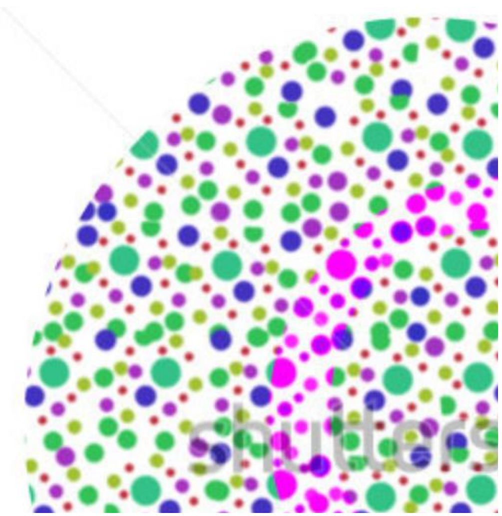
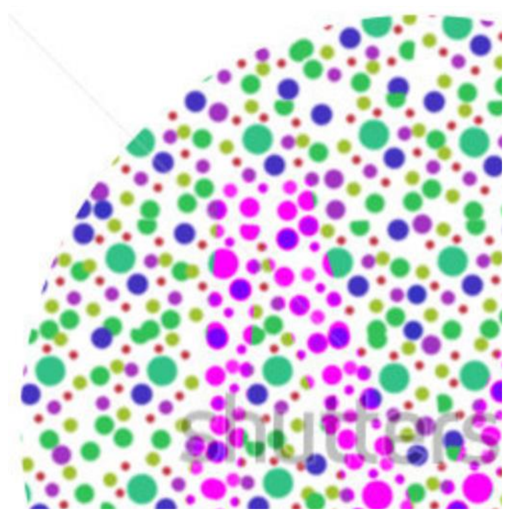
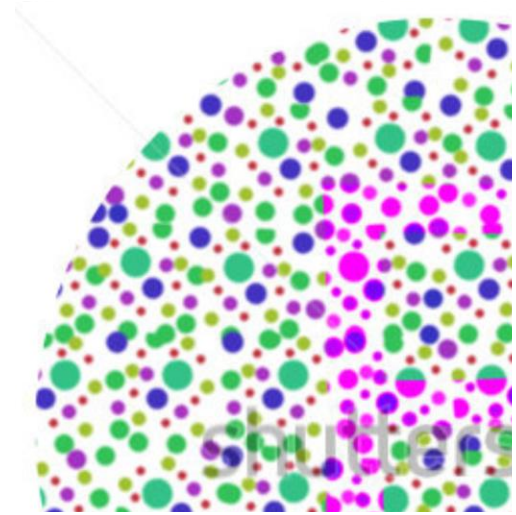
Systematics of the CME search and backgrounds

Gang Wang (UCLA)







Chiral Magnetic effect:

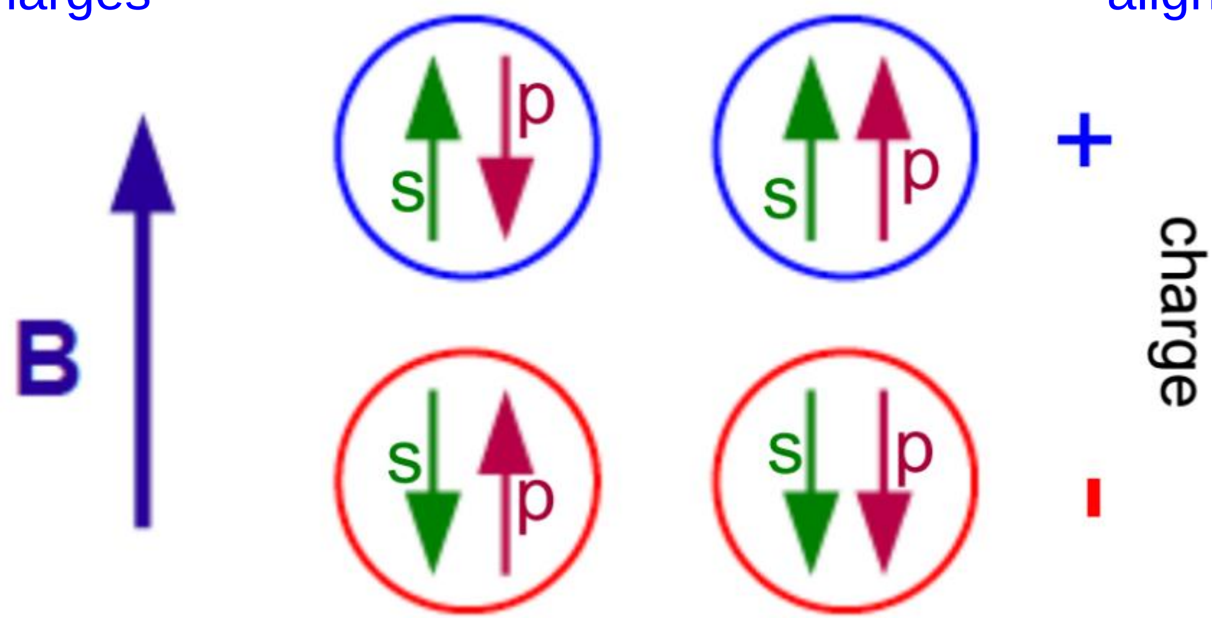
magnetic field + chirality = current

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

chirality

left | right

handedness:
momentum and spin,
aligned or anti-aligned



negative goes up
positive goes down

positive goes up
negative goes down

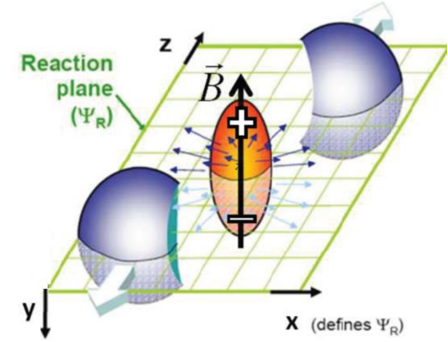
courtesy of P.Sorensen

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



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

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

P-even quantity: still sensitive to charge separation

background effects: largely cancel out

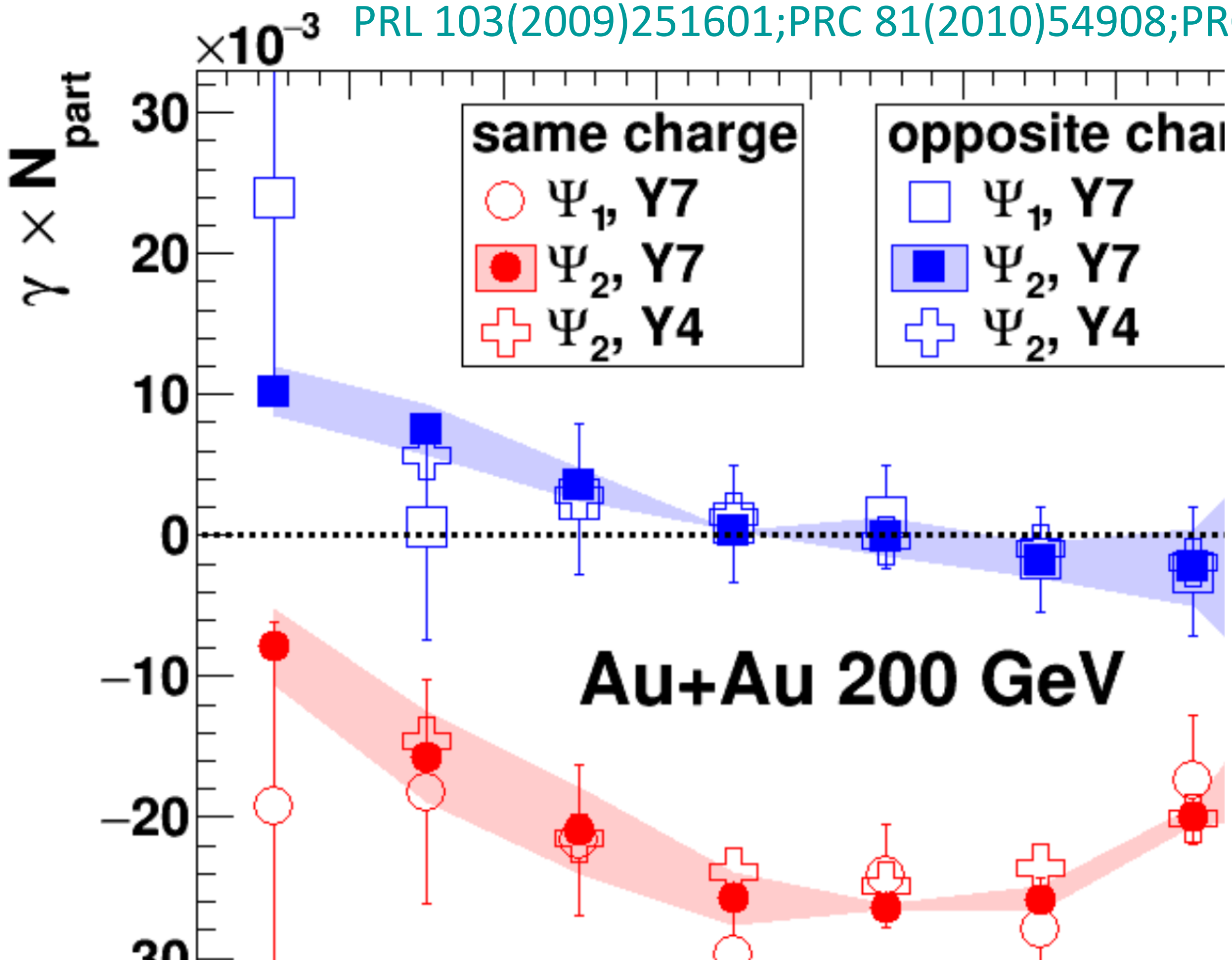
Directed flow: expected to be the same for SS and OS

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

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

Charge separation signal

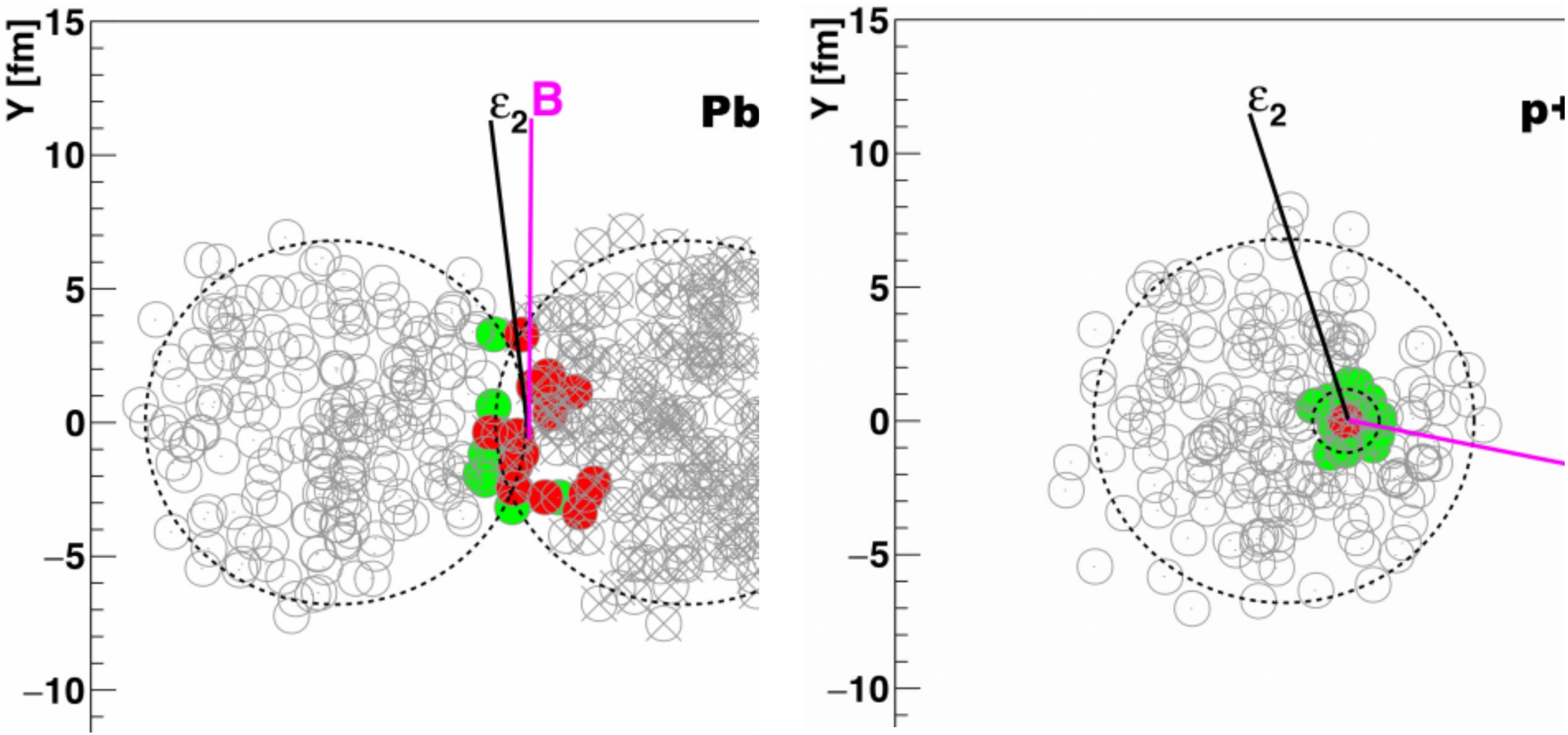
PRL 103(2009)251601;PRC 81(2010)54908;PRC 88 (2013) 64911



- ➢ $\gamma_{os} > \gamma_{ss}$, consistent with CME expectation
- ➢ Confirmed with 1st-order EP (from spectator neutron v_1)
  - ➢ non-flow is not a dominant contribution in large systems
  - ➢ what about small systems?

Small systems

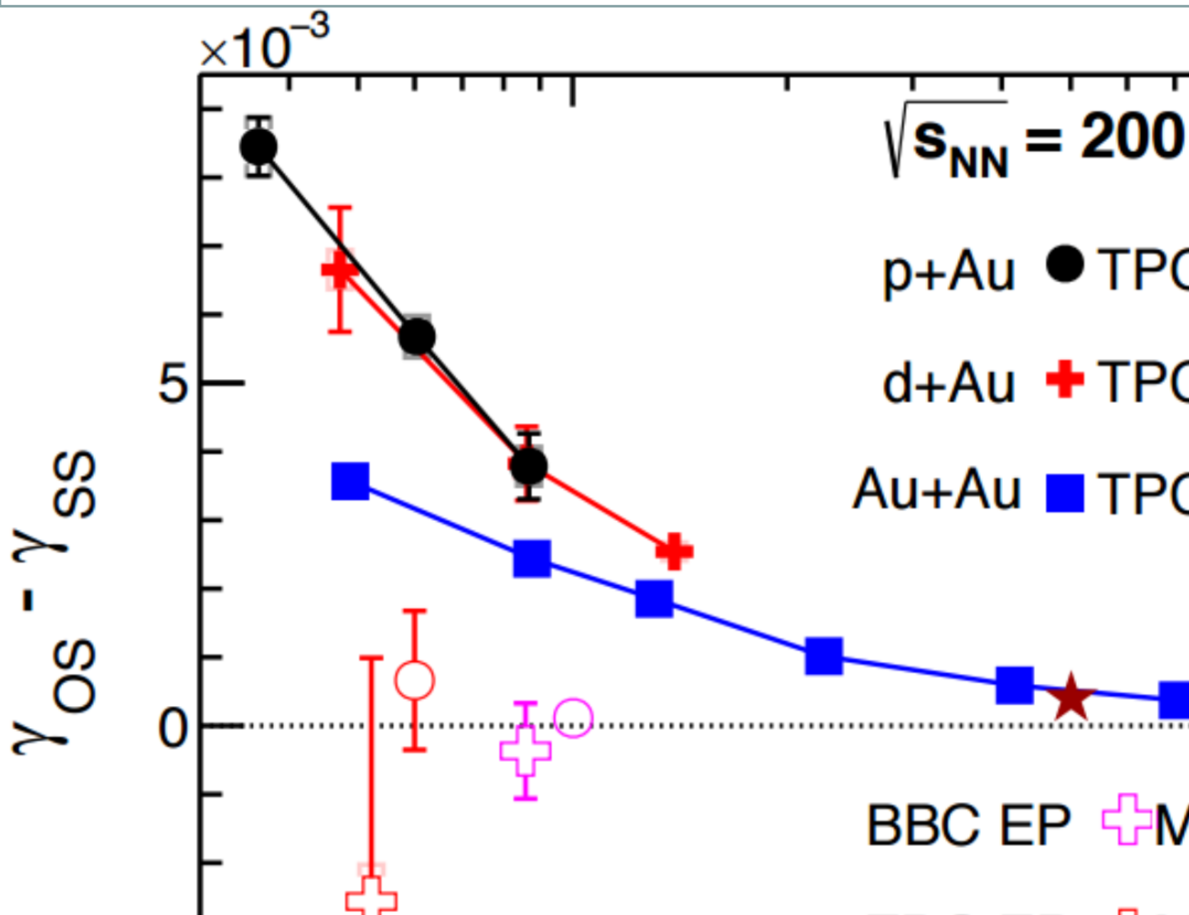
R. Belmont and J.L. Nagle, arXiv:1610.07964



