# Anisotropic Flow in $\sqrt{s_{NN}}$ = 200 GeV Cu+Cu and Au+Au collisions at RHIC - PHENIX

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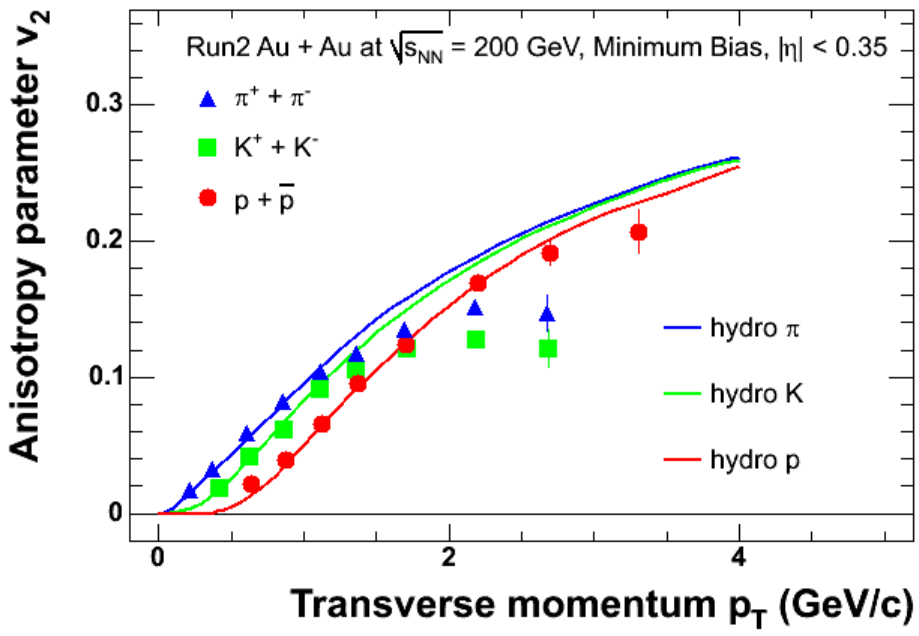
for the PHENIX collaboration

August 5, 2005

Quark Matter 2005

# Introduction

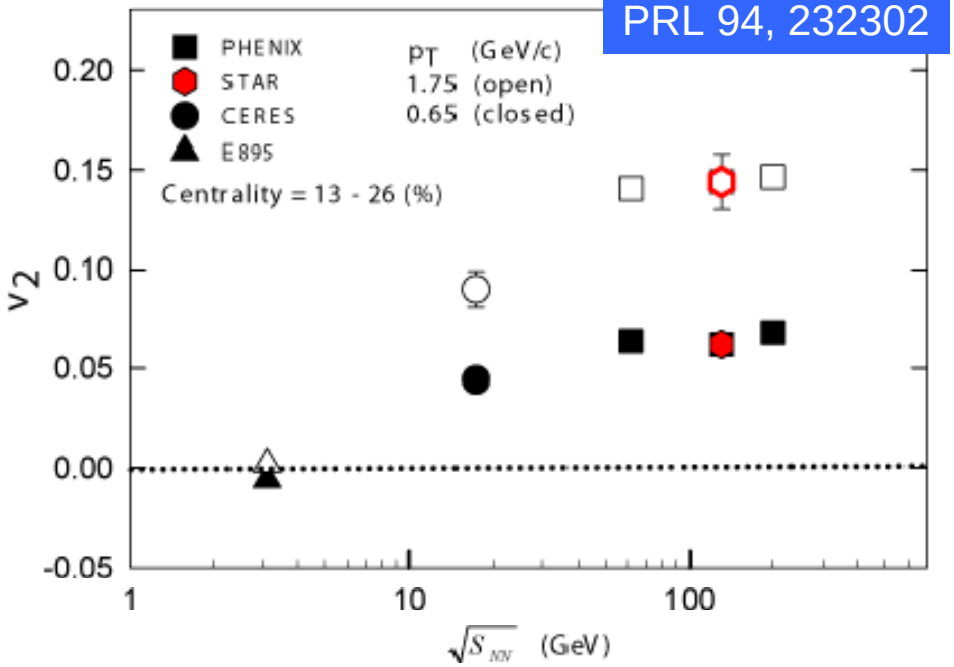
PRL 91, 182301




## Identified hadron $v_2$

- Early thermalization
- Constituent quark scaling
  → Partonic collectivity

PRL 94, 232302




## Energy dependence

- Saturation of $v_2$ at RHIC
- 50 % increase from SPS

# Motivation

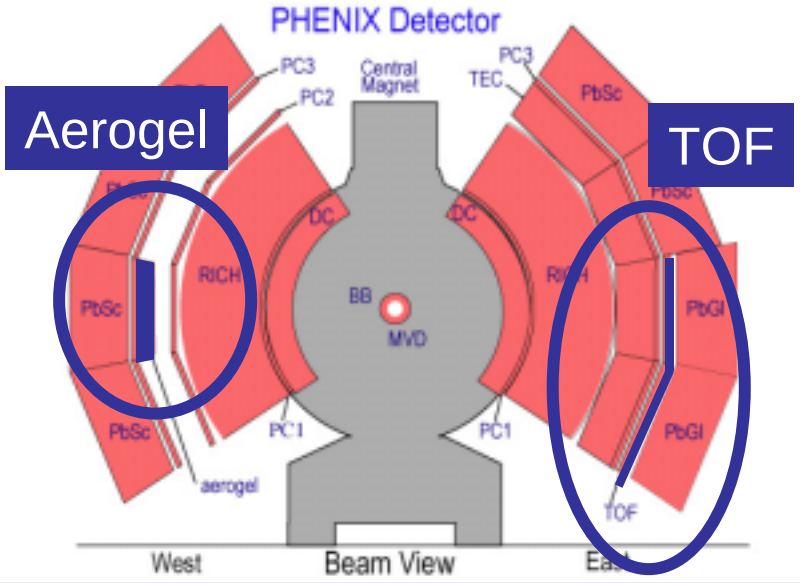
- Anisotropic flow can be reasonably described with hydrodynamical model at RHIC.
- Hydrodynamics predict large $v_2$ and several scaling relations
  - $v_4/(v_2)^2$ scaling
  - Eccentricity scaling
  - Scaling with system size
- It is crucial to test these scaling in order to understand the system properties.

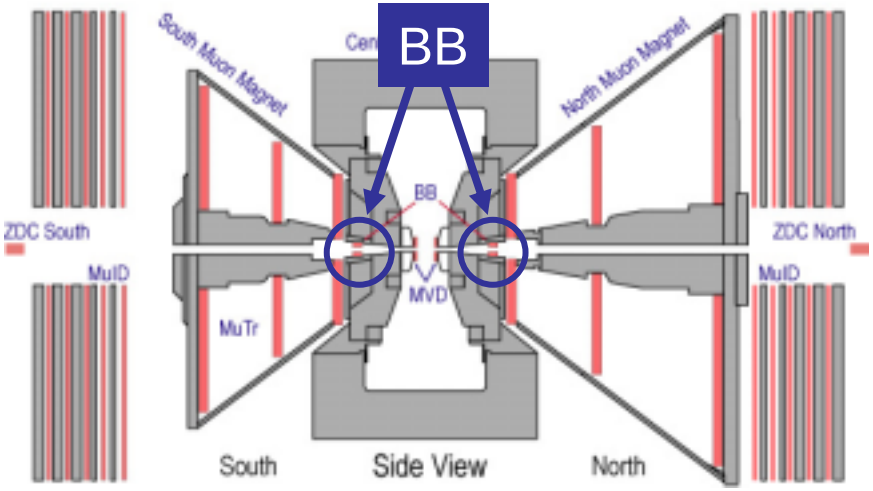
# Outline

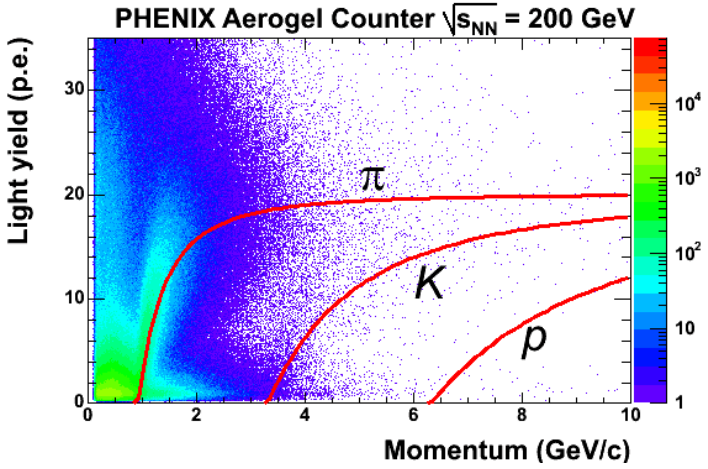
## Recent results of event anisotropy at PHENIX

- $v_4$ for unidentified and identified hadrons in Au+Au
  - Scaling ratio, $v_4/(v_2)^2$
- $v_2$ for identified hadrons in Au+Au
  - Intermediate $p_T$
  - Charm, $\phi$
- System size dependence of $v_2$
  - Eccentricity scaling
- Summary

# Analysis method




## Event plane

- Beam-Beam Counter, $|\eta| \sim 3 - 4$.
- Large rapidity gap ($\Delta\eta \sim 3$) → could reduce non-flow contribution

## PID

- High resolution Time-of-Flight
  - $\pi$/K separation ~ 3 GeV/c, K/p separation ~ 5 GeV/c
- Aerogel Cherenkov Counter
  - Higher $p_T$ PID with combining EMC timing information

