Non-identical particle femtoscopy at STAR

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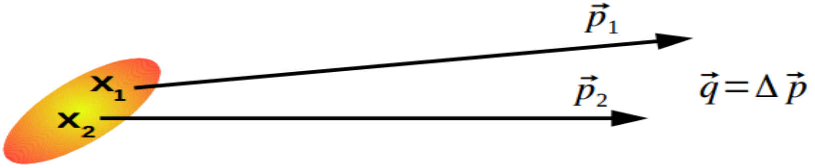
NICA days 2017

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

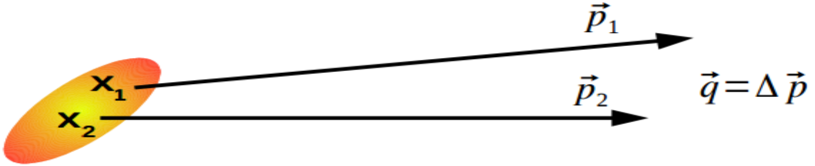
We can use a two-particle correlation to measure one of the smallest sizes in the nature ($\sim 10^{-15} m$)

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

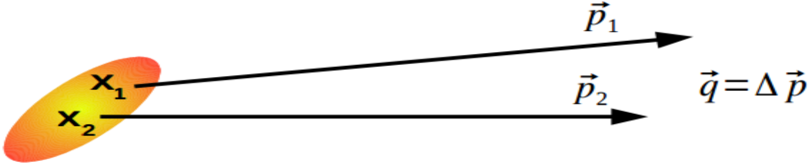


- analyze many pairs of particles $(\vec{p_1}, \vec{x_1})$ and $(\vec{p_2}, \vec{x_2})$ with relative momentum $\vec{q} = \vec{p_1} - \vec{p_2}$
- calculate correlation function (CF) of pairs:

$$CF(\vec{p_1}, \vec{p_2}) = \frac{P_2(\vec{p_1}, \vec{p_2})}{P_1(\vec{p_1})P_1(\vec{p_2})}$$

$P_2(\vec{p_1}, \vec{p_2})$ — 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



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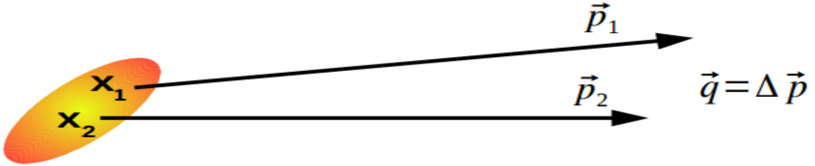
- experimental correlation function:

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

Correlation Function



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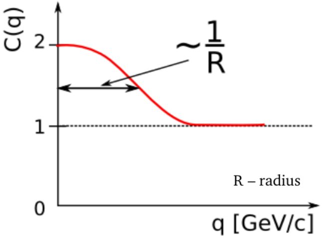
$$CF(\vec{p_1}, \vec{p_2}) = \frac{P_2(\vec{p_1}, \vec{p_2})}{P_1(\vec{p_1})P_1(\vec{p_2})}$$

- 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
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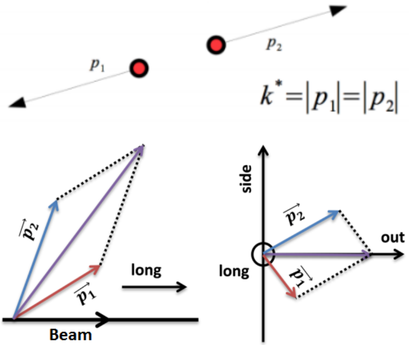
Coordinate system



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

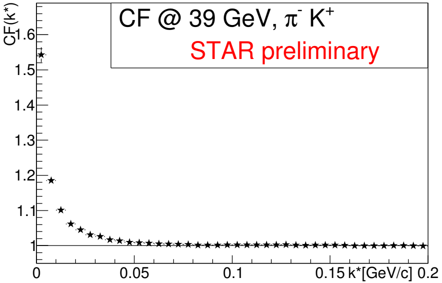
G. Bertsch, M. Gong, and M. Tohyama. Phys. Rev. C37:1896-1900, 1988
S. Pratt. Phys. Rev. D33:1314, 1986

