Jet Fragmentation and Baryon Production

- Jet fragmentation
- Why we should expect medium effects
- Energy loss effects on the fragmentation function
- Medium effects on baryon production
  near a "bath" of quarks & antiquarks

Barbara Jacak
Stony Brook University
Nov. 8, 2004

Analog of hard x-ray probe of EM plasma

- **Want to know**

  pressure, viscosity, equation of state,

  thermalization time & extent

  determine from collective behavior

- **Other plasma properties**

  radiation rate, collision frequency, conductivity,
  opacity, Debye screening length

  what is interaction σ of q,g in the medum?

  need short wavelength strongly interacting probe

  transmission probability

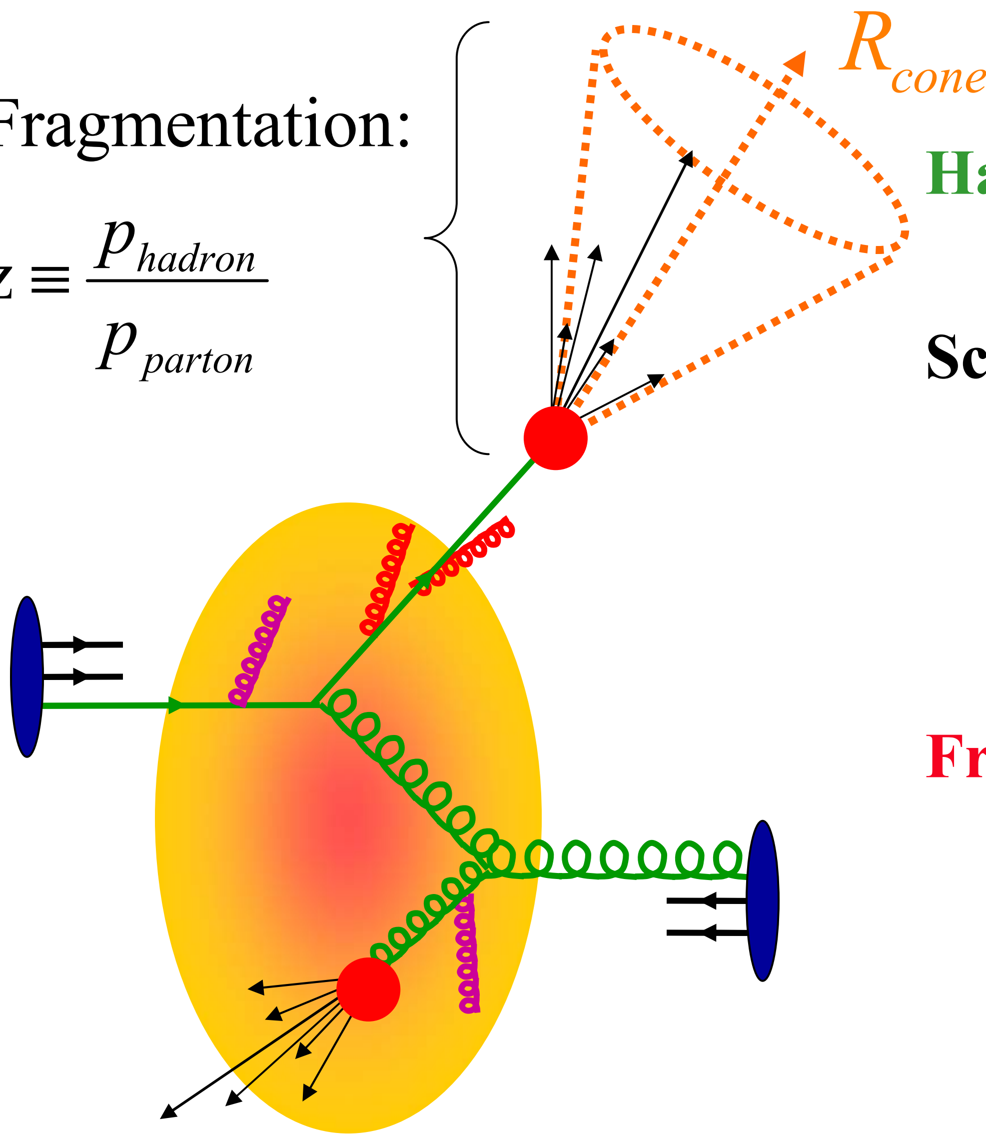
  jet quenching via R_{AA}

- ***high momentum q,g are the probes!***

Hard quarks & gluons → jets

Fragmentation:

$$z \equiv \frac{p_{hadron}}{p_{parton}}$$



Hard scattering happens early

- **affected by initial state nucleus**

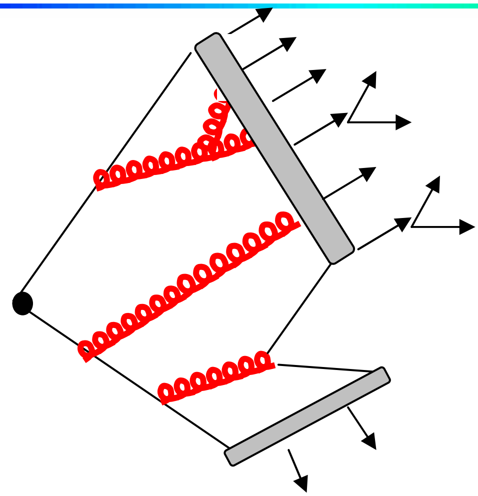
Scattered partons propagate

- **fast quarks, gluons traverse the interesting stuff**
- **radiate gluons**
- **interact with QGP partons**

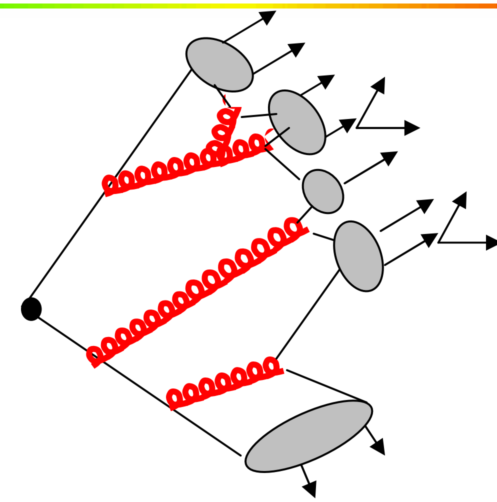
Fragmentation is last step

- **described by phenomenological fragmentation function**
- **outside the medium (?)**

Jet Fragmentation in vacuum



OR



String Breaking

Used in Lund Model & PYTHIA

ARIADNE splits color dipoles

Shower gluons add kinks to strings

Hadrons formed when string breaks into two (multiple times)

→ L-R symmetric splitting function

$$F(z) = (1-z)^a/z \exp(-bM_T^2/z)$$

Cluster Fragmentation

Used in HERWIG

Parton evolves by showering until coupling is small; $g \rightarrow q+\bar{q}$bar

Neighbors combine to color singlets

Clusters are superposition of meson resonances;decay according to phase space

→ no clear functional form in z

Formation time of fragmentation hadrons

- **Uncertainty principle relates hadron formation time to hadron size, R_h and mass, m_h**
  In laboratory frame: $\tau_f \sim R_h (E_h / m_h)$
  consider 2.5 GeV p_T hadrons
  $\tau_f \sim$ 9-18 fm/c for pions; $R_h \sim$0.5-1 fm
  $\tau_f \sim$ 2.7 fm/c for baryons ($R_h \sim$1 fm)
- **Alternatively, consider color singlet dipoles from combination of q & $\bar{q}$ from gluon splitting**
  Using gluon formation time, can estimate
  $\tau_f \sim 2E_h (1-z)/(k_T^2+m_h^2)$
  for z = 0.6-0.8 and $k_T \sim \Lambda_{QCD}$: τ_f baryons ~ 1-2 fm/c

R(Au nucleus) ~ 7 fm
→ Baryon formation is INside the medium!

Energy loss effect: increased gluon radiation

- **Initial state multiple scattering**
- **Energy loss**

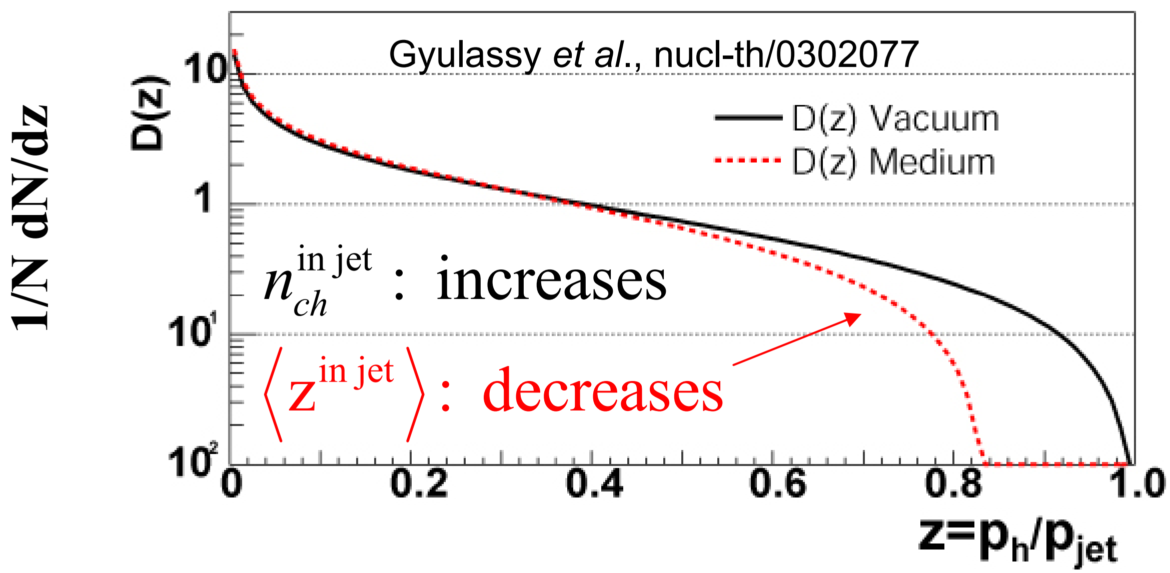
$$\left\langle \Delta k_T^2 \right\rangle \propto \int \rho_g(x)\, dx$$

$$\left\langle \Delta E \right\rangle \propto \int x\, \rho_g(x)\, dx$$

I. Vitev, nucl-th/0308028

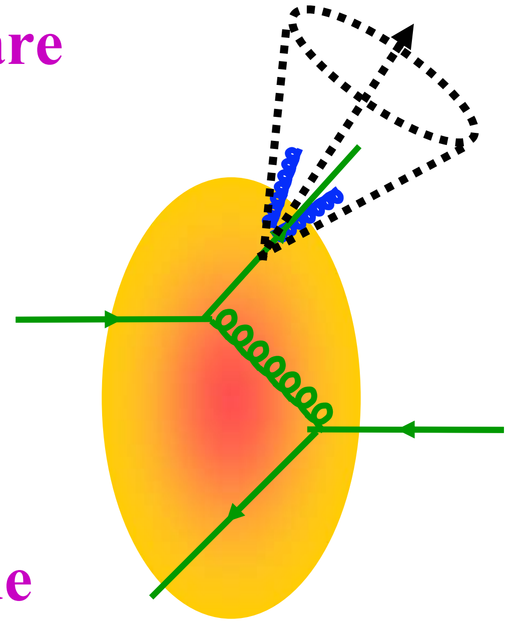
<u>Induced Gluon Radiation</u>

- ~collinear ⇒gluons in cone
- "Softened" fragmentation



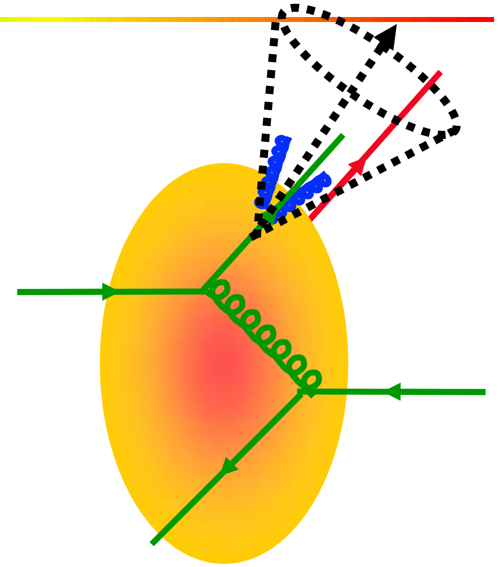
But, things are more complicated

Radiated gluons are collinear (inside jet cone)



Can also expect a jet “wake” effect, medium particles “kicked” alongside the jet by energy they absorb

Fries, Bass & Mueller
nucl-th/0407102



And expect hard-soft recombination

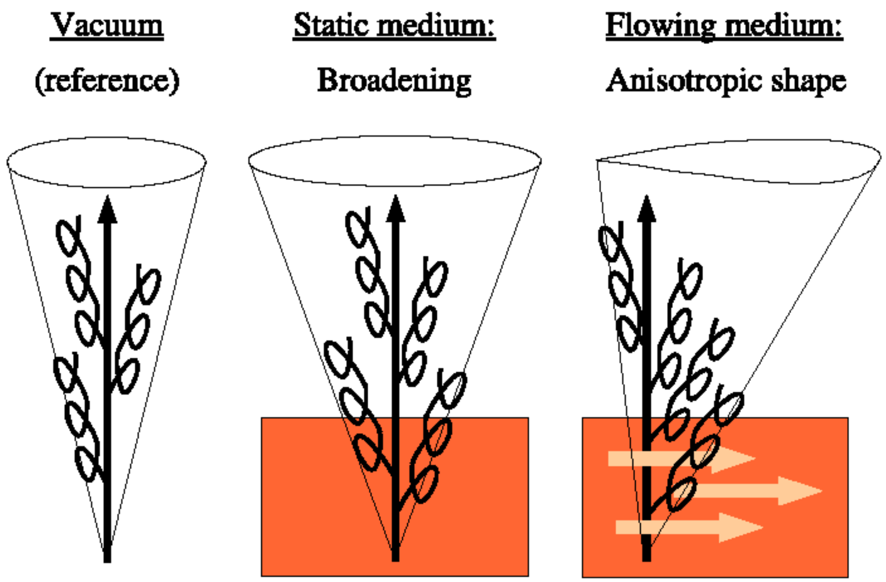
C.M. Ko et al, Hwa & Yang
PRC68, 034904, 2003
PRC67, 034902, 2003
nucl-th/0401001 & 0403072

How is baryon number conservation ensured in these mechanisms?

