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

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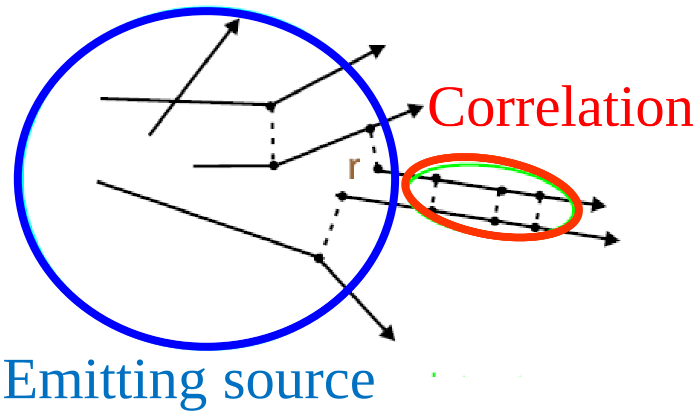
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

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
  - Strong FSI …

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

- Solving for the source is difficult → assumptions

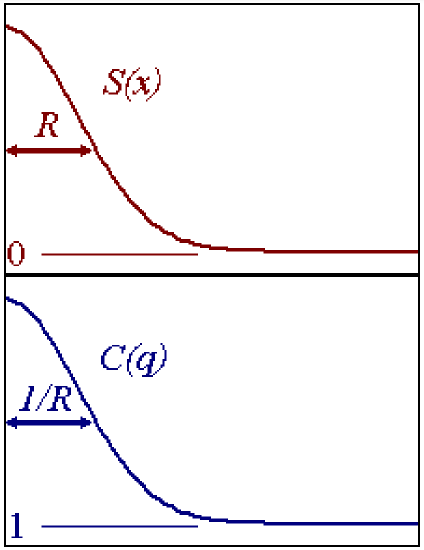
Gaussian radii and LCMS

- **Gaussian source:**

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

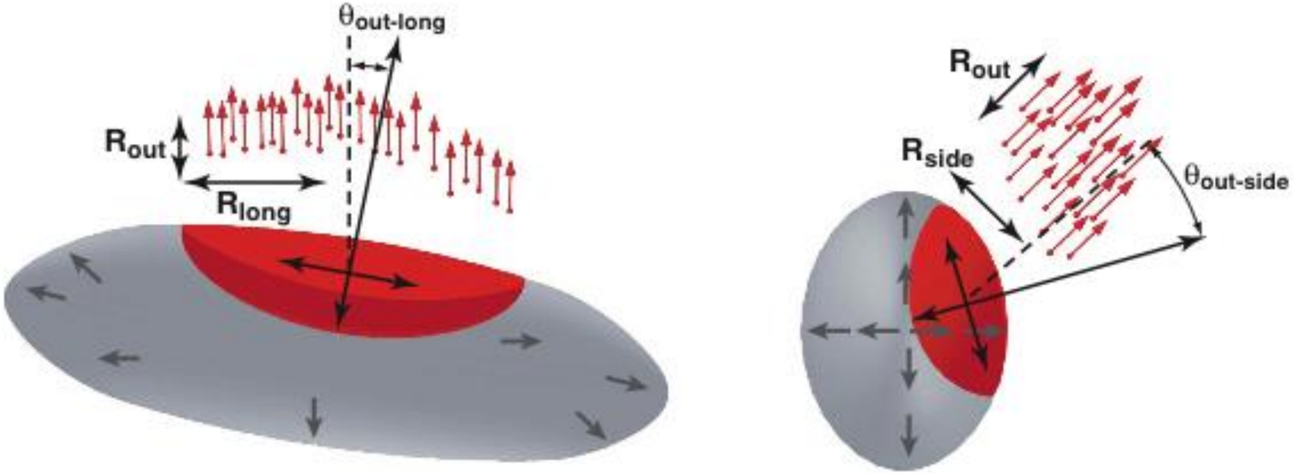
- **Correlation → HBT radii**

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



- **Homogeneity regions**

Reflect the size of the source from where particles are emitted with similar velocity



LCMS (not invariant)

Out: along average pair transverse momentum
Long: beam direction
Side: orthogonal to both

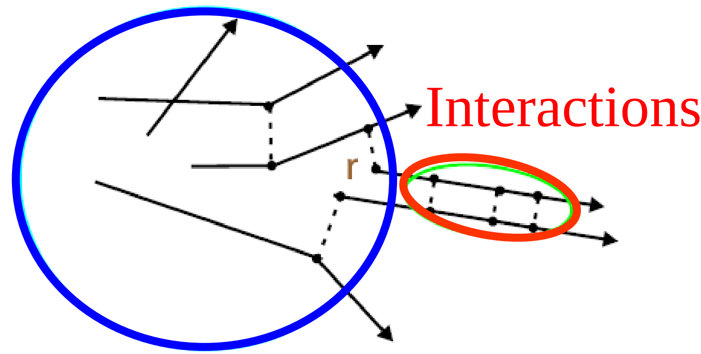
$$C(q) = 1 + \lambda \exp\left(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2\right)$$

Source imaging

Physics in shape: dynamics, resonance decays, rescattering…

- Koonin-Pratt equation (1D)

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



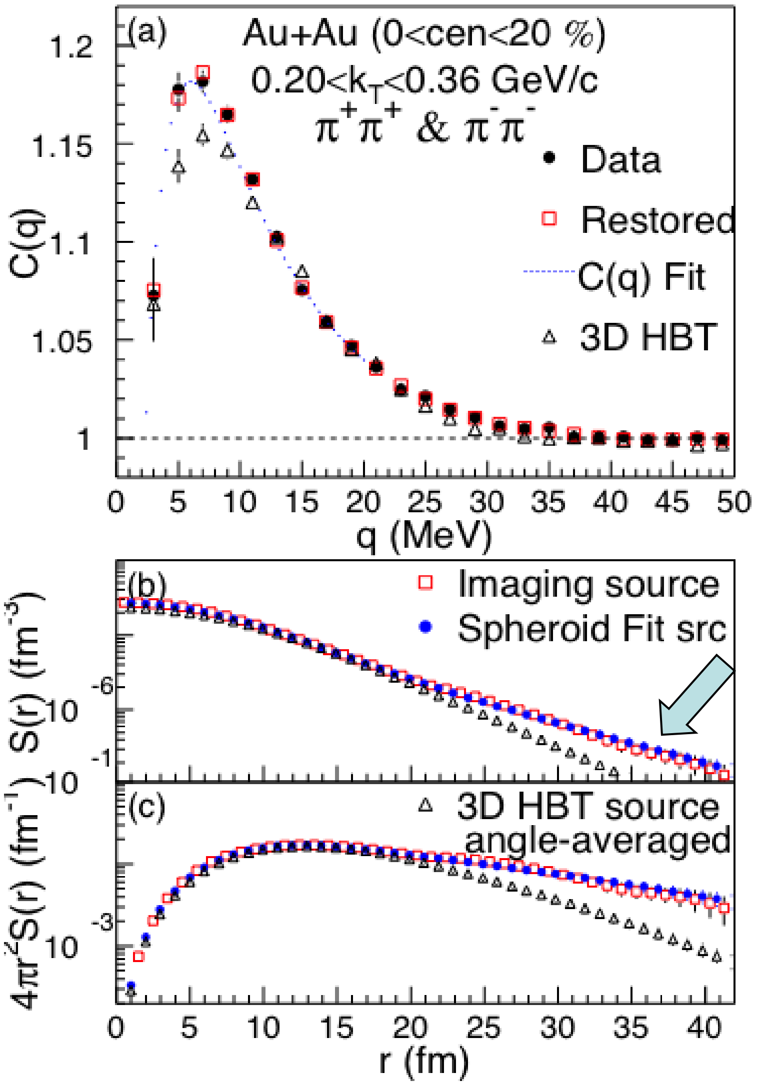
- Imaging: Obtain $S(\mathbf{r})$ directly
  - No assumptions for the shape of source
  - Kernel includes **all** interactions (QM, FSI)
- Numerical inversion of the equation
  - No analytical solution, hence some limitations and approximations (integral cutoff, finite resolution …)
  - Assumptions (e.g. 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
  - Contribution of long-lived resonance decays

PHENIX, PRL 98, 132301 (2007)



Rescattering or resonances?

Hadronic Rescattering Code

- Cascade model, few resonances: ρ, Δ, K* ; ω ; η, η’, Φ, Λ
- Causality-keeping scatterings
- p-dependent cross sections

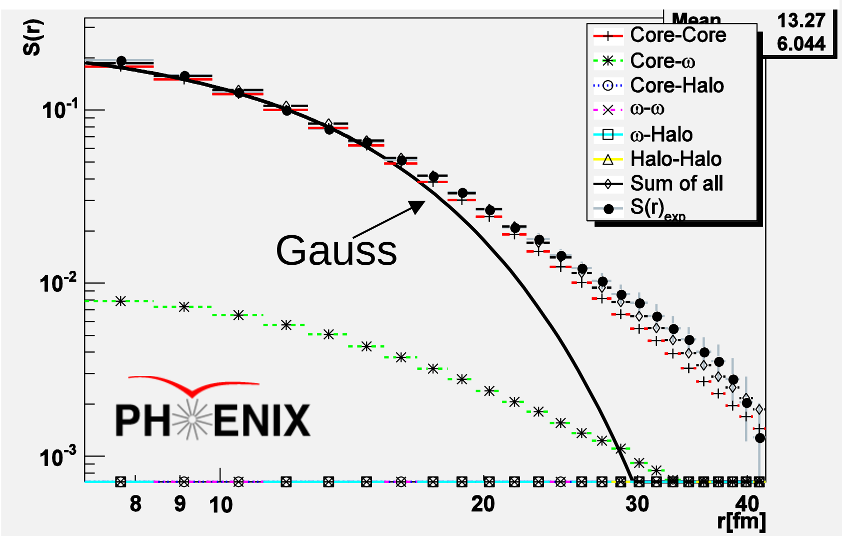
T. J. Humanic, Int. J. Mod. Phys. E 15 (2006)

THERMINATOR Single Freezeout

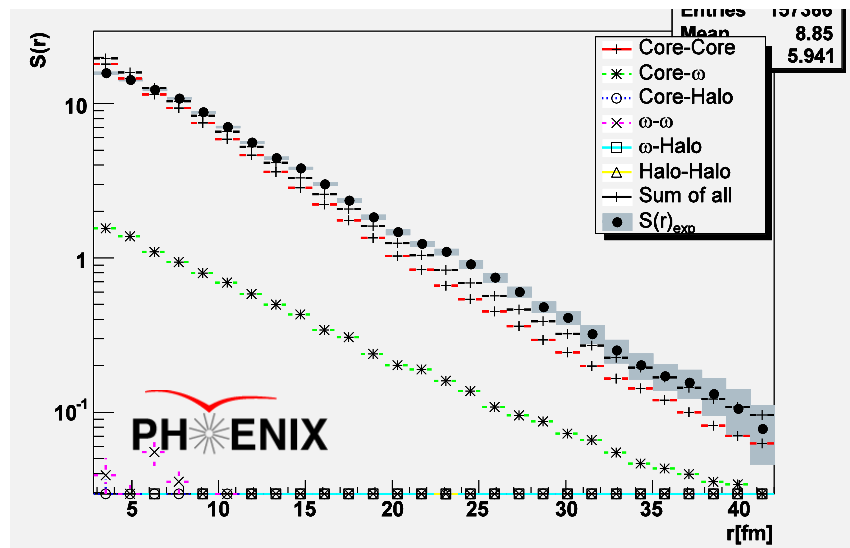
- Universal T, μ_{I3}, μ_B , μ_S
- Single hyper-ellipsoid FO surface
- Many resonances (385)
- no rescattering

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

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



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



- Both HRC and THERMINATOR describe the 1D pion source

Different, but similar underlying mechanism:
Anomalous diffusion in an expanding system vs. dying-out resonances

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:

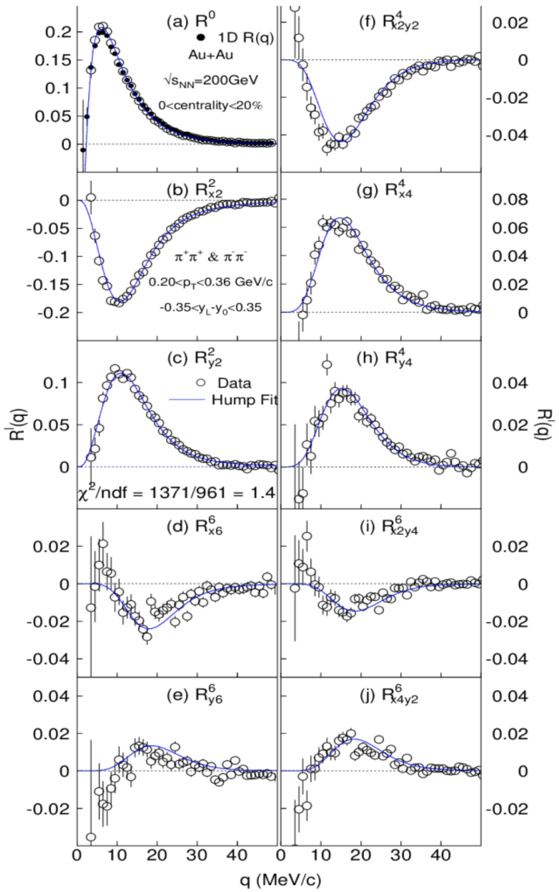
$$R(\mathbf{q}) = C(\mathbf{q}) - 1 = 4\pi \int dr^3 K(\mathbf{q},\mathbf{r}) S(\mathbf{r}) \quad (3)$$

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

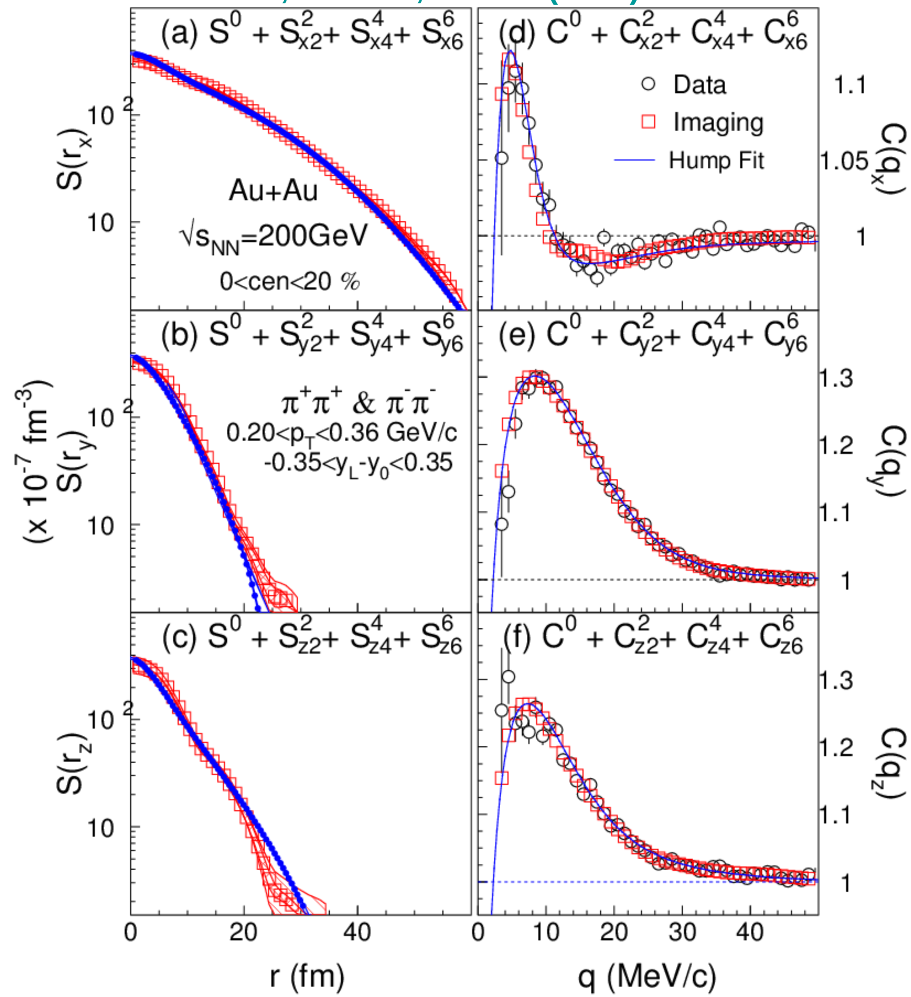
Invert (2) $\Rightarrow$ $$S^l_{\alpha_1 \ldots \alpha_l} = \frac{(2l+1)!!}{l!} \int \frac{d\Omega_q}{4\pi} A^l_{\alpha_1 \ldots \alpha_l}(\Omega_q) S(\mathbf{q})$$

3D pion imaging (PHENIX)



Correlation moments (0th, 2nd, 4th, 6th order)

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

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

Hump:

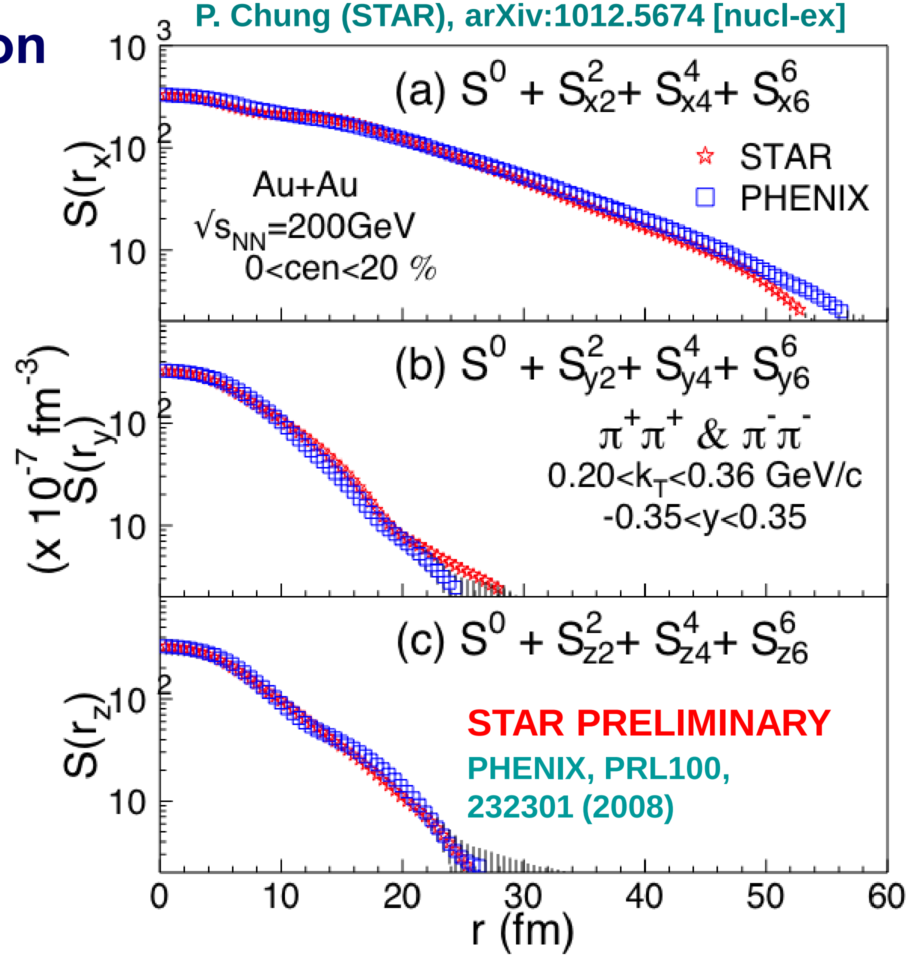
$$S^H(r_x, ry, rz) = e^{-F_s\left[\left(\frac{r_x}{2R_{xs}}\right)^2+\left(\frac{r_y}{2R_{ys}}\right)^2+\left(\frac{r_z}{2R_{zs}}\right)^2\right]-F_l\left[\left(\frac{r_x}{2R_{xl}}\right)^2+\left(\frac{r_y}{2R_{yl}}\right)^2+\left(\frac{r_z}{2R_{zl}}\right)^2\right]}$$

$$F_s = \frac{1}{1+(r/r_0)^2}, \quad F_l = 1 - F_s$$

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
- Well described by a hump fit
- 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

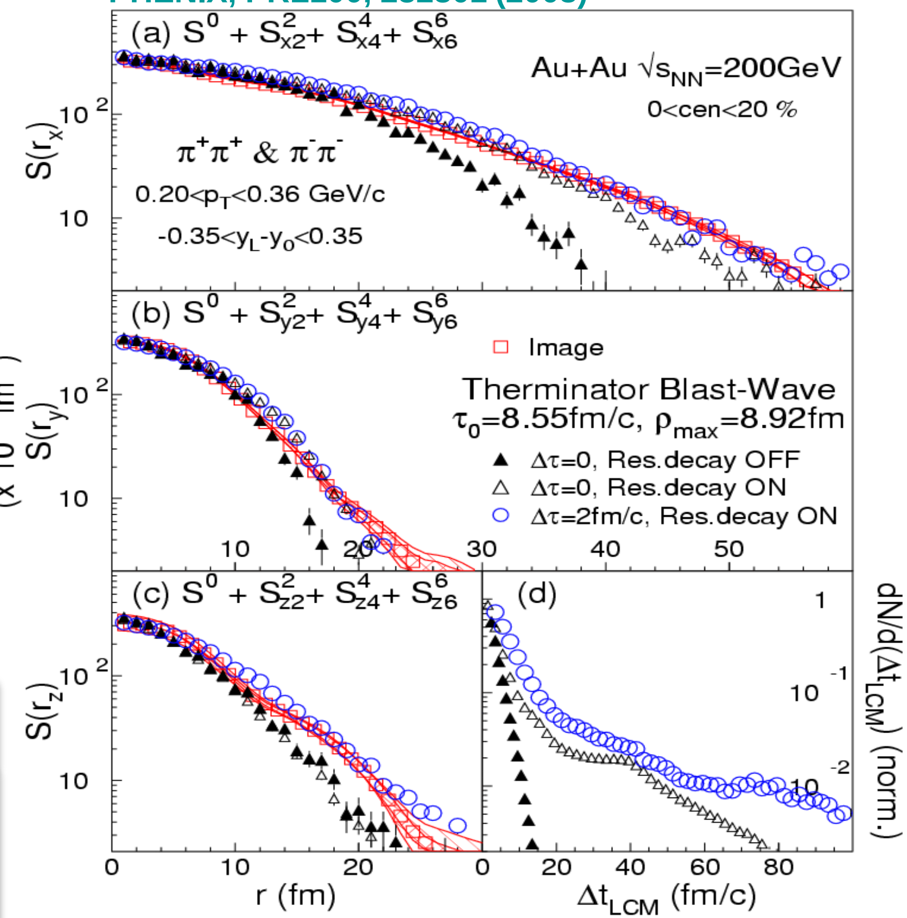
- Therminator B/W model description
  - Iff resonance contributions ON, and
  - Iff **non-zero emission duration**

$\Delta\tau \sim 2$ 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)

