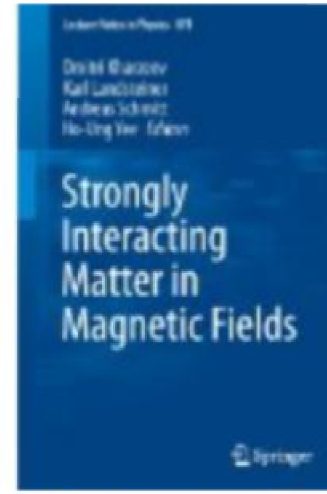
Experimental Overview of the Search for Chiral Effects at RHIC

Gang Wang (UCLA)

1. CME -- charge separation w.r.t reaction plane
2. CMW -- v_2 of π and *K* vs charge asymmetry
3. CVE -- see talks by Mike Lisa and Liwen Wen

A personal selection from many results that search for chiral effects. For more complete reviews:



DK, K. Landsteiner, A. Schmitt, H.U.Yee (Eds), "Strongly interacting matter in magnetic fields", Springer, 2013; arxiv:1211.6245

DK, "The chiral magnetic effect and anomaly-induced transport", Prog.Part.Nucl.Phys. 75 (2014) 133; arxiv: 1312.3348

DK, "Topology, magnetic field and strongly interacting matter", Ann. Rev. Nucl. Part. Science 65 (2015) 193; arxiv: 1501.01336;

DK, J.Liao, S.Voloshin, G.Wang, "Chiral magnetic effect in high-energy nuclear collisions – a status report", Prog.Part.Nucl.Phys. 88 (2016) 1; arxiv: 1511.04050

Chiral Magnetic Effect: magnetic field + chirality = current

The chiral anomaly of QCD creates differences in the number of left and right handed quarks.

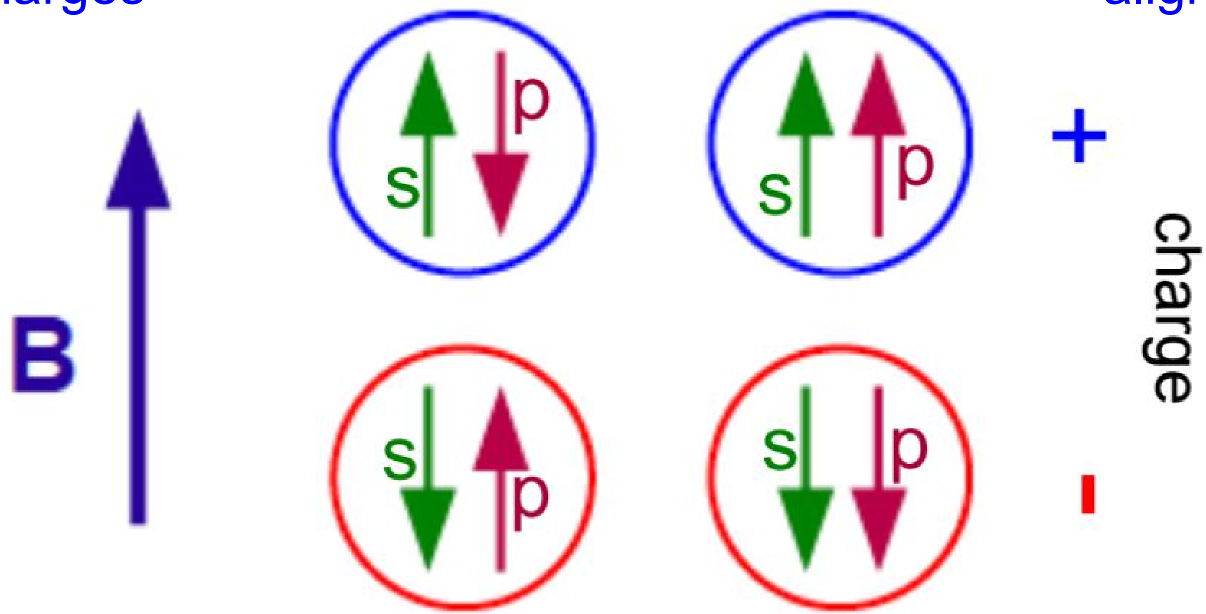
a similar mechanism in electroweak theory likely accounts for the matter/antimatter asymmetry of our universe

spin alignment in B-field:
opposite directions for opposite charges

handedness:
momentum and spin, aligned or anti-aligned

chirality

left right



negative goes up
positive goes down

positive goes up
negative goes down

courtesy of P.Sorensen

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

An excess of right or left handed quarks lead to a current flow along the magnetic field.

Chiral magnetic effect in $ZrTe_5$

nature physics

Qiang Li, Dmitri E. Kharzeev, Cheng Zhang, Yuan Huang, I. Pletikosić, A. V. Fedorov, R. D. Zhong, J. A. Schneeloch, G. D. Gu & T. Valla

Nature Physics 12, 550 (2016)

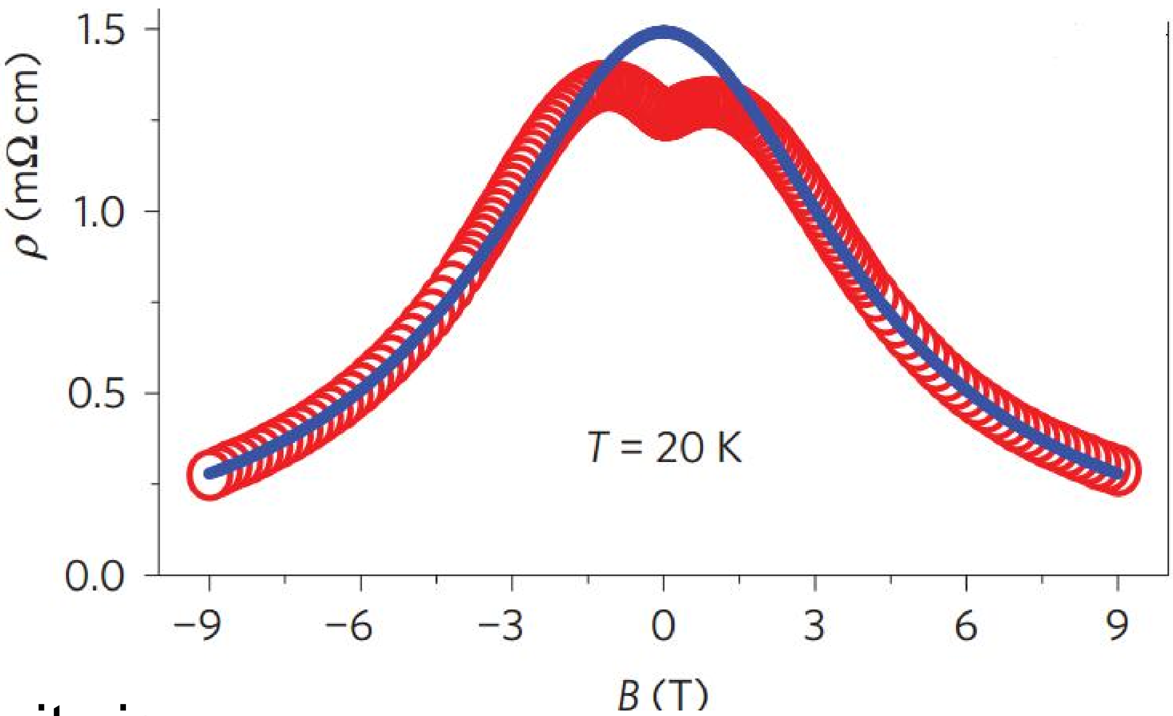
$$\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Man-made chirality:

$$\mu_5 = \frac{3}{4}\frac{v^3}{\pi^2}\frac{e^2}{\hbar^2 c}\frac{\mathbf{E}\cdot\mathbf{B}}{T^2+\frac{\mu^2}{\pi^2}}\tau_V$$

When E||B, CME conductivity is

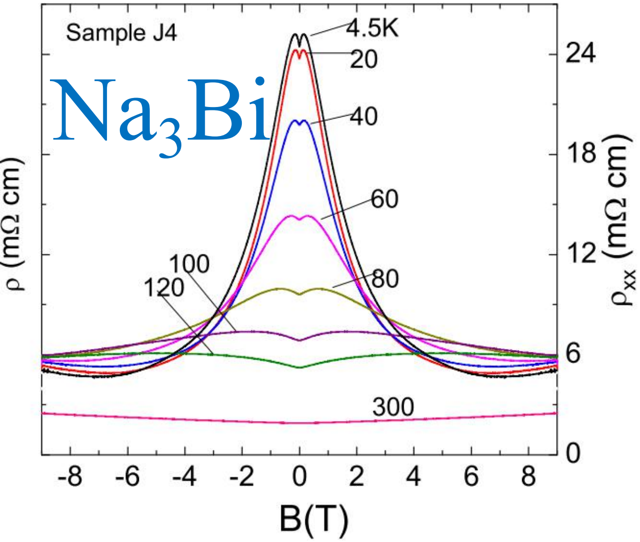
$$\sigma^{zz}_{\mathrm{CME}} = \frac{e^2}{\pi\hbar}\frac{3}{8}\frac{e^2}{\hbar c}\frac{v^3}{\pi^3}\frac{\tau_V}{T^2+\frac{\mu^2}{\pi^2}}B^2$$



B dependence of the negative magnetoresistance is nicely fitted with CME contribution to the electrical conductivity.

A whole industry of CME in semimetals...

Dirac semimetal



Na_3Bi

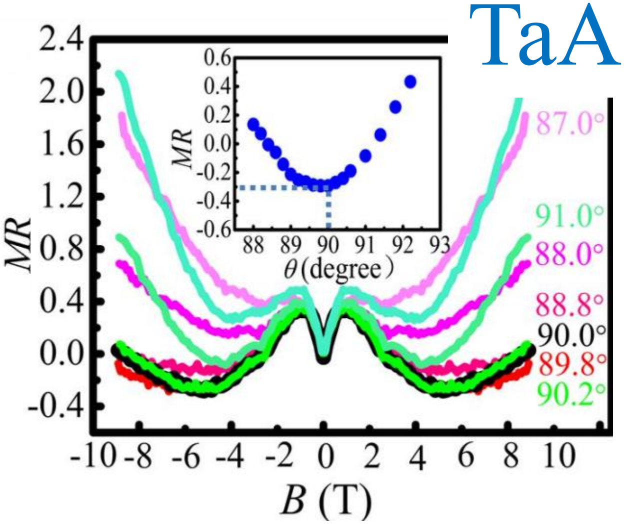
$ZrTe_5$ - Q. Li, D. Kharzeev, et al (BNL and Stony Brook Univ.) arXiv:1412.6543; Nature Physics 12, 550 (2016)

Na_3Bi - J. Xiong, N. P. Ong et al (Princeton Univ.) arxiv:1503.08179; Science 350:413,2015

Cd_3As_2 - C. Li et al (Peking Univ. China) arxiv:1504.07398; Nature Commun. 6, 10137 (2015).

Weyl semimetal

TaAs



TaAs - X. Huang et al (IOP, China) arxiv:1503.01304; Phys. Rev. X 5, 031023

NbAs - X. Yang et al (Zhejiang Univ. China) arxiv:1506.02283

NbP - Z. Wang et al (Zhejiang Univ. China) arxiv:1504.07398

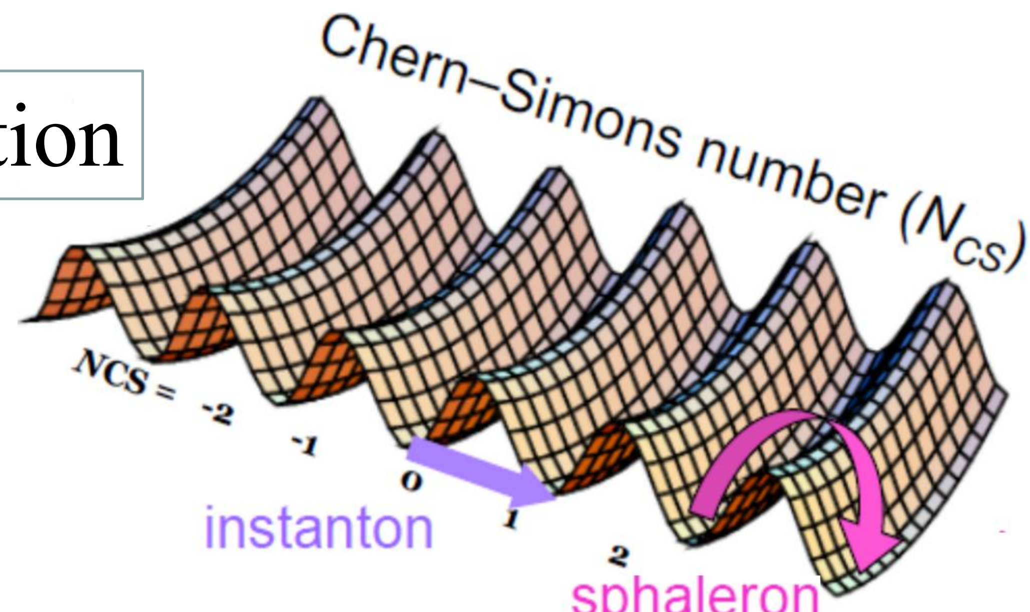
TaP - Shekhar, C. Felser, B. Yang et al (MPI-Dresden) arxiv:1506.06577

Why study CME in heavy-ion collisions?

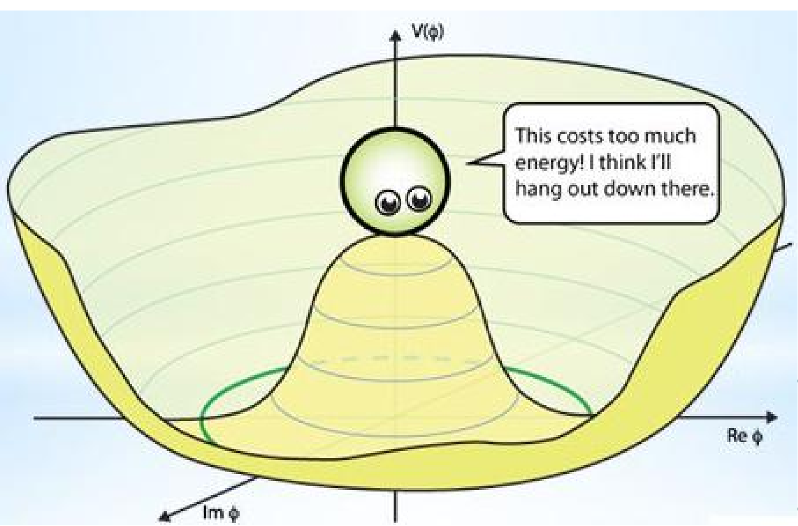
Understand 1) the strong B field and many fancy effects

Y. Hirono, D. E. Kharzeev and Y. Yin PRD 92,125031 (2015)

2) vacuum transition

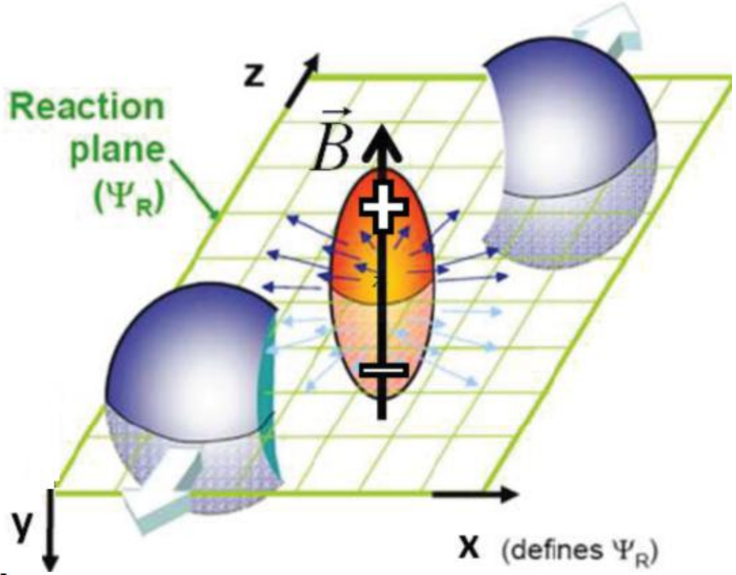


D. Diakonov, Prog. Part. Nucl. Phys. 51, 173 (2003)



3) chiral symmetry restoration

CME observable: direct measurement?

