Search for Chiral Effects with PID

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Central China Normal University

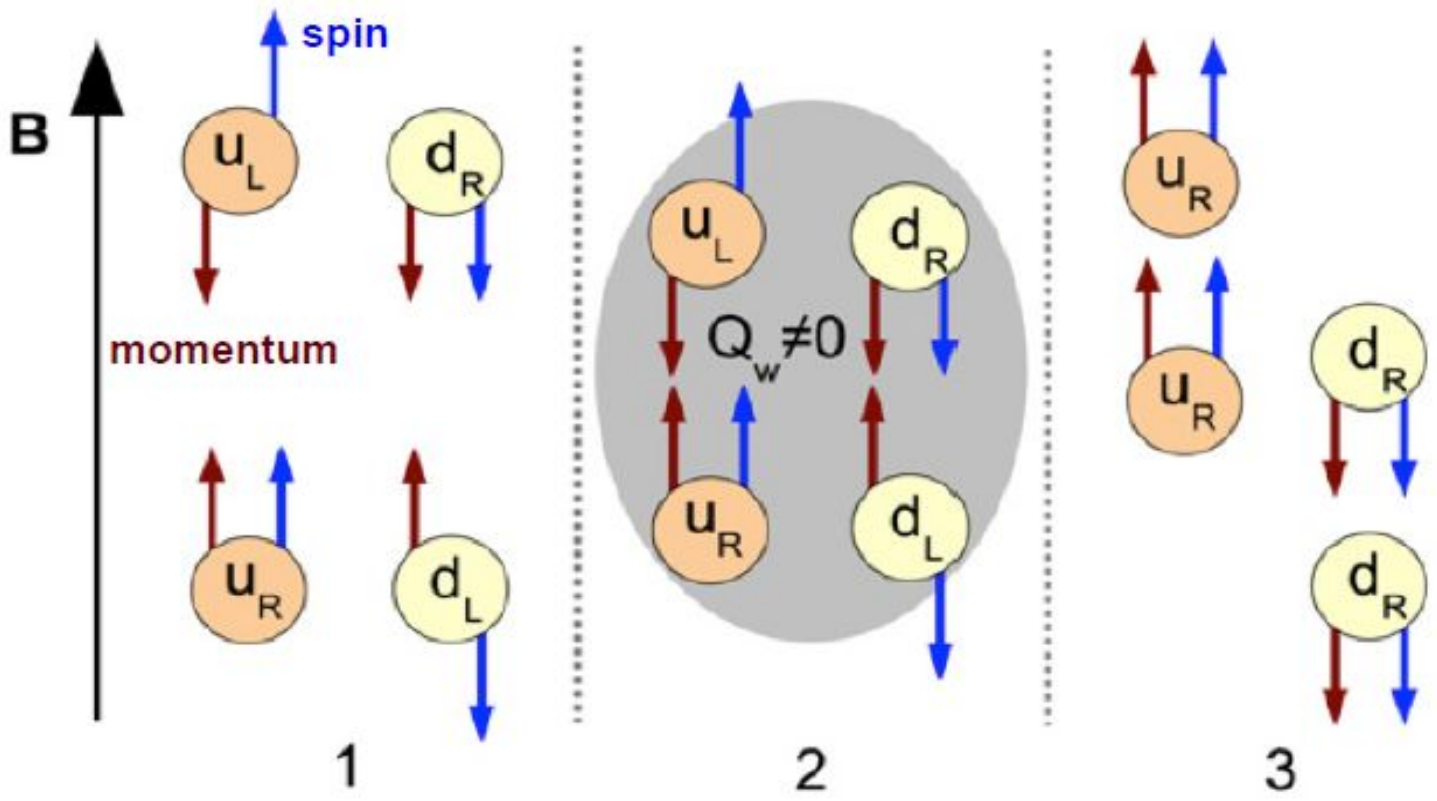
Outline

- Motivation
- Experimental Results
  - Chiral Magnetic Effect (CME)
  - Chiral Magnetic Wave (CMW)
  - Chiral Vortical Effect (CVE)
- Outlook

Phys. Rev. Lett. 103(2009)251601
Phys. Rev. C 81(2010)54908
Phys. Rev. C 88(2013)64911
Phys. Rev. C 89(2014)44908
Phys. Rev. Lett 113(2014)052302
Phys. Rev. Lett 110(2013)012301

Phys. Rev. Lett 114(2015)252302
PRL Editors' Suggestion

Chiral Magnetic Effect



Chiral Magnetic Effect **(CME):** finite chiral charge density induces an electric current along external magnetic field.

$$j_V = \frac{N_c e}{2\pi^2}\mu_A B \quad \rightarrow \quad \text{electric charge separation along } B \text{ field}$$

D. E. Kharzeev, L. D. McLerran, and H. J. Warringa, Nuclear Physics A 803, 227 (2008)

Chiral Vortical Effect

Chiral Magnetic Effect vs **Chiral Vortical Effect**

Chirality Imbalance (μ_A)

Magnetic Field ($\omega\ \mu_e$) → Electric Charge (j_e)

Fluid Vorticity ($\omega\ \mu_B$) → Baryon Number (j_B)

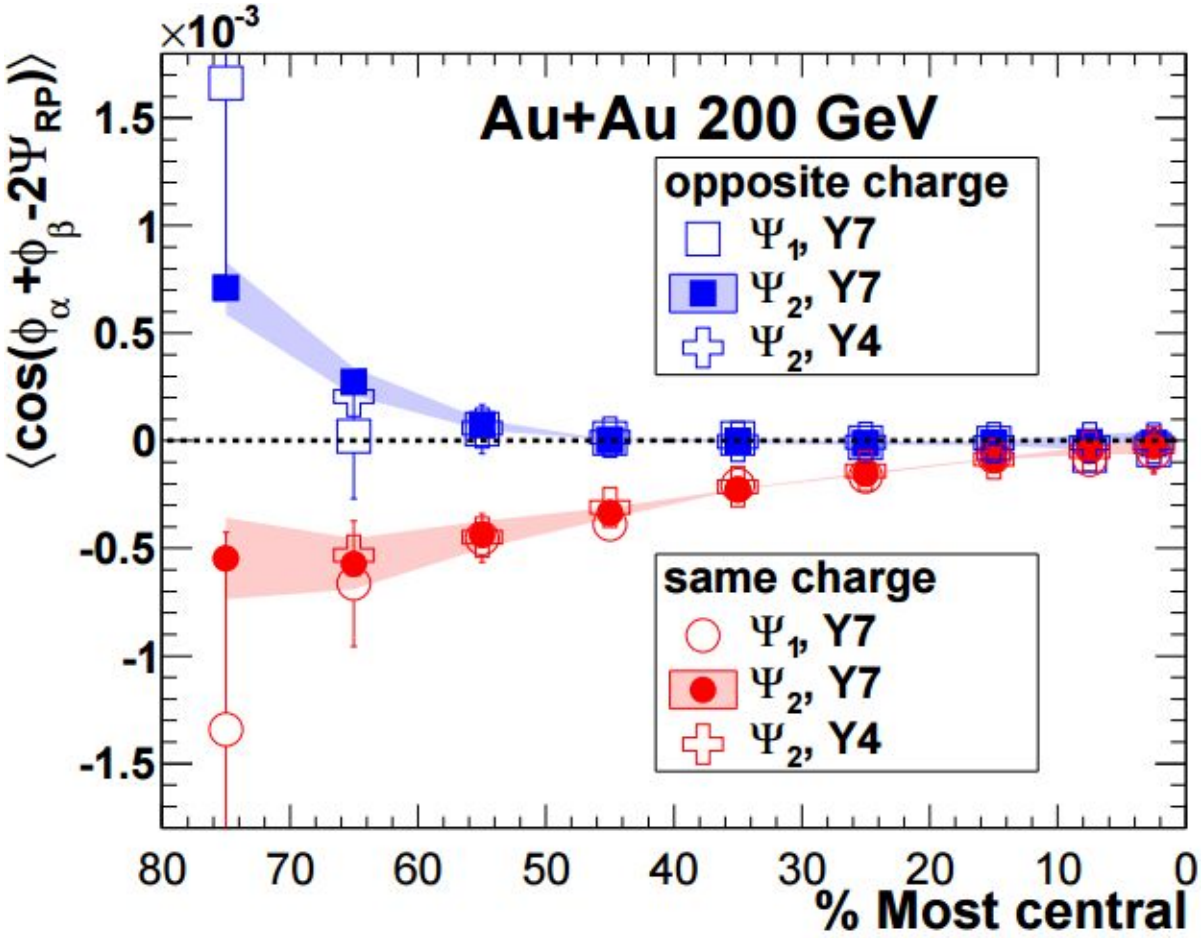
D. Kharzeev, D. T. Son, PRL 106 (2011) 062301

$$\langle \cos(\phi_{\Lambda} + \phi_{\mathrm{p}} - 2\Psi_{RP}) \rangle$$

correlate Λ–p to search for the Chiral Vortical Effect

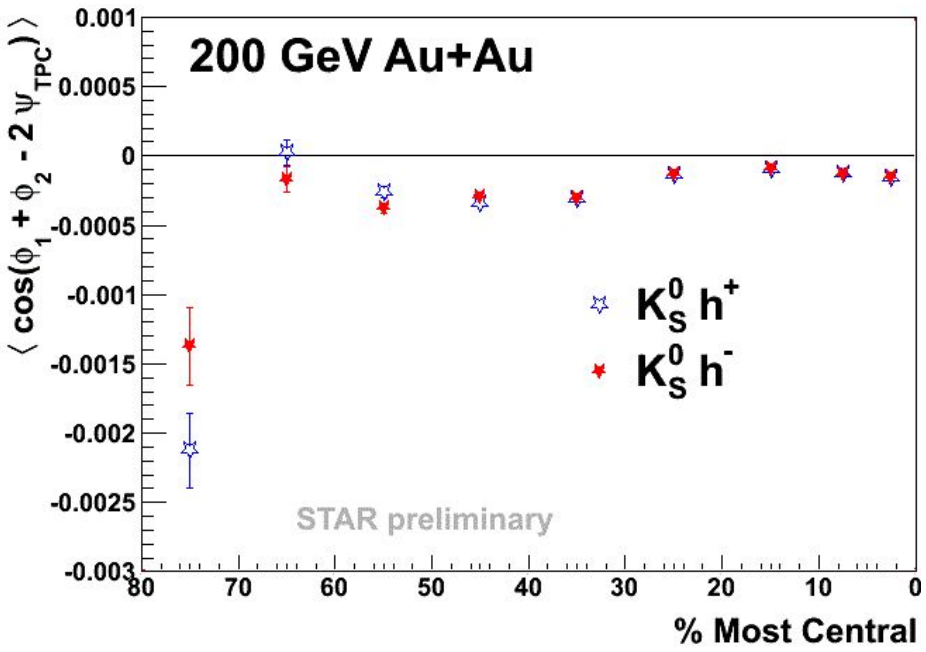
Charge separation: $h^{\pm}$-$h^{\pm}$

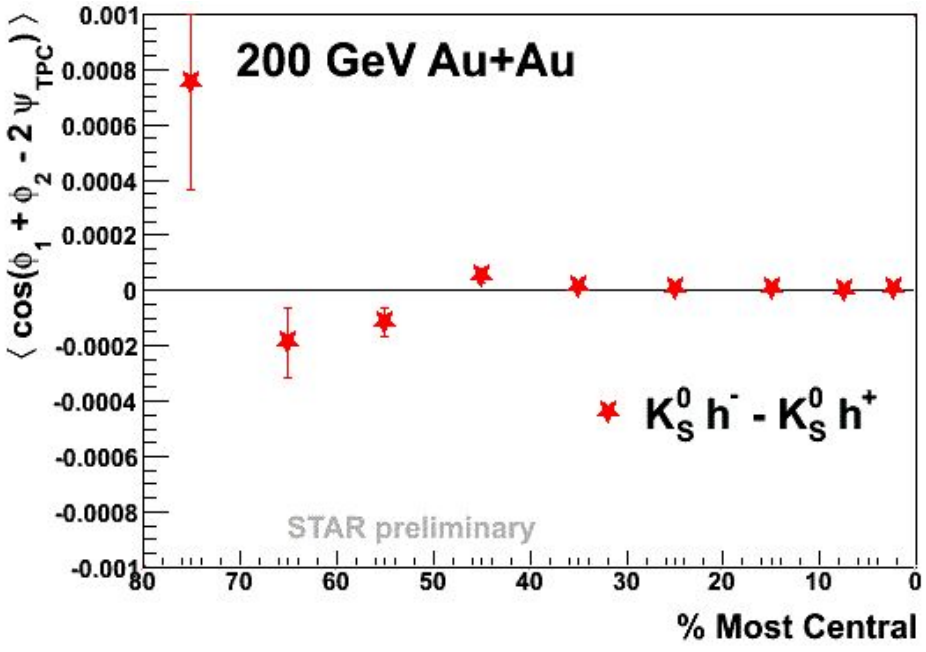
Phys. Rev. Lett. 103(2009)251601;Phys. Rev. C 81(2010)54908;Phys. Rev. C 88 (2013) 64911



- $\gamma_{os} > \gamma_{ss}$, consistent with CME expectation
- what if we replace one of the $h^{\pm}$ with a neutral particle?

