Observation of the electromagnetic field effect via charge-dependent directed flow in isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV

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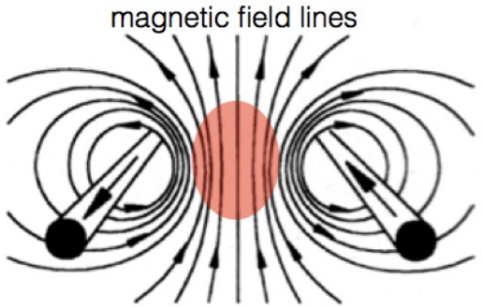
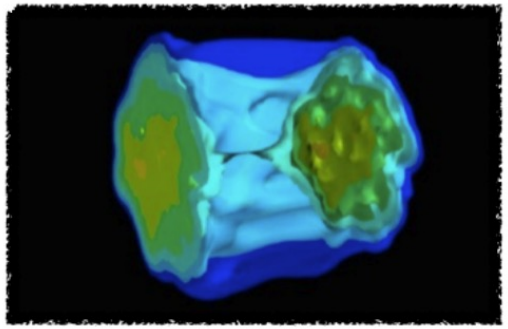
Electromagnetic field in heavy-ion collisions

- An ultra strong magnetic field will be created in heavy-ion collisions ($eB \sim m^2{}_\pi$ at the top RHIC energy)
- we study interaction between the EM field and the QGP medium

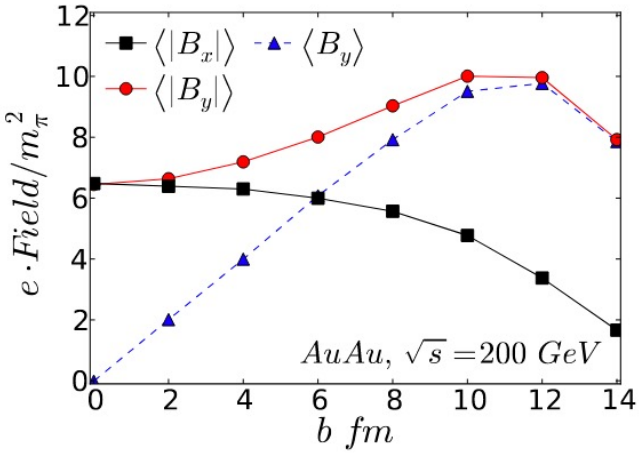




- Two currents in opposite beam direction : Magnetic fields of the two sources add up.

- With this magnetic field, interesting phenomena, such as the Chiral Magnetic Effect (CME) can be observed.

B-field based on on MC Glauber



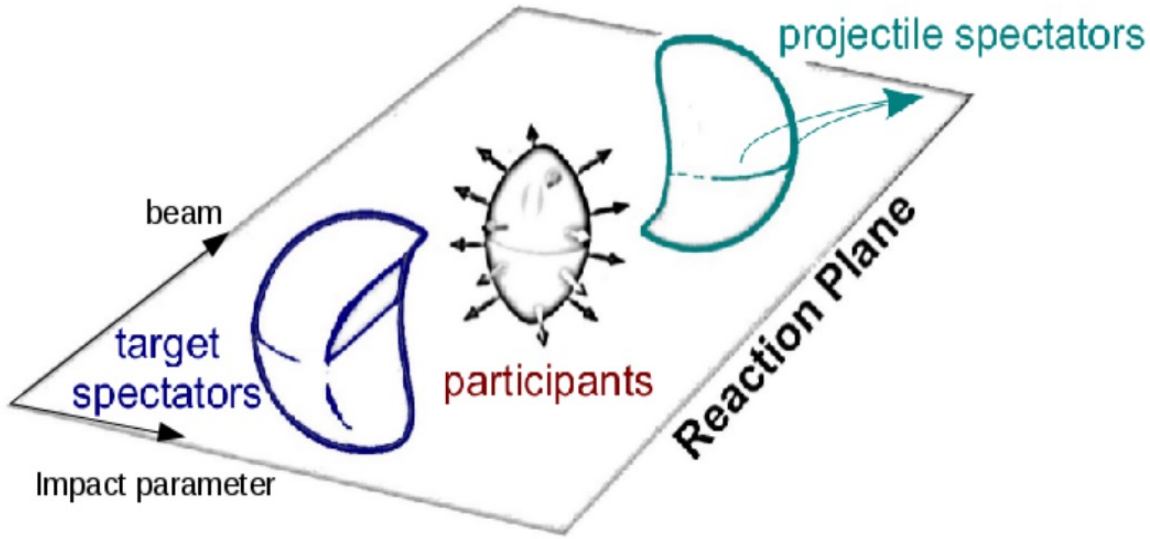
(A. Bzdak and V.S. Phys.Lett. B710 (2012) 171)

