Kaon Freeze-out Dynamics in $\sqrt{s_{NN}}$=200 GeV Au+Au Collisions at RHIC*

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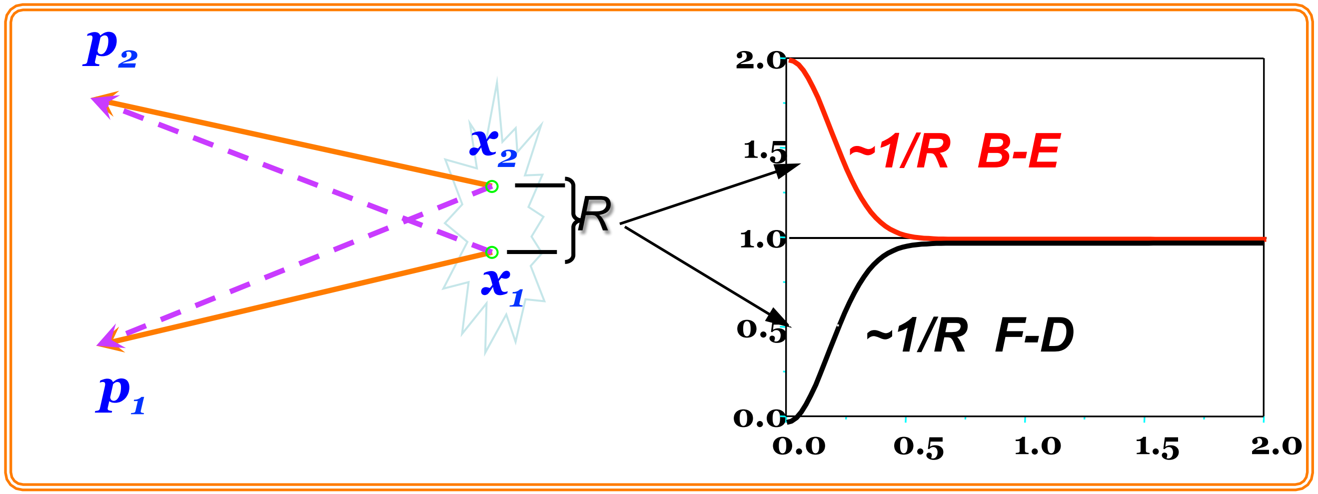
*) arXiv:1302.3168 [nucl-ex] accepted in Phys. Rev. C

Correlation femtoscopy in a nutshell (1/3)



$$C^{ab}_{\vec{P}}(\vec{q}) = \frac{d^6N^{ab}/(dp_a^3 dp_b^3)}{\left(d^3N^a/dp_a^3\right)\left(d^3N^b/dp_b^3\right)}$$

$$\vec{P} = \vec{p}_a + \vec{p}_b$$

$$\vec{q} = \frac{1}{2}(\vec{p}_a - \vec{p}_b)$$

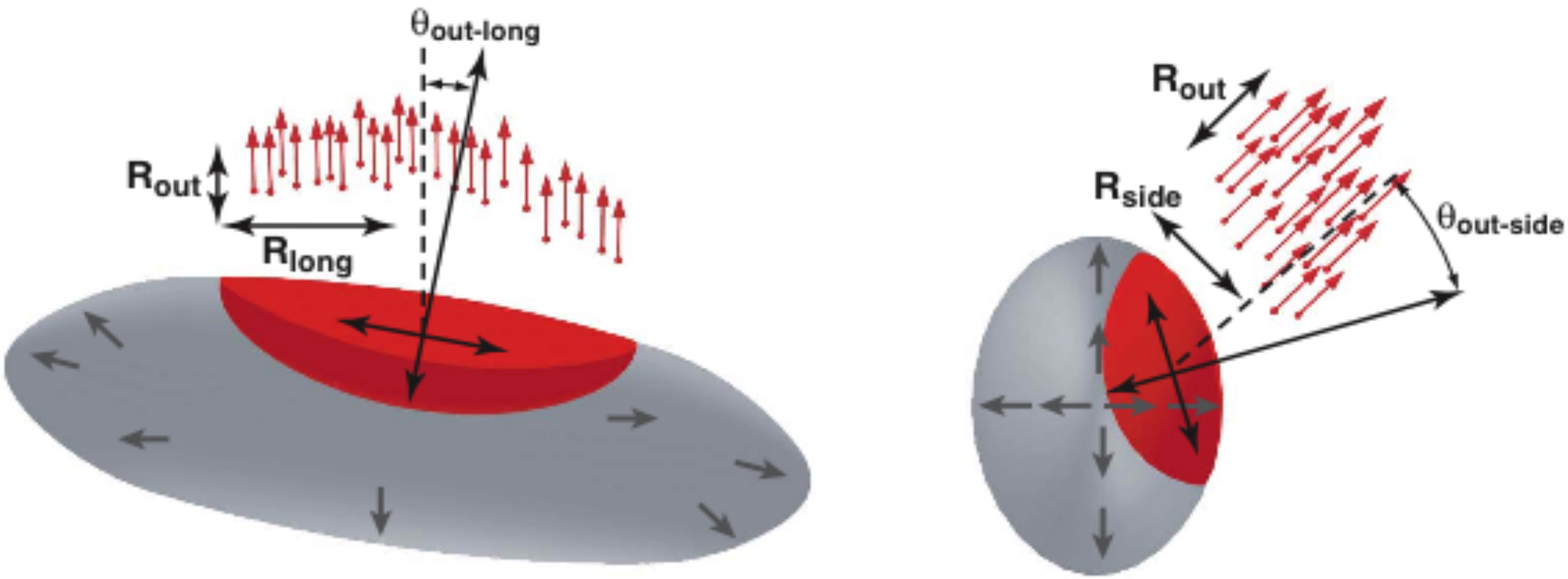
Correlation function of two identical bosons/fermions at small momentum difference q shows effect of quantum statistics.

Height/depth of the B-E/F-D bump λ is related to the fraction ($\lambda^{1/2}$) of particles participating in the enhancement.

Its width scales with the emission radius as R^{-1}.

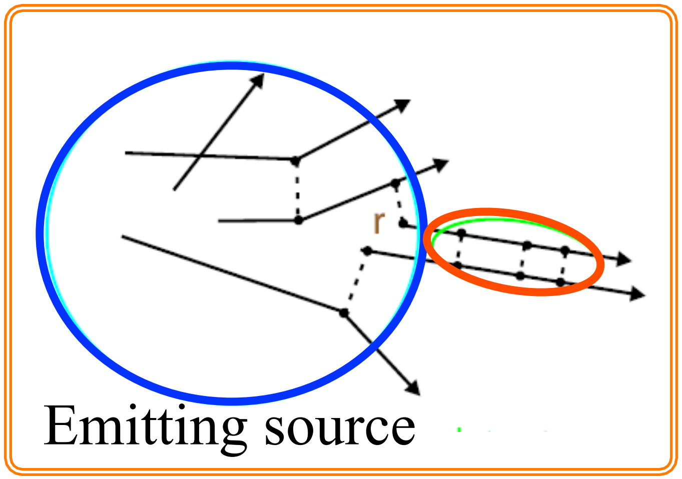
Correlation femtoscopy in a nutshell (2/3)

The correlation is determined by the size of region from which particles with roughly the same velocity are emitted



⇒ Femtoscopy measures size, shape, and orientation of homogeneity regions

Correlation femtoscopy in a nutshell (3/3)



1D Koonin-Pratt equation

$$C(q)-1=4\pi\int K(q,r)S(r)r^2\,dr$$

Correlation function

Encodes FSI

Source function (Distribution of pair separations in the pair rest frame)

Kernel K(q,r) is independent of freeze-out conditions

S(r) is often assumed to be Gaussian ⇒ HBT radii

Other option: Inversion of linear integral equation to obtain source function

⇒ Model-independent analysis of emission shape (goes beyond Gaussian shape assumption)

Source Imaging

Technique devised by
D. Brown and P. Danielewicz
PLB398:252, 1997
PRC57:2474, 1998

Geometric information from imaging.

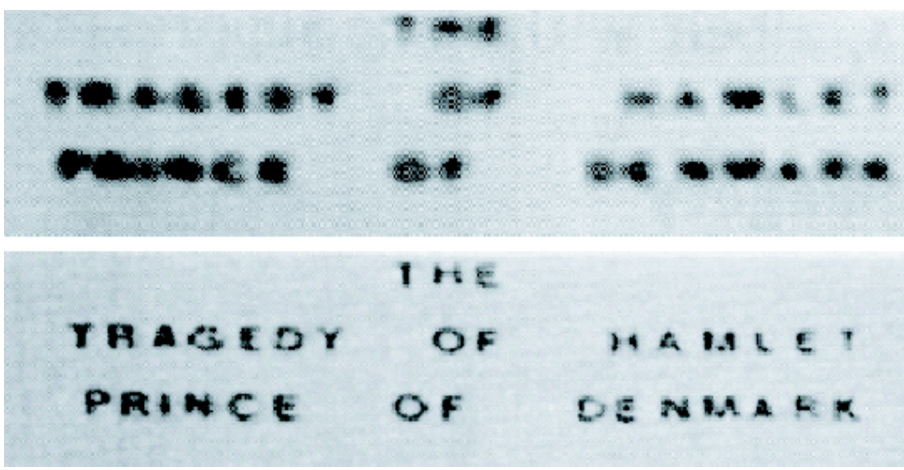
$$R(q) = \int K(q,r) S(r) r^2 \, dr$$

General task:
From data w/errors, R(q), determine the source S(r).
Requires inversion of the kernel K.

Optical recognition: K - blurring function, max entropy method

R:

S:



Any determination of source characteristics from data, unaided by reaction theory, is an imaging.

