Charge-dependent anisotropic flow in Cu+Au collisions

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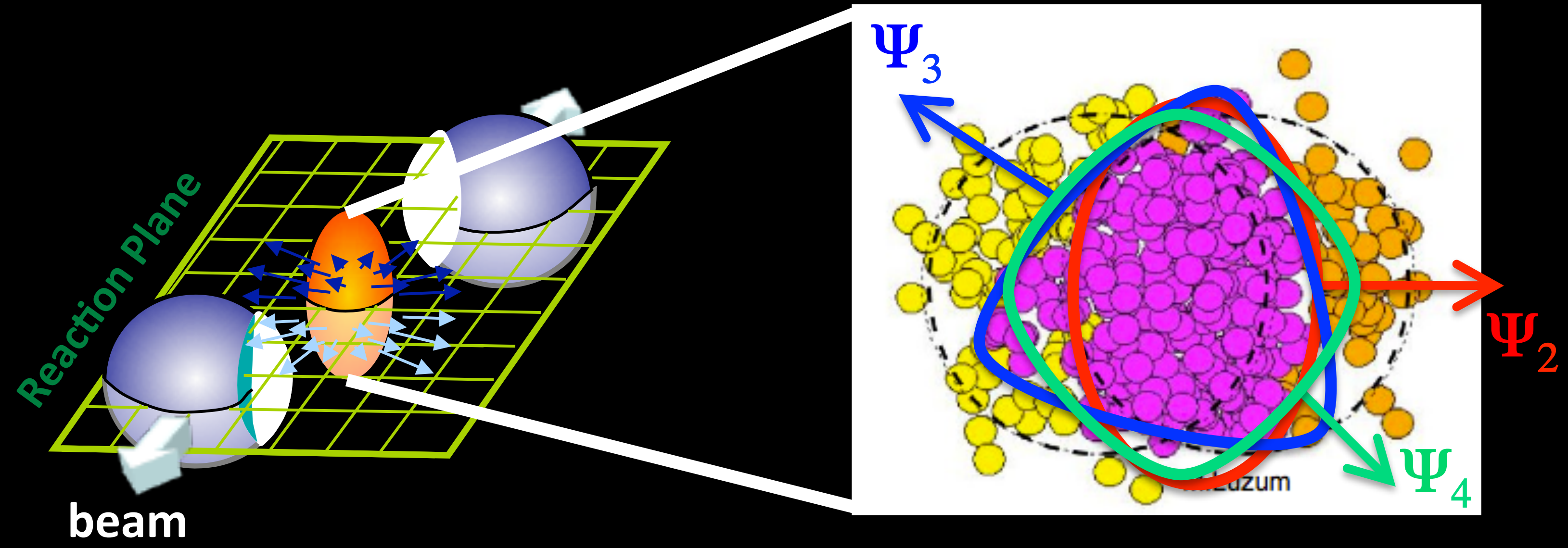
Quark Matter 2015
Kobe (神戸)

Azimuthal anisotropy v_n

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



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

A. Poskanzer and S. Voloshin PRC58,1671 (1998)

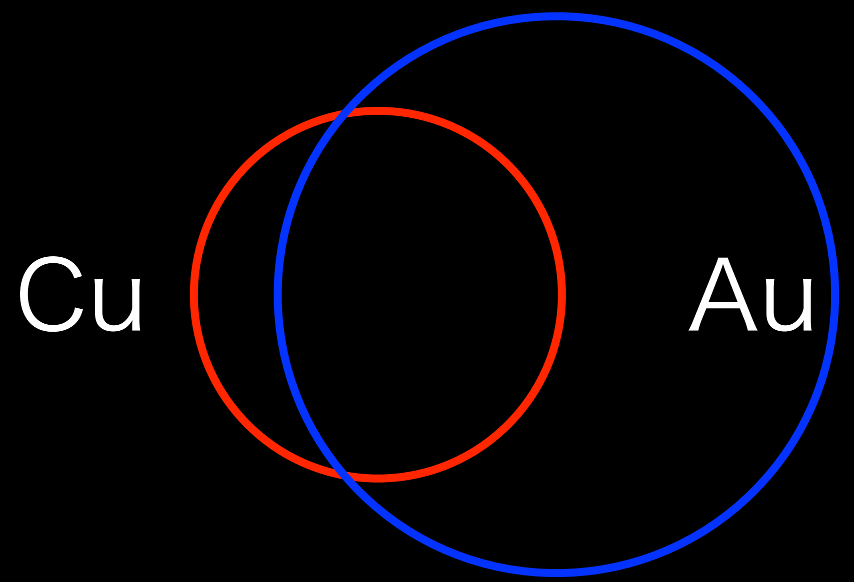
Directed flow (v_1): sensitive to EoS and phase transition

Elliptic(v_2), Triangular(v_3), ···: sensitive to η/s and initial fluctuations

Many experimental and theoretical studies so far

Cu+Au collisions

- Flexibility of RHIC
  - Au+Au, Cu+Cu collisions
  - d+Au, ^{3}He+Au, p+A collisions @ 200 GeV
  - U+U collisions @ 193 GeV
  - Cu+Au collisions @ 200 GeV ←**this talk**



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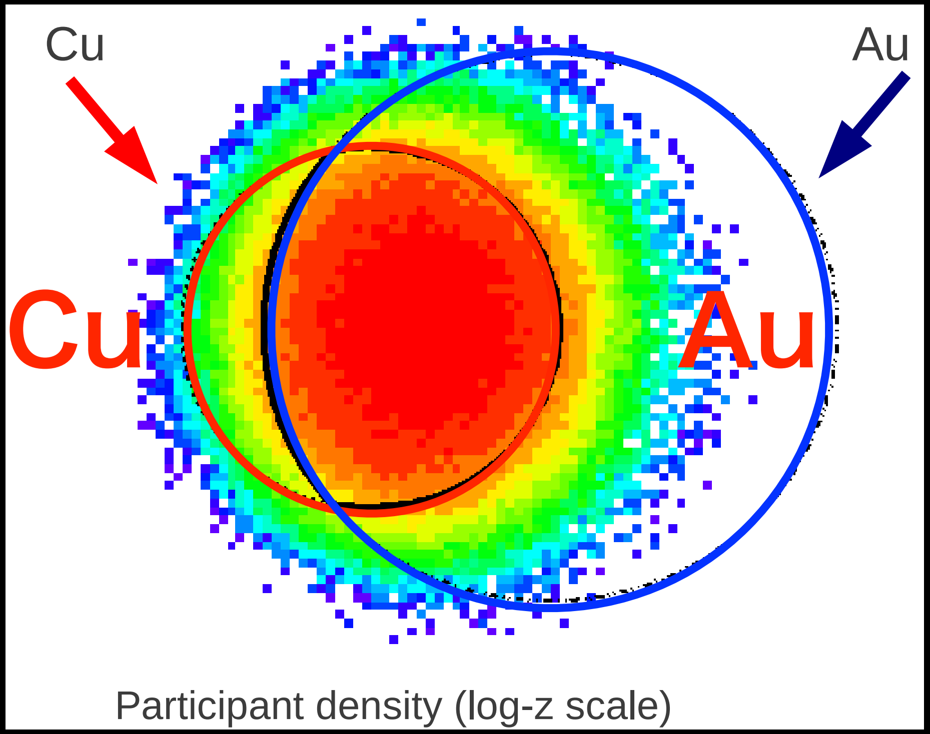

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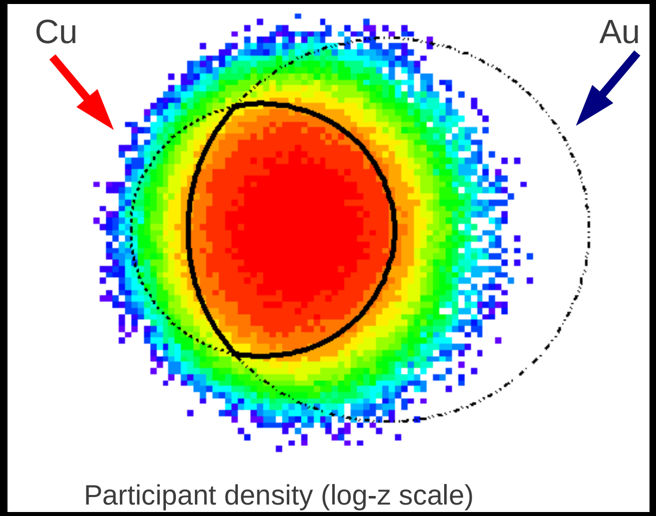
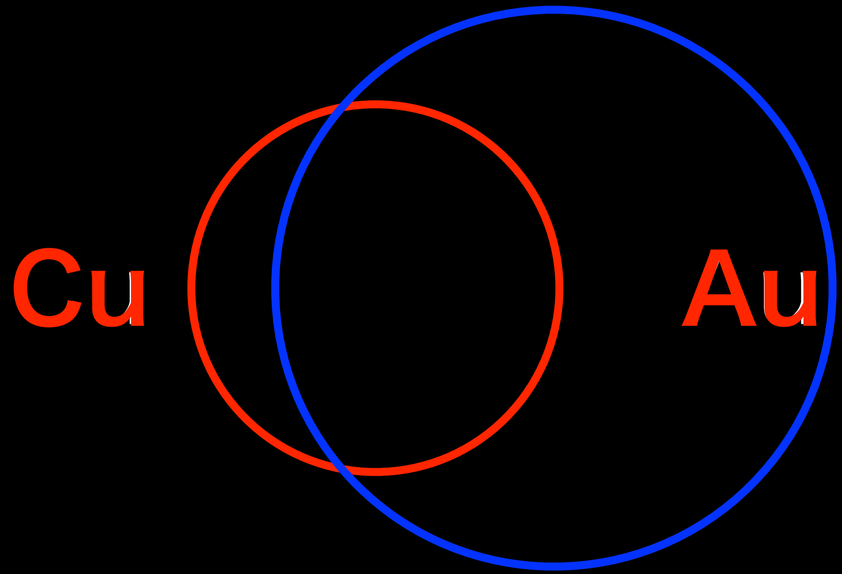
A. Iordanova, RHIC&AGS2013





Asymmetric density profile
Asymmetric pressure gradient

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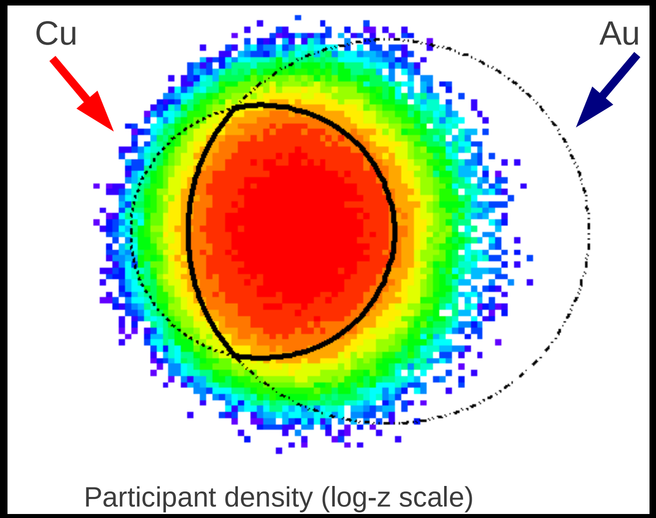

