# Global and Collective Dynamics at PHENIX

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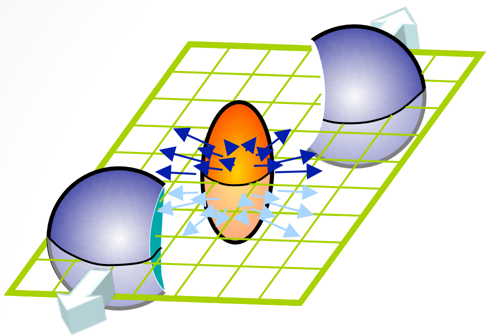
“Heavy Ion collisions in the LHC era” in Quy Nhon

# outline

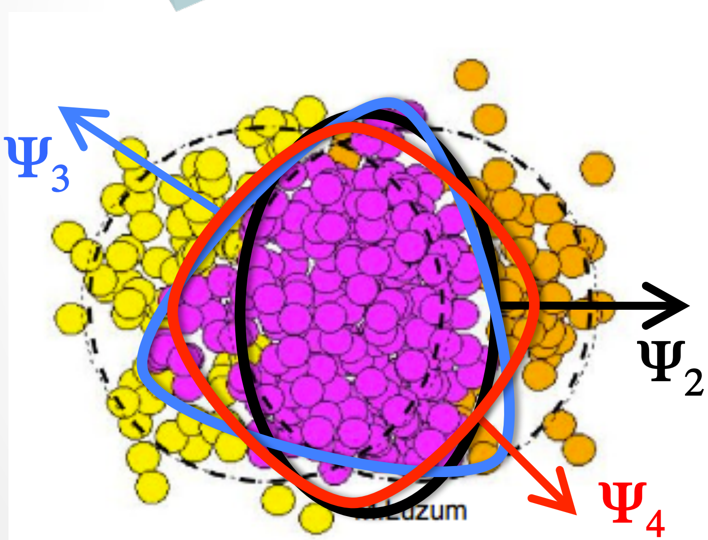
- Introduction of $v_n$
- Higher harmonic flow ($v_n$) of Identified particle
- 2 particle correlations with $v_n$
- Azimuthal HBT w.r.t event plane
- Summary

# Higher harmonic event plane

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



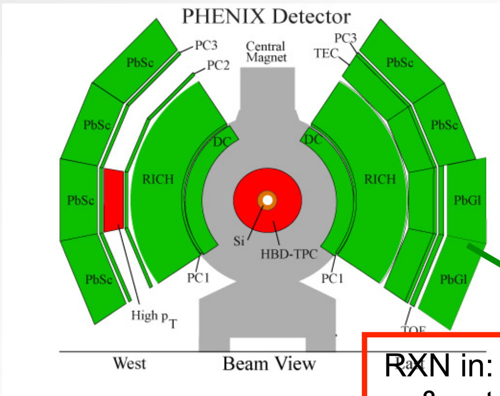
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2)$$
$$+2v_3 \cos 2(\phi - \Psi_3)$$
$$+2v_4 \cos 2(\phi - \Psi_4)$$

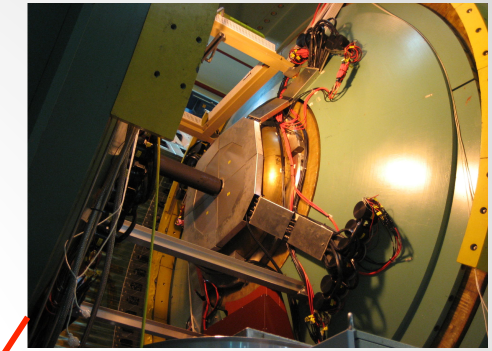


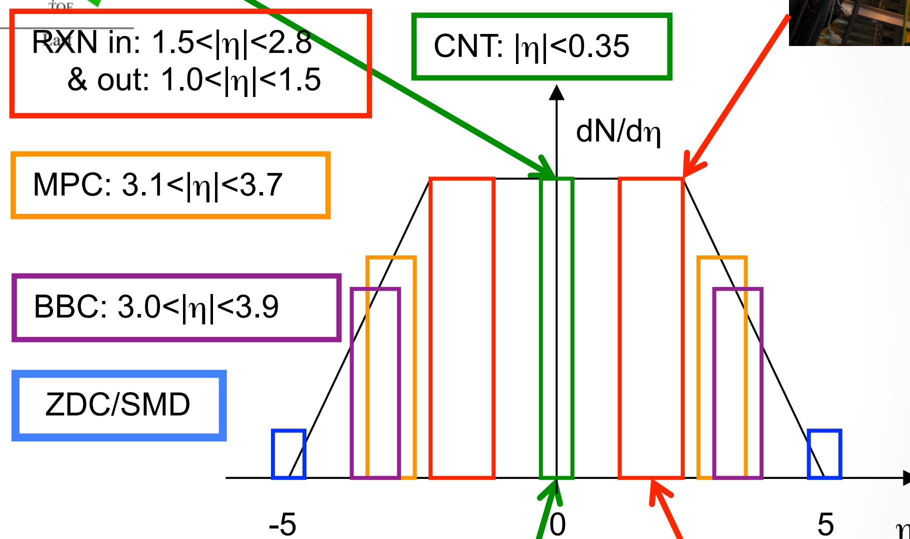

$$v_n = \langle \cos n(\phi - \Psi_n) \rangle$$

$\Psi_n$ : Higher harmonic event plane
$\varphi$ : Azimuthal angle of emitted particles

