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

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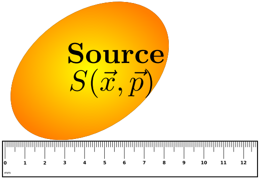
Femtoscopy

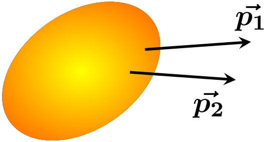


Impossible to examine the particle emitting source directly

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

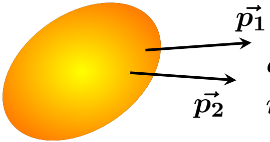
Femtoscopy measures space-time characteristics of the source through momentum correlations

Femtoscopy



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

Femtoscopy



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

experiment | theory (models)

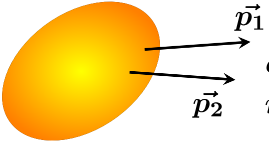
$$C(\vec{q}) = \frac{A(\vec{q})}{B(\vec{q})}$$

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

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

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

Femtoscopy



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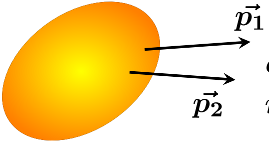

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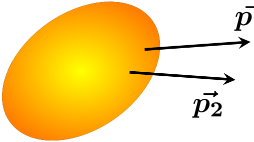
Femtoscopy

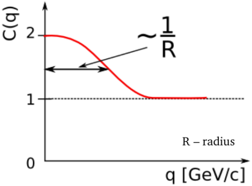


$\vec{p_1}$

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

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

$\vec{p_2}$



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

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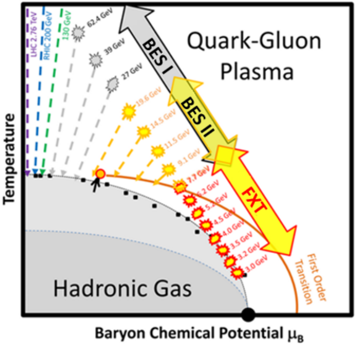
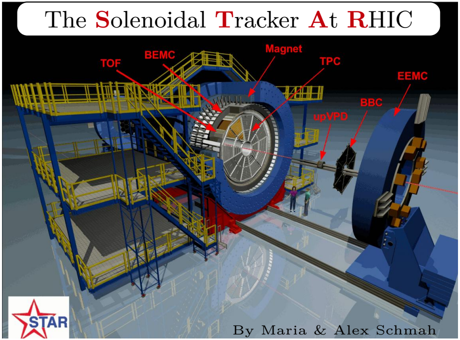
Introduction

- **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 ($p\Omega$)



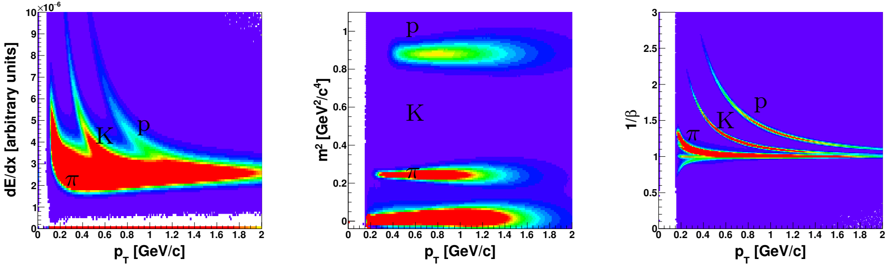
Nucl. Phys. A 967, 808 (2017)

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 & $1/\beta$



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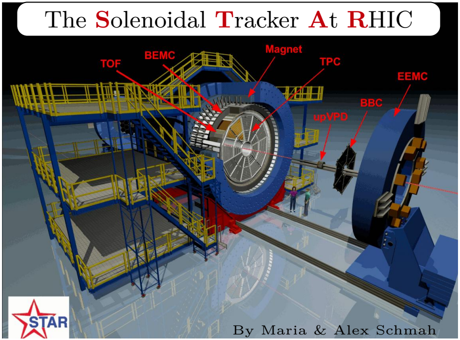

