

Non-identical particle femtoscopy at STAR

Paweł Szymański (for the STAR collaboration)

Warsaw University of Technology



XIII Polish Workshop on Relativistic Heavy-Ion Collisions
6-7 January 2018, Wroclaw

HBT interferometry (Hanbury-Brown, Twiss)

Intensity interferometry → allows to study size of the emitting source by measuring a momentum distribution of emitted particles.

Originally this effect was used to study properties of stars

We can use two-particle correlations to measure one of the smallest sizes in the nature ($\sim 10^{-15} m$)

Correlation Function



- analyze many pairs of particles (\vec{p}_1, \vec{x}_1) and (\vec{p}_2, \vec{x}_2) with relative momentum $\vec{q} = \vec{p}_1 - \vec{p}_2$

Correlation Function



- analyze many pairs of particles (\vec{p}_1, \vec{x}_1) and (\vec{p}_2, \vec{x}_2) with relative momentum $\vec{q} = \vec{p}_1 - \vec{p}_2$
- calculate correlation function (CF) of pairs:

$$CF(\vec{p}_1, \vec{p}_2) = \frac{P_2(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p}_1)P_1(\vec{p}_2)}$$

$P_2(\vec{p}_1, \vec{p}_2)$ — probability of observing two particles with momentum \vec{p}_1 and \vec{p}_2 at the same time and the same place
 $P_1(\vec{p}_1), P_1(\vec{p}_2)$ — probability of observing two particles with momentum \vec{p}_1 and \vec{p}_2 separately

Correlation Function



- analyze many pairs of particles (\vec{p}_1, \vec{x}_1) and (\vec{p}_2, \vec{x}_2) with relative momentum $\vec{q} = \vec{p}_1 - \vec{p}_2$
- calculate correlation function (CF) of pairs:
- experimental correlation function:

$$CF(\vec{p}_1, \vec{p}_2) = \frac{P_2(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p}_1)P_1(\vec{p}_2)}$$

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

Correlation Function



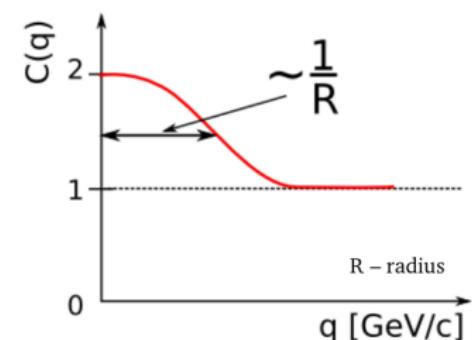
- analyze many pairs of particles (\vec{p}_1, \vec{x}_1) and (\vec{p}_2, \vec{x}_2) with relative momentum $\vec{q} = \vec{p}_1 - \vec{p}_2$

- calculate correlation function (CF) of pairs:

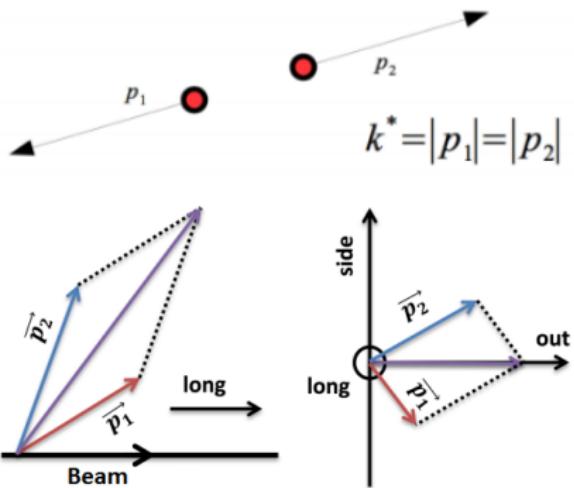
$$CF(\vec{p}_1, \vec{p}_2) = \frac{P_2(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p}_1)P_1(\vec{p}_2)}$$

- calculate size of the source

$P_2(\vec{p}_1, \vec{p}_2)$ — probability of observing two particles with momentum \vec{p}_1 and \vec{p}_2 at the same time and the same place
 $P_1(\vec{p}_1), P_1(\vec{p}_2)$ — probability of observing two particles with momentum \vec{p}_1 and \vec{p}_2 separately



Coordinate system



Master's Thesis, Sebastian Siejka

The pair rest frame

The pair center rests ($\vec{p}_1 = -\vec{p}_2$)

k^* — first particle's momentum

A Bertsch-Pratt coordinate system:

- long → determined by the beam axis
 - out → determined by the direction of the pair momentum in the transverse plane
 - side → perpendicular to the long and out axes

G. Bertsch, M. Gong, and M. Tohyama.

Phys. Rev. C37:1896-1900, 1988

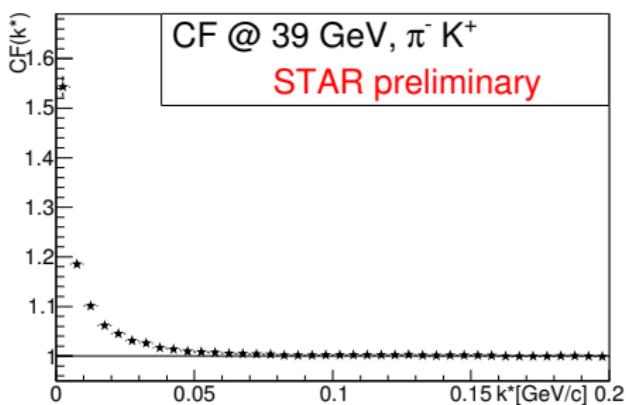
S. Pratt. Phys. Rev. D33:1314, 1986

Final State Interactions (FSI)

