Warsaw University of Technology

Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Geometry and Dynamics in Heavy-ion Collisions Seen by the Femtoscopy Method in the STAR experiment

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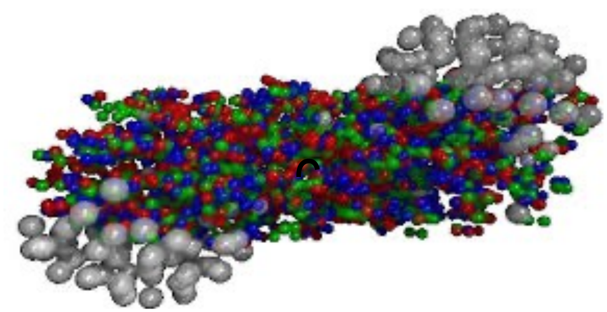

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40th International Conference on High Energy Physics; 28 July - 06 August 2020; virtual conference

Outline

Introduction

- HIC and HBT method
- Correlation femtoscopy: method, frames, correlations, measures, …
- RHIC / STAR

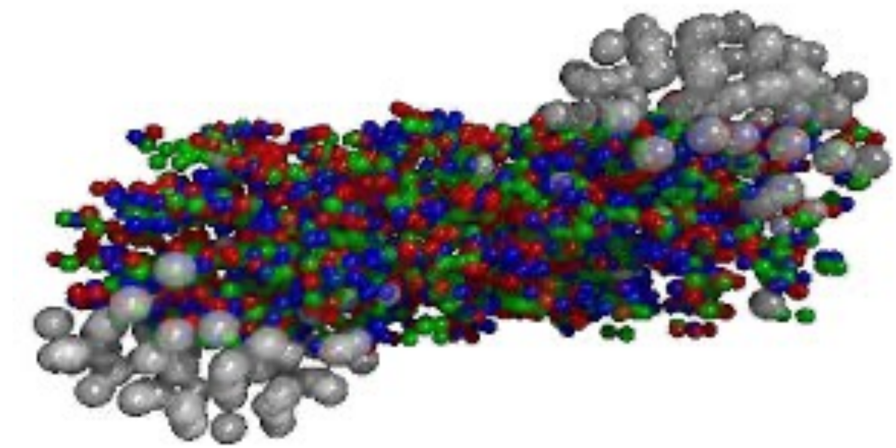
Results

a) Strong **interactions** between (anti)baryons

b) Femtoscopy of strange baryons

c) Beam Energy Scan Program (BES):

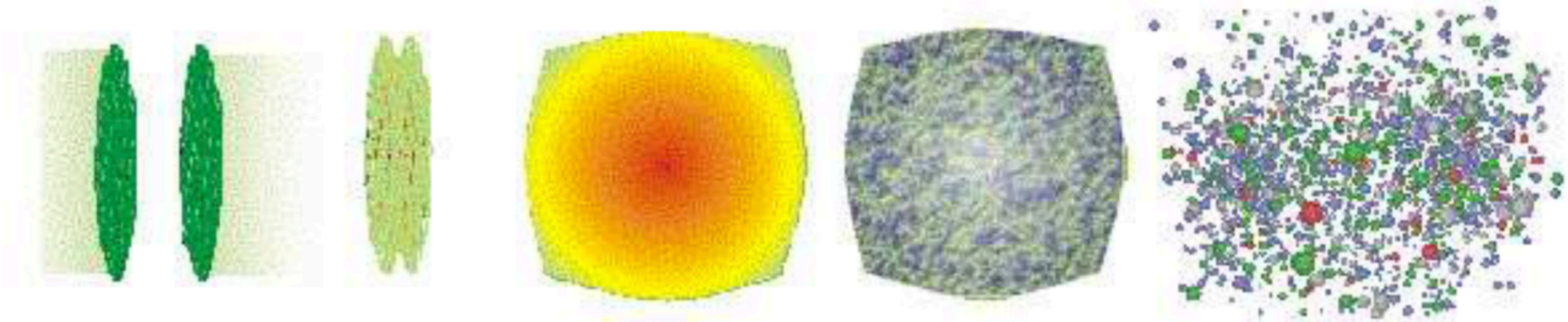
- identical pion femtoscopy
- **geometry**: centrality dependencies
  energy dependencies
  system (of pair) dependencies
- **dynamics**: centrality dependencies
  energy dependencies
  system (of pair) dependencies

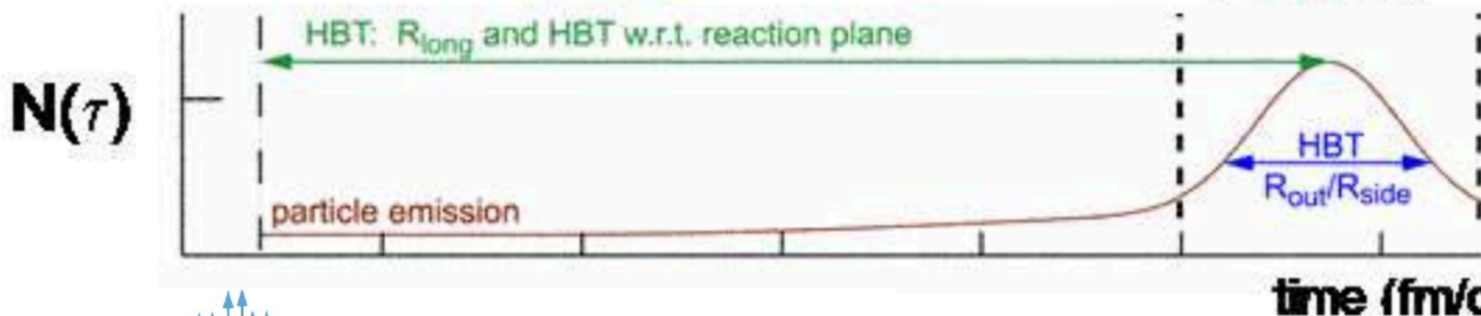


Conclusions

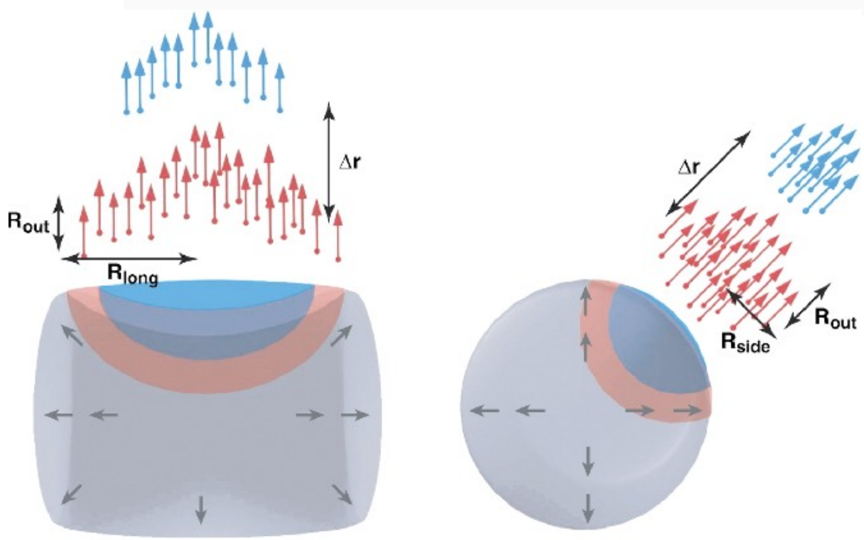
Introduction

Heavy-Ion collision and **HBT** method





Plot borrowed from Mike Lisa



Lisa MA, et al. 2005.
Annu. Rev. Nucl. Part. Sci. 55:357–402

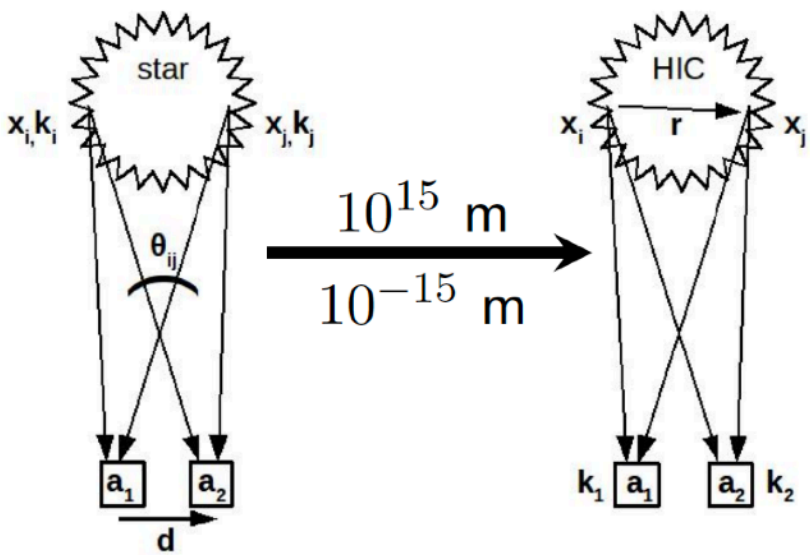
Homogeneity region

long - beam axis
out - pair transverse **p**
side - perpendicular to out and long

Correlation **femtoscopy**

Size: ~10^{-15} m (**fm**)
Time: ~10^{-23} s

Impossible to measure directly!



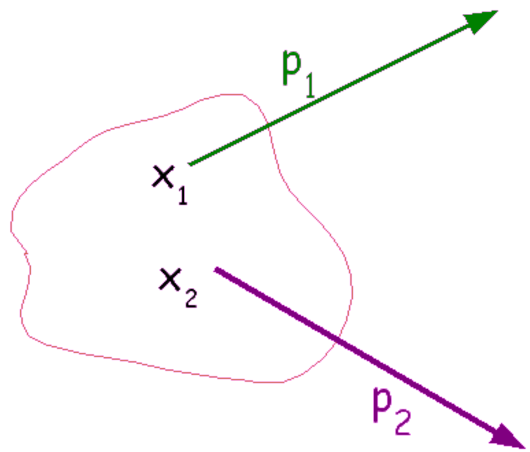
Femtoscopy (**HIC**) inspired by **H**anbury **B**rown and **T**wiss interferometry method (**Astronomy**)

but!

- different scales,
- different measured quantities
- different determined quantities

Femtoscopic correlations and correlation function

S(x,p) – **emission function**:
the distribution of source density
probability of finding particle with x and p



x_1, x_2 - space-time sizes and dynamics
(**can not** be measured directly) →

Close velocity correlations

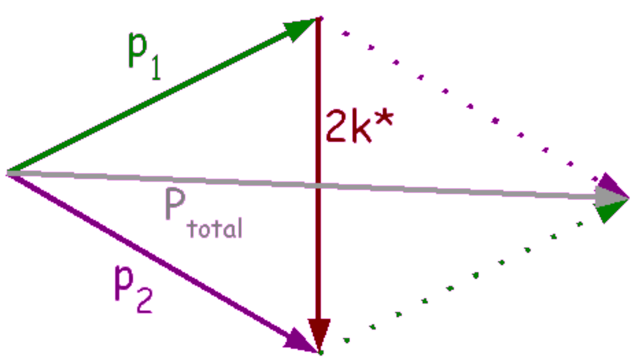
(HBT + FSI) ←

p_1, p_2 - momenta and momentum difference
(**can** be measured directly)