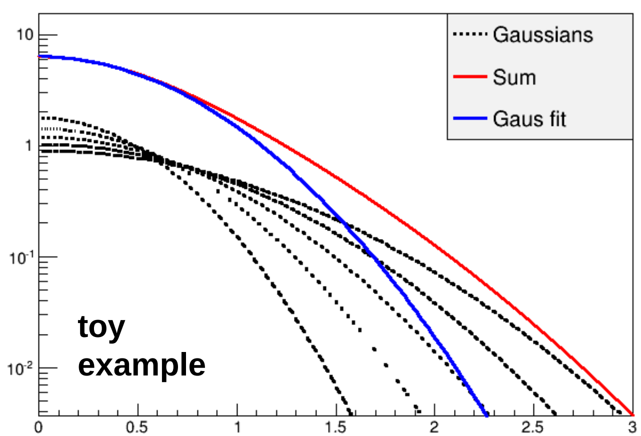


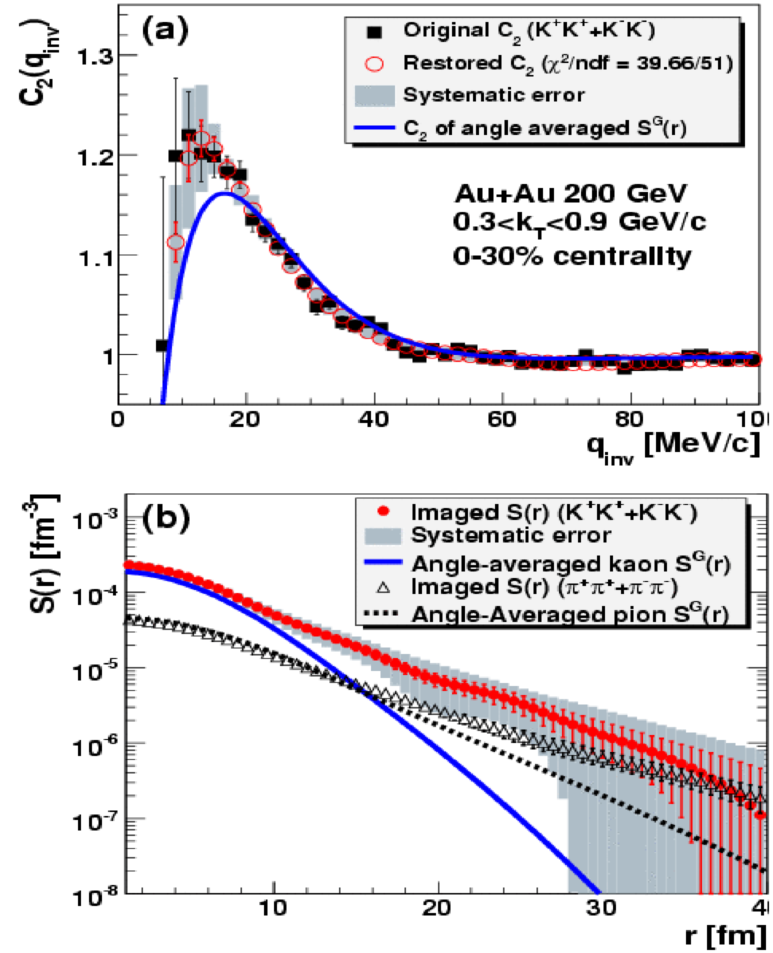
Inset: B/W emission duration in lab frame

Source profiles

Kaons: A cleaner probe

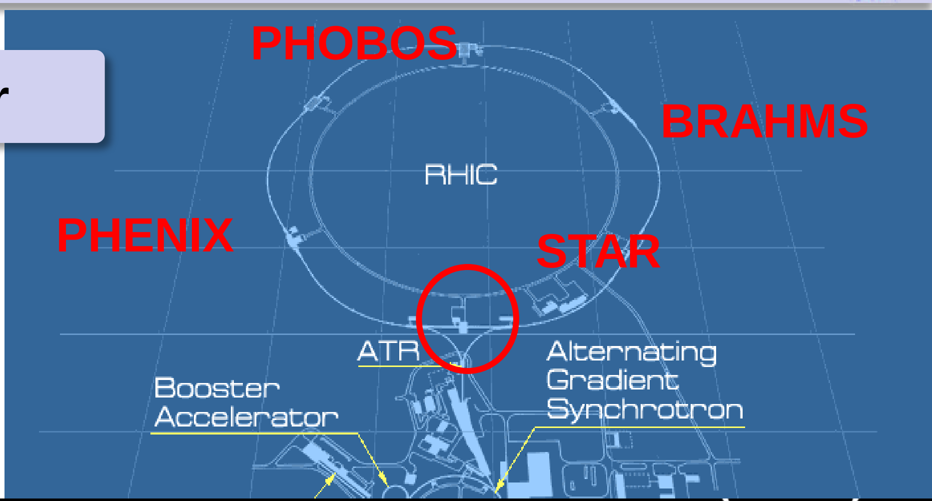
- Less feed-down, less rescattering
  - Interpretation more straightforward
  - More difficult due to ~10 less statistics
- PHENIX 1D Kaon source: an even larger non-Gaussian component
  - Seemingly favors rescattering explanation against resonances
- Interpretation caveat: wide k_T (N_{part}) bin
 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





PHENIX, PRL 103, 142301 (2009)

RHIC/STAR



The Relativistic Heavy Ion Collider

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)

PHENIX & STAR

- complement and x-check each other

Continuous improvements

The Solenoidal Tracker at RHIC

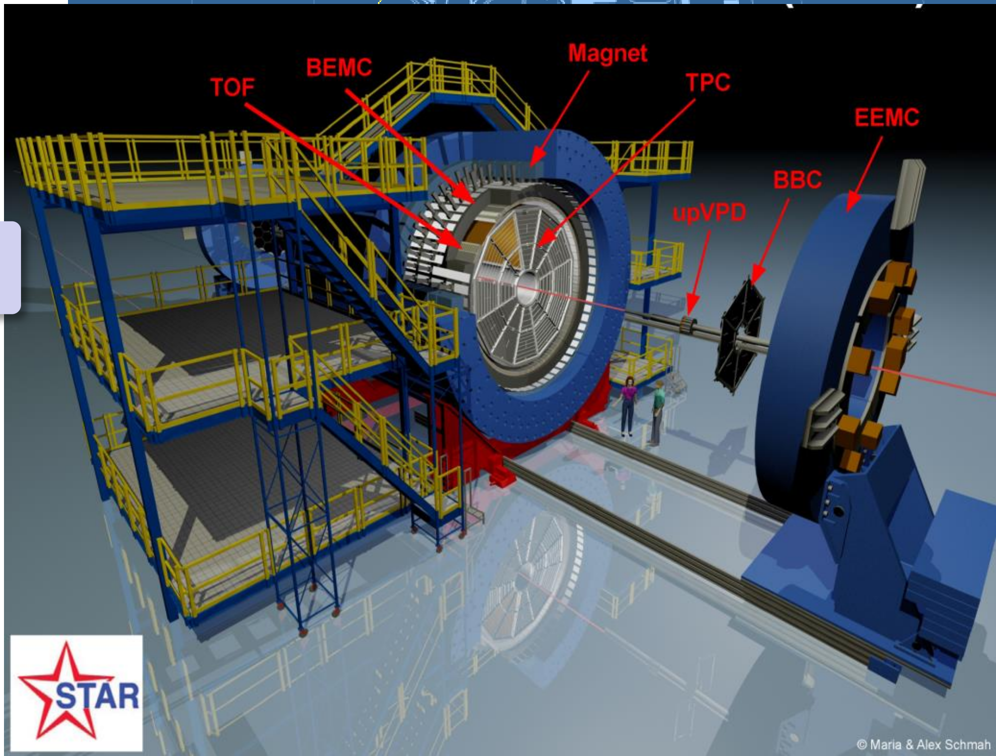
Time Projection Chamber

- ID via energy loss (dE/dx)
- Momentum (p)

