STAR Femtoscopy

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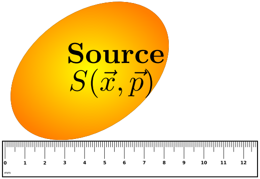
Femtoscopy

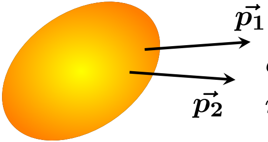


Impossible to examine the particle
emitting source directly

size $\sim 10^{-15}$ m
lifetime $\sim 10^{-23}$ s

Femtoscopy measures space-time characteristics
of the source through momentum correlations

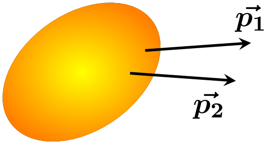
Femtoscopy



$$\vec{q} = \Delta\vec{p}$$

$$\vec{r} = \Delta\vec{x}$$

Femtoscopy



$$\vec{q} = \Delta\vec{p}$$
$$\vec{r} = \Delta\vec{x}$$

$$C(\vec{p}_1, \vec{p}_2) = \frac{P_{12}(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p_1})P'_1(\vec{p_2})}$$

experiment

theory (models)

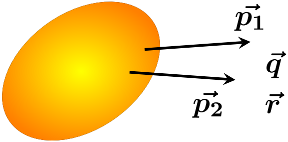
$$C(\vec{q}) = \frac{A(\vec{q})}{B(\vec{q})}$$

$$C(\vec{q}) = \int d^3r S(\vec{q},\vec{r})|\Psi(\vec{q},\vec{r})|^2$$

$A(\vec{q})$ - correlated
$B(\vec{q})$ - uncorrelated

$S(\vec{q},\vec{r})$ - emission function
$\Psi(\vec{q},\vec{r})$ - pair wave function

Femtoscopy



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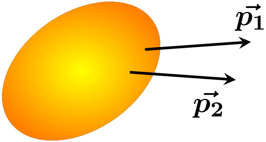

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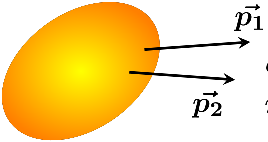

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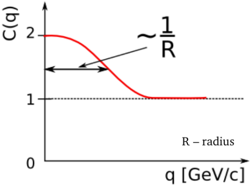
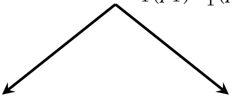


calculate size (R) of the source

$$C(\vec{p}_1, \vec{p}_2) = \frac{P_{12}(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p_1})P'_1(\vec{p_2})}$$



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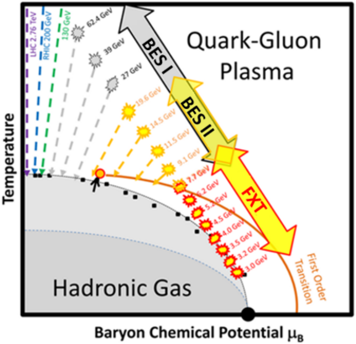
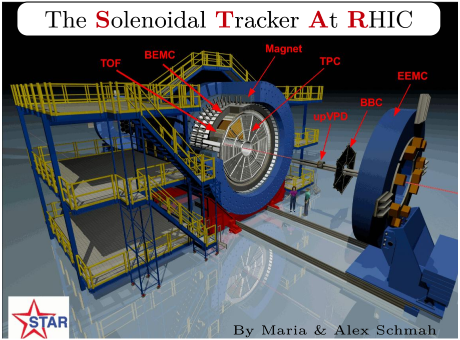
Introduction

- **Kaon femtoscopy (geometry):** provides complementary information to pions
    - less affected by resonance decays
    - contain strange quark
    - heavier than pions
- **Proton femtoscopy (geometry):**
    - provide additional information about source characteristics
- **Non-identical particle femtoscopy (geometry + dynamics):**
    - examination of asymmetry in emission process between two kinds of particles (πK, πp, Kp)



Nucl. Phys. A 967, 808 (2017)

