Source imaging in RHIC $\sqrt{s_{NN}}$=200 GeV Au+Au collisions

Róbert Vértesi
robert.vertesi@ujf.cas.cz

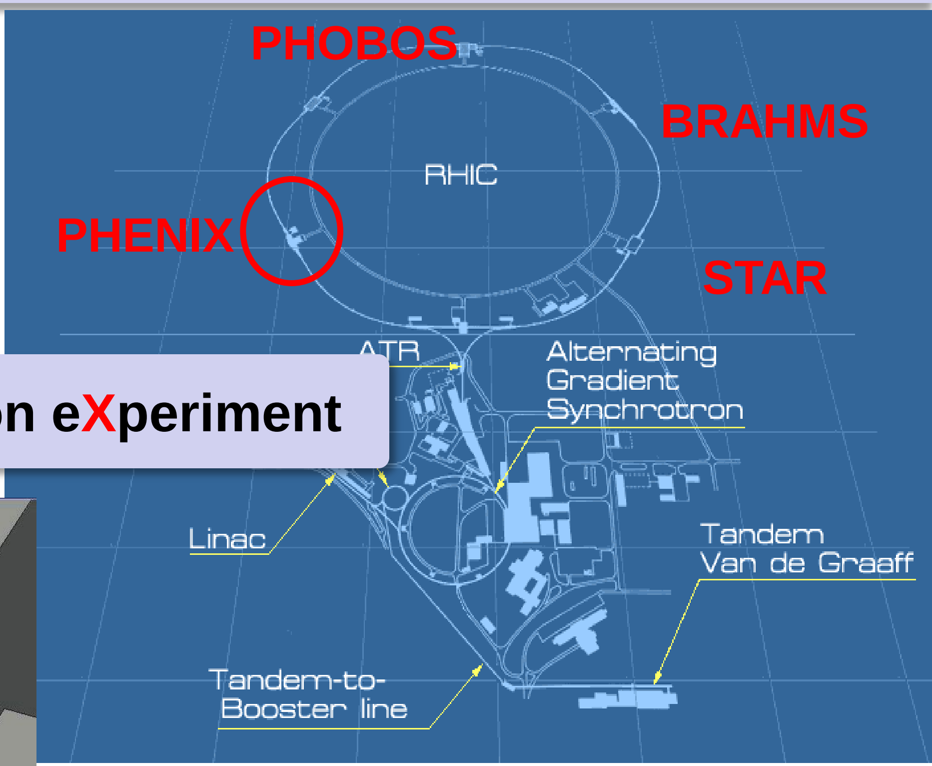
Nuclear Physics Institute
Czech Academy of Sciences

evropský sociální fond v ČR
EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

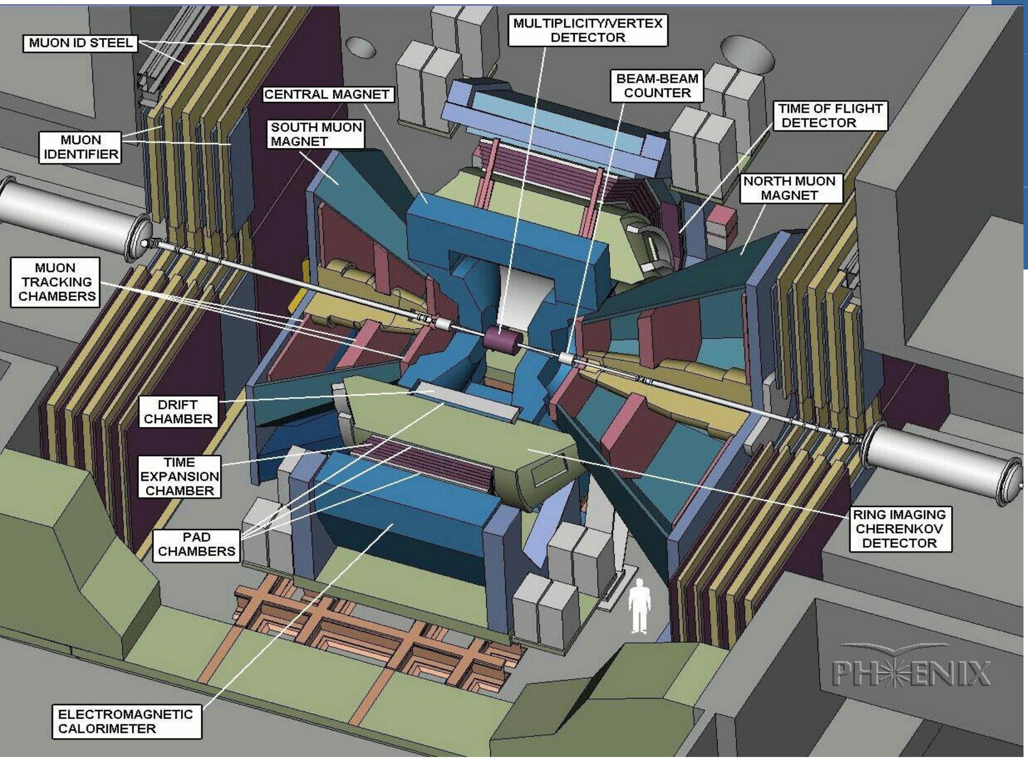
RHIC/PHENIX

RHIC: Broad physics program

- Heavy ions: Au+Au, Cu+Cu, U+U, $\sqrt{s_{NN}}$=7.7–200 GeV
- Polarized protons up to $\sqrt{s}$ = 510 GeV
- Asymmetric systems (d+Au, Cu+Au)



A Pioneering High Energy Nuclear Ion eXperiment



Calorimetry and leptons

- π^0, η up to 20 GeV/c, direct photons
- e^+e^- pairs, $\mu^\pm$ (forward), heavy quarkonia (J/ψ)

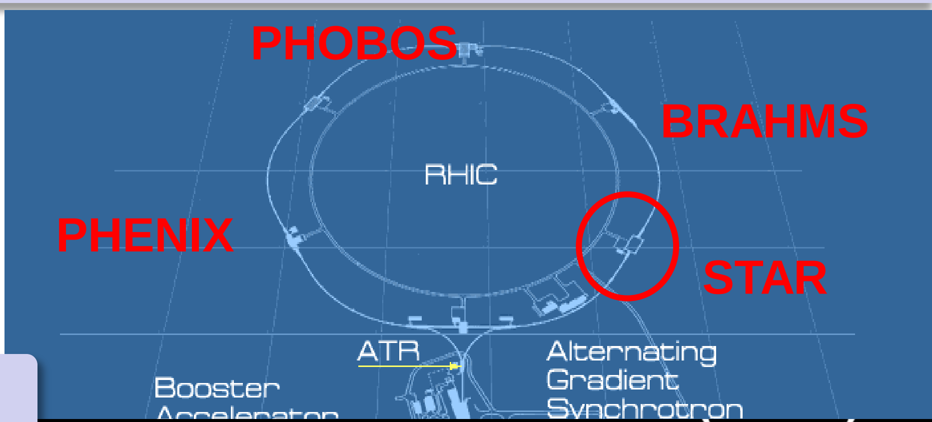
Tracking

- Drift and pad chambers, dipole magnet
- **High-rate data taking**
- **Limited acceptance** (Mid-rapidity $|\eta|<0.35$, 2 x $\pi/2$ in azimuth)

RHIC/STAR

RHIC: Broad physics program

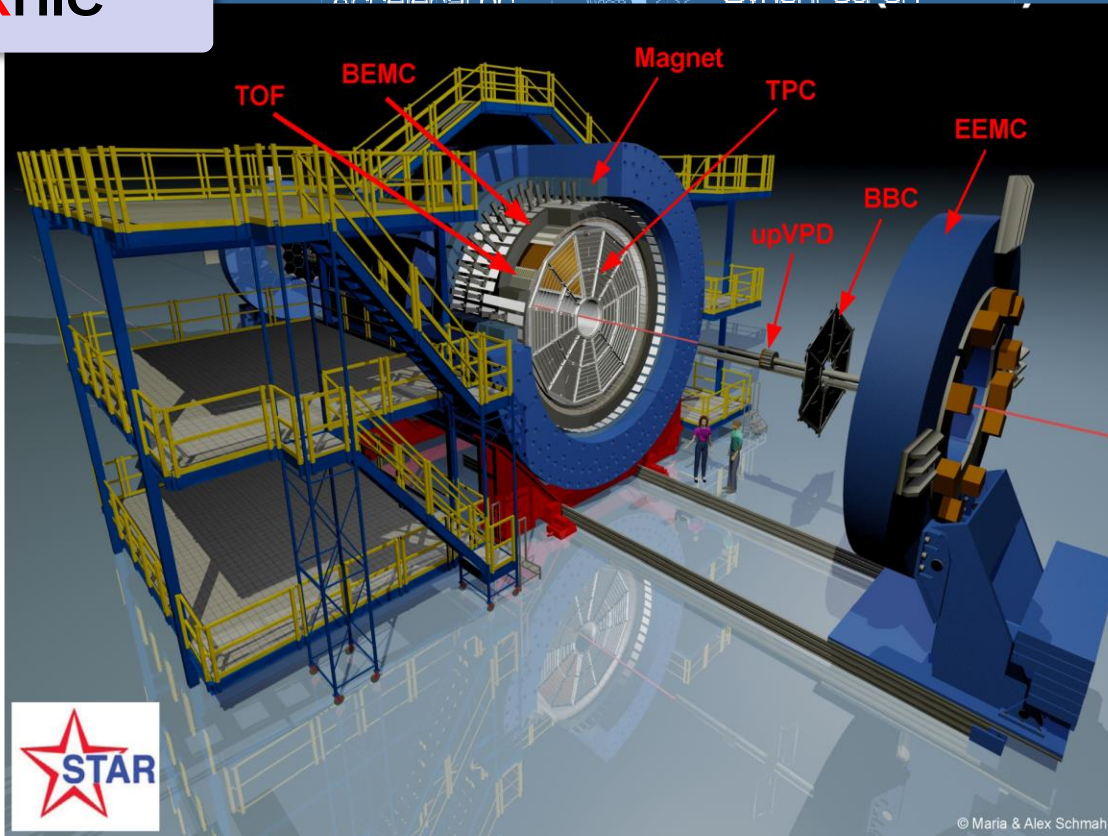
- Heavy ions: Au+Au, Cu+Cu, U+U, $\sqrt{s_{NN}}$=7.7–200 GeV
- Polarized protons up to $\sqrt{s}$ = 510 GeV
- Asymmetric systems (d+Au, Cu+Au)



The Solenoidal Tracker at RHIC

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

  for different energies and particles

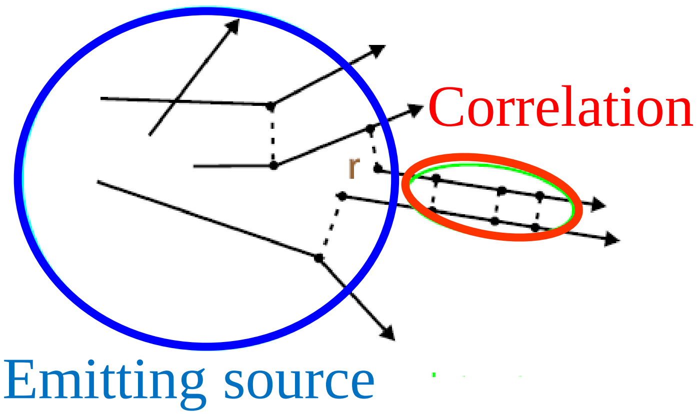


Both experiments:
continuous improvements
to meet evolving physics goals
New subsystems for enhanced PID, rates, coverage…

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:

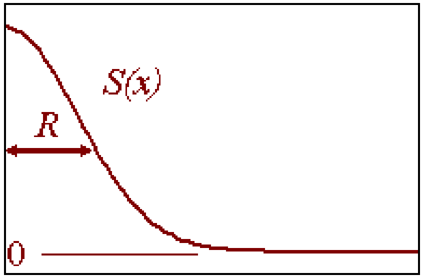
$$C_2(k_1,k_2) = \frac{N_2(k_1,k_2)}{N_1(k_1)N_1(k_2)} \simeq 1 + \left|\frac{\tilde{S}(q,K)}{\tilde{S}(0,K)}\right|^2 \quad \tilde{S}(q,K) = \int \mathrm{d}x S(x,k) \mathrm{e}^{iqx}$$
$$q = k_1 - k_2, K = 0.5(k_1+k_2)$$

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

Gaussian source approximation

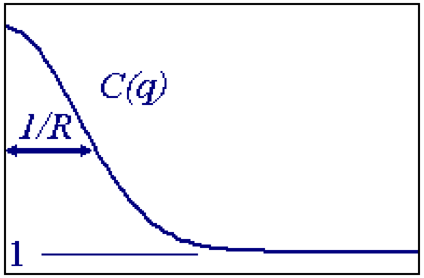
- If the source is approximated with Gaussian:

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



- 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

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

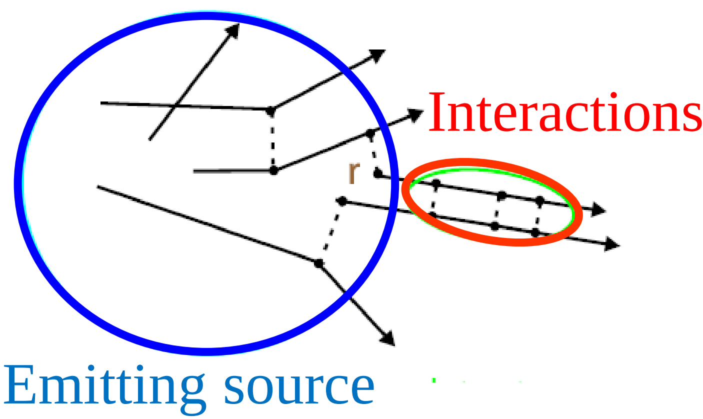
- Do not necessarily reflect the geometrical size

Source imaging

Physics in shape: dynamics, resonance decays, rescattering…

- Koonin-Pratt equation (1D)

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



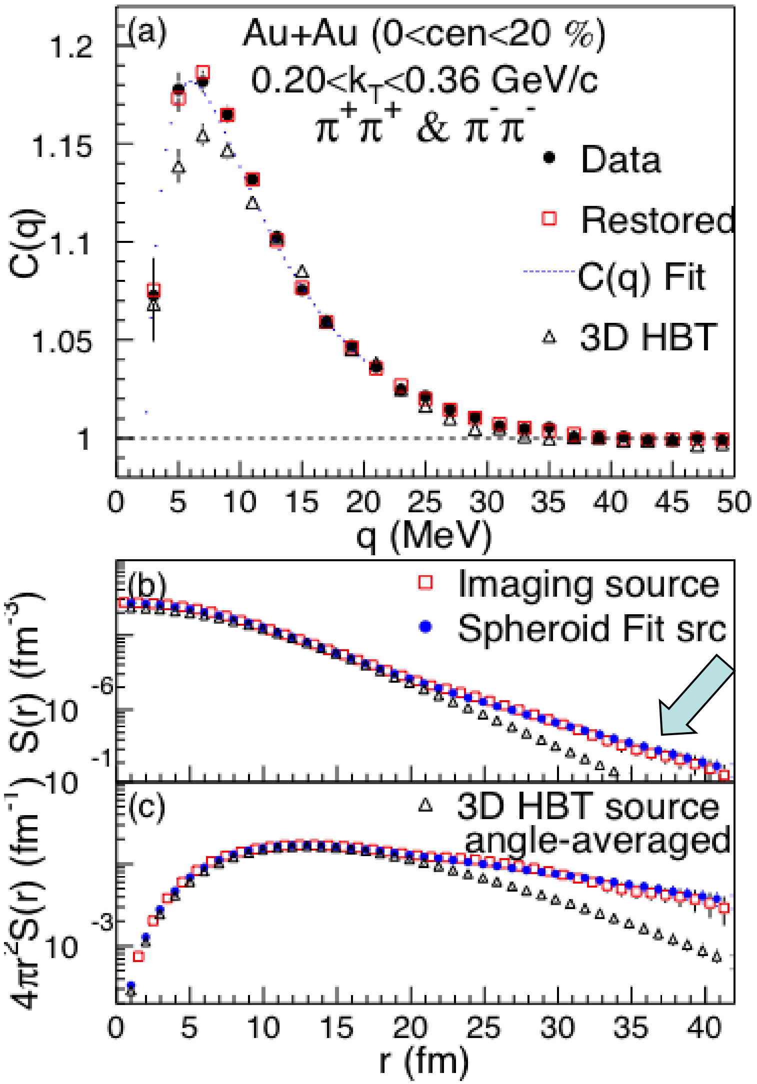
- Imaging: Obtain S(**r**) directly
  - No assumptions for the shape of source
  - Kernel includes **all** interactions (QM, FSI)
- Numerical inversion of the equation
  - No analytical solution, hence some limitations and approximations (integral cutoff, finite resolution …)
  - Assumptions (e.g. weak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

D. A. Brown, P. Danielewicz, Phys.Lett. B398, 252 (1997)

Pion images

- PHENIX Year 2002 data
  - low $k_T = (p_{T,1}+p_{T,2})/2$
  - C from data ~ C restored from image
    → Imaging process can be trusted
- A heavy, non-Gaussian tail is present in the 1D pion source
- Several interpretations suggested
  - Non-zero emission duration
  - Anomalous diffusion due to rescattering in the hadronic phase
  - Conribution of long-lived resonance decays

PHENIX, PRL 98, 132301 (2007)



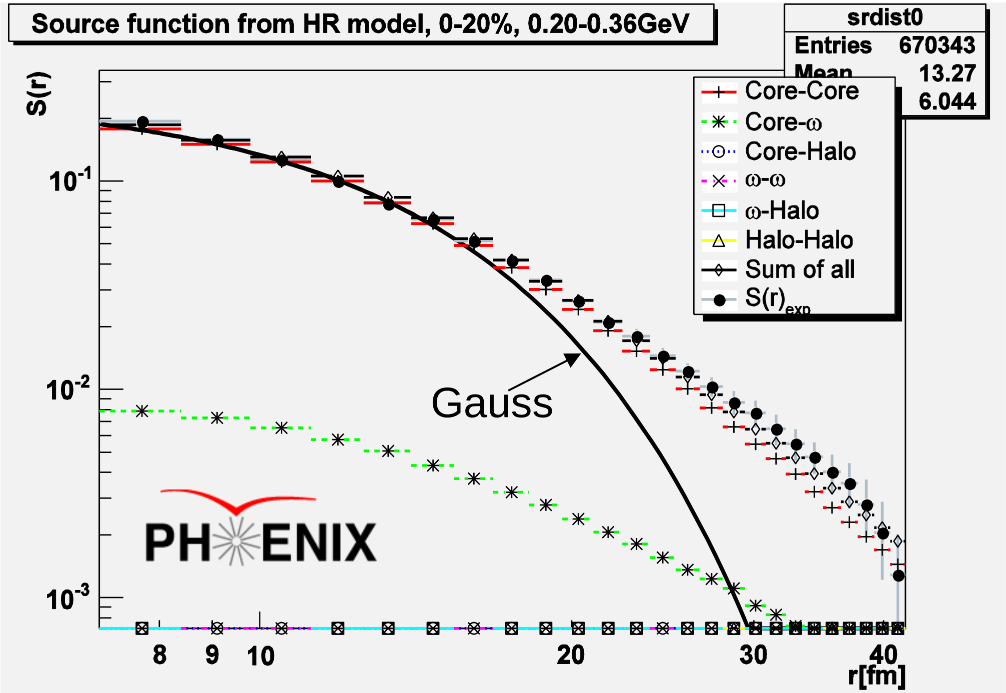
Rescattering

Hadronic Rescattering Code

Simple but smart cascade model
- Only a few resonances (ρ, Δ, K* ; ω ; η, η', Φ, Λ)
- Causality kept in all scatterings
- p-dependent cross sections

Shown to be working
- Describes spectra, v_2, HBT radii for both SPS and RHIC
- Insensitive to initial conditions
- Similar predictions to exact hydro
- Sensitive to PID (π, K, p)

T. J. Humanic, Int. J. Mod. Phys. E 15 (2006)



Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007)

- HRC able to describe the observed 1D pion source

  Note: model limitations lead to breakdown for higher k_T bin (not shown)
- Underlying mechanism: anomalous diffusion
  - Diffusion with fixed mean free path: Central Limit Theorem → Gaussian distrib.
  - Expanding system, changing x-section: Gnedenko–Kolmogorov → Lévy distrib.

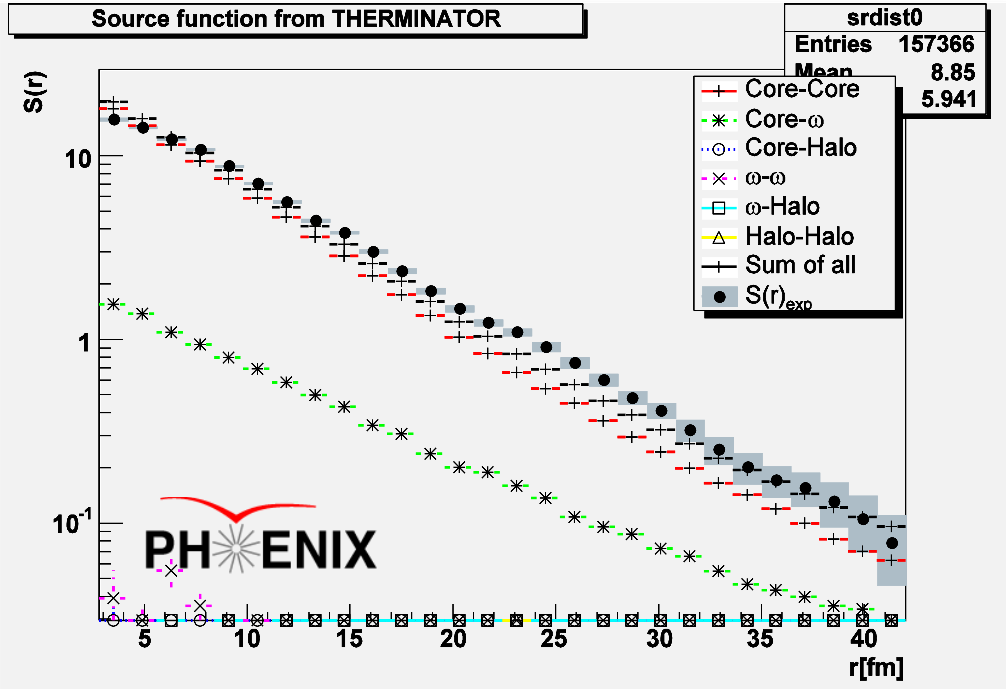
Resonances

THERMINATOR Single Freezeout

Cracow Single Freezeout model
- Particle phase-space according to FD, BE distributions
- Thermal & chem. eq. same time
- Universal T, μ_{I3}, μ_B , μ_S
- Single hyper-ellipsoid FO surface

Hadronic phase
- Many resonances (385)
- No rescattering

Kisiel et al., Comput.Phys.Commun. 174 (2006)



