Azimuthal angle dependence of pion femtoscopy in $\sqrt{s_{NN}}$ = 200 GeV Cu+Au collisions at STAR

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for the STAR collaboration
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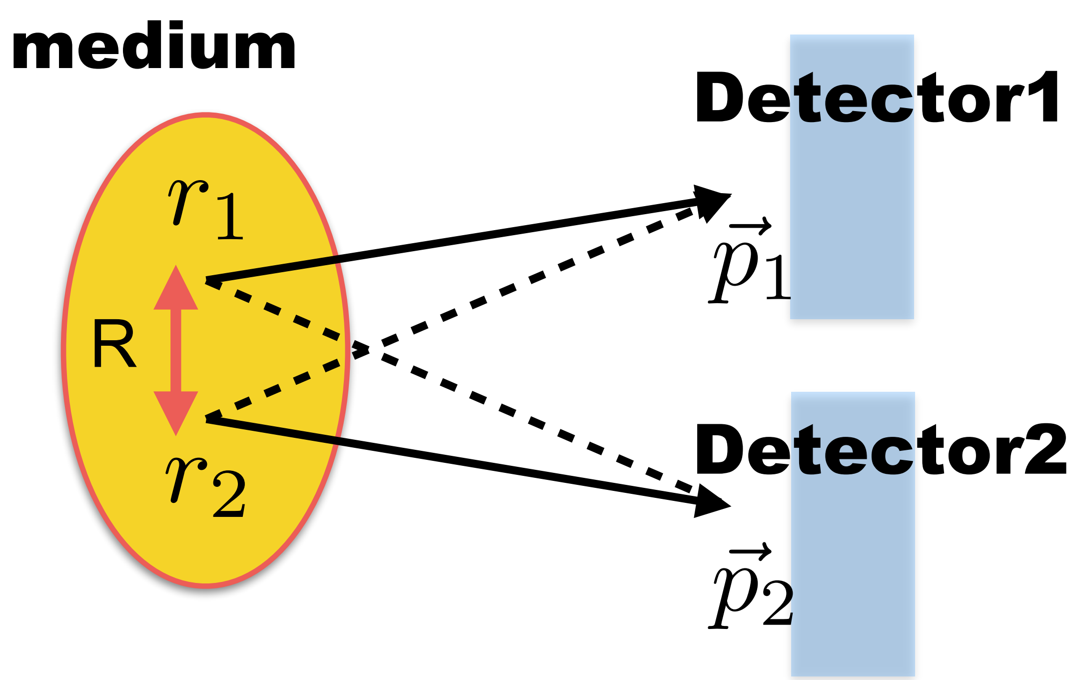
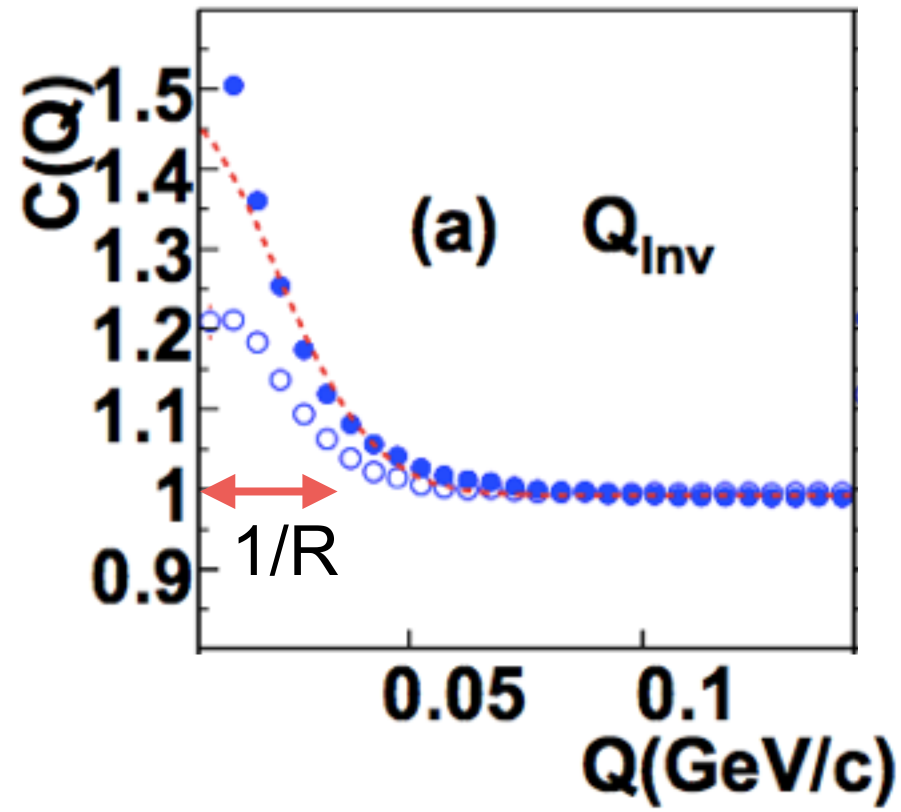
JPS/APS meeting @ Hawaii

HBT interferometry

- HBT can scope **the source size at kinetic freeze-out**
  - ✓ Measure quantum interference between two identical particles





STAR Collaboration, Phys. Rev. Lett. 87 (2001) 82301

- **Theory**

$$C_2 = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} \approx 1 + \exp(-R^2 Q_{inv}^2)$$

$$\vec{q} = \vec{p_2} - \vec{p_1} \quad Q_{inv} = \sqrt{q_x^2 + q_y^2 + q_z^2 - q_0^2}$$

- **Experimentally**

$$C(q) = \frac{N(q)}{D(q)}$$

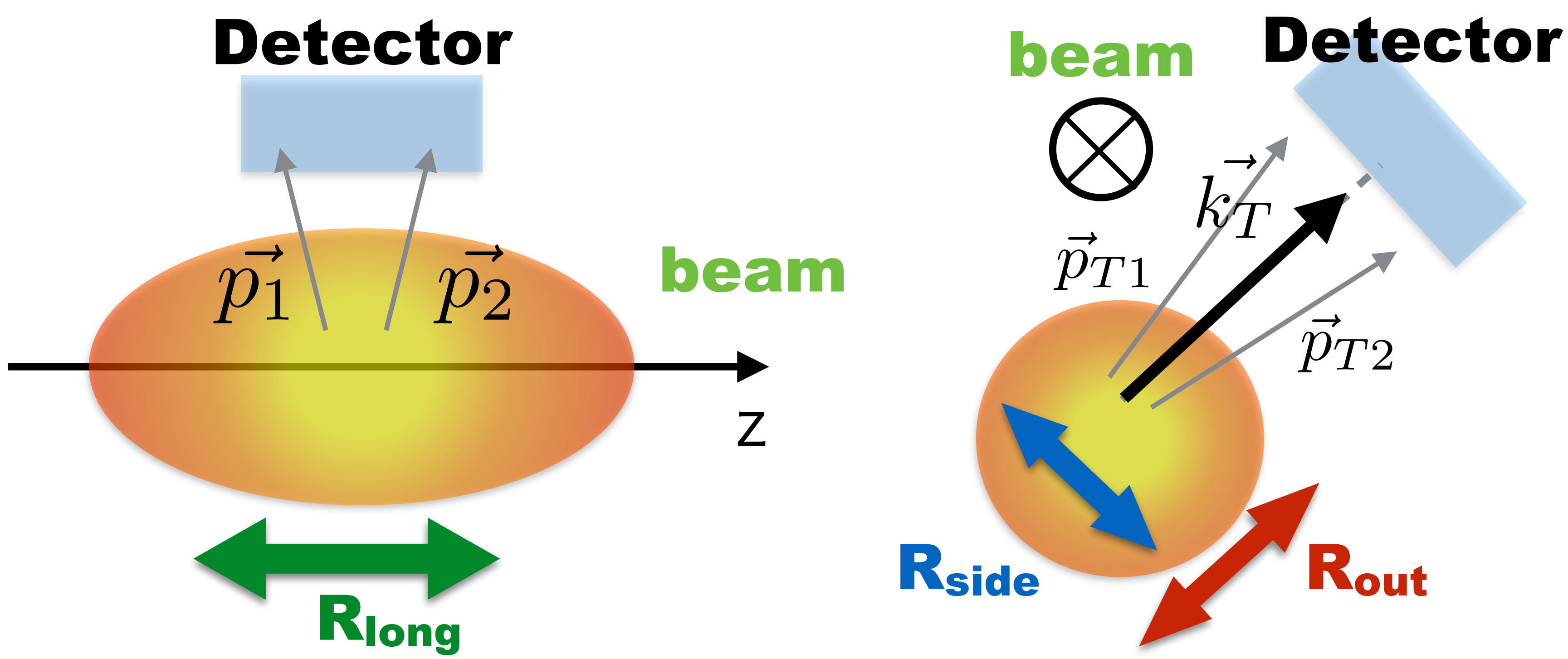
- **Event mixing**

N: pair distribution in same event (real)
D: pair distribution in different event (mix)

- Make correlation function as a function of relative momentum (q)
- We can extract the source radius by fitting with theoretical formula.