- ψ_1 reflects B direction → related to CME
- ψ_2 reflects ε_2 (eccentricity) → related to backgrounds
- ψ_1 and ψ_2 are correlated in large systems, not in small systems
- non-flow also plays different roles in small and large systems

ψ$_1$ and ψ$_2$, and non-flow

- Sizable Δγ in p+Au and d+Au w.r.t 2nd-order EP fom TPC
  - similar or higher magnitudes than peripheral Au+Au
- Δγ disappears in p+Au w.r.t 1st-order EP from ZDC
- Δγ also disappears in p+Au w.r.t BBC EP
  - short range non-flow with TPC EP

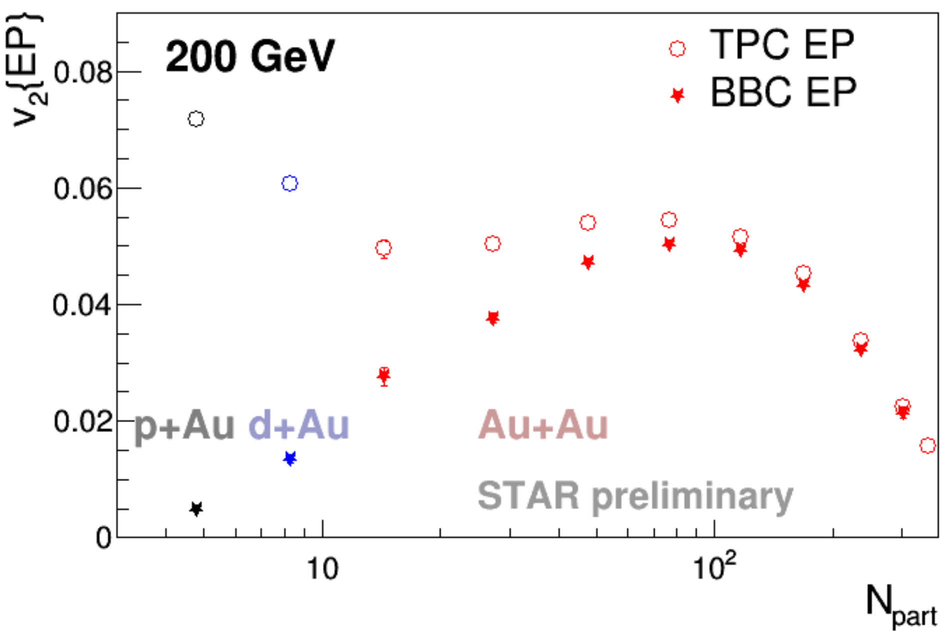


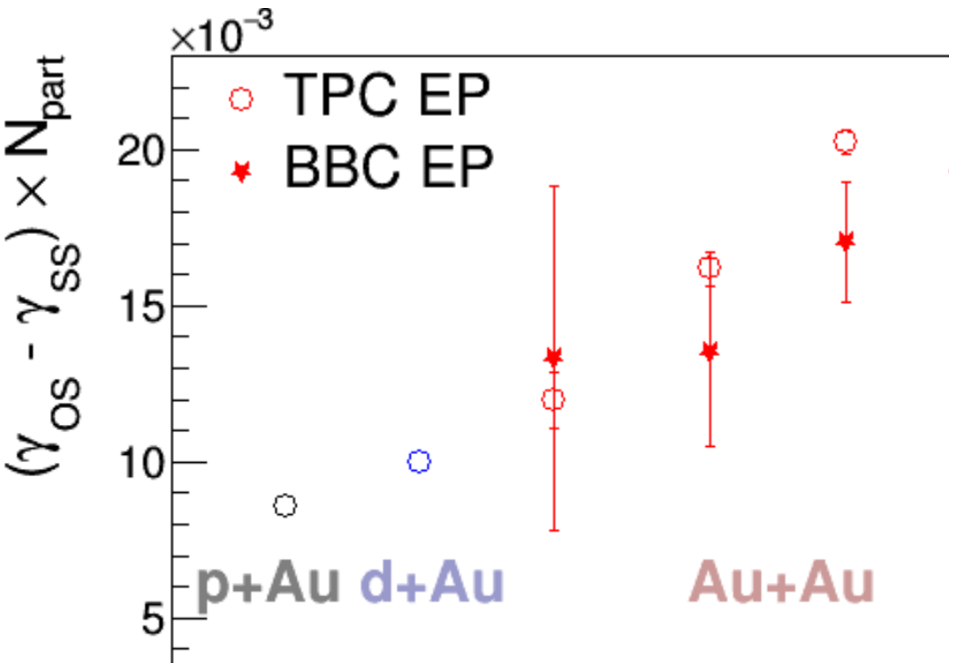
Time Projection Chamber:
Beam-Beam Counter: 3.8 <

- MB (minimum bias trigger)
- HT (High Tower): trigger on electromagnetic energy

Non-flow in small systems

- Enhancement of v_2{TPC EP} in p+Au and d+Au: non-flow
- v_2{BBC EP} instead decreases toward p+Au/d+Au
- Important to have η gap between EP and particles of interest



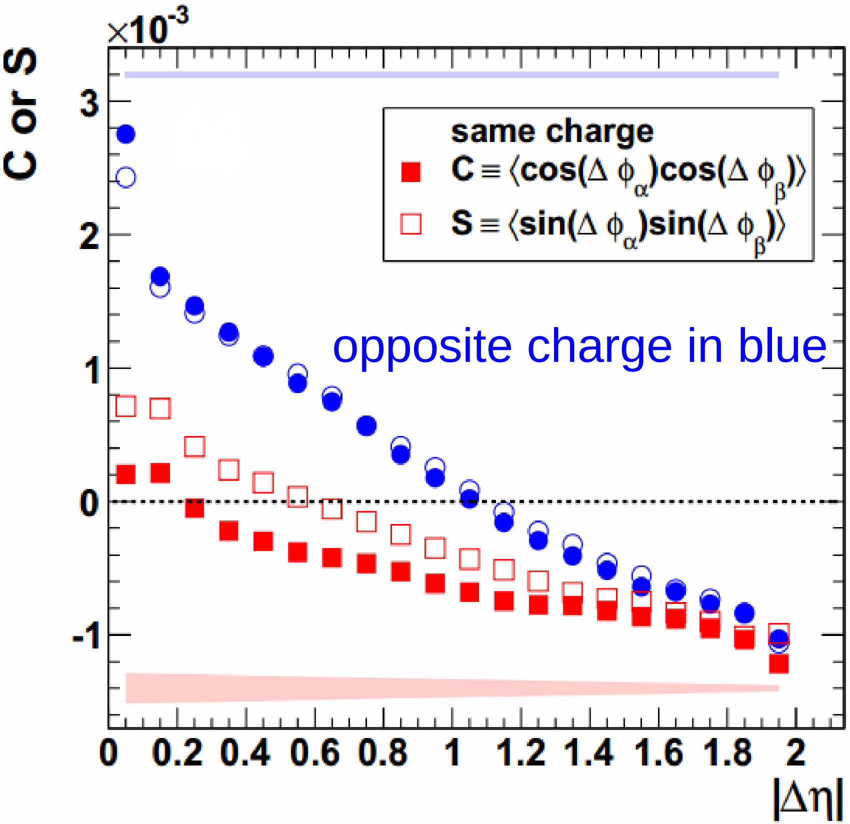


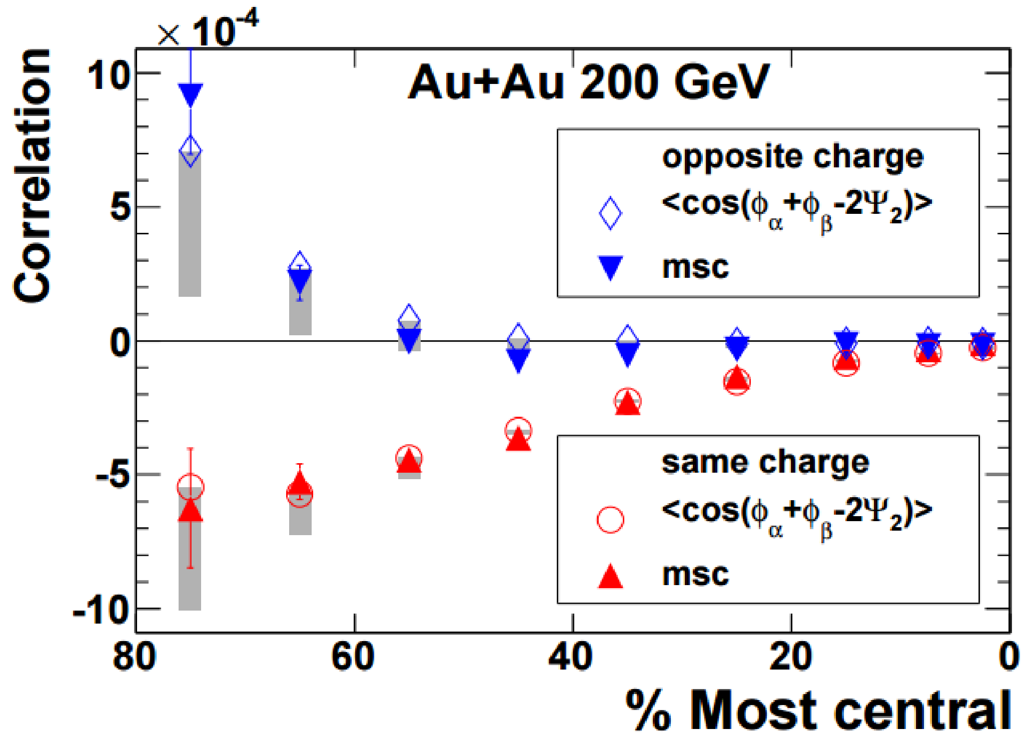
- Δγ{TPC EP} mostly short range non-flow in p+Au/d+Au
- In larger systems, TPC EP and BBC EP give consistent results
  - non-flow is not a dominant contribution in large systems
  - corroborate the conclusion with ZDC EP

Short range correlations

200 GeV Au+Au: 40 - 60%

Phys. Rev. C 88 (2013) 64911



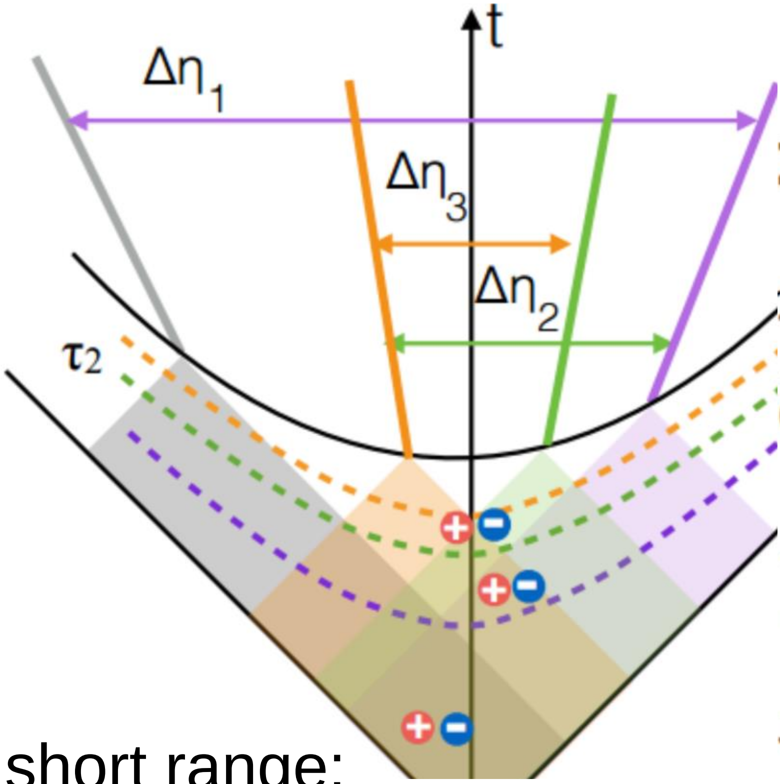


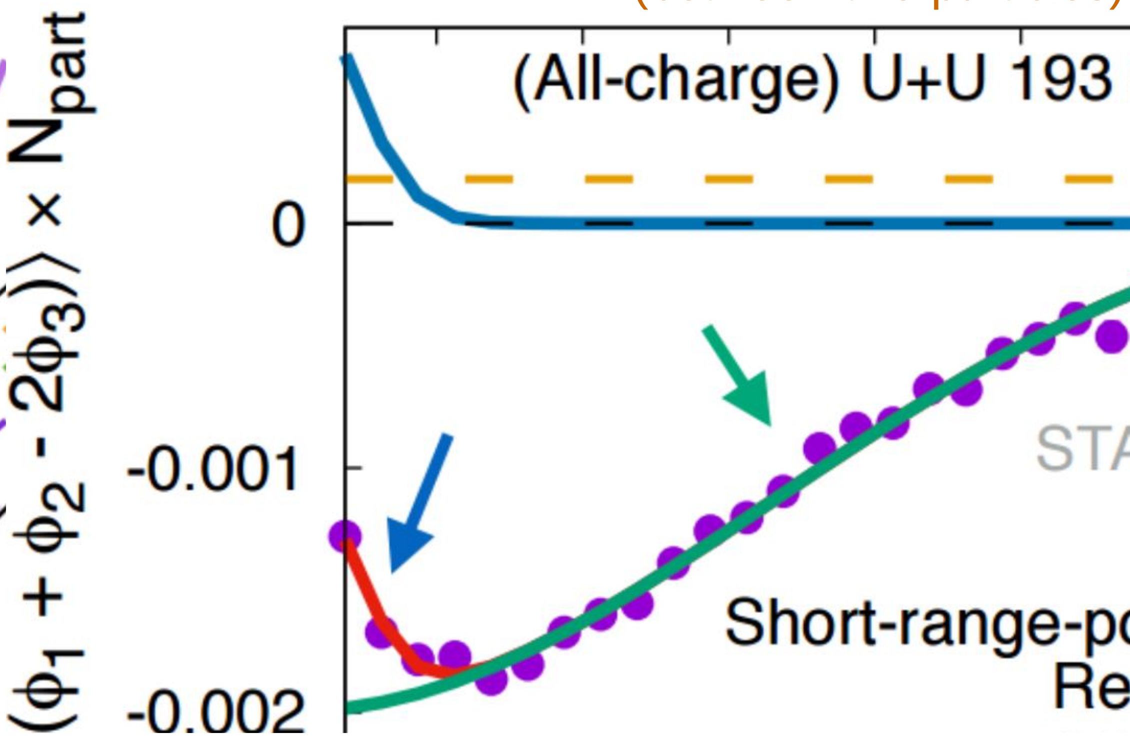
- Prominent correlations exist at small Δp_T and $\Delta\eta$
- Probably due to HBT+Coulomb
- Excluding small Δp_T and $\Delta\eta$:
  - significant effect in peripheral collisions (small systems)

Closer look at short-range correlations

early-time charge separation → long-range correlations in Δη

(between two particles)



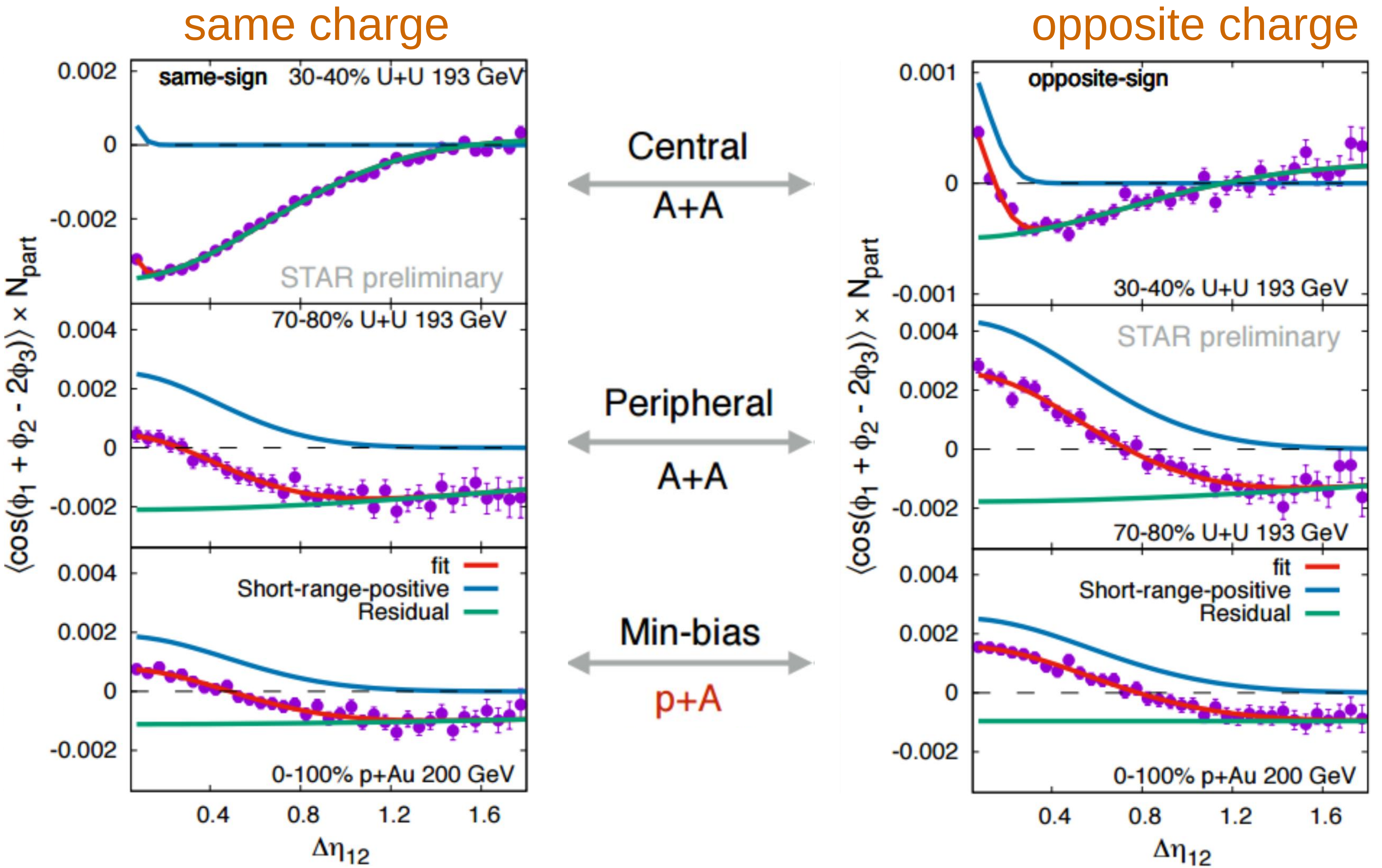


short range:

$$\Delta\phi \rightarrow 0, \Delta\eta \rightarrow 0 : C_{112} = \langle\cos(\phi_1(\eta_1)+\phi_2(\eta_2)-2\phi_3)$$

