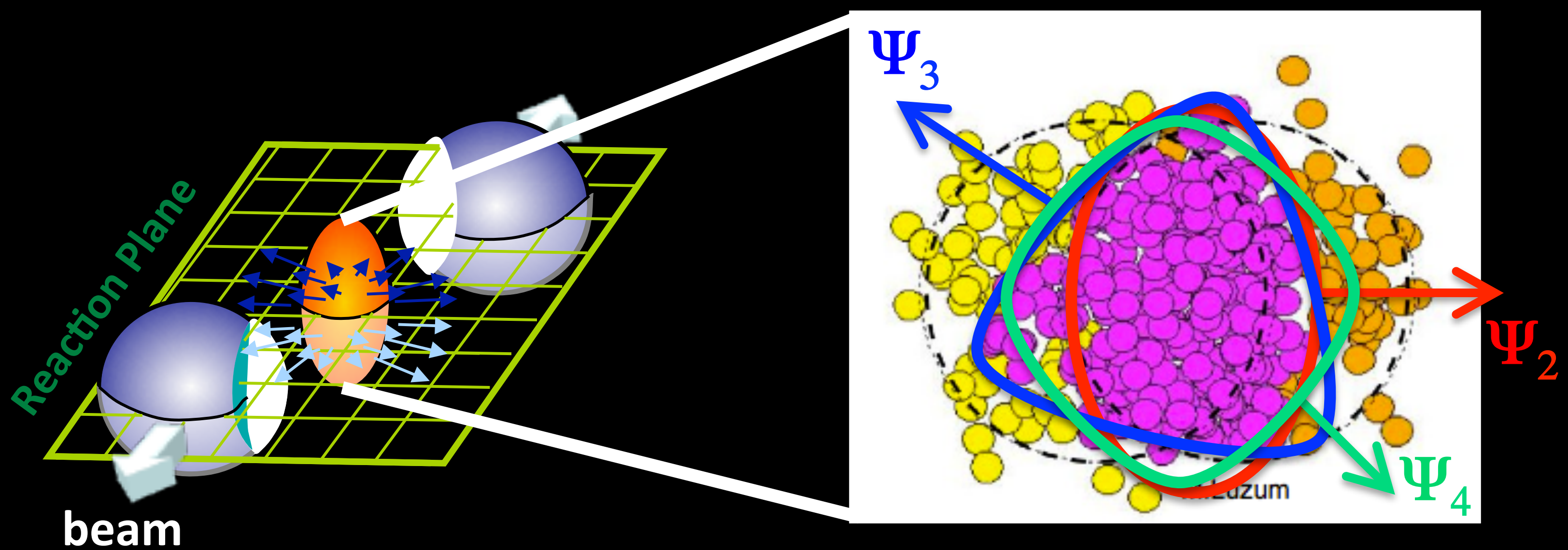
Charge-dependent directed flow in Cu+Au collisions

Takafumi Niida for the STAR Collaboration
Wayne State University

Initial Stages 2016
@Instituto Superior Técnico, Lisbon

STAR Azimuthal anisotropy

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



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

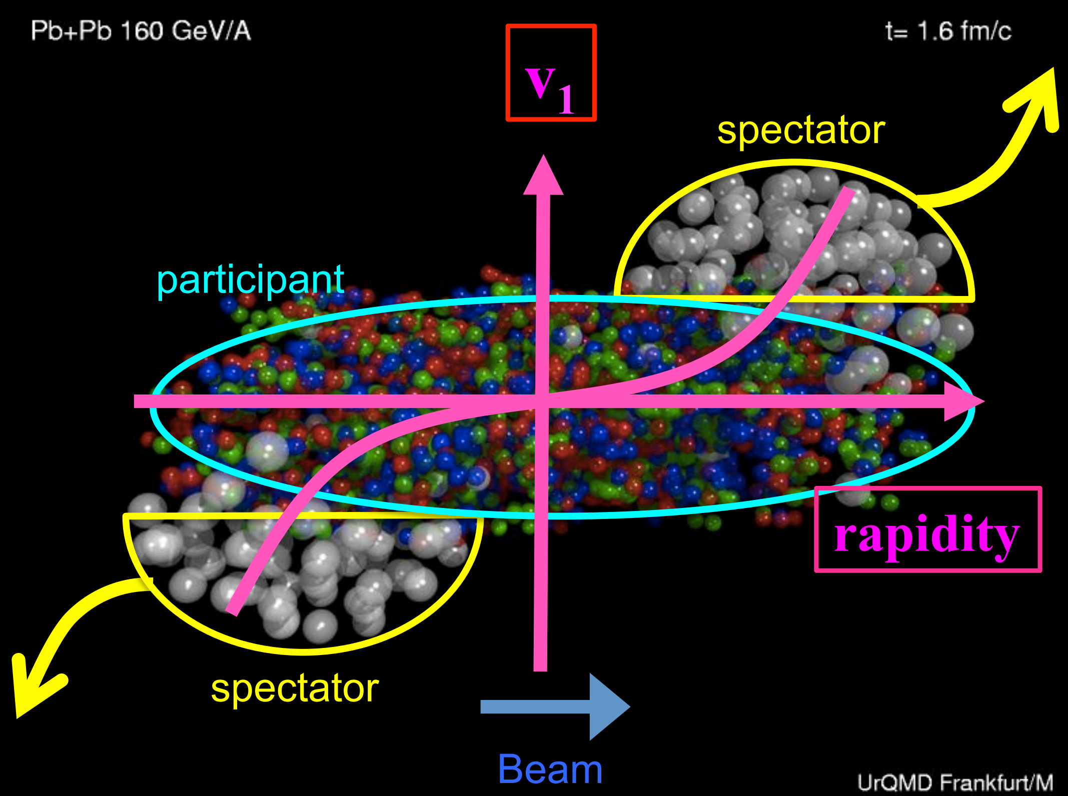
$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]$$

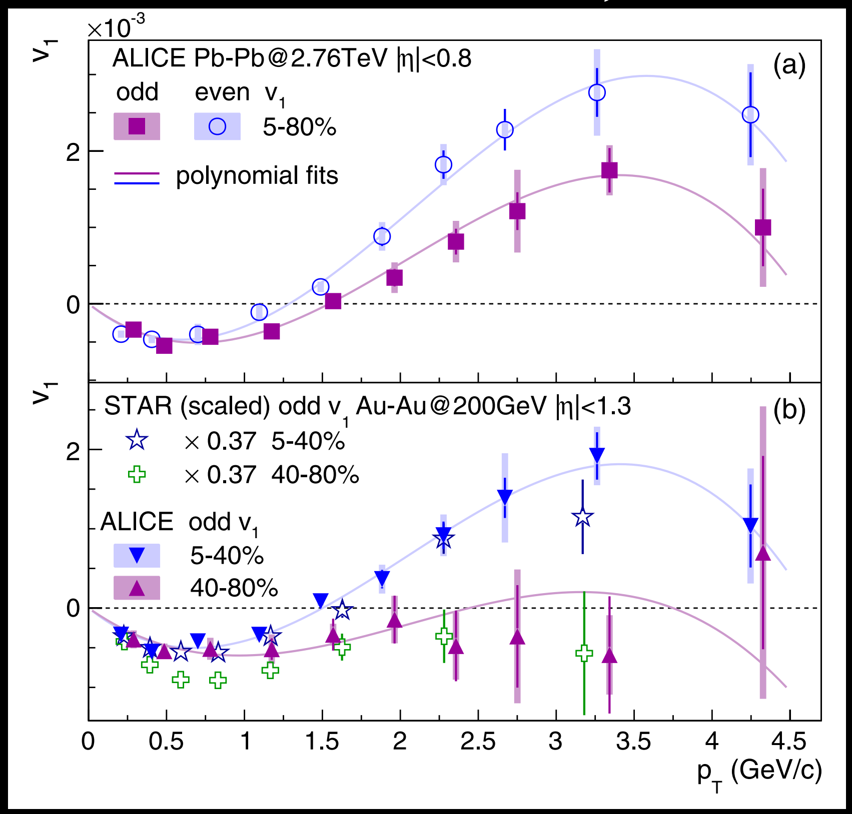
Directed flow (v_1): sensitive to EoS and phase transition
Elliptic(v_2), Triangular(v_3), ···: sensitive to η/s and initial fluctuations

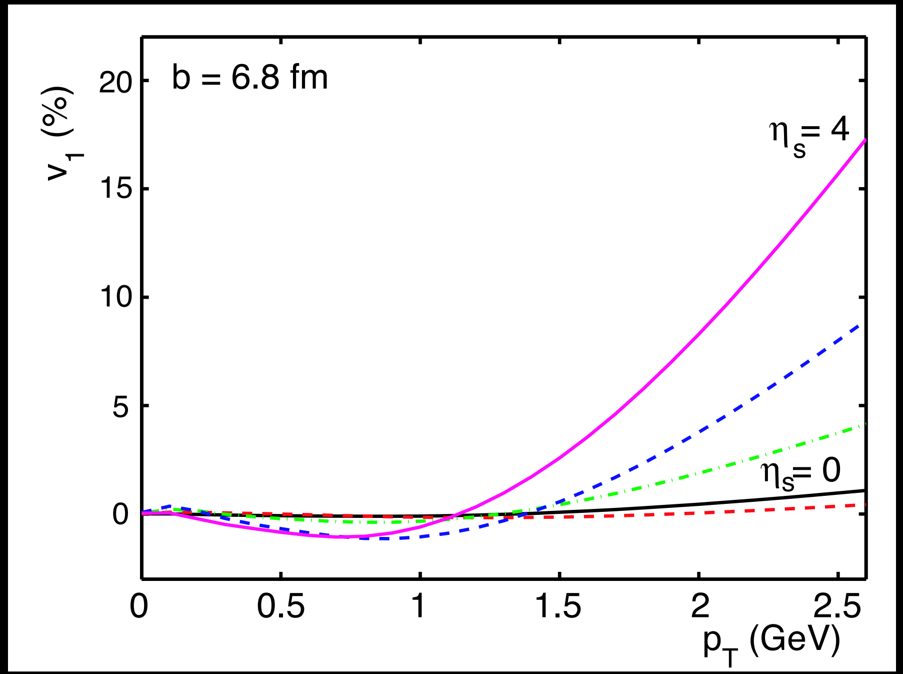
Csernai and Rohrich, PLB458, 454 (1999)
Gale et al., PRL110, 012302 (2013)

Directed flow in A+A

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





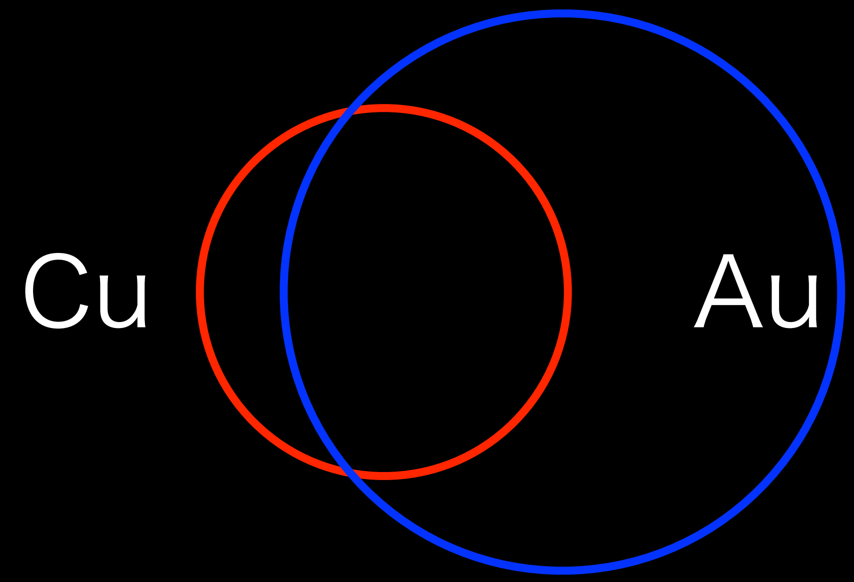


U. Heinz and P. Kolb, J.Phys.G30 (2004) S1229

- v_1 in A+A collisions
  - v_1 is caused by the initial density asymmetry
  - $\langle v_1 \rangle$ at $\eta=0$ 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

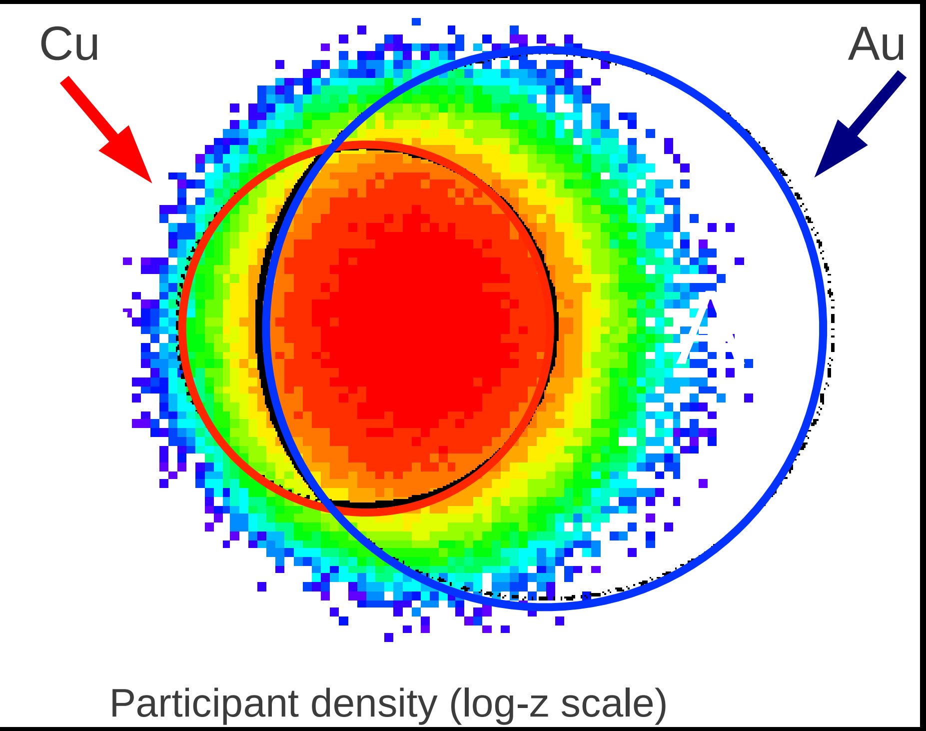
How about in asymmetric collisions?