The shape of non-identical particle CF depends on FSI:

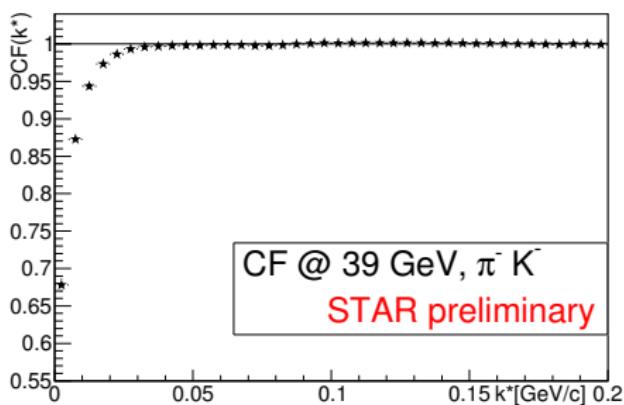
- Strong Interaction
- Coulomb force*

Correlation between unlike-sign pairs



- Quantum Statistic effect

Correlation between like-sign pairs



Space-time asymmetry

$$\cos(\Psi) > 0$$

Catching up

C_+ function

Long time of
effective
interaction.

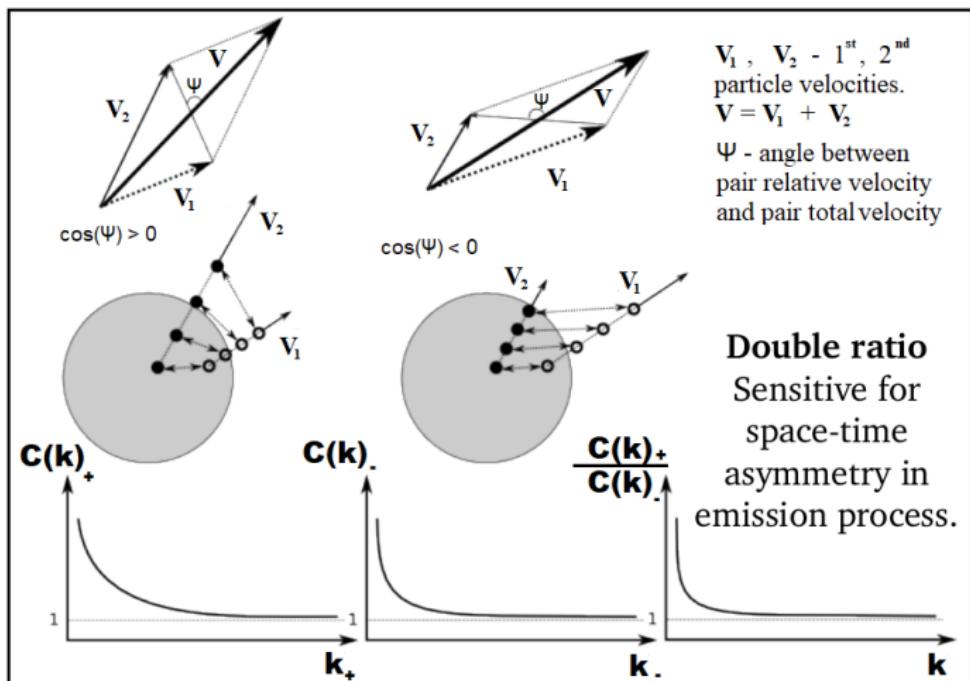
Strong correlation.

$$\cos(\Psi) < 0$$

Run away

C- function
Short time of
effective
interaction.

Weak correlation.



Space-time asymmetry

CFs are calculated in two groups of pairs:

- $C_+(k^*)$ — pions catch up with kaons
 - $C_-(k^*)$ — pions move away from kaons
-

C_+/C_- shows a larger deviation from unity \rightarrow pions and kaons are not emitted at the same place and/or time

C_+ and C_- are identical \rightarrow the average space-time emission points of pions and kaons are the same

Data selection

	π	K	p
p_T [GeV/c]	[0.1, 1.2]	[0.1, 1.2]	[0.4, 2.5]
p [GeV/c]	[0.1, 1.2]	[0.1, 1.2]	[0.4, 3.0]
$ N\sigma $	< 3.0		
Z [cm]	[-30.0, 30.0]		
$ \eta $	< 0.5		
m^2 [GeV 2 /c 4]	[0.01, 0.03]	[0.21, 0.28]	[0.76, 1.03]
DCA [cm]	< 3.0		

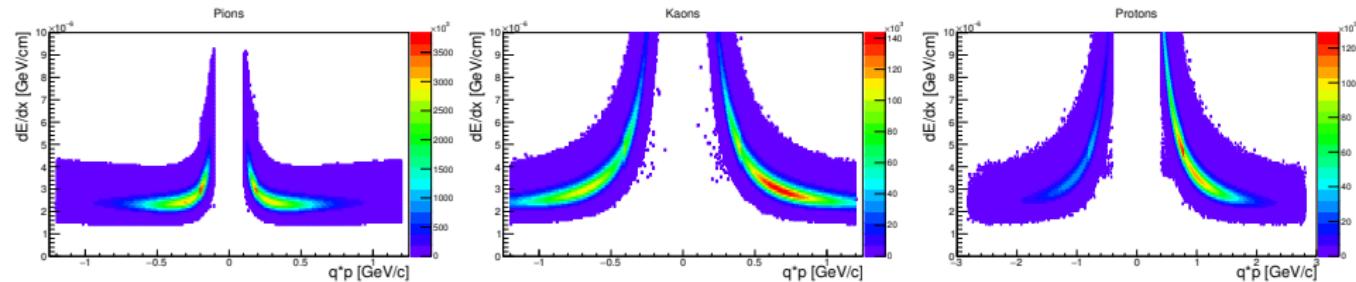
Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV
 πK Centrality bins: 0-10%, 10-30%, 30-70%
 $\pi p, Kp$ Centrality bin: 0-10%