Inversion procedure

$$R(q) \equiv C(q) - 1 = 4\pi \int dr r^2 K(q,r) S(r)$$

$$K(q,r) = \frac{1}{2} \int d\cos\theta_{\vec{q},\vec{r}} \left[\left| \phi(\vec{q},\vec{r}) \right|^2 - 1 \right]$$

Freeze-out occurs after the last scattering. ⟹ Only Coulomb & quantum statistics effects included in the kernel.

Expand into B-spline basis

$$S(r) = \sum_j S_j \cdot B_j(r)$$

$$C^{Th}(q_i) = \sum_j K_{ij} \cdot S_j$$

$$K_{ij} = \int dr \cdot K(q_i, r) B_j(r)$$

Vary S_j to minimize χ^2

$$\chi^2 = \frac{\left(C^{Expt}(q_i) - \sum_j K_{ij} \cdot S_j \right)^2}{\left(\Delta C^{Expt}(q_i) \right)^2}$$

D. A. Brown, P. Danielewicz: UCRL-MA-147919

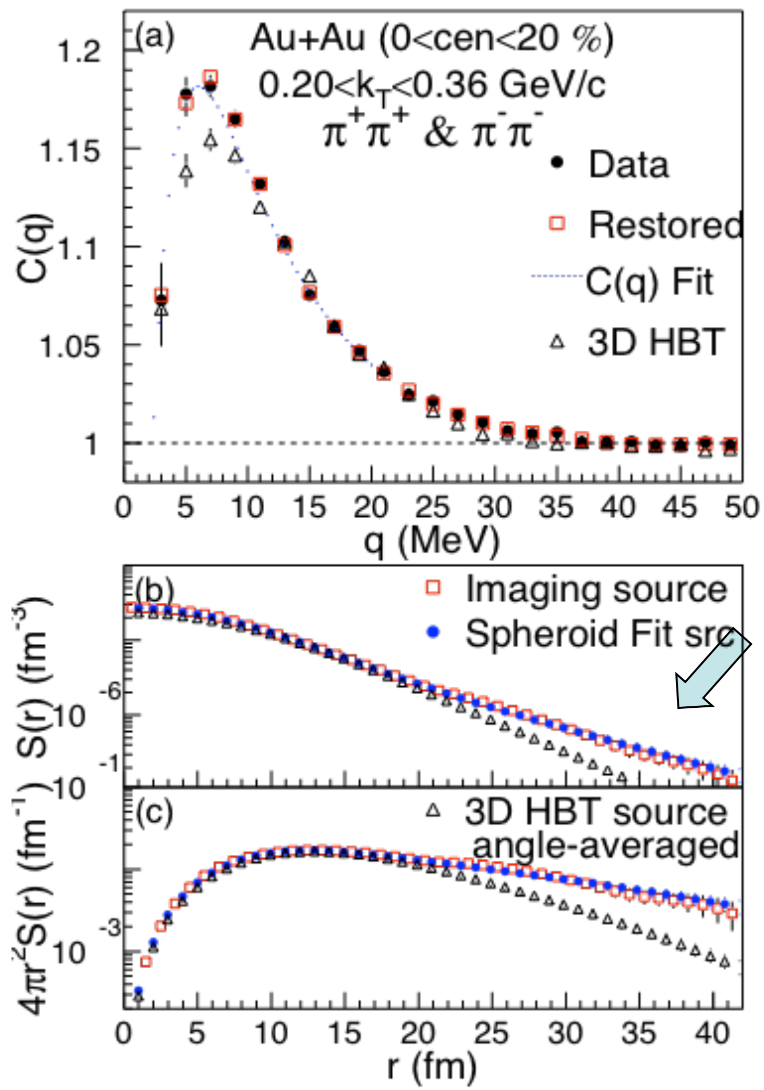
Why Kaons?

- Pion source shows a heavy, non-Gaussian tail
- Interpretation is problematic

  Tail attributed to decays of long-lived resonances, non-zero emission duration etc.
- Kaons: cleaner probe

  less contribution from resonances
- PHENIX 1D kaon result shows also a long non-Gaussian tail

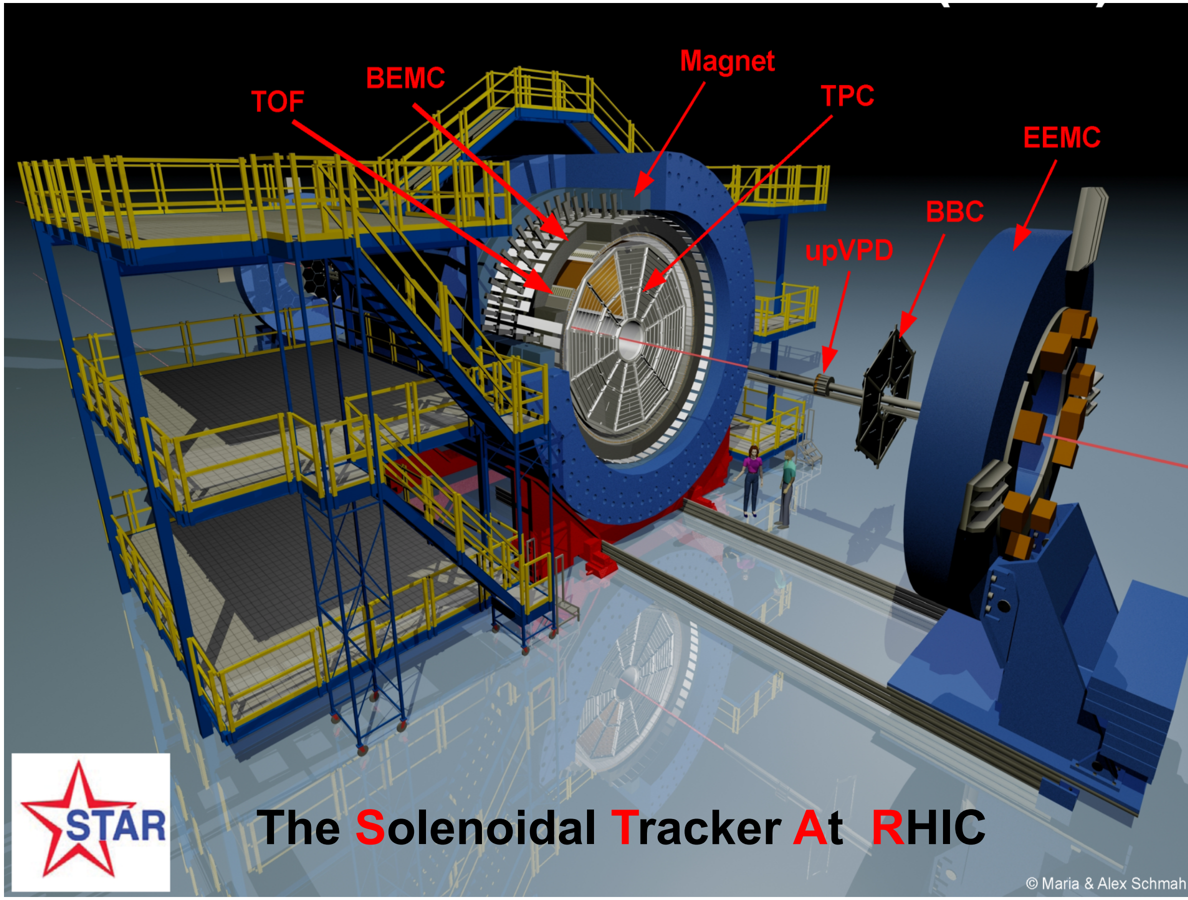
PHENIX, PRL 98:132301,2007



The STAR Experiment

- Time Projection Chamber
  - ID via energy loss (dE/dx)
  - Momentum (p)
- Full azimuth coverage
- Uniform acceptance