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

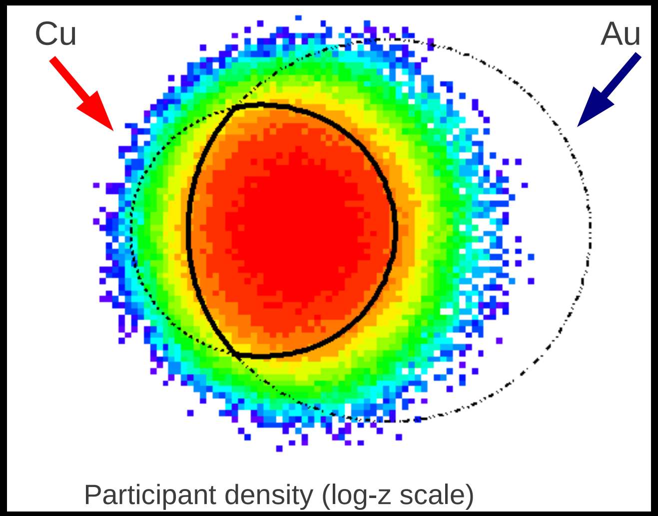
Cu+Au collisions

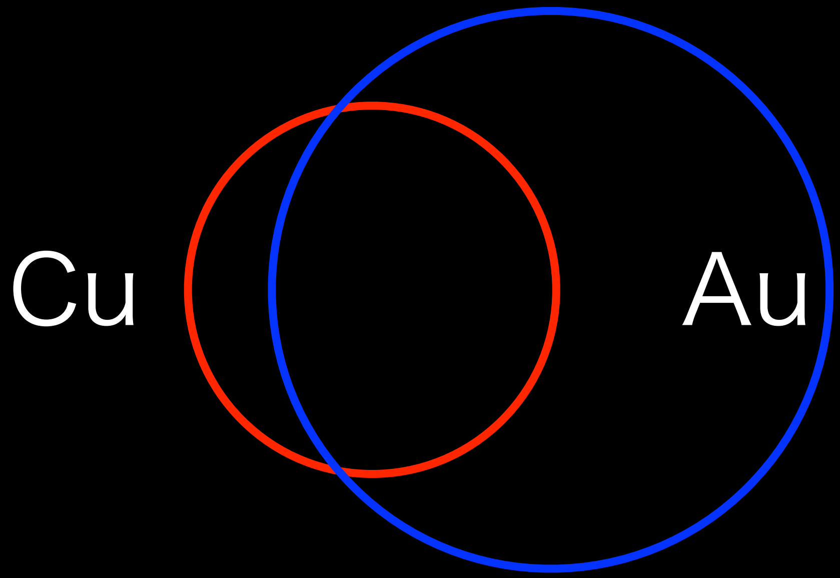


- Intrinsic asymmetric density
  - larger directed flow compared to A+A collisions?
- Sizable initial electric field
  - pointing from Au to Cu, due to the charge difference (# of protons) in both spectators

Cu+Au collisions

plot from A. Iordanova,
@RHIC&AGS users meeting 2013



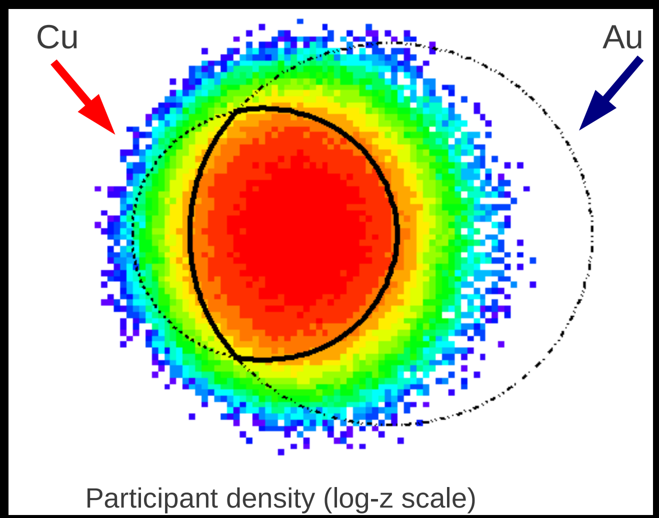


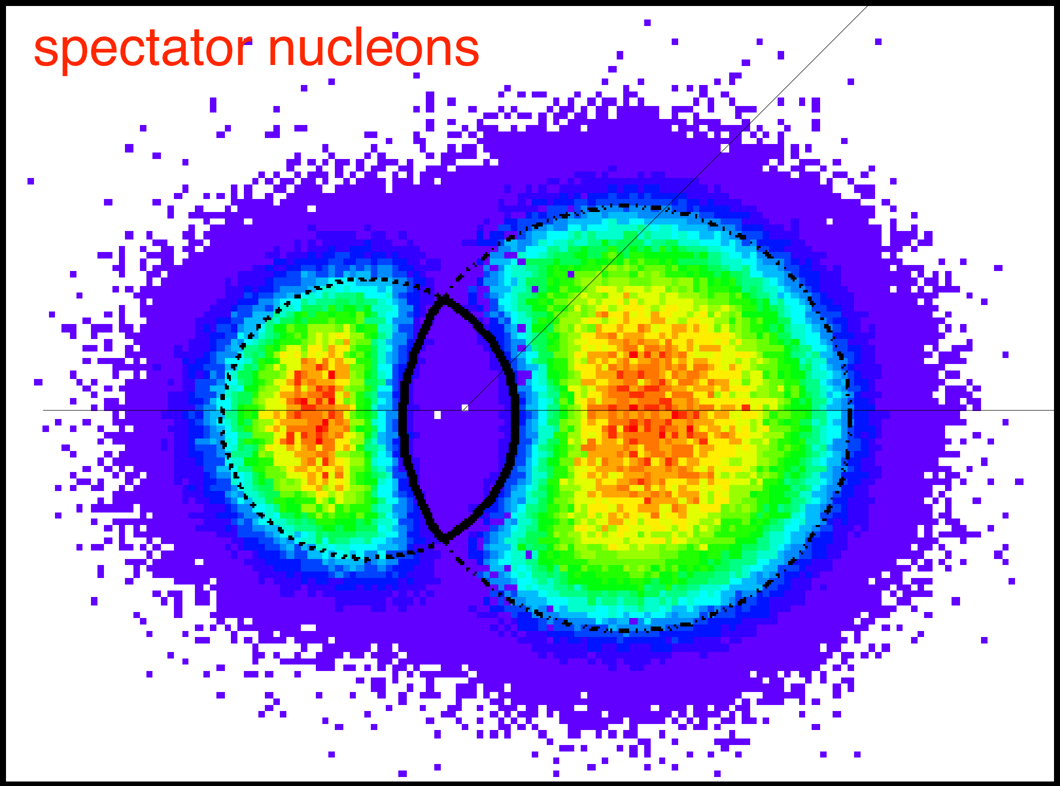
Asymmetric density profile
Asymmetric pressure gradient

- 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

plot from A. Iordanova, @RHIC&AGS users meeting 2013



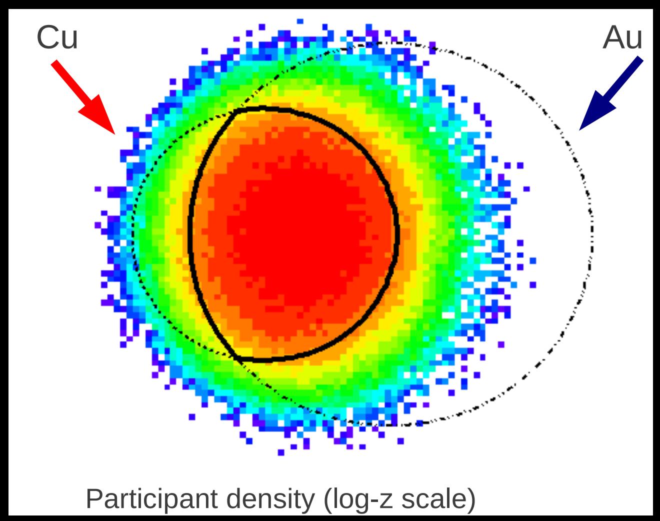


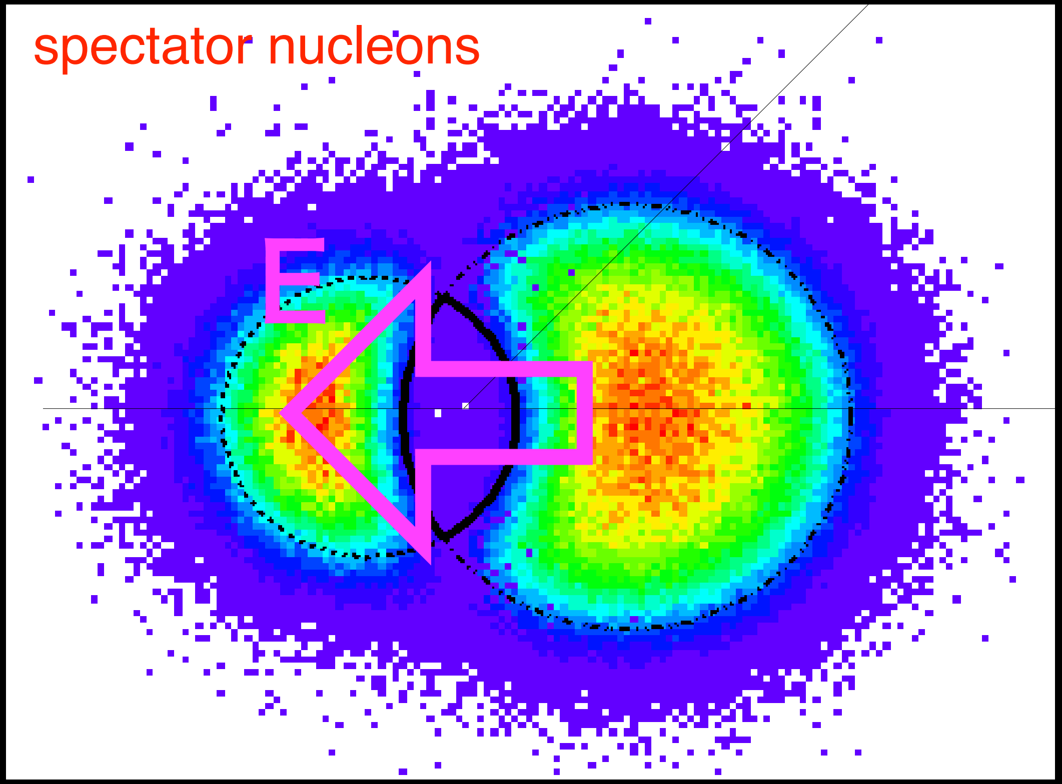
Asymmetric density profile
Asymmetric pressure gradient

