Current Status of the CME Search and Isobaric Collisions at RHIC

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6/18/17

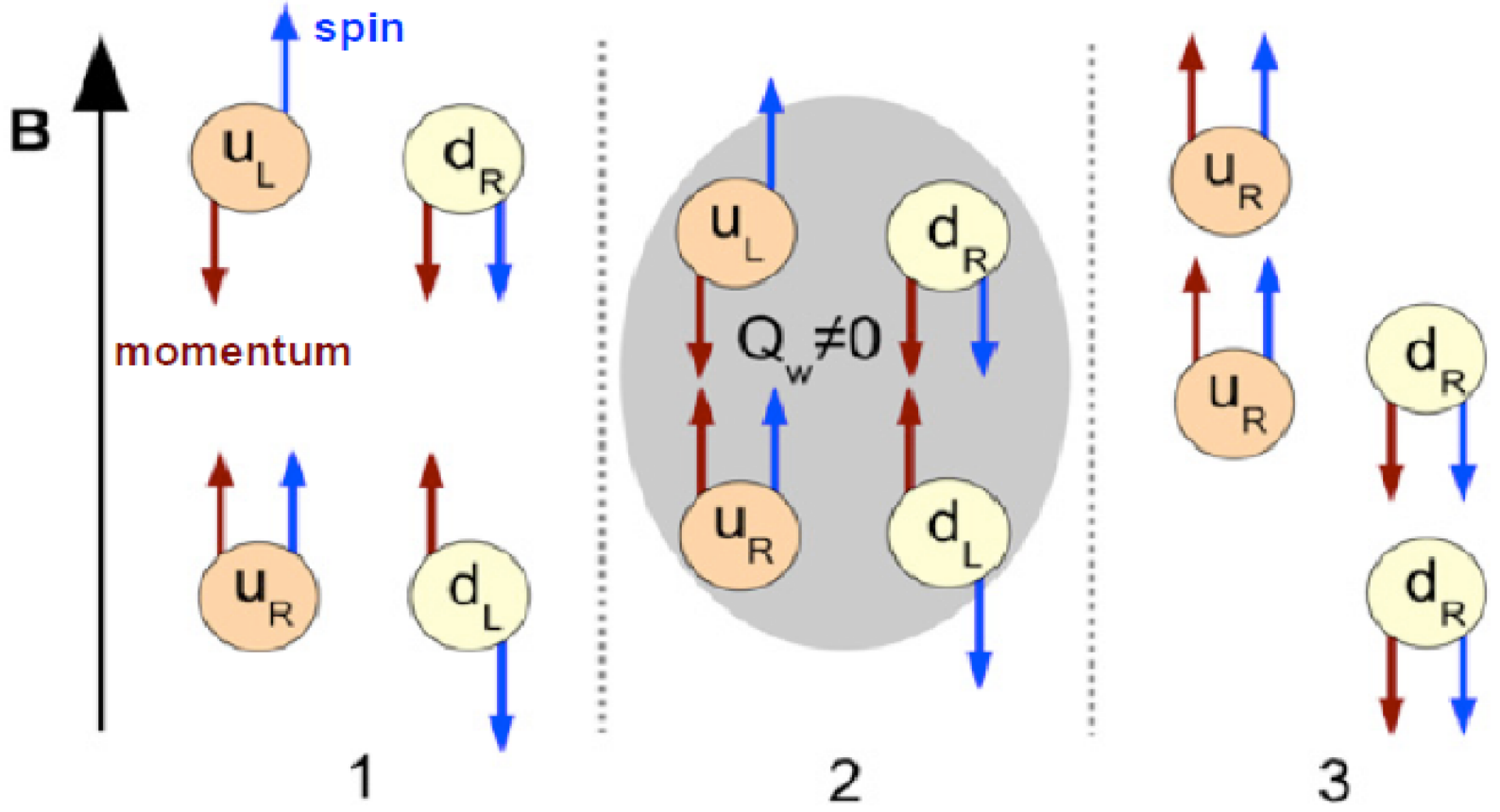
Outline

- Physics Motivation and Observables

- Correlation Measurements:
  - γ, κ_K for identified particles in Au+Au
  - γ for charged hadrons in U+U, p+Au, d+Au

- Isobaric Collisions (Ru+Ru and Zr+Zr) Projection:
  - B field difference
  - Charge separation signal difference
  - Significance vs background level
  - A few by-products

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"!

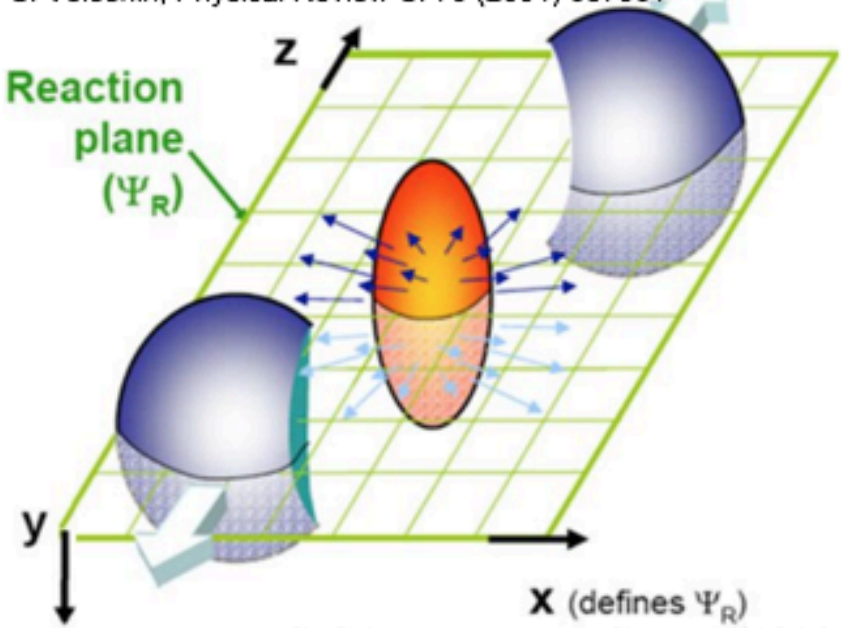
$$\gamma = \langle cos(\phi_\alpha + \phi_\beta - 2\psi_{RP})\rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta}\rangle + B_{in}] - [\langle a_\alpha a_\beta\rangle + B_{out}]$$

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

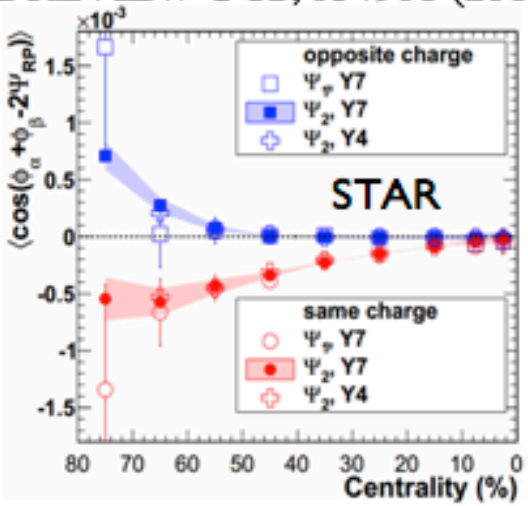
Background effects: could cancel out, but flow-related background may still exist.

P-even quantity: still sensitive to separation effec, 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).

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

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

$$\Downarrow$$

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

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

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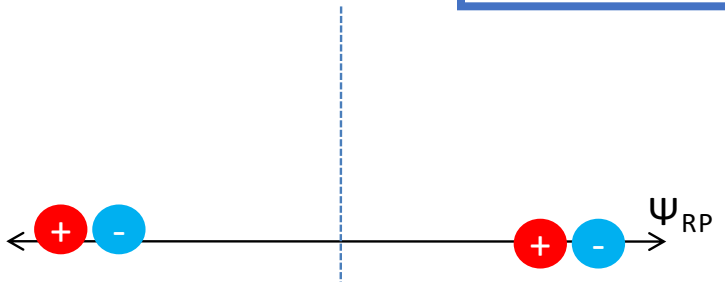

- ✓ Flow
- ✓ Momentum Conservation
- ✓ Local Charge Conservation
- ✓ Decay

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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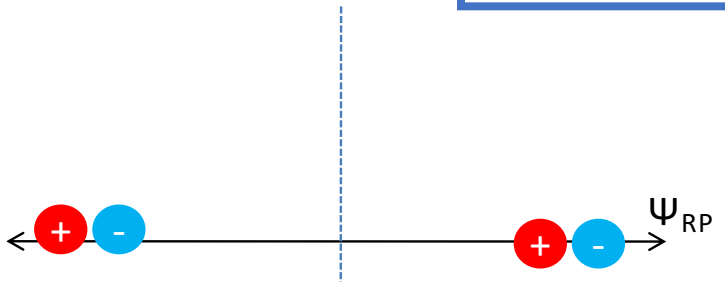

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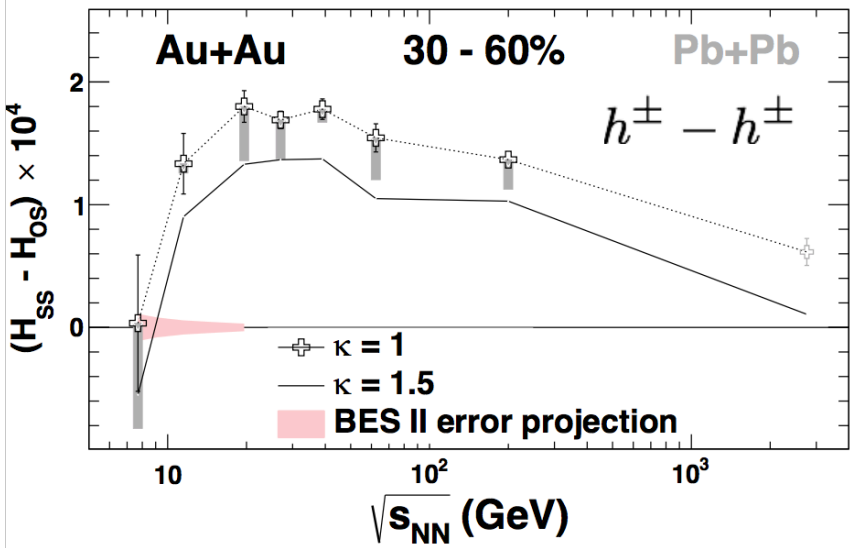

STAR, Phys. Rev. Lett 113 (2014) 052302

- 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 background + signal

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$$\xRightarrow{\Delta H = 0} \boxed{\kappa_K = \frac{\Delta\gamma}{v_2 \Delta\delta}}$$

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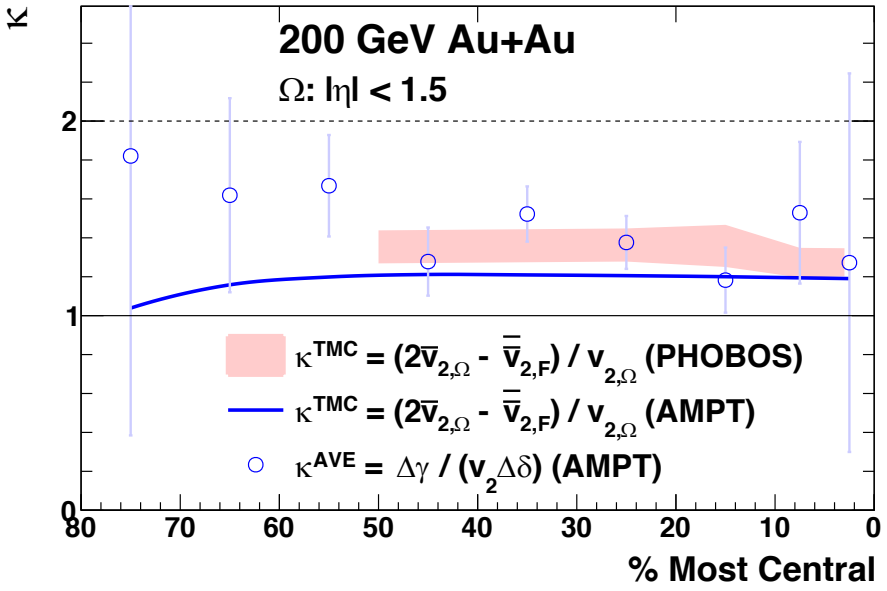

Assumption: κ from background is beam-energy, centrality and particle independent and between 1 to 2!

