Recent results from high-energy heavy-ion collisions experiments at RHIC

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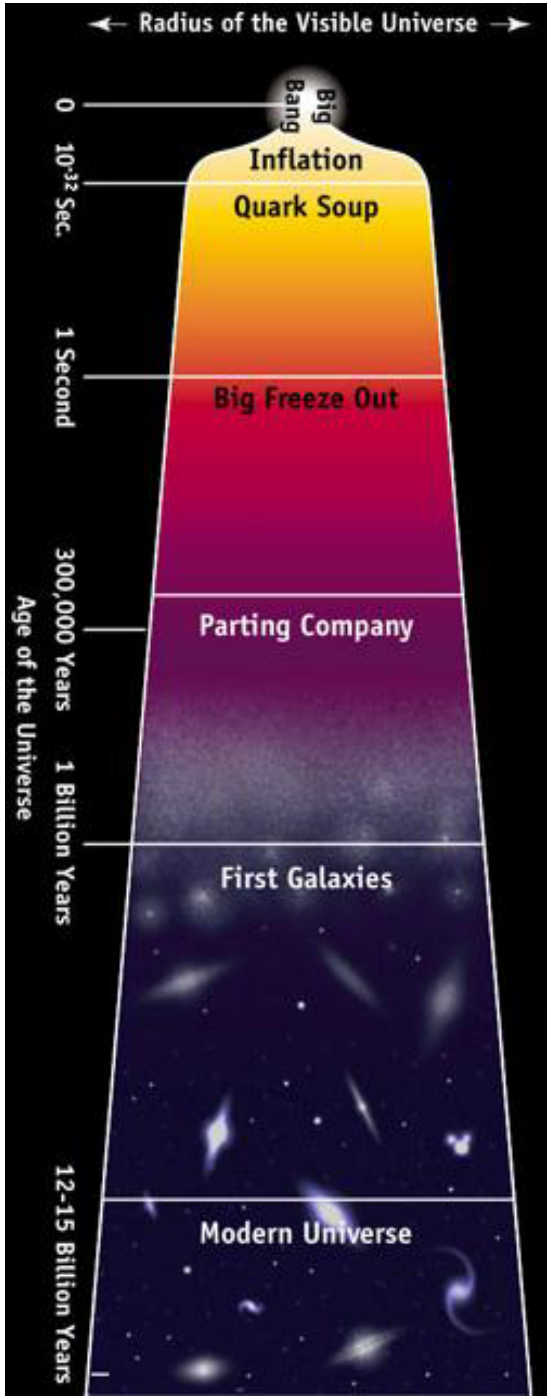
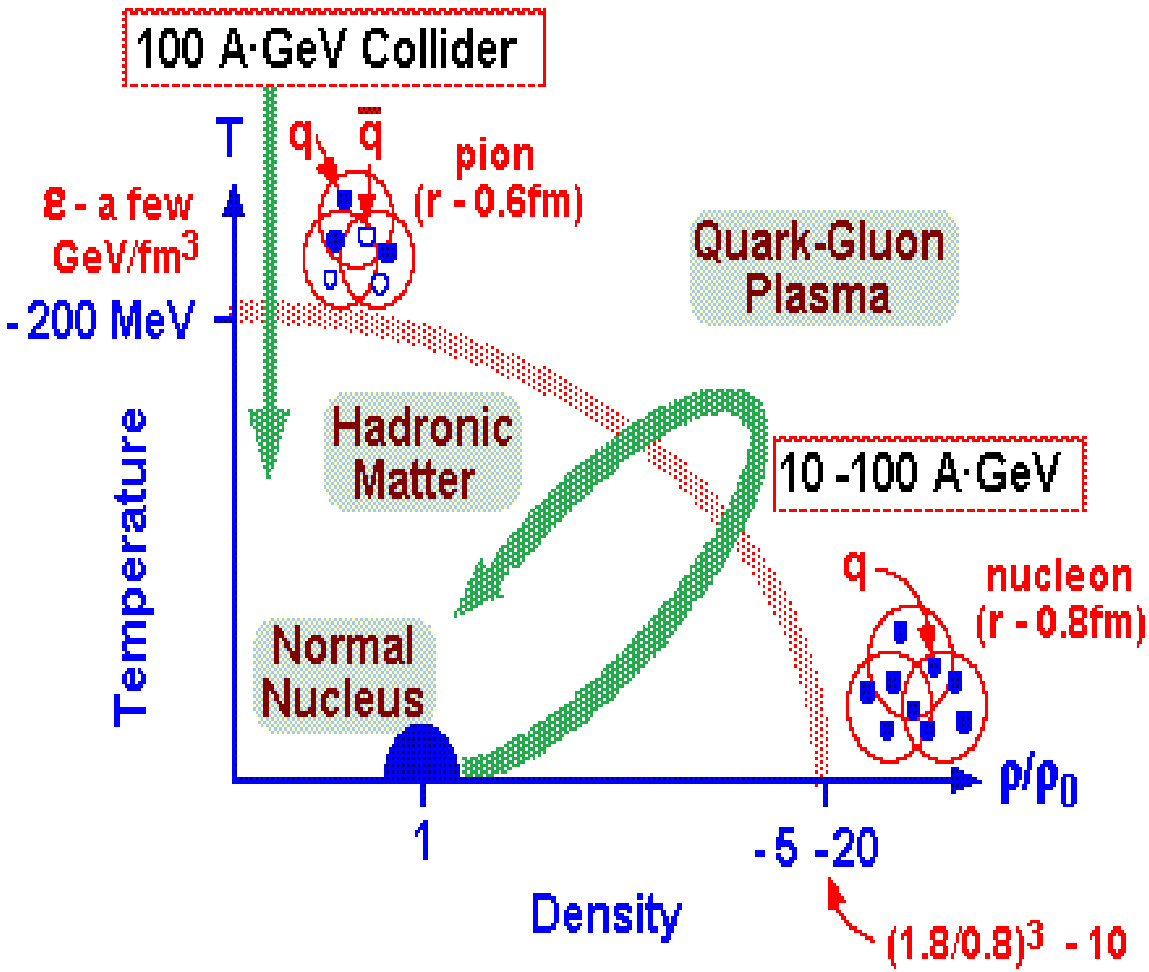
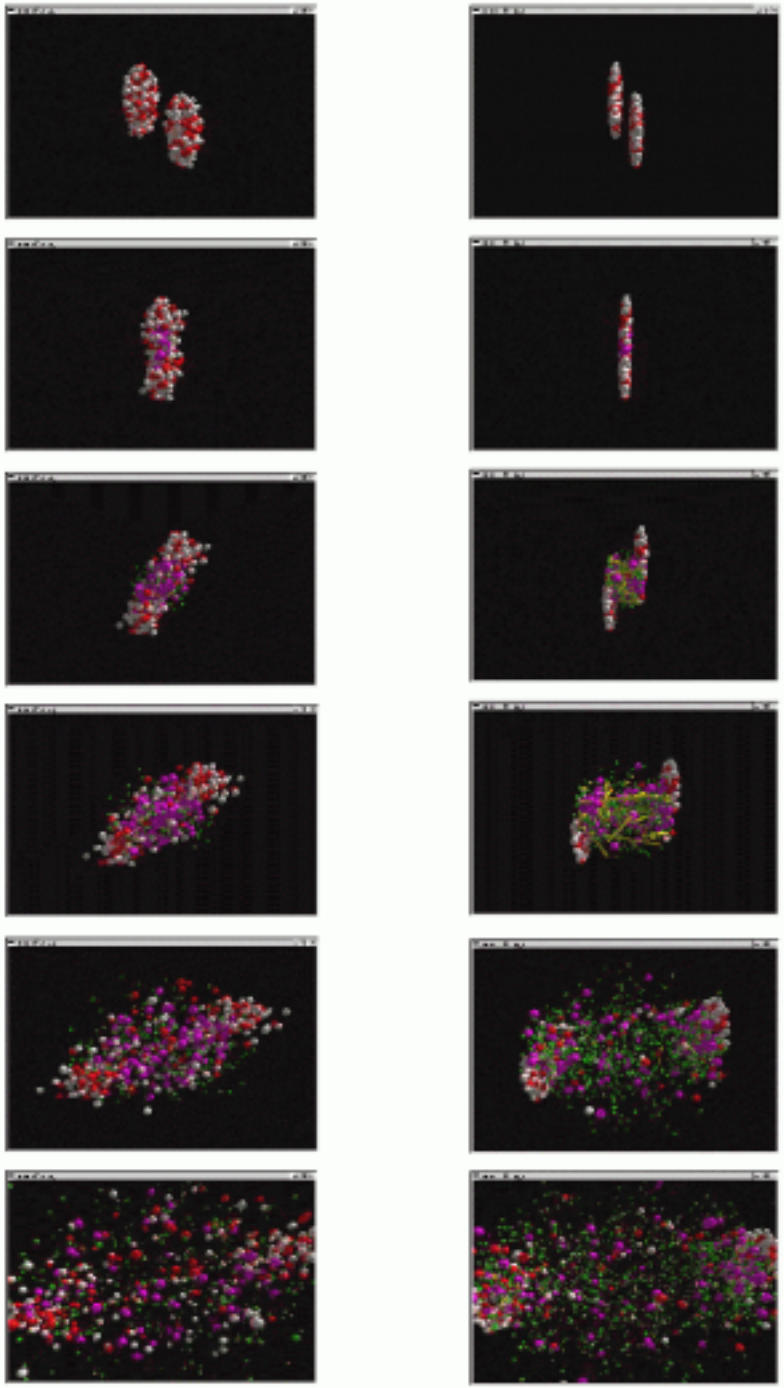
Contents

High pT suppression
Au+Au w.r.t. p+p and d+Au
Back-to-back jets
Rare probes
Expansion and flow



Quark-gluon-plasma



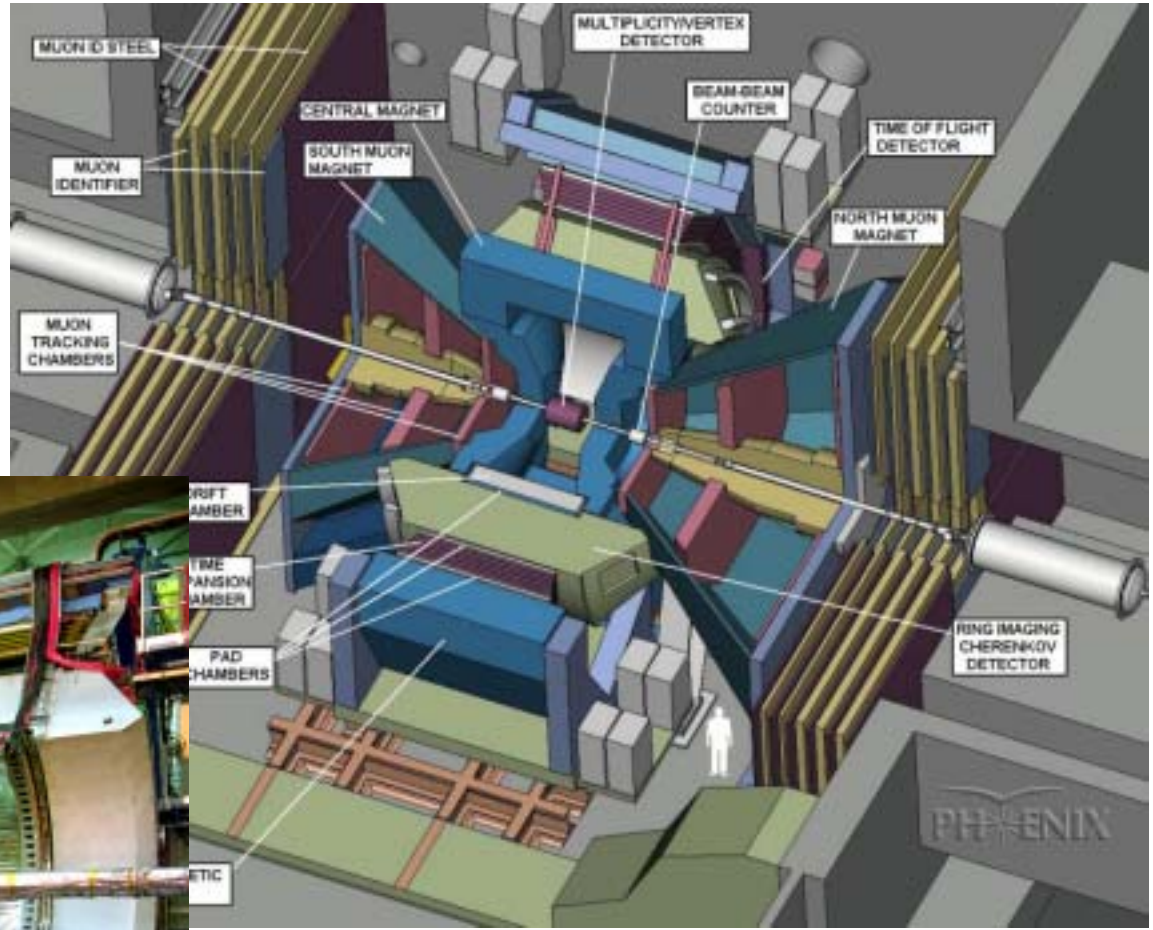


Au+Au collisions in sqrt(s_{NN})=200GeV with

Relativistic Heavy Ion Collider (RHIC) at BNL

PHENIX

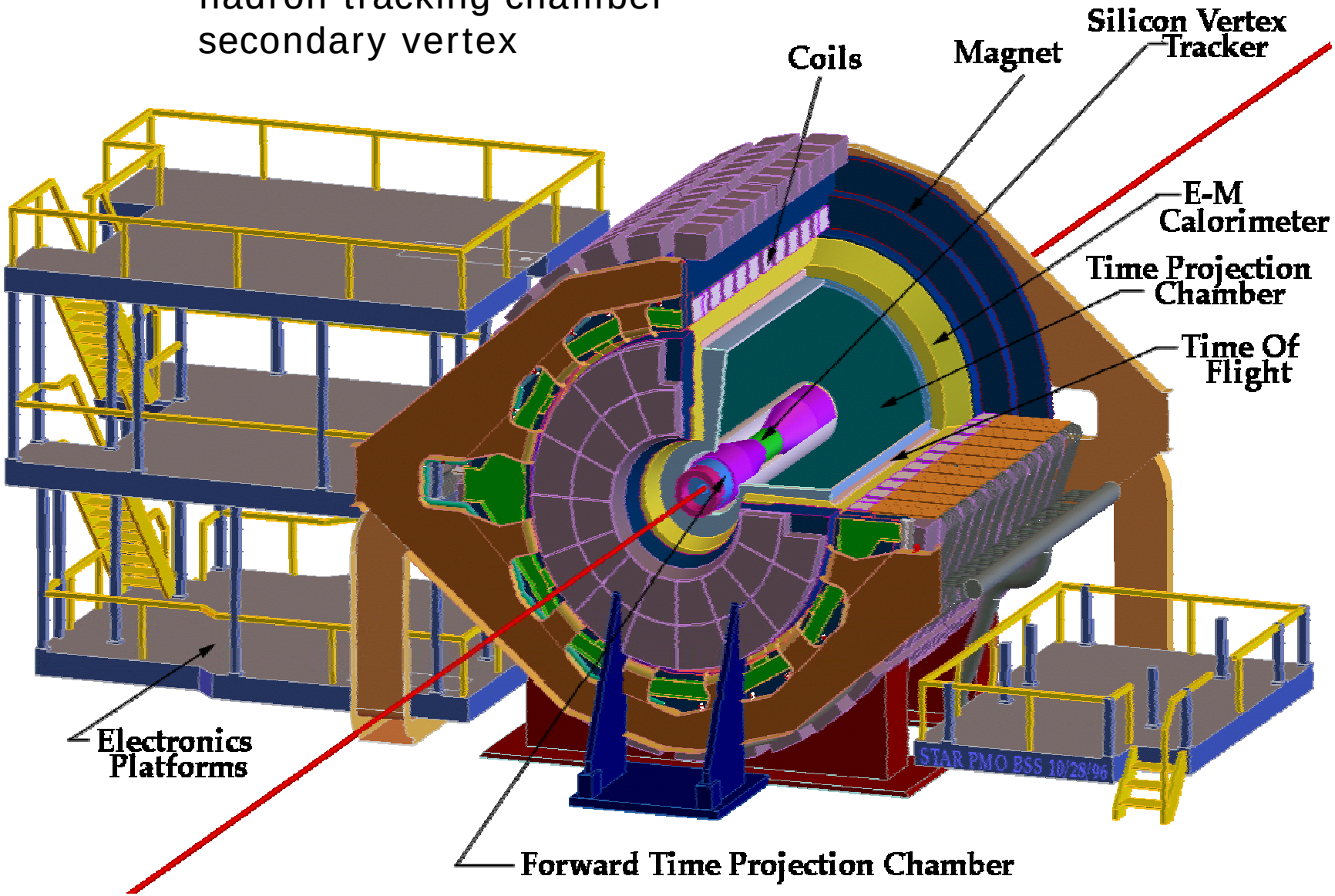
Hadron PID
Electron/muon
Photon



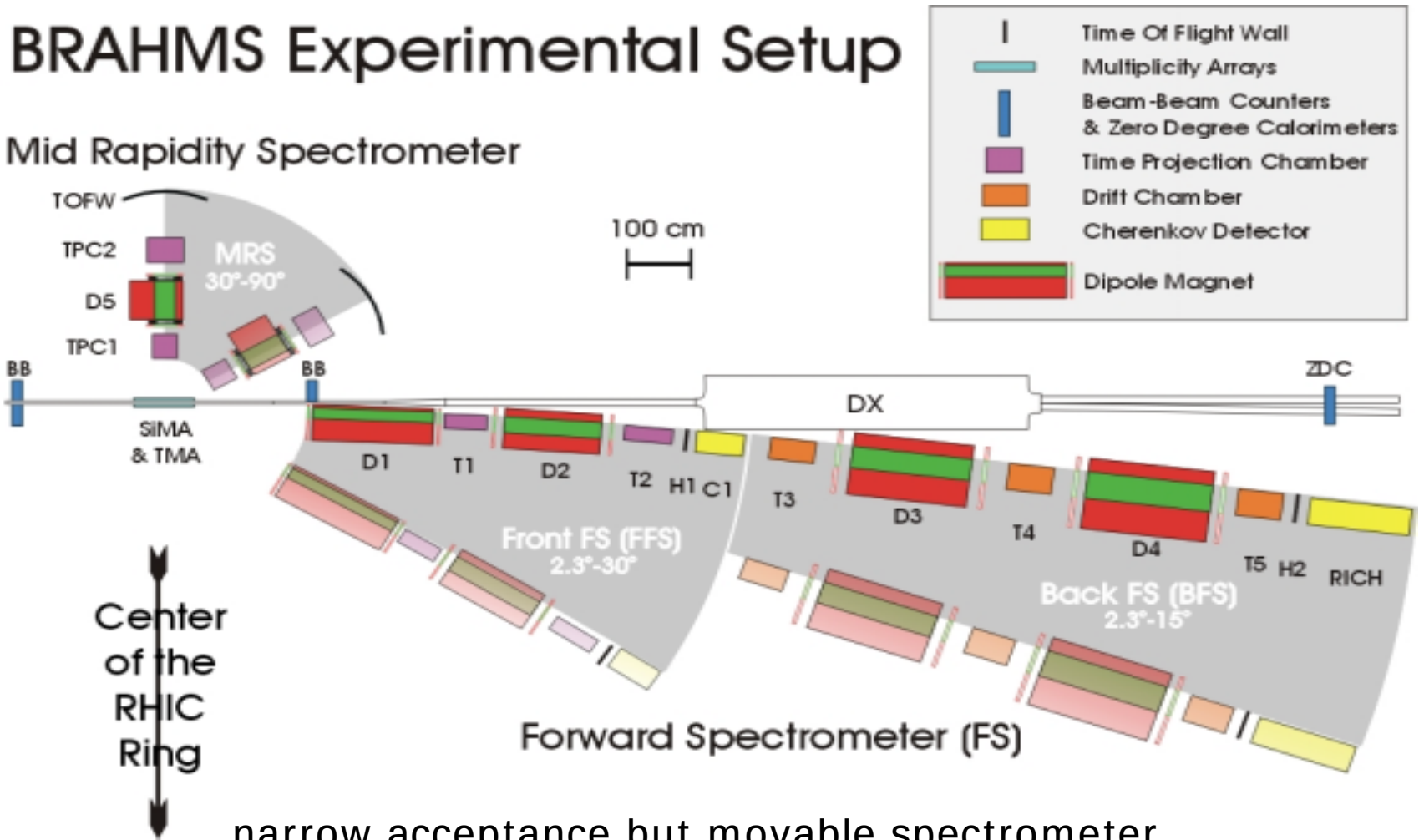
mid-rapidity hadron/electron/
photon spectrometer