- 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

plot from A. Iordanova, @RHIC&AGS users meeting 2013



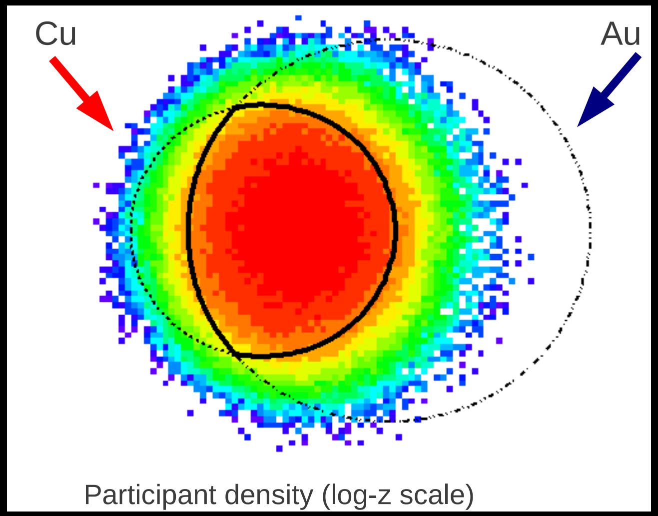


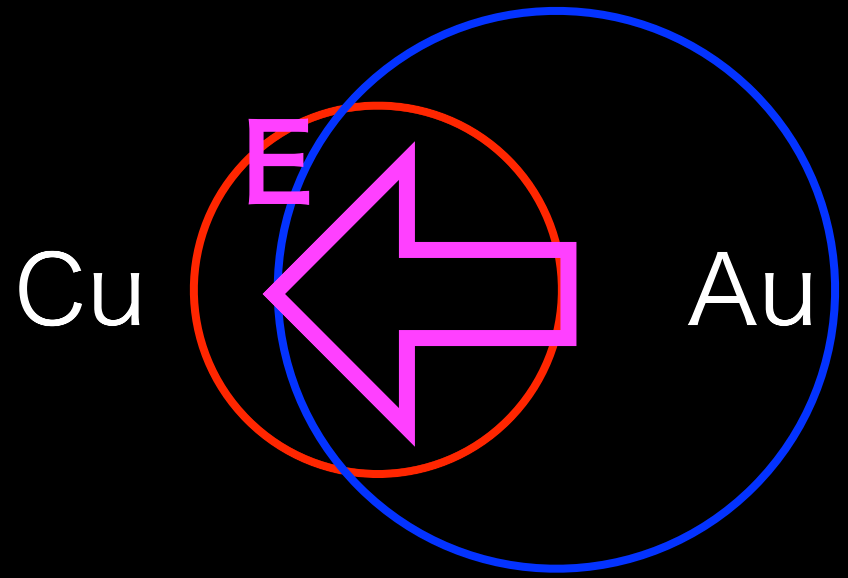
Asymmetric density profile
Asymmetric pressure gradient

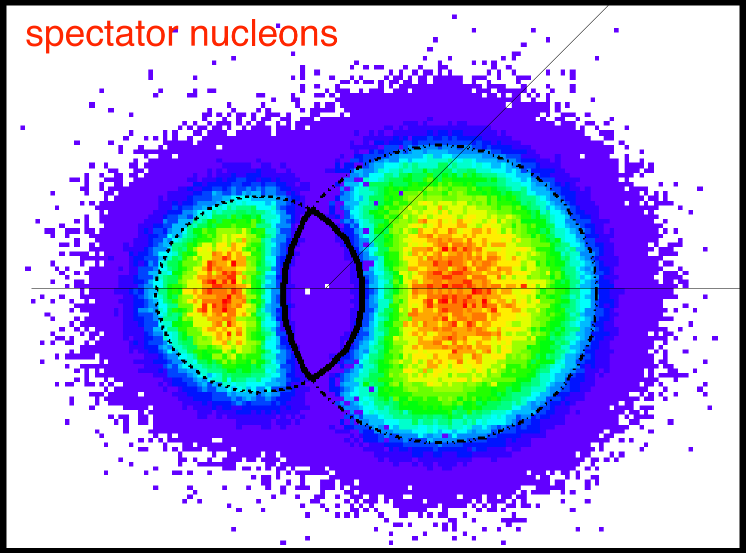
- Intrinsic asymmetric density
  - larger directed flow compared to A+A collisions?
- Sizable initial electric field
  - pointing from Au to Cu, due to the charge difference (# of protons) in both spectators

Cu+Au collisions

plot from A. Iordanova, @RHIC&AGS users meeting 2013





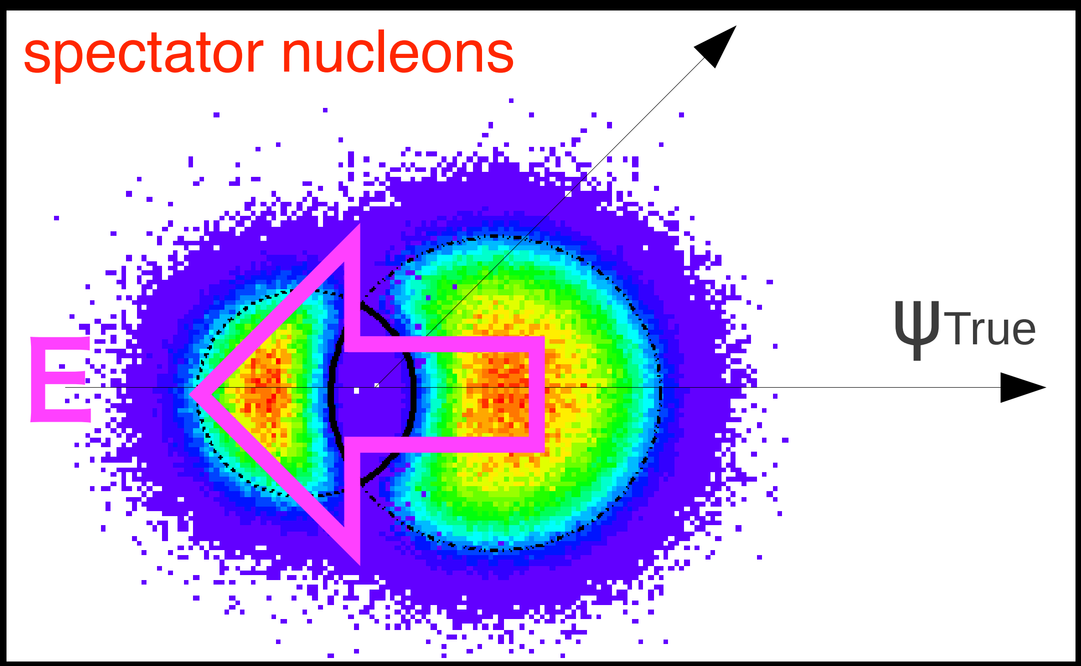


Asymmetric density profile
Asymmetric pressure gradient

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, 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, which appears as **charge dependence of v_1**
  - Y. Hirono et al., Phys. Rev. C90, 021903 (2014), sensitive to the electric conductivity

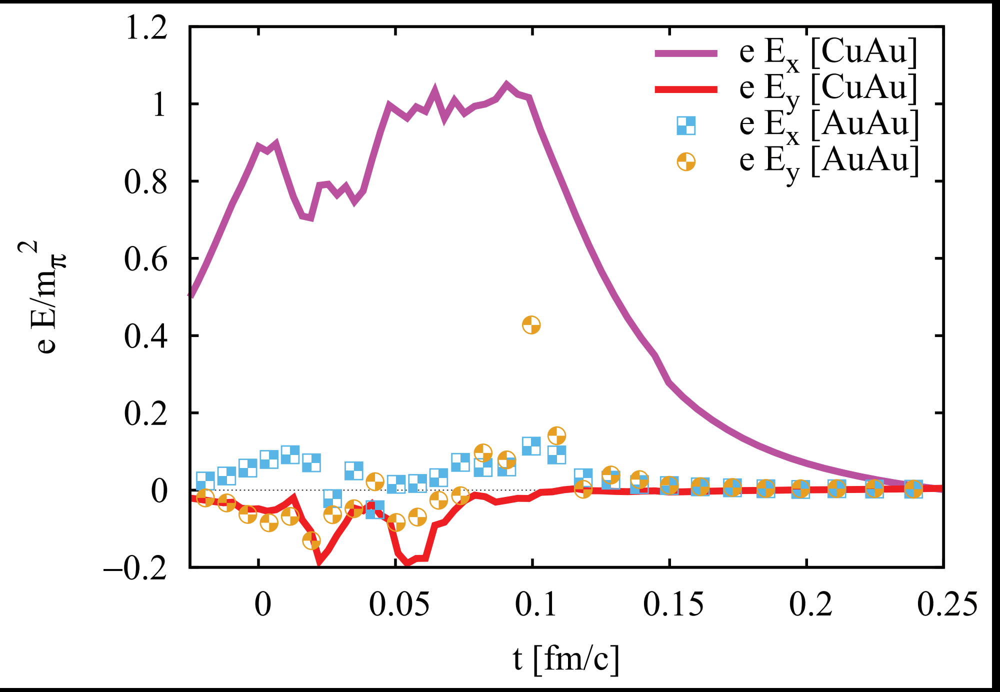
Note: This idea was first reported at IS2013 conference by Y. Hirono

Probe into quark creation time?

Probe into quark creation time?

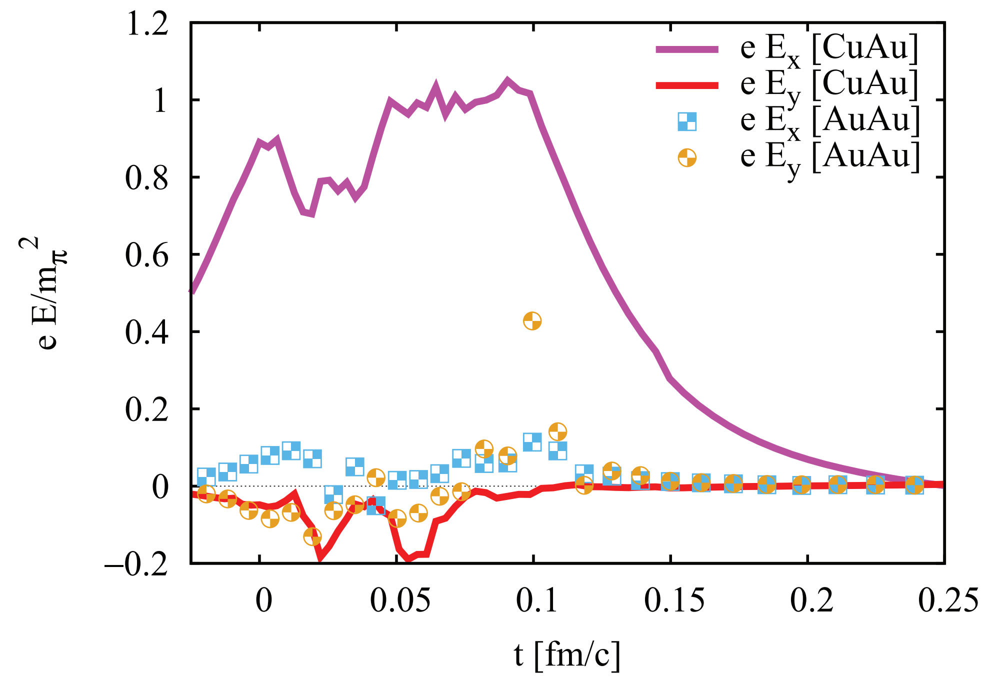
- Life time of E-field would be very short
  - No signal if there are no quarks (charges) when E-field is strong
  - In other words, sensitive to the number of quark & anti-quark at very early stage (V. Voronyuk et al., PRC90.064903)

PRC90.064903, Parton-Hadron String Dynamics



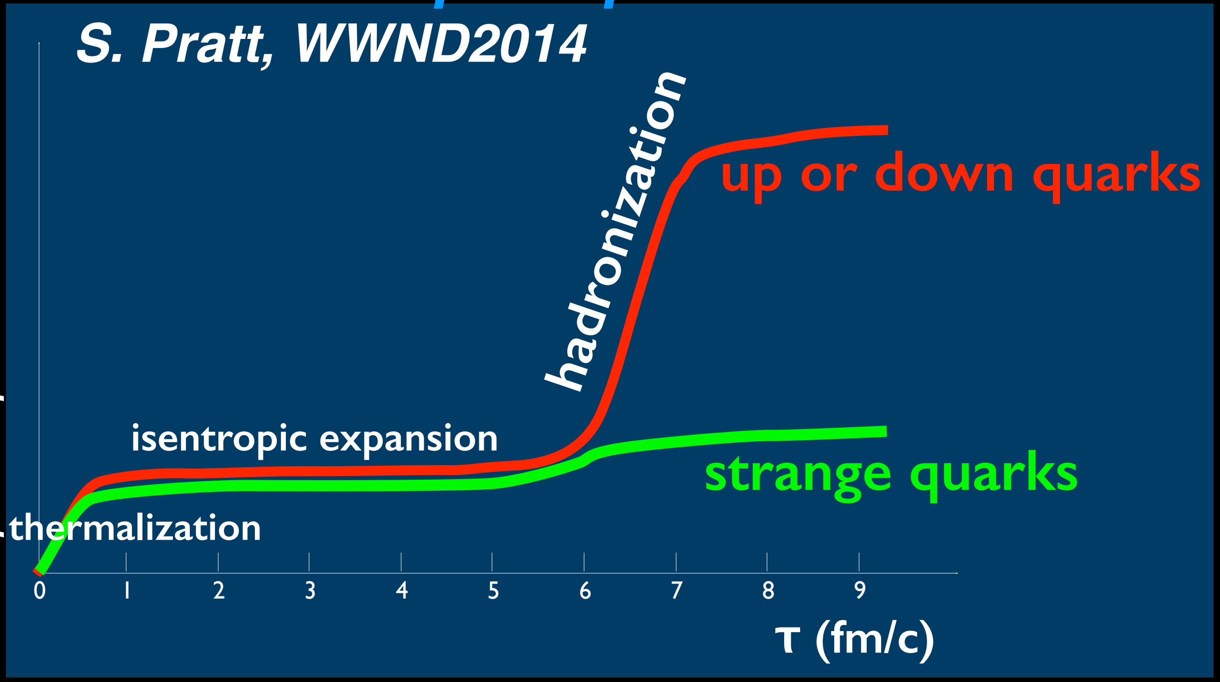
Probe into quark creation time?