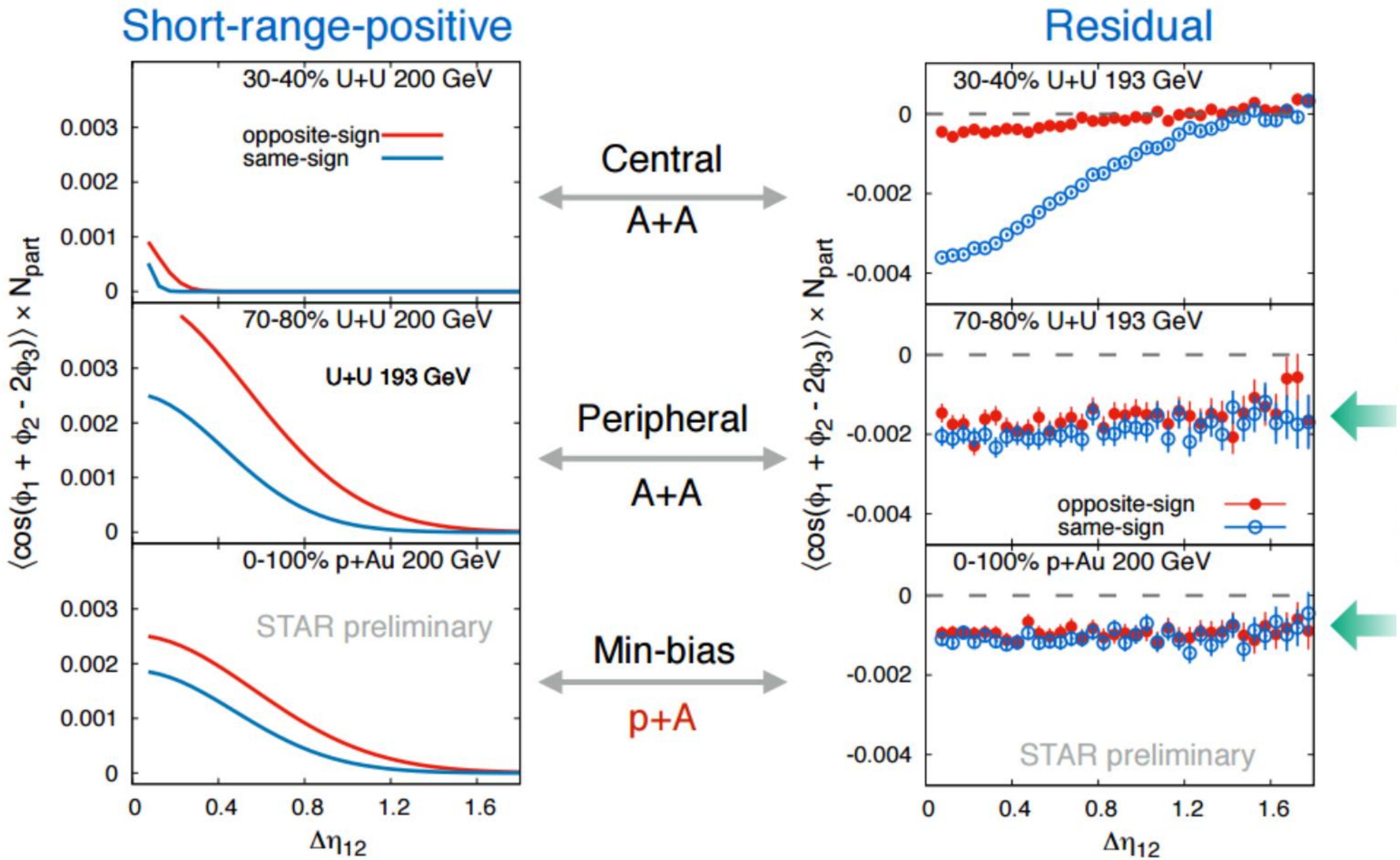
$$C_{112}(\Delta\eta_{12}) = \boxed{A^{+}_{SR}\, e^{-(\Delta\eta)^2/2\sigma^2_{SR}}} - \boxed{A^{-}_{IR}\, e^{-(\Delta\eta)^2/2\sigma}}$$

Large and small systems



p+Au data are very similar to peripheral U+U.

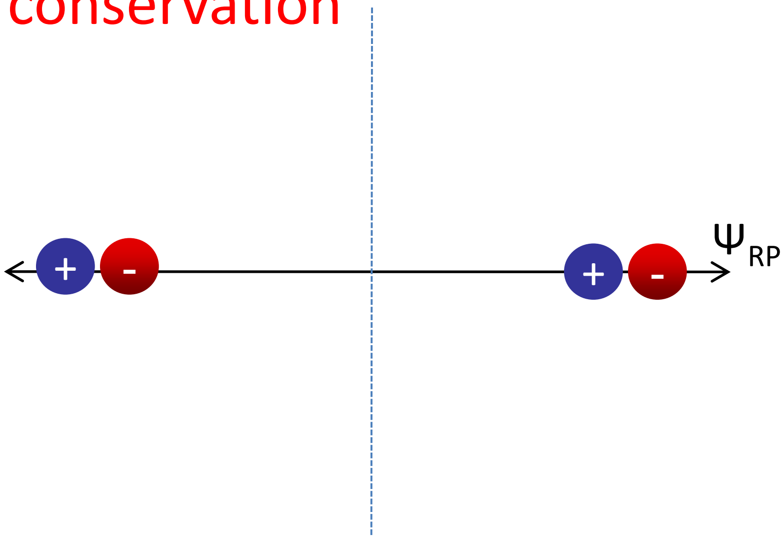
Residual



- ➢ p+A & peripheral A+A → dominated by short-range correlations
- ➢ Finite residual in large systems → not necessarily true CME signal.

Flow-related background

An example with no charge separation:
v_2 + local charge conservation/decay + momentum conservation



$\gamma_{SS} = -1$
$\delta_{SS} = -1$ → $H_{SS}^{\kappa=1}=0$

$v_2 = 1$

$\gamma_{OS} = 0$
$\delta_{OS} = 0$ → $H_{OS}^{\kappa=1}=0$

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

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

With κ=1, *H* tells the truth.
But this is an over-simplified example. In reality, κ could deviate from 1.

A cumulant way

$$
\begin{aligned}
&\cos(\varphi_1+\varphi_2-2\psi_{\mathrm{RP}}) \\
&=\cos(\varphi_1-\varphi_2+2\varphi_2-2\psi_{\mathrm{RP}}) \\
&=\cos(\varphi_1-\varphi_2)\cos(2\varphi_2-2\psi_{\mathrm{RP}})-\sin(\varphi_1-\varphi_2)\sin(2\varphi_2-2\psi_{\mathrm{RP}})
\end{aligned}
$$

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

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

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

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

The cumulant approach indicates $\kappa \sim 1$.

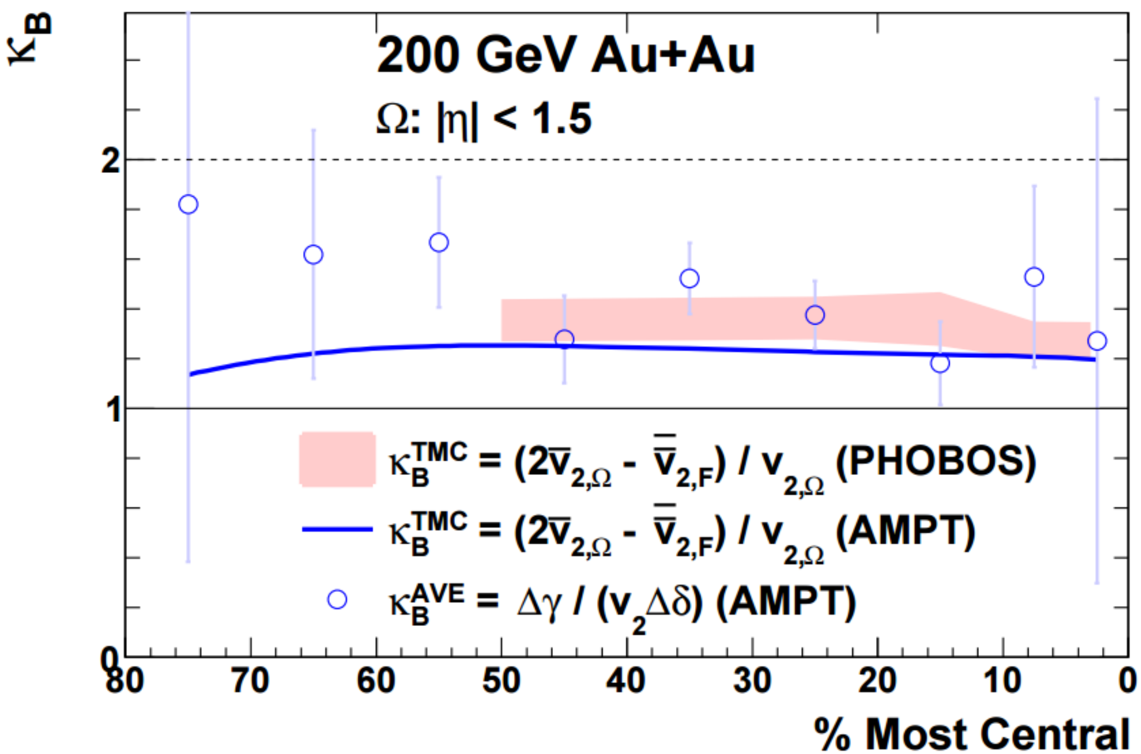
κ_B: background level

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 $\longrightarrow$ $\kappa_B^{TMC} \in [1.2, 1.4]$.

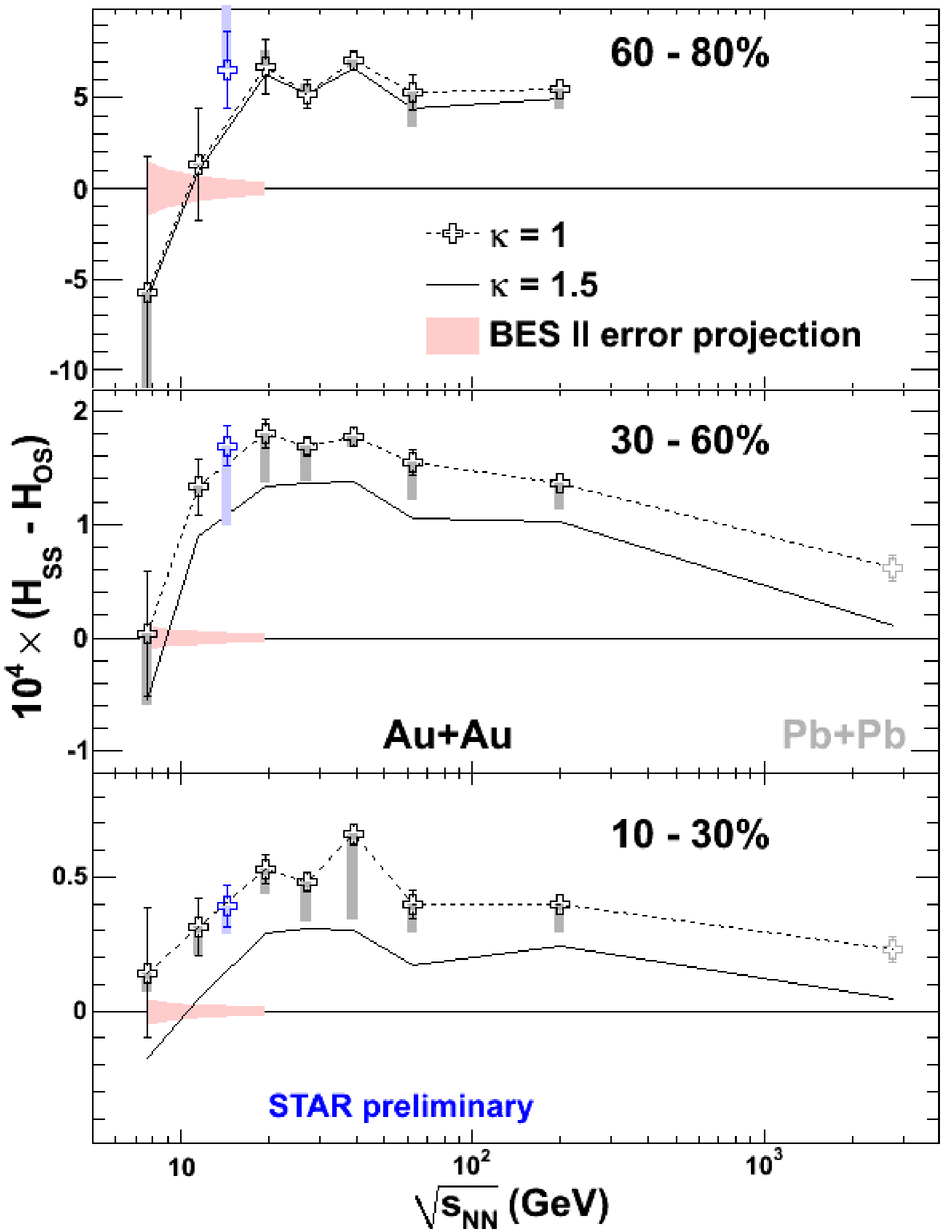
Other effects:
Local Charge Conservation (LCC) and resonance decay.

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)

ΔH^{κ} at Beam Energy Scan

STAR, PRL 113 (2014) 052302



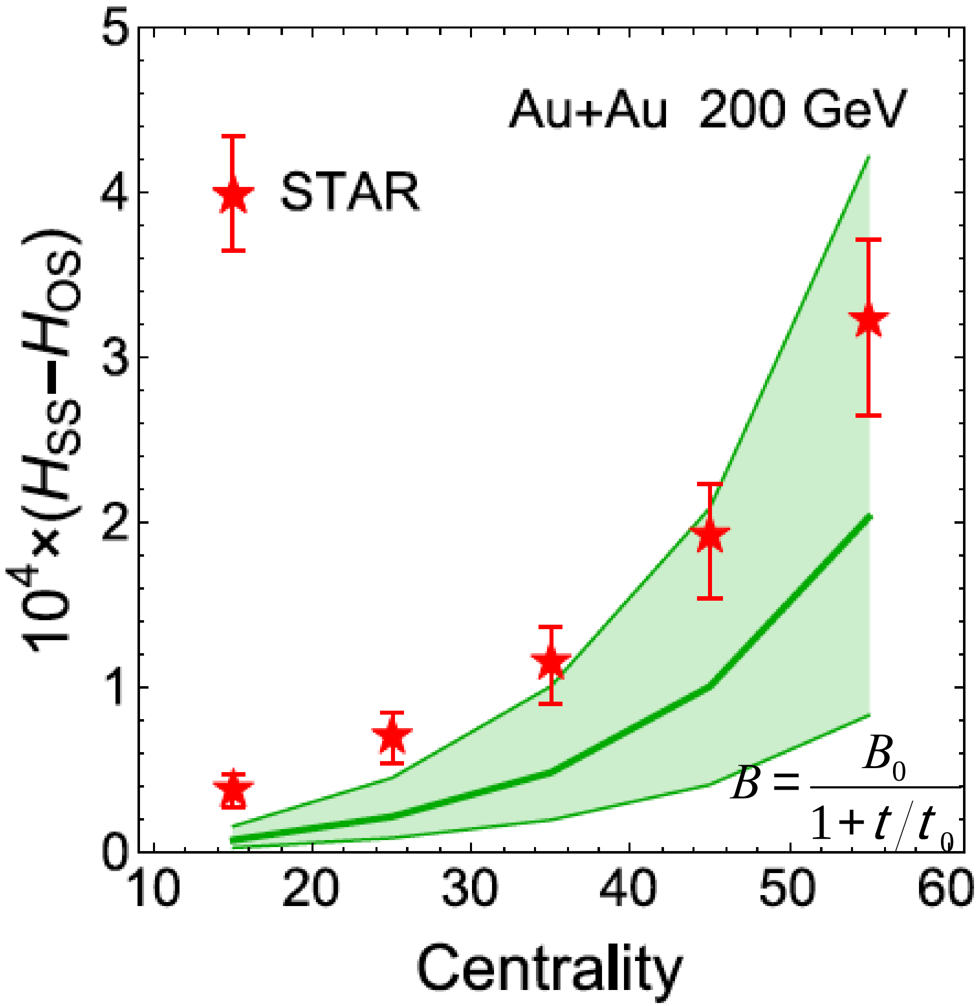
$$H^{\kappa} = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$$

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 (ΔH) 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 ...

