Significant charge splitting of rapidity-odd directed flow and its implication on electromagnetic effect in Au+Au, Ru+Ru, and Zr+Zr collisions from STAR

Diyu Shen (dyshen@fudan.edu.cn), Fudan University, *for the STAR Collaboration*

Abstract

Heavy-ion collisions can produce an ultra-strong magnetic field, the evolution of which was predicted to decrease (increase) the directed flow slope, dv_1/dy, for positively (negatively) charged particles. In this work, we study this effect with large statistics datasets accumulated for Au+Au, $^{96}_{44}$Ru+$^{96}_{44}$Ru, and $^{96}_{40}$Zr+$^{96}_{40}$Zr isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV, and Au+Au collisions at $\sqrt{s_{NN}}$ = 27 GeV. The charge dependent dv_1/dy splitting, $\Delta(dv_1/dy)$, will be presented for $\pi^{\pm}$, $K^{\pm}$, and (anti)proton. A finite $\Delta(dv_1/dy)$ between protons and anti-protons has been observed and it **changes from positive to negative as a function of centrality** from central to peripheral collisions. **This is the first observation of a significant negative $\Delta(dv_1/dy)$ between proton and anti-protons.** A similar decreasing trend of slope difference between K^+ and K^- has also been observed in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and 27 GeV, and in isobar collisions with less significance. The slope difference between π^+ and π^- is negative and decreases as a function of centrality in Au+Au collisions at $\sqrt{s_{NN}}$ = 27 GeV, while no significant slope difference is observed in Au+Au and isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV. Our measurements of significant negative $\Delta(dv_1/dy)$ cannot be explained by conventional mechanisms (e.g. transported quarks), **but qualitatively agree with the theoretical prediction with an ultra-strong electromagnetic field in peripheral collisions.**

