Towards Measurements of Chiral Effects Using Identified Particles from STAR

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2/7/17

Outline

I. Physics Motivation and Observables

II. STAR Experiment

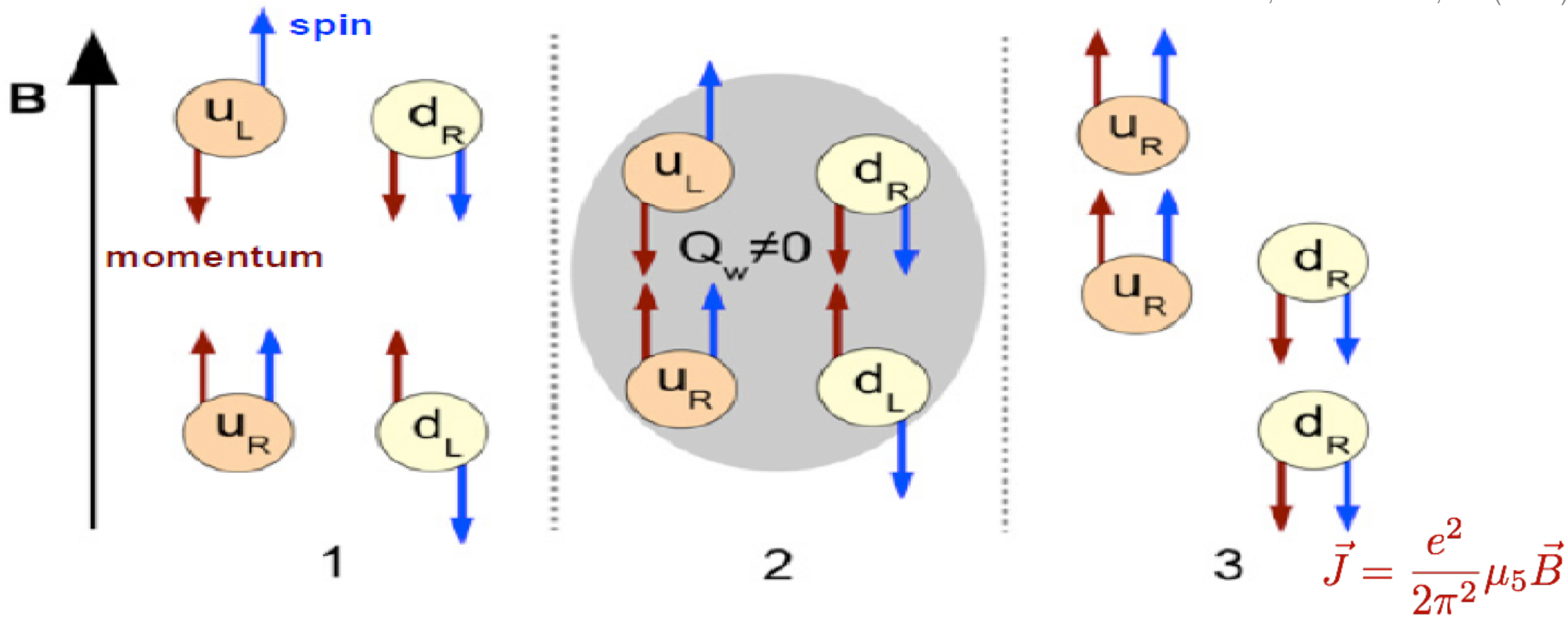
III. Correlation Measurements

- γ, κ_K for identified particles in Au+Au.
- γ for charged hadrons in p+Au, d+Au.
- Search for Chiral Magnetic Wave (CMW) in p+Au.

IV. Summary & Outlook

Chiral Magnetic Effect (CME)

D. Kharzeev, etc. NPA 803, 227(2008)



Non-zero topological charge induces excess of right or left handed quarks. Under strong magnetic field (B), an electric current along B direction is generated and leads to electric charge separation.

Observable: γ correlator

We investigate the charge dependent two-particle correlations with respect to the reaction plane:

$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2a_{\pm} sin(\phi^{\pm} - \Psi_{RP})$$

Direct measurement of "a" would yield zero value. So we need "three point-correlator"—observable "γ"!

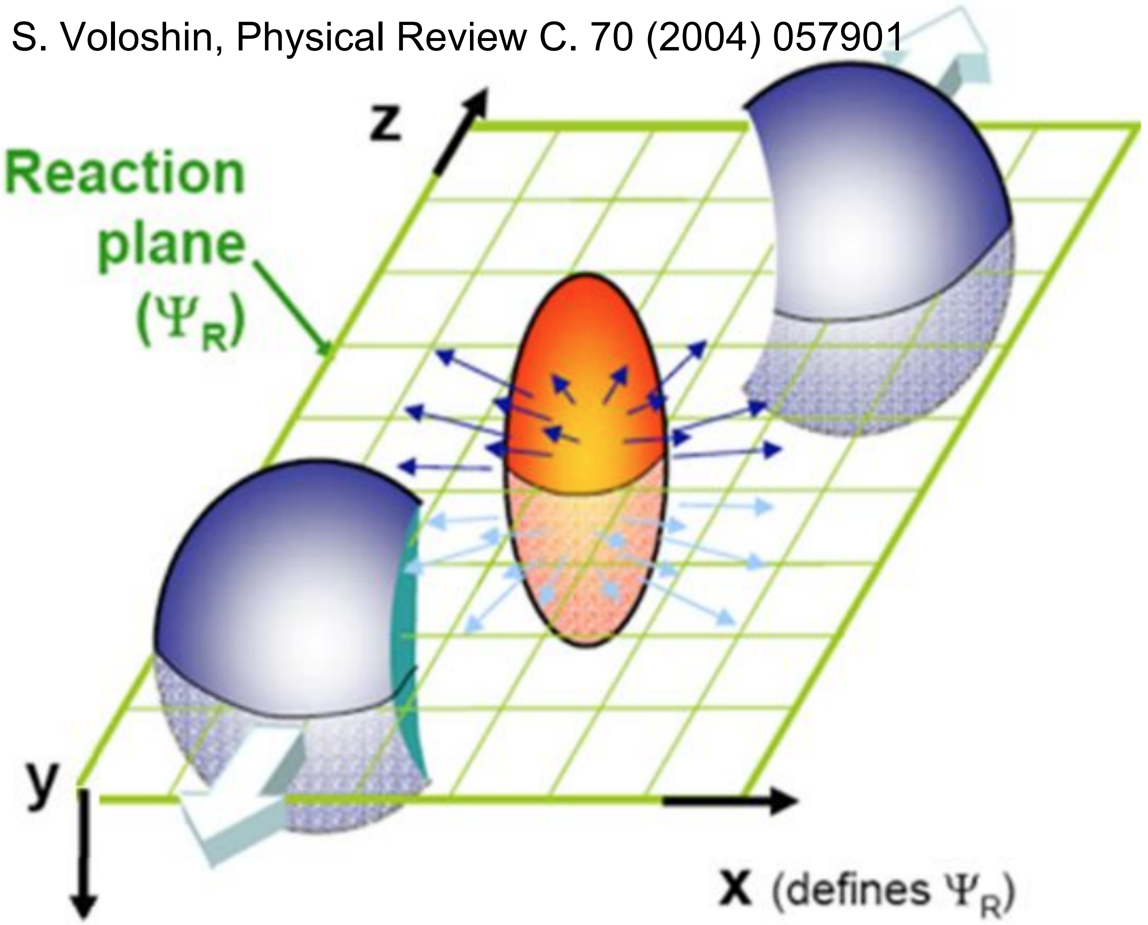
$$\gamma = \langle cos(\phi_\alpha + \phi_\beta - 2\psi_{RP})\rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta}\rangle + B_{in}] - [\langle a_\alpha a_\beta\rangle + B_{out}]$$

Directed flow: expected to be same for "same sign" and "opposite sign"

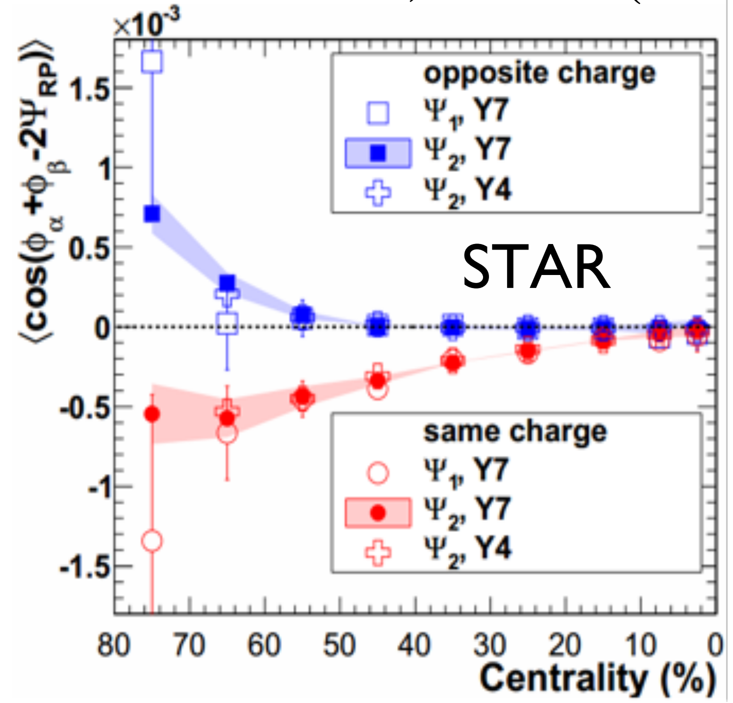
Background effects: could cancel out, but flow-related background may still exist.

P-even quantity: still sensitive to separation effect, i.e., different for "same sign" and "opposite sign"

S. Voloshin, Physical Review C. 70 (2004) 057901



PHYSICAL REVIEW C **81**, 054908 (2010)



Background!

A. Bzdak, V. Koch and J. Liao, Lect. Notes Phys. 871, 503 (2013).

$$\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H$$

$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\psi_{ep}) \rangle = \kappa v_2 F - H \Rightarrow \kappa = \frac{\Delta\gamma + \Delta H}{v_2(\Delta\delta - \Delta H)}$$

$$\Downarrow$$

$$H = \frac{\kappa v_2 \delta - \gamma}{1 + \kappa v_2}$$

F: Flow-related backgrounds
H: Charge separation signal
Δ: OS – SS

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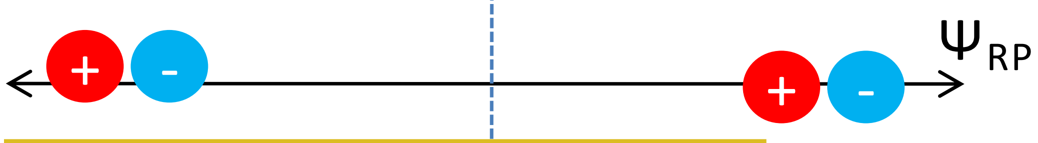

- ✓ Flow
- ✓ Momentum Conservation
- ✓ Local Charge Conservation
- ✓ Decay

Correlators:

$\gamma_{ss} = -1$

$\delta_{ss} = -1 \qquad H_{ss}^{\kappa=1} = 0$

$v_2 = 1$

$\gamma_{os} = 0 \qquad H_{os}^{\kappa=1} = 0$

$\delta_{os} = 0$

H is more robust!

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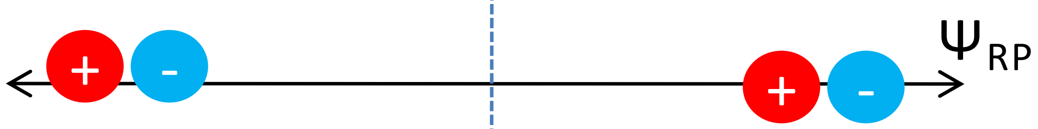

- ✓ Flow
- ✓ Momentum Conservation
- ✓ Local Charge Conservation
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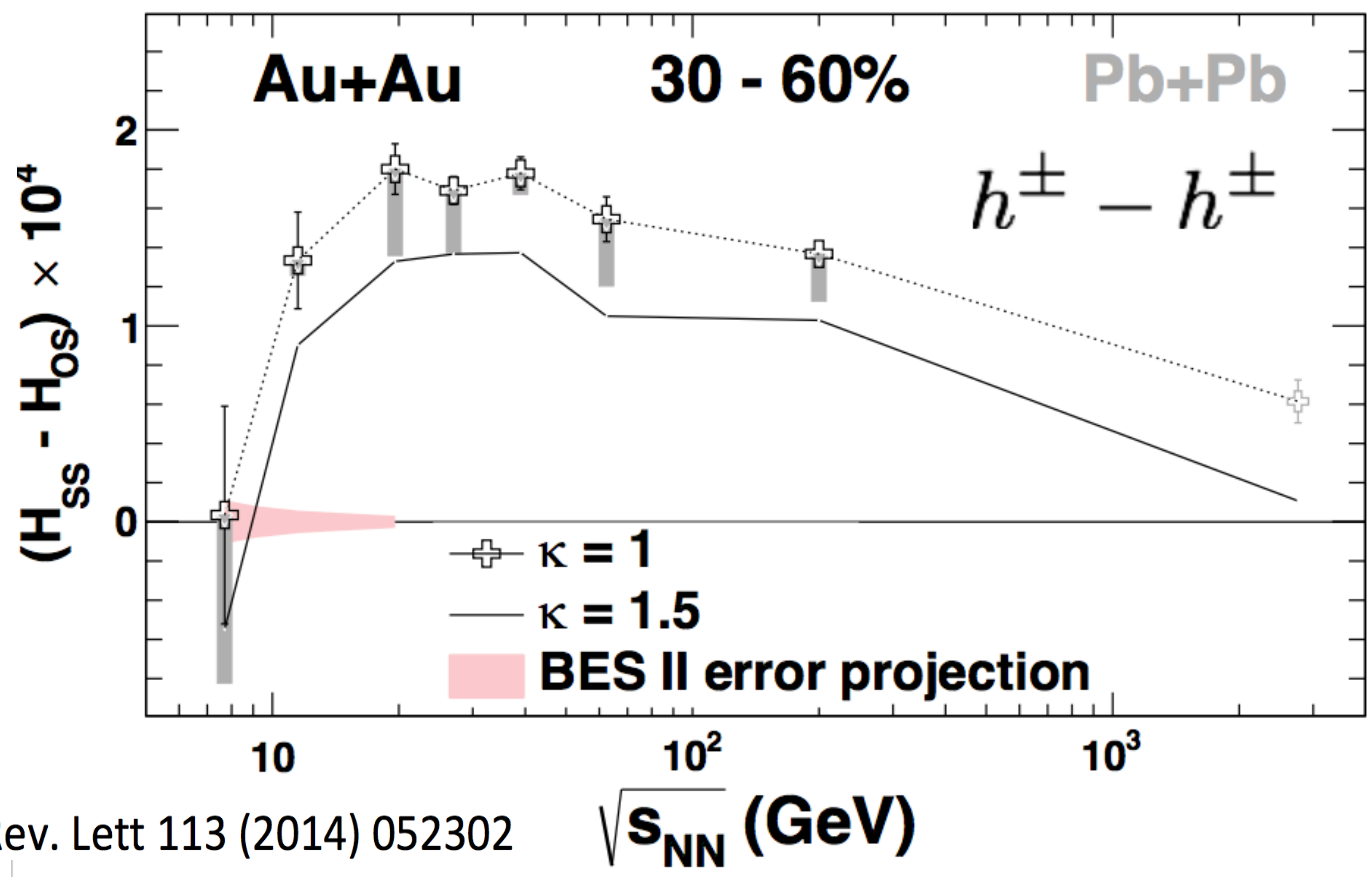

STAR, Phys. Rev. Lett 113 (2014) 052302

Correlators:

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$\delta_{ss} = -1$ $\quad H_{ss}^{\kappa=1} = 0$

$v_2 = 1$

$\gamma_{os} = 0$ $\quad H_{os}^{\kappa=1} = 0$

$\delta_{os} = 0$

H is more robust!

