Warsaw University of Technology

Faculty of Physics

WARSAW UNIVERSITY OF TECHNOLOGY

What can we learn from femtoscopy?

Hanna Paulina Zbroszczyk

e-mail: hanna.zbroszczyk@pw.edu.pl

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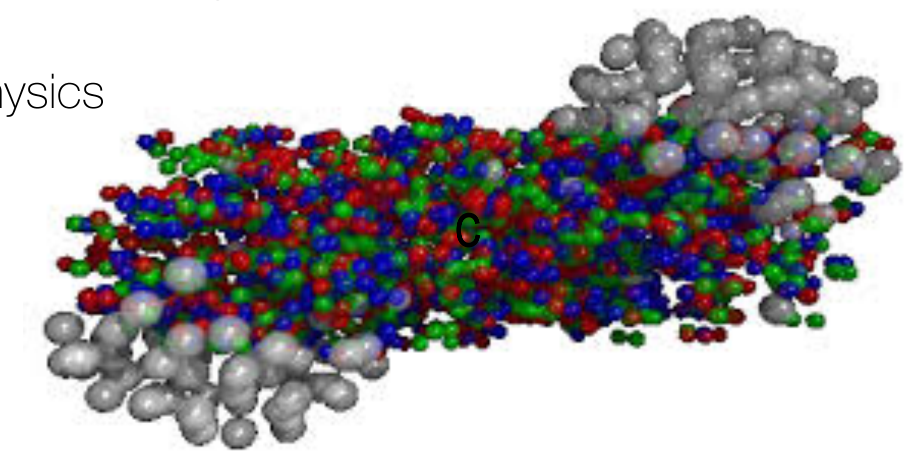


Zimanyi Winter School; Budapest, 2-6 December 2019

Outline

Introduction

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

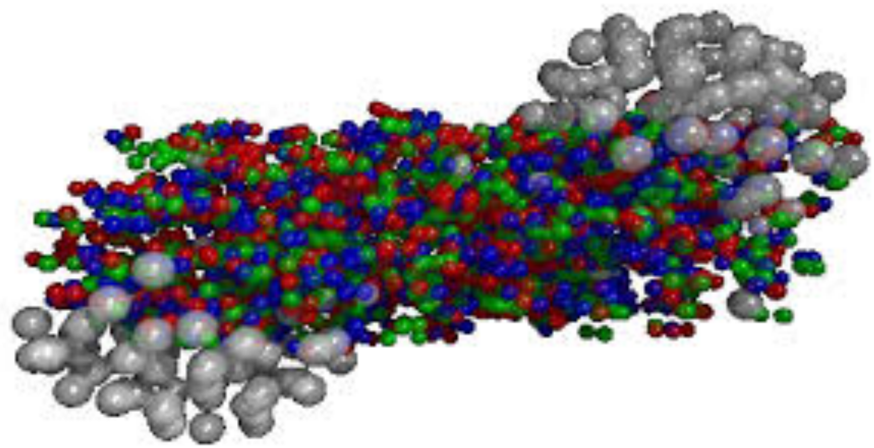
Results

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

b) Femtoscopy of strange baryons

c) Beam Energy Scan Program (BES):

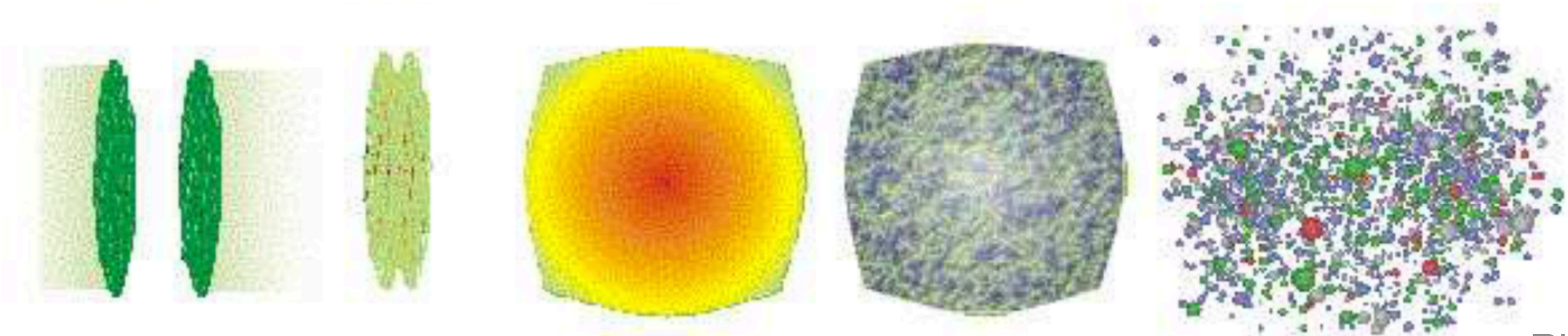
- identical pion femtoscopy
- **geometry**: centrality dependencies
  energy dependencies
  system (of pair) dependencies
- **dynamics**: centrality dependencies
  energy dependencies
  system (of pair) dependencies

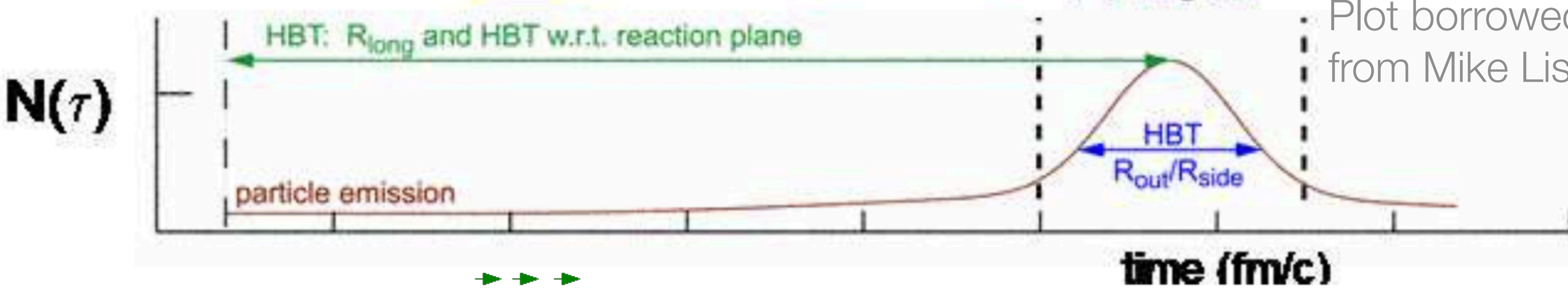


Conclusions

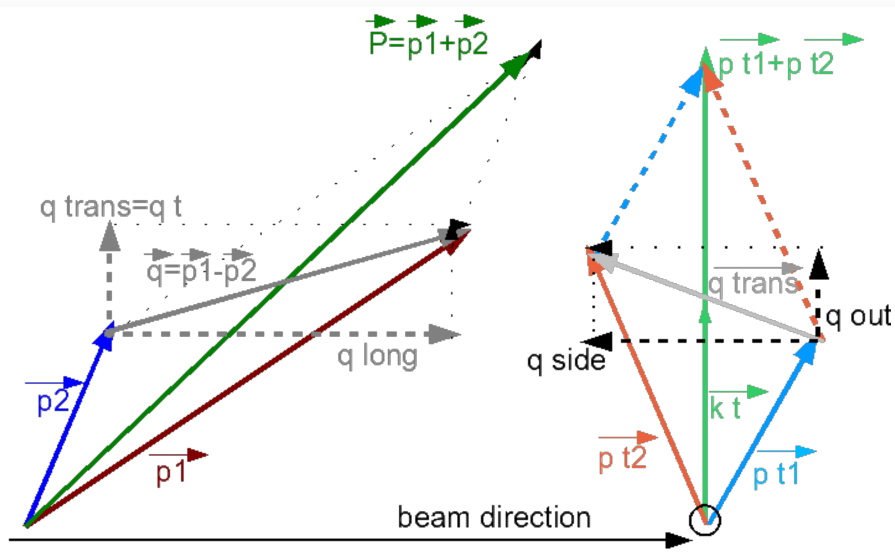
Introduction

Heavy-Ion collision and **HBT** method





Plot borrowed from Mike Lisa



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!

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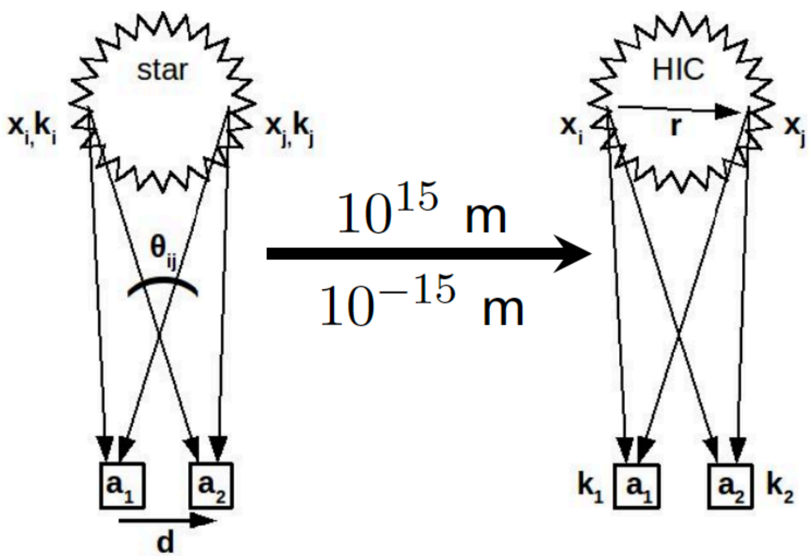
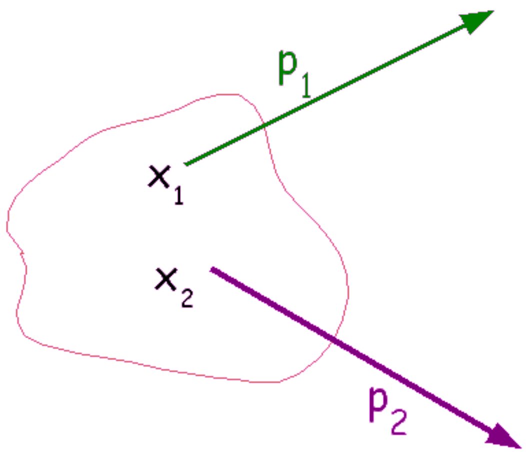


Femtoscopy (**HIC**) inspired by **H**anbury **B**rown and **T**wiss interferometry method (**Astronomy**)

but!

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

Femtoscopic correlations



x_1, x_2 - space-time sizes and dynamics

(**can not** be measured directly) →

Close velocity correlations

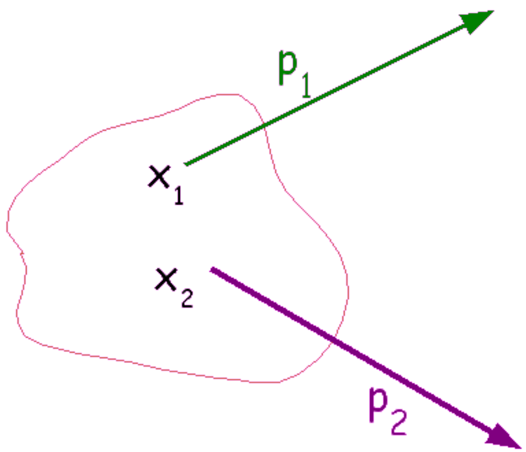
(HBT + FSI) ←

p_1, p_2 - momenta and momentum difference

(**can** be measured directly)

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) →

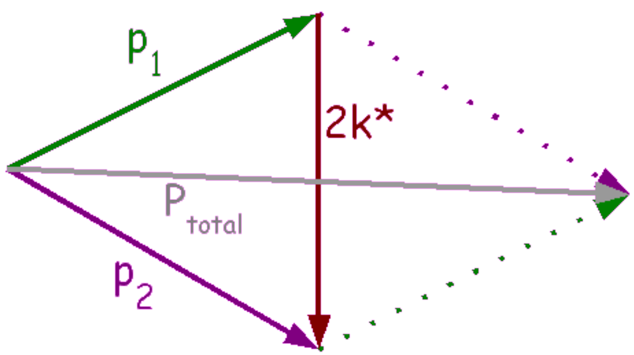
Close velocity correlations
(HBT + FSI) ←