  for different energies and particles

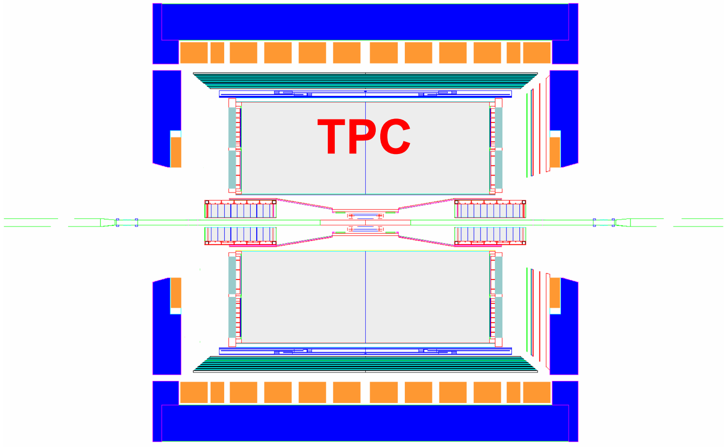


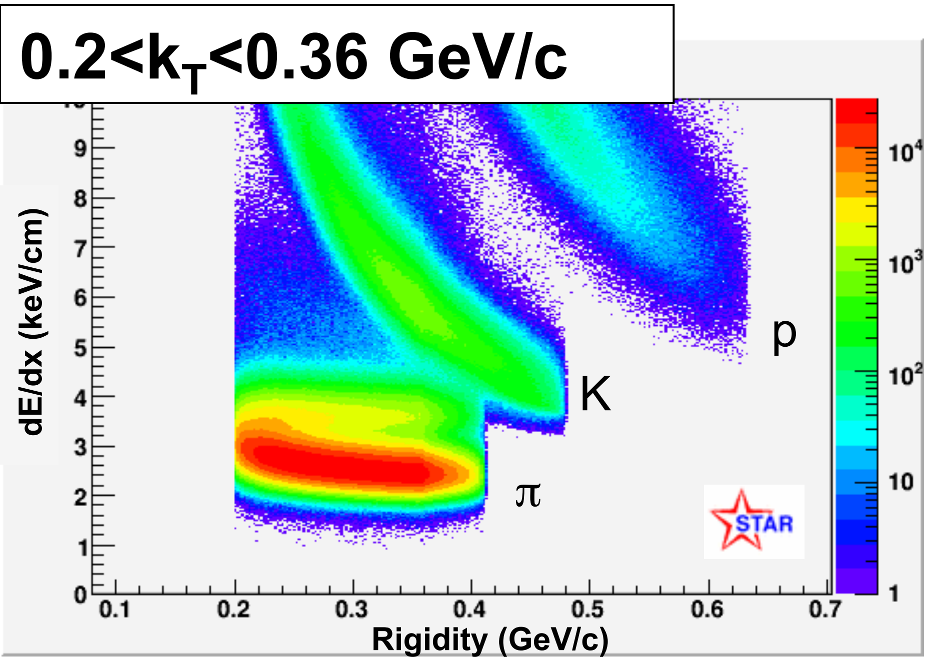
Kaon femtoscopy analyses

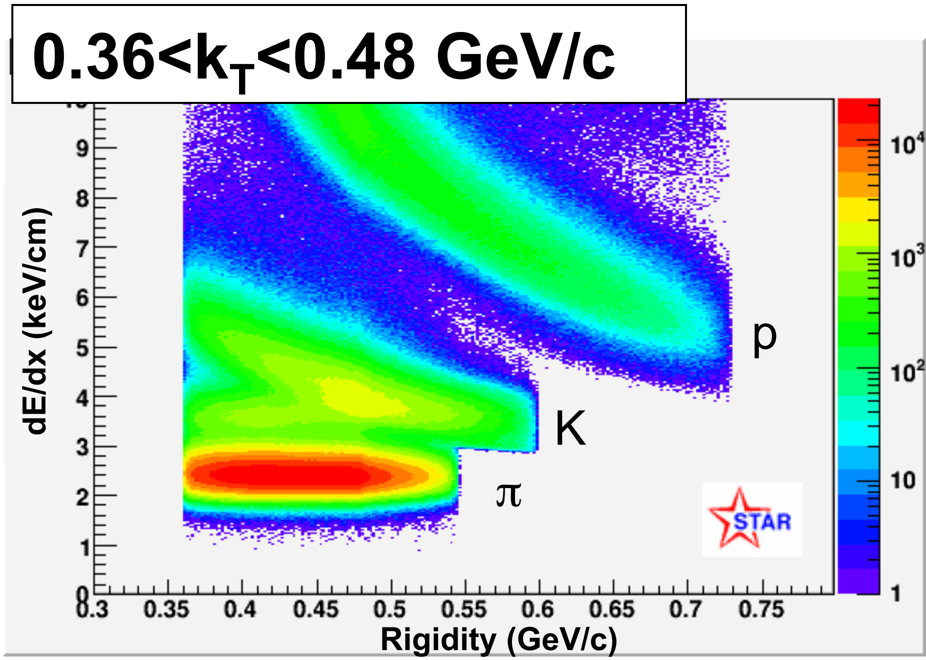
Au+Au @ $\sqrt{s_{NN}}$=200 GeV

Mid-rapidity |y|<0.5

1. Source shape: 20% most central
   Run 4: 4.6 Mevts, Run 7: 16 Mevts
2. m_T-dependence: 30% most central
   Run 4: 6.6 Mevts







PID cut applied

1. Source shape analysis

- dE/dx: nσ(Kaon)<2.0 and nσ(Pion)>3.0 and nσ(electron)>2.0

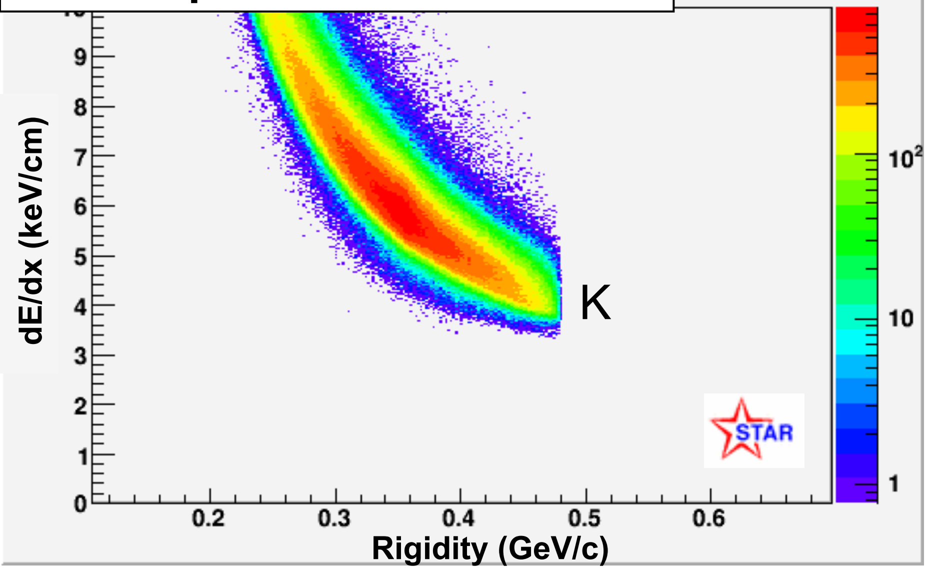
  nσ(X) :deviation of the candidate dE/dx from the normalized distribution of particle type X at a given momentum

