Search for Chiral Effects with Identified Particles in Heavy Ion Collisions

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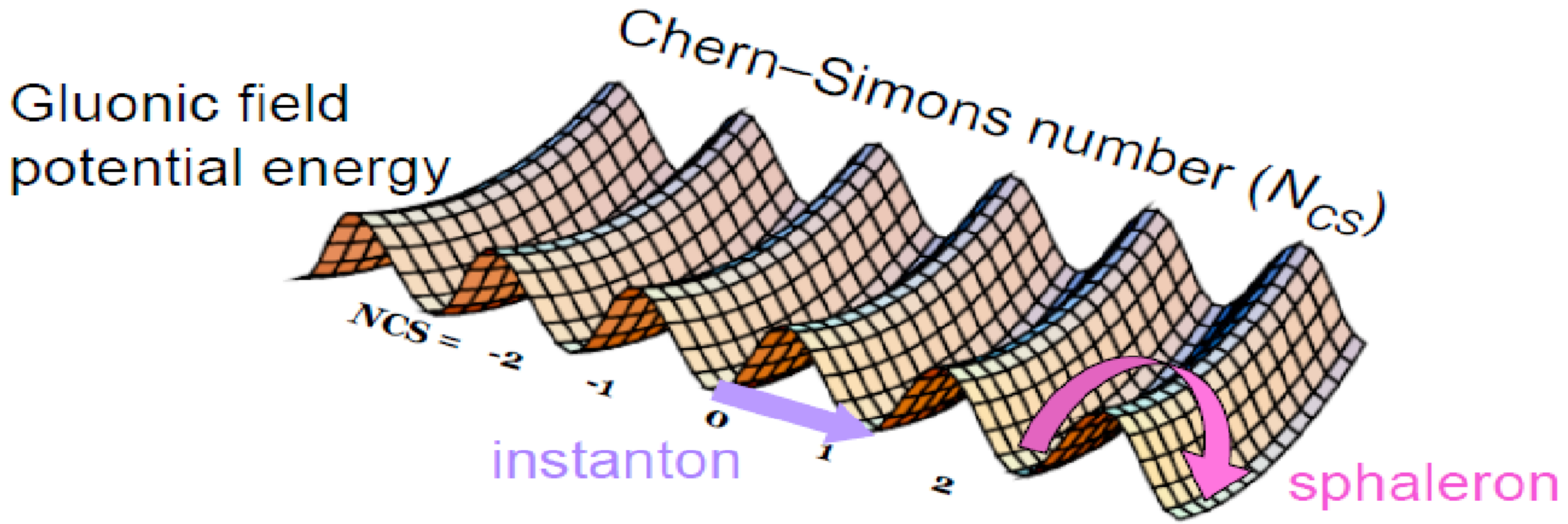
Outline

- Physics Motivation
- STAR Experiment
- Two Case Studies on Search for Chiral Effects @ STAR
- Background Study
- Summary

QCD Vacuum Transition



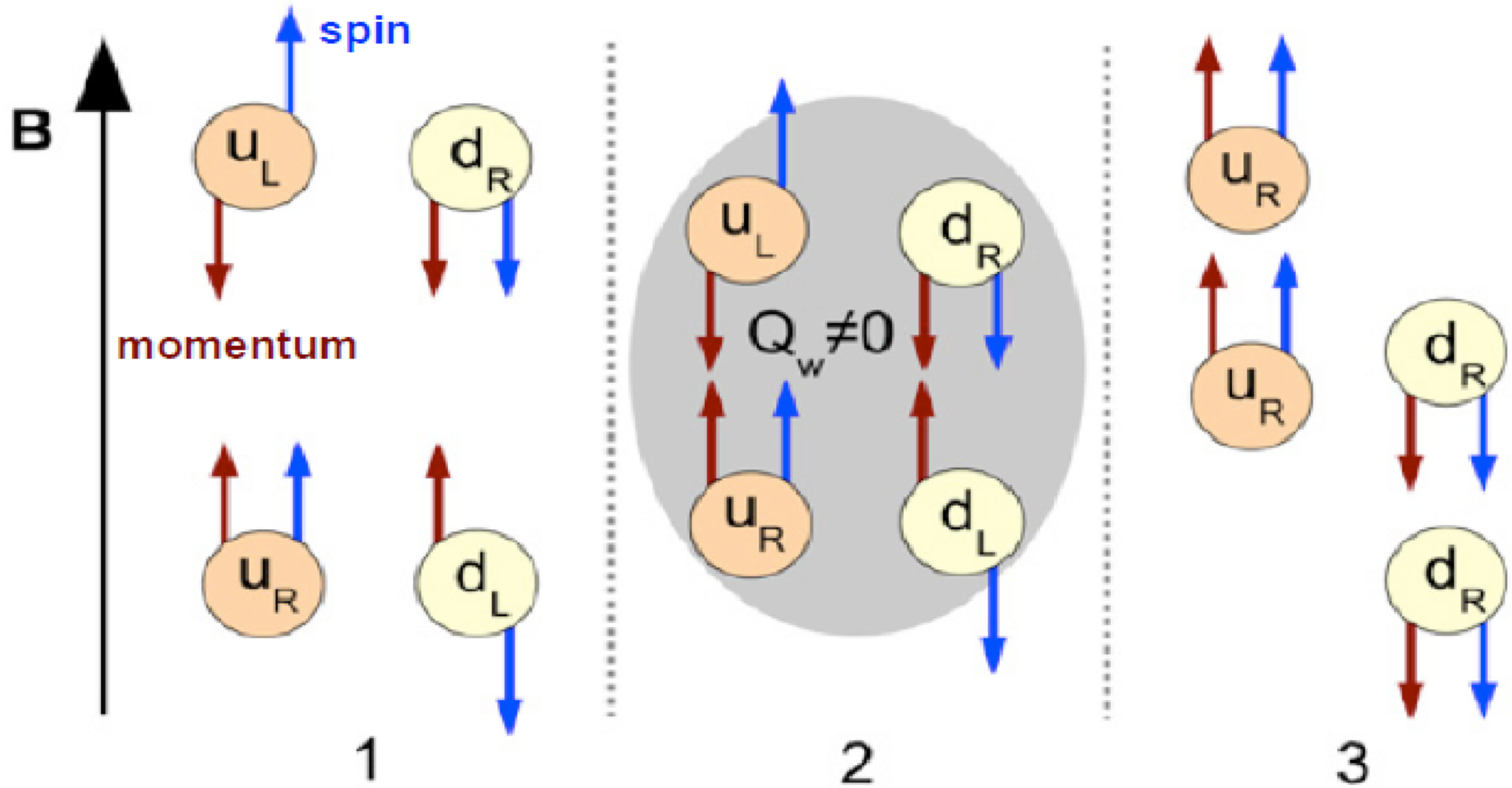
$$N_L^f - N_R^f = 2Q_W\,,\;\; Q_W \neq 0 \rightarrow \mu_A \neq 0$$

QCD vacuum transition:

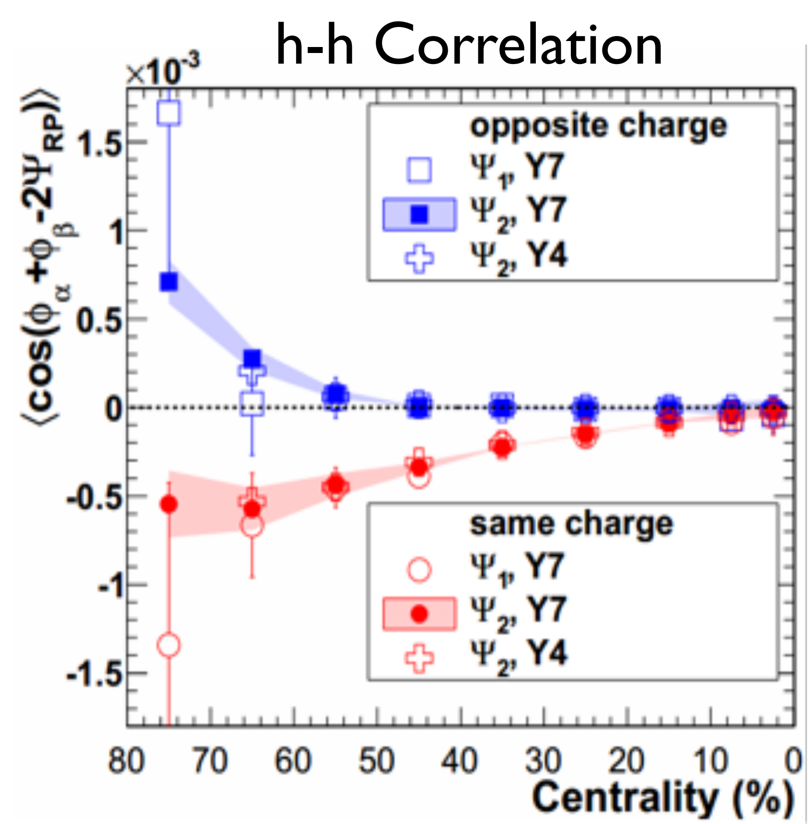
- **nonzero topological charge**
- **chirality imbalance (local parity violation)**

Chiral Magnetic Effect(CME)

D. Kharzeev, etc. NPA 803, 227(2008)



h-h Correlation



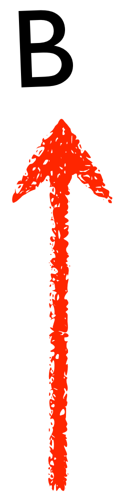
Phys. Rev. C 88 (2013) 64911

$$j_V = \frac{N_c e}{2\pi^2}\mu_A B$$ ➔ electric charge separation along *B* field

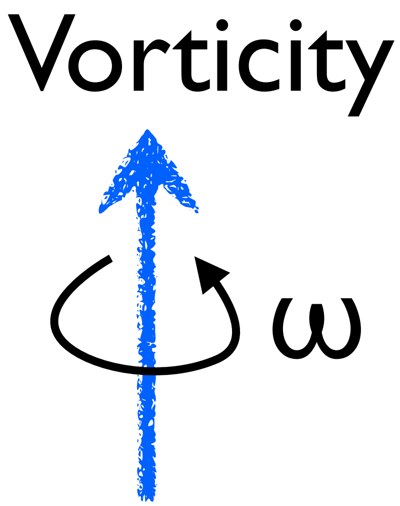
Configuration with non-zero topological charge converts left(right)-handed fermions to right(left)-handed fermions, generating electromagnetic current along B direction and leading to electric charge separation .

Chiral Vortical Effect (CVE)

Chiral Magnetic Effect	vs	Chiral Vortical Effect
Chirality Imbalance (μ_A)	--	Chirality Imbalance (μ_A)
Magnetic Field ($\omega\mu_e$)	--	Fluid Vorticity ($\omega\mu_B$)
↓		↓
Electric Charge (j_e)	--	Baryon Number (j_B)
Electric charge separation		Baryonic charge separation



