Emission angle and particle mass dependence of HBT interferometry in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

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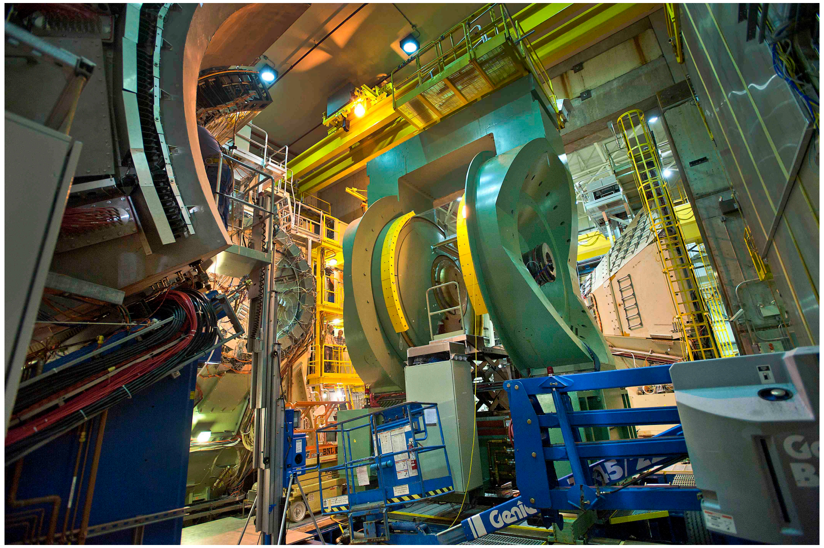
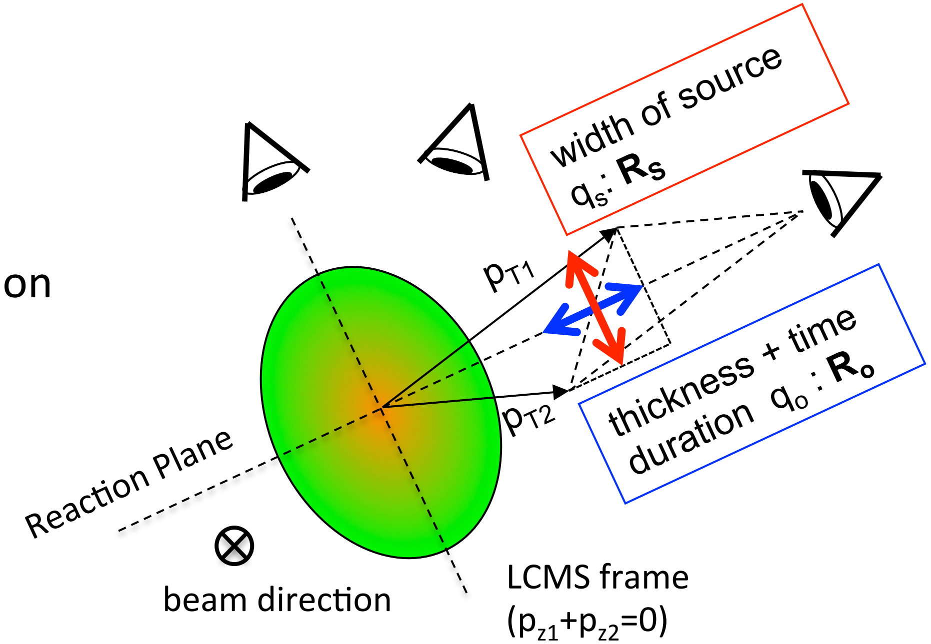
Experimental setup and analysis

centrality (BBC $|\eta|$=3-3.9)
event plane (RXN $|\eta|$=1-2.8)
charged particle tracking ($|\eta|$<0.35)
π/K PID by EMcal-TOF

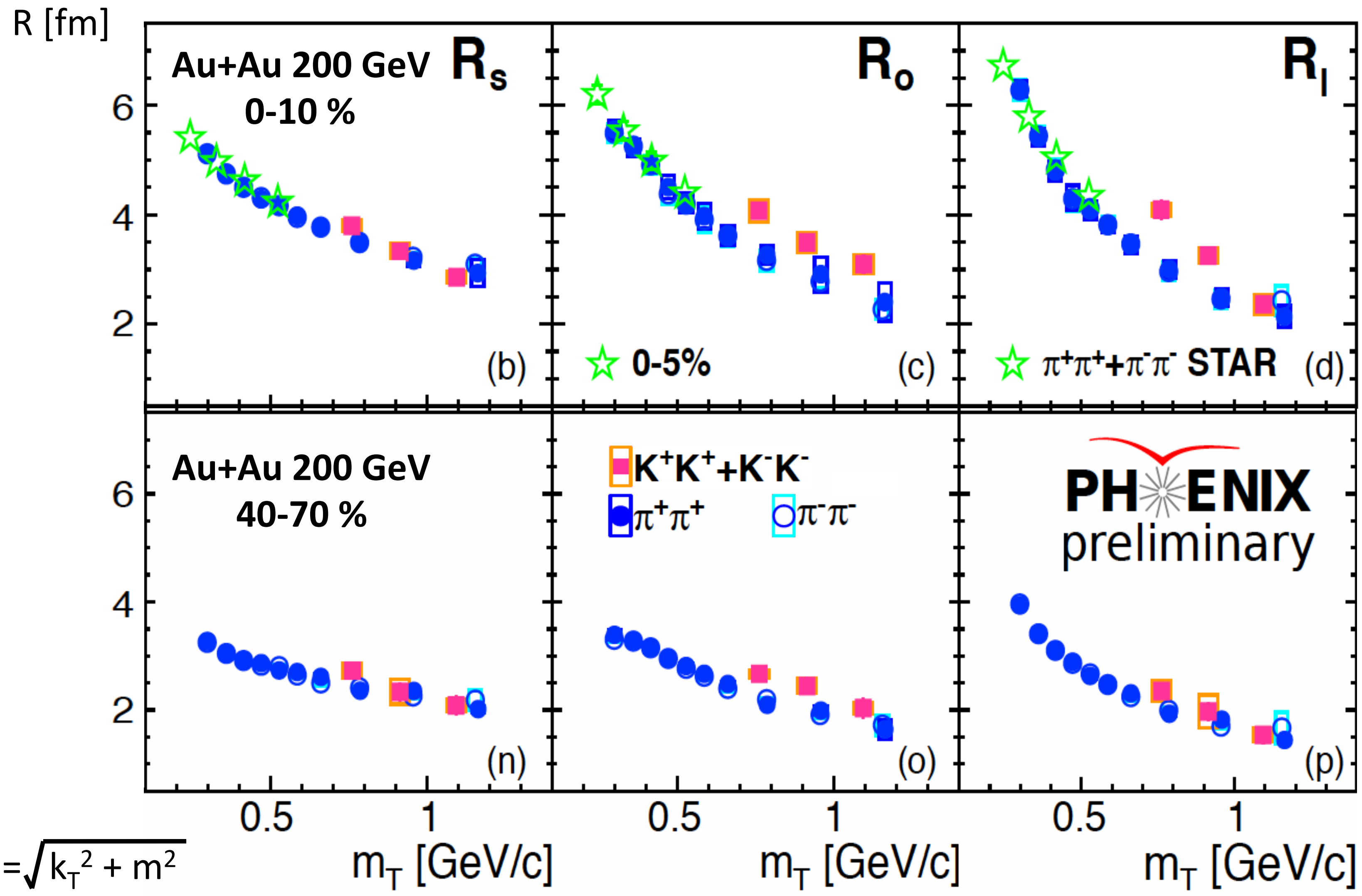
$$C_2 = P(p_1,p_2) / \{P(p_1)P(p_2)\} \sim 1+ |\tilde{\rho}(q)|^2$$
$$= C_2^{core} + C_2^{halo}$$
$$= [\lambda\ (1+G)\ F_{coul}] + [1-\lambda]$$
$$G = \exp(- R_s^2 q_s^2 - R_o^2 q_o^2 - R_L^2 q_L^2 - 2R_{os}^2 q_o q_s)$$

s : (sideward) geometrical size
o : (outward) geometry and time duration
L : (longitudinal) beam direction
os : outward-sideward cross term
F_{coul} : coulomb correction factor
λ : fraction of pairs in the core





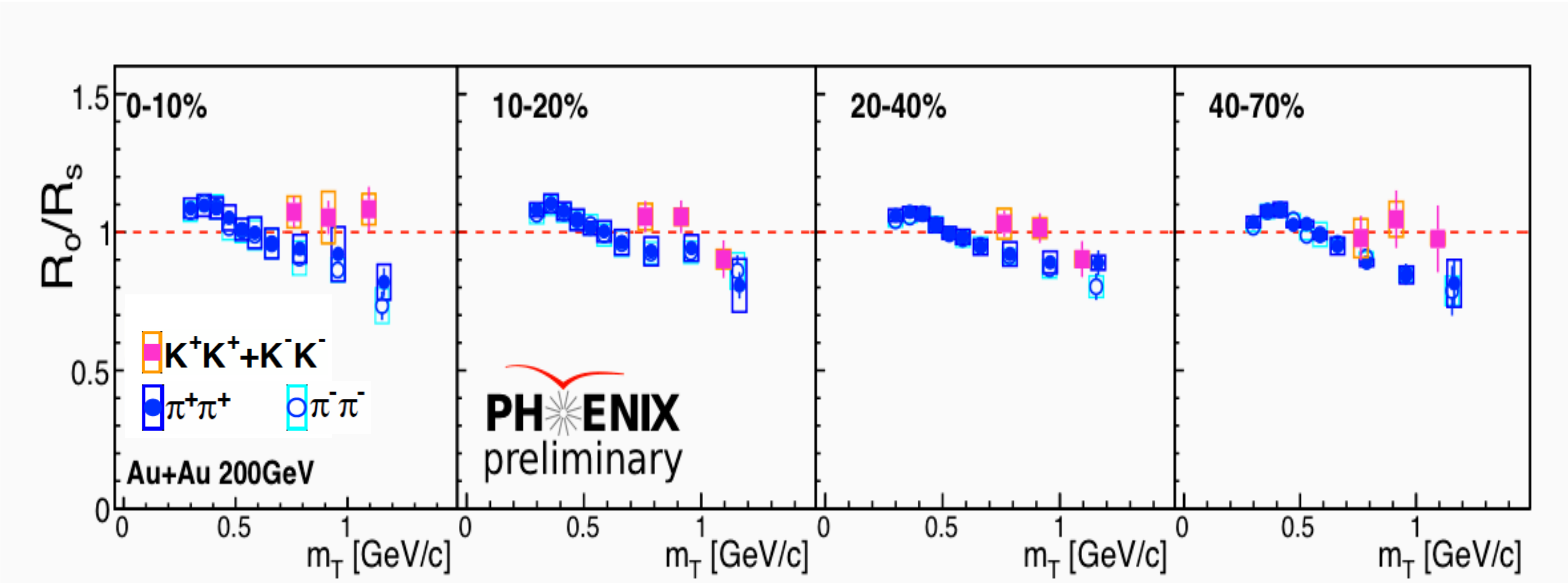
m_T dependence of 3D HBT radii



$m_T = \sqrt{k_T^2 + m^2}$

1. strong m_T dependence indicates strong radial flow in central collisions
2. breaking of the m_T scaling between π and K (improved stat. + sys. error)