And EVEN MORE complicated

- ❖ Edward's conic flow: a pressure wave or "super wake"
  i.e. medium response to the energy deposited by jets
- ❖ Correlations of jet fragments with flowing medium

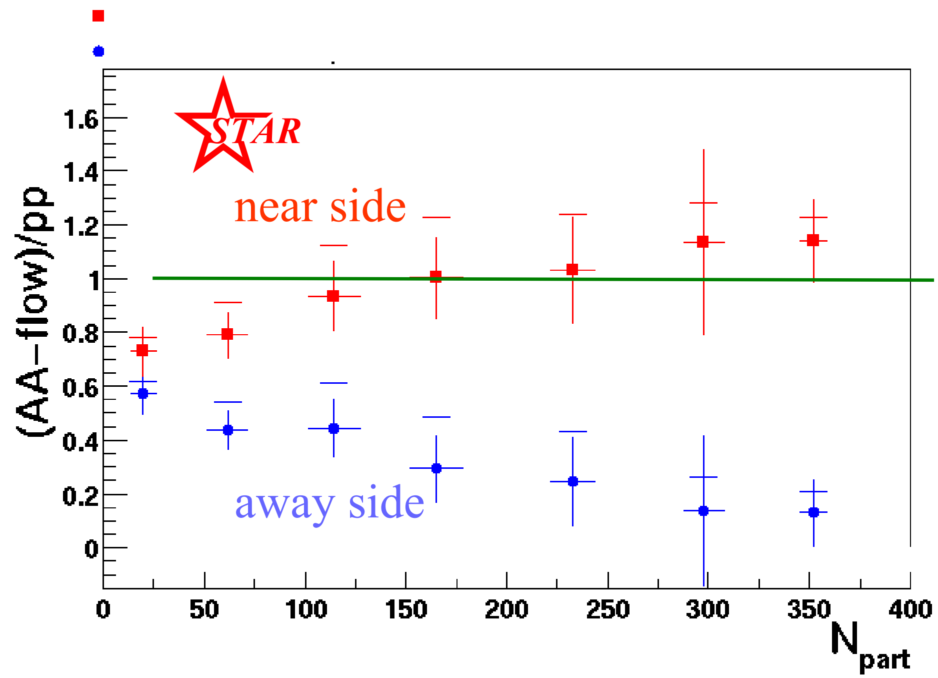
Armesto, Salgado & Wiedemann, hep-ph/0405301

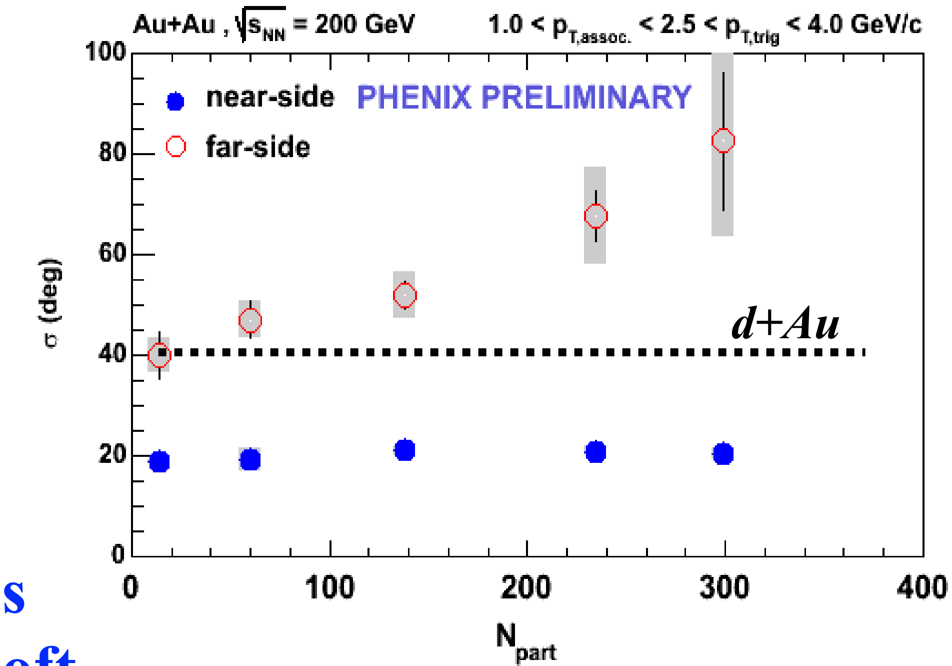


Both consistent with features in data with modest jet fragment energy

Does jet fragmentation have a meaning in presence of medium?
Mechanisms mix up medium & radiated partons
New tool to see conductivity & correlations in medium at ~1 fm/c??

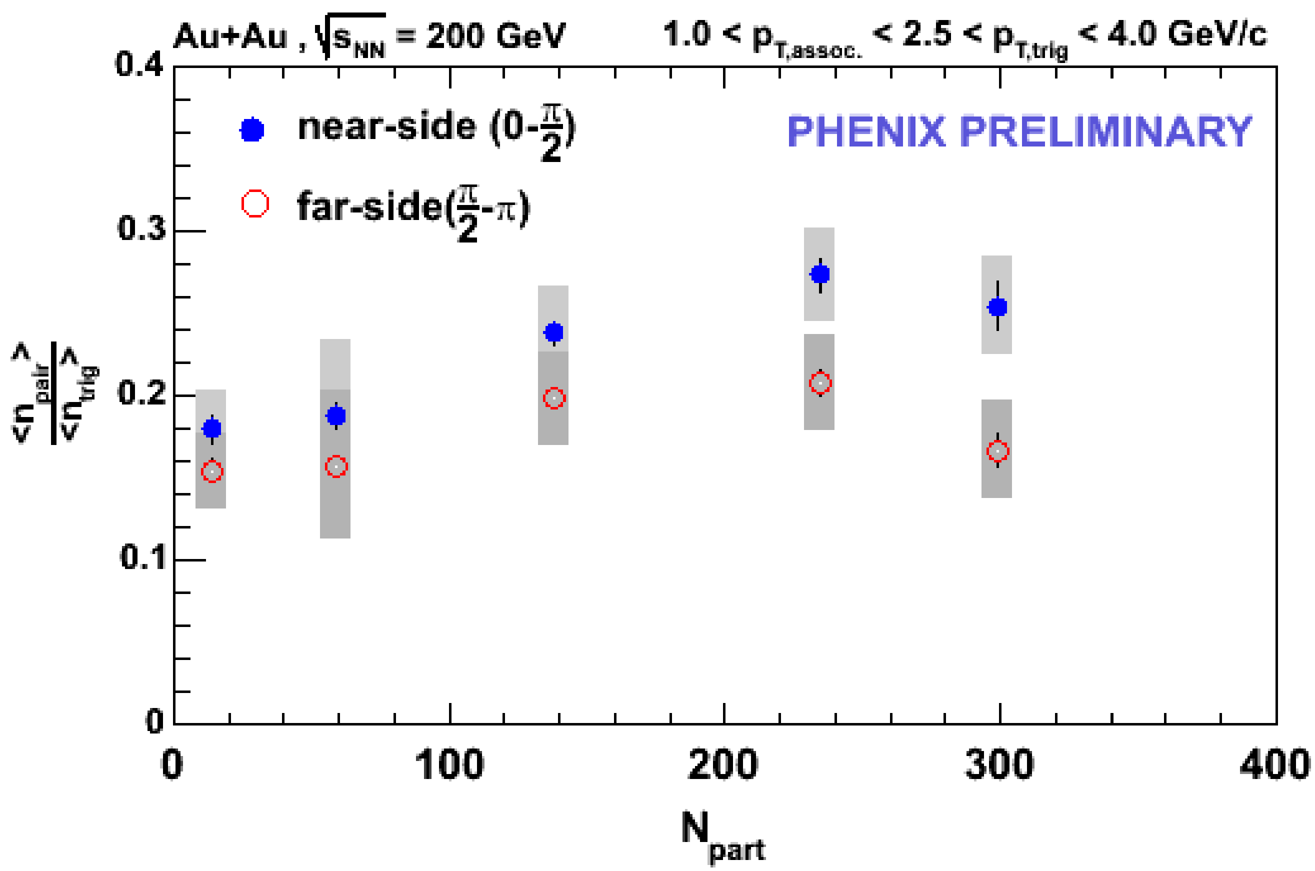
Data say: away side jet suppression/broadening





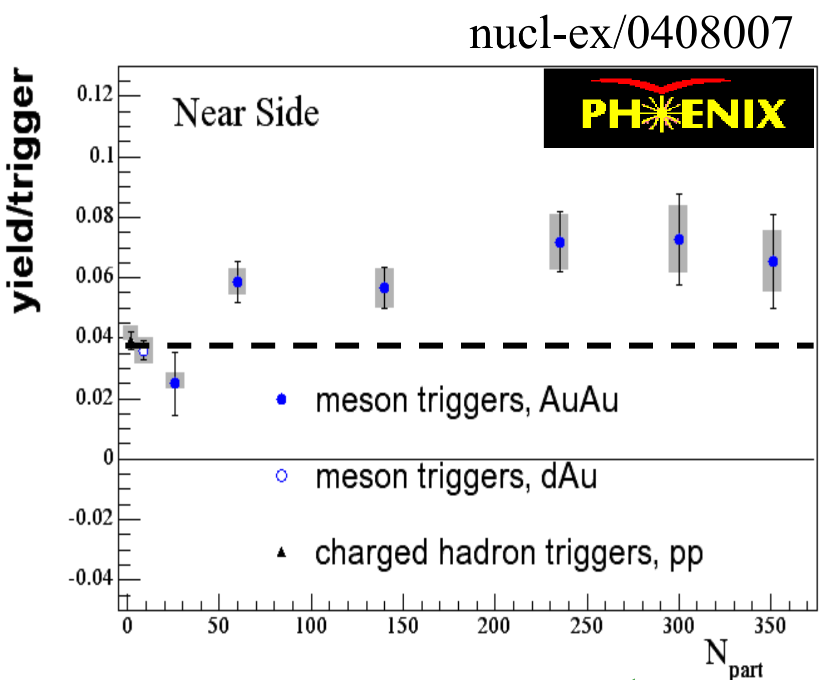
And "interesting" shape changes for correlations of sufficiently soft associated particles