# $v_n$ measurement via Event plane method





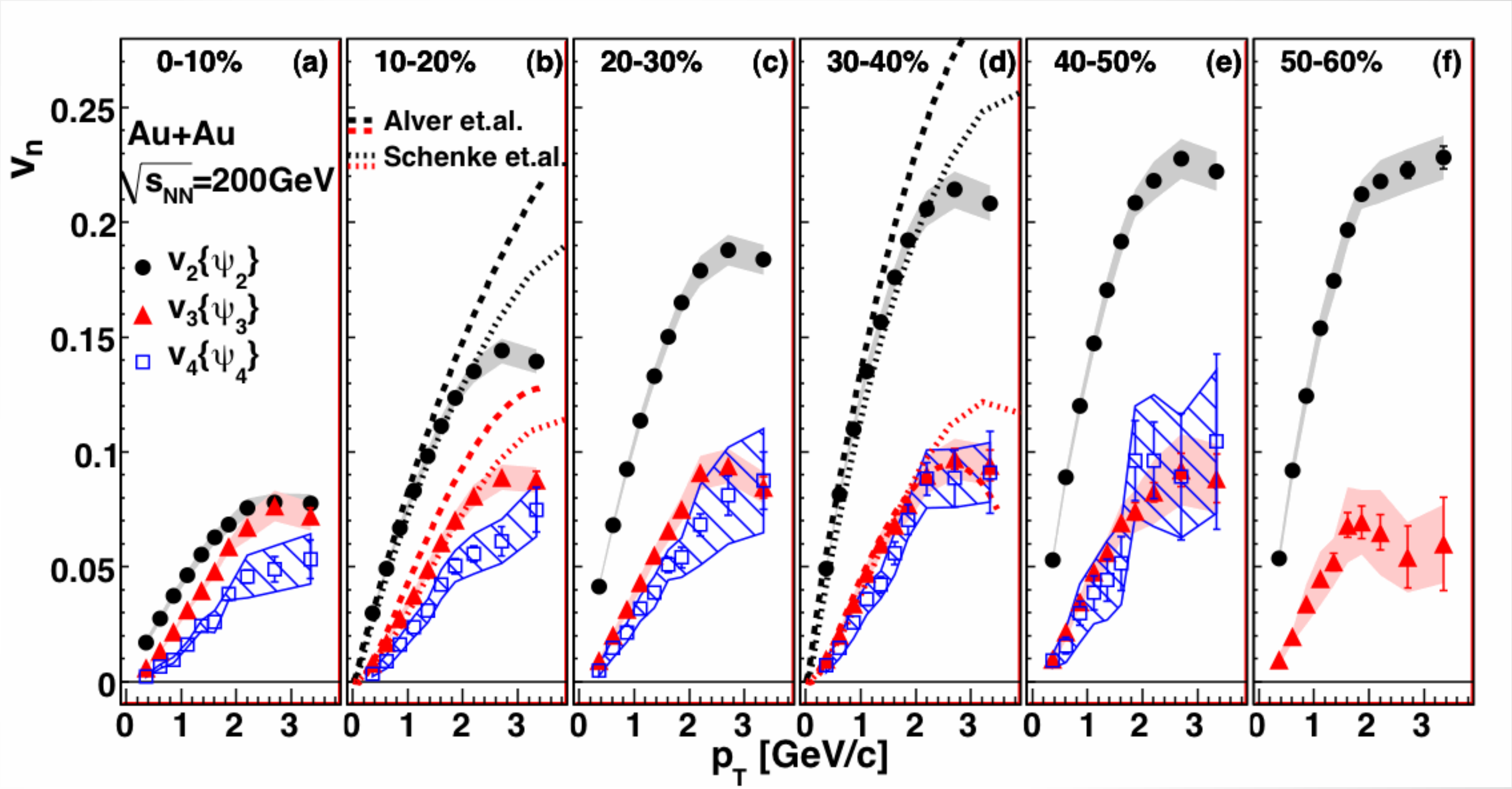

$$v_n = \langle \cos n(\phi - \Psi_n) \rangle$$

$\Psi_n$ : Determined by forward detector RXN

$\varphi$ : Measured at mid-rapidity

# Charged hadron $v_n$ at PHENIX

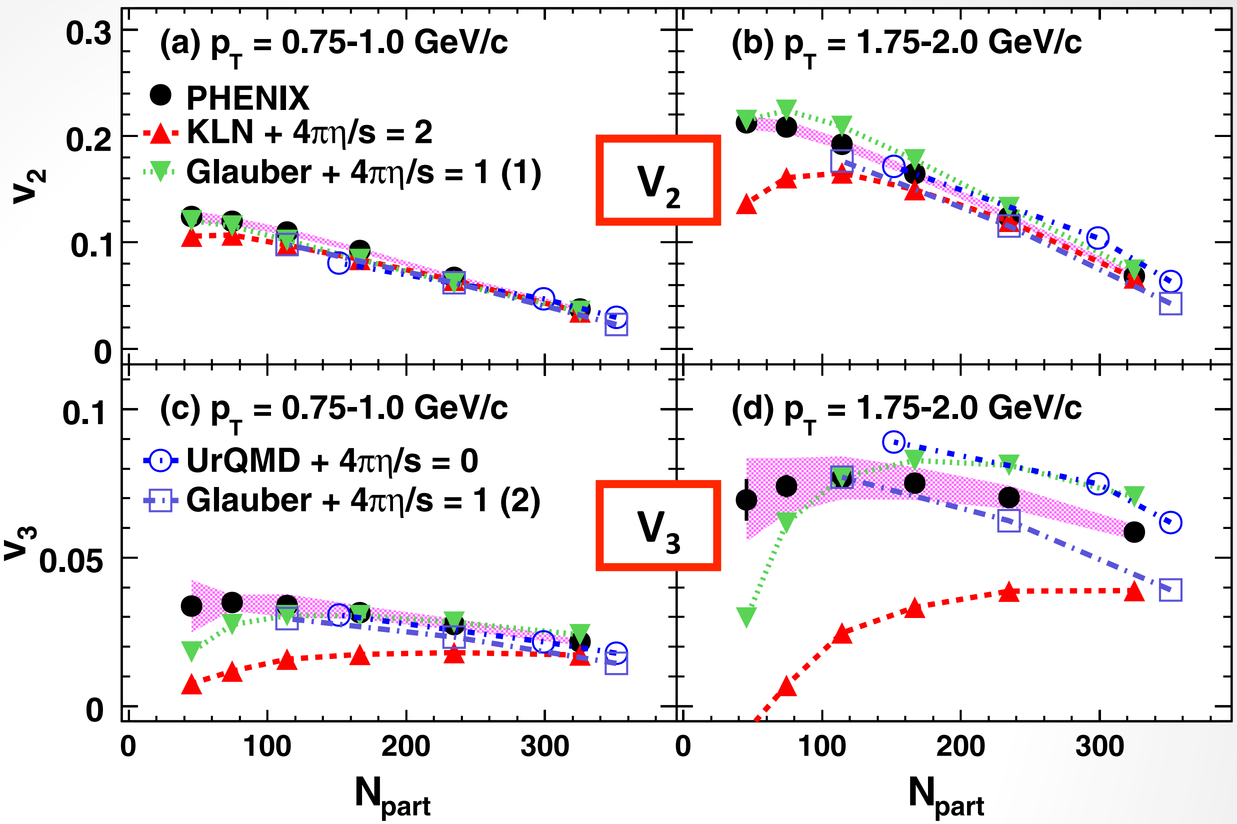
*PRL.107.252301*




- $v_2$ 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

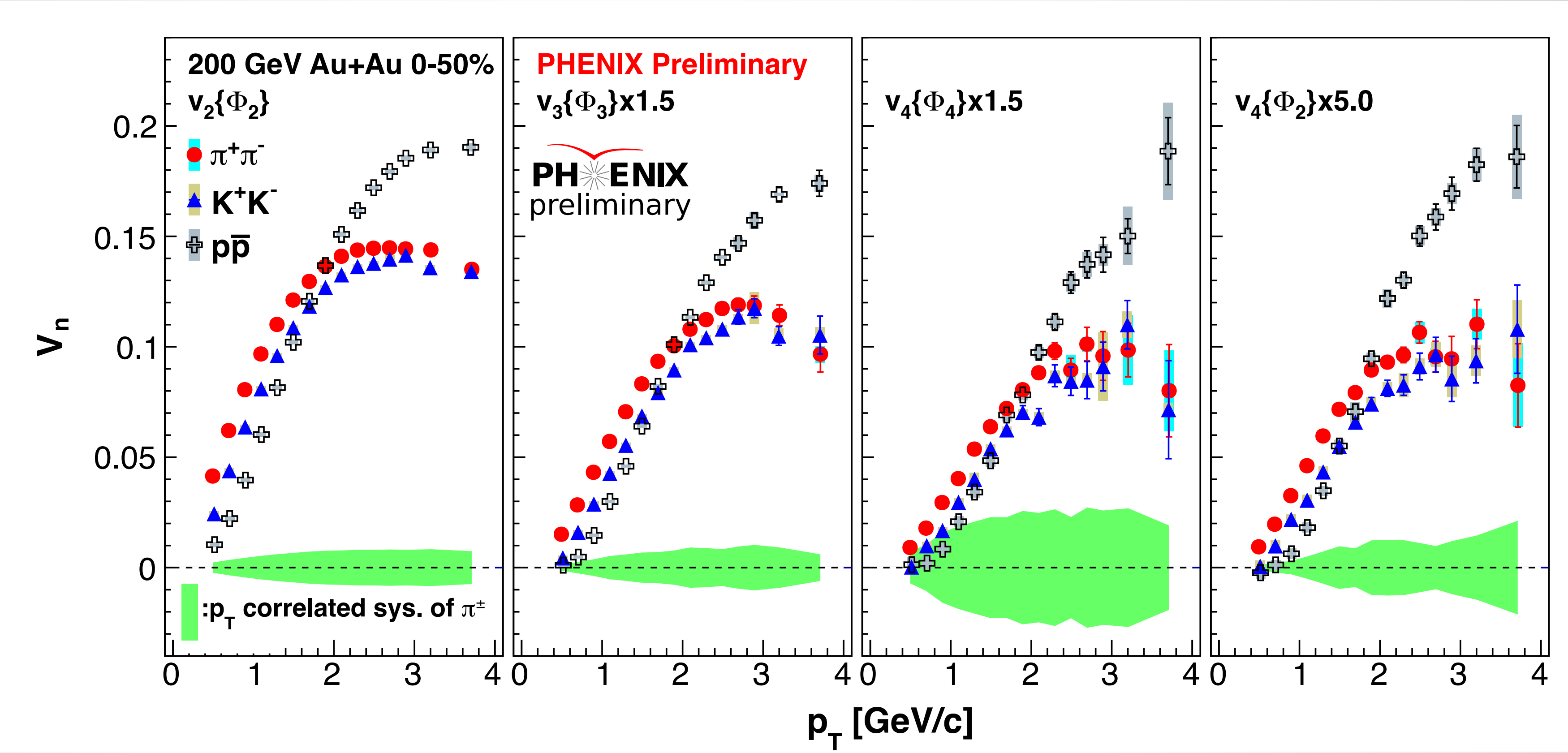
# Recent Results at PHENIX

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

# Motivation of PID $v_n$

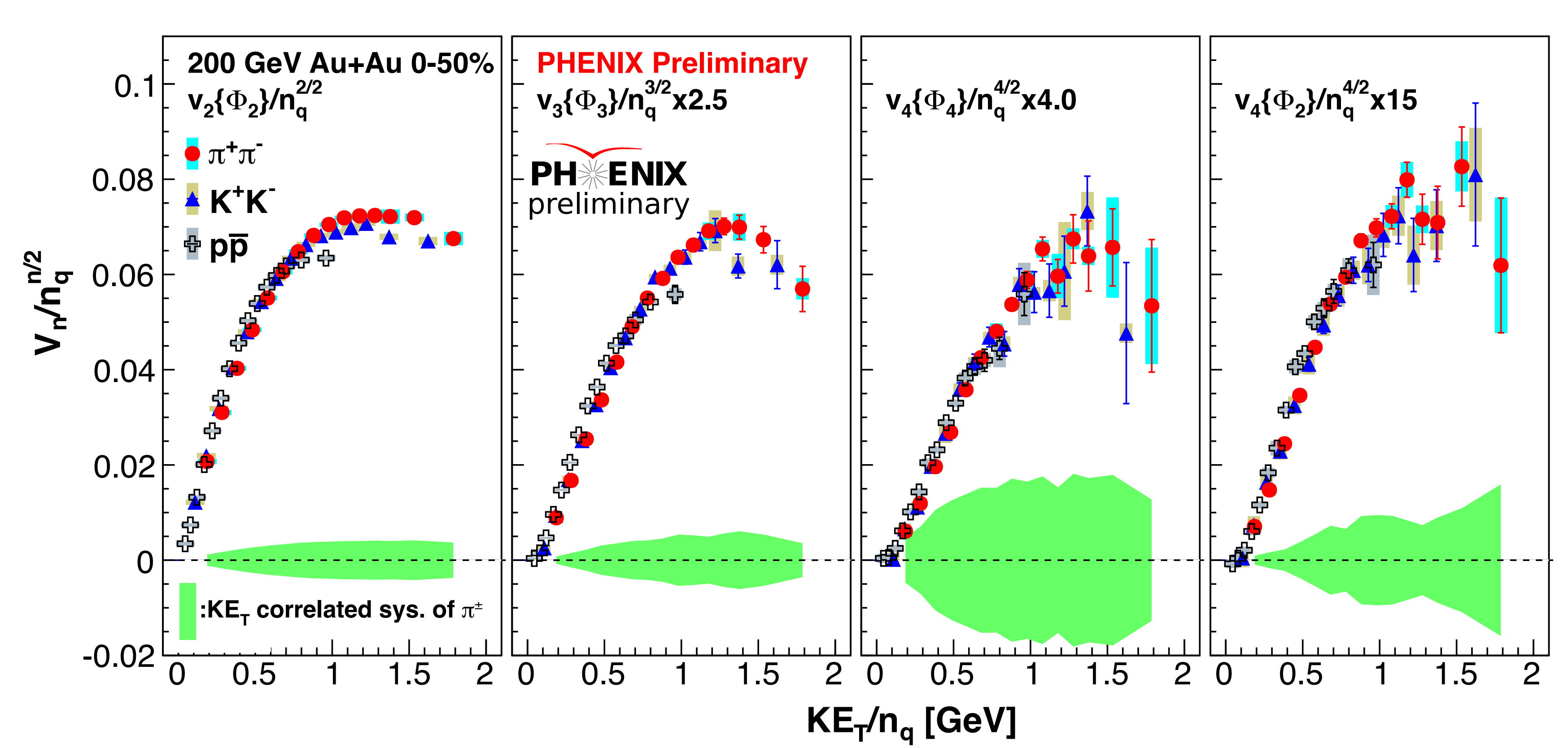
- $v_n$ is sensitive probe to the QGP bulk property
- Important to check the following features seen in $v_2$
  - ✧Mass splitting at low $p_T$
  - ✧Baryon/Meson difference at mid $p_T$
  - ✧How is the scaling property of $v_n$ ?