Collision geometry and the directed flow

Asymmetry in coordinate space converts into momentum asymmetry with respect to the symmetry plane due to interaction,

$$\frac{dN}{d\phi} = \frac{1}{2\pi}[1+2\sum_{n=1}^{\infty} v_n \cos(n(\phi-\Psi_s))] \longrightarrow v_n = \langle \cos(n[\phi-\Psi_s]) \rangle$$

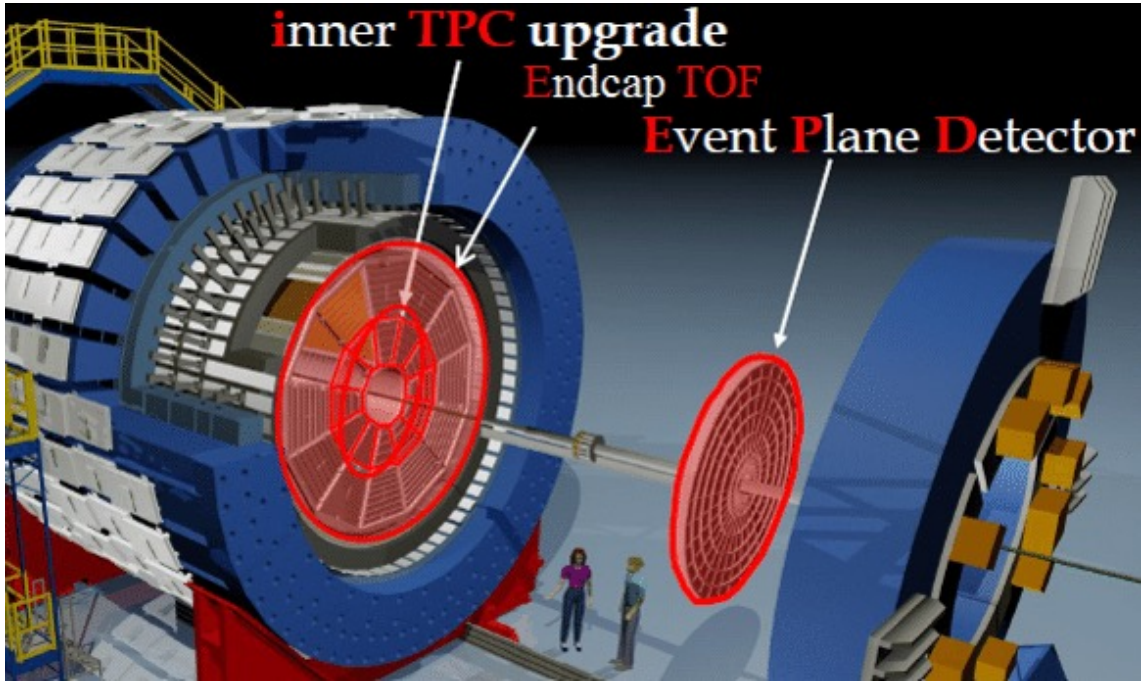
Directed flow: $v_1 = \langle \cos(\phi - \Psi) \rangle$



- Probe early stage of the collisions, where strong EM-field expected.
- 1st order event plane angle measured by Zero Degree Calorimeters (ZDC)
- Here, the rapidity-odd component of v_1 will be reported

Selyuzhenkov and S. Voloshin, PRC 77 (2008), 034904
A.M.Poskanzer, S.A.Voloshin,PRC 58 (1998), 1671-1678

