

Geometry and dynamics of particle production seen by femtoscopic probes in the STAR experiment

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**Warsaw University
of Technology**



**Faculty
of Physics**

WARSAW UNIVERSITY OF TECHNOLOGY

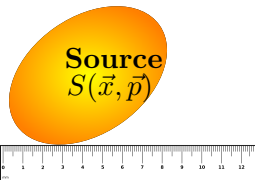


**NATIONAL SCIENCE CENTRE
POLAND**



Strangeness in Quark Matter 2019
Bari, Italy, 09-15.06.2019

Supported by the Polish National Science Centre grant no. 2017/27/B/ST2/01947



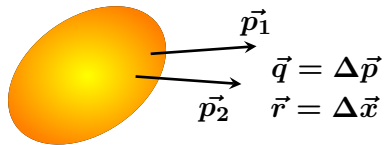
Impossible to examine the particle
emitting source directly

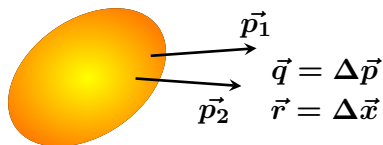
$$\text{size} \sim 10^{-15} \text{ m}$$

$$\text{life time} \sim 10^{-23} \text{ s}$$

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

Femtoscropy





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

experiment

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

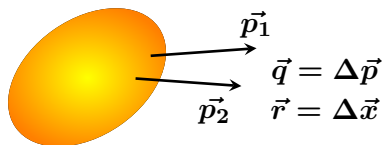
$A(\vec{q})$ - correlated
 $B(\vec{q})$ - uncorrelated

theory (models)

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

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

Femtoscscopy



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

experiment

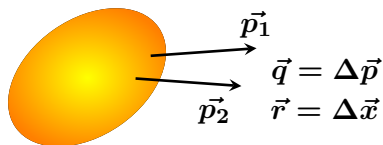
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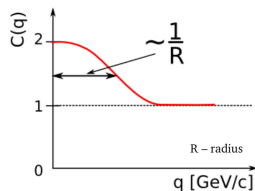
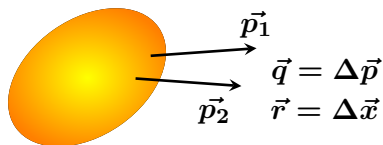
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Femtoscscopy



calculate size (R) of the source

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

experiment

theory (models)

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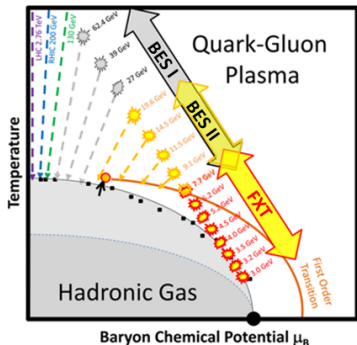
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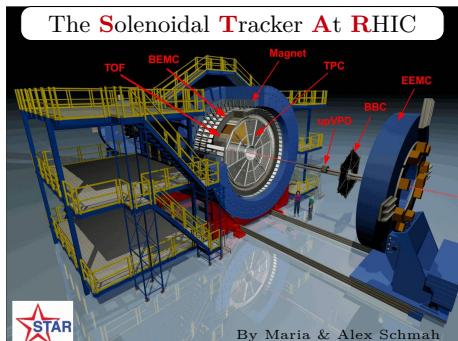
Introduction

- **Kaon femtoscopy (geometry):**
provides complementary information to pions
 - ▶ less affected by resonance decays
 - ▶ contain strange quark
 - ▶ heavier than pions
- **Non-identical particle femtoscopy (geometry + dynamics):**
 - ▶ examination of asymmetry in emission process between two kinds of particles (πK)
 - ▶ measuring Final State Interactions ($p\Omega$)



Nucl. Phys. A 967, 808 (2017)