- $0.2 < p_T < 0.4$ GeV/c

2. m_T-dependent analysis

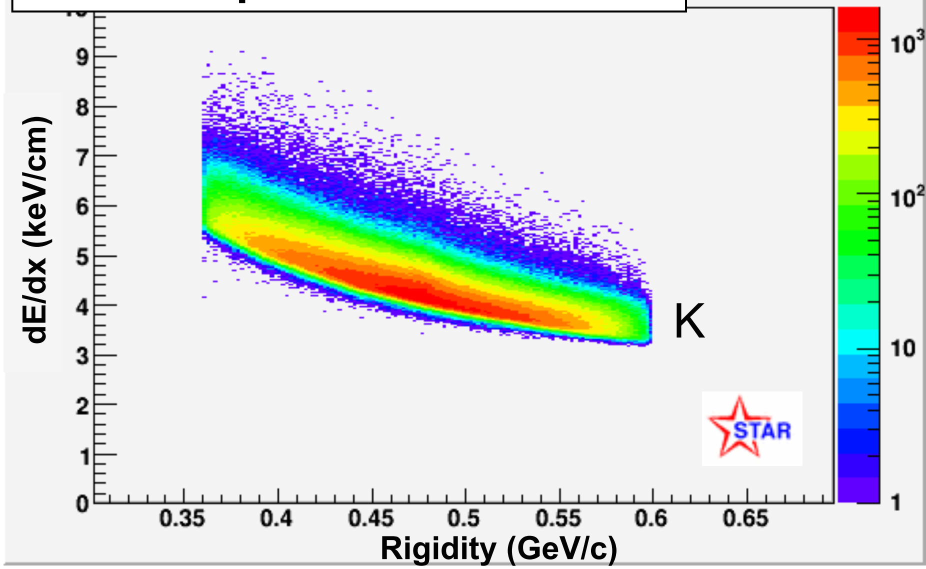
-1.5< nσ(Kaon)<2.0

$0.2<k_T<0.36$ GeV/c



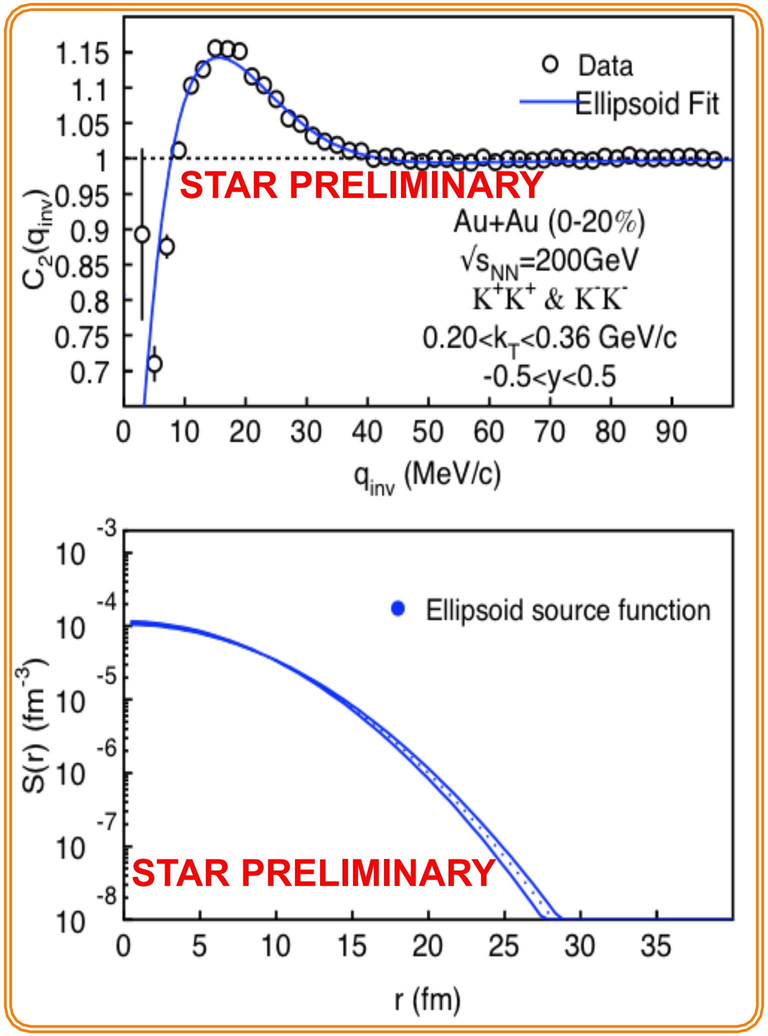
-0.5< nσ(Kaon)<2.0

$0.36<k_T<0.48$ GeV/c

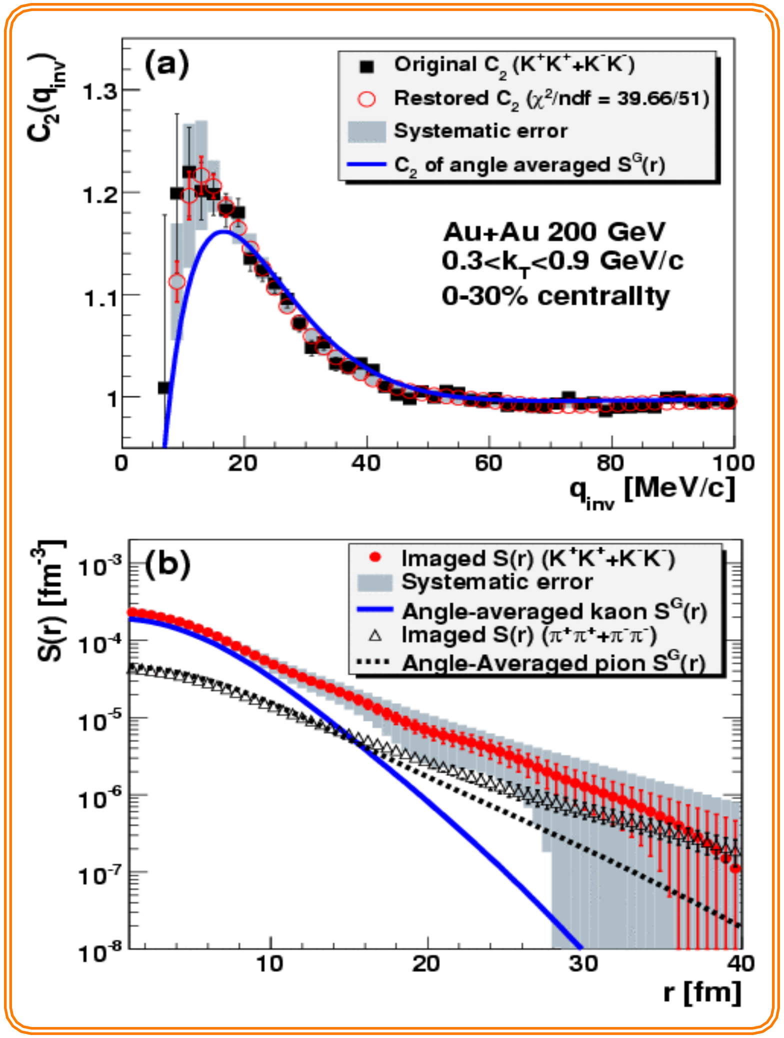


1D analysis result

34M+83M=117M (K^+K^+ & K^-K^-) pairs



PHENIX, PRL 103:,142301, 2009



STAR data well described by a single Gaussian. Contrary to PHENIX no non-gaussian tails observed. May be due to a different k_T-range: STAR bin is 4x narrower.

3D source shapes

Expansion of R(q) and S(r) in Cartesian Harmonic basis

Danielewicz and Pratt, Phys.Lett. B618:60, 2005

$$R(\mathbf{q}) = \sum_l \sum_{\alpha_1 \ldots \alpha_l} R^l_{\alpha_1 \ldots \alpha_l}(q) A^l_{\alpha_1 \ldots \alpha_l}(\Omega_q) \quad (1)$$

$$S(\mathbf{r}) = \sum_l \sum_{\alpha_1 \ldots \alpha_l} S^l_{\alpha_1 \ldots \alpha_l}(r) A^l_{\alpha_1 \ldots \alpha_l}(\Omega_q) \quad (2)$$

α_i = x, y or z
x = out-direction
y = side-direction
z = long-direction

3D Koonin-Pratt:

$$R(\mathbf{q}) = C(\mathbf{q}) - 1 = 4\pi \int dr^3 K(\mathbf{q}, \mathbf{r}) S(\mathbf{r}) \quad (3)$$

Plug (1) and (2) into (3) $\Rightarrow$

$$R^l_{\alpha_1 \ldots \alpha_l}(q) = 4\pi \int dr^3 K_l(q, r) S^l_{\alpha_1 \ldots \alpha_l}(r) \quad (4)$$

Invert (1) $\Rightarrow$

$$R^l_{\alpha_1 \ldots \alpha_l}(q) = \frac{(2l+1)!!}{l!} \int \frac{d\Omega_q}{4\pi} A^l_{\alpha_1 \ldots \alpha_l}(\Omega_q) R(\mathbf{q})$$

Invert (2) $\Rightarrow$

$$S^l_{\alpha_1 \ldots \alpha_l} = \frac{(2l+1)!!}{l!} \int \frac{d\Omega_q}{4\pi} A^l_{\alpha_1 \ldots \alpha_l}(\Omega_q) S(\mathbf{q})$$

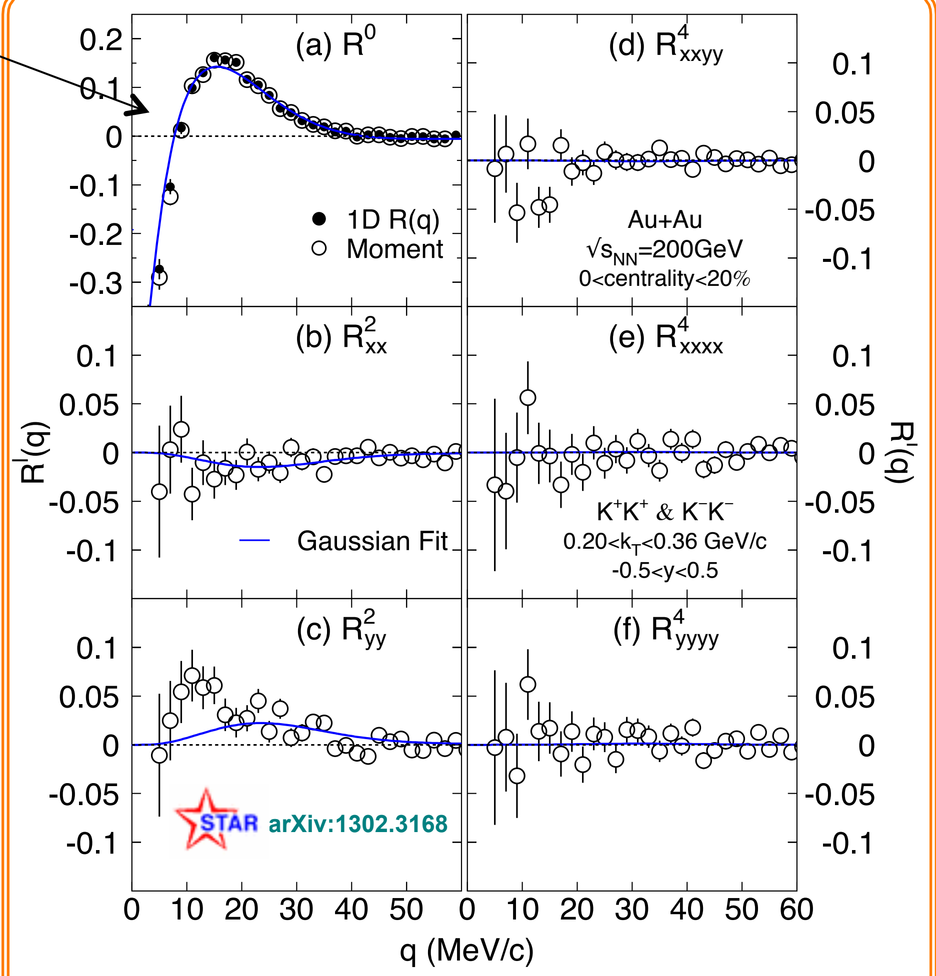
Shape analysis

- ℓ=0 moment agrees 1D $C(q)$
  Higher moments relatively small
- Trial function form for $S(r)$: 4-parameter ellipsoid (3D Gauss)

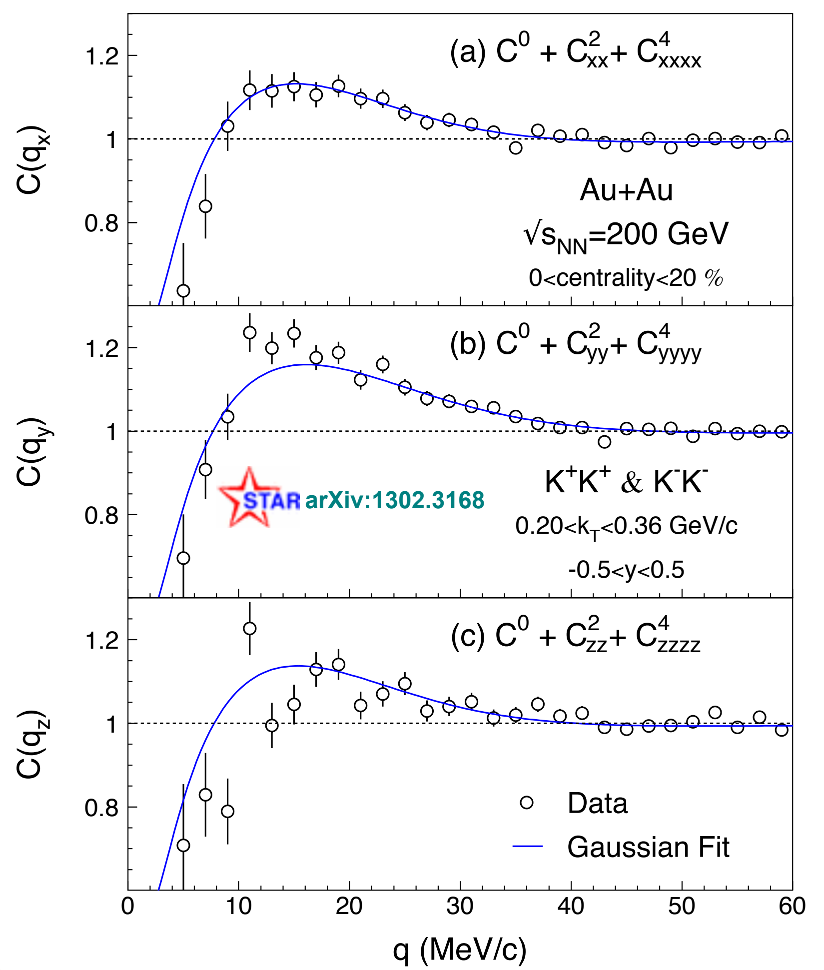
$$S^G(x,y,z) \equiv \frac{\lambda}{\left(2\sqrt{\pi}\right)^3 r_x r_y r_z} \exp\left[-\left(\frac{x^2}{4r_x^2}+\frac{y^2}{4r_y^2}+\frac{z^2}{4r_z^2}\right)\right]$$

