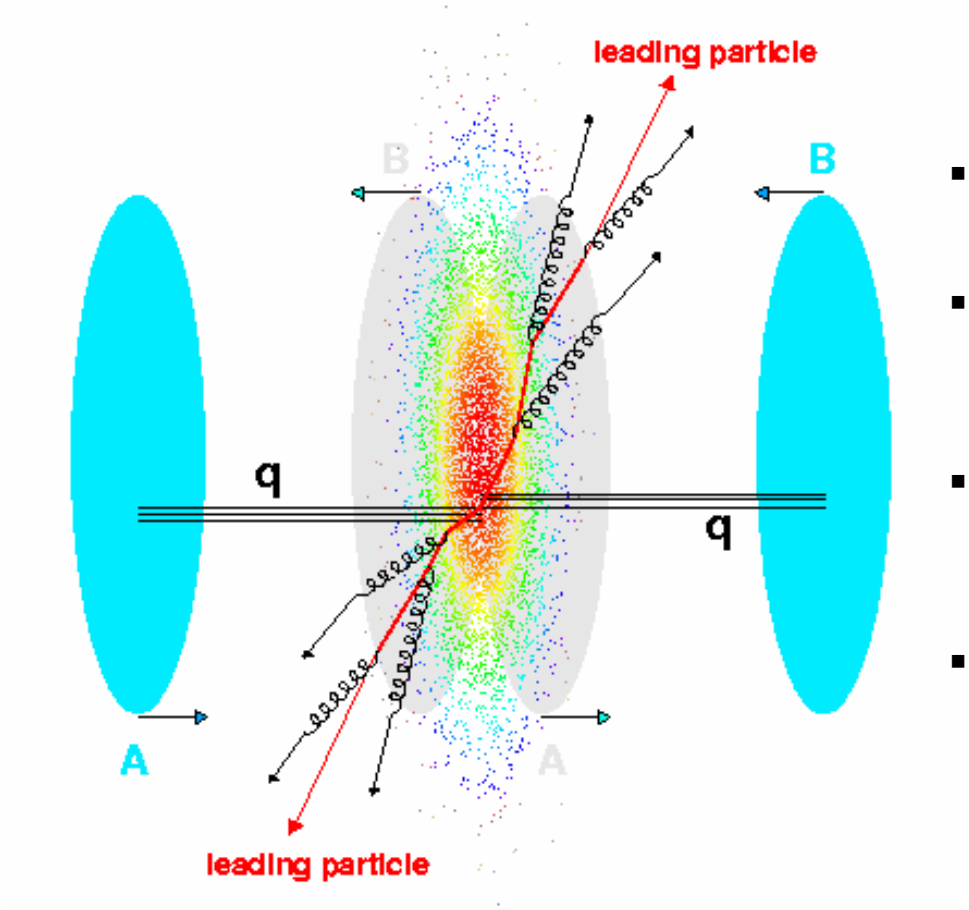
Hard Scattering at RHIC:
Where We've Been, Where We're Going

John Lajoie
Iowa State University

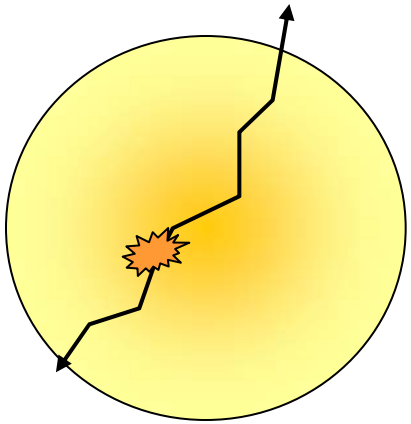
- Hard scattering as a probe of dense matter
- Results from RHIC Run-1 and Run-2
  - suppression of high-p_T spectra
  - particle correlations
- Future directions

Hard Scattering in RHI Collisions

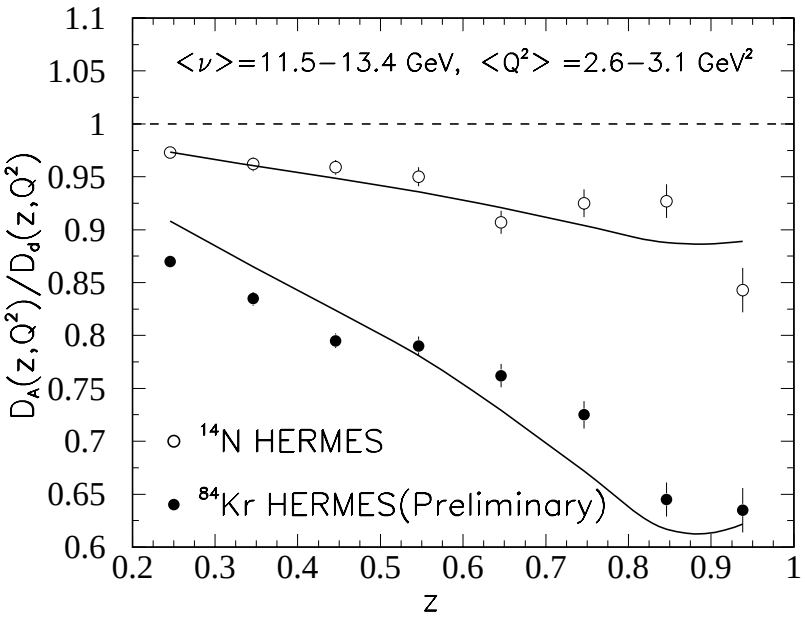


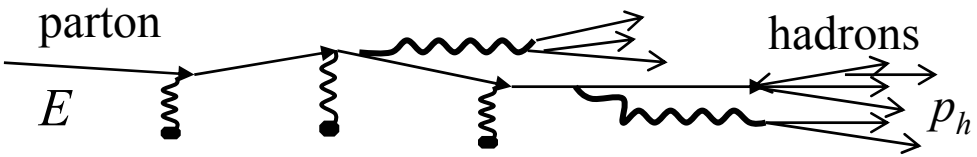
- Produced early in the collision (τ<1fm/c)
- Evolution is sensitive to QCD medium, primarily through energy loss
- Not possible to observe jets directly in RHI collisions – large overall particle density
- Identify jets through leading particles and correlations.

Parton Energy Loss



E. Wang and X.N. Wang, hep-ph/0202105



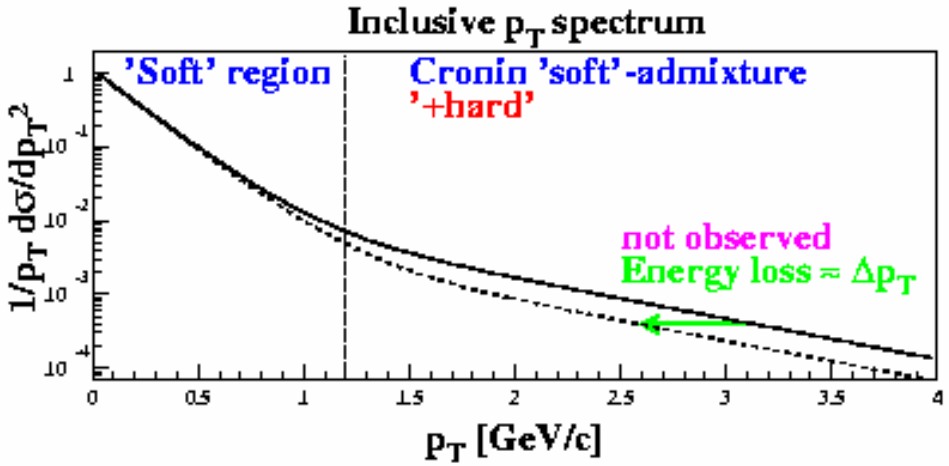


Energy loss in cold nuclear matter (HERMES data):

