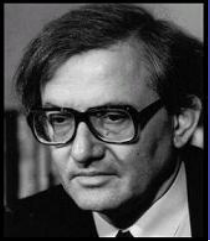


12th Zimányi Winter School on Heavy Ion Physics

Kaon source imaging with the STAR experiment

in 200 GeV Au+Au collisions at RHIC

Róbert **Vértesi**
(for the STAR collaboration)

Nuclear Physics Institute
Czech Academy of Sciences

3 December 2012

evropský sociální fond v ČR

EVROPSKÁ UNIE

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

OP Vzdělávání pro konkurenceschopnost

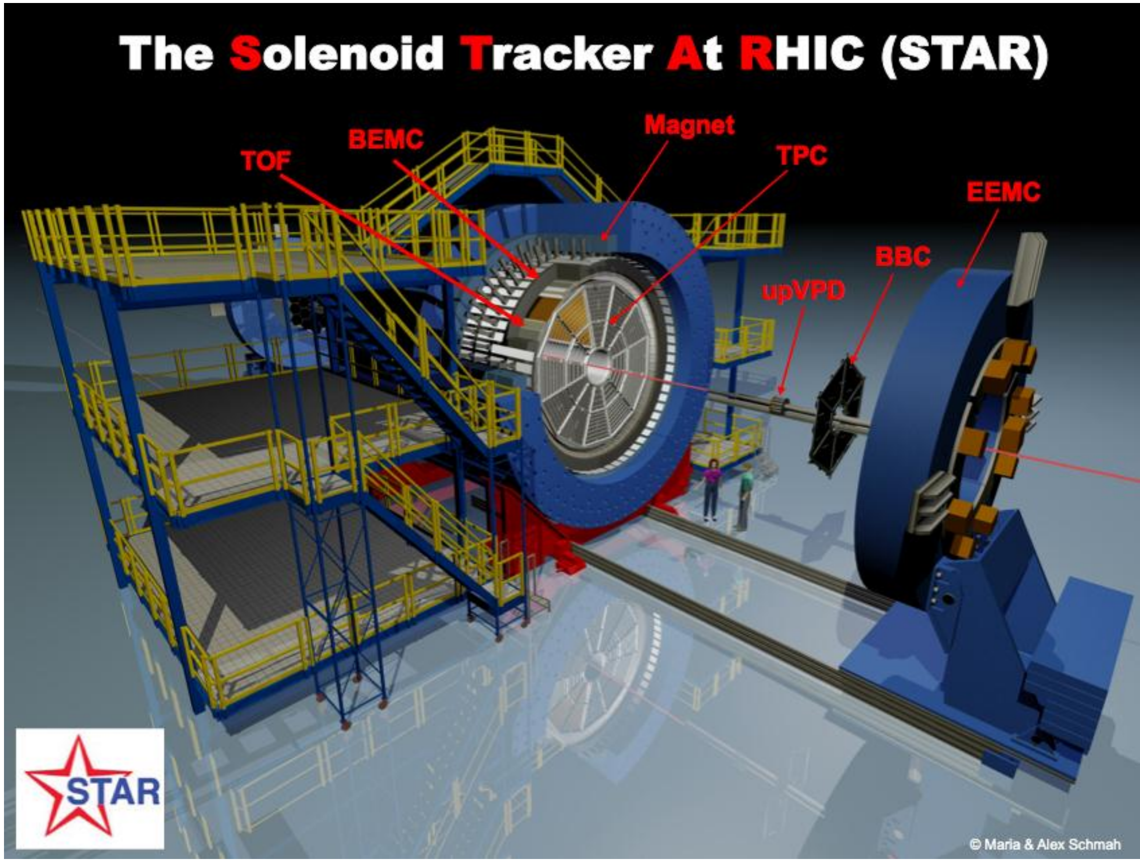
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

The RHIC facility

- Two independent rings
  - 3,9 km long each
- Collides heavy ions...
  - **Au+Au**, **Cu+Cu**, **U+U**...
  - $\sqrt{s_{NN}}$= 7,7 – 200 GeV
- ...and protons
  - **p+p** up to $\sqrt{s}$ = 500 GeV
  - Different polarization patterns
- Asymmetric setups
  - **d+Au, Cu+Au …**
- 4 experiments
  - All different capabilities
  - PHENIX, STAR (the „large” ones)
  - PHOBOS, BRAHMS (completed)

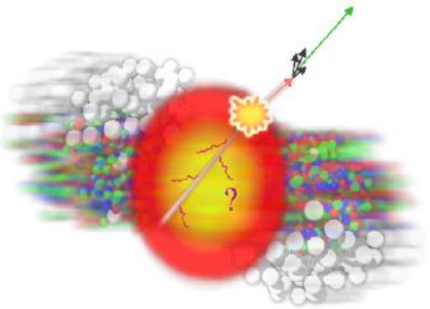
The STAR Experiment

- Time Projection Chamber
  - dE/dx
  - Momentum
- Time of Flight detector
  - Velocity (1/β)
- Electromagnetic Calorimeter
  - E/p
  - trigger

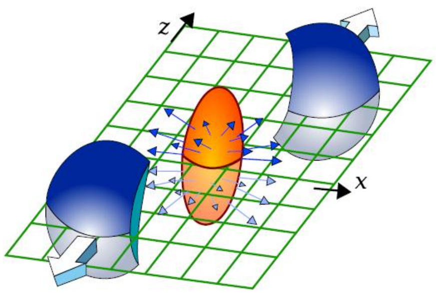


Hot nuclear matter

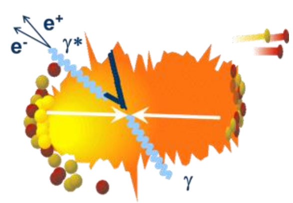
Nucl. Phys. A 757 (2005) p1 ; p28; p102 ; p184 [white papers]



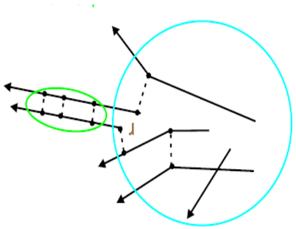
- Extremely dense
  - Au+Au: jet suppression
    No effect in d+Au
  - → Strongly interacting, new state of matter
    $\lambda \sim 3$ fm (5 GeV jet)



- Perfect fluid of quarks
  - Contradicts expectations
  - Degrees of freedom: quarks
  - Viscosity consistent with theoretical limit
    $\eta/s \sim \hbar/4\pi$, $c_s = 0.35c$



- Quark Gluon Plasma (sQGP)
  Phys.Rev.Lett. 104, 132301 (2010)
  - Thermal radiation, T_{init}~4 x 10^{12} K
    T_{init}>300 MeV>>$T_{Hagedorn}$, ε_{init}~15 GeV/fm^3 ,$p_{init} \geq 1.5$ GeV/fm^3



- Evolution of the particle source?
  - Dynamics, space-time extent ←correlations

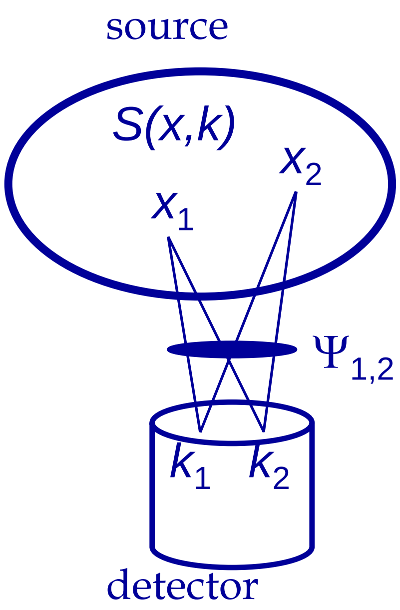
HBT source and correlation

The invariant correlation function

$$C_2(k_1,k_2) = \frac{N_2(k_1,k_2)}{N_1(k_1)N_1(k_2)} \simeq 1 + \left|\frac{\tilde{S}(q,K)}{\tilde{S}(0,K)}\right|^2$$

$$N_1(k_1) = \int S(x_1,k_1)|\Psi_1|^2 \mathrm{d}x_1$$

$$N_2(k_1,k_2) = \int S(x_1,k_1)S(x_2,k_2)|\Psi_{1,2}|^2 \mathrm{d}x_1 \mathrm{d}x_2$$



