Kaon femtoscopy at the STAR experiment

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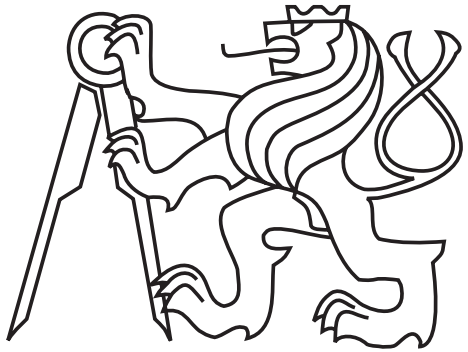
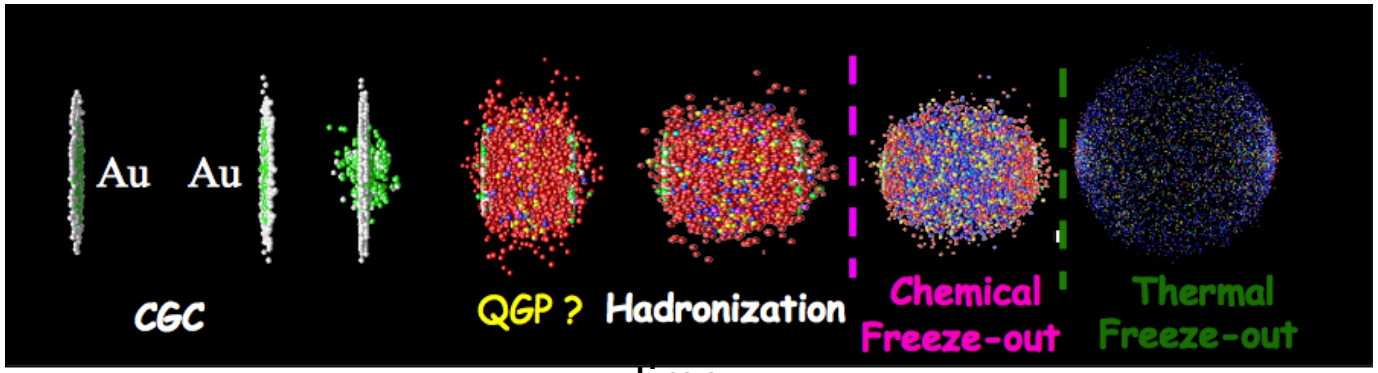
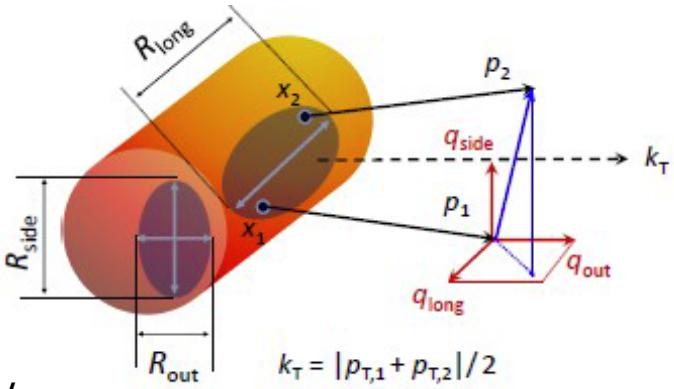
Winter school on heavy ion physics
Budapest, Hungary

5th – 9th December 2016



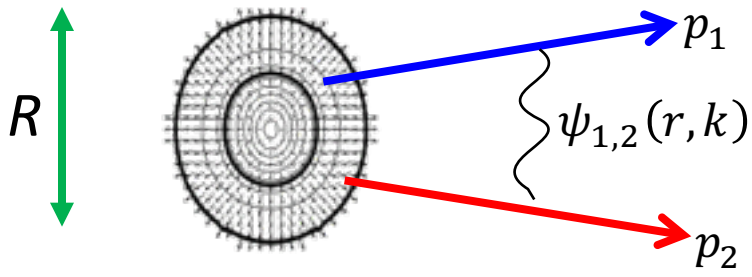
Femtoscopy

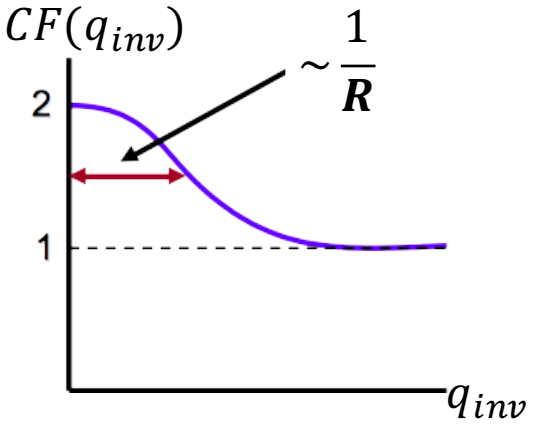




- Study space-time extents of the source at the thermal freeze-out
- Correlation function: $CF(p_1, p_2) = \int d^3r S(r,k) \left|\psi_{1,2}(r,k)\right|^2$

$$r = x_1 - x_2 \quad q_{inv} = p_1 - p_2 = 2k^*$$





Motivations for kaon femtoscopy

In comparison with the most abundant pions, there are following advantages

- Less feed-down – smaller contamination with non-primary kaons from resonance decays
- Smaller cross section – information about a different stage of the collision evolution
- Kaons contain strange quark

However, more difficult due to a factor of 10 smaller statistics

Results can serve as constraints for hydrodynamic models – Are models able to simultaneously describe results from pion and kaon femtoscopy?

Kaon femtoscopy

STAR Experiment is great for such measurements

- Excellent PID and large detector acceptance
- Run 11: 200 GeV Au+Au collisions – one of the largest available dataset
- Different collision energies: 200 GeV + BES (7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 GeV)

This talk will present:

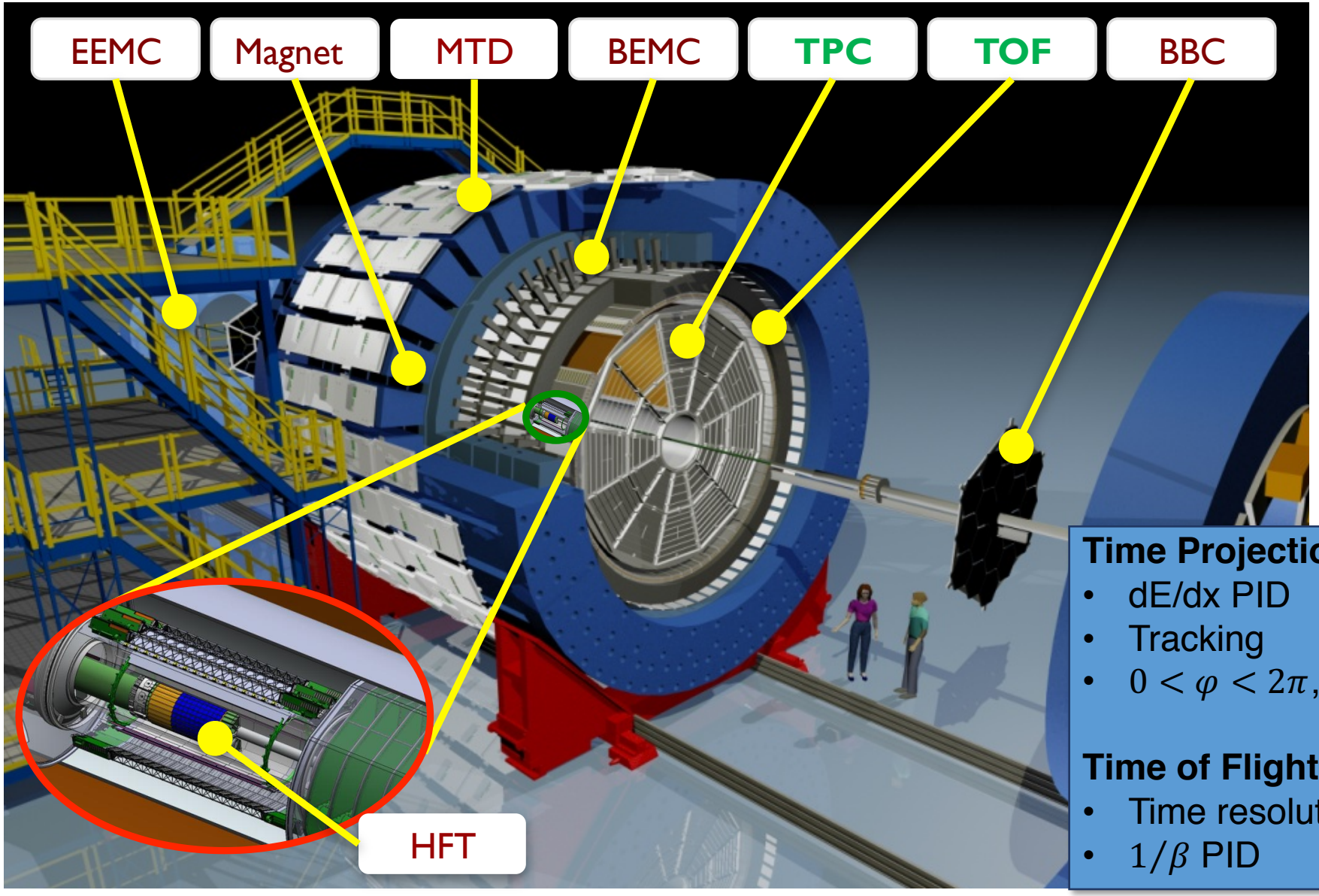
- Results from 200 GeV: $K^{\pm}K^{\pm}$ femtoscopic radii + Blast-wave model
- Study of possible difference between K^+ and K^- source sizes for BES
- $K^{\pm}K^{\pm}$ femtoscopic radii as a function of collision energy
- K^+K^- femtoscopy

Similar study was recently performed by ALICE: Pb+Pb collisions at 2.76 TeV

- 3D $K^{\pm}K^{\pm}$ femtoscopic radii were measured for several centrality and m_T bins
- Observed breaking of approximate "m_T-scaling"

Nucl.Phys. A956 (2016) 373-376

STAR Experiment at RHIC



Time Projection Chamber
- dE/dx PID
- Tracking
- $0 < \varphi < 2\pi$, $|\eta| < 1$

Time of Flight
- Time resolution < 80ps
- $1/\beta$ PID

Extraction of source radii from CF

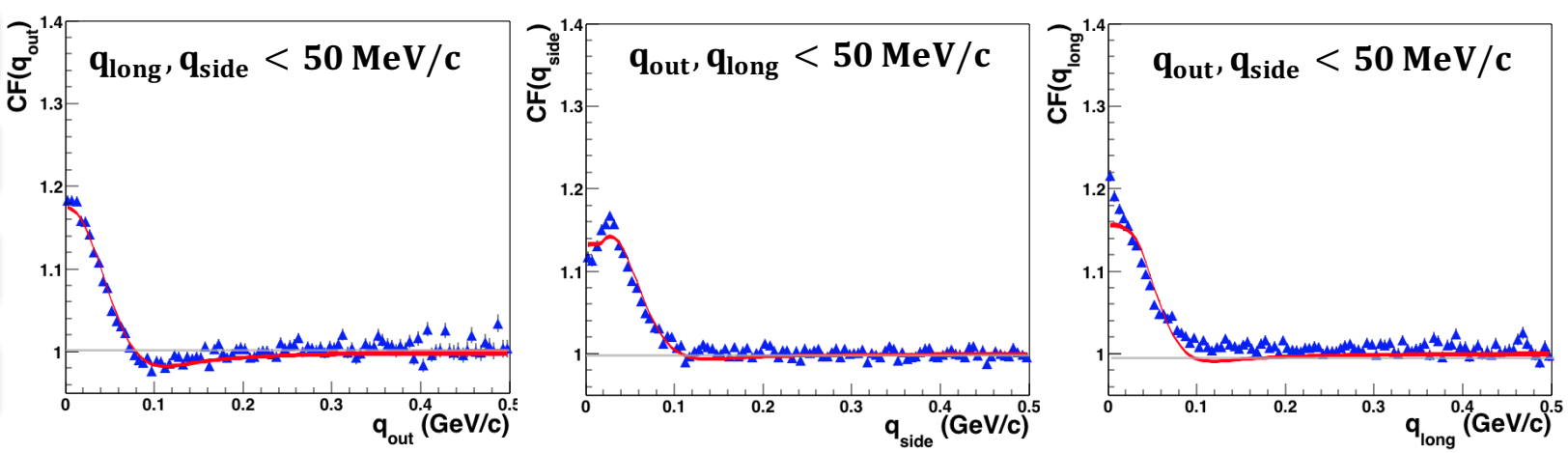
- Used standard Bowler-Sinyukov procedure: *Phys. Lett., B270:69–74, 1991*

1D: $CF(q_{inv}) = \left[(1-\lambda) + \lambda K(q_{inv}, R_{inv})(1+\exp(-q_{inv}^2 R_{inv}^2)\right]\mathcal{N},$

3D: $CF(q_o, q_s, q_l) = \left[(1-\lambda) + \lambda K(q_{inv}, R_{inv})\left(1+\exp\left(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2\right)\right)\right]\mathcal{N},$

- R_{inv}, R_o, R_s, R_l – source radii
- λ parameter – correlation strength
- $\mathcal{N}$ – normalization
- $K(q_{inv}, R_{inv})$ – Coulomb function

- **Fit example:** projection of 3D correlation function
  - data (points) vs the best fit (lines)
  - good agreement with data