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

Single- and two-particle distributions

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

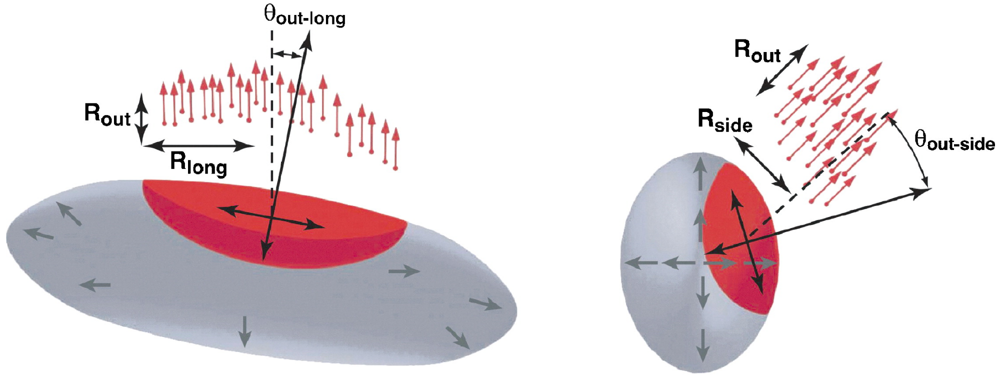
$$P_2(p_1,p_2) = E_1 E_2 \frac{dN}{d^3p_1 d^3p_2} = \int d^4x_1 S(x_1,p_1)\, d^4x_2 S(x_2,p_2)\, \Phi(x_2, p_2 | x_1, p_1)$$



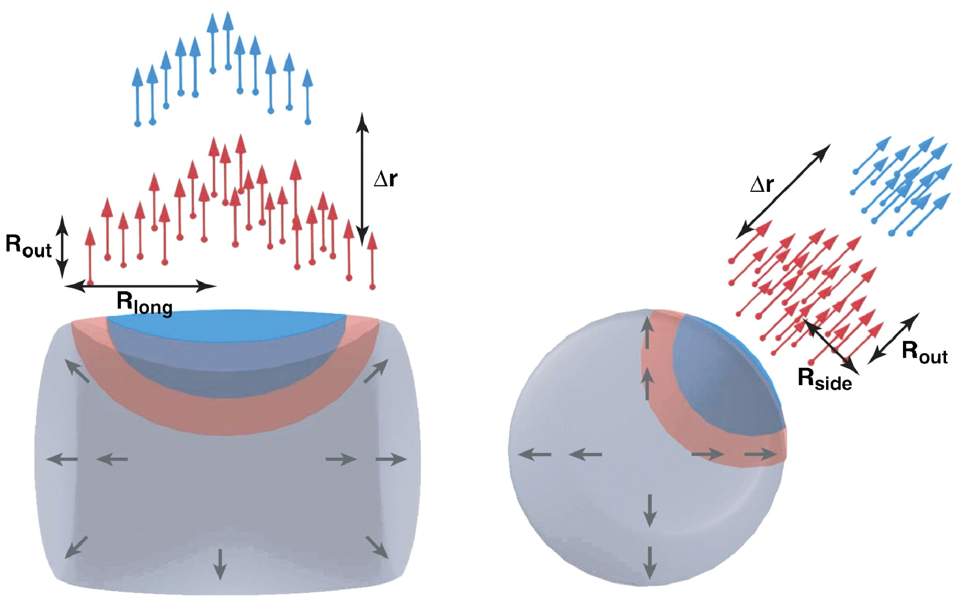
Correlation function

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

What does femtoscopy measure?



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

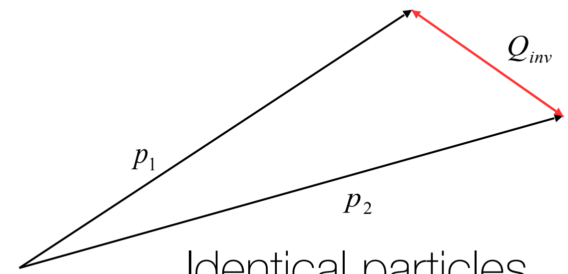


Lisa MA, et al. 2005.
Annu. Rev. Nucl. Part. Sci. 55:357–402

Homogeneity region

Q_{inv}

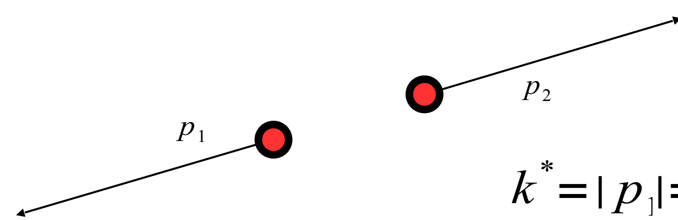
Longitudinal Co-Moving System - **LCMS**



Identical particles

k^*

Pair Rest Frame - **PRF**

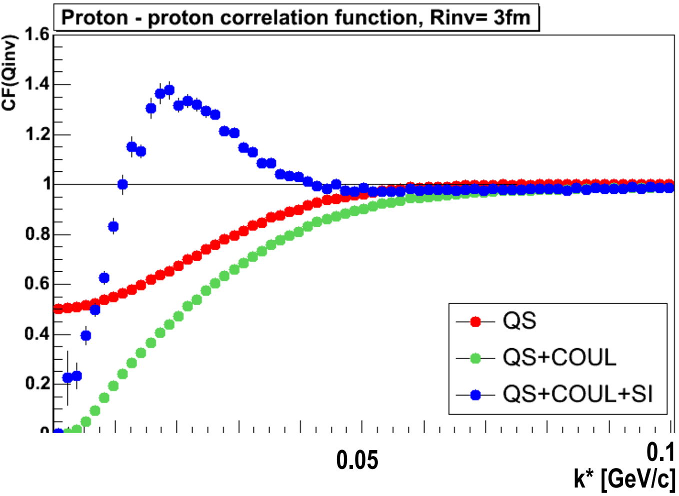


$k^* = |p_1| = |p_2|$

Nonidentical particles

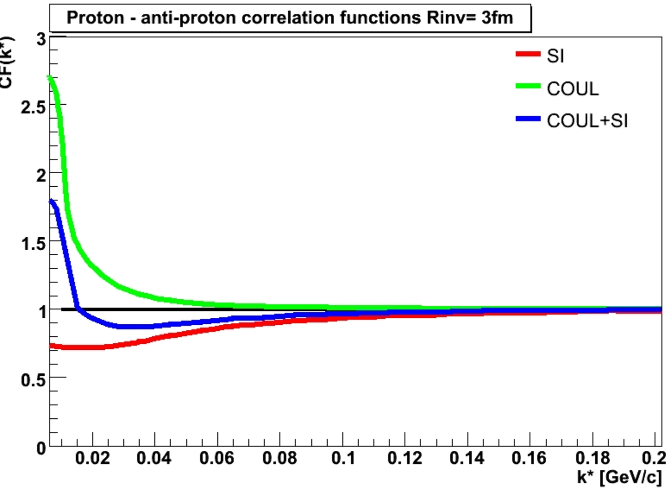
$Q_{inv} = 2k^*$ for $m_1 = m_2$

Effects and interactions



Identical baryon- baryon

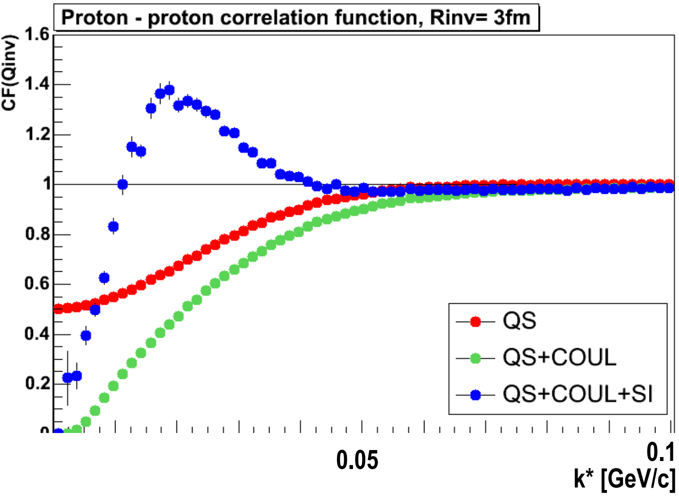
- Quantum Statistics- **QS**
- Final State Interactions- **FSI**
    - Coulomb
    - Strong



Non-identical baryon- (anti)baryon

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

Effects and interactions



Identical baryon- baryon

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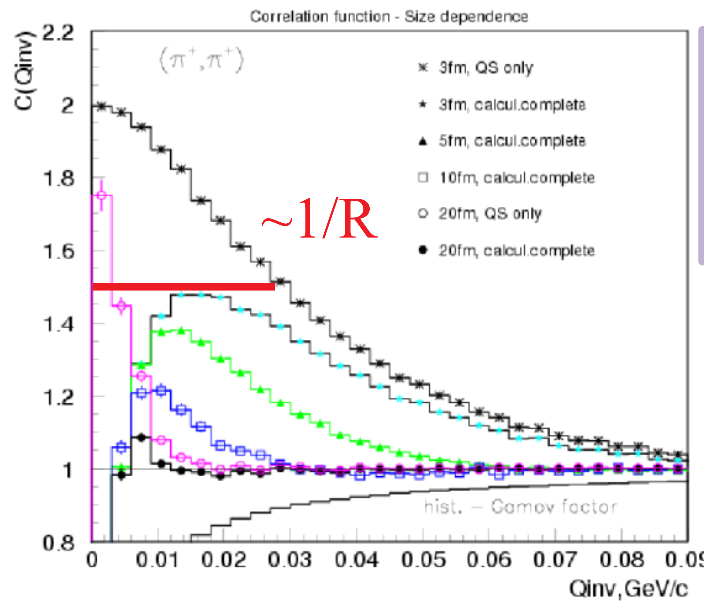
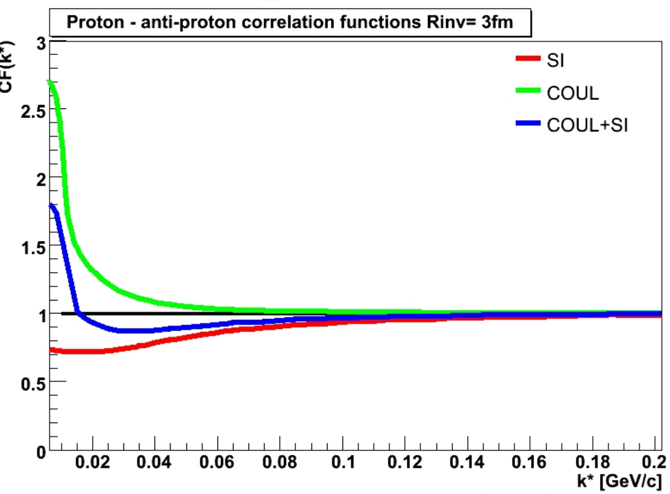