PRC90.064903,
Parton-Hadron String Dynamics



- Life time of E-field would be very short
  - No signal if there are 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)

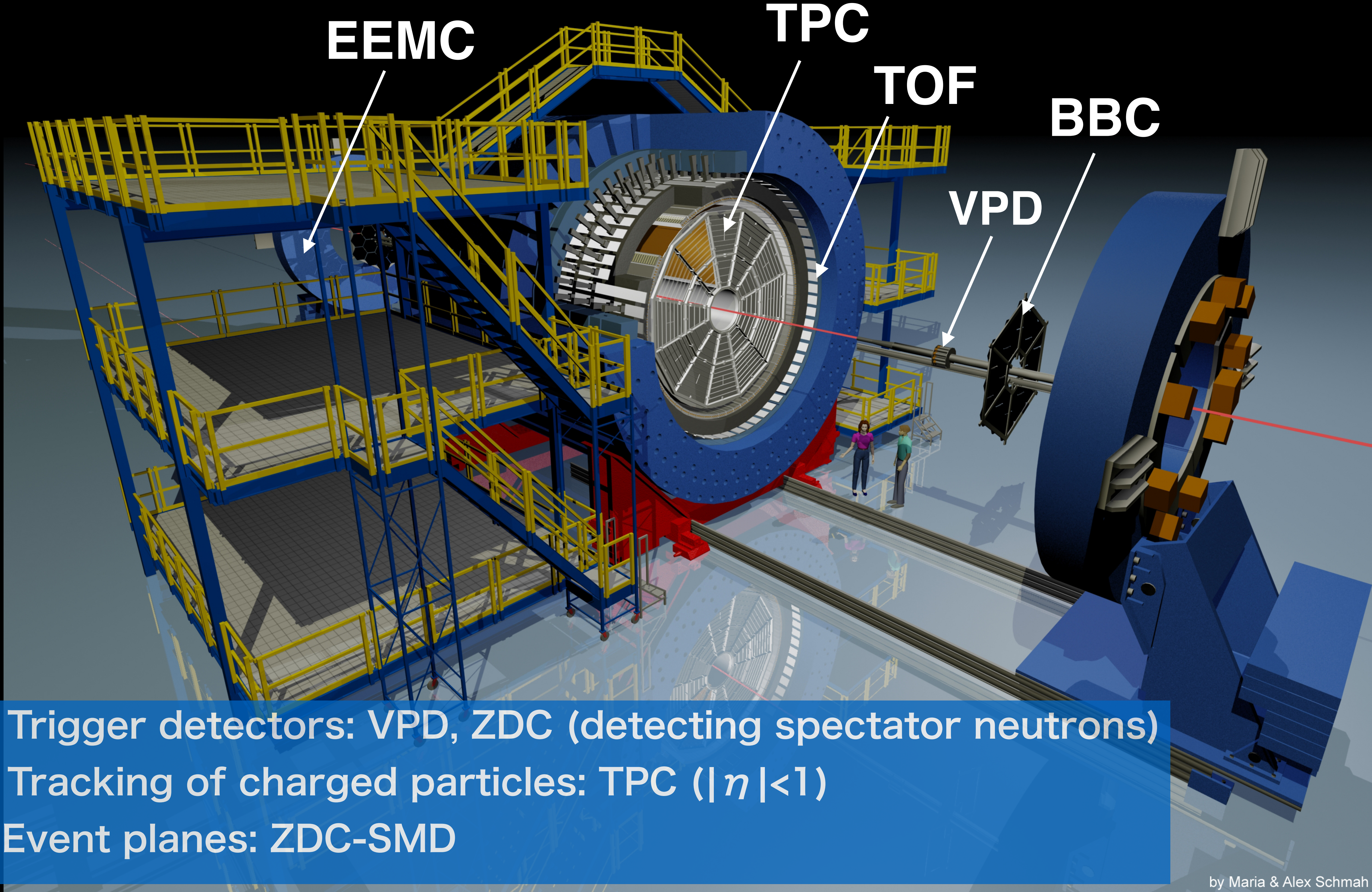
Two-wave of quark production



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

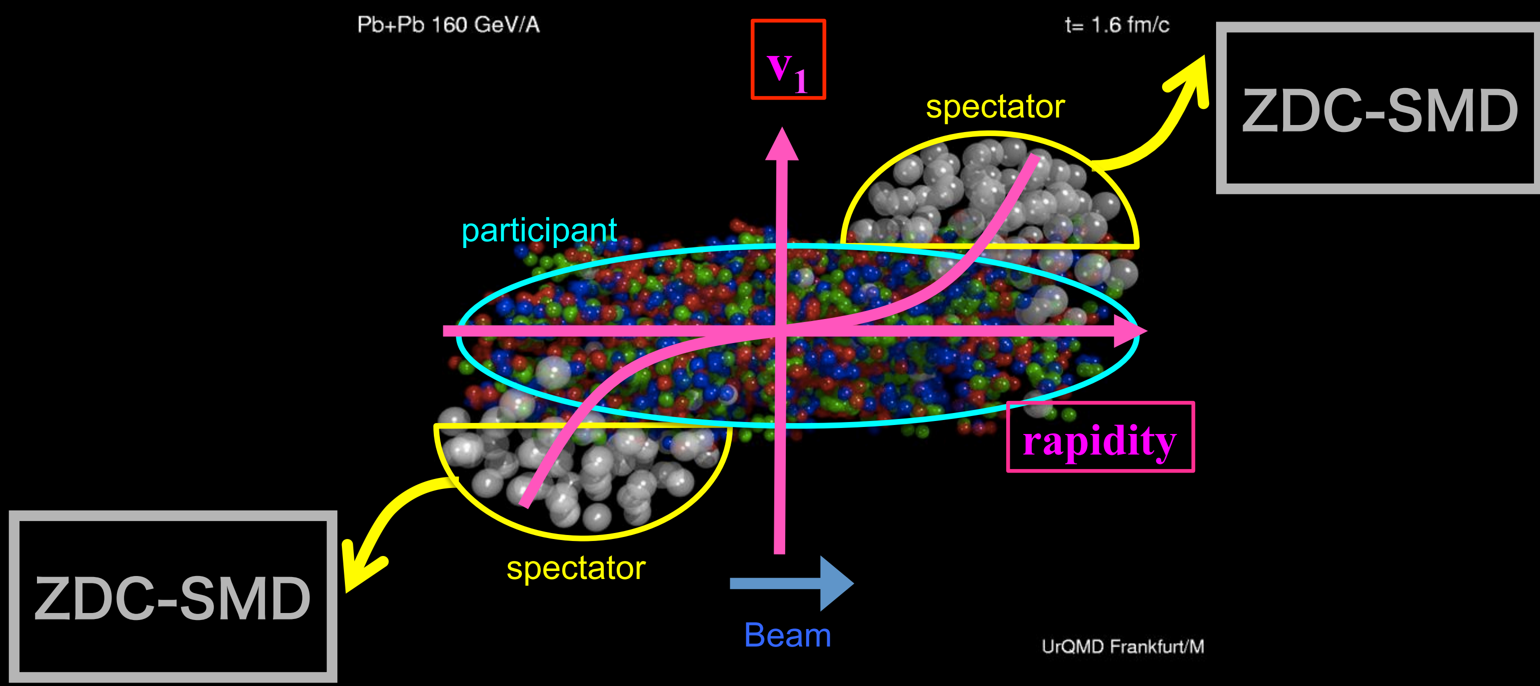
T. Niida, IS2016

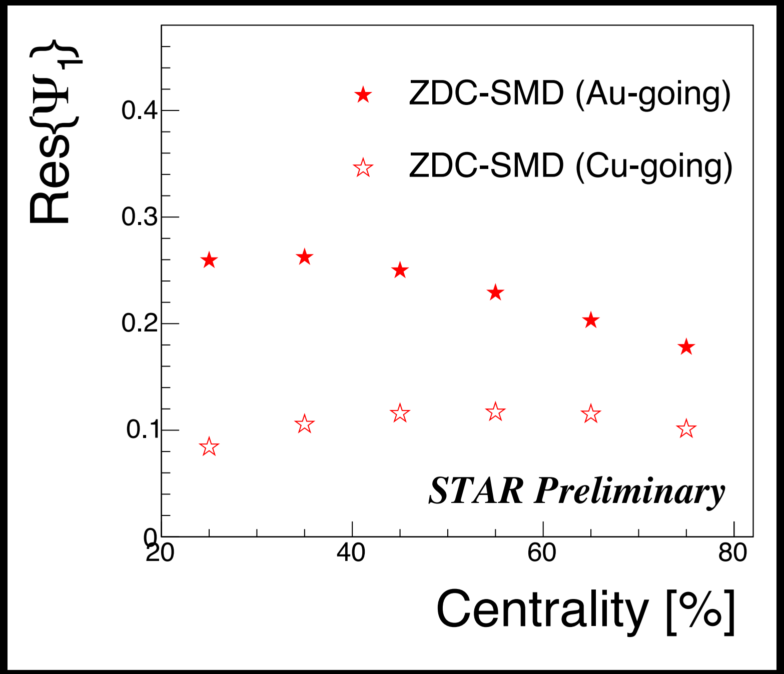
Solenoidal Tracker At RHIC (STAR)