- κ is a factor near unity that can be estimated by background models.
- Finite $H_{ss} - H_{os}$ signal is observed in Au+Au collisions at $\sqrt{s_{NN}} \geq 19.6$ GeV for $h^{\pm}h^{\pm}$.

κ_K: scaled bg+signal

A. Bzdak, V. Koch and J. Liao, Lect. Notes Phys. 871, 503 (2013).

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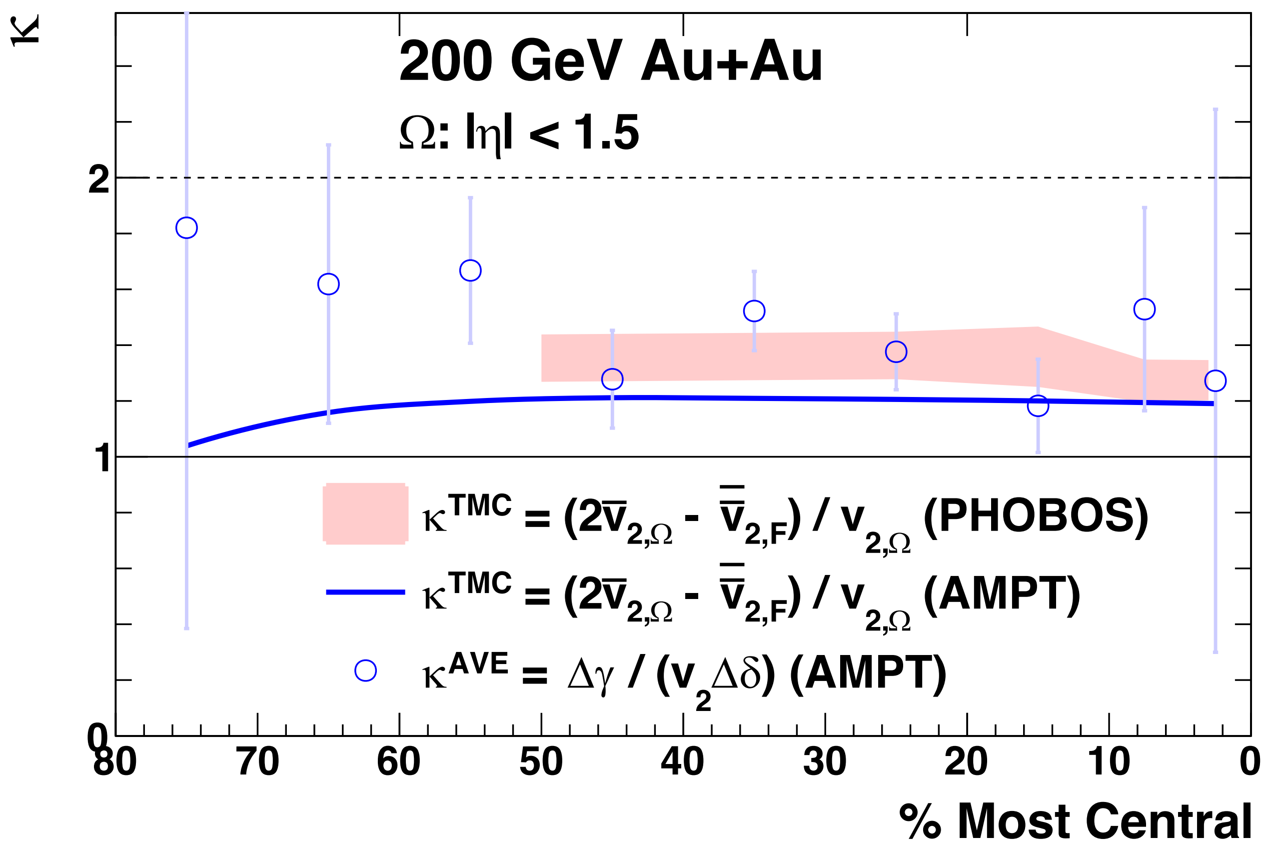
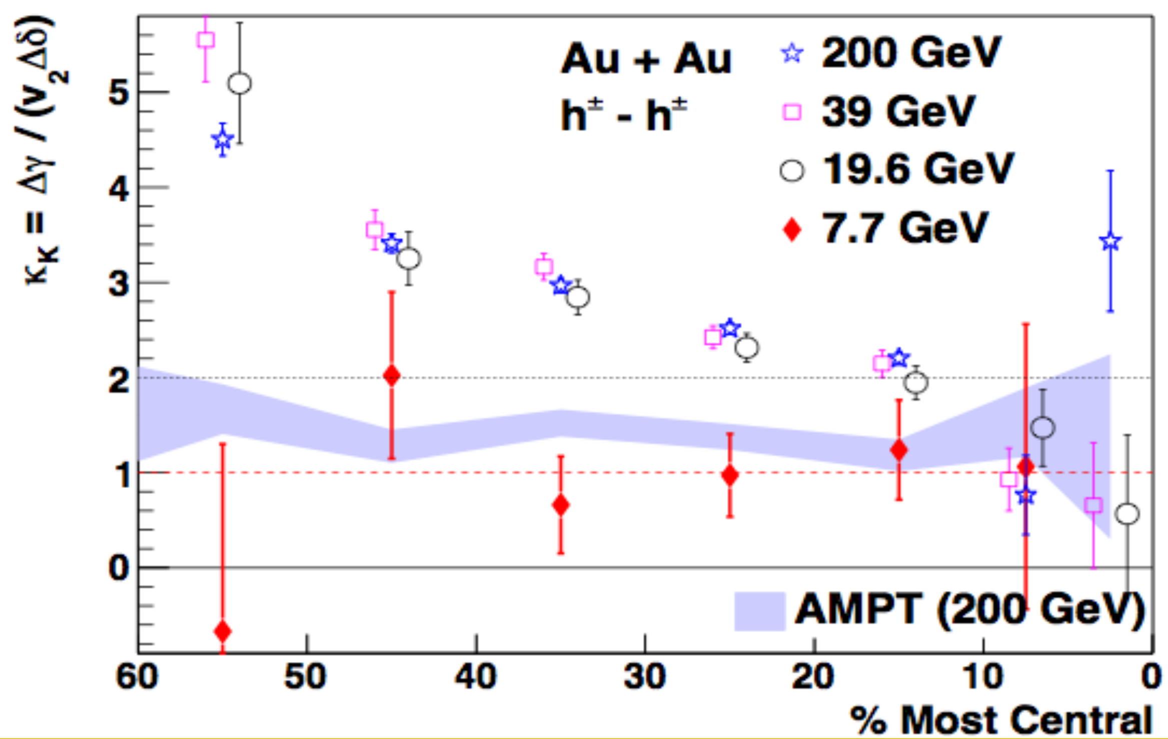
$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\psi_{ep}) \rangle = \kappa v_2 F - H \Rightarrow \boxed{\kappa = \frac{\Delta\gamma + \Delta H}{v_2(\Delta\delta - \Delta H)}} \xrightarrow{\Delta H = 0} \boxed{\kappa_K = \frac{\Delta\gamma}{v_2 \Delta\delta}}$$





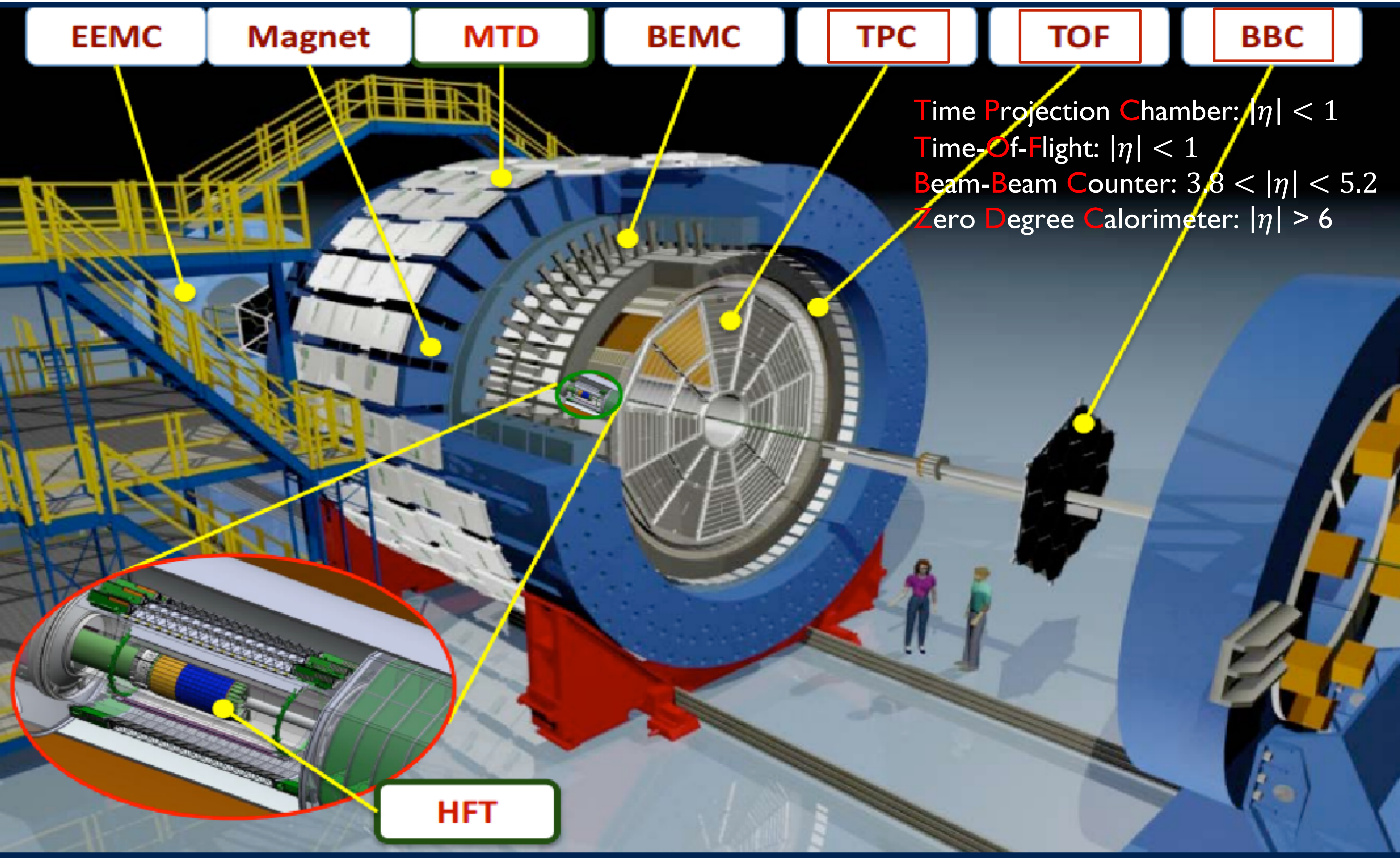
Assumption: κ from background is beam-energy, centrality and particle idependent and between 1 to 2!

- At the extreme, we introduce κ_K such that $\Delta H = 0$. If $\kappa_K > \kappa$ ($H_{ss-os} > 0$), there could be extra physics, like CME.
- κ_K at 7.7 GeV shows weak centrality dependence with values within [1, 2].
- At energies >= 19.6 GeV, κ_K shows higher values than 2 in mid central and mid peripheral collisions.
- κ_K is not applicable in peripheral collisions due to non-flow correlations.

