Charge-dependent flow in Cu+Au collisions

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  - He^3+Au collisions @ 200 GeV
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  - p+Al collisions ←**running now**

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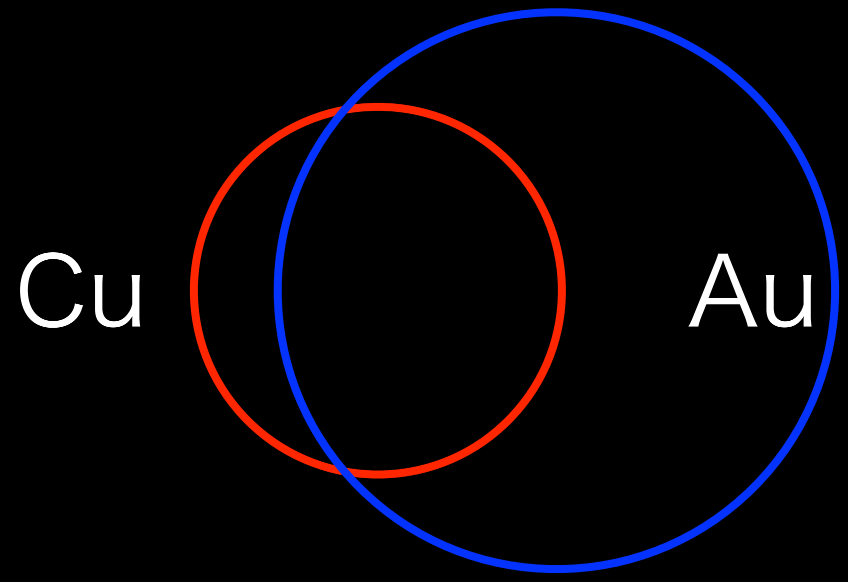

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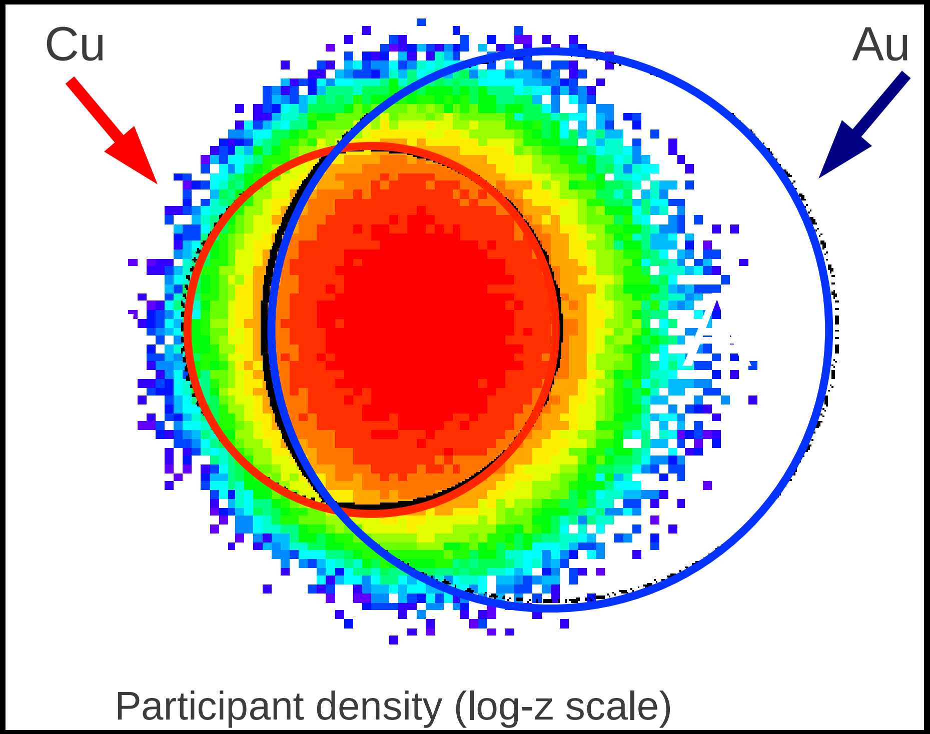

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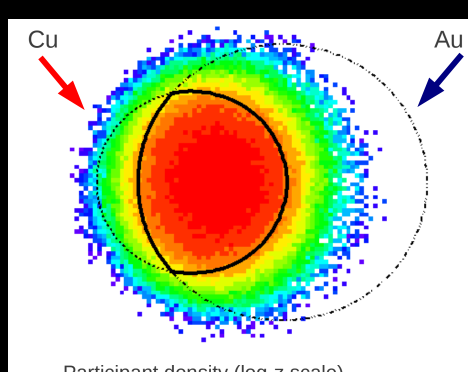

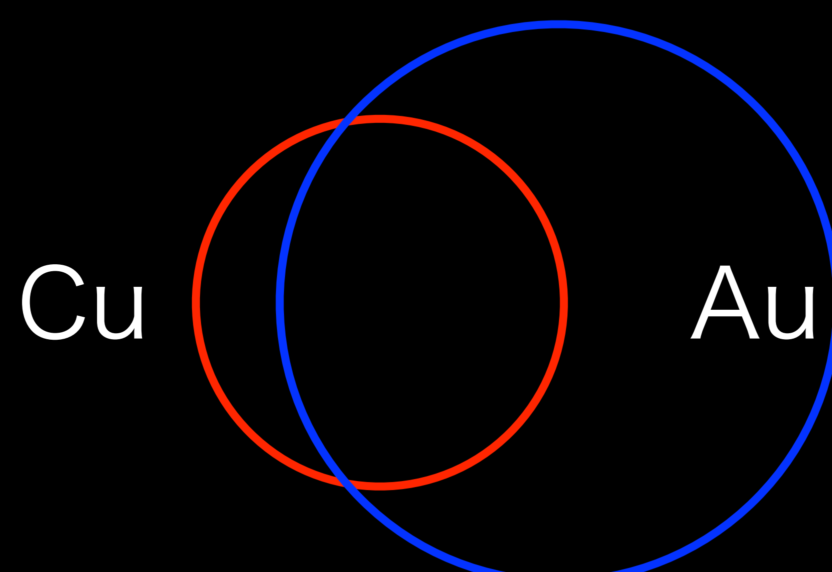

asymmetric density profile
asymmetric pressure gradient

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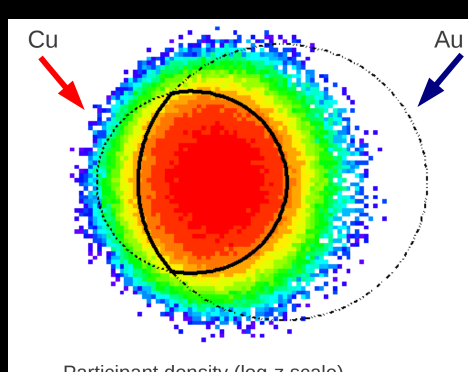