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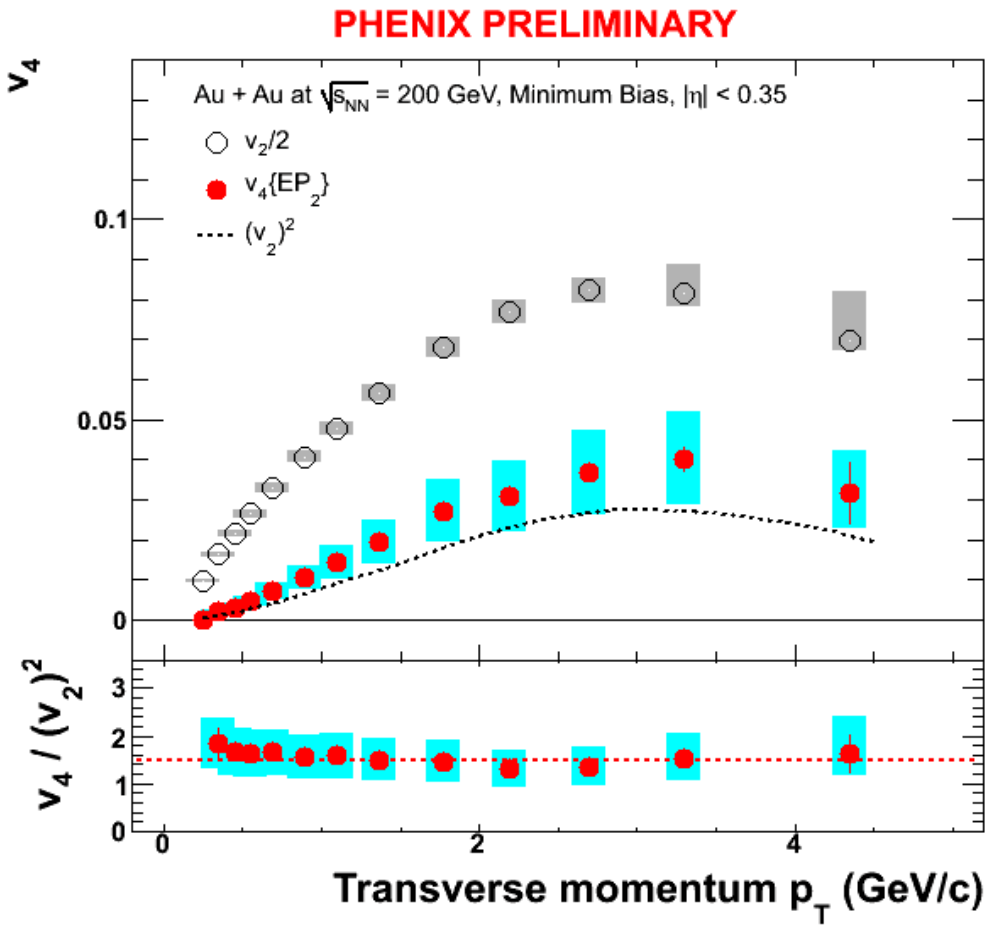
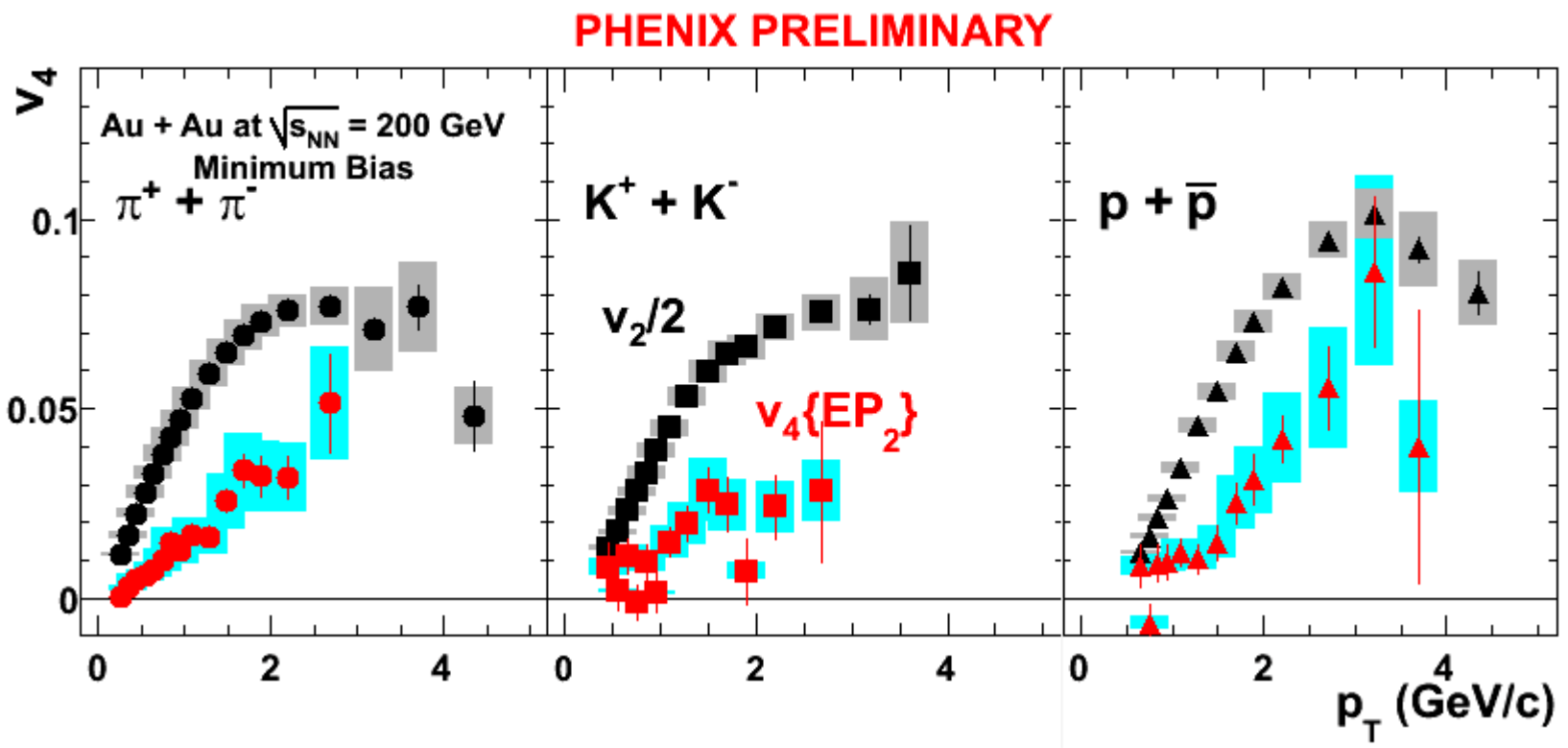
# *Scaling of $v_4$*

# $v_4\{EP_2\}$ vs $p_T$



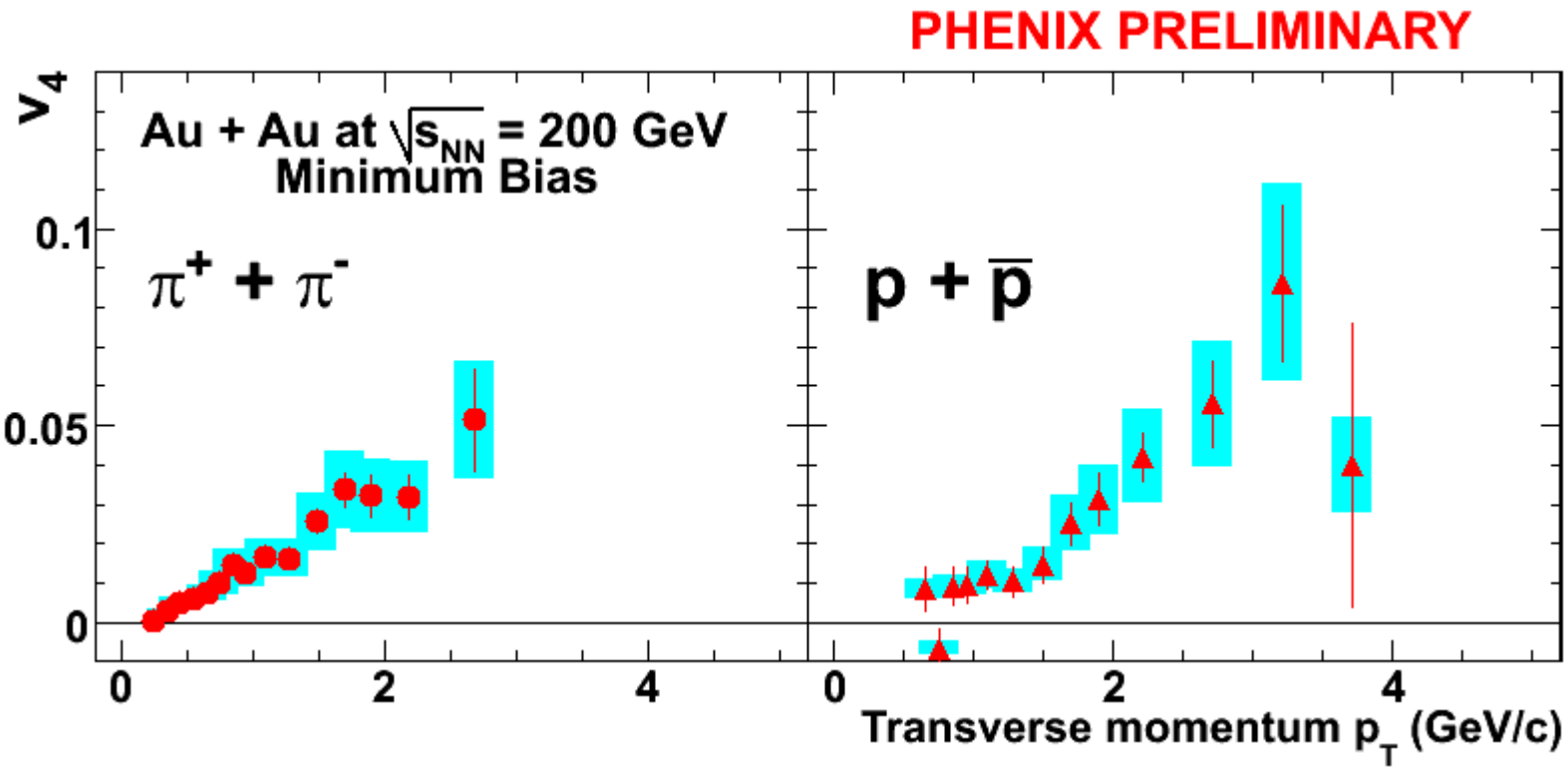

- $v_4\{EP_2\}$
  - $v_4$ with respect to the second harmonic BBC event plane.
- Very large $v_2$ at RHIC !
  - Hydro works.
- $v_4 \sim (v_2)^2$ (Ollitrault)
- $v_4/(v_2)^2 \sim 1.5$, flat.
- consistent with STAR results (1.2).

