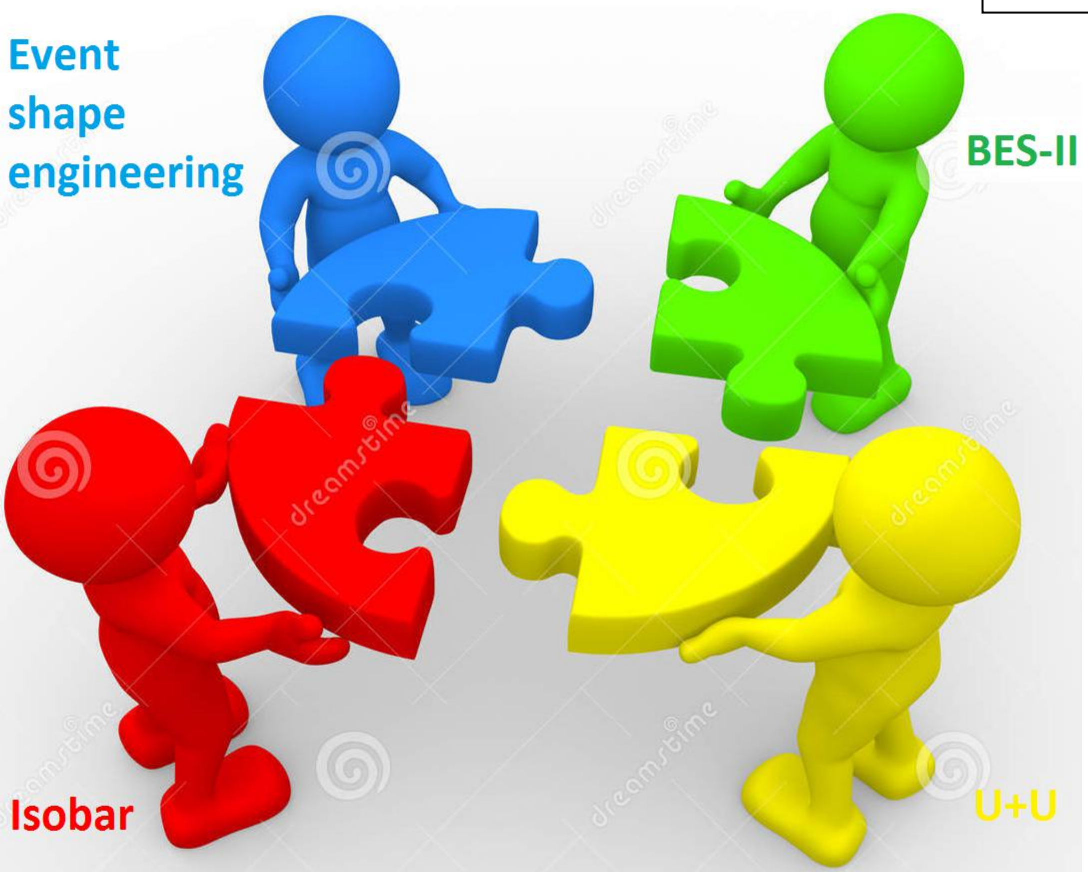
Solutions from

- analysis:
  - event-shape engineering
- data
  - BES-II
  - U+U
  - Isobaric collisions

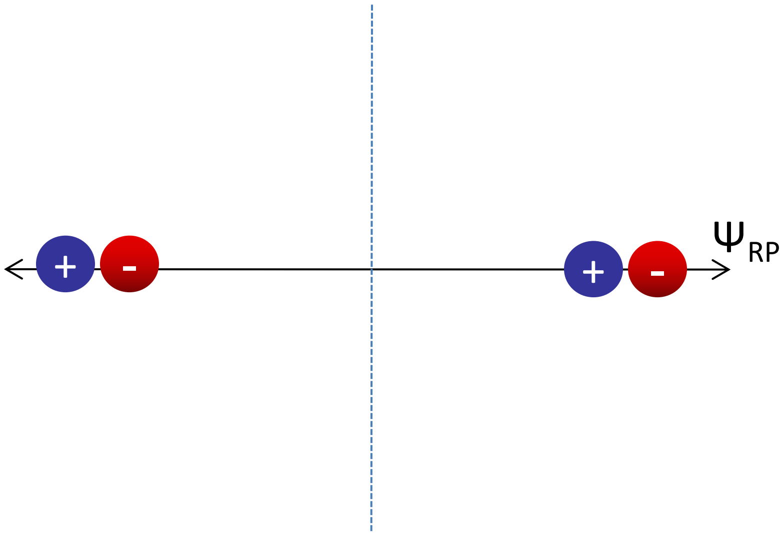


Gang Wang (UCLA)

Flow-related background in γ

An example with no charge separation:

v_2 + local charge conservation/decay + momentum conservation



$\gamma_{SS} = -1$

$\delta_{SS} = -1$

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

$v_2 = 1$

$\gamma_{OS} = 0$

$\delta_{OS} = 0$

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

$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle = \kappa v_2 F - H \quad \longrightarrow \quad H^{\kappa} = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$$

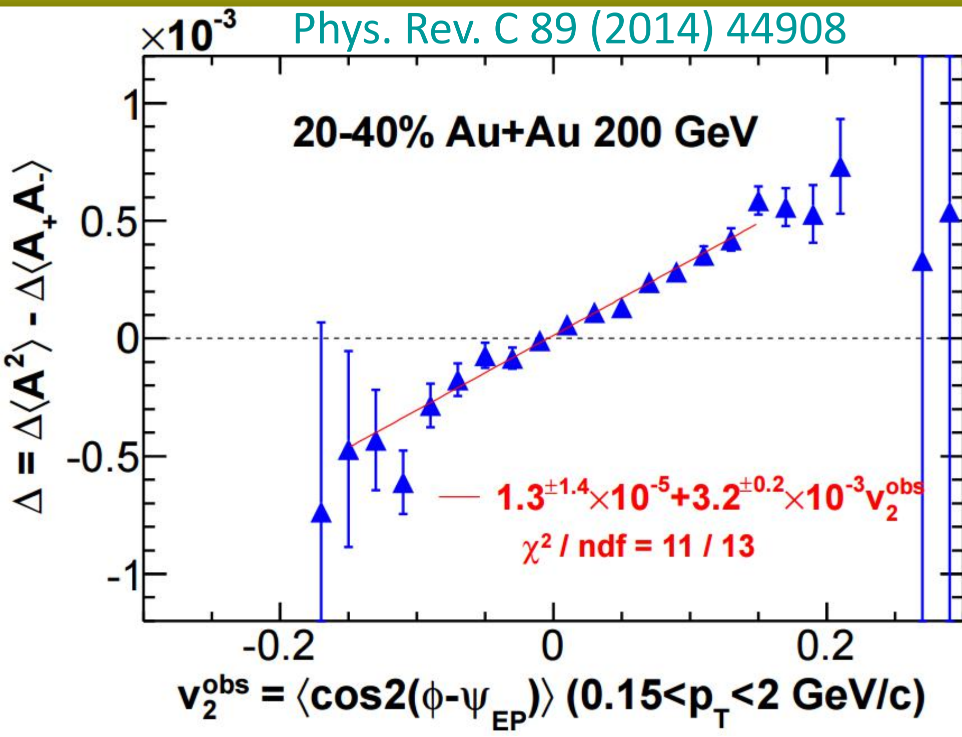
$$\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H,$$

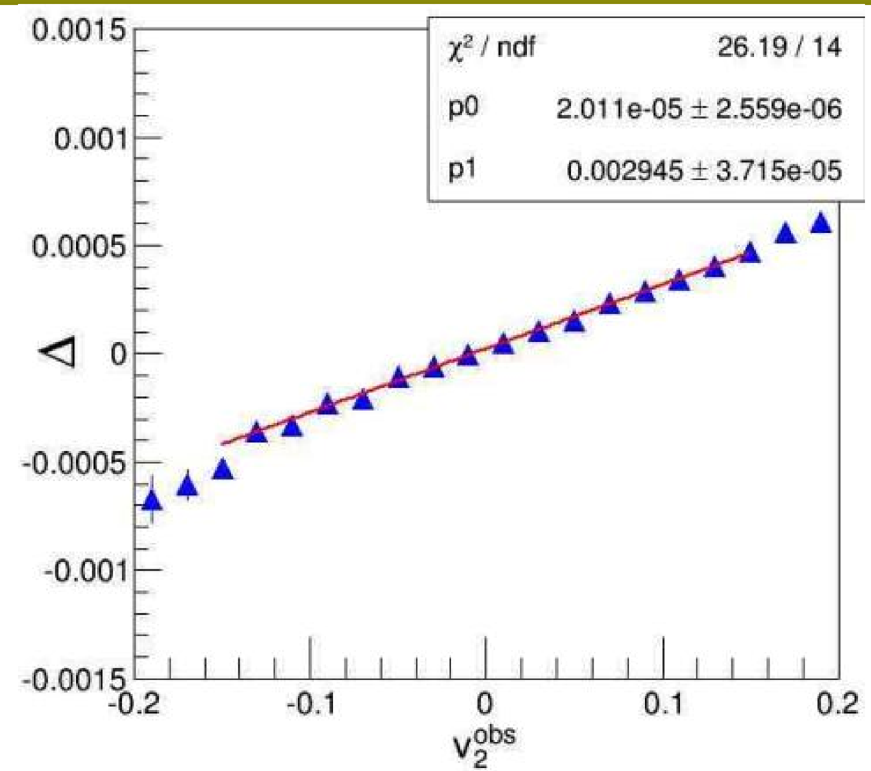
A. Bzdak, V. Koch and J. Liao, Lect. Notes Phys. 871, 503 (2013).

If we can select *spherical* events via Event-Shape Engineering (ESE): flow background will disappear. The question is how.

Event-shape engineering

Phys. Rev. C 89 (2014) 44908



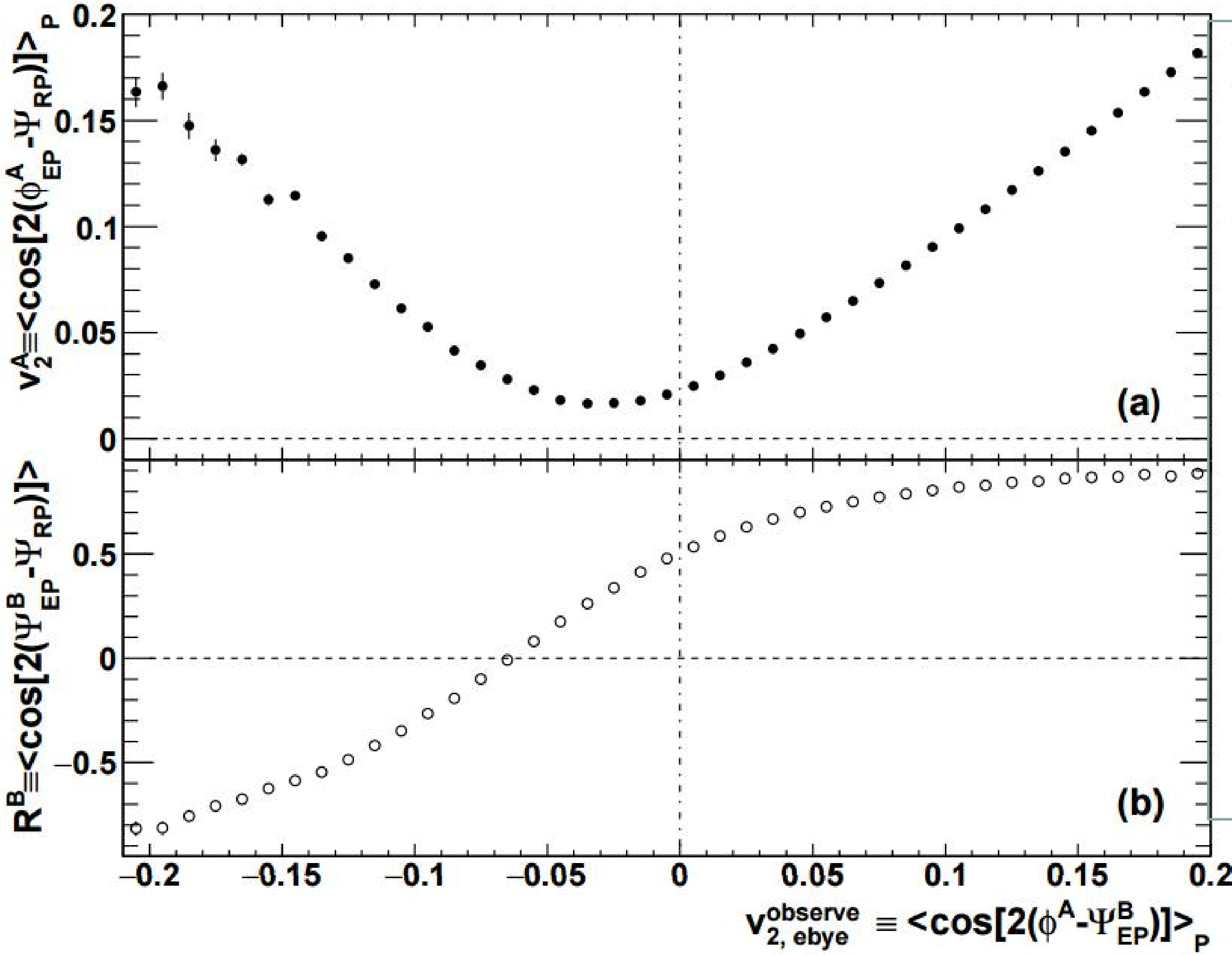


$\Delta = 1.3 \pm 1.4(stat.)^{+4.0}_{-1.0}(syst.) \times 10^{-5}$

$\Delta(v_2^{obs} = 0) = 2.0 \pm 0.3(stat.) \times 10^{-5}$

- A condition on observed v_2 is applied to remove flow-related bg.
- Previously, when $v_2^{obs} = 0$, the signal was consistent with zero!
- Now, new measurements with higher statistics report finite signal: 7σ!
- Beam energy dependence also looks similar to that of γ.