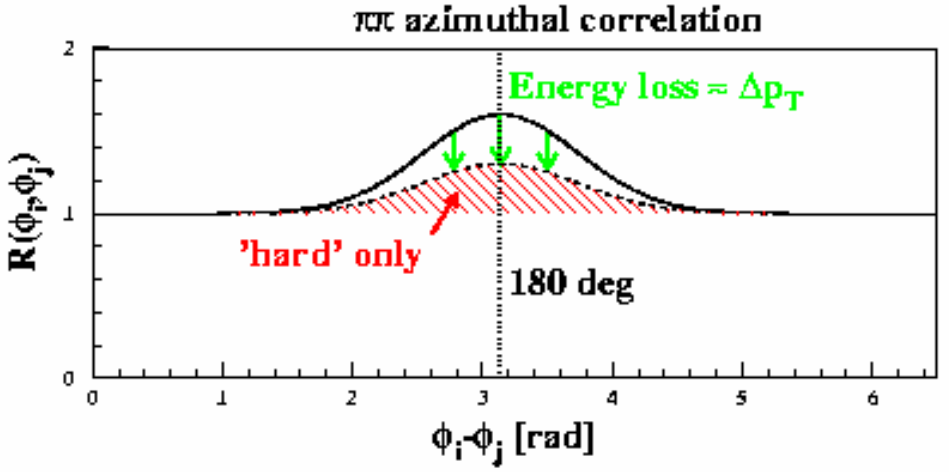
$$\left(\frac{dE}{dx}\right) \approx 0.5\, GeV / fm$$

Jet Quenching Signals

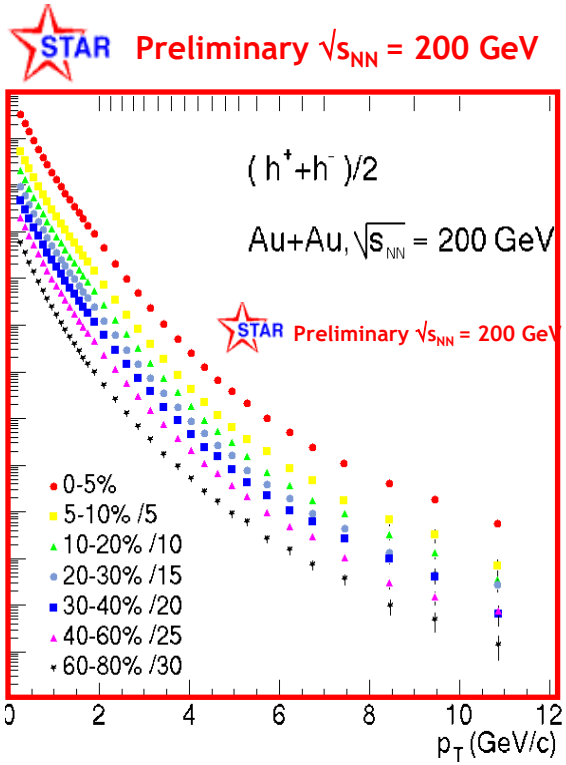
- Energy loss will modify the high-p_T spectra of produced particles (compared to pp)

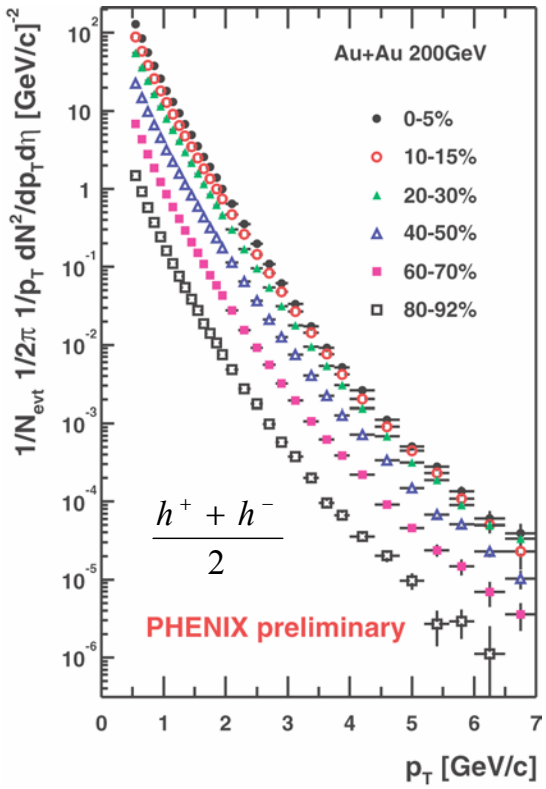


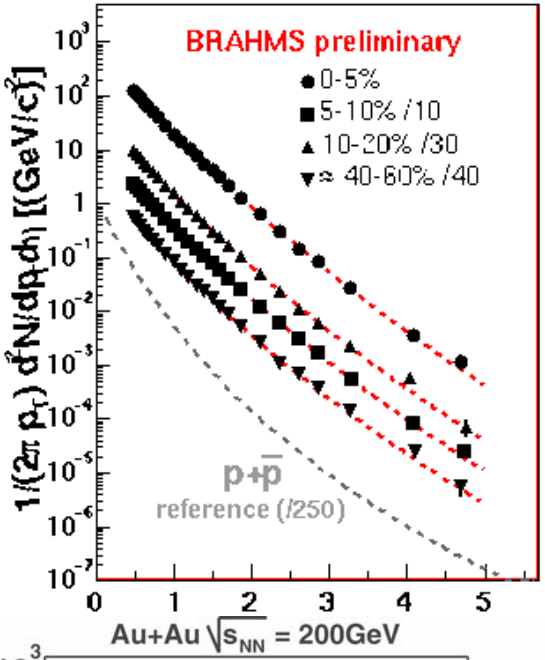
- Angular correlations between particles will show a suppression of the jet signal compared to pp collisions.