# PID $v_4\{EP_2\}$



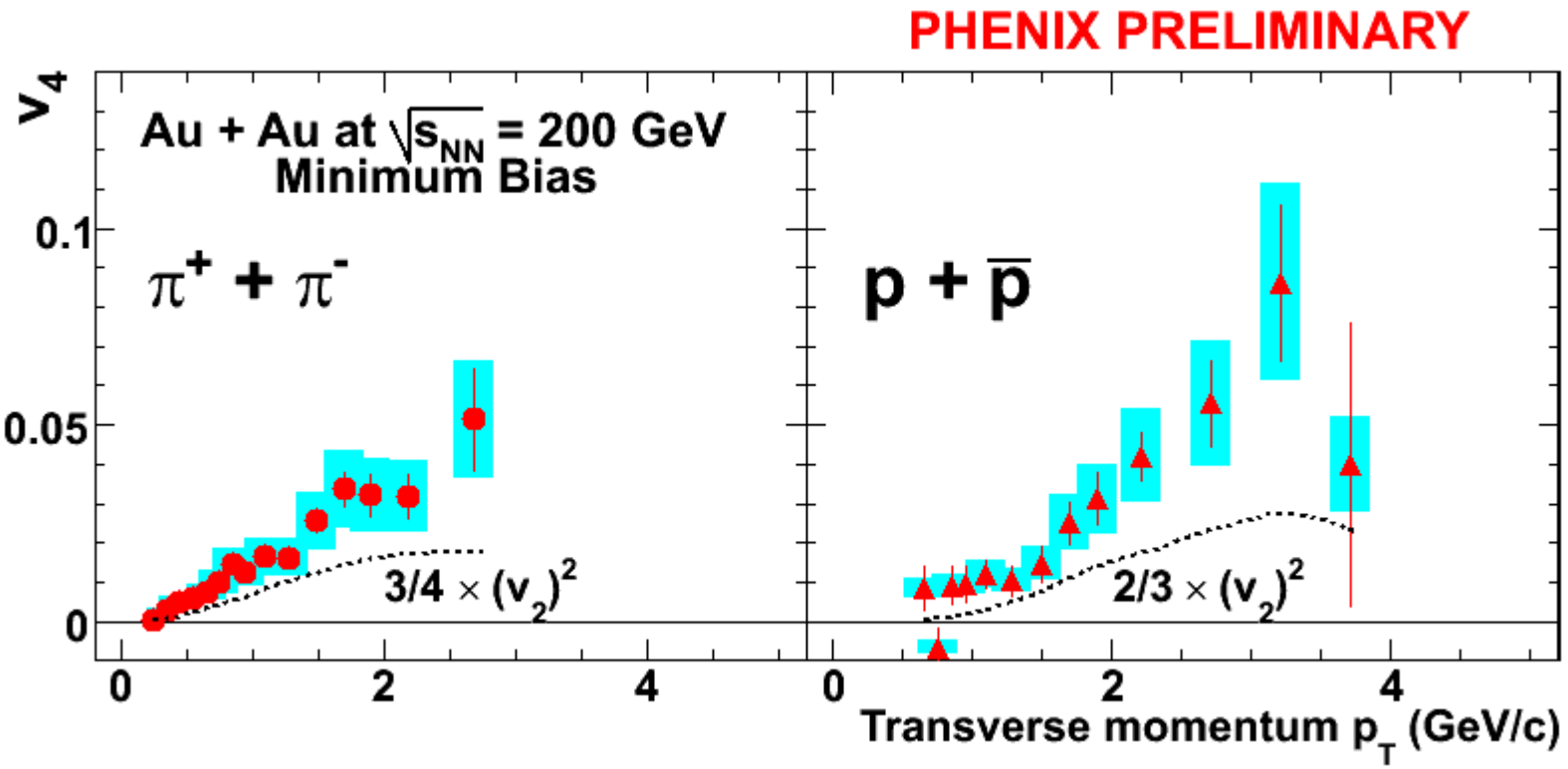

- $v_4$ measurement for identified hadrons.
- How about the scaling for identified hadrons ?

# $v_4/(v_2)^2$ scaling ratio



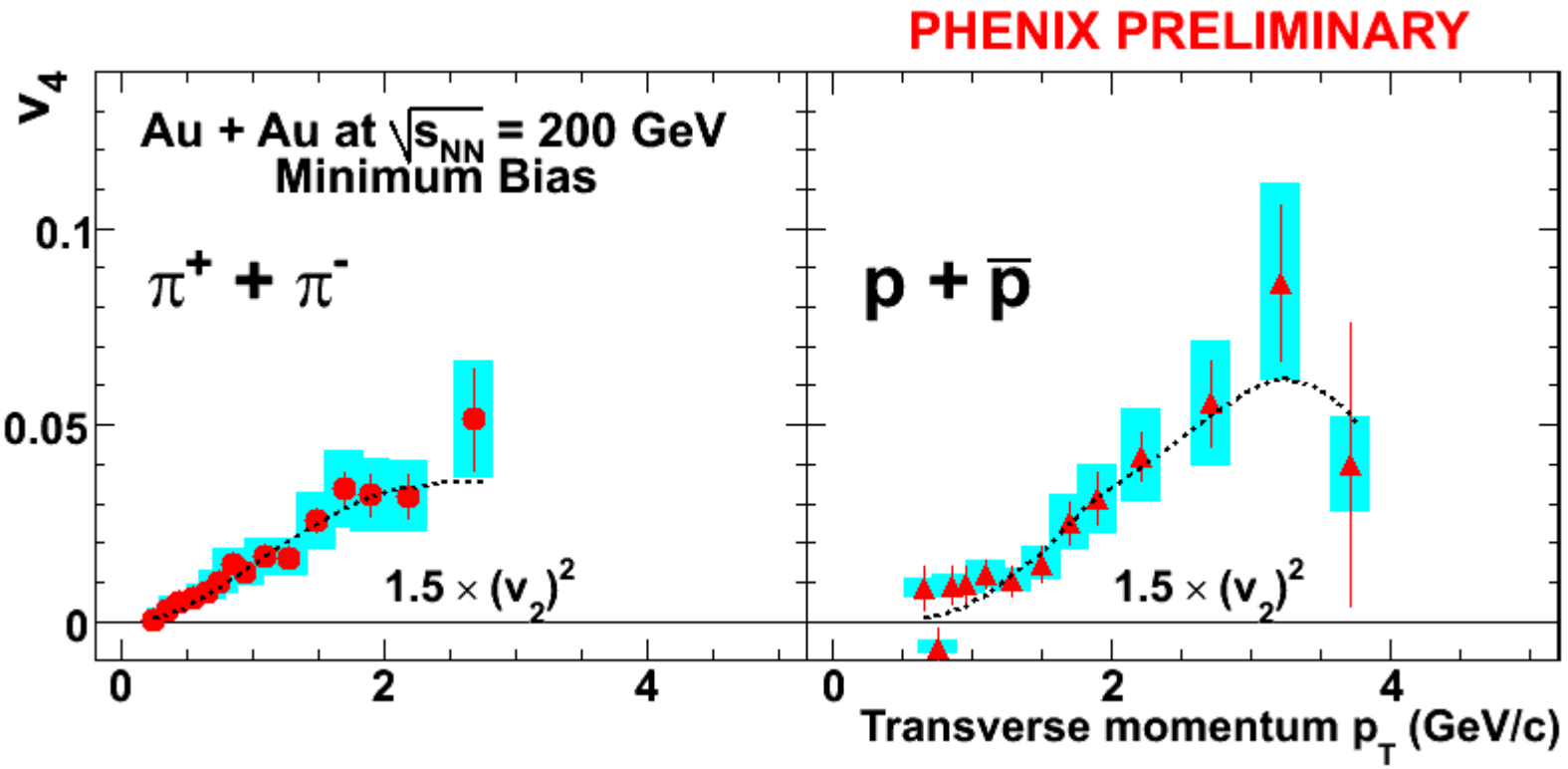

- Meson, baryon comparison

# $v_4/(v_2)^2$ scaling ratio




- Meson, baryon comparison
- Simple coalescence calculation, meson ~ 3/4, baryon ~ 2/3 (Kolb et al, PRC 69, 051901) → underestimate

# $v_4/(v_2)^2$ scaling ratio




- Meson, baryon comparison
- Simple coalescence calculation, meson ~ 3/4, baryon ~ 2/3 (Kolb et al, PRC 69, 051901) → underestimate
- Data seems to be scaled by 1.5

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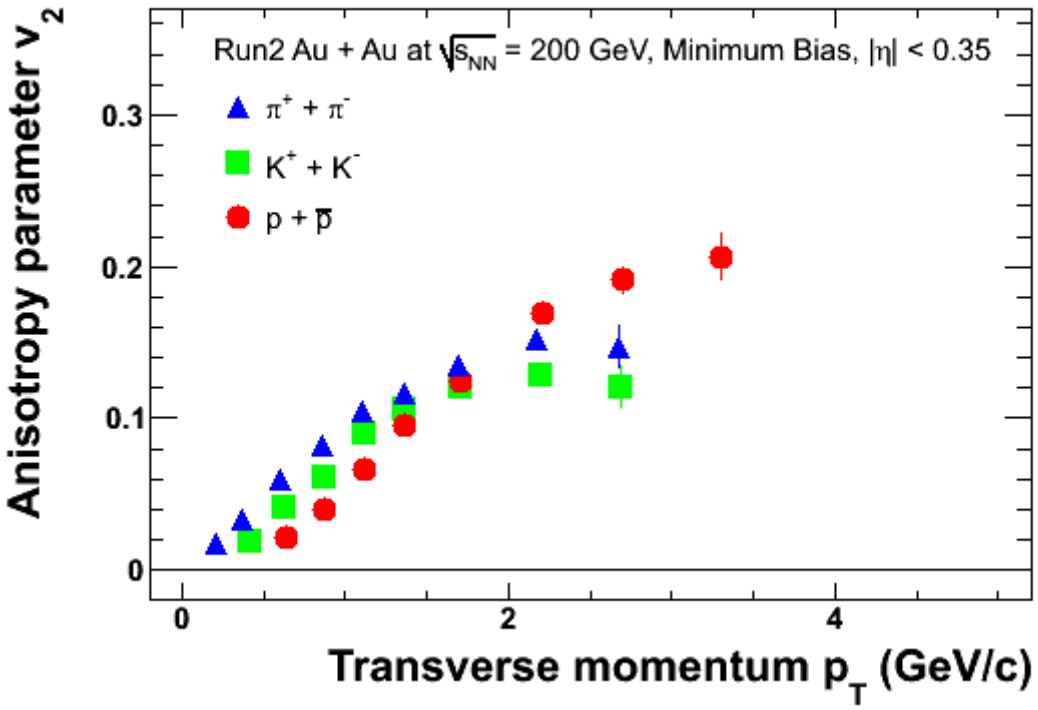
# *Identified hadron* $v_2$

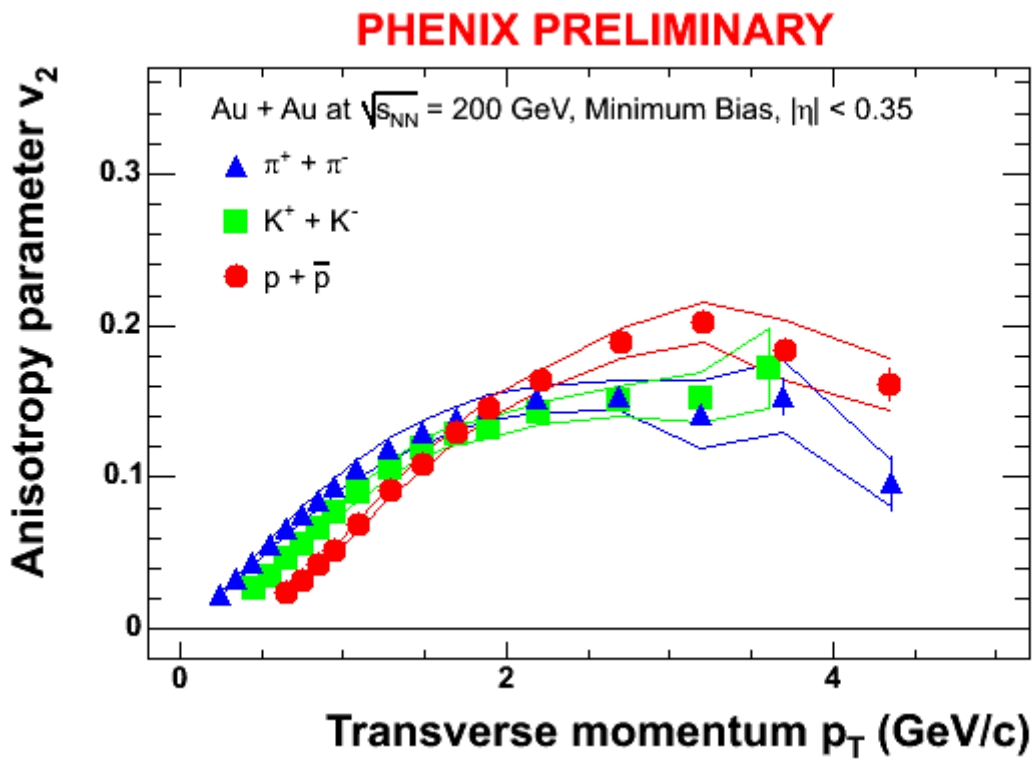
# What's new ?