Model comparison

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



- CME requires a magnetic field, massless quarks, and axial charge **at the same time**
- Anomalous hydrodynamic calculations with κ_B =1.2, with the range of [1, 1.5].
- Model and STAR data are compatible
- Another way to look at it ...

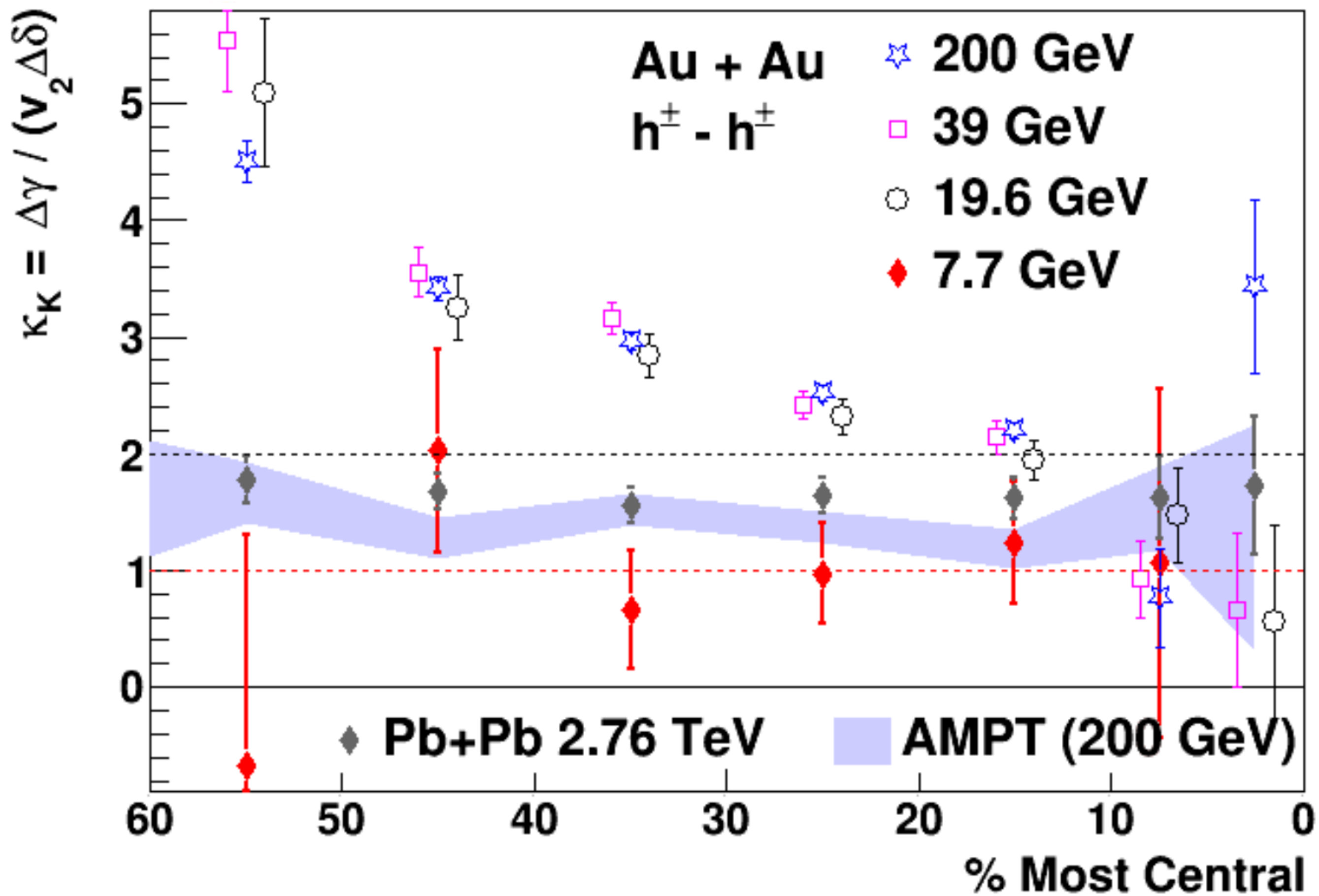
Y. Jiang, S. Shi, Y. Yin, J. Liao, arXiv:1611.04586

κ_K: normalized (signal + background)

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

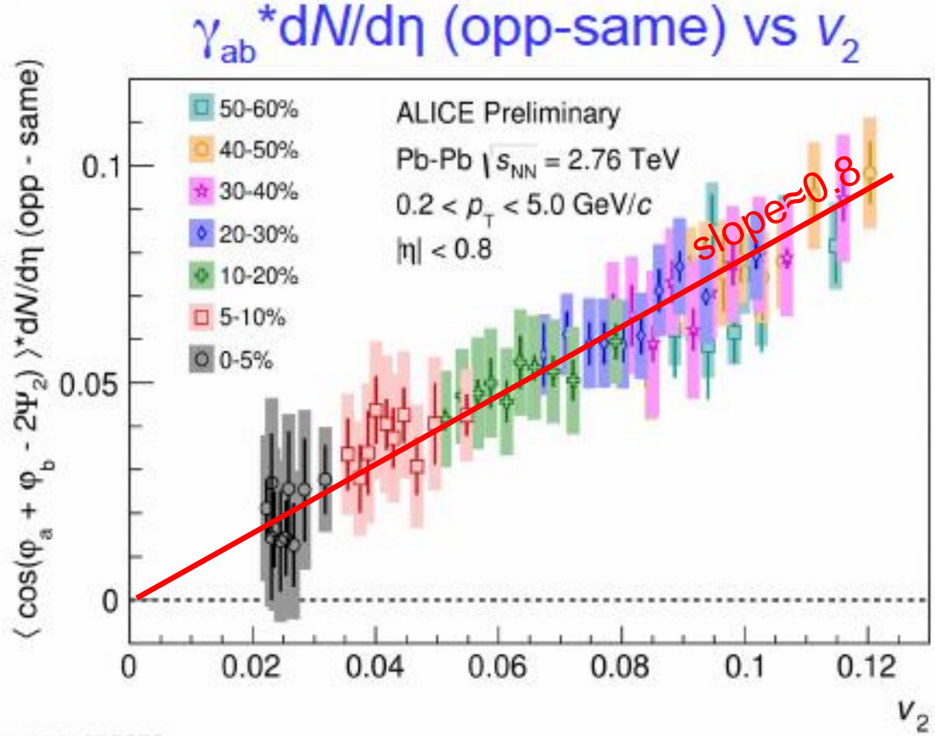
If $\kappa_K > \kappa_B$ for real data, there could be extra physics like the CME.

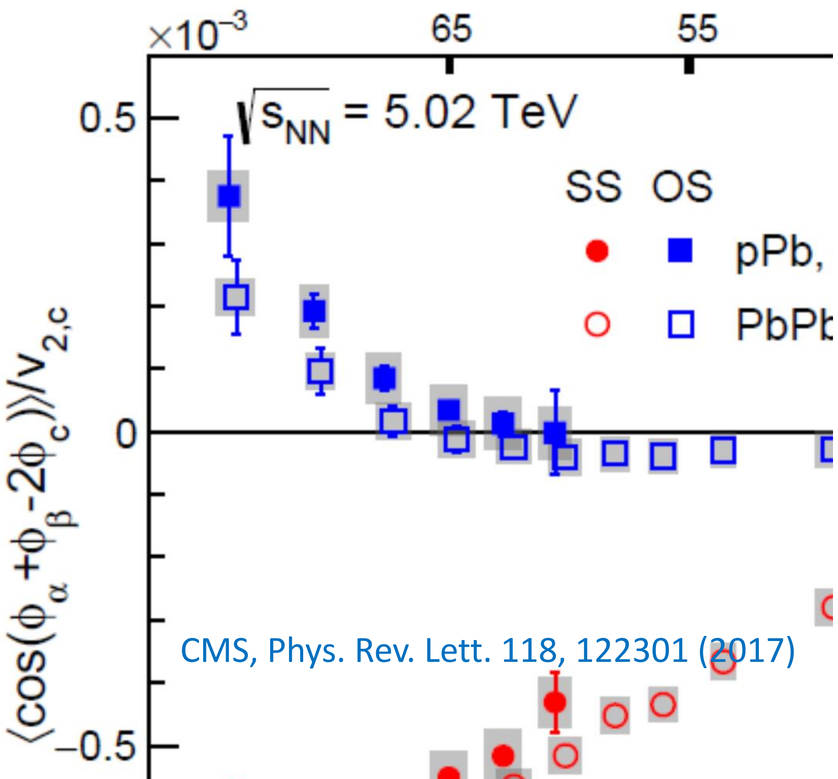
STAR, PRL113 (2014) 052302; ALICE, PRL110 (2013) 021301.



No CME at high energies?

ALICE (2.76 TeV Pb+Pb) event-shape engineering results show the signal is consistent with pure v_2 background.





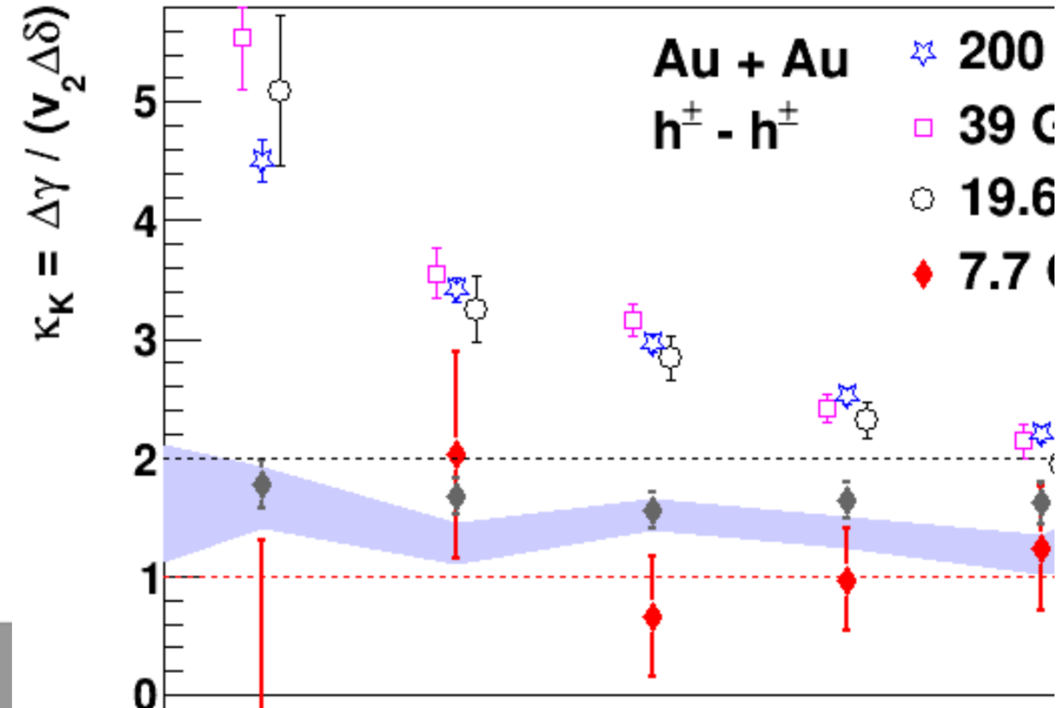
CMS (5 TeV) results show γ consistent between p+Pb and Pb+Pb: both are pure flow-backgrounds?

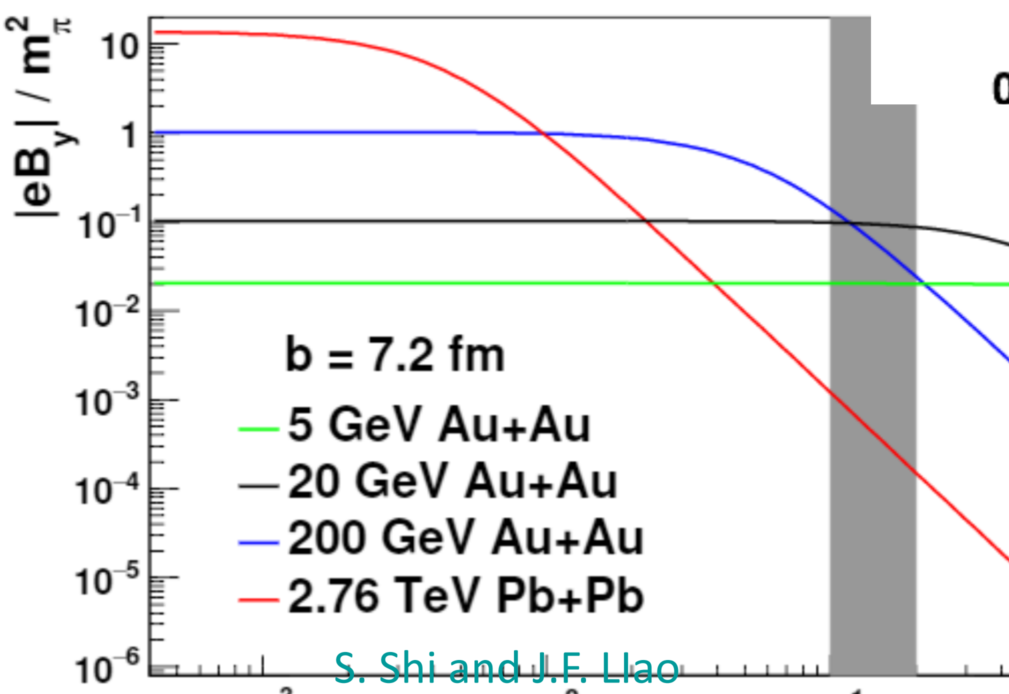
No CME at high energies?

