# Searches for Chiral Effects and Prospects for Isobaric Collisions at STAR/RHIC

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CPOD 2017

8/8/17

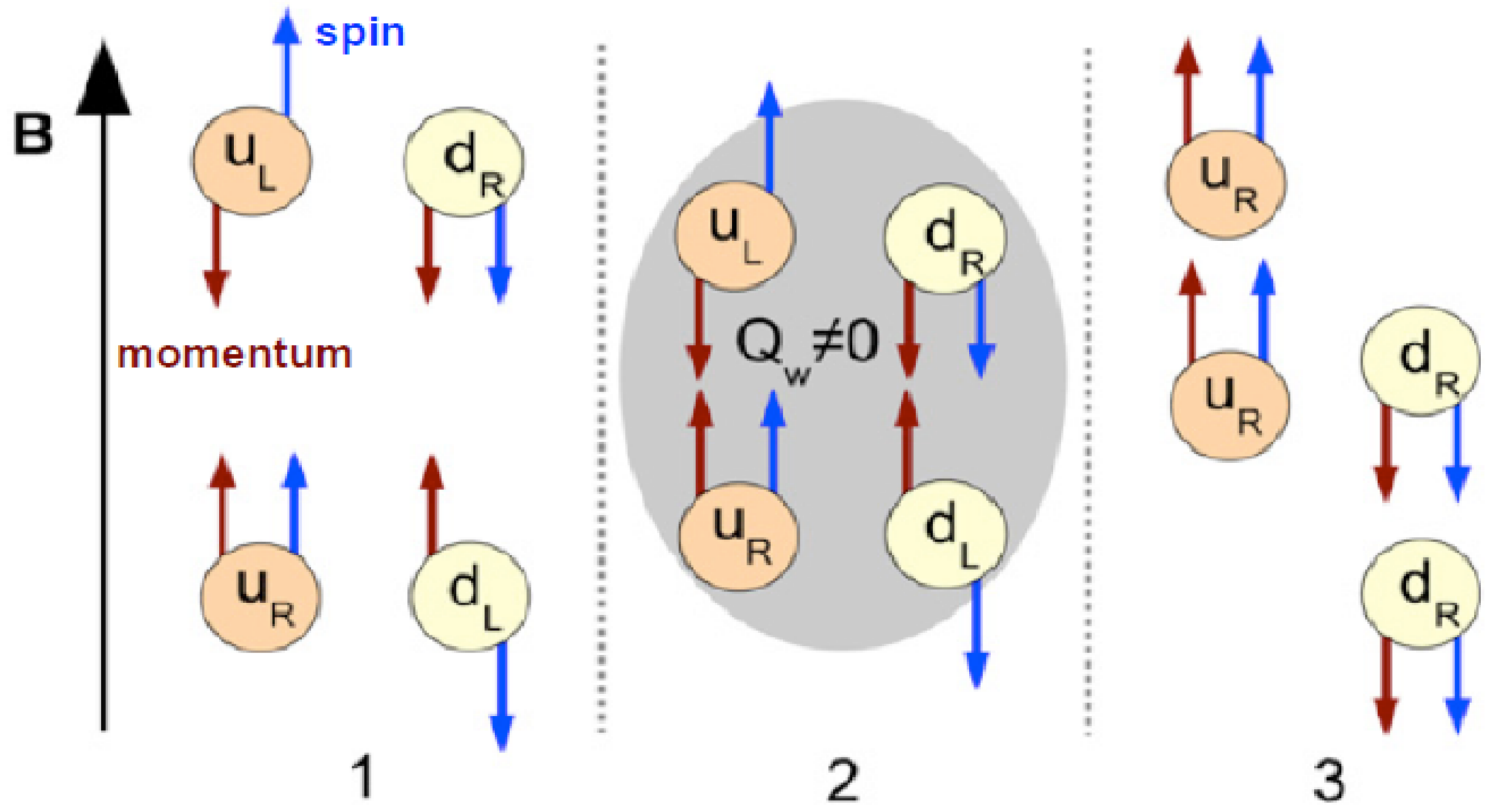
STAR

UCLA

# Outline

- Physics motivation and observables
- Correlation measurements with the so-called $\gamma$ and $\kappa_K$:
  - $\gamma, \kappa_K$ for identified particles in Au+Au
  - $\gamma$ for charged hadrons in U+U, p+Au, d+Au
  - $\kappa_K$ projection in BES phase II
- Isobaric collisions (Ru+Ru and Zr+Zr) projection:
  - Charge separation signal difference
  - Significance vs background level
  - Other physics opportunities

# Chiral Magnetic Effect (CME)




$$\vec{J} = \frac{e^2}{2\pi^2}\mu_5\vec{B}$$

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"!

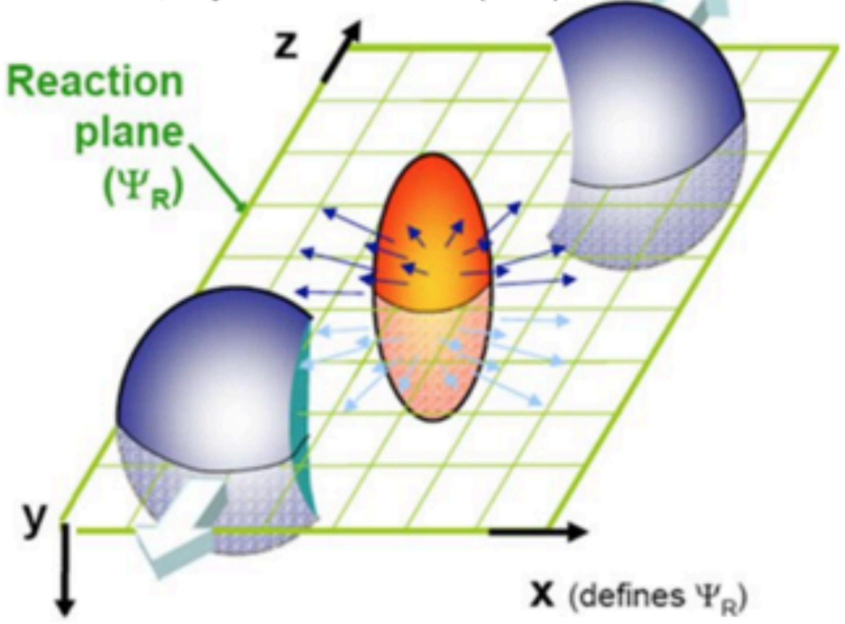
$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + [B_{\mathrm{in}}] - [B_{\mathrm{out}}] + \langle a_\alpha a_\beta \rangle]$$

Direct flow:
Expected to be the same for "same sign" and "opposite sign".

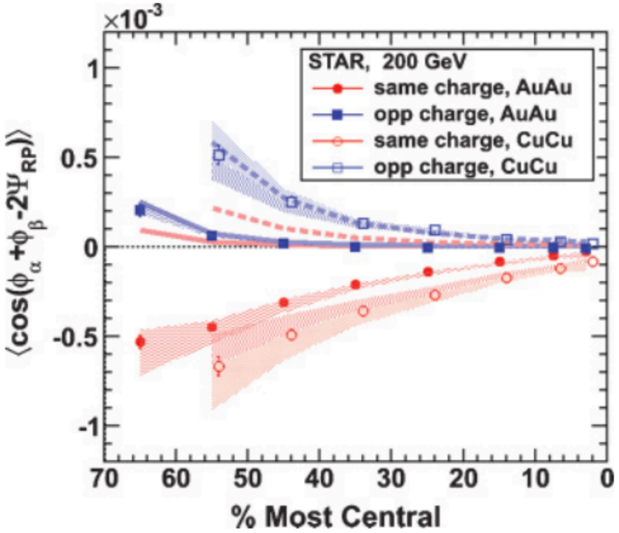
Background effects:
Flow-related background may not be canceled out.

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




STAR, PRC 81 (2010). 054908



# 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:*

$\gamma_{ss} = -1$

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

$v_2 = 1$

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

$\delta_{os} = 0$

H is more robust!

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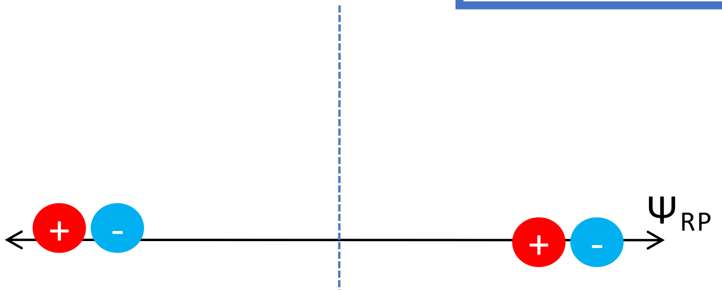


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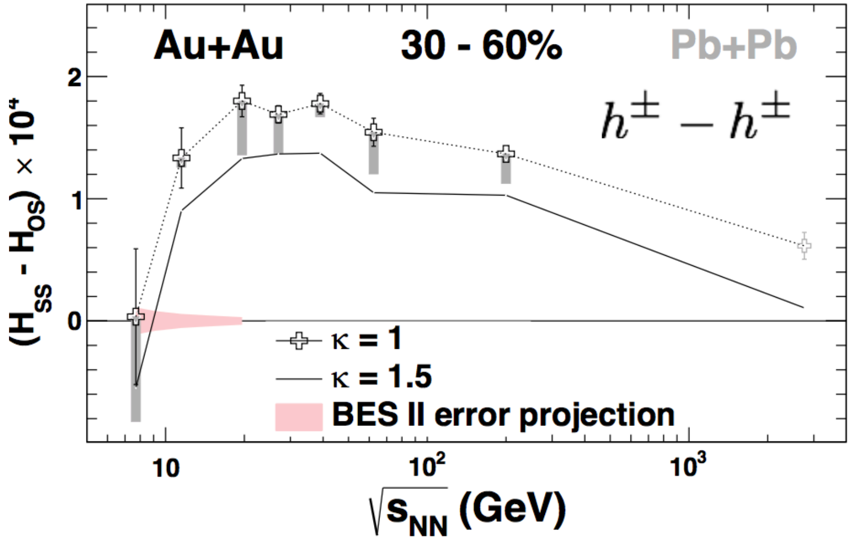
H is more robust!




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

- κ is a parameter near unity that can be estimated by background models.
- Finite $H_{ss} - H_{os}$ signal is observed in Au+Au collisions at $\sqrt{s_{NN}} \geq 11.5$ GeV for $h^{\pm}h^{\pm}$.

# $\kappa_K$: scaled background + signal

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

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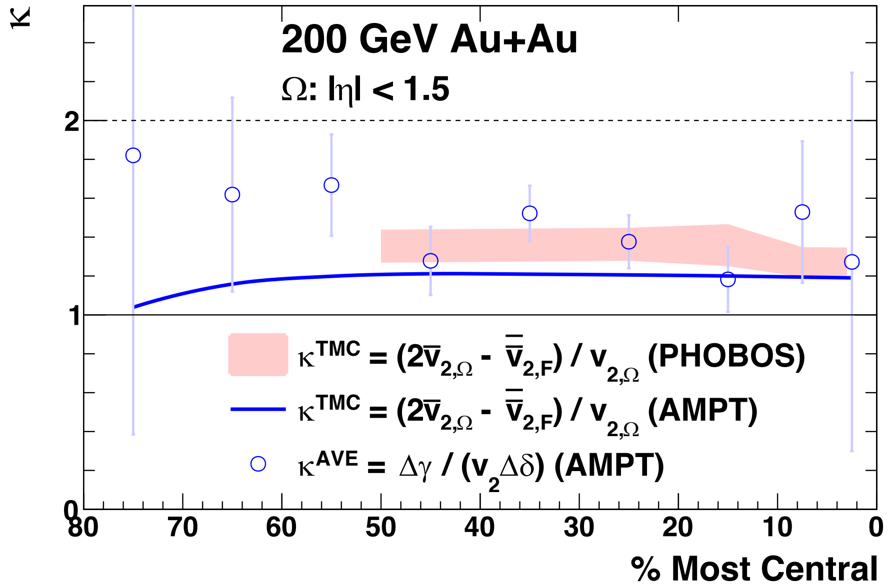


Assumption: $\kappa$ from background is beam-energy, centrality and particle independent and between 1 to 2!