Forward-rapidity muon
spectrometer

STAR large acceptance
hadron tracking chamber
secondary vertex



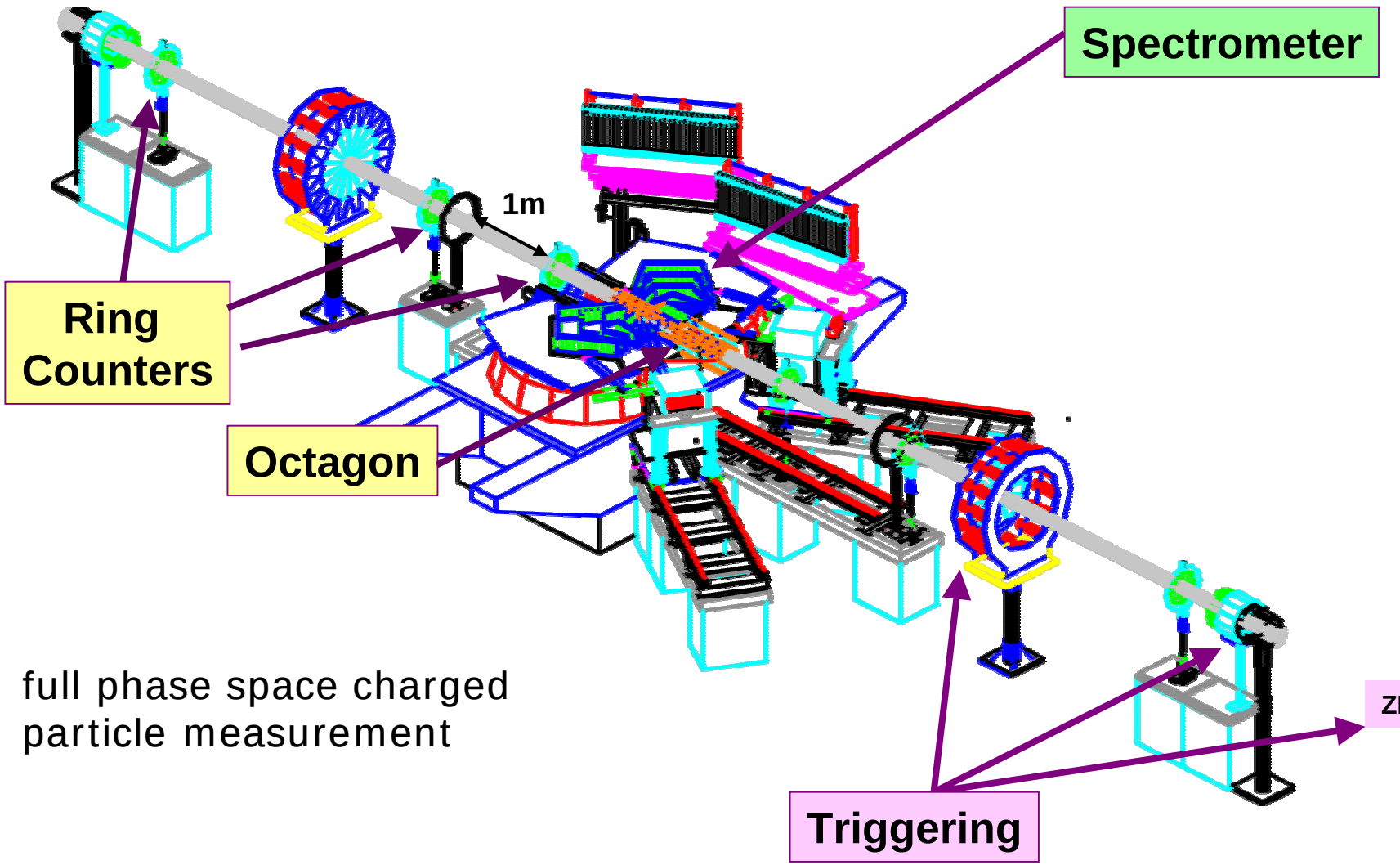
BRAHMS Experimental Setup



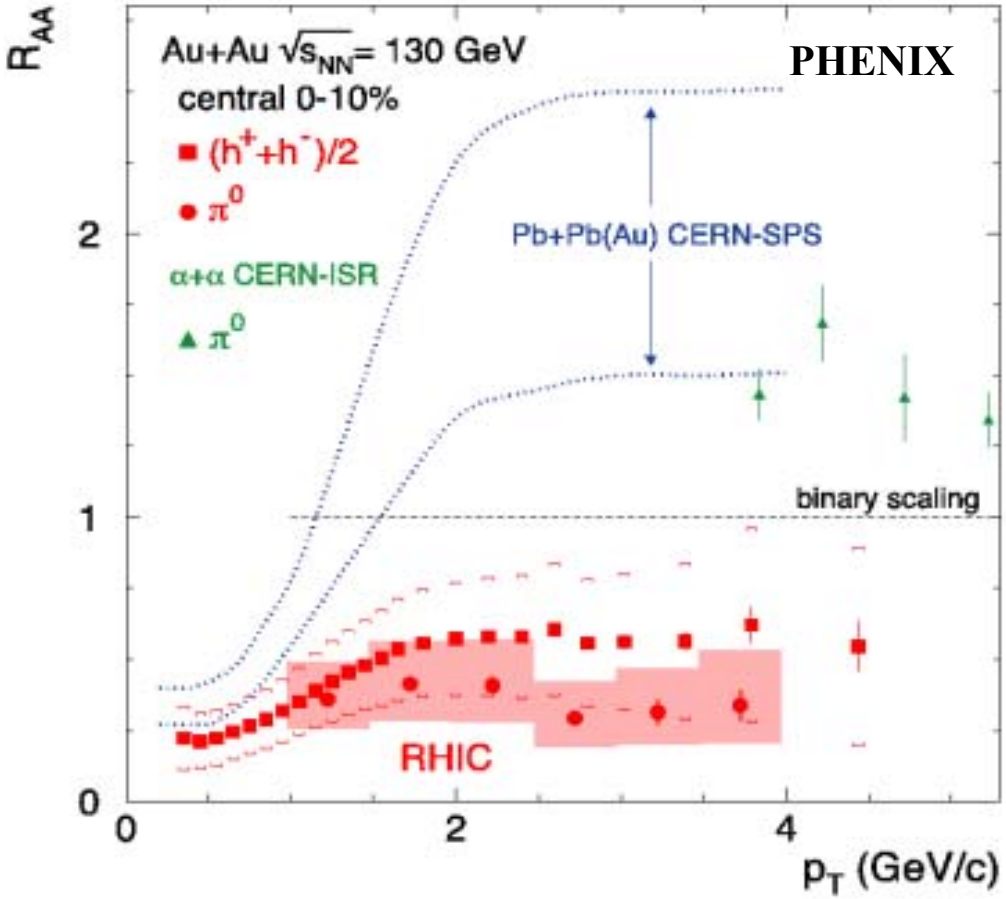
narrow acceptance but movable spectrometer
hadron PID

PHOBOS

ZDC

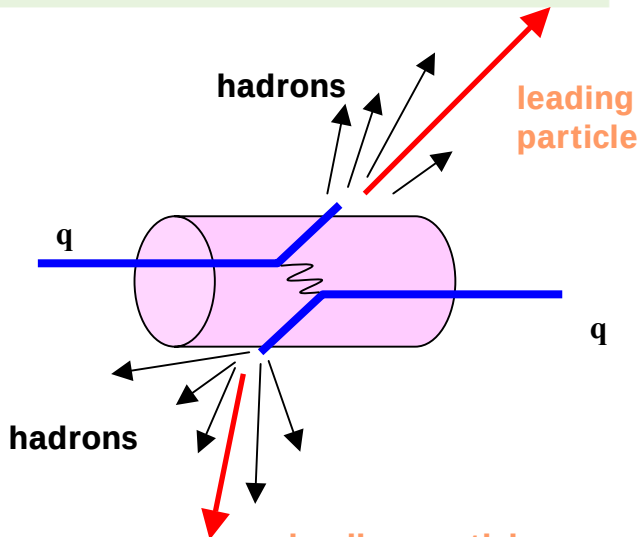


full phase space charged particle measurement

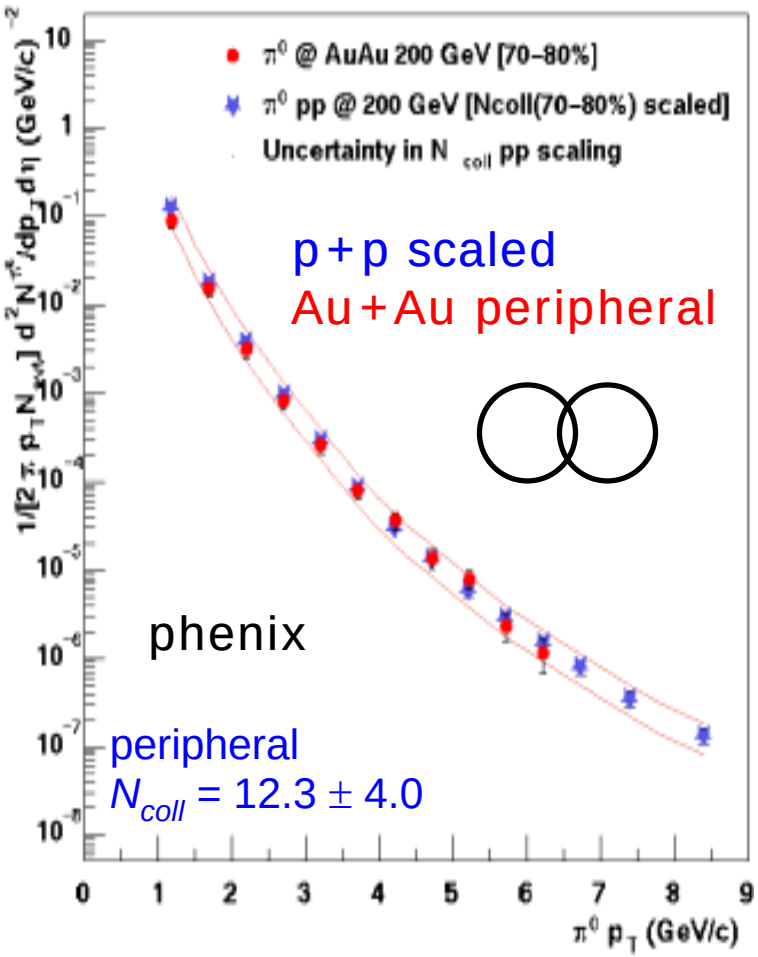


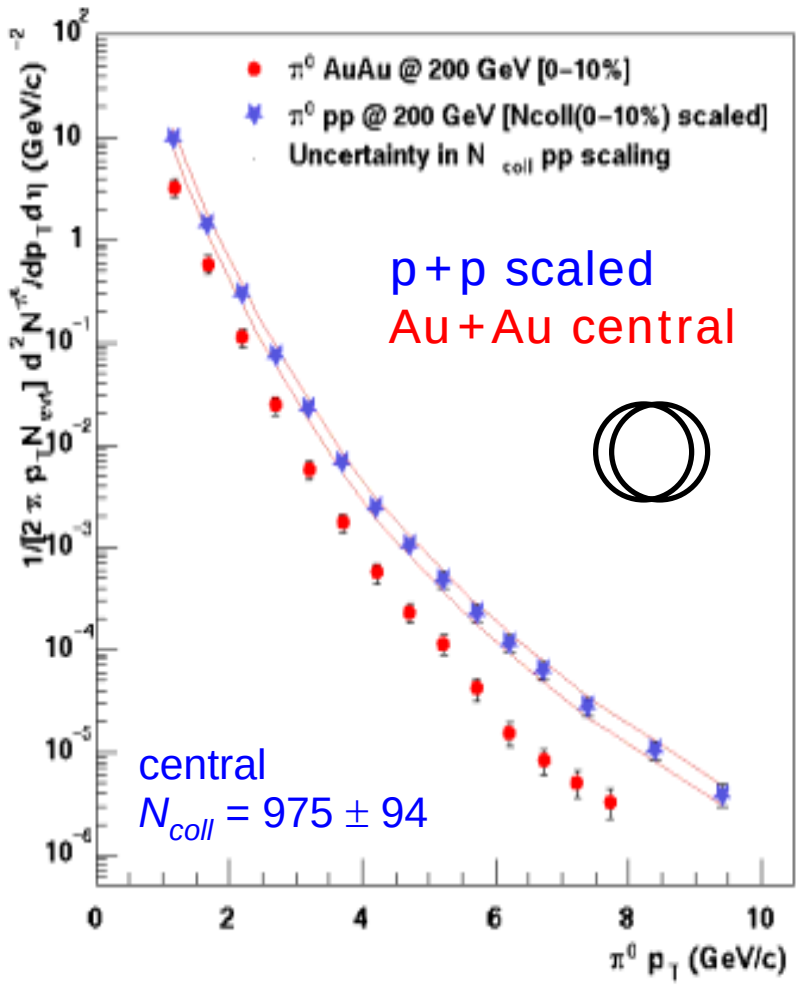
Jet-quenching

schematic view of jet production

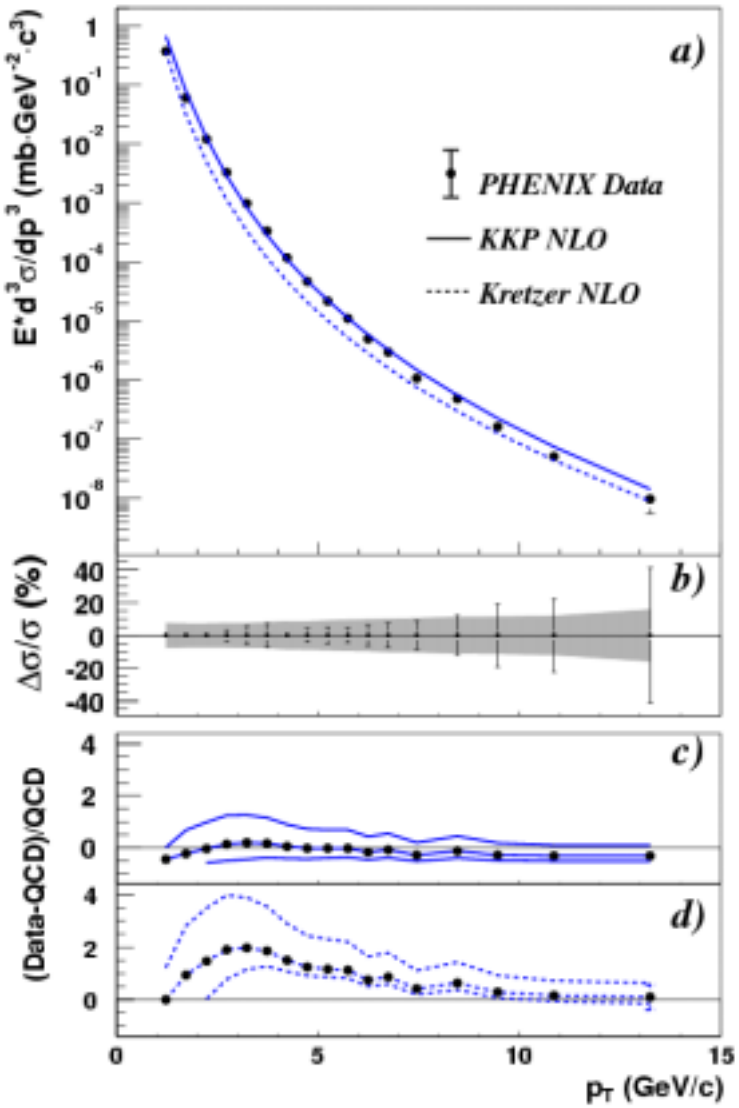


neutral pion pT distribution in Au+Au and p+p



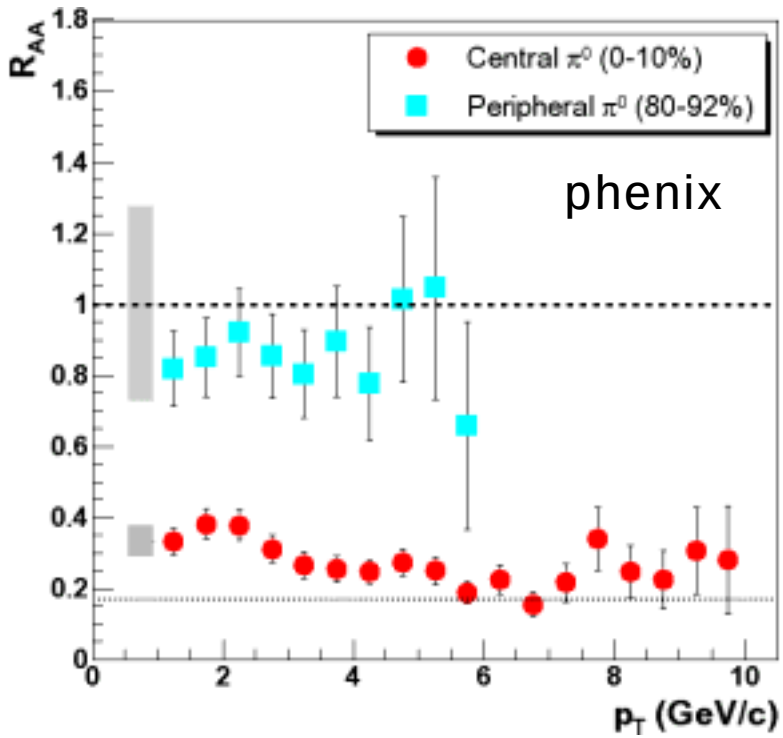


p+p at 200GeV

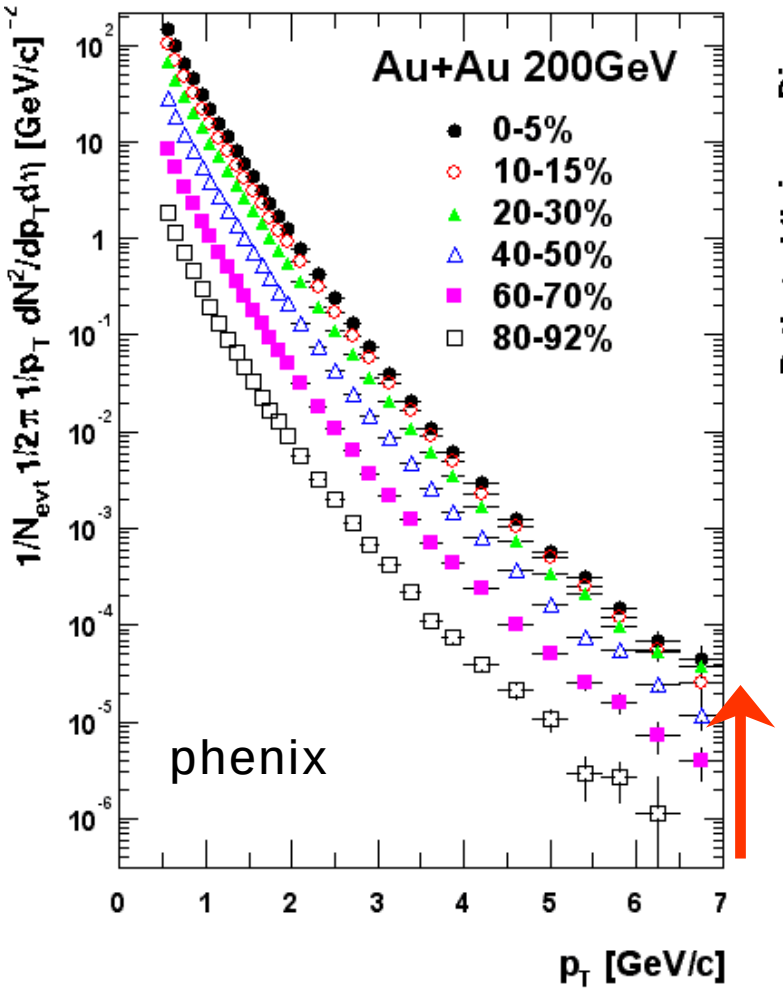


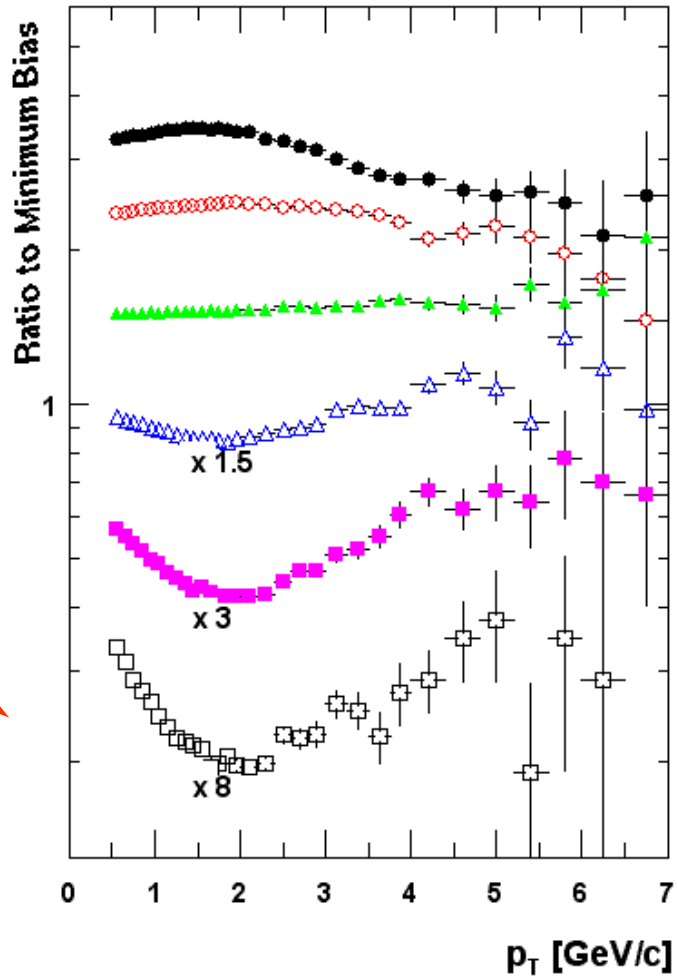
Au+Au at 200GeV

$$R_{AA}(p_T) = \frac{\frac{1}{N_{evt}}\frac{d^2N^{A+A}}{dp_T d\eta}}{\frac{< N_{binary} >}{\sigma_{inel}^{N+N}}\frac{d^2\sigma^{N+N}}{dp_T d\eta}}$$



charged hadron distribution in Au+Au





“Central”

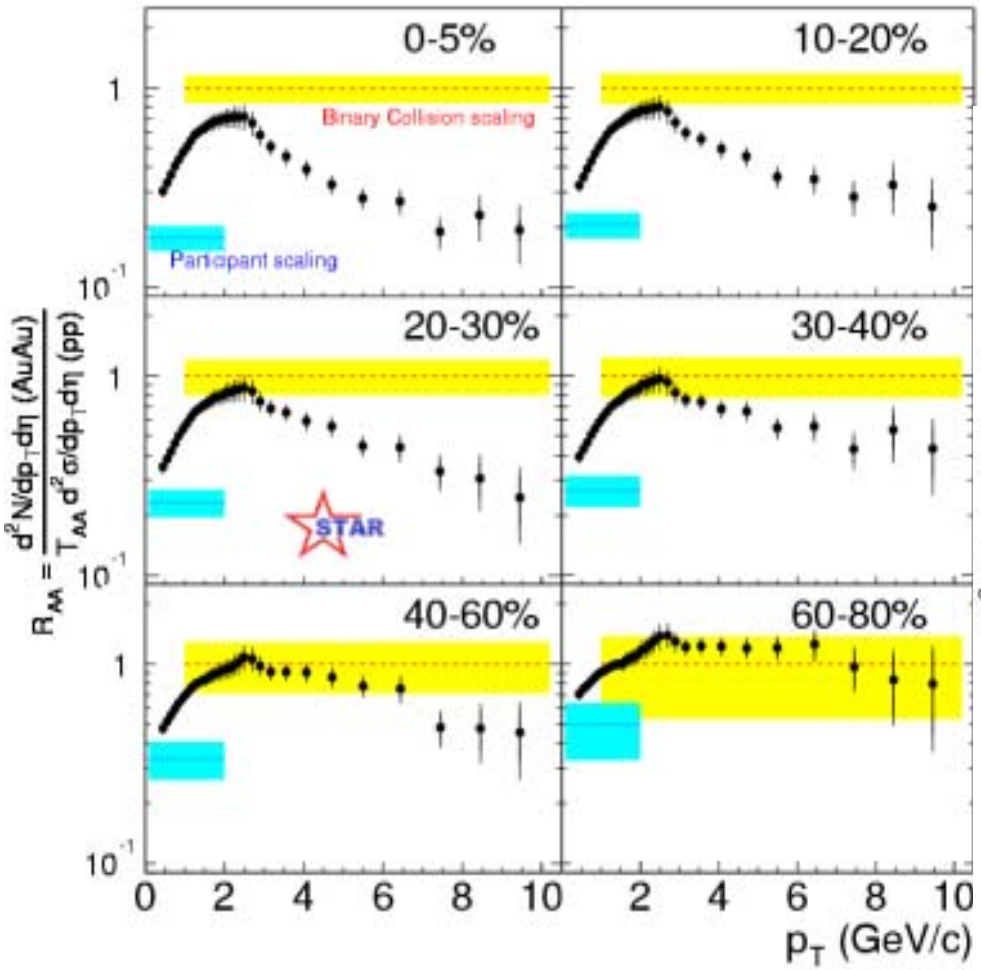
Nuclear Physics

Particle Physics

“Peripheral”