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

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

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

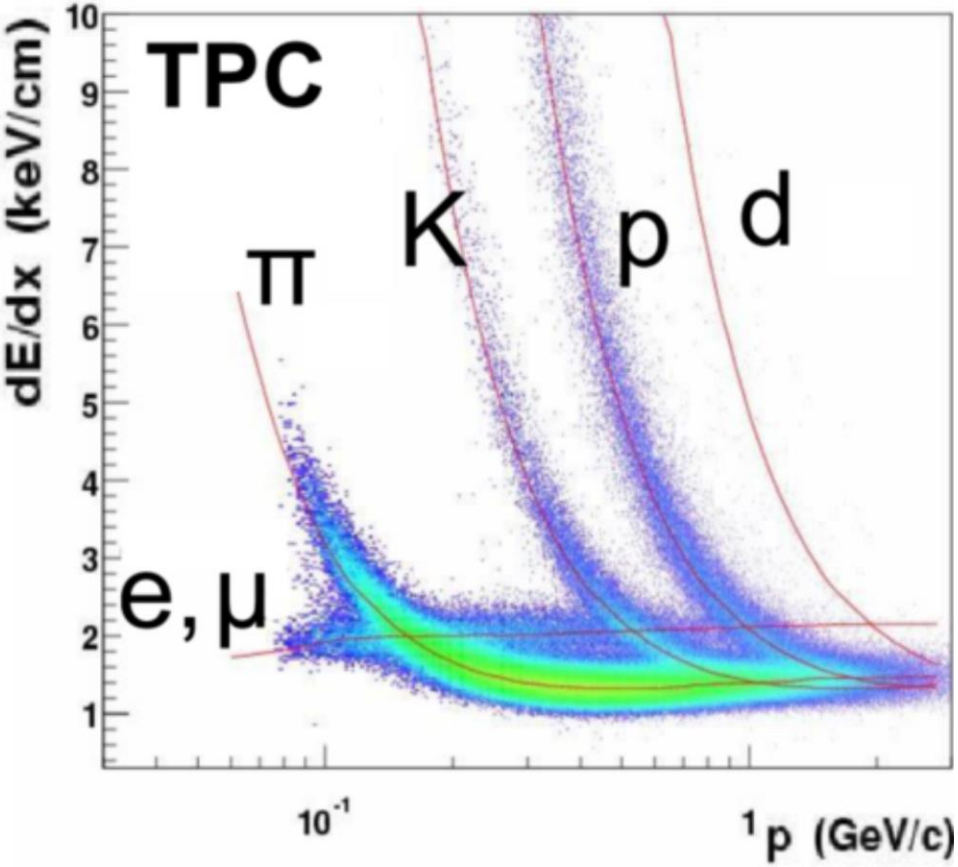


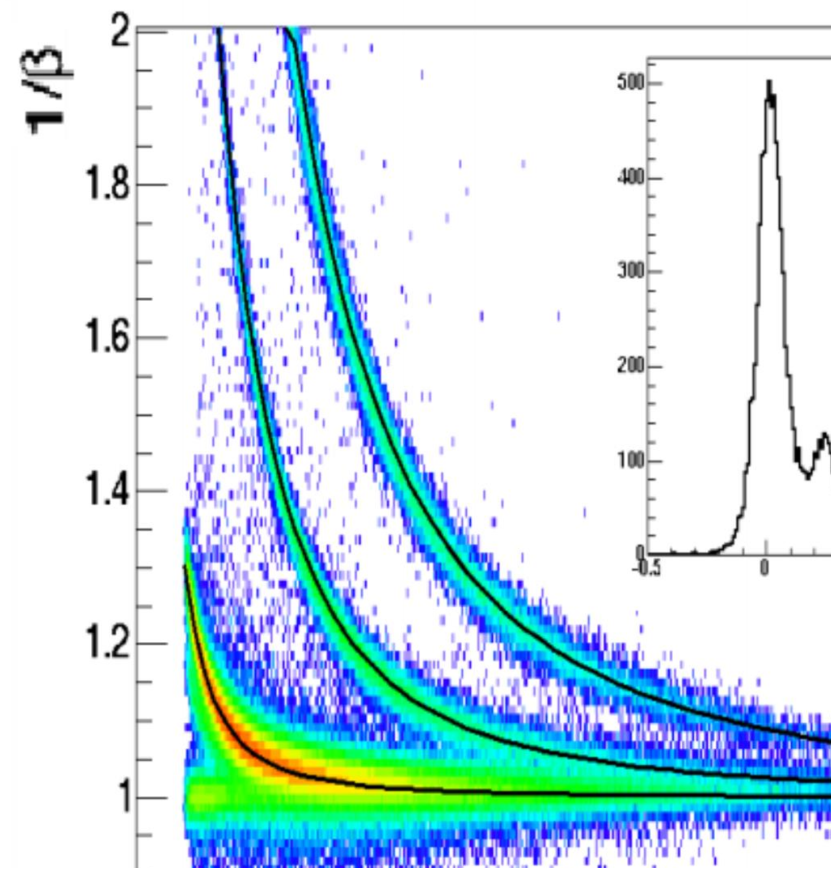


S. Shi and J.F. Liao

- 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

Particle identification

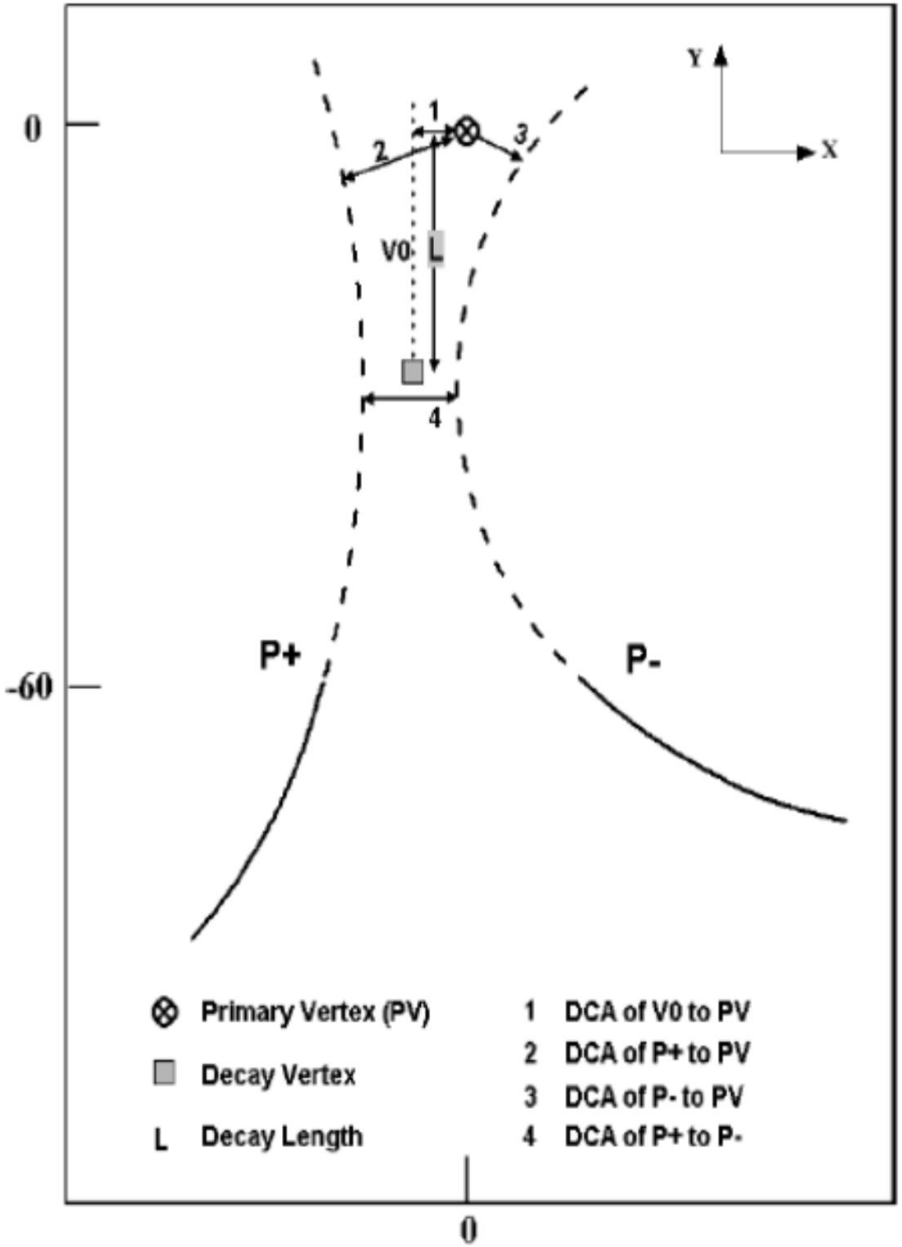




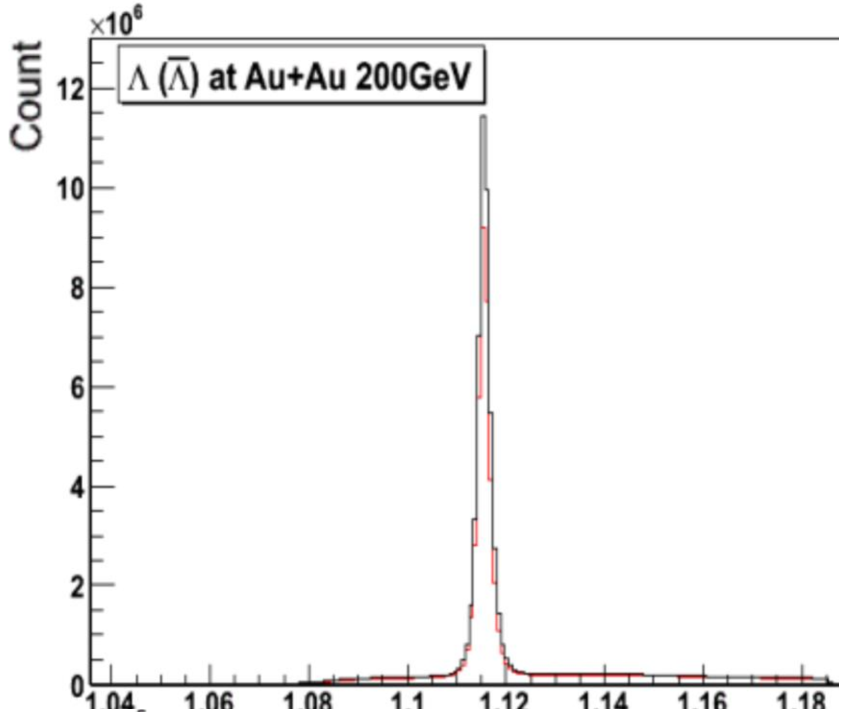
Time Projection Chamber (TPC) measures the mean energy loss per distance travelled of swift charged particles.

Time-of-Flight (TOF) measures the flight duration, hence velocity ($\beta = v/c$) of swift charged particles.

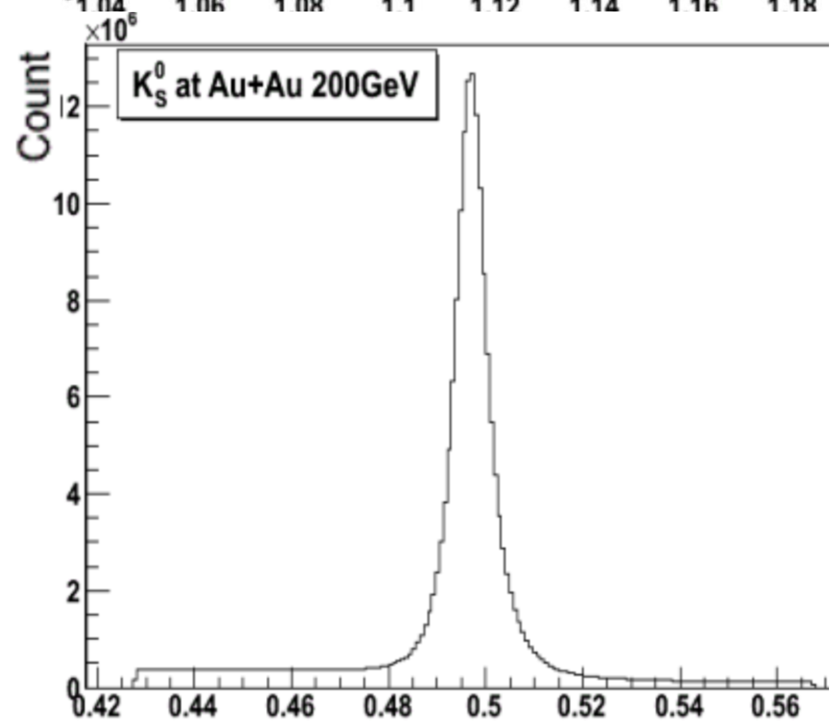
Λ (K^0_S)



Y
X
0
-60
0
1
2
3
V0
L
4
P+
P-
Primary Vertex (PV)
Decay Vertex
L Decay Length
1 DCA of V0 to PV
2 DCA of P+ to PV
3 DCA of P- to PV
4 DCA of P+ to P-

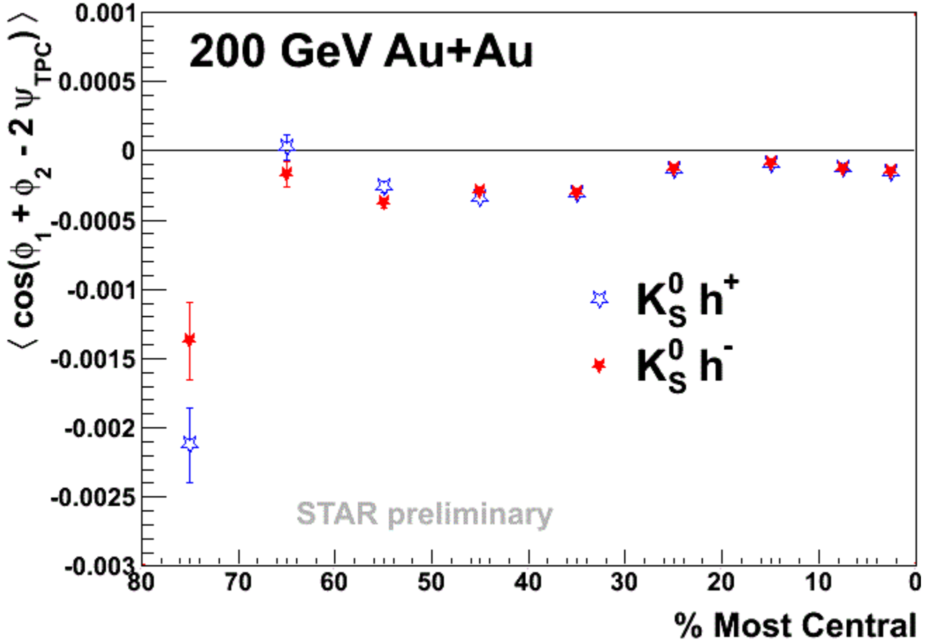


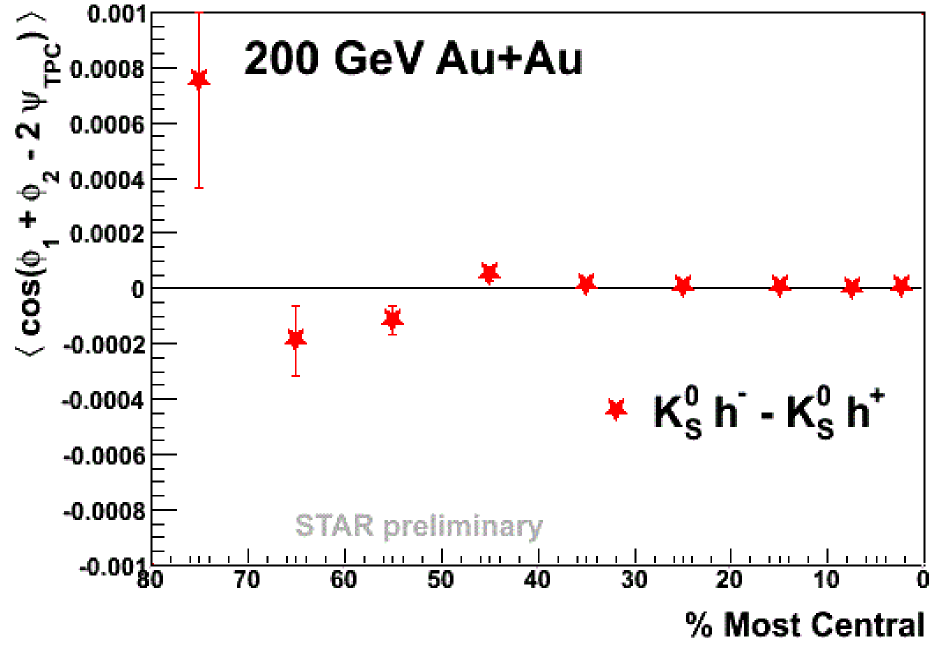
×10^6
Count
Λ (Λ̄) at Au+Au 200GeV
0
2
4
6
8
10
12
1.04
1.06
1.08
1.1
1.12
1.14
1.16
1.18



×10^6
Count
K^0_S at Au+Au 200GeV
0
2
4
6
8
10
12
0.42
0.44
0.46
0.48
0.5
0.52
0.54
0.56

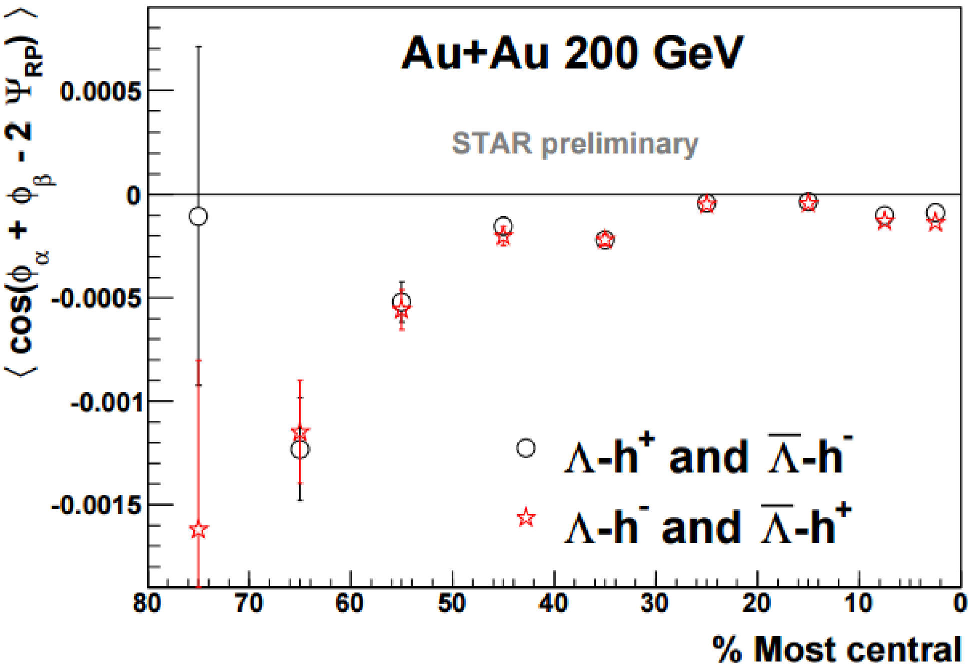
K^0_S-hadron correlation

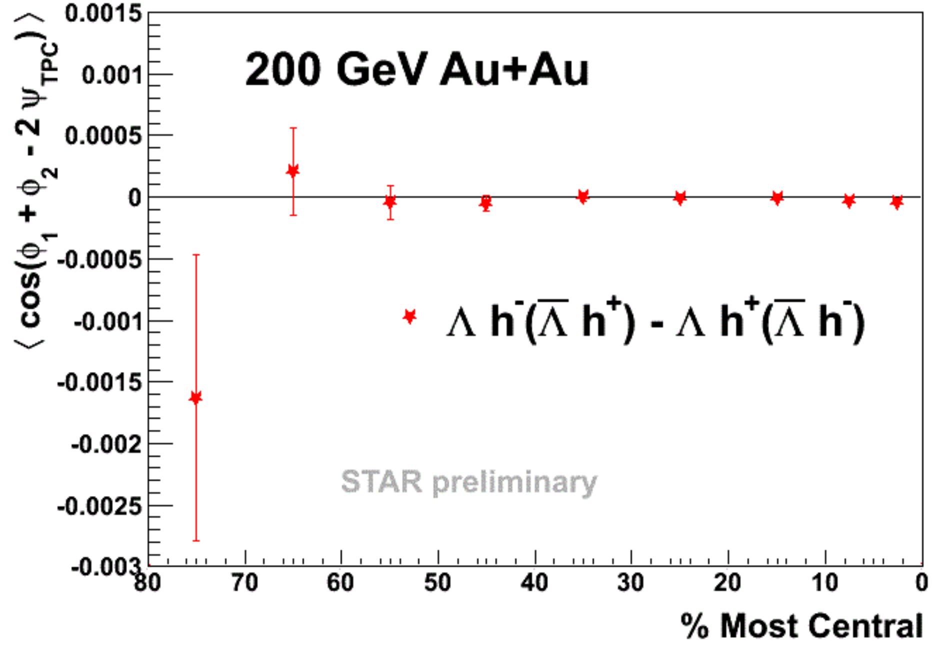




- K^0_S-h^- consistent with K^0_S-h^+: no charge-dependence
- The separation observed in $h^\pm$-$h^\pm$ is due to electric charge
- Strange quarks participate in the chiral dynamics in the same way as u and d.