Single- and two-particle distributions

$$P_1(p) = E\frac{dN}{d^3p} = \int d^4x\, S(x,p)$$

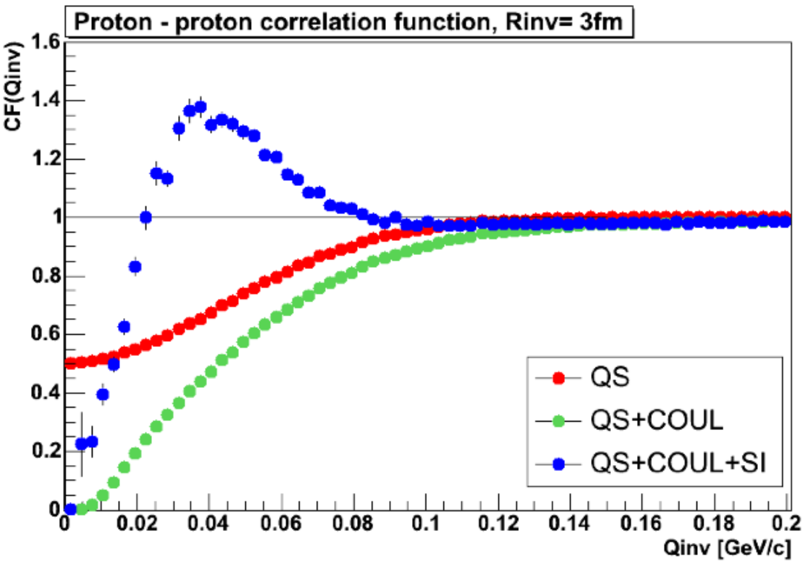
$$P_2(p_1,p_2) = E_1E_2\frac{dN}{d^3p_1d^3p_2} = \int d^4x_1 S(x_1,p_1)\, d^4x_2 S(x_2,p_2)\,\Phi(x_2, p_2 | x_1, p_1)$$



Correlation function

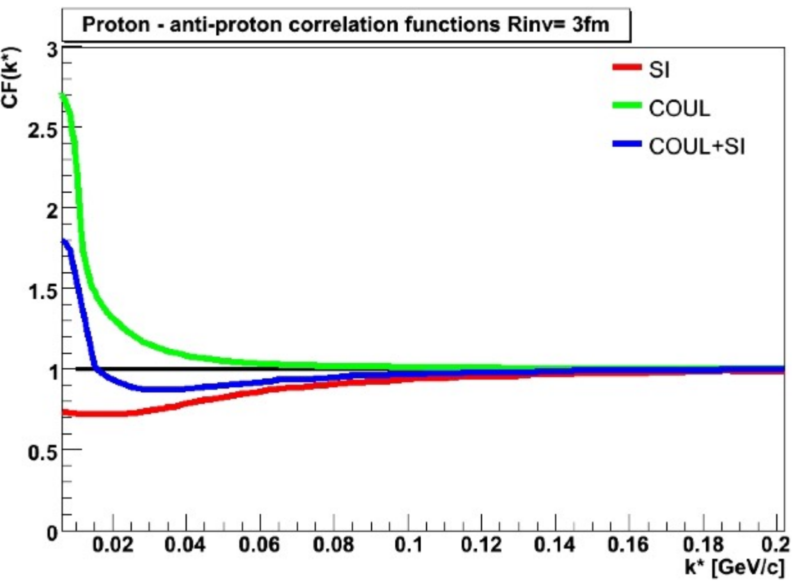
$$C(p_1,p_2) = \frac{P_2(p_1,p_2)}{P_1(p_1)P_1(p_2)}$$

Effects and interactions



Identical pairs:

- Quantum Statistics- **QS**
- Final State Interactions- **FSI:** Coulomb, Strong

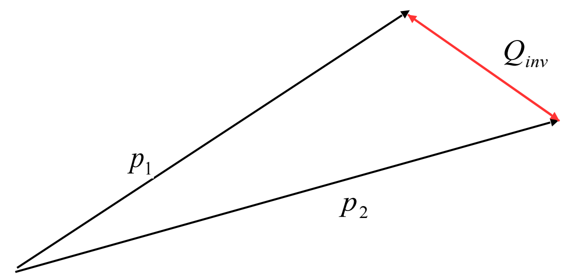


Non-identical pairs:

- Final State Interactions- **FSI:** Coulomb, Strong

Longitudinal Co-Moving System - **LCMS**

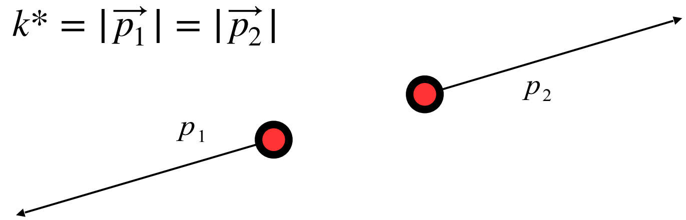
$$\overrightarrow{p_{1,L}} + \overrightarrow{p_{2,L}} = 0$$



$$Q_{inv} = \sqrt{(p_1 - p_2)^2 - (E_1 - E_2)^2} \text{ if } \quad m_1 = m_2$$

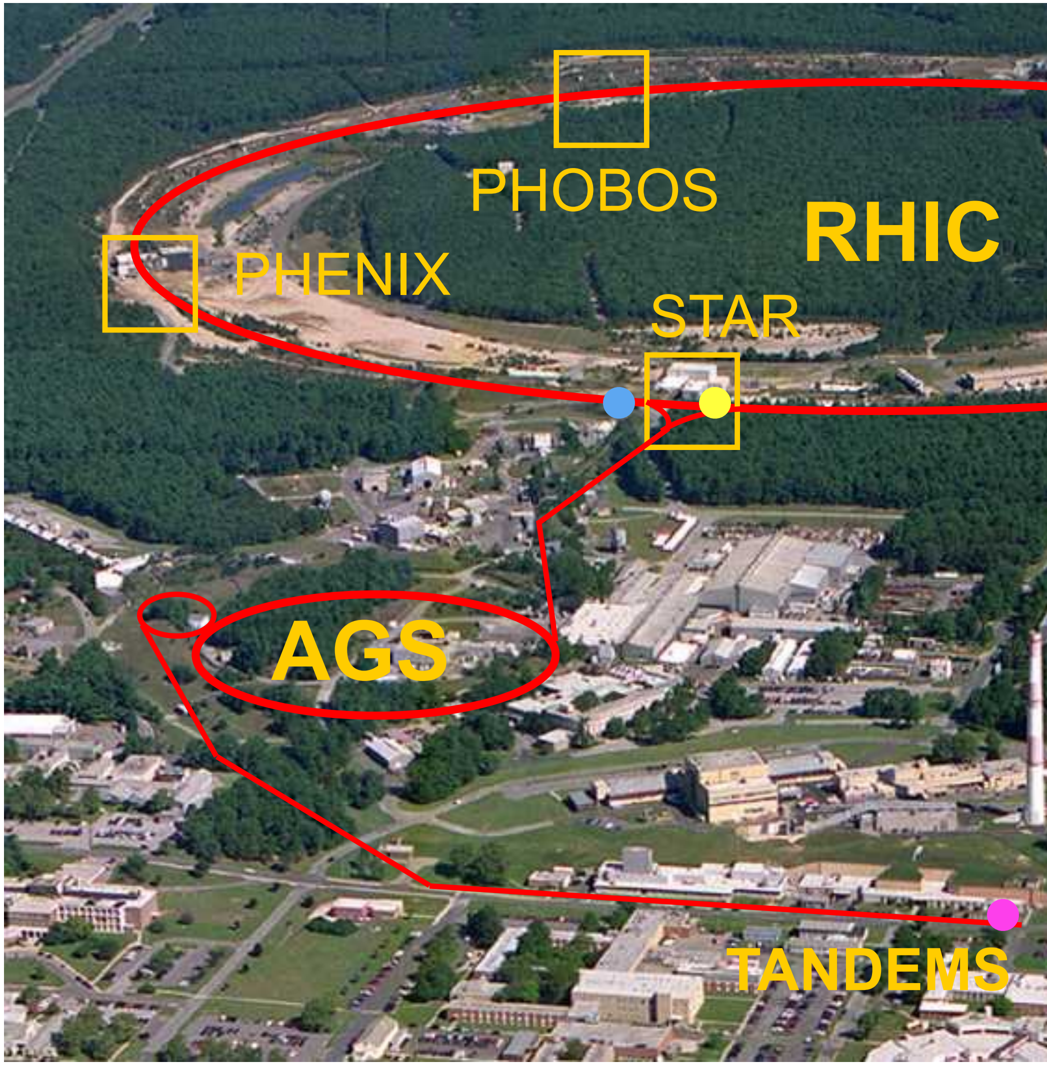
Pair Rest Frame - **PRF**

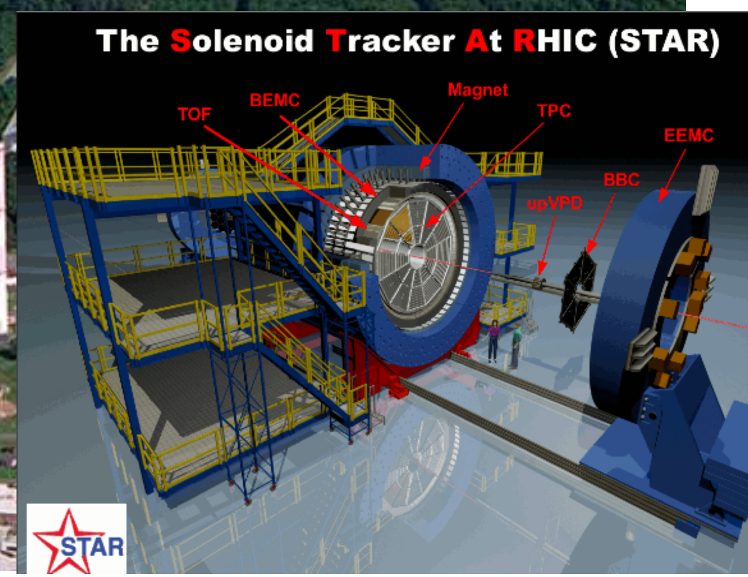
$$k* = |\overrightarrow{p_1}| = |\overrightarrow{p_2}|$$



$$Q_{inv} = 2k* \text{ if } \quad m_1 = m_2$$

Relativistic Heavy Ion Collider (**RHIC**)
Brookhaven National Laboratory (**BNL**), Upton