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

Directed flow measurement



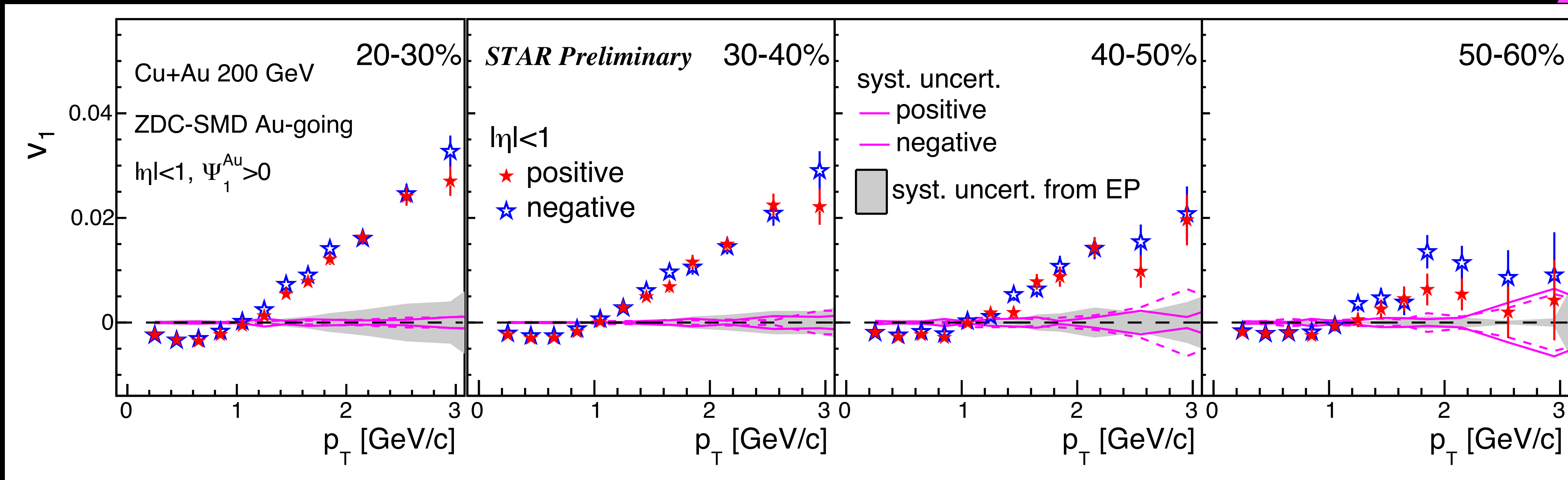


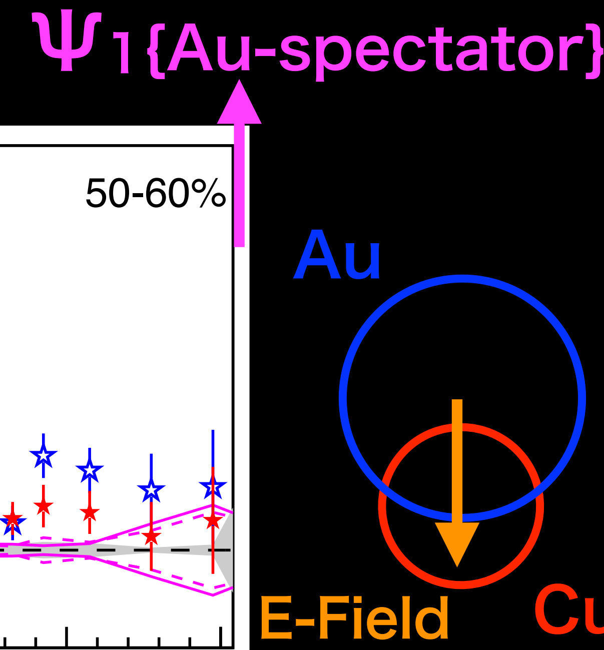
$$v_1 = \langle \cos(\phi - \Psi_1) \rangle / \mathrm{Res}\Psi_1$$

- Ψ_1 determined by Zero Degree Calorimeter (ZDC) and Shower Max Detector (SMD)
  - measure the energy and position of spectator neutrons
- Spectator deflects "outward" from the center of collisions (not "inward")
  - S. Voloshin and TN, arXiv:1604.04597
  - **provides the direction of E-field**

Charge-dependent directed flow

Cu-going direction: $\eta > 0$



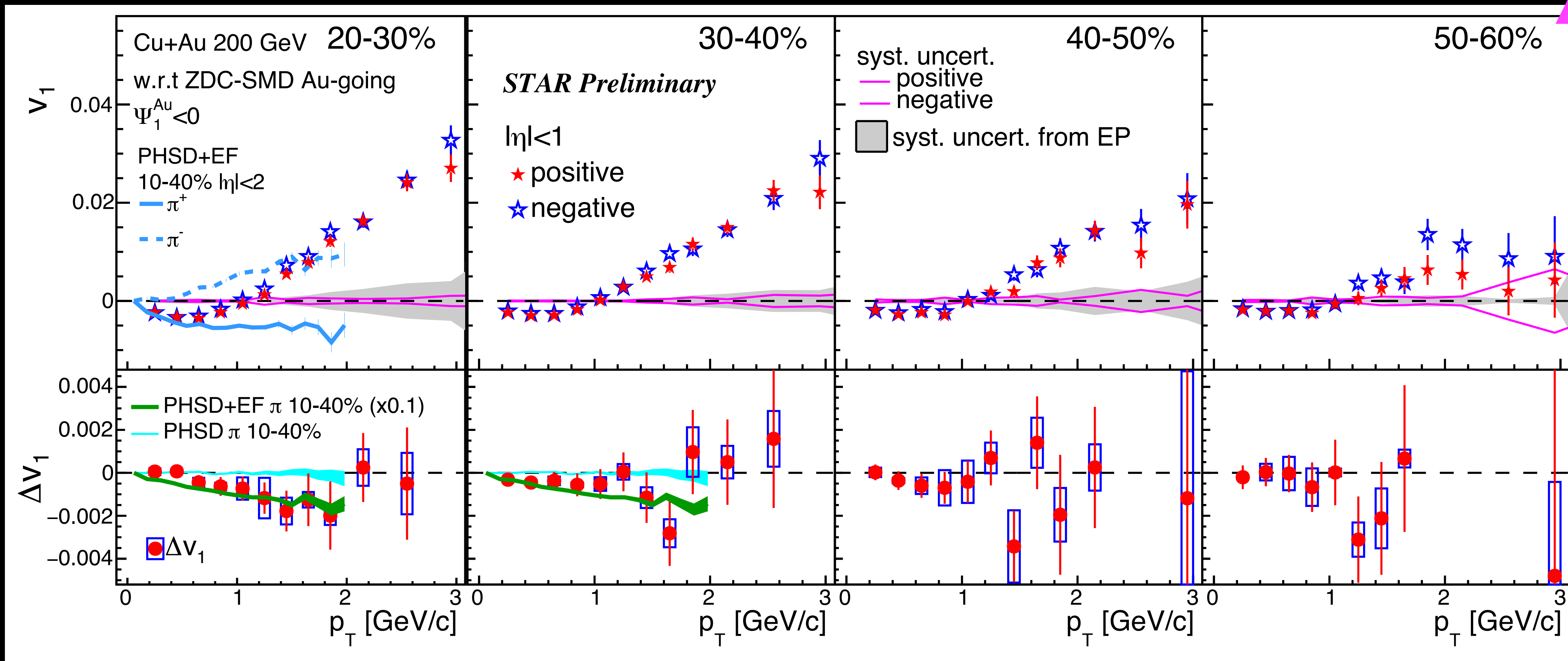


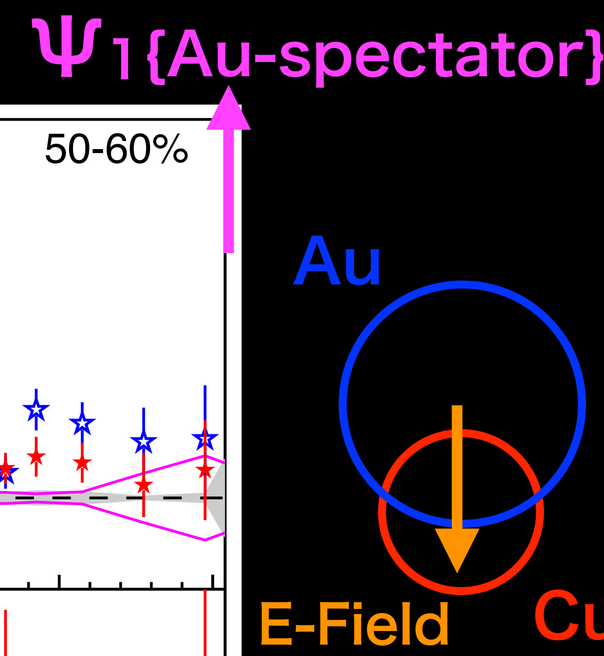
$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

- Sizable v_1 measured relative to Ψ_1{ZDC-SMD} in Au-going side ($\Psi_1^{Au}<0$)
  - v_1 becomes smaller in more peripheral collisions
  - Sign change of v_1 around p_T=1GeV/c to balance the momentum (more low p_T particles in Cu-side, 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 (ALICE, PRL111.23202)
  - Note: v_1^{even} in A+A is only due to density fluctuations

Charge-dependent directed flow



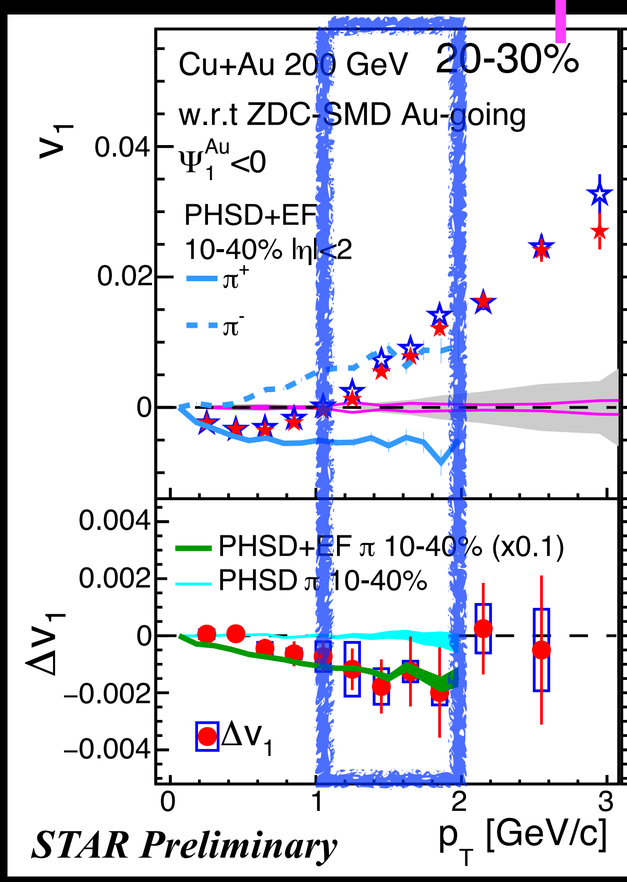


- $\Delta v_1 = v_1(h^+) - v_1(h^-)$, and v_1~1%, Δv_1<0.2%
  - Δv_1 looks to be negative in p_T<2 GeV/c,
  - similar p_T dependence to **PHSD model with the electric field (PHSD+EF)** (PRC90.064903), but smaller by a factor of 10