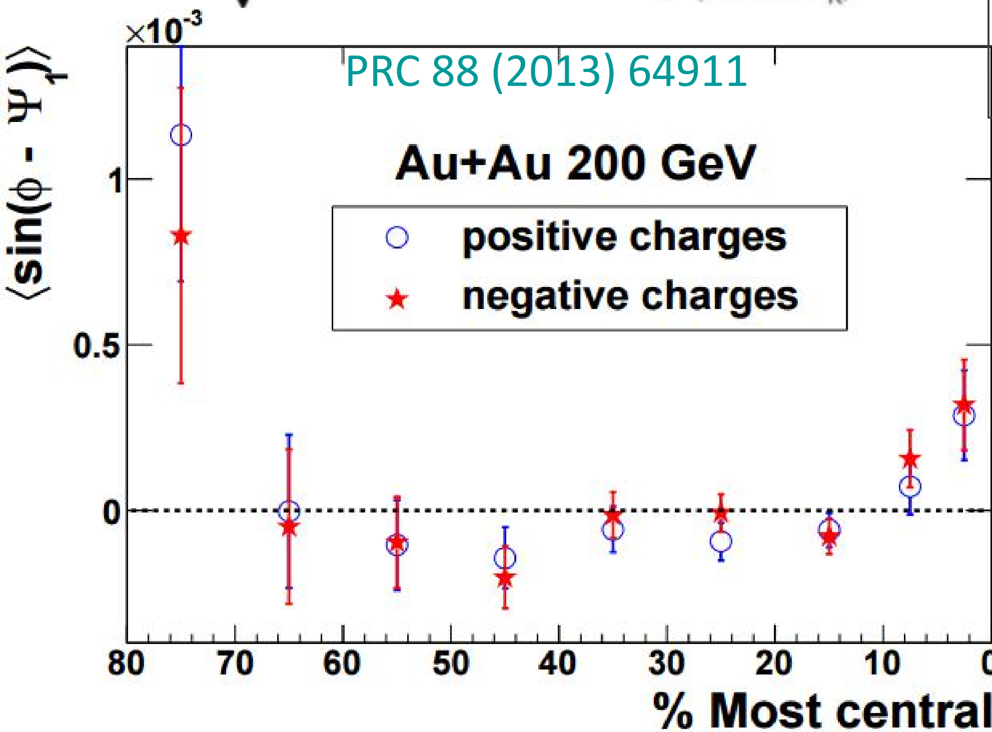


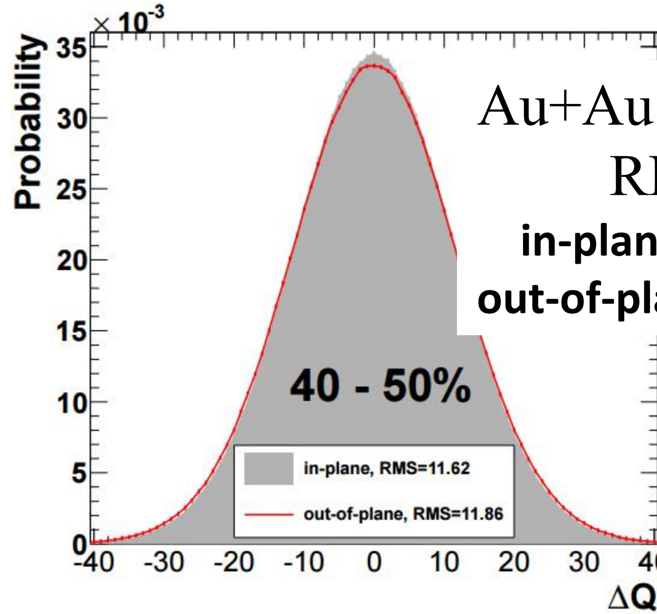
$$\frac{dN_\pm}{d\phi} \propto 1 + 2a_\pm \cdot \sin\left(\phi^\pm - \Psi_{RP}\right)$$

A direct measurement of *P*-odd quantity *"a"* should yield *zero*.

There should be more out-of-plane charge fluctuation than in-plane.
Indeed, we see this effect, which is on percent level!

PRC 88 (2013) 64911





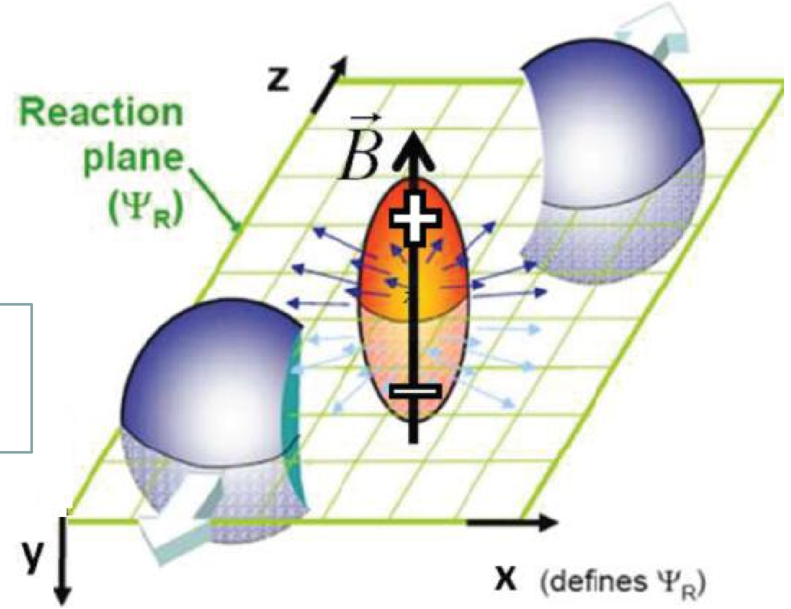
Au+Au 200 GeV
RMS:
in-plane = 11.62
out-of-plane = 11.86

CME observable: γ correlator

S. Voloshin, PRC 70 (2004) 057901

A better way to quantify the extra charge fluctuation.

A few similar observables yield similar results



$$\gamma = \left\langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \right\rangle$$

$$= \left[\left\langle v_{1,\alpha} v_{1,\beta} \right\rangle + B_{in} \right] - \left[\left\langle a_\alpha a_\beta \right\rangle + B_{out} \right]$$

Directed flow: expected to be the same for SS and OS

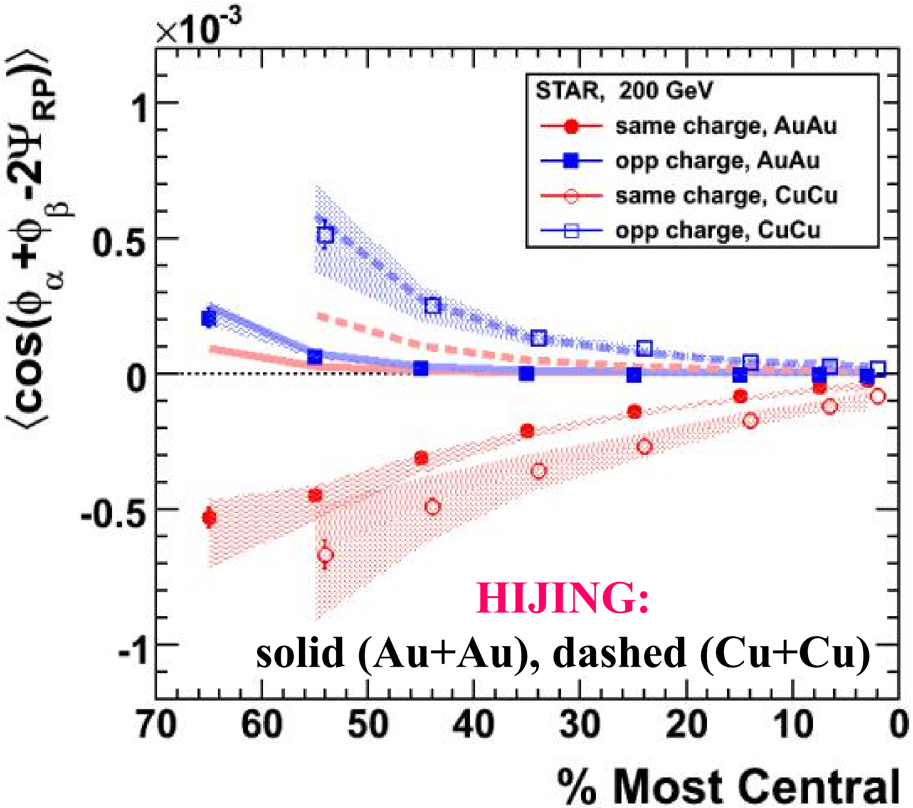
background effects: largely cancel out

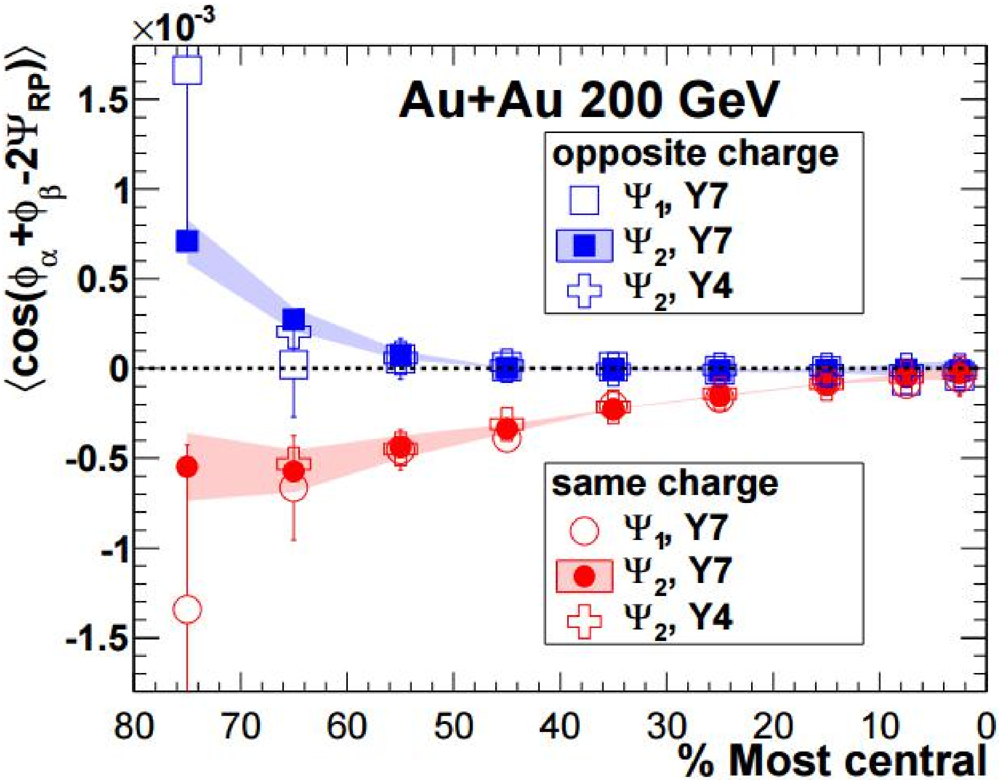
P-even quantity: still sensitive to charge separation

$$\frac{B_{in} - B_{out}}{B_{in} + B_{out}} = v_{2,cl} \frac{\left\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{cl}) \right\rangle}{\left\langle \cos(\phi_\alpha - \phi_\beta) \right\rangle}$$

Charge separation signal

PRL 103(2009)251601;PRC 81(2010)54908;PRC 88 (2013) 64911

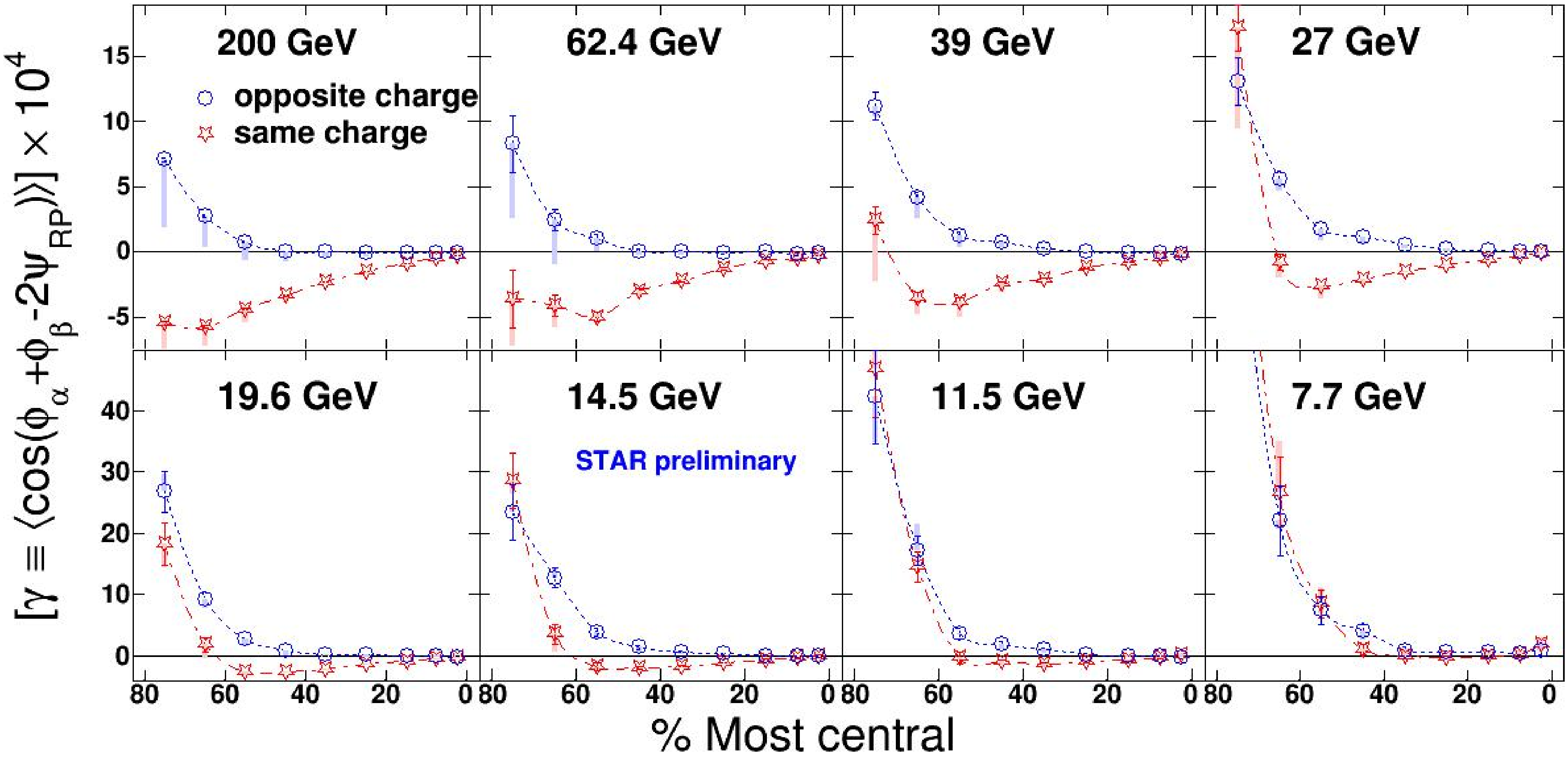




- γ_{os} > γ_{ss}, consistent with CME expectation
- signal in Cu+Cu larger than Au+Au: later-stage effect?
- Consistent between different years (2004 and 2007)
- Confirmed with 1st-order EP (from spectator neutron v_1)

Beam Energy Scan

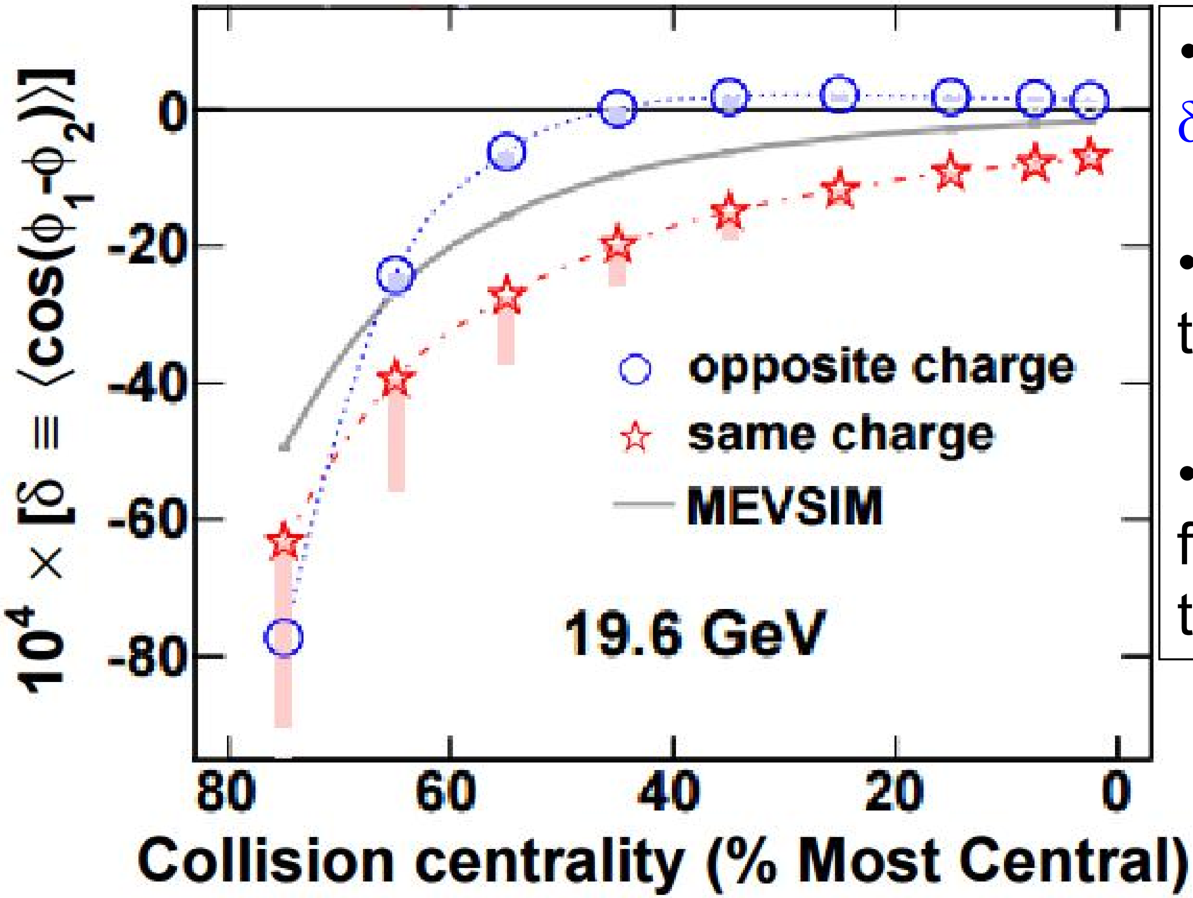
PRL 113 (2014) 052302



At lower beam energies, charge separation starts to diminish.

