NATIONAL SCIENCE CENTRE
POLAND

EXCELLENCE INITIATIVE
RESEARCH
UNIVERSITY

Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Strange hadron correlations in Heavy-Ion collisions at RHIC energies and below

Hanna Paulina Zbroszczyk

Faculty of Physics, Warsaw University of Technology

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

14th International Conference on **Hypernuclear and Strange Particle Physics**,
June 27 – July 1, 2022; Prague, Czech Republic

Outline

Introduction

- QCD phase diagram
- HIC and femtoscopy method

Results

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

b) Motivation to Y-N and Y-Y **correlations**

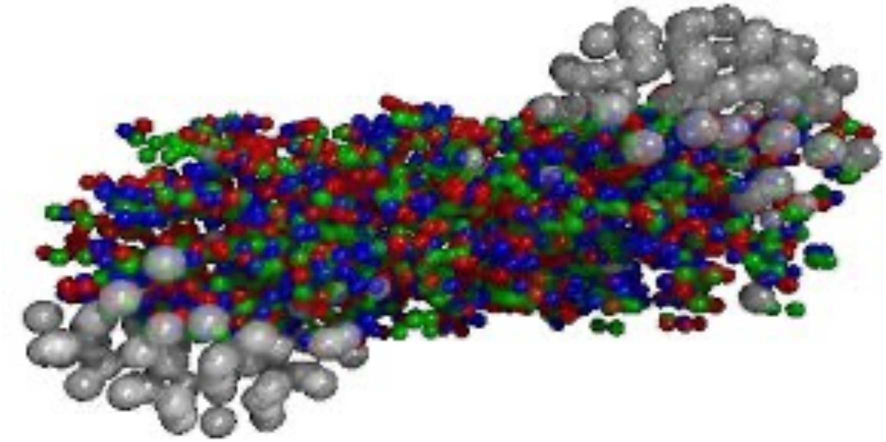
c) Femtoscopy of **strange baryons** and their interactions

d) Possible **bound states**

e) **Coalescence** production of deuterons

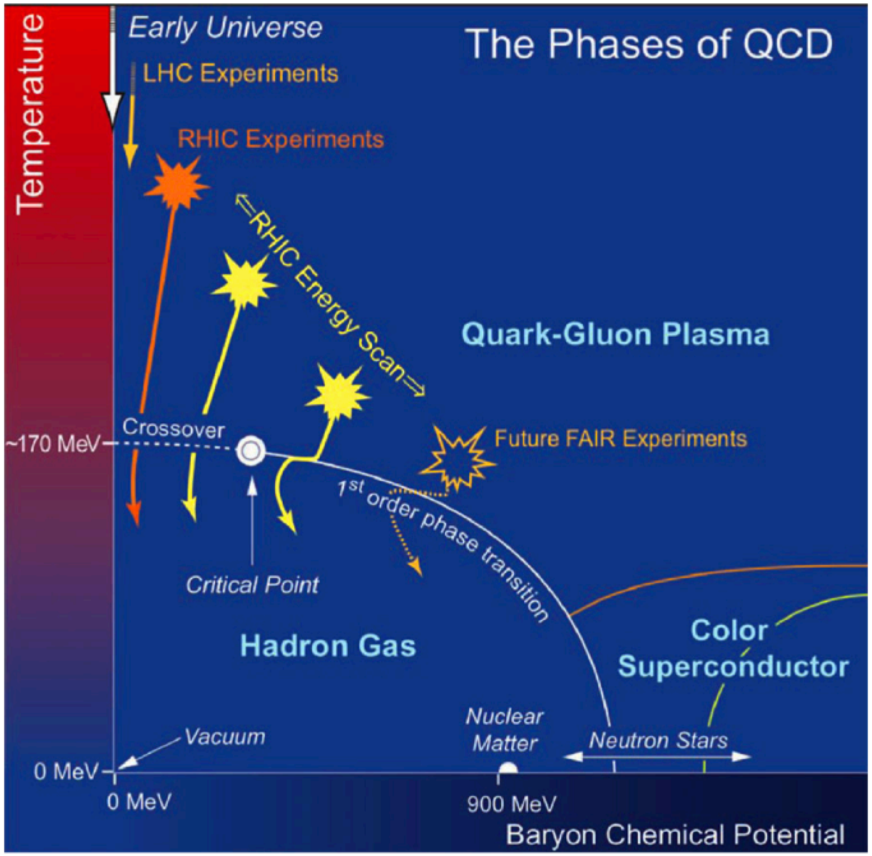
f) **Nonidentical** particle correlation

Summary and conclusions

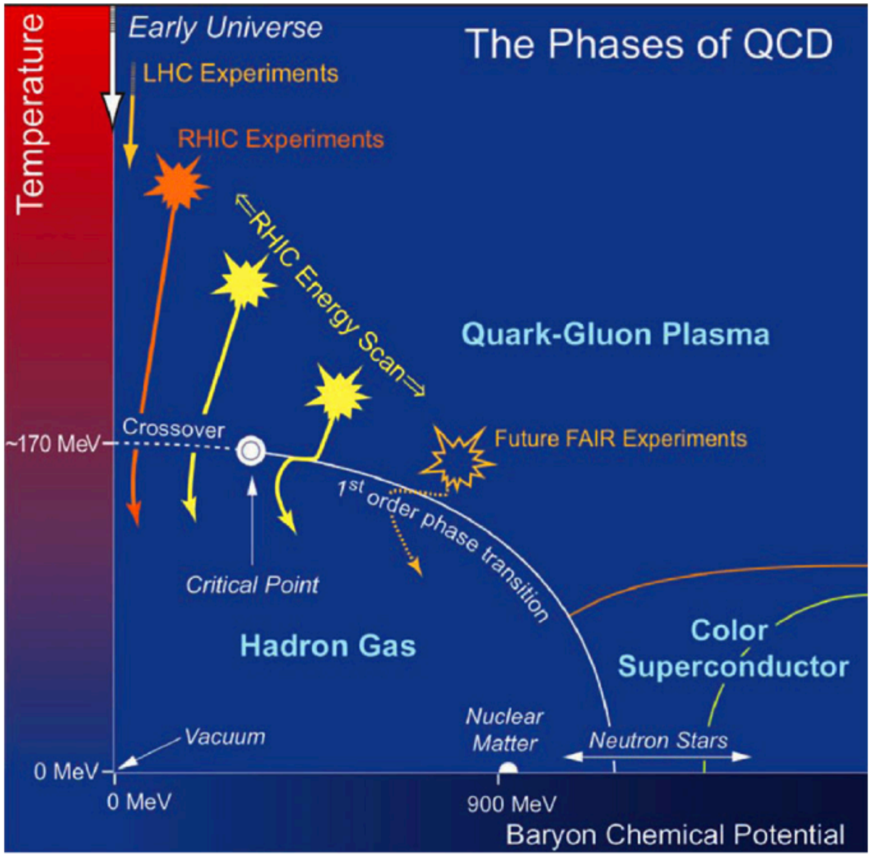