STAR detector

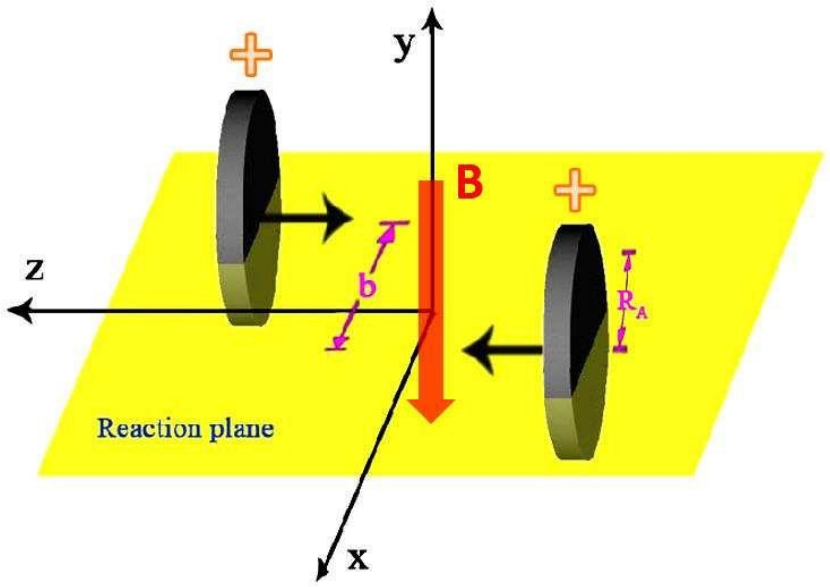


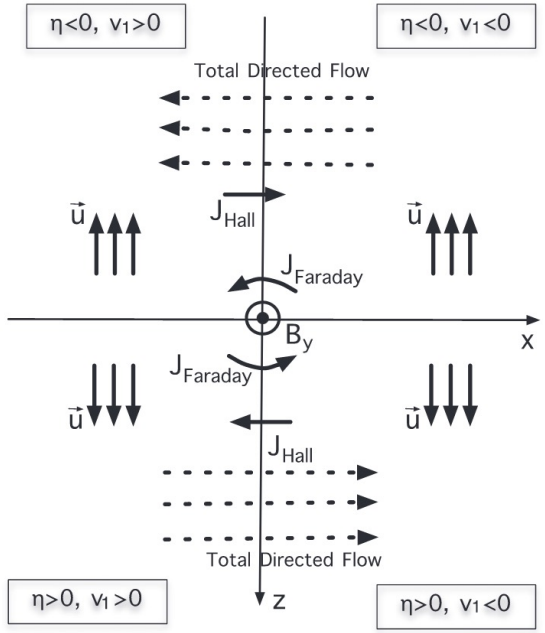
(Journal of Physics: Conference Series 742 (2016) 012022)

- TPC ($|\eta| < 1$, $0 < \phi < 2\pi$) + TOF ($|\eta| < 0.9$) for PID.
- ZDC ($|\eta| > 6.3$) for 1st order event plane reconstruction
- Analyzed data sets : Ru+Ru and Zr+Zr at $\sqrt{s_{NN}}$ = 200 GeV (year-2018)

- The reconstructed event plane distortion from detector non-uniformity and/or beam offset are corrected using the recentering and flattening methods.
- Event plane resolution calculated from correlation between west and east ZDC and used for the correction.

Probing EM-field via charge dependent v_1 splitting





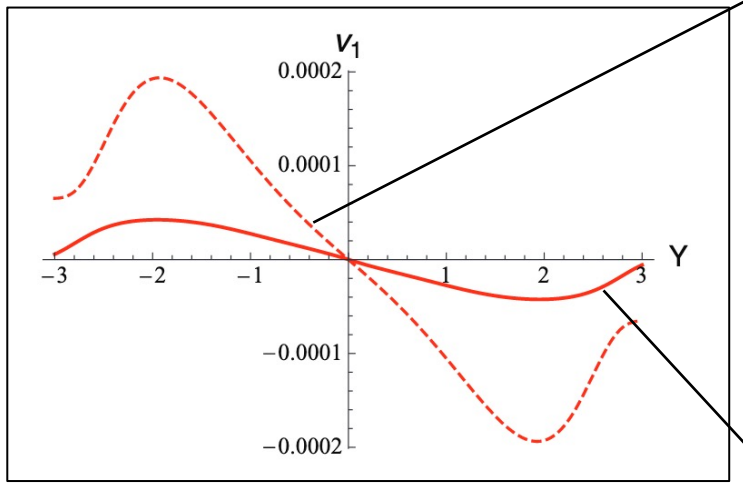
(U. Gürsoy, D. Kharzeev, and K. Rajagopal, Phys. Rev. C 89, 054905 (2014))