3D HBT radii

- **Bertsch-Pratt Parameterization** (Phys. Rev. D 33, 72 , Phys. Rev. C 37, 1896 (1988))



$$\vec{k}_T = \frac{1}{2}(\vec{p}_{T1} + \vec{p}_{T2})$$

$$\vec{q}_{out} \parallel \vec{k}_T$$

$$\vec{q}_{side} \perp \vec{k}_T$$

- **3 dimensional radii use**

✓ **R_{long} : Source size parallel to the beam direction**

✓ **R_{out} : Source size parallel to the pair transverse momentum (k_T)**

✓ **R_{side} : Source size perpendicular to R_{out} and R_{long}**

✓ Fitting function:

$$C(\vec{q}) = N[(1-\lambda) + \lambda K(\vec{q})(1 + G(\vec{q}))]$$

$$G(\vec{q}) = \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2)$$

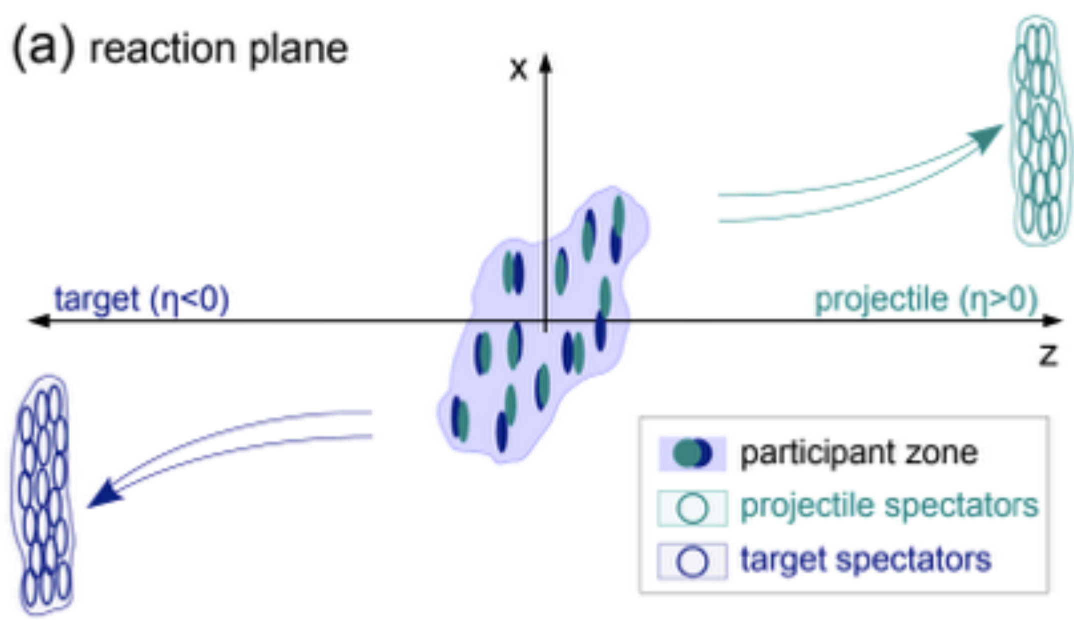
N : Normalization , K(q) : Coulomb correction, λ: Correlation strength

✓ **Correlation function is expanded to 3 dimensional (out , side and long axis)**

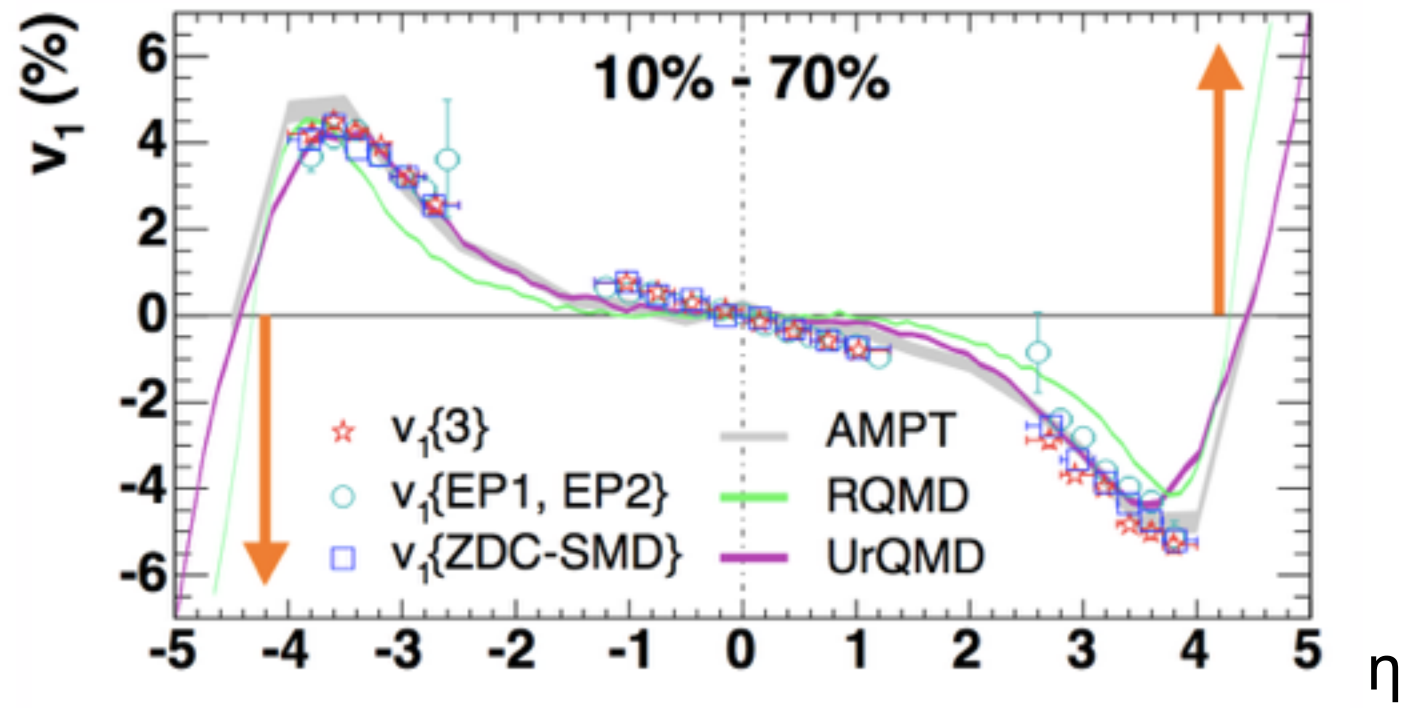
✓ **Extract radii parameters 3 dimensionally**

Directed flow

ALICE Collaboration, Phys. Rev. Lett. 111 (2013) 232302



STAR Collaboration, Phys. Rev. C 73 (2006) 34903



Au+Au 62.4 GeV, Charged particle v_1

The direction of flow for spectator neutrons (measured in ZDC).