Charge may not be conserved in this version of AMPT

Wen, Wen & Wang, arXiv: 1608.03205

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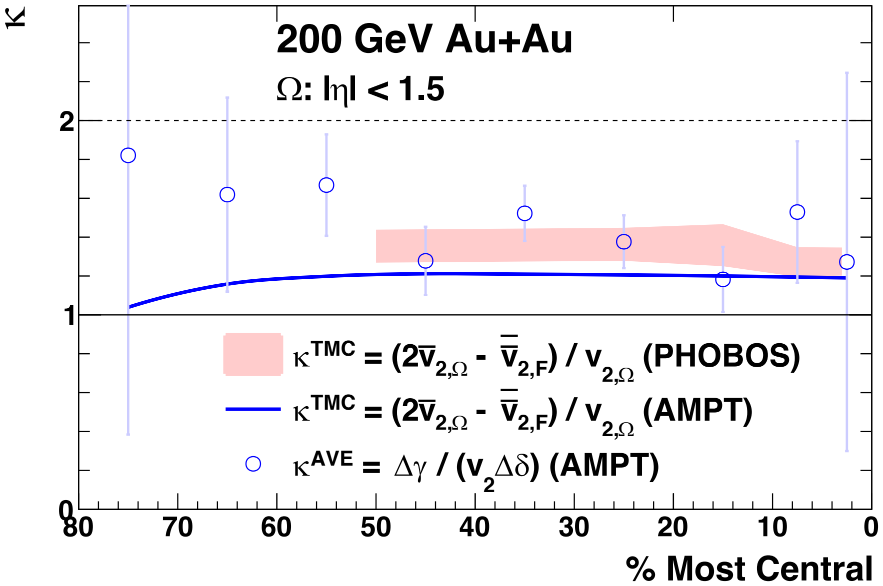


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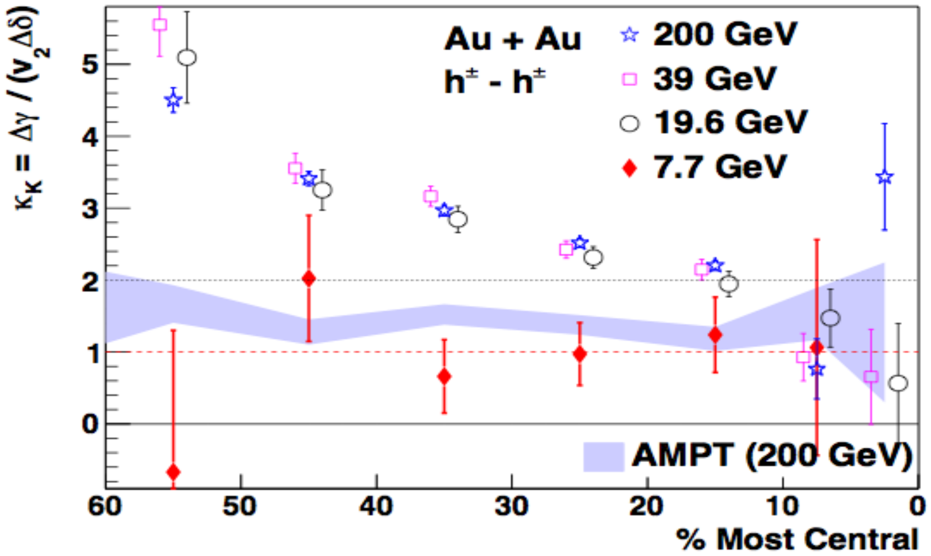
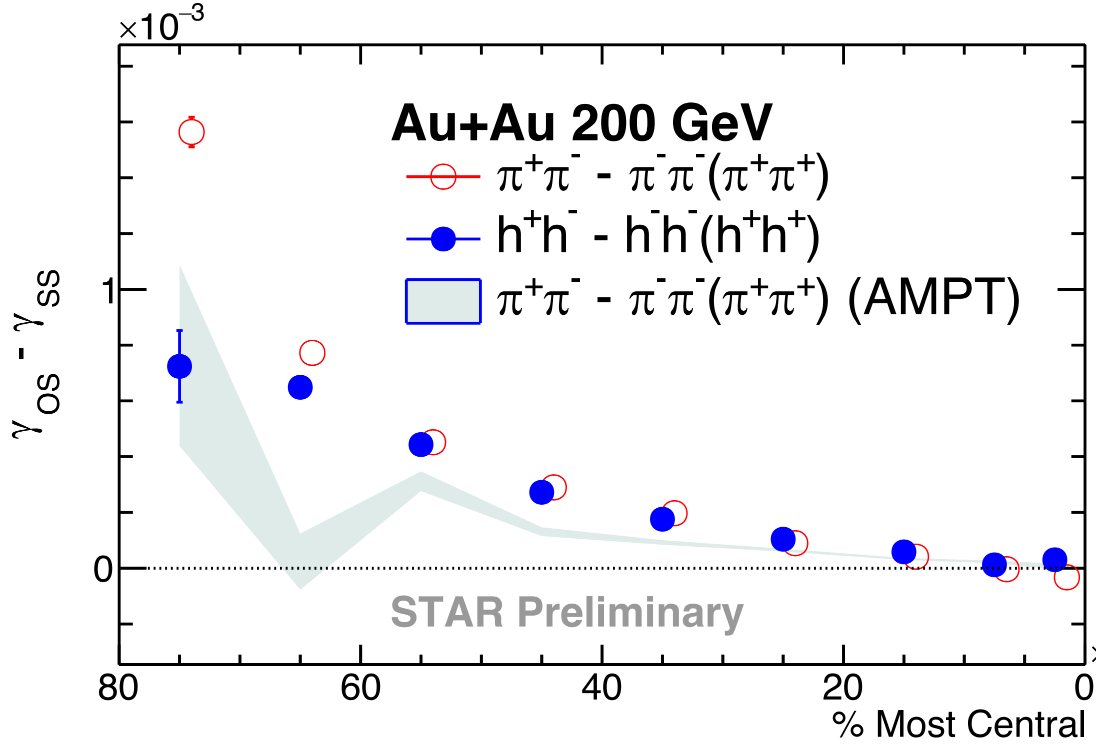


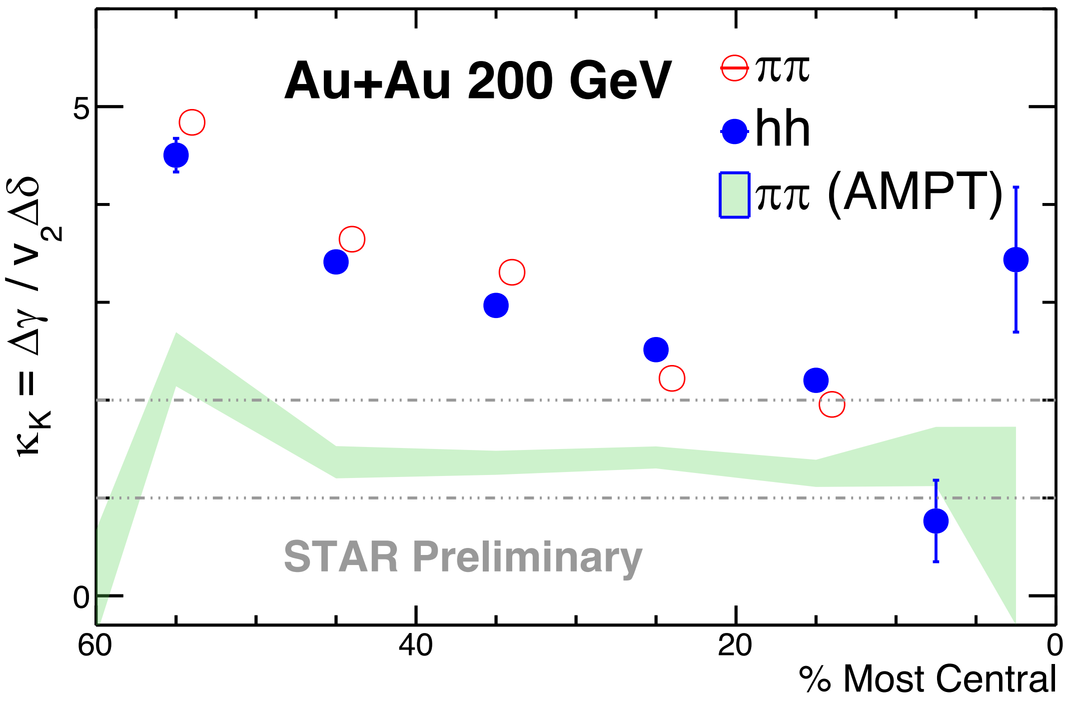

STAR, Phys. Rev. Lett. **113** (2014), 052302,

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

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

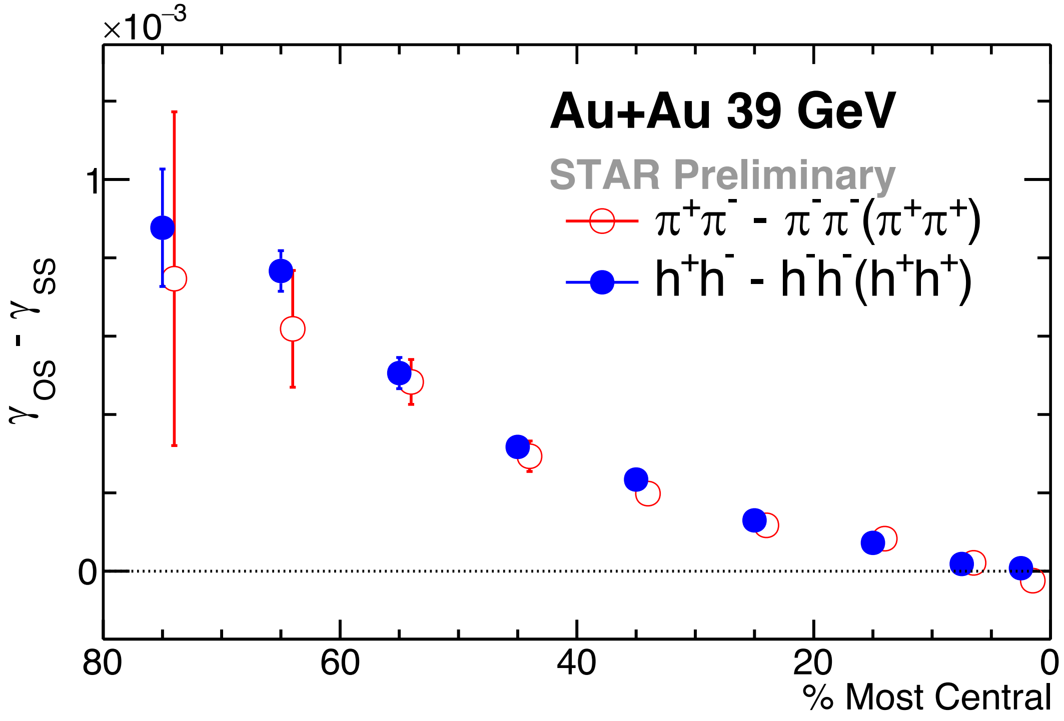
- $\Delta\gamma$ for $\pi\pi$ in Au+Au 200 GeV shows similar values to charged hadrons.
- $\kappa_K$ for mid-central and mid-peripheral collisions is much larger than the background level (1.0 to 2.0) estimated from AMPT.