- Beam direction: z direction ; Impact parameter: x direction; Reaction Plane: xz
- Magnetic field B to point in the +y direction
- Time varying $\vec{B}$ induces $\vec{E}$ field => Faraday effect
- Expansion velocity, u of the conducting QGP produced in the collision points in the +z (−z) direction.
- Lorentz force results in an electric current perpendicular to both the u and B, akin to the classical Hall effect

Charge dependent v_1 splitting

- Faraday and Hall effects are competing effects - Net effect affects v_1
- If Faraday effect is dominant, $\Delta v_1 = v_1^+ - v_1^-$ decrease a function of rapidity.

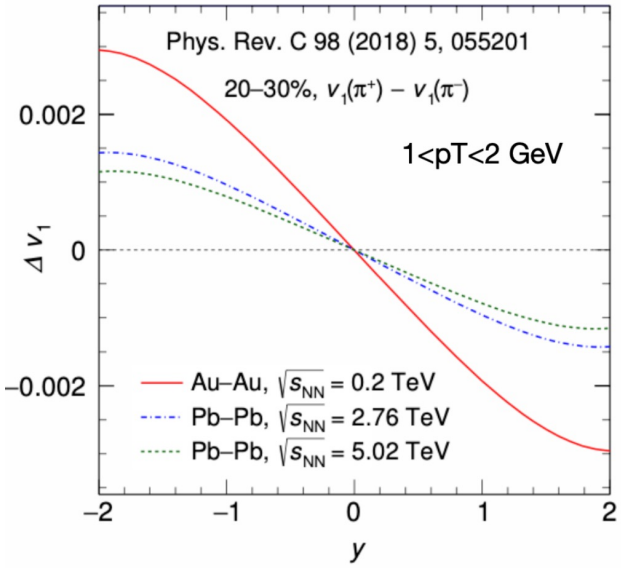
(Positive charged pions)



Turn off the Hall effect, keeping only the Faraday effect

(U. Gürsoy, D. Kharzeev, and K. Rajagopal, Phys. Rev. C 89, 054905 (2014))

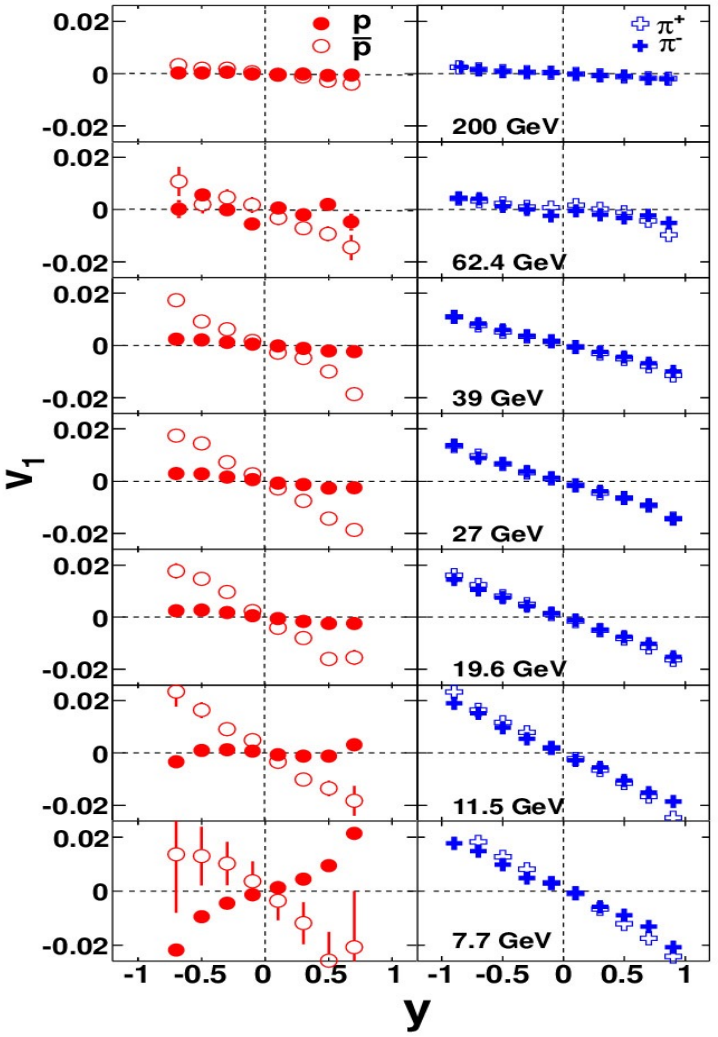
Includes both the Hall and the Faraday effects (Faraday effect is stronger)



