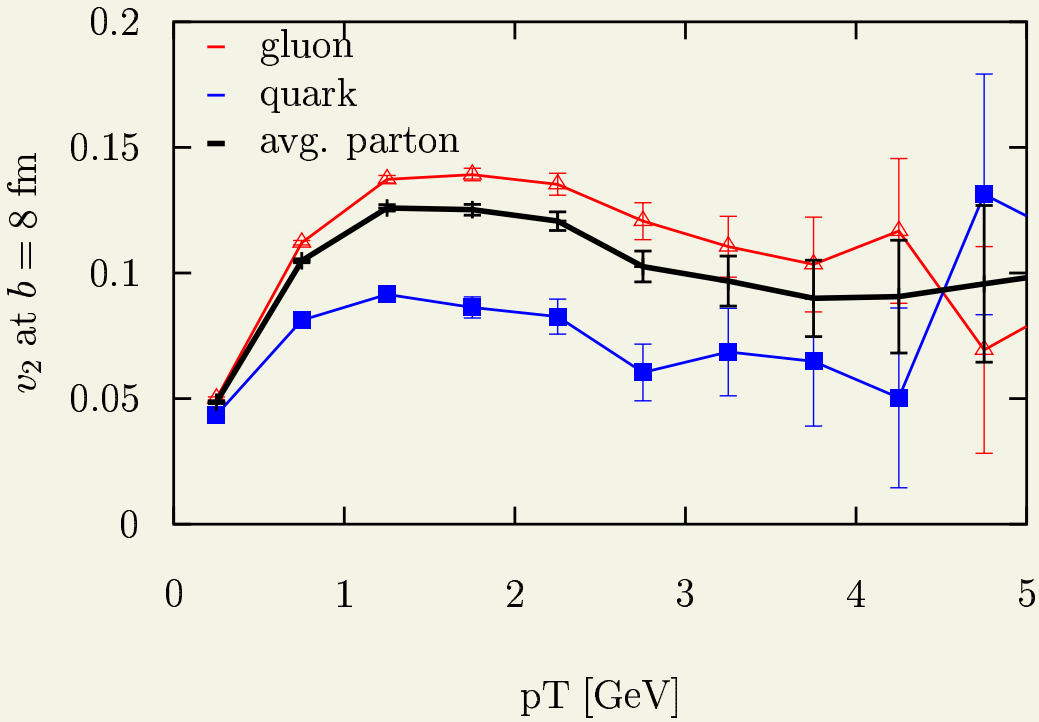
Parton elliptic flow vs $p_\perp$

generic behavior

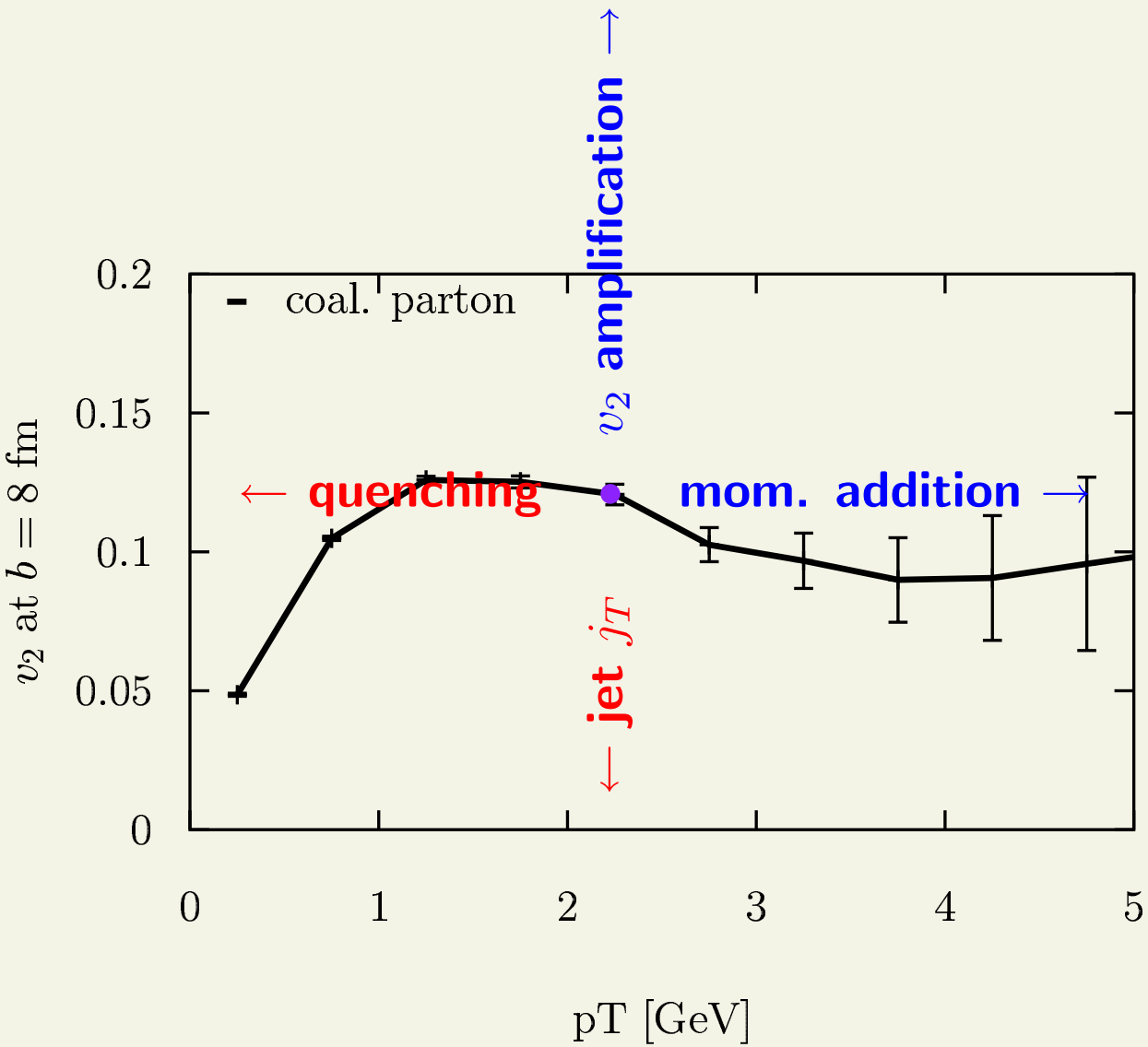
D.M & Gyulassy, ('01)



current study ($\sigma_{gg} = 10$ mb, $b = 8$ fm)



