Recent results on directed flow measurements in Cu+Au and Au+Au collisions at RHIC

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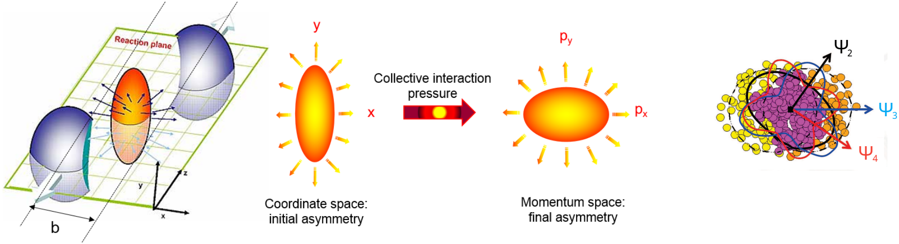
Introduction

- Immadiately after an A+A collision, the overlap region defined by the nuclear geometry is almond shaped, with shortest axis along the impact parameter vector.
- Multiple interactions between particles in the evolving system change the initial coordinate space asymmetry into final momentum space asymmetry.



The observed anisotropy is usually expressed as a Fourier series expansion in azimuthal angle ϕ of produced particles:

$$E\frac{\mathrm{d}^3N}{\mathrm{d}p^3} = \frac{1}{p_\mathrm{T}}\frac{\mathrm{d}^3N}{\mathrm{d}\phi\,\mathrm{d}p_\mathrm{T}\,\mathrm{d}y} = \frac{1}{2\pi p_\mathrm{T}}\frac{E}{p}\frac{\mathrm{d}^2N}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}\eta}\left(1+2\sum_{n=1}^{\infty}\mathrm{v}_n(p_\mathrm{T},\eta)\cos\left(n(\phi-\Psi_n)\right)\right)$$

Ψ_n – azimuthal angle of the n-th order symmetry plane of the initial geometry,
$\mathrm{v}_n \equiv \langle \mathrm{e}^{in(\phi-\Psi_n)}\rangle = \langle\cos n(\phi-\Psi_n)\rangle$ - magnitude of the n-th flow harmonics.

Flow harmonics

- The v_n coefficients characterize quantitatively the event anisotropy. Each term in the series corresponds to a different harmonic flow:

  $\mathbf{v_1}$ - directed flow, is the consequence of momentum conservation,
  $\mathbf{v_2}$ - elliptic flow, arises from the initial geometry of the overlap zone,
  $\mathbf{v_3}$ - triangular flow (and also higher flow harmonics) are due to fluctuations in collisions and colliding nuclei.

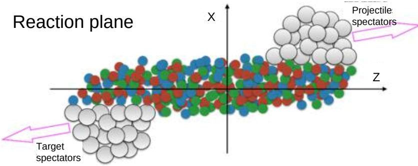
- Elliptic flow is well described (for $p_{\mathrm{T}} < 2$ GeV) by viscous hydrodynamic models with extremaly small ratio shear viscosity to entropy density, η/s.
- Higher harmonic flow coefficients provide additional constraints on QGP models and on the initial conditions in HI collisions.
- There exist no single model that satisfactorily explains the directed flow dependencies on centrality, collsion energy, system size, rapidity, p_{T}, and on particle type.
- This clearly indicates that an important piece in our picture of ultrarelativistic collisions is still missing, and better understanding of the directed flow may affect many conclusions made solely on the elliptic flow measurements, as the initial conditions that would be required for its satisfactory description could lead to stronger or weaker elliptic flow.
- As the directed flow originates in the initial-state spatial and momentum asymmetries in the transverse plane, it might be intimately related to the vorticity in the system.

