Azimuthally Sensitive Pion Interferometry in Au+Au Collisions at $\sqrt{s_{NN}}$=200GeV

Jason Newby
Lawrence Livermore National Laboratory
for the PHENIX Collaboration

Second Joint Meeting of the Nuclear Physics Division of the APS and JPS, Maui

PHENIX

UCRL-PRES-217427
This work was performed under the auspices of the U.S. Department of Energy
by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48

Why Interferometry?

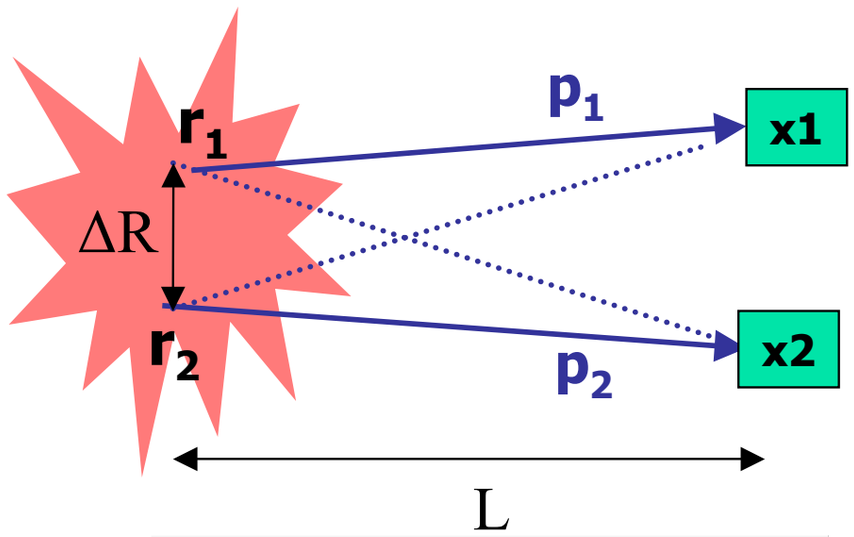
- Initial State Geometry of Heavy-Ion collisions is calculated from nuclear geometry. Nuclear overlap: N_{part}, N_{binary}, Initial Volume, Eccentricity
- Experimentally, we measure particle momentum distributions.
- Theoretical models use these experimental measures to validate a description of the evolution from some initial state geometry to a final state momentum distribution.
- Femtoscopy measures space-time evolution of the system at kinetic freeze-out and further constrains these models.
- Describing the HBT source dimensions at freeze-out has been a challenge for full hydrodynamic calculations.

HBT Introduction

Quantum Statistical Correlation

Hanbury-Brown, Twiss (1960)
Golhaber, Goldhaber, Lee, Pais (1960)

Wave-Function of Identical Bosons must be symmetrized.

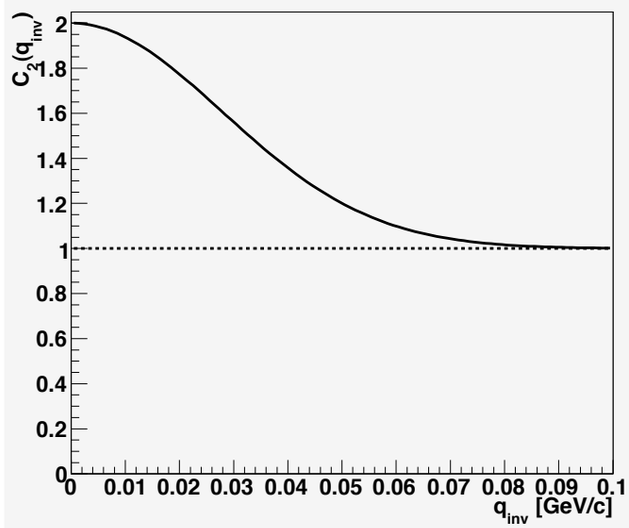


$$\psi_2(p_1,p_2) = \frac{1}{\sqrt{2}}\left\{A(p_1,r_1)e^{ip_1(x_1-r_1)}A(p_2,r_2)e^{ip_2(x_2-r_2)} \pm A(p_1,r_2)e^{ip_1(x_1-r_2)}A(p_2,r_1)e^{ip_2(x_2-r_1)}\right\}$$

$$P_2(p_1,p_2) = \int \rho(r_1)\rho(r_2)d^4r_1d^4r_2A^2(p_1,r_1)A^2(p_2,r_2) \pm \left|\int \rho(r)d^4rA(p_1,r)A(p_2,r)e^{-ir(p_1-p_2)}\right|^2$$

$$C_2(p_1,p_2) \equiv \frac{P_2(p_1,p_2)}{P(p_1)P(p_2)} = 1 + \left|\tilde{\rho}(q)\right|^2$$

