Charge-dependent directed flow in Cu+Au collisions

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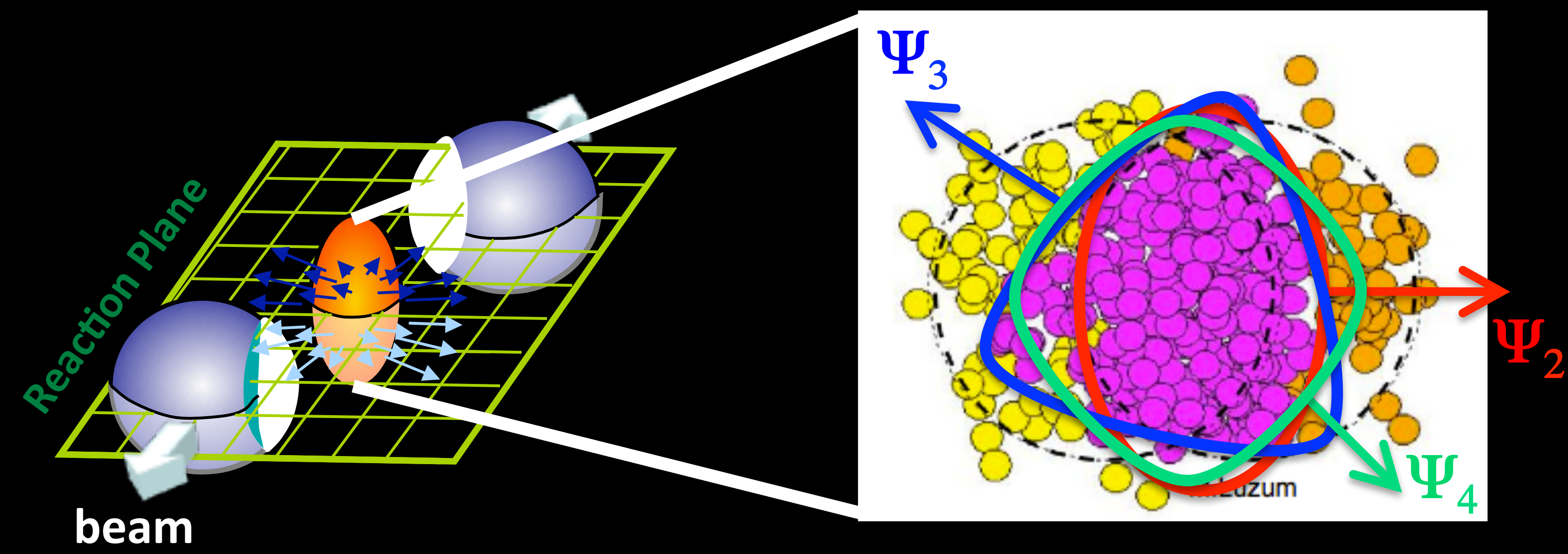
QCD Chirality Workshop 2016 @UCLA

Azimuthal anisotropy

- Anisotropies in momentum-space originate from anisotropies in initial geometry (including fluctuations)

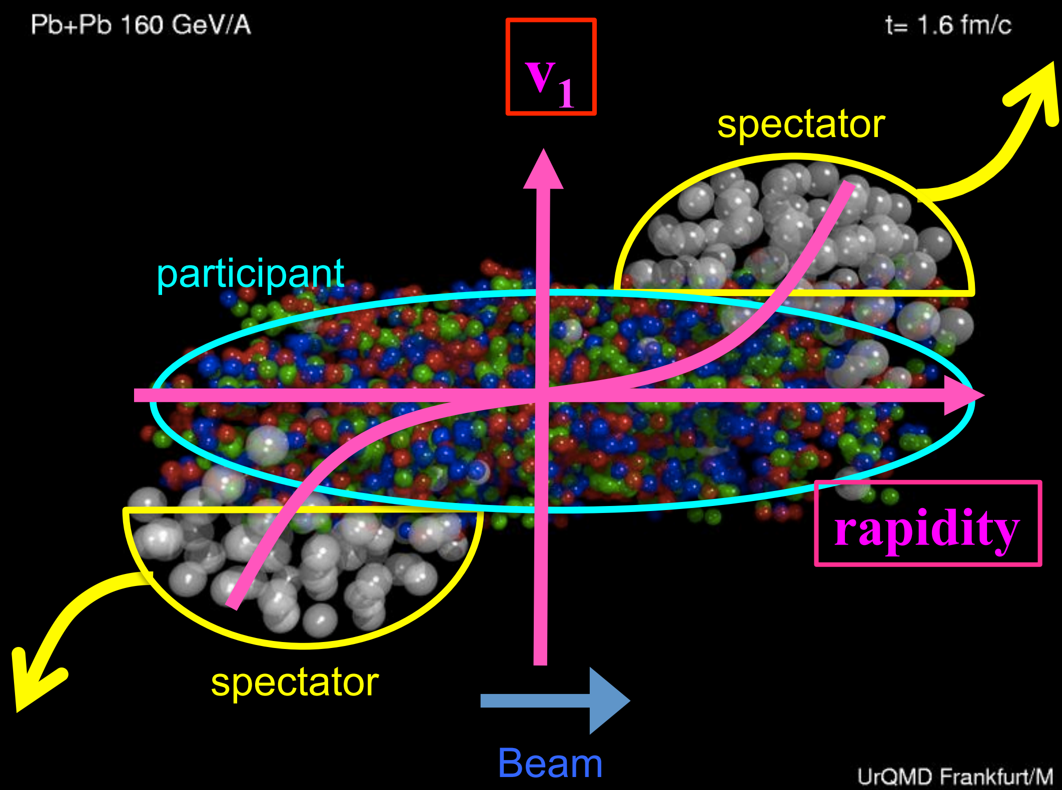


$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]$$

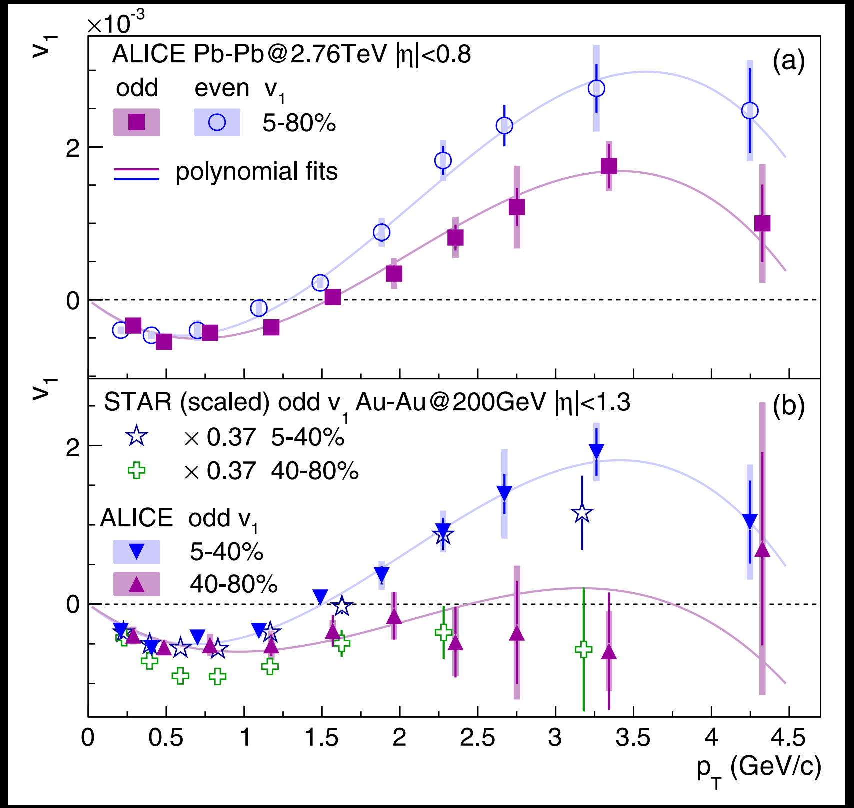
Voloshin and Zhang, Z.Phys.C70, 665
Alver and Roland, PRC81, 054905

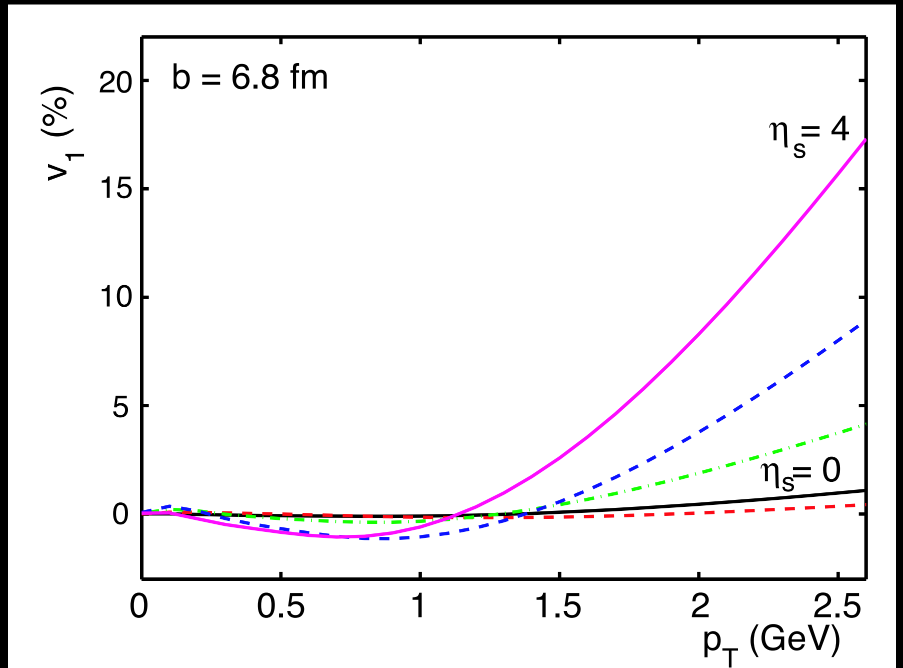
Directed flow (v_1): sensitive to EoS and phase transition
Elliptic(v_2), Triangular(v_3), ···: sensitive to η/s and initial fluctuations

Directed flow in A+A



v_1 in Au+Au vs Pb+Pb ALICE, PRL111.23202



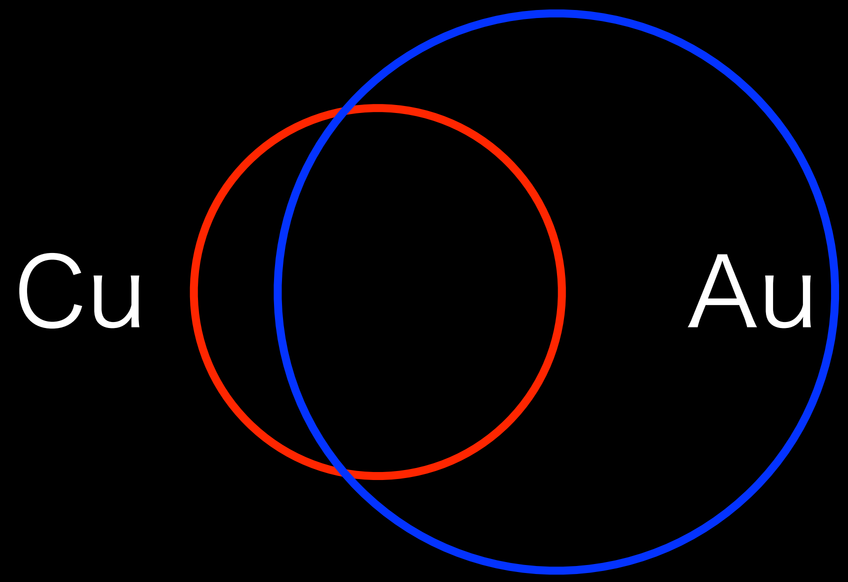


U. Heinz and P. Kolb, J.Phys.G30 (2004) S1229

- v_1 in A+A collisions
  - v_1 is caused by the initial density asymmetry
  - $\langle v_1 \rangle$ at η=0 is zero due to symmetric density
  - non zero $v_1(p_T)$ comes from the density fluctuation
    - Note: $\langle p_x \rangle$=0 if no kick from spectators

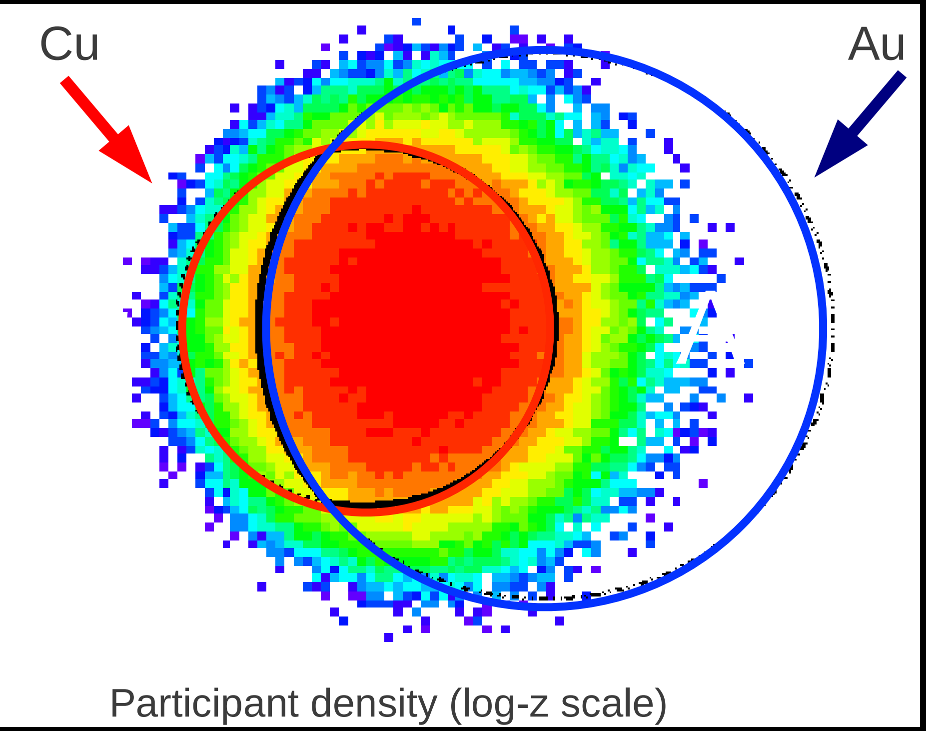
How about in asymmetric collisions?

