Kaon Femtoscopy in $\sqrt{s_{NN}}$=200 GeV Au+Au Collisions at STAR

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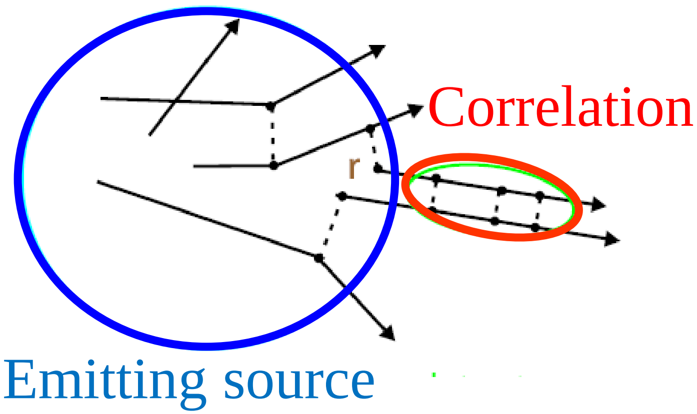
OP Vzdělávání pro konkurenceschopnost

INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Femtoscopy

- Boson emitting source:
  - Symmetric two-boson wave function



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

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

Bose-Einstein Correlation / Hanbury-Brown–Twiss effect

Info about shape and evolution of the particle emitting source

- Correlation function:

$$C_2(k_1, k_2) = \frac{N_2(k_1, k_2)}{N_1(k_1)N_1(k_2)} \simeq 1 + \left| \frac{\tilde{S}(q, K)}{\tilde{S}(0, K)} \right|^2 \quad \tilde{S}(q, K) = \int \mathrm{d}x S(x, k) \mathrm{e}^{iqx}$$

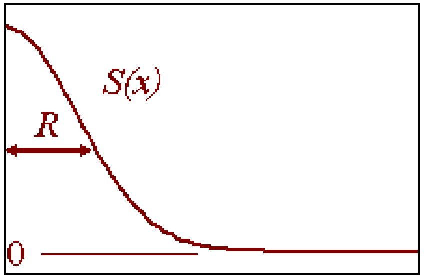
$$q = k_1 - k_2, K = 0.5(k_1 + k_2)$$

- Final state interactions
  - Compensating the Coulomb force $C_0(q) = C_{raw}(q) K_{coulomb}^{-1}$
  - Strong FSI …
- Solving for the source is difficult → assumptions

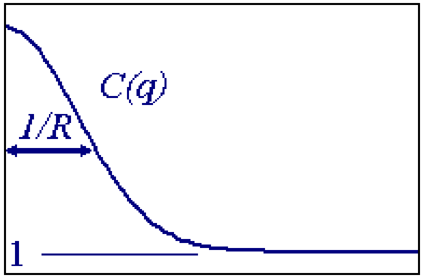
Source approximation w/ Gaussian

- 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

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

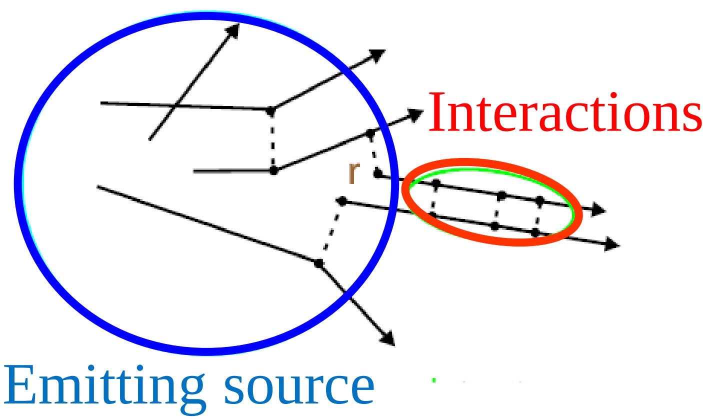
- Do not necessarily reflect the geometrical size

Source imaging

Physics in shape: dynamics, resonance decays, rescattering…

- Koonin-Pratt equation (1D)

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



- Imaging: Obtain S(**r**) directly
  - No assumptions for the shape of source
  - Kernel includes **all** interactions (QM, FSI)
- Numerical inversion of the equation
  - No analytical solution, hence some limitations and approximations (integral cutoff, finite resolution …)
  - Assumptions (e.g. weak dependence in single particle sources)
  - Needs statistics, stability is a question

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

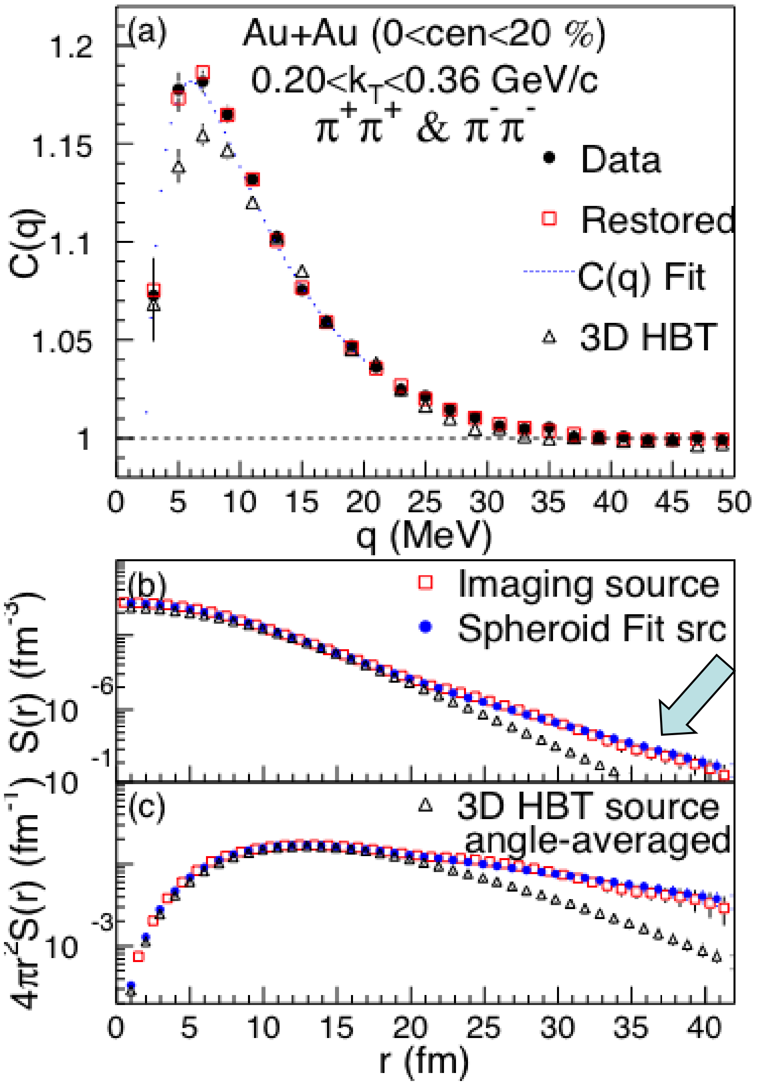
Why Kaons?

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

  Tail attributed to decays of long-lived resonances and/or non-zero emission duration
- Kaons: cleaner probe