- The slope of Au+Au (200 GeV) > Pb-Pb(2.76 TeV) > Pb-Pb (5.02 TeV)

Effect of transported quarks to the charge dependent v_1 splitting

Particle		# transported quark	Sign of v_1	v_1
Proton	p (uud)	3	$v_1^p > 0 \; at \; \eta > 0$	$v_1^p > v_1^{\bar{p}}$ at $\eta > 0$
	$\bar{p}$ ($\bar{u}\bar{u}\bar{d}$)	0	$v_1^{\bar{p}} < 0 \; at \; \eta > 0$	
Kaon	K^+ ($u\bar{s}$)	1	$v_1^{K^+} > 0 \; at \; \eta > 0$	$v_1^{K^+} > v_1^{K^-}$ at $\eta > 0$
	K^- ($\bar{u}s$)	0	$v_1^{K^-} < 0 \; at \; \eta > 0$	
Pion	π^+ ($u\bar{d}$)	1	$v_1^{\pi^+} < 0 \; at \; \eta > 0$	(#d > #u) as Au is neutron rich
	π^- ($d\bar{u}$)	1	$v_1^{\pi^+} < 0 \; at \; \eta > 0$	$v_1^{\pi^-} > v_1^{\pi^+}$ at $\eta > 0$

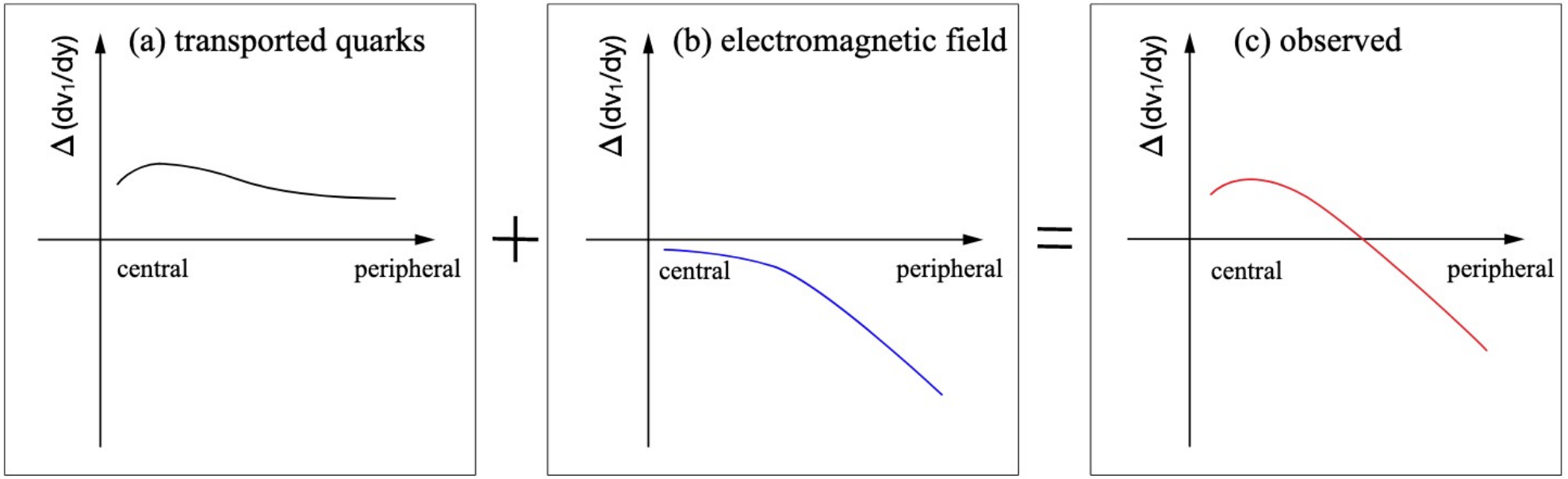


(L. Adamczyk *et al.* (STAR Collaboration) Phys. Rev. Lett. 112, 162301 (2014)

