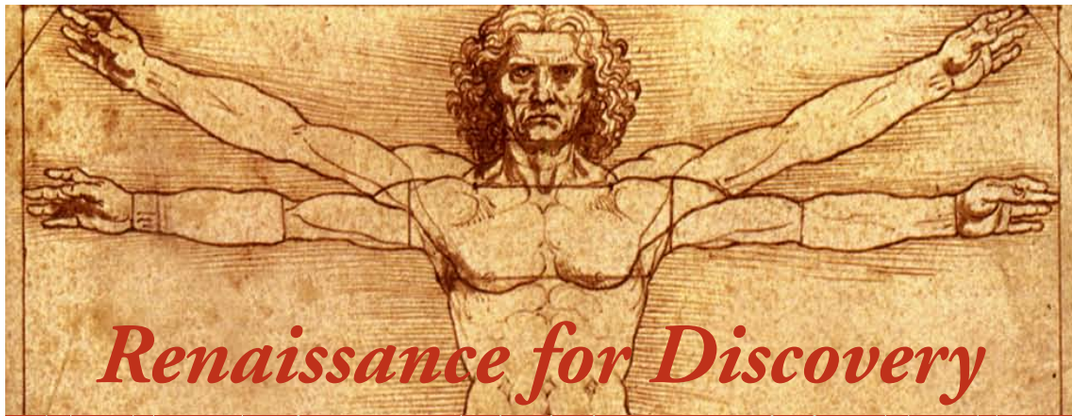
PHENIX HBT Measurements

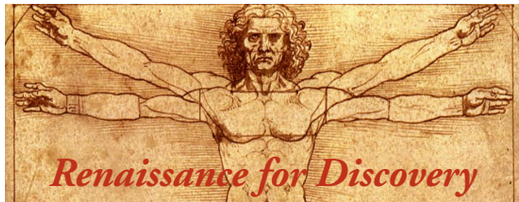
Jason Newby (LLNL)
for the PHENIX Collaboration

RHIC AGS Users' Meeting 2006



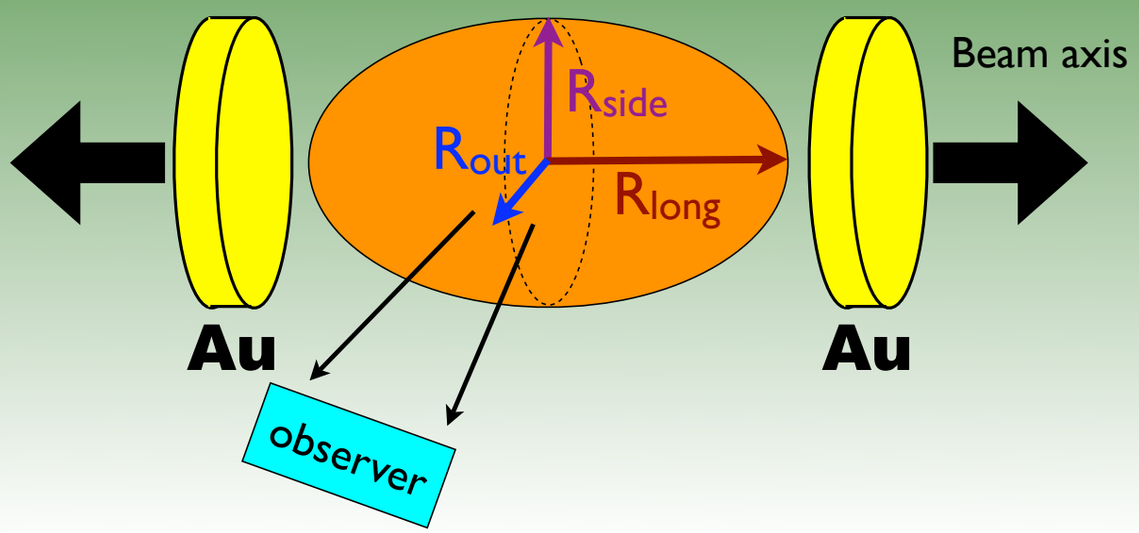
What does HBT offer?

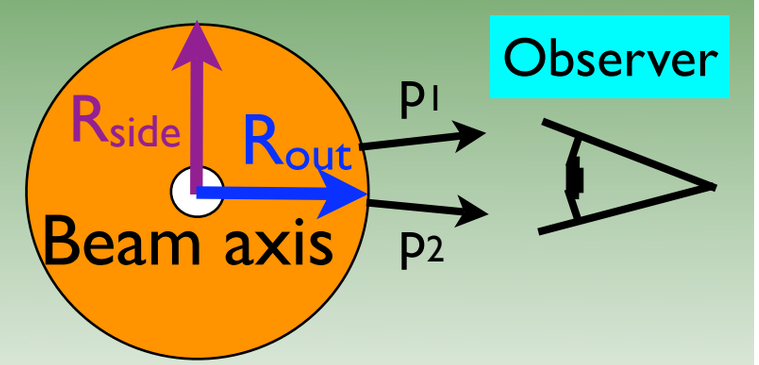
- Femtoscopy utilizes Quantum Statistical (BEC) or Final State Interactions (Coulomb, Strong) that dominate multi-particle correlations at small separations in phase space to measure space-time structure.
- Multi-particle Femtoscopy is the most direct measurement we have of the space-time evolution of Heavy Ion Collisions at the freeze-out surface.
- Assuming Gaussian profiles, 1D and 3D radii are extracted from two-particle correlations in momentum difference distributions.
- Emerging Imaging Techniques make no assumptions of the profile offering sensitivity to finer structure.

