Measurement of system size dependence of directed flow of protons (anti-protons) at RHIC

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Abstract

The directed flow (v_1) is a sensitive probe of the initial state conditions in heavy ion collisions. One key initial condition is the presence of a strong electromagnetic field, which induces charge splitting between particles and antiparticles and has important implications for the QCD phase transition and the properties of the Quark-Gluon Plasma (QGP) [1]. Another crucial aspect of the initial state is the deposition of baryon, which can be specifically probed through the directed flow, offering insights into baryon transport within the QGP [2]. In this work, we shall present measurements of directed flow (v_1) for $\pi^{\pm}$, $K^{\pm}$ and p($\bar{p}$) in Au+Au, isobar (Ru+Ru, Zr+Zr) collisions at $\sqrt{s_{NN}}$ = 200 GeV, and U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV, as recorded by the STAR experiment at RHIC. For the first time, we observe a clear system size dependence in the slope, dv_1/dy, for p($\bar{p}$) and the difference in slope between particle and antiparticle, $\Delta(dv_1/dy)$, while the sum of the slopes for baryons (p + $\bar{p}$) shows no dependence. In contrast, neither the difference nor the sum of the v_1 slopes for mesons ($\pi^{\pm}$, $K^{\pm}$) shows system size dependence [3]. This behavior is qualitatively reproduced by a hydrodynamic model, providing insights into baryon deposition and transport. Additionally, the observed $\Delta(dv_1/dy)$ pattern across different systems may also help constrain the strength of electromagnetic fields and the conductivity of the medium.

Electromagnetic Field Effects on v_1

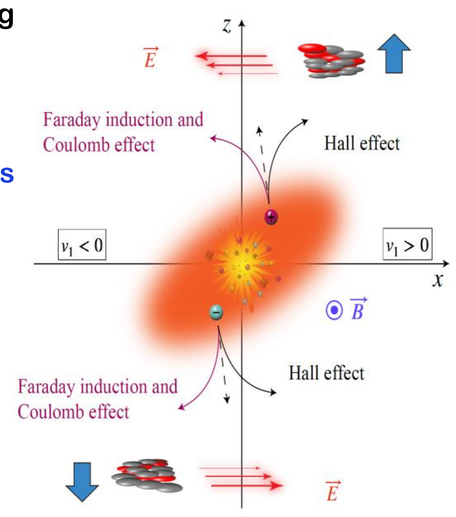
In the expanding QGP, quarks experience following electromagnetic effects:

- **Hall Effect:** F = q (v x B) by Lorentz Force
- **Coulomb Effect:** E by spectator nucleons
- **Faraday Induction:** decreasing B as spectators fly away

These electromagnetic forces provide opposite contribution of v_1 to particles with opposite charges, resulting a net current flowing in the medium (QGP) given as:

$$I_{(total)} = I_{(Hall)} + I_{(Faraday)}$$

Directed Flow (v_1)



The splitting of v_1 between particle and antiparticle is measured as Δv_1, the difference in v_1 slope between positively and negatively charged particles, and is written as:

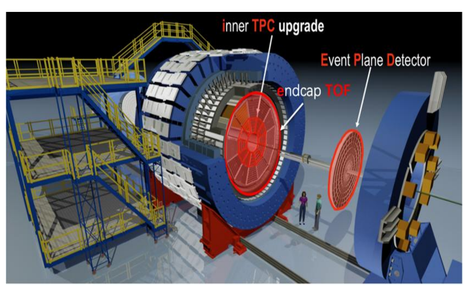
$$\Delta v_1 = (dv_1^+/dy - dv_1^-/dy)$$

Baryon Transport Effects on v_1

In central collisions, where the electromagnetic field strength is negligible, the inclusion of electromagnetic field effects does not influence the splitting between protons and anti-protons. This suggests that the observed system size dependence of $\Delta(dv_1/dy)$ for protons in central collisions arises solely from enhanced baryon stopping in larger collision systems. However, in semi-central and peripheral collisions, both baryon diffusion and electromagnetic field effects contribute to the Δv_1 splitting [2].