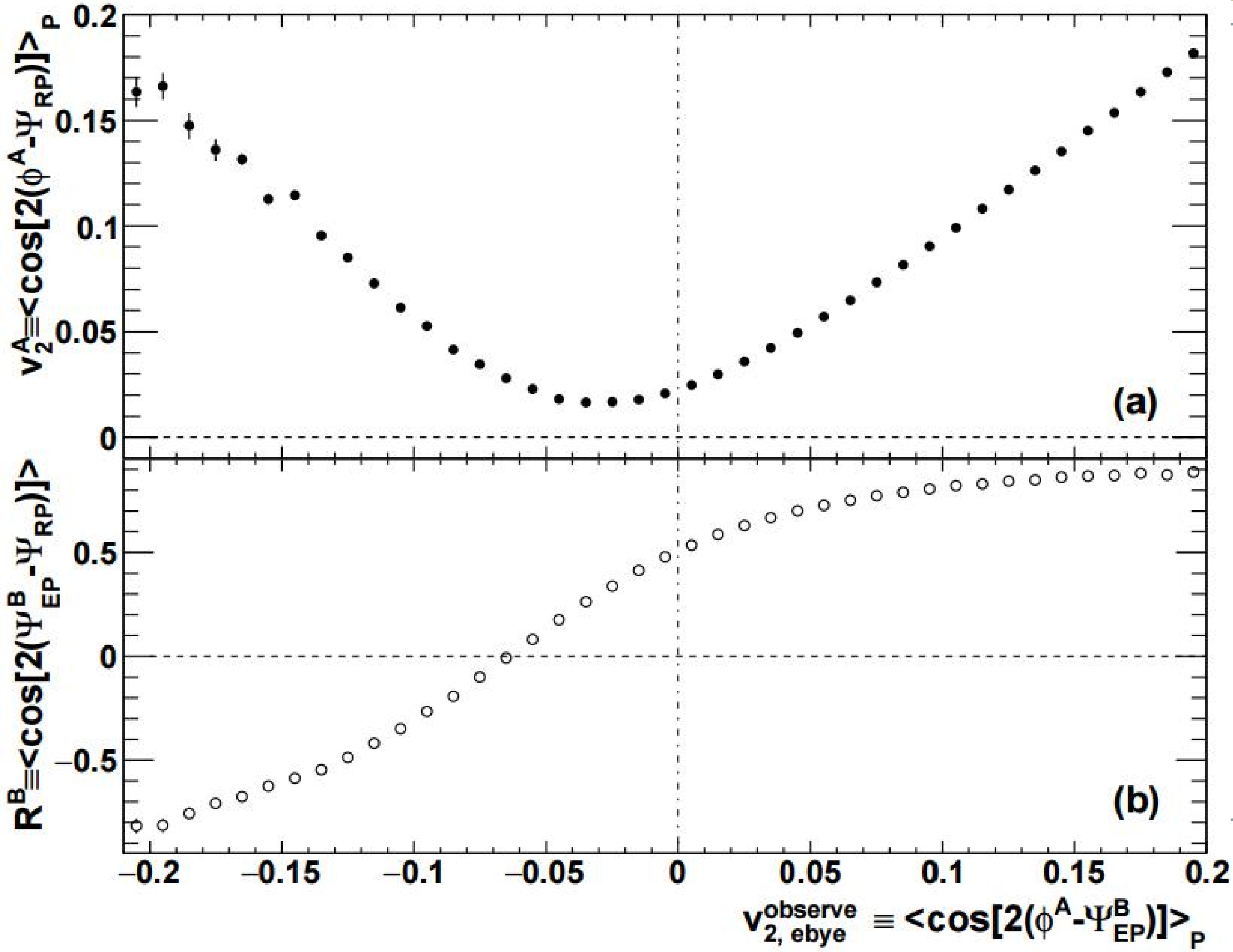
Is v_2^{obs} a good handle?



- Simple Monte Carlo simulations
- Input v_2 = 5%
- 200 h^+ and 200 h^-
- Each event splits into 2 sub events
- One provides particles, and the other provides EP.

- $v_2^{obs} = 0$ doesn't mean the true $v_2^A = 0$.
- $v_2^A = 0$ can never be achieved with the handle of v_2^{obs}!
- The EP resolution changes with v_2^{obs}, and can go negative!

Is v_2^{obs} a good handle?



- Simple Monte Carlo simulations
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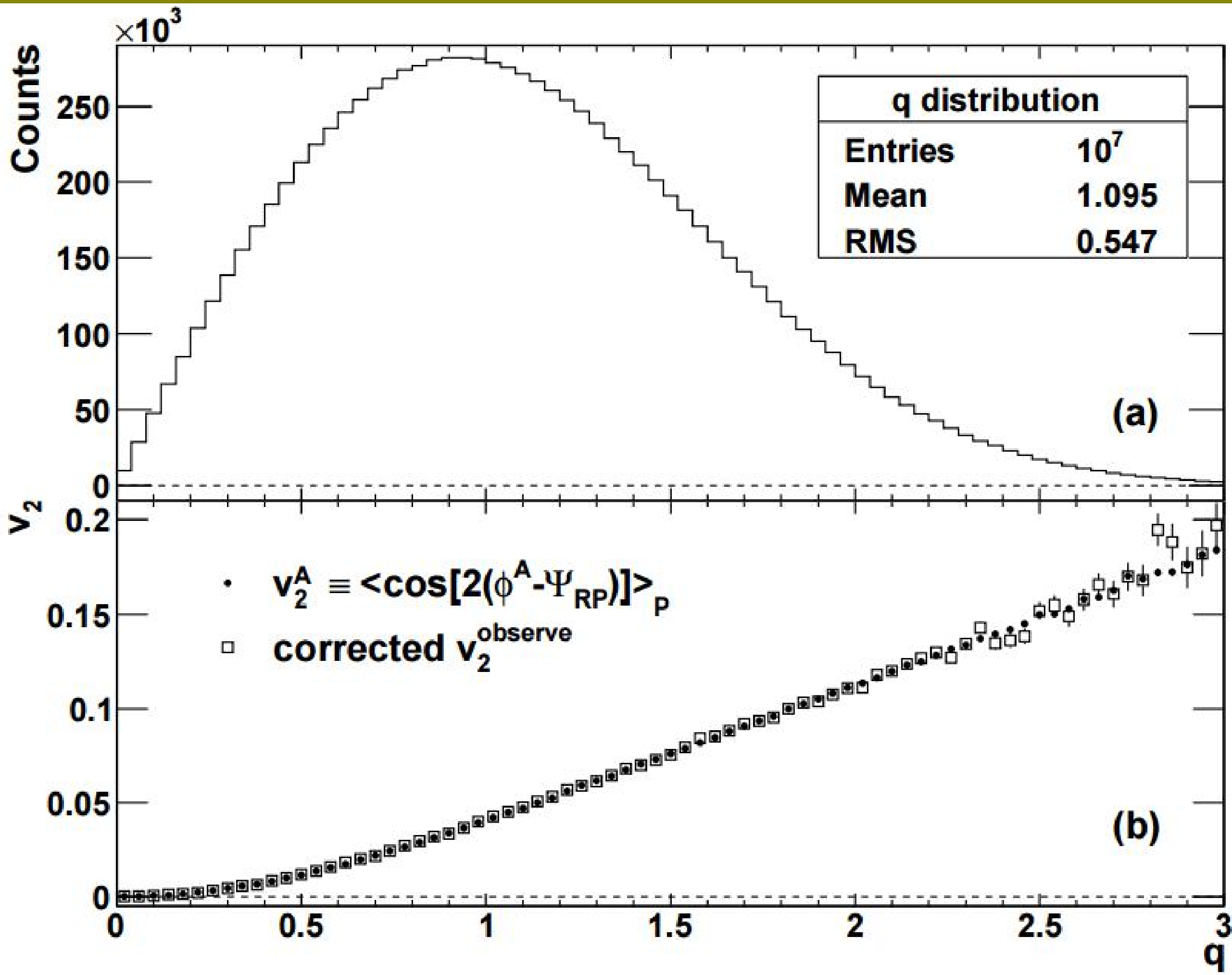
- $v_2^{obs} = 0$ doesn't mean the true $v_2^A = 0$.
- $v_2^A = 0$ can never be achieved with the handle of v_2^{obs}!
- The EP resolution changes with v_2^{obs}, and can go negative!
- Factorization "$v_2^A = v_2^{obs}$ / EP res" breaks down!

q is a good handle



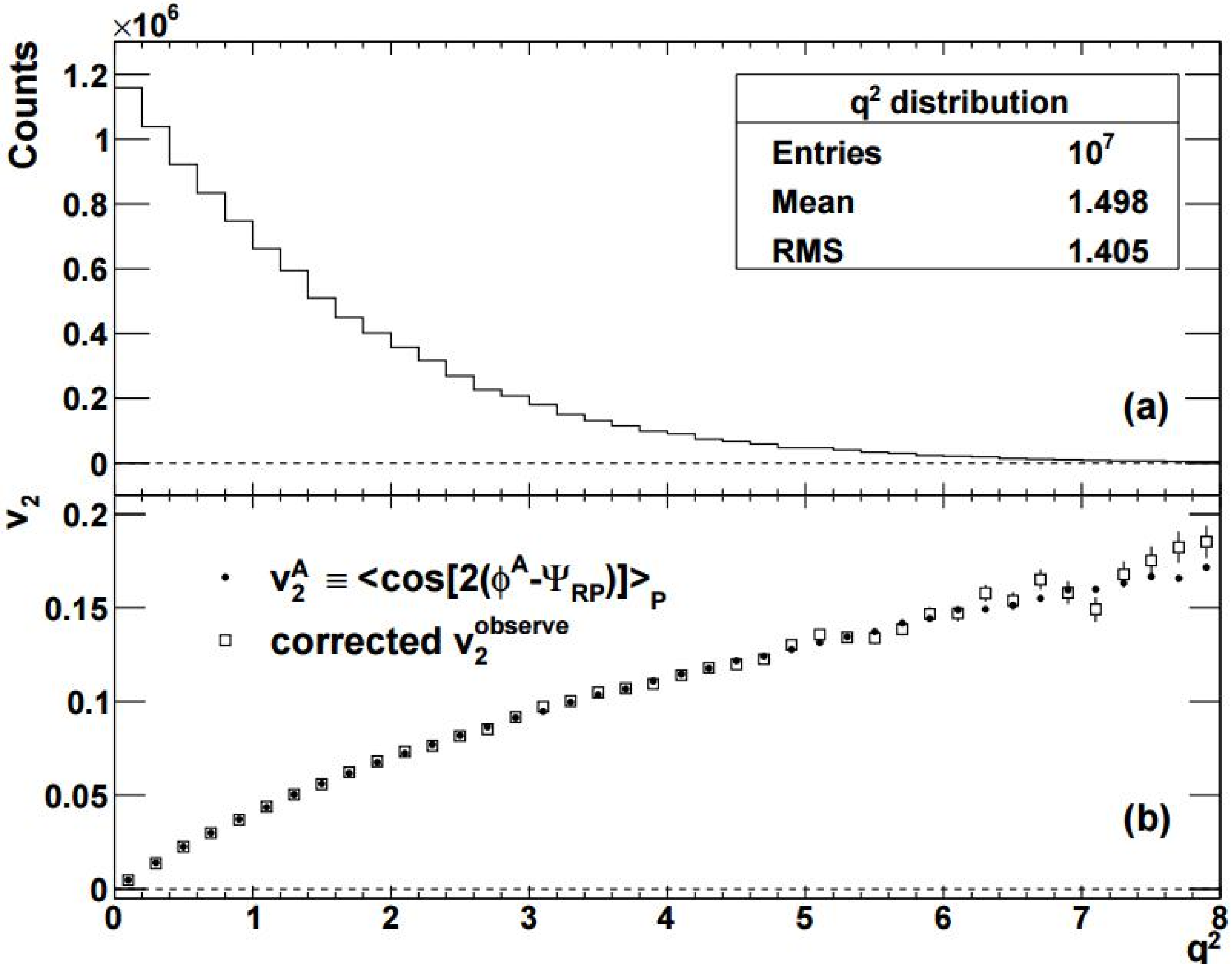
q is the magnitude of the flow vector of the sub event (A) under study.

$$q_x^A = \frac{1}{\sqrt{N}} \sum_i^N \cos(2\phi_i^A)$$

$$q_y^A = \frac{1}{\sqrt{N}} \sum_i^N \sin(2\phi_i^A)$$

- When q is used to select each event class, things are back to normal.
- Factorization "$v_2^A = v_2^{obs}$ / EP res" is valid again!
- However, the region of our interest ($q \approx 0$) has very few events.

q^2 is a better handle



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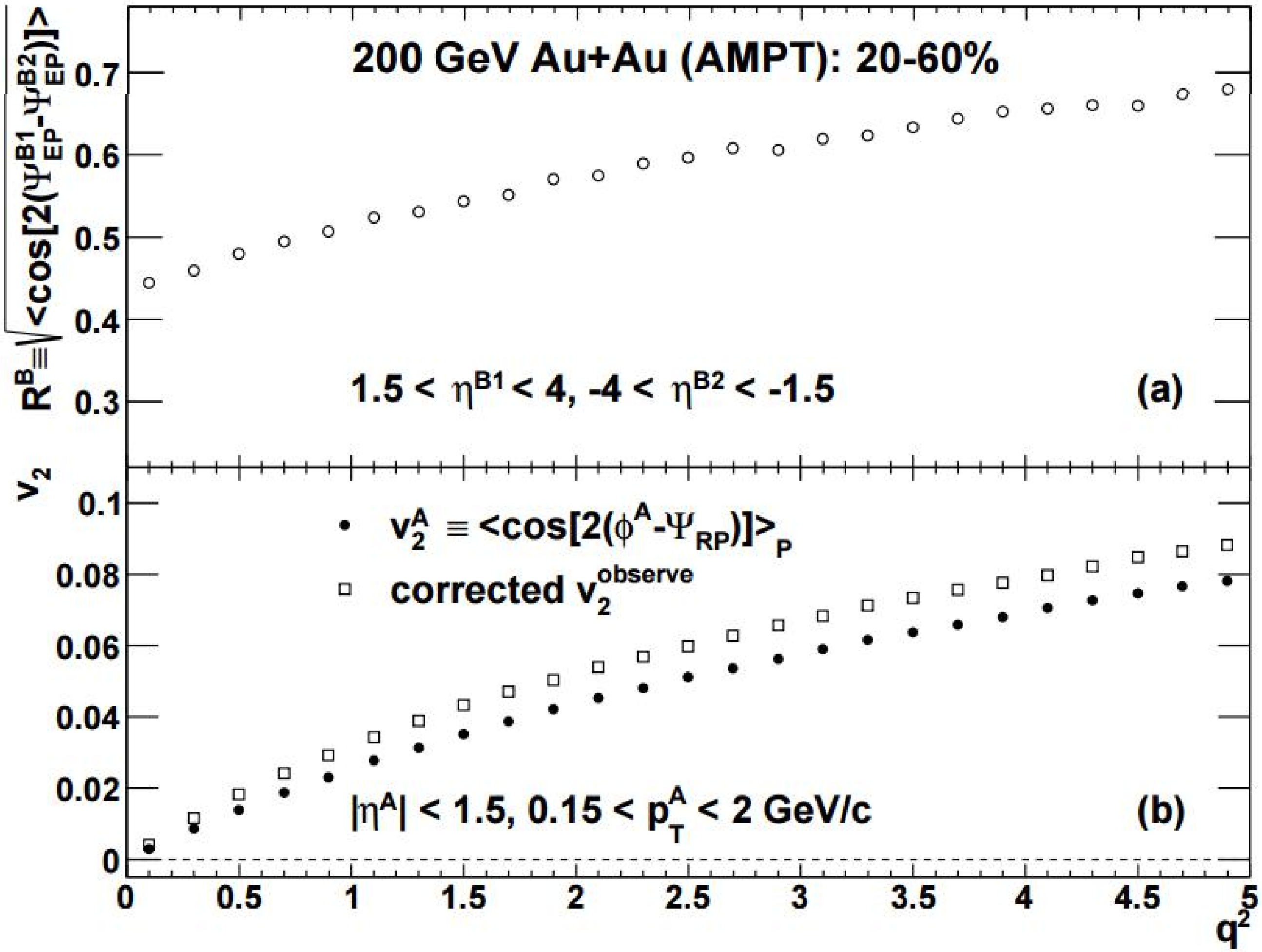
$$q_y^A = \frac{1}{\sqrt{N}} \sum_i^N \sin(2\phi_i^A)$$

- q^2 inherits the good property from q.
- Factorization "$v_2^A = v_2^{obs}$ / EP res" is still valid!
- The phase space is squeezed towards the region of our interest ($q \approx 0$).
- Almost linear in v_2 vs q^2 near $q \approx 0$.