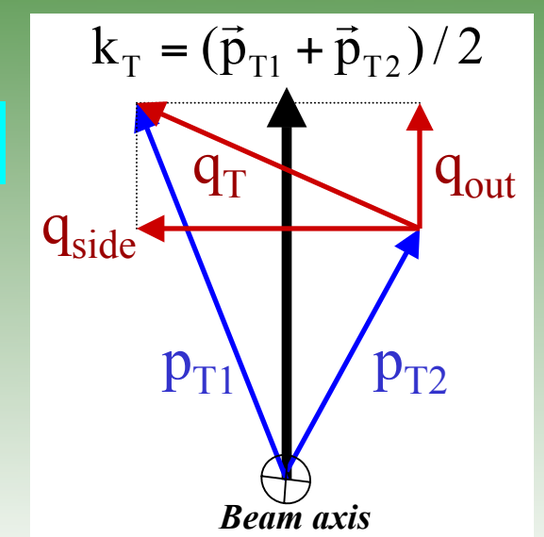


HBT in Heavy-Ions

Bertsch-Pratt parameterization







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

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

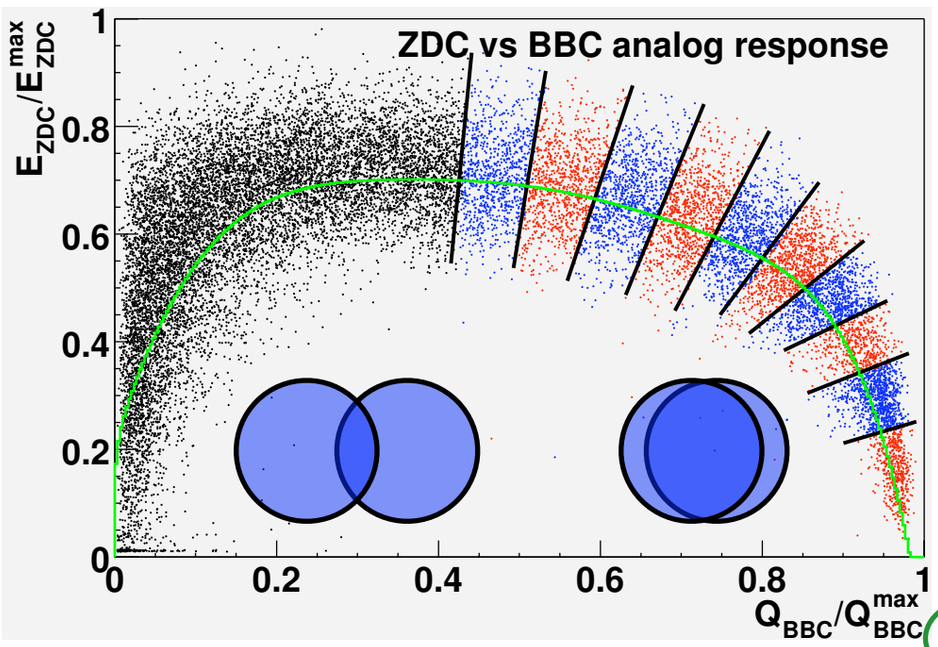
Fraction of Chaotic Emission

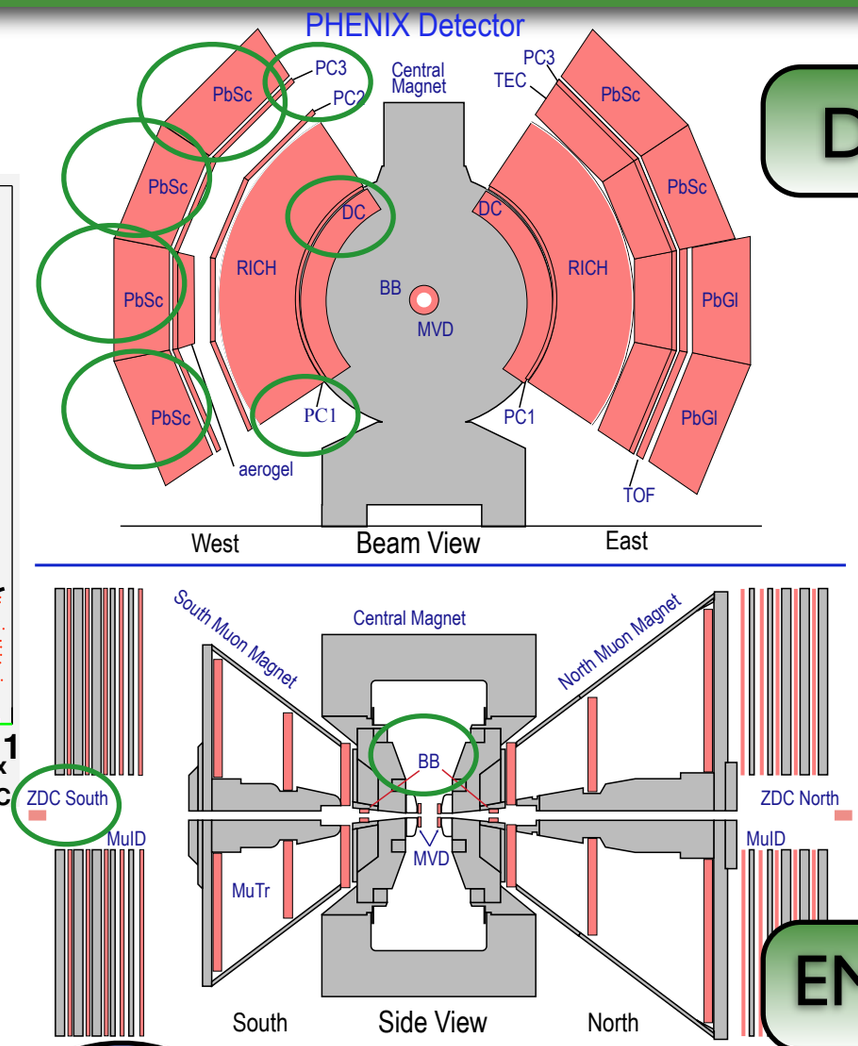
Coulomb Interaction

Halo of long lived resonances

PHENIX Detector

BBC/ZDC Centrality

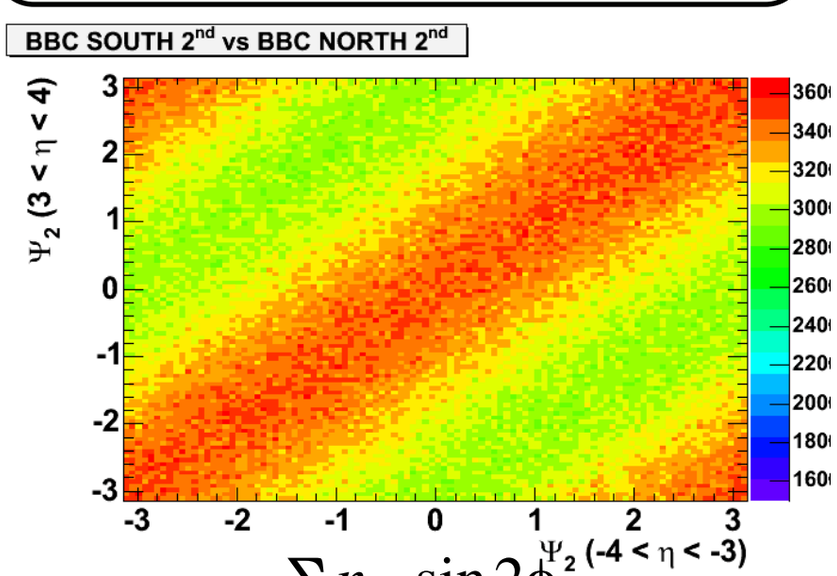


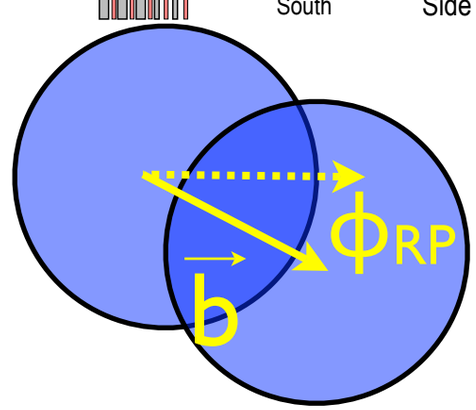


DC/PC Track-Mom Reco

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

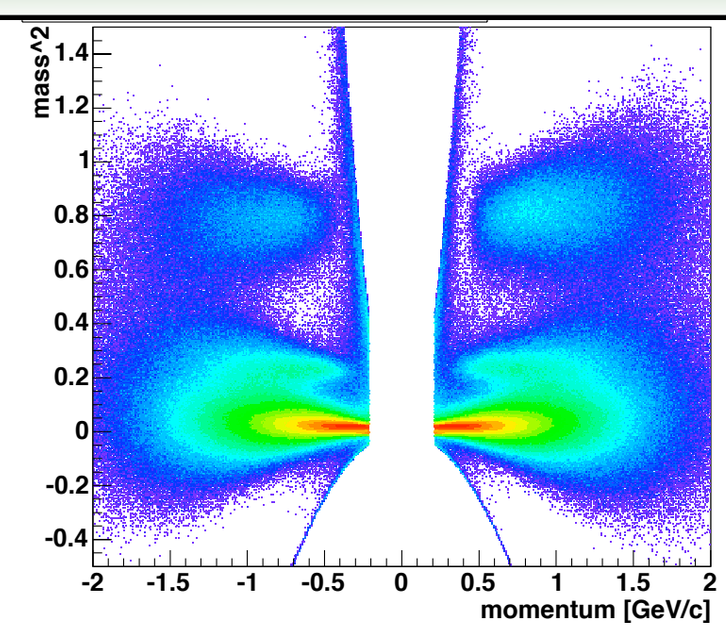
BBC Reaction Plane





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

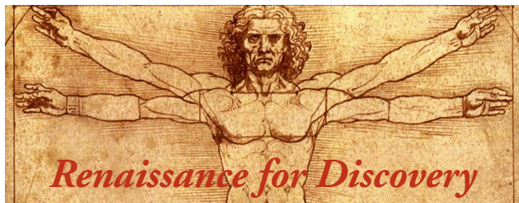
EMC Particle Identification



PHENIX HBT Overview

- PHENIX HBT analyses of $K^{+/-}$,$\pi^{+/-}$, p:
  - Gaussian 1D/3D Radii from C_2
    - Full/Partial Coulomb Correction
    - Bowler-Sinyukov Core-Halo
    - Full Koonin-Pratt
  - Levy Fits to 2/3 Particle Correlations
  - 1D Source Imaging

	$\pi^{+/-}$	$K^{+/-}$	p
Au+Au 130	3D (k_T)		
Run 2 Au+Au 200	3D (k_T,N_p)	1D	1D
Run 4 Au+Au 200	AzHBT 1D Image	3D 1D Image	

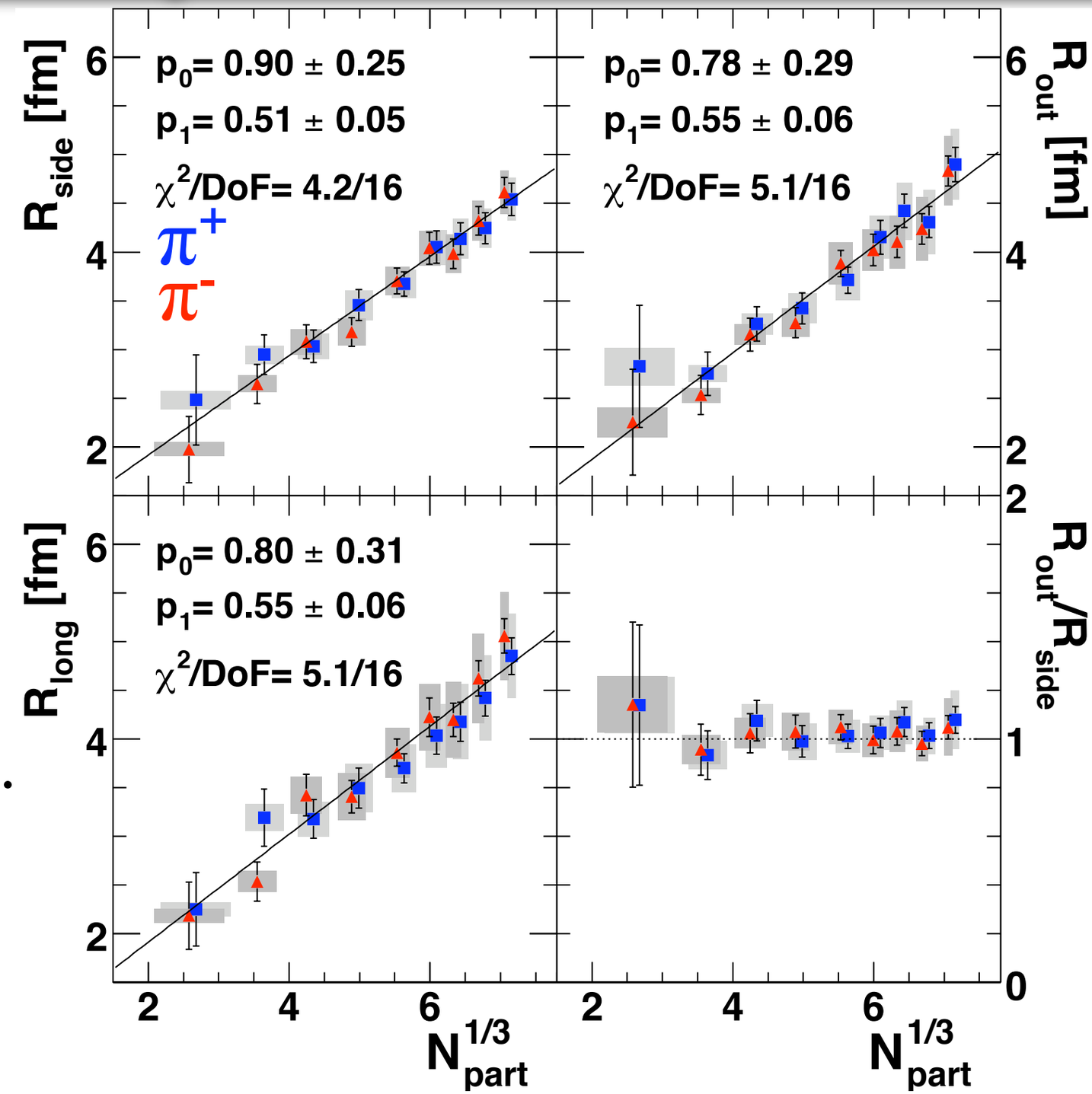


System Size Dependence

200 GeV Au+Au

PRL93(2004)152302

- Larger initial systems "appear" larger
- $N_p^{1/3}$ scaling of the pion source
- HBT Radii are dominated by geometric length scales.
- Expected long emission duration would increase R_{out}/R_{side} : not observed.