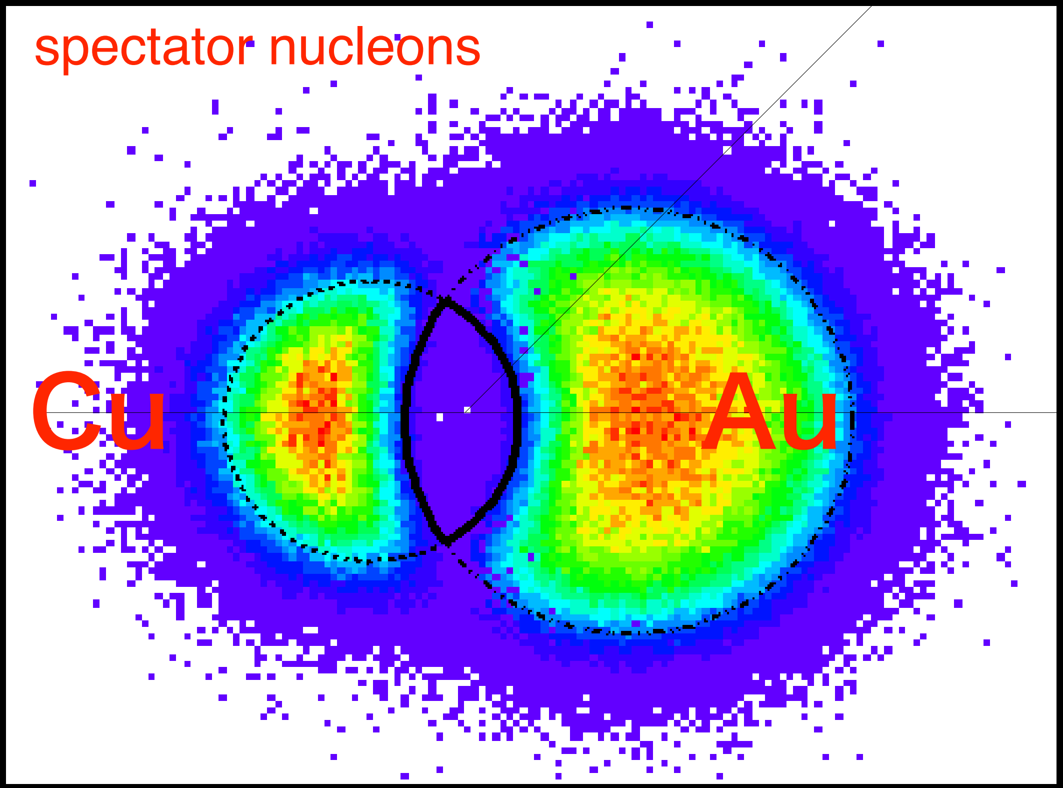

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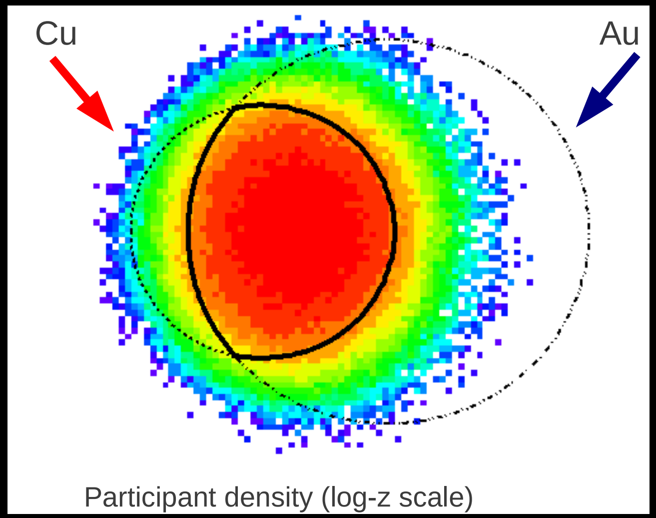
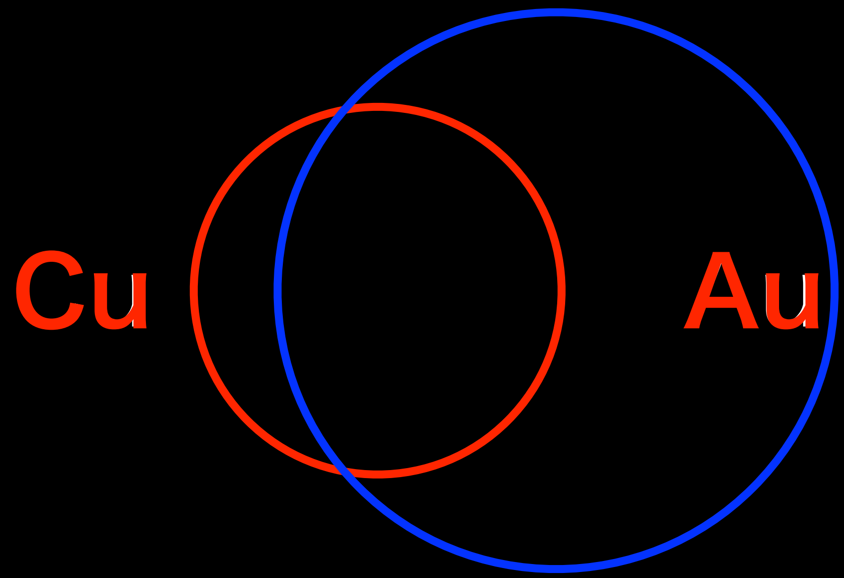
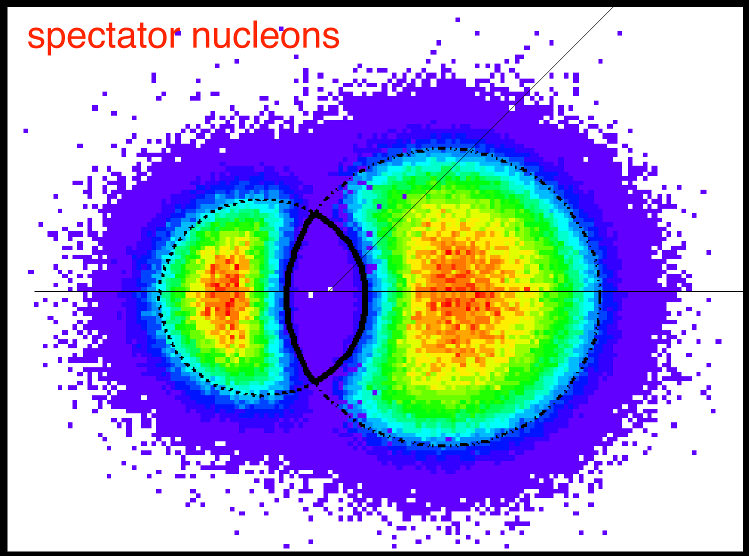






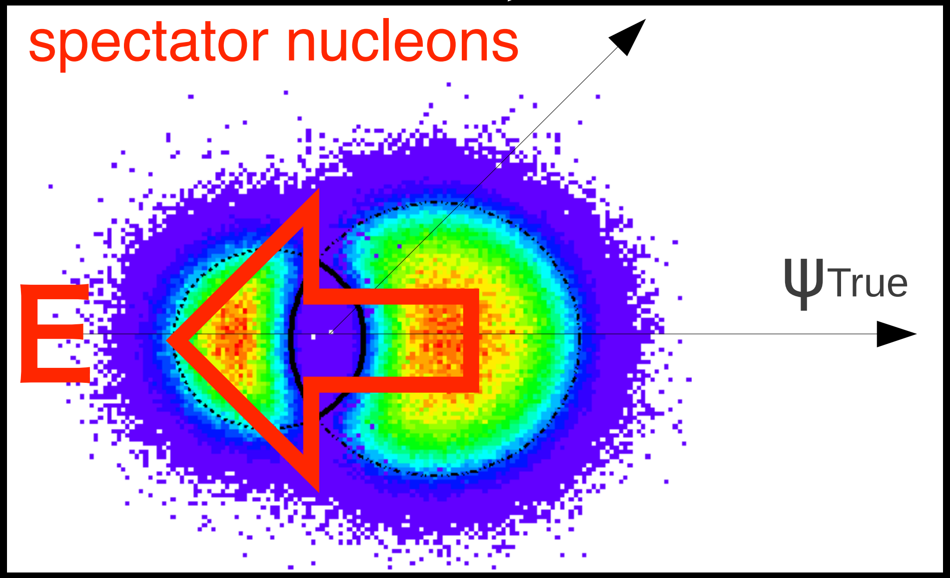
Asymmetric density profile
Asymmetric pressure gradient

Dipole-like charge distribution by spectators

Why interesting?

- Sizable E-field pointing from Au to Cu, due to different number of protons in both spectators

A. Iordanova, RHIC&AGS2013



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- Sizable E-field pointing from Au to Cu, due to different number of protons in both spectators
- Expect **charge dependence of directed flow**
  - Electric conductivity of QGP (Y. Hirono et al., PRC90.021903)
  - Sensitive to the quark/anti-quark creation time (V. Voronyuk et al., PRC90.064903)
- Understanding the time evolution of quark density is also important for theoretical prediction of CME/CMW

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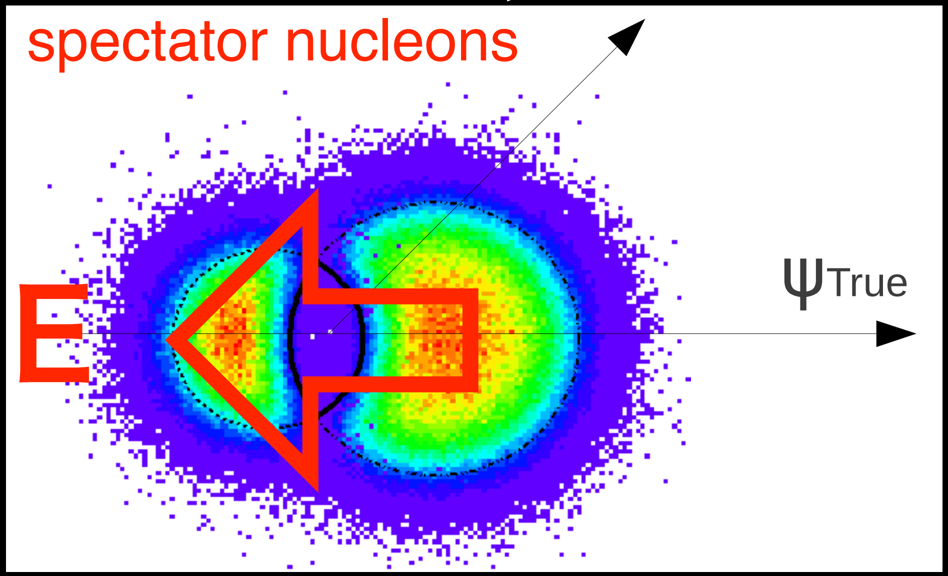

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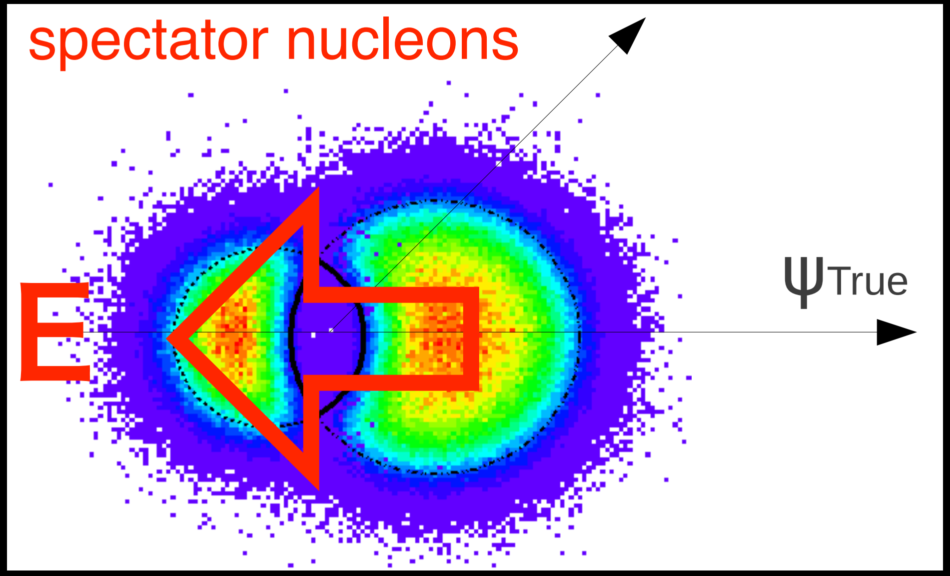
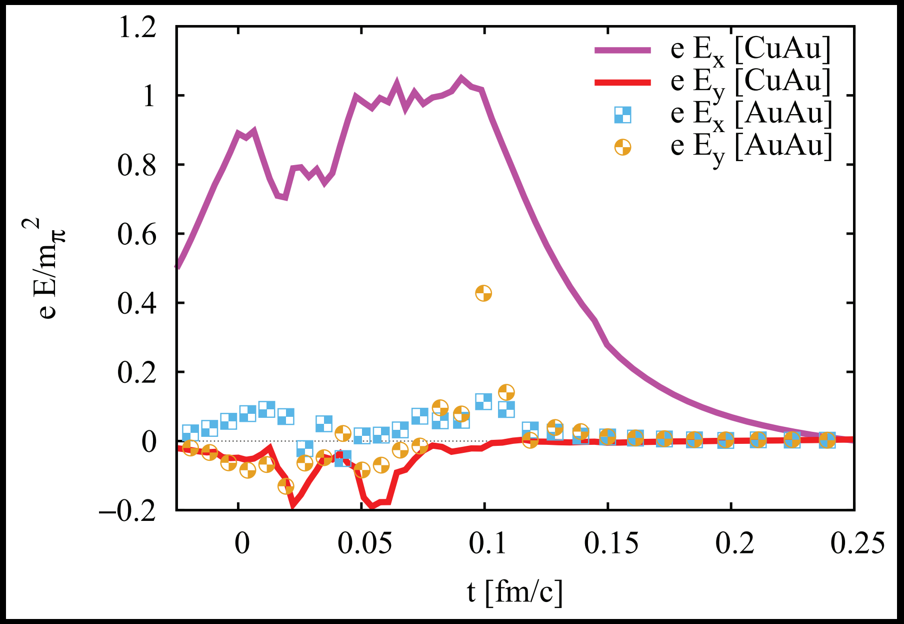


Life time of E-field (~0.25fm/c)