- 2 concentric rings of 1740 superconducting magnets
- 3.8 km circumference

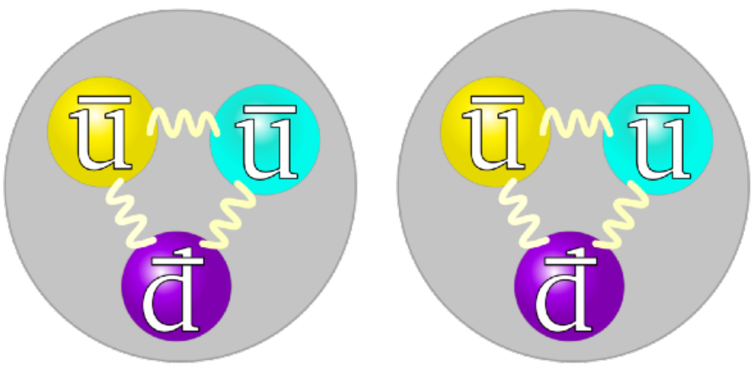
Results

a) Proton Femtoscopy @200 GeV

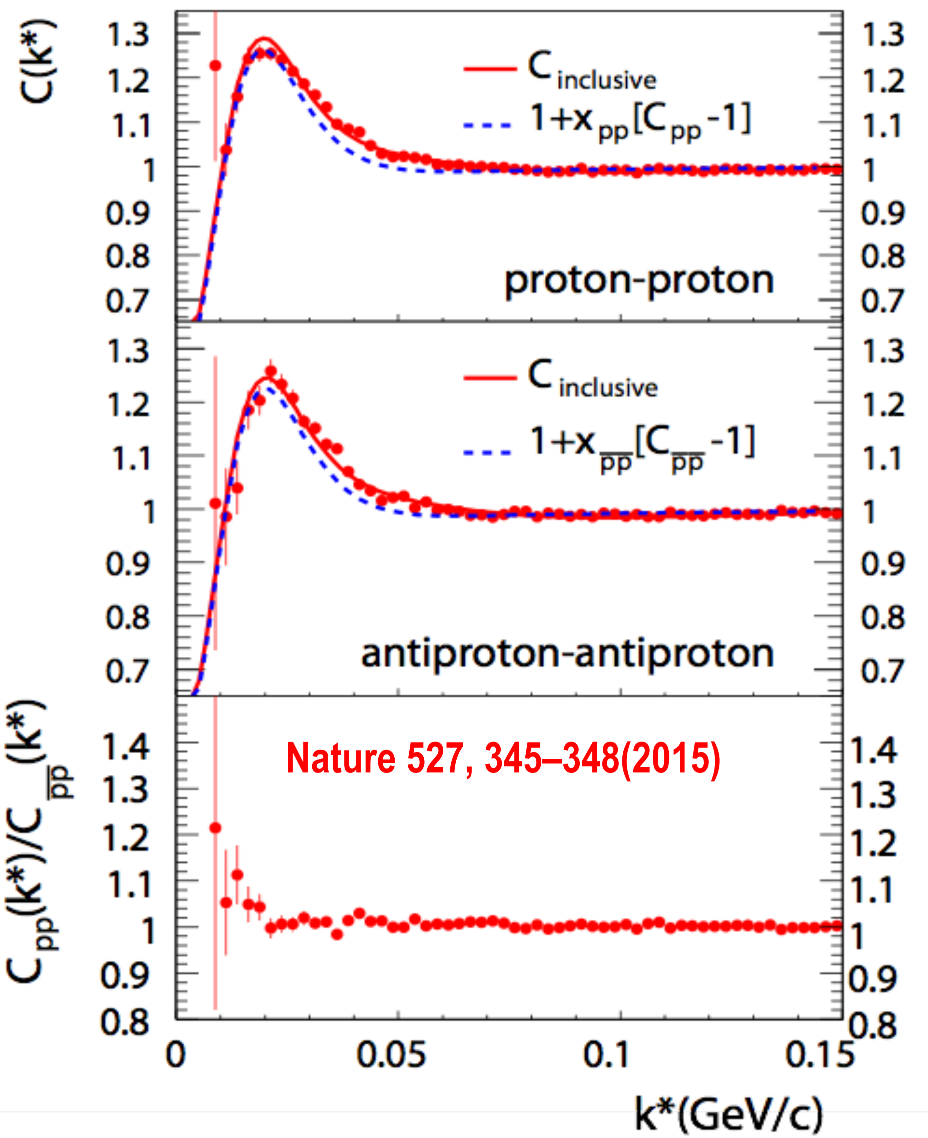
So far, the knowledge on **nuclear force** has been derived from studies made on **nucleon** or / and **nuclei**.

Nuclear force between **anti-nucleons** is studied for the first time.

The knowledge of **interaction** between two **anti-protons** is fundamental to understand the properties of more sophisticated anti-nuclei.

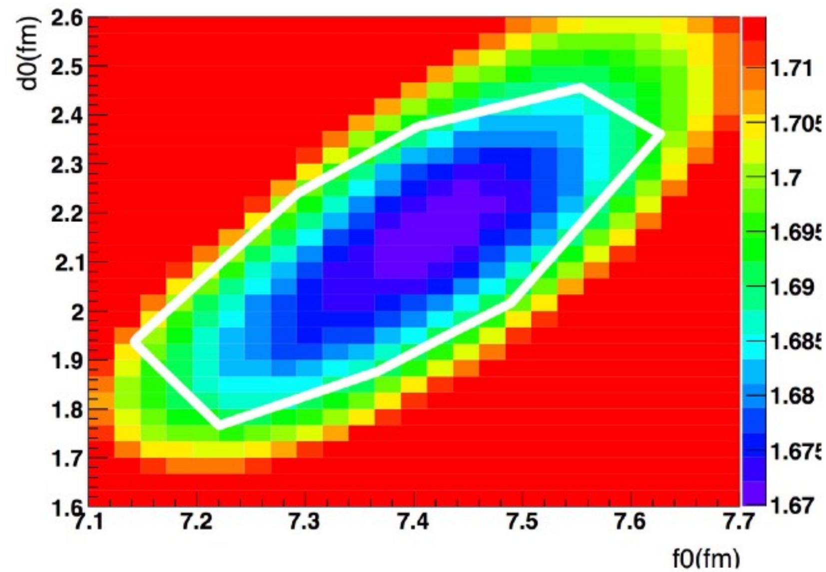


a) Strong interactions between anti-nucleons



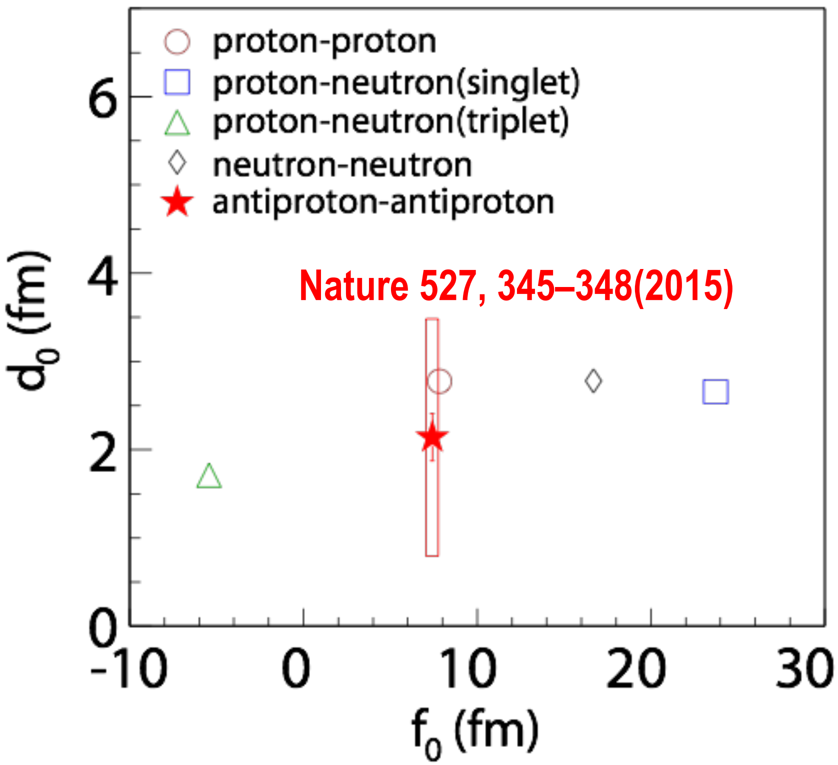
Fit results:
p-p CF,
R=2.75±0.01fm; χ2/NDF = 1.66;

antiproton-antiproton CF,
R=2.80±0.02fm , f_0=7.41±0.19fm,
d_0=2.14±0.27fm; χ2/NDF=1.61



$\chi^2/NDF(f_0,d_0)$ map of the results between measured function and fitted one to find the best values of f_0, d_0 parameters

a) Strong interactions between anti-nucleons



- f_0 and d_0 for the antiproton-antiproton interaction consistent with parameters for the proton-proton interaction.
- Descriptions of the interaction among antimatter (based on the simplest systems of anti-nucleons) determined.
- A quantitative verification of matter-antimatter symmetry in context of the forces responsible for the binding of (anti)nuclei.

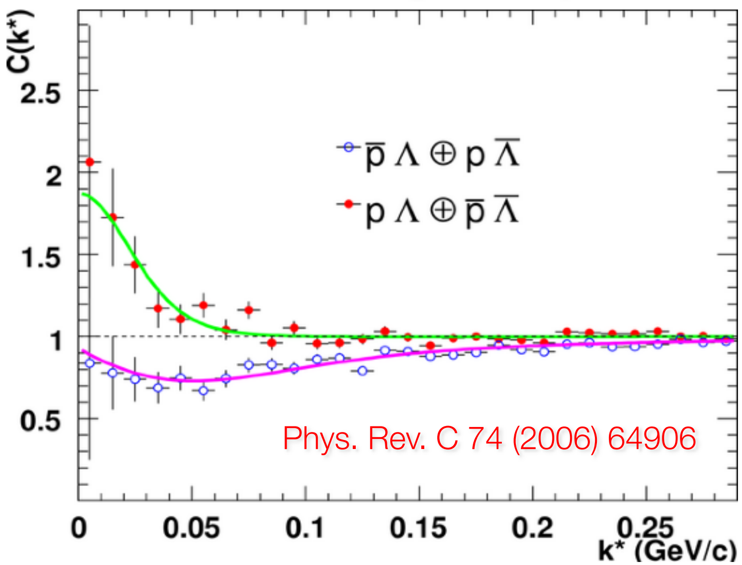
The scattering length f_0: determines low-energy scattering.
The elastic cross section, σ_e , (at low energies) determined solely by the scattering length, $\lim_{k\to 0} \sigma_e = 4\pi f_0^2$

d_0 - the effective range of strong interaction between two particles.
It corresponds to the range of the potential in an extremely simplified scenario - the square well potential.

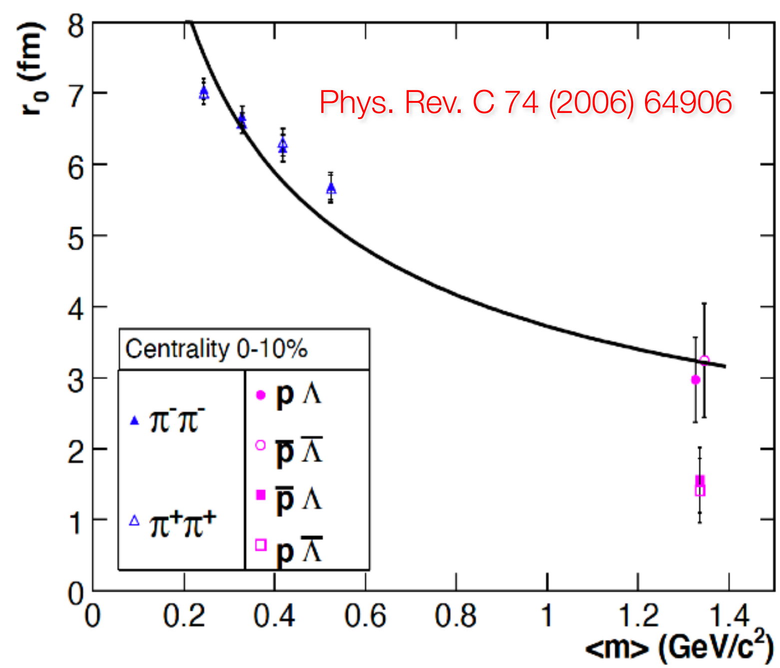
f_0 and d_0 - two important parameters of strong interaction between two particles.
Theoretical correlation function depends on: source size, k^* ,f_0 and d_0.