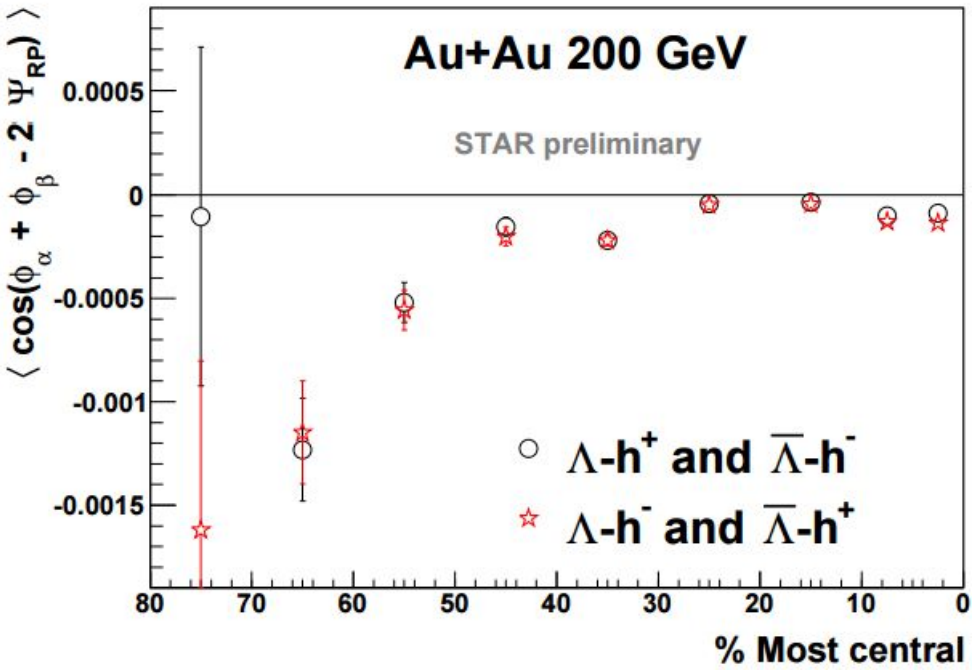
K^0_S-hadron correlation

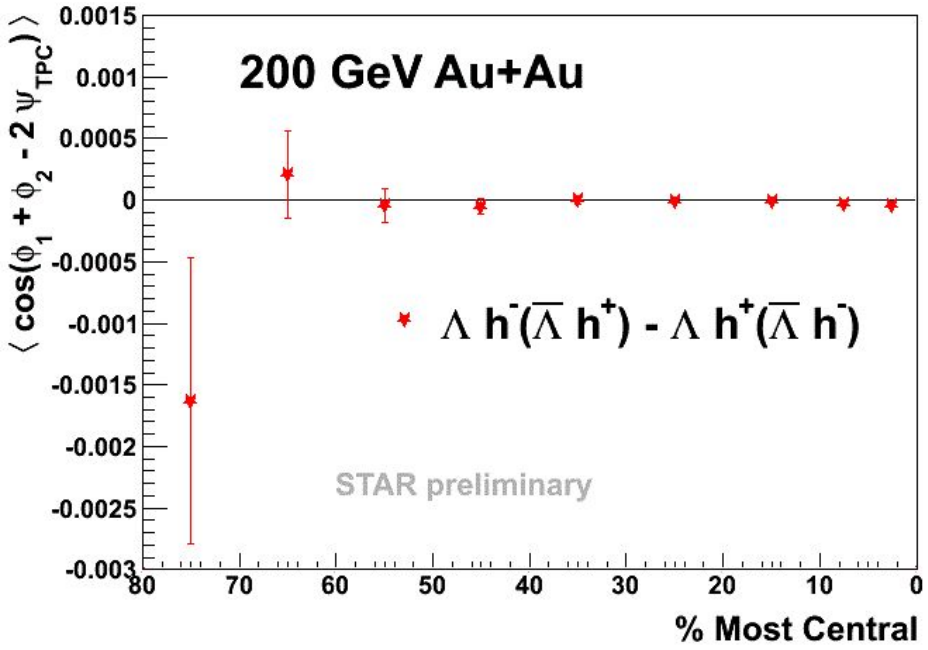




- K^0_S-h^- consistent with K^0_S-h^+: no charge-dependence
- the separation observed in $h^{\pm}$-$h^{\pm}$ is due to electric charge

Λ-hadron correlation



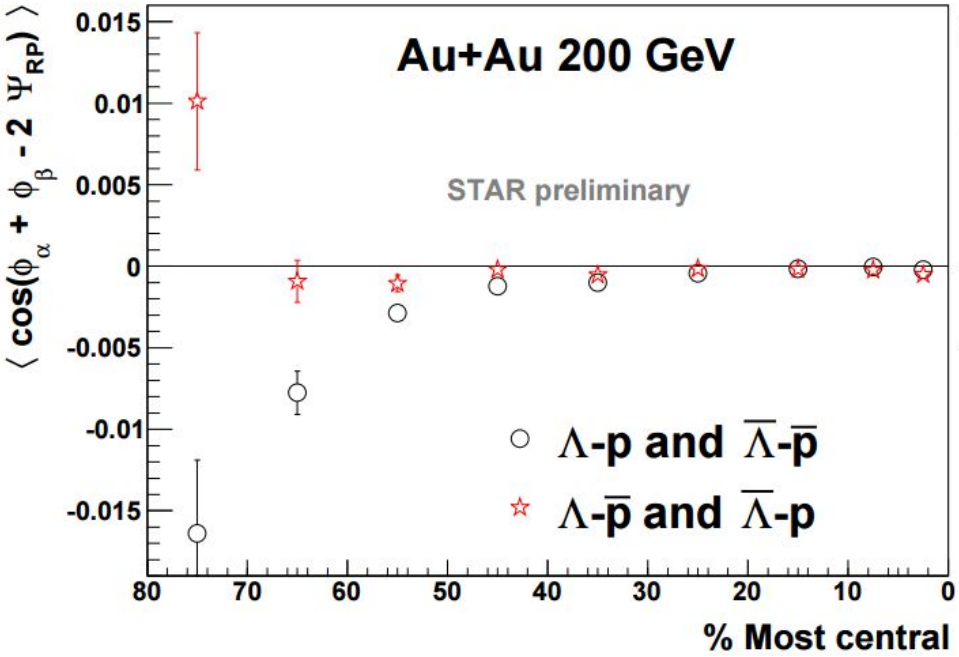


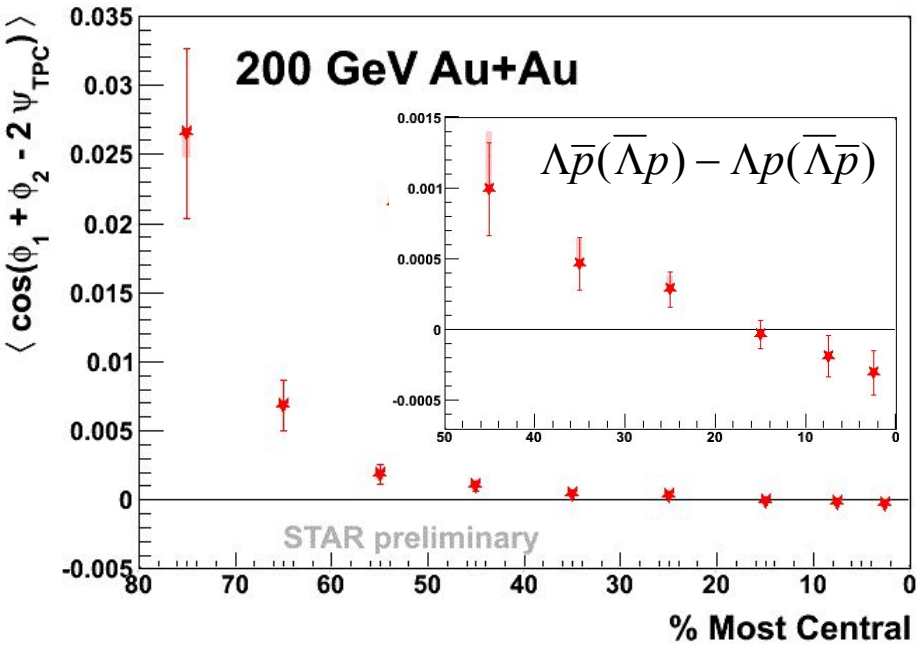
- Λ-h± also show no charge-dependent separation
(protons and antiprotons have been excluded from h±)

- s quarks participate in the chiral dynamics in a similar way as u/d

- Λ-h± also provides a baseline for Λ-p correlations

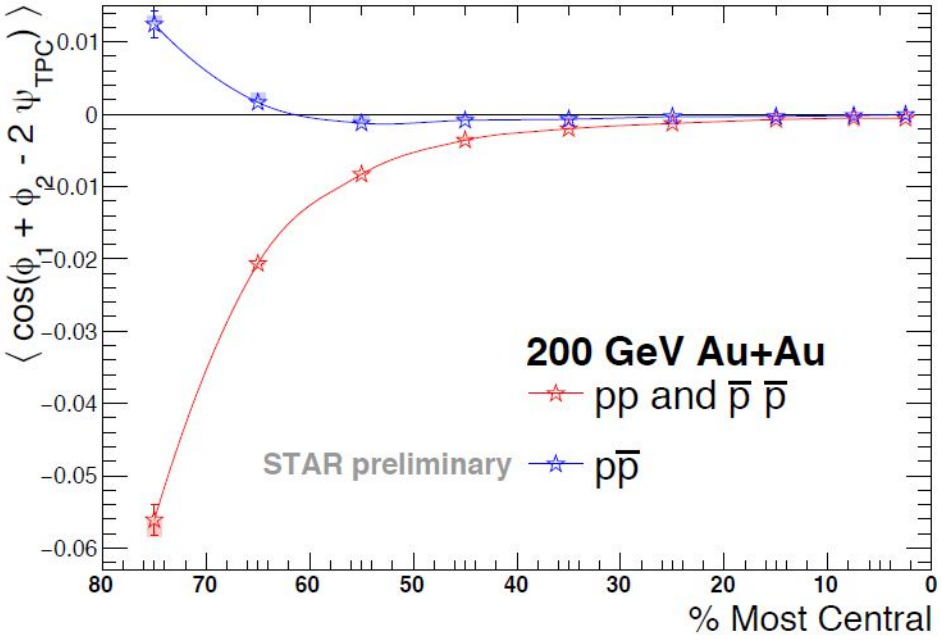
Λ-p correlation

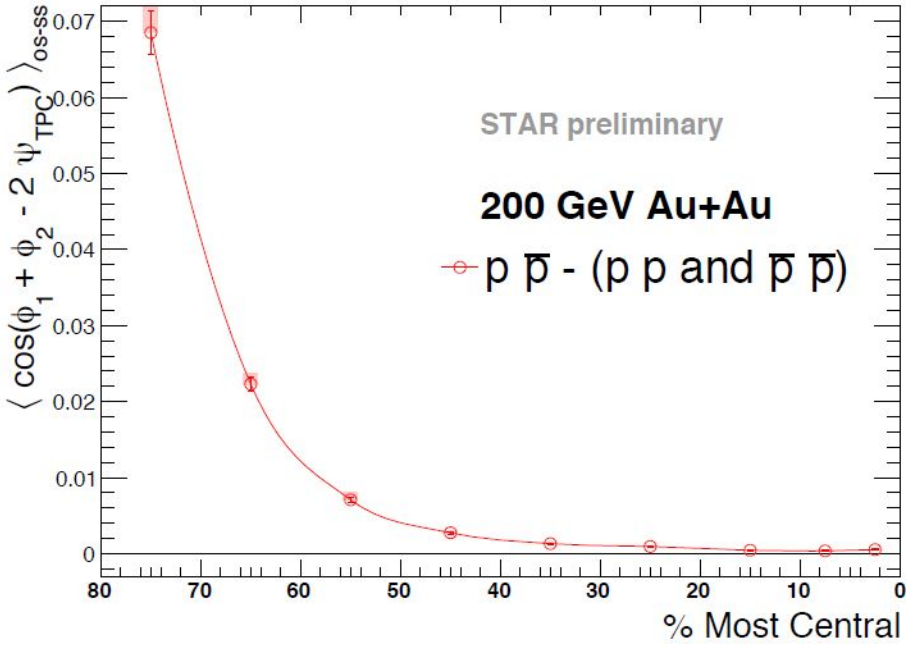




- same baryon number: Λp and $\bar{\Lambda}\bar{p}$
- opposite baryon number: $\Lambda\bar{p}$ and $\bar{\Lambda}p$
- "same B" < "oppo B" in mid-central and peripheral collisions: consistent with the **CVE** expectation.