Full azimuth coverage

Uniform acceptance

for different energies and particles



Kaon femtoscopy analyses

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

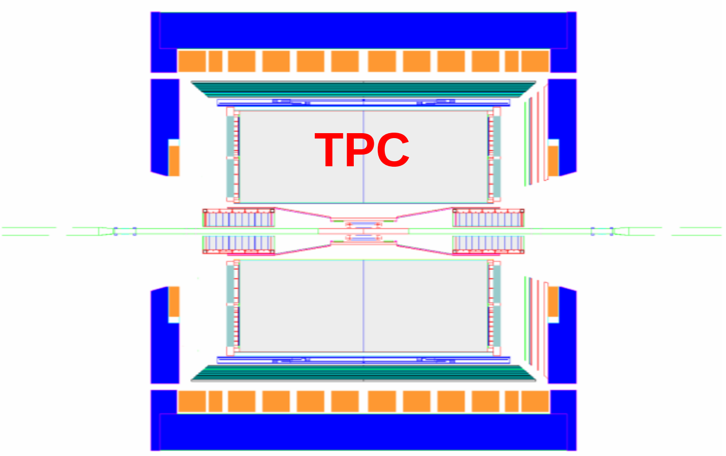
Mid-rapidity |y|<0.5

1. Source shape: 20% most central

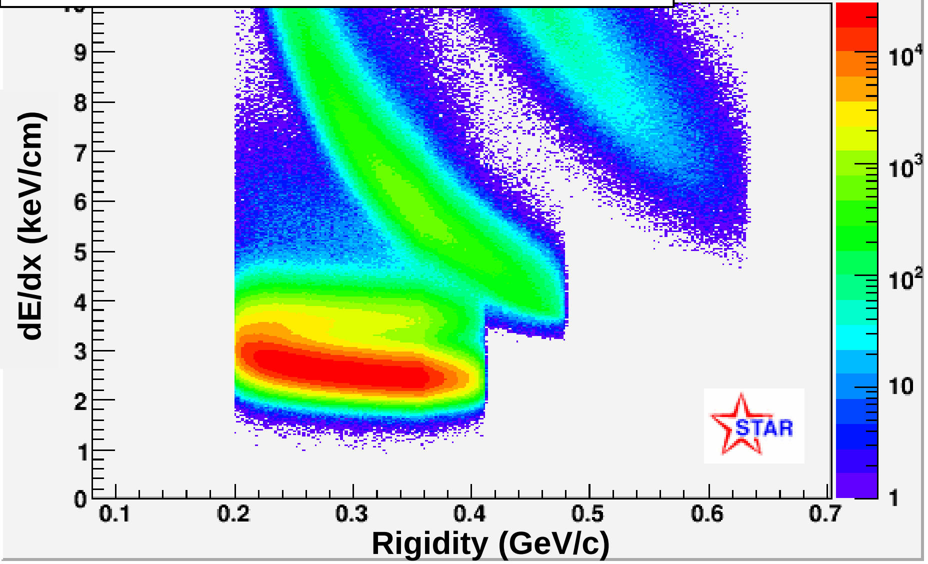
   Run 4: 4.6 Mevts, Run 7: 16 Mevts

2. m_T-dependence: 30% most central

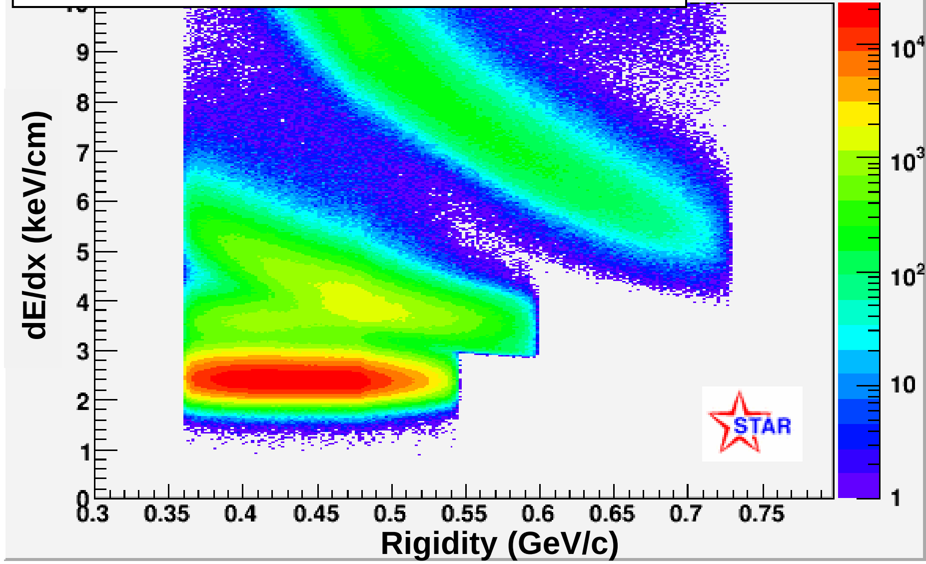
   Run 4: 6.6 Mevts



$0.2<k_T<0.36$ 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

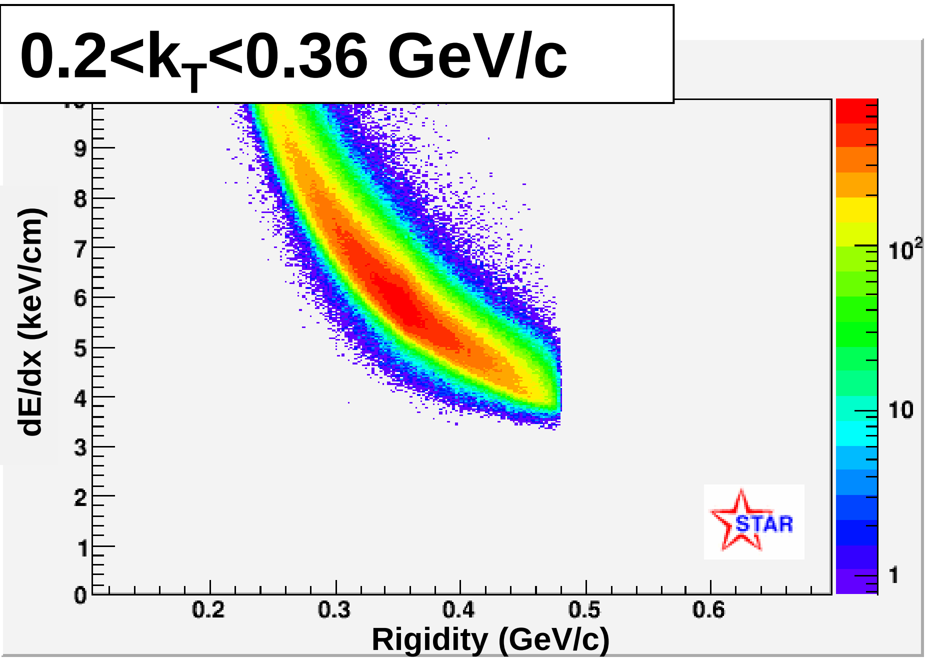
  nσ(X) :deviation of the candidate dE/dx from the normalized distribution of partice type X at a given momentum

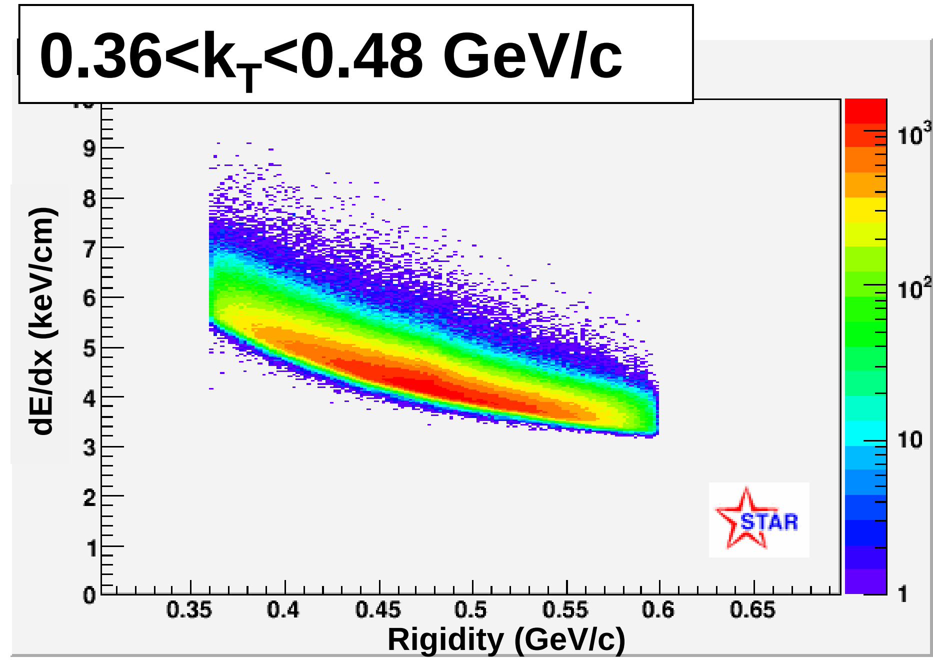
- $0.2 < p_T < 0.4$ GeV/c

2. m_T-dependent analysis

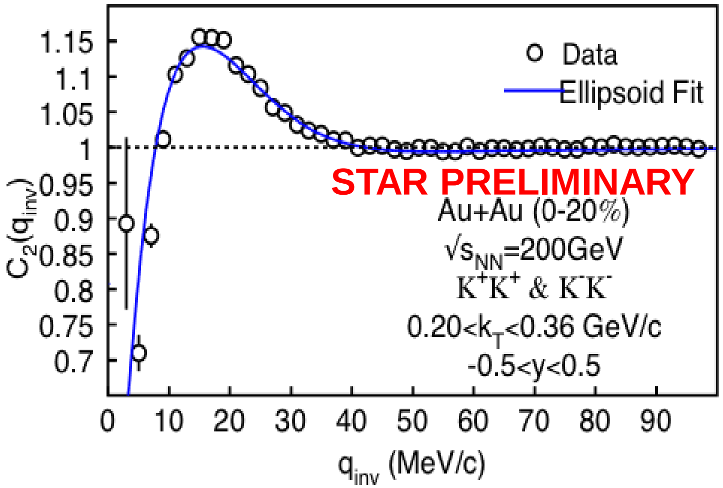
-1.5< nσ(Kaon)<2.0

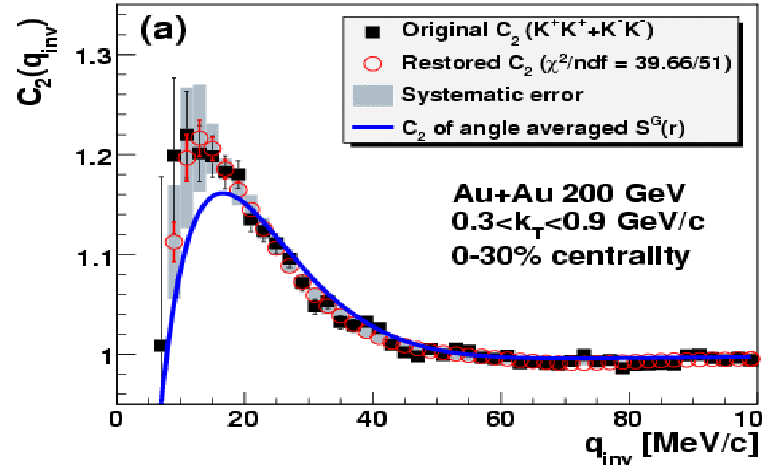
-0.5< nσ(Kaon)<2.0

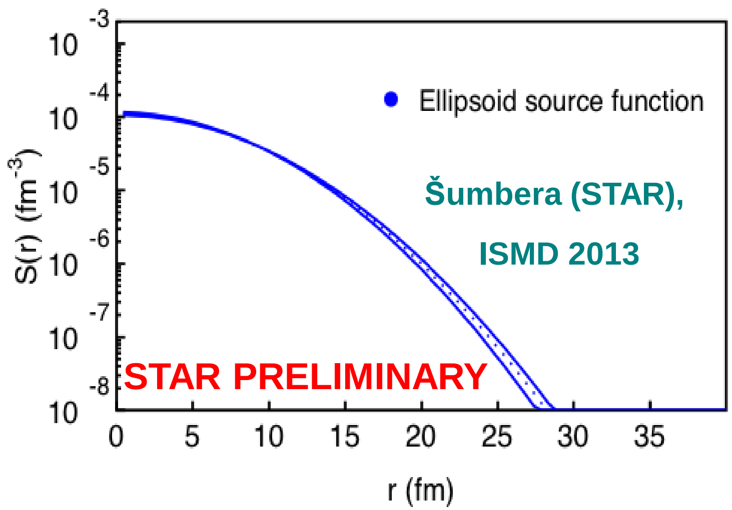


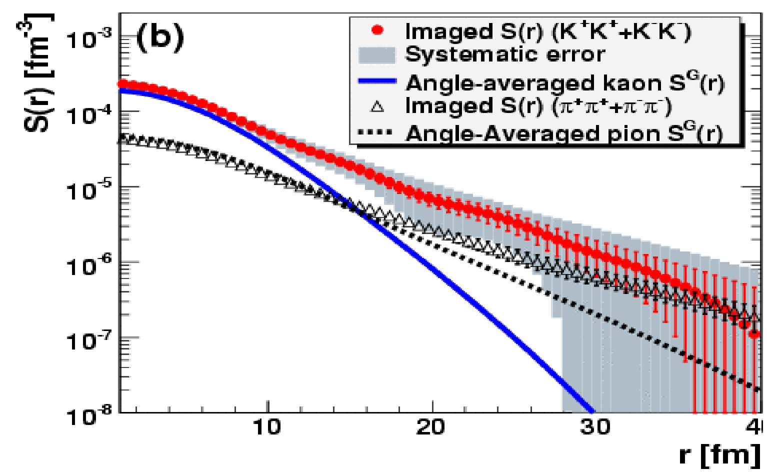


Kaons: STAR vs. PHENIX









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 Shape analysis

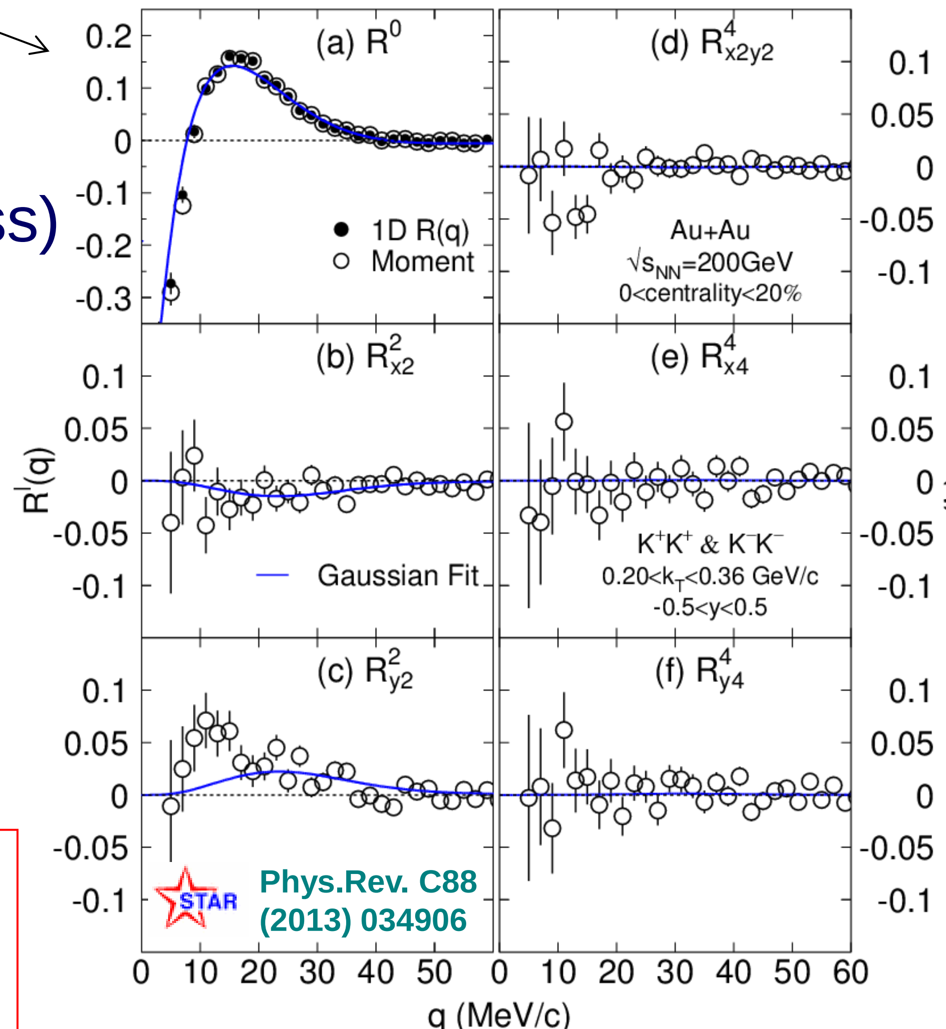
- ℓ=0 moment agrees 1D C(q)