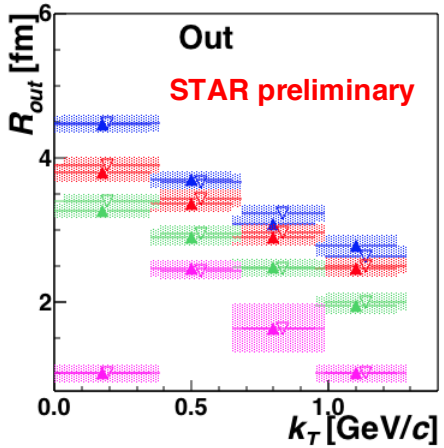
STAR preliminary

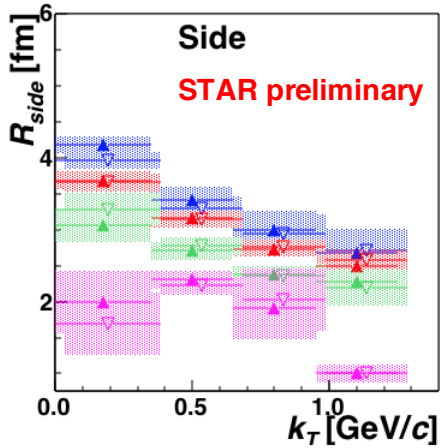
200 GeV K^+K^+

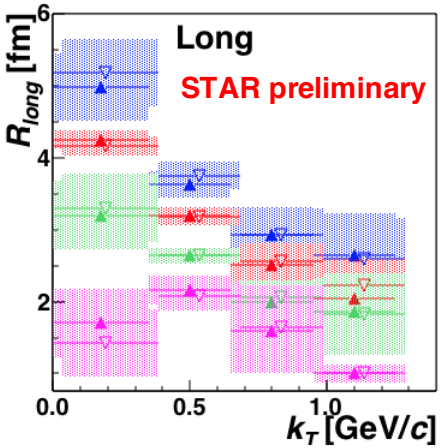
Centrality 0-10%

$0.35 < k_T < 0.65$ GeV/c

Results from 200 GeV: 3D Kaon source radii

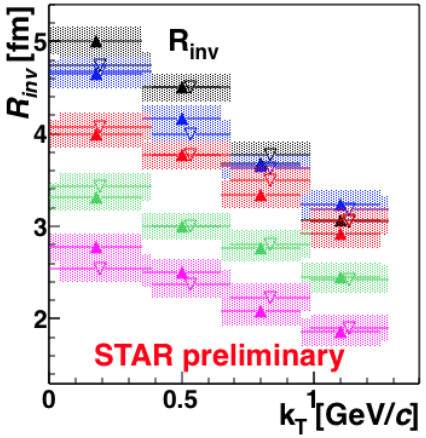






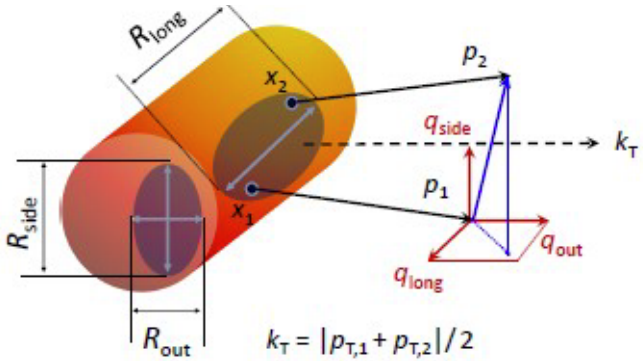
3D Kaon HBT parameters

K^+K^+	K^-K^-
▲ 0-10%	▽ 0-10%
▲ 10-30%	▽ 10-30%
▲ 30-50%	▽ 30-50%
▲ 50-75%	▽ 50-75%



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

K^+K^+	K^-K^-
▲ 0-5%	▽ 0-5%
▲ 5-10%	▽ 5-10%
▲ 10-30%	▽ 10-30%
▲ 30-50%	▽ 30-50%
▲ 50-75%	▽ 50-75%



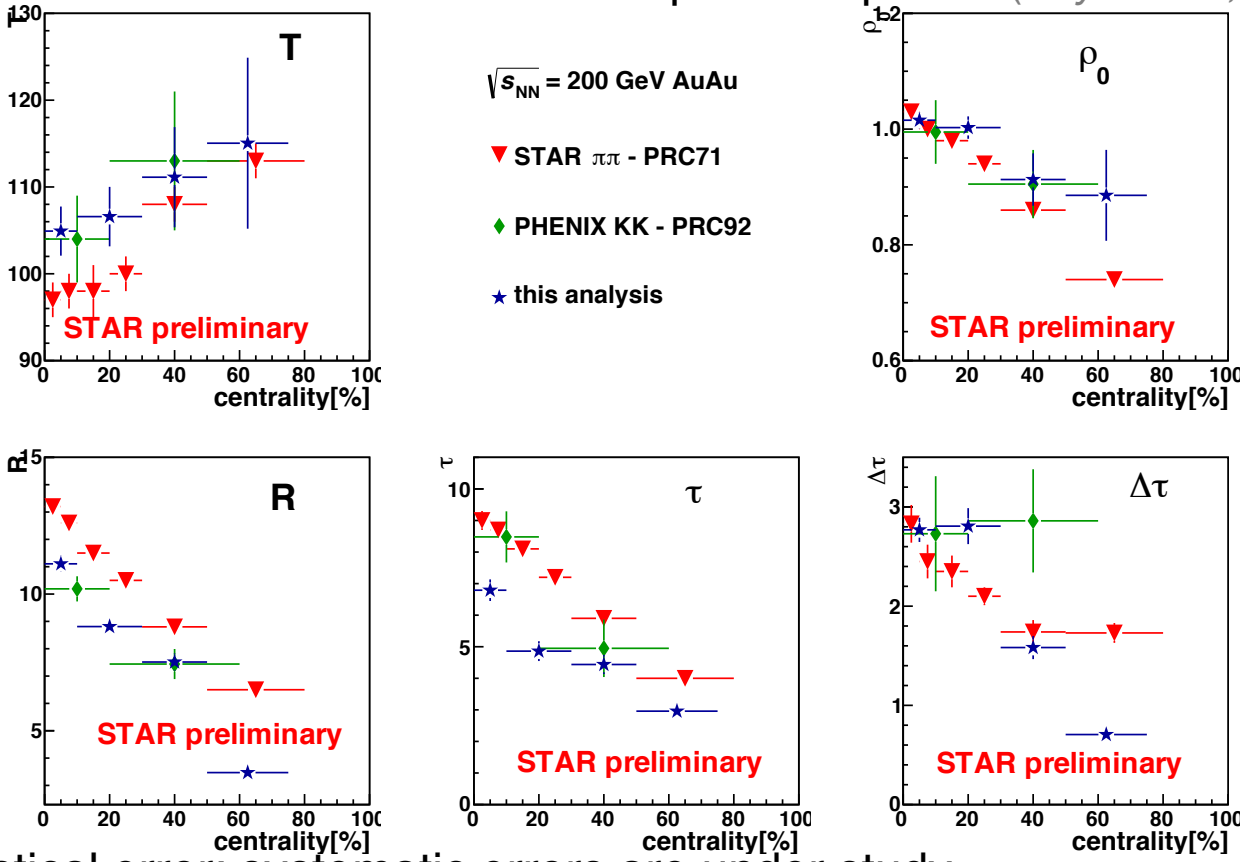
$$k_T = \left(\frac{\overrightarrow{p_1} + \overrightarrow{p_2}}{2}\right)_T$$