PRL 91, 182301



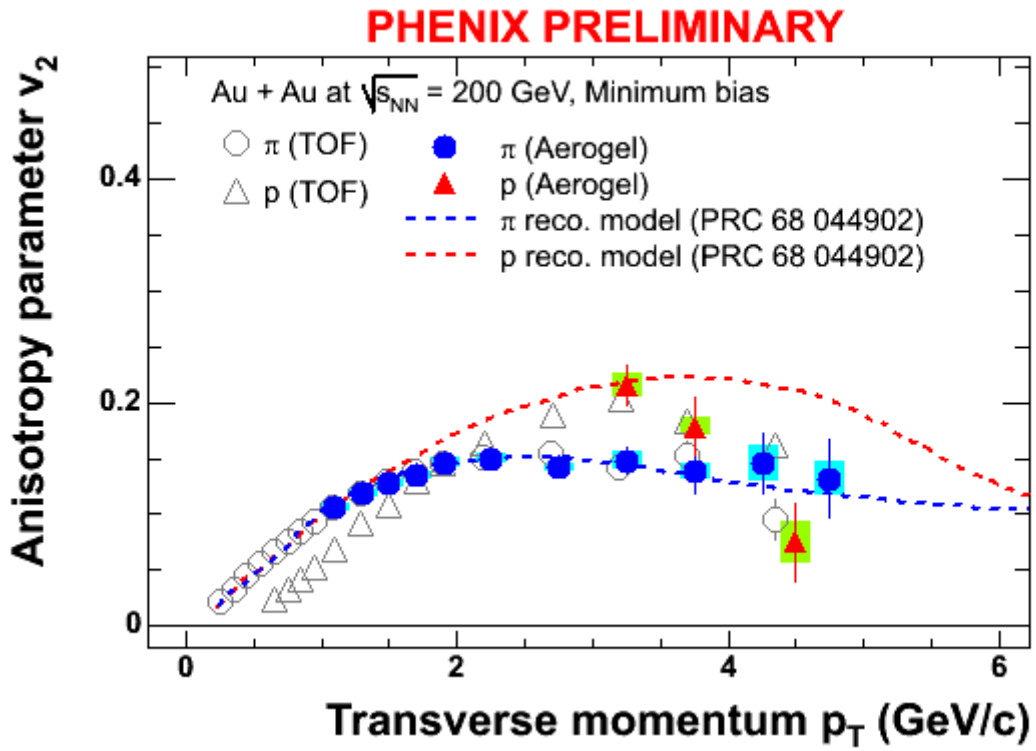

- Run2002 Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
- Measured at High resolution Time-of-Flight counter.
- π/K/p $v_2$
  - π/K ~ 3 GeV/c
  - p ~ 4 GeV/c

# What's new ?



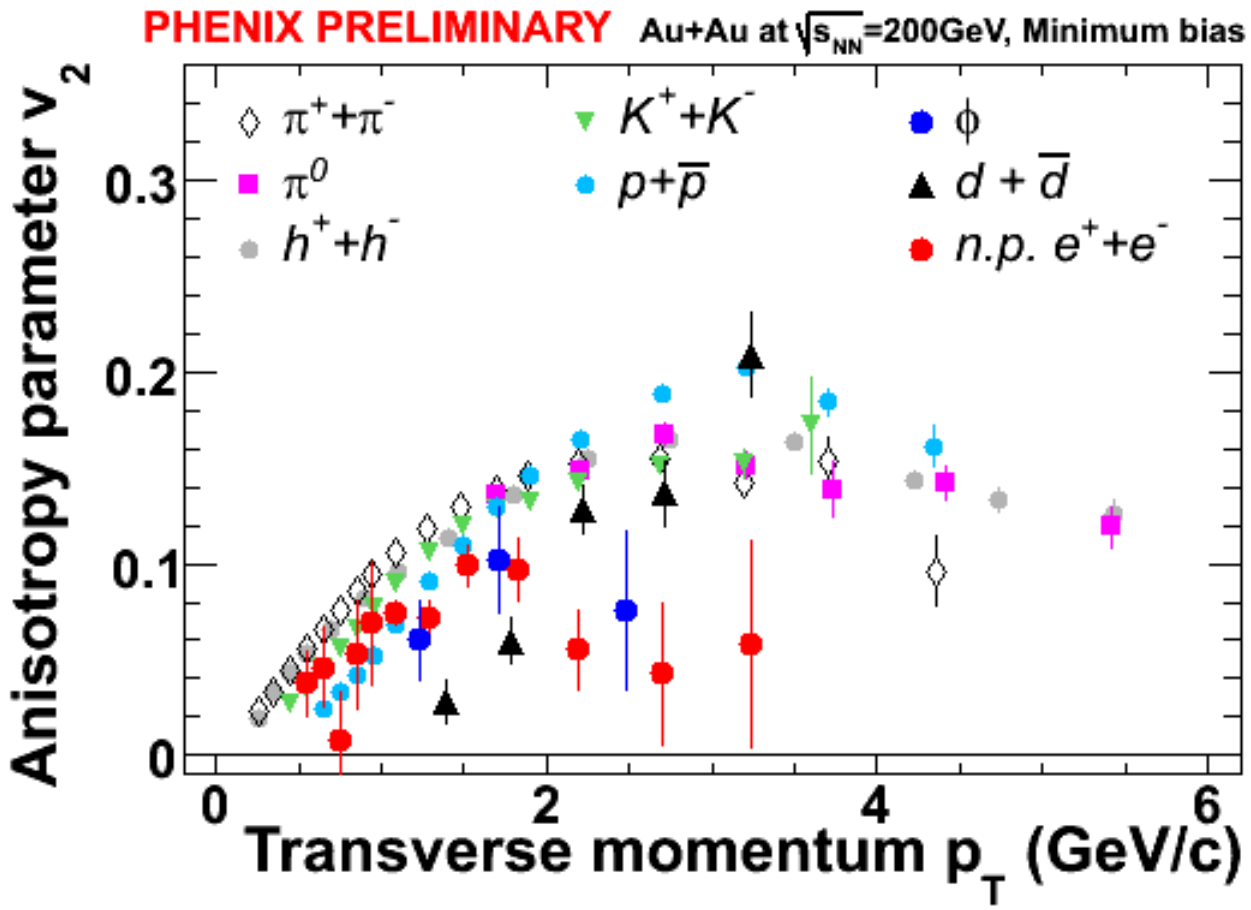

- High statistics in Run2004 Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
- Extend $p_T$ for $\pi$/K/p with simultaneous 3 gaussian fitting to mass square distribution
  - $\pi$, p  $p_T < 5$ GeV/c
  - K, $p_T < 4$ GeV/c

# Aerogel




- Aerogel can cover much higher $p_T$.
- Pion is quite consistent with reco model.
- Proton seems to decrease for $p_T$ = 4 – 5 GeV/c
  - Similar trend in TOF.
  - Need further study at higher $p_T$

# All identified particles




$\pi^0$ : D. L. Winter (talk), K. Miki (poster)

n.p. electron S. A. Butsyk (talk), S. Sakai (poster)

$\phi$ : D. Pal (talk)

- Charm has strong flow ! → thermalization
- $\phi$ is also flowing ! → partonic collectivity