Depends on relative and average momenta

$$q = k_1 - k_2, K = 0.5(k_1 + k_2)$$

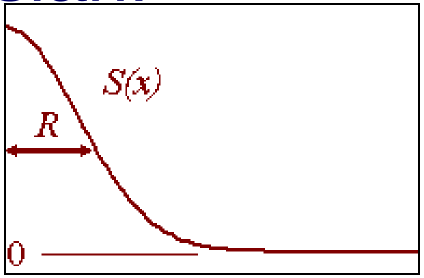
Includes Fourier-transformed form of the source

$$\tilde{S}(q,K) = \int \mathrm{d}x S(x,k) \mathrm{e}^{iqx}$$

Gaussian approximation

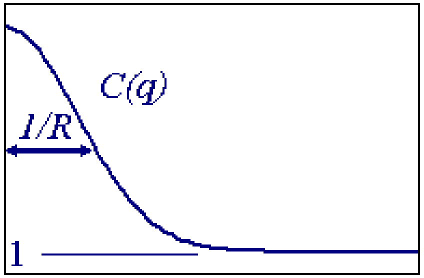
- If the source is approximated with Gaussian:

$$S(x) \sim \exp\left(-\frac{r_x^2}{2R_x^2} - \frac{r_y^2}{2R_y^2} - \frac{r_z^2}{2R_z^2}\right)$$



- Then the correlation function is also Gaussian:

$$C(q) - 1 \sim \exp\left(-q_x^2 R_x^2 - q_y^2 R_y^2 - q_z^2 R_z^2\right)$$



- These radii are the so-called HBT radii
- Often specified in the LCMS system (not invariant)
  - **Out**: direction of the mean transverse momentum of the pair
  - **Side**: orthogonal to out
  - **Long**: beam direction

$$C(q) = 1 + \lambda \exp\left(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2\right)$$

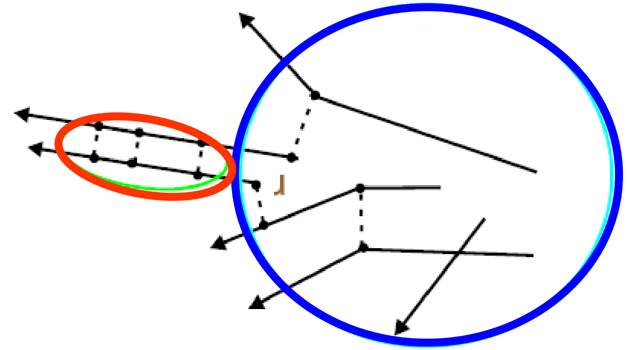
- Do not necessarily reflect the geometrical size

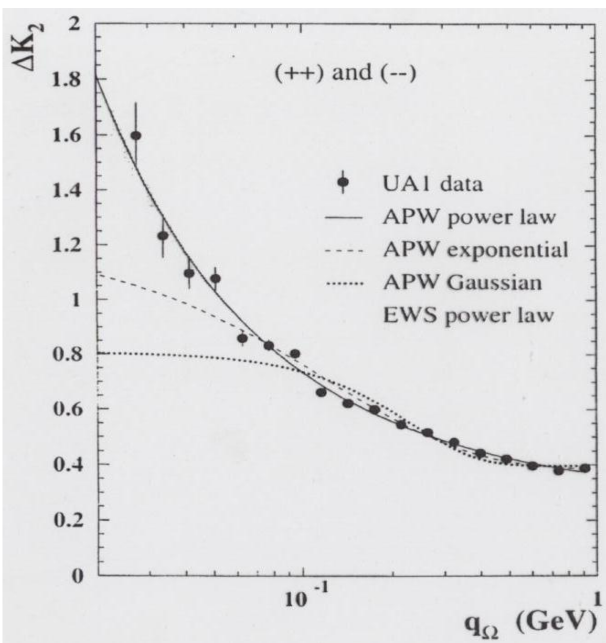
Complications...

Our source is not Gaussian

- Sometimes Gaussian assumption is meaningless
- Example: Lévy-function

$$C_0 - 1 \sim \lambda \exp(-|qR|^{\alpha})$$





Final State Interactions

- Coulomb force
  (Have to correct for this)

$$C_0(q) = C_{\mathrm{raw}}(q) K_{\mathrm{coulomb}}^{-1}$$

1. K_{coulomb} is computed analytically
2. C_0 is fitted, R, λ ,α determined

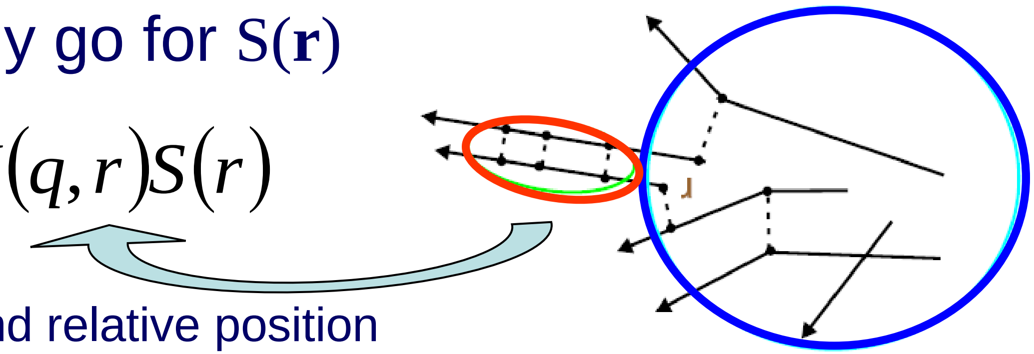
- Strong FSI …

Source Imaging – a general way

D. A. Brown, P. Danielewicz, nucl-th/9701010

- Instead of $C_{raw}(q)$ we directly go for $S(\mathbf{r})$

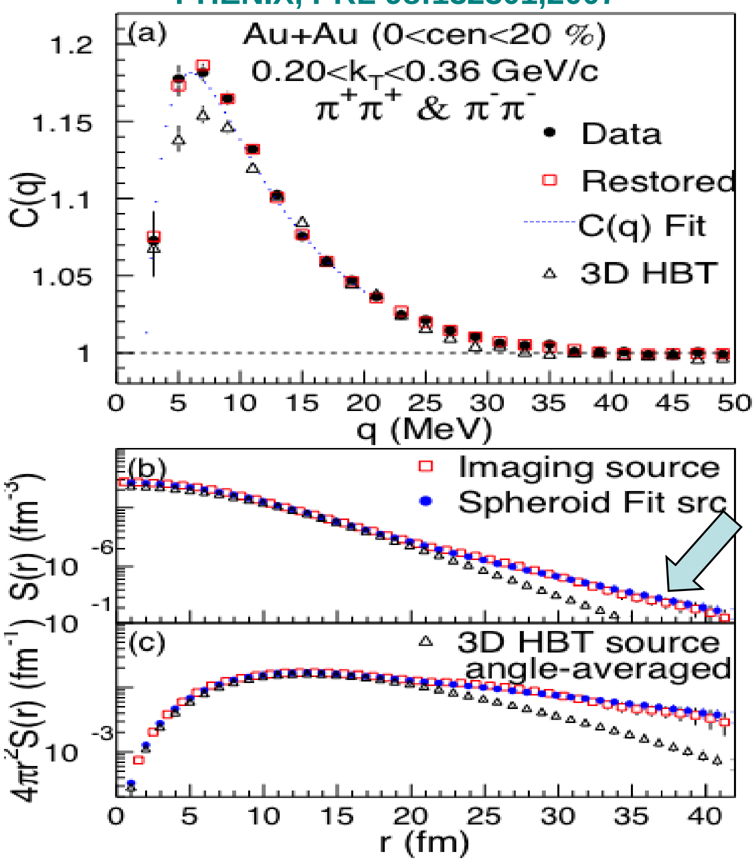
$$C(q)-1=4\pi\int drr^2K(q,r)S(r)$$



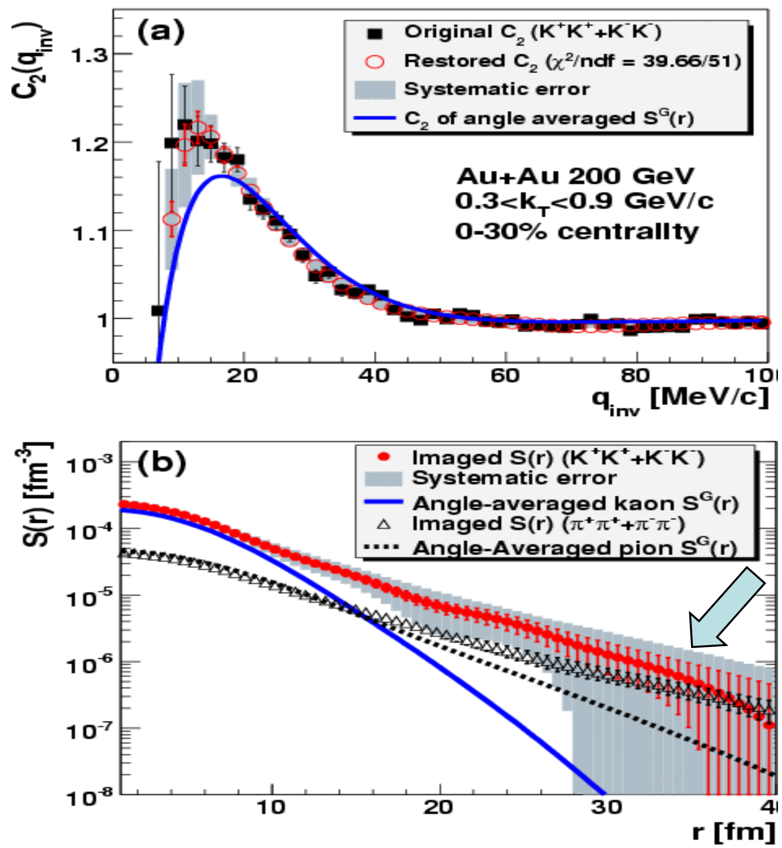
  - 2-particle source function and relative position
  - Evaluated in a specific transverse momentum range
- Numerically invert this equation
  - No analytical solution, hence systematic errors
  - But **no assumtions for the shape** of the source
  - Final state interactions included as well as Coulomb interactions
- Approximations during FT $\hat{S}(q)$
  - Assumption of weak dependence in single particle sources
  - Computation is numerical, ie. integration cut-off, though finite resolution in $\mathbf{r}$
  - Derived $S(r)$ formula has further assumptions...

