Jets at RHIC: How Do We Do It and What Have We Learned?

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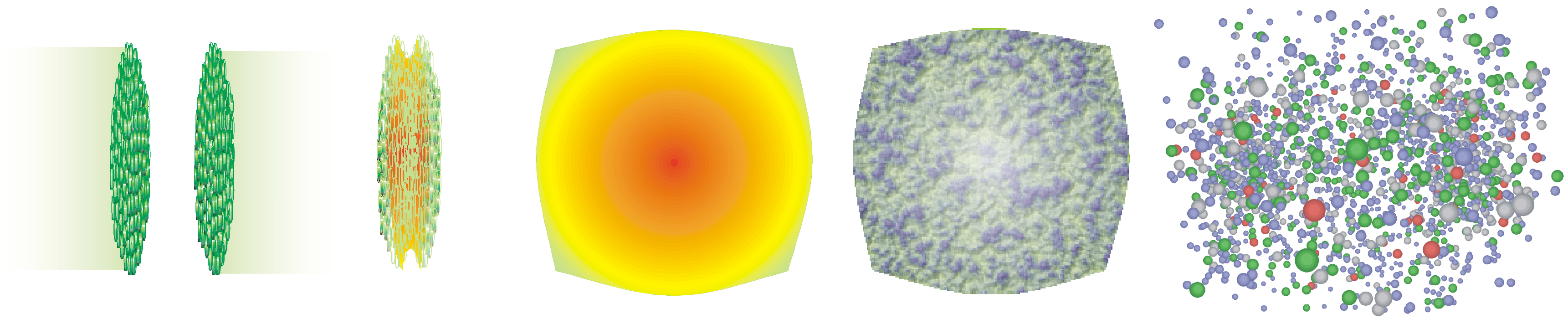
Understanding the Matter @ RHIC

- goal: use calibrated hard probes to understand, on a microscopic level, the produced matter
- challenge: these probes interact through full time evolution of the system

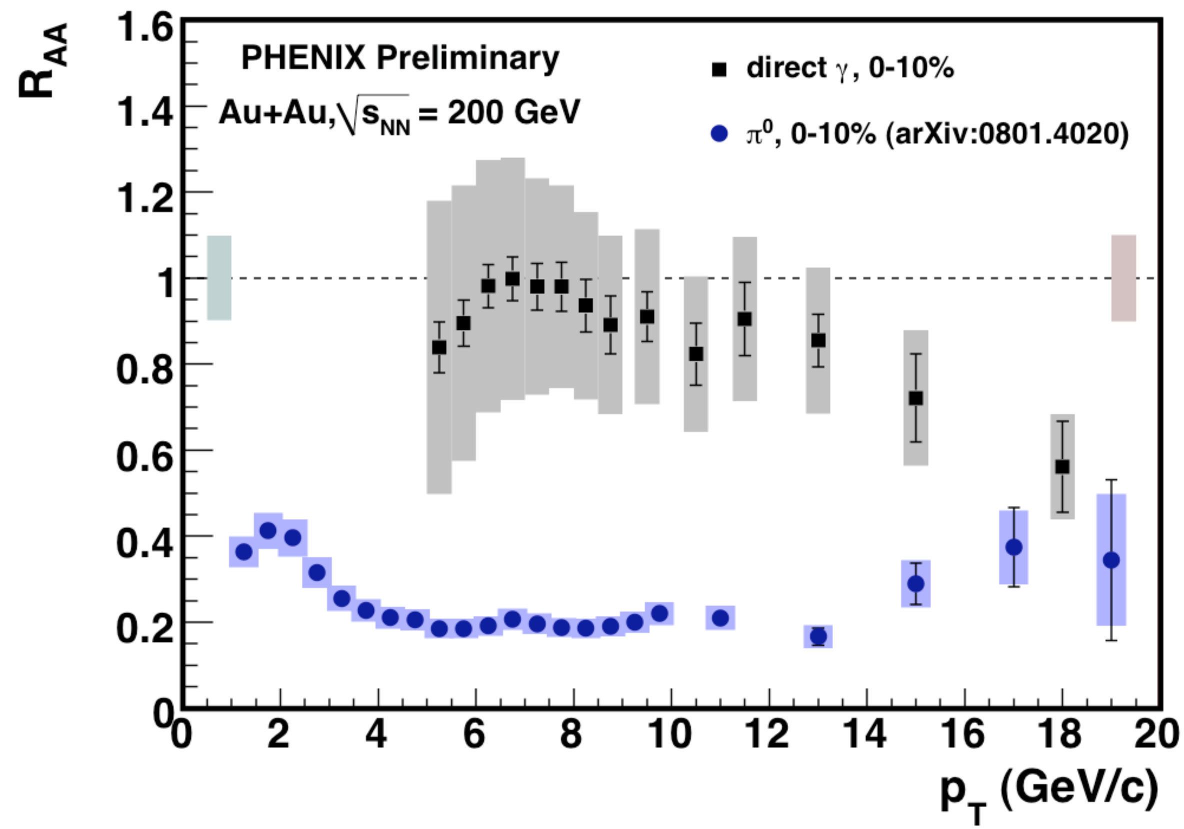


Energy Loss

$$R_{AA}(p_T) = \frac{\frac{1}{N_{evt}} \frac{d^2N^{AA}}{dp_T d\eta}}{\frac{\langle N_{coll} \rangle}{\sigma_{inel}^{pp}} \frac{d^2\sigma^{pp}}{dp_T d\eta}}$$

$R_{AA} = 1$

no nuclear effects



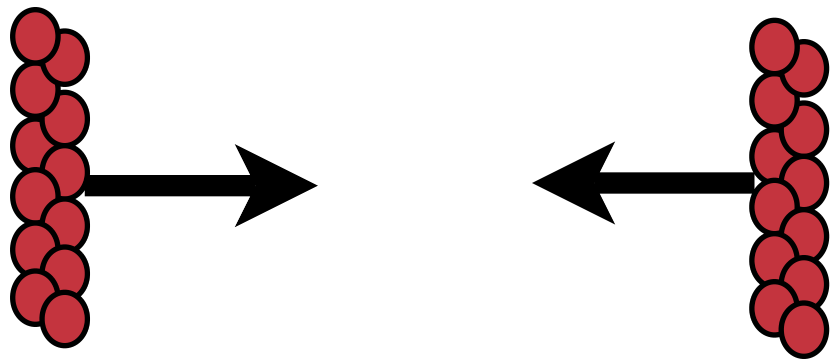
π^0: very large suppression → very opaque matter

where is the lost energy?

Classifying Collisions

- **impact parameter**: not measurable, disfavored for historical reasons
- **centrality**: fraction of the Au+Au cross section with a smaller impact parameter (0% centrality => b=0fm)
  - this is how data is classified for analysis
- **number of participating nucleons (Npart)**: how many nucleons from both Au nuclei interact
- **number of binary collisions (Ncoll)**: number of equivalent p+p collisions in the initial state, how we expect hard scattering to scale

Types of Collisions



central collision

b small

N_{part} ~ 2*A

N_{coll} large

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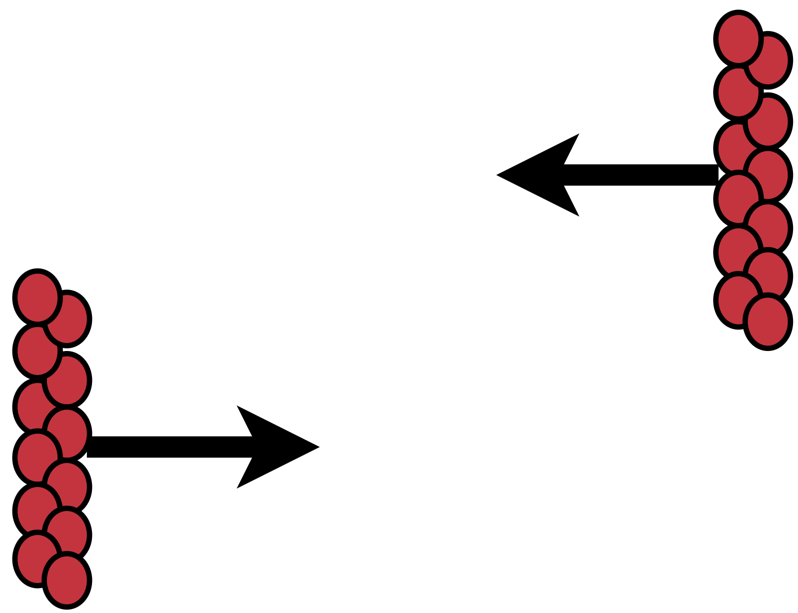
peripheral collision