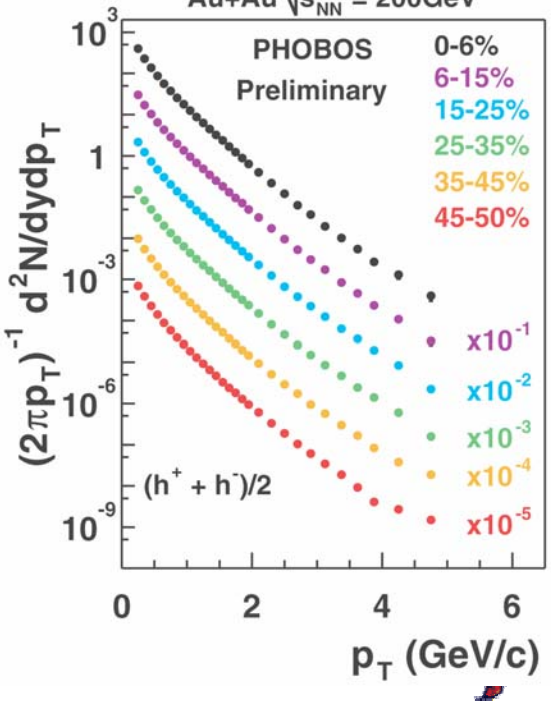


Charged Hadron Spectra



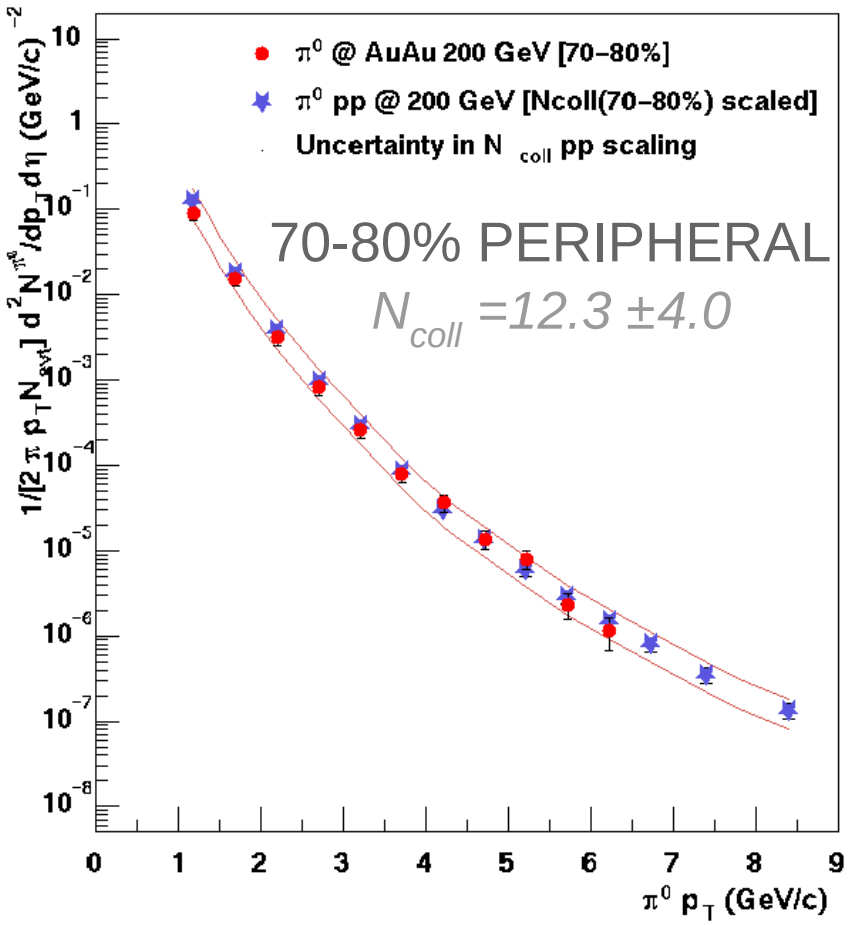


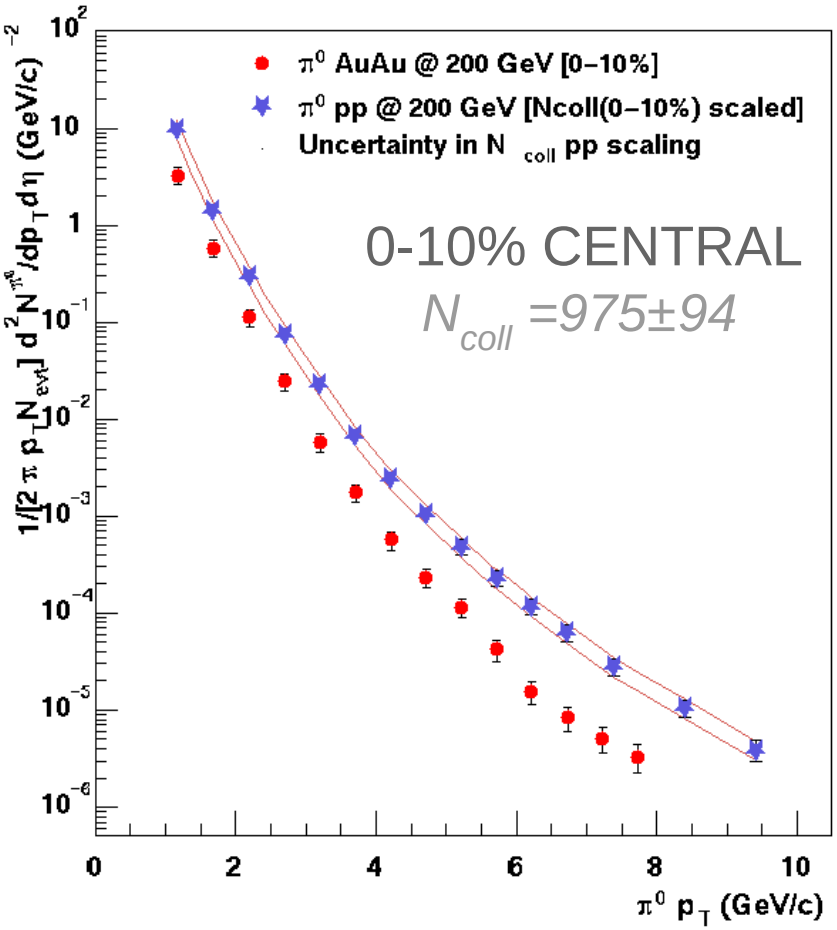




π^0 Spectra

PHENIX Preliminary



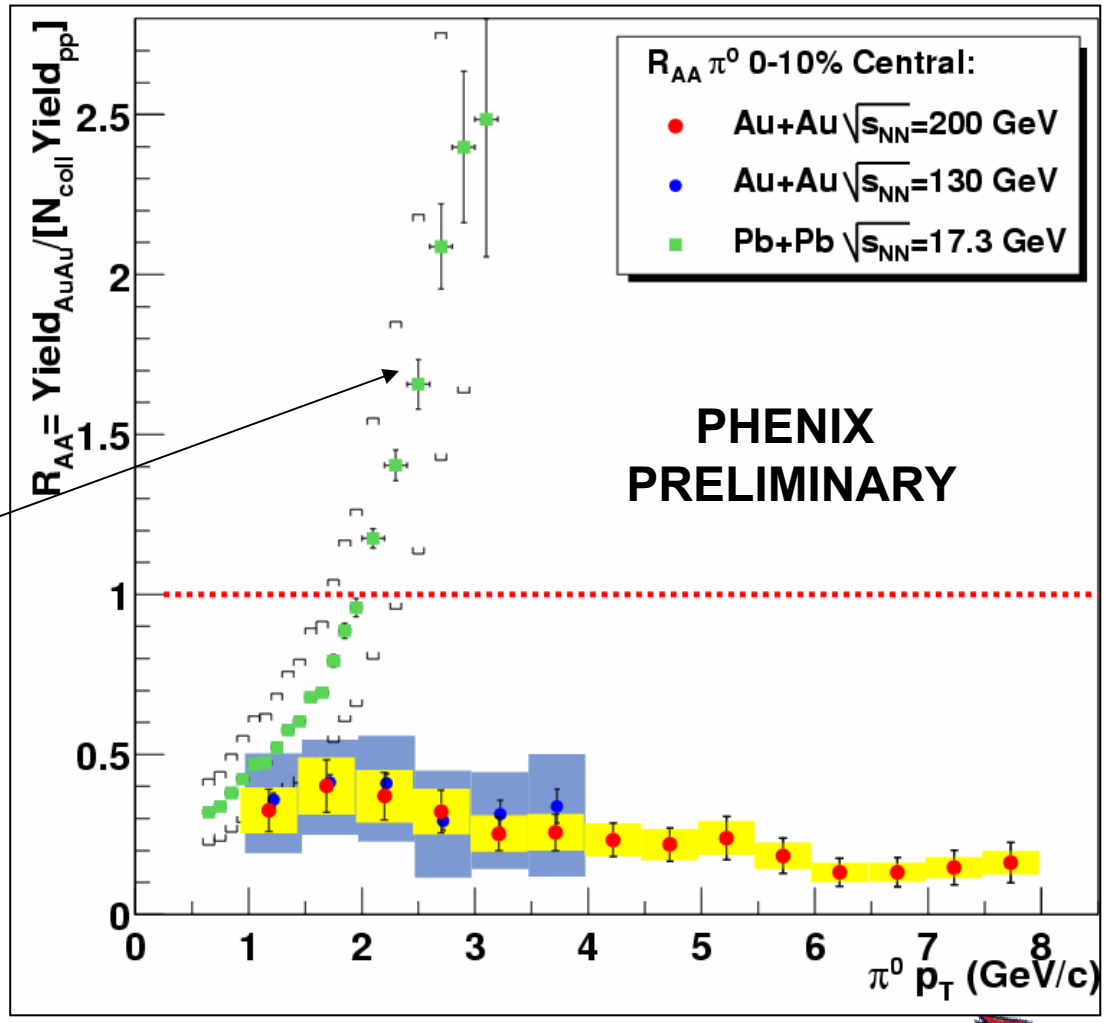


Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{1/N_{events}\, d^2N^{AA}/dp_T d\eta}{\langle N_{binary}\rangle (d^2\sigma_{pp}/dp_T d\eta / \sigma^{pp}_{inelastic})} =$$

