Three-dimensional Kaon Source Extraction from STAR Experiment at RHIC

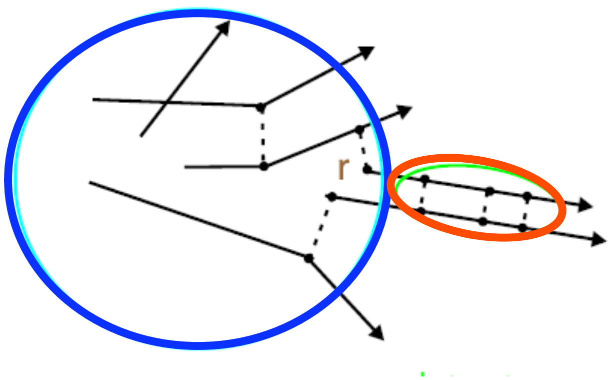
Michal Šumbera
NPI ASCR Prague
(for the STAR Collaboration)

Outline

- Why and how to extract the source shape?
- 1D source extraction: previous and recent results
- Kaon data analysis details
- 3D source shape analysis: Cartesian surface – spherical harmonic decomposition technique
- 3D source function extraction: correlation moments fitting
- Comparison to thermal blast wave model
- Conclusions

Source imaging

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



Kernel is independent of freeze-out conditions

Inversion of linear integral equation to obtain source function

1D Koonin-Pratt equation

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

Correlation function

Encodes FSI

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

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

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 last scattering. ⟹ Only Coulomb & quantum statistics effects included the kernel.

$$S(r) = \sum_j S_j \cdot B_j(r)$$ *Expansion into B-spline basis*

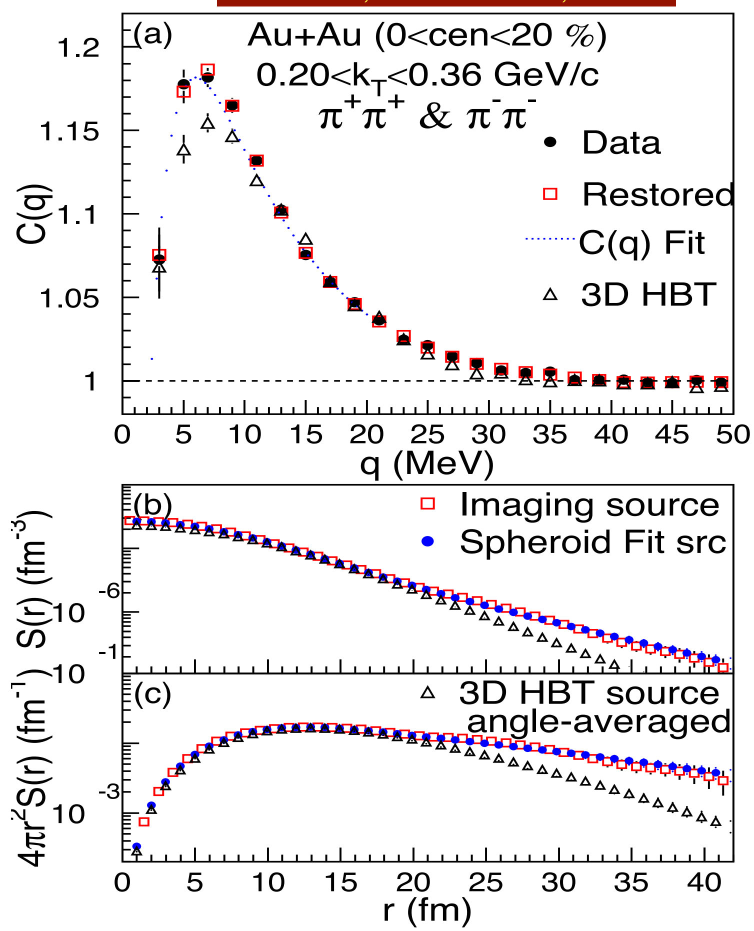
$$C^{Th}(q_i) = \sum_j K_{ij} \cdot S_j$$

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

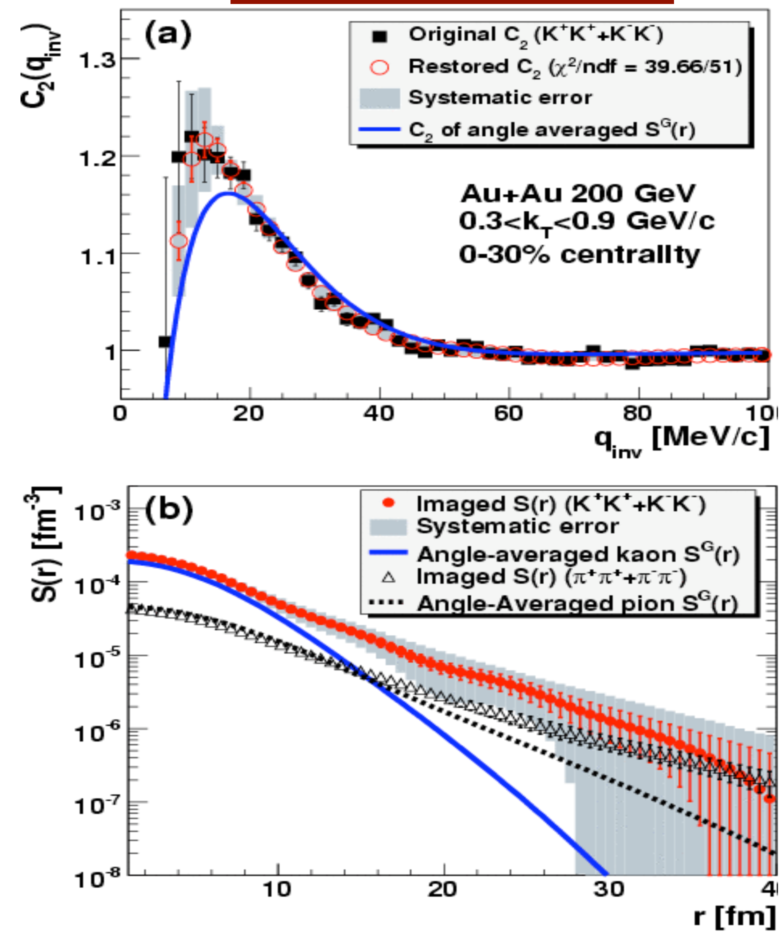
$$\chi^2 = \frac{\left(C^{Expt}(q_i) - \sum_j K_{ij} \cdot S_j \right)^2}{\left(\Delta C^{Expt}(q_i) \right)^2}$$

