# Non-identical particle femtoscopy at STAR

Paweł Szymański (for the STAR collaboration)

Warsaw University of Technology

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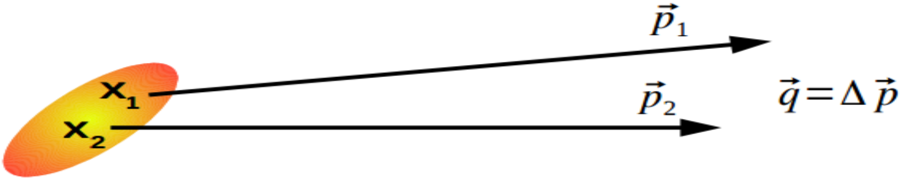
# HBT interferometry (Hanbury-Brown, Twiss)

Intensity interferometry $\rightarrow$ 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

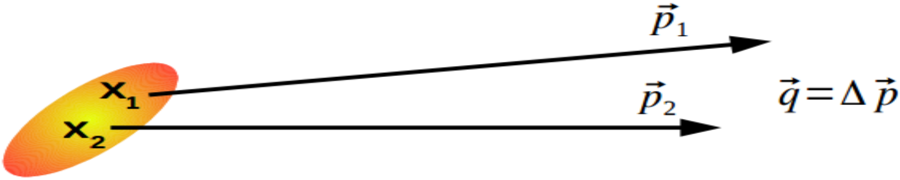
We can use a two-particle correlation to measure one of the smallest sizes in the nature ($\sim 10^{-15} m$)

# 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



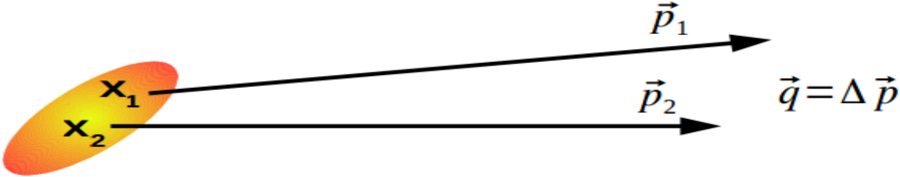

- analyze many pairs of particles $(\vec{p_1}, \vec{x_1})$ and $(\vec{p_2}, \vec{x_2})$ with relative momentum $\vec{q} = \vec{p_1} - \vec{p_2}$
- calculate correlation function (CF) of pairs:

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

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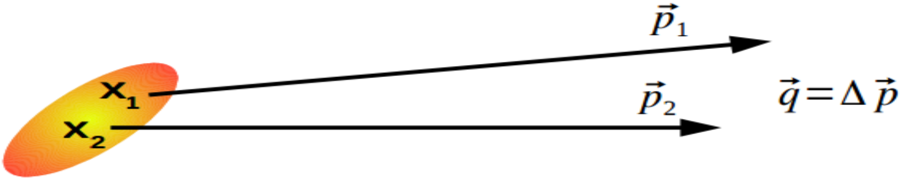
$$CF(\vec{p_1}, \vec{p_2}) = \frac{P_2(\vec{p_1}, \vec{p_2})}{P_1(\vec{p_1})P_1'(\vec{p_2})}$$

experimental correlation function:

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

# Correlation Function




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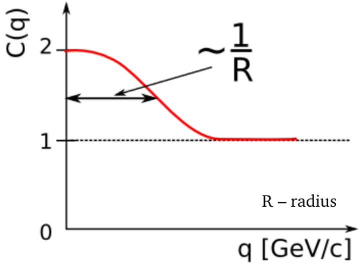



- calculate size of the source

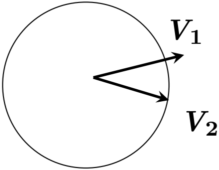
$P_2(\vec{p_1}, \vec{p_2})$ — probability of observing two particles with momentum $\vec{p_1}$ and $\vec{p_2}$ at the same time and the same place

$P_1(\vec{p_1}), P_1'(\vec{p_2})$ — probability of observing two particles with momentum $\vec{p_1}$ and $\vec{p_2}$ separately

# Non-identical particle combinations

## Time asymmetry

$t_1 \neq t_2$
$\Delta r = 0$




$t_1 > t_2$ - Catching up

$t_1 < t_2$ - Run away

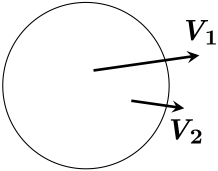
t — emission time

r — emission point distance from the center

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

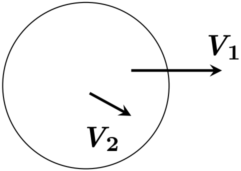
## Space asymmetry

$t_1 = t_2$
$\Delta r \neq 0$




Catching up

$t_1 = t_2$
$\Delta r \neq 0$




Run away

**Catching up**
longer interaction,
strong correlation
**Running away**
shorter interaction,
weaker correlation

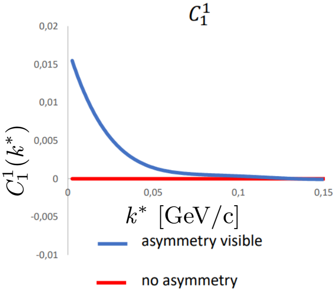
# Spherical Harmonics

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

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

$C_0^0 \rightarrow$ sensitive to the size of the emitting source (shapes same as correlation function)