v_2-related background

PRL 113 (2014) 052302



- Against CME expectation, $\delta_{OS} > \delta_{SS}$
- Overwhelming bg, larger than any CME effect.
- Combine information from γ and δ, and retrieve the CME contribution, *H*

$$
\begin{aligned}
\gamma &\equiv \langle\cos(\phi_1 + \phi_2 - 2\Psi_{RP})\rangle = \kappa v_2 F - H \\
\delta &\equiv \langle\cos(\phi_1 - \phi_2)\rangle = F + H,
\end{aligned}
$$

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

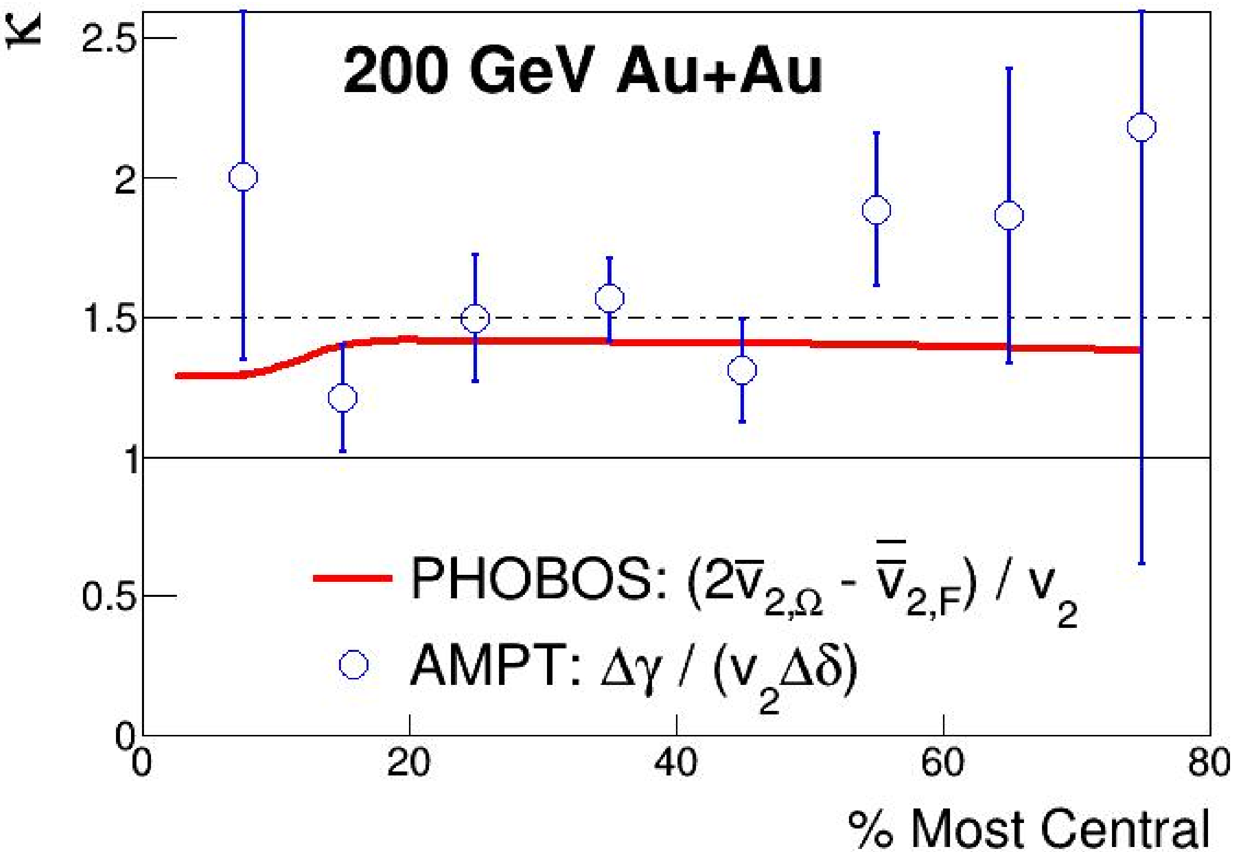
κ estimates

If γ measurements are dominated by v_2 + trans. momentum conservation,

$$\gamma / \delta \approx 2\overline{v}_{2,\Omega} - \overline{\overline{v}}_{2,F}$$

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

where F and Ω denote particle averages in the full phase-space and the detector acceptance, respectively. **TMC:** $\kappa \approx (2\overline{v}_{2,\Omega} - \overline{\overline{v}}_{2,F}) / v_2$

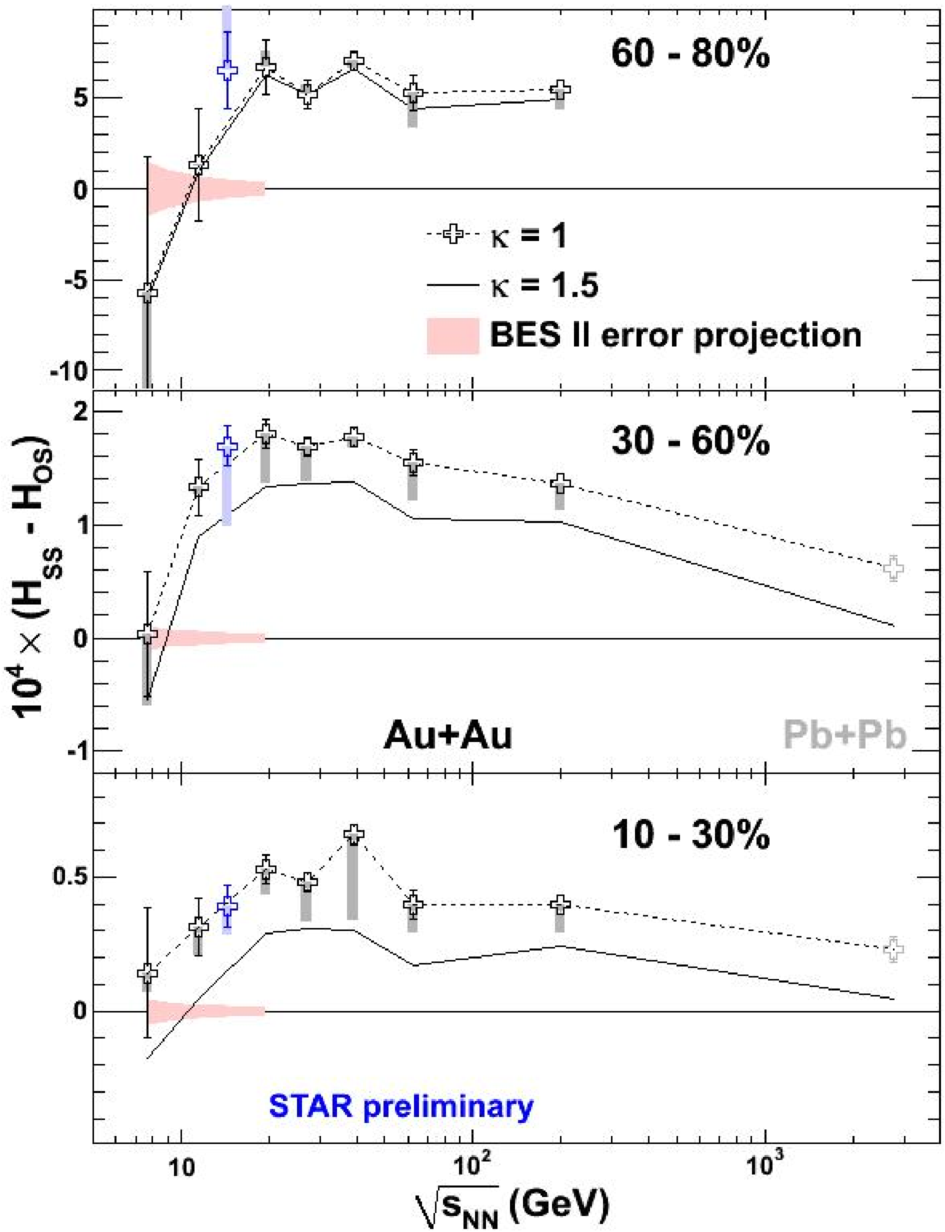


Other effects: **Local Charge Conservation (LCC)** and **resonance decay.** AMPT indicates similar **κ** with **Δγ/(v_2Δδ)**.

PHOBOS, PRC 72 014904 (2005); PRC 83 024913 (2001)

CME contribution

PRL 113 (2014) 052302



$$H^{\kappa} = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$$

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

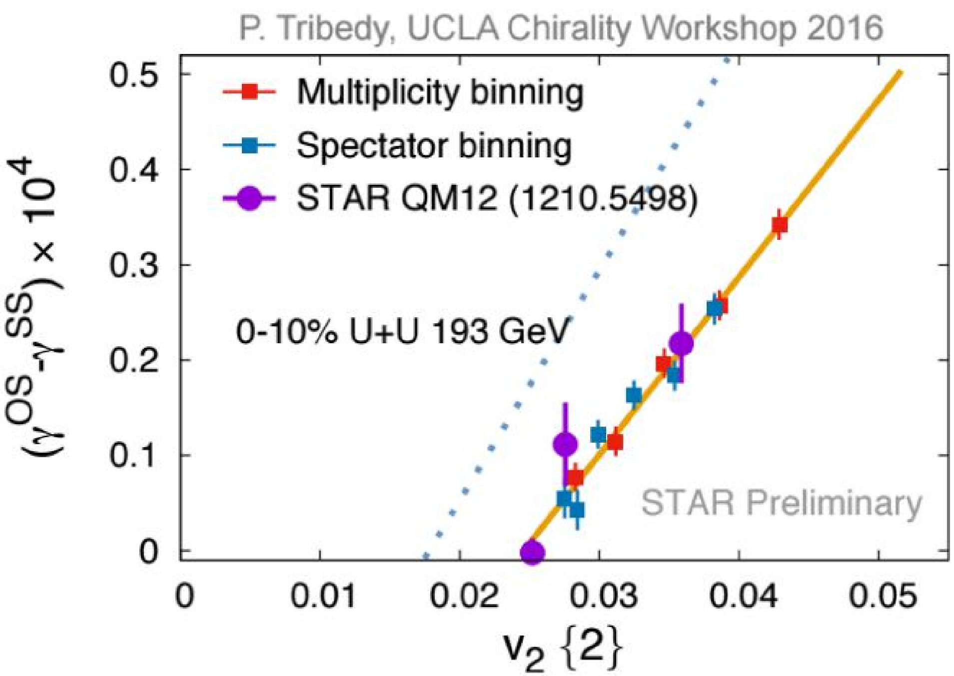
- κ is roughly contained in the range of [1, 1.5].
- CME signal (ΔH) decreases to 0 from 19.6 to 7.7 GeV
- Probable domination of hadronic interactions over partonic ones
- Need more study of κ and more statistics

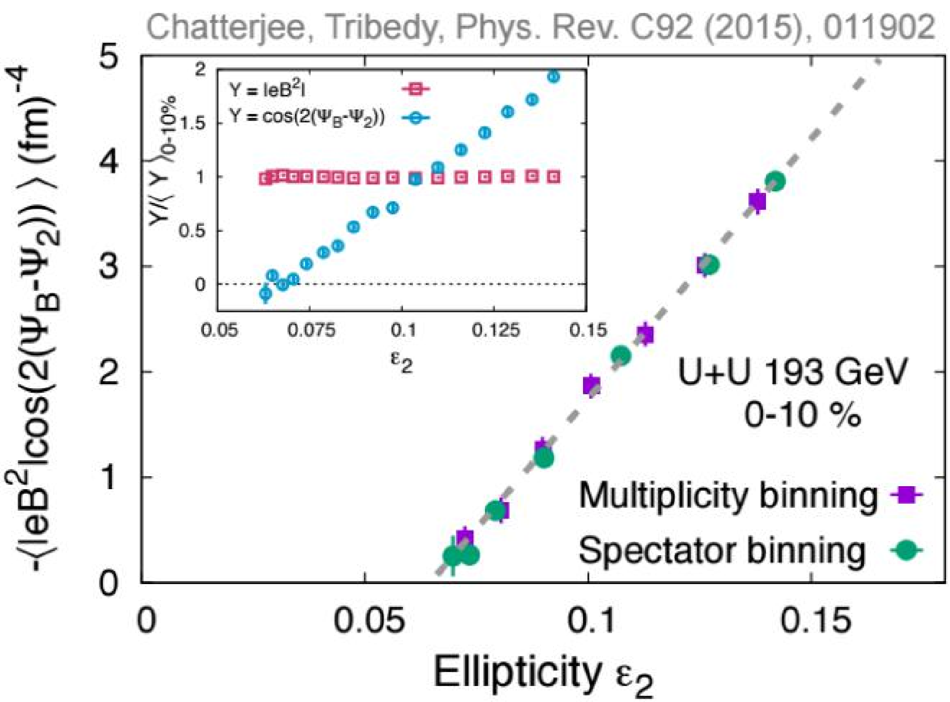
U+U

To disentangle the signal and the background, we vary

1) the background (central Au+Au and U+U)

2) the signal (min.bias Zr+Zr and Ru+Ru)





$\Delta\gamma$ in central U+U collisions follows the projected B-field, not v_2.

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	~
CME	>
CMW	>
CVE	~

MC Glauber

- Glauber parameters re-adjusted to make Wood-Saxon correct
- 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.