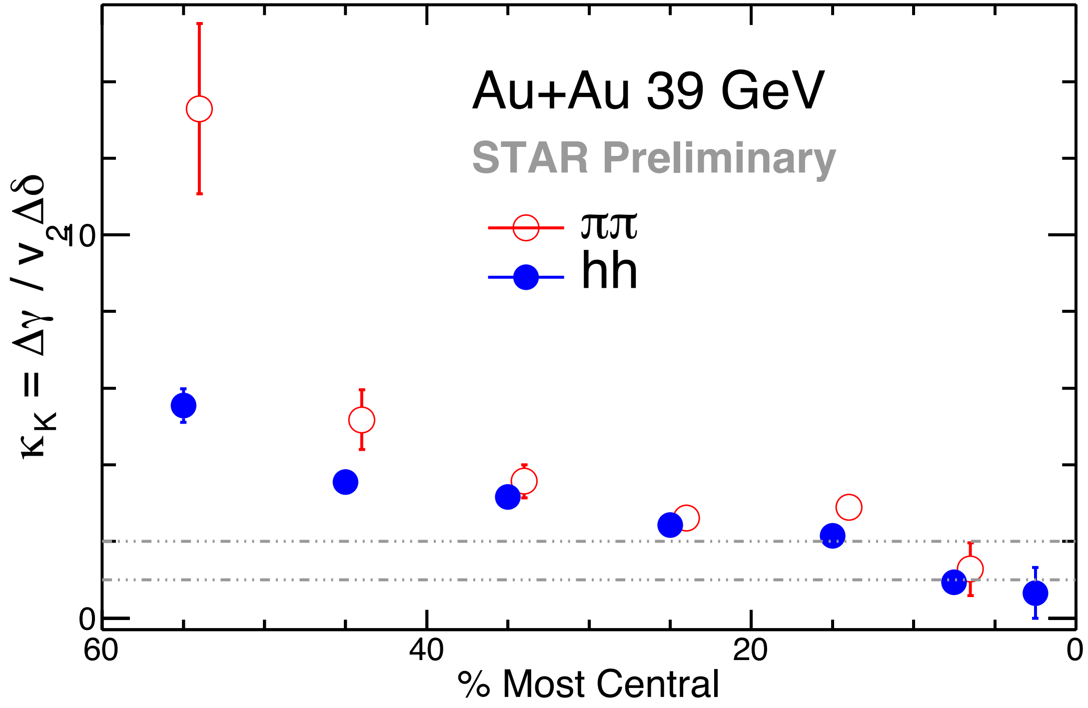


# $\pi\pi$ correlation, Au+Au 39 GeV

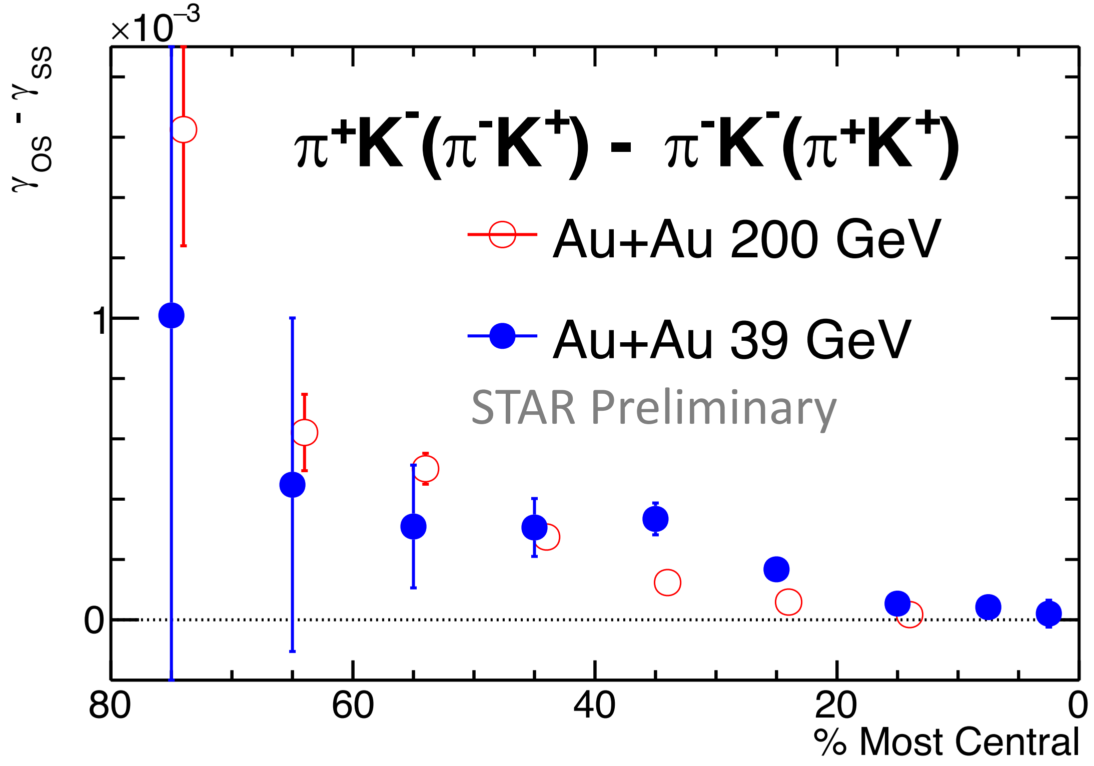
- Au+Au 39 GeV $\pi\pi$ pair $\Delta\gamma$ shows similar magnitude to charged hadron's at the same energy.
- $\kappa_K$ is higher than 2 except in central collisions.

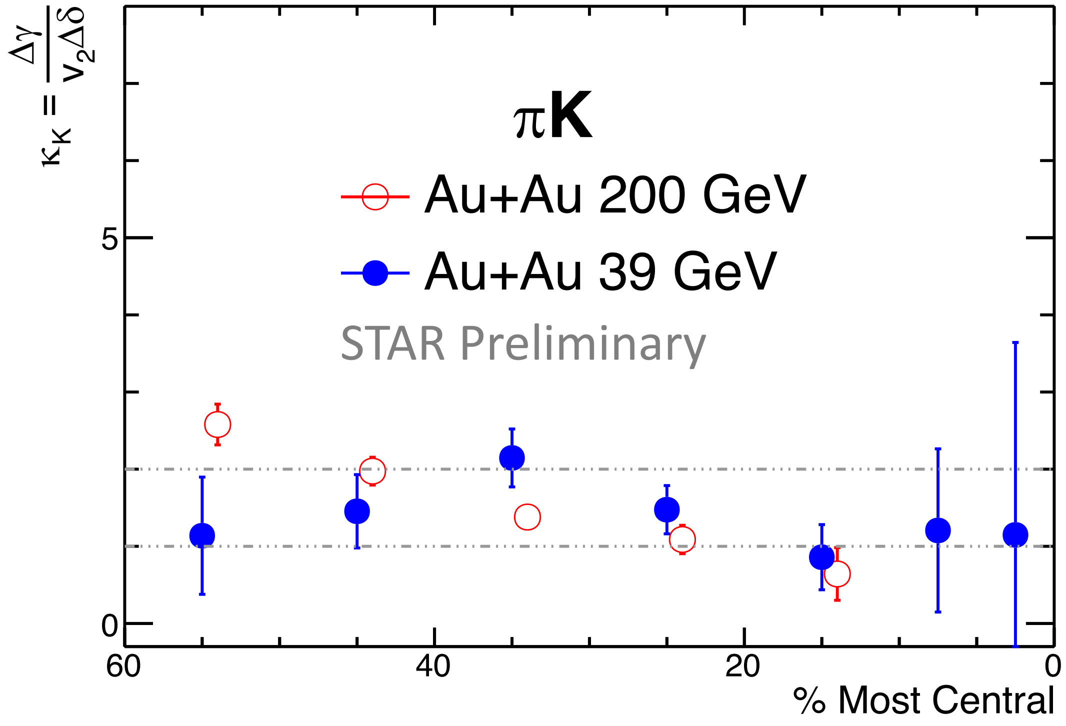


# $\pi K$ correlation

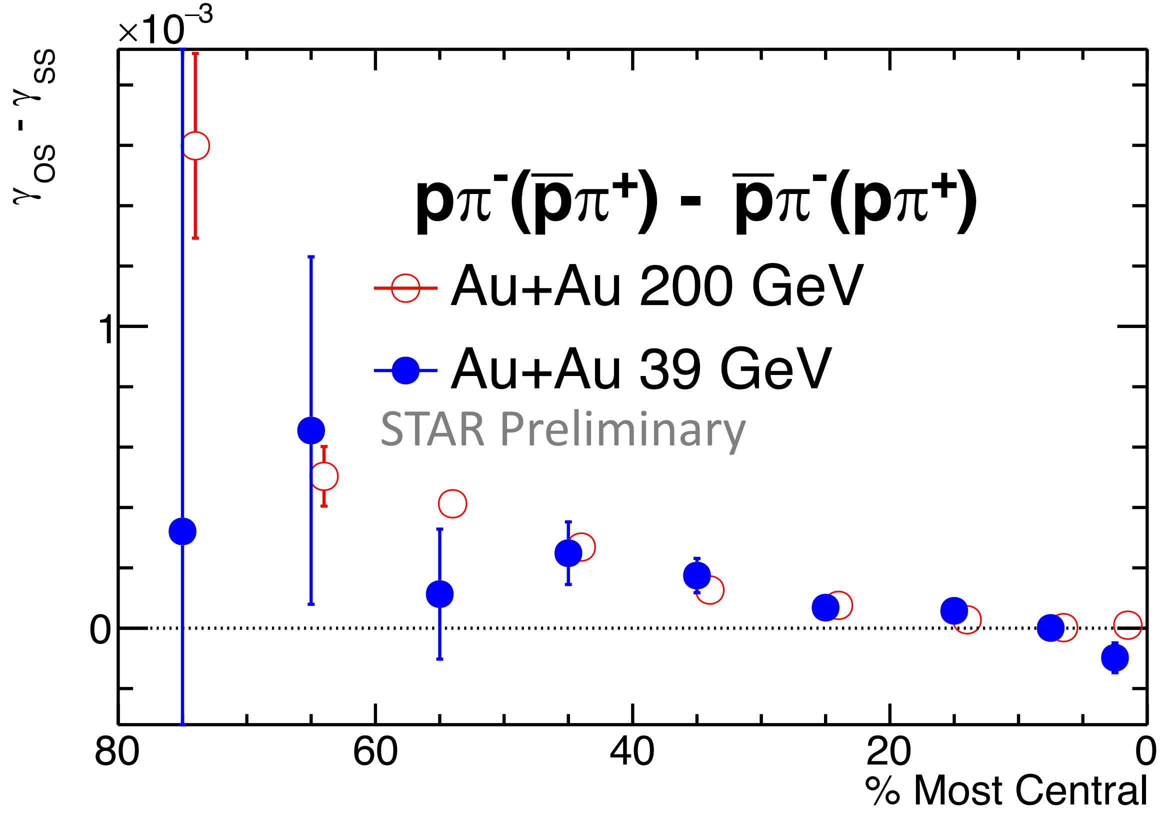
- $\Delta\gamma$ for $\pi K$ pair is finite in Au+Au at both 200 GeV and 39 GeV.
- $\kappa_K$ values are close to or below 2, making it hard to distinguish from background.