The STAR experiment



Time Projection Chamber

PID: dE/dx

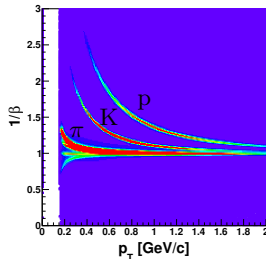
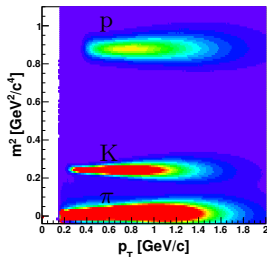
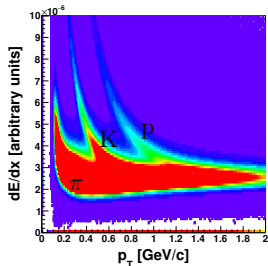
Tracking

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

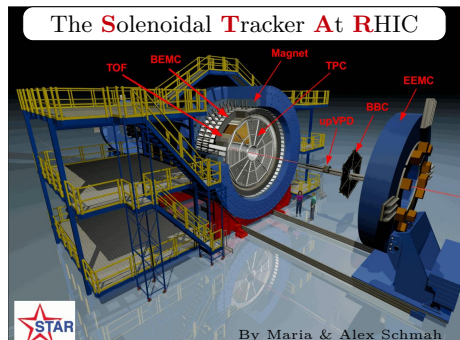
Time-Of-Flight

Time resolution < 80 ps

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



The STAR experiment



Time Projection Chamber

PID: dE/dx

Tracking

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

Time-Of-Flight

Time resolution < 80 ps

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

$\sqrt{s_{NN}}$ [GeV]	7.7	11.5	39		
			(0-10%)	(10-30%)	(30-70%)
#events [mln]	0.24	1.3	11.7	25.7	45.4

Longitudinally Co-Moving System (LCMS)

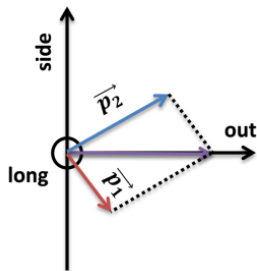
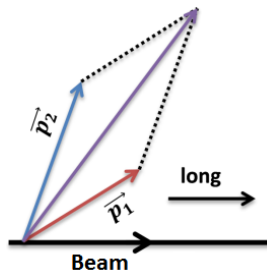
G. Bertsch, et al. S. Pratt.
Phys. Rev. C37, 1896, (1988) Phys. Rev. D33, 1314 (1986)

Long: sensitive to the longitudinal dynamics and evolution time

Out: sensitive to the geometrical size, emission time and space-time correlation

Side: sensitive to the geometrical size

$$k_T = \frac{|p_{T,1} + p_{T,2}|}{2}$$



Reference frame

Pair Rest Frame (PRF)



$$k_T = \frac{|p_{T,1} + p_{T,2}|}{2}$$

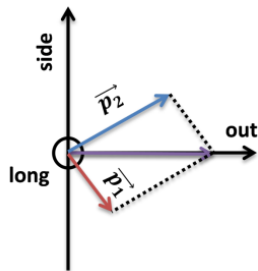
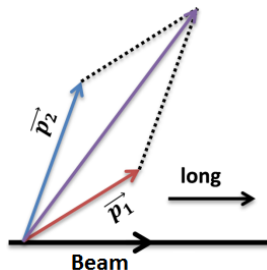
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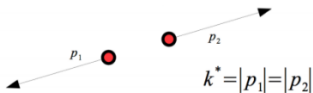
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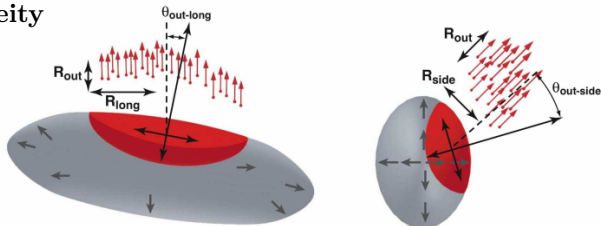
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Region of homogeneity



$$k_T = \frac{|p_{T,1} + p_{T,2}|}{2}$$

Ann. Rev. Nucl. Part. Sci 55, 357 (2005)
Phys. Lett. B356, 525 (1995)

