Global and Collective Dynamics at PHENIX

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University of Tsukuba

"Heavy Ion collisions in the LHC era" in Quy Nhon

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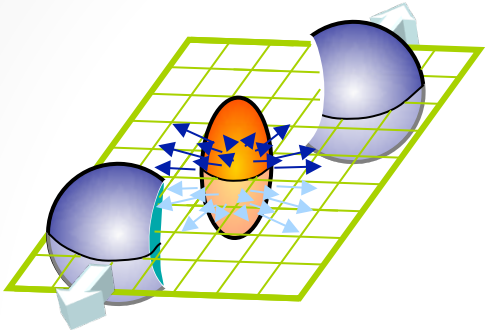
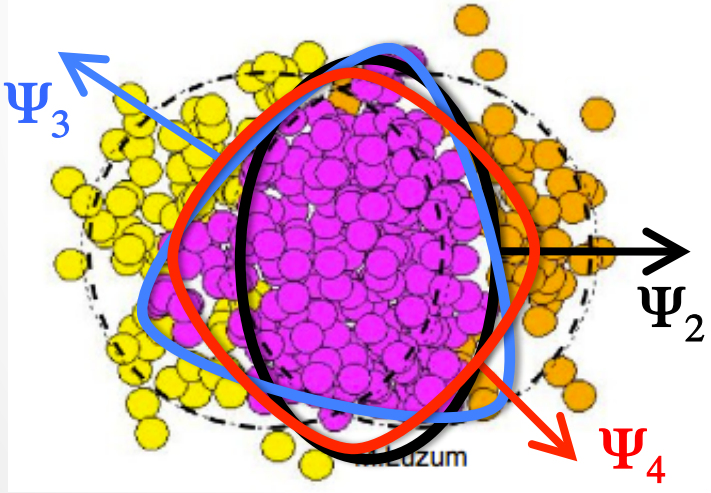
outline

- Introduction of v_n
- Higher harmonic flow (v_n) of Identified particle
- 2 particle correlations with v_n
- Azimuthal HBT w.r.t event plane
- Summary

Higher harmonic event plane

- Initial density fluctuations cause higher harmonic flow v_n
- Azimuthal distribution of emitted particles:



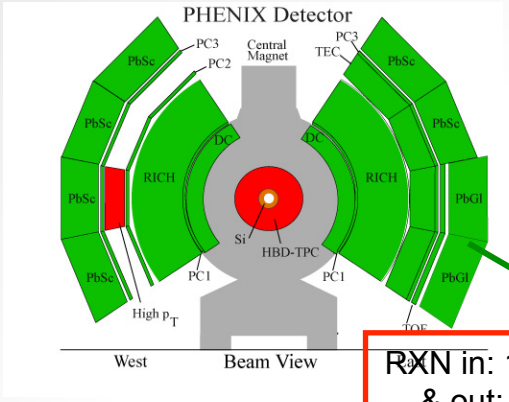


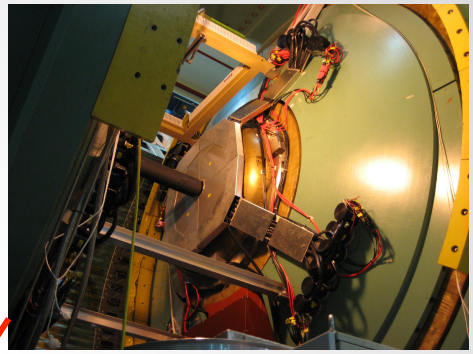
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2) + 2v_3 \cos 2(\phi - \Psi_3) + 2v_4 \cos 2(\phi - \Psi_4)$$

$$v_n = \left\langle \cos n(\phi - \Psi_n) \right\rangle$$

Ψ_n : Higher harmonic event plane
φ : Azimuthal angle of emitted particles

v_n measurement via Event plane method





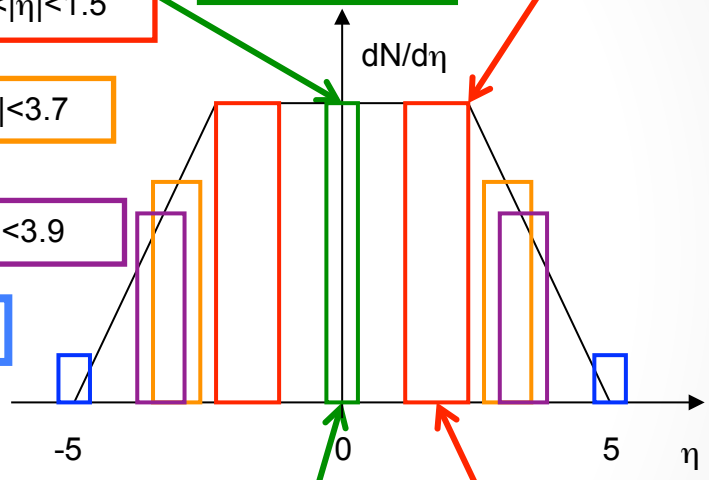
RXN in: 1.5<|η|<2.8
& out: 1.0<|η|<1.5

CNT: |η|<0.35

MPC: 3.1<|η|<3.7

BBC: 3.0<|η|<3.9

ZDC/SMD



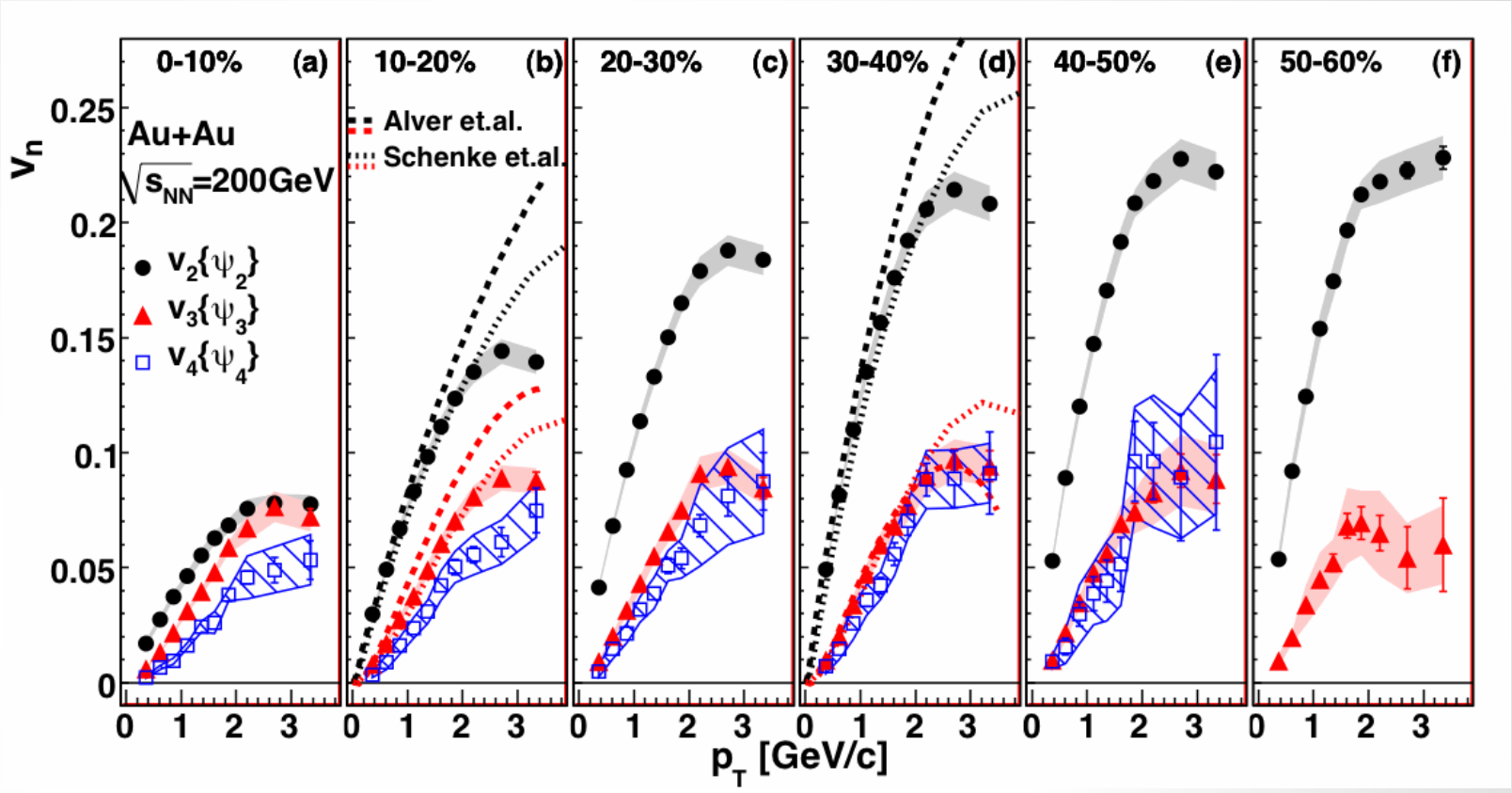
$$v_n = \left\langle \cos n\left(\phi - \Psi_n\right) \right\rangle$$

Ψ_n : Determined by forward detector RXN

φ : Measured at mid-rapidity

Charged hadron v_n at PHENIX

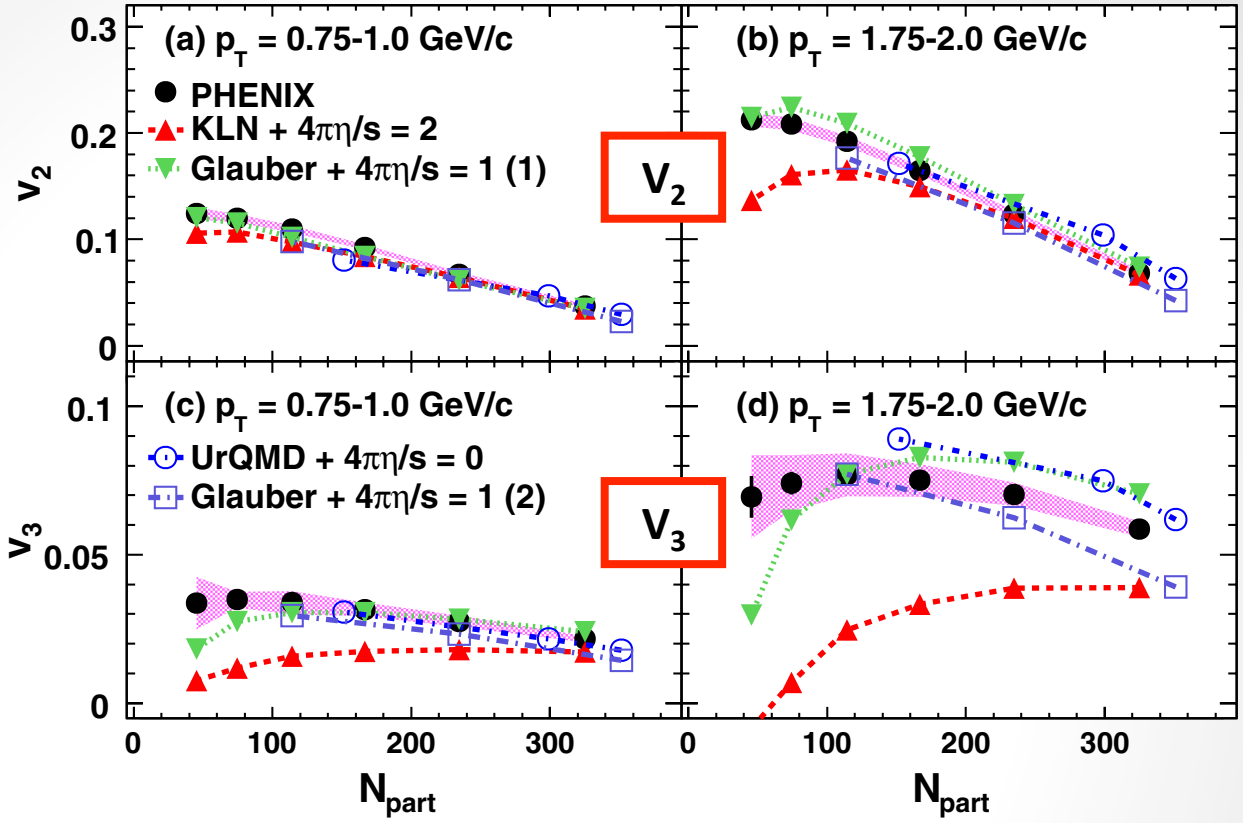
PRL.107.252301



- v_2 increases with increasing centrality, but v3 doesn't
- v_3 is comparable to v_2 in 0-10%
- v_4 has similar dependence to v_2

v_3 breaks degeneracy

PRL.107.252301



- v_3 provides new constraint on hydro-model parameters
  - ✧ Glauber & 4πη/s=1 : works better
  - ✧ KLN & 4πη/s=2 : fails