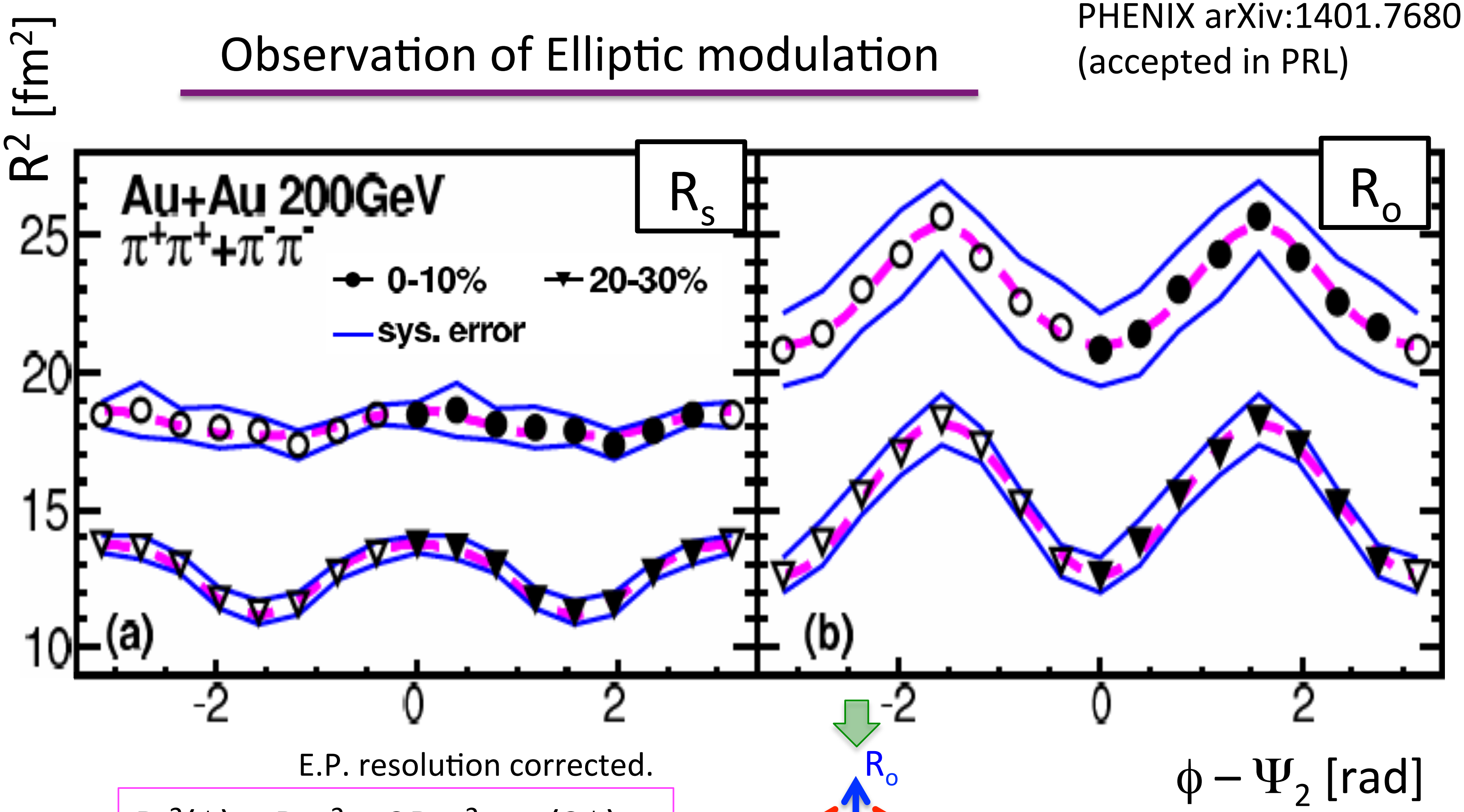
R_{out}/R_{side} ratio vs m_T for ππ and KK



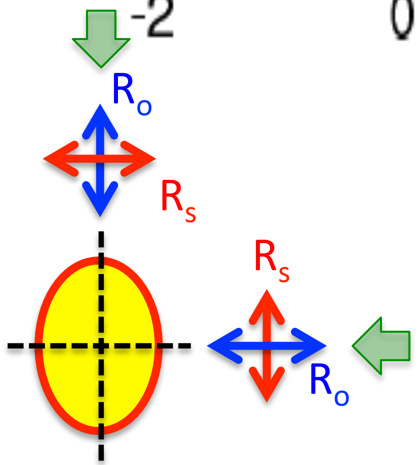
0. If $R_o/R_s=1$, then $\Delta\tau=0$ for static source.
1. $R_o/R_s\sim1$ does not mean sudden freeze-out for expanding source.
2. possible indication of longer duration time for K than for π

Observation of Elliptic modulation

PHENIX arXiv:1401.7680
(accepted in PRL)



E.P. resolution corrected.



$R_s^2(\phi) = R_{s,0}^2 + 2R_{s,2}^2 \cos(2\phi)$

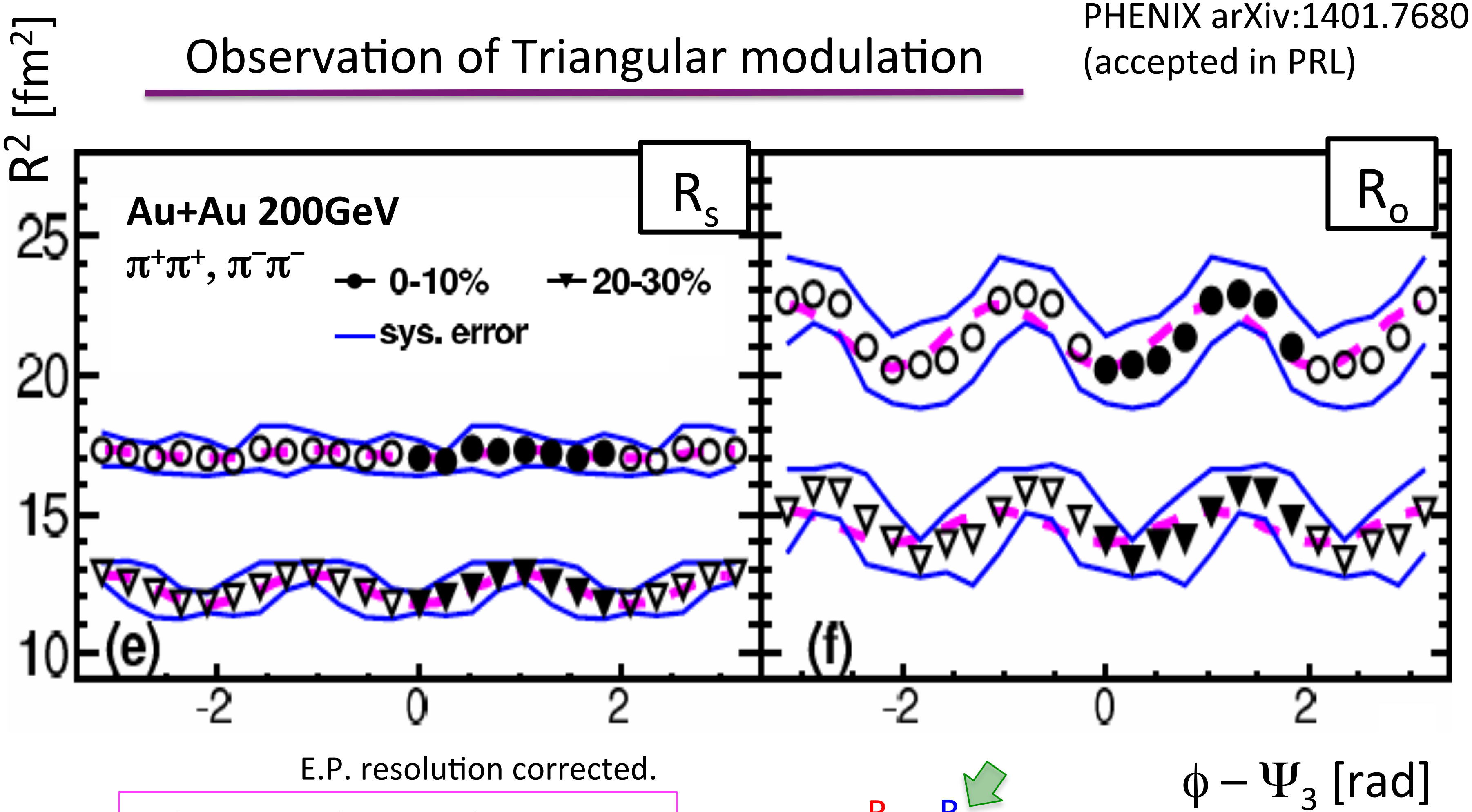
$R_o^2(\phi) = R_{o,0}^2 + 2R_{o,2}^2 \cos(2\phi)$

ε_2^{final} : $2R_{s,2}^2 / R_{s,0}^2$

$-2R_{o,2}^2 / R_{o,0}^2$

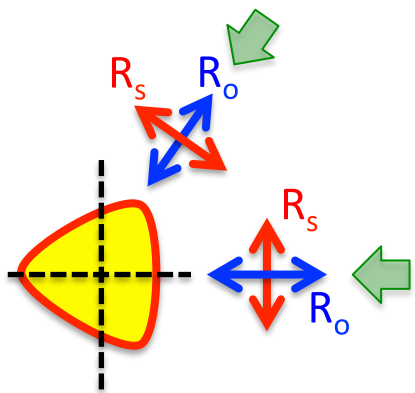
Observation of Triangular modulation

PHENIX arXiv:1401.7680
(accepted in PRL)

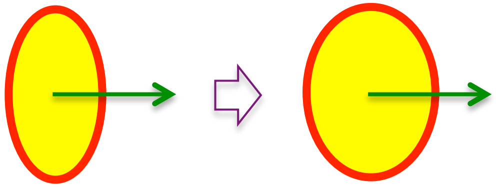


E.P. resolution corrected.

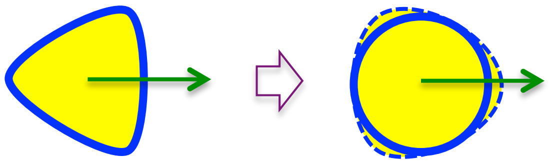
$R_s^2(\phi) = R_{s,0}^2 + 2R_{s,3}^2 \cos(3\phi)$
$R_o^2(\phi) = R_{o,0}^2 + 2R_{o,3}^2 \cos(3\phi)$
ε_3^{final} : $2R_{s,3}^2 / R_{s,0}^2$
$-2R_{o,3}^2 / R_{o,0}^2$



initial -> final
eccentricity
($\varepsilon_2^{initial}$ -> ε_2^{final})