Cu+Au collisions



- Intrinsic asymmetric density
  - larger directed flow compared to A+A collisions?
- Sizable initial electric field
  - pointing from Au to Cu, due to the charge difference (# of protons) in both spectators

Cu+Au collisions



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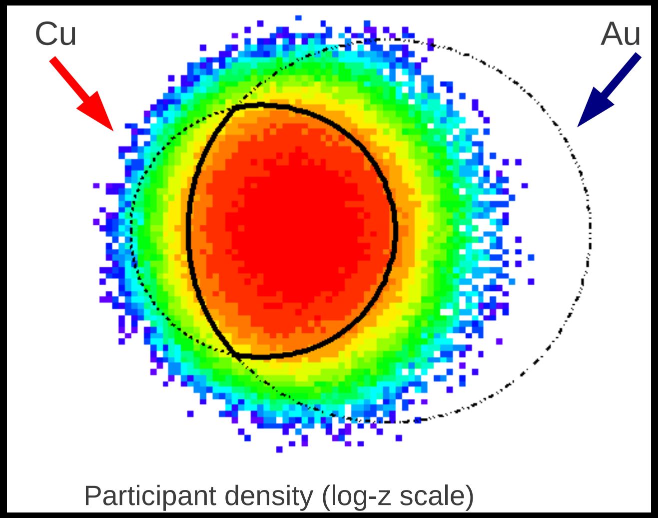
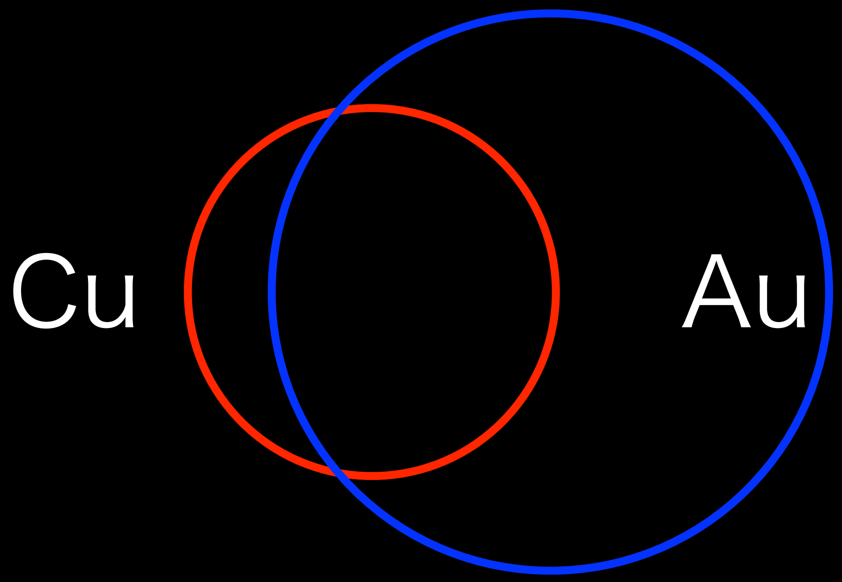
Cu+Au collisions

A. Iordanova, RHIC&AGS2013





Asymmetric density profile
Asymmetric pressure gradient

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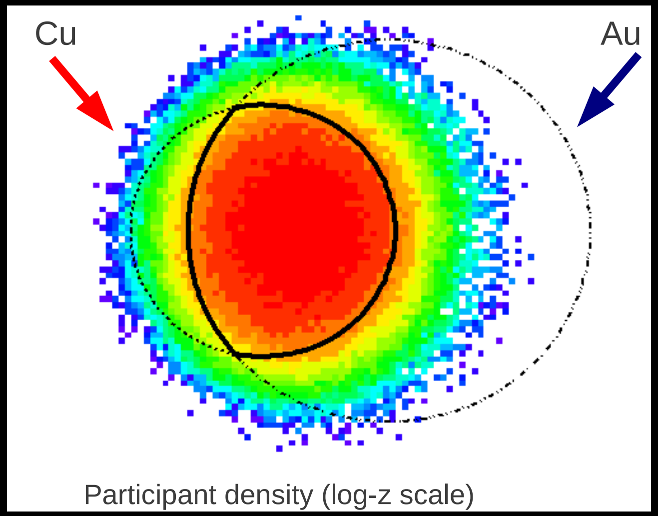

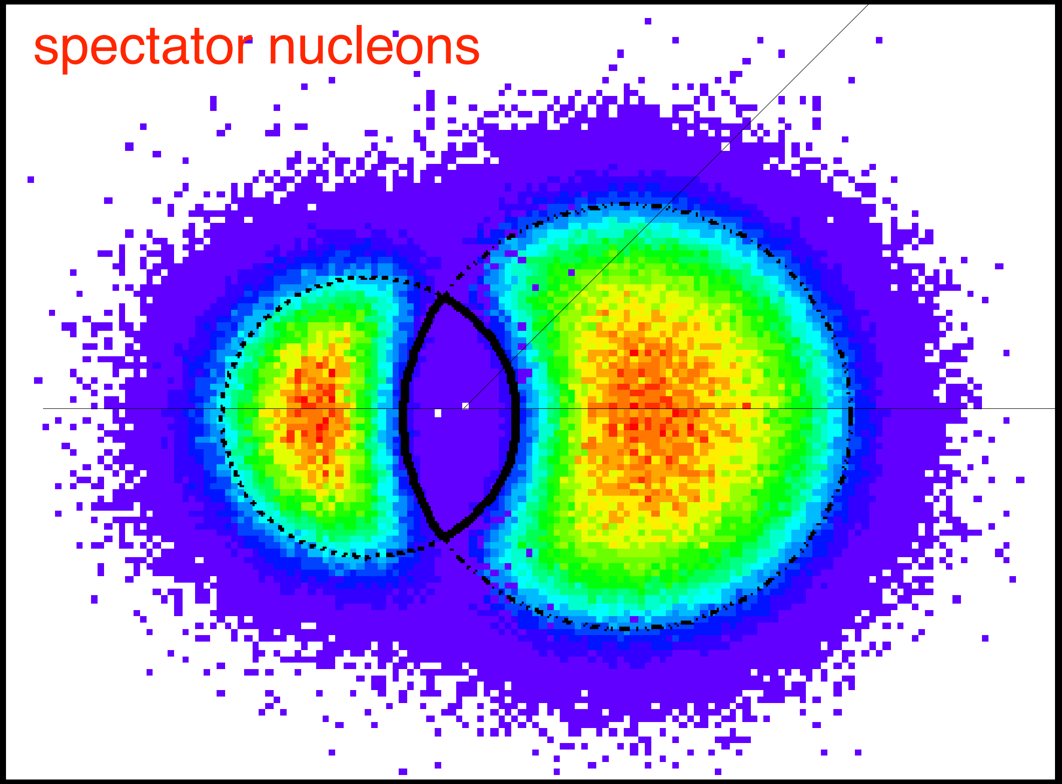

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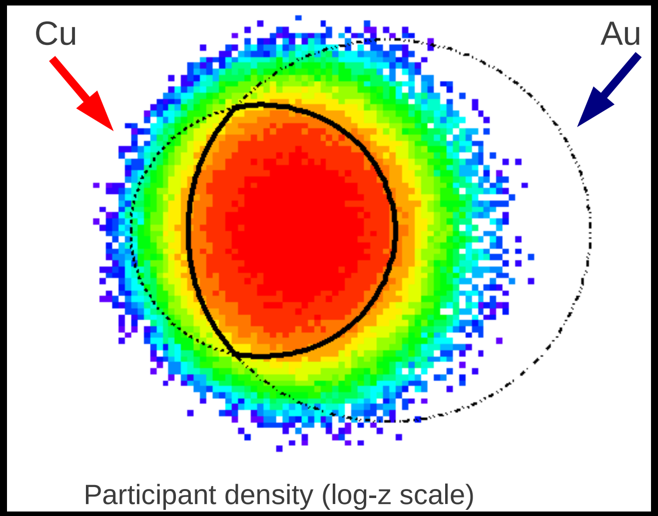

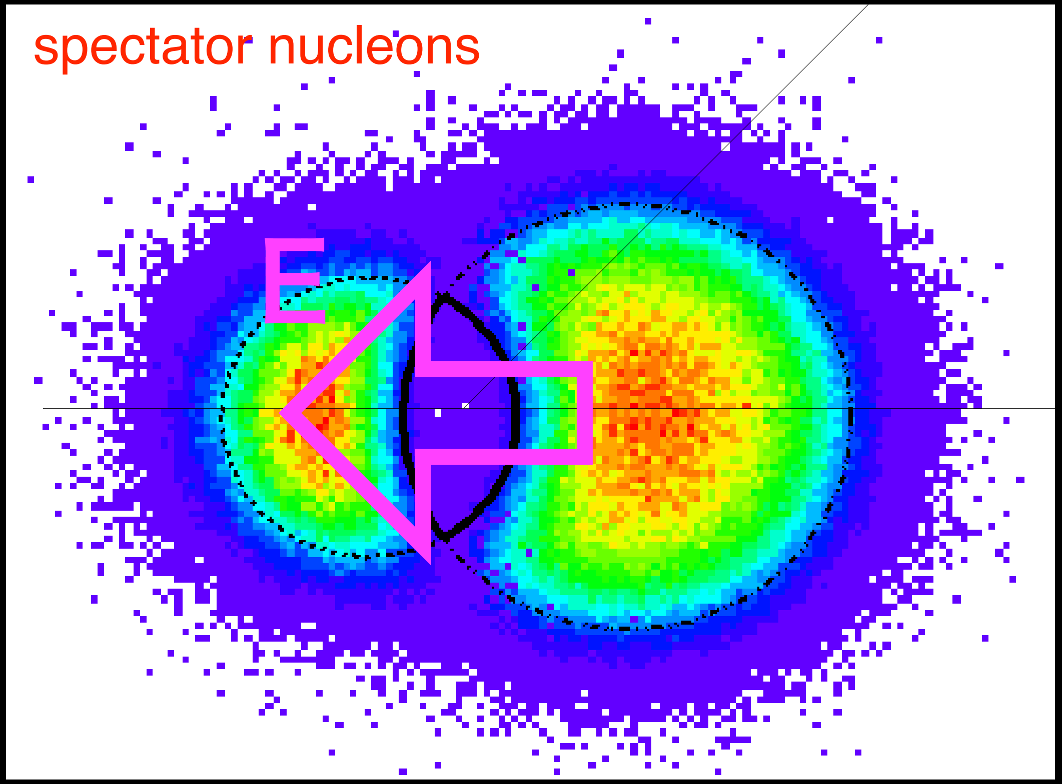

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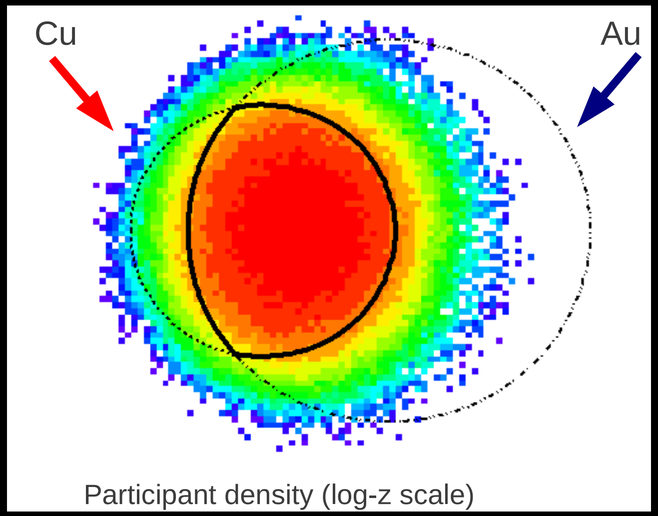
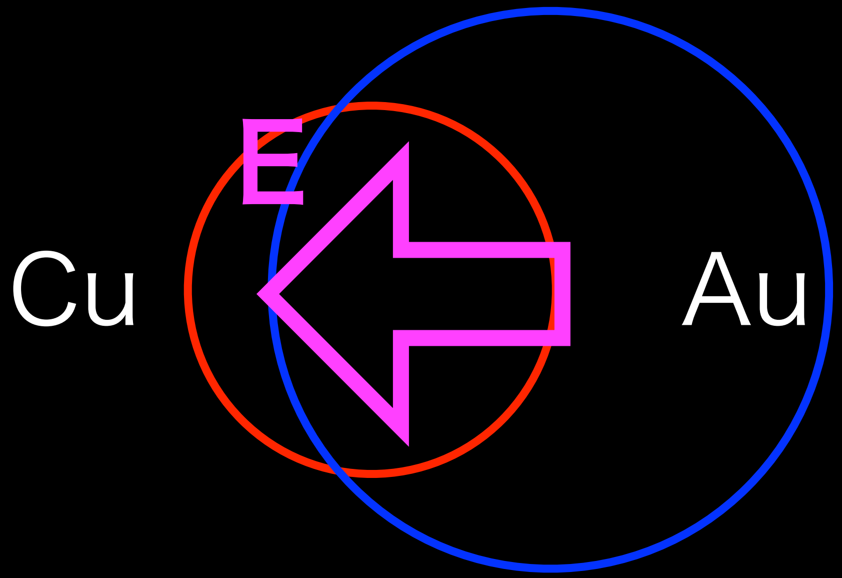
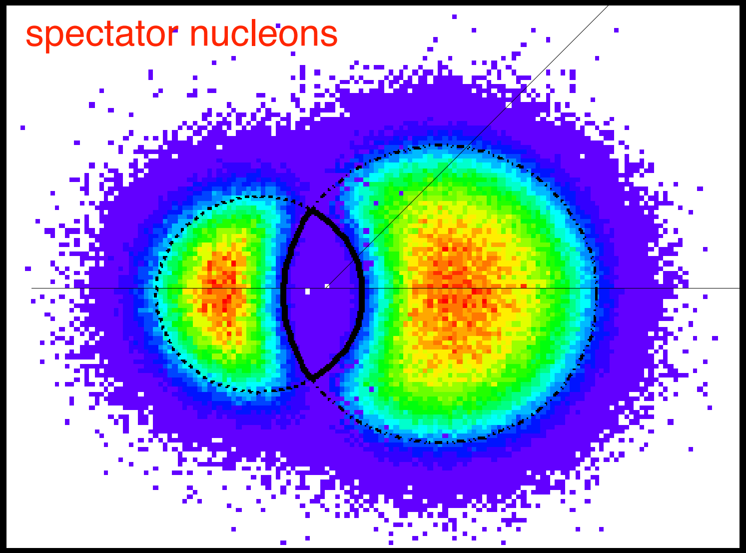






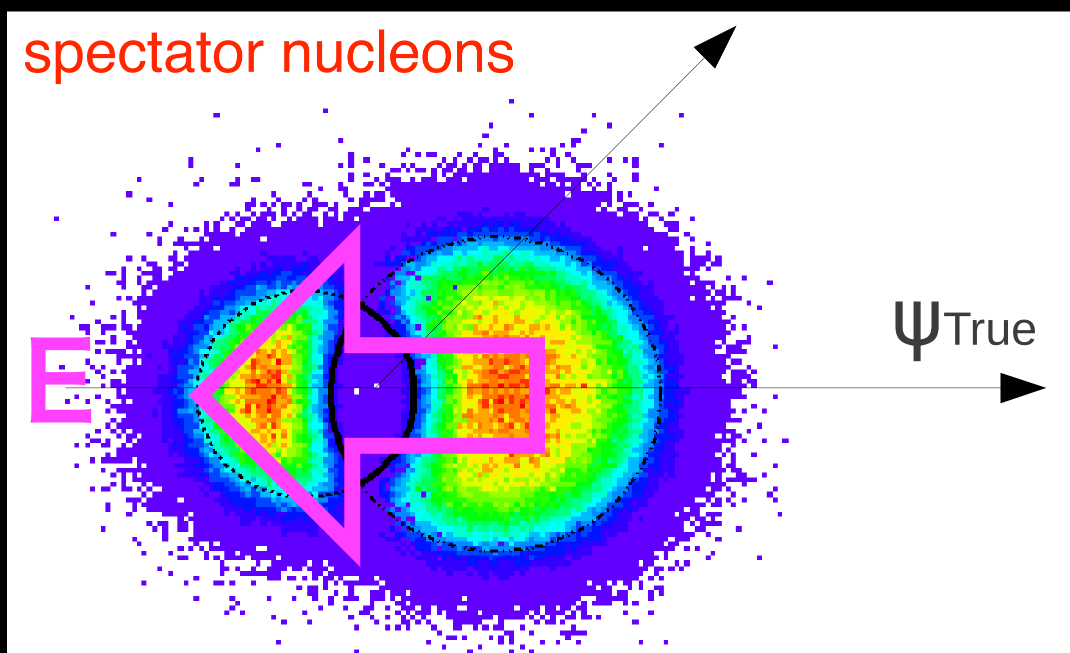
Asymmetric density profile
Asymmetric pressure gradient

Dipole-like charge distribution by spectators

- Intrinsic asymmetric density
  - larger directed flow compared to A+A collisions?
- Sizable initial electric field
  - pointing from Au to Cu, due to the charge difference (# of protons) in both spectators

Effect of the electric field

If we have the electric field (E-field), azimuthal distribution of particles can be written:



$$\frac{dN^{\pm}}{d\phi} \propto 1 + 2v_1\cos(\phi - \Psi_1) \pm d_E\cos(\phi - \psi_E)$$

d_E : strength of dipole deformation induced by E-field (proportional to the electric conductivity)

ψ_E : azimuthal angle of E-field

- Positive particles move to the direction along E-field, and negative particles go to the opposite
- Appear as **charge dependence of v_1**
  - Y. Hirono et al., PRC90.021903
  - sensitive to the electric conductivity

Probe into quark creation time?