  less contribution from resonances

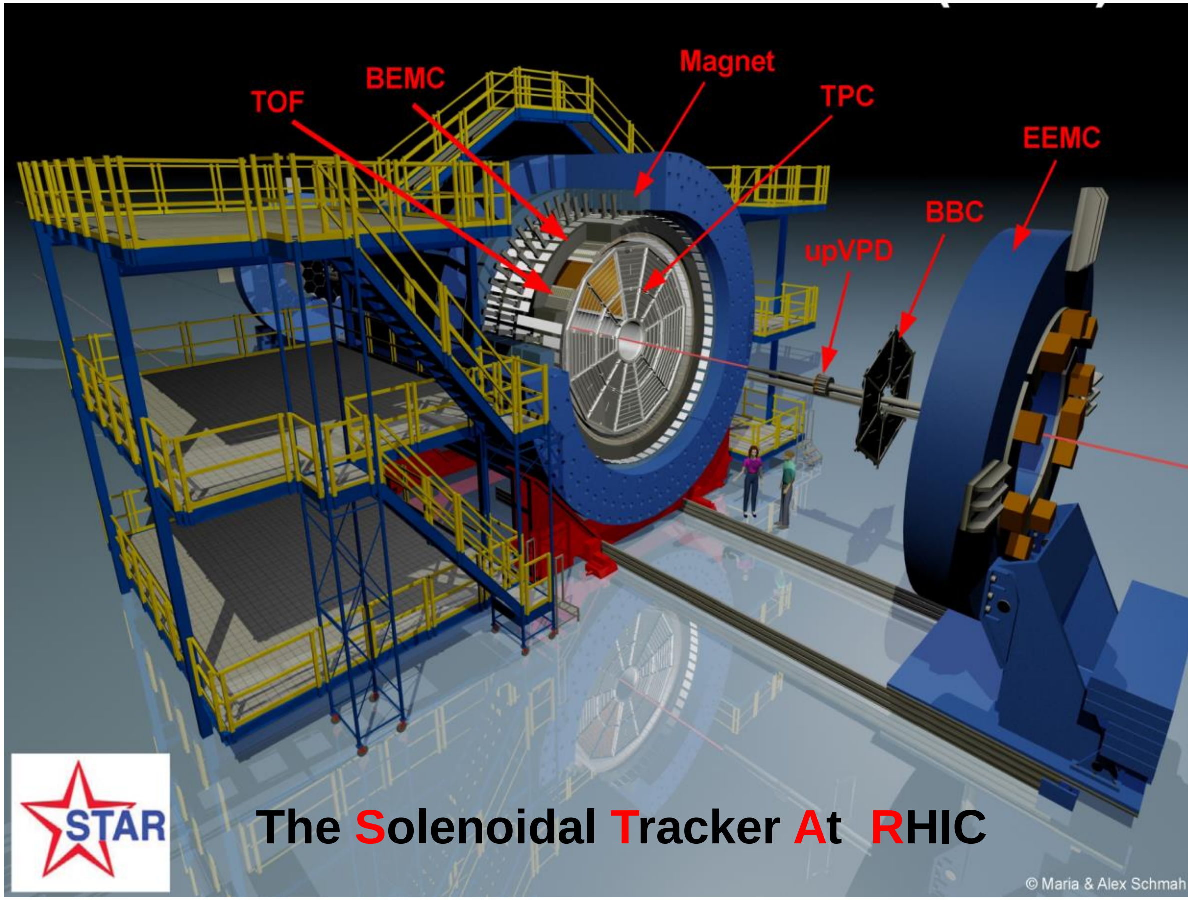
PHENIX, PRL 98:132301,2007



The STAR Experiment

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

  for different energies and particles

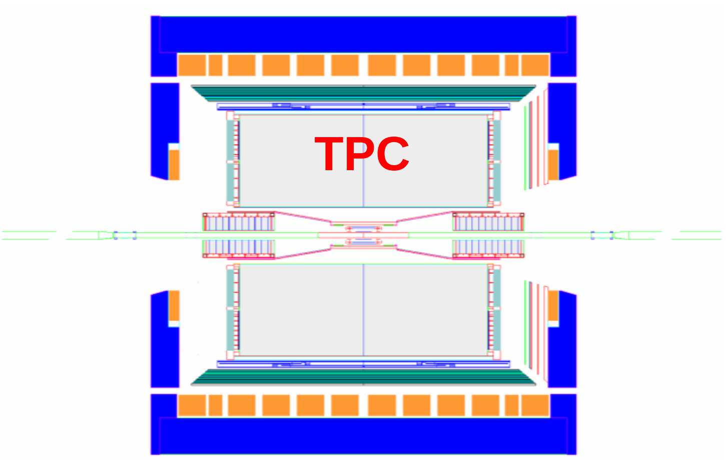


Kaon femtoscopy analyses

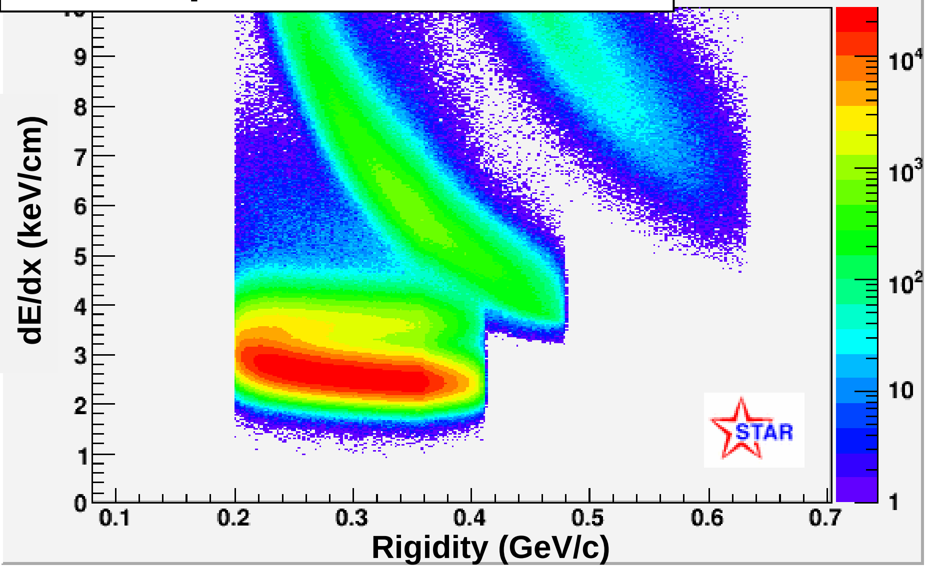
Au+Au @ $\sqrt{s_{NN}}$=200 GeV

Mid-rapidity |y|<0.5

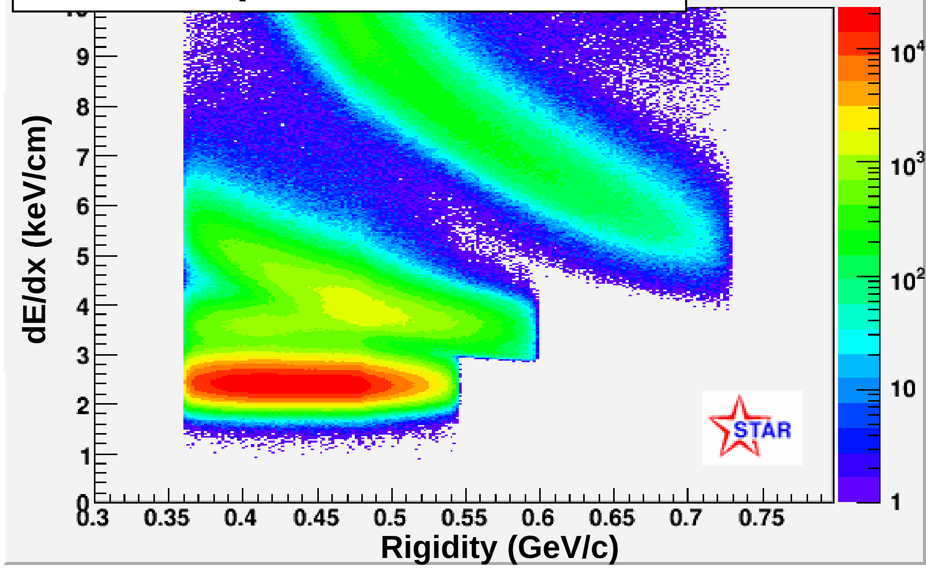
1. Source shape: 20% most central
   Run 4: 4.6 Mevts, Run 7: 16 Mevts
2. m_T-dependence: 30% most central
   Run 4: 6.6 Mevts



$0.2<k_T<0.36$ GeV/c



$0.36<k_T<0.48$ GeV/c



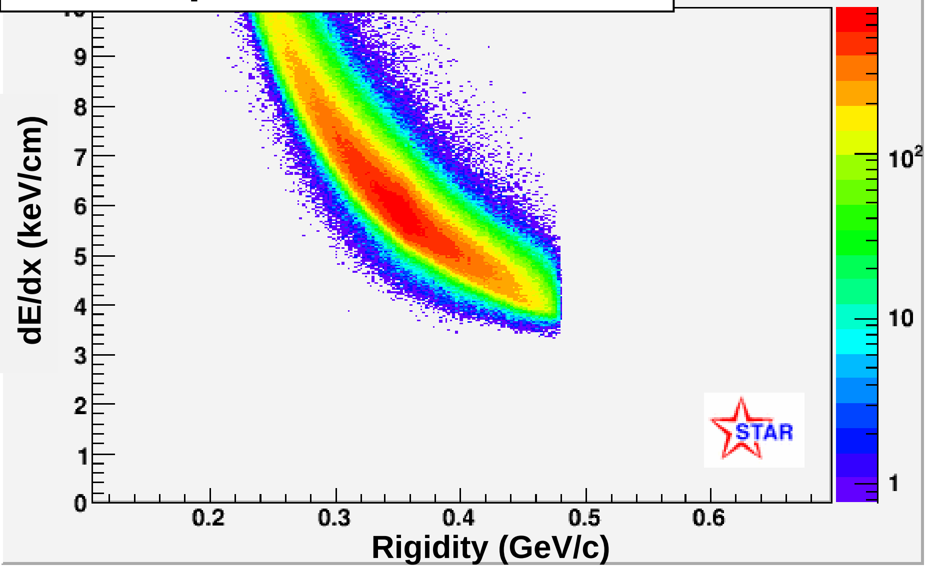
PID cut applied

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 partice type X at a given momentum
   - $0.2 < p_T < 0.4$ GeV/c
2. m_T-dependent analysis