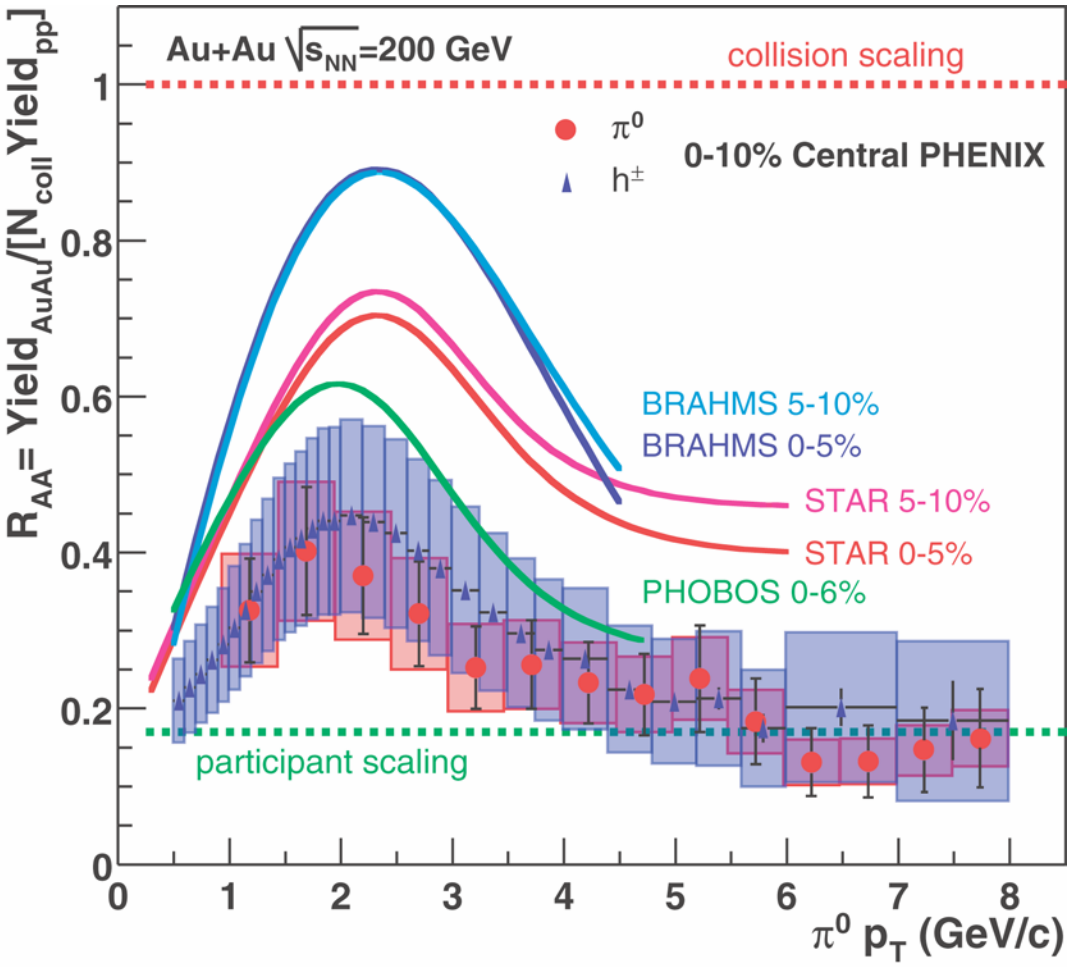
$$\frac{Yield_{central}/\langle N_{binary}\rangle_{central}}{Yield_{pp}}$$

"Cronin Effect" due to initial state parton scattering.



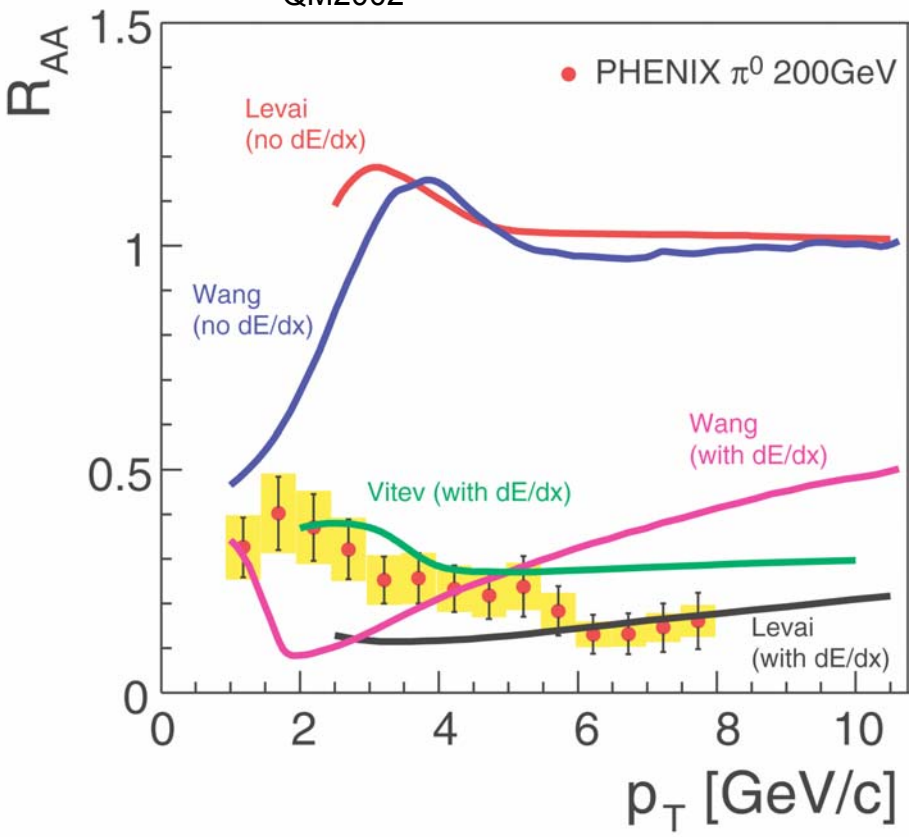
Combined Suppression Results

- All RHIC experiments show suppression, details remain to be worked out.
- PHENIX uses pp reference; STAR, BRAHMS and PHOBOS use UA1 reference

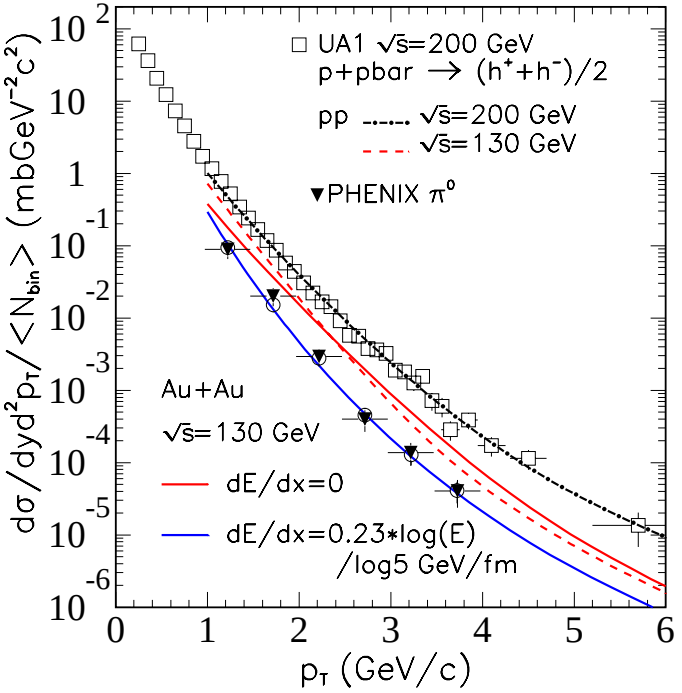


Suppression - Theory

- P. Levai, Nucl.Phys.A698 (2002) 631
- X.N. Wang, Phys.Rev.C61 (2000) 064910
- I. Vitev, QM2002



E. Wang and X.N. Wang, hep-ph/0202105

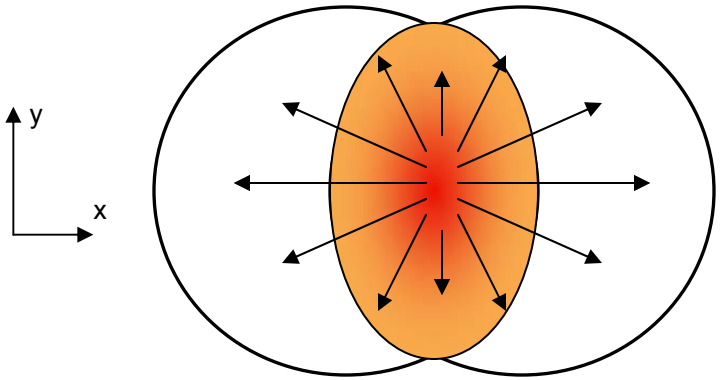


$$\left(\frac{dE}{dx}\right) \approx 7.3\,GeV/fm$$

15 times that in cold nuclear matter!