# $v_n$ 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 $v_n$ : $v_n(KE_T/n_q)/n_q^{n/2}$

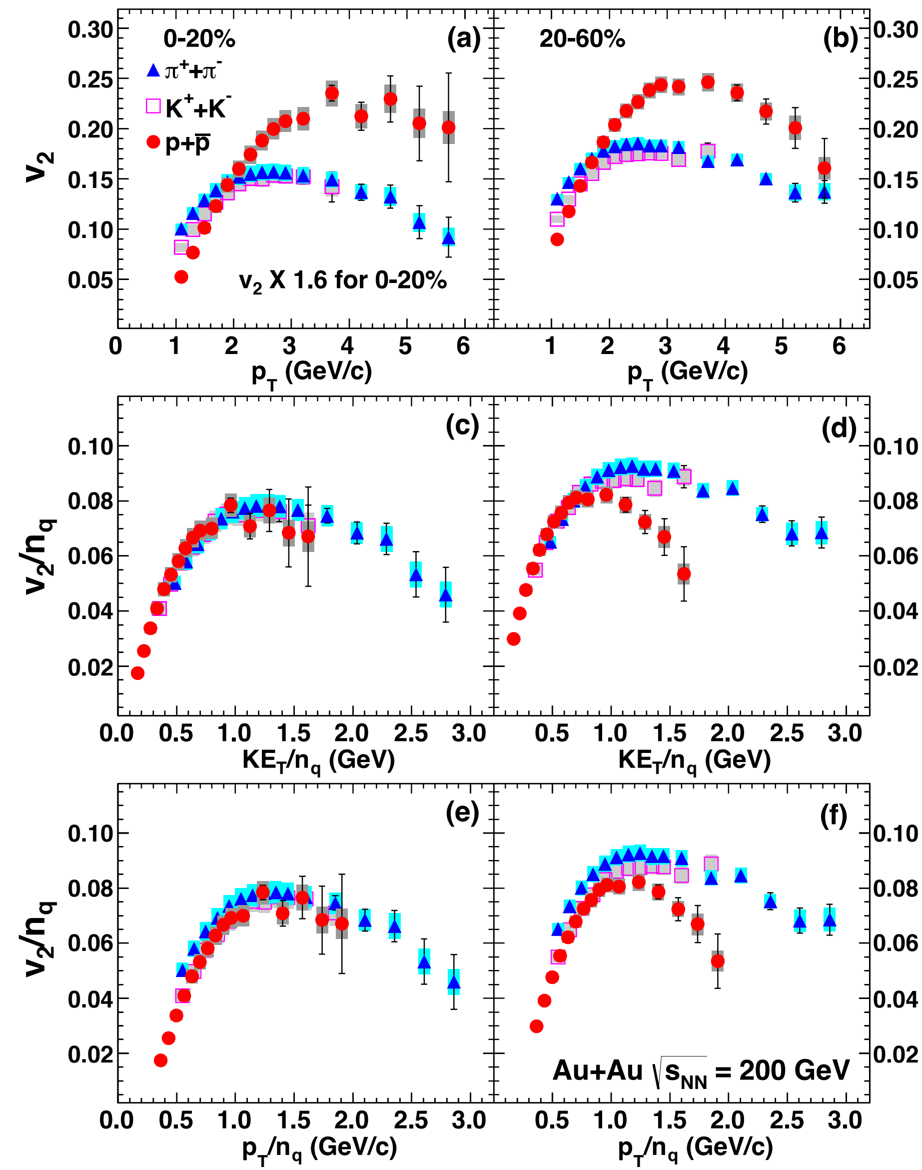
# PID $v_2$ at high $p_T$

*PRC.85.064914(2012)*

- Extend PID to high $p_T$ 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

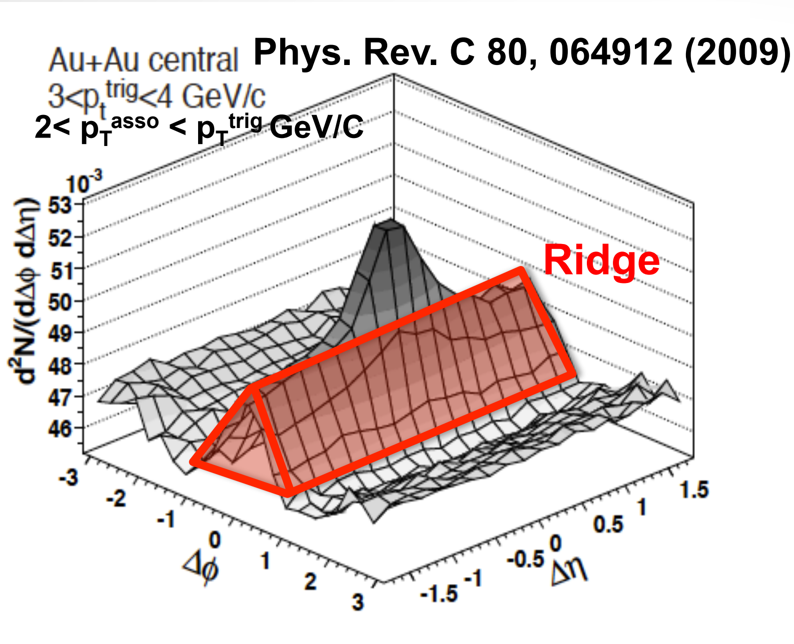
0-20%   20-60%

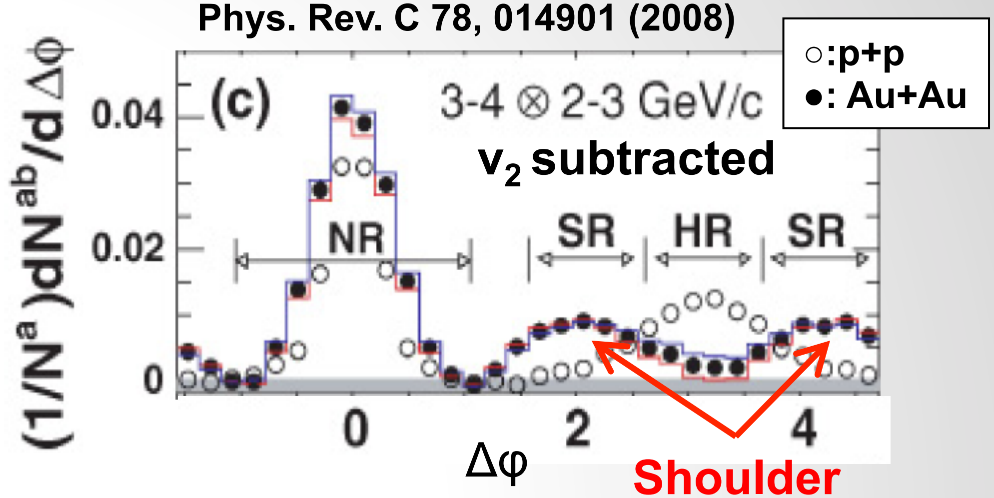


# Recent Results at PHENIX

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

# Motivation of 2 particle correlations with $v_n$



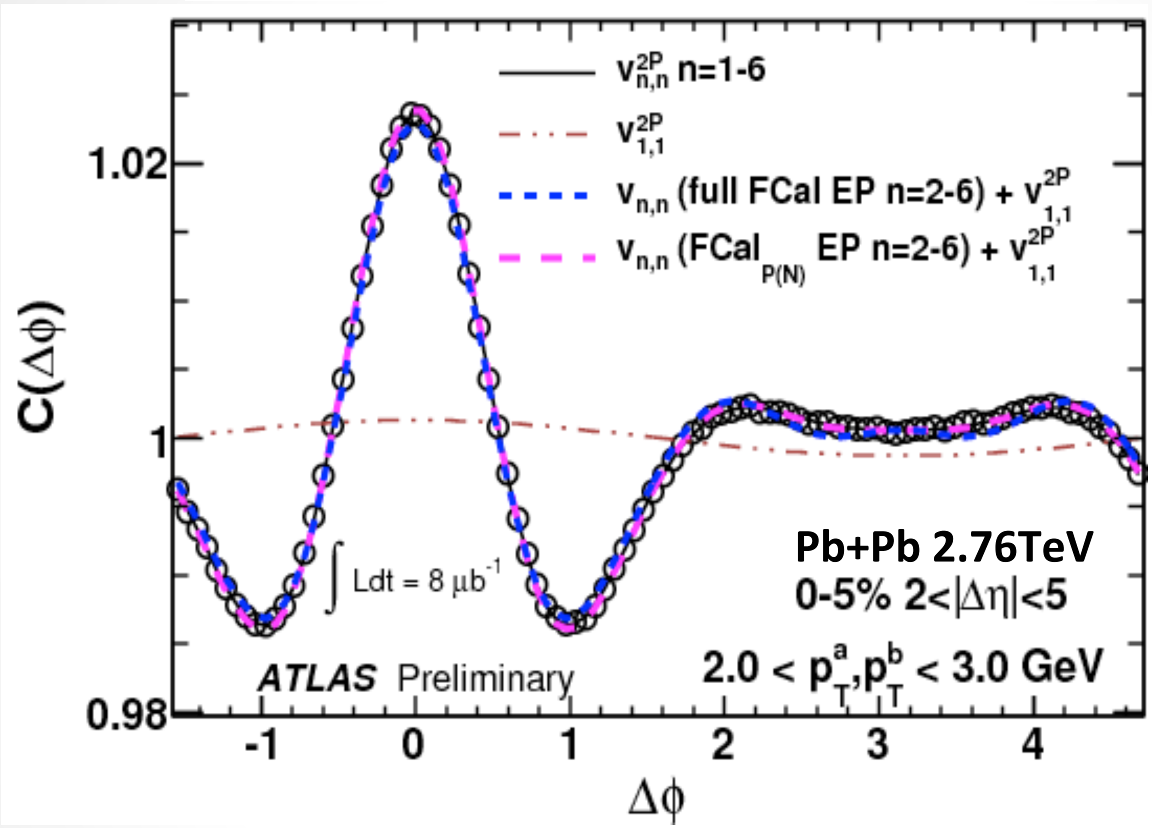

$$Jet(\Delta\phi) = CF(\Delta\phi) - b_0 Flow(\Delta\phi)$$

- **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**

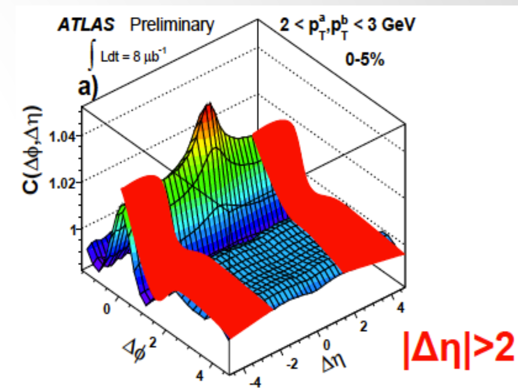
# 2 particle correlations with |Δη| gap

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

From 2PC method — From EP method

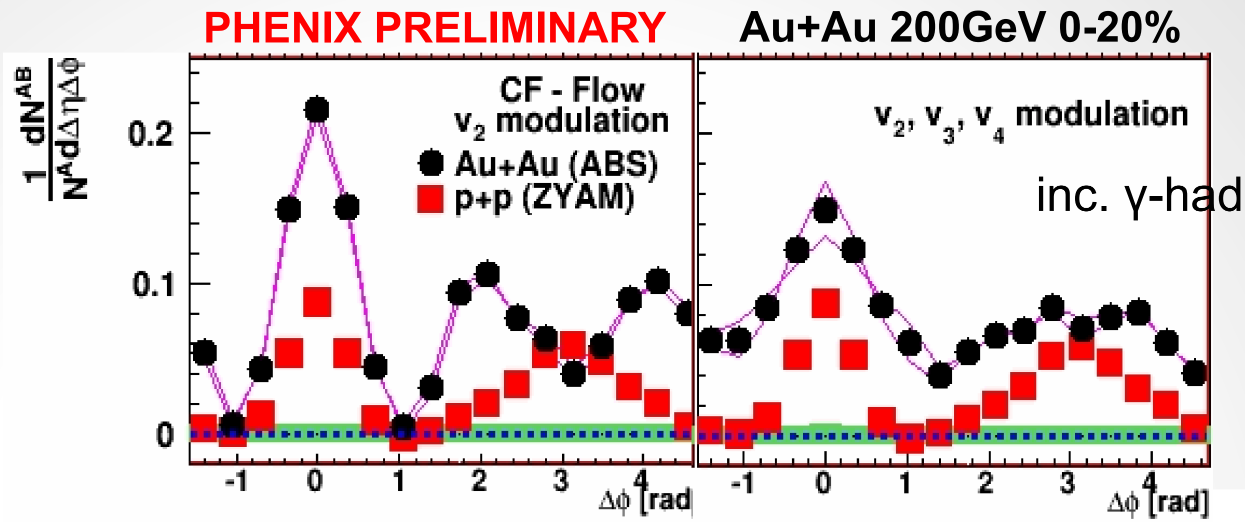


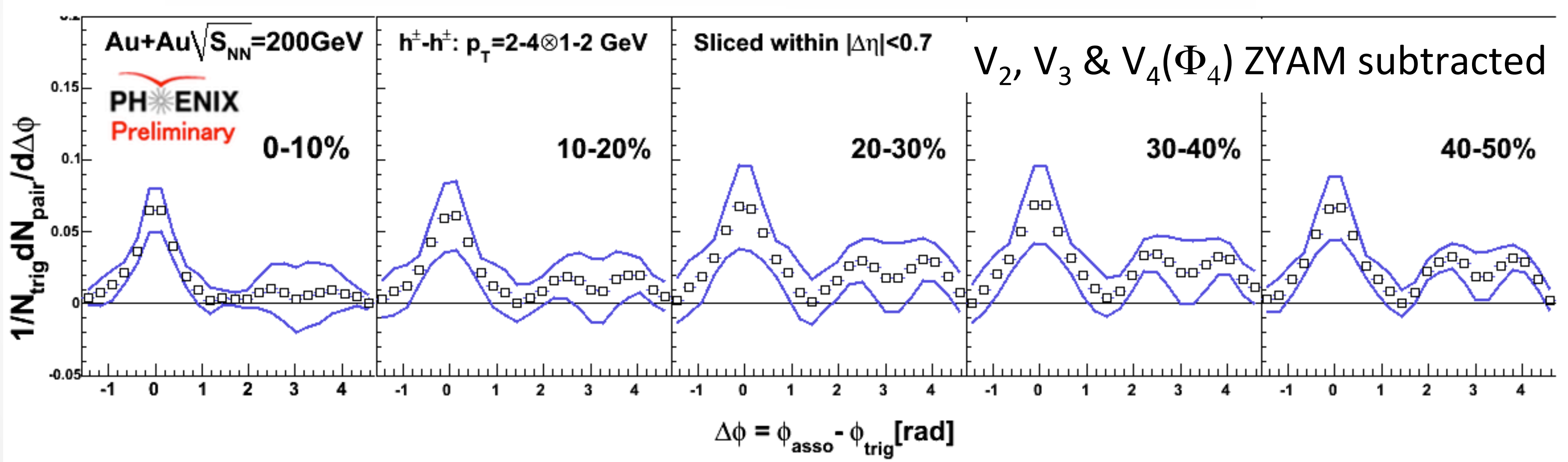