- Fit to C(q): technically a simultaneous fit on 6 independent moments $R^{\ell}_{\alpha 1\ldots\alpha\ell}$, $0 \le \ell \le 4$
- Result: statistically good fit

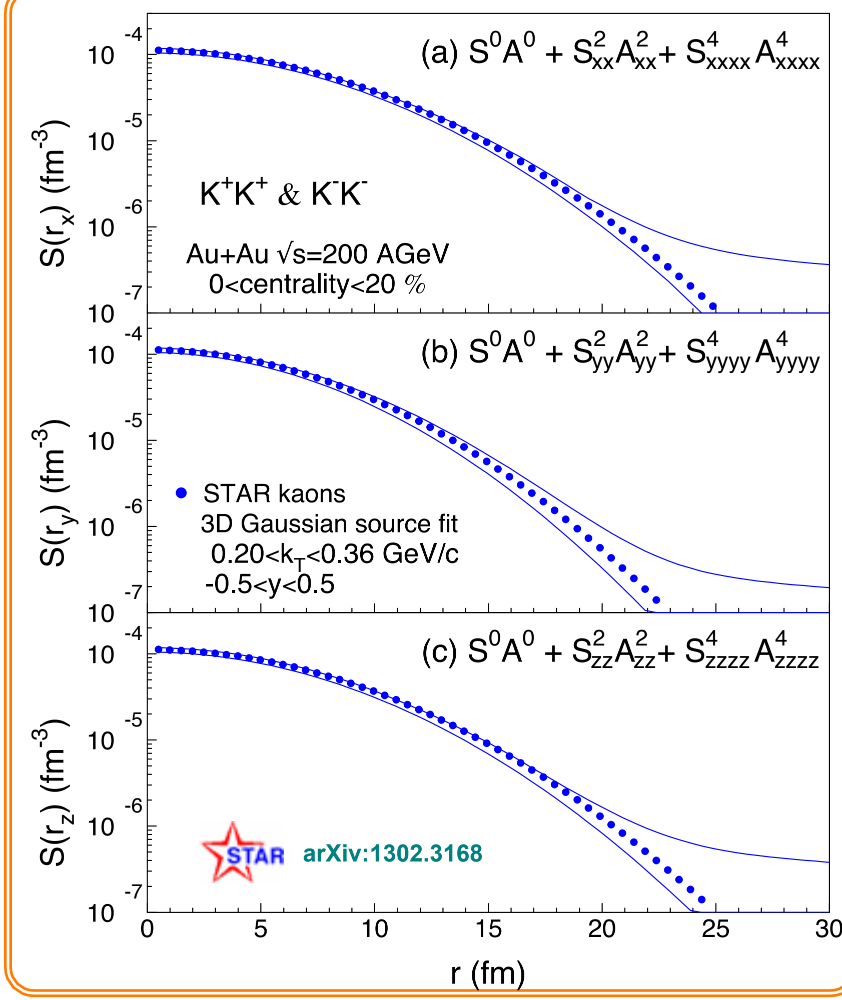
Run4+Run7	$\lambda = 0.48 \pm 0.01$
200 GeV Au+Au	$r_x = (4.8 \pm 0.1)$ fm
Centrality<20%	$r_y = (4.3 \pm 0.1)$ fm
0.2 < k_T < 0.36 GeV/c	$r_z = (4.7 \pm 0.1)$ fm



Correlation profiles and source



$$C(q_x) \equiv C(q_x,0,0)$$
$$C(q_y) \equiv C(0,q_y,0)$$
$$C(q_z) \equiv C(0,0,q_z)$$



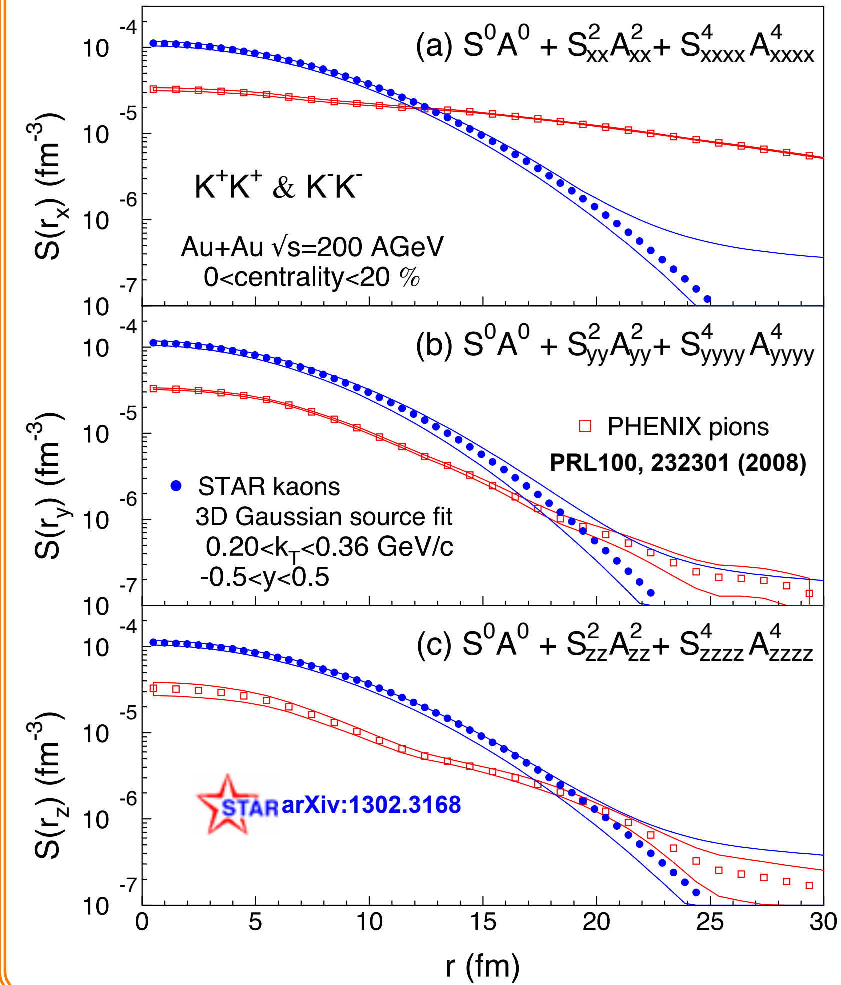
Gaussian source fit with error band

N.B.: Low statistics shows up as systematic uncertainty on shape assumption

Source: Data comparison

kaon vs. pion: different shape

- **Long pion tail caused by resonances and/or emission duration?**
- **Sign of different freeze-out dynamics?**