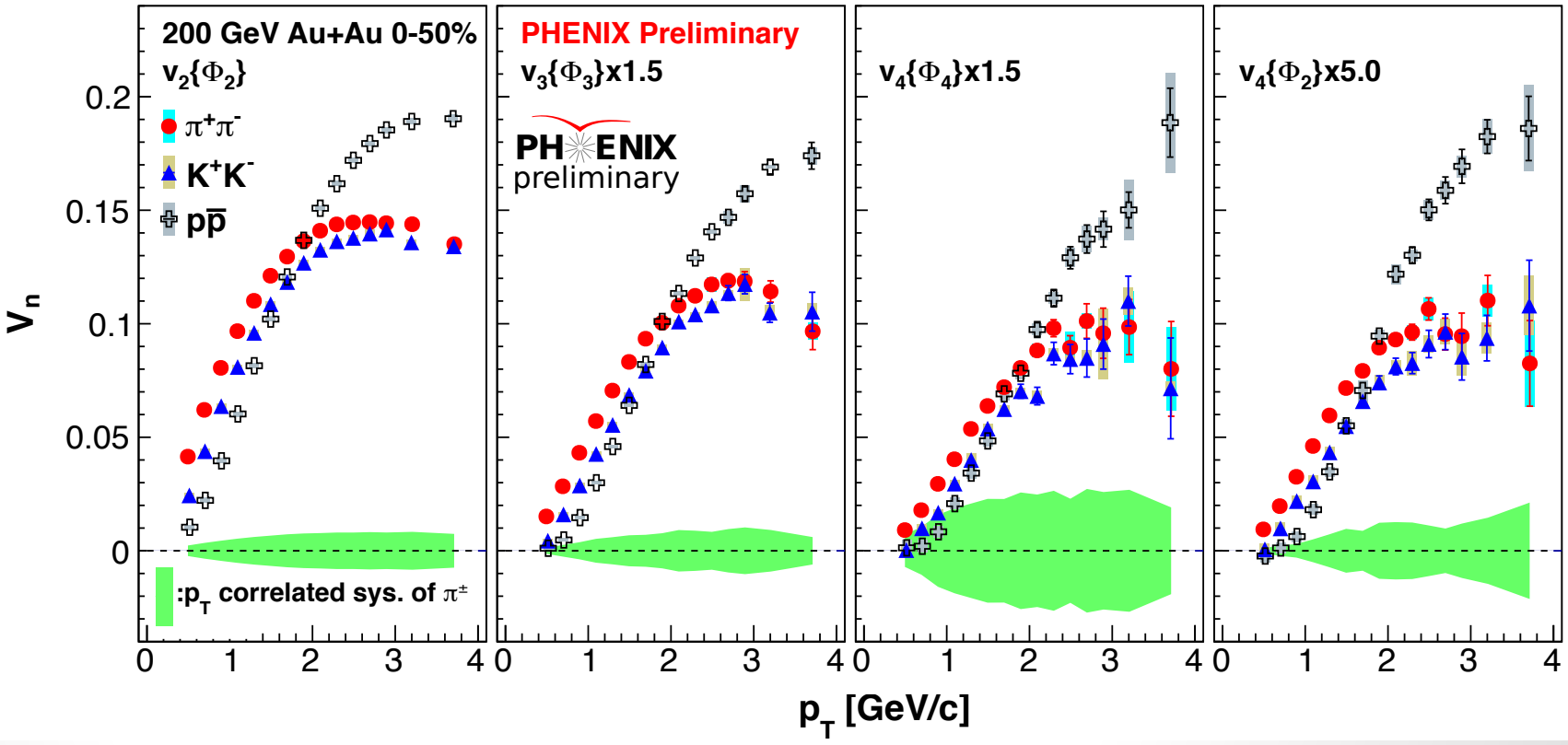
Recent Results at PHENIX

- v_n of Identified particle
- 2 particle correlations with vn
- Azimuthal HBT w.r.t event plane

Motivation of PID v_n

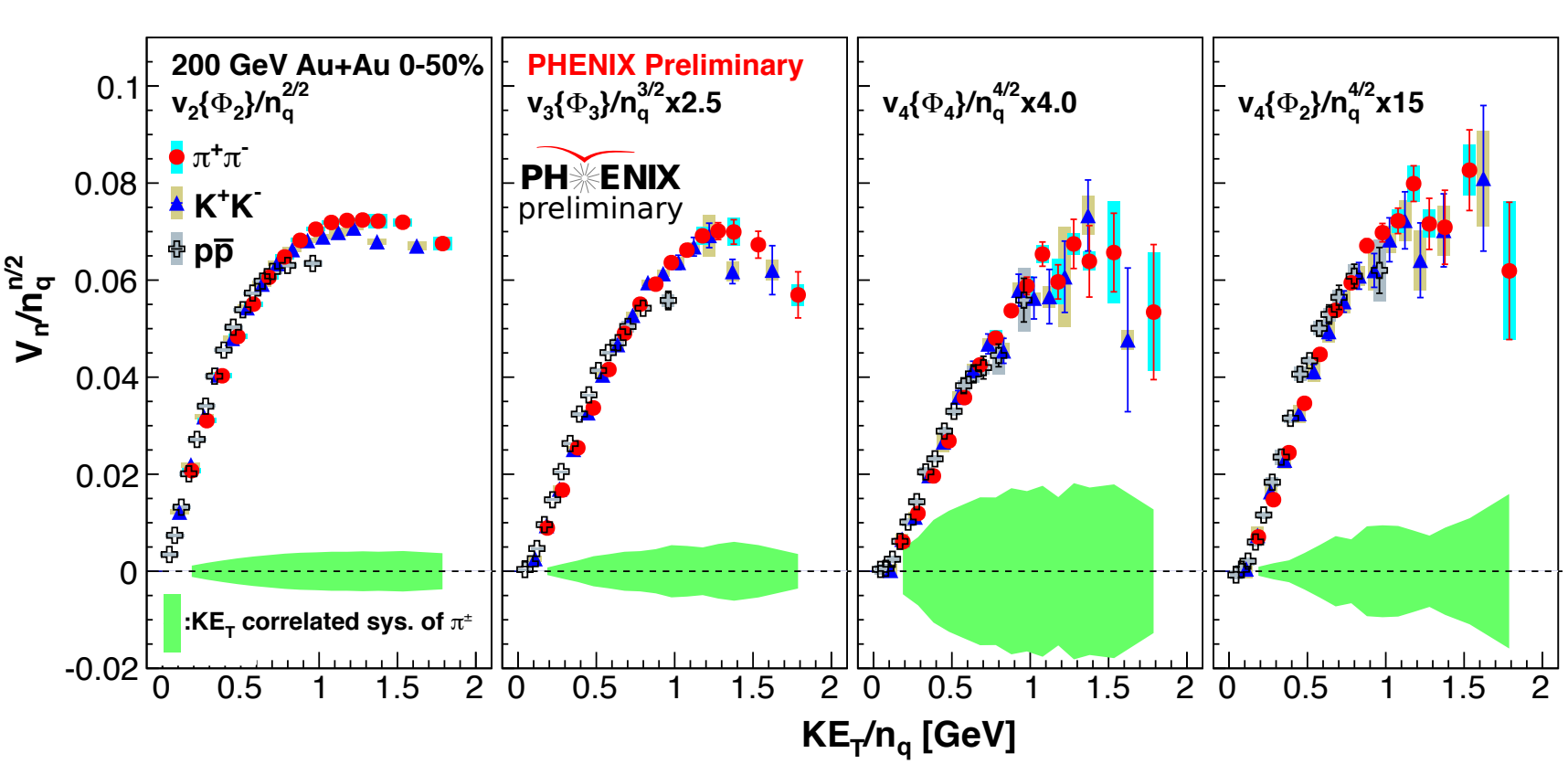
- **v_n is sensitive probe to the QGP bulk property**
- **Important to check the following features seen in v_2**
  - ✧Mass splitting at low pT
  - ✧Baryon/Meson difference at mid pT
  - ✧How is the scaling property of vn ?

v_n of Identified particle



- Mass splitting at low p_T : Hydrodynamics
- Baryon/Meson difference at mid p_T : Quark coalescence

PID v_n with modified scaling

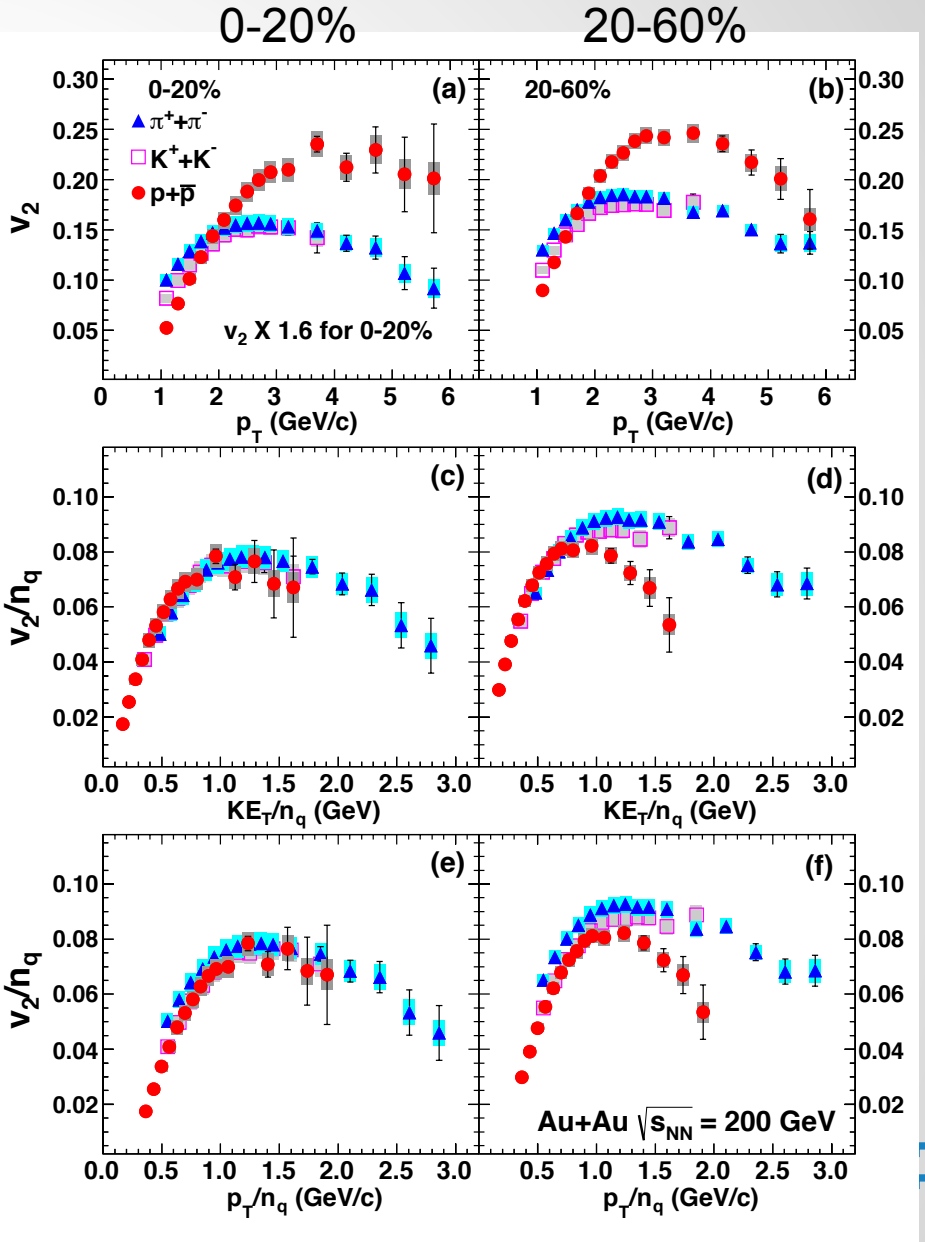


- Known n_q scaling fails in v_3, v_4
- Modified scaling works well for v_n : $v_n(KE_T/n_q)/n_q^{n/2}$

PID v_2 at high p_T

PRC.85.064914(2012)

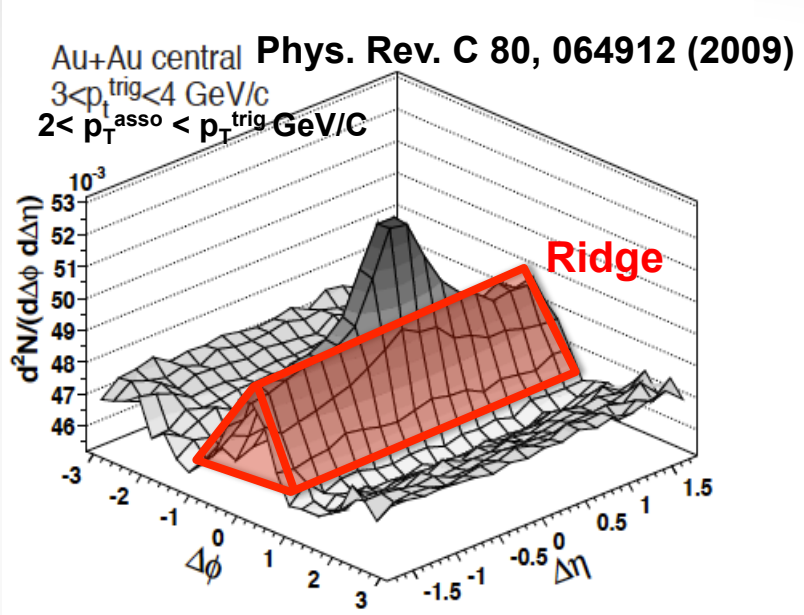
- Extend PID to high pT by combining TOF(MRPC) and Aerogel Cherenkov Counter
- Quark number scaling is better for KE_T/n_q than p_T/n_q
- But it breaks at KE_T/n_q~0.7GeV for non-central collisions