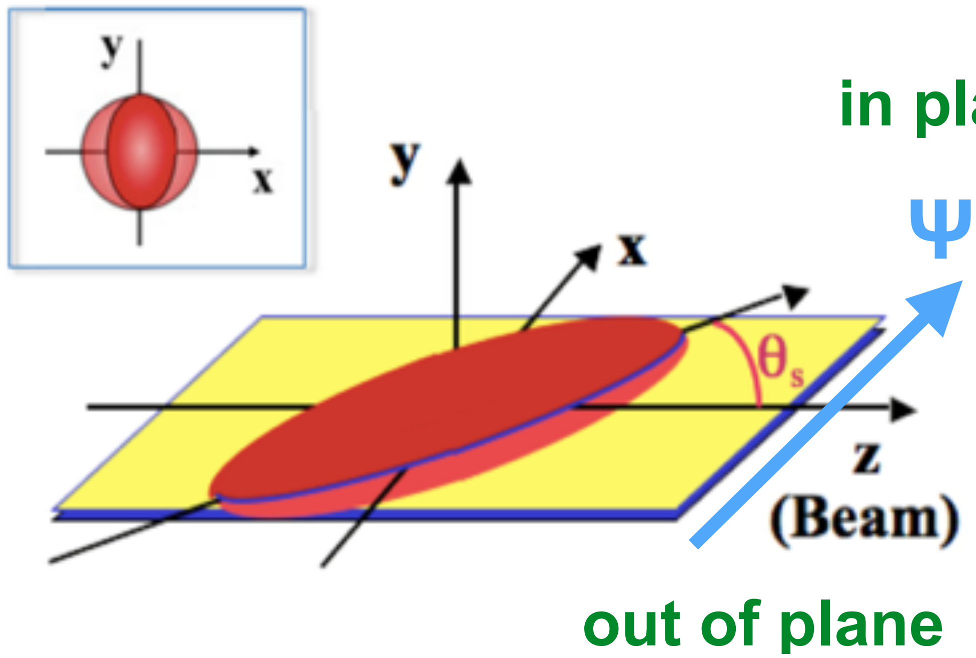
- ✓ **Directed flow is generated by the interaction between spectator and participant particles.**
- ✓ **Quantified by the 1st harmonic in the Fourier expansion as v_1**

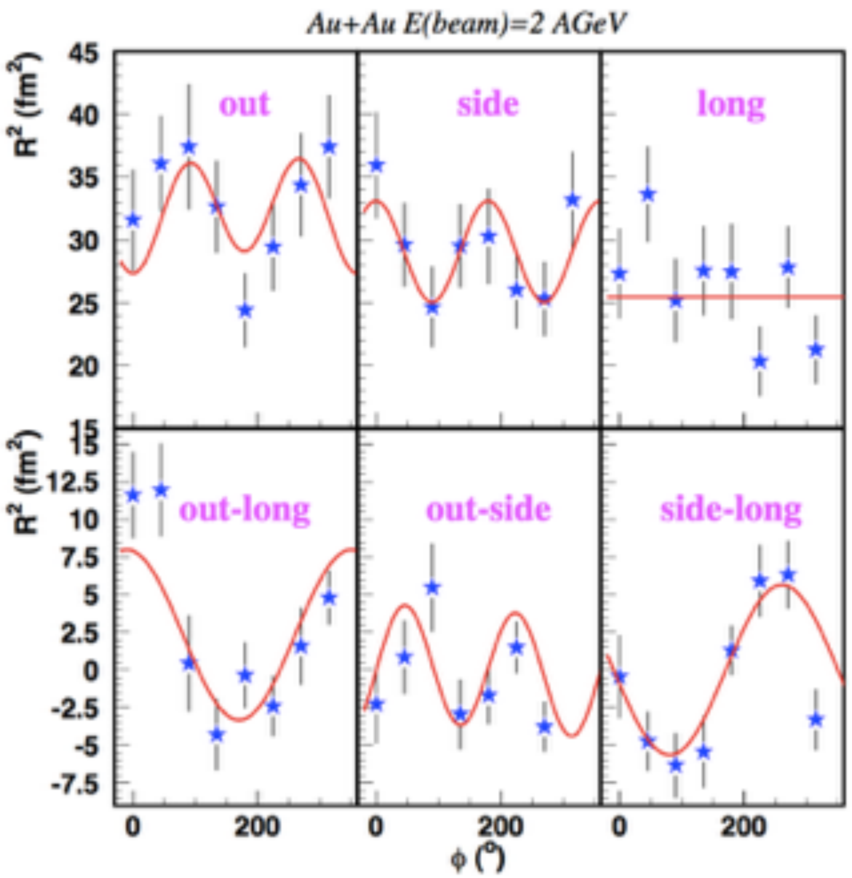
$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

- ✓ **$v_1(\eta)$ is crossing 0 by 3 times at around midrapidity, forward and backward rapidity**
- ✓ **The direction of flow have different sign between participant and spectator**

HBT radii w.r.t. Ψ_1

M A Lisa et al. New J. Phys. 13 (2011) 065006





- One can predict one of the origin of directed flow is the "tilt of the medium"
- HBT measurement w.r.t. Ψ_1 can scope directly this "tilt" by including cross terms in fit function.

✓ Fit function with cross term:

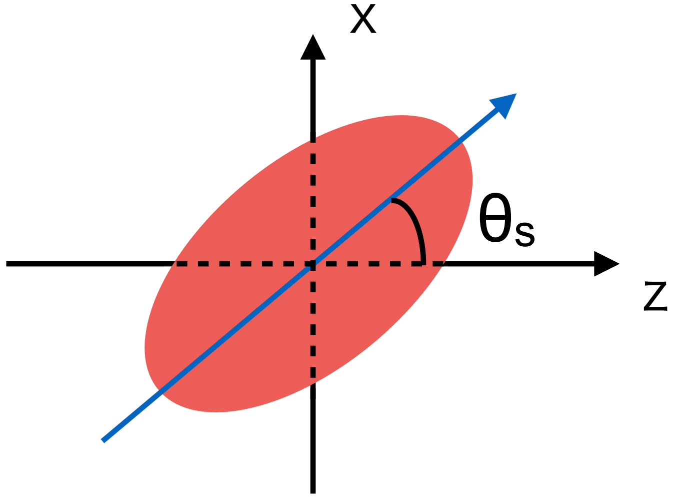
$$C(\vec{q}) = N[(1-\lambda) + \lambda K(\vec{q})(1+G(\vec{q}))]$$

$$G(\vec{q}) = \exp(-R^2_{out}q^2_{out} - R^2_{side}q^2_{side} - R^2_{long}q^2_{long} - 2R^2_{os}q_{out}q_{side} - 2R^2_{ol}q_{out}q_{long} - 2R^2_{sl}q_{side}q_{long})$$

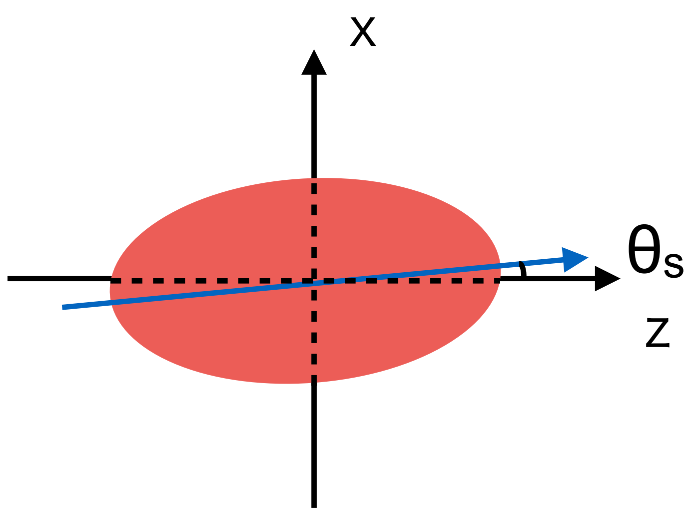
- Important parameters: R_{ol} , R_{sl}
- If final source is tilted, R_{ol} and R_{sl} cross terms will have oscillation w.r.t. Ψ_1