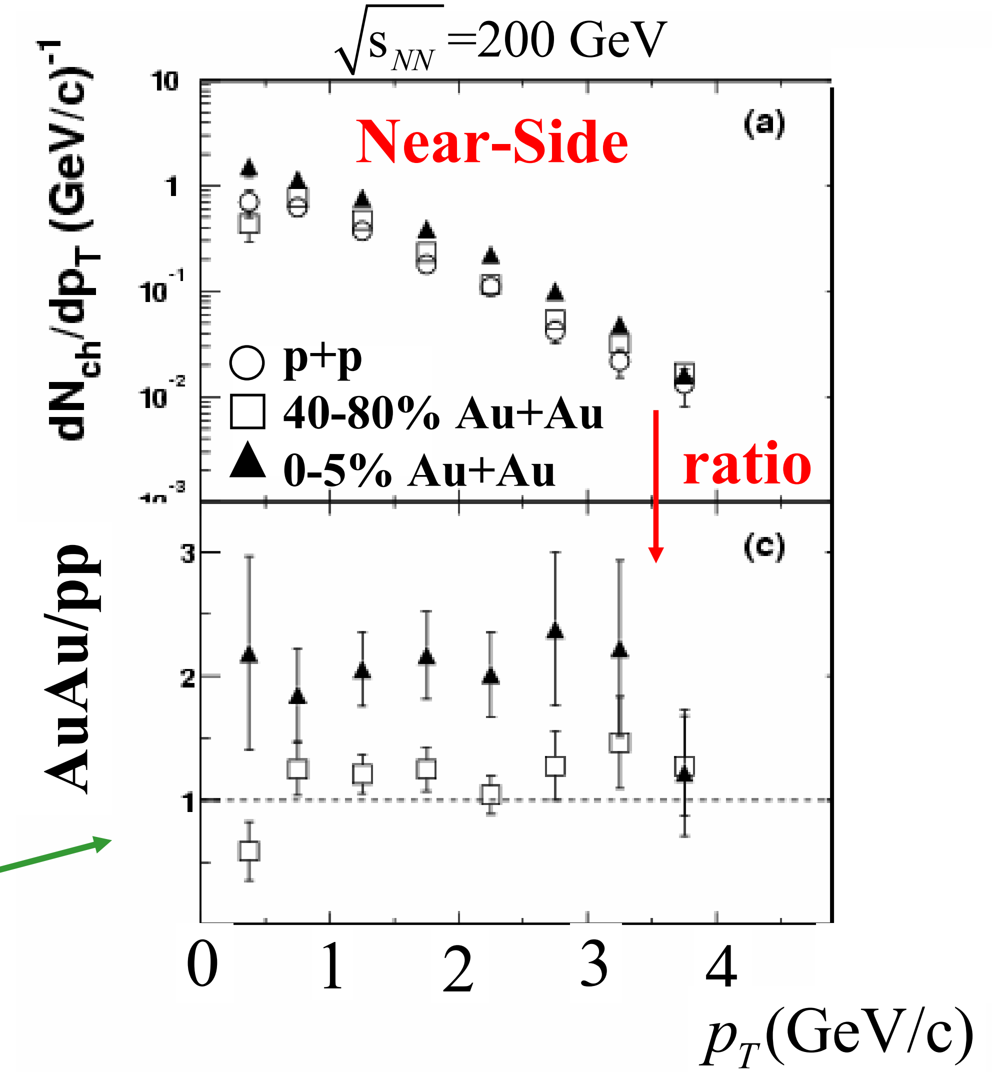
Yields on away side



Integrated over 90 degrees

More partners on same side





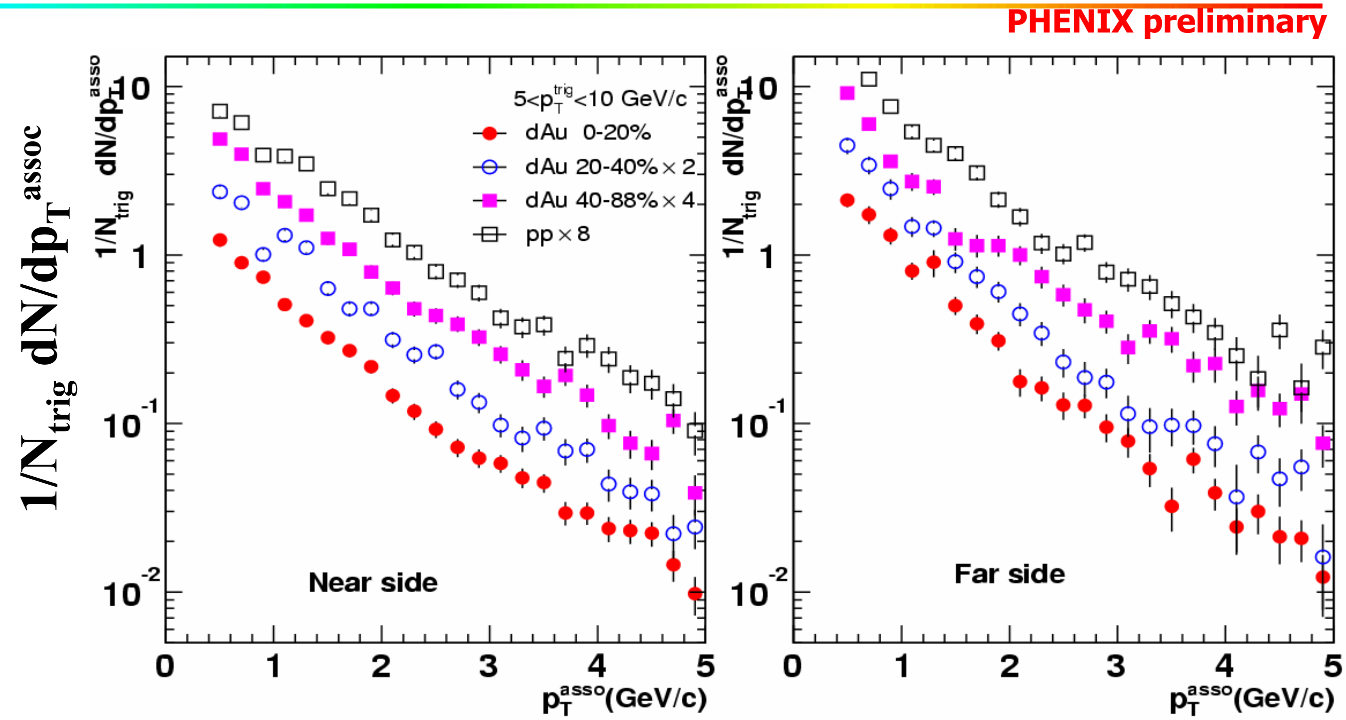
In 55° $\Delta\phi$ and small $\Delta\eta$

In large $\Delta\eta$

$\langle N_{ch}^{\text{in jet}} \rangle$

Must measure own reference!

Our jets are soft.
Trigger bias from high p_T hadron.



jet multiplicity unchanged with d+Au centrality vs. pp

STAR $1/N_{trig}\, dN/dp_T^{assoc}$ shown on previous slide

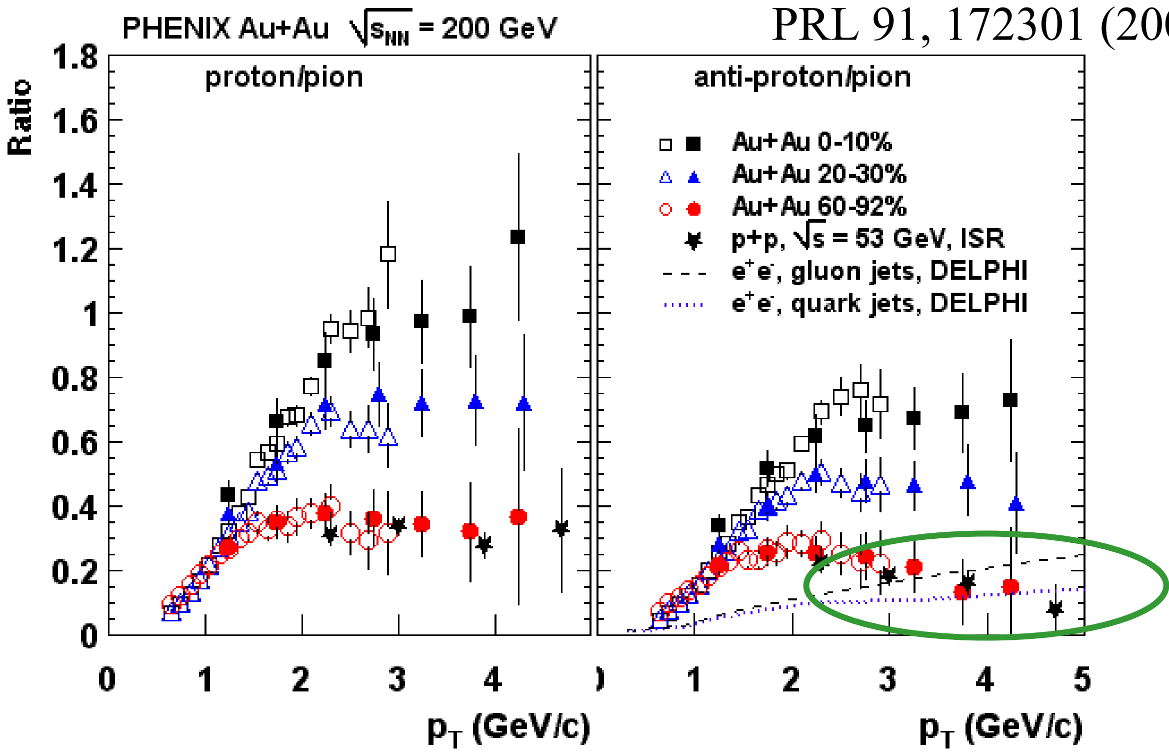
+ full jet reconstruction in dAu (shown at QM04)

But, we need to figure out the QUESTION to ask in Au+Au!

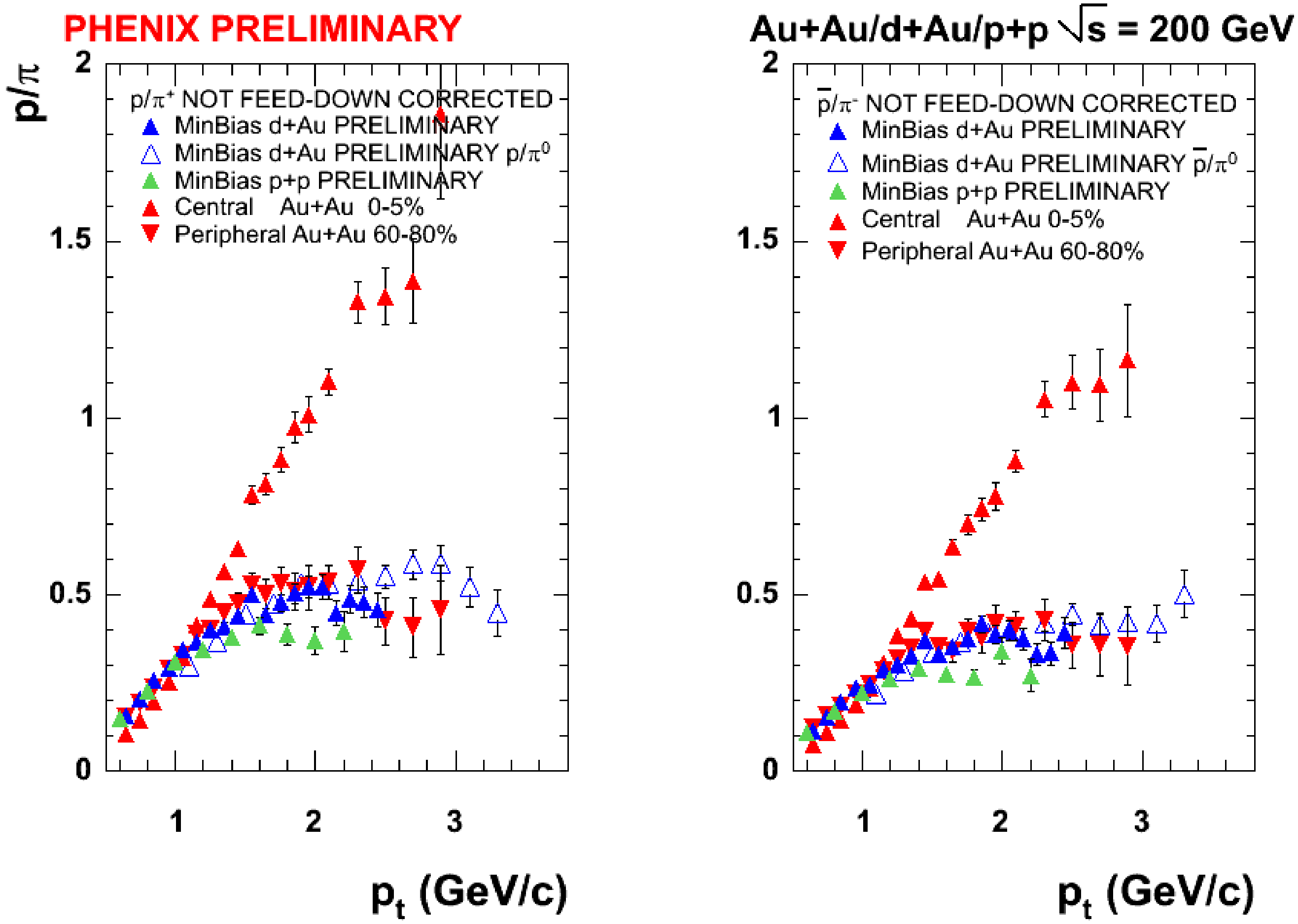
What about baryons?

- Formed via diquarks in string fragmentation
- Reduced phase space due to high mass in cluster decay
- Suppressed relative to mesons by factor of ~10

PRL 91, 172301 (2003)



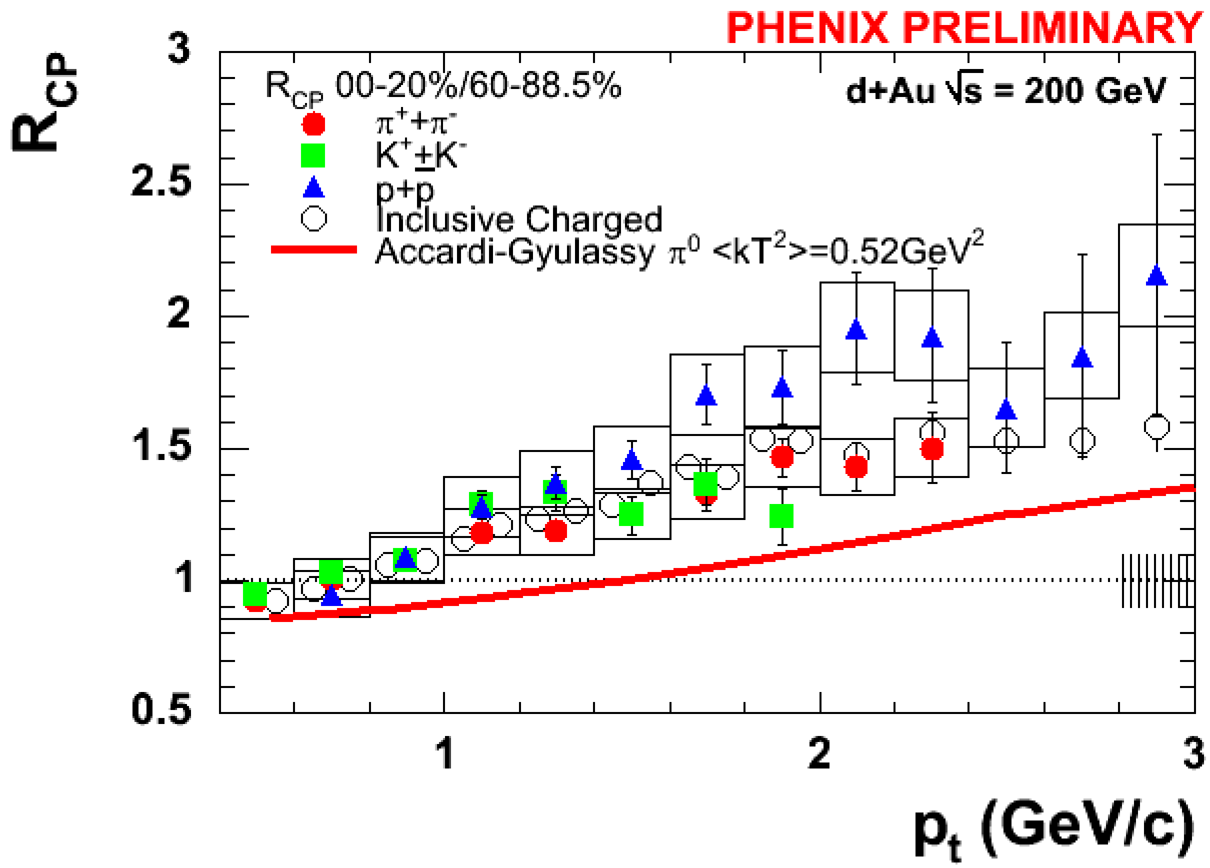
Baryons already different in p+A



Nuclear medium modifies initial state

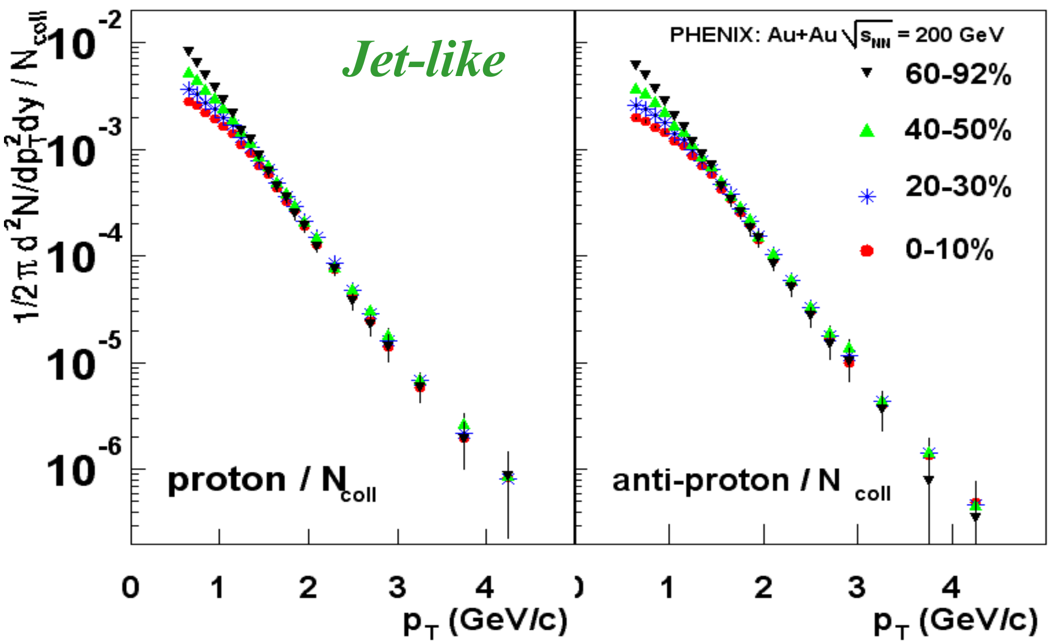
Cronin effect for baryons larger than for mesons