Width of correlation function **~ 1/R**



Non-identical baryon- (anti)baryon

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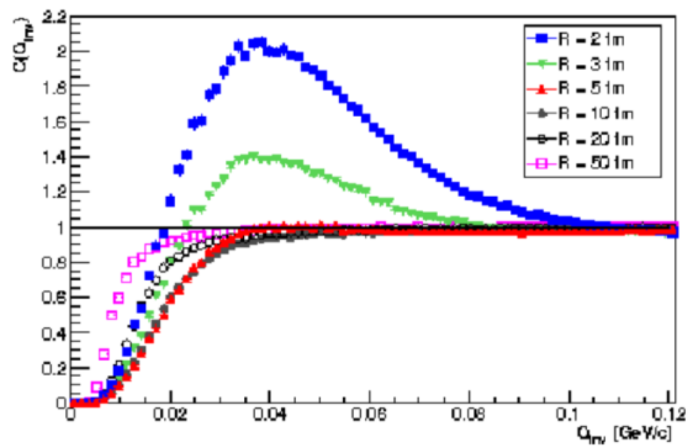
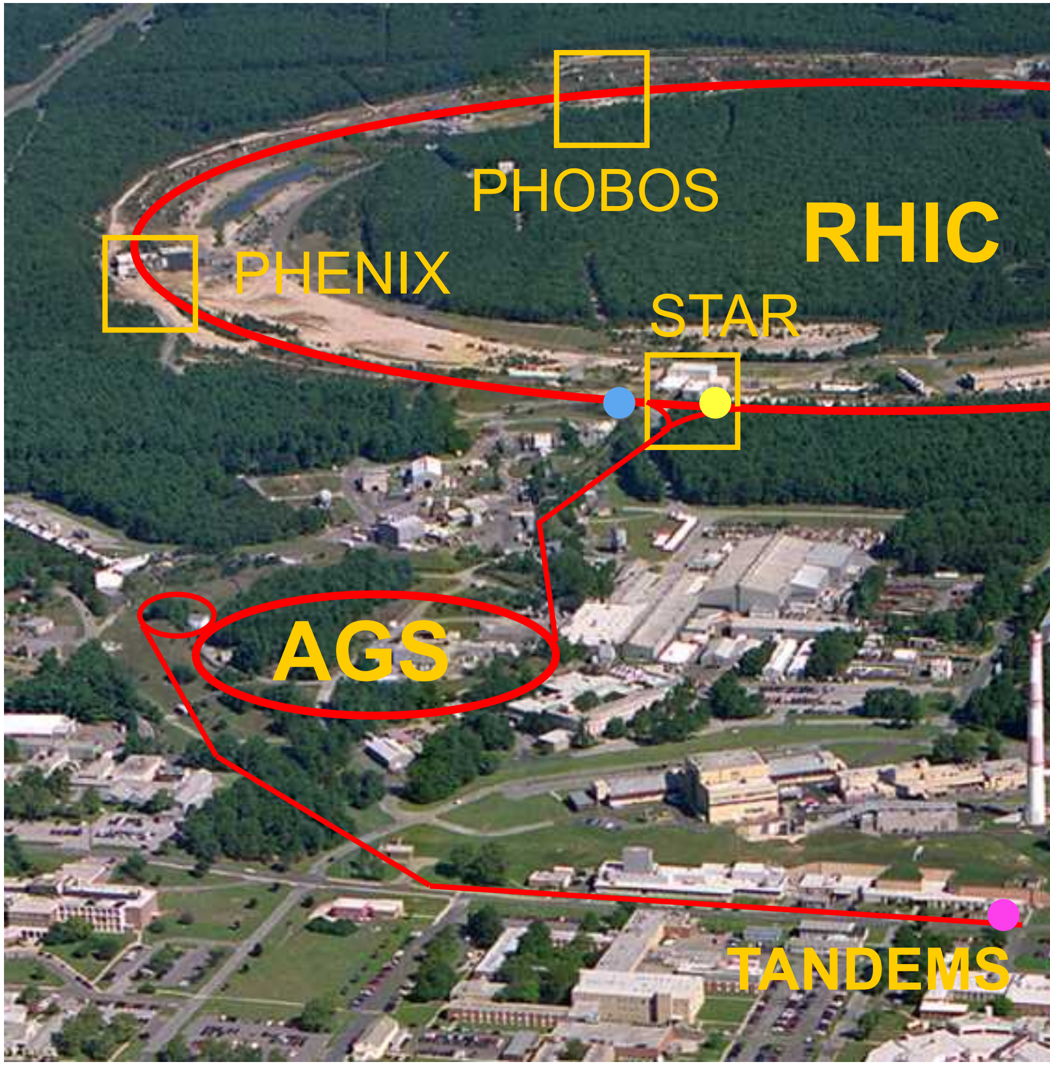
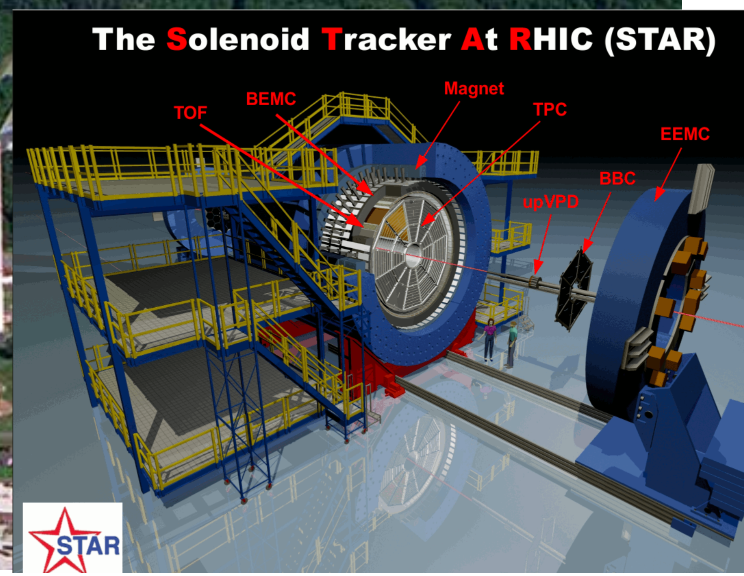


Bigger source and weaker correlation

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





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

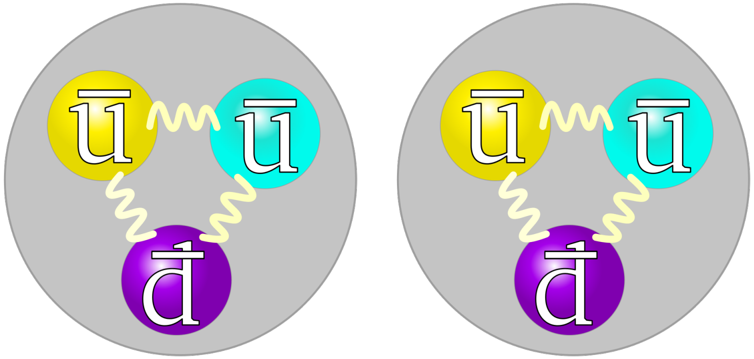
Results

a) Proton Femtoscopy @200 GeV

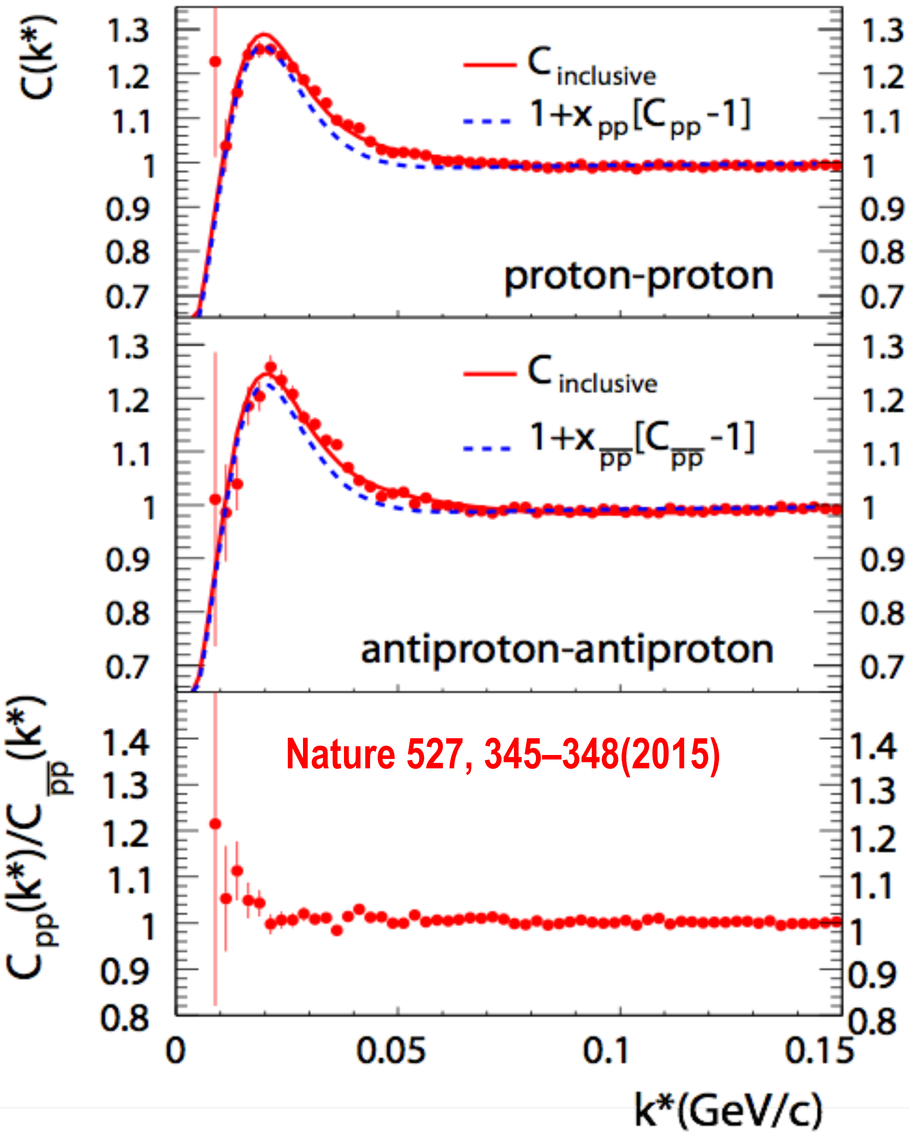
So far, the knowledge on **nuclear force** was derived from studies made on **nucleon** or / and **nuclei**.

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.



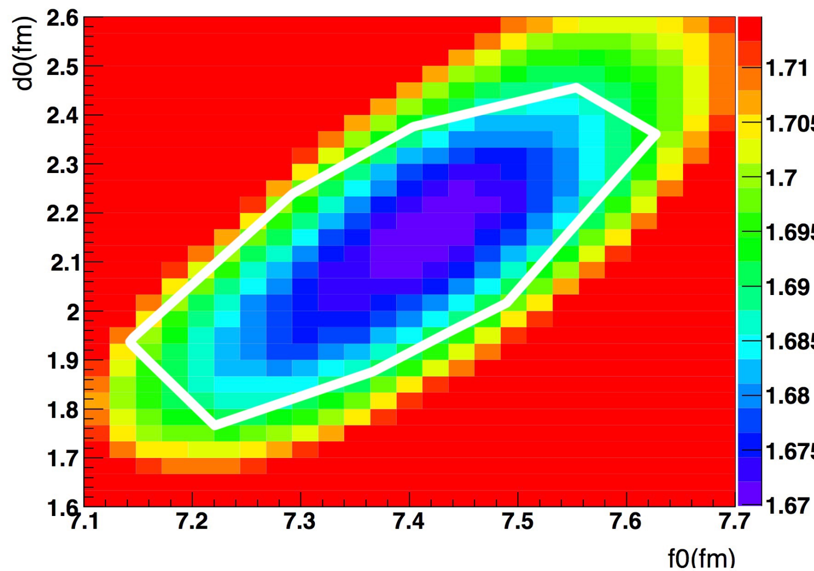
a) Strong interactions between anti-nucleons



Fit results:

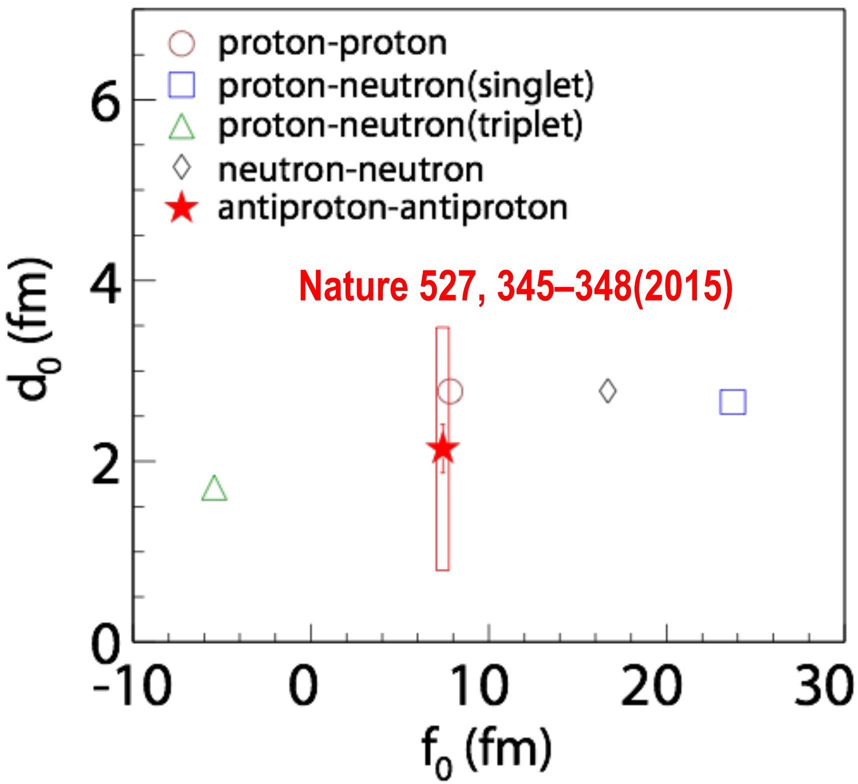
p-p CF,
R=2.75±0.01fm; $\chi2/NDF = 1.66$;

antiproton-antiproton CF,
R=2.80±0.02fm , f_0=7.41±0.19fm,
d_0=2.14±0.27fm; $\chi2/NDF=1.61$



$\chi^2/NDF(f_0,d_0)$ 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.