PHENIX 1D pions and kaons

PHENIX, PRL 98:132301,2007



PHENIX, PRL 103:142301,2009



- Observed long tail in 1D pion correlation
- Attributed to resonance decays and non-zero emission duration
- Former contradicted by even more pronounced tail in kaon C

3D source shape analysis

STAR

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:

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

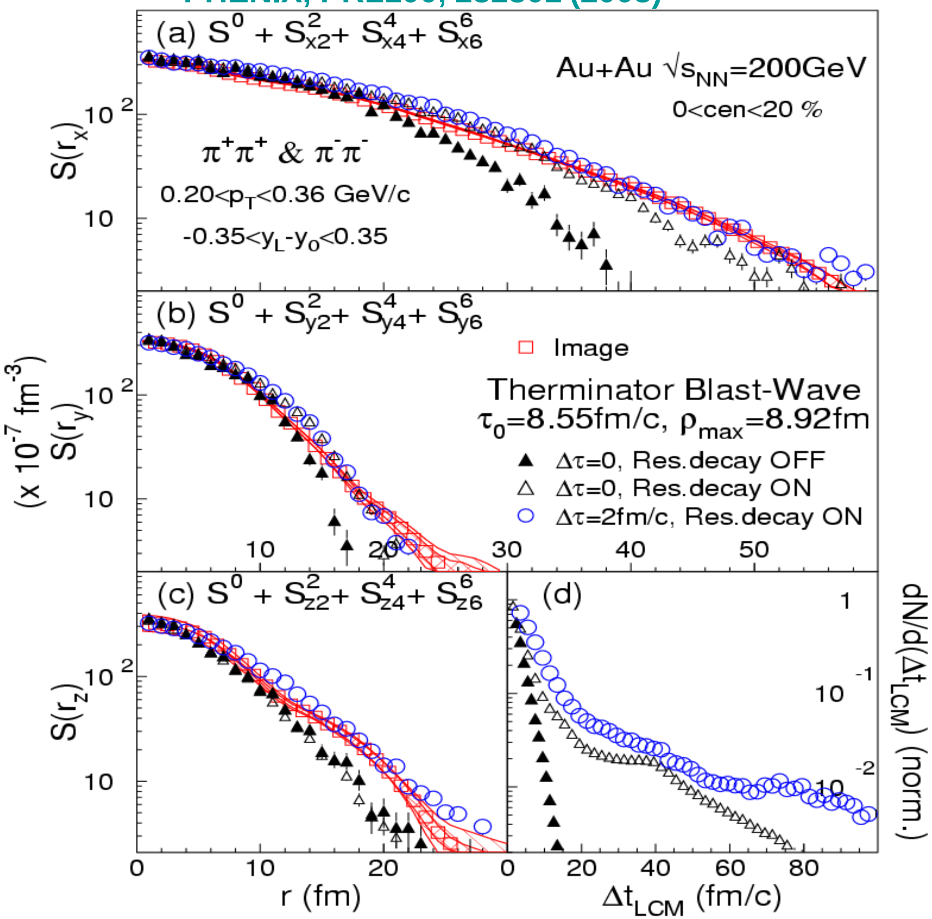
Plug (1) and (2) into (3) $\Rightarrow$ $R^l_{\alpha_1 \ldots \alpha_l}(q) = 4\pi \int dr^3 K_l(q,r) S^l_{\alpha_1 \ldots \alpha_l}(r) \quad (4)$

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

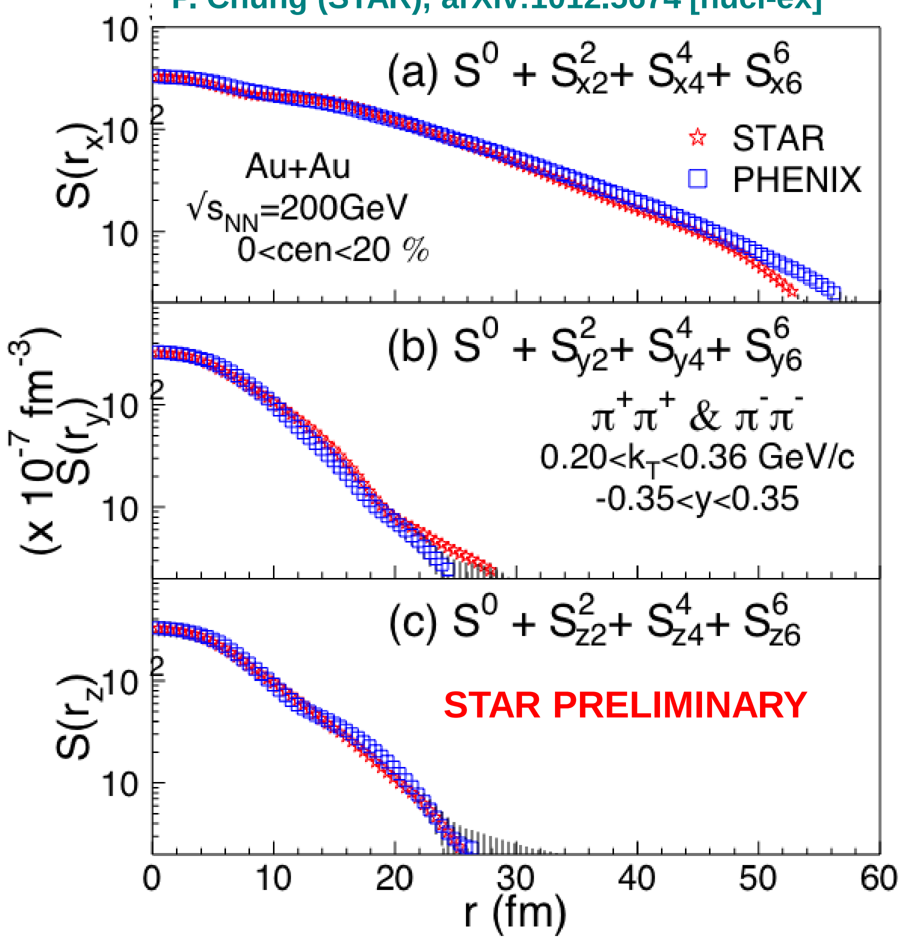
Invert (2) $\Rightarrow$ $S^l_{\alpha_1 \ldots \alpha_l} = \frac{(2l+1)!!}{l!} \int \frac{d\Omega_q}{4\pi} A^l_{\alpha_1 \ldots \alpha_l}(\Omega_q) S(\mathbf{q})$

3D pions, PHENIX vs. STAR

PHENIX, PRL100, 232301 (2008)