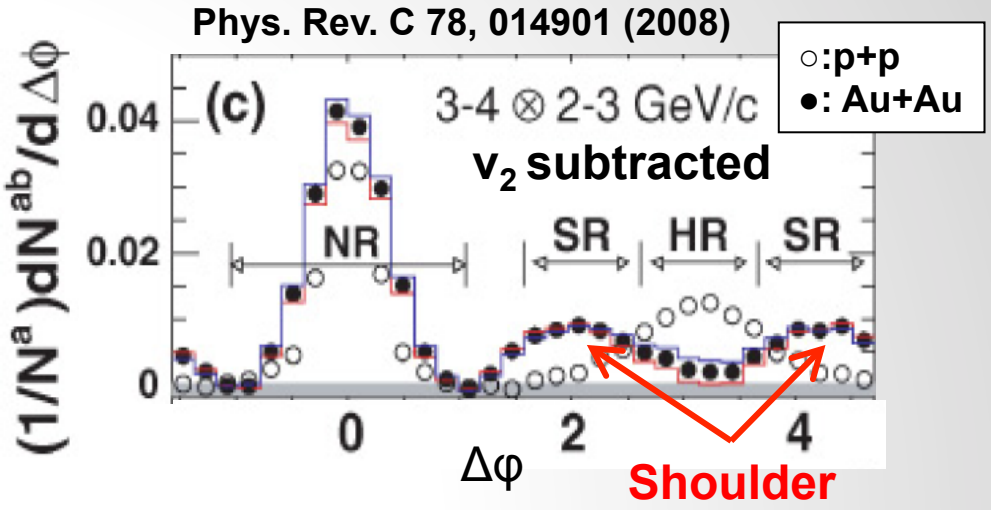


Recent Results at PHENIX

- v_n of Identified particle
- **2 particle correlations with v_n**
- Azimuthal HBT w.r.t event plane

Motivation of 2 particle correlations with v_n





$$Jet(\Delta\phi) = CF(\Delta\phi) - b_0 Flow(\Delta\phi)$$

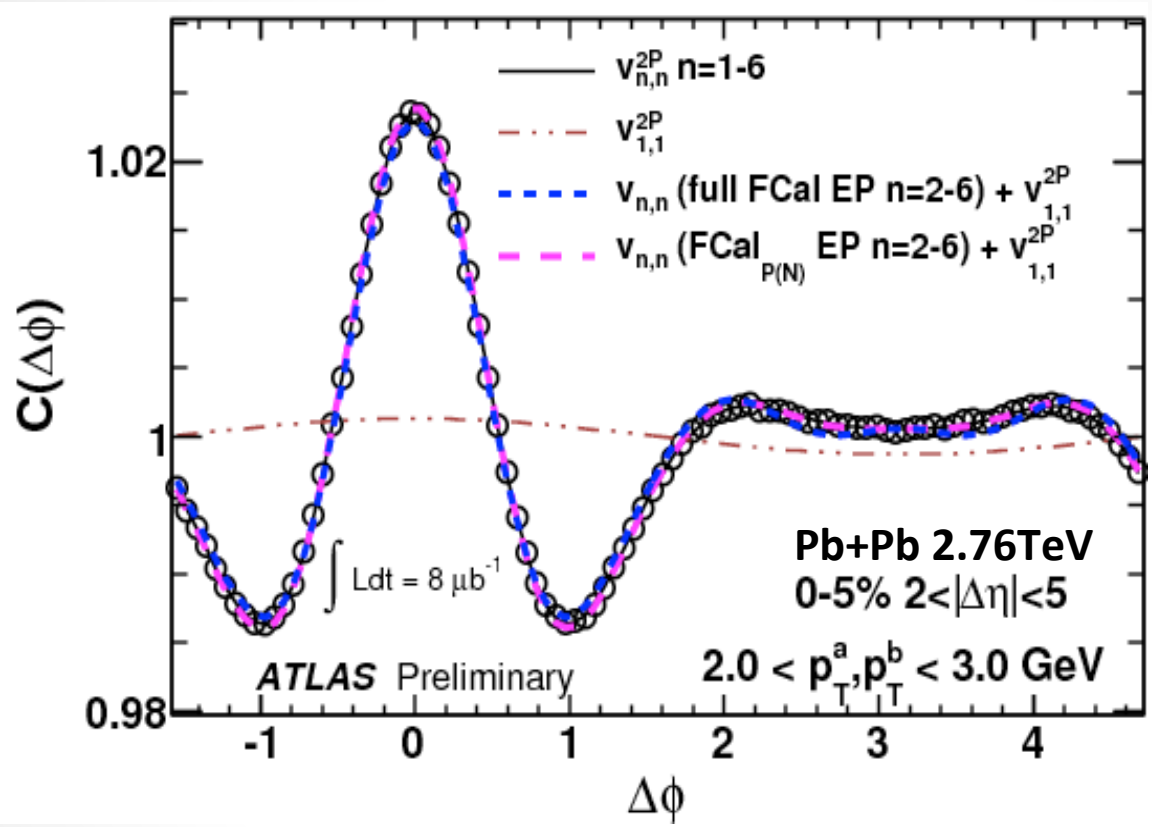
- **Ridge and Shoulder can be seen in Δφ-Δη correlation**
  - ✧They can be explained by v_n ?
- **v_n subtractions are needed to get real jet correlations**

2 particle correlations with |Δη| gap

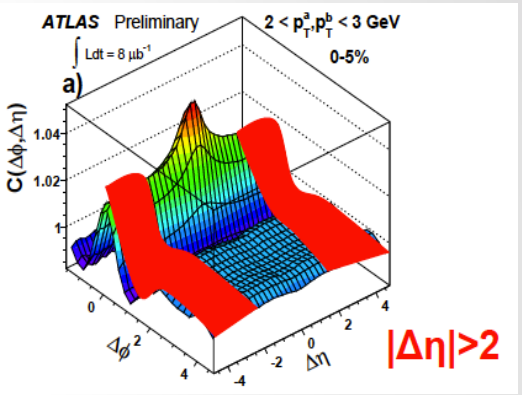
$$C(\Delta\phi) = b^{2P}\left(1 + 2v_{1,1}^{2P}\cos\Delta\phi + 2\sum_{n=2}^{6} v_n^{EP} v_n^{EP}\cos n\Delta\phi\right)$$

From 2PC method

From EP method

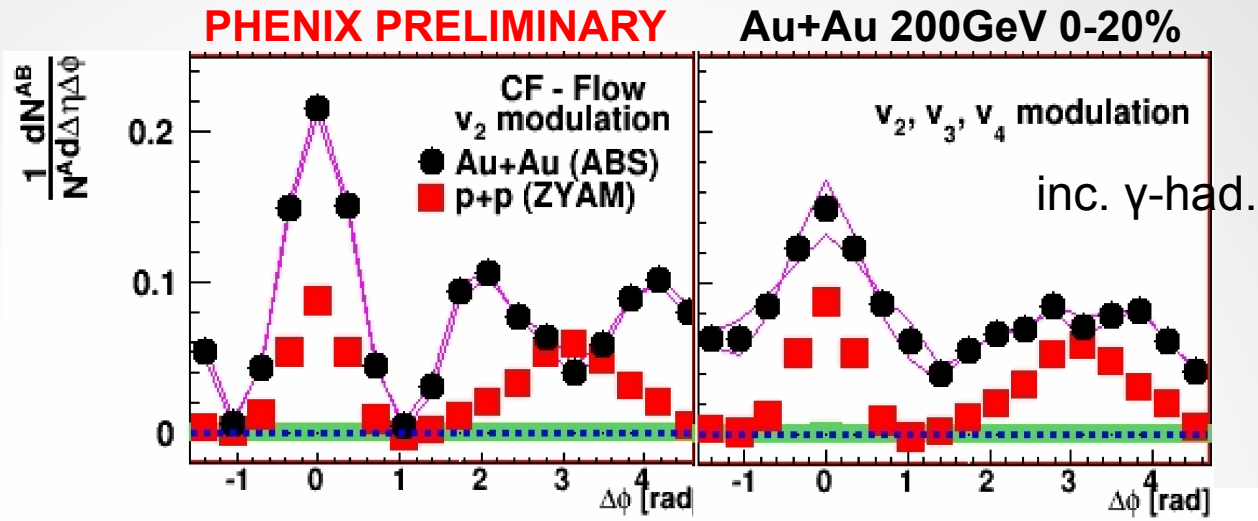


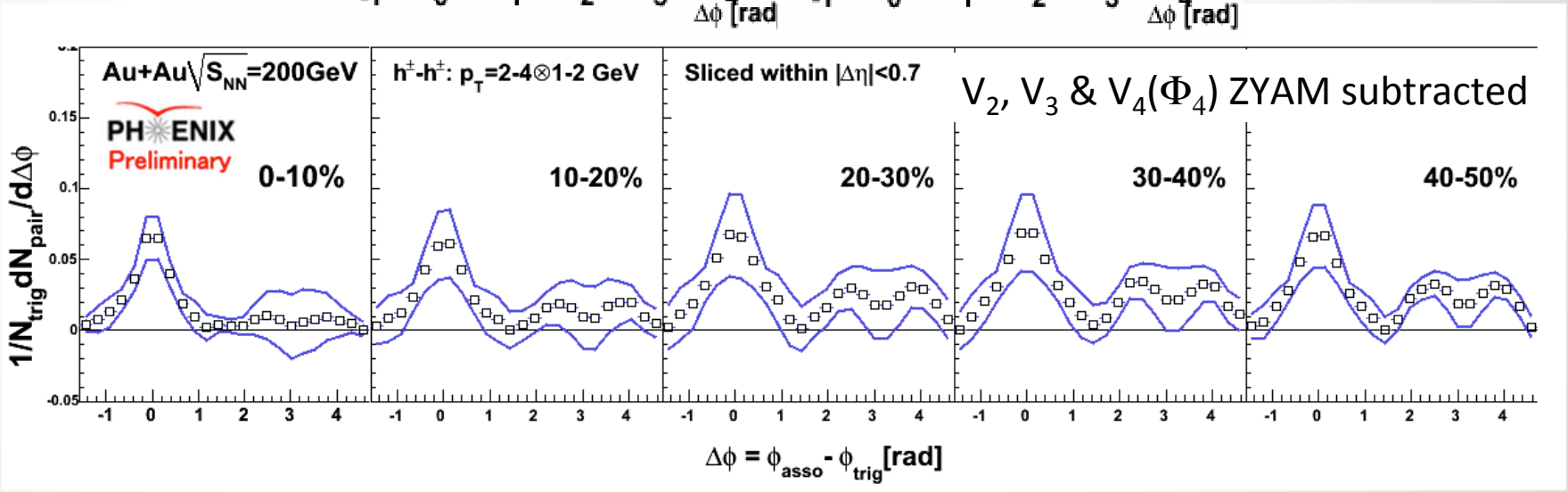
QM'11 J. Jia ATLAS Flow Plenary



- v_n reproduce Ridge & Shoulder well in 0-5%

2 particle correlations without |Δη| gap





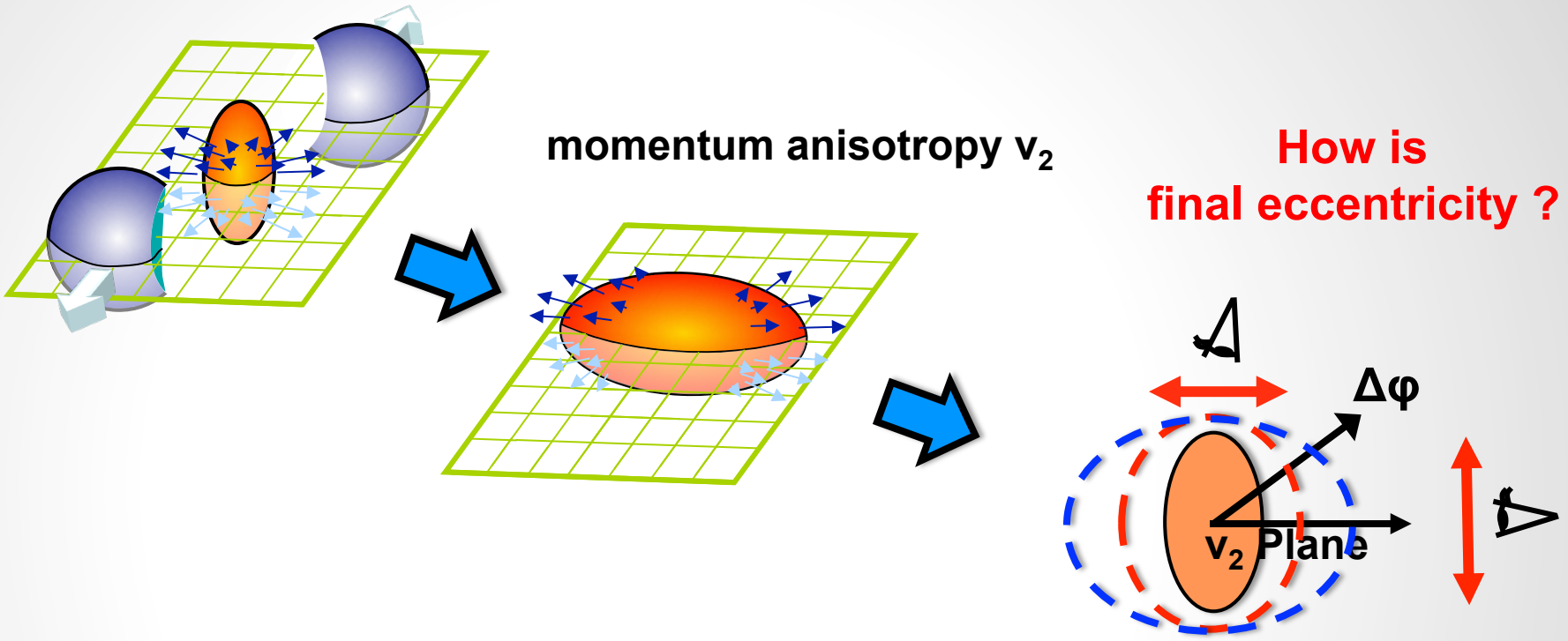
- Most-central : Away side yield are suppressed
- Mid-central : Away side yield still remain