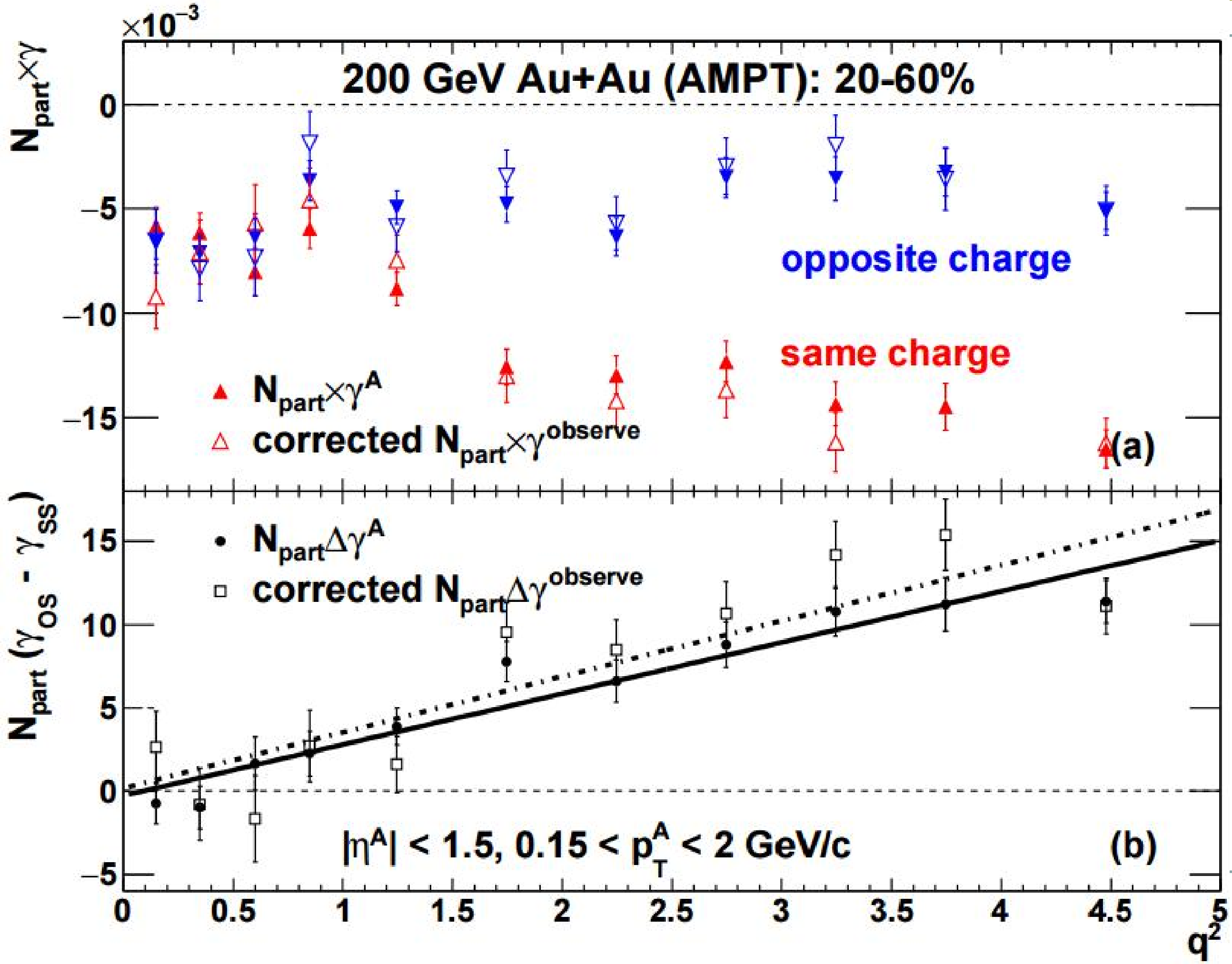
$v_2(q^2)$ in AMPT



- no CME in AMPT
- particles $|\eta|<1.5$
- EPs: $1.5<|\eta|<4.5$
- Positive EP resol.
- v_2 not correctable?
- AMPT is more realistic than the simplified Monte Carlo, and v_2 w.r.t participant plane is larger than v_2 w.r.t reaction plane

The most important thing is:
at $q^2 = 0$, the real v_2 and the resolution-corrected v_2 both go to 0!
That means "spherical" events.

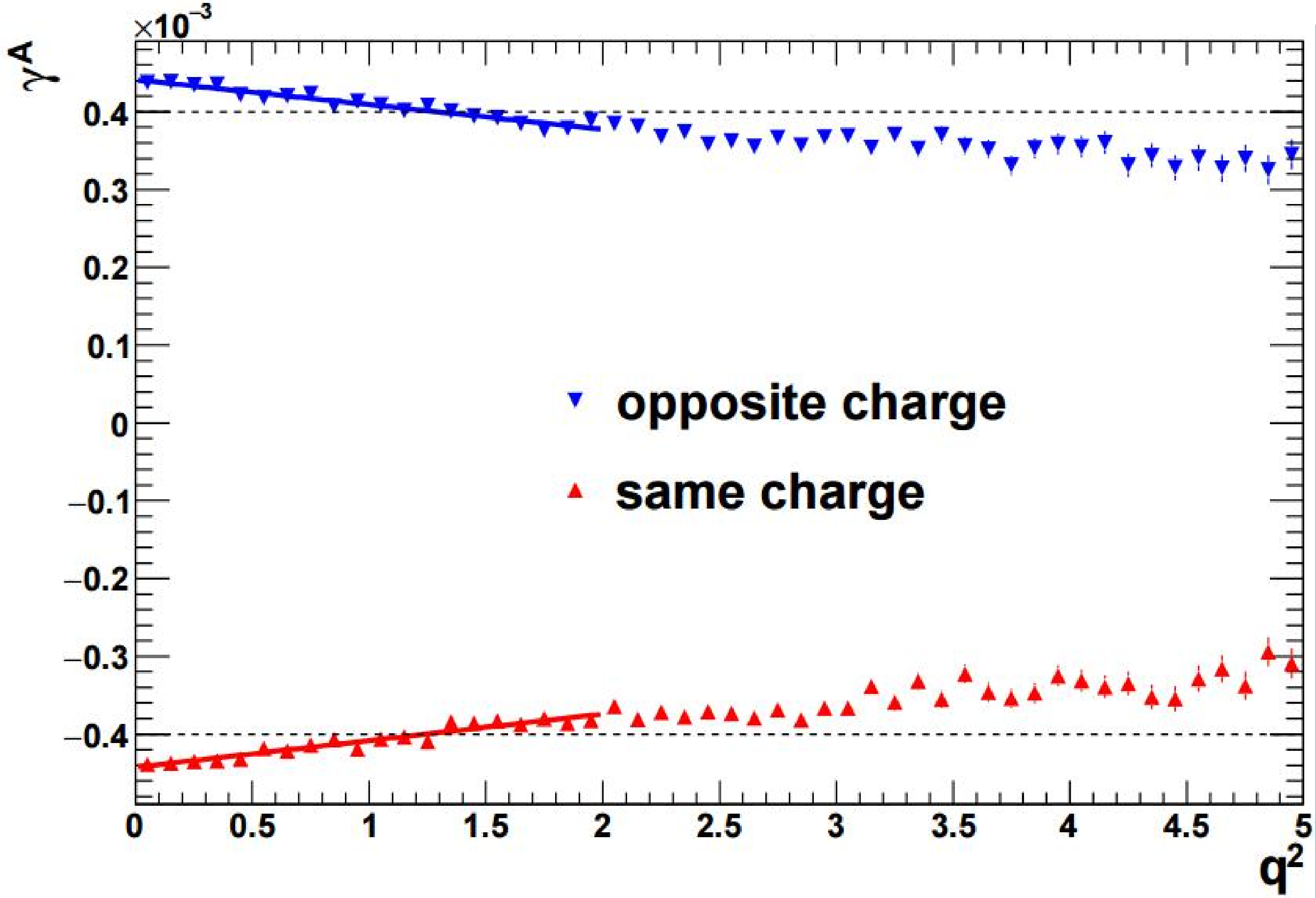
$\gamma(q^2)$ AMPT



- no CME in AMPT
- particles $|\eta|<1.5$
- EPs: $1.5<|\eta|<4.5$
- γ is correctable.
- $\Delta\gamma$ goes to 0 when q^2 goes to 0!
- Almost linear relationship makes extrapolation easy

The most important thing is:
at $q^2 = 0$, the real $\Delta\gamma$ and the resolution-corrected $\Delta\gamma$ both go to 0!
The flow background disappears in selected "spherical" events.

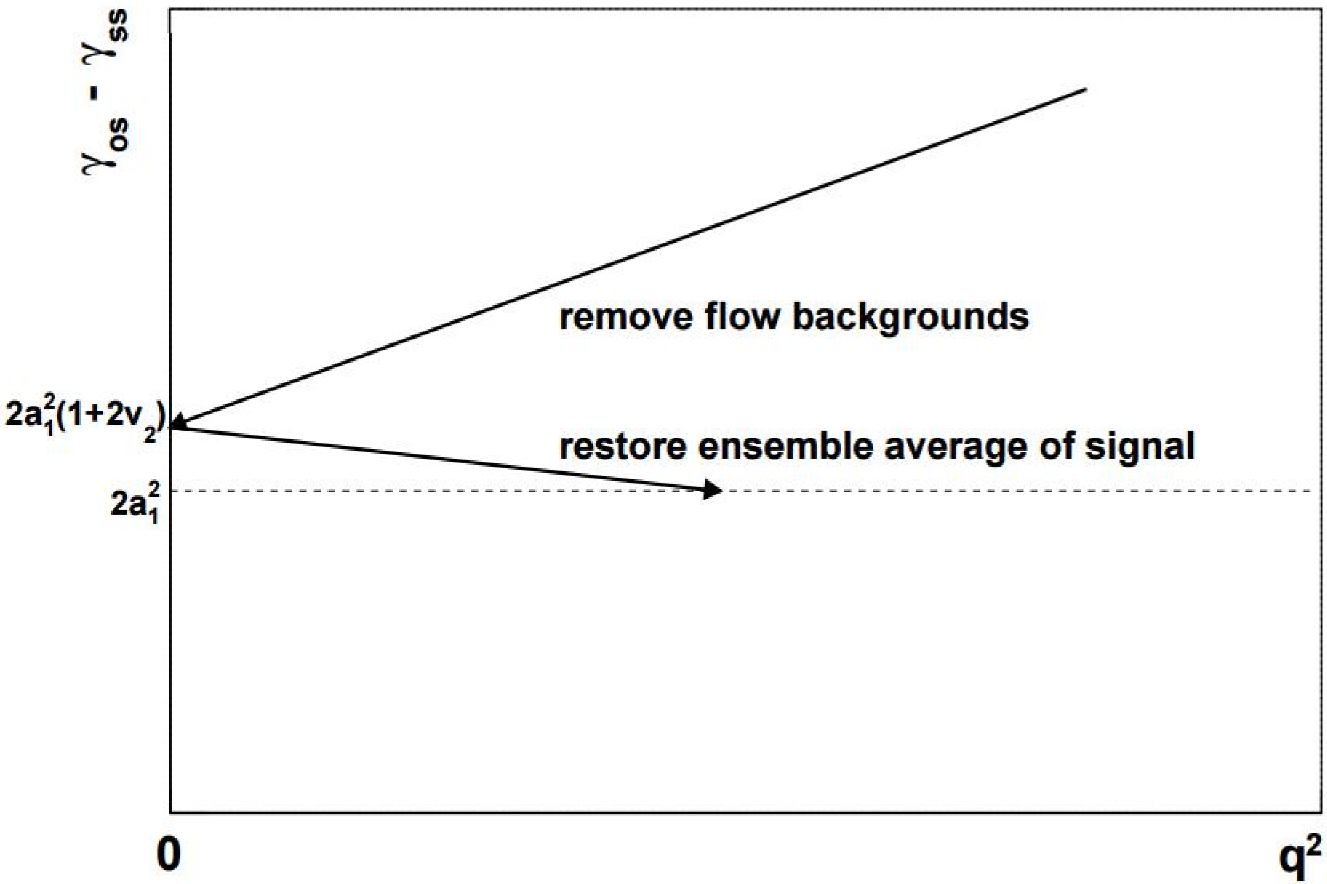
Artificial effect



- Simple Monte Carlo simulations
- Input v_2 = 5%
- Input a_1 = 2%
- 200 h^+, 200 h^-
- projection to q^2=0 artificially magnifies the CME signal.

- There is an intrisic correlation between q^2 and γ.
- At q^2=0, flow bg vanishes, but the CME signal is exaggerated.

The full recipe



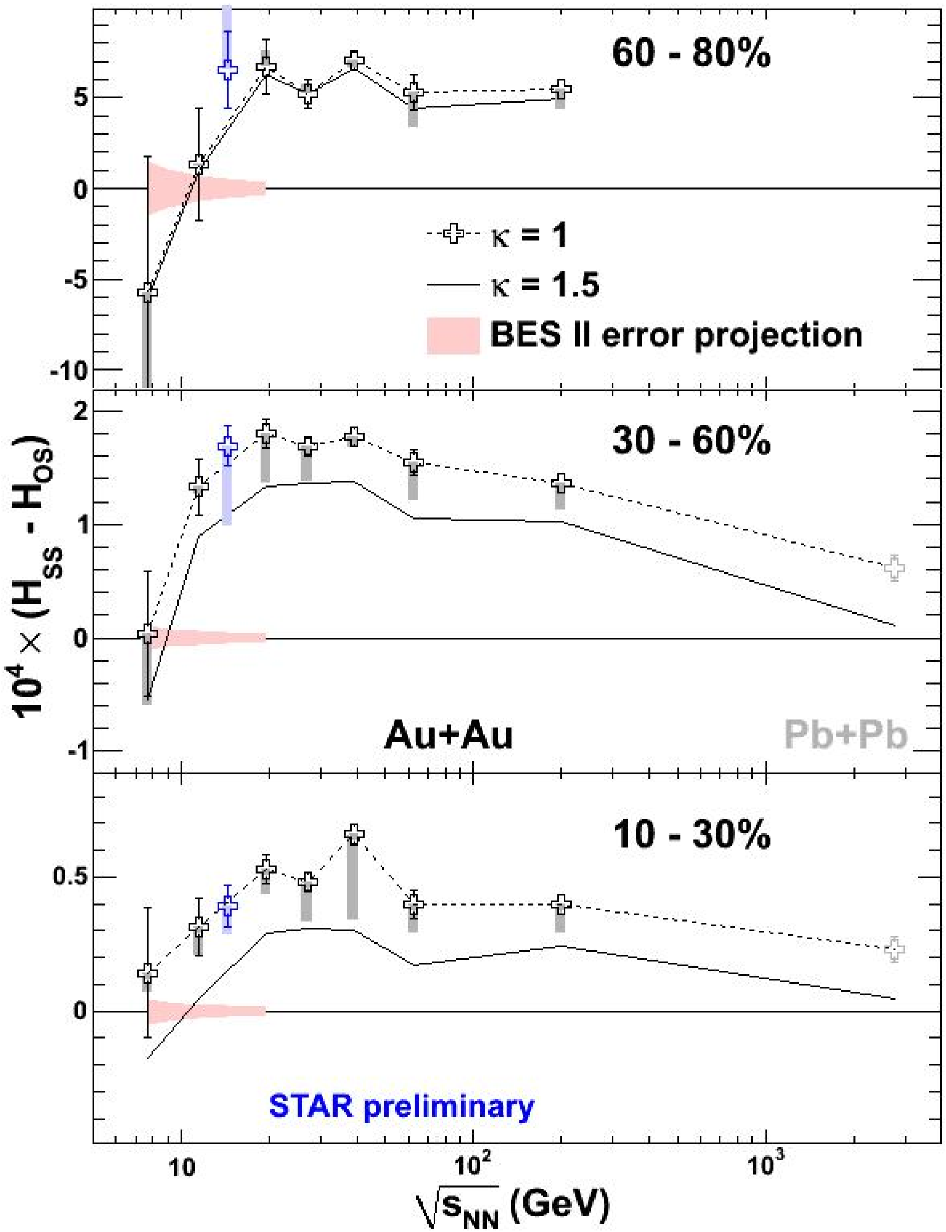
4 steps:

- calculate q and γ for each event
- fill a profile of γ vs q^2
- extrapolate the trend to $q^2 = 0$
- divide Δγ at q^2=0 by $(1+2v_2)$.