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

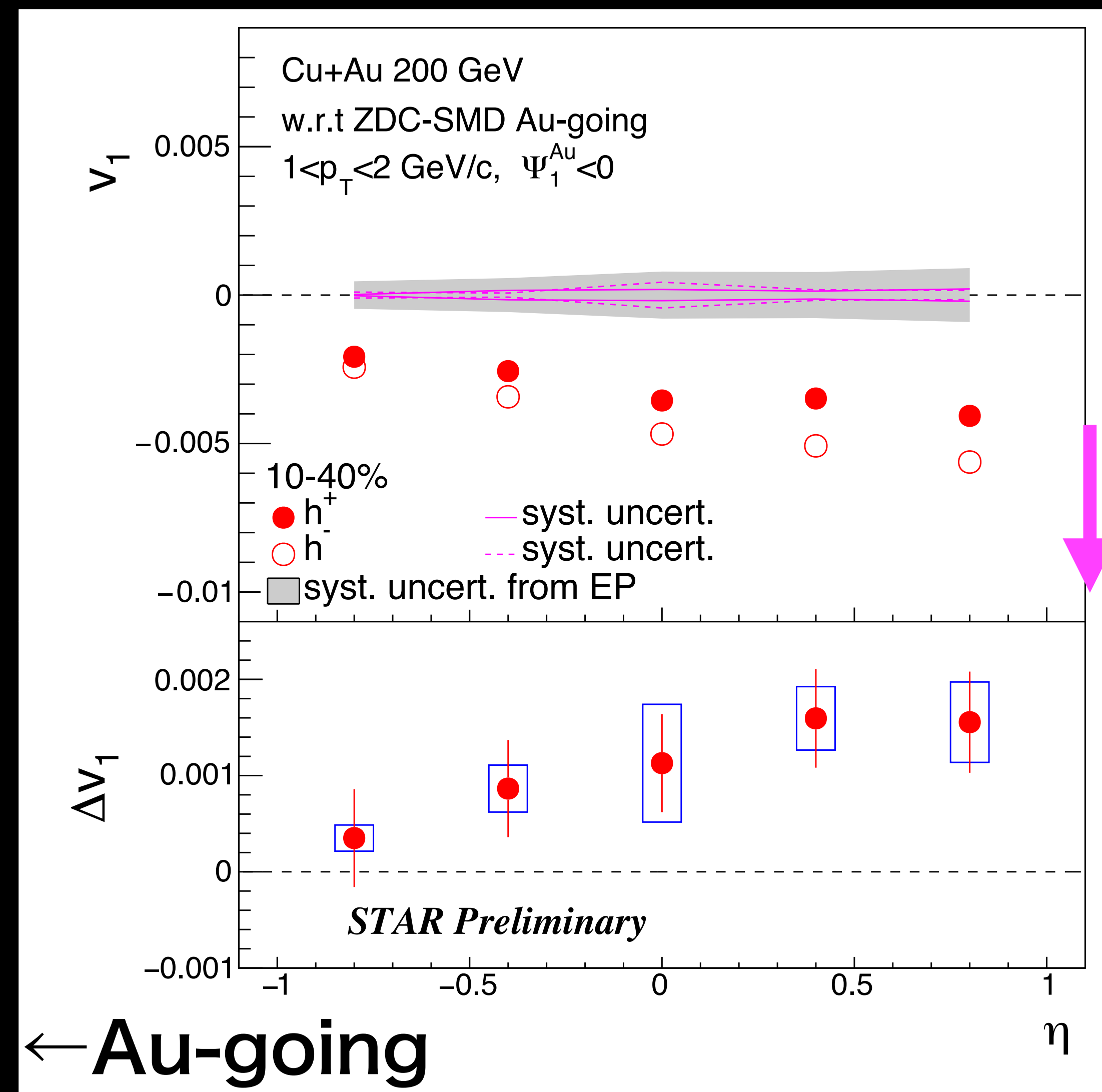
η dependence of v_1

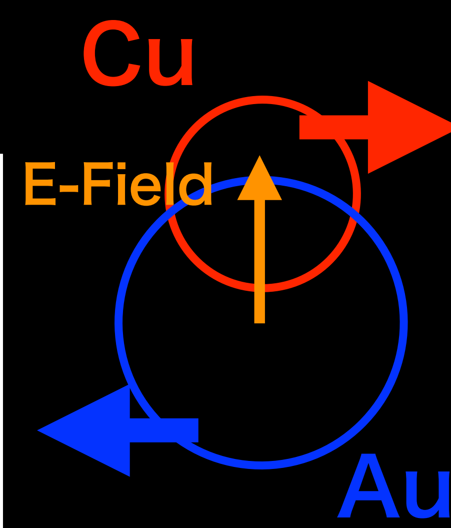
Ψ_1 {Au-spectator}



p_T=1-2

Note:
opposite def.
in sign of v_1

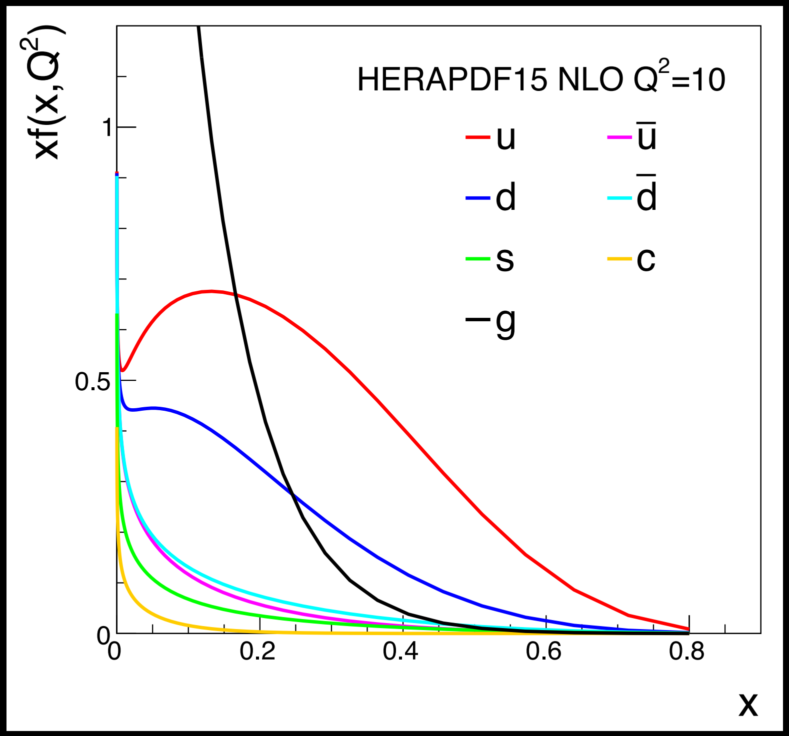




Ψ_1 {Au-spectator}

- Charge-difference can be seen in $-1<\eta<1$ and $1<p_T<2$ GeV/c
  - Difference appears to be larger in Cu-going direction
  - Opposite trend to the PHSD model

How many quarks at initial state?



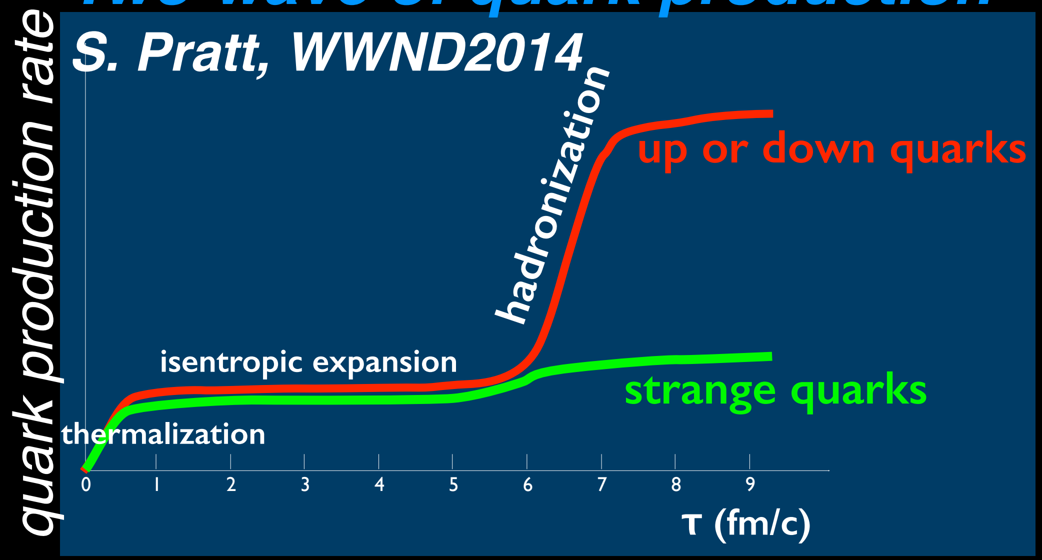
http://hepdata.cedar.ac.uk/

- 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

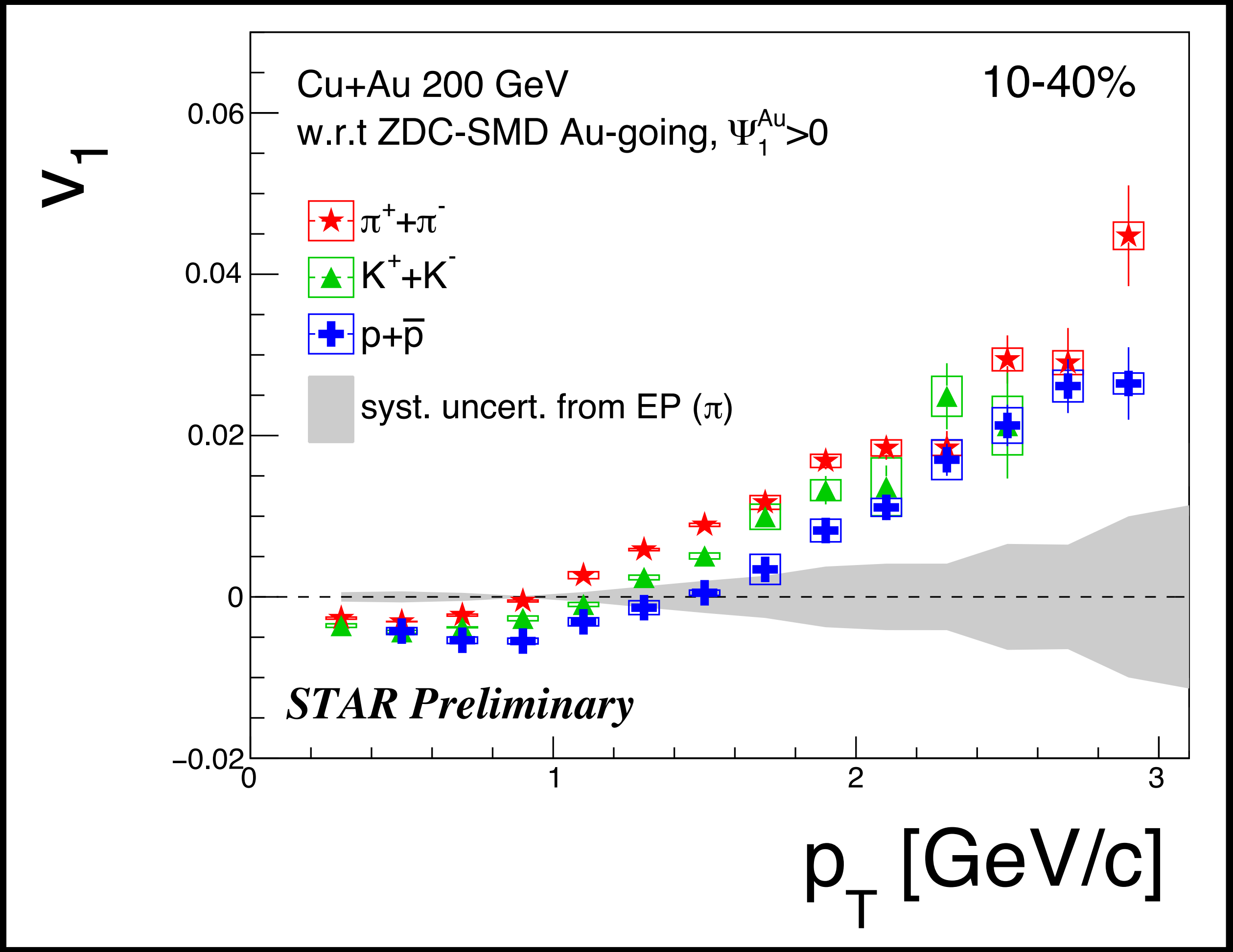


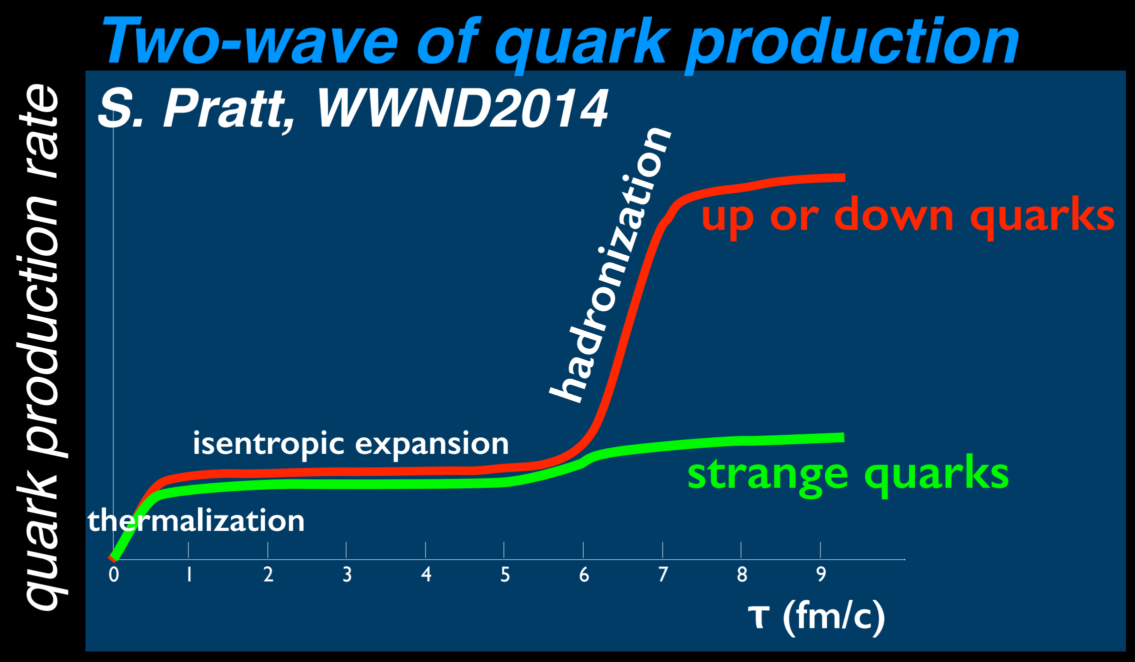
<u>Small fraction of initial quarks to all quarks produced in the collision!</u>

Supporting "two-wave scenario"?