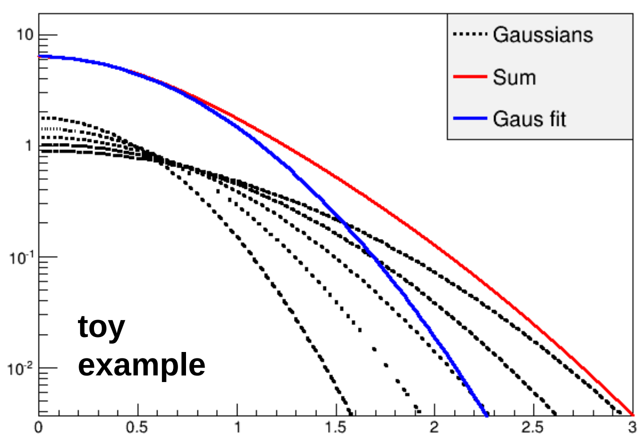
R.V. (PHENIX), WWND 2007 proc. [arXiv:0706.4409]

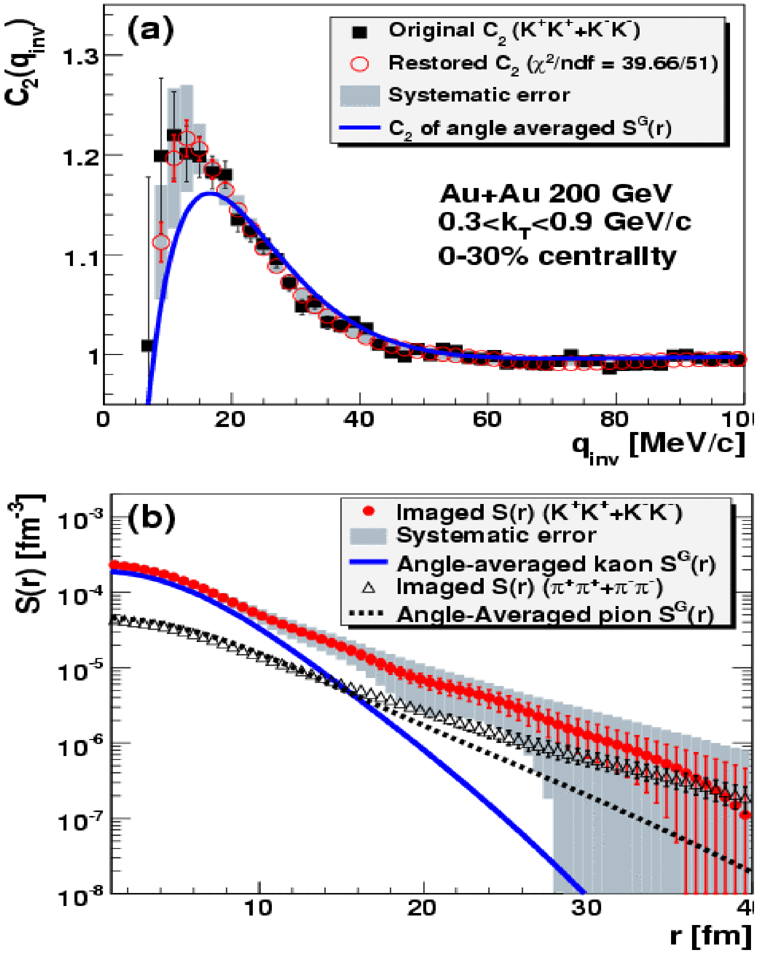
- Single FO with resonances: also yields a relatively good description
  - Parameters tuned for PHENIX HBT

  Note: model limitations cause problems at r→0 (not shown)
- Underlying mechanism: many long lived resonances
  - Different contributions die out gradually
  - Continuously increasing mean lifetimes provide a random variable with time-dependent mean and variance → similar effect to anomalous diffusion

Kaons: A cleaner probe

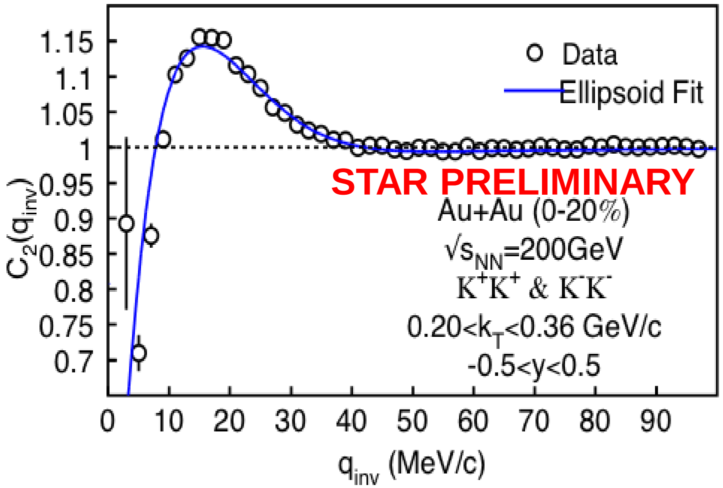
- Less feed-down, less rescattering
  - Interpretation more straightforward
  - More difficult due to ~10 less statistics
- PHENIX 1D Kaon source: an even larger non-Gaussian component
  - Seemingly favors rescattering explanation against resonances
- Interpretation caveat: wide k_T (N_{part}) bin
  - Different k_T → Gaussians with different radii → convolute to non-Gaussian

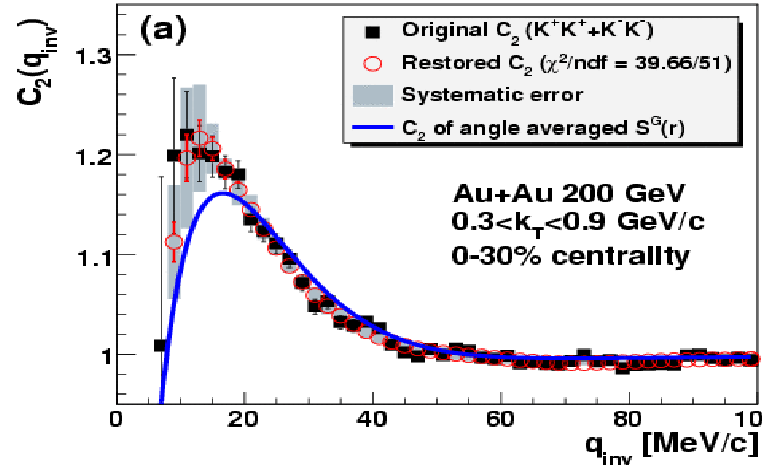


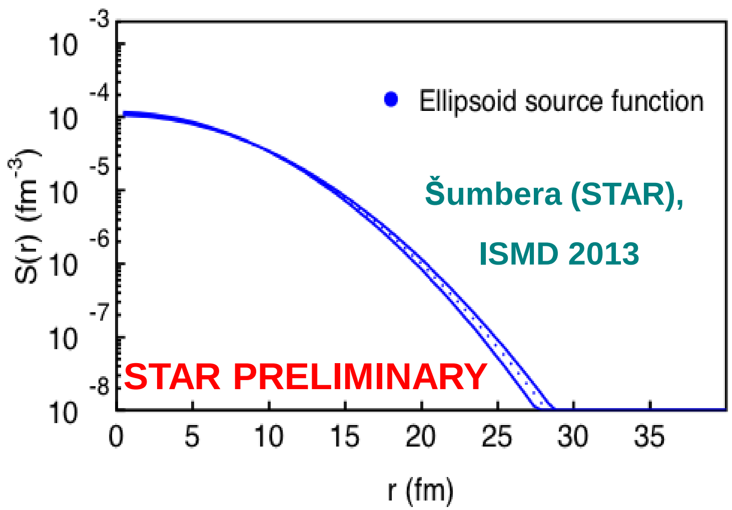


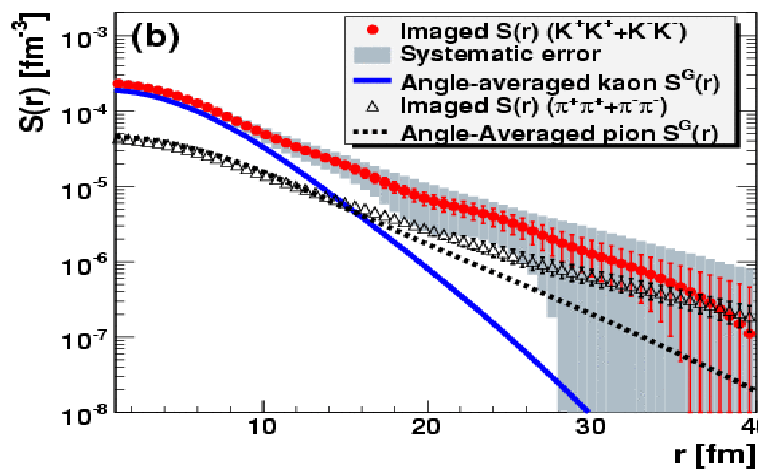
PHENIX, PRL 103, 142301 (2009)

Kaons: STAR vs. PHENIX









PHENIX, PRL 103, 142301 (2009)

- STAR preliminary 1D source in narrow k_T bin consistent with Gaussian
  - $0.20<k_T<0.36$ GeV , compared to $0.3<k_T<0.9$ GeV

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

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

3D images: figuring out more about freeze-out dynamics!

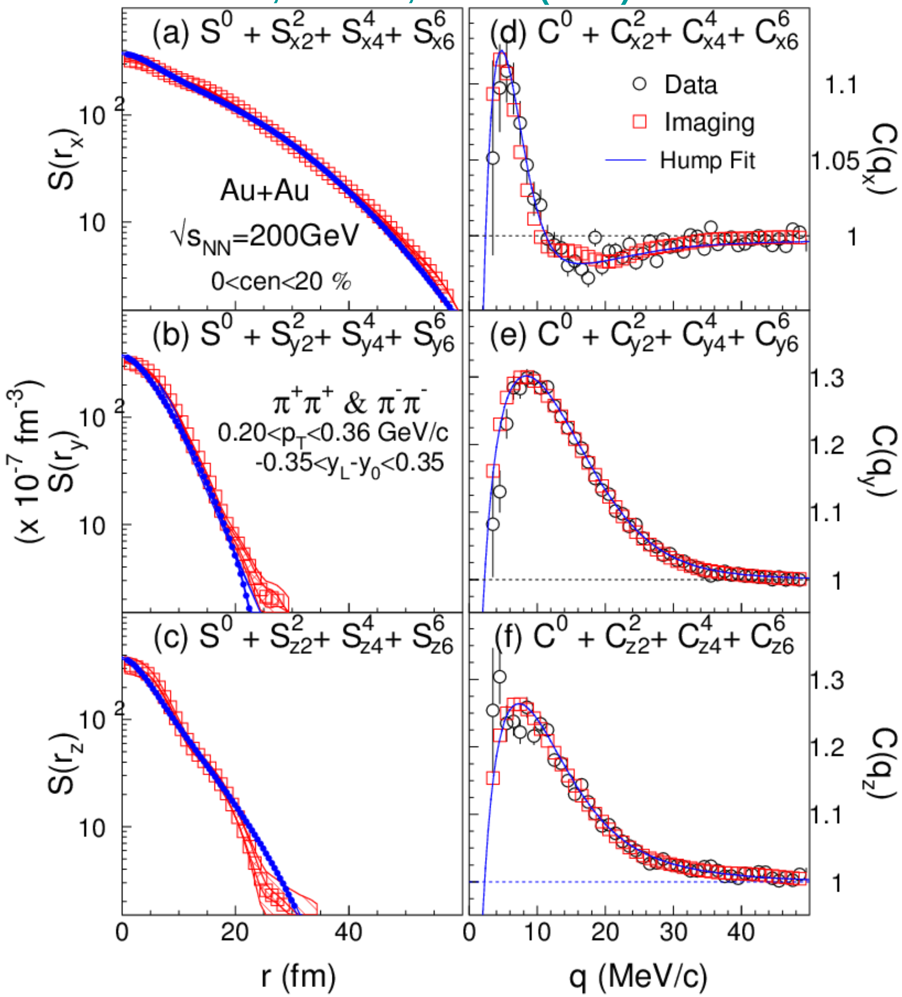
3D pion correlation and source

- **Elongated source in "out"** direction
  - Moments up to the 6th order
  - Elliptic **and** non-Gaussian
  - 1D radii determined by side/long