Q. Y. Shou, Y. G. Ma, P. Sorensen, A. H. Tang, F. Videbæk, H. Wang, PLB749,215 (2015)

		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*

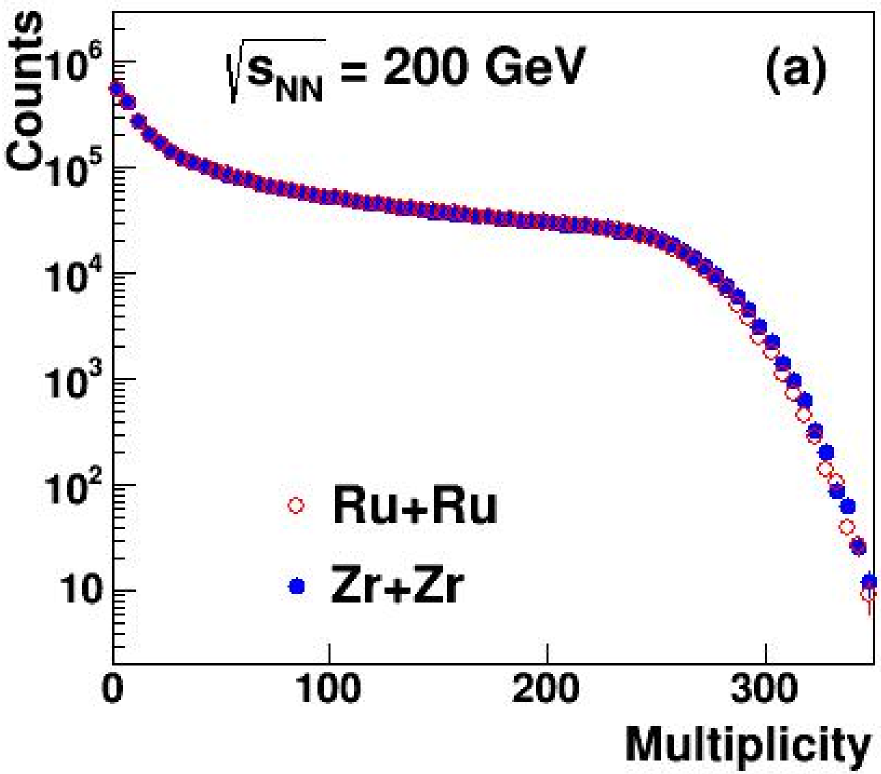
case 1: Zr96 Set 1 β2 < Ru96 Set 1 β2

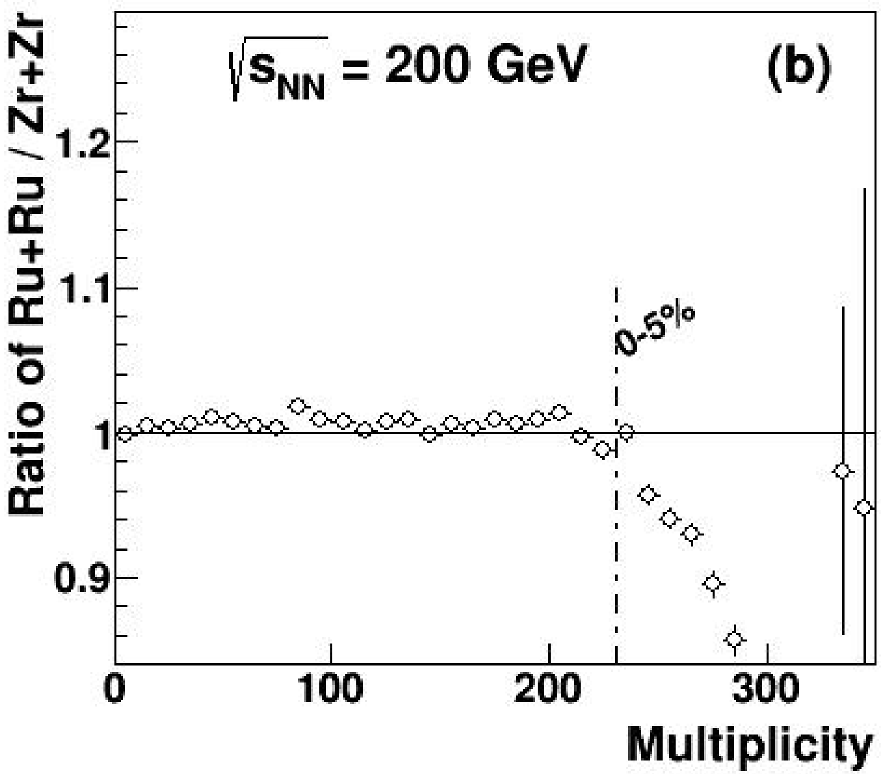
case 2: Zr96 Set 2 β2 > Ru96 Set 2 β2

multiplicity: Case 1

- Parameters from B(E2)↑ measured in e-A scattering experiment
- The ratio is close to 1 except for 0-5% most central events

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

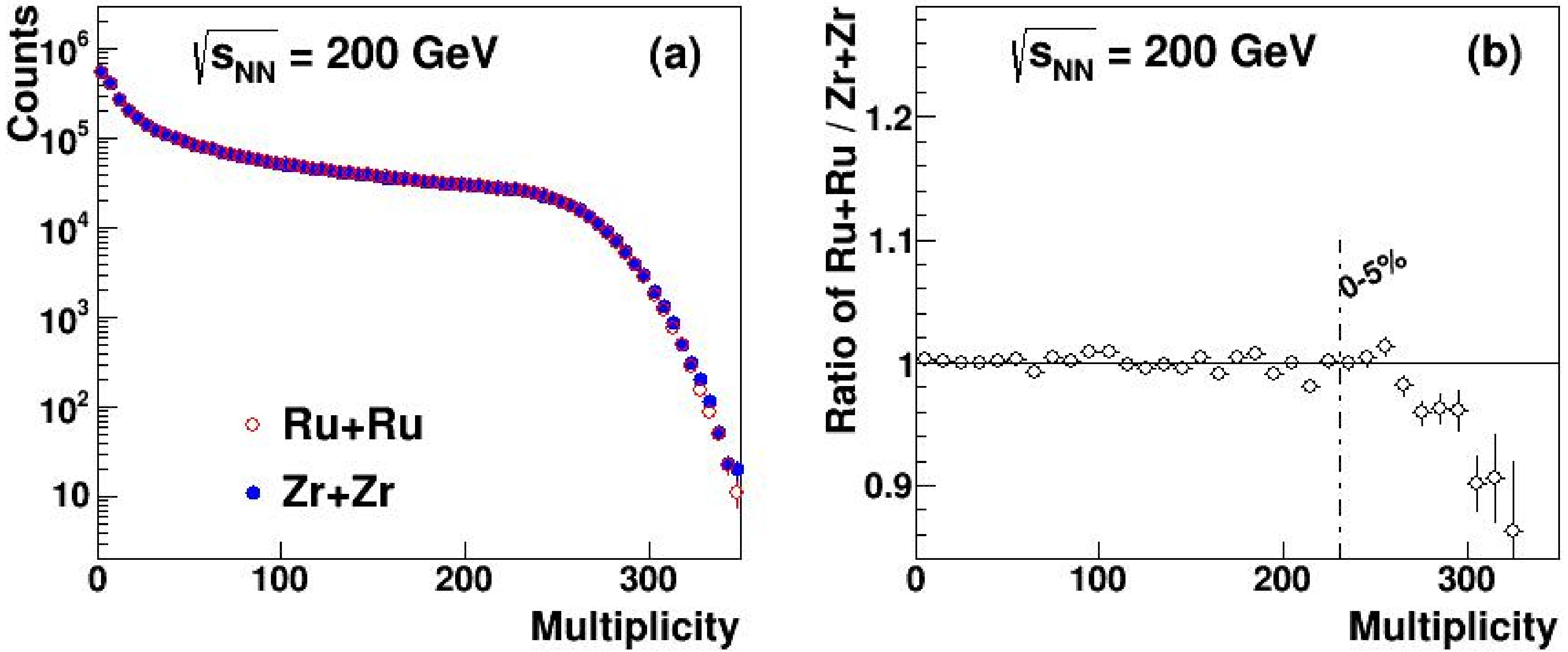




multiplicity: Case 2

- Parameters from a comprehensive model deduction
- The ratio is close to 1 except for 0-5% most central events

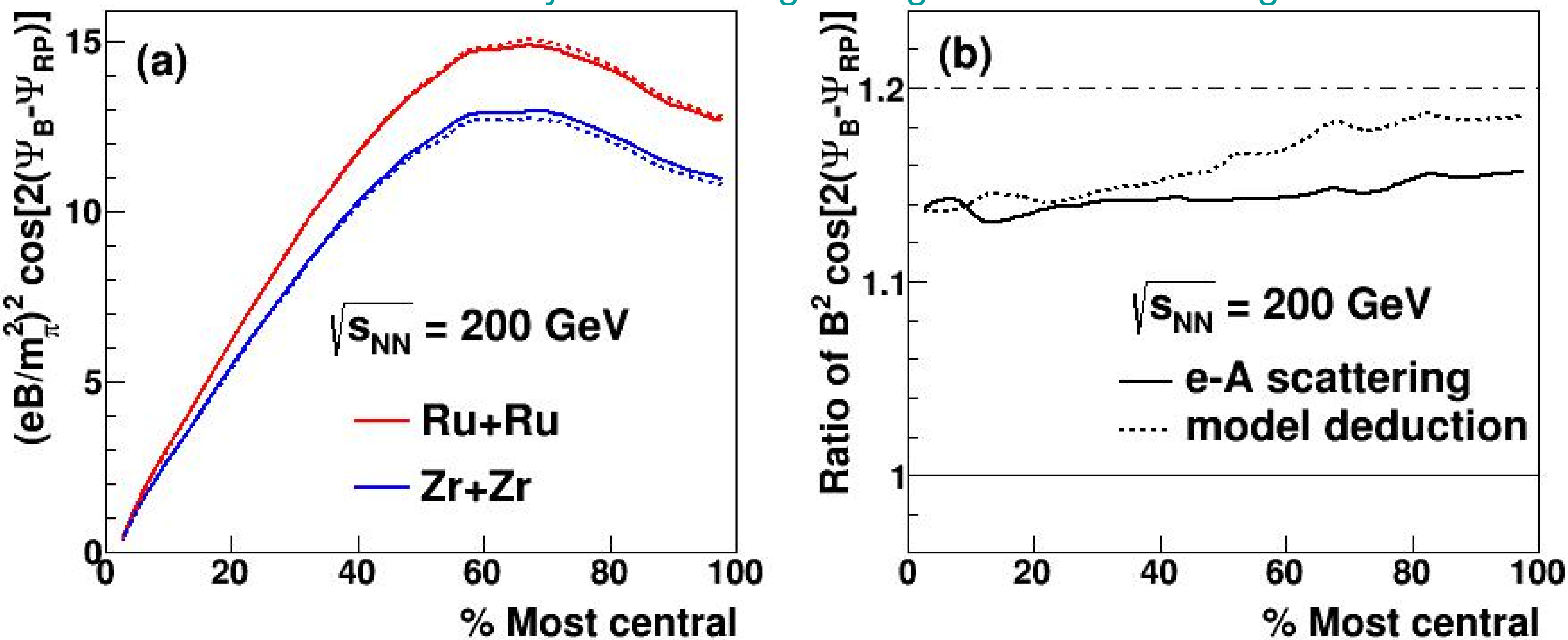
	R_0 [fm]	a(d) [fm]	β_2
^{96}Zr	5.06	0.46	0.18
^{96}Ru	5.13	0.46	0.03



B field

- B calculated at t=0, at one point (center of mass of participants)
- B field slightly affected by β_2
- The ratio in B^2 is close to 1.18 for peripheral events
- Reduces to 1.14 for central events

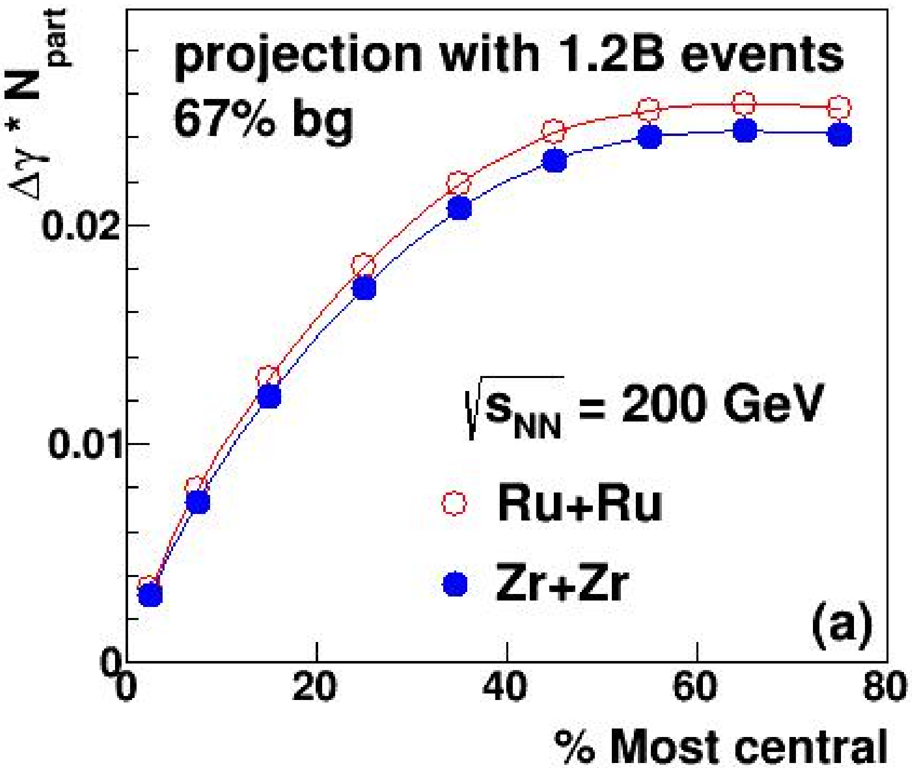
Courtesy of Xu-Guang Huang and Wei-Tian Deng

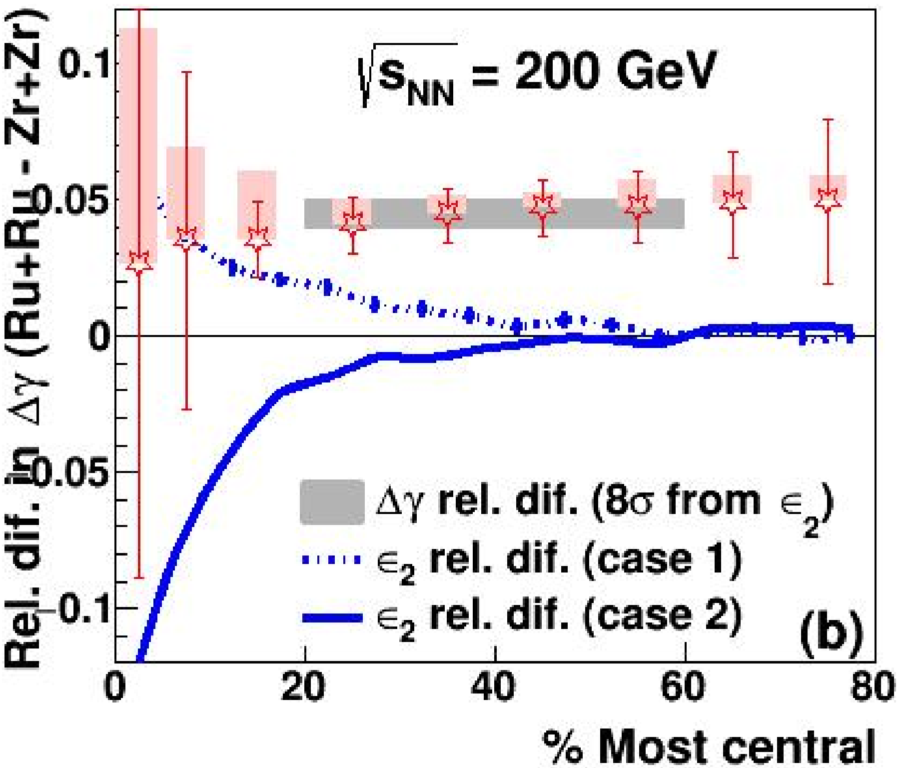


W. -T. Deng and X. -G. Huang, PRC 85 (2012) 044907; PLB 742 (2015)296

charge separation: γ (2/3 bg)

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

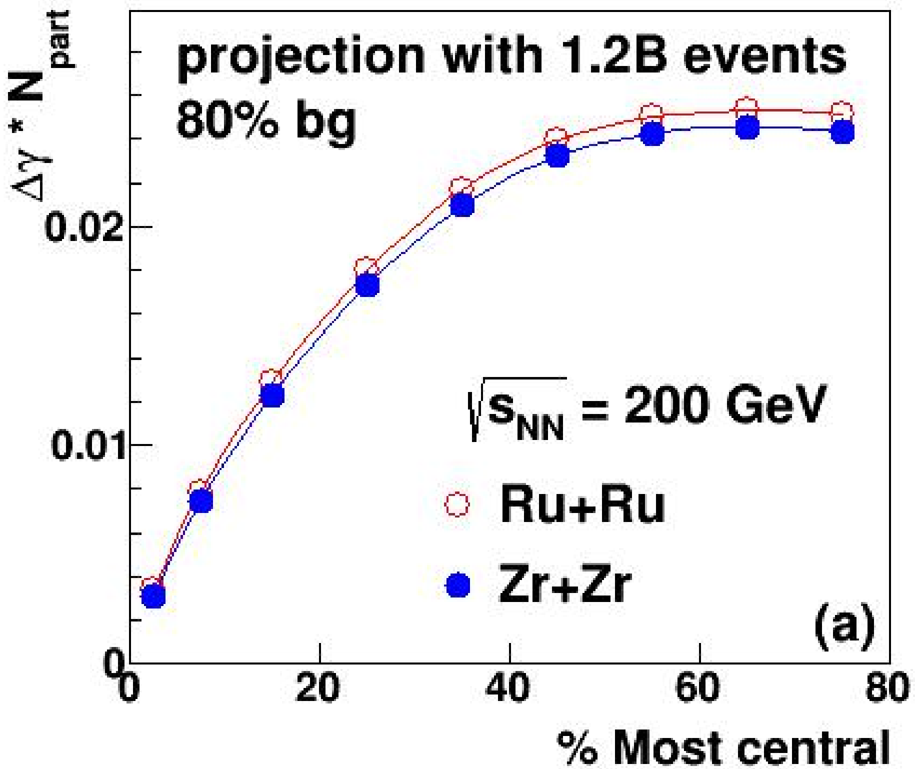


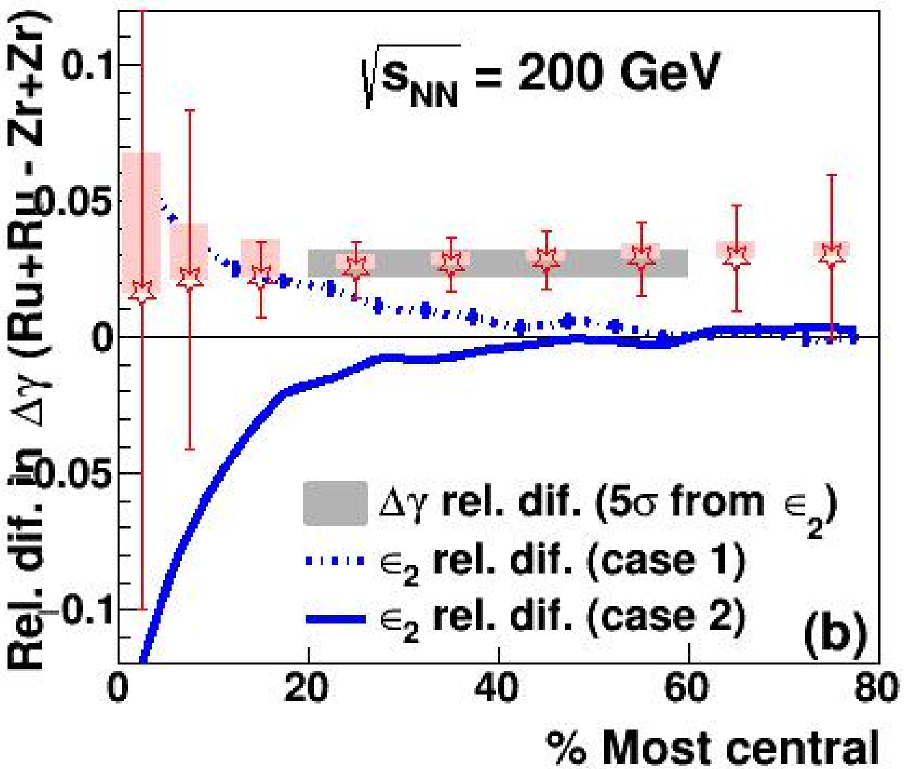


red star: case 1; pink box: case 2

charge separation: γ (80% bg)

- Projection with 1.2B events from each collision type
- If it's v_2-driven, rel. dif. will follow eccentricity (~0 for 20-60%)
- If it's 20% CME-driven, the difference in Δγ is 5σ above ε_2.