Previous 1D source imaging results

PHENIX, PRL 98:132301,2007



PHENIX, PRL 103:142301,2009

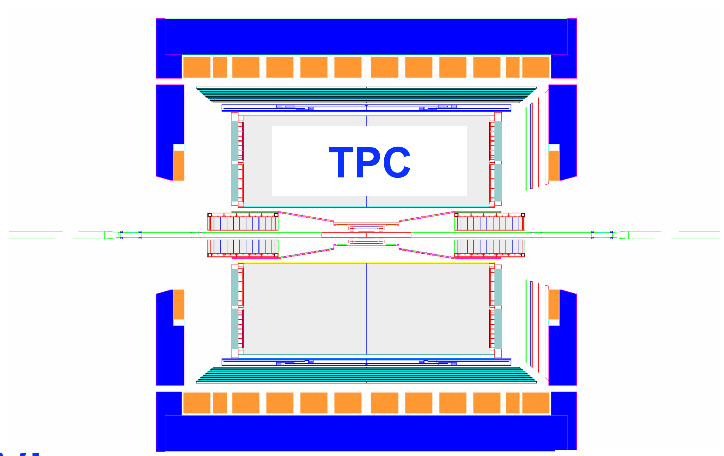


Observed long non-gaussian tails attributed to non-zero particle emision duration and contribution of long-lived resonances

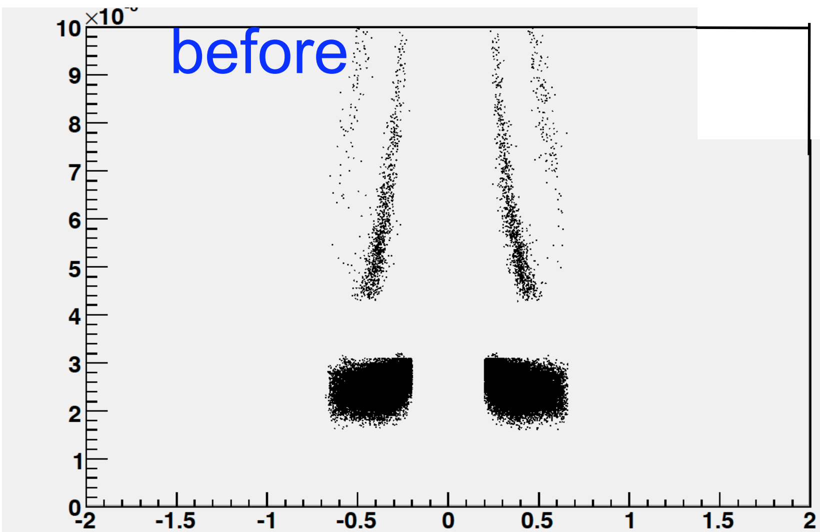
Kaon data analysis

20% most central Au+Au @ $\sqrt{s_{NN}}$=200 GeV
Run 4: 4.6 Mevts, Run 7: 16 Mevts

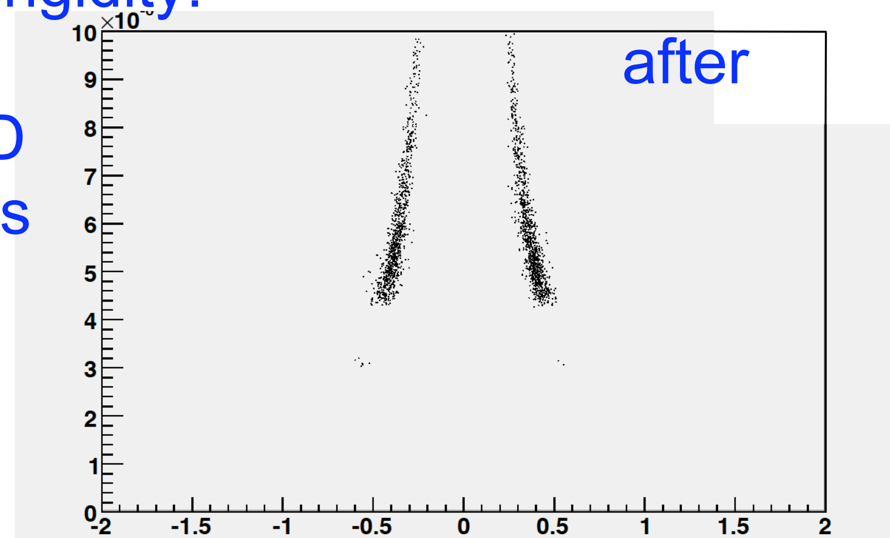
Particle ID selection via TPC dE/dx:
NSigmaKaon<2.0 && NSigmaPion>3.0
&& NSigmaElectron>2.0



dE/dx vs rigidity:



PID cuts



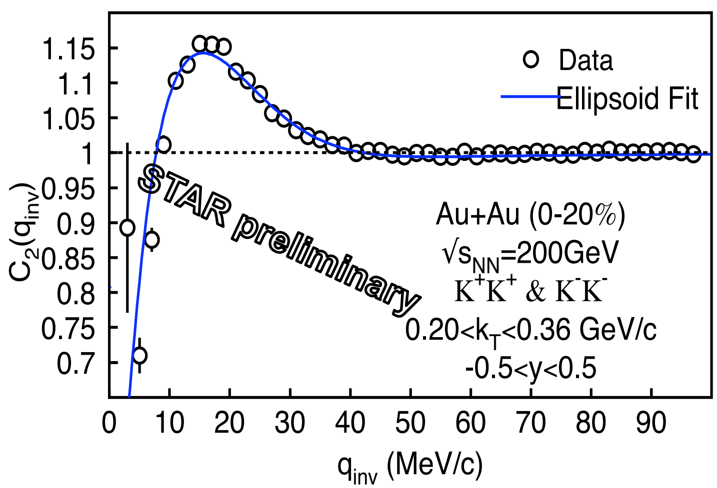
$|y| < 0.5$ & $0.2 < p_T < 0.4$ GeV/c

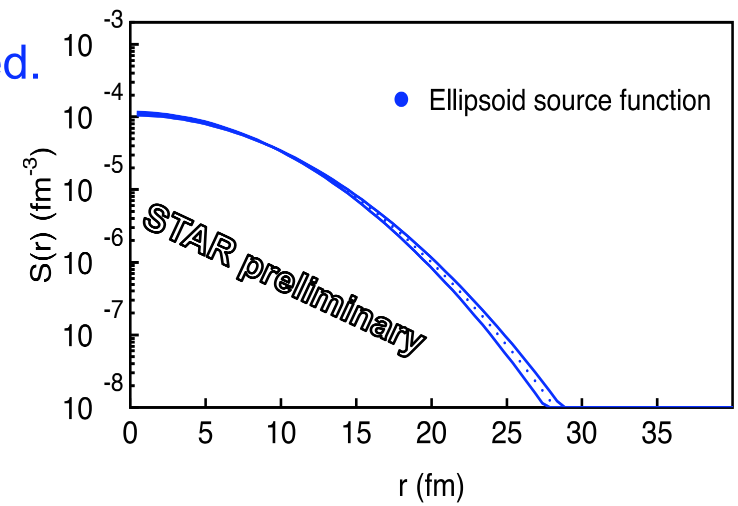
STAR kaon 1D source shape result

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

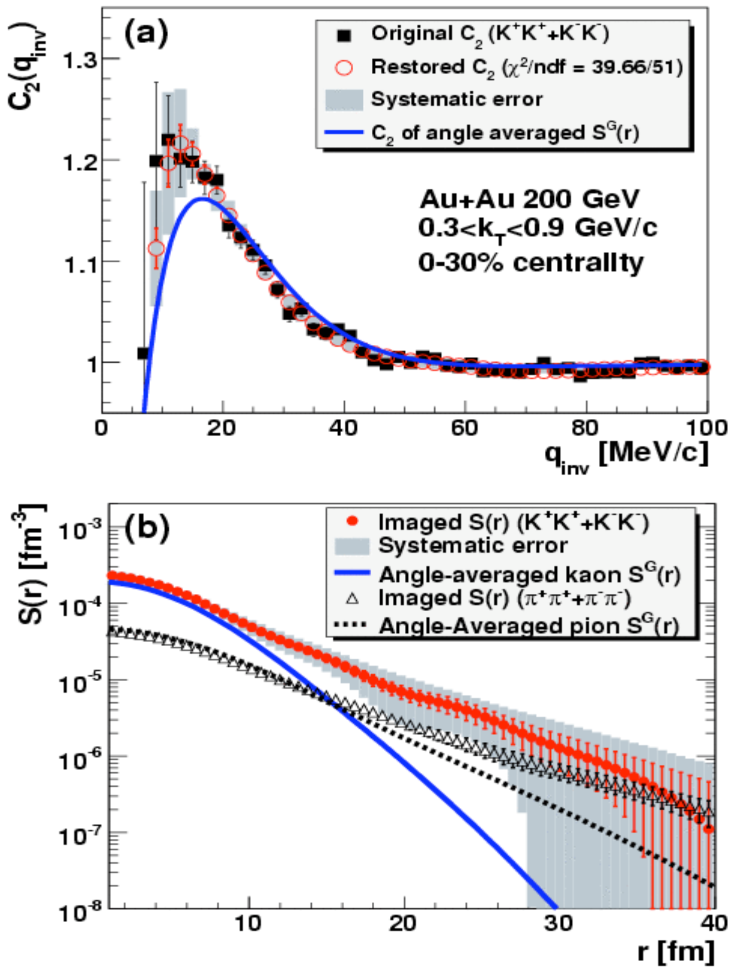
STAR data are well described by Gaussian, contrary to PHENIX no non-gaussian tails are observed.

May be due to a different k_T-range: STAR bin is 4x narrower.





PHENIX, PRL 103:142301,2009



3D source shape analysis

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

STAR

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

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

$$S(\vec{r}) = \sum_l \sum_{\alpha_1 \ldots \alpha_l} S^l_{\alpha_1 \ldots \alpha_l}(r)\, A^l_{\alpha_1 \ldots \alpha_l}(\Omega_r) \quad (2)$$

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

3D Koonin-Pratt:

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

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

$$R^l_{\alpha_1 \ldots \alpha_l}(q) = 4\pi \int dr\, r^2 K_l(q, r) S^l_{\alpha_1 \ldots \alpha_l}(r) \quad (4)$$