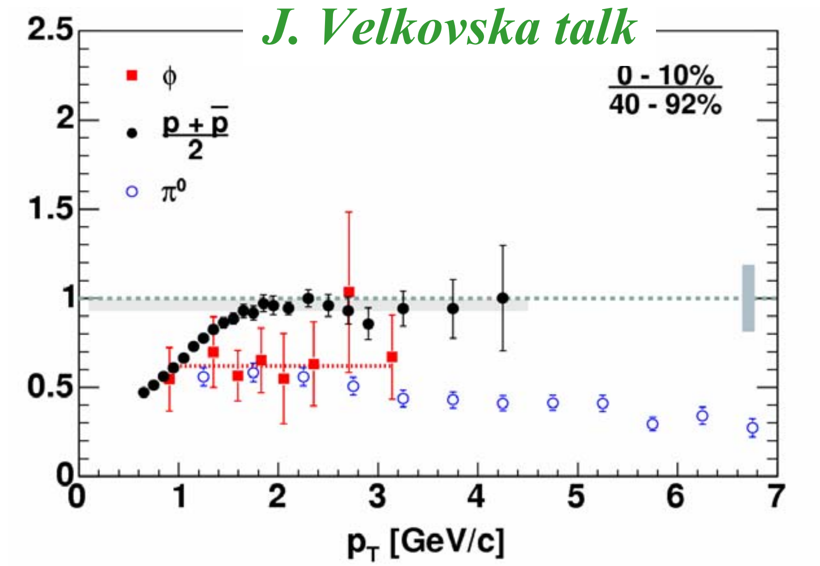
(as at lower energy)



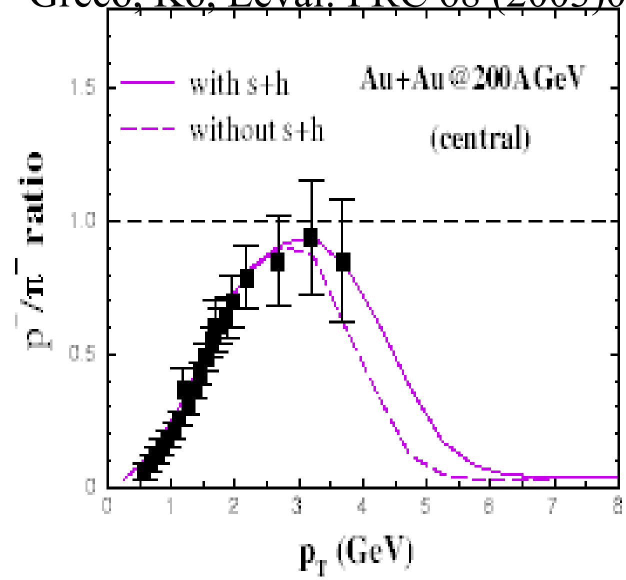
Shouldn't initial state scattering and fragmentation factorize?!
R. Hwa says medium already matters in d+Au

In Au+Au baryons scale with N_{coll} !





Greco, Ko, Levai: PRC 68 (2003)034904



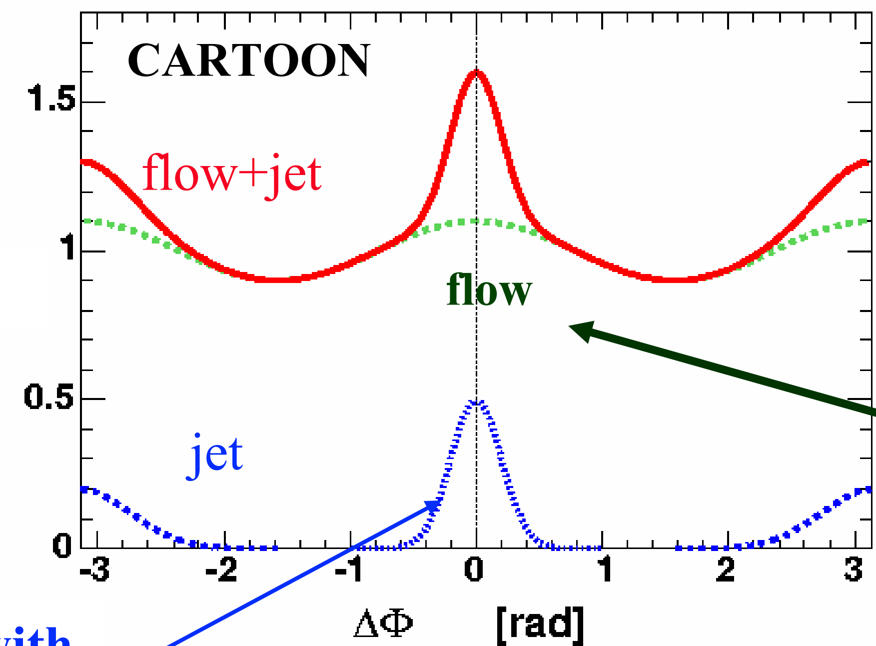
But observed enhancement can be explained by recombination of thermal quarks from an expanding quark gluon plasma. *NON Jet-like!*

do jet analysis with identified triggers

includes ALL triggers (even those with no associated particles in the event)

combinatorial background large in Au+Au!

$$\frac{1}{N_{trig}}\frac{dN}{d\Delta\phi}$$



Measure with mixed events; Collective flow causes another correlation in them:

$$B(1+2v_2(p_T^{trig})v_2(p_T^{assoc})\cos(2\Delta\phi))$$

associated particles with non-flow angular correlations -> jets!

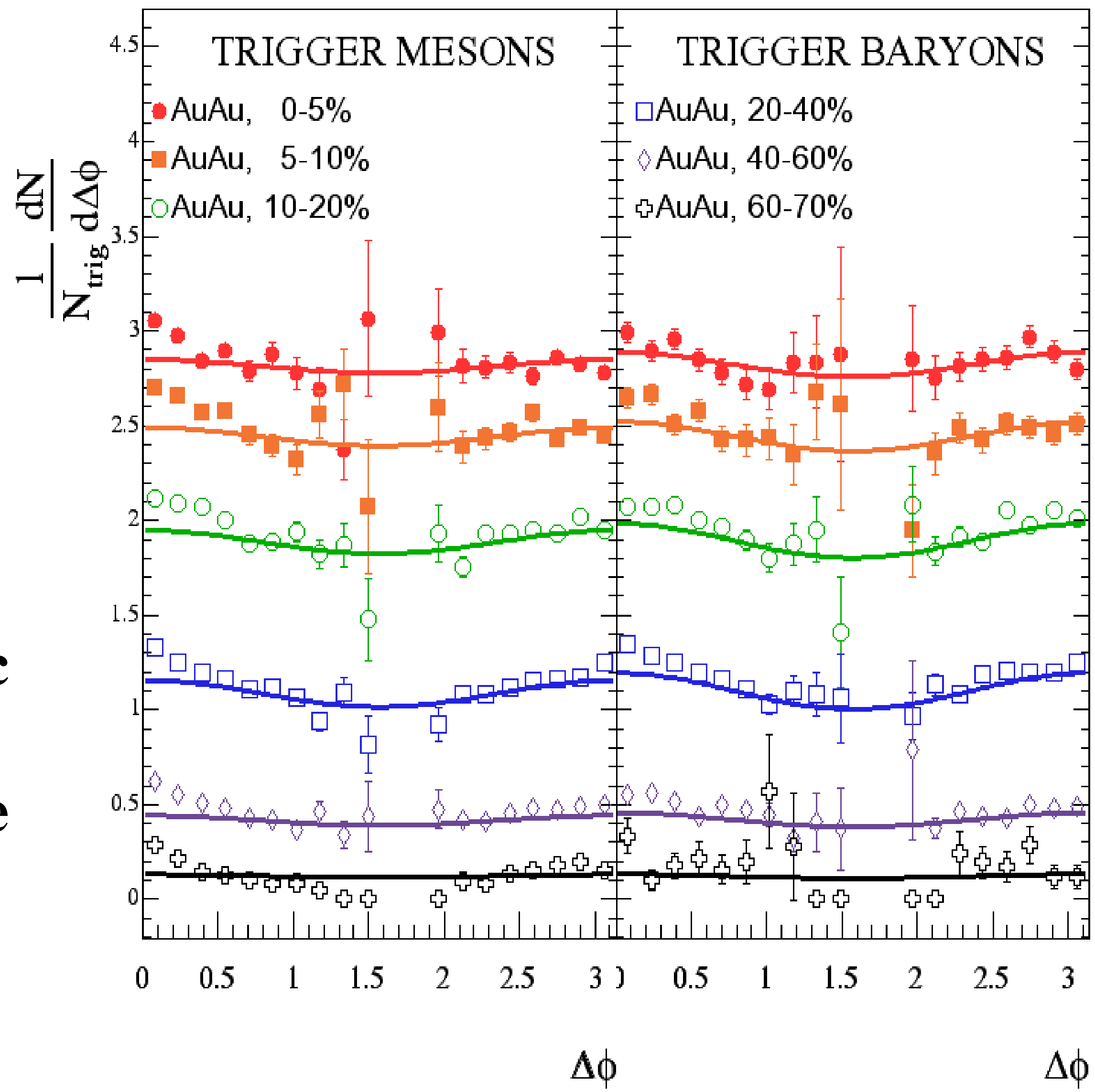
2 particle correlations

Select particles with p_T= 2.5-4.0GeV/c

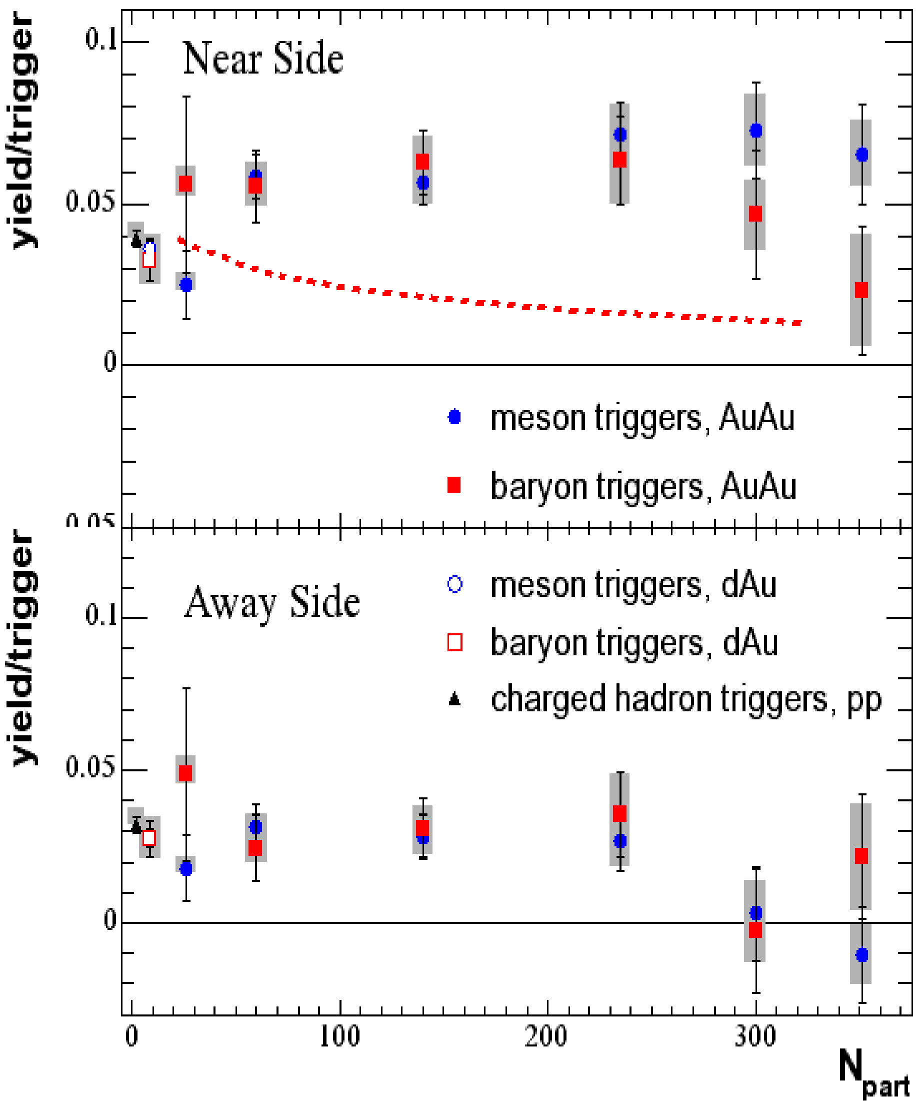
Identify them as mesons or baryons via time-of-flight

Find second particle with p_T = 1.7-2.5GeV/c

Plot distribution of the pair opening angles; integrate over 55°



intermediate p_T baryons ARE from jets



Jet partner ~ equally likely for trigger baryons & mesons!