Charge may not be conserved in this version of AMPT

Wen, Wen & Wang, arXiv: 1608.03205

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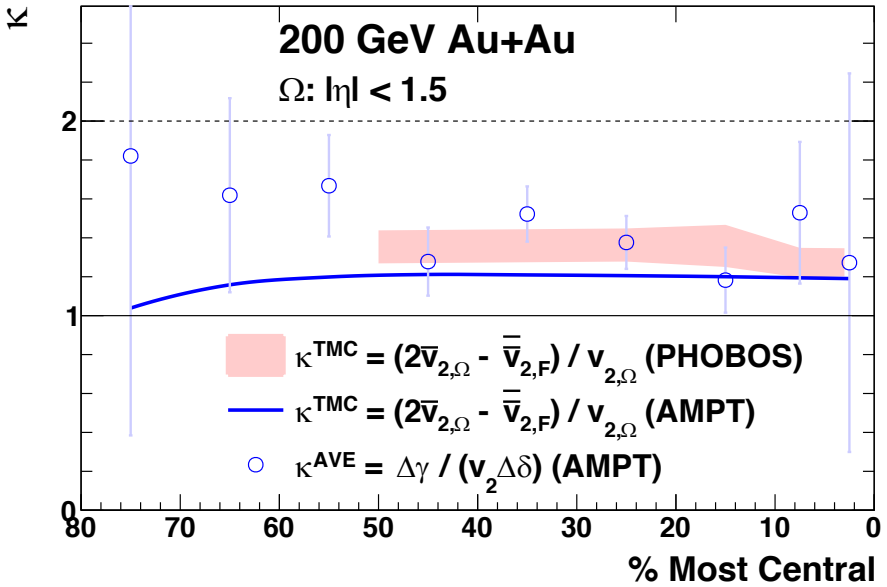

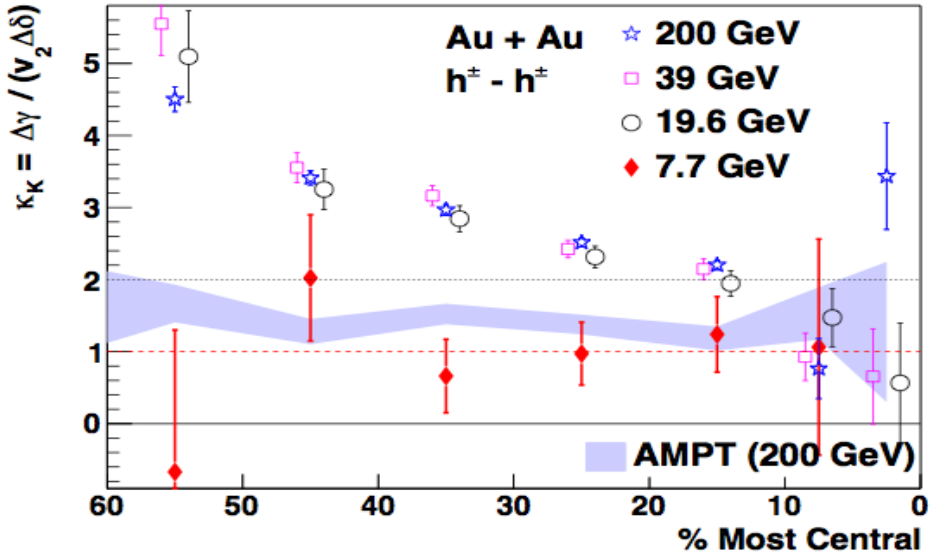

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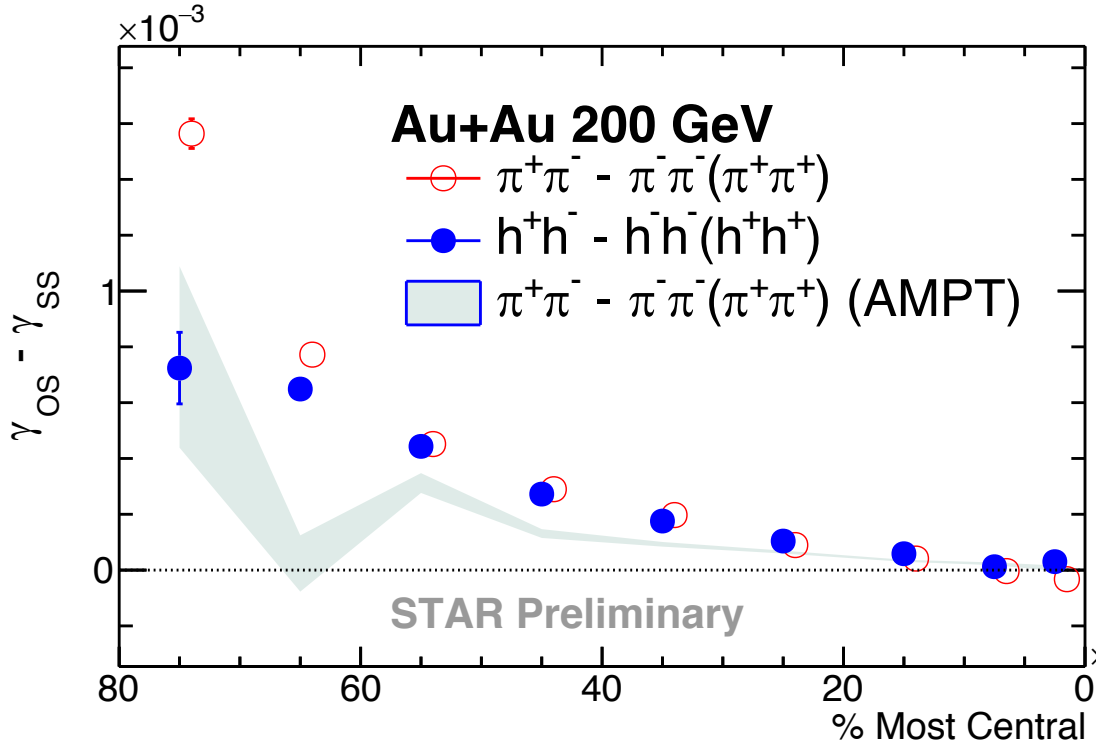
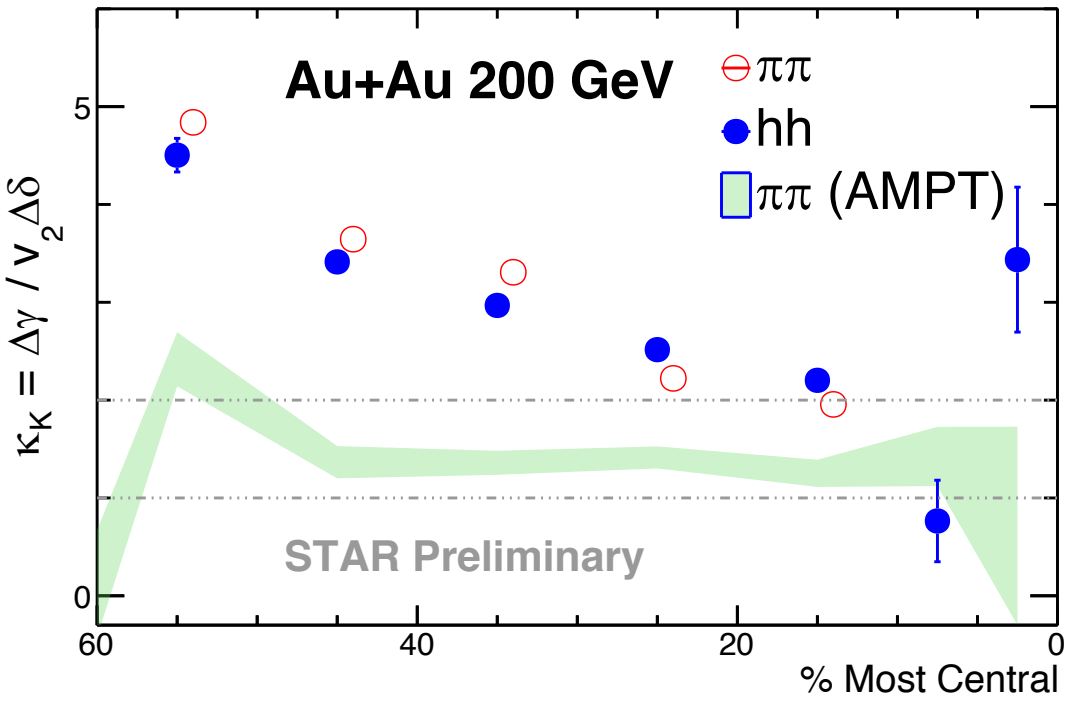
- At the extreme, we introduce κ_K such that $\Delta H = 0$. If $\kappa_K > \kappa$ ($H_{ss-os} > 0$), there could be extra physics, like CME.
- κ_K at 7.7 GeV shows weak centrality dependence with values within [1, 2].
- At energies >= 19.6 GeV, κ_K shows higher values than 2 in mid central and mid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

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

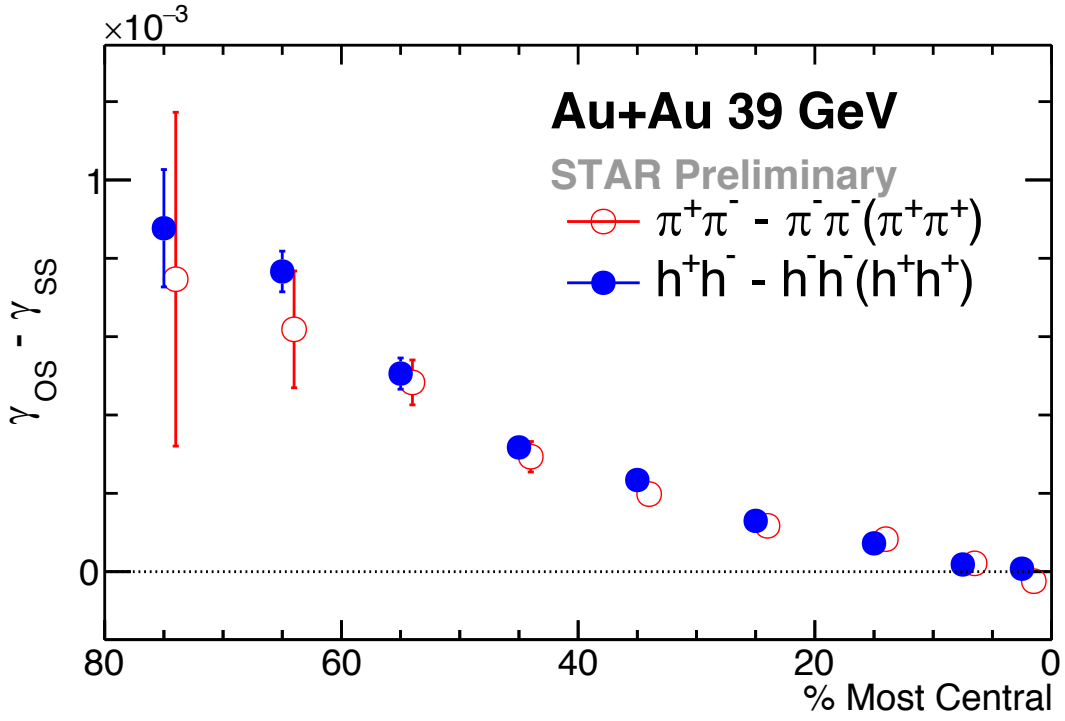
- $\Delta\gamma$ for $\pi\pi$ in Au+Au 200 GeV shows similar value to charged hadrons'.
- κ_K for mid central and mid peripheral collisions is much larger than the background level (1.0 to 2.0) estimated from AMPT.