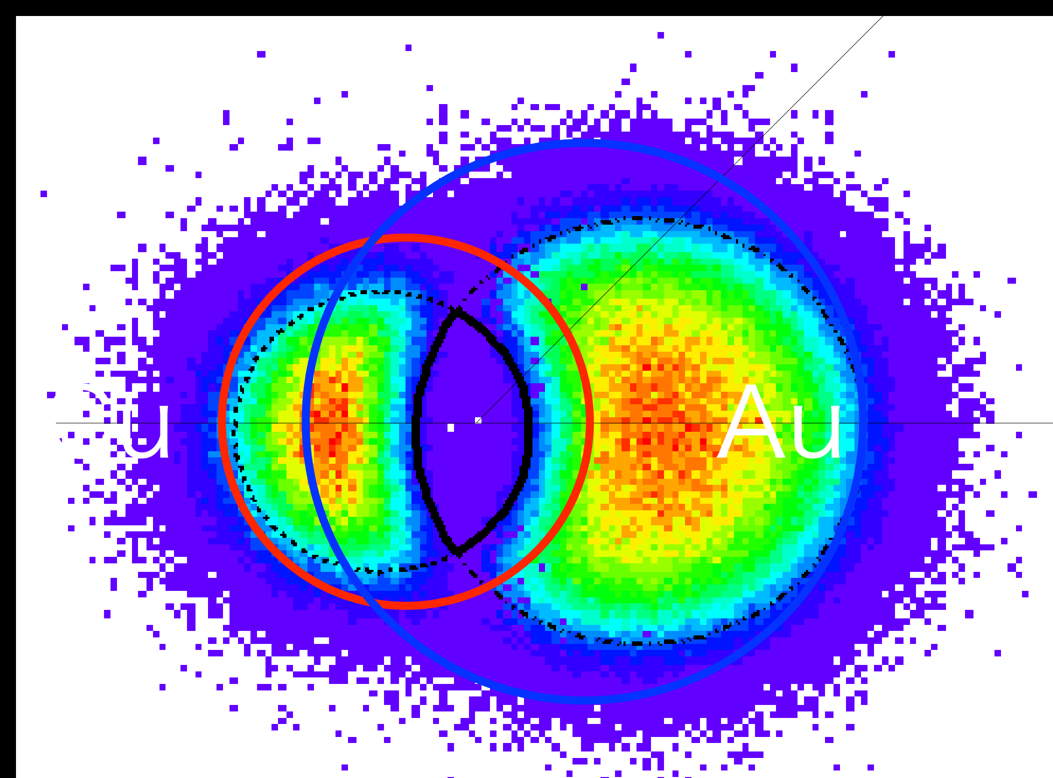

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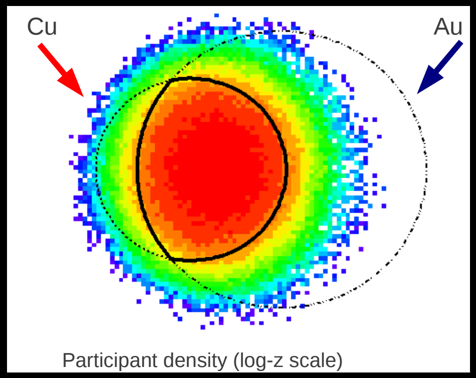

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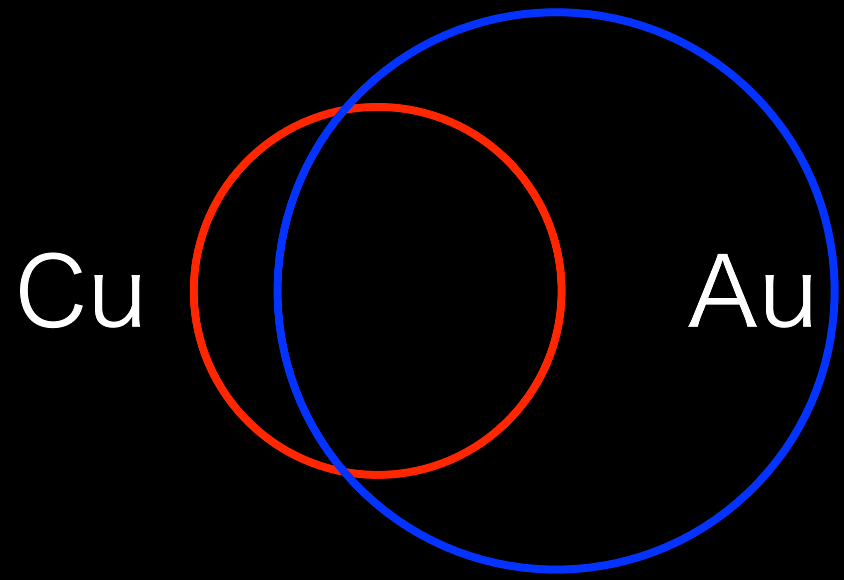
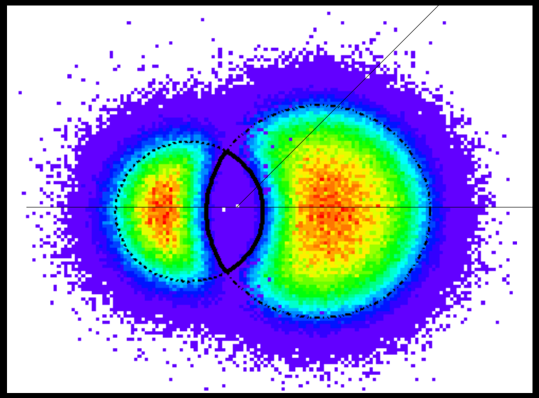




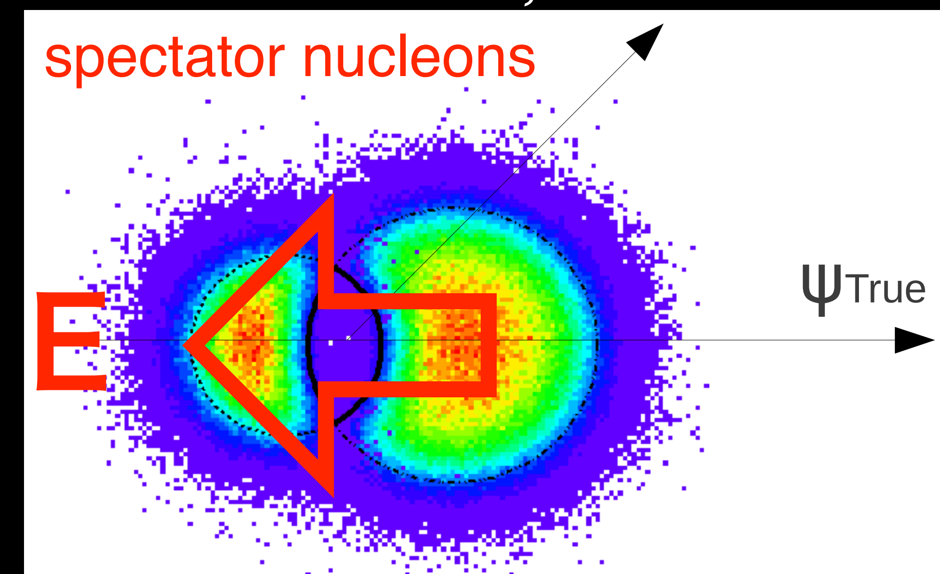
dipole-like charge distribution by spectators

Why interesting?
- Cu+Au collisions -

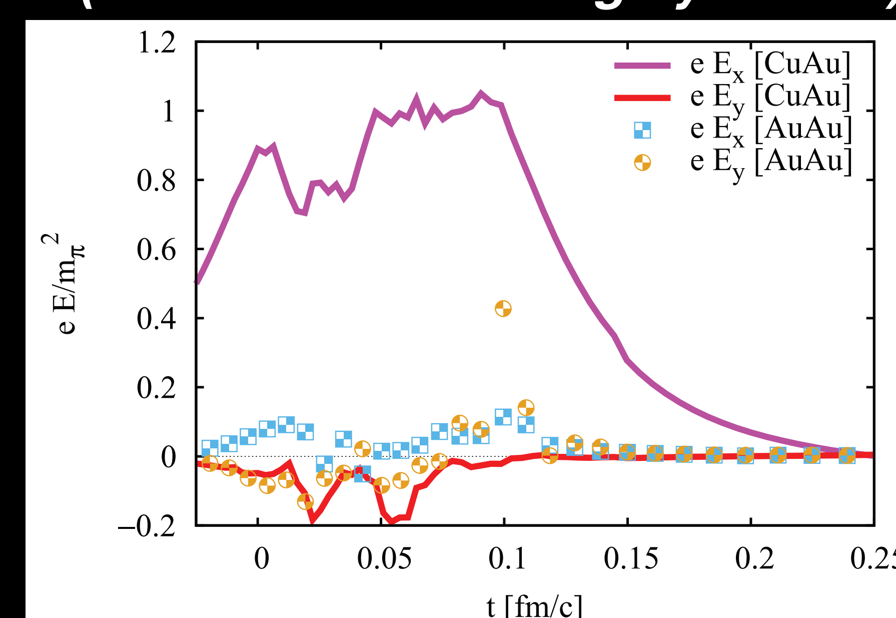
- Sizable E-field pointing from Au to Cu, due to different number of protons in both spectators
- Expect charge separation of directed flow due to a dipole deformation
  - Electric conductivity of QGP? (PRC90.021903)
  - Would be sensitive to the quark/anti-quark creation time (a life time of E-field ~0.25 fm/c) (PRC90.064903)

- Higher-order flow would be also interesting to study η/s with hydrodynamic models under asymmetric pressure gradient
  - PLB717(2012)287