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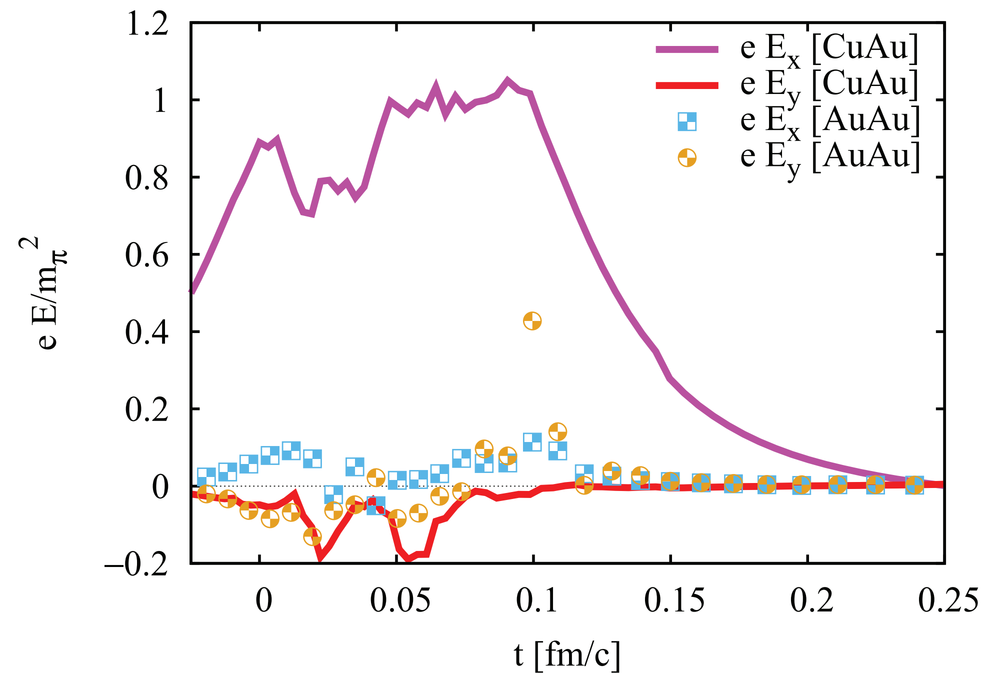
PRC90.064903,
Parton-Hadron String Dynamics



- Life time of E-field would be very short
  - No signal if there is no quarks (charges) when E-field is strong
  - In other words, sensitive to the number of quark/anti-quark at very early stage
(V. Voronyuk et al., PRC90.064903)

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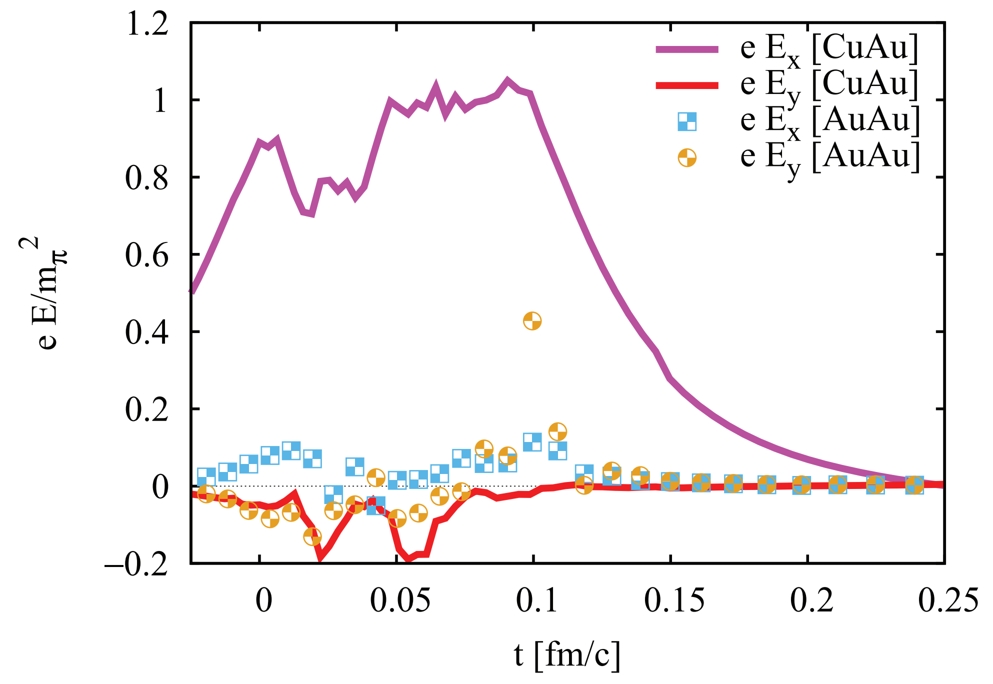

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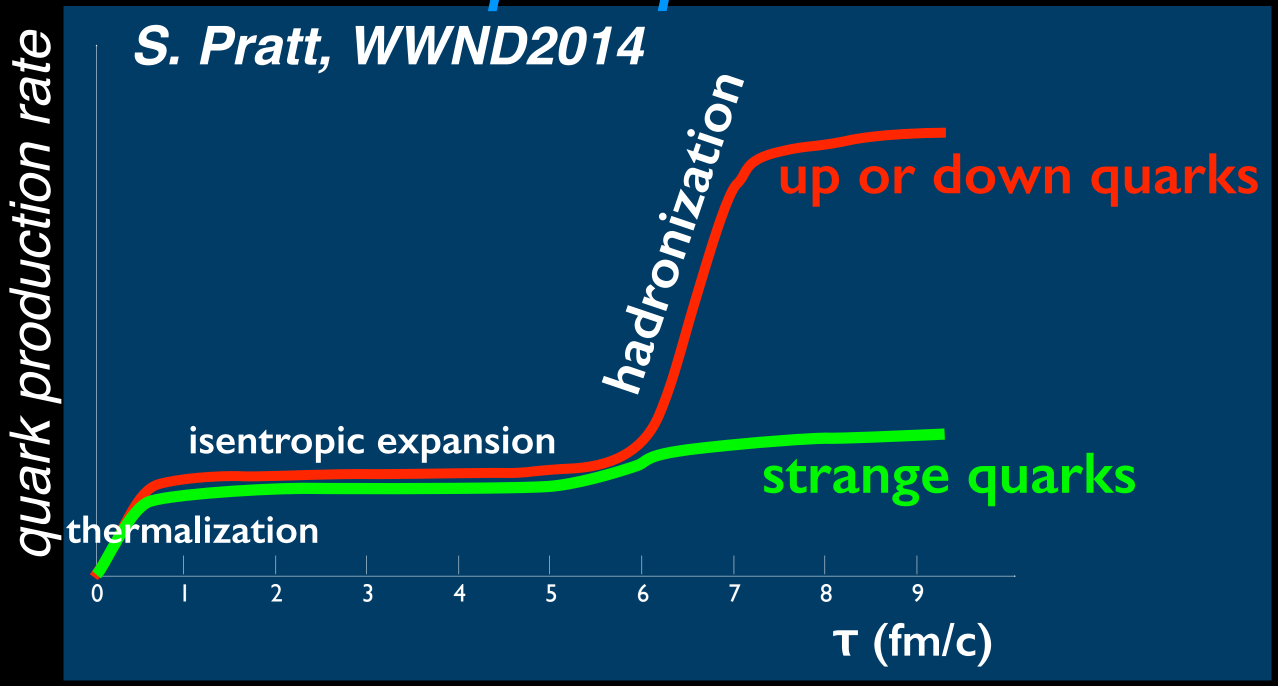
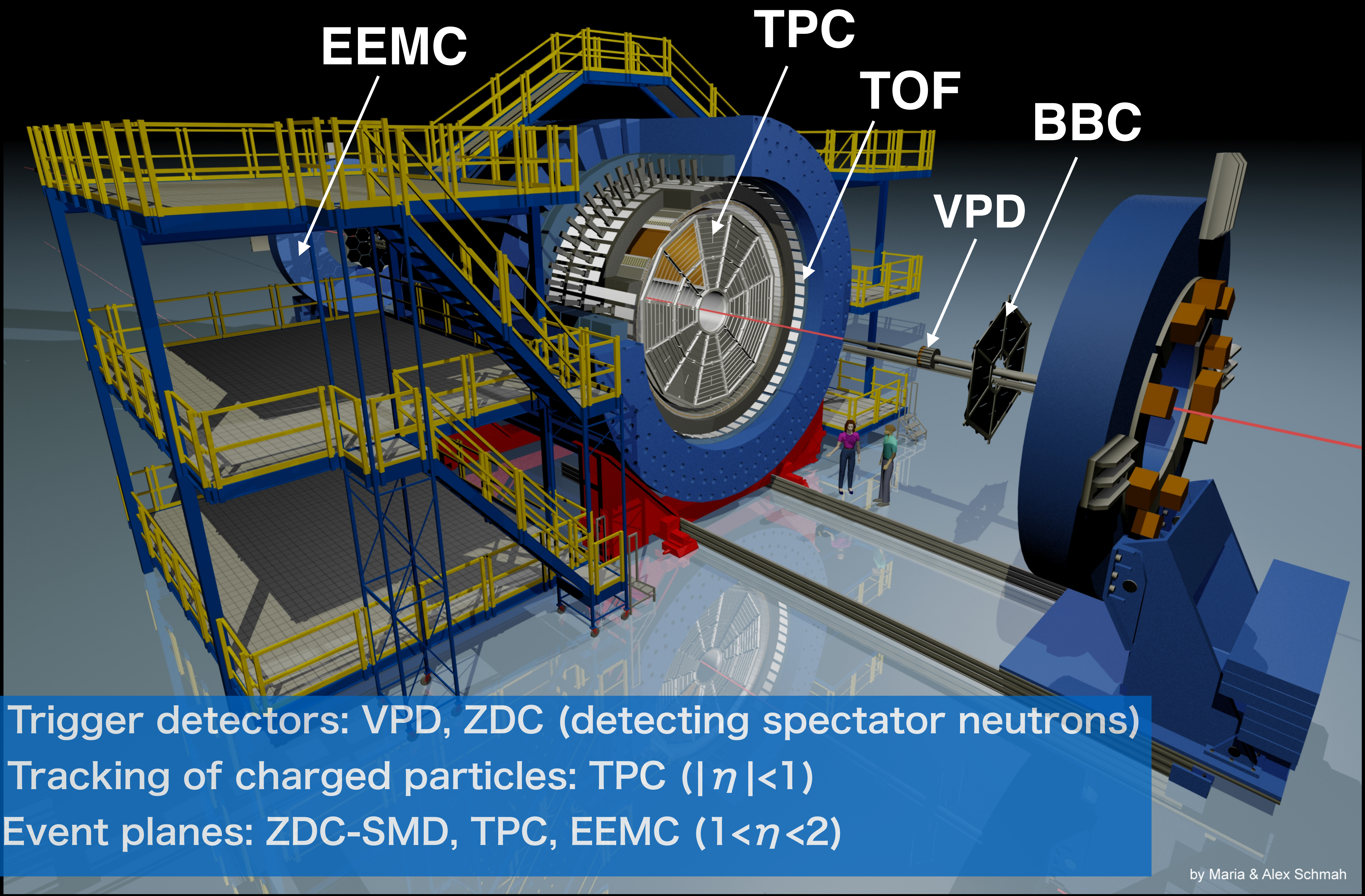
Two wave of quark production



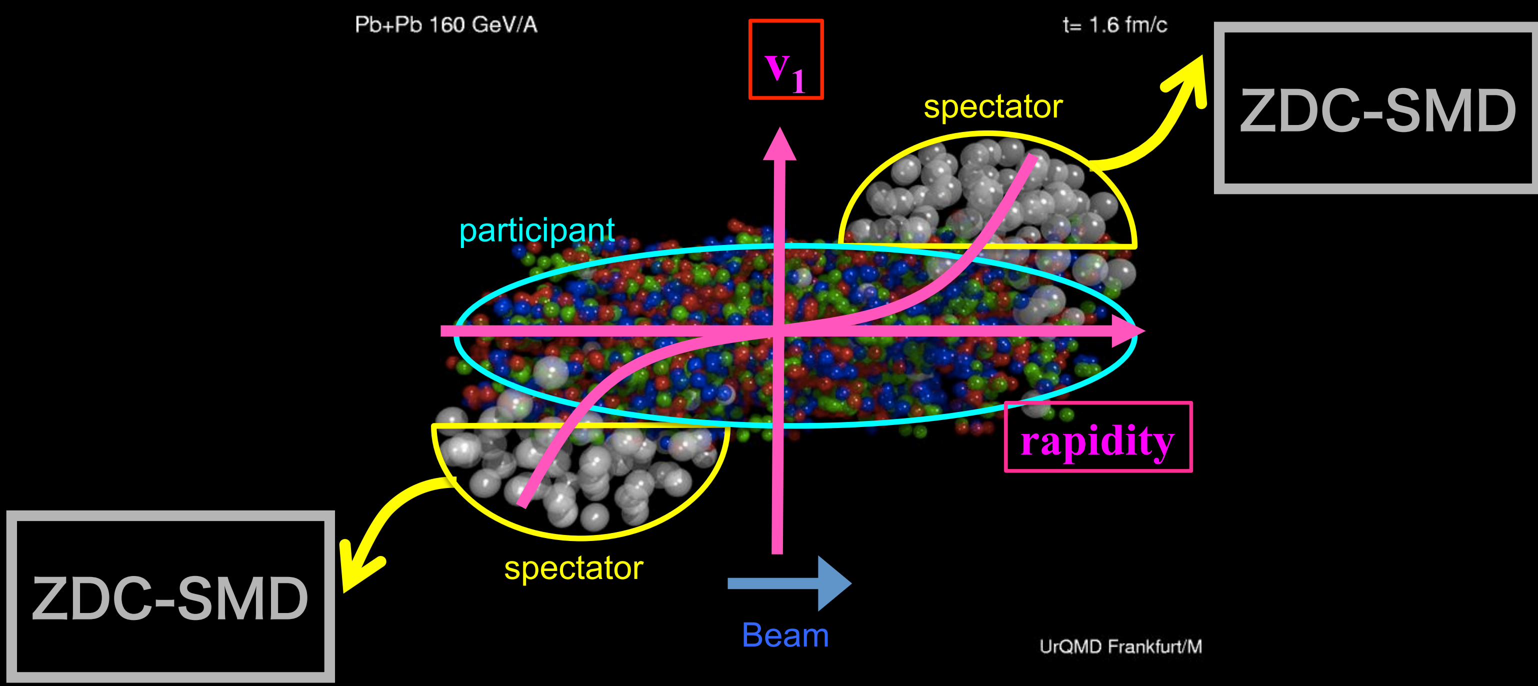
- Probe into the time evolution of quark production
- Also important input for theoretical prediction of CME/CMW

