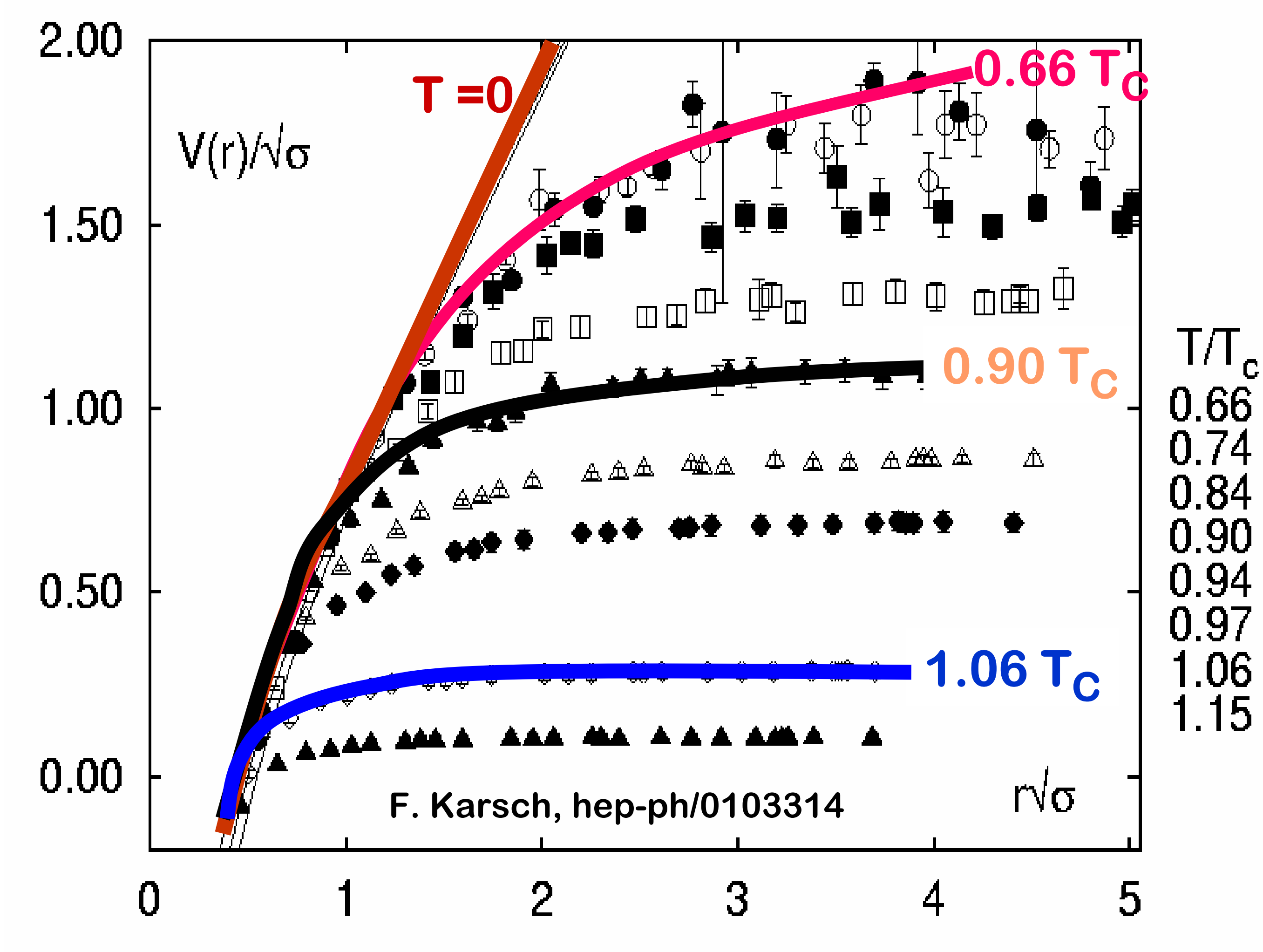
Recent Results from the PHENIX Experiment at RHIC

John Lajoie, Iowa State University
for the PHENIX Collaboration

- **The Quark-Gluon Plasma**
- **The PHENIX Experiment**
- **Bulk Matter Observables**
    - Energy Density, Expansion, Freeze-Out
- **Penetrating Probes**
    - Jets, Leptons
- **Outlook**

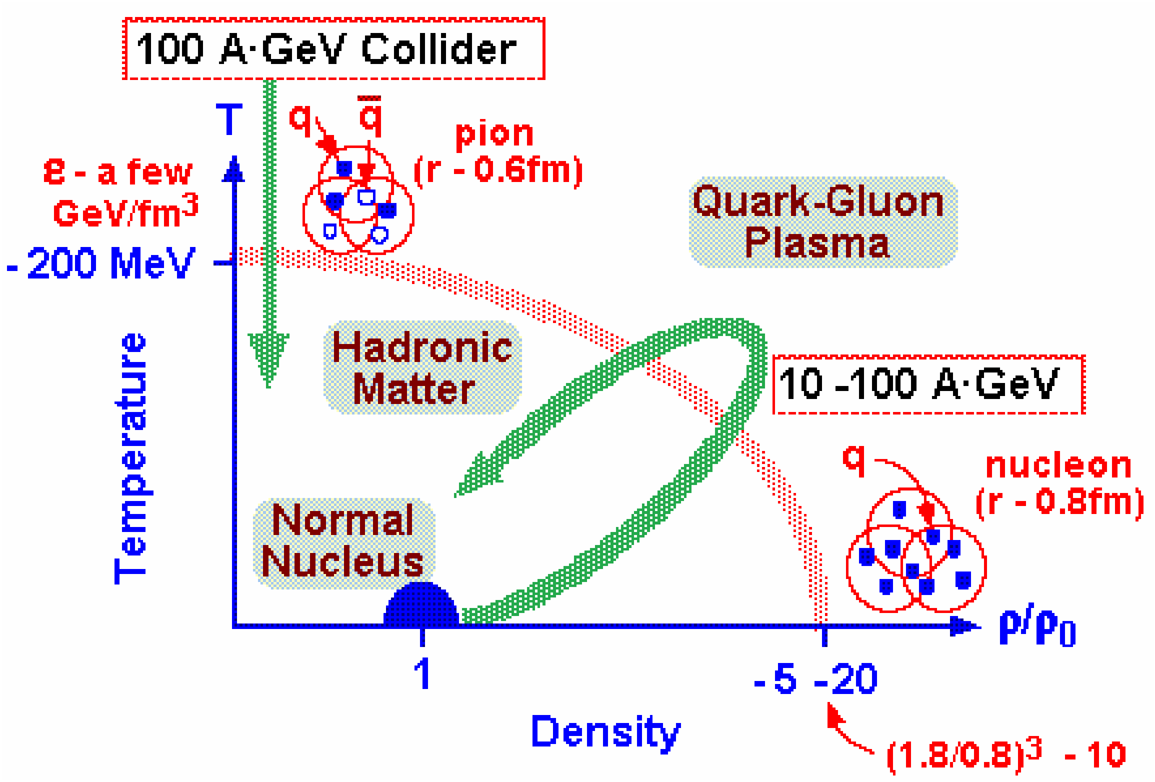
Melting the Perturbative Vacuum

- Lattice QCD indicates a dramatic change in the strong potential above a critical temperature.
- $T_C \sim 150$MeV



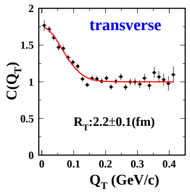
The Quark-Gluon Plasma

- Use collisions of heavy nuclei to create a high energy density.
- Correlate observables of final state with probes of matter at earlier time scales.



The PHENIX Experiment

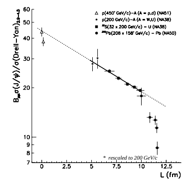
NA44



single particle distributions

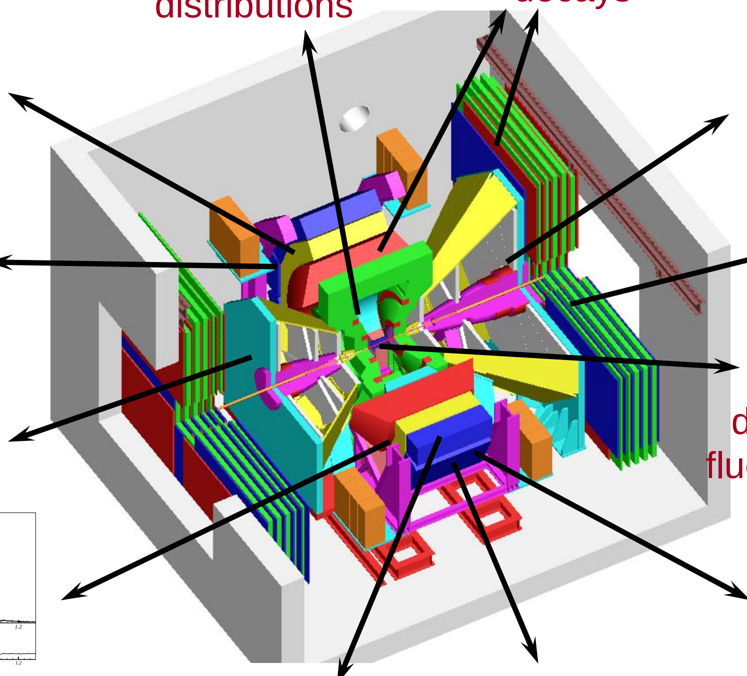
semi-leptonic D decays

NA50



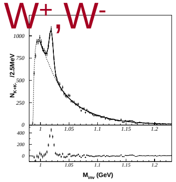
strangeness production

heavy flavor decay



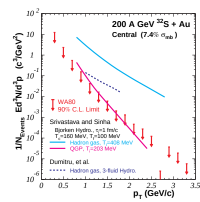
spin program W^+,W^-

N_{ch}, $dN_{ch}/d\eta$, fluctuations

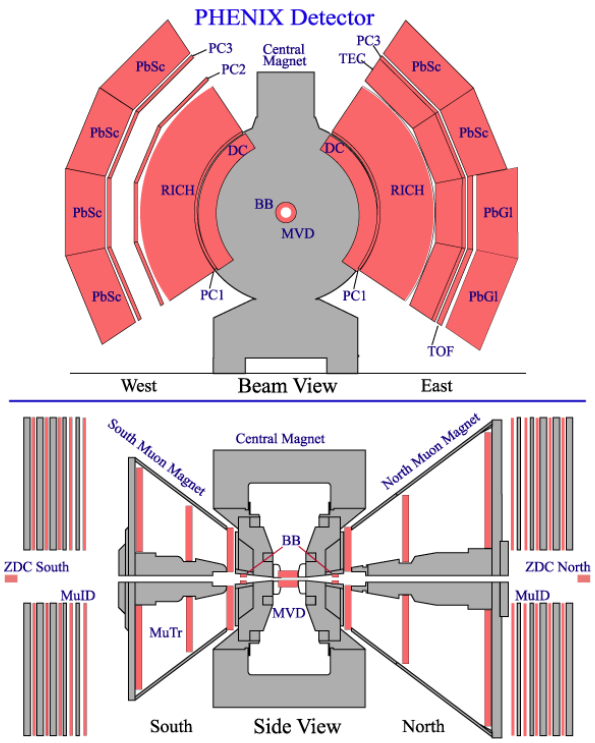


E859

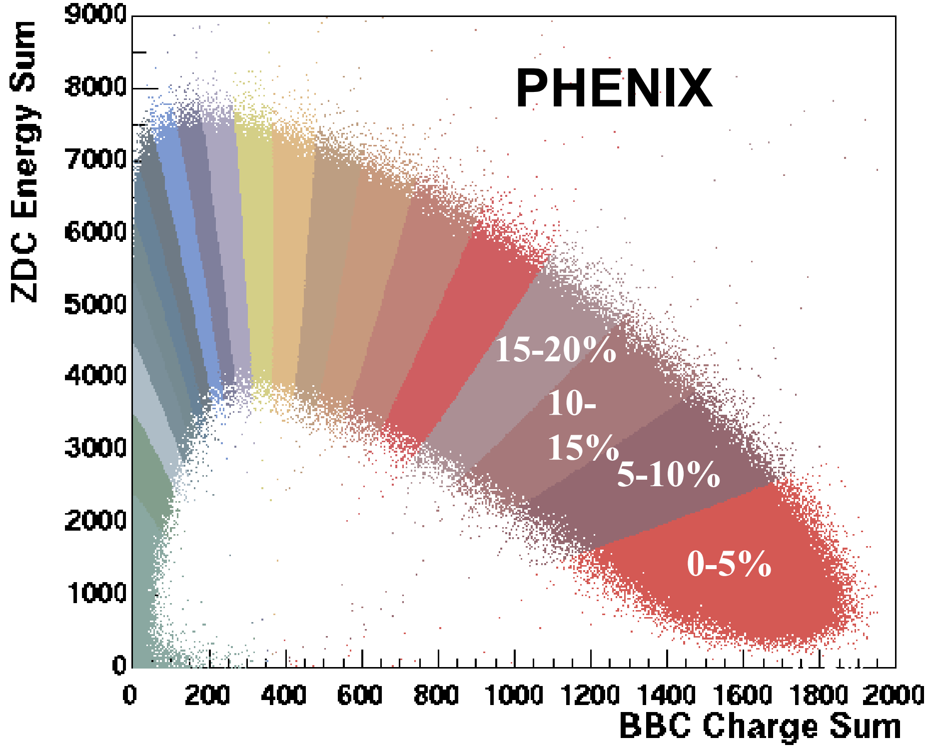
jet quenching

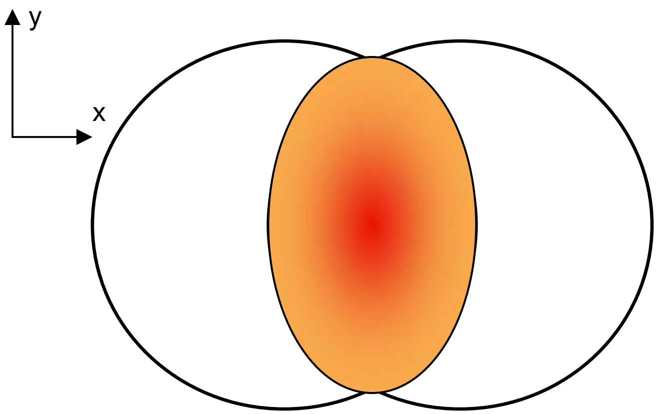


WA80



Collision Geometry





- Relate observables to nuclear overlap
- Use models to relate observables to N_{part}, N_{binary} (N_{coll})