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

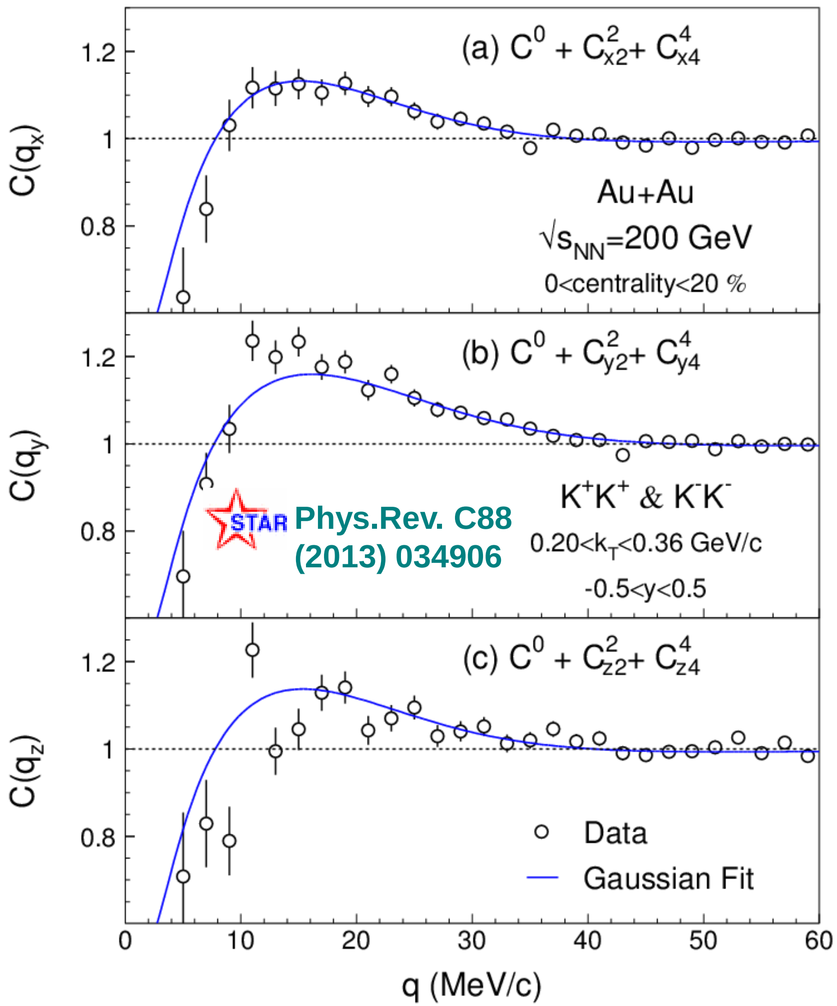
$$S^G(x,y,z) \equiv \frac{\lambda}{\left(2\sqrt{\pi}\right)^3 r_x r_y r_z} \exp\left[-\left(\frac{x^2}{4r_x^2} + \frac{y^2}{4r_y^2} + \frac{z^2}{4r_z^2}\right)\right]$$

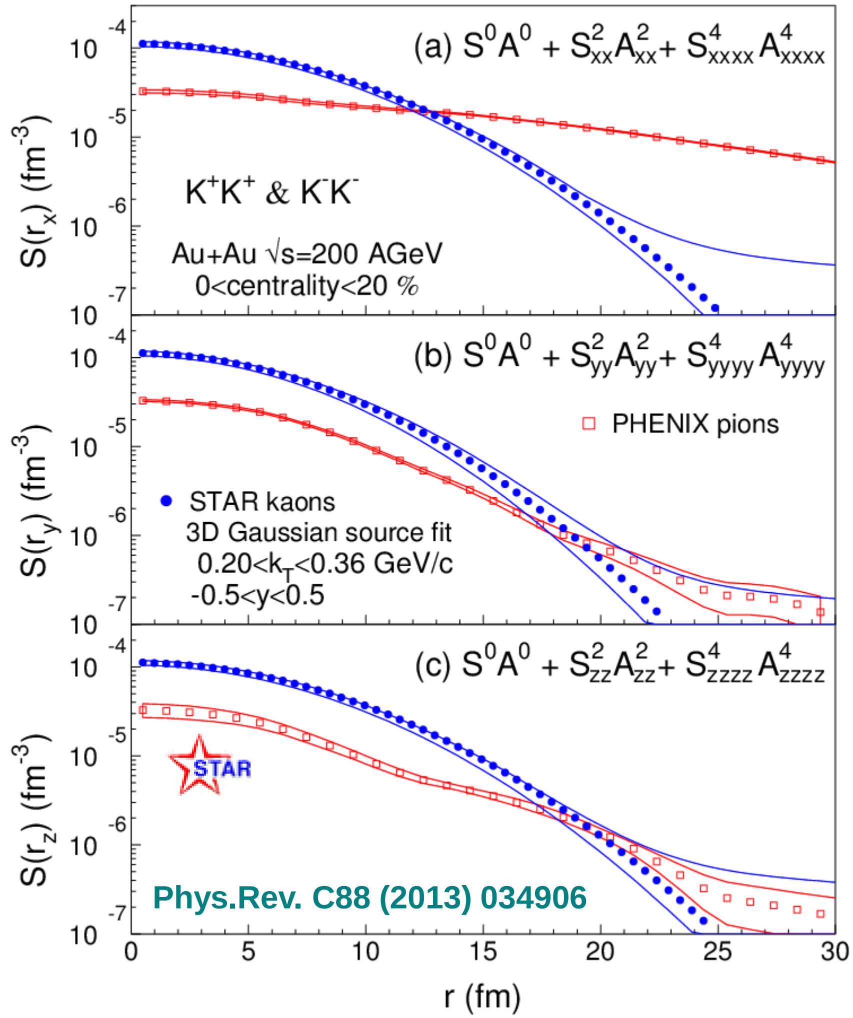
- Fit to C(q): technically a simultaneous fit on 6 independent moments $R^{\ell}_{\alpha 1 \ldots \alpha \ell}$, $0 \le \ell \le 4$
- Result: statistically good fit

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



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)

3D kaon source: Model comparison

Therminator B/W model

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

Hydrokinetic model

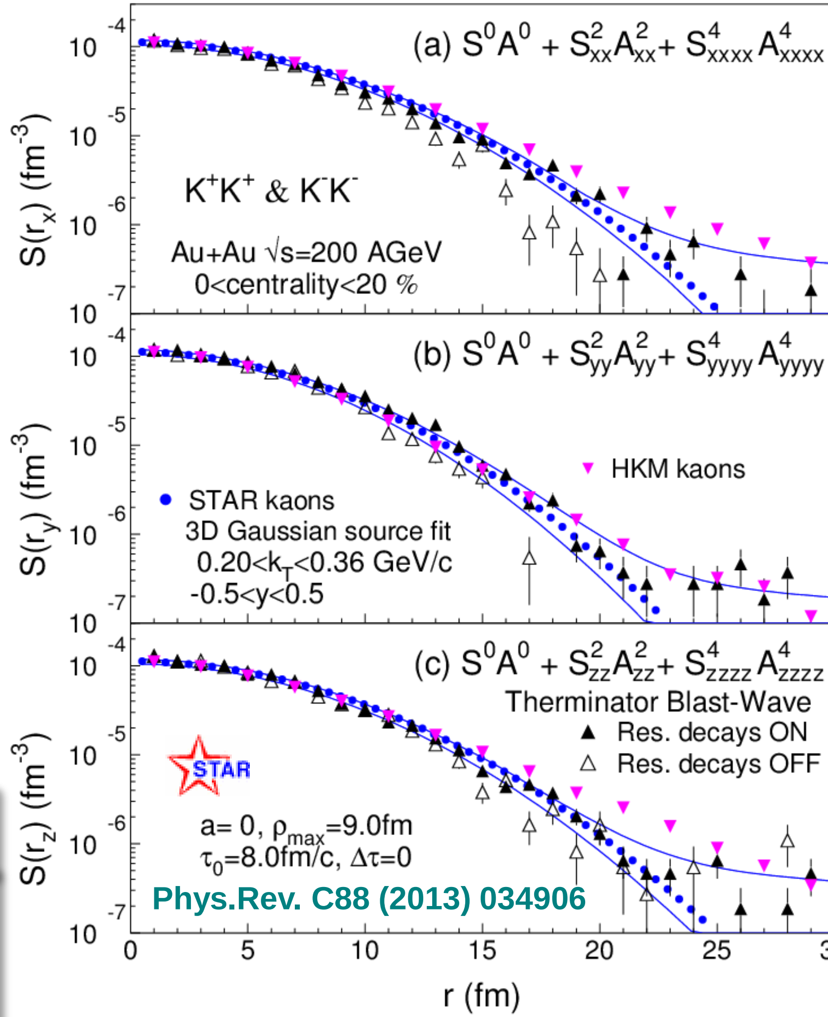
- Consistent in "side"
- Slightly more tail (r>15fm) in "out" and "long"

Hybrid Hydrokinetic Model (hHKM)

PRC81, 054903 (2010)

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

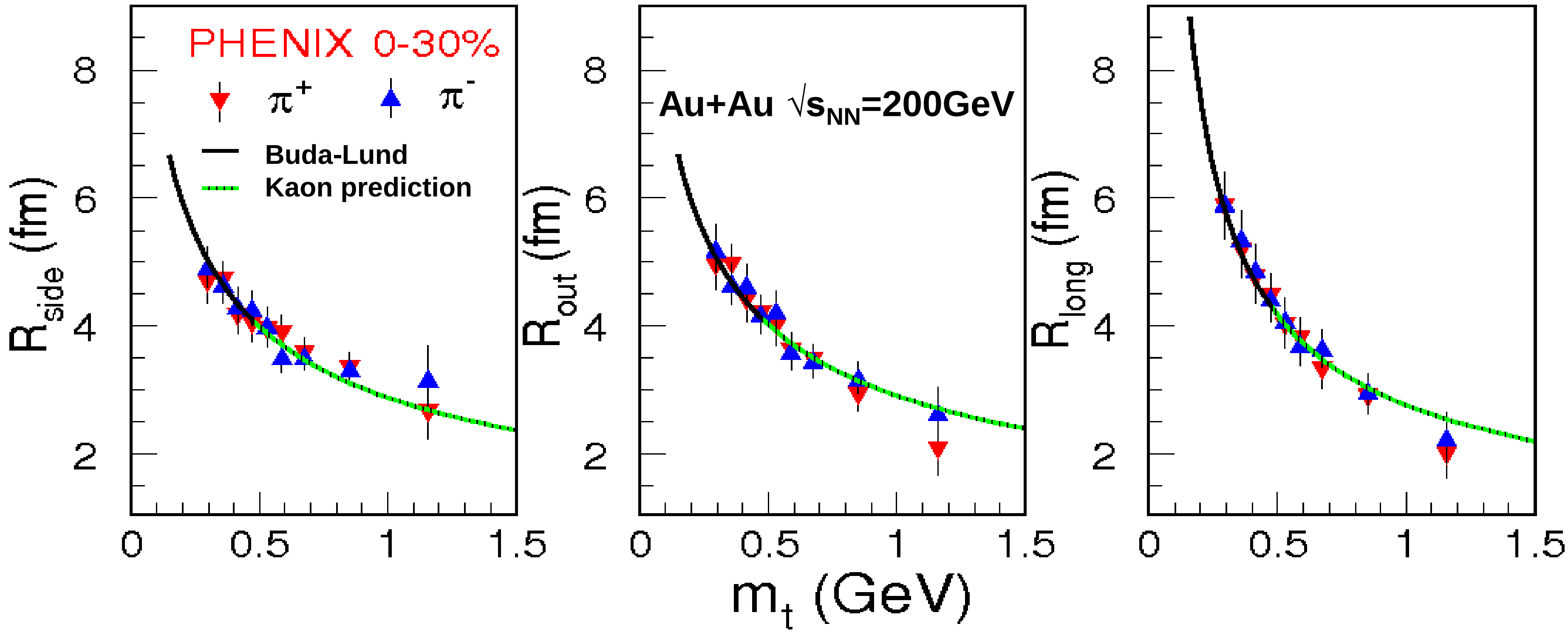
Gets many RHIC observables right



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

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

Radii vs. m_T in perfect hydro



Model: M. Csanád and T. Csörgő: arXiv:0801.0800[nucl-th]
Data: PHENIX, PRL 93, 152302 (2004)

- Excellent description of PHENIX charged pion data
- Inherent m_T-scaling predicts the same dependence for Kaons

Buda-Lund model

- Perfect hydrodinamics
- Analitic solutions fitted to the data
- Extremely powerful: SPS to RHIC, η distributions, HBT radii vs. azimuth, flow etc.

