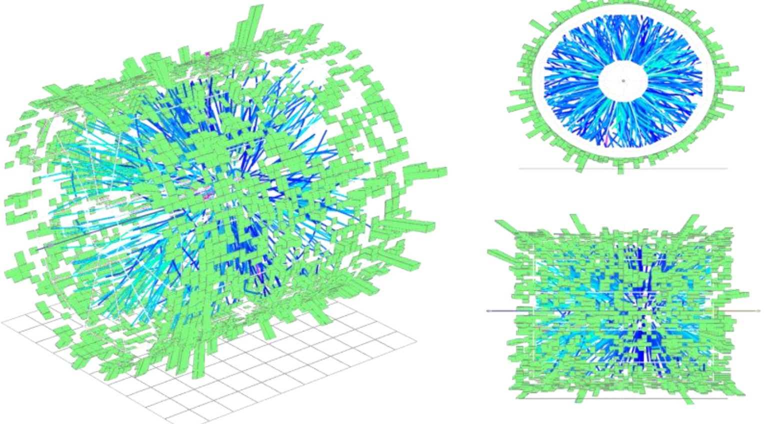
Femtoscopic probes with strange particles in STAR



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XIV Workshop on Particle Correlations and Fluctuations

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Outline

- Motivation
- Correlation femtoscopy
- The STAR experiment
- Pion and kaon results from BES-I and FXT
- pΩ correlations at 200 GeV
- Summary

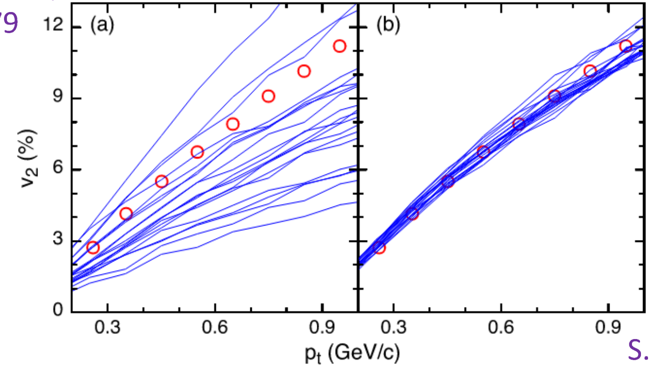
Motivation

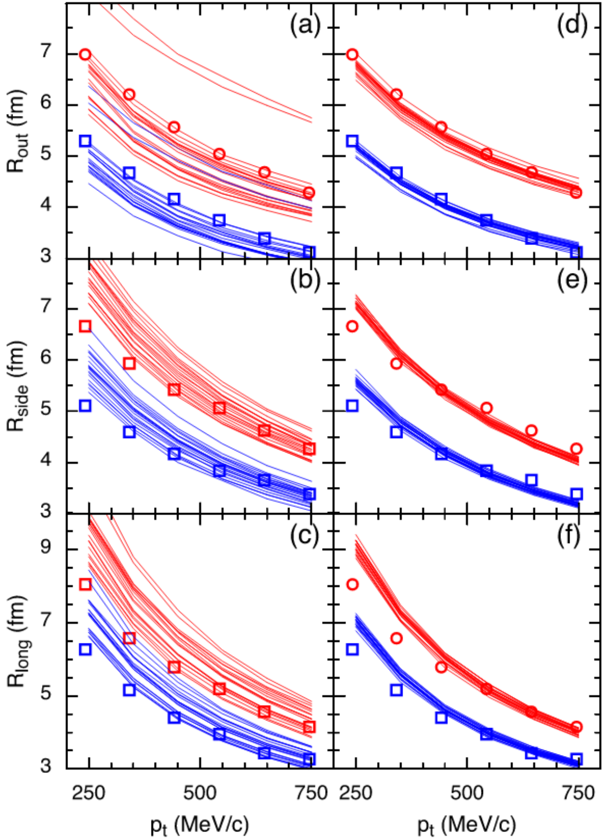
- Access to the spatial and temporal information about the particle-emitting source at kinetic freeze-out

- Different particle species are sensitive to various effects (Final State Interactions (FSI), transport properties, asymmetries, etc…)

V.M. Shapoval et al. NPA 968 (2017) 391
M.A. Lisa et al. Ann. Rev. Nucl. Part. Sci. 55 (2005) 357
D.H. Rischke, M. Gyulassy. NPA 608 (1996) 479
R. Lednicky et al. Phys. Lett. B 373 (1996) 30

- Model constraints





S. Pratt et al. Phys. Rev. Lett. 114 (2015) 202301

Correlation Function

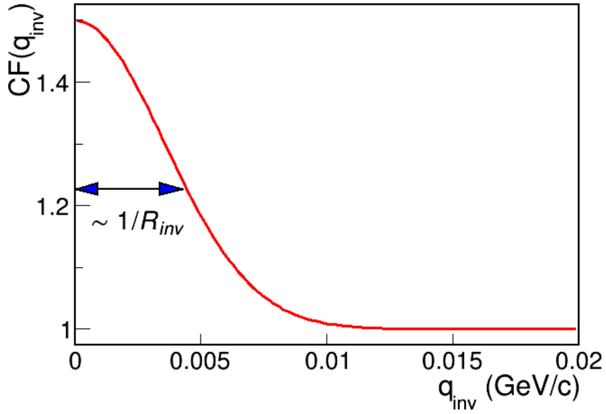
- Two-particle correlation function (CF):

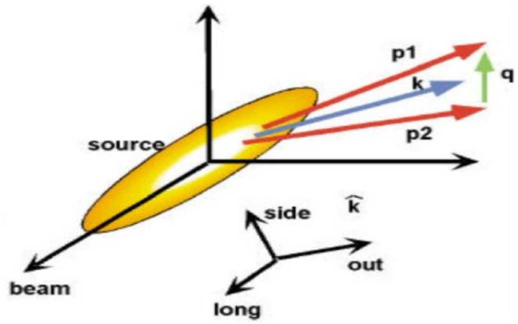
  $CF(p_1, p_2) = \int d^4r\, S(r, k)\, |\Psi_{1,2}(r, k)|^2$

  $r = x_1 - x_2$ and $q \equiv q_{inv} = p_1 - p_2$
- Experimentally:

  $CF(q) = A(q)/B(q)$

  - A(q) – contain quantum statistical (QS) correlations and final state interactions (FSI)
  - B(q) – obtained via mixing technique (does not contain QS and FSI)





The relative pair momentum can be projected onto the Bertsch-Pratt, out-side-long system:

q_{long} – along the beam direction

q_{out} – along the transverse momentum of the pair

q_{side} – perpendicular to longitudinal and outward directions

Correlation functions are constructed in Longitudinally Co-Moving System (LCMS), where $p_{1z}+p_{2z}=0$

S. Pratt. Phys. Rev. D 33 (1986) 1314

G. Bertsch. Phys. Rev. C 37 (1988) 1896

Fitting Procedure

- Femtoscopic radii are extracted by fitting C(**q**) with (Bowler-Sinyukov procedure):

$$C(q_{out}, q_{side}, q_{long}) = N\left[1 - \lambda + \lambda K(q_{inv})\left(1 + \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2)\right)\right]$$