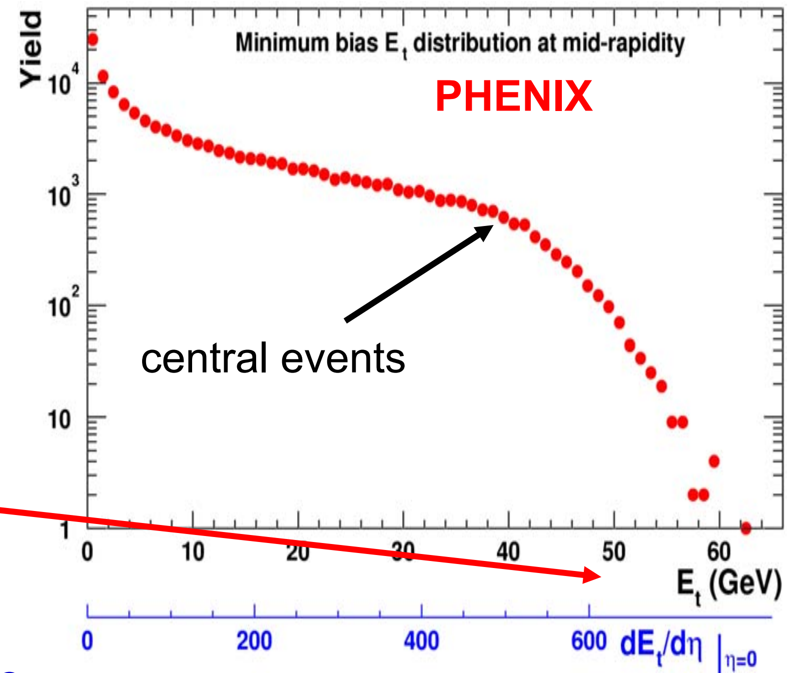
Energy Density

- What is the energy density achieved?
- How does it compare to the expected phase transition value ?

Bjorken formula for thermalized energy density

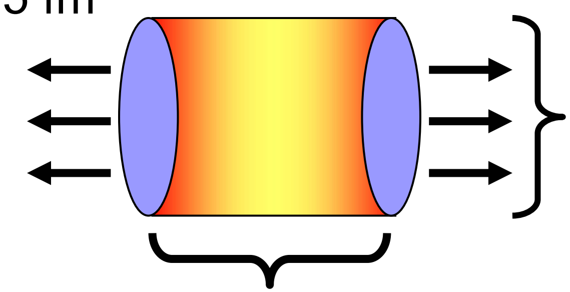
$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

EMCAL



~6.5 fm

time for system to thermalize (τ_0 ~ 1 fm/c)



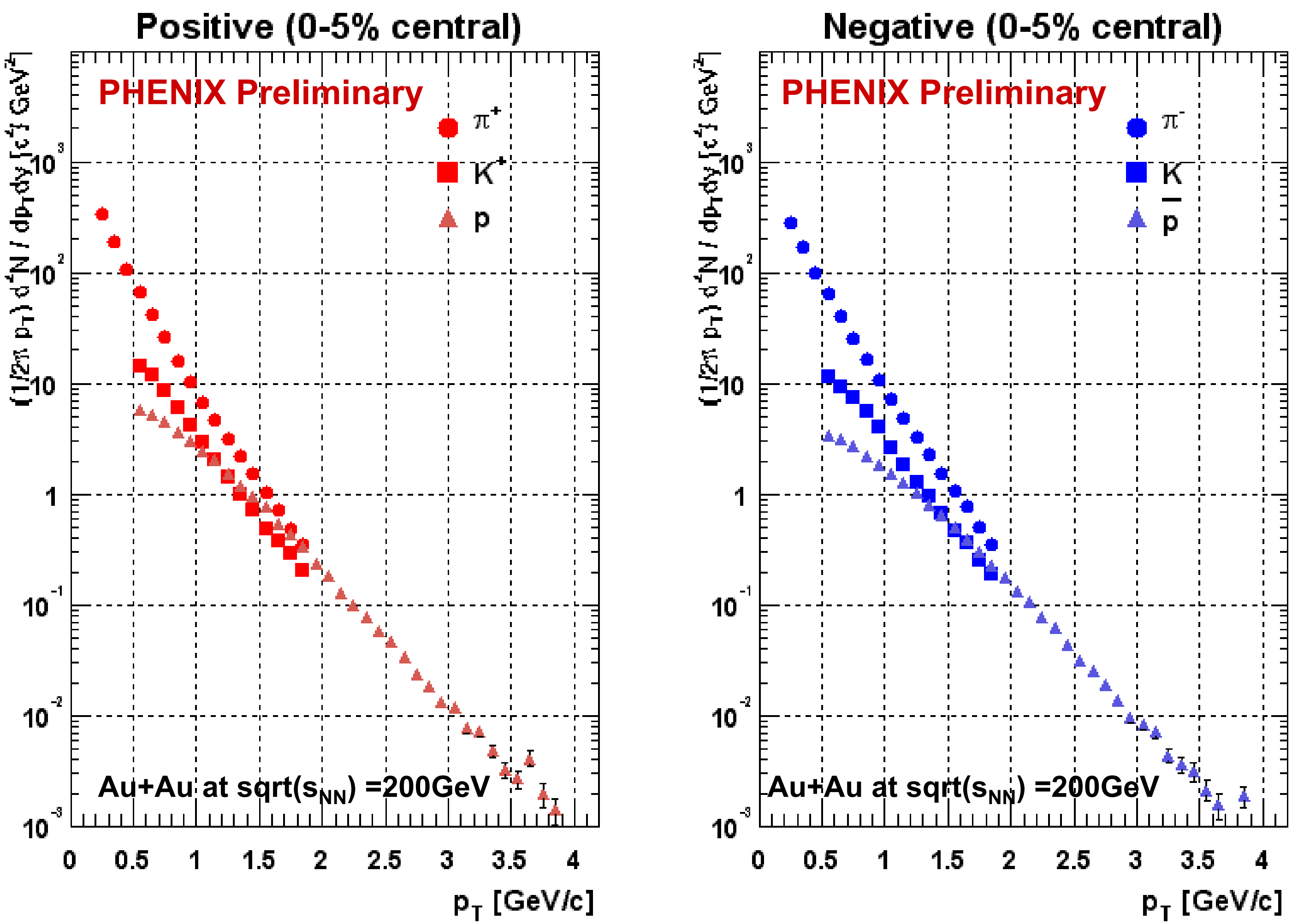
πR^2

$$dz = \tau_0 dy$$

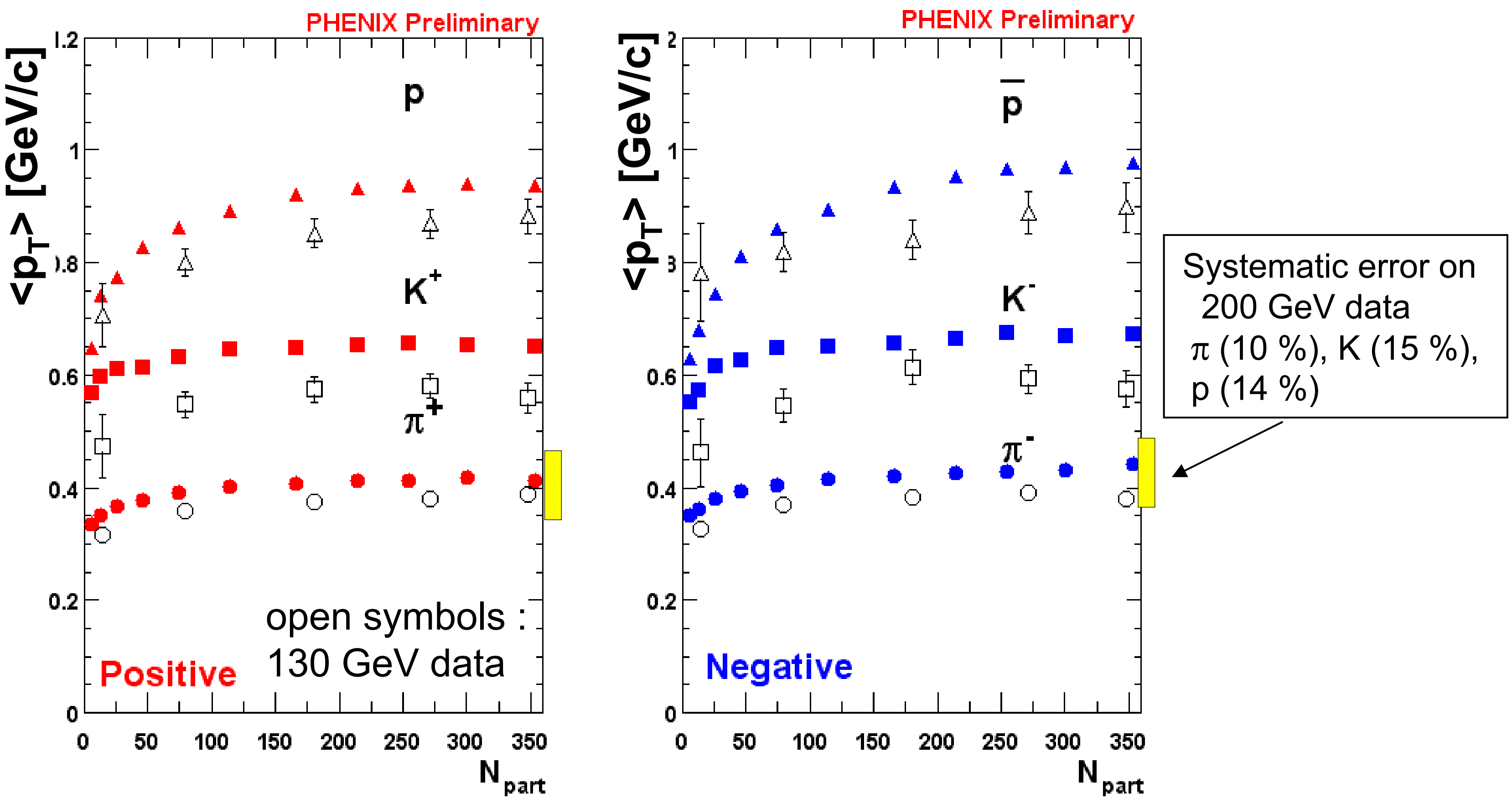
ε_{Bj} ~ 5 GeV/fm^3

~30 times normal nuclear density
~<u>1.5 to 2 times higher</u> than any previous experiments