Recent Results at PHENIX

- Particle Identified v_n
- 2 particle correlations with vn
- **Azimuthal HBT w.r.t event plane**

Motivation of Azimuthal HBT w.r.t v_2 plane

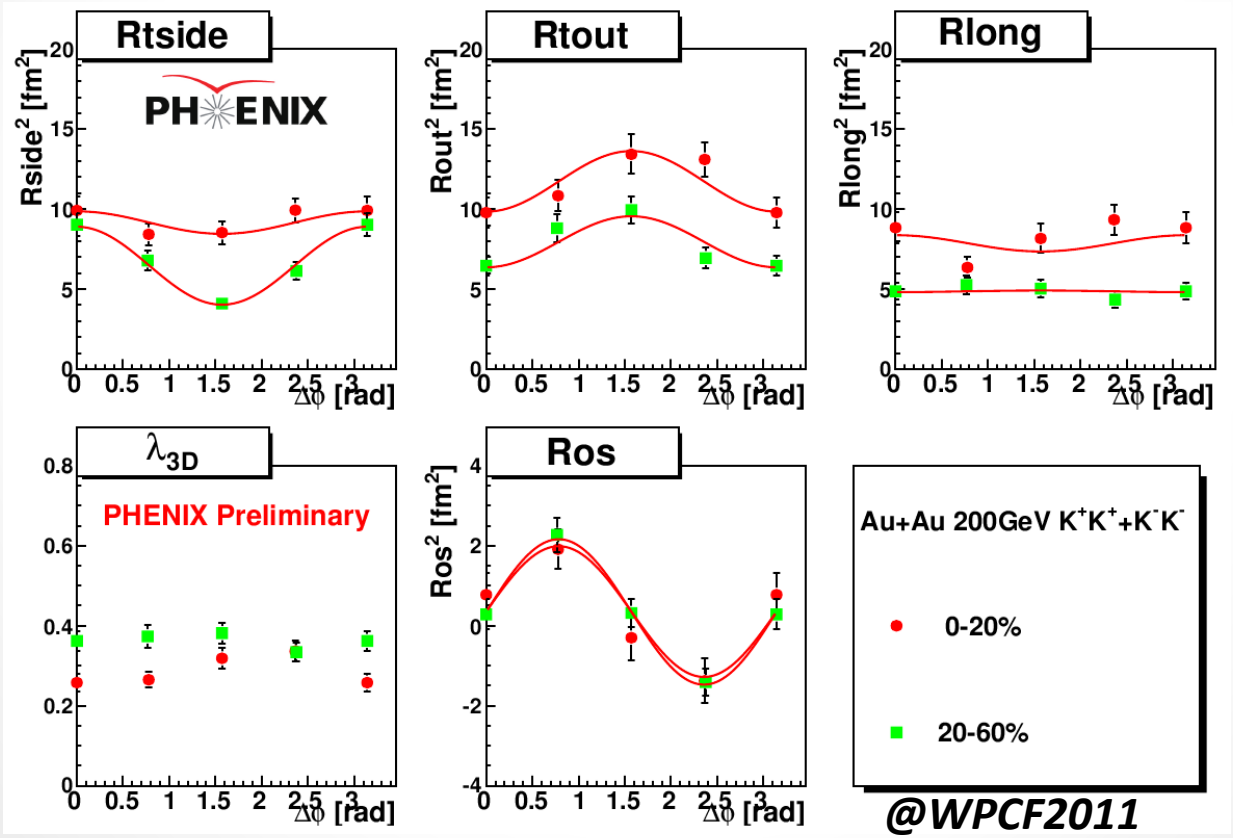
Initial spatial anisotropy (eccentricity)

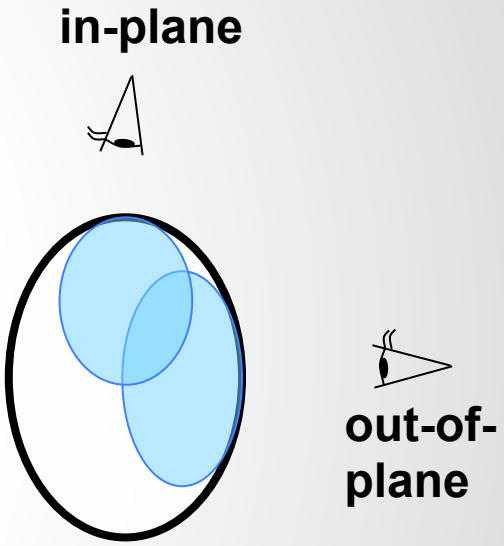


- **Final eccentricity can be measured by azimuthal HBT**
  - ✧It depends on Initial eccentricity, pressure gradient, expansion time, and velocity profile etc
  - ✧Good probe to investigate system evolution

Azimuthal HBT radii for kaons

- Observed oscillation for R_{side}, R_{out}, R_{os}
- Final eccentricity is defined as $\varepsilon_{final} = 2R_{s,2} / R_{s,0}$
  - $R^2_{s,n} = \left\langle R^2_{s,n}(\Delta\phi)\cos(n\Delta\phi)\right\rangle$ PRC70, 044907 (2004)



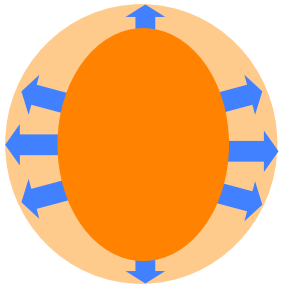


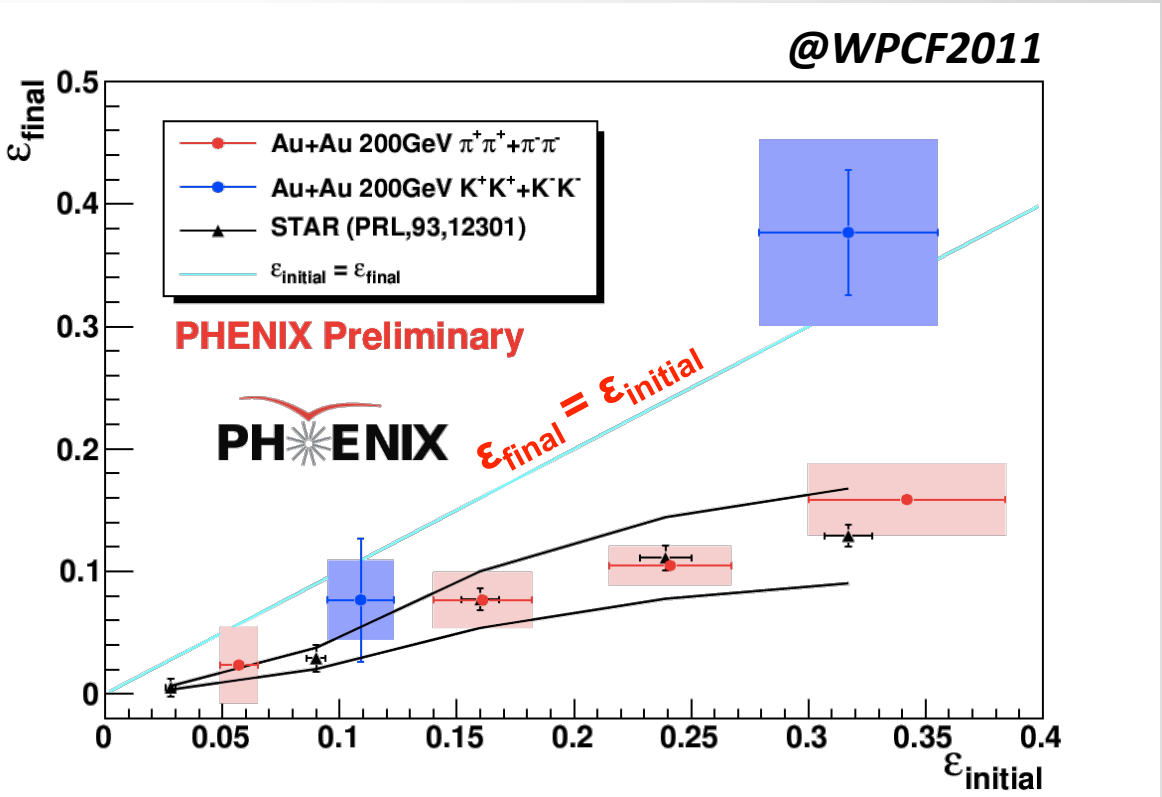
Eccentricity at freeze-out

PRC70, 044907 (2004)

$$R^2_{s,n} = \left\langle R^2_{s,n}(\Delta\phi)\cos(n\Delta\phi)\right\rangle$$

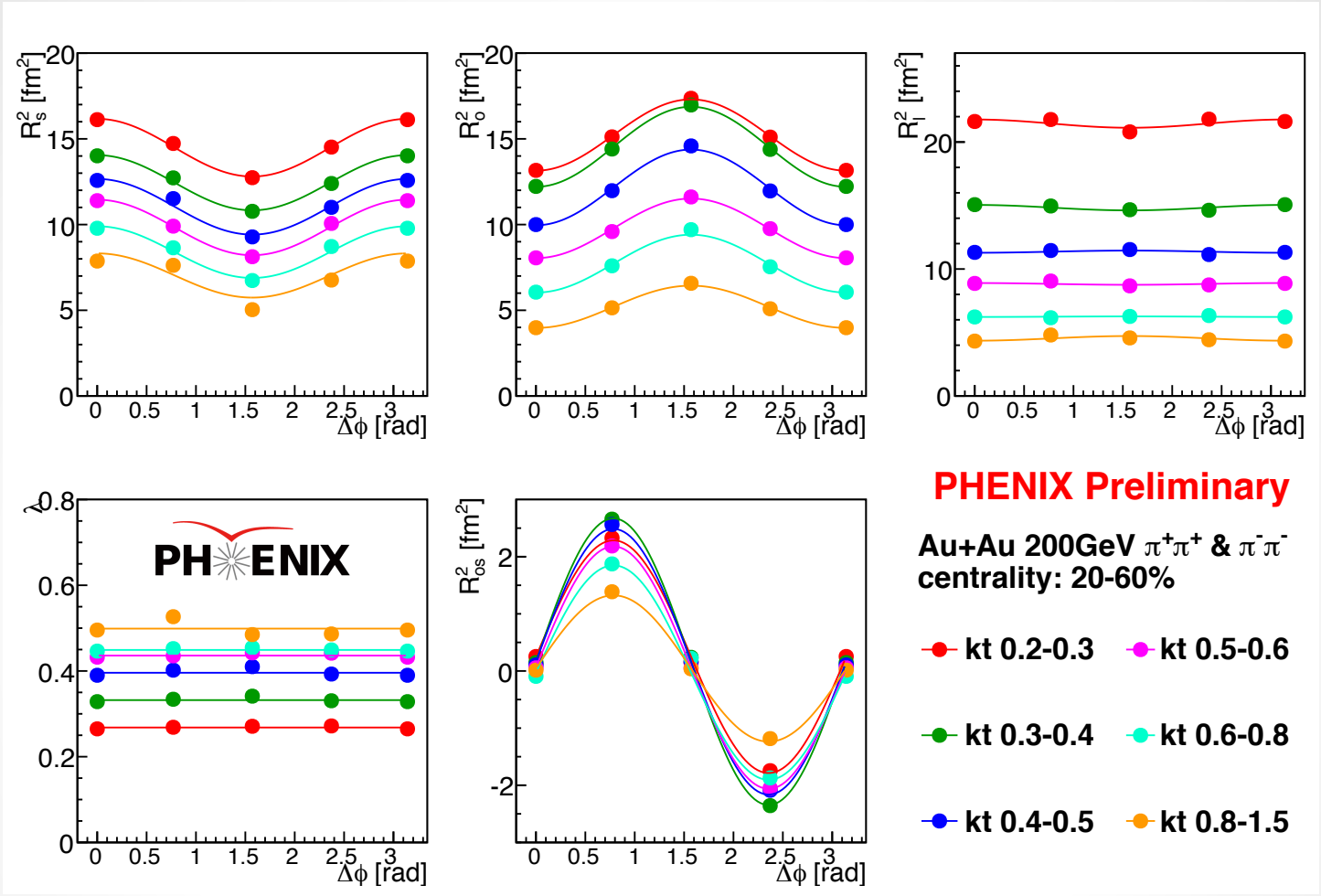
$$\varepsilon_{final} = 2\frac{R^2_{s,2}}{R^2_{s,0}}$$

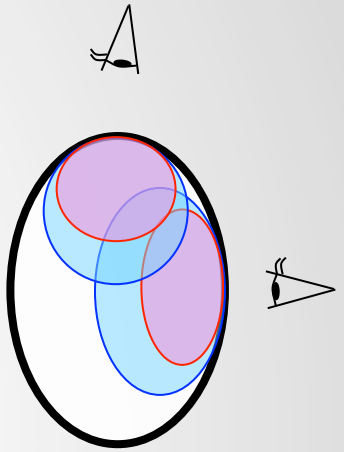




- **$\varepsilon_{final} \approx \varepsilon_{initial}/2$ for pion**
  - ✧ Indicates that source expands to in-plane direction, and still elliptical
  - ✧ PHENIX and STAR results are consistent
- **$\varepsilon_{final} \approx \varepsilon_{initial}$ for kaon**
  - ✧ Freeze-out time is faster than that of pion?
  - ✧ Due to different m_T between π/K?