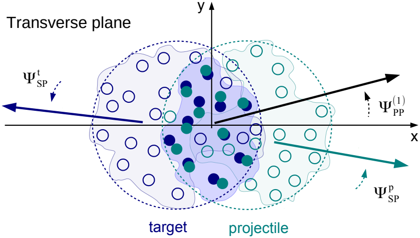
Flow harmonics and symmetry planes

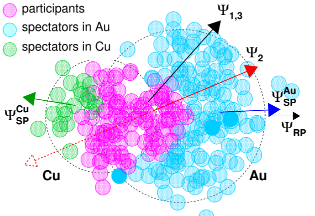
- In an ideal case the angles Ψ_n correspond to the reaction plane angle Ψ_{RP}. In practice they can differ and depend on n.

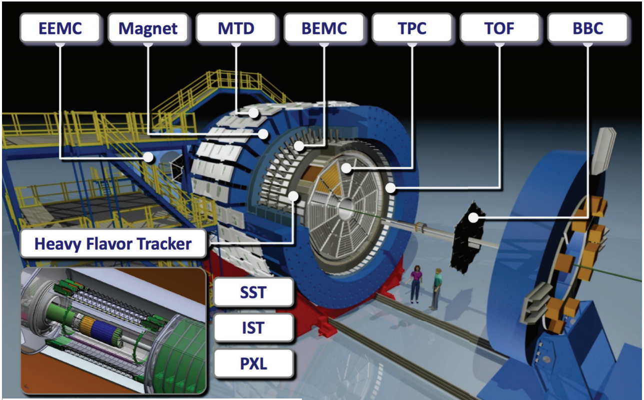
- Because of event-by-event fluctuations in the initial energy density of the collision one usualy defines other symmetry planes:
  - projectile (Ψ^p_{SP}) and target (Ψ^t_{SP}) spectator angles – defined by the projectile and target spectators, respectively.
  - participant plane angle (Ψ_{PP}) – defined by dipol asymmetry of the initial energy density,
  - fluctuations leading to a dipol asymmetry in the transverse plane lead to nonzero directed flow i.e. dipole flow, even at midrapidity. The direction (azimuthal angle) of the dipole asymmetry Ψ_1^{dipole} can be approximated by

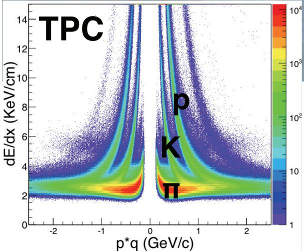
$$\Psi_{1,3} = \operatorname{arc\,tg}\left(\langle r^3 \sin\phi\rangle / \langle r^3 \cos\phi\rangle\right) + \pi$$

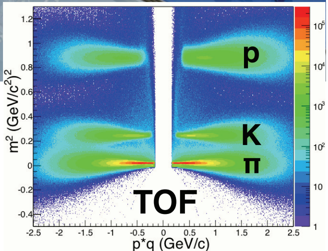






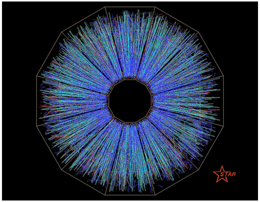






STAR detector

- TPC: dE/dx, L



- ToF: measures $\beta = \frac{L}{ct}$, $m^2c^2 = p^2\left(1/\beta^2 - 1\right)$
- TPC and ToF coverage: $|\eta| < 1,\ 0 < \phi < 2\pi$
- BBC: Scintilator tiles located at $3.3 < |\eta| < 5$
- ZDC-SMD: Calorimeters located at $z = \pm 18$ m from IP, with position detectors inserted between the modules.

Event plane determination and resolution

- Use event plane angles $\psi_n^{\rm obs}$ as estimates of the angles Ψ_n (PRC 58 (1998) 1671).
- Define the components of the event flow vector Q_n as:

$$Q_{n,x} = \sum_i w_i \cos(n\phi_i) = Q_n \cos(n\psi_n^{\rm obs}), \quad Q_{n,y} = \sum_i w_i \sin(n\phi_i) = Q_n \sin(n\psi_n^{\rm obs})$$

where w_i is the weight for particle i ($p_{\rm T}, E_{\rm T}$ or ADC depending on the detector used).