- γ at q^2=0 is not equal to the ensemble average of γ.
- A correction factor of $(1+2v_2)$ needs to be applied.
- Note here q^2 directly comes from the sub event that provides particles of interest, unlike other methods where q or q^2 comes from a different sub event.

ΔHκ at BES-I

STAR, 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).

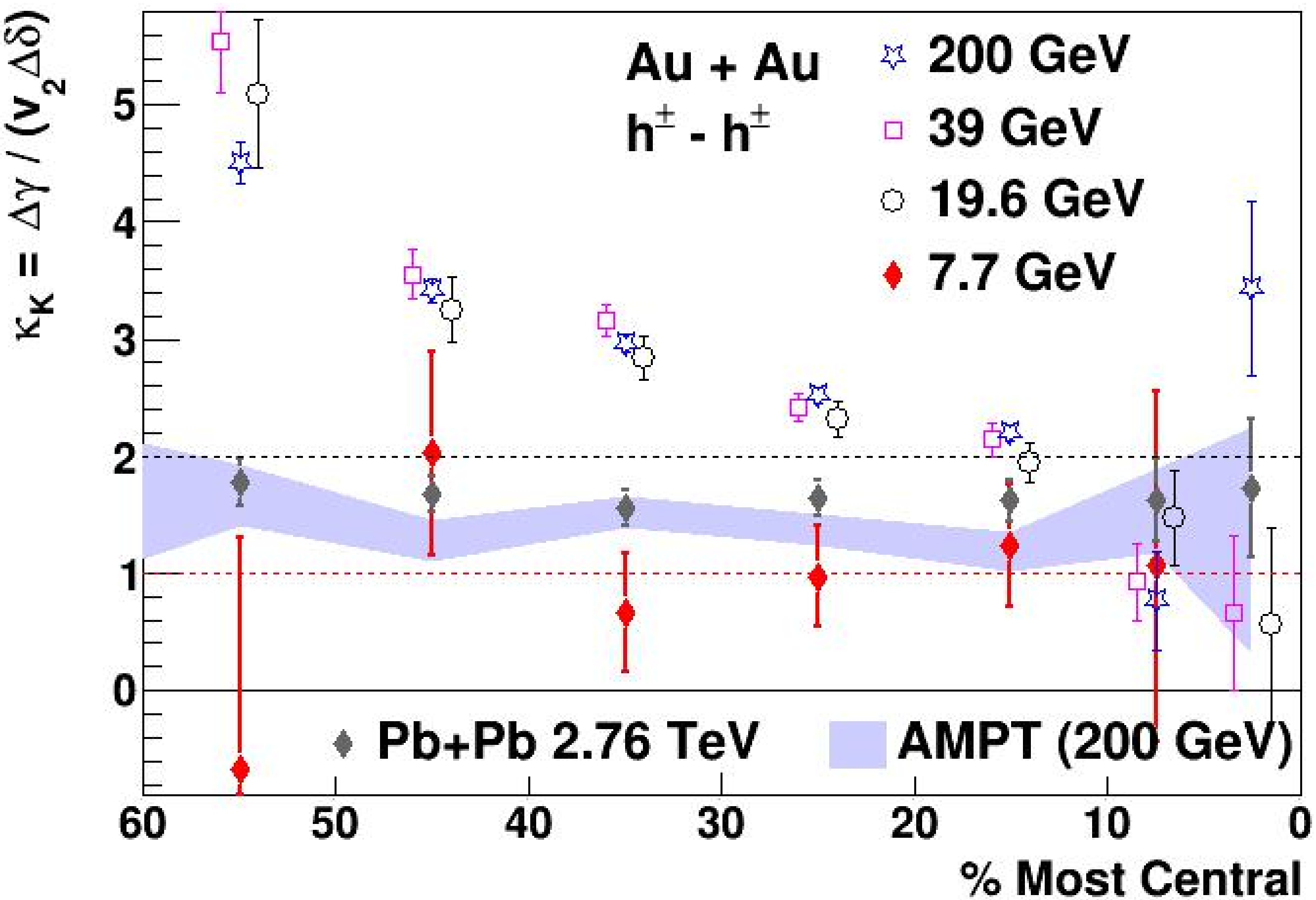
- κ_B is roughly contained in the range of [1, 1.5].
- CME signal (Δ*H*) decreases to 0 from 19.6 to 7.7 GeV
- Probable domination of hadronic interactions over partonic ones
- Need more more statistics
- Another way to look at it …

κ_K: normalized (signal + background)

$$\kappa_B \equiv \frac{\Delta\gamma + \Delta H}{v_2(\Delta\delta - \Delta H)}, \qquad \kappa_K \equiv \kappa_B(\Delta H = 0) = \frac{\Delta\gamma}{v_2 \Delta\delta}.$$

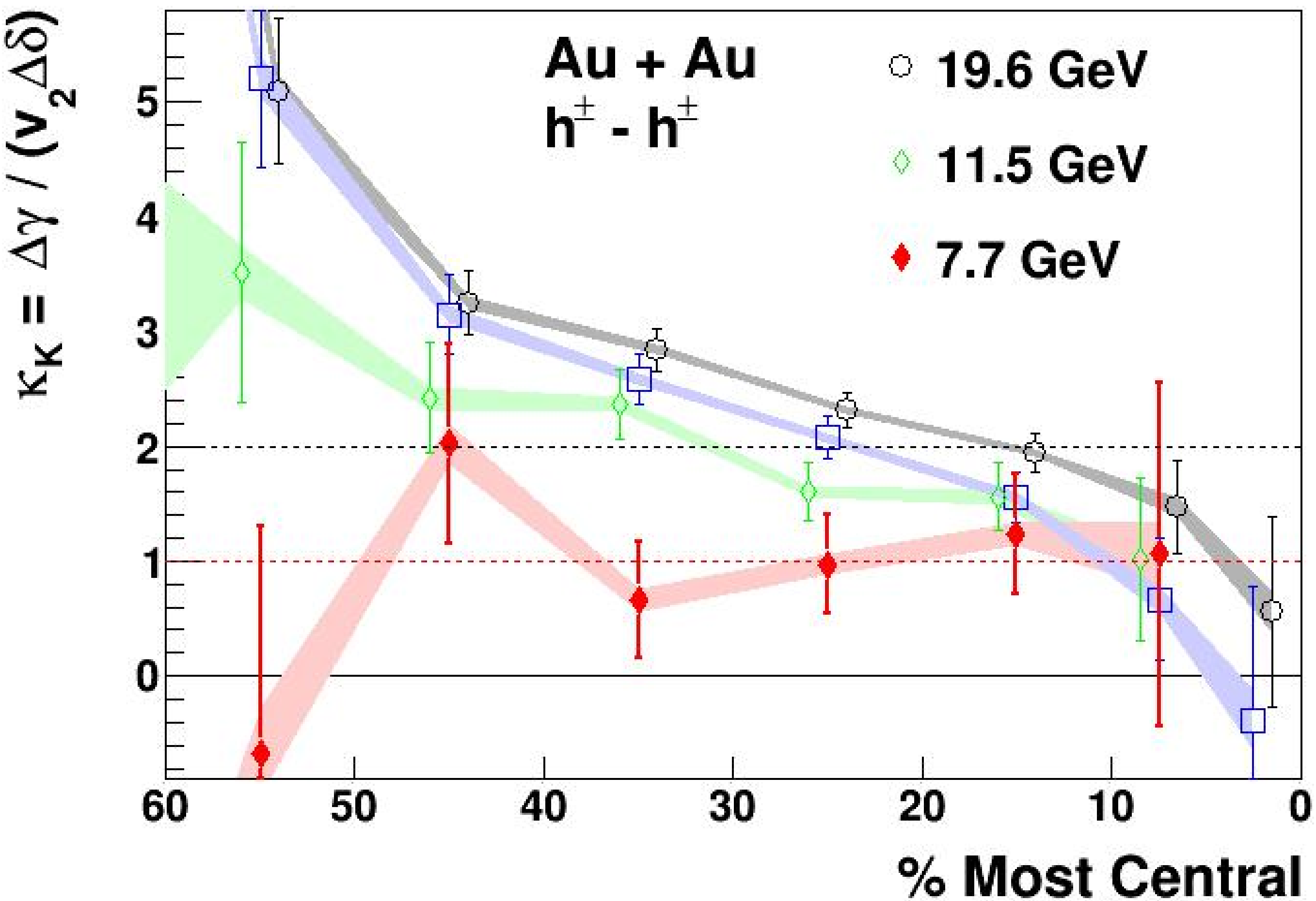
If $\kappa_K > \kappa_B$ for real data, there could be extra physics like the CME.

STAR, PRL113 (2014) 052302; ALICE, PRL110 (2013) 021301.

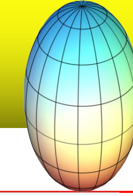


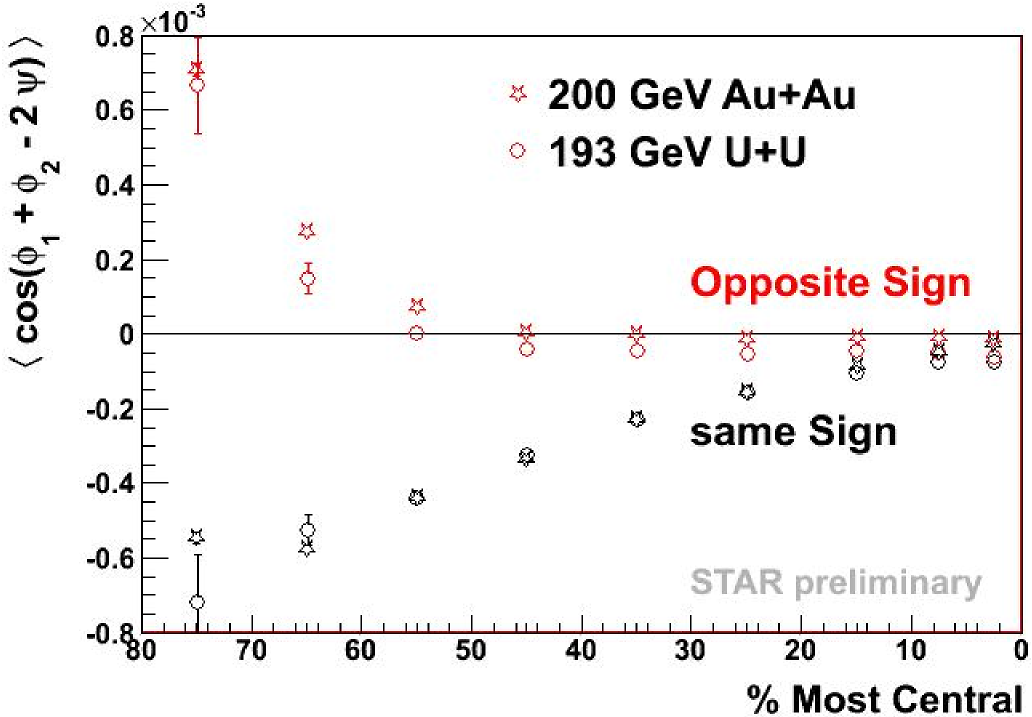
Projection for BES-II

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



U+U



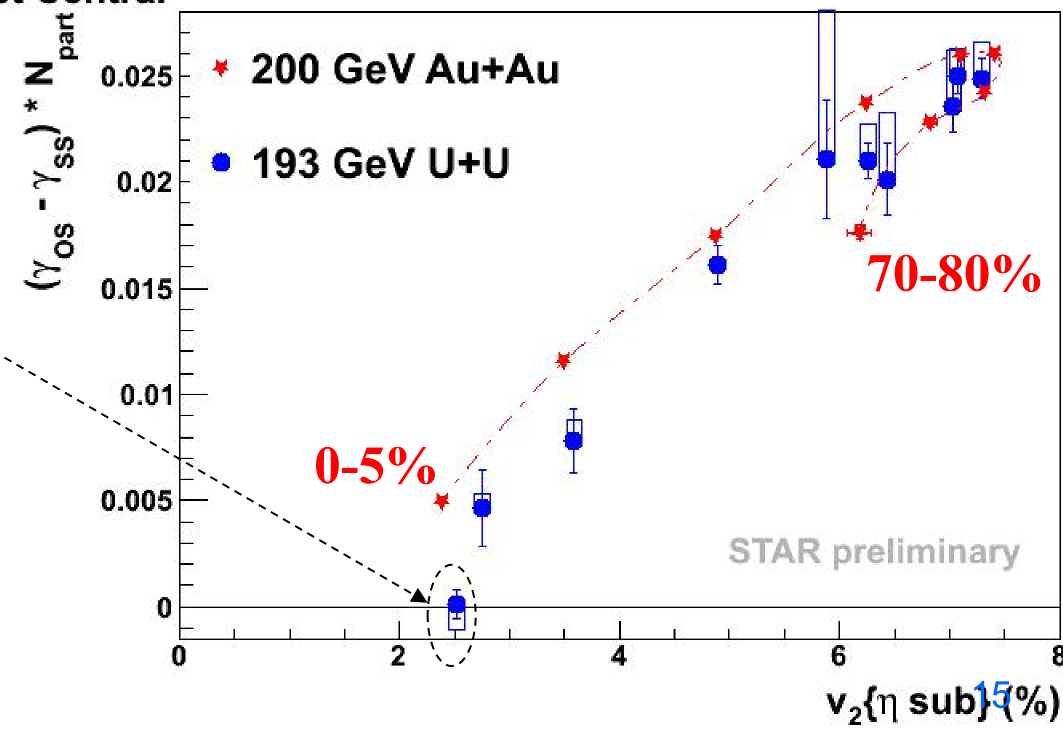


To disentangle the signal and the background, we vary

1) the background (central Au+Au and U+U, or p+Au)

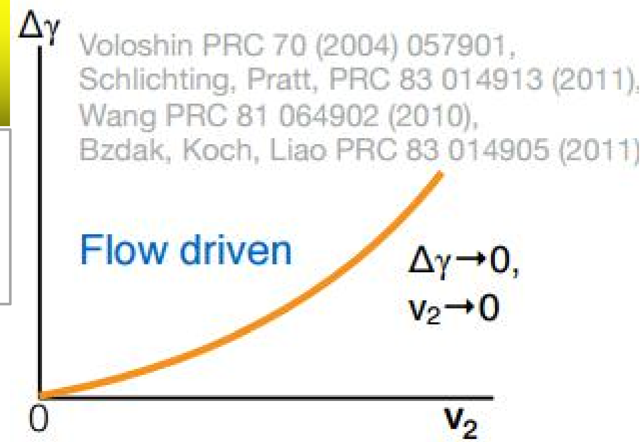
2) the signal (min.bias Zr+Zr and Ru+Ru)

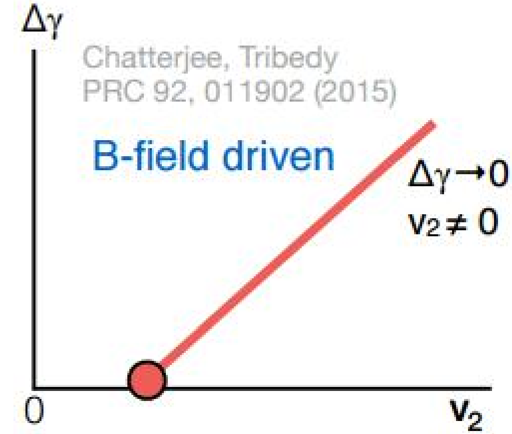
- A dedicated trigger for events with 0-1% spectator neutrons.
- With magnetic field suppressed, the charge separation signal disappears (and v_2 is still ~2.5%).