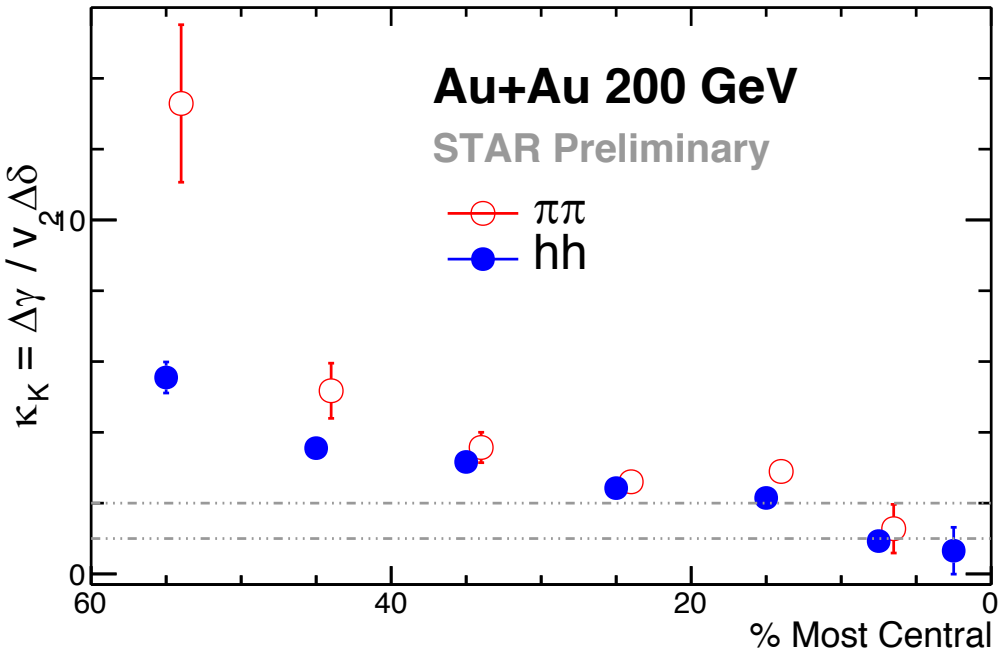




$\pi\pi$ correlation, Au+Au 39 GeV

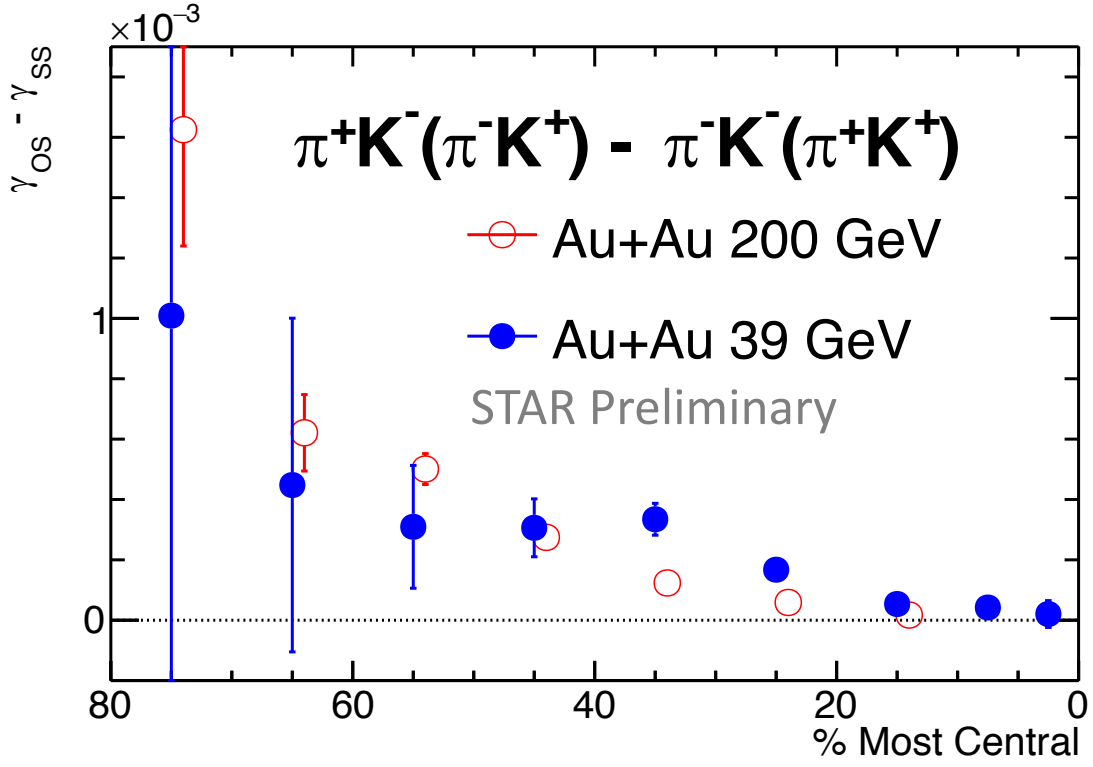
- Au+Au 39 GeV $\pi\pi$ pair $\Delta\gamma$ shows similar magnitude to charged hadron's at the same energy.
- κ_K is higher than 2 except in central collisions.

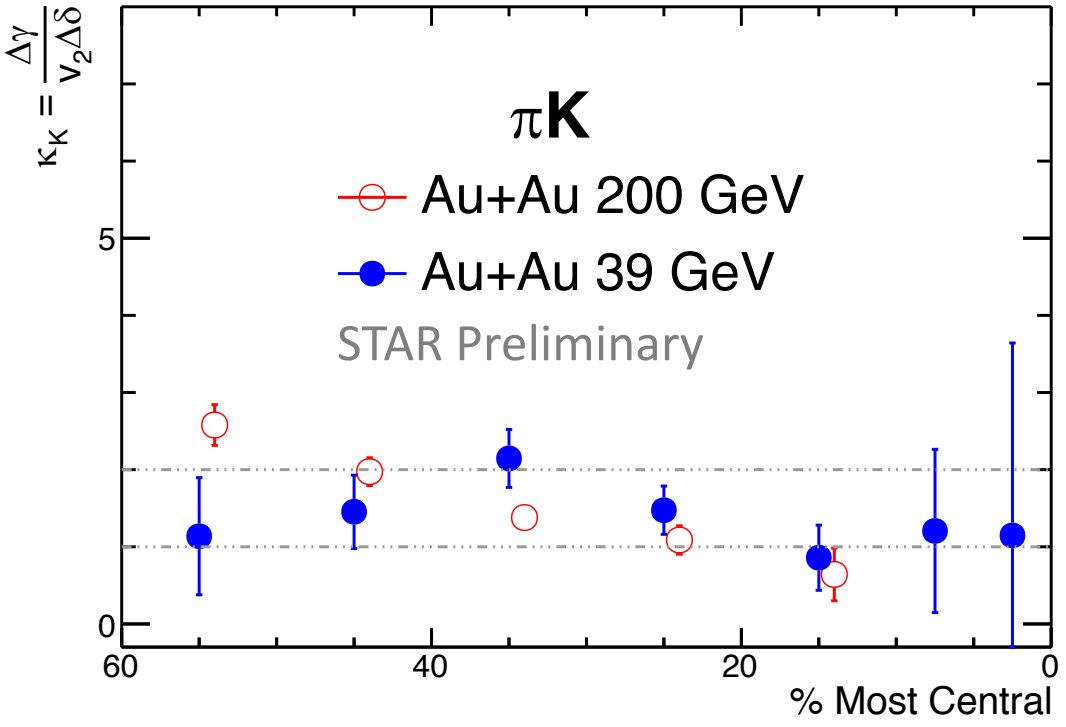




πK correlation

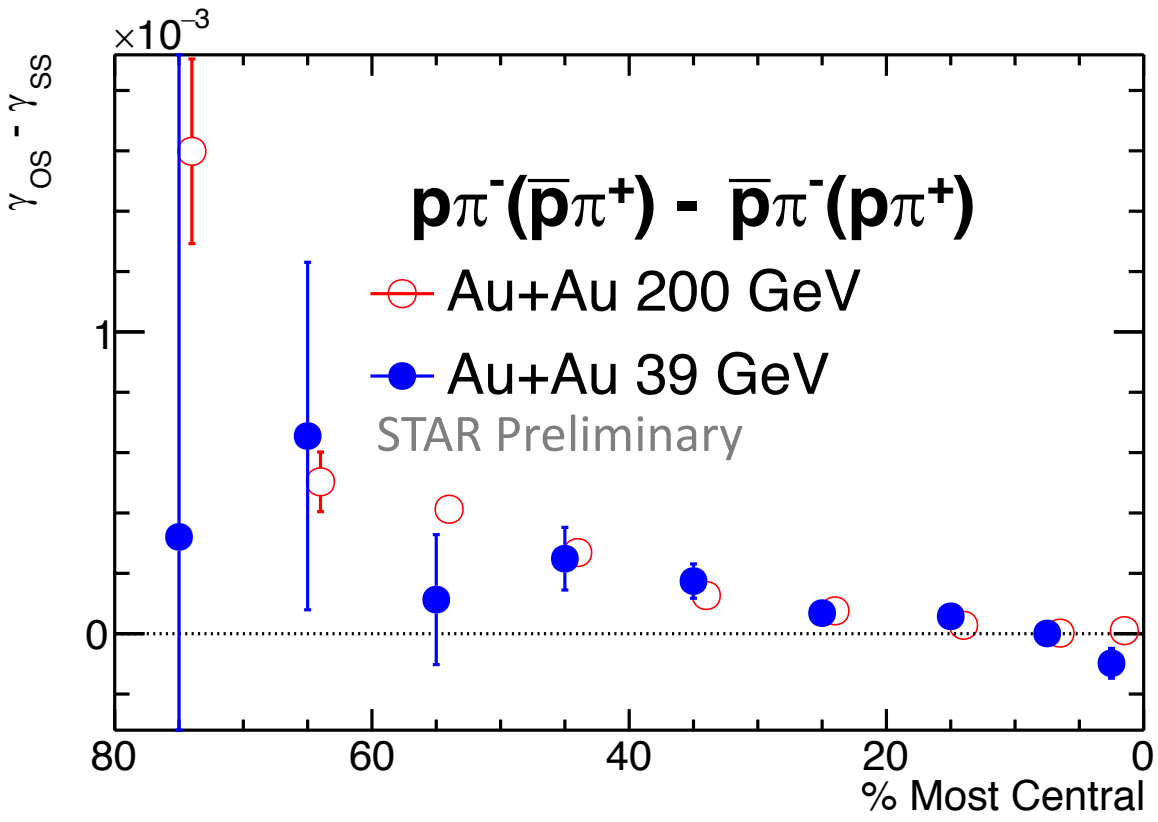
- $\Delta\gamma$ for πK pair is finite in Au+Au at both 200 GeV and 39 GeV.
- κ_K values are close to or below 2, making it hard to distinguish from background.

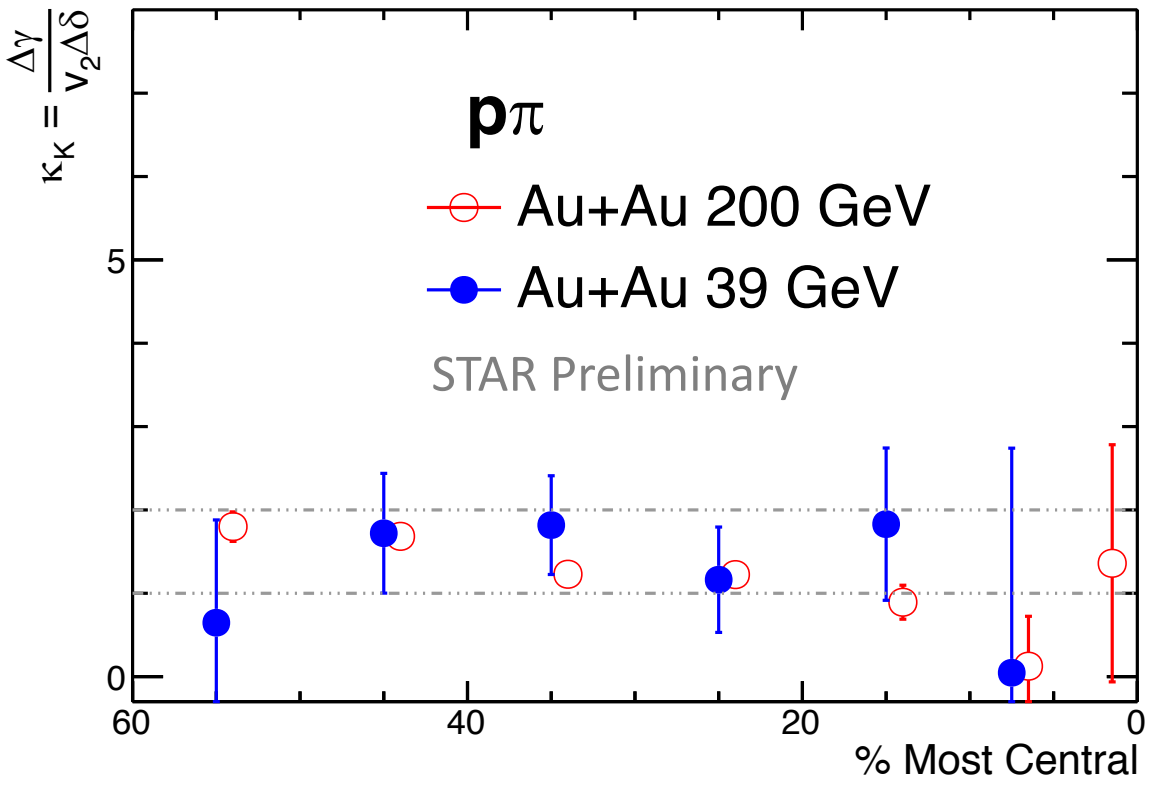




$p\pi$ correlation

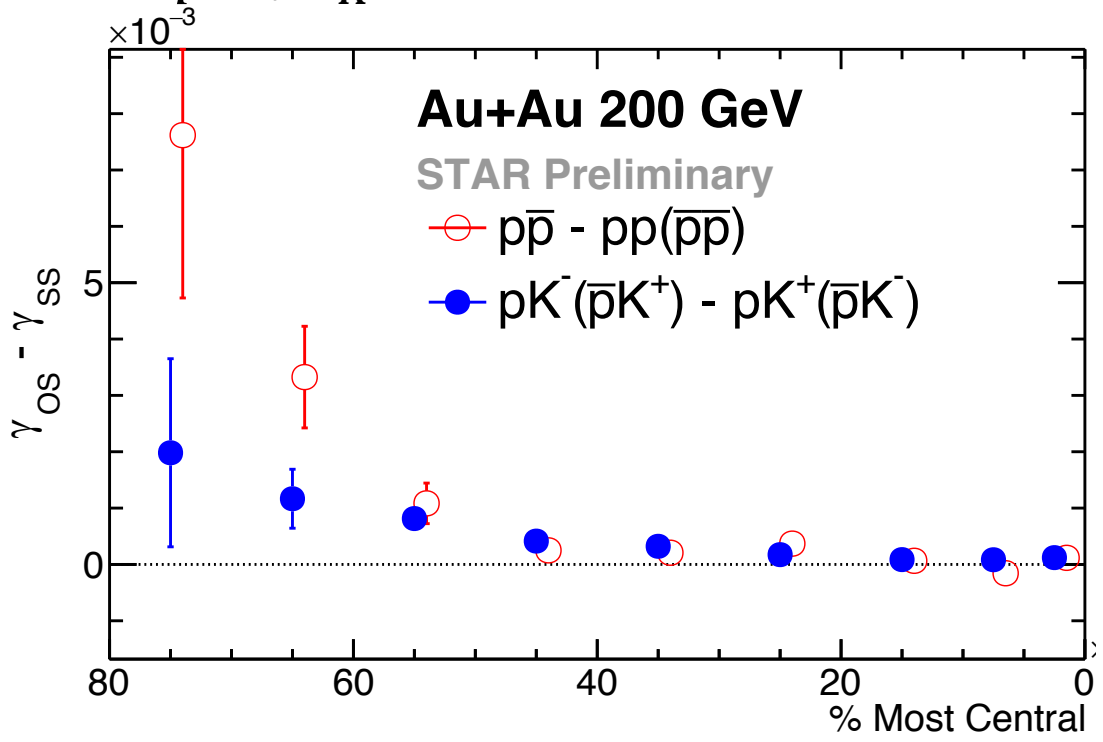
- $\Delta\gamma$ for $p\pi$ pair is finite in Au+Au at both 200 GeV and 39 GeV.
- κ_K values are close to or below 2, making it hard to distinguish from background.