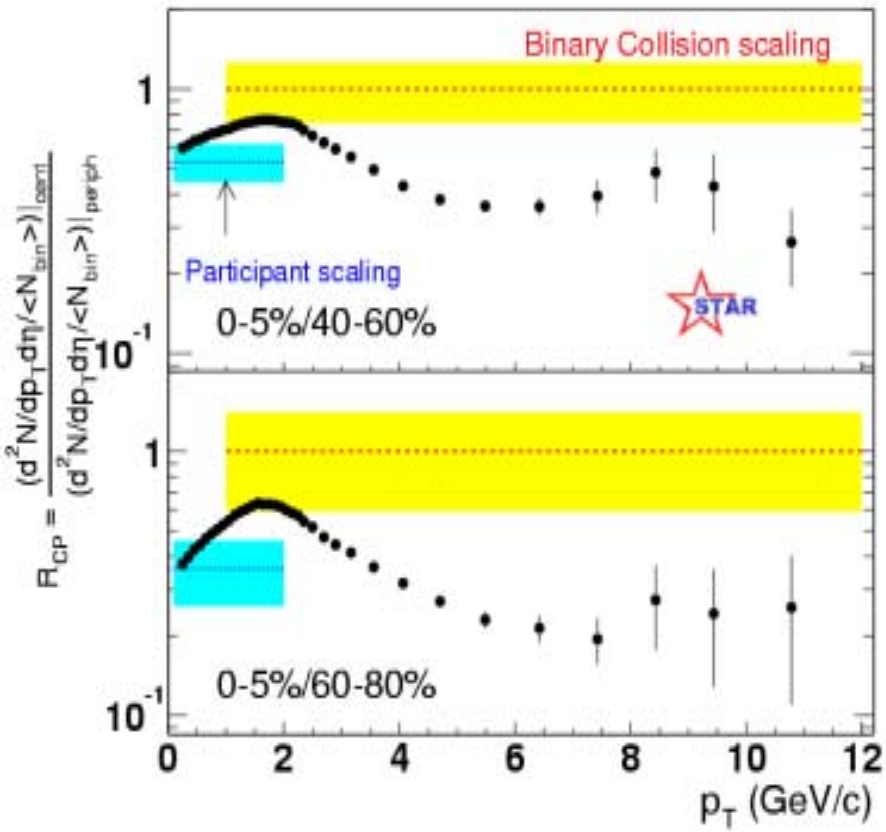
K. Adcox et al, Phys Lett B561 (2003) 82-92

charged hadron scaling in Au+Au

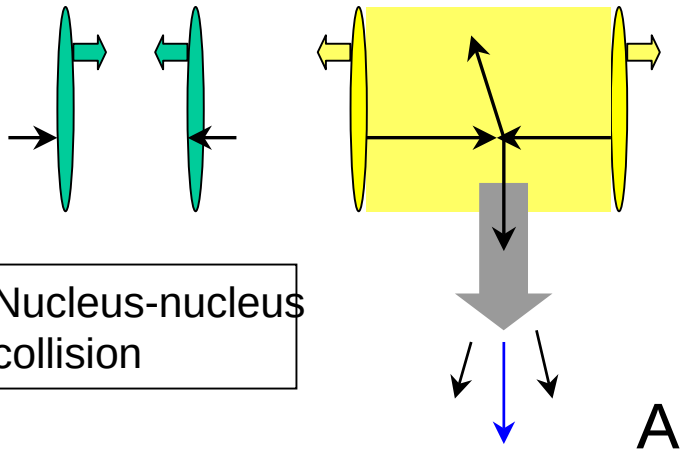


relative to p+p data

star

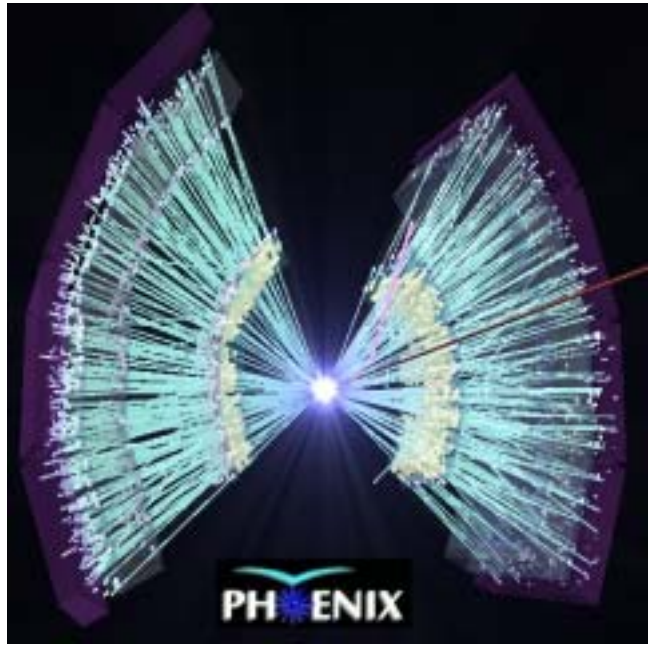


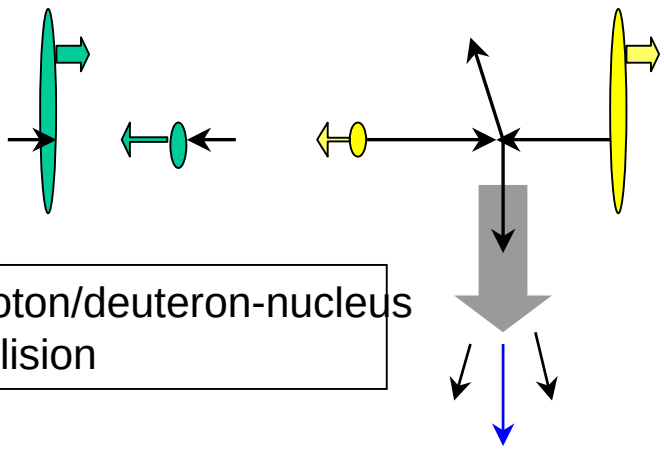
relative to peripheral



Nucleus-nucleus collision

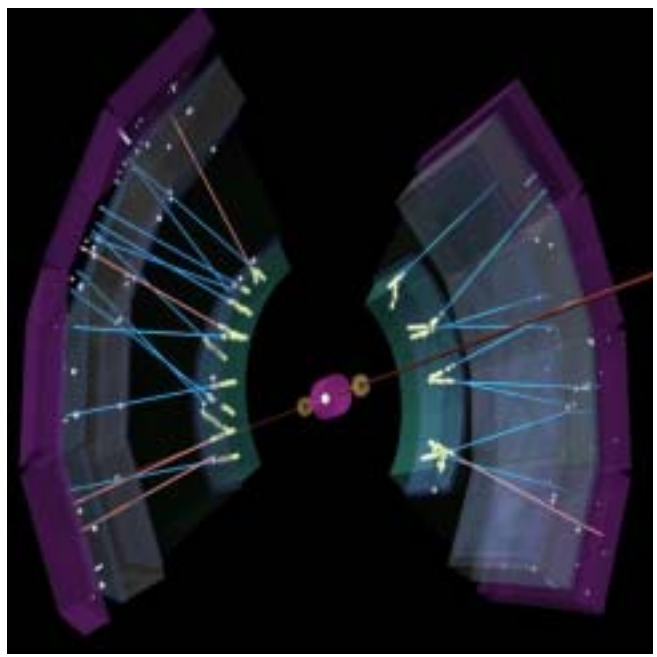
Au + Au



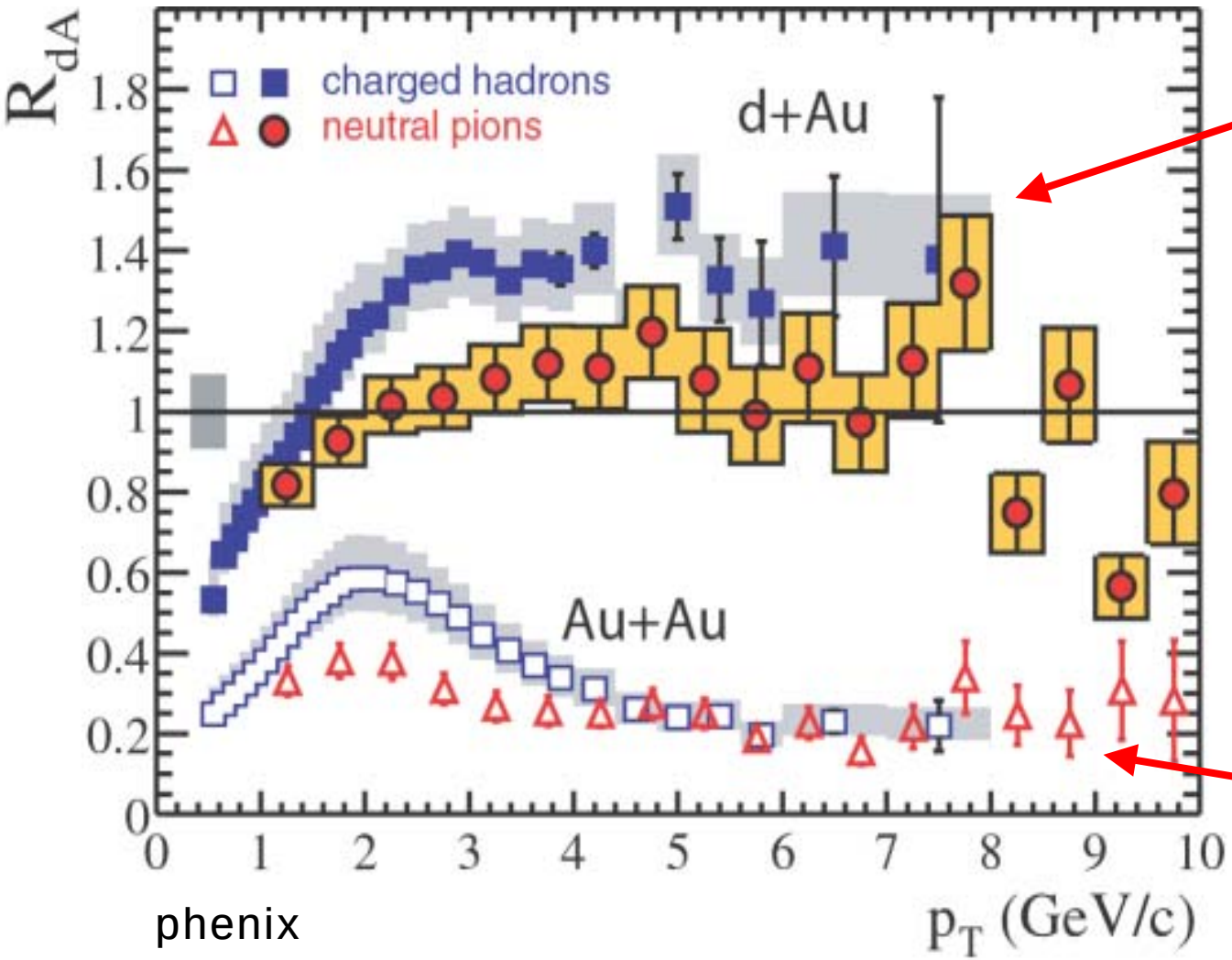


Proton/deuteron-nucleus collision

d + Au



charged hadrons vs neutral pions



d+Au

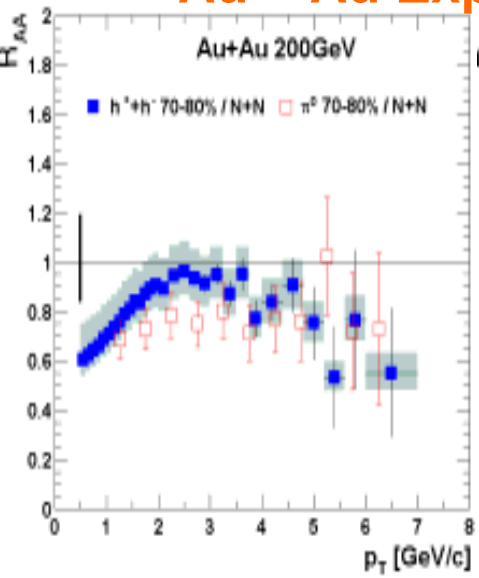
Initial State Effects Only

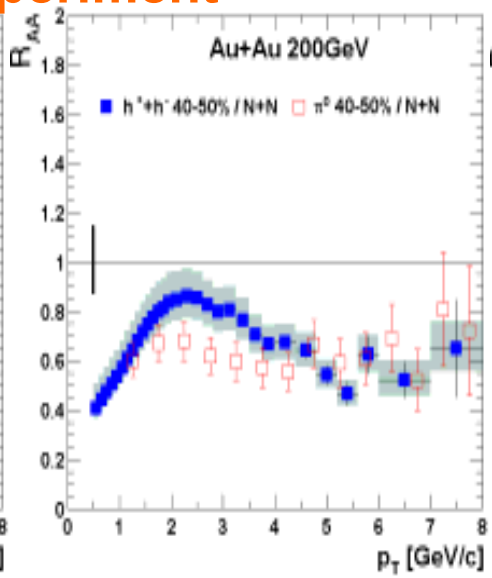
Au+Au

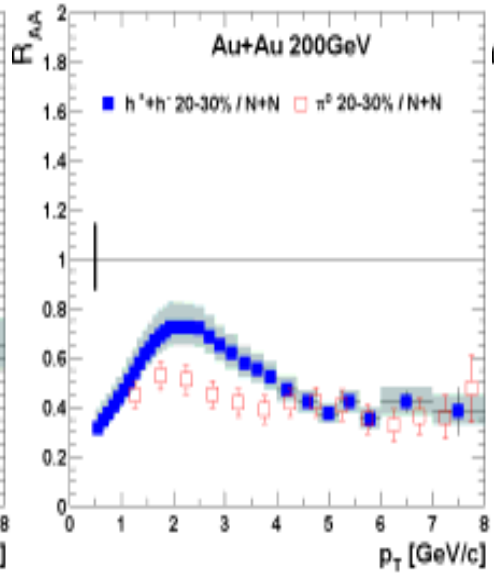
Initial + Final State Effects

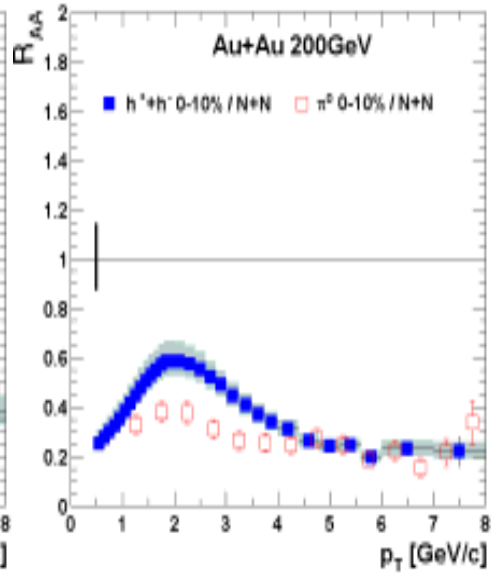
phenix

Au + Au Experiment

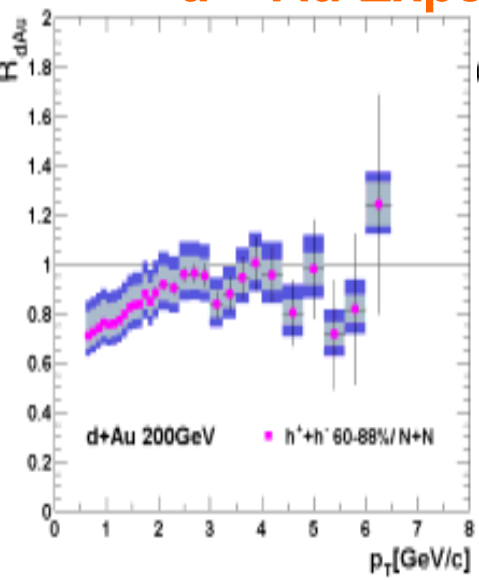


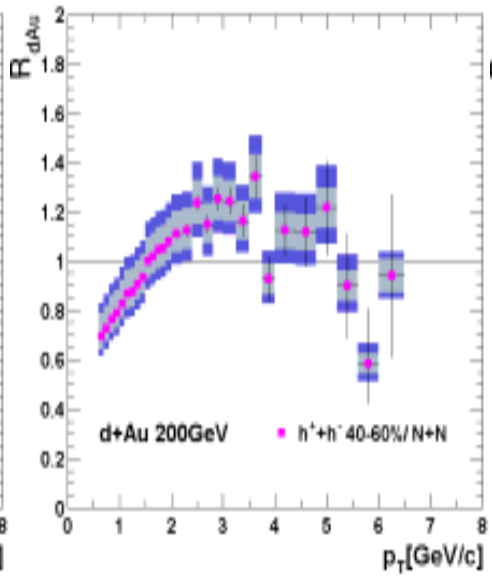


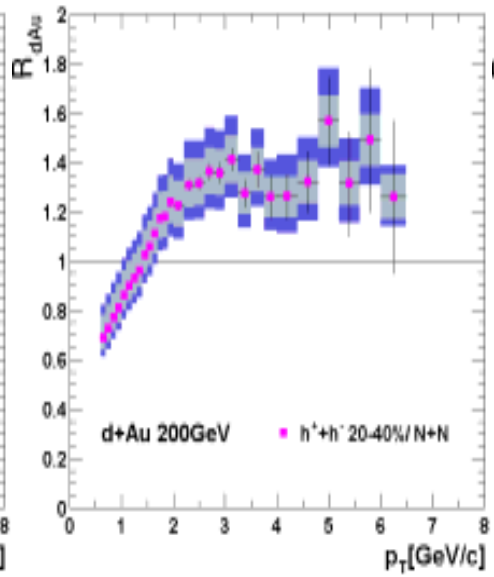


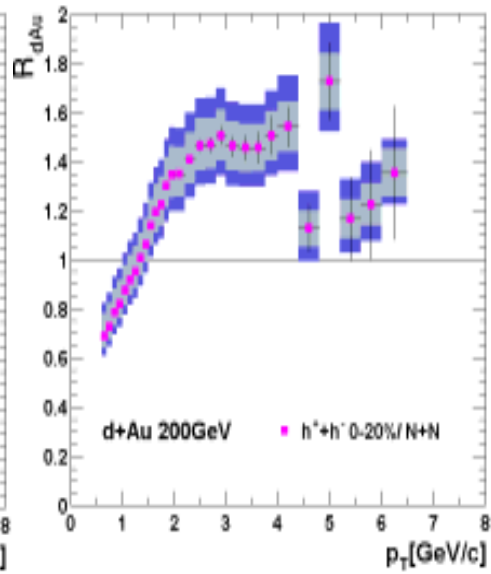


d + Au Experiment

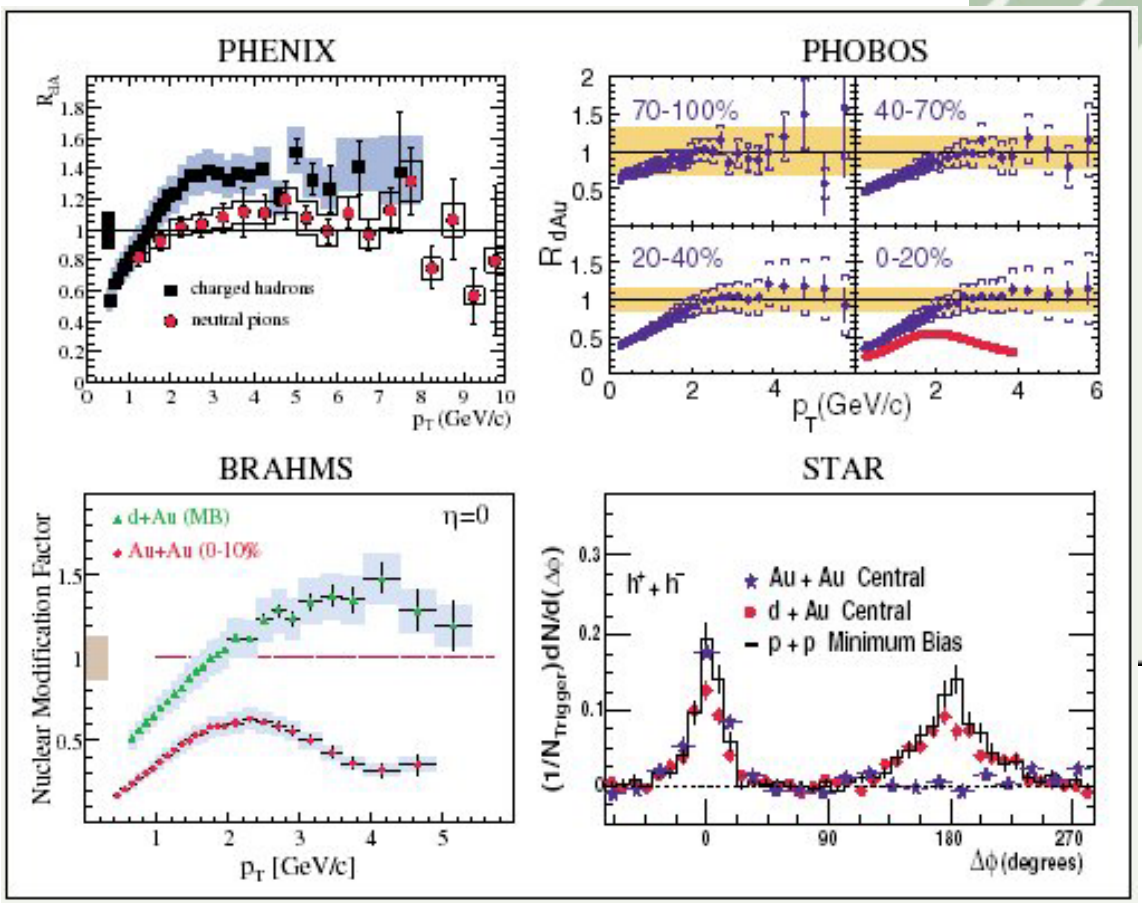


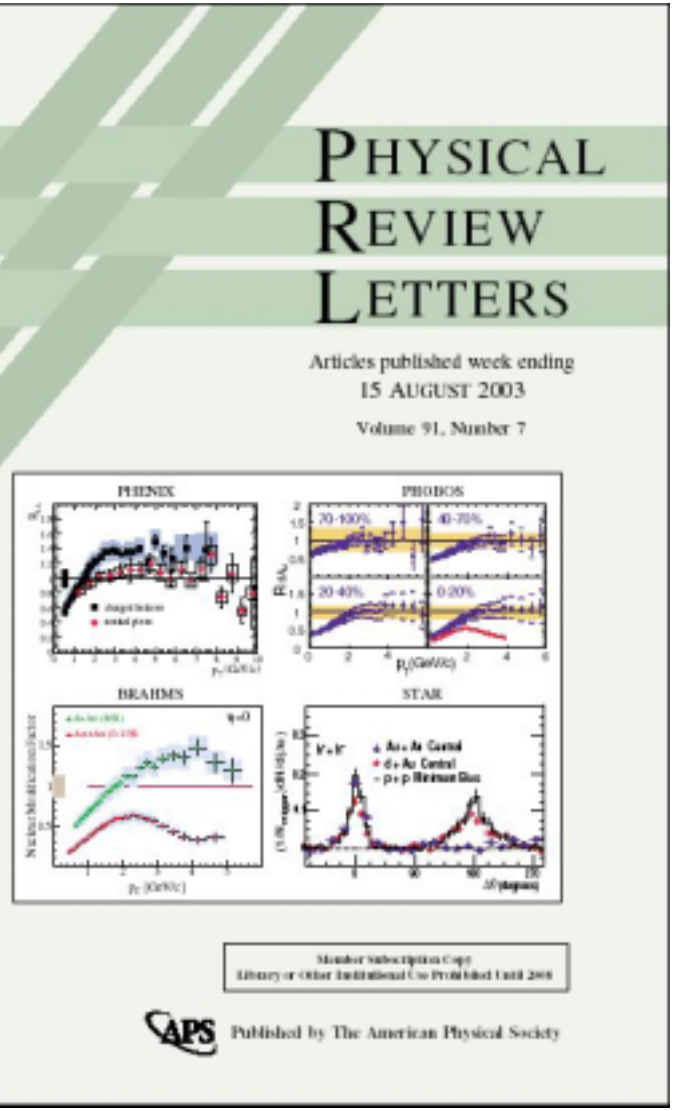


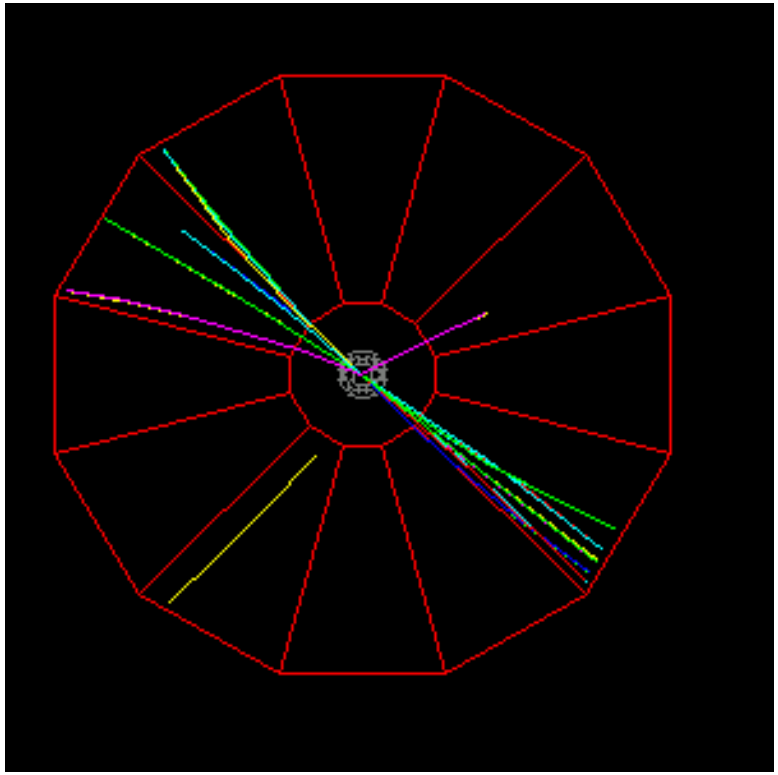




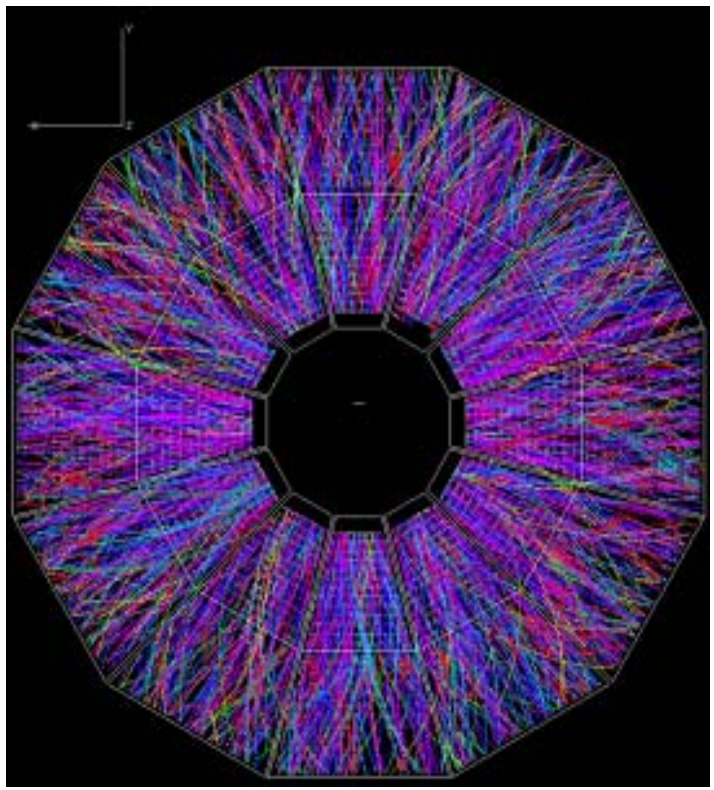
4 experiments agree remarkably well and published simultaneously!!