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




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

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

A. Kisiel and D.A. Brown
Phys. Rev. C80:064911 2009

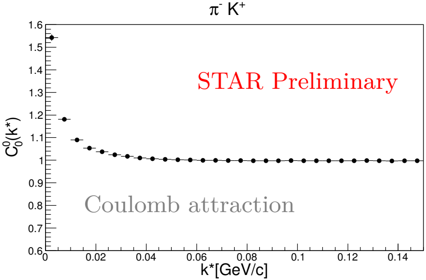
A. Kisiel
Phys. Rev. C81:064906 2010

# Final State Interactions (FSI)

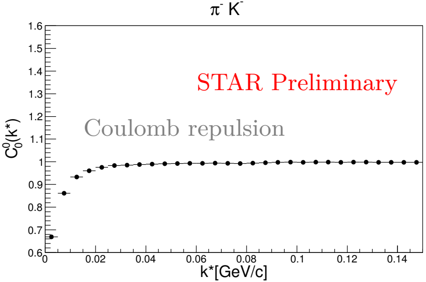
**The shape of non-identical particle CF depends on FSI:**

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

Correlation between unlike-sign pairs

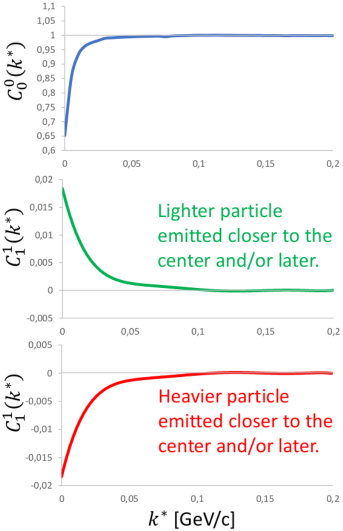



Correlation between like-sign pairs

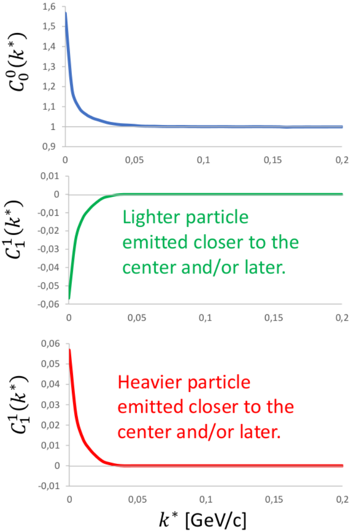


# Which particle...?

## Like-sign particle combinations




## Unlike-sign particle combinations

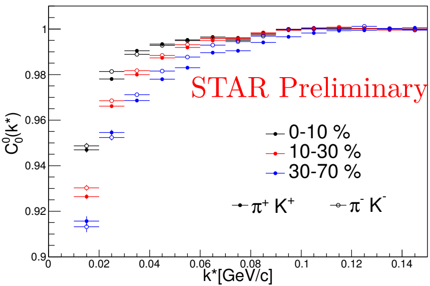


# Results

# Centrality dependence

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

like-sign $\pi - K$ @ Au+Au 39 GeV

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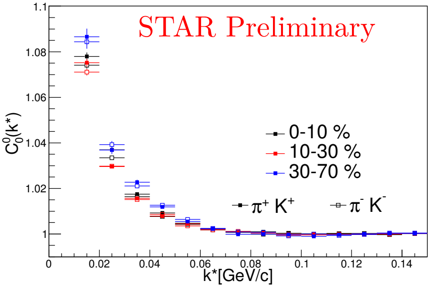