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$\sqrt{s_{NN}}$ [GeV]	7.7	11.5	39 (0-10%)	39 (10-30%)	39 (30-70%)
#events [mln]	0.24	1.3	11.7	25.7	45.4

Reference frame

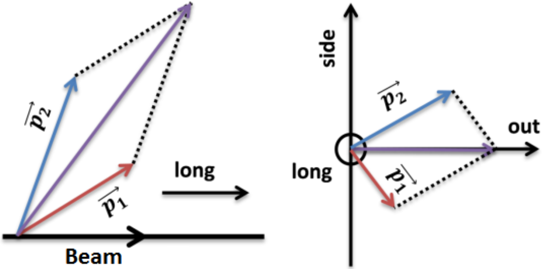
Longitudinally Co-Moving System (LCMS)

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

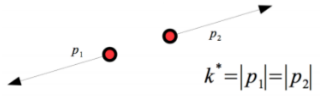
***Side*:** sensitive to the geometrical size



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

Reference frame

Pair Rest Frame (PRF)



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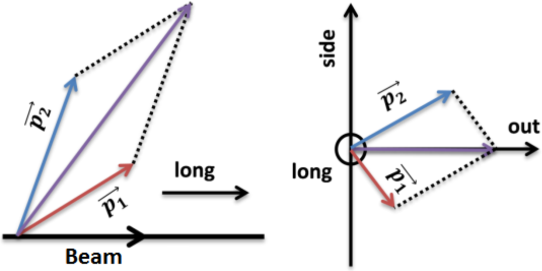

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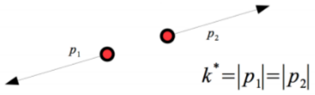

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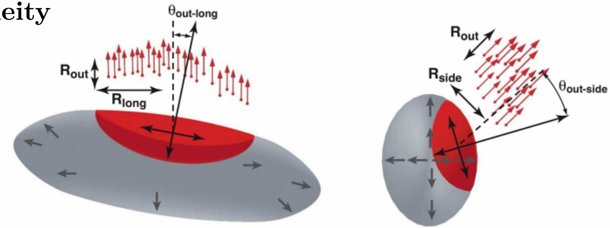
Region of homogeneity



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

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

Kaons — fitting procedure

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

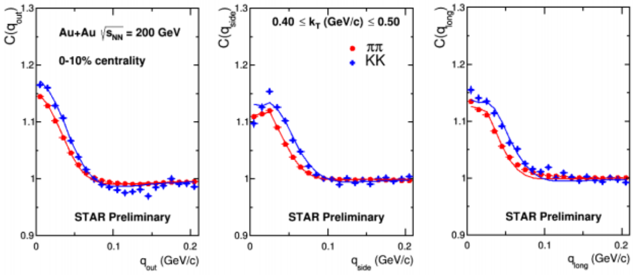
Bowler-Sinyukov formula:

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

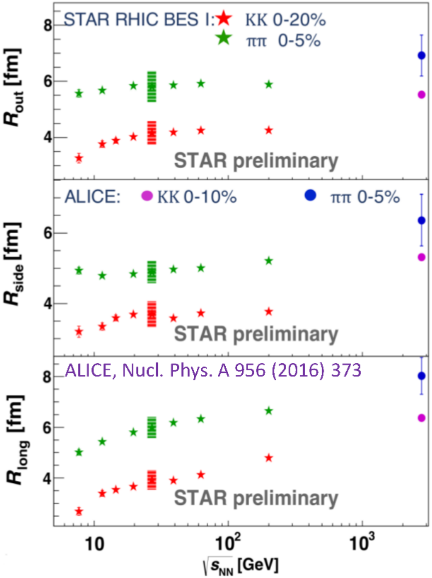
λ - the correlation strength
$K(q_{inv})$ - Coulomb factor