PRC90.064903, Parton-Hadron String Dynamics



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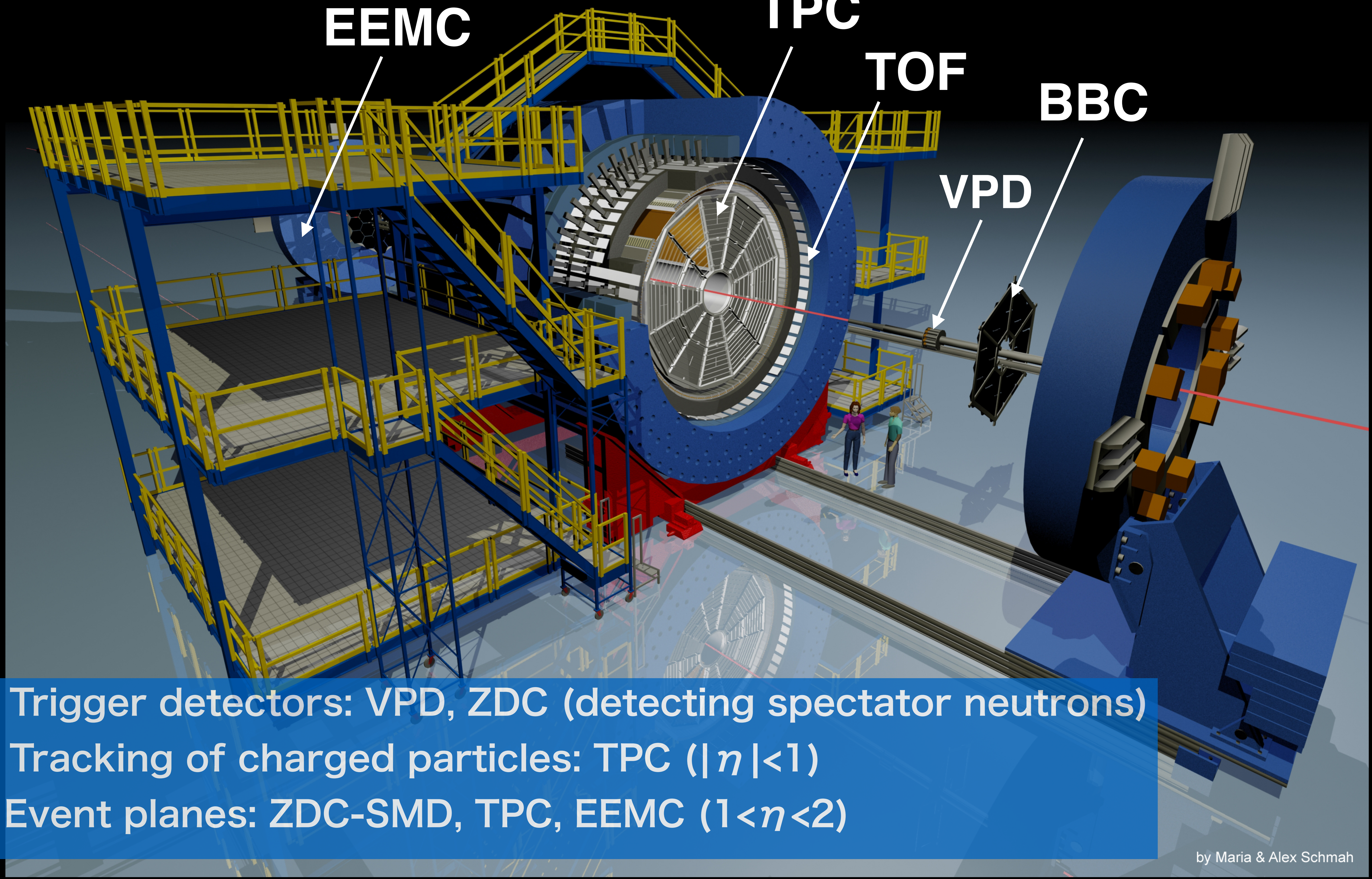
Solenoidal Tracker At RHIC (STAR)



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

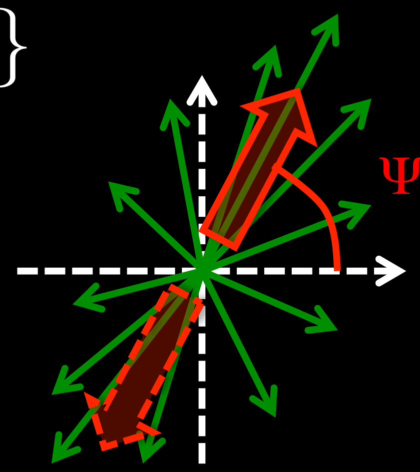
Measurements of azimuthal anisotropies

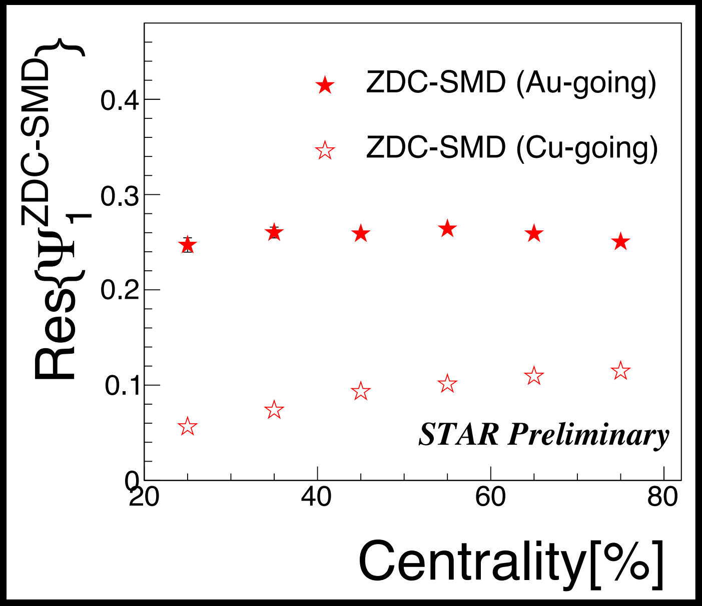
Event plane method

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

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

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

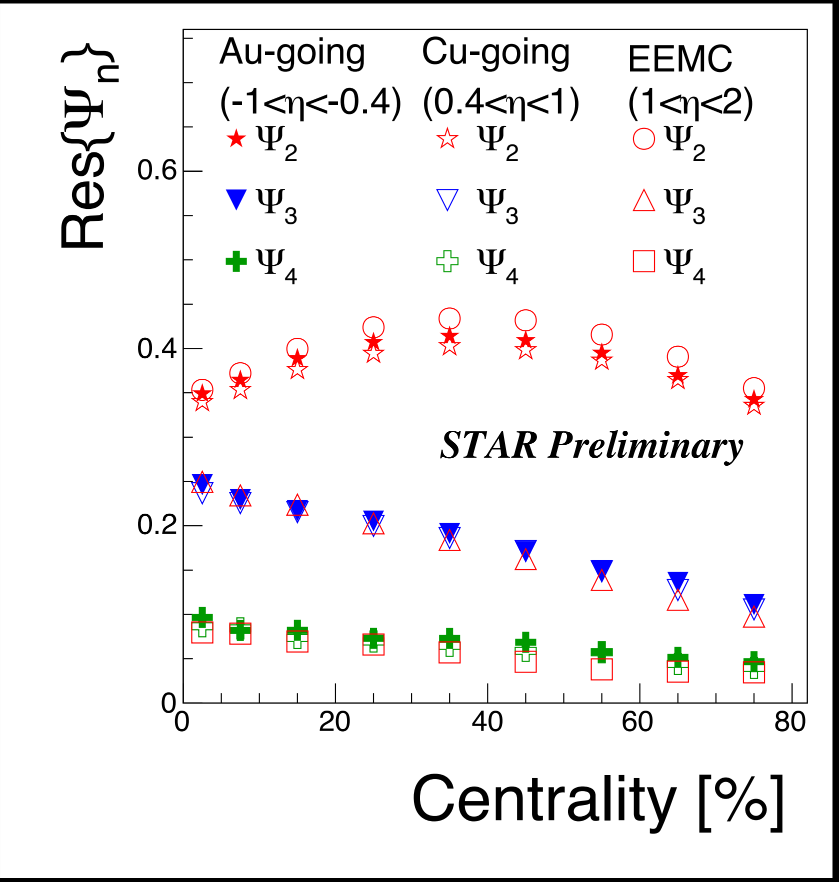




Scalar product method

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

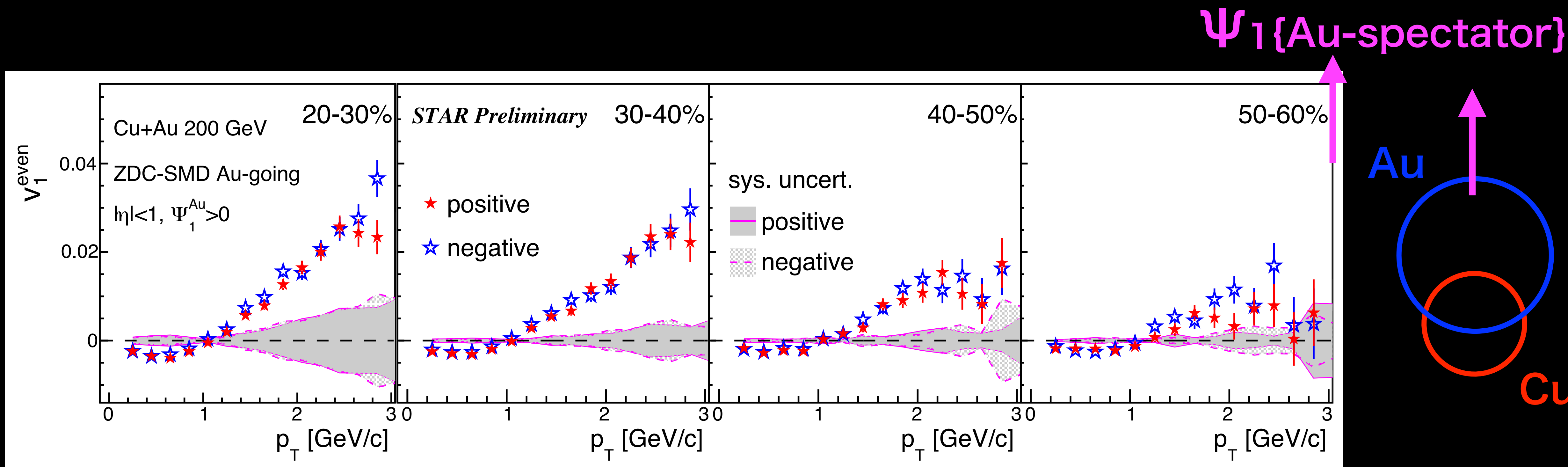
$$v_n = \frac{\langle \vec{Q}_n^{F(B)} \cdot \vec{u} \rangle}{\sqrt{\langle \vec{Q}_n^F \cdot \vec{Q}_n^B \rangle}}$$



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

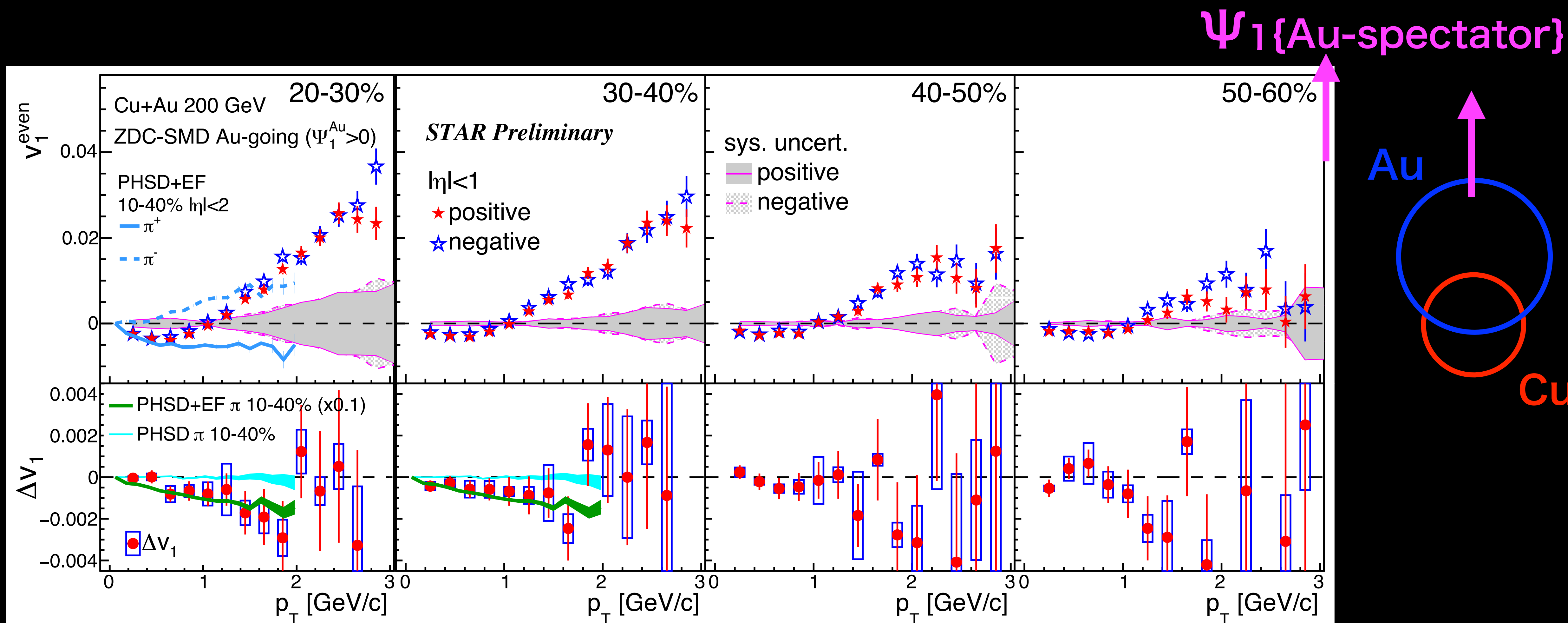


$$v_1^{\rm even} = \langle \cos(\phi - \Psi_1) \rangle$$

- Sizable v_1^{even} measured relative to Ψ_1{ZDC-SMD} in Au-going side (Ψ_1^{Au}>0)
  - 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
  - v_1^{even} become smaller in more peripheral collisions
- v_1 in Cu+Au is larger than that in Au+Au
  - Asymmetric density causes sizable v_1 (U. Heinz and P. Kolb, arXiv:nucl-th/0403044)
  - Note: In A+A collisions, v_1^{even} is only due to density fluctuations

Very small charge difference... but let's see more detail !