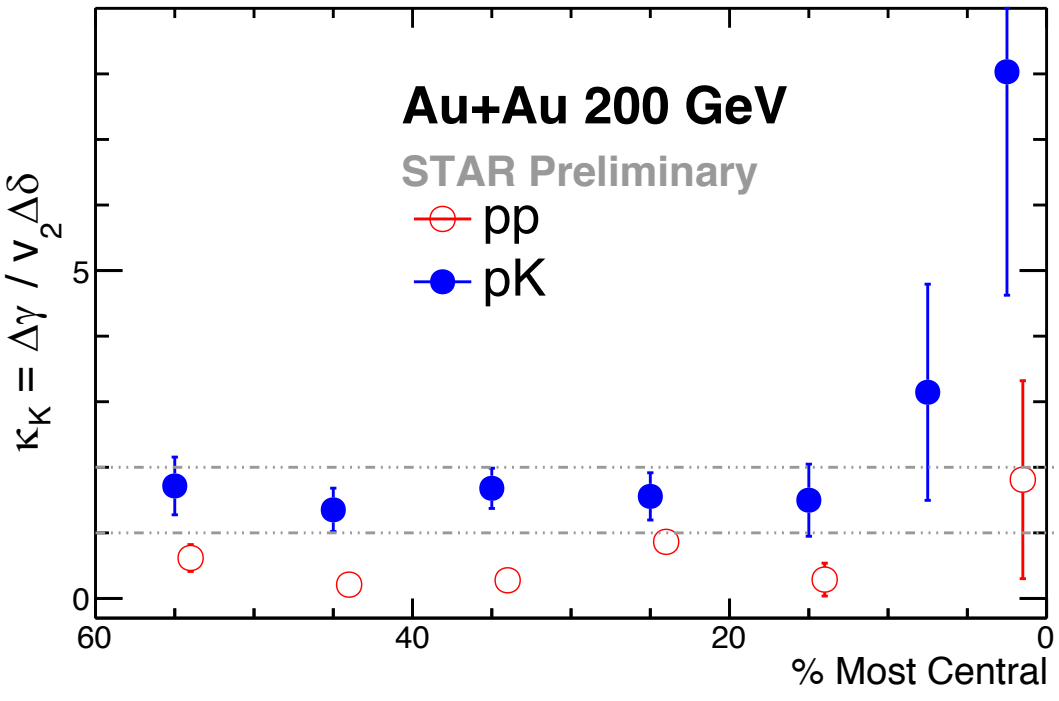




pp and pK correlation

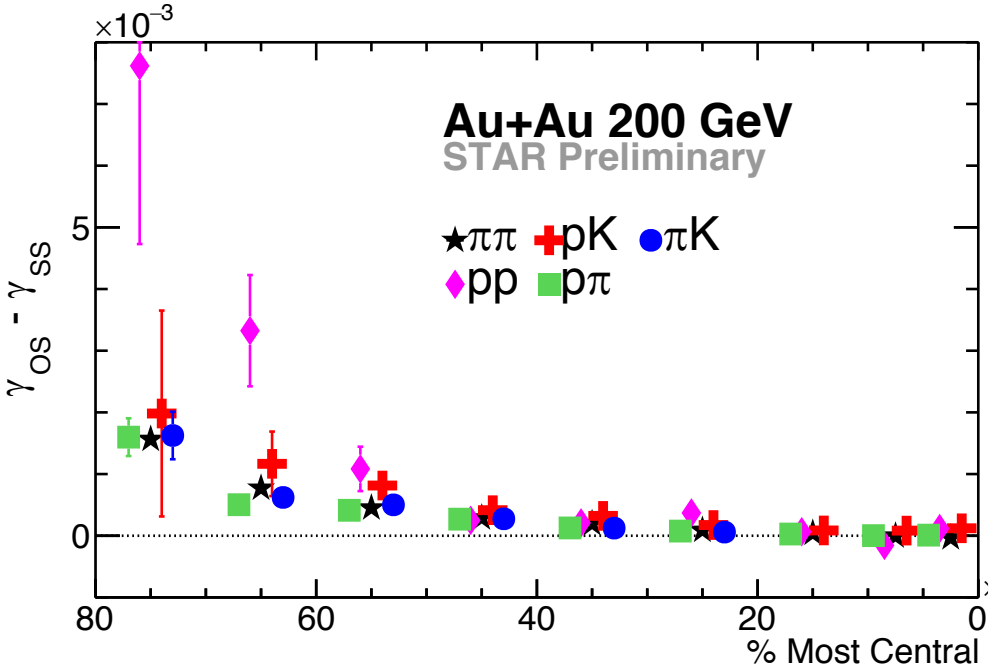
- pp pairs in Au+Au 200 GeV show large $\Delta\gamma$.
- $\Delta\gamma$ for pK has smaller values, but still finite in peripheral and mid central collissions.
- κ_K for pp is lower than 2 or even 1 in some centrality bins. This behavior might be due to annihilation effect.
- For pK , κ_K fluctuates between1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

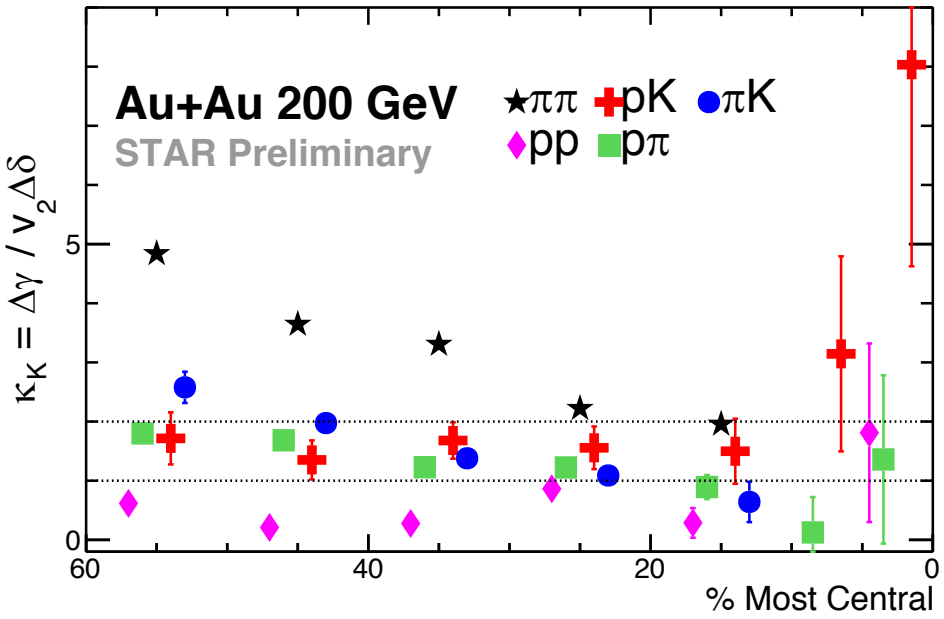




PID Summary

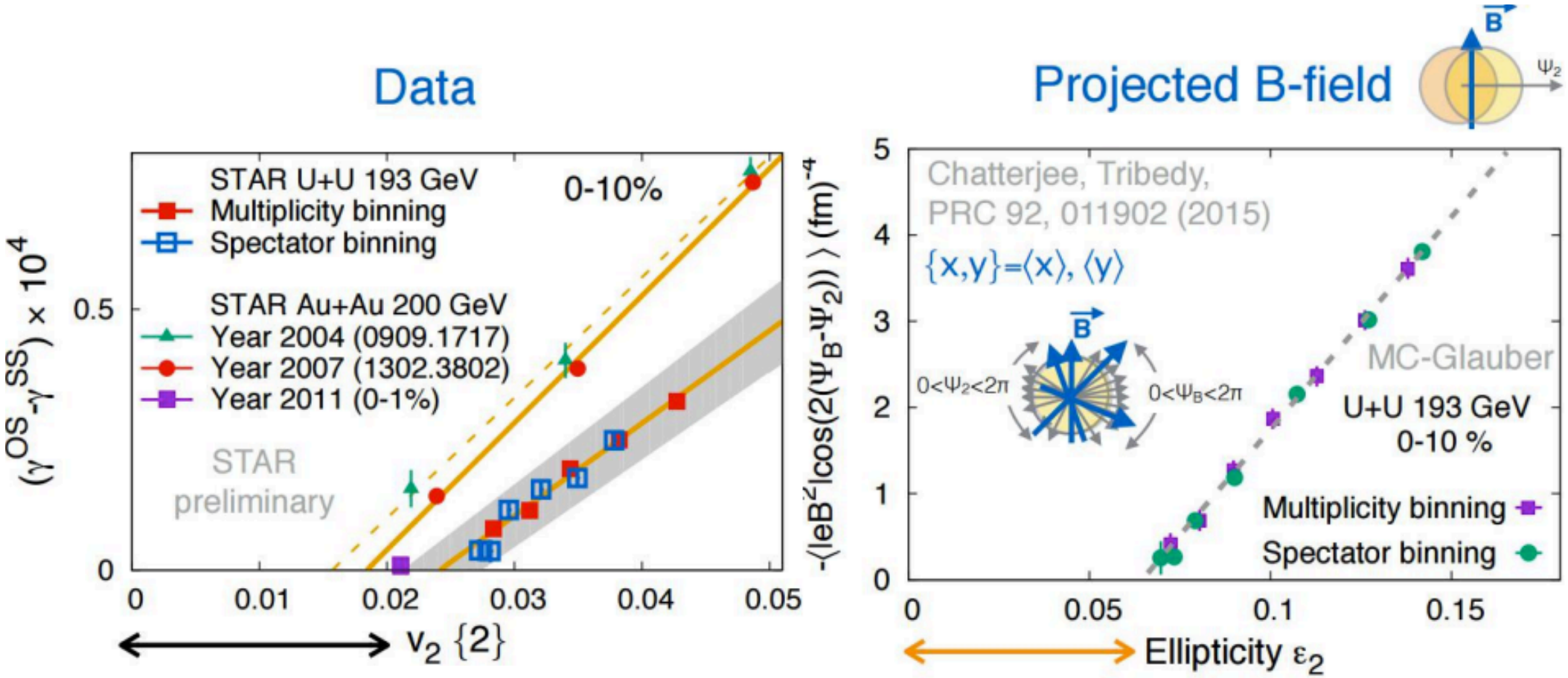
- $\Delta\gamma$ for all PID pairs is finite in peripheral and mid central Au+Au collisions at 200 GeV
- κ_K for $\pi\pi$ is higher than estimated background in mid peripheral and mid central collisions. Other pairs are close to or within background range of 1.0 to 2.0
- pp shows large $\Delta\gamma$,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





U+U?

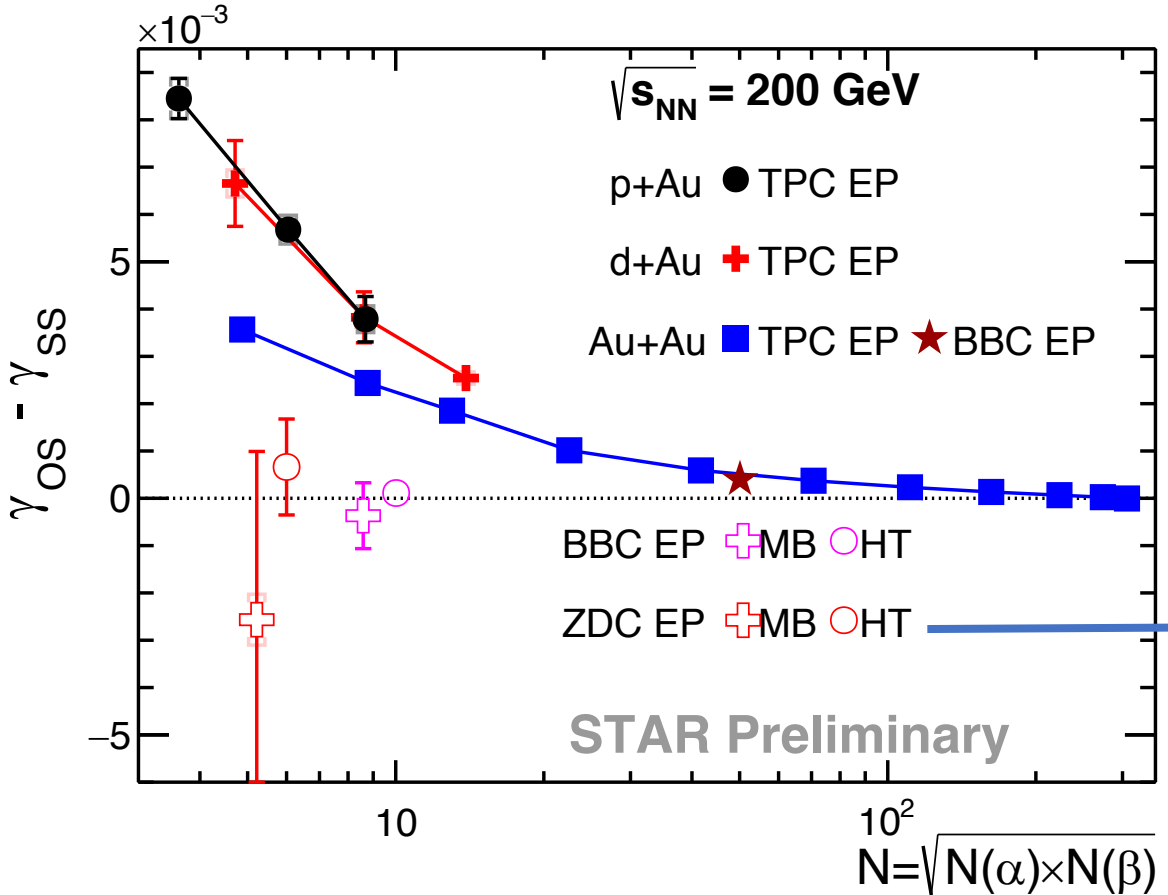
- Why we need U+U collisions?
  - To disentangle the signal and the background by varying the background (trying to minimize flow background by selecting the most central collisions in UU)



Projected B-field vs ϵ_2 can provide a natural explanation to data.