Charge may not be conserved in this version of AMPT

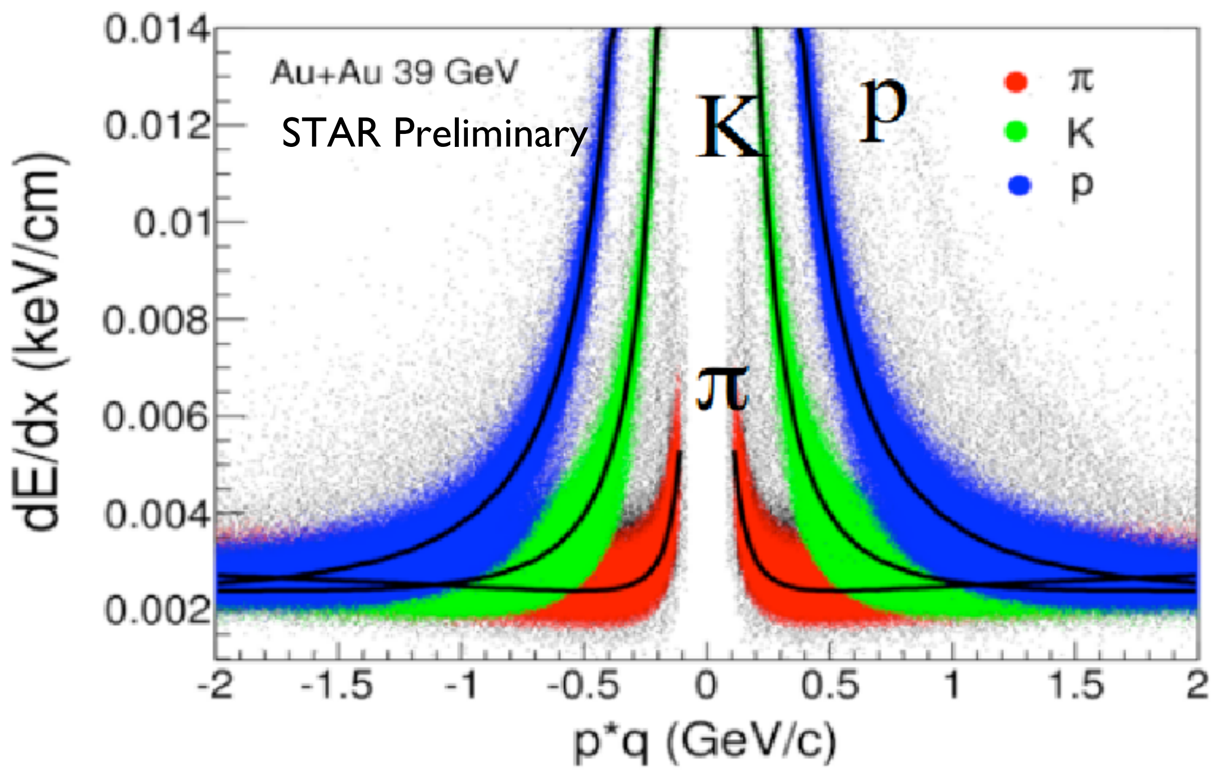
Wen, Wen & Wang, arXiv: 1608.03205

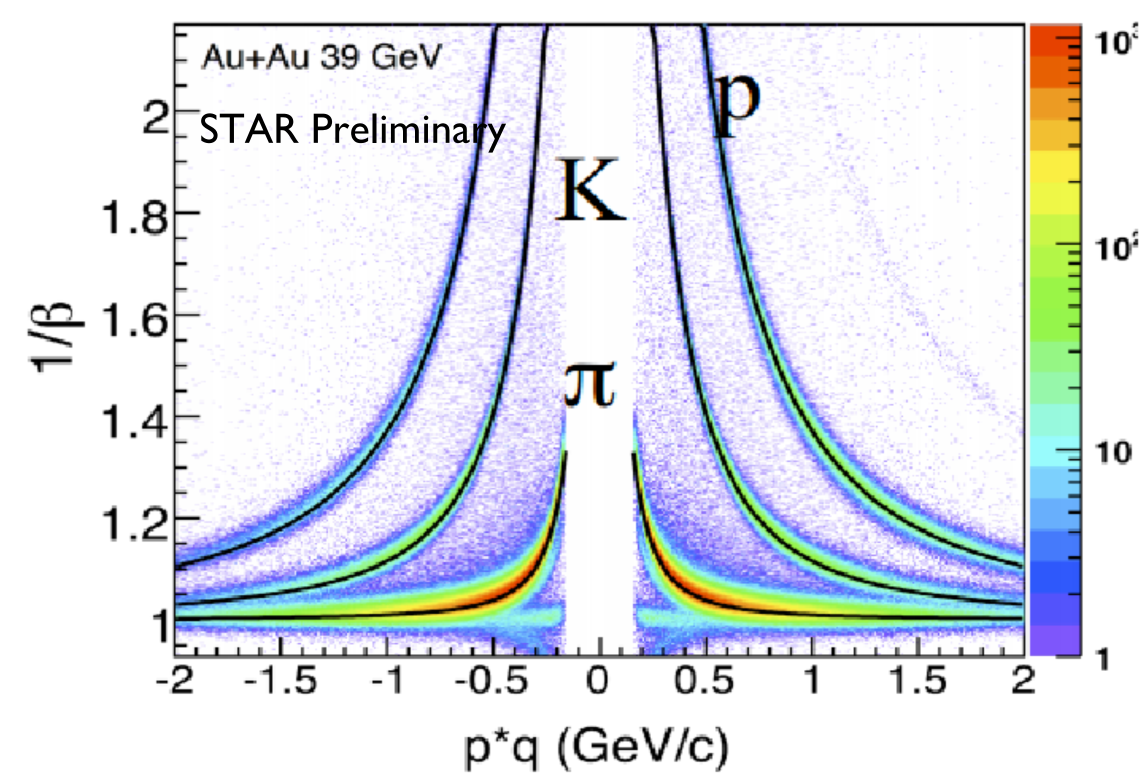
Solenoidal Tracker At RHIC (STAR)

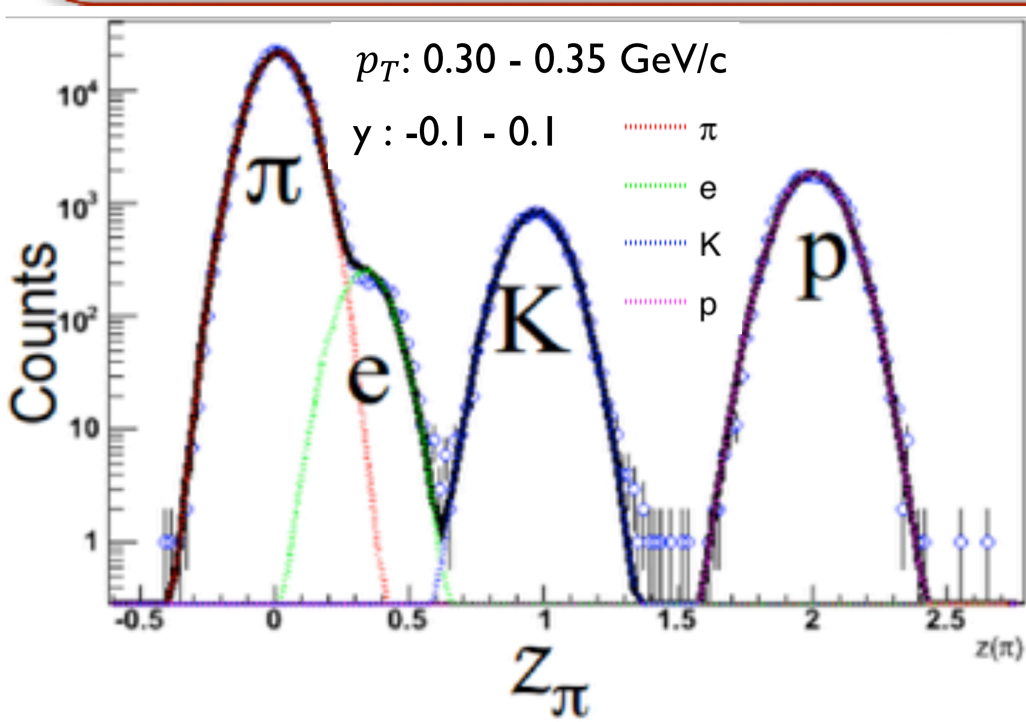


STAR Particle Identification

TPC $\sqrt{s_{NN}}$ **= 39 GeV Au + Au Collisions** **TPC+ToF**





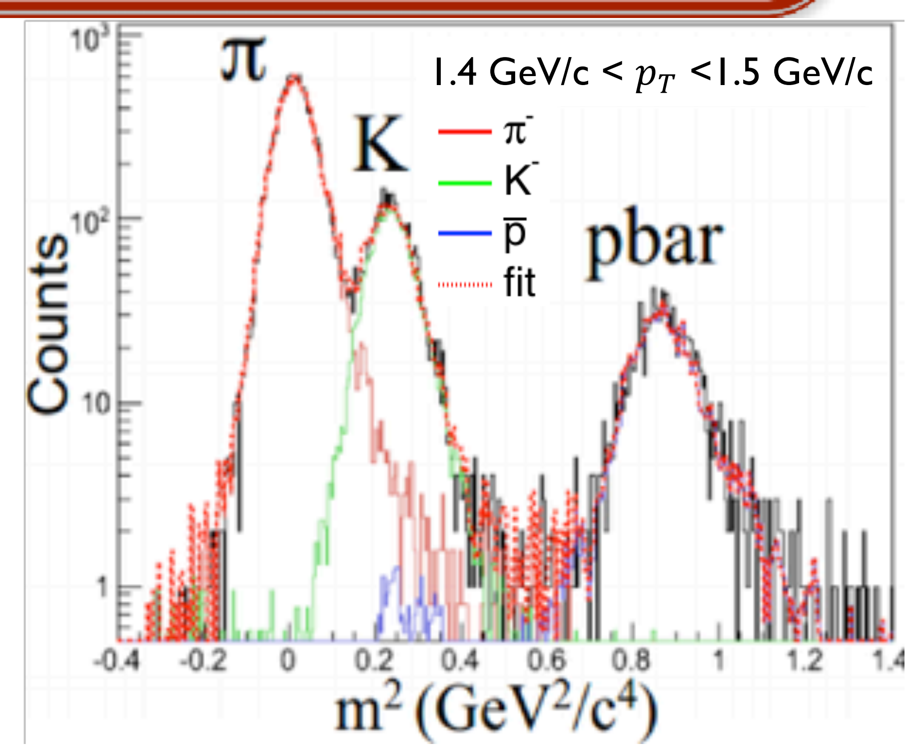


$$z = \log\left(\frac{(dE/dx)_{meas.}}{(dE/dx)_{theory}}\right)$$

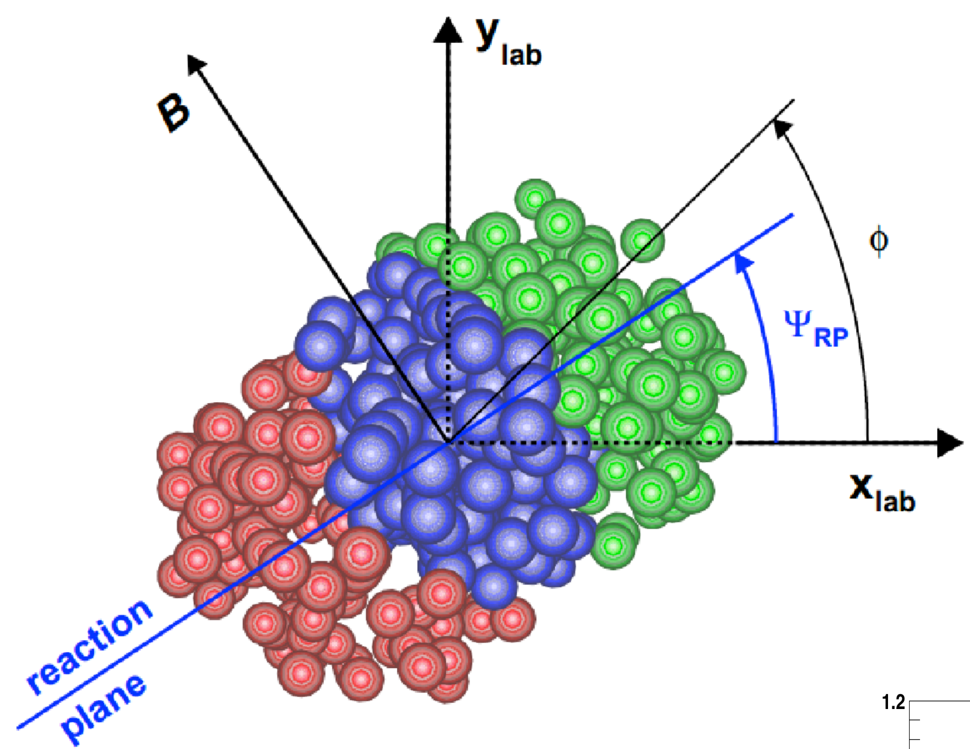
H. Bichsel, NIM A. 562 (2006) 154

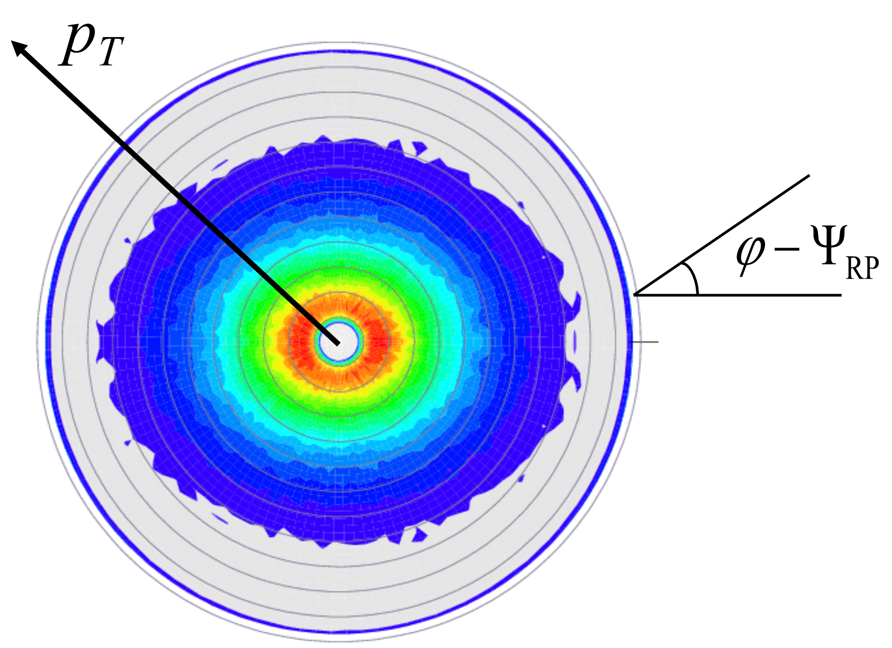
$$m^2 = p^2\left(\frac{c^2t^2}{L^2} - 1\right)$$