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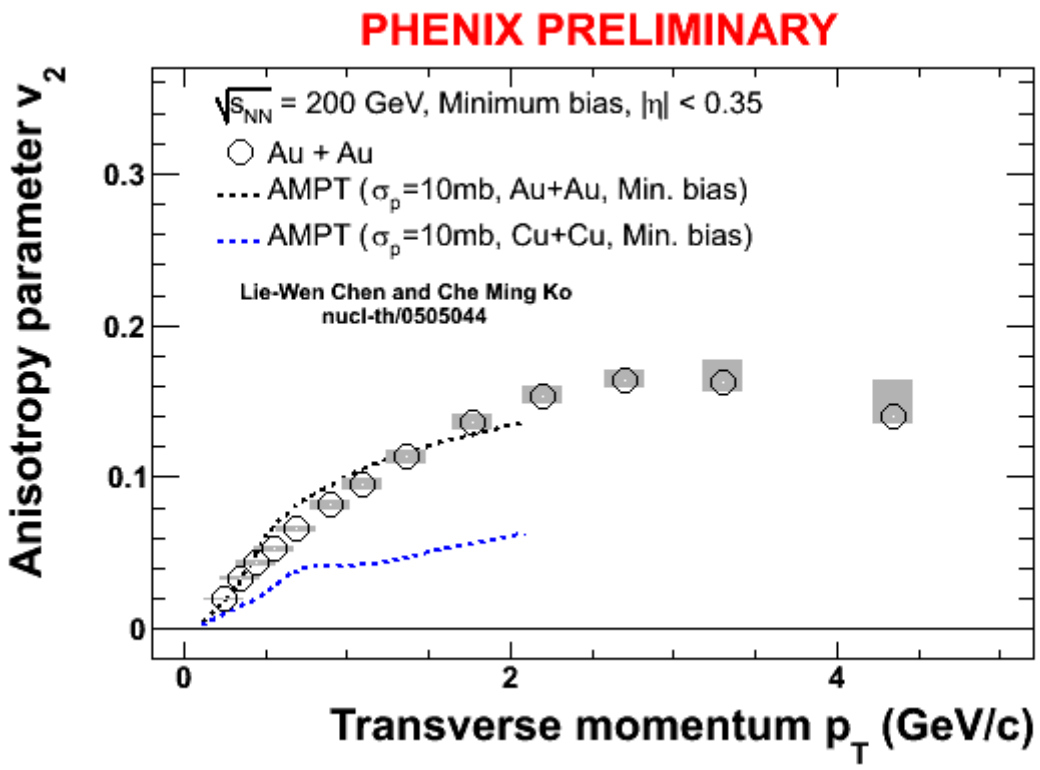
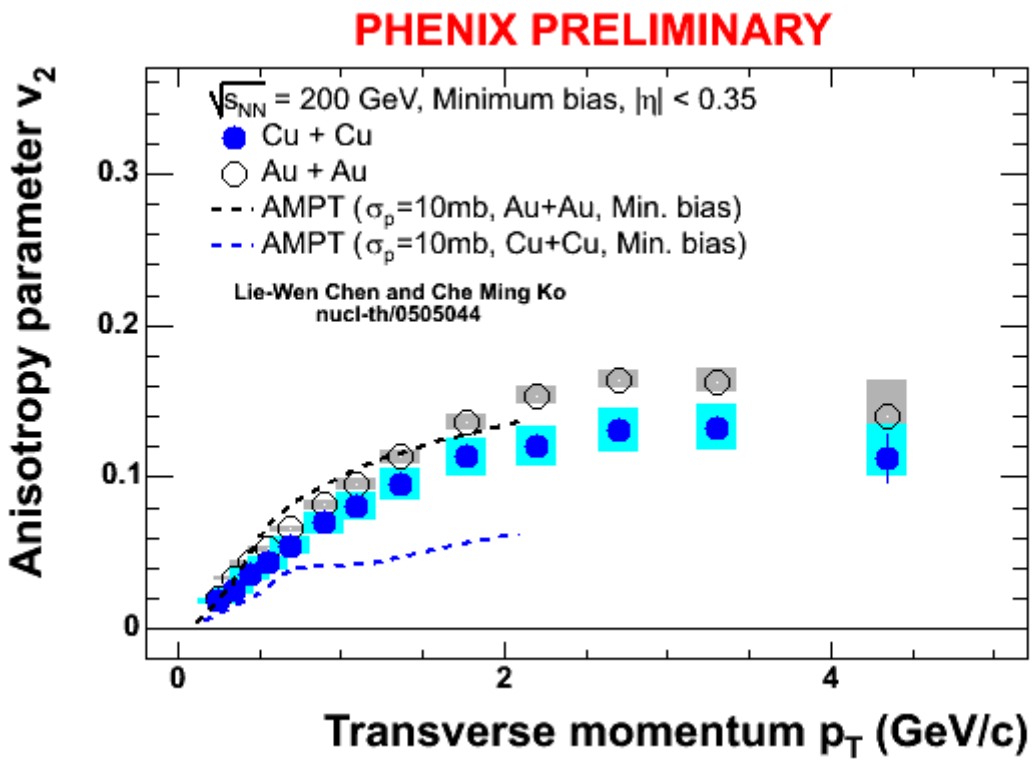
# *System size dependence Au+Au vs Cu+Cu*

# Linear scaling ?



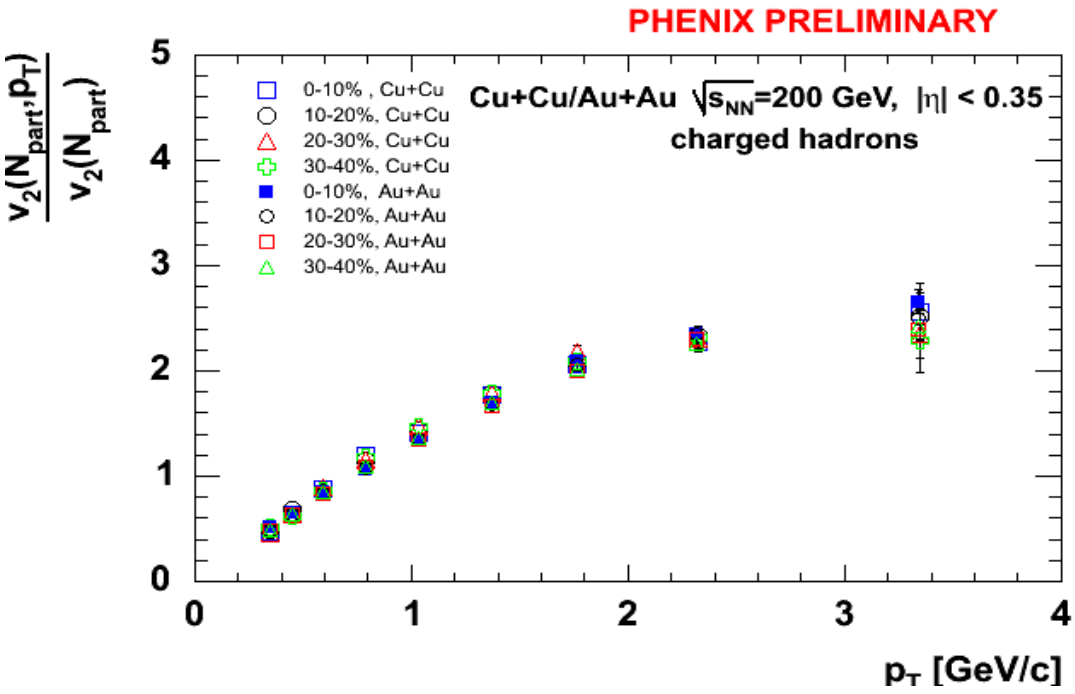

- AMPT
  - An approximate linear scaling with the system size.
  - $v_2$(Cu+Cu) ~ 0.3 * $v_2$(Au+Au)

# Linear scaling ?




- AMPT
  - An approximate linear scaling with the system size.
  - $v_2$(Cu+Cu) ~ 0.3 * $v_2$(Au+Au)
- First results of $v_2$ in smaller system, Cu+Cu
  - < 10 % of total data
- $v_2$ seems to NOT scale by system size linearly.
  - $v_2$(Cu) ~ 0.84 * $v_2$(Au)

# Eccentricity scaling

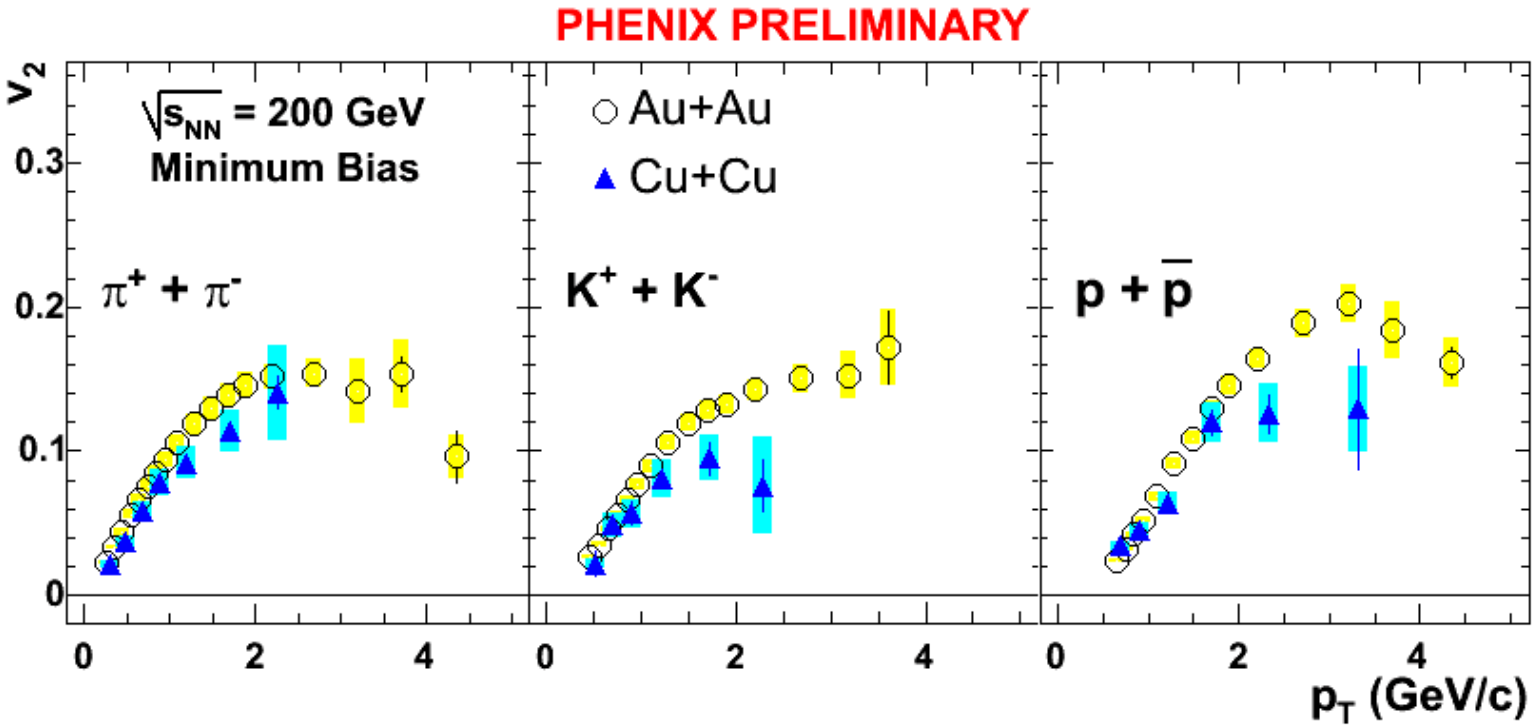



See poster
by A. Taranenko

- $v_2$(integral) ~ ε
- $v_2(p_T)/v_2$(integral)
  - Reduce systematic errors related to eccentricity calculation and event plane resolution.
- Scaling would be roughly independent of the system size

  → Suggest that hydrodynamical regime is reached in central - mid-central Cu+Cu collisions.

# Constituent quark scaling




- Smaller $v_2$ in Cu+Cu
- Similar trend for identified hadron $v_2$ in Cu+Cu compared to that in Au+Au
- Constituent quark scaling in Cu+Cu ?
  - Need much more statistics

# Summary

## $v_4$ scaling

- $v_4/(v_2)^2$ scaling ratio ~ 1.5 for both unidentified and identified hadrons.
  - larger by factor 2 – 3 from model prediction.

## Identified hadron $v_2$

- Proton $v_2$ seems to decrease around $p_T$ ~ 4 – 5 GeV/c.
  - Further study need to be done at higher $p_T$.
- Charm, $\phi$ has a strong flow !

## Scaling with system size

- The scaling of $v_2$ with system size seems to not linear.
- Eccentricity scaling would be roughly independent of the system size
  - Suggest that hydro regime is reached in central – mid-central Cu+Cu collisions.
- Similar tendency of identified hadron $v_2$ in Cu+Cu compared to Au+Au is observed.