N – normalization factor
λ – correlation strength
$K(q_{inv})$ – Coulomb correction
R_{side} ~geometrical size of the system
R_{out} ~ geometrical size + particle emission duration
R_{long} ~ medium lifetime

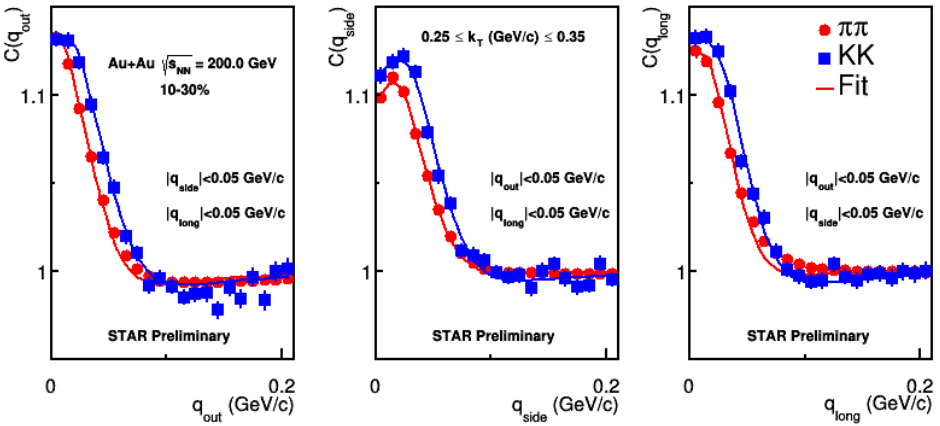
Yu. Sinyukov et al. Phys. Lett. B 432 (1998) 248
M. Bowler. Phys. Lett. B 270 (1991) 69

- Fit using Log-likelihood method
  E-802. Phys. Rev. C 66 (2002) 054906

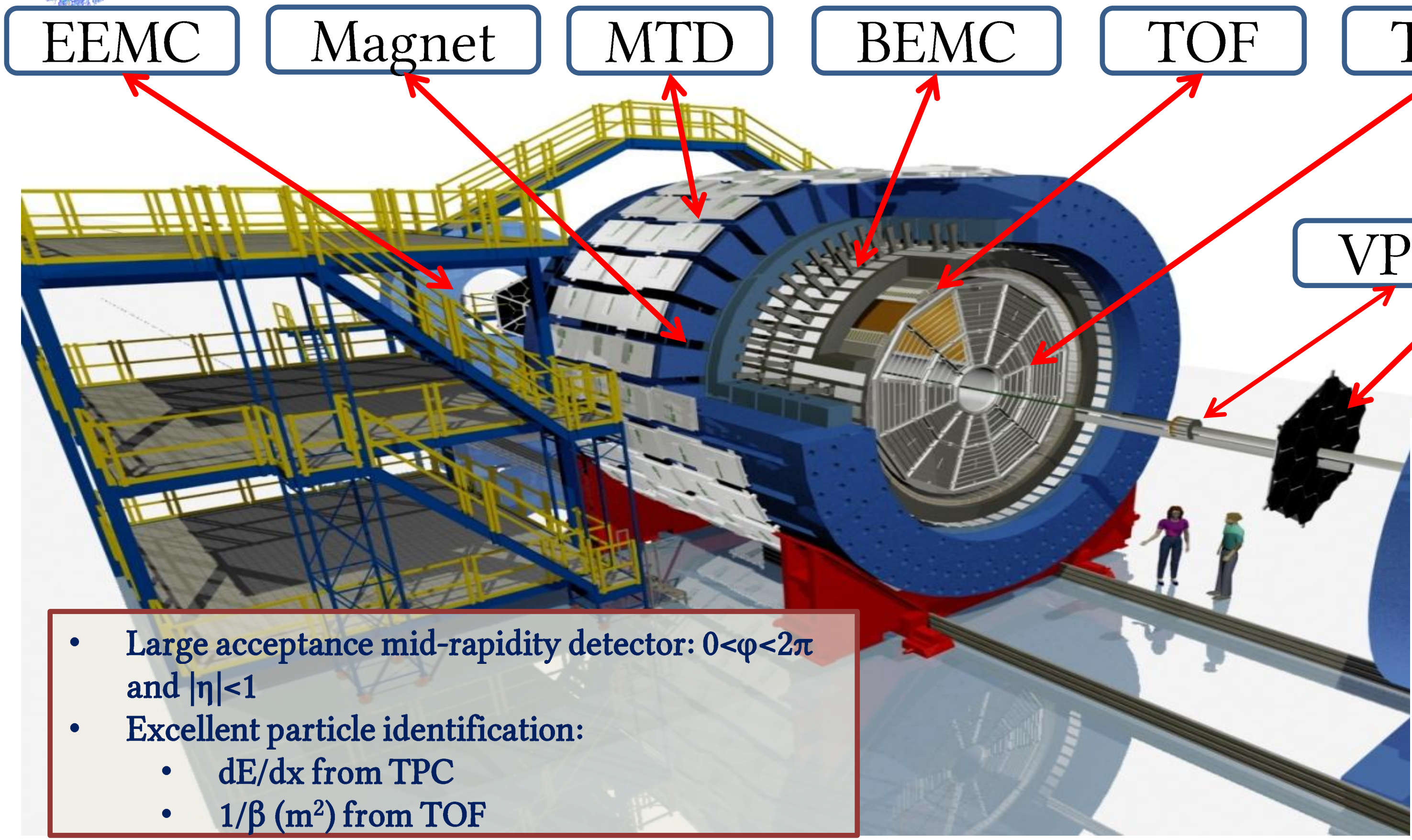
$$\chi^2 = -2\left[A\ln\left(\frac{C(A+B)}{A(C+1)}\right) + B\ln\left(\frac{A+B}{B(C+1)}\right)\right], C = \frac{A}{B}$$