- Shape described well by a double Gaussian, or "hump" function

$$S^H(r_x, ry, rz) = e^{-F_s\left[\left(\frac{r_x}{2R_{xs}}\right)^2+\left(\frac{r_y}{2R_{ys}}\right)^2+\left(\frac{r_z}{2R_{zs}}\right)^2\right]}$$
$$\times\, e^{-F_l\left[\left(\frac{r_x}{2R_{xl}}\right)^2+\left(\frac{r_y}{2R_{yl}}\right)^2+\left(\frac{r_z}{2R_{zl}}\right)^2\right]}$$
$$F_s = \frac{1}{1+(r/r_0)^2}, \quad F_l = 1 - F_s$$

PHENIX, PRL100, 232301 (2008)



Source profiles

$S(r_x) \equiv C(r_x,0,0)$
$S(r_y) \equiv C(0,r_y,0)$
$S(r_z) \equiv C(0,0,r_z)$

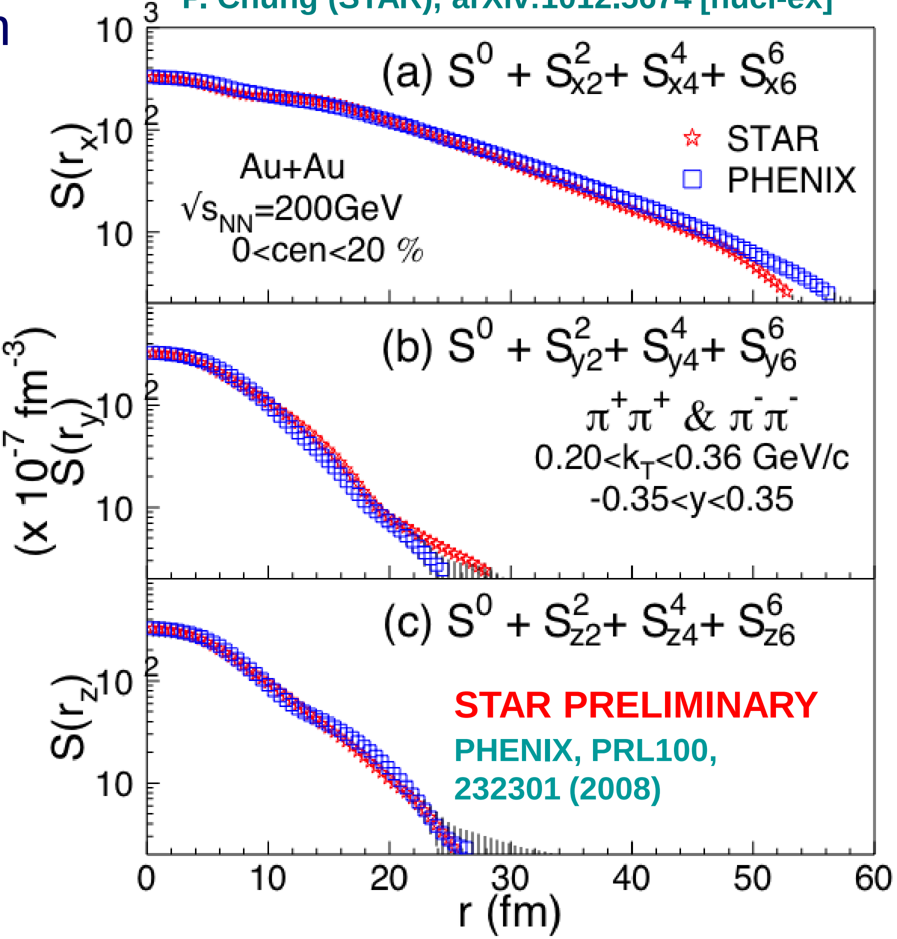
Correlation profiles

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

3D pion images: STAR vs. PHENIX

- **Elongated source in "out"** direction
  - Moments up to the 6th order
  - Elliptic **and** non-Gaussian
  - 1D radii determined by side/long
- STAR and PHENIX measurements are consistent
  - Two different detectors with different properties and acceptance
  - Good agreement with same cuts
  - Attests to the reliability of results

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



Source profiles

3D pion images vs. B/W model

- **Elongated source in "out"** direction
  - Moments up to the 6th order
  - Elliptic **and** non-Gaussian
  - 1D radii determined by side/long

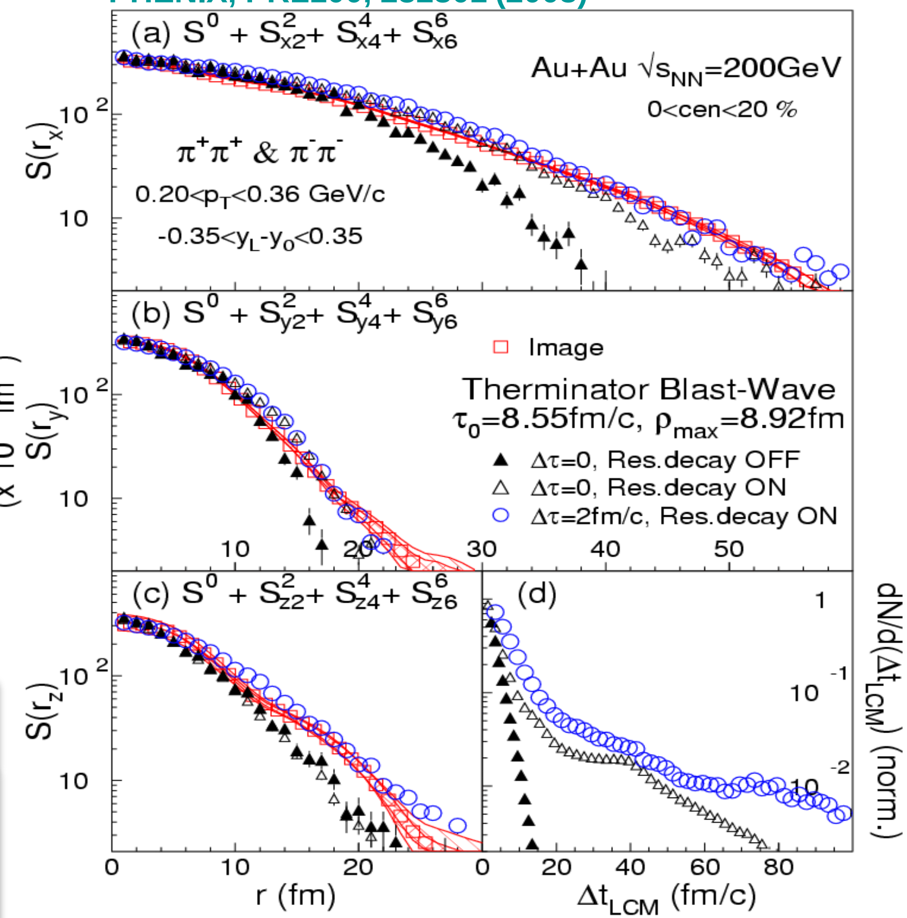
- Therminator B/W model description
  - Iff resonance contributions ON, and
  - Iff **non-zero emission duration**

$\Delta\tau \sim 2$ fm/c

THERMINATOR Blast-Wave model

- Expansion: $v_r(\rho)=(\rho/\rho_{max})/(\rho/\rho_{max}+v_t)$.
- Thermal emission at proper time τ, $\rho=\rho_{max}$.
- Freeze-out occurs at $\tau = \tau_0 + a\rho$.
- LAB emission time $t^2 = (\tau_0 + a\rho)^2 + z^2$.
- Finite emission duration $\Delta\tau$ in lab frame

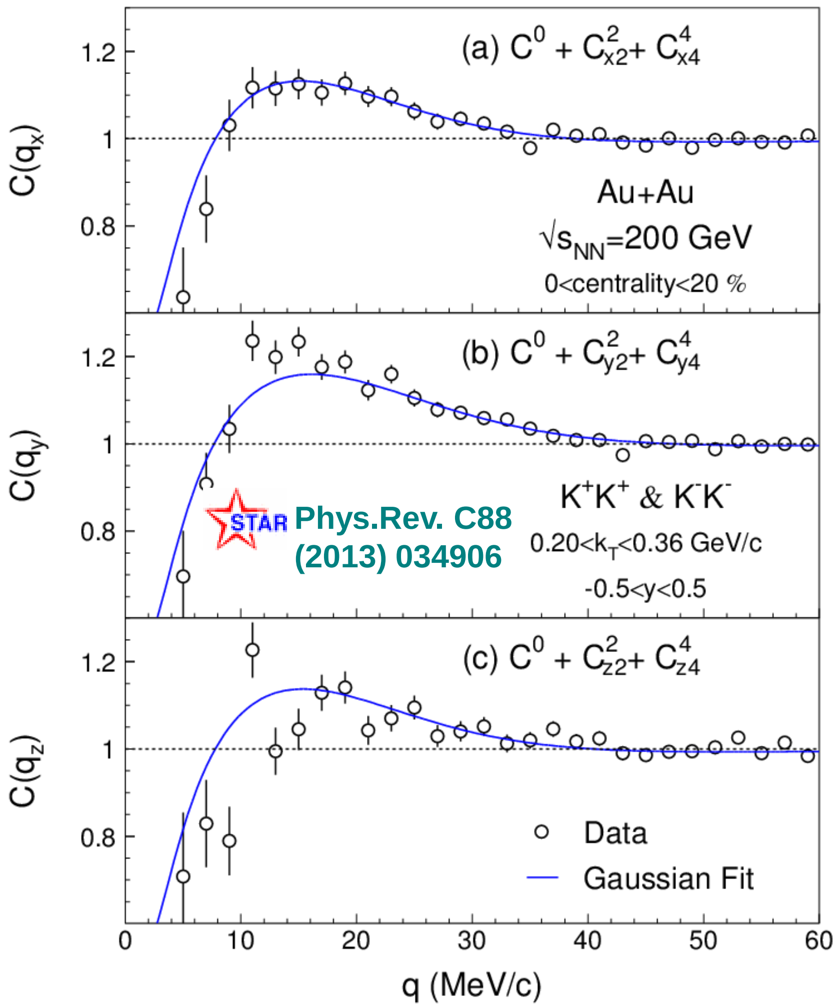
PHENIX, PRL100, 232301 (2008)