γ correlation in p+Au and d+Au

- 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
- $\Delta\gamma$ diappears in p+Au when η gap is introduced between EP and particles of interest: $\Delta\gamma$ in TPC EP results mostlv from short range correlation.

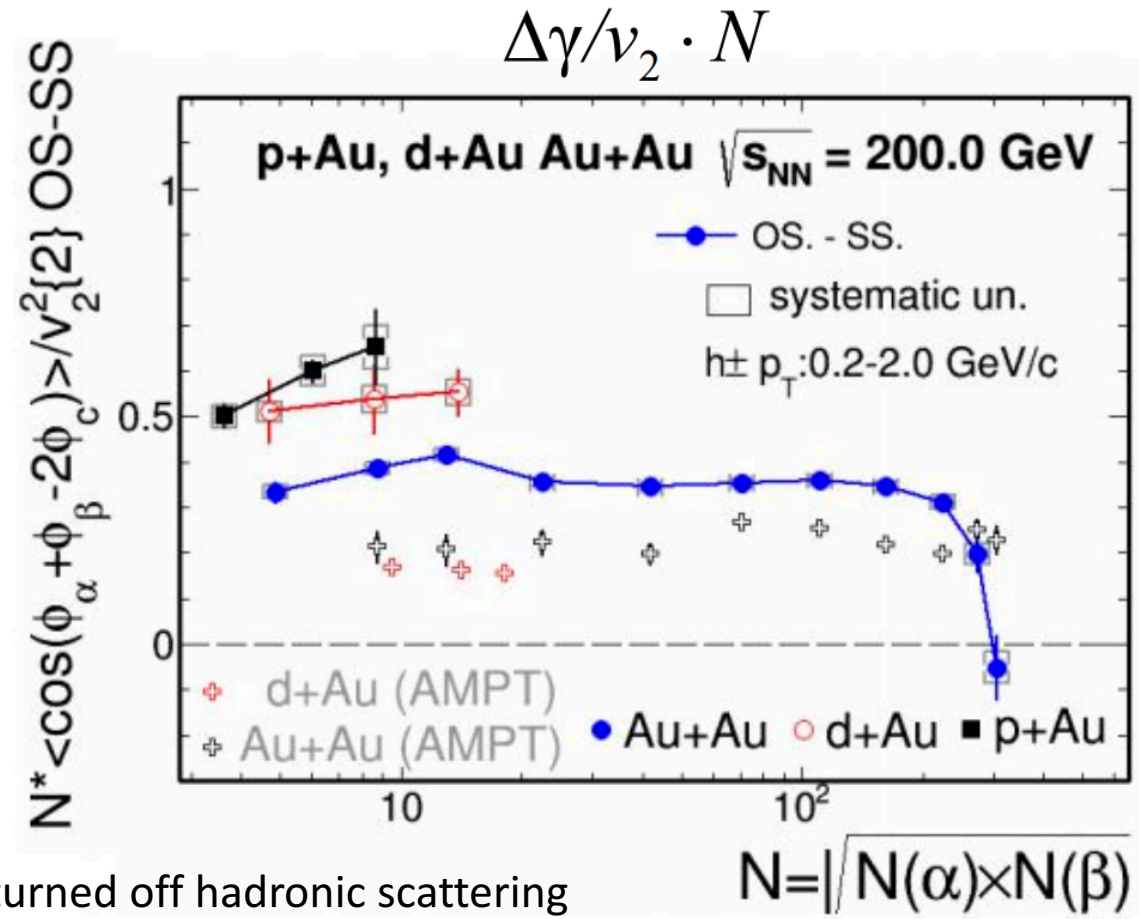


Time Projection Chamber: $|\eta| < 1$
Beam-Beam Counter: $3.8 < |\eta| < 5.2$
Zero Degree Calorimeter: $6 < |\eta|$

HT (High Tower): trigger on electromagnetic energy

γ correlation in p+Au and d+Au

- $\Delta\gamma \cdot N/v_2$ 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.



This version of AMPT turned off hadronic scattering

Isobars

- What is Isobar?
  - 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

	${}^{96}_{44}Ru + {}^{96}_{44}Ru$ v.s. ${}^{96}_{40}Zr + {}^{96}_{40}Zr$
Flow	~
CME	>
CMW	>
CVE	~

Wood-Saxon in MC Glauber

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

- Set 1: B(E2)↑ measured in e-A scattering experiment
- Set 2: comprehensive model deduction
- Uncertainty in β_2 presents an opportunity or a by-product

		R0	a (d)	β2
Zr96	Set 1	5.07	0.48	0.06
	Set 2	5.05	0.45	0.18
Ru96	Set 1	5.14	0.46	0.13
	Set 2	5.13	0.45	~0.03*

case 1

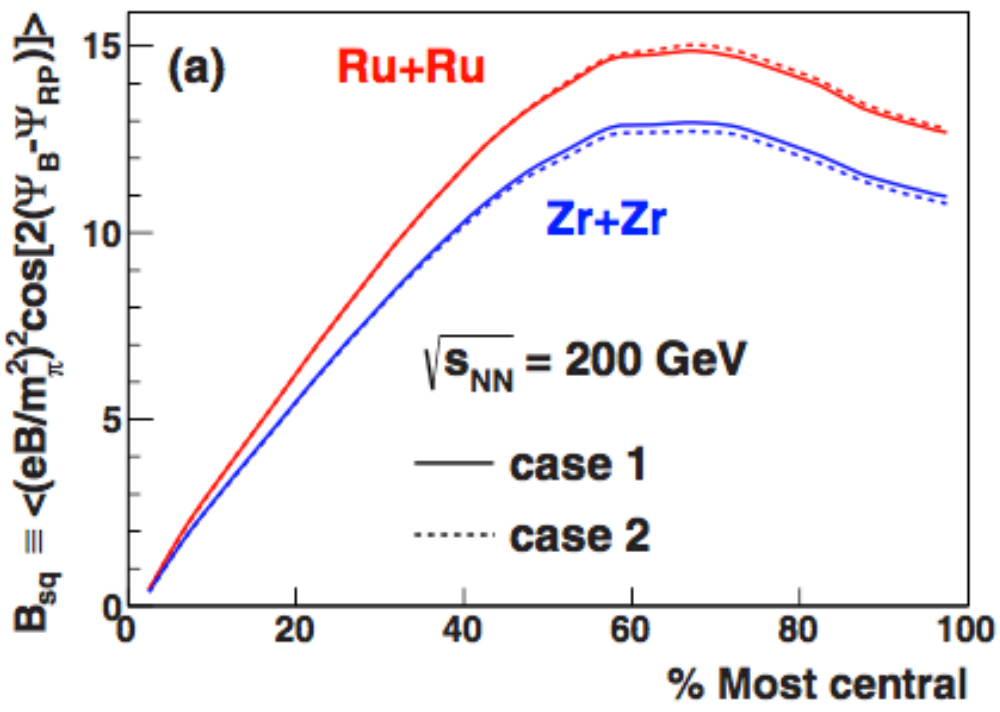
<

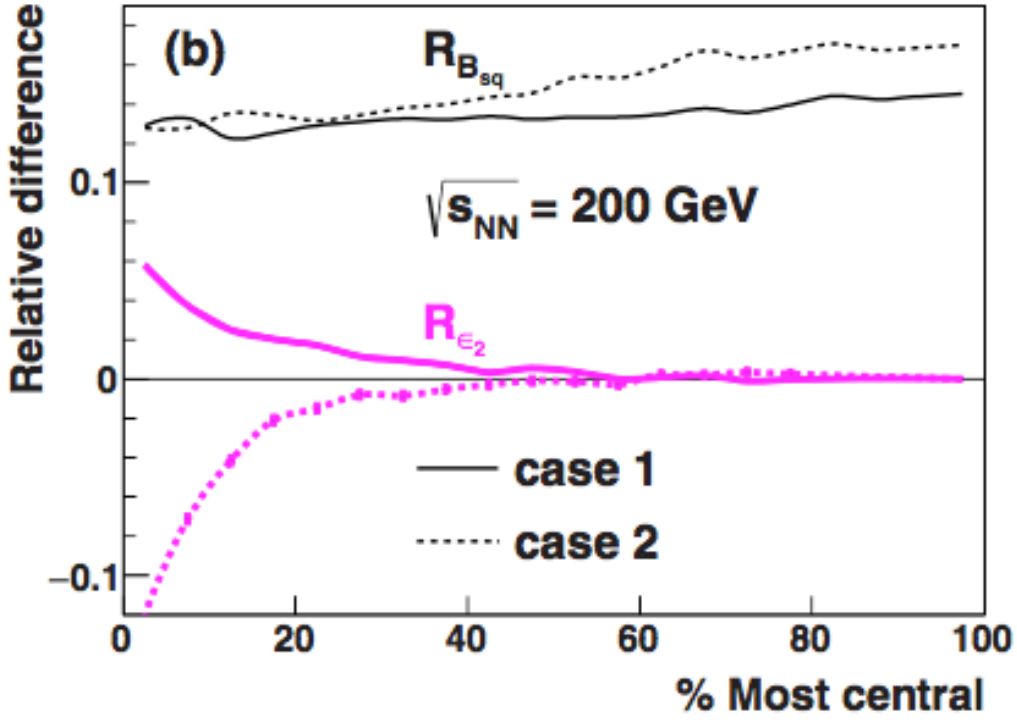
>

case 2

B Field

- B calculated at t=0, at one point (center of mass of participants)
- B field slightly affected by β_2
- Relative difference in B^2 is 15-18% for peripheral events
- Reduces to 13% for central collisions