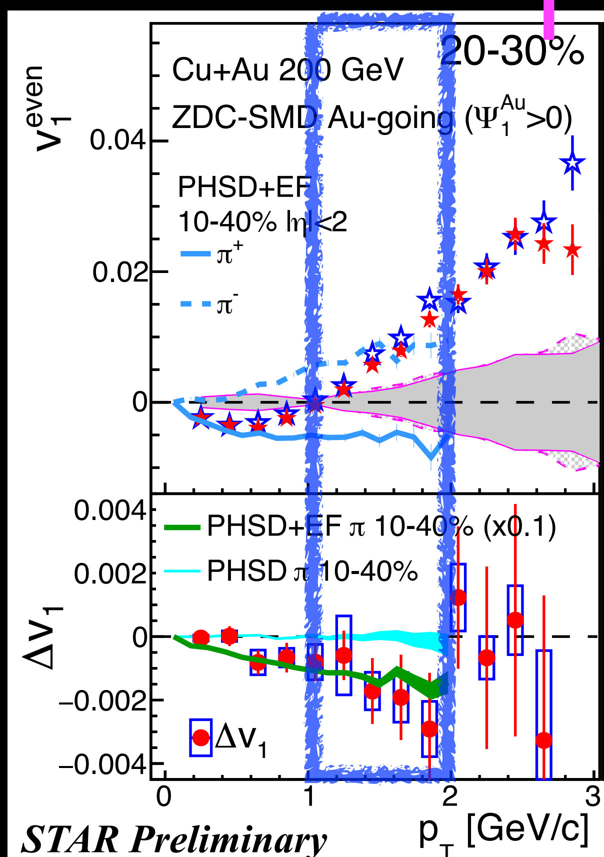
Charge-dependent directed flow



- $\Delta v_1 = v_1(h^+) - v_1(h^-)$, 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 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 early time and affected by the E-field

η dependence of v1

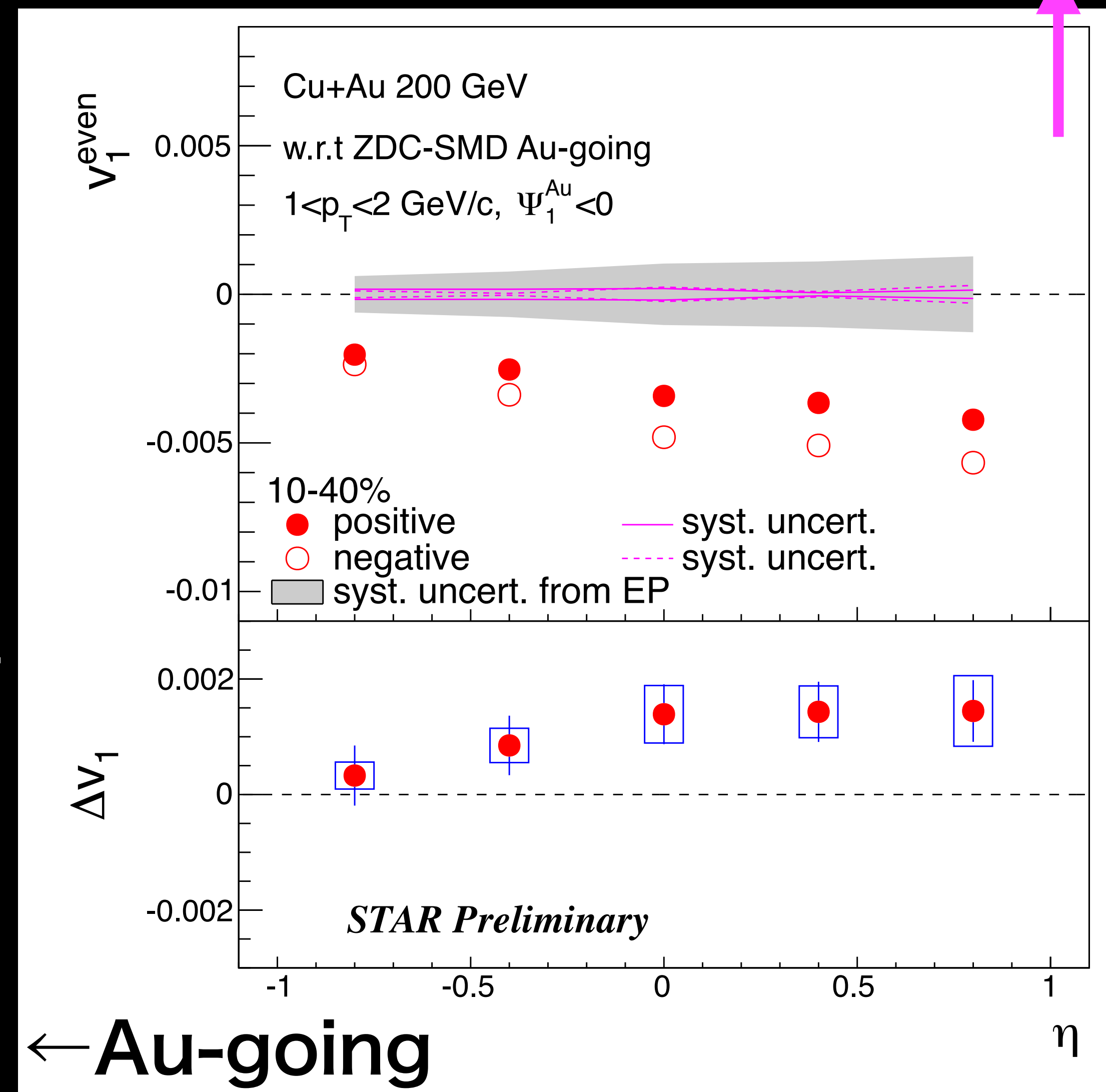
Ψ_1 {Au-spectator}

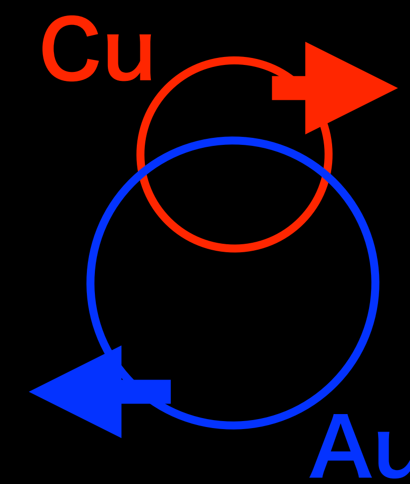


pT=1-2

Note:
opposite def.
in sign of v1

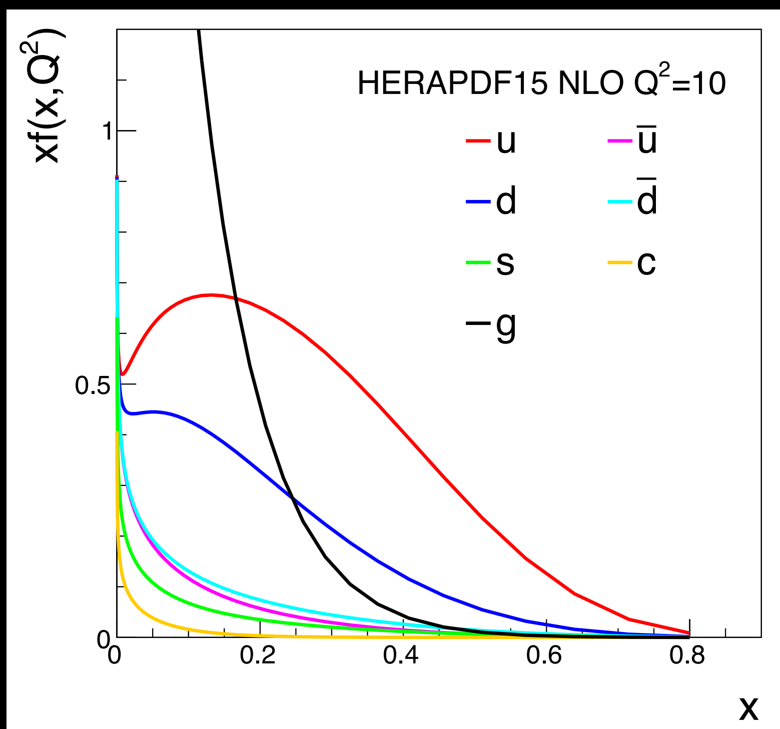
Ψ_1 {Cu-spectator}





- v_1^{even} w.r.t to Ψ_1 {ZDC-SMD} in Au-going side defined as Ψ_1^{Au}<0
- Charge-difference can be seen in $-1<\eta<1$ and $1<p_T<2$ GeV/c
  - Difference looks larger in Cu-going direction

How many quarks at initial state?



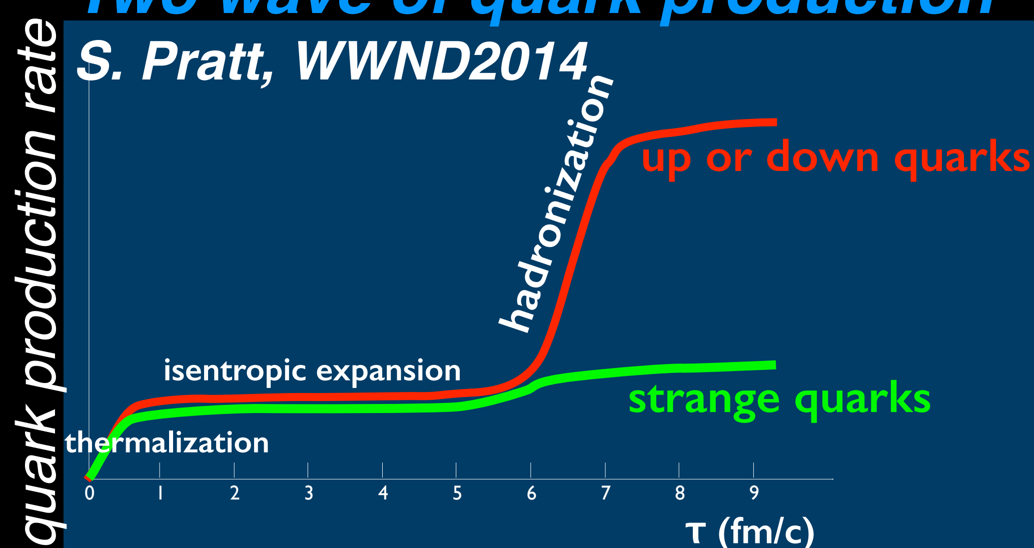
http://hepdata.cedar.ac.uk/

- 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

Two wave of quark production



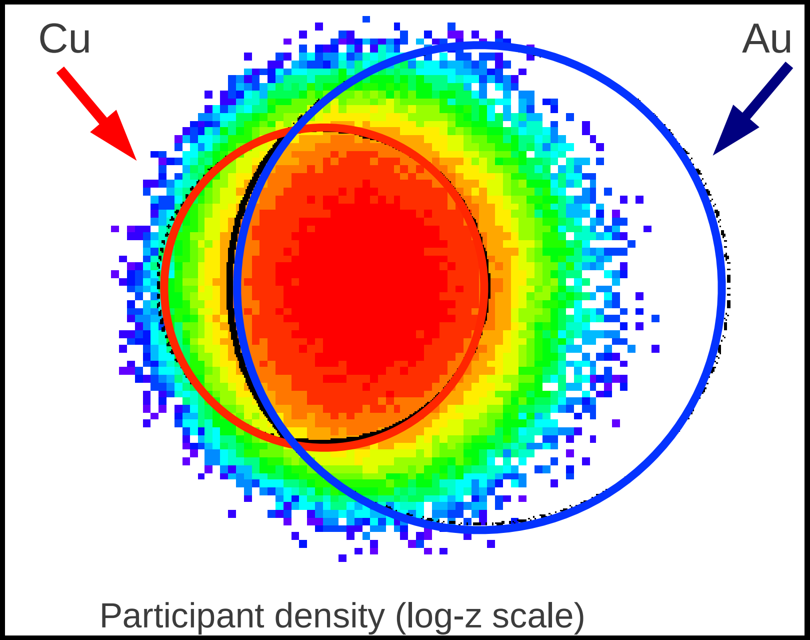
<u>Suggest small fraction of initial quarks to all quarks!</u>

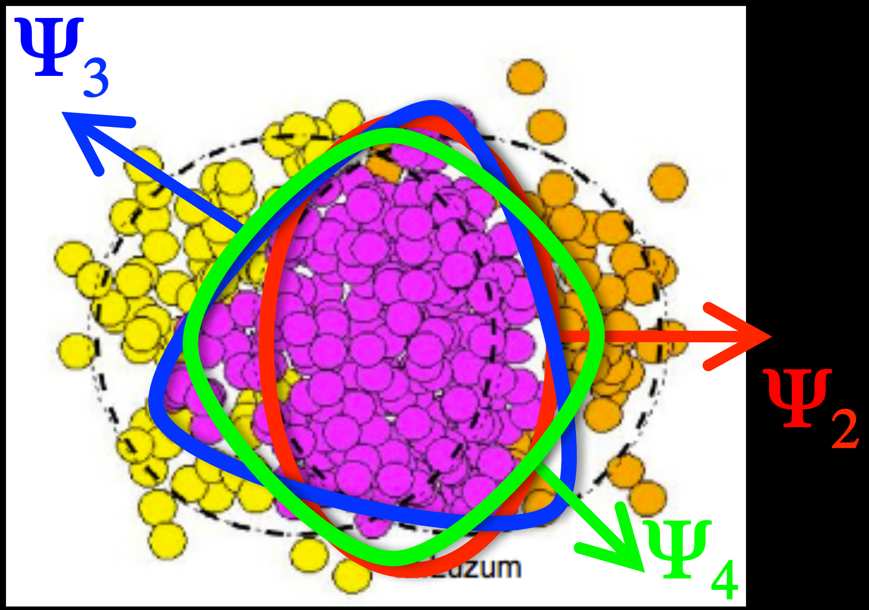
- Possible explanation?
  - Two wave scenario of light quark production
  - small fraction of quarks created at early time