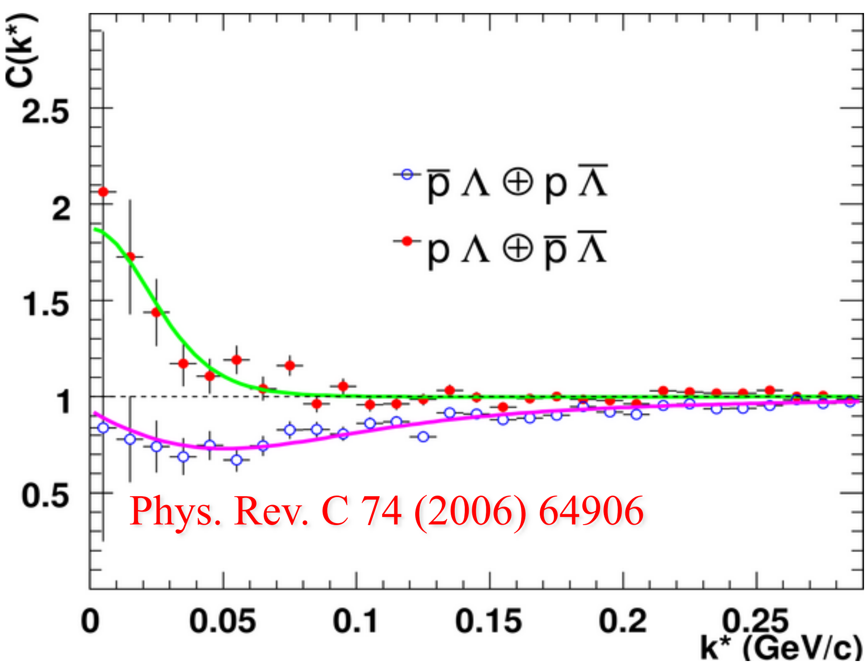
b) Strange Baryon Correlations (Including Λ Hyperons)

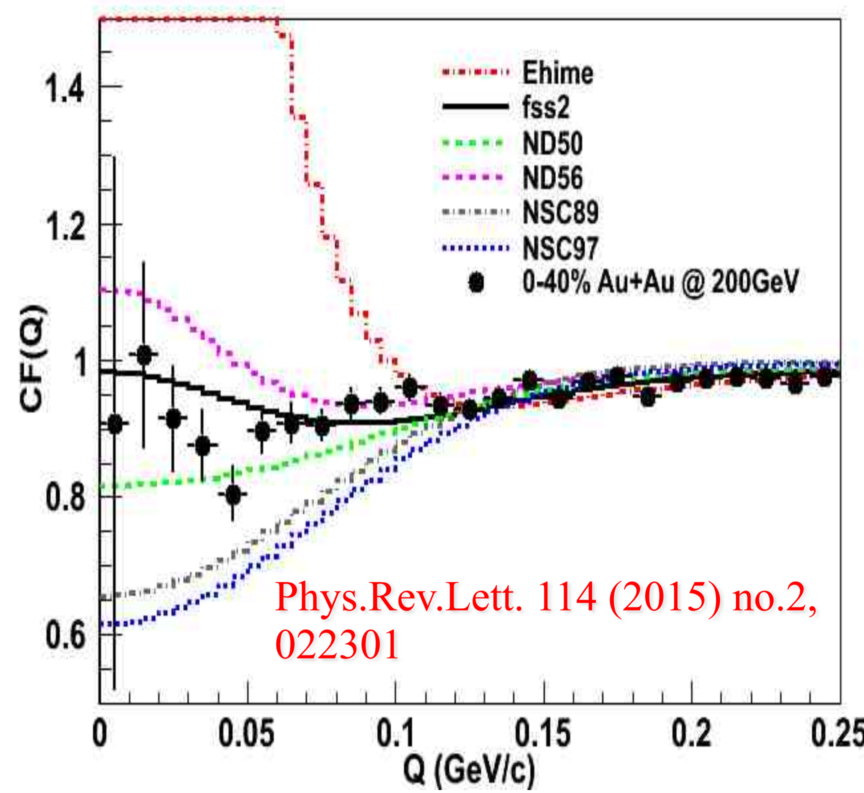
proton-lambda correlations:
sensitive to the Strong FSI only

lambda-lambda correlations:
sensitive to the Quantum Statistical effects and Strong FSI

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





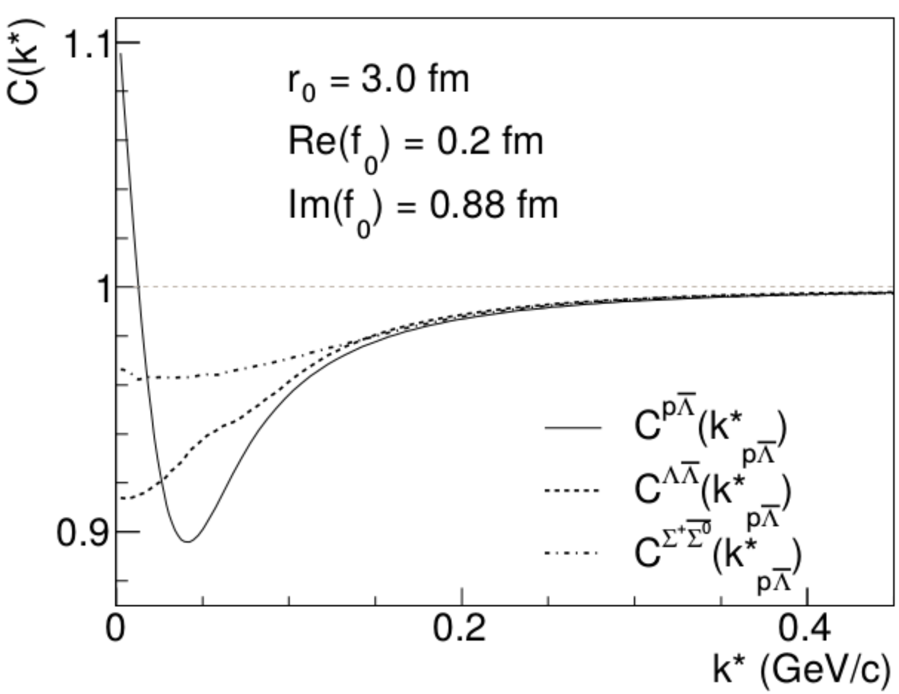
b) Strange Baryon Correlations (Including Λ Hyperons)

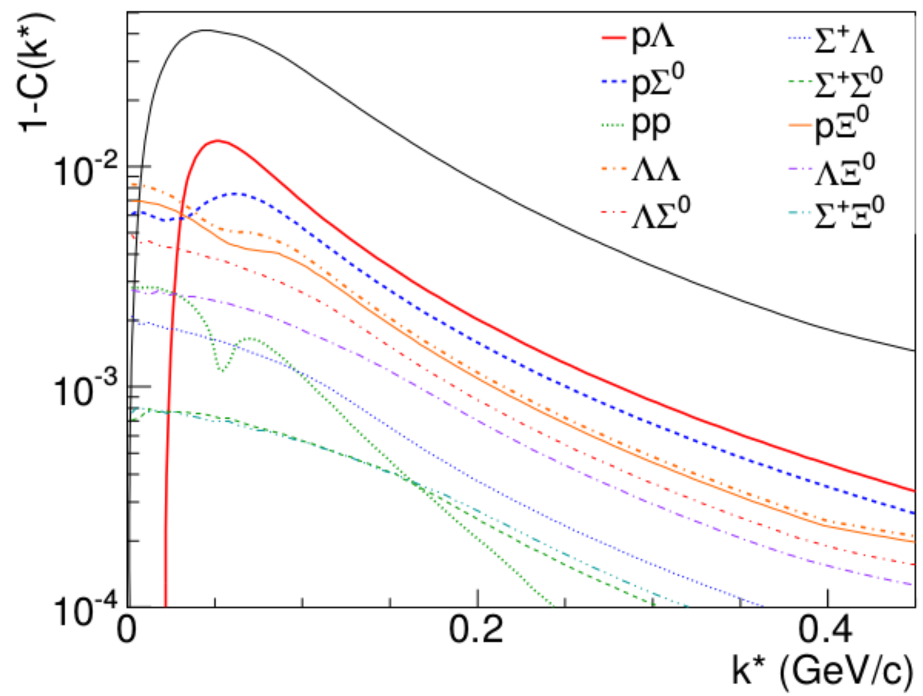
For residual correlations correction see talk by S. Siejka

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

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

HZ, A. Kisiel, M. Szymański
Phys.Rev. C89 (2014) no.5, 054916





b) Strange Baryon Correlations (including p-Ω)

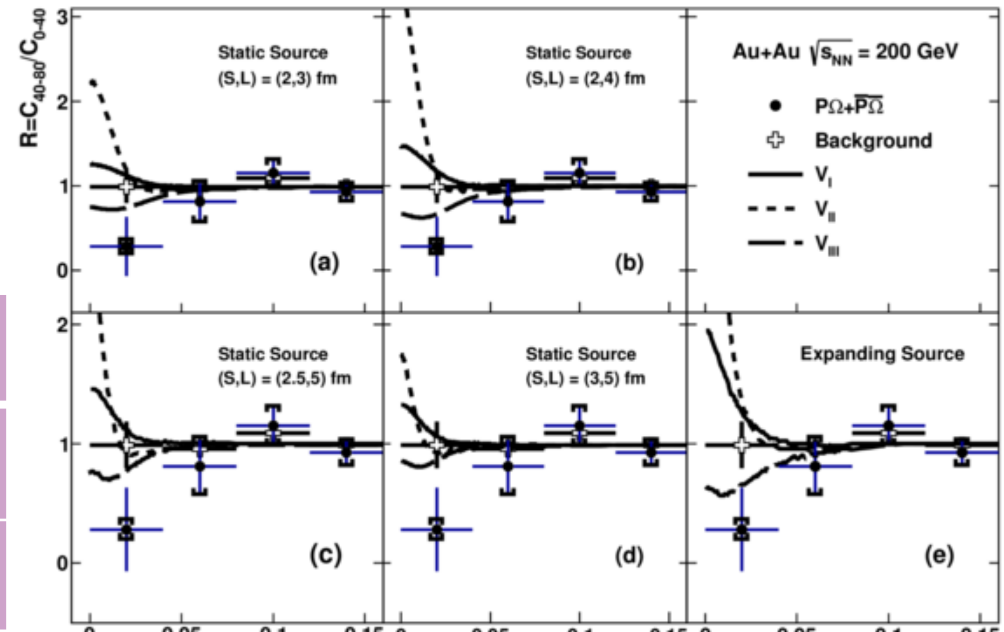
Binding energy Ebin [MeV]
Scattering length a0 [fm]
Effective range reff [fm]
for 3 scenarios:
K. Morita et al. Phys. Rev. C 94, 031901 (2016)

	V1	V2	V3
Ebin [MeV]	-	6.3	26.9
a0 [MeV]	-1.12	5.79	1.29
reff [MeV]	-1.16	0.96	0.65

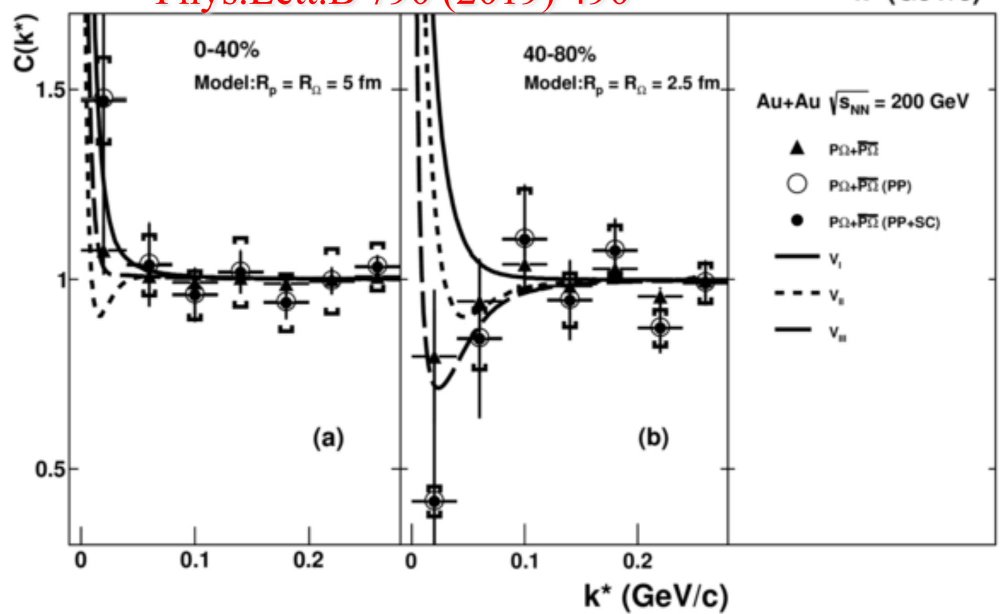
A comparison of the measured correlation functions from Au+Au collisions with theoretical predictions