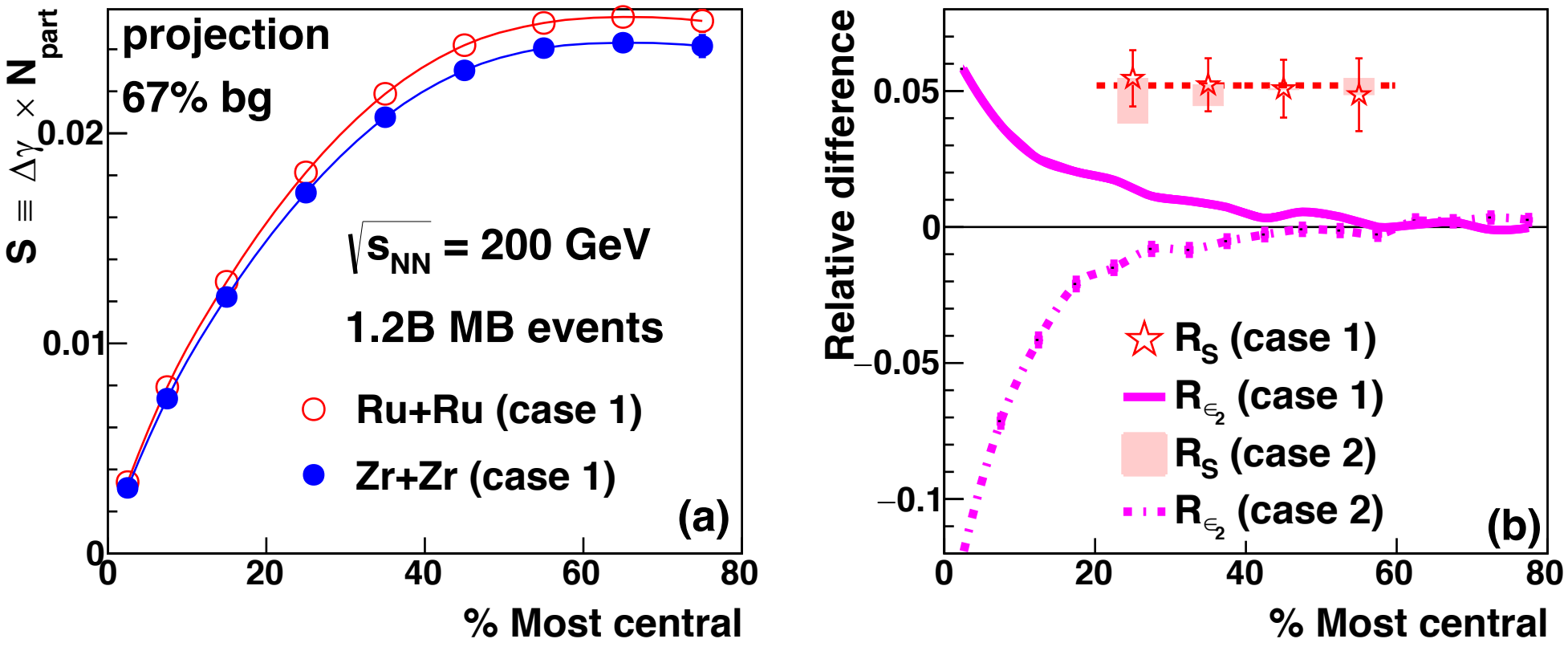




W. -T. Deng, X. -G. Huang, G.-L. Ma and G. Wang, Phys. Rev. C 94, 041901 (2016).

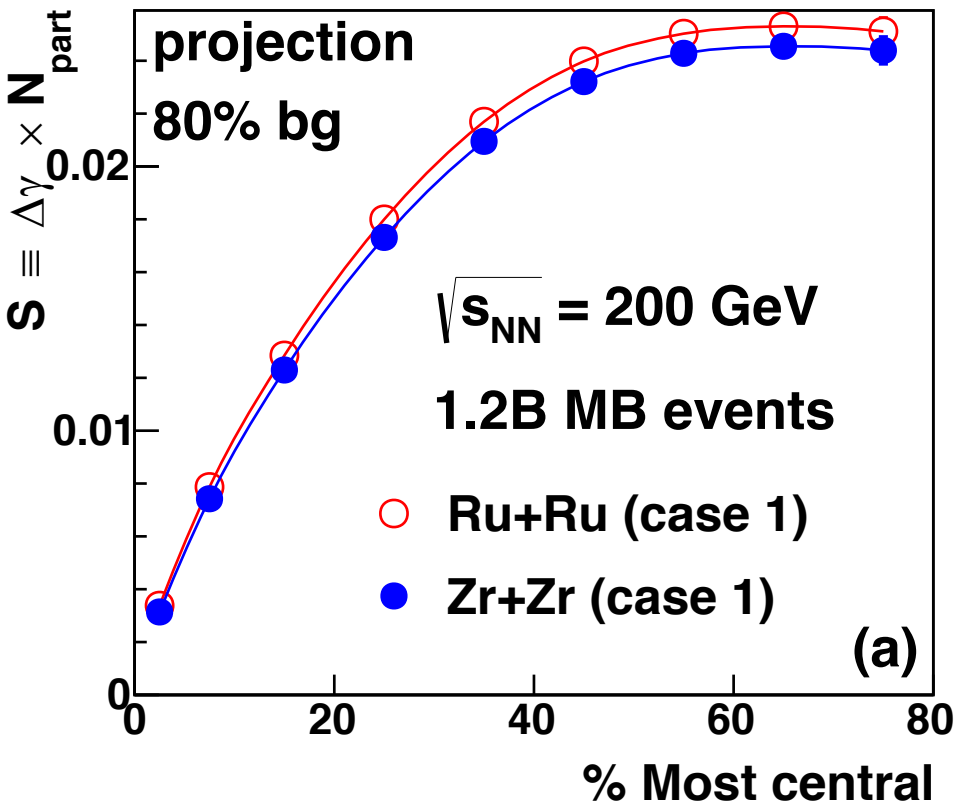
Charge Separation: γ (2/3 background)

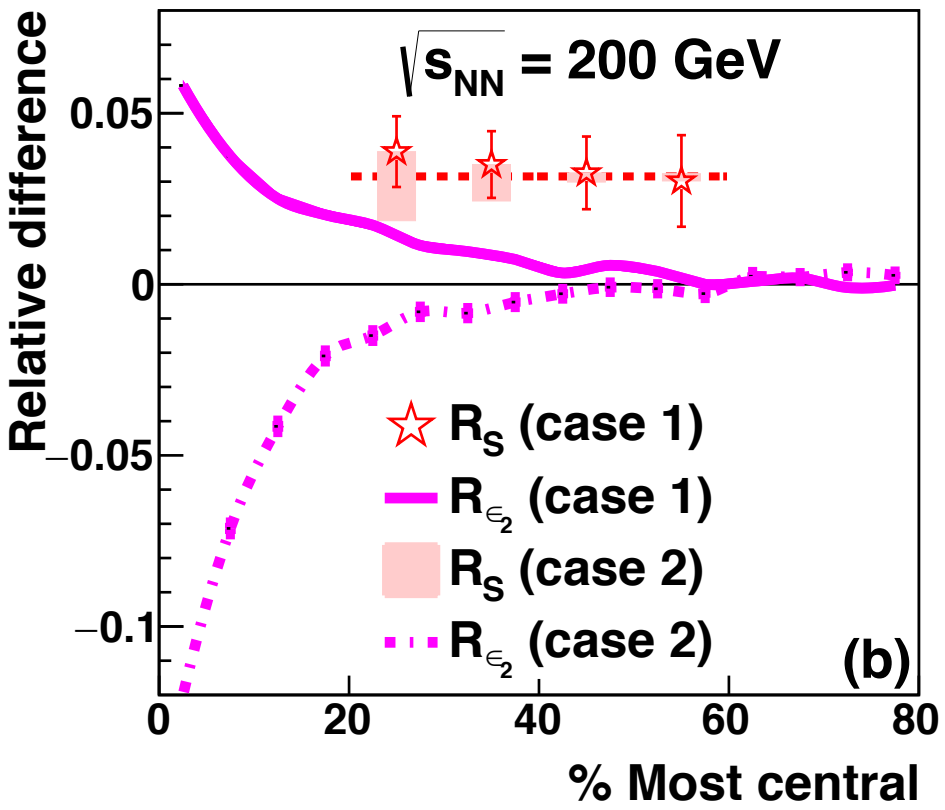
- Projection with 1.2B events from each collision type
- If it's v_2-driven, rel. diff. follow eccentrity (~0 for 20-60%)
- If it's 1/3 CME-driven, the difference in $\Delta\gamma$ is 8σ above ϵ_2



Charge Separation: γ (80% background)

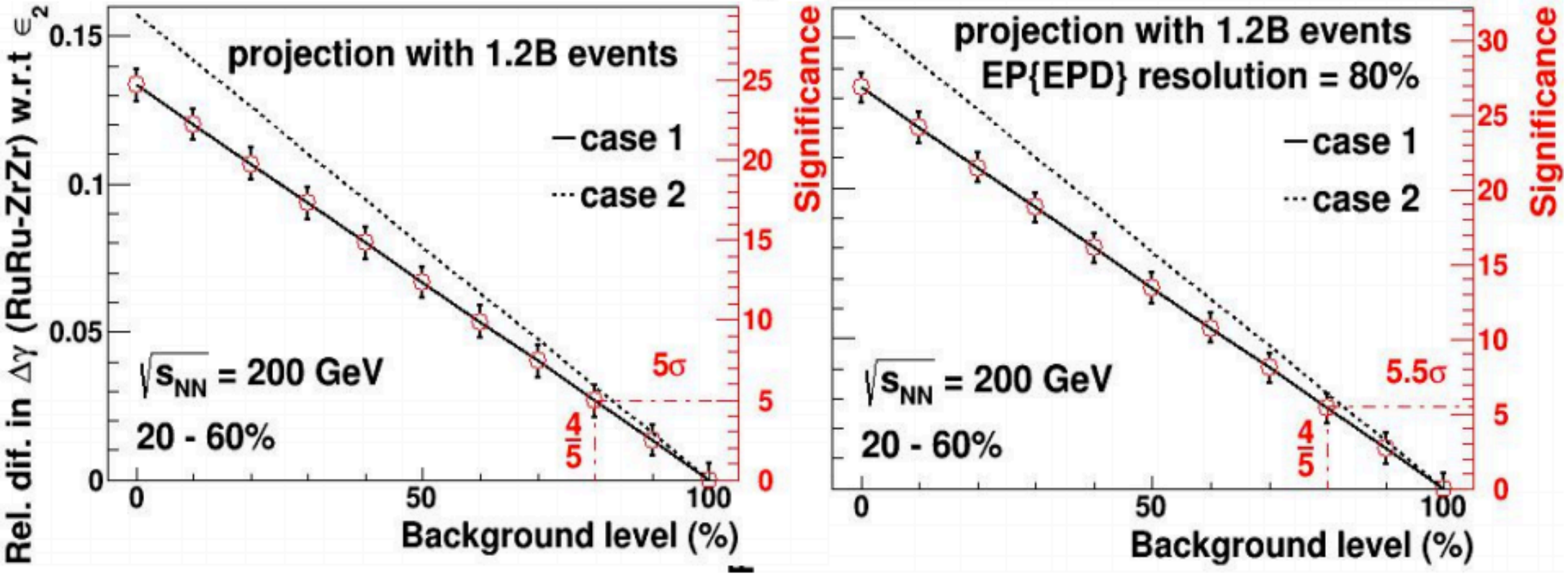
- Projection with 1.2B events from each collision type
- If it's v_2-driven, rel. diff. follow eccentrity (~0 for 20-60%)
- If it's 20% CME-driven, the difference in $\Delta\gamma$ is 5σ above ϵ_2





Significance vs. Background

- Projection with 1.2 B events from each collision type
- Significance of the difference in $\Delta\gamma$ depends on bg level
- Case2 is slightly better than case 1



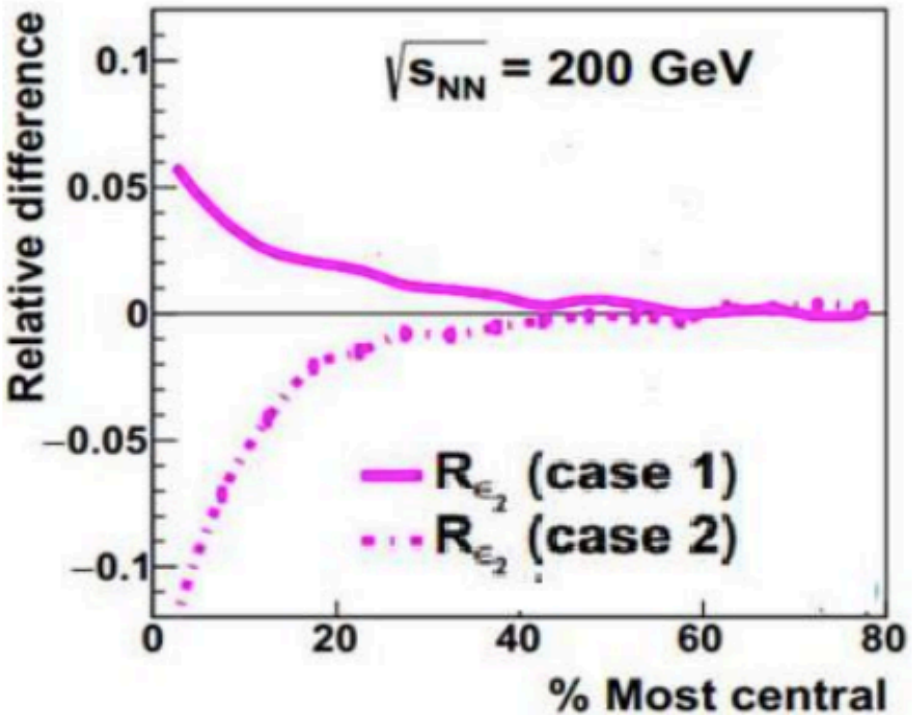
By-product I: Zr and Ru, which is more deformed?

	R_0 [fm]	a(d) [fm]	β_2
^{96}Zr	5.06	0.46	0.06
^{96}Ru	5.13	0.46	0.13

case 1

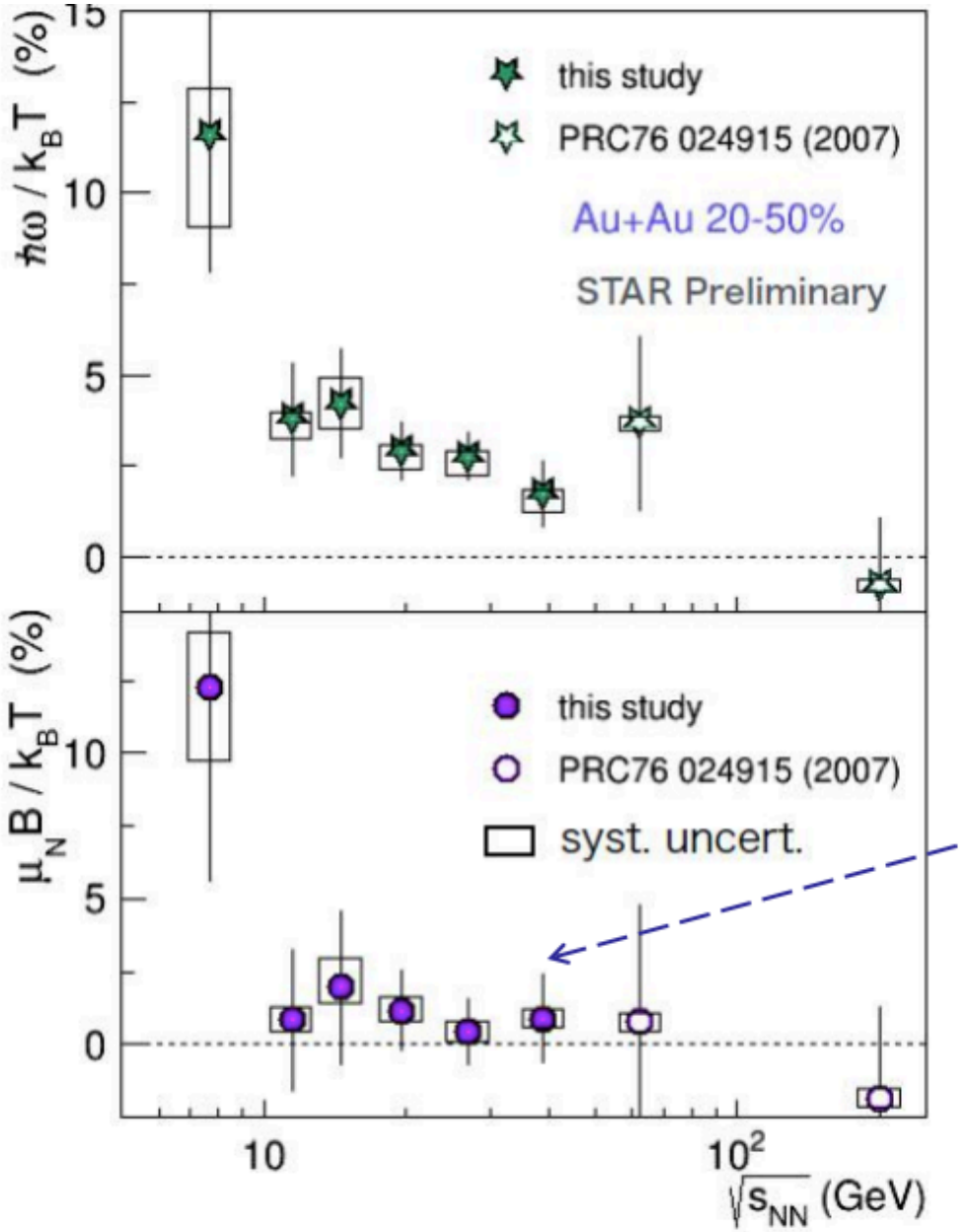
	R_0 [fm]	a(d) [fm]	β_2
^{96}Zr	5.06	0.46	0.18
^{96}Ru	5.13	0.46	0.03