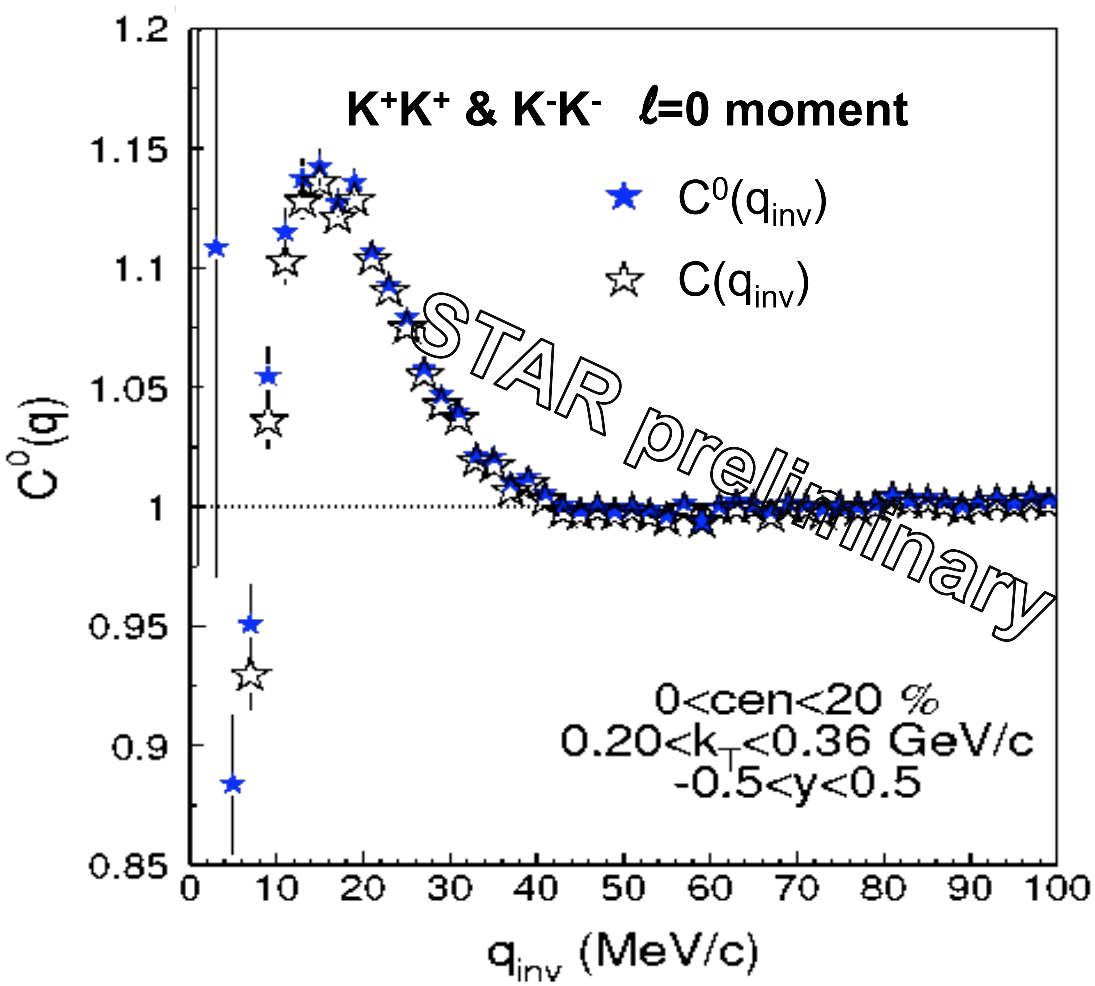
Invert (1) $\Rightarrow$

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

Invert (2) $\Rightarrow$

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

$C^0(q_{inv})$ vs $C(q_{inv})$: comparison



Extracting 3D source function

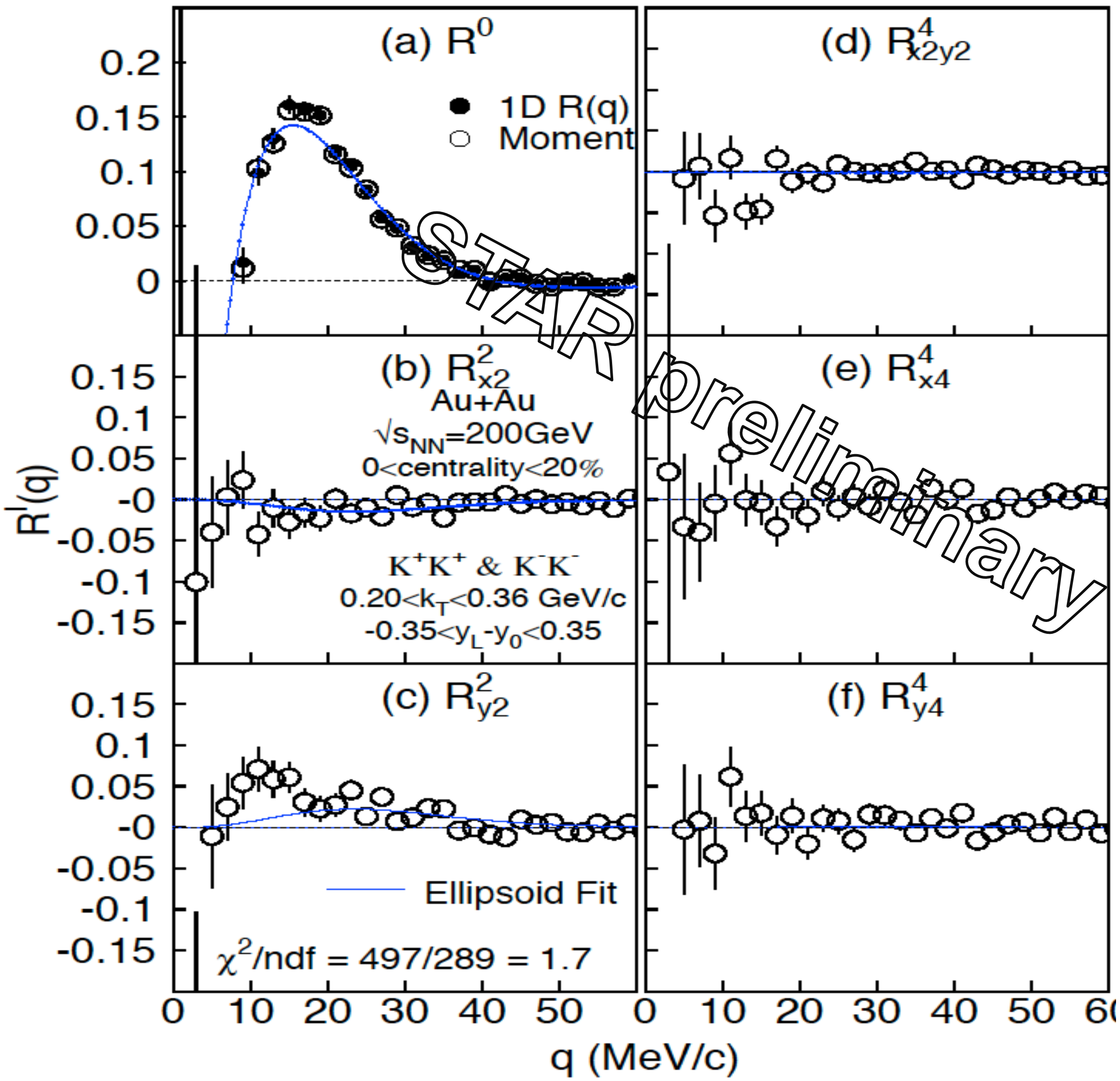
- Fit to the 3D correlation function with a trial functional form for S(r).
- Trial function: 4-parameter ellipsoid (3D Gaussian)

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

- Since the 3D correlation function has been decomposed into its independent moments, this is equivalent to a simultaneous fit of 6 independent moments with the trial functional form.