T. Niida, QM2015

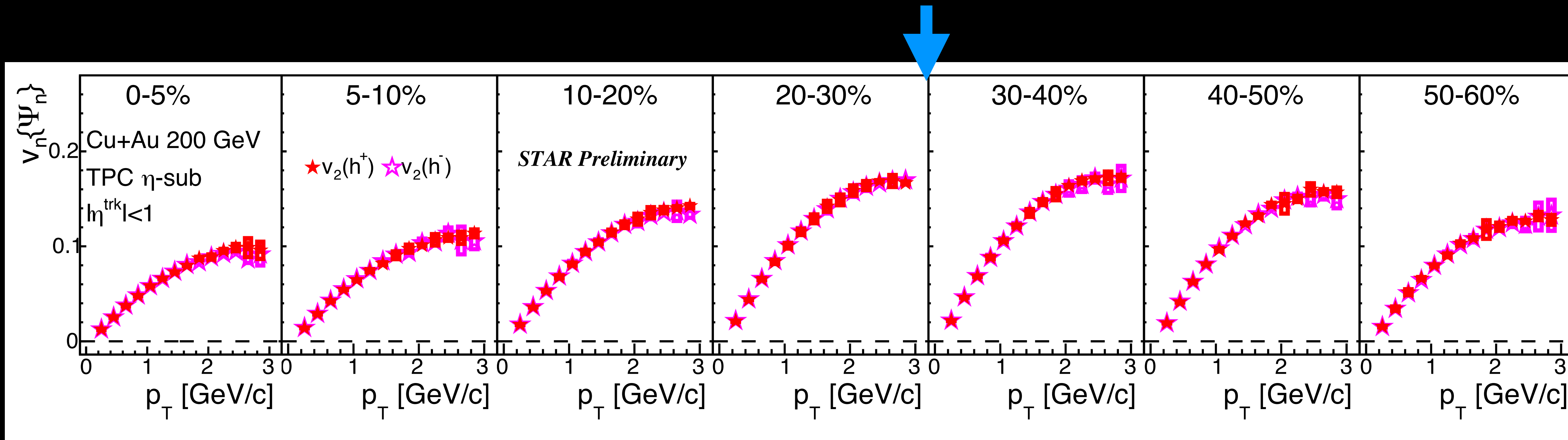
Higher-order flow

- 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



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

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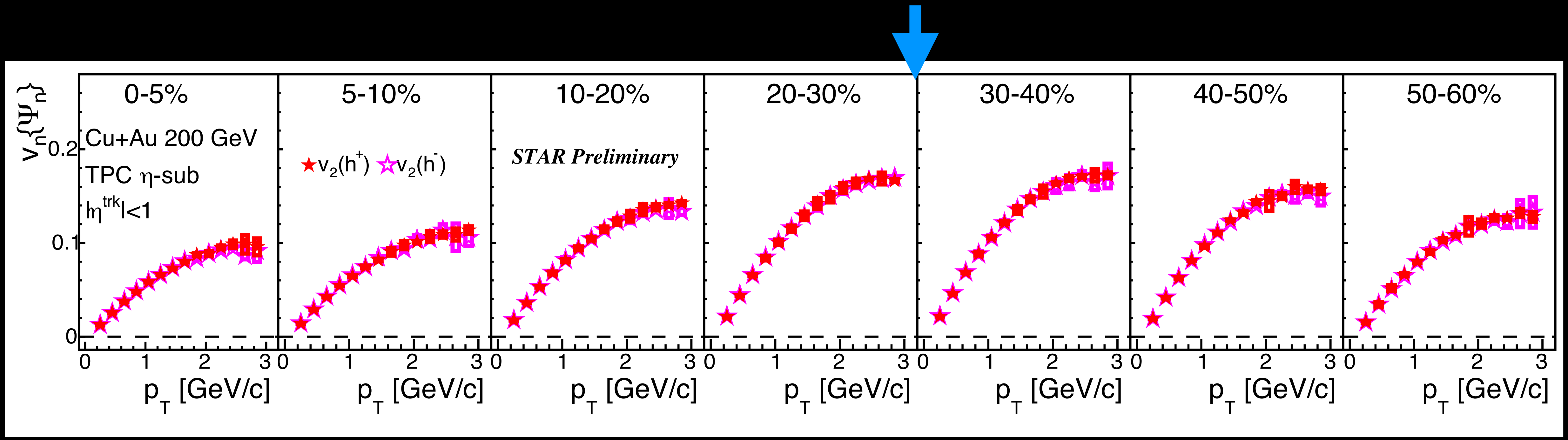

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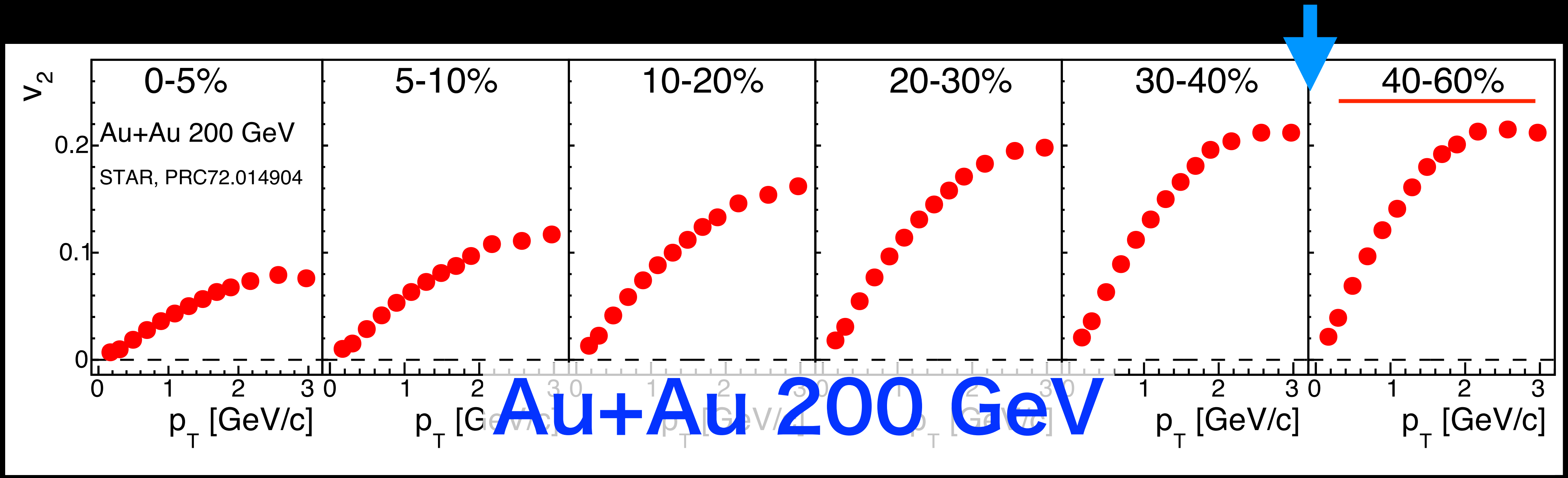

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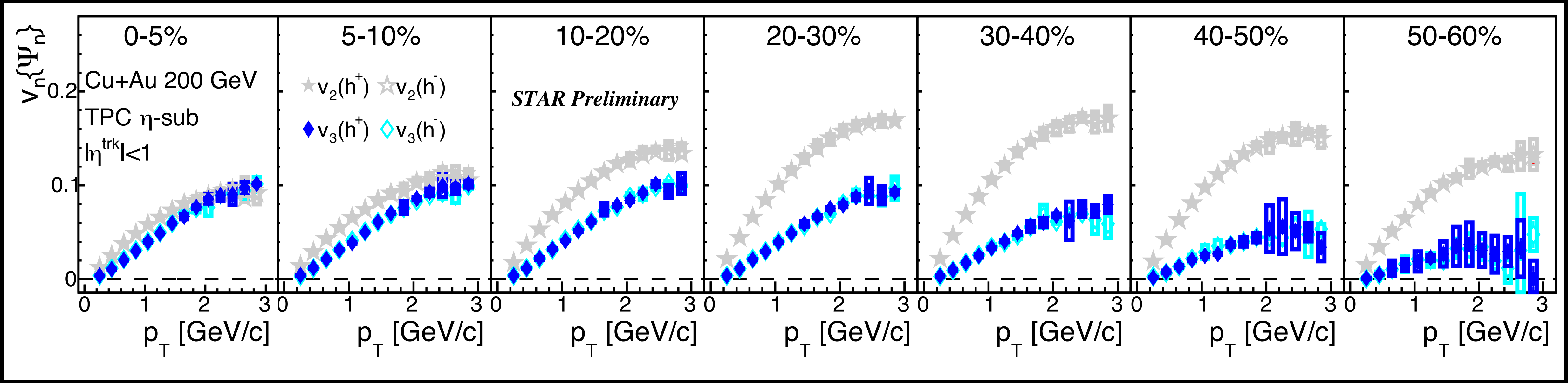

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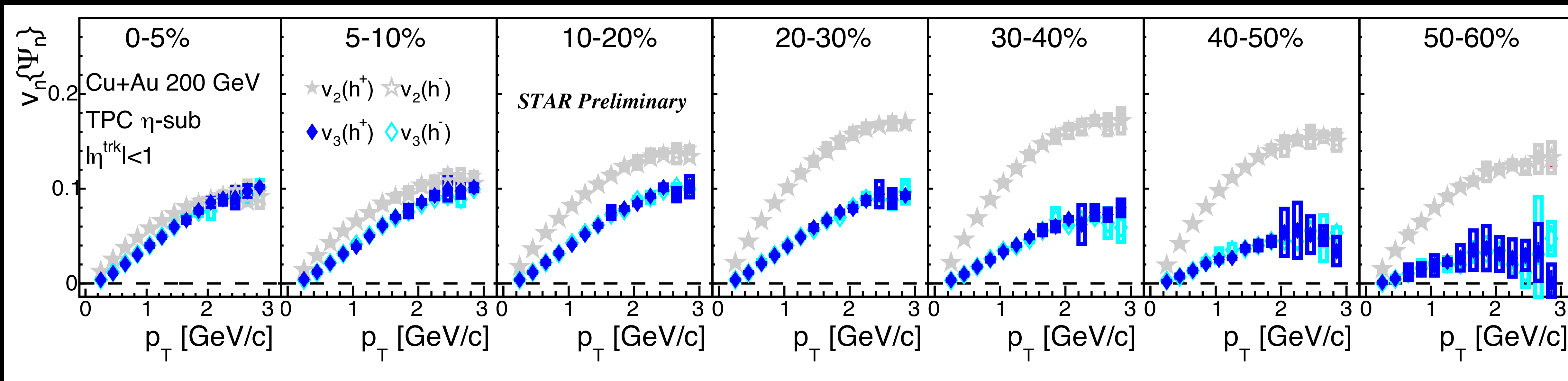
  - due to the intrinsic triangularity in addition to fluctuations?