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

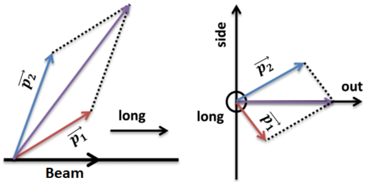
Y. Sinyukov, et al.
Phys. Lett. B432, 248 (1997)



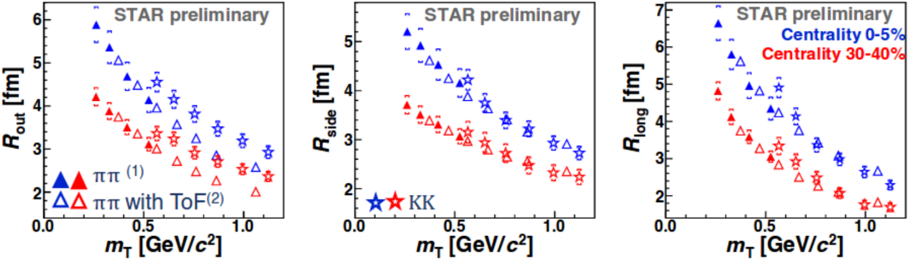
Radii from BES-I



- 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



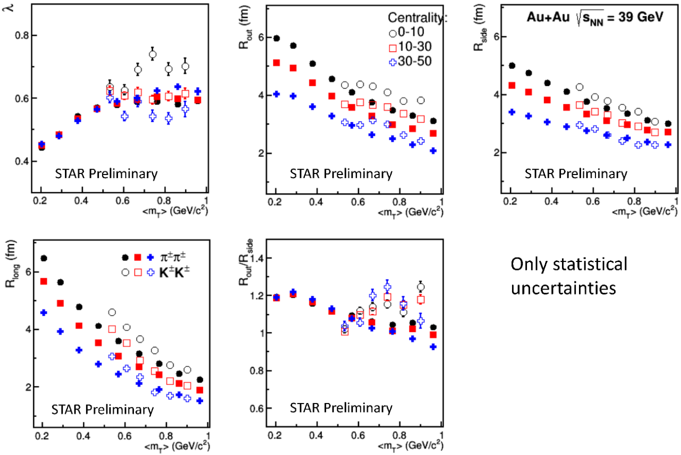
Results from 200 GeV



- 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



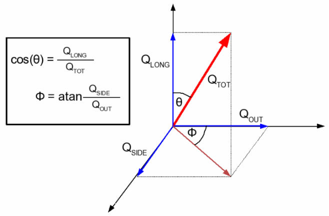
Only statistical uncertainties

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

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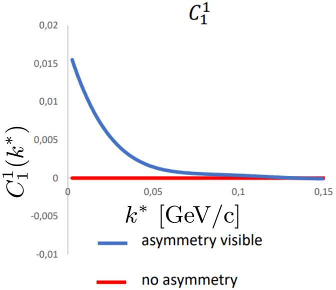
$C_0^0 \rightarrow$ sensitive to the size of the emitting source (shapes same as correlation function)

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



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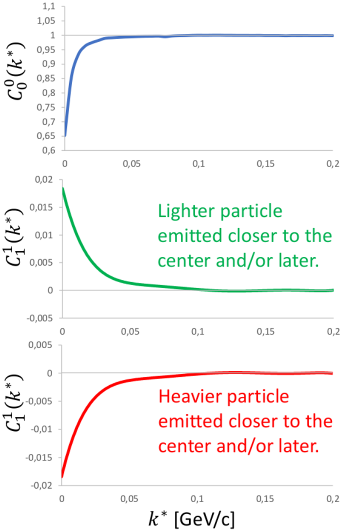
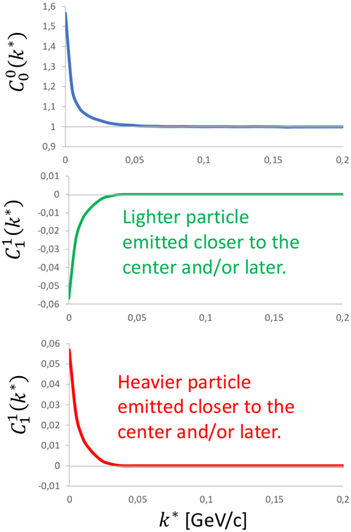
Which particle...?