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



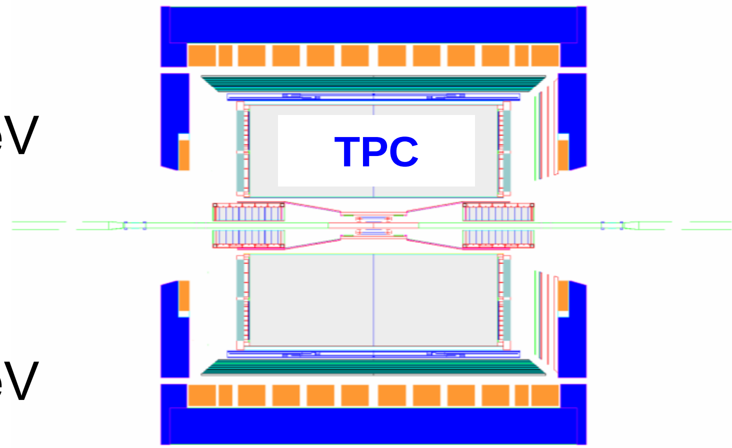
Elongated source in "out" direction

Therminator Blast Wave model suggests non-zero emission duration

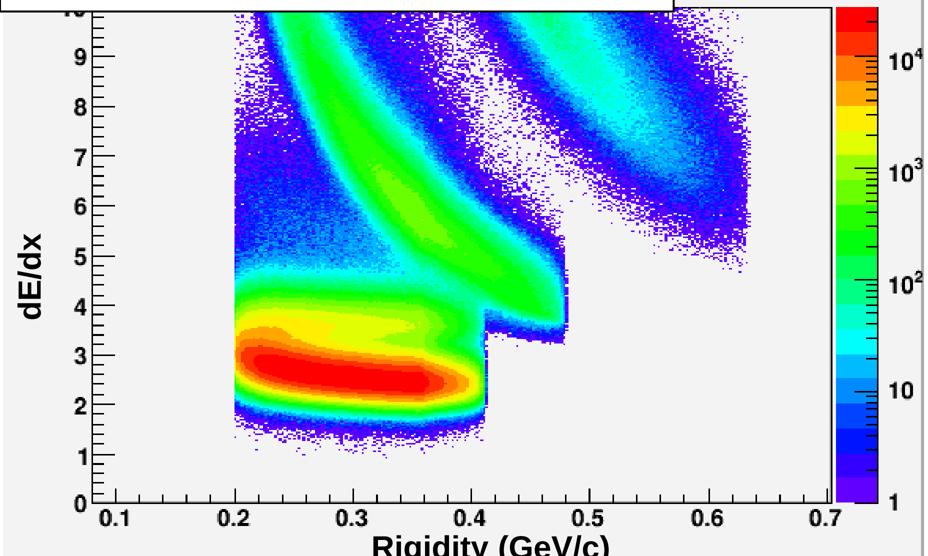
Very good agreement of PHENIX and STAR 3D pion source images

Kaon analyses

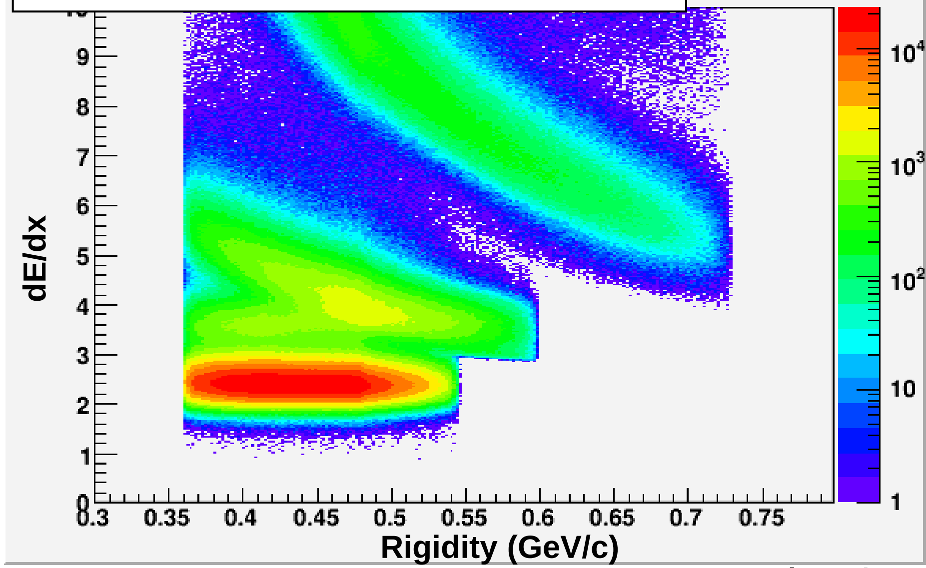
- Dataset #1 (Source shape analysis)
  - 20% most central Au+Au @ √sNN=200 GeV
  - Run 4: 4.6 Mevts, Run 7: 16 Mevts
- Dataset #2 (mT-dependent analysis)
  - 30% most central Au+Au @ √sNN=200 GeV
  - Run 4: 6.6 Mevts



0.2<kT<0.36 GeV/c



0.36<kT<0.48 GeV/c

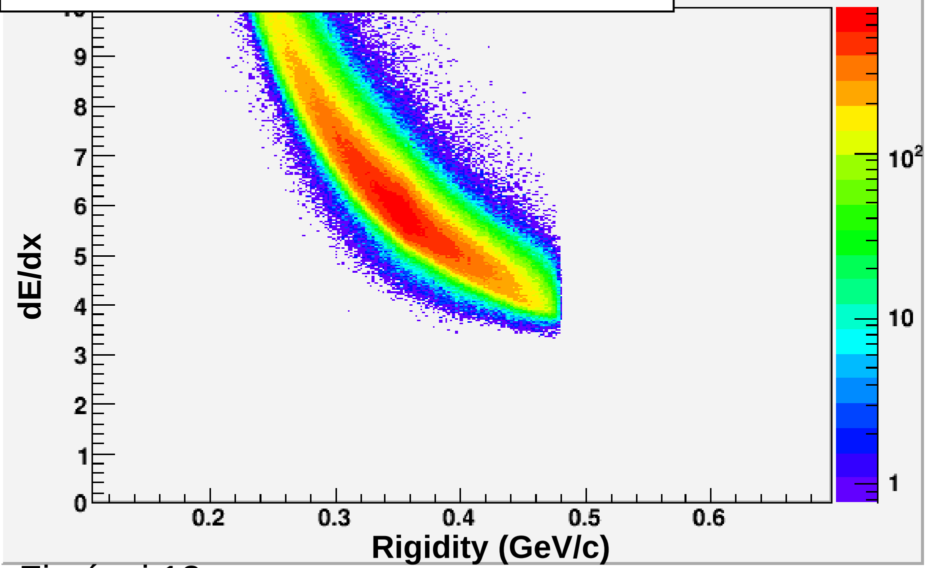


PID cut applied

- Dataset #1 (Source shape analysis)
  - dE/dx: σ(Kaon)<2.0 and σ(Pion)>3.0 and σ(electron)>2.0
  - |y| < 0.5
  - 0.2 < pT < 0.4 GeV/c
- Dataset #2 (mT-dependent analysis)