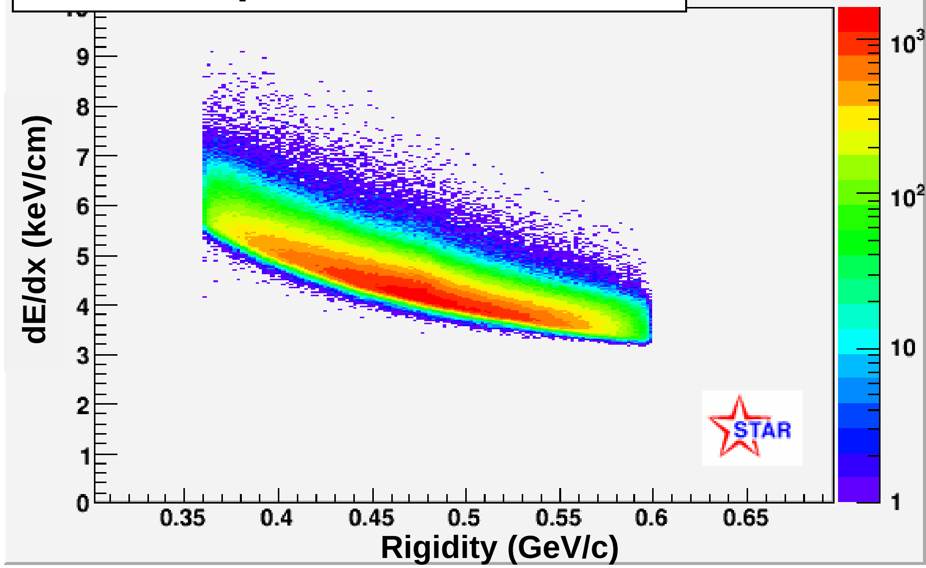
-1.5< nσ(Kaon)<2.0

$0.2<k_T<0.36$ GeV/c



-0.5< nσ(Kaon)<2.0

$0.36<k_T<0.48$ GeV/c



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)

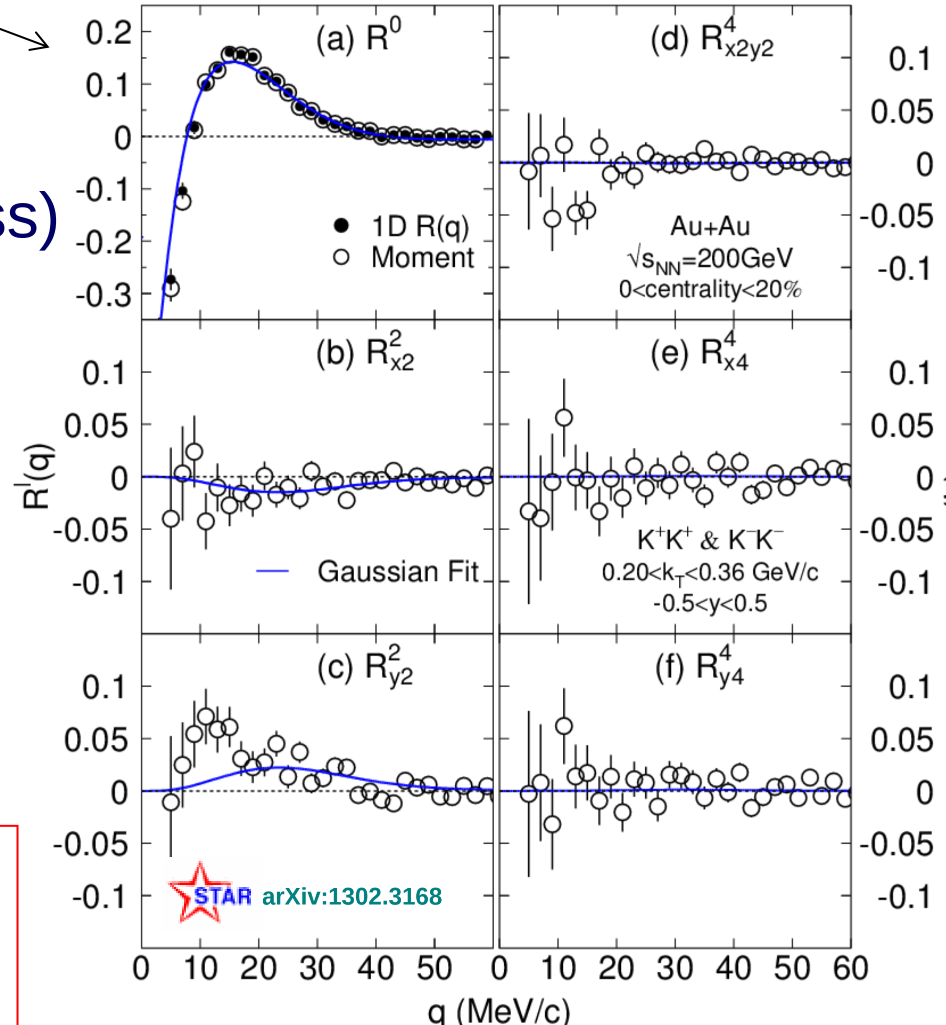
  Higher moments relatively small
- Trial funcional form for S(r): 4-parameter ellipsoid (3D Gauss)

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

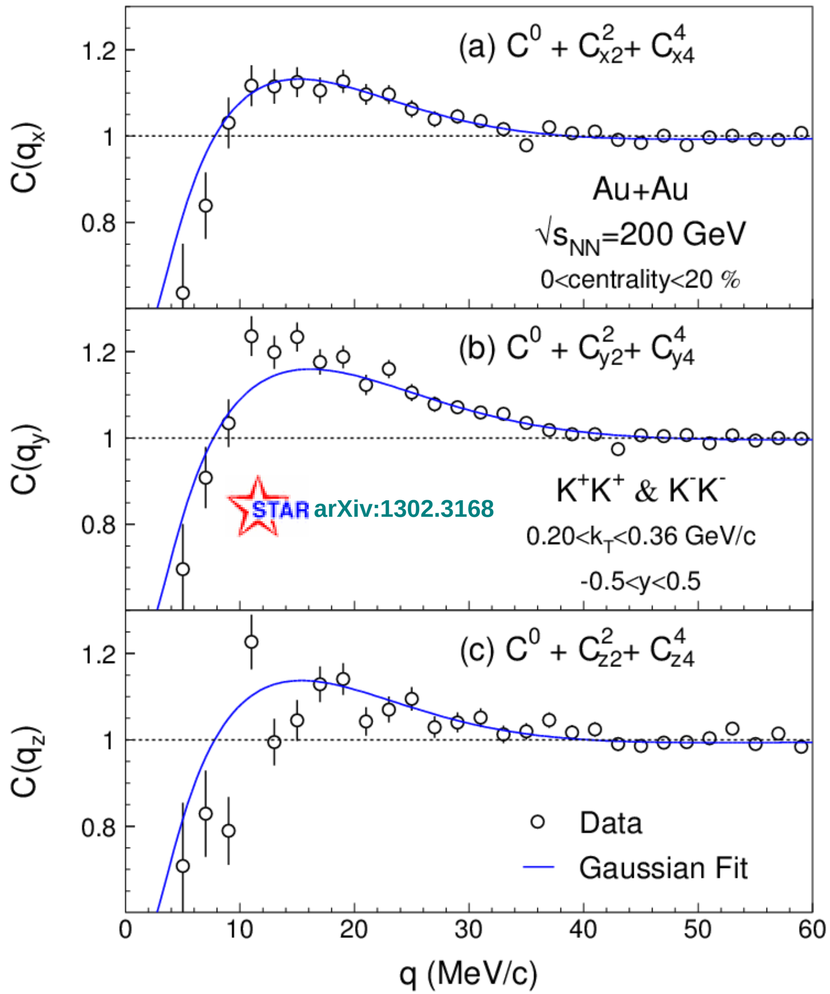
- Fit to C(q): technically a simultaneous fit on 6 independent moments