Kaons — fitting procedure

$$S(\vec{r}) \sim \exp\left(-\frac{r_o^2}{4R_o^2} - \frac{r_s^2}{4R_s^2} - \frac{r_l^2}{4R_l^2}\right)$$
$$|\Psi(\vec{q}, \vec{r})|^2 = 1 + \cos(\vec{q}\vec{r})$$

Bowler-Sinyukov formula:

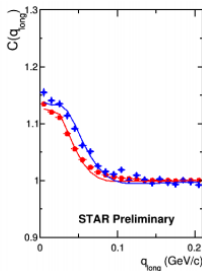
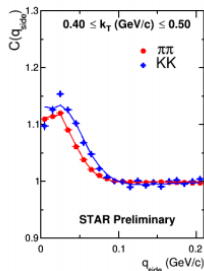
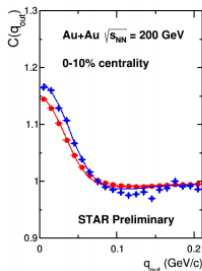
$$C(q_o, q_s, q_l) = 1 - \lambda + \lambda K(q_{inv}) (1 + \exp[-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2])$$

λ - the correlation strength

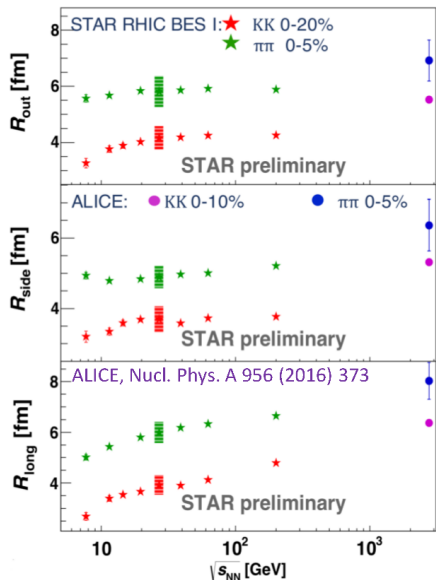
$K(q_{inv})$ - Coulomb factor

M. Bowler
Phys. Lett. B270, 69 (1991)

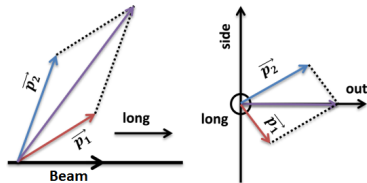
Y. Sinyukov, et al.
Phys. Lett. B432, 248 (1997)



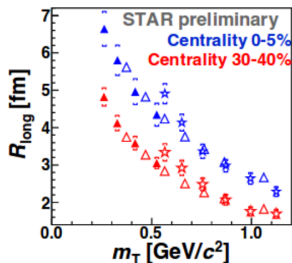
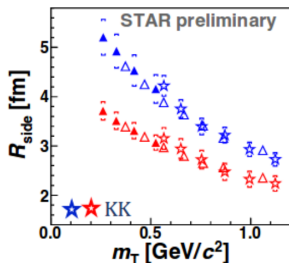
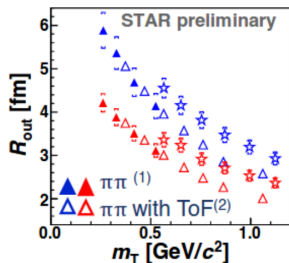
Radii from BES-I



- R_{side} spatial source evolution in the transverse direction
- R_{out} related to spatial and time components
- R_{long} temperature of kinetic freezeout and source lifetime