Higher-order azimuthal anisotropy



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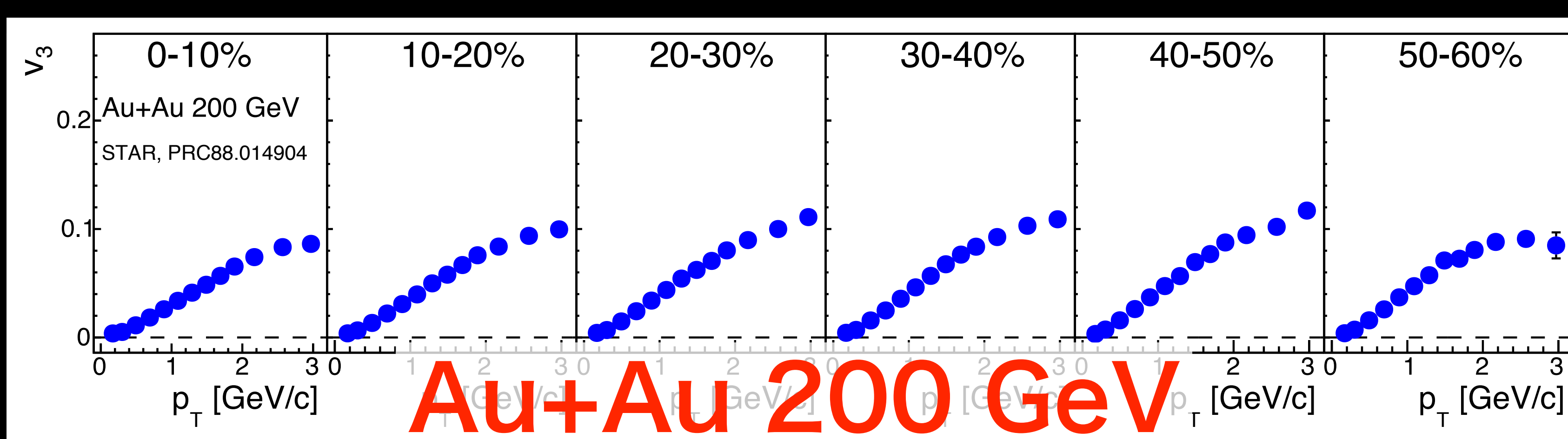

T. Niida, QM2015

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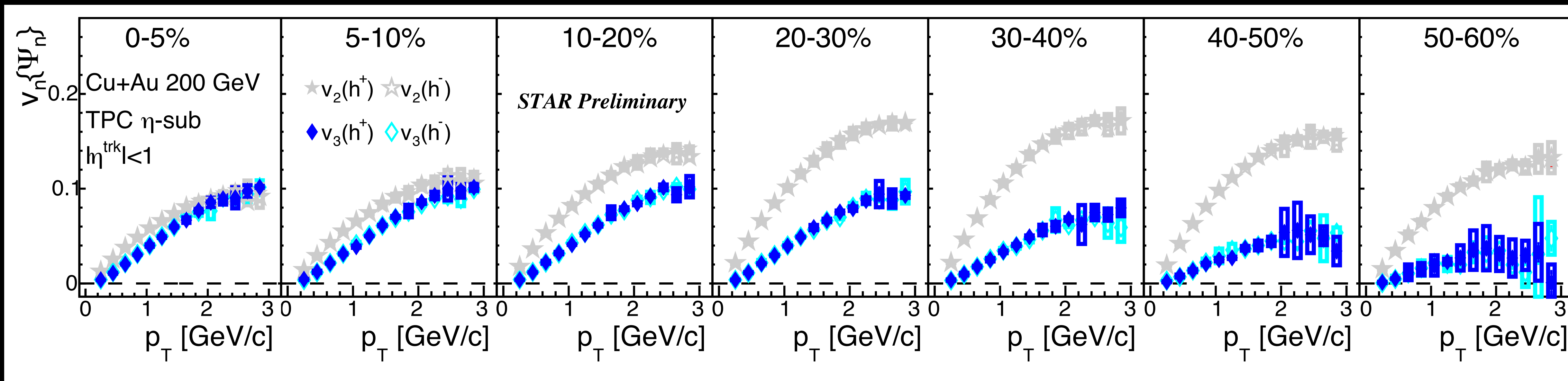

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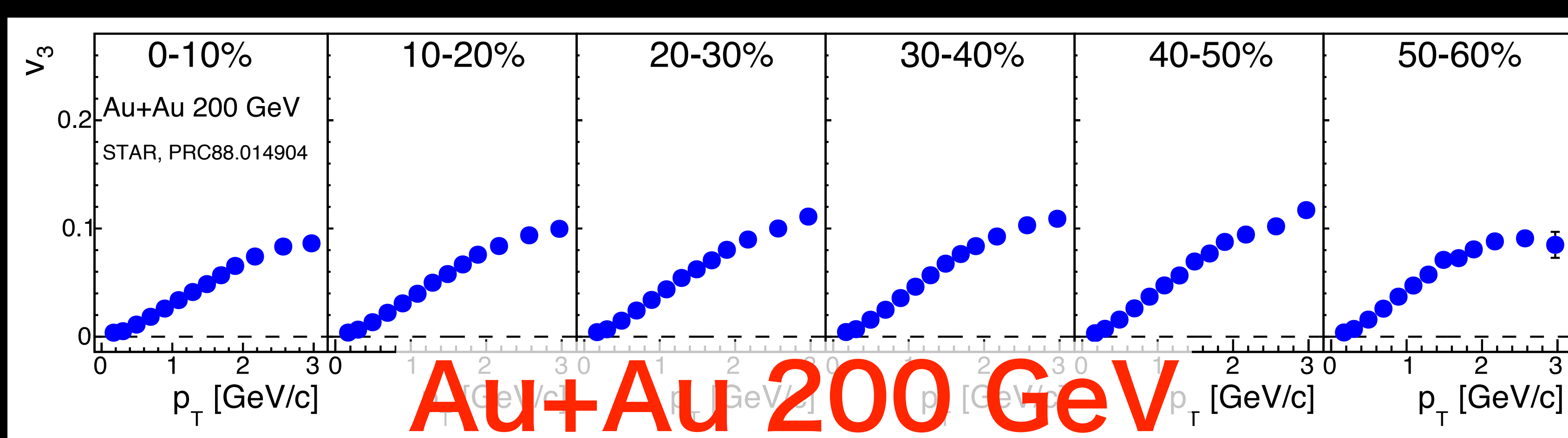
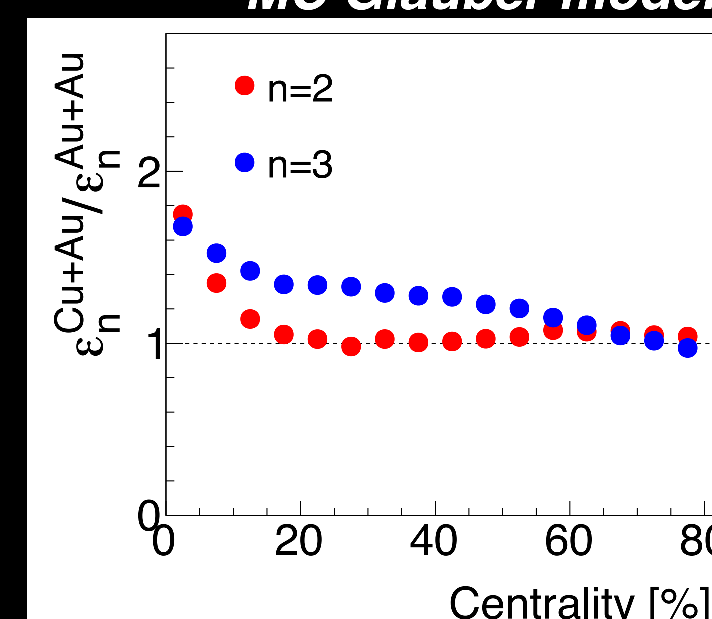


MC Glauber model



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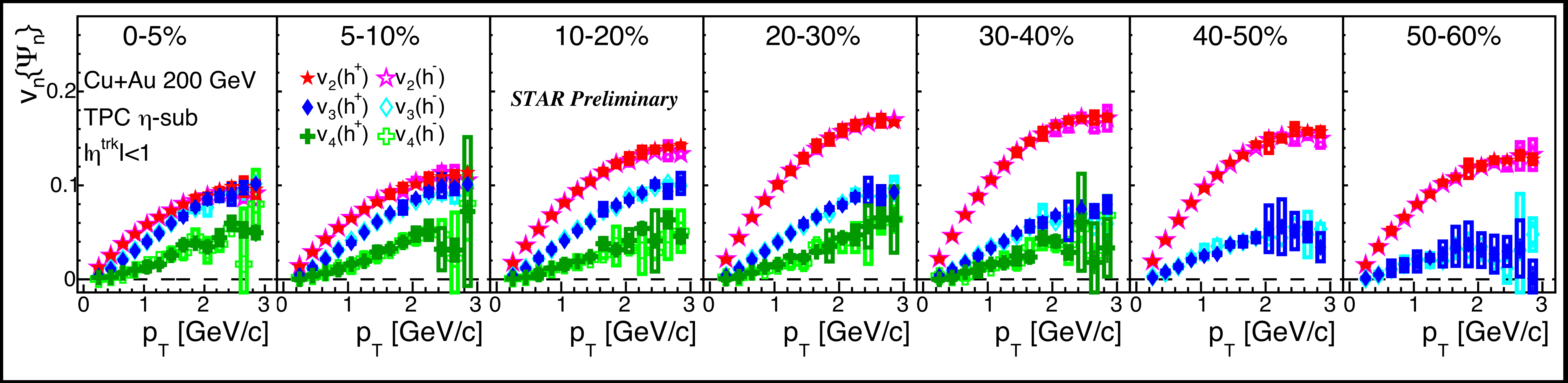
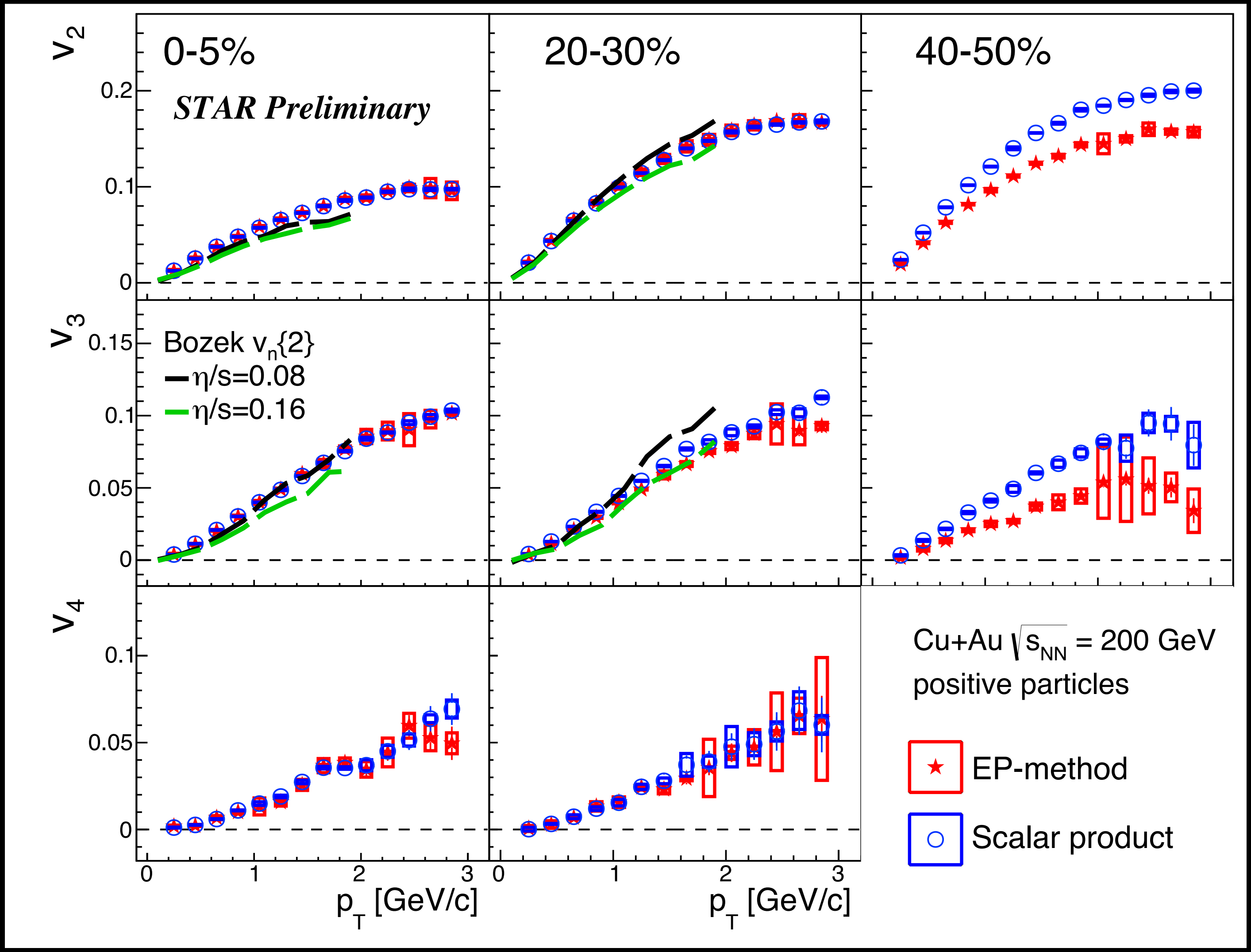


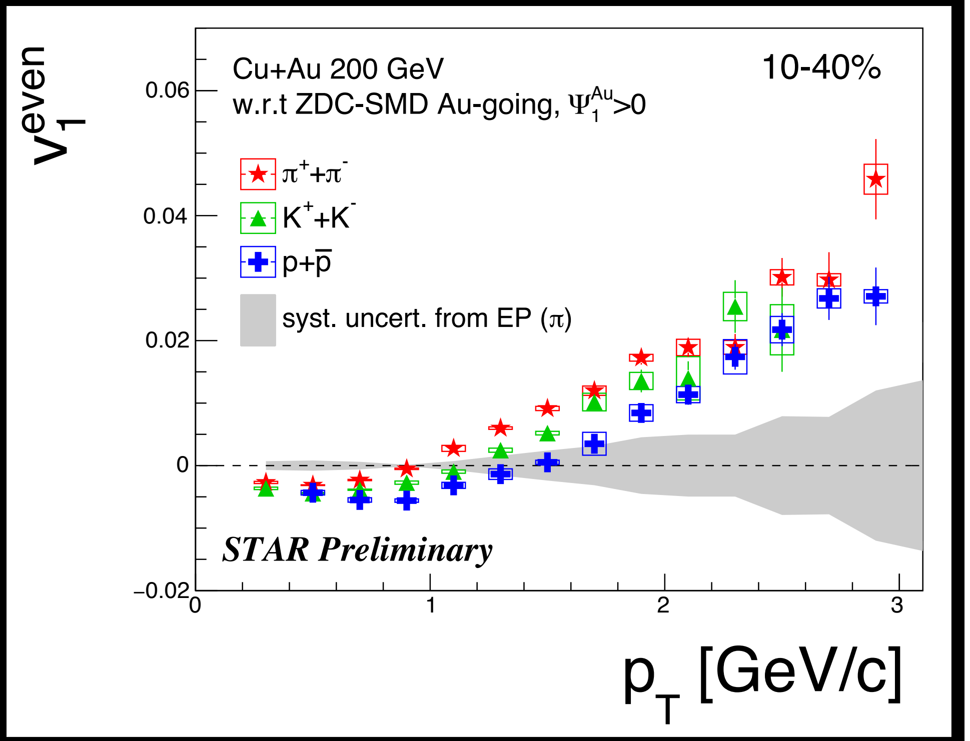
- v_2 peaks at more central collisions (~30%) than in Au+Au (40-50%)
- Stronger centrality dependence of v_3 compared to Au+Au
  - due to the intrinsic triangularity in addition to fluctuations?
- Finite v_4 is observed
  - weaker centrality dependence than Au+Au
- No charge dependence for v_n (n>=2)