Final State Interactions (FSI)

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

- Strong Interaction
- ***Coulomb force***
- ~~Quantum Statistic effect~~

Correlation between unlike-sign pairs



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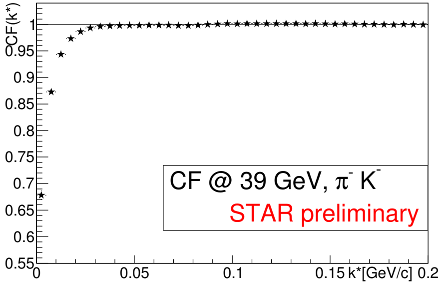


Space-time asymmetry

$\cos(\boldsymbol{\Psi}) > \mathbf{0}$

Catching up

C_+ function

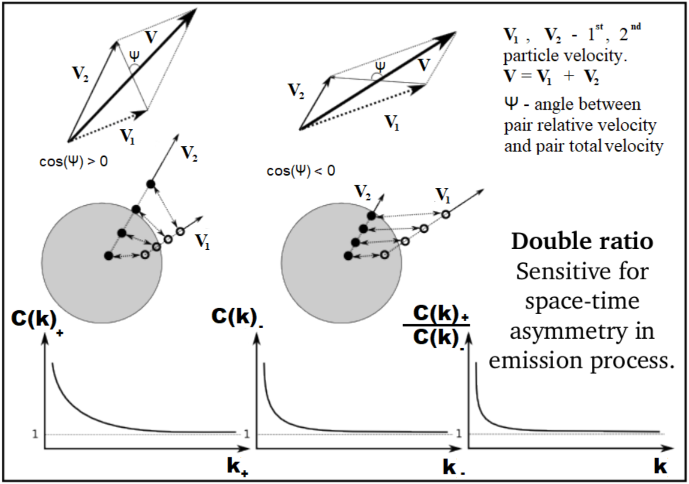
Long time of effective interaction. Strong correlation.

$\cos(\boldsymbol{\Psi}) < \mathbf{0}$

Run away

C_- function

Short time of effective interaction. Weak correlation.



R. Lednicky, et al., Phys. Rev. Lett. B373, 30-34 (1996)

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 → pions and kaons are not emitted at the same place and/or time

C_+ and C_- are identical → 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]
$\lvert N\sigma \rvert$	< 3.0		
Z [cm]	[-30.0, 30.0]		
$\lvert\eta\rvert$	< 0.5		
m^2 [GeV^2/c^4]	[0.01, 0.03]	[0.21, 0.28]	[0.76, 1.03]
DCA [cm]	< 3.0		

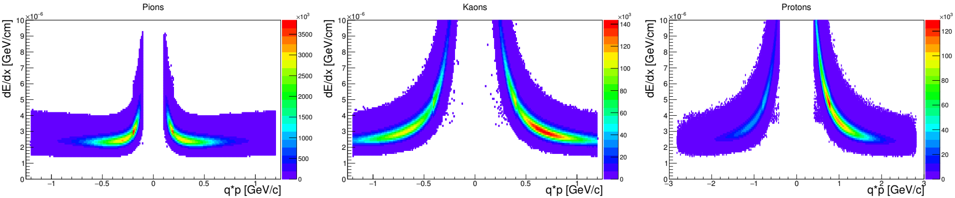
Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV
πK Centrality bins: 0-10%, 10-30%, 30-70%
πp, Kp Centrality bin: 0-10%