c=velocity of light,
L=path length



TPC Event Plane Reconstruction

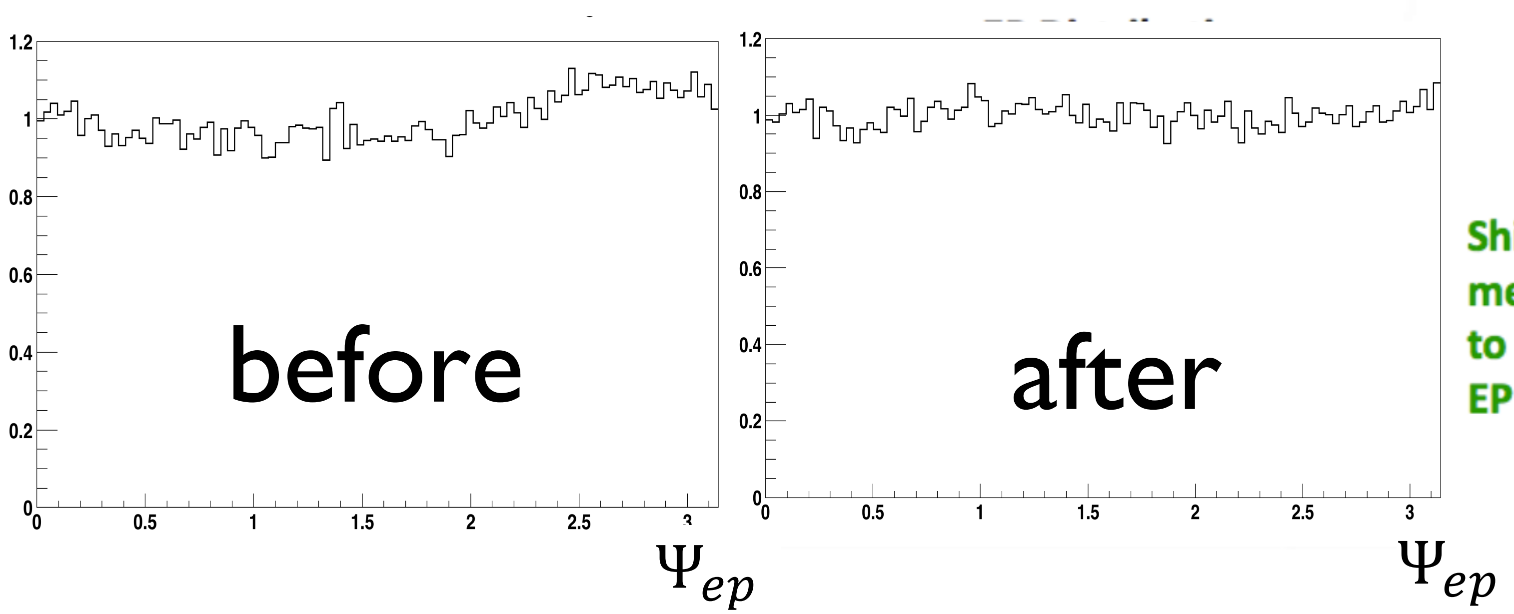




$$Q_n \cos(n\Psi_n) = Q_x = \sum_i w_i \cos(n\phi_i)$$

$$Q_n \sin(n\Psi_n) = Q_y = \sum_i w_i \sin(n\phi_i)$$

$$\Psi_n = \left(\tan^{-1}\frac{Q_y}{Q_x}\right)/n$$



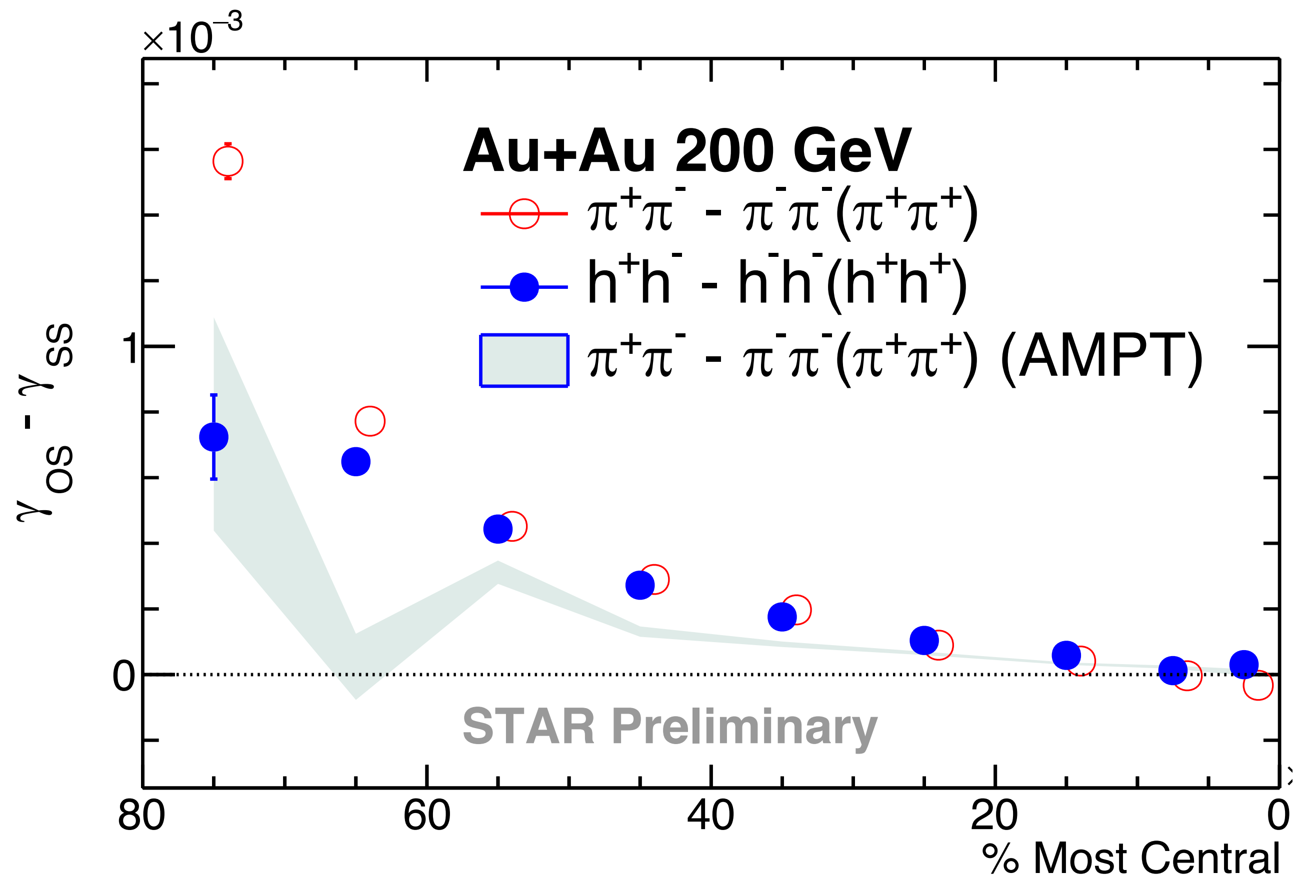
E877, Phys. Rev. C 56 (1997) 3254

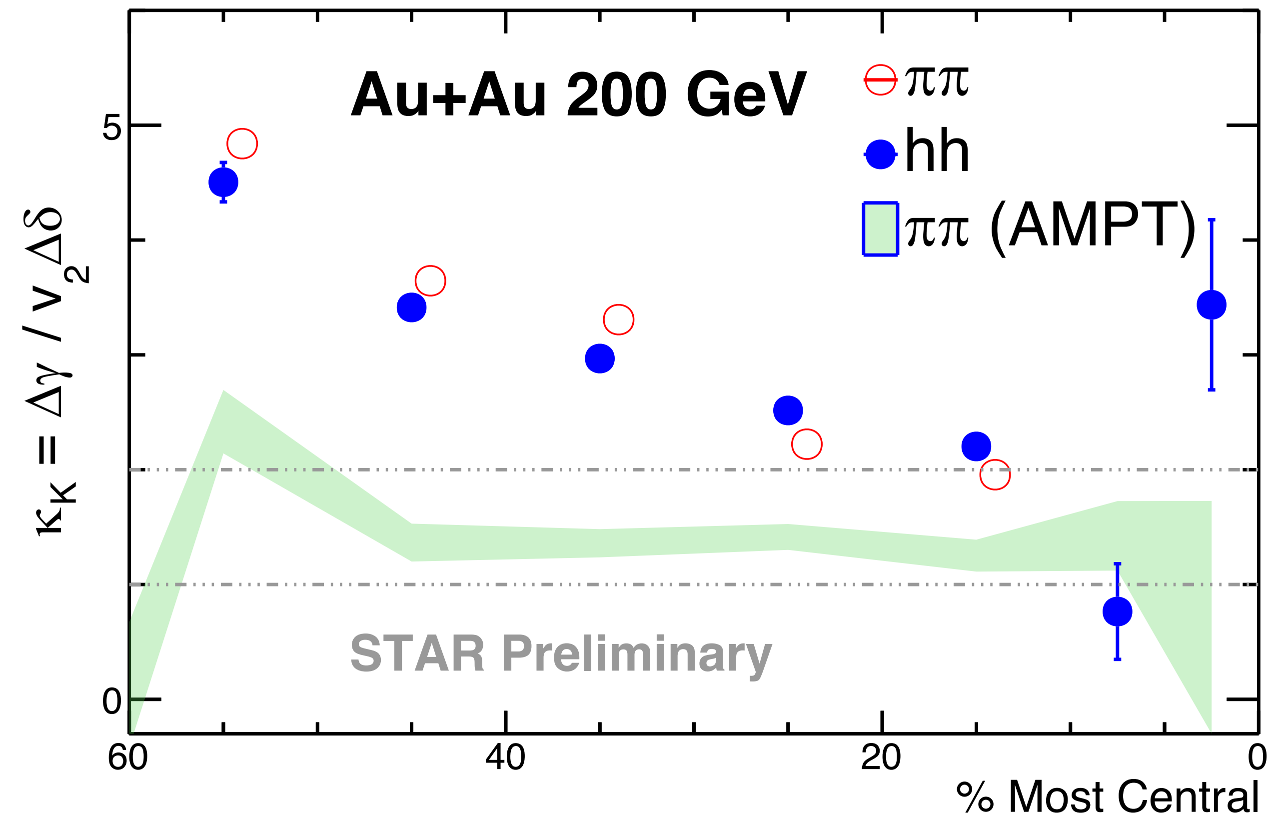
Shifting method used to flatten the EP distribution

The estimated reaction plane is called the event plane.

Other methods are also used in this study to reconstruct event planes by using BBC and ZDC in small systems.

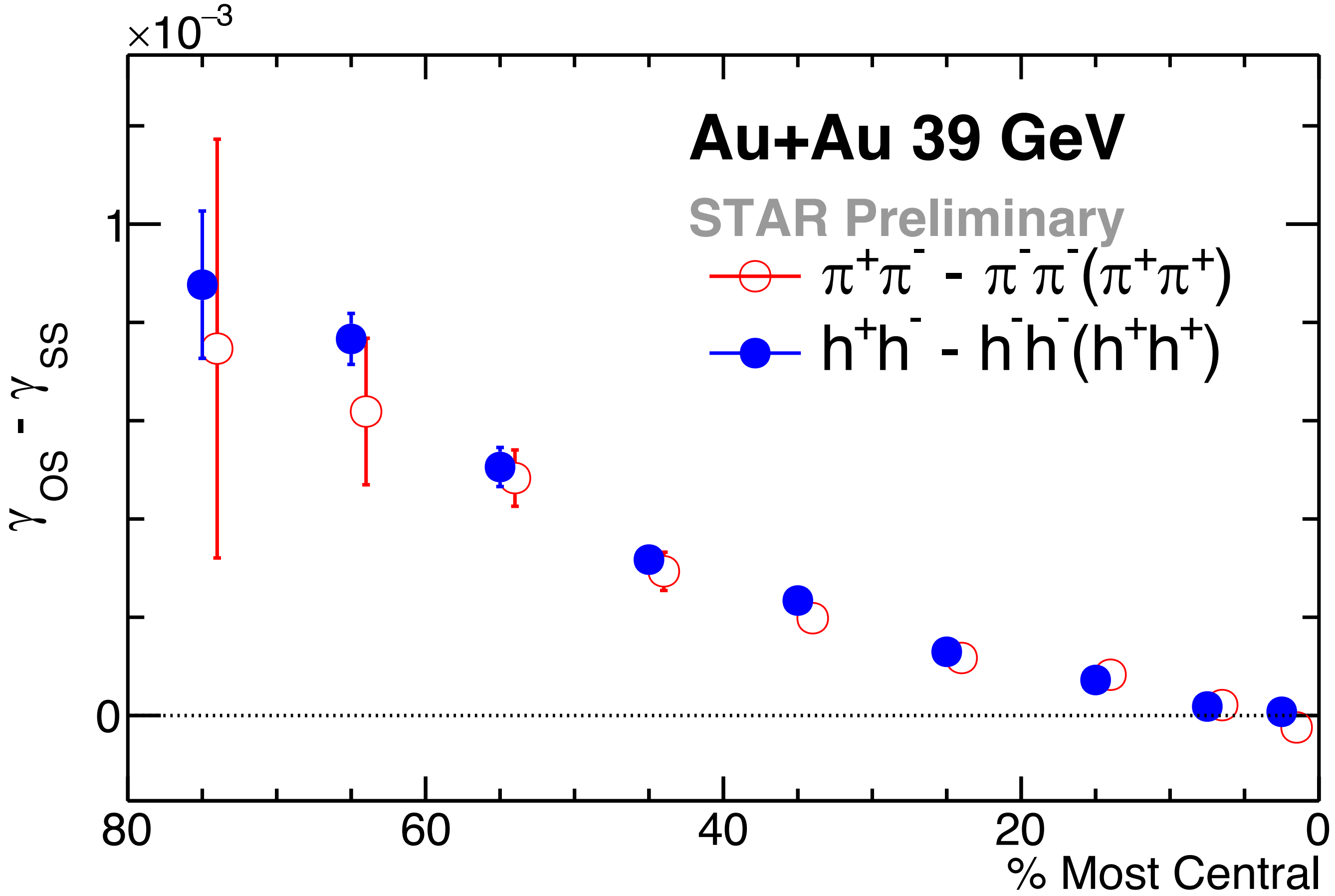
$\pi\pi$ correlation, Au+Au 200 GeV

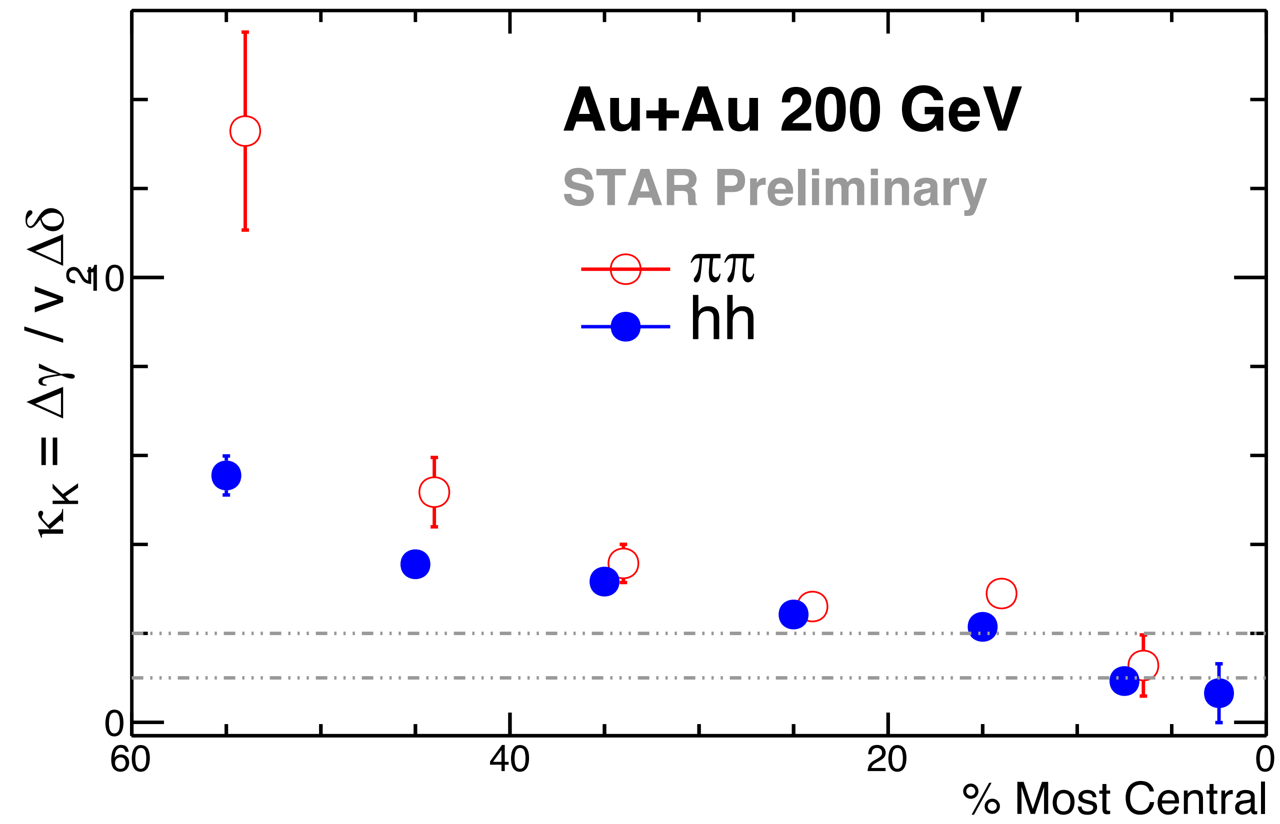




- $\Delta\gamma$ for $\pi\pi$ in Au+Au 200 GeV shows similar value to charged hadrons'.
- κ_K for mid central and mid peripheral collisions is much larger than the background level (1.0 to 2.0) estimated from AMPT.