Particle Spectra

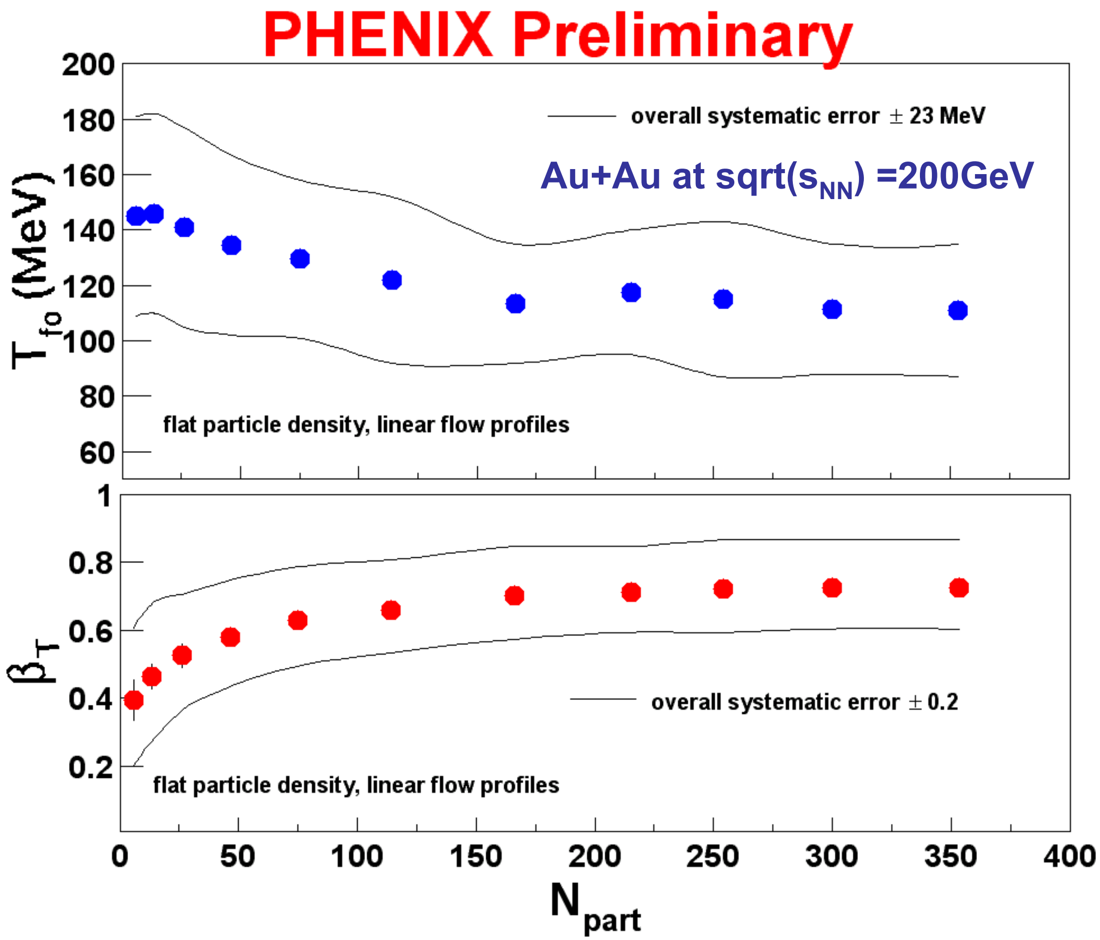


$\langle p_T \rangle$ vs. Centrality



- $\langle p_T \rangle$ consistent with hydrodynamic picture
- Increases with N_{part}, then saturates

Hydrodynamic Expansion



Most central collisions for 200 GeV data:

Freeze-out Temperature

$T_{fo} = 110 \pm 23$ MeV

Transverse flow velocity

$\beta_T = 0.7 \pm 0.2$

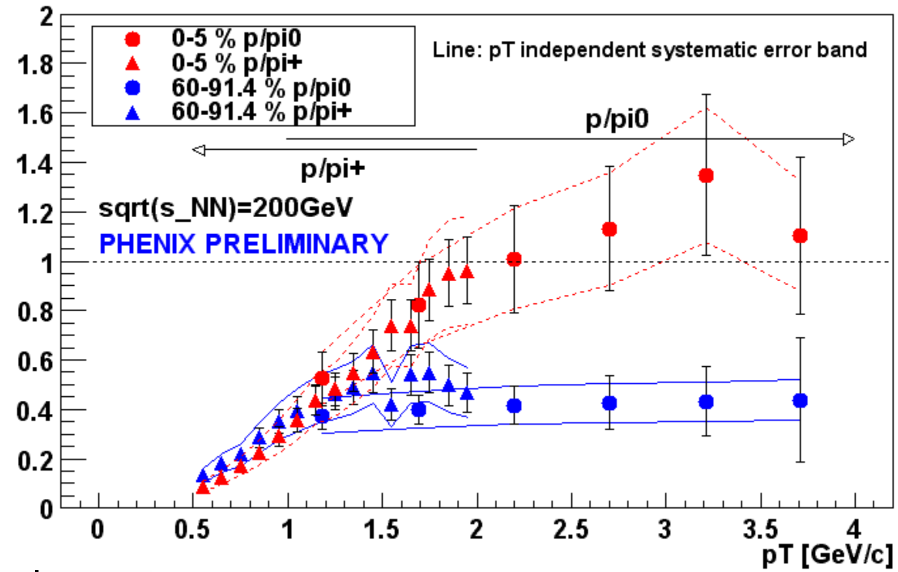
(Not corrected for resonance feed-down.)

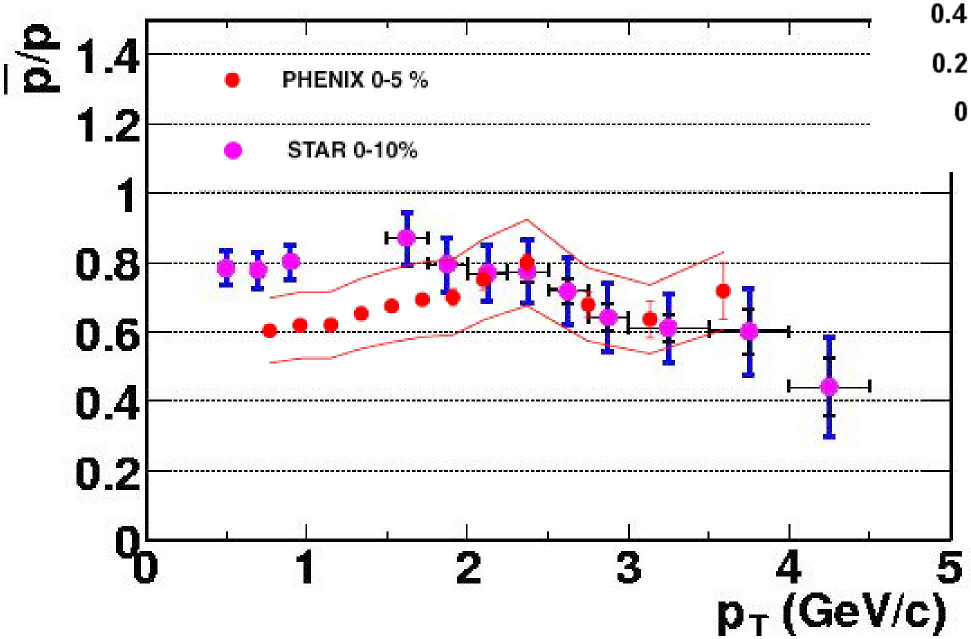
Ref: E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. C 48, 2462 (1993)

β_T increases from peripheral to mid-central ($N_{part} < 150$) and tends to saturate for central collisions.

Particle Composition

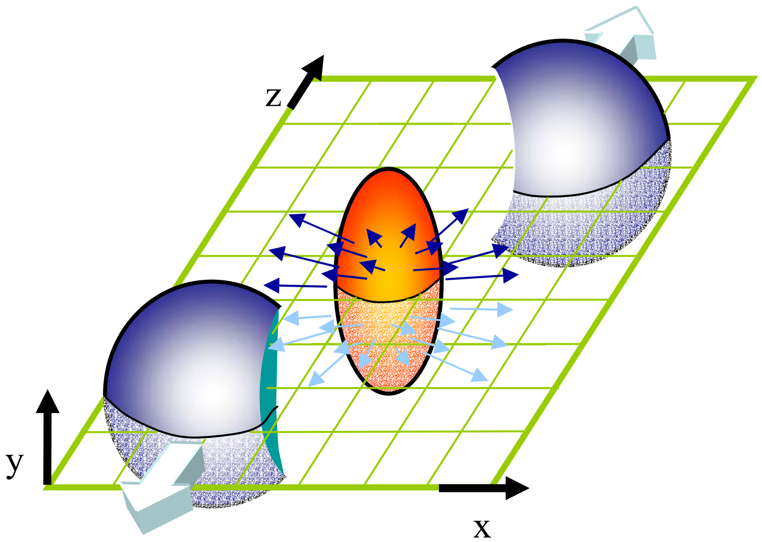
- Particle composition changing as a function of p_T, centrality
  - $p/\pi^0 \sim 1$ at ~3 GeV/c
  - p/pbar falling at higher p_T (?)
- Baryon transport by junctions?

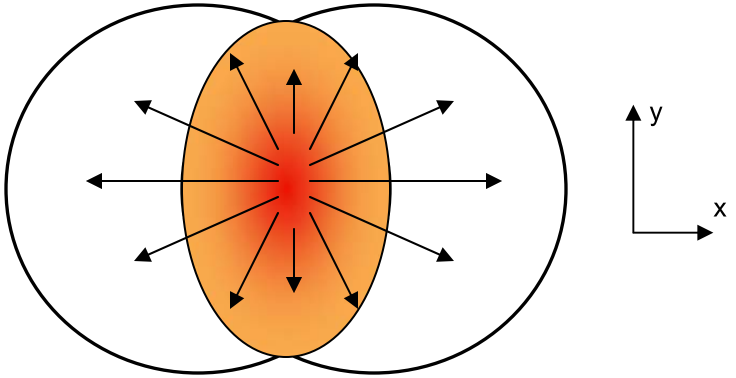




Extended PID capabilities required!

Elliptic Flow





Pressure gradient converts position space anisotropy to momentum space anisotropy.

- Characterize particle correlations by a Fourier decomposition:

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

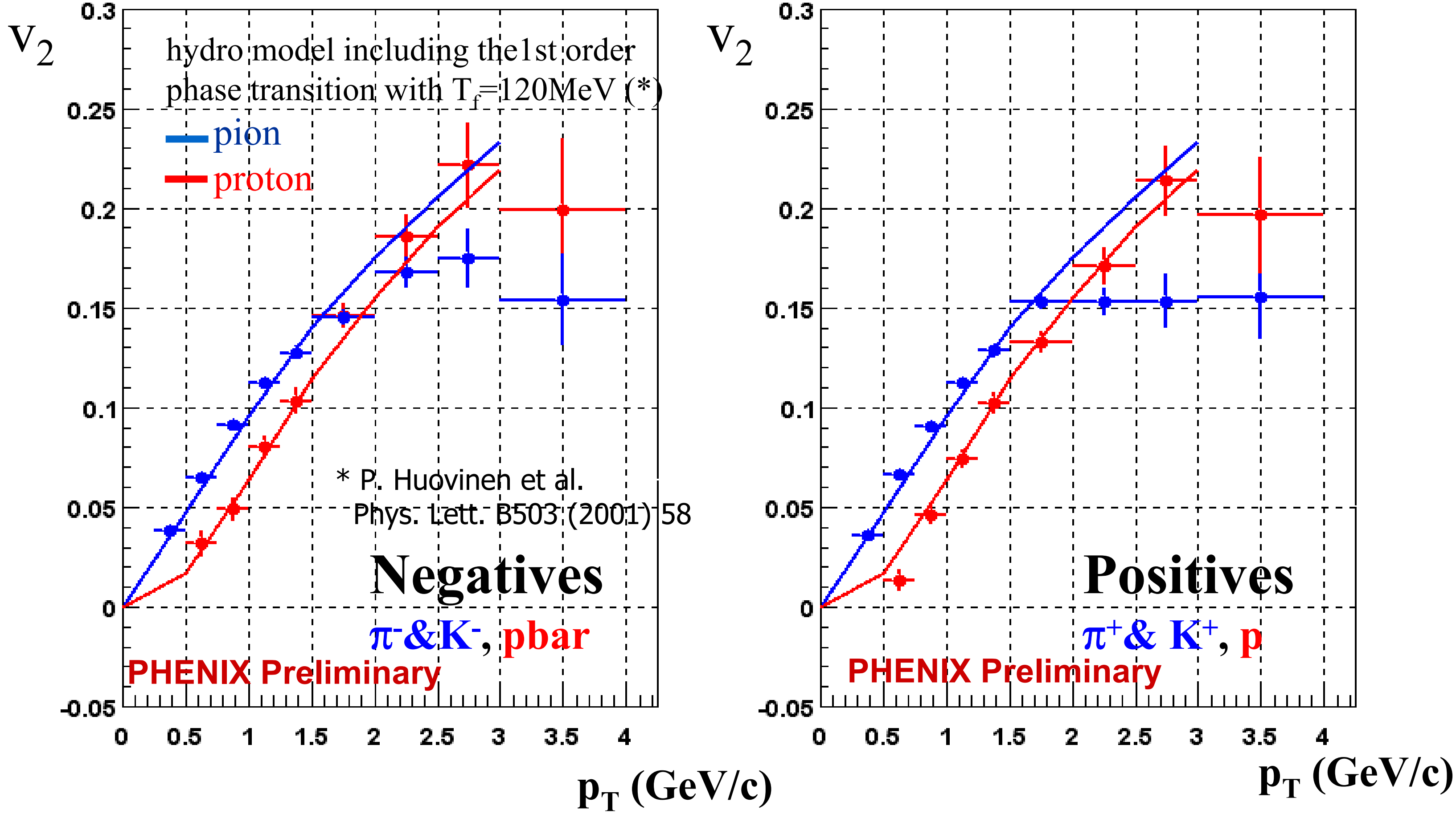
$$\Delta\phi = \phi_i - \phi_j$$

OR

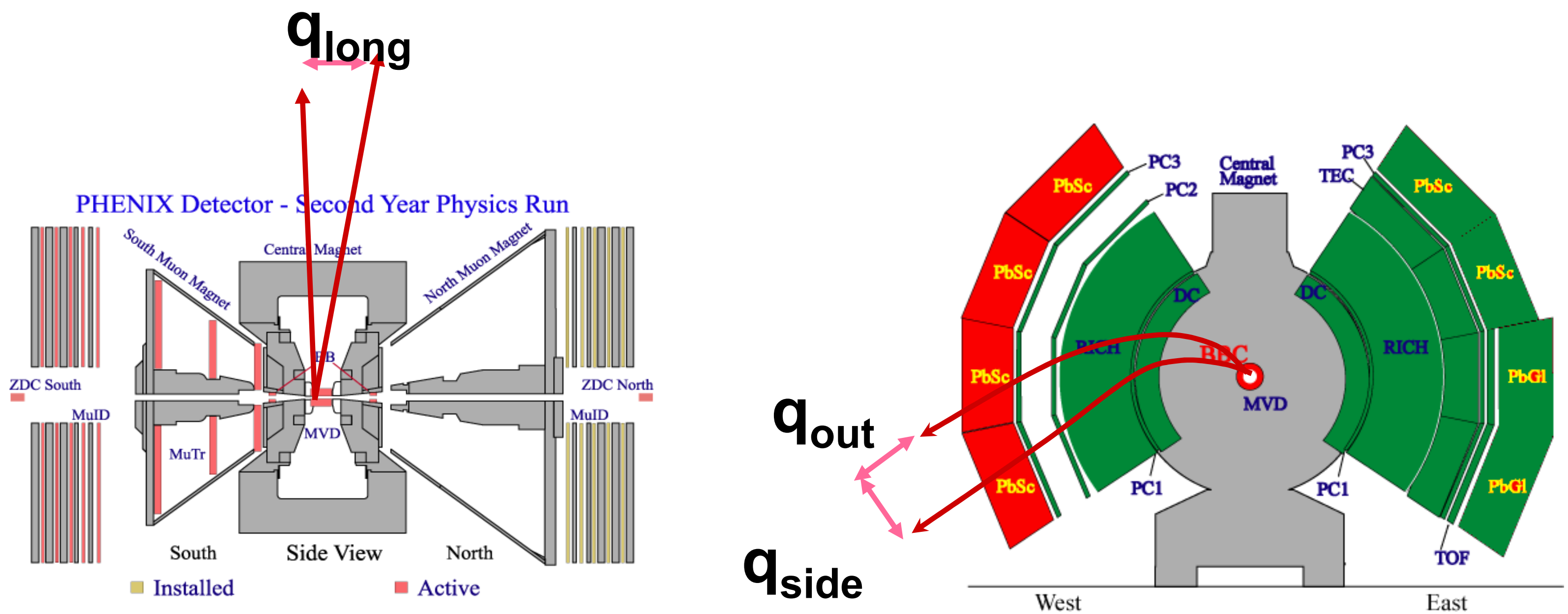
$$\Delta\phi = \phi_{lab} - \psi_{plane}$$

Elliptic Flow of Identified Hadrons

Au+Au at sqrt(s_{NN}) =200GeV, Minimum bias, Reaction Plane | η |=3~4



Two Particle Correlations (HBT)



- Full analytic coulomb corrections.
- Taking account two track separations.
- 50 M Minimum-bias data sample.

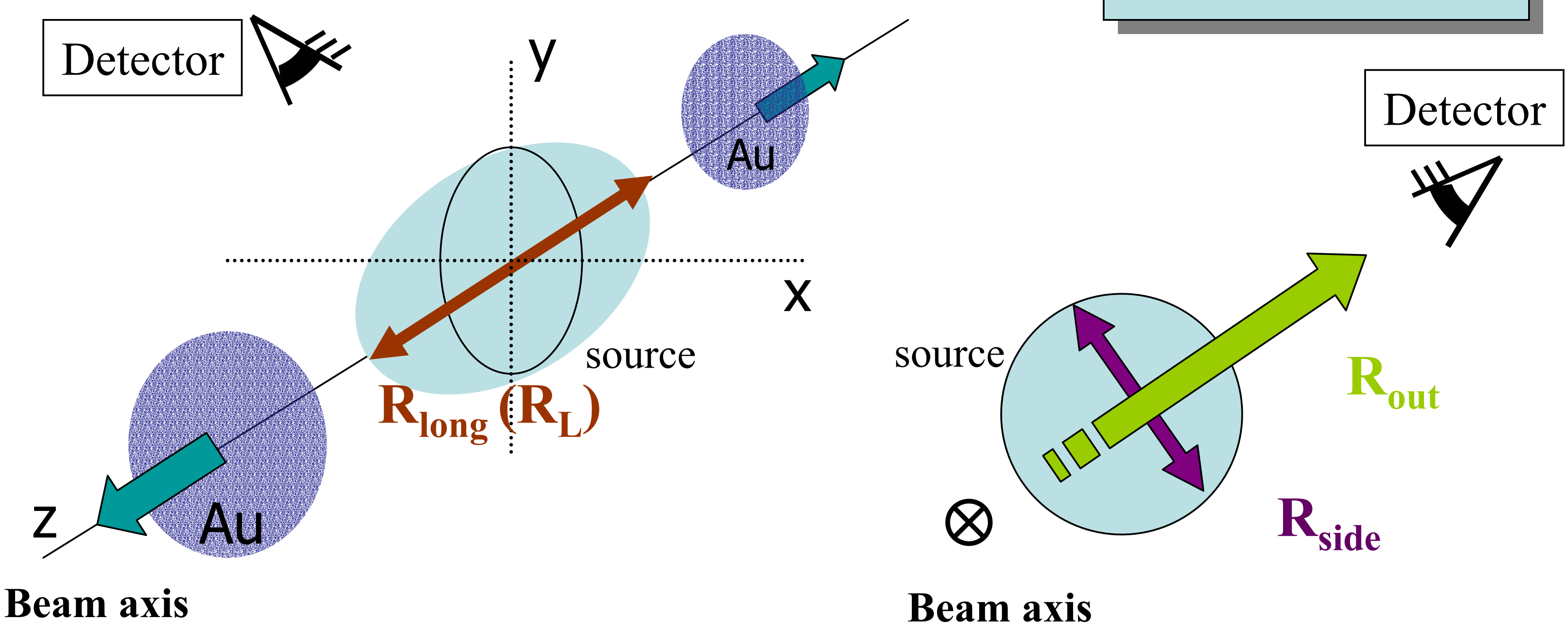
Bertsch-Pratt Parametrization

$$C_2 \equiv 1+\lambda \exp\left(-R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2 - R_{long}^2 q_{long}^2\right)$$

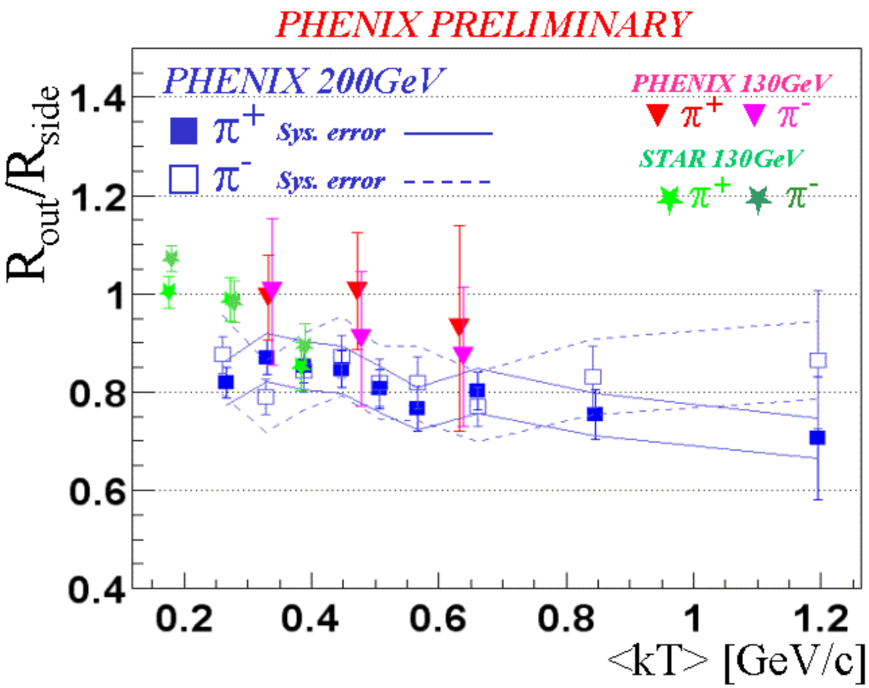
In LCMS frame

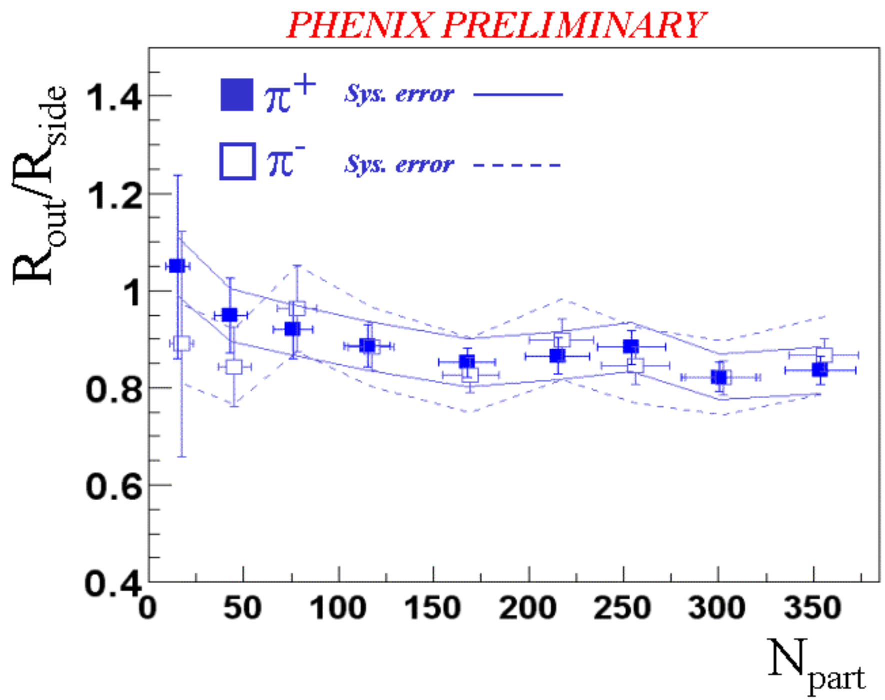
The duration time

$$\Delta t = \sqrt{R_{OUT}^2 - R_{SIDE}^2} / \beta$$



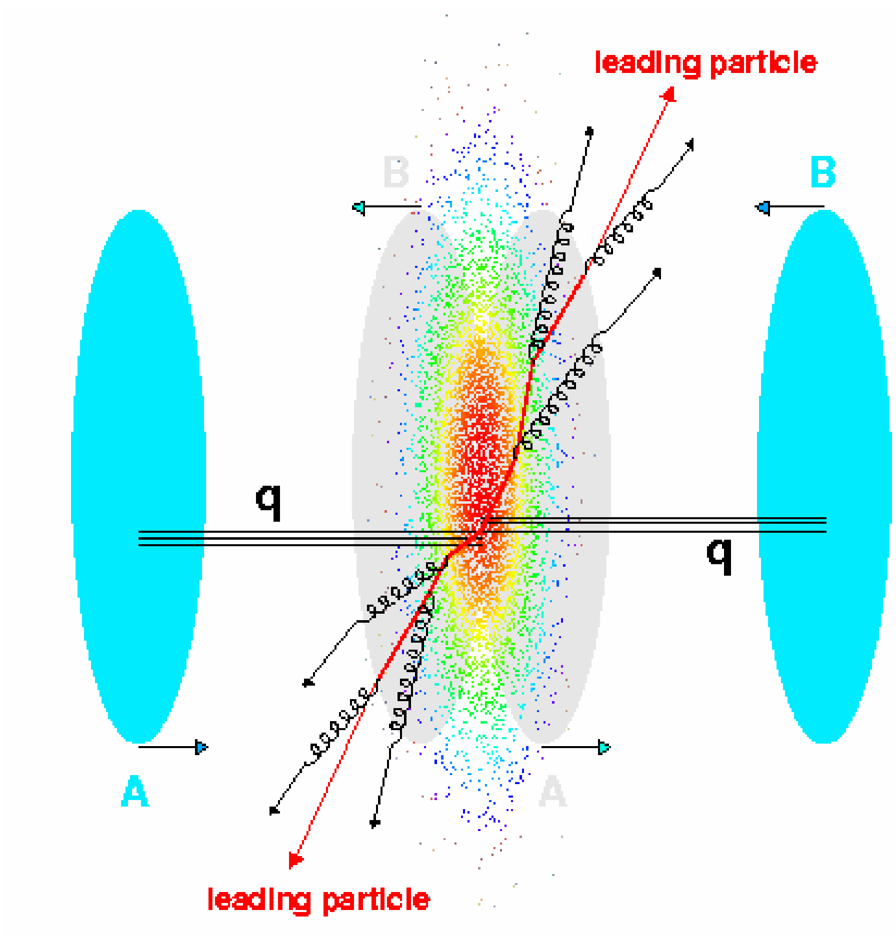
HBT Puzzle?