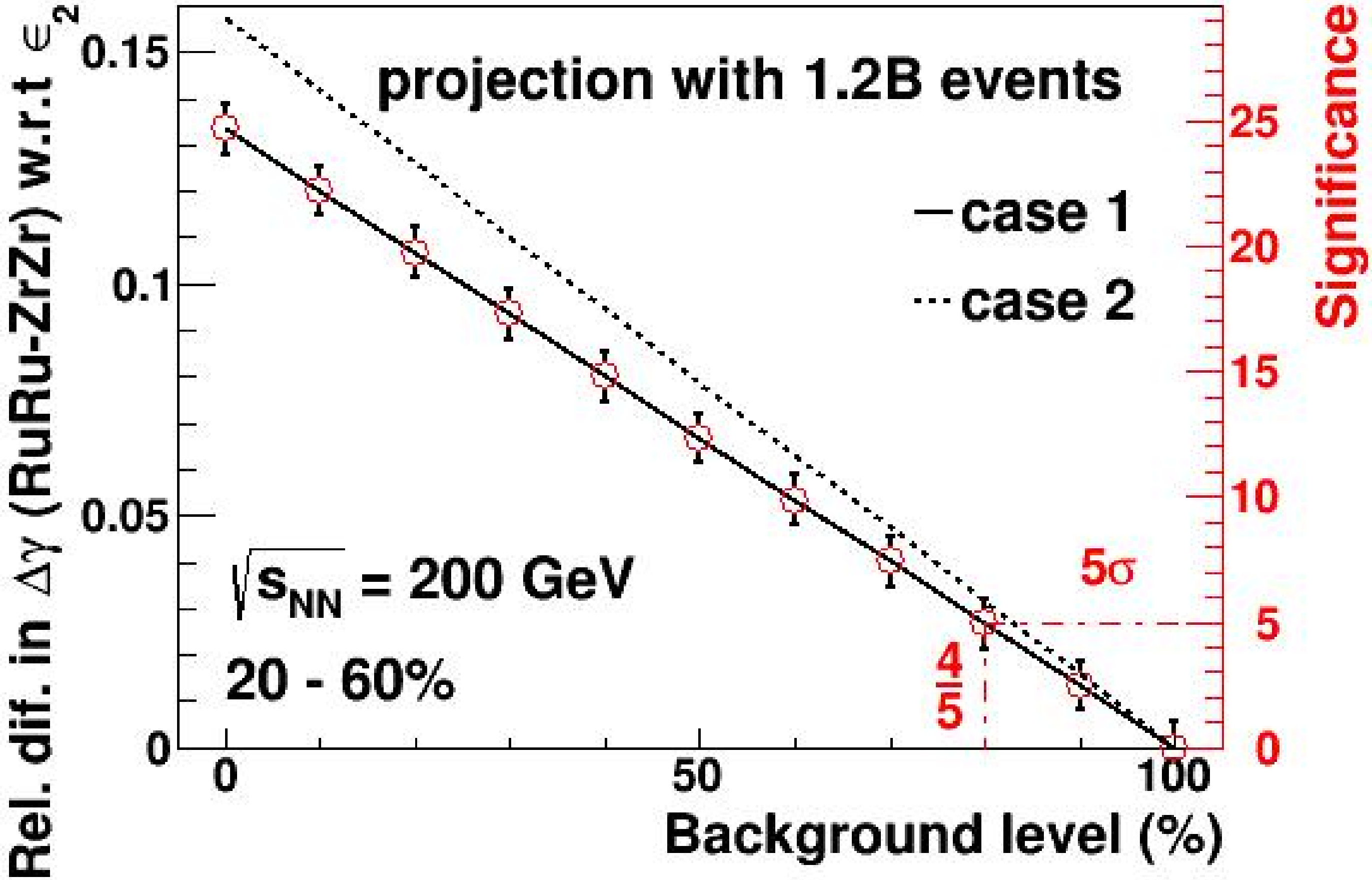




red star: case 1; pink box: case 2

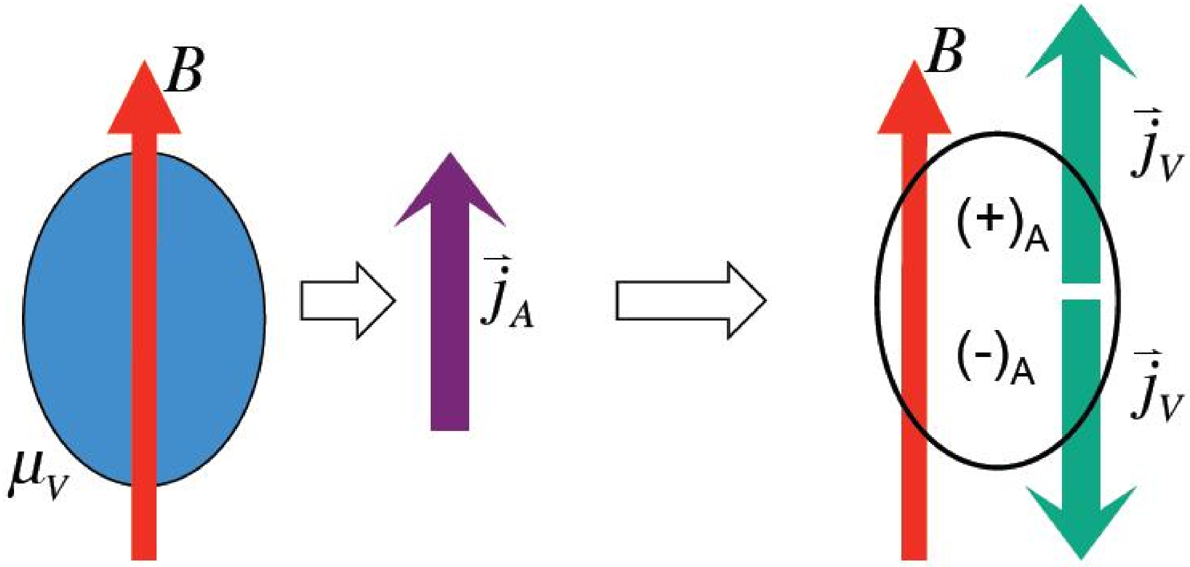
significance vs bg

- Projection with 1.2B events from each collision type
- significance of the difference in Δγ depends on bg level
- case 2 is slightly better than case 1



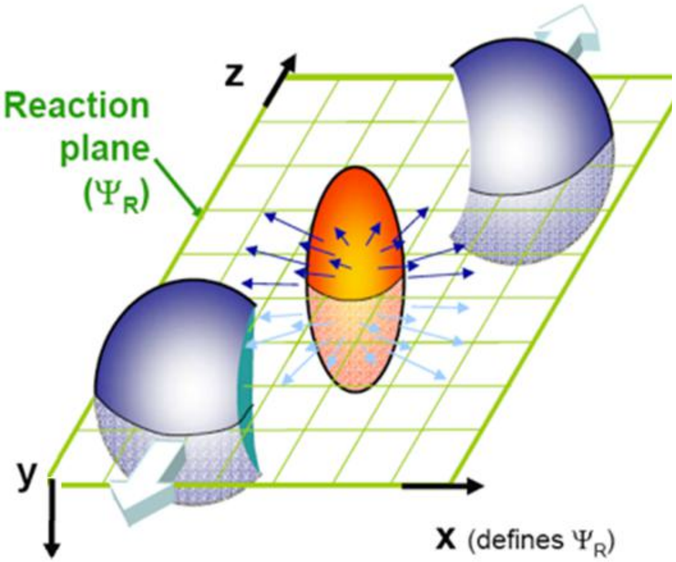
Hopefully isobaric collisions will have final word on background!

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



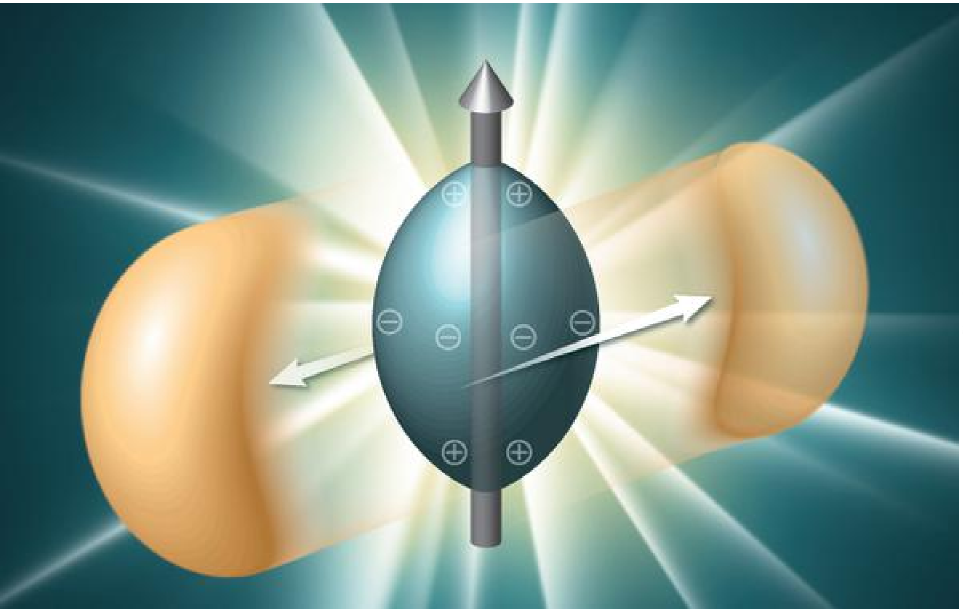
$$j_A = \frac{N_c e}{2\pi^2}\mu_V B \qquad j_V = \frac{N_c e}{2\pi^2}\mu_A B$$

Chiral Separation Effect | **Chiral Magnetic Effect**

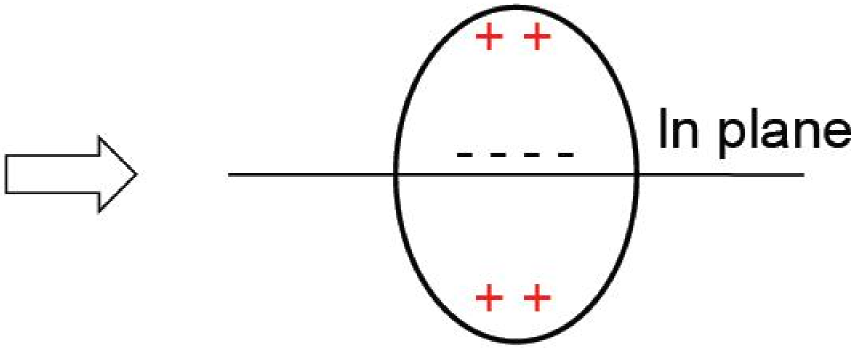


CSE + CME → Chiral Magnetic Wave:
- collective excitation
- signature of chiral symmetry restoration

Observable



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



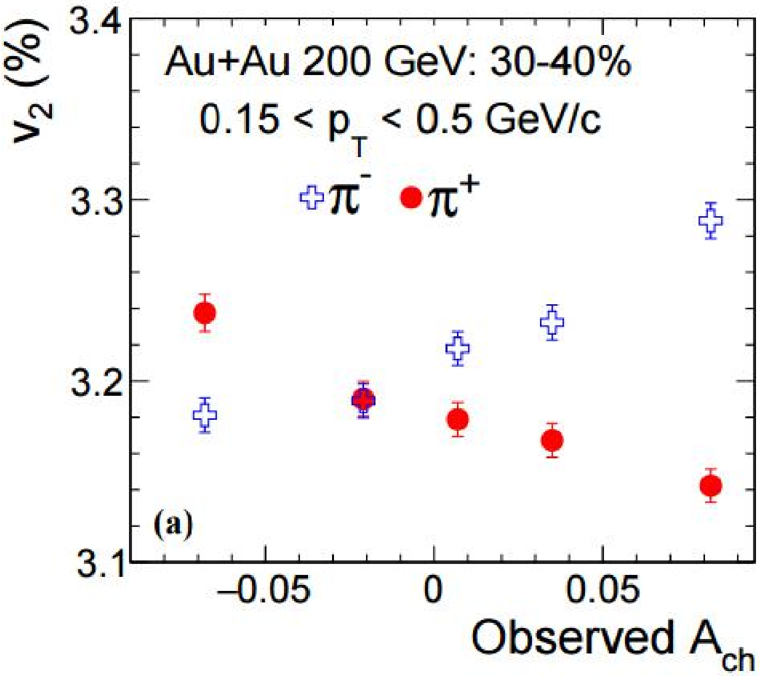
Formation of electric quadrupole: $v_2^{\pm} = v_2^{\text{base}} \mp \left(\frac{q_e}{\bar{\rho}_e}\right) A_{\text{ch}}$,

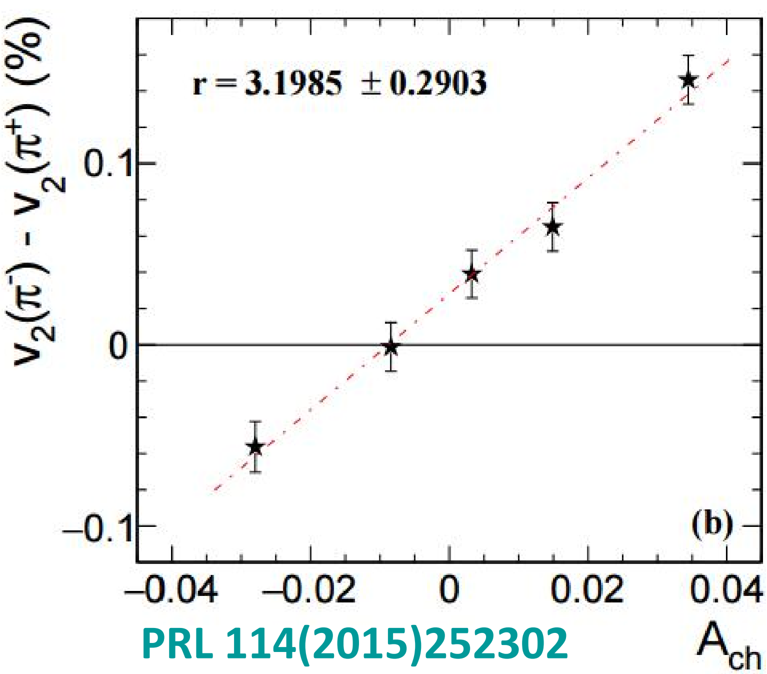
(q_e: quadrupole moment; $\bar{\rho}_e$: net charge density)