Λ-hadron correlation

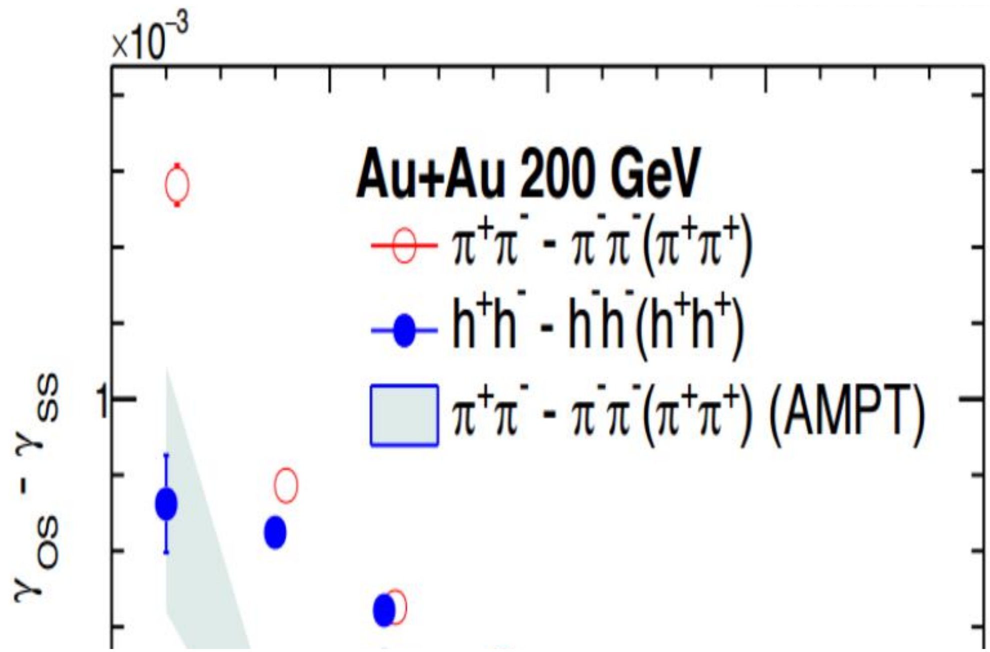


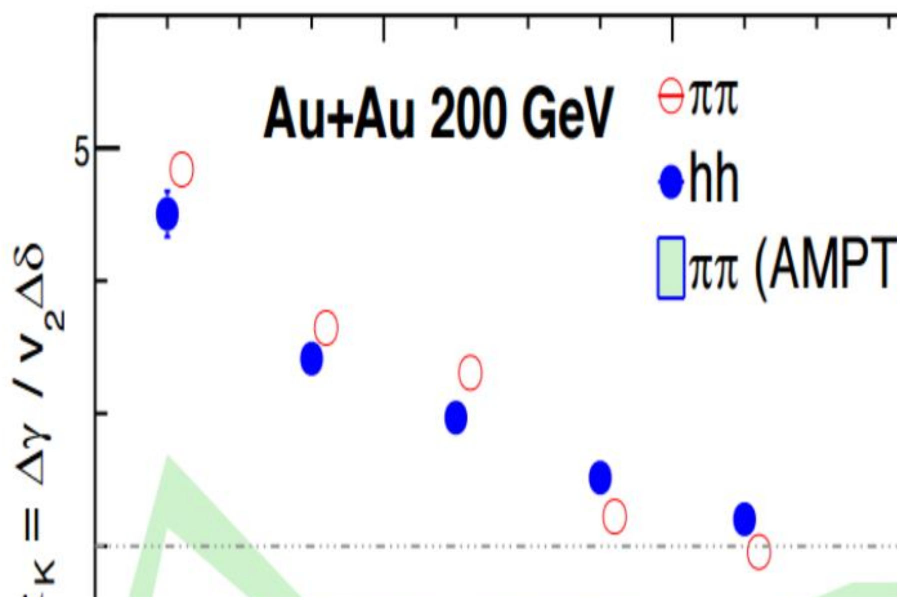


- Λ-$h^{\pm}$ also show no charge-dependent separation
  - (protons and antiprotons have been excluded from $h^{\pm}$)
- s quarks participate in the chiral dynamics in a similar way as u/d
- Λ-$h^{\pm}$ also provides a baseline for Λ-p correlations

PID κ_K: π-π

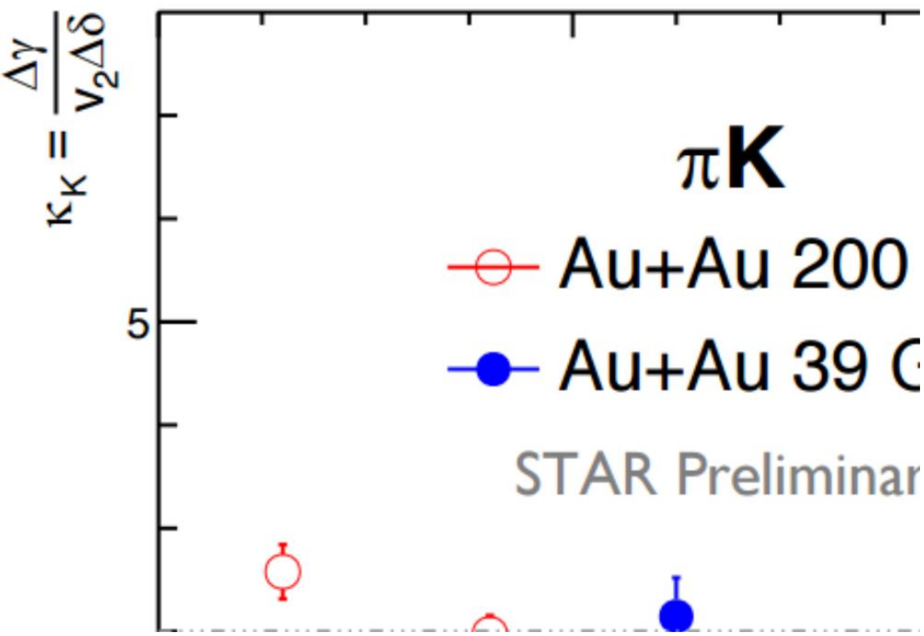
- Δγ for π-π is similar to *h*-*h* in Au+Au at 200 GeV.
  - also 39 GeV (not shown here).
- $\kappa_K > \kappa_B$ for mid-central and mid-peripheral collisions.
  - κ_B estimated from AMPT

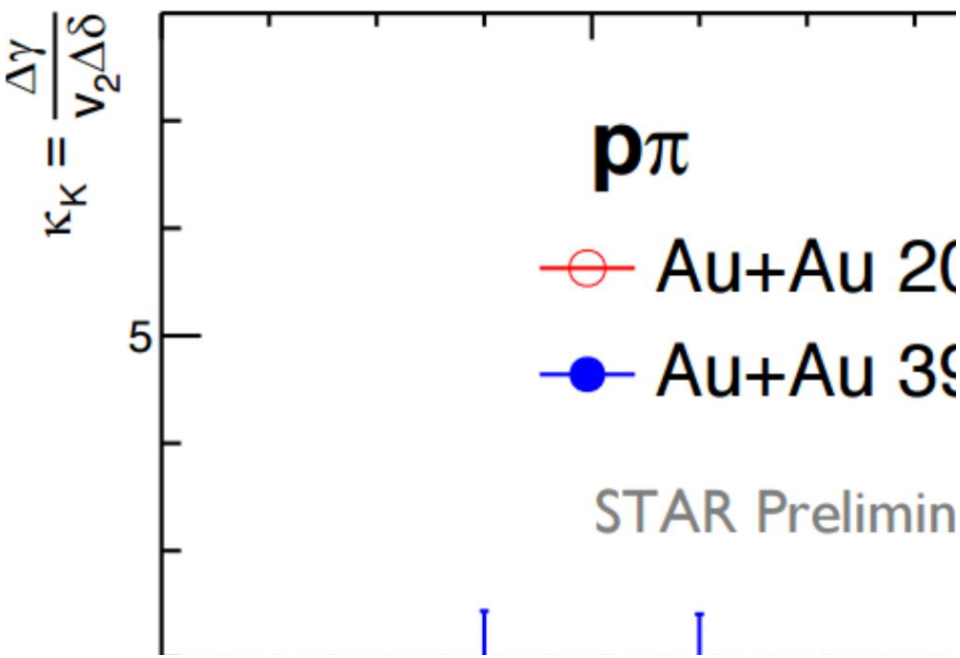




PID κ_K: π-K and p-π

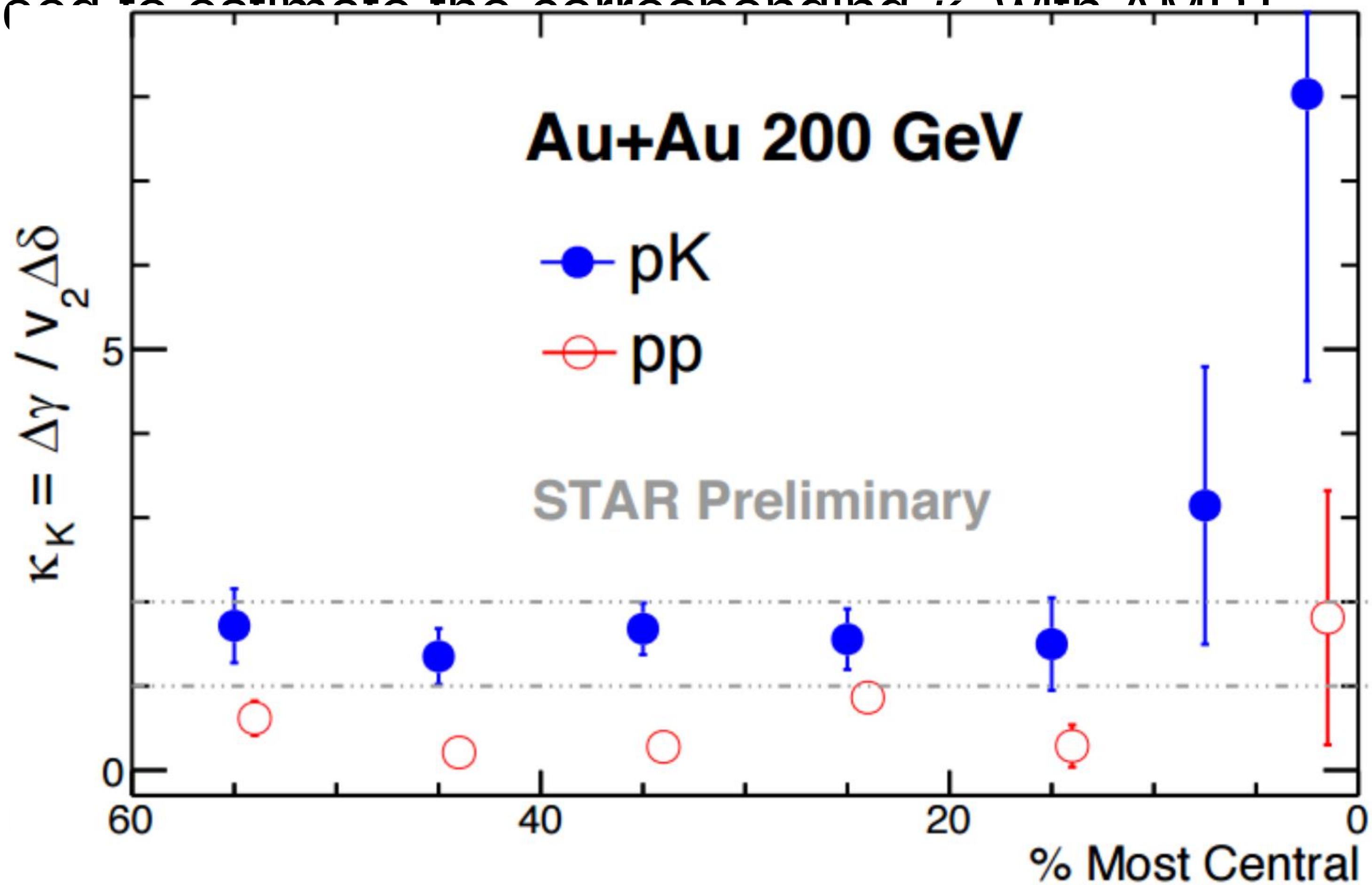
- κ_K for π-K and *p*-π are mostly between 1 and 2 in Au+Au at 200.
  - also true at 39 GeV
- hard to distinguish the observable from the flow background





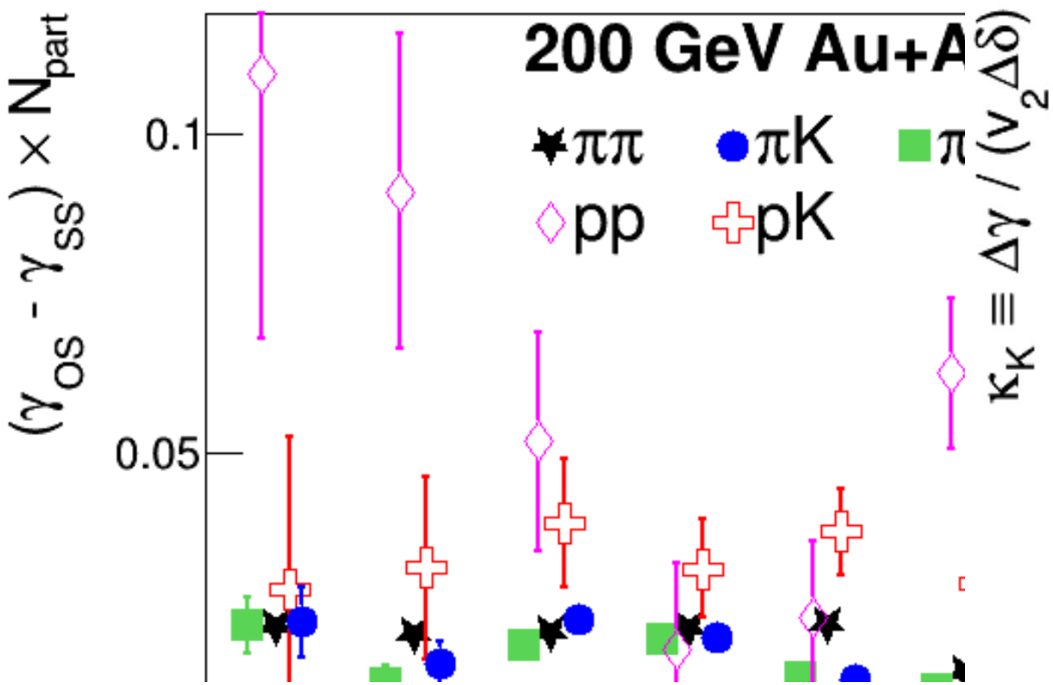
PID κ_K: *p*-*K* and *p*-*p*

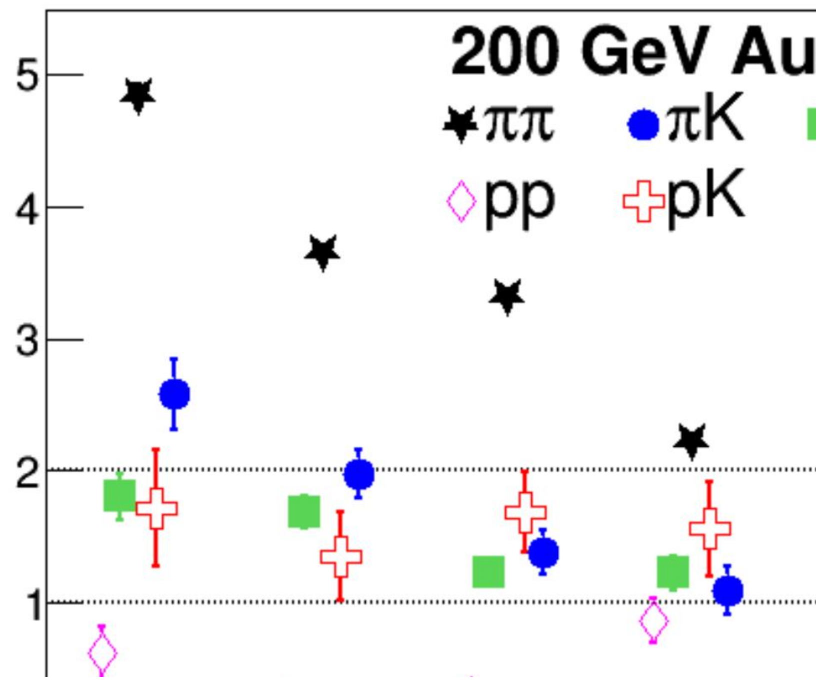
- κ_K for *p*-*K* is similar to the cases for π-K and *p*-π in Au+Au at 200.
  - hard to distinguish the observable from the flow background
- κ_K for *p*-*p* is even below 1.
  - n[illegible]