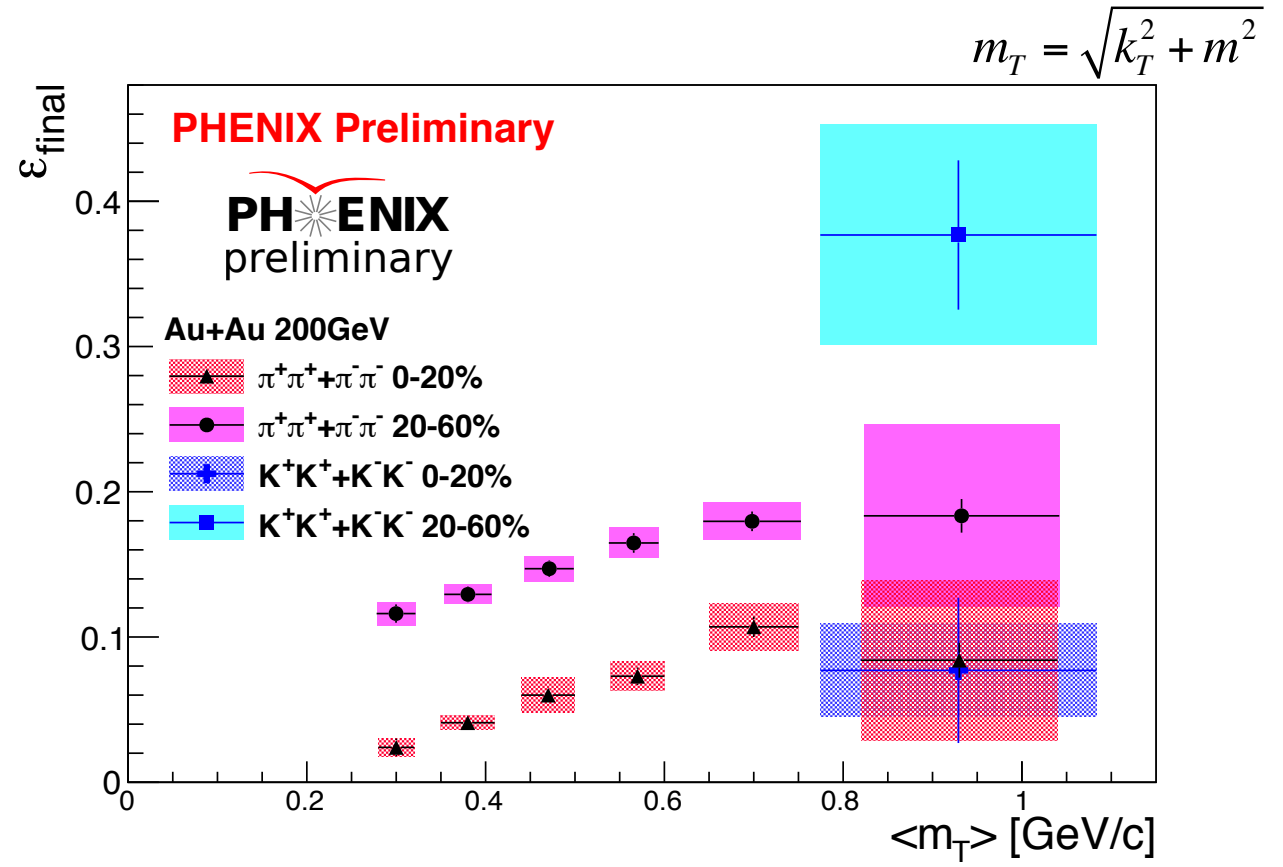
k_T dependence of azimuthal pion HBT radii





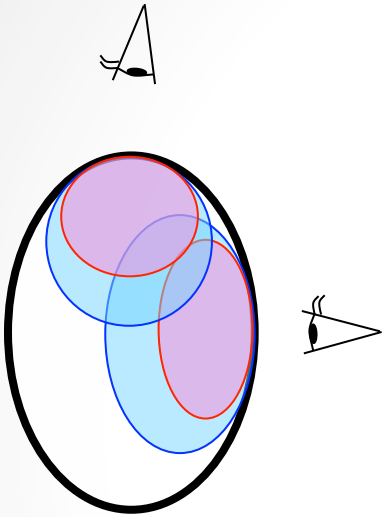
- Oscillation can be seen in R_s, R_o, and R_{os} for each kT regions

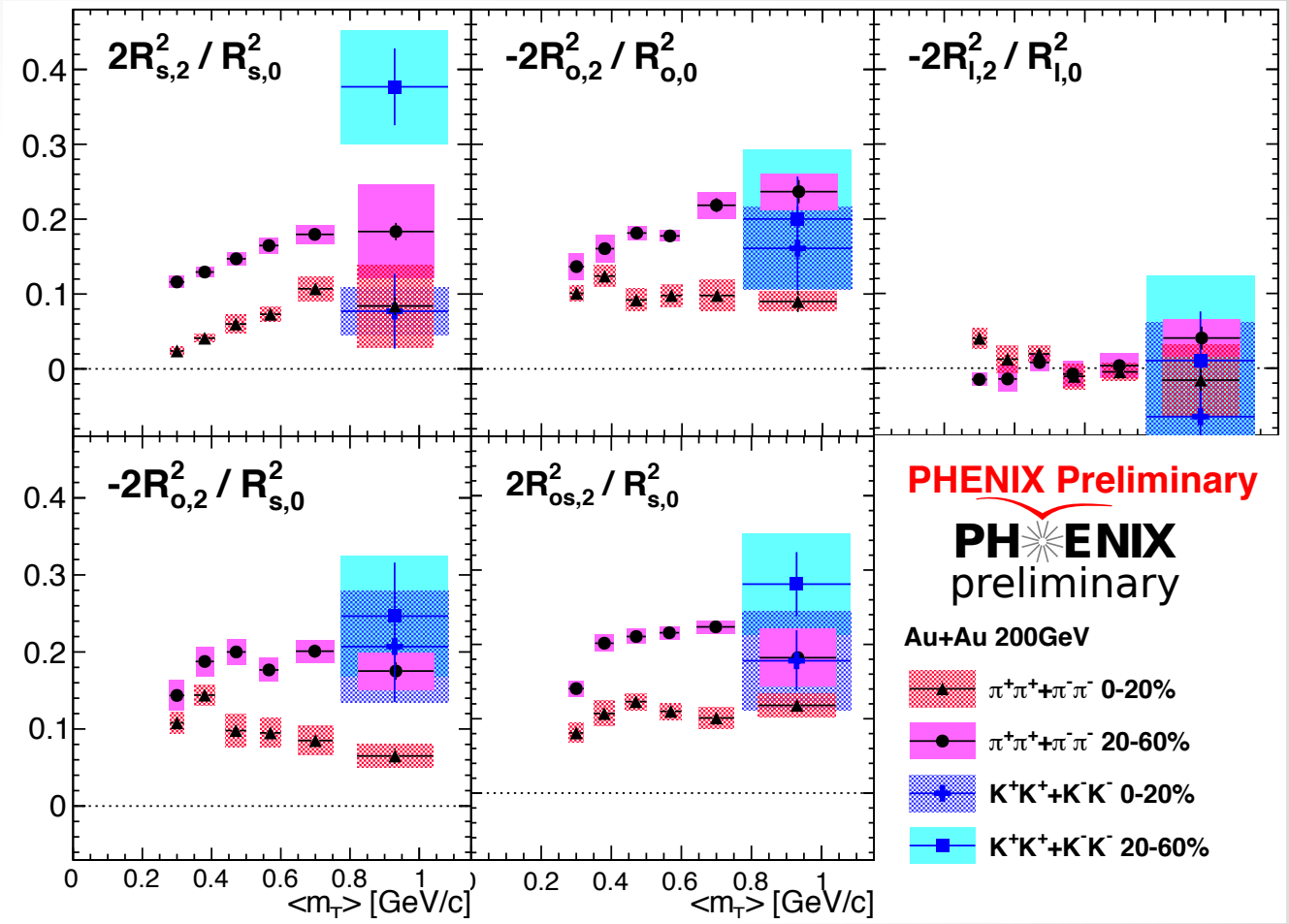
m_T dependence of ε_{final}



- ε_{final} of pions increases with m_T in most/mid-central collisions
- There is still difference between π/K even in same m_T
  - ✧ But the difference is at most within 2 σ of systematic errors

m_T dependence of relative amplitude



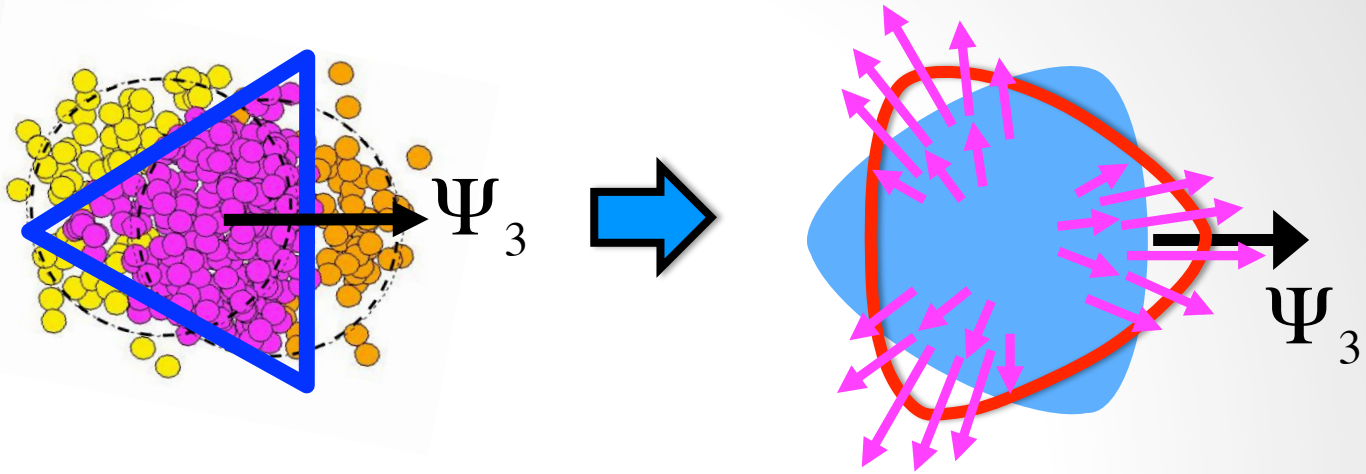


- **Relative amplitude of R_{out} in 0-20% doesn't depend on m_T**
  - ✧Does it indicate emission duration between in-plane and out-of-plane is different ?