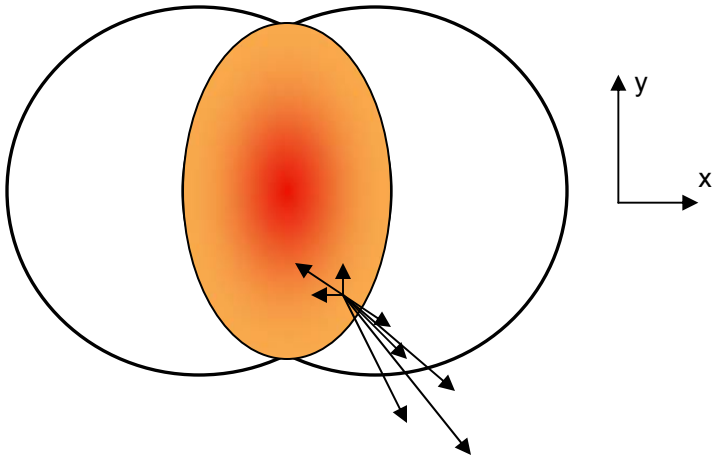
Collision Geometry, Anisotropy

Bulk (Hydrodynamic) Matter (low p_T)



Pressure gradient converts position space anisotropy to momentum space anisotropy.

Jet Evolution (high p_T)



Energy loss results anisotropy based on location of hard scattering in collision volume.

Particle Correlations

- Characterize particle correlations by a Fourier decomposition:

$$\frac{dN}{d\Delta\phi} \propto \left(1 + 2v_2^2 \cos(2\Delta\phi)\right)$$

$$\Delta\phi = \phi_i - \phi_j$$

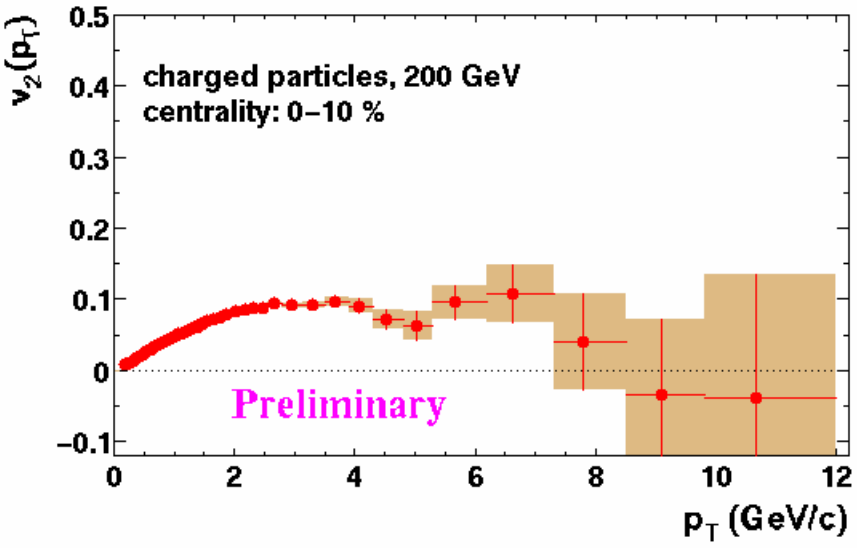
OR

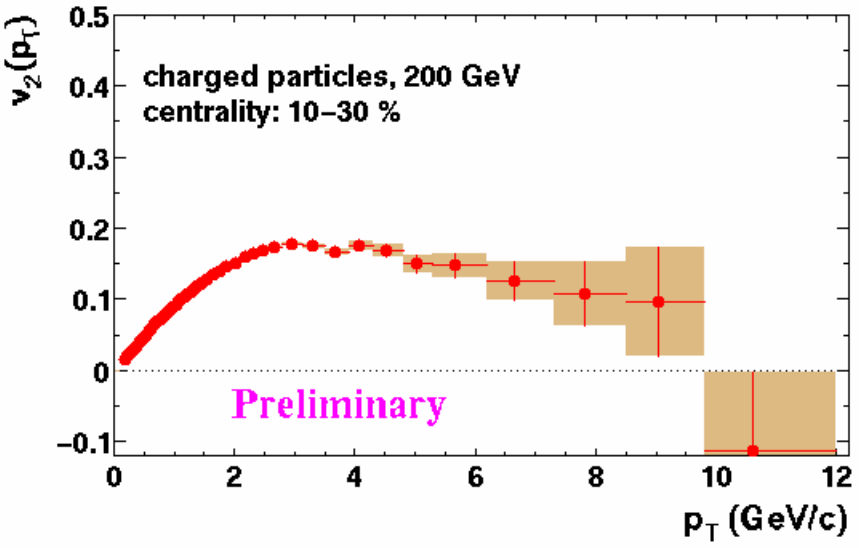
$$\Delta\phi = \phi_{lab} - \psi_{plane}$$

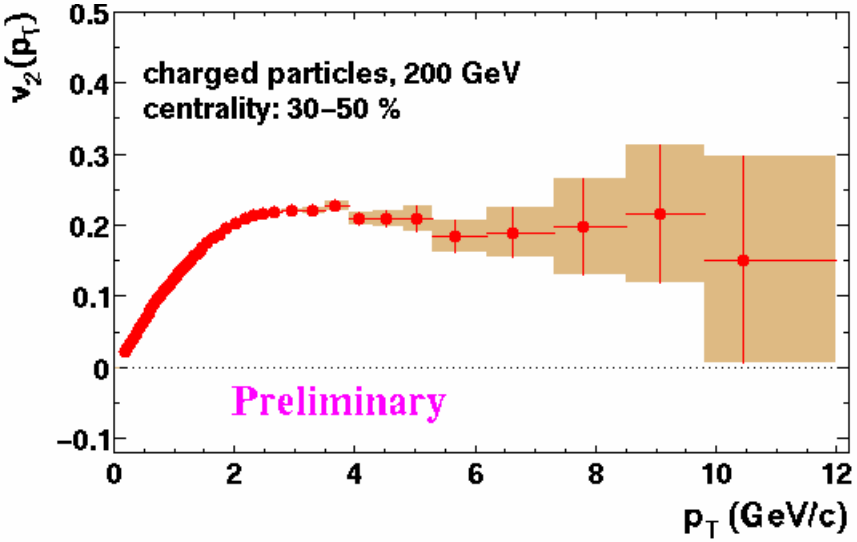
- At low p_T v_2 is dominated by bulk hydrodynamics, at high p_T a nonzero v_2 may be an indication of energy loss

- Correlate particles in $\Delta\phi$, $\Delta\eta$ space, look for jet signal

Elliptic Flow at High-p_T

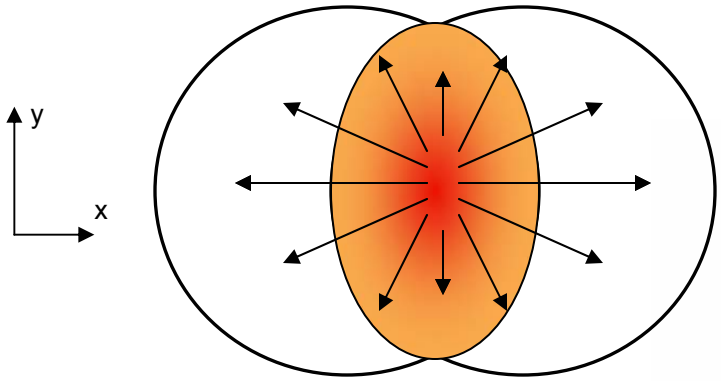






- **STAR** charged hadron elliptic flow out to p_T = 12 GeV/c !
  - finite v_2 p_T = ~6 GeV/c
  - Absolute v_2 too high to be just jet quenching (Shuryak)?