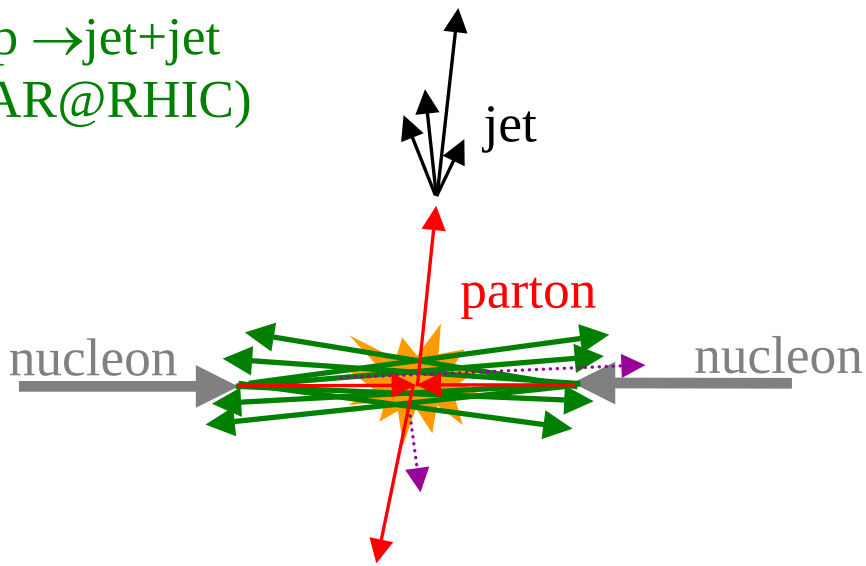




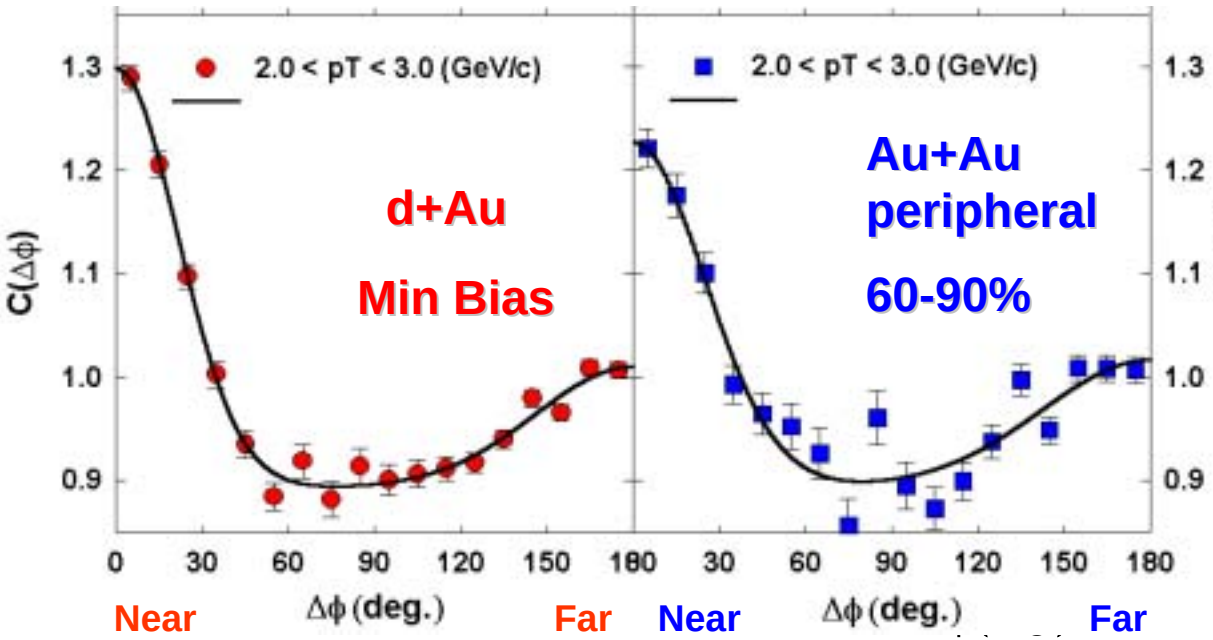
Find this…….in this



p+p →jet+jet
(STAR@RHIC)

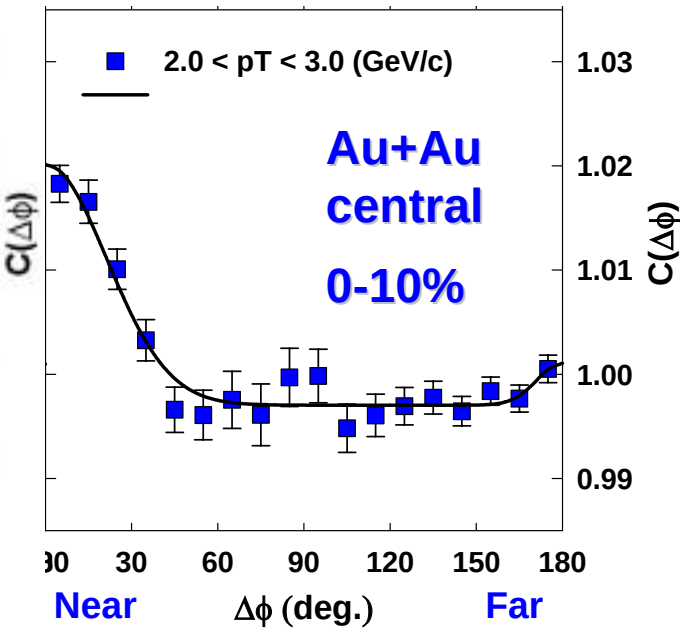


Au+Au →???
(STAR@RHIC)

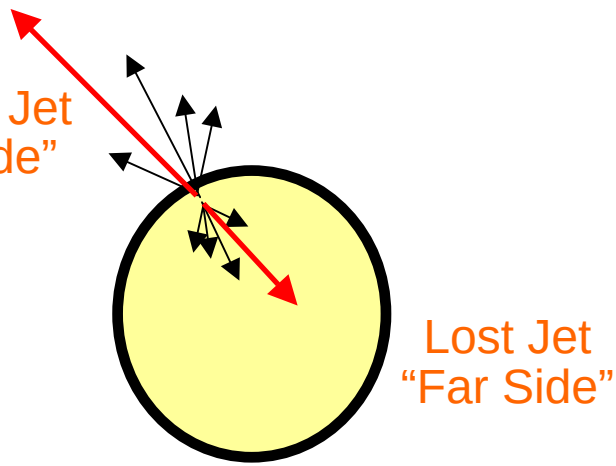


PHENIX Preliminary

PHENIX Preliminary



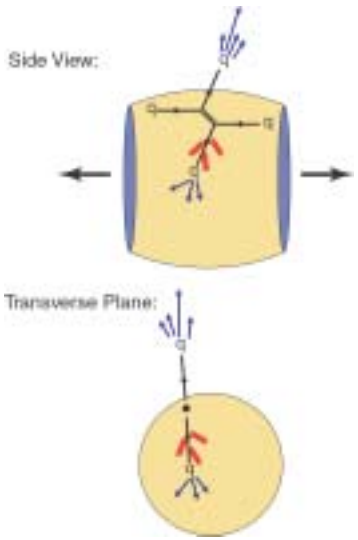
PHENIX Preliminary

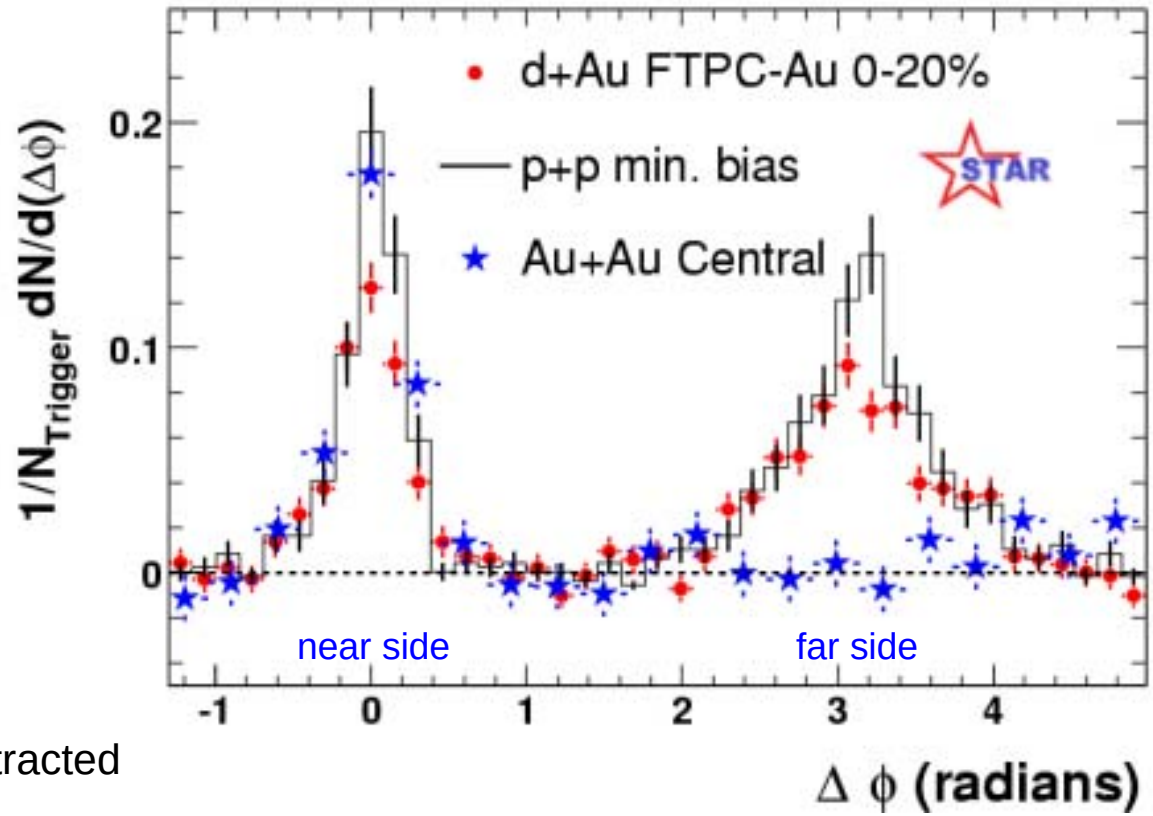


Au+Au peripheral similar to d+Au
Disappearance of Far side jets in Au+Au central

d+Au data similar to p+p

Disappearance of Far side jets in Au+Au central

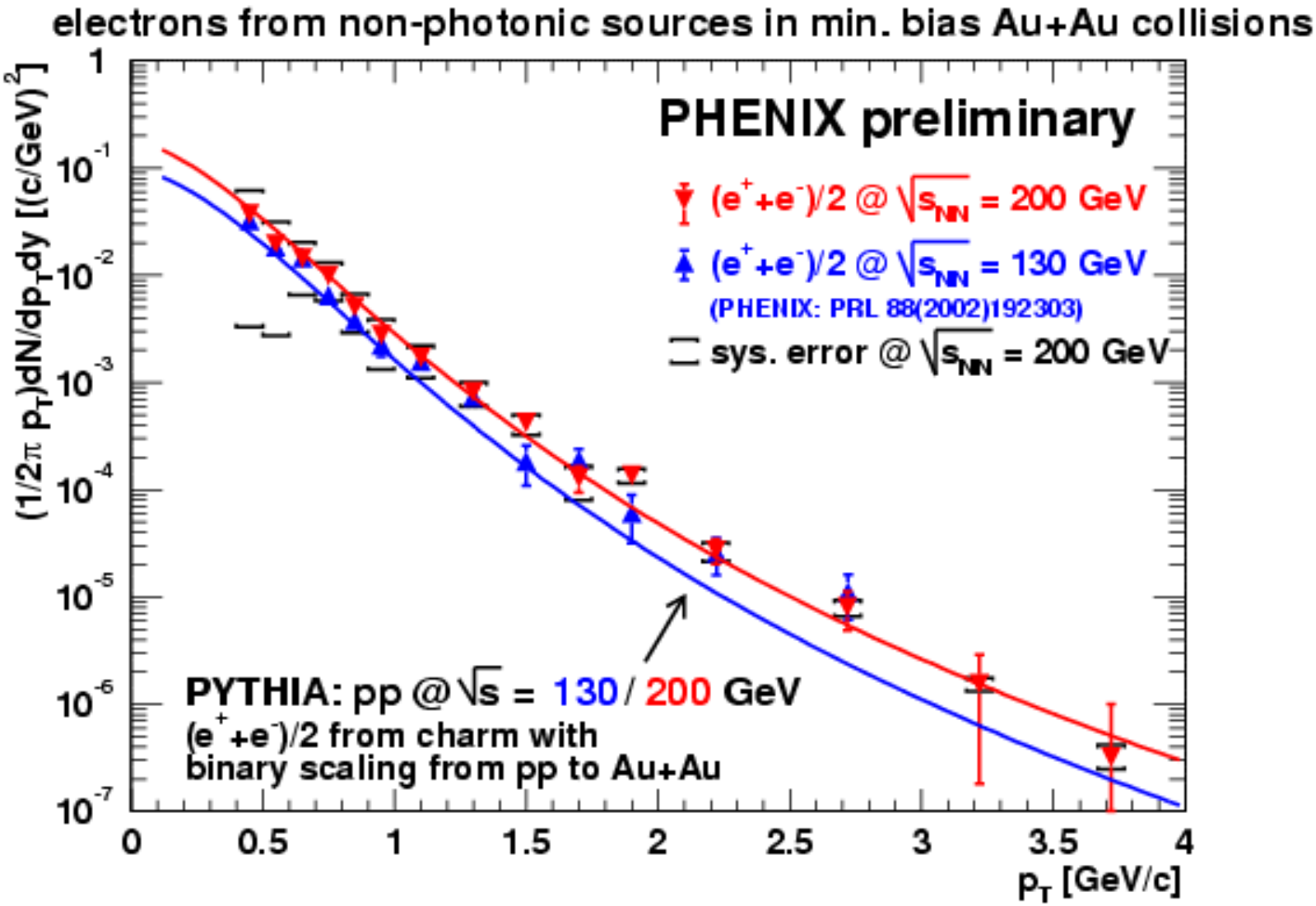




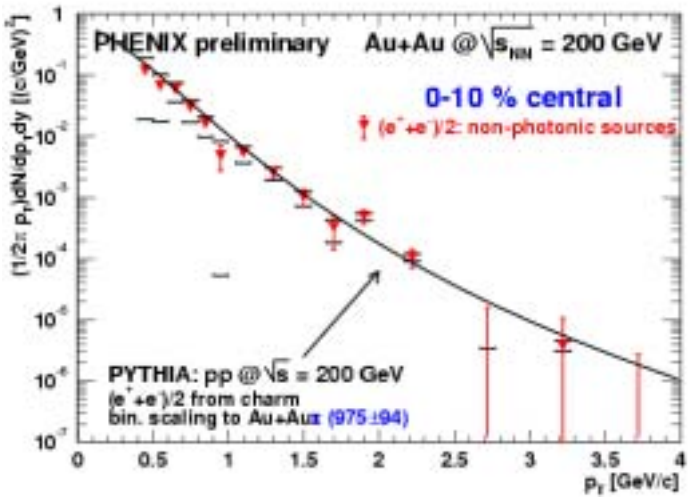
$\sqrt{s_{NN}}$ = 200 GeV

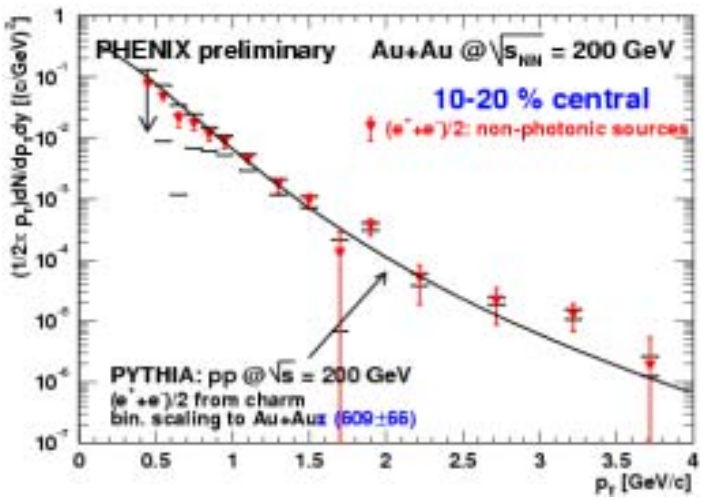
pedestal and flow subtracted

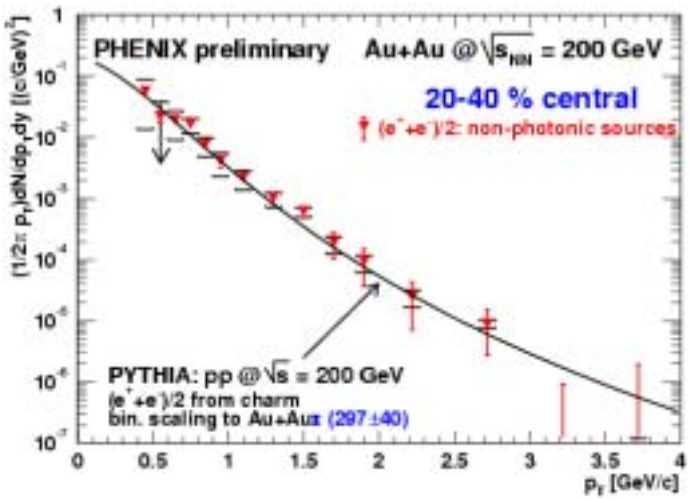
Single electron measurement at phenix

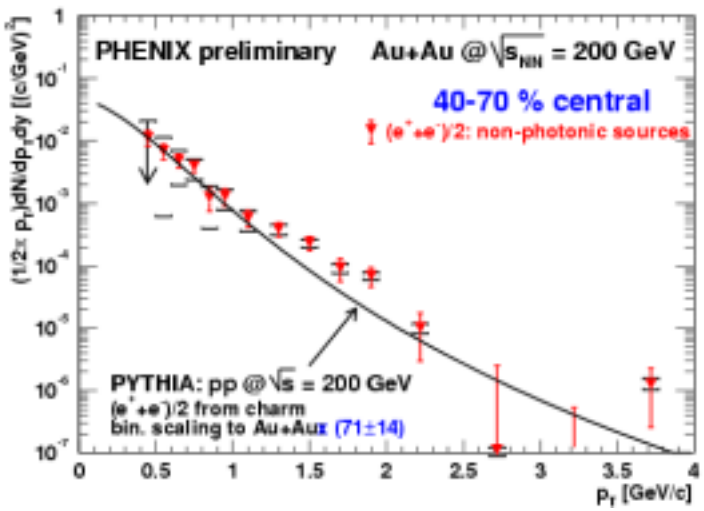


centrality dependence of charmed electron





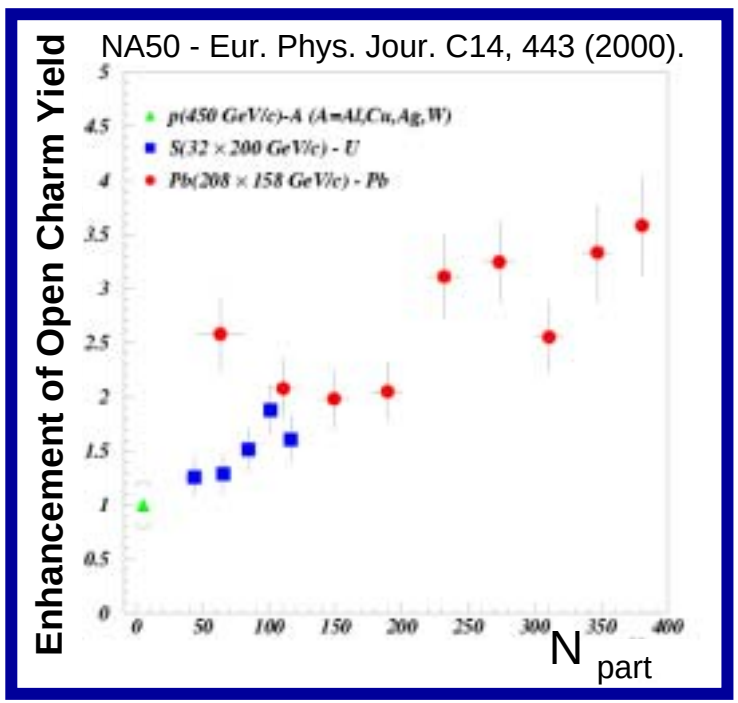


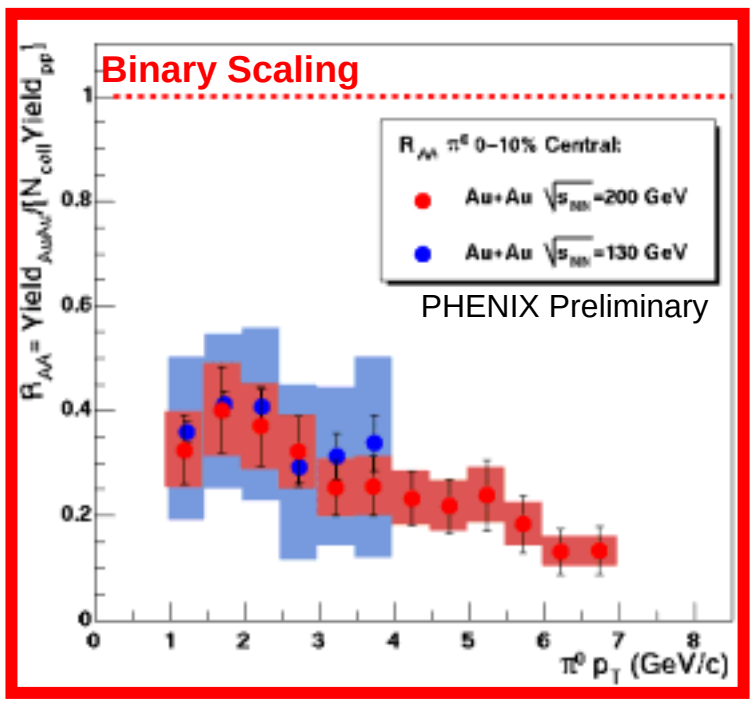


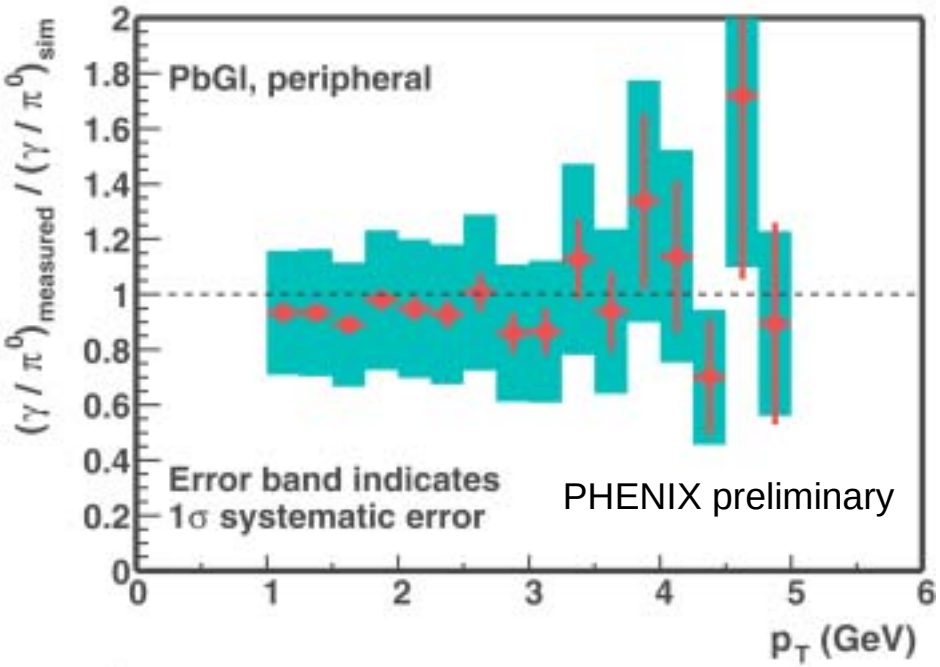
Our electron data is consistent with binary scaling within our current statistical and systematic errors.