b large

N_{part} small

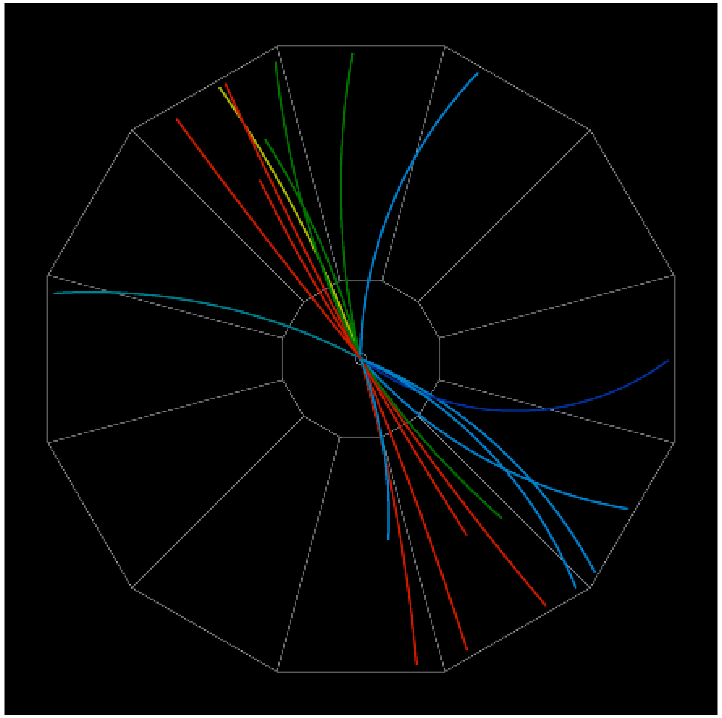
N_{coll} small



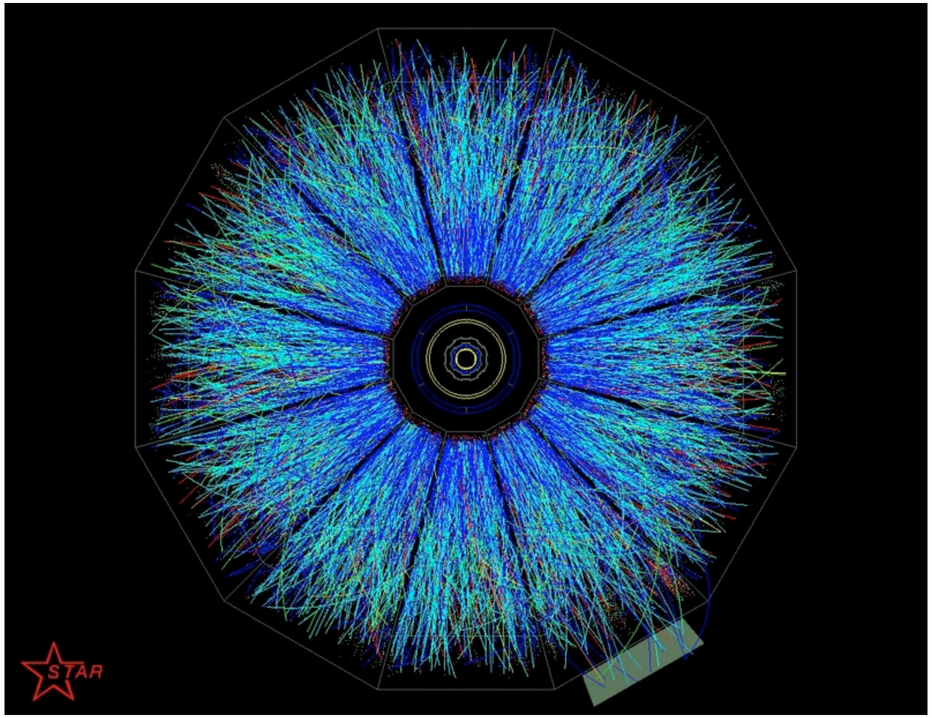
Anne M. Sickles, March 25, 2008

How Do We Find Jets?

find this...

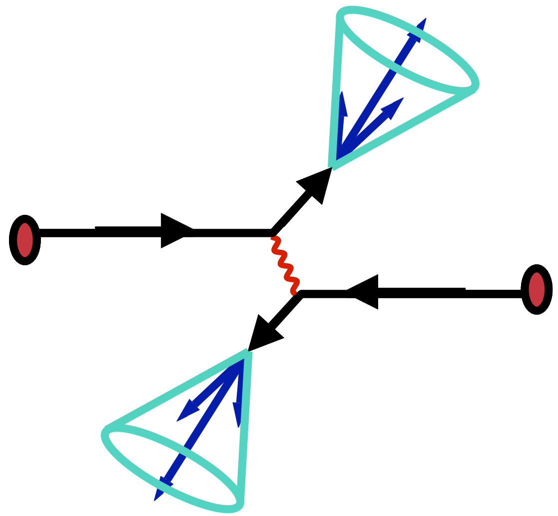


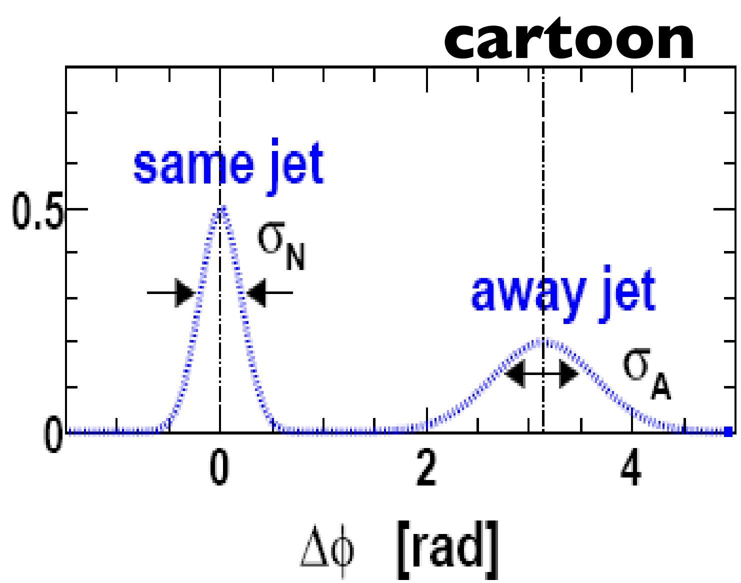
in this



- statistically: two particle correlations
- problem: huge background from uncorrelated particles

2 particle correlations

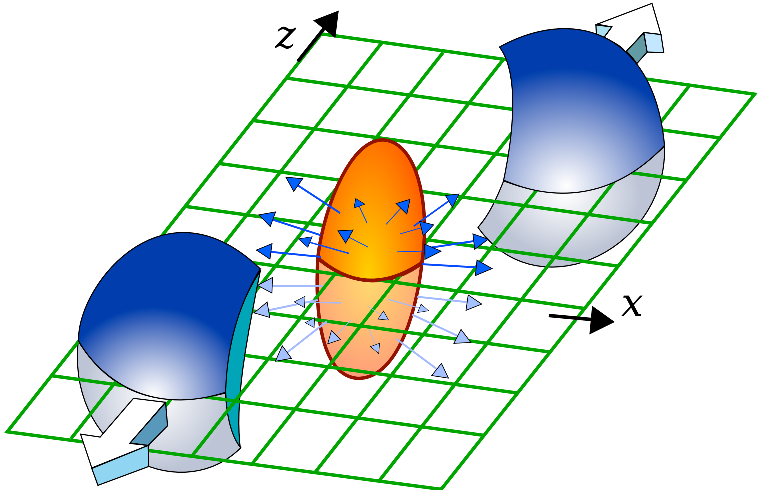




- "trigger" on high p_T particles to find a hard scattering
- count lower p_T particles to study medium interactions
- comparison of Au+Au and p+p allows measurements of matter's effect on jet properties

Δφ: azimuthal angle around beam direction

First Problem: v_2



Reaction Plane

- if angle of particles w/respect to reaction plane measured:

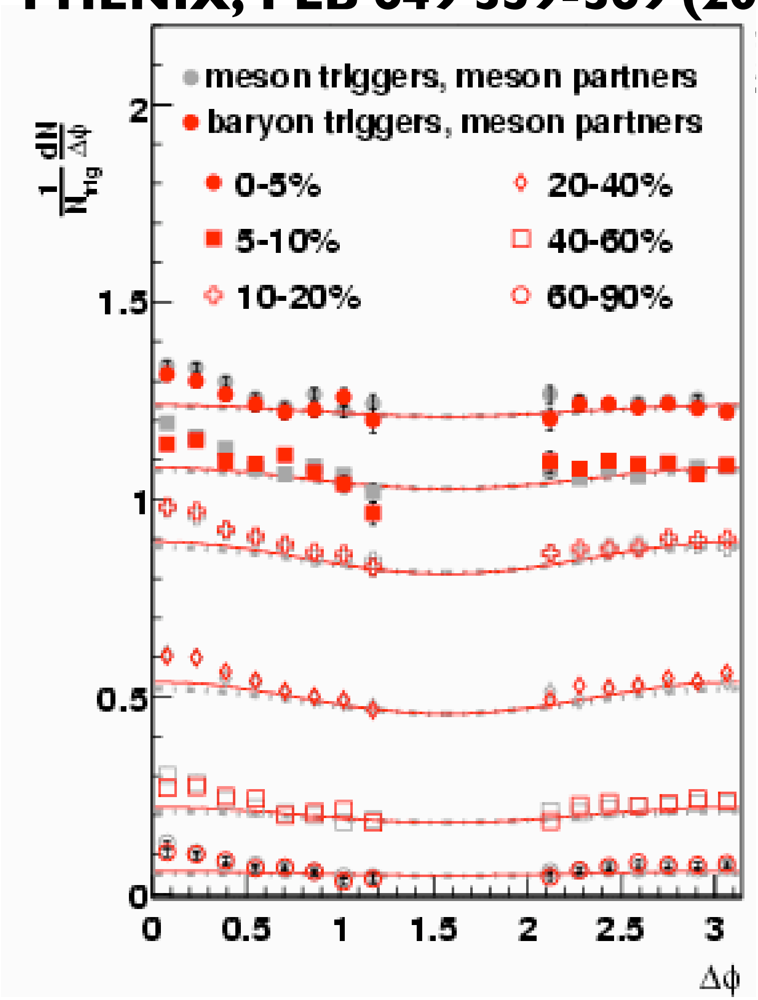
$$\frac{dN}{d(\Psi - \phi)} \propto 1 + 2v_2 \cos(\Psi - \phi) + \ldots$$

- if the angle of two particles w/respect to each other is measured:

$$\frac{dN}{d\Delta\phi} \propto 1 + 2v_{2,trig}v_{2,part} \cos(\Delta\phi)$$

Big Problem: The Background from Other Stuff in the Event

PHENIX, PLB 649 359-369 (2007)



- S/B ~1% in central collisions
- 1st order approximation:
  - background rate product of the singles rate
- however, real events have an additional physics correlation, the real impact parameter
  - we can only classify events with a finite resolution

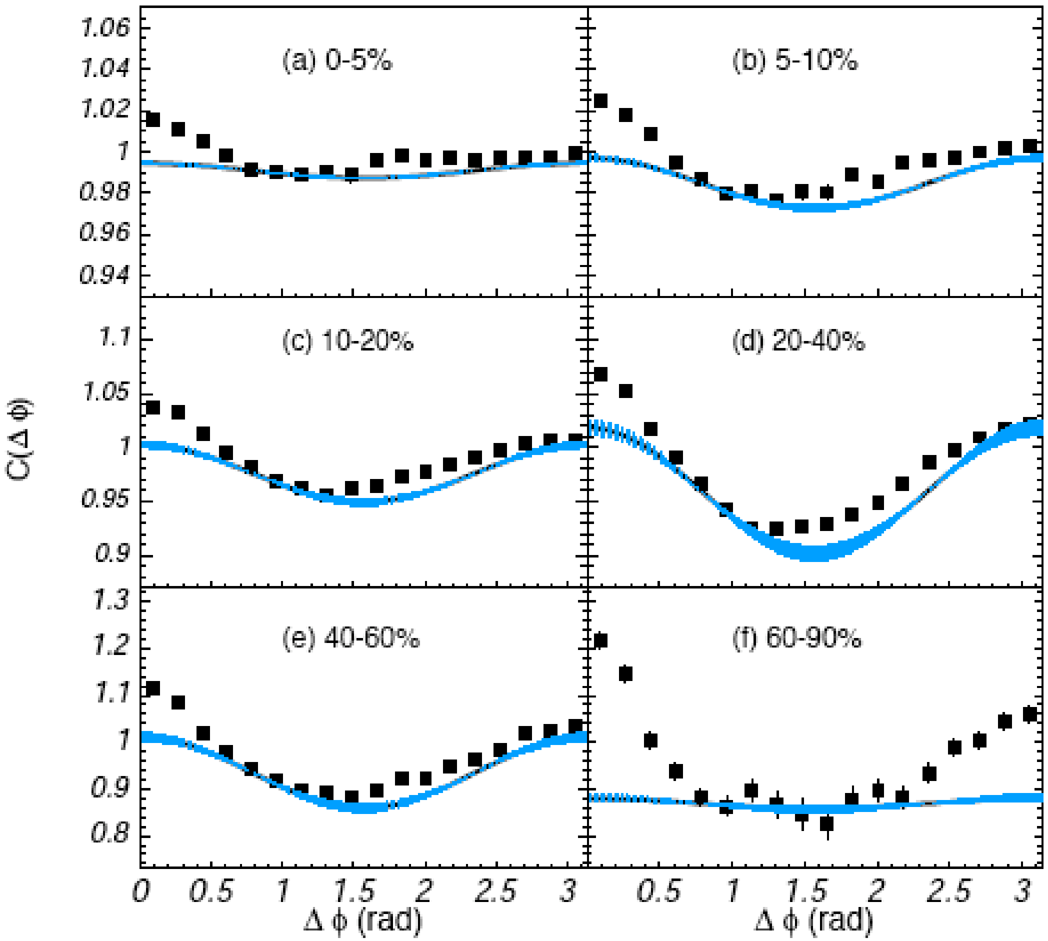
Modeling the Correlations

- We use a model of the distributions of nucleons in the nuclei
  - it's the same one that we us to calculate the number of equivalent p+p collisions for R_{AA}, so we think it's robust
  - in this Monte Carlo we calculate the size of the centrality correlations, based on measurements of particle production as a function of centrality and use that to correct the data
- in central collisions correction is ~0.2%
  - but, if the S/B is 1% it's crucial

more detail: A. Sickles, et al, nucl-ex/0702007

Other Method of Determinig the Background

- Assume something about the signal shape:
  - fit Gaussian jet peaks
  - assume the jet(ΔΦ) has signal free region
    - a lower limit on jet signal
- to the level of our errors, far, these methods agree



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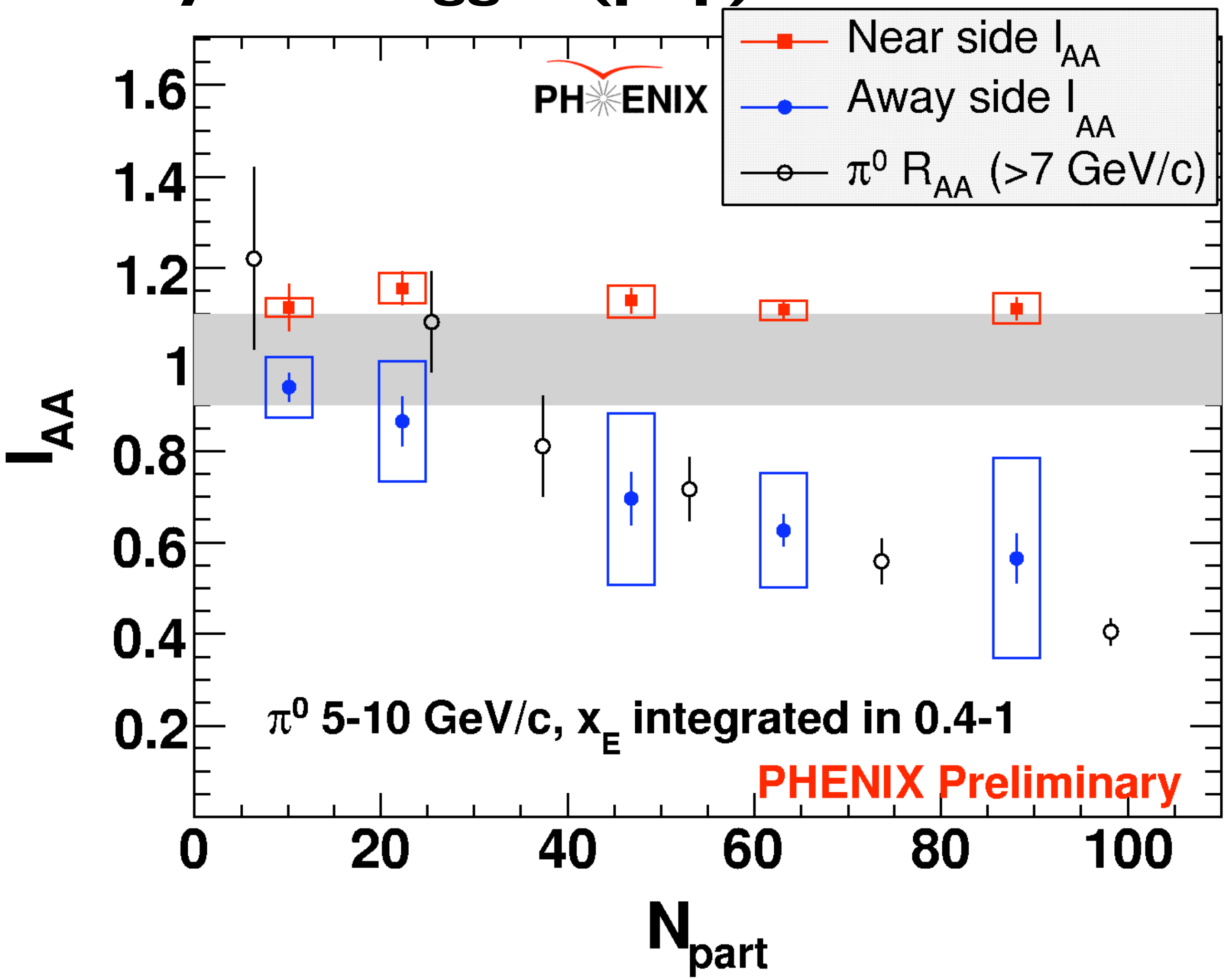
Can We See the Radiation?