The STAR Experiment

- Solenoidal Tracker at RHIC (STAR) is a multipurpose detector with full (2π) azimuthal coverage and wide acceptance ($|\eta| < 1.5$)
- The EPD and ZDC detectors are used for event plane reconstruction in STAR, EPD ($2.1<|\eta|<5.1$) and ZDC-SMD($|\eta|>6.3$)
- **Excellent Particle Identification:**
  - ✓ Tracking of charged particles using TPC
  - ✓ Momentum reconstruction using TPC
  - ✓ Energy loss (dE/dx) using TPC
  - ✓ mass square information using TOF



Methodology

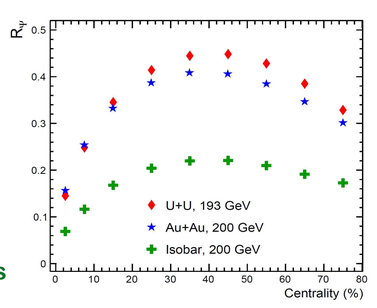
Directed Flow (v_1) is the first harmonic flow coefficient in the Fourier expansion of Azimuthal distributions of produced particles with respect to reaction plane. It describes the collective sideward motion of the produced particles and nuclear fragments, and carries information from the early stages of collision.

$$v_1 = \langle \cos(\phi - \Psi_1^{EP}) / R\{\Psi_1^{EP}\} \rangle$$

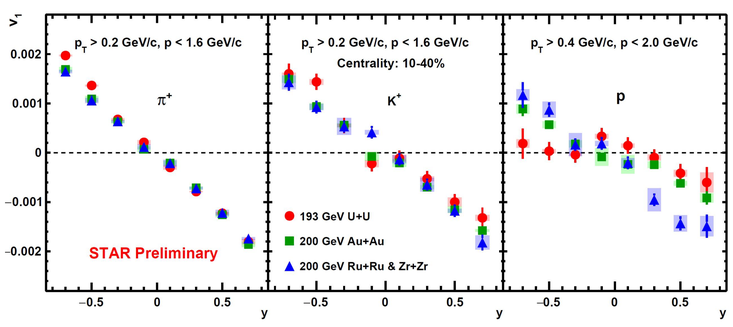
Where, ϕ is the azimuthal angle of the outgoing particles, Ψ_1^{EP} is event plane azimuthal angle reconstructed using ZDC detector and R represents the event plane resolution.

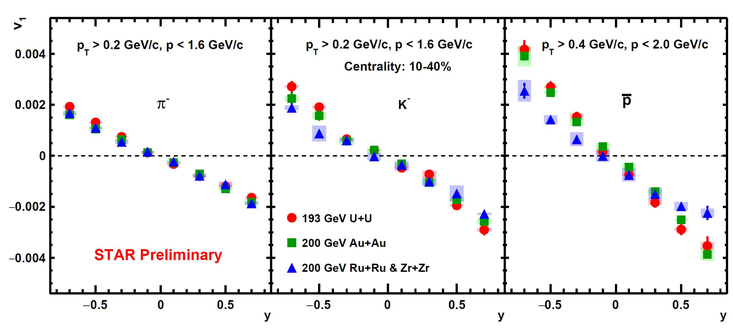
Event-Plane (EP) method is used to compute v_1 in which we estimate the reaction plane, called the event plane, from the observed event plane angle determined from the anisotropic flow itself. Basically, the analysis is carried out in four steps:

1- Datasets and Events Selection
2- Event Plane reconstruction
3- Particle Identification: π, k, p ---- TPC & TOF cuts
4- Directed Flow (v_1) extraction