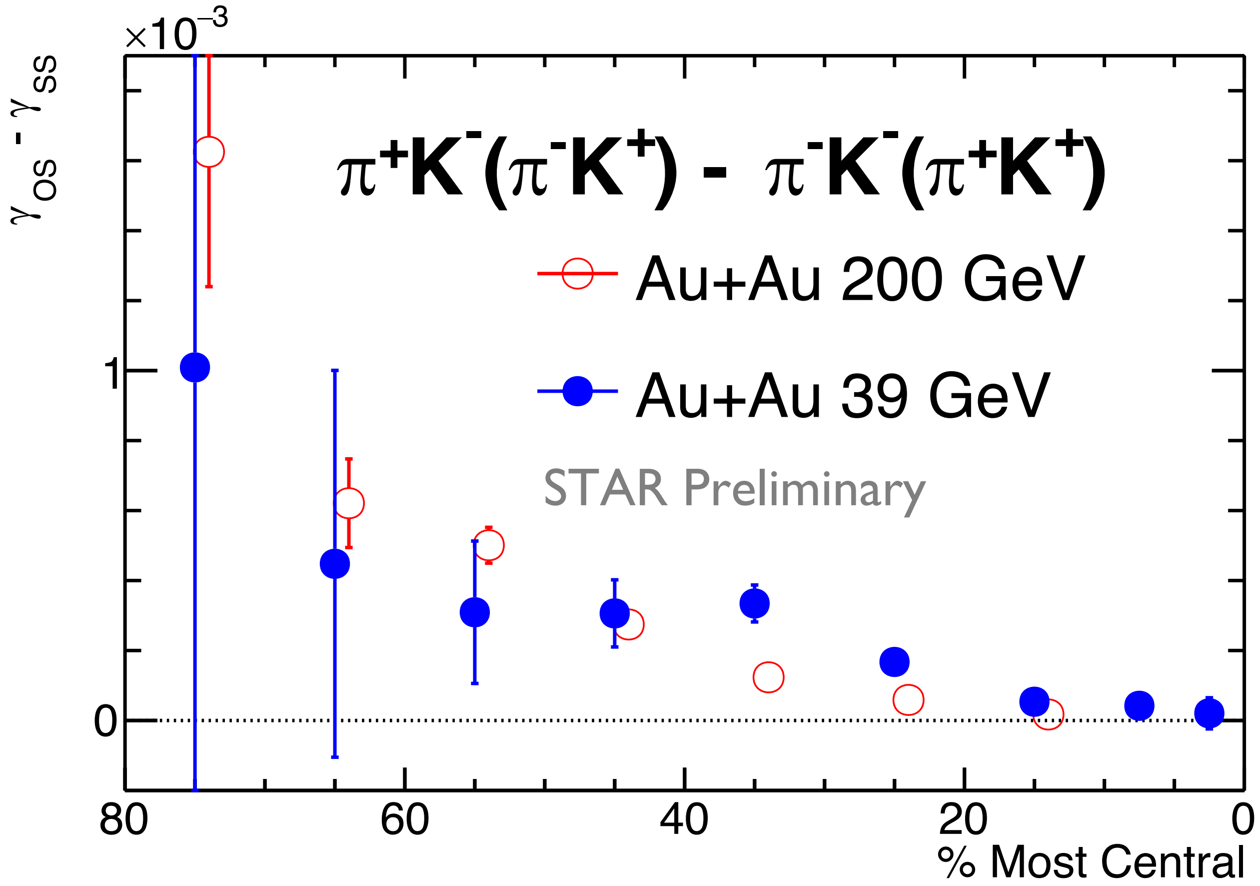
$\pi\pi$ correlation, Au+Au 39GeV

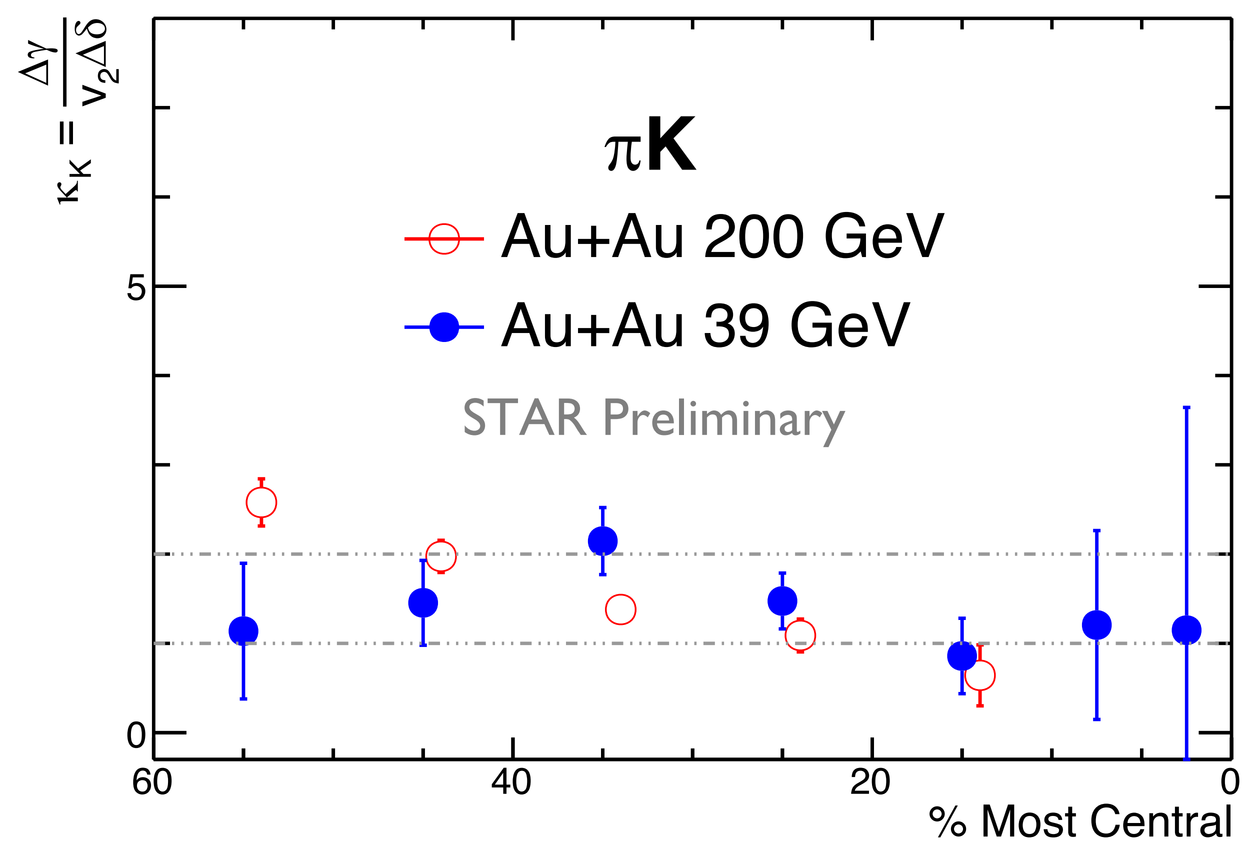




- Au+Au 39 GeV $\pi\pi$ pair $\Delta\gamma$ shows similar magnitude to charged hadron's at the same energy.
- κ_K is higher than 2 except in central collisions.