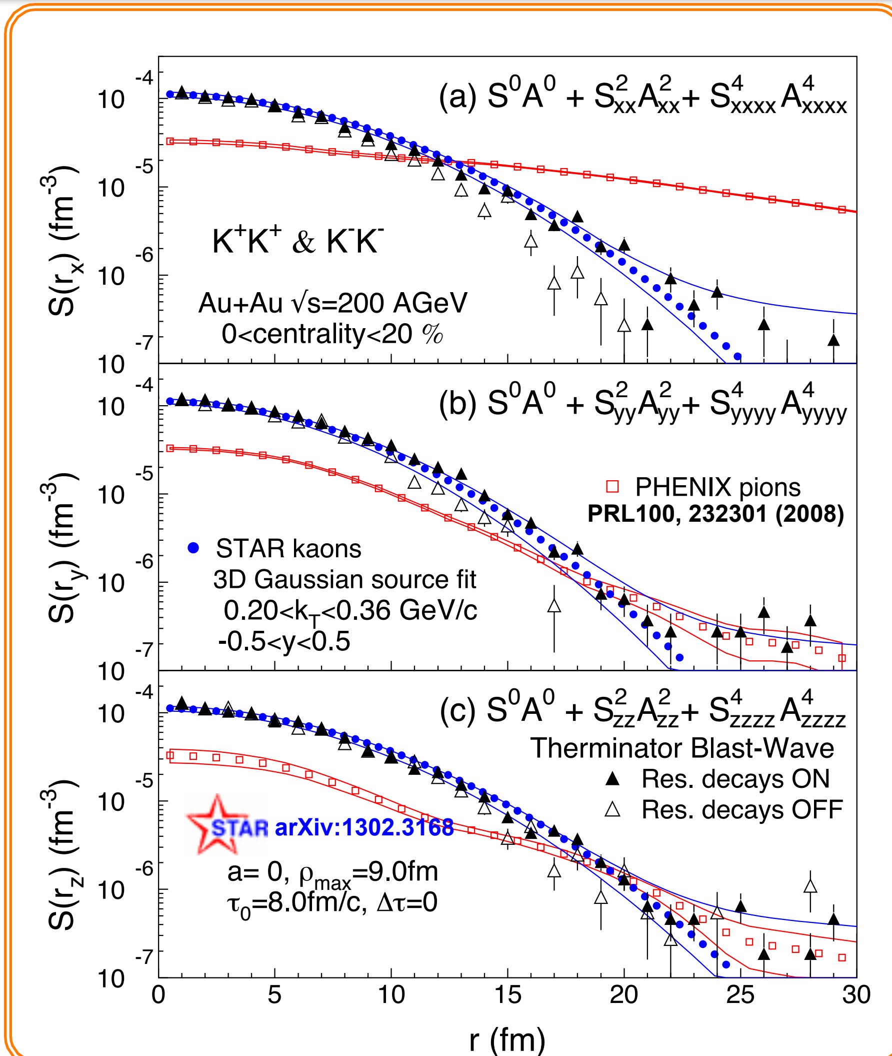
Source: Model comparison

Therminator

- Blast-wave model (STAR tune):
  - Expansion: $v_t(\rho)=(\rho/\rho_{max})/(\rho/\rho_{max}+v_t)$
  - Freeze-out occurs at $\tau = \tau_0 + a\rho$.
  - Finite emission duration $\Delta\tau$
- Kaons: Instant freeze-out ($\Delta\tau = 0$, compare to $\Delta\tau\sim 2$ fm/c of pions) at $\tau_0 = 0.8$ fm/c
- Resonances are needed for proper description

Hydrokinetic model

- Hybrid model
  - Glauber initial+Hydro+UrQMD
- Consistent in "side"
- Slightly more tail (r>15fm) in "out" and "long"

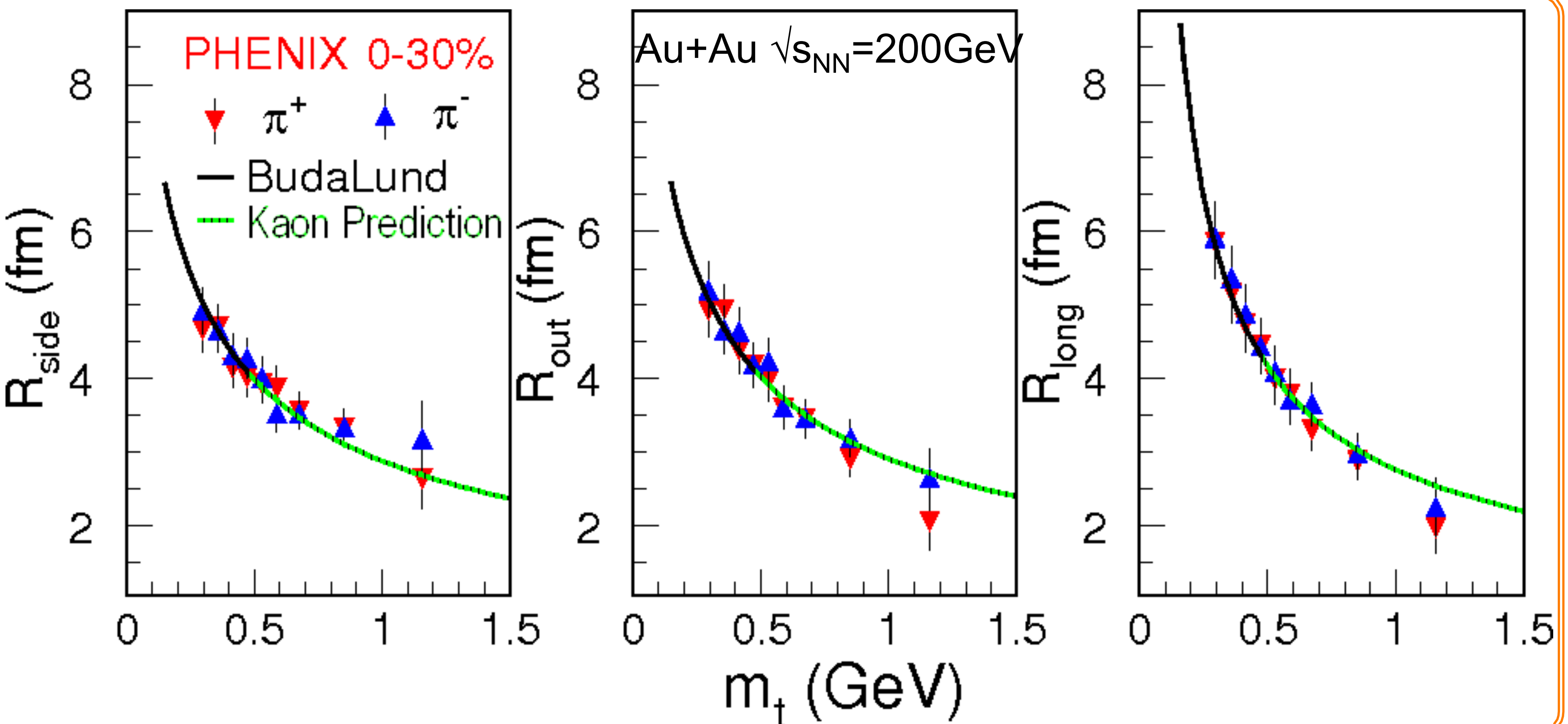


Therminator: Kisiel, Taluc, Broniowski, Florkowski, Comput. Phys. Commun. 174 (2006) 669.

HKM: PRC81, 054903 (2010)
data from Shapoval, Sinyukov, private communication

RHIC pion radii and perfect fluid hydrodynamics

M. Csanád and T. Csörgő: arXiv:0800.0801[nucl-th]



Excellent description of PHENIX pion data (PRL 93:152302, 2004) using exact solutions of perfect fluid hydrodynamics (Buda-Lund).

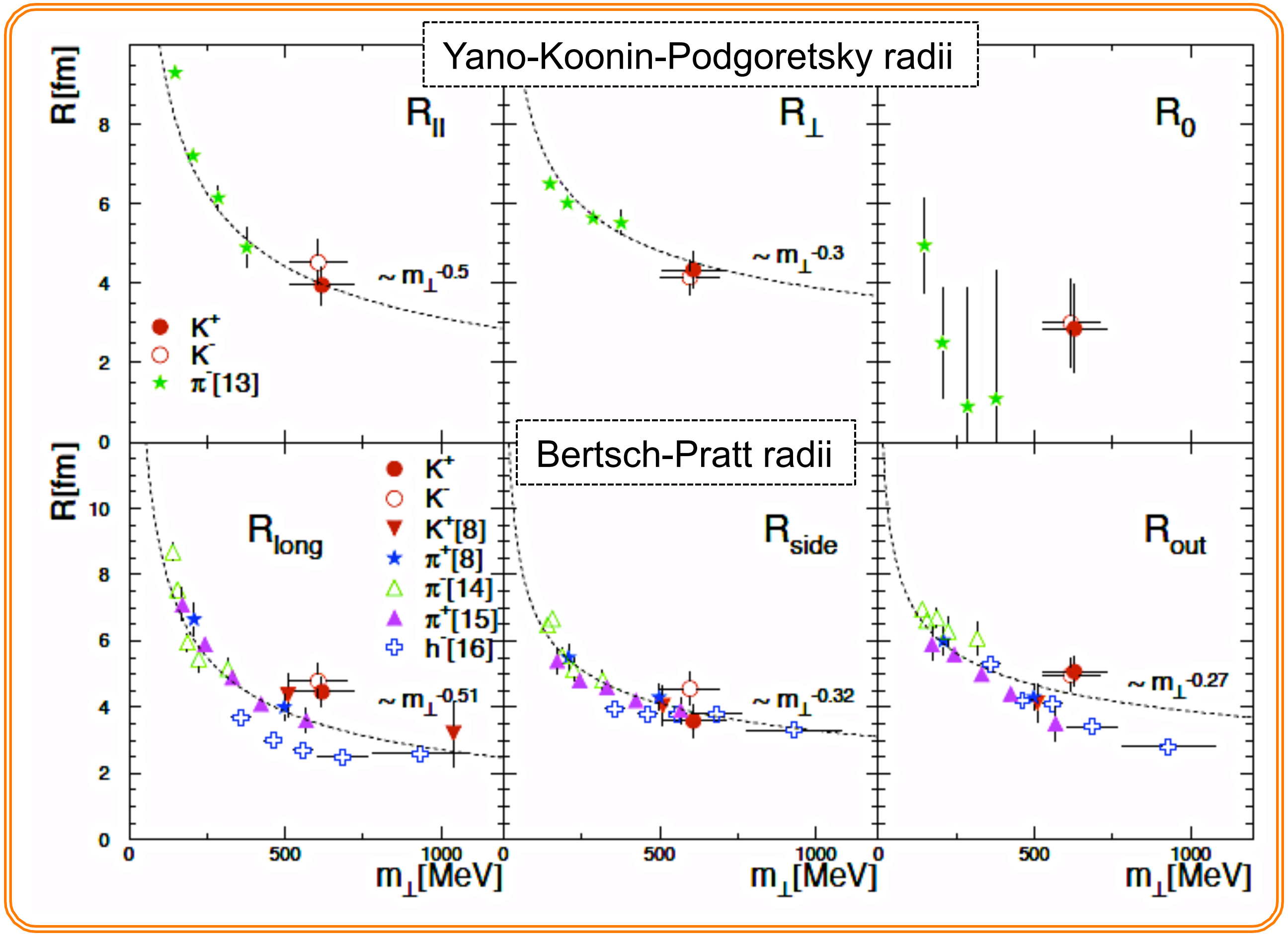
Ideal hydro has inherent m_T-scaling ⇒ predicts kaon radii m_T-dependence