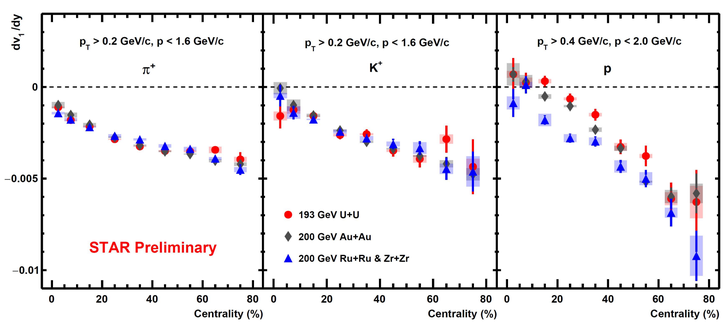


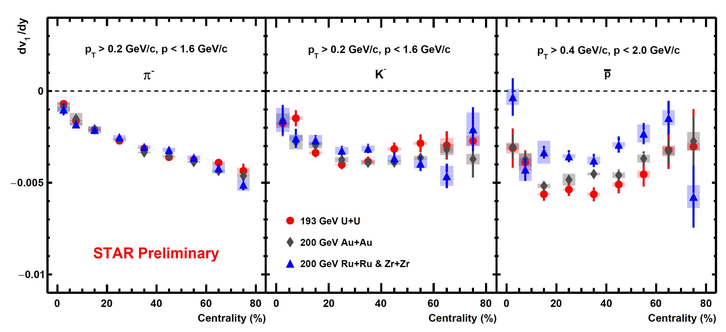
Rapidity dependence: $v_1(y)$



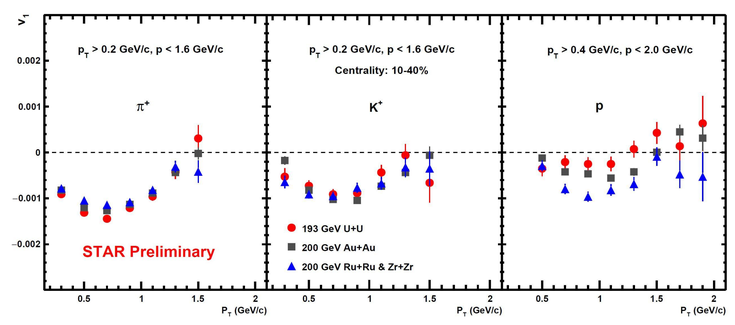


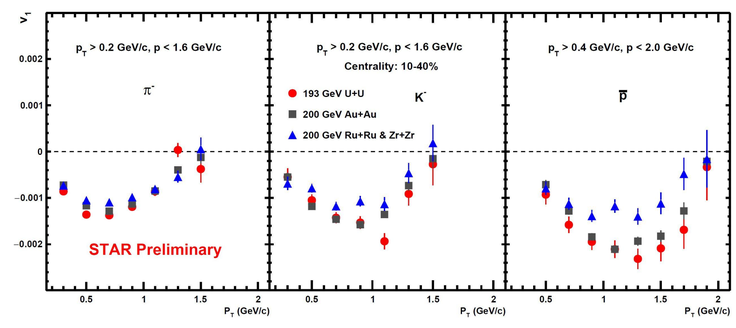
Centrality Dependence of Slope (dv_1/dy)