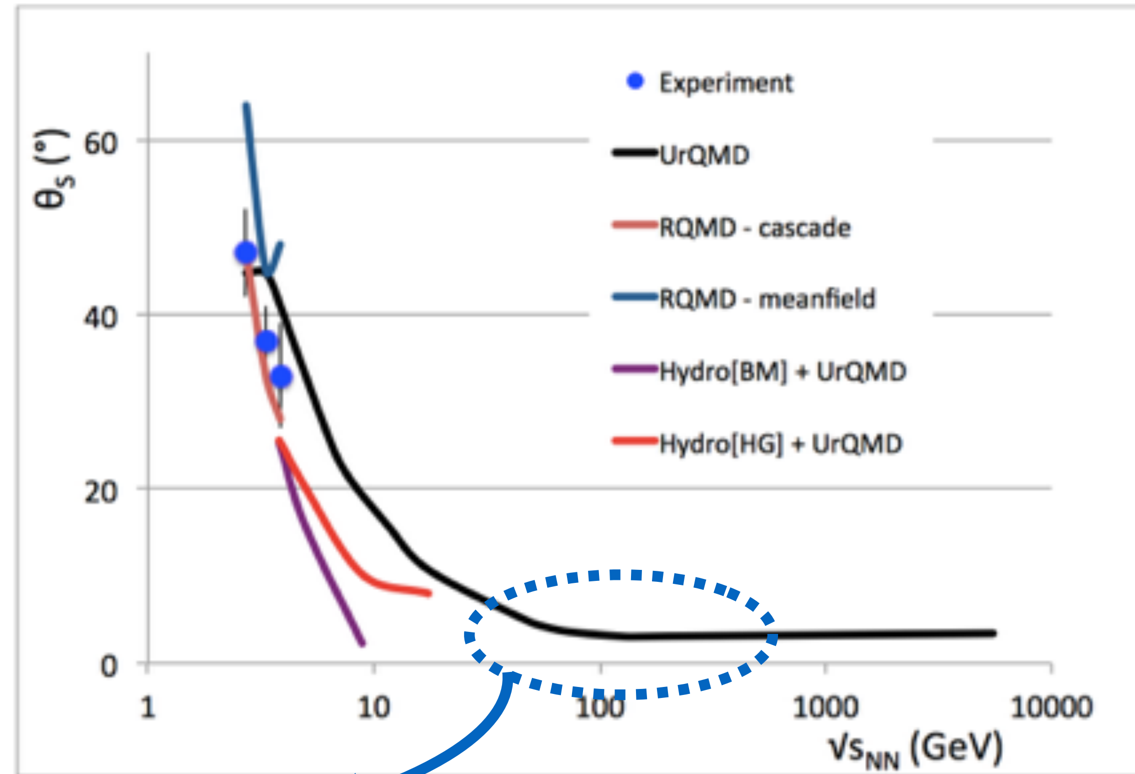
Motivation

- ✓ Low energy



- ✓ High energy expectation





Is there a signal ?

M A Lisa et al. New J. Phys. 13 (2011) 065006

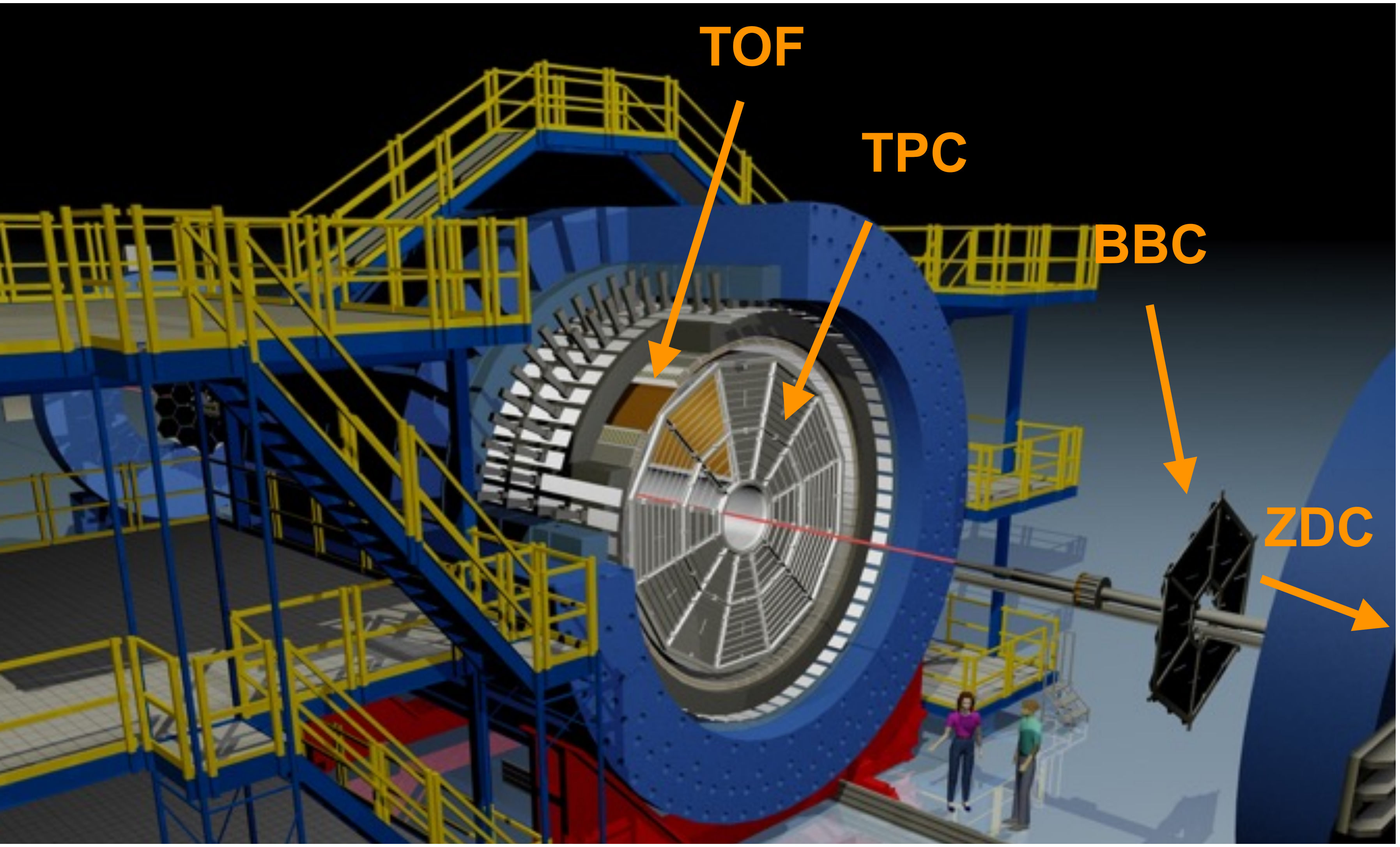
Tilt angle

$$\theta_s = \frac{1}{2}tan^{-1}\left(\frac{-4R^2_{sl,1}}{R^2_{l,0} - R^2_{s,0} + 2R^2_{s,2}}\right)$$

- **Fit function:**
  $R^2_{\mu,0} + 2\,R^2_{\mu,1}\cos(\varphi-\Psi_1) + 2\,R^2_{\mu,2}\cos(2(\varphi-\Psi_1))$, (μ = o, s, ol)
  $R^2_{\mu,0} + 2\,R^2_{\mu,1}\sin(\varphi-\Psi_1) + 2\,R^2_{\mu,2}\sin(2(\varphi-\Psi_1))$, (μ = os, sl)

- **Experimentally, source tilt has been only measured at low energies.**
- **Tilt angle is inversely proportional to the beam energy**
- **In RHIC energy (200 GeV), source tilt value is expected nearly 0 or signal is very small.**
  - **✓ Measure HBT w.r.t Ψ_1 and scope tilt signal using both Au+Au and Cu+Au in 200 GeV**
  - **✓ Cu+Au have initial density asymmetry…**
    -> How does it affect HBT measurement ?

The STAR detector



Time Projection Chamber (TPC)
- Main tracking detector, $|\eta| < 1.0$, full azimuth

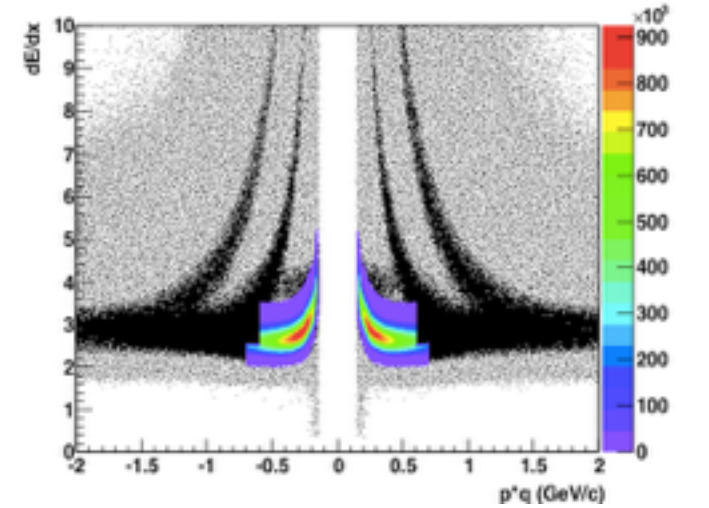
Zero Degree Calorimeter (ZDC)
- $|\eta| > 6.3$
- Measure spectator neutron
- event plane reconstruction using spectator neutrons

Beam-Beam Counters (BBC)
- $3.3 < |\eta| < 5$
- event plane reconstruction using participants