Kaon Participant Scaling

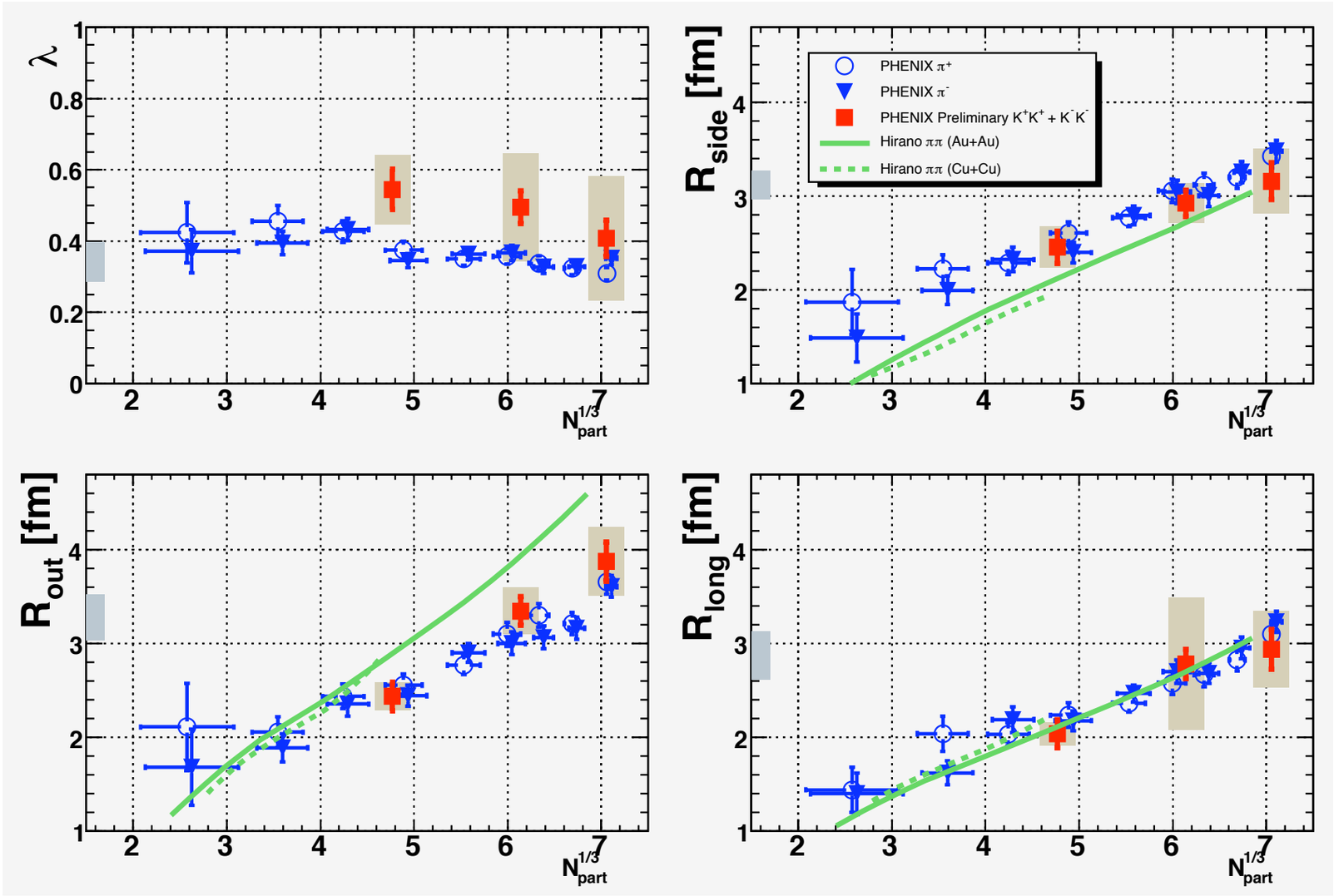
Au+Au 200 GeV

Pion $\langle m_T \rangle = 0.47$

Kaon $\langle m_T \rangle = 0.89$

R_{out} , R_{side} scaled to match kaon $\langle m_T \rangle$

Hydro agreement with data is quite good.



A. Enokizono, DNP Maui 2005

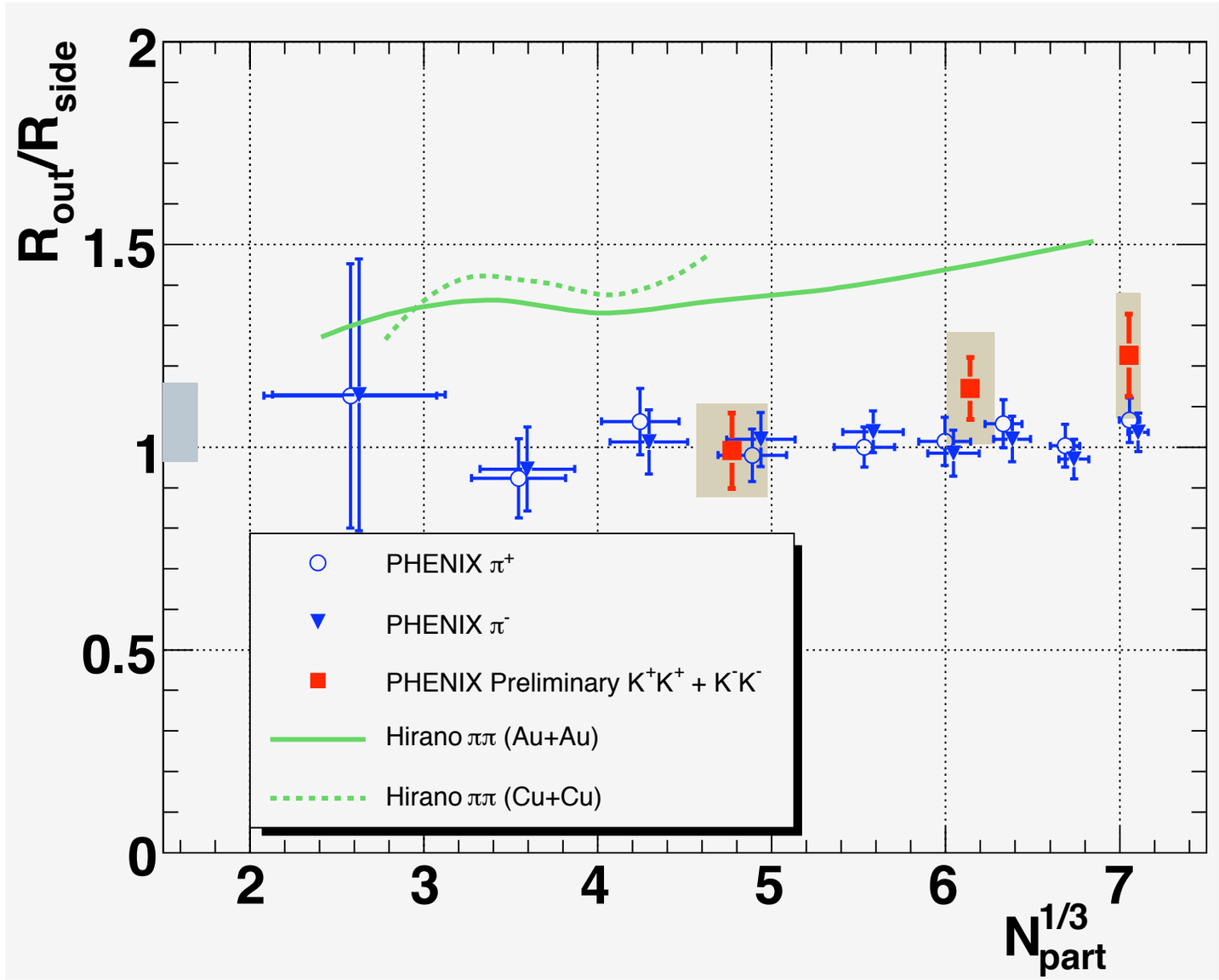
(T.Hirano, Y.Nara, Partial Chemical Freeze-out, NPA743('04)305)

Kaon R_{out}/R_{side}

Au+Au 200 GeV

Pion $\langle m_T \rangle = 0.47$
Kaon $\langle m_T \rangle = 0.89$

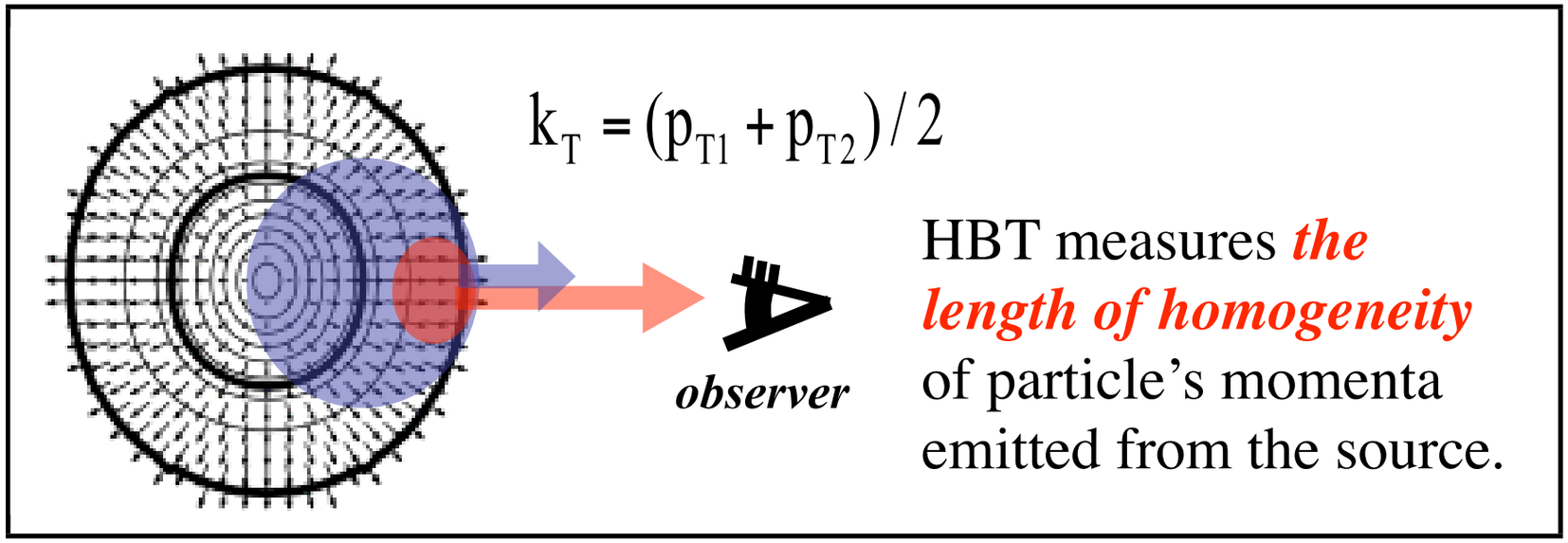
R_{out} , R_{side} scaled to match kaon $\langle m_T \rangle$



"Hint" of $R_{out}/R_{side} > 1$ for central collsions.