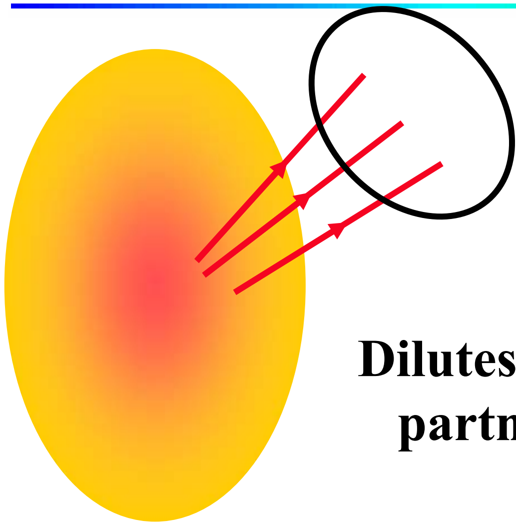
Same side: slight decrease with centrality for baryons

Dilution from boosted thermal p, pbar?

Away side: partner rate as in p+p confirms jet source of baryons!

"disappearance" of away-side jet into narrow angle for both baryons and mesons

What's going on?

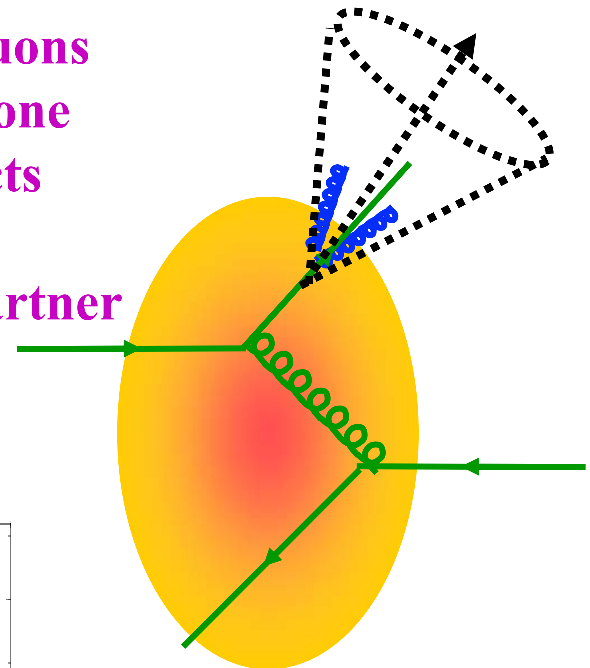


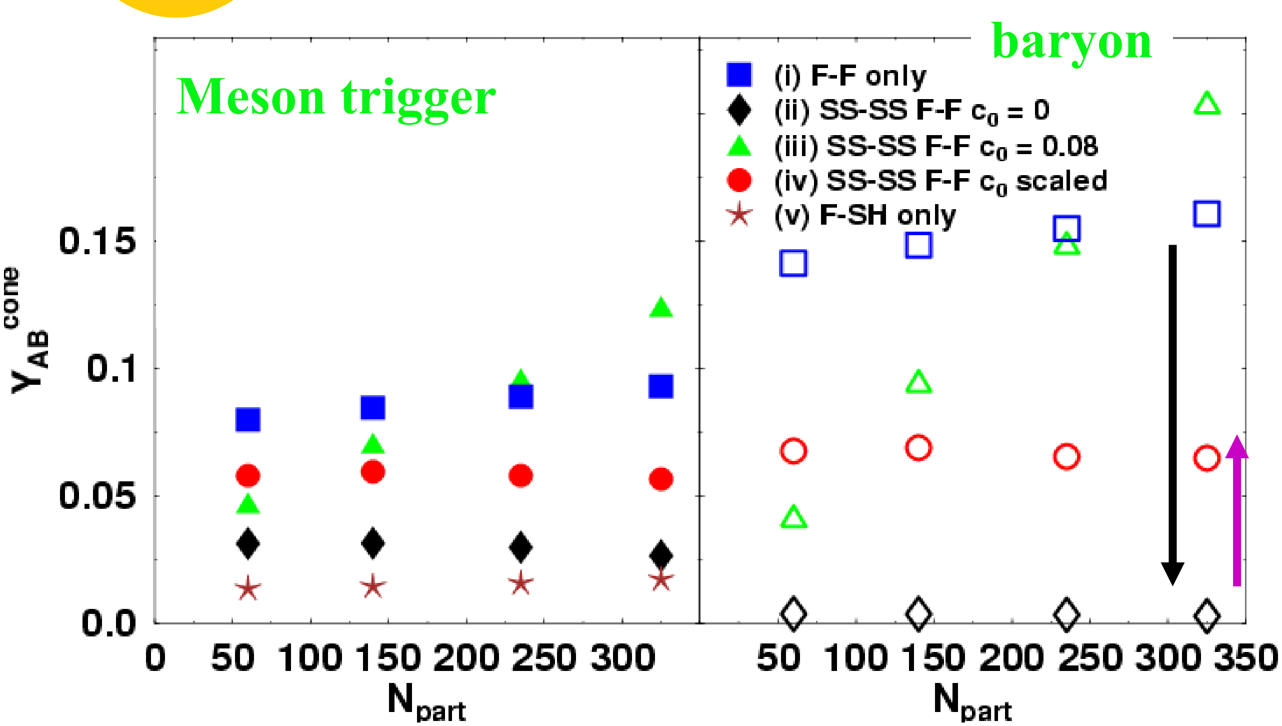
Thermal quark recombination

Dilutes jet partner yield

Radiated gluons inside jet cone + wake effects

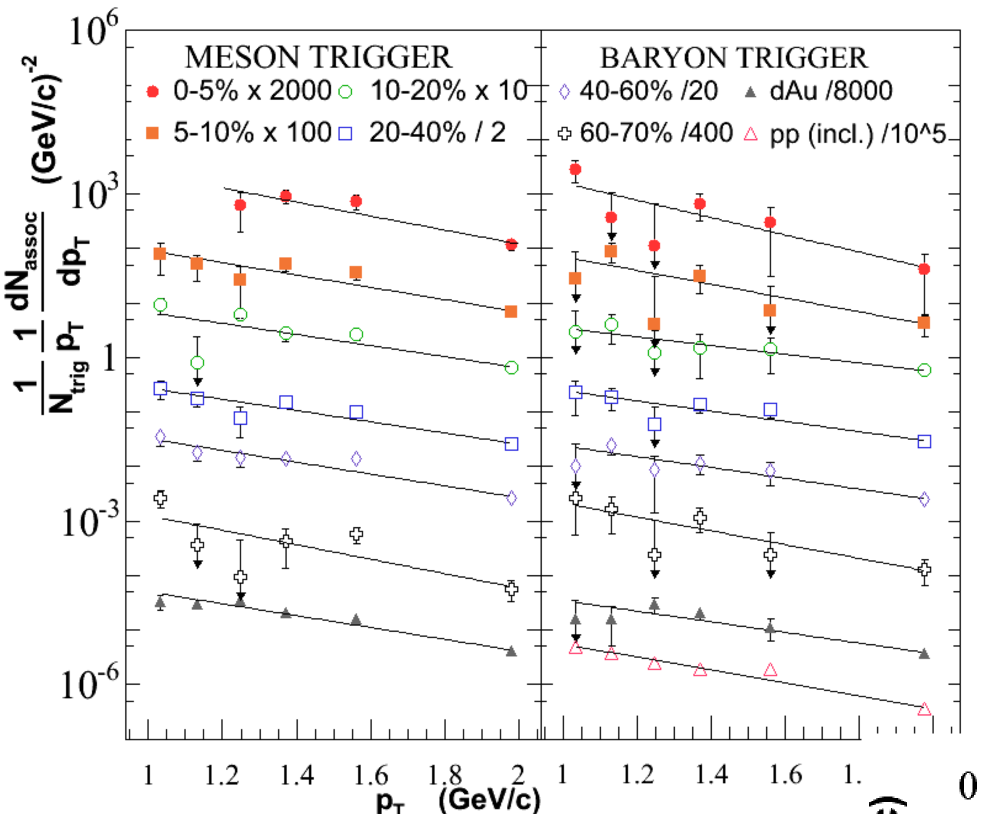
Increases partner yield





Fries, Bass & Mueller
nucl-th/0407102

Jet partner distribution on trigger side



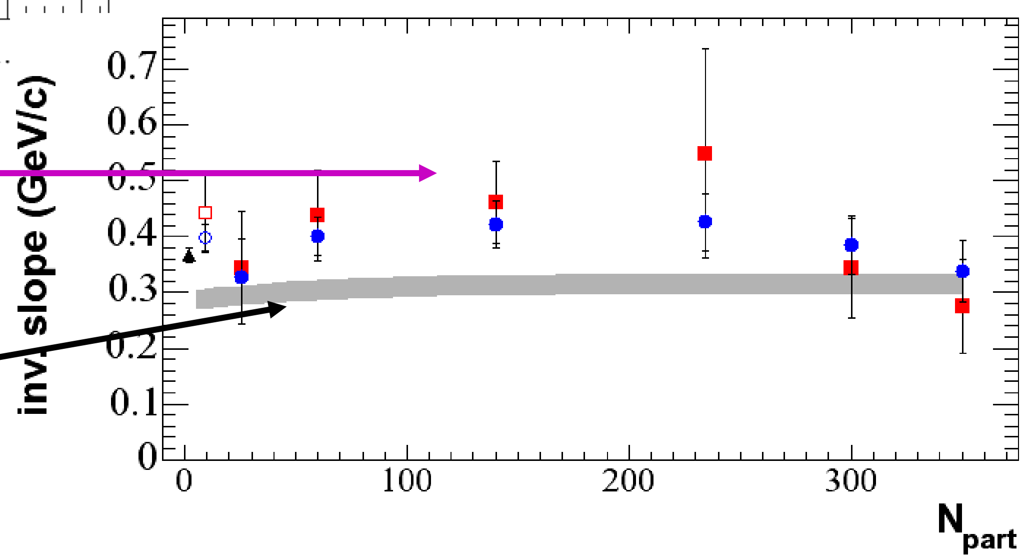
Corrected to jet yield according to fragmentation symmetric in ϕ,η

Partner spectrum flatter, as expected for jet source

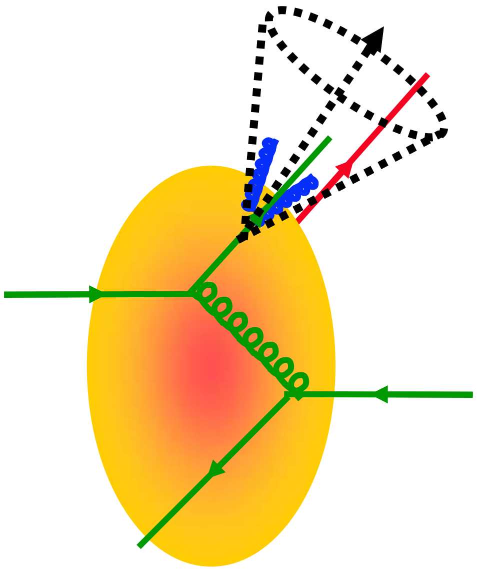
Partners soften in most central collisions