- **k_T and centrality dependence of HBT radii is observed**
  - Source radii increase with the centrality and decrease with pair transverse momentum
- 1D & 3D: Uncertainty is dominated by systematic error, which is obtained by varying the fit range

Results – Kaon source radii & Blast-wave model

Phys.Rev., C70:044907, 2004

- Blast-wave parameterization can provide additional insight into the freeze-out configuration
- Simultaneous fit of kaon source radii and particle spectra (*Phys. Rev., C69:034909, 2004*)



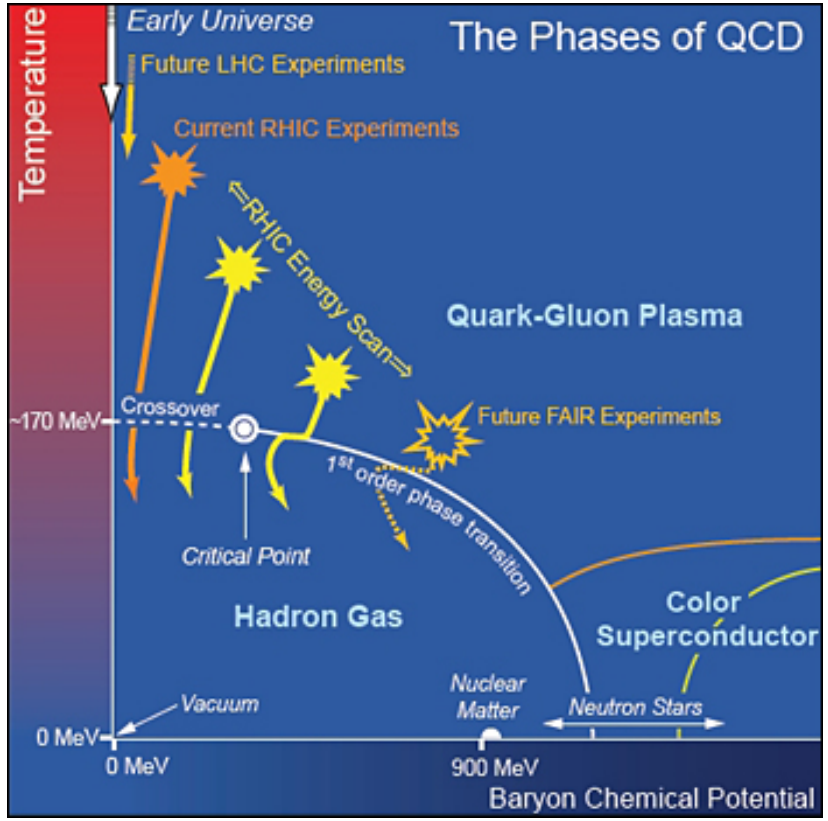
- Only statistical error; systematic errors are under study
- Comparison of PHENIX results with these results – consistent within errors
- Difference between pion and kaon parameters can indicate earlier decoupling of kaons

Kaon femtoscopy for BES

RHIC Beam Energy Scan

- One of the main physics program at the RHIC
- The goal of Beam Energy Scan:
  - Find the QCD critical point
  - 1st order phase transition signs
  - Turn-off sQGP signatures

$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	#Events	#Weeks	Year
200	20	350 M	11	2010
62.4	70	67 M	1.5	2010
39.0	115	130 M	2	2010
27.0	155	70 M	1	2011
19.6	205	36 M	1.5	2011
14.5	260	20 M	3	2014
11.5	315	12 M	2	2010
7.7	420	4 M	4	2010



3D femtoscopic analysis of charged kaons

- Smaller cross section of K^+ - N than K^- - N
- Hence the measured radii for K^+ and K^- can be different due to rescattering in hadronic phase

Spherical harmonics decomposition of CF

- Possible difference is studied via Spherical harmonics decomposition of 3D K^+K^- CF
- SHD of CF is one of the most efficient representation of CF
  - Uses *all* of the data to show the shape of the correlation function
- Harmonic moments:

$$A_{l,m}(Q_{total}) = \frac{1}{\sqrt{4\pi}} \int \mathrm{d}\phi \, \mathrm{d}(\cos\theta) CF(Q_{total}, \theta, \phi) Y_{l,m}(\theta, \phi),$$

where the spherical coordinate are: ϕ, θ and Q_{total}:

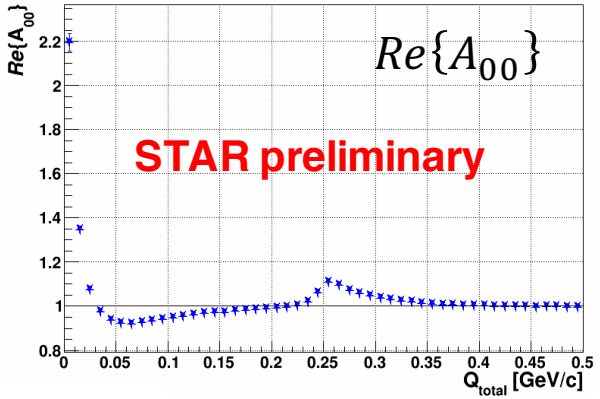
$$q_{OUT} = Q_{total} \sin\theta \cos\phi \qquad q_{SIDE} = Q_{total} \sin\theta \sin\phi \qquad q_{LONG} = Q_{total} \cos\theta$$

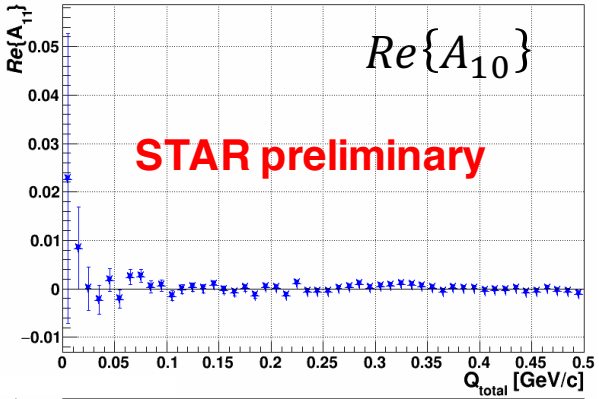
- Then correlation function can be rewritten as

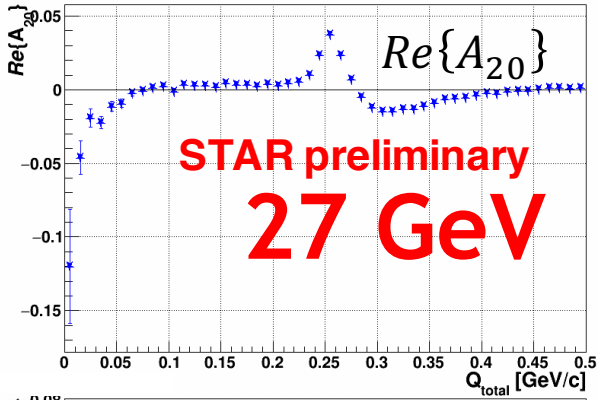
$$CF(Q_{total}, \theta, \phi) = \sqrt{4\pi} \left(\sum_{l=0}^{\infty} \sum_{m=-l}^{l} A_{l,m}(Q_{total}) Y^*_{l,m}(\theta, \phi) \right)$$