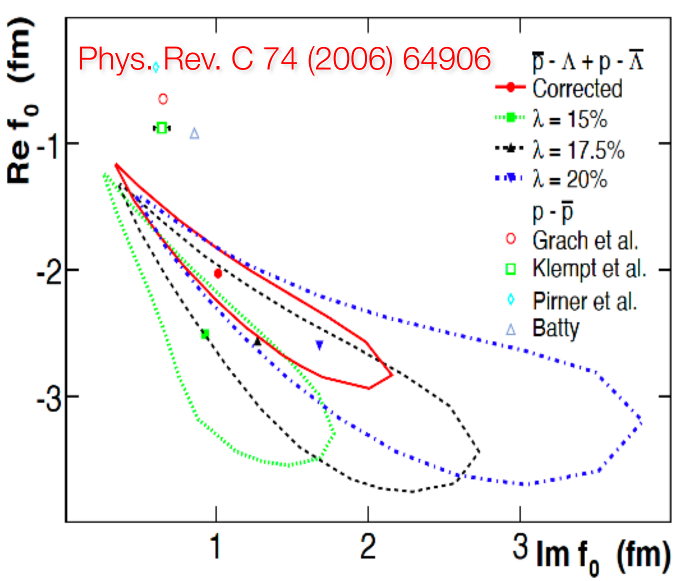
b) Strange Baryon Correlations (Including Λ Hyperons)

$p - \Lambda$ correlations:
sensitive to the Strong FSI only



System	r_0 (fm)
$p - \Lambda$	$2.97 \pm 0.34^{+0.19}_{-0.25} \pm 0.2$
$\overline{p} - \overline{\Lambda}$	$3.24 \pm 0.59^{+0.24}_{-0.14} \pm 0.2$
$p - \Lambda \oplus \overline{p} - \overline{\Lambda}$	$3.09 \pm 0.30^{+0.17}_{-0.25} \pm 0.2$
$\overline{p} - \Lambda$	$1.56 \pm 0.08^{+0.10}_{-0.14} \pm 0.3$
$p - \overline{\Lambda}$	$1.41 \pm 0.10 \pm 0.11 \pm 0.3$
$\overline{p} - \Lambda \oplus p - \overline{\Lambda}$	$1.50 \pm 0.05^{+0.10}_{-0.12} \pm 0.3$





<u>$p - \Lambda$ correlations: contain contributions from</u>
<u>**Residual** feed-down **Correlations (RC)**</u>

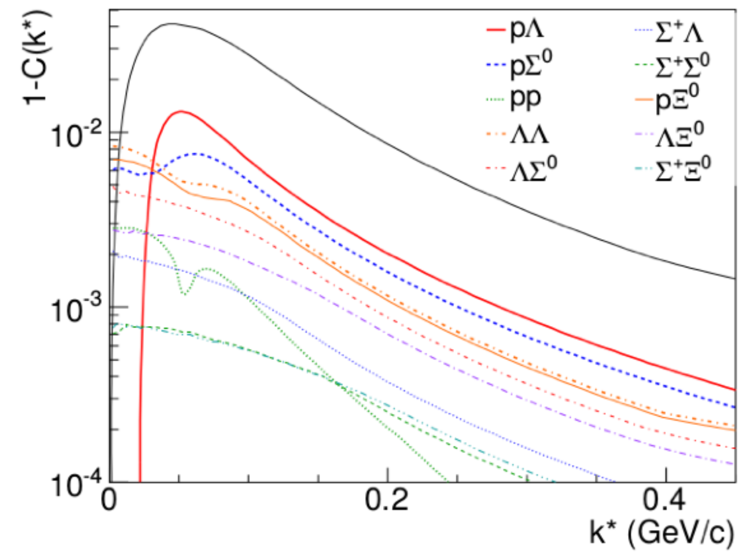
b) Strange Baryon Correlations (Including Λ Hyperons)

$$C^{X\bar{Y}\to p\bar{\Lambda}}(k^*_{p\bar{\Lambda}}) = \frac{\int C^{X\bar{Y}}(k^*_{X\bar{Y}})W(k^*_{X\bar{Y}},k^*_{p\bar{\Lambda}})dk^*_{X\bar{Y}}}{\int W(k^*_{X\bar{Y}},k^*_{p\bar{\Lambda}})dk^*_{X\bar{Y}}}.$$

$$C(k^*_{p\bar{\Lambda}}) = 1+\lambda_{p\Lambda}\left(C^{p\bar{\Lambda}}(k^*_{p\bar{\Lambda}})-1\right) + \sum_{X\bar{Y}}\lambda_{XY}\left(C^{X\bar{Y}}(k^*_{p\bar{\Lambda}})-1\right)$$

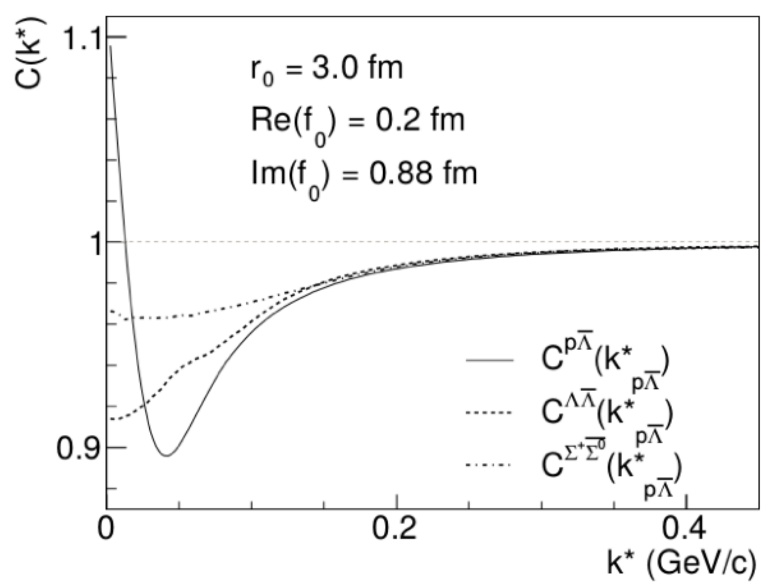
$p-\Lambda$ correlations: contain contributions from **Residual** feed-down **Correlations (RC)**

Removing residual contribution pure correlation signal leads to **similar source sizes** in case of $p-\Lambda$ and $p-\bar{\Lambda}$



Phys.Rev. C89 (2014) no.5, 054916

HZ, A. Kisiel, M. Szymański

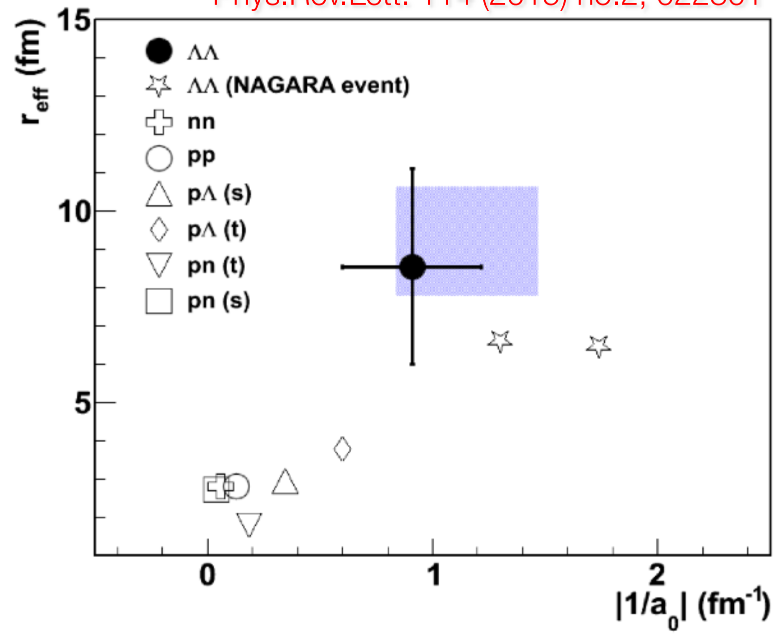


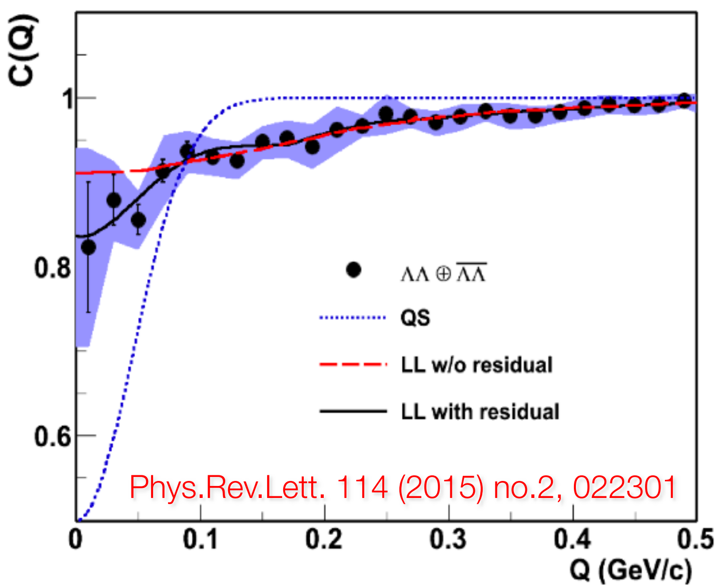
b) Strange Baryon Correlations (Including Λ Hyperons)

$\Lambda - \Lambda$ correlations:
sensitive to the Quantum Statistical effects and Strong FSI

<u>lambda-lambda correlations: contain contributions from **Residual** feed-down **Correlations (RC)**</u>

Phys.Rev.Lett. 114 (2015) no.2, 022301





- strength of the $\Lambda - \Lambda$ interaction is weak;
- nonexistence of a $\Lambda\Lambda$ resonance
- limit on the yield of a deuteron-like bound **H**-dibaryon is also reported.

b) Strange Baryon Correlations (including p-Ω)

Binding energy **E_{bin}** [MeV]

Scattering length **a_0** [fm]

Effective range **r_{eff}** [fm]

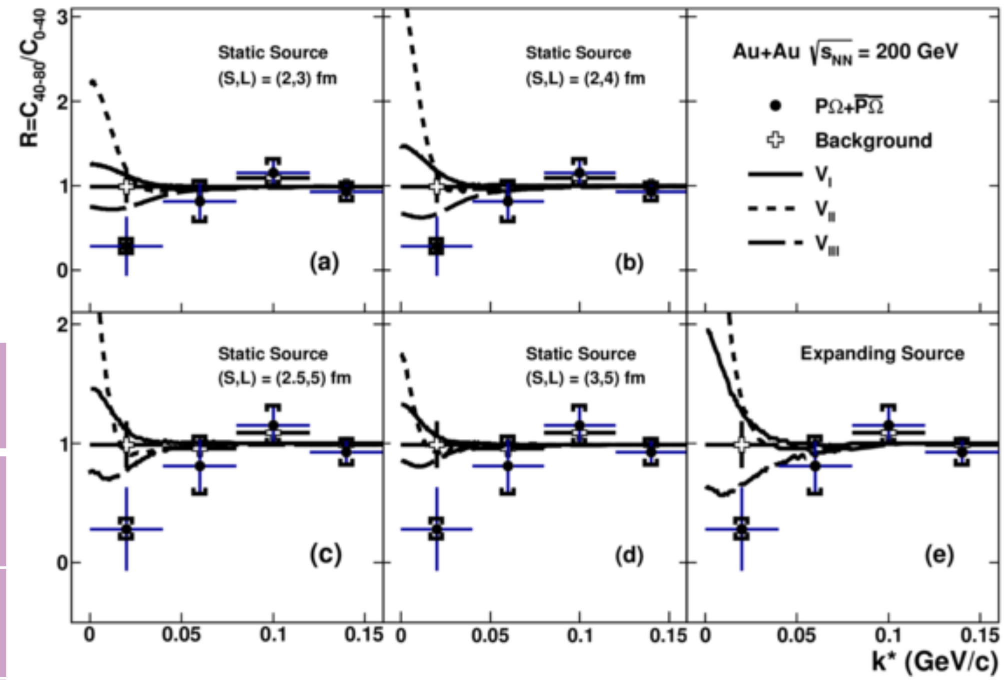
for 3 scenarios:

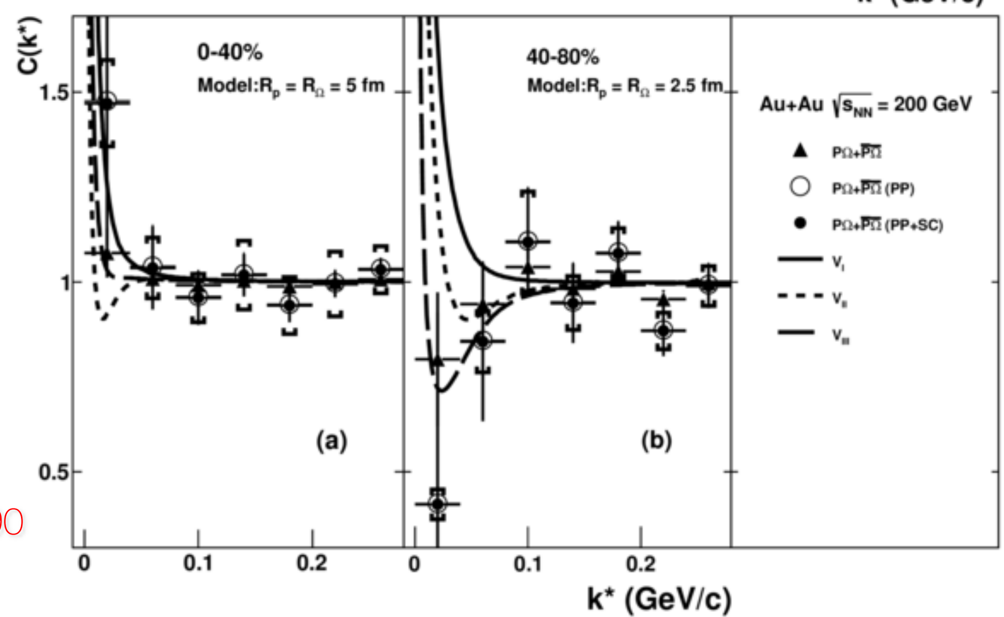
K. Morita et al. Phys. Rev. C 94, 031901 (2016)