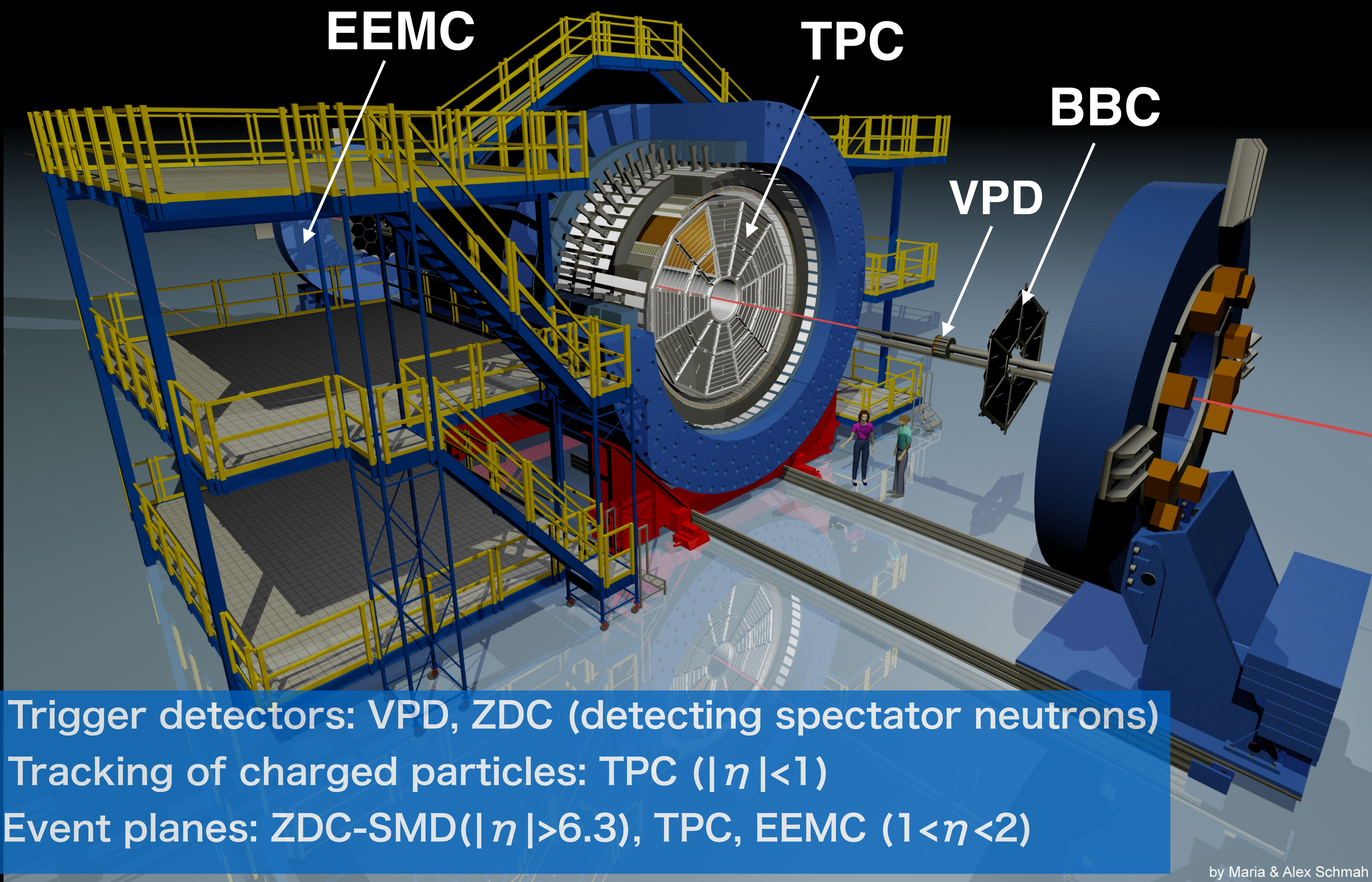
A. Iordanova, RHIC&AGS2013



E-field from PHSD, PRC90.064903 (Parton-hadron string dynamics)



Solenoidal Tracker At RHIC



- Trigger detectors: VPD, ZDC (detecting spectator neutrons)
- Tracking of charged particles: TPC ($|\eta|<1$)
- Event planes: ZDC-SMD($|\eta|>6.3$), TPC, EEMC ($1<\eta<2$)

v_n measurements

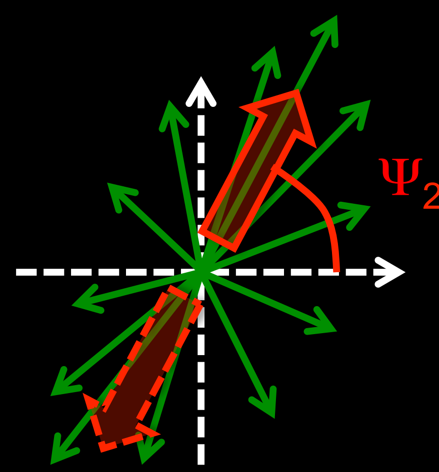
- Event plane method
  - Ψ_1 determined by ZDC-SMD measuring spectator neutrons
  - Ψ_n (n>1) determined by TPC(η-sub) and EEMC

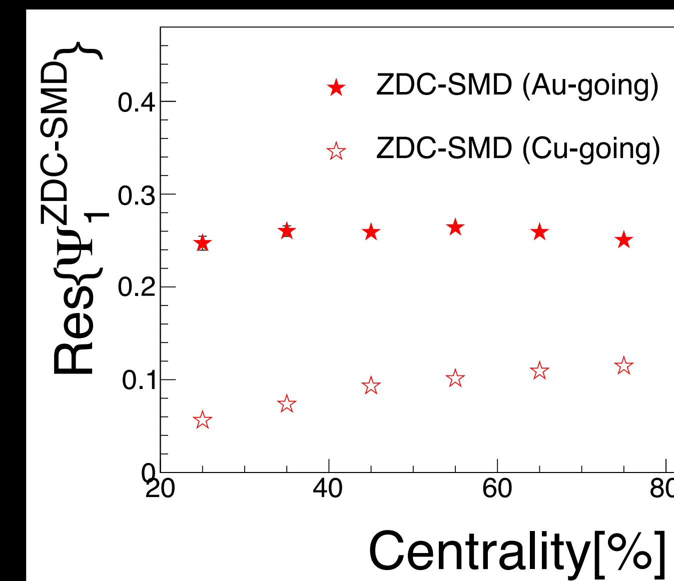
$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$$