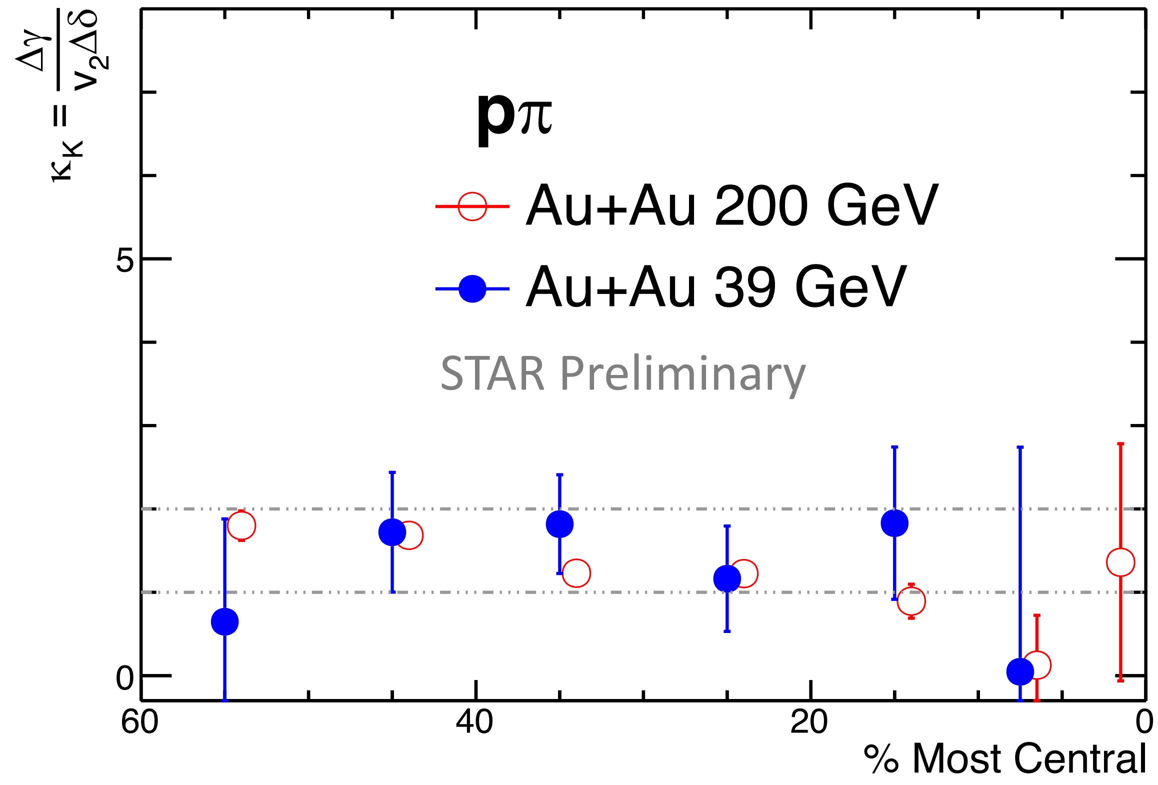


# $p\pi$ correlation

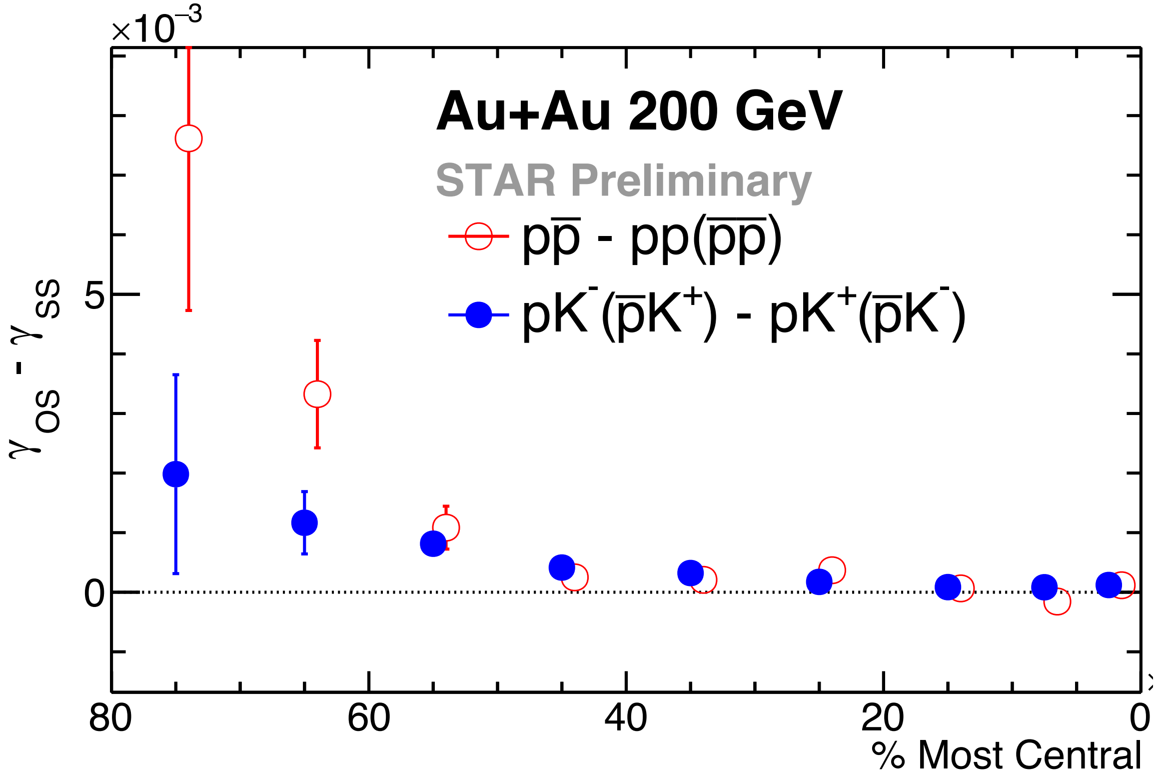
- $\Delta\gamma$ for $p\pi$ pair is finite in Au+Au at both 200 GeV and 39 GeV.
- $\kappa_K$ values are close to or below 2, making it hard to distinguish from background.

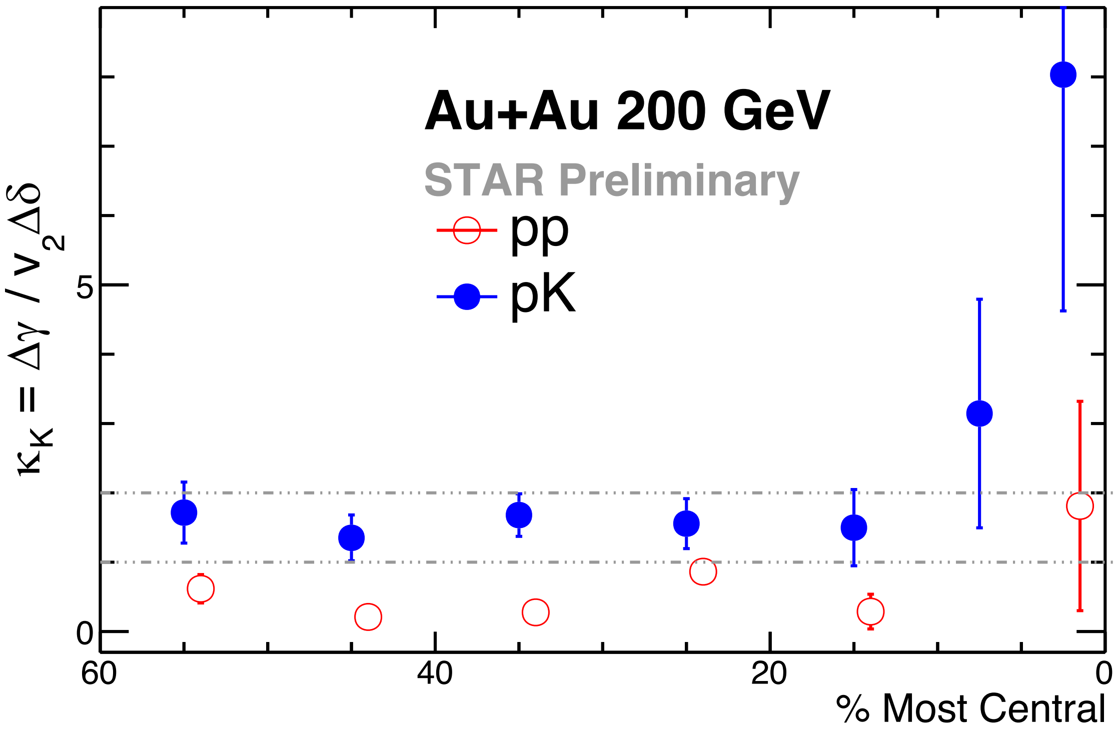


# $pp$ and $pK$ correlation

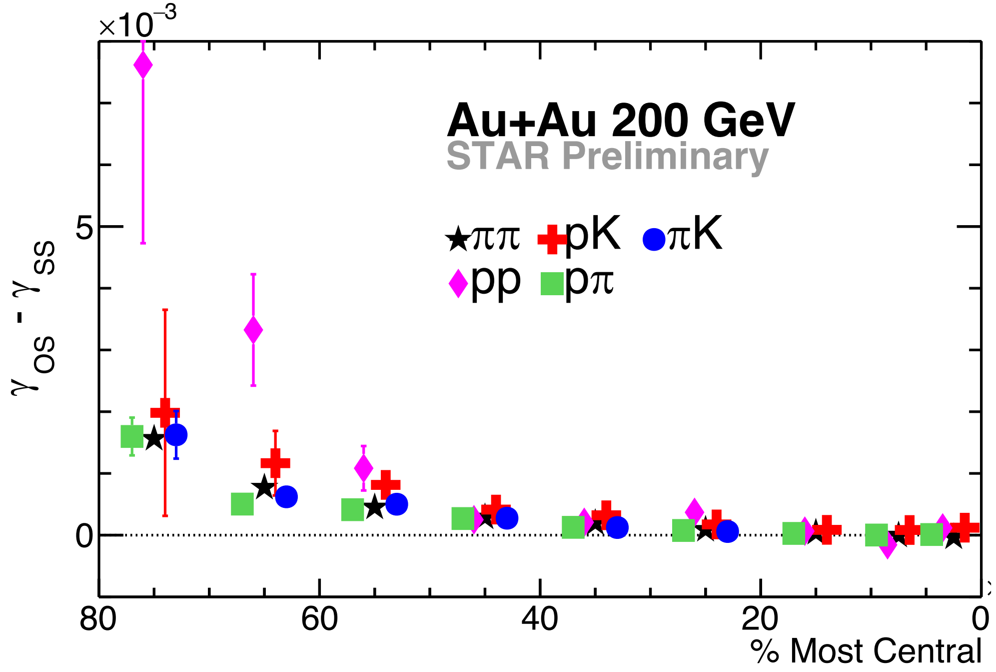
- $pp$ pairs in Au+Au 200 GeV show large $\Delta\gamma$
- $\Delta\gamma$ for $pK$ has smaller values, but still finite in peripheral and mid-central collisions.
- $\kappa_K$ for $pp$ is lower than 2 or even 1 in some centrality bins.
- For $pK$ , $\kappa_K$ fluctuates between 1 and 2.