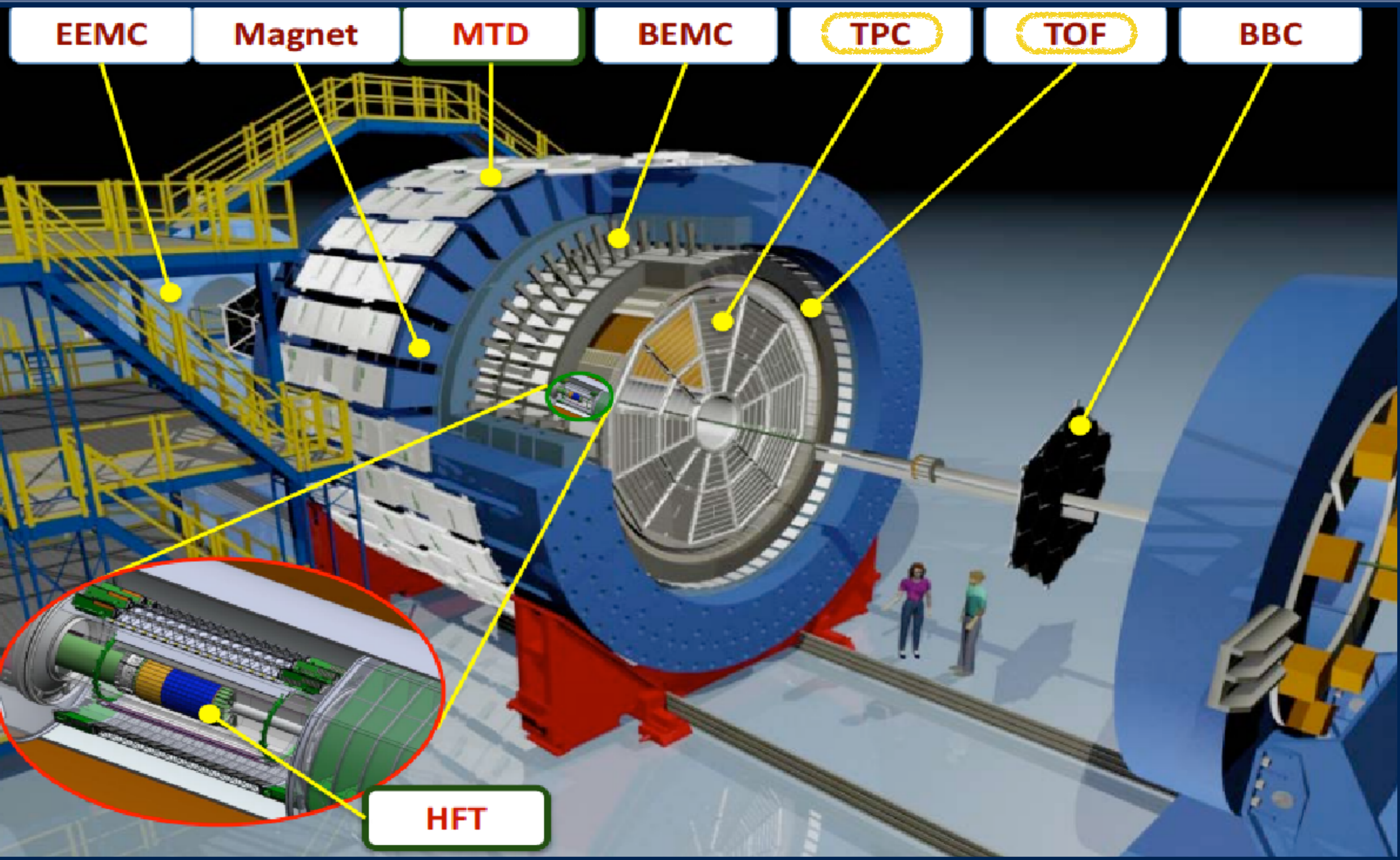
Peak magnetic field ~ **10^{15} Tesla !** (Kharzeev et al. NPA 803 (2008) 227)



Λ–p correlation measurement($\gamma = \ < cos(\varphi_\Lambda + \varphi_p - 2\Phi_{RP}) >$) can be used to search for the Chiral Vortical Effect

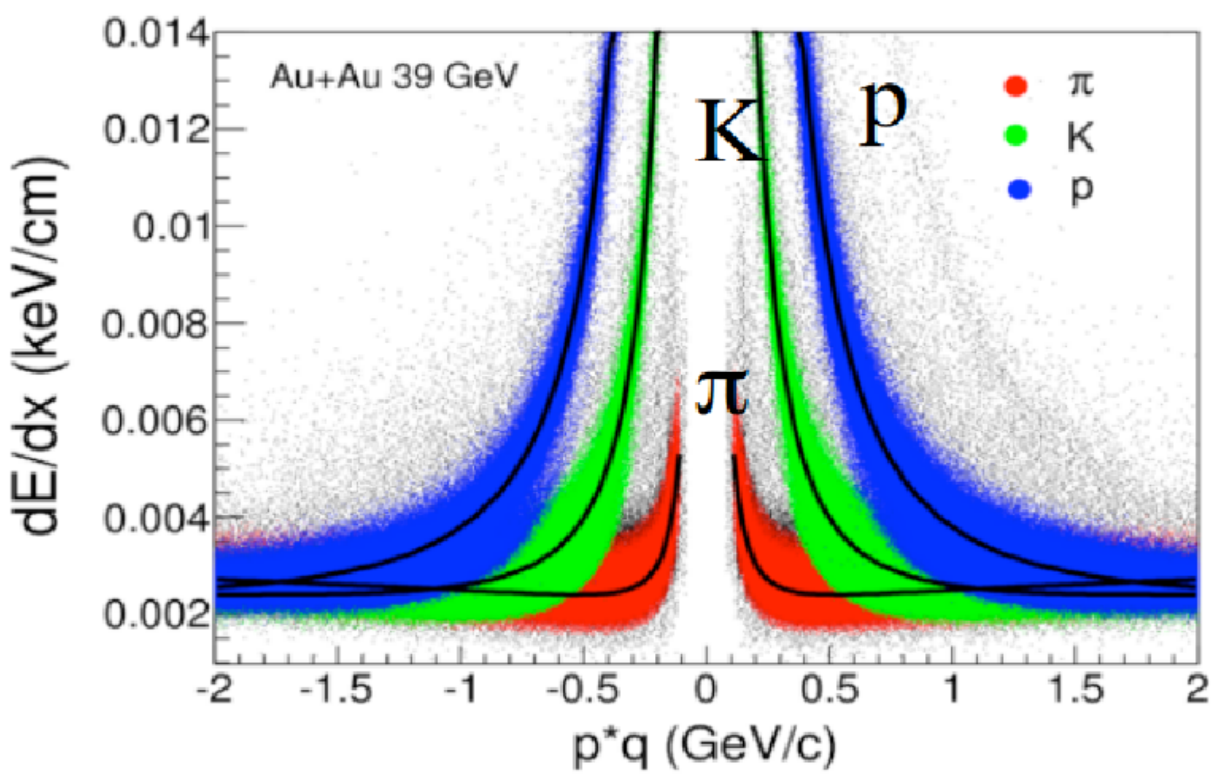
D. Kharzeev, A. Zhitnitsky, NPA797:67-79(2007)
D. Kharzeev, D. T. Son, PRL 106 (2011) 062301

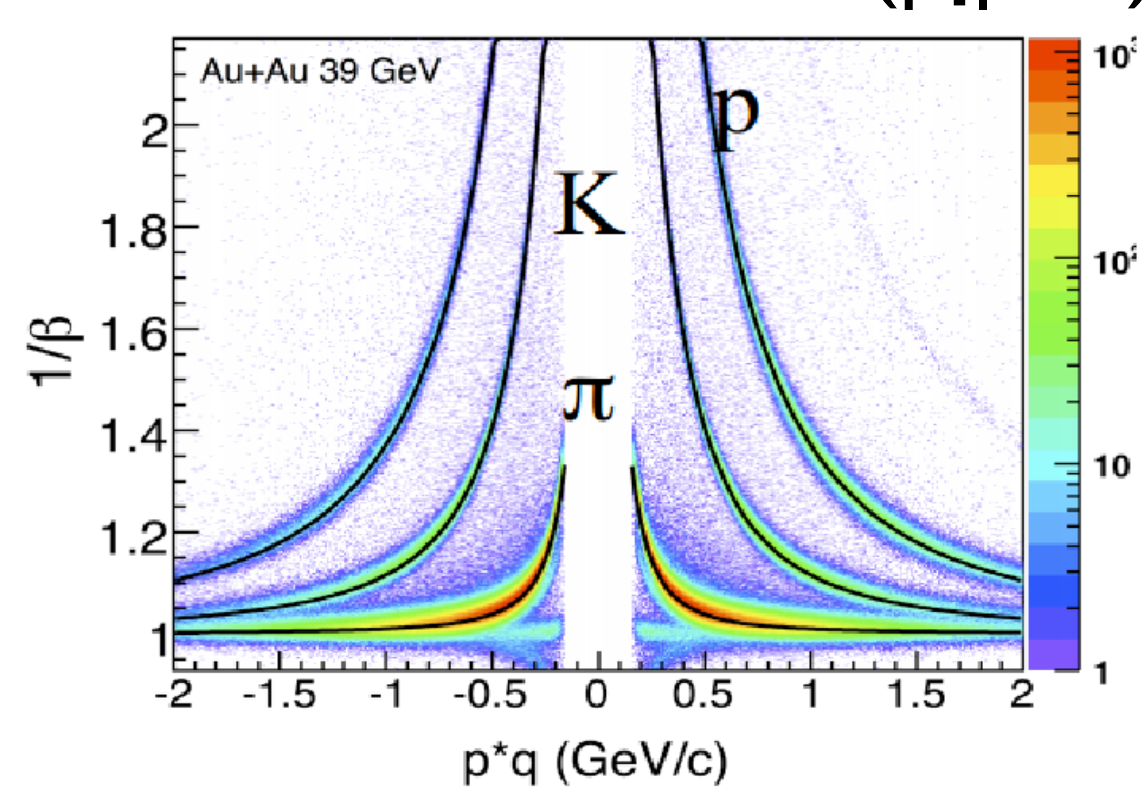
Solenoidal Tracker At RHIC (STAR)