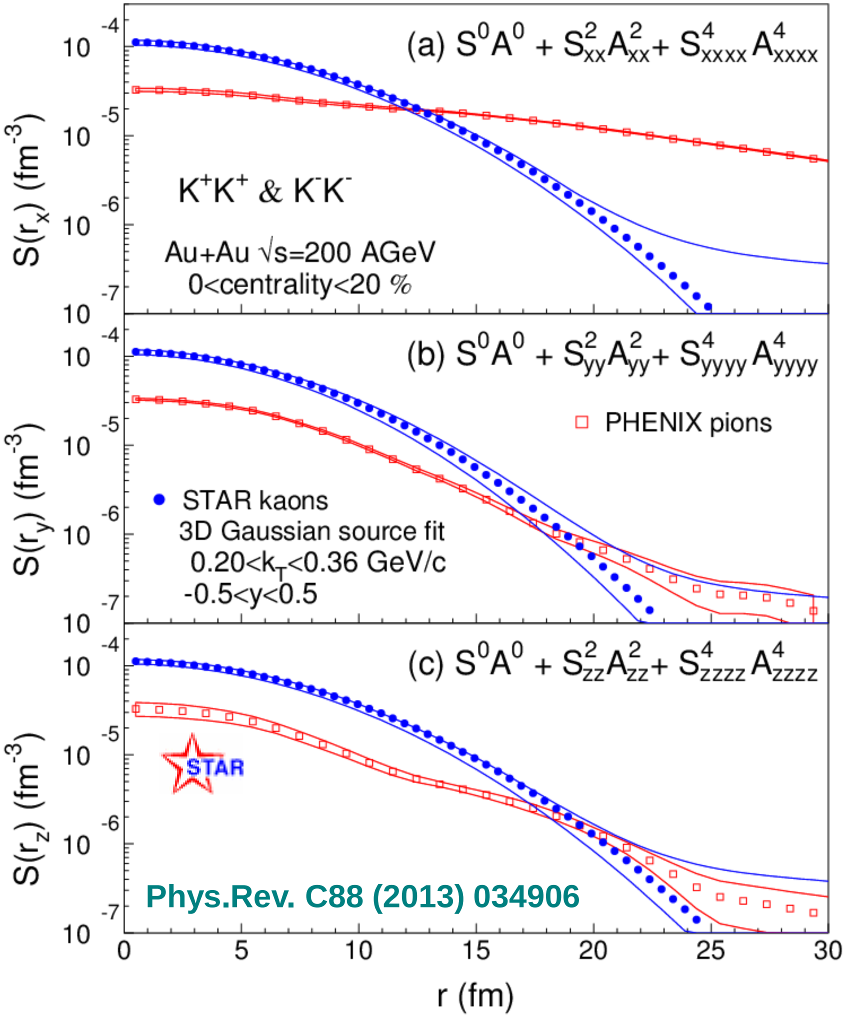


Inset: B/W emission duration in lab frame

Source profiles

3D kaon correlation and source





- **3D Kaon correlation** moments and profiles **consistent with Gaussian**

- Source Gaussian fit shown
- Uncertainties include shape assumption (error dominated low statistics)

See talk of **M. Girard** for STAR

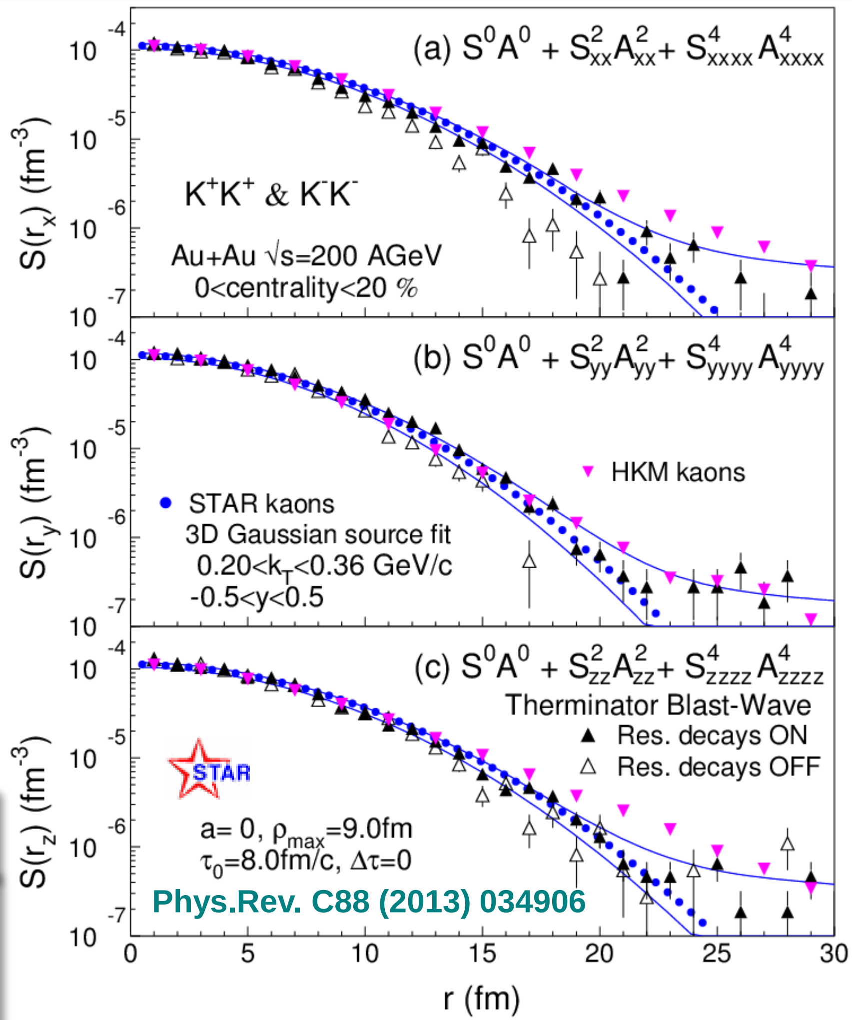
3D kaon source: Model comparison

Thermiantor B/W model

- Kaons: Instant freeze-out
  $\Delta\tau = 0$ (contrary to pions!)
- Parameters tuned for STAR kaons!
- Resonances are needed

Hydrokinetic model

- Consistent in "side"
- Slightly more tail (r>15fm) in "out" and "long"



Hybrid Hydrokinetic Model (hHKM)

PRC81, 054903 (2010)

- Glauber initial conditions
- Pure hydro expansion
- Hadronic cascade with UrQMD

Gets many RHIC observables right

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

HKM data: Shapoval, Sinyukov, Karpenko , arXiv:1308.6272 [hep-ph]

Summary

Long-range component in pion source of RHIC $\sqrt{s_{NN}}$=200 GeV Au+Au collisions observed by PHENIX, confirmed by STAR

- Source is elongated in the “out” direction
- “long” and “side” are similar

Contrary to PHENIX, STAR does not observe the heavy tail in source functions for (central) Kaons

- The k_T range for PHENIX, however, is 9x wider than for STAR

No one over-simplified model explains the observables simultaneously – multiple contributions

- Resonance contributions are required to describe the source shapes
- Kaons and pions may also be subject of different freeze-out dynamics
- Rescattering taken into account by successful models

Thank You!

Backup slides follow…

Imaging: Inversion procedure

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

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

Expansion in B-spline basis

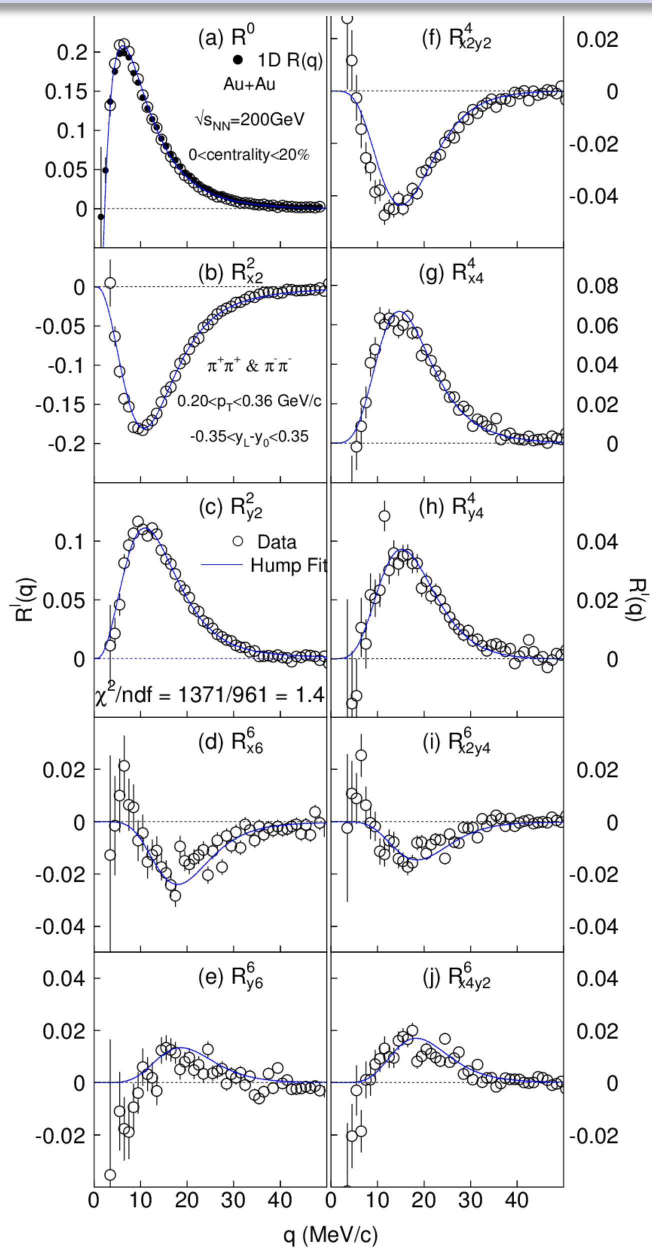
$$C_i^{Th}(q) = \sum_j K_{ij} \cdot S_j$$

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

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

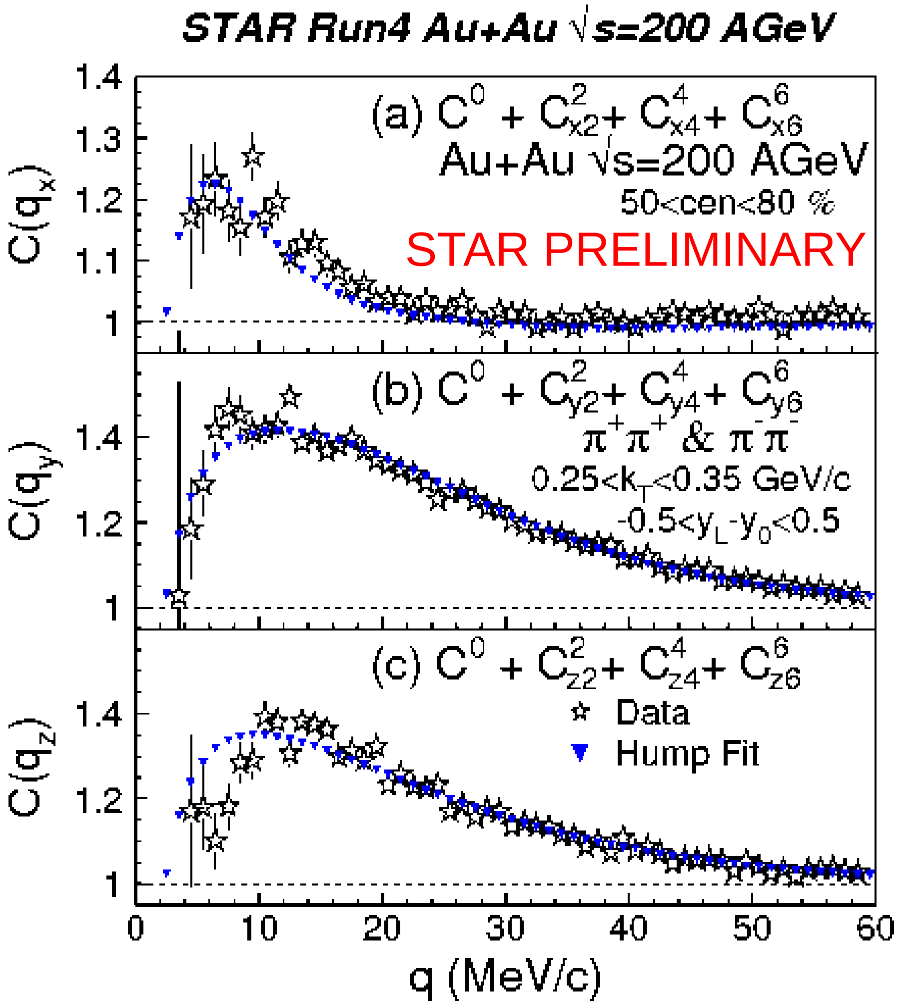
Freeze-out occurs after last scattering
Hence only Coulomb & BE effect included in kernel