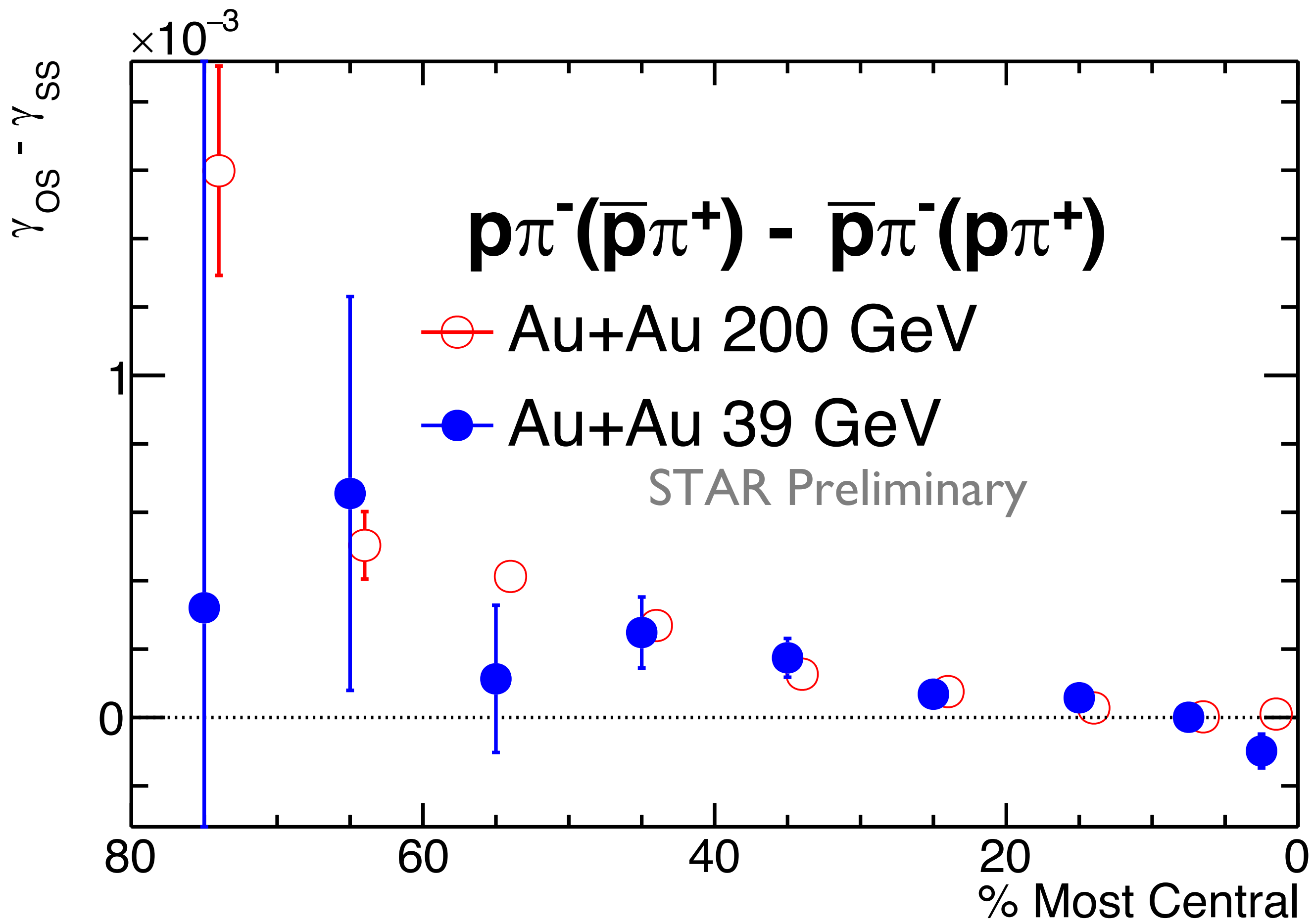
πK correlation

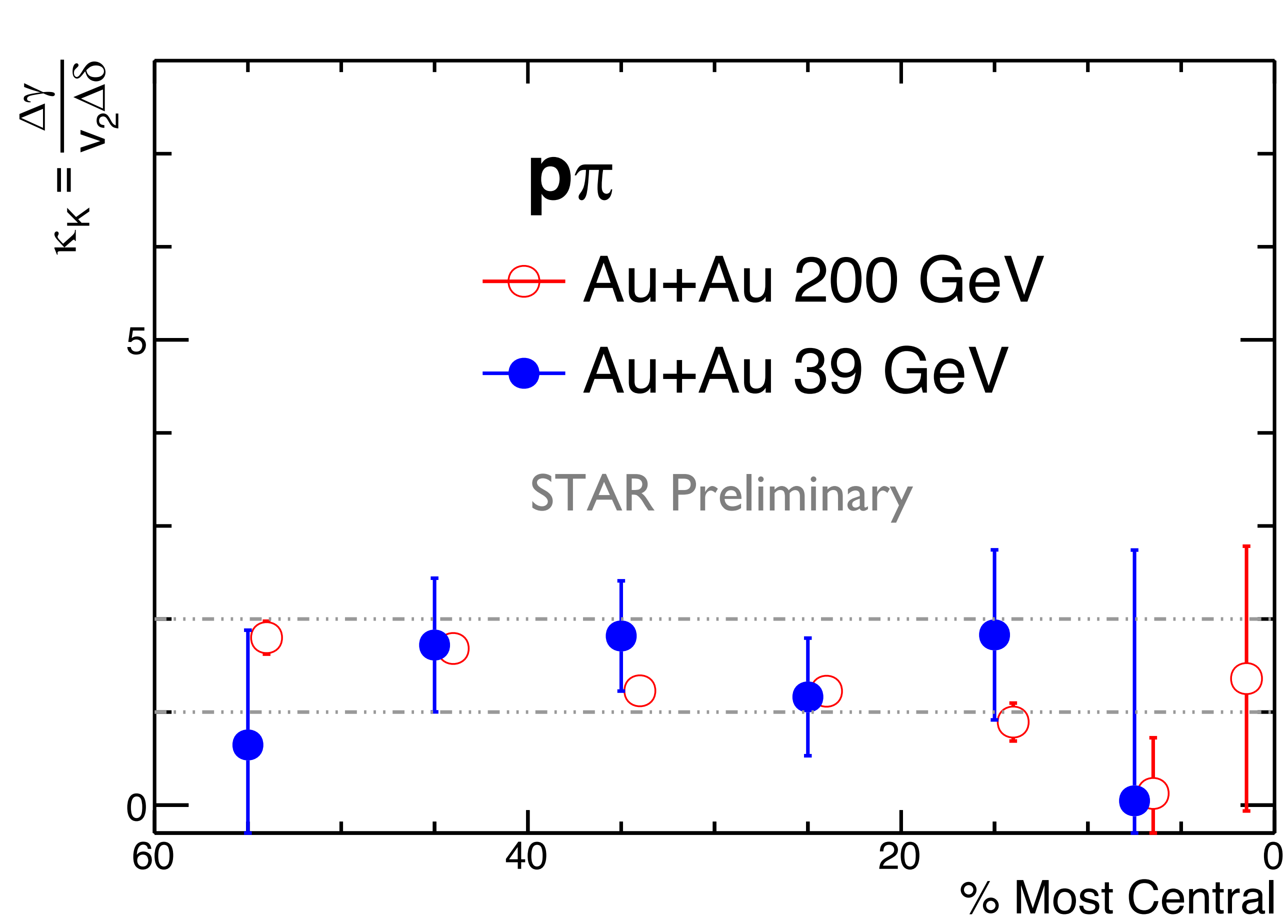




- $\Delta\gamma$ for πK pair is finite in Au+Au at both 200 GeV and 39 GeV.
- κ_K values are close to or below 2, making it hard to distinguish from background.

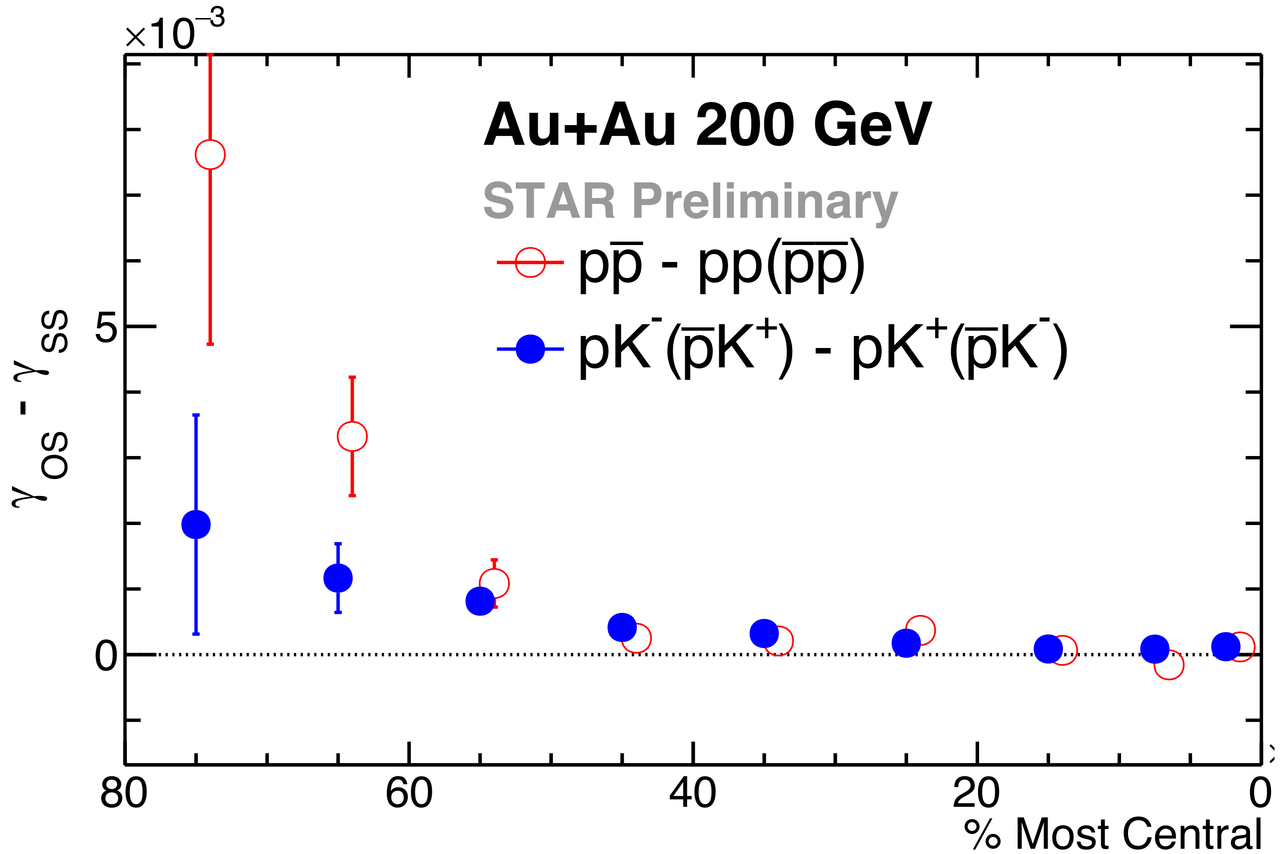
$p\pi$ correlation

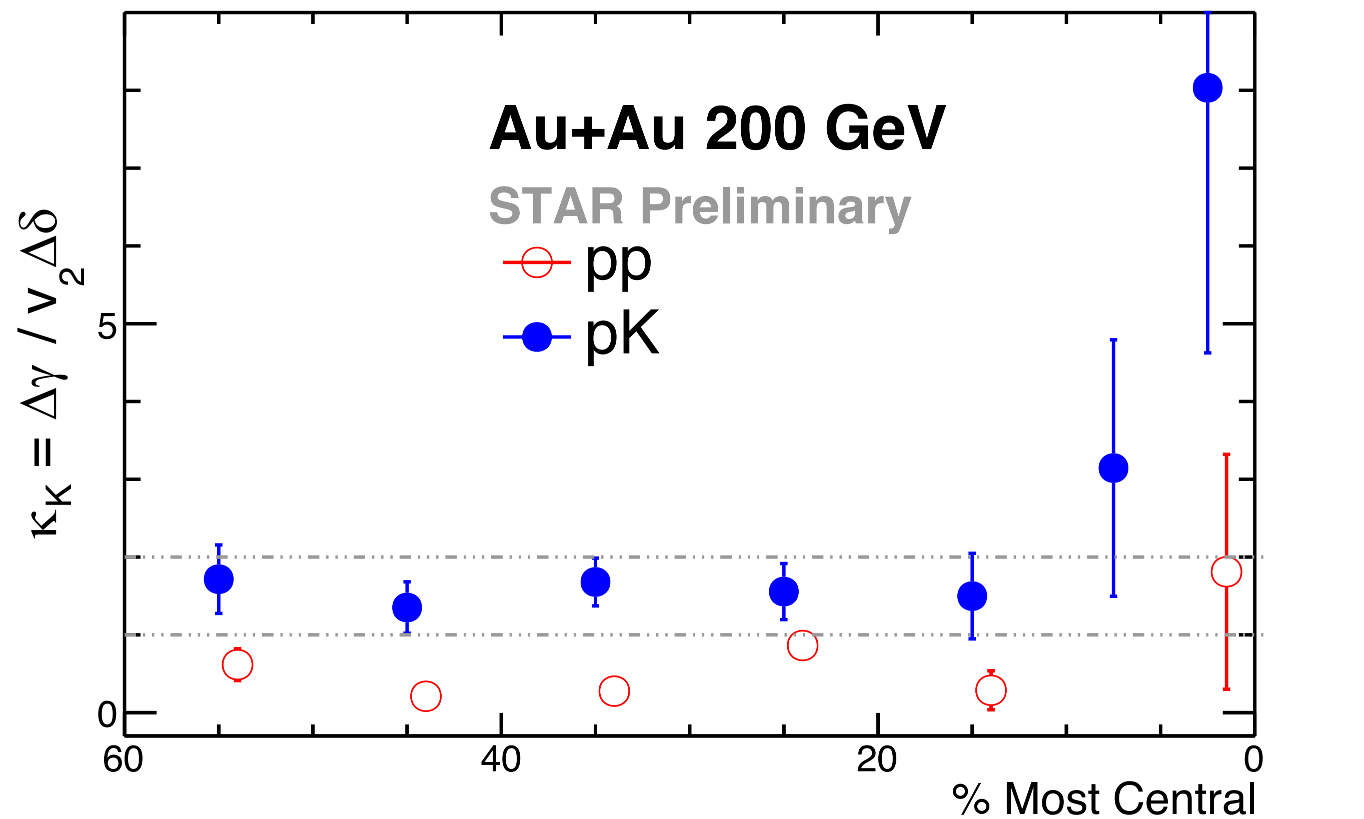




- $\Delta\gamma$ for $p\pi$ pair is finite in Au+Au at both 200 GeV and 39 GeV.
- κ_K values are close to or below 2, making it hard to distinguish from background.