The STAR experiment


The **S**olenoidal **T**racker **A**t **R**HIC

By Maria & Alex Schmah

Time Projection Chamber

PID: dE/dx

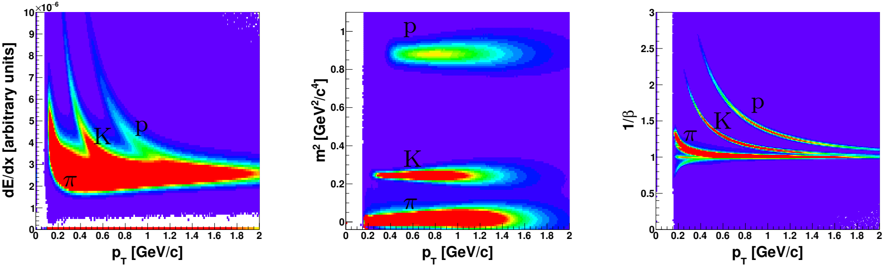
Tracking

$0 < \phi < 2\pi$, $|\eta| < 1$

Time-Of-Flight

Time resolution < 80 ps

PID: m^2 & $1/\beta$

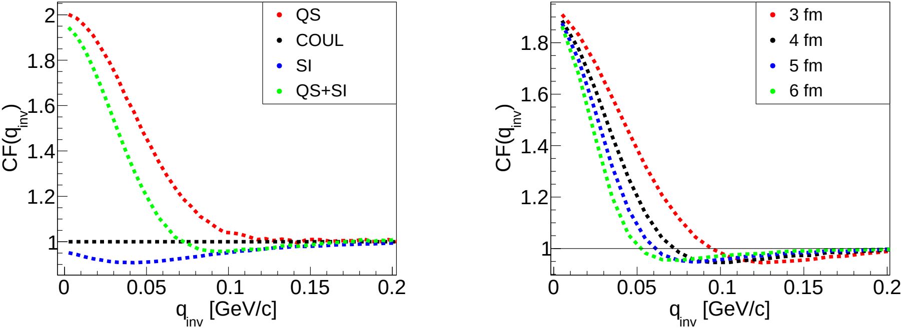


Neutral kaon femtoscopy

Neutral kaon correlation function

The shape of correlation function depends on:

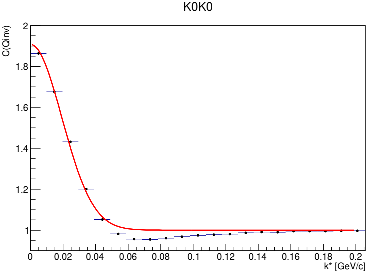
- Quantum Statistical effects (QS)
- Final State Interactions (FSI):
  - ~~Coulomb Interaction (COUL)~~
  - Strong Interaction (SI)



Fitting procedure

The QS correlation function (Gaussian):

$$C(q_{inv}) = 1 + \lambda exp(-R_{inv}^2 q_{inv}^2)$$



λ — the correlation strength

R_{inv} — the size of the particle emitting source

Fitting procedure

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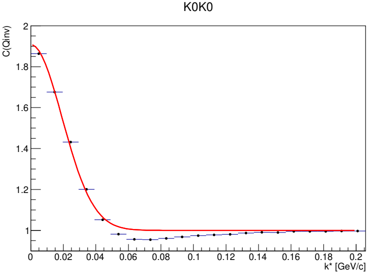
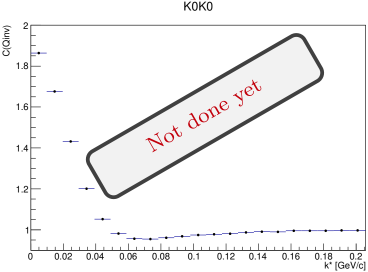
$$C(q_{inv}) = 1 + \lambda exp(-R_{inv}^2 q_{inv}^2)$$

Final State Interaction

Lednicky & Lyuboshitz model:

R. Lednicky and V.L. Lyuboshitz, Sov. J. Nucl. Phys. 35, 770 (1982)



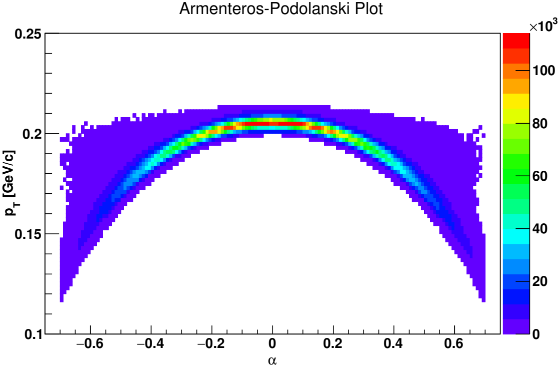


Not done yet

λ — the correlation strength

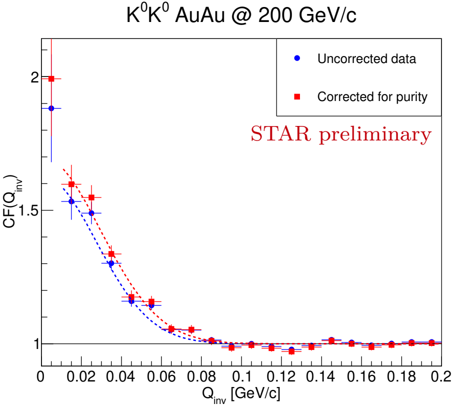
R_{inv} — the size of the particle emitting source