DCA - Distance of Closest Approach

Data selection

	π	K	p
ToF threshold [GeV/c]	0.2	0.41	0.8

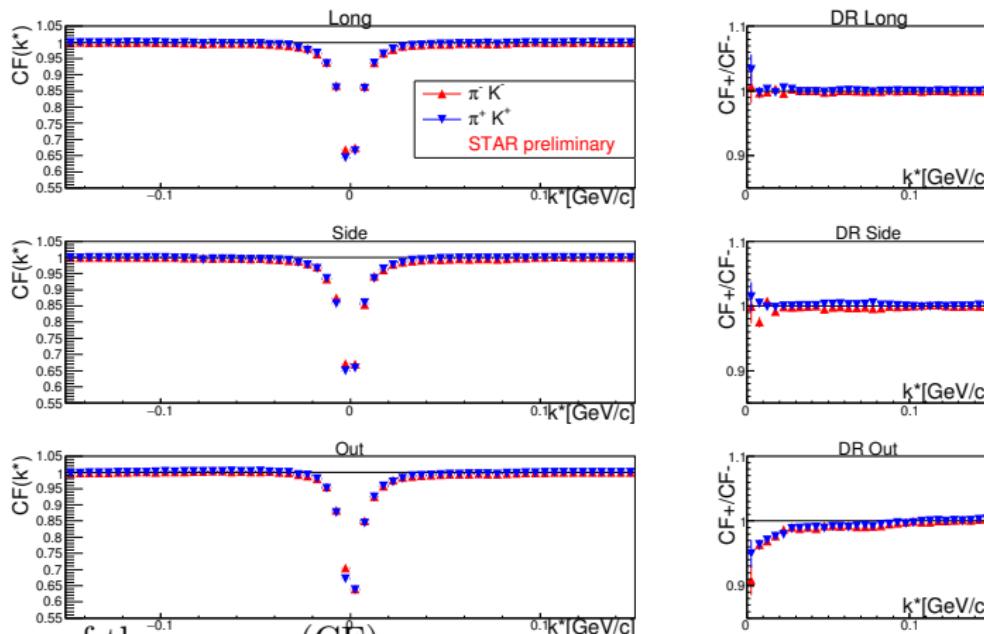
- $p >$ ToF threshold \Rightarrow TPC + ToF
 $p <$ ToF threshold and information from ToF \Rightarrow TPC + ToF
 $p <$ ToF threshold and no information from ToF \Rightarrow TPC



Correlation Function (CF) & Double Ratio (DR) Pion-Kaon

π^+K^+/π^-K^- : CF & DR

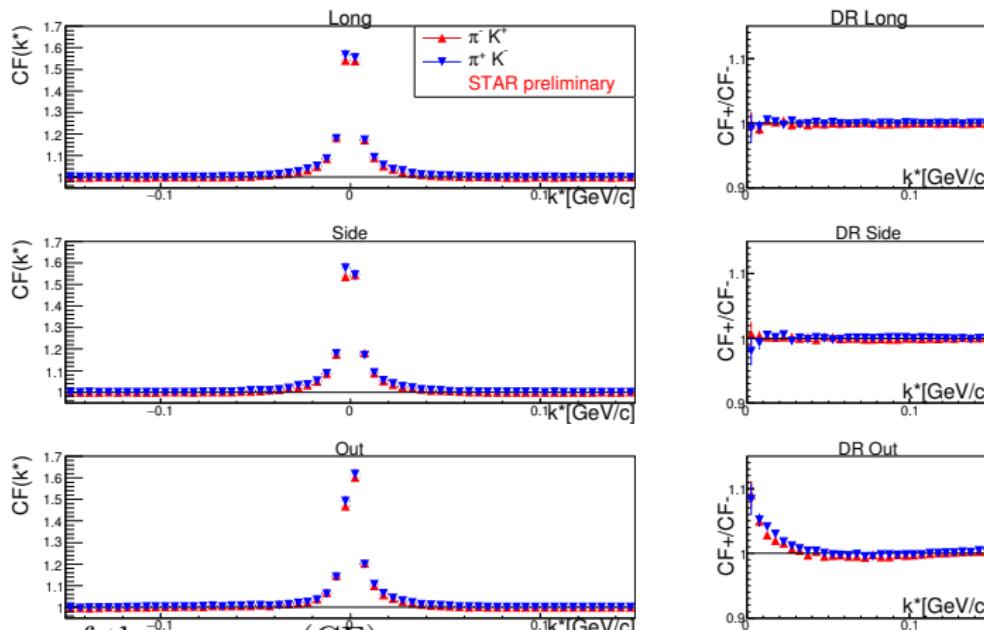
Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV



Similar sizes of the sources (CF)

Visible asymmetry on DR function in out direction

Pions are emitted closer to the center and/or later than kaons

π^+K^-/π^-K^+ : CF & DRAu+Au collisions at $\sqrt{s_{NN}} = 39$ GeV

Similar sizes of the sources (CF)