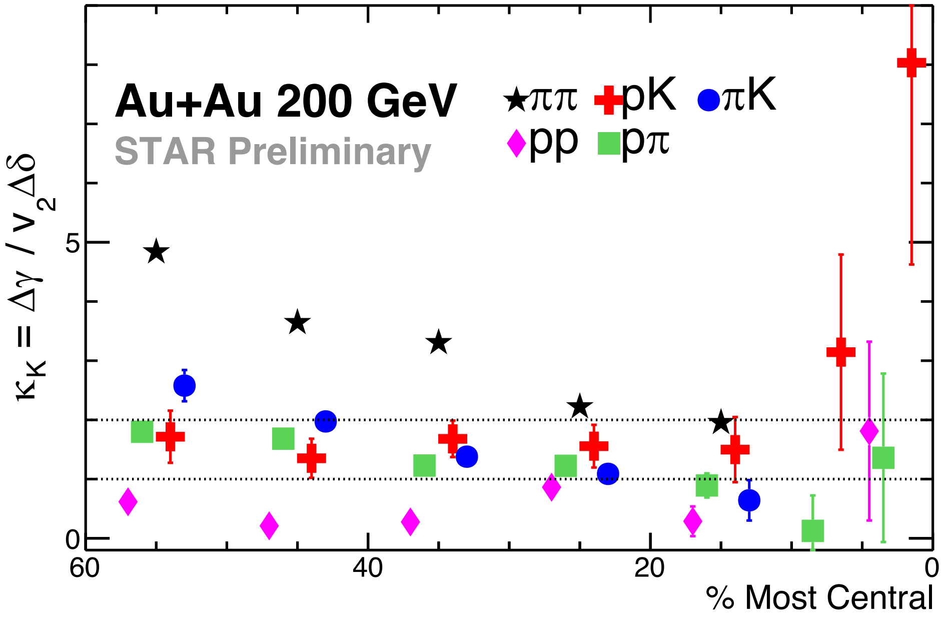


# PID Summary

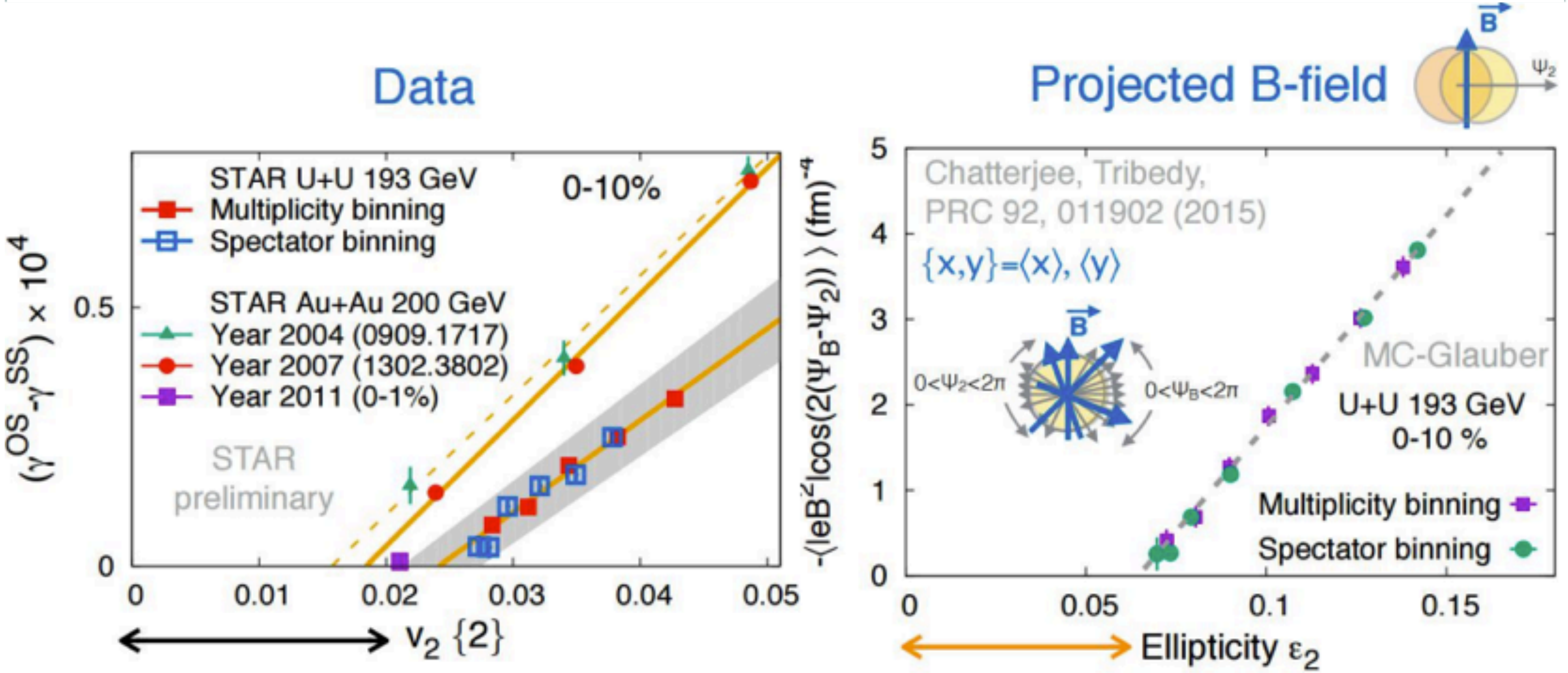
- $\Delta\gamma$ for all PID pairs is finite in peripheral and mid-central Au+Au collisions at 200 GeV
- $\kappa_K$ for $\pi\pi$ is higher than estimated background in mid-central collisions. Other pairs are close to or within background range of 1.0 to 2.0
- pp shows large $\Delta\gamma$ , but $\kappa_K$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



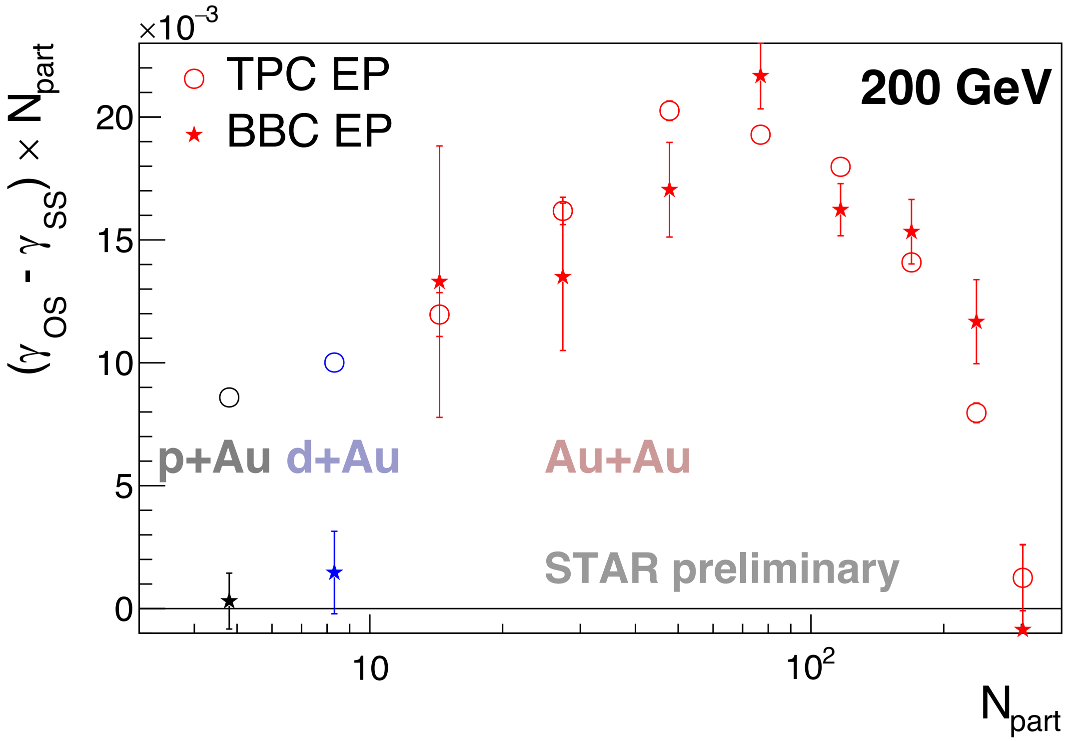
# U+U?

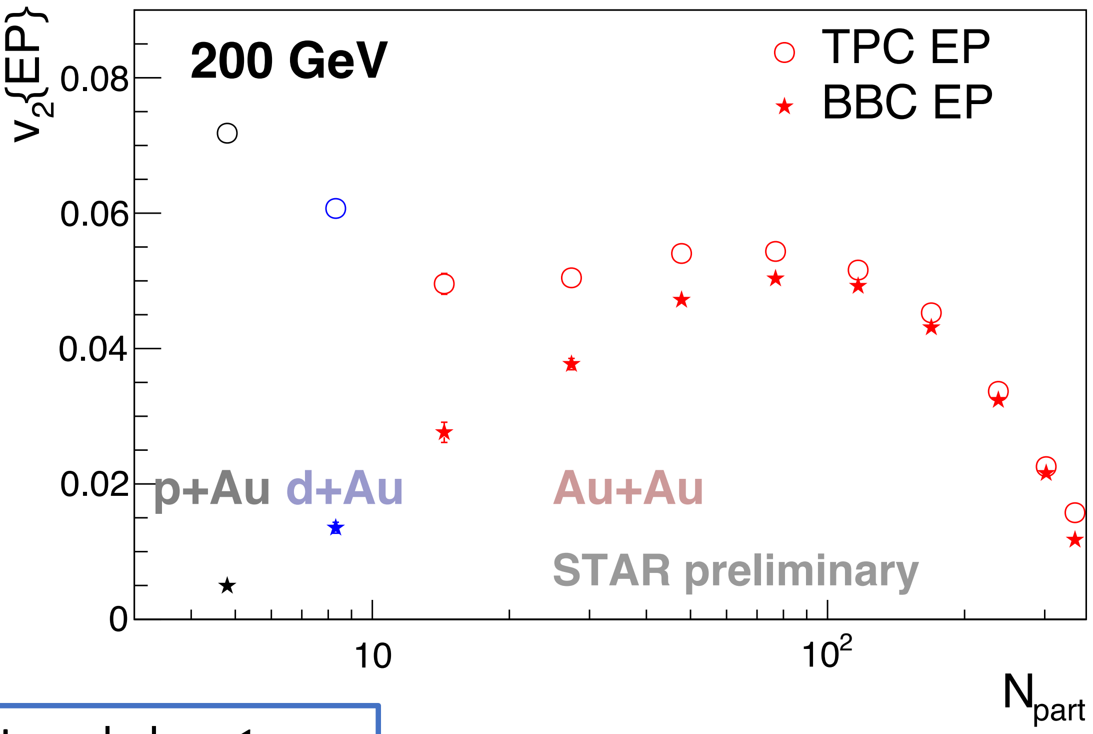
- Why we need U+U collisions?
  - To disentangle the signal and the background by varying the background (trying to minimize flow background by selecting the most central collisions in UU)
  - Similar pattern observed in $\Delta\gamma$ vs $v_2$ and projected B-field vs $\epsilon_2$ suggests magnetic field may be the driven force of observed $\Delta\gamma$ signal.



# $\gamma$ correlation in p+Au and d+Au

- Sizable $\Delta\gamma$ in p+Au and d+Au w.r.t $2^{nd}$ –order event plane (EP) $\psi_2$ from TPC.
- $\Delta\gamma$ disappears in p+Au and d+Au when $\eta$ gap is introduced between EP and particles of interest: $\Delta\gamma$ in TPC EP results mostly from short range correlation (this can also be seen from difference between TPC and BBC $v_2$).

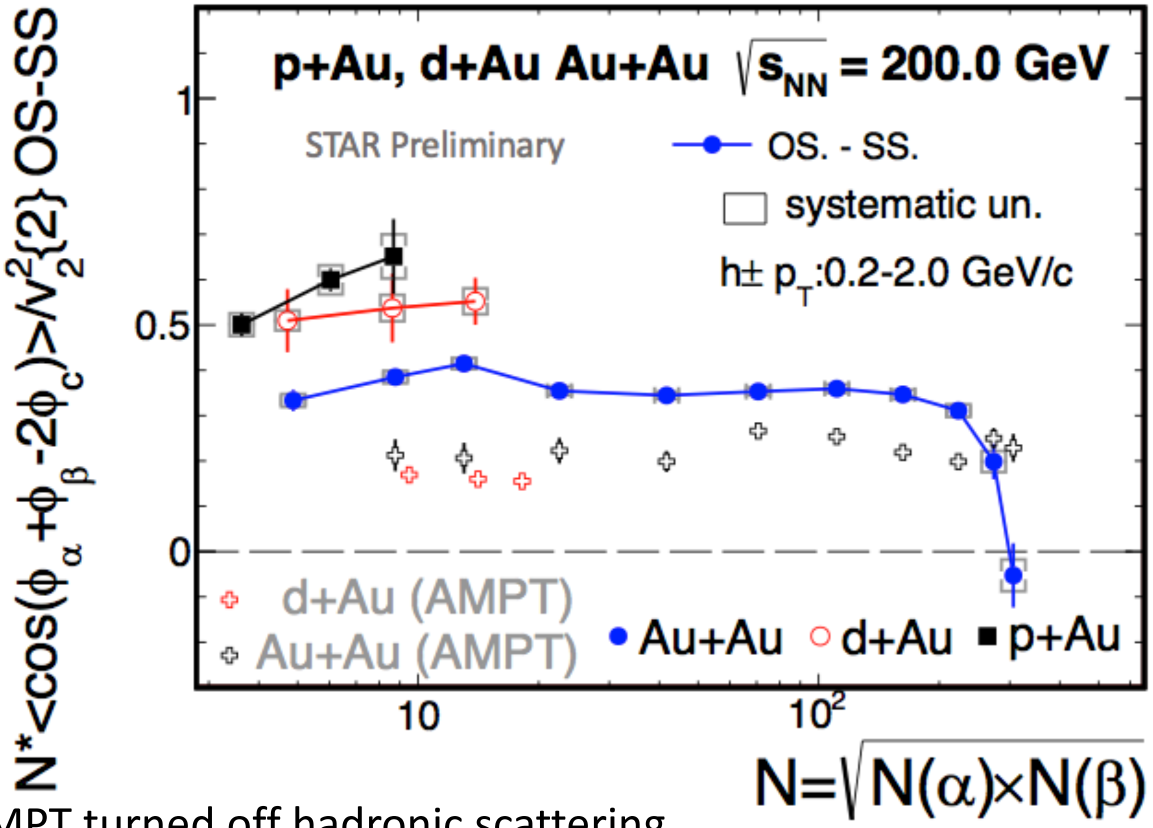



Time Projection Chamber: $|\eta| < 1$
Beam-Beam Counter: $3.3 < |\eta| < 5.2$

# $\gamma$ correlation in p+Au and d+Au

- $\Delta\gamma \cdot N/v_2$ from AMPT (hadronic scattering is 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 w.r.t. TPC event plane.
- $\Delta\gamma \cdot N/v_2$ from AMPT accounts for ~1/3 of the observed signal in d+Au w.t.r. TPC event plane.