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

Identified Particle v_1





- Mass ordering at low p_T
  - Can be explained by the radial flow (S. Voloshin, PRC55.R1630(1997))
- Would be interesting to look at charge-dependent kaons
  - To test the two-wave scenario, where **s** and **u** quark productions would be expected to be different

Summary

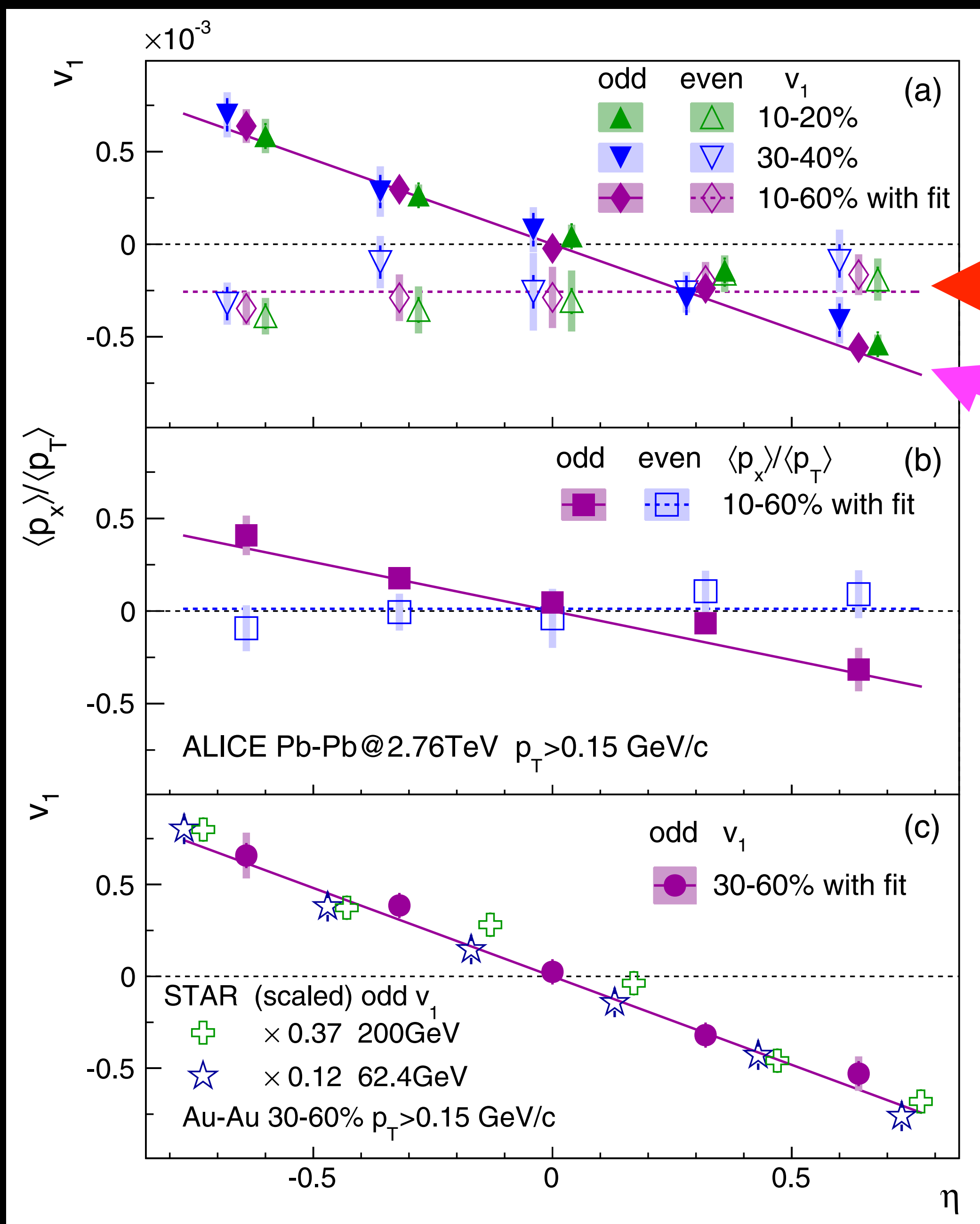
- Charge-dependent directed flow in Cu+Au collisions has been measured at the STAR experiment
  - Charge dependence of v_1, consistent with an existence of the initial electric field, has been observed
  - The magnitude of the difference, Δv_1, is much smaller than the PHSD model prediction, likely indicating that the number of initial (anti-)quarks are very small when the E-Field is strong ($t<0.25$ fm/c)
  - Simple estimate based on the parton distribution functions is consistent with the above interpretation

Thank you for your attention!

Back up

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

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



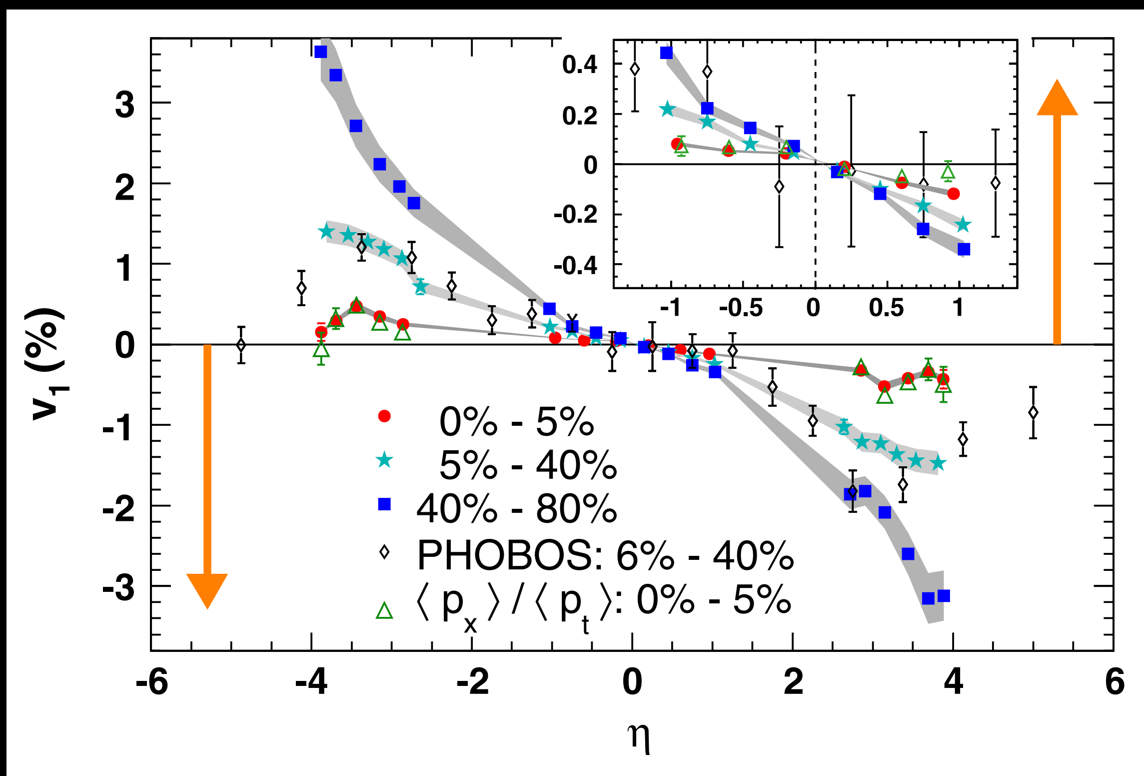
even component independent of η

odd component

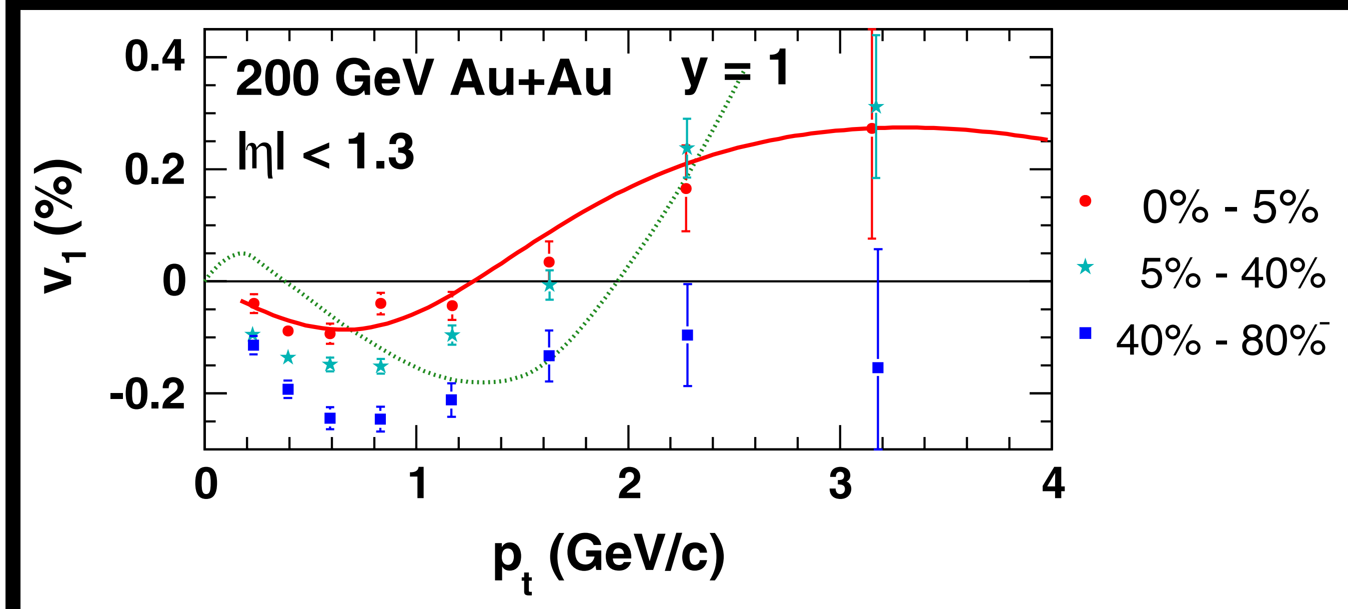
$$v_1^{\text{odd}}\{\Psi_{\text{SP}}\} = [v_1\{\Psi_{\text{SP}}^p\} + v_1\{\Psi_{\text{SP}}^t\}]/2$$

$$v_1^{\text{even}}\{\Psi_{\text{SP}}\} = [v_1\{\Psi_{\text{SP}}^p\} - v_1\{\Psi_{\text{SP}}^t\}]/2.$$

v_1^{odd} in Au+Au 200GeV



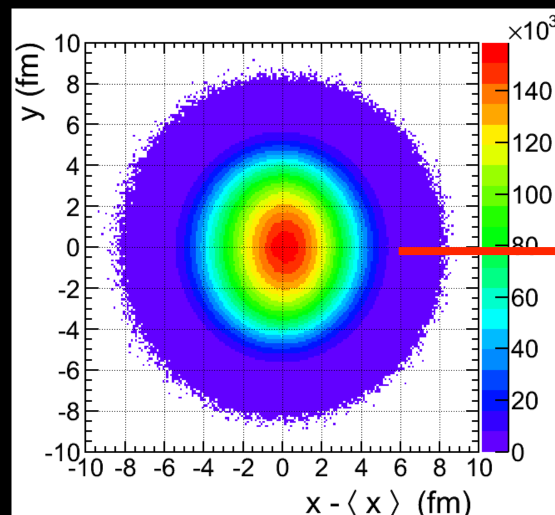
STAR, PRL101.252301



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

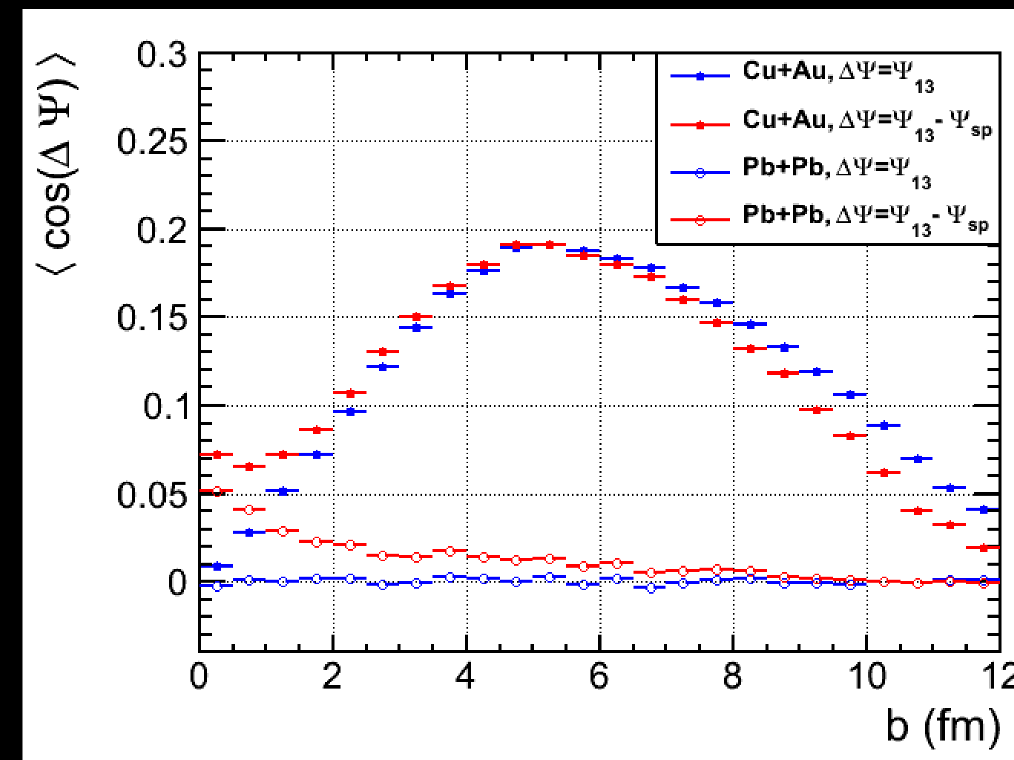
$$v_1^{\mathrm{odd}} = \langle sgn(\eta)\cos(\phi - \Psi_1)\rangle$$