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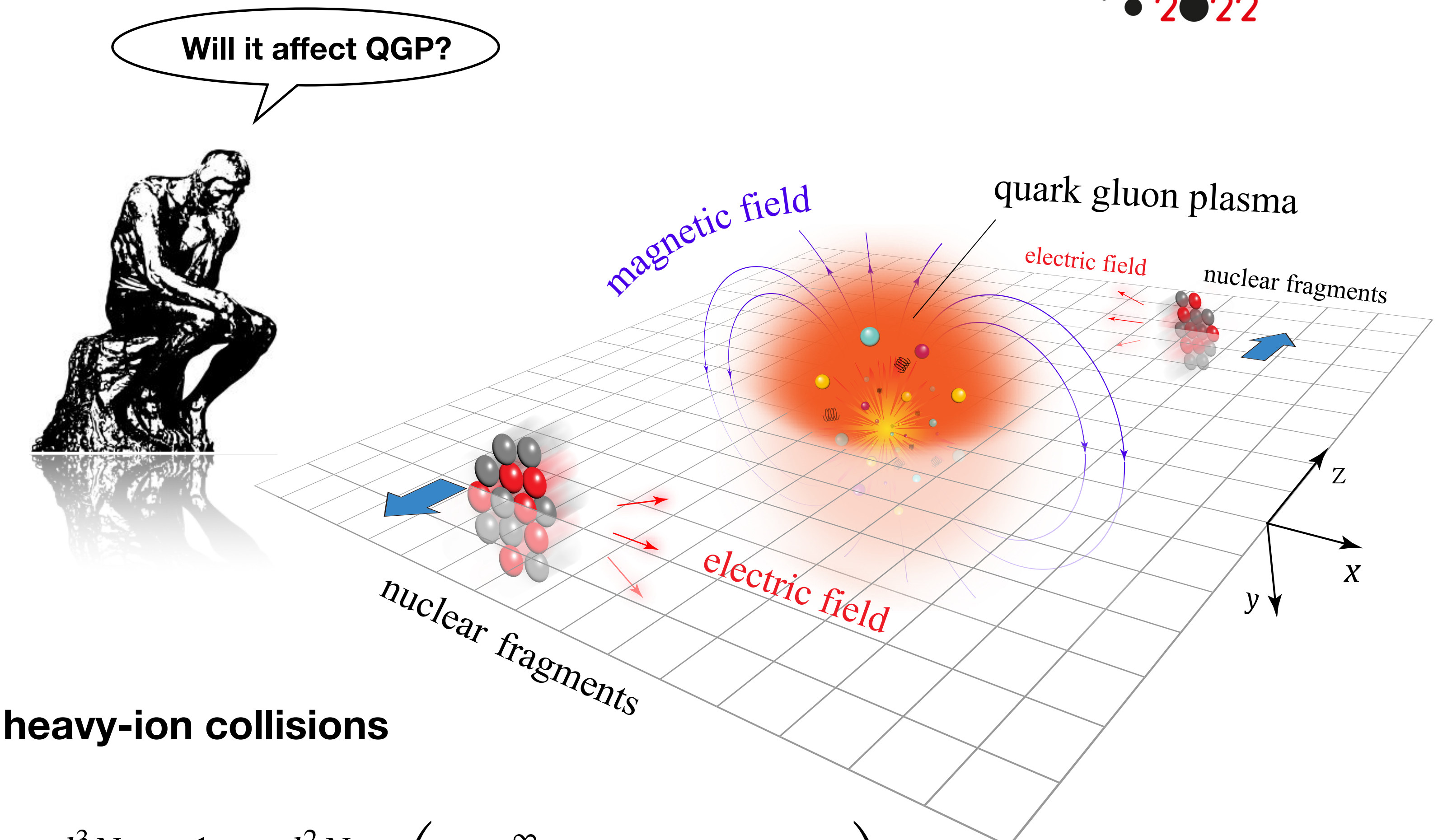
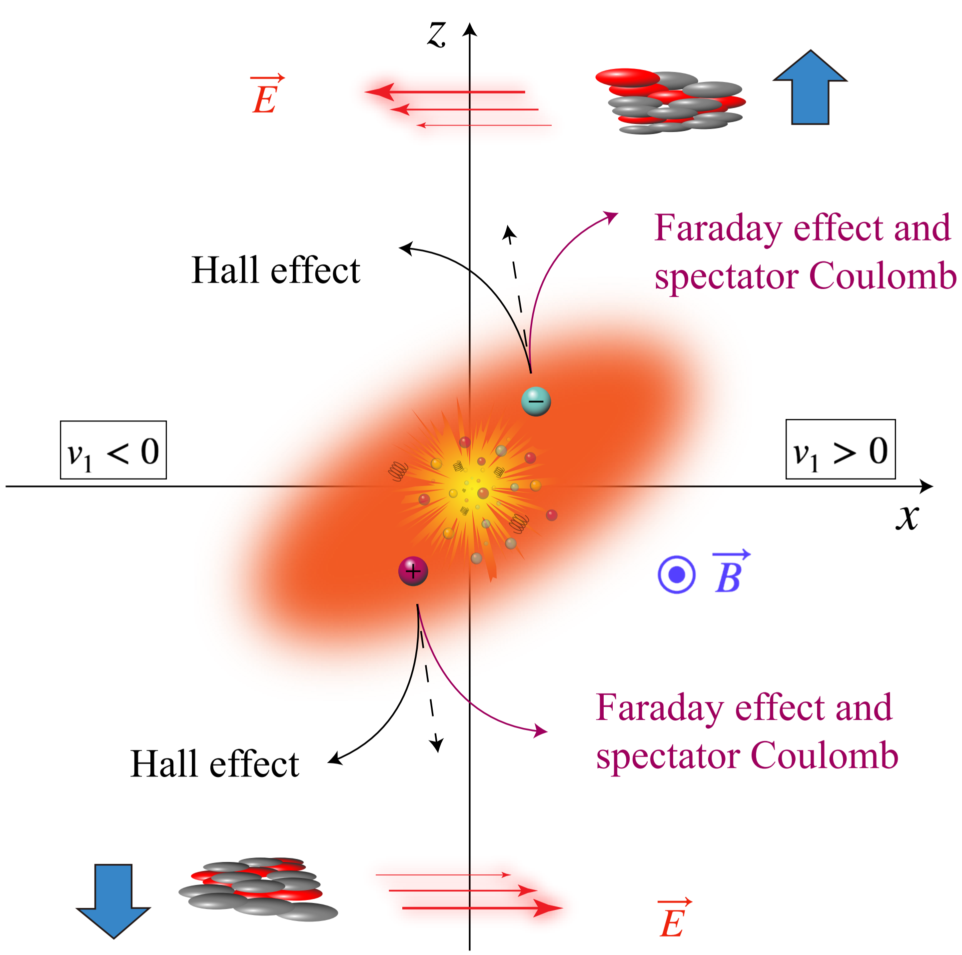
I. Electromagnetic field in heavy-ion collisions

- An ultra-strong magnetic field can be generated by nuclear fragments.
- Extremely short life time, depending on the conductivity of produced matter.