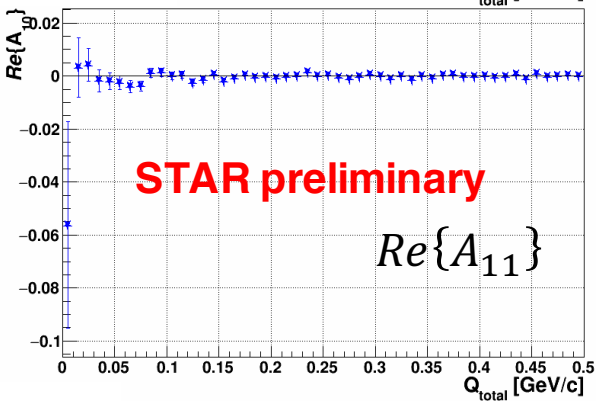
- Instead of $CF(Q_{total}, \theta, \phi)$, we will study harmonic moments $Re\{A_{l,m}(Q_{total})\}$:
  - $Re\{A_{0,0}(Q_{total})\} = 1\mathrm{D}$ CF
  - $Re\{A_{1,0}(Q_{total})\}$ and $Re\{A_{2,1}(Q_{total})\}$ must vanish due to symmetries
  - $Re\{A_{1,1}(Q_{total})\}$ sensitive to asymmetry between particle sources
  - $Re\{A_{2,0}(Q_{total})\}$ and $Re\{A_{2,2}(Q_{total})\}$ contains information about source size

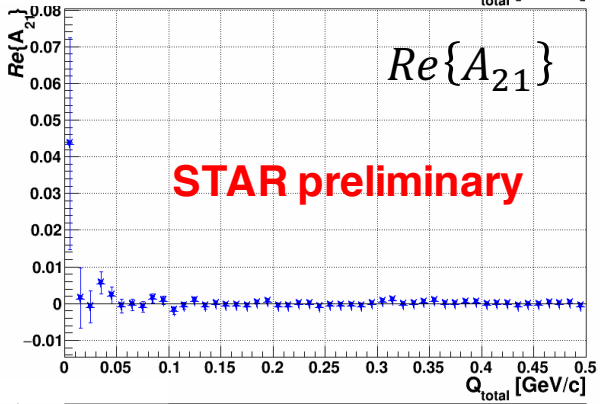
Spherical harmonics decomposition of CF

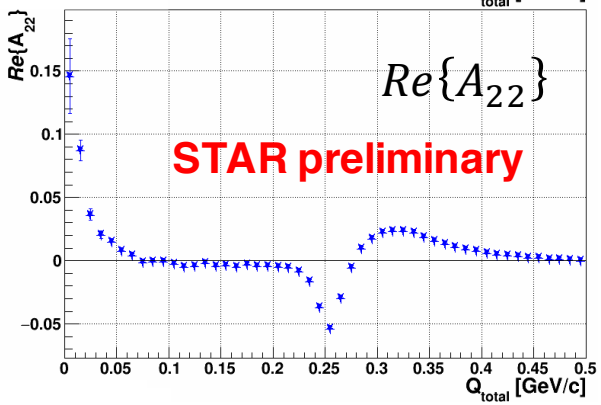










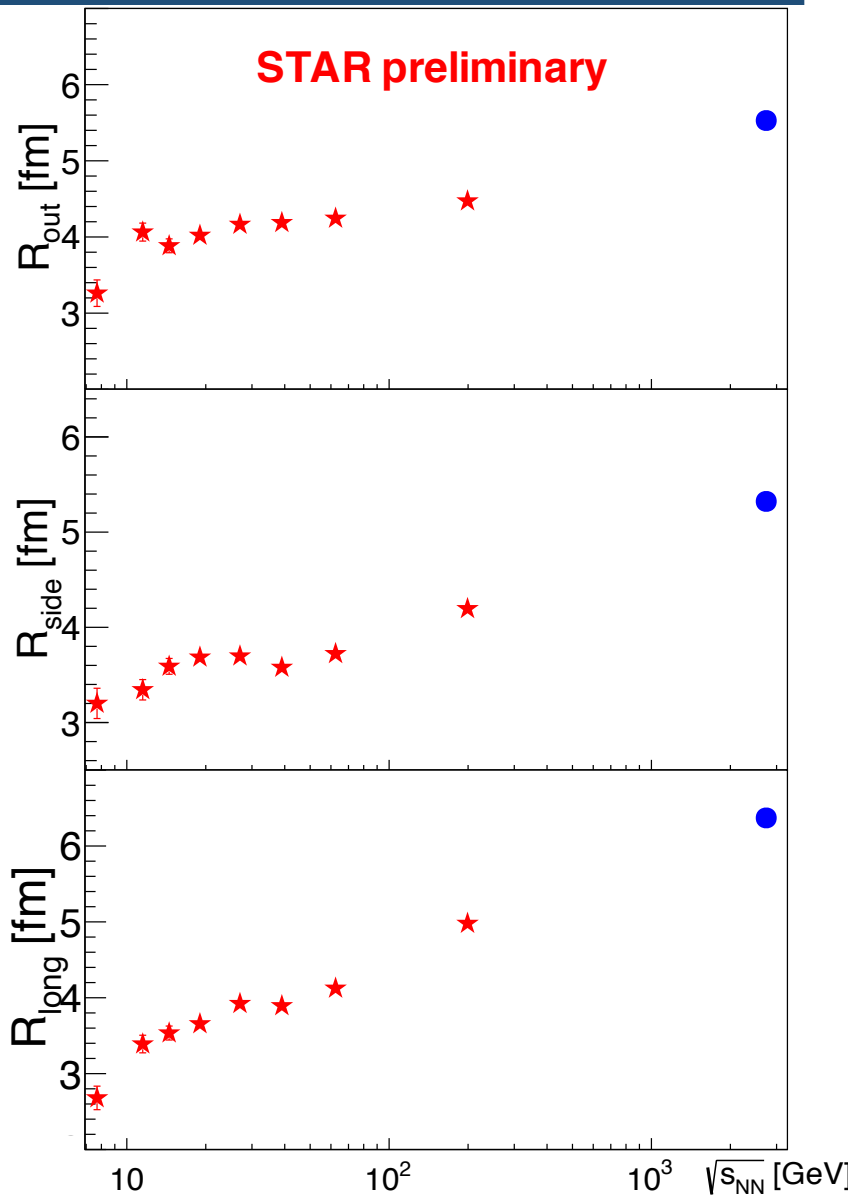


- Example of SHD of CF
- For all BES energies $Re\{A_{1,1}(Q_{total})\}$ vanish within errors
- There isn‘t asymmetry between particle sources -> we can merge K^+K^+ & K^-K^- pairs for BES energies