	V_1	V_2	V_3
E_{bin} [MeV]	-	6.3	26.9
a_0 [MeV]	-1.12	5.79	1.29
r_{eff} [MeV]	-1.16	0.96	0.65

A comparison of the measured correlation functions from Au+Au collisions with theoretical predictions

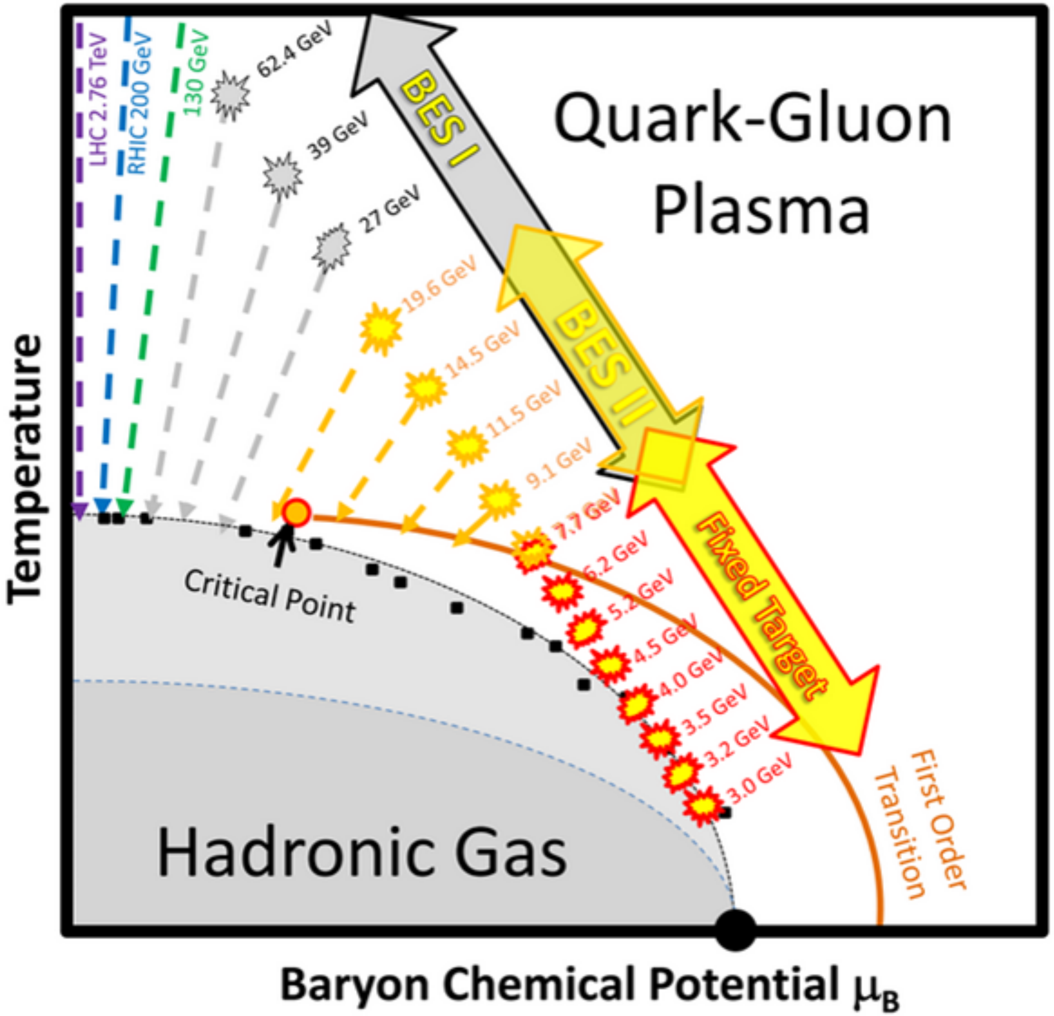
Scattering length is positive and favor pΩ bound state hypothesis





Phys.Lett.B 790 (2019) 490

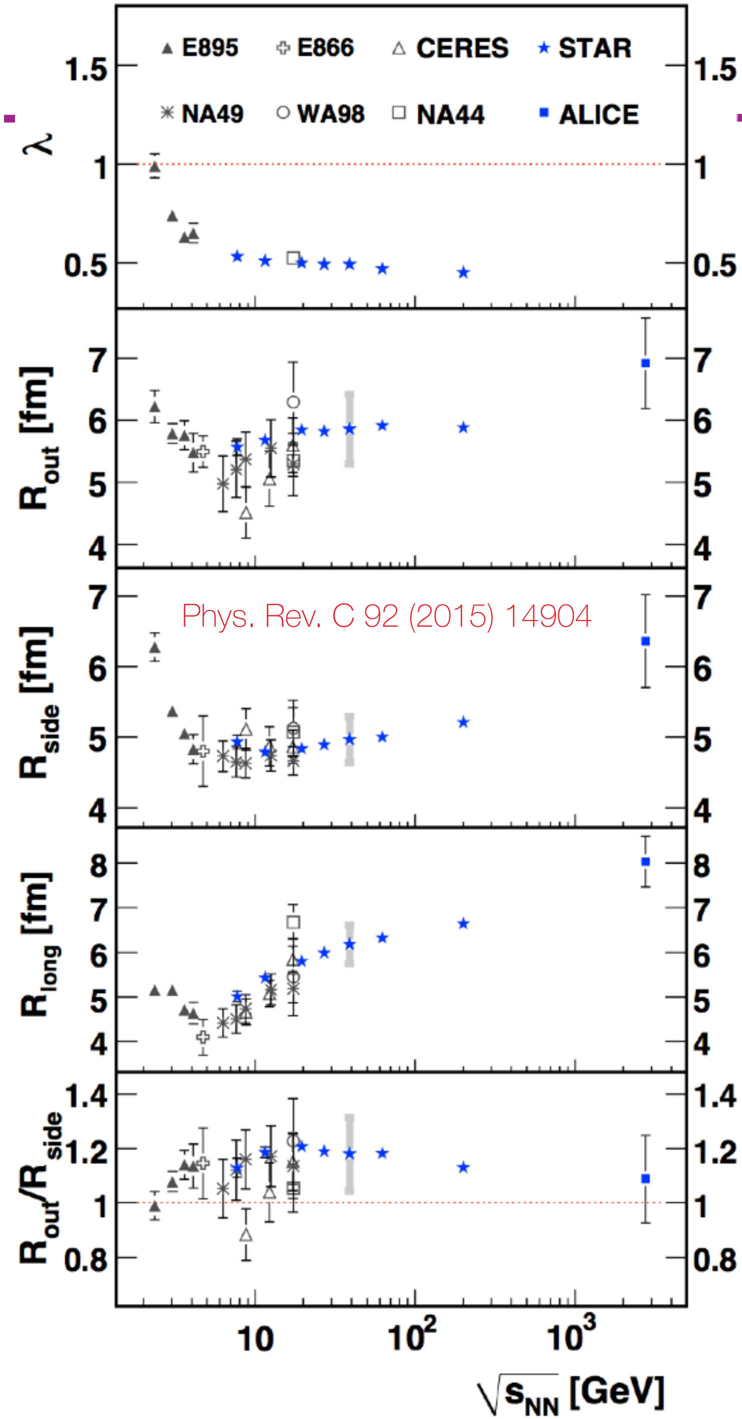
c) Program **B**eam **E**nergy **S**can



RHIC **Top Energy**
p+p, p+Al, p+Au, d+Au,
^{3}He+Au, Cu+Cu, Cu+Au,
Ru+Ru, Zr+Zr, Au+Au, U+U
QCD at high energy density/temperature
Properties of QGP, EoS

Beam **E**nergy **S**can
Au+Au 7.7-62 GeV
- QCD phase transition
- Search for critical point
- Turn-off of QGP signatures
- Chiral symmetry restoration

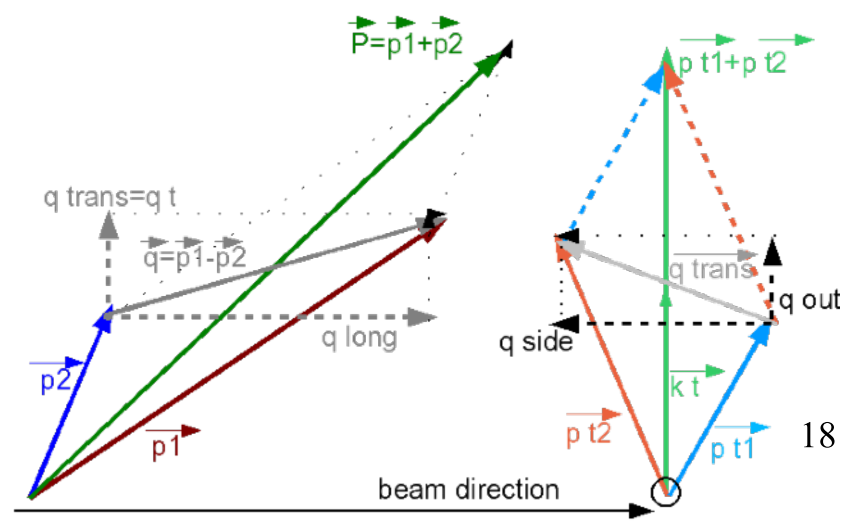
Fixed-**T**arget Program
Au+Au =3.0-7.7 GeV
High baryon density regime with 420-720 MeV