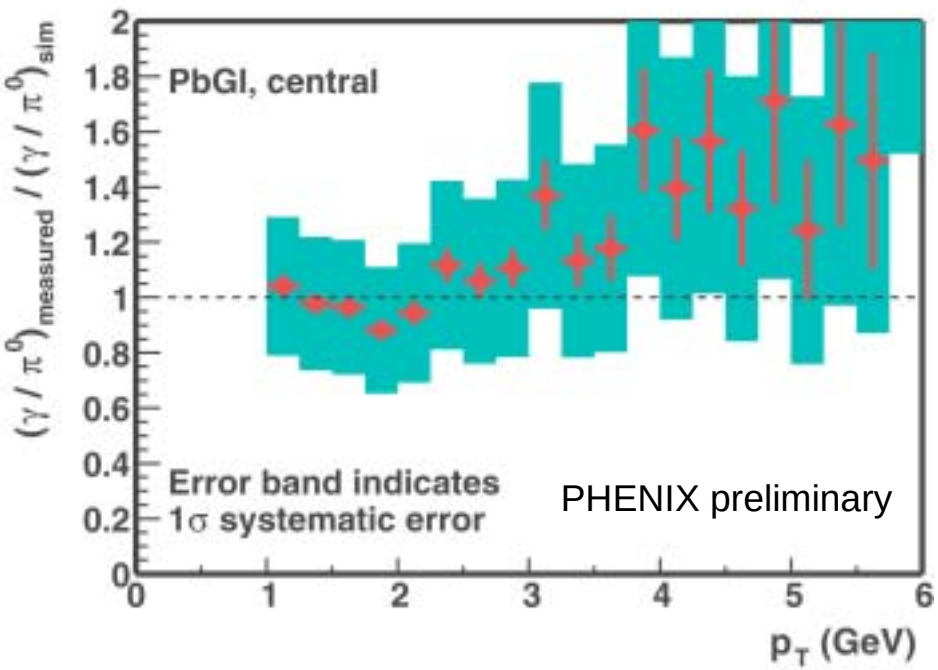
NA50 has inferred a factor of ~3 charm enhancement at lower energy (SPS). We do not see this large effect at RHIC.

PHENIX observes a factor of ~3-4 suppression in high pT p0 relative to binary scaling. We do not see this large effect in the single electrons from charm.





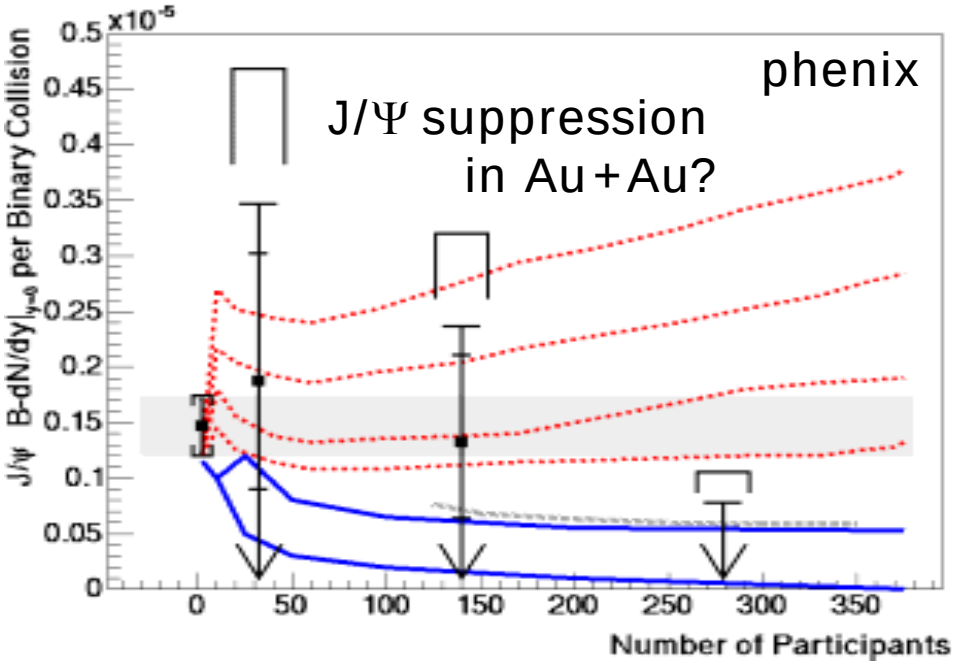


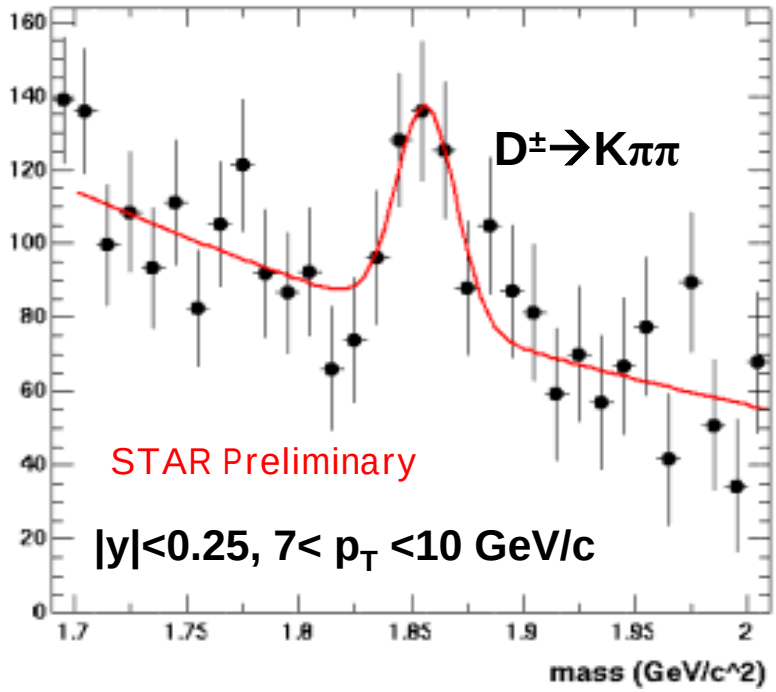


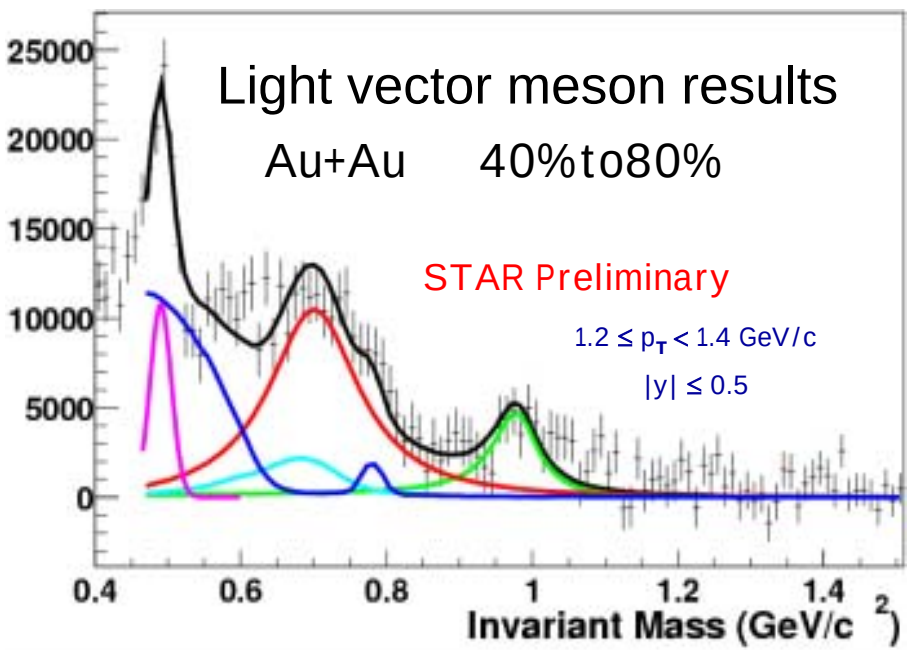
photon measurements at phenix

---looking for direct photon signal---

Reconstruction of charm mesons

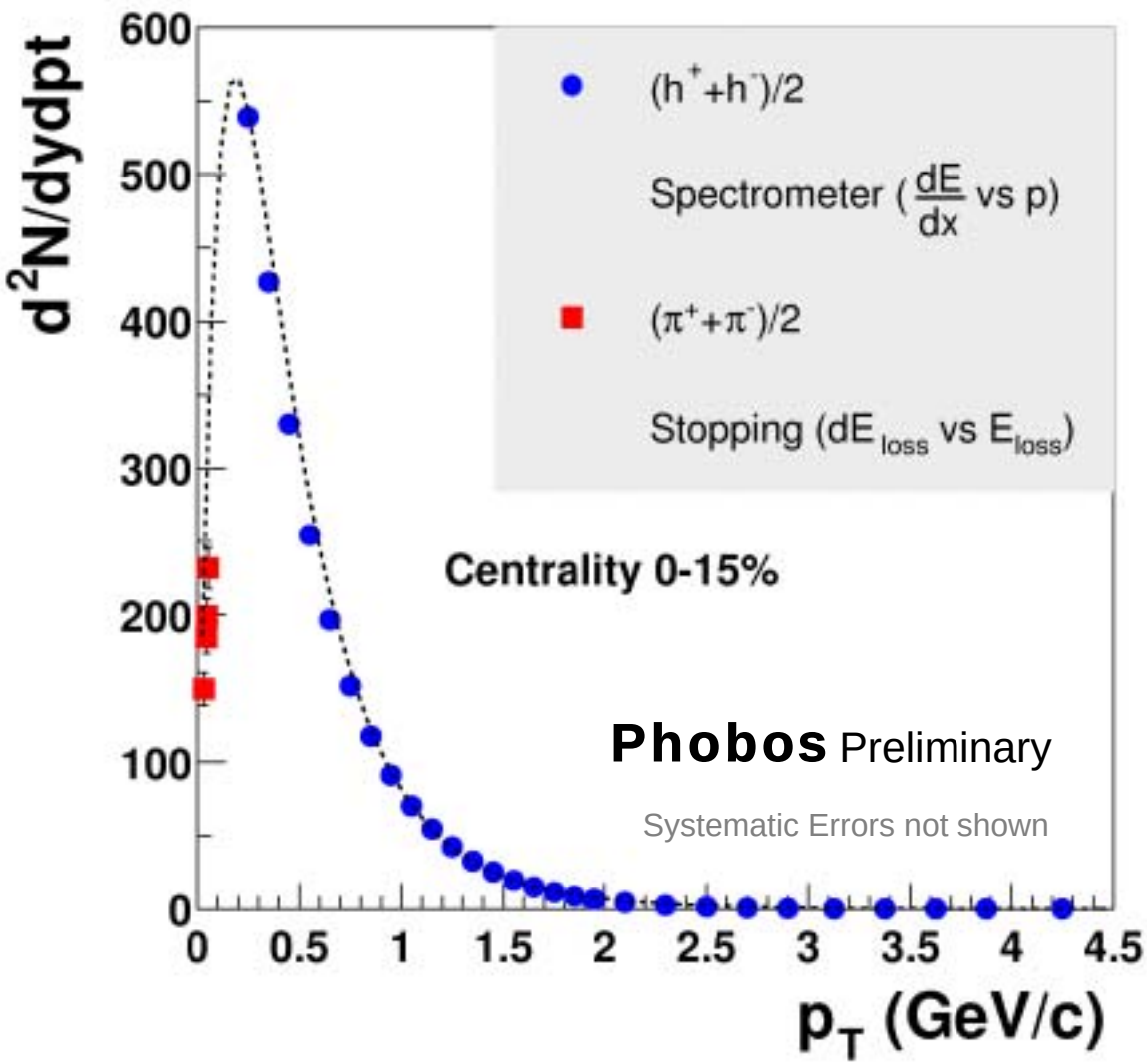


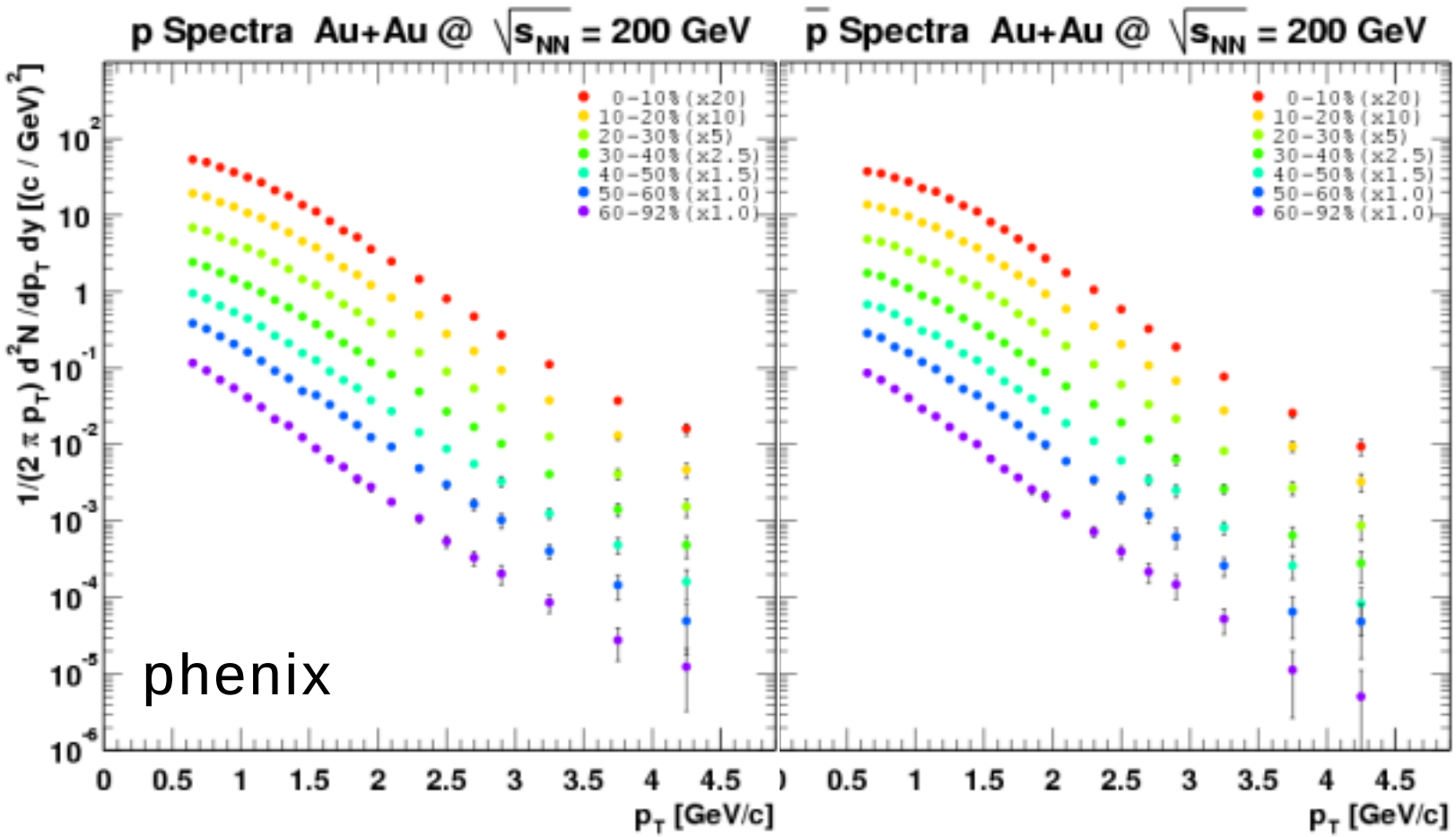


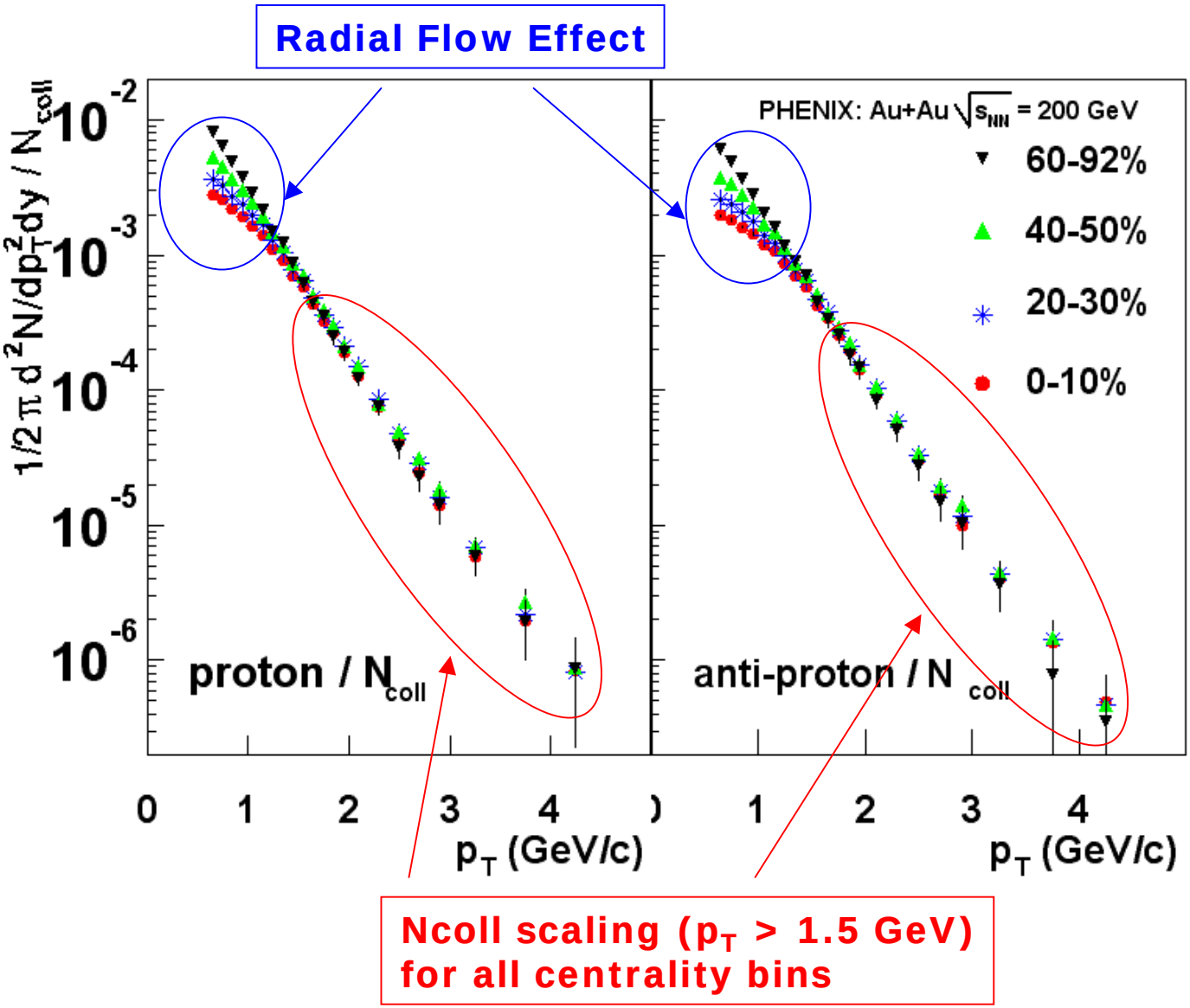


challenging...

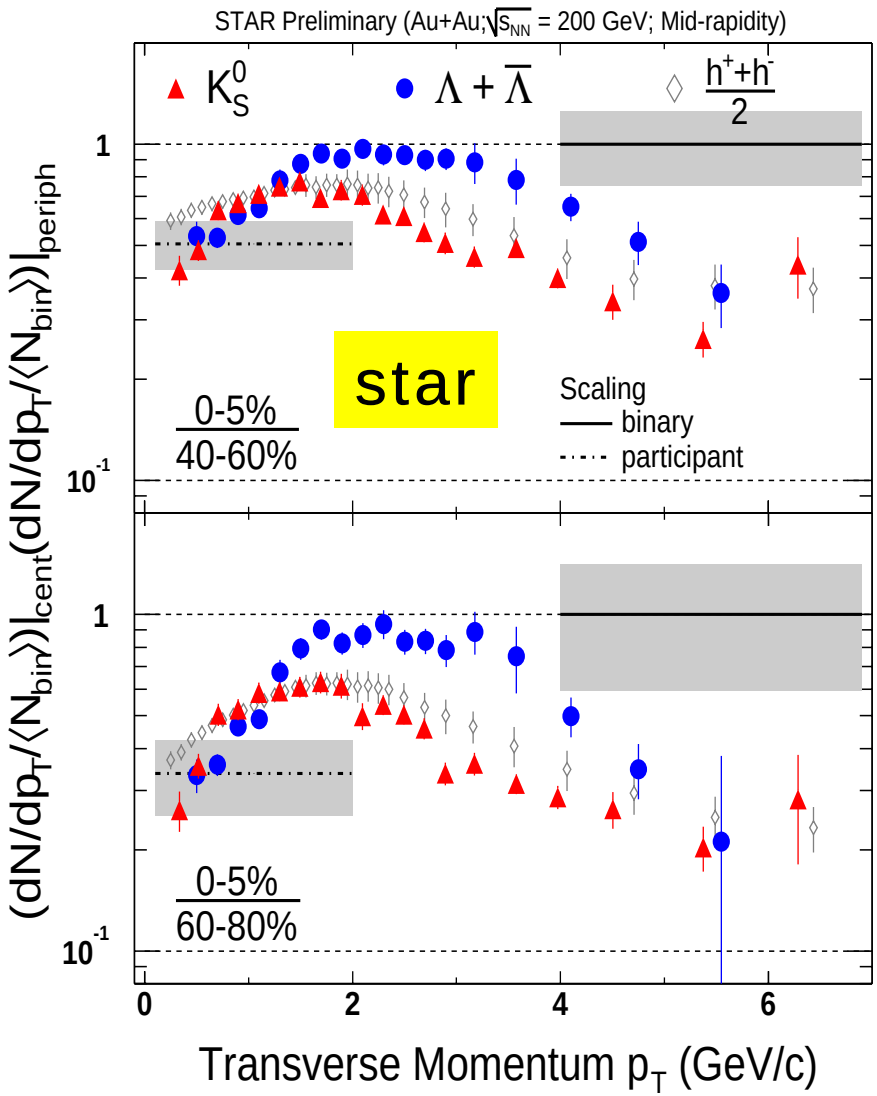
Dominant particles are at low pT.