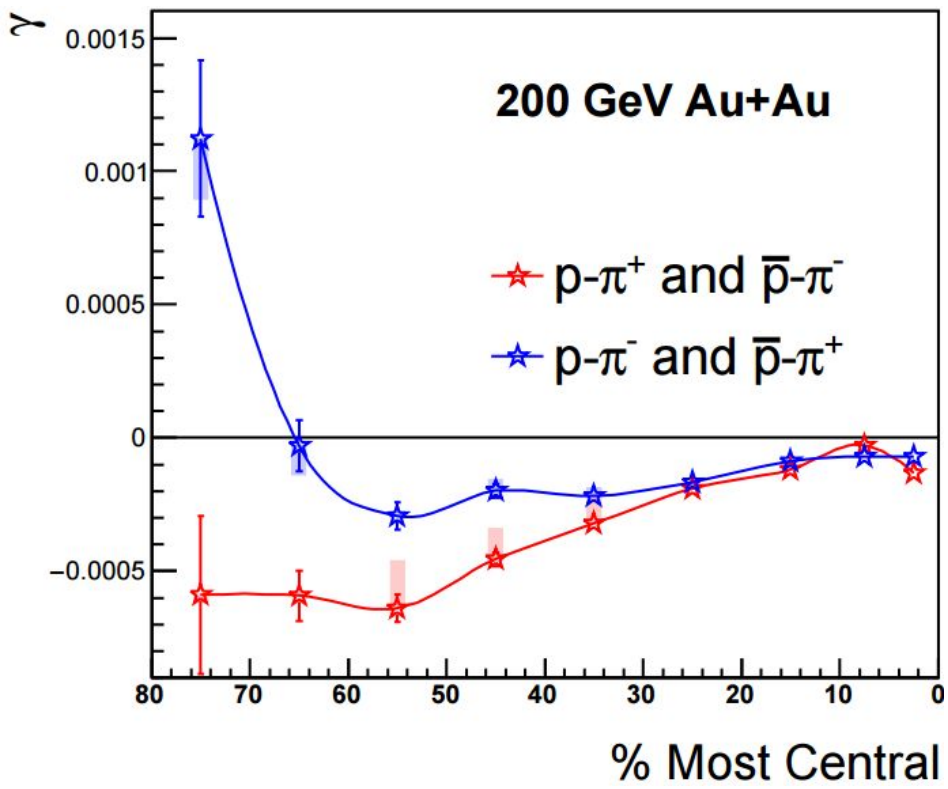
p-p correlation

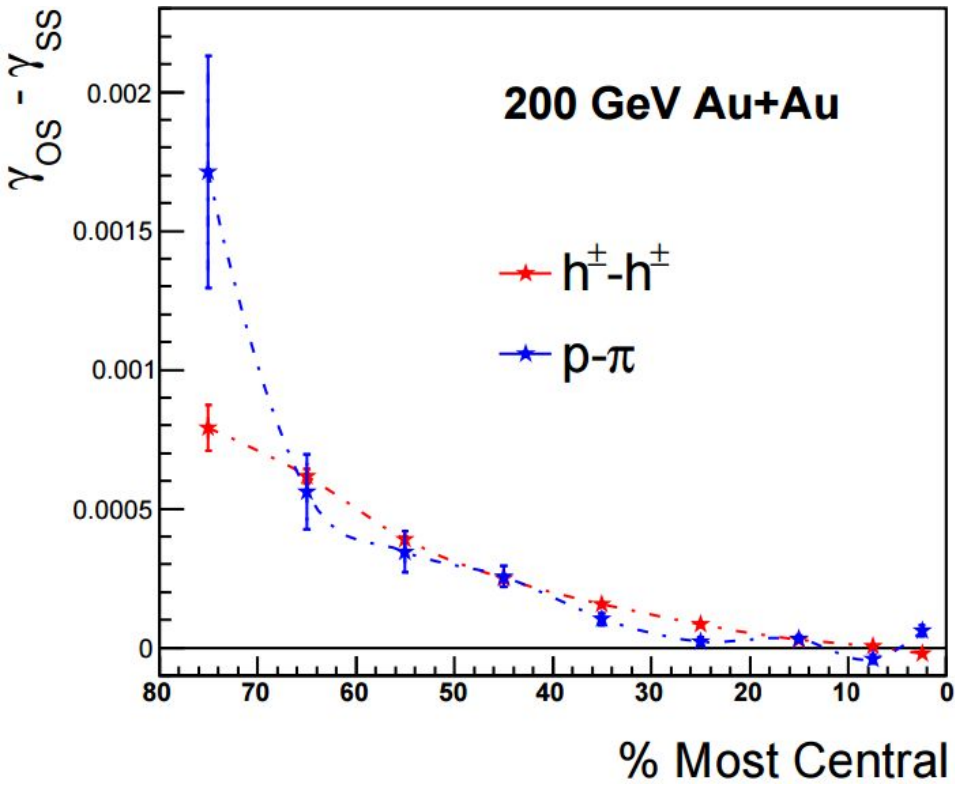




- (anti)protons have both electric and baryonic charge
- p-p correlations are supposed to contain both **CME** and **CVE**
- largest charge separation signal ever seen!
- worry about p-p contamination in $h^{\pm}$-$h^{\pm}$

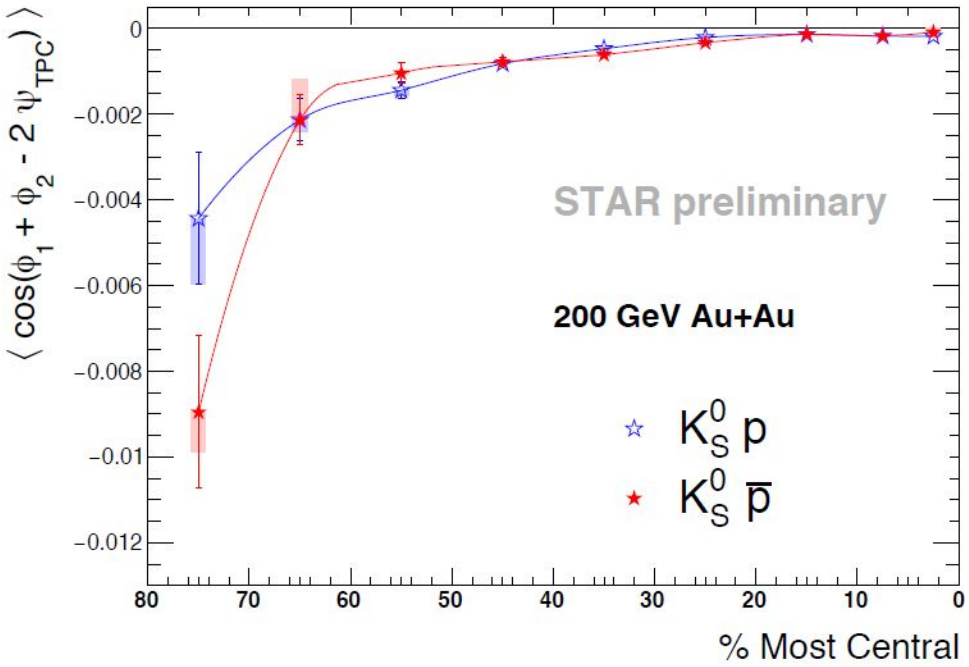
p-π correlation

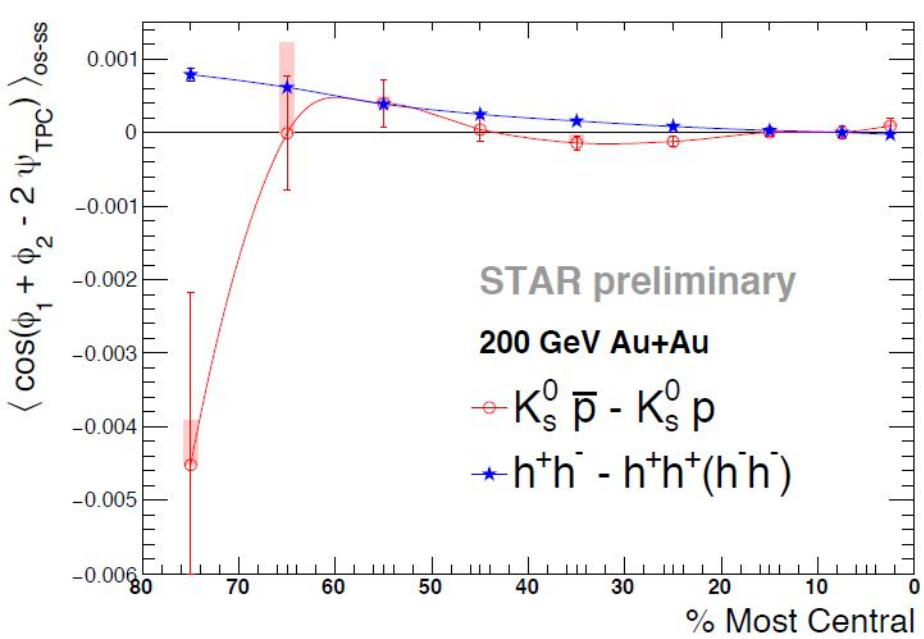




- p-π correlations are supposed to contain only **CME**
- charge separation signal similar between p-π and $h^{\pm}$-$h^{\pm}$ (contribution from Λ decay estimated to be negligible)
- suggest similar underlying physics (**CME**) **for** p-π and $h^{\pm}$-$h^{\pm}$, and small p-p contamination in $h^{\pm}$-$h^{\pm}$

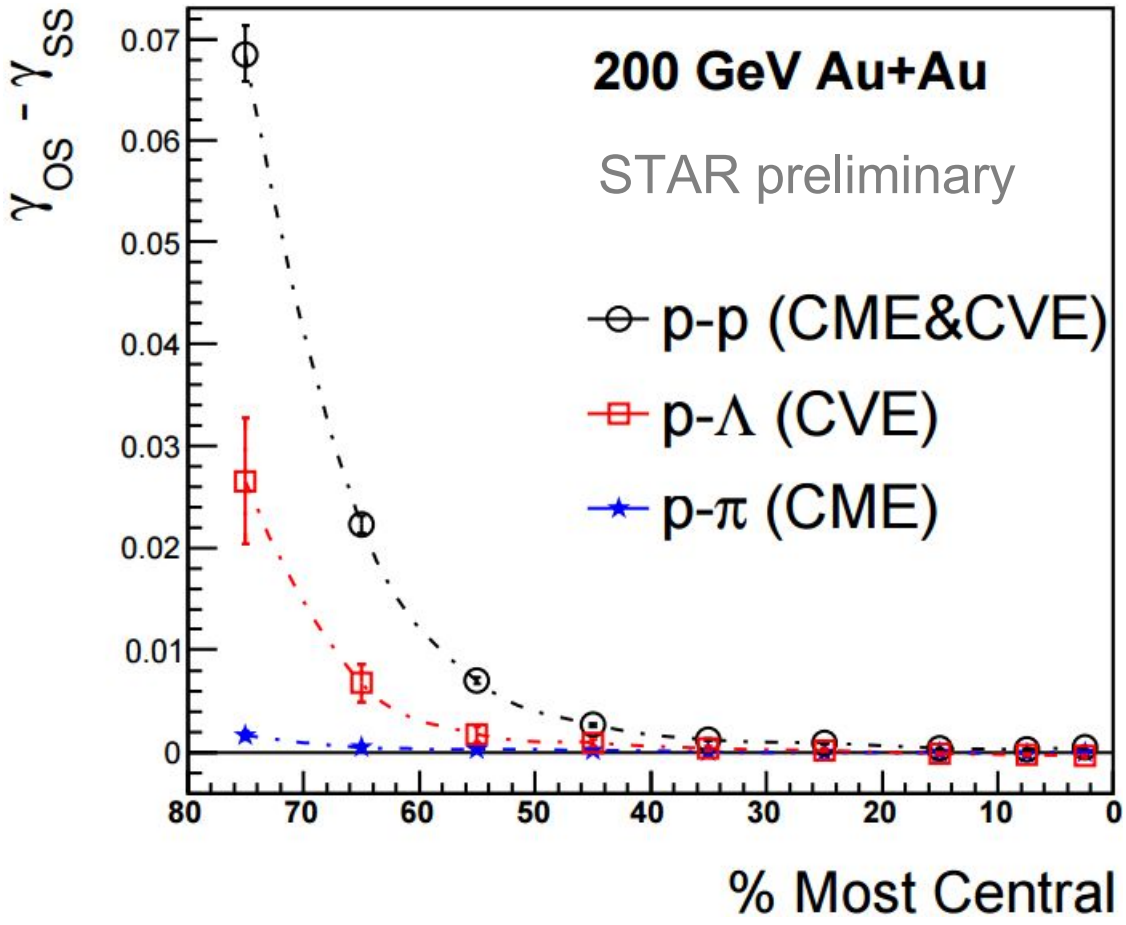
p-K^0_S correlation





- K^0_S have neither electric nor baryonic charge
- p-K^0_S are supposed to contain no **CME** or **CVE**
- consistent with no charge separation
- need more statistics to be more conclusive

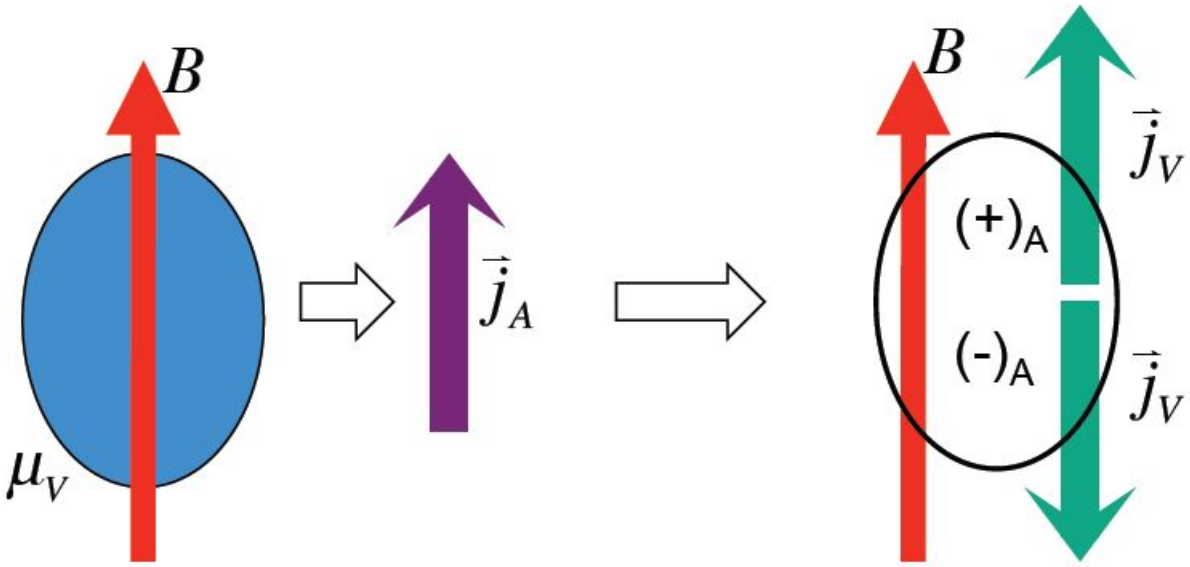
Hierarchical structure



- a clear hierarchical structure
- qualitatively meet the expectation of **CME** and **CVE**
- further study: more PID, flow bg and comparison with theory