  $R^{\ell}_{\alpha 1 \ldots \alpha \ell}$, $0 \le \ell \le 4$
- 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

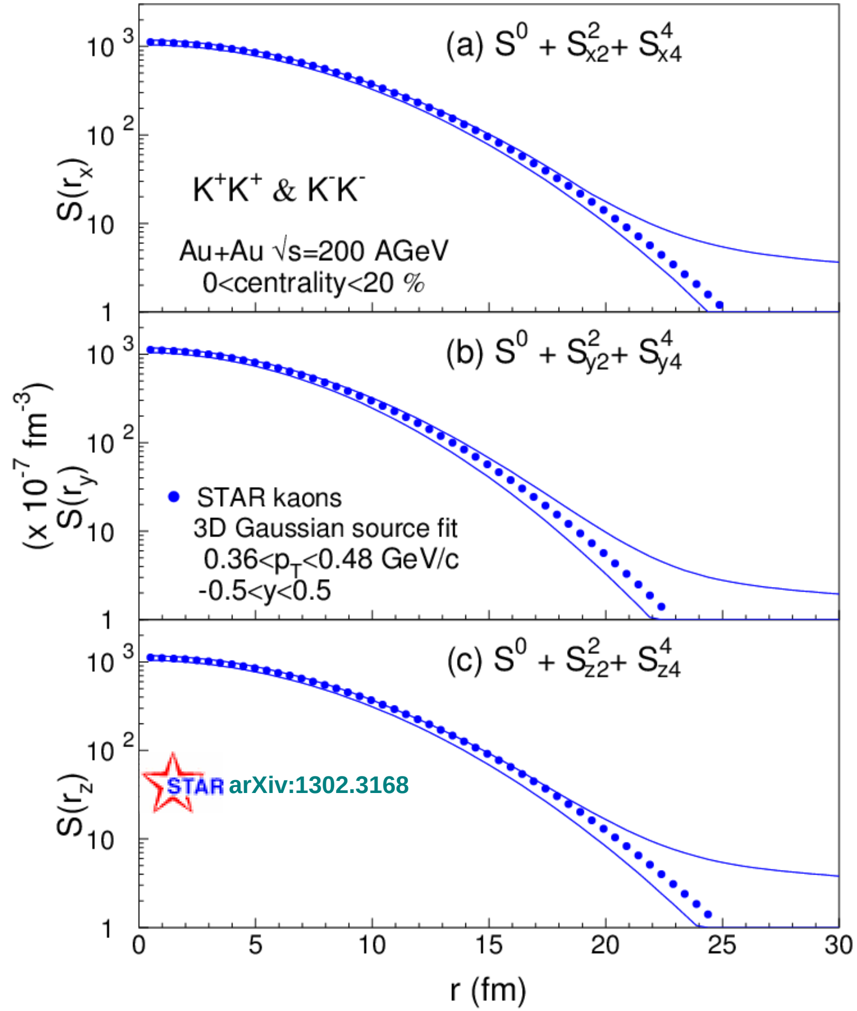


Correlation profiles and source



Correlation profiles

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



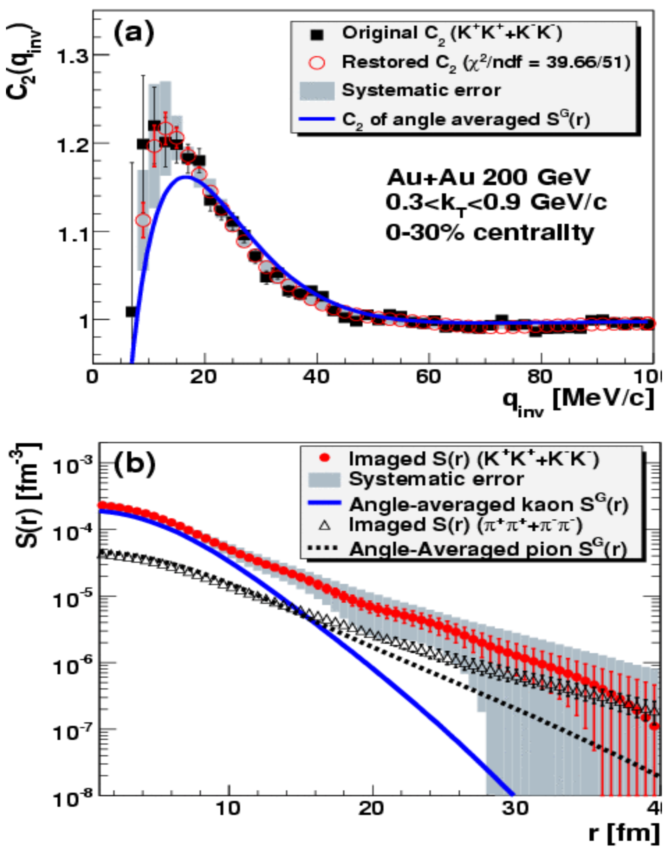
Gaussian source fit with error band

Note: Low statistics shows up as systematic uncertainty on shape assumption

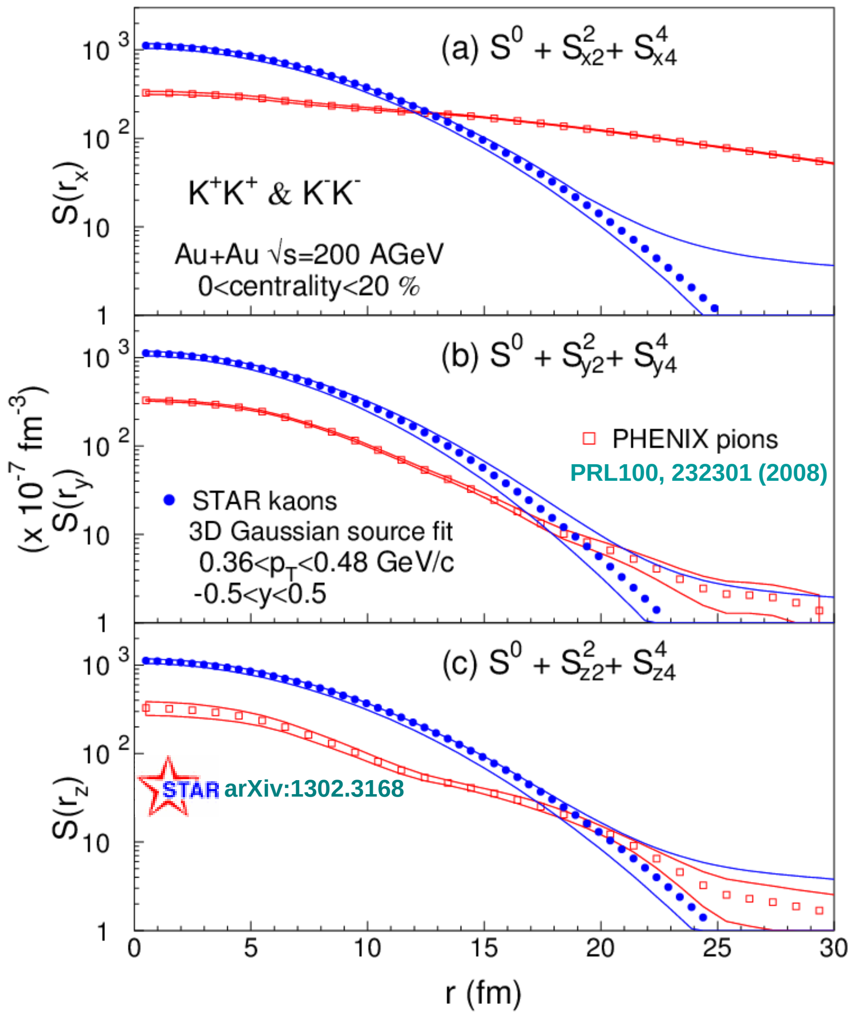
Source: Data comparison

1D PHENIX kaon:

- Observed long tail, possibly due to wide k_T bin
  ($0.3<k_T<0.9$ GeV)



PHENIX, PRL 103, 142301 (2009)



Kaon vs. Pion: different shape

- **Long pion tail caused by resonances?**
- **Sign of different freeze-out dynamics?**