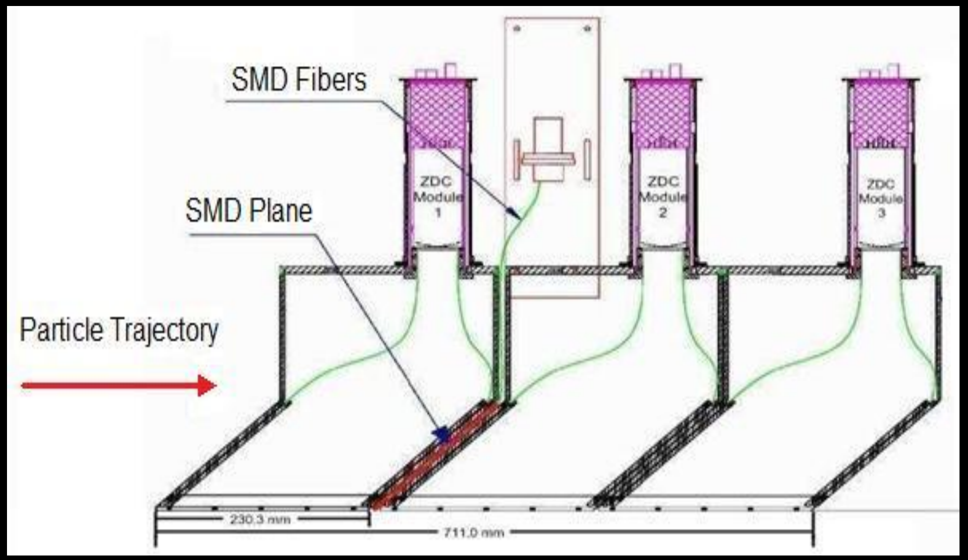
Solenoidal Tracker At RHIC (STAR)



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

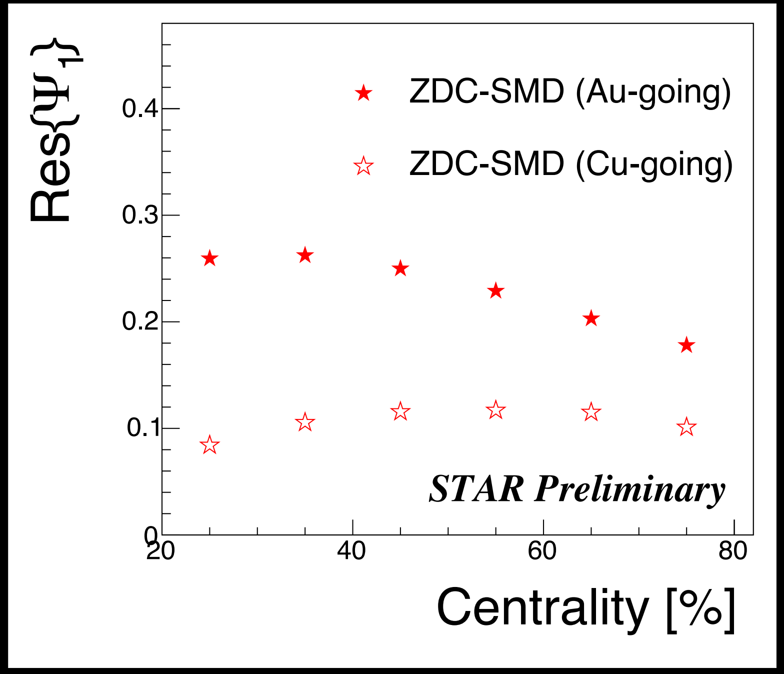
Directed flow measurement





- Ψ_1 **determined by Zero Degree Calorimeter (ZDC) and Shower Max Detector (SMD)**
  - measure the energy and position of spectator neutrons
  - located at $|\eta|>6.3$
- **Minimize the non-flow contribution like the momentum conservation and any other effects**

$$v_1 = \langle \cos(\phi - \Psi_1) \rangle / \mathrm{Res}\Psi_1$$



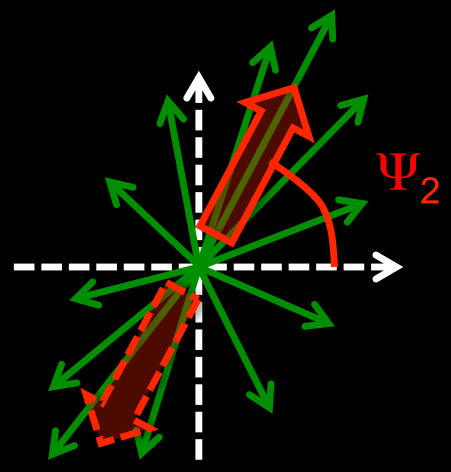
Measurements of azimuthal anisotropies

Event plane method

- Ψ_n (n>1) determined by TPC(η-sub) and EEMC

$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle / \mathrm{Res}\{\Psi_n\}$$

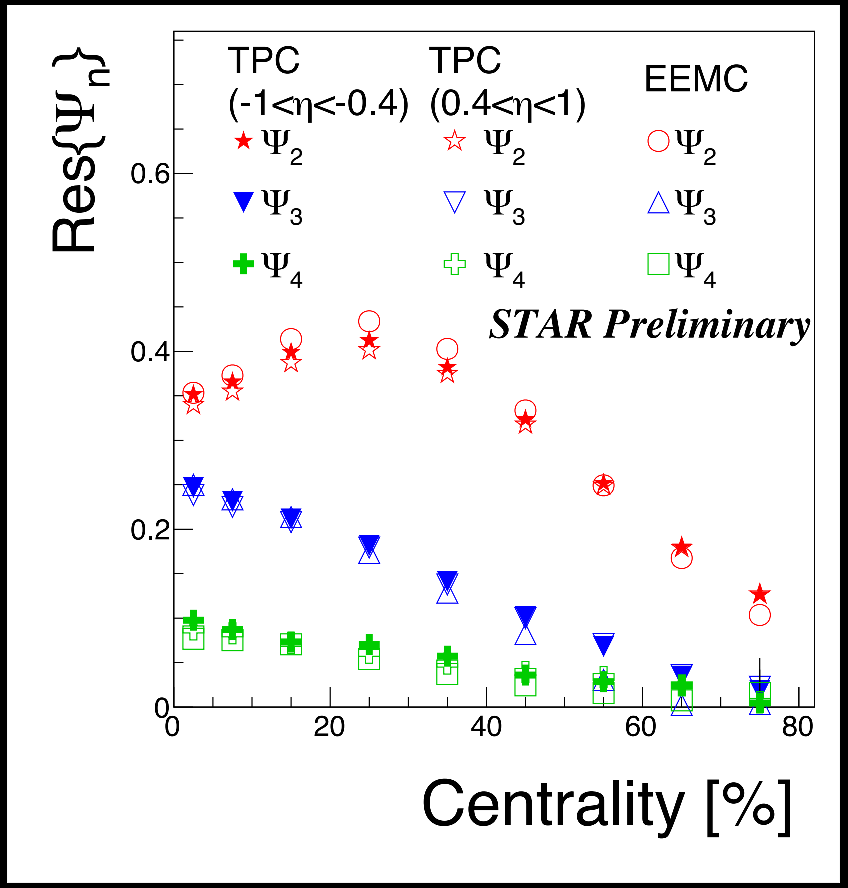
$$\Psi_n = \frac{1}{n}\tan^{-1}(Q_{n,y}/Q_{n,x})$$
$$Q_{n,x} = \Sigma w_i \cos(n\phi)$$
$$Q_{n,y} = \Sigma w_i \sin(n\phi)$$



Scalar product method

- STAR, PRC66.034904 (2002)
- v_n (n>1) using flow vectors determined by TPC-tracks in forward and backward region

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

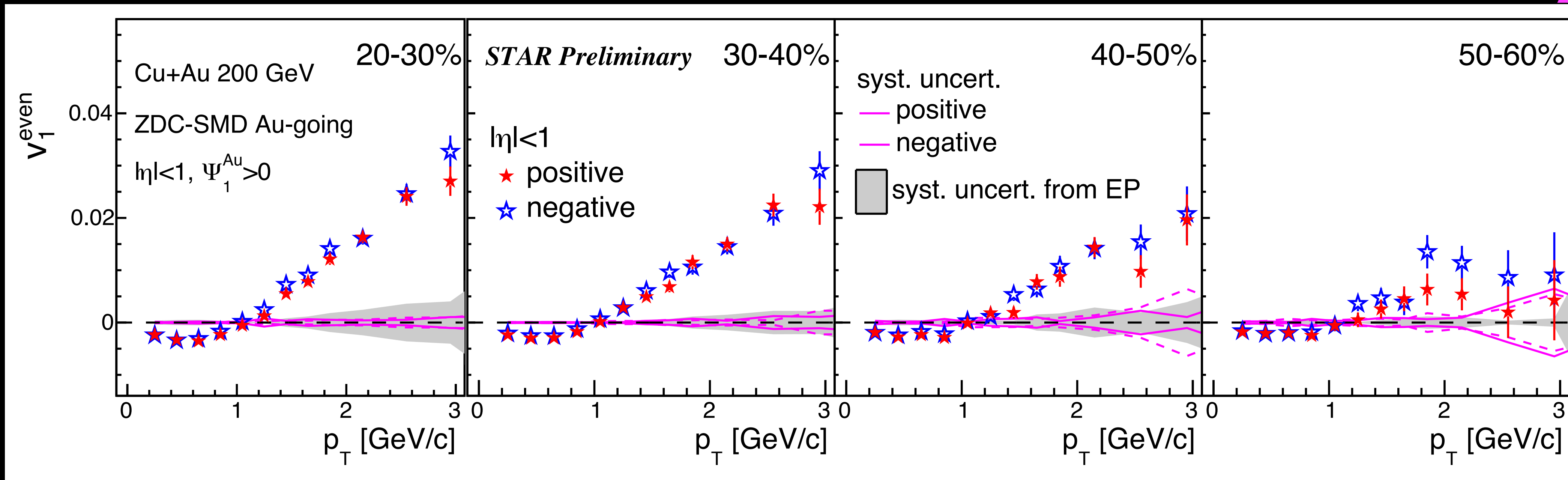


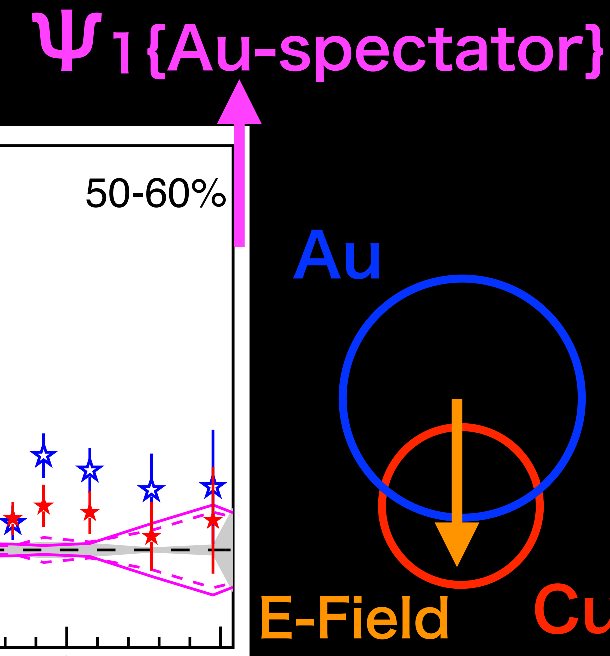
Systematic uncertainty

- 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

Cu-going direction: η>0



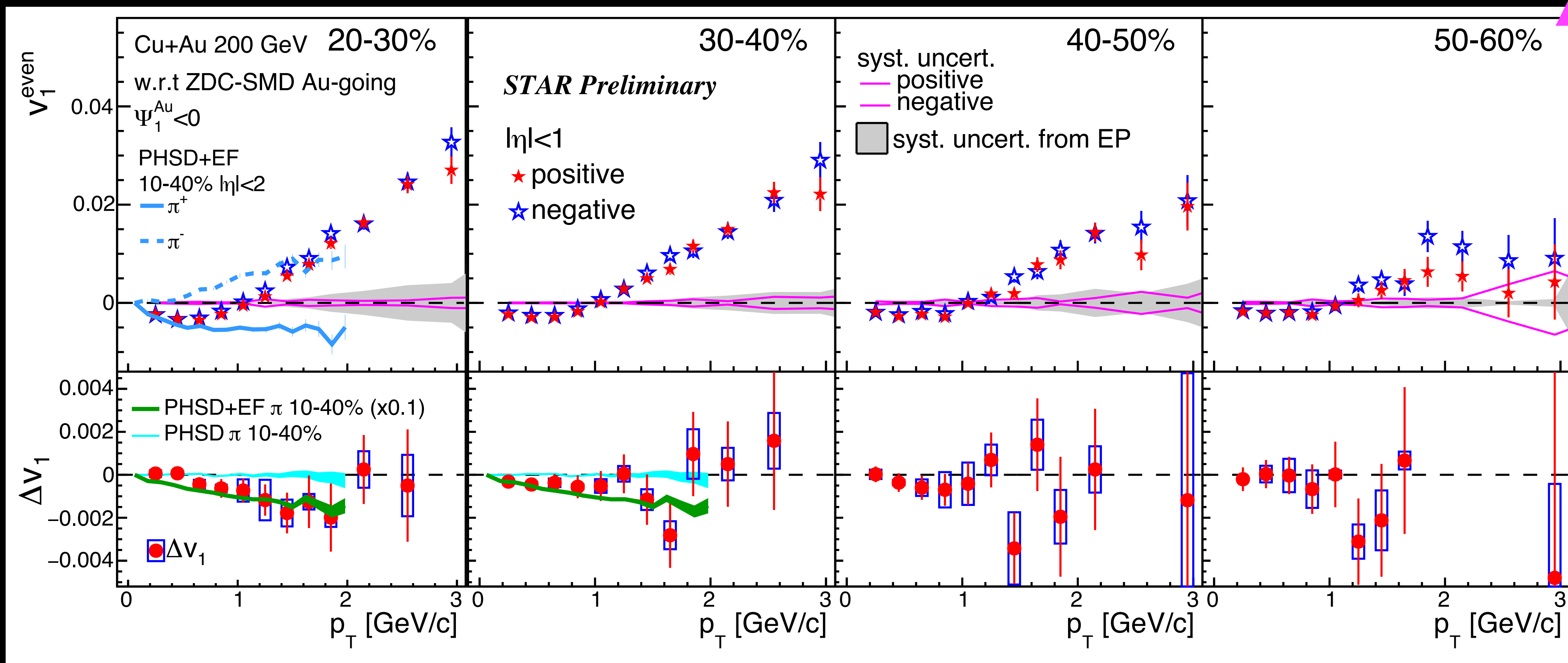


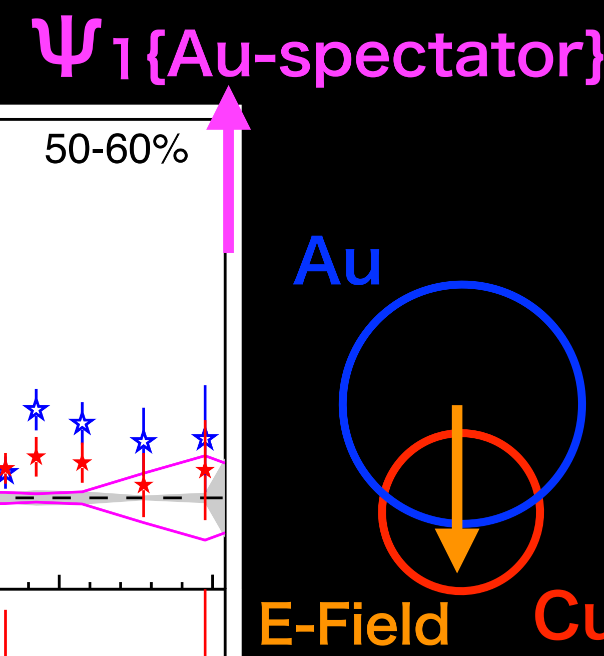
$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