$$\Psi_n = \frac{1}{n} \tan^{-1}(Q_{n,y}/Q_{n,x})$$

$$Q_{n,x} = \Sigma w_i \cos(n\phi)$$

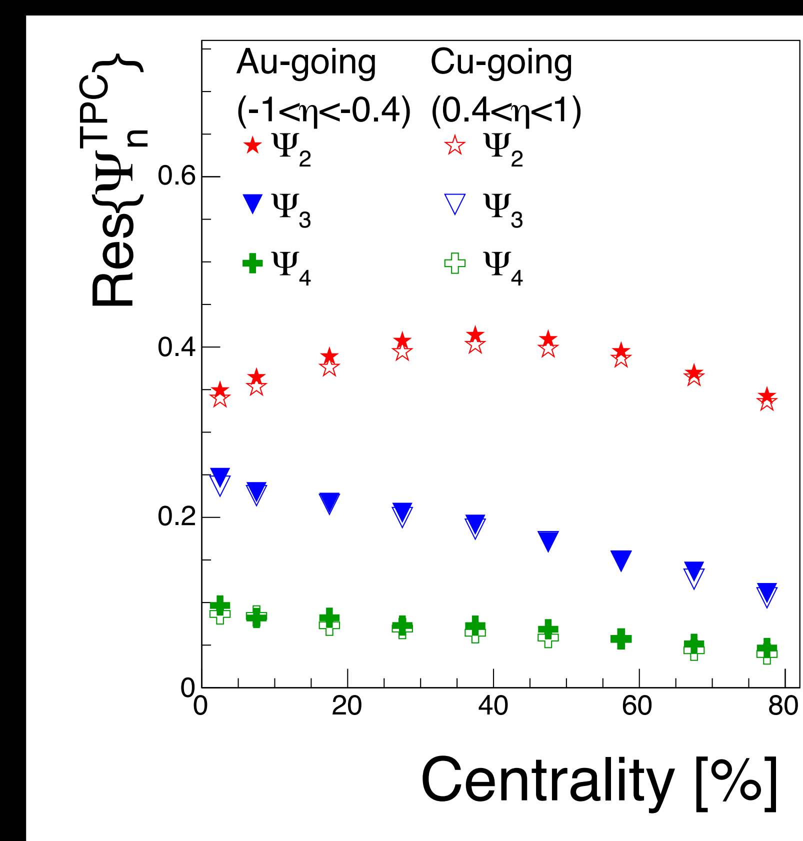
$$Q_{n,y} = \Sigma w_i \sin(n\phi)$$





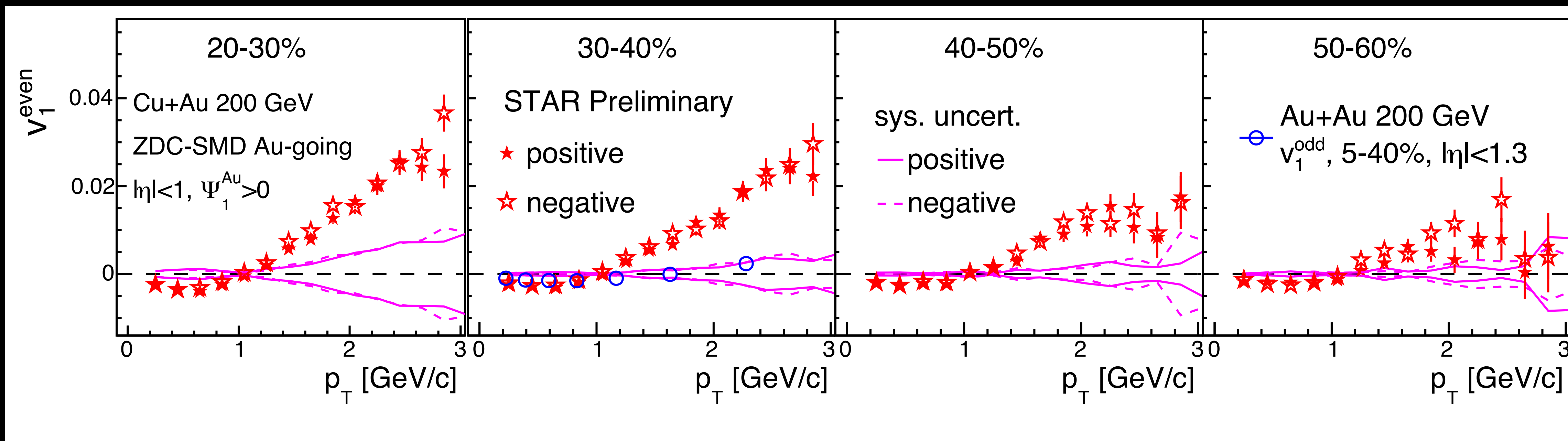
- Scalar product method
  - v_n (n>1) using flow vectors determined by TPC-tracks in forward and backward region

$$v_n = \frac{\langle \vec{Q}_n^{F(B)} \cdot \vec{u} \rangle}{\sqrt{\langle \vec{Q}_n^F \cdot \vec{Q}_n^B \rangle}}$$



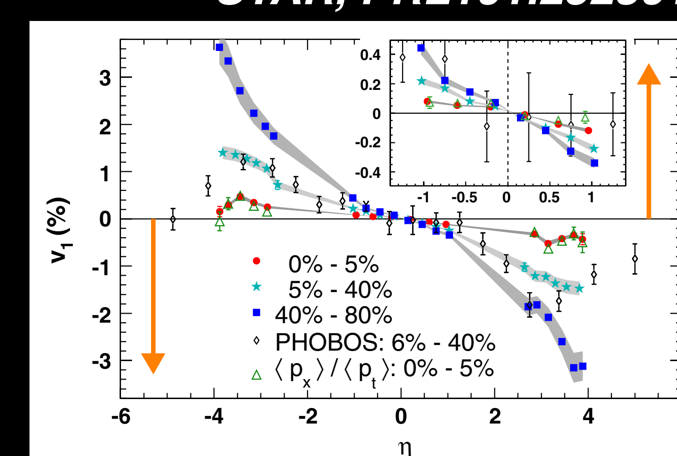
- Systematic uncertainty
  - variation of track selection
  - For v_1, EP resolutions from different 3-sub events
  - For v_n, difference between TPC η-sub and EEMC

Charge-dependent directed flow

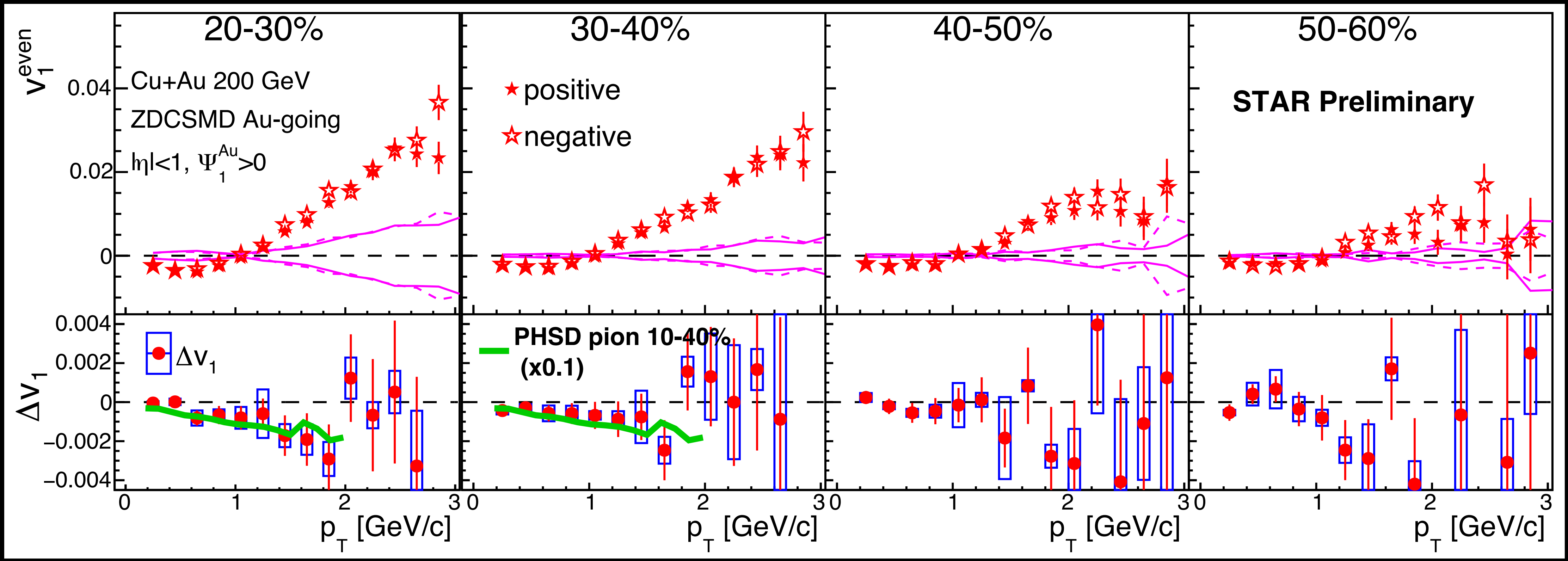


- Sizable v_1^{even} measured relative to ZDC-SMD plane in Au-going side, where Ψ_1^{Au}>0
  - $v_1^{\mathrm{even}} = \langle \cos(\phi - \Psi_1) \rangle \qquad v_1^{\mathrm{odd}} = \langle sgn(\eta) \cos(\phi - \Psi_1) \rangle$
  - In Au+Au collisions, v_1^{odd} ~0.1% (v_1^{even} would be small because of sign-flipped symmetry on η), which is only due to density fluctuations
- Negative v_1 in p_T<1GeV/c: more low p_T particles in Cu-side
  - due to asymmetric pressure gradient?
- Positive v_1 in p_T>1GeV/c: more high p_T particles in Au-side
  - due to jet and/or corona by higher initial density in Au-side?
- Much smaller difference between positive and negative particles