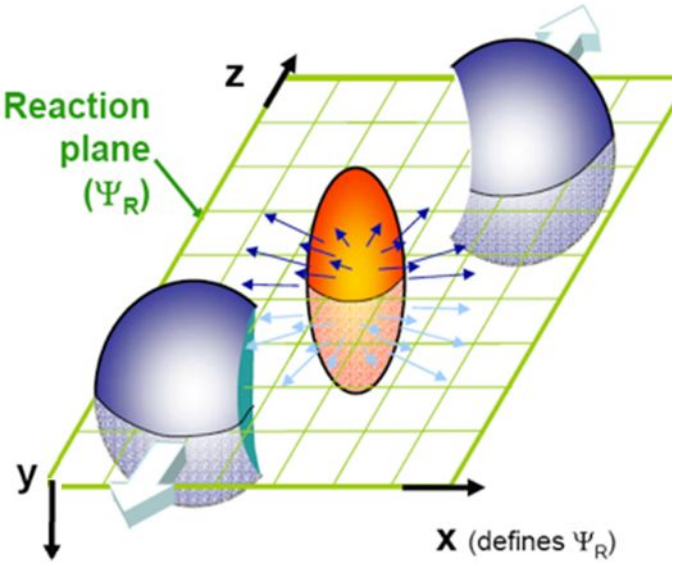
CMW

Peak magnetic field ~
10^{15} Tesla !
(Kharzeev et al. NPA 803 (2008) 227)



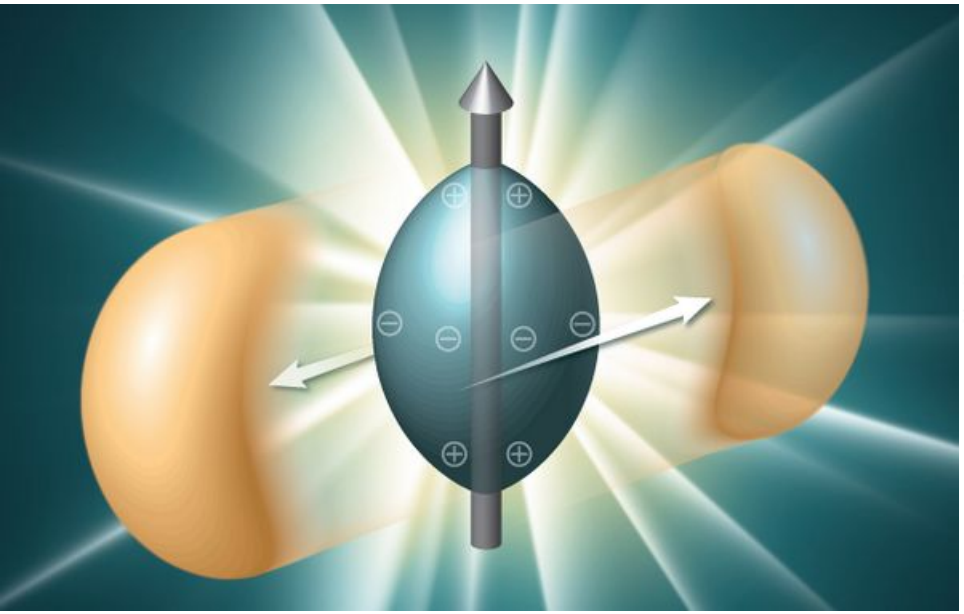
$$j_A = \frac{N_c e}{2\pi^2}\mu_V B \qquad j_V = \frac{N_c e}{2\pi^2}\mu_A B$$

Chiral Separation Effect | **Chiral Magnetic Effect**

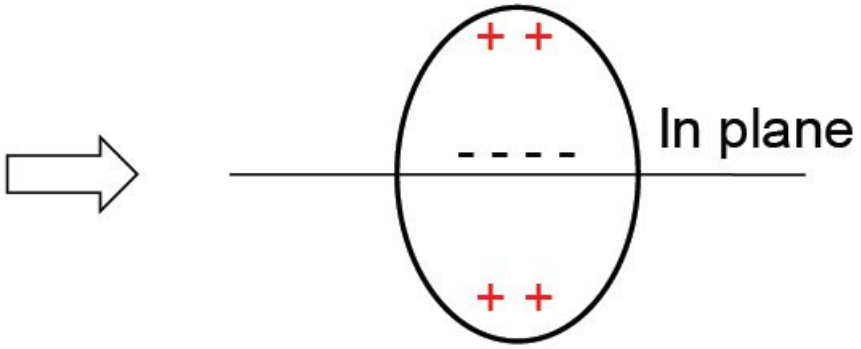


CSE + CME → Chiral Magnetic Wave:
- collective excitation
- signature of chiral symmetry restoration

Observable



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



quadrupole moment

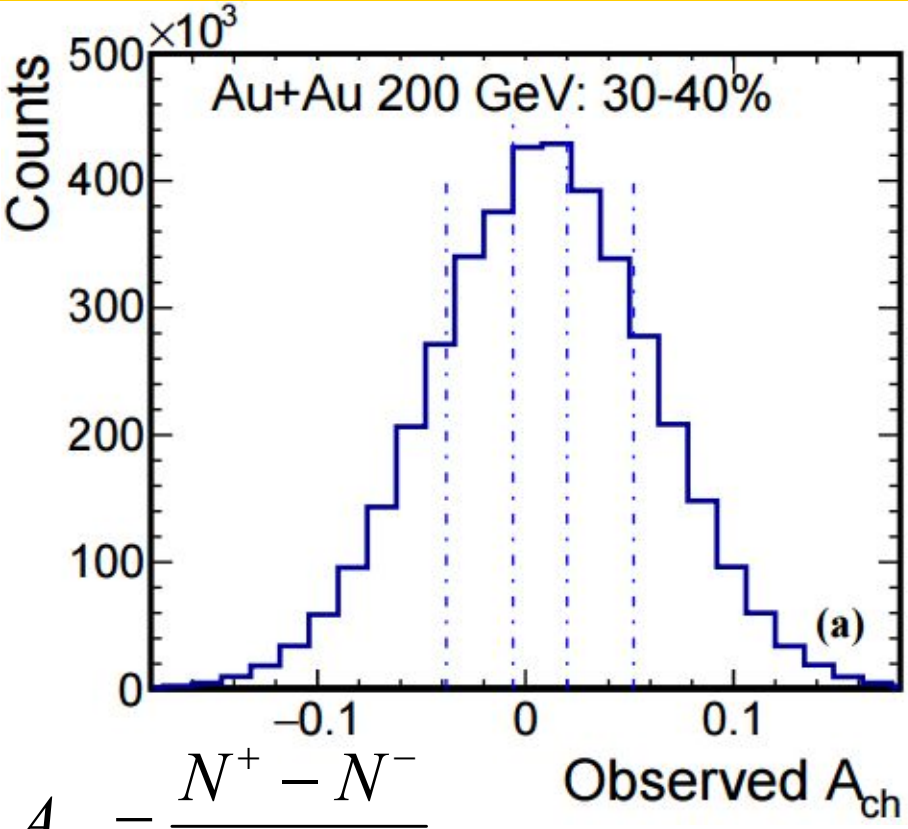
Formation of electric quadrupole: $v_2^{\pm} = v_2^{\text{base}} \mp \left(\frac{q_e}{\overline{\rho}_e} \right) A_{\text{ch}}$,

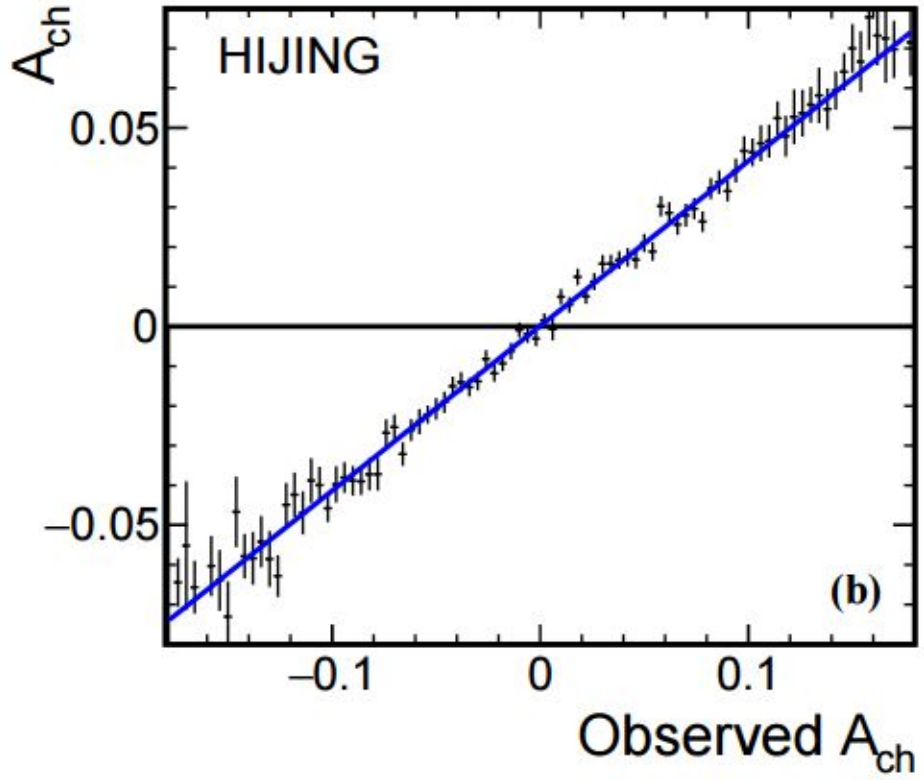
net charge density

where charge asymmetry is defined as $A_{\text{ch}} = \frac{N^+ - N^-}{N^+ + N^-}$.

Then π^- v_2 should have a positive slope as a function of A_{ch},
and π^+ v_2 should have a negative slope with the same magnitude.

Observed charge asymmetry

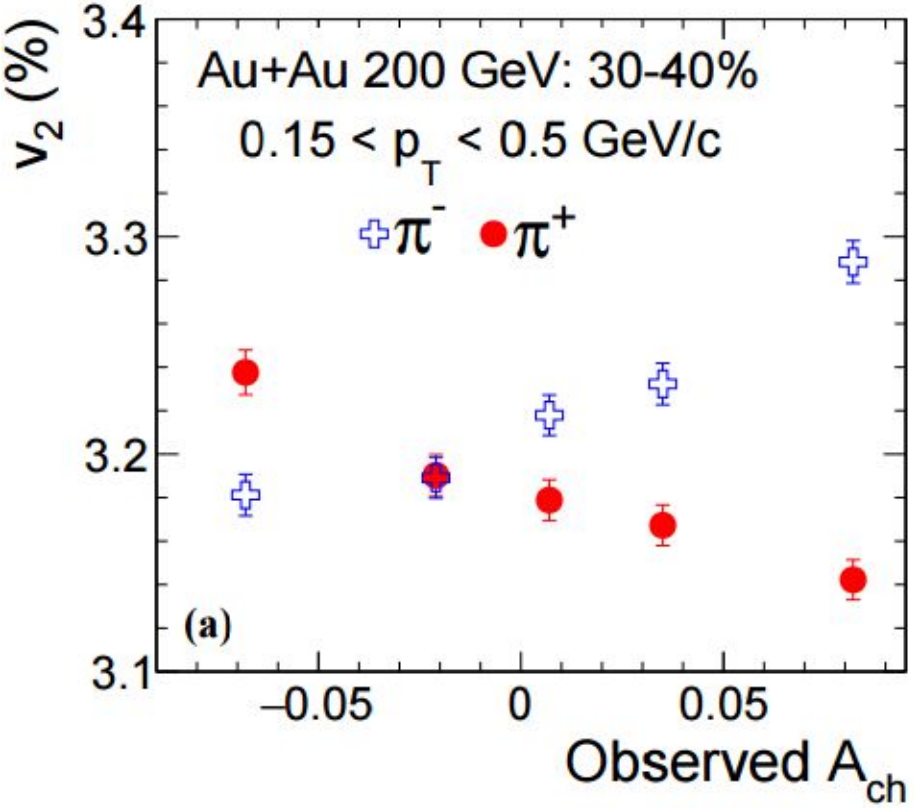


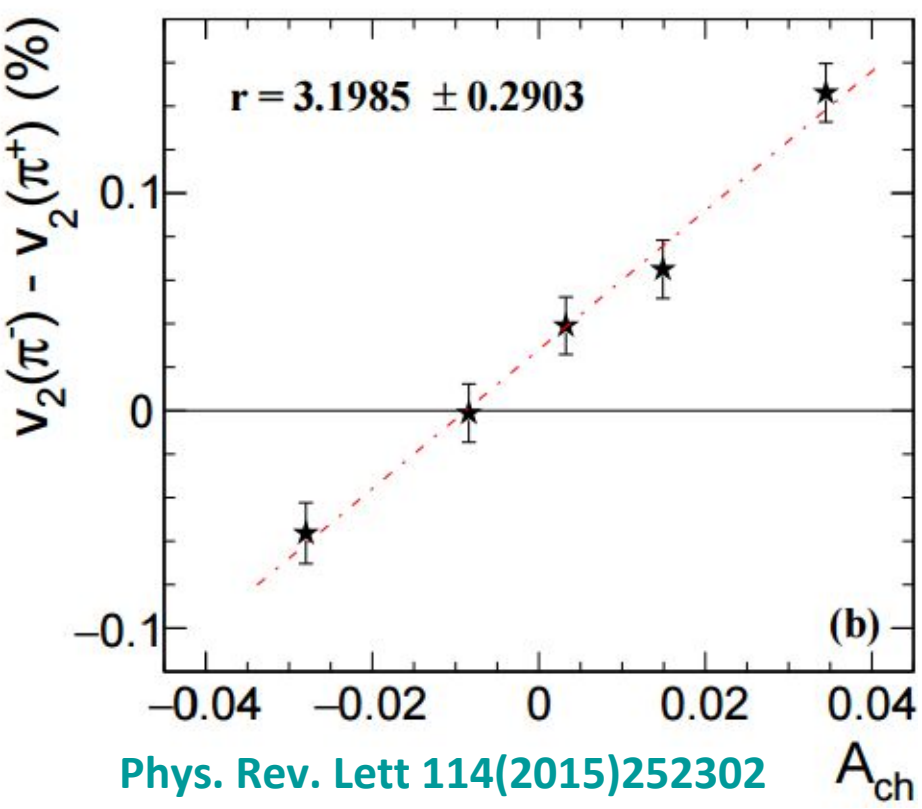


$$A_{\mathrm{ch}} = \frac{N^{+} - N^{-}}{N^{+} + N^{-}}$$

- N^{+} (N^{-}) is the number of positive (negative) particles within $|\eta|<1$.
- The distribution was divided into 5 bins, with roughly equal counts.
- Tracking efficiency was corrected with help of HIIJNG.