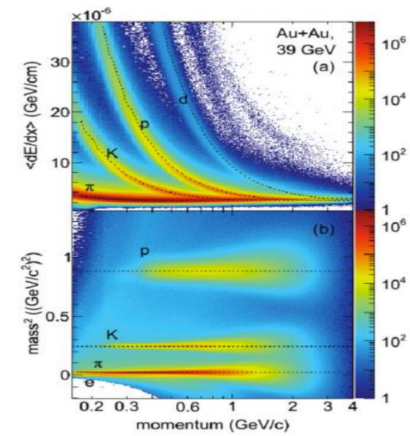
- Fit example

Out, side and long projections of ππ and KK correlation functions and fits



The Solenoidal Tracker At RHIC





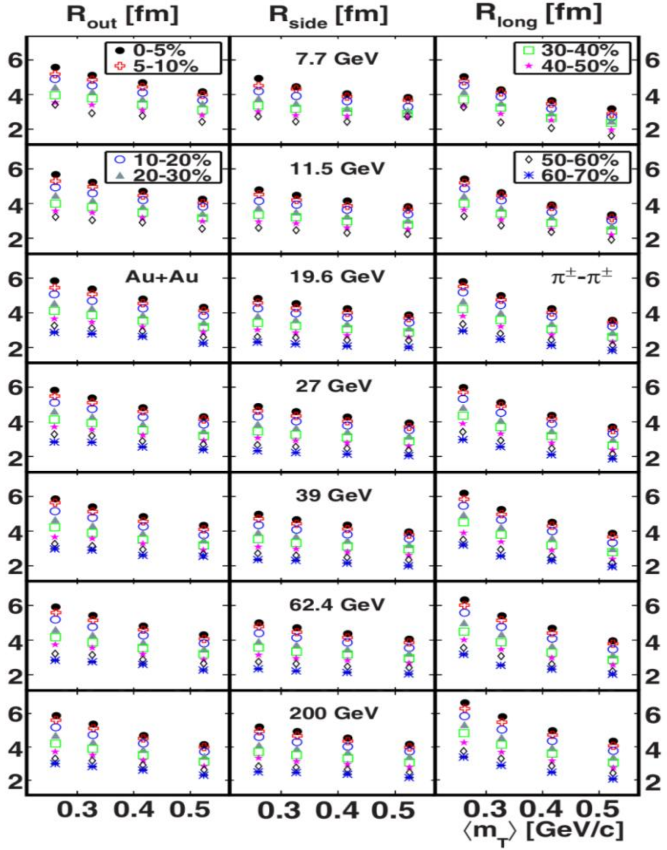
- Large acceptance mid-rapidity detector: $0<\varphi<2\pi$ and $|\eta|<1$
- Excellent particle identification:
  - dE/dx from TPC
  - $1/\beta$ (m^2) from TOF

Previous Pion Results from STAR

- Pion correlations have been extensively measured in STAR
- The decrease of the femtoscopic radii with increasing transverse mass $m_T = \sqrt{k_T^2 + m^2}$ is attributed to the hydrodynamic flow in heavy-ion collisions
- To make the comparison with kaons, the extension to the higher m_T is needed.
- Particle identification with TPC and TOF

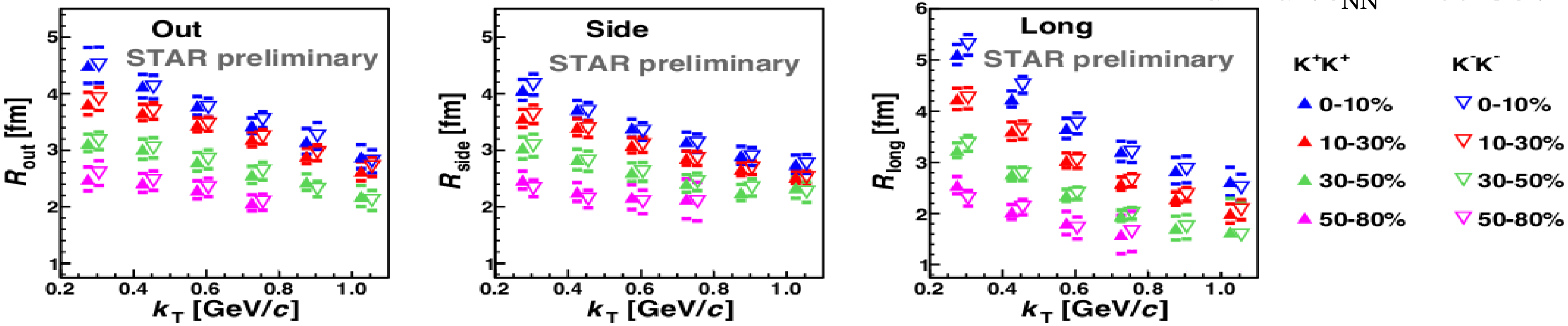
Event and pair cuts	Same as in STAR, PRC 92 (2015) 014904
Track cuts:	$\lvert\eta\rvert<1$, nHits>15
PID: if no TOF (dE/dx)	0.15 < p (GeV/c) < 0.45 π: $\lvert n\sigma_{\pi}\rvert<2$, $\lvert n\sigma_{other}\rvert>2$ K: $\lvert n\sigma_{K}\rvert<2$, $\lvert n\sigma_{other}\rvert>2$
PID: If TOF (m^2+dE/dx)	0.15 < p (GeV/c) < 1.45 π: $\lvert n\sigma_{\pi}\rvert<3$, $-0.02 < m_{\pi}^2\ (GeV/c^2)^2 < 0.062$ K: $\lvert n\sigma_{K}\rvert<3$, $0.20 < m_K^2\ (GeV/c^2)^2 < 0.32$

STAR. PRC 92 (2015) 014904



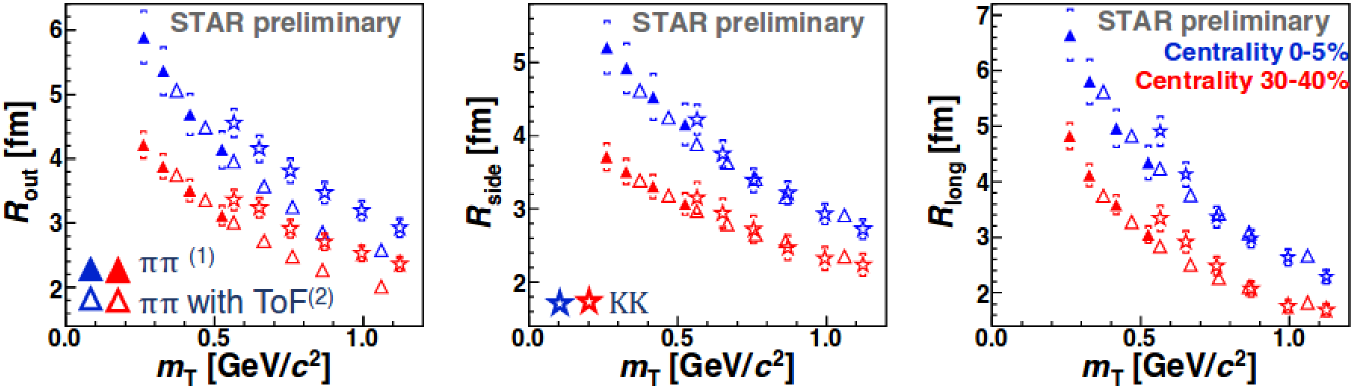
Charged kaons at top RHIC energy

Au+Au $\sqrt{s_{NN}}$ = 200 GeV



- Measured femtoscopic radii for positive and negative kaon pairs agree with each other within the uncertainties
- Extracted radii decrease with increasing transverse momentum – influence of the collective radial flow S. Akkelin et al. Phys. Lett. B 356 (1995) 525