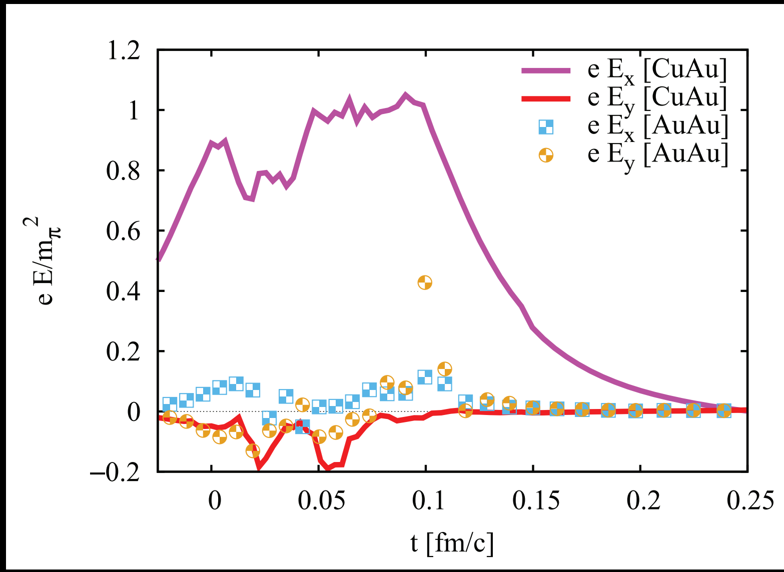
v_1 in Au+Au, STAR, PRL101.252301



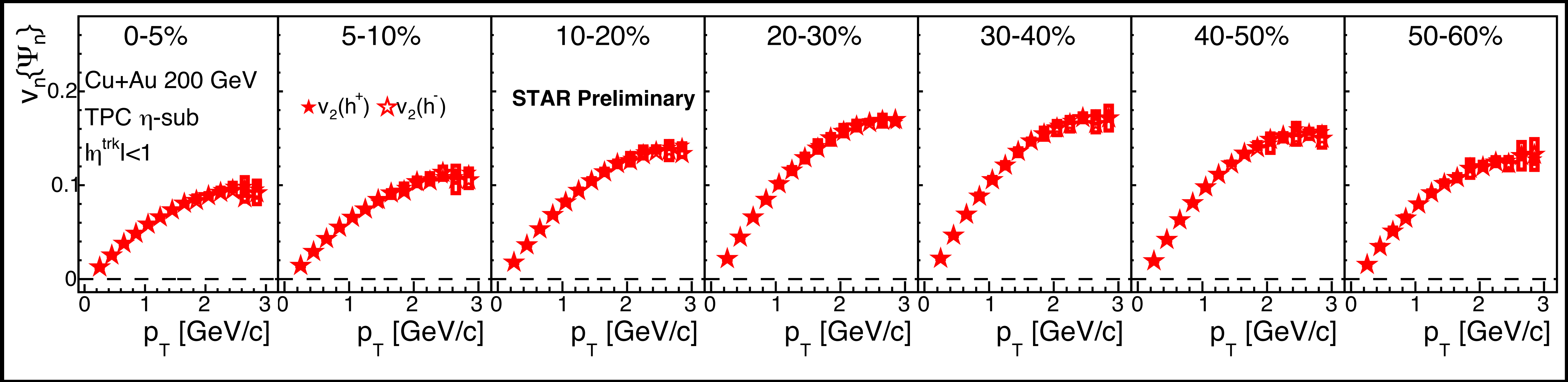
Charge-dependent directed flow



- $\Delta v_1 = v_1(h^+) - v_1(h^-)$, and v_1~1%, Δv_1<0.2%
  - Δv_1 looks to be negative in p_T<2 GeV/c,
  - similar p_T dependence to PHSD model (PRC90.064903), but smaller by <u>a factor of 10</u>
- Quarks existing at an earlier time than the life time of E-field (~0.25 fm/c) would be very small
  - consistent with "two wave" scenario of light quark production

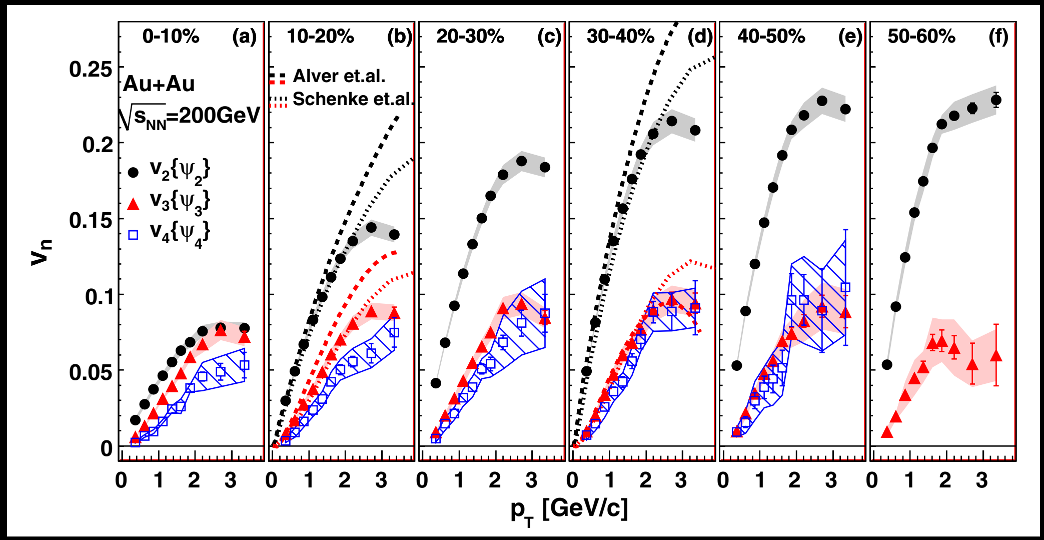


Higher-order flow



- v_2 peaks at more central collisions than Au+Au collisions
  - 40-50% in Au+Au (and Cu+Cu), 30-40% in Cu+Au

PHENIX, PRL107.252301



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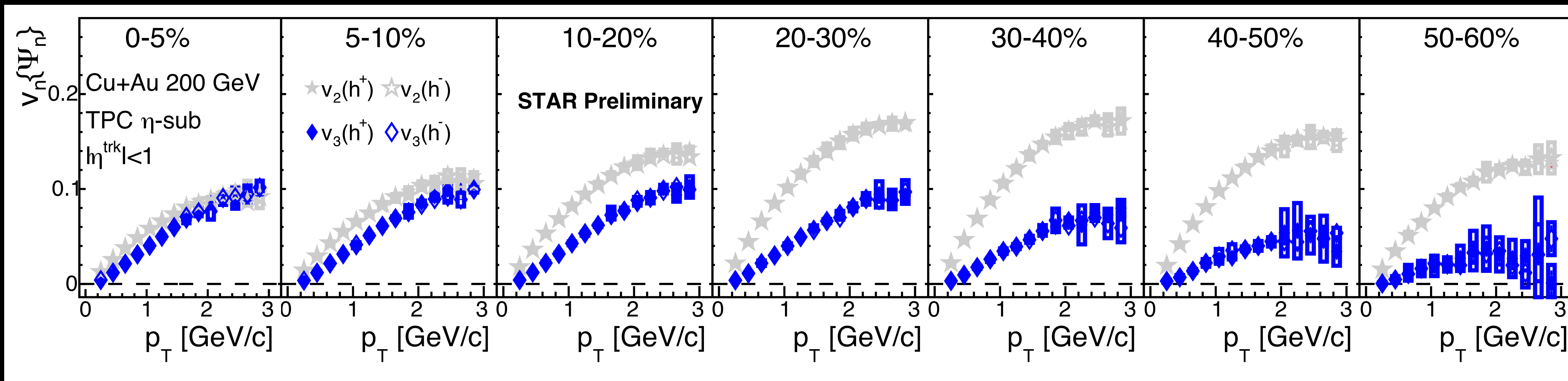