- Sizable v_1 measured relative to Ψ_1{ZDC-SMD} in Au-going side (Ψ_1^{Au}<0)
  - v_1 become smaller in more peripheral collisions
  - Negative v_1 in p_T<1GeV/c: more low p_T particles in Cu-side
  - Positive v_1 in p_T>1GeV/c: more high p_T particles in Au-side

- Larger v_1 compared to A+A collisions
  - $|v_1^{even}|$~0.2% in Pb+Pb 2.76TeV, $|v_1^{odd}|$~0.3% in Au+Au 200GeV
  - Note: v_1^{even} in A+A is only due to density fluctuations

Charge-dependent directed flow



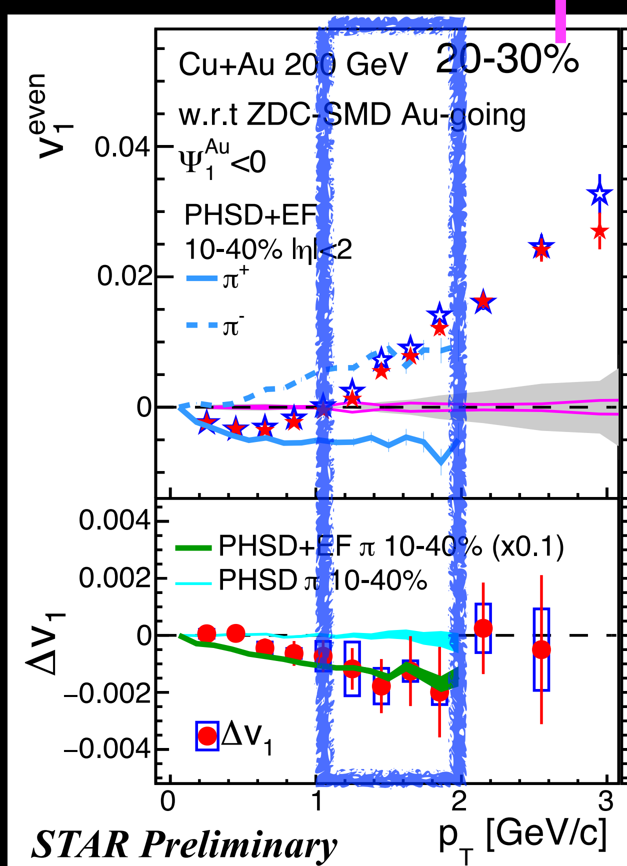


- $\Delta v_1 = v_1(h^+) - v_1(h^-)$, and $v_1 \sim 1\%$, $\Delta v_1 < 0.2\%$
  - Δv_1 looks to be negative in $p_T < 2$ GeV/c,
  - similar p_T dependence to PHSD model (PRC90.064903), but **smaller by a factor of 10**

- Finite Δv_1 indicates the **existence of E-field**
- Small Δv_1 indicates the **number of quarks at times earlier than the E-field life time(~0.25 fm/c) would be very small**
  - PHSD assumes all partons are present at t~0 and affected by the E-field

η dependence of v1

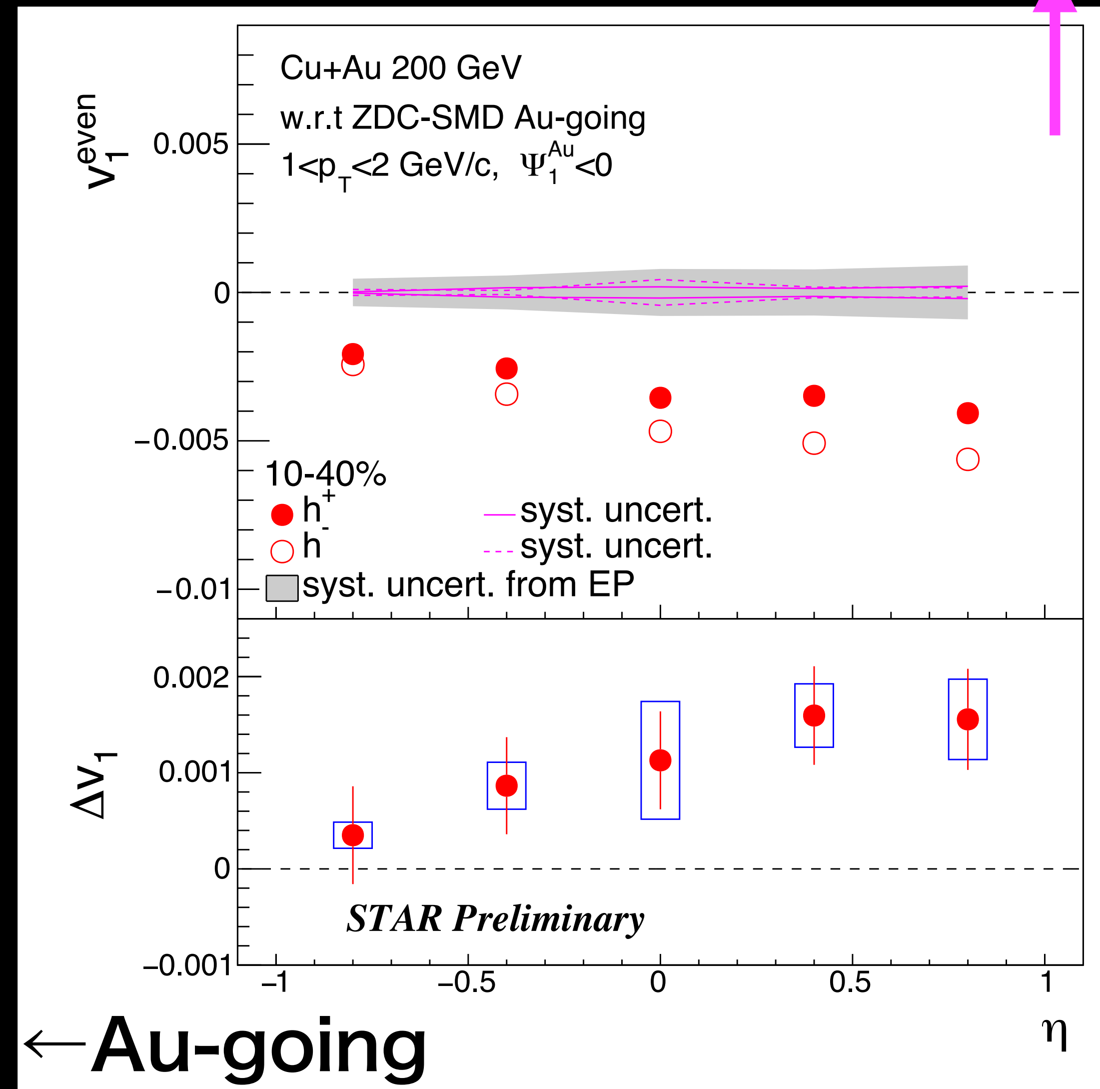
Ψ_1 {Au-spectator}

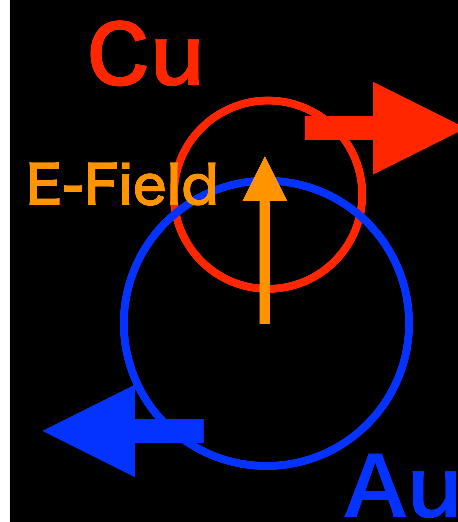


pT=1-2

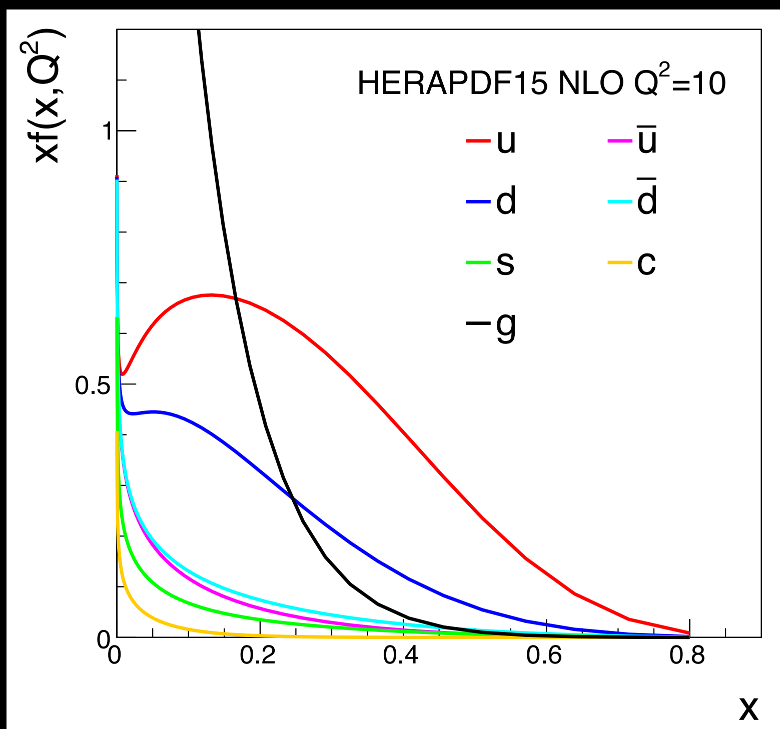
Note:
opposite def.
in sign of v1

Ψ_1 {Cu-spectator}





- Charge-difference can be seen in -1<η<1 and 1<p_T<2 GeV/c
  - Difference looks larger in Cu-going direction
  - Opposite trend to the PHSD model, related to asymmetric # of participants in forward and backward rapidity?



http://hepdata.cedar.ac.uk/

How many quarks at initial state?

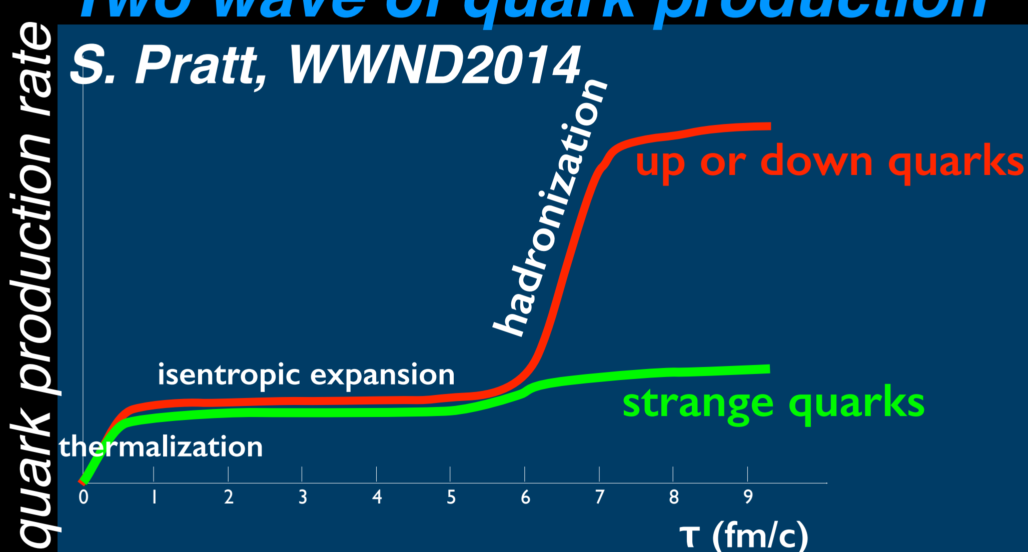
- Rough estimate from PDF
  - Quark density in PDF →Quarks at initial state
  - Quarks + Gluons in PDF →All quarks created
    - Assuming gluons are converted to 2 quarks at final state

$$x \sim \frac{p_T}{\sqrt{s}} e^{\eta}$$

  - $0.2<p_T<1$ GeV/c, $|\eta|<1$, $\sqrt{s}$=200 GeV → $4\times10^{-4} < x < 0.01$
  - Initial quarks/All quarks created **~15%**, which is close to 10% obtained from Δv_1+PHSD model

Suggest small fraction of initial quarks to all quarks!

Two wave of quark production

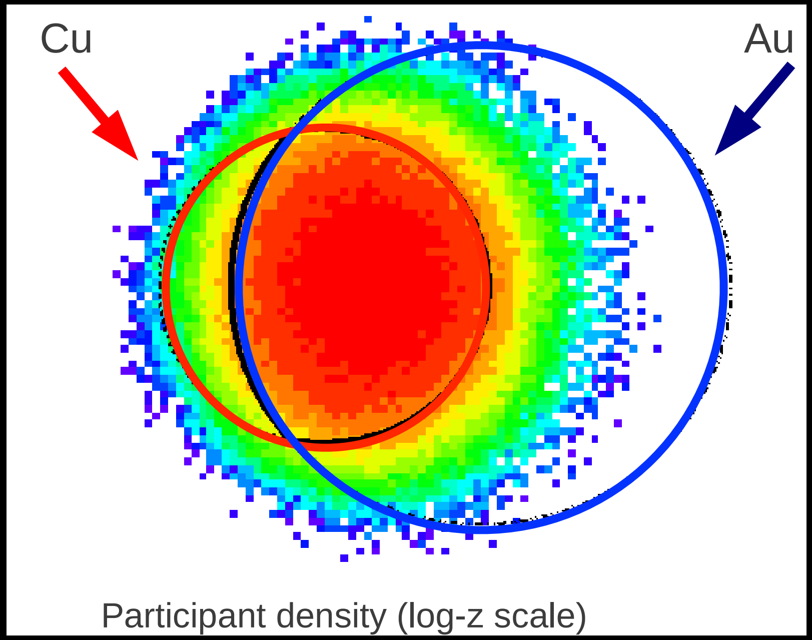


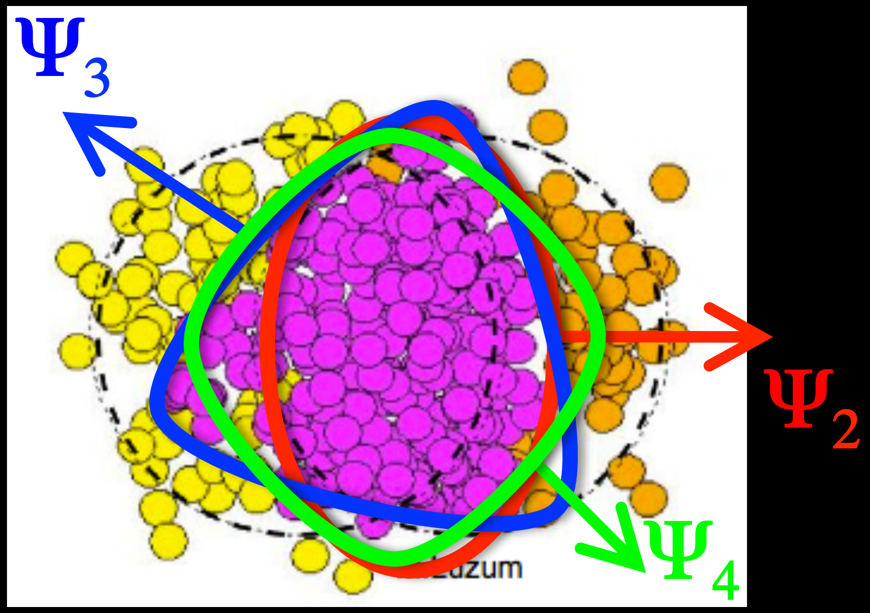
Possible explanation?