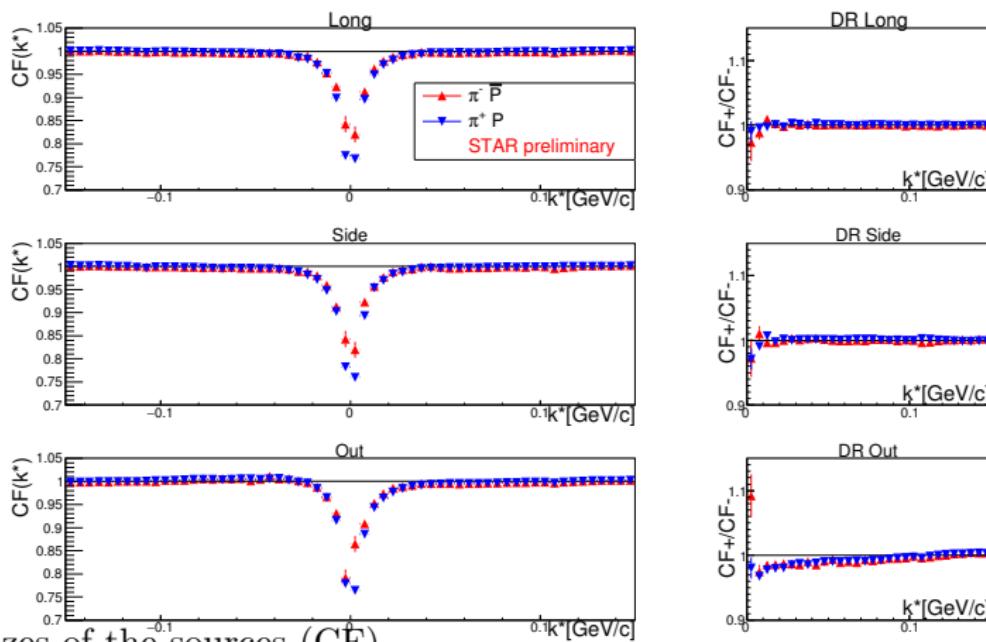
Visible asymmetry on DR function in out direction

Pions are emitted closer to the center and/or later than kaons

Correlation Function (CF) & Double Ratio (DR) Pion-Proton

$\pi^+ p/\pi^- \bar{p}$: CF & DR

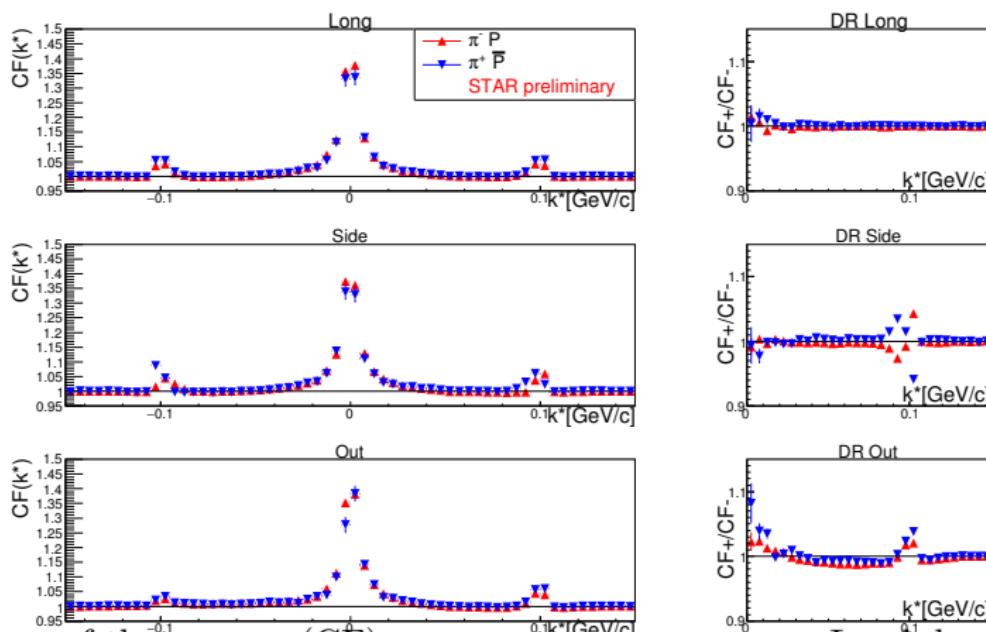
Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV



Similar sizes of the sources (CF)