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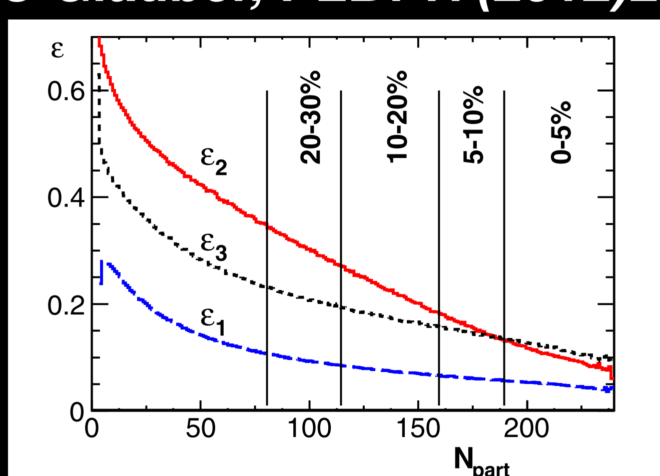
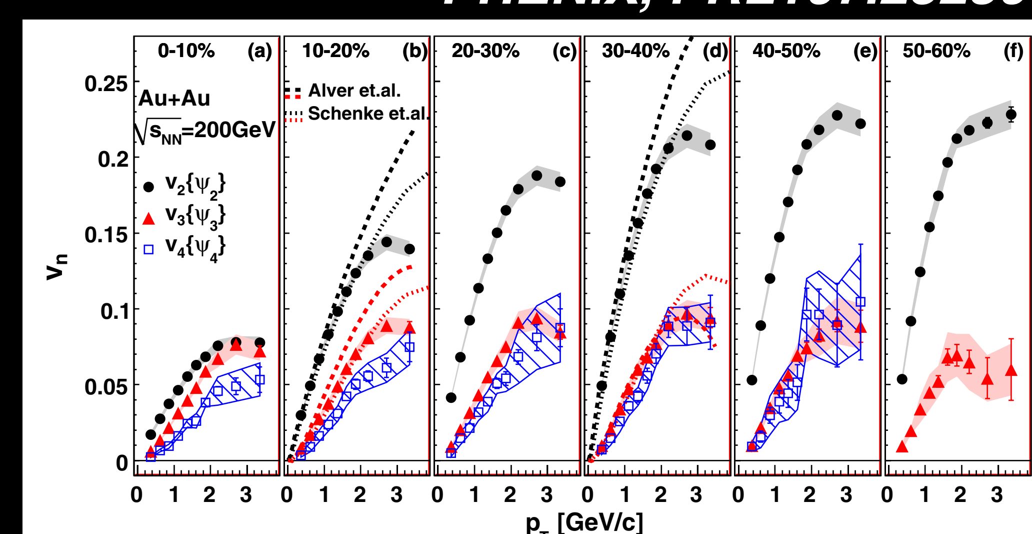
  - 40-50% in Au+Au (and Cu+Cu), 30-40% in Cu+Au
- v_3 seems to decrease in more peripheral collisions
  - due to the intrinsic triangularity in addition to fluctuations?

PHENIX, PRL107.252301

MC Glauber, PLB717(2012)287





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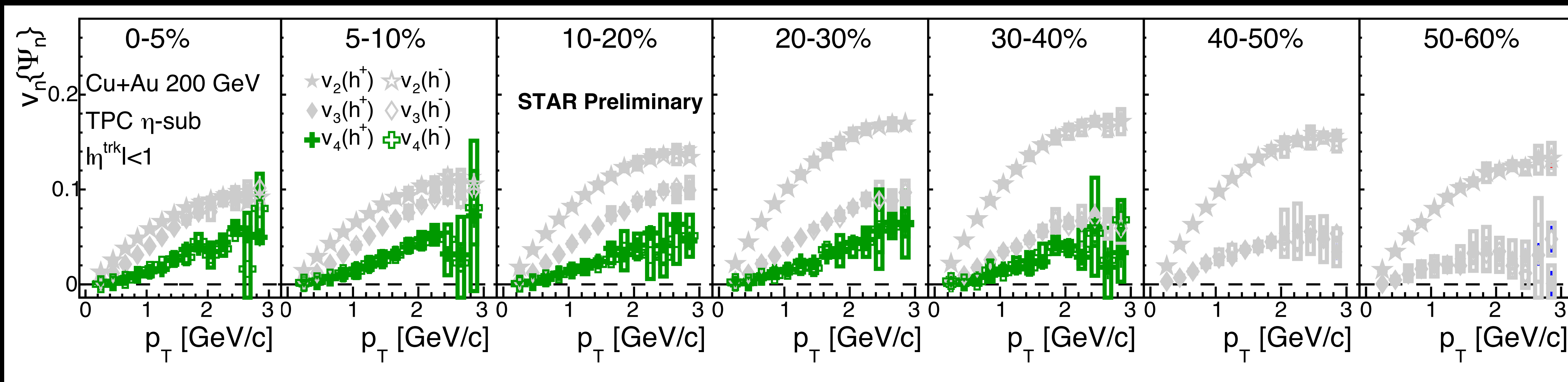

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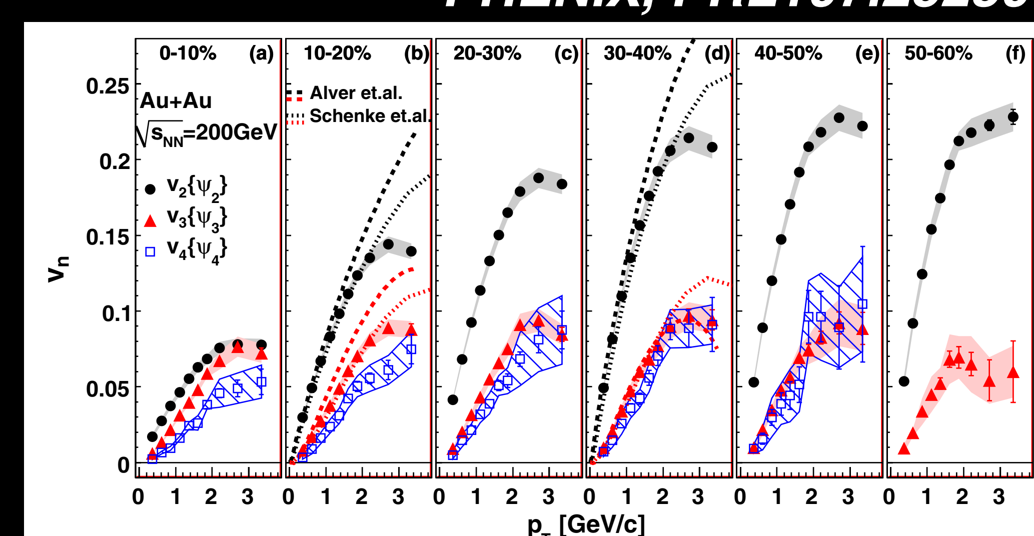
- Finite v_4 is observed
  - weak centrality dependence

PHENIX, PRL107.252301



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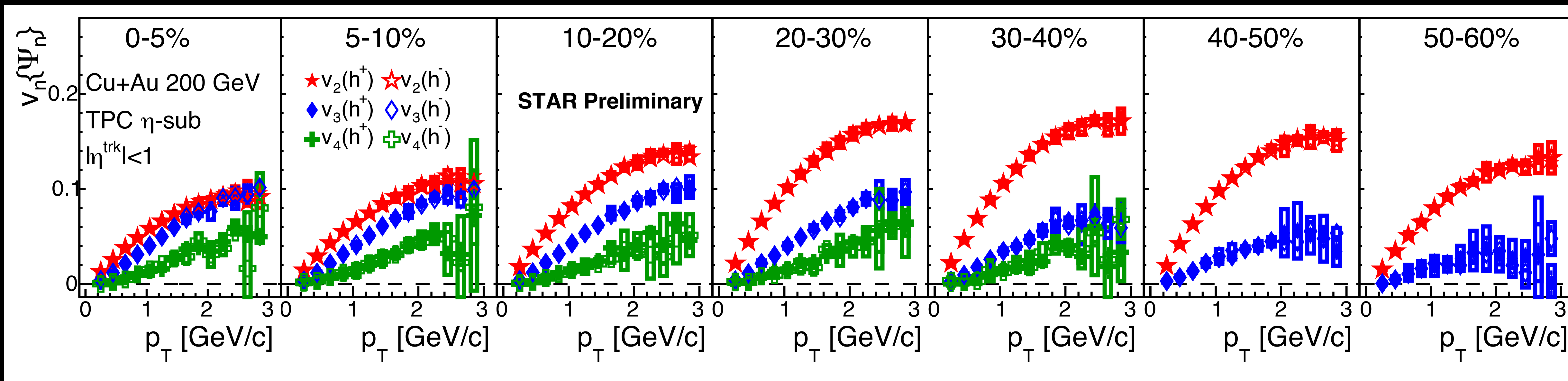