Armenteros-Podolanski plot



signal region is symmetric
other particles, e.g. λ & $\bar{\lambda}$, are not noticeable

K^0K^0 correlation functions, $\sqrt{s_{NN}} = 200$ GeV



Before purity correction

Radius [fm]	λ
5.08 ± 0.19	0.630 ± 0.051

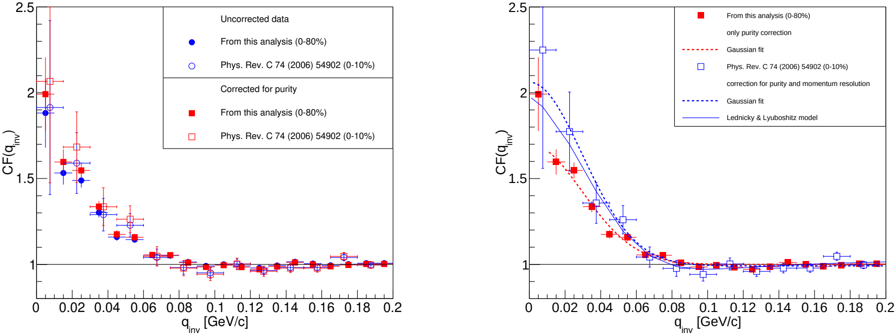
After purity correction

Radius [fm]	λ
4.72 ± 0.20	0.701 ± 0.056

Smaller values of source's radii after corrections (larger statistical uncertainties) and different values of λ parameter (larger for correlations after corrections)

K^0K^0 CFs, $\sqrt{s_{NN}} = 200$ GeV, comparison

Neutral kaon interferometry in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
Phys. Rev. C 74 (2006) 54902



	Radius [fm]
This analysis	4.72 ± 0.20
STAR results	5.02 ± 0.61

$K^0 K^0$ CFs, $\sqrt{s_{NN}} = 200$ GeV, comparison

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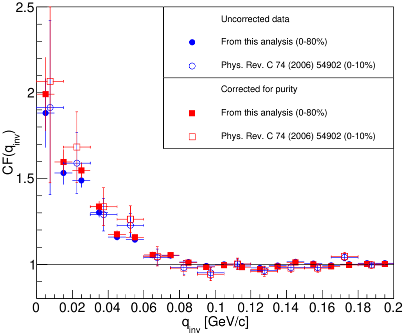
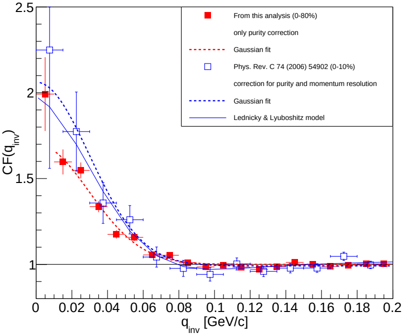
Phys. Rev. C 74 (2006) 54902





- similar source sizes are obtained
- shape of the correlation functions before and after applying purity correction is similar

Neutral kaon femtoscopy — future plan

- Next step:
    - Analysis in centrality bins: central (0-10%) and non-central (10-70%)
- Future plan:
    - Lower BES energies (39 GeV and 54 GeV)
    - Analyze $K^0 K^{ch}$ pairs

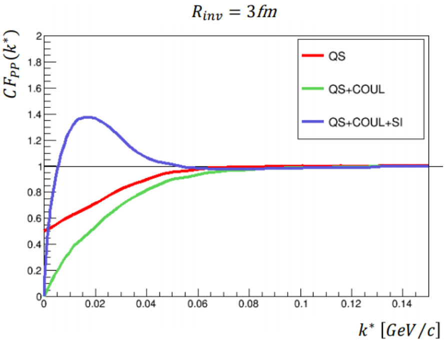
Proton femtoscopy

Proton correlation function

The shape of CF depends on:

proton-proton

- Quantum Statistical effects (QS)
- Final State Interactions (FSI):
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)