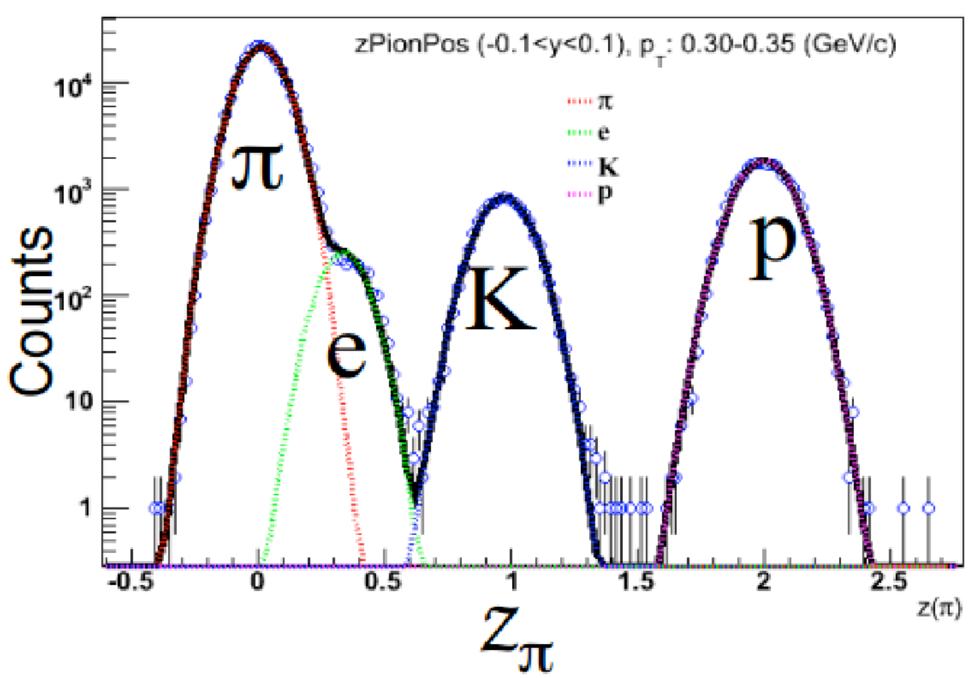


STAR Particle Identification

TPC $\sqrt{s_{NN}}$ **= 39 GeV Au + Au Collisions** ***TPC+ToF*** **(|η| < 1)**





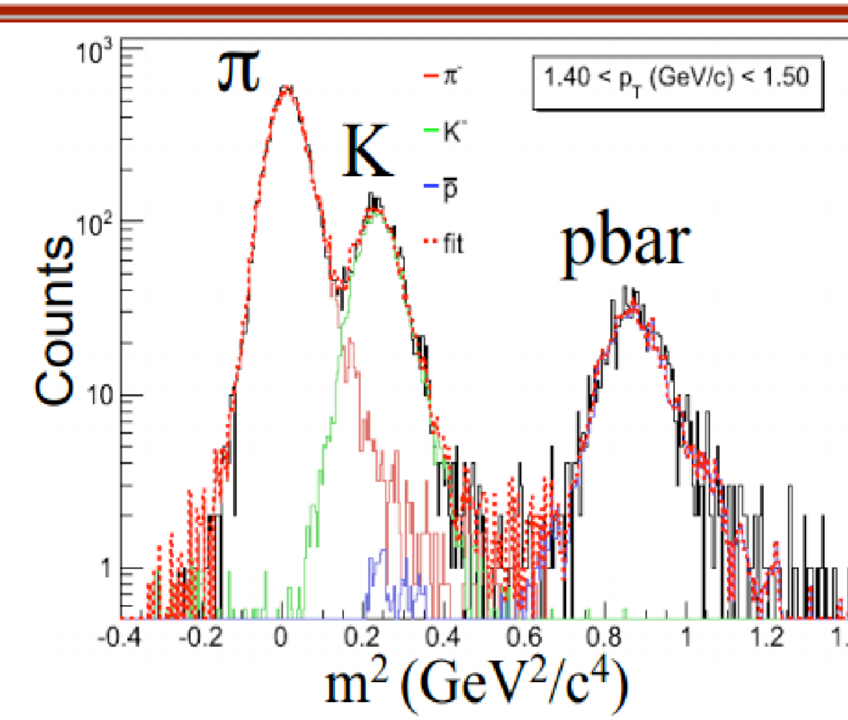


$$z = \log\left(\frac{(dE/dx)_{meas.}}{(dE/dx)_{theory}}\right)$$

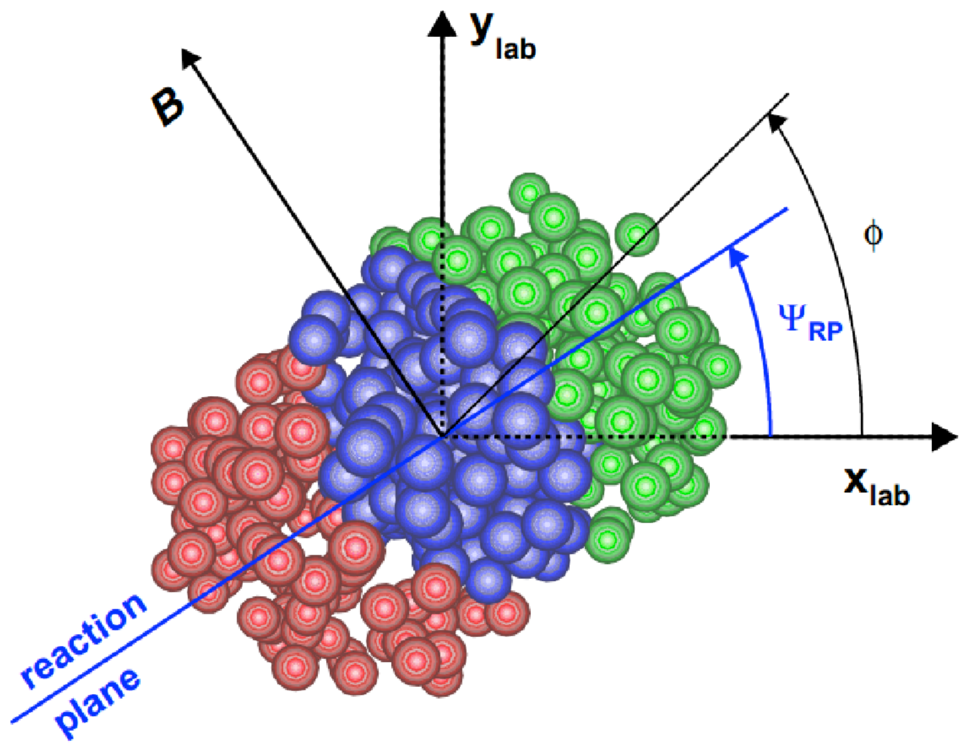
H. Bichsel, NIM A. 562 (2006) 154

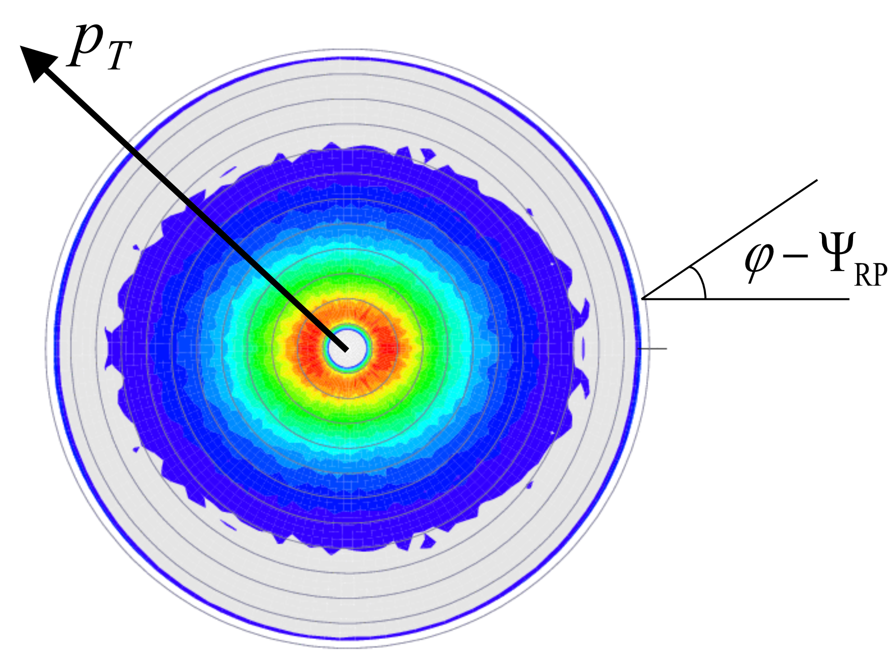
$$m^2 = p^2\left(\frac{c^2t^2}{L^2} - 1\right)$$

c=velocity of light,
L=path length



Define Event Plane

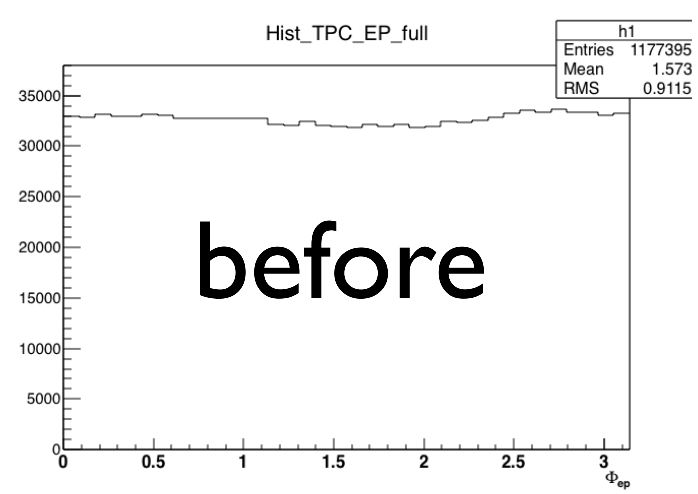


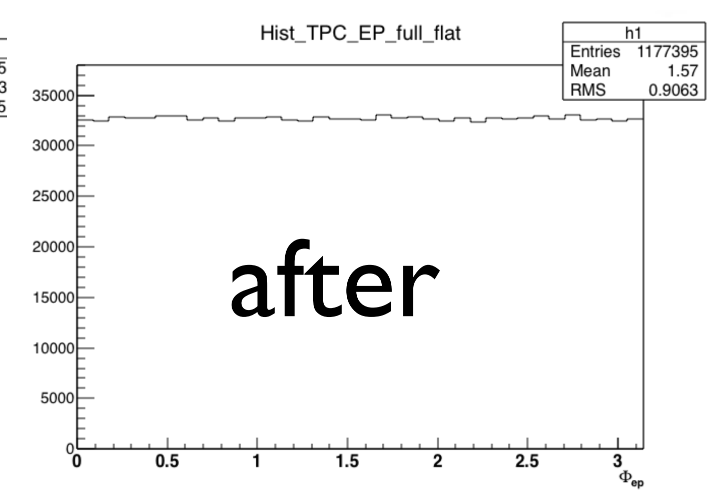


$$Q_n \cos(n\Psi_n) = Q_x = \sum_i w_i \cos(n\phi_i)$$

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

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



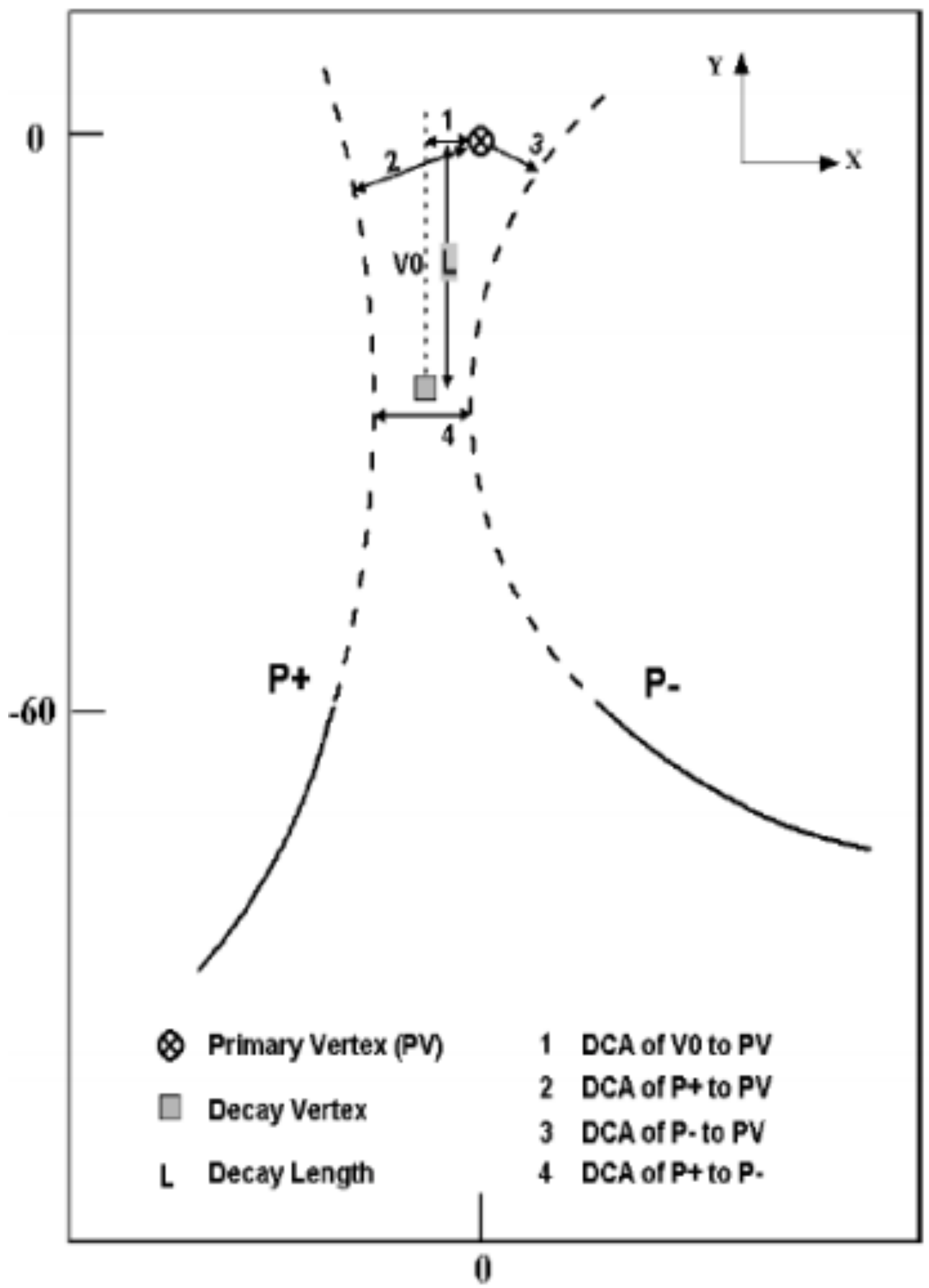


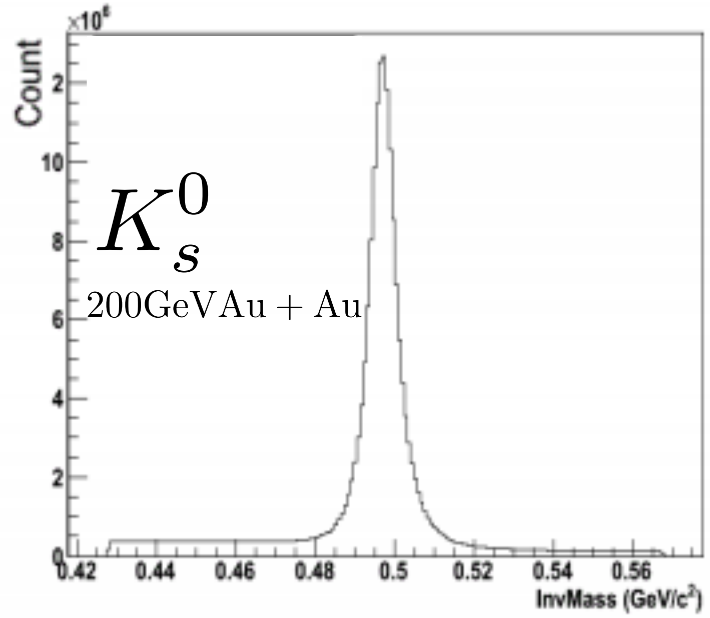
Shifting method used to flatten the EP distribution.