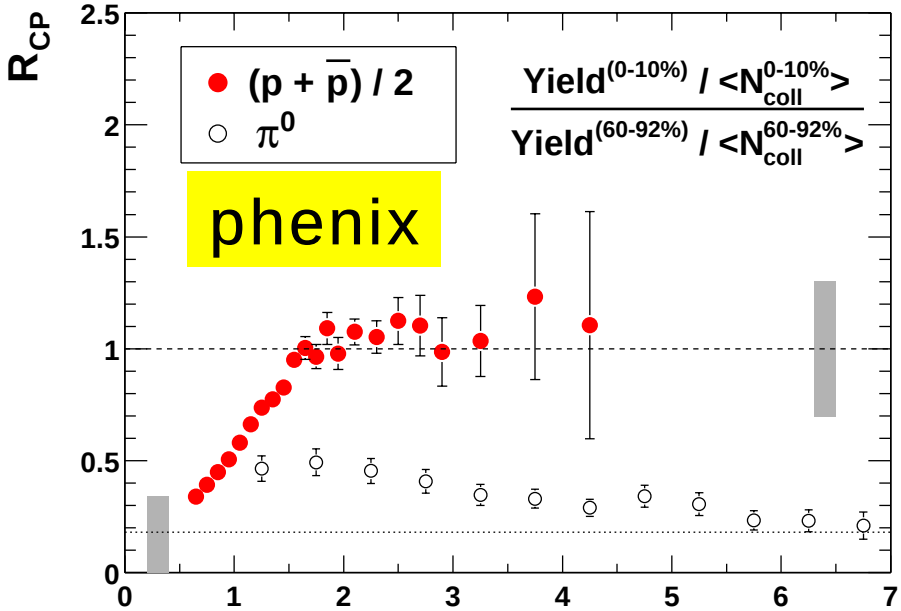


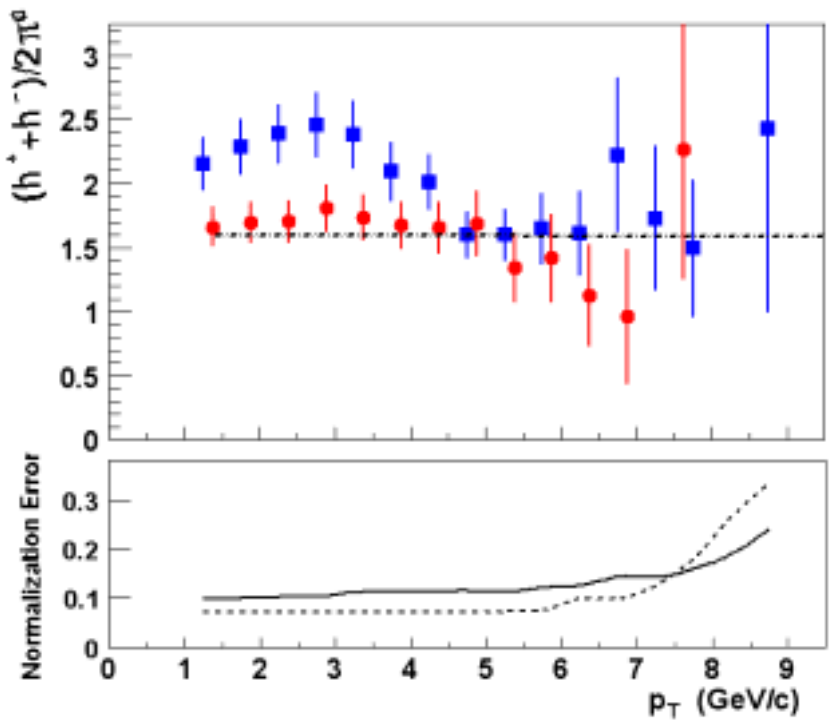

p Spectra Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV
$\bar{p}$ Spectra Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV
0-10%(x20)
10-20%(x10)
20-30%(x5)
30-40%(x2.5)
40-50%(x1.5)
50-60%(x1.0)
60-92%(x1.0)
$1/(2\pi p_T)\, d^2N/dp_T\, dy\ [(c/GeV)^2]$
p_T [GeV/c]
phenix

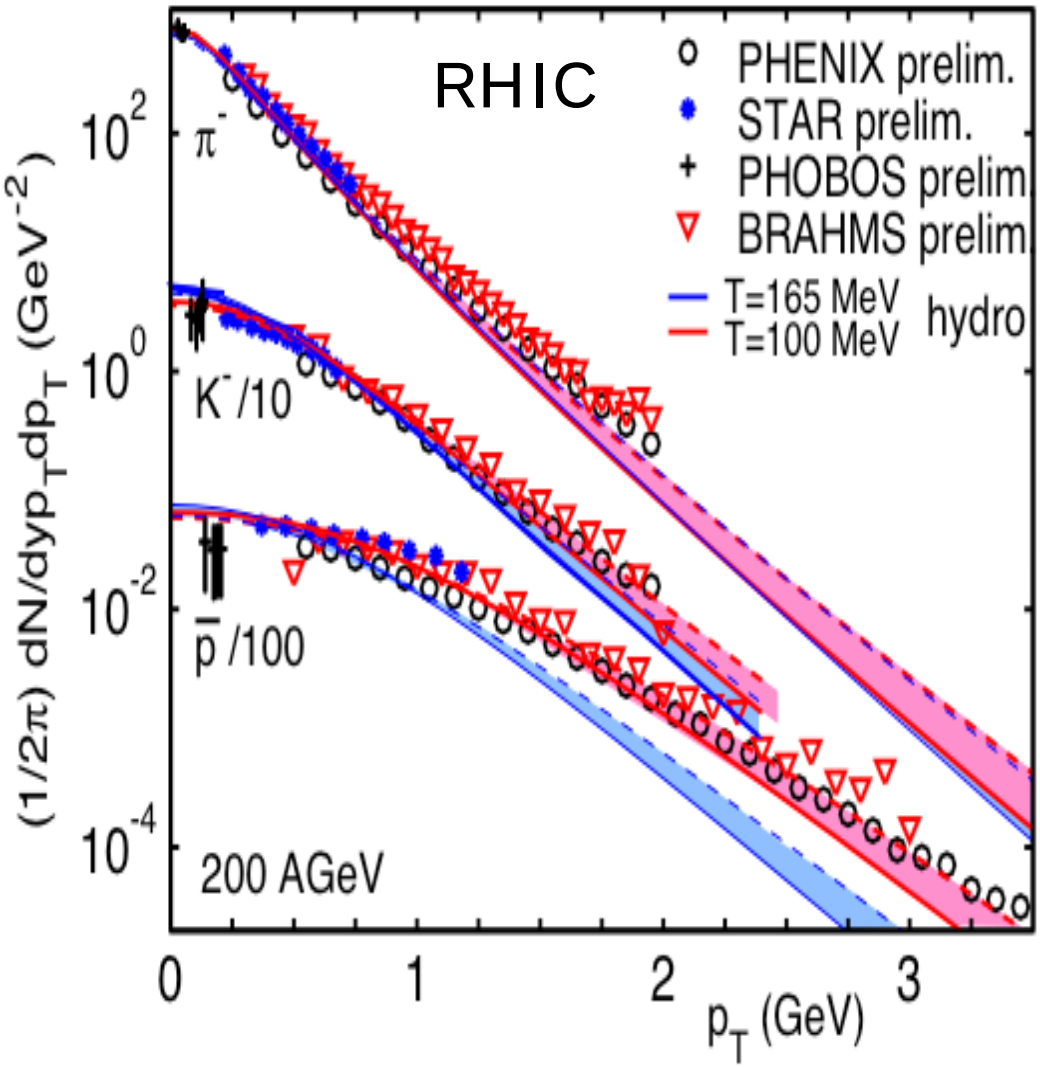

Radial Flow Effect
PHENIX: Au+Au $\sqrt{s_{NN}}$ = 200 GeV
60-92%
40-50%
20-30%
0-10%
$1/2\pi\, d^2N/dp_T^2dy / N_{coll}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
proton / N_{coll}
anti-proton / N_{coll}
0
1
2
3
4
p_T (GeV/c)
Ncoll scaling (p_T > 1.5 GeV)
for all centrality bins

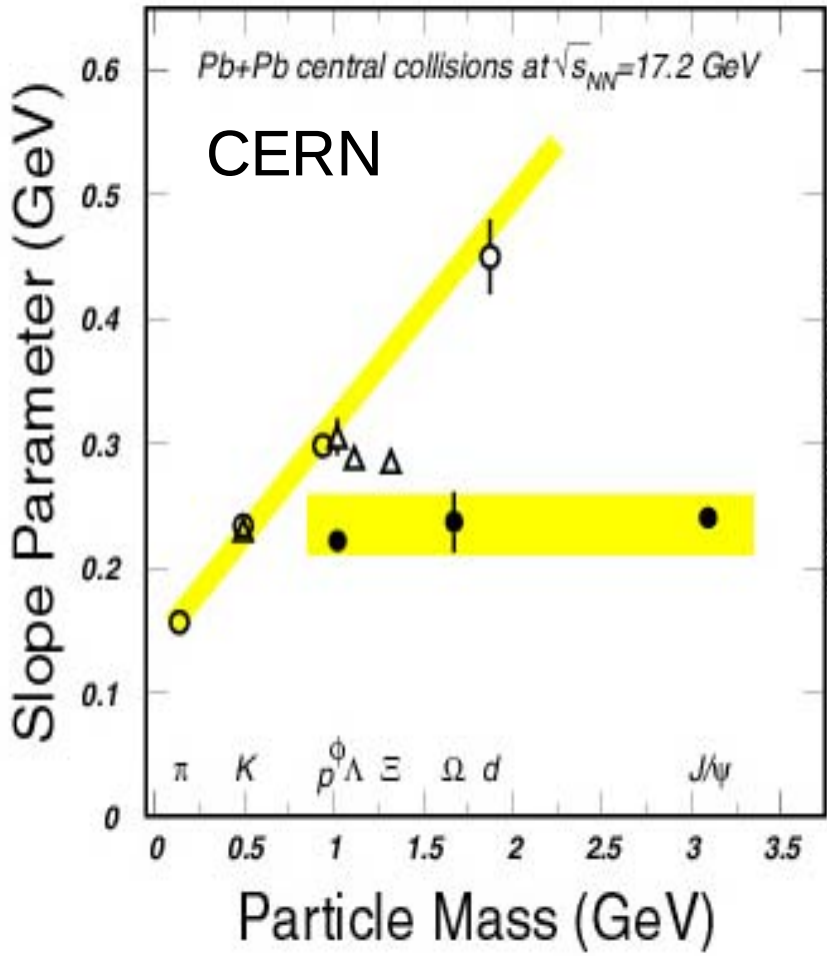
particle dependence on suppression in Au+Au 200GeV







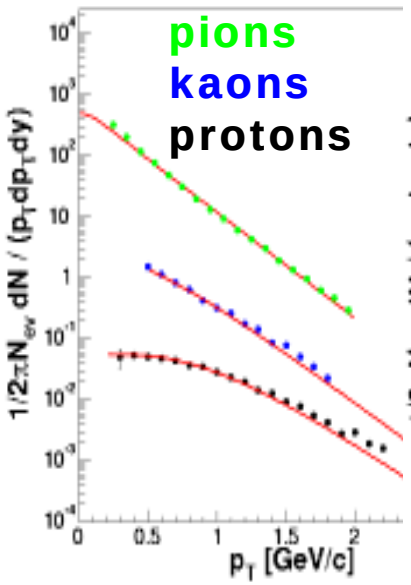

RHIC
PHENIX prelim.
STAR prelim.
PHOBOS prelim
BRAHMS prelim
T=165 MeV
T=100 MeV
hydro
π^-
$K^-/10$
$\bar{p}/100$
200 AGeV
$(1/2\pi)\, dN/dy p_T dp_T\ (GeV^{-2})$
p_T (GeV)

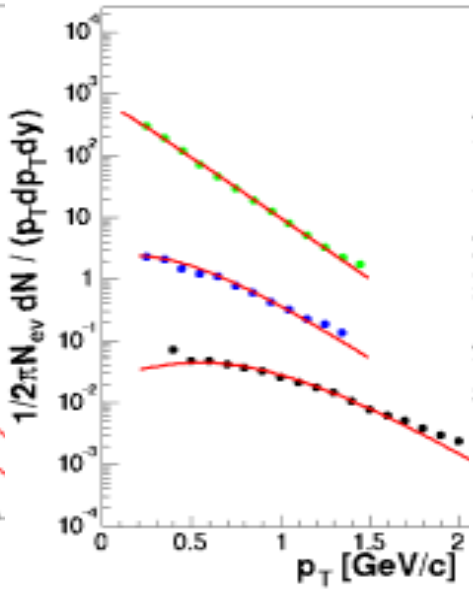

CERN
Pb+Pb central collisions at $\sqrt{s_{NN}}$=17.2 GeV
Slope Parameter (GeV)
Particle Mass (GeV)
π K p φ Λ Ξ Ω d J/ψ

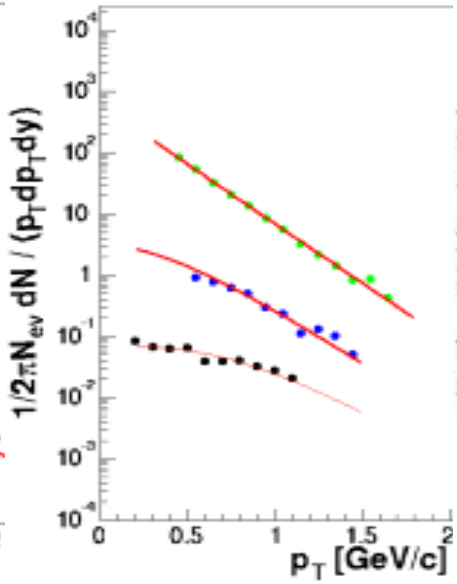
Transverse flow (radial expansion)

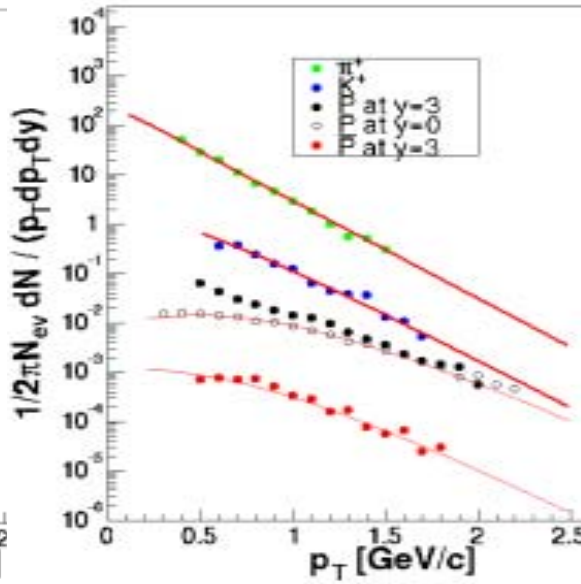
brahms

y ~ 0	y ~ 1	y ~ 2	y ~ 3

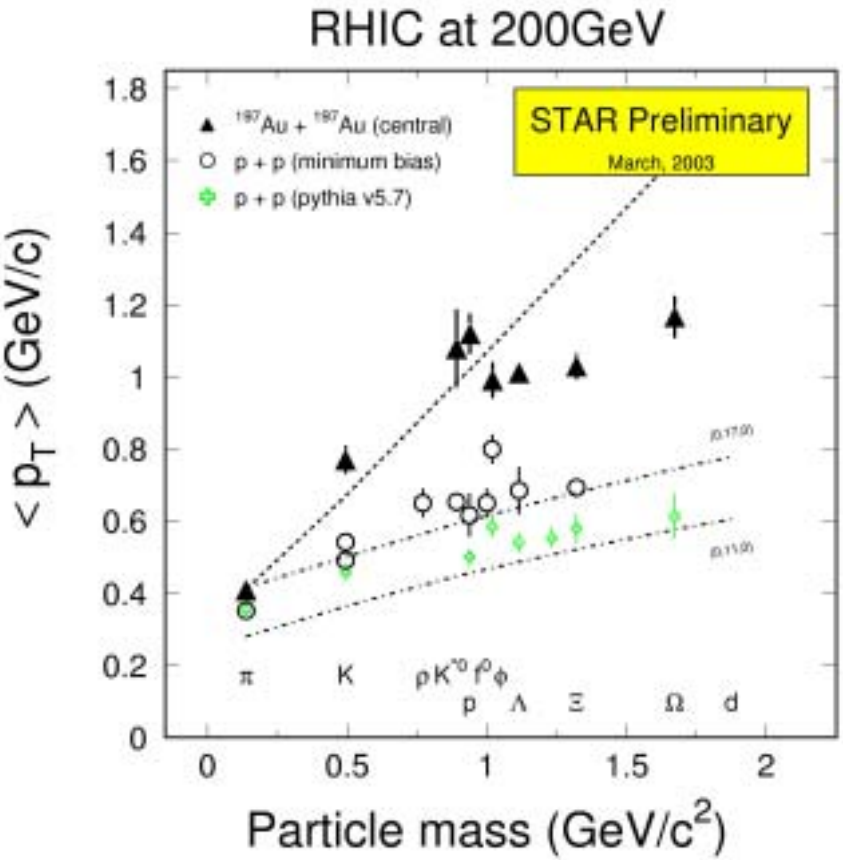


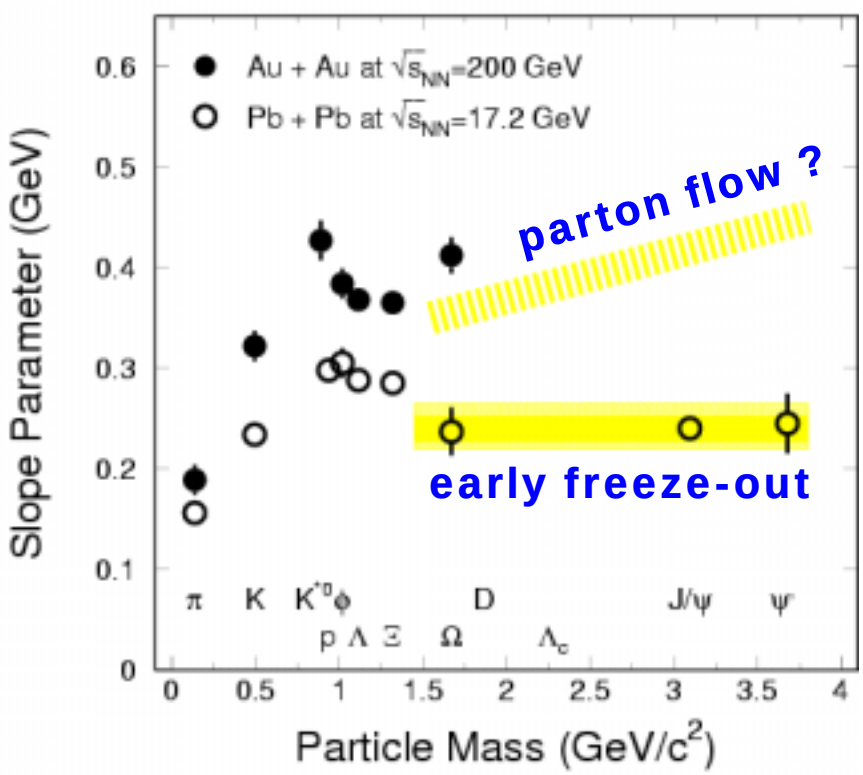




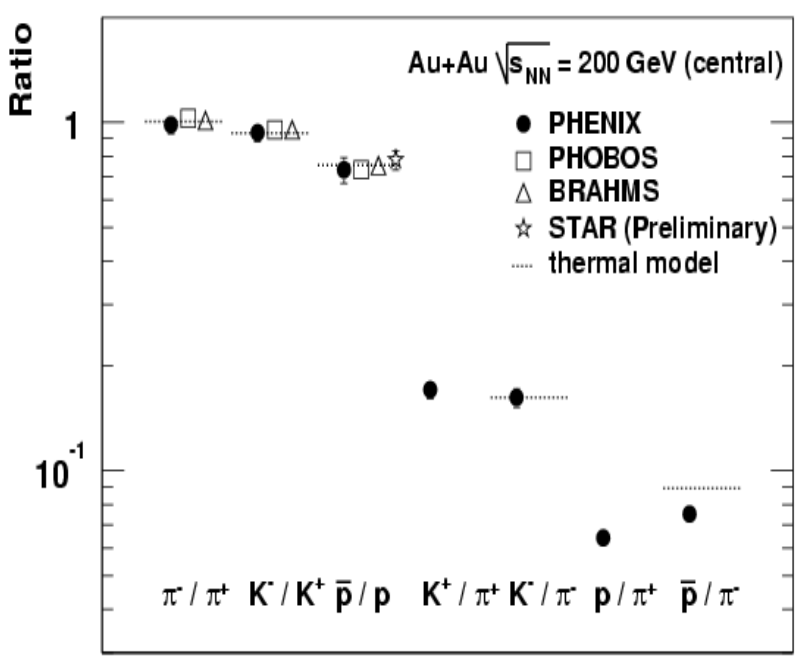


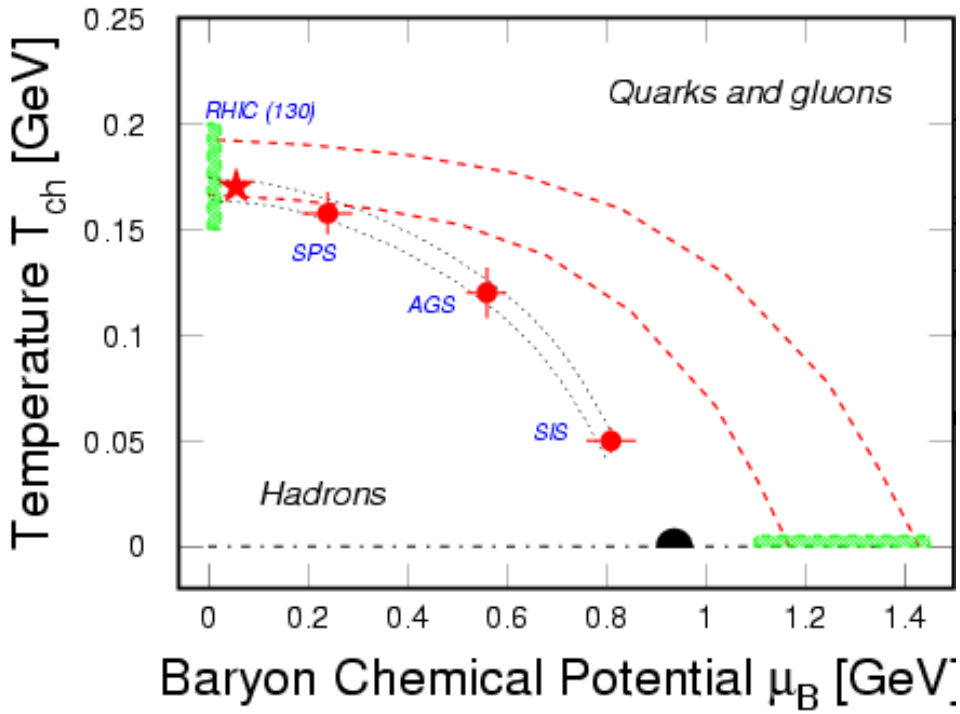
χ^2 / NDF = 6.7	χ^2 / NDF = 6.6	χ^2 / NDF = 1.9	χ^2 / NDF = 1.2
β_T = 0.53	β_T = 0.57	β_T = 0.47	β_T = 0.42
T = 138. MeV	T = 115 MeV	T = 135. MeV	T = 140 MeV