A. Enokizono, DNP Maui 2005
(T.Hirano, Y.Nara, Partial Chemical Freeze-out, NPA743('04)305)

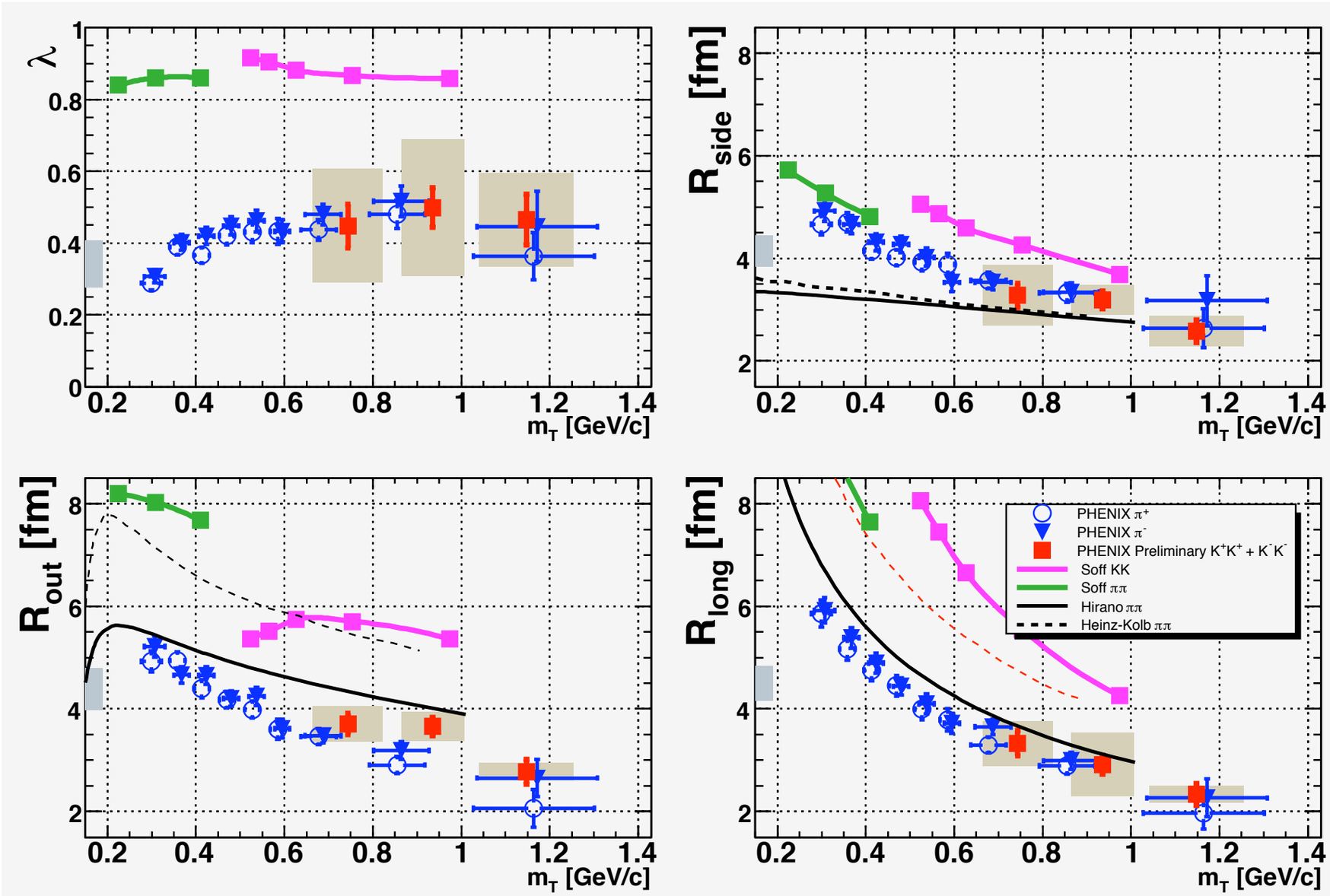
x-p Correlations



- HBT actually measures the space-time structure of "regions of homogeneity"
- Relativistic Expansion reduces the length of homogeneity for high momentum pairs.

$$R_{long} \propto \frac{1}{\sqrt{m_T}}$$

Kaon m_T Dependence



A. Enokizono, DNP Maui 2005

Hydro+UrQMD Tc=160MeV

(S. Soff, hep-ph/0202240)

3D Hydro

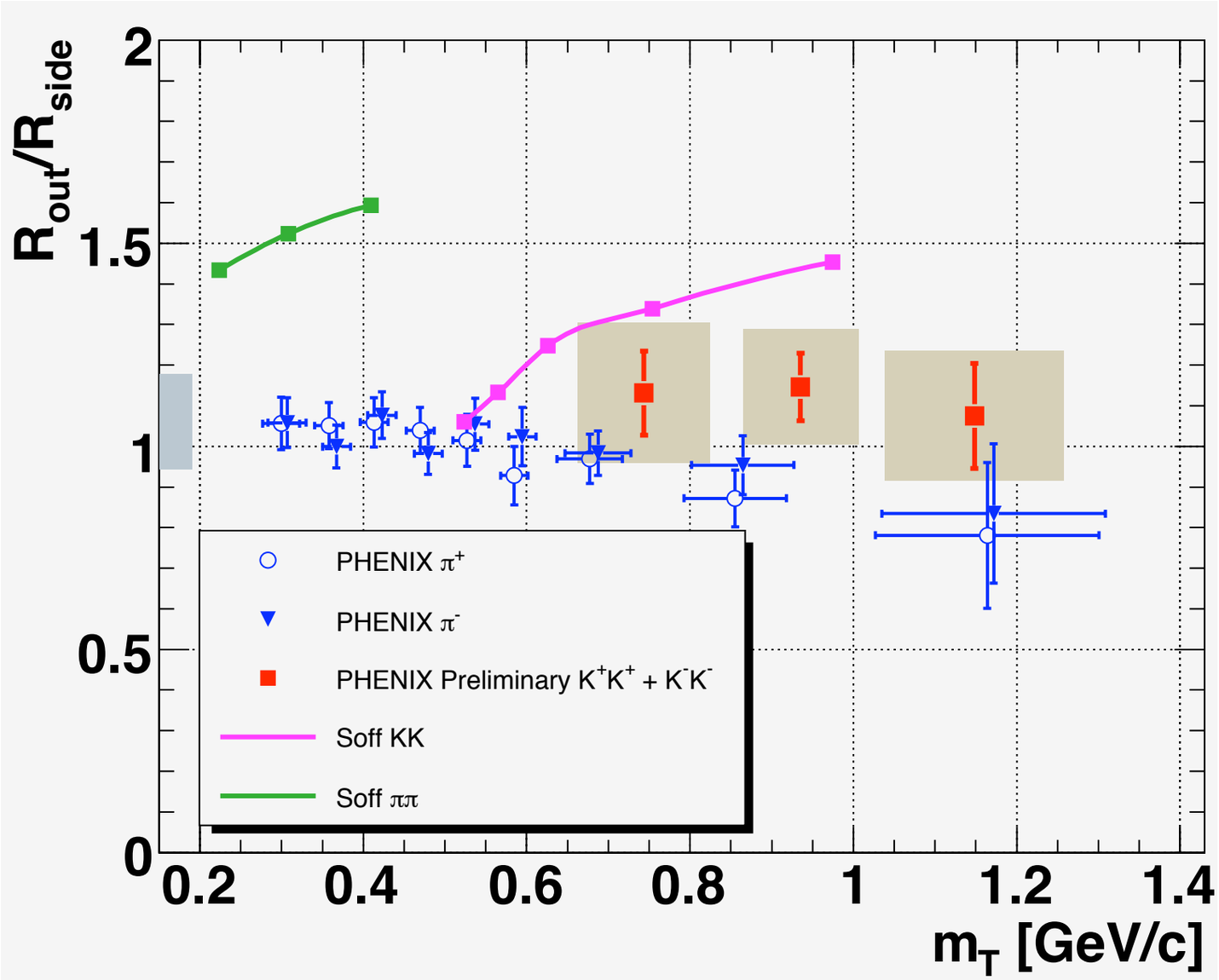
Hirano, PRC66(2002)054905

2D+1 Hydro

Heinz-Kolb, hep-ph/0204061

Small rescattering in hadronic phase.

R_{out}/R_{side} m_T Dependance

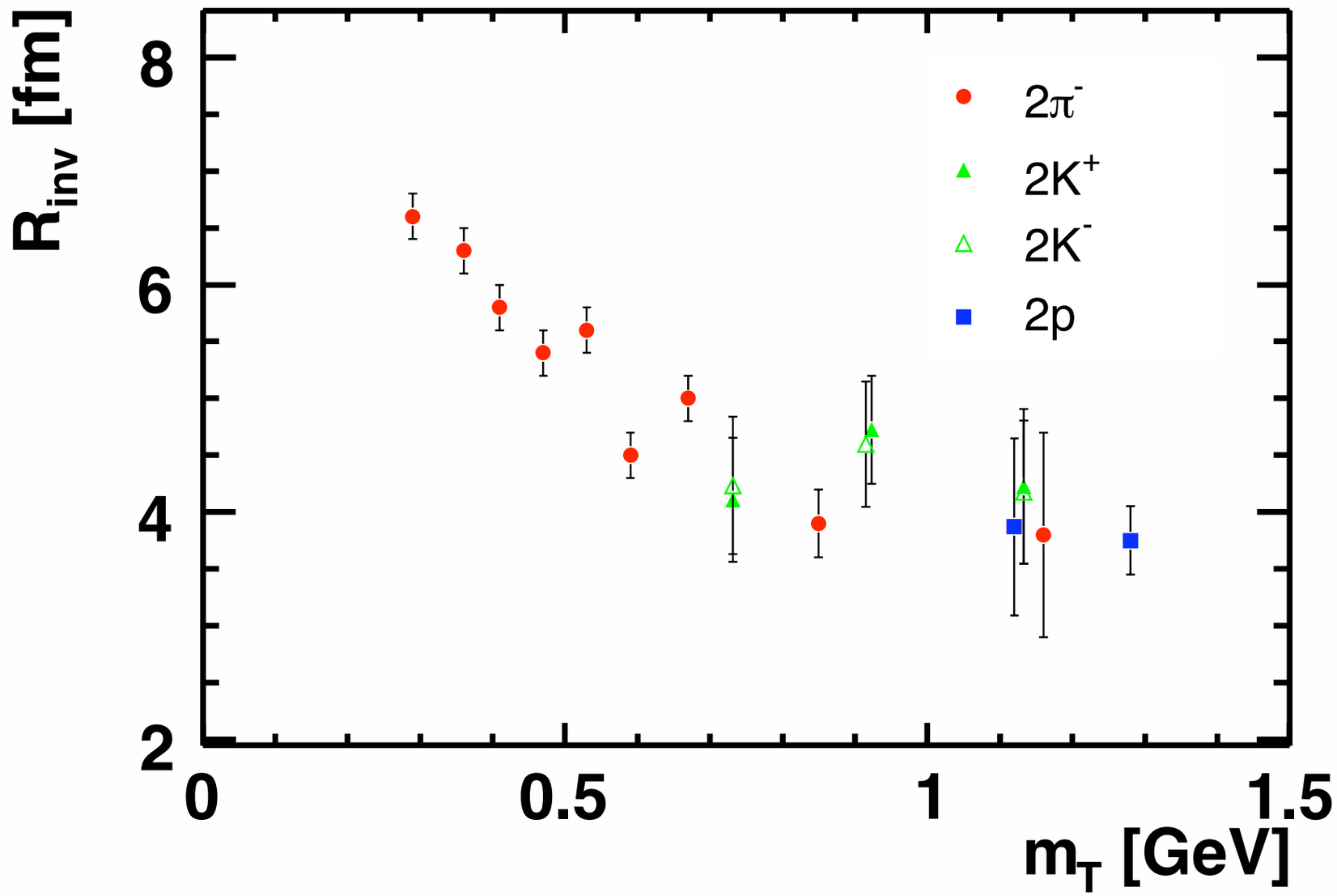


A. Enokizono, DNP Maui 2005

Hydro+UrQMD (S. Soff, hep-ph/0202240, Tc=160MeV)