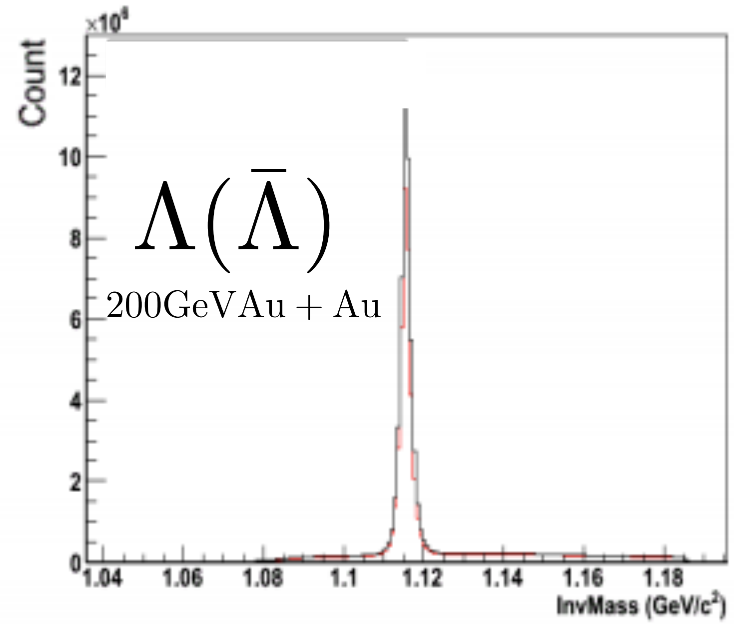
E877, Phys. Rev. C 56 (1997) 3254

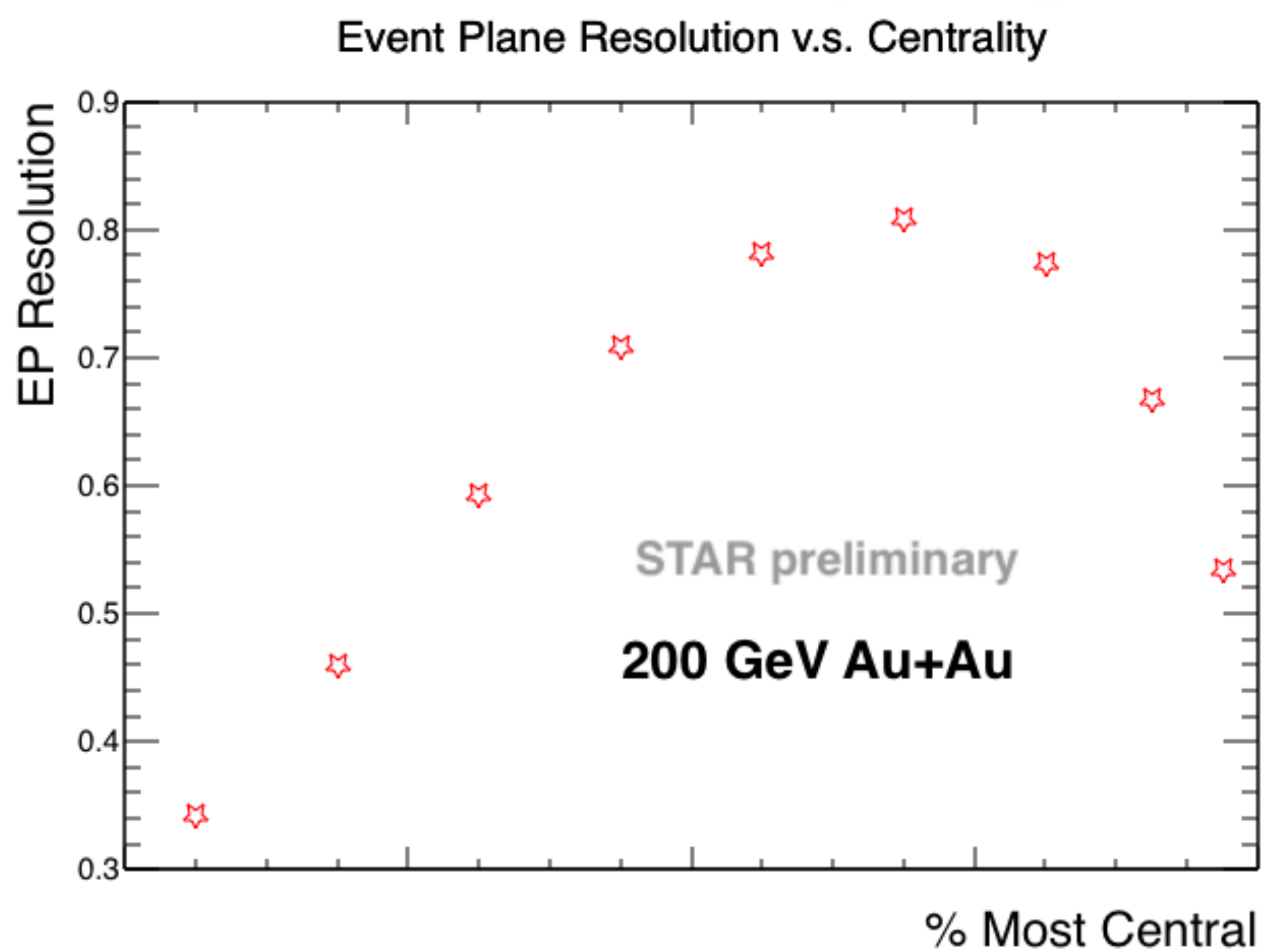
The estimated reaction plane is called the event plane.

Lambda/Ks0 and Event Plane Reconstruction





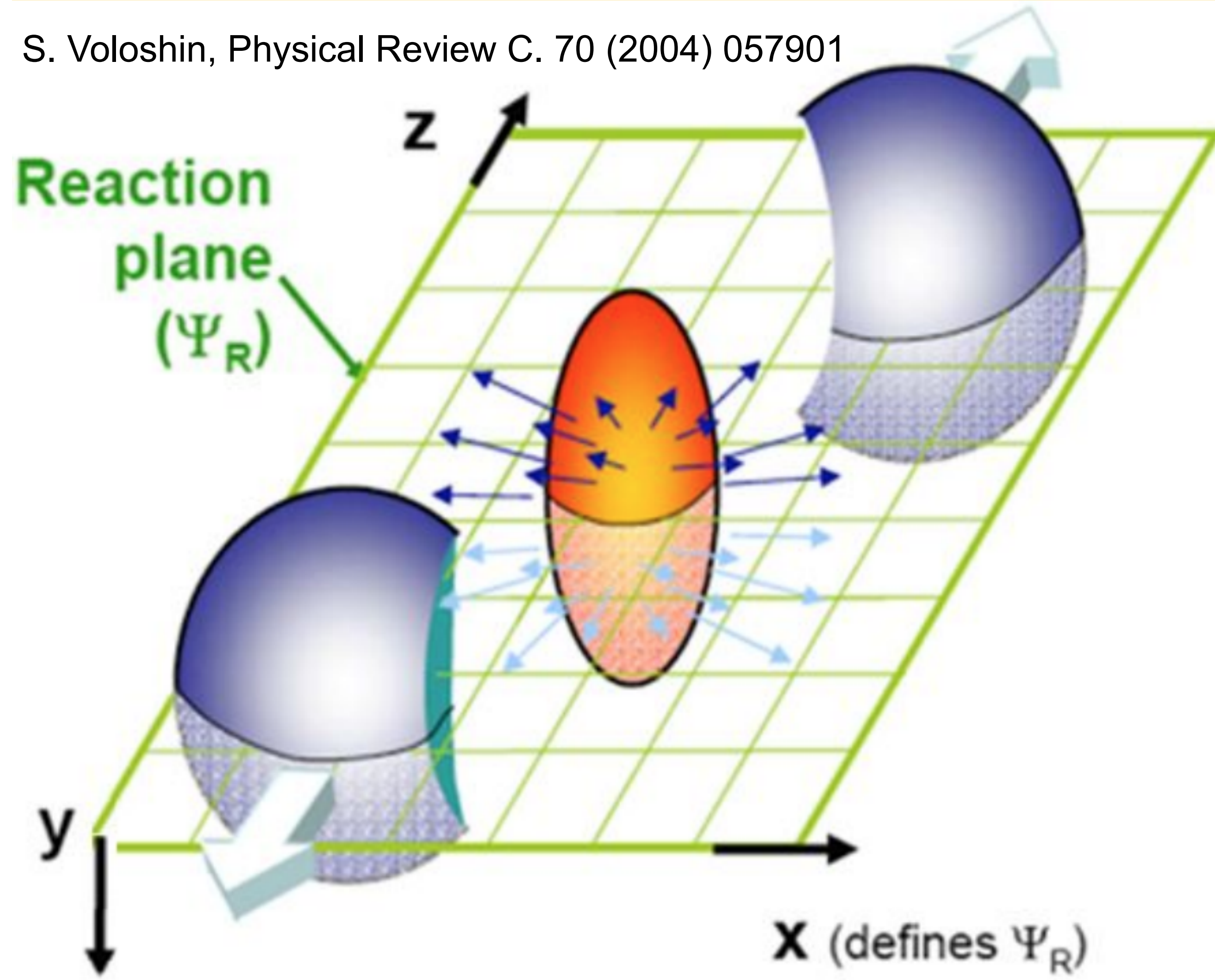




Observable: γ correlator

We investigate the charge dependent two-particle correlations with respect to the reaction plane:

S. Voloshin, Physical Review C. 70 (2004) 057901



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

Direct measurement of "a" would yield zero value. So we need "three-point-correlator"—observable "gamma"!

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

Background effects(insensitive to event plane orientation)

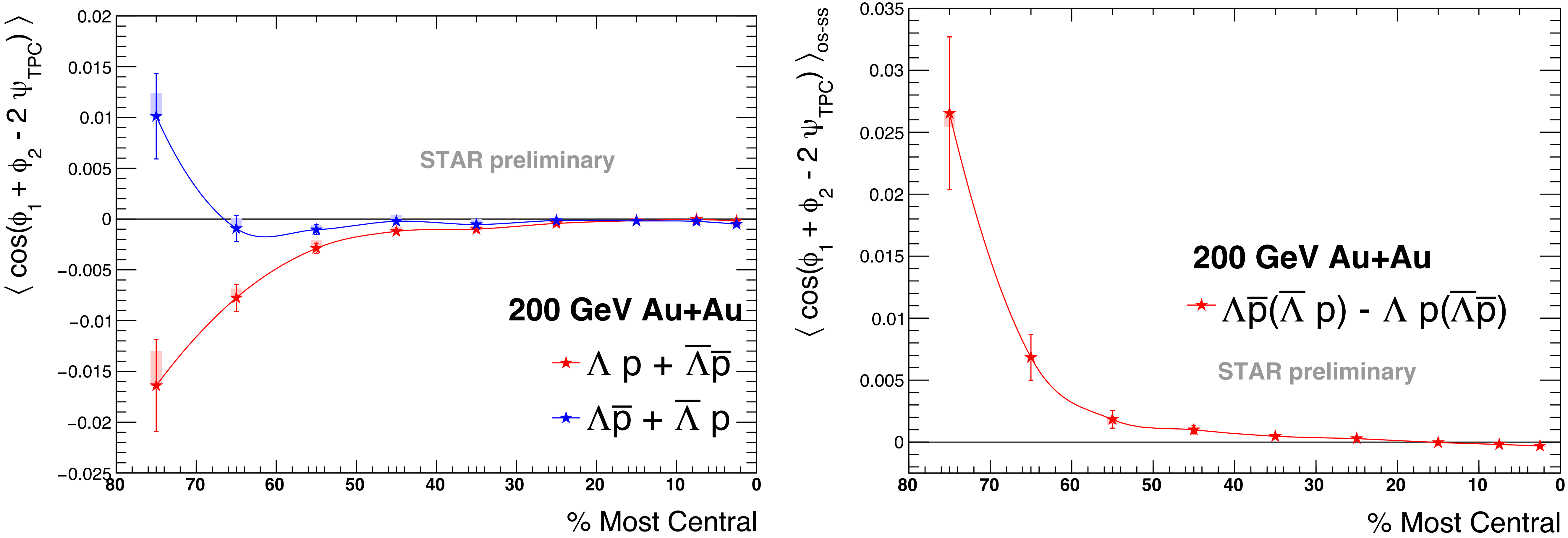
Directed flow: expected to be same for "same sign" and "opposite sign"

Background effects(insensitive to event plane orientation)

P-even quantity: still sensitive to separation effect, i.e., different for "same sign" and "oppo sign"