Results from 200 GeV



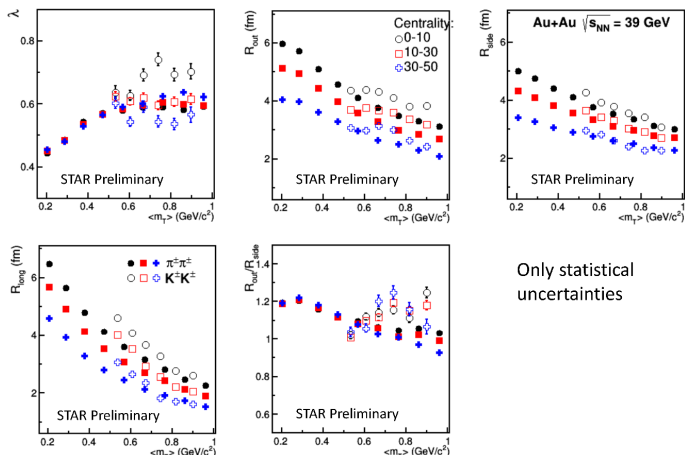
- R_{side} trend for kaons is similar to that of pions
- R_{out} and R_{long} of pion and kaon source radii follow different m_T dependences
- $R_{long}(K) > R_{long}(\pi)$
 - ▶ contribution from long-lived resonances at the kinetic freeze-out?(³)

(1) STAR, Phys. Rev. C 92, 014904 (2015)

(2) STAR Preliminary

(3) Y. Sinyukov, et al. Nucl. Phys. A 946, 227 (2016)

Results from 39 GeV



Only statistical uncertainties

- R_{long} & R_{out} are larger for kaons at the same $m_T \rightarrow$ breaking of the m_T -scaling
- R_{side} radii for pions and kaons are closer than in other directions

Pion-kaon femtoscopy — Spherical harmonics (SH)

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

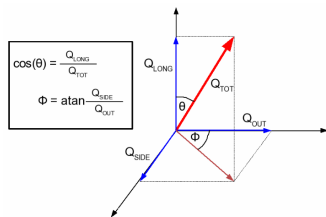
$$C(\mathbf{q}) = \sum_{l,m} C_l^m(q) Y_l^m(\theta, \phi) \quad C_l^m(q) = \int_{\Omega} C(q, \theta, \phi) Y_l^m(\theta, \phi) d\Omega$$

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)

Z. Chajecki and M. Lisa
Phys. Rev. C78, 064903 (2008)

A. Kisiel and D.A. Brown
Phys. Rev. C80, 064911 (2009)

A. Kisiel
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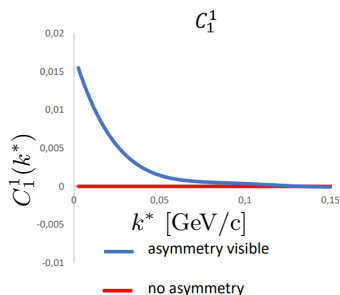
$Y_l^m(\theta, \phi)$ - spherical harmonic function

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θ and ϕ - polar and azimuthal angle

$C_0^0 \rightarrow$ 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)
Phys. Rev. C75, 034907 (2007)

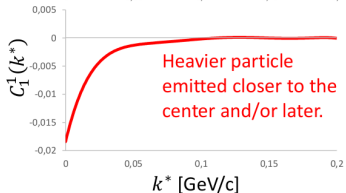
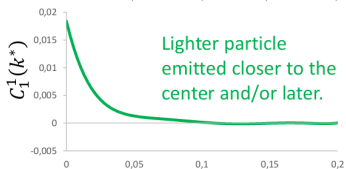
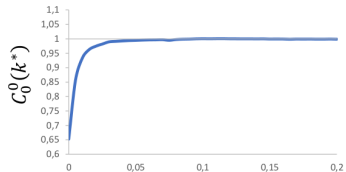
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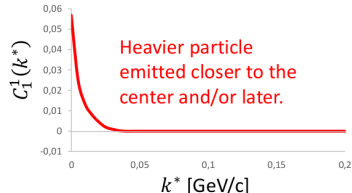
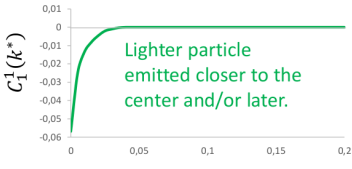
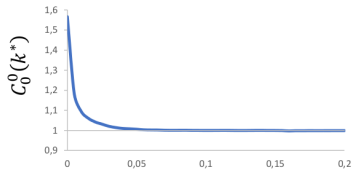
A. Kisiel
Phys. Rev. C81, 064906 (2010)

Which particle...?