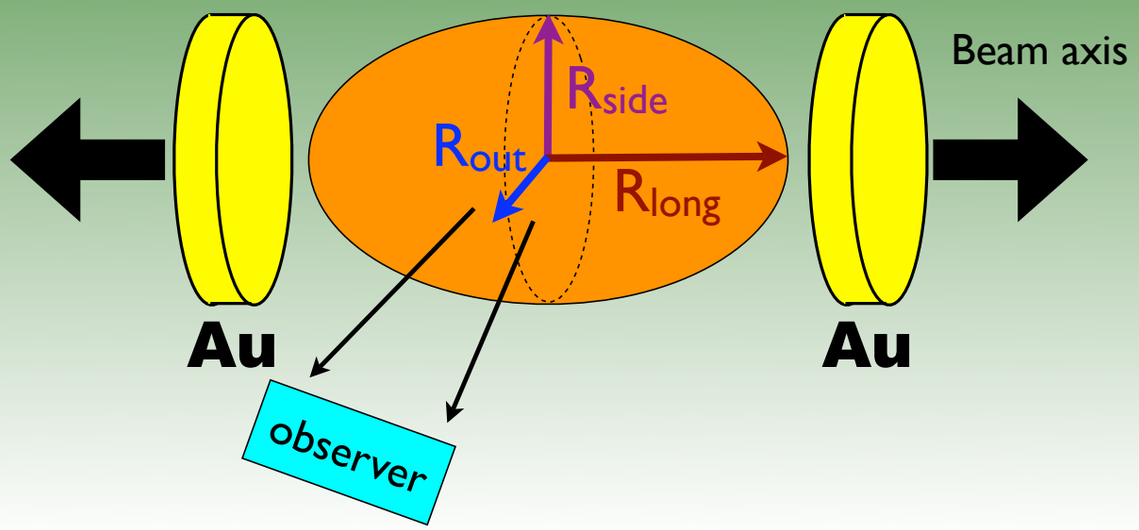
$(q=p_1-p_2)$

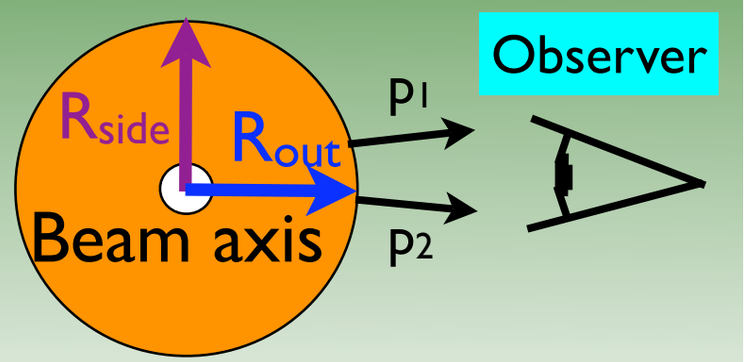


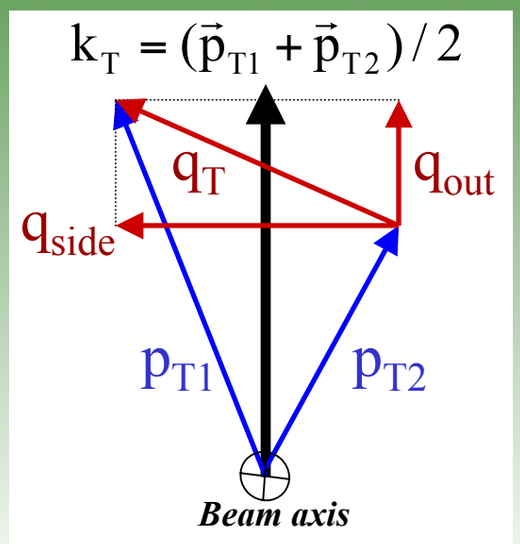
Enhancement of Pair Production at small relative momentum.

HBT in Heavy-Ions

Bertsch-Pratt parameterization







Bowler-Sinyukov Phys. Lett. B270,69 (1991) Phys. Lett. B432,249 (1998)

$$C_2(\vec{q}) = (1-\lambda) + \lambda \exp\left[-R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2 - R_{long}^2 q_{long}^2 - R_{so}^2 q_{side} q_{out}\right] K_{Coul}(q_{inv})$$

Fraction of Chaotic Emission

Coulomb Interaction

Halo of long lived resonances

Azimuthal HBT

Out-of-Plane
Observer
Φ= 90°

R_{side} R_{out}

Heinz et al. PRC66,044903(2002)

$R_\mu^2(\Phi) = R_{\mu,0}^2 + R_{\mu,n}^2 \cos(n\Phi)$ {μ=s,o,l}

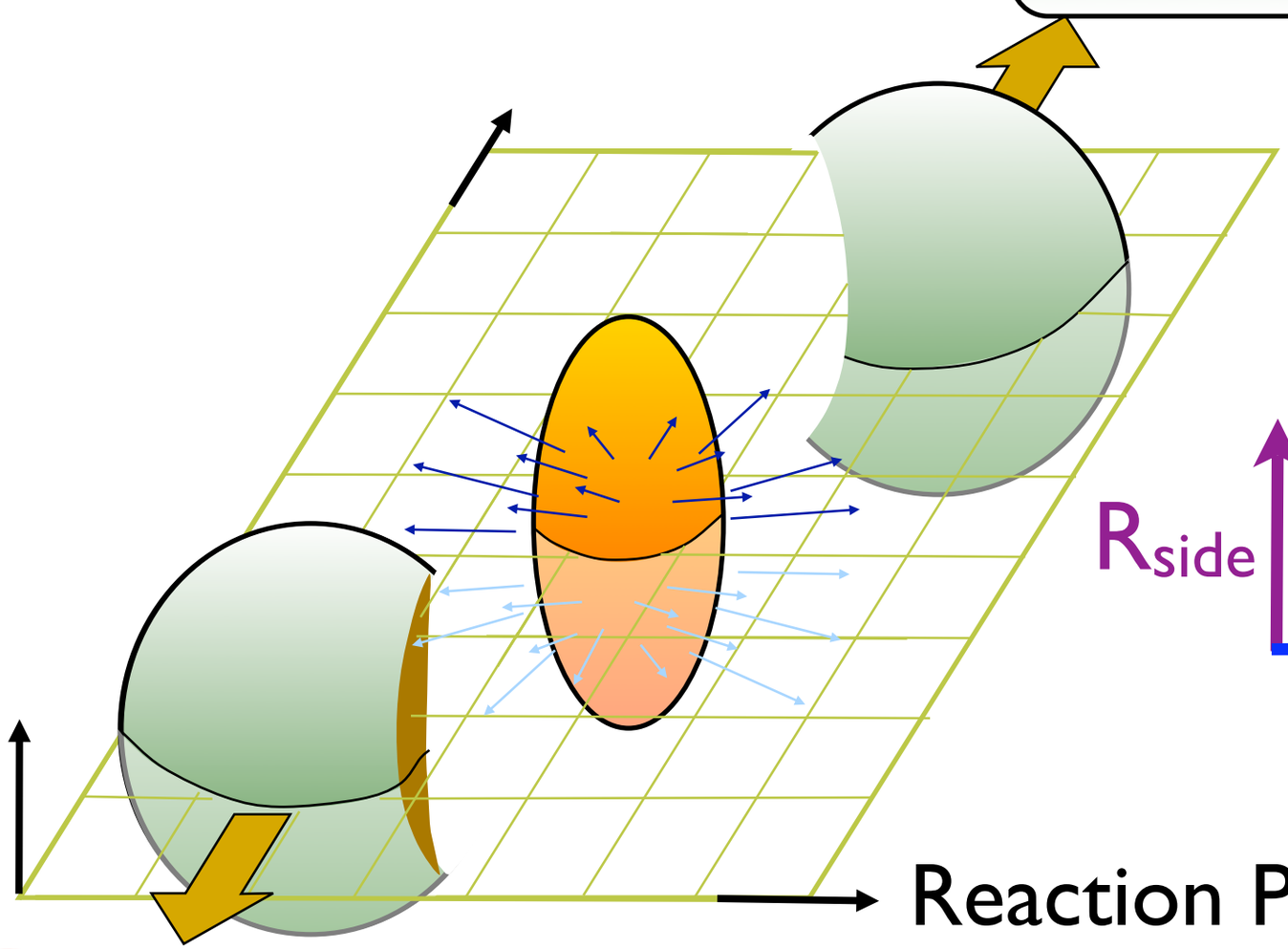
$R_{s,2}^2>0$ $R_{o,2}^2<0$

$R_{so}^2(\Phi) = R_{so,0}^2 + R_{so,n}^2 \sin(n\Phi)$

$R_{os,2}=0$ $R_{os,2}>0$

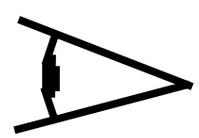
Pair Ordering
($p_{z,2} > p_{z,1}$)