RHIC at 200GeV
STAR Preliminary
March, 2003
197Au + 197Au (central)
p + p (minimum bias)
p + p (pythia v5.7)
< pT > (GeV/c)
Particle mass (GeV/c2)
π K ρ K*0 f0 φ p Λ Ξ Ω d


Au + Au at √sNN=200 GeV
Pb + Pb at √sNN=17.2 GeV
parton flow ?
early freeze-out
Slope Parameter (GeV)
Particle Mass (GeV/c2)
π K K*0 φ D J/ψ ψ'
p Λ Ξ Ω Λc

Thermal freeze-out parameters from the particle ratios

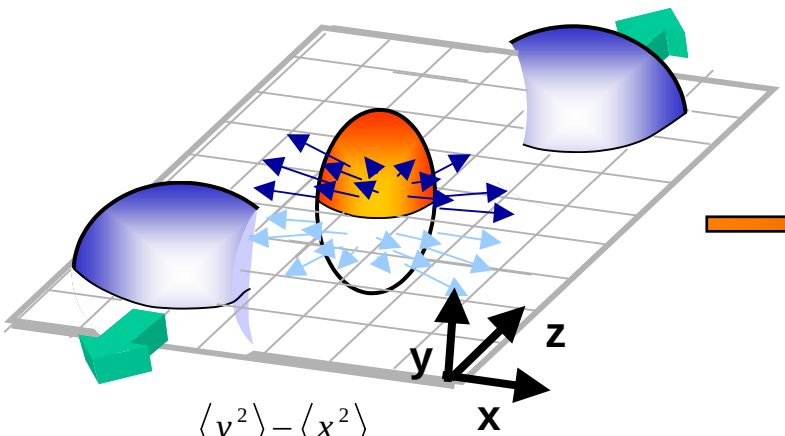




- **Almost complete reconstruction of particle ratios by the statistical thermal model.**
- **Thermal model prediction in AuAu 200 GeV central.**

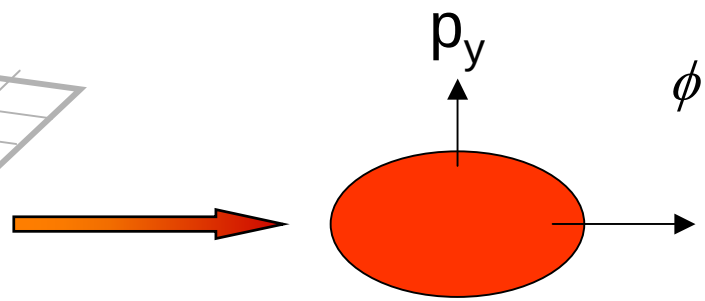
T_{ch} = 177 MeV, m_B = 29 MeV

Event anisotropy (elliptic flow)



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

initial spatial anisotropy



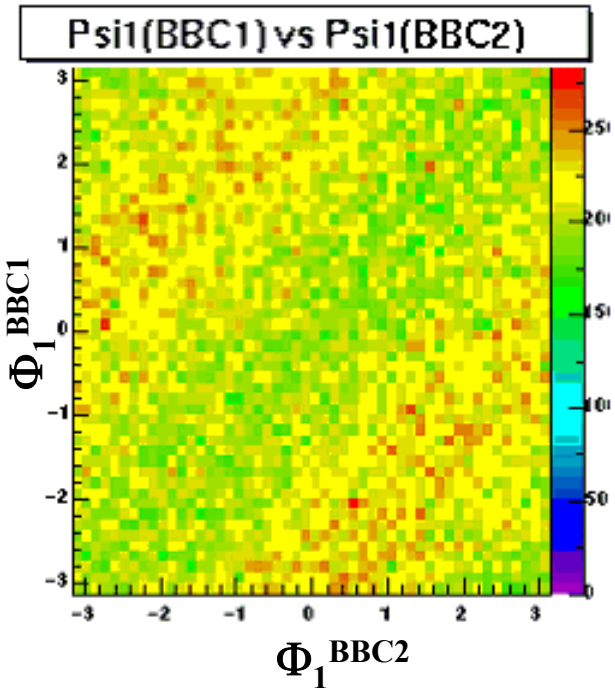
$$\phi = \operatorname{atan} \frac{p_y}{p_x}$$

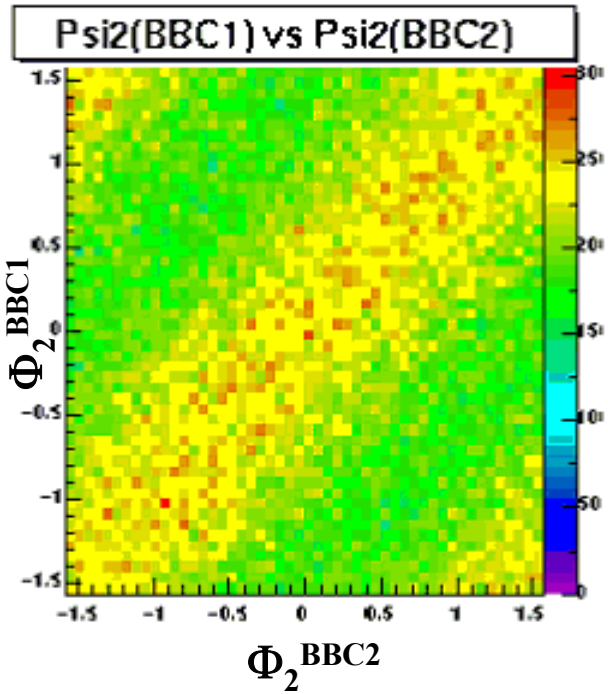
$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

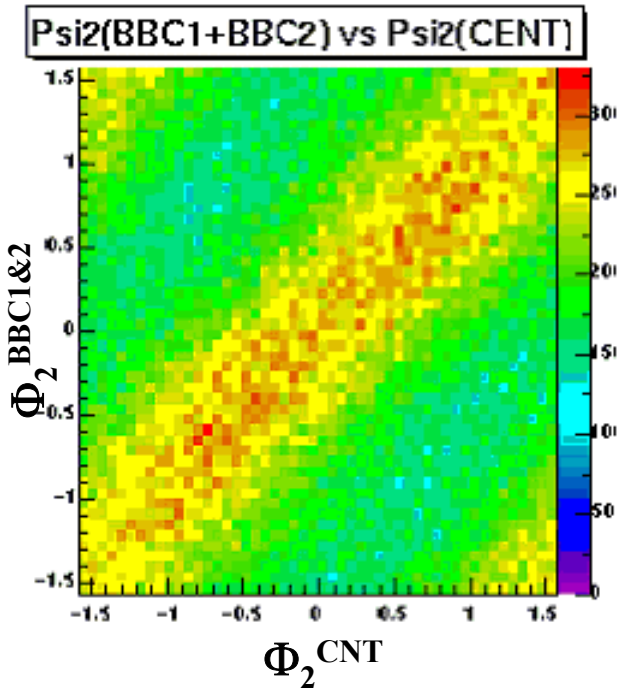
anisotropy in momentum space

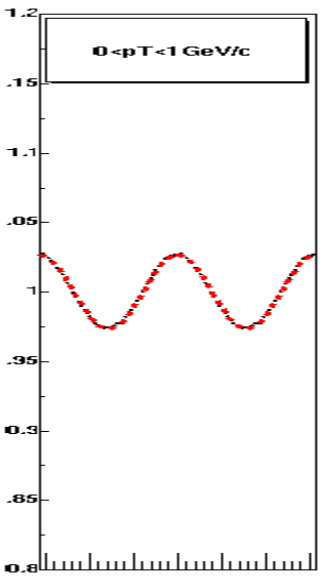
$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2v_1\cos(\phi - \Psi_R) + 2v_2\cos(2(\phi - \Psi_R) + \ldots\right)$$

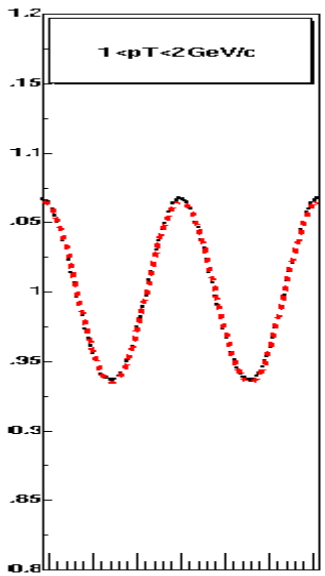
isotropic **directed** **elliptic**

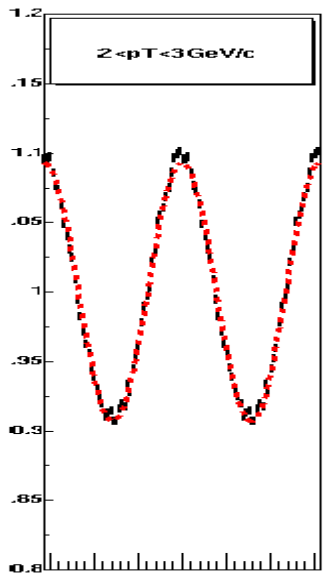

Psi1(BBC1) vs Psi1(BBC2)
Φ_1^{BBC1}
Φ_1^{BBC2}

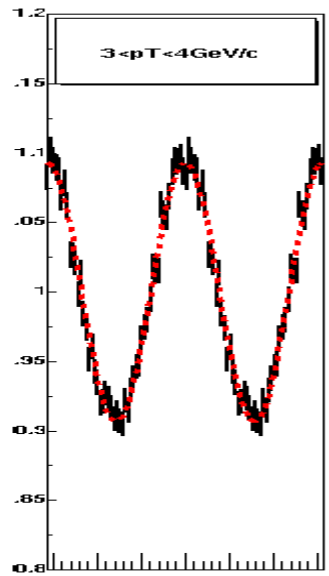

Psi2(BBC1) vs Psi2(BBC2)
Φ_2^{BBC1}
Φ_2^{BBC2}

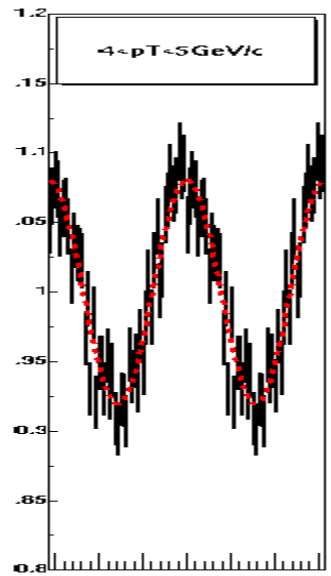

Psi2(BBC1+BBC2) vs Psi2(CENT)
$\Phi_2^{BBC1\&2}$
Φ_2^{CNT}

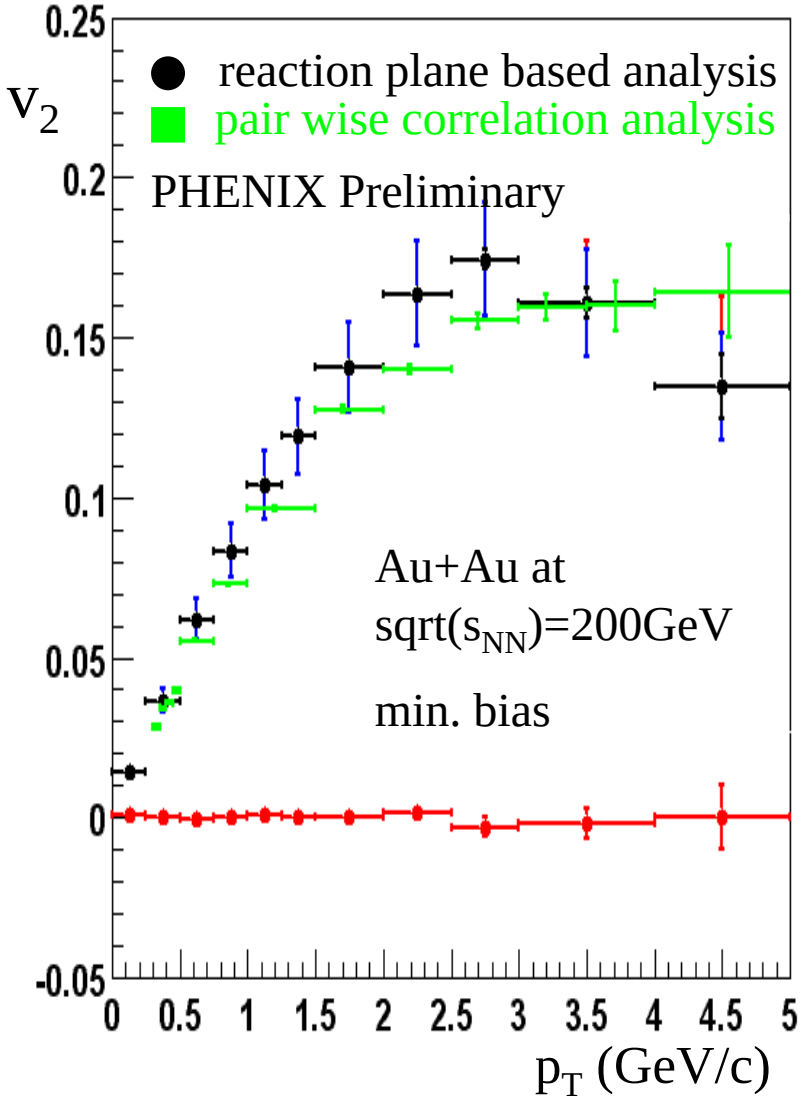

0<pT<1 GeV/c

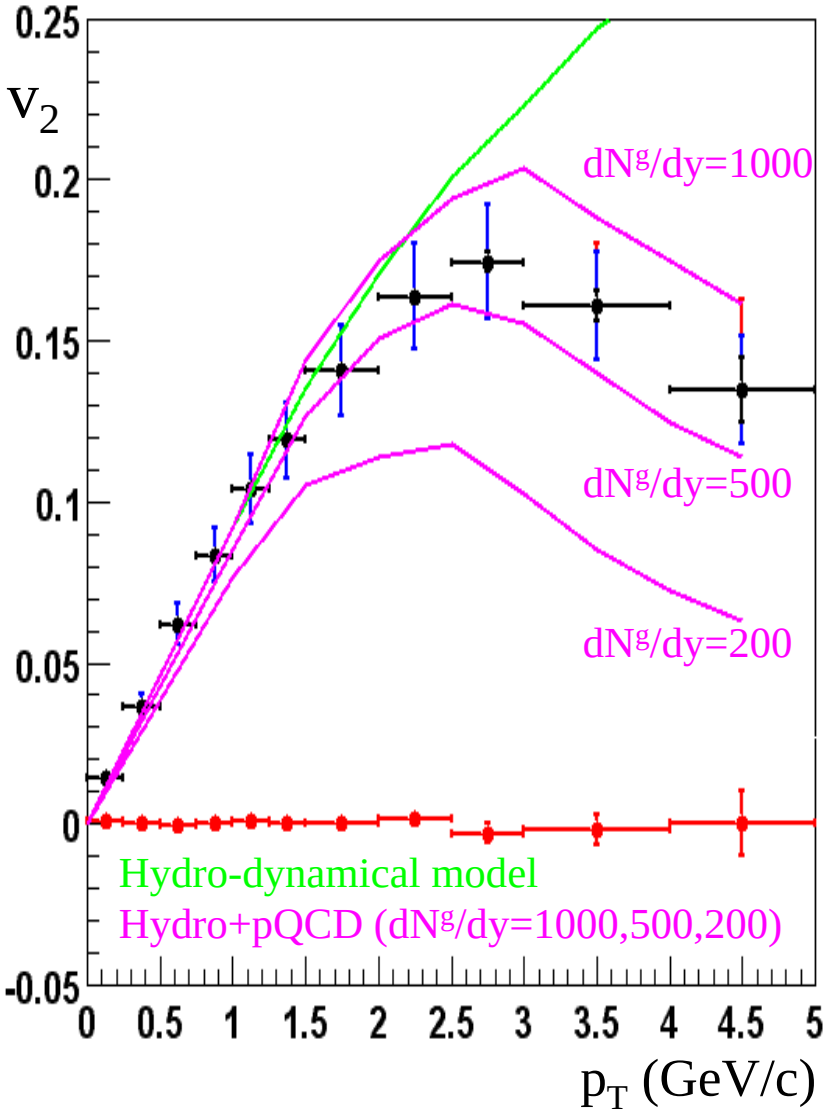

1<pT<2 GeV/c


2<pT<3 GeV/c

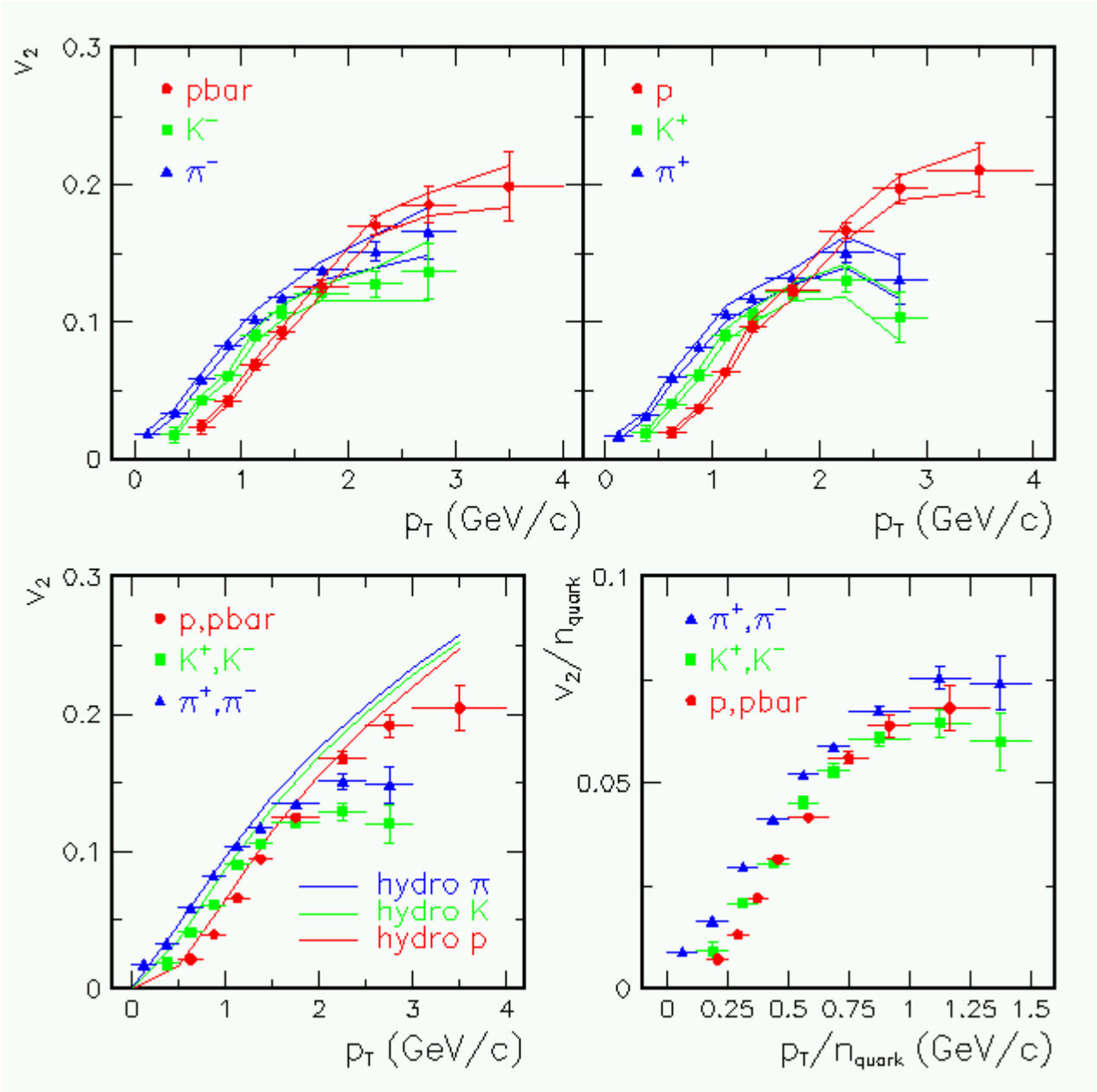

3<pT<4 GeV/c


4<pT<5 GeV/c

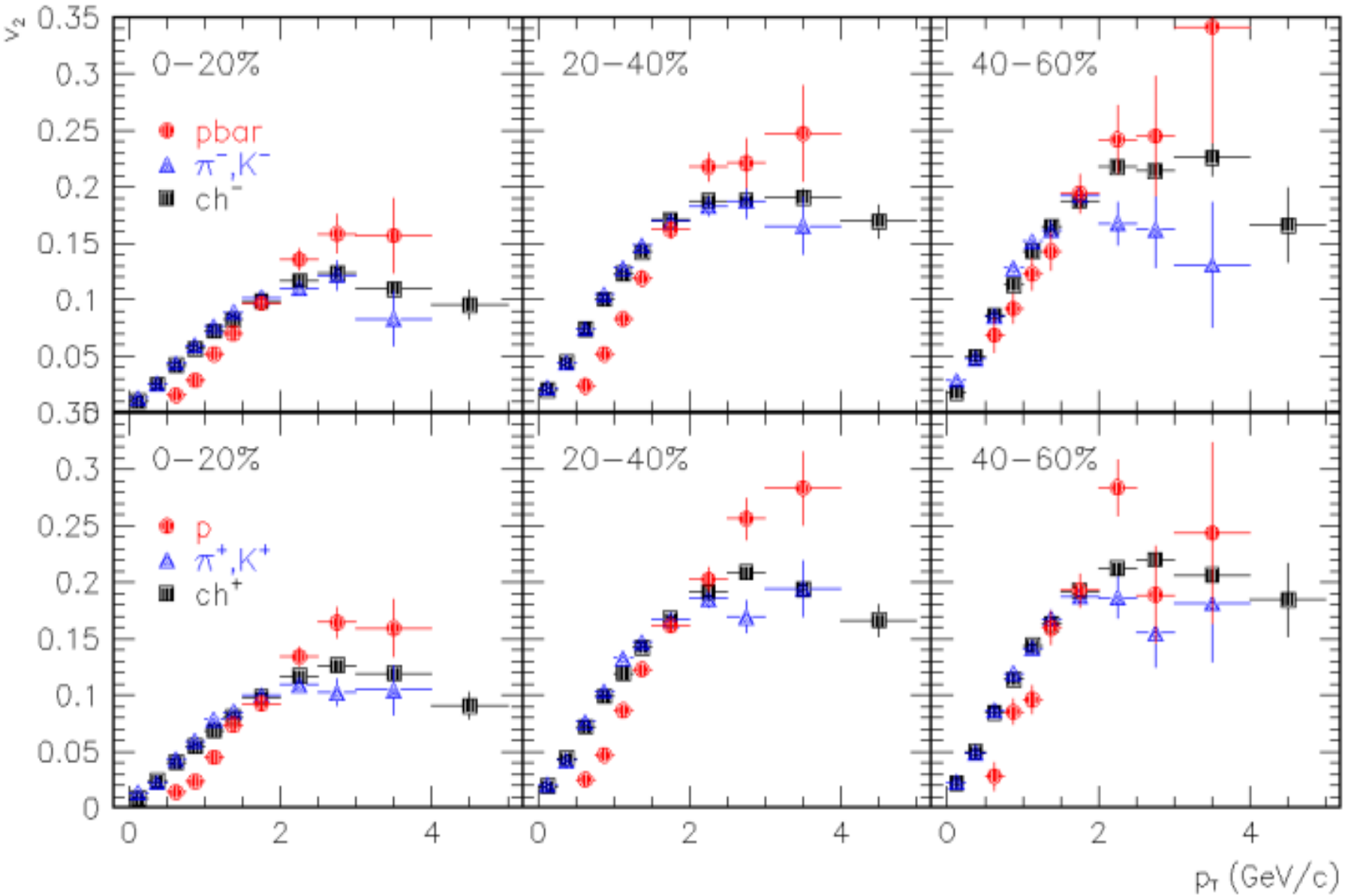

reaction plane based analysis
pair wise correlation analysis
PHENIX Preliminary
Au+Au at
sqrt(s_NN)=200GeV
min. bias
v2
pT (GeV/c)