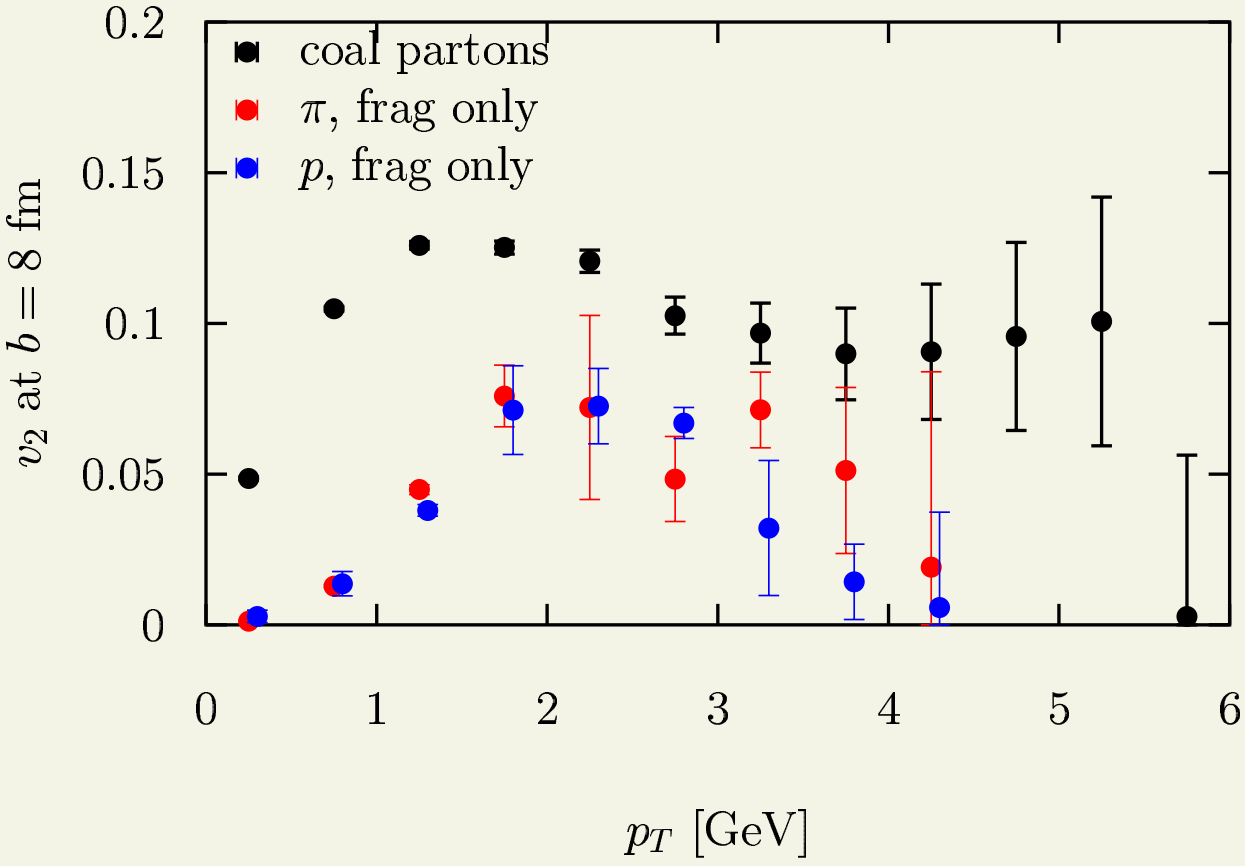
Coalescence versus fragmentation



- competing effects in all "directions"

Elliptic flow - fragmentation alone

($\sigma_{gg} = 10$ mb, $b = 8$ fm)