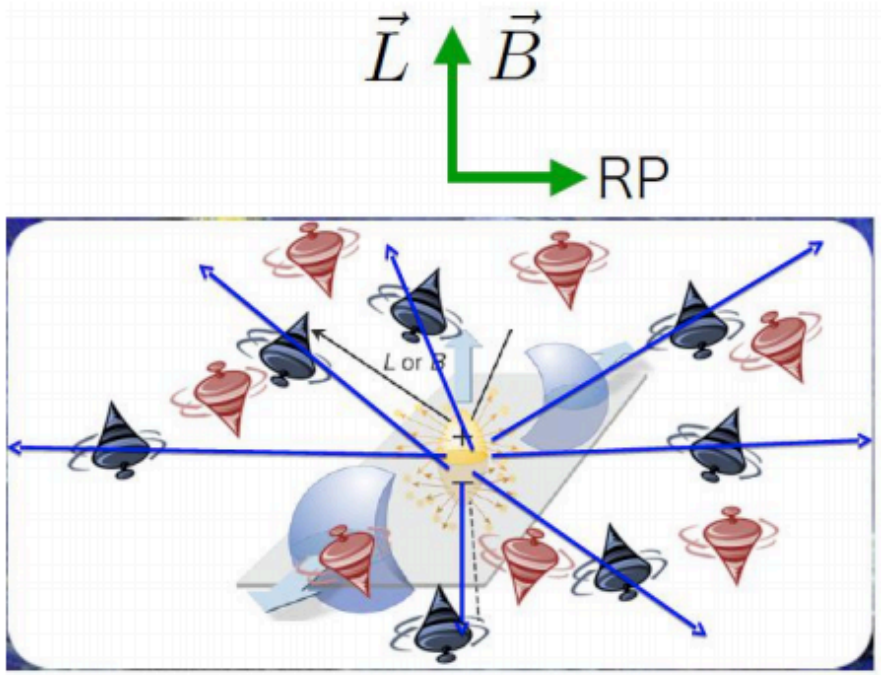
case 2



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

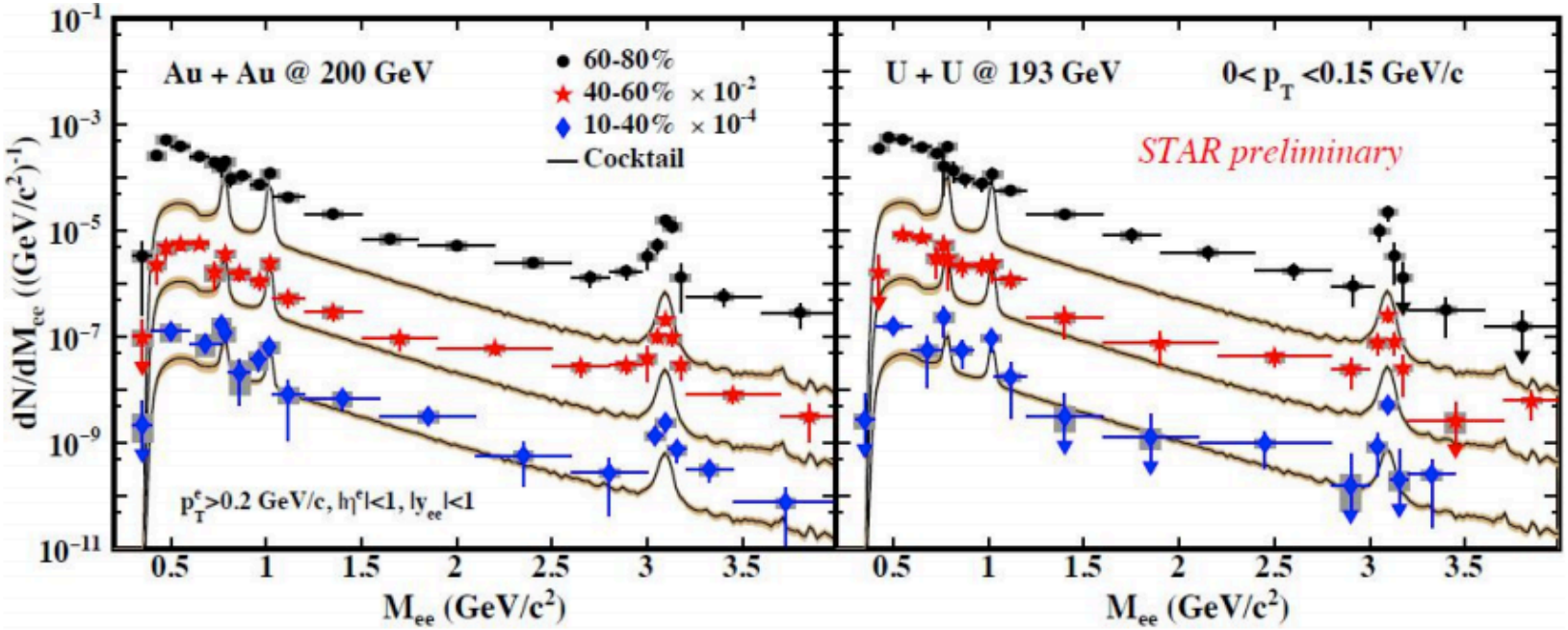
By-product II: Λ global polarization



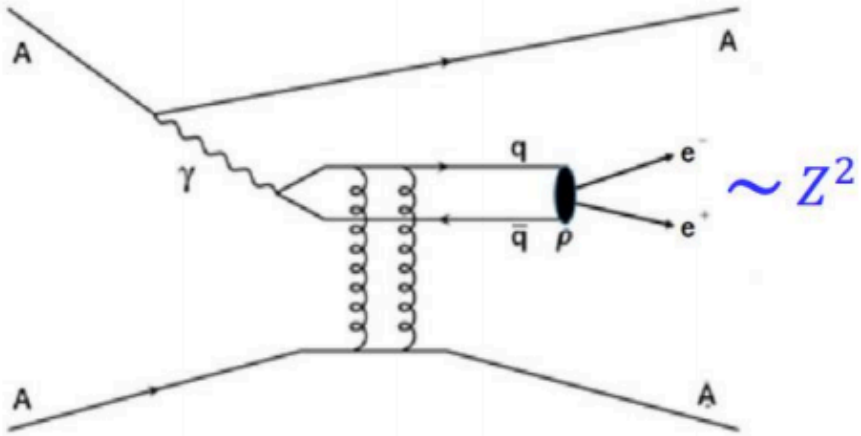


Expect 10% difference between Zr+Zr and Ru+Ru, if it is due to magnetic field. Need beam energy scan.

By-product III: di-lepton at very low p_T

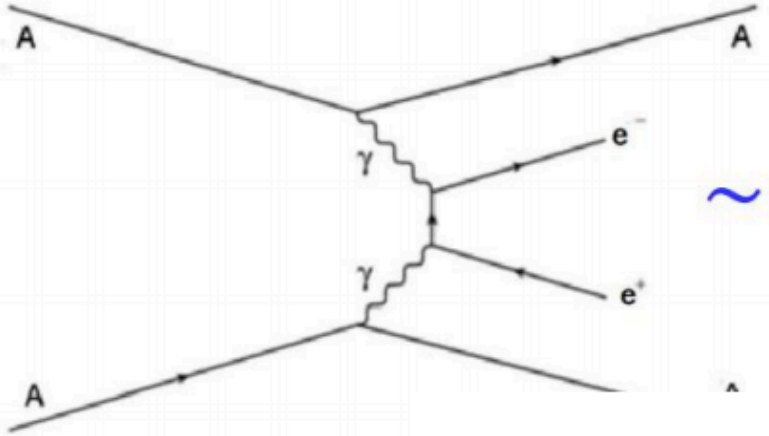


Scenario 1: photonuclear interaction



$\sim Z^2$

Scenario 2: two-photon process



$\sim Z^4$

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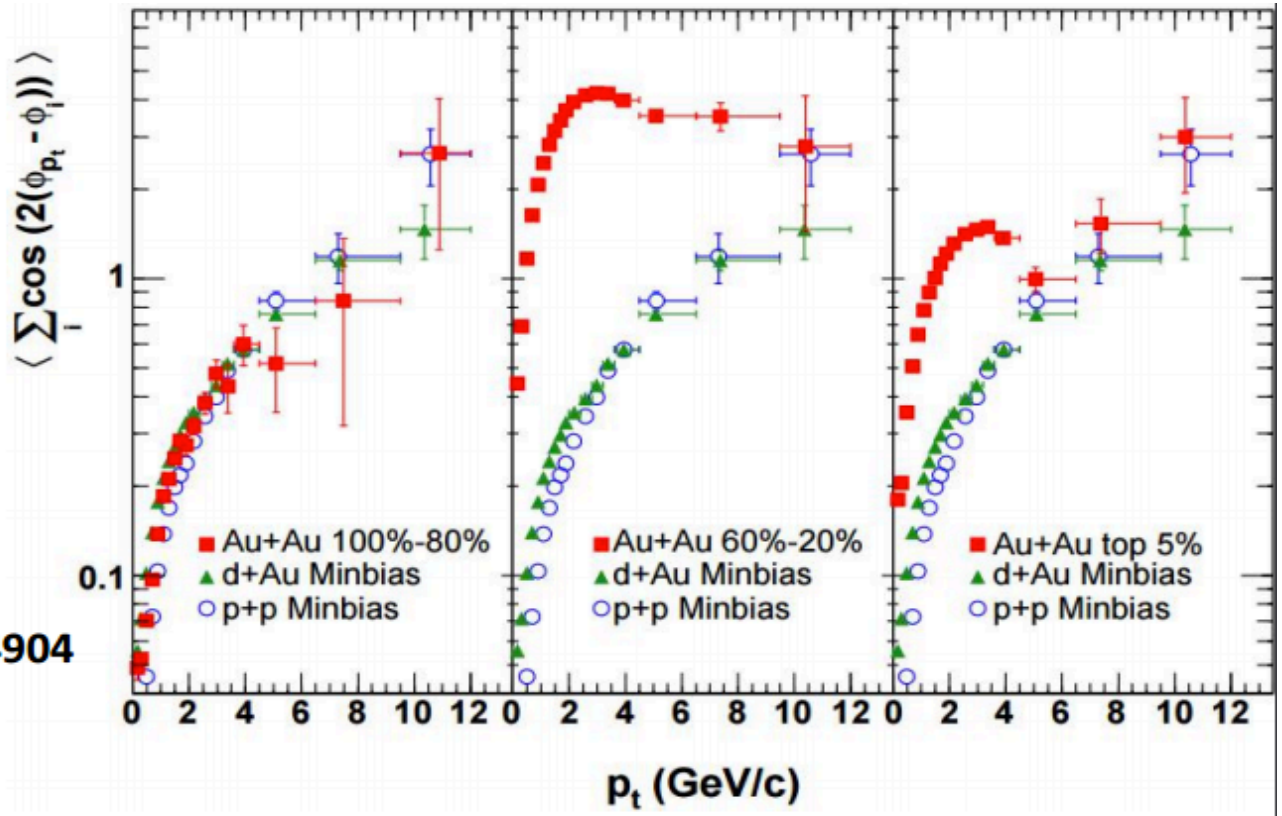
Summary

- 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.
- Search for Chiral Magnetic Effect in p+Au/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.
- Isobaric Collisions:
  - With 1.2B MB events, significance of the difference in $\Delta\gamma$ between Ru+Ru and Zr+Zr can reach at least 5σ if background level is as high as 80%.