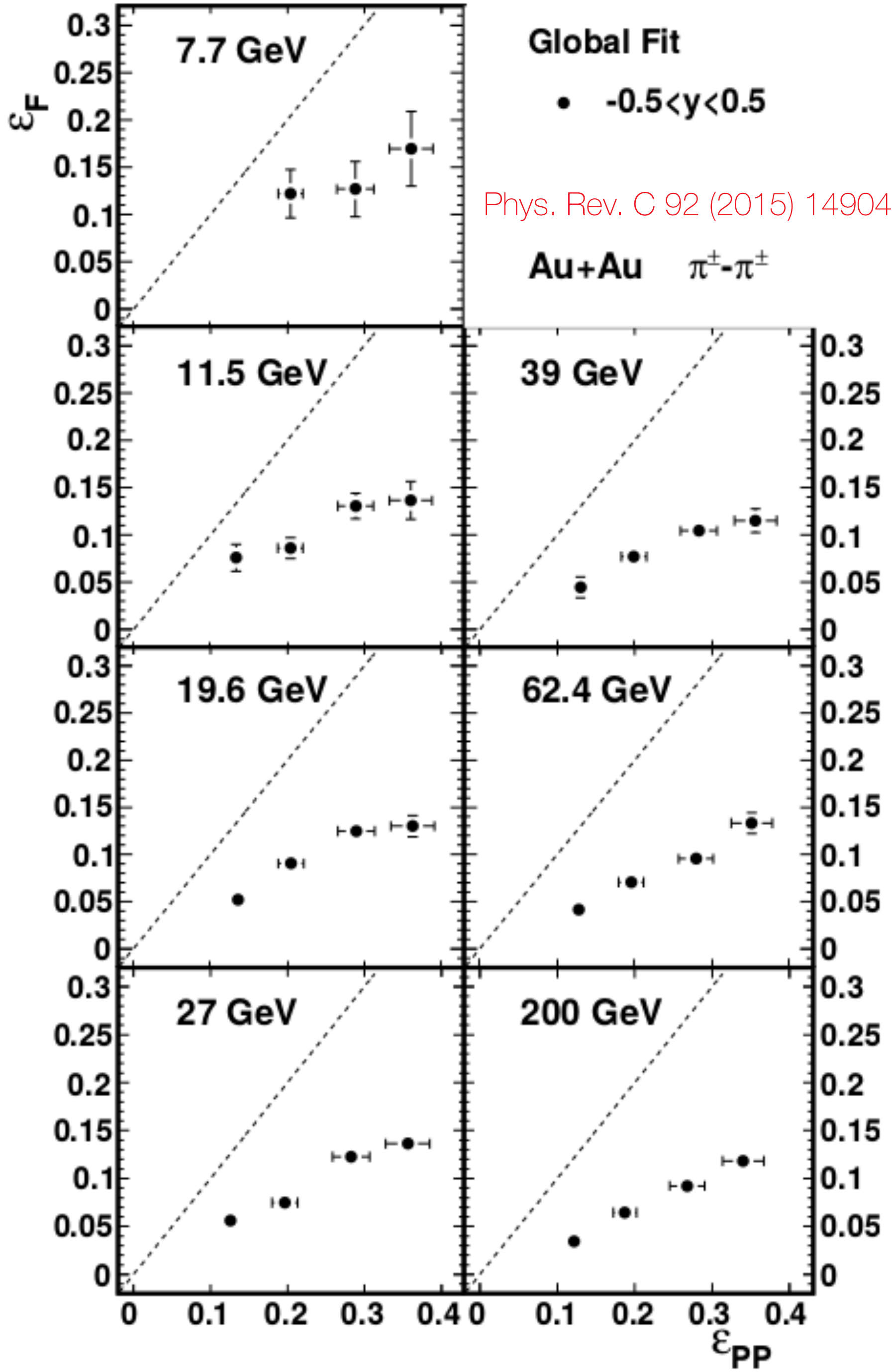
Program BES

- → R_{side} spatial source evolution in the transverse direction
- → R_{out} related to spatial and time components
- → R_{out}/R_{side} (before!) signature of phase transition
- → $R_{out}^2 - R_{side}^2 = \Delta\tau^2 \beta_t^2$; $\Delta\tau$ – emission time
- → R_{long} temperature of kinetic freeze-out and source lifetime

$$C(\vec{q}) = (1-\lambda) + K_{\mathrm{Coul}}(q_{\mathrm{inv}})\lambda$$
$$\times \exp\left(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2 - 2q_o q_s R_{os}^2 - 2q_o q_l R_{ol}^2\right)$$



Program BES



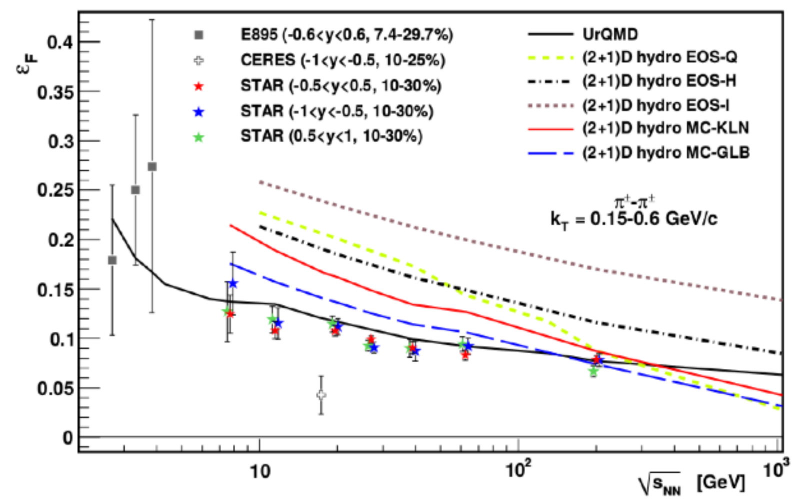
Phys. Rev. C 92 (2015) 14904

$$\varepsilon_{PP} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_x^2 + \sigma_y^2}. \qquad \varepsilon_F = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} \approx 2\frac{R_{s,2}^2}{R_{s,0}^2}$$

$$\sigma_x^2 = \{x^2\} - \{x\}^2 \text{ and } \sigma_y^2 = \{y^2\} - \{y\}^2$$

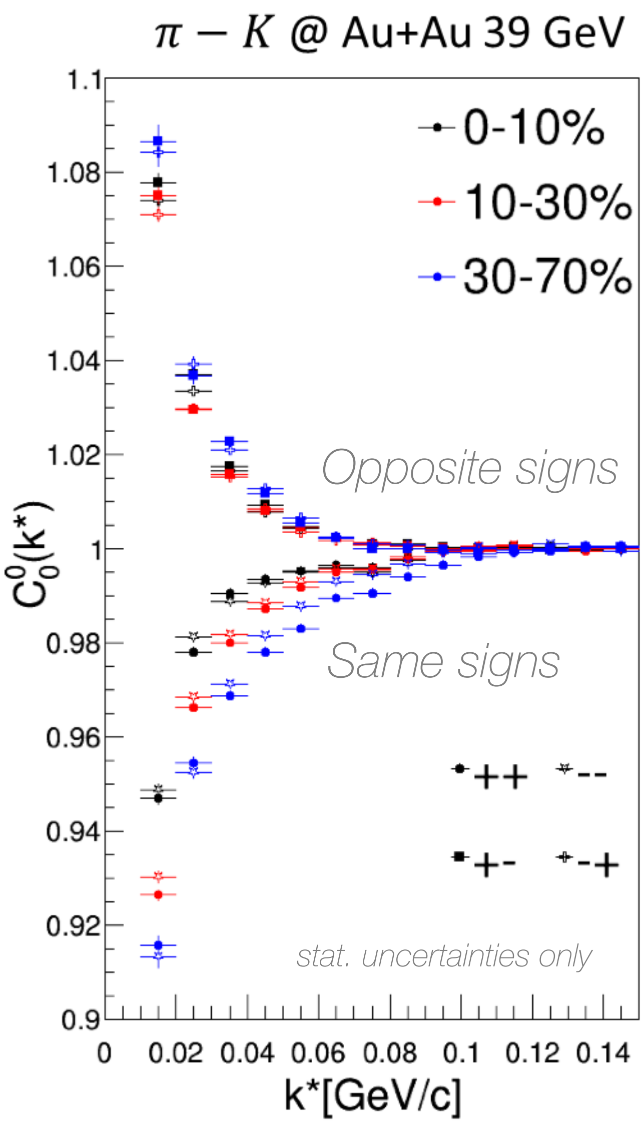
$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2\sum_{n=2,4,6\ldots} R_{\mu,n}^2 \cos(n\Phi) \qquad (\mu = o, s, l, ol)$$

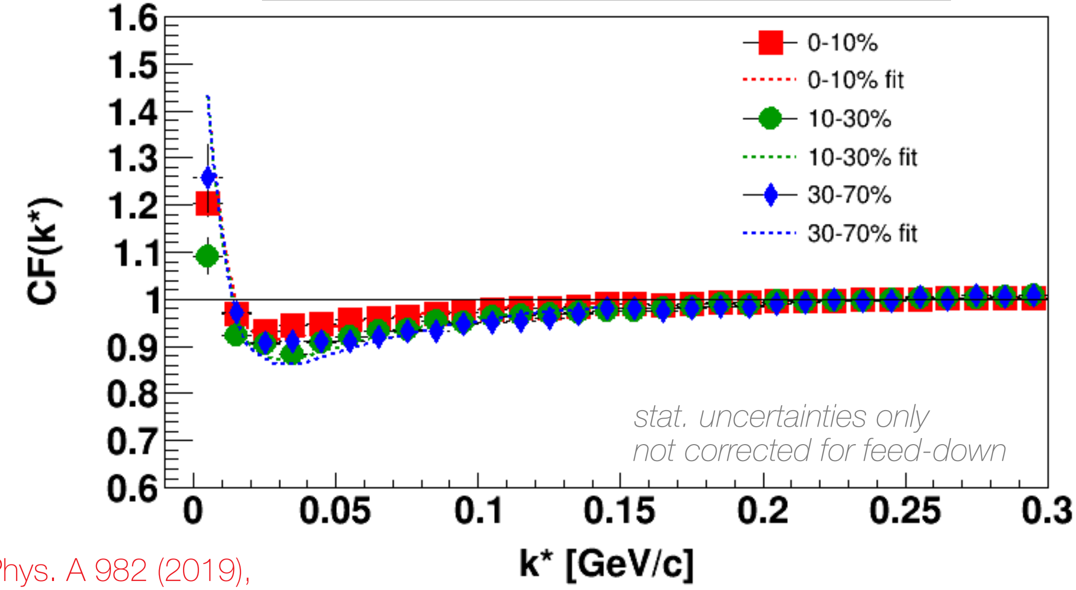
$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2\sum_{n=2,4,6\ldots} R_{\mu,n}^2 \sin(n\Phi) \qquad (\mu = os)$$



System evolves faster in the reaction plane than in the direction perpendicular to it

Geometry: dependence on collision **centrality**





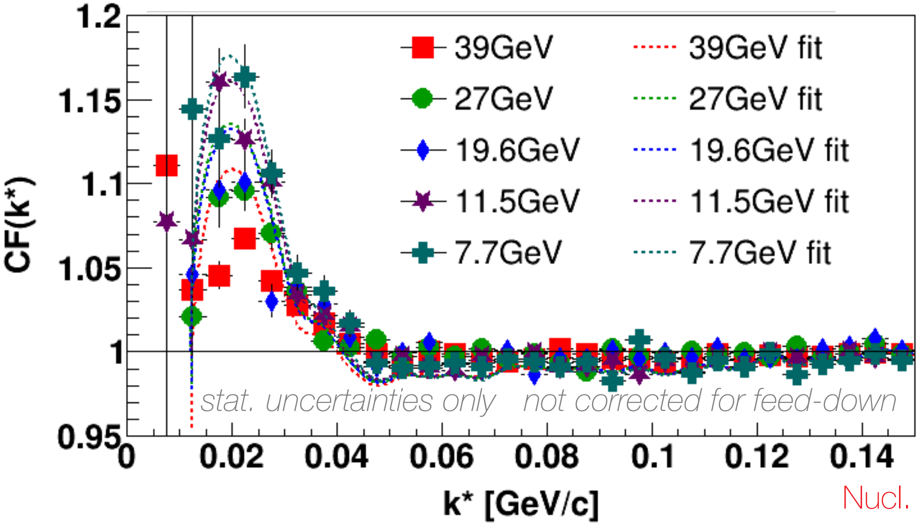
Nucl. Phys. A 982 (2019), 359-362

Clear centrality dependence
$R(0\text{–}10\%) > R(10\text{–}30\%) > R(30\text{–}70\%)$

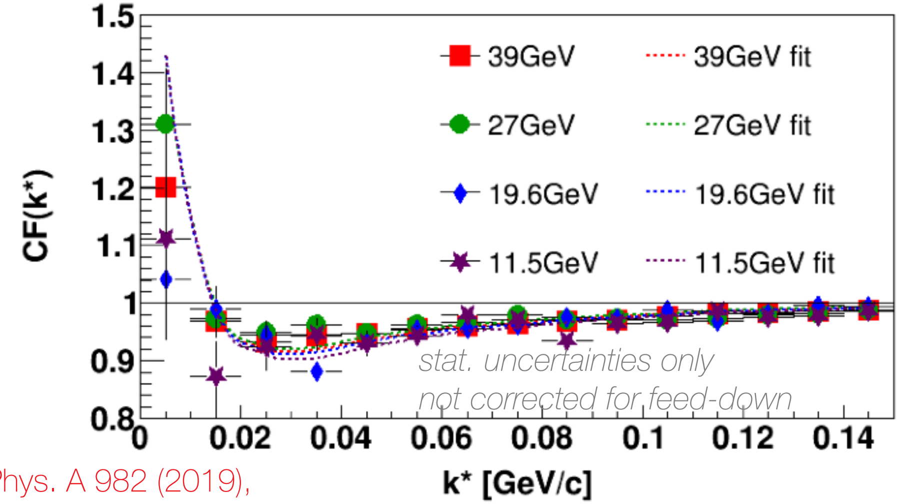
centrality	R_{inv} $p - \bar{p}$ [fm]
0-10%	$\mathbf{3.39} \pm 0.12 \pm 0.14$
10-30%	$\mathbf{2.69} \pm 0.10 \pm 0.12$
30-70%	$\mathbf{2.56} \pm 0.09 \pm 0.12$