- Two wave scenario of light quark production, where small fraction of quarks are created at early time

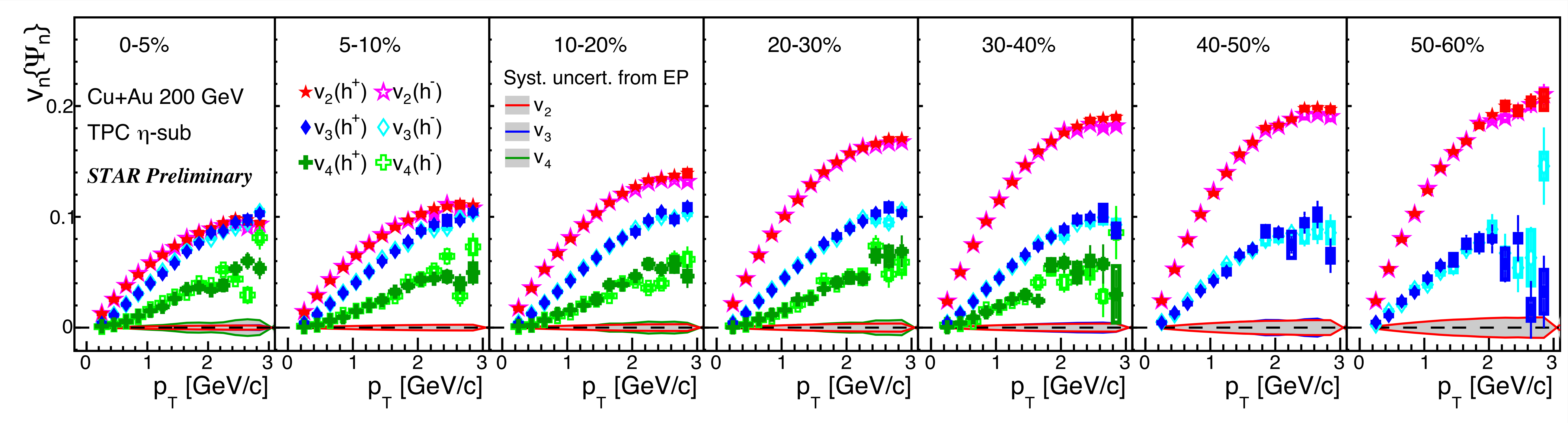
Higher-order flow

- Higher-order flow under the asymmetric pressure gradient
  - Any difference from symmetric collisions, especially in odd components?
  - Good test of the hydrodynamic model which reasonably describes the symmetric collisions



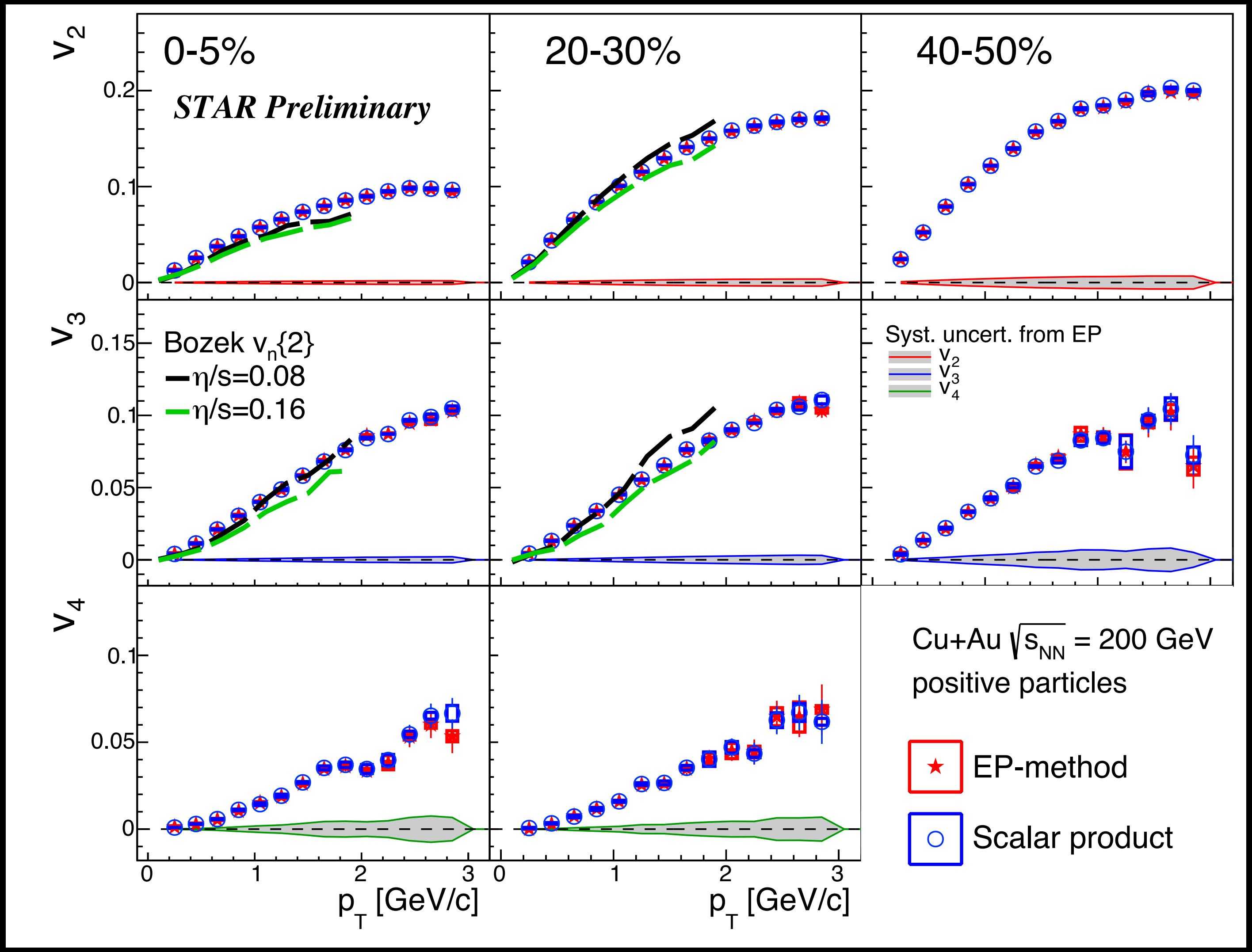


Higher-order azimuthal anisotropy



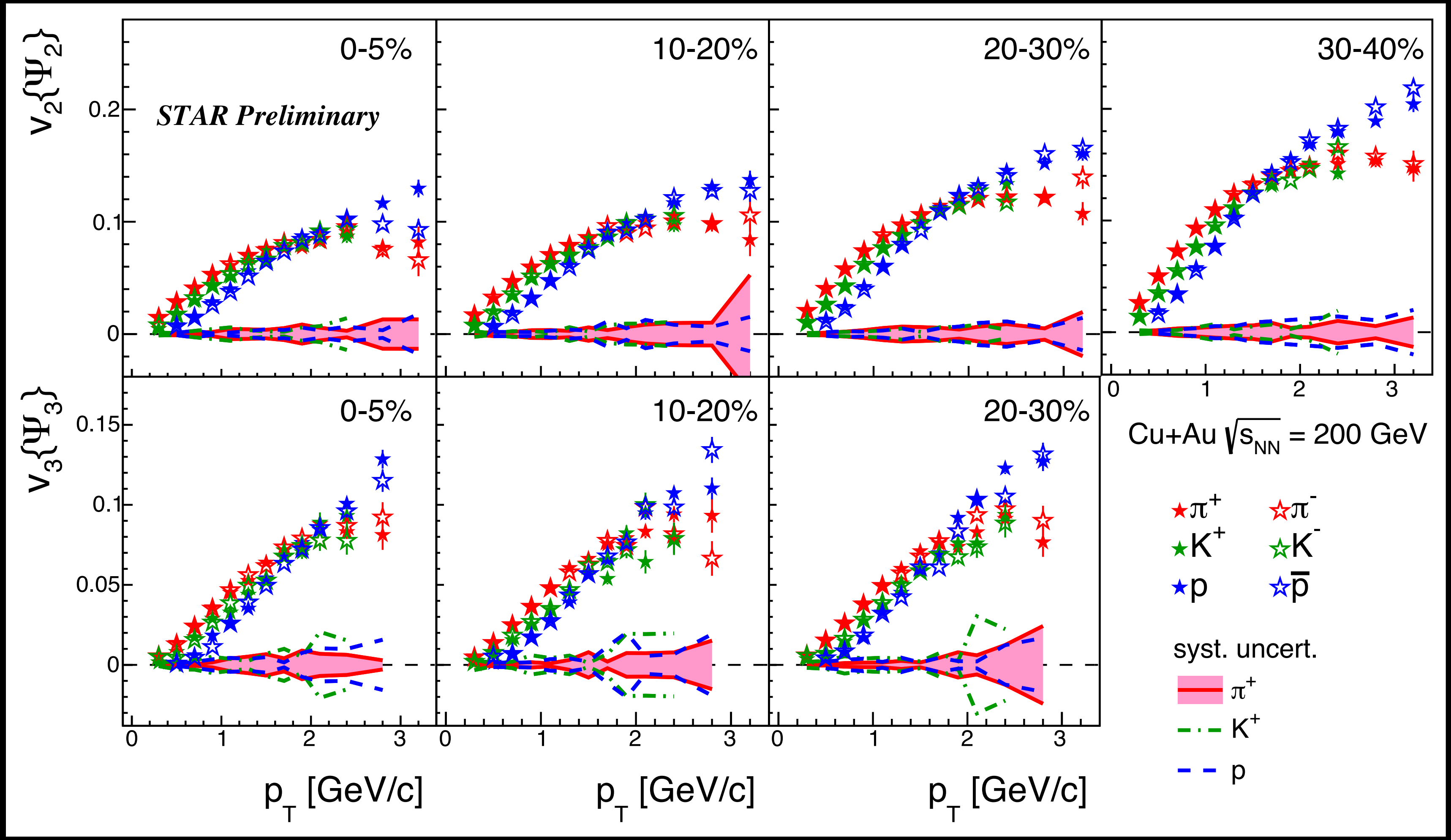
- Centrality dependence of v_2 is similar to Au+Au
- Weak centrality dependence of v_3 as seen in Au+Au
  - Slightly larger in most central events due to the intrinsic triangularity?
- Finite v_4 is observed
  - weaker centrality dependence than Au+Au
- No charge dependence for v_n (n>=2)

Comparison with Hydro-model



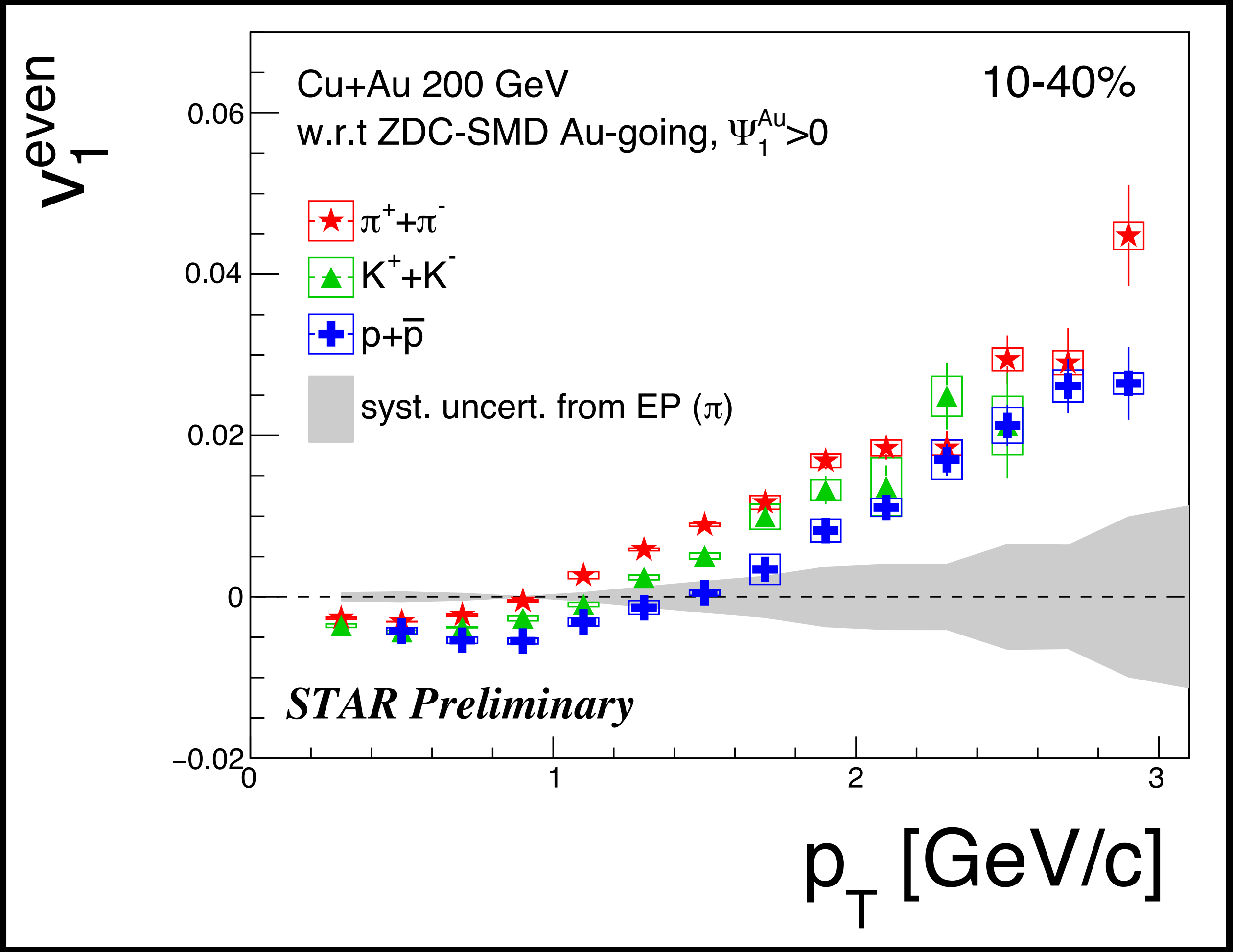
- $v_n\{EP\}$ is in good agreement with $v_n\{SP\}$
- v_2 and v_3 are described well by e-b-e viscous hydrodynamic model
  - Bozek, PLB.717(2012)287
  - The data are close to the model calculations with η/s=0.08 and 0.16

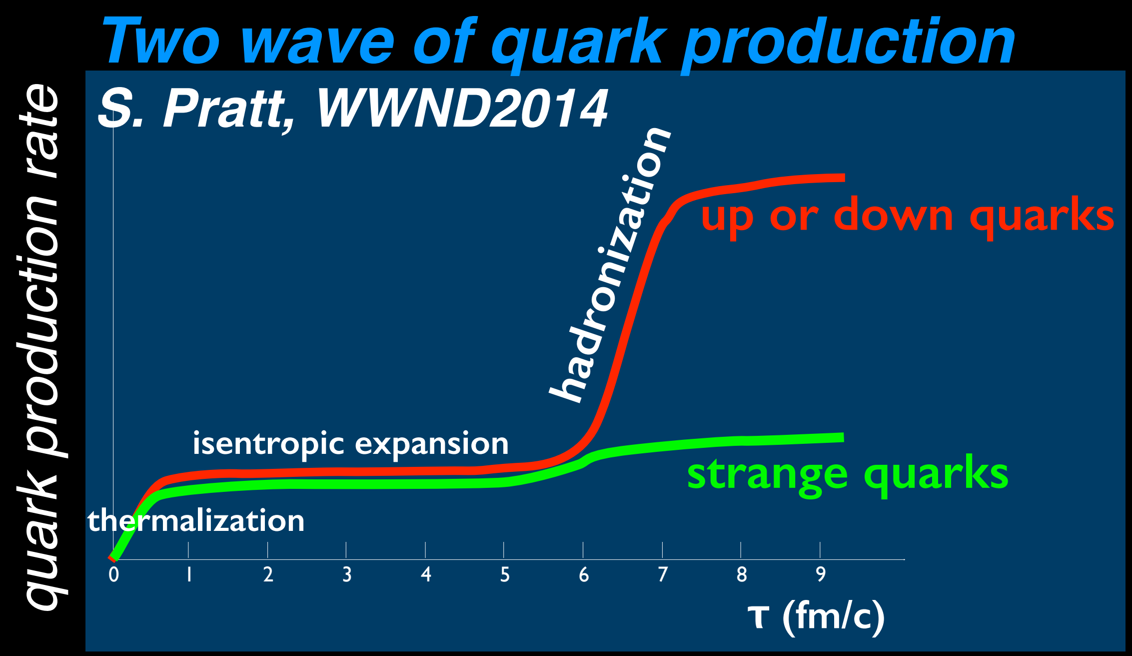
Identified Particle v_n



- π /K/p identification by TPC + TOF
- Similar trends observed in A+A collisions
  - Mass ordering at low p_T (effect of radial flow)
  - Baryon/meson splitting at intermediate p_T (partonic flow)