Jet partners

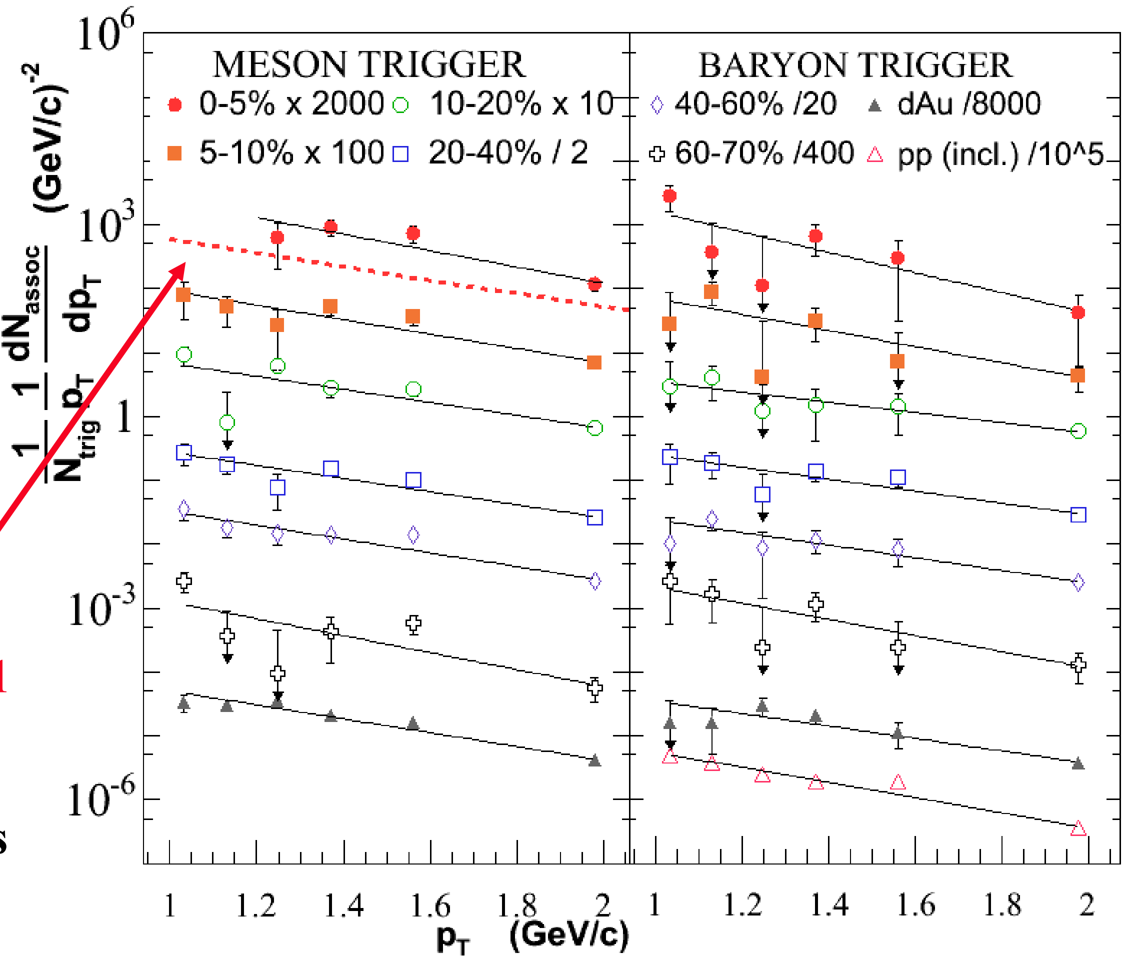
Inclusive



Compare to hard-soft recombination



π trigger & π associated
Hwa & Yang nucl-th/0407081

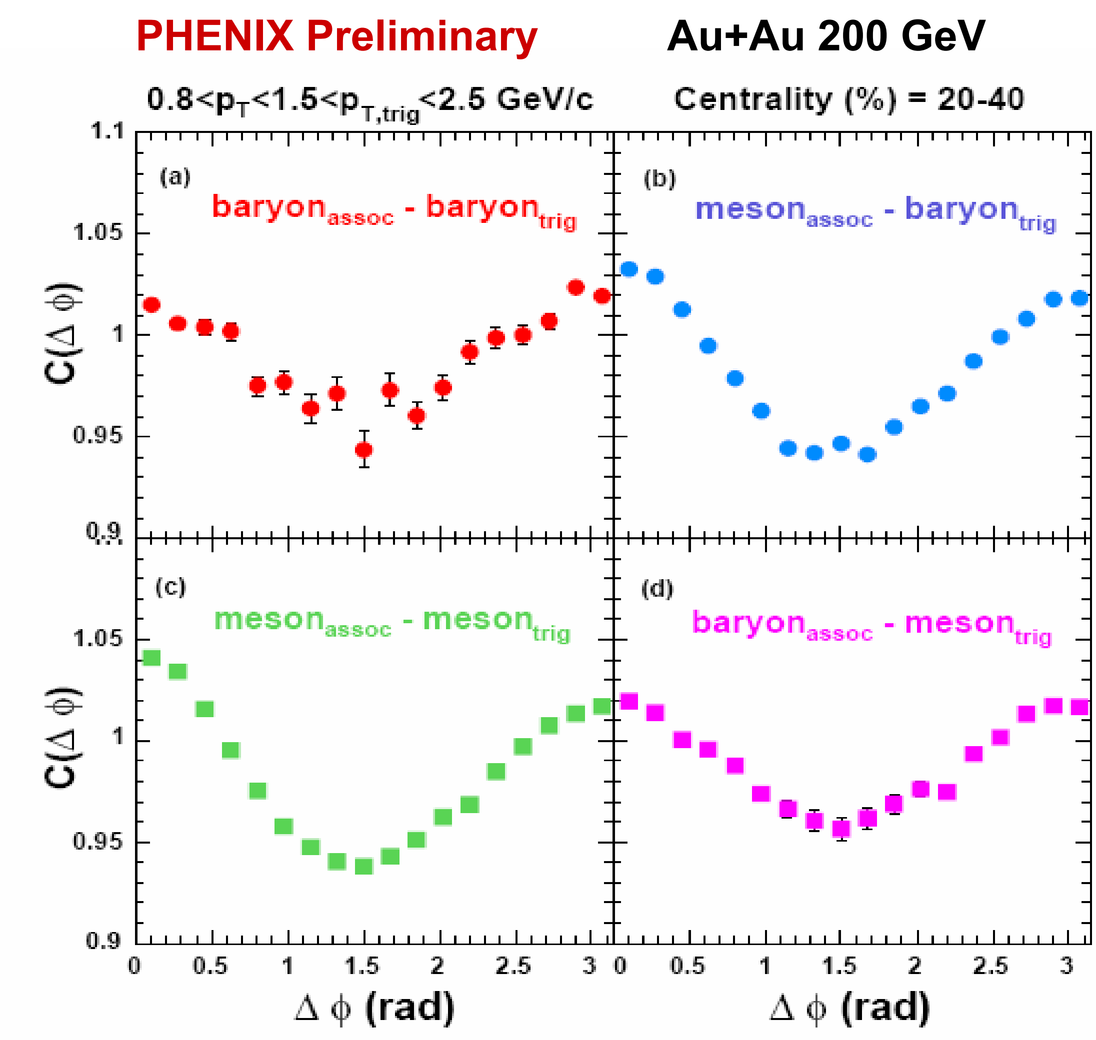


Soft-hard recomb. also explains baryon Cronin effect!
No jet-correlated medium flow

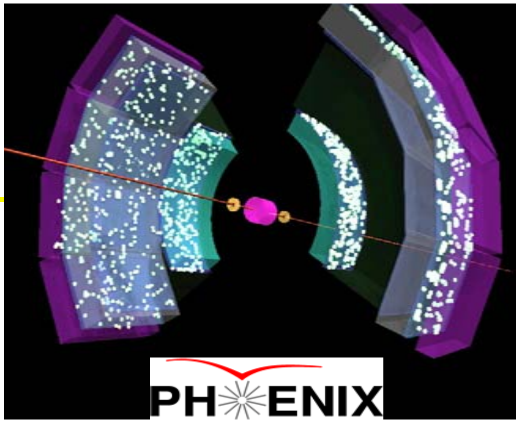
Conclusions

- **Baryon excess has a very significant jet component**
  Dilution becoming visible in most central collisions?
- **Jet fragmentation is modified by the medium!**
  Baryon production enhanced
  Au+Au jets richer in soft hadrons than p+p or d+Au
  Away side jet gets complicated
  Moderate p_T associated particles have significant medium splash? Should we call them jet fragments??
- **A new probe!**
  Leading & association baryons → q,qbar correlations in the medium
  Mapping the splash → how the medium conducts energy

Fun to come…

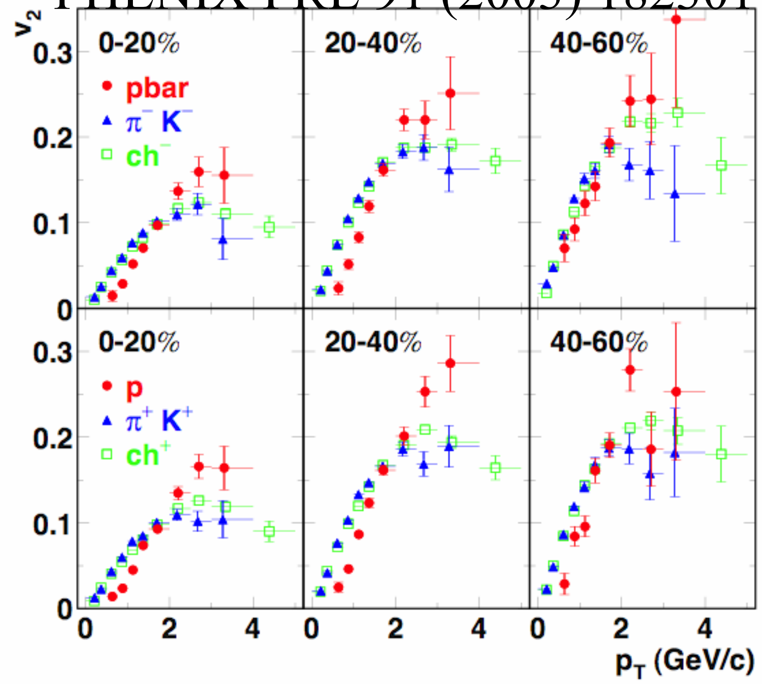

PHENIX Preliminary
Au+Au 200 GeV
0.8<p_T<1.5<p_T,trig<2.5 GeV/c
Centrality (%) = 20-40
(a)
baryon_assoc - baryon_trig
(b)
meson_assoc - baryon_trig
(c)
meson_assoc - meson_trig
(d)
baryon_assoc - meson_trig
C(Δ φ)
Δ φ (rad)
1.1
1.05
1
0.95
0.9
0
0.5
1
1.5
2
2.5
3

Jets in PHENIX

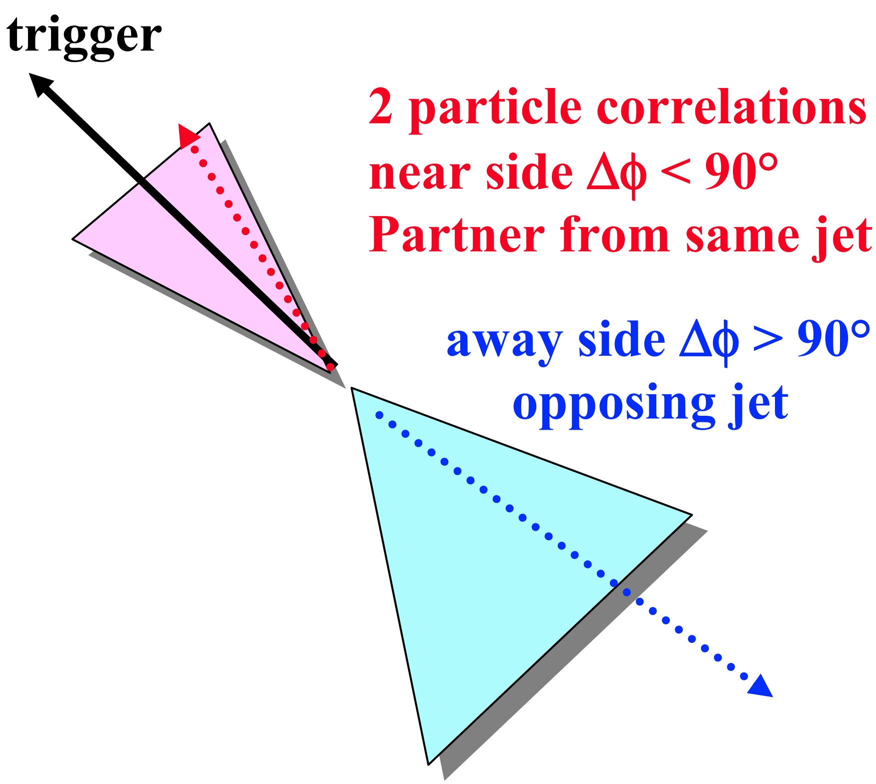


- Large multiplicity of charged particles
  --solution: find jets in a statistical manner
  using angular correlations of particles
  mixed events give combinatorial background
- 2 x 90 degree acceptance in phi and |η|<0.35
  --solution: correct for azimuthal acceptance,
  but not for η acceptance
- Elliptic flow correlations
  --solutions:
  use published strength values
  and subtract
  (could integrate over 90°
  to integrate all even
  harmonics to zero)

PHENIX PRL 91 (2003) 182301



So, do jet analysis on identified baryons



Trigger:

hadron with $p_T > 2.5$ GeV/c

Identify as baryon or meson

Biased, low energy, high z jets!

Plot $\Delta\phi$ of associated partners

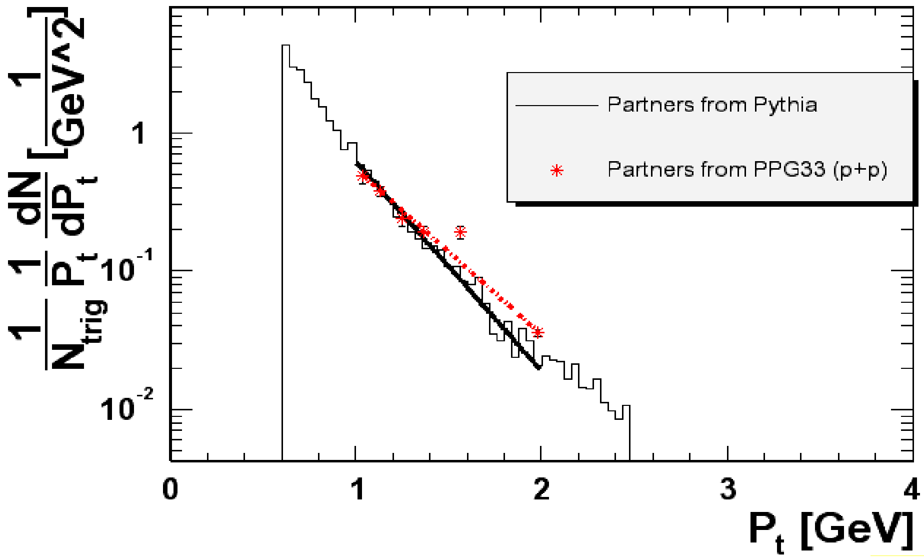
Count associated lower p_T particles for each trigger

→ "conditional yield"