- The event plane angle from Q_n reads: $\psi_n^{\rm obs} = \frac{1}{n} \operatorname{arc\,tg}\left(\frac{Q_{n,y}}{Q_{n,x}}\right)$
- The first-order event plane for v_1 is obtained from ZDC-SMD as follows:

$\langle S\rangle = \sum_i S_i w_{S_i} / \sum_i w_{S_i}$ where $S \equiv X, Y$

$\psi_1^{\rm obs} = \operatorname{arc\,tg}(\langle Y\rangle/\langle X\rangle)$

- Define event plane resolution as:

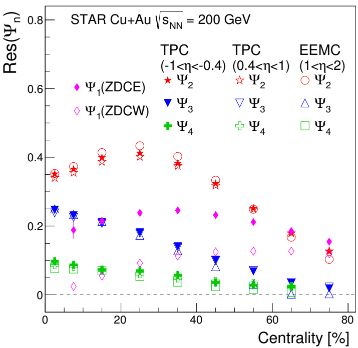
$\mathrm{Res}\{\psi_n^{\rm obs}\} = \langle\cos n(\psi_n^{\rm obs} - \Psi_{\rm RP})\rangle$

- Event plane resolution from 2 subevent method:

$\mathrm{Res}\{\psi_n^{A(B)}\} = \sqrt{\langle\cos(n(\psi_n^A - \psi_n^B))\rangle}$

- Event plane resolution from 3 subevent method:

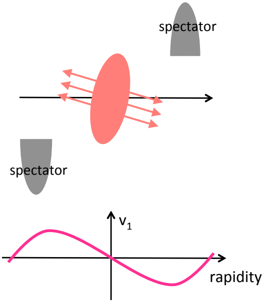
$$\mathrm{Res}\{\psi_n^A\} = \sqrt{\frac{\langle\cos n(\psi_n^A - \psi_n^B)\rangle\langle\cos n(\psi_n^A - \psi_n^C)\rangle}{\langle\cos n(\psi_n^B - \psi_n^C)\rangle}}$$



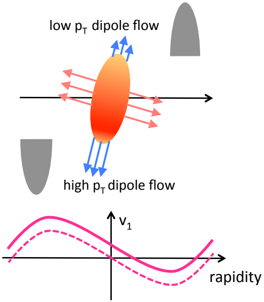
Origin of the directed flow

- In hydrodynamic models, the rapidity dependence of v_1 is reproduced through "tilted" source initial conditions: $\mathrm{v}_1(p_\mathrm{T})$ is a monotonic function of p_T and dependence of $\langle p_x \rangle(\eta) \equiv \langle p_\mathrm{T} \cos(\phi - \Psi_1) \rangle$ is directly related to $\mathrm{v}_1(\eta)$.
- Additional contribution to v_1 might come from dipol-like pressure gradients, with the sign of the average contribution to v_1 determined by low p_T particles.
- Difference in the number of participants in the projectile and target nuclei leads to a shift of the position of the centre-of-mass of participating nucleons - this results in the shape of $\mathrm{v}_1(\eta)$ to stay mostly unchanged but the entire $\mathrm{v}_1(\eta)$ curve be shifted in the direction of rapidity where more participants move.

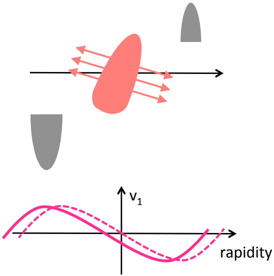
Tilted source (TS)