proton-antiproton

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- Final State Interactions (FSI):
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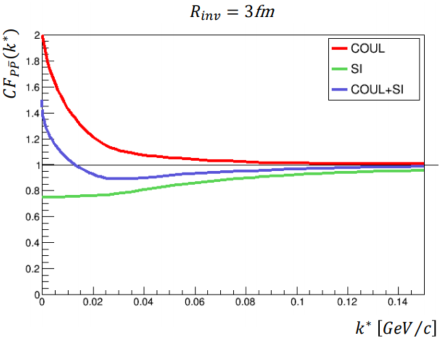
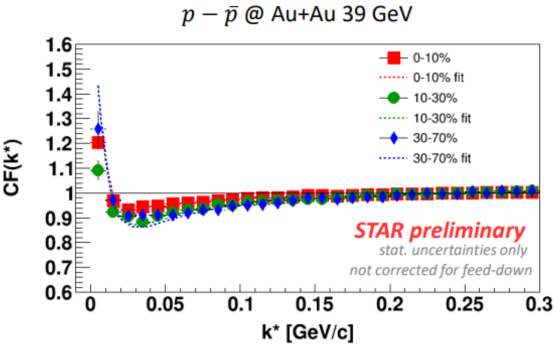


$p\bar{p}$ correlation function



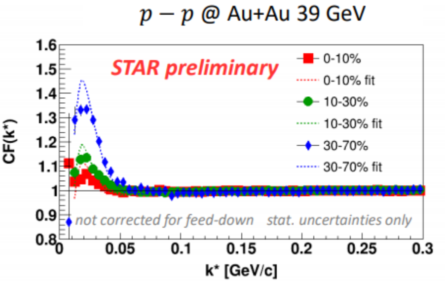
Clear centrality dependence

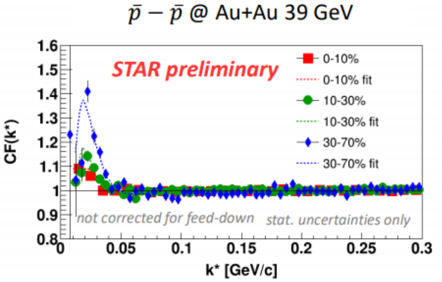
R(0-10%) > R(10-30%) > R(30-70%)

centrality	R_{inv} $p - \bar{p}$ [fm]
0-10%	$3.69 \pm 0.12 \pm 0.14$
10-30%	$2.69 \pm 0.10 \pm 0.12$
30-80%	$2.56 \pm 0.09 \pm 0.12$

QM 2018

$pp/\bar{p}\bar{p}$ correlation function





centrality	R_{inv} $p-p$ [fm]	R_{inv} $\bar{p}-\bar{p}$ [fm]	R_{inv} $p-\bar{p}$ [fm]
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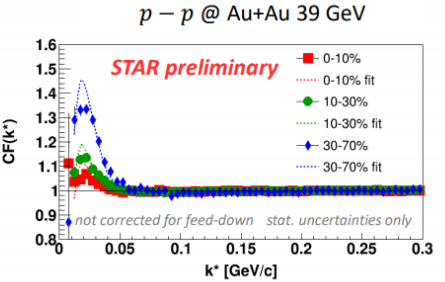
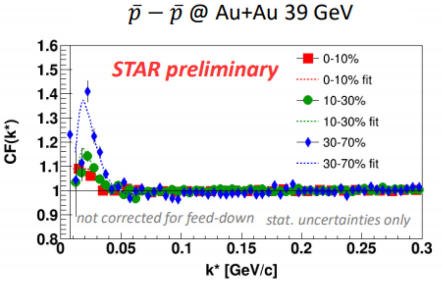
30-80%	$2.72 \pm 0.07 \pm 0.07$	$2.95 \pm 0.11 \pm 0.08$	$2.56 \pm 0.09 \pm 0.12$

No significant difference between $p-p$ and $\bar{p}-\bar{p}$ correlation functions

QM 2018

$pp/\bar{p}\bar{p}$ correlation function


$p-p$ @ Au+Au 39 GeV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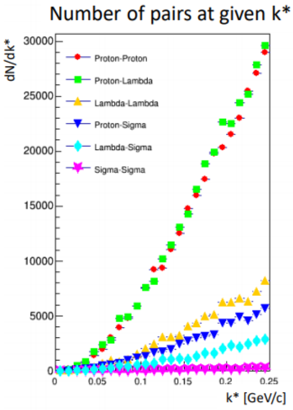
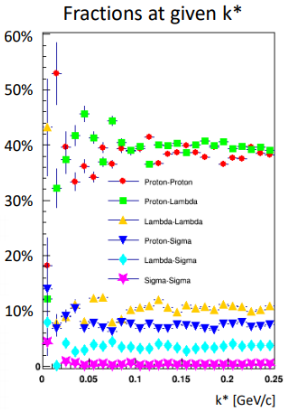
Radii from $p-p$ and $\bar{p}-\bar{p}$ systems differ from radii from $p-\bar{p}$ system → residual correlations contaminate correlation functions