Central U+U

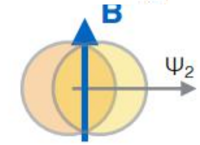
Two scenarios:
flow- and B-field-driven

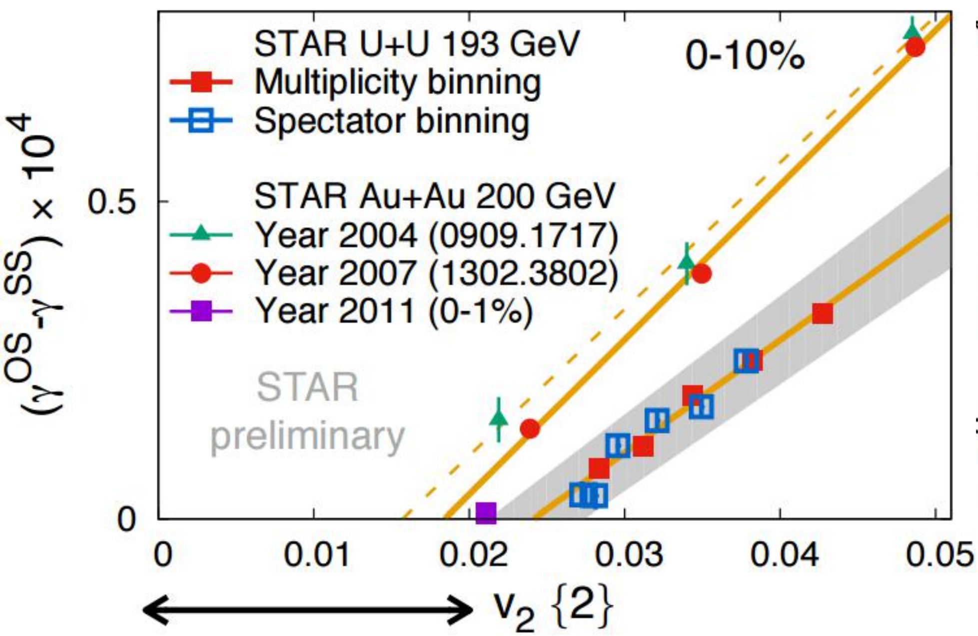


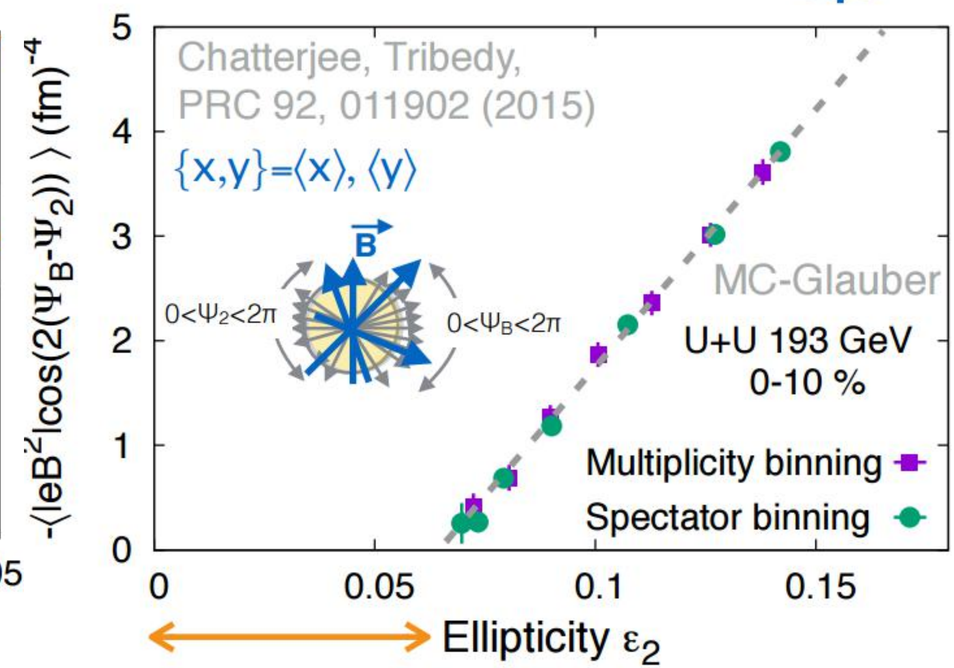


Data

Projected B-field



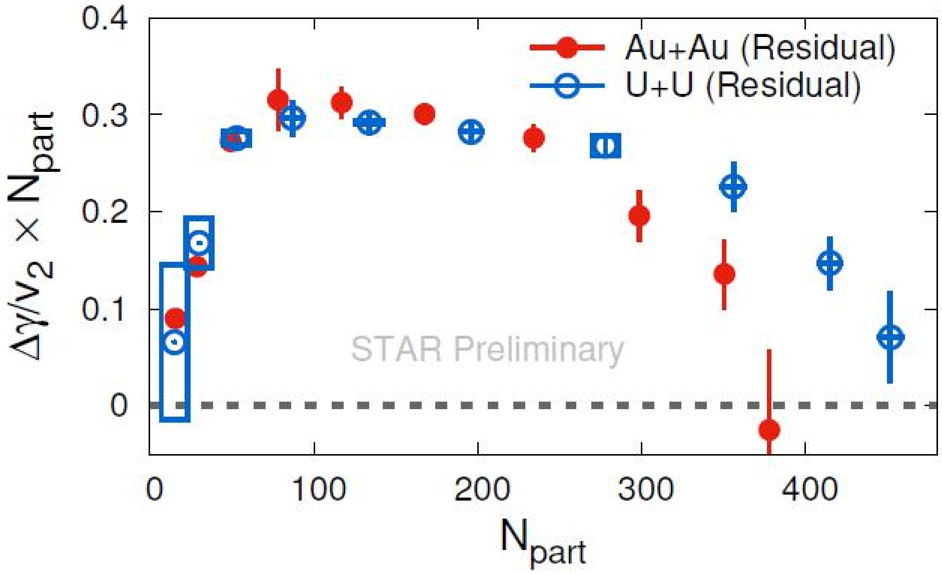


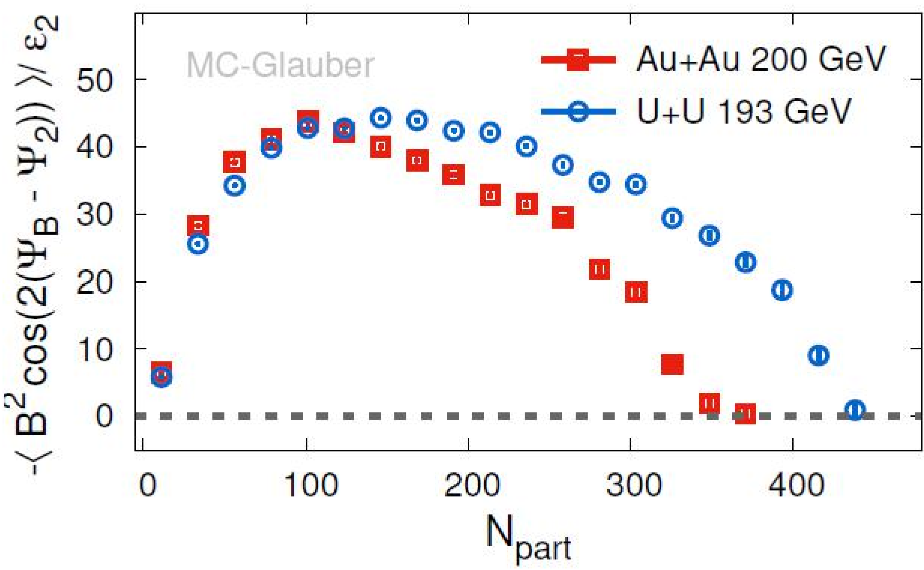


Projected B-field vs ε_2 can provide a natural explanation to data.

Not-so-central U+U and Au+Au

- Between Au and U, there is a change in Z by 13: different signal
- Background expectation $\Delta\gamma_{\text{Background}} \approx \frac{v_2}{N}$





- Short-range correlations have been removed from $\Delta\gamma$.
- Au+Au is lower than U+U at large N_{part}.
- In a pure bg scenario this plot should be flat & universal.
- Data resemble the magnetic field scaled by ε_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		~	

Wood-Saxon in *MC Glauber*

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

- 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 <

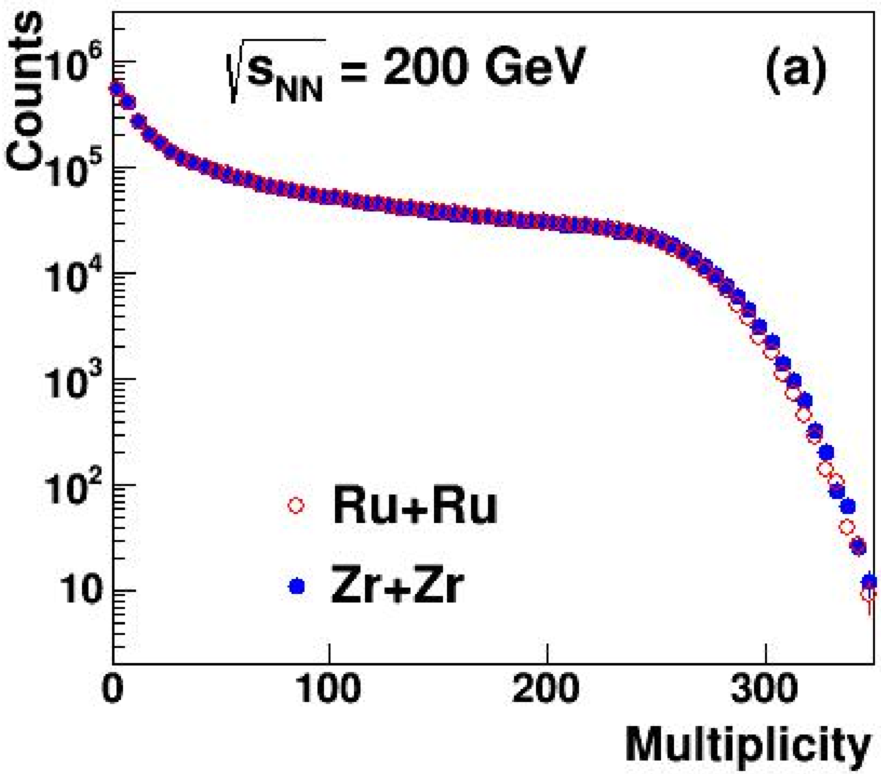
> case 2

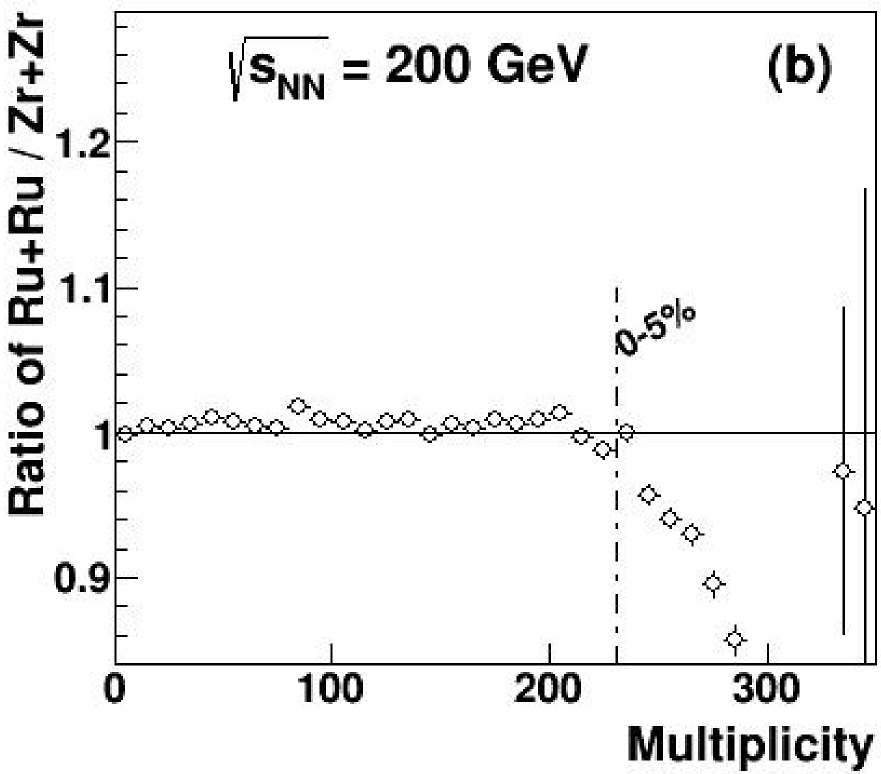
Q. Y. Shou, Y. G. Ma, P. Sorensen, A. H. Tang, F. Videbæk, H. Wang, PLB749,215 (2015)