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- v_3 seems to decrease in more peripheral collisions
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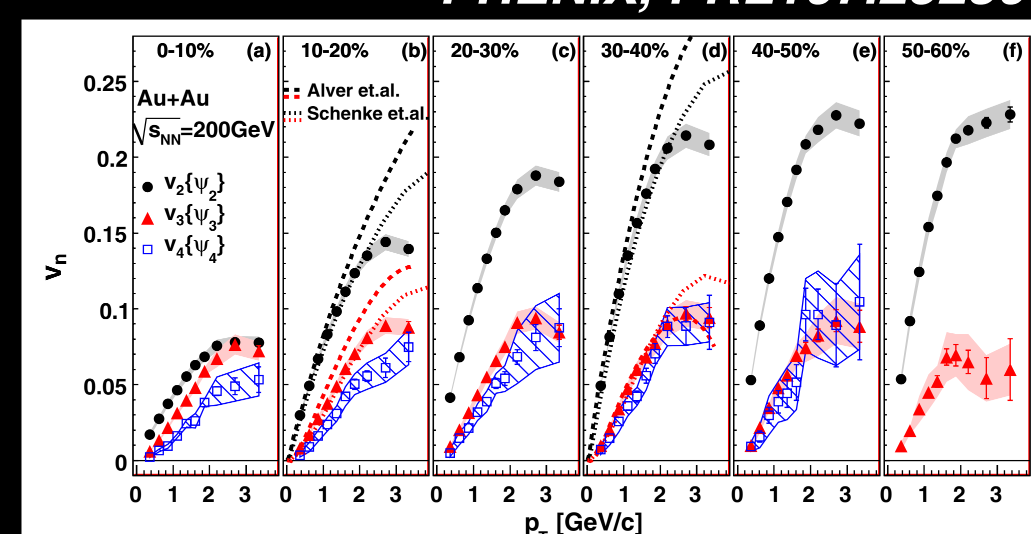
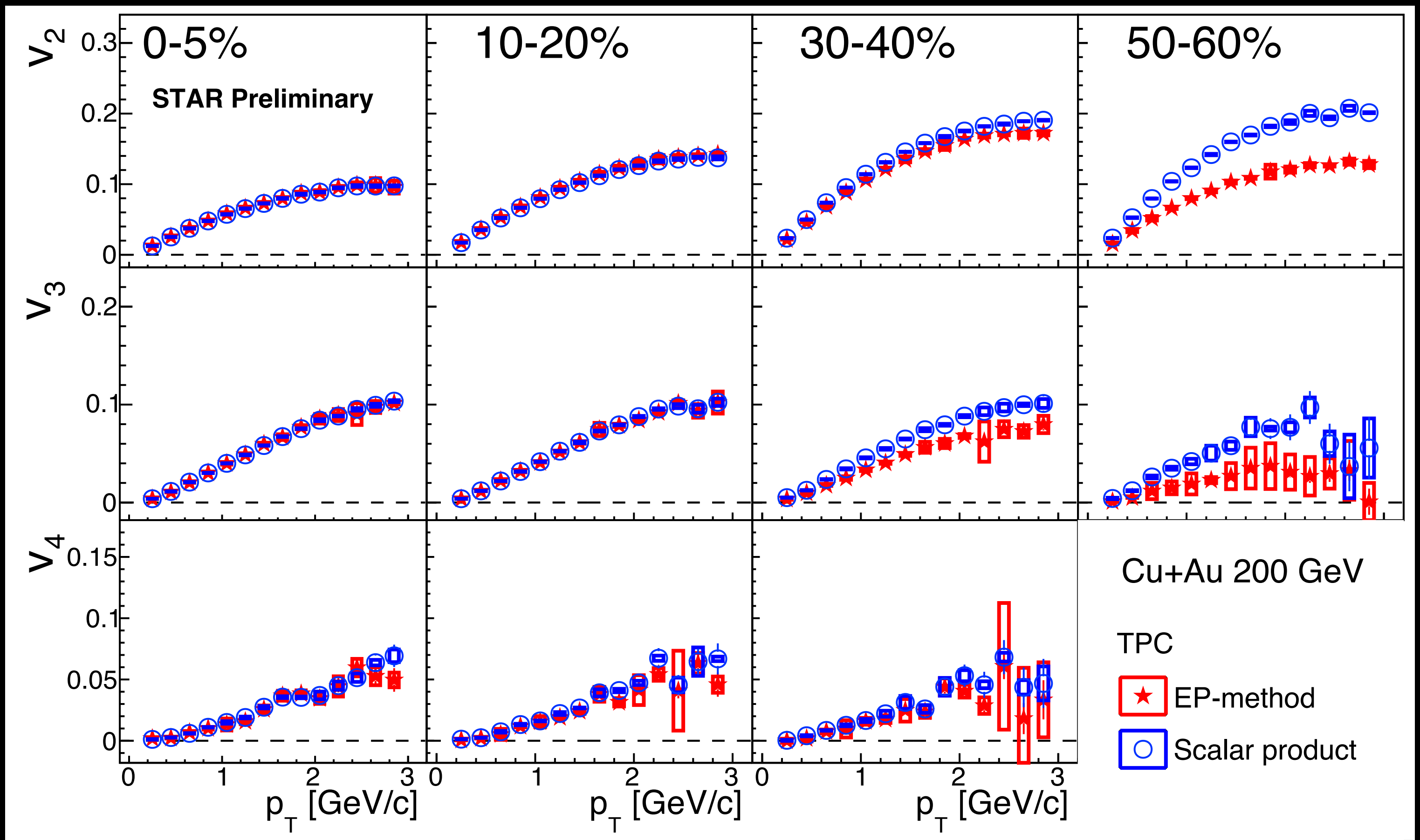
- Finite v_4 is observed
  - weak centrality dependence
- No charge dependence for v_n (n>=2)

PHENIX, PRL107.252301



$v_n\{EP\}$ vs $v_n\{SP\}$



- v_n with scalar product method were measured for check
  - Good agreement with EP-method in central collisions
  - Start to deviate in more peripheral collisions, which can be understood by different sensitivity to non-flow

Summary

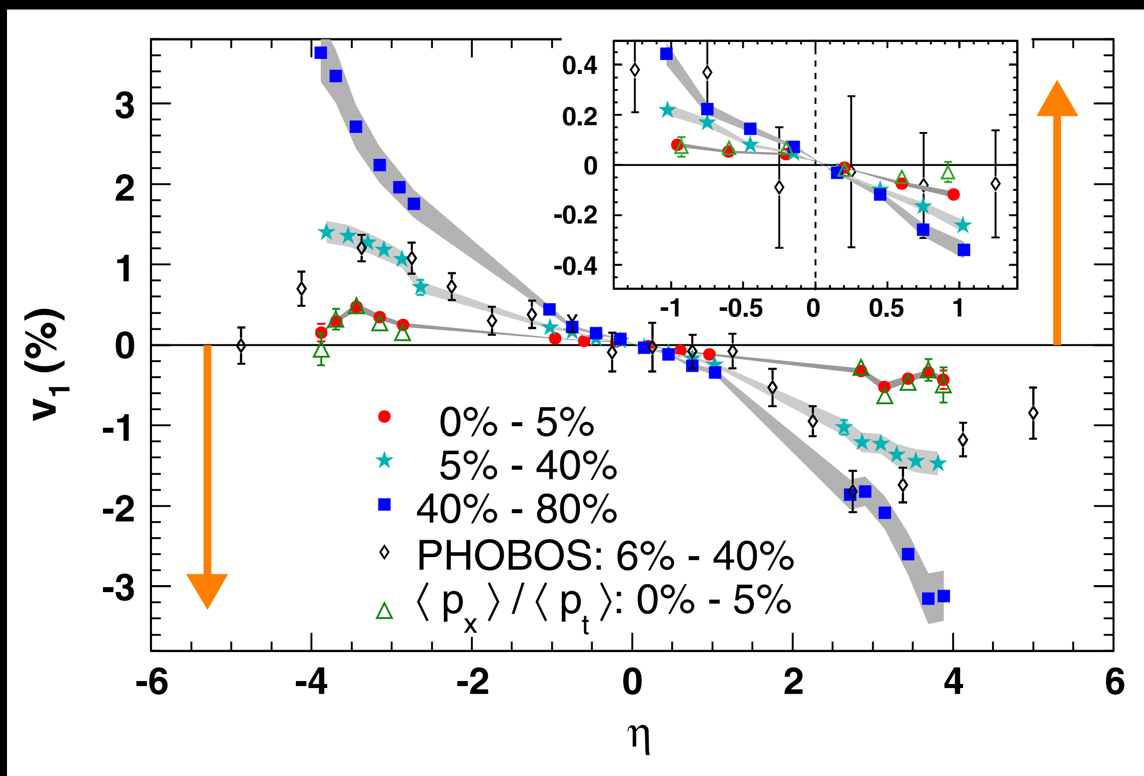
- Charge-dependent directed flow in Cu+Au collisions have been presented
  - The difference between $v_1(h^+)$ and $v_1(h^-)$ has the same sign and pT dependence as PHSD model prediction, which may be a direct evidence of the predicted initial electric field
  - Δv_1 is much smaller than the model, which indicates the number of (anti-)quarks existing at an earlier time ($t<0.25$ fm/c) would be a small fraction of all (anti-)quarks produced
  - A quantitative comparison with model is on-going