Like-sign particle combinations



Unlike-sign particle combinations



Pion-kaon femtoscopy — asymmetry

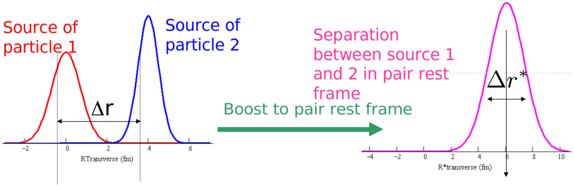
$$C(\vec{q}) = \int |\Psi(\vec{q},\vec{r})|^2 S(\vec{r}) d^3r$$

known — unknown

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

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

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



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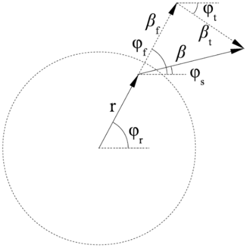

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assumption: $\sigma_{side} = \sigma_{out}$, $\sigma_{long} = 1.3\sigma_{out}$

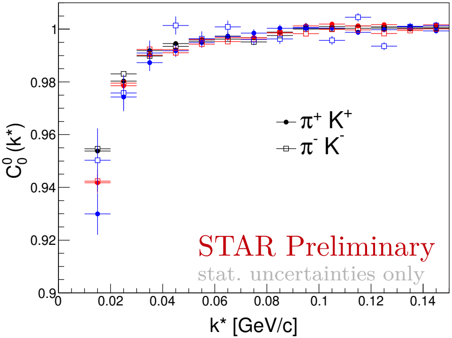
$$\beta_{particle} = \beta_f + \beta_t$$

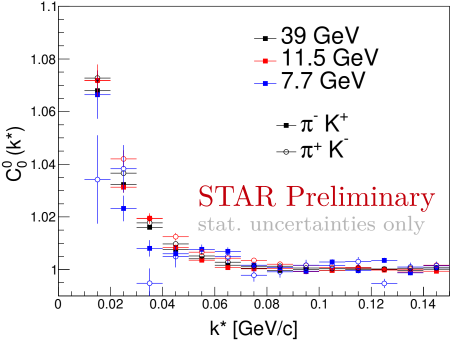
β_f — collective (flow) velocity

β_t — thermal (random) velocity

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

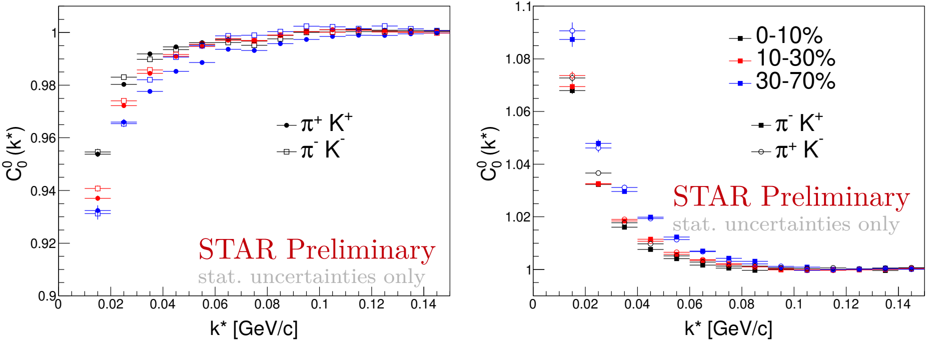
Energy dependence





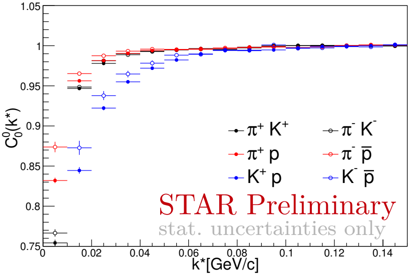
- Visible energy dependence
- Higher statistics for lowest energy needed (BES-II)