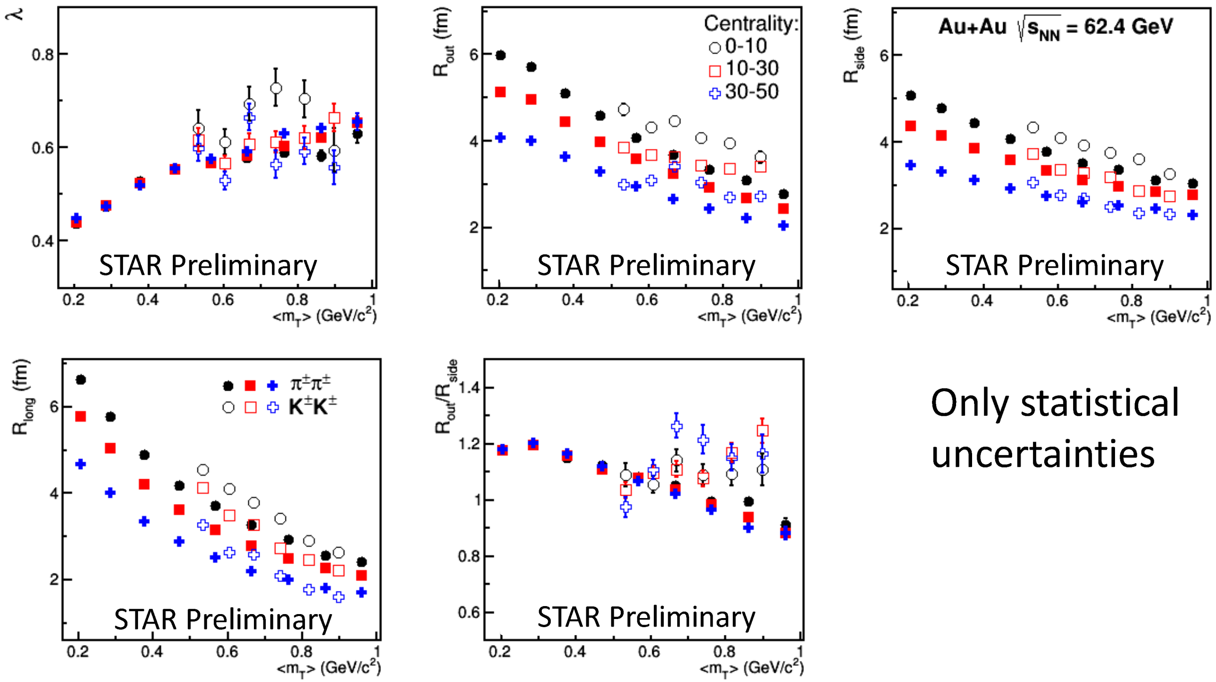
Results from 200 GeV



- Extending transverse mass region (up to 1 GeV/c^2) using particle identification from the Time-Of-Flight detector
- Pion results are consistent with the previous analysis[(1)]
- 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 (2015) 014904
(2) This analysis: STAR Preliminary
(3) Yu.M. Sinyukov, et al. Nucl. Phys. A 946 (2015) 227

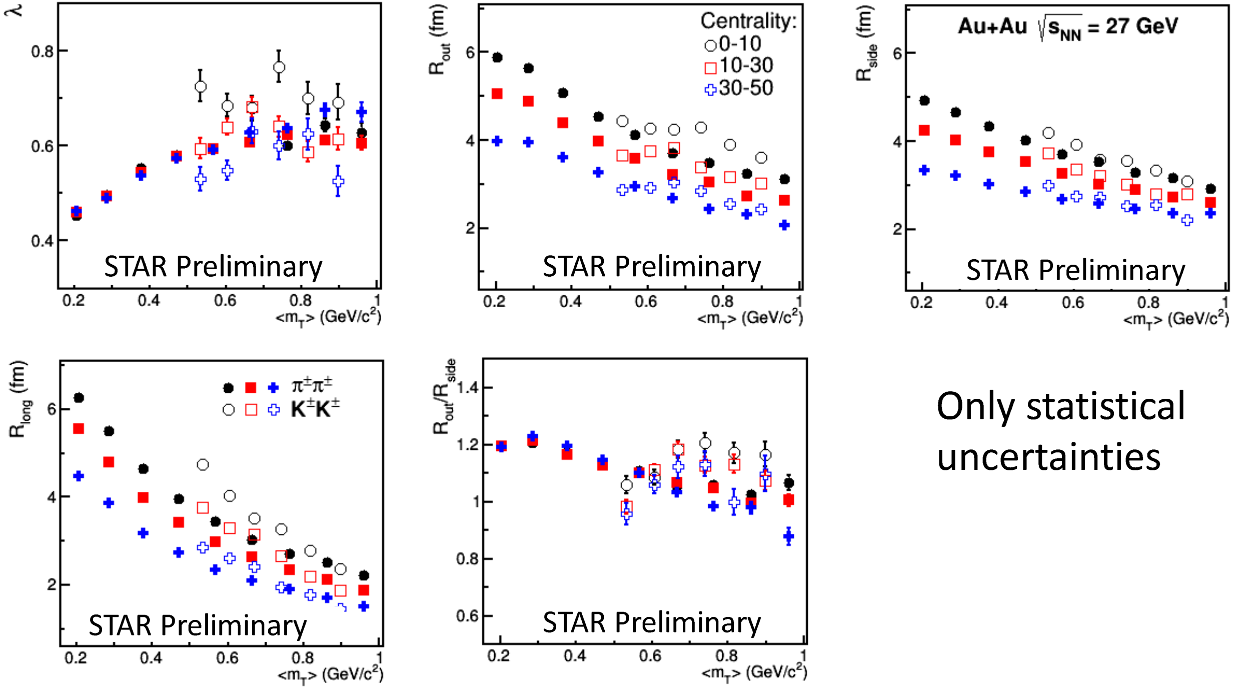
Results from 62.4 GeV



Only statistical uncertainties

- Kaon femtoscopic radii in outward and longitudinal directions are generally larger than those for pions at the same m_T → breaking of the m_T-scaling
- In the sideward direction, the pion and kaon radii are closer than in other directions

Results from 27 GeV



Only statistical uncertainties

- Kaon femtoscopic radii in outward and longitudinal directions are generally larger than those for pions at the same m_T → breaking of the m_T-scaling
- In the sideward direction, the pion and kaon radii are similar