$$I_{AA} = \frac{\text{yield/trigger (Cu+Cu)}}{\text{yield/trigger (p+p)}}$$

Cu+Cu, 200GeV

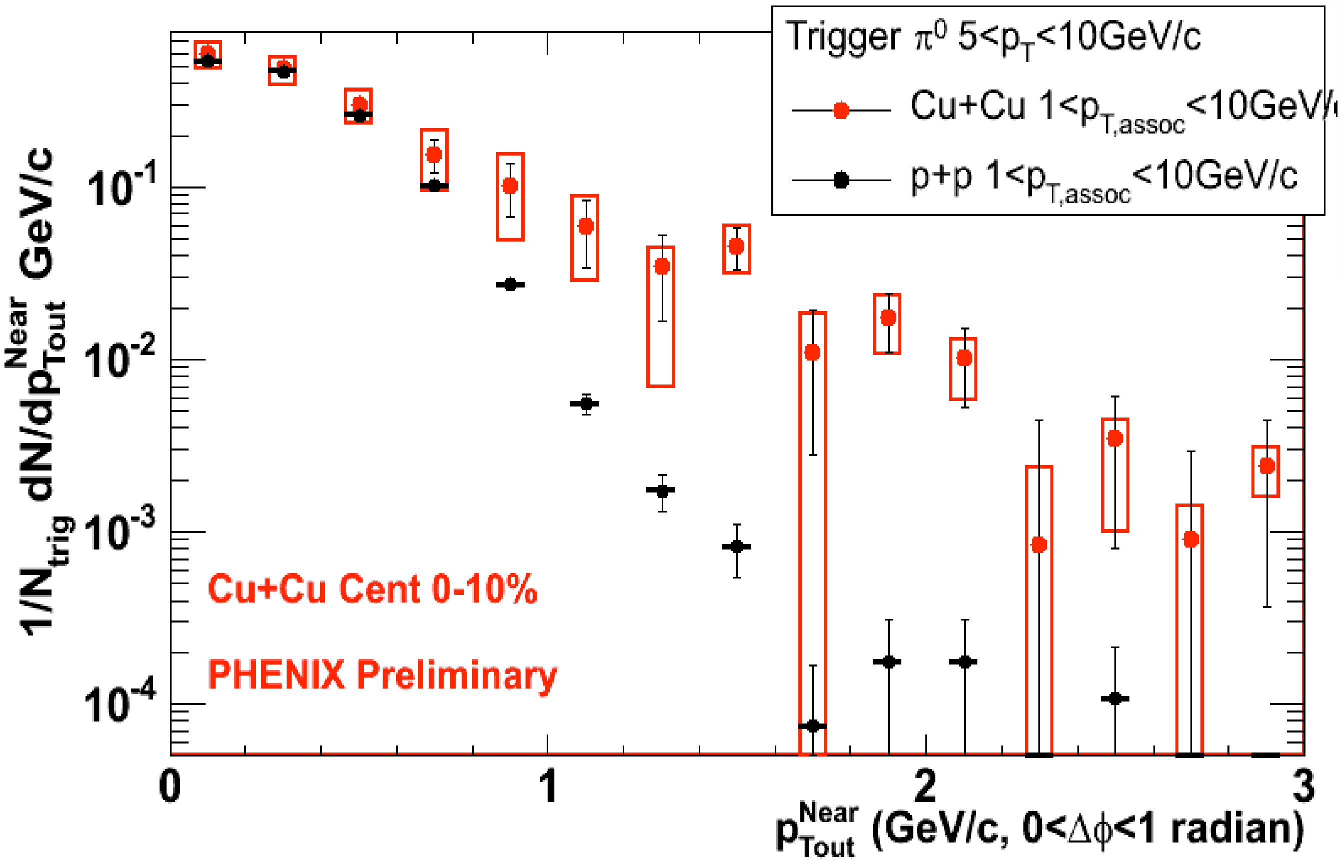


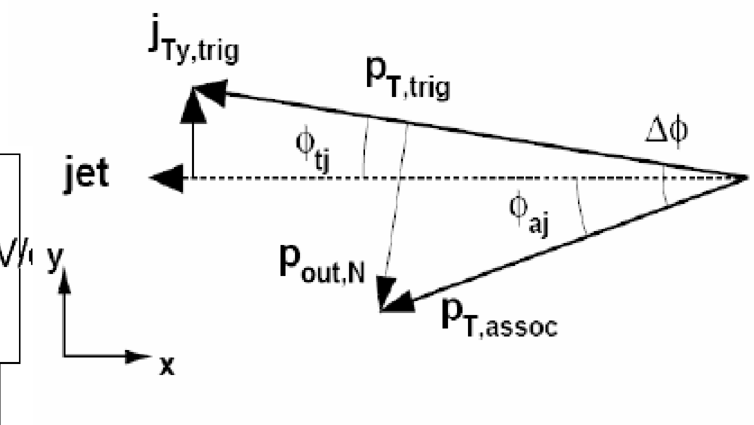
conditional yields constant: vacuum fragmentation

single particle suppression: energy loss

J. Jia, QM2006

Can We See the Radiation?





$p_{Tout} = p_{T,assoc} \sin(\Delta\phi)$

much harder distribution in Cu+Cu

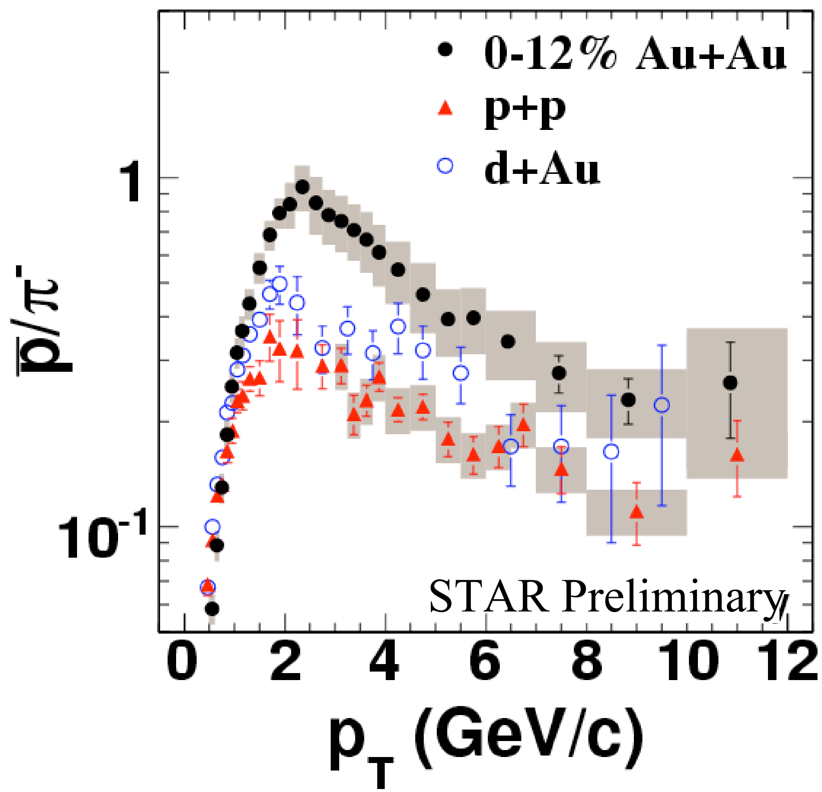
energy lost in the medium!