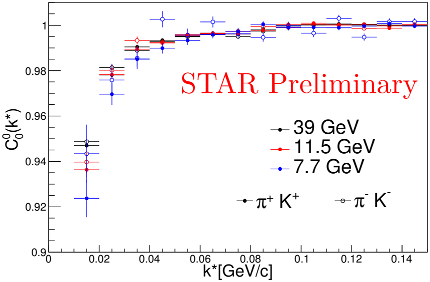

**Clear centrality dependence**

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

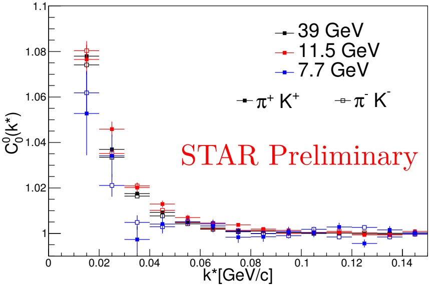
# Energy dependence

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

like-sign $\pi - K$: 0-10%




unlike-sign $\pi - K$: 0-10%



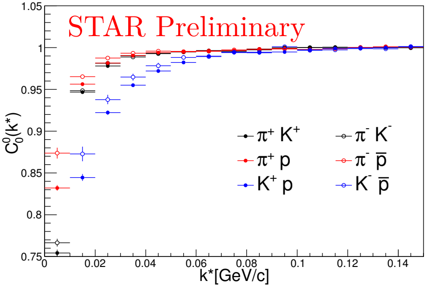

No significant dependence on energy.

Required source parameters to compare.

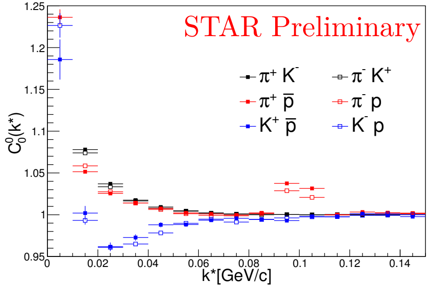
# System dependence

**Clear system dependence**

like-sign @ Au+Au 39 GeV 0-10%




unlike-sign @ Au+Au 39 GeV 0-10%




**Like sign: correlations are dominated by Coulomb interaction**

Coulomb strength depends on Bohr radius of the pair

K-p — lowest Bohr radius → strongest correlation

# System dependence

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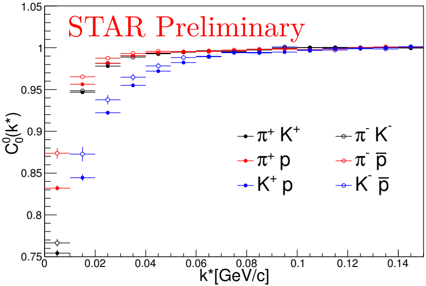


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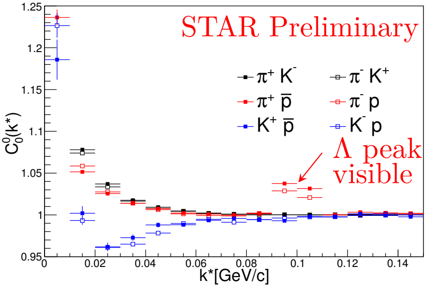


**Unlike sign: interaction more complicated**

Λ peak visible in pion-proton

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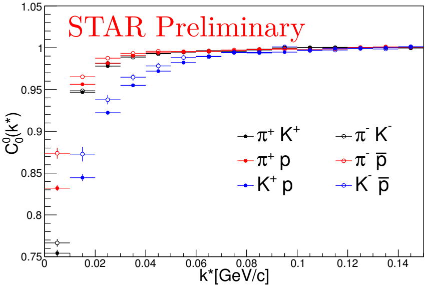


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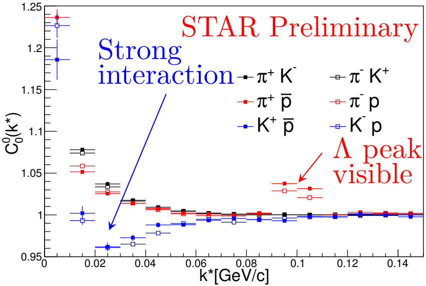


**Unlike sign: interaction more complicated**

$\Lambda$ peak visible in pion-proton

strong interaction not negligible in kaon-proton

# Emission asymmetry — centrality dependence

$C_1^1 \rightarrow$ sensitive to the space-time emission asymmetry

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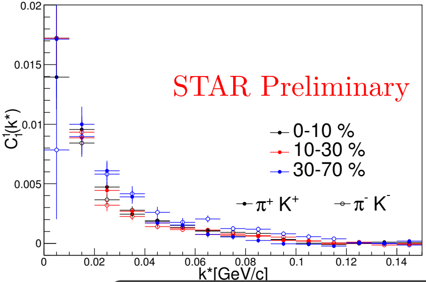


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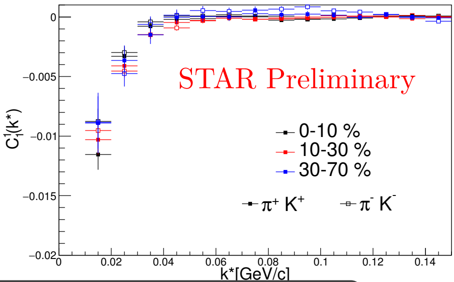