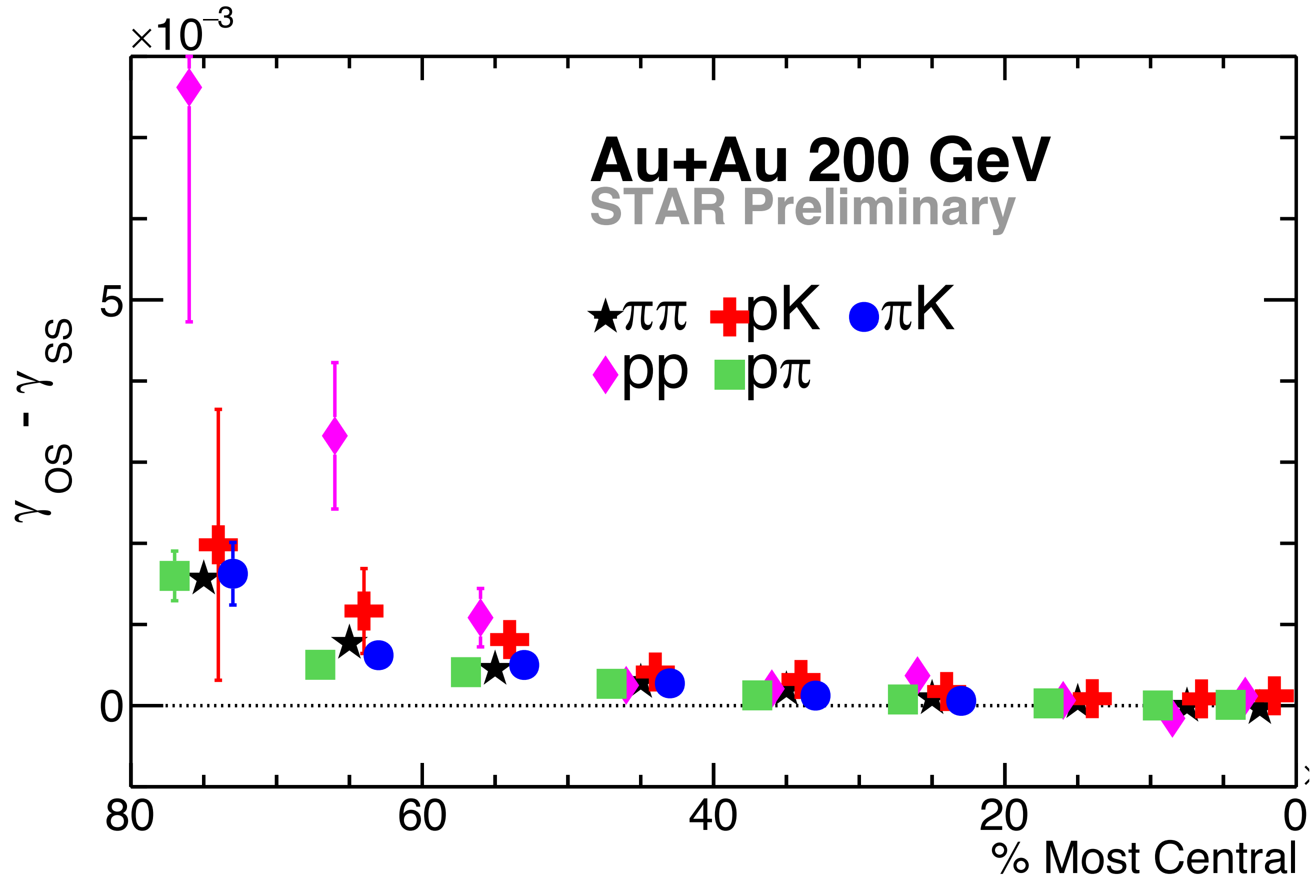
pp and pK correlation

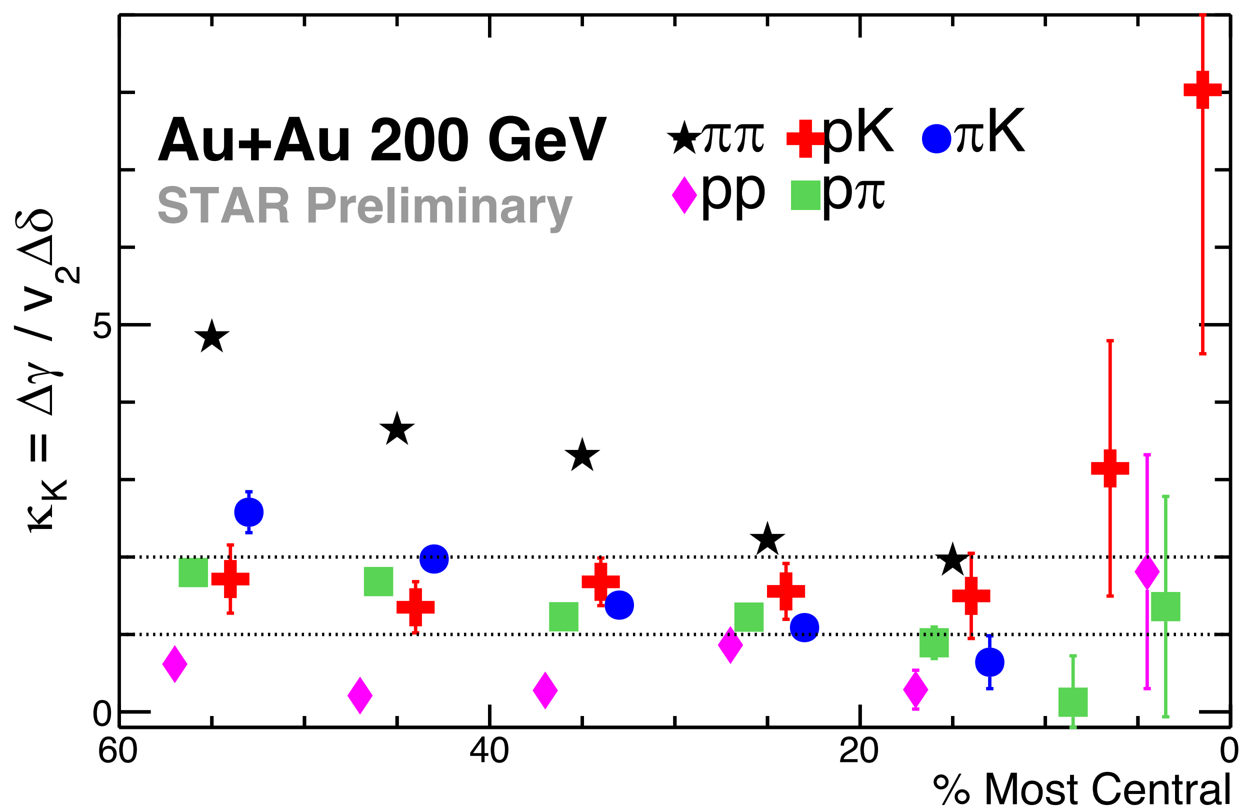




- pp pairs in Au+Au 200 GeV show large $\Delta\gamma$.
- $\Delta\gamma$ for pK has smaller values, but still finite in peripheral and mid central collissions.
- κ_K for pp is lower than 2 or even 1 in some centrality bins. This behavior might be due to annihilation effect.
- For pK , κ_K fluctuates between1 and 2.

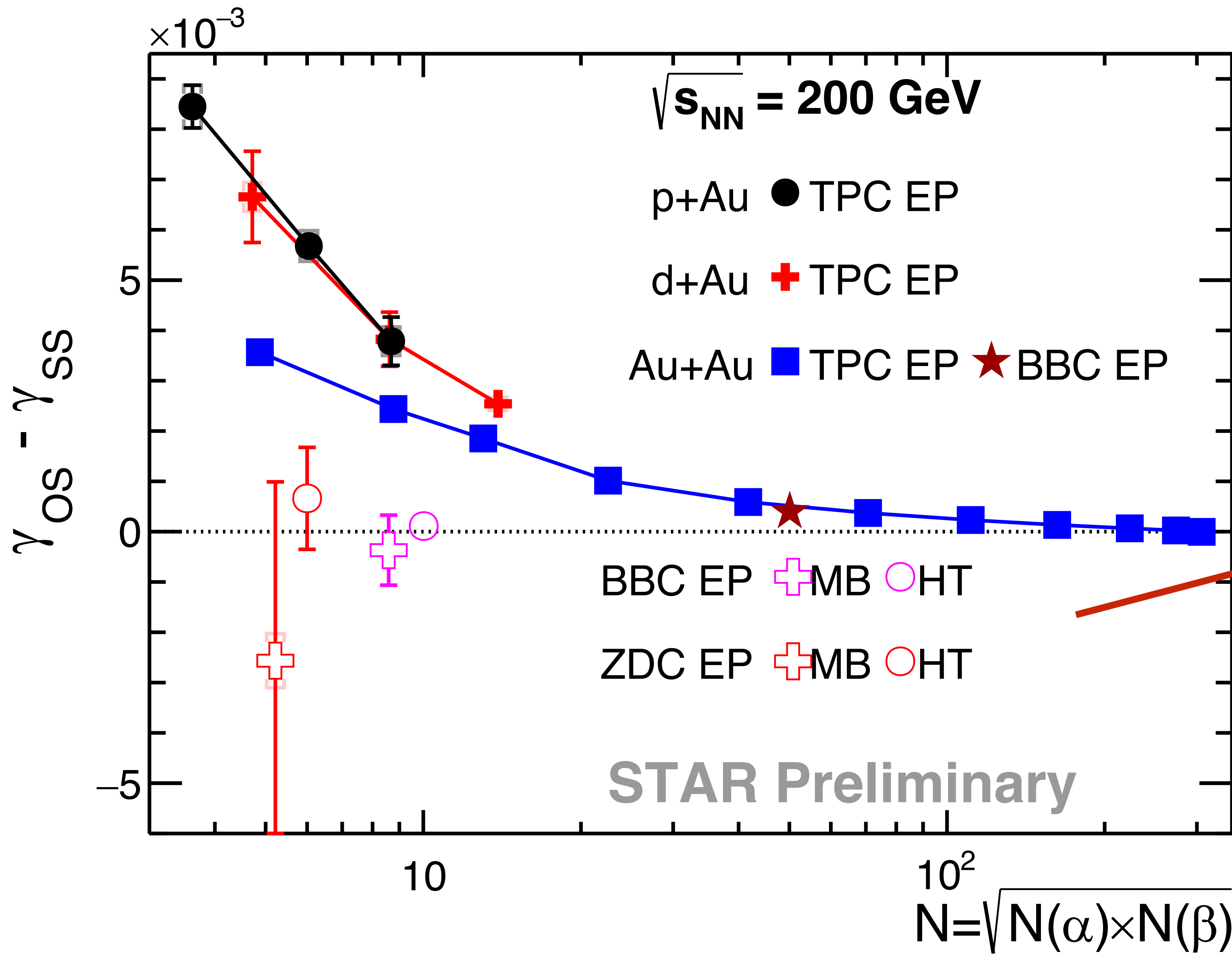
PID summary





- $\Delta\gamma$ for all PID pairs is finite in peripheral and mid central Au+Au collisions at 200 GeV.
- κ_K for $\pi\pi$ is higher than estimated background in mid peripheral and mid central collisions. Other pairs are close to or within background range of 1.0 to 2.0.
- pp shows large $\Delta\gamma$, but κ_K is not fully understood yet.

γ correlation in p+Au and d+Au



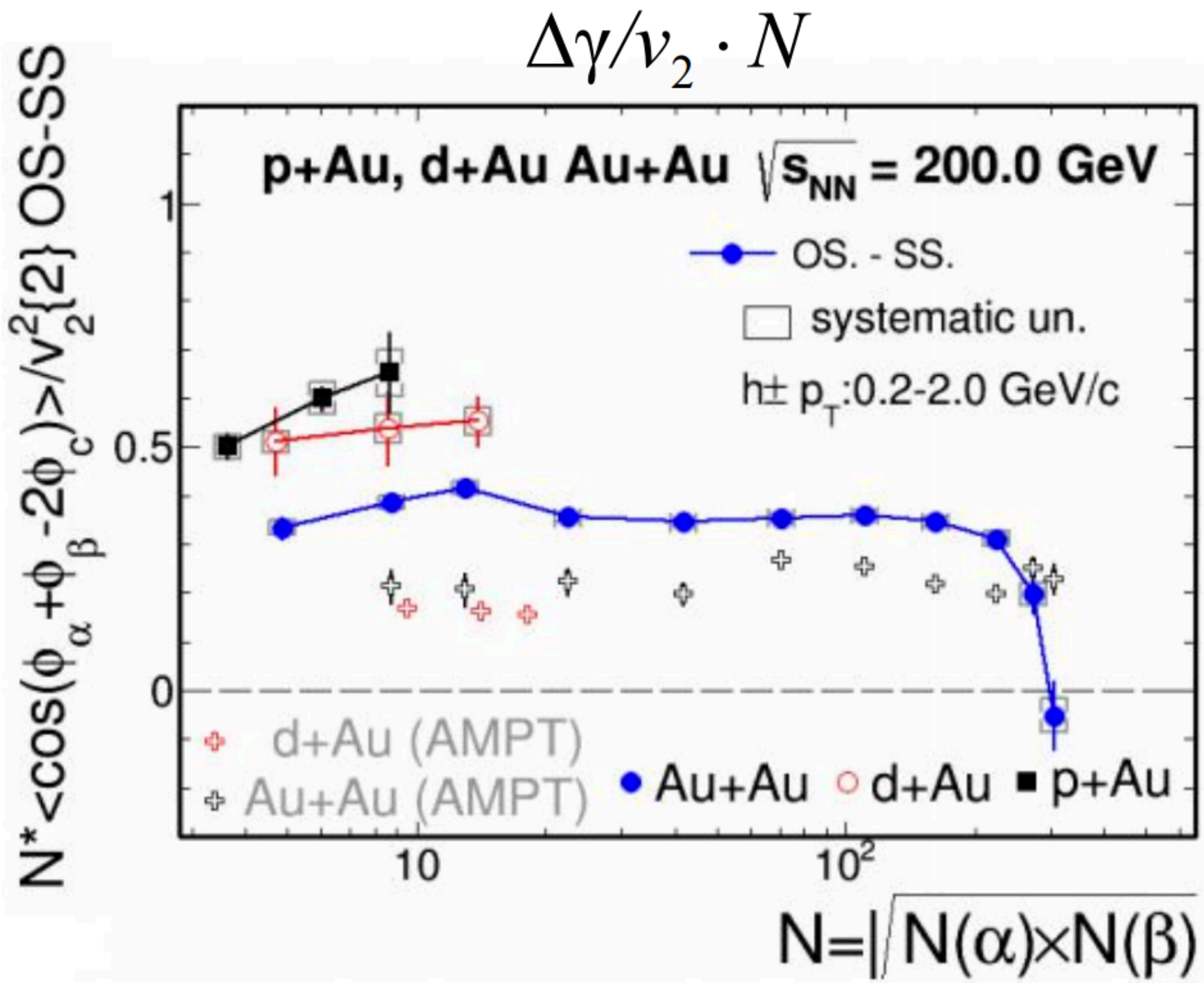
Time Projection Chamber: $|\eta| < 1$
Beam-Beam Counter: $3.8 < |\eta| < 5.2$
Zero Degree Calorimeter: $6 < |\eta|$

HT (High Tower): trigger on electromagnetic energy

See J. Zhao's poster(A12)

- Sizable $\Delta\gamma$ in p+Au and d+Au w.r.t. 2nd-order event-plane(EP) Ψ_2 from TPC, the magnitude is similar to or higher than Au+Au.
- $\Delta\gamma$ disappears in p+Au when η gap is introduced between EP and particles of interest: $\Delta\gamma$ in TPC EP results mostly from short range correlation.

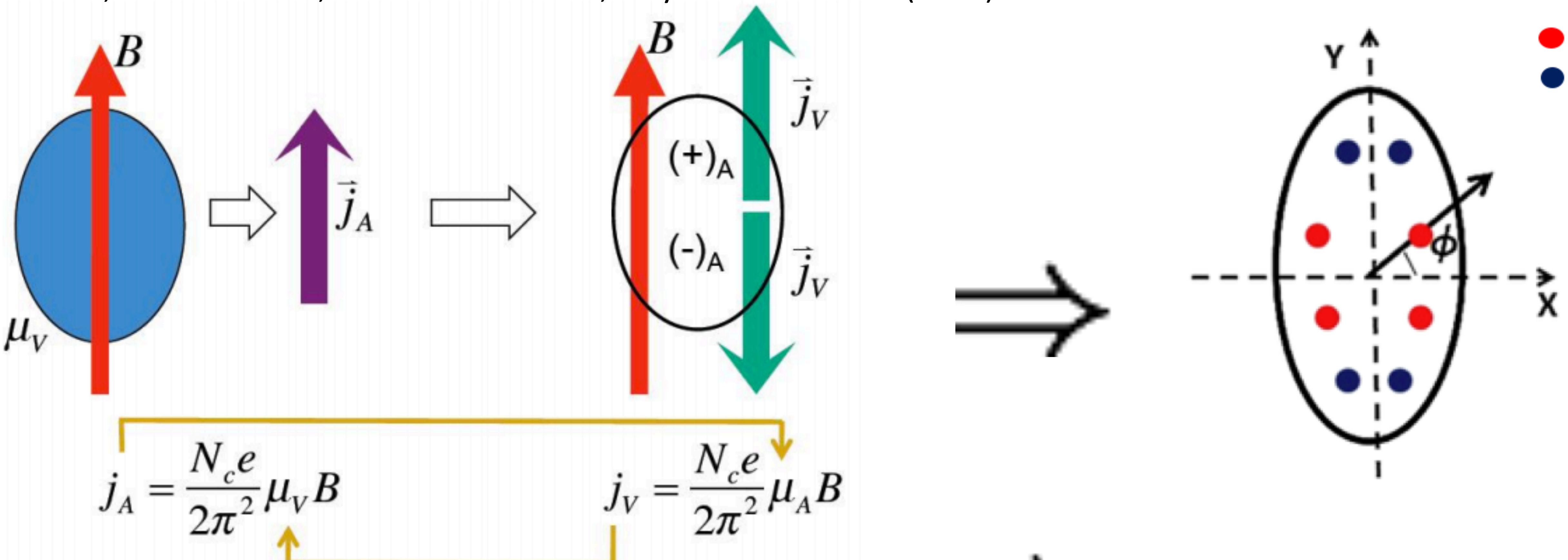
Another scaling scheme



- $\Delta\gamma \cdot N/v_2$ from AMPT (hadronic scattering turned off) does not match data in central events, but accounts for ~2/3 of the observed signal from peripheral to mid-central Au+Au.
- $\Delta\gamma \cdot N/v_2$ from AMPT accounts for ~1/3 of the observed signal in d+Au.