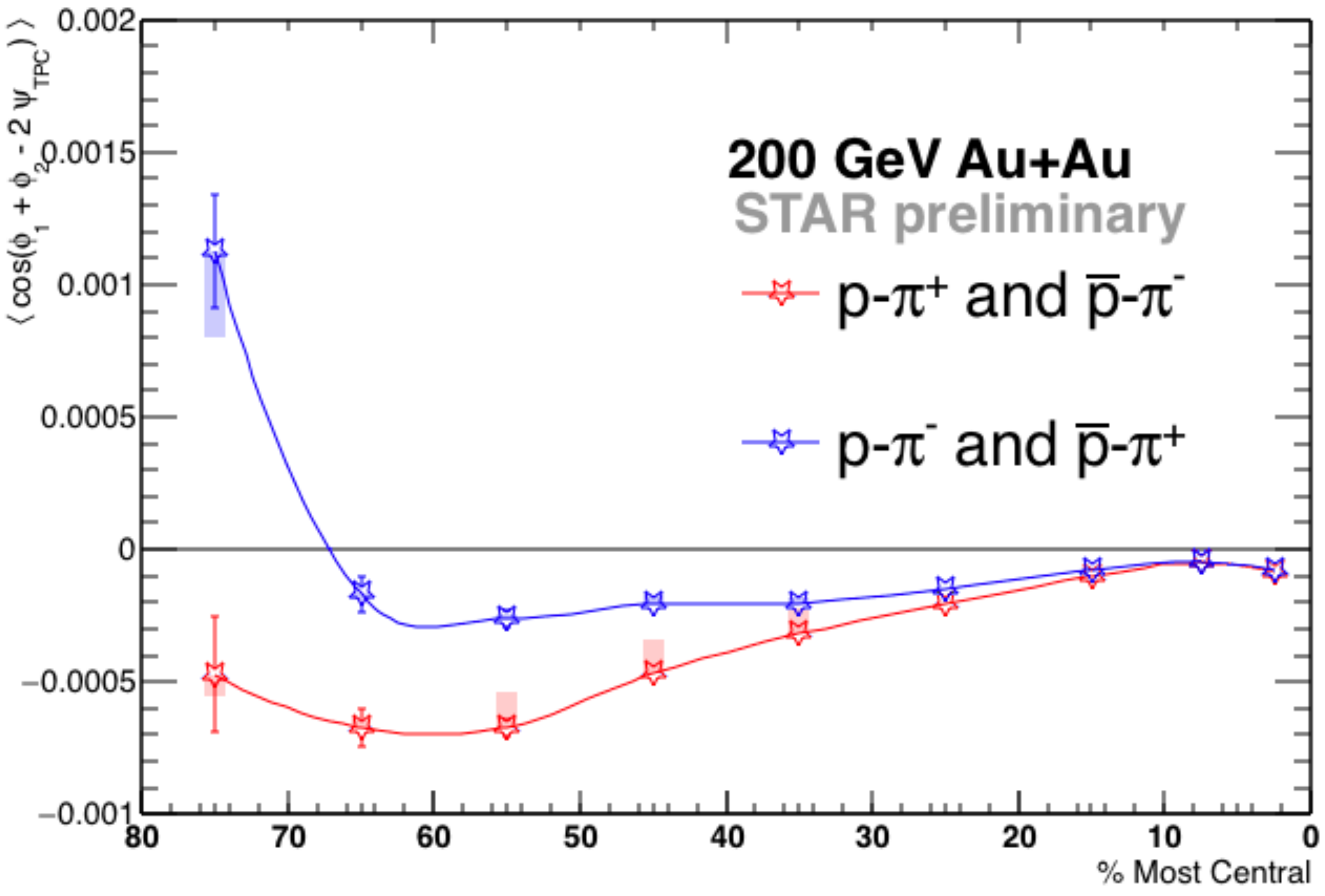
Same & opposite sign : correlated particles (α, β)have same (opposite)electric/baryonic charge.

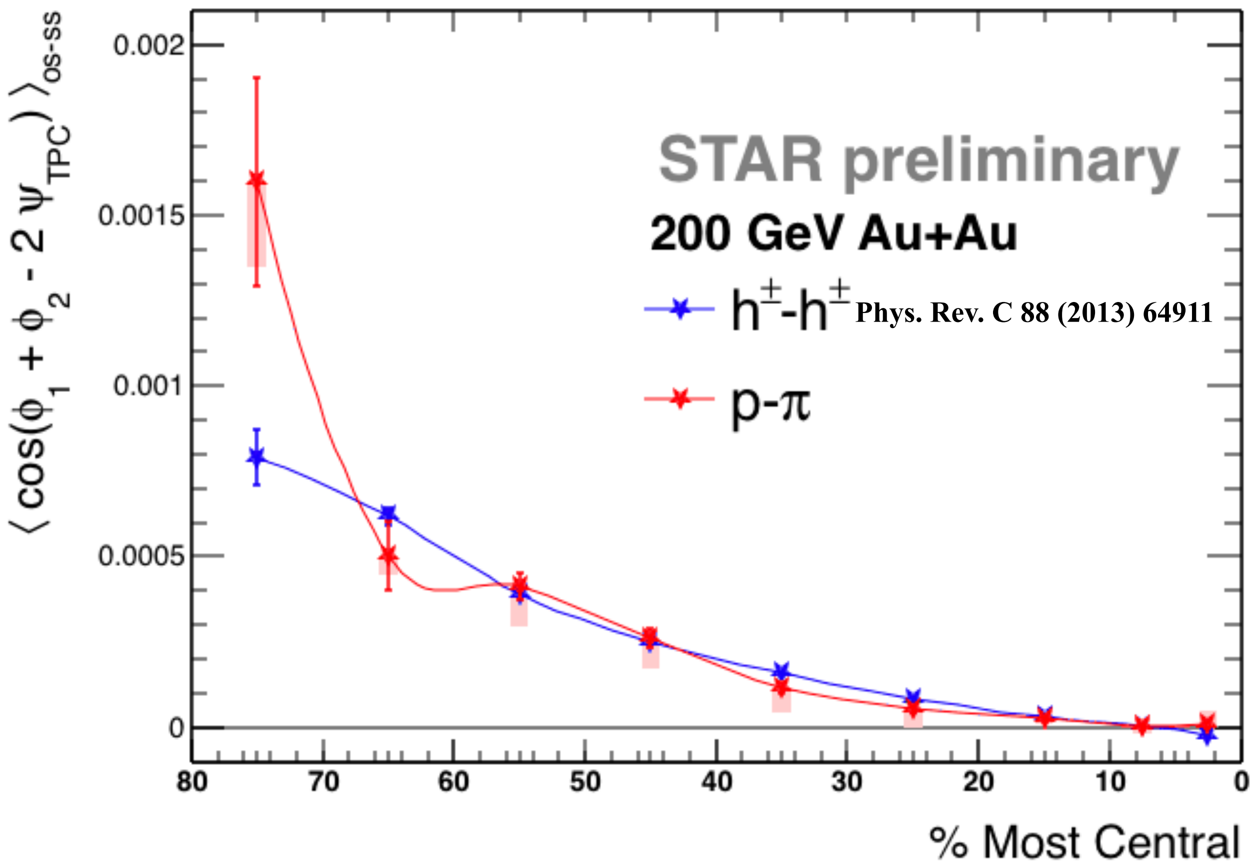
PID Correlation I



As CVE expected, significant baryonic charge separation signal is observed. The magnitude is larger than electric charge separation signal of h-h correlations.

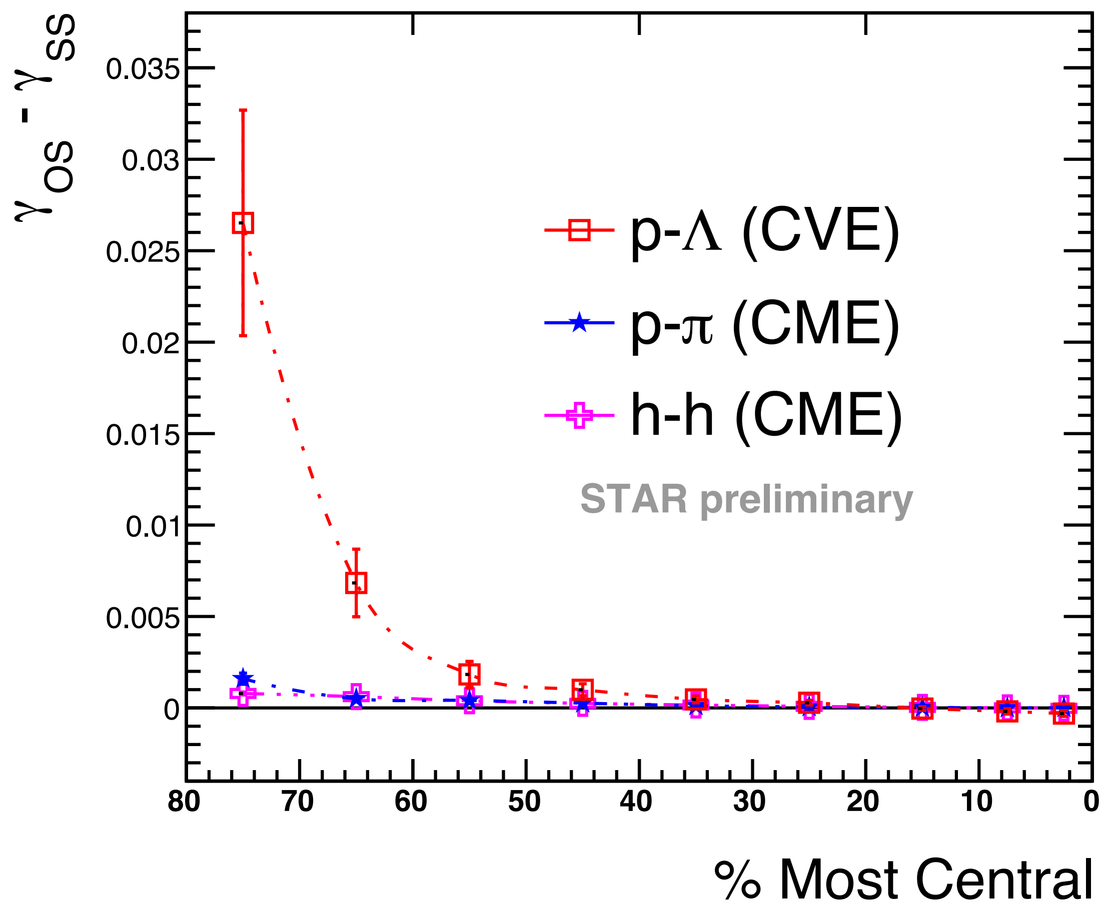
PID Correlation II

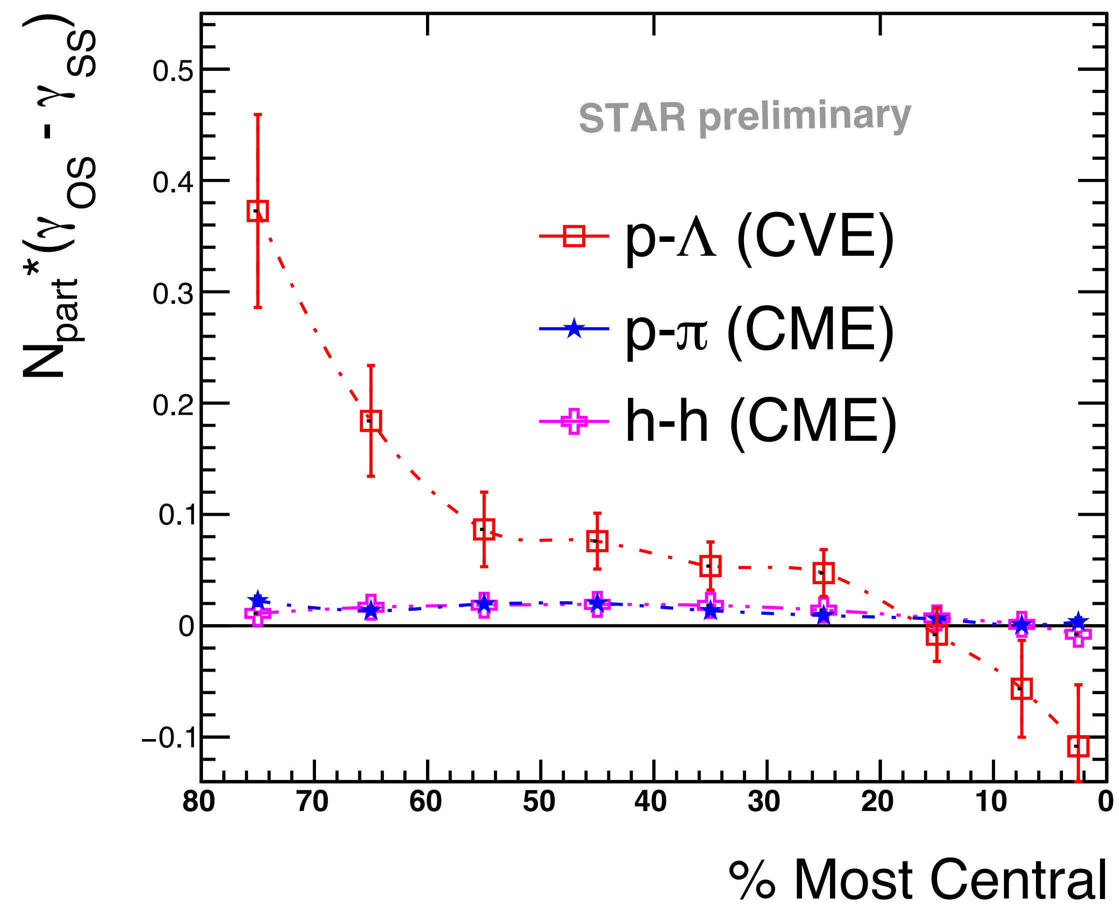




As a systematic check of h-h correlation, proton-pion correlation shows similar separation signal as h-h, suggesting similar underlying physics(CME) as expected.