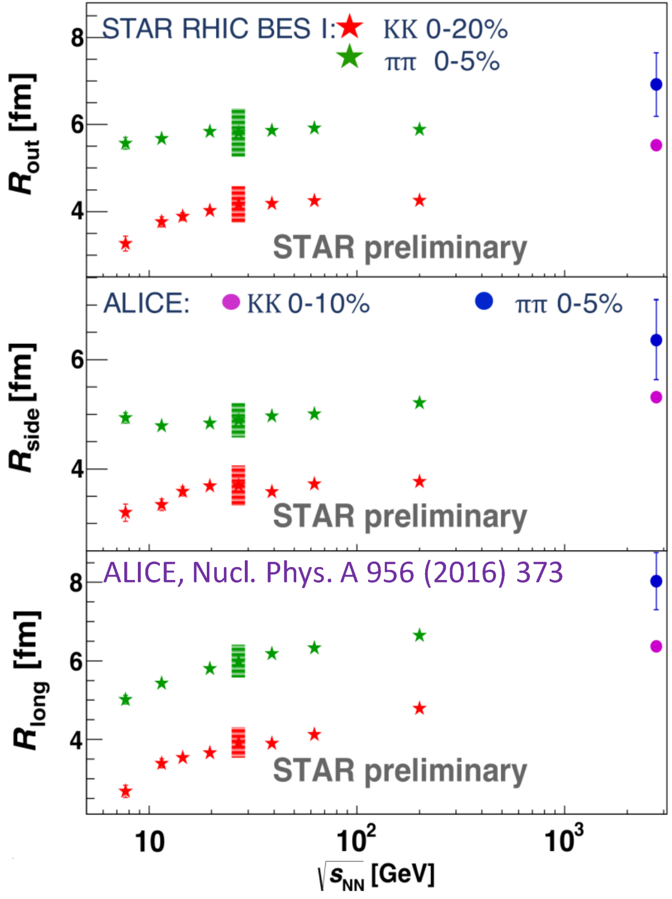
Radii from Beam Energy Scan I

Shaded boxes represent systematic uncertainties

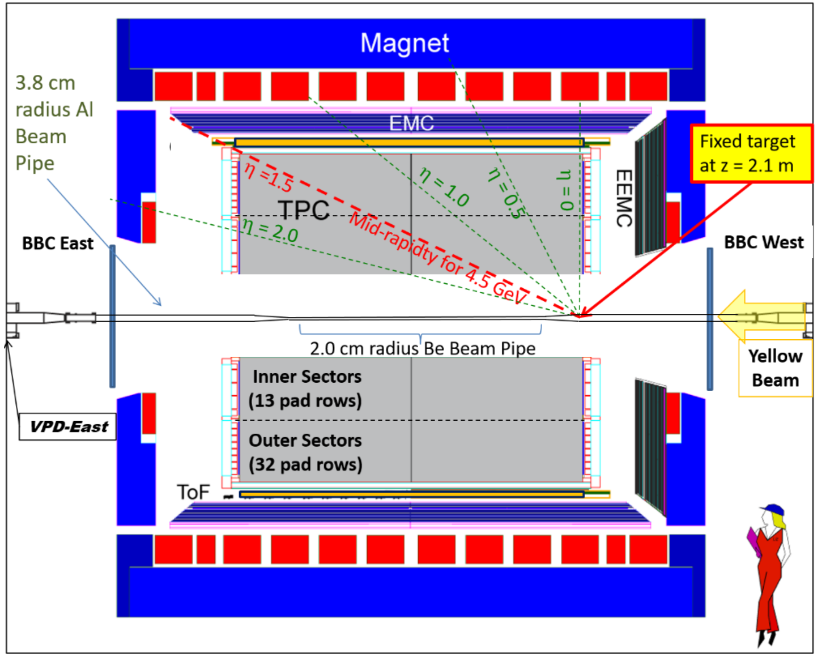
The extracted femtoscopic radii smoothly increase with increasing collision energy

The values of R_{out} and R_{side} for both pions and kaons show a very small increase at the RHIC energies and slightly larger at the LHC

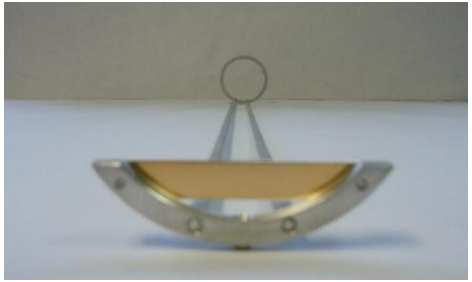
The values of R_{long} suggest that the system lives longer at the LHC energy