Pairs Boosted
LCMS ($p_{z,1}=-p_{z,2}$)



$$\varepsilon = \frac{\langle y^2\rangle - \langle x^2\rangle}{\langle y^2\rangle + \langle x^2\rangle} \approx \frac{2R_{s,2}^2}{R_{s,0}^2}$$

R_{side} R_{out}

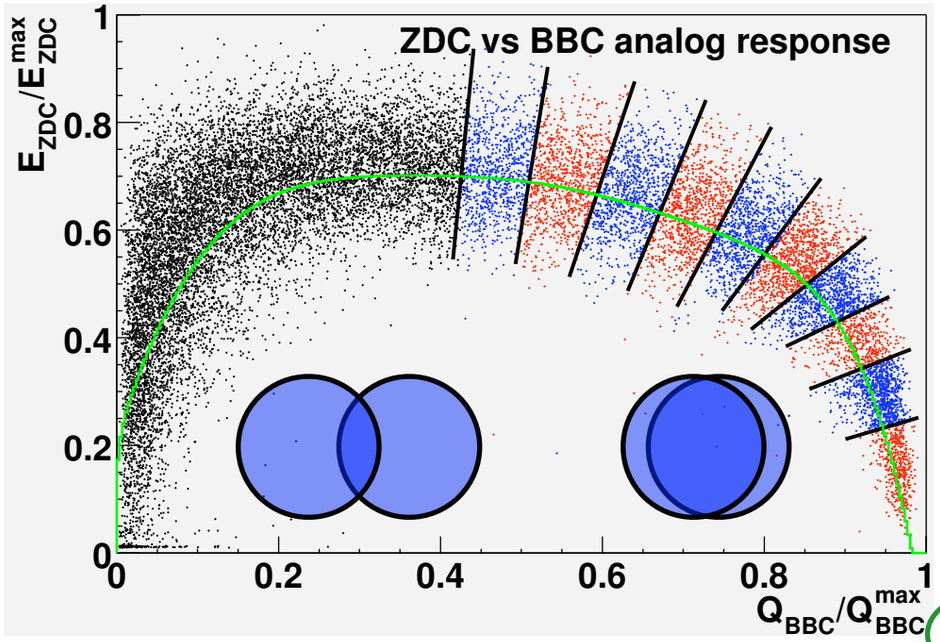


In-Plane
Observer
Φ= 0°

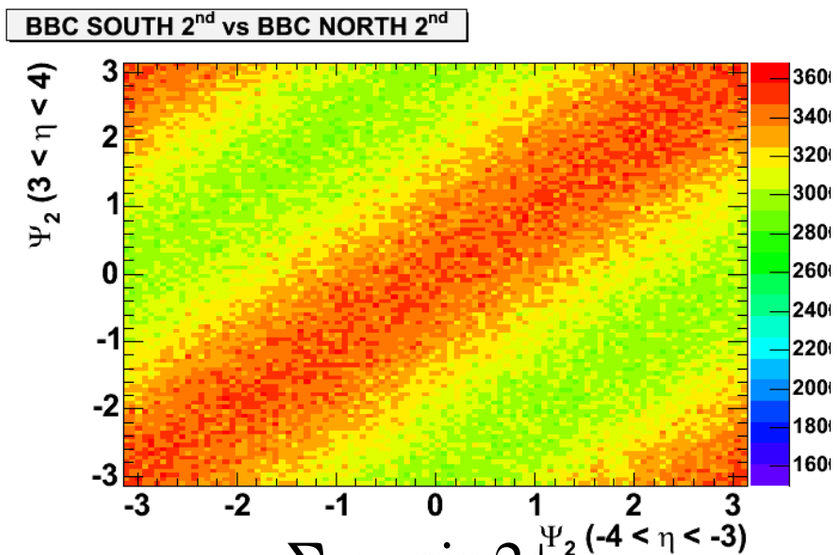
Reaction Plane

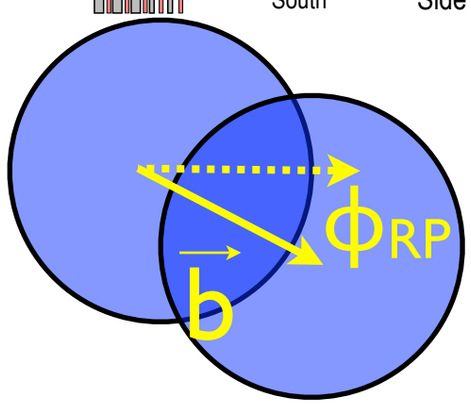
PHENIX Detector

BBC/ZDC Centrality

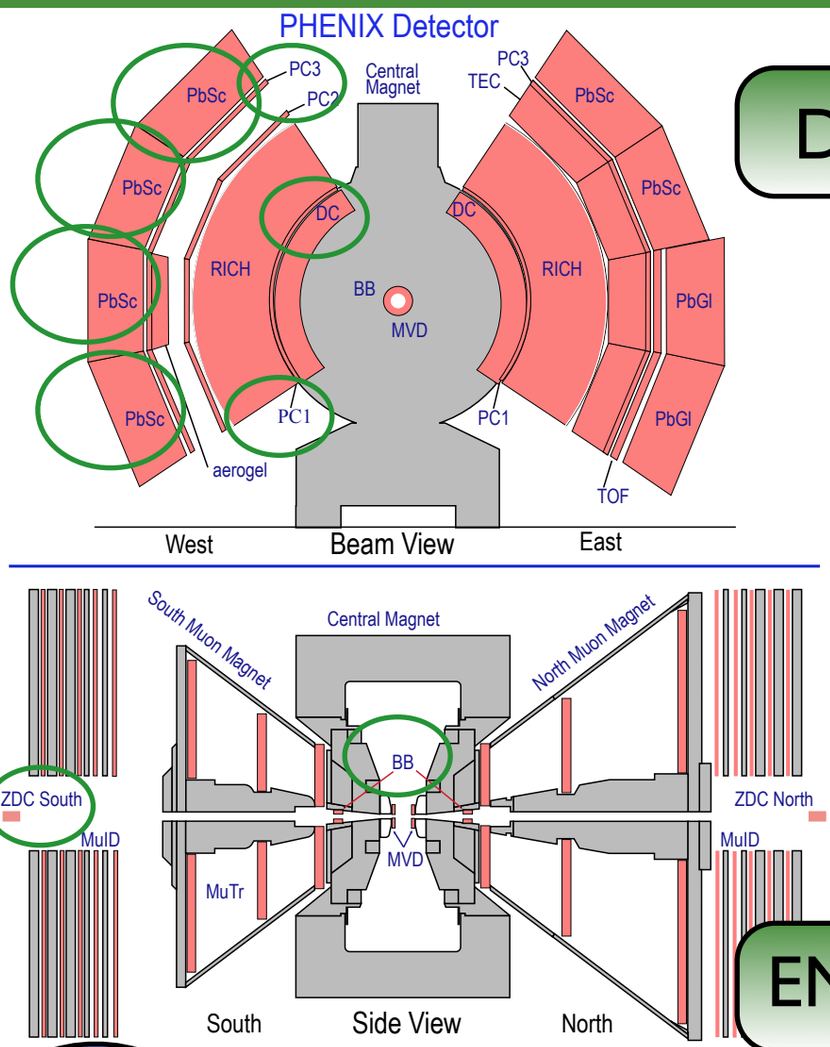


BBC Reaction Plane





$$\tan 2\Phi_{RP} = \frac{\sum n_{ch} \sin 2\phi_{PMT}}{\sum n_{ch} \cos 2\phi_{PMT}}$$

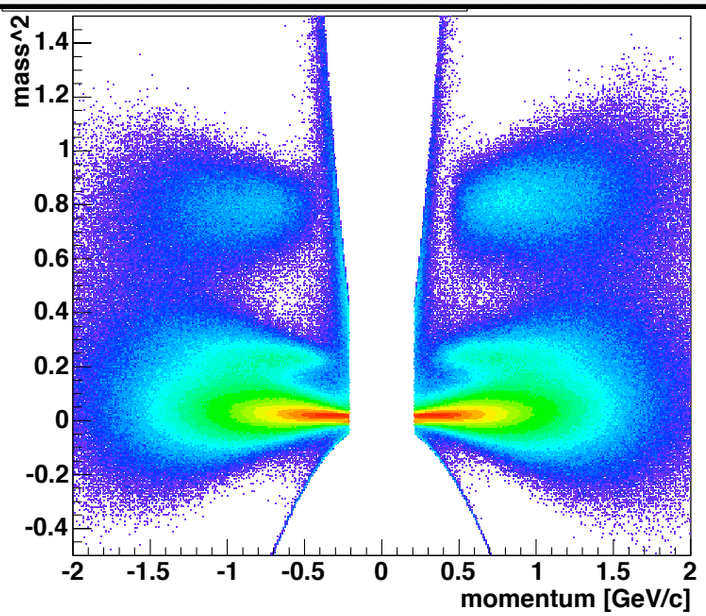


DC/PC Track-Mom Reco

$\delta p/p \sim 1\%$

Path Length

EMC Particle Identification



Analysis Overview

~500M Minimum Bias Au+Au $\sqrt{s_{NN}}$=200GeV

Tracks Selection:

- Good track quality, detector matching
- Pion Identification 2σ
- Kaon Rejection 2σ

Pair Selection: Exclude track pairs within inefficient regions of Drift Chamber and EMCal

Two-Particle Like-Sign Pion Correlation

$$C_2(\vec{q},\phi_{pair}) = \frac{A(\vec{q},\phi_{pair})}{M(\vec{q},\phi_{pair})}$$

Actual Pairs
Event Mixing

Reaction Plane Correction Applied to A & M

Heinz et al. PRC66,044903(2002)

Fit the C_2 of 4 Centralities for 8 Azimuthal bins.

Singles Cuts	Cut
Track Quality	31 ll 63
PC3 Matching	3σ
EMC Matching	2σ
EMC ToF	< 60 ns
PID	nPion < 2σ nKaon > 2σ
EMC West	

Two-Track Cuts	Cut
Distance EMC	> 16 cm
DC dPhi Cut (dz < 6cm)	0.06 rad
DC dPhi Cut (dz > 6 cm)	0.03 rad
Ghosting	(-1 cm < dz <0) && dphi < 0.04

Event Mixing	
ZVtx	60 bins (-30, 30)
Centrality	10% (10-20%)
Reaction Plane	30 bins

Centrality	Pairs (qinv < 50 MeV)
10 - 20 %	47M
20 - 30 %	24 M
30 - 40 %	12M
40 - 60 %	5.4M

Centrality	$\sqrt{(2\langle\cos 2(\phi_N - \phi_S)\rangle)}$
10-20 %	0.37
20-30 %	0.41
30-40 %	0.38
40-60 %	0.29