v_2 vs A_{ch}





Phys. Rev. Lett 114(2015)252302

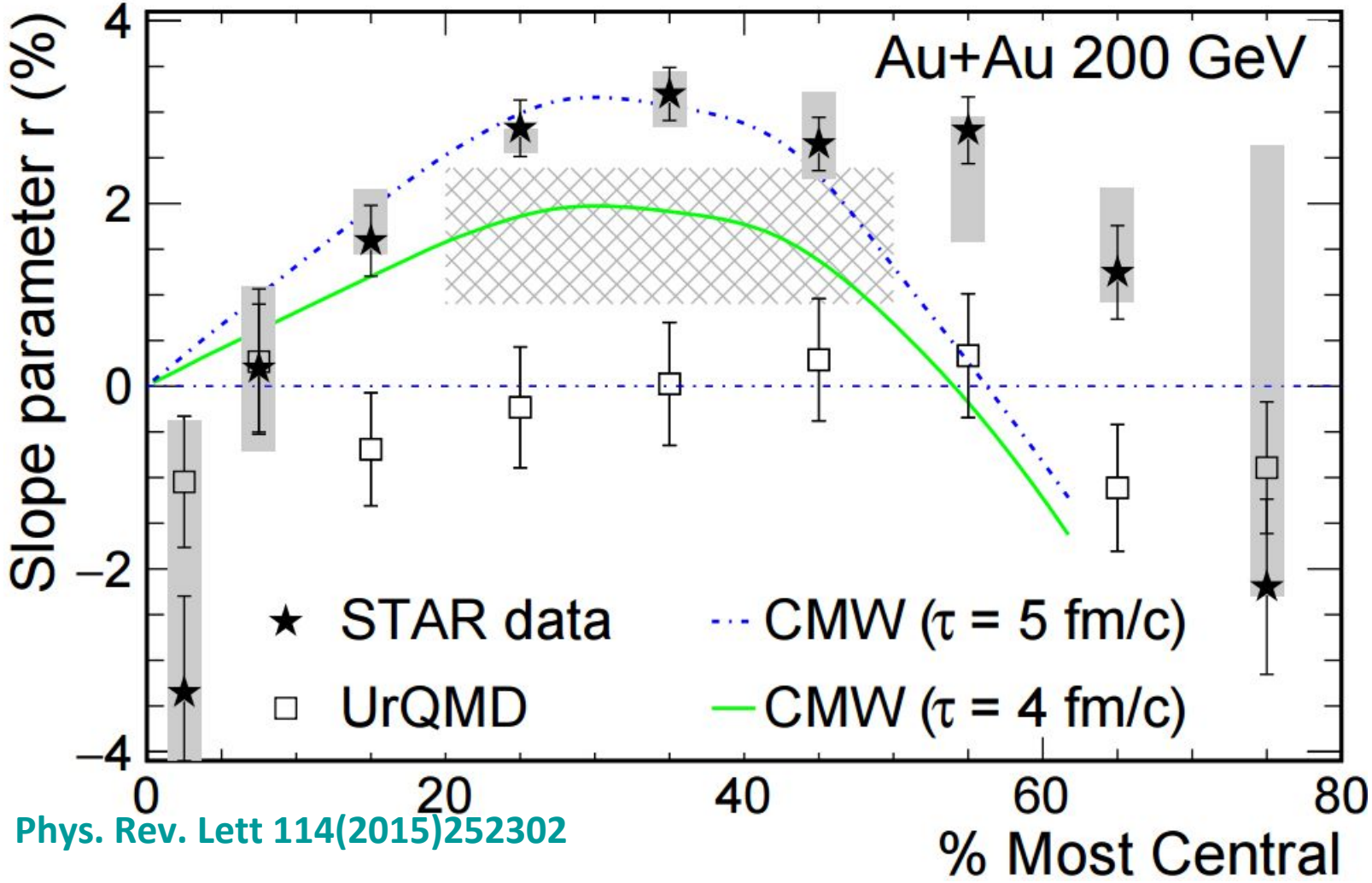
- Clear A_{ch} dependence of $v_2\{2\}$
- $v_2(A_{\mathrm{ch}})$ slopes for $\pi^{\pm}$:
  - opposite sign
  - similar magnitude

$$v_2^{\pm} = v_2^{\mathrm{base}} \mp \left(\frac{q_e}{\overline{\rho}_e}\right) A_{ch}$$

- Δv_2 vs A_{ch} may have a non-zero intercept: other physics?

Slope vs centrality

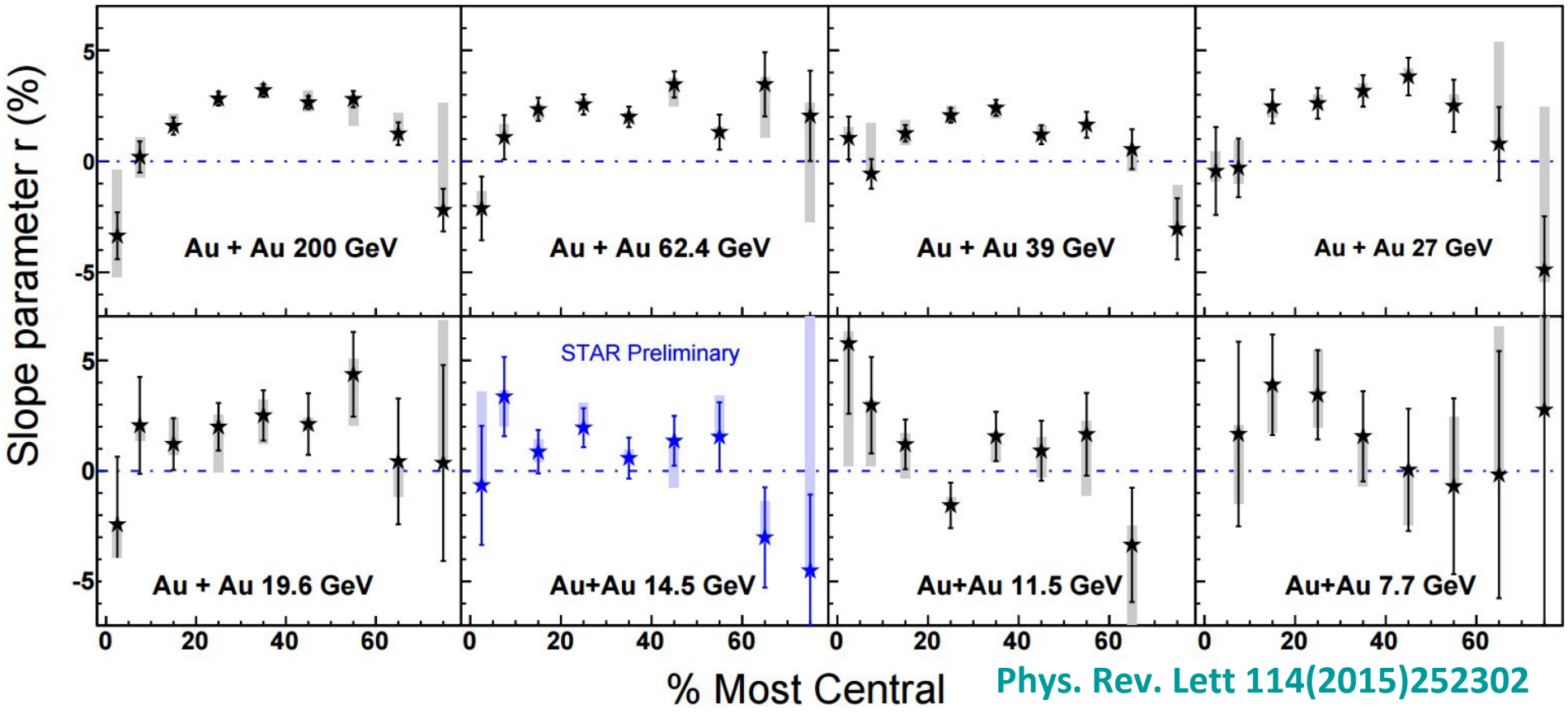
Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, arXiv:1208.2537v1 [hep-ph].



Phys. Rev. Lett 114(2015)252302

Similar trends between data and theoretical calculations with CMW. UrQMD can not reproduce the slopes.

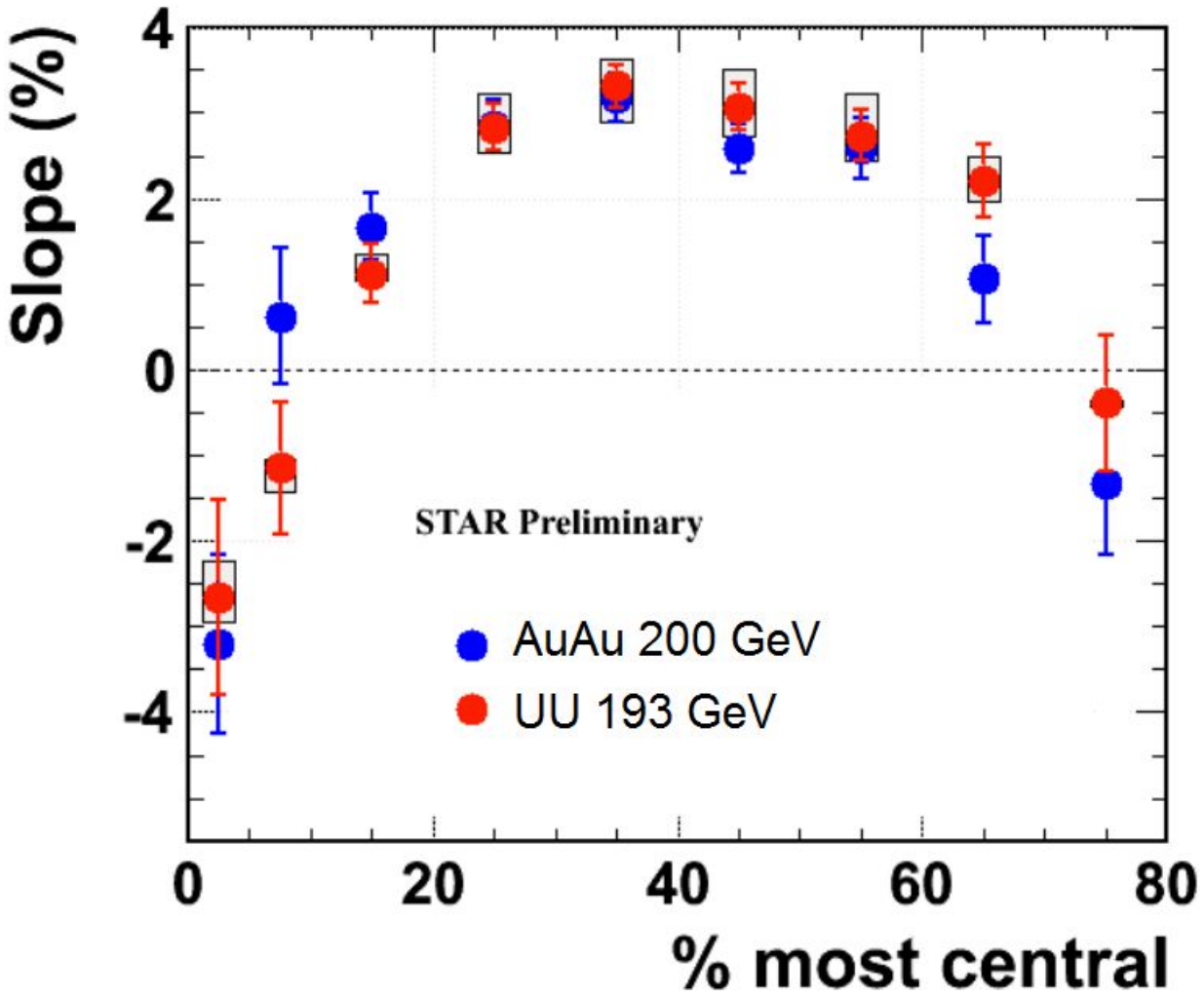
Beam Energy Scan



Phys. Rev. Lett 114(2015)252302

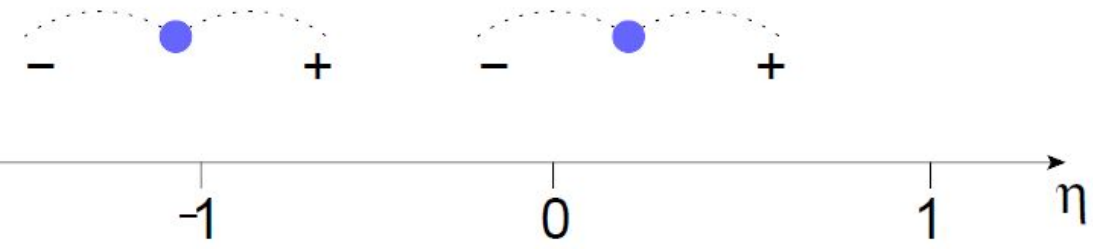
Similar trends are observed for different beam energies down to 19.6 GeV. Below 19.6 GeV, more statistics are needed.