TS + asymmetric density gradient

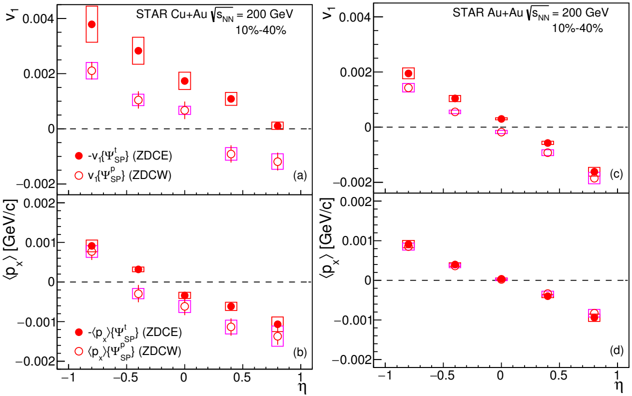


TS + asymmetric participants



Directed flow of unidentified hadrons

- Measurement of v_1 of charged particles as a function of pseudorapidity with respect to target and projectile spectator planes.
- Use of event plane method to obtain $\mathrm{v}_1 = \dfrac{\langle \cos(\phi - \psi_1^{\mathrm{obs}}) \rangle}{\mathrm{Res}(\Psi_1)}$
- Projectile spectators deflect on average along the impact parameter vector.
- The sign of v_1 measured with respect to the target spectator plane has been reversed.
- A finite difference is seen between v_1 measured with respect to each spectaror plane.



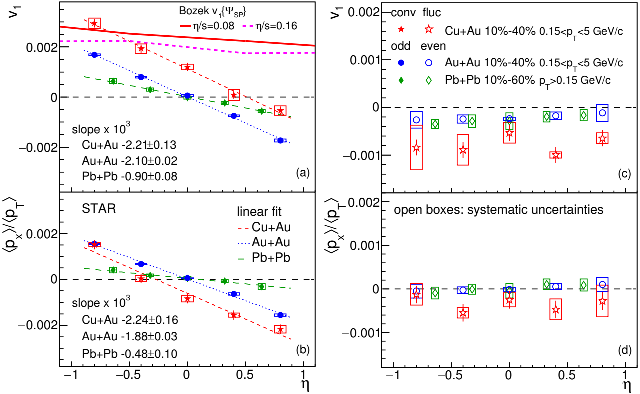
- This indicates existence of a fluctuation (or rapidity even for Au+Au) component of v_1 in both symmetric and asymmetric collision systems.
- Mean p_{T} projected onto the spectator plane:

$$\langle p_x \rangle = \frac{\langle p_{\mathrm{T}} \cos(\phi - \psi_1^{\mathrm{obs}}) \rangle}{\mathrm{Res}(\Psi_1)}$$

- Small difference is seen between results with two spectator planes in Cu+Au.

Conventional and *fluctuation* components of v_1

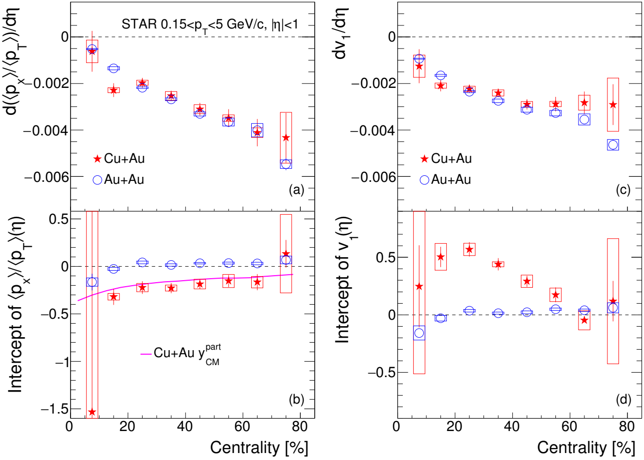
- For a nonfluctuating nuclear matter distribution, the directed flow in the participant zone develops along the impact parameter direction.
- In symmetric collisions v_1 is an antisymmetric function of rapidity: $v_1^{odd}(\eta) = -v_1^{odd}(-\eta)$
- Due to EbyE fluctuations in the initial energy density, the directed flow can develop a rapidity-symmetric component, $v_1^{even}(\eta) = v_1^{even}(-\eta)$, which does not vanish at $\eta = 0$.
- Define: $v_1^{odd} = \frac{1}{2}\left(v_1\{\Psi_{SP}^{p}\} - v_1\{\Psi_{SP}^{t}\}\right), \quad v_1^{even} = \frac{1}{2}\left(v_1\{\Psi_{SP}^{p}\} + v_1\{\Psi_{SP}^{t}\}\right)$
- Different nomenclature in asymmetric collisions: odd $\rightarrow$ conv; even $\rightarrow$ fluc