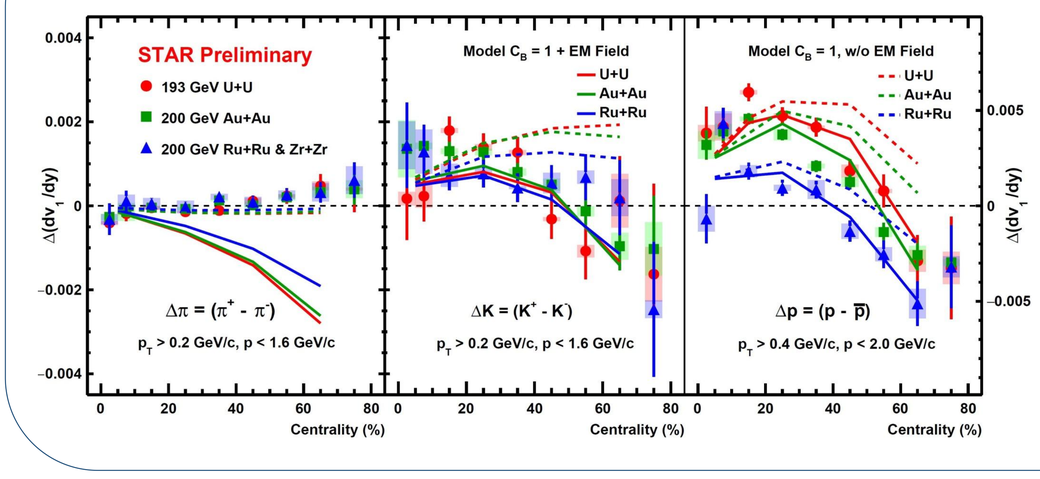
p_T dependence: $v_1(pt)$





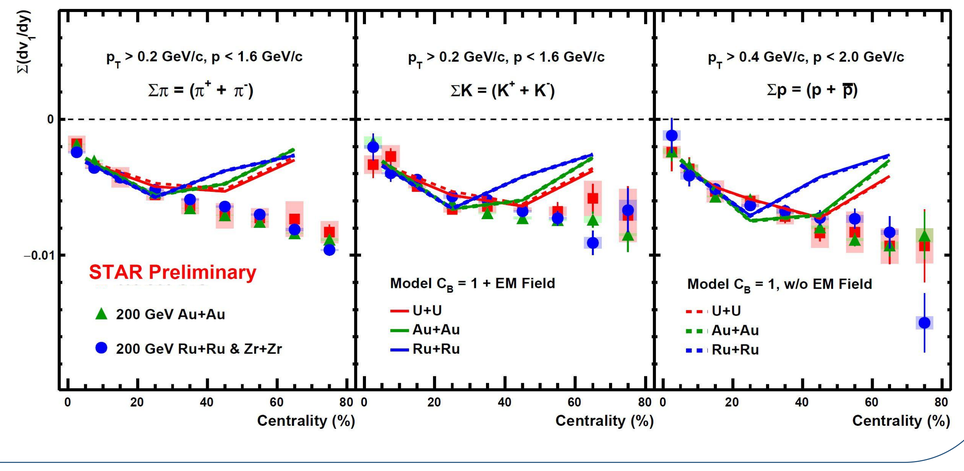
❖ **Slope (dv_1/dy):** (a) No system size dependence for mesons ($\pi^{\pm}$, $K^{\pm}$) among the three different collision systems
(b) For protons the magnitude of the slope of the isobar > AuAu > UU and the ordering of the slopes is opposite for antiproton

$\Delta(dv_1/dy)$ and $\Sigma(dv_1/dy)$ for U+U, Au+Au & Isobar Collisions



❖ **$\Delta(dv_1/dy)$:**
- ➢ pions → Isobar ~ Au+Au ~ U+U
- ➢ kaons → Isobar ~ Au+Au ~ U+U
- ➢ protons → U+U > Au+Au > Isobar

❖ **$\Sigma(dv_1/dy)$:**
- ➢ pions → Isobar ~ Au+Au ~ U+U
- ➢ kaons → Isobar ~ Au+Au ~ U+U
- ➢ protons → Isobar ~ Au+Au ~ U+U



Summary

- ➢ We observed a system size dependent v_1 and $\Delta(dv_1/dy)$ for protons (antiprotons) among three different collision systems at similar collision energy.
- ➢ However, the v_1 of mesons ($\pi^{\pm}$, $K^{\pm}$) as well as total baryons (p + $\bar{p}$) are found to be independent of system size (consistent with previous findings at RHIC).
- ➢ These results help to understand baryon deposition (baryon stopping mechanism) in heavy-ion collisions and provide strong constraint on baryon transport.
- ➢ A hydrodynamic model with baryon transport combined with electromagnetic field and medium conductivity (σ = 0.023 fm^{-1}) can explain the system size dependence of kaon and proton delta dv_1/dy [2].

References

1. STAR Collaboration, Phys. Rev. X 14, 011028
2. T. Parida et al. arXiv: 2305.08806, 2503.04660
3. STAR Collaboration, Phys. Rev. Lett. 101, 252301

The STAR Collaboration

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