Scattering length is positive and favor pΩ bound state hypothesis

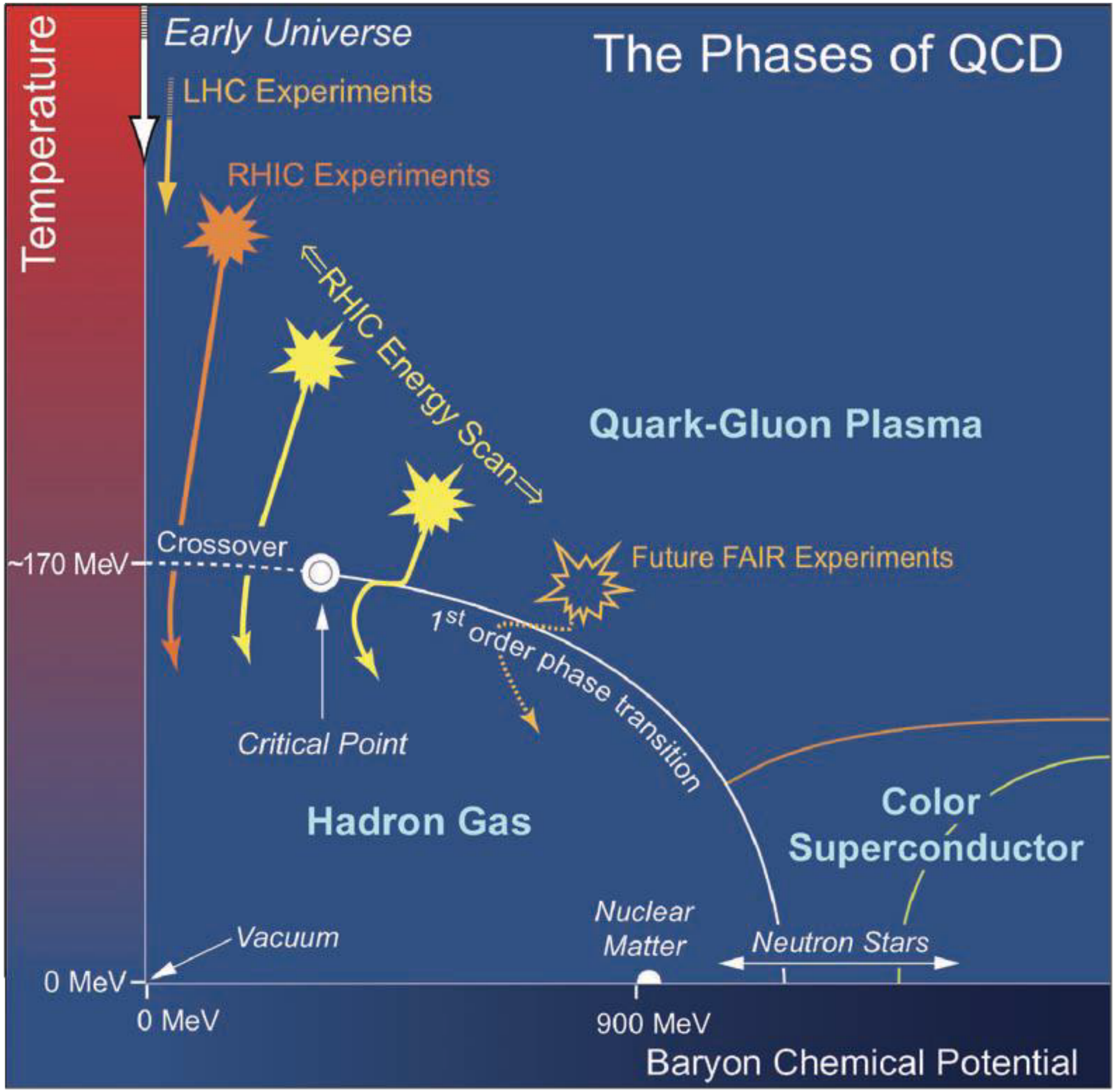
For strange meson correlations see talk by D. Pawłowska



Phys.Lett.B 790 (2019) 490



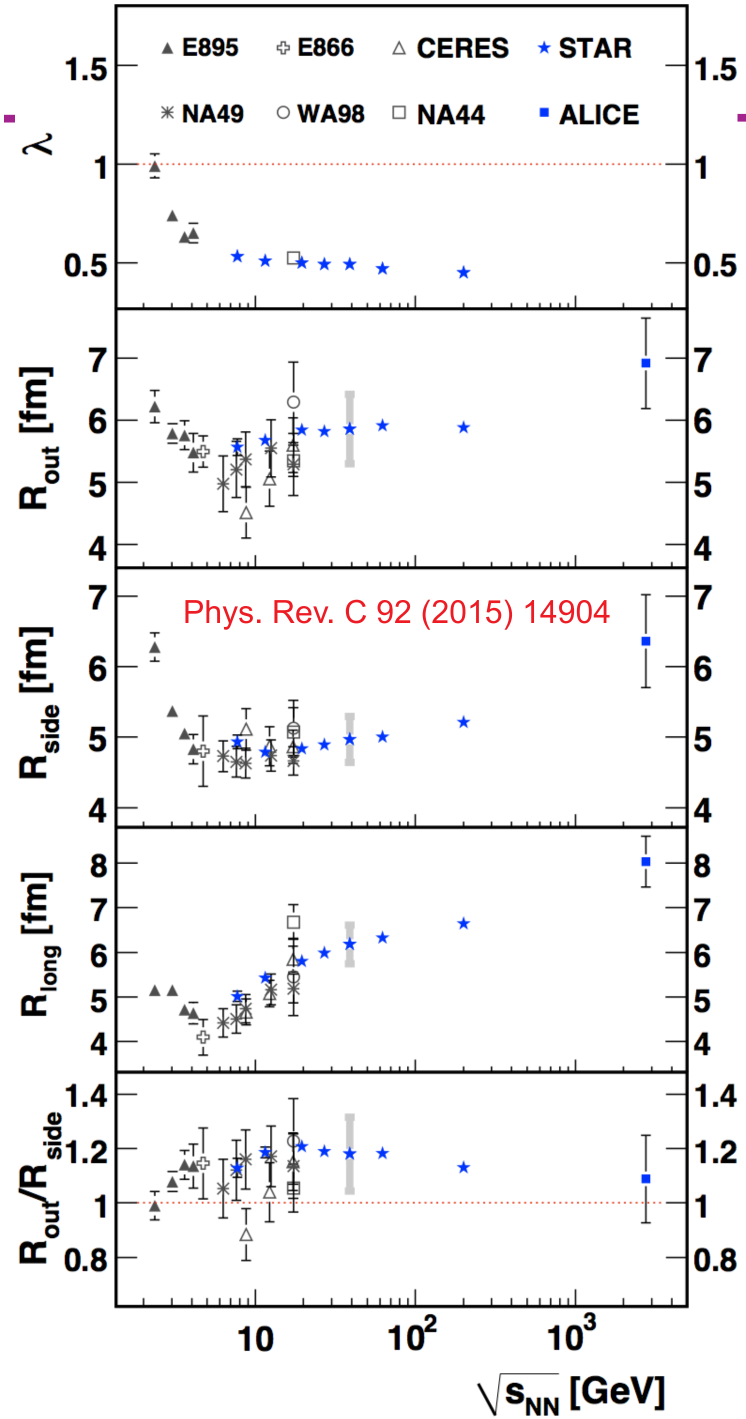
c) Program **B**eam **E**nergy **S**can



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

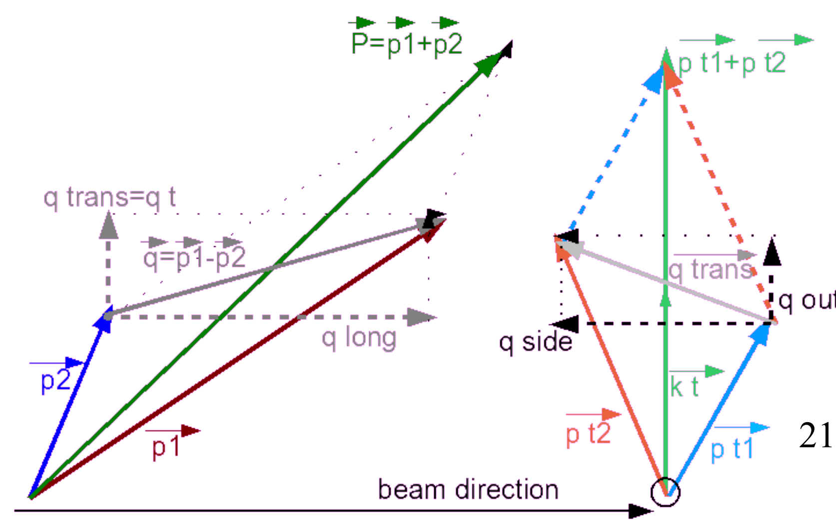
Fixed-Target Program
Au+Au =3.0-7.7 GeV
High baryon density regime
with 420-720 MeV