Chiral Effects Hierarchy

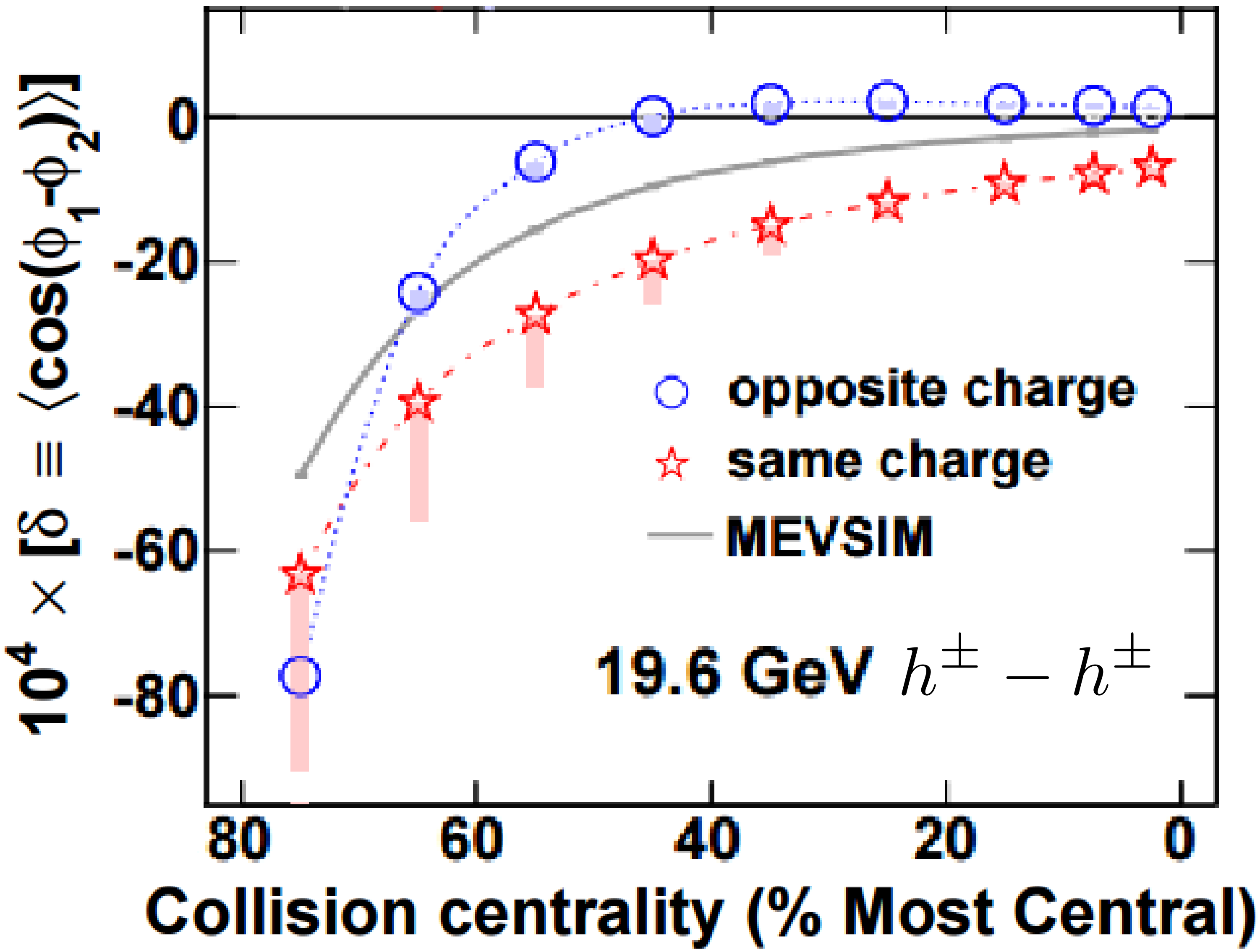




Identified particle correlation case studies show hierarchical structure of chiral effects. From Npart scaling plot, we can observe within error bars, separation signals are consistent with zero.

Background!

Phys. Rev. Lett 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*

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

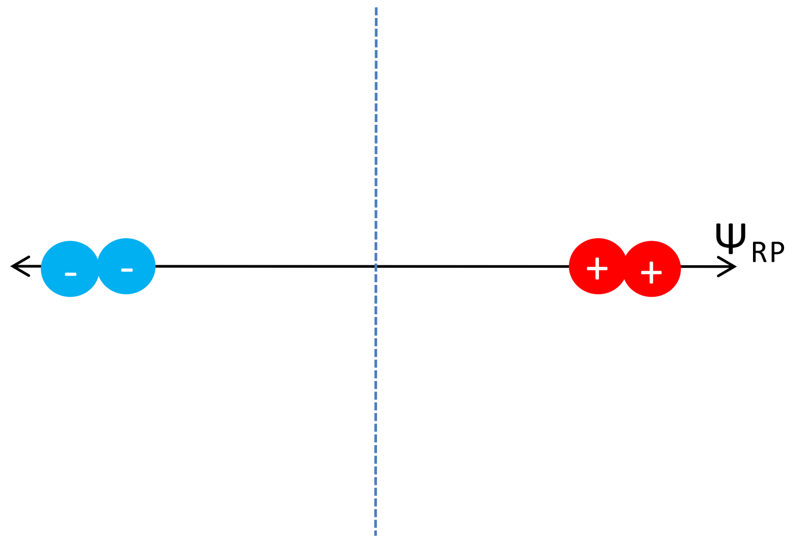
$$\delta \equiv \langle\cos(\phi_1 - \phi_2)\rangle = F + H$$

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

F: Flow-related background
H: charge separation signal

Two simple examples: why H is better?

v2 + momentum conservation



$\gamma_{SS} = 1$
$\delta_{SS} = 1$

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

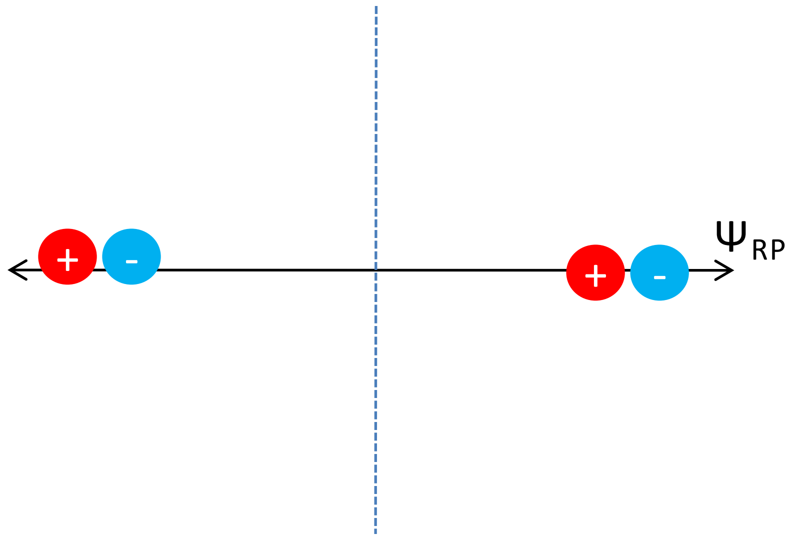
$v_2 = 1$

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

$\gamma_{OS} = -1$
$\delta_{OS} = -1$

v2 + momentum conservation + local charge conservation + decay

H is more robust.



$\gamma_{SS} = -1$
$\delta_{SS} = -1$

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

$v_2 = 1$

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

$\gamma_{OS} = 0$
$\delta_{OS} = 0$

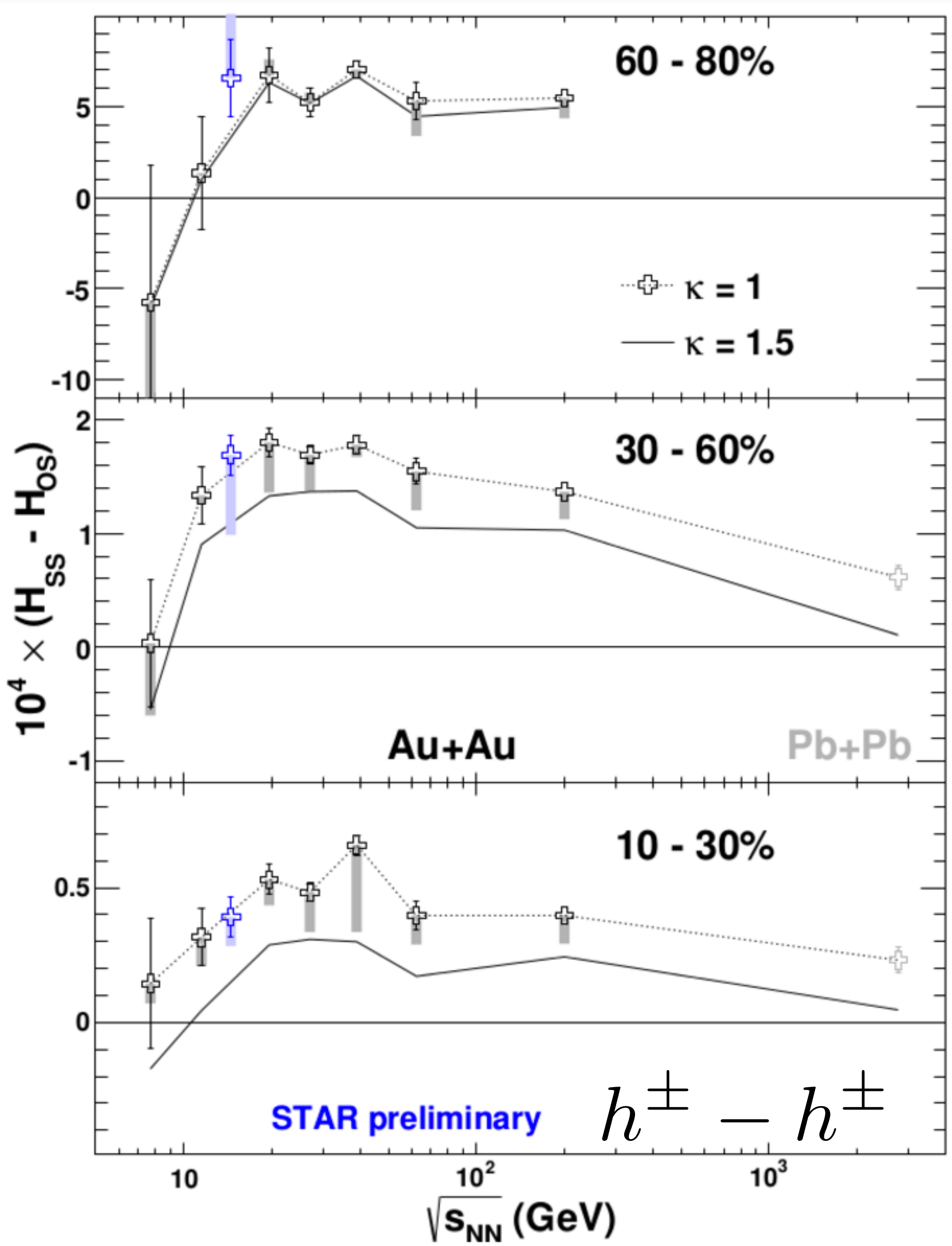
$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\psi_{ep}) \rangle = \kappa v_2 F - H$$
$$\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H$$

$=> H = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$

F: Flow-related background
H: charge separation signal

Background-free Observable(H Correlator)

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



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

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

$$=> H = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$$

- ▷ **κ** could deviate from 1 due to a finite detector acceptance and theoretical uncertainties
- ▷ The CME signal decreases to zero in the interval between 19.6 and 7.7 GeV
- ▷ Need better theoretical estimate of κ and better statistics

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

κ = ? Transverse Momentum Conservation

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

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

we have introduced certain weighted moments of v_2:

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

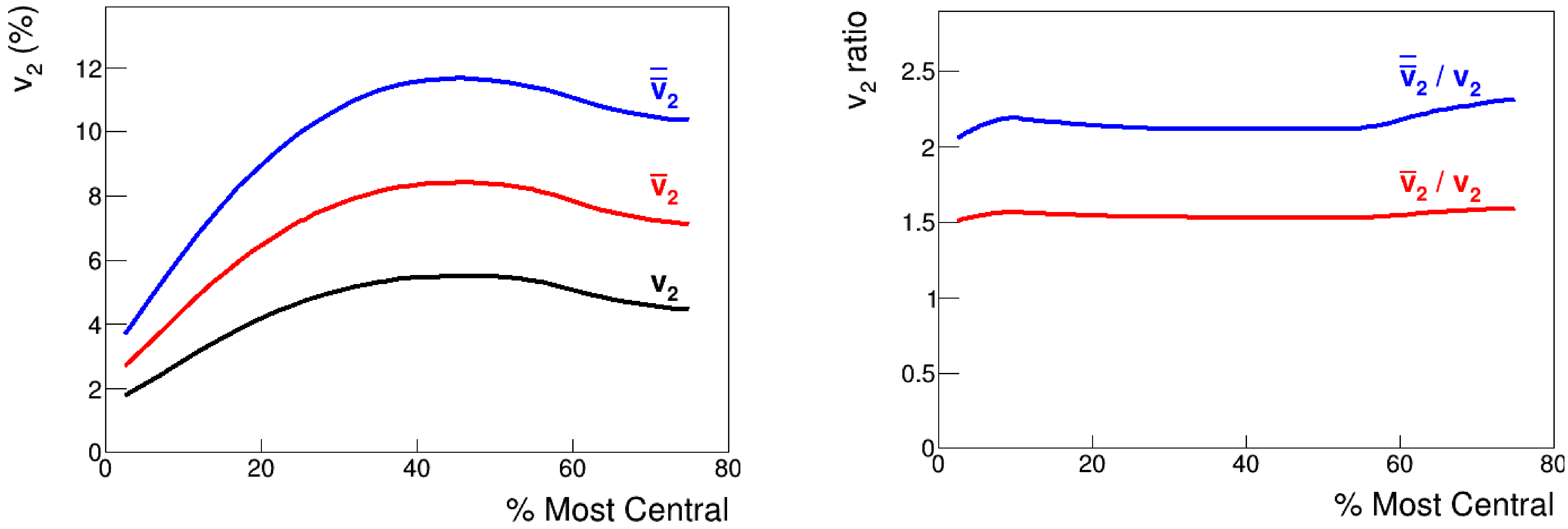
If our measurements are dominated by this type of background,

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

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).

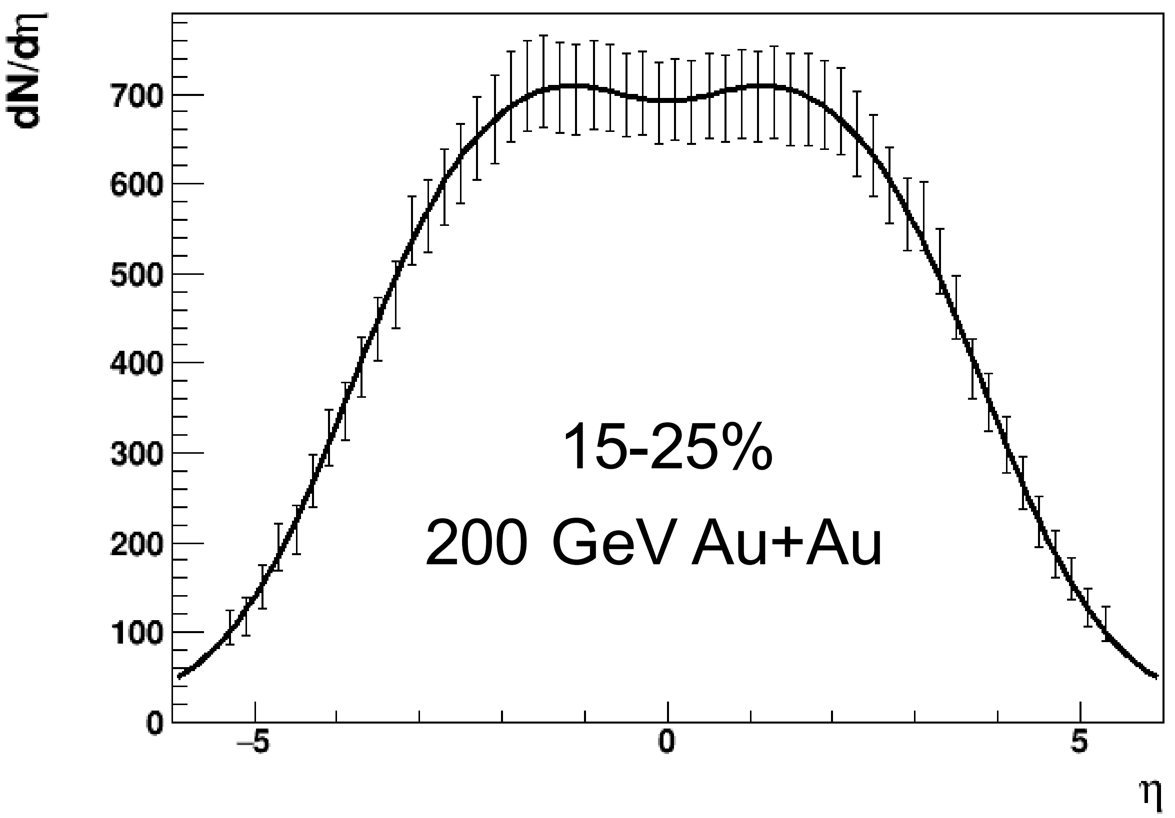
Data driven estimation of κ (I)

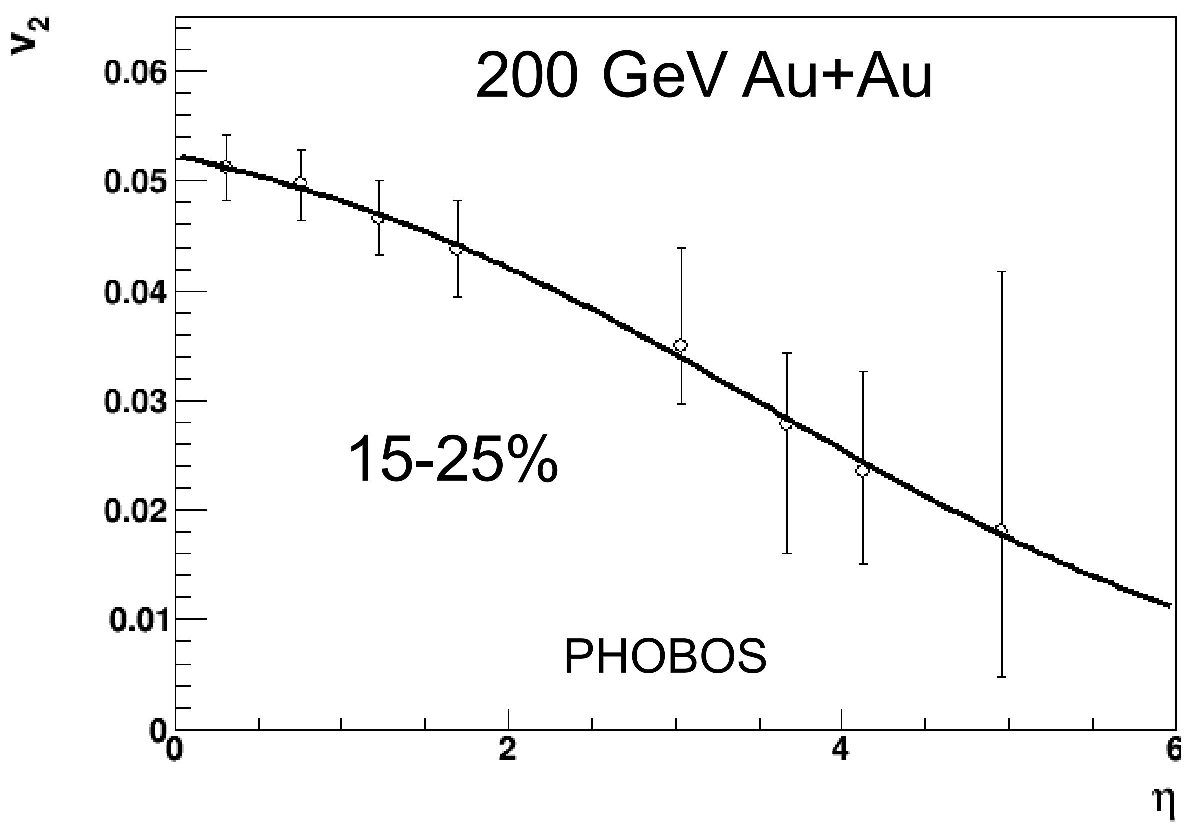


$$\bar{v}_2 = \frac{\langle v_2(p_t,\eta)p_t\rangle}{\langle p_t\rangle}, \quad \bar{\bar{v}}_2 = \frac{\langle v_2(p_t,\eta)p_t^2\rangle}{\langle p_t^2\rangle}$$

The ratios of the pt-weighted v2 over conventional v2 are almost constant across centralities. This result enables us to use v2 to estimate pt or pt squared weighted v2.

Data driven estimation of κ (II): $v_{2,\Omega}$ and $v_{2,F}$

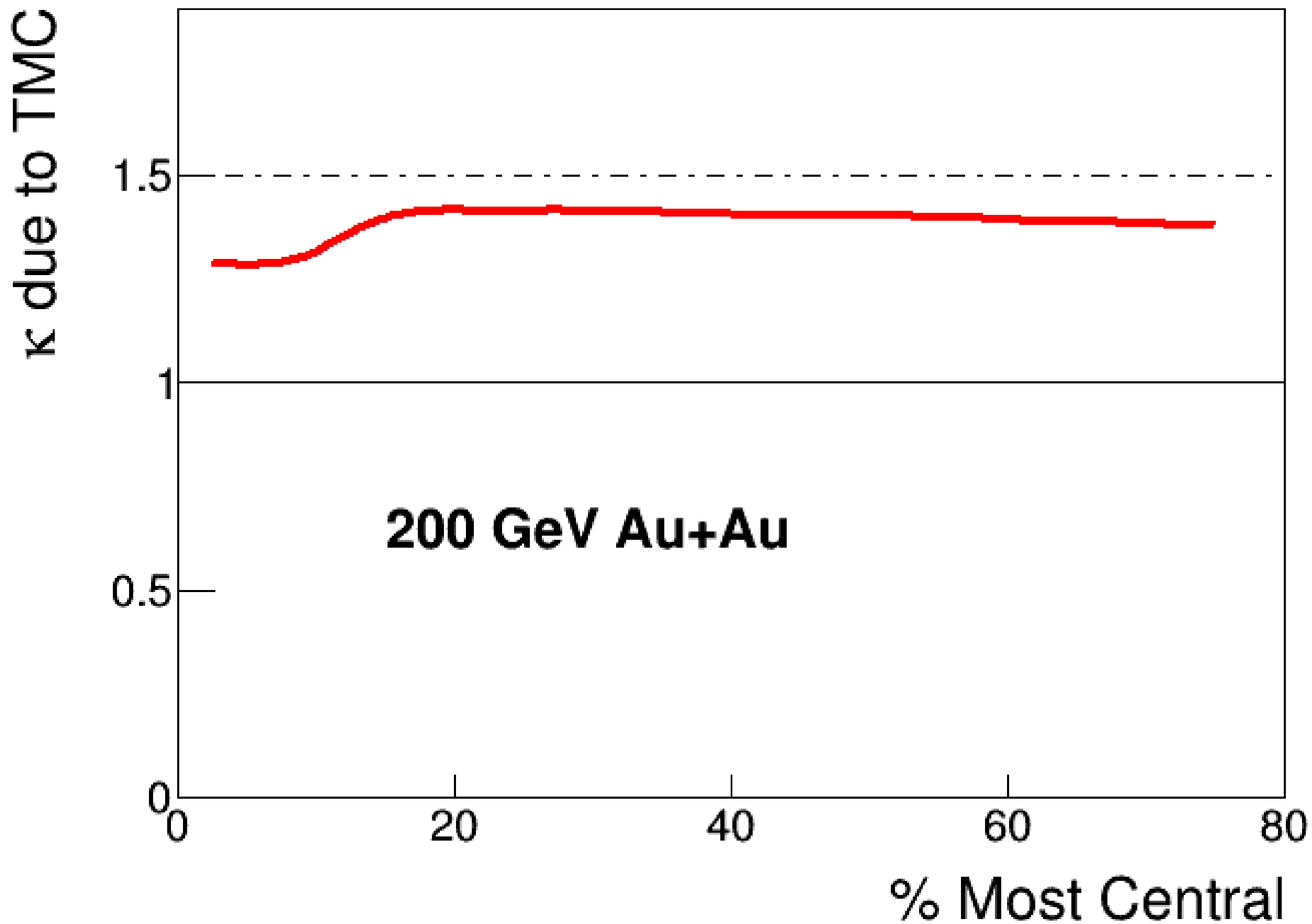




PHOBOS, PRC 72 014904 (2005); PRC 83 024913 (2001)