Energy dependence of kaon source radii

World dataset from kaon femtoscopy

- Results from BES(7.7, 11.5, 14.5, 19.6, 27, 39, 62.5) and results from ALICE *Nucl.Phys. A956 (2016) 373-376*
  - BES: centrality 0-20%, $0.20 < k_T < 0.50$ GeV/c
  - 200 GeV: centrality 0-10%, $0.05 < k_T < 0.35$ GeV/c
  - 2.76 TeV: centrality 0-10%, $< k_T > \sim 0.35$ GeV/c
- Only statistical errors (smaller than point size)
- Kaon source radii increase with increasing collision energy
  - R_{long} increases - longer emission duration
  - R_{side} and R_{out} increases - larger system at the moment of the particles emission
- Similar trends as results from pion femtoscopy



Femtoscopy with unlike-sign kaons

Higher statistics also allow new possibilities:

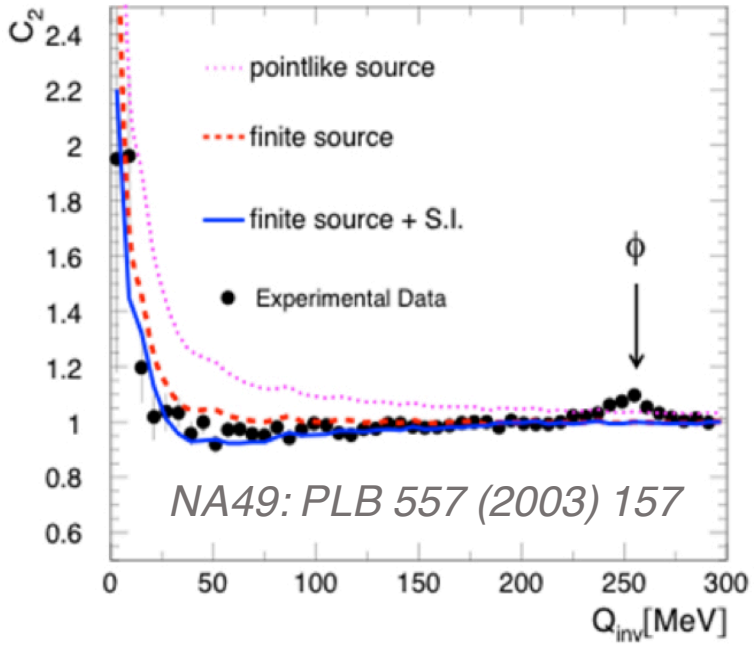
Femtoscopy with narrow resonance

Lednicky: Phys.Part.Nucl. 40 (2009) 307-352
Pratt et al.: PRC 68 (2003) 054901

- Using strong final-state interaction via the resonance decay
  - Predicted to be sensitive to source spatial extent than measurement at low q_{inv}
  - Statistically advantageous
- Challenge - extension of femtoscopic formalism to higher q_{inv}

K^+K^- correlations:

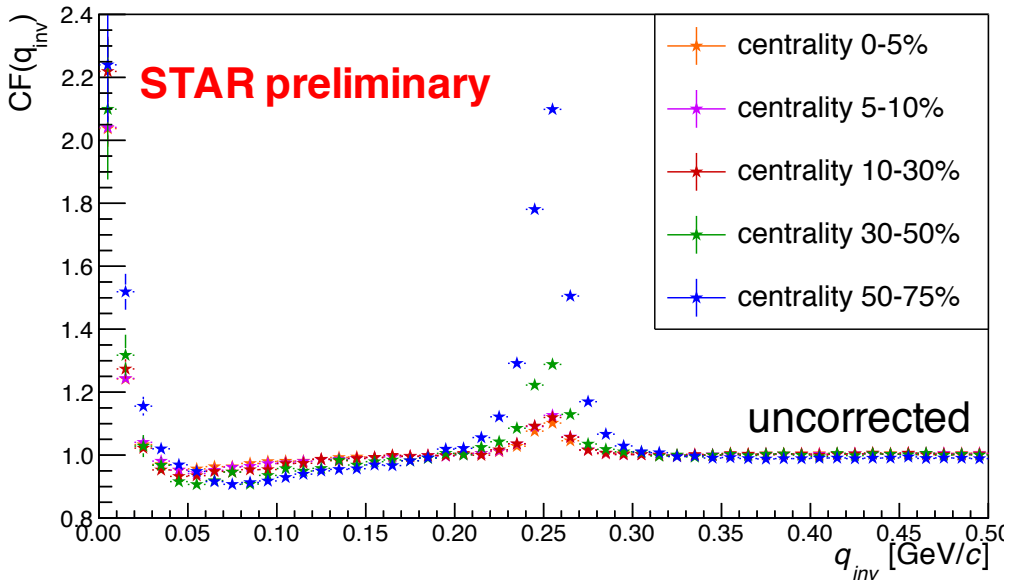
- Coulomb and strong final state interaction
- $\phi(1020)$ resonance
  - $k^* = 126\,\mathrm{MeV}/c$, $\Gamma = 4.3\ \mathrm{MeV}/c^2$
- First systematic study



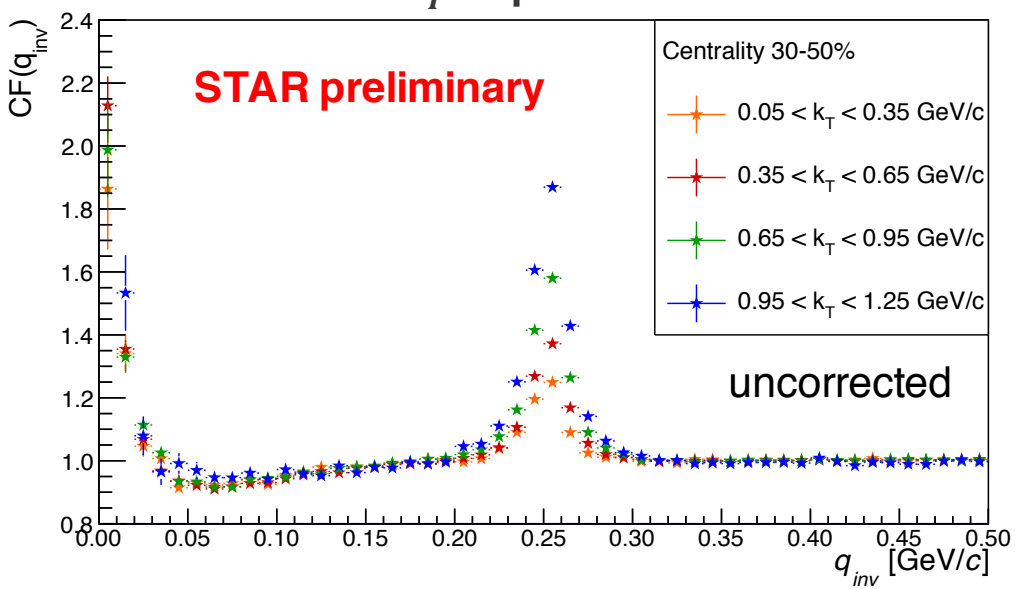
NA49: PLB 557 (2003) 157

Raw unlike-sign kaon correlation functions

Centrality dependence



k_T dependence



200 GeV Au+Au collisions

- CFs are sensitive to the source size
- In particular, **unlike-sign kaon CF is sensitive in the region of the resonance**
- In order to **compare experimental** unlike-sign kaon correlation functions to **theoretical predictions**, **the purity corrections** were done