# Flow talks, posters

- Talks
  - D. L. Winter ($\pi^0$, charged hadron at high $p_T$) Parallel1, 3a (Aug. 5, Fri.)
    - PHENIX measurement of particle yield at high $p_T$ with respect to the reaction plane in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
  - D. Pal ($\phi$ meson) Parallel1, 1b (Aug. 5, Fri.)
    - Nuclear Modifications and elliptic flow measurements for $\phi$ mesons at $\sqrt{s_{NN}}$ = 200 GeV d+Au and Au+Au collisions by PHENIX
- Posters
  - B. E. Norman ($v_1$, $v_2$ at MVD) Poster1, 49 (Aug. 4 – 5)
    - Azimuthal anisotropy at intermediate rapidity in $\sqrt{s_{NN}}$ = 200 GeV Au-Au collisions using the PHENIX MVD
  - S. Sakai (electron $v_2$) Poster1, 51 (Aug. 4 – 5)
    - The azimuthal anisotropy of electrons from heavy flavor decays in $\sqrt{s_{NN}}$ = 200 GeV Au-Au collisions by PHENIX
  - A. Taranenko (identified hadron $v_2$ in Au+Au and Cu+Cu) Poster1, 52 (Aug. 4 – 5)
    - Scaling properties of azimuthal anisotropy at RHIC
  - K. Miki ($\pi^0$, photon $v_2$) Poster1, 192 (Aug. 4 – 5)
    - Measurement of inclusive photon and direct photon $v_2$ in $\sqrt{s_{NN}}$ = 200 GeV Au-Au collision with PHENIX experiment at RHIC
  - M. Konno (Aerogel $v_2$) Poster1, 222 (Aug 6 – 8)
    - Identified charged hadron production at high pT in $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions

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- Debrecen University, Debrecen, Hungary
- Eövös Loránd University (ELTE), Budapest, Hungary
- Banaras Hindu University, Banaras, India
- Bhabha Atomic Research Centre (BARC), Bombay, India
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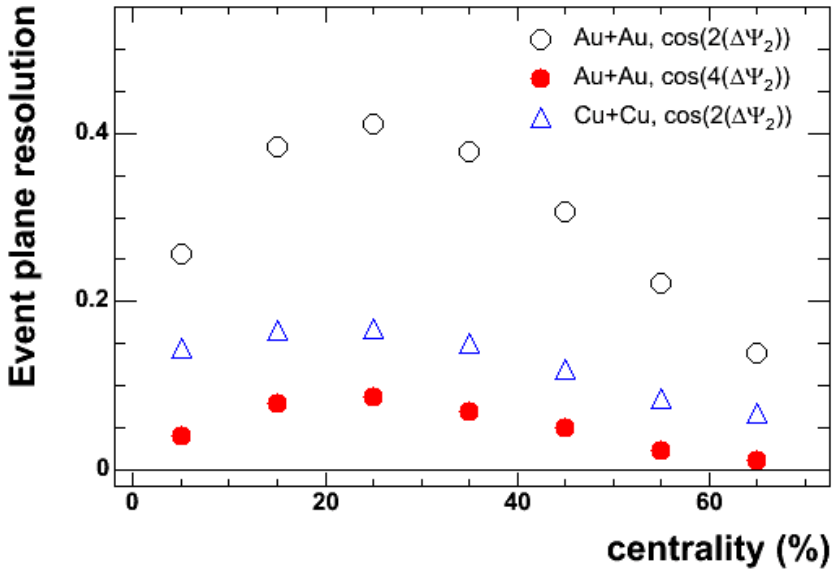
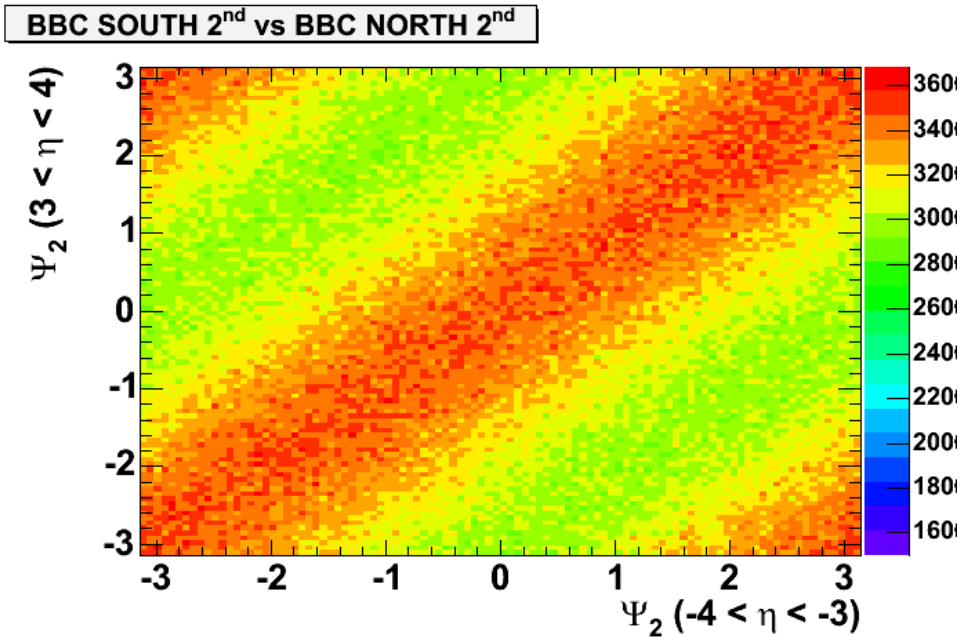
*as of March 2005

# Back up

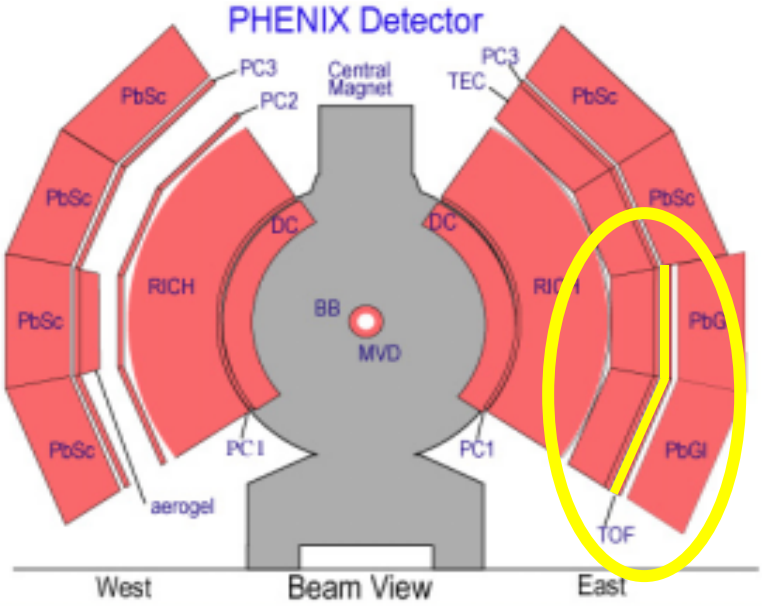
# Event plane Method

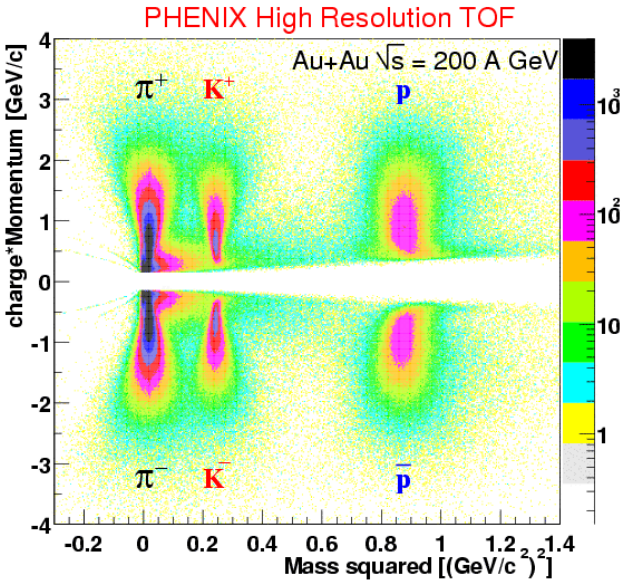



- Determine event plane at Beam-Beam Counter ($|\eta| \sim 3 - 4$)
- Measure event anisotropy in PHENIX central arm ($|\eta|<0.35$)
- Large rapidity gap ($\Delta\eta \sim 3$)→ Reduce non-flow effect

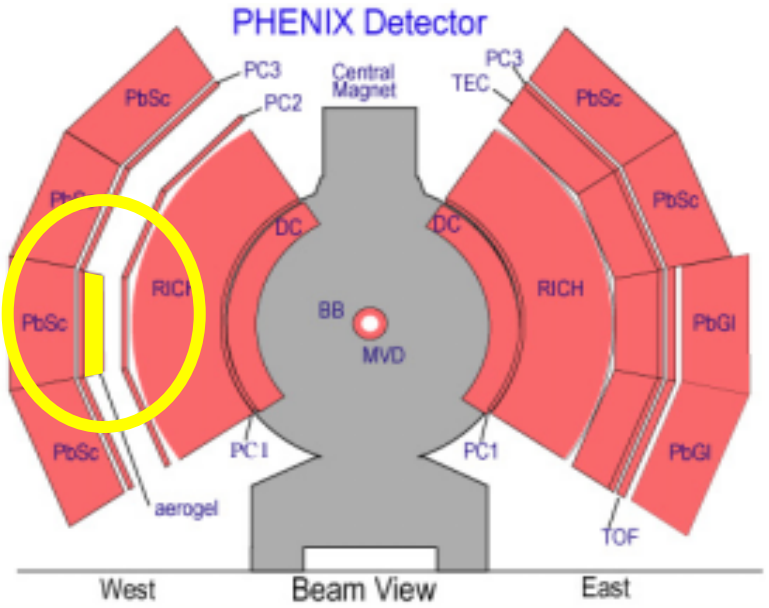
# Charged Particle identification at PHENIX

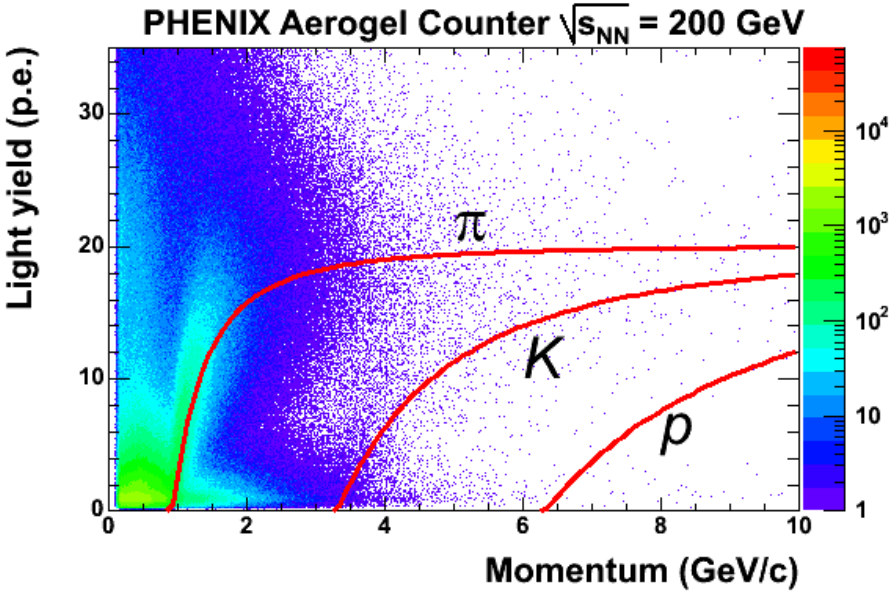



- High resolution Time-of-flight
  - π/K separation ~ 3 GeV/c, K/p separation ~ 5 GeV/c