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

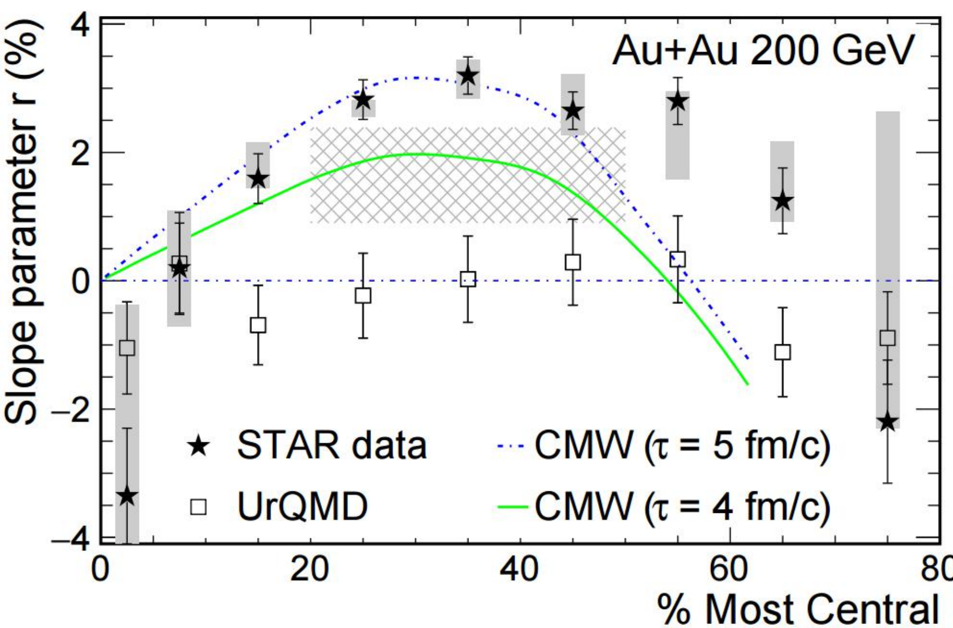
Then π^- v_2 should have a positive slope as a function of A_{ch},
and π^+ v_2 should have a negative slope with the same magnitude.

v_2 vs A_{ch}





PRL 114(2015)252302



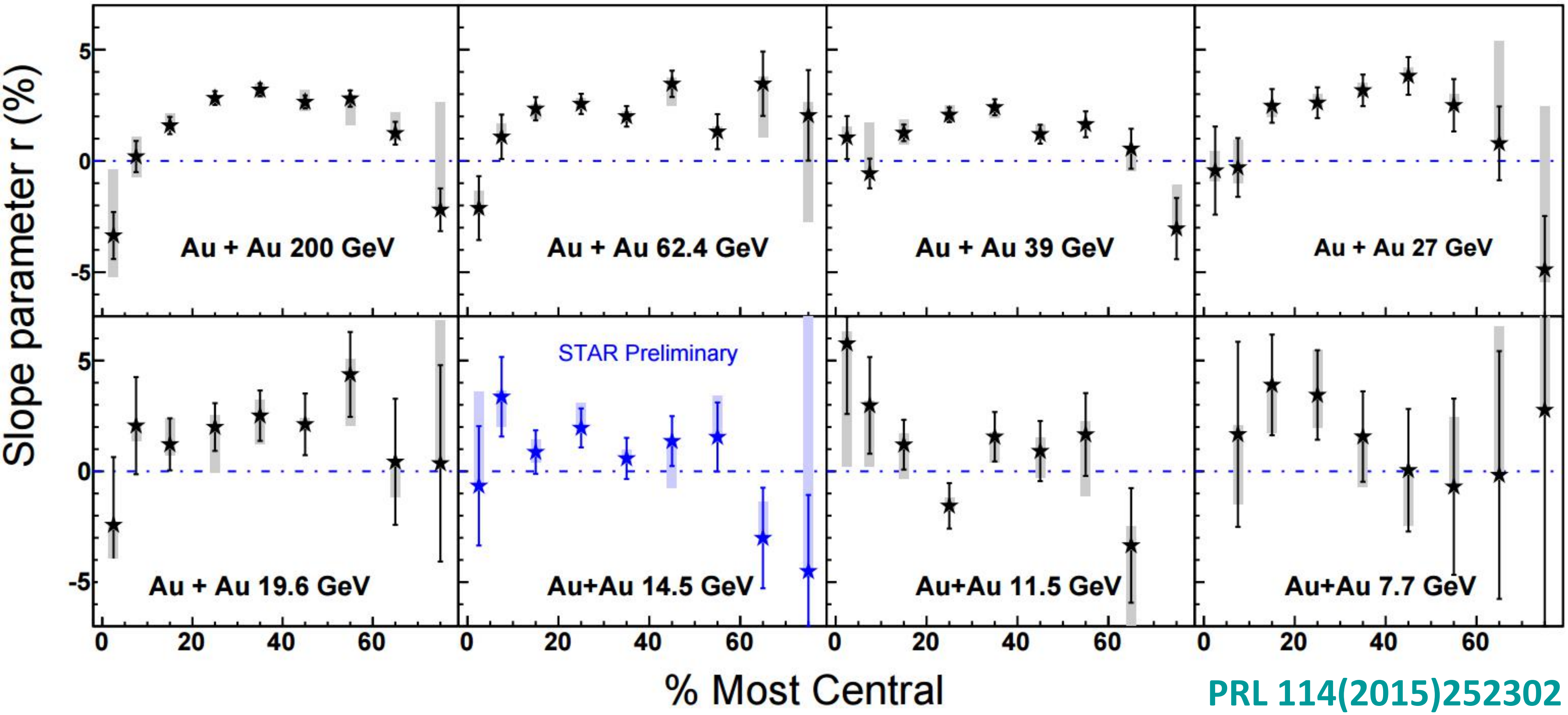
Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, arXiv:1208.2537v1 [hep-ph].

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

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

Beam Energy Scan

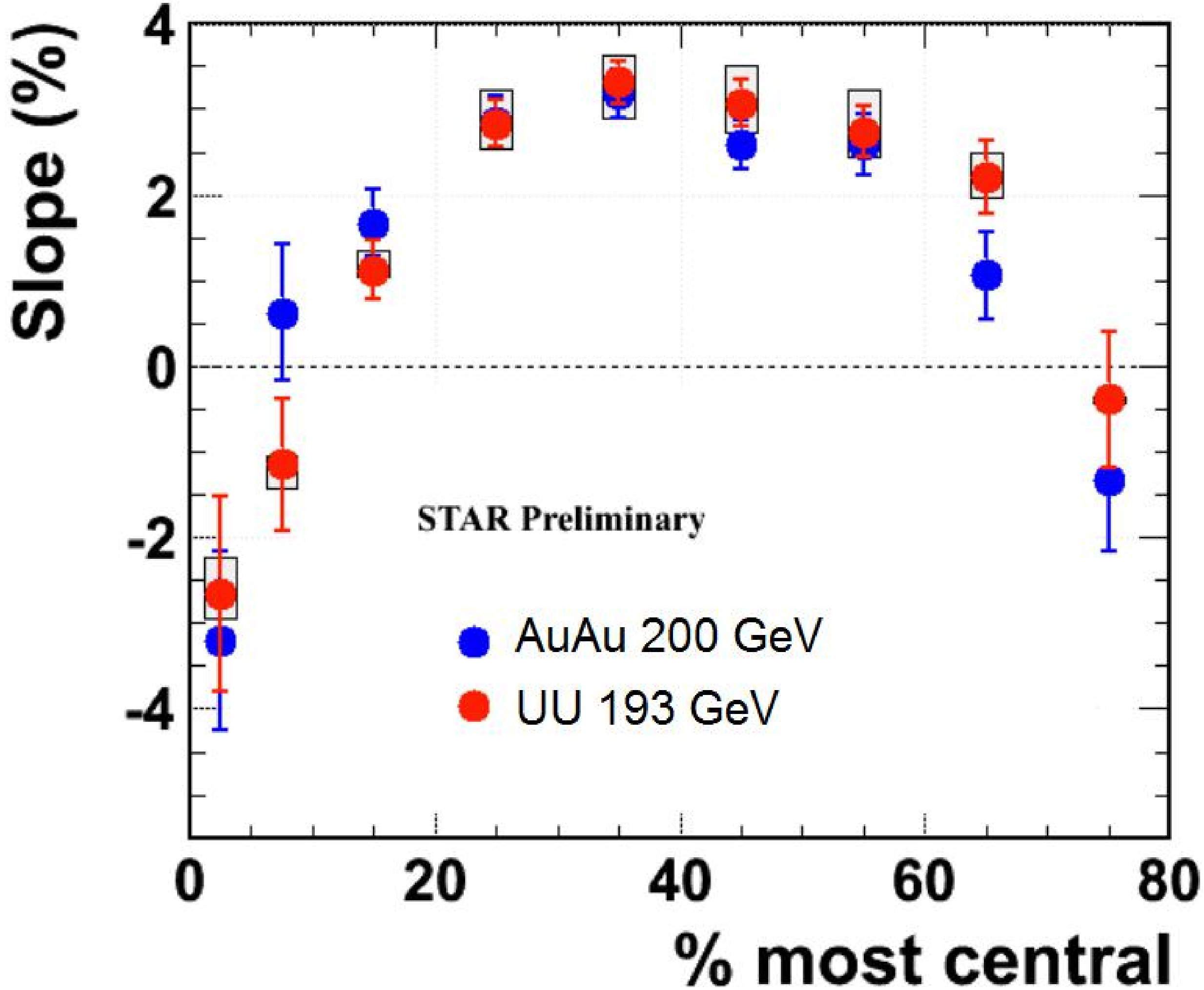
Similar trends are observed for different beam energies down to 19.6 GeV. Below 19.6 GeV, more statistics are needed.



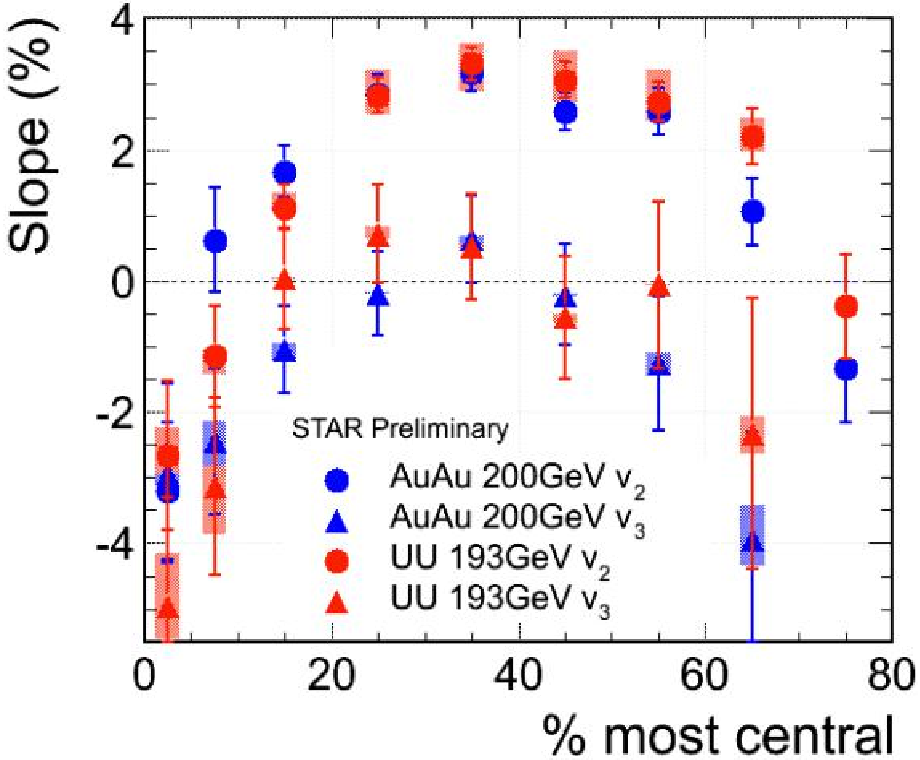
PRL 114(2015)252302

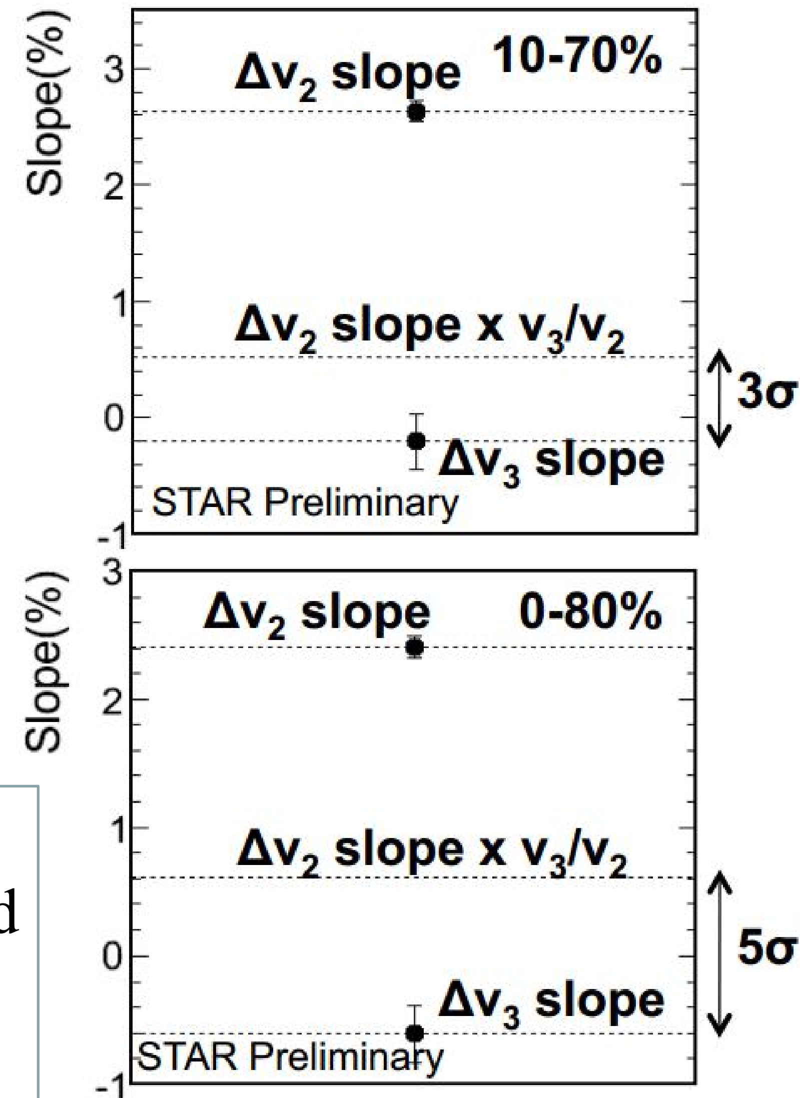
U+U

Similar pattern and magnitude seen in U+U collisions.