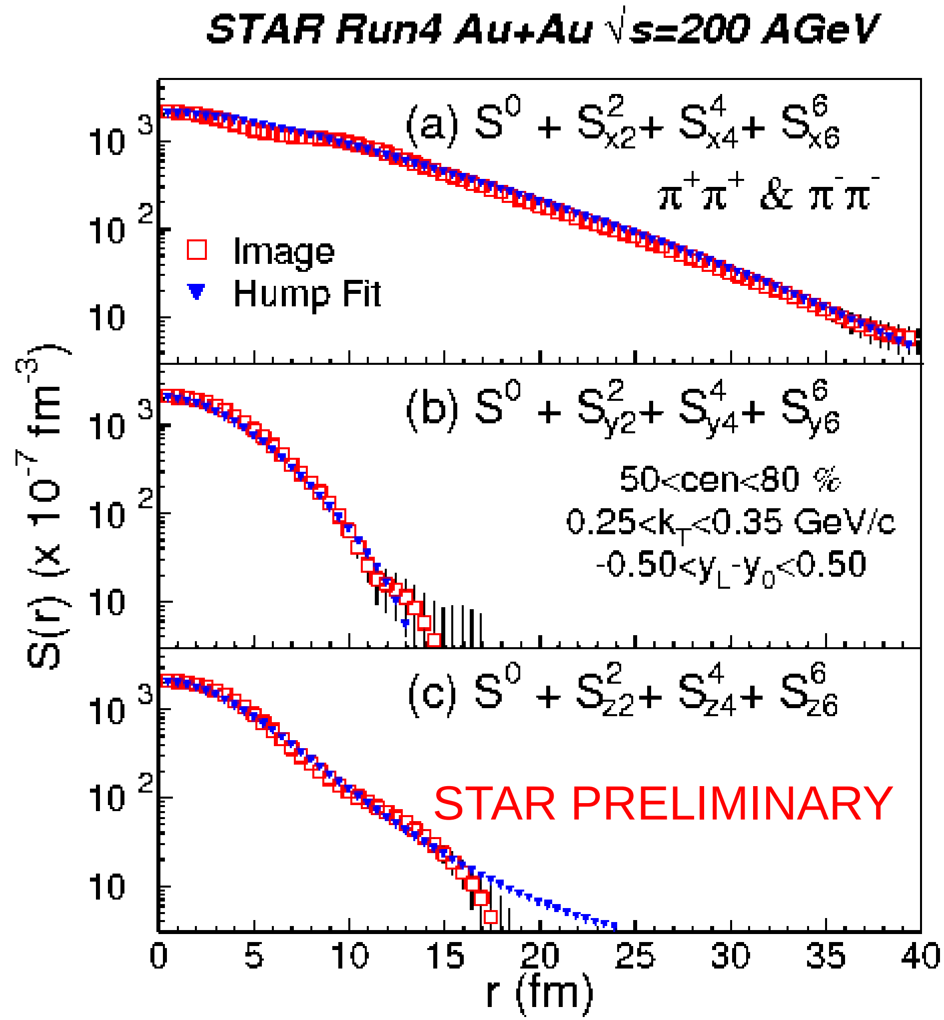
PHENIX pion moments



PHENIX, PRL100, 232301 (2008)

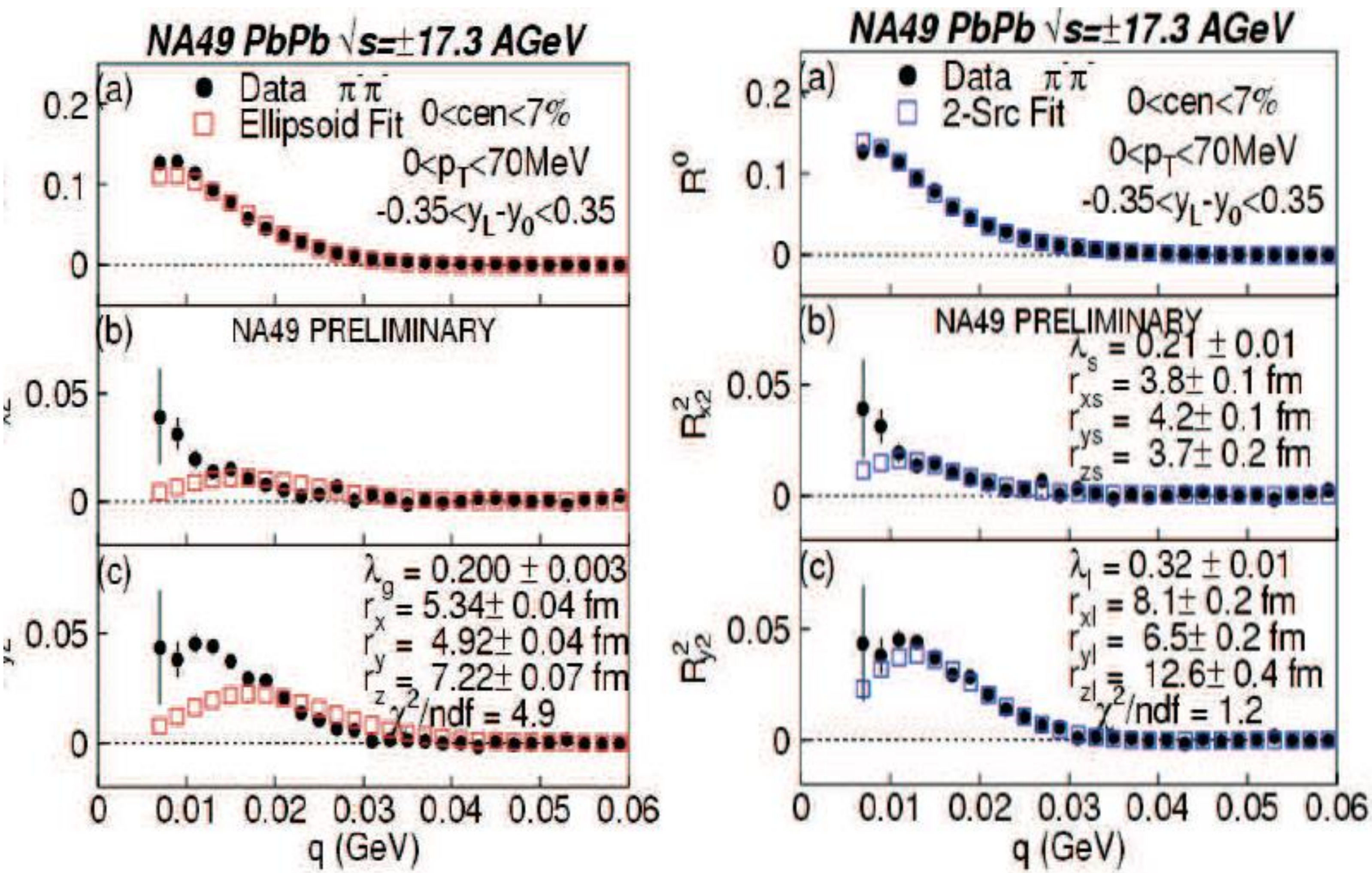
Peripheral pions in STAR



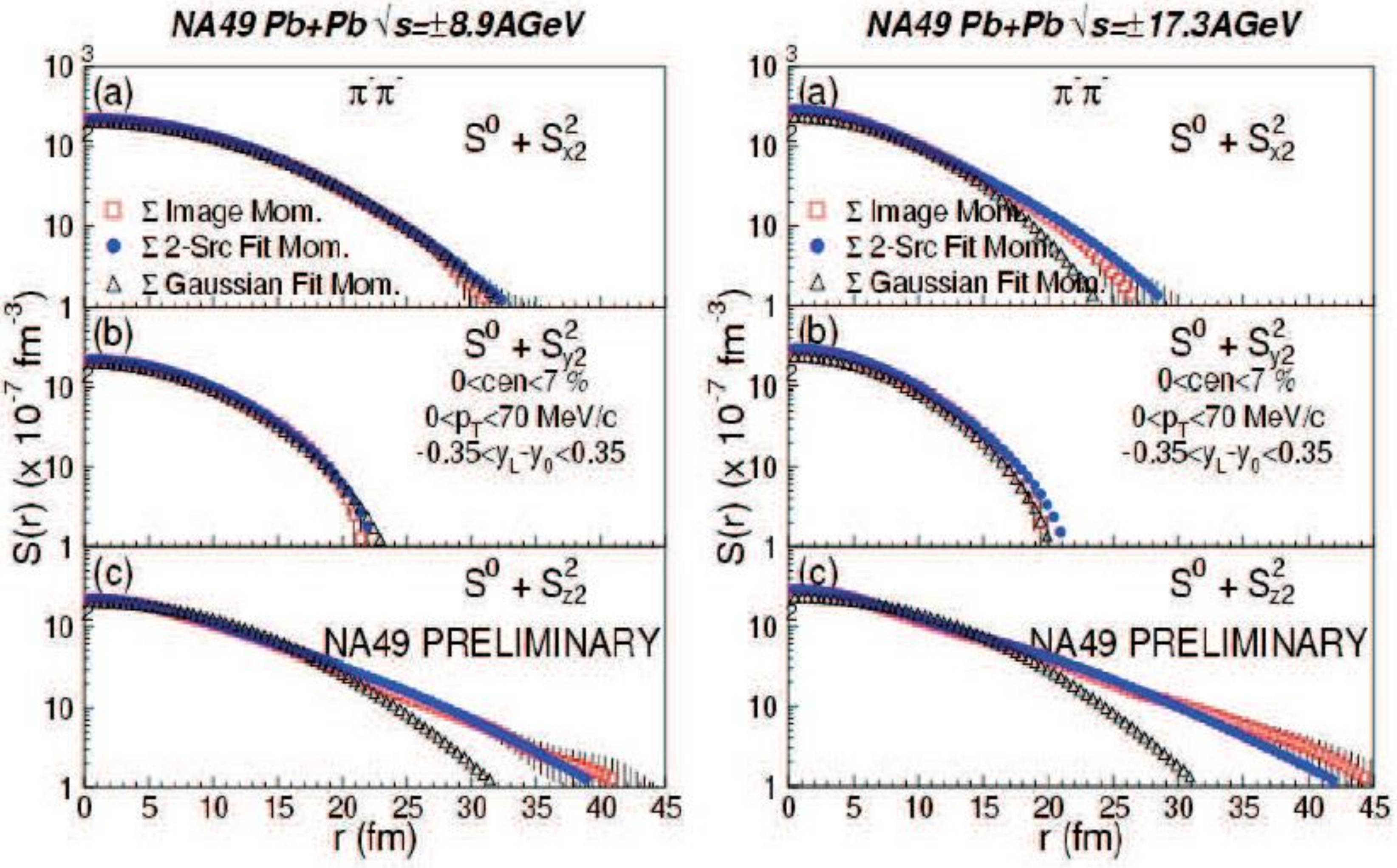


P. Chung (STAR), WPCF 2010

NA49 pions in Pb+Pb - correlation



NA49 pions in Pb+Pb - sources



Kaon source shape

- ℓ=0 moment agrees 1D C(q)