Like-sign particle combinations



Unlike-sign particle combinations



Pion-kaon femtoscopy — asymmetry

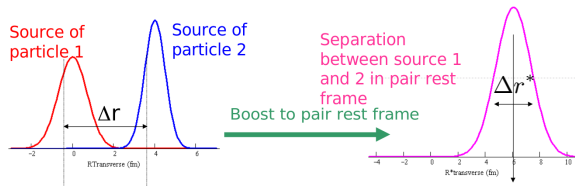
$$C(\vec{q}) = \int |\Psi(\vec{q}, \vec{r})|^2 S(\vec{r}) d^3r$$

known
unknown

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

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

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



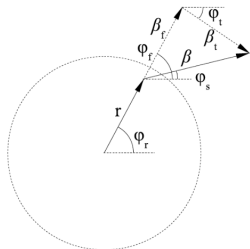
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$$\beta_{particle} = \beta_f + \beta_t$$

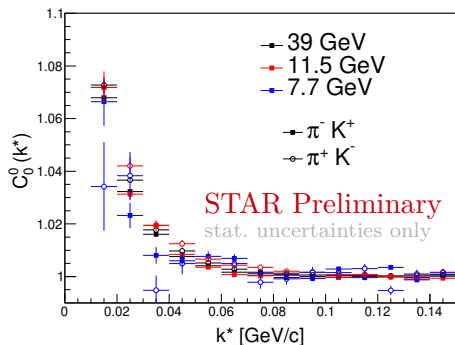
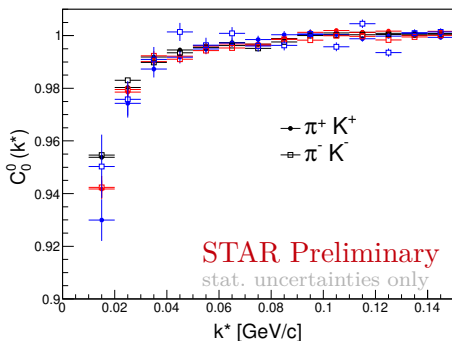
β_f — collective (flow) velocity

β_t — thermal (random) velocity

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

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

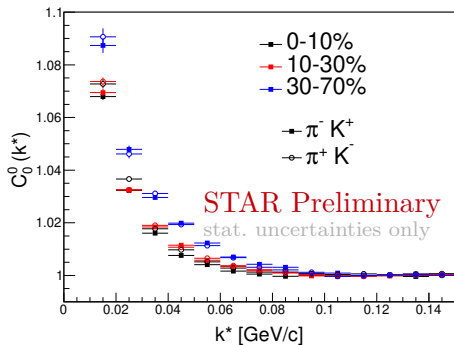
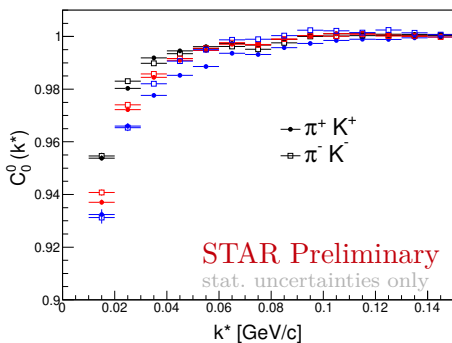
Energy dependence



- Visible energy dependence

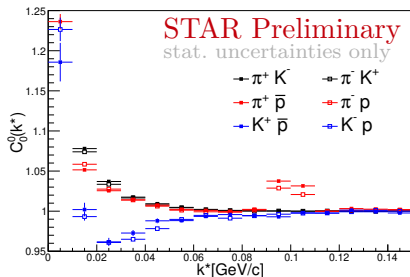
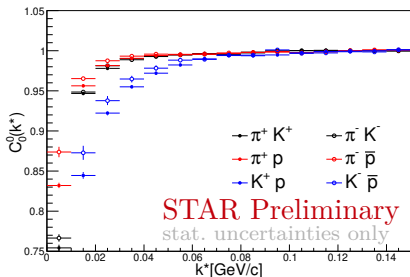
- Higher statistics for lowest energy needed (BES-II)