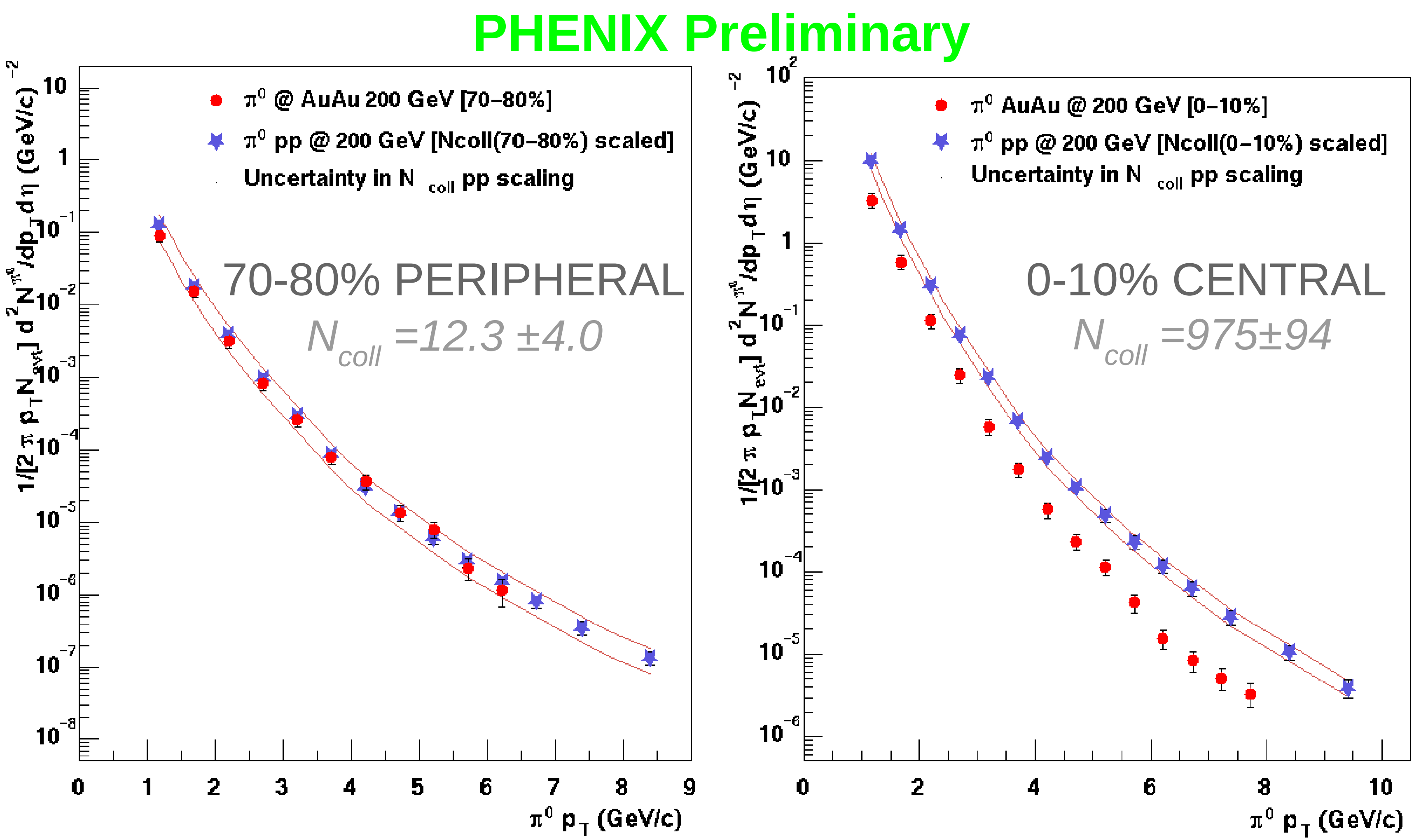
- **R_{out}/R_{side} ~ 1 – very short duration of emission!**
- **No dependence on <k_T> or N_{part}.**

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.

π^0 Spectra



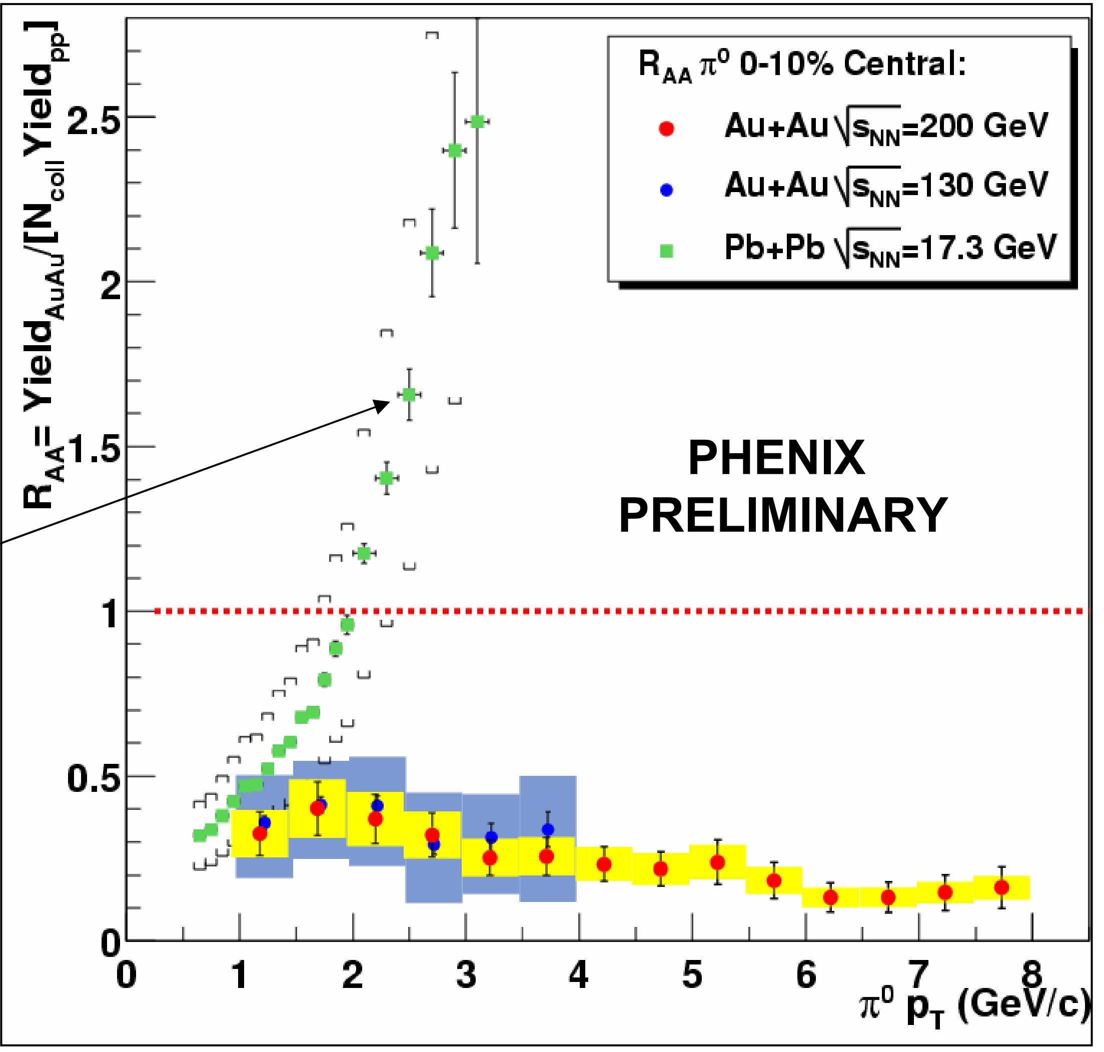
PHENIX Preliminary
π^0 @ AuAu 200 GeV [70-80%]
π^0 pp @ 200 GeV [Ncoll(70-80%) scaled]
Uncertainty in N_{coll} pp scaling
70-80% PERIPHERAL
N_{coll} =12.3 ±4.0
$1/[2\pi p_T N_{evt}] d^2N^{\pi^0}/dp_T d\eta$ (GeV/c)$^{-2}$
π^0 p_T (GeV/c)
π^0 AuAu @ 200 GeV [0-10%]
π^0 pp @ 200 GeV [Ncoll(0-10%) scaled]
Uncertainty in N_{coll} pp scaling
0-10% CENTRAL
N_{coll} =975±94
$1/[2\pi p_T N_{evt}] d^2N^{\pi^0}/dp_T d\eta$ (GeV/c)$^{-2}$
π^0 p_T (GeV/c)

Nuclear Modification Factor

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

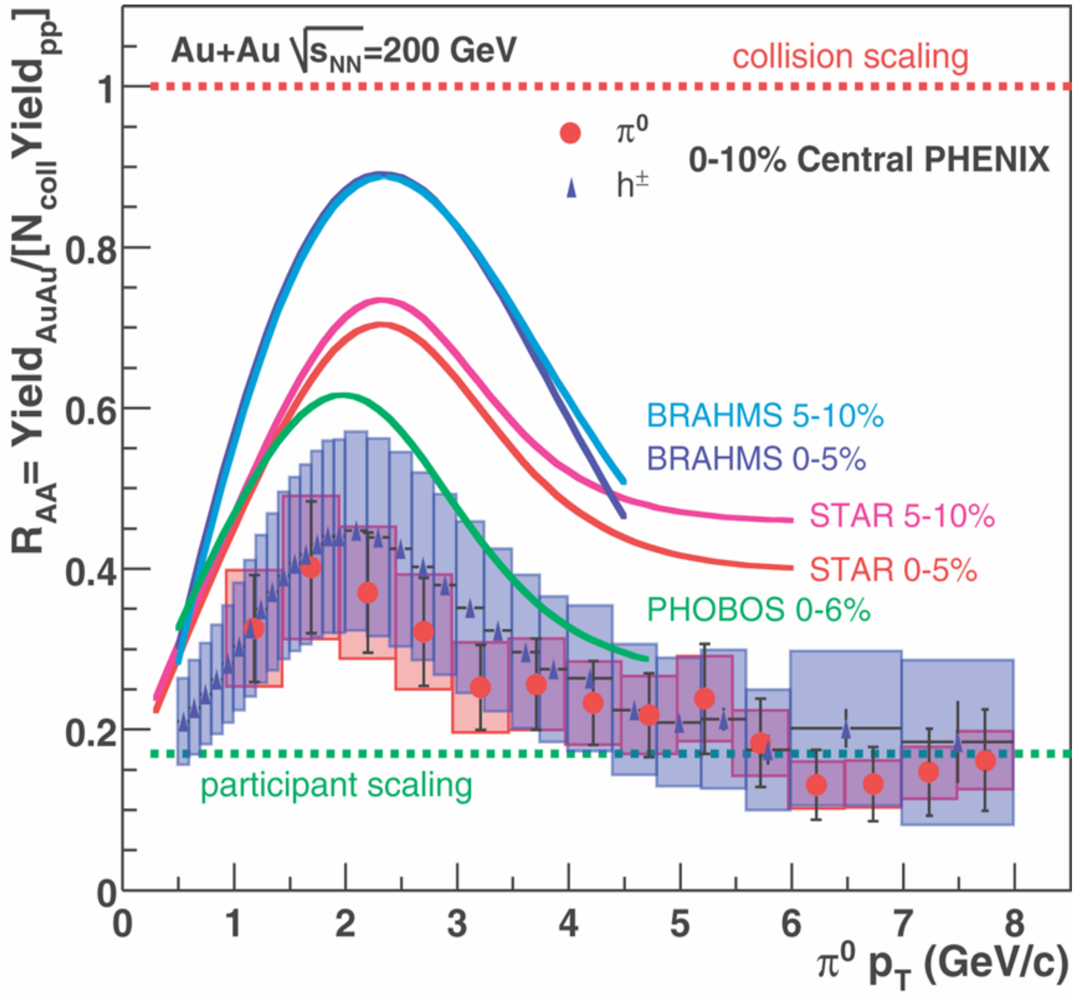
$$\frac{Yield_{central} / \langle N_{binary}\rangle_{central}}{Yield_{pp}}$$

“Cronin Effect” due to initial state parton scattering.