Kaons give no indication of long emission duration

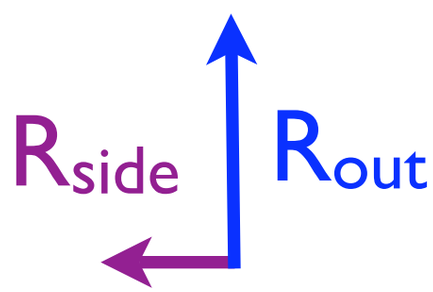
1D Species Dependence



Protons follow the pion and kaon trend.
No species dependence observed.

Azimuthal HBT

Out-of-Plane Observer
$\Phi = 90^\circ$



Heinz et al. PRC66,044903(2002)

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

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

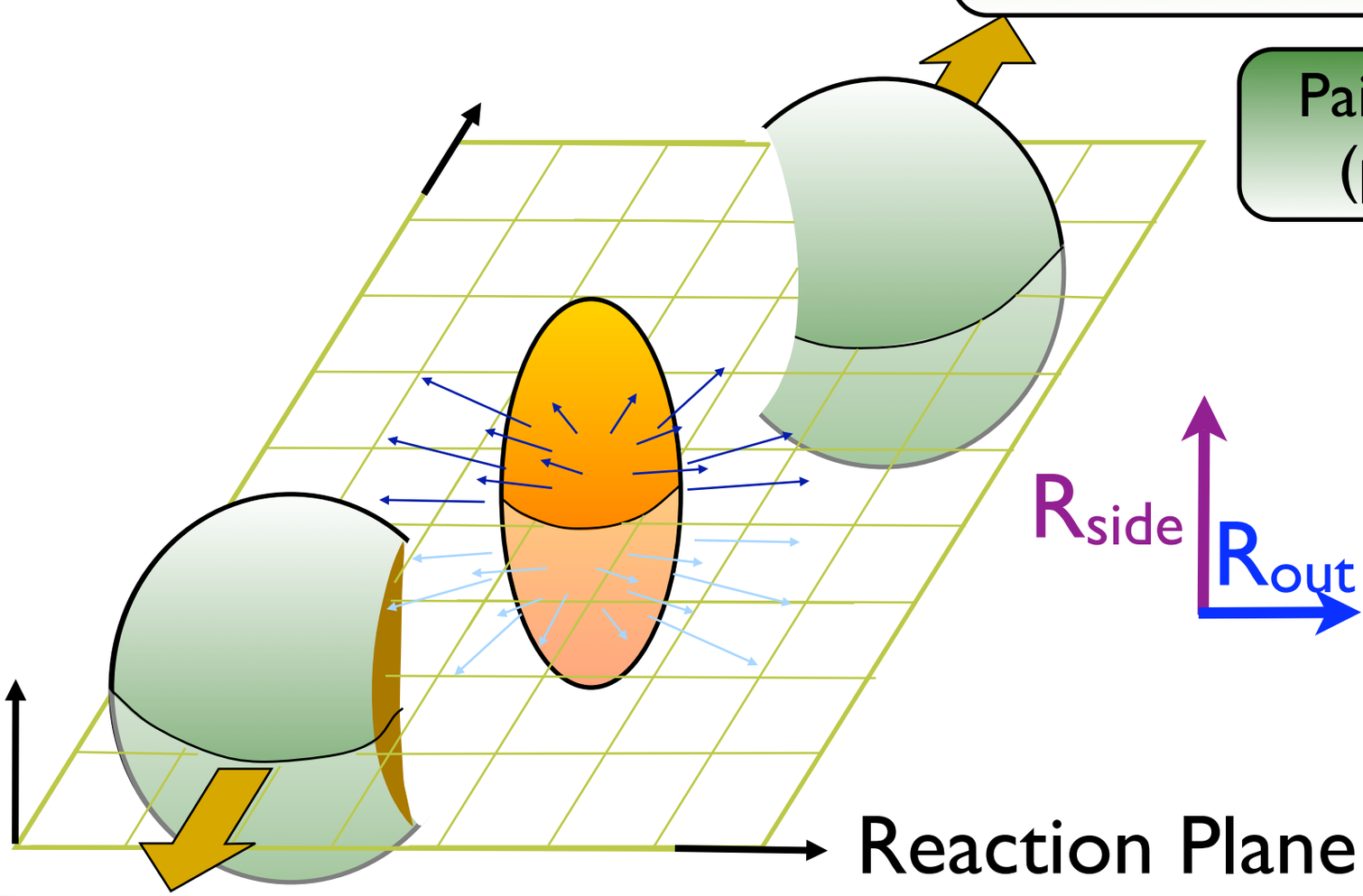
$$R_{so}^2(\Phi) = R_{so,0}^2 + R_{so,n}^2 \sin(n\Phi)$$

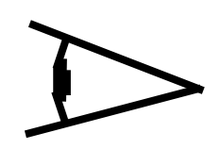
$$R_{os,2}=0 \qquad R_{os,2}>0$$

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

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

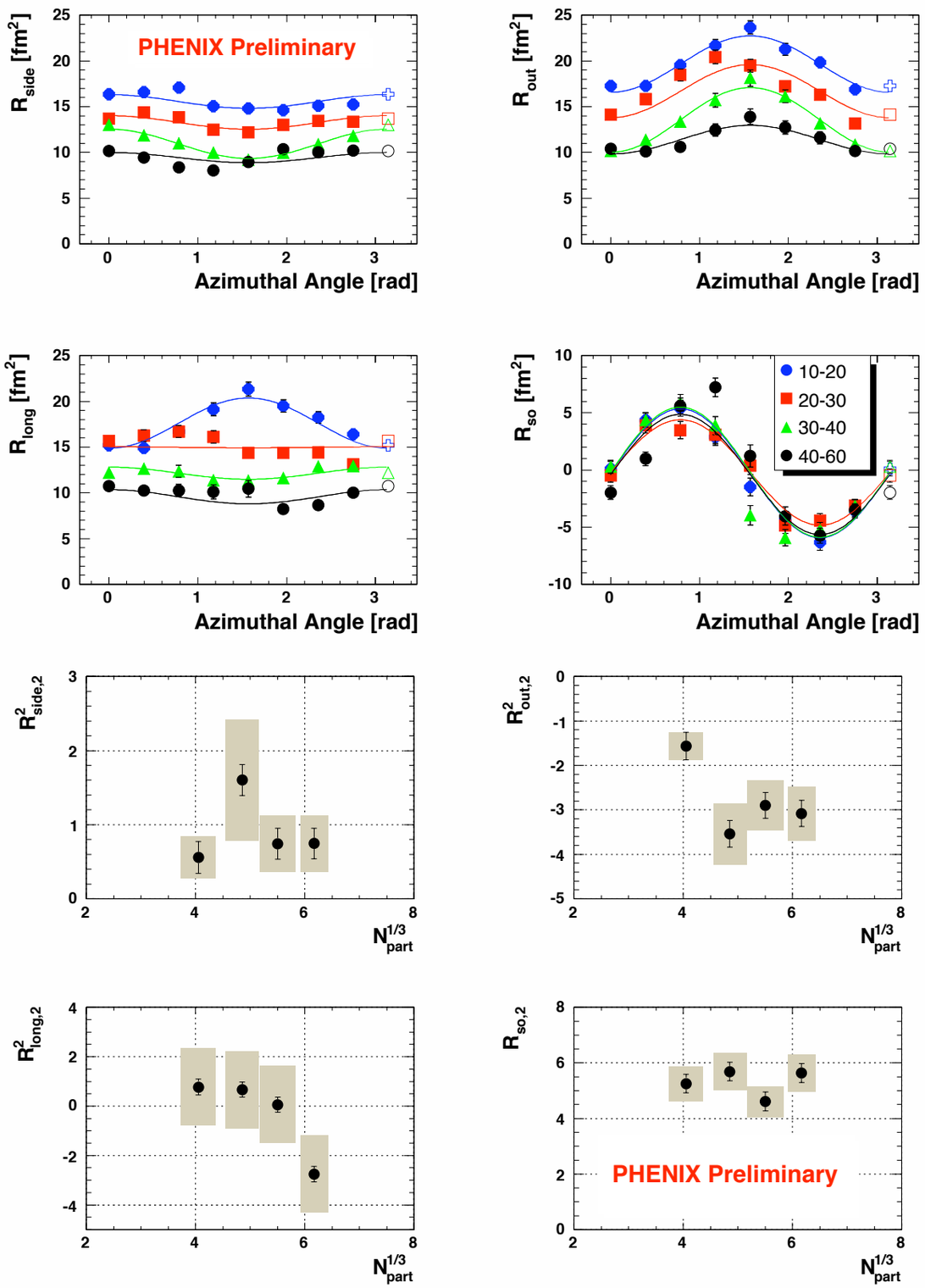
$$\varepsilon = \frac{\langle y^2\rangle - \langle x^2\rangle}{\langle y^2\rangle + \langle x^2\rangle} \approx \frac{2R_{s,2}^2}{R_{s,0}^2}$$