Density asymmetry in Cu+Au



Ψ_{13}

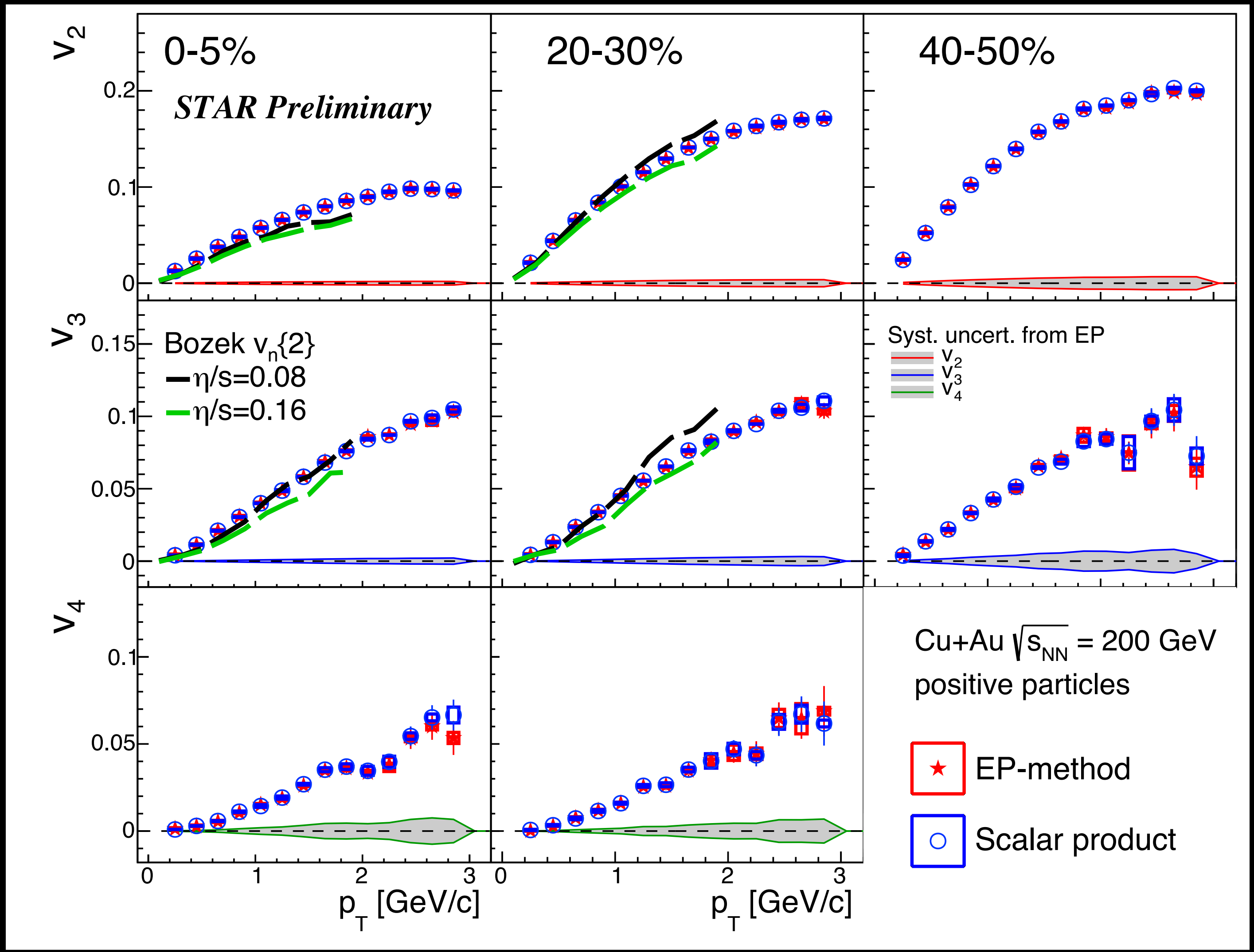
S. Voloshin and T. N, arXiv:1604.04597



$$\varepsilon_{13,x} = \varepsilon_{13}\cos(\Psi_{13}) = -\left\langle r^3\cos(\phi)\right\rangle / \left\langle r^3\right\rangle$$
$$\varepsilon_{13,y} = \varepsilon_{13}\sin(\Psi_{13}) = -\left\langle r^3\sin(\phi)\right\rangle / \left\langle r^3\right\rangle$$

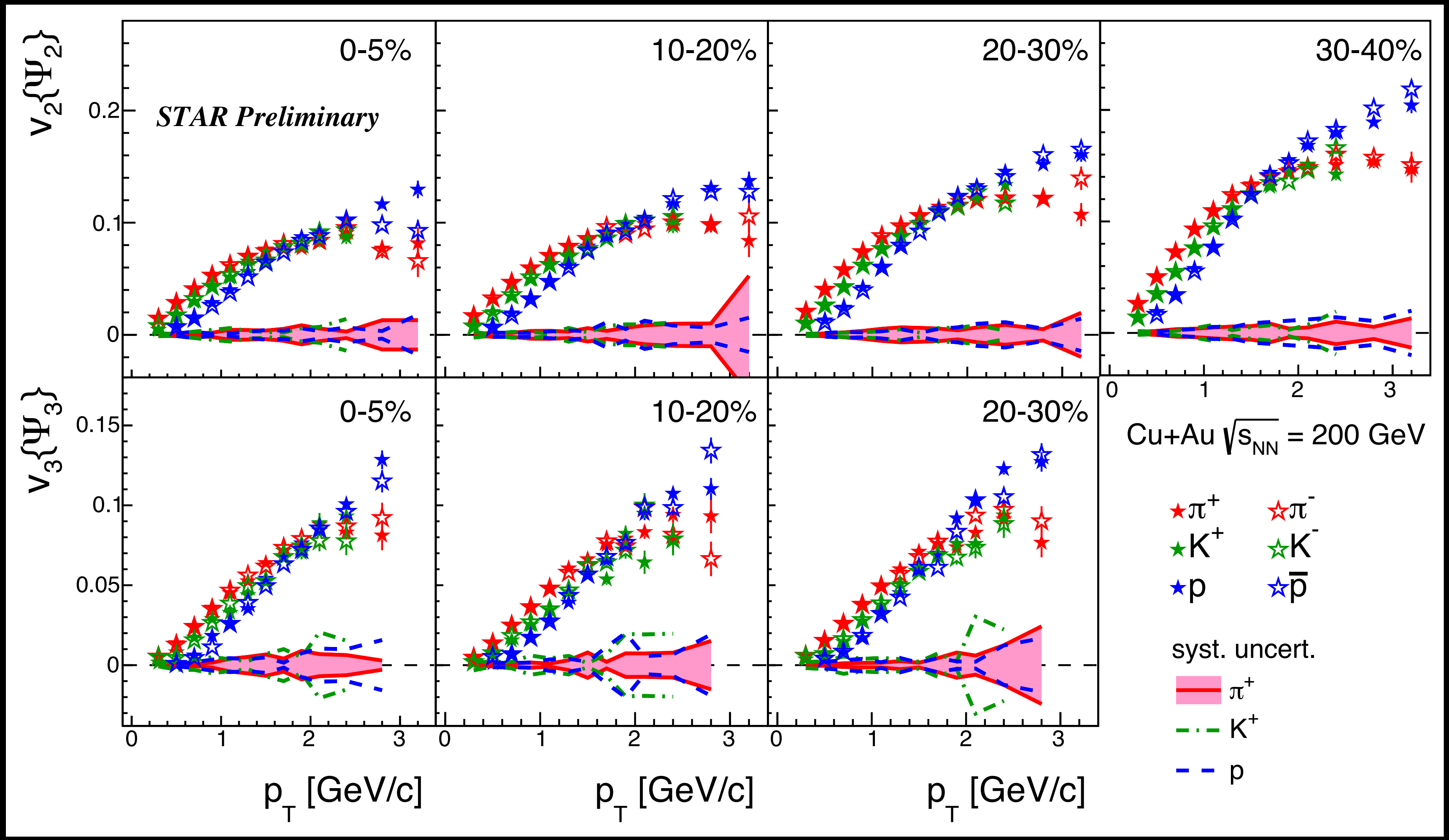
- Ψ_{13} points to the direction where the density gradient is steeper
  = direction to which more high pT particles are emitted
- Significantly larger <cos($\Delta\Psi_{13}$)> in Cu+Au
  →Larger density asymmetry
- In Au+Au, <cos($\Delta\Psi_{13}$)>=0
  but weak correlation between Ψ_{13} and spectator plane Ψ_{SP}

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)

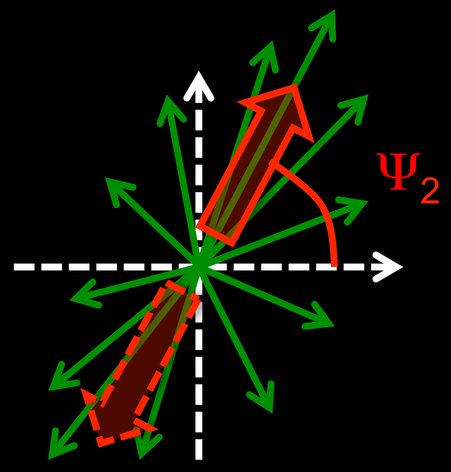
Measurements of azimuthal anisotropies

Event plane method

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

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

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



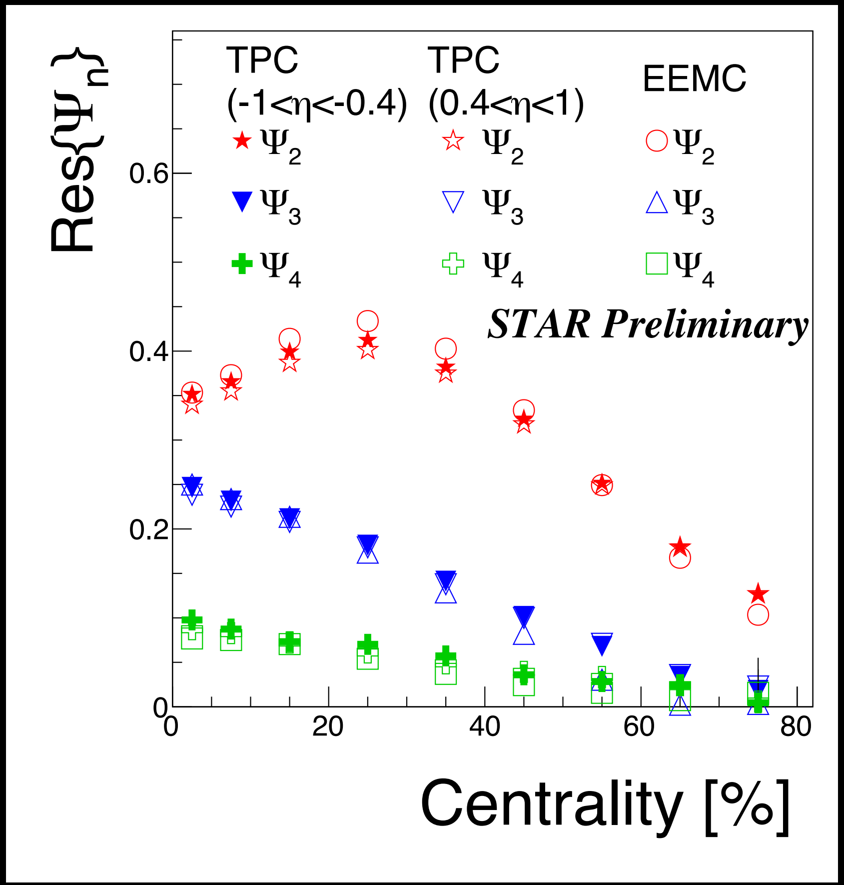
Scalar product method

- 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



T. Niida, IS2016