Independent correlation moments

$R^{\ell}_{\alpha_1 \ldots \alpha_\ell}$, $0 \leq \ell \leq 4$



Extracted 3D Gaussian fit parameters:

$\lambda = 0.48 \pm 0.01$

$r_x = (4.8 \pm 0.1)$ fm

$r_y = (4.3 \pm 0.1)$ fm

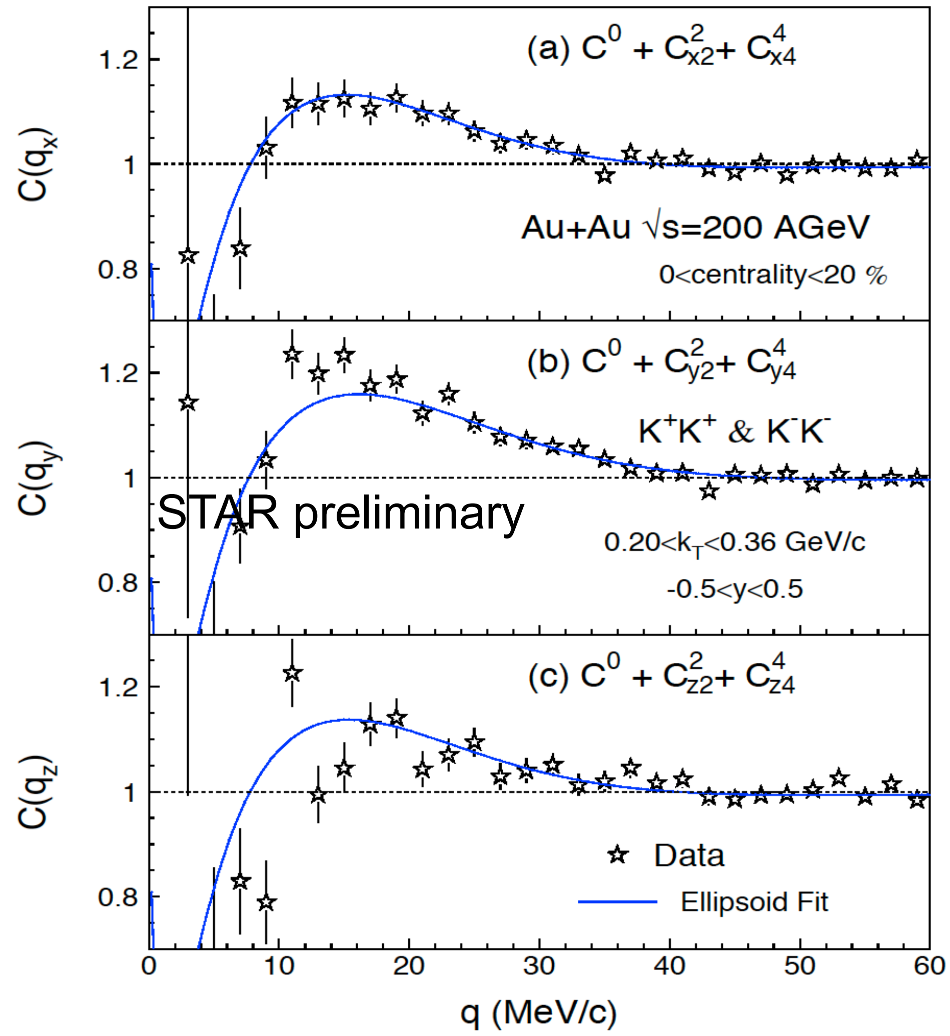
$r_z = (4.7 \pm 0.1)$ fm

Kaon correlation function profiles

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

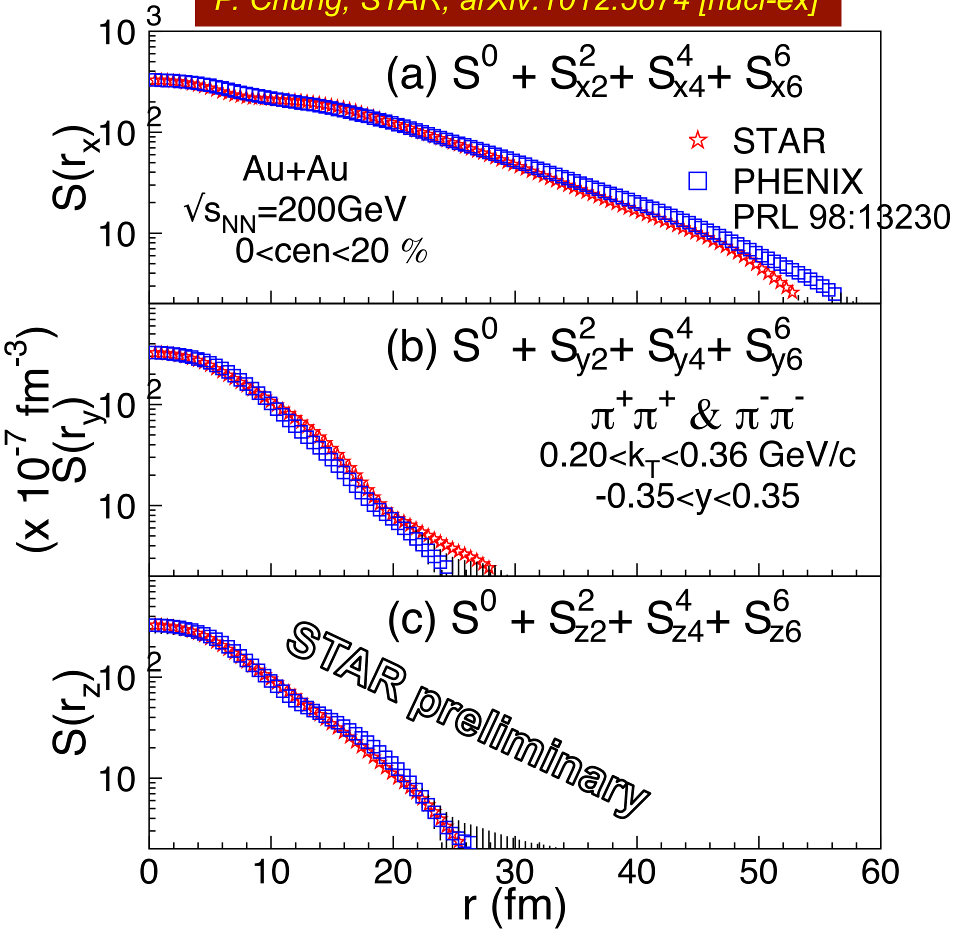
$C(q_y) \equiv C(0,q_y,0)$

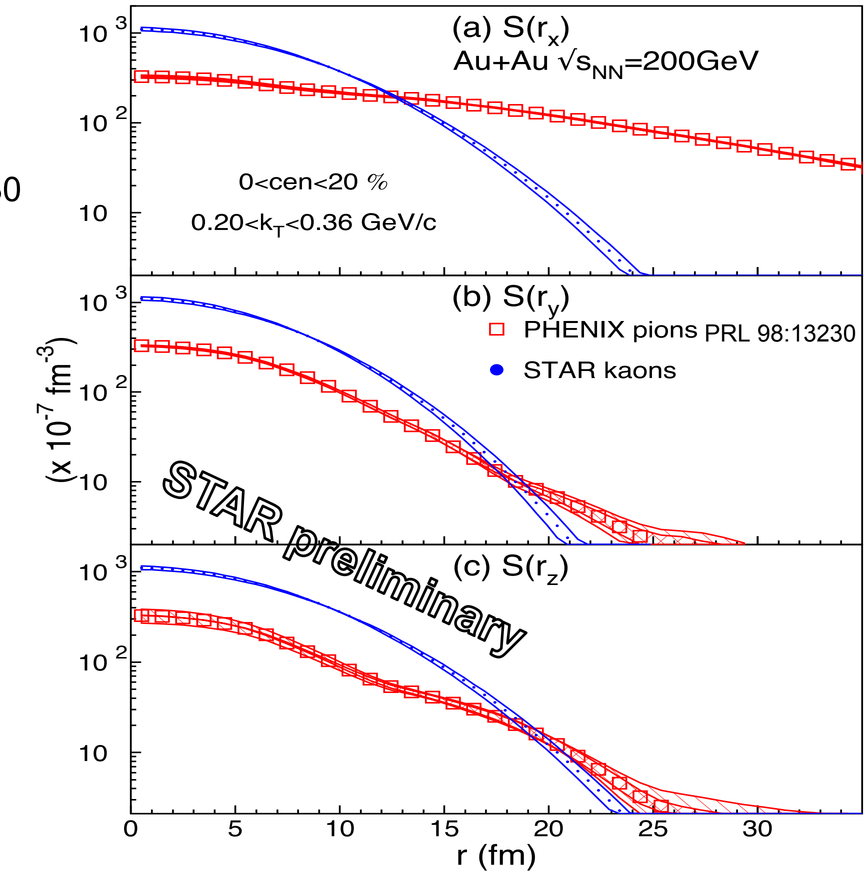
$C(q_z) \equiv C(0,0,q_z)$



Kaon vs. pion 3D source shape

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





Very good agreement on 3D pion source shape between PHENIX and STAR

Pion and kaon 3D source shapes are very different: Is this due to the different dynamics?