H. Pei, SQM2007

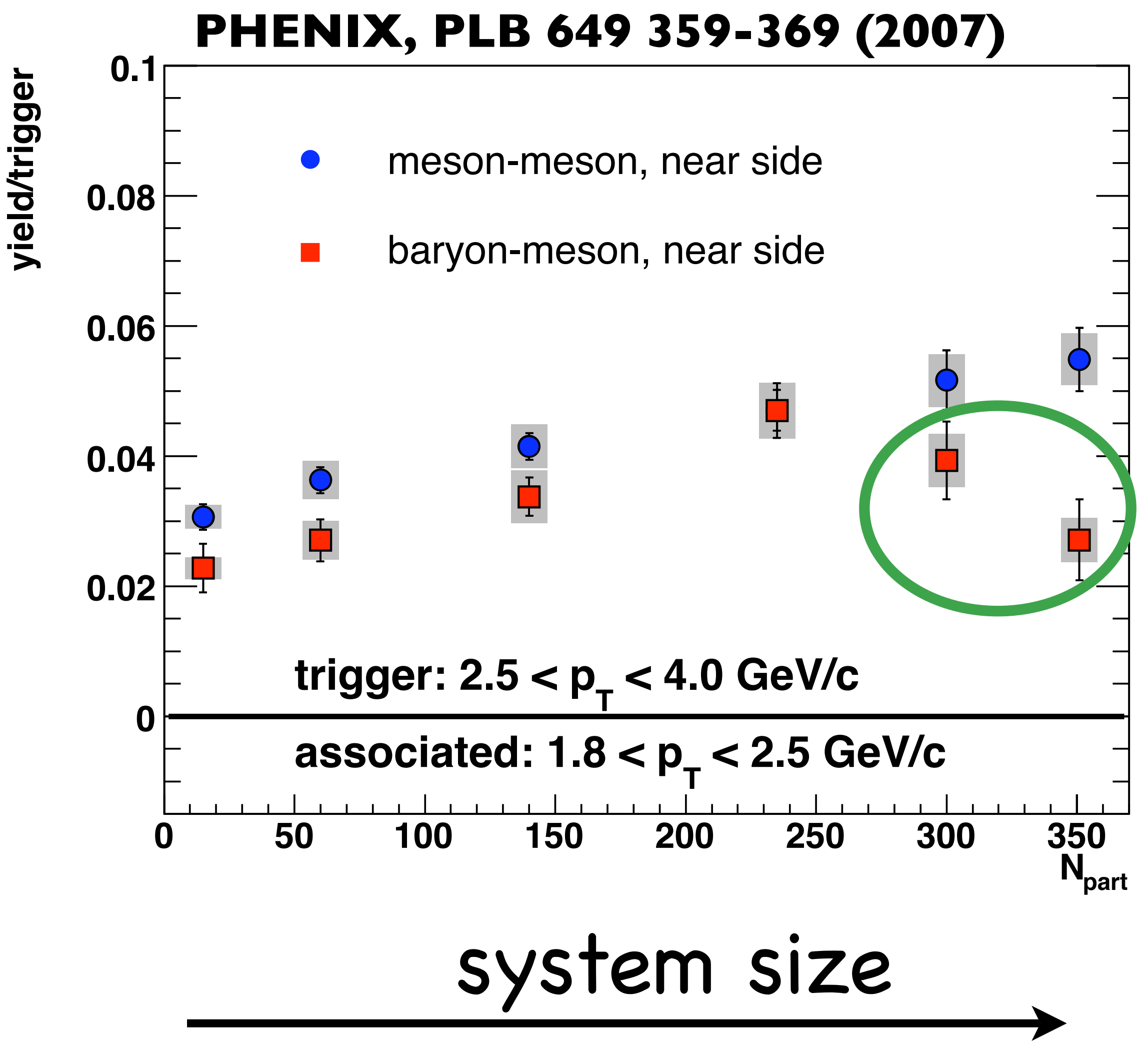
Protons & Anti-Protons

- dramatic changes to particle composition at moderate p_T
  - QCD higher twist effects
  - sensitivity to properties of the matter

Anti-Baryon to meson ratio



where do protons come from?



increase → correlated lost energy

decrease only in the most central: large system allows through only color transparent protons (?)

Correlations Between Baryons

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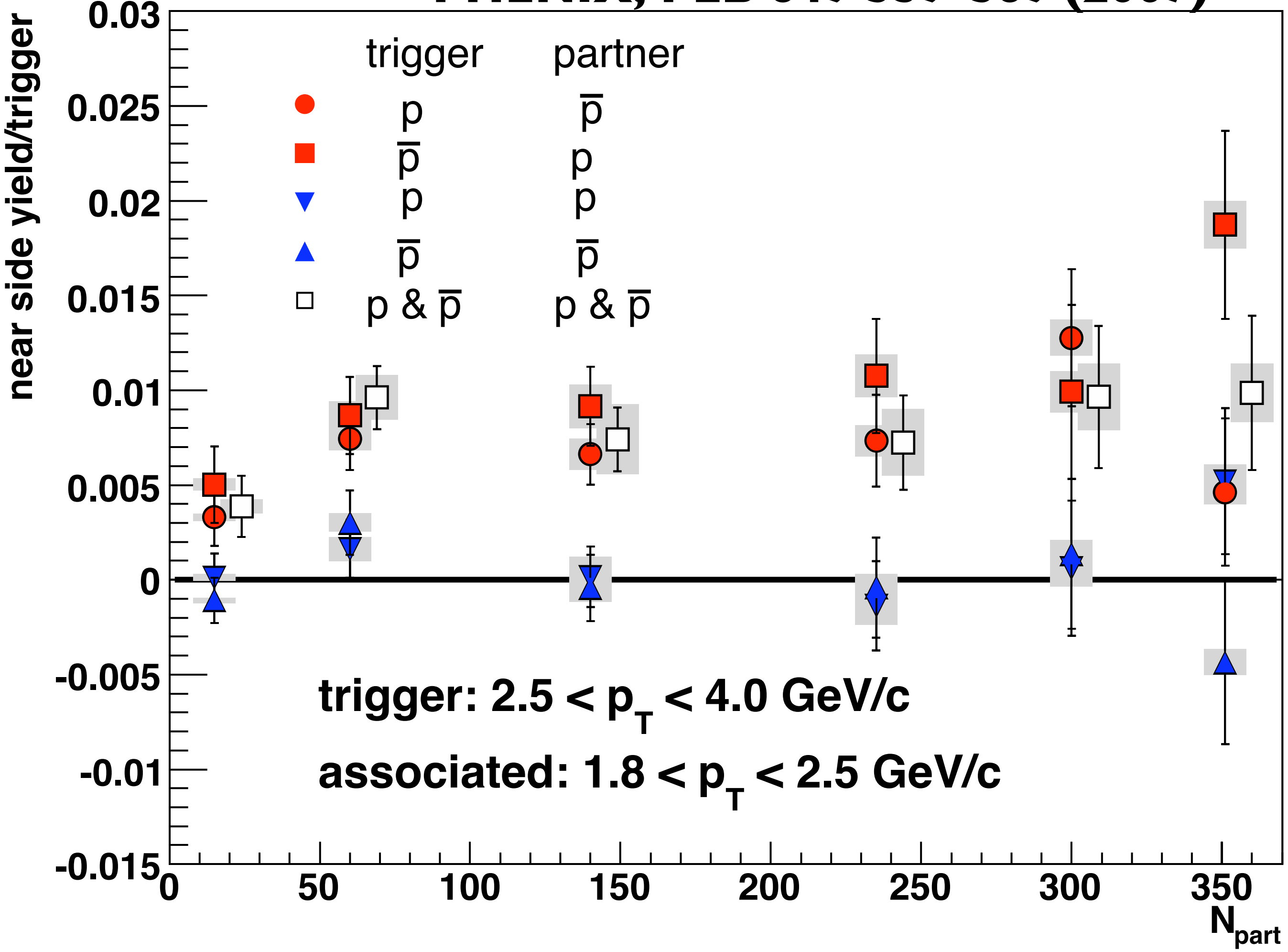
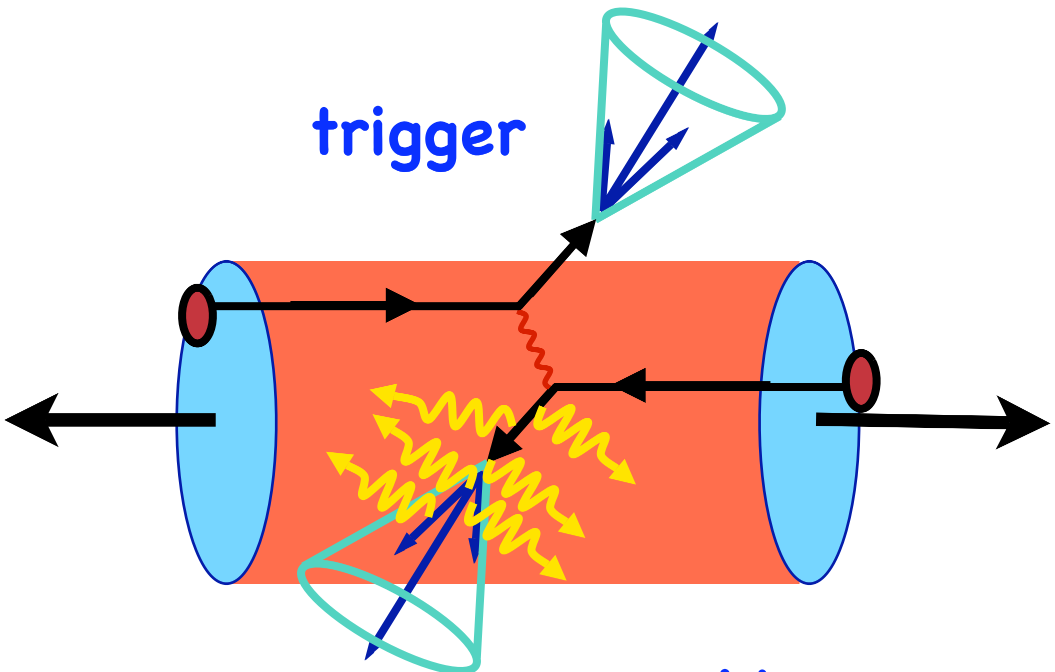


opposite sign pairs: CORRELATED

same sign pairs: NO CORRELATION

- we expect to conserve baryon number, of course
- not clear what these data are telling us
  - more statistics would help, especially for the most central collisions