QM'11 J. Jia ATLAS Flow Plenary




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

# 2 particle correlations without |Δη| gap



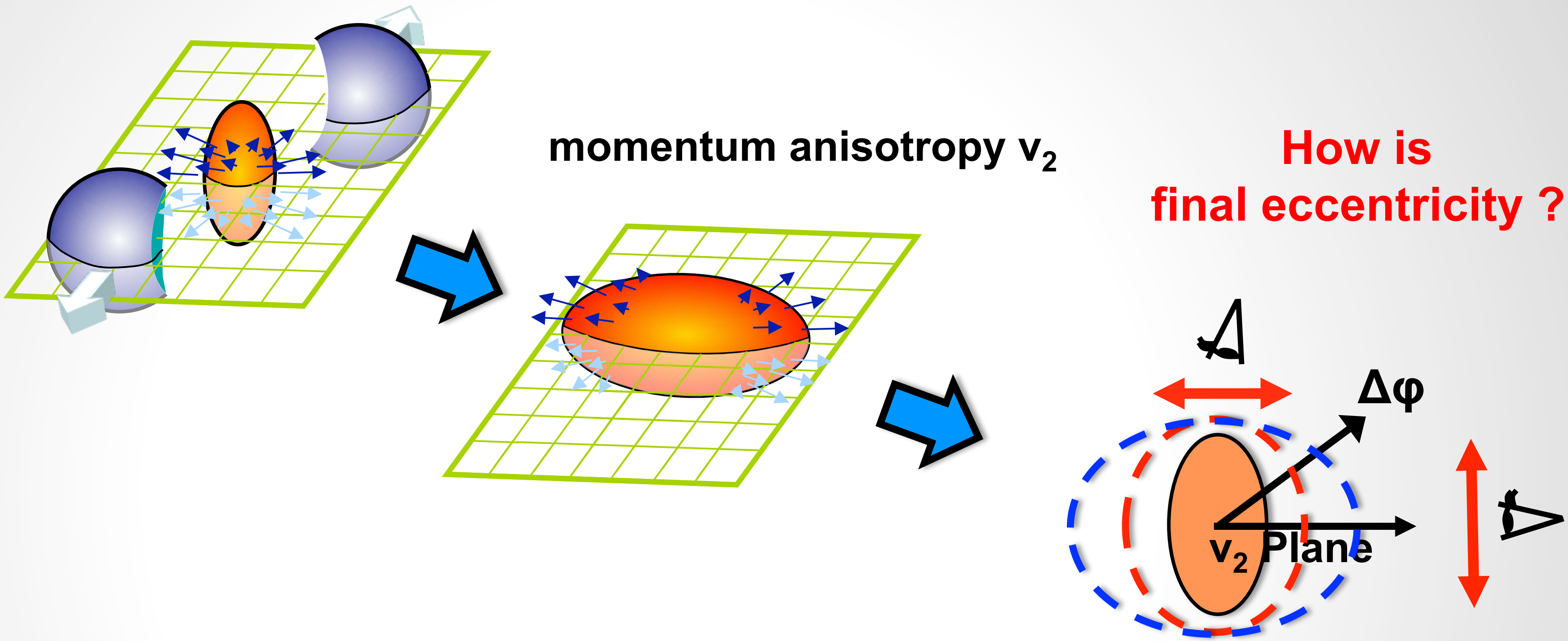

- Most-central : Away side yield are suppressed
- Mid-central : Away side yield still remain

# 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

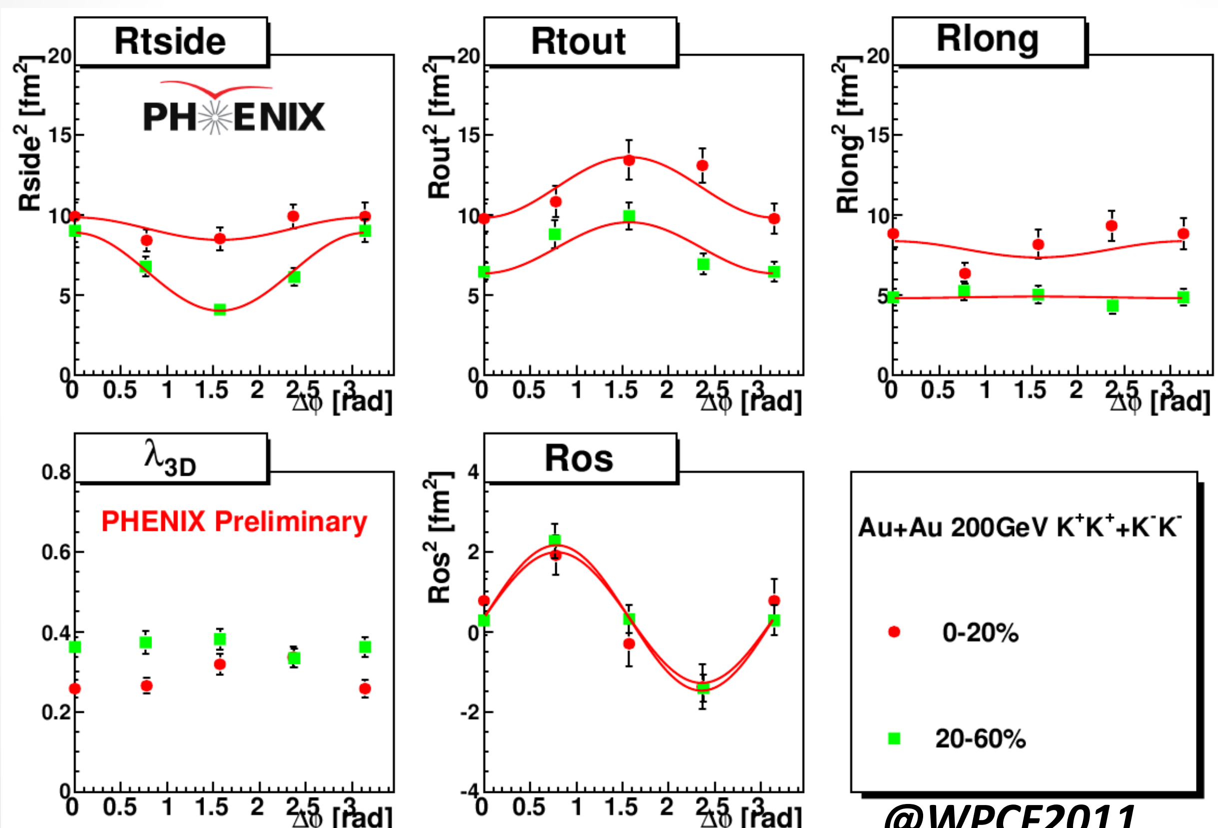
**Initial spatial anisotropy (eccentricity)**

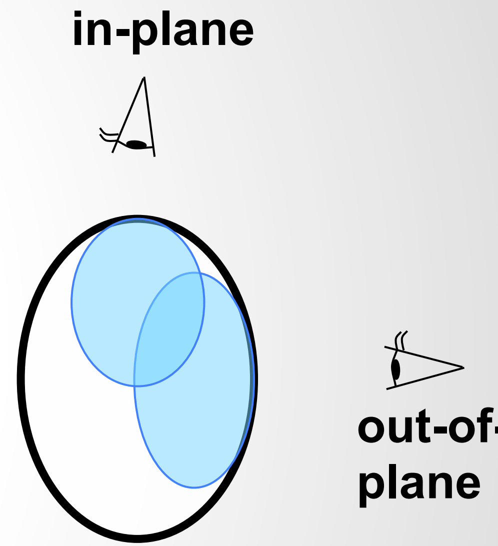



- **Final eccentricity can be measured by azimuthal HBT**
  - ✧It depends on Initial eccentricity, pressure gradient, expansion time, and velocity profile etc
  - ✧Good probe to investigate system evolution

# Azimuthal HBT radii for kaons

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



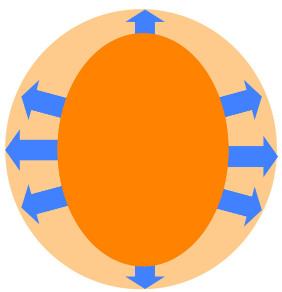



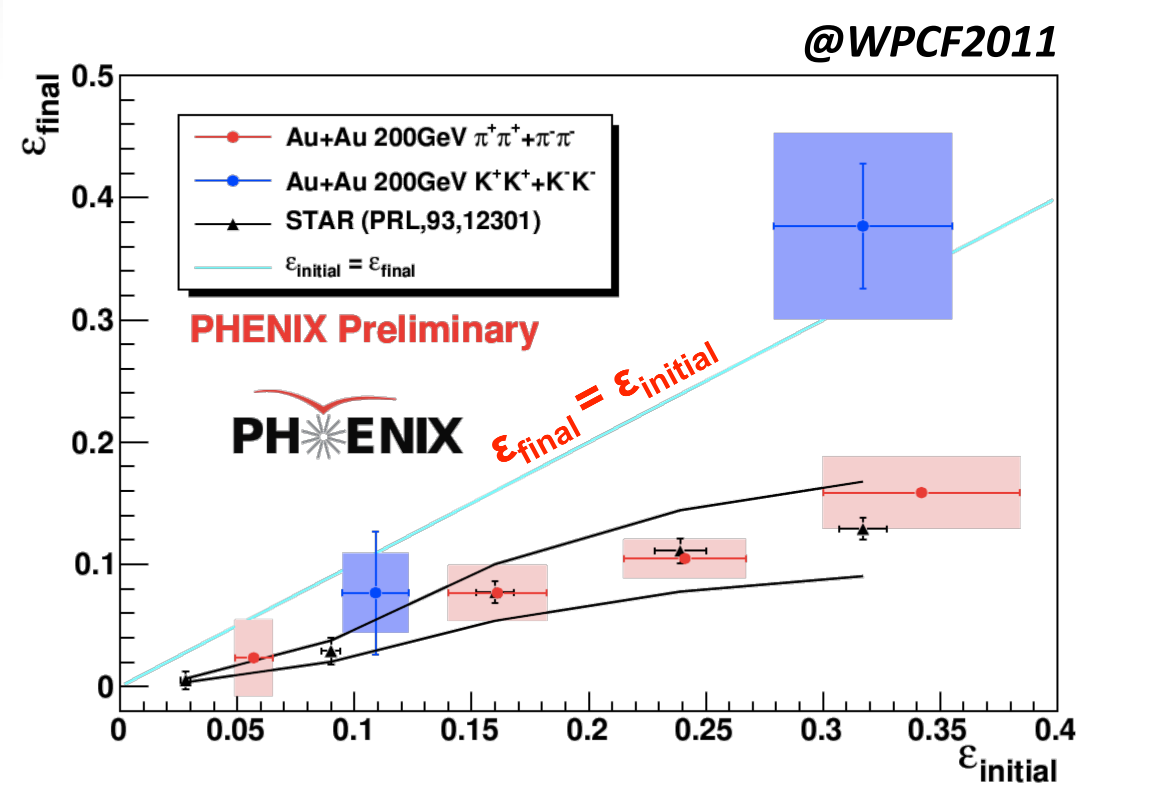
# Eccentricity at freeze-out

PRC70, 044907 (2004)