Dependence on collision **energy**

$p-p$: Au+Au 0-10%



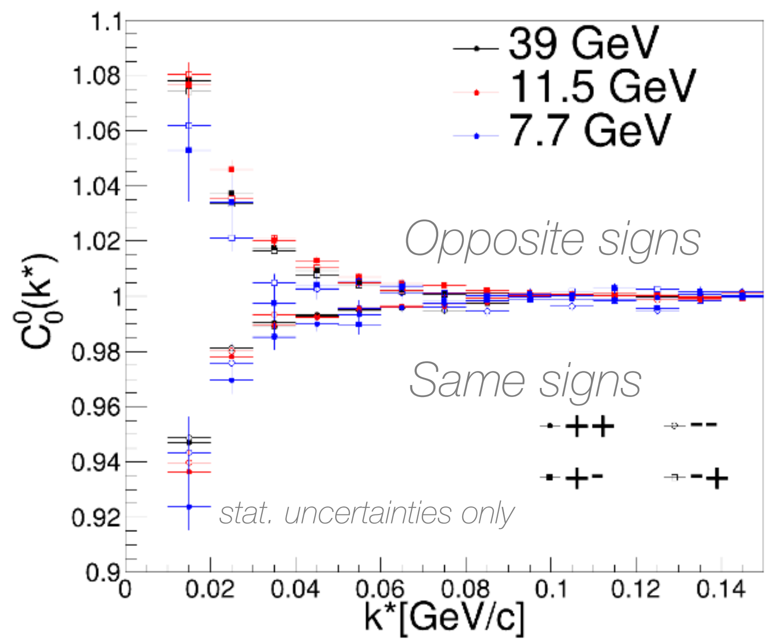
$p-\bar{p}$: Au+Au 0-10%



Nucl. Phys. A 982 (2019), 359-362

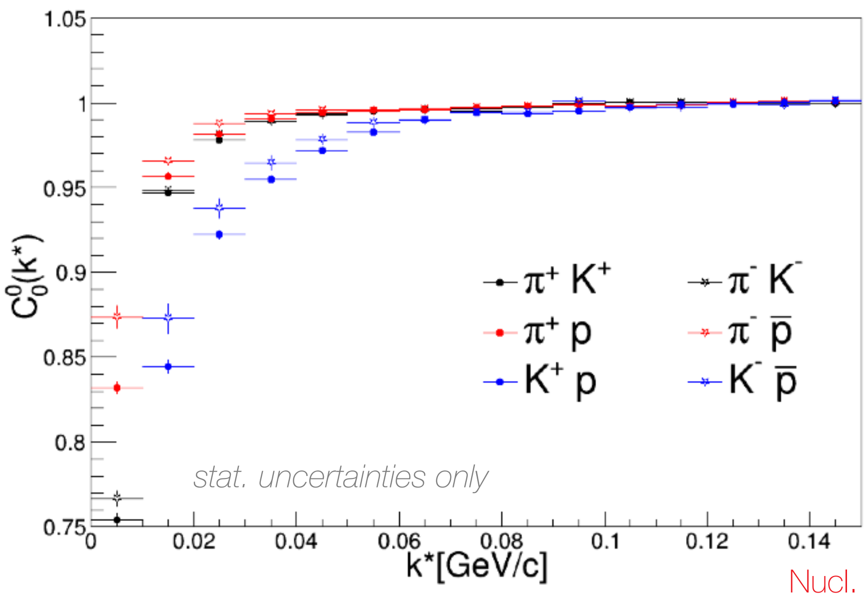
energy	R_{inv} $p-p$ [fm]	R_{inv} $p-\bar{p}$ [fm]
7.7 GeV	$\mathbf{3.59} \pm 0.16 \pm 0.19$	
11.5 GeV	$\mathbf{3.66} \pm 0.08 \pm 0.05$	$\mathbf{3.30} \pm 0.42 \pm 0.28$
19.6 GeV	$\mathbf{3.82} \pm 0.15 \pm 0.06$	$\mathbf{3.32} \pm 0.25 \pm 0.13$
27 GeV	$\mathbf{3.80} \pm 0.12 \pm 0.08$	$\mathbf{3.49} \pm 0.25 \pm 0.16$
39 GeV	$\mathbf{4.00} \pm 0.15 \pm 0.02$	$\mathbf{3.39} \pm 0.12 \pm 0.14$

$\pi-K$: Au+Au 0-10 %

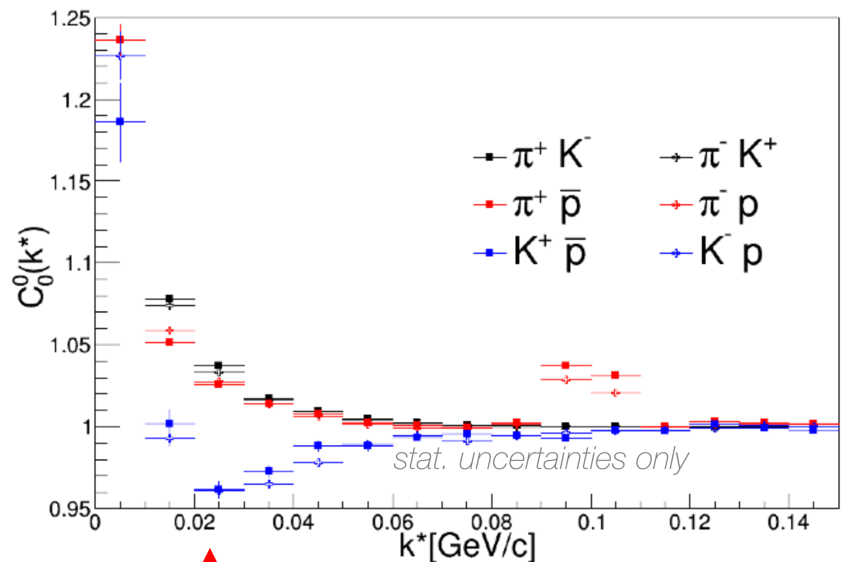


Dependence on interacting **system**

Same charges 0-10% @ Au+Au 39 GeV



Opposite charges 0-10% @ Au+Au 39 GeV



Nucl. Phys. A 982 (2019), 359-362

Determined by **Coulomb** Interactions

$C_0^0(K-p)$ **different shape due to strong interaction**

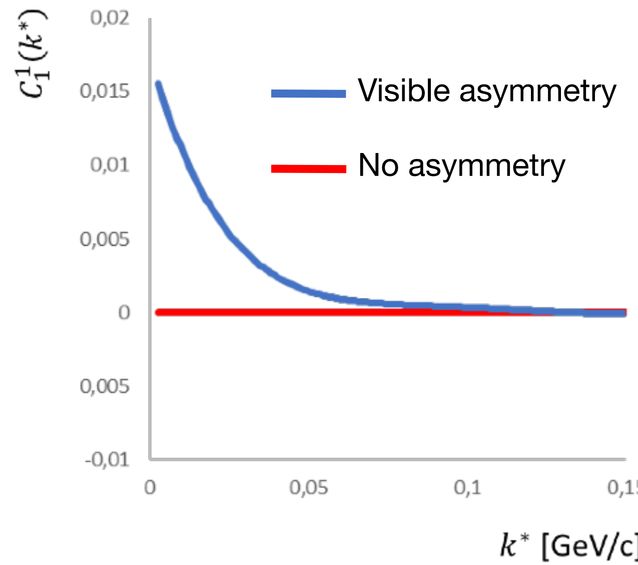
Determined by full **FSI**: **Coulomb** and **Strong** interactions (kaon-proton)

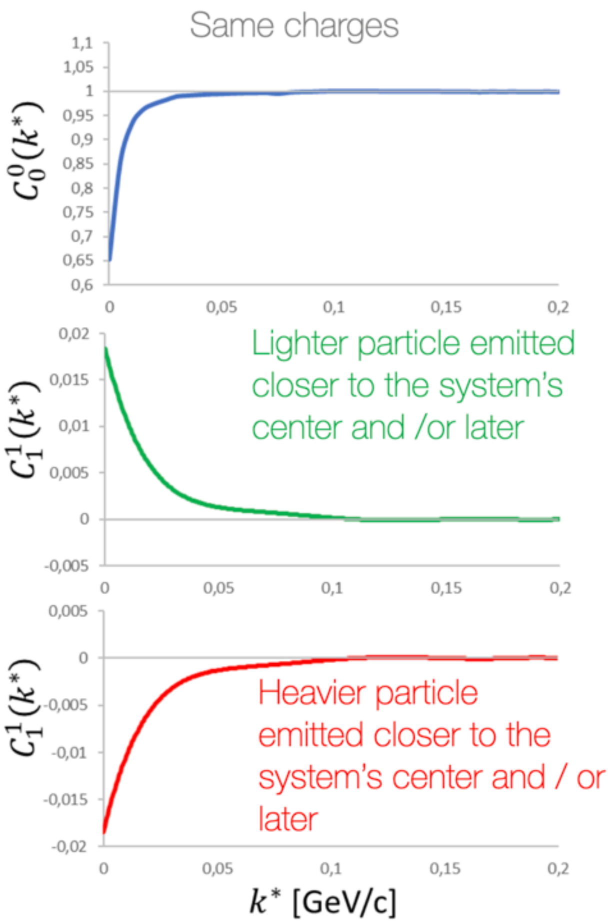
Spherical harmonics

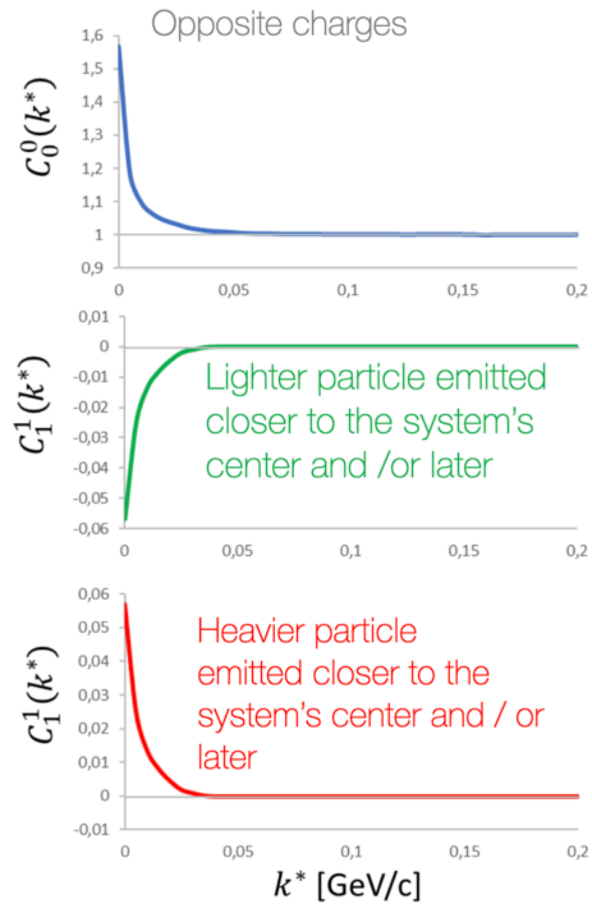
$C(\boldsymbol{q}) = \sum_{l,m} C_l^m(q) Y_l^m(\theta,\phi)$ $\qquad$ $C_l^m(q) = \int_\Omega C(q,\theta,\phi) Y_l^m(\theta,\phi) d\Omega$

Ω – full solid angle
$Y_l^m(\theta,\phi)$ – spherical harmonic function
$q = |\boldsymbol{q}|, \theta, \phi$ – spherical coordinates