Surface Bias



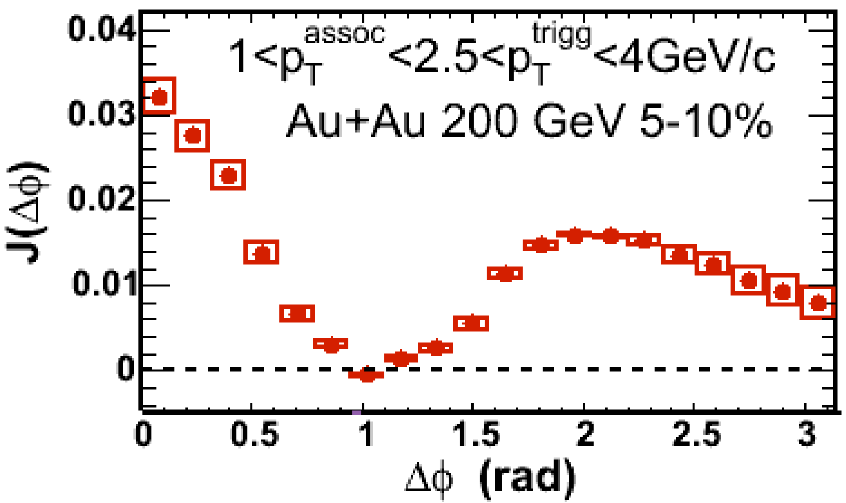
- because of the large energy loss the trigger is biased toward small matter path lengths

- then the away side biased toward long path lengths in the matter

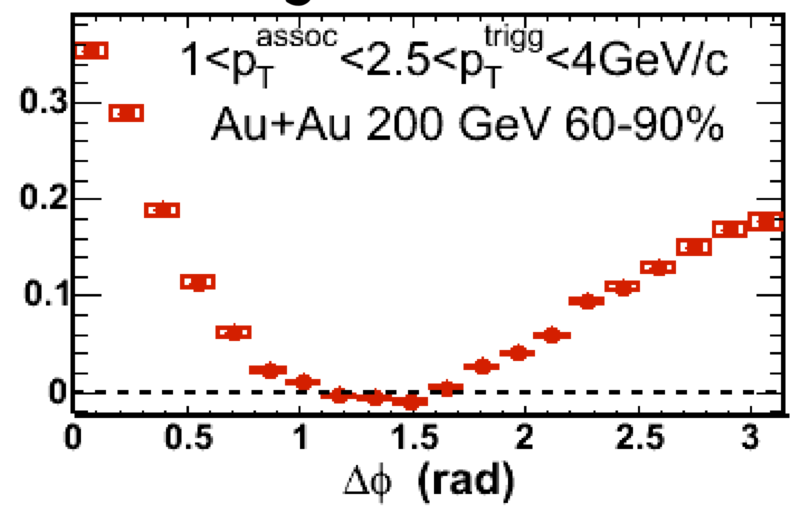
  - maximal interactions with the matter

Conical Structure?