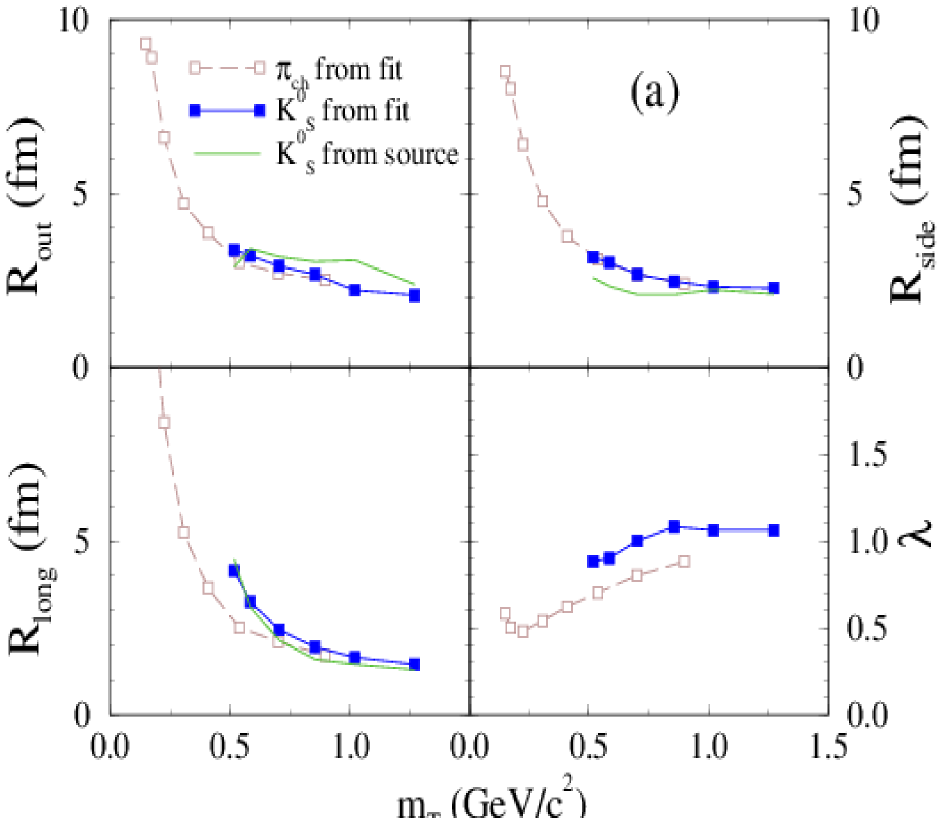
Csörgő, Lörstad, Phys. Rev. C54, 1390 (1996).

Radii vs. m_T: AMPT prediction

- Larger radii for K^0_s than for charged pions
  - Prediction from 2003
  - *Note*: similar radii expected for K^0_S as for K^{+-}
- Radii from source ~ from fit
  - Less non-Gaussianity for K^0_S than for pions

A Multi-Phase Transport Model

- Initial conditions from HIJING
- Parton cascade (ZPC)
- Lund fragmentation
- Relativistic transport (ART) for hadron scattering

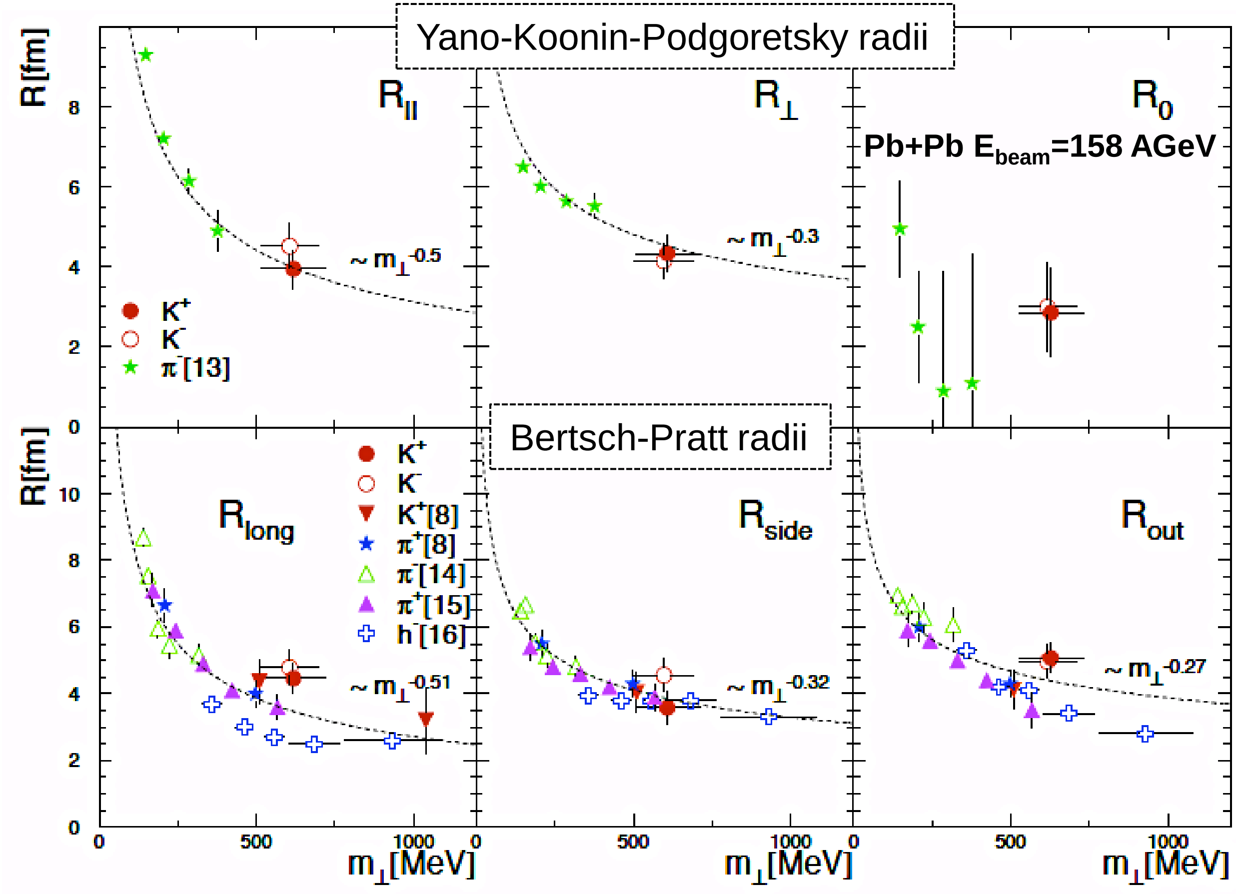


Lin, Ko, J.Phys. G30 (2004) S263 [nucl-th/0305069]

Radii vs. m_T: SPS data

- "The kaon radii are fully consistent with pions and the hydrodynamic expansion model. "
- "Pions and kaons seem to decouple simultaneously."

Note:
sizeable uncertainties (horizontal and vertical)

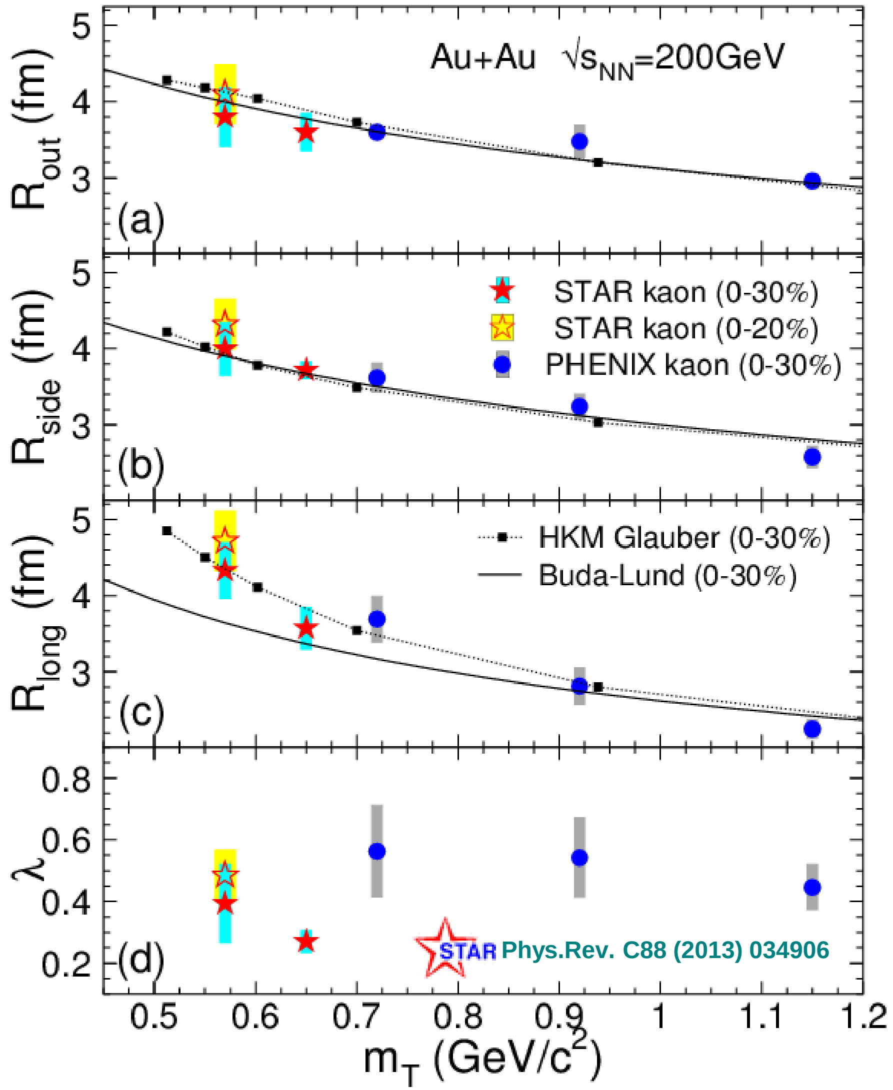


NA49, Phys. Lett B557 (2003) 157

[8] NA44, Phys. Rev. Lett 87 (2001) 112301
[14] WA98, Nucl. Phys. A698 (2002) 647c
[15] NA45, Nucl.Phys. A714 (2003) 124
[16] WA97, J.Phys. G 27 (2001) 2325

Radii vs. m_T: STAR @RHIC

- Radii: rising trend at low m_T
  - Strongest in “long”
- Buda-Lund model
  - 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



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

Summary

STAR performed the first model-independent extraction of kaon 3D images

- in RHIC $\sqrt{s_{NN}}$=200 GeV central Au+Au data
- Contrary to pions, no heavy tail observed in “out”
- Results are consistent with a Gaussian source

The m_T-scaling of HBT radii appears not to be perfect

- The Gaussian radii of Kaons indicate a steeper rise in the “long” direction for low m_T values than expected from pions
- This suggests that kaons and pions decouple differently

Multiple models were compared to the results

- Kaons and pions may be subject to different freeze-out dynamics
- Resonances have to be included for a proper description of data
- Most successful models include rescattering

Thank You!