- $v_1 = v_1^{odd(conv)} + v_1^{even(fluc)}$
- The v_1^{conv} in Cu+Au has a similar slope to v_1^{odd} in Au+Au, with intercept shifted to forward direction
- $v_1^{even(fluc)}$ not depend on η, with absolute values larger in Cu+Au than in Au+Au, due to larger initial density fluctuations.
- Behaviour of $\langle p_x\rangle/\langle p_T\rangle$ is similar to that of v_1.

Centrality dependence of slopes and intercepts

- Similar slopes of v_1 and $\langle p_x\rangle/\langle p_\mathrm{T}\rangle$ are expected for a tilted source models.
- The intercepts of $\langle p_x\rangle$ follow very closely the shift in rapidity of the center of mass of the system, $y_{CM} \approx \frac{1}{2}\ln\left(N_\mathrm{part}^\mathrm{Au}/N_\mathrm{part}^\mathrm{Cu}\right)$, from Glauber simulation.
- Centrality dependence of the difference in v_1 and $\langle p_x\rangle$ intercepts is mostlly determined by the decorrelation between the dipole flow direction $\Psi_{1,3}$ and the spectator planes.



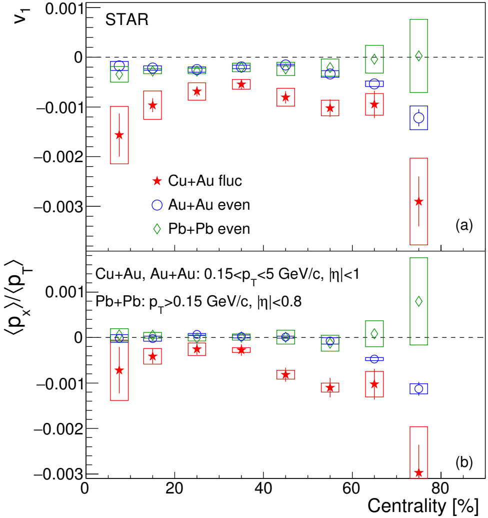
- In tilted source scenario the slope of $\langle p_x\rangle/\langle p_\mathrm{T}\rangle$ is expected to be 50% larger than the slope of v_1.
- Relative contribution from the source tilt is about 2/3 at the top RHIC collision energy:

$$r = \frac{(d\mathrm{v}_1/d\eta)^\mathrm{tilt}}{d\mathrm{v}_1/d\eta} \approx \approx \frac{2}{3}\frac{(1/p_\mathrm{T})(d\langle p_x\rangle/d\eta)}{d\mathrm{v}_1/d\eta}$$

and decreasing to about 1/3 at the LHC energy.

Centrality dependence of even (fluc) components

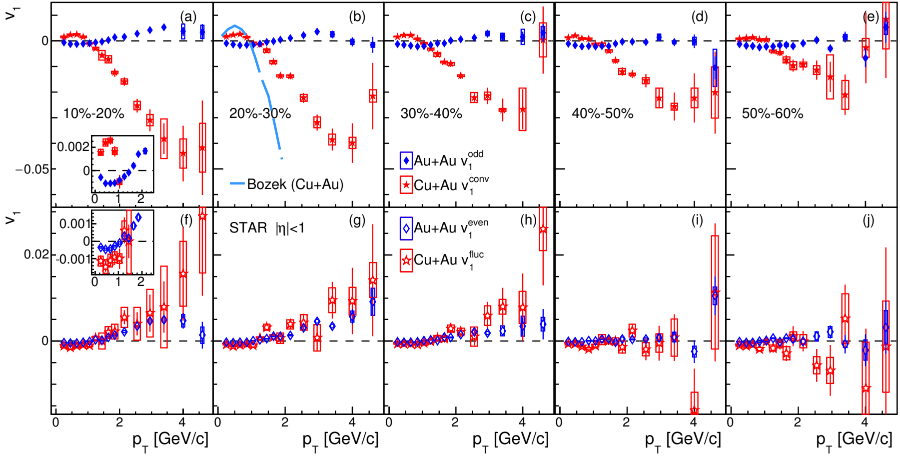
- The of v_1^{even} for Au+Au and Pb+Pb have a weak centrality dependence and are consistent except in most peripheral collisions.