Visible asymmetry on DR function in out direction

Pions are emitted closer to the center and/or later than protons

$\pi^+ \bar{p}/\pi^- p$: CF & DRAu+Au collisions at $\sqrt{s_{NN}} = 39$ GeV

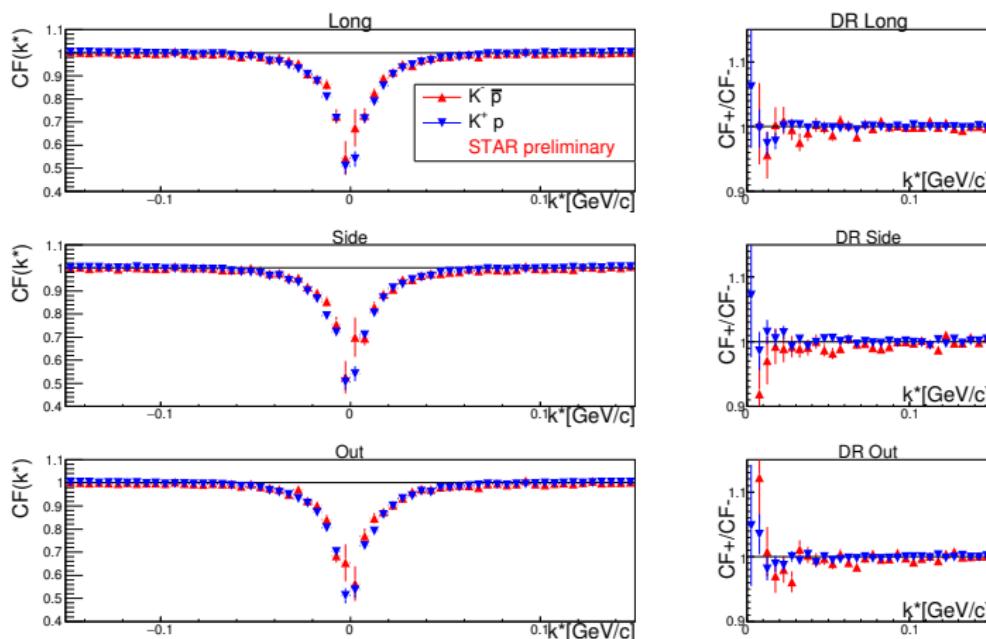
Similar sizes of the sources (CF)

Visible asymmetry on DR function in out direction

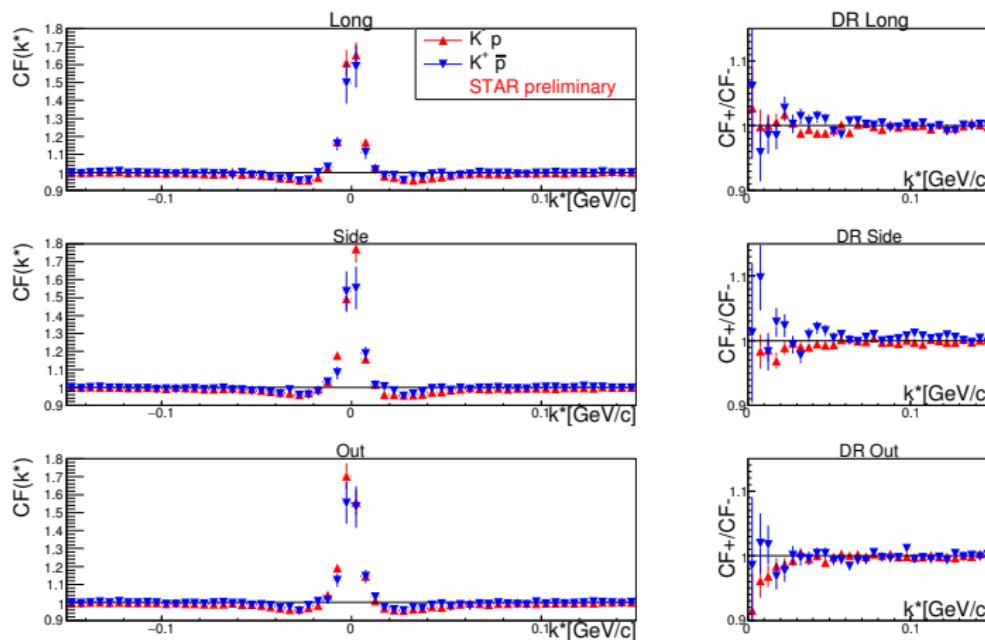
Pions are emitted closer to the center and/or later than protons

Lambda peaks at
 $|k^*| \sim 0.1$ GeV/c

Correlation Function (CF) & Double Ratio (DR) Kaon-Proton

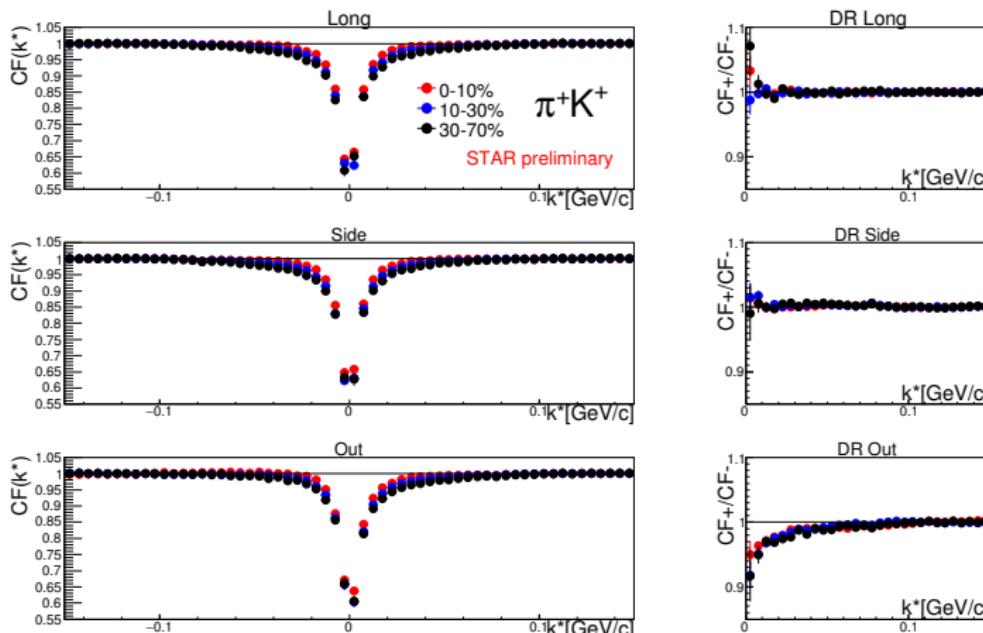
$K^+ p / K^- \bar{p}$: CF & DRAu+Au collisions at $\sqrt{s_{NN}} = 39$ GeV