DCA - Distance of Closest Approach

Data selection

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

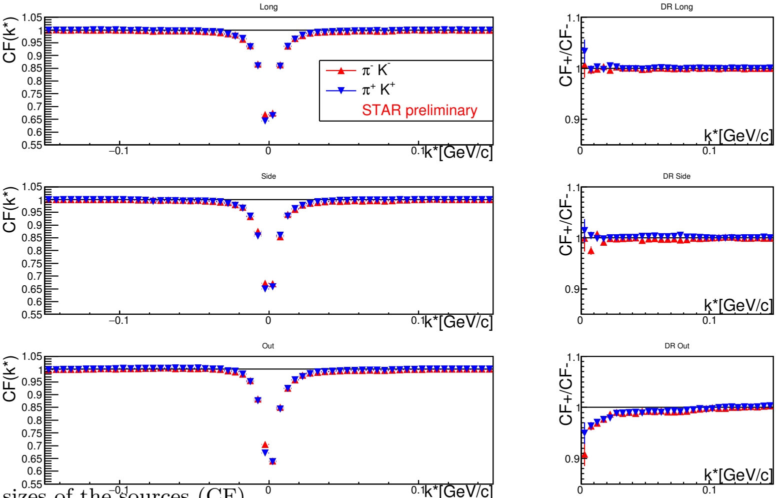
p > ToF threshold ⇒ TPC + ToF
p < ToF threshold and information from ToF ⇒ TPC + ToF
p < ToF threshold and no information from ToF ⇒ TPC



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

π^+K^+/π^-K^-: CF & DR

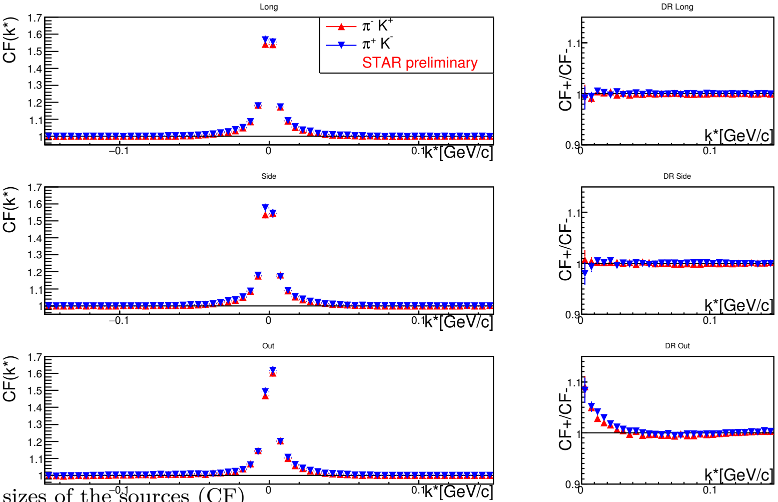
Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV



- Similar sizes of the sources (CF)
- Visible asymmetry on DR function in out direction
- Pions are emmited closer to the center and/or later than kaons

$\pi^+ K^- / \pi^- K^+$: CF & DR

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

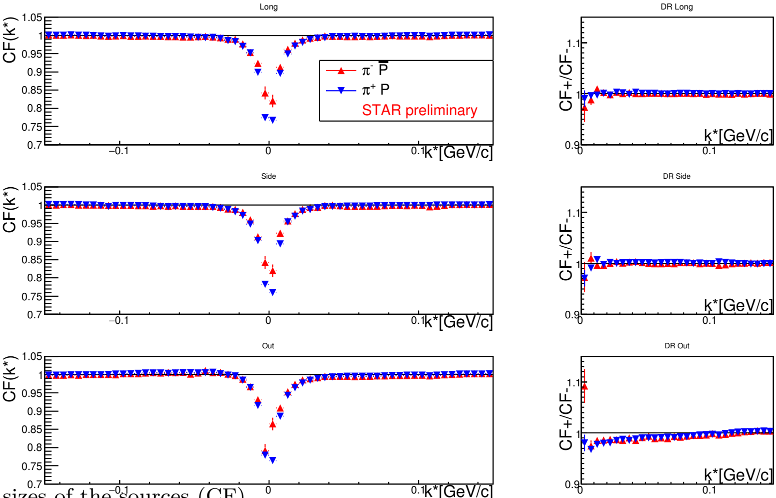


Similar sizes of the sources (CF)
Visible asymmetry on DR function in out direction
Pions are emmited closer to the center and/or later than kaons