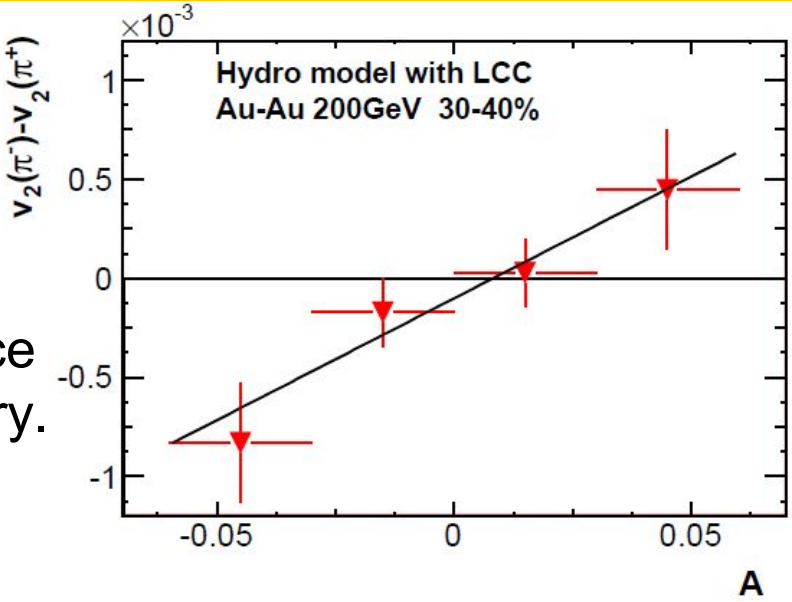
U+U



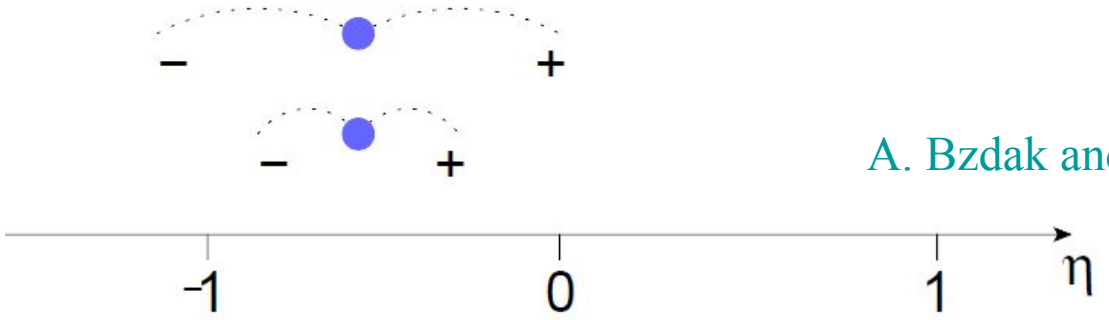
Similar pattern and magnitude seen in U+U collisions.

Alternative interpretation: LCC





- Clusters located close to acceptance boundary produce one pion outside boundary.
- v_2 decreases with $|\eta|$.

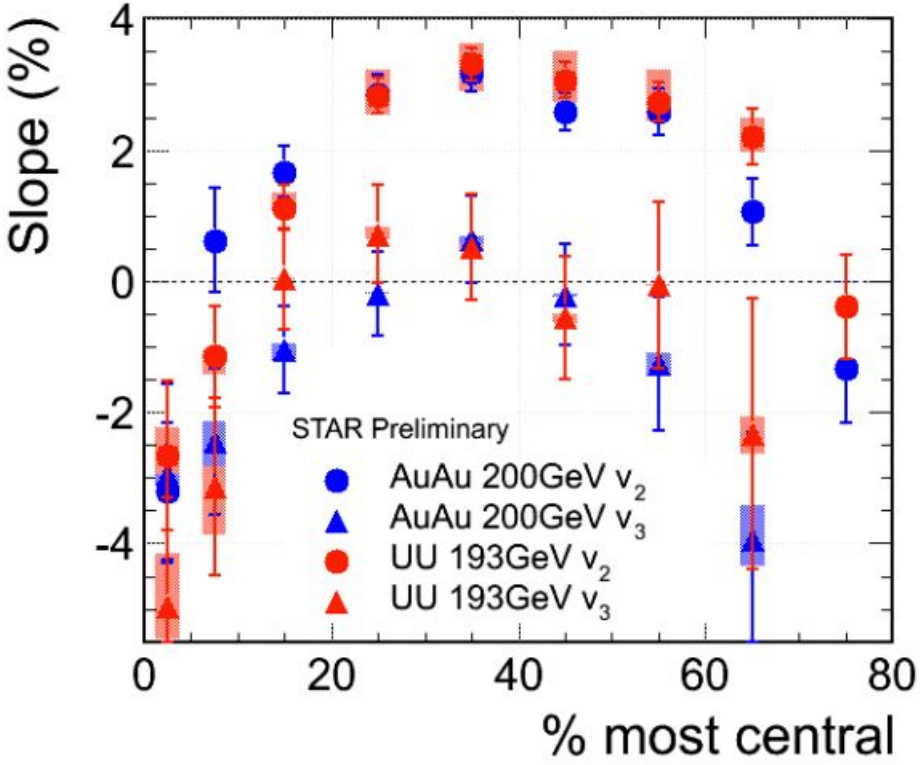


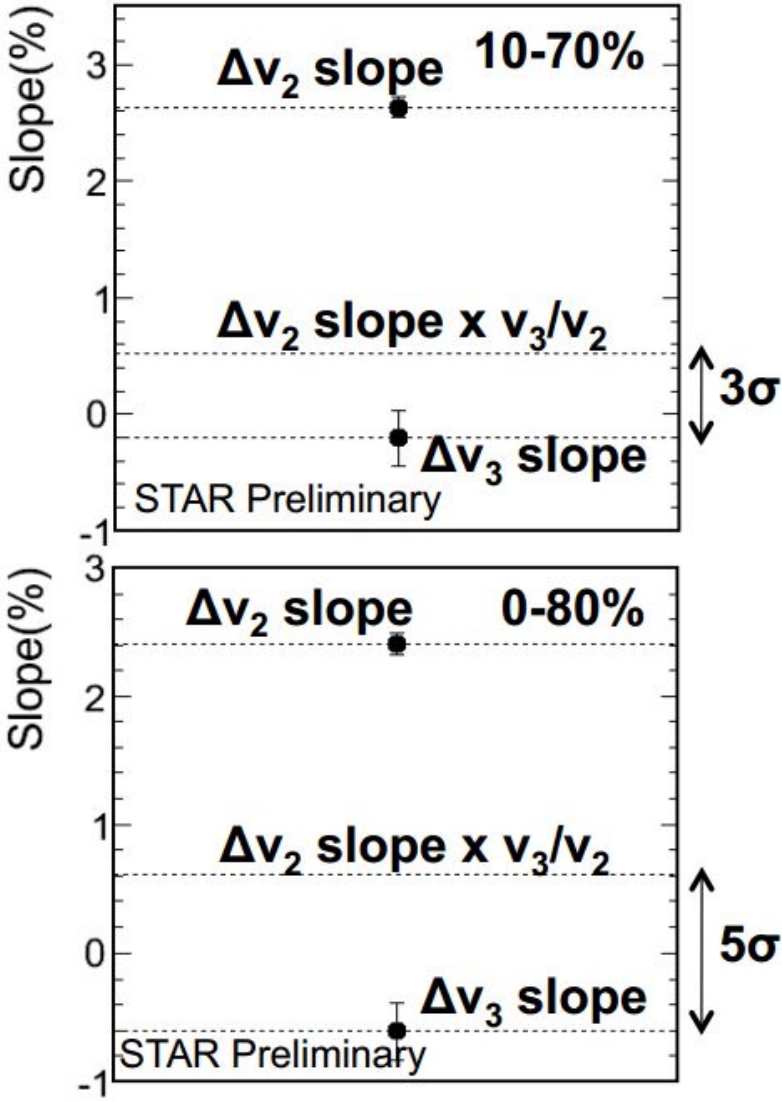
A. Bzdak and P. Bozek, Phys. Lett. B 726 (2013) 239

- Clusters with low p_T have particles more separated in η than high-p_T clusters.
- v_2 increases with p_T.

- η dependence of v_2 weaker than what this paper used
- mean p_T in data is constant vs A_{ch} (no 2nd effect)
- the LCC effect estimated to be 10 times smaller than data

Δv_3 slope

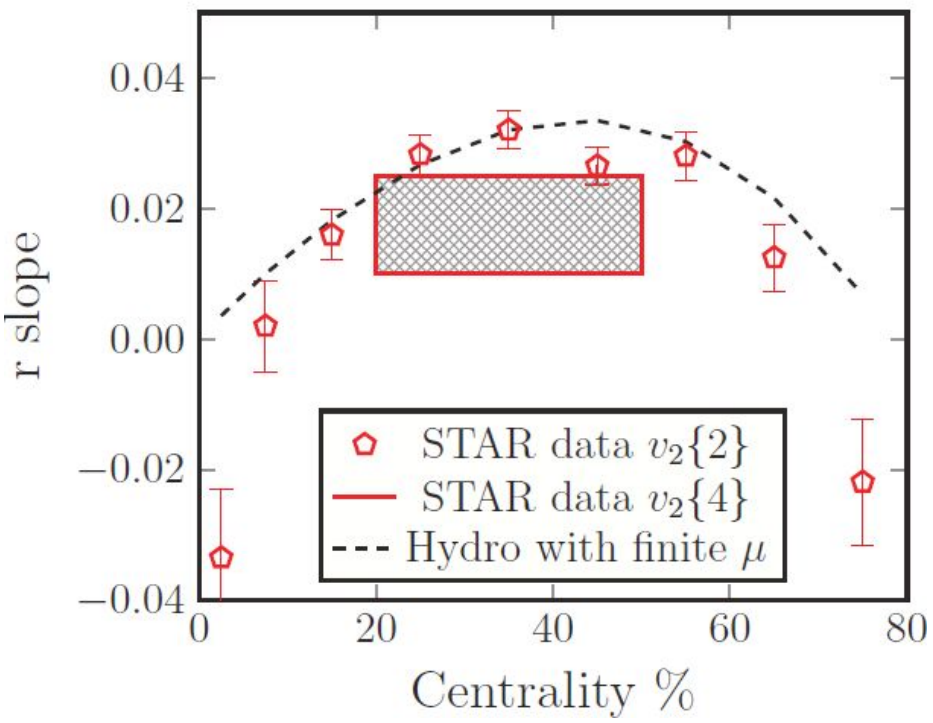


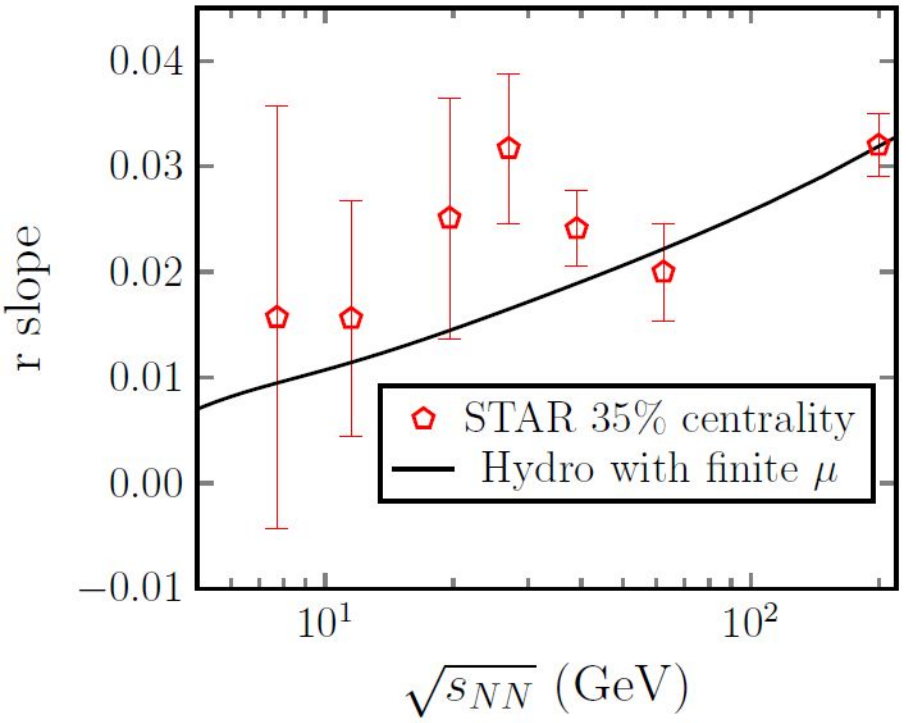


Local charge conservation may introduce A_{ch} dependence of $\Delta v_2(\pi)$. Then one should see **slope-for-Δv_3 / slope-for-Δv_2 ~ v_3/v_2** (Bzak & Bozek PLB 726 239 (2013)).

Our measurement for Δv_3 indicates that such mechanism alone cannot explain data.