Comparison of 1D unlike-sign to theoretical model

- Extracted radii from like-sign kaon femtoscopy are used for theoretical calculation of unlike-sign correlation function

- **Gauss + Lednický model of final-state interaction**

  Lednicky: Phys.Part.Nucl. 40 (2009) 307-352

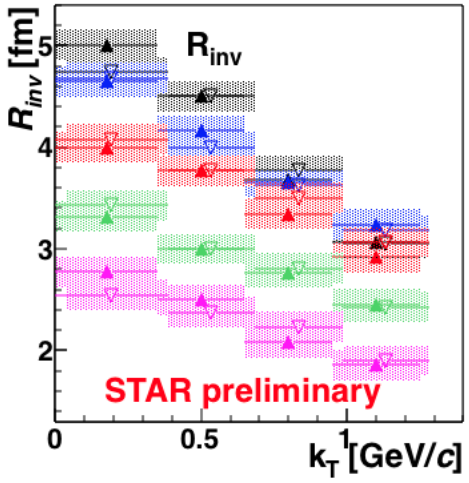
  - Includes $\phi(1020)$ resonance due to the FSI

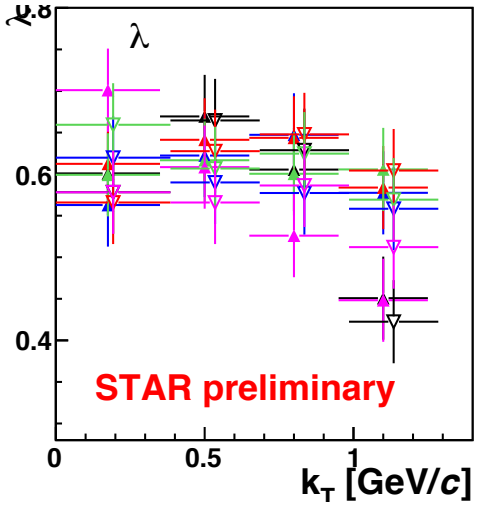
    $$CF(p_1,p_2) = \int d^3r S(r,k)\left|\psi_{1,2}(r,k)\right|^2$$

  - Gaussian parameterization of source size – source size R_{inv} is extracted from the like-sign correlation function fit

  - The theoretical function is transformed to the experimental one via:
    $CF^{exp} = \left(CF^{theo} - 1\right)\lambda + 1$
    in order to compare to an experimental correlation function, which is corrected for impurities

Experimental data for theoretical calculation

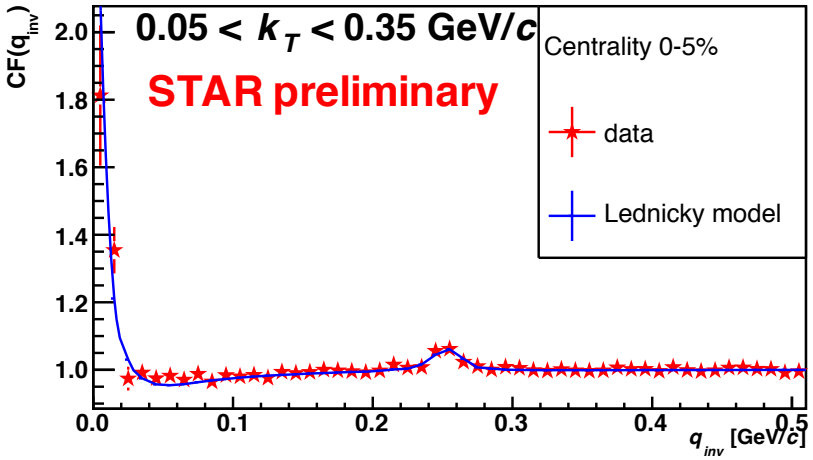


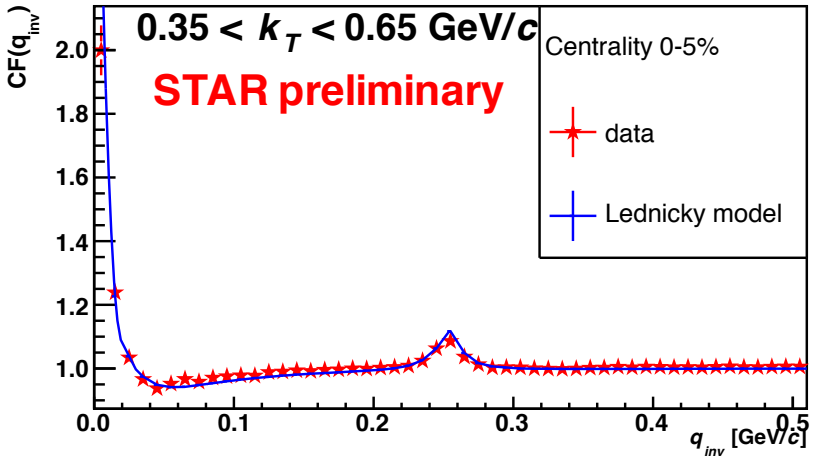


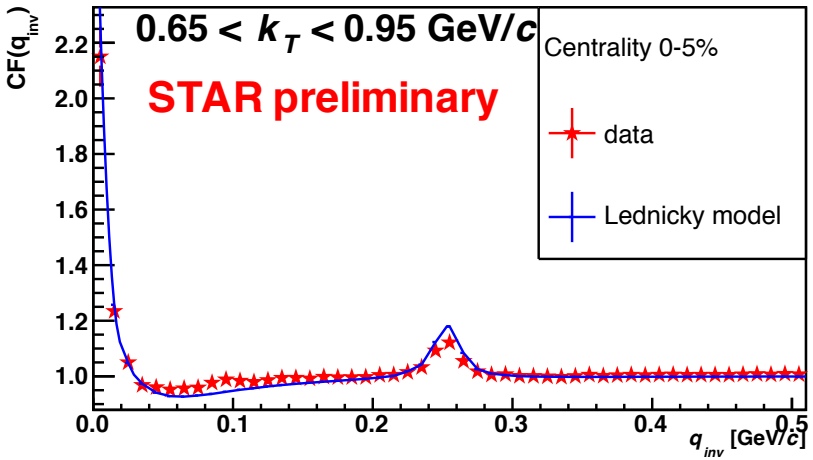
Comparison of 1D unlike-sign to Lednický model