TOF & TPC detector

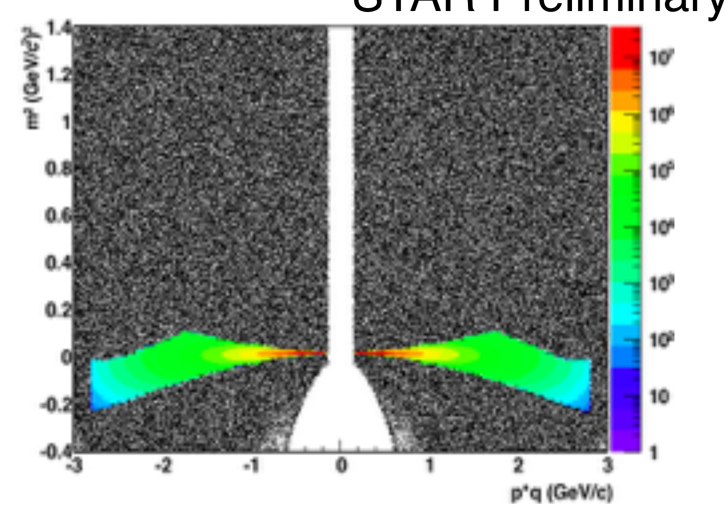
✓Use PID (particle identification)

TPC (dE/dx) STAR Preliminary



TOF (time of flight)

STAR Preliminary



✓Pion selected

Analysis

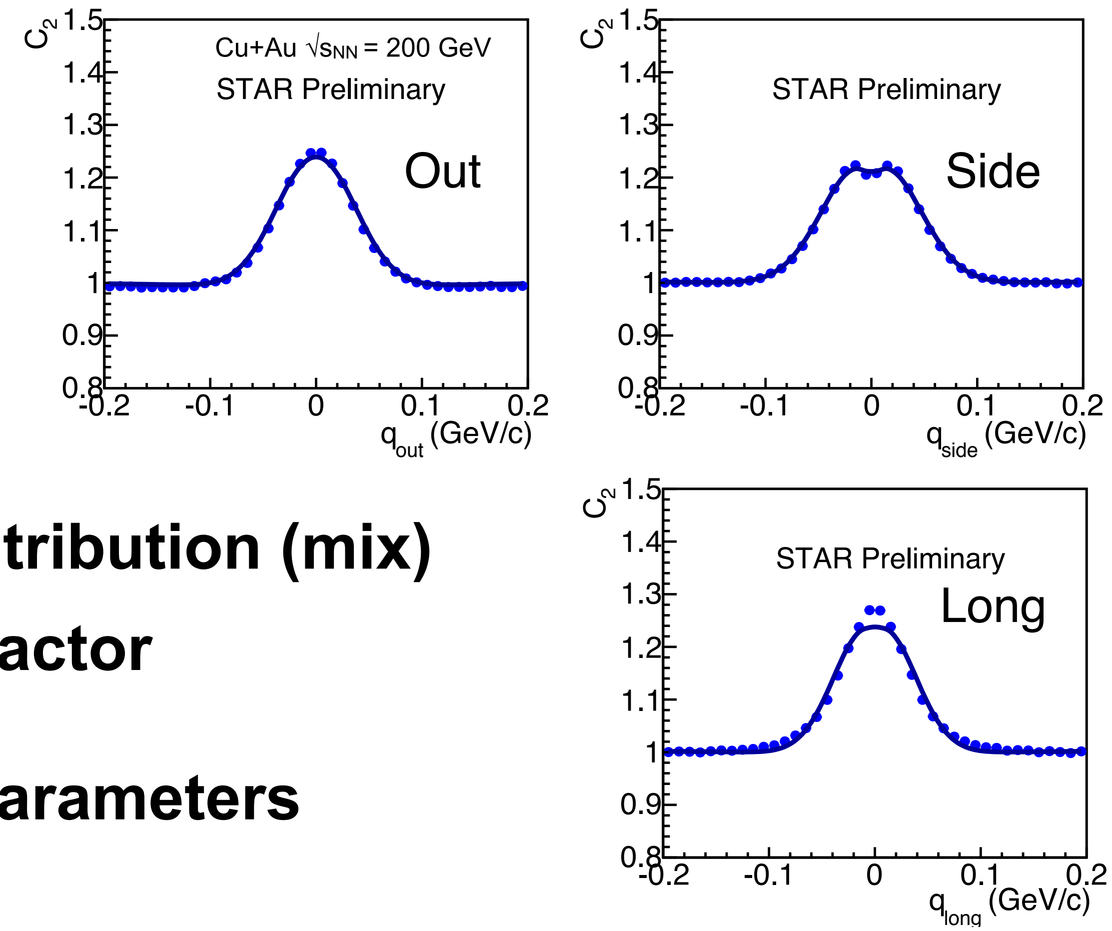
- **Cu+Au 200 GeV, Au+Au 200 GeV**
- **Number of events: Cu+Au ~ 45 M**
  Au+Au ~ 200 M
- **Correlation function**

$$C(q) = \frac{N(q)}{D(q)}$$

N: pair distribution (real)
D: different event pair distribution (mix)

- **Estimate coulomb interaction correction factor**
  K(q) : coulomb correction
- **Fit correlation function and extract radii parameters**

$$C(\vec{q}) = N[(1-\lambda) + \lambda K(q)(1 + G(\vec{q}))]$$



✓ Azimuthally-integrated analysis

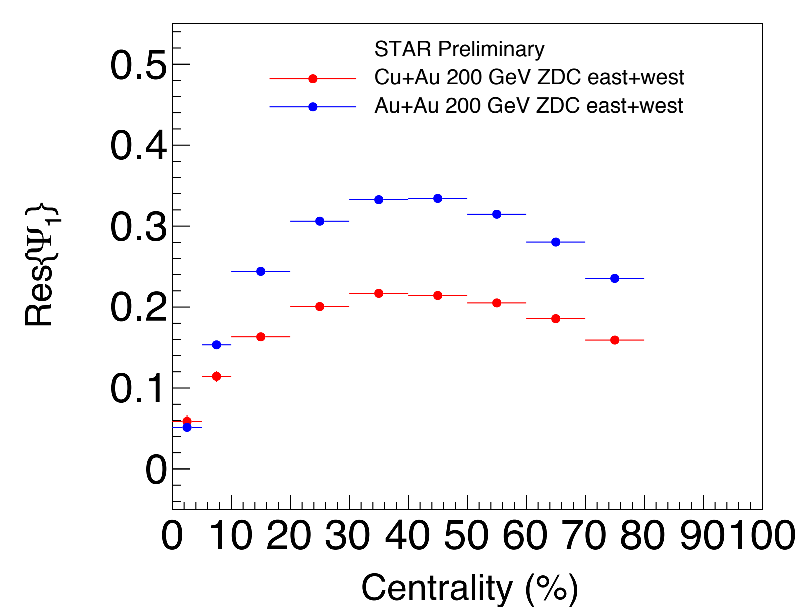
$$G(\vec{q}) = \exp(-R^2_{out}q^2_{out} - R^2_{side}q^2_{side} - R^2_{long}q^2_{long})$$

✓ Azimuthal-angle-dependent HBT analysis

$$G(\vec{q}) = \exp(-R^2_{out}q^2_{out} - R^2_{side}q^2_{side} - R^2_{long}q^2_{long} - 2R^2_{os}q_{out}q_{side} - 2R^2_{ol}q_{out}q_{long} - 2R^2_{sl}q_{side}q_{long})$$