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

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

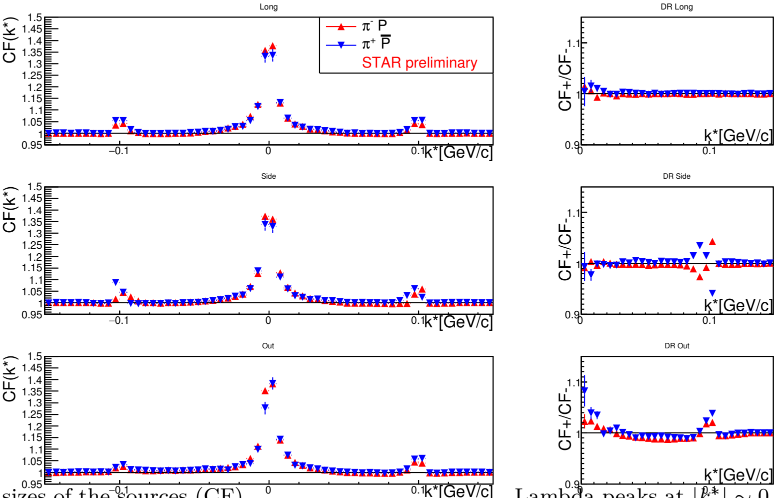
Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV



Similar sizes of the sources (CF)
Visible asymmetry on DR function in out direction
Pions are emmited closer to the center and/or later than protons

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

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



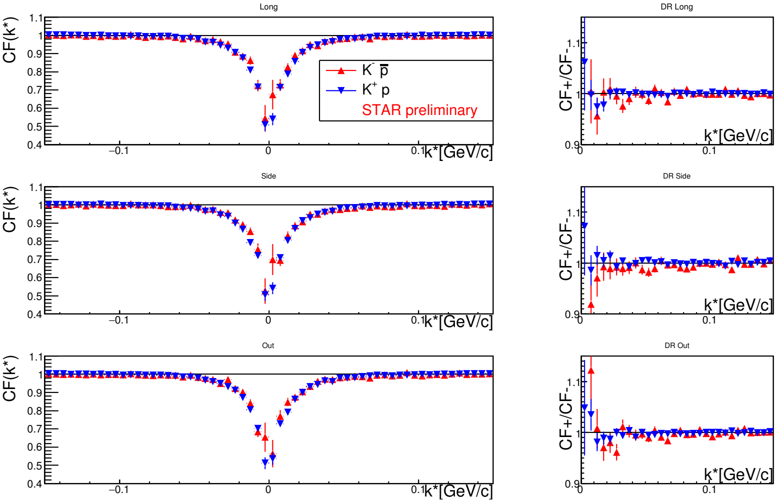
Similar sizes of the sources (CF)
Visible asymmetry on DR function in out direction
Pions are emmited closer to the center and/or later than protons

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

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

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

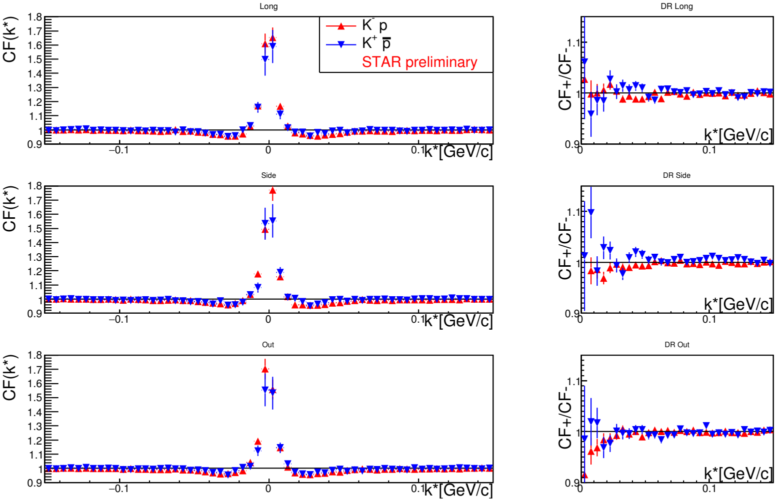
Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV



Similar sizes of the sources (CF)