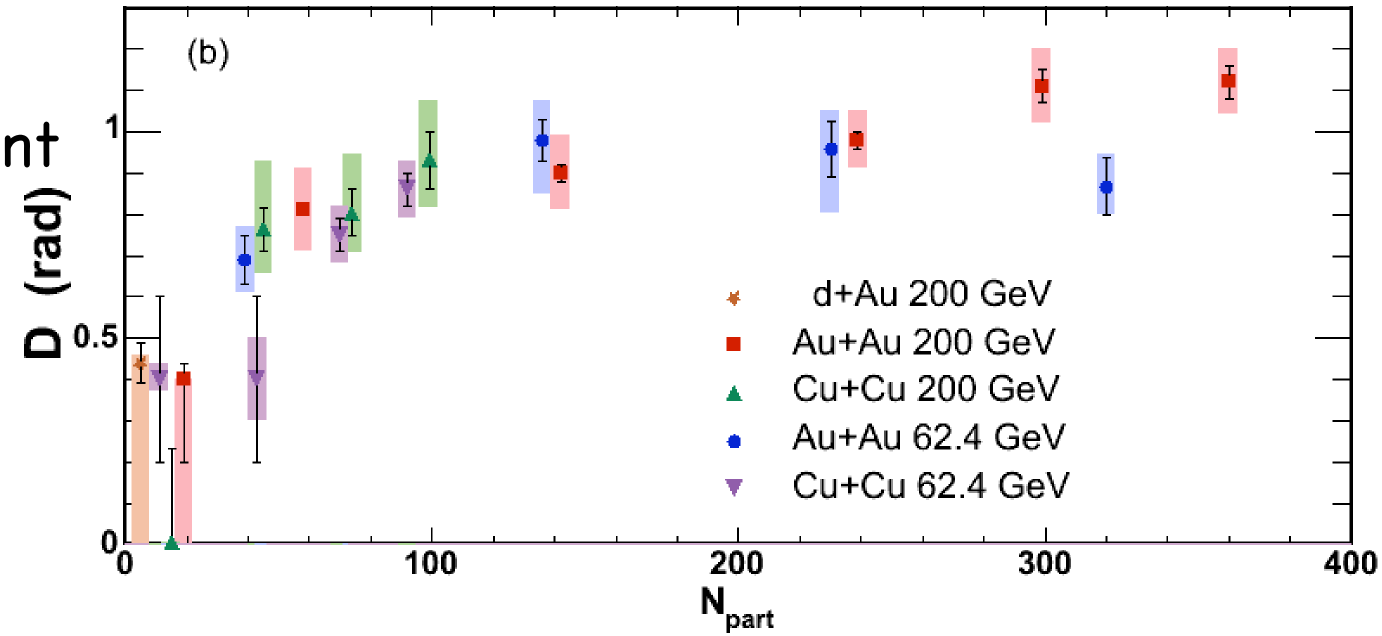
Head On Au+Au: Peak ~ π-1



Glancing Au+Au: Peak ~ π

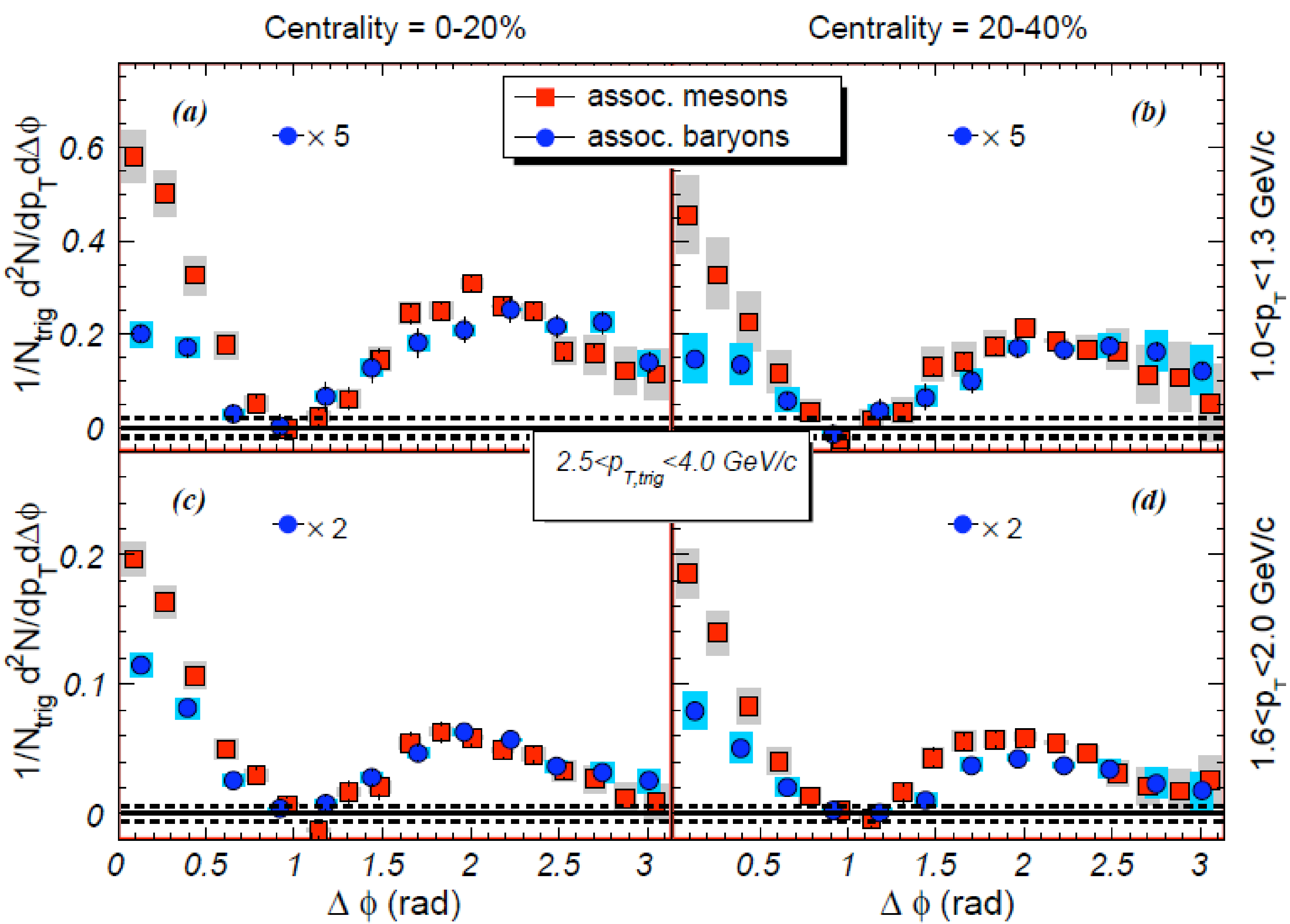


Peak Displacement From π



PHENIX, PRL 98 232302, 2007

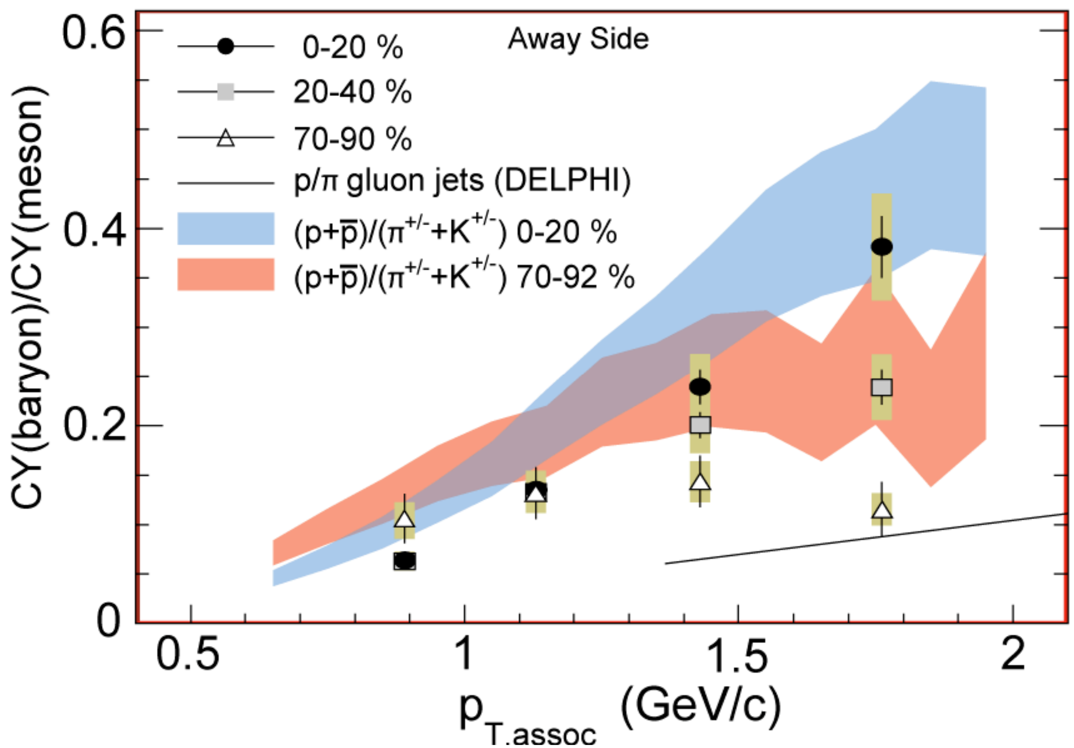
Particle Composition in the Cone?



PHENIX, arxiv:0712.3033[nucl-ex]

Cone & Bulk Matter Have Similar Particle Composition

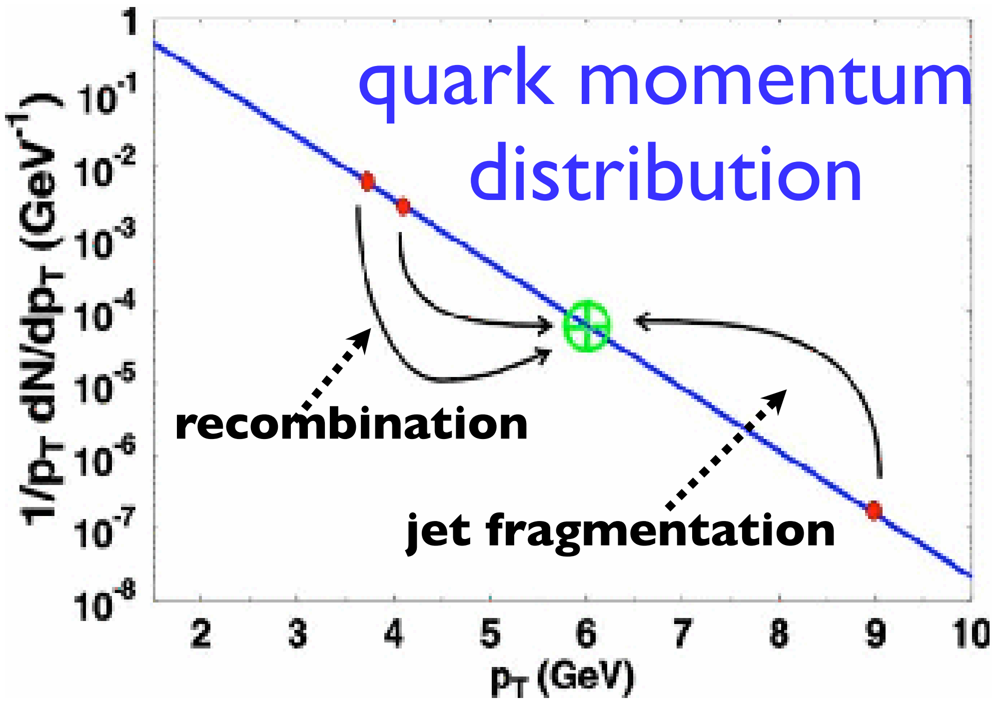
PHENIX, arxiv:0712.3033[nucl-ex]



- Away side hadronizes with the bulk matter
- Evidence that lost jet energy is thermalized?

coalescence in the final state

the idea: quarks from the matter, close together in phase space can combine to form final state hadrons