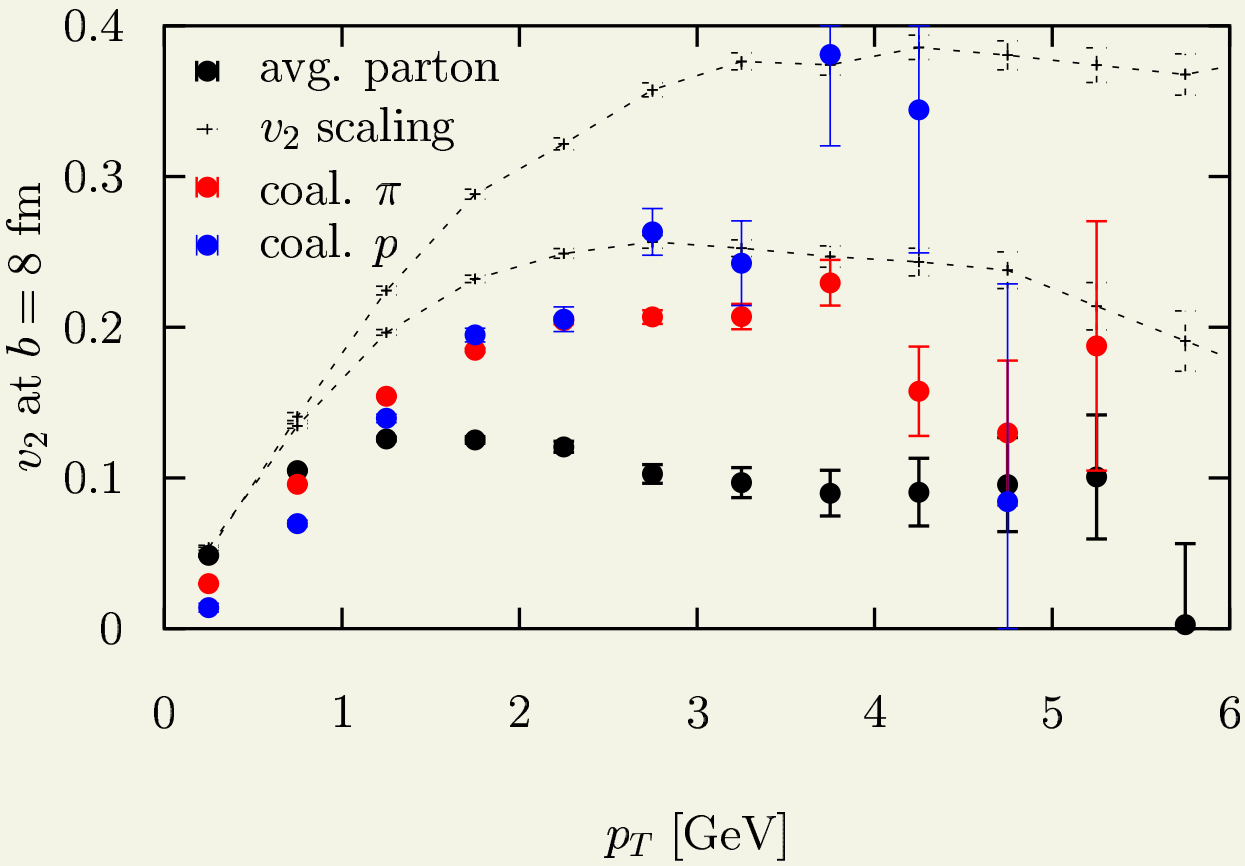


- **both π and p flow are reduced, especially at low $p_\perp$**

- **due to jet width ("j_T random walk"), absent from collinear "$D(z)$" FFs**