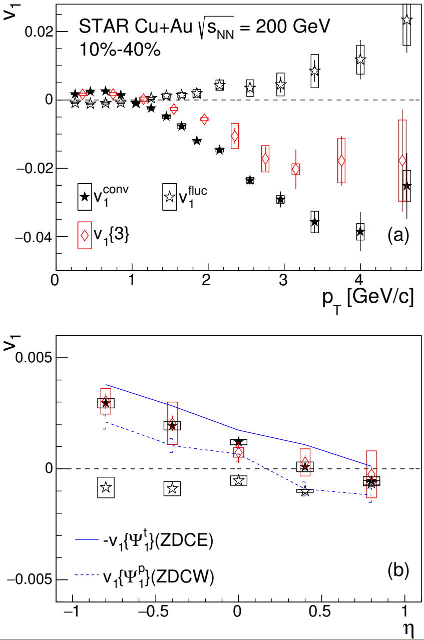
- $\langle p_x^{\mathrm{even}} \rangle$ in both Au+Au and Pb+Pb are consistent with zero - this may suggest that the dipole-like fluctuations in initial state have little dependence on system size and collision energy.
- v_1^{fluc} and $\langle p_x^{\mathrm{fluc}} \rangle$ for Cu+Au has a larger magnitude than in symmetric collisions over entire centrality range.

Dependence of the directed flow on transverse momentum

- The $v_1^{\rm conv}$ in Cu+Au collisions exhibits a sign change around $p_{\rm T} = 1$ GeV and its magnitude at both low and high $p_{\rm T}$ becomes smaller for peripheral collisions.
- Similar $p_{\rm T}$ and centrality dependencies (although with opposite sign) are observed in $v_1^{\rm fluc}$
- The signal of both $v_1^{\rm odd}$ and $v_1^{\rm even}$ in Au+Au are smaller than in Cu+Au but, at least in central collisions, they still show the sign change in the $p_{\rm T}$ dependence.



Directed flow from three point correlator



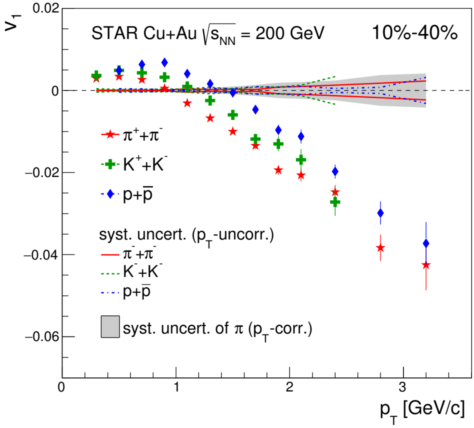
- Directed flow can be also measured with three point correlator (PRC 72, 014904 (2005)):

$$\mathrm{v}_1\{3\} = \frac{\langle \cos\phi + \psi_1^{\mathrm{obs}} - 2\psi_2^{\mathrm{obs}} \rangle}{\mathrm{Res}(\Psi_1) \times \mathrm{Res}(\Psi_2)}$$