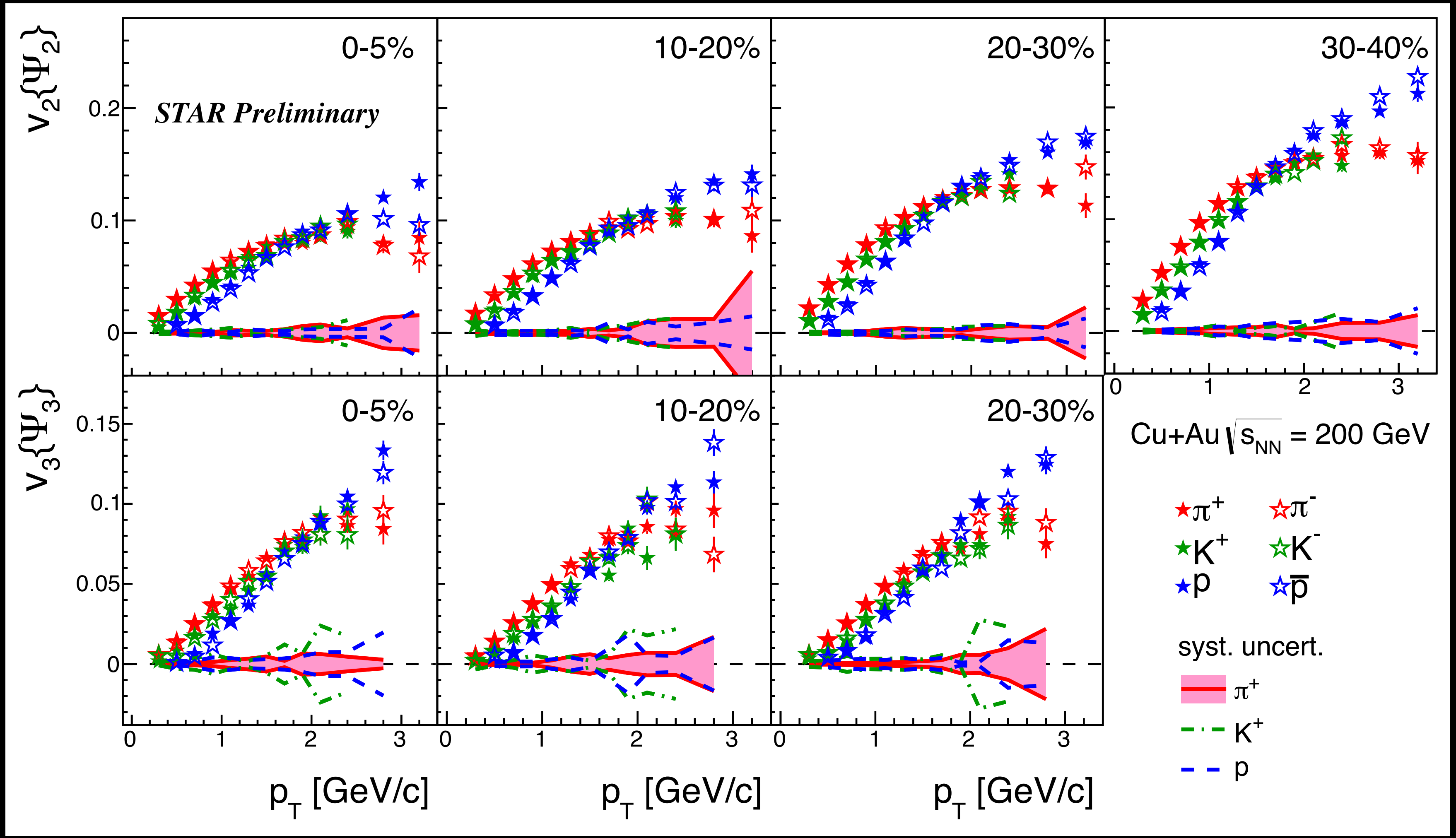
Comparison with Hydro-model



- 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
- v_n\{EP\} is in good agreement with v_n\{SP\} in more central collisions
  - Difference in peripheral collisions due to different sensitivity to flow fluctuations (S. Voloshin et al., arXiv:0809.2949)

Identified Particle v_n





- π /K/p identification by TPC + TOF
- Mass ordering at low p_T for v_1, v_2, and v_3 (effect of radial flow)
- Baryon/meson splitting at intermediate p_T for v_2 and v_3

Analysis on charge-dependent v_1, especially for kaon, is ongoing!

Summary

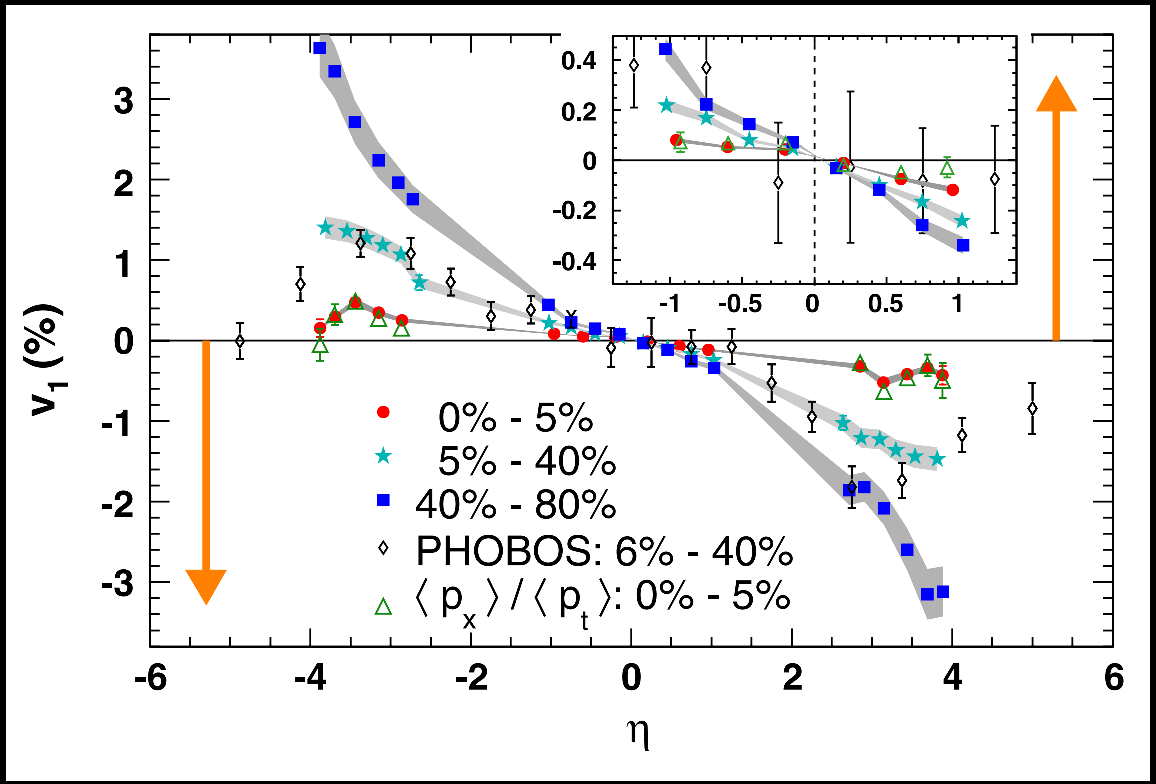
- Charge-dependent directed flow in Cu+Au collisions
  - Charge difference of v_1 was observed, which is consistent with an existence of the initial electric field
  - The fraction of initial (anti-)quarks could be constrained by the magnitude of Δv_1

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

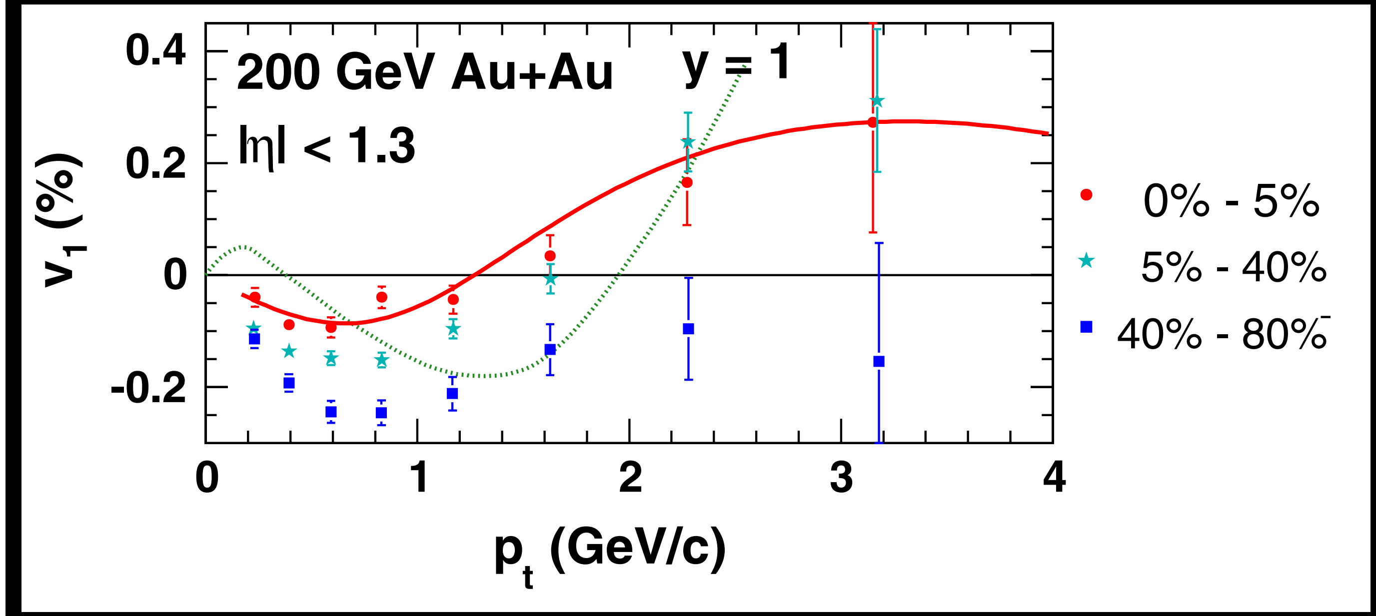
Thank you for your attention!