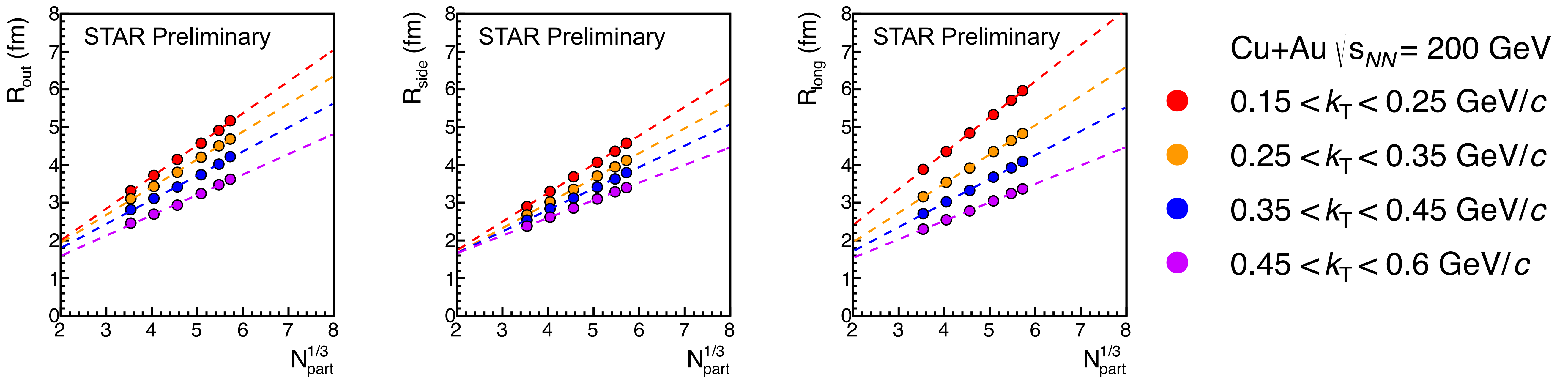
- **Event plane reconstruction**
  ✓ ZDC east + west plane used

✓ ZDC east + west plane is defined based of the sign of ZDC west (η > 0) (with flipped sign of ZDC east (η < 0))

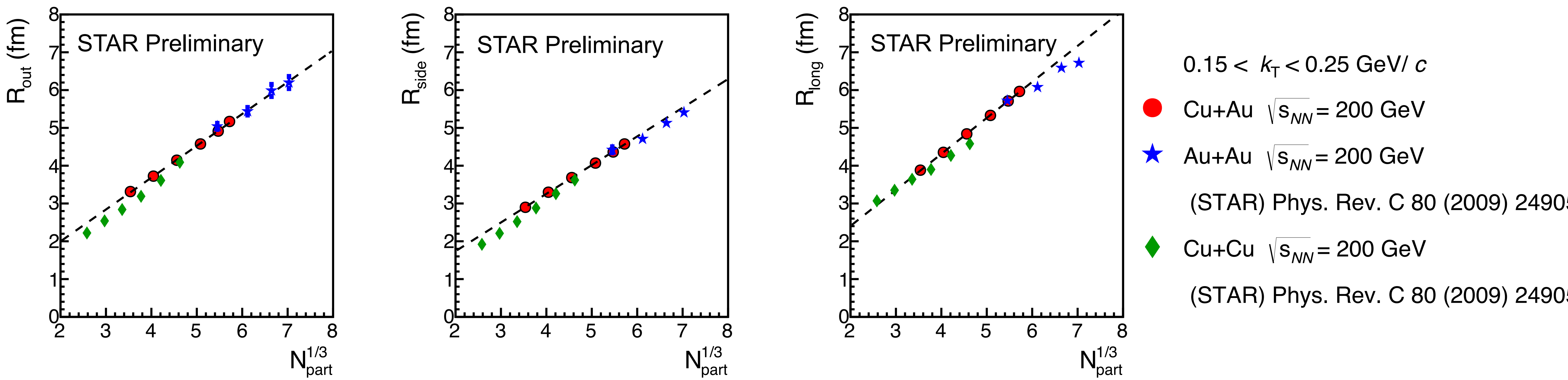


N_{part} dependence

✓ Cu+Au 200 GeV

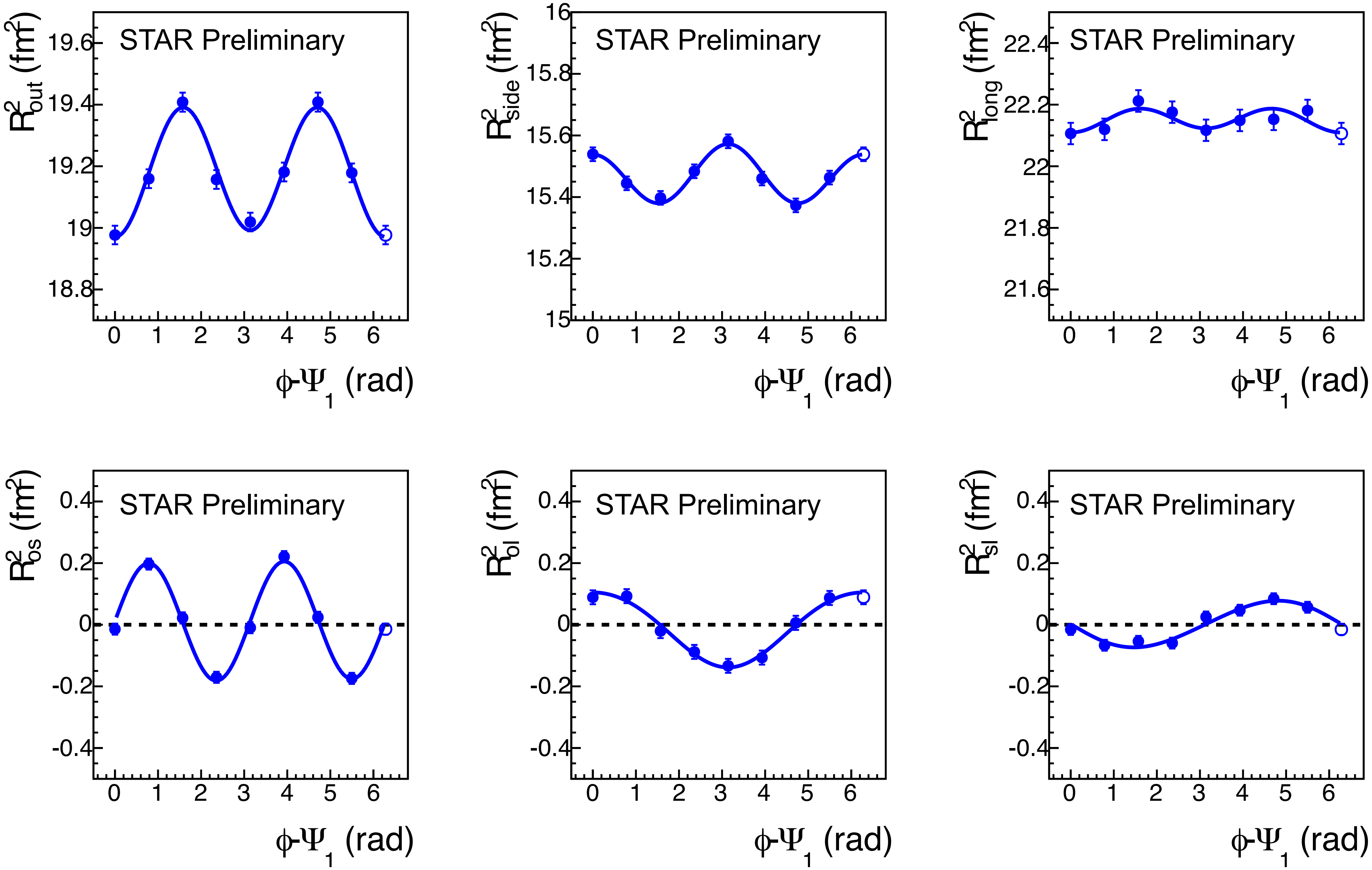


✓ Comparison of System size



- **$N_{part}^{1/3}$ corresponds to the source radius at the collision time.**
- **Checked HBT radii $\propto N_{part}^{1/3}$**
- **HBT radii have an approximate common linear dependence on $N_{part}^{1/3}$ regardless of system size differences.**