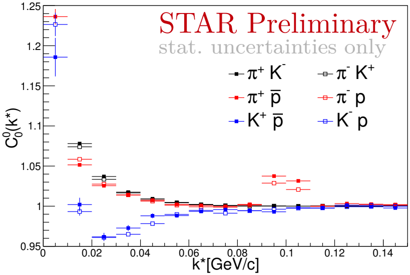
Centrality dependence, $\sqrt{s_{NN}} = 39$ GeV



- 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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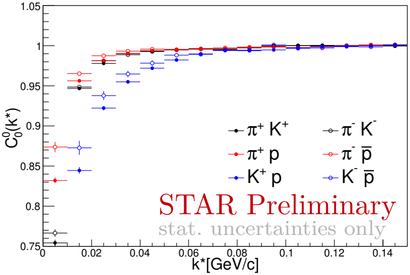

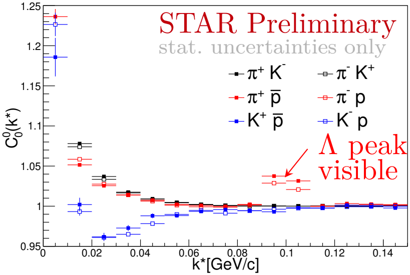

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- Kp $\rightarrow$ strongest correlation

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

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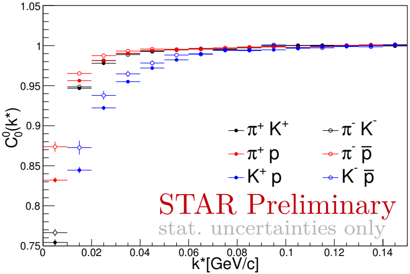
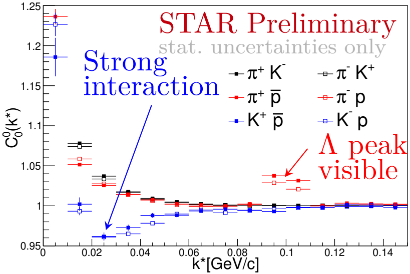
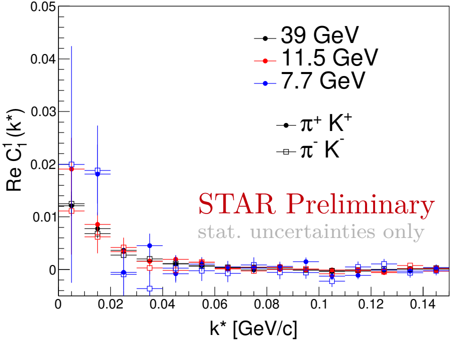