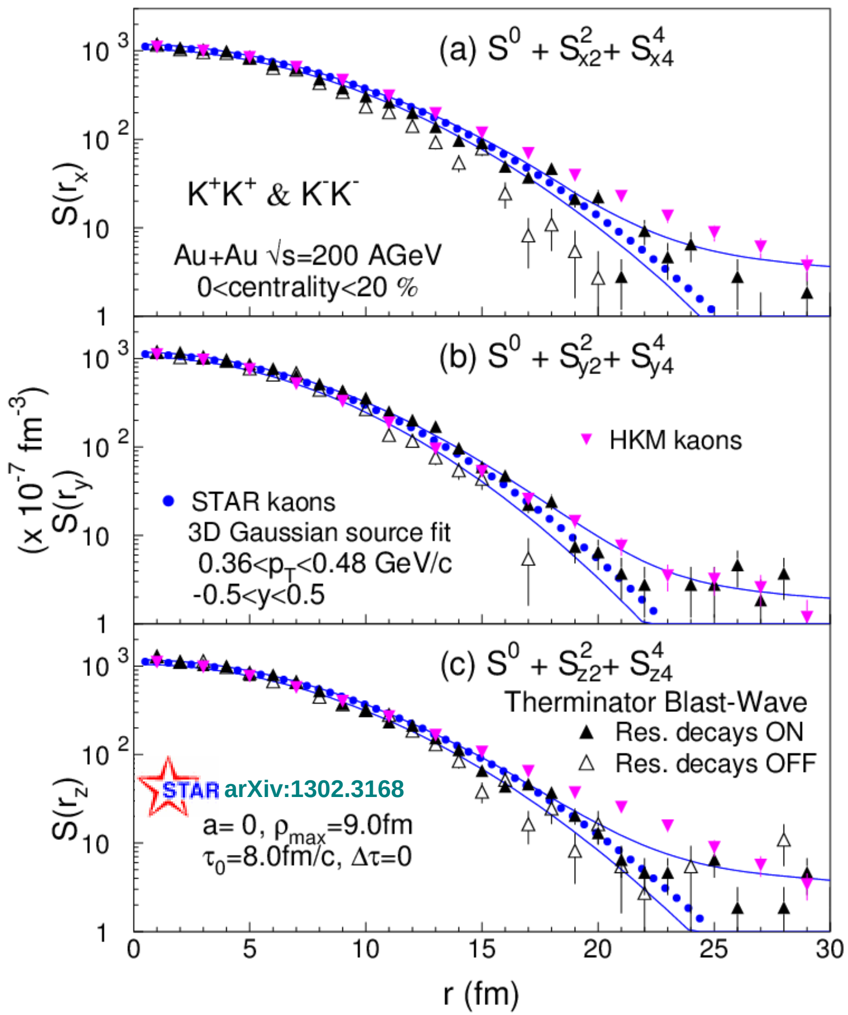
Source: Model comparison

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 time $\Delta\tau$ in lab frame
- Kaons: Instant freeze-out ($\Delta\tau = 0$, compare to $\Delta\tau$~2 fm/c of pions) at τ_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”

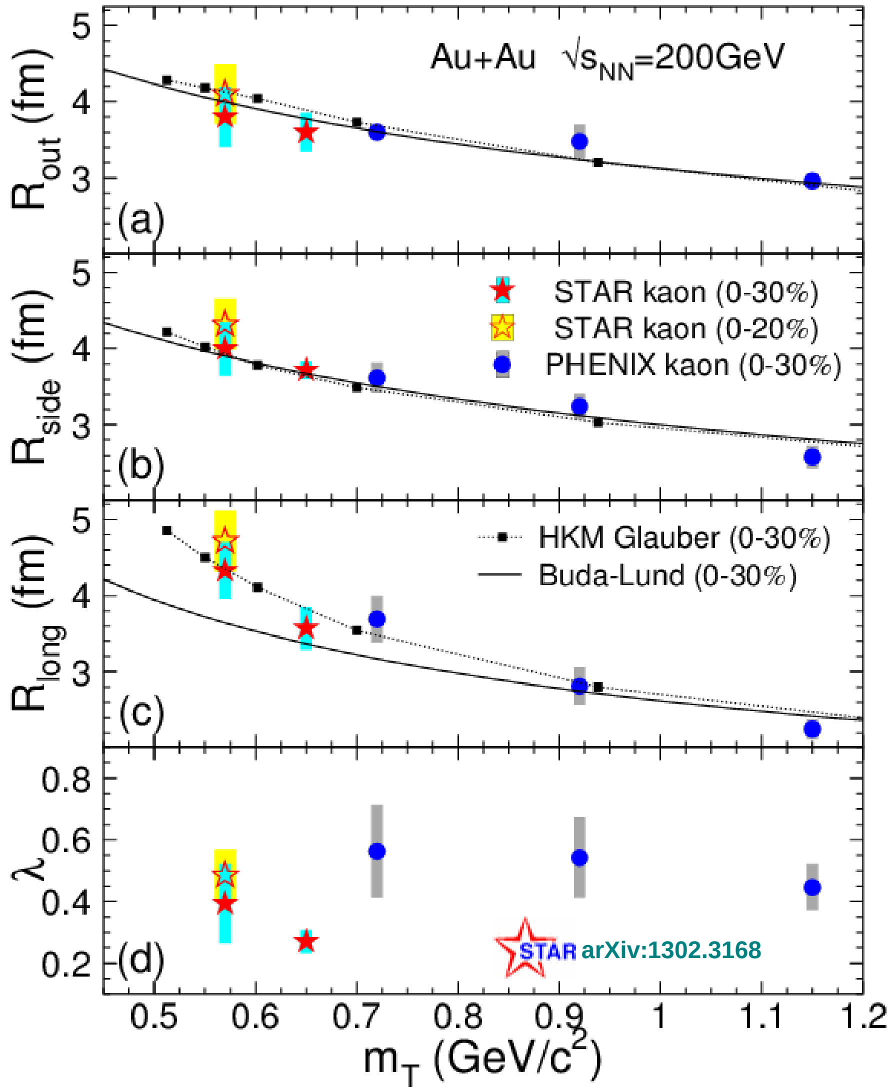


Therminator: Kisiel, Taluc, Broniowski, Florkowski, Comput. Phys. Commun. 174 (2006) 669.