- Transported quarks have different v_1 than the produced
- v_1 splitting can be affected by EM-field and transported quarks

Effect of transported quarks + EM-field to the charge dependent v_1 splitting

Illustration for proton and anti-proton :



Transported quarks have positive dv_1/dy

(Y. Guo et al., Phys. Rev. C 86, 044901 (2012))
(L. Adamczyk et al. (STAR), Phys. Rev. Lett. 112, 162301 (2014))

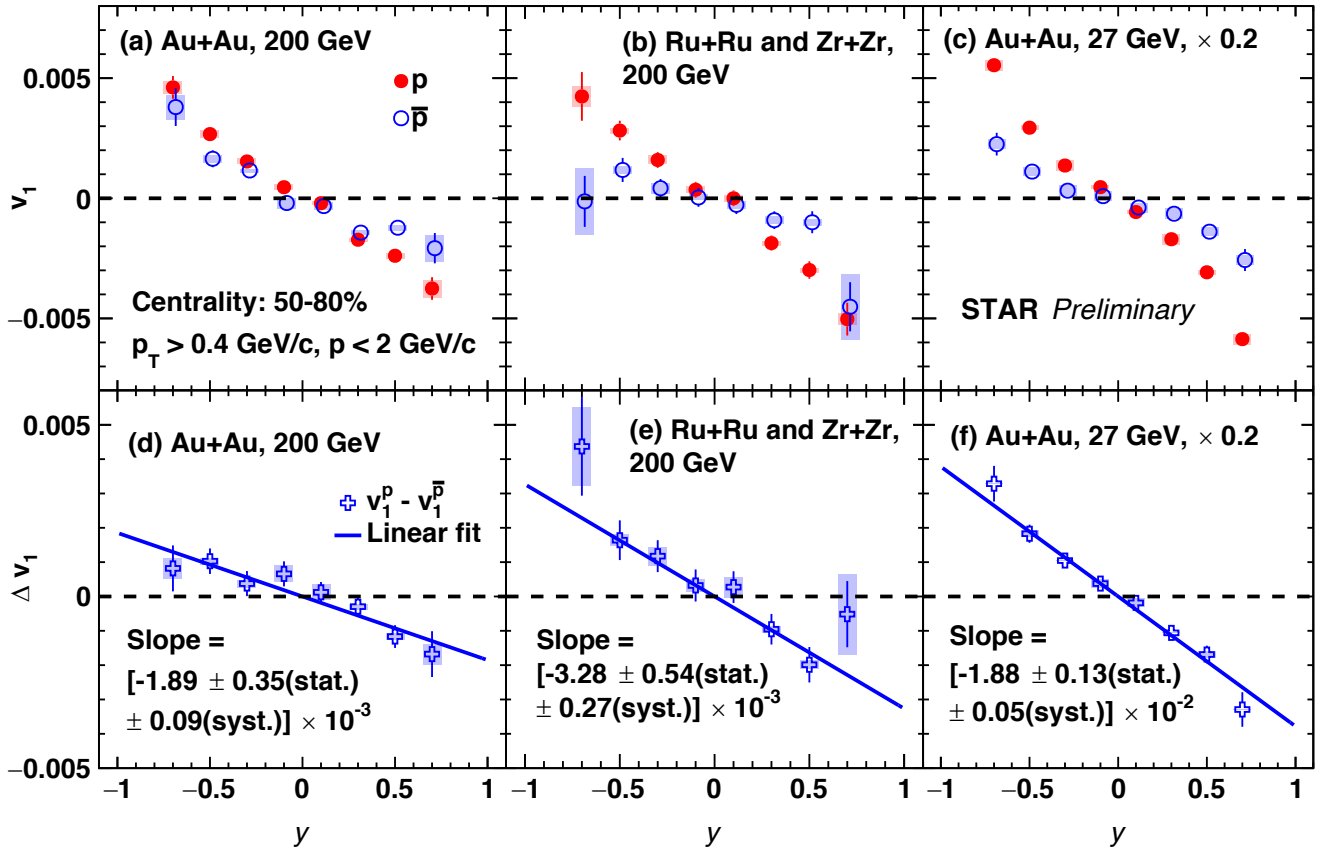
Faraday effect/spectator Coulomb dominate over Hall effect