3D Correlations

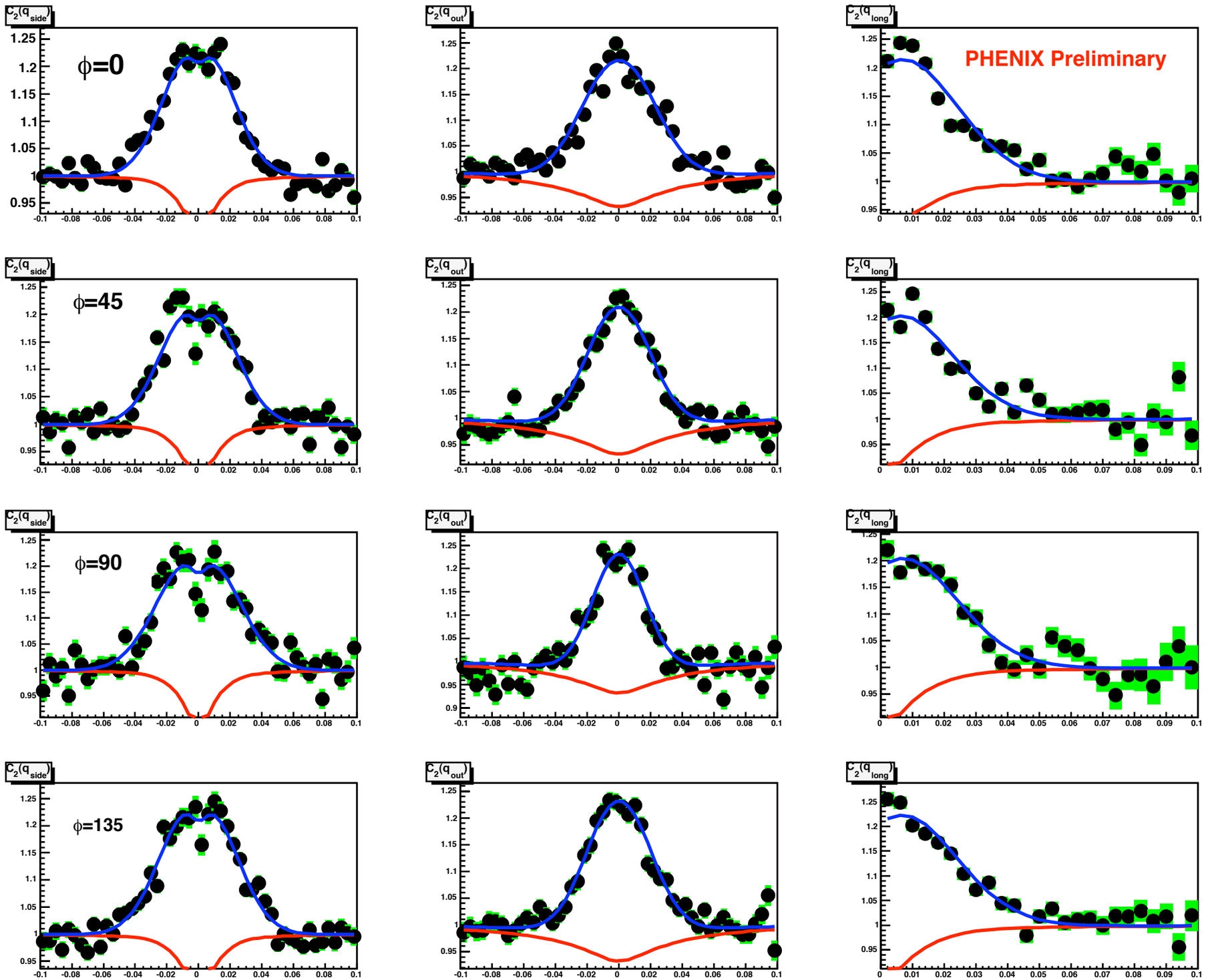
In-Plane

30-40% Central
$\pi^+\pi^+ + \pi^-\pi^-$

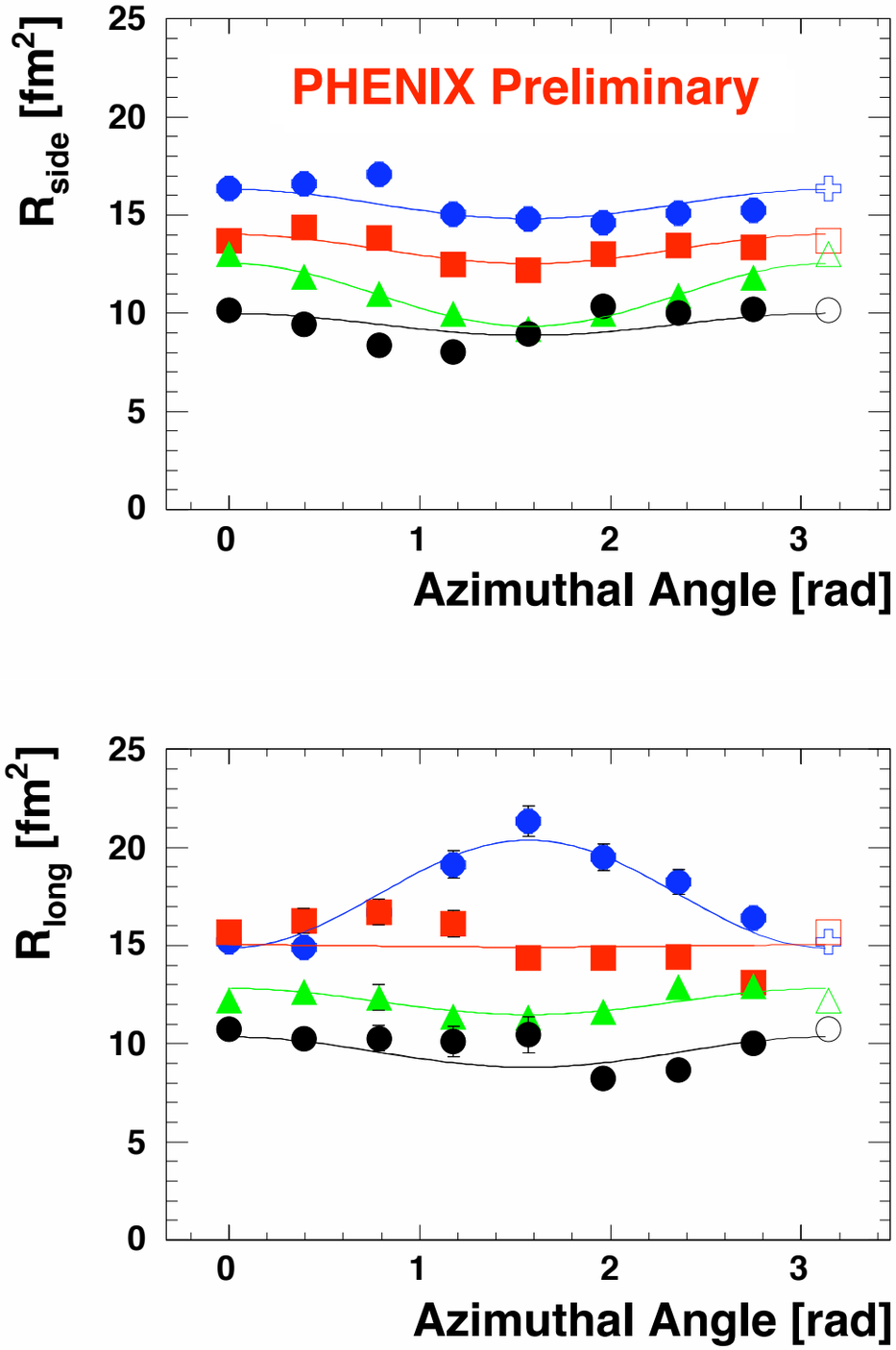
- Correlation
- Sinyukov Fit
- Coulomb Weights