  where ψ_1^{obs} and ψ_2^{obs} were taken from different subevents and ϕ is azimuthal angle of particles in rapidity region different from those subevents.
- $\mathrm{v}_1\{3\}$ does not use spectator planes and helps to partly remove non-flow effects.
- $\mathrm{v}_1\{3\}$ is consistent with $\mathrm{v}_1^{\mathrm{conv}}$ for $p_{\mathrm{T}} < 1$ GeV, but becomes greater for $1 < p_{\mathrm{T}} < 4$ GeV.
- $\mathrm{v}_1\{3\}$ includes both conventional and fluctuation components of v_1.
- The "conv" component in $\mathrm{v}_1\{3\}$ should be the same as measured by event plane method, but the "fluc" component might be different due to different correlations of the spectator and participant planes with $\Psi_{1,3}$.

Directed flow of identified hadrons

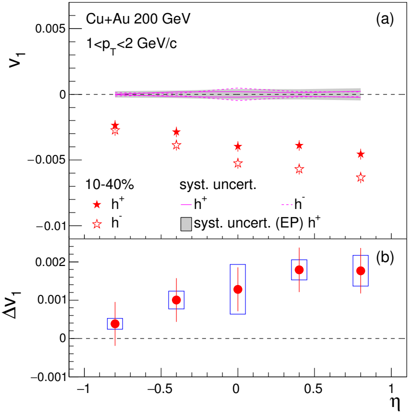
- Directed flow of pions, kaons and (anti)protons measured with respect to the target (Au) spectator plane ($\mathrm{v}_1 = -\mathrm{v}_1\{\Psi^t_{\mathrm{SP}}\}$).
- For $p_\mathrm{T} < 2$ GeV there is clear particle type dependence reflecting the effect of particle mass in interplay of the radial and directed flow.
- Not so clear particle type dependence for $p_\mathrm{T} > 2$ GeV due to the large uncertainties.

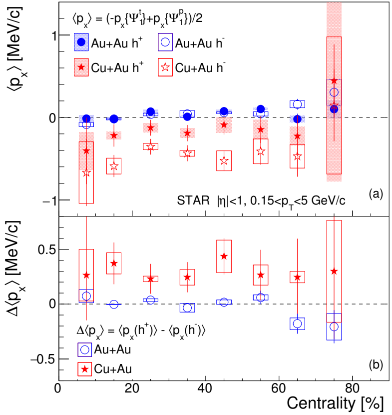


- Measurement of identified particle v_1 with respect to projectile (Cu) spectator plane is difficult due to small statistics of identified particles and poor event plane resolution.
- No attempt to decompose the measured v_1 into the conventional and fluctuation components.

Charge dependence of directed flow

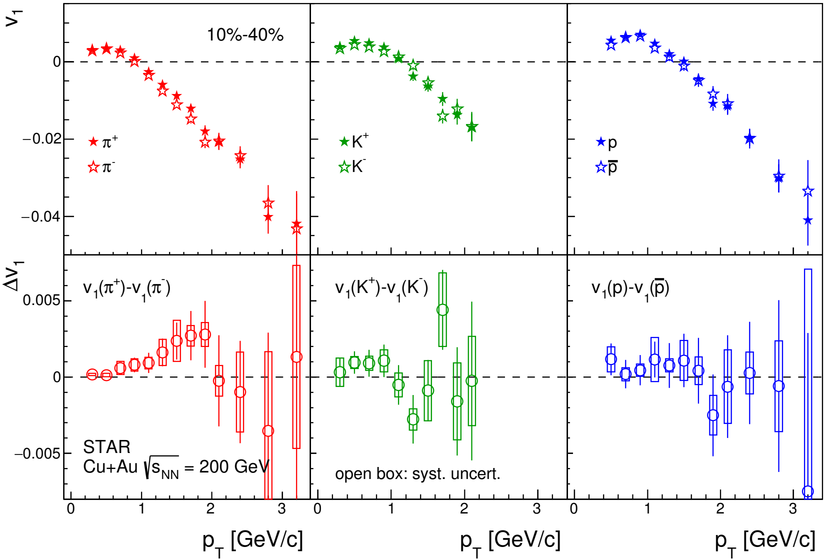
- A finite difference in directed flow between positively and negatively charged particle is observed in Cu+Au collisions due to asymmetry in the electric charge of the nuclei.
- Similarily there is clear difference between observed $\langle p_x \rangle$ of positive and negative particles in Cu+Au but not in Au+Au collisions.
- However, this difference is much smaller (~ 30 times!) than expected from rough calculations, what might suggest that the numbers of quarks and antiquarks are overestimated at the time when the initial electric field is strong.