Elliptic flow from coalescence alone

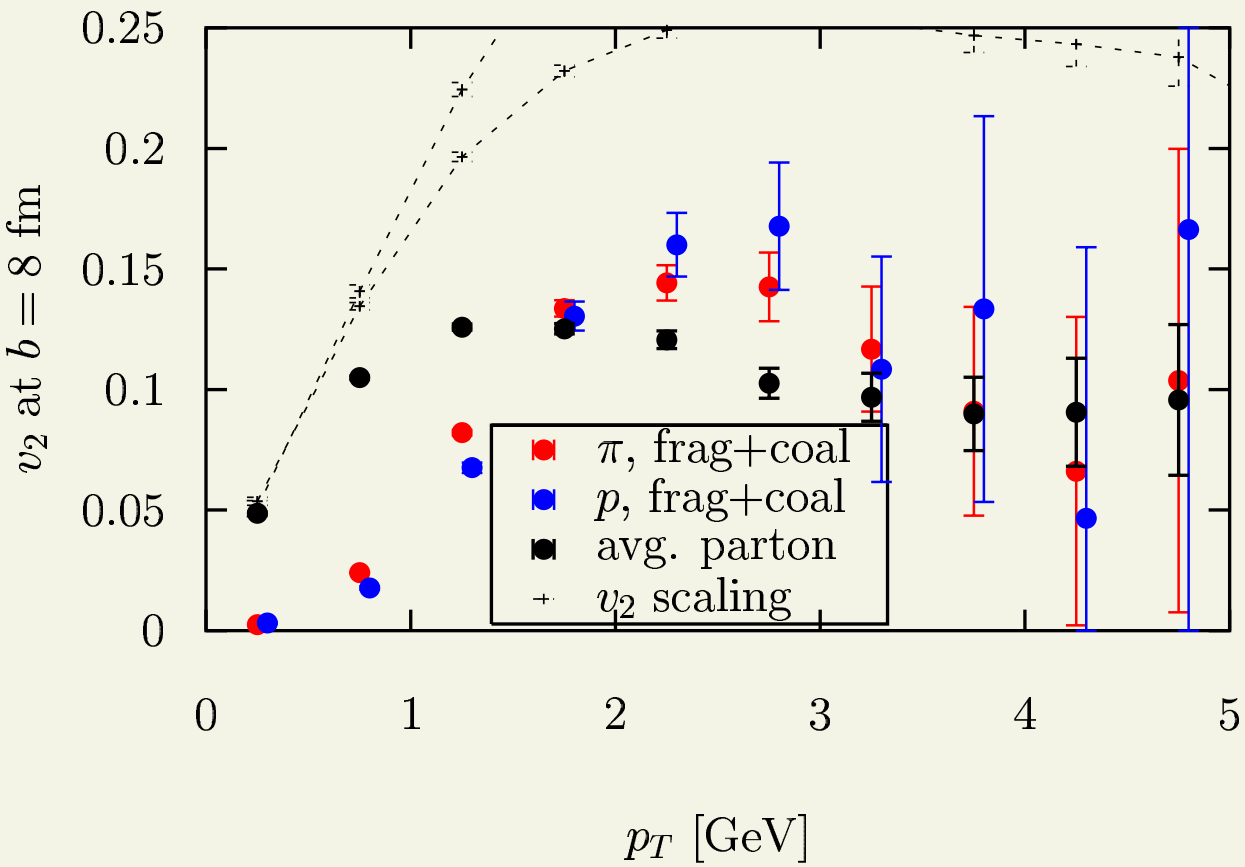
primary π **and** p **from coalescence** ($\sigma_{gg} = 10$ mb, $b = 8$ fm)