Δ v_3 slope



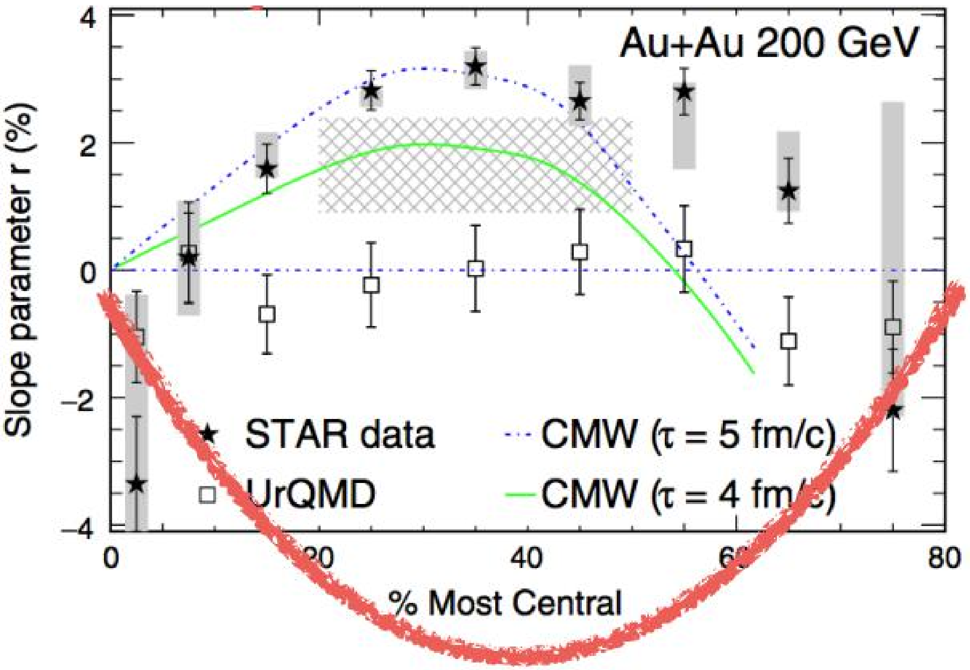


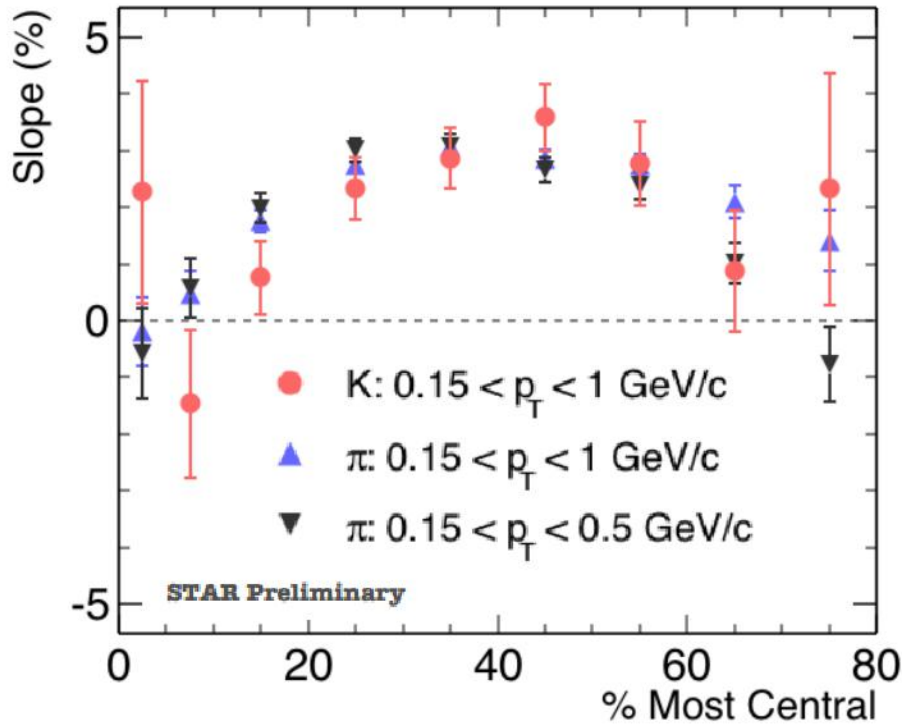
Local charge conservation may introduce A_{ch} dependence of $\Delta v_2(\pi)$. Then one should see **slope-for-Δv_3 / slope-for-Δv_2 ~ v_3/v_2** (Bzak & Bozek PLB 726(2013)239).

STAR measurement:

such mechanism alone cannot explain data.

kaon Δv_2 slope

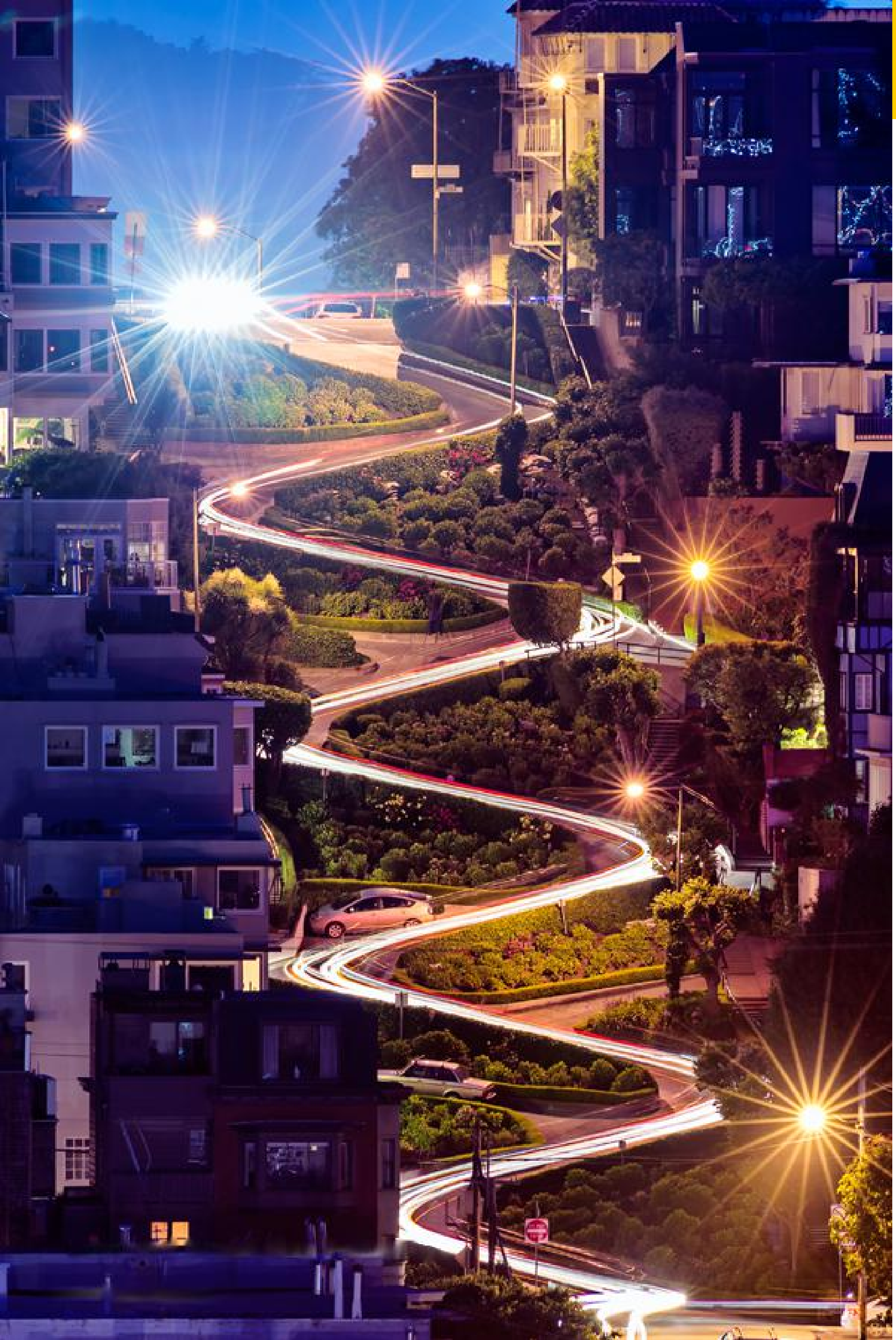




Hydrodynamics study (no CMW): kaon slope should be opposite to π slope with larger magnitude, since
$v_2(\pi^+) < v_2(\pi^-)$
$v_2(K^+) > v_2(K^-)$

Y. Hatta et al. NPA 947 (2016) 155

STAR measurements: kaon slope parameters behave similarly to those of π, not opposite.



Summary

a long and winding road,
and still miles to go ...

but highlights here
and there ...

Backup slides

Transverse momentum conservation

$$\gamma = -\frac{1}{N_{\text{tot}}} \frac{\langle p_t \rangle_\Omega^2}{\langle p_t^2 \rangle_F} \frac{2\bar{v}_{2,\Omega} - \bar{\bar{v}}_{2,F} - \bar{\bar{v}}_{2,F}(\bar{v}_{2,\Omega})^2}{1 - (\bar{\bar{v}}_{2,F})^2},$$

$$\delta = -\frac{1}{N_{\text{tot}}} \frac{\langle p_t \rangle_\Omega^2}{\langle p_t^2 \rangle_F} \frac{1 + (\bar{v}_{2,\Omega})^2 - 2\bar{\bar{v}}_{2,F}\,\bar{v}_{2,\Omega}}{1 - (\bar{\bar{v}}_{2,F})^2},$$

we have introduced certain weighted moments of v_2:

$$\bar{v}_2 = \frac{\langle v_2(p_t,\eta) p_t \rangle}{\langle p_t \rangle}, \qquad \bar{\bar{v}}_2 = \frac{\langle v_2(p_t,\eta) p_t^2 \rangle}{\langle p_t^2 \rangle}.$$

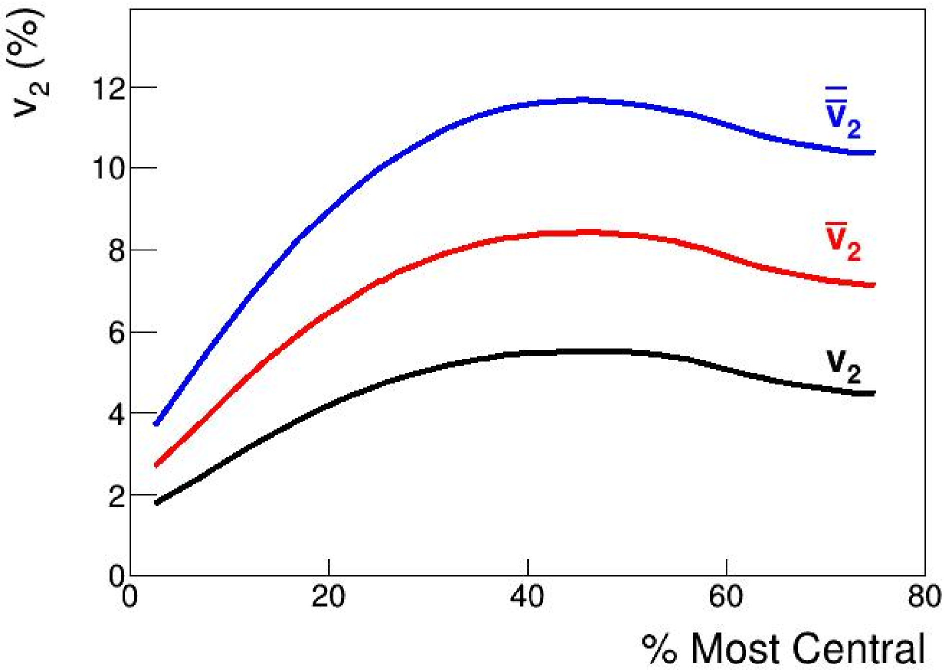
If our measurements are dominated by this type of background,

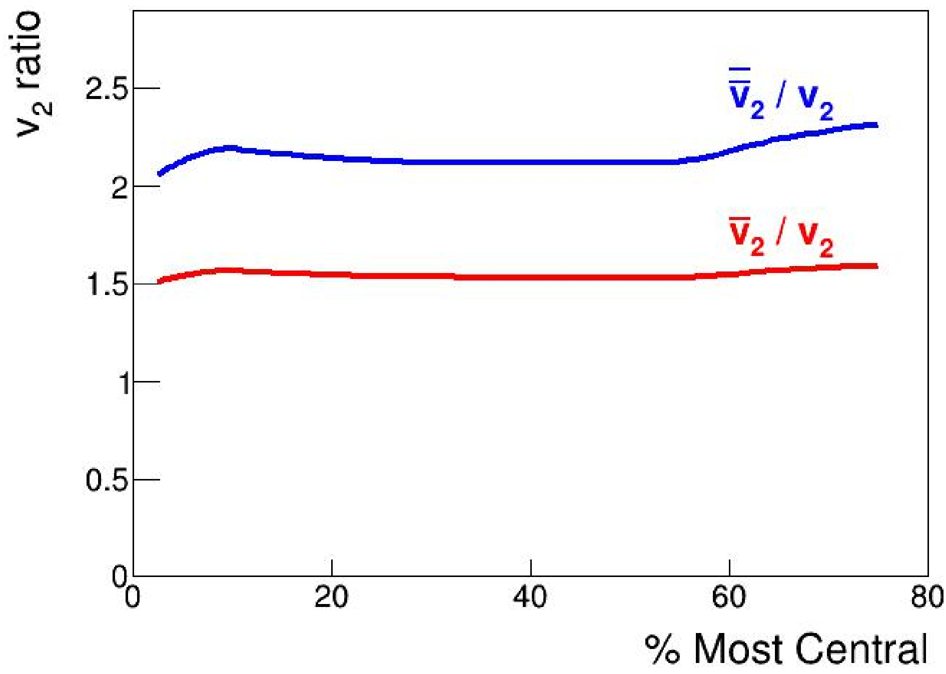
$$\gamma / \delta \approx 2\bar{v}_{2,\Omega} - \bar{\bar{v}}_{2,F}$$

where F and Ω denote particle averages in the full phase-space and the detector acceptance, respectively.

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

$v_2, \bar{v}_2$ and $\bar{\bar{v}}_2$

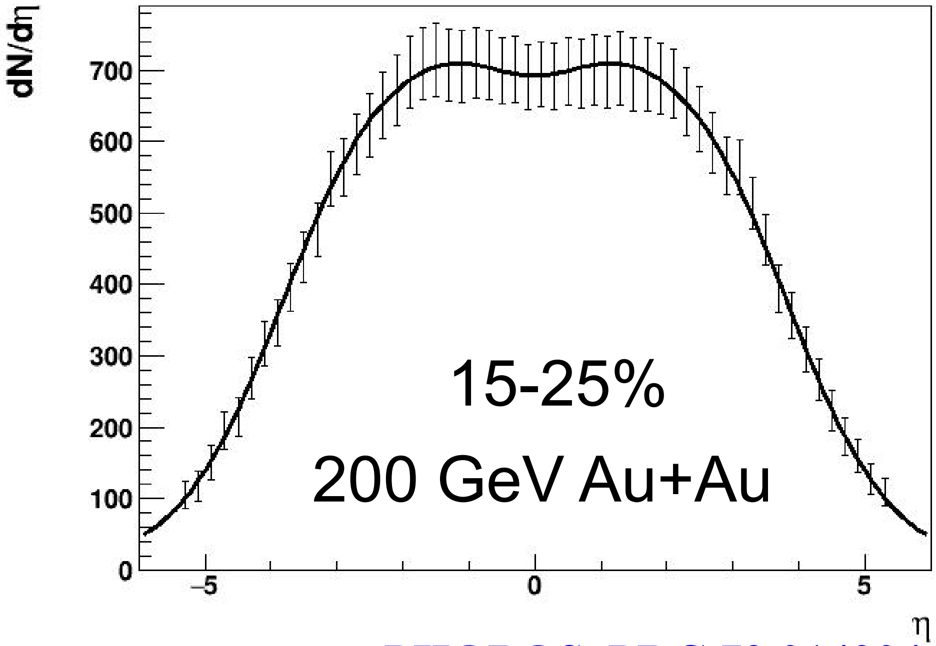


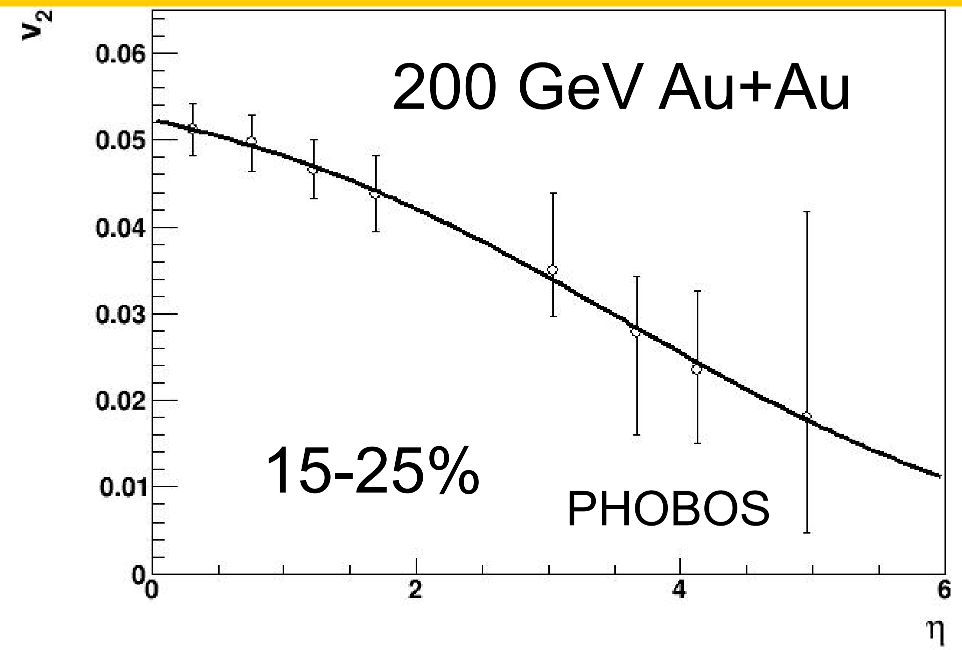


$$\bar{v}_2 = \frac{\langle v_2(p_t, \eta) p_t \rangle}{\langle p_t \rangle}, \qquad \bar{\bar{v}}_2 = \frac{\langle v_2(p_t, \eta) p_t^2 \rangle}{\langle p_t^2 \rangle}$$

The ratios of the p_T-weighted v_2 over conventional v_2 are almost constant over centrality.