C00 → source **size**
C11 → space-time **asymmetry**







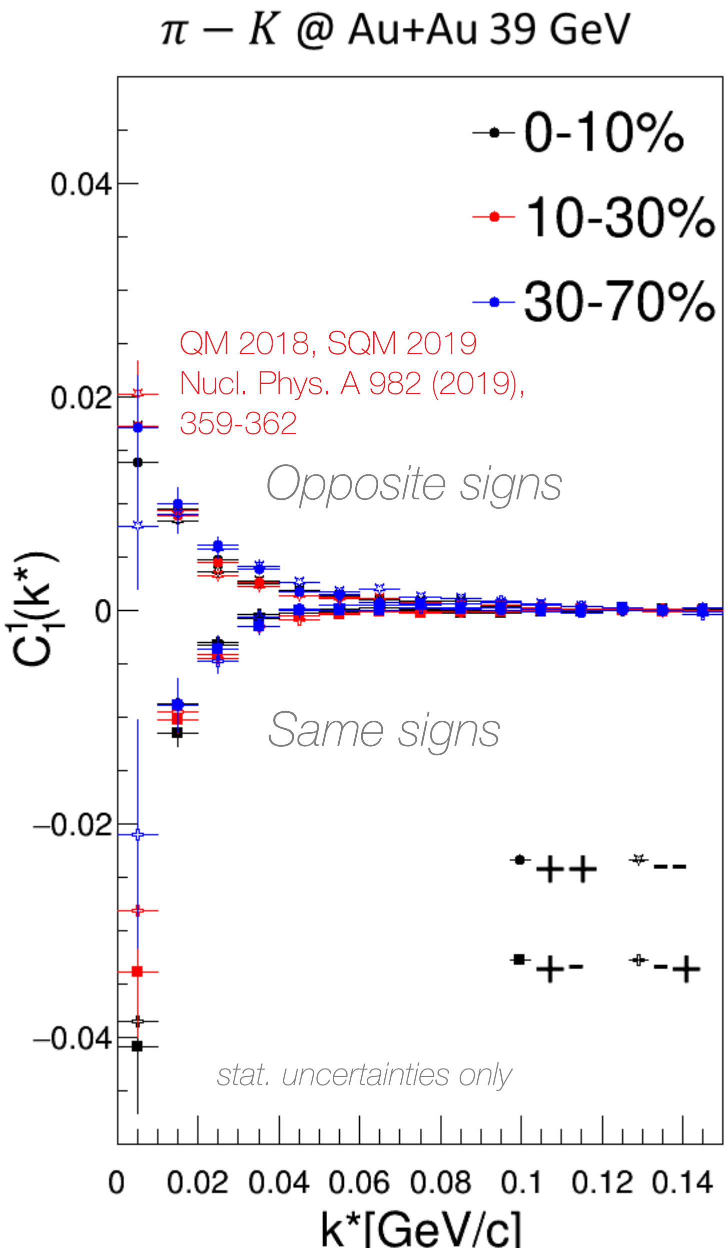
P. Danielewicz and S.Pratt.
Phys. Lett. B618: 60 2005

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

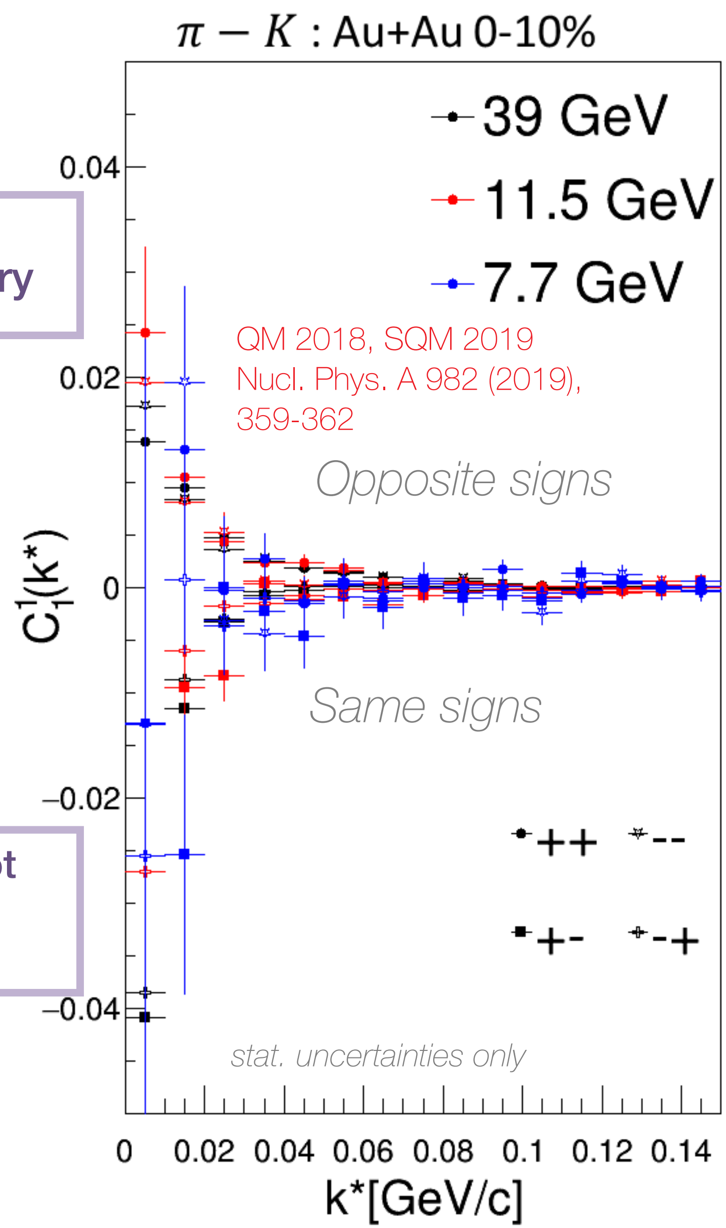
A. Kisiel
Phys. Rev. C81:064906 2010

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

Source dynamics: **centrality** and **energy** dependencies



Clear signal of emission asymmetry

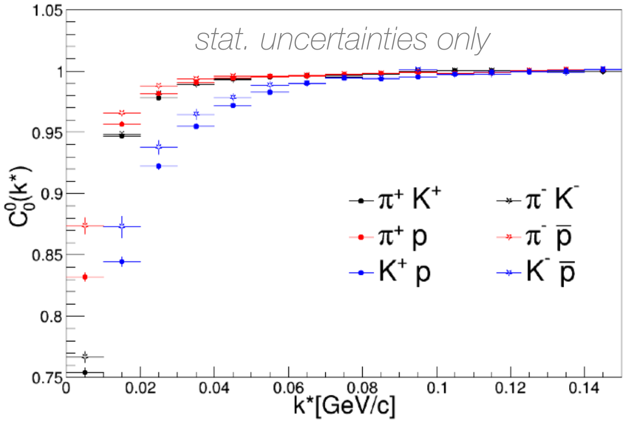


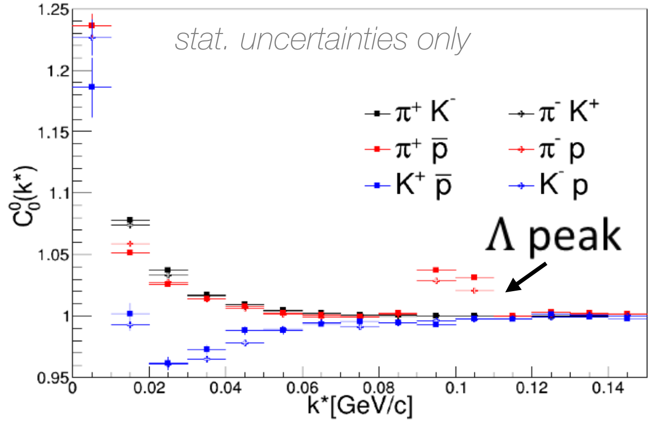
Asymmetry does not disappear in lower energies

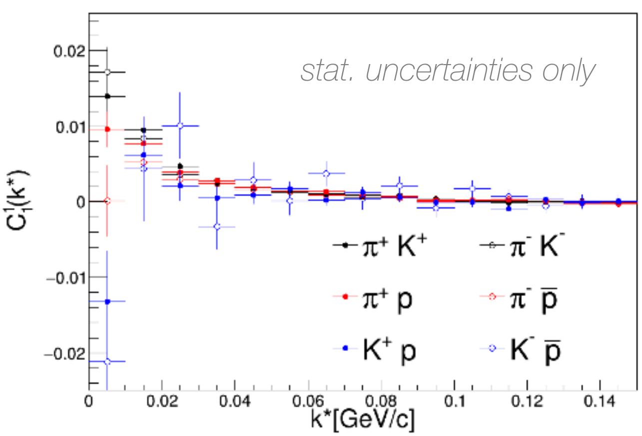
Source dynamics: **system** dependence

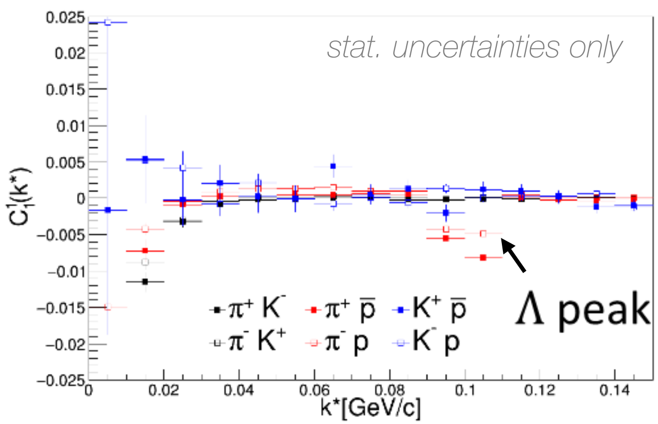
Like-sign 0-10% @ Au+Au 39 GeV

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







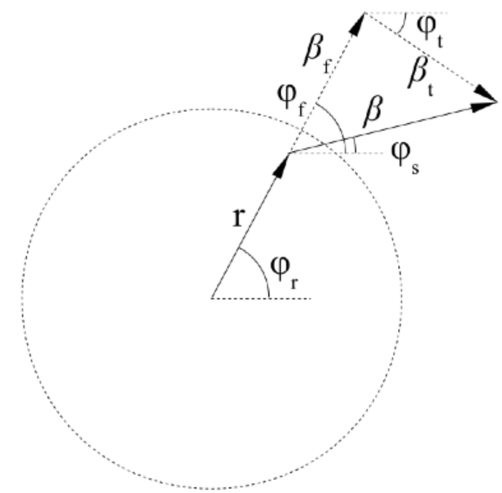


QM 2018, SQM 2019
Nucl. Phys. A 982 (2019), 359-362

Heavier particles directed towards edge of the source.

Heavier particles freeze-out earlier

Phys. Rev. C81:064906 2010



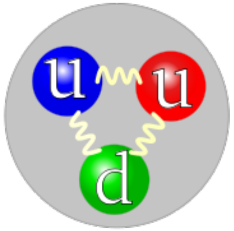
$$\langle x_{out} \rangle = \frac{\langle r\beta_f \rangle}{\left\langle \sqrt{\beta_t^2 + \beta_f^2} \right\rangle} = \frac{r_0 \beta_0 \beta}{\beta_0^2 + T/m_t},$$

β_f - the same for both particles

$\beta_t \sim 1/m_T$ - smaller for heavier particles

Conclusions & Summary

Summary



Correlation **femtoscopy** probes the system:

- **interaction:**
- First attempt to determine strong forces responsible for binding anti-nuclei;
- A quantitative verification of matter-antimatter symmetry (forces responsible for the binding of anti-nuclei);
- Strong interaction between strange (Λ, Ω) particles is investigated;
- **geometry**:
- Pure geometrical information: source parametrized in 3D space (out-side-long), also seen w.r.t. reaction plane;
- Source's lifetime, particle duration, temperature of kinetic freeze-out, etc..;
- **dynamics:**
- emission sequence (particle of which type is emitted earlier or later);
- collectivity seen through homogeneity region.

Thank you for Your attention