More Elliptic Flow

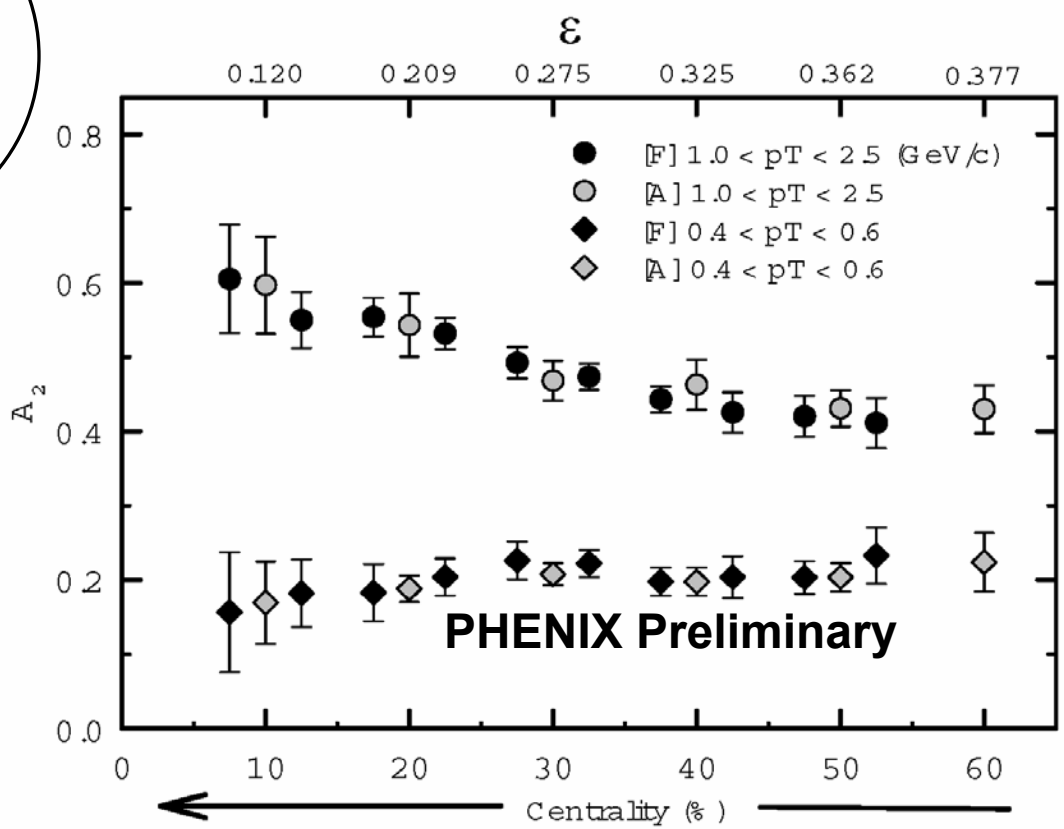


Scaled elliptic flow:

$$A_2 = \frac{v_2}{\varepsilon}$$

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

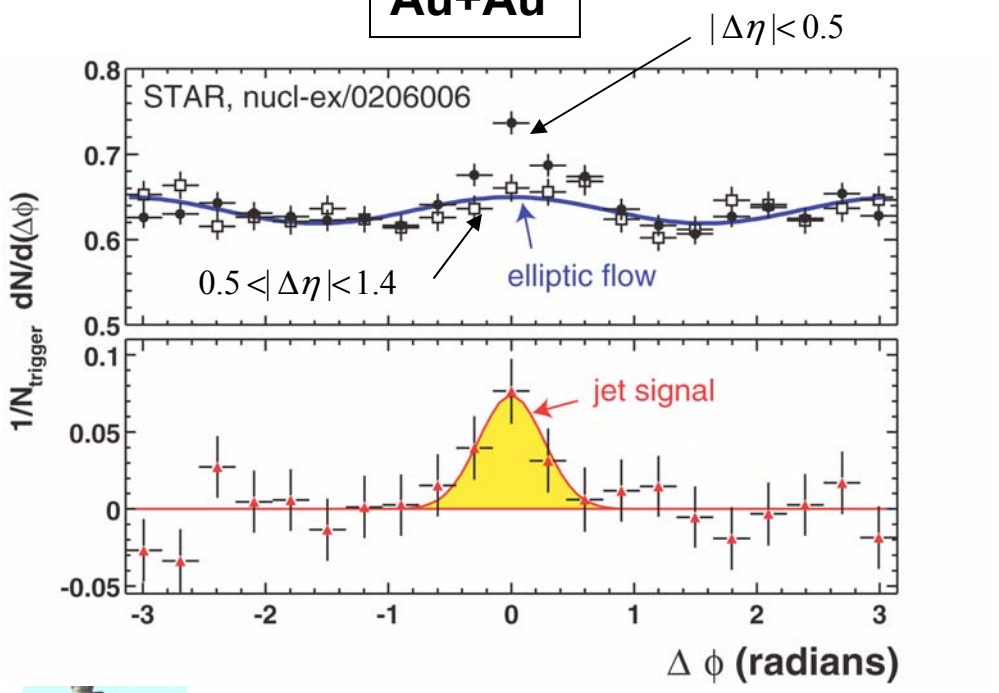
K. Adcox et al., nucl-ex/0204005



$\Delta\phi$, $\Delta\eta$ Correlations

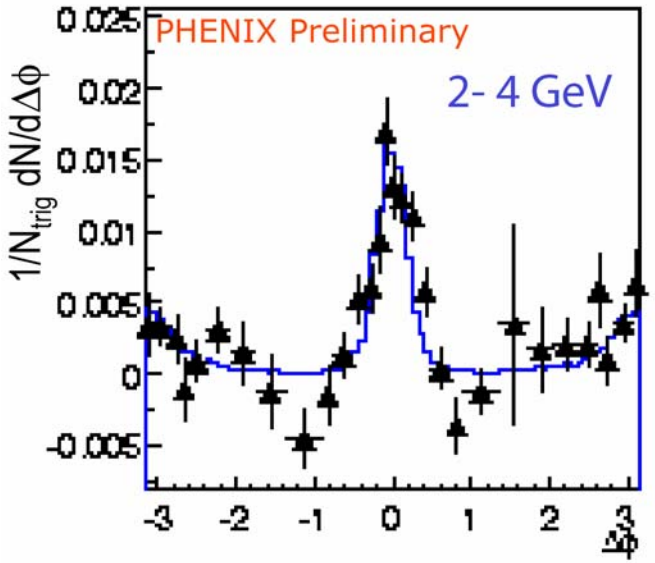
- near-side correlation of charged tracks (**STAR**)
  - trigger particle p_T = 4-6 GeV/c
  - $\Delta\phi$ distribution for p_T > 2 GeV/c