Similar sizes of the sources (CF)

$K^+ \bar{p}/K^- p$: CF & DRAu+Au collisions at $\sqrt{s_{NN}} = 39$ GeV

Similar sizes of the sources (CF)

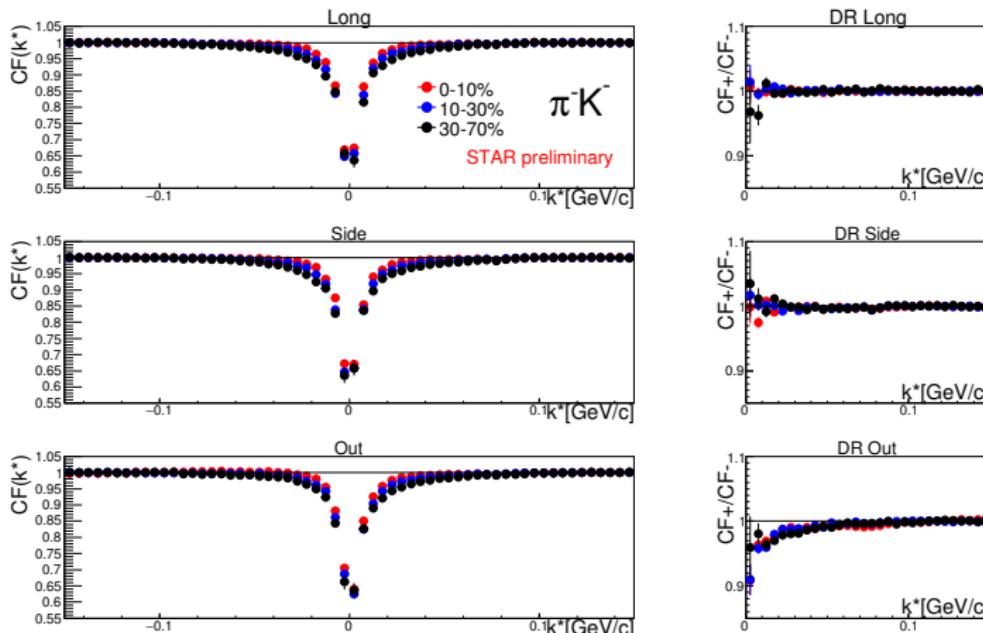
Correlation Function (CF) & Double Ratio (DR) Pion-Kaon - dependence on centrality

π^+K^+ : CF & DRAu+Au collisions at $\sqrt{s_{NN}} = 39$ GeV

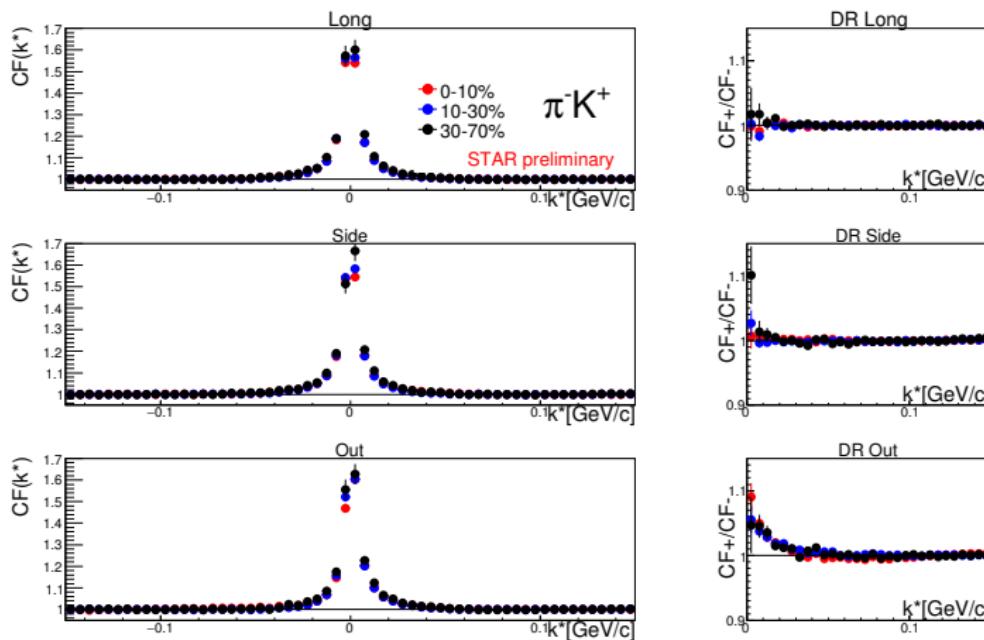
Sizes of the sources (CF) and asymmetries (DR)
are similar