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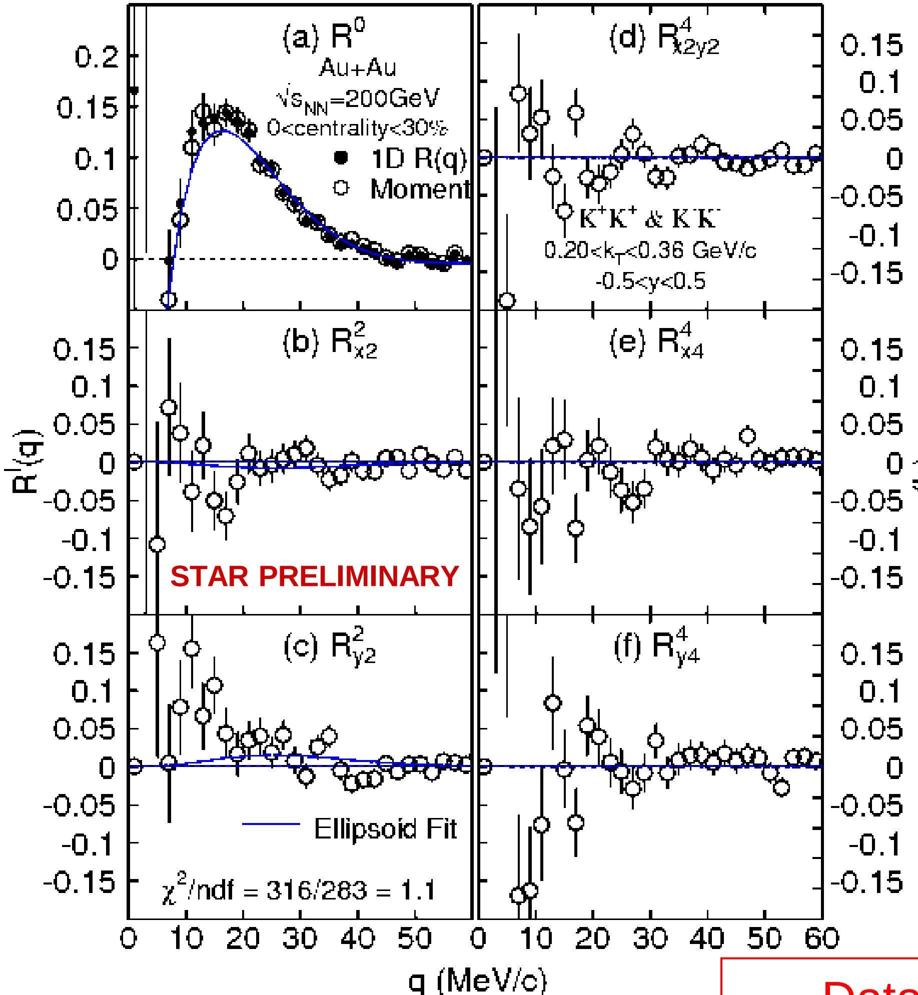
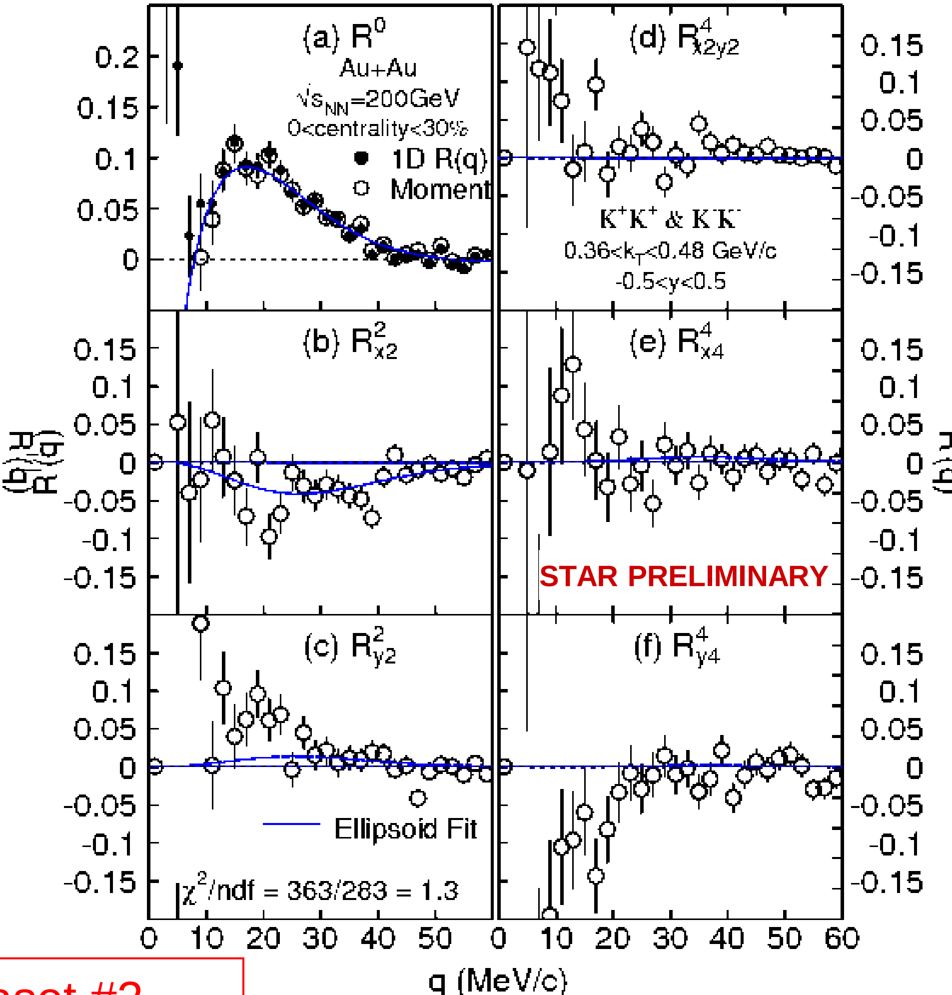
STAR Collaboration