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

Transverse mass dependence

- 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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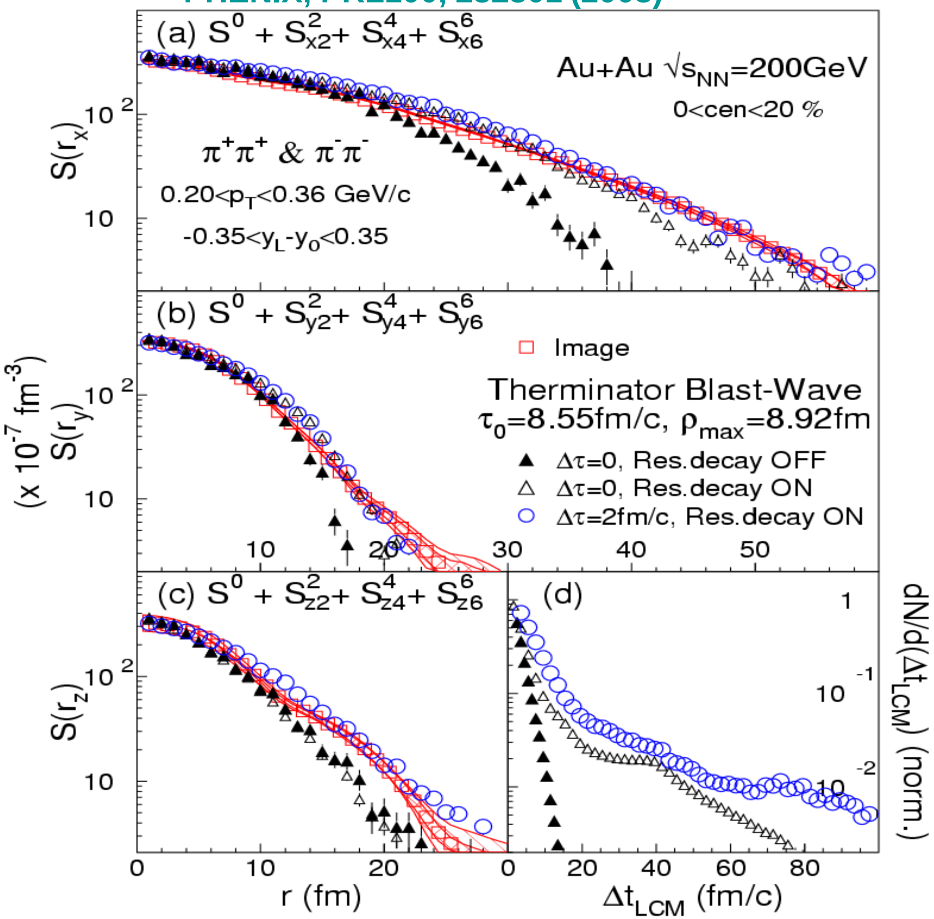
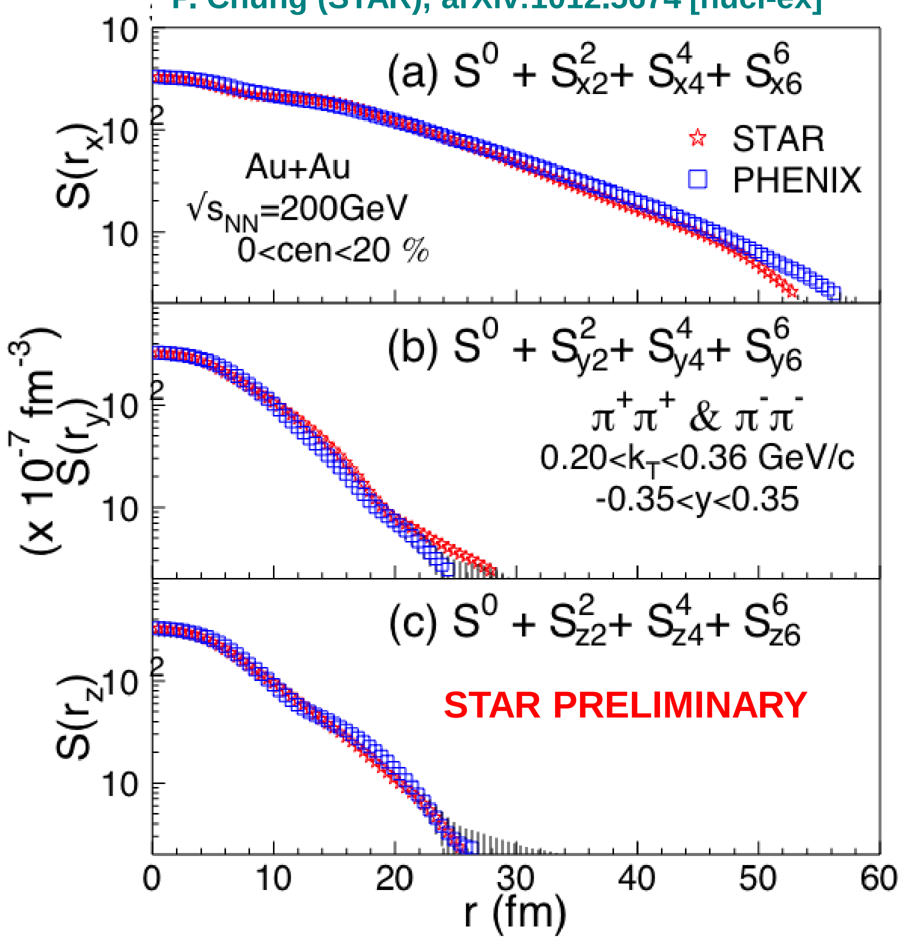
STAR Collaboration

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

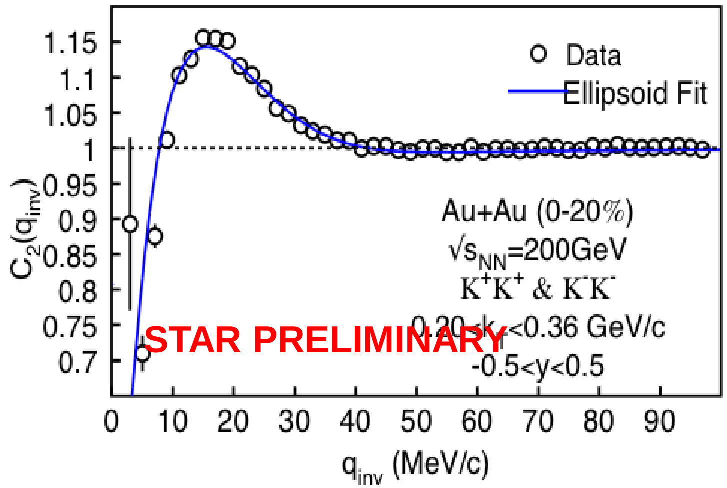
Very good agreement of PHENIX and STAR 3D pion source images

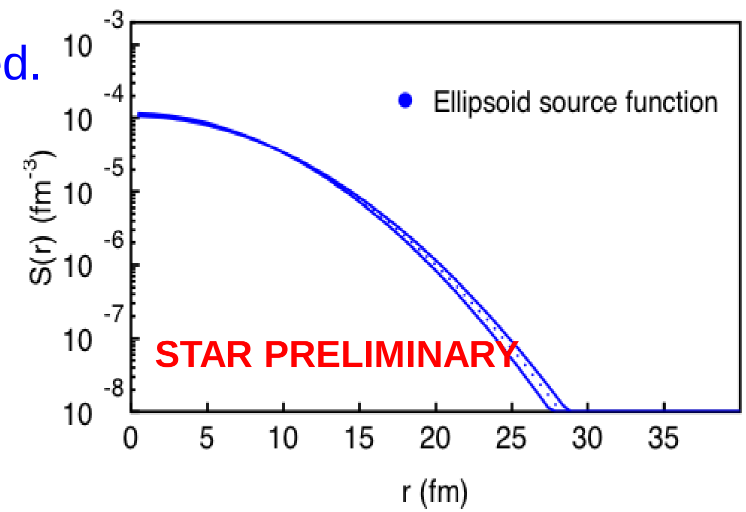
STAR 1D kaons

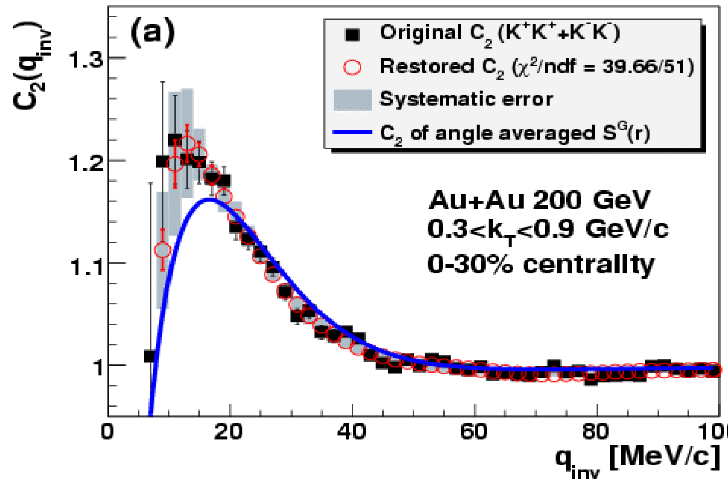
34M+83M=117M K^+K^+ & K^-K^- pairs

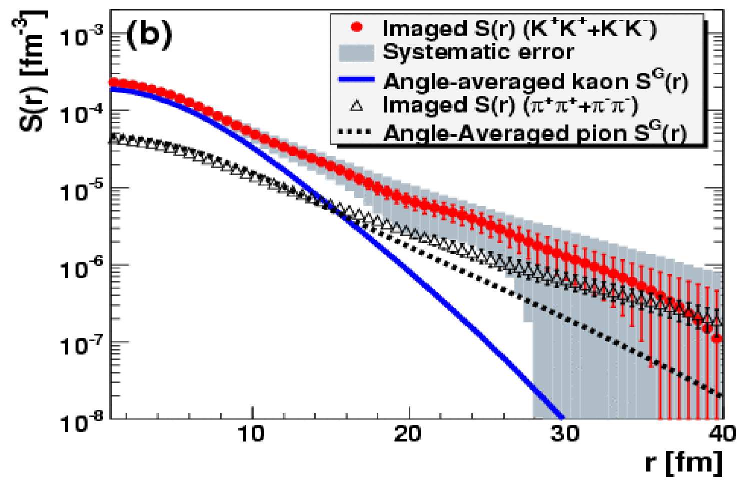
STAR data are well described by Gaussian, contrary to PHENIX no non-gaussian tails are observed.