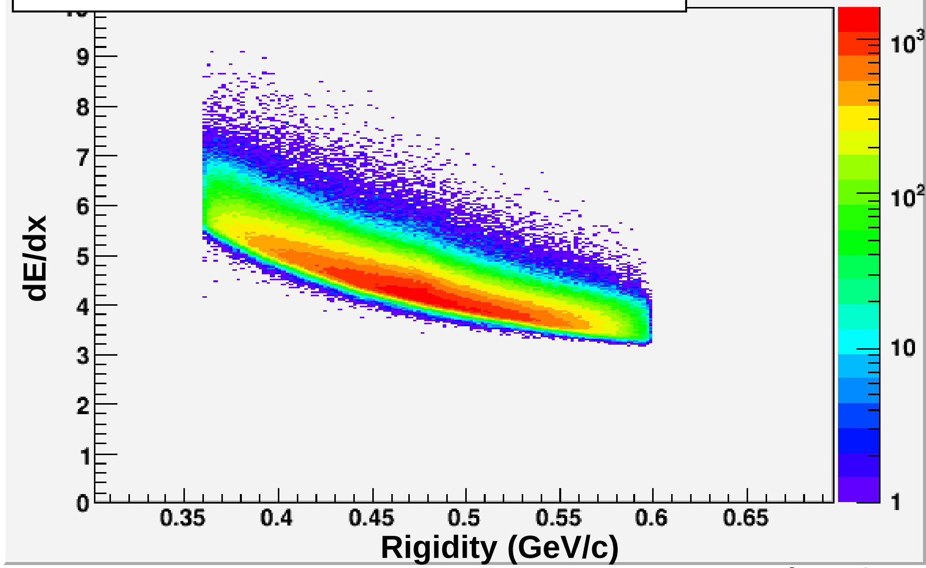
-1.5<σ(Kaon)<2.0

0.2<kT<0.36 GeV/c

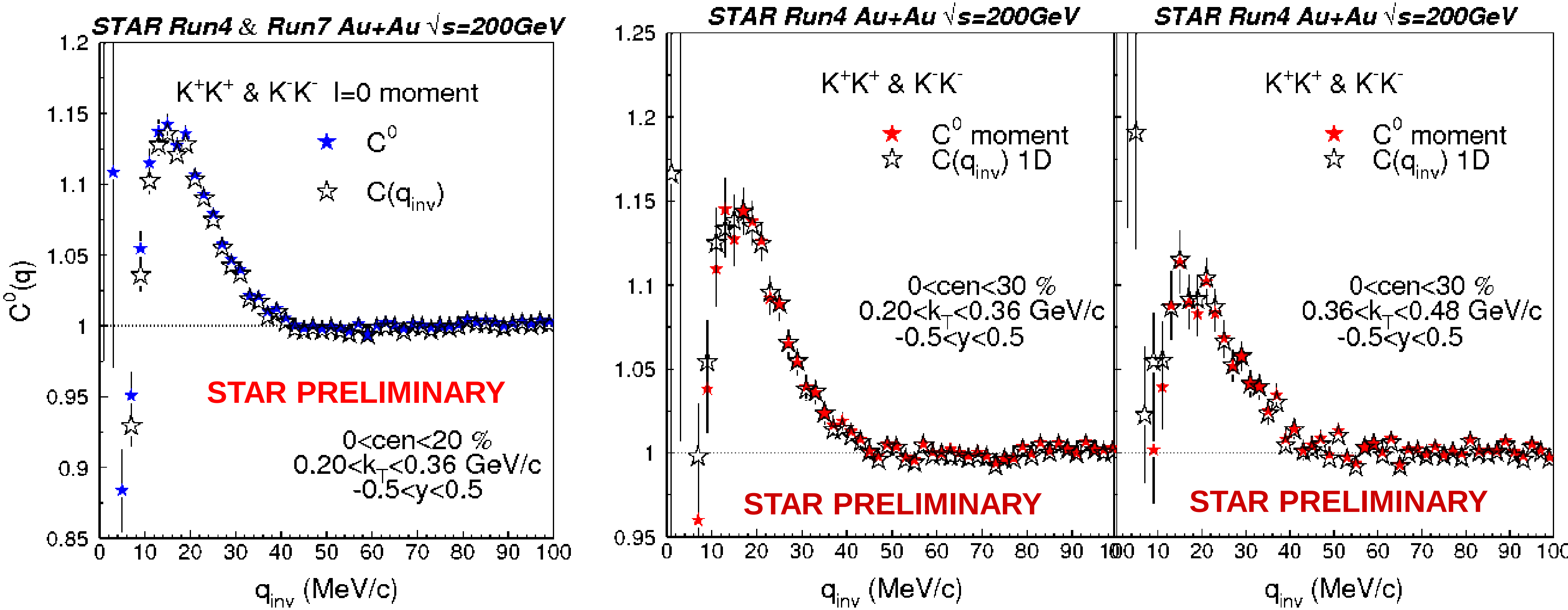


-0.5<σ(Kaon)<2.0

0.36<kT<0.48 GeV/c



Kaon $C_0(q_{inv})$ vs. $C(q_{inv})$



l=0 moment in agreement with 1D C(q)

Fit to correlation moments #1

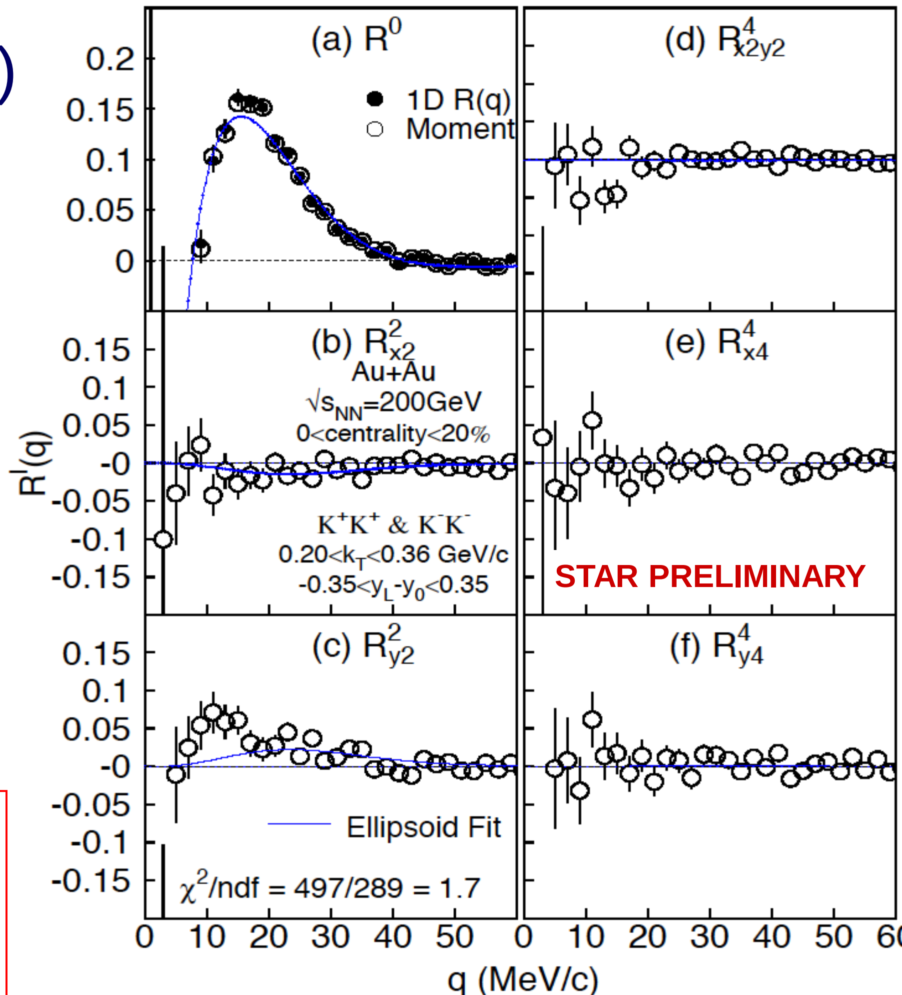
- Trial funcional form for S(r): 4-parameter ellipsoid (3D Gauss)

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

- Fit to C(q): technically a simultaneous fit on 6 independent moments $R^l_{\alpha 1 \ldots \alpha l}$, $0 \leq l \leq 4$

- Result: statistically good fit

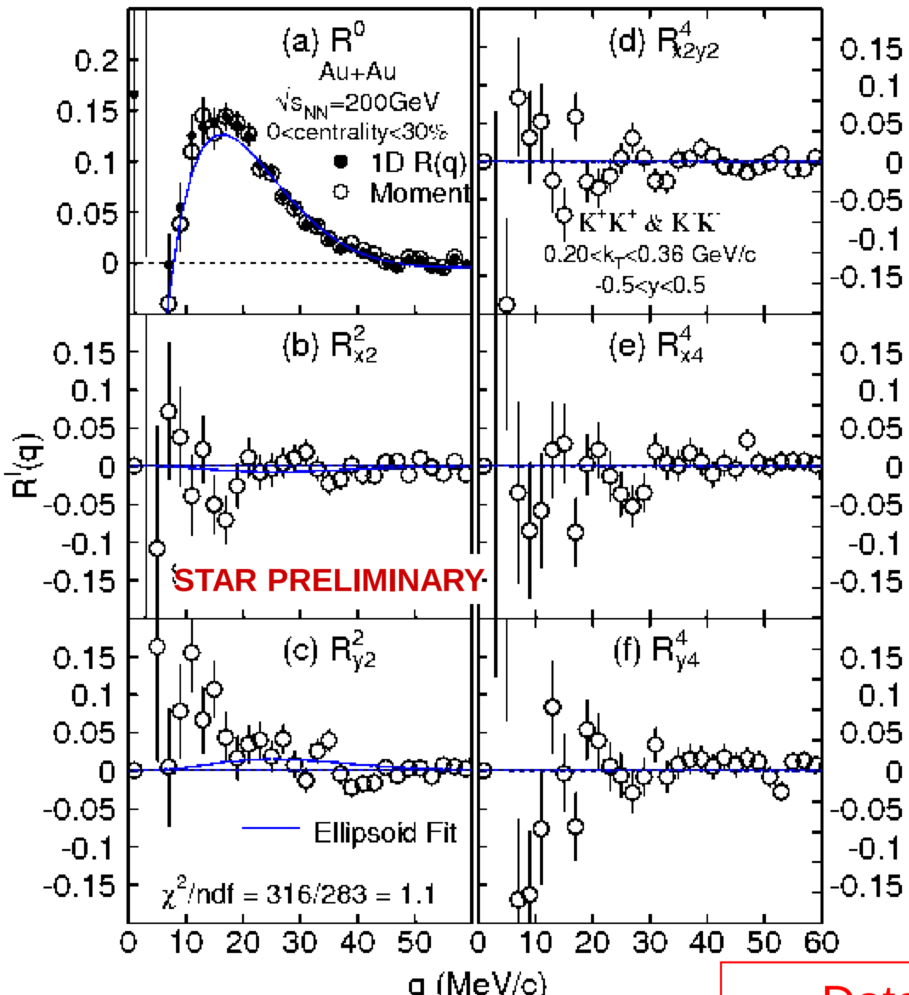
Dataset #1	$\lambda = 0.48 \pm 0.01$
Run4+Run7	$r_x = (4.8 \pm 0.1)$ fm
Cent<20%	$r_y = (4.3 \pm 0.1)$ fm
0.2<kT<0.36 GeV/c	$r_z = (4.7 \pm 0.1)$ fm