Chiral Magnetic Wave(CMW)

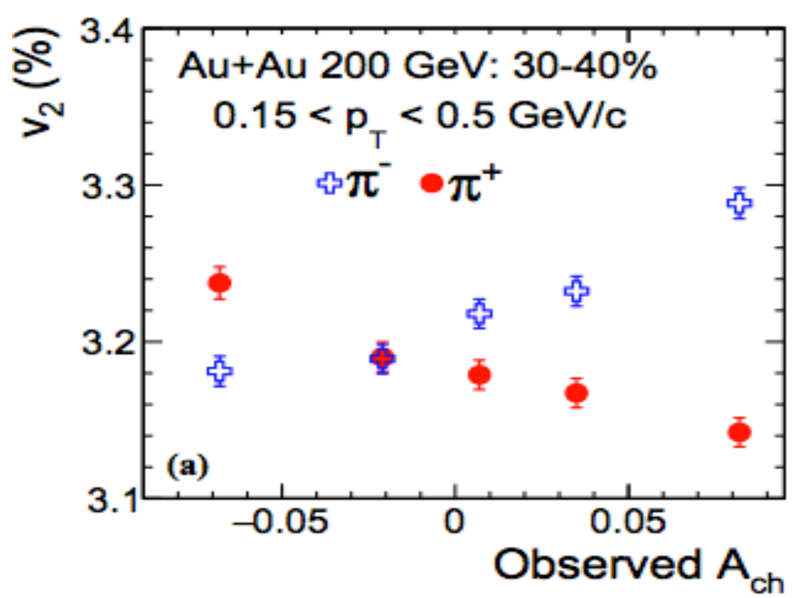
Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, Phys. Rev. Lett. 107 (2011)052303



Chiral Separation Effect + Chiral Magnetic Effect → Chiral Magnetic Wave

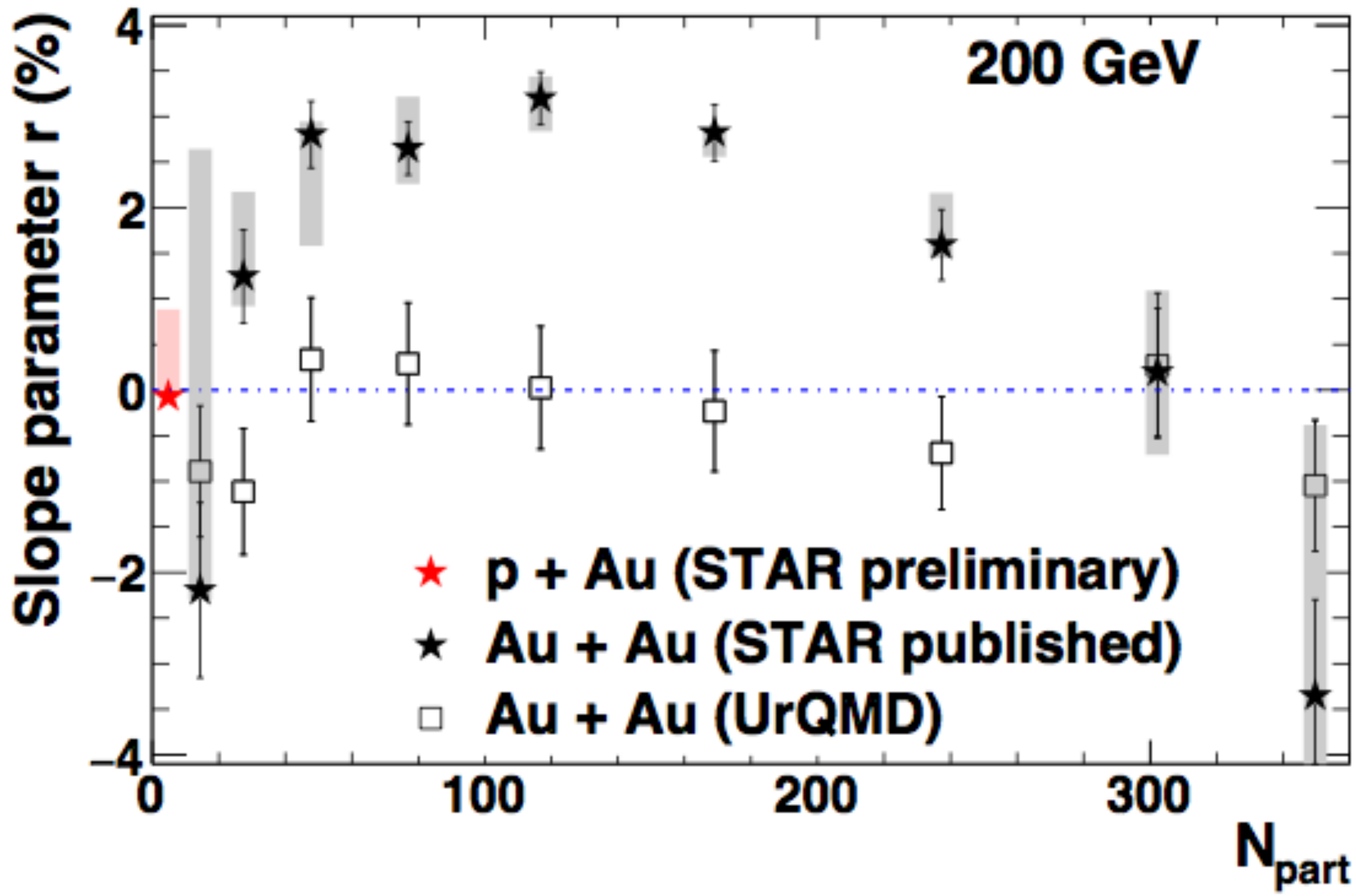
Formation of electric quadrupole moment results from CMW: the "poles" of fireball acquire additional positive charges while the "equator" acquires additional negative charges.

Observable: $v_2^{\pm} = v_2^{base} \mp \left(\frac{q_e}{\bar{\rho}_e}\right) A_{ch} = v_2^{base} \mp \frac{r}{2} A_{ch}$



STAR, Phys. Rev. Lett. **114** (2015) 252302

Chiral Magnetic Wave in p+Au?



STAR, Phys. Rev. Lett. **114** (2015) 252302

- The slope, r of $\Delta v_2(A_{ch})$ between π^+ and π^- was used to search for CMW;
- Similar to peripheral Au+Au 200 GeV, r is consistent with zero in p+Au 200 GeV;

Summary and Outlook

Summary:

a. Search for Chiral Magnetic Effect in Au+Au:

- κ_K for $\mathrm{h}^{\pm}\mathrm{h}^{\pm}$ and $\pi\pi$ in Au+Au 200 GeV is larger than AMPT background.
- κ_K of other identified pairs, $\pi K, p\pi, pK$, is hard to distinguish from background.
- κ_K for pp needs further investigation.

b. Search for Chiral Magnetic Effect in p+Au and d+Au:

- $\Delta\gamma$ for $\mathrm{h}^{\pm}\mathrm{h}^{\pm}$ in p+Au and d+Au 200 GeV shows sizable magnitude using TPC event plane.
- $\Delta\gamma$ disappears when introducing η gap (>2) between particles of interest and event plane in p+Au 200 GeV.

c. Search for Chiral Magnetic Wave in p+Au:

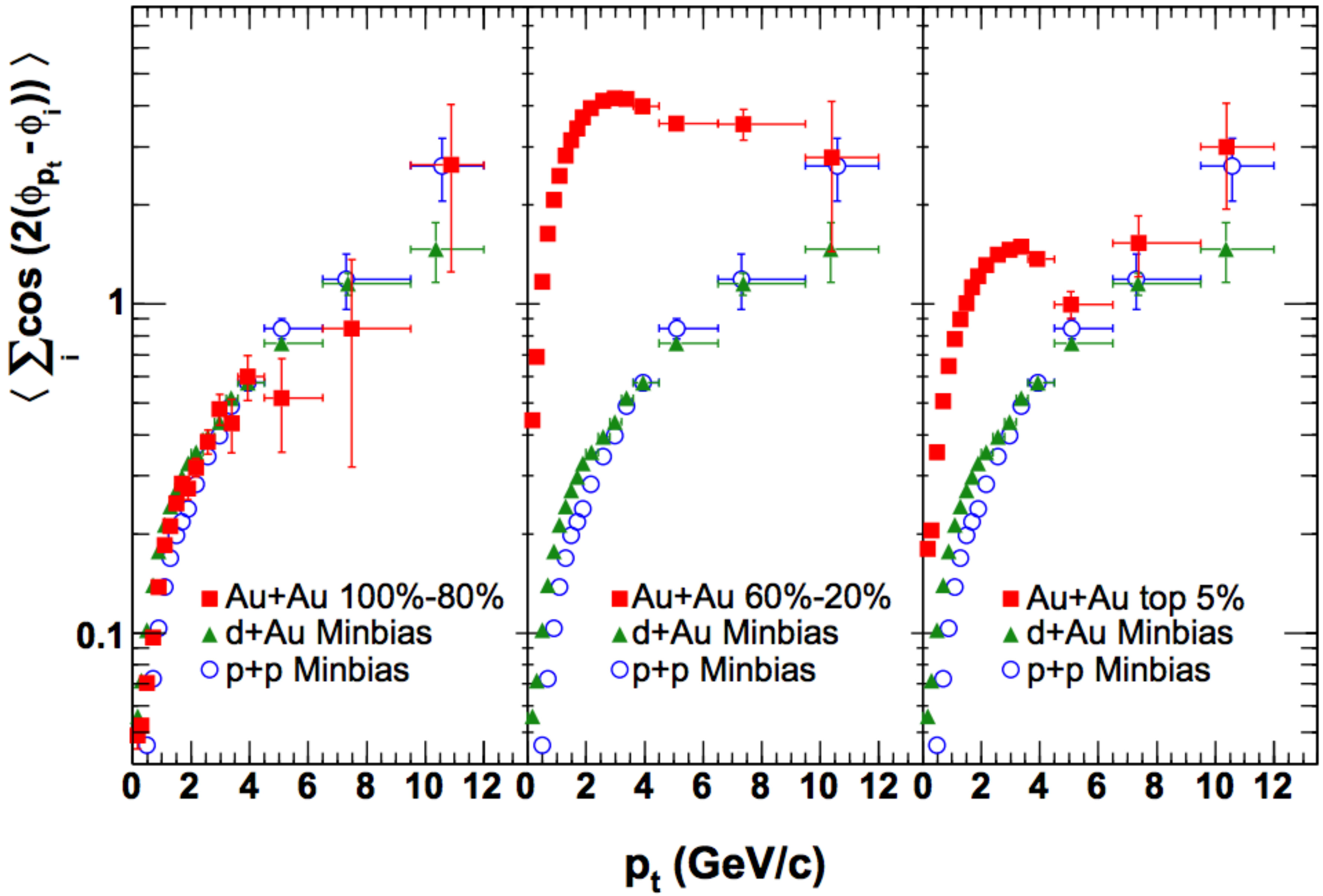
- In p+Au 200 GeV collisions, the observable r is consistent with zero.

Outlook:

Isobar collisions, ${}^{96}_{44}Ru$ + ${}^{96}_{44}Ru$ and ${}^{96}_{40}Zr$+ ${}^{96}_{40}Zr$, maintaining flow magnitude and varying magnetic field, provide an exciting opportunity to justify the physics beyond flow-related background. Stay tuned for STAR in 2018!

Back up slides

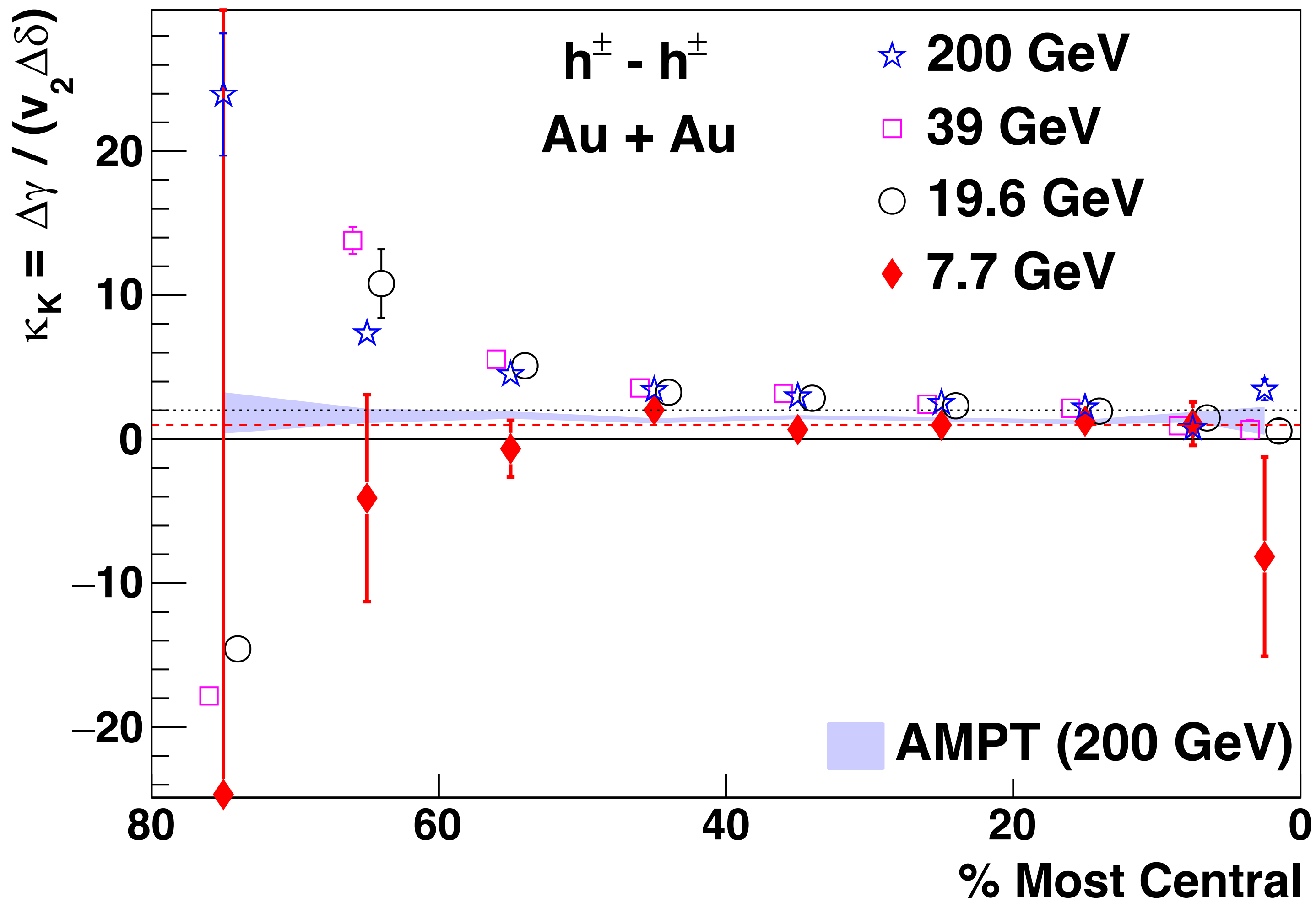
Non-flow in peripheral collisions



PHYSICAL REVIEW C 72, 014904 (2005)

- Non-flow dominated in peripheral Au+Au collisions

Peripheral κ_K?



Phys. Rev. Lett. **113** (2014) 52302