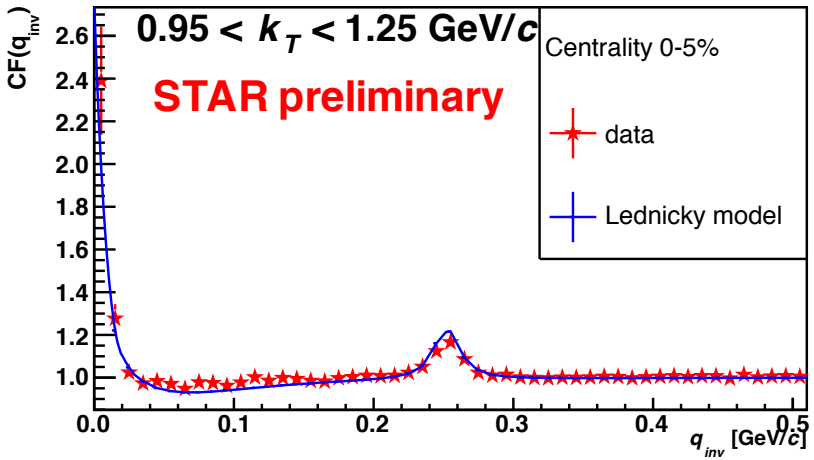
- Lednický model reproduces overall structure of the observed correlation function

Centrality 0-5 %





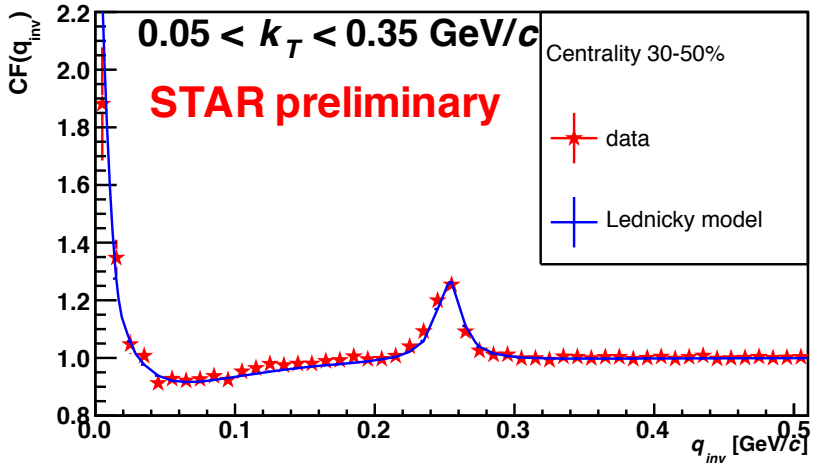


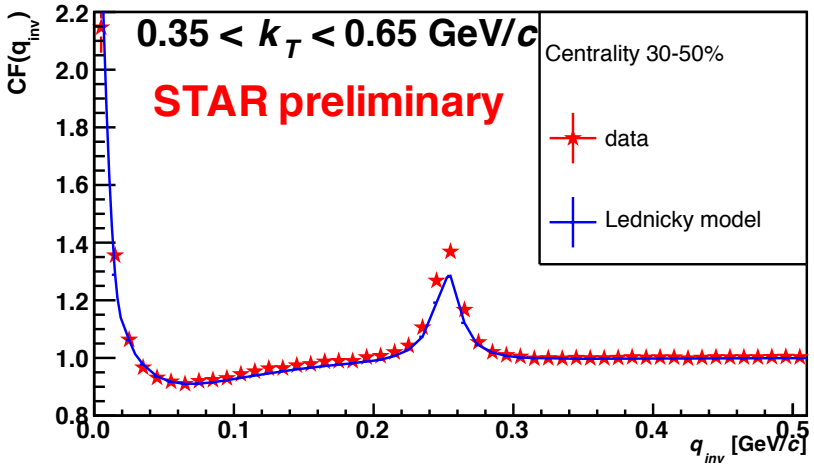


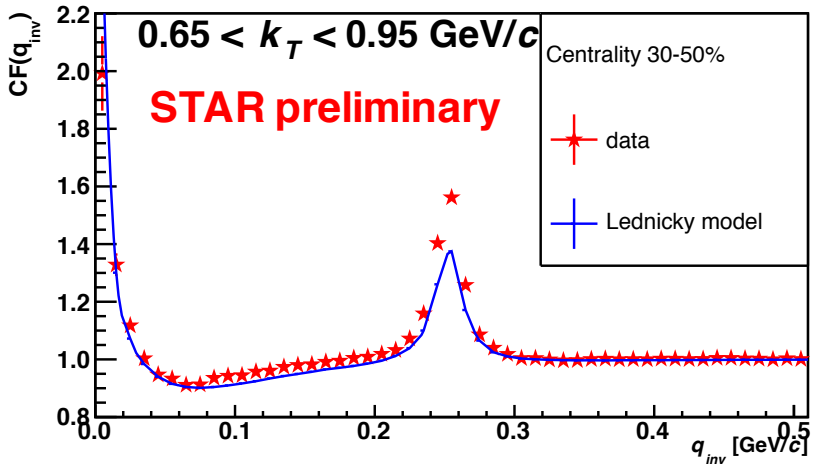
Comparison of 1D unlike-sign to Lednický model

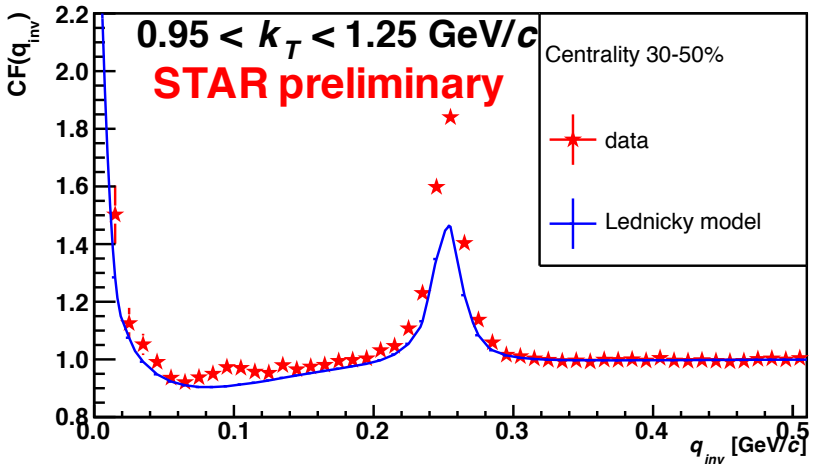
- Model underpredicts the strength of the correlation functions in the region of resonance for smaller source – it can be interpreted as a breakdown of femtoscopic formalism in region of resonance

Centrality 30-50 %









Conclusions & Outlook

Measurement of K^+K^+ & K^-K^- correlations in Au+Au collisions at 200 GeV

- Used data from Run 11 – one of the largest data set
- Extraction of source radii R_{out}, R_{side} and R_{long} from 3D CF
- Typical centrality and k_T dependence
- Source radii used for Blast-wave model to extract freeze-out configuration
  - Results show difference between pion and kaon parameters

Measurement of K^+K^+ & K^-K^- correlations in Au+Au collisions for BES

- No difference between K^+ and K^- source radii
- Extraction of source radii R_{out}, R_{side} and R_{long} from 3D CF
- Energy dependence of source radii

Measurement of K^+K^- correlations in Au+Au collisions at 200 GeV

- Strong centrality and k_T dependence in $\phi(1020)$ region

Outlook

- Comparison with pion femtoscopy
- Hydrodynamic model comparison

The End

Thank you for your attention