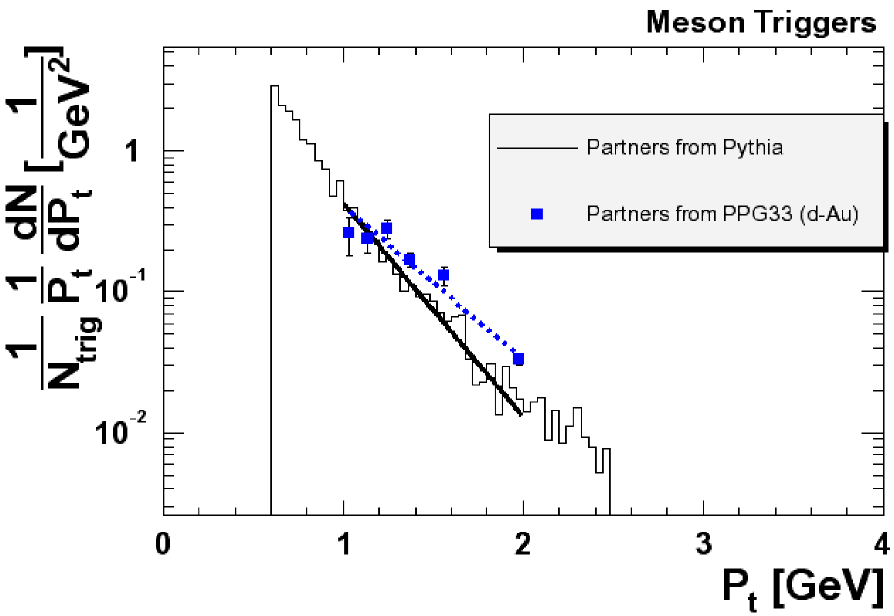
Near side yield: number of jet associated particles from same jet in specified p_T bin

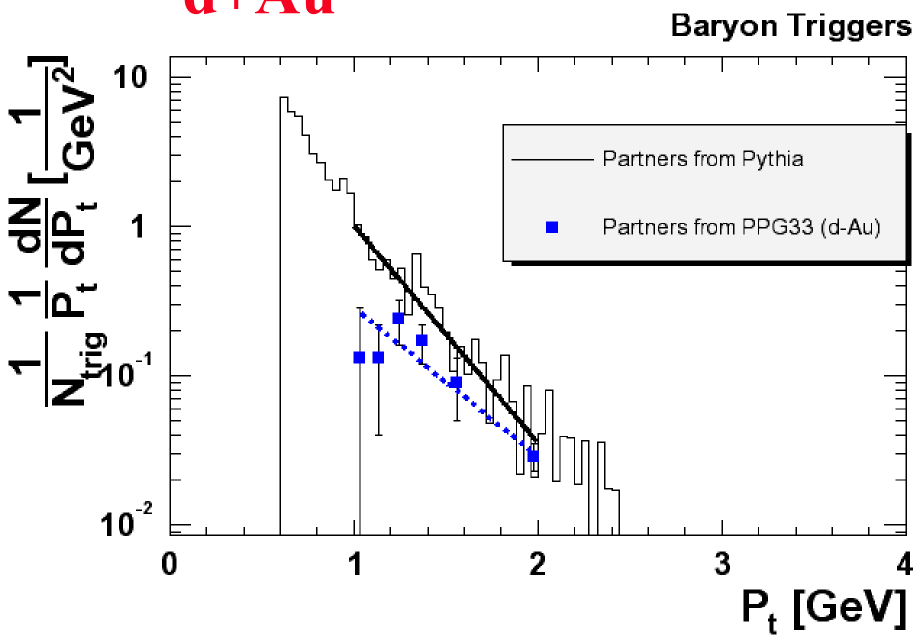
Away side yield: jet fragments from opposing jet

Compare p+p and d+Au to PYTHIA



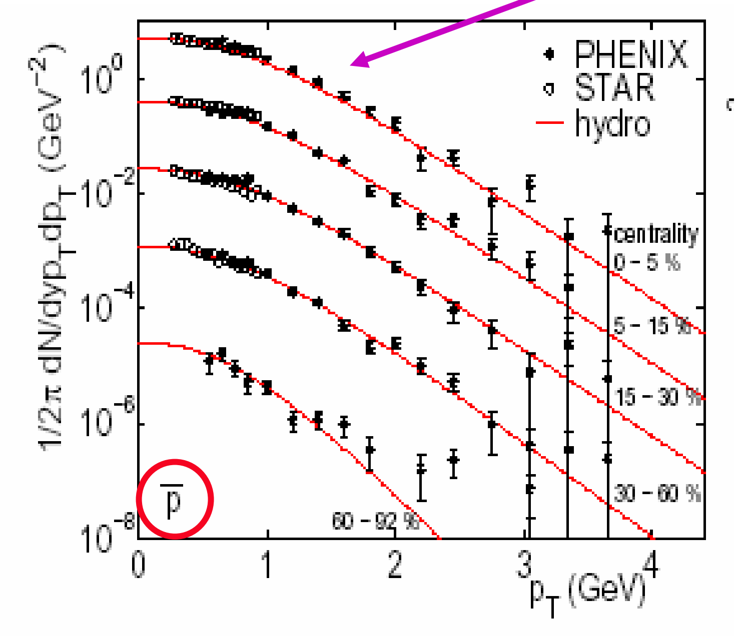
d+Au



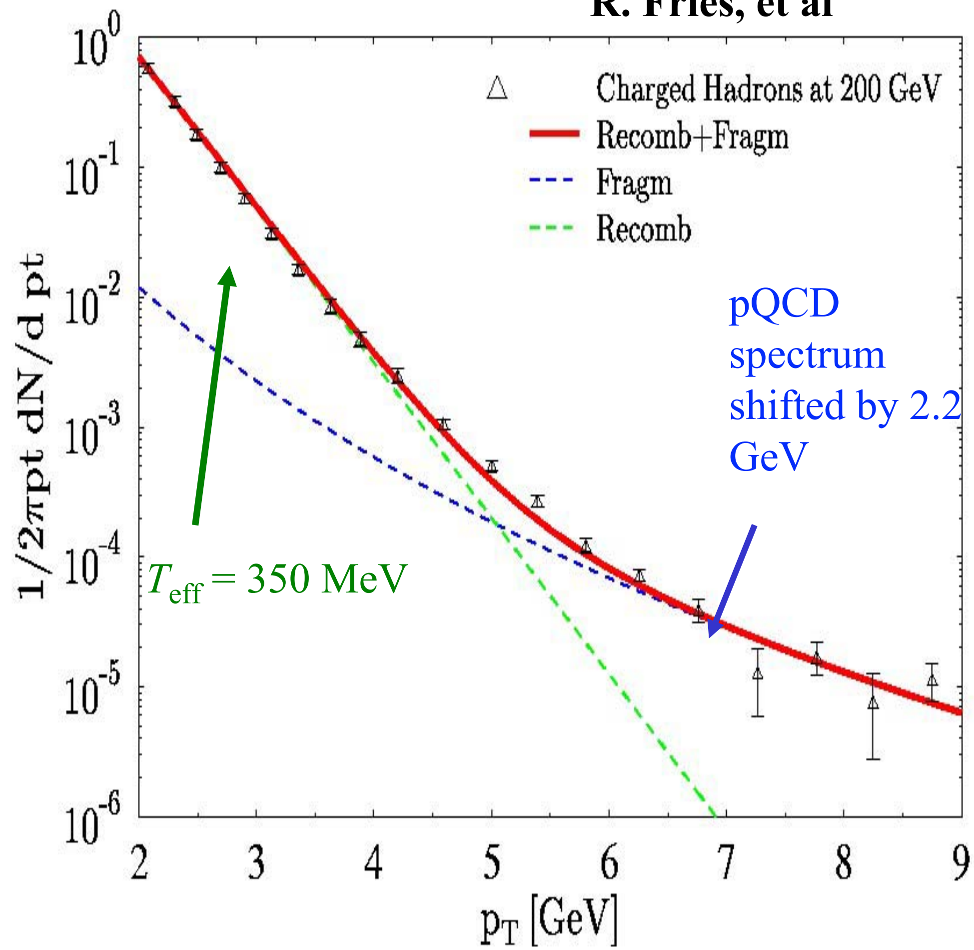


Are extras from the (soft) underlying event?

Hydro. expansion at low p_T + jet quenching at high p_T.



R. Fries, et al



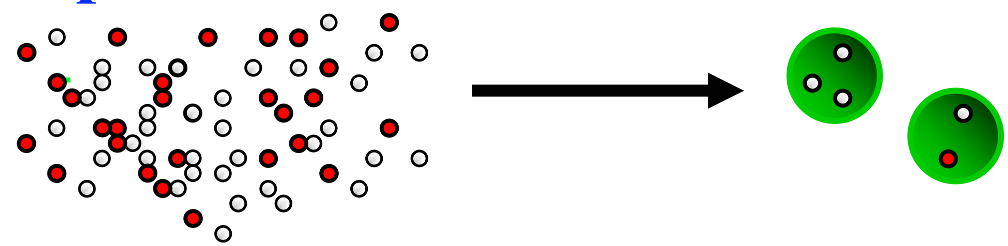
Coalesce (recombine) boosted quarks → hadrons

enhances mid p_T hadrons

baryons especially

Phase space filled with partons:coalesce into hadrons

Use lowest Fock state, i.e. valence quarks



- **ReCo of hadrons: convolution of Wigner functions**

$$\frac{dN_M}{d^3P} = \sum_{a,b} \int \frac{d^3R}{(2\pi)^3} \int \frac{d^3q d^3r}{(2\pi)^3} W_{ab}(R-\frac{r}{2}, \frac{P}{2}-q; R+\frac{r}{2}, \frac{P}{2}+q)\Phi_M(r,q)$$

$W_{ab}(1;2) = w_a(1)w_b(2)$

- **Where does ReCo win?**

Exponential: $w \sim Ae^{-p_T/T}$

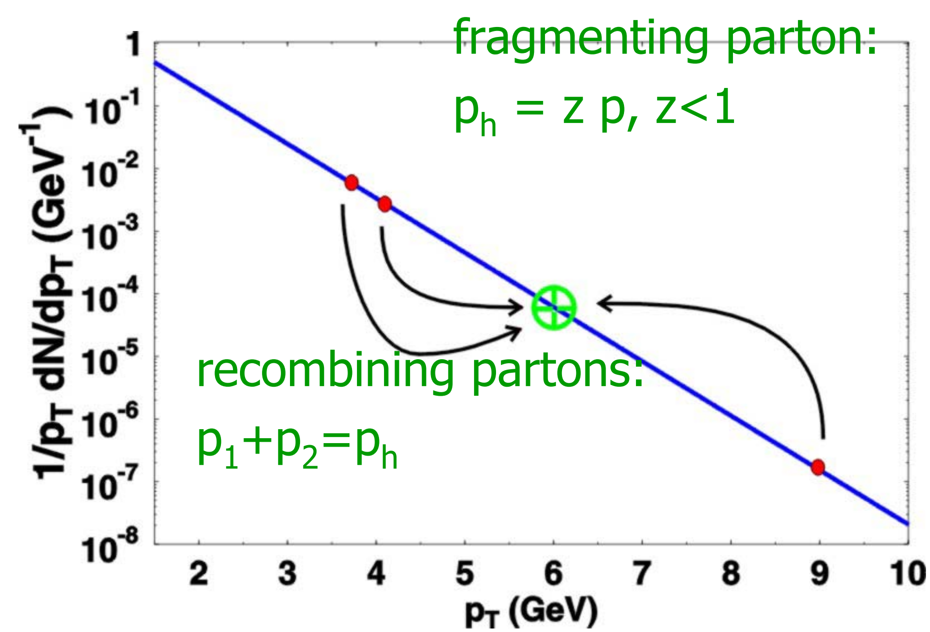
$$N_{\text{frag}} = w \otimes D \sim Ae^{-P_T/\langle z \rangle T} \langle D \rangle$$