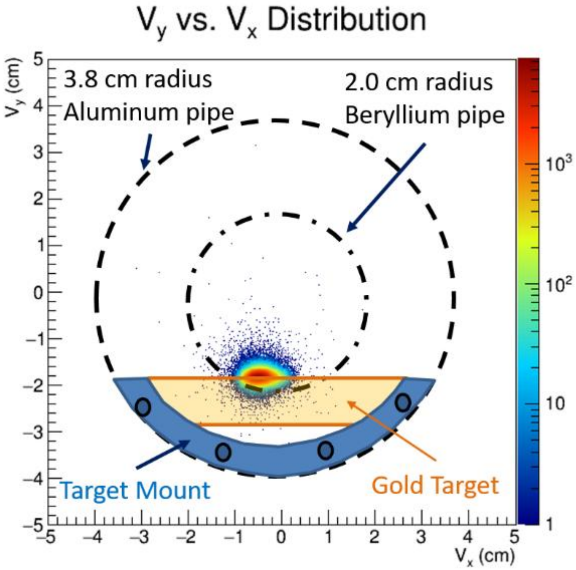


The STAR Fixed-Target (FXT) Program



A 1 mm thick (4% inter. prob.) gold target

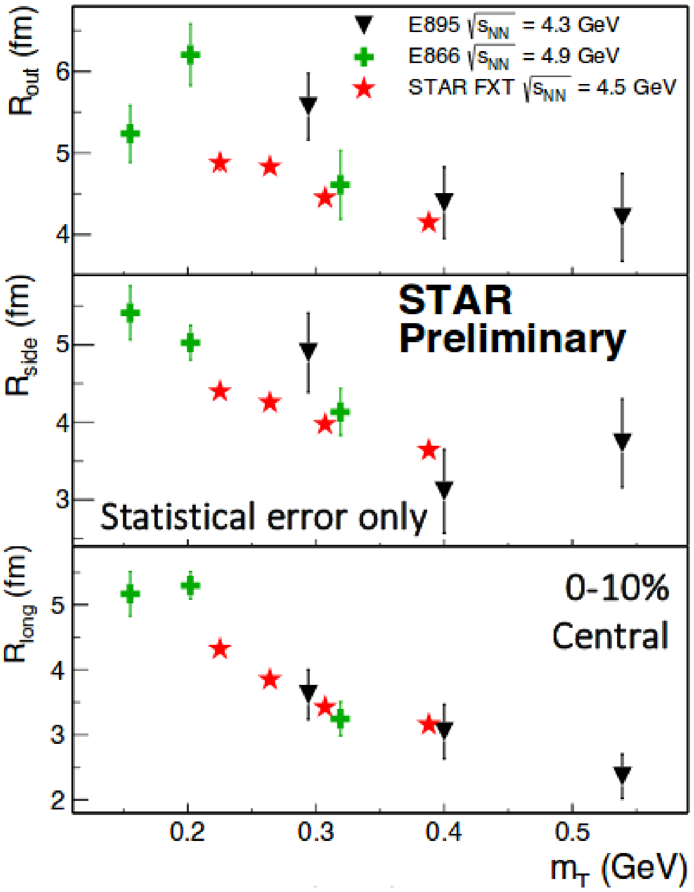


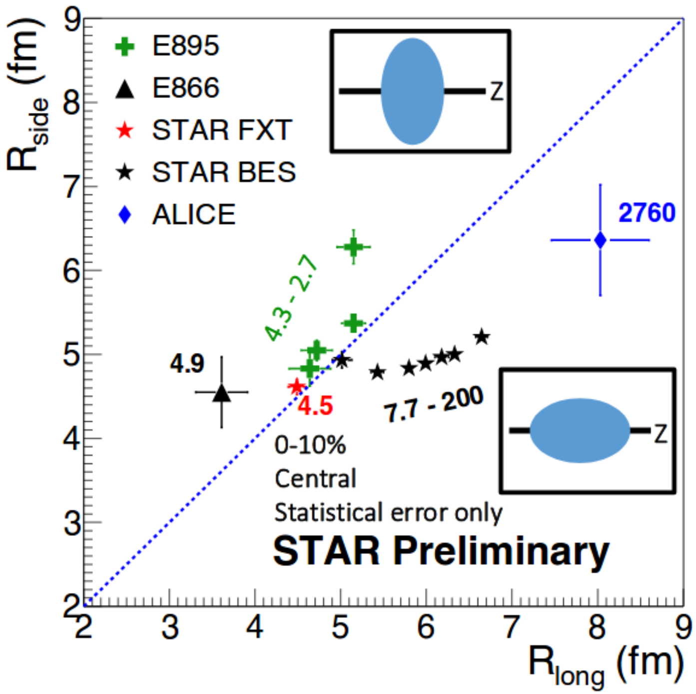


- 1.3M events from half hour test run (2014), top 30% central trigger, Au+Au $\sqrt{s_{NN}}$=4.5 GeV
- Full data taking $\sqrt{s_{NN}}$=3.0-7.7 GeV starting 2018

[RHIC Beam Use Request For Runs 18 and 19 (The STAR Collaboration)]

Pion Femtoscopy from FXT





E866. Phys. Rev. C 66 (2002) 054096
E895 .Phys. Rev. Lett. 84 (2000) 2798
ALICE. Phys. Rev. B 696 (2011) 328
STAR. Phys. Rev. C 92 (2015) 014904

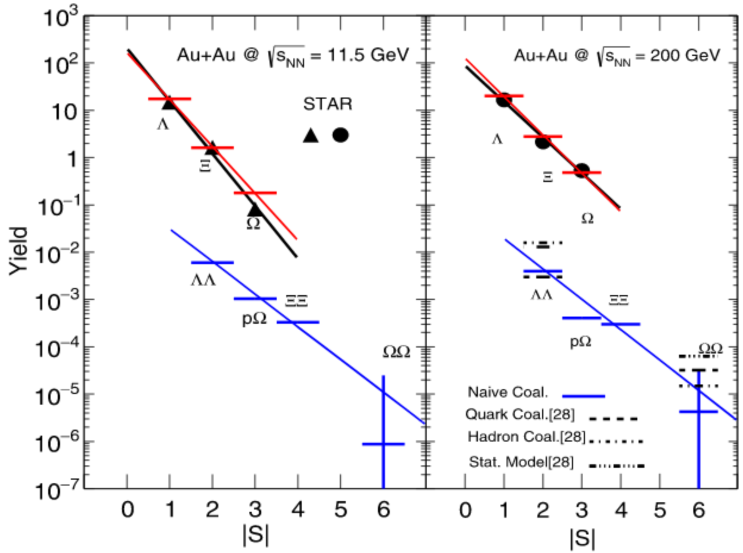
- Consistent with results from AGS experiments
- Apparent source shape evolves from oblate to prolate, as energy increases
- Increased longitudinal expansion above FXT energy

Exotics in the Strangeness Sector

Standard model:
baryons (3 quarks), mesons (quark-antiquark)

Quark Bag Model (1977):
Jaffe predicted H-dibaryon ($\to\Lambda\Lambda$) made of six quarks (uuddss)
R. Jaffe, Phys. Rev. Lett. 38 (1977) 195
R. Jaffe, Phys. Ref. Lett. 38 (1977) 617(E)

Exotic hadrons - long-standing challenge in hadron physics
Dibaryon systems: $\Lambda\Lambda$, NΩ, $\Xi\Xi$, $\Omega\Omega$, . . .



N. Shah et al. Phys. Lett. B 754 (2016) 6

- Nucleon-Ω (NΩ): a strangeness=-3 dibaryon is stable against strong decay
- Heavy-ion collisions:
  - Hot and dense, strongly interacting partonic matter
  - Good environment for exotic hadron production

T. Goldman et al., Phys. Rev. Lett. 59 (1987) 627
H. Pang et al., Phys. Rev. C69 (2004) 065207
H. Pang et al., Phys. Rev. C70 (2004) 035204

pΩ Dibaryon

The ways to study

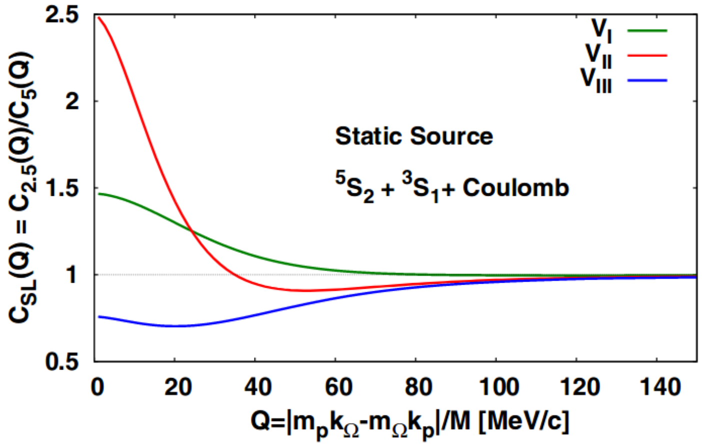
- Invariant mass method
  - Large combinatorial background
- Two-particle correlation functions
  - Final state interaction, exotic particles

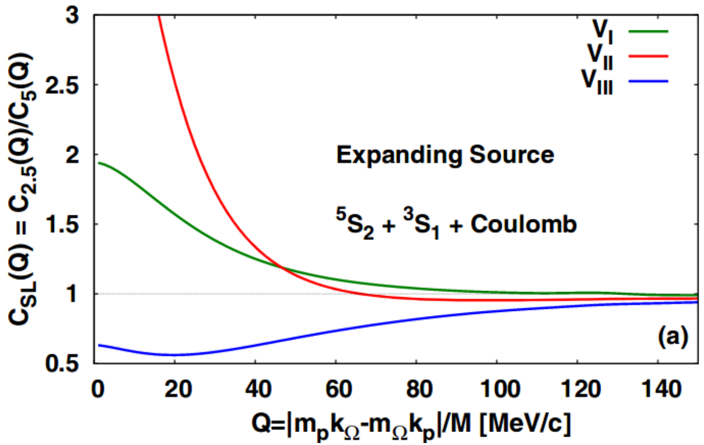
The ratio of correlation function between small and large collision systems can be used to extract strong interactions between proton and Ω

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

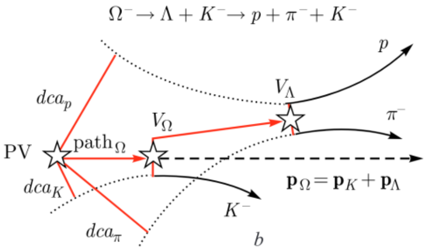
TABLE I. Binding energy (E_B), scattering length (a_0), and effective range (r_{eff}) with and without the Coulomb attraction in the $p\Omega$ system. Physical masses of the proton and Ω are used.