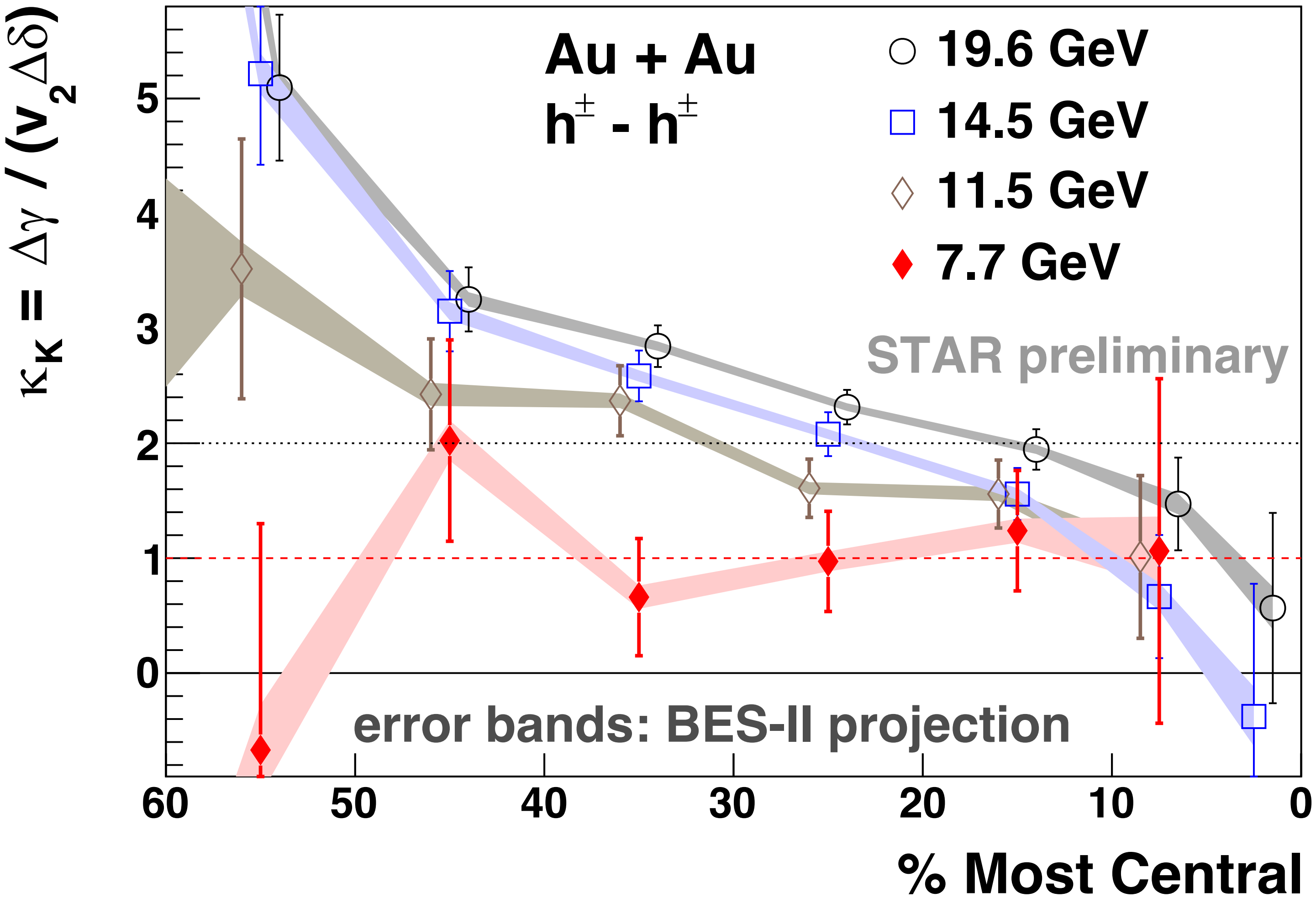





This version of AMPT turned off hadronic scattering

# Projection for BES II

| $\sqrt{s_{NN}}$(GeV) | 19.6 | 14.5 | 11.5 | 7.7 |
|---|---|---|---|---|
| # of evts (M) | 400 | 300 | 230 | 100 |




Error bars: BES I
Error bands: BES II projection

# Isobars

- What are Isobars?
  - Isobars are nuclides of different chemical elements that have the same number of nucleons.
  - Examples: ${}^{96}_{44}Ru$ and ${}^{96}_{40}Zr$
- Why isobaric collisions?
  - Up to 10% variation in B field
  - Flow (major source of background) magnitude will stay almost the same

| | ${}^{96}_{44}Ru + {}^{96}_{44}Ru$ vs. ${}^{96}_{40}Zr + {}^{96}_{40}Zr$ |
|---|---|
| Flow | Similar |
| CME | Greater than |
| CMW | Greater than |
| CVE | Similar |

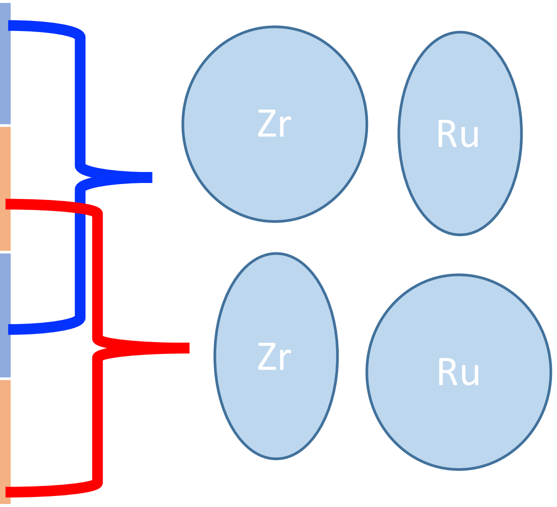
# Woods-Saxon in MC Glauber

$$\rho(r,\theta) = \frac{\rho_0}{1 + \exp[(r - R_0 - \beta_2 R_0 Y_2^0(\theta)/a]}$$

$\rho_0$: 0.16 $fm^{-3}$, normal nuclear density
$R_0$: "radius" of the nucleus
$a$: surface diffuseness parameter
$\beta_2$: deformity of the nucleus

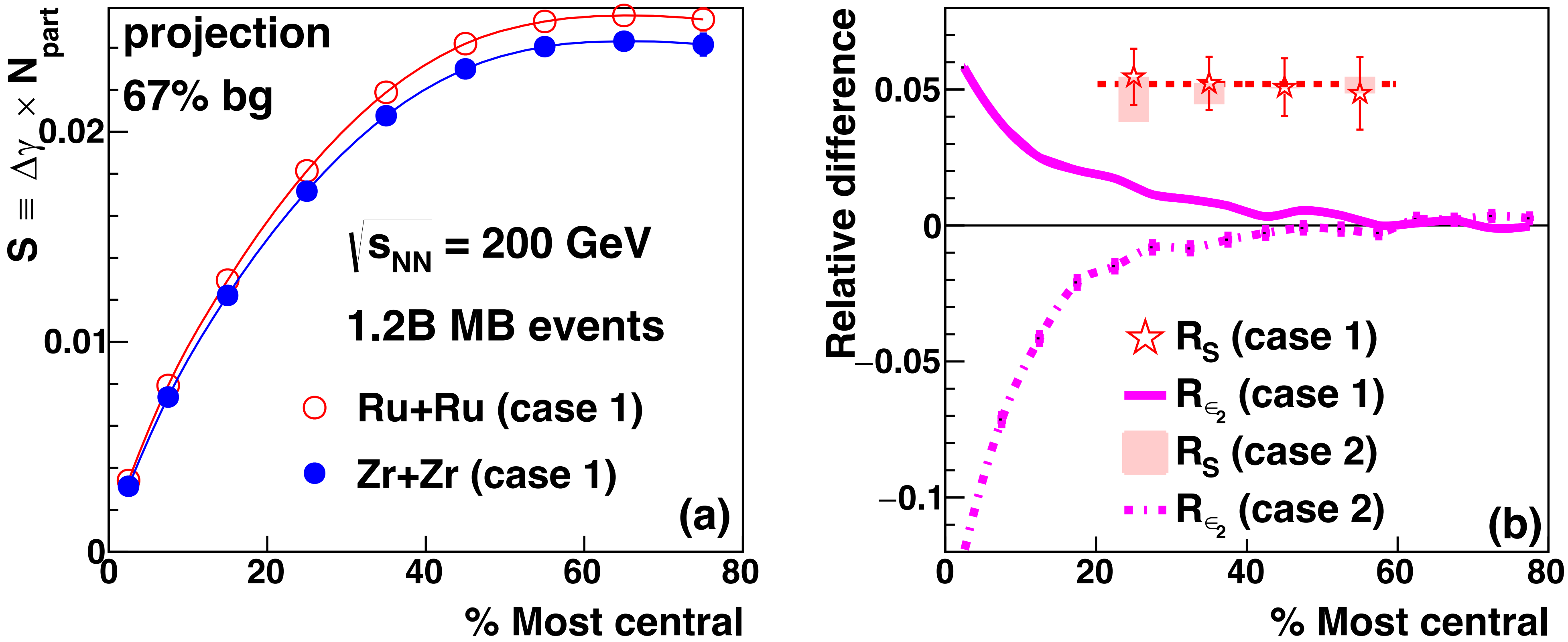
- Case 1: e-A scattering experiment. Atom. Data Nucl. Data Tabl. **78**, 1 (2001); **107**, 1 (2016)
- Case 2: comprehensive model deduction. Atom. Data Nucl. Data Tabl. **59**, 185 (1995).
- Uncertainty in $\beta_2$ presents an opportunity or a by-product of the planned study.

| | | $R_0$ | a(d) | $\beta_2$ |
|---|---|---|---|---|
| Zr96 | Case 1 | 5.07 | 0.48 | 0.06 |
| | Case 2 | 5.05 | 0.45 | 0.18 |
| Ru96 | Case 1 | 5.14 | 0.46 | 0.13 |
| | Case 2 | 5.13 | 0.45 | 0.03 |



# Charge Separation: $\gamma$ (2/3 background)

- Projection with 1.2B events from each collision type
- If it's $v_2$-driven, relative difference follow eccentricity (~0 for 20-60%)
- If it's 1/3 CME-driven, the difference in $\Delta\gamma$ is $8\sigma$ above $\epsilon_2$