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



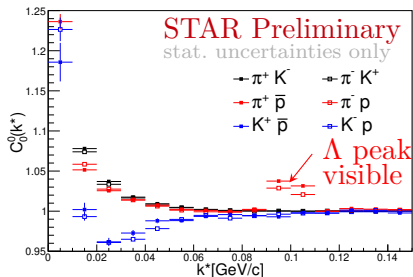
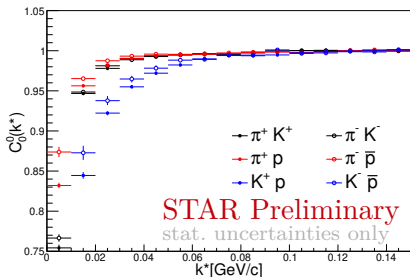
- Visible centrality dependence

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



- Like sign pairs are dominated by Coulomb
- Kp \rightarrow strongest correlation

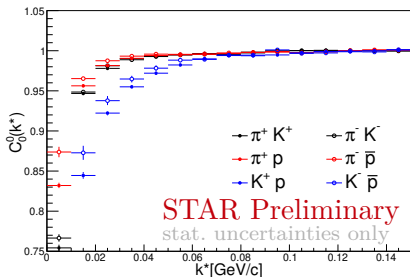
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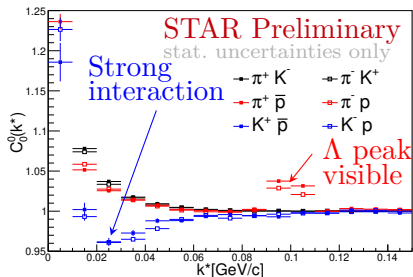
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- Unlike sign more complicated
- Λ peak visible in pion-proton

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

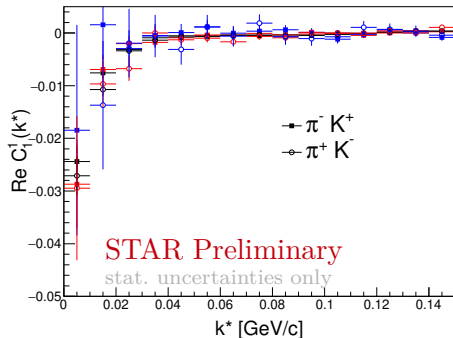
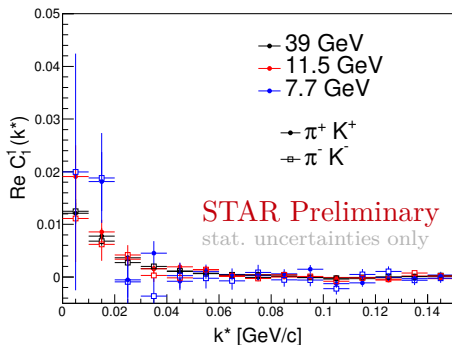


- Like sign pairs are dominated by Coulomb
- Kp \rightarrow strongest correlation



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

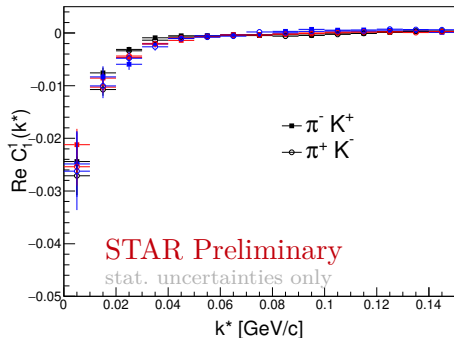
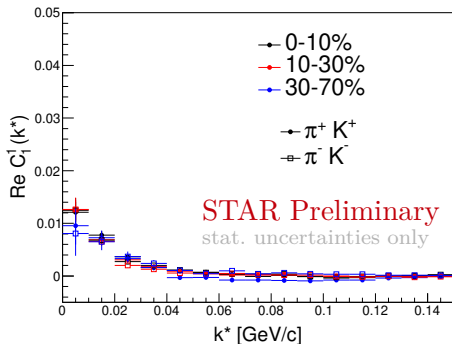
Source dynamics — energy dependence