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

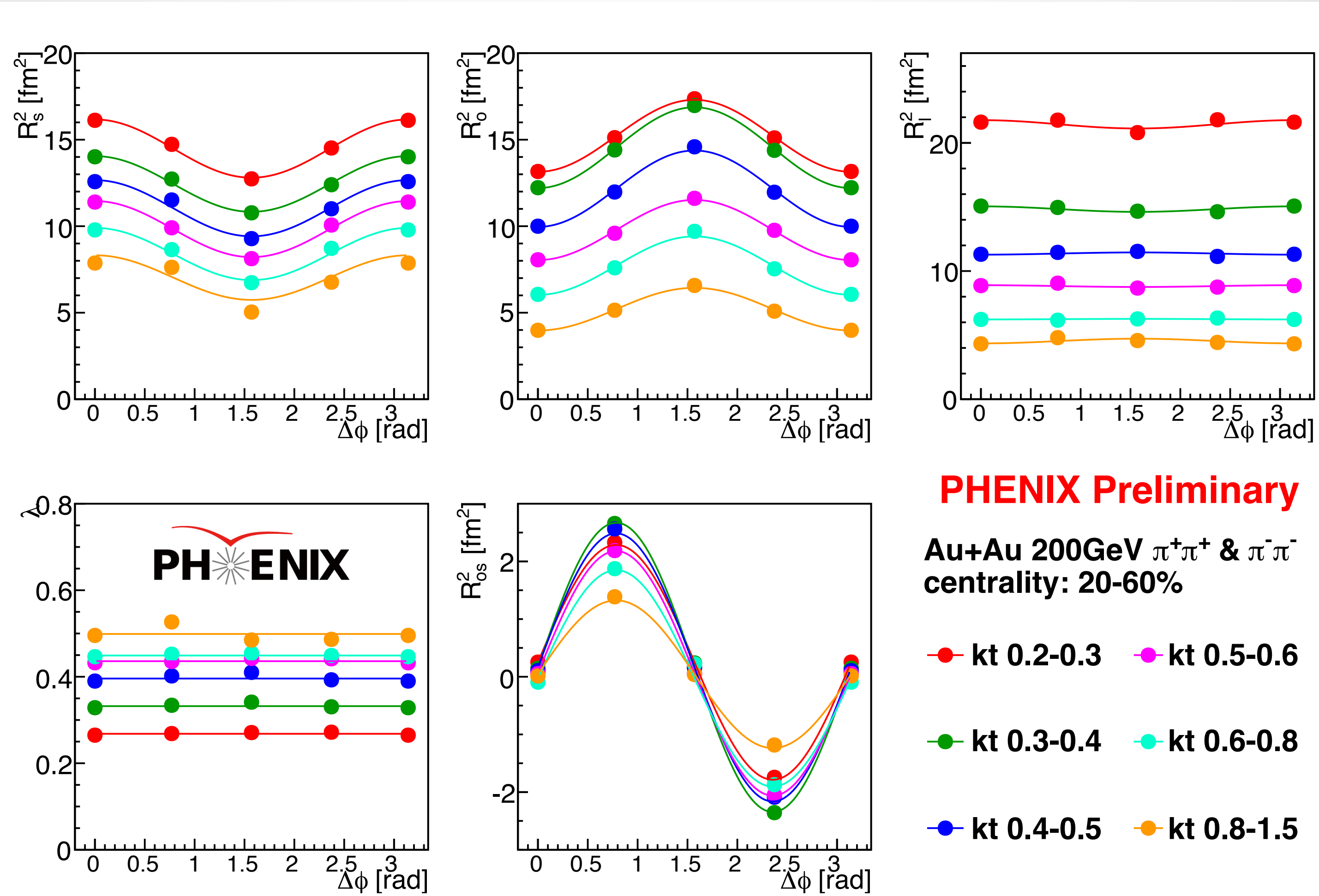
$$\varepsilon_{final} = 2\frac{R^2_{s,2}}{R^2_{s,0}}$$

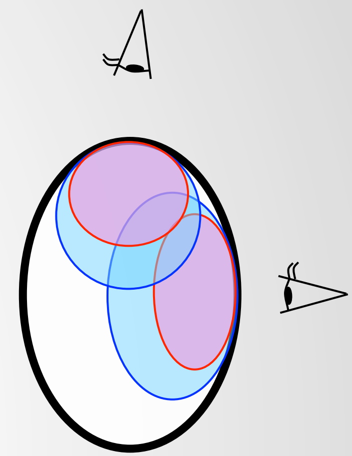





- **$\varepsilon_{final} \approx \varepsilon_{initial}/2$ for pion**
  - ✧ Indicates that source expands to in-plane direction, and still elliptical
  - ✧ PHENIX and STAR results are consistent
- **$\varepsilon_{final} \approx \varepsilon_{initial}$ for kaon**
  - ✧ Freeze-out time is faster than that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

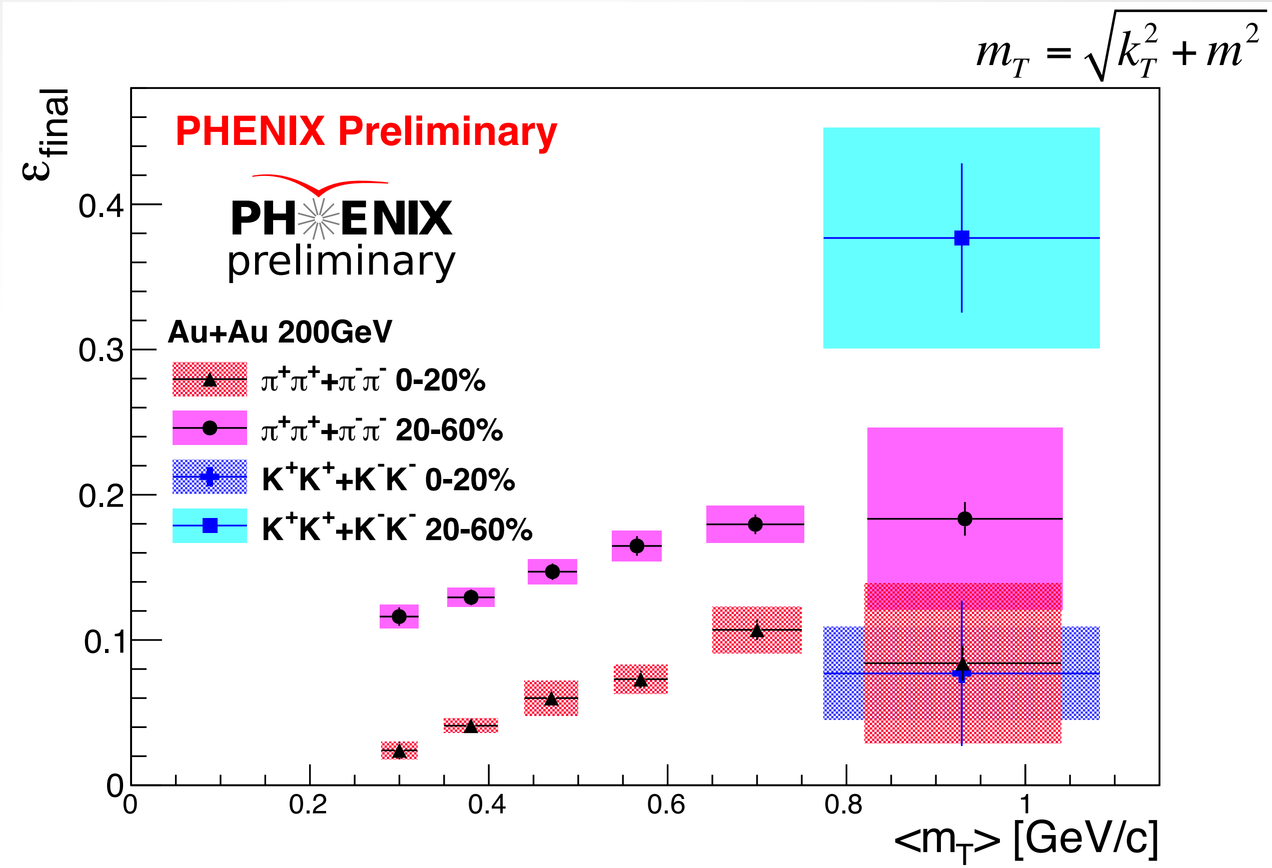
# $k_T$ dependence of azimuthal pion HBT radii



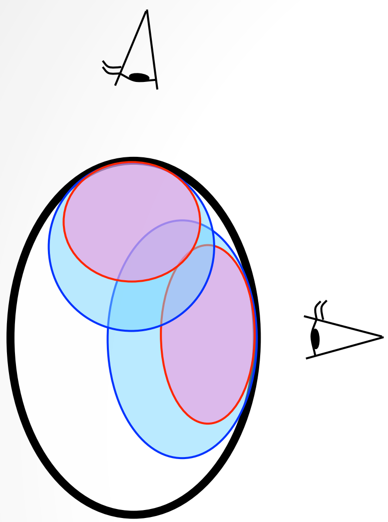
- Oscillation can be seen in $R_s$, $R_o$, and $R_{os}$ for each kT regions

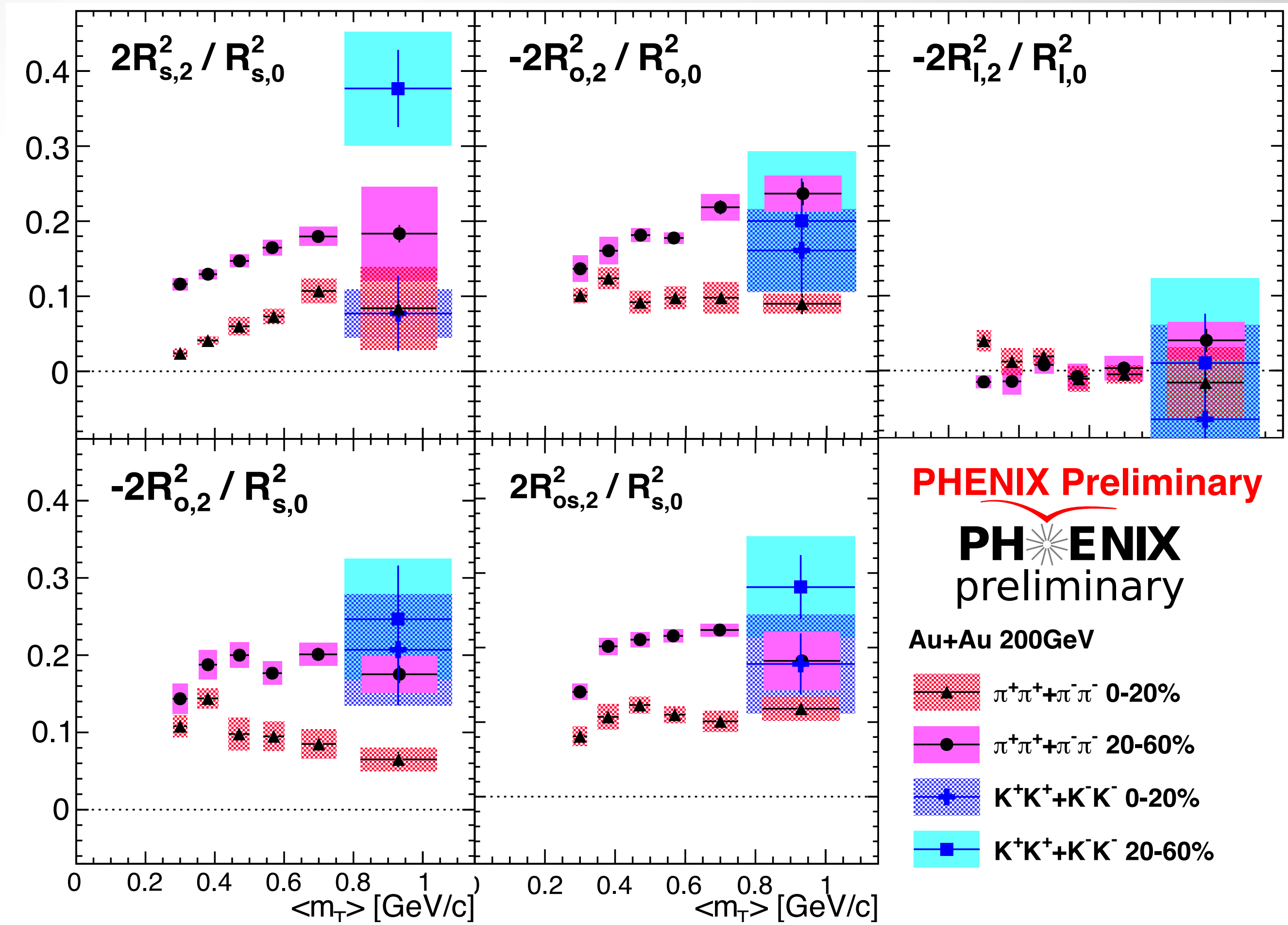
# $m_T$ dependence of $\varepsilon_{final}$