Back up

v_1^{odd} in Au+Au 200GeV



STAR, PRL101.252301

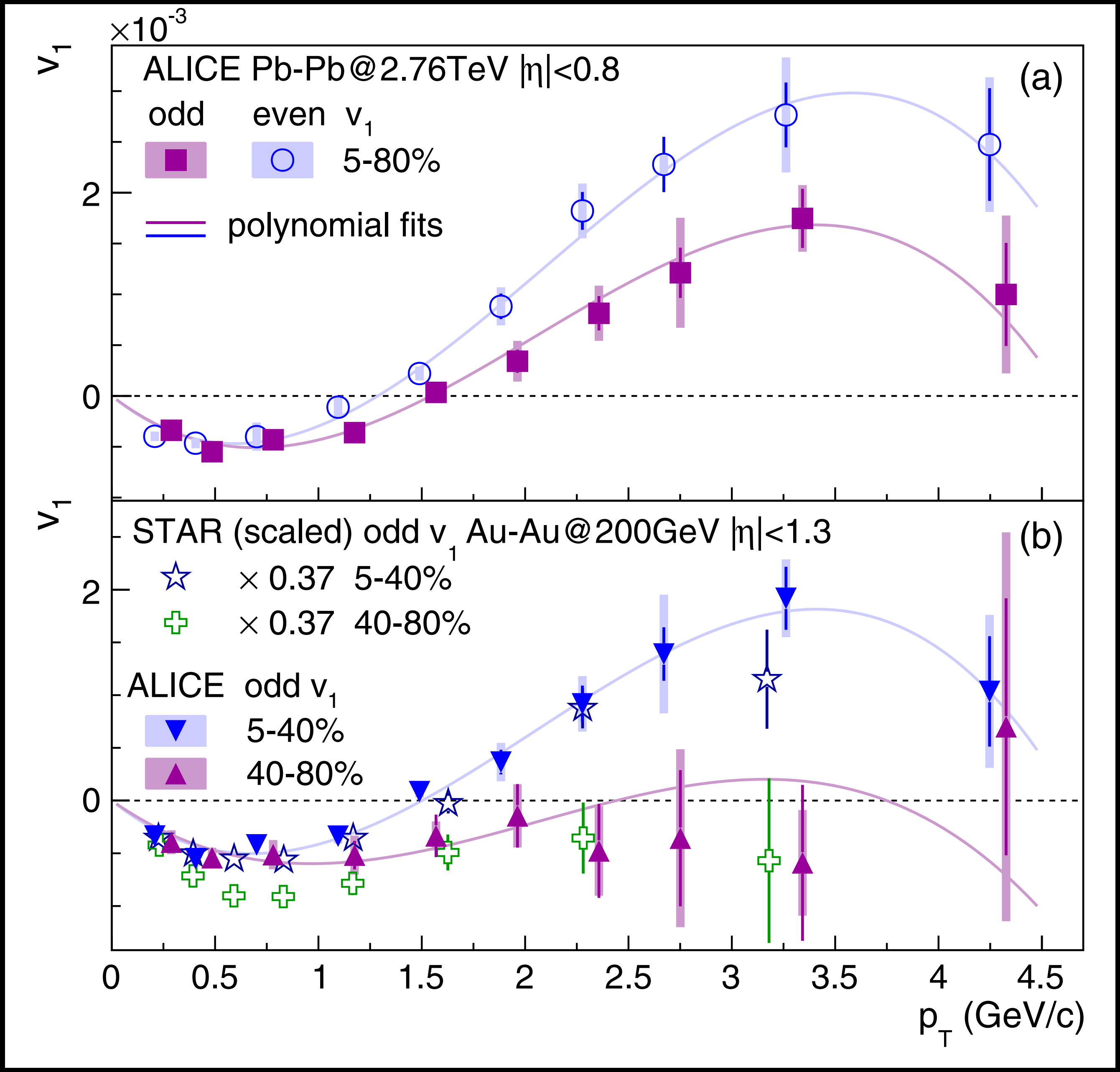


- Small signal of v_1 at mid-rapidity in Au+Au collisions

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

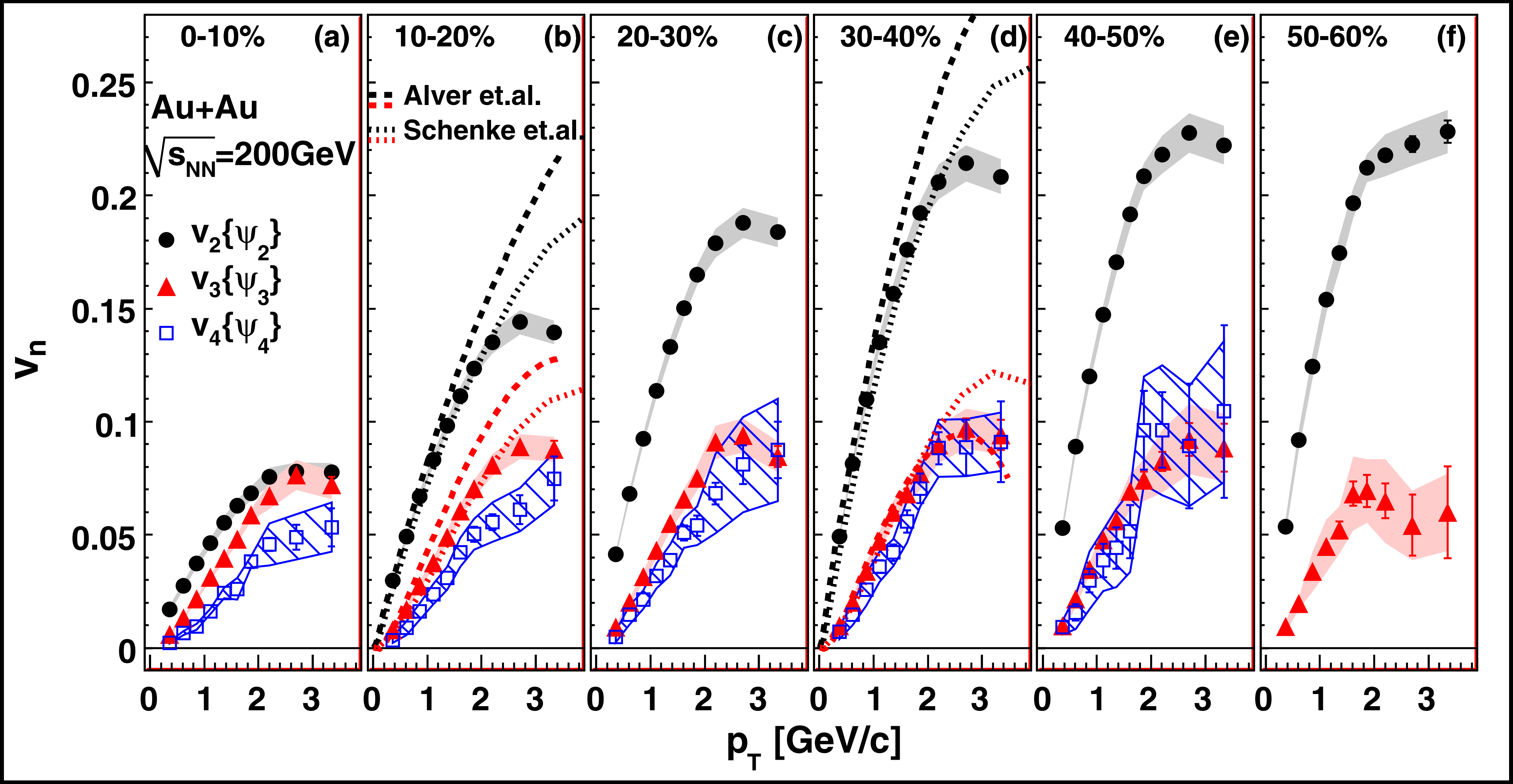
v_1^{even} and v_1^{odd} in Pb+Pb 2.76 TeV

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

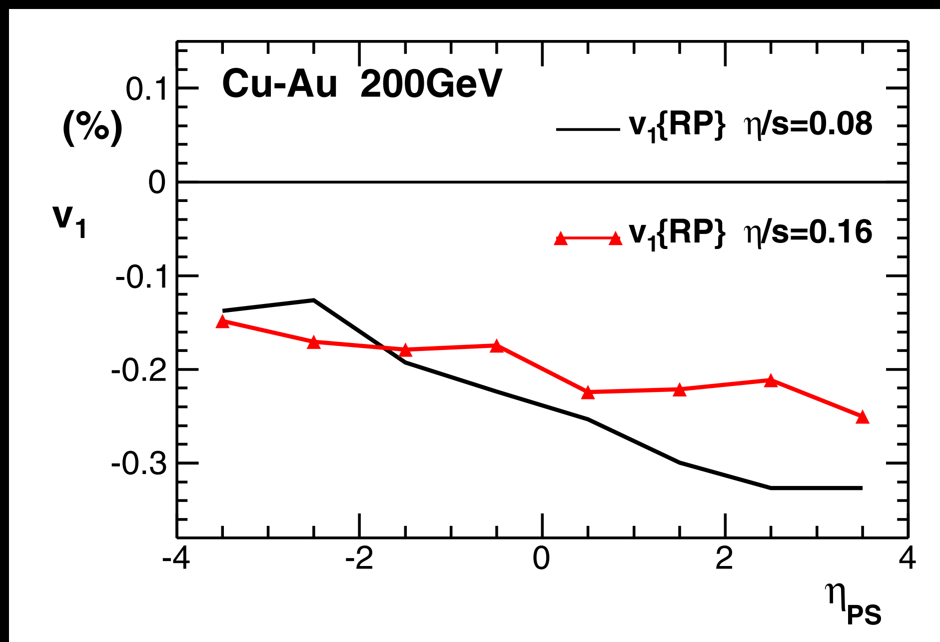


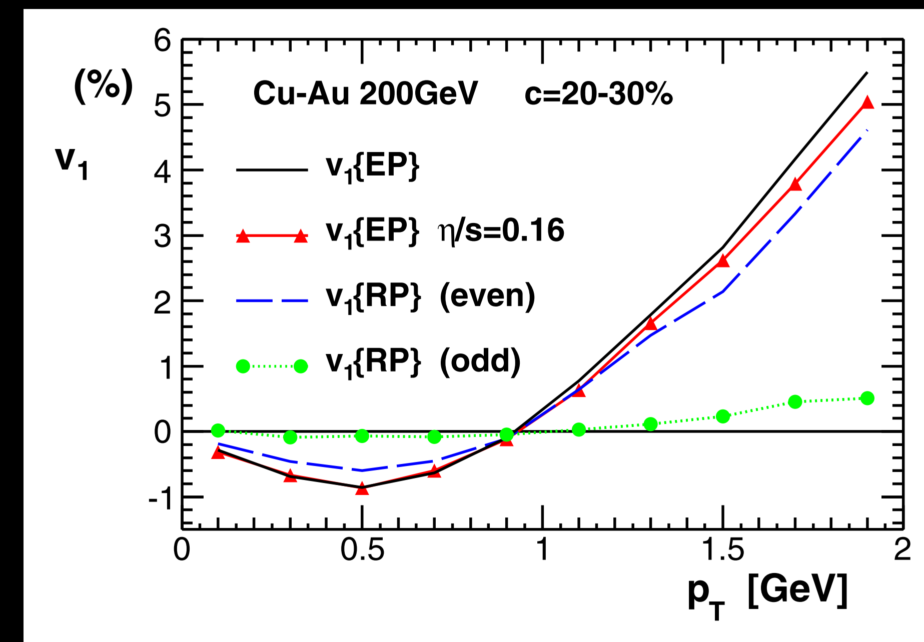
Higher-order flow in Au+Au

PHENIX, PRL107.252301



E-b-e viscous hydrodynamics in Cu+Au





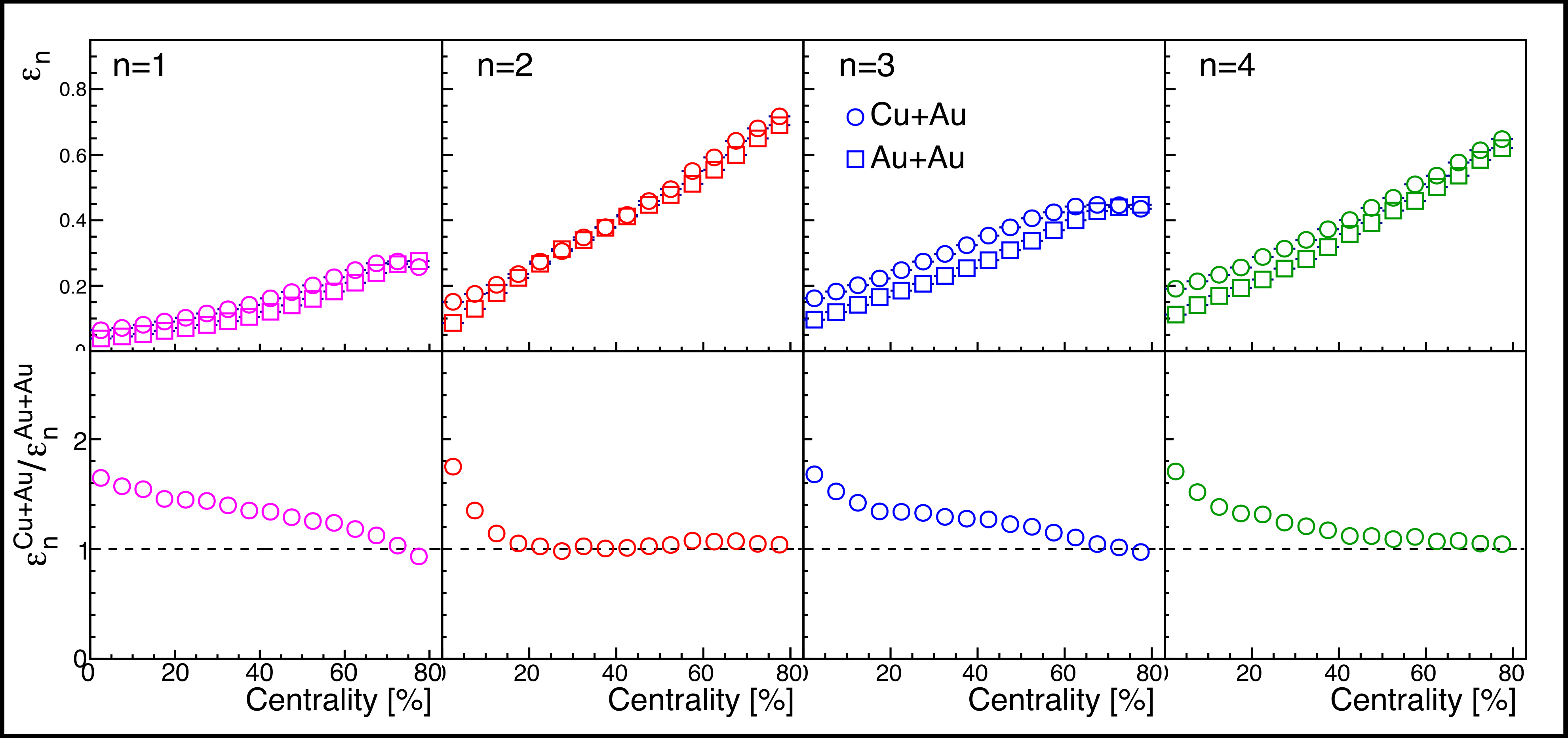
P. Bozek, PLB717(2012)287

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

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

Initial spatial anisotropy Cu+Au vs Au+Au

MC Glauber simulation



$$\varepsilon_n = \frac{\langle r^n \cos[n(\phi - \Psi_n)]\rangle}{\langle r^n \rangle}$$

※ r^3 weight for n=1