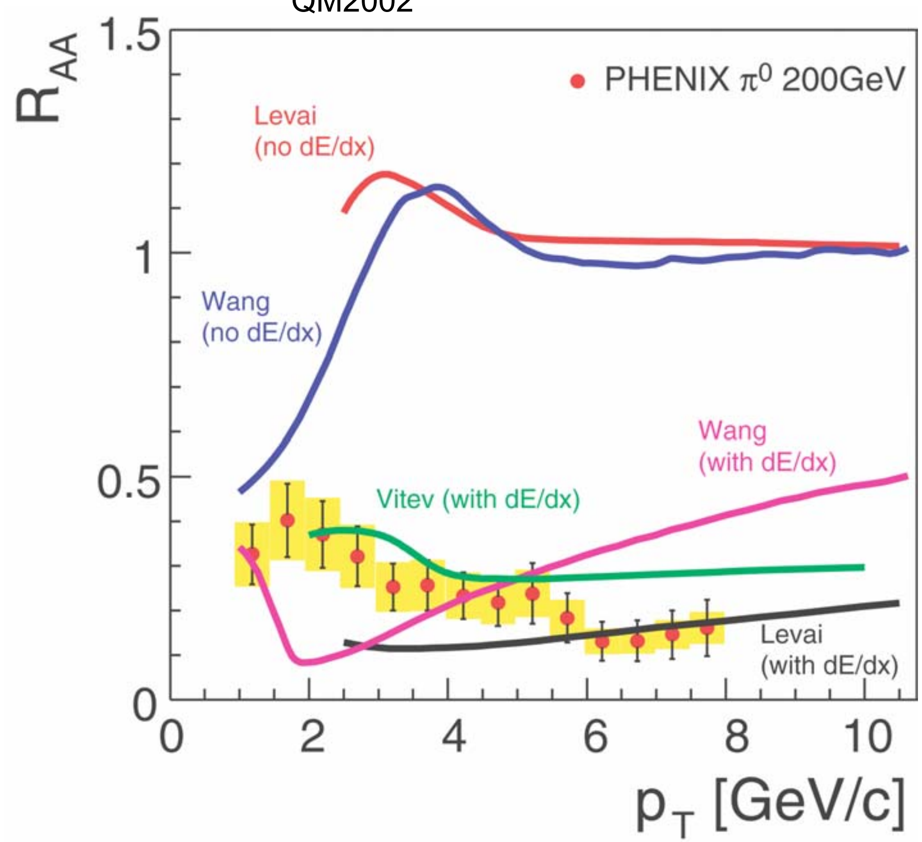
Combined Suppression Results

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

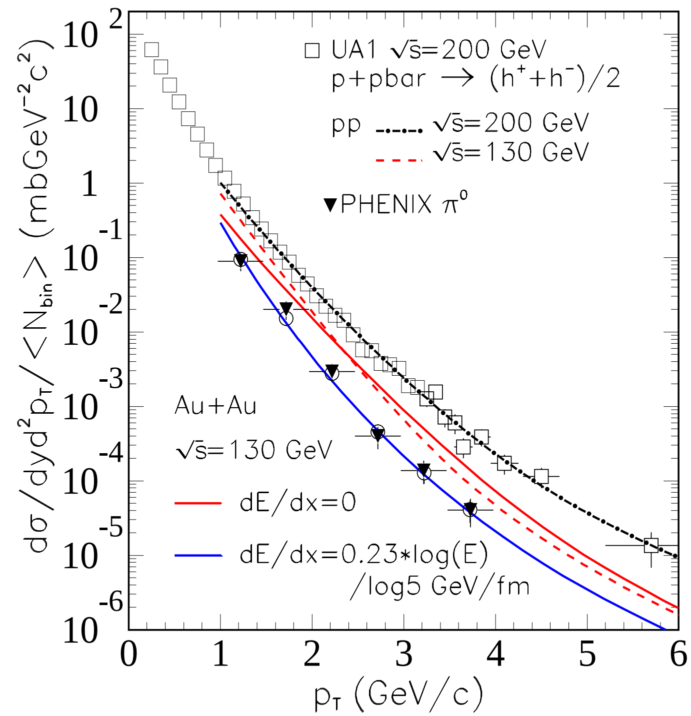


Suppression - Theory

- 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

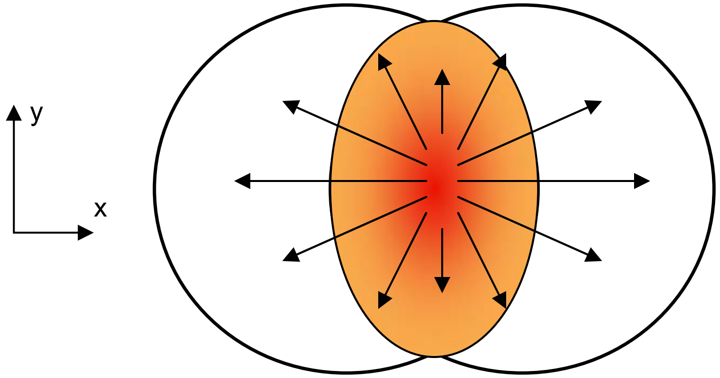


$$\left(\frac{dE}{dx}\right) \approx 7.3\, GeV / fm$$

15 times that in cold nuclear matter!

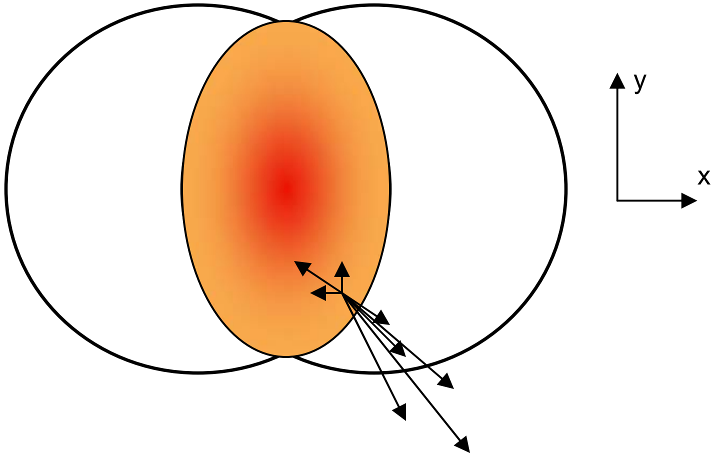
Collision Geometry, Anisotropy

Bulk (Hydrodynamic) Matter (low p_T)



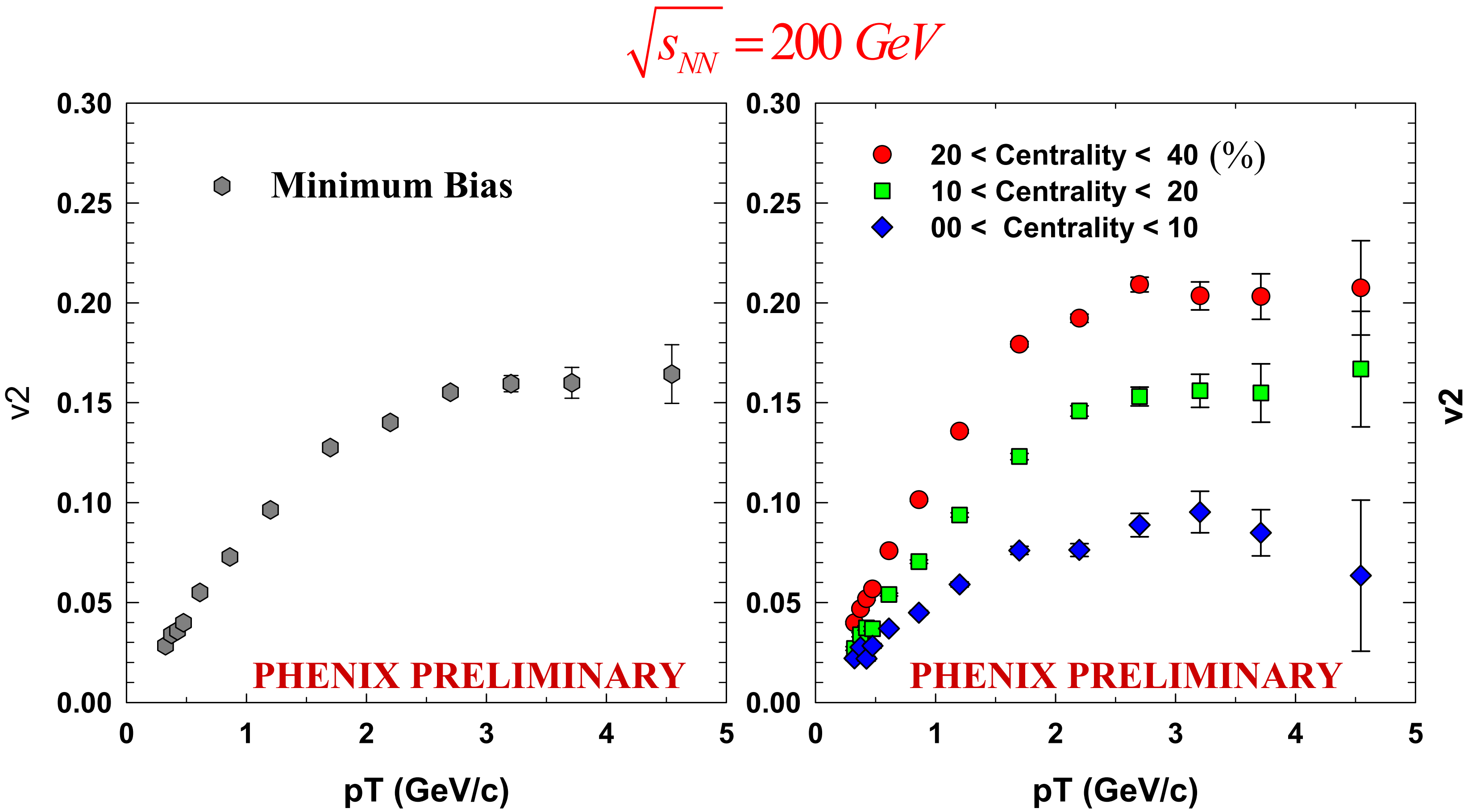
Pressure gradient converts position space anisotropy to momentum space anisotropy.

Jet Evolution (high p_T)



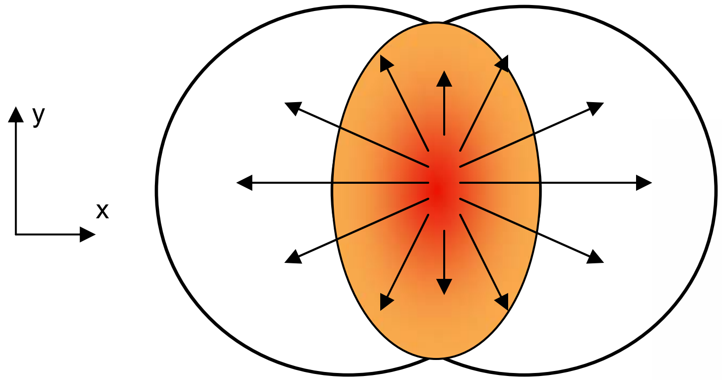
Energy loss results anisotropy based on location of hard scattering in collision volume.

v_2 at High p_T



$\sqrt{s_{NN}} = 200\ GeV$
Minimum Bias
PHENIX PRELIMINARY
20 < Centrality < 40 (%)
10 < Centrality < 20
00 < Centrality < 10
PHENIX PRELIMINARY
v2
v2
pT (GeV/c)
pT (GeV/c)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5

Scaled Elliptic Flow

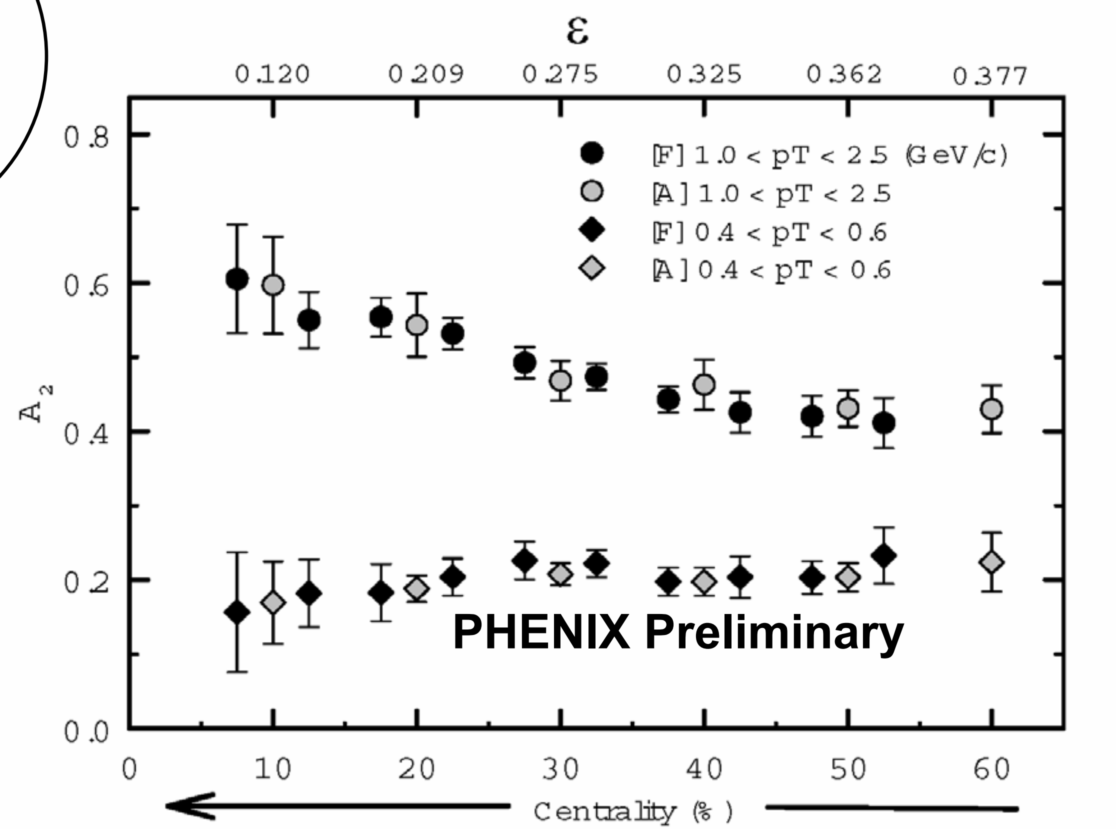


Scaled elliptic flow:

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

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

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

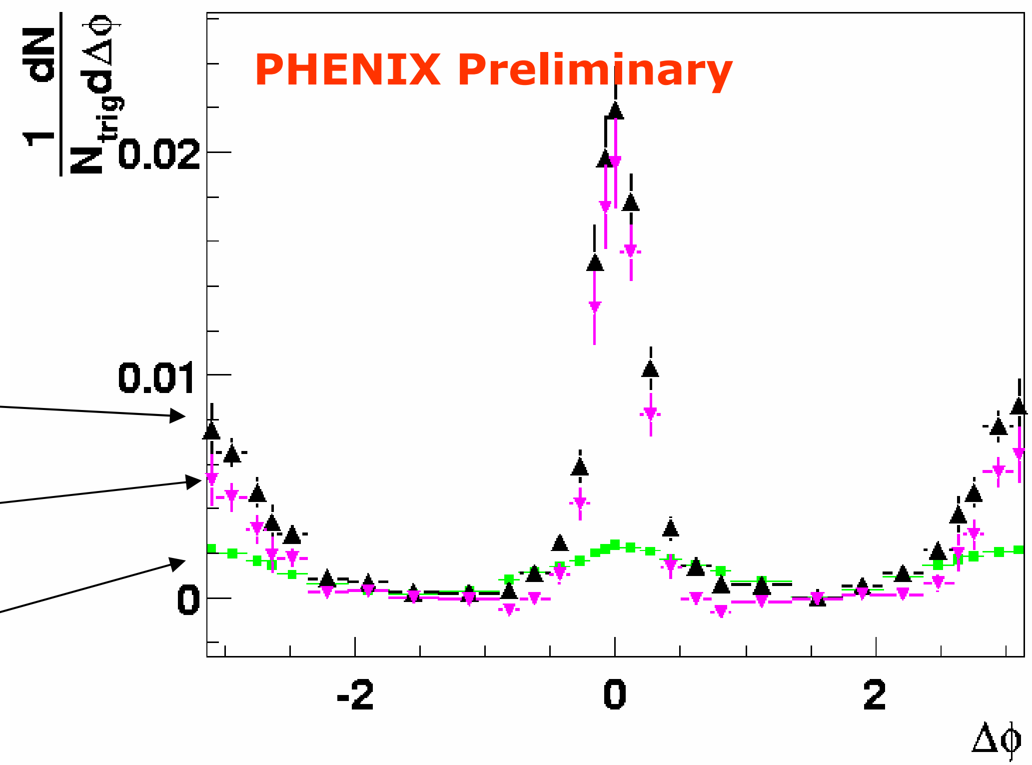


Δφ, Δη Correlations

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

- Clear jet structure observed

pp@200GeV

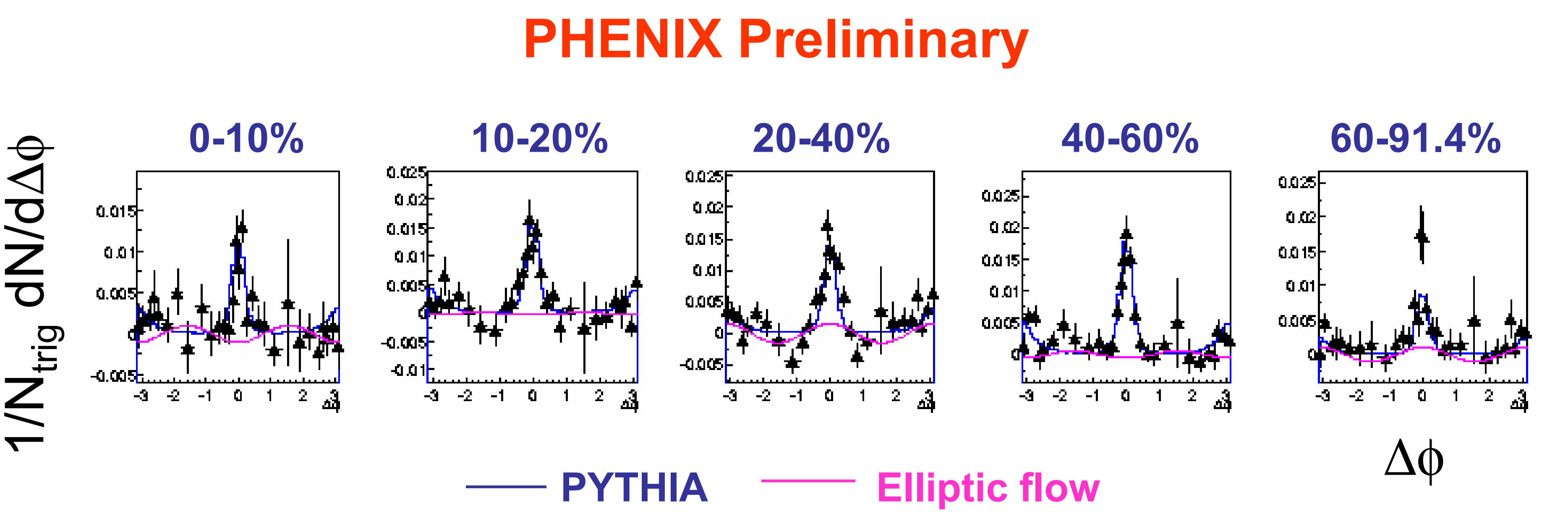


black: pair distribution

purple: subtracted distribution

green: mixed events

Jets in Au+Au

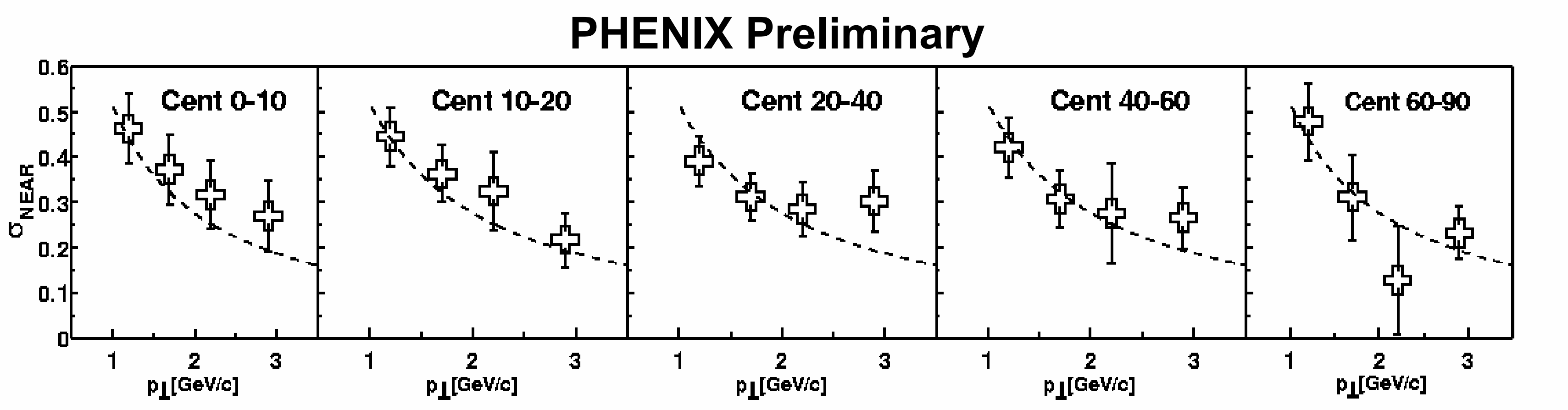


trigger photon p_T > 2.5 GeV/c

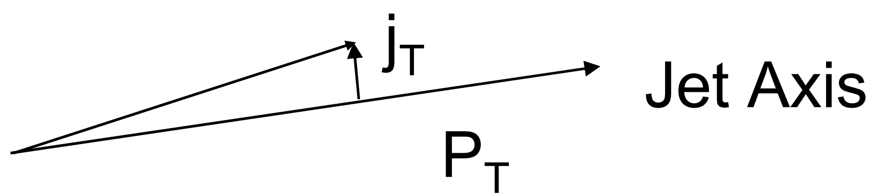
$\Delta\phi$ distribution for p_T = 2-4 GeV/c

- Jet correlations observed across all centralities.

Near Side Correlation Width



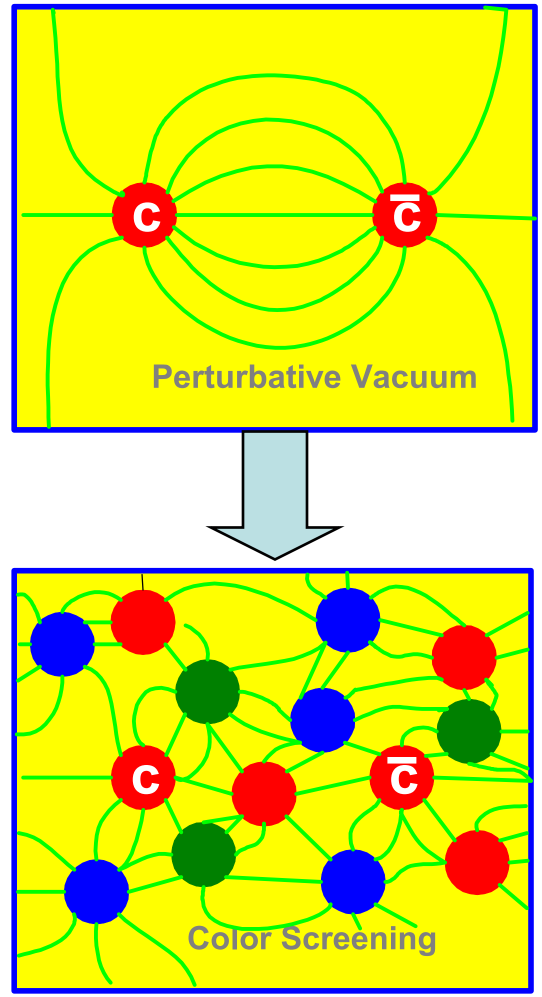
The dashed line (not a fit) corresponds to a constant $j_{\perp}$=400 MeV.
(transverse momentum with respect to "jet" axis)



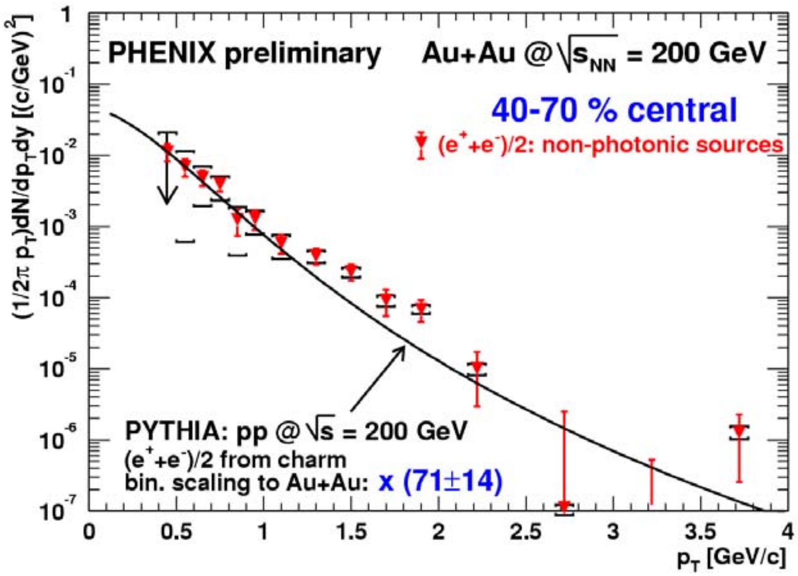
Charm Production

- Color screening in deconfined medium can suppress production of charmonium bound states.

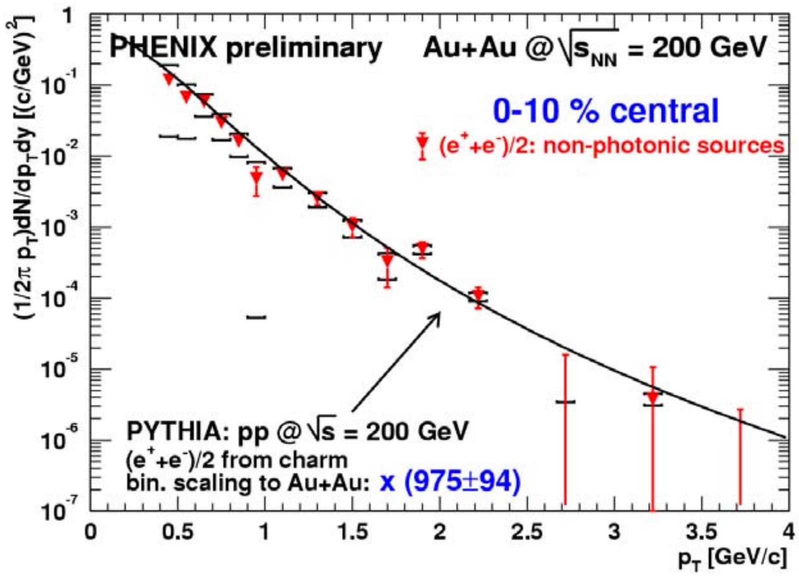
- Need to quantify overall level of charm production before we can talk about suppression.