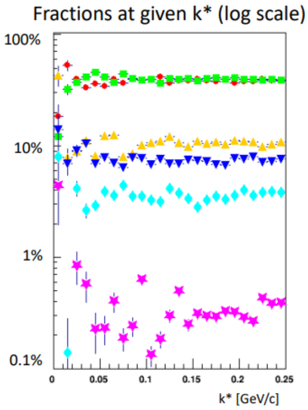
QM 2018

Proton femtoscopy — future plan

- Next step:
  - Correction of residual contamination


Number of pairs at given k*


Fractions at given k*


Fractions at given k* (log scale)

Non-identical particle femtoscopy

Asymmetry

$$C(\vec{q}) = \int |\Psi(\vec{q},\vec{r})|^2 S(\vec{r}) d^3r$$

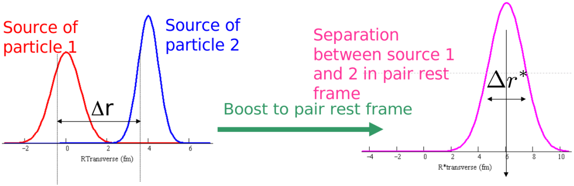
known

unknown

R. Lednicky, et al.
Phys. Lett. B373, 30 (1996)

$$S(\vec{r}) = exp(-\frac{(r_{out}-\mu_{out})^2}{\sigma_{out}^2} - \frac{r_{side}^2}{\sigma_{side}^2} - \frac{r_{long}^2}{\sigma_{long}^2})$$

μ_{out} — asymmetry in the *outward* direction
assumption: $\sigma_{side} = \sigma_{out}$, $\sigma_{long} = 1.3\sigma_{out}$



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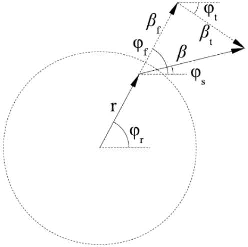


A. Kisiel
Phys. Rev. C81, 064906 (2010)

μ_{out} — asymmetry in the *outward* direction
assumption: $\sigma_{side} = \sigma_{out}$, $\sigma_{long} = 1.3\sigma_{out}$

$$\beta_{particle} = \beta_f + \beta_t$$

β_f — collective (flow) velocity

β_t — thermal (random) velocity

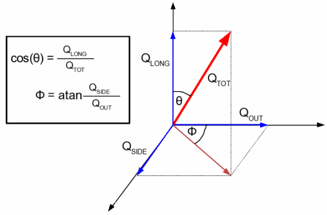
Emission asymmetry arises in a system where both thermal and collective velocities exist and are comparable in magnitude

Spherical harmonics (SH)

SH representation of 3D correlation function as a set of 1D plots

$$C(\mathbf{q}) = \sum_{l,m} C_l^m(q) Y_l^m(\theta, \phi) \qquad C_l^m(q) = \int_\Omega C(q, \theta, \phi) Y_l^m(\theta, \phi) d\Omega$$

Ω - full solid angle
$Y_l^m(\theta, \phi)$ - spherical harmonic function
$q = |\mathbf{q}|$ - pair relative momentum
θ and ϕ - polar and azimuthal angle



P. Danielewicz and S. Pratt.
Phys. Lett B618, 60 (2005)
Phys. Rev. C75, 034907 (2007)

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Ω - full solid angle
$Y_l^m(\theta, \phi)$ - spherical harmonic function
$q = |\mathbf{q}|$ - pair relative momentum
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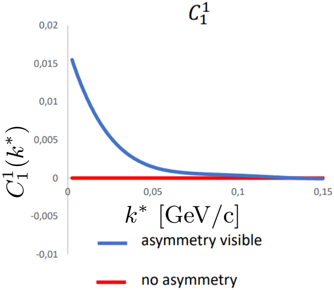
$C_0^0 \rightarrow$ sensitive to the size of the emitting source (shapes same as correlation function)

$C_1^1 \rightarrow$ sensitive to the spacetime emission asymmetry



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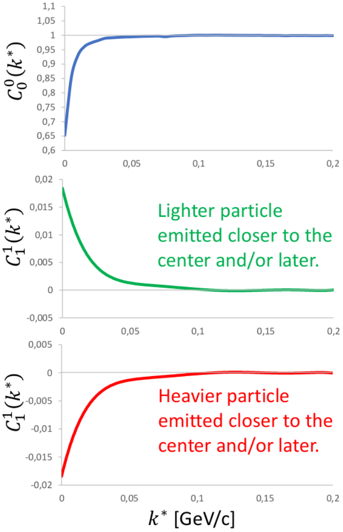
Which particle...?