- $\varepsilon_{final}$ 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

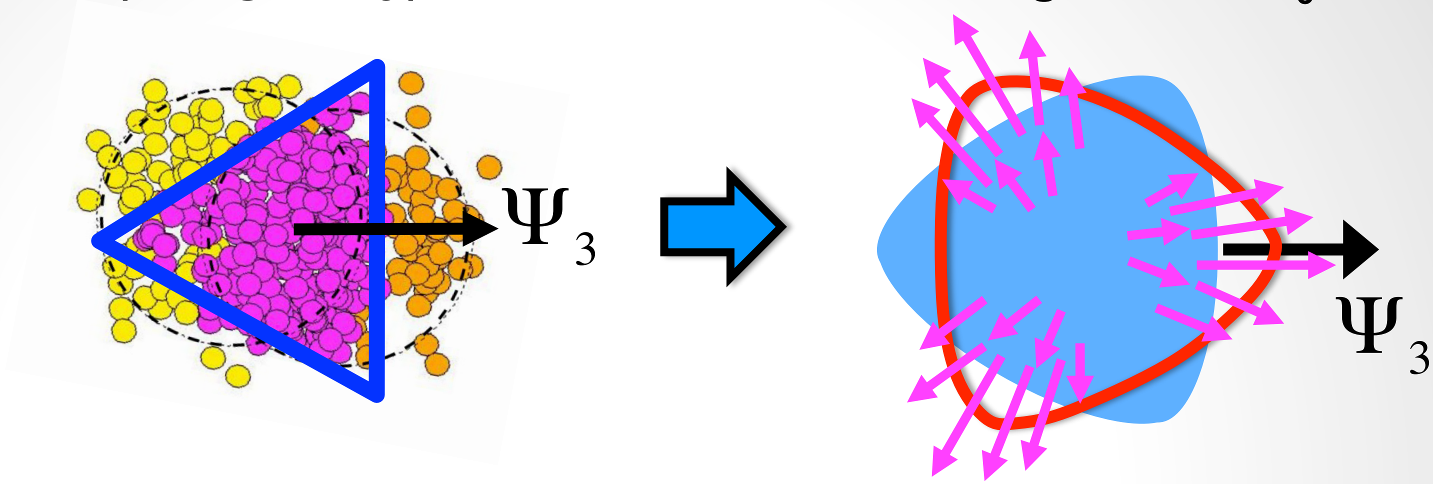
# $m_T$ dependence of relative amplitude






- **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



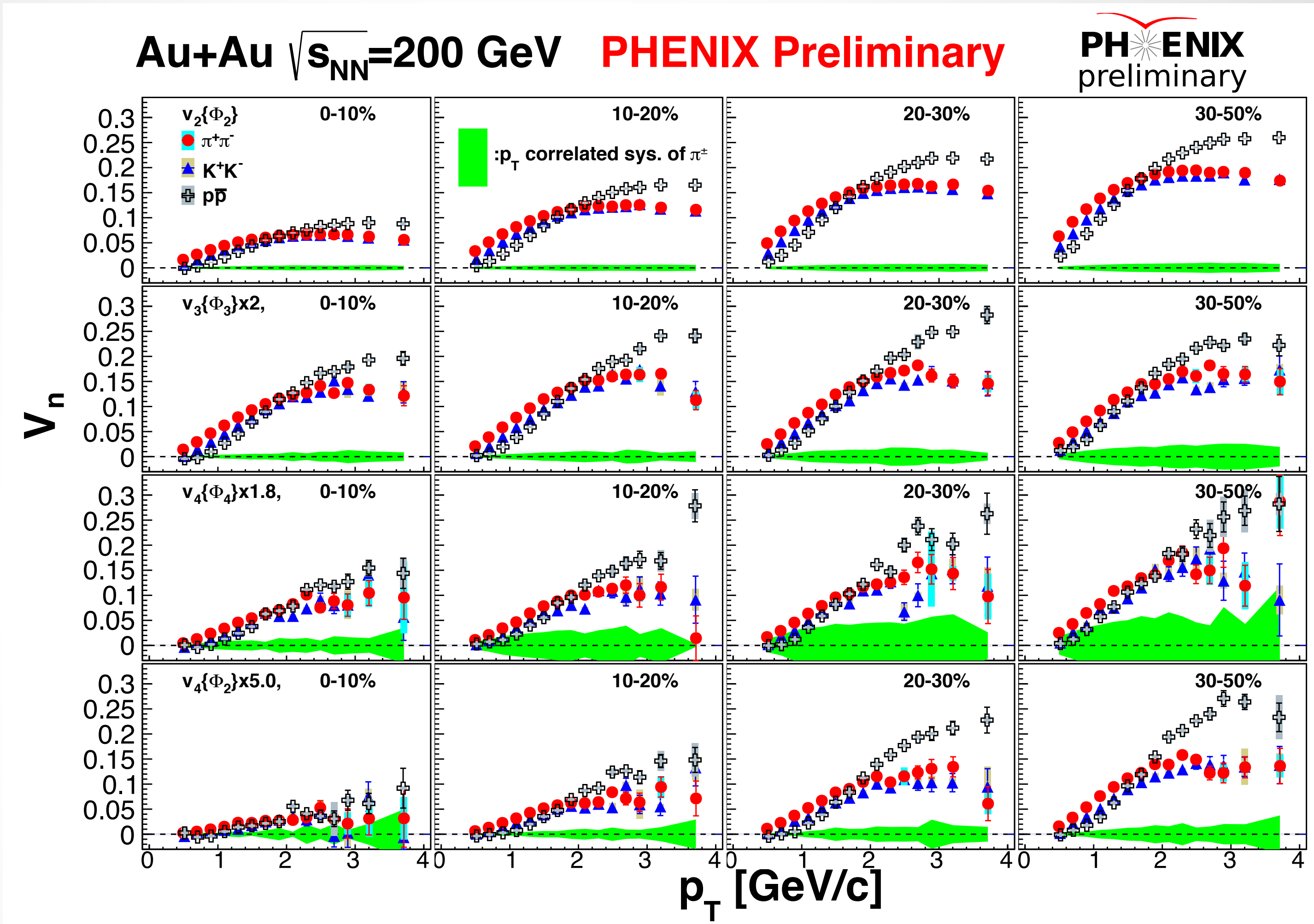

- **Final triangularity could be observed by azimuthal HBT w.r.t $v_3$ plane($\Psi_3$) if it exists at freeze-out**
  - Detailed information on space-time evolution can be obtained
- **Analysis is ongoing**

# 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**
  - ✧$\varepsilon_{final}$ increase with $m_T$, while relative $R_{out,2}$ doesn't depend on $m_T$ in central collisions
  - ✧Difference of $\varepsilon_{final}$ between π/K is seen even in same $m_T$, but note it is within 2σ of sys. error