Probe EM-field via charge splitting of v_1 in heavy-ion collisions

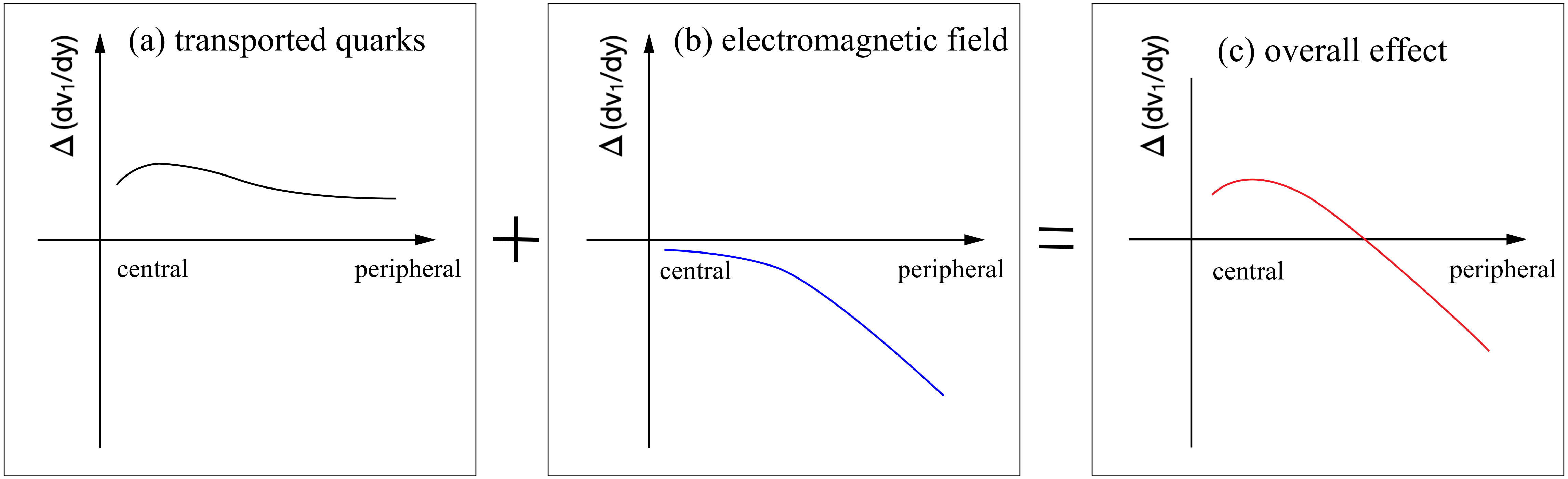


$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi)]\right)$$

- Lorentz force results in sideward motion, referred to Hall effect.
- Decrease of B field induces Faraday current in direction opposite to Hall effect.
- Electric force from spectator coulomb.
- ☑ Result in charge splitting of directed flow v_1.

II. Probe EM-field via charge splitting of v_1 in heavy-ion collisions

Illustration for proton and anti-proton:

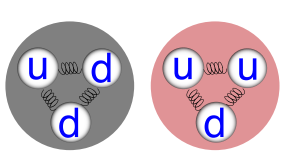


As transported quarks have positive dv_1/dy[1][2],

Faraday effect/spectator Coulomb dominate over Hall effect[3][4],

$$\Delta(dv_1/dy) = dv_1^+/dy - dv_1^-/dy$$

	dv_1/dy		dv_1/dy		
$p : uud$ $\bar{p} : \bar{u}\bar{u}\bar{d}$	$p > \bar{p}$	+	$p < \bar{p}$	=	Positive if transported quarks + Hall win Negative if Faraday + Coulomb win
$K^+ : u\bar{s}$ $K^- : \bar{u}s$	$K^+ > K^-$		$K^+ < K^-$		Positive if transported quarks + Hall win Negative if Faraday + Coulomb win
$\pi^+ : u\bar{d}$ $\pi^- : \bar{u}d$	$\pi^- > \pi^+$		$\pi^- > \pi^+$		Negative