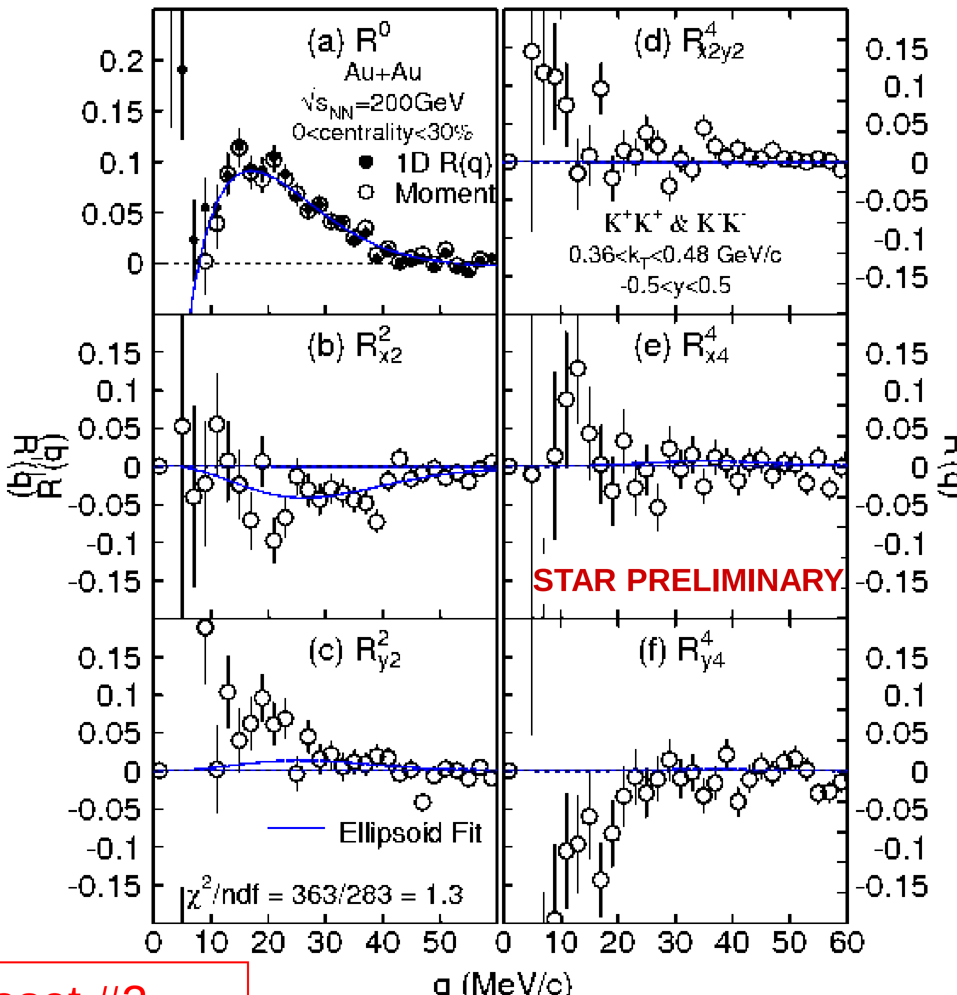


Fit to correlation moments #2

0.2<kT<0.36 GeV/c

0.36<kT<0.48 GeV/c

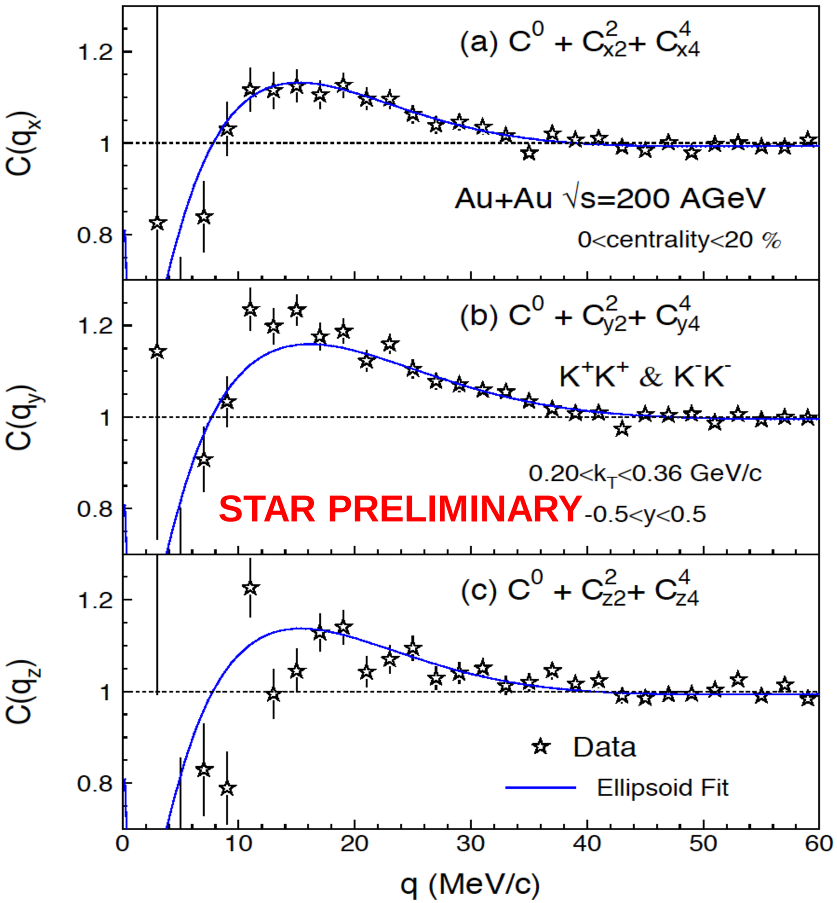




Dataset #2

Run4 Cent<30%

3D Kaon source vs. Model

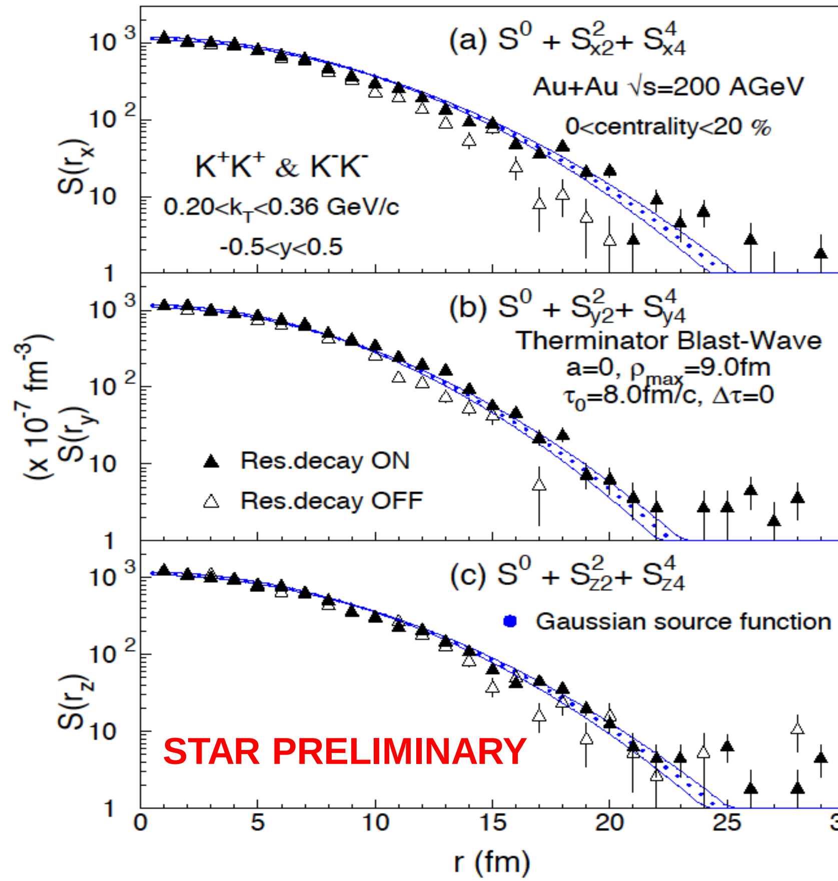


Correlation profiles

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

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

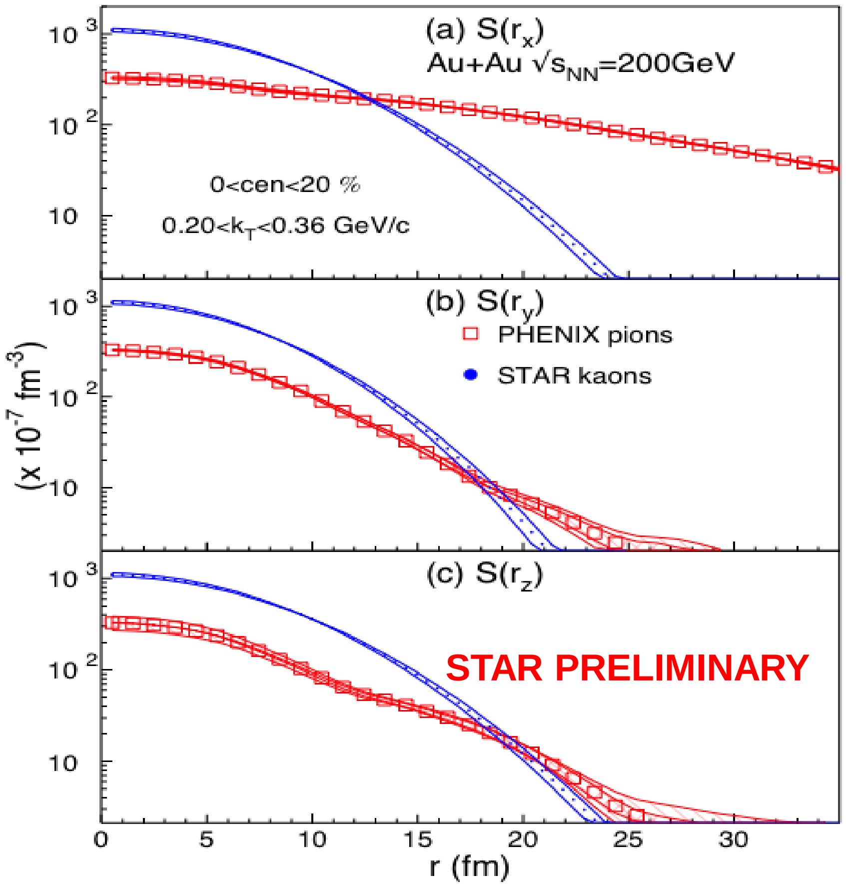
$C(q_z) \equiv C(0,0,q_z)$



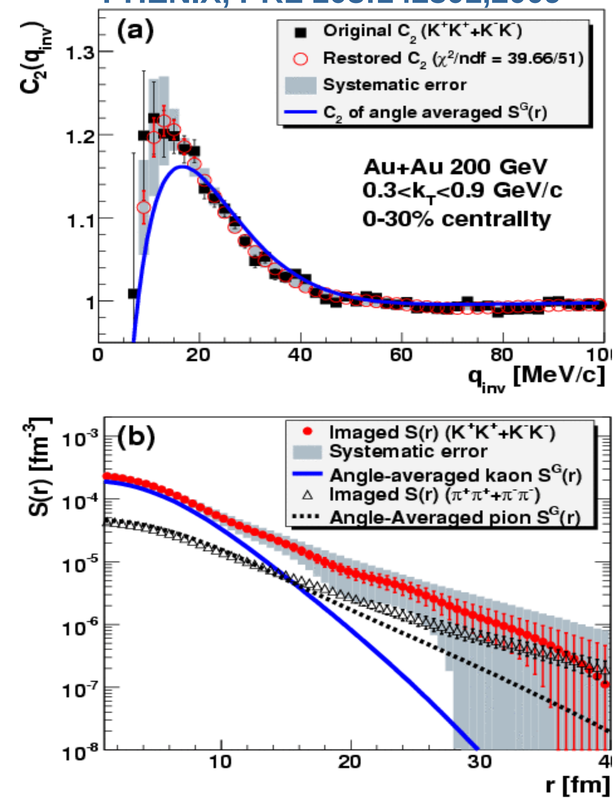
Source consistent with Therminator Blast Wave model w/ resonances

- Instant freeze-out at τ_0 = 0.8 fm/c
- Zero emission duration

Data comparison



PHENIX, PRL 103:142301,2009



Kaon vs. Pion: different shape

- **Gaussian, no long tail present**
- **Sign of different freeze-out dynamics?**

Note: systematic errors for kaons are not represented

1D PHENIX kaon:

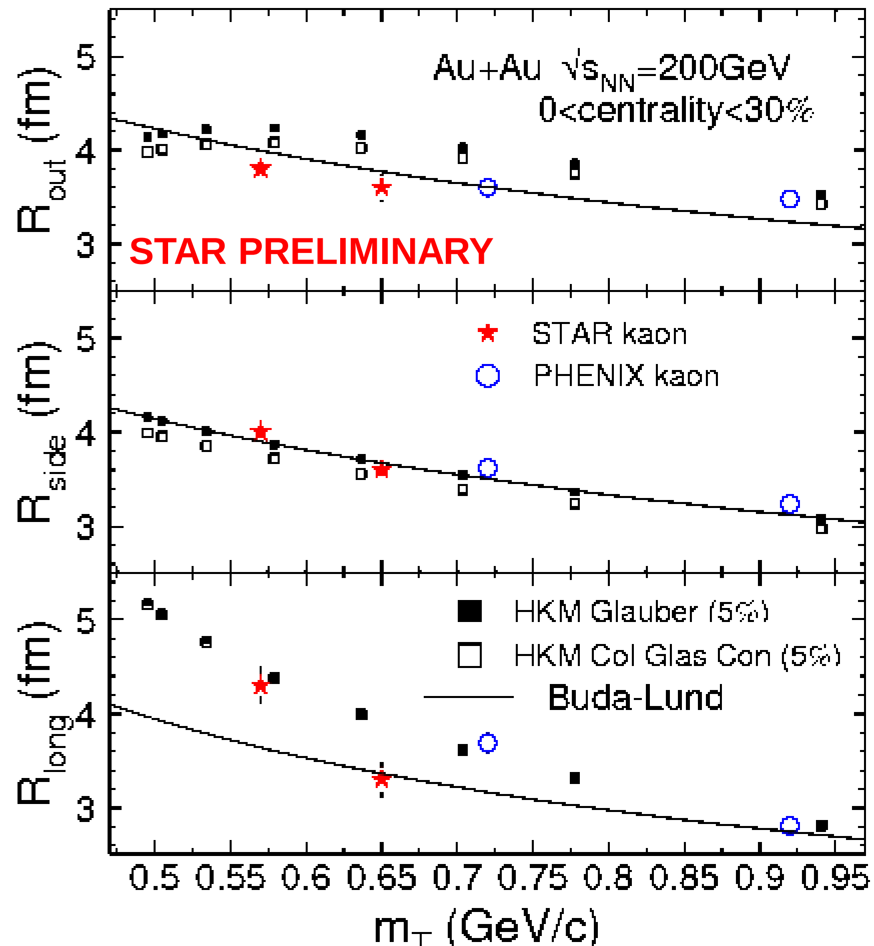