- **both π and p are below scaling curve, by 20-40%(!)**

- **some "mass effect" ($v_2^p < v_2^\pi$) generated at low $p_\perp$**

v_2 from coalescence + fragm.



- **flow amplification reduced**

- **baryon-meson splitting disappeared**

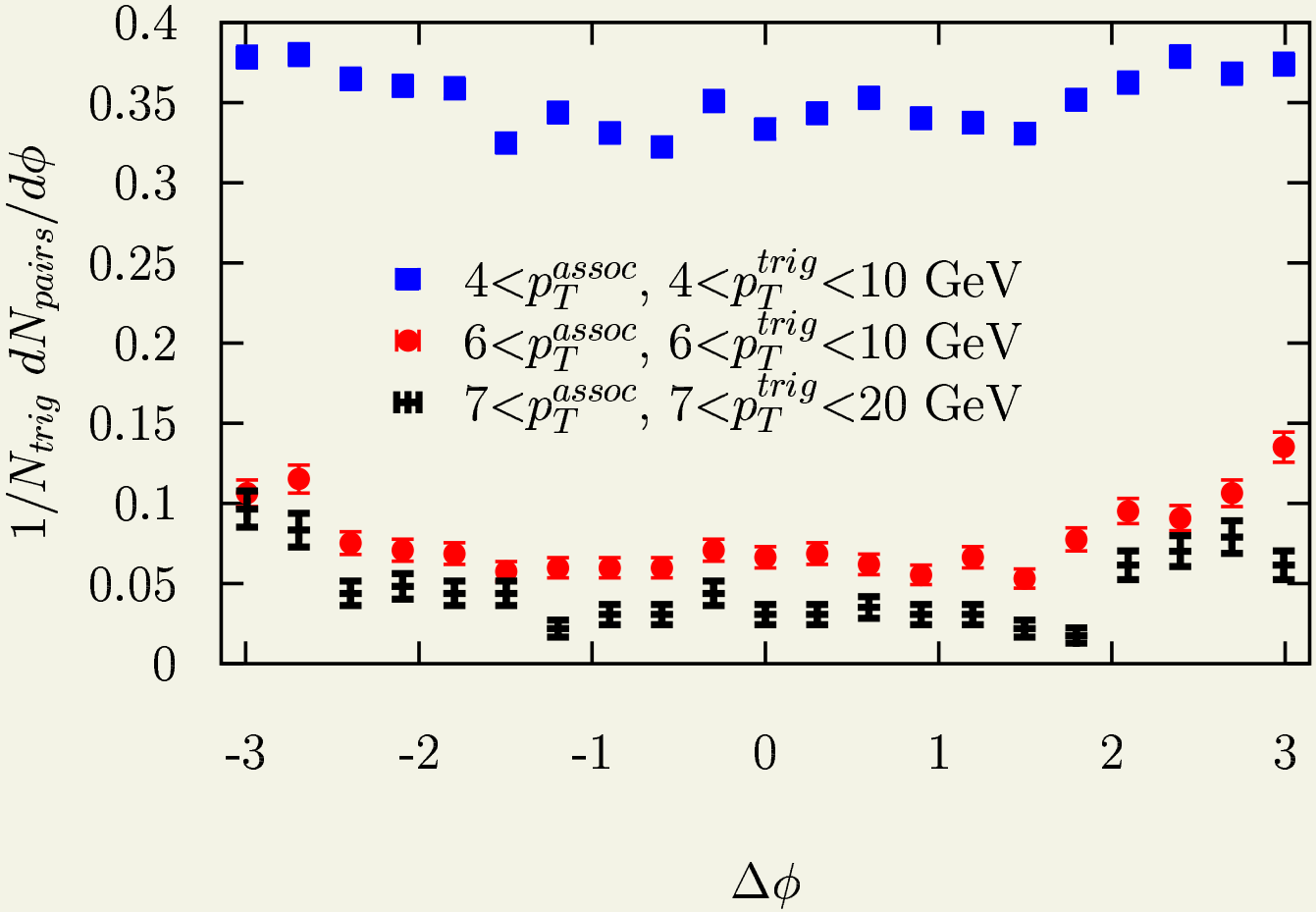
Holy Grail: Angular correlations

unfortunately, not enough statistics yet

need $10 - 100\times$ **more (**$=$ **several 100 - 1000 GHz** $\times$ **week)**