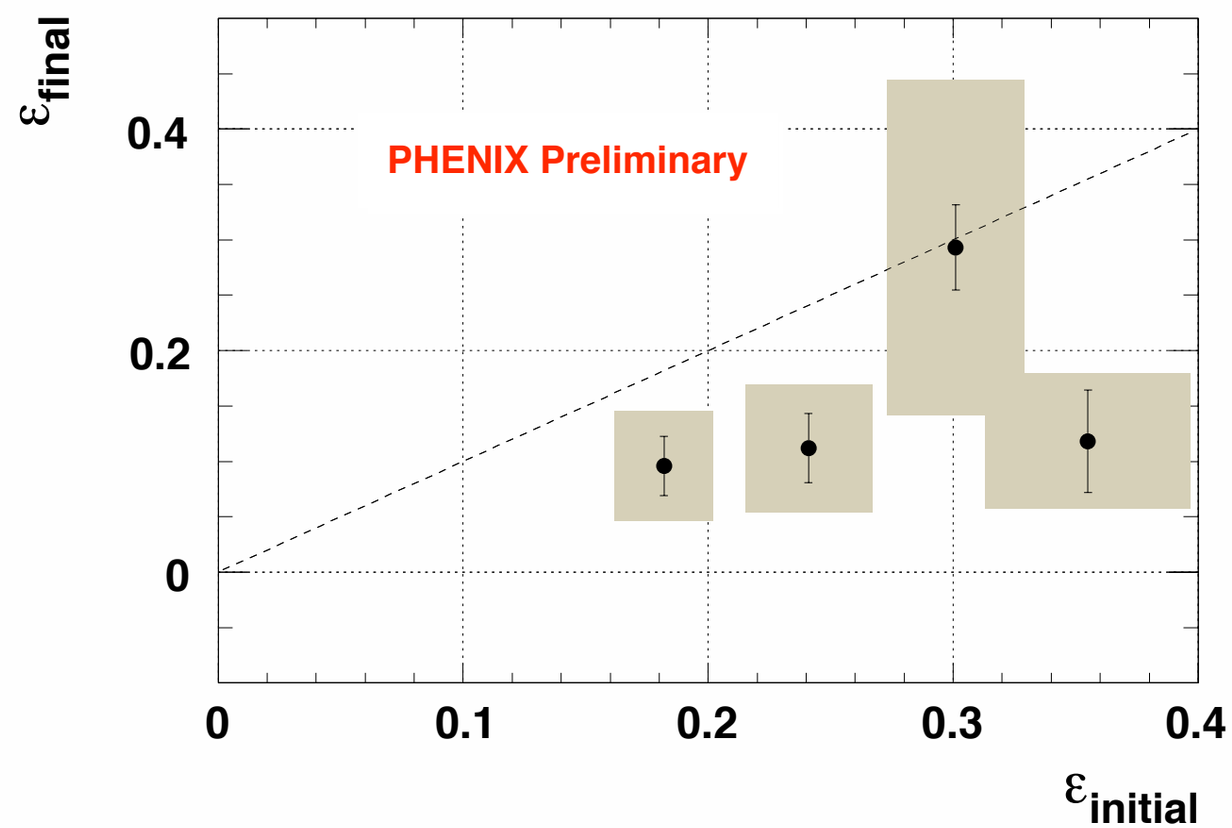


In-Plane Observer
$\Phi = 0^\circ$

Eccentricity Final State vs Initial



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



Final state eccentricity ~ ⅓ to ½ of initial eccentricity.

Reduction of systematic errors in progress.

Testing the Core-Halo

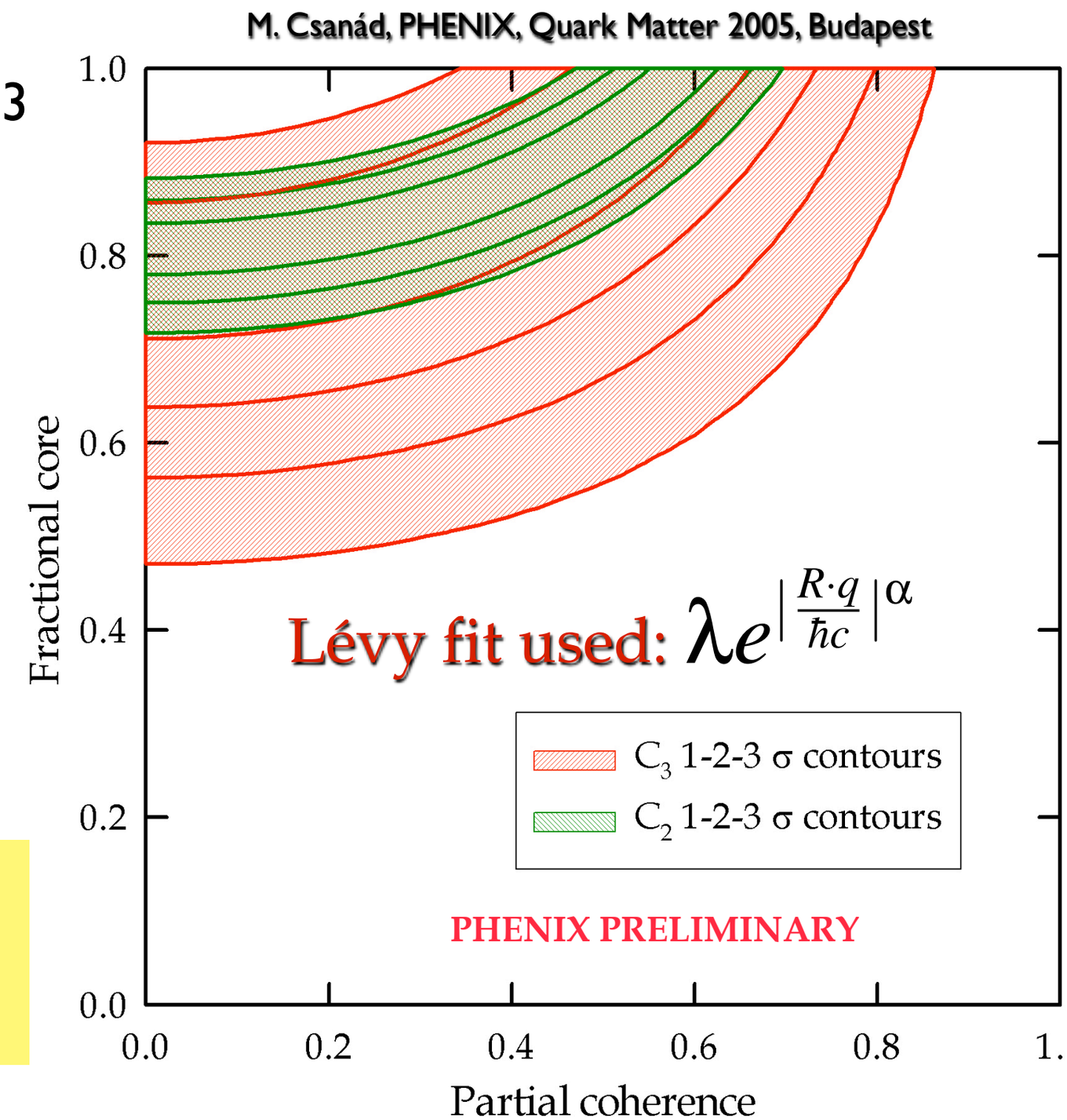
- λ from π-π C_2 and C_3
- Constrain coherent and extended source contributions

hep-ph/0001233, Nucl. Phys. B329 (1990) 357

$$f_c(p) = N_c(p)/N_1(p)$$
$$p_c(p) = N_c^p(p)/N_c(p)$$

$N_1(p)$ … Invariant mom. distr.
$N_c(p)$ … Core fraction
$N_c^p(p)$ … Part. coh. fraction

λ alone - unable to unambiguously distinguish resonance contribution vs extended source



$$C_2(p_1 \simeq p_2) = 1 + f_c^2[(1-p_c)^2 + 2p_c(1-p_c)]$$
$$C_3(p_1 \simeq p_2 \simeq p_3) = 1 + 3f_c^2[(1-p_c)^2 + 2p_c(1-p_c)] + 2f_c^3[(1-p_c)^3 + 3p_c(1-p_c)^2]$$

Source Imaging

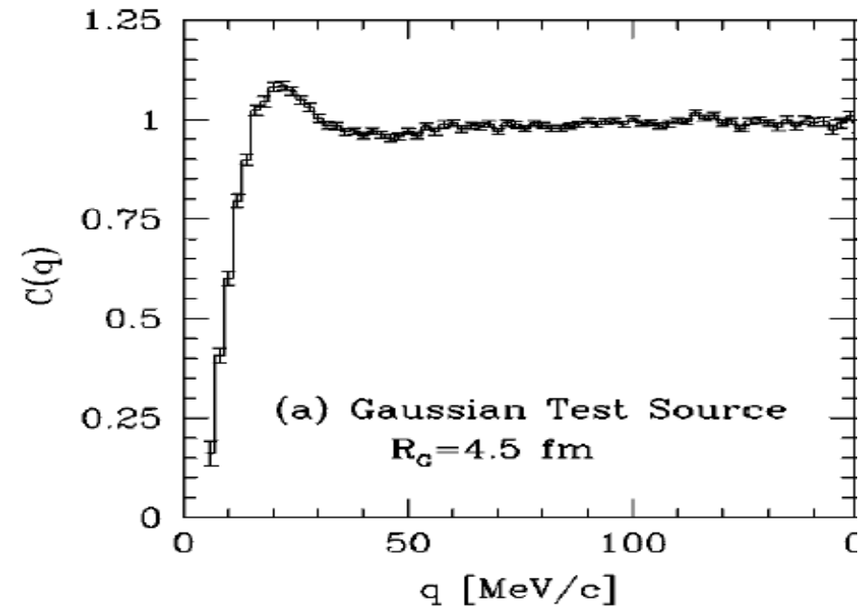
$$R^{\text{obs}}_{\vec{P}}(\vec{q}) \equiv C^{\text{obs}}_{\vec{P}}(\vec{q}) - 1 = \int d\vec{r} K(\vec{q},\vec{r}) S_{\vec{P}}(\vec{r})$$