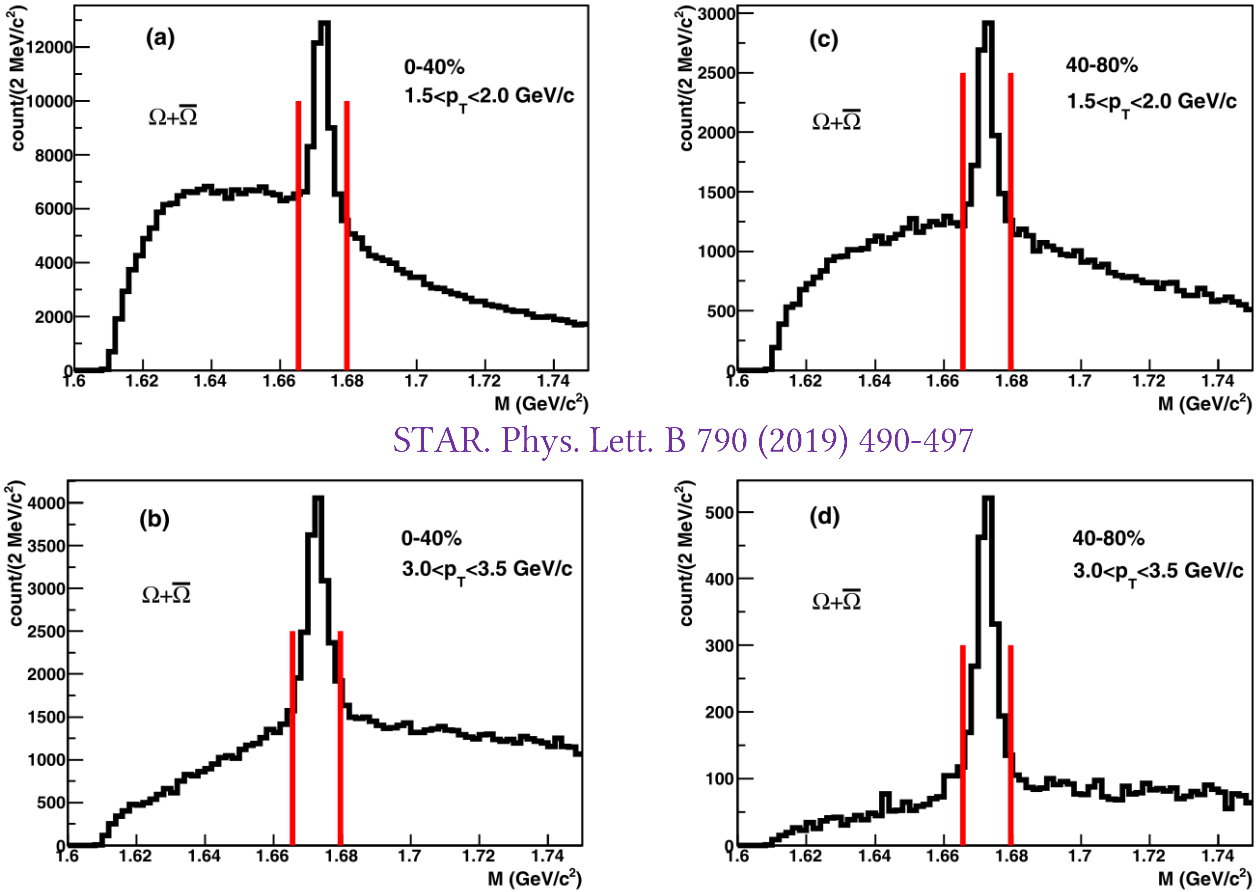
Spin-2 $p\Omega$ potentials		V_I	V_{II}	V_{III}
Without Coulomb	E_B (MeV)		0.05	24.8
	a_0 (fm)	−1.0	23.1	1.60
	r_{eff} (fm)	1.15	0.95	0.65
With Coulomb	E_B (MeV)		6.3	26.9
	a_0 (fm)	−1.12	5.79	1.29
	r_{eff} (fm)	1.16	0.96	0.65





Hyperon Reconstruction



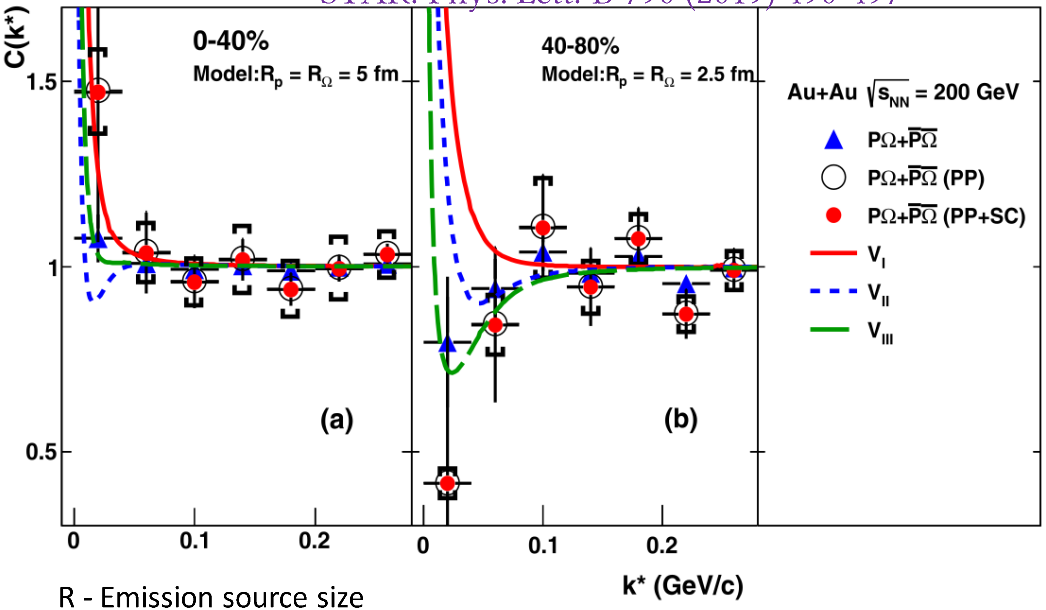


STAR. Phys. Lett. B 790 (2019) 490-497

- Daughter tracks identified using information from TPC and TOF
- Topological reconstruction
- 0-40% centrality: 38065 ± 195 proton-Ω 8816 ± 94 antiproton-Ω
- 40-80% centrality: 3037 ± 55 proton-Ω 679 ± 26 antiproton-Ω

pΩ Correlation Functions

STAR. Phys. Lett. B 790 (2019) 490-497



R - Emission source size
Caps – Systematic uncertainties

Comparison of 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}

Pair purity, P(k*), correction procedure (**PP**):

$$C'(k^*) = \frac{C_{\text{measured}}(k^*) - 1}{P(k^*)} + 1$$

where P(k*) was calculated as Sig/(Sig+Bkg) for hyperons, and purity of the proton is a product of identification probability and fraction of primary protons (from HRG)