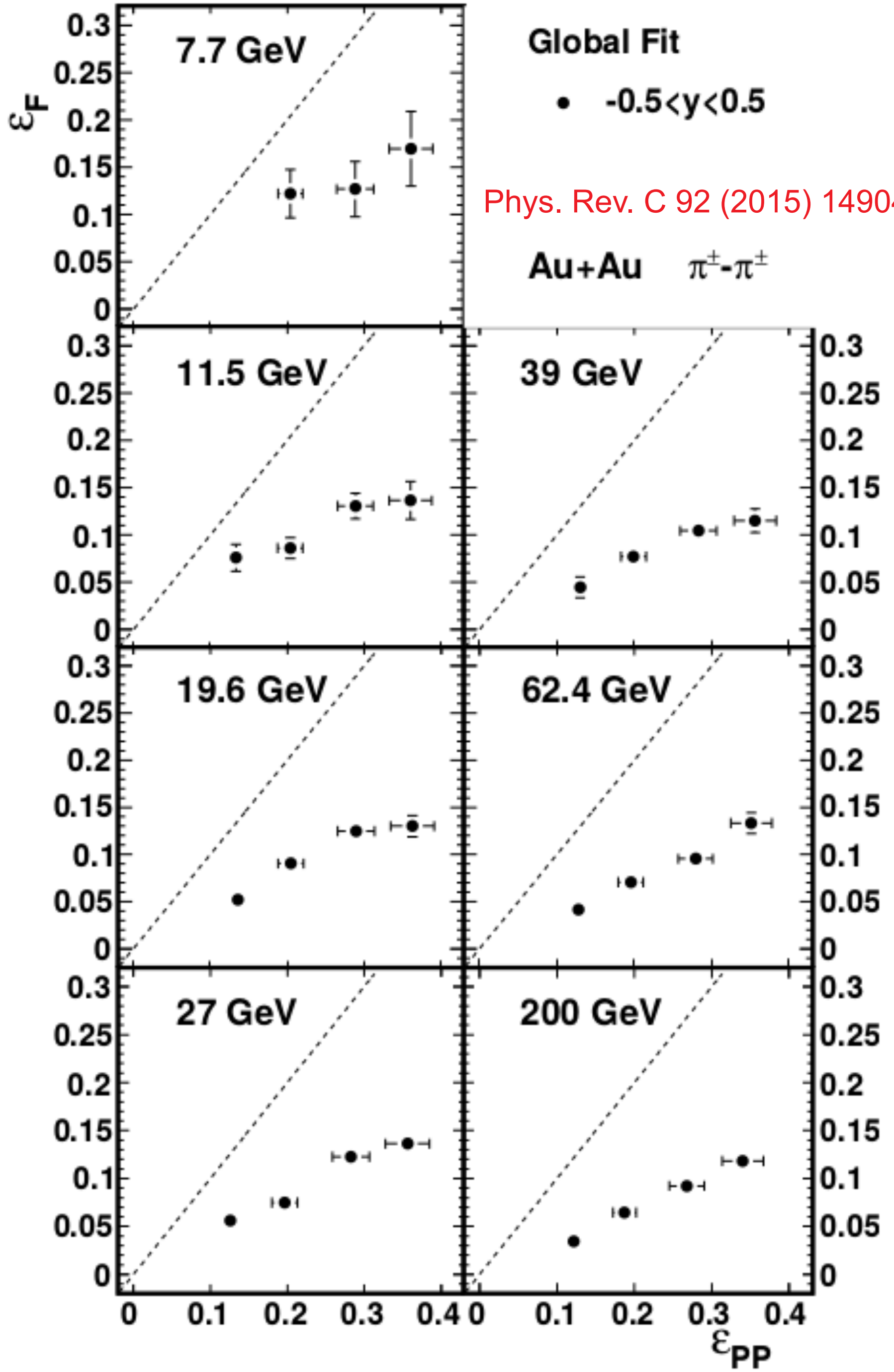
Program BES

- → 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



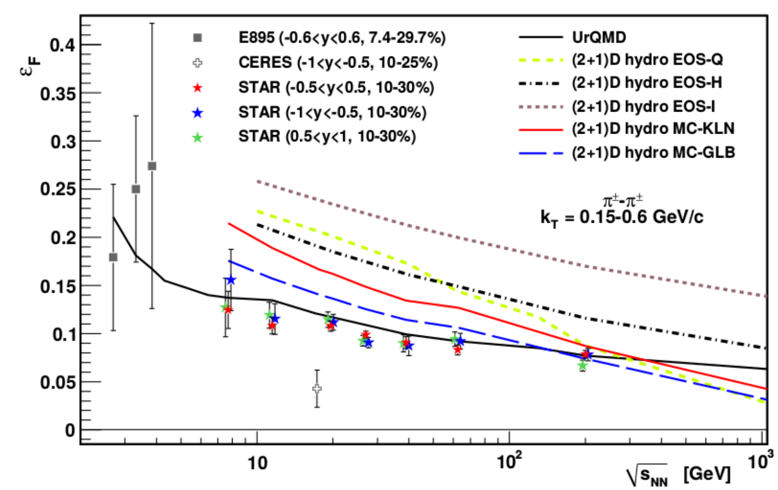
Phys. Rev. C 92 (2015) 14904

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

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

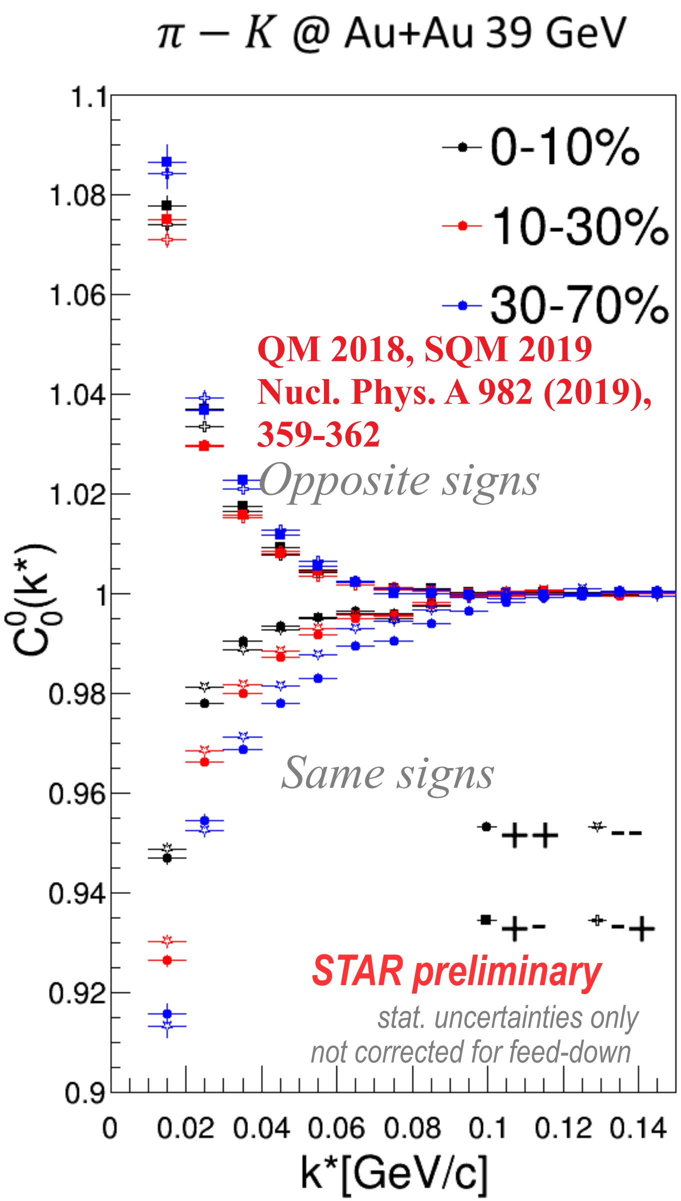
$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2\sum_{n=2,4,6\ldots} R_{\mu,n}^2 \cos(n\Phi) \qquad (\mu = o, s, l, ol)$$

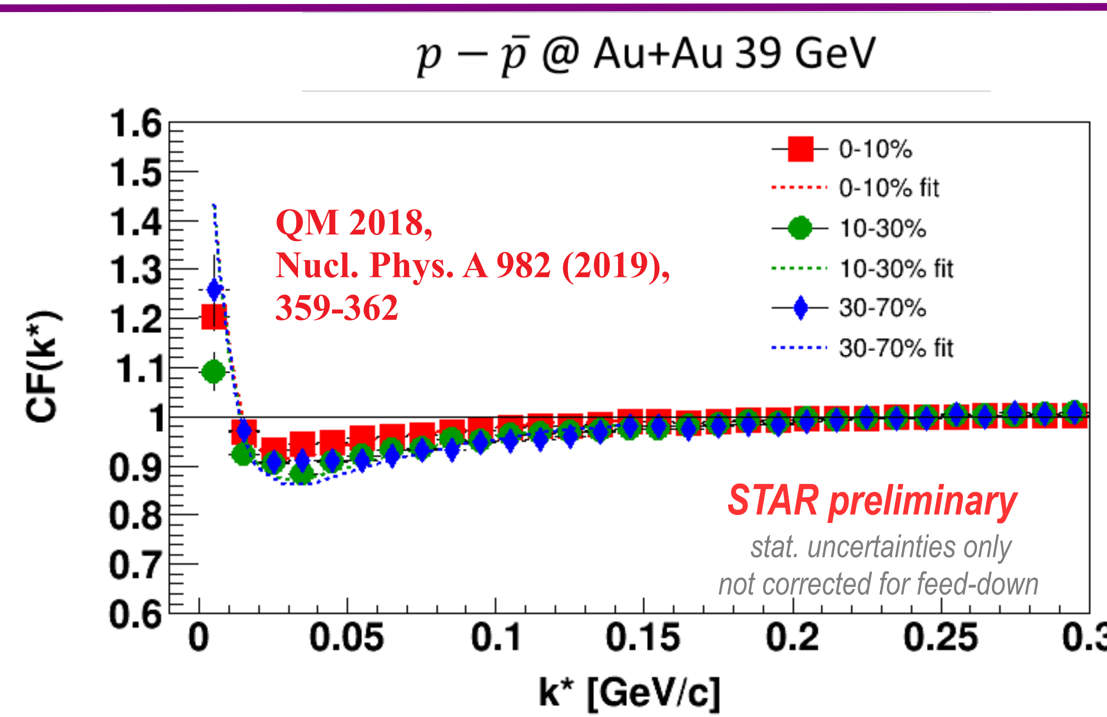
$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2\sum_{n=2,4,6\ldots} R_{\mu,n}^2 \sin(n\Phi) \qquad (\mu = os)$$



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

Geometry: dependence on collision **centrality**

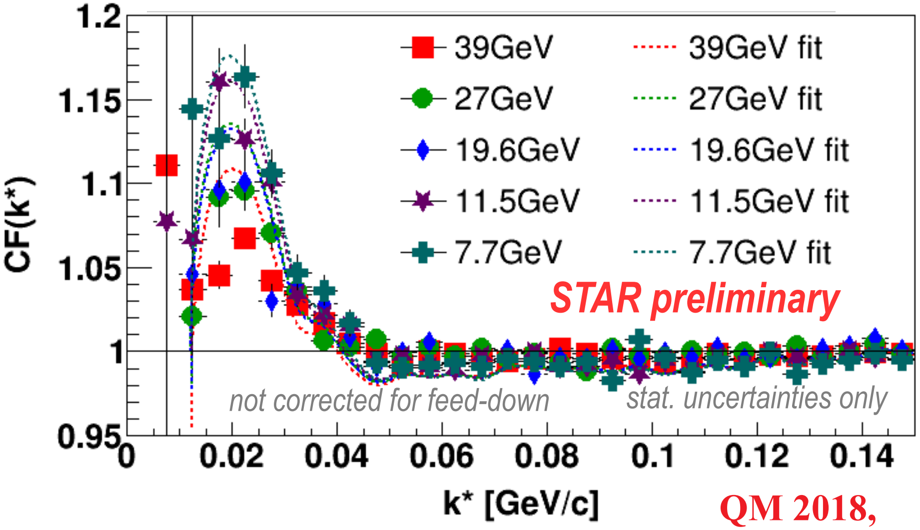




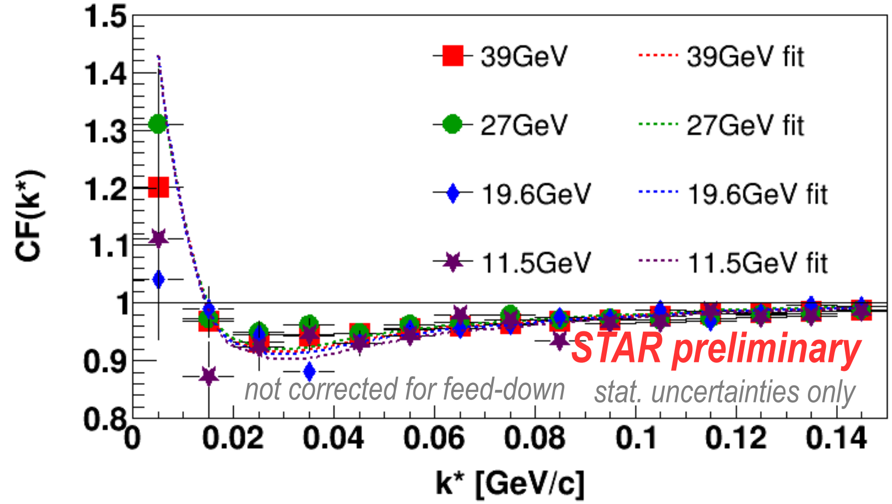
Clear **centrality** dependence
R(0-10%) > R(10-30%) > R(30-70%)