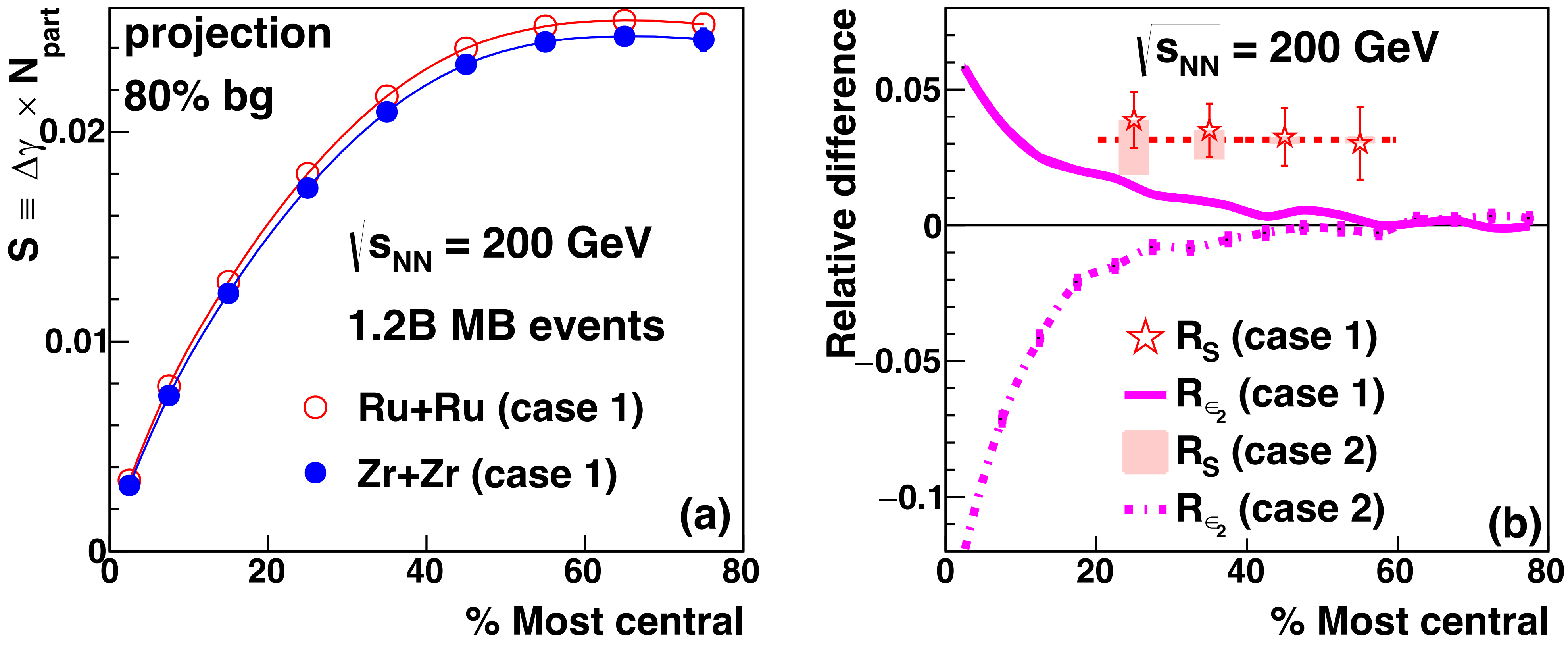




W. -T. Deng, X. -G. Huang, G.-L. Ma and G. Wang, Phys. Rev. C 94, 041901 (2016).

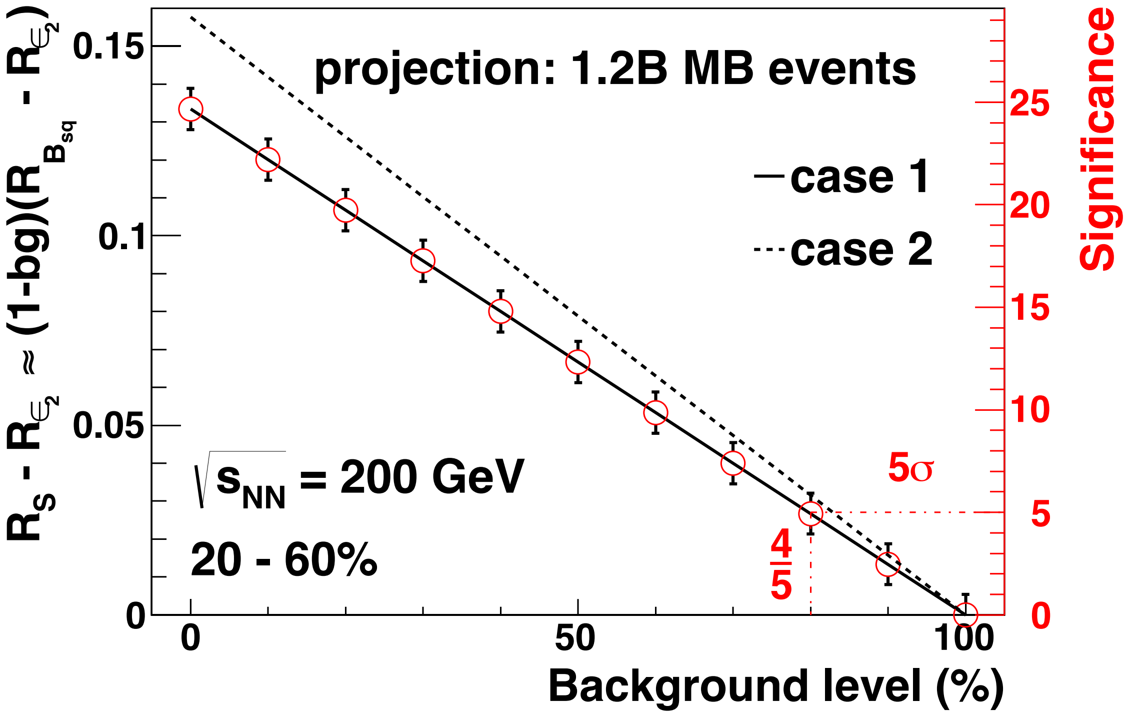
# Charge Separation: γ (80% background)

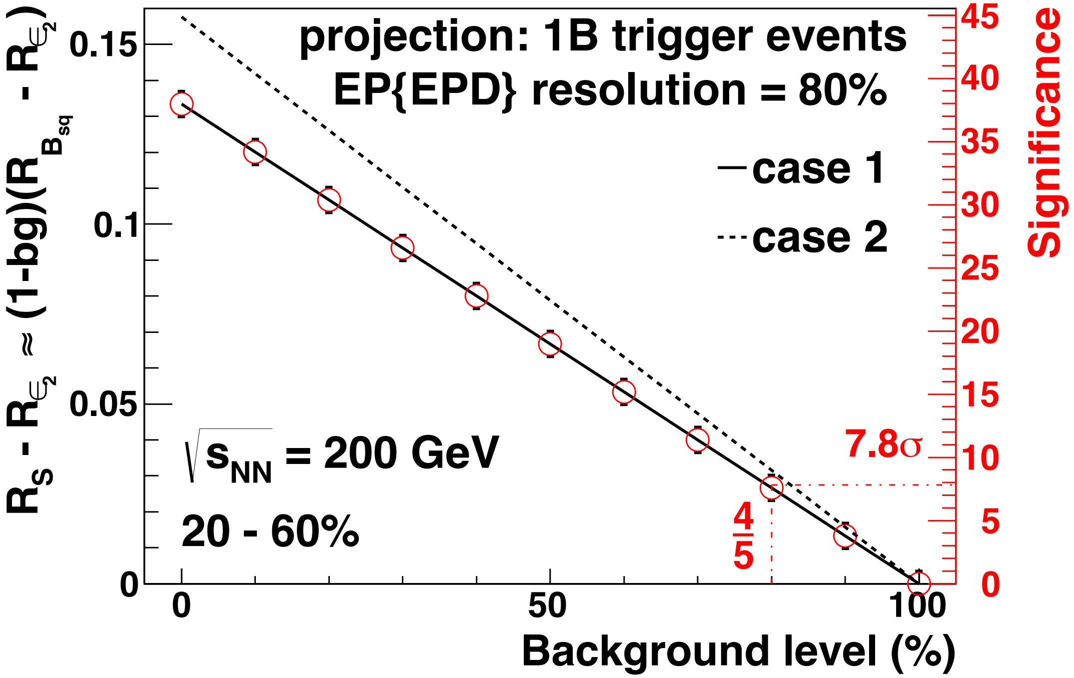
- Projection with 1.2B events from each collision type
- If it's $v_2$-driven, relative difference follow eccentricity (~0 for 20-60%)
- If it's 20% CME-driven, the difference in $\Delta\gamma$ is $5\sigma$ above $\epsilon_2$



# Significance vs. Background

- Projection with 1.2B events from each collision type
- Significance of the difference in $\Delta\gamma$ depends on background level
- Case 2 is slightly better than case 1
- New EPD detector may help achieve 7.8$\sigma$ significance with 1B events and 80% background level



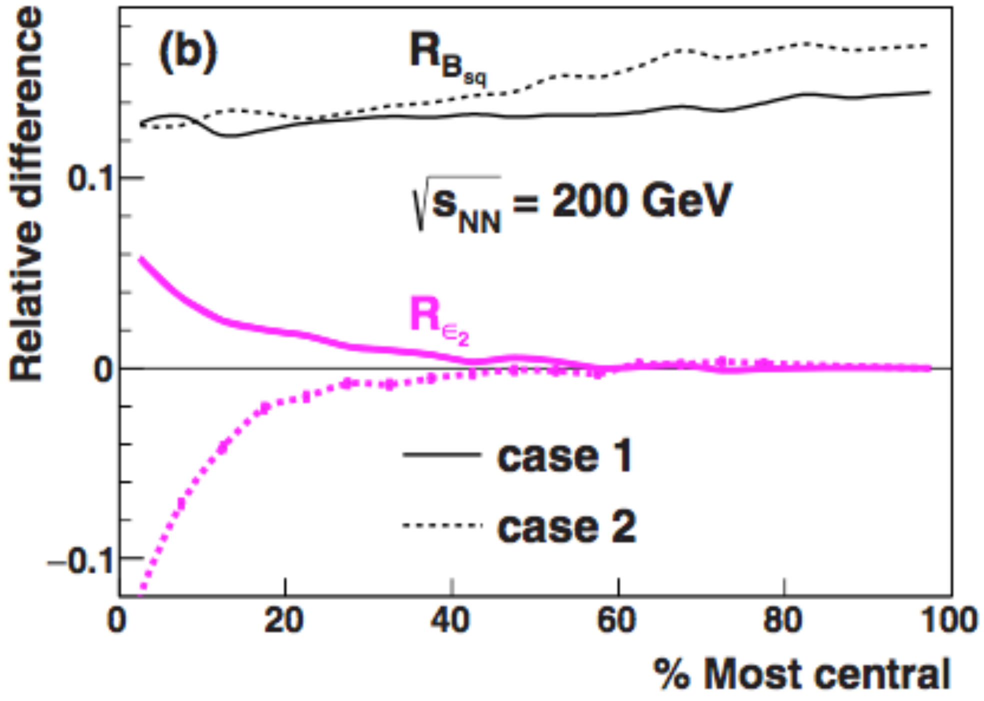
# Zr and Ru, which is more deformed?

| | $R_0$ [fm] | a(d) [fm] | $\beta_2$ |
|---|---|---|---|
| $^{96}Zr$ | 5.06 | 0.46 | 0.06 |
| $^{96}Ru$ | 5.13 | 0.46 | 0.13 |

case 1

| | $R_0$ [fm] | a(d) [fm] | $\beta_2$ |
|---|---|---|---|
| $^{96}Zr$ | 5.06 | 0.46 | 0.18 |
| $^{96}Ru$ | 5.13 | 0.46 | 0.03 |