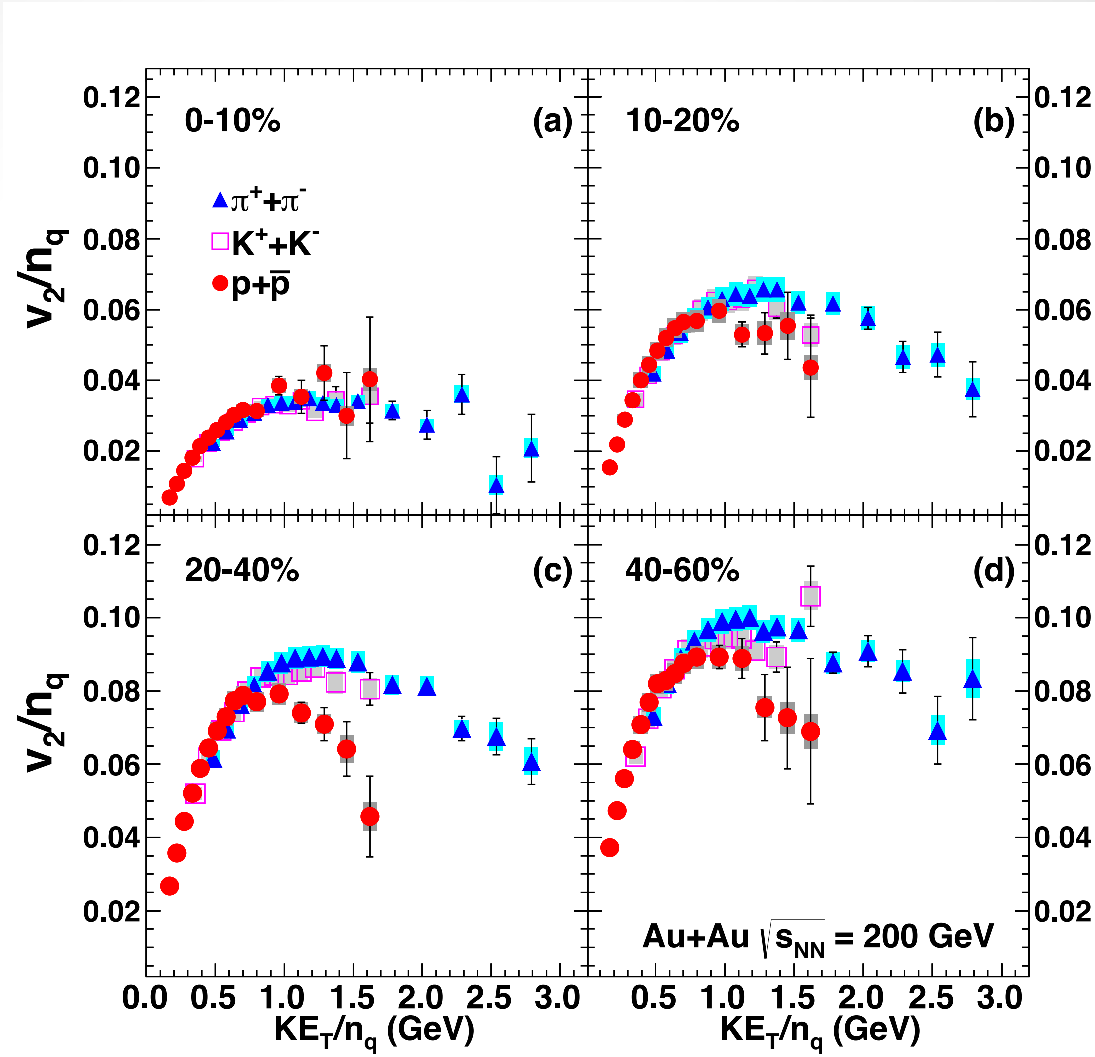
# Back up

# PID $v_n$ vs centralarity



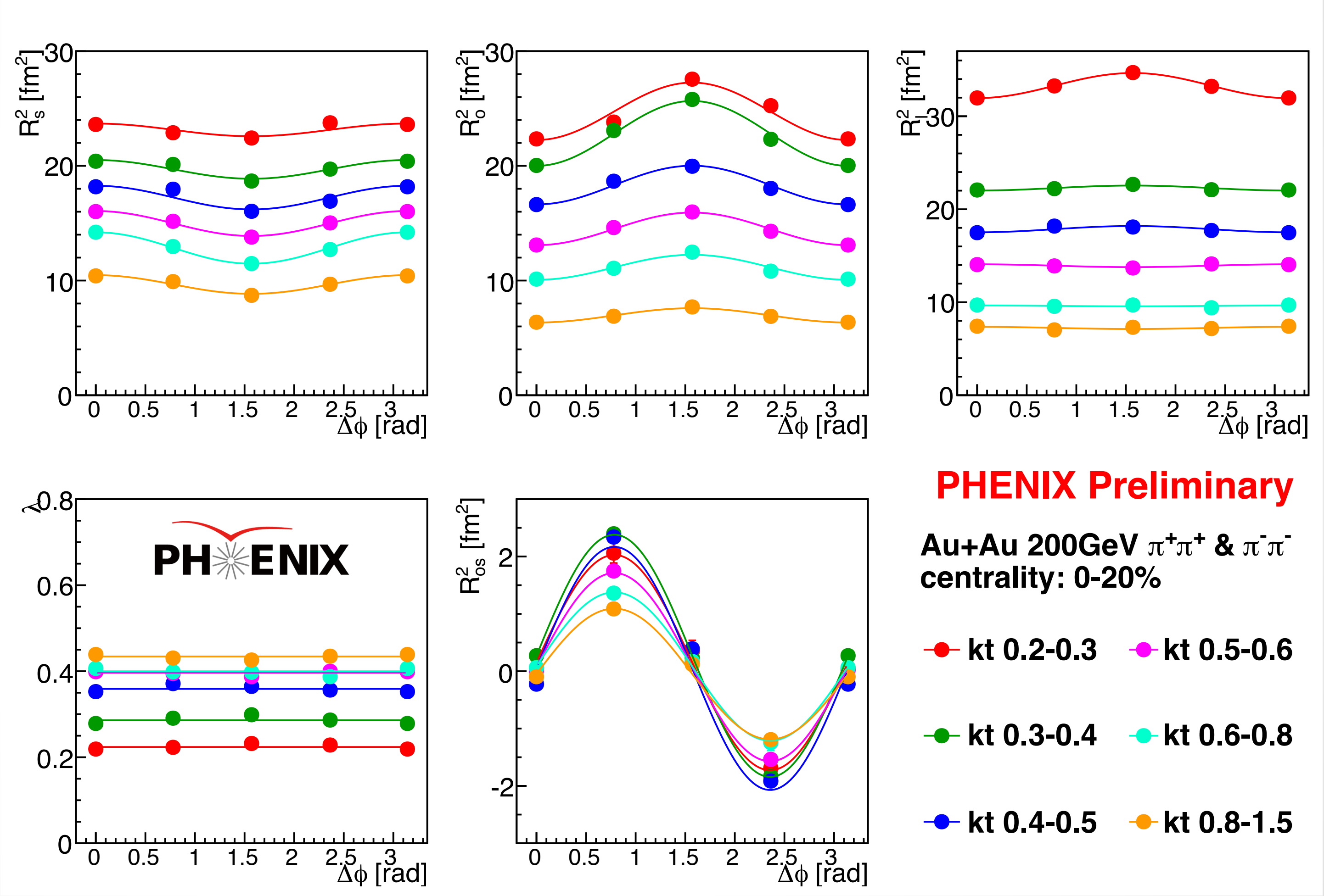

Same trends are seen in each centrality bins

# "$v_2$ 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

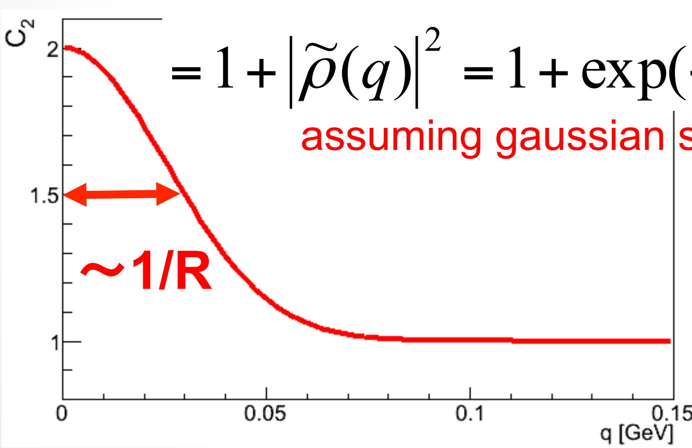
$$\vec{q} = \vec{p}_1 - \vec{p}_2$$

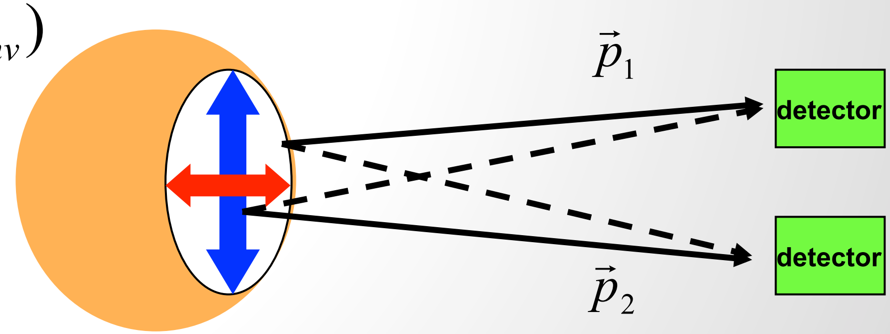
$$\vec{k}_T = \frac{\vec{p}_1 + \vec{p}_2}{2}$$

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

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

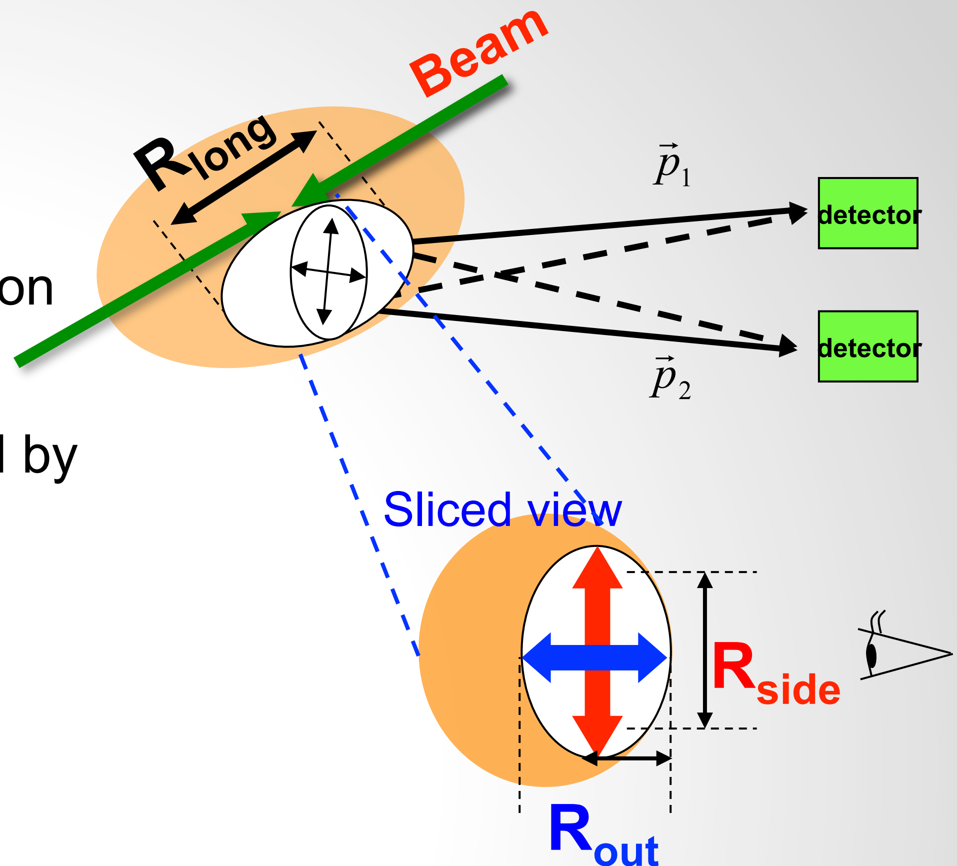
assuming gaussian source



# 3D HBT radii

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



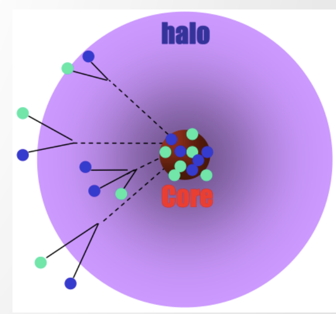

$$C_2 = C_2^{core} + C_2^{halo}$$

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

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

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

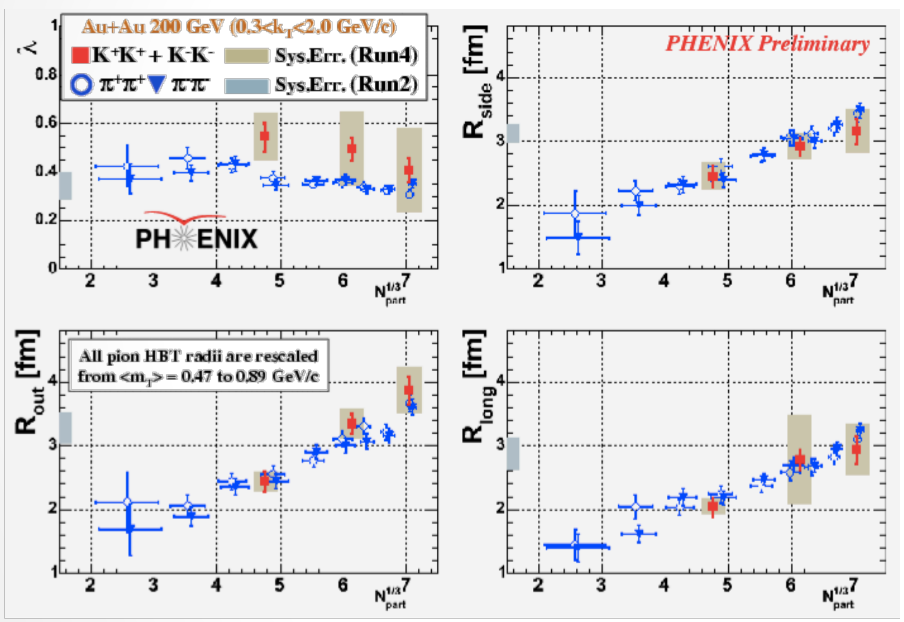
**$R_{long}$: Longtudinal size**
**$R_{side}$: Transverse size**
**$R_{out}$: Transverse size + emission duration**
**$R_{os}$: Cross term between Out and Side**



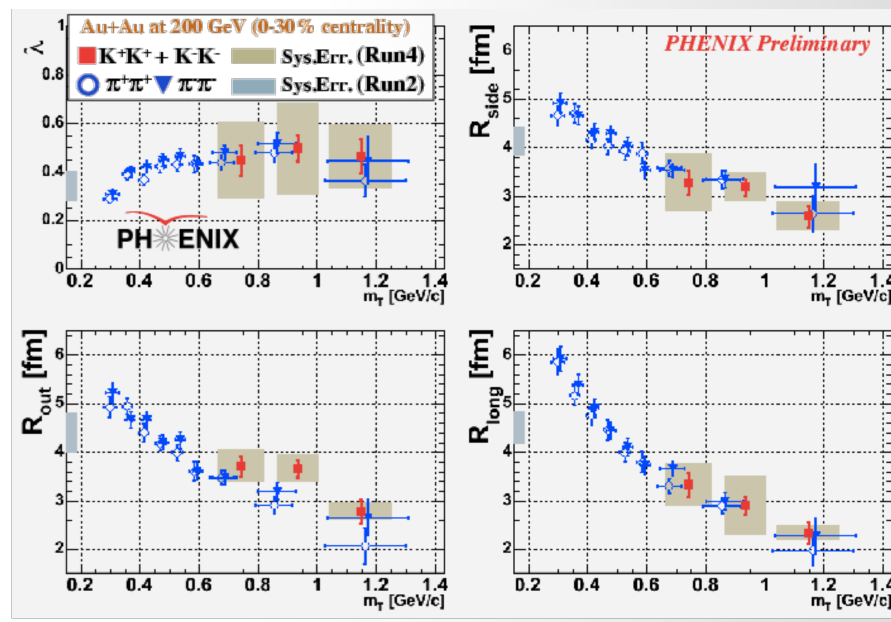
# The past HBT Results for charged pions and kaons

- **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**

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

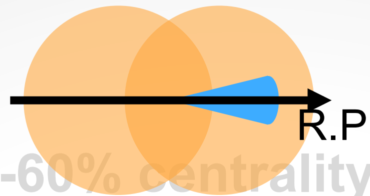
  - ✧ Ratio of real and mixed q-distribution of pairs
    q: relative momentum

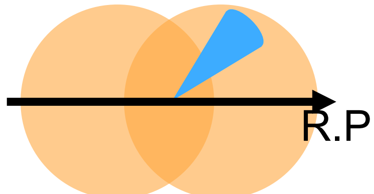
- **Correction of event plane resolution**
  - ✧ U.Heinz et al, PRC66, 044903 (2002)
- **Coulomb correction and Fitting**
  - ✧ By Sinyukov's fit function
  - ✧ Including the effect of long lived resonance decay

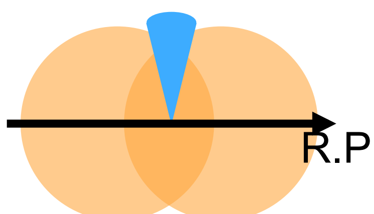
$$C_2 = C_2^{core} + C_2^{halo}$$
$$= [\lambda(1+G)F] + [1-\lambda]$$
$$G = \exp(-R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2 - R_{long}^2 q_{long}^2 - 2R_{os}^2 q_{side} q_{out})$$