Dependence on collision **energy**

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

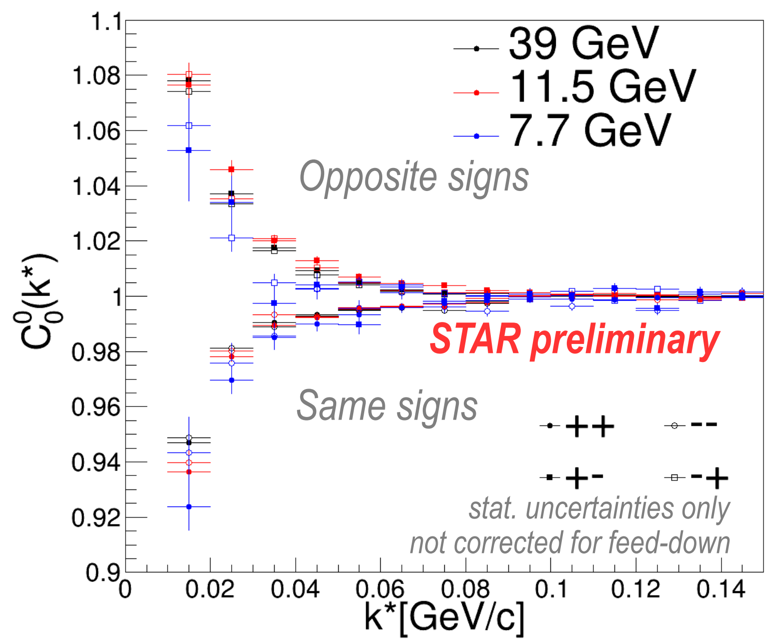


$p - \bar{p}$: Au+Au 0-10%



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

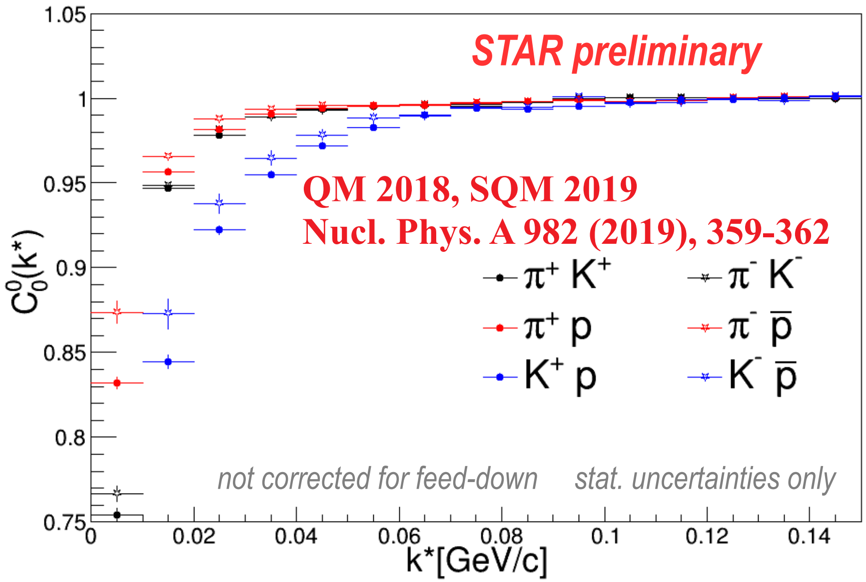
$\pi - K$: Au+Au 0-10 %



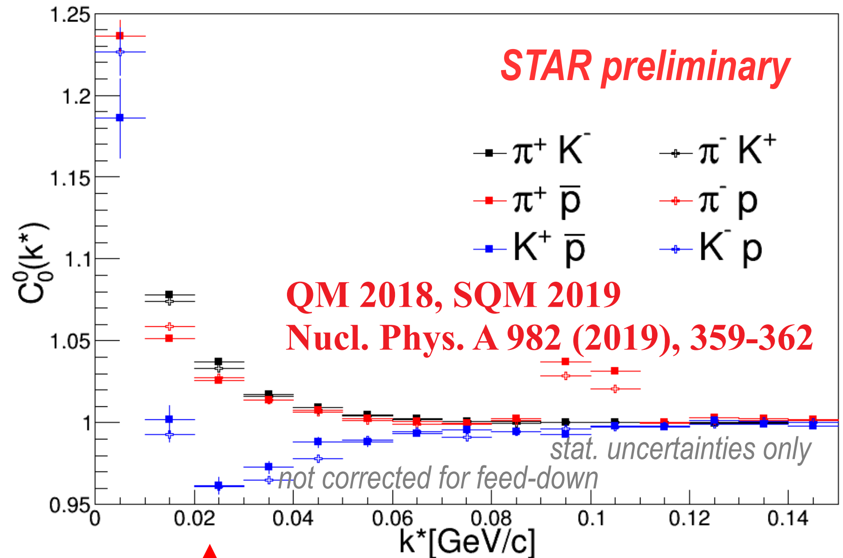
Clear **energy** dependence
R(39 GeV> > R(11.5 GeV) > R(7.7 GeV)

Dependence on interacting **system**

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



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



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

Determined by **Coulomb** Interactions

Clear **system** dependence

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

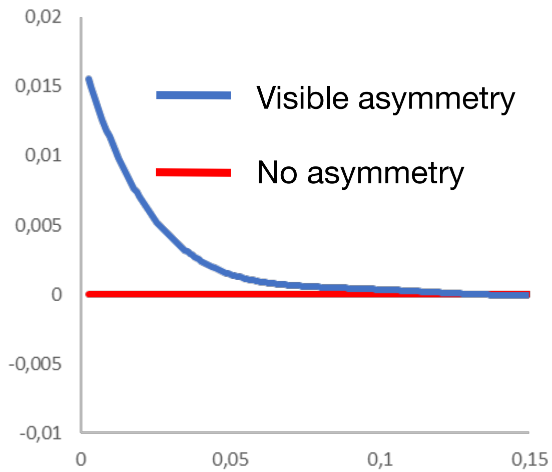
For non-identical particle correlations see talk by P. Szymański

Dynamics: Space-time asymmetry in emission process

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

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**

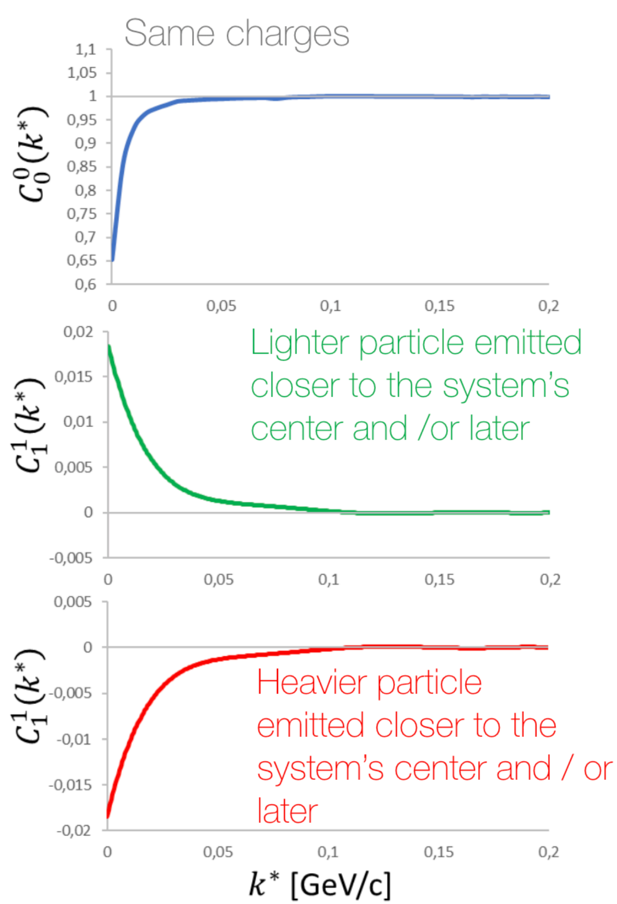


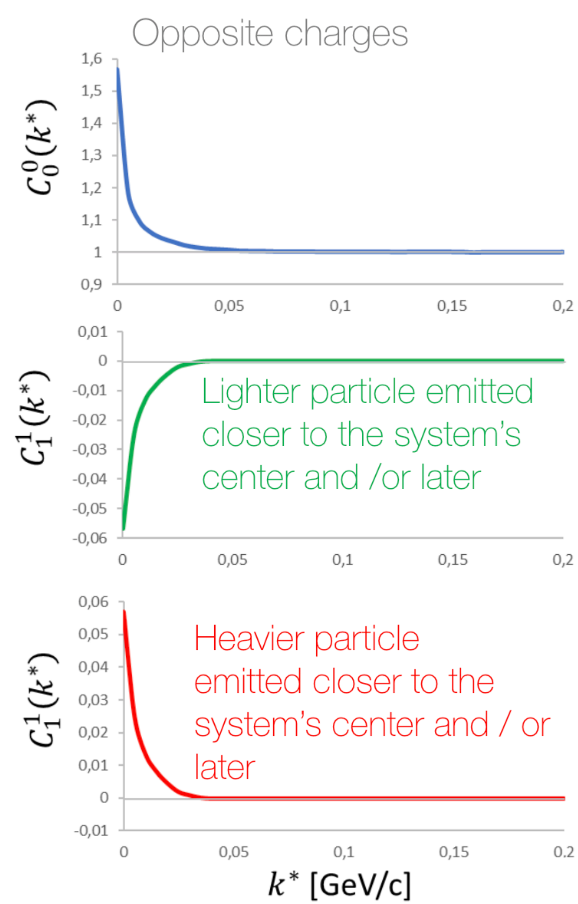
A. Kisiel
Phys. Rev. C81:064906 2010

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

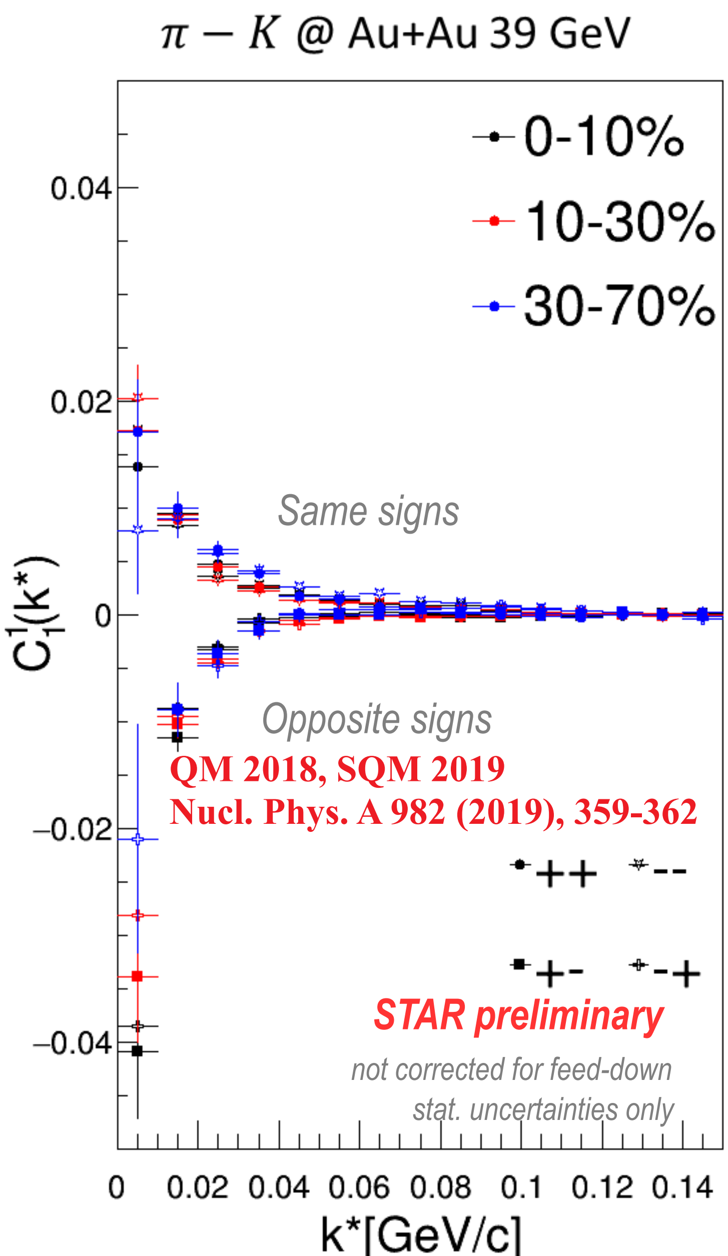
P. Danielewicz and S.Pratt.
Phys. Lett. B618: 60 2005