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





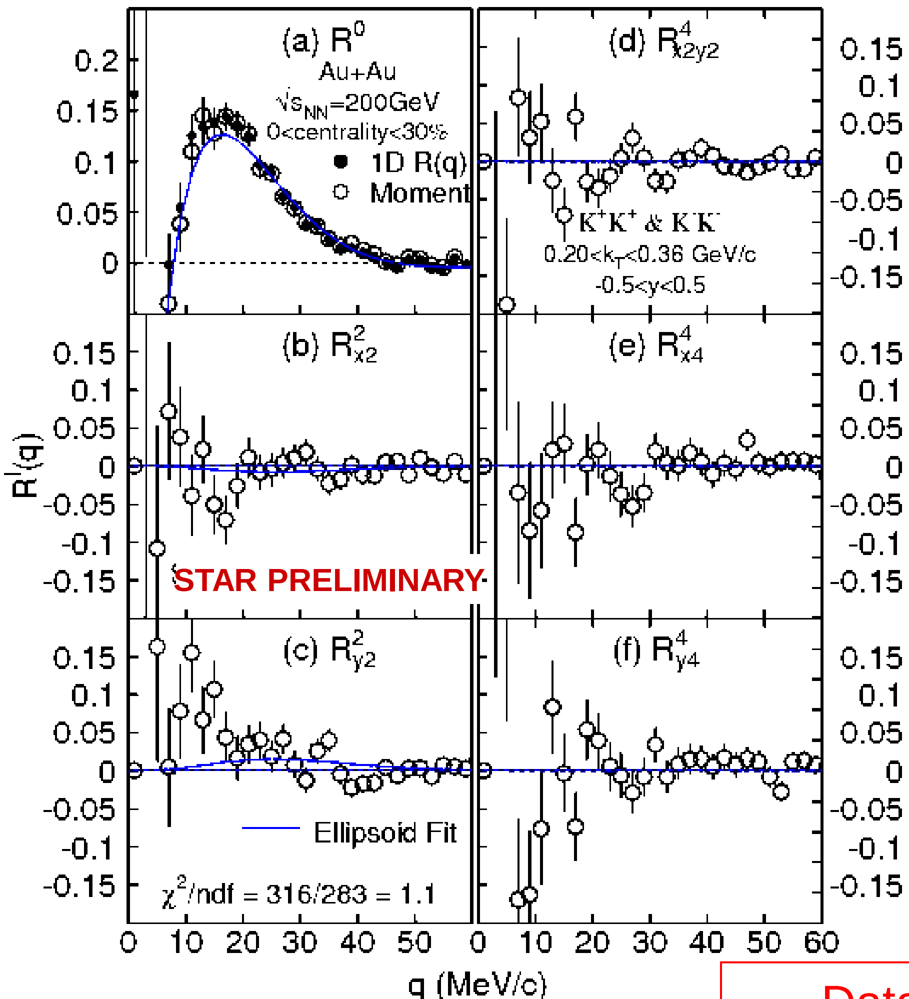


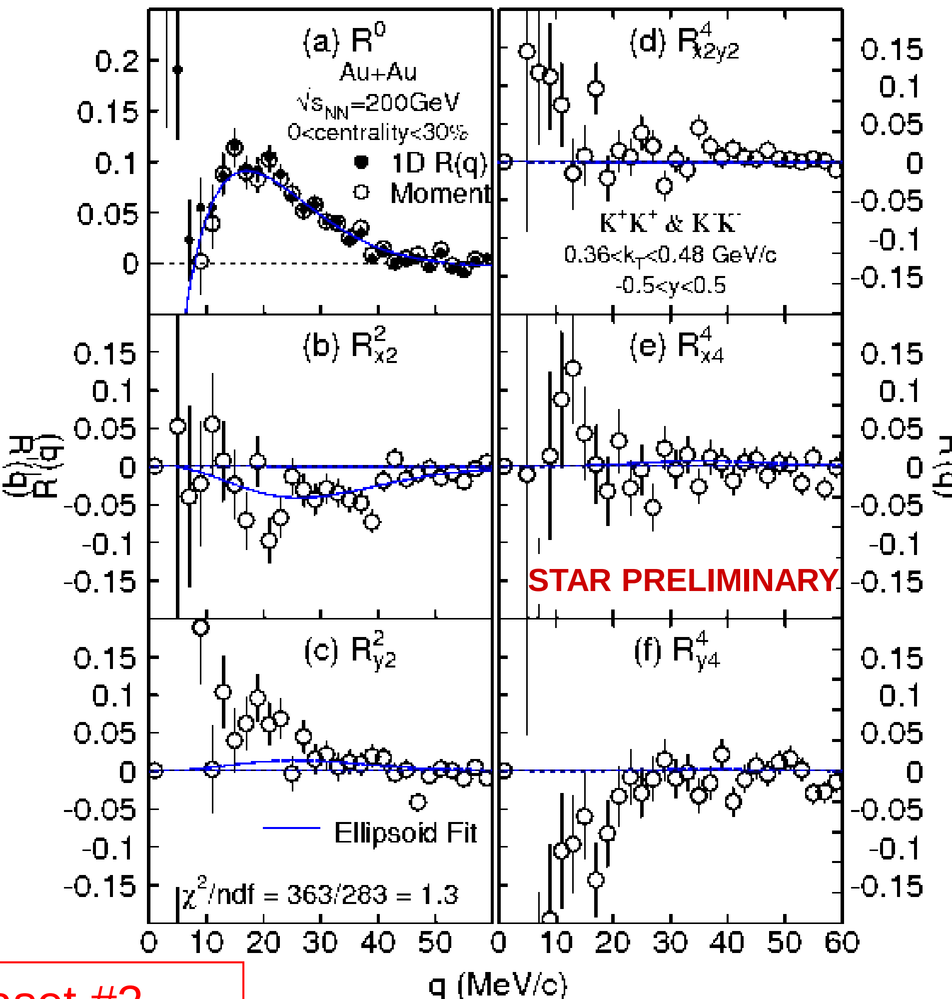


Fit to correlation moments #2

0.2<kT<0.36 GeV/c

0.36<kT<0.48 GeV/c





Dataset #2

Run4 Cent<30%

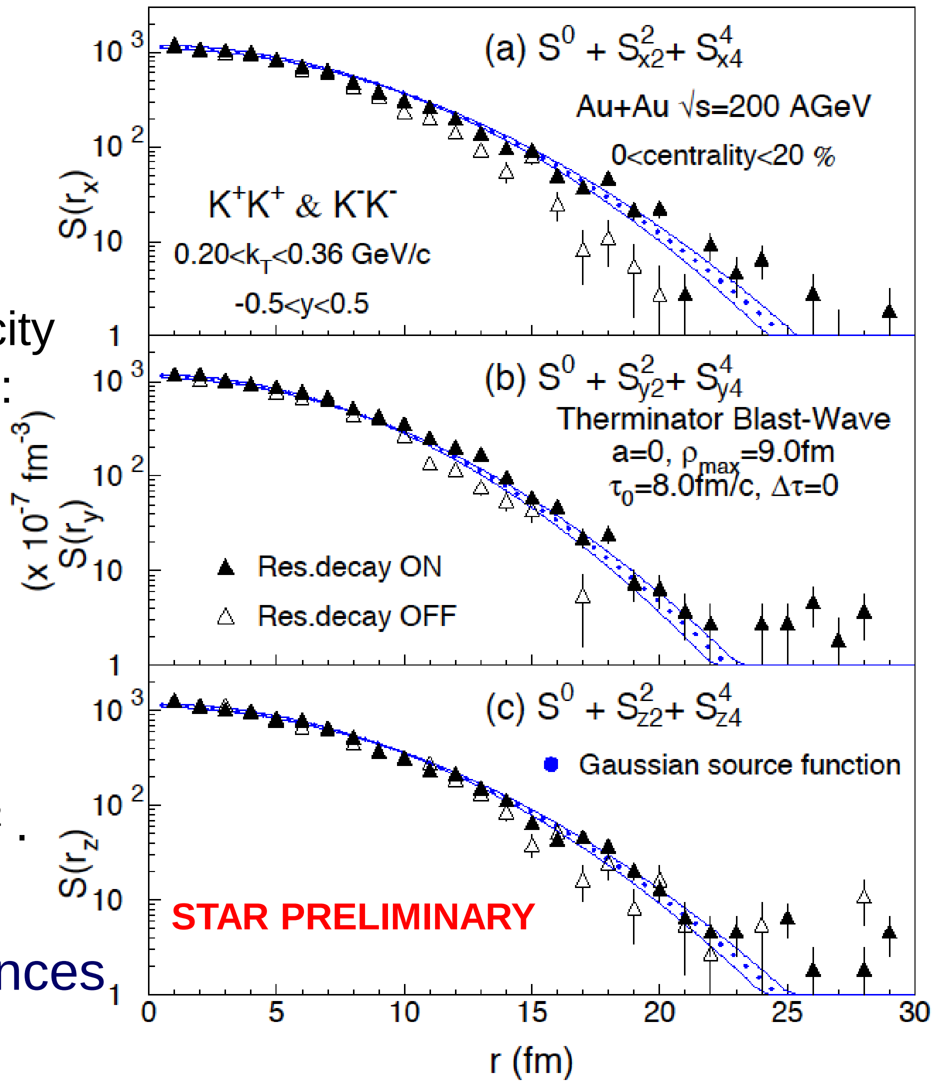
Model comparison: thermal BW

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 $\Delta\tau$

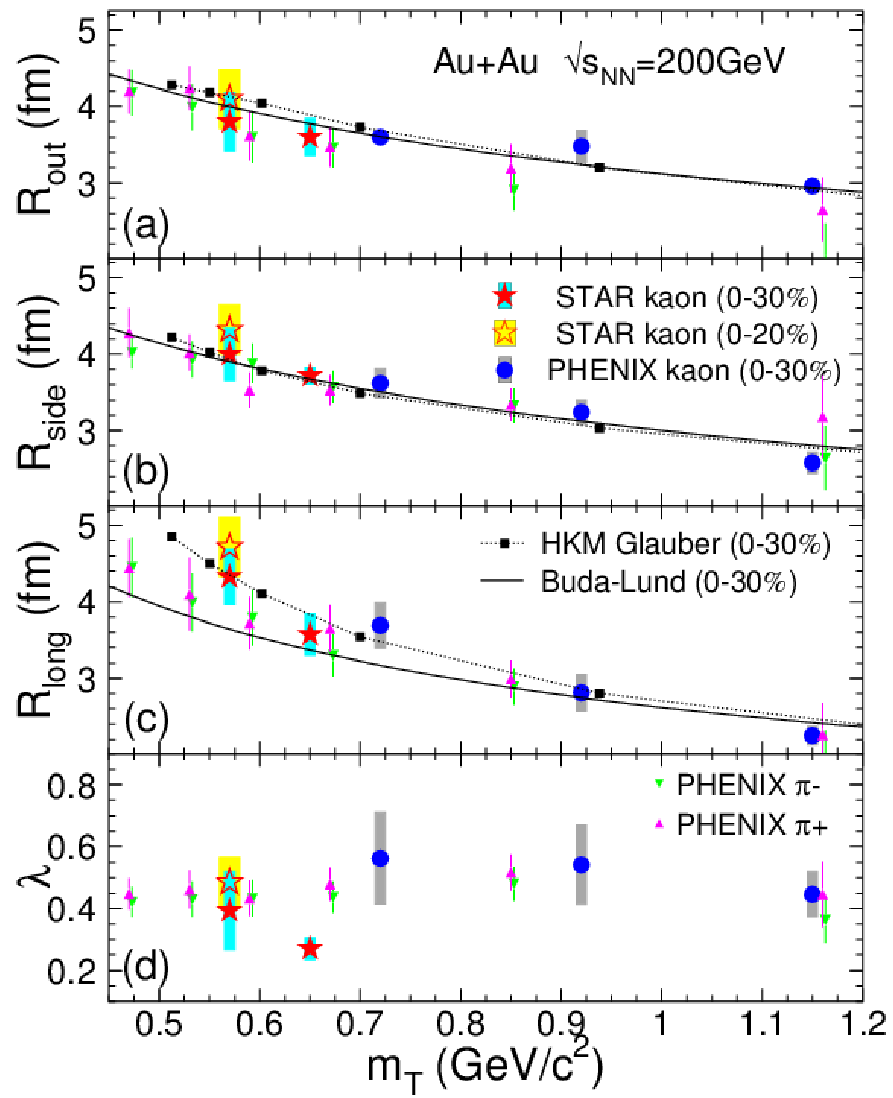


Source consistent with BW and resonances

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

Radii vs. mT, pion, kaon

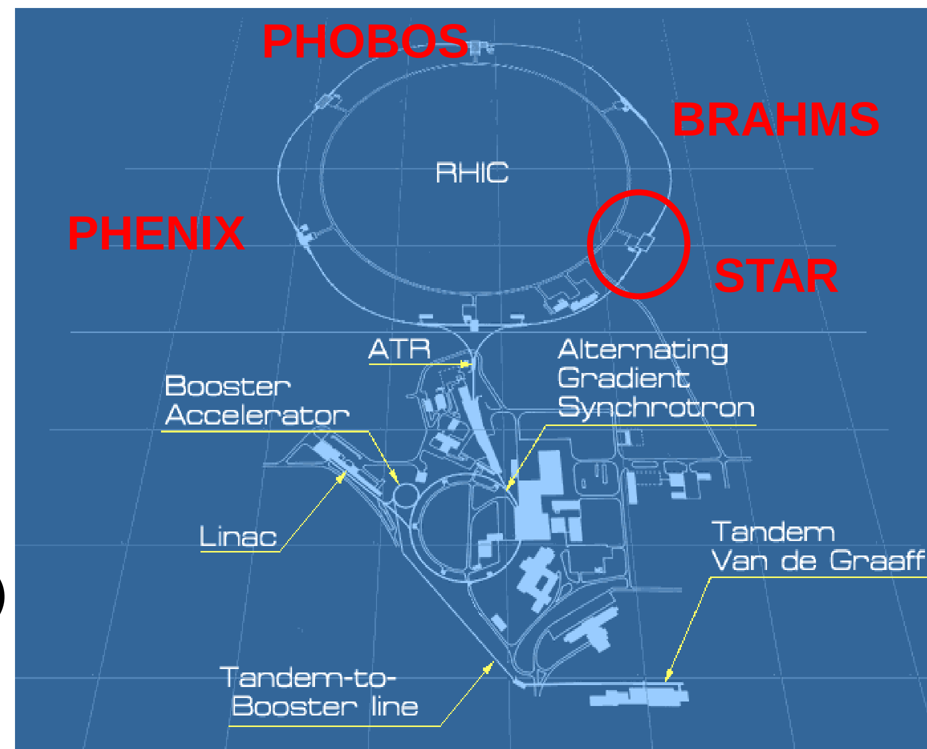
- STAR kaons
- PHENIX pions +,–
- Buda-Lund
- HKM



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

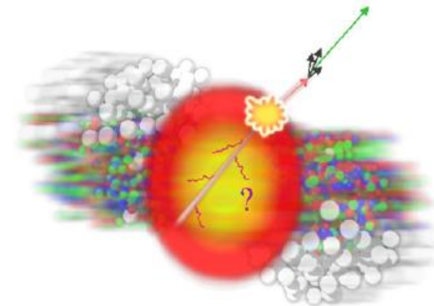
The RHIC facility

- 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)