Azimuthal HBT w.r.t v_3 plane

Initial spatial fluctuation (triangularity)

momentum anisotropy triangular flow v_3



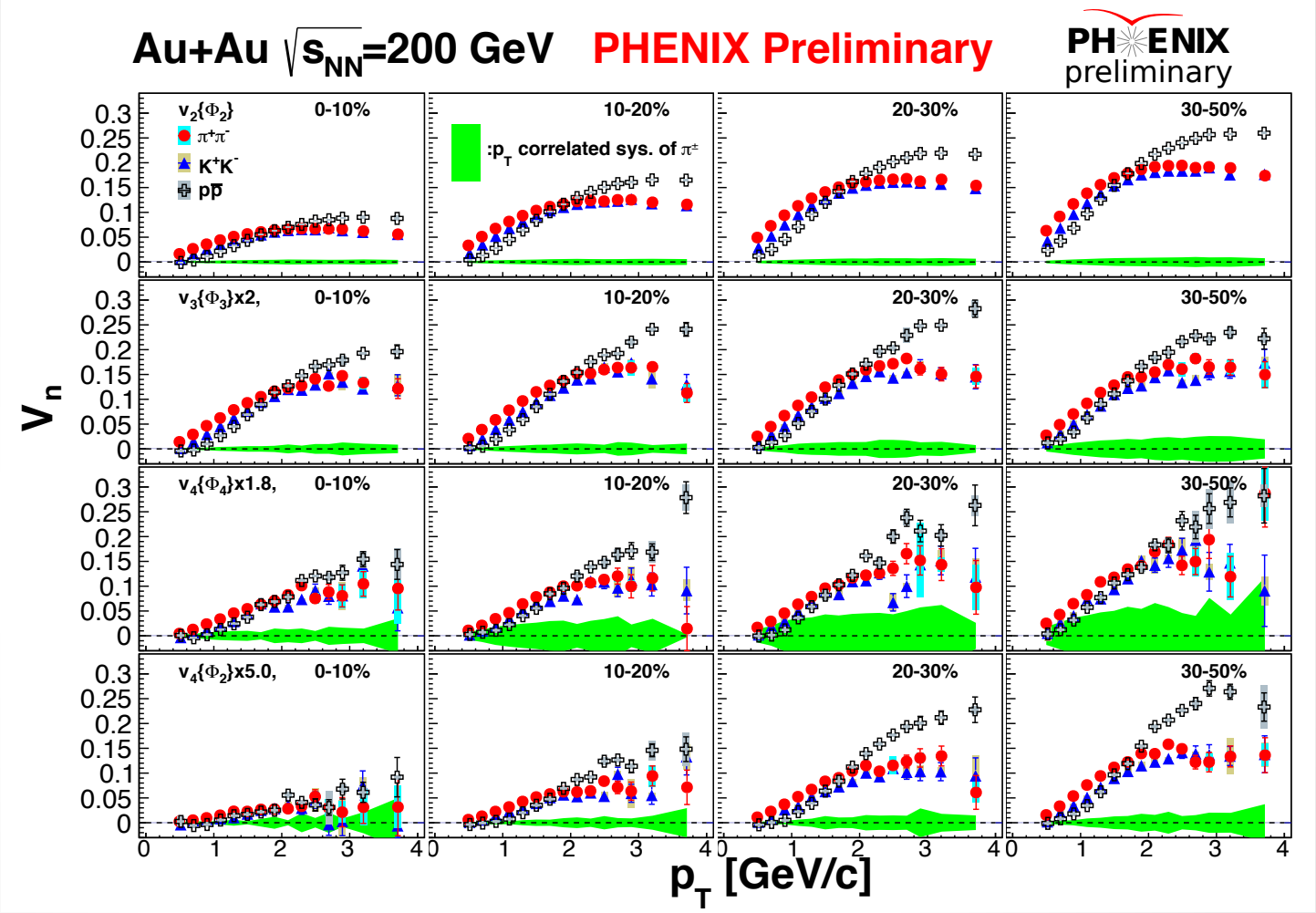
- **Final triangularity could be observed by azimuthal HBT w.r.t v_3 plane(Ψ_3) if it exists at freeze-out**
  - ✧Detailed information on space-time evolution can be obtained
- **Analysis is ongoing**

Summary

- **v_n of Identified particle**
  - ✧PID v_n have been measured
  - ✧Modified scaling $v_n(KE_T/n_q)/n_q^{n/2}$ works well for v_n
  - ✧Quak number scaling for v_2 breaks at high p_T in non-central collisions
- **2 particle correlations with v_n**
  - ✧ Away side yield are suppressed in most central collisions, but still remain in non-central collisions
- **Azimuthal HBT w.r.t v_2 plane**
  - ✧ε_{final} increase with m_T, while relative $R_{out,2}$ doesn't depend on mT in central collisions
  - ✧Difference of ε_{final} between π/K is seen even in same m_T, but note it is within 2σ of sys. error

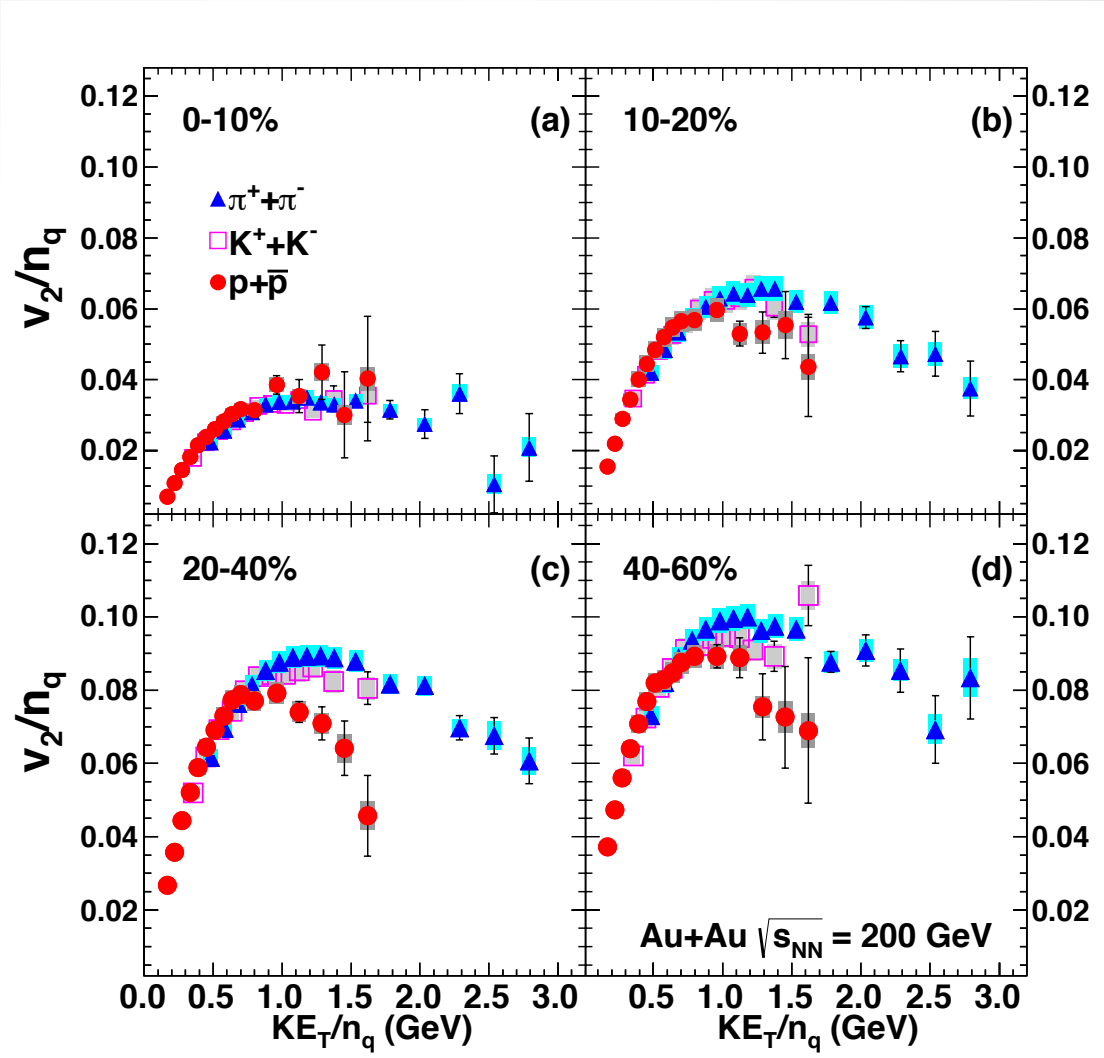
Back up

PID v_n vs centralarity



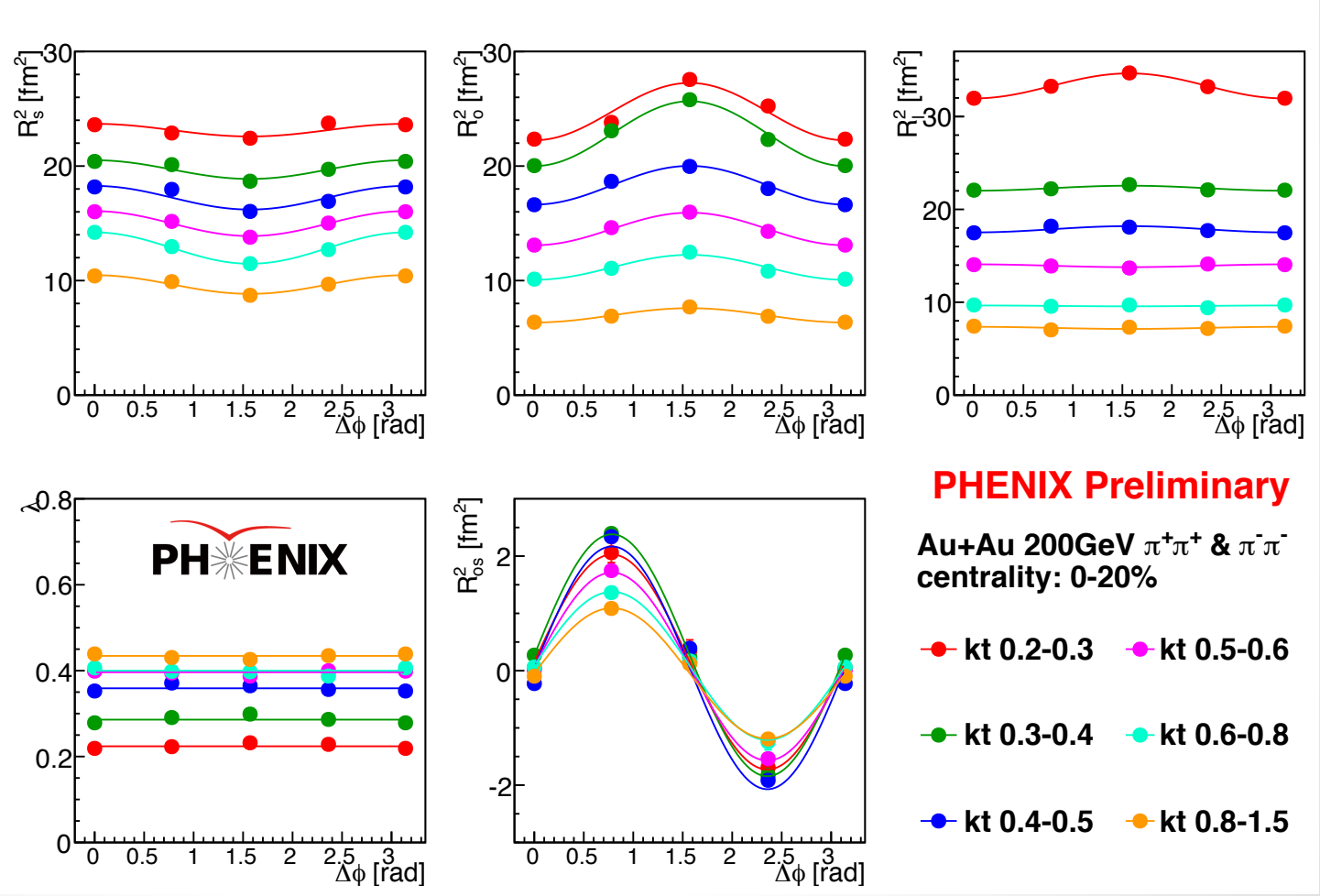
Same trends are seen in each centrality bins

"v_2 at high p_T" vs centrality



Scaling starts breaking at 10-20%

m_T dependence of azimuthal pion HBT radii in 0-20%



What is HBT ?

- Quantum interference between identical two particles
- Powerful tool to explore space-time evolution in HI collisions
- HBT can measure the source size and shape at freeze-out, Not whole size But homogeneity region in expanding source

$$C_2 = \frac{P(\vec{p}_1, \vec{p}_2)}{P(\vec{p}_1) \cdot P(\vec{p}_2)}$$

$P(p_1)$: Probability of detecting a particle
$P(p_1,p_2)$: Probability of detecting pair particles

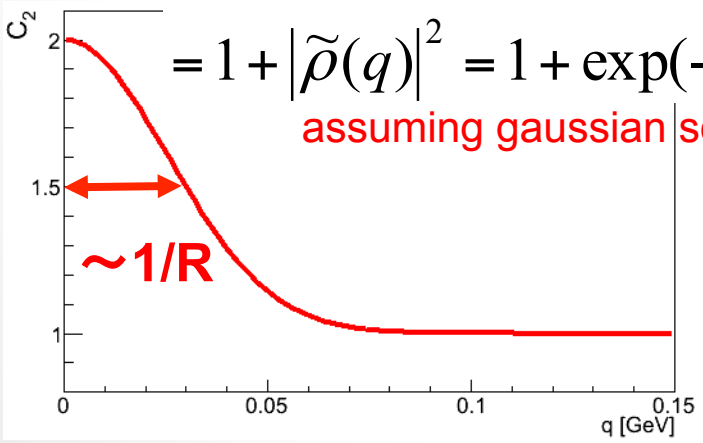
$$\vec{q} = \vec{p}_1 - \vec{p}_2$$

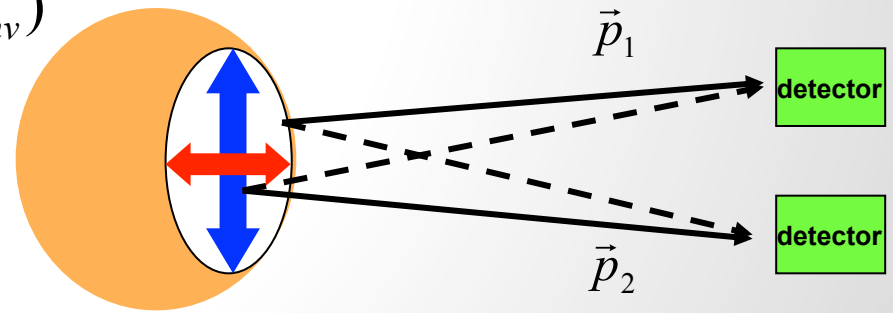
$$\vec{k}_T = \frac{\vec{p}_1 + \vec{p}_2}{2}$$