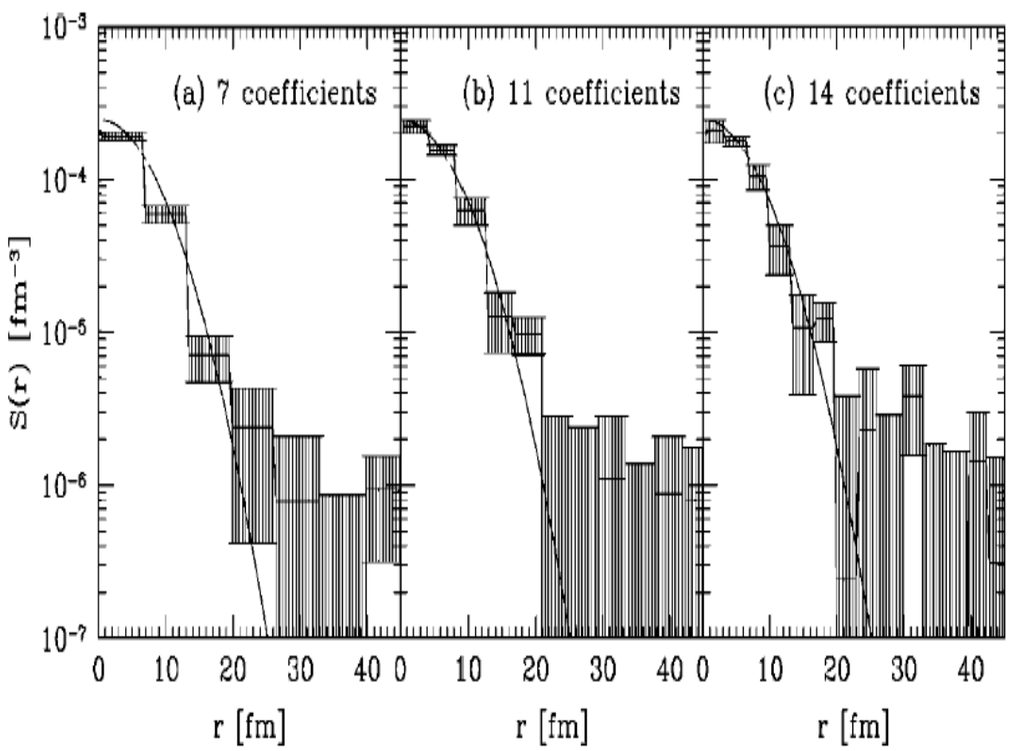
$$K(\vec{q},\vec{r}) = \left|\Phi_{\vec{q}}(\vec{r})\right|^2 - 1$$

is kernel which can be calculated from BEC and known final state interactions of pairs.

$$S_{\vec{P}}(\vec{r})$$

is source function which represents the emission probability of pairs at r in the pair CM frame.





S(r) is expanded in a function basis.

$$S(\mathrm{r}) = \sum_{i=1}^{N_M} S_i B_i(\mathrm{r}) \qquad \Delta S(\mathrm{r}) = \sqrt{\sum_{i,j=1}^{N_M} \Delta^2 S_{ij} B_i(\mathrm{r}) B_j(\mathrm{r})}$$

Imaging by minimization of χ^2

$$\div^2 = \sum_i \left(R_i^{\text{obs}} - \sum_j K_{ij} S_j\right)^2 \Big/ \ {}^2 R_{ii}^{\text{obs}}$$

Most probable source function is

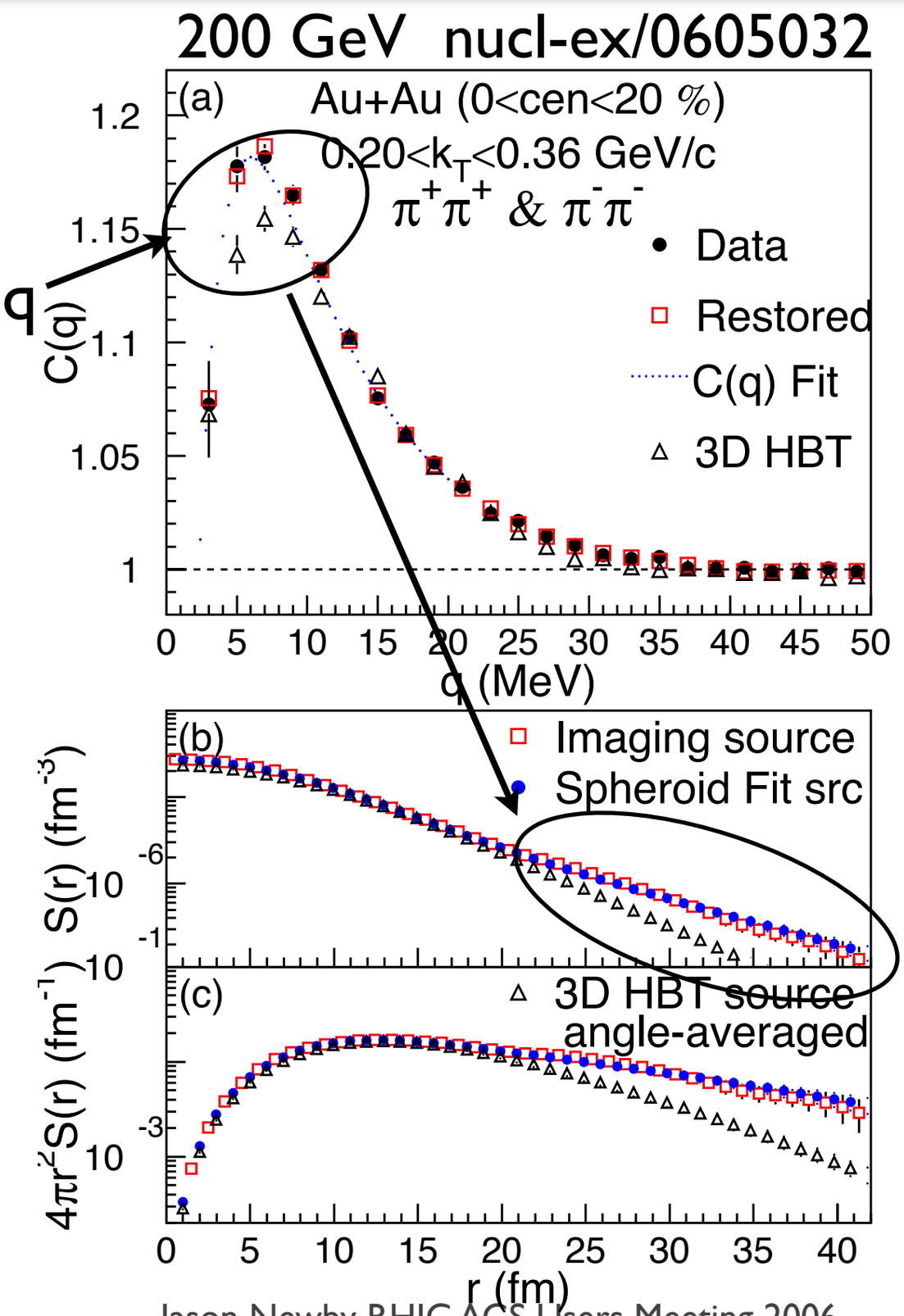
$$S = \ddot{A}^2 S \times K^T \times (\ddot{A}^2 R^{\text{obs}})^{-1} \times R^{\text{obs}}$$

$$\ddot{A}^2 S = \left(K^T \times (\ddot{A}^2 R^{\text{obs}})^{-1} \times K\right)^{-1}$$

D.A. Brown and P. Danielewicz
Phys. Rev. C. 64, 014902 (2001)

Measured 1D Source Image

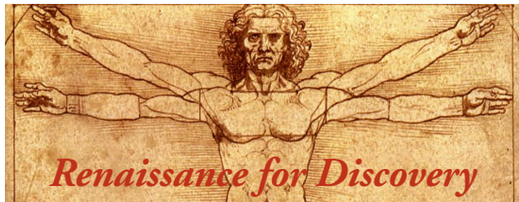
Excess at small q



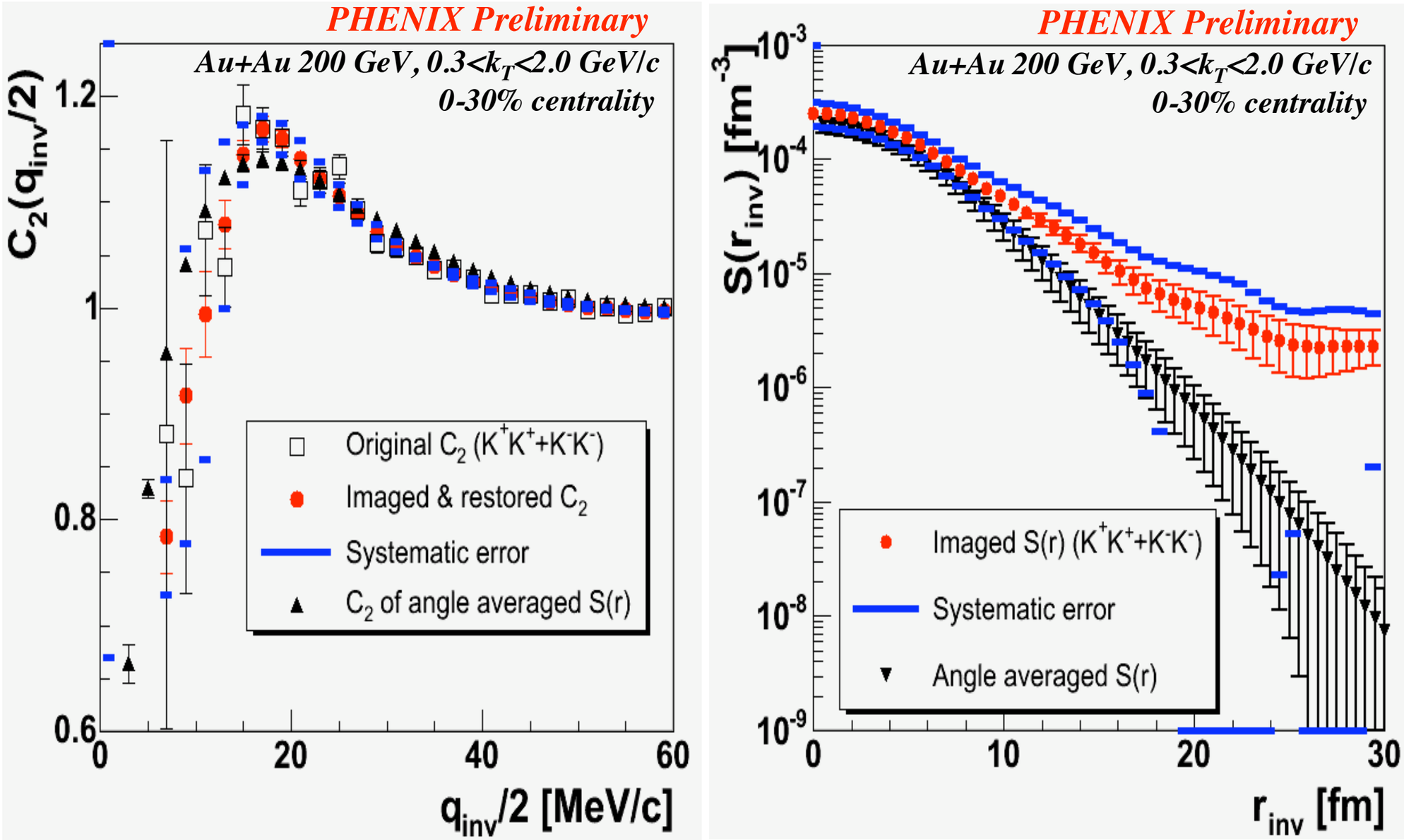
$$S(r) = \frac{\lambda\, R_{\rm eff} \times e^{-\frac{r^2}{4R_T^2}}\, \mathrm{erfi}(\frac{r}{2R_{\rm eff}})}{(8\pi R_T^2 R_0 r)}$$