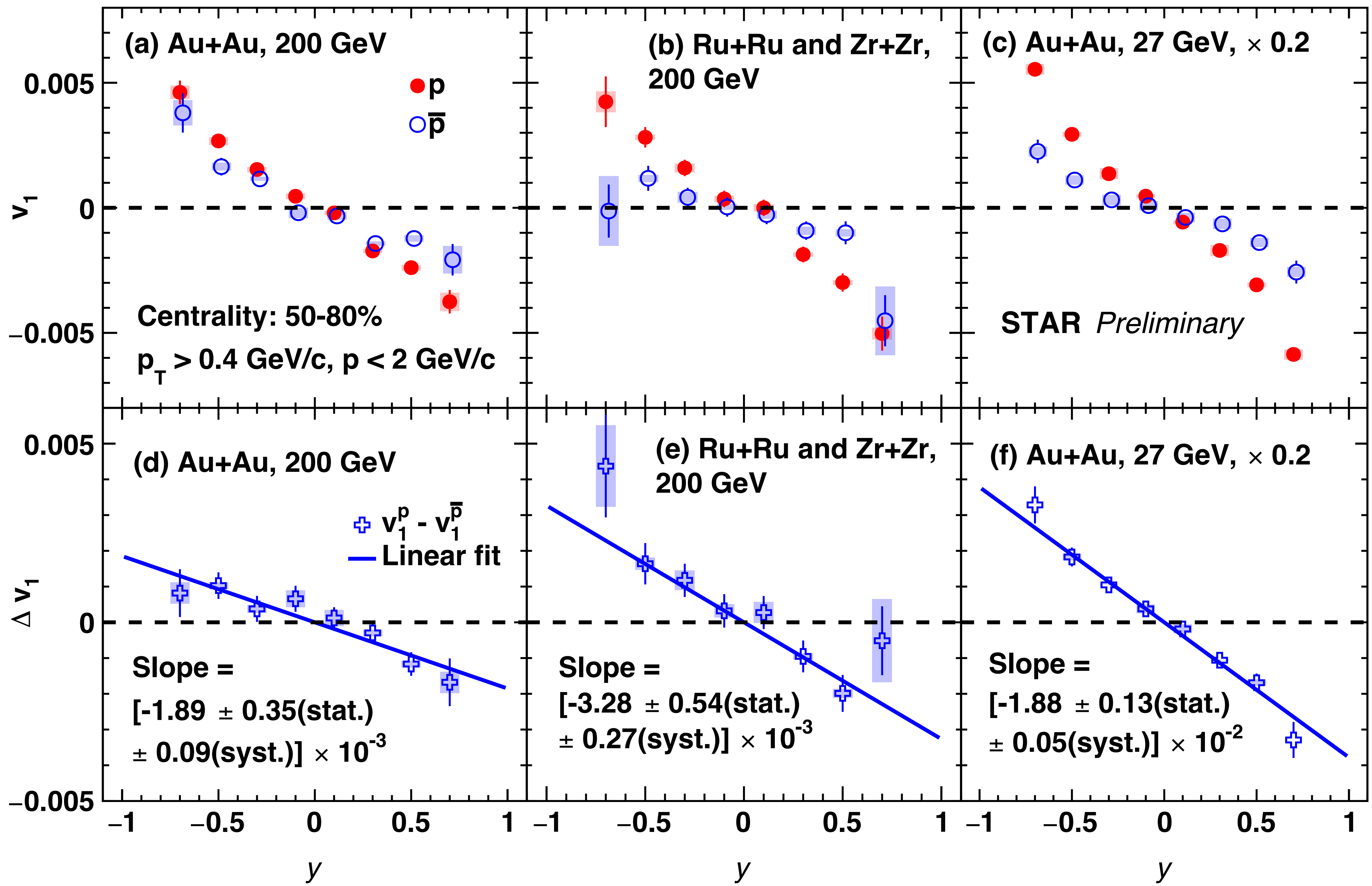


(#d>#u, Au neutron rich)