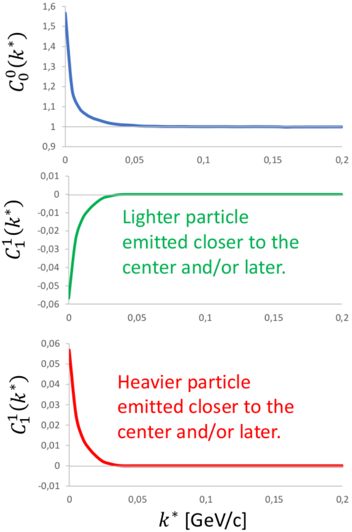
Like-sign particle combinations



Lighter particle emitted closer to the center and/or later.

Heavier particle emitted closer to the center and/or later.

Unlike-sign particle combinations



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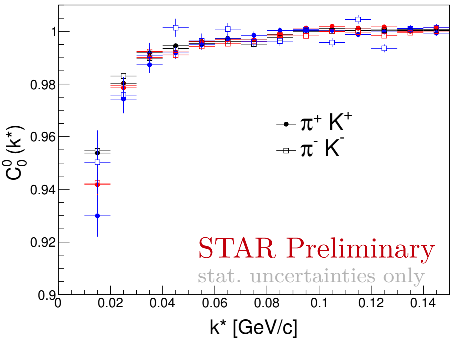
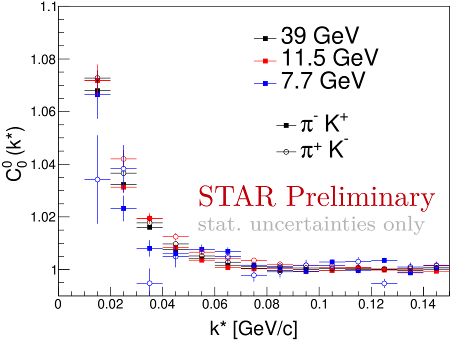
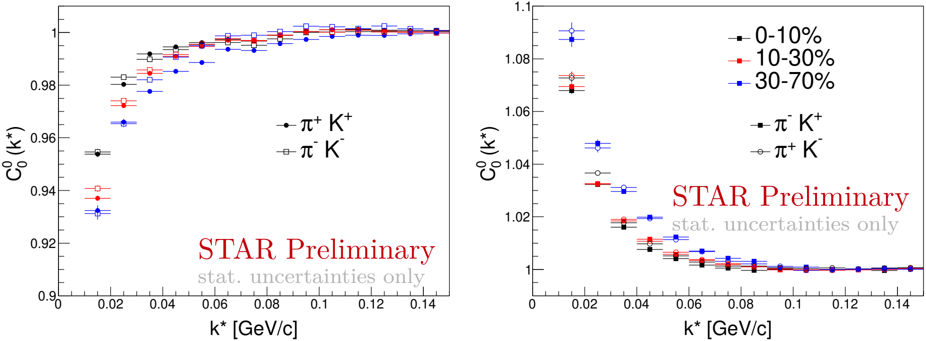
Energy dependence





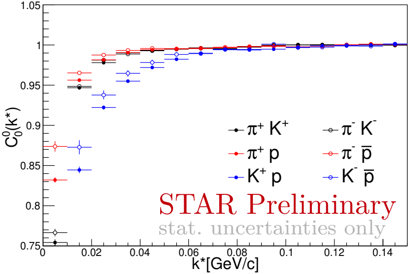
- Visible energy dependence
- Higher statistics for low energies are needed (BES-II)

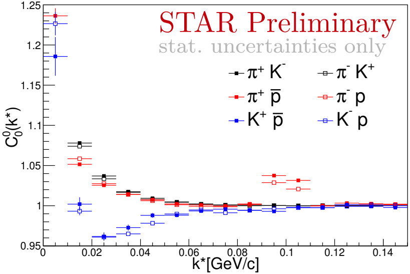
Centrality dependence, $\sqrt{s_{NN}} = 39$ GeV