- Observed long tail due to wide kT bin?

0.3<kT<0.9 GeV

Transverse mass dependence

P. Chung (STAR), PoS WPCF2011 (2011) 036

- Rising trend at low mT
- Buda-Lund model
  - Inherent mT-scaling
  - Works perfectly for pions
  - Deviates from kaons in the "long" direction in the lowest mT bin
- HKM (Hidro-kinetic model)
  - Describes all trends
  - Some deviation in the "out" direction
  - Note the different centrality definition



Note: systematic errors are not represented here

Buda-Lund: 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 $\sqrt{s_{NN}}$=200 GeV central RHIC data
- Comparison with Therminator model 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

The End

Thank You

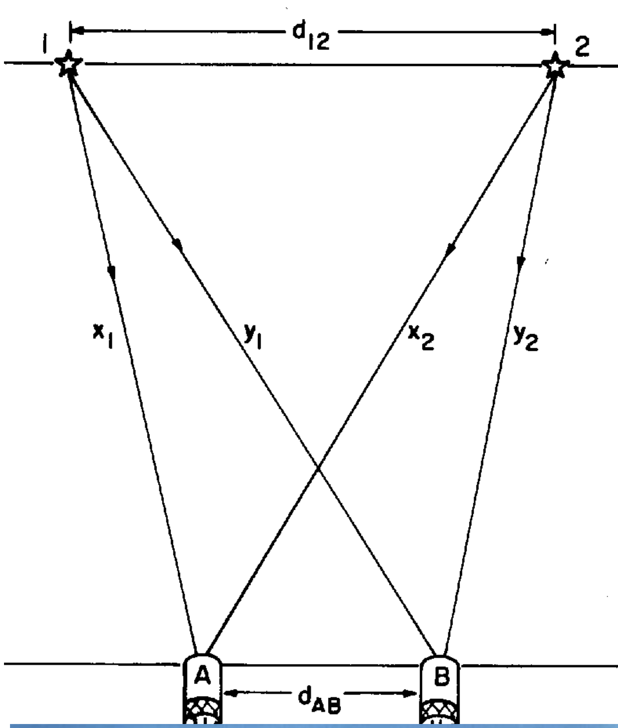
for your attention

backup slides follow…

The HBT effect

- History
  - „Interference between two different photons can never occur.”