$v_{2,\Omega}$ and $v_{2,F}$





PHOBOS, PRC 72 014904 (2005); PRC 83 024913 (2001)

centrality	$v_{2,\Omega}$ (%)	$v_{2,F}$ (%)	$v_{2,F}/v_{2,\Omega}$
3-15%	3.17	2.66	0.84
15-25%	5.04	3.97	0.79
25-50%	6.21	4.87	0.78

A cumulant way

$$\cos(\varphi_1 + \varphi_2 - 2\psi_{RP})$$
$$= \cos(\varphi_1 - \varphi_2 + 2\varphi_2 - 2\psi_{RP})$$
$$= \cos(\varphi_1 - \varphi_2)\cos(2\varphi_2 - 2\psi_{RP}) - \sin(\varphi_1 - \varphi_2)\sin(2\varphi_2 - 2\psi_{RP})$$

If we take the "cumulant" approach, a "v_2-free" correlator will be

$$\gamma^{cumulant} = \langle\langle \cos(\varphi_1 + \varphi_2 - 2\psi_{RP})\rangle\rangle$$
$$= \langle \cos(\varphi_1 + \varphi_2 - 2\psi_{RP})\rangle - \langle \cos(\varphi_1 - \varphi_2)\rangle \cdot \langle \cos(2\varphi - 2\psi_{RP})\rangle$$
$$= \gamma - \delta \cdot v_2$$

$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP})\rangle = \kappa v_2 F - H$$
$$\delta \equiv \langle \cos(\phi_1 - \phi_2)\rangle = F + H,$$

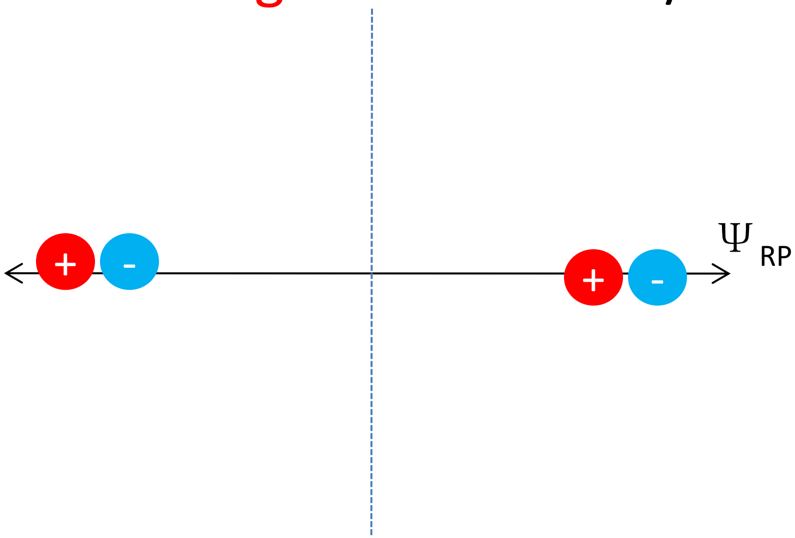
→ $$H^{\kappa} = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$$

The cumulant approach indicates κ~1.

An example

no charge separation:

local charge conservation/decay + momentum conservation + v_2



$\gamma_{SS} = -1$

$\delta_{SS} = -1$

$\rightarrow H_{SS}^{\kappa=1}=0$

$v_2 = 1$

$\rightarrow H_{OS}^{\kappa=1}=0$

$\gamma_{OS} = 0$

$\delta_{OS} = 0$

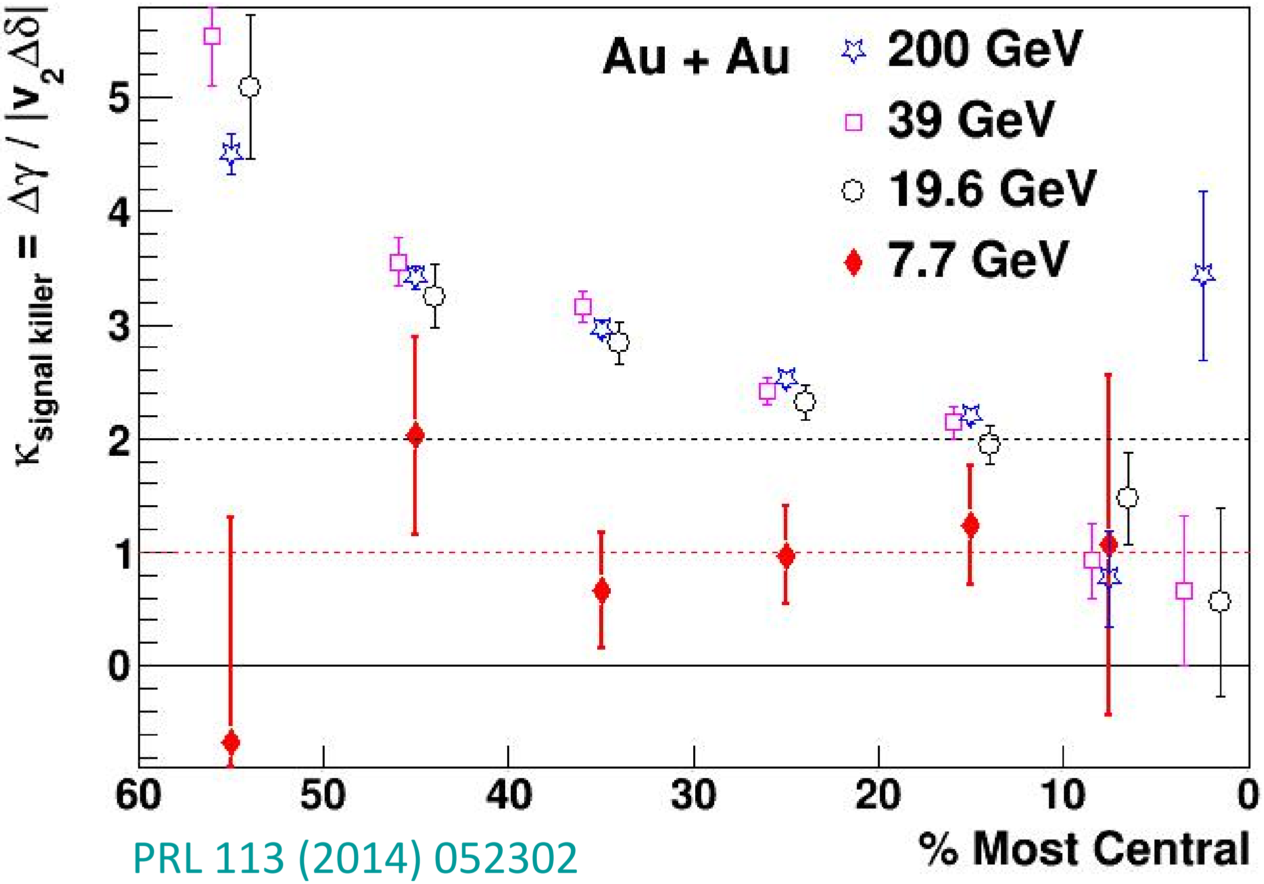
With κ=1, *H* tells the truth.

The charge independent bg = -1/2 = -v_2/N. Here N =2, # of clusters.

$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle = \kappa v_2 F - H$$
$$\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H,$$

$$\rightarrow H^{\kappa} = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$$

$\kappa_{\text{CME killer}} = \Delta\gamma / |v_2 \Delta\delta|$



PRL 113 (2014) 052302

- $\kappa_{\text{CME killer}}$ quantifies how hard to kill the CME signal in data.
- From 200 to 19.6 GeV, $\kappa_{\text{CME killer}}$ has a centrality dependence.
- At 7.7 GeV, it seems to be always consistent with 1.

MC Glauber

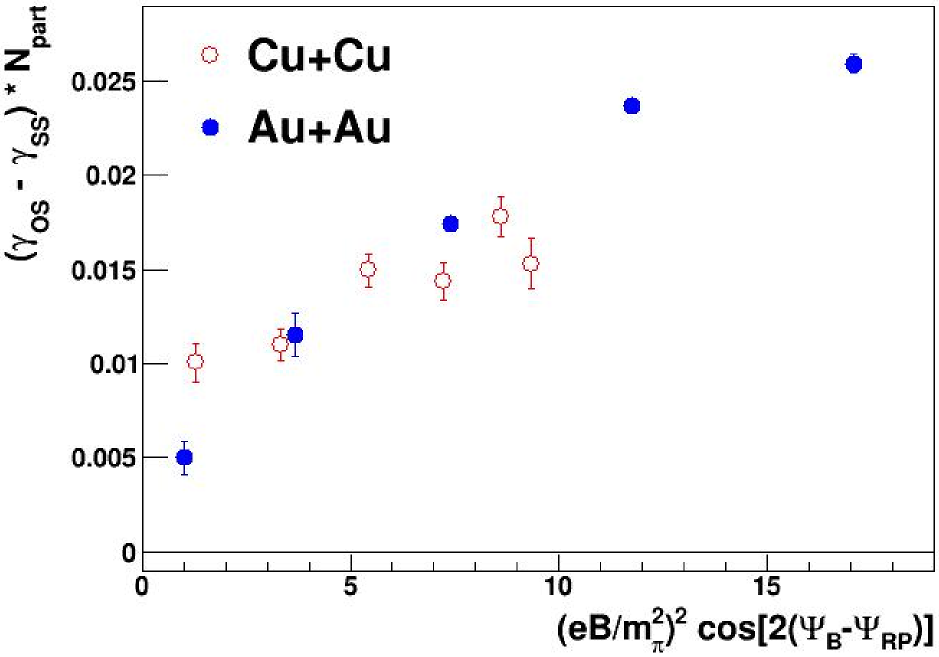
- Glauber parameters re-adjusted to make Wood-Saxon correct
- Set 1: B(E2)↑ measured in e-A scattering experiment
- Set 2: comprehensive model deduction

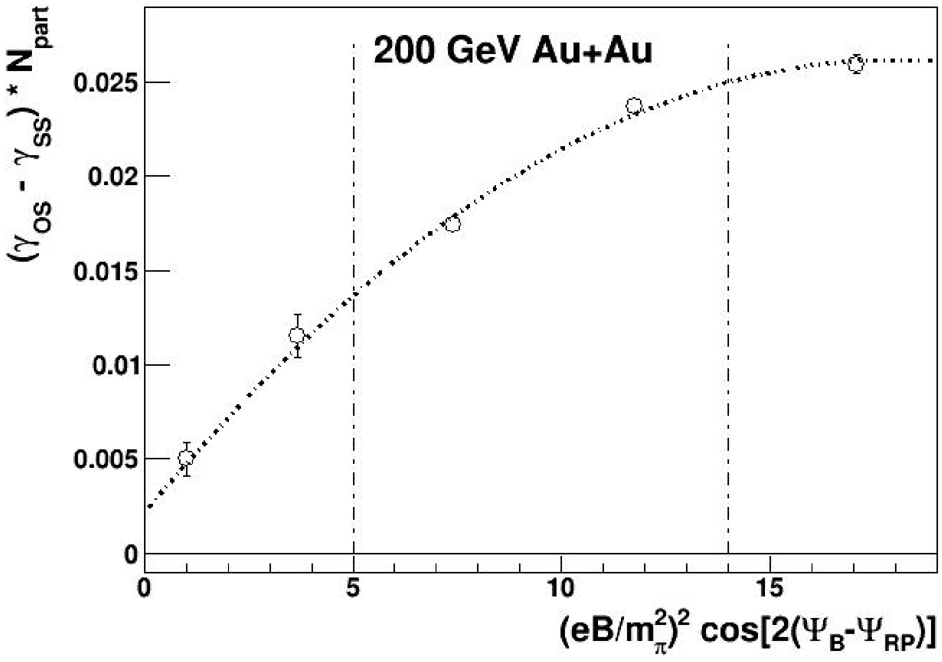
Q. Y. Shou, Y. G. Ma, P. Sorensen, A. H. Tang, F. Videbæk, H. Wang, Phys. Lett. B 749, 215 (2015)

			R0	a (d)	β2	β4
Zr96	Set 1	old	5.0212	0.574	0.08	/
		new	5.07	0.48	0.06	
	Set 2	old	5.0212	0.574	0.217	0.01
		new	5.05	0.45	0.18	0.01
Ru96	Set 1	old	5.0845	0.567	0.1579	/
		new	5.14	0.46	0.13	
	Set 2	old	5.0845	0.567	0.053	0.009
		new	5.13	0.45	~0.03*	0.009

200 GeV: γ

- $\Delta\gamma \cdot N_{part}$ magnitudes are similar for Au+Au and Cu+Cu.
- Zr+Zr and Ru+Ru are supposed to sit between them.
- The 20-60% isobar collisions cover (5, 14) in the x axis.
- Au+Au has better statistics and a wider B range: a better projection.
- $\Delta\gamma \cdot N_{part}$ is a smooth function of B^2 for Au+Au 200 GeV.



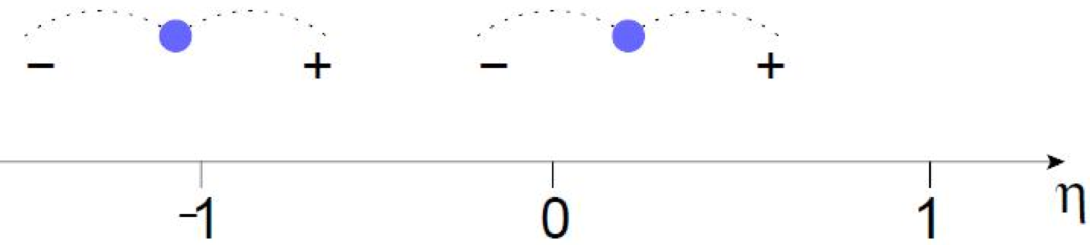


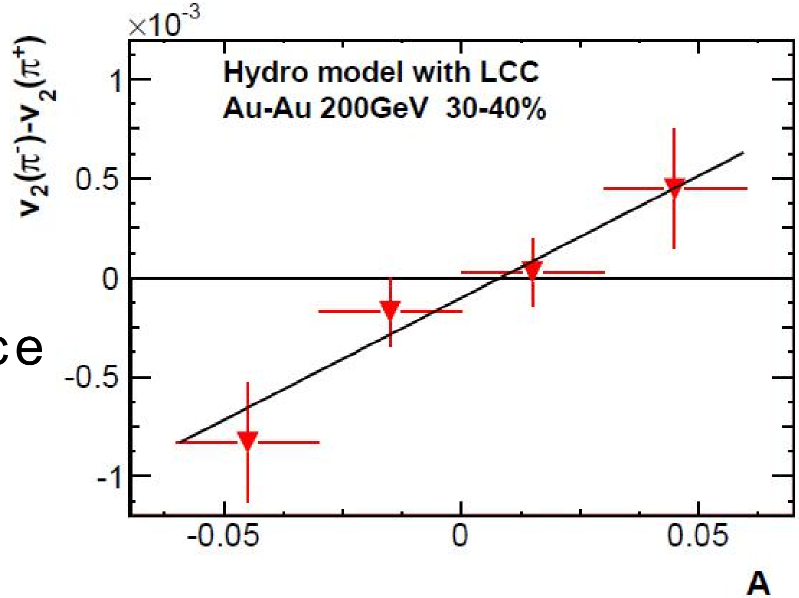
$^{136}_{54}$Xenon and $^{136}_{58}$Cerium

- relative charge difference ~7.4% instead of 10% (in Zr and Ru)
- signal difference reduces to ~15% from ~20%
- the same significance level requires double statistics

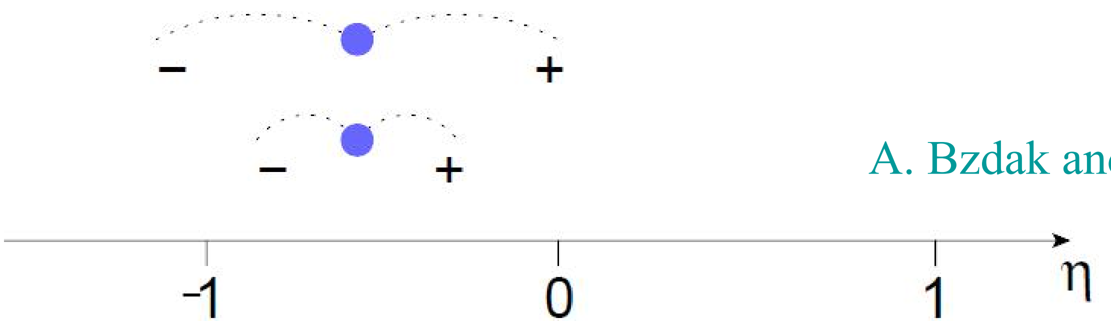
	$^{136}_{54}$Xenon	$^{136}_{58}$Cerium
NA	8.86%	0.185%
R_0 (fm)	5.66	5.66
a (fm)	0.55	0.55
β_2(Set1)	0.0949	0.1707
β_2(Set2)	0	0.192
β_4(Set2)	0	0.14

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

$\Delta v_2(A_{ch})$ slope in isobaric collisions

- The slope parameter is also expected to differ, if CMW driven
- With 700M events, the ratio is 1σ above 1
- Here we assume r ∝ B.