- Clear signal of emission asymmetry

- Visible energy dependence

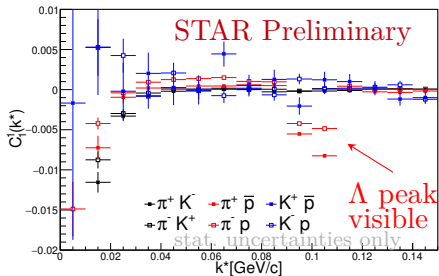
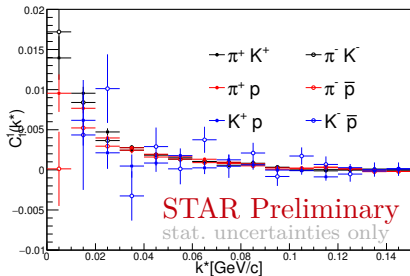
Source dynamics — centrality dependence



- Clear signal of emission asymmetry

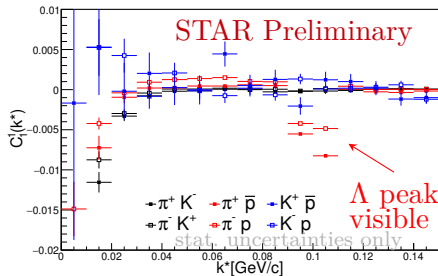
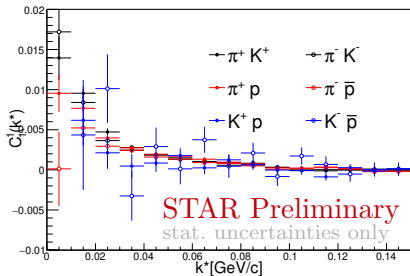
- Visible centrality dependence

Source dynamics — system dependence



- Visible signal of emission asymmetry

Source dynamics — system dependence



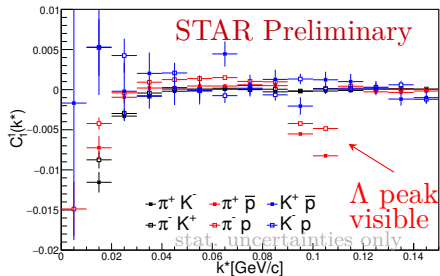
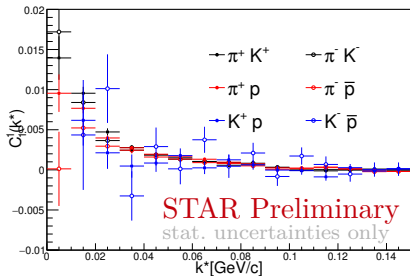
- Visible signal of emission asymmetry

- 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

$p\Omega$ dibaryon

The ways to study

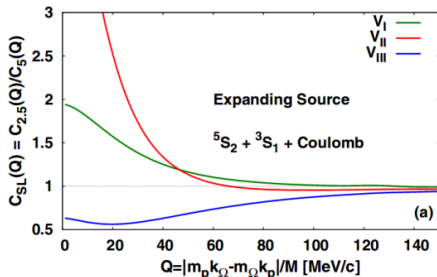
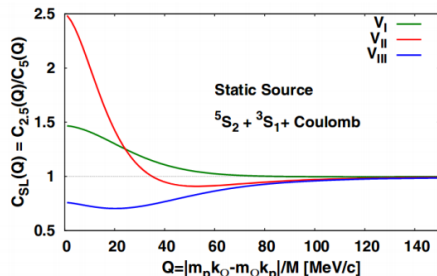
- Invariant mass method
(Large combinatorial background)
- Two-particle correlation functions
(Final State Interactions, exotic particles)

The ratio of correlation function between small and large collision systems can be used to extract strong interactions between proton and Ω