Brown *et al.* PRC64(2001)014902

⇒Excess at large R



Kaon ID Source Image

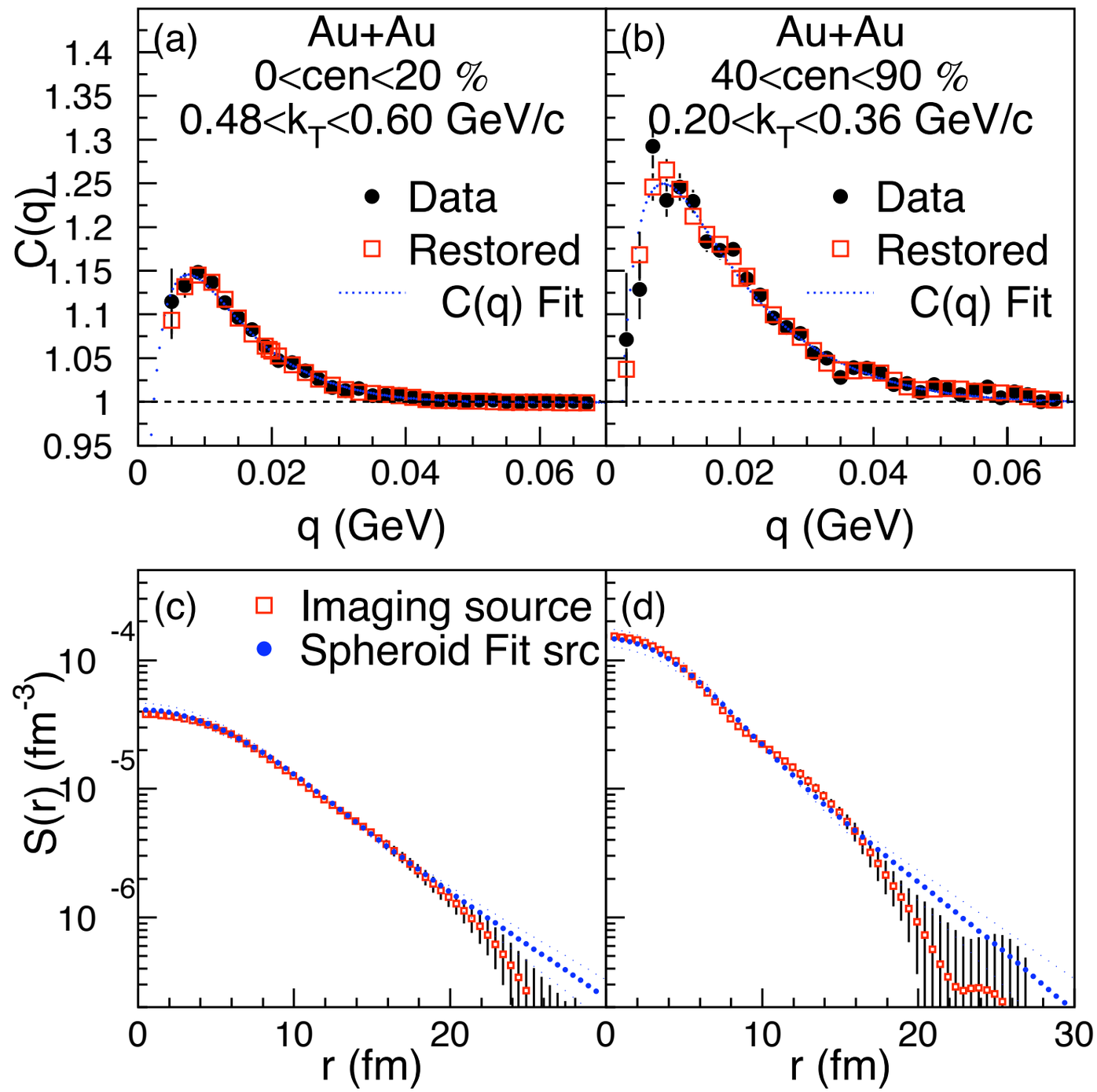


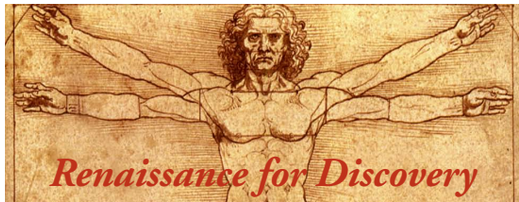
A. Enokizono, DNP Maui 2005

Kaon source image also has hint of long-range compontent.

Can we isolate the excess?

Long Range source not equally present in all kinematic regions.



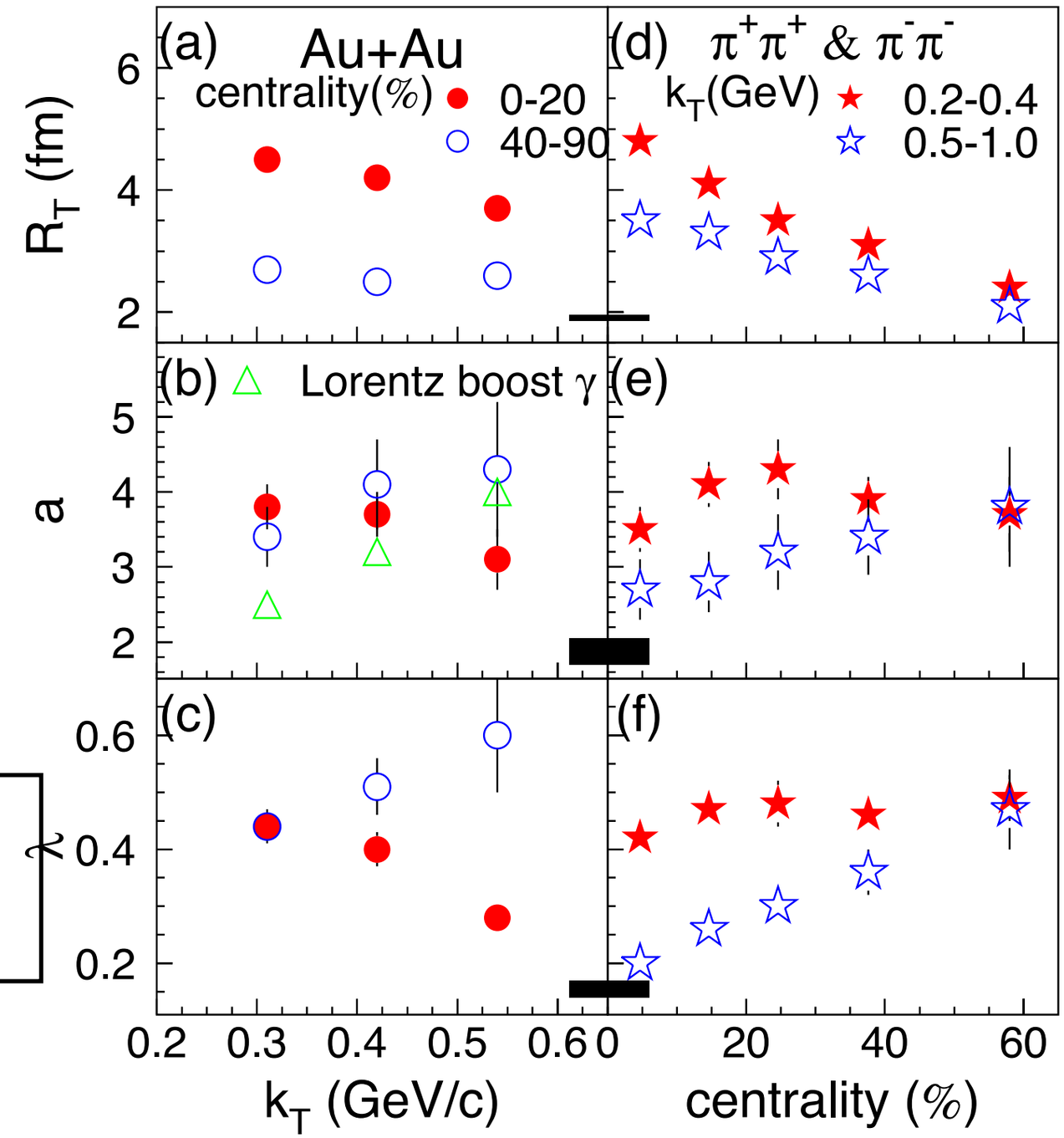


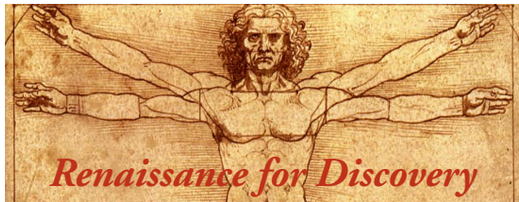
k_T, Centrality Systematics

Long Range contribution most prominent at low-k_T and in most central collisions.

$$R_O = a \times R_T$$

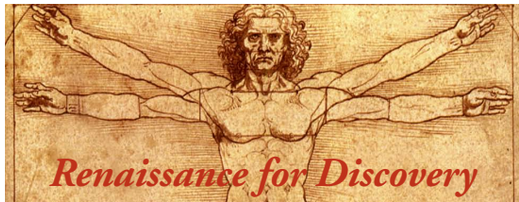
λ fraction of π pairs contributing to the source





Summary

- PHENIX has measured two-particle correlations of π's, K's, and protons and three-particle correlations for π's.
- 2π and 2K source radii demonstrate consistent $N_p^{1/3}$ scaling.
- 2π, 2K, and 2p 1D source Radii demonstrate consistent m_T scaling.
- 2π and 2K 3D source radii demonstrate consistent m_T scaling without indication of long emission duration nor significant hadronic rescattering.
- 1D Imaging analyses of 2π indicate long range component that is most strongly present at low-k_T and central collisions.
- Preliminary 1D Imaging analyses of 2K are also consistent with long range component.
- Images from Hydrodynamic calculations should be quantitatively compared with experimental images.



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PHENIX

13 Countries; 62 Institutions; 550 Participants*

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- University of Colorado, Boulder, CO, USA
- Columbia University, Nevis Laboratories, Irvington, NY 10533, USA
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