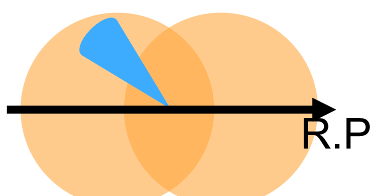
# Correlation function

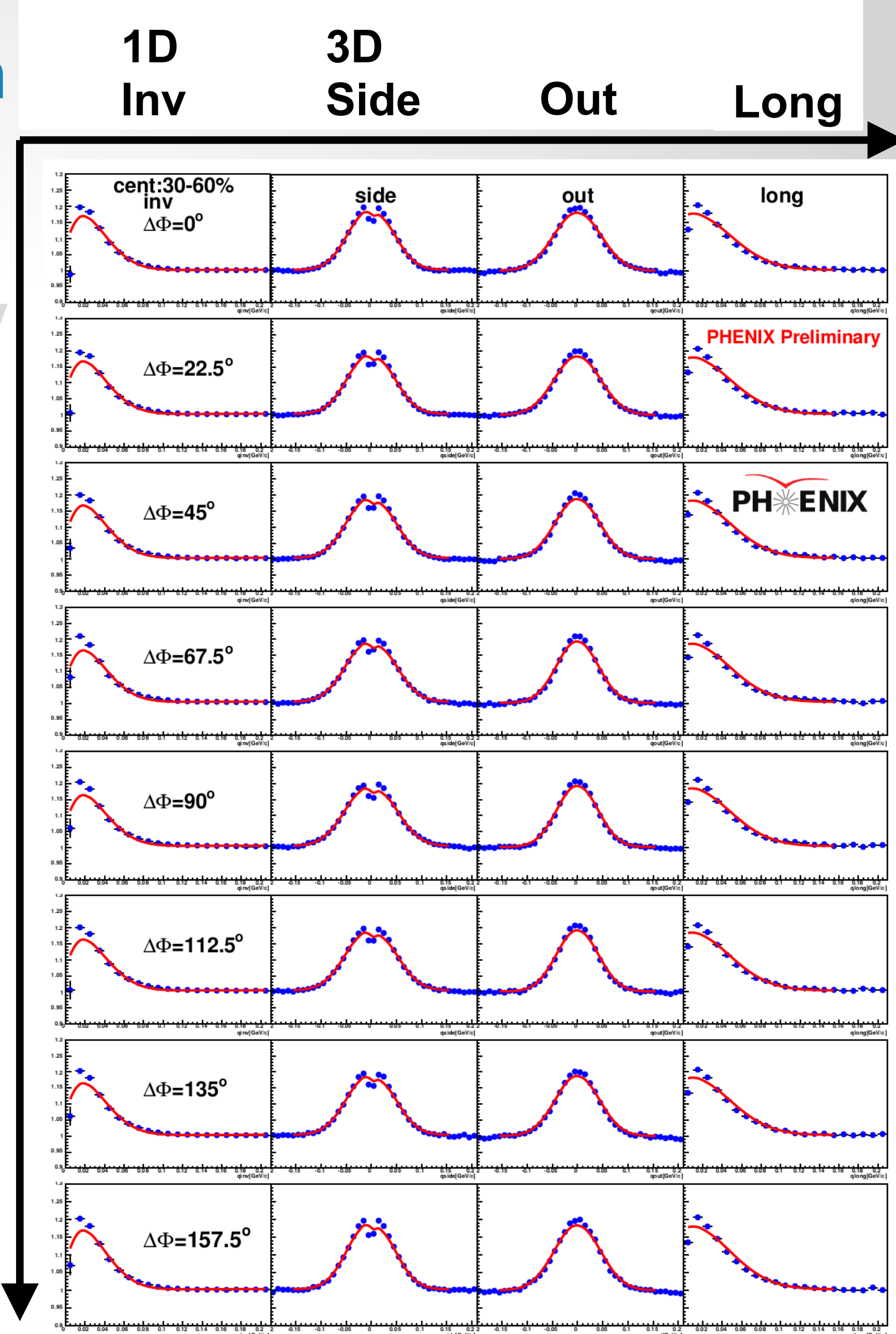
- Raw $C_2$ for 30-60% centrality
- Solid lines is fit functions



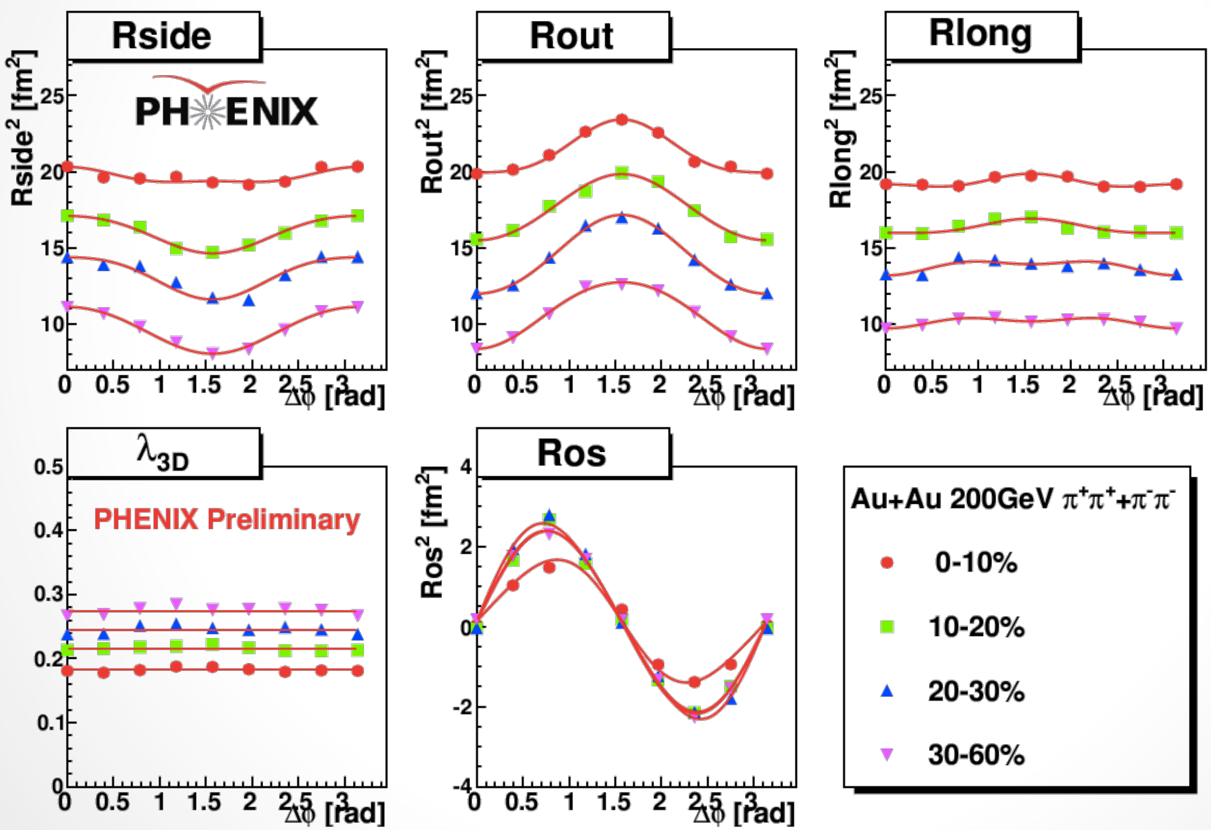



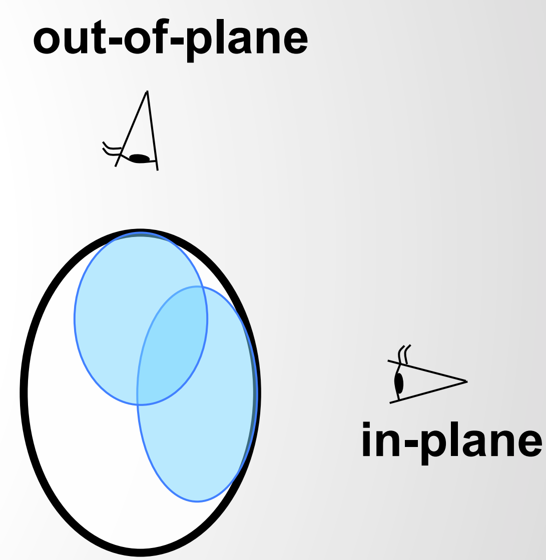



# Azimuthal HBT radii for pions

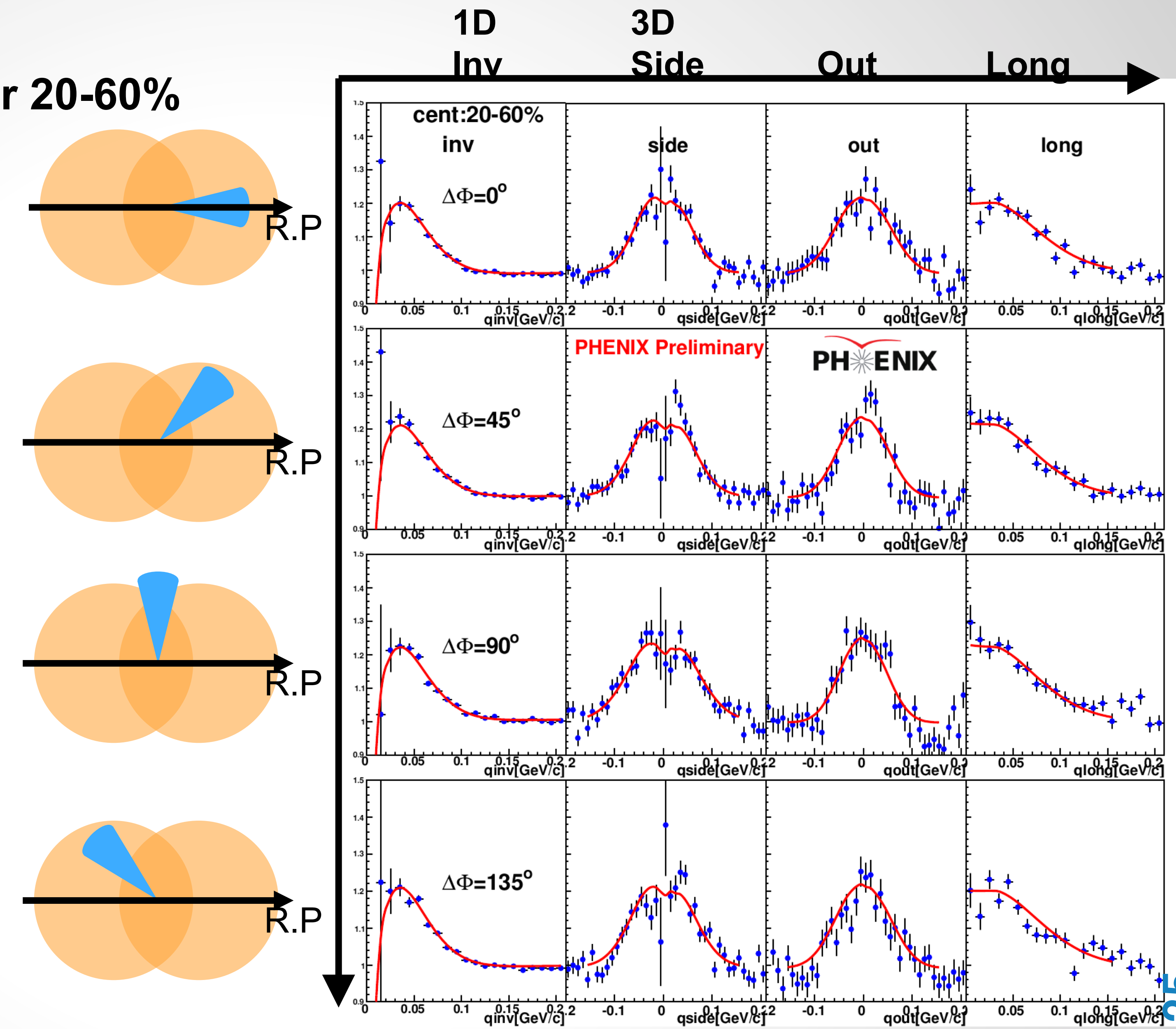
- Observed oscillation for $R_{side}$, $R_{out}$, $R_{os}$
- Rout in 0-10% has oscillation
  - ✧ Different emission duration between in-plane and out-of-plane?



# Correlation function for charged kaons

- **Raw $C_2$ for 20-60%**



# STAR Result (w.r.t psi2)

- **PRL.93, 012301(2004)**