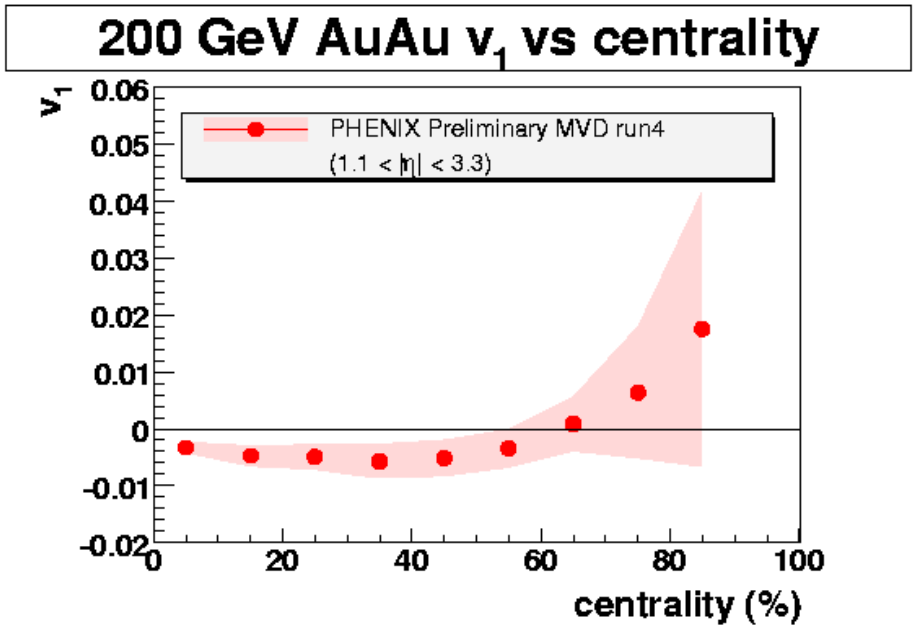
# Charged Particle identification at PHENIX



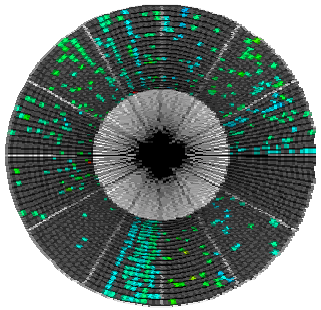




- High resolution Time-of-flight
  - $\pi$/K separation ~ 3 GeV/c, K/p separation ~ 5 GeV/c
- Aerogel counter → Threshold type Cherenkov counter
- Combined Aerogel + TOF (EMC) → PID in higher $p_T$.

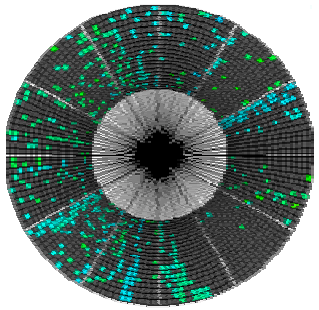
# $v_1$ at MVD




North MVD Hits



South MVD Hits

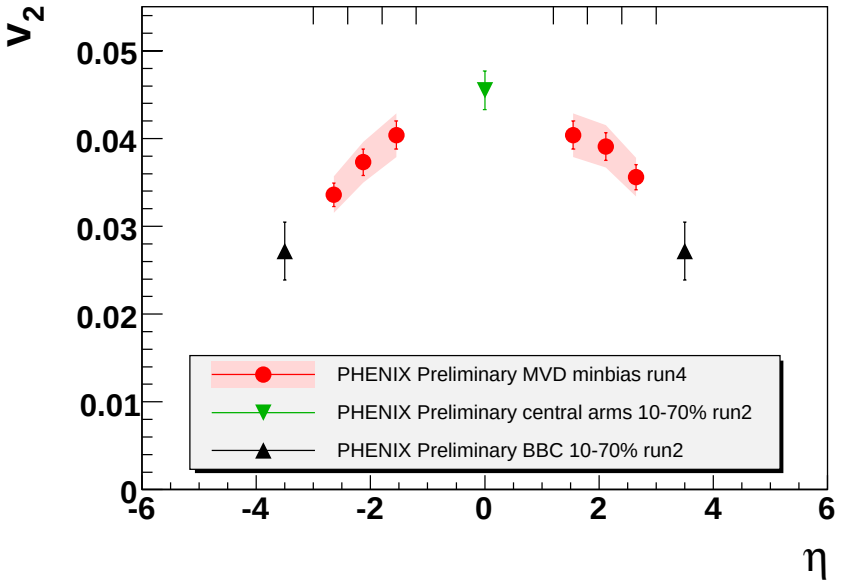


- $v_1$ measurement at PHENIX MVD with respect to the 1st harmonic BBC event plane.
- Cover intermediate rapidity between PHENIX central arm and BBC, $|\eta| \sim 1 - 3$