π^-K^- : CF & DR

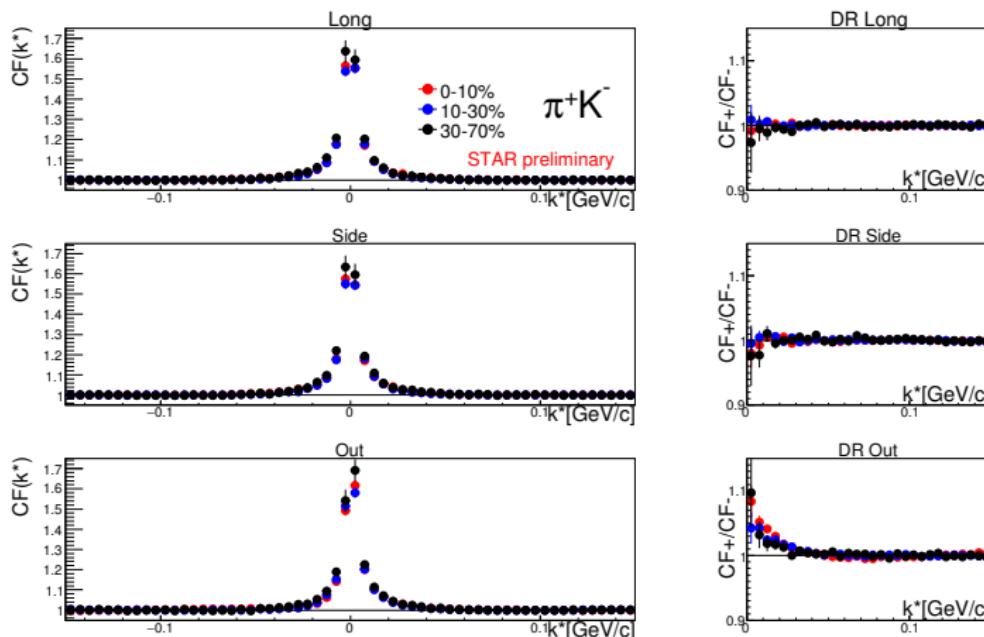
Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV



Sizes of the sources (CF) and asymmetries (DR)
are similar

π^-K^+ : CF & DRAu+Au collisions at $\sqrt{s_{NN}} = 39$ GeV

Sizes of the sources (CF) and asymmetries (DR)
are similar

π^+K^- : CF & DRAu+Au collisions at $\sqrt{s_{NN}} = 39$ GeV

Sizes of the sources (CF) and asymmetries (DR)
are similar

CF & DR summary

- Pion-kaon
 - source sizes are similar
 - visible asymmetry in out direction
- Pion-proton
 - source sizes are similar
 - visible asymmetry in out direction
- Kaon-proton
 - source sizes are similar
- Pions are emitted closer to the center of the system or/and later than kaons
- Pions are emitted closer to the center of the system or/and later than protons

Pion-kaon source sizes (CF) and asymmetries (DR) looks similar in different centrality bins

Spherical Harmonics C_{00} , C_{11}

Spherical harmonic decomposition → one of the most advanced representations of the correlation function

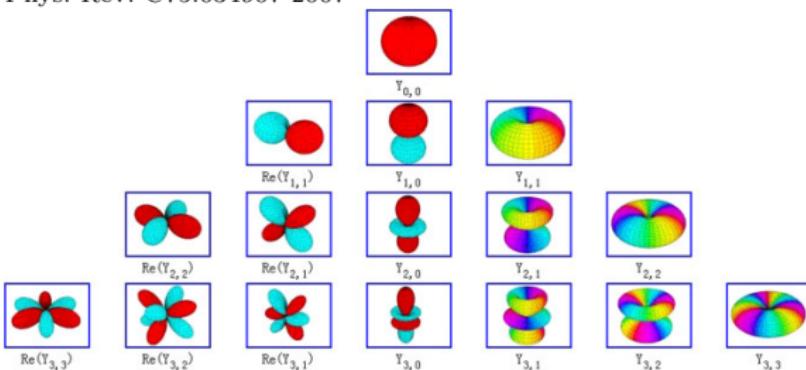
P. Danielewicz and S. Pratt.
Phys. Lett. B618: 60, 2005

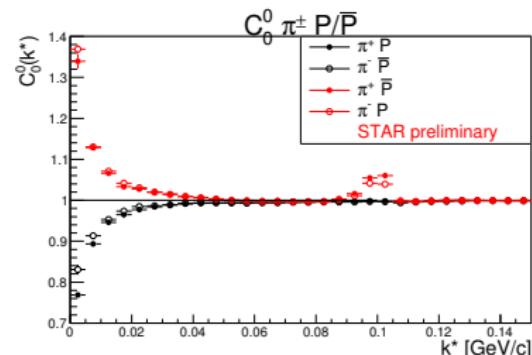
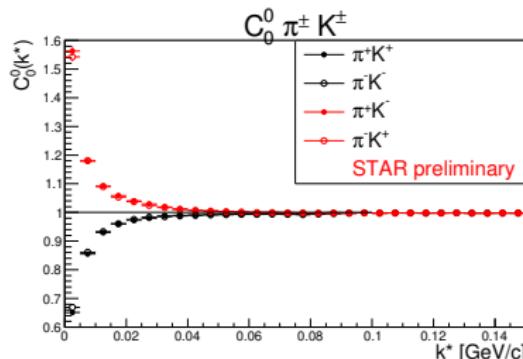
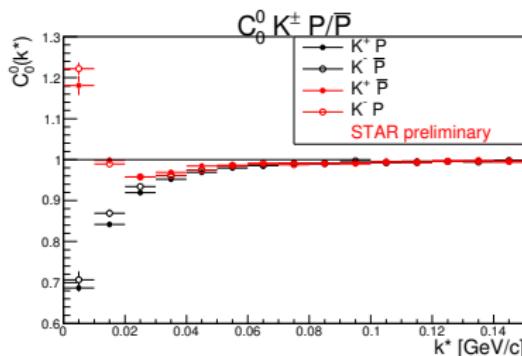
P. Danielewicz and S. Pratt,
Phys. Rev. C75:034907 2007