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

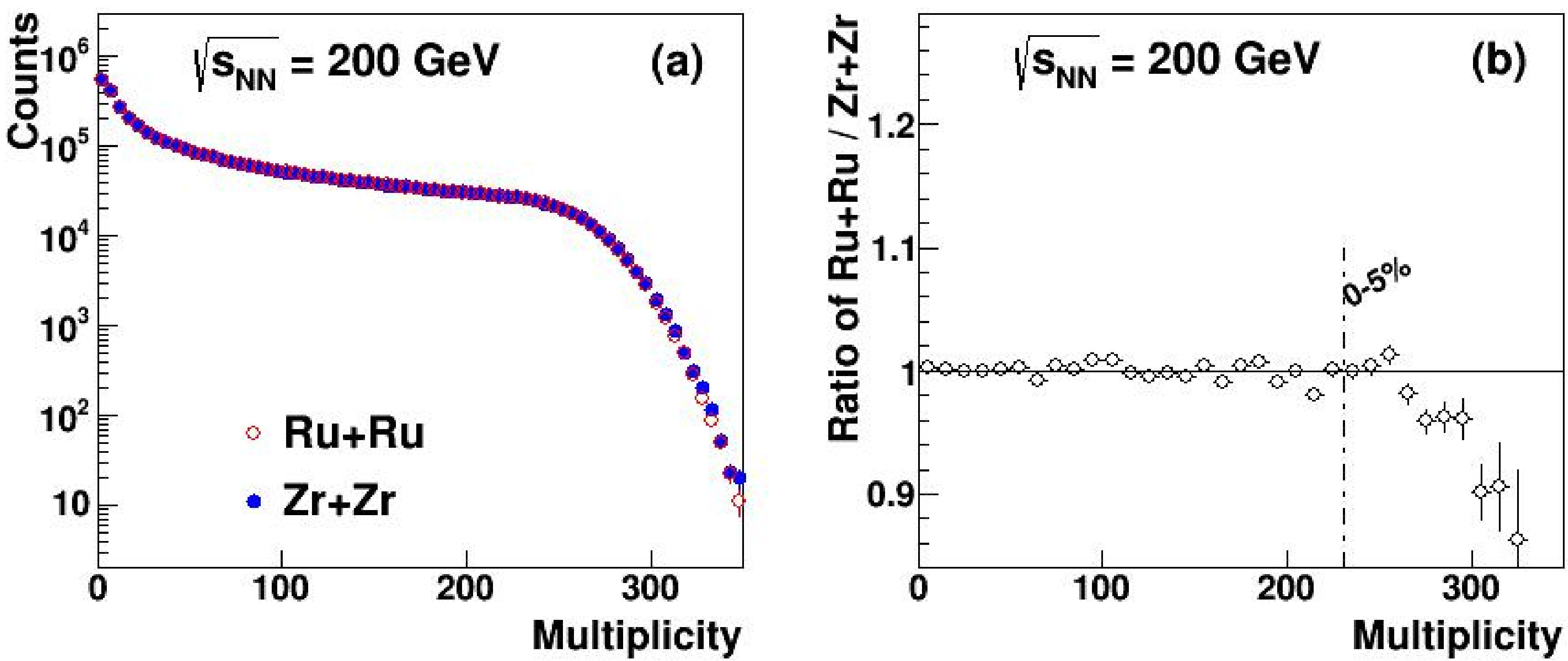




multiplicity: Case 2

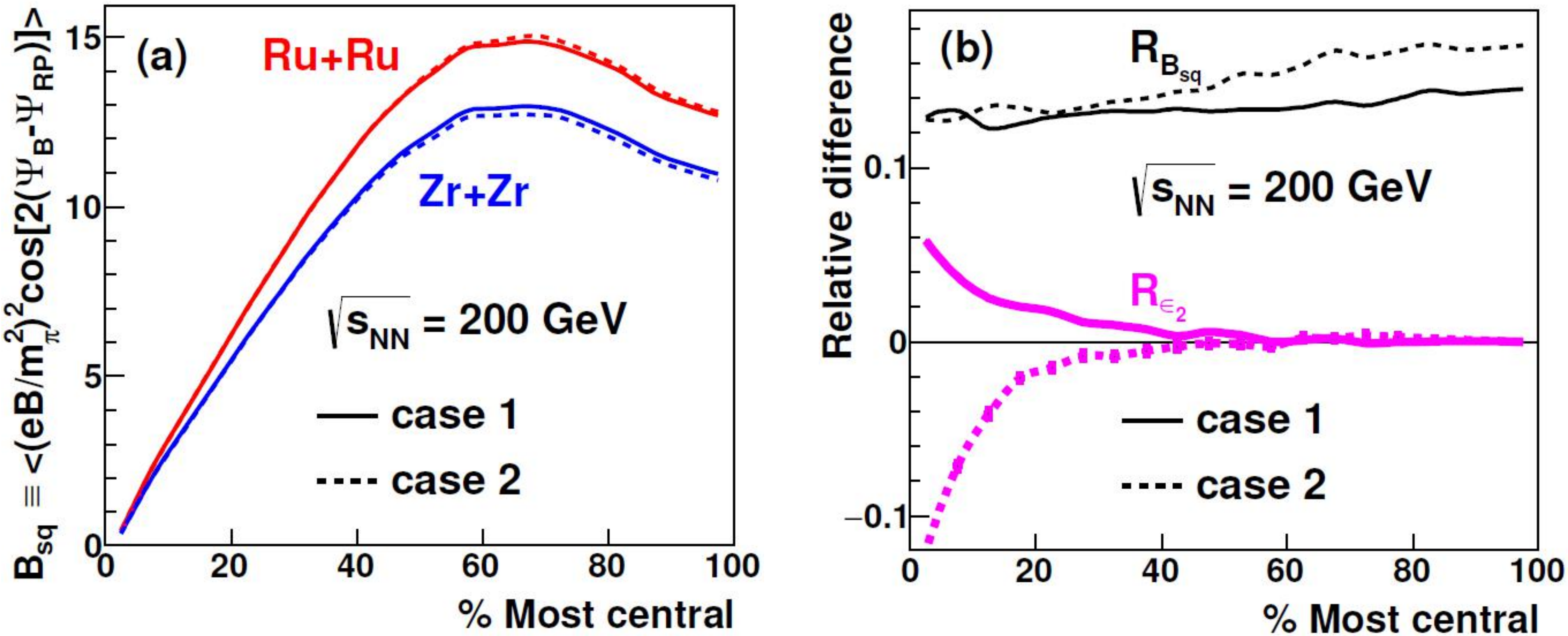
- Parameters from a comprehensive model deduction
- The ratio is close to 1 except for 0-5% most central events

	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

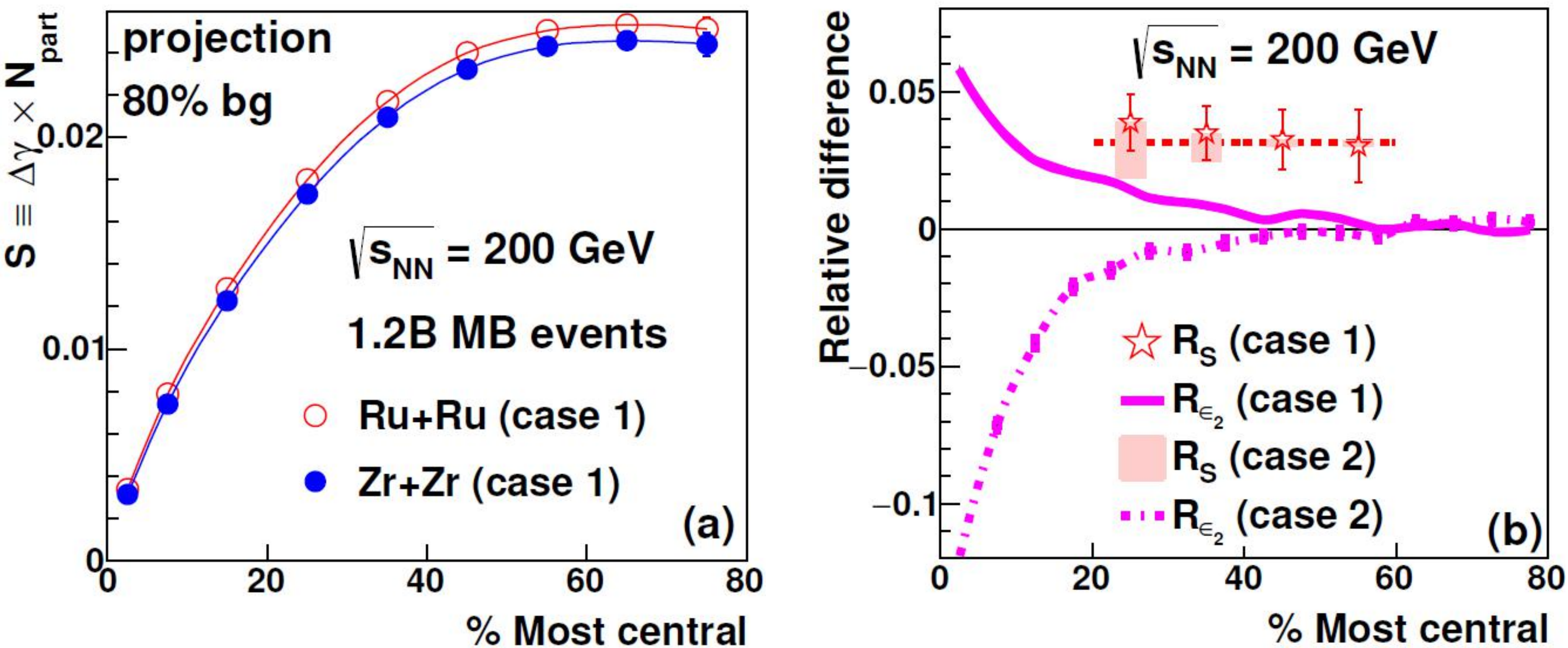
- B calculated at t=0, at one point (center of mass of participants)
- B field slightly affected by β_2
- The ratio in B^2 is close to 1.18 for peripheral events
- Reduces to 1.14 for central events



W-T Deng, X-G Huang, G-L Ma, and GW,. Phys. Rev., C94:041901, 2016.

charge separation: γ (80% bg)

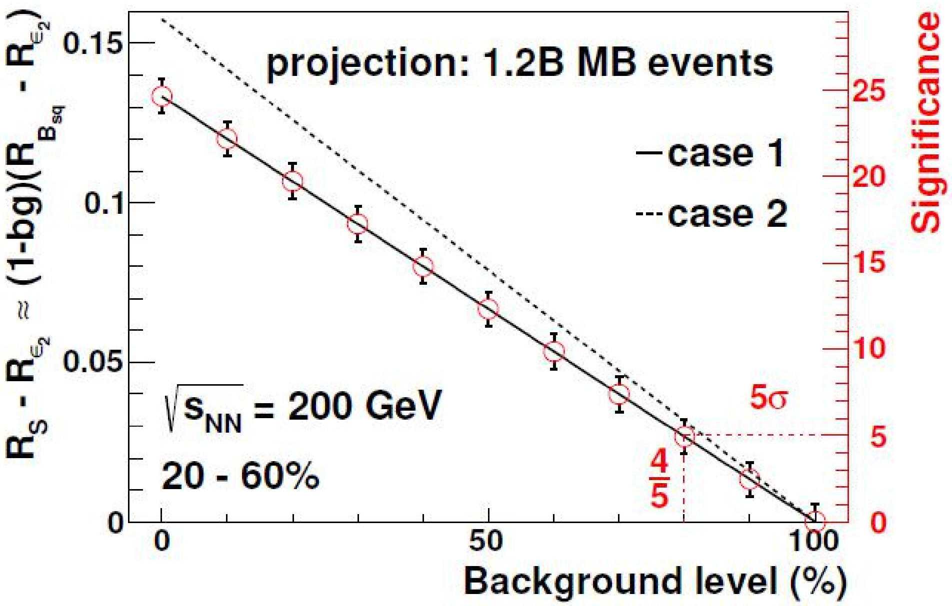
- Projection with 1.2B MB events from each collision type.
- If it's v_2-driven, rel. dif. will follow eccentricity.
- If it's 20% CME-driven, the difference in $\Delta\gamma$ is 5σ above ε_2.

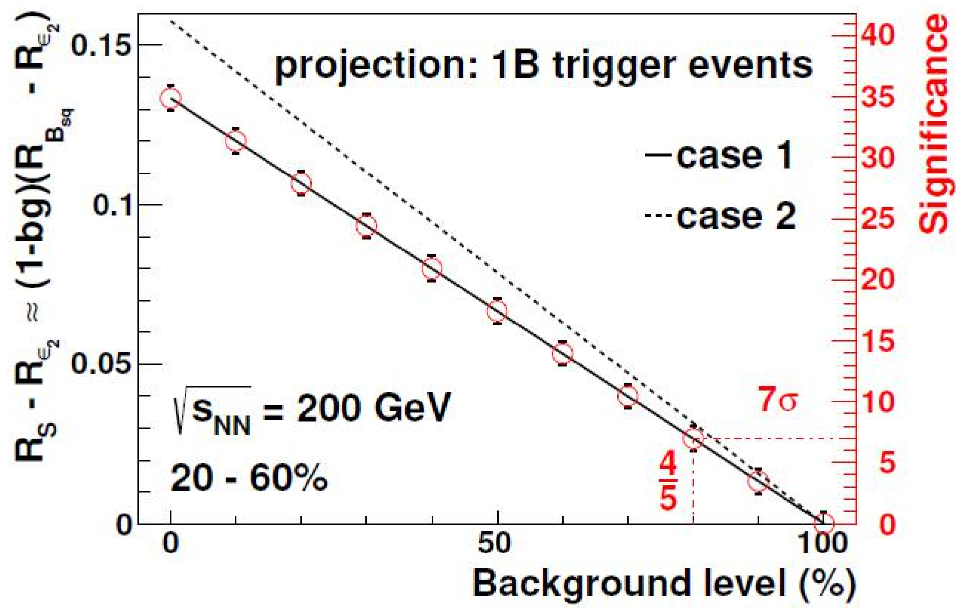


W-T Deng, X-G Huang, G-L Ma, and GW,. Phys. Rev., C94:041901, 2016.

significance vs bg

- Projection with 1.2B MB events from each collision type
- A dedicated trigger can double the *useful* data.
- significance of the difference in Δγ depends on bg level
- case 2 is slightly better than case 1 (reality between them)





Hopefully isobaric collisions will have final word on background!