Neutron Proton

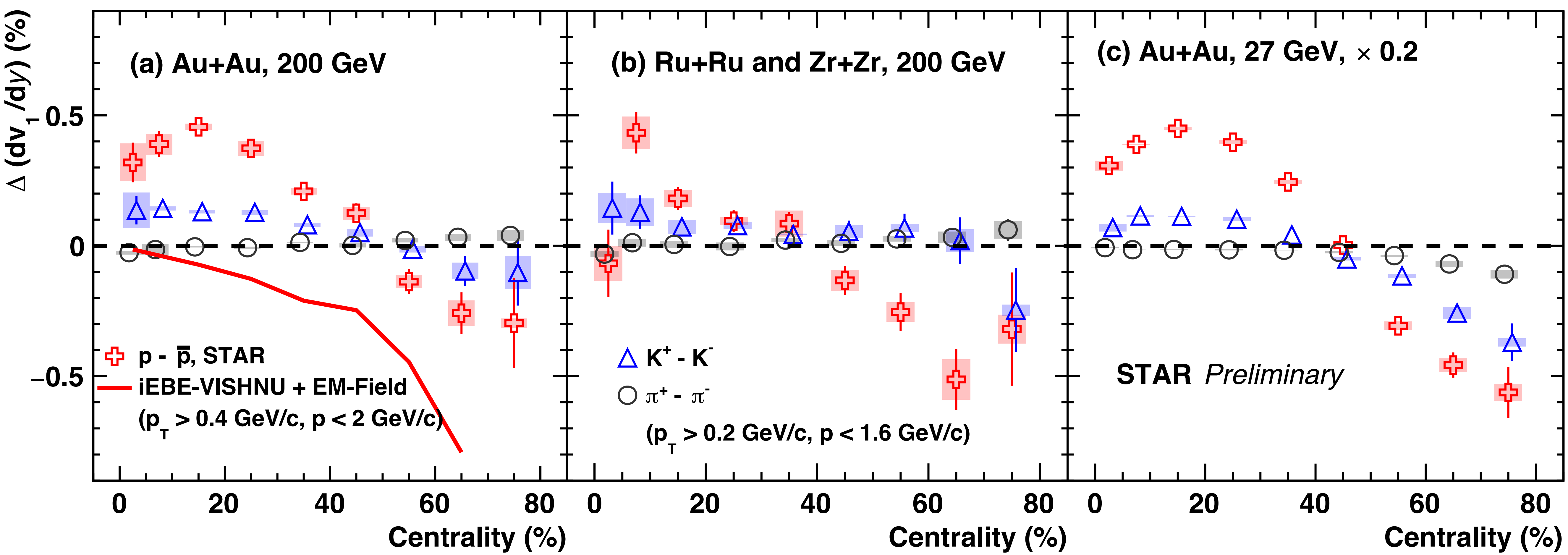
[1] Y. Guo et al., Phys. Rev. C 86, 044901 (2012)
[2] L. Adamczyk et al. (STAR), Phys. Rev. Lett. 112, 162301 (2014)
[3] U. Gursoy et al. Phys. Rev. C 98, 055201 (2018)
[4] U. Gursoy et al. Phys. Rev. C 89, 054905 (2014)

III. Charge splitting of v_1 in 50-80% A+A collisions



- First observation of negative $\Delta dv_1/dy$ between p and $\bar{p}$ in all the systems(energies) with significance larger than 5σ, which can not be explained by transported quarks.
- ~5 times larger in lower energy, which could be the longer lifetime of magnetic field.

IV. Charge splitting of v_1 as a function of centrality



iEBE-VISHNU + EM-Field: U. Gursoy et al. Phys. Rev. C 98, 055201 (2018)

- ☑ Decreasing trend of $\Delta dv_1/dy$ as a function of centrality.
- ☑ Negative $\Delta dv_1/dy$ in peripheral, which is consistent with the dominance of Faraday/Coulomb effect.