Comparison to thermal BW model

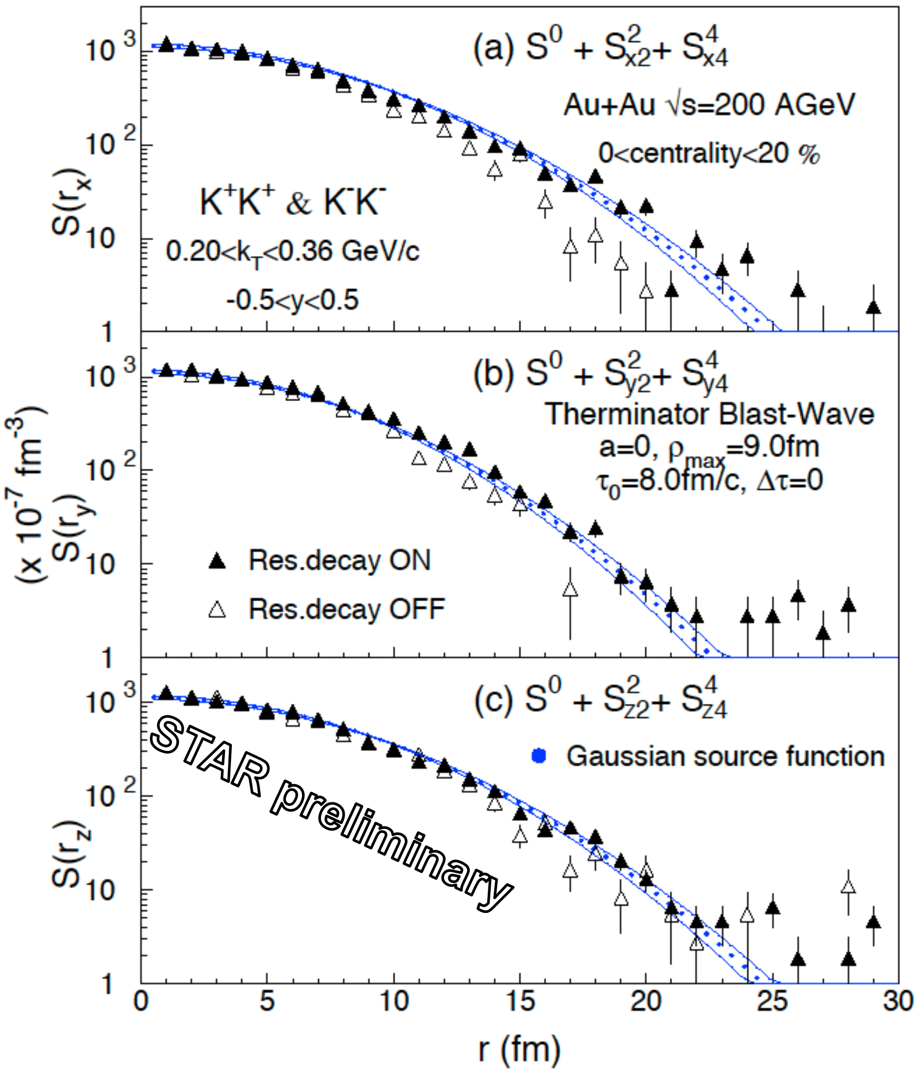
Thermінator

Therminator (A. Kisiel *et al.*, **Phys. Rev. C 73:064902 2006**) basic ingredients:

1. Longitudinal boost invariance.
2. Blast-wave expansion with transverse velocity profile semi-linear in transverse radius ρ: $v_r(\rho)=(\rho/\rho_{max})/(\rho/\rho_{max}+v_t)$. Value of $v_t = 0.445$ comes from the BW fits to particle spectra from Au+Au @ 200GeV: STAR, PRC 79:034909, 2009.
3. Thermal emission takes place at proper time τ, from a cylinder of infinite longitudinal size and finite transverse dimension ρ_{max}.

Freeze-out occurs at $\tau = \tau_0 + a\rho$.
Particles which are emitted at (z, ρ) have LAB emission time $t^2 = (\tau_0 + a\rho)^2 + z^2$.

Emission duration is included via $\Delta\tau$.