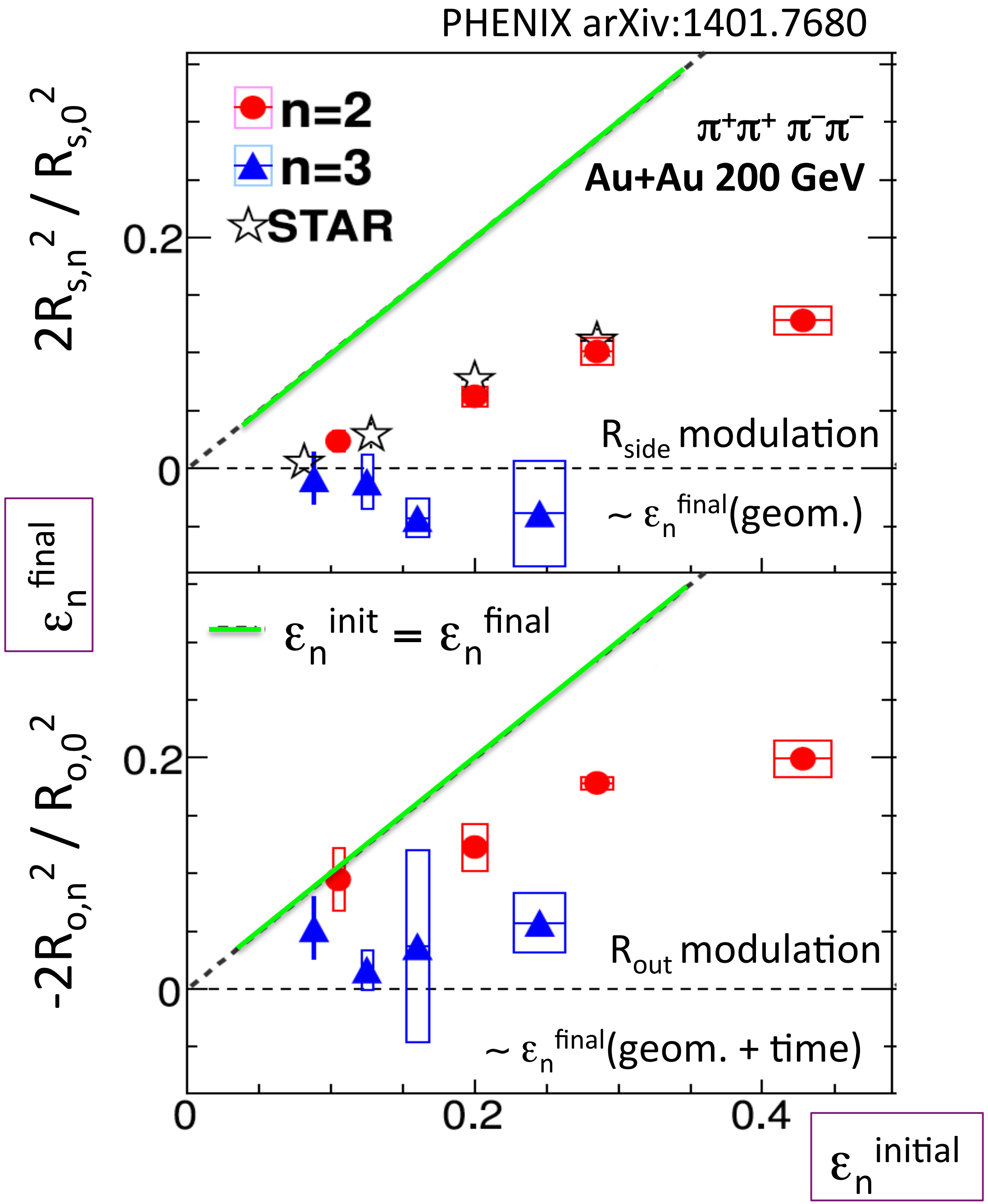


initial -> final
triangularity
($\varepsilon_3^{initial}$ -> ε_3^{final})

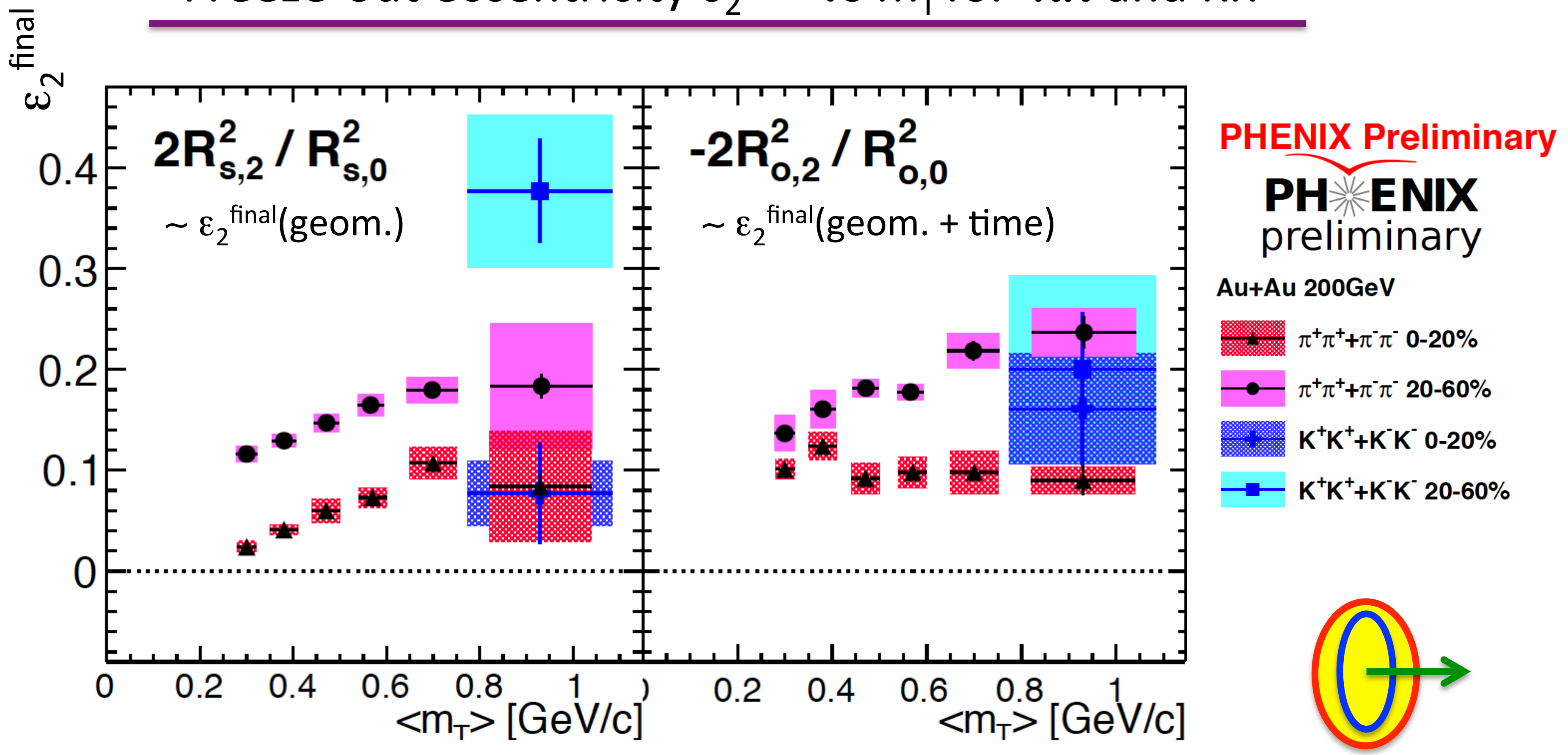


$\varepsilon_2^{final} \sim 0.5\ \varepsilon_2^{initial}$

$\varepsilon_3^{finial} \sim 0$



Freeze-out eccentricity ε_2^{final} vs m_T for $\pi\pi$ and KK

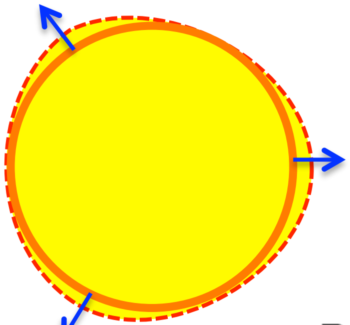


1. "ε_2 vs m_T" and "v_2 vs p_T" --- spatial and momentum anisotropy at freeze-out
2. The larger ε_2^{final} for K could mean earlier emission time for K than for π

k_T dependence of final triangularity ε_3^{final}

1. small freeze-out triangularity ($e_3 \sim 0$)
   $R(\phi) = R_0 [1 - 2 e_3 \cos(3\phi)]$

2. finite triangular flow ($\beta_3 > 0$)
   $\beta_T(\phi) = \beta_0 [1 + 2 \beta_3 \cos(3\phi)]$



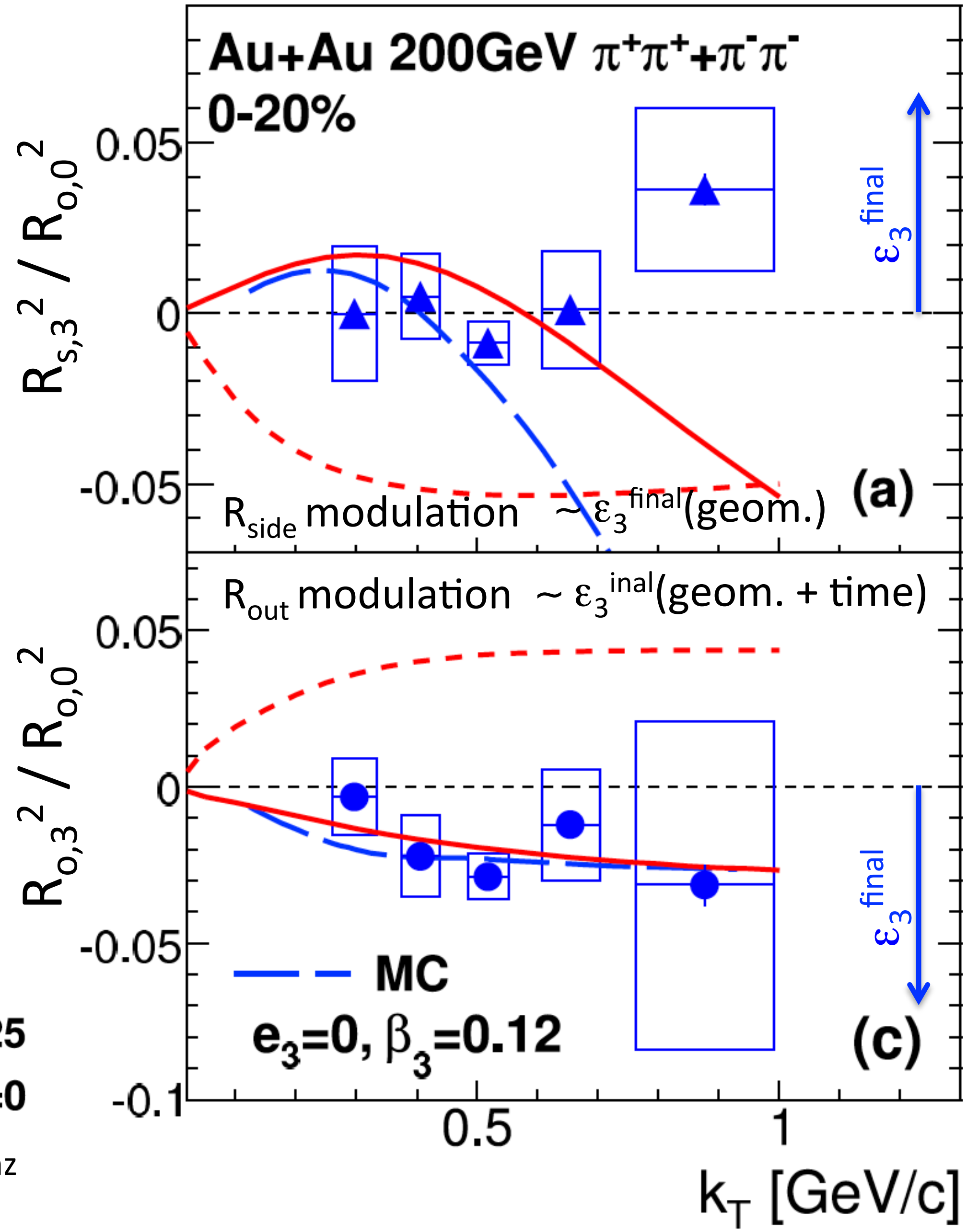
PRC88,044914

— $\bar{\varepsilon}_3$=0, $\bar{v}_3$=0.25

- - - $\bar{\varepsilon}_3$=0.25, $\bar{v}_3$=0

C. J. Plumberg, C. Shen, and U. Heinz

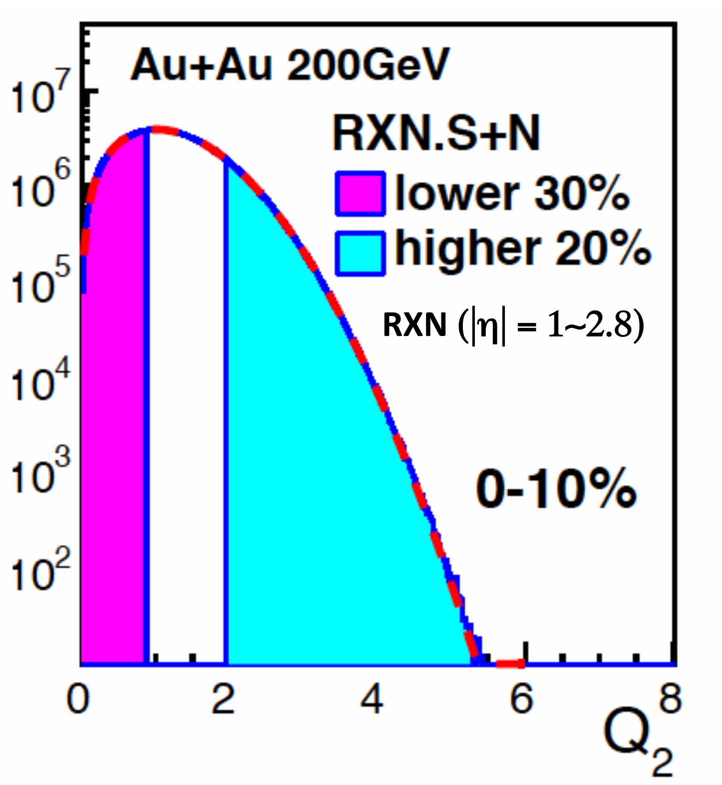
PHENIX arXiv:1401.7680

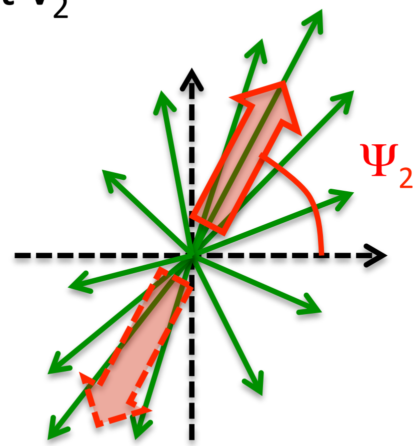


Event Shape Engineering (arXiv:1208.4563)

flow-vector Q_2 distribution reflects event-by-event v_2

$\varepsilon_2^{initial} \sim Q_2 \sim v_2 \sim \varepsilon_2^{final}$





- Flow-vector :

$Q_{2,x} = \Sigma\, w_i \cos(2\phi_i)$

$Q_{2,y} = \Sigma\, w_i \sin(2\phi_i)$

- Event Plane :

$\Psi_2 = \mathrm{atan2}(Q_{2,y}, Q_{2,x}) / 2$

- Length of flow-vector Q_2 :

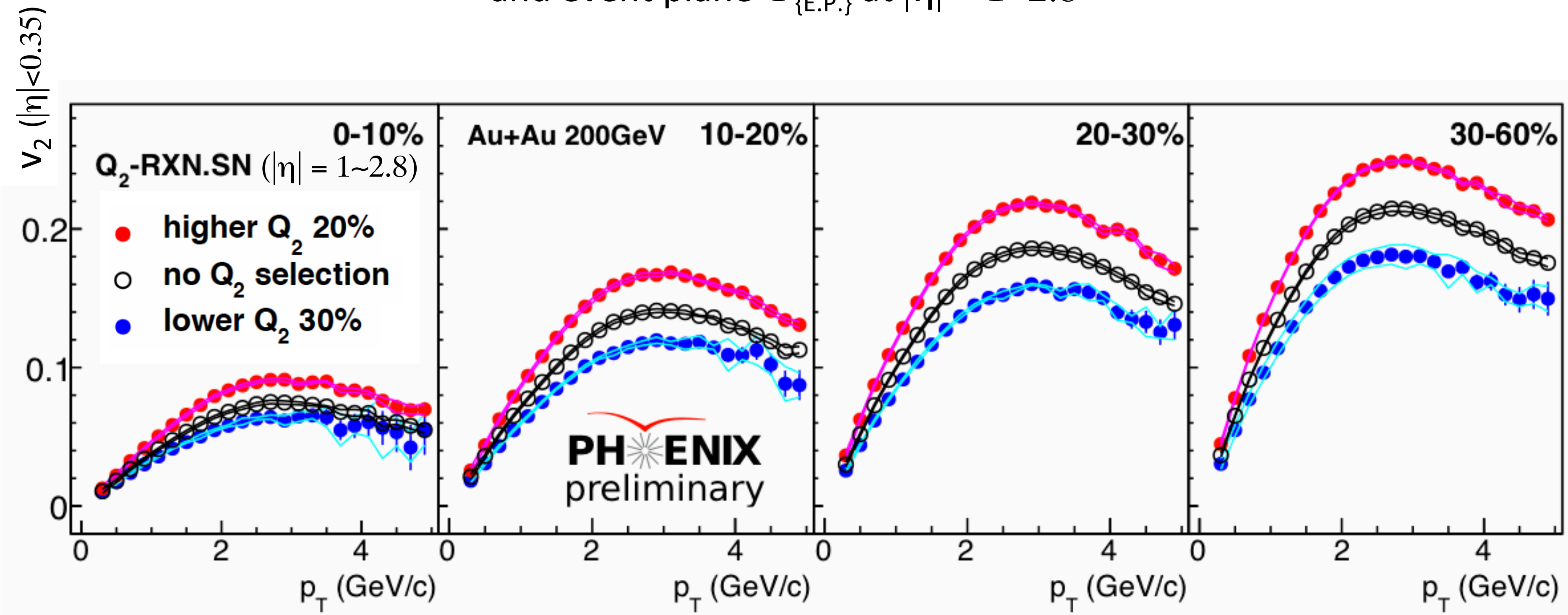
$Q_{2,raw} = \sqrt{Q_{2,x}^2 + Q_{2,y}^2} / \sqrt{\Sigma\, w_i}$

- Re-normalization of Q_2 :

$Q_2 \sim Q_{2,raw} / \langle Q_{2,raw} \rangle$

v_2 measured at central rapidity ($|\eta| < 0.35$)

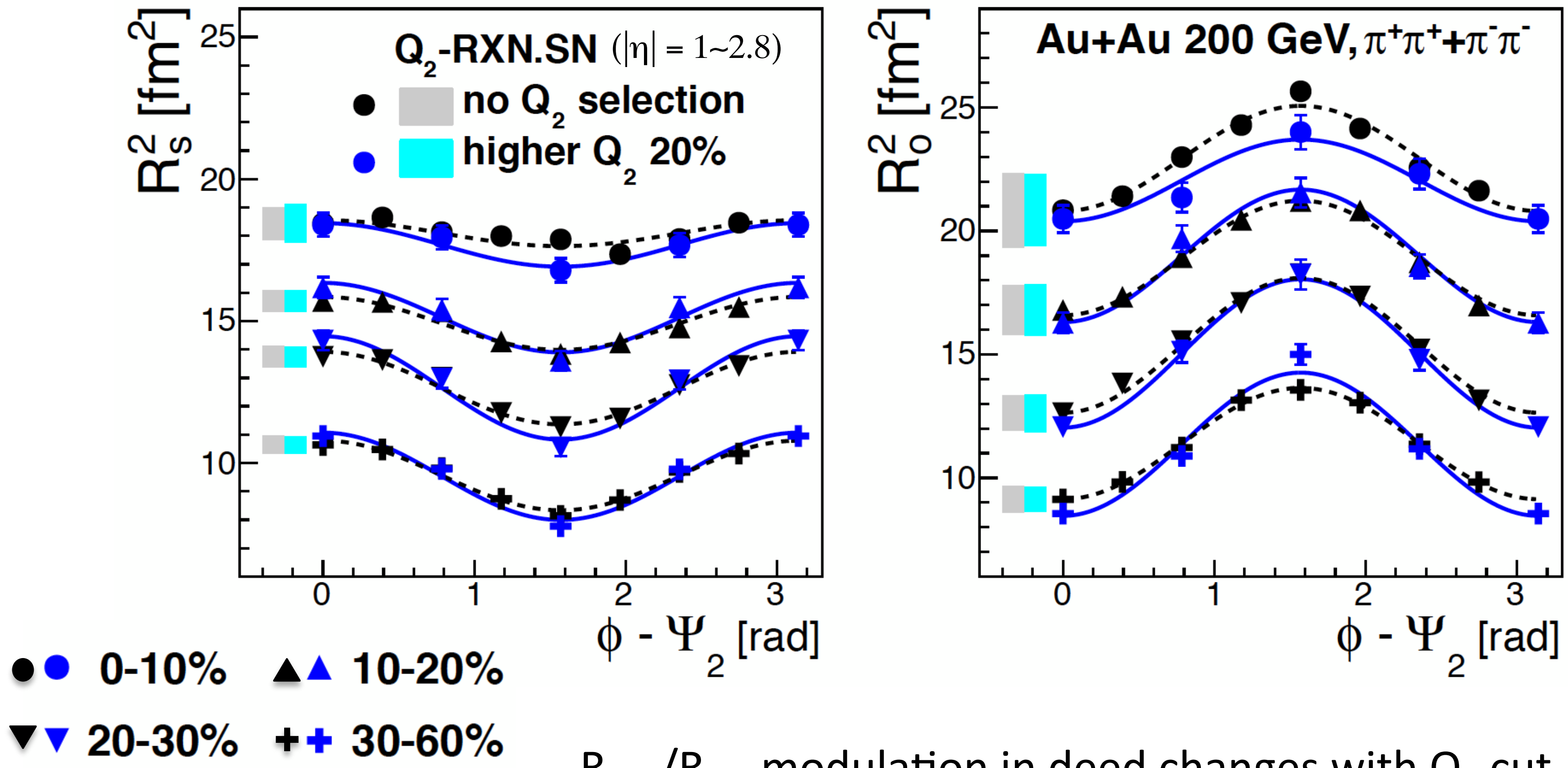
with Q_2-vector selection at $|\eta| = 1\sim2.8$
and event plane $\Psi_{\{E.P.\}}$ at $|\eta| = 1\sim2.8$



Confirmed the engineering on v_2 with Q_2 selection in forward rapidity

R_{side} and R_{out} vs $\phi-\Psi_2$ with/without Q_2 cut

$\pi\pi$ HBT measurement at $|\eta| < 0.35$
with Q_2-vector selection at $|\eta| = 1\sim2.8$
and event plane $\Psi_{\{E.P.\}}$ at $|\eta| = 1\sim2.8$

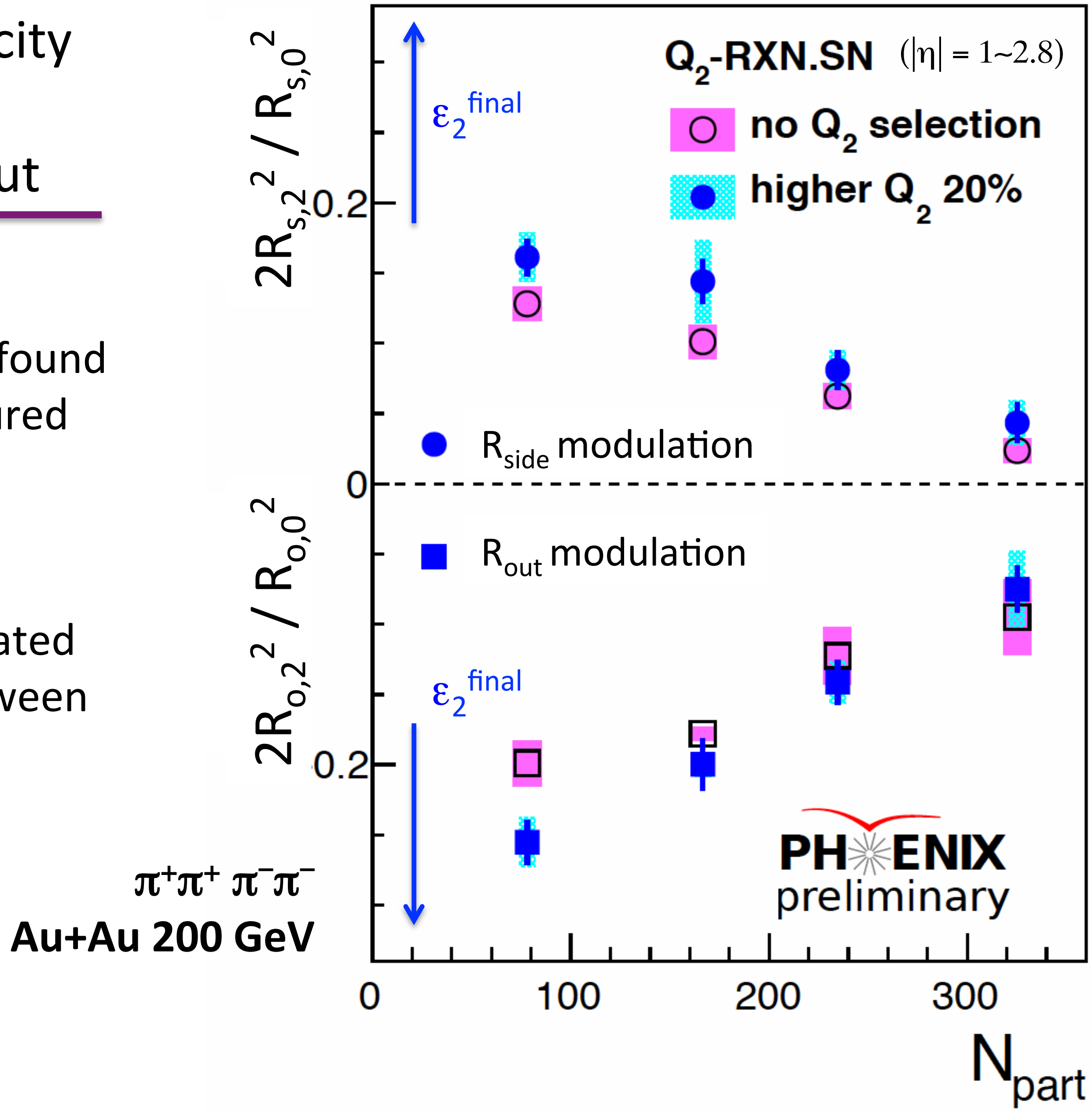


R_{side}/R_{out} modulation in deed changes with Q_2 cut.

Freeze-out eccentricity ε_2^{final} vs N_{part} with/without Q_2-cut

1. Higher $Q_2(v_2)$ cut has found to increase the measured ε_2^{final} by HBT radii.
   $Q_2(v_2)$ -> ε_2^{final}

2. It is most likely originated from the relation between $\varepsilon_2^{initial}$ and ε_2^{final}.



Summary and outlook

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- HBT radius parameters with $\pi\pi$ or KK

  K source might indicate earlier and longer duration time than π source.

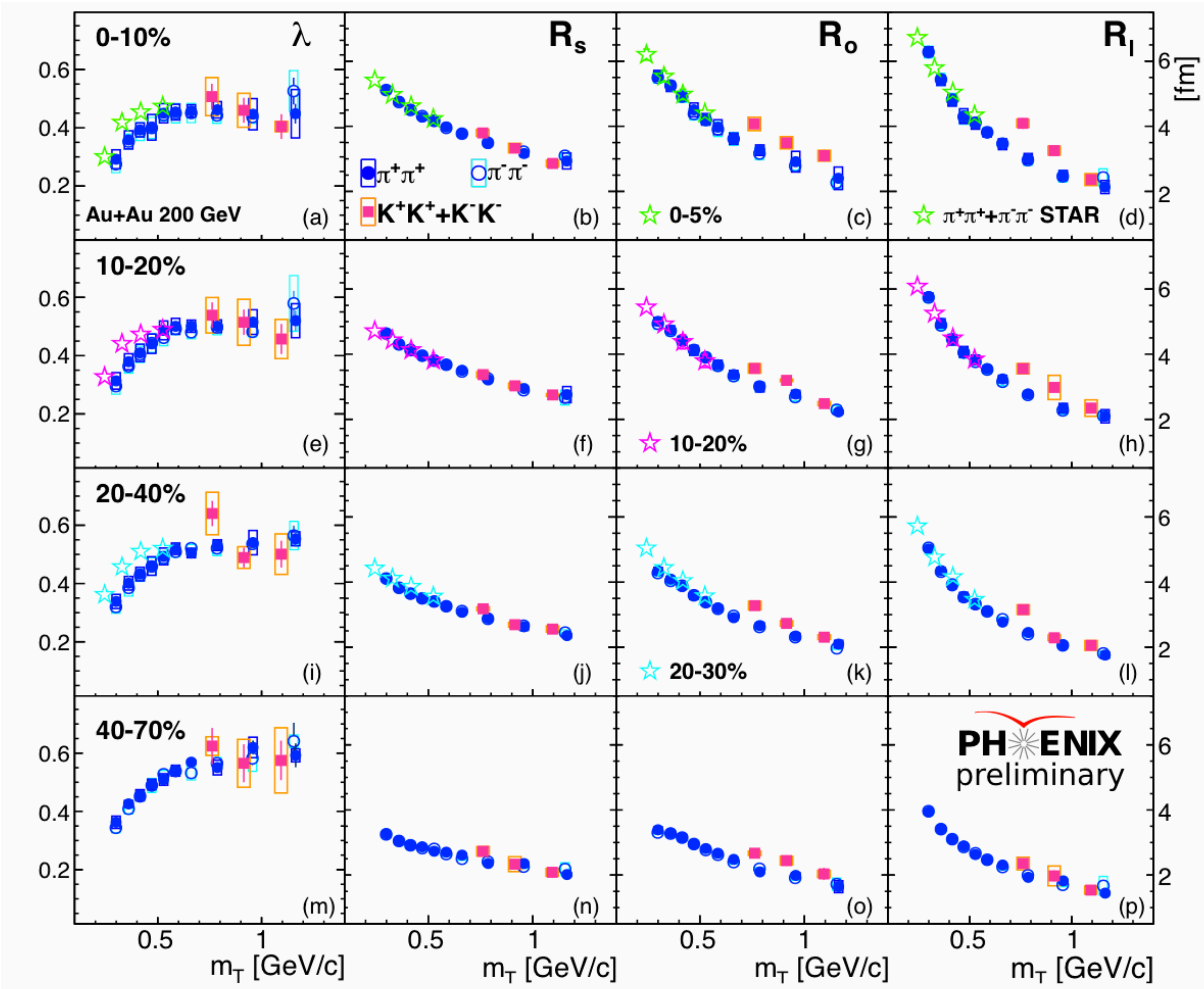
- Azimuthal dependent radii w.r.t. Ψ_2 or Ψ_3

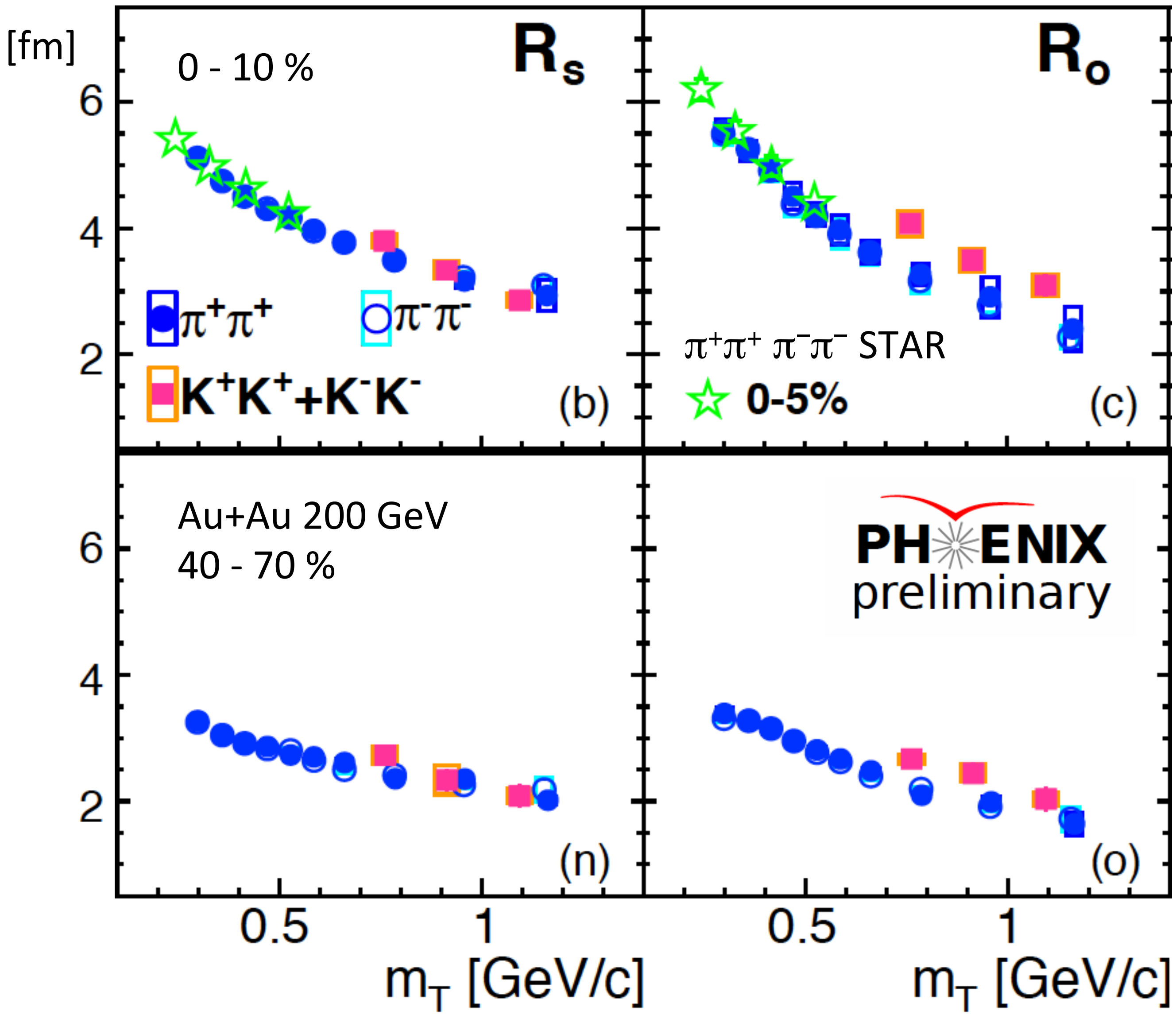
  ε_3^{final} is mostly quenched in contrast to ε_2^{final} case, which is also consistent with PIDed v_n measurements.

- Q_2-vector event selection

  Large $Q_2(v_2)$ selection enhances ε_2^{final}.
  connection between $\varepsilon_2^{initial}$ and ε_2^{final}
  Q_3 selection etc…

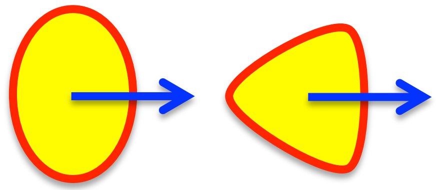
Dr. Takafumi Niida


0-10%
λ
R_s
R_o
R_l
[fm]
Au+Au 200 GeV
$\pi^+\pi^+$
$\pi^-\pi^-$
$K^+K^+ + K^-K^-$
0-5%
$\pi^+\pi^+ + \pi^-\pi^-$ STAR
(a)
(b)
(c)
(d)
10-20%
10-20%
(e)
(f)
(g)
(h)
20-40%
20-30%
(i)
(j)
(k)
(l)
40-70%
PHENIX
preliminary
(m)
(n)
(o)
(p)
m_T [GeV/c]

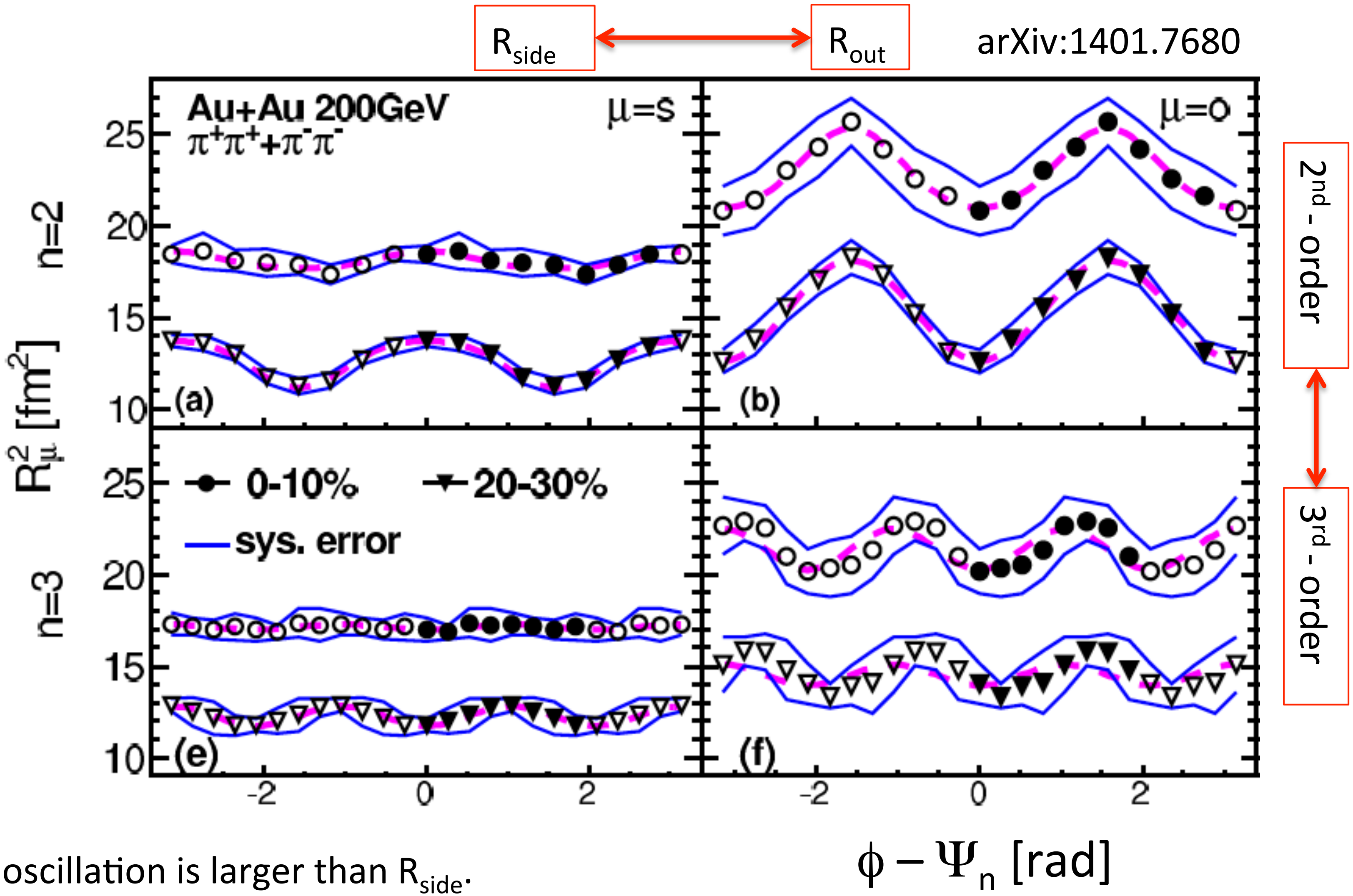


[fm]
0 - 10 %
R_s
R_o
6
4
2
$\pi^+\pi^+$
$\pi^-\pi^-$
$K^+K^++K^-K^-$
(b)
$\pi^+\pi^+$ $\pi^-\pi^-$ STAR
0-5%
(c)
Au+Au 200 GeV
40 - 70 %
(n)
PHENIX
preliminary
(o)
0.5
1
m_T [GeV/c]

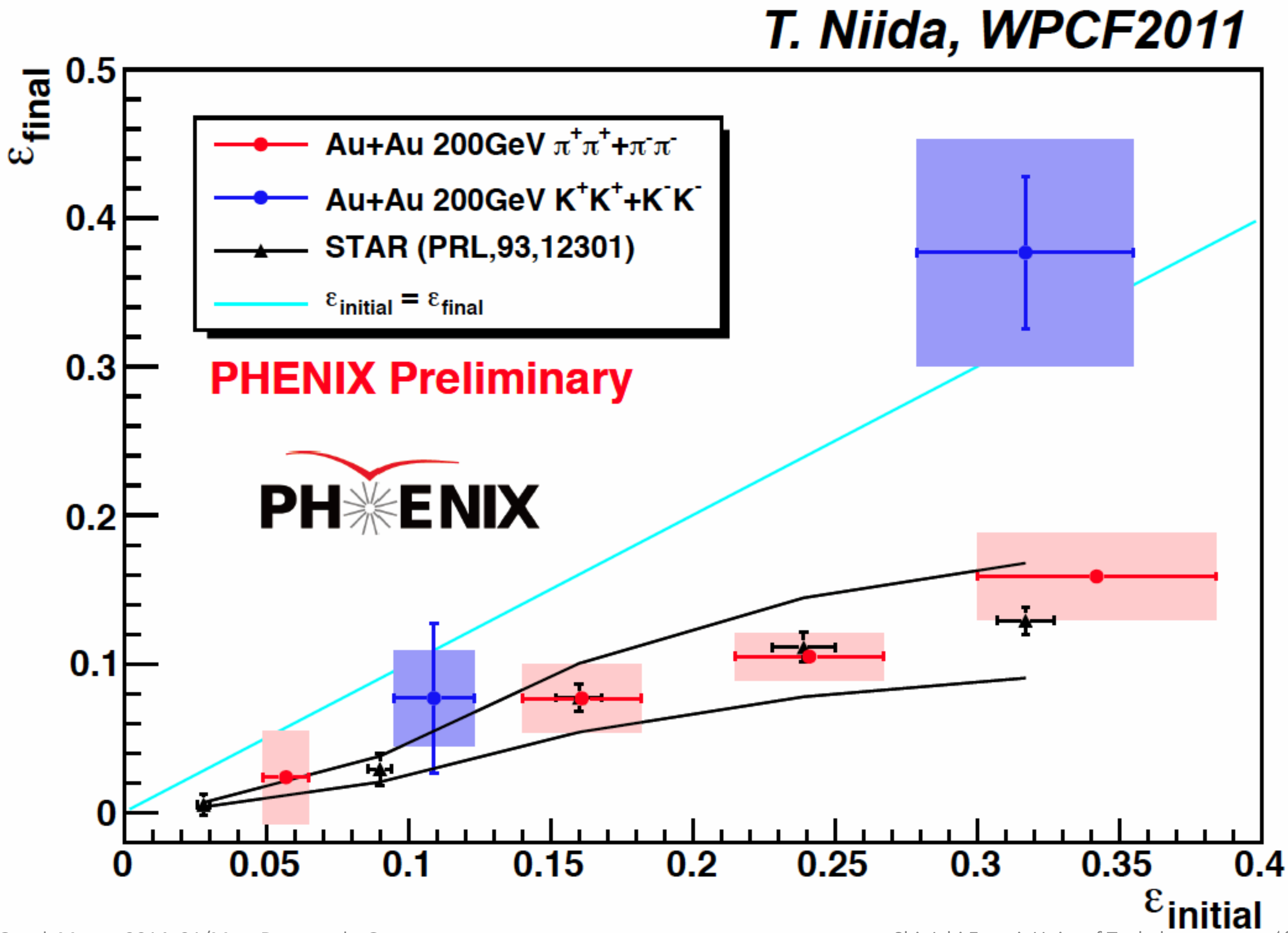
Observation of Elliptic/Triangular dependences

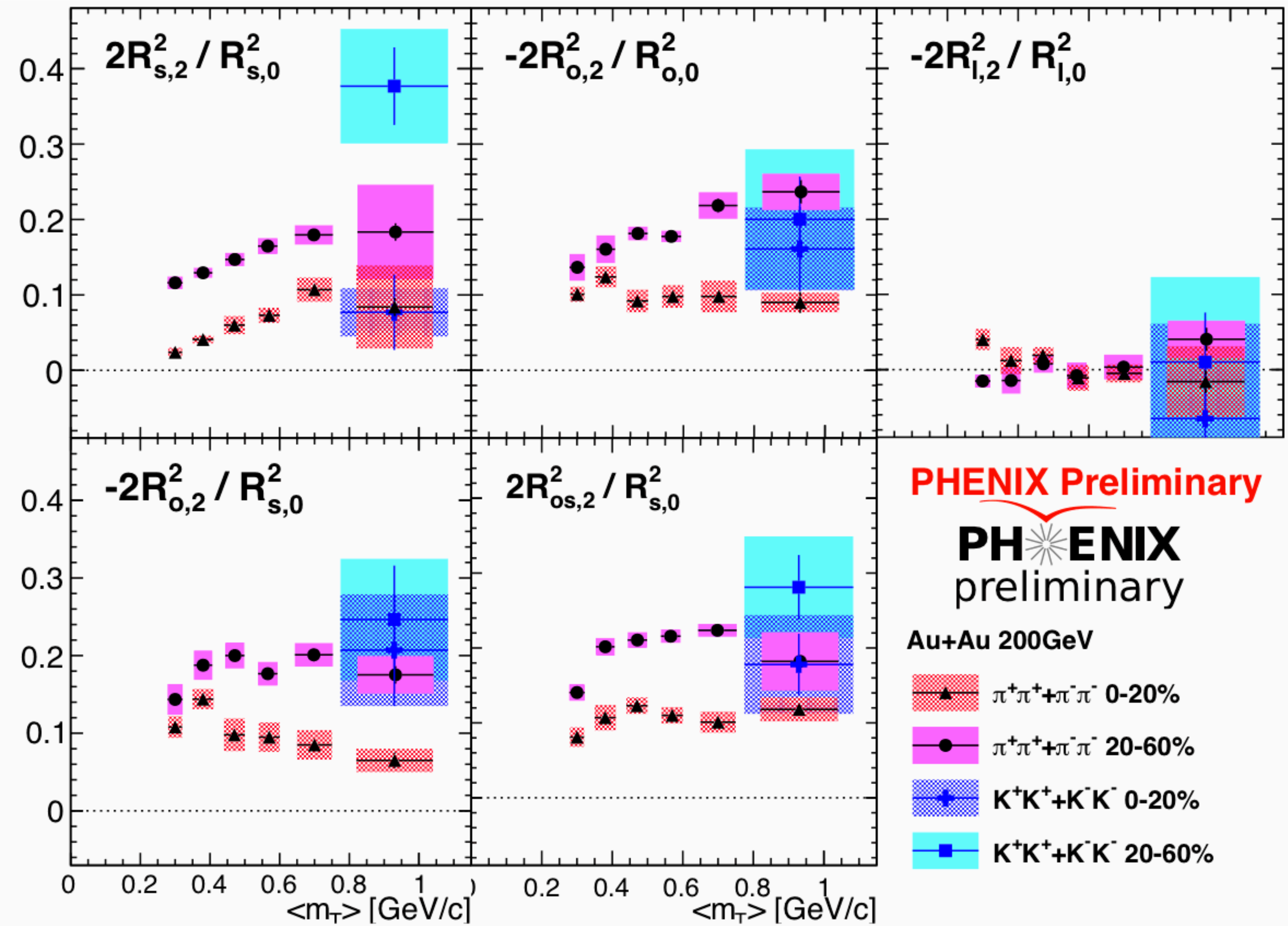


arXiv:1401.7680

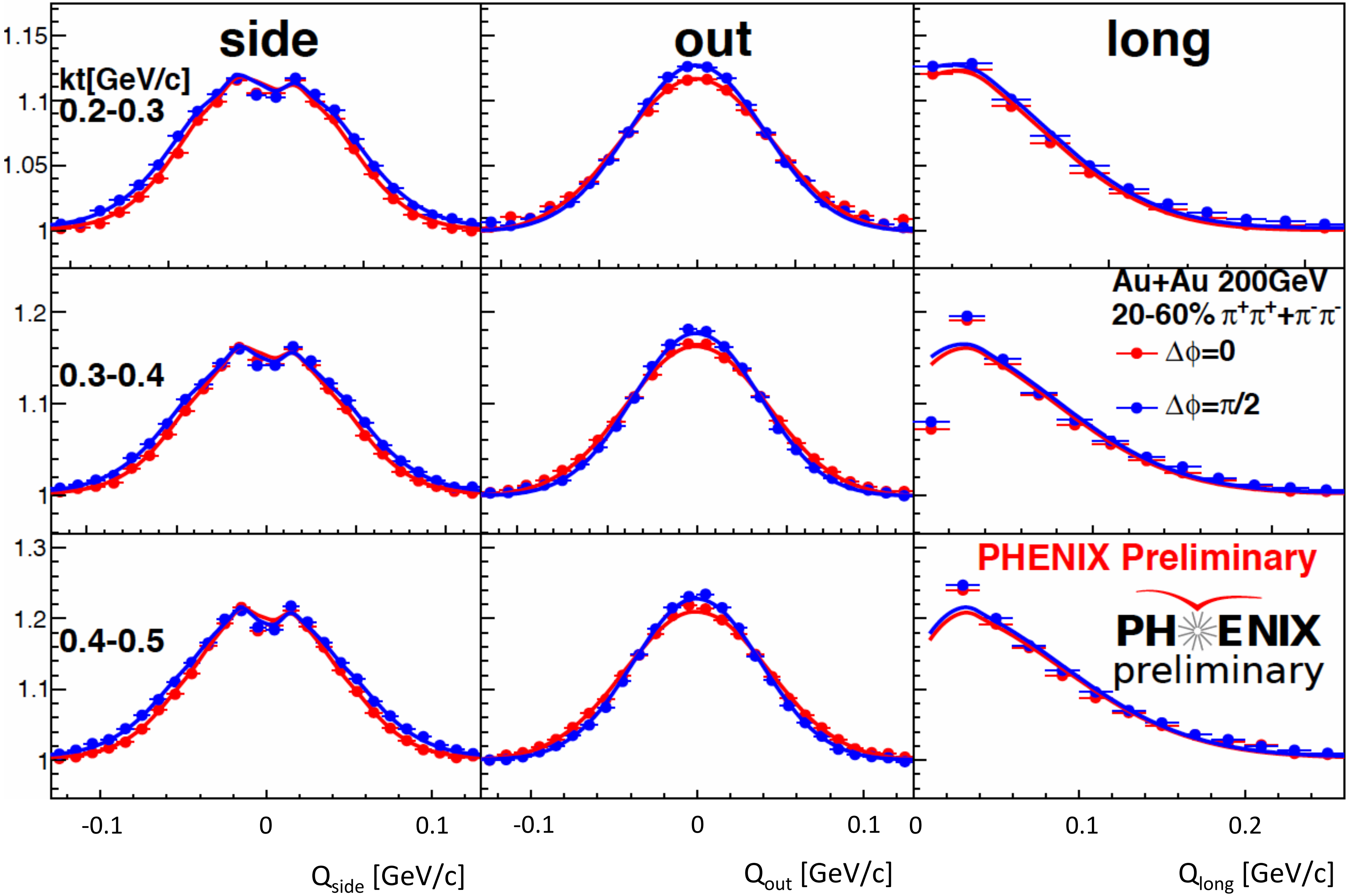


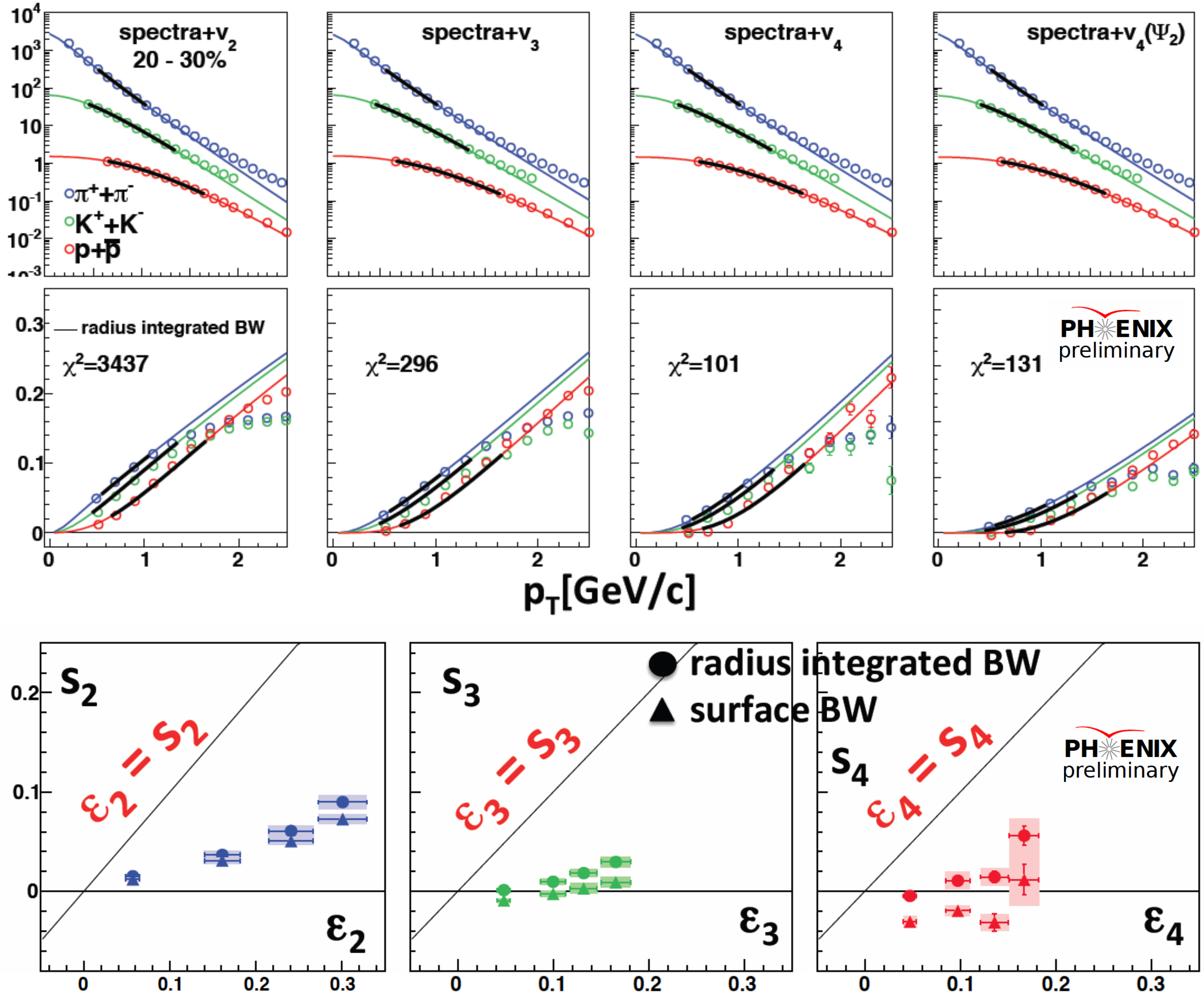
R_{out} oscillation is larger than R_{side}.
Possible opposite sign between 2nd and 3rd for R_{side}

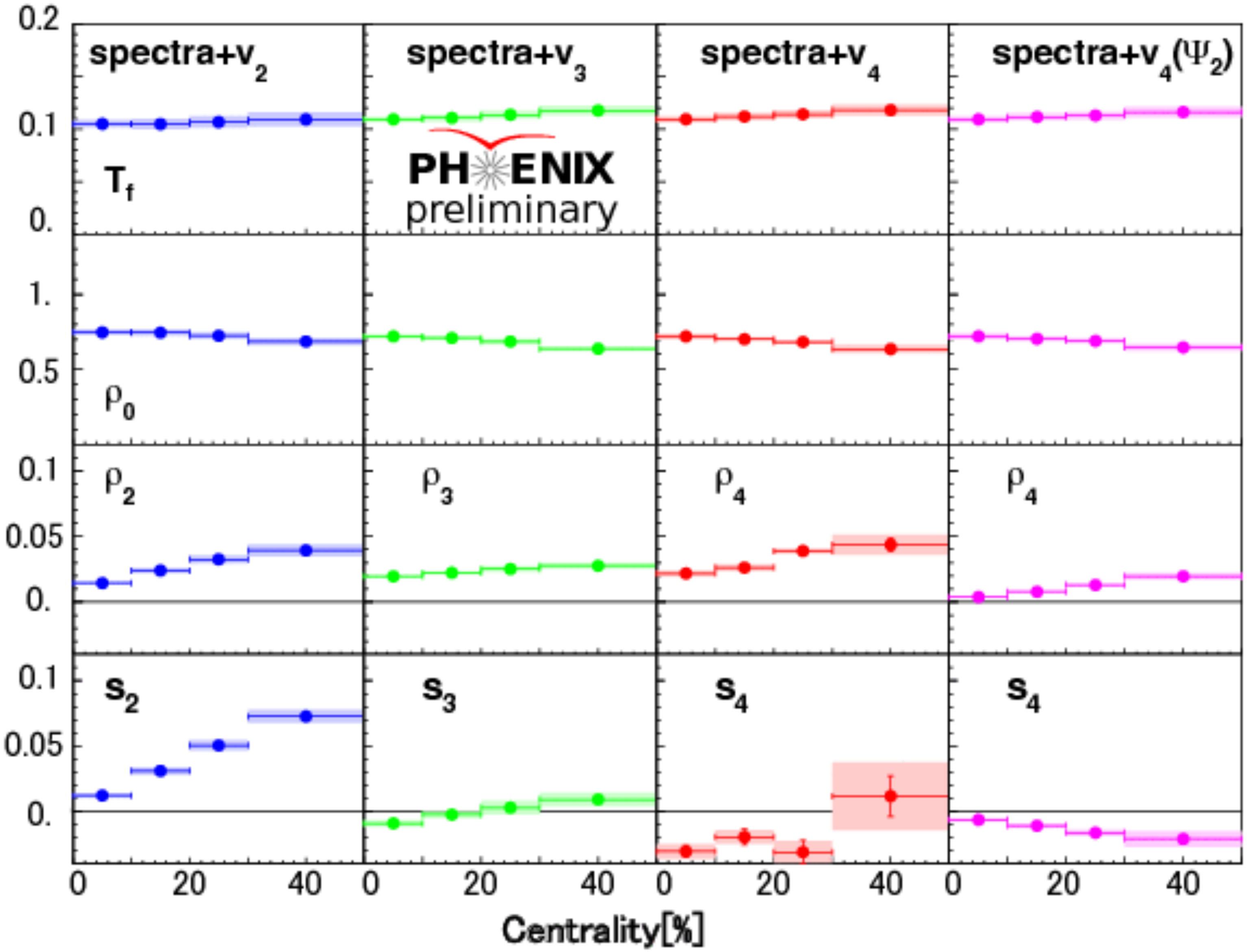

T. Niida, WPCF2011
Au+Au 200GeV π⁺π⁺+π⁻π⁻
Au+Au 200GeV K⁺K⁺+K⁻K⁻
STAR (PRL,93,12301)
ε_initial = ε_final
PHENIX Preliminary
PHENIX
ε_final
ε_initial
0
0.1
0.2
0.3
0.4
0.5
0.05
0.15
0.25
0.35

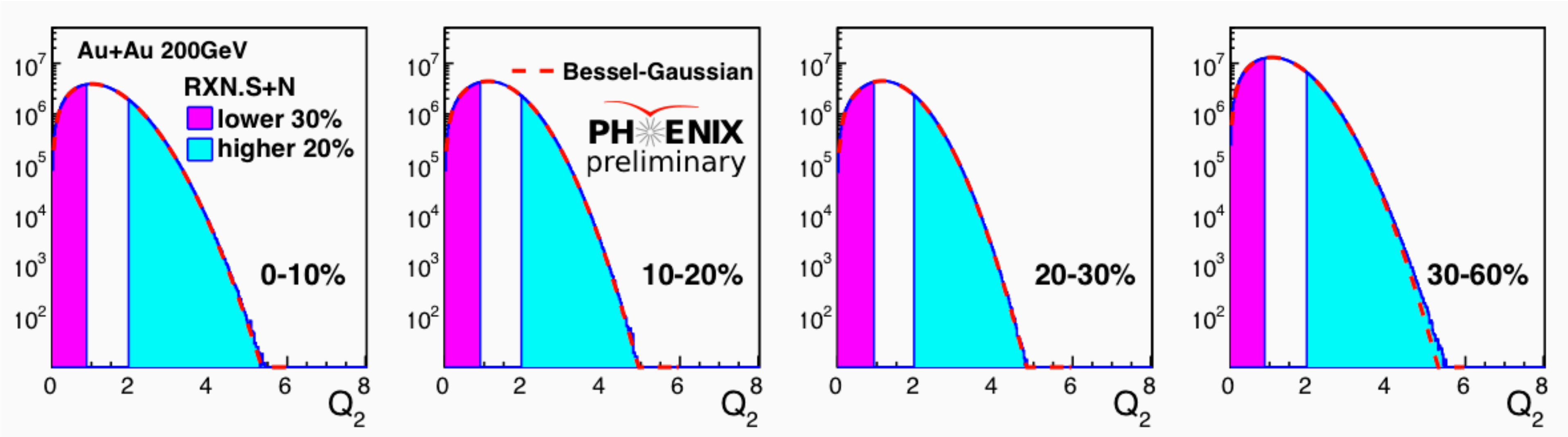


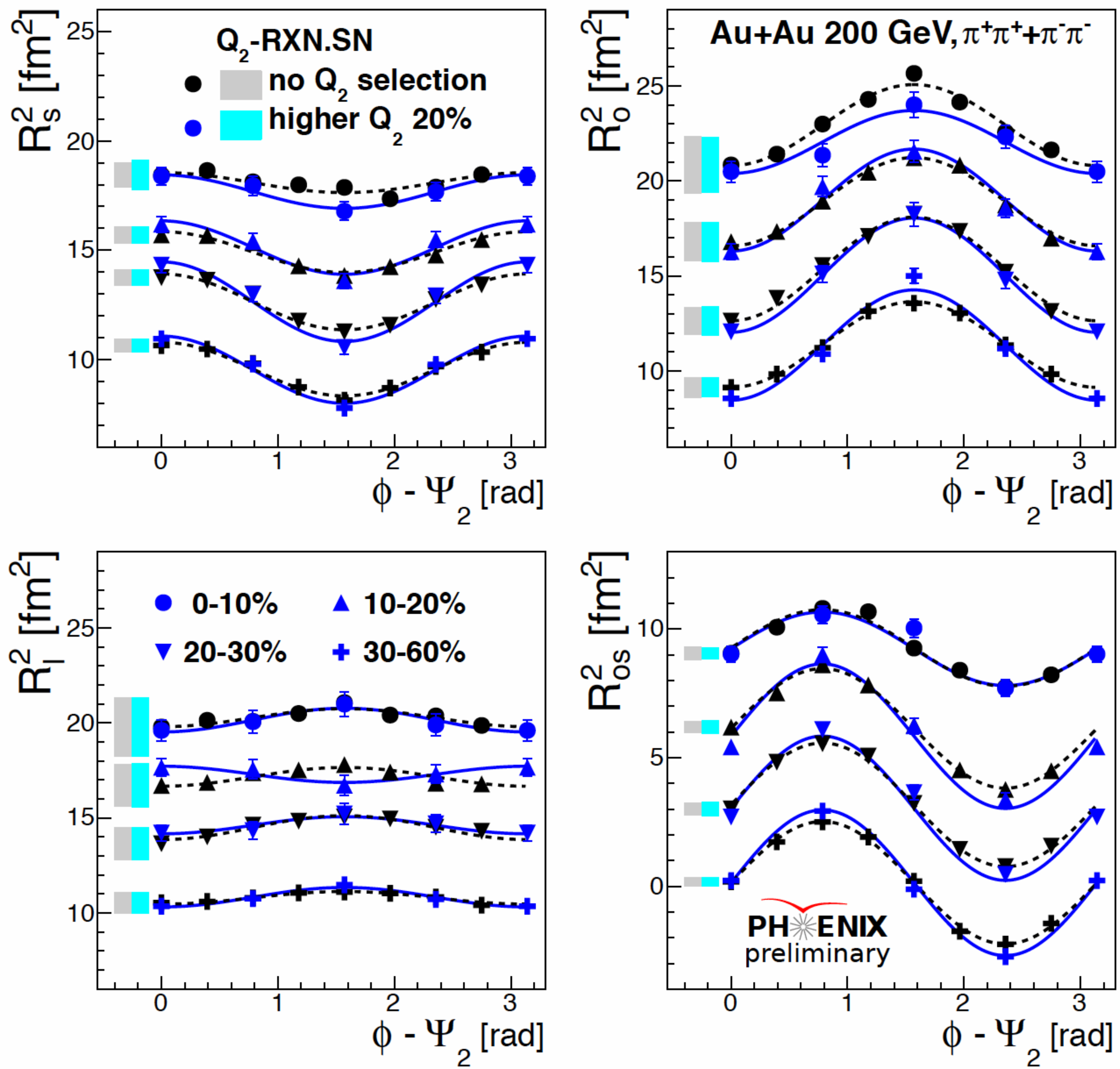
$2R^2_{s,2} / R^2_{s,0}$
$-2R^2_{o,2} / R^2_{o,0}$
$-2R^2_{l,2} / R^2_{l,0}$
$-2R^2_{o,2} / R^2_{s,0}$
$2R^2_{os,2} / R^2_{s,0}$
PHENIX Preliminary
PHENIX
preliminary
Au+Au 200GeV
$\pi^+\pi^+ + \pi^-\pi^-$ 0-20%
$\pi^+\pi^+ + \pi^-\pi^-$ 20-60%
$K^+K^+ + K^-K^-$ 0-20%
$K^+K^+ + K^-K^-$ 20-60%
$\langle m_T \rangle$ [GeV/c]

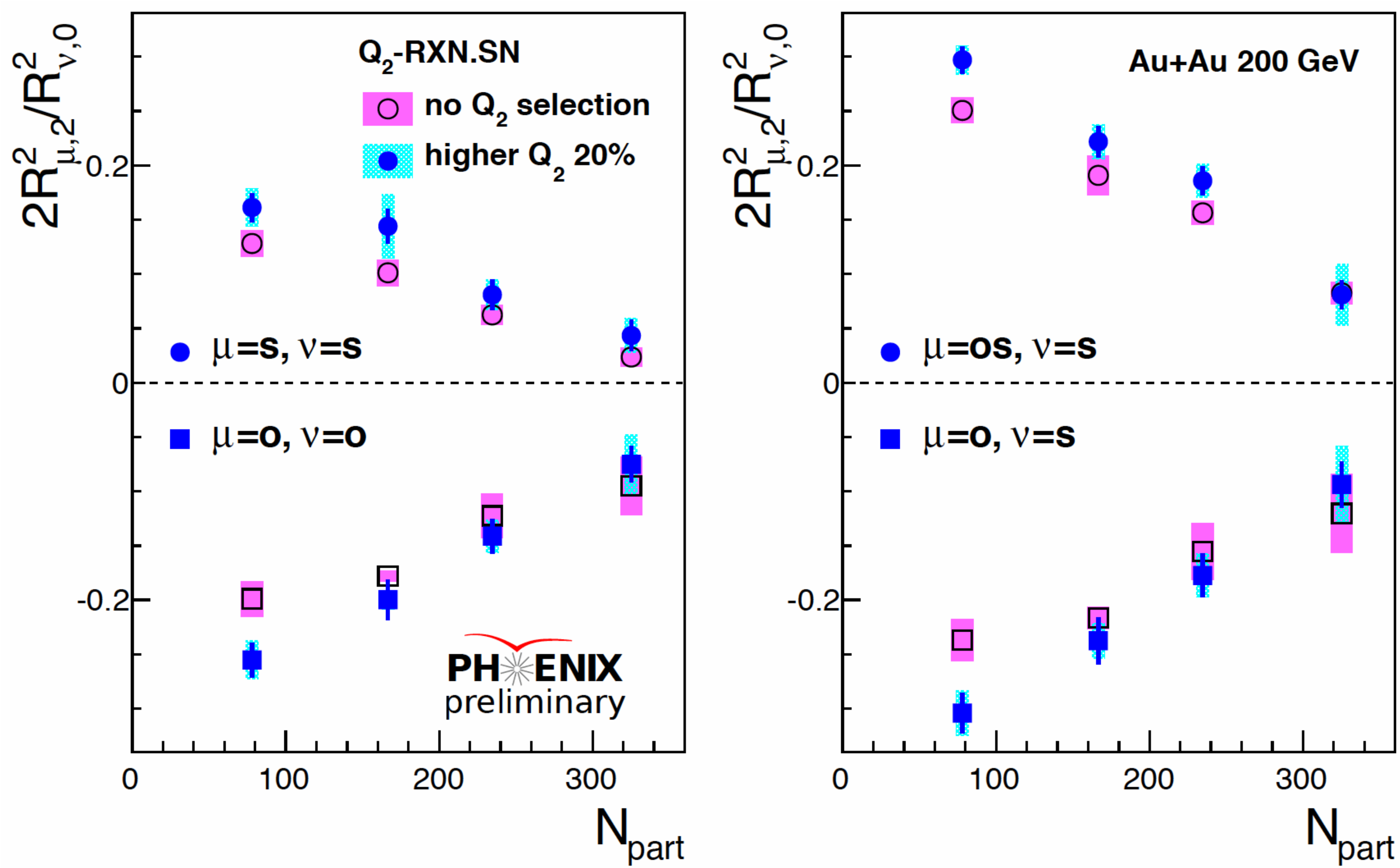

side
out
long
kt[GeV/c]
0.2-0.3
0.3-0.4
0.4-0.5
1.15
1.1
1.05
1
1.2
1.3
Au+Au 200GeV
20-60% π+π+ +π-π-
Δφ=0
Δφ=π/2
PHENIX Preliminary
PHENIX
preliminary
-0.1
0
0.1
0.2
Q_side [GeV/c]
Q_out [GeV/c]
Q_long [GeV/c]


spectra+v2
20 - 30%
spectra+v3
spectra+v4
spectra+v4(Ψ2)
π⁺+π⁻
K⁺+K⁻
p+p̄
radius integrated BW
χ²=3437
χ²=296
χ²=101
χ²=131
PHENIX preliminary
pT[GeV/c]
radius integrated BW
surface BW
s2
s3
s4
ε2 = s2
ε3 = s3
ε4 = s4
ε2
ε3
ε4
PHENIX preliminary


spectra+v2
spectra+v3
spectra+v4
spectra+v4(Ψ2)
Tf
ρ0
ρ2
ρ3
ρ4
ρ4
s2
s3
s4
s4
PHENIX preliminary
0.2
0.1
0.
1.
0.5
0.1
0.05
0.
0.1
0.05
0.
0
20
40
Centrality[%]


Au+Au 200GeV
RXN.S+N
lower 30%
higher 20%
0-10%
Bessel-Gaussian
PHENIX
preliminary
10-20%
20-30%
30-60%
Q_2


Q_2-RXN.SN
no Q_2 selection
higher Q_2 20%
Au+Au 200 GeV, π⁺π⁺+π⁻π⁻
0-10%
10-20%
20-30%
30-60%
R²_s [fm²]
R²_o [fm²]
R²_l [fm²]
R²_os [fm²]
φ - Ψ_2 [rad]
PHENIX
preliminary


Q2-RXN.SN
no Q2 selection
higher Q2 20%
μ=s, ν=s
μ=o, ν=o
PHENIX
preliminary
Au+Au 200 GeV
μ=os, ν=s
μ=o, ν=s
0.2
0
-0.2
0
100
200
300
N_part