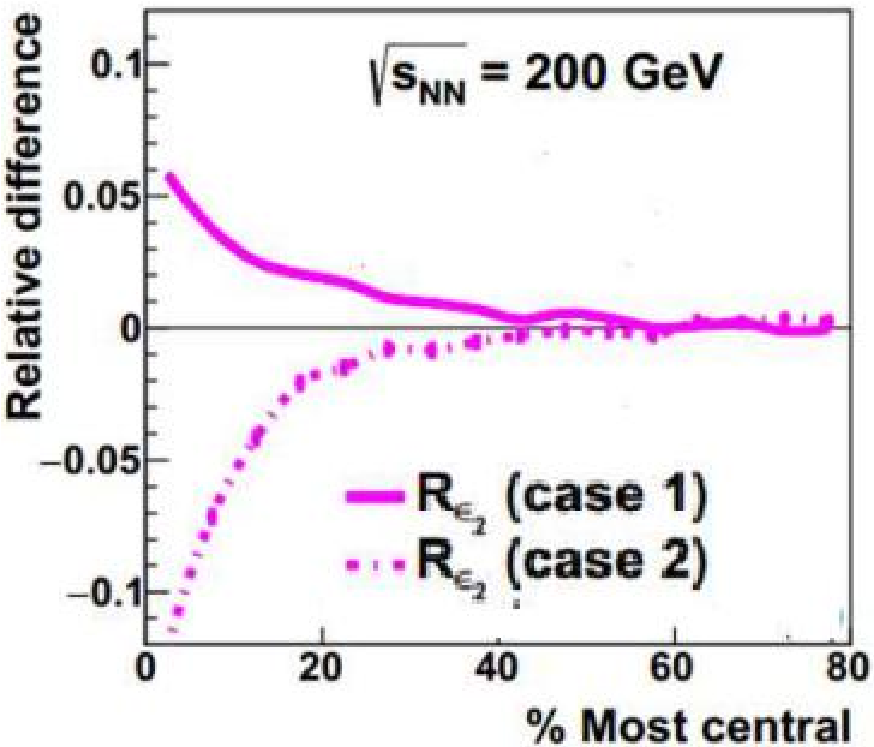
By-product: deformity

	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

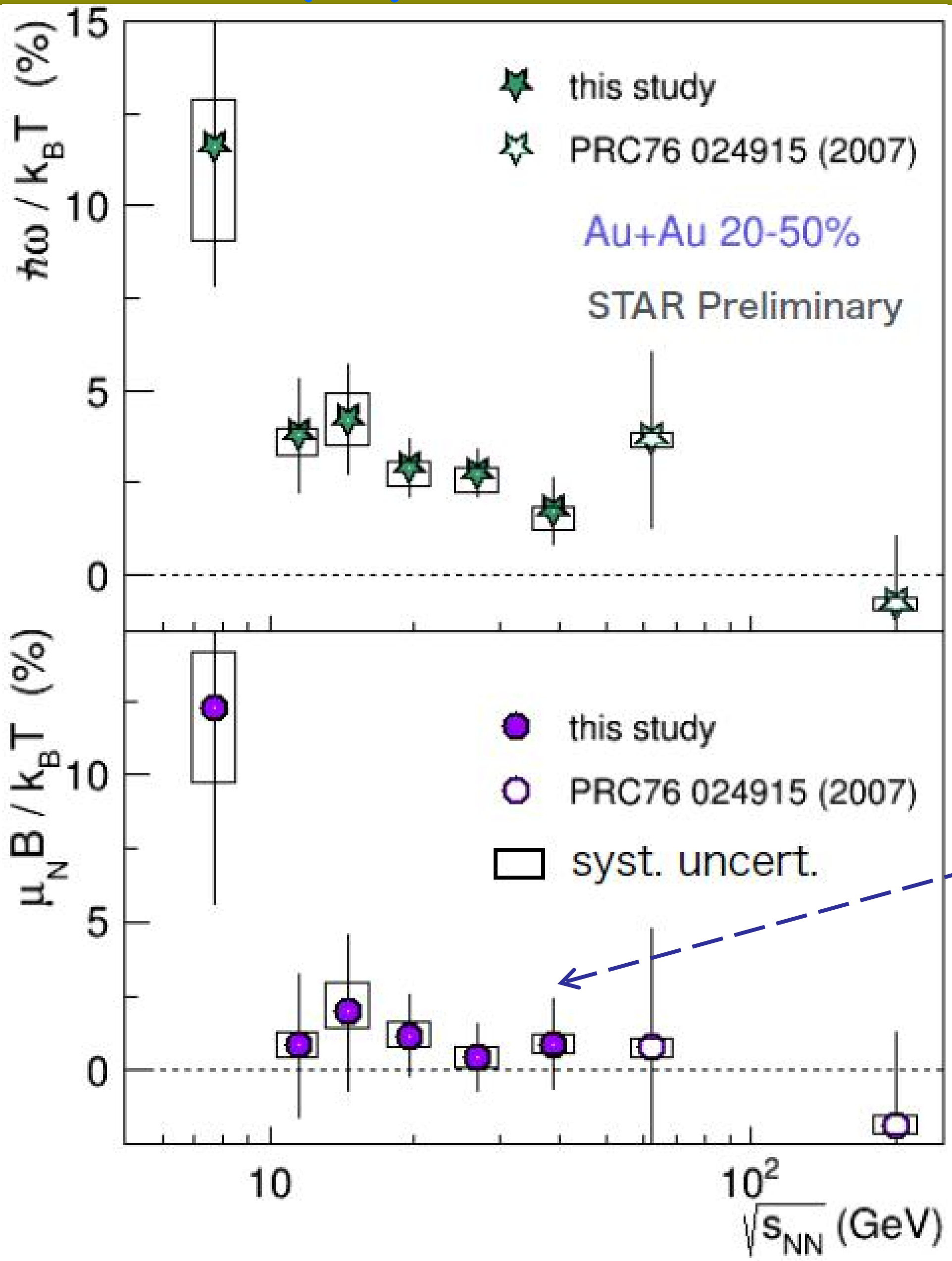
	R_0 [fm]	a(d) [fm]	$β_2$
^{96}Zr	5.06	0.46	0.18
^{96}Ru	5.13	0.46	0.03

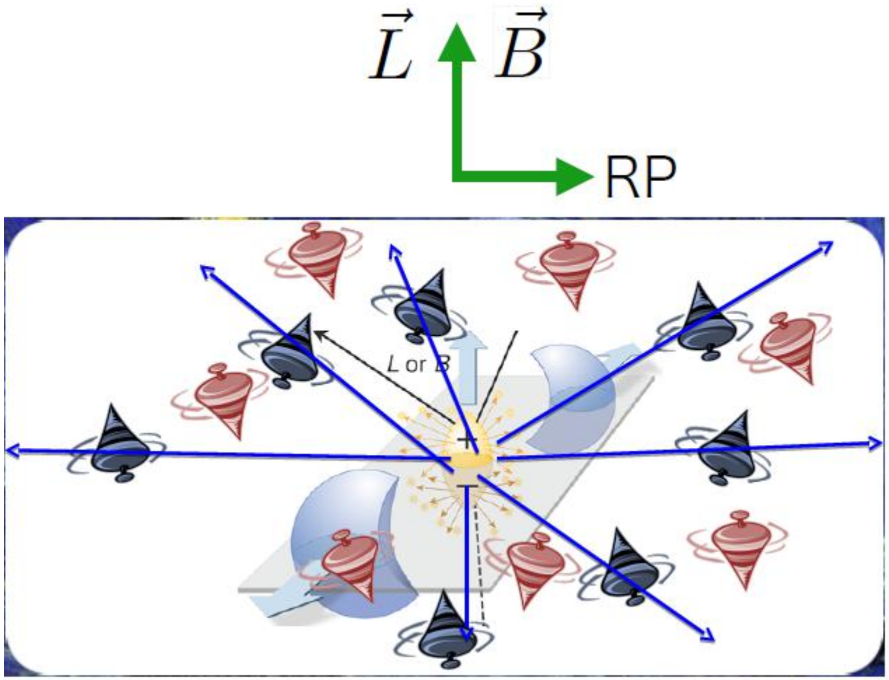
case 2



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

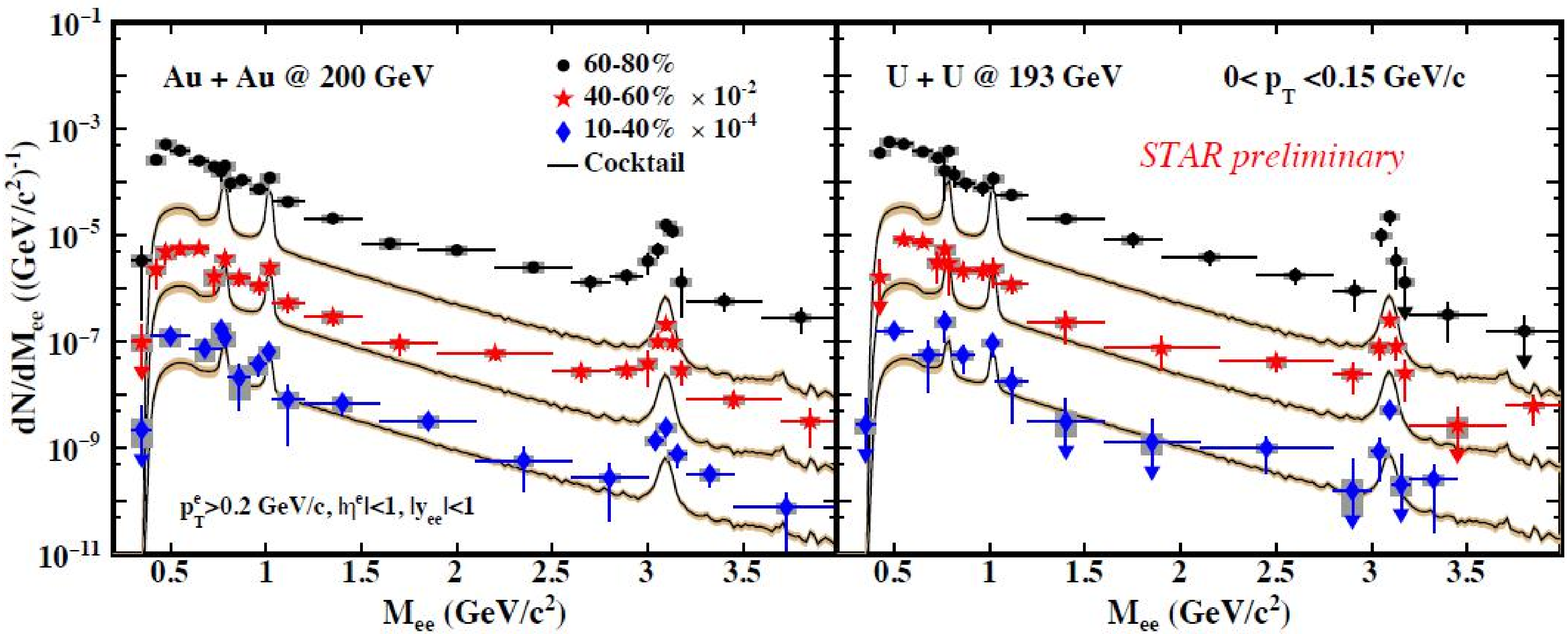
By-product: Λ global polarization



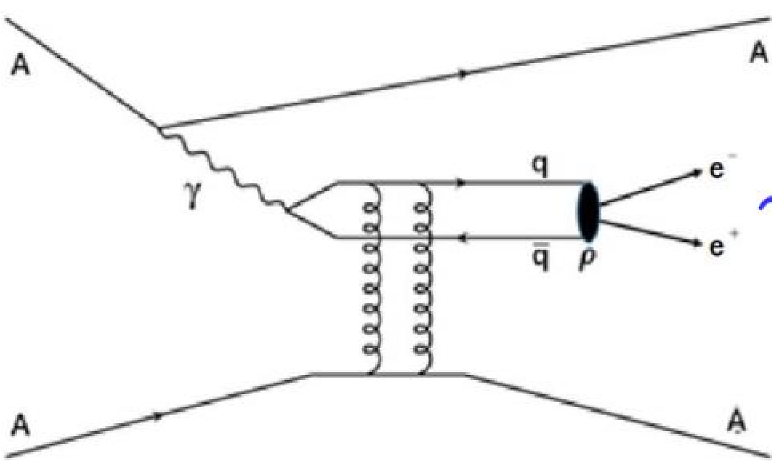


Expect 10% difference between Zr+Zr and Ru+Ru, if it is due to magnetic field. Need beam energy scan.

By-product: di-leption at very low p_T

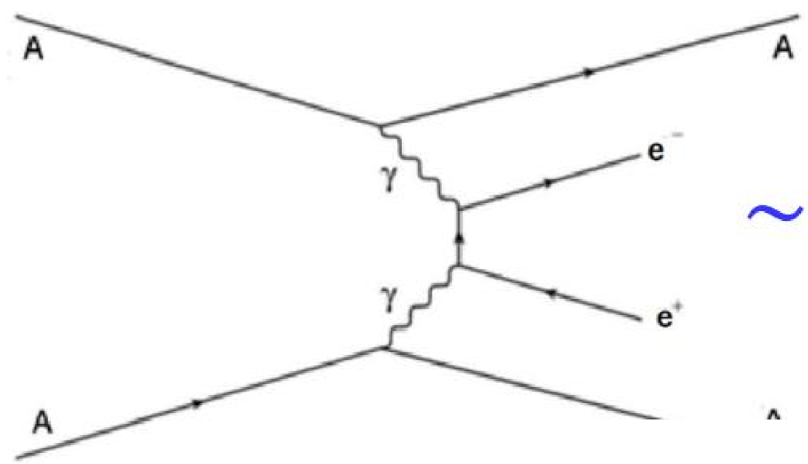


Scenario 1: photonuclear interaction



$\sim Z^2$

Scenario 2: two-photon process

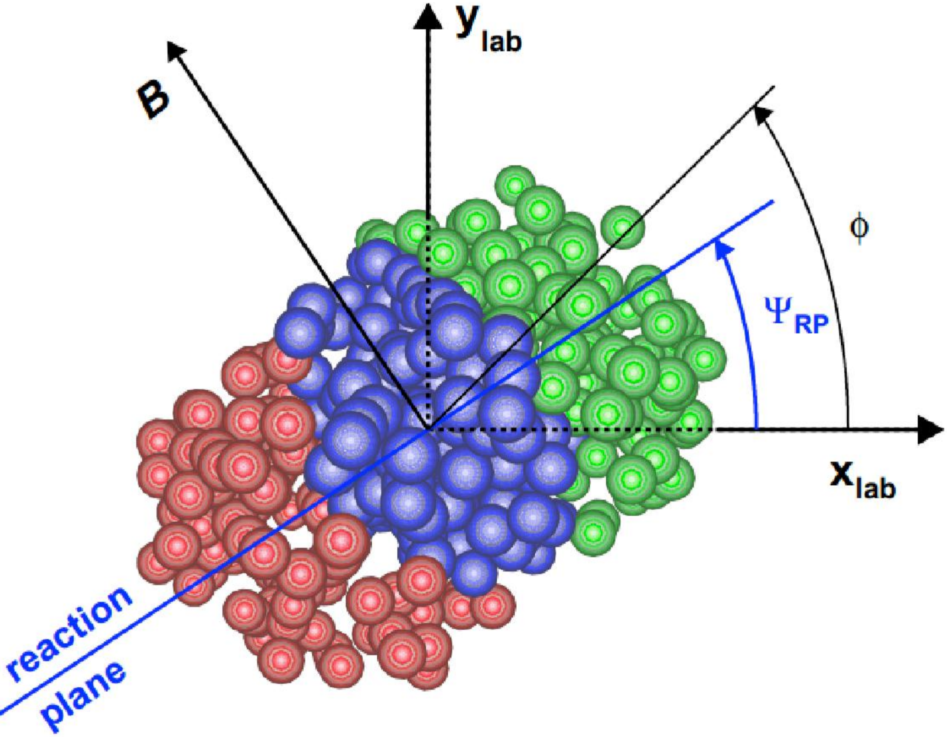


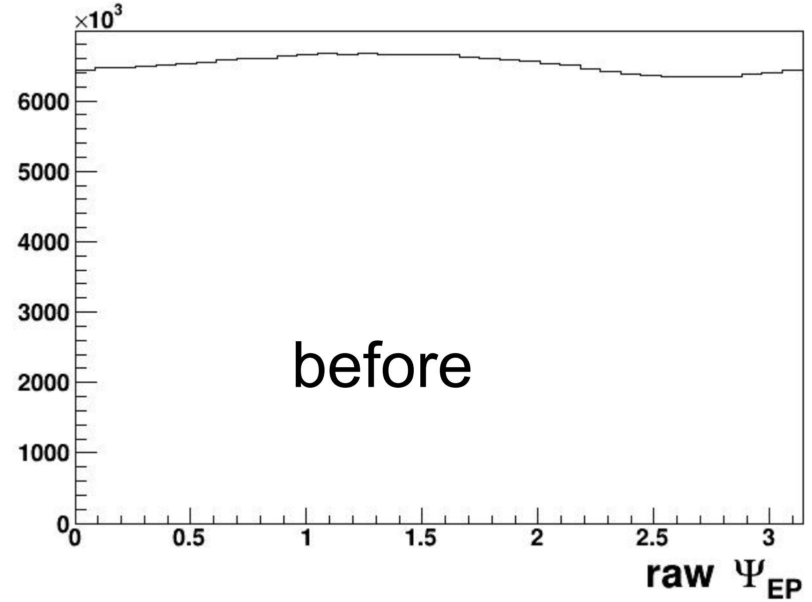
$\sim Z^4$

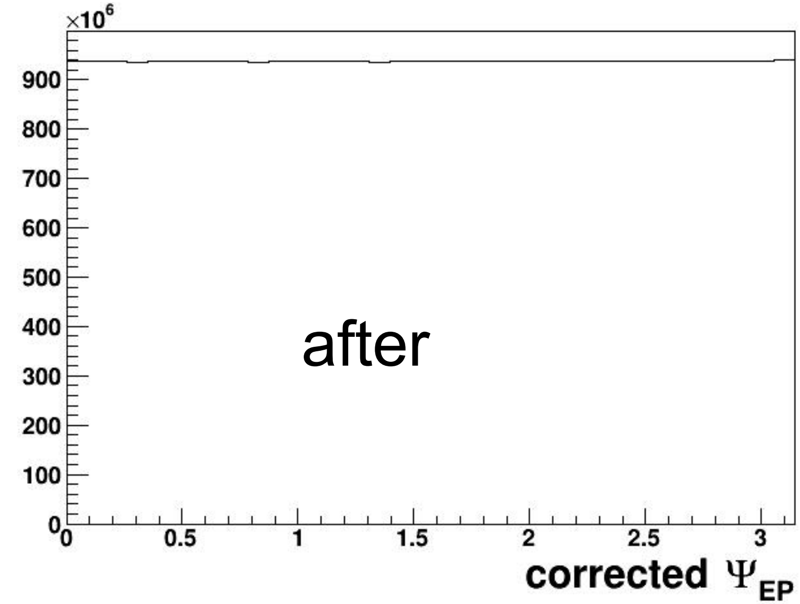
A Way Out

Back-up slides

Event plane







The estimated reaction plane is called the event plane.