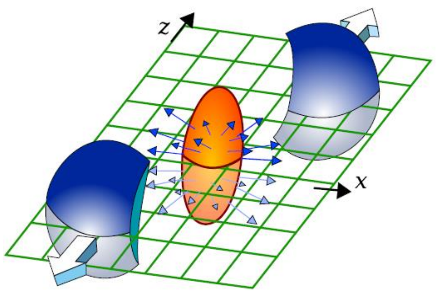
Hot nuclear matter

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



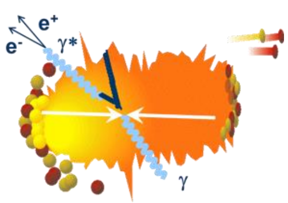
- Extremely dense
  - Au+Au: jet suppression
No effect in d+Au
  - → Strongly interacting, new state of matter

    $\lambda \sim 3$ fm (5 GeV jet)



- Perfect fluid of quarks
  - Contradicts expectations
  - Degrees of freedom: quarks
  - Viscosity consistent with theoretical limit

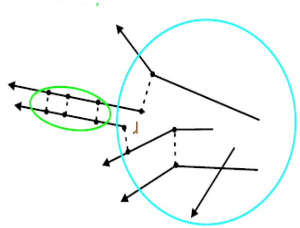
    $\eta/s \sim \hbar/4\pi$, $c_s = 0.35c$



- Quark Gluon Plasma (sQGP)

  Phys.Rev.Lett. 104, 132301 (2010)
  - Thermal radiation, $T_{init} \sim 4 \times 10^{12}$ K

    $T_{init} > 300$ MeV $>> T_{Hagedorn}$, $\varepsilon_{init} \sim 15$ GeV/fm^3 ,$p_{init} \geq 1.5$ GeV/fm^3



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