$$N_{\text{reco}} = w \otimes \Phi \otimes w \sim A^2 e^{-P_T/T}$$

Power law: $w \sim p_T^{-\alpha}$

$$N_{\text{frag}} \sim P_T^{-\alpha}$$

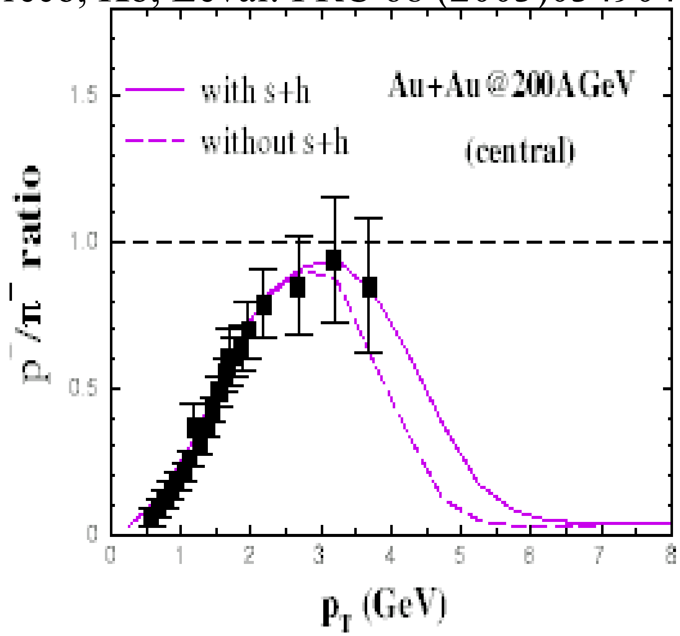
$$N_{\text{reco}} \sim P_T^{-2\alpha}$$



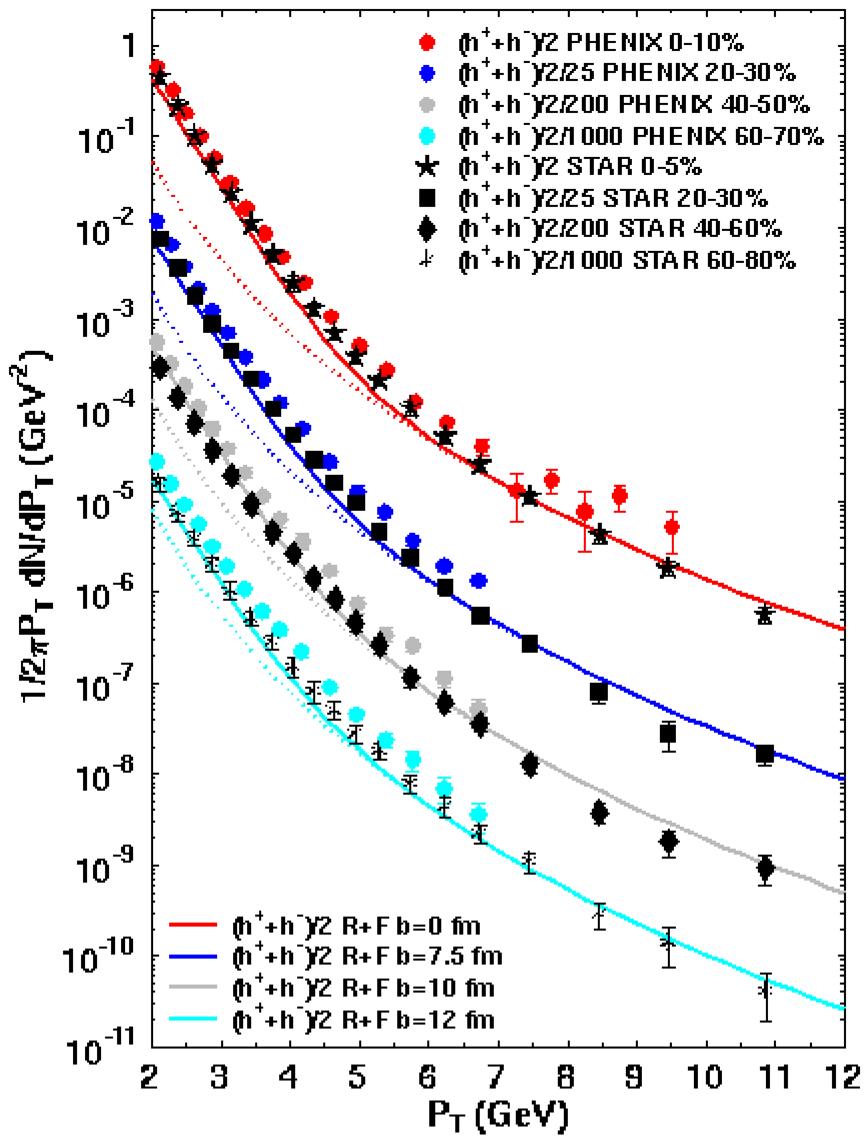
R. Fries

Coalescence Model results

Greco, Ko, Levai: PRC 68 (2003)034904

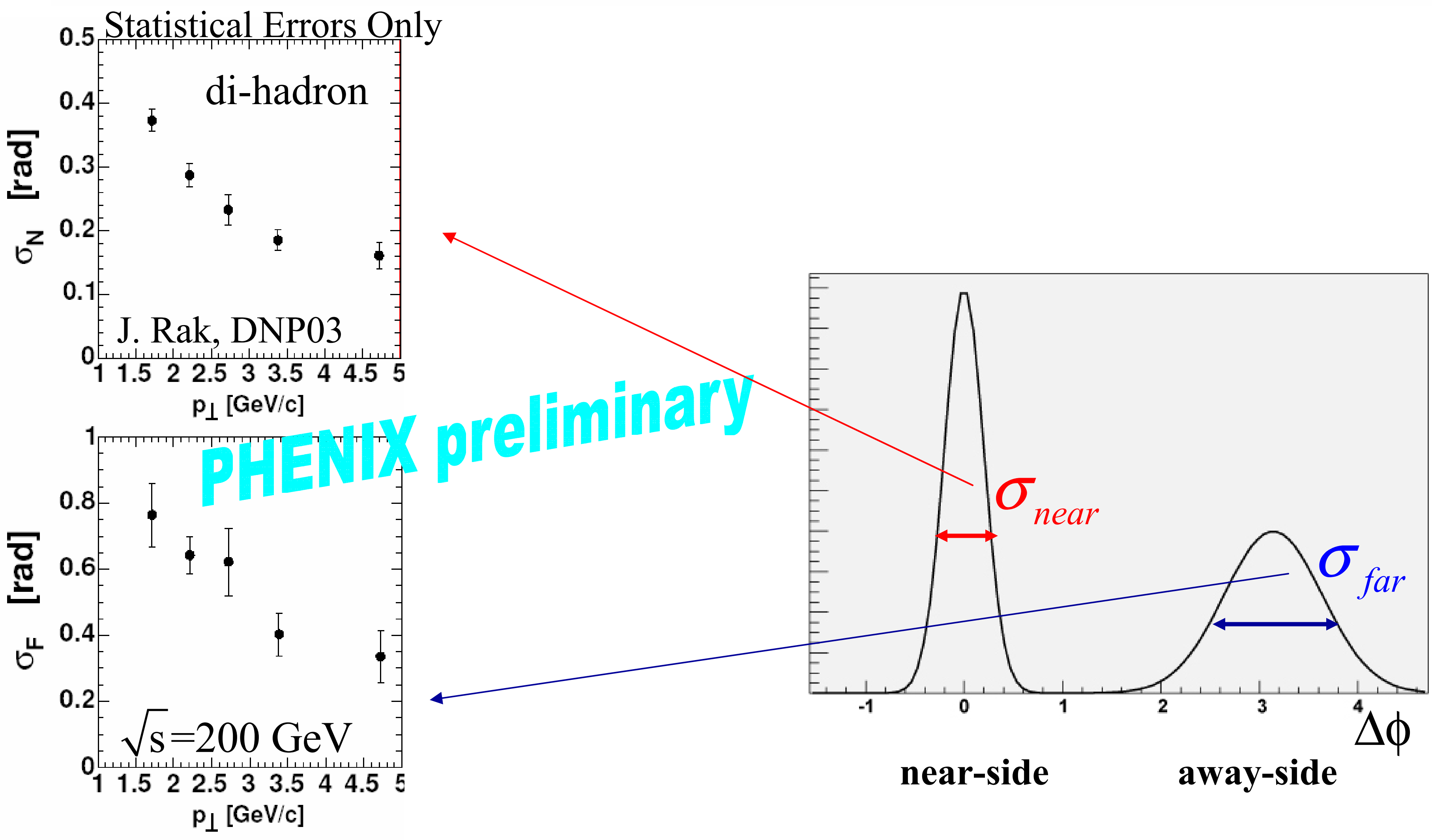


Fries et al: Phys.Rev. C68 (2003) 044902



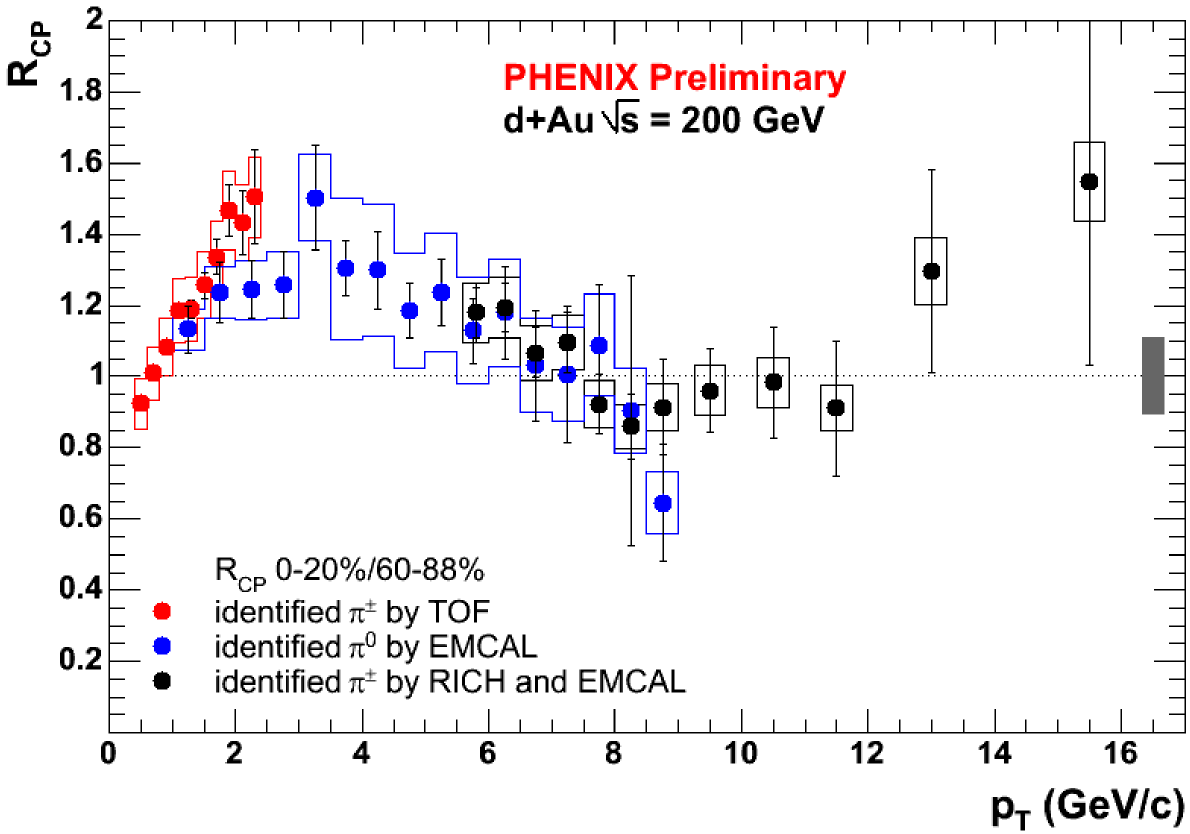
- **particle ratios and spectra OK**
- **intermediate p_T hadrons from coalescence of flowing partons NOT from jets, so no jet-like associated particles**

k_T, j_T at RHIC from p+p Data



Pions in 3 detectors in PHENIX

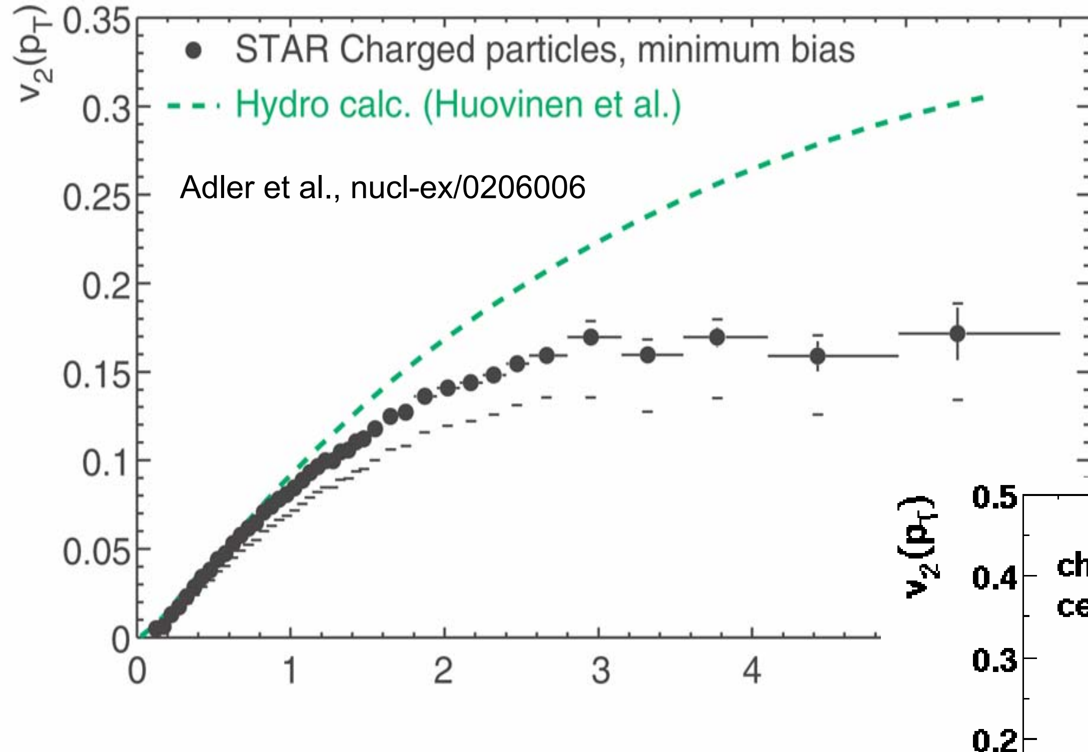
- Charged pions from TOF
- Neutral pions from EMCAL
- Charged pions from RICH+EMCAL

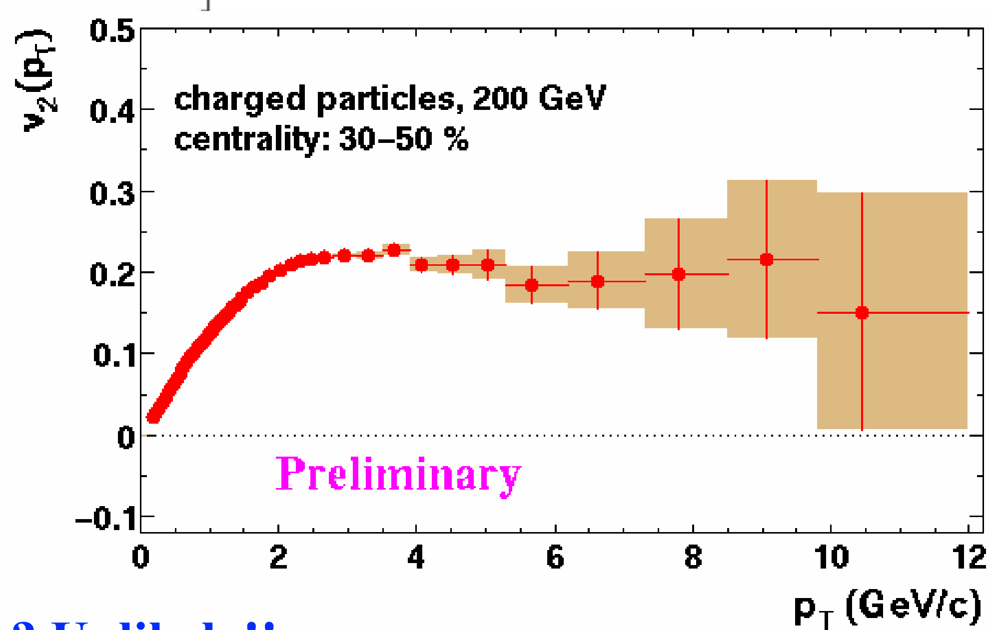


Cronin effect gone at $p_T \sim 8$ GeV/c

A puzzle at high p_T

Nu Xu





- Still flowing at p_T = 8 GeV/c? Unlikely!!