Identified Particle v_1





- Mass ordering at low p_T is seen as well as v_2 and v_3
  - this is also explained by the radial flow (Voloshin et al., NPA638,455(1998))
- Would be interesting to look at charge-dependent kaons
  - To test the two wave scenario, where s and u quark productions are supposed to be different

Summary

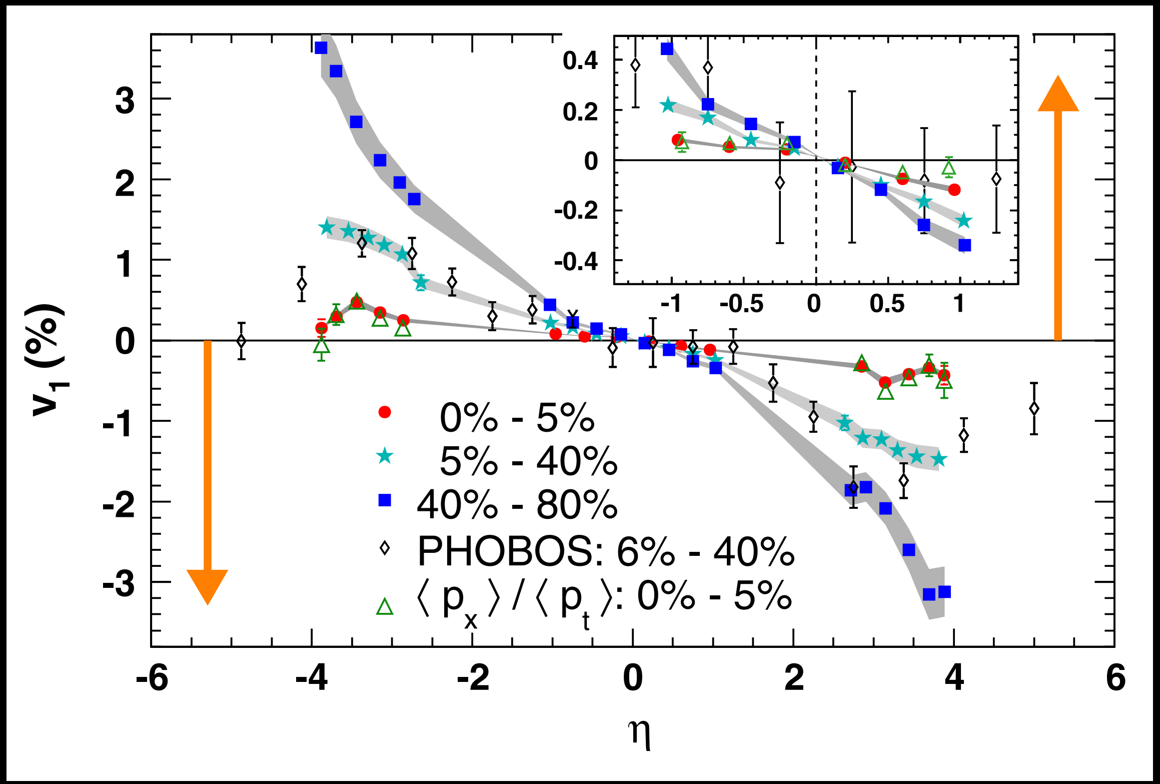
- Charge-dependent directed flow in Cu+Au collisions
  - Charge difference of v_1 was observed, which is consistent with an existence of the initial electric field
  - Observed $\Delta v1$ is much smaller than the PHSD model prediction, likely indicating that the number of initial (anti-)quarks would be very small when the E-Field is strong ($t<0.25$ fm/c)
  - Simple estimate with PDF is consistent with the above interpretation
- Important input for understanding the time evolution of quark density, which also leads to better estimate of CME/CMW signals

- Higher-order flow (v_2-v_4) in Cu+Au
  - v_3 has a similar centrality dependence to Au+Au, and v_4 has a weaker centrality dependence than Au+Au
  - PID v_1, v_2, and v_3 have been presented

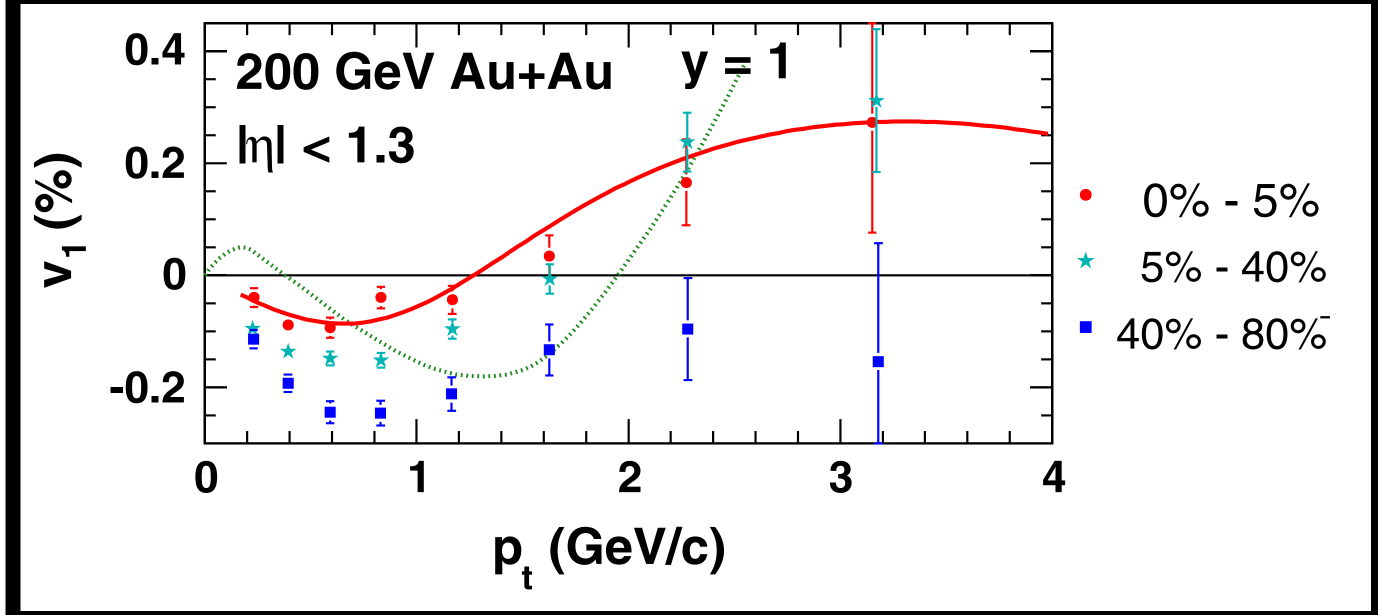
Thank you for your attention!

Back up

v_1^{odd} in Au+Au 200GeV



STAR, PRL101.252301

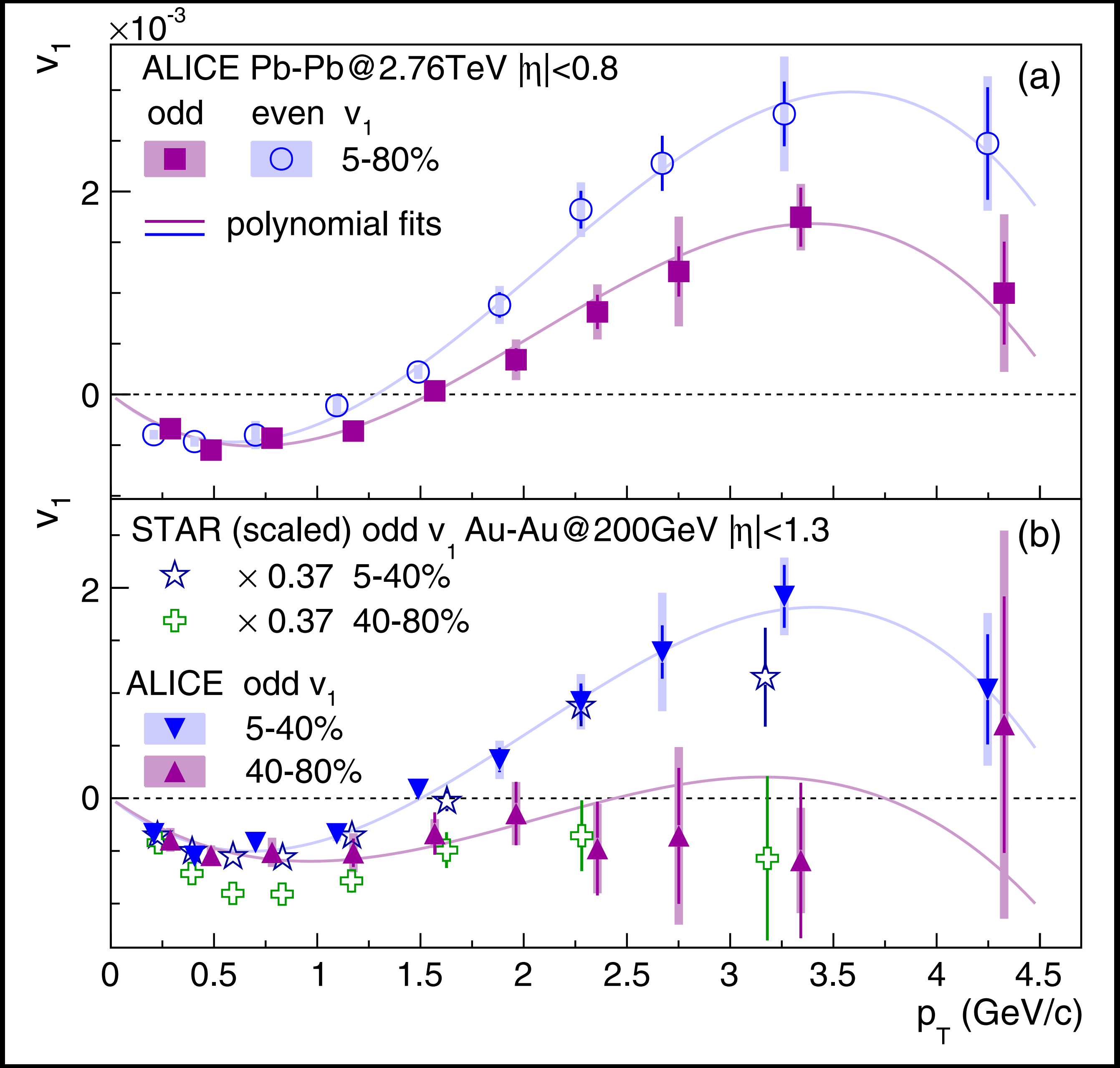


- Small signal of v_1 at mid-rapidity in Au+Au collisions

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

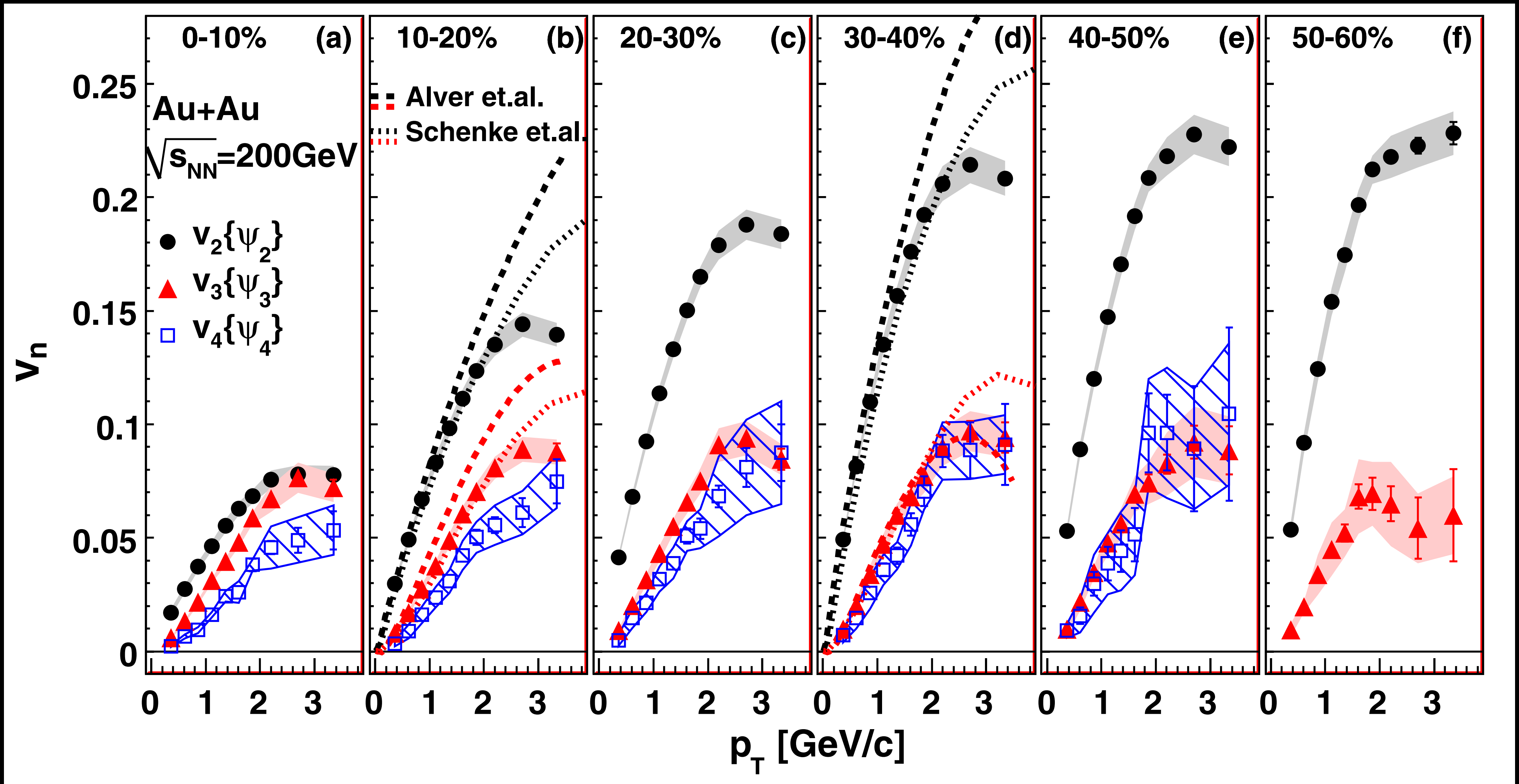
v_1^{even} and v_1^{odd} in Pb+Pb 2.76 TeV