SPS results on pions and kaons

S.V. Afanasiev *et al.* (NA49 Coll).: Phys. Lett B557(2003)157

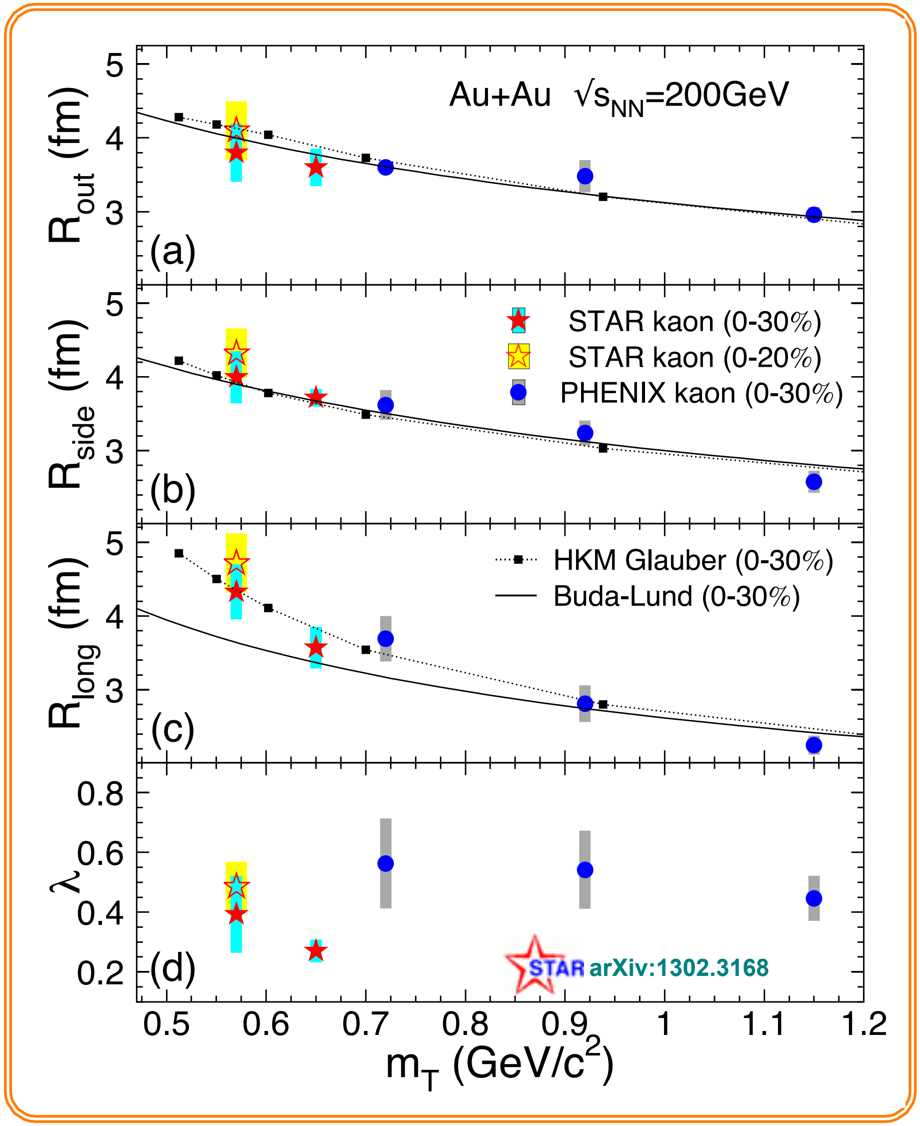
- “The kaon radii are fully consistent with pions and the hydrodynamic expansion model. “

- “Pions and kaons seem to decouple simultaneously.”



Kaon RHIC result

- Radii: rising trend at low m_T
  - Strongest in "long"
- Buda-Lund model
  - Perfect hydrodynamics, inherent m_T-scaling
  - Works perfectly for pions
  - Deviates from kaons in the "long" direction in the lowest m_T bin
- HKM (Hydro-kinetic model)
  - Describes all trends
  - Some deviation in the "out" direction
  - Note the different centrality definition



Buda-Lund: M. Csanád, arXiv:0801.4434v2
HKM: PRC81, 054903 (2010)

Summary

- First model-independent extraction of kaon 3D source shape presented
- No significant non-Gaussian tail is observed in RHIC $\sqrt{s_{NN}}$=200 GeV central Au+Au data
- Model comparison indicates that kaons and pions may be subject to different dynamics
- The m_T-dependence of the Gaussian radii indicates that m_T-scaling is broken in the “long” direction

Thank You!

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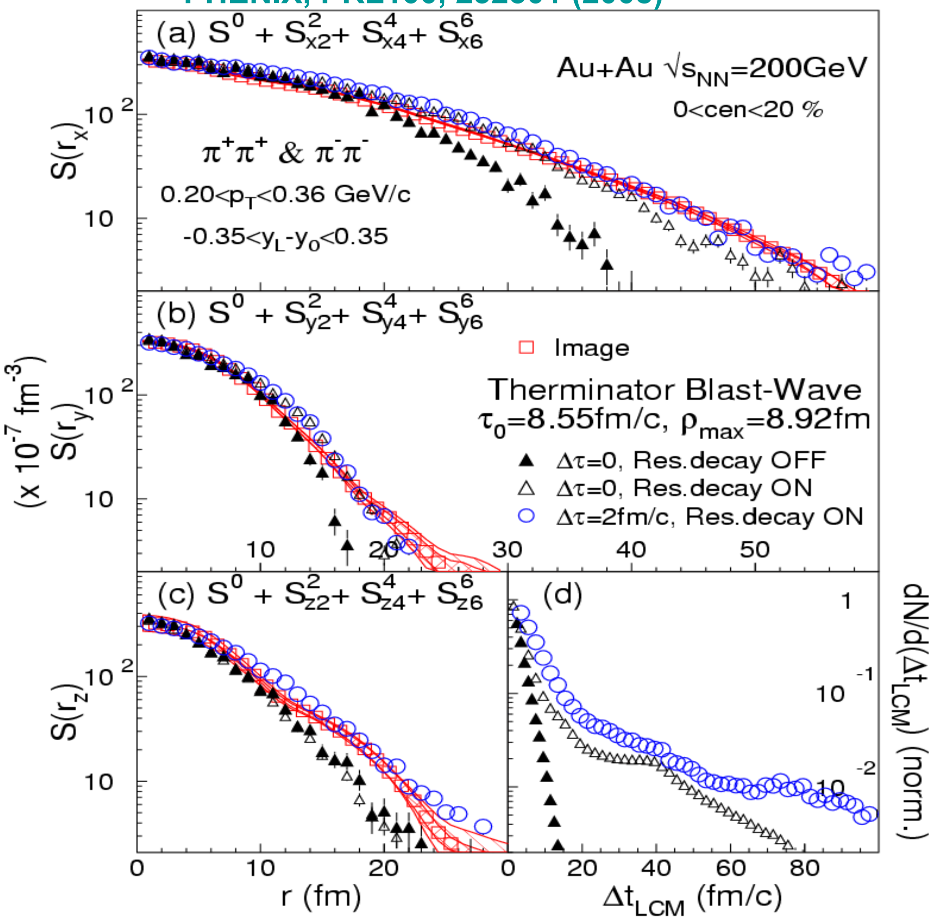
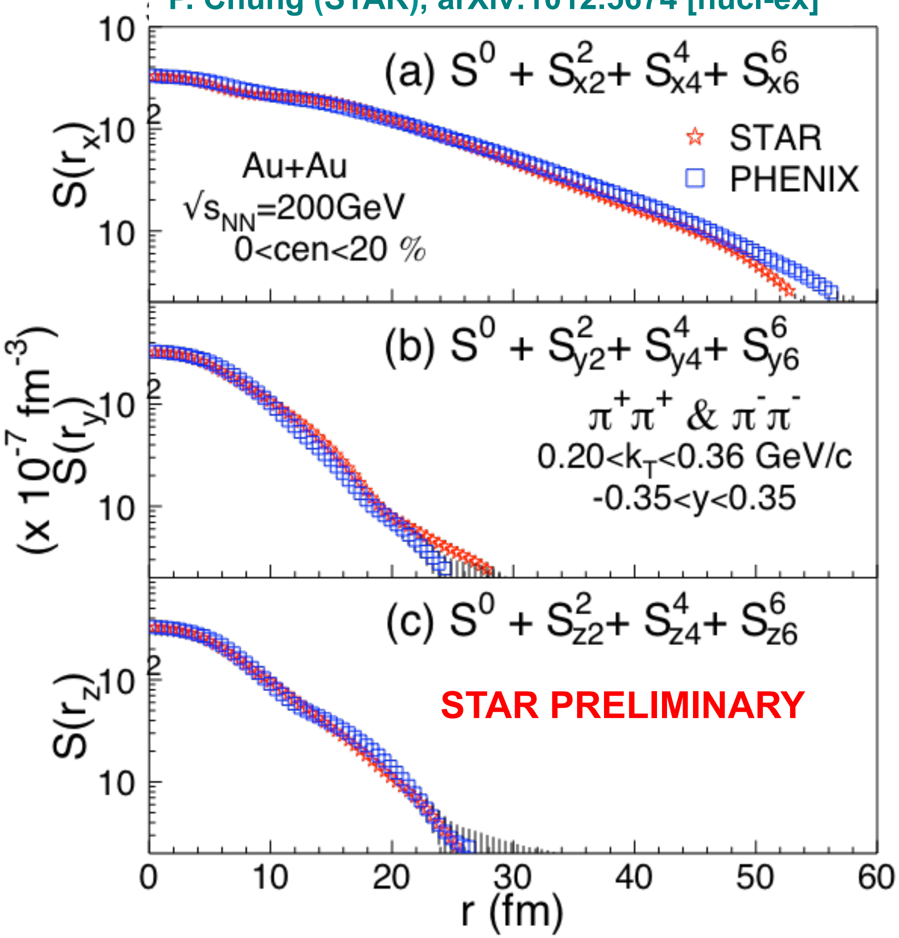
STAR Collaboration