Back up slides

Collectivity v.s. non-flow

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



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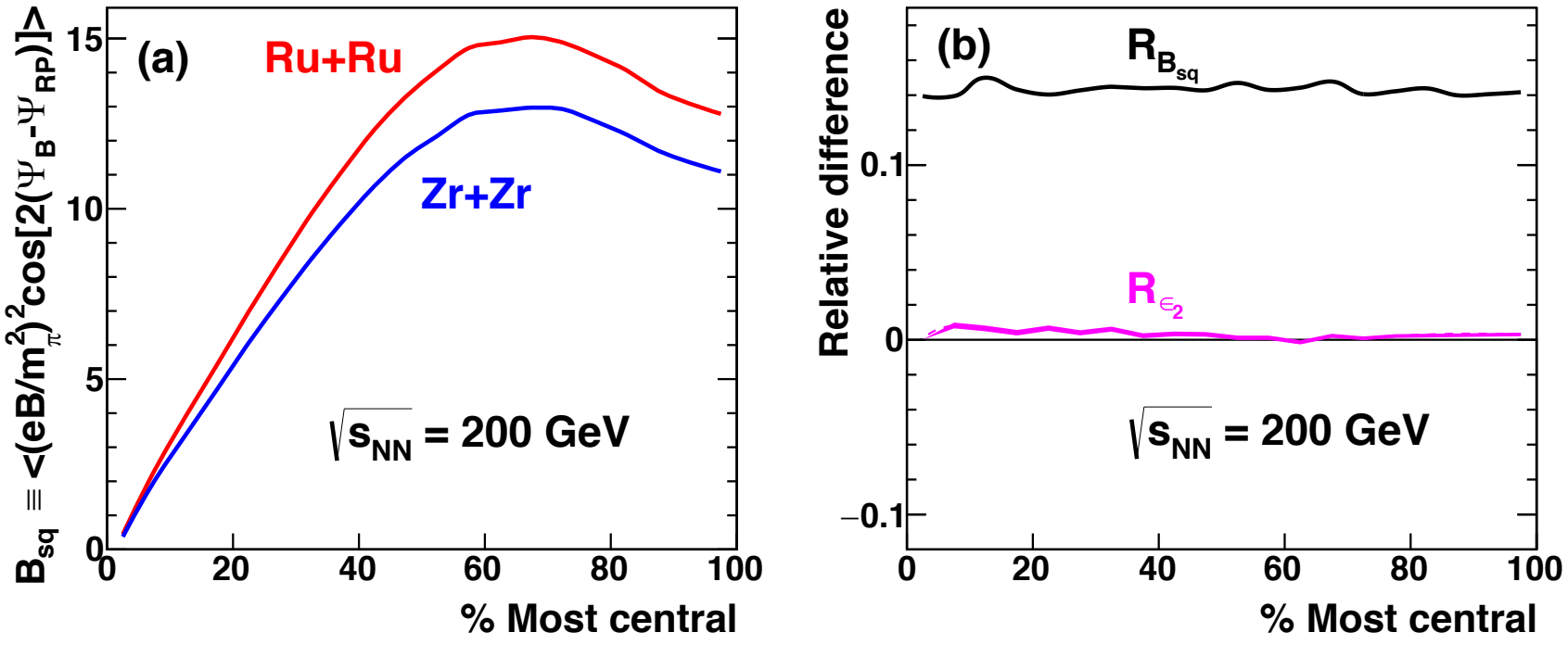
- Note 1: collectivity does not imply a specific physical interpretation (i.e. collectivity ≠ hydro)
- Note 2: correlations between particles which do not have a "collective" origin (jets, resonance decays, momentum conservation) are commonly called "non-flow"...

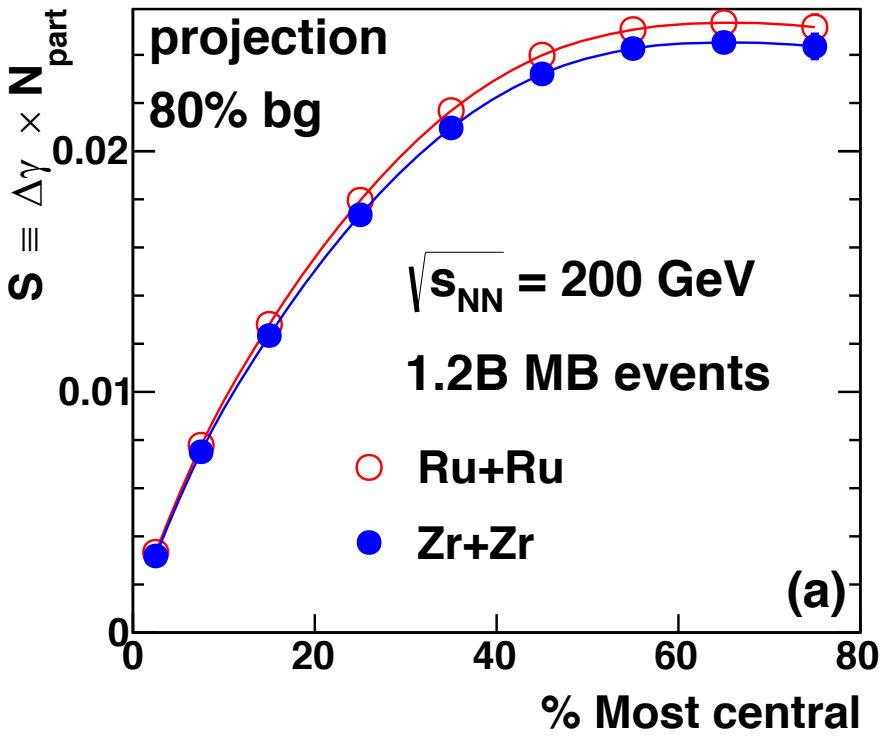
Isobaric Collision Projection with the Most Likely Case

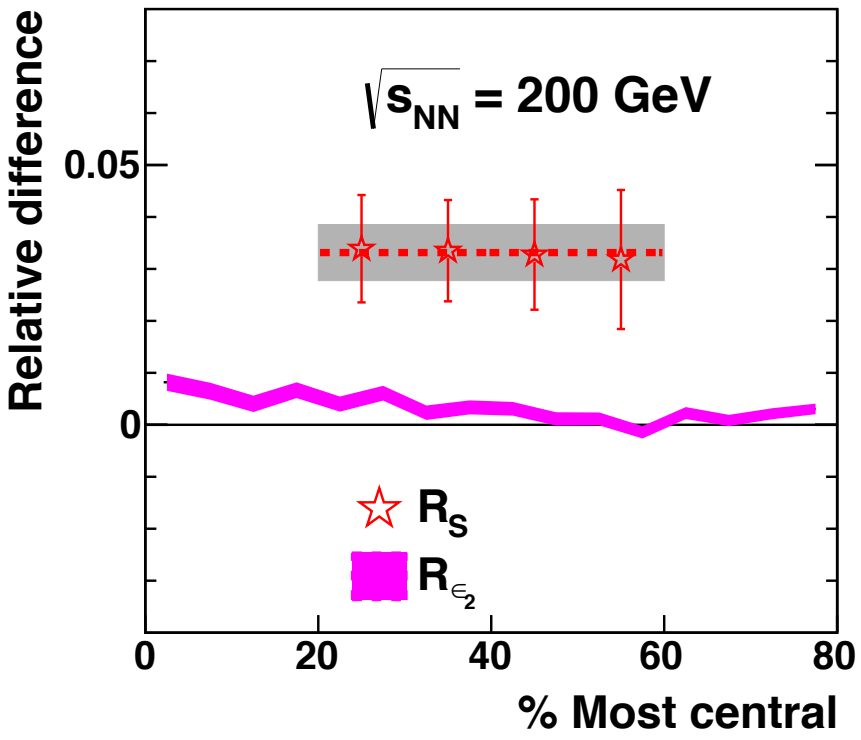
- Most likely values of β_2 for Ru and Zr:
  - https://arxiv.org/pdf/1606.09056.pdf (Zr)
  - PRC92,064317(2015) (Ru)
- Relative difference in B^2 is ~14% across centrality bins
- Relative difference in eccentricity is close to zero

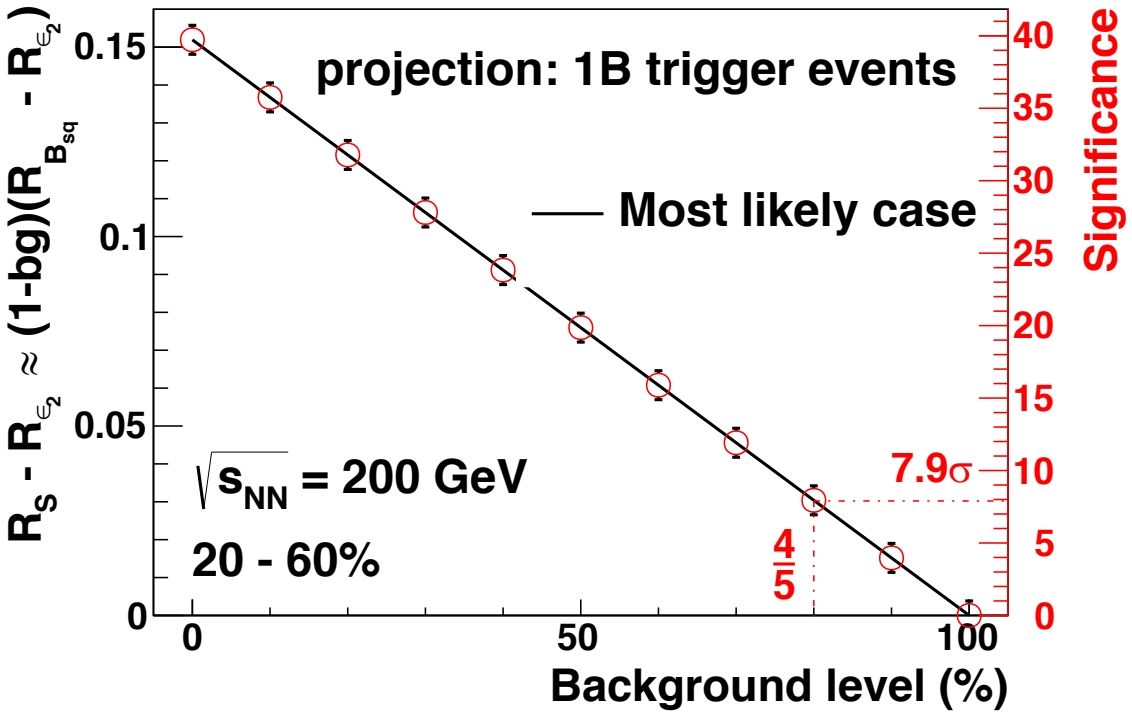
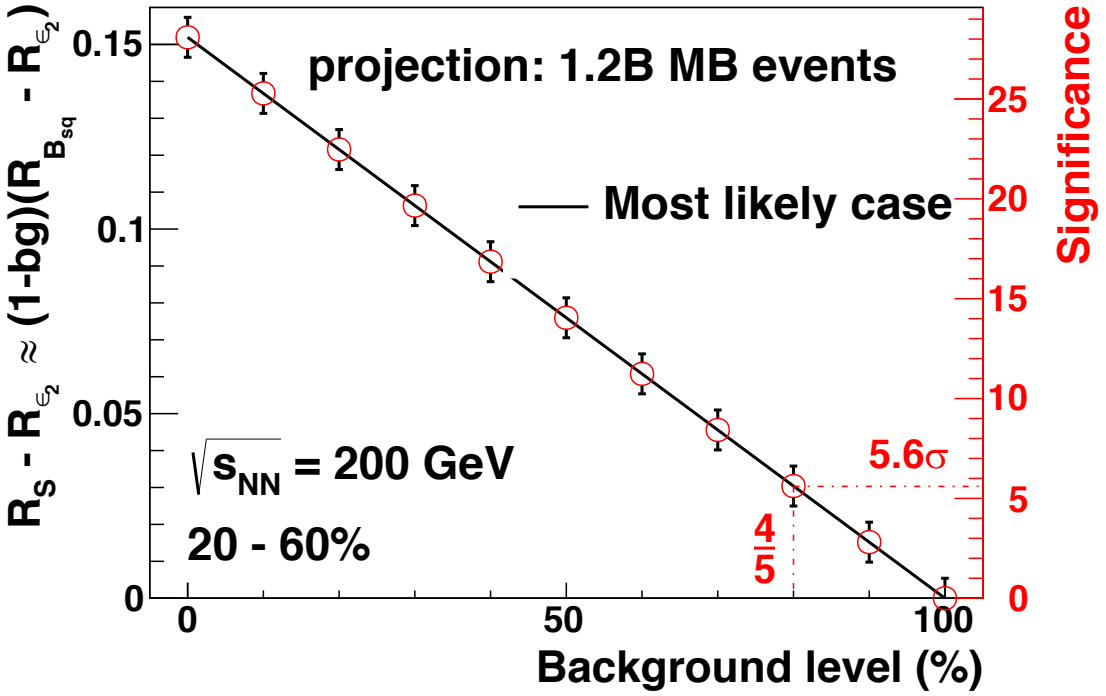


Isobaric Collision Projection with the Most Likely Case

- If it's 20% CME-driven, the difference in $\Delta\gamma$ is >> 5σ above ϵ_2





Isobaric Collision Projection with the Most Likely Case

- 1B trigger events / 1.2B MB events can provide 7.9σ/ 5.6σ significance, given the background level is 80%