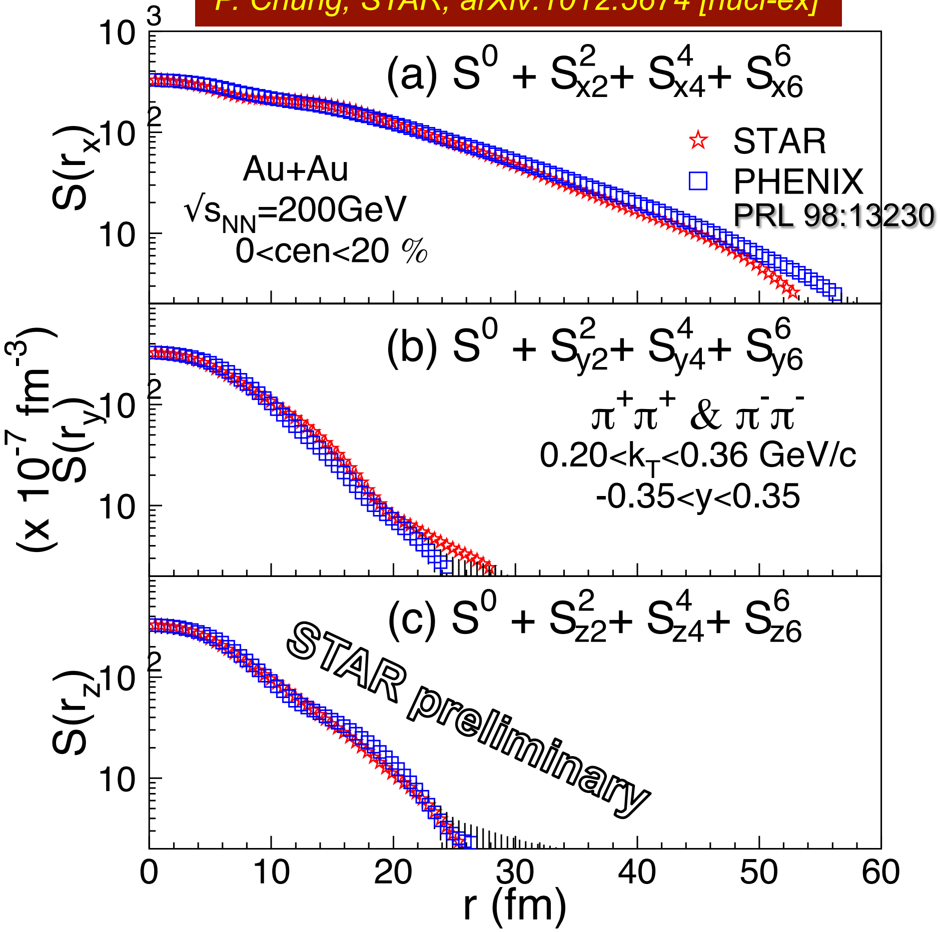
Conclusions

- First model-independent extraction of kaon 3D source shape.
- Source function of mid-rapidity, low-momentum kaons from 20% most central Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV is Gaussian – no significant non-Gaussian tail is observed.
- Comparison with Therminator model indicates kaon emission from a fireball with transverse dimension and lifetime which are consistent with values from two-pion interferometry.
- In contrast to pions, kaons are emitted instantaneously in the source element rest frame from a freeze-out hypersurface with no $\rho-\tau$ correlation.
- Kaons and pions may be subject to different dynamics owing to their emission over different timescales.