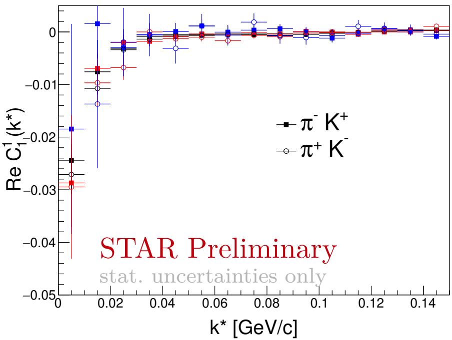


- Like sign pairs are dominated by Coulomb
- Kp → strongest correlation

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

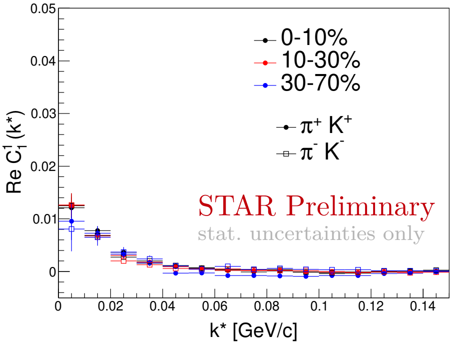
Source dynamics — energy dependence

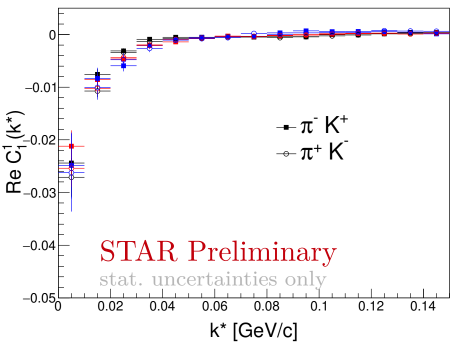




- Clear signal of emission asymmetry
- Visible energy dependence

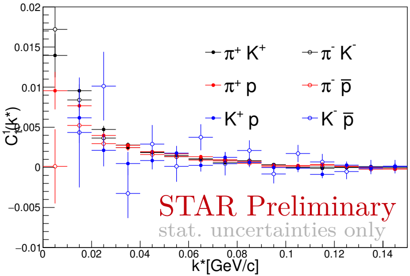
Source dynamics — centrality dependence

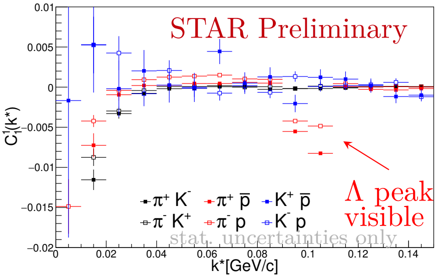




- Clear signal of emission asymmetry
- Visible centrality dependence

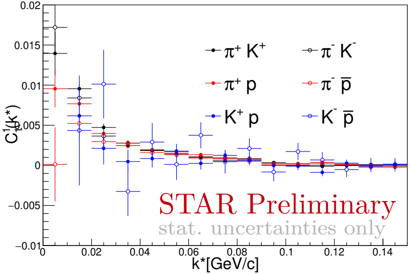
Source dynamics — system dependence

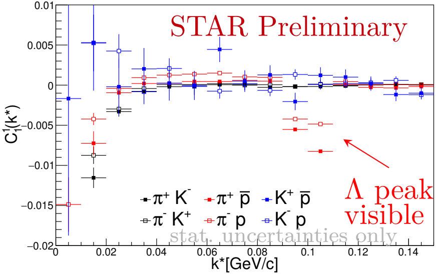




- Visible signal of emission asymmetry

Source dynamics — system dependence



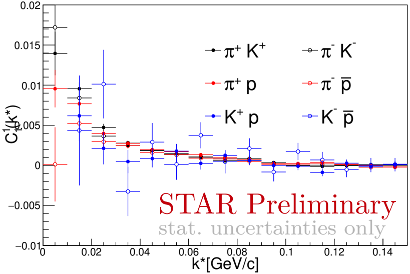


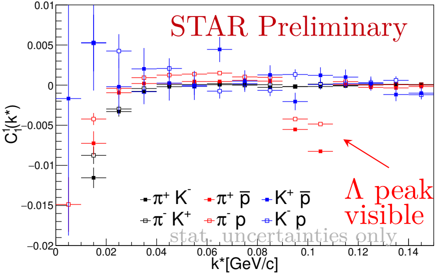
- Visible signal of emission asymmetry
- Expected ordering of particles — confirmed