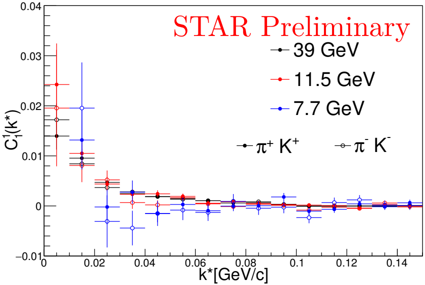

**Clear signal of emission asymmetry**

pions are emitted closer to center and/or later than kaons

# Emission asymmetry — energy dependence

$C_1^1 \rightarrow$ sensitive to the space-time emission asymmetry

like-sign $\pi - K$: 0-10%

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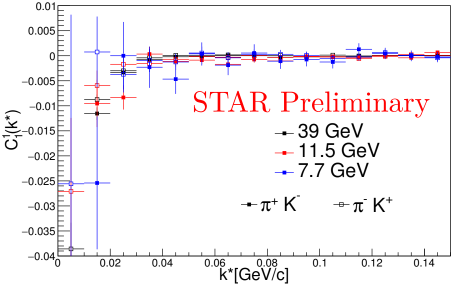


**Clear signal of emission asymmetry**

asymmetry does not disappear for low energies

# Emission asymmetry — system dependence

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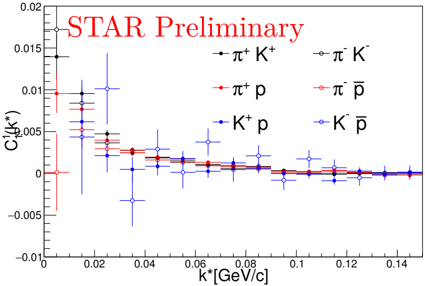


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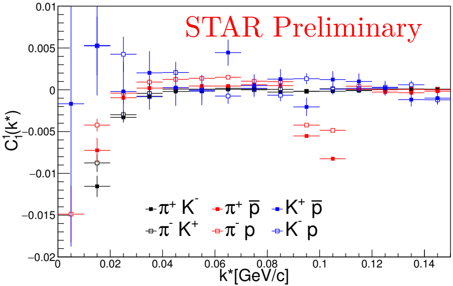

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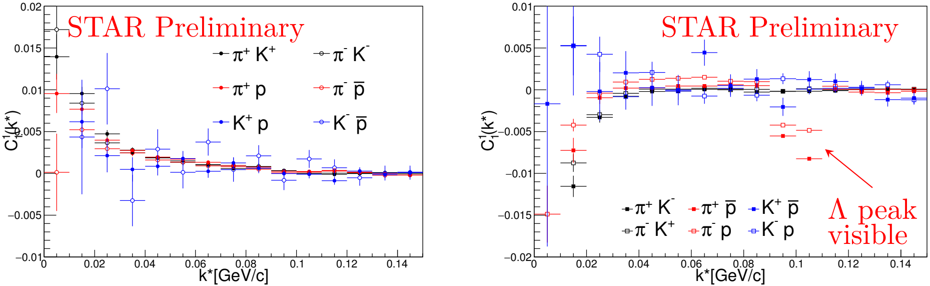


Expected ordering of particles:
Lighter particle is emitted closer to the center and/or later.

A. Kisiel Phys. Rev. C81:064906 2010

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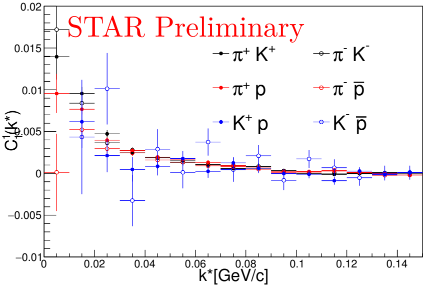


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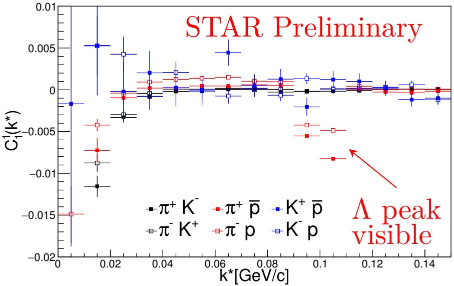


Heavier particles pushed by flow towards the edge of the source more strongly than lighter particles. Heavier particles freeze-out earlier.

A. Kisiel Phys. Rev. C81:064906 2010

# Summary

**Geometry:**

- Significant centrality and system dependence of the source size at BES energies
- **Strong interaction is not negligible in kaon-proton**

**Dynamics:**

- Clear signal of emission asymmetry for particles with different masses at BES energies
- Asymmetry does not disappear for low energies
- **Lighter particles are emitted closer to the center of the source and/or later than heavier particles — flow pushes heavier particles harder to the edge**

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**Thank you for your attention!**