Out of Plane

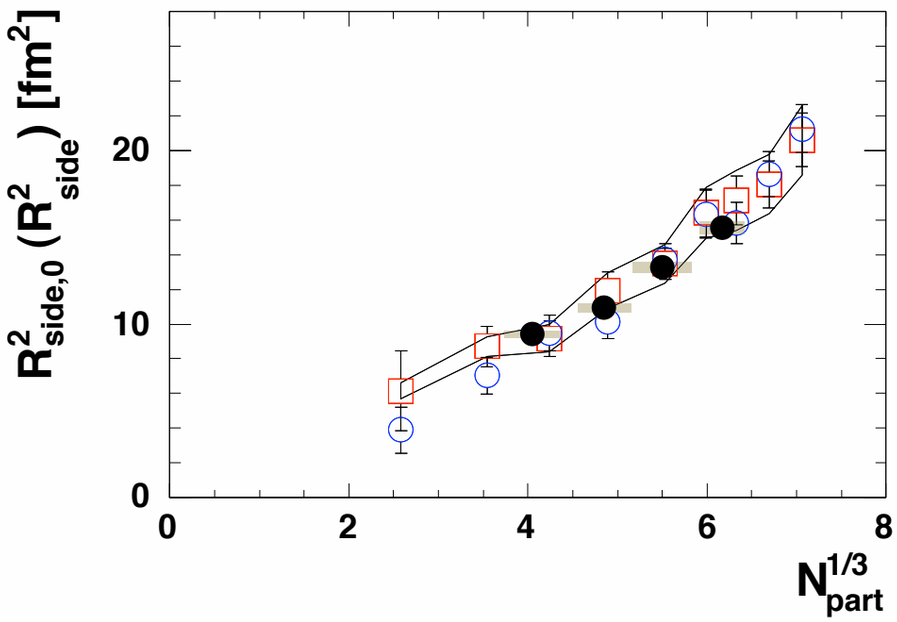
$C_2(q_{side})$ q_{other}< 20MeV $C_2(q_{out})$ $C_2(q_{long})$