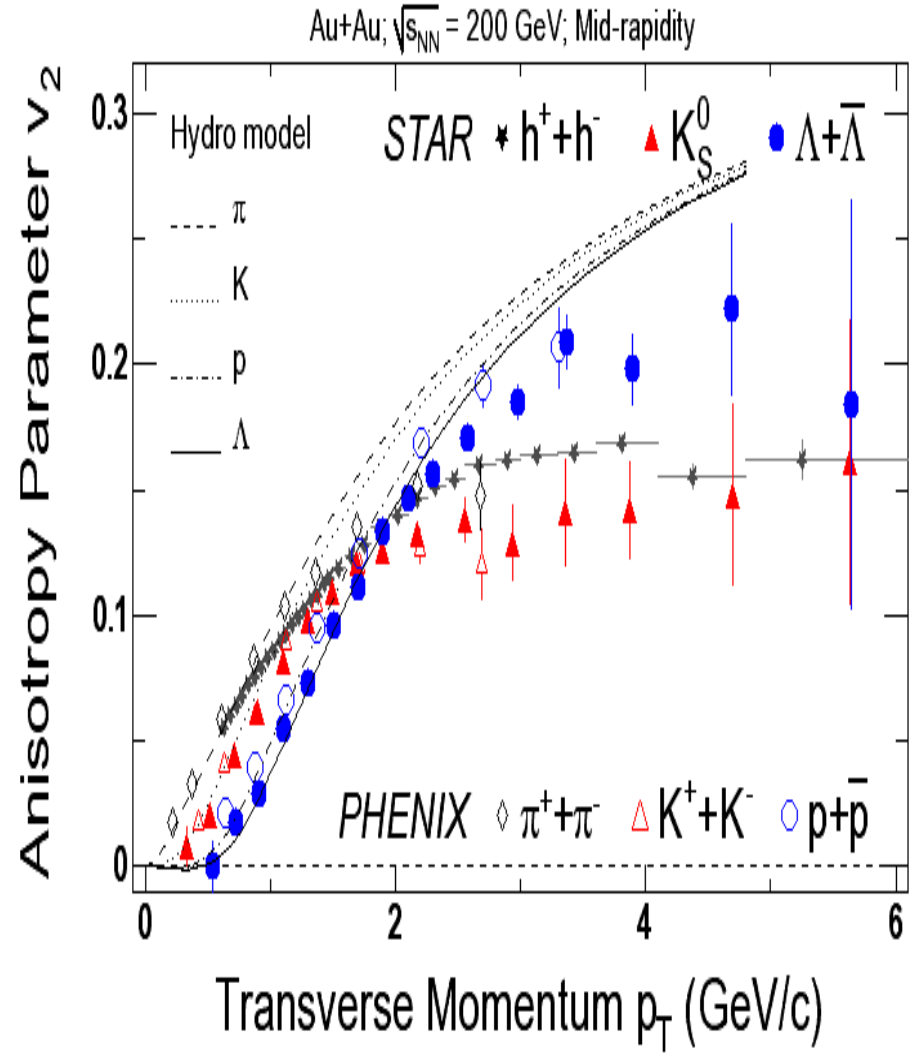

dNg/dy=1000
dNg/dy=500
dNg/dy=200
Hydro-dynamical model
Hydro+pQCD (dNg/dy=1000,500,200)
v2
pT (GeV/c)

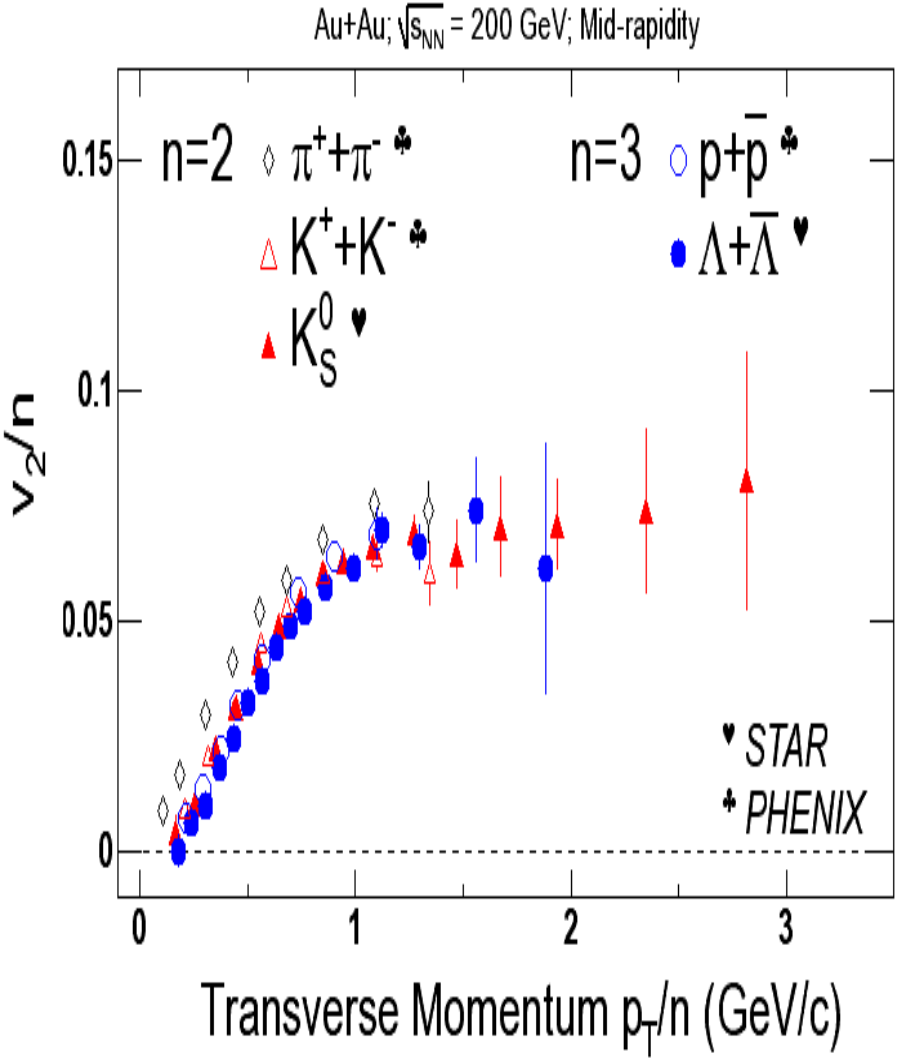
PHENIX


v2
pbar
K−
π−
p
K+
π+
pT (GeV/c)
p,pbar
K+,K−
π+,π−
hydro π
hydro K
hydro p
v2/nquark
pT/nquark (GeV/c)

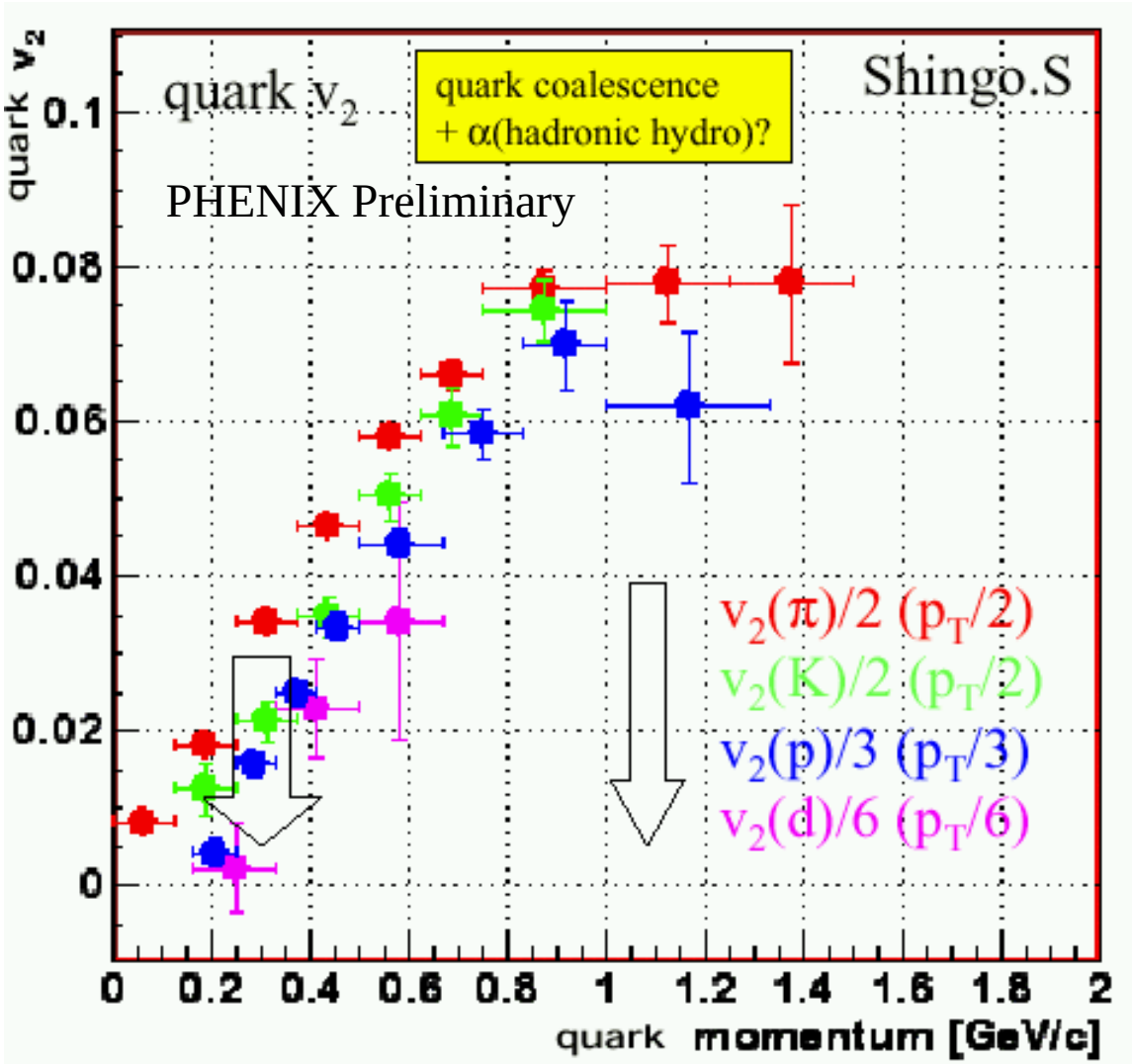
PHENIX


v_2
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0−20%
20−40%
40−60%
pbar
π^-,K^-
ch^-
p
π^+,K^+
ch^+
0
2
4
p_T (GeV/c)


Au+Au; $\sqrt{s_{NN}}$ = 200 GeV; Mid-rapidity
Anisotropy Parameter v_2
Hydro model
π
K
p
Λ
STAR ★ h^++h^- ▲ K^0_S ● Λ+$\bar{\Lambda}$
PHENIX ◊ π^++π^- △ K^++K^- ○ p+$\bar{p}$
0.3
0.2
0.1
0
0
2
4
6
Transverse Momentum p_T (GeV/c)

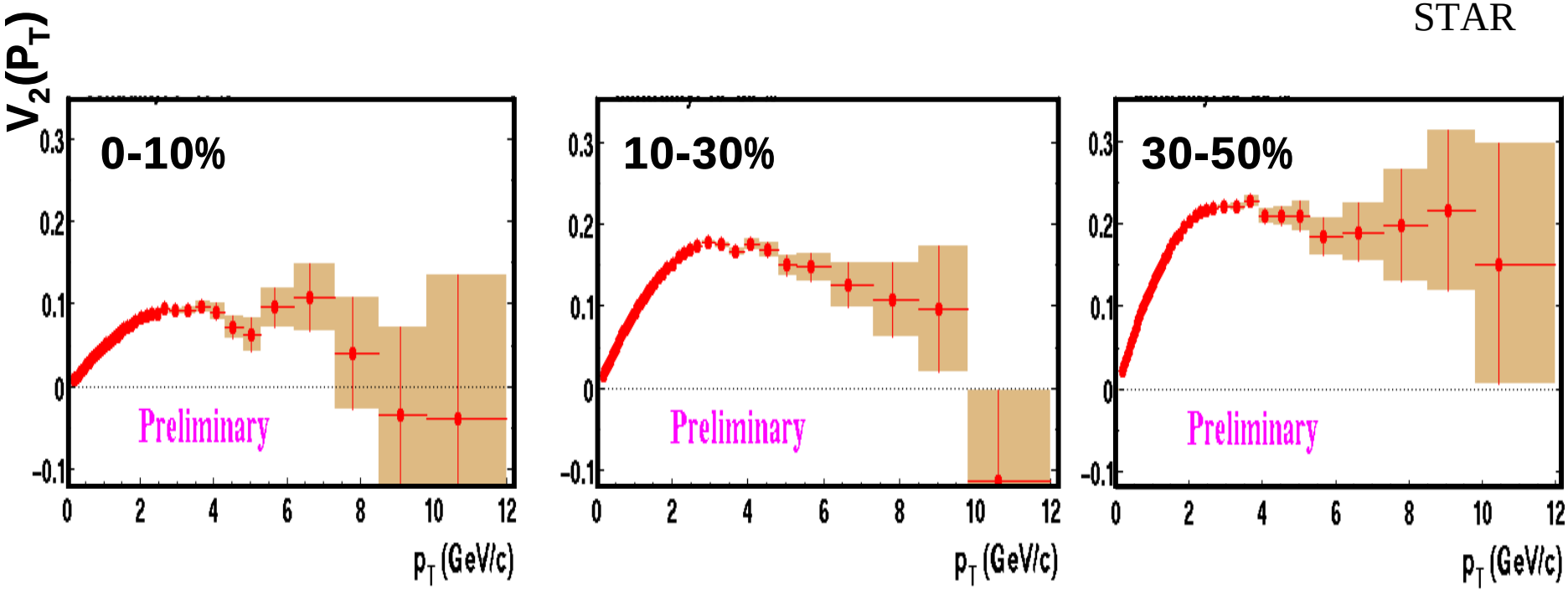

Au+Au; $\sqrt{s_{NN}}$ = 200 GeV; Mid-rapidity
v_2/n
n=2 ◊ π^++π^- ♣
△ K^++K^- ♣
▲ K^0_S ♥
n=3 ○ p+$\bar{p}$ ♣
● Λ+$\bar{\Lambda}$ ♥
♥ STAR
♣ PHENIX
0.15
0.1
0.05
0
0
1
2
3
Transverse Momentum p_T/n (GeV/c)

quark flow or hadron flow



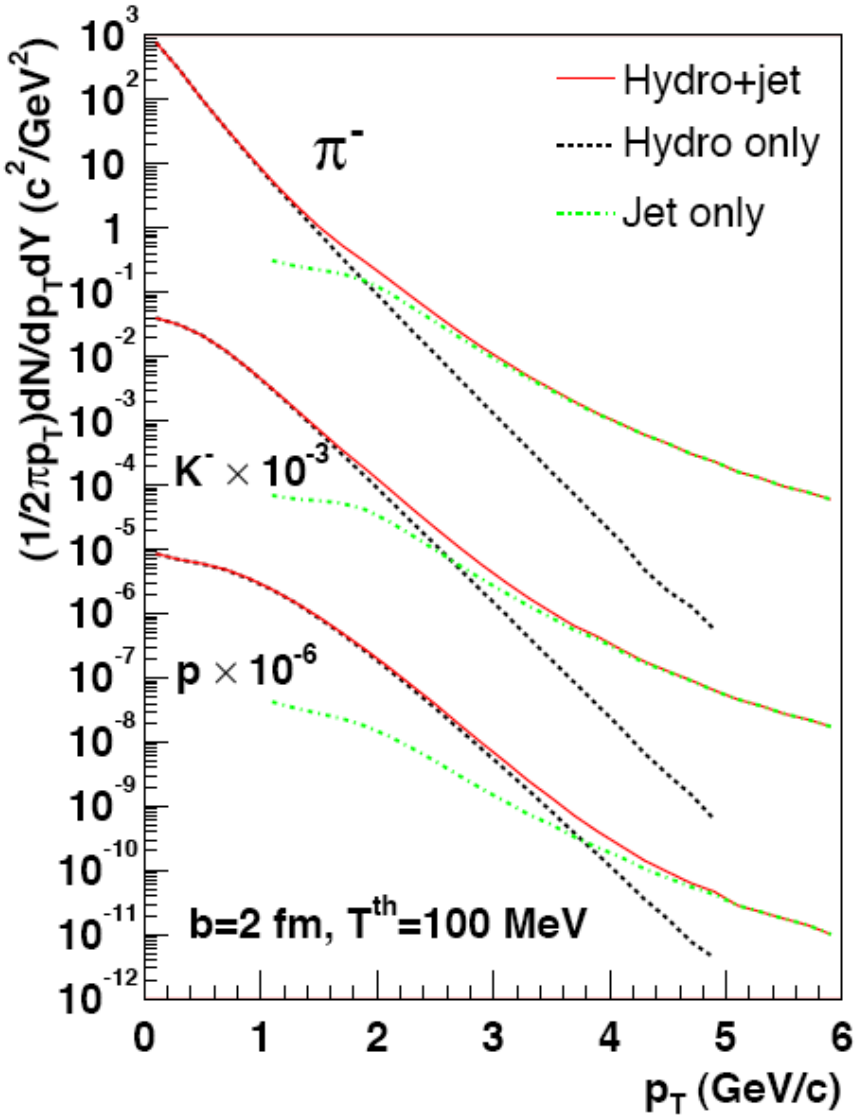
High pT v2 is finite.

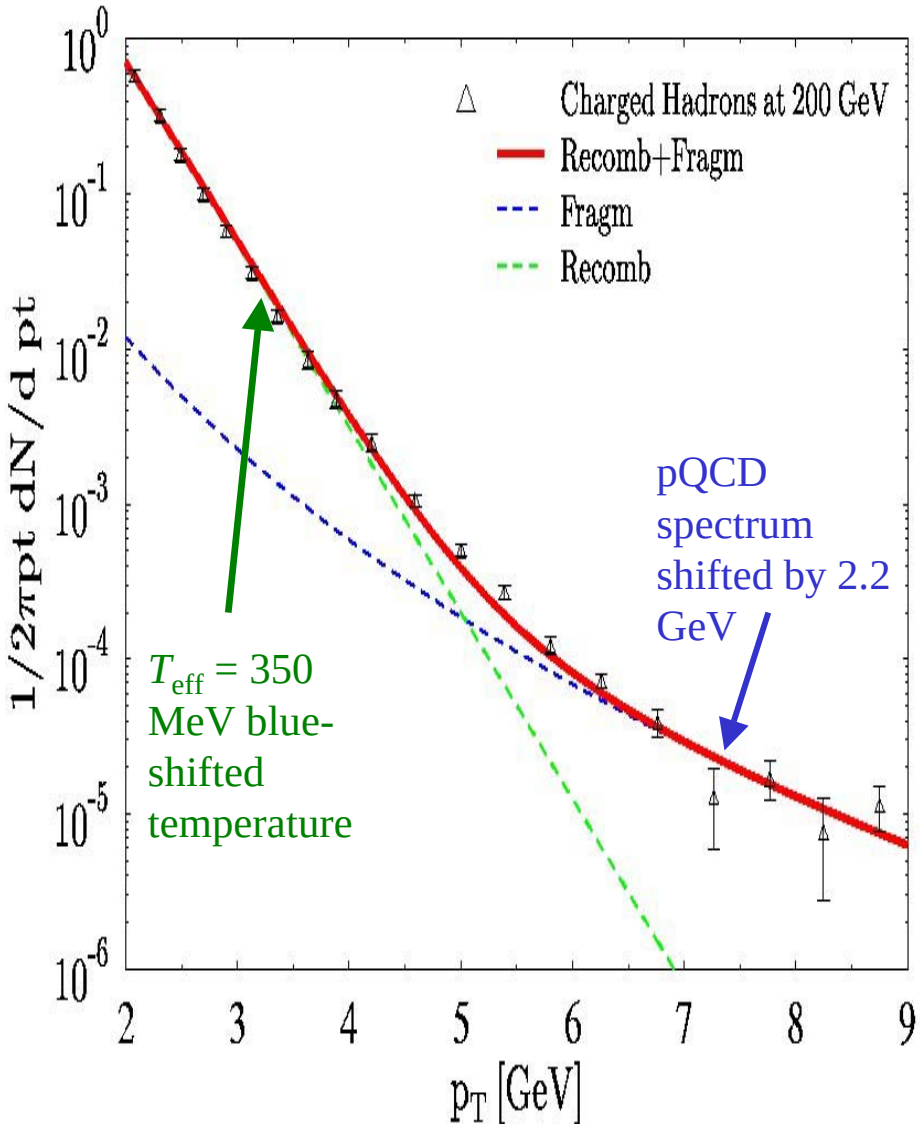
STAR

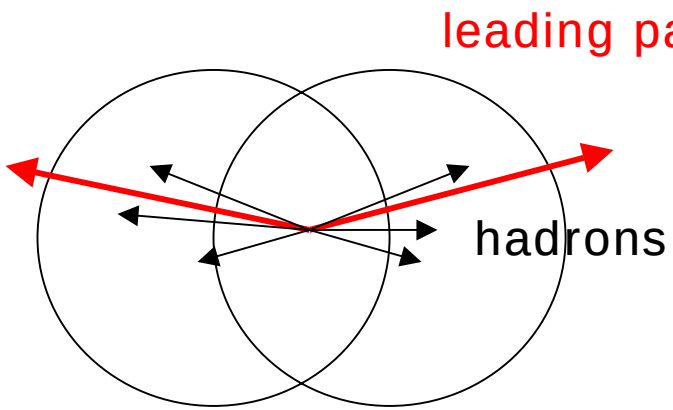


Jets should be flowing.

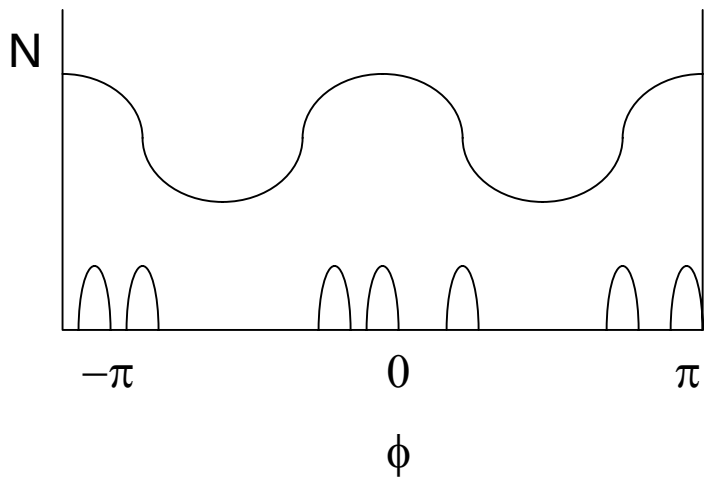
Because...


Hydro+jet
Hydro only
Jet only
π⁻
K⁻ × 10⁻³
p × 10⁻⁶
b=2 fm, T^th=100 MeV
(1/2πp_T)dN/dp_T dY (c²/GeV²)
p_T (GeV/c)


Charged Hadrons at 200 GeV
Recomb+Fragm
Fragm
Recomb
T_eff = 350 MeV blue-shifted temperature
pQCD spectrum shifted by 2.2 GeV
1/2πpt dN/d pt
p_T [GeV]



Q: Are jets source of v2?
Q: Does reaction zone make flowing jets?



Summary

Suppression during final state interaction.
Disappearance of back-to-back jets.
No suppression for open charm.
quark/parton radial/elliptic flow.

...

Quark-gluon-plasma ?

...

Not yet.