Alternative interpretation: μ_I

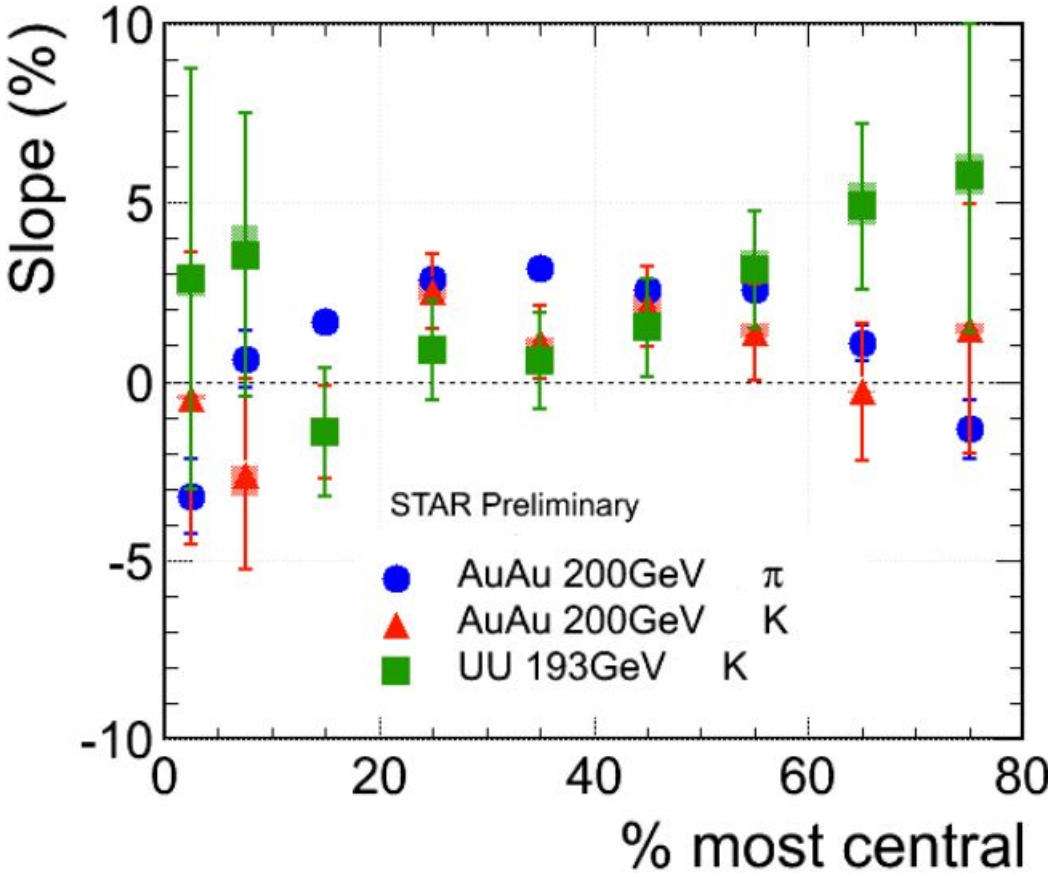




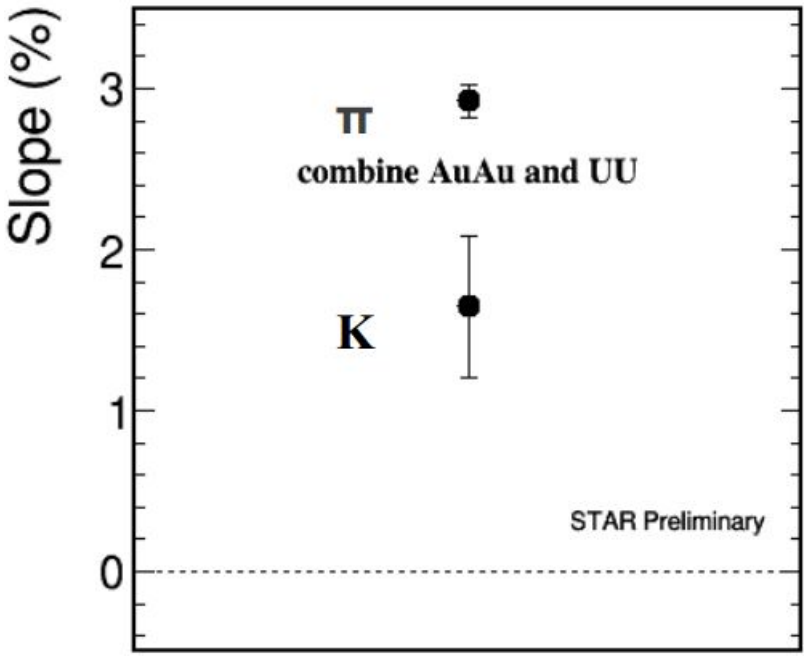
Y. Hatta, A. Monnai, B.W. Xiao, arXiv:1507.04690v1

- Δv_2 and A_{ch} are linked with μ_I
- reproduce centrality and beam-energy dependence of r
- predict a similar Δv_3 slope as LCC (previous slide)
- predict a negative kaon slope

Kaon



20-60% collisions



With the same electric quadruple of QGP upon chemical freezeout, CMW expects a similar/weaker effect for kaons (Y. Burnier, D. Kharzeev, J.g Liao, and H. Yee, PRL 107 052303)

What we learned so far

- Charge asymmetry dependece of pion v_2 has been observed.
  - $v_2(A_{ch})$ showed opposite slopes for π^+ and π^-
  - similarity between data and calculations with CMW
  - similar centrality dependence from 200 GeV down to 19.6 GeV
  - confirmed with UU
  - finite slopes for kaons, with similar/smaller magnitudes

- On the other hand
  - UrQMD and AMPT (w/o CMW) showed no such effects
  - Δv_3 results consistent with zero

- Further systematic checks to do
  - acceptance effect

Outlook: Isobars

Isobars are atoms (nuclides) of different chemical elements that have the same number of nucleons.

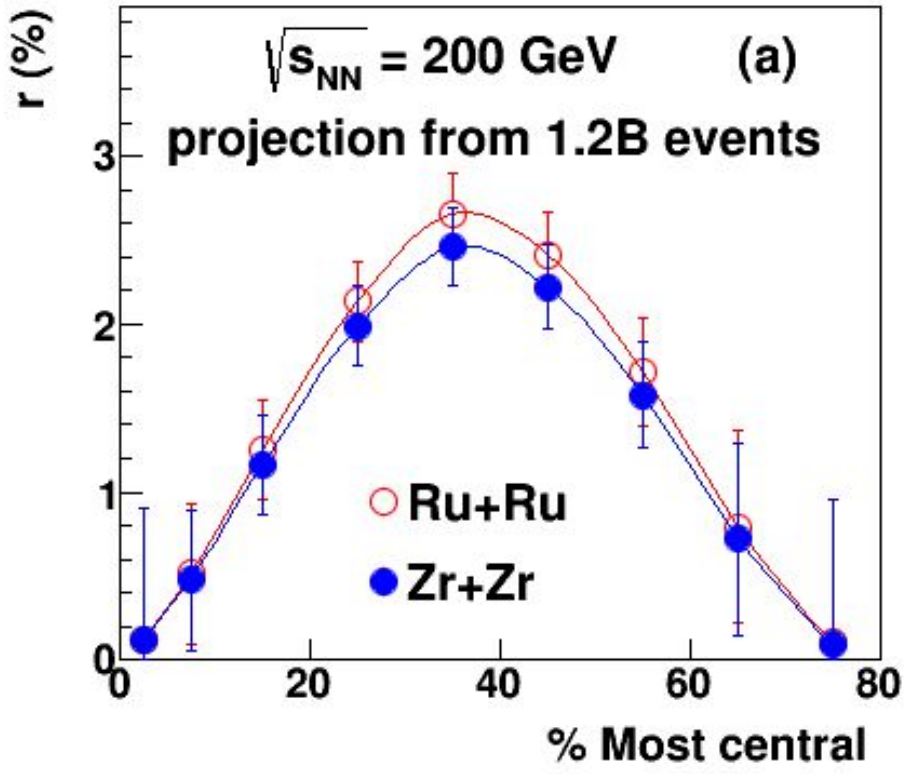
For example, $^{96}_{44}$Ruthenium and $^{96}_{40}$Zirconium:

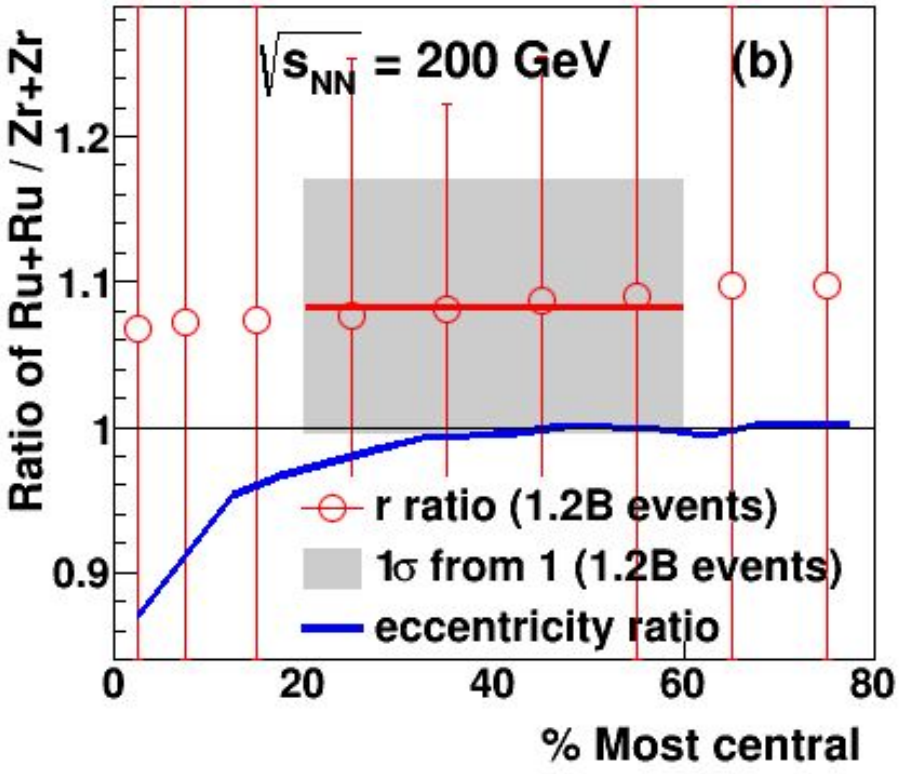
Up to 10% variation in B field

	$^{96}_{44}$Ru+$^{96}_{44}$Ru vs $^{96}_{40}$Zr+$^{96}_{40}$Zr
Flow	~
CMW	>
CME	>
CVE	=

Isobars: $\Delta v_2(A_{ch})$ slope

- The slope parameter is also expected to differ
- With 1.2B events, the ratio is 1σ above 1
- Need more statistics