    P. A. M. Dirac, The Principles of Quantum Mechanics, Oxford, 1930
  - Robert Hanbury Brown and Richard Q. Twiss, (engineers, worked in radio astronomy) found **correlation between photons from different sources**.
  - „In fact to a surprising number of people the idea that the arrival of photons at two separated detectors can ever be correlated was not only heretical but patently absurd, and they told us so in no uncertain terms, in person, by letter, in print, and by publishing the results of laboratory experiments, which claimed to show that we were wrong …”
- Astronomical usage
  - Intensity interferometry in radio astronomy
  - Angular diameter of a main sequence star measured

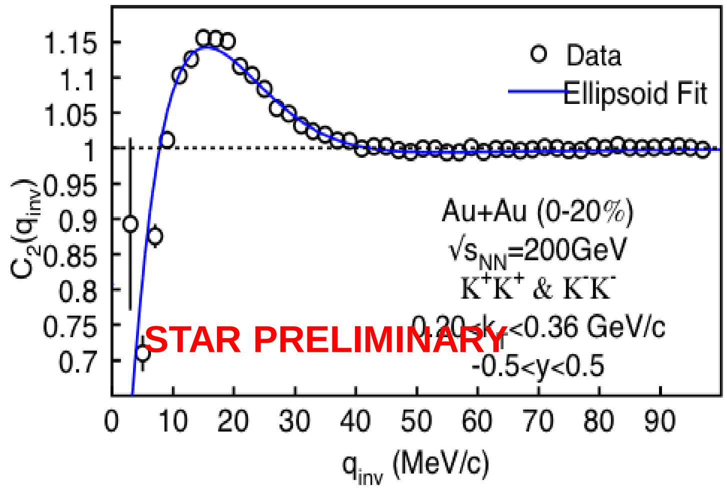


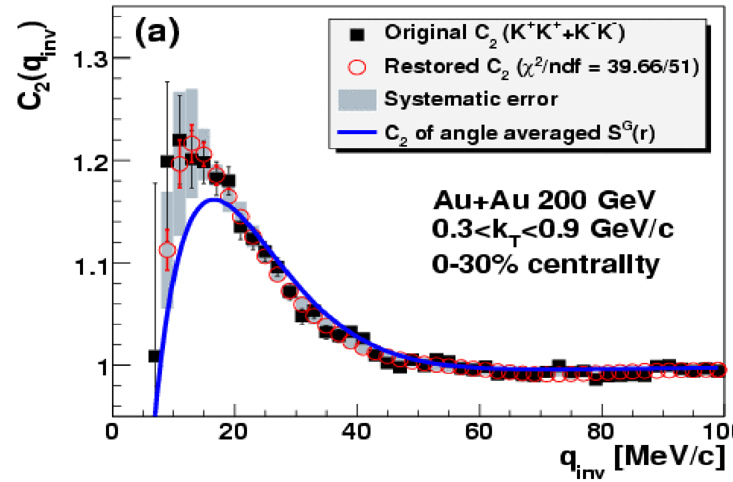
STAR 1D kaons

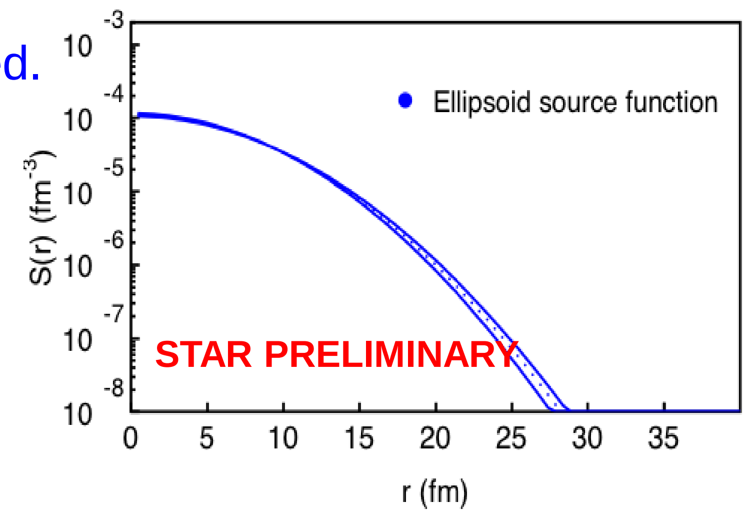
34M+83M=117M K^+K^+ & K^-K^- pairs

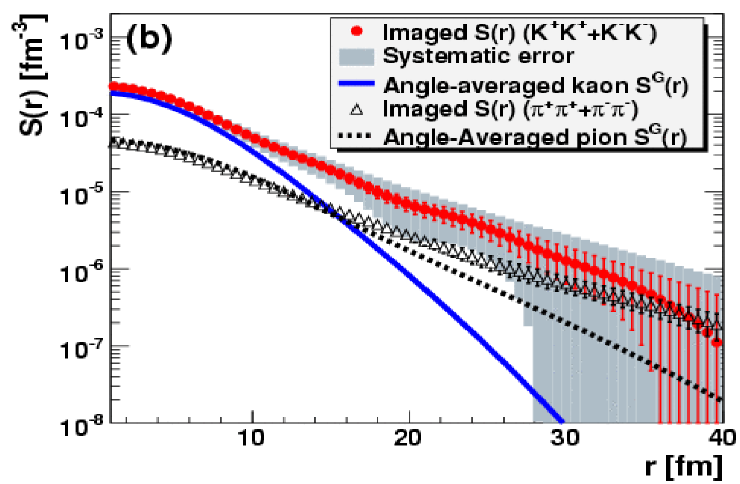
STAR data are well described by Gaussian, contrary to PHENIX no non-gaussian tails are observed.

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









Model comparison: thermal BW

Therminator

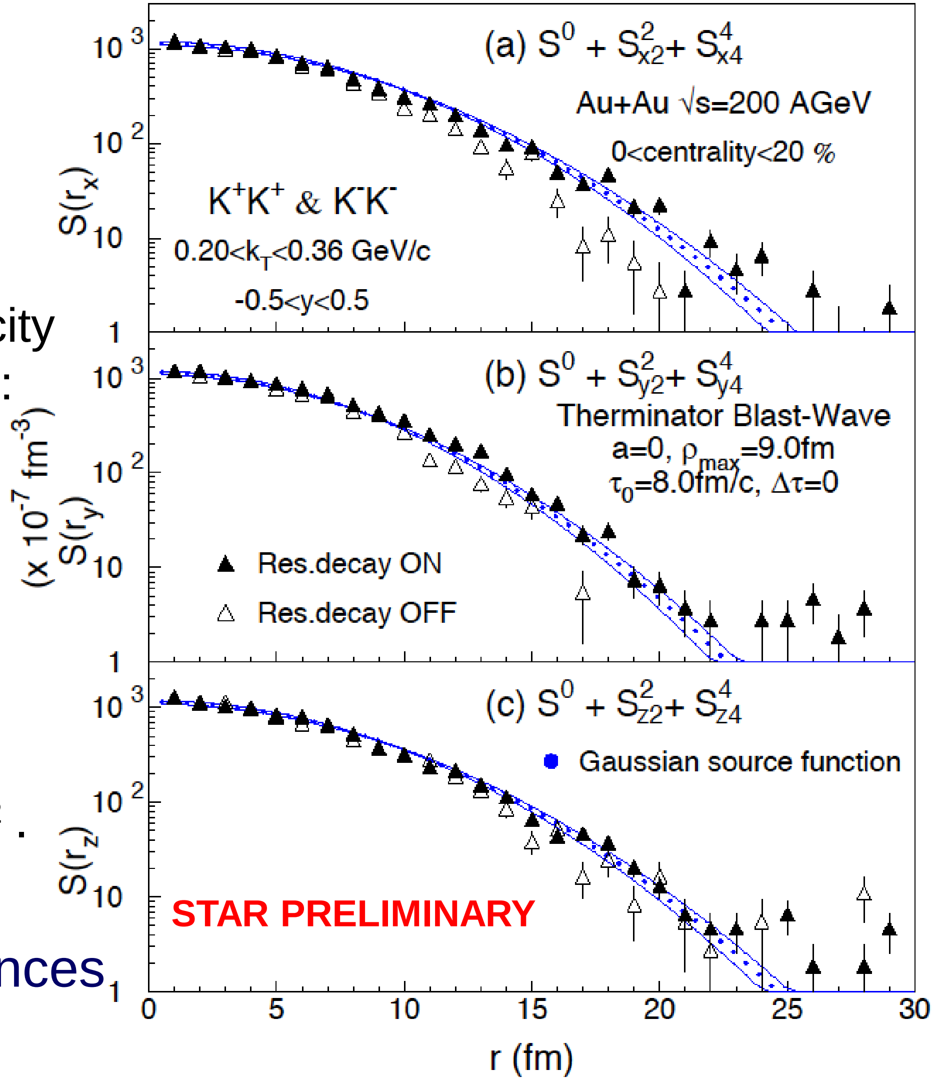
(A Thermal Heavy Ion Generator)

A. Kisiel et al., Phys. Rev. C 73:064902 2006

- Longitudinal boost invariance
- **Blast-wave** expansion: transverse velocity profile semi-linear in transverse radius ρ: $v_t(\rho)=(\rho/\rho_{max})/(\rho/\rho_{max}+v_t)$; $v_t=0.445$ from BW fits to particle spectra
- Thermal emission at proper time τ, from an infinite cylinder radius ρ_{max}
- Freeze-out occurs at $\tau = \tau_0 + a\rho$.
- Particles which are emitted at (z, ρ) have LAB emission time $\tau^2 = (\tau 0 + a\rho)^2 + z^2$.
- Finite emission duration $\Delta\tau$

Source consistent with BW and resonances

- Instant freeze-out at $\tau_0 = 0.8$ fm/c
- Zero emission duration



R. Vértesi