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

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

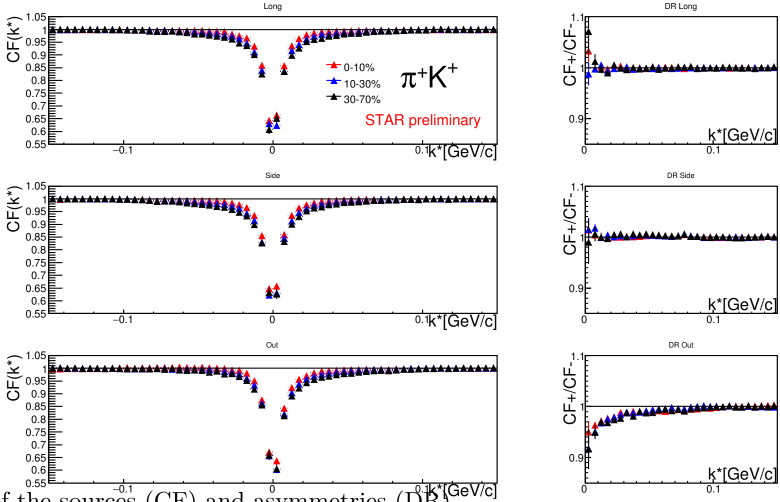


Similar sizes of the sources (CF)

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

$\pi^+ K^+$: CF & DR

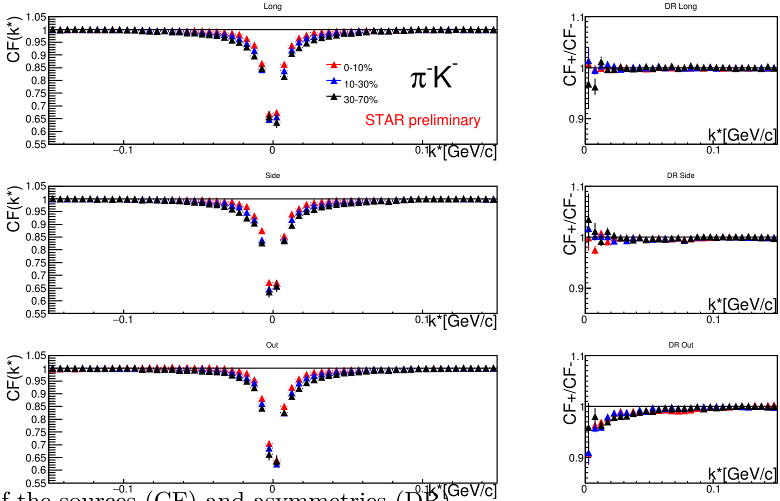
Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV



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

$\pi^- K^-$: CF & DR

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



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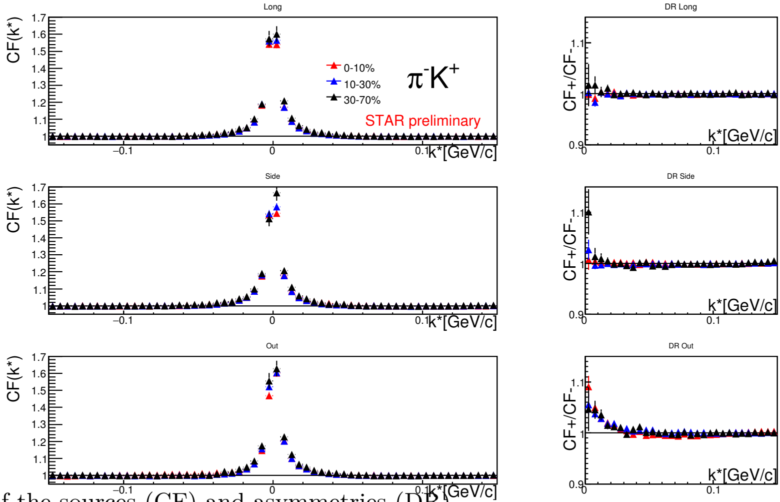