3D pions, PHENIX and STAR

PHENIX, PRL100, 232301 (2008)



P. Chung (STAR), arXiv:1012.5674 [nucl-ex]



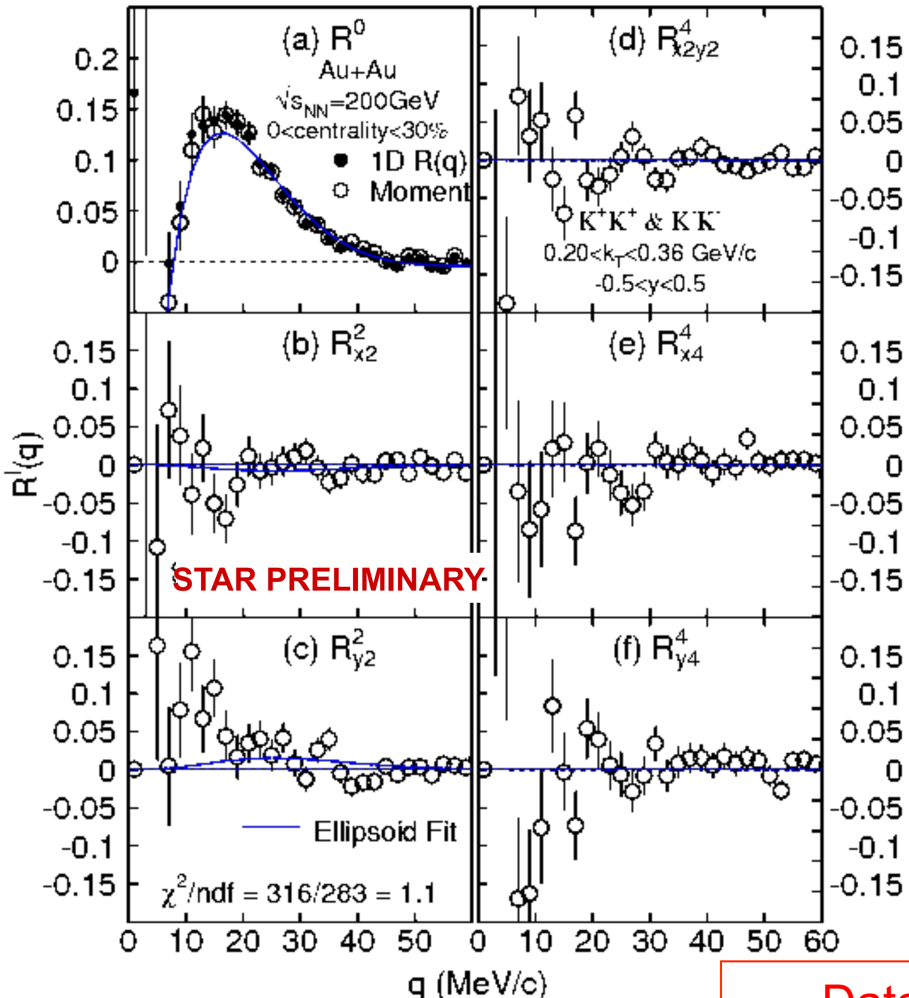
Elongated source in "out" direction

Therminator Blast Wave model suggests non-zero emission duration

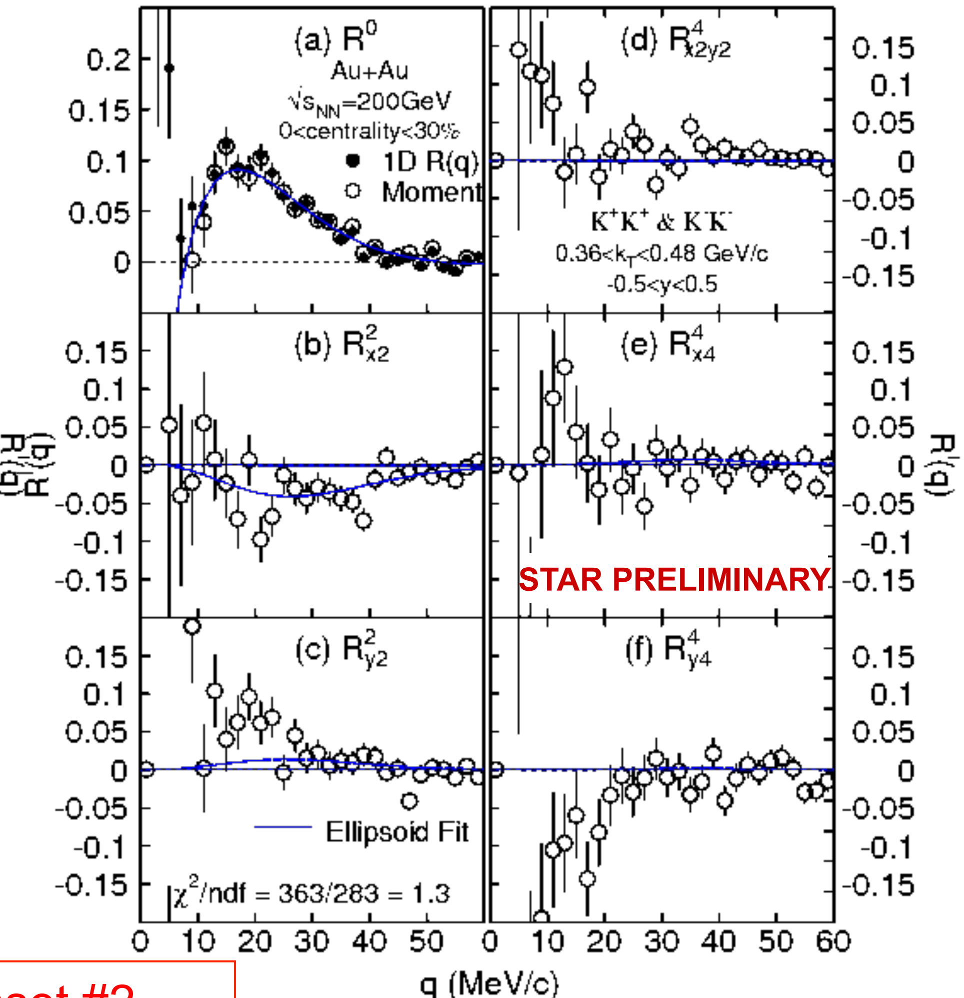
Very good agreement of PHENIX and STAR 3D pion source images

Fit to correlation moments

0.2<kT<0.36 GeV/c



0.36<kT<0.48 GeV/c



Dataset #2
Run4 Cent<30%

Source parameters

Year	2004+2007	2004	
Centrality	0–20%	0–30%	
k_T [GeV/c]	0.2–0.36	0.2–0.36	0.36–0.48
R_x [fm]	4.8±0.1±0.2	4.3±0.1±0.4	4.5±0.2±0.3
R_y [fm]	4.3±0.1±0.1	4.0±0.1±0.3	3.7±0.1±0.1
R_z [fm]	4.7±0.1±0.2	4.3±0.2±0.4	3.6±0.2±0.3
λ	0.49±0.02±0.05	0.39±0.01±0.09	0.27±0.01±0.04
χ^2/ndf	497/289	316/283	367/283

TABLE I. Parameters obtained from the 3-D Gaussian source function fits for the different datasets. The first errors are statistical, the second errors are systematic.

Cartesian harmonics basis

- Based on the products of unit vector components, $n_{\alpha 1}\, n_{\alpha 2}$, …, $n_{\alpha \ell}$. Unlike the spherical harmonics **they are real**.
- Due to the normalization identity **$n^2_x + n^2_y + n^2_z = 1$**, at a given $\ell \geq 2$, the different component products **are not linearly independent** as functions of spherical angle.
- At a given ℓ, the products are spanned by spherical harmonics of rank $\ell' \leq \ell$, with ℓ' of the same evenness as ℓ.

$A^{(1)}_x = n_x$	$A^{(3)}_{xyz} = n_x\, n_y\, n_z$
$A^{(2)}_{xx} = n_x^2 - 1/3$	$A^{(4)}_{xxxx} = n_x^4 - (6/7) n_x^2 + 3/35$
$A^{(2)}_{xy} = n_x\, n_y$	$A^{(4)}_{xxxy} = n_x^3\, n_y - (3/7) n_x\, n_y$
$A^{(3)}_{xxx} = n_x^3 - (3/5) n_x$	$A^{(4)}_{xxyy} = n_x^2\, n_y^2 - (1/7) n_x^2 - (1/7) n_y^2 + 1/35$
$A^{(3)}_{xxy} = n_x^2\, n_y - (1/5) n_y$	$A^{(4)}_{xxyz} = n_x^2\, n_y\, n_z - (1/7) n_y\, n_z$

Spherical Harmonics basis

$$\mathcal{R}_{\ell m}(q) = (4\pi)^{-1/2} \int \mathrm{d}\Omega_{\mathbf{q}}\, Y^*_{\ell m}(\Omega_{\mathbf{q}})\, \mathcal{R}(\mathbf{q})\,,$$

$$\mathcal{S}_{\ell m}(r) = (4\pi)^{-1/2} \int \mathrm{d}\Omega_{\mathbf{r}}\, Y^*_{\ell m}(\Omega_{\mathbf{r}})\, \mathcal{S}(\mathbf{r}).$$

- Disadvantage: connection between the geometric features of the real source function S(r) and the complex valued projections $S_{\ell m}(r)$ is not transparent.

- $Y_{\ell m}$ harmonics are convenient for analyzing quantum angular momentum, but are clumsy for expressing anisotropies of real-valued functions.