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



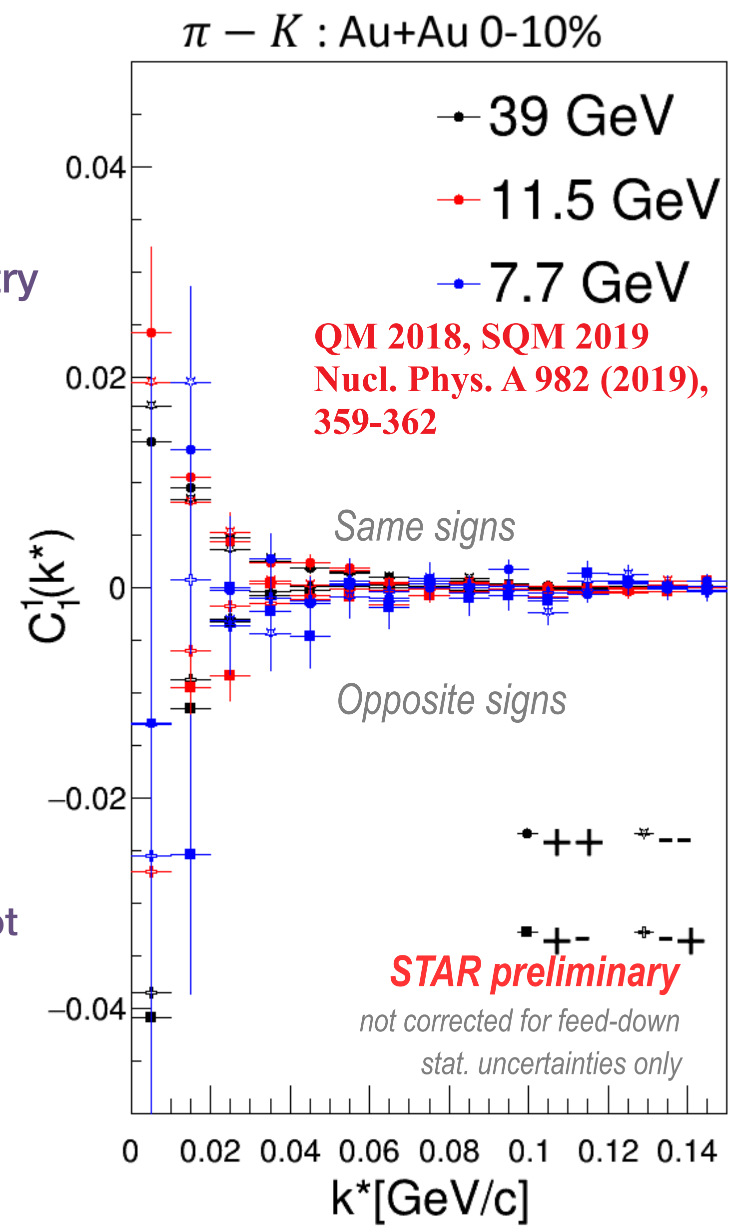


Dynamics: **centrality** and **energy** dependencies



Clear signal of emission asymmetry

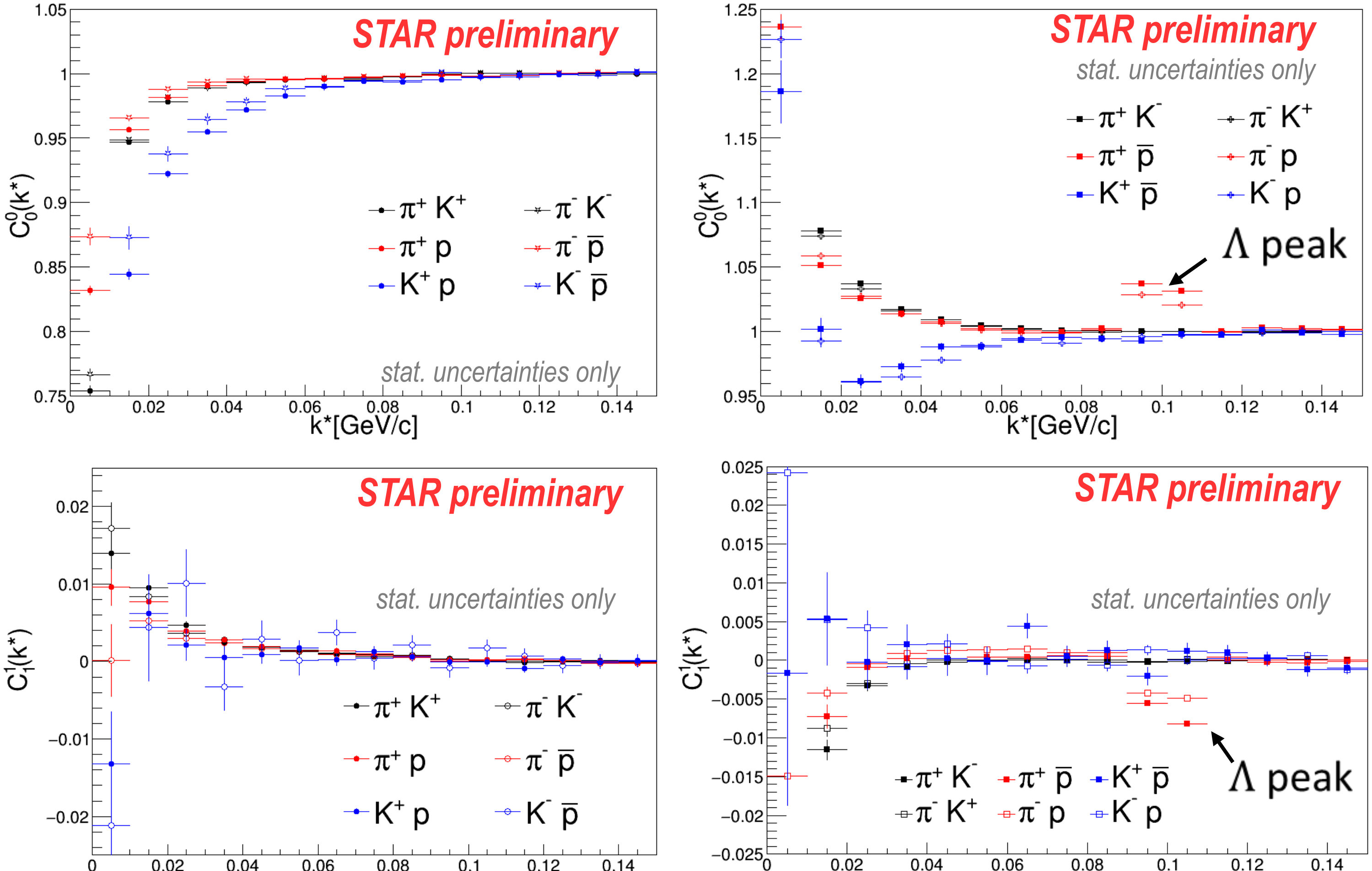
Asymmetry does not disappear in lower energies



Source dynamics: **system** dependence

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

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



Heavier particles directed towards edge of the source.

Heavier particles freeze-out earlier

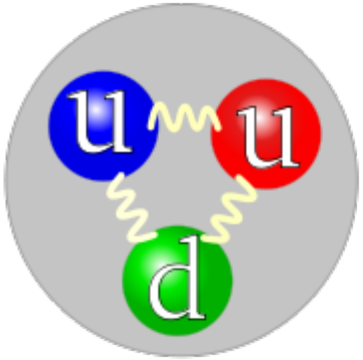
Phys. Rev. C81:064906 2010

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

Conclusions & Summary

Summary

Correlation **femtoscopy** probes the source:
- **geometry** (sizes)
- **dynamics** (evolution process, emission sequence, ..)
- **interactions** (strong, Coulomb)



Summary

Correlation **femtoscopy** probes the source:
- **geometry** (sizes)
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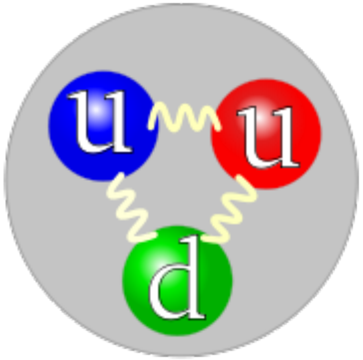
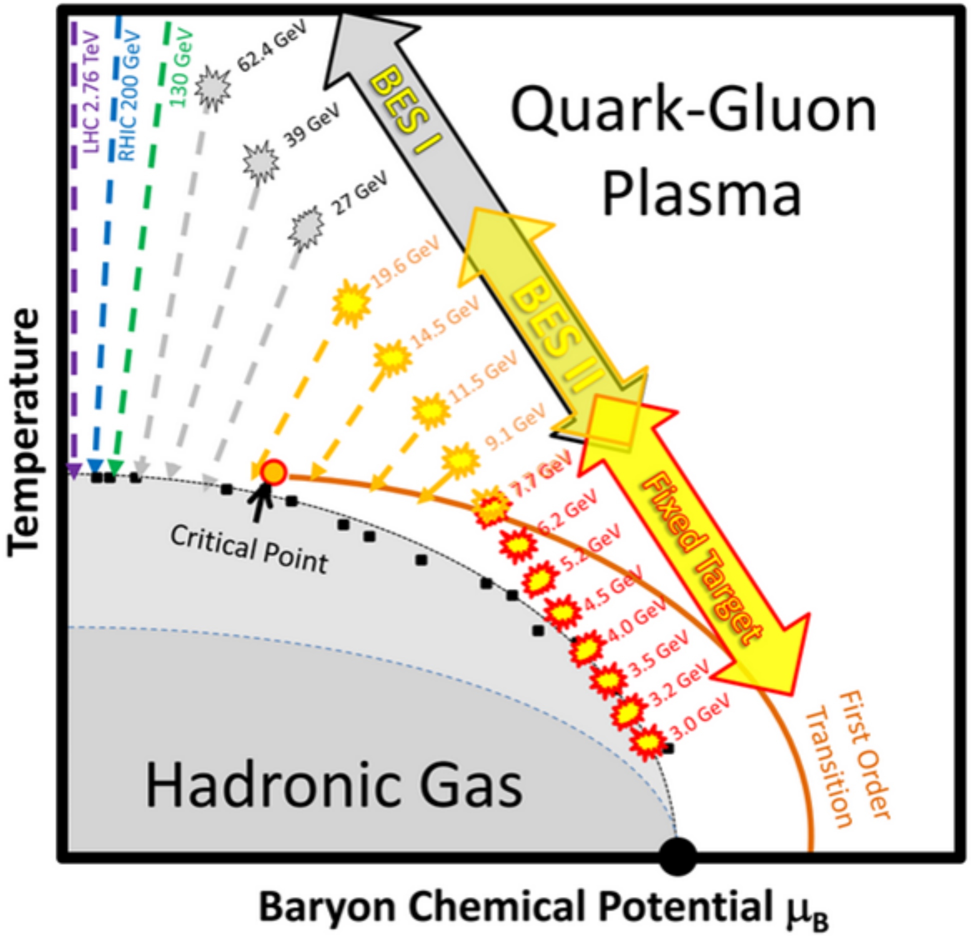
Thank you for Your attention



Back-up slides

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



BES Program goals:

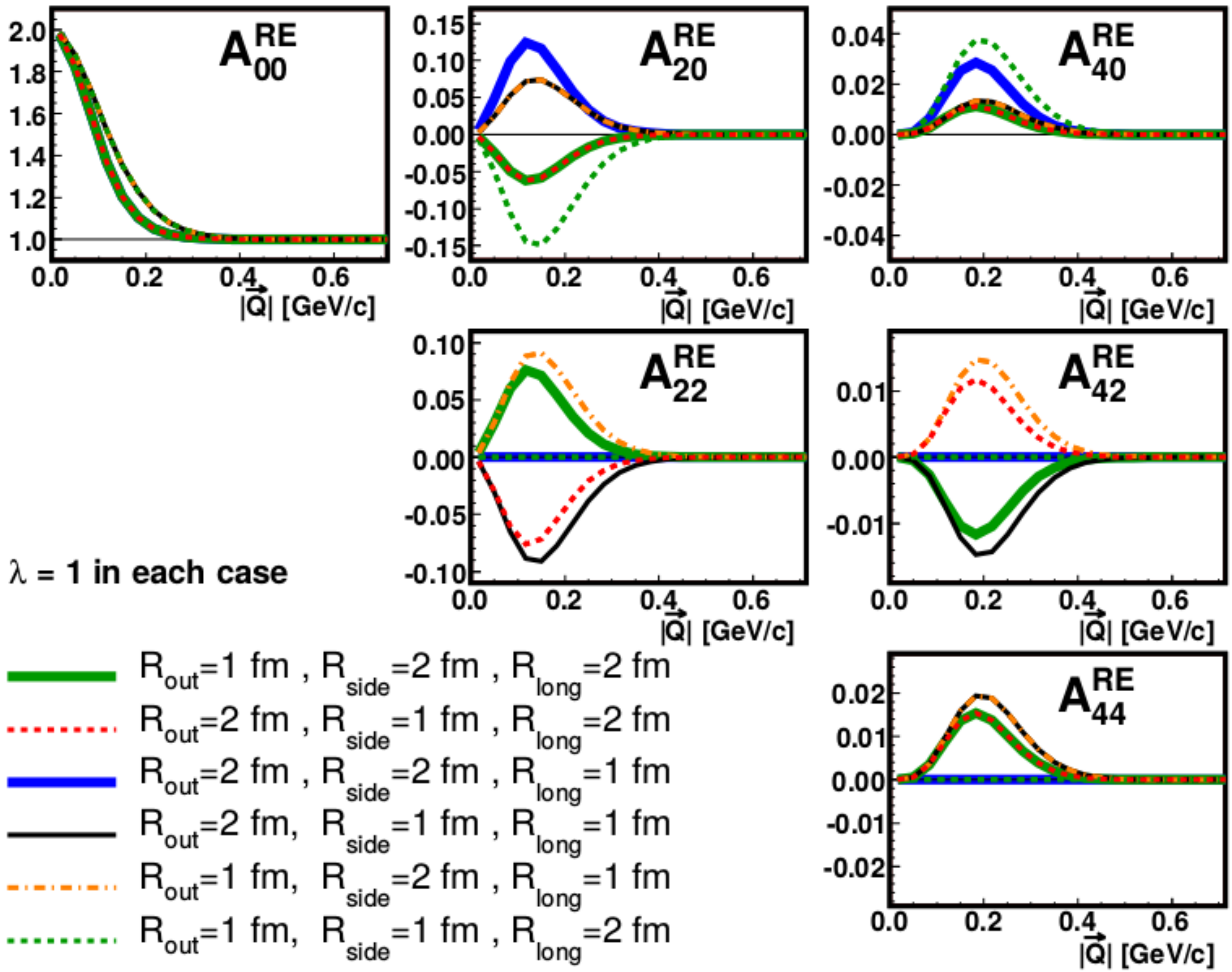
Study QCD Phase Diagram

1) localize where the QGP is not registered

2) signatures of the 1st order Phase transition

3) localize the Critical Point

Spherical Harmonics



Source dynamics