Au+Au

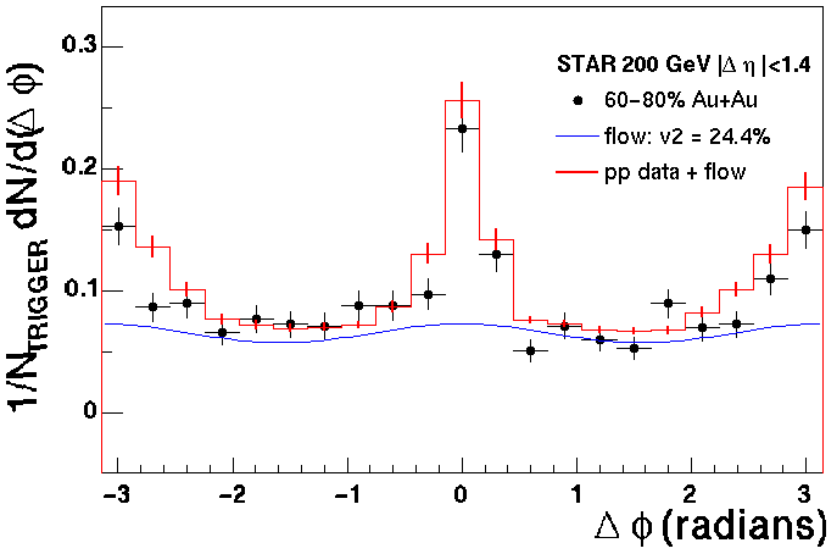


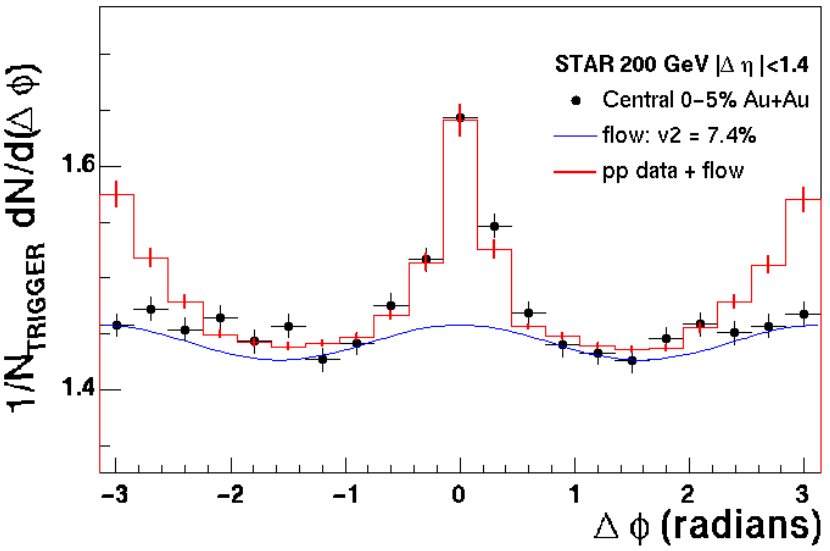
- γ (π^0) triggered events (**PHENIX**)
  - trigger photon p_T > 2.5 GeV/c
  - $\Delta\phi$ distribution for p_T = 2-4 GeV/c

p+p

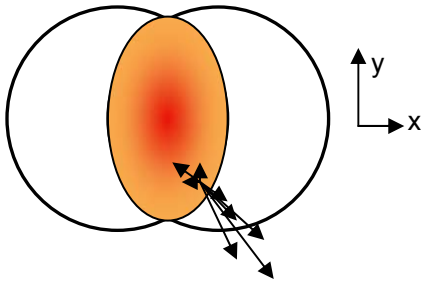


Systematics

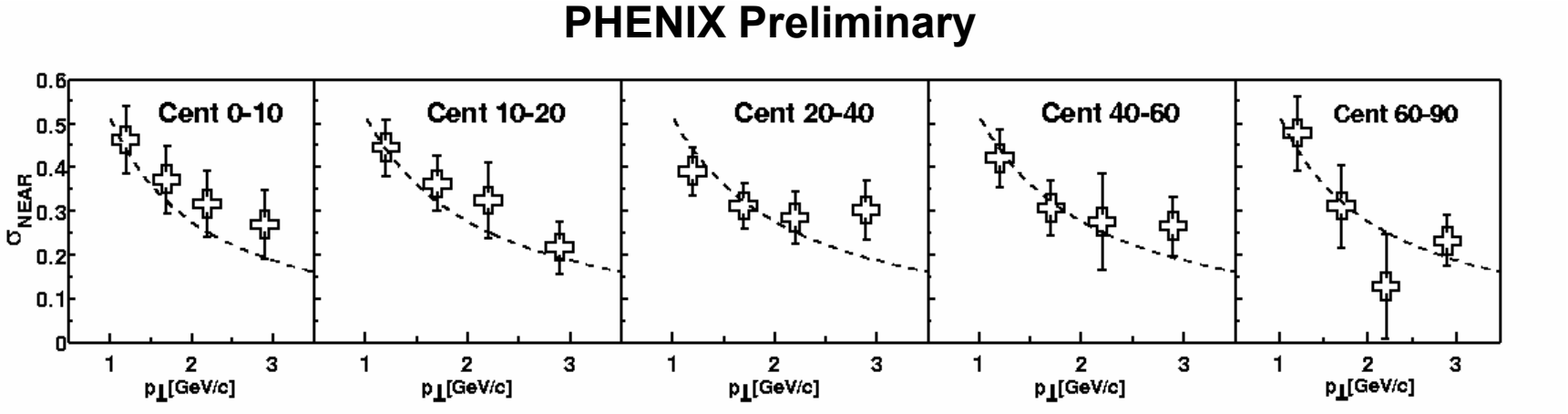




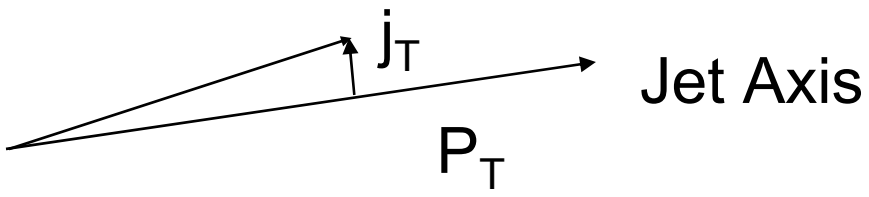
- Near-side jet consistent with pp (plus flow)
- Far-side correlation suppressed for more central collisions



Near Side Correlation Width



The dashed line (not a fit) corresponds to a constant $j_\perp$=400 MeV.
(transverse momentum with respect to "jet" axis)



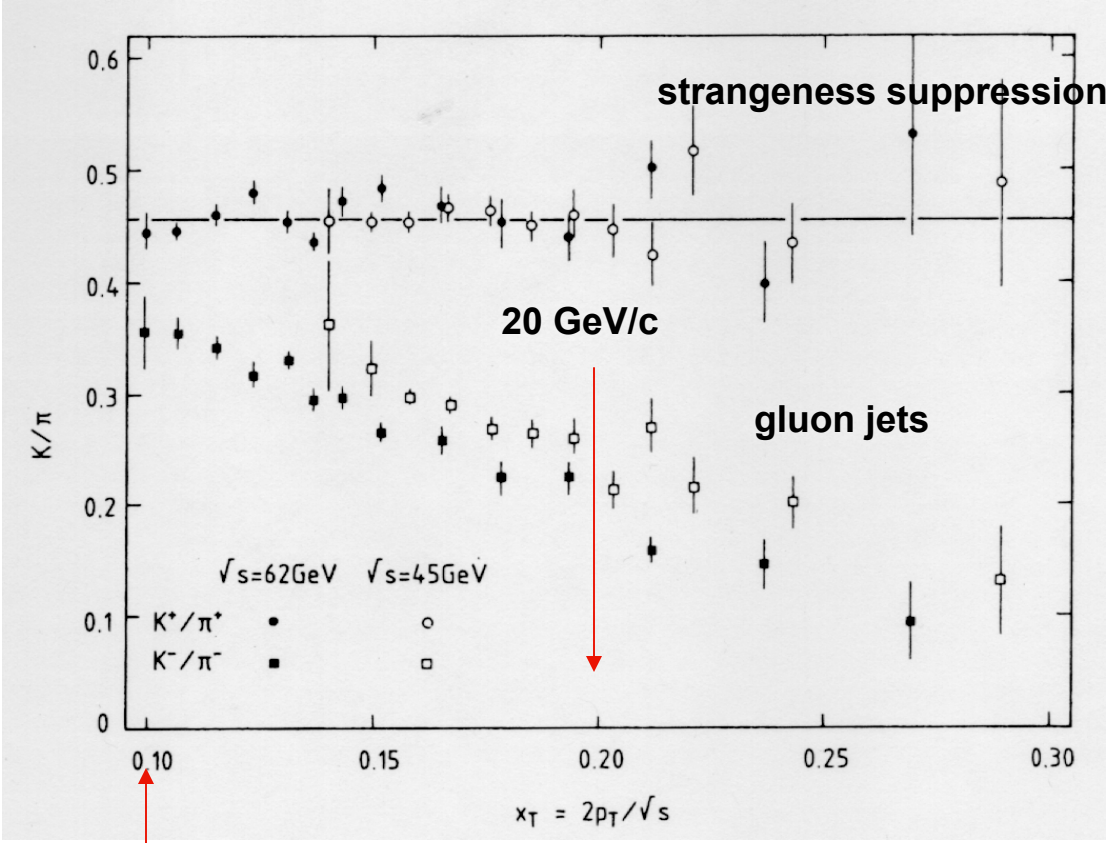
Jet Quenching – Quarks vs. Gluons

Gluons expected to suffer larger energy loss than quarks.