K. Morita et al. Phys. Rev. C 94, 031901 (2016)

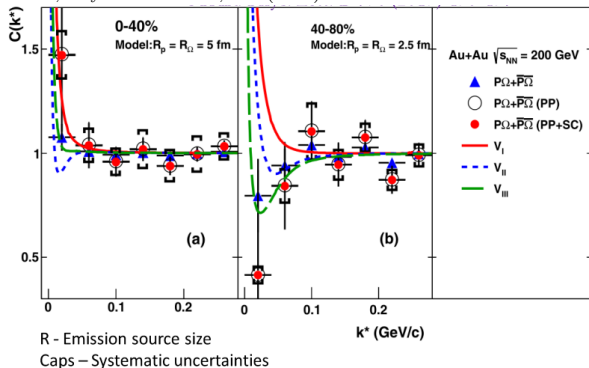
TABLE I. Binding energy (E_B), scattering length (a_0), and effective range (r_{eff}) with and without the Coulomb attraction in the $p\Omega$ system. Physical masses of the proton and Ω are used.

Spin-2 $p\Omega$ potentials		V_I	V_{II}	V_{III}
Without Coulomb	E_B (MeV)		0.05	24.8
	a_0 (fm)	-1.0	23.1	1.60
	r_{eff} (fm)	1.15	0.95	0.65
With Coulomb	E_B (MeV)		6.3	26.9
	a_0 (fm)	-1.12	5.79	1.29
	r_{eff} (fm)	1.16	0.96	0.65



$p\Omega$ correlation functions

STAR, Phys. Lett. B 790, 490 (2019)



K. Morita et al. Phys. Rev. C 94, 031901 (2016)

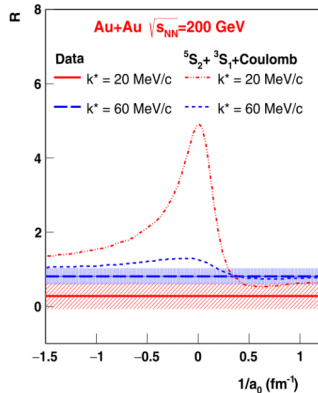
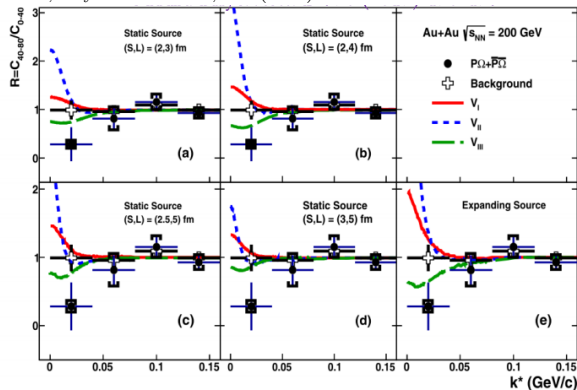
Binding energy (E_b), scattering length (a_0) and effective range (r_{eff}) for the Spin-2 proton- Ω potentials [24].

Spin-2 $p\Omega$ potentials	V_I	V_{II}	V_{III}
E_b (MeV)	-	6.3	26.9
a_0 (fm)	-1.12	5.79	1.29
r_{eff} (fm)	1.16	0.96	0.65

Comparison of the measured $p\Omega$ correlation functions from 0-40% and 40-80% central Au+Au collisions with the predictions for $p\Omega$ interaction potentials V_I , V_{II} and V_{III}

$p\Omega$ correlation functions

STAR, Phys. Lett. B 790, 490 (2019)



- Data favor a positive scattering length for the $p\Omega$ interaction
- Positive scattering length and measured ratio less than unity for $k^* < 40$ MeV/c (within 1σ) favors $p\Omega$ interaction potential V_{III} with $E_b \sim 27$ MeV for proton and Ω

Geometry:

- Femtoscopy is sensitive to the homogeneity length
- Visible centrality, system and energy dependence of source size at BES energies
- Pion and kaon radii seem to follow different m_T dependence

Dynamics:

- Clear signal of emission asymmetry for pion-kaon systems
 - ▶ which implies collectivity effects
- Lighter particles are emitted closer to the center and/or later

Hadron physics:

- Obtained data indicate that the scattering length is positive and favor $p\Omega$ bound state hypothesis

Thank you for your attention