- Higher-order flow (v_2-v_4) have also been measured
  - v_2 and v_3 look to have slightly different centrality dependence from Au+Au, especially v_3, which decreases in more peripheral collisions

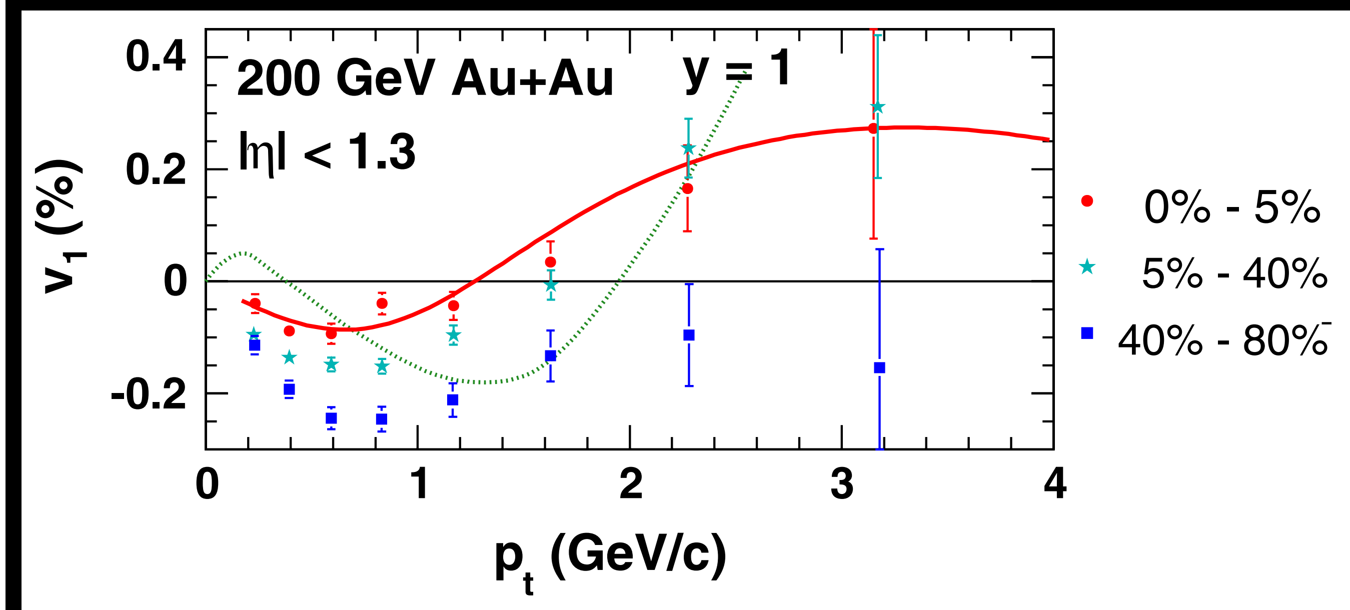
Thank you for your attention!

Back up

v_1 in Au+Au 200GeV



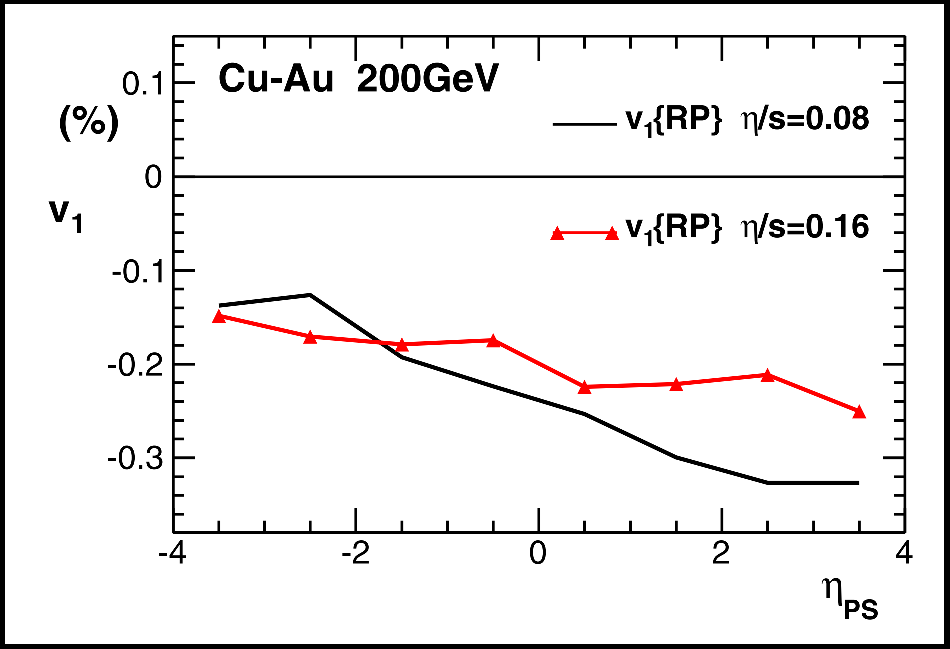
STAR, PRL101.252301

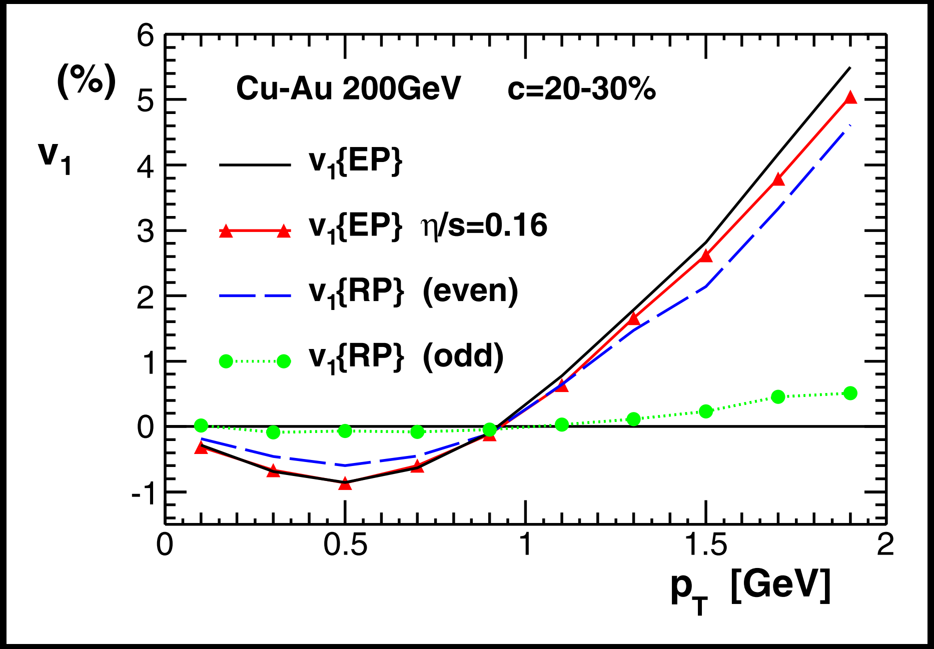


- Small signal of v_1 at mid-rapidity in Au+Au collisions

$$v_1^{\mathrm{odd}} = \langle sgn(\eta) \cos(\phi - \Psi_1) \rangle$$

E-b-e viscous hydrodynamics in Cu+Au





P. Bozek, PLB717(2012)287

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