Summary on PID

- $\Delta\gamma$ for π-π/*π-K*/*p*-π/*p-K*/*p-p* all show **sizable charge separation signals** for mid-central and mid-peripheral collisions at 200 GeV.
- κ_K values, however, fall into **3 groups**.
  - **π-π**: higher than 2 for 20-60% most central collisions
  - *π-K*/*p*-π/*p-K*: between 1 and 2
  - *p-p*: below 1

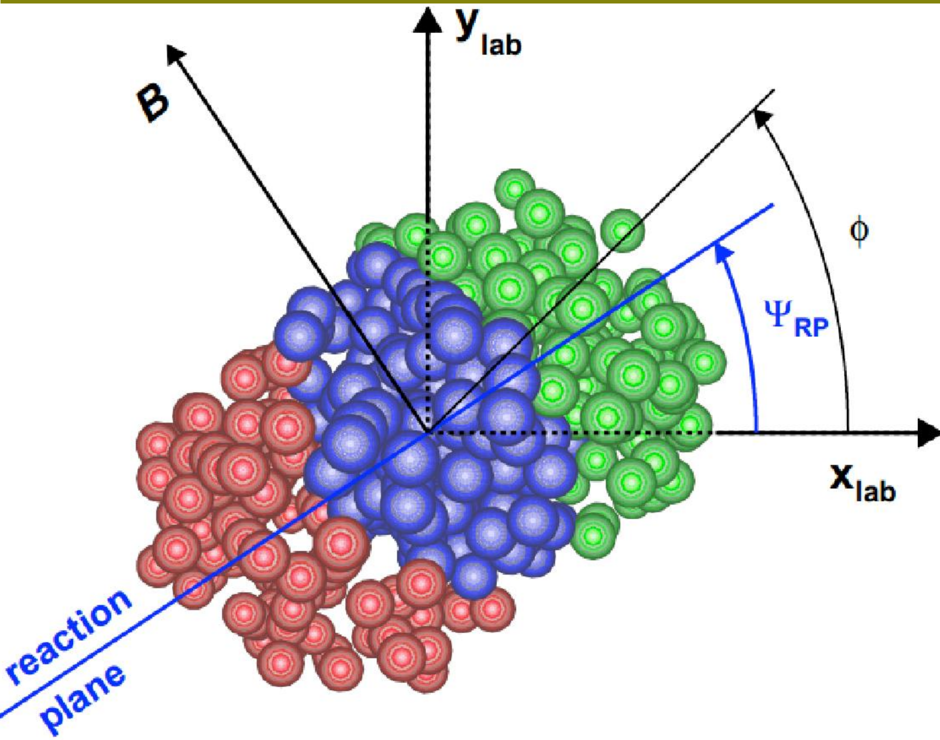





SOLUTION 1
SOLUTION 3
SOLUTION 2

Back-up slides

Event plane

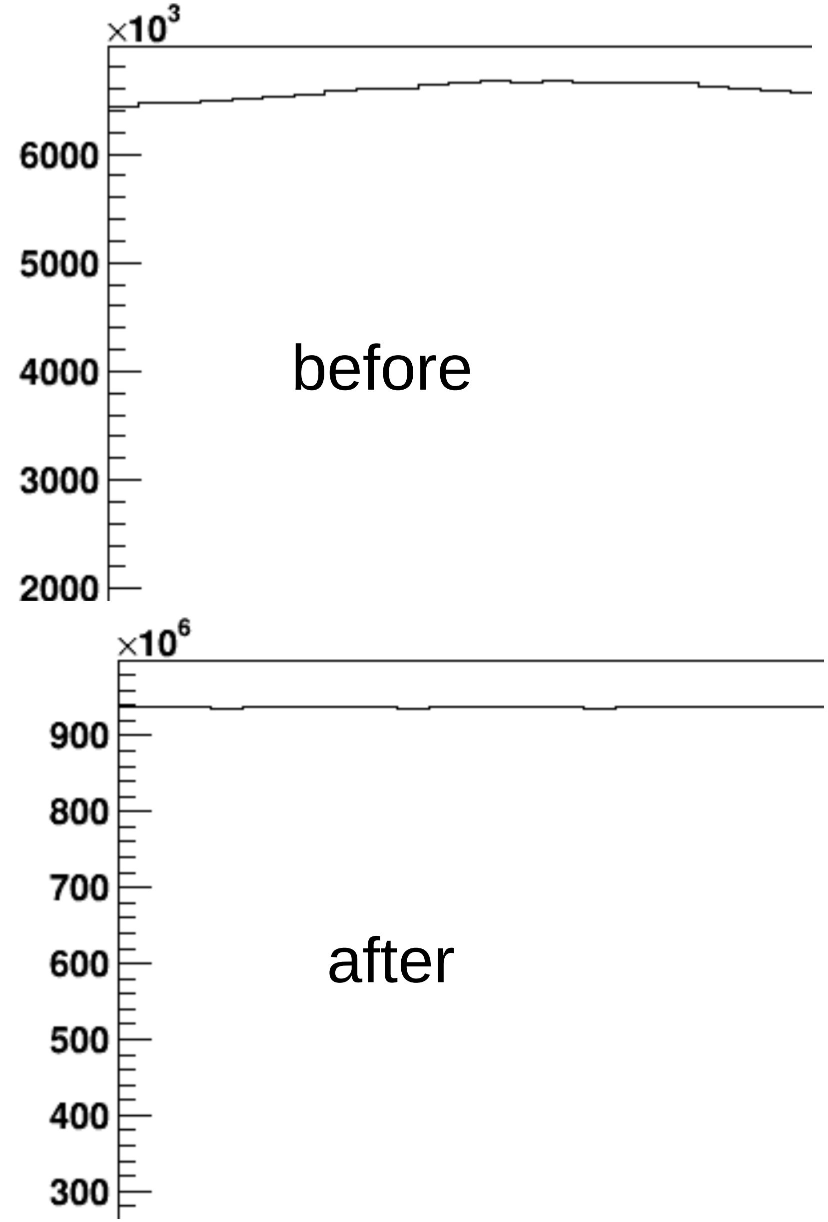


The estimated reaction plane is called the event plane.

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

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

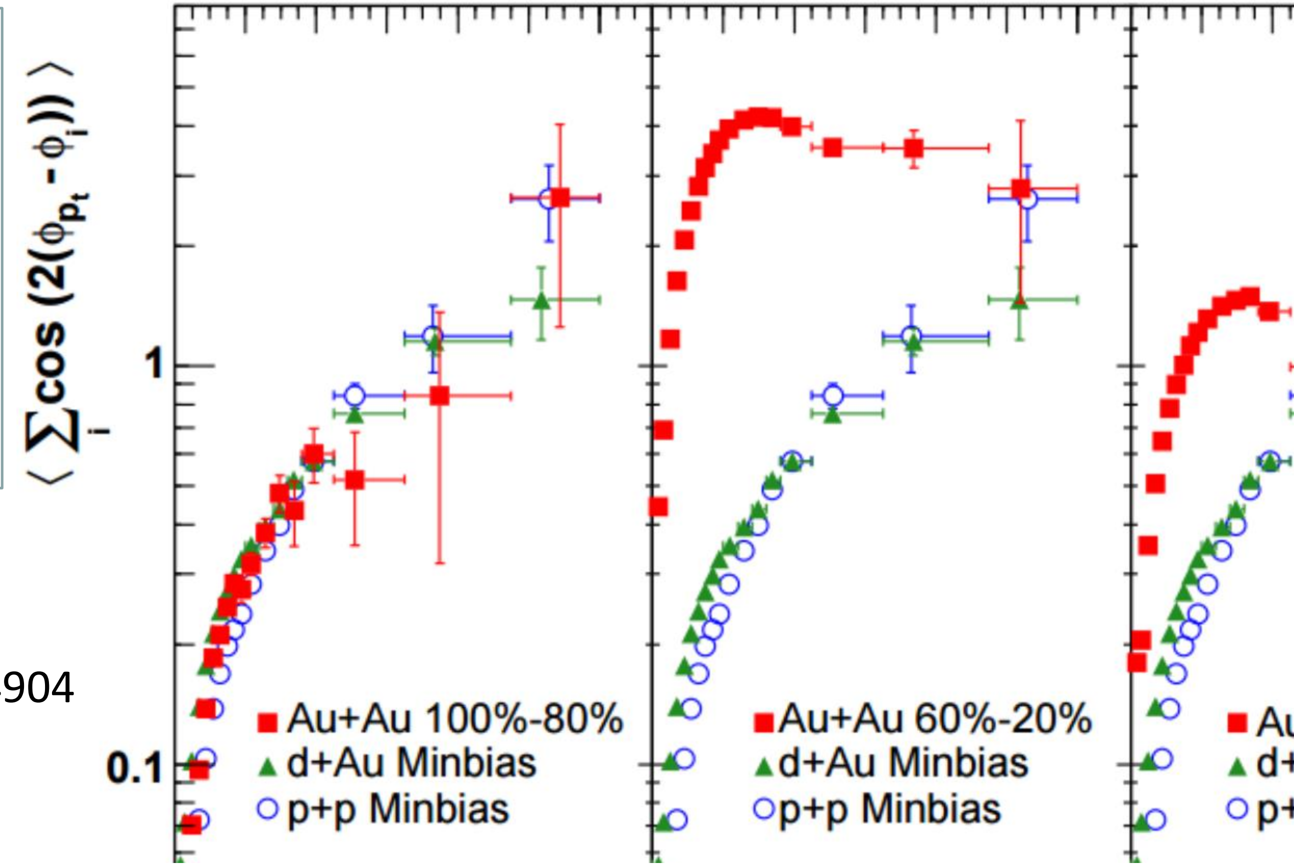
$$\Psi_n = \left(\tan^{-1}\frac{Q_y}{Q_x}\right)/n$$



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

Collectivity vs non-flow

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

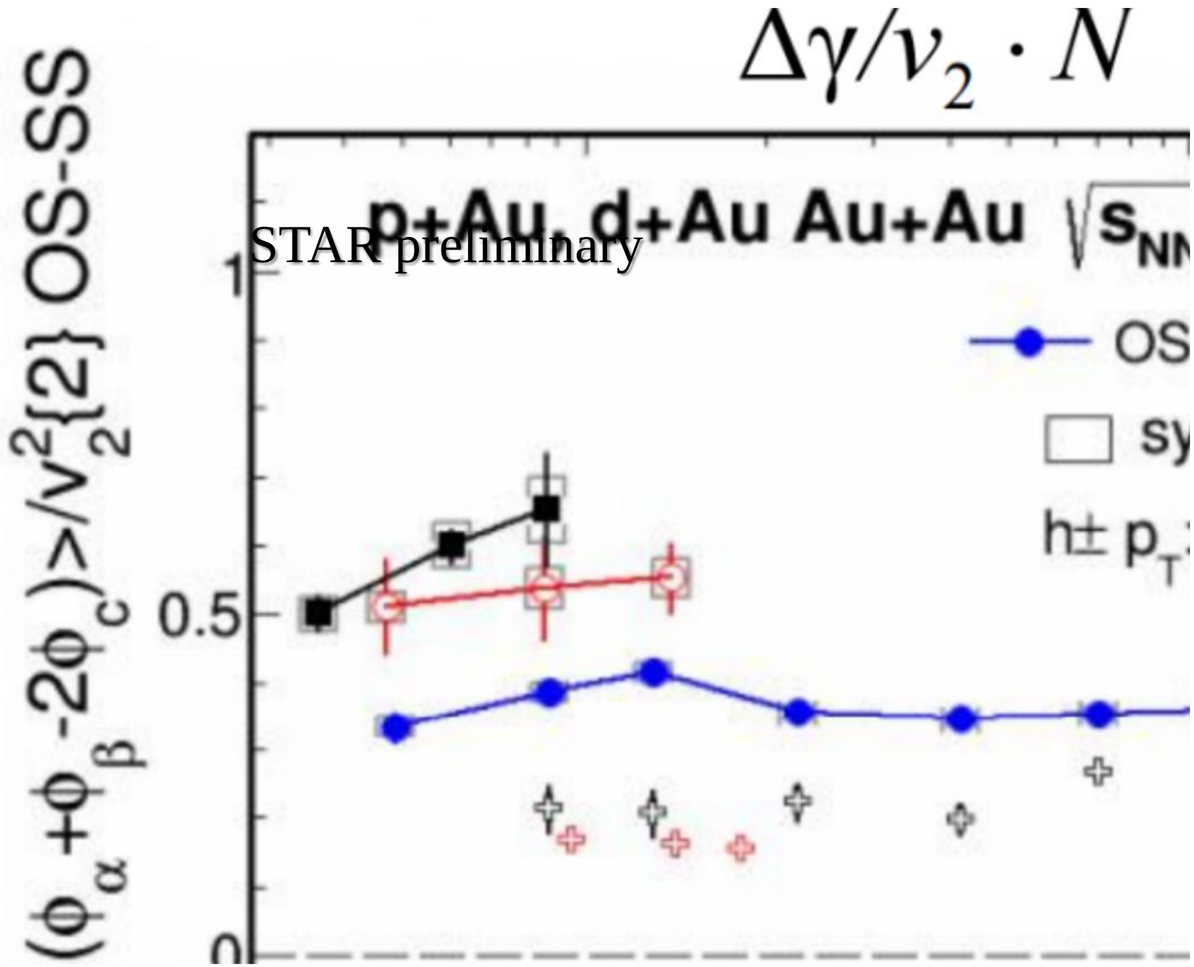


STAR, Phys. Rev. C 72 (2005) 14904

- 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"...

p+Au/d+Au

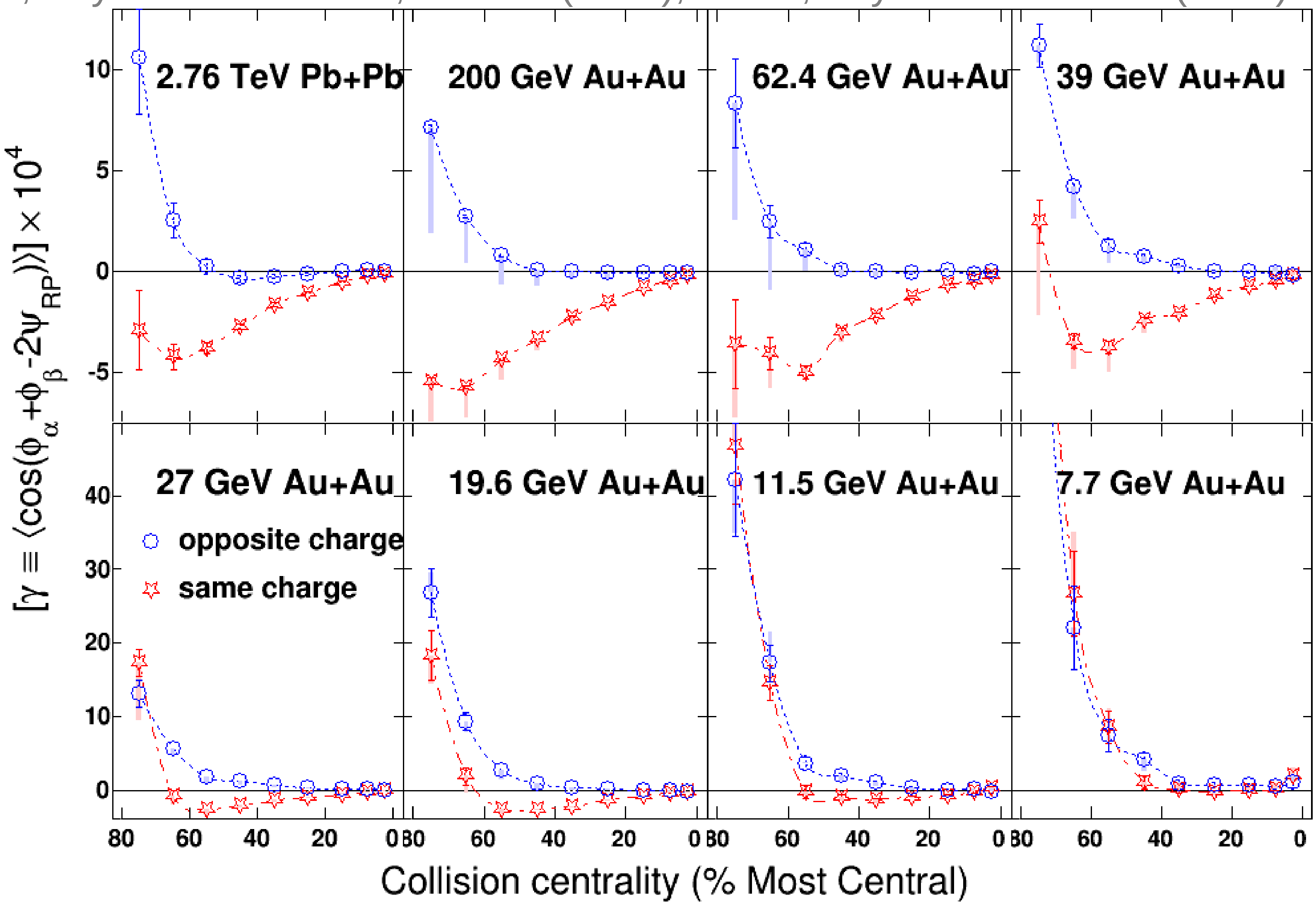
- $\Delta\gamma/v_2 \cdot N$ is another measure for the flow background.
- AMPT accounts for ~2/3 (1/3) of the observed data in Au+Au (d+Au)
- Central Au+Au events are not well described by AMPT.