- Visible centrality dependence

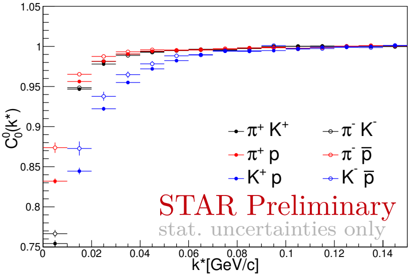
System dependence, $\sqrt{s_{NN}} = 39$ GeV, 0-10%

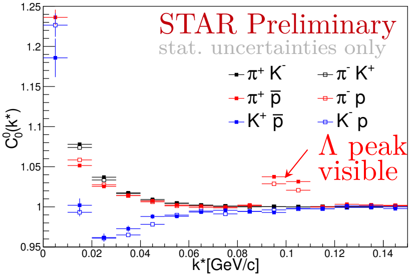




- Like-sign pairs are dominated by Coulomb
- Kp → strongest correlation

System dependence, $\sqrt{s_{NN}} = 39$ GeV, 0-10%





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- Unlike-sign CFs are more complicated
- Λ peak is visible in pion-proton

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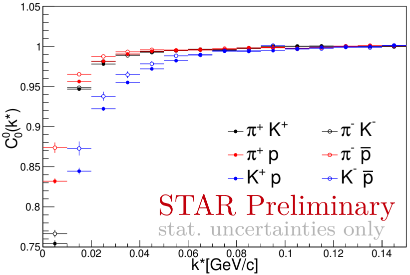
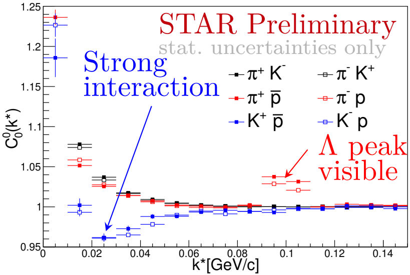




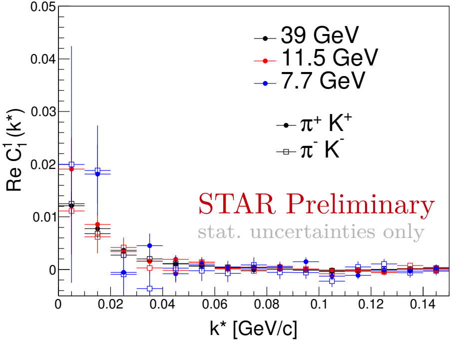
Strong interaction

Λ peak visible

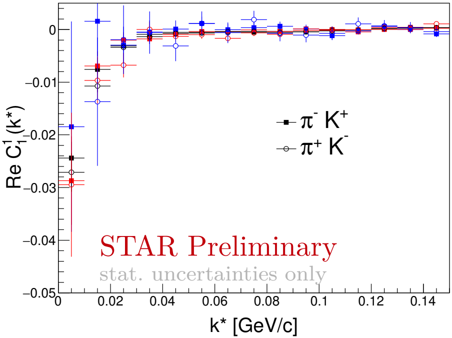
- Like-sign pairs are dominated by Coulomb
- Kp → strongest correlation

- Unlike-sign CFs are more complicated
- Λ peak is visible in pion-proton
- Strong interaction is not negligible in Kp