(U. Gursoy et al. Phys. Rev. C 98, 055201 (2018))
(U. Gursoy et al. Phys. Rev. C 89, 054905 (2014))

$\Delta(dv1/dy) = dv^{+}_1/dy - dv^{-}_1/dy$

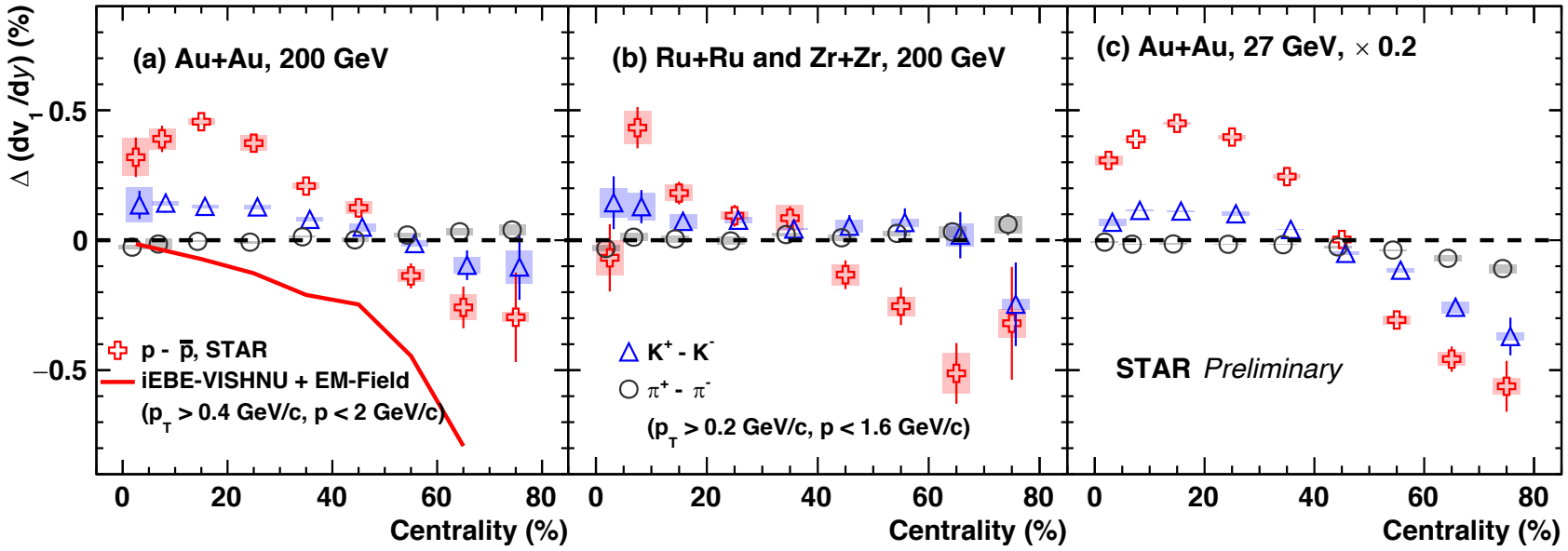
Charge splitting of v_1 in 50-80% A+A collisions

- First observation of negative $\Delta dv_1/dy$ between p and $\bar{p}$ for peripheral collisions
- Significance larger than 5σ
- can not be explained by transported quarks → effect of EM-field ?



- Steeper in lower energy => longer lifetime of magnetic field

Charge splitting of v_1 as a function of centrality



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

- $\Delta dv_1/dy$ is decreasing as a function of centrality for protons.
- Negative $\Delta dv_1/dy$ in peripheral collisions => dominance of Faraday/Coulomb effect.
- The splitting is also observed between K^+ and K^- but is less significant than pions.

Summary

- Charge dependent directed flow provides a probe to EM effect as well as transported quarks.

- $\Delta dv_1/dy$ between protons and anti-protons changes sign from positive value in central collisions to negative value in peripheral collisions

  - ✓ Positive $\Delta dv_1/dy$ in central collisions : transported quark contribution
  - ✓ Significant negative $\Delta dv_1/dy$ in peripheral collisions : dominance of Faraday/Coulomb effect.

- Sign of $\Delta dv_1/dy$ for protons in peripheral collisions consistent with expectation from iEBE-VISHNU + EM-Field model, and consistent with expectation from dominance of Faraday/Coulomb over Hall effect.

Thank you!!