v_1 in Au+Au vs Pb+Pb
ALICE, PRL111.23202

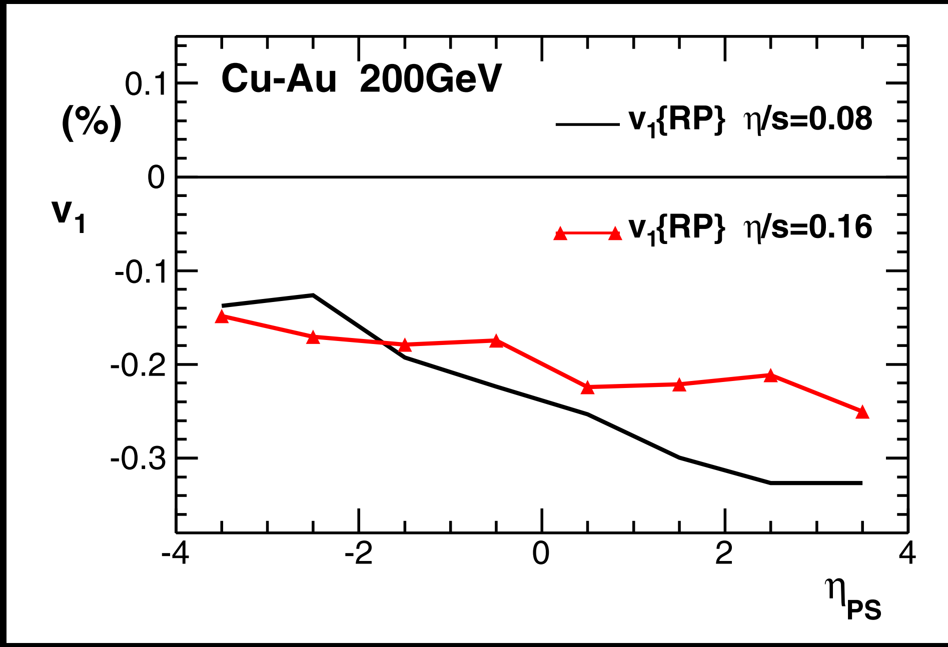


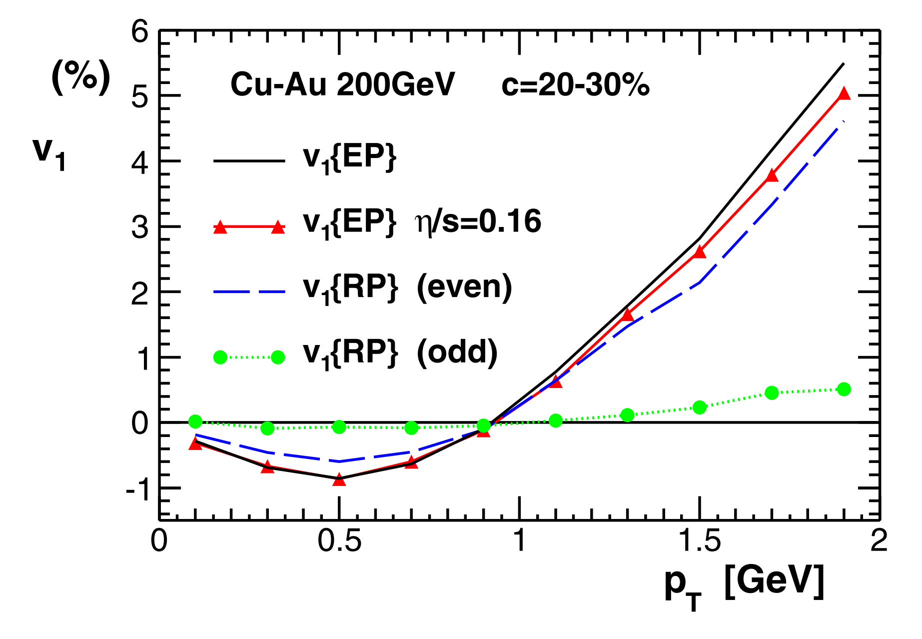
Higher-order flow in Au+Au

PHENIX, PRL107.252301



E-b-e viscous hydrodynamics in Cu+Au



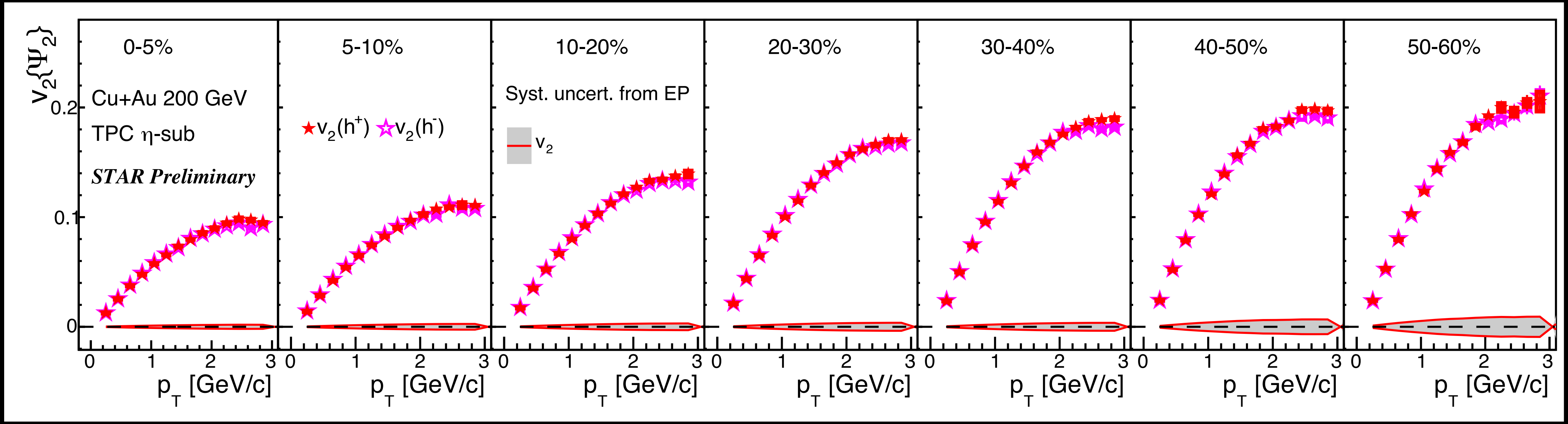


P. Bozek, PLB717(2012)287

$$v_1^{\text{even}} = \langle \cos(\phi - \Psi_1) \rangle$$

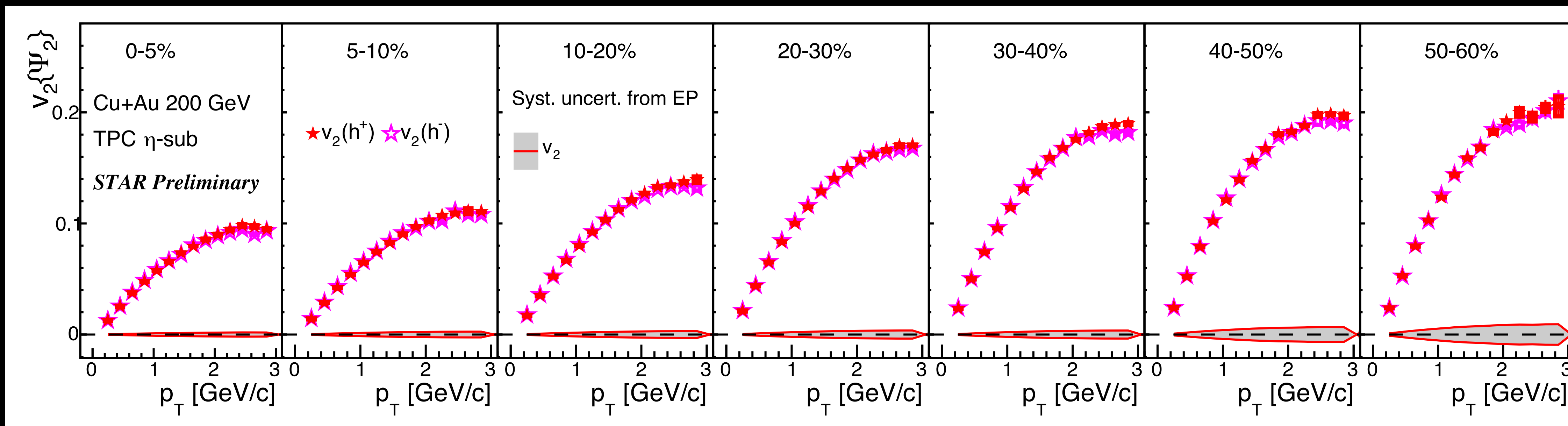
$$v_1^{\text{odd}} = \langle sgn(\eta) \cos(\phi - \Psi_1) \rangle$$

Higher-order azimuthal anisotropy

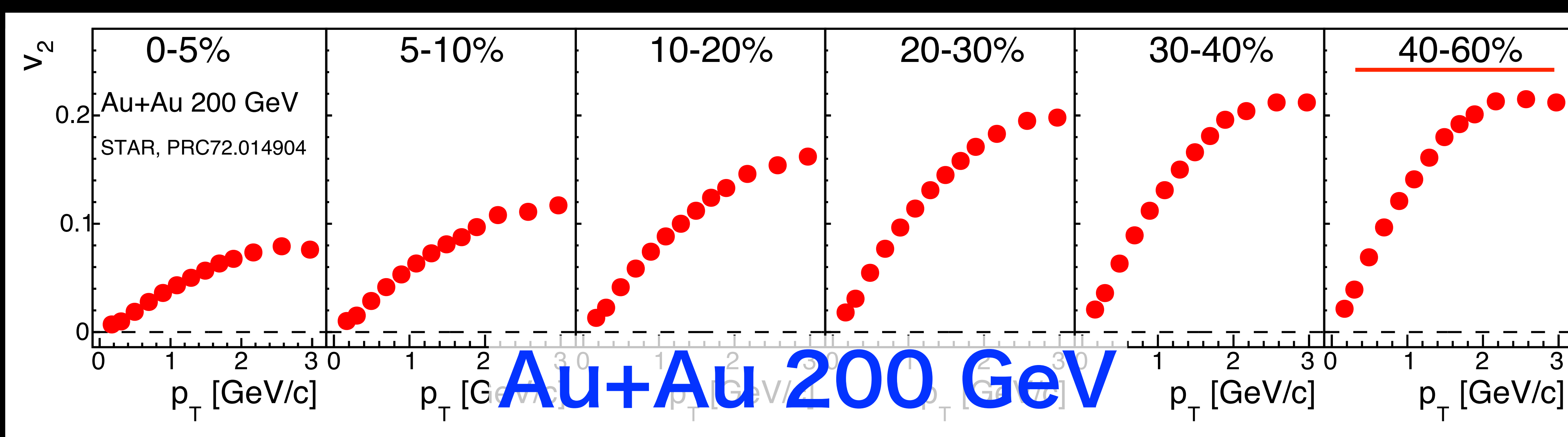


- Centrality dependence of v_2 is similar to Au+Au

Higher-order azimuthal anisotropy

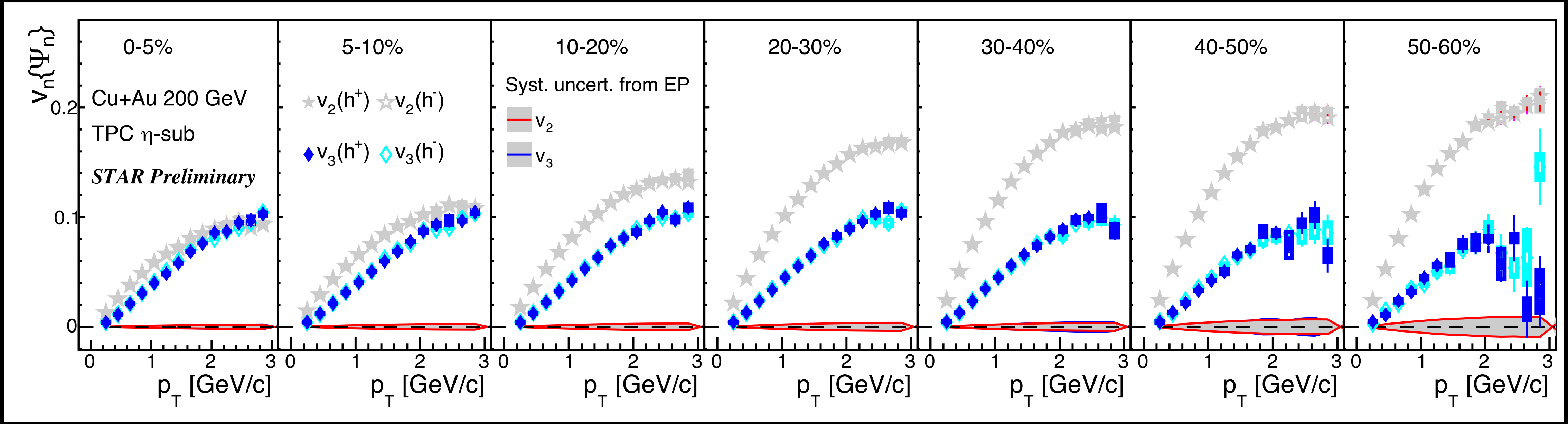


- Centrality dependence of v_2 is similar to Au+Au



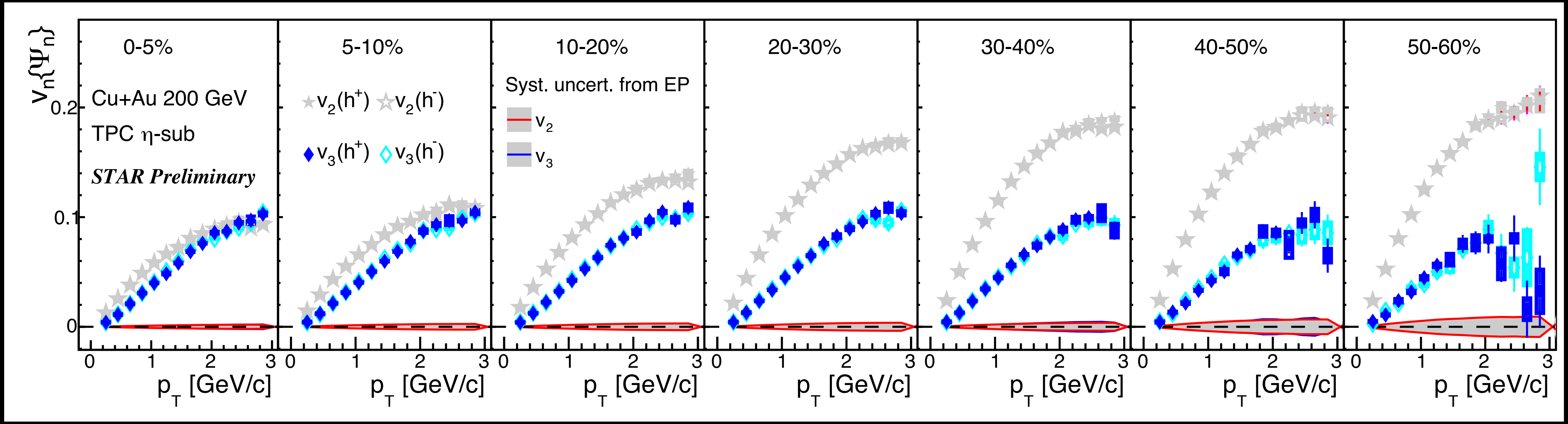
Au+Au 200 GeV

Higher-order azimuthal anisotropy



- Centrality dependence of v_2 is similar to Au+Au
- Weak centrality dependence as seen in Au+Au
  - Slightly larger in most central events due to the intrinsic triangularity?

Higher-order azimuthal anisotropy



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