This version of AMPT turned off hadronic scattering.

Beam energy scan

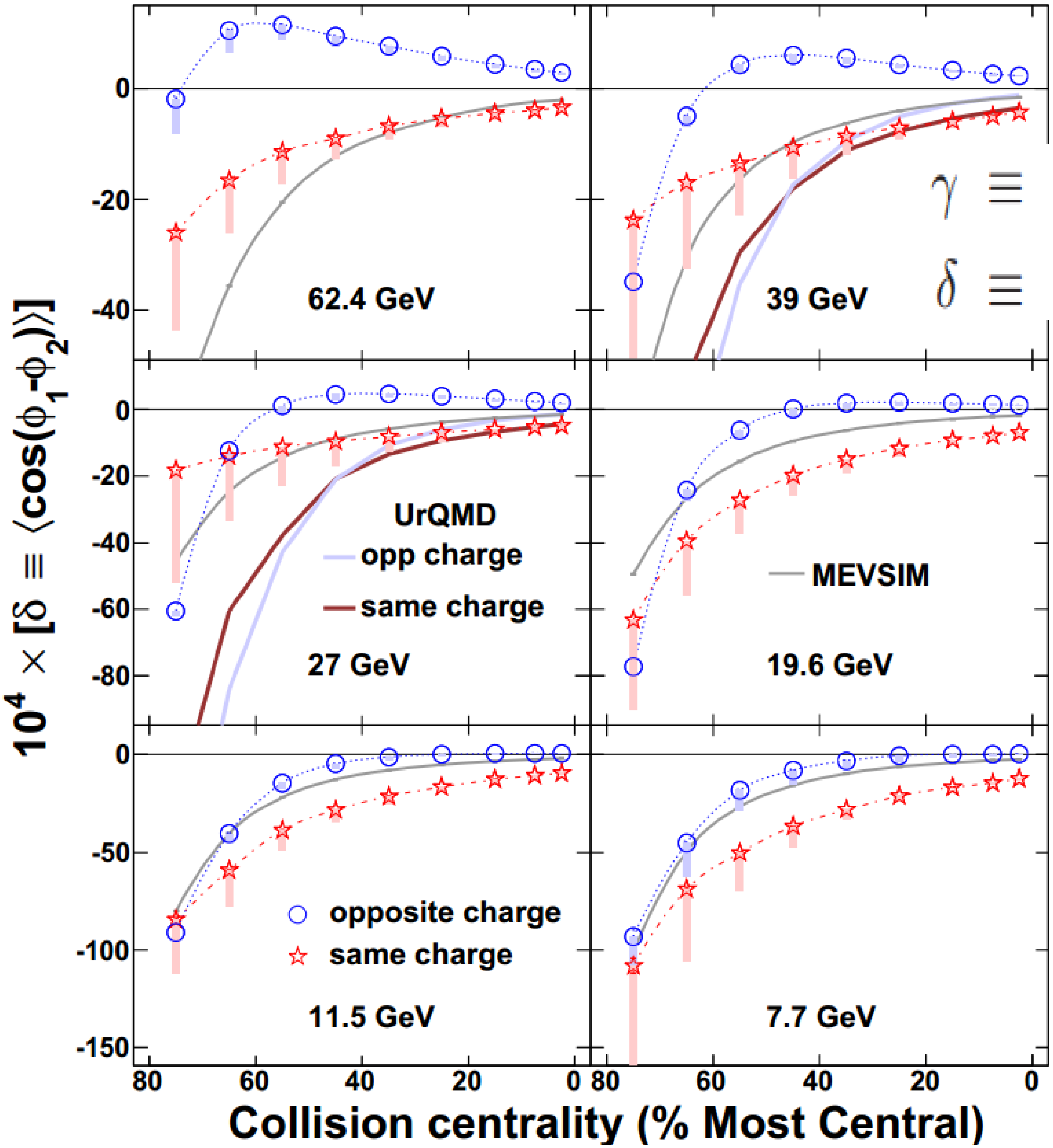
ALICE, Phys. Rev. Lett. 110, 012301 (2013); STAR, Phys. Rev. Lett 113 (2014) 052302



At lower beam energies, charge separation starts to diminish.

Flow-related background

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



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

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

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

- Against CME expectation, δ_{OS} is above δ_{SS}
- indicate overwhelming background larger than any possible CME effect.
- try to combine information from γ and δ to retrieve the CME contribution, H

Transverse momentum conservation

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

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

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

we have introduced certain weighted moments of v_2:

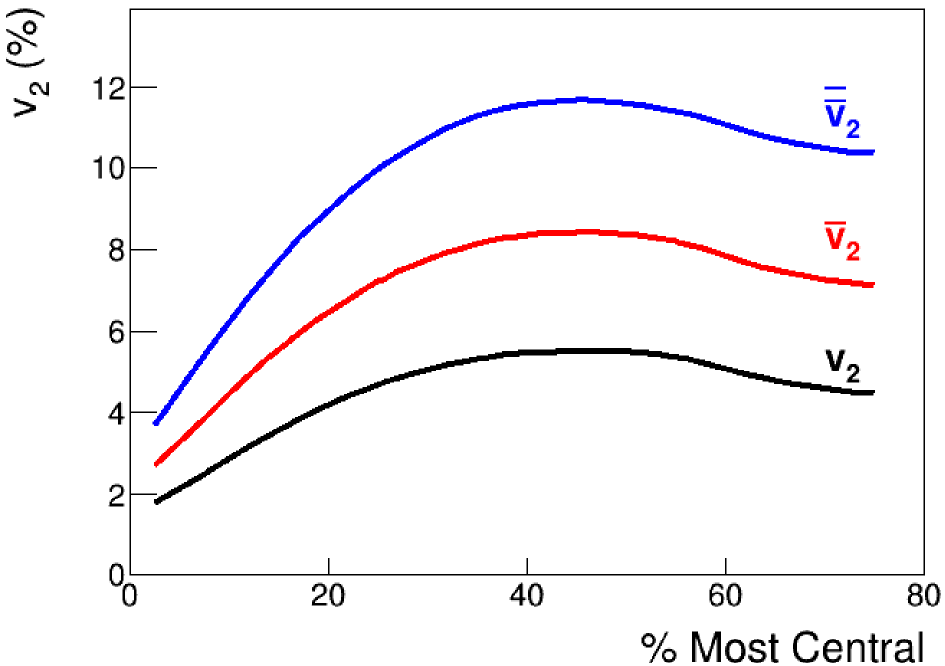
$$\bar{v}_2 = \frac{\langle v_2(p_t,\eta) p_t \rangle}{\langle p_t \rangle}, \qquad \bar{\bar{v}}_2 = \frac{\langle v_2(p_t,\eta) p_t^2 \rangle}{\langle p_t^2 \rangle}.$$

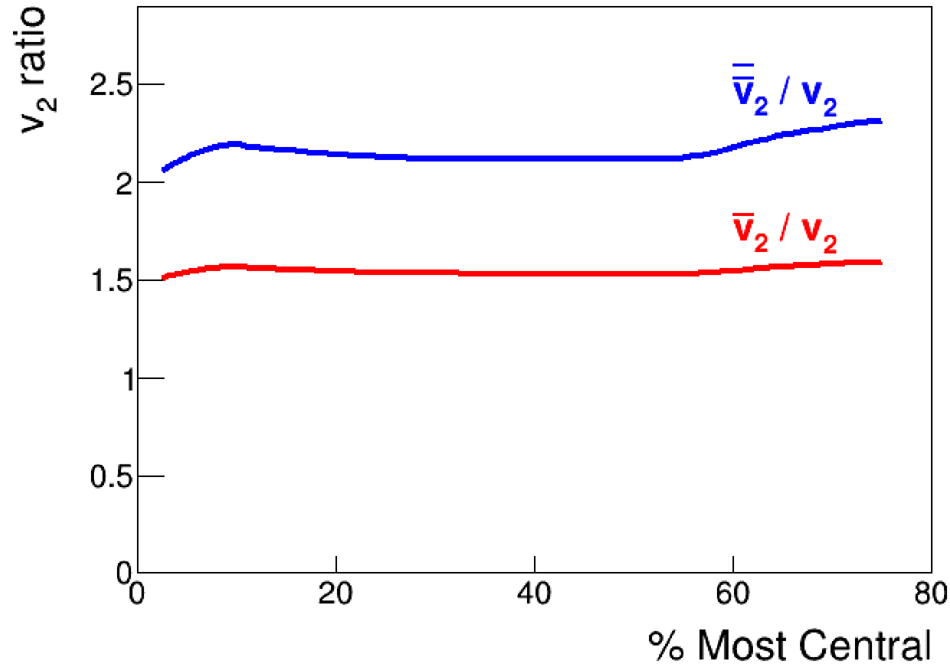
If our measurements are dominated by this type of background,

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

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

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

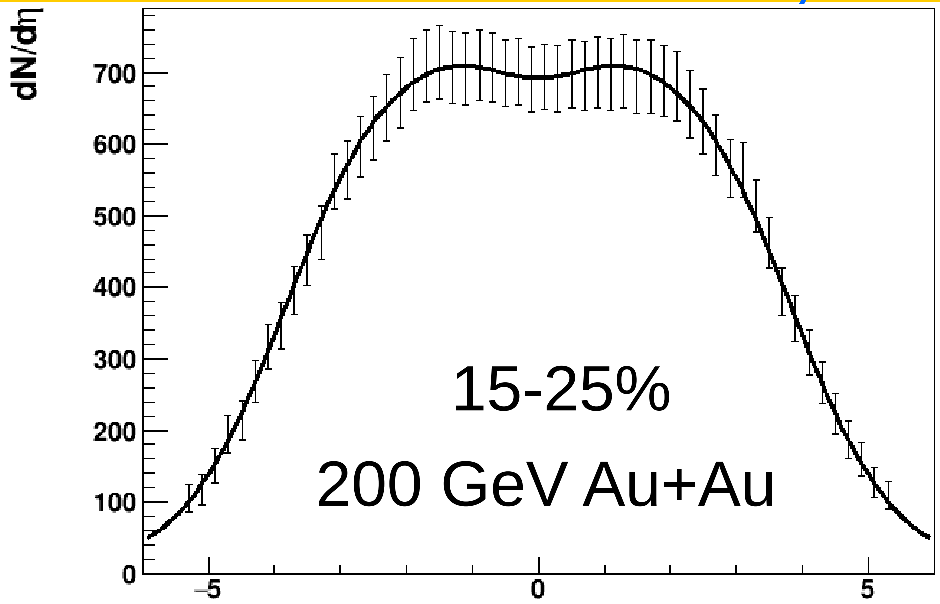


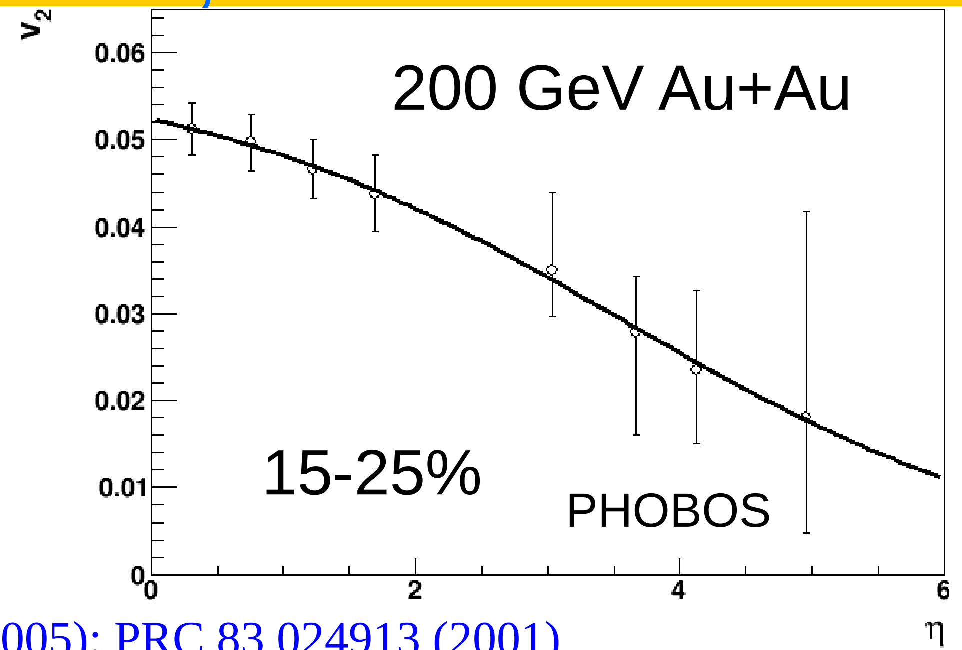


$$\bar{v}_2 = \frac{\langle v_2(p_t, \eta) p_t \rangle}{\langle p_t \rangle}, \qquad \bar{\bar{v}}_2 = \frac{\langle v_2(p_t, \eta) p_t^2 \rangle}{\langle p_t^2 \rangle}$$

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

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

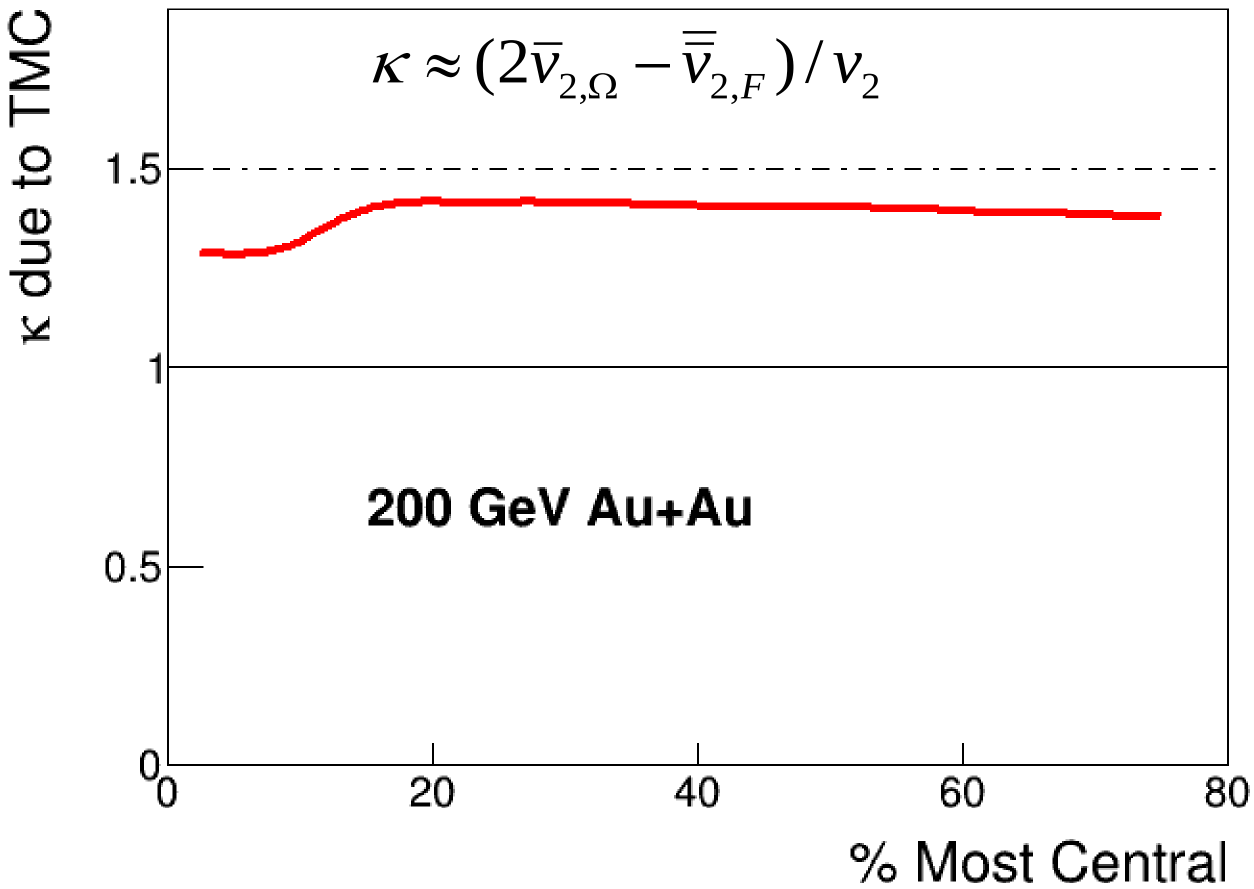




PHOBOS, PRC 72 014904 (2005); PRC 83 024913 (2001)

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

κ due to TMC



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

Other effects: Local Charge Conservation (LCC) and resonance decay.
A rough estimate of κ in the next slide.