Charge dependence of v_1 for identified particles

- Clear charge dependence of v_1 for π^+ and π^- is observed. For Kaons and (anti)protons there are no significant differences within current experimental precision.



Summary

- Directed flow for inclusive as well as identified charged particles was measured as a function of η and p_{T} over a wide centrality range in Cu+Au and Au+Au collisions.
- The measured directed flow in Cu+Au and Au+Au collisions at RHIC is consistent with a picture of the directed flow originating from the initial source tilt and the initial density asymmetry.
- Relative contribution to the $\mathrm{v}_1^{\mathrm{odd}}$ slope from the initial tilt is about 2/3 in mid-central collisions at RHIC and the rest comes from the rapidity-dependent density asymmetry.
- The mean transverse momentum projected onto the spectator plane $\langle p_x \rangle$ shows charge dependence in Cu+Au but not in Au+Au collisions. The observed difference can be explained by the initial electric field due to charge difference in Cu and Au spectator protons

Backup slides

Directed flow from a tilted source

Derivation of the relation between v_1 and $\langle p_x \rangle$ in the tilted source scenario (based on S.A. Voloshin, PRC 55, R1630 (1997)).

- Let us denote the invariant particle distribution as $\dfrac{d^3N}{d^2p_{\mathrm{T}}dy} \equiv J_0(p_{\mathrm{T}}, y)$
- A small tilt in xz plane by an angle γ leads to a change in the x component of the momentum $\Delta p_x = \gamma p_z = \gamma p_{\mathrm{T}} / \operatorname{tg}(\theta) = \gamma p_{\mathrm{T}} \sinh \eta$
- The particle distribution in a tilted coordinate system reads:

$$J \approx J_0 + \frac{\partial J_0}{\partial p_{\mathrm{T}}} \frac{\partial p_{\mathrm{T}}}{\partial p_x} \Delta p_x = J_0 \left(1 + \frac{\partial \ln J_0}{\partial p_{\mathrm{T}}} \cos\phi \, p_{\mathrm{T}} \, \gamma \sinh\eta \right)$$

- From the above one gets: $\mathrm{v}_1(p_{\mathrm{T}}) = \dfrac{1}{2} \gamma \, p_{\mathrm{T}} \sinh\eta \, \dfrac{\partial \ln J_0}{\partial p_{\mathrm{T}}}$
- Heavier particle spectra have less steep dependence on p_{T}, which leads to the mass dependence of $\mathrm{v}_1(p_{\mathrm{T}})$ - heavier particles have smaller v_1 at a given p_{T}.
- Integrating over p_{T}, and using p_{T} weight for $\langle p_x \rangle$ calculation leads to the following ratio of slopes:

$$\frac{\frac{1}{p_{\mathrm{T}}} \frac{d\langle p_x \rangle}{d\eta}}{\frac{d\mathrm{v}_1}{d\eta}} = \frac{1}{p_{\mathrm{T}}} \frac{\langle p_{\mathrm{T}}^2 \frac{\partial \ln J_0}{\partial p_{\mathrm{T}}} \rangle}{\langle p_{\mathrm{T}} \frac{\partial \ln J_0}{\partial p_{\mathrm{T}}} \rangle}$$

- For both the exponential form of $J_0(p_{\mathrm{T}})$ (approximately describing the spectra of light particles) and the Gaussian form (better suited for description of protons), this ratio equals 1.5.