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

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

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

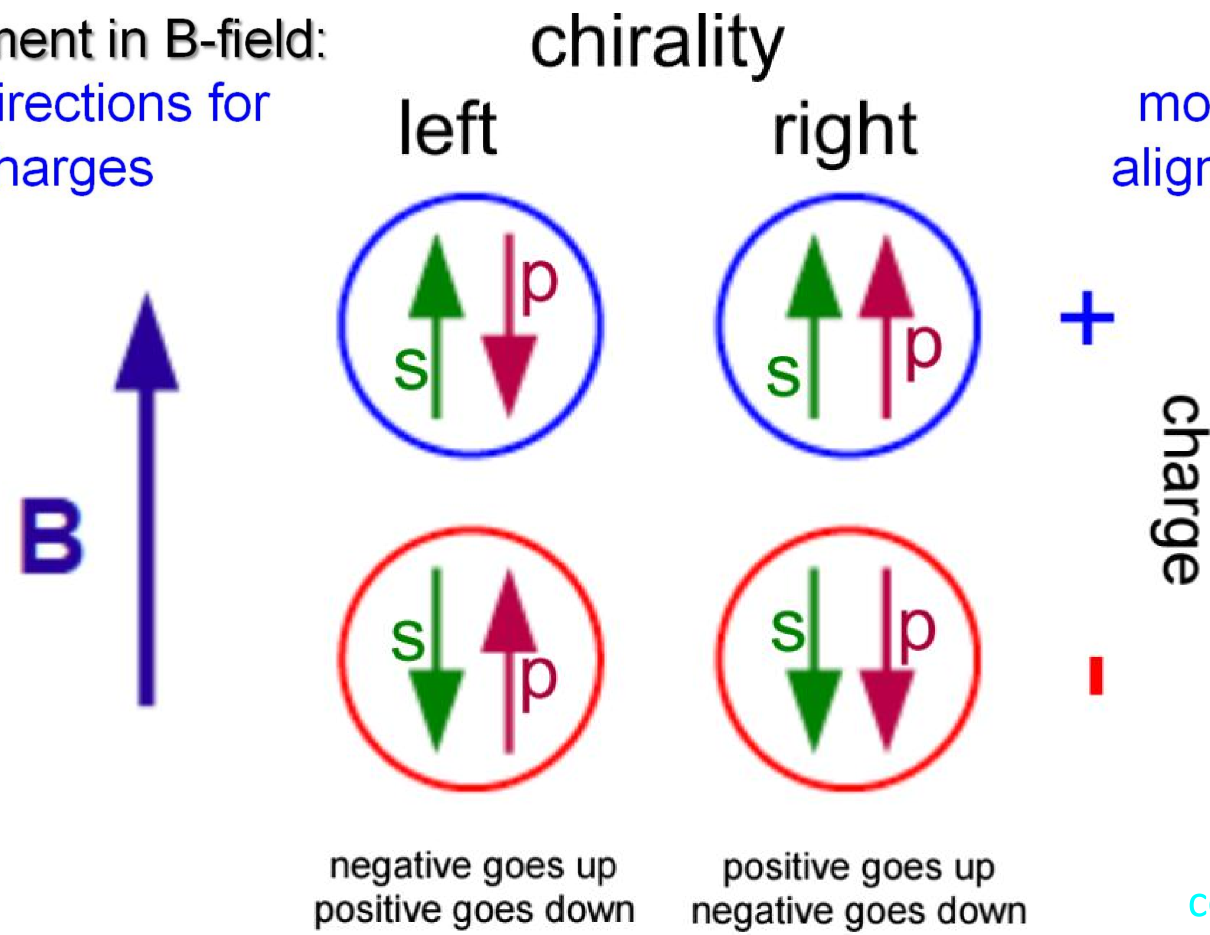
E877, Phys. Rev. C 56 (1997) 3254

Chiral Magnetic effect:

magnetic field + chirality = current

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

handedness:
momentum and spin,
aligned or anti-aligned



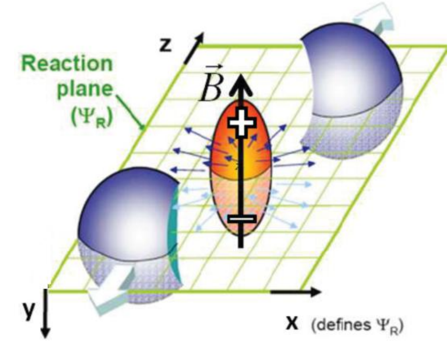
courtesy of P.Sorensen

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

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

CME observable: γ correlator

S. Voloshin, PRC 70 (2004) 057901



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

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

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

background effects: largely cancel out

P-even quantity: still sensitive to charge separation

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

both flow (global collectivity w.r.t the reaction plane)
and non-flow (correlations unrelated to the reaction plane: jet, decay, HBT, momentum conservation …)

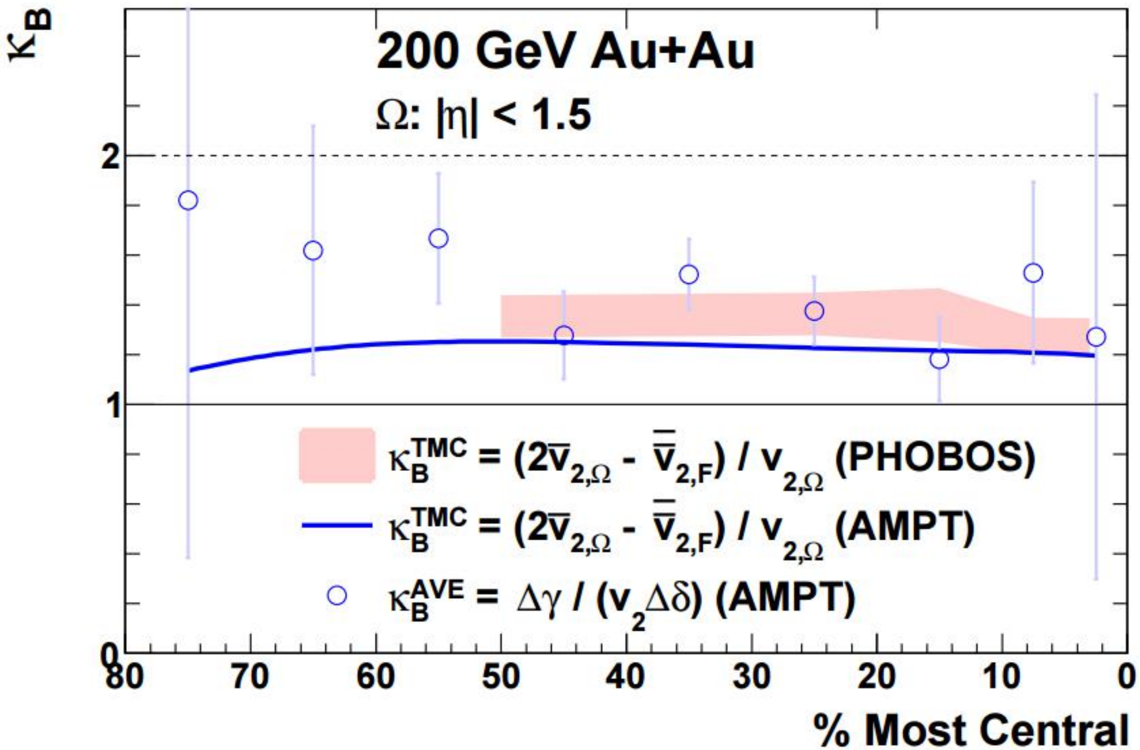
κ_B: background level

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: $\kappa_B^{TMC} \approx (2\overline{v}_{2,\Omega} - \overline{\overline{v}}_{2,F}) / v_{2,\Omega}$



F. Wen, L. Wen and G. Wang, arXiv:1608.03205

PHOBOS v_2@200GeV Au+Au $\longrightarrow$ $\kappa_B^{TMC} \in [1.2, 1.4]$.

Other effects:
Local Charge Conservation (LCC) and resonance decay.

AMPT shows similar κ_B with v_2 or with $\Delta\gamma/(v_2\Delta\delta)$.

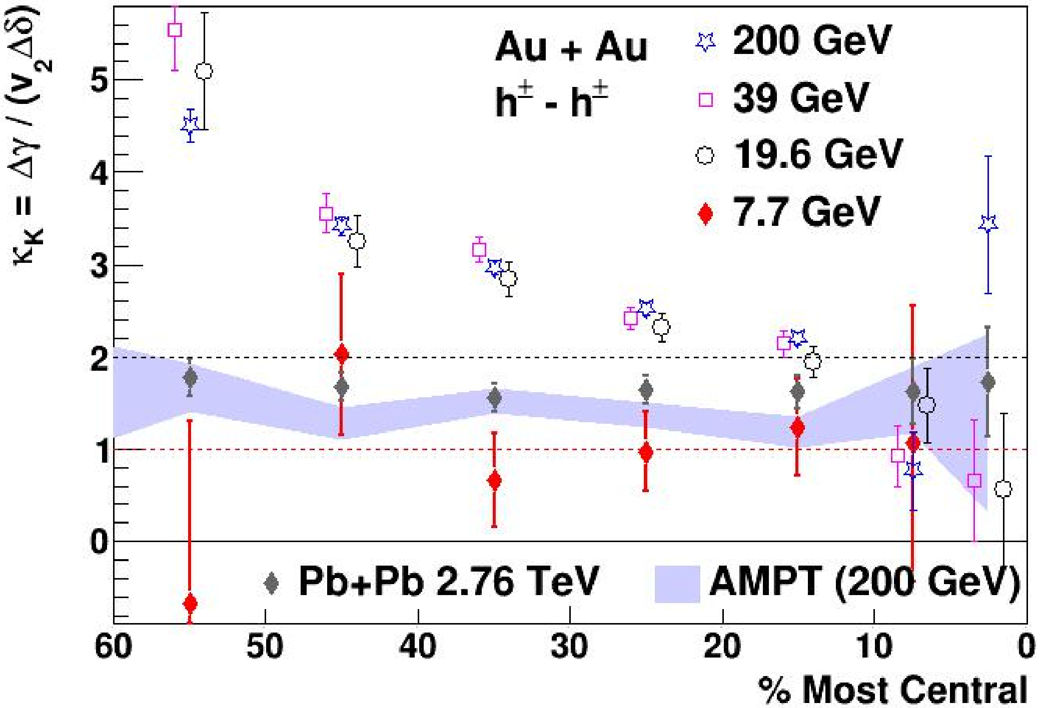
PHOBOS, PRC 72 014904 (2005); PRC 83 024913 (2001)

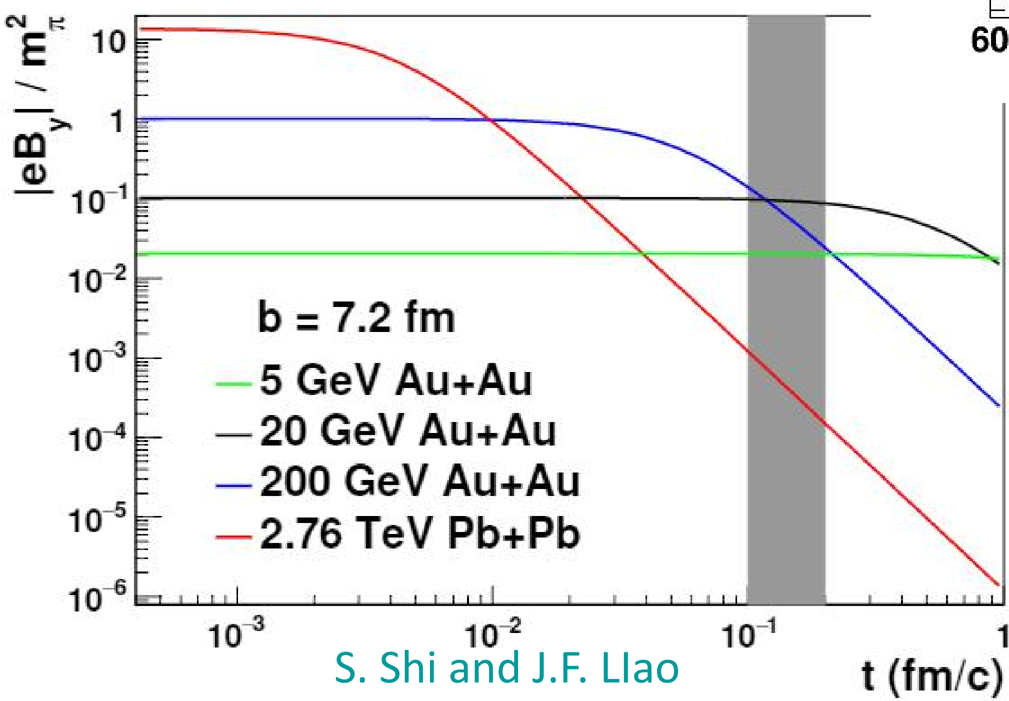
No CME at high energies?

$$\kappa_K \equiv \frac{\Delta\gamma}{v_2 \Delta\delta}$$

$\kappa_K \sim \kappa_B$ for both very low and very high collision energies:

- low energies, no QGP
- high energies, no B field?





- t=0: B@2.76 TeV is 13 times stronger than B@200 GeV
- t=0.01fm/c, they are the same
- t=0.1~0.2 fm/c, B@2.76 TeV is lower than B@200 GeV by a few orders of magnitude

S. Shi and J.F. Llao