Single Inclusive Electrons



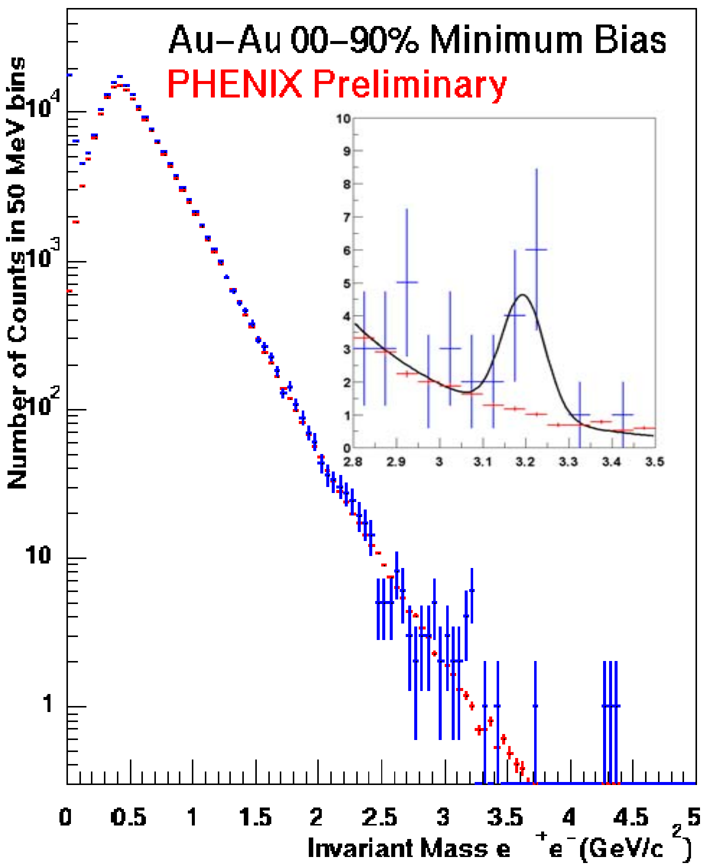
- PHENIX measured e^+e^- spectra from non-photonic sources – charm!
- Level and p_T dependence consistent with e^+e^- from scaled PYTHIA
- Analysis of p+p data ongoing to allow direct comparison



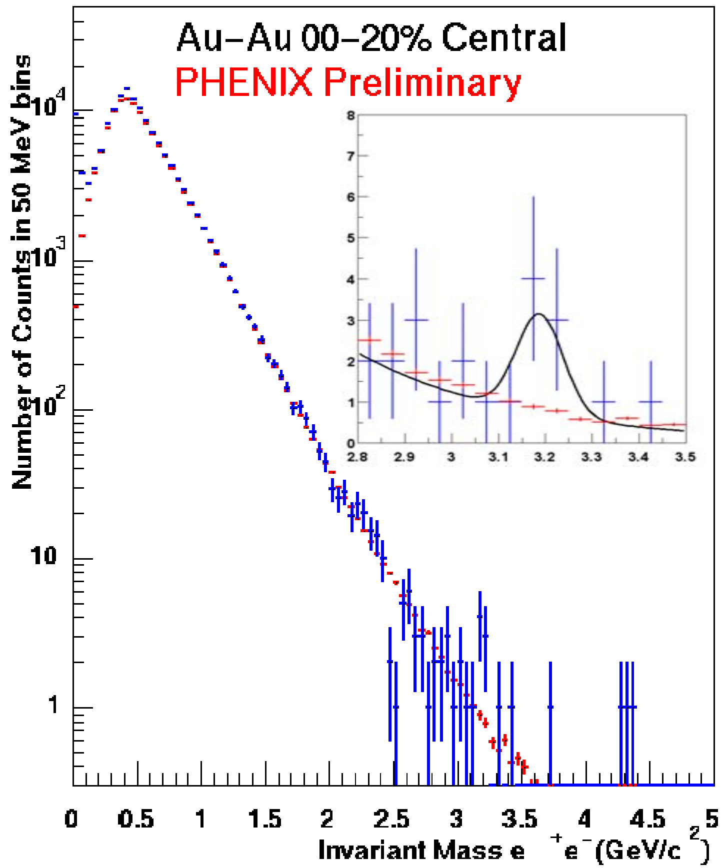
- Reduced quenching for heavy quarks – "dead zone" effect

e^+e^- Invariant Mass Spectra

$N_{J/\Psi} = 10.8 \pm 3.2$ (stat) $+ 3.8 - 2.8$ (sys)

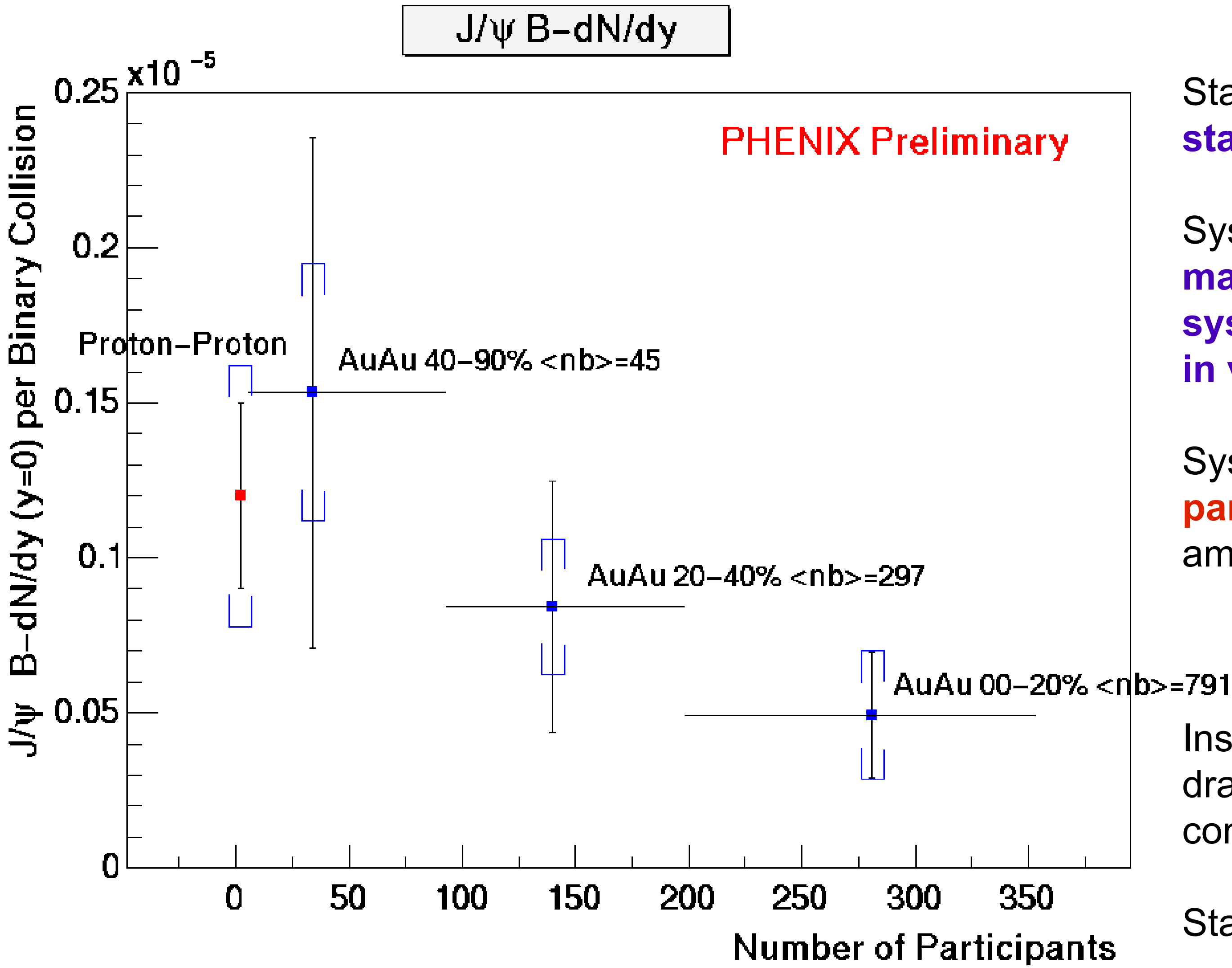


$N_{J/\Psi} = 5.9 \pm 2.4$ (stat) ± 0.7 (sys)



- Low statistics, but proof of principle!

J/Ψ Production



Statistical errors are **standard deviations**

Systematic errors are **maximum plausible systematic spreads in values**

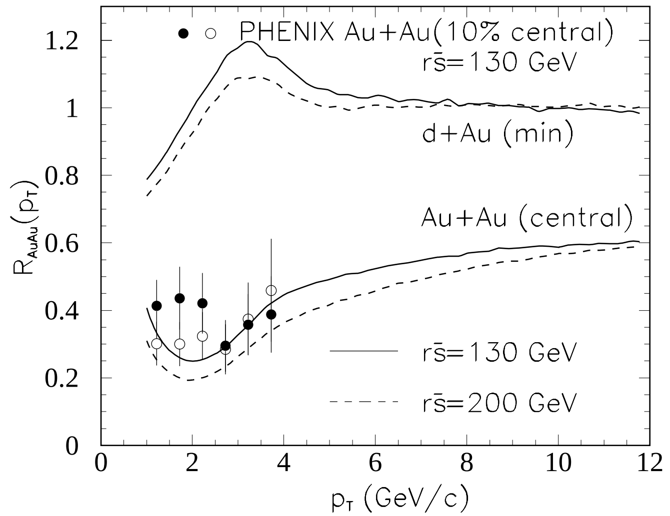
Systematic errors are **partly correlated** among all points

Insufficient statistics to draw any firm conclsions at this time.

Stay tuned….

What's Coming for Run-3?

- d+Au collisions a top priority provides a baseline for RHI data



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

- Additional statistics in p+p running with two muon arms, MuID trigger

Summary

PHENIX has begun to explore the matter created in Au+Au collisions at RHIC:

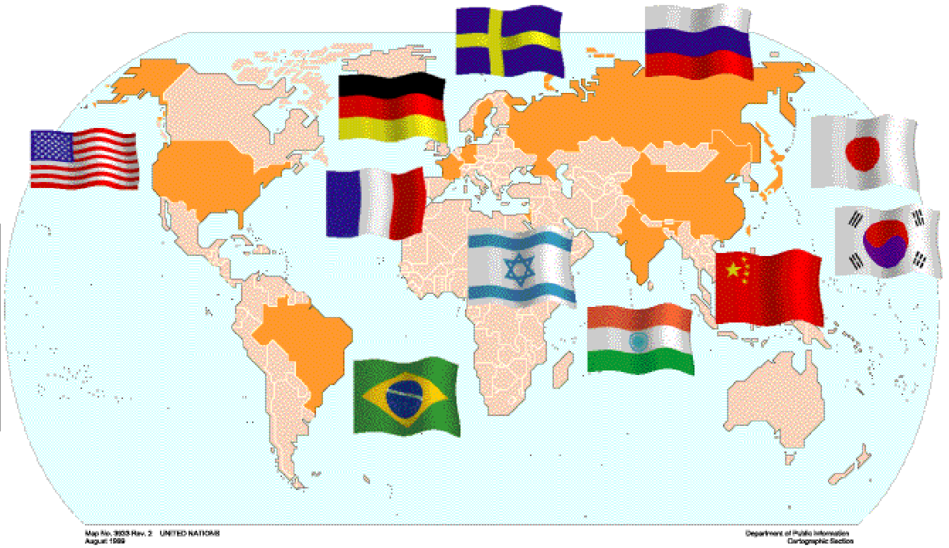
- High energy density created in central collisions **(ε_{BJ} ~ 5 GeV/fm^3)**
- Expanding (exploding) particle source **(β_T = 0.7)**
- Early thermalization **(significant elliptic flow)**
- Short duration of particle emission **(R_{out}/R_{side} ~1)**
- Energy loss of hard scattered partons **(R_{AA} < 1, large v_2 at high p_T)**
- Just getting started with leptonic probes

There is a lot more exciting physics to come!

Pioneering High Energy Ion Experiment

PHENIX

11 Countries
51 Institutions
400+ Collaborators



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IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, BP1, F-91406, Orsay, France
LPNHE-Palaiseau, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France
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Banaras Hindu University,Banaras, India
Bhabha Atomic Research Centre (BARC),Bombay, India
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