Fit to correlation moments #2

0.2<kT<0.36 GeV/c

0.36<kT<0.48 GeV/c

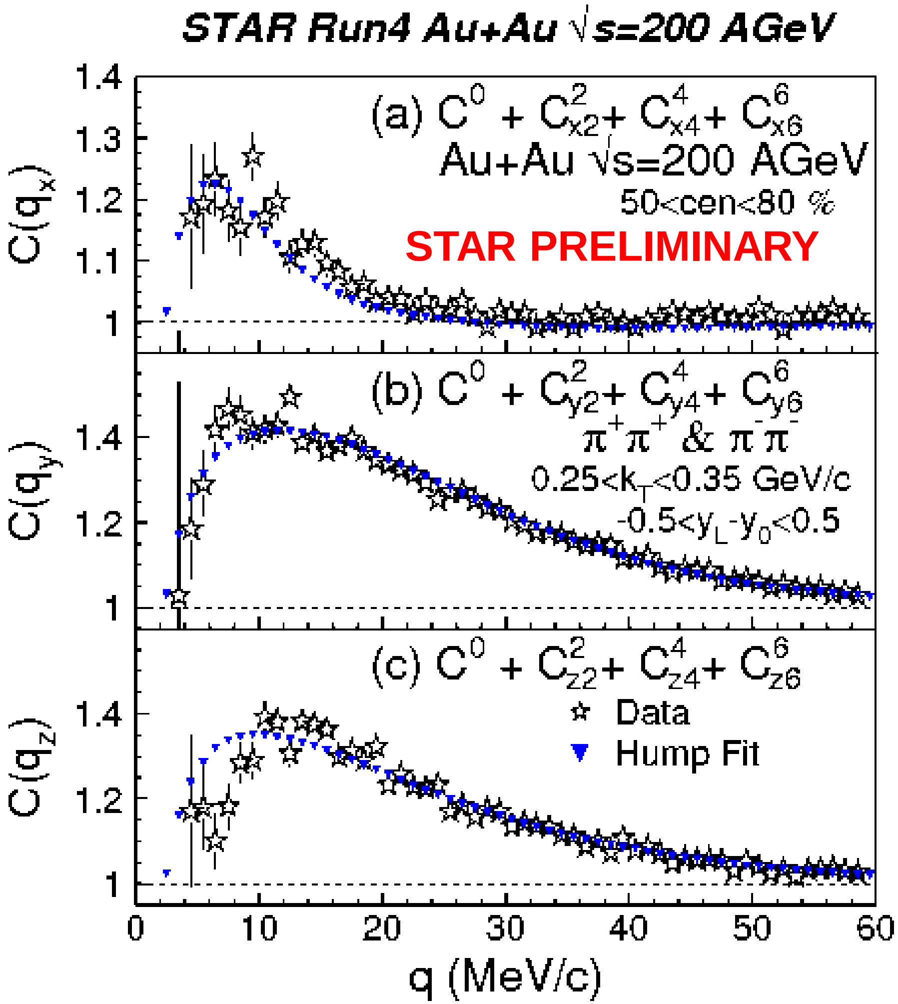


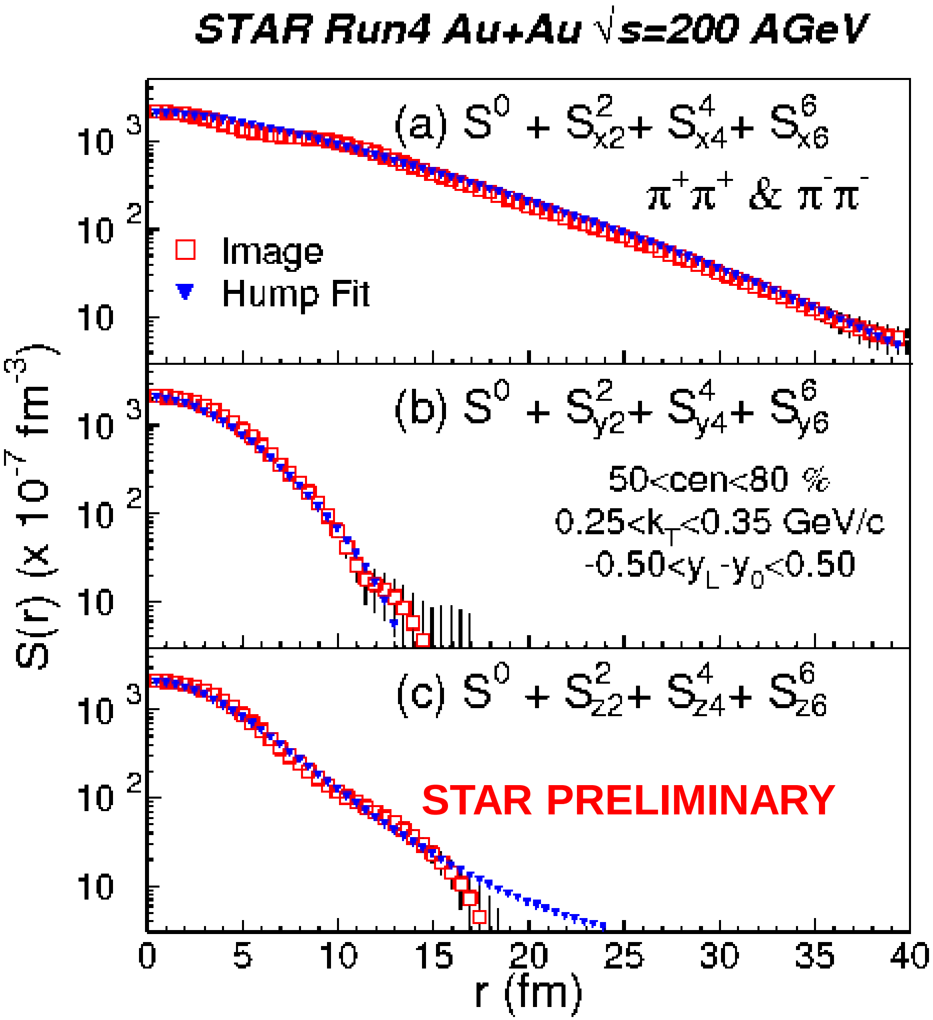


Dataset #2

Run4 Cent<30%

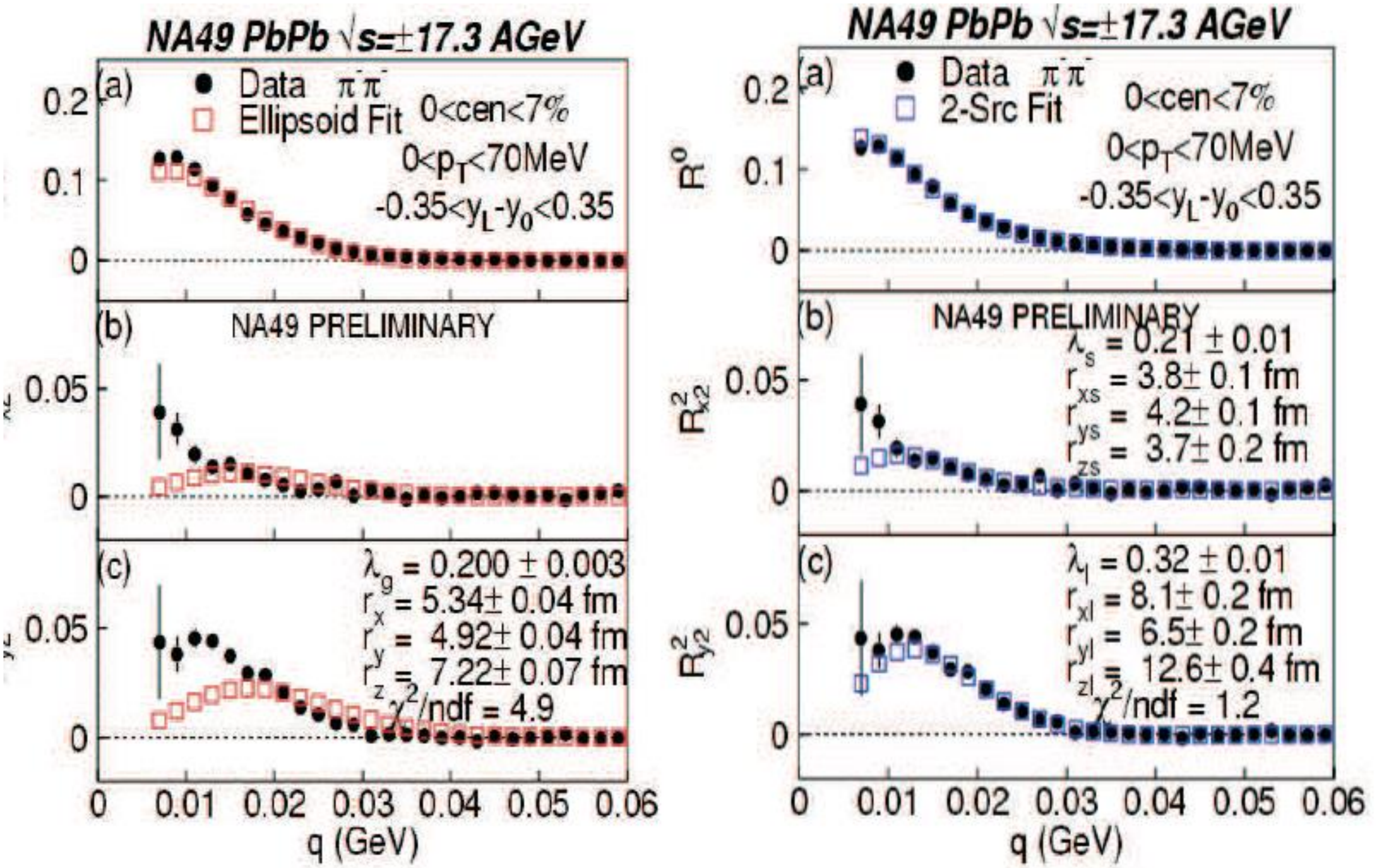
Peripheral pions in STAR



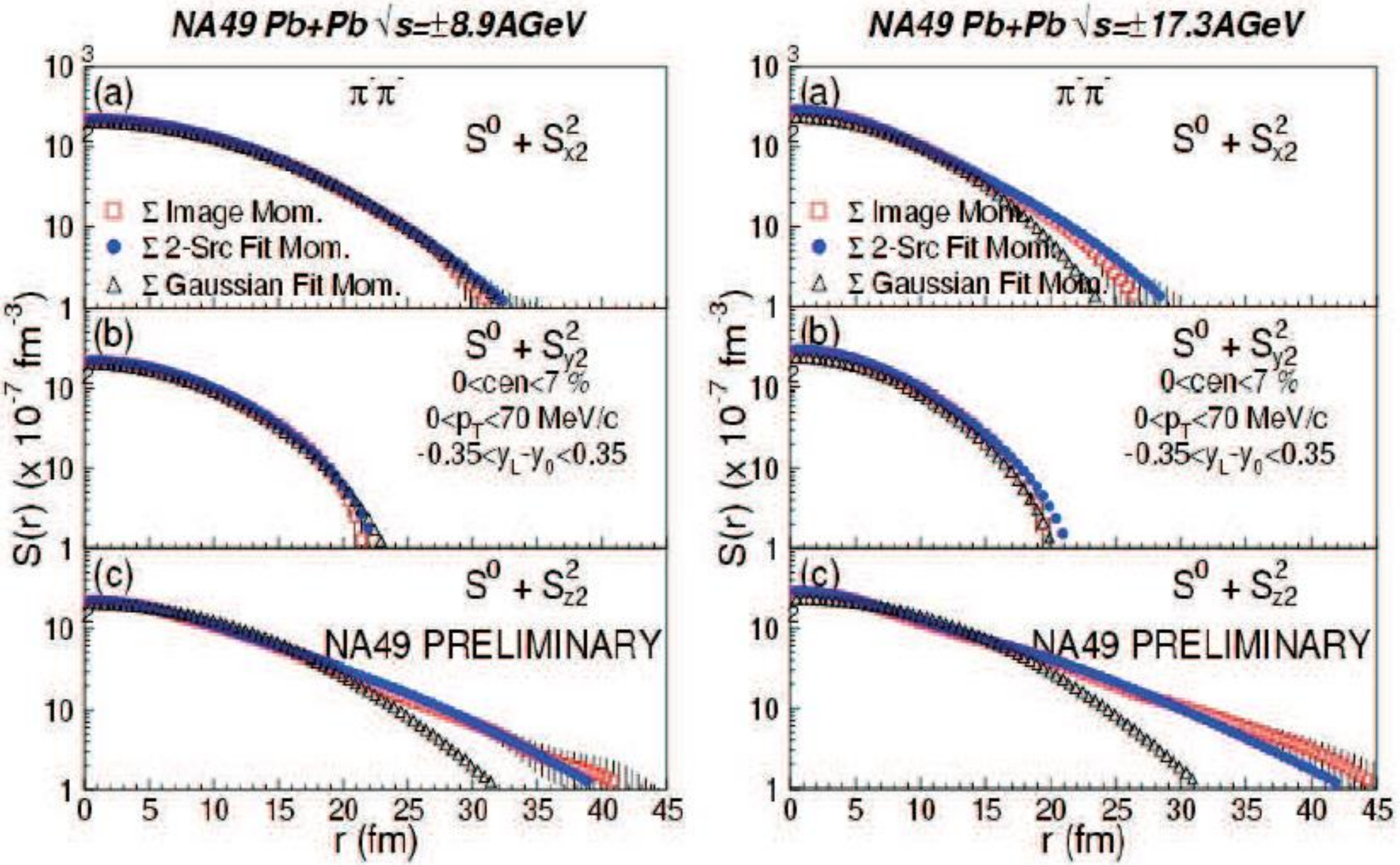


P. Chung (STAR), WPCF 2010

NA49 pions in Pb+Pb - correlation



NA49 pions in Pb+Pb - sources



Rescattering

Hadronic Rescattering Code

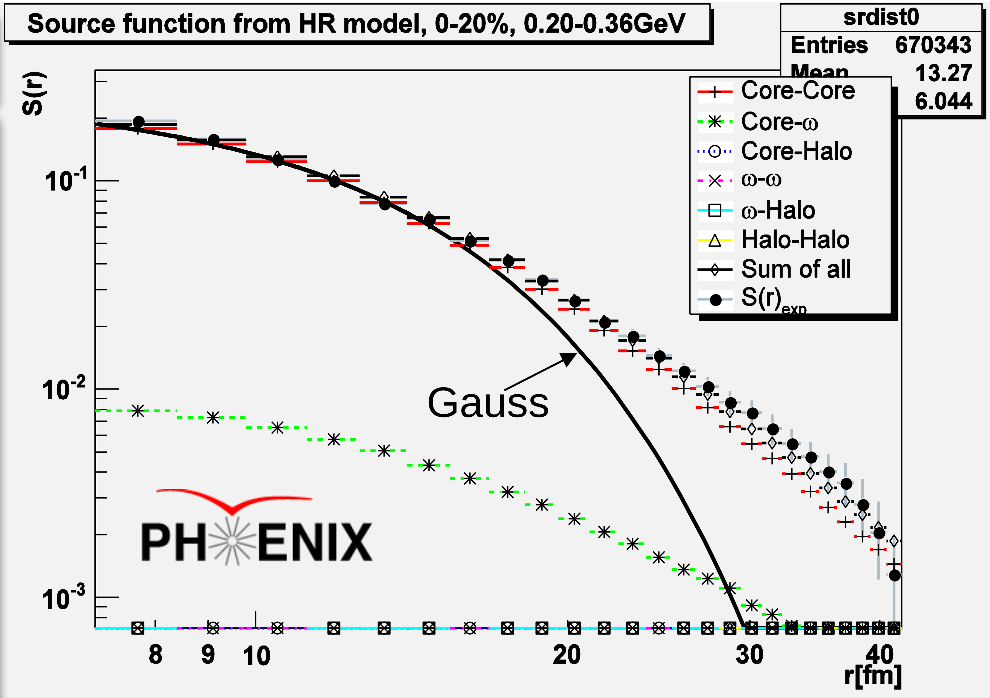
Simple but smart cascade model

- 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.

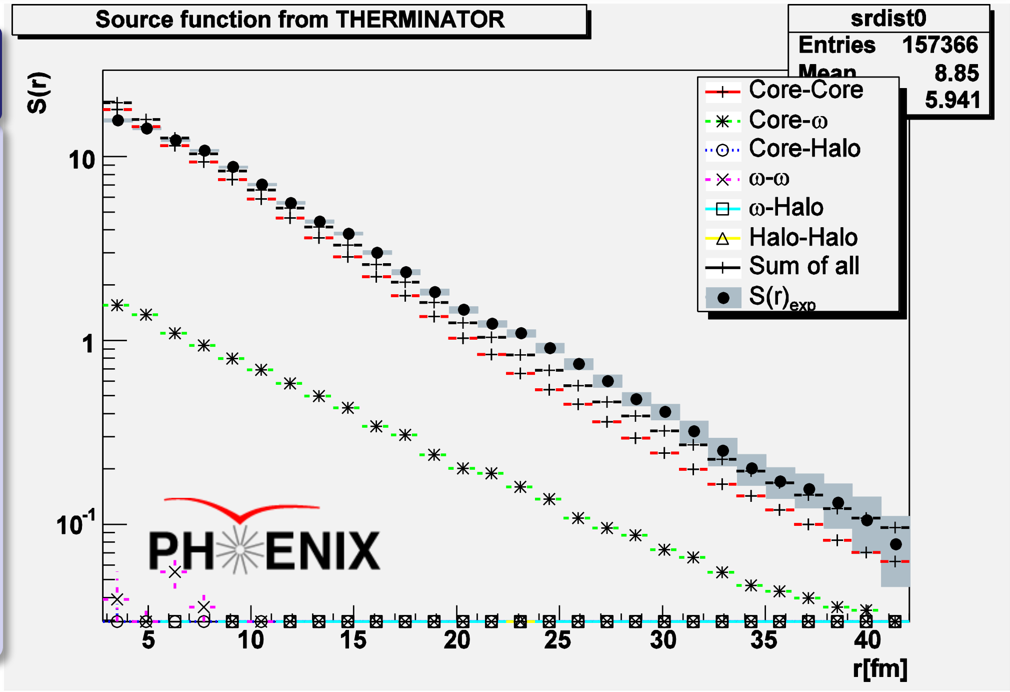
Resonances

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