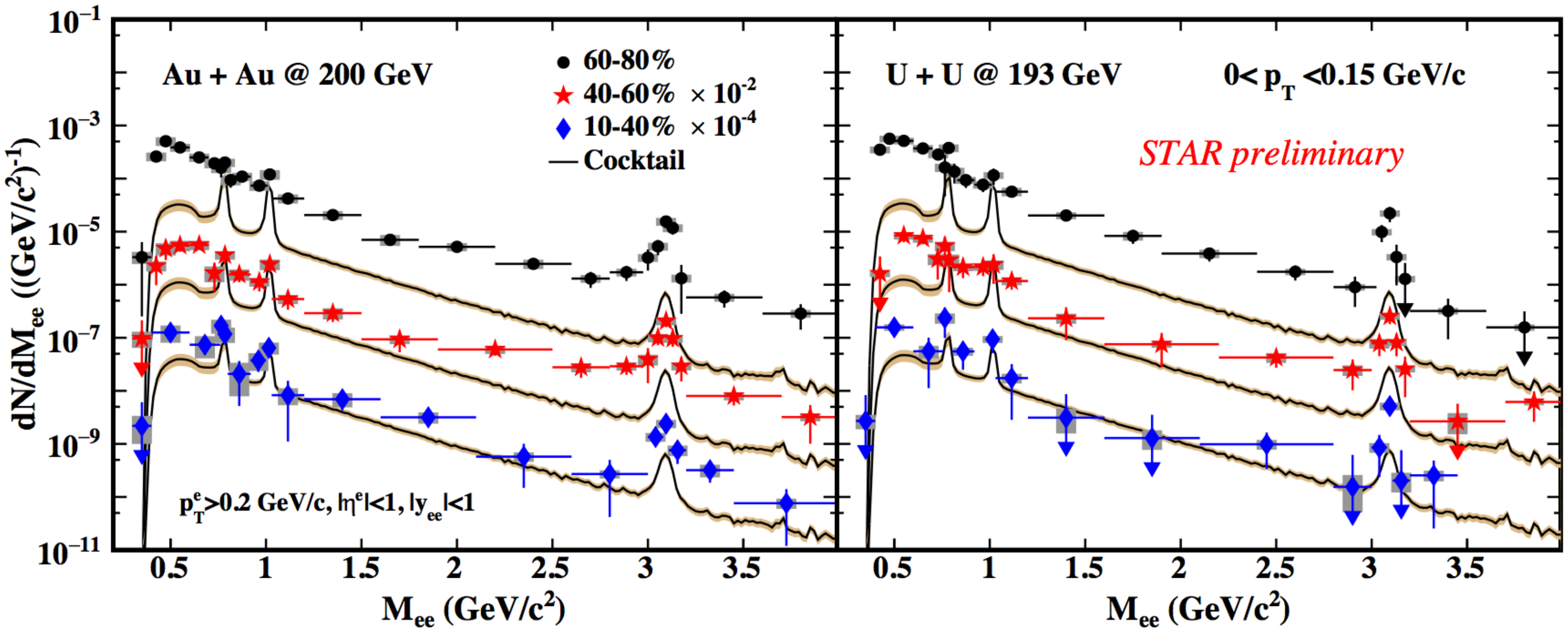
case 2



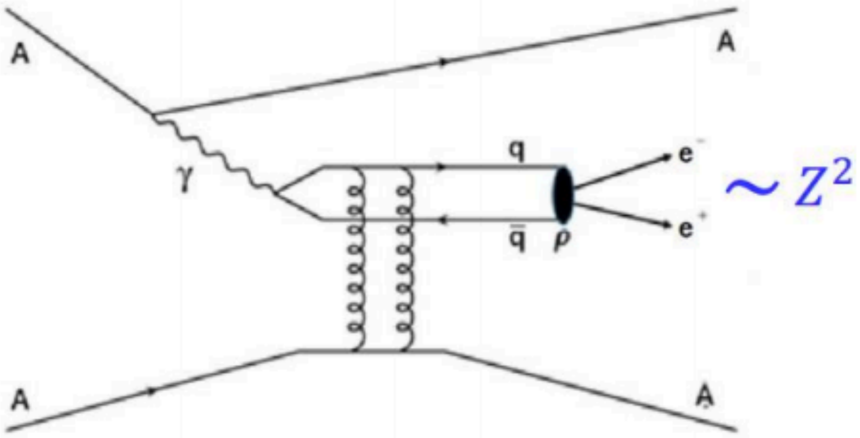

$v_2$ measurements in central collisions will tell us which is more deformed.

W. -T. Deng, X. -G. Huang, G.-L. Ma and G. Wang, Phys. Rev. C 94, 041901 (2016).

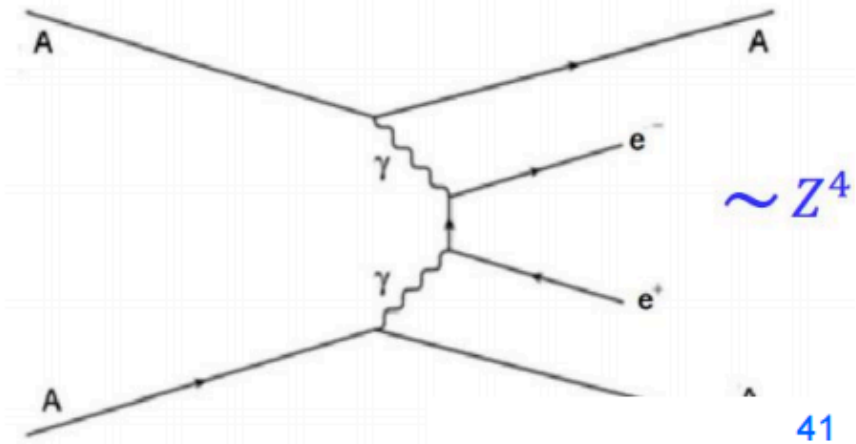
# Zr and Ru: di-lepton production mechanisms at very low $p_T$




**Scenario 1: photonuclear interaction**




**Scenario 2: two-photon process**



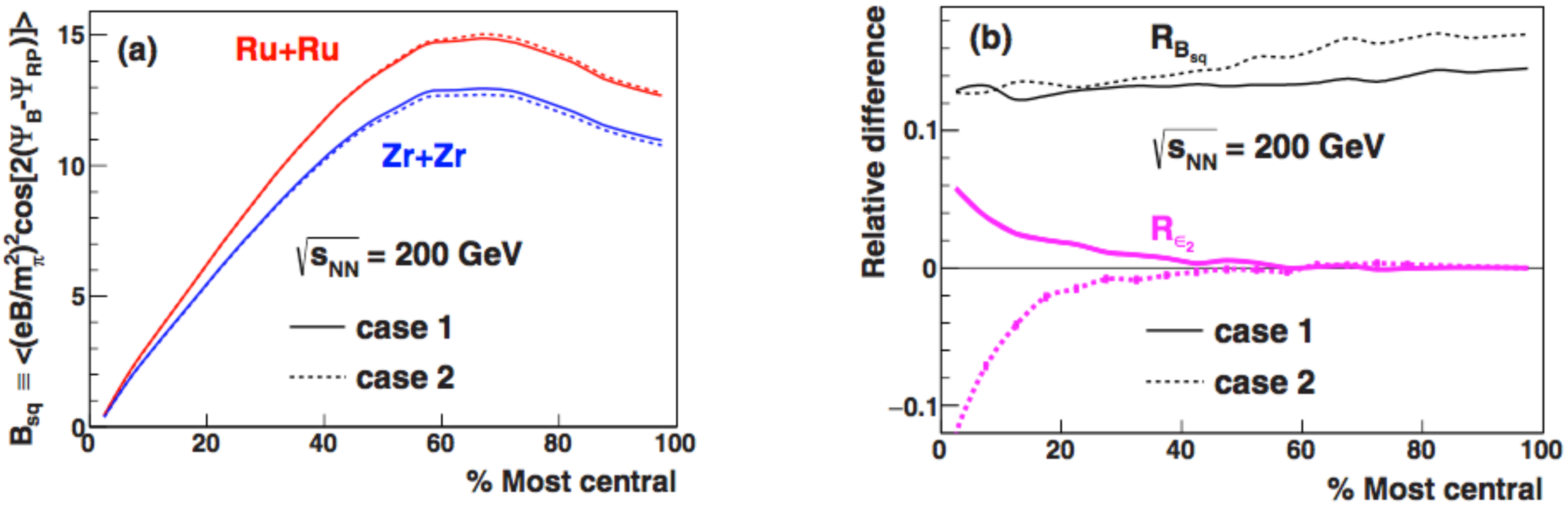
# Summary

- Search for Chiral Magnetic Effect in Au+Au:
  - $\kappa_K$ for $\mathrm{h^{\pm}h^{\pm}}$ and $\pi\pi$ in mid-central Au+Au 200 GeV is larger than those from AMPT background.
  - $\kappa_K$ of other identified pairs, $\pi K, p\pi, pK$, is hard to distinguish from the background.
  - $\kappa_K$ for $pp$ needs further investigation.
  - BESII will significantly reduce statistical uncertainties.
- Search for Chiral Magnetic Effect in p+Au/d+Au:
  - $\Delta\gamma$ for $\mathrm{h^{\pm}h^{\pm}}$ in p+Au and d+Au 200 GeV is significant when using TPC event plane.
  - $\Delta\gamma$ disappears when introducing $\eta$ gap (>2) between particles of interest and event plane in p+Au and d+Au 200 GeV.
- Isobaric Collisions:
  - With 1.2B MB events, significance of the difference in $\Delta\gamma$ between Ru+Ru and Zr+Zr can reach at least 5$\sigma$ if background level is as high as 80%. EPD may improve this to 7.8$\sigma$ with 1B events.

Back up slides

# B Field

- B calculated at t=0, at one point (center of mass of participants)
- B field slightly affected by $\beta_2$
- Relative difference in $B^2$ is 15-18% for peripheral events
- Reduces to 13% for central collisions

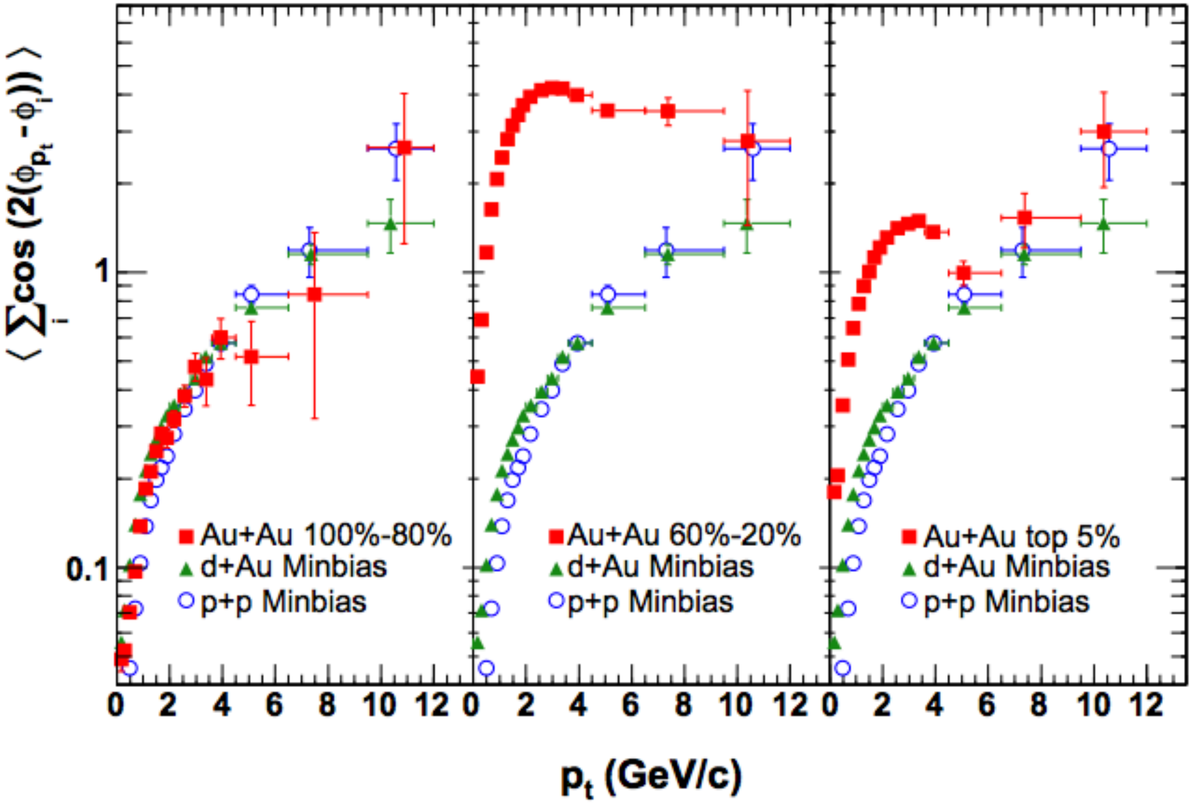




W. -T. Deng, X. -G. Huang, G.-L. Ma and G. Wang, Phys. Rev. C 94, 041901 (2016).

# Collectivity vs. non-flow

What is collectivity?
A working definition:
multiple particles correlated across rapidity due to a common source




STAR, PRC 72 (2005) 14904

- Note 1: collectivity does not imply a specific physical interpretation (i.e. collectivity ≠ hydro)
- Note 2: correlations between particles which do not have a "collective" origin (jets, resonance decays, momentum conservation) are commonly called "non-flow"...