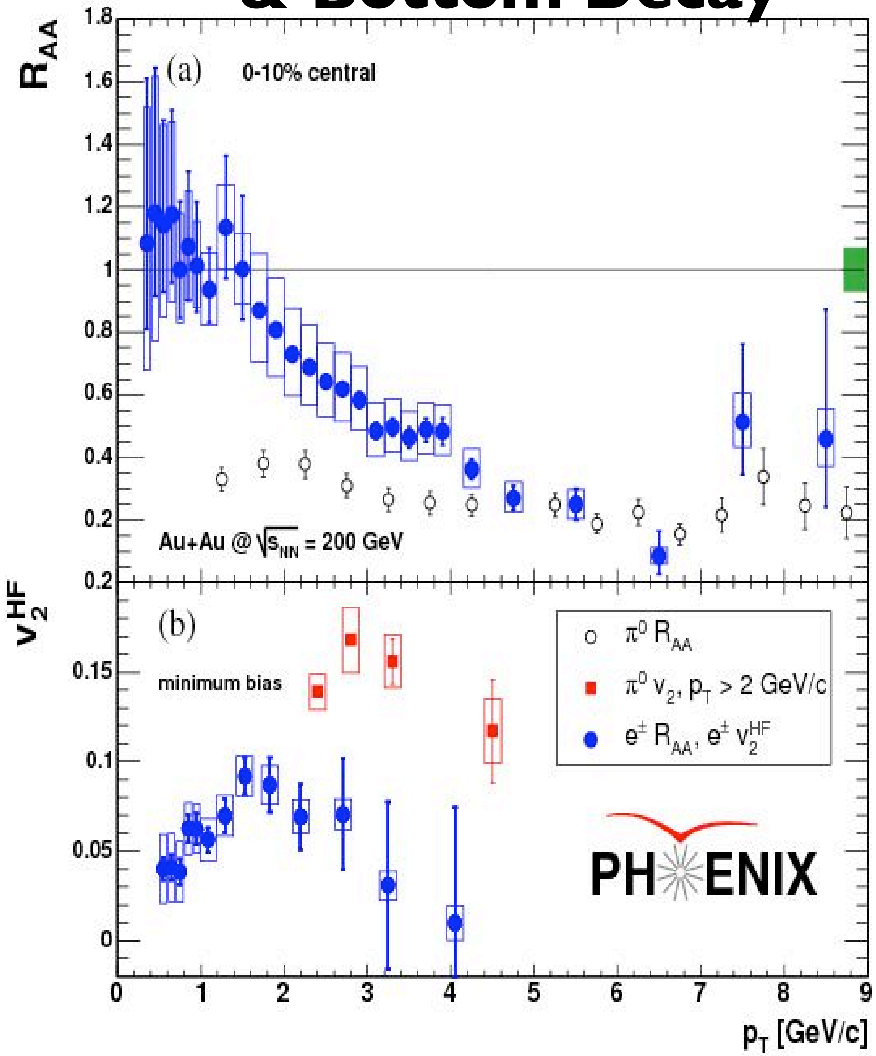
- favors baryons as long as the quark p_T spectrum is exponential
  - at high p_T, quark spectrum will develop power law behavior and fragmentation should dominate
- issues: gluons, energy & momentum conservation, entropy...

review: R. Fries J.Phys.G30:S853-S860,2004

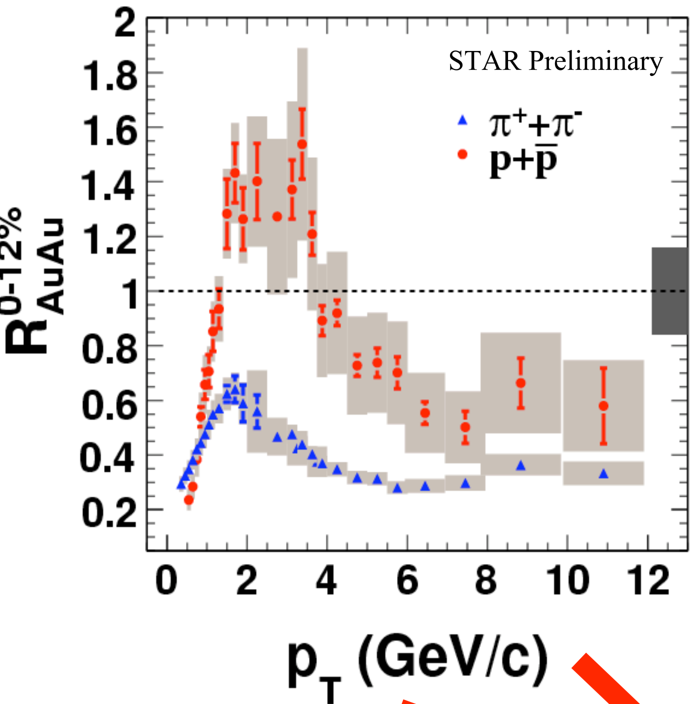
Where Next?

- charm & bottom suppressed & flow with the matter, despite their large mass
- there are a lot of exotic ideas to explain this
  - coalescence, hadrons formed⇔dissociated in the matter,...
- but we don't know anything about the correlations
- how does the matter respond?

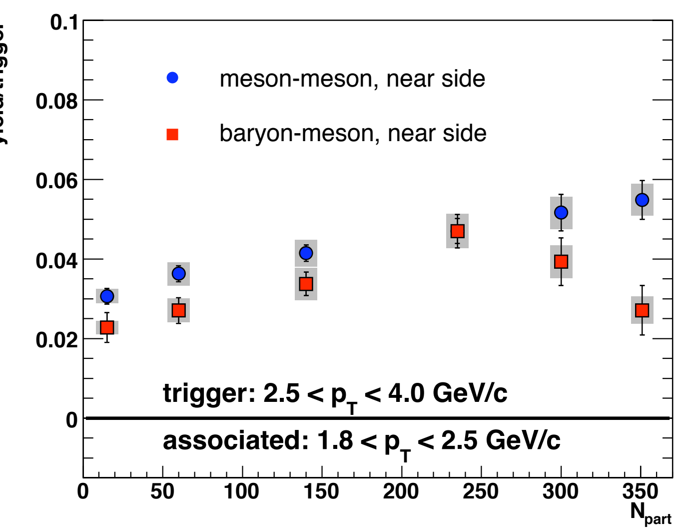
Electrons from Charm & Bottom Decay



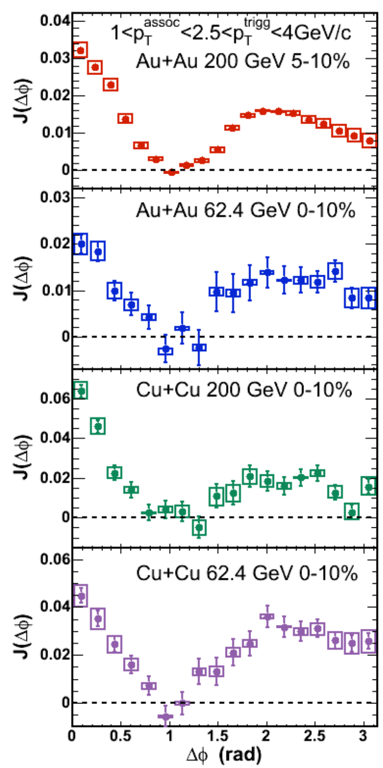
An Analogy



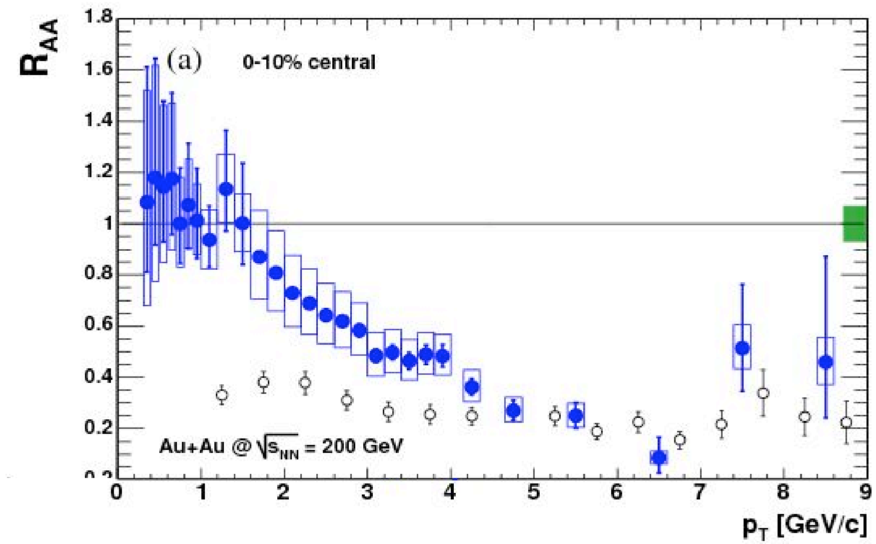
STAR Preliminary
$\pi^+ + \pi^-$
$p + \bar{p}$
$R_{AuAu}^{0-12\%}$
p_T (GeV/c)



meson-meson, near side
baryon-meson, near side
trigger: 2.5 < p_T < 4.0 GeV/c
associated: 1.8 < p_T < 2.5 GeV/c
N_{part}



$1 < p_T^{assoc} < 2.5 < p_T^{trigg} < 4$ GeV/c
Au+Au 200 GeV 5-10%
Au+Au 62.4 GeV 0-10%
Cu+Cu 200 GeV 0-10%
Cu+Cu 62.4 GeV 0-10%
J(Δφ)
Δφ (rad)



R_{AA}
(a) 0-10% central
Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV
p_T [GeV/c]

??

Goal: Tomography

- we want to use hard probes to understand the microscopic properties of the matter
- right now we see large effects depending on hadron type, this means that hadron formation is influenced by the matter, or it's remnants, either:
  - providing information about the matter itself
  - or, hiding that information behind some relatively uninteresting hadronic processes
  - either way we have to figure it out experimentally

Path Forward

- Qualitatively new measurements with charm and bottom correlations
  - a void of measurements, so any result aids our understanding of how heavy quarks interact with the matter & how that's different than how light quarks interact
- More quantitative measurements with light quarks:
  - role of hadronization needs to be understood, to disentangle from hot matter effects--this is an experimental issue