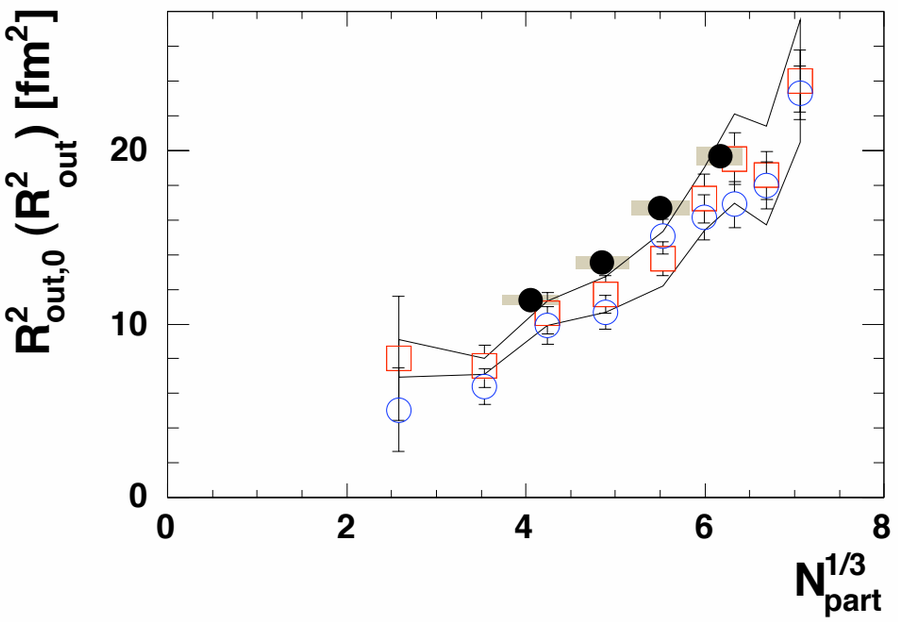


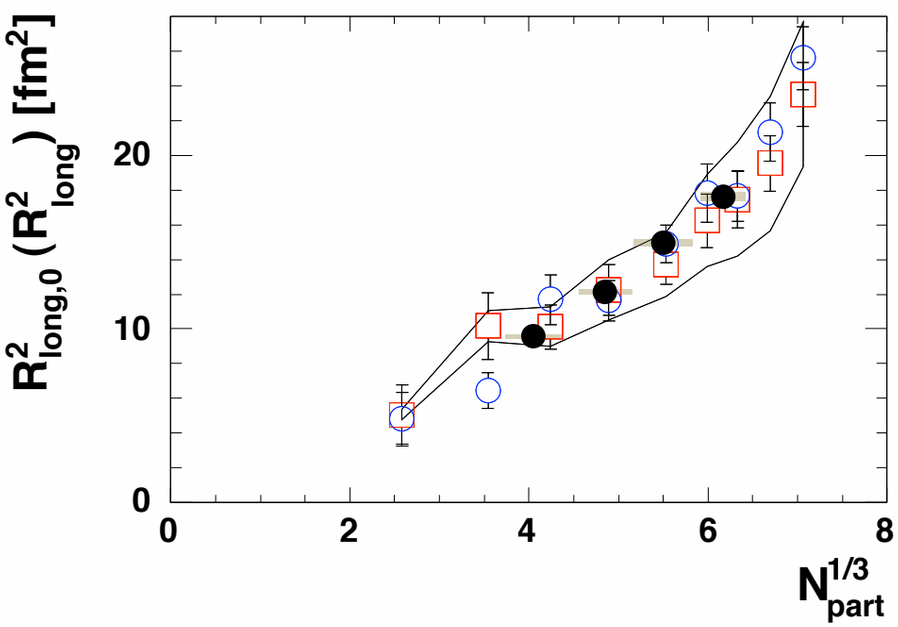
Azimuthal Dependence



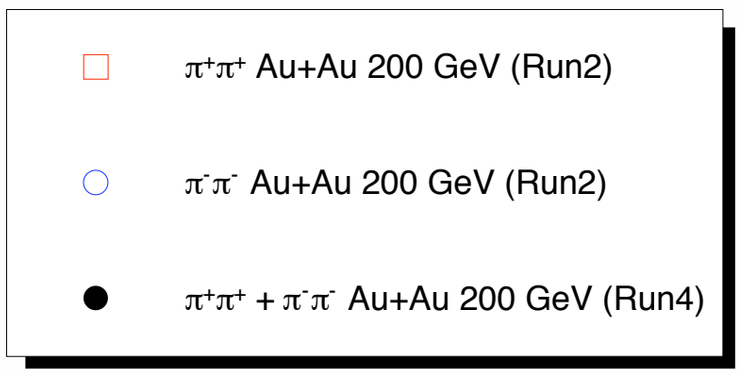
Traditional HBT Comparison