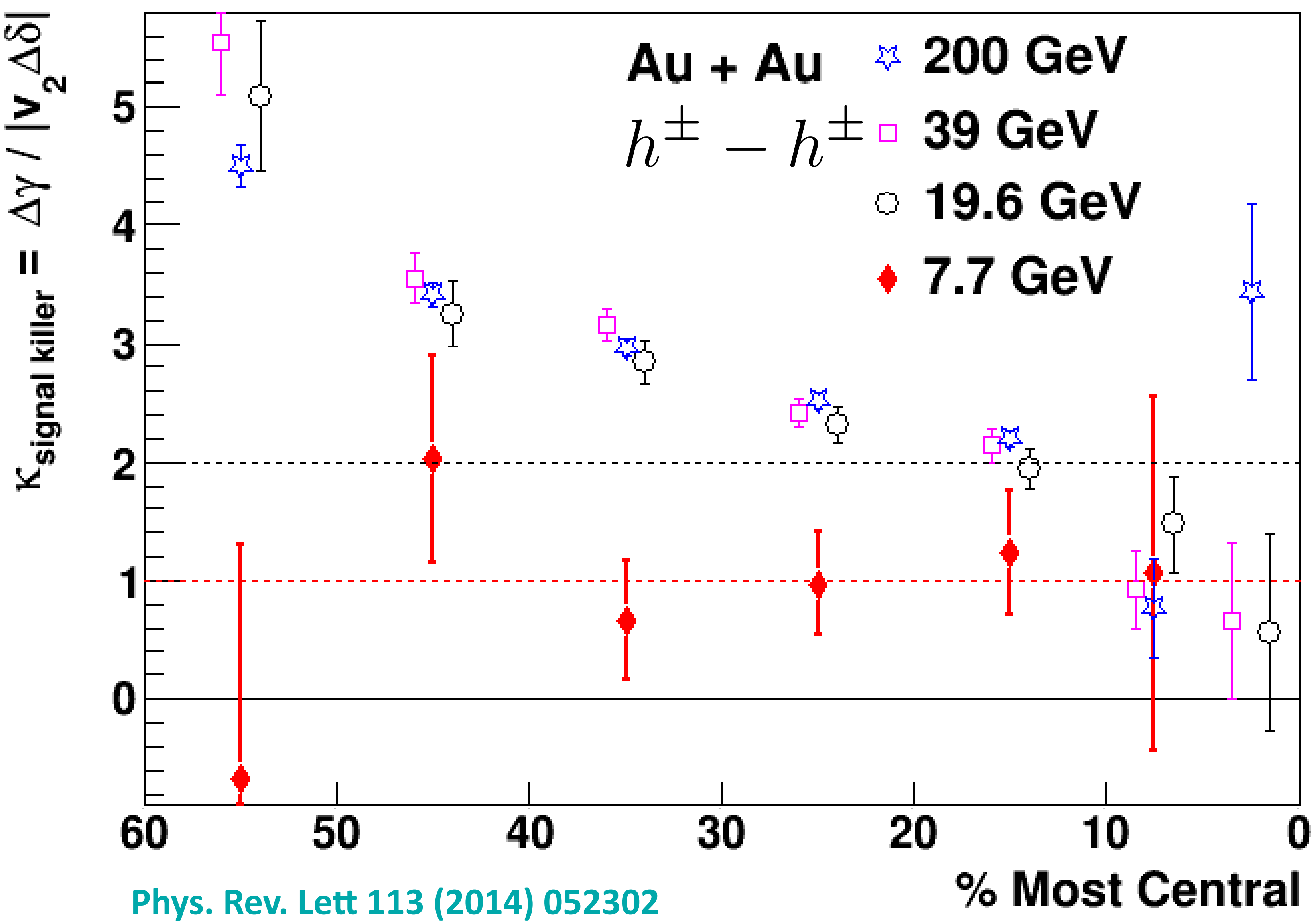
centrality	$v_{2,\Omega}$ (%)	$v_{2,F}$ (%)	$v_{2,F}/v_{2,\Omega}$
3-15%	3.17	2.66	0.84
15-25%	5.04	3.97	0.79
25-50%	6.21	4.87	0.78

κ due to Transverse Momentum Conservation



- **κ** is almost constant across different centrality bins. But this is for TMC effect only.
- Other background effects(Local Charge Conservation, resonance decay…) may be different and the final **κ** will be the average of all these effects(estimated to be ~1-2, but still need more investigations).

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



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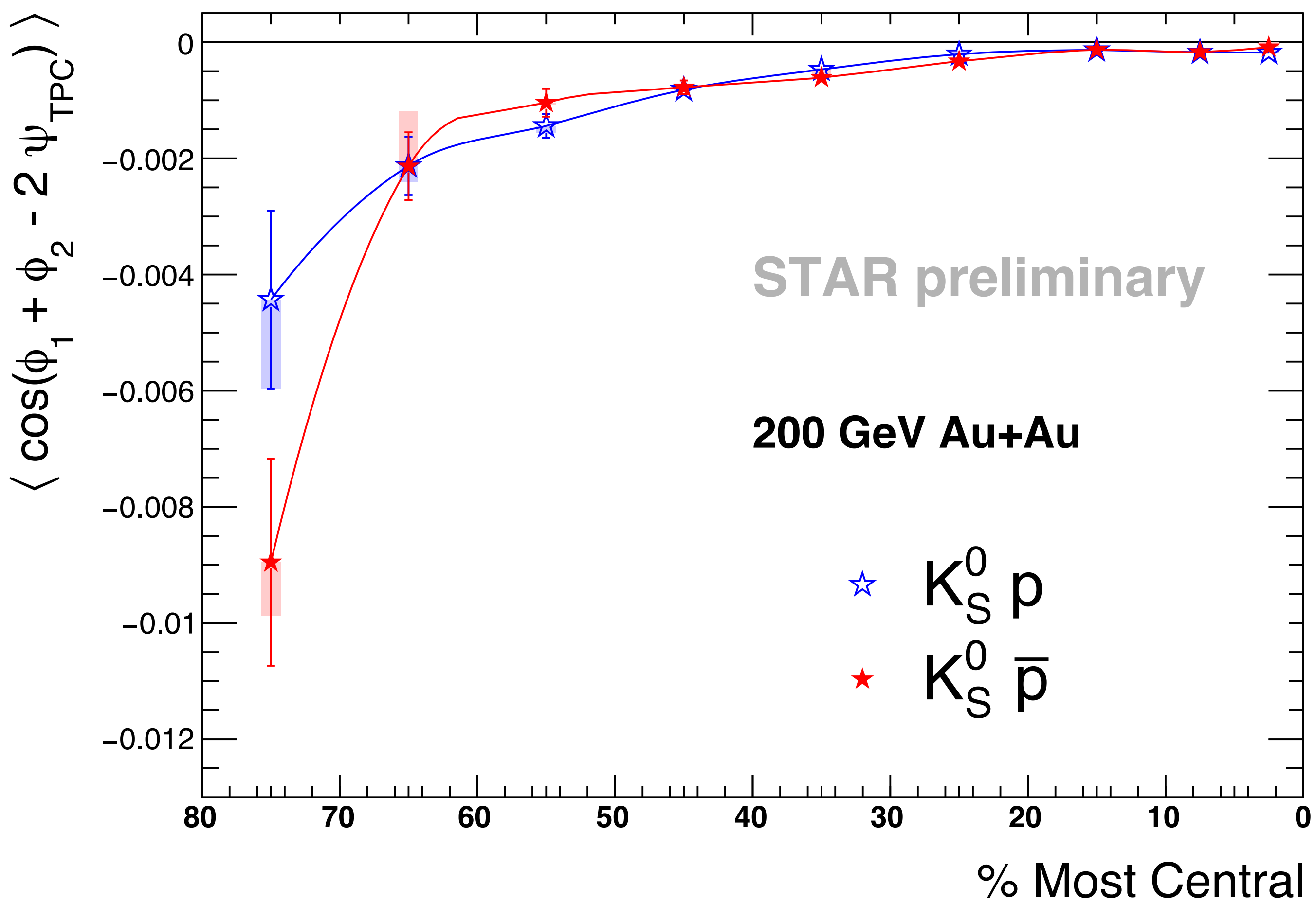
1. $\kappa_{\text{signal killer}}$ is value required to make H zero.
2. From 200 to 19.6GeV, $\kappa_{\text{signal killer}}$ has centrality dependence and is always above the estimation of estimated κ(i.e., our signals are safe).

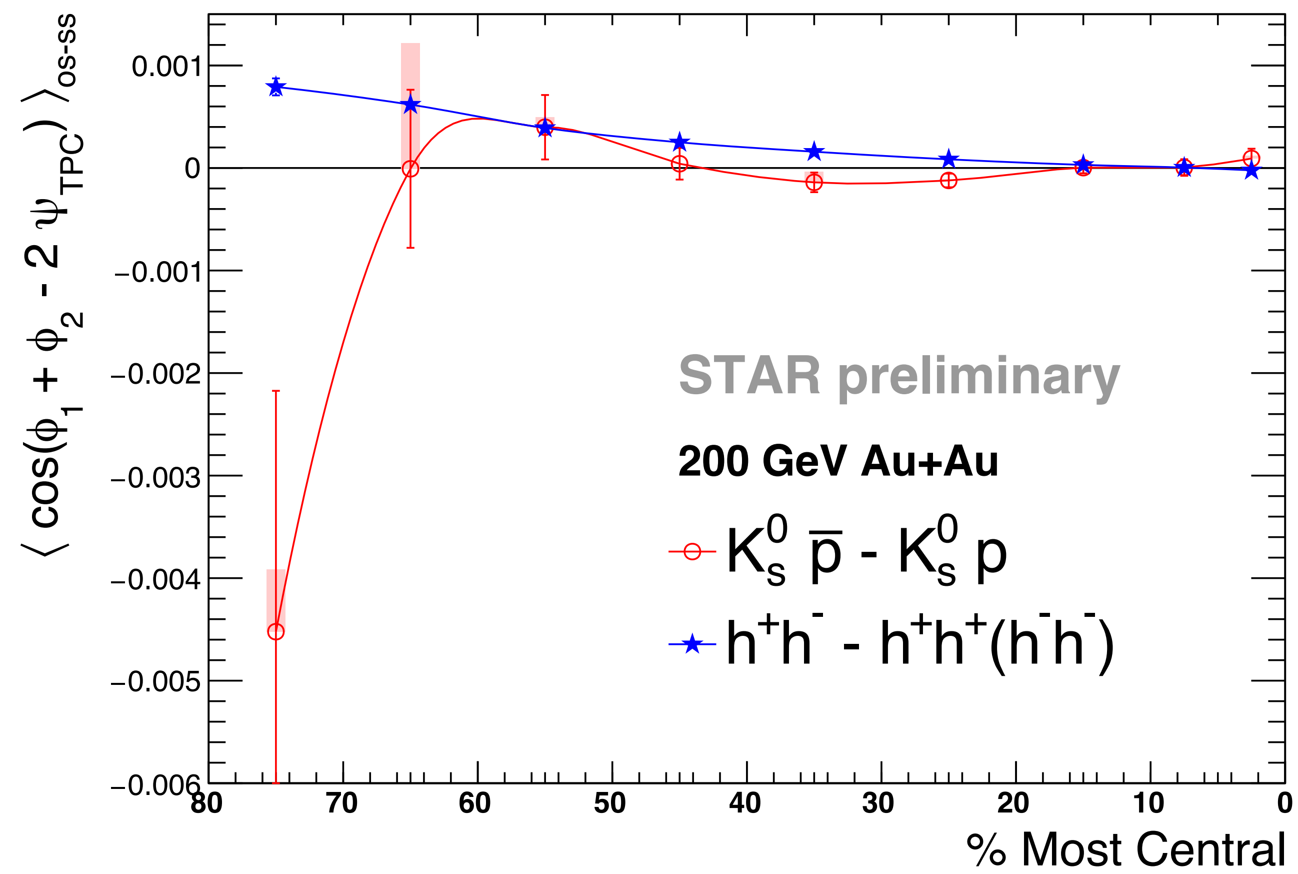
Summary

- Two identified particle correlation studies are presented, which show different intensity levels of (baryonic/electric) charge separation signal($p - \Lambda > p - \pi$);
- A data-driven study of flow-related background is presented and shows our charge separation signal is robust with bg-free correlator(H).
- The hierarchical structure of chiral effects(CVE > CME) is revealed from experimental measurements of identified particles correlation in heavy ion collisions.

backup slides

PID Correlation IV





As a background check of proton-pion correlation, proton-K_s^0 shows zero separation signal. But more statistics are needed to make strong conclusion.