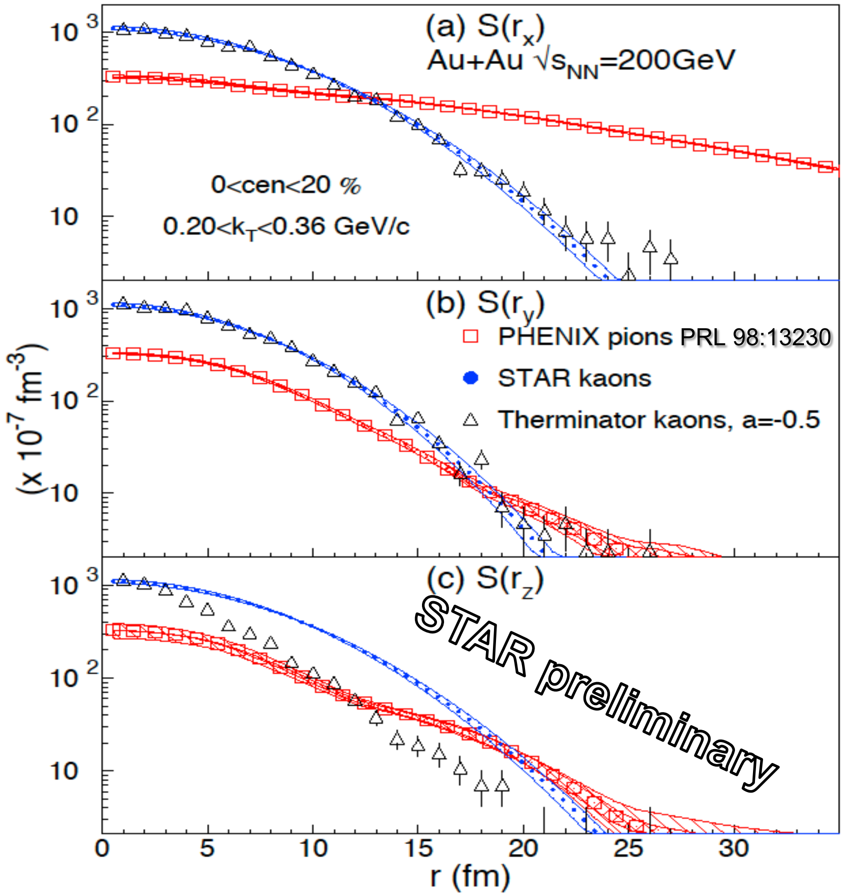
Backup slides

Kaon vs. pion 3D source shape

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



Very good agreement on 3D pion source shape between PHENIX and STAR



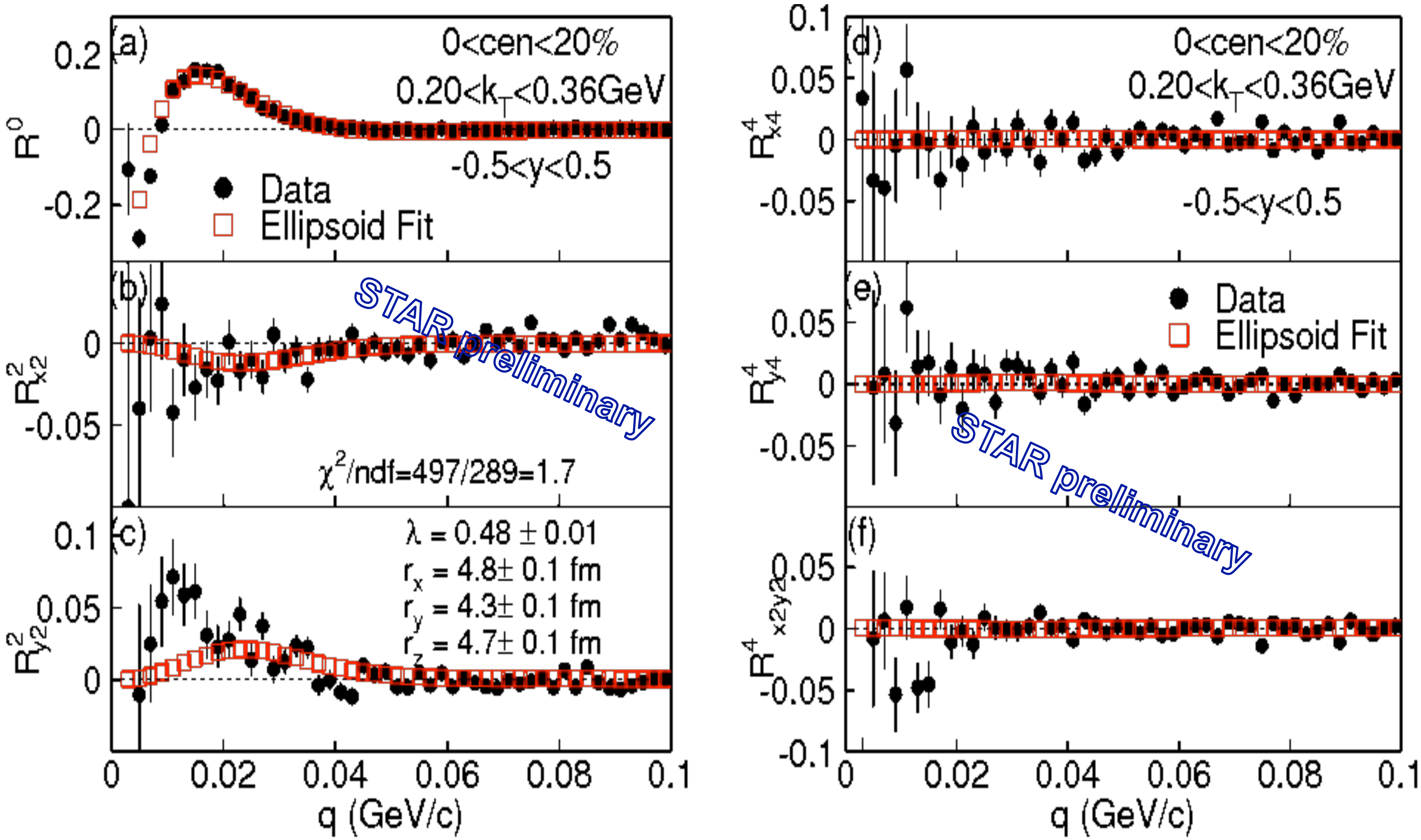
Pion and kaon 3D source shapes are very different: Is this due to the different dynamics?

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.

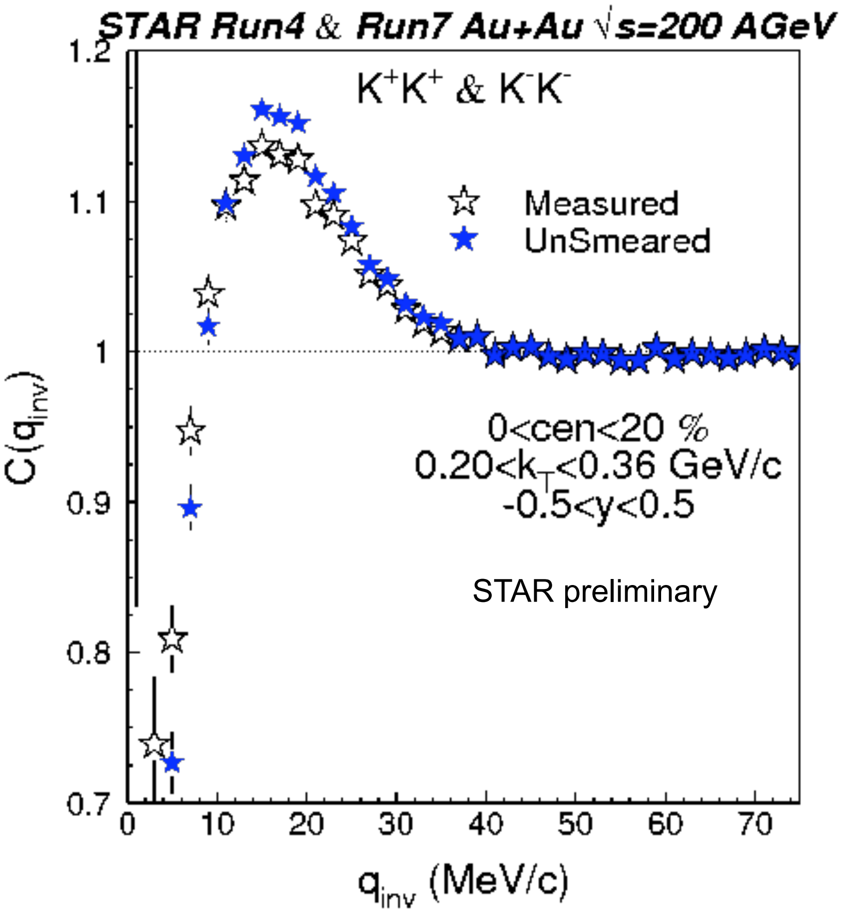
$\mathcal{A}^{(1)}_{x} = n_x$	$\mathcal{A}^{(3)}_{xyz} = n_x\, n_y\, n_z$
$\mathcal{A}^{(2)}_{xx} = n_x^2 - 1/3$	$\mathcal{A}^{(4)}_{xxxx} = n_x^4 - (6/7)n_x^2 + 3/35$
$\mathcal{A}^{(2)}_{xy} = n_x\, n_y$	$\mathcal{A}^{(4)}_{xxxy} = n_x^3\, n_y - (3/7)n_x\, n_y$
$\mathcal{A}^{(3)}_{xxx} = n_x^3 - (3/5)n_x$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

Ellipsoid fit



Momentum resolution correction

1D C(q) Corrected vs C(q) UnSmeared



1D C(q) UnSmeared vs C^0 (q) UnSmeared)