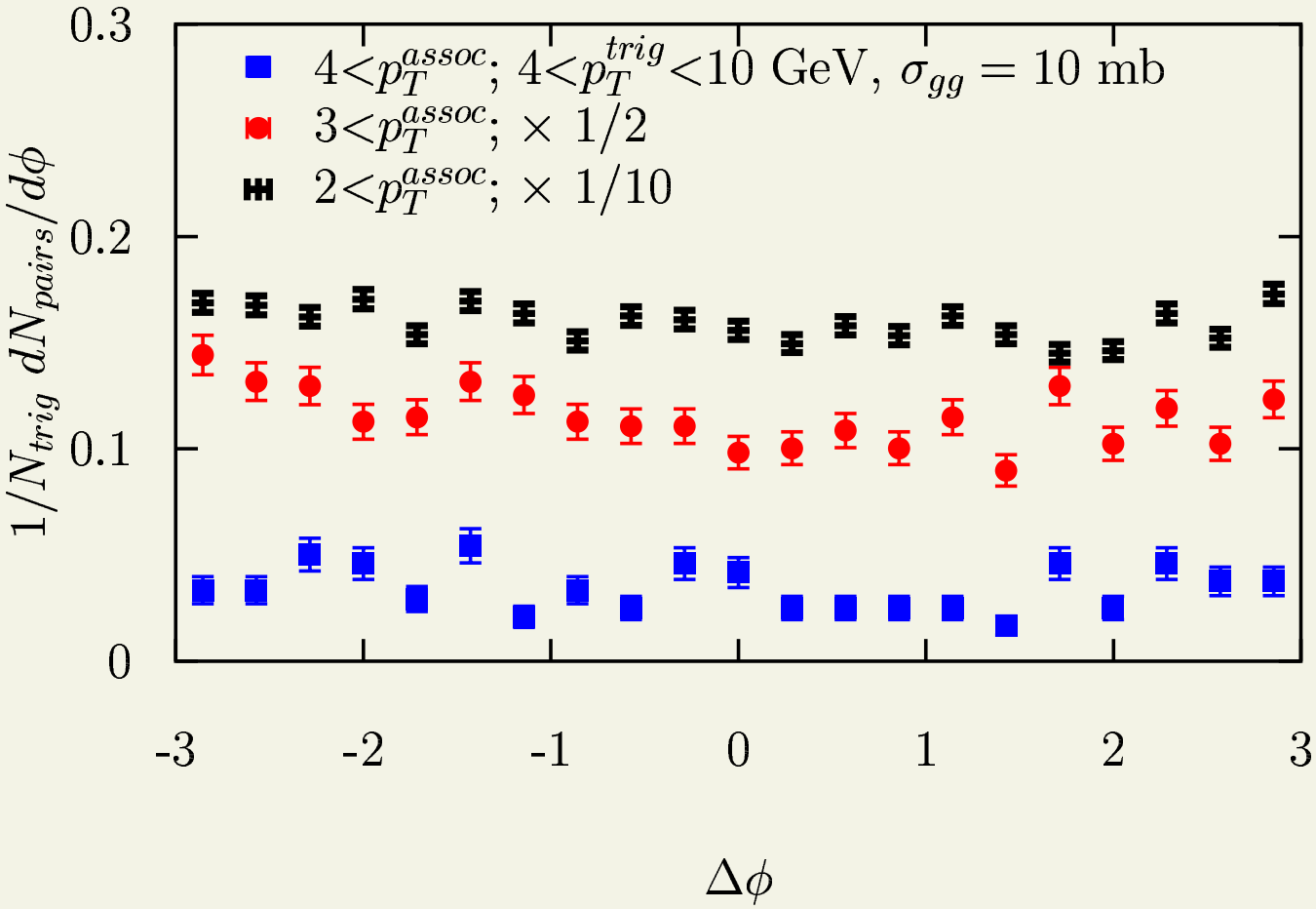
$\rightarrow$ **a major undertaking**

parton-parton angular correlations in AuAu <u>initial condition</u>, $|\eta| < 0.7$



- can indeed see a weak away-side dijet correlation

parton-parton angular correlations in AuAu <u>at freezeout</u>, $\sigma_{gg} = 10$ mb, $|\eta| < 0.7$



- is the away-side dijet still there??

Expectations regarding correlations

- coalescence "window" $1.5 < p_\perp < 4$ **GeV**

  - **this is where coalescence yield was dominant**

- **in coal. window, hadron correlations would reflect correlations on parton level**

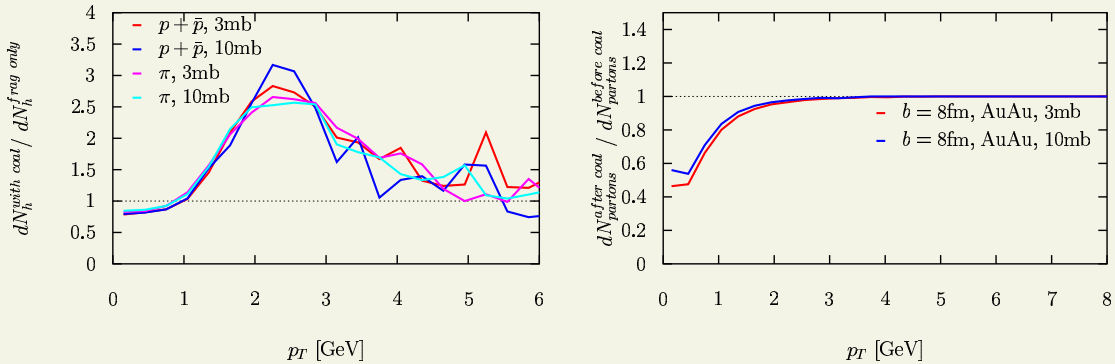
  in this study, only two kinds: - **elliptic flow**
  - **dijet correlation (away-side)**

  in principle, many more, **e.g.:** - **quark-antiquark corr. (e.g., from $g \to q\bar{q}$)**
  - **flavor corr.**
  - **color corr.**

- **Measurements of identified hadron correlations in the "coalescence window" would provide a way to i) study parton-parton correlations and ii) test consistency of coalescence models (or any other model).**

Conclusions

- **coalescence can dominate hadroproduction at intermediate $1.5 < p_\perp < 4$ GeV**
  (provided color neutralizes easily)



- **spacetime effects ($x-p$ corr., "diffuse" freezeout) can have significant influence**

  basic features - elliptic flow scaling, enhanced B/M ratio - did no longer hold

- **clearly further studies required:**

  - higher statistics & independent confirmation

  - extension to other observables (esp. correlations) and centralities ($b \neq 8$ fm)

  - find out what it takes to preserve features of the simple coal. models