Use leading particle to tag the flavor of the jet:

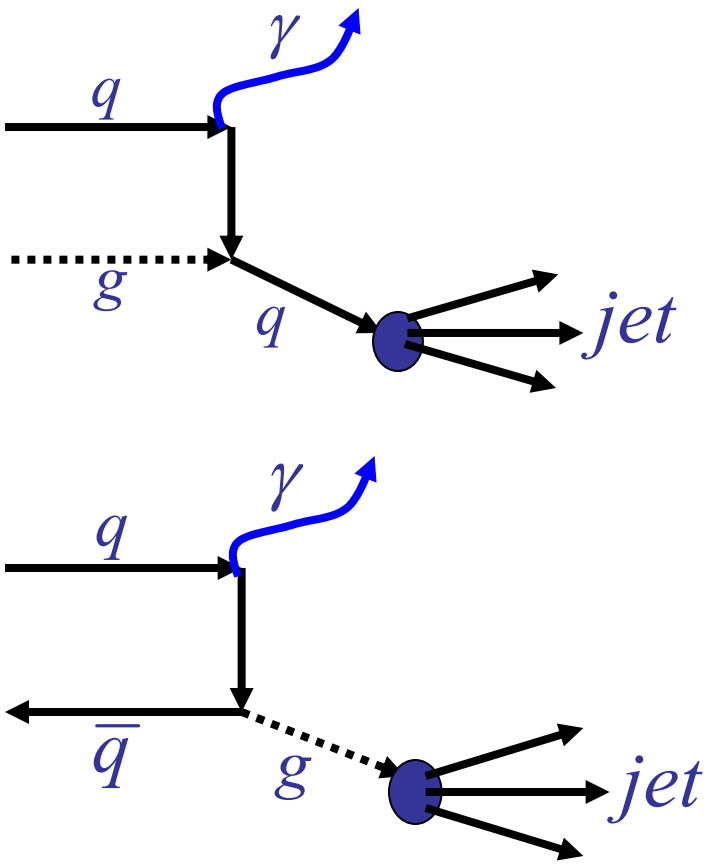
K^-, pbar produced by gluon fragmentation.

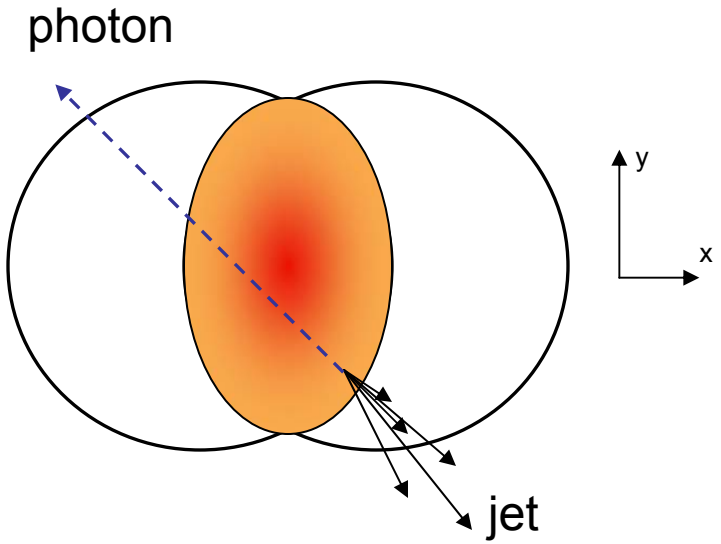
Need extended PID capabilities!



A. Breakstone et al., Phys. Lett. B, 135 (1984) 510

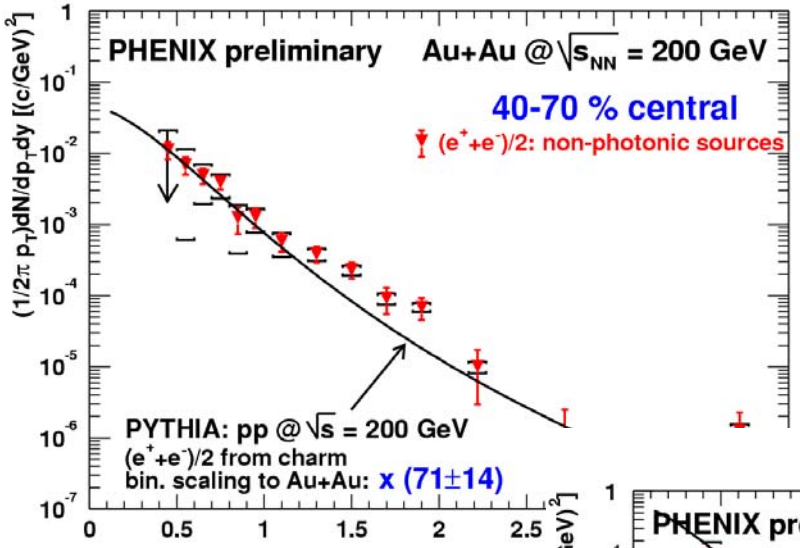
Photon Tagged Jets

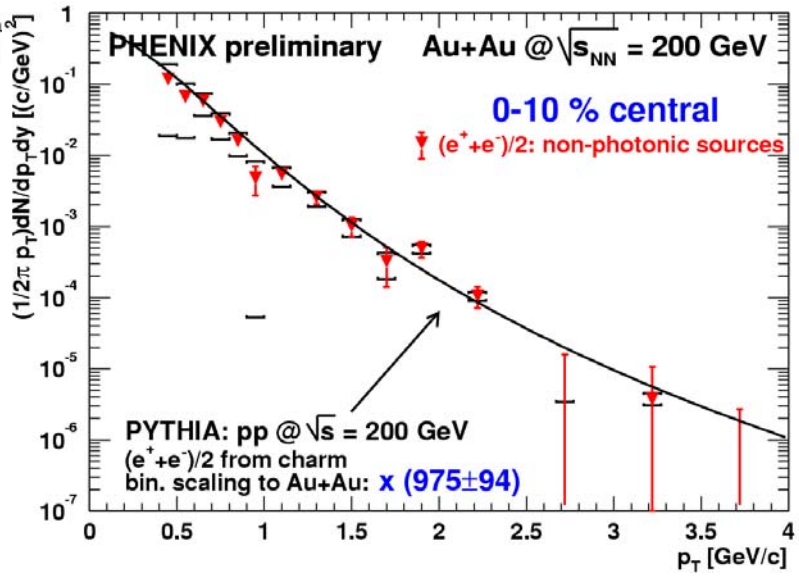




- Photon sets energy scale, measure effective fragmentation function of jet
- Issues of rate, acceptance and background

Energy Loss of Heavy Quarks





- Reduced quenching for heavy quarks – “dead zone” effect
- PHENIX measured e^+e^- spectra from non-photonic sources – charm!
- Level and p_T dependence consistent with e^+e^- from scaled PYTHIA

Summary

- Intriguing evidence that we have created a dense medium at RHIC!

- All RHIC experiments show evidence of jet suppression
- Direct evidence for jets in STAR, PHENIX
- Much work remains to be done!
  - quantitative measure of suppression, pp reference
  - d+Au reference data (Run-3)
  - particle composition at high p_T
  - gamma-jet correlations
  - energy loss of heavy quarks
  - …