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

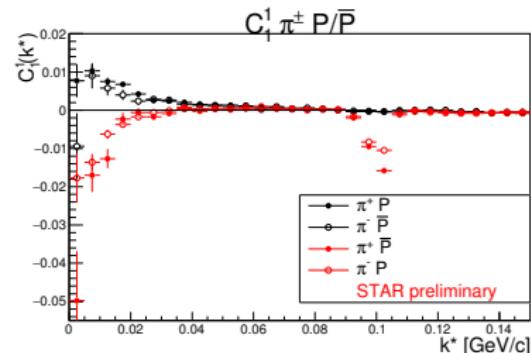
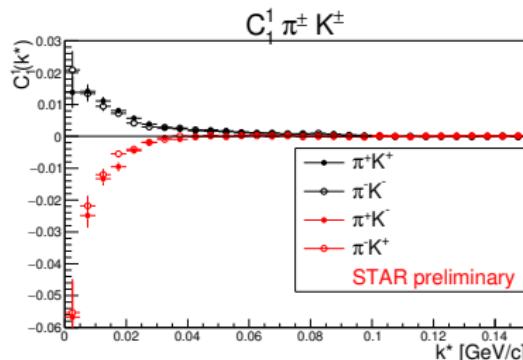
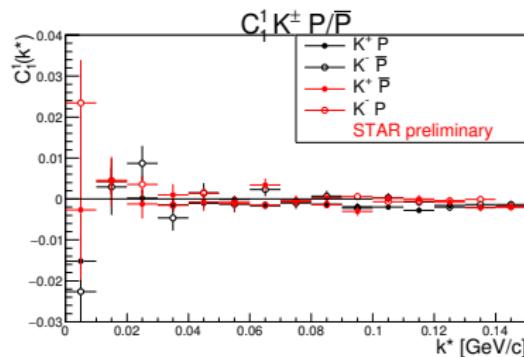
$$C_l^m(q) = \int_{\Omega} C(q, \theta, \phi) Y_l^m(\theta, \phi) d\Omega$$

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



Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV $C_0^0 \rightarrow$ sensitive to the size of the emitting sourceLambda peaks at $|k^*| \sim 0.1$ GeV/c

Similar sizes of the sources

Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV $C_1^1 \rightarrow$ sensitive to the emission asymmetryLambda peaks at $|k^*| \sim 0.1$ GeV/c

Similar asymmetries

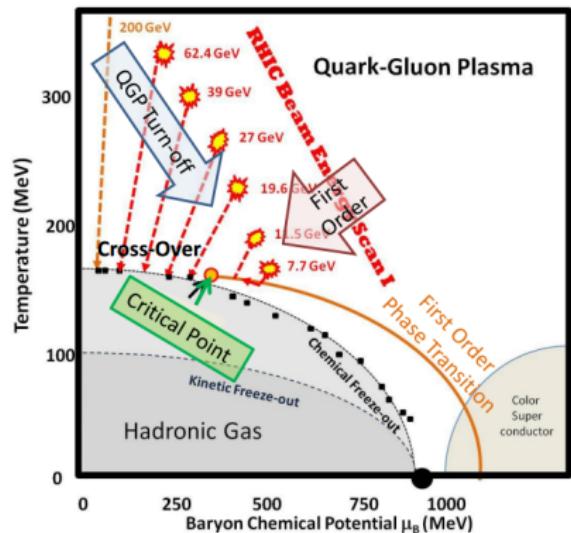
Summary

- Similar source sizes (from CF and C_0^0 functions)
- Double ratios and C_1^1 functions show the asymmetries →
 - pions are emitted closer to the center of the system or/and later than kaons
 - pions are emitted closer to the center of the system or/and later than protons
- Sizes of the sources and asymmetries looks similar for different centrality bins (for πK systems)
- Estimation of the emission parameters is in progress

Future plan

Analyze all BES energies
(7.7, 11.5, 19.6, 27, 39, 62.4 GeV)
and find answers:

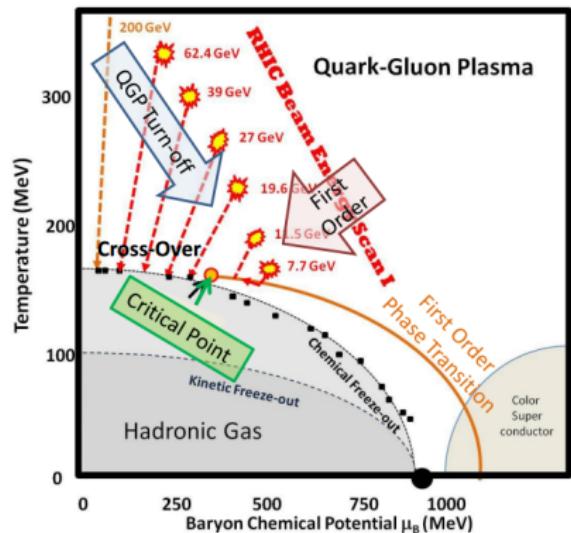
- If or how pion-kaon sources changes with energy?
- If or how asymmetry in emission process looks for all BES energies?



Future plan

Analyze all BES energies
(7.7, 11.5, 19.6, 27, 39, 62.4 GeV)
and find answers:

- If or how pion-kaon sources changes with energy?
- If or how asymmetry in emission process looks for all BES energies?



Thank you for your attention!