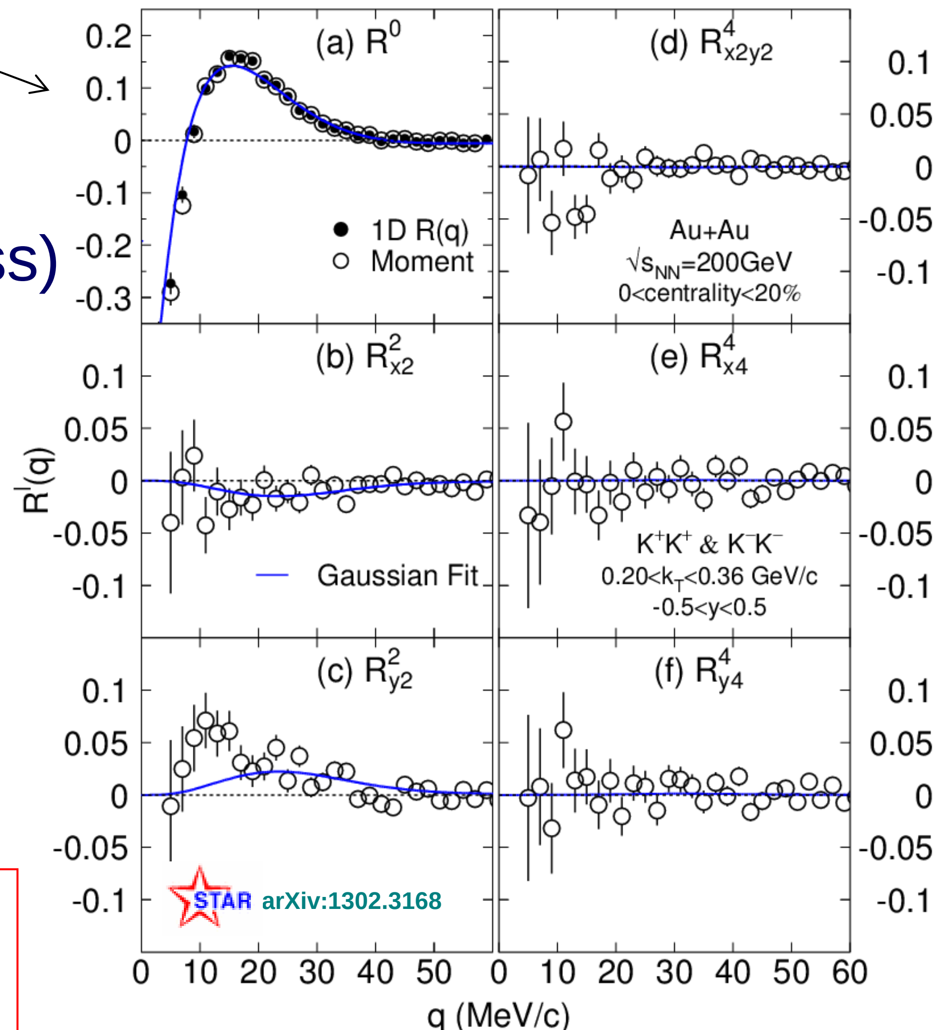
  Higher moments relatively small
- Trial funcional form for S(r): 4-parameter ellipsoid (3D Gauss)

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

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

  $R^{\ell}_{\alpha 1 \dots \alpha \ell}$, $0 \le \ell \le 4$
- Result: statistically good fit

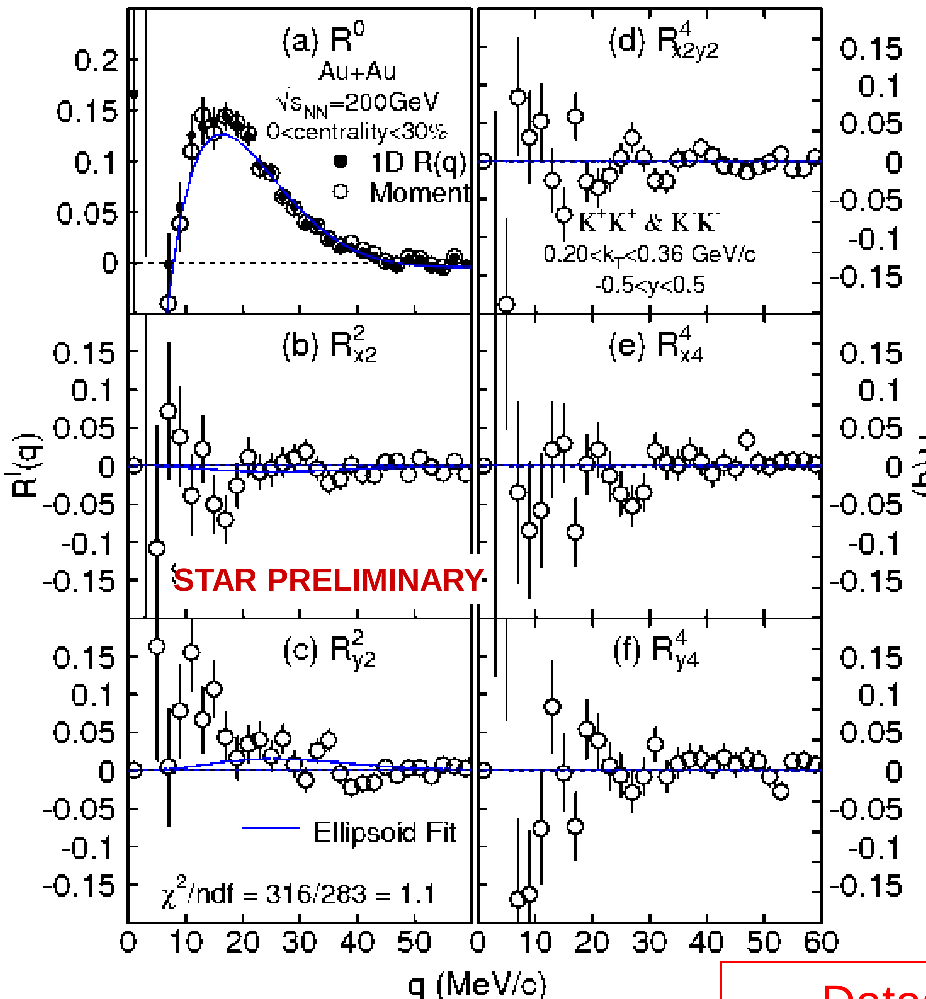
Run4+Run7	$\lambda = 0.48 \pm 0.01$
200 GeV Au+Au	$r_x = (4.8 \pm 0.1)$ fm
Centrality<20%	$r_y = (4.3 \pm 0.1)$ fm
0.2 < k_T < 0.36 GeV/c	$r_z = (4.7 \pm 0.1)$ fm