$$\vec{q}_{side} \perp \vec{k}_T, \quad \vec{q}_{out} // \vec{k}_T$$

$$= 1 + \left|\tilde{\rho}(q)\right|^2 = 1 + \exp(-R_{inv}^2 q_{inv}^2)$$

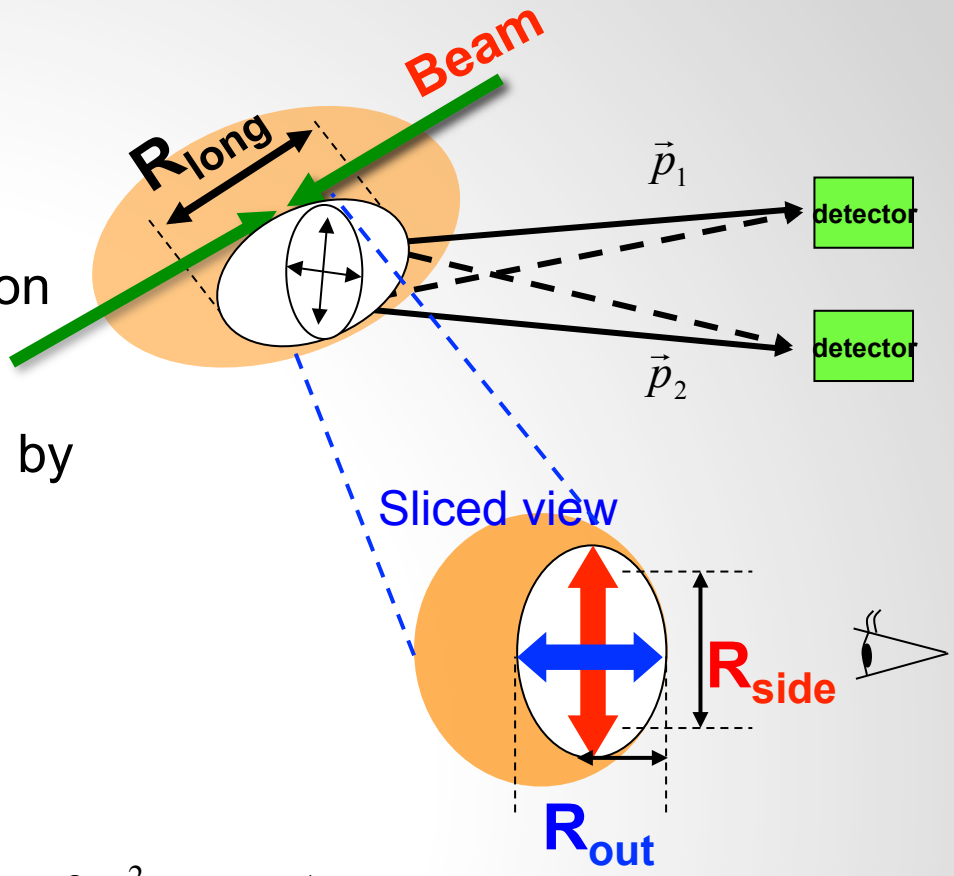
assuming gaussian source





3D HBT radii

- **"Out-Side-Long" system**
  - ✧ Bertsch-Pratt parameterization
- **Core-halo model**
  - ✧ Particles in core are affected by coulomb interaction



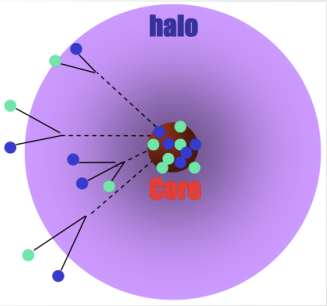
$$C_2 = C_2^{core} + C_2^{halo}$$

$$= [\lambda(1+G)F] + [1-\lambda]$$

$$G = \exp(-R_{inv}^2 q_{inv}^2)$$

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

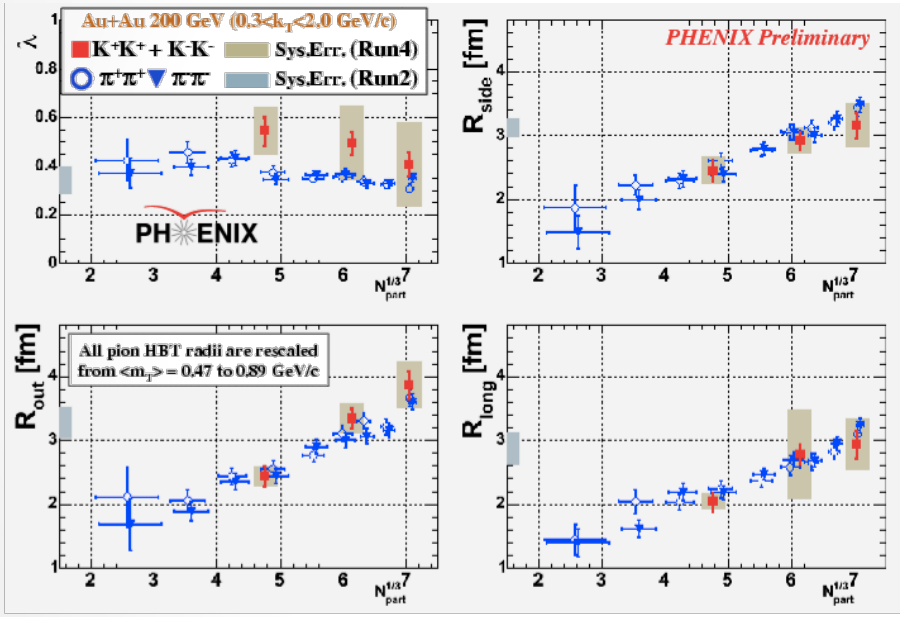
R_{long}: Longtudinal size
R_{side}: Transverse size
R_{out}: Transverse size + emission duration
R_{os}: Cross term between Out and Side



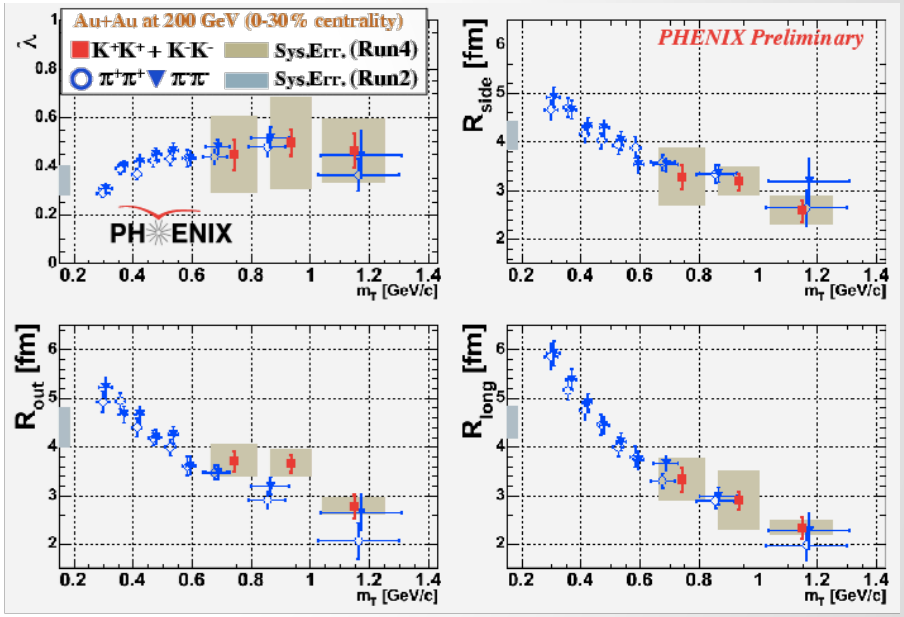
The past HBT Results for charged pions and kaons

- **Centrality / m_T dependence have been measured for pions and kaons**
  - ✧ No significant difference between both species

centrality dependence



m_T dependence



Analysis method for HBT

- **Correlation function**

$$C_2 = \frac{R(q)}{M(q)}$$

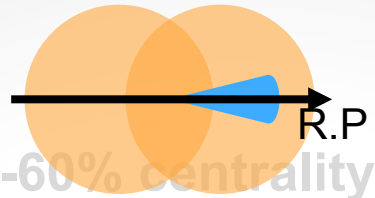
  - ✧ Ratio of real and mixed q-distribution of pairs
    q: relative momentum

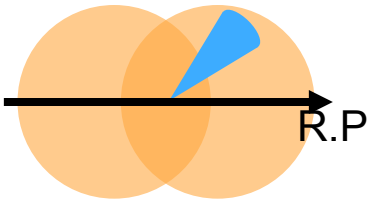
- **Correction of event plane resolution**
  - ✧ U.Heinz et al, PRC66, 044903 (2002)
- **Coulomb correction and Fitting**
  - ✧ By Sinyukov's fit function
  - ✧ Including the effect of long lived resonance decay

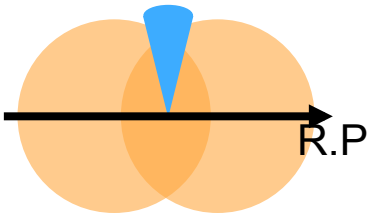
$$C_2 = C_2^{core} + C_2^{halo}$$
$$= [\lambda(1+G)F] + [1-\lambda]$$
$$G = \exp(-R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2 - R_{long}^2 q_{long}^2 - 2R_{os}^2 q_{side} q_{out})$$

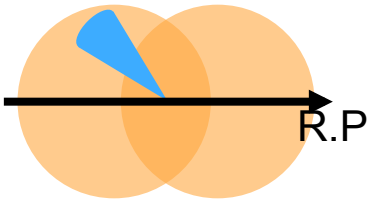
Correlation function

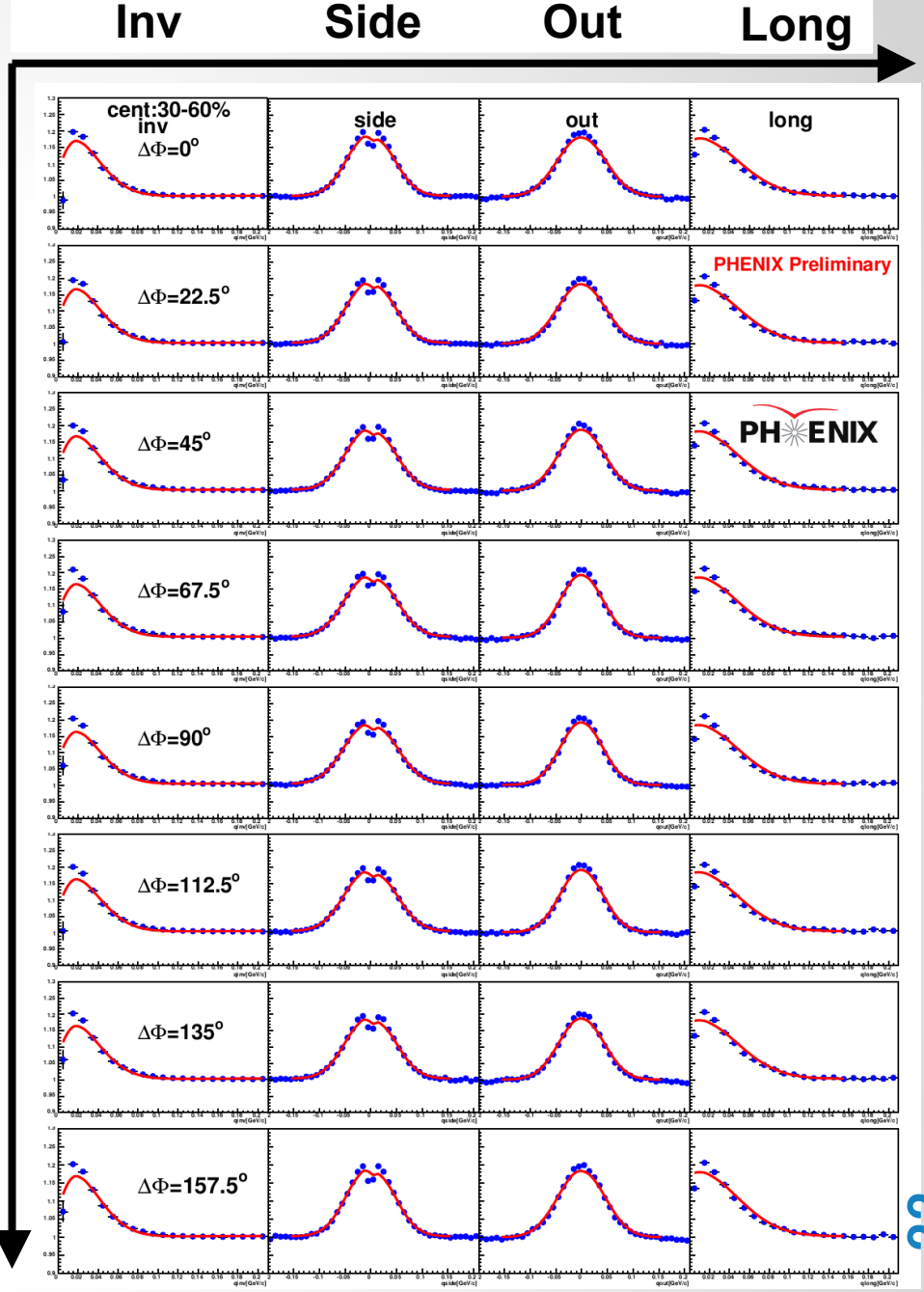
- Raw C_2 for 30-60% centrality
- Solid lines is fit functions