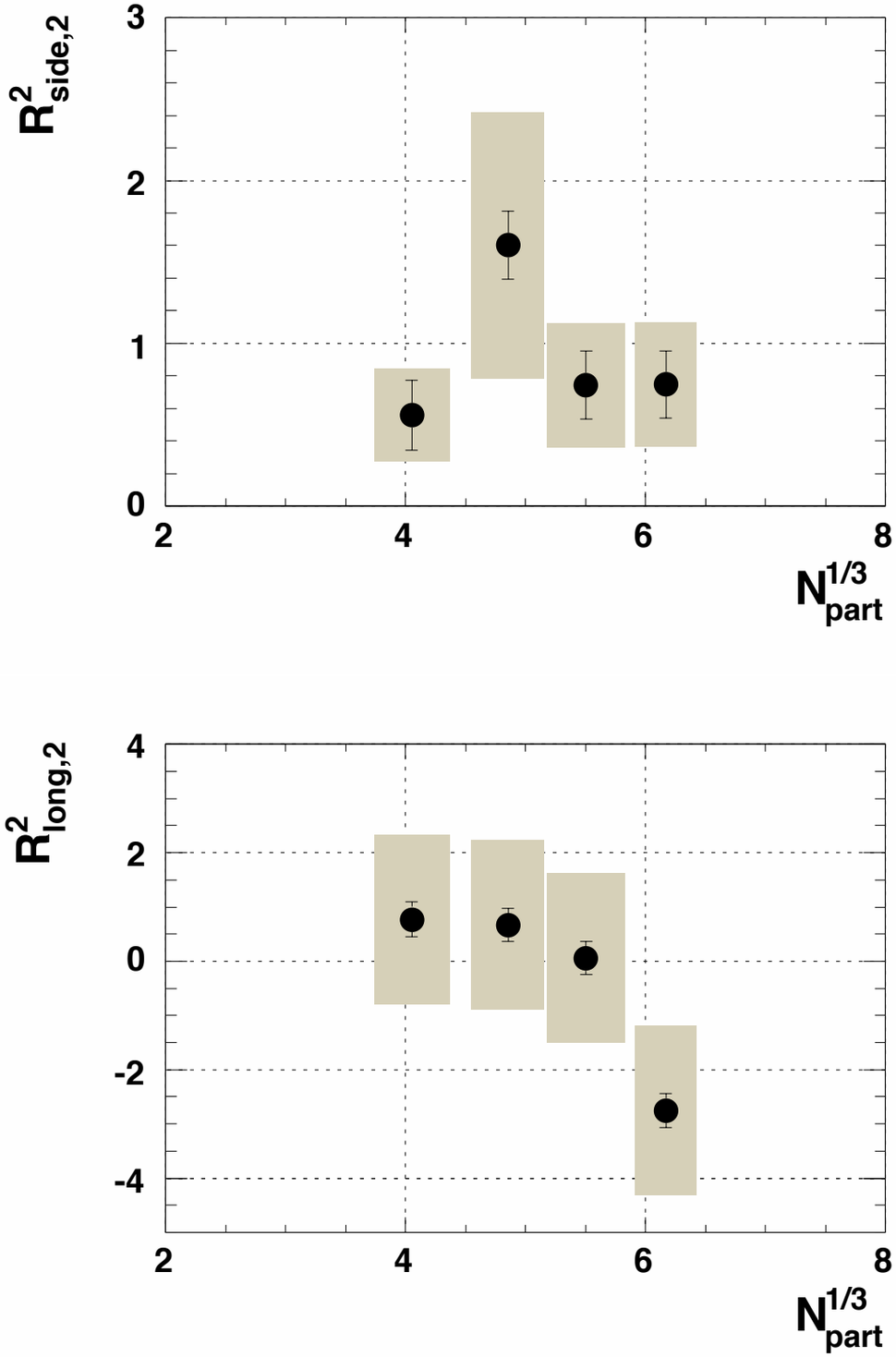


PHENIX Preliminary



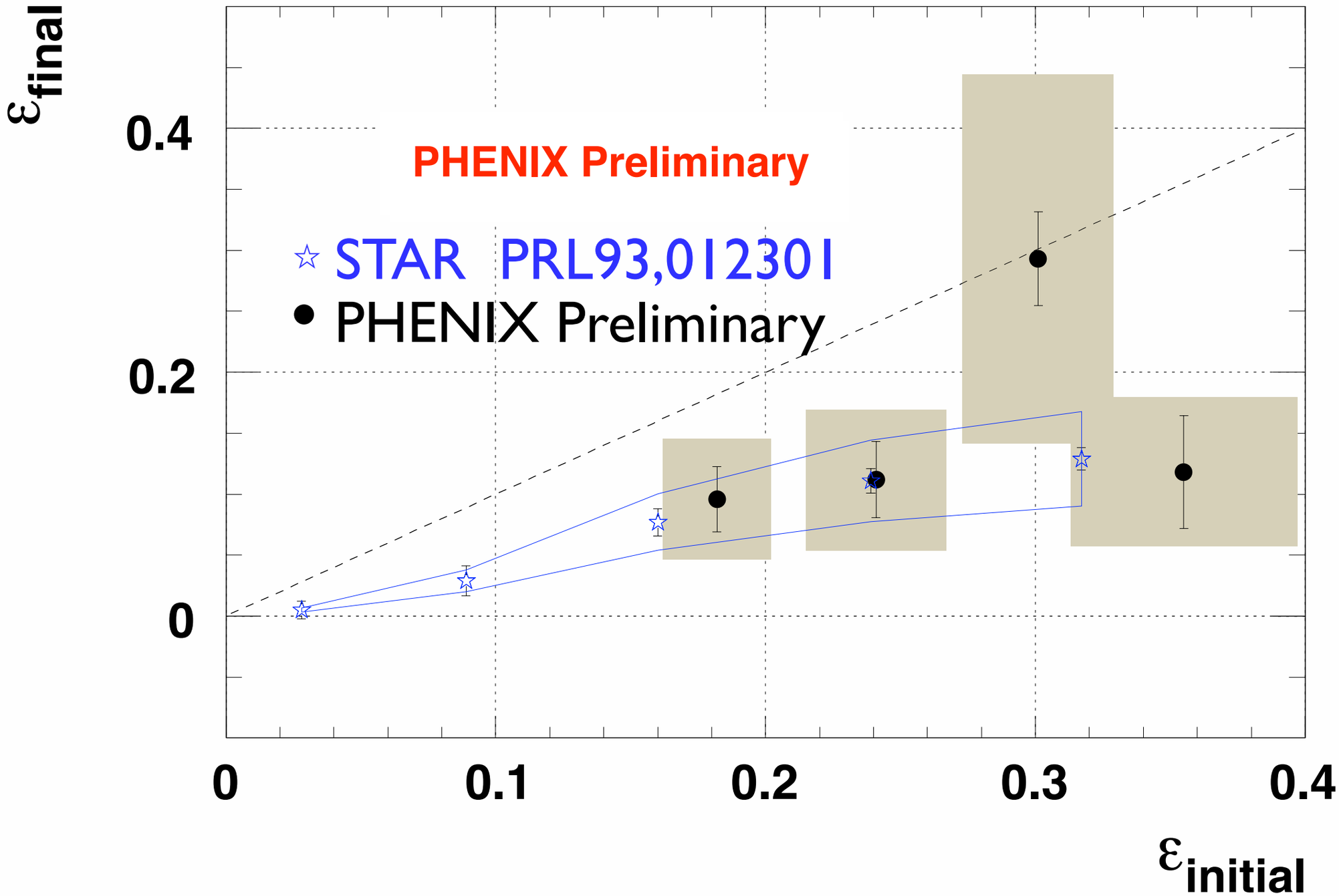
Quantitative agreement with Run2 traditional HBT results.