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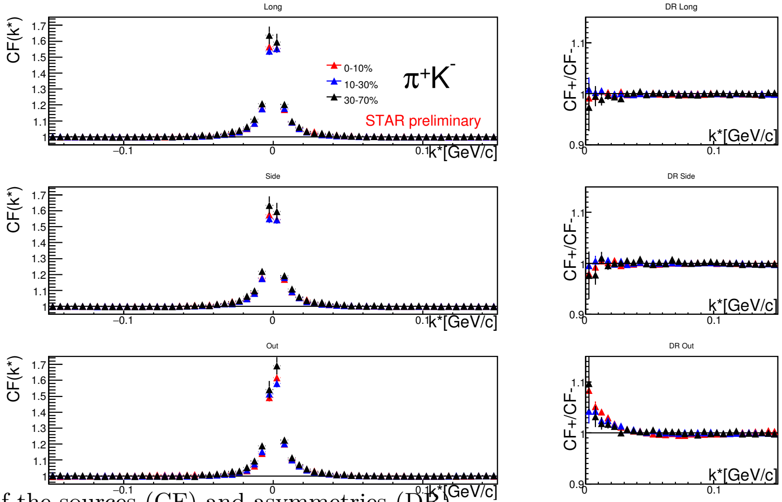


Sizes of the sources (CF) and asymmetries (DR) are similar

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

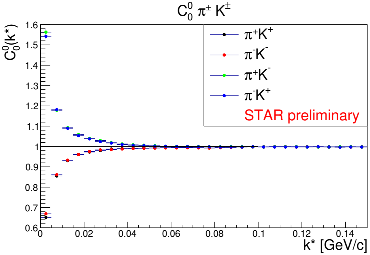
$$C(\mathbf{q}) = \sum_{l,m} C_l^m(q)\, Y_l^m(\theta, \phi)$$

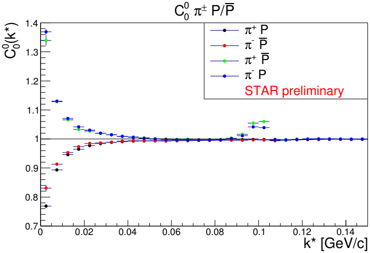
$$C_l^m(q) = \int_\Omega C(q, \theta, \phi)\, Y_l^m(\theta, \phi)\, d\Omega$$

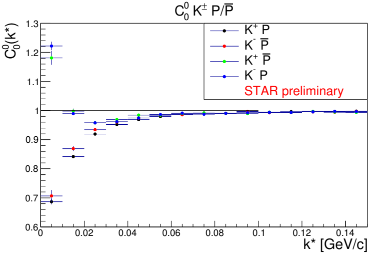
Ω - full solid angle
$Y_l^m(\theta, \phi)$ - spherical harmonic function
$q = |\mathbf{q}|$, θ and ϕ - spherical coordinates

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

$C_0^0 \rightarrow$ sensitive to the size of the emitting source

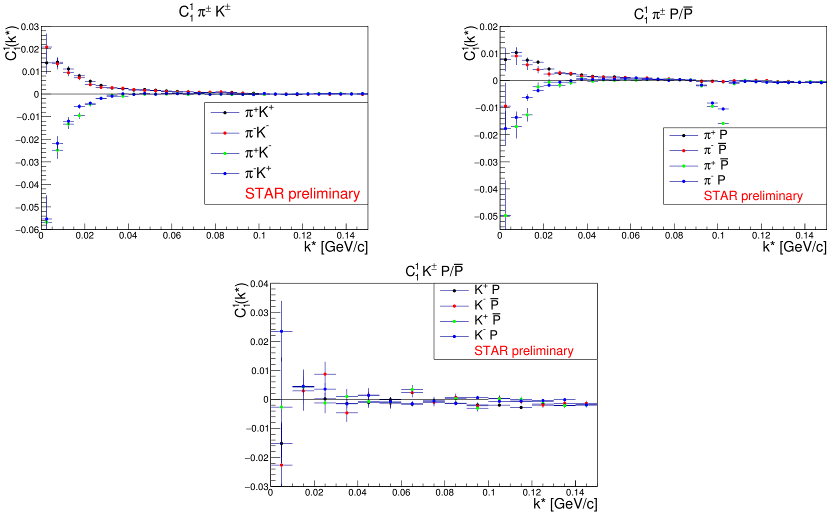






Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV

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



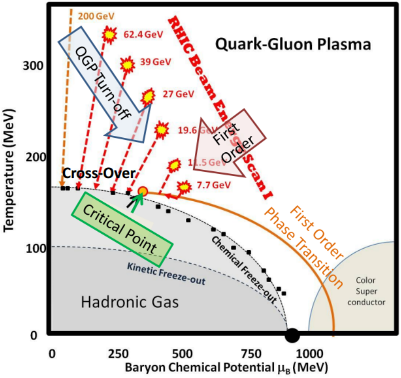
Summary

- Similar source sizes (from CF and C_0^0 functions)
- Double ratios and C_1^1 functions show the asymmetries $\rightarrow$
  - 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 source changes with energy?
- If or how asymmetry in emission process looks for all BES energies?