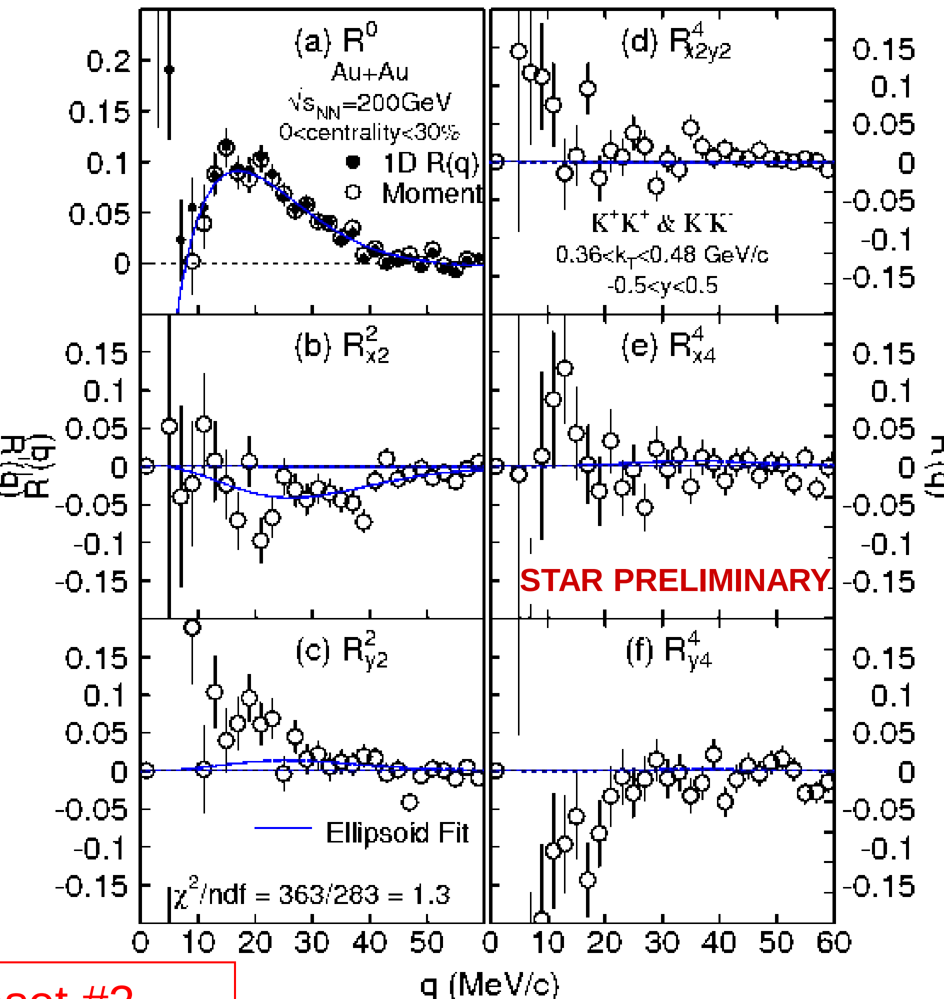
See **M. Girard** for STAR

Fit to correlation moments by kT

0.2<kT<0.36 GeV/c



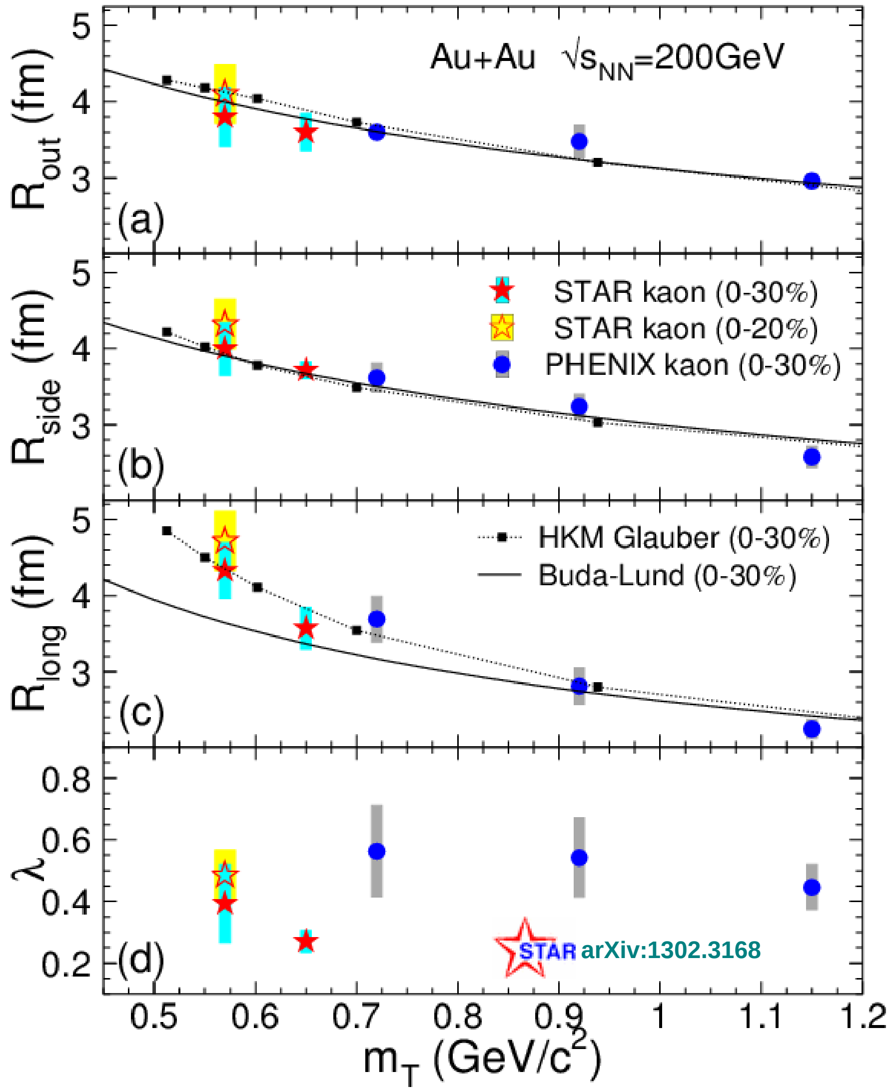
0.36<kT<0.48 GeV/c



Dataset #2
Run4 Cent<30%

Transverse mass dependence

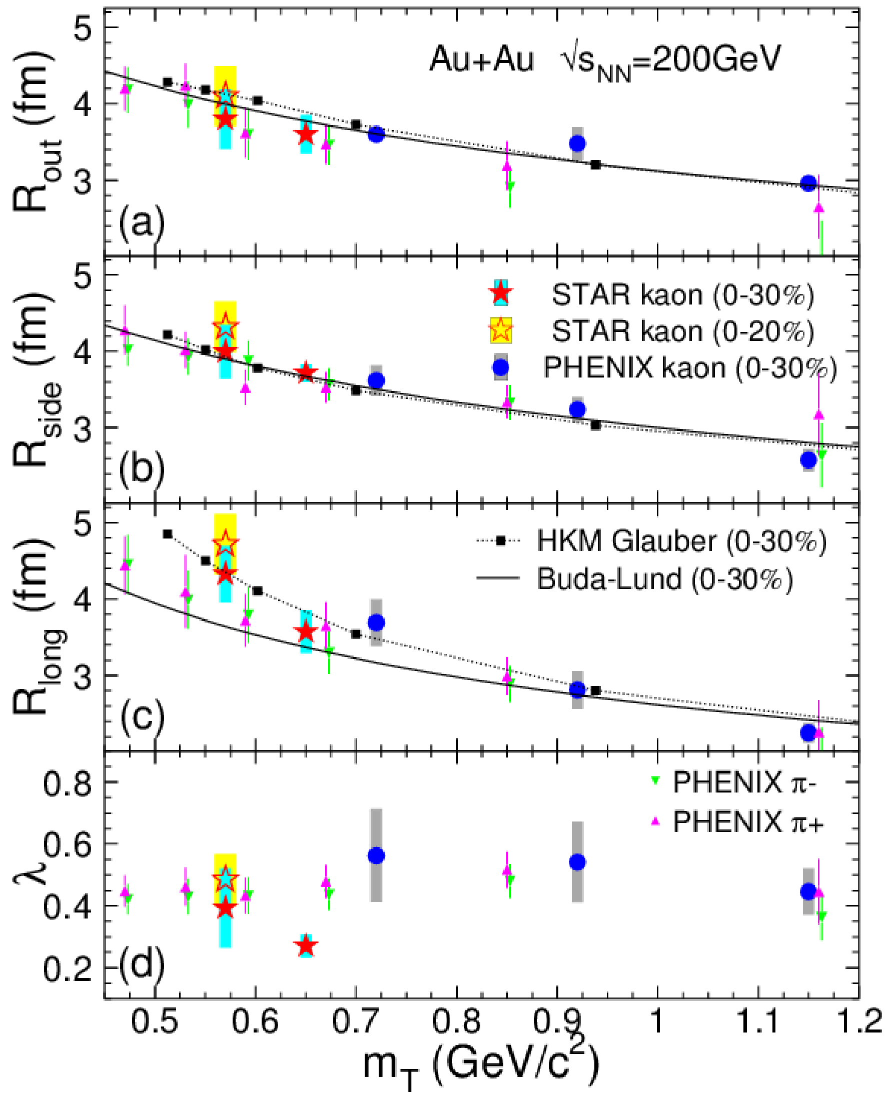
- Radii: rising trend at low m_T
  - Strongest in “long”
- Buda-Lund model
  - Perfect hydrodynamics, inherent m_T-scaling
  - Works perfectly for pions
  - Deviates from kaons in the “long” direction in the lowest m_T bin
- HKM (Hydro-kinetic model)
  - Describes all trends
  - Some deviation in the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



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

Radii vs. mT, pion, kaon

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



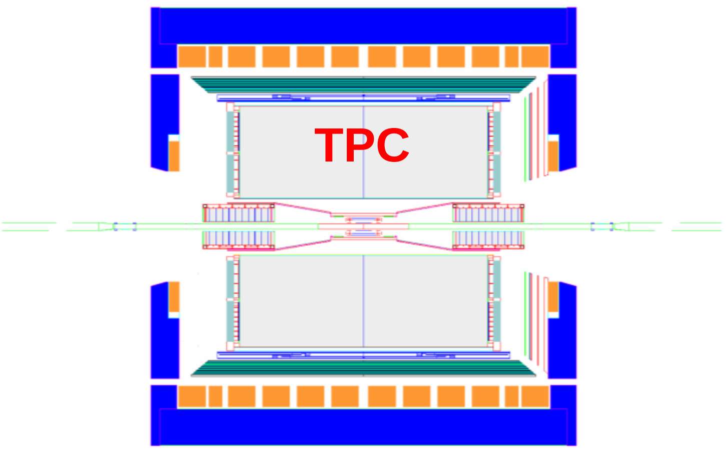
Buda-Lund: M. Csanád, arXiv:0801.4434v2
HKM: PRC81, 054903 (2010)

Kaon femtoscopy analyses

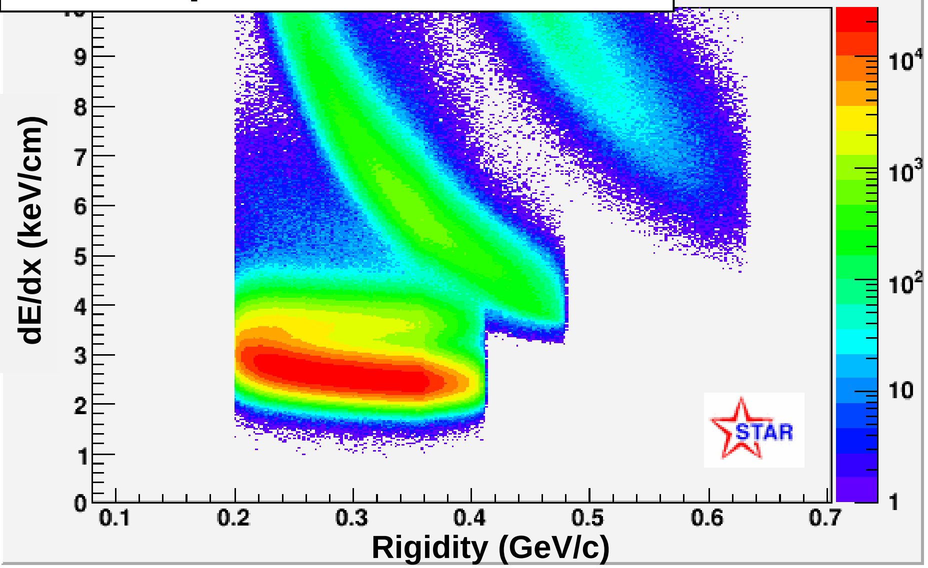
Au+Au @ $\sqrt{s_{NN}}$=200 GeV

Mid-rapidity |y|<0.5

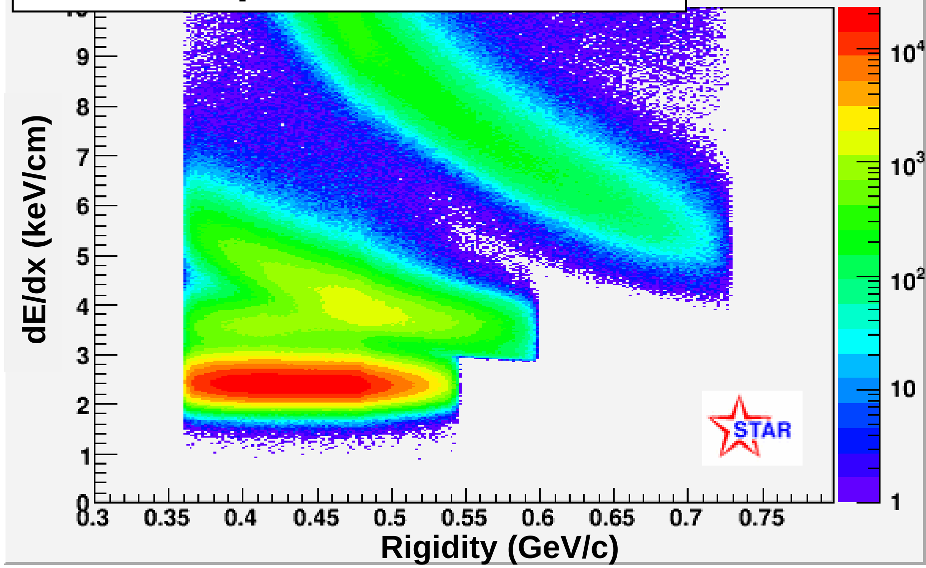
1. Source shape: 20% most central
   Run 4: 4.6 Mevts, Run 7: 16 Mevts
2. m_T-dependence: 30% most central
   Run 4: 6.6 Mevts



$0.2<k_T<0.36$ GeV/c



$0.36<k_T<0.48$ GeV/c



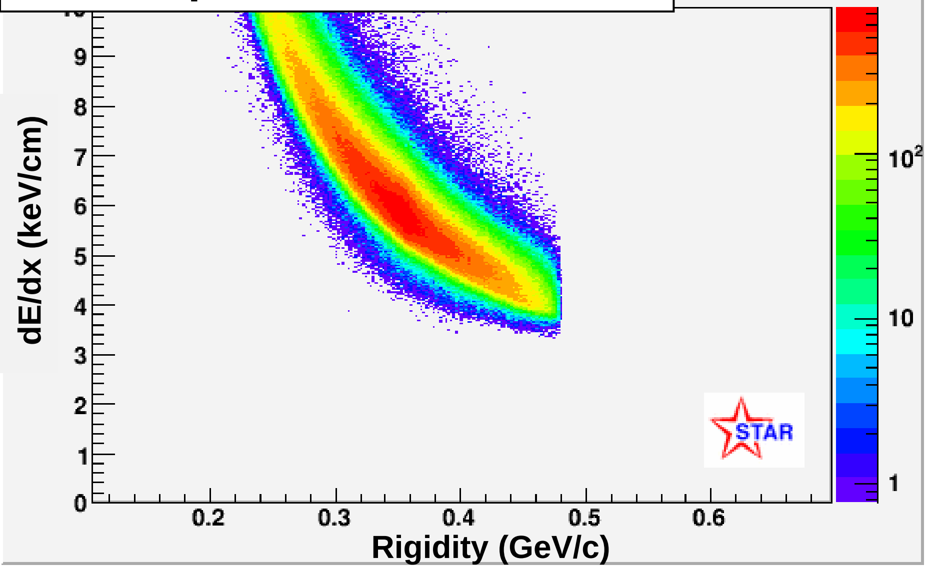
PID cut applied

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