Correlation functions have been corrected for the momentum resolution effect (**SC**):

$$C(k^*) = \frac{C'(k^*)C_{\text{in}}(k^*)}{C_{\text{res}}(k^*)}$$

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

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

Small to Large System Ratios

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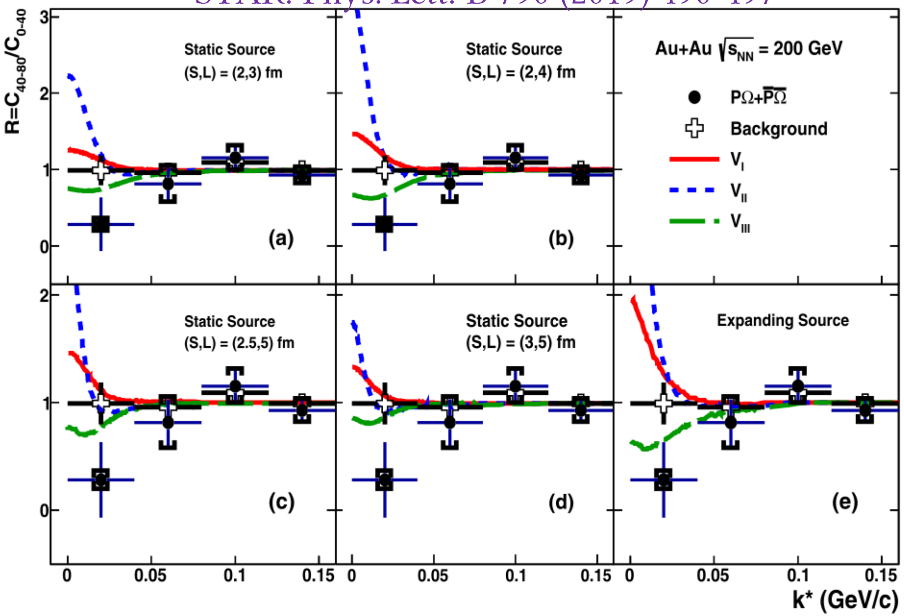

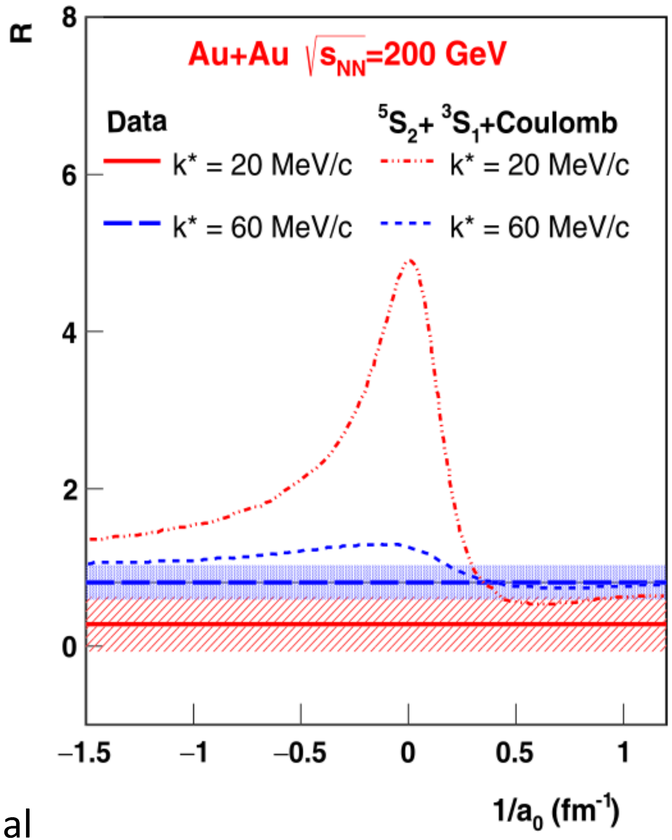

- Data favor a positive scattering length for the pΩ interaction
- The positive scattering length and the measured ratio of the pΩ correlation* function from peripheral to central collisions less than unity for k <40 MeV/c (within 1σ) favors the pΩ interaction potential V_{III} with E_b ∼27 MeV for proton and Ω

Summary

- BES-I results
  - Centrality and m_T dependence of the $\pi\pi$ and KK femtoscopic parameters has been measured
  - Pion and kaon radii seem to follow different m_T dependence
  - Model comparisons are in progress
- FXT results:
  - Consistent with results from AGS
  - Apparent source shape evolves from oblate to prolate, as energy increases
- $p\Omega$:
  - The first measurement of the $p\Omega$ correlation functions in heavy-ion collisions
  - Due to limited statistics, it is not possible to extract the interaction parameters
  - The measured ratio of CFs from peripheral to central collisions within 1 σ indicates that the scattering length is positive for the $p\Omega$ interaction and favors the $p\Omega$ bound state hypothesis

Backup slides

Hyperon selection criteria

Selection criteria for Ω and $\bar{\Omega}$ reconstruction.

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Selection criteria	0–40%		40–80%
	$p_T < 2.5$ GeV/c	$p_T > 2.5$ GeV/c	All p_T
Ω DCA	< 0.6 cm	< 0.7 cm	< 0.8 cm
Λ DCA	> 0.4 cm	> 0.3 cm	> 0.3 cm
DL(Ω)	> 4.0 cm	> 4.0 cm	> 4.0 cm
DL(Λ)	> 6.0 cm	> 6.0 cm	> 5.0 cm
$\|(V_\Omega - V_{PV}) \times p_\Omega\| / \|V_\Omega - V_{PV}\|\|p_\Omega\|$	< 0.05	< 0.08	< 0.15
$DL(\Omega) < DL(\Lambda)$	Yes	Yes	Yes
proton DCA	> 0.8 cm	> 0.8 cm	> 0.6 cm
pion DCA	> 2.0 cm	> 2.0 cm	> 1.8 cm
bachelor DCA	> 1.2 cm	> 1.2 cm	> 1.0 cm
proton to pion DCA	< 0.8 cm	< 0.8 cm	< 1.0 cm
Λ DCA to bachelor	< 0.8 cm	< 0.8 cm	< 1.0 cm
$\|M_\Lambda - 1.1156\|$ GeV/c^2	< 0.007 GeV/c^2	< 0.007 GeV/c^2	< 0.007 GeV/c^2
$\|M_\Omega - 1.672\|$ GeV/c^2	< 0.007 GeV/c^2	< 0.007 GeV/c^2	< 0.007 GeV/c^2