Source dynamics — energy dependence

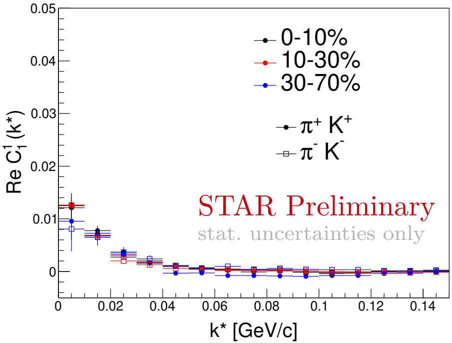


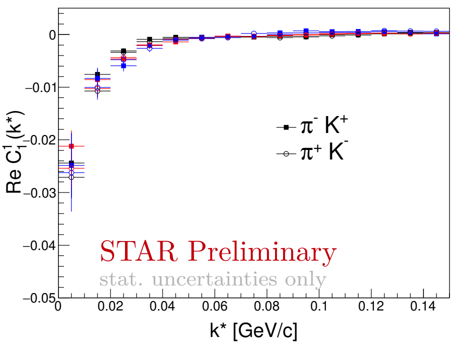
- Clear signal of emission asymmetry



- Visible energy dependence

Source dynamics — centrality dependence





- Clear signal of emission asymmetry

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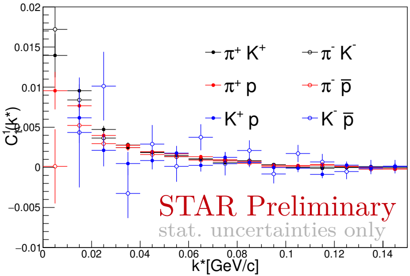
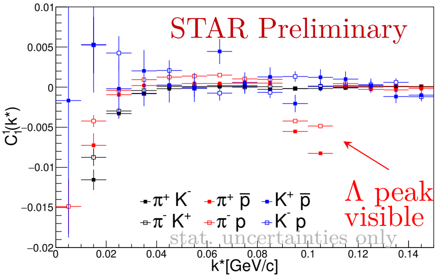
Source dynamics — system dependence





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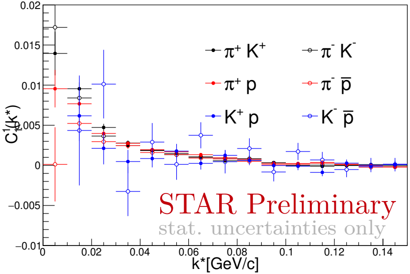
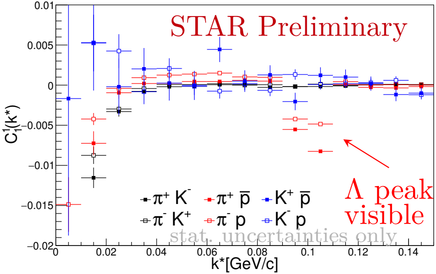




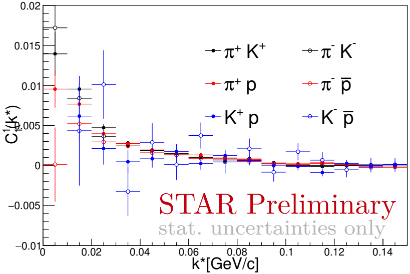
- Visible signal of emission asymmetry

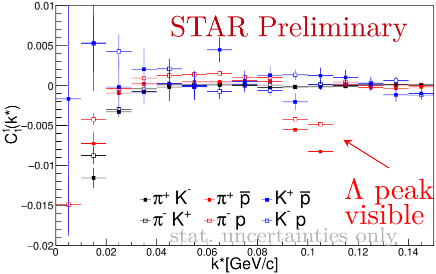
- Expected ordering of particles — confirmed

Lighter particle is emitted closer to the center and/or later.

R. Lednicky, et al., Phys. Lett. B272, 20 (1996)
STAR, Phys. Rev. Lett. 91, 262302 (2003)
A. Kisiel, Phys. Rev. C81, 064906 (2010)

Source dynamics — system dependence

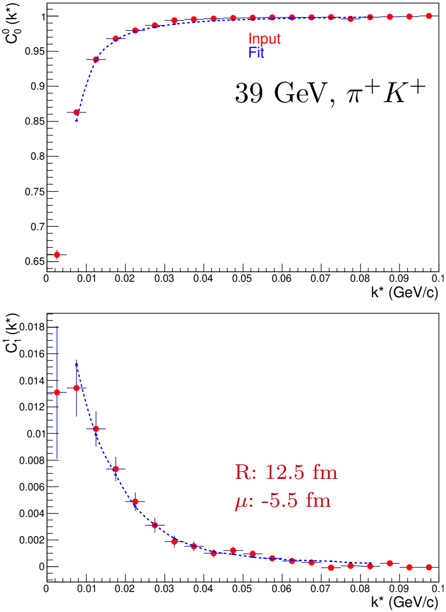




- Visible signal of emission asymmetry
- Expected ordering of particles — confirmed

We are sensitive to collective effects

Non-identical particle femtoscopy — future plan



39 GeV, π^+K^+

R: 12.5 fm

μ: -5.5 fm

- Next step:
  - Obtain source parameters using CorrFit

Summary

- **Kaon femtoscopy (geometry):**
    - neutral kaon correlations at $\sqrt{s_{NN}} = 200$ GeV in minimum-bias events (0-80%)
    - purity correction is done
    - source sizes using Gaussian fit are obtained
    - comparison with published data (from 2006):
        - ★ similar shape of the correlation functions and extracted femtoscopic parameters

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  - CF contaminated by residual correlations — residual correction required
- **Non-identical particle femtoscopy (geometry + dynamics):**
  - Strong interaction not negligible in kaon-proton
  - Clear signal of emission asymmetry for particles with different masses
  - Asymmetry does not disappear for low energies