HBT radii w.r.t. Ψ_1 in Au+Au



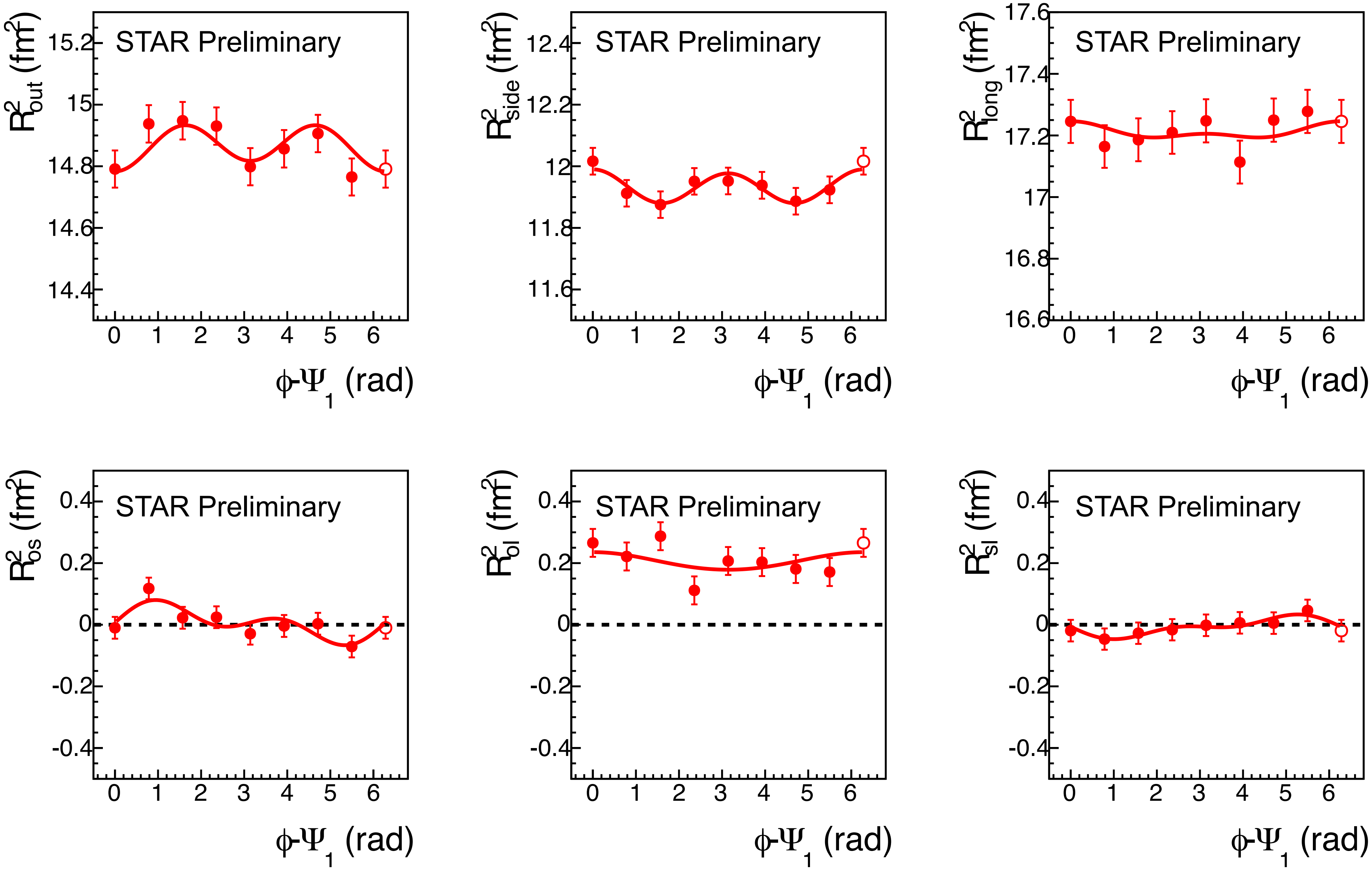
Au+Au $\sqrt{s_{NN}}$ = 200 GeV
$|\eta| < 1$
Centrality 10 - 50 %
$0.15 < k_T < 0.6$ GeV/c
$\pi^+\pi^+$ and $\pi^-\pi^-$ combined

- **E.P. resolution correction is not applied**

- **Note that $\varphi - \Psi_1 = 0$ point is replotted at $\varphi - \Psi_1 = 2\pi$**

- **R_{out}, R_{side} and R_{os} have a 2nd-order oscillation due to the elliptic source shape with respect to Ψ_1**
- **Small (but ≠ 0) 1st-order oscillation can be found in R_{ol} and R_{sl} due to source tilt signal.**
- **These results indicate that the source shape at freeze-out is tilted even at top RHIC energy.**

HBT radii w.r.t. Ψ_1 in Cu+Au



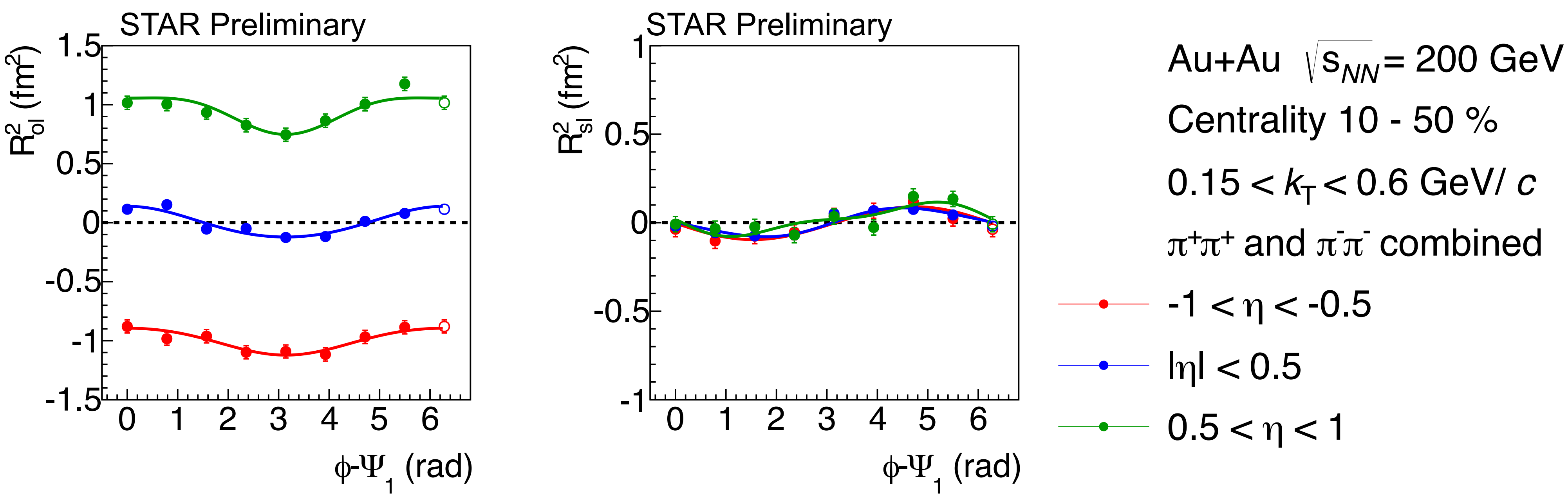
Cu+Au $\sqrt{s_{NN}}$ = 200 GeV
$|\eta| < 1$
Centrality 10 - 50 %
$0.15 < k_T < 0.6$ GeV/c
$\pi^+\pi^+$ and $\pi^-\pi^-$ combined

- **E.P. resolution correction is not applied**

- **For all extra radii, oscillation is small as compared to Au+Au results due to poor event plane resolution**
- **In R_{ol}, average magnitude is shifted from 0 because center of mass rapidity is not 0 (shift to Au-going side ($\eta < 0$))**
- **Trends are similar to those from Au+Au collisions**

HBT radii w.r.t. Ψ_1

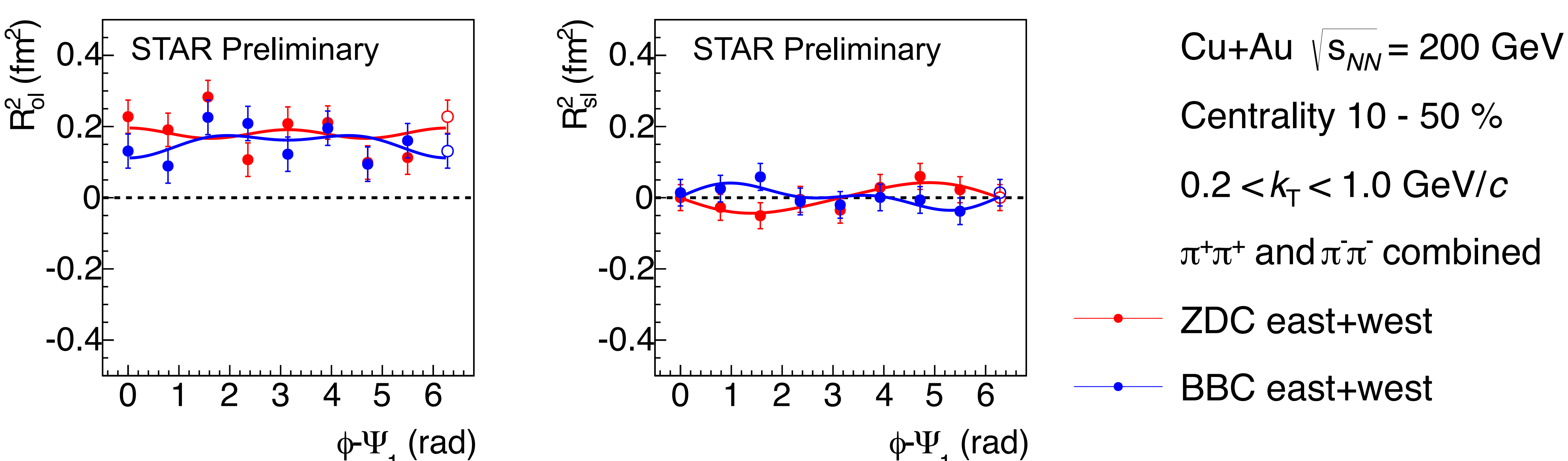
✓ η dependence in Au+Au 200 GeV



- **E.P. resolution correction is not applied**

- **Average R_{ol} value has η dependence (similar effect is seen in Cu+Au results).**
- **The 1st-order oscillation amplitude does not have significant dependence on η -> 1st-order oscillations have same sign in all eta region.**