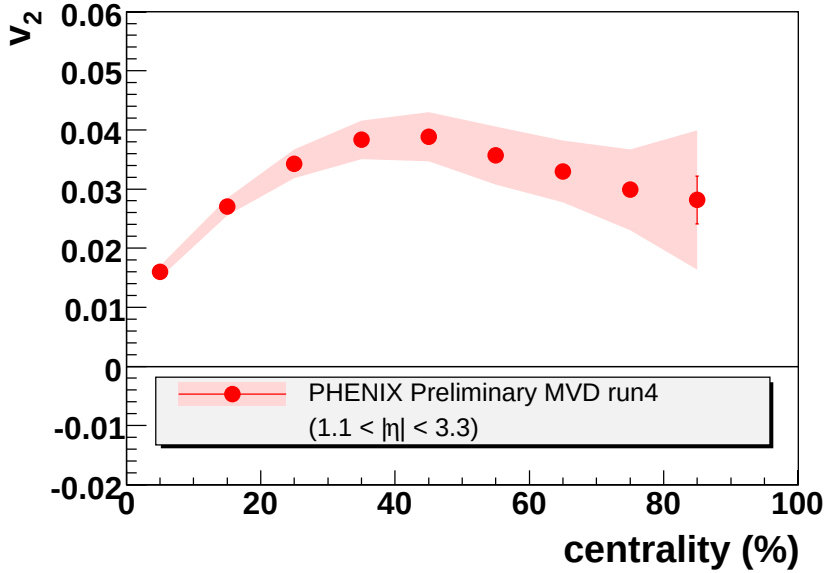
See Poster by B. E. Norman

# $v_2$ at MVD

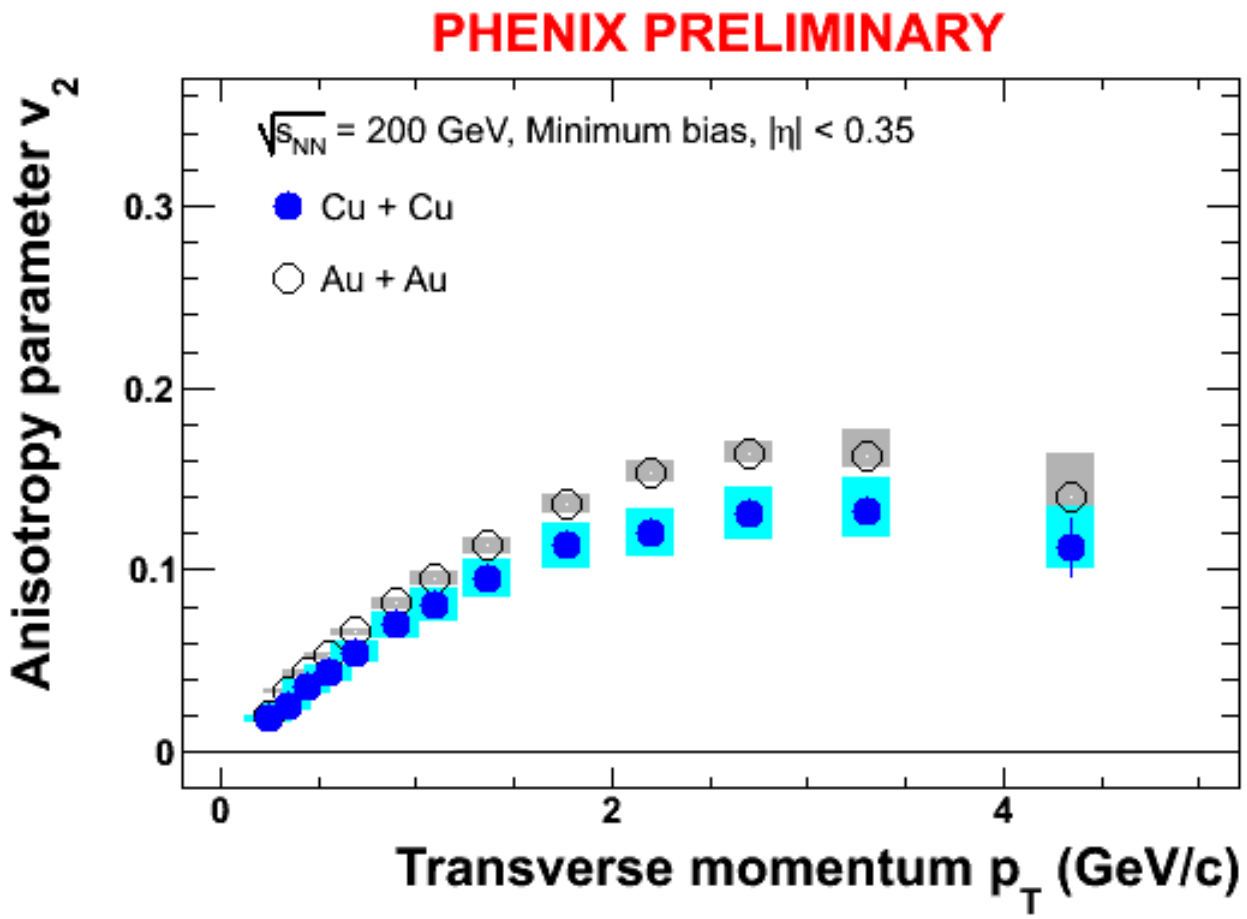
## 200 GeV AuAu $v_2$ vs $\eta$



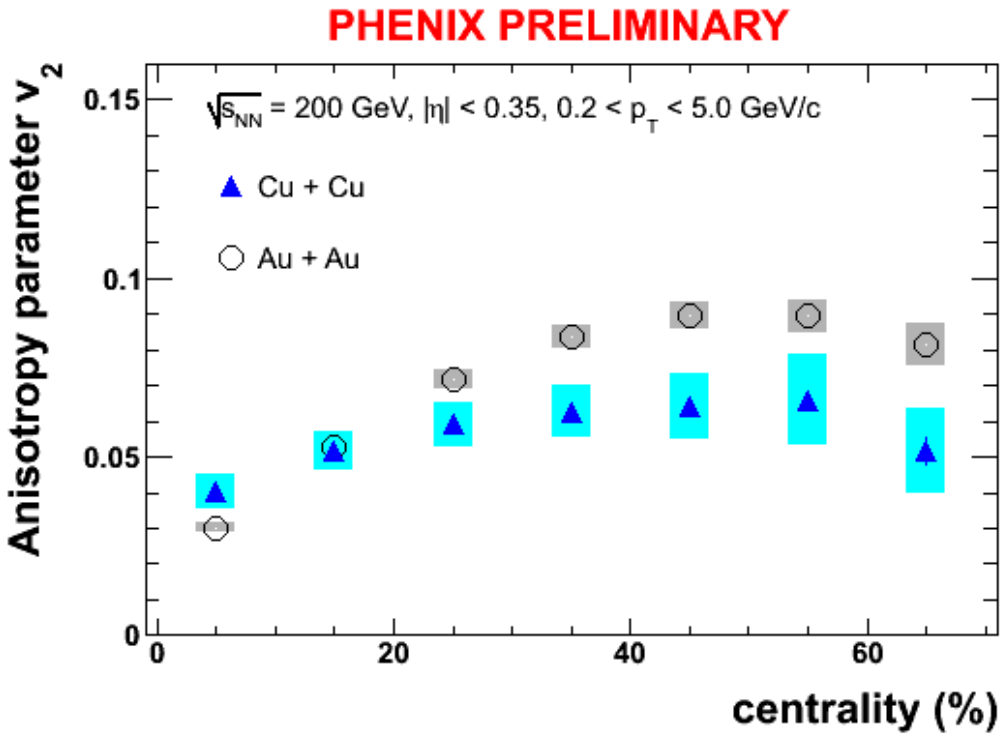

## 200 GeV AuAu $v_2$ vs centrality

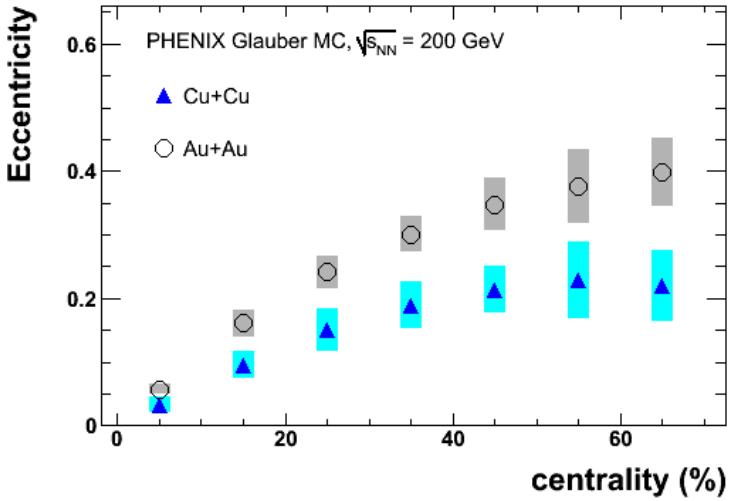


# $v_2$ vs $p_T$, minimum bias

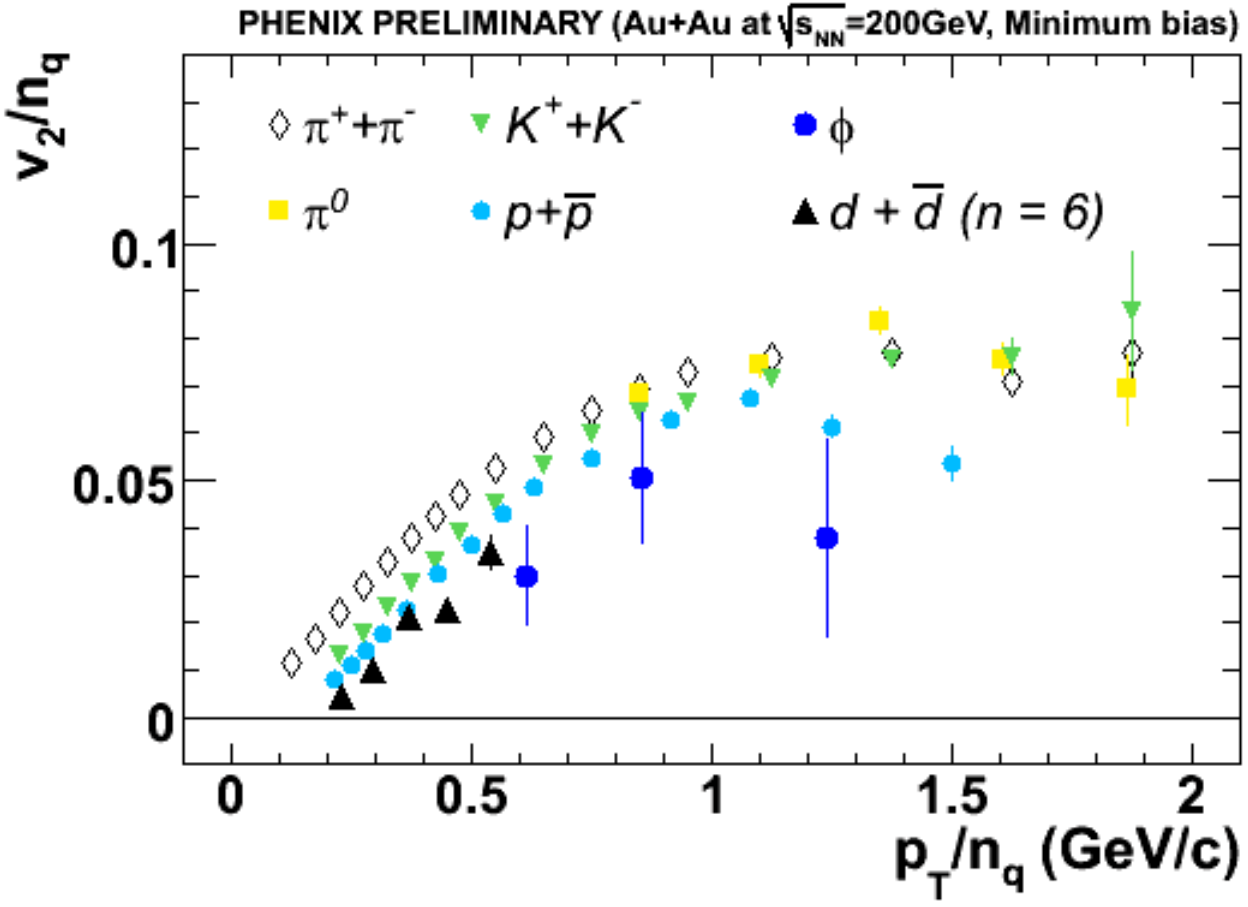
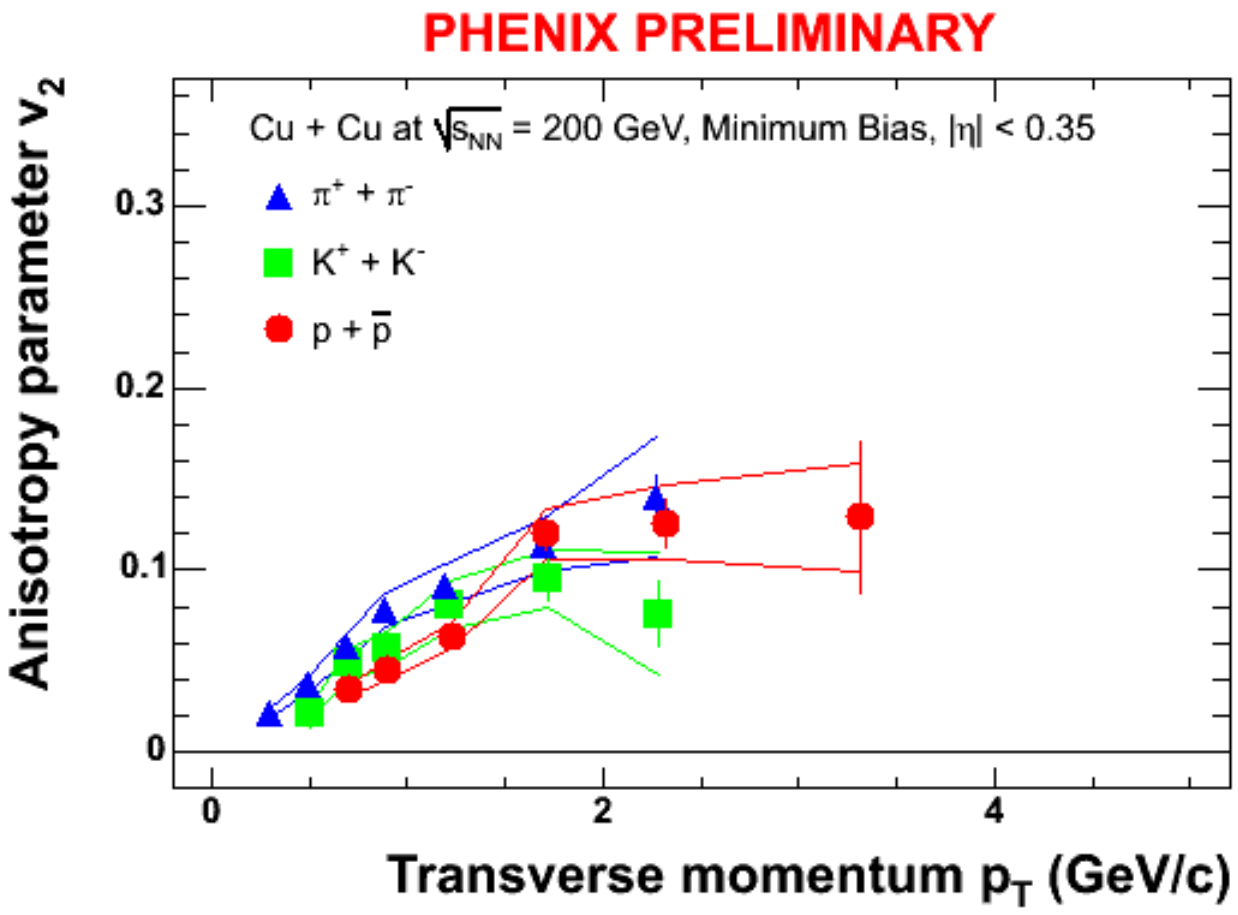


# Centrality depedence



# Constituent quark scaling



# PID v2 in Cu+Cu