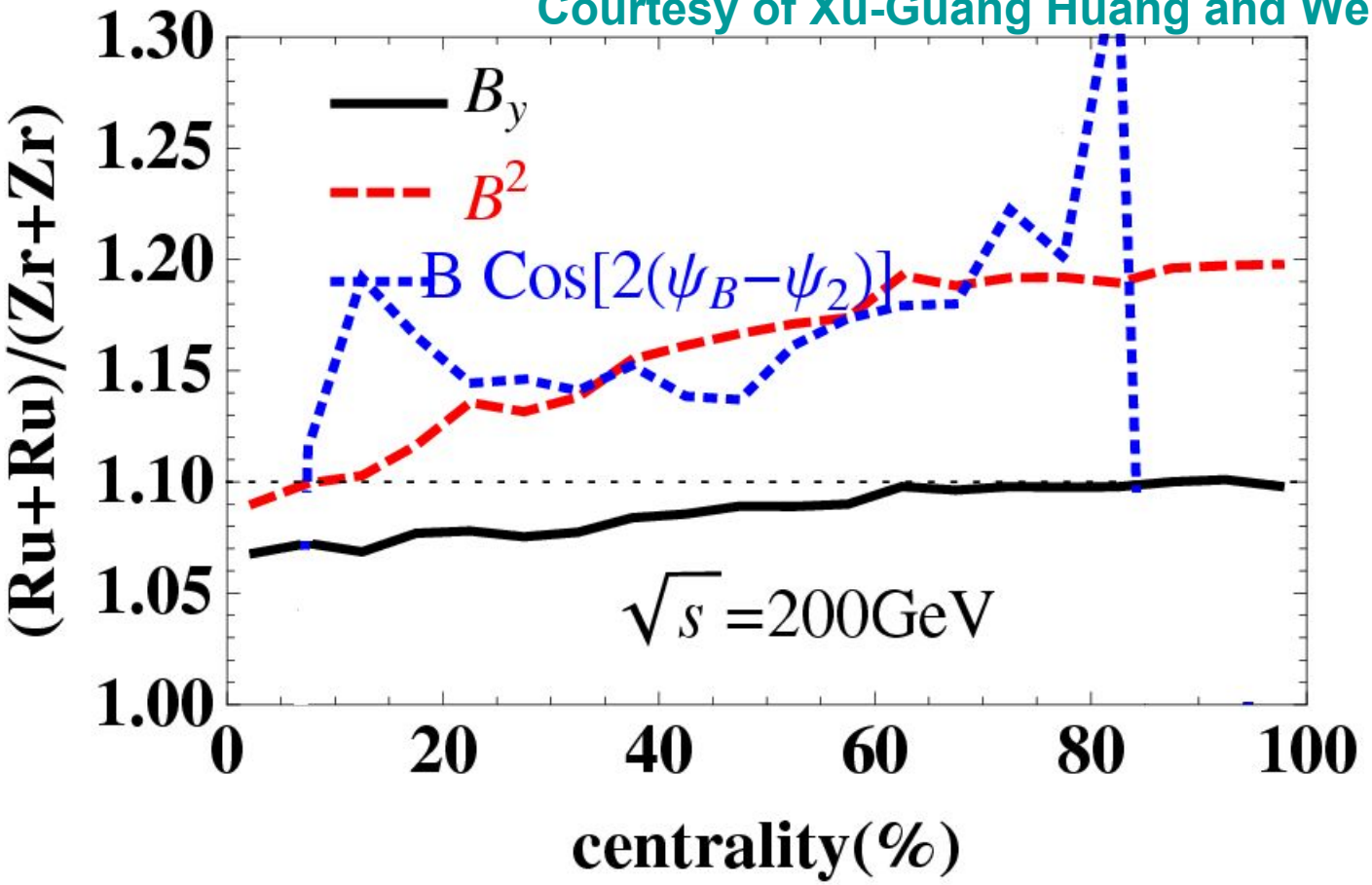


Backup slides

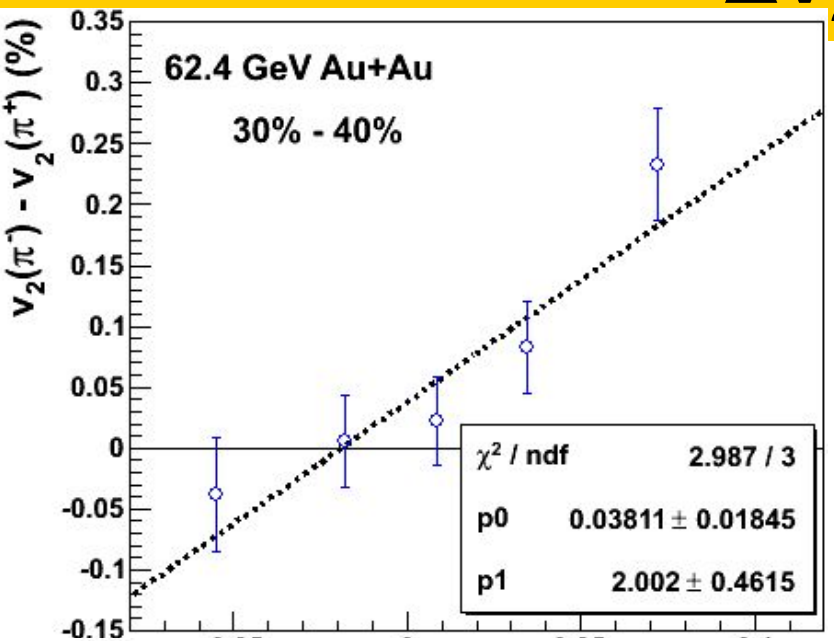
Isobars: B field

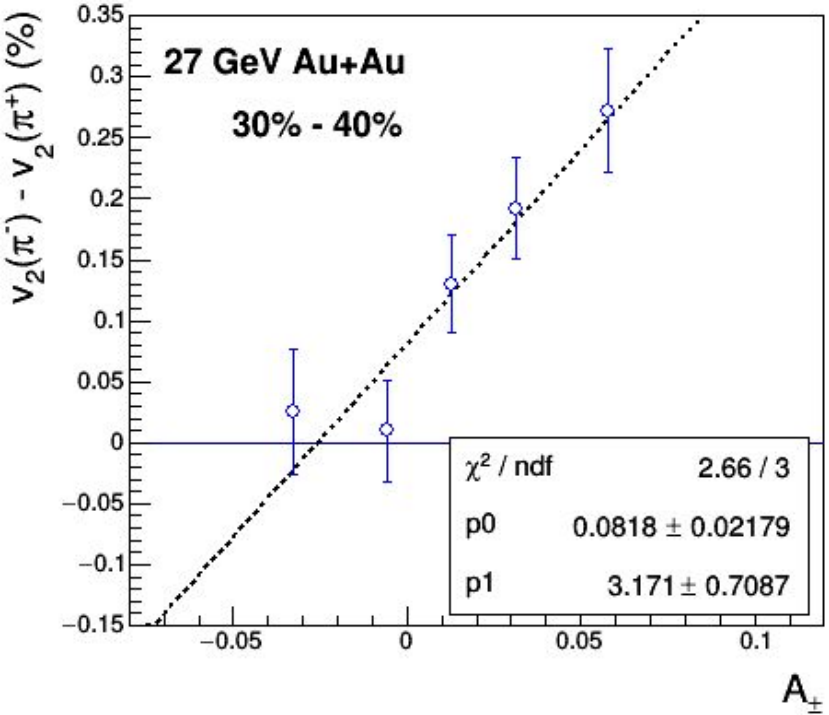
- Which B quantity is sensitive to the charge separation?
- The ratio is similar in term of ~ B^2 for 20-60% collisions
- B•cos(2Δφ) may be more realistic, with a bigger difference
- We use B_y for simplicity

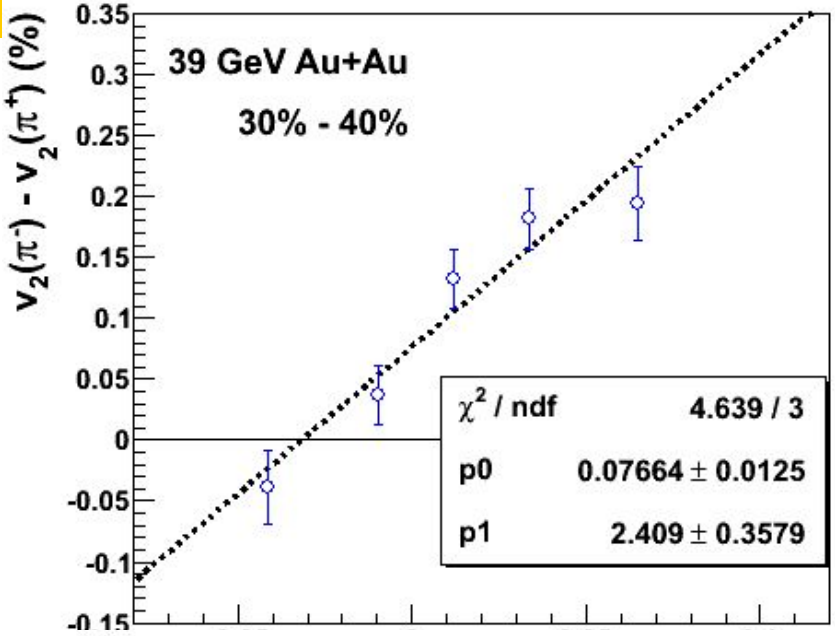
Courtesy of Xu-Guang Huang and Wei-Tian Deng

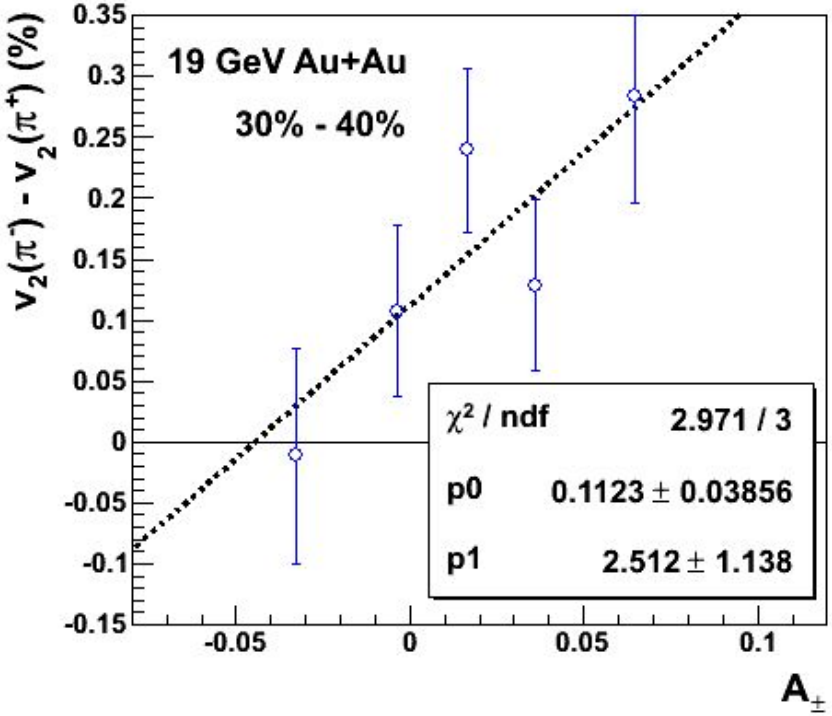


Δv_2@BES

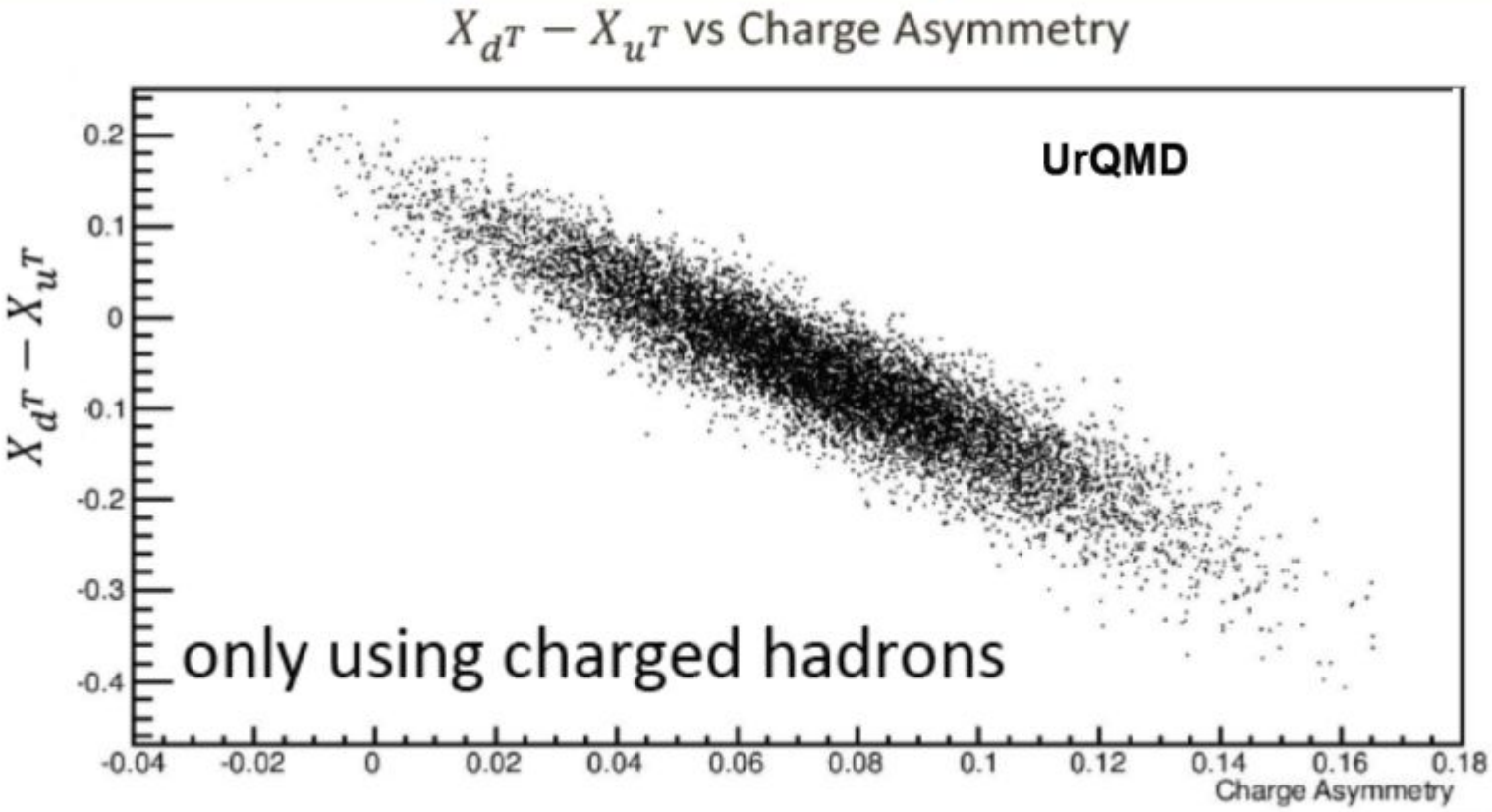

62.4 GeV Au+Au
30% - 40%
$v_2(\pi^-) - v_2(\pi^+)$ (%)
χ^2 / ndf 2.987 / 3
p0 0.03811 ± 0.01845
p1 2.002 ± 0.4615


27 GeV Au+Au
30% - 40%
$v_2(\pi^-) - v_2(\pi^+)$ (%)
χ^2 / ndf 2.66 / 3
p0 0.0818 ± 0.02179
p1 3.171 ± 0.7087
$A_\pm$


39 GeV Au+Au
30% - 40%
$v_2(\pi^-) - v_2(\pi^+)$ (%)
χ^2 / ndf 4.639 / 3
p0 0.07664 ± 0.0125
p1 2.409 ± 0.3579


19 GeV Au+Au
30% - 40%
$v_2(\pi^-) - v_2(\pi^+)$ (%)
χ^2 / ndf 2.971 / 3
p0 0.1123 ± 0.03856
p1 2.512 ± 1.138
$A_\pm$

Multi-component Coalescence (MCC) + Quark Transport



Pearson coefficient : -0.92 → Strong negative correlation

$$\Delta v_2{}^{\pi} \equiv v_2{}^{\pi^-} - v_2{}^{\pi^+} = \boxed{(X_{d^T} - X_{u^T})}(v_2{}^{T} - v_2{}^{P})$$

John Campbell's poster.