✓ Difference between participant and spectator Ψ_1 planes in Cu+Au 200 GeV



- **E.P. resolution correction is not applied**

- **The 1st-order oscillation sign is opposite -> The same relation to v_1 measurement could be seen.**

- **BBC: v_1 sign is negative (3.3 < η < 5)**
- **ZDC: v_1 sign is positive (η > 6.3)**

Summary

- **Azimuthally integrated HBT radii**
  - ✓ HBT radii seems to be proportional to $N_{part}^{1/3}$.

- **Azimuthal angle dependence of HBT radii w.r.t. Ψ_1**
  - ✓ Source tilt signal has been measured at 200 GeV.
  - ✓ Average R_{ol} value can be shifted in case of non-zero center-of-mass rapidity
  - ✓ The 1st-order oscillation shows opposite sign between event planes defined by participants and spectators

Outlook

- Perform event plane resolution correction and evaluate tilt angle
- Comparison between Au+Au and Cu+Au collisions quantitatively in azimuthal-angle-dependent HBT analysis
- Examine beam energy dependence in BES-II with high statistics and good event plane resolution due to installation of Event Plane Detector (EPD)

Back up

Data set

Au+Au 200 GeV using Data set

- Run11 minimum bias
- Events ~ 200 M

Event selection

- $|v_z| < 25$ cm
- $|v_r| < 2$ cm
- $|v_z - v_z^{vpd}| < 3$ cm

Track selection

- $0.15 < p_T < 0.8$ GeV/c
- $|\eta| < 1.0$
- nHitsFit >= 15
- nHitsFit/nHitsPoss >= 0.52
- DCA < 3 cm

Cu+Au 200 GeV using Data set

- Run12 minimum bias
- Events: ~ 45 M

Event Selection

- $|v_z| < 30$ cm
- $|v_r| < 2$ cm
- $|v_z - v_z^{vpd}| < 3$ cm

Track selection

- 0.15 < Pt < 2 GeV/c (for N_{part} dependence)
- 0.15 < Pt < 0.8 GeV/c (for Ψ_1 dependence)
- $|\eta| < 1$
- nHitsFit >= 15
- nHitsdEdx >= 10
- nHitsFit/nHitsPoss >= 0.52
- DCA < 3 cm

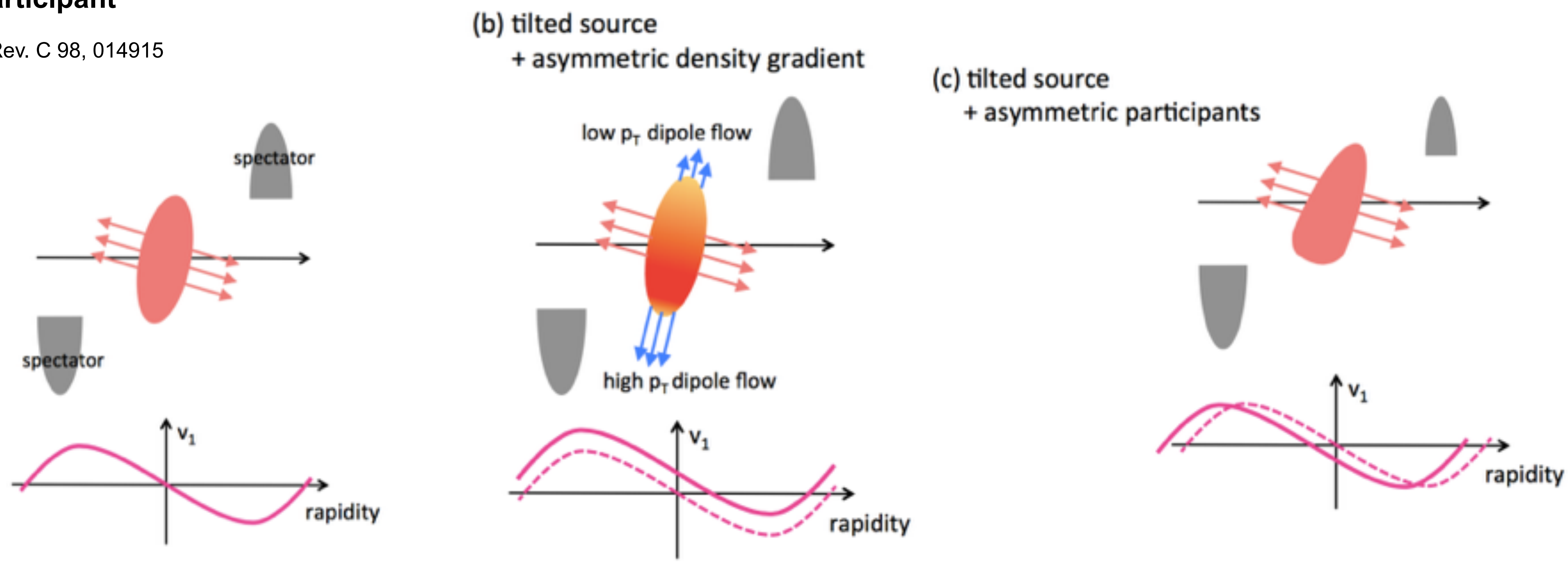
Cu+Au collisions

STAR Collaboration, Phys. Rev. C 98 (2018) 14915

Directed flow

Participant

Phys. Rev. C 98, 014915



✓ Cu+Au has asymmetric density gradient and it arise "dipole flow".
-> It dump up directed flow signals. (Fig. (b))

✓ In addition, Cu+Au collisions have a different number of participant between forward and backward directions.
-> It shifts directed flow to the center of mass rapidity (Fig.(c))

Event plane resolution correction

$$N(\boldsymbol{q},\Phi_j)=N_{\mathrm{exp}}(\boldsymbol{q},\Phi_j)+2\sum_{n=1}^{n_{\mathrm{bin}}}\zeta_{n,m}(\Delta)[N_{c,n}^{\mathrm{exp}}(\boldsymbol{q})\cos(n\Phi_j) + N_{s,n}^{\mathrm{exp}}(\boldsymbol{q})\sin(n\Phi_j)], \quad (44)$$

$$\zeta_{n,m}(\Delta)=\frac{n\Delta/2}{\sin(n\Delta/2)\langle\cos(n(\psi_m-\psi_R))\rangle_p}-1. \quad (45)$$

← Res{Ψ_m}

- The correction is performed to q distribution (N denotes the count of each qbin)

$$N_{s,n}^{\mathrm{exp}}(\boldsymbol{q})\equiv\langle N_{\mathrm{exp}}(\boldsymbol{q},\Phi)\sin(n\Phi)\rangle = \frac{1}{n_{\mathrm{bin}}}\sum_{j=1}^{n_{\mathrm{bin}}}N_{\mathrm{exp}}(\boldsymbol{q},\Phi_j)\sin(n\Phi_j),$$

$$N_{c,n}^{\mathrm{exp}}(\boldsymbol{q})\equiv\langle N_{\mathrm{exp}}(\boldsymbol{q},\Phi)\cos(n\Phi)\rangle = \frac{1}{n_{\mathrm{bin}}}\sum_{j=1}^{n_{\mathrm{bin}}}N_{\mathrm{exp}}(\boldsymbol{q},\Phi_j)\cos(n\Phi_j),$$

- **Correlation of event planes with different orders (e.g. 1st - 2nd) should be taken into account.**