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

pΩ dibaryon

The ways to study

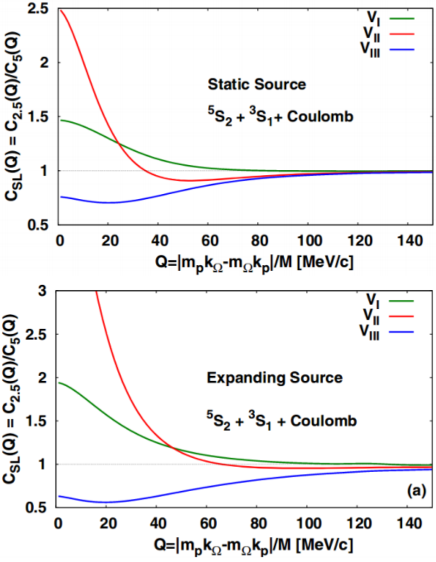
- Invariant mass method
  (Large combinatorial background)
- Two-particle correlation functions
  (Final State Interactions, exotic particles)

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)

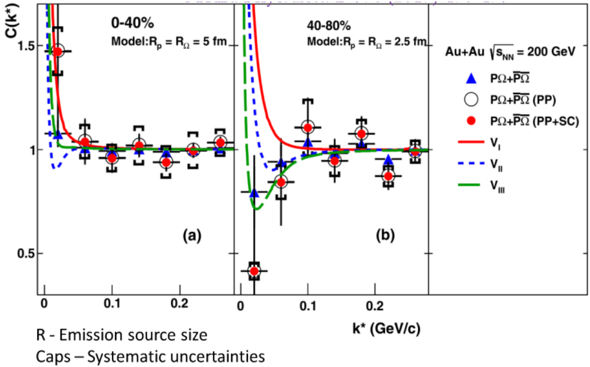
TABLE I. Binding energy (E_B), scattering length (a_0), and effective range ($r_{\rm eff}$) with and without the Coulomb attraction in the $p\Omega$ system. Physical masses of the proton and Ω are used.

Spin-2 $p\Omega$ potentials		$V_{\rm I}$	$V_{\rm II}$	$V_{\rm III}$
Without Coulomb	E_B (MeV)		0.05	24.8
	a_0 (fm)	−1.0	23.1	1.60
	$r_{\rm eff}$ (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
	$r_{\rm eff}$ (fm)	1.16	0.96	0.65



pΩ correlation functions

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



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

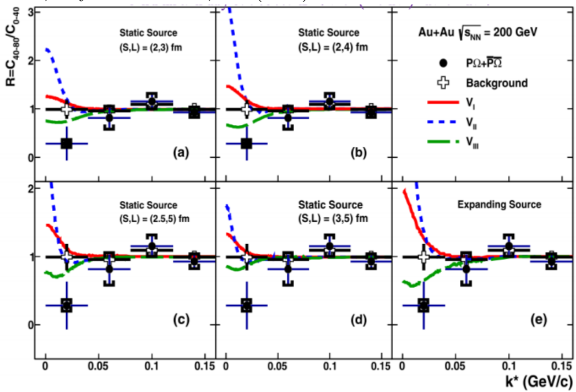
Binding energy ($\mathbf{E_b}$), scattering length ($\mathbf{a_0}$) and effective range ($\mathbf{r_{eff}}$) for the Spin-2 proton–Ω potentials [24].

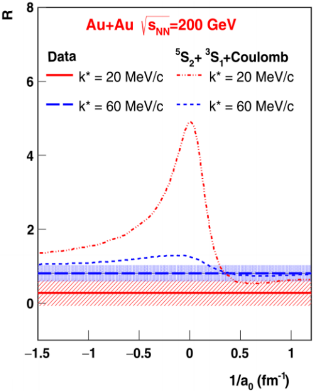
Spin-2 pΩ potentials	V_I	V_{II}	V_{III}
$\mathbf{E_b}$ (MeV)	–	6.3	26.9
$\mathbf{a_0}$ (fm)	−1.12	5.79	1.29
$\mathbf{r_{eff}}$ (fm)	1.16	0.96	0.65

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

pΩ correlation functions

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





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

Summary

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 pΩ bound state hypothesis

Summary

Thank you for your attention