Azimuthal Oscillations in Radii



Eccentricity Final State vs Initial

$\epsilon \approx 2R_{s,2}/R_{s,0}$



Summary and Conclusions

- PHENIX has measured azimuthal dependence of HBT Radii of the Pion emitting source in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
  - We observe expected even oscillations in R_{side} and R_{out}
  - We observe expected odd oscillations in R_{so}.
  - We also observe even oscillations in R_{long}. T. Hirano (NPA743('04)305)
    - Eccentricity measurements are consistent with STAR result.
- Quantitative comparisons with models will require reduced statistical and systematic errors
  - 2 x more statistics to be analyzed.
  - Better understanding of Two-Track efficiencies will reduced systematic errors.
  - Explore k_T dependence.

- University of São Paulo, São Paulo, Brazil
- Academia Sinica, Taipei 11529, China
- China Institute of Atomic Energy (CIAE), Beijing, P. R. China
- Peking University, Beijing, P. R. China
- Charles University, Faculty of Mathematics and Physics, Ke Karlovu 3, 12116 Prague, Czech Republic
- Czech Technical University, Faculty of Nuclear Sciences and Physical Engineering, Brehova 7, 11519 Prague, Czech Republic
- Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague, Czech Republic
- Laboratoire de Physique Corpusculaire (LPC), Universite de Clermont-Ferrand, 63 170 Aubiere, Clermont-Ferrand, France
- Dapnia, CEA Saclay, Bat. 703, F-91191 Gif-sur-Yvette, France
- IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, BP1, F-91406 Orsay, Fra
- Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS-IN2P3, Rout Saclay, F-91128 Palaiseau, France
- SUBATECH, Ecòle des Mines at Nantes, F-44307 Nantes France
- University of Muenster, Muenster, Germany
- KFKI Research Institute for Particle and Nuclear Physics at the Hungari Academy of Sciences (MTA KFKI RMKI), Budapest, Hungary
- Debrecen University, Debrecen, Hungary
- Eövös Loránd University (ELTE), Budapest, Hungary
- Banaras Hindu University, Banaras, India
- Bhabha Atomic Research Centre (BARC), Bombay, India
- Weizmann Institute, Rehovot, 76100, Israel
- Center for Nuclear Study (CNS-Tokyo), University of Tokyo, Tanashi, Tokyo 188, Japan
- Hiroshima University, Higashi-Hiroshima 739, Japan
- KEK - High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
- Kyoto University, Kyoto, Japan
- Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki, Japan
- RIKEN, The Institute of Physical and Chemical Research, Wako, Saitama 351-0198, Japan
- RIKEN – BNL Research Center, Japan, located at BNL
- Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan
- Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan
- University of Tsukuba, 1-1-1 Tennodai, Tsukuba-shi Ibaraki-ken 305-8577, Japan
- Waseda University, Tokyo, Japan
- Cyclotron Application Laboratory, KAERI, Seoul, South Korea
- Kangnung National University, Kangnung 210-702, South Korea
- Korea University, Seoul, 136-701, Korea
- Myong Ji University, Yongin City 449-728, Korea
- System Electronics Laboratory, Seoul National University, Seoul, South Korea
- Yonsei University, Seoul 120-749, Korea
- IHEP (Protvino), State Research Center of Russian Federation "Institute for High Energy Physics", Protvino 142281, Russia
- Joint Institute for Nuclear Research (JINR-Dubna), Dubna, Russia
- Kurchatov Institute, Moscow, Russia
- PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia
- Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Vorob'evy Gory, Moscow 119992, Russia
- Saint-Petersburg State Polytechnical Univiversity, Politechnicheskayastr, 29, St. Petersburg, 195251, Russia

PHENIX

13 Countries; 62 Institutions; 550 Participants*

- Lund University, Lund, Sweden
- Abilene Christian University, Abilene, Texas, USA
- Brookhaven National Laboratory (BNL), Upton, NY 11973, USA
- University of California - Riverside (UCR), Riverside, CA 92521, USA
- University of Colorado, Boulder, CO, USA
- Columbia University, Nevis Laboratories, Irvington, NY 10533, USA
- Florida Institute of Technology, Melbourne, FL 32901, USA
- Florida State University (FSU), Tallahassee, FL 32306, USA
- Georgia State University (GSU), Atlanta, GA, 30303, USA
- University of Illinois Urbana-Champaign, Urbana-Champaign, IL, USA
- Iowa State University (ISU) and Ames Laboratory, Ames, IA 50011, USA
- Los Alamos National Laboratory (LANL), Los Alamos, NM 87545, USA
- Lawrence Livermore National Laboratory (LLNL), Livermore, CA 94550, USA
- University of New Mexico, Albuquerque, New Mexico, USA
- New Mexico State University, Las Cruces, New Mexico, USA
- Department of Chemistry, State University of New York at Stony Brook (USB), Stony Brook, NY 11794, USA
- Department of Physics and Astronomy, State University of New York at Stony Brook (USB), Stony Brook, NY 11794, USA
- Oak Ridge National Laboratory (ORNL), Oak Ridge, TN 37831, USA
- University of Tennessee (UT), Knoxville, TN 37996, USA
- Vanderbilt University, Nashville, TN 37235, USA

*as of March 2005