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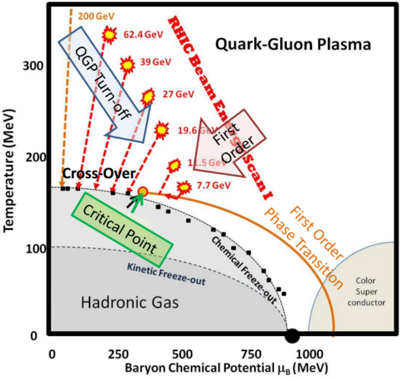

Thank you for your attention!

BACKUP

„To study the sensitivity to the source size, we increase the overall size but keep the radius ratios the same. The results are plotted in Fig. 12. All components show some sensitivity, but C_0^0 is affected the most."

Kisiel, A., "Non-identical particle femtoscopy at $\sqrt{s_{NN}} = 200$ GeV in hydrodynamics with statistical hadronization" Phys. Rev. C 81, 064906 (2010)

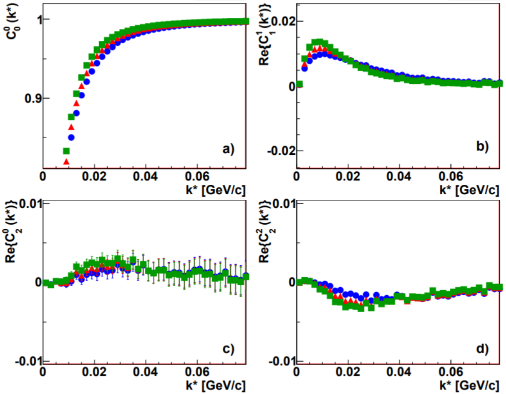

FIG. 12: (Color on-line) SH components of the correlation function for $R_{out} = 8$ fm, $R_{side} = R_{long} = 4$ fm, $\mu_{out} = -4$ fm (blue dots), $R_{out} = 10$ fm, $R_{side} = R_{long} = 5$ fm, $\mu_{out} = -5fm$ (red triangles), $R_{out} = 12$ fm, $R_{side} = R_{long} = 6$ fm, $\mu_{out} = -6$ fm (green squares).

„In the next step (shown in Fig. 13) we keep the source size the same, while we increase the emission asymmetry (μ_{out}). The main sensitivity is in the $\Re C_1^1$ component.”

Kisiel, A., ”Non-identical particle femtoscopy at $\sqrt{s_{NN}} = 200$ GeV in hydrodynamics with statistical hadronization” Phys. Rev. C 81, 064906 (2010)

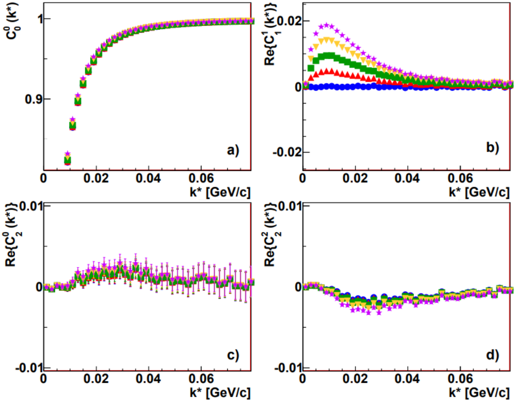

FIG. 13: (Color on-line) SH components of the correlation function for $R_{out} = 10$ fm, $R_{side} = R_{long} = 6$ fm. Emission asymmetry μ_{out} is changed from 0 fm (blue dots) via -2 fm (red up-triangles), -4 fm (green squares), -6 fm (yellow down-triangles), up to -8 fm (violet stars).