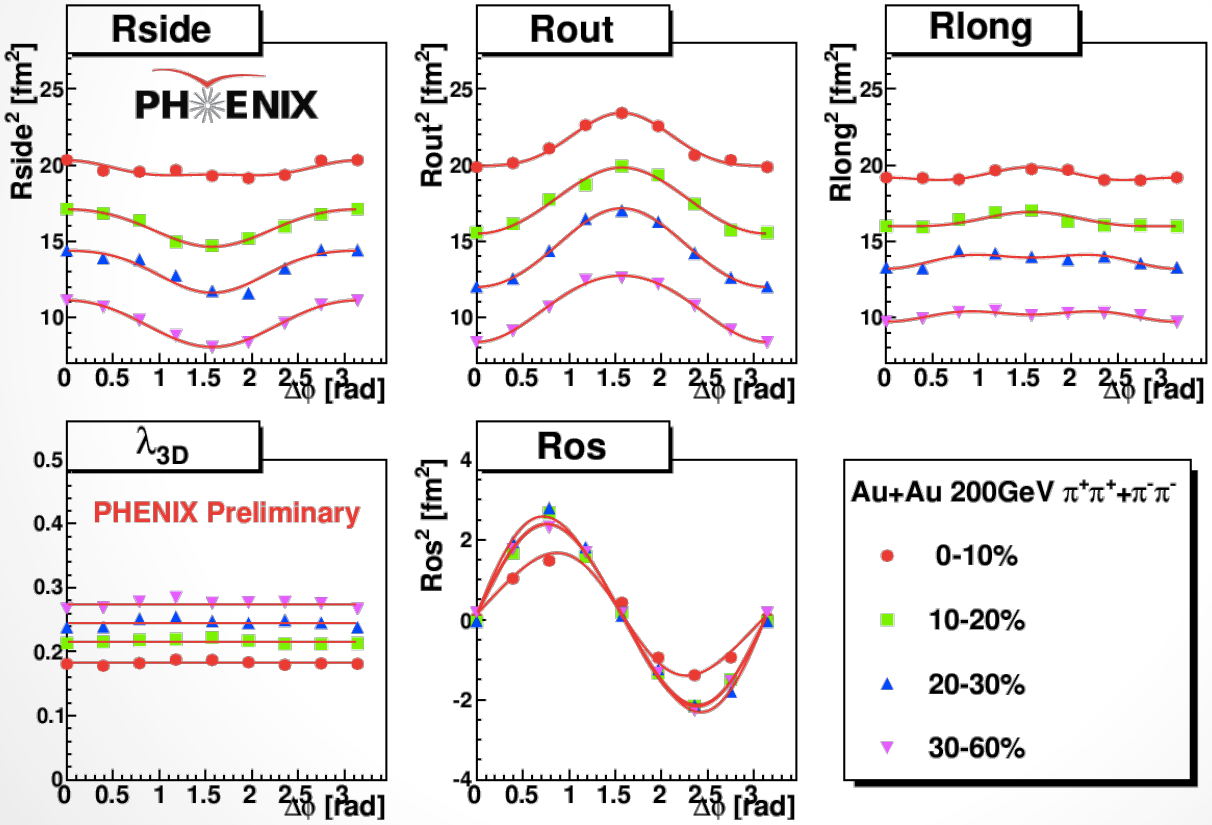


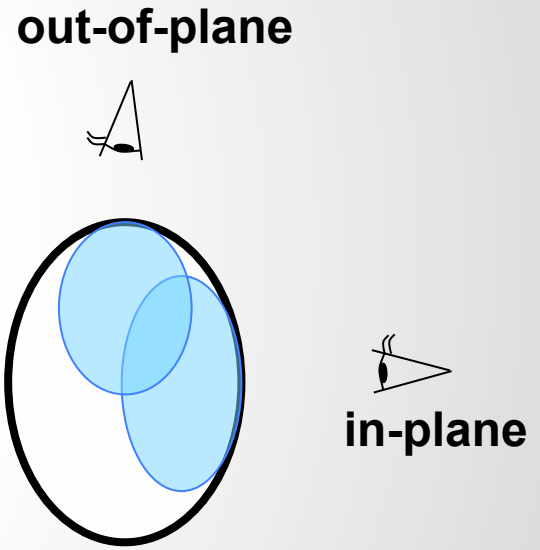




Azimuthal HBT radii for pions

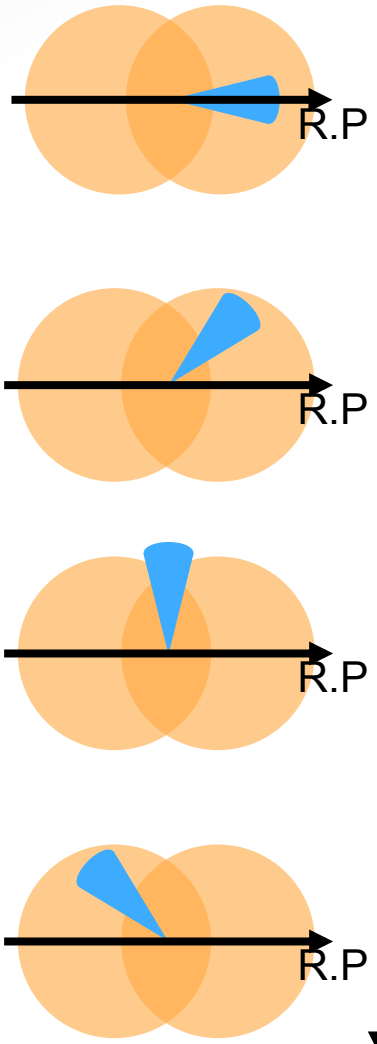
- **Observed oscillation for R_{side}, R_{out}, R_{os}**
- **Rout in 0-10% has oscillation**
  - ✧ Different emission duration between in-plane and out-of-plane?

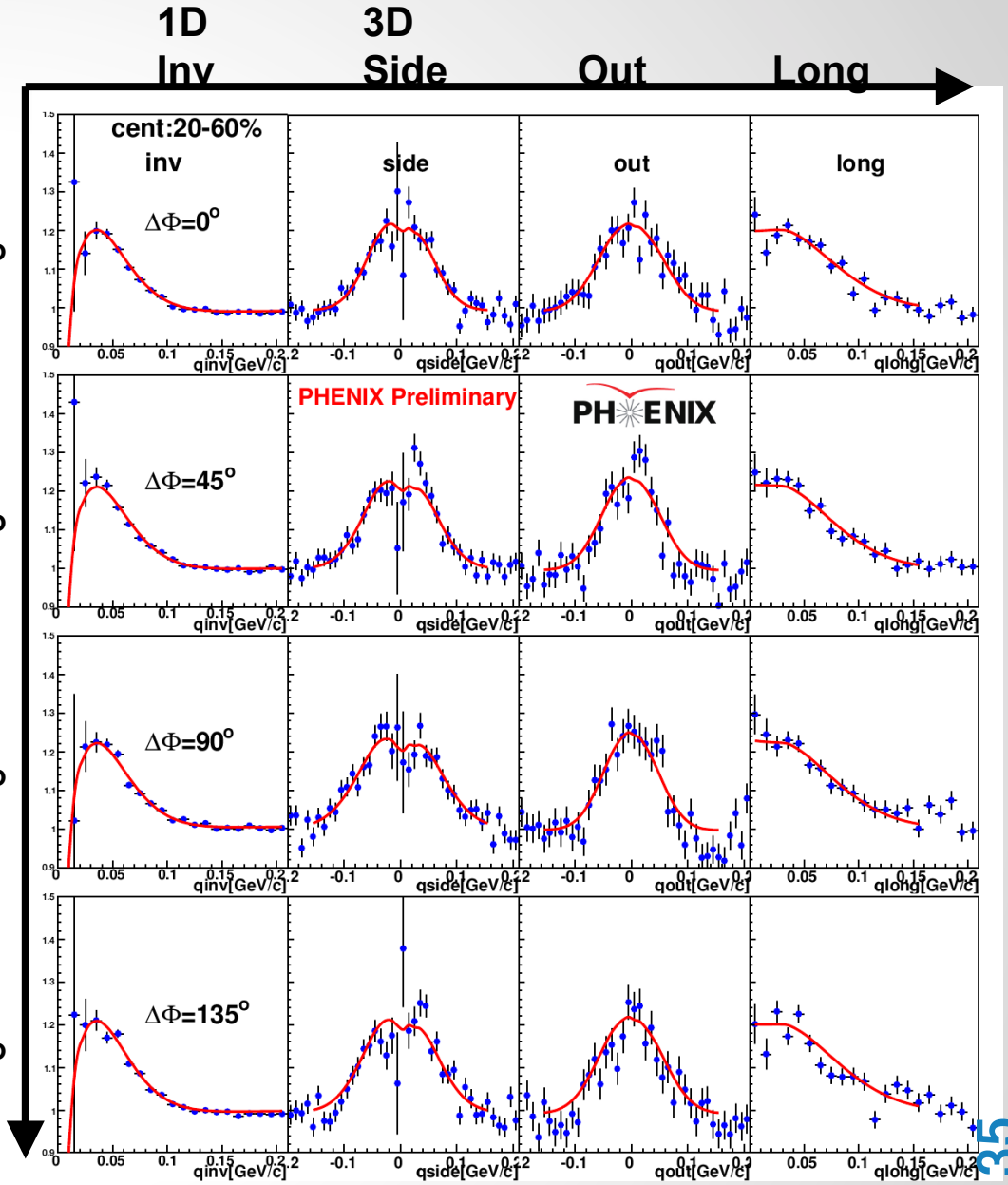


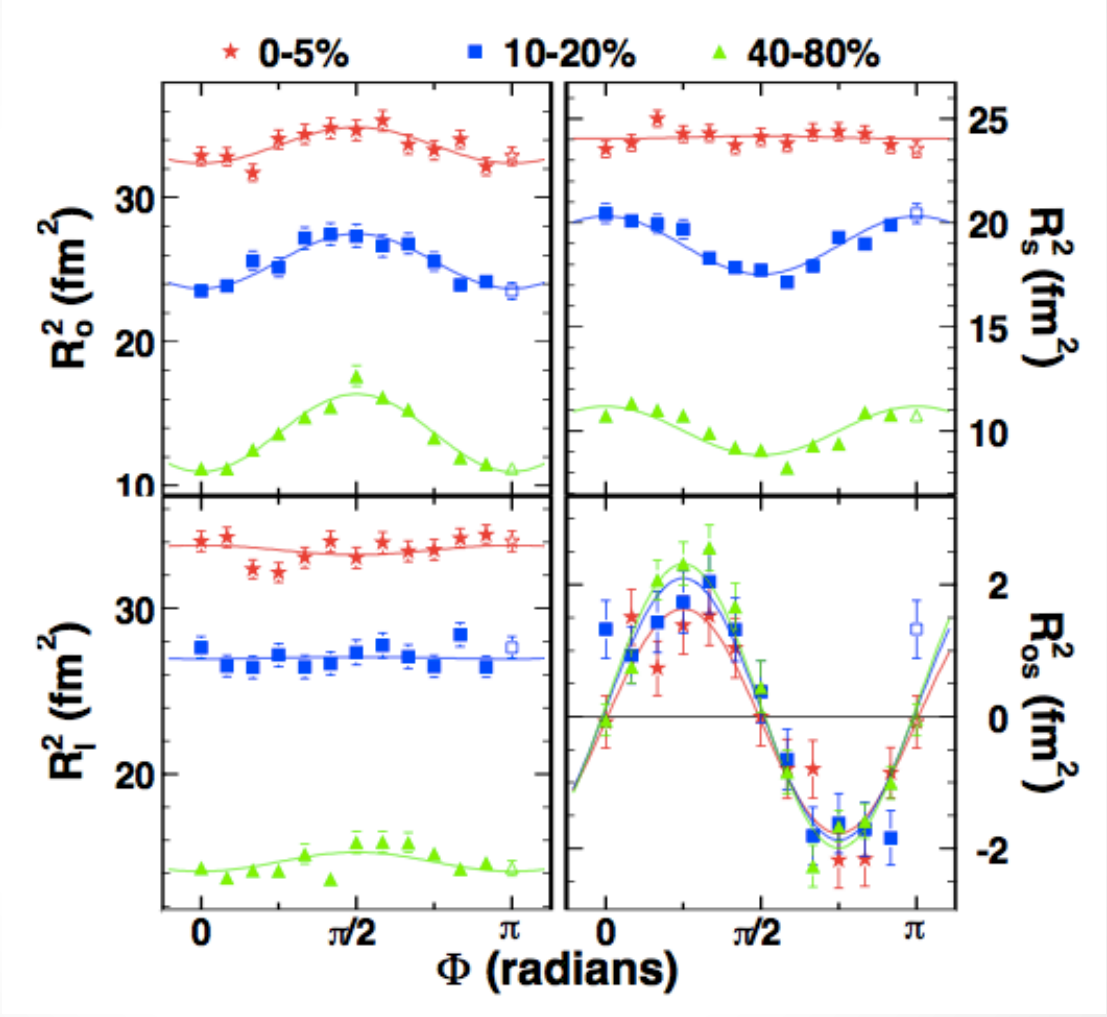


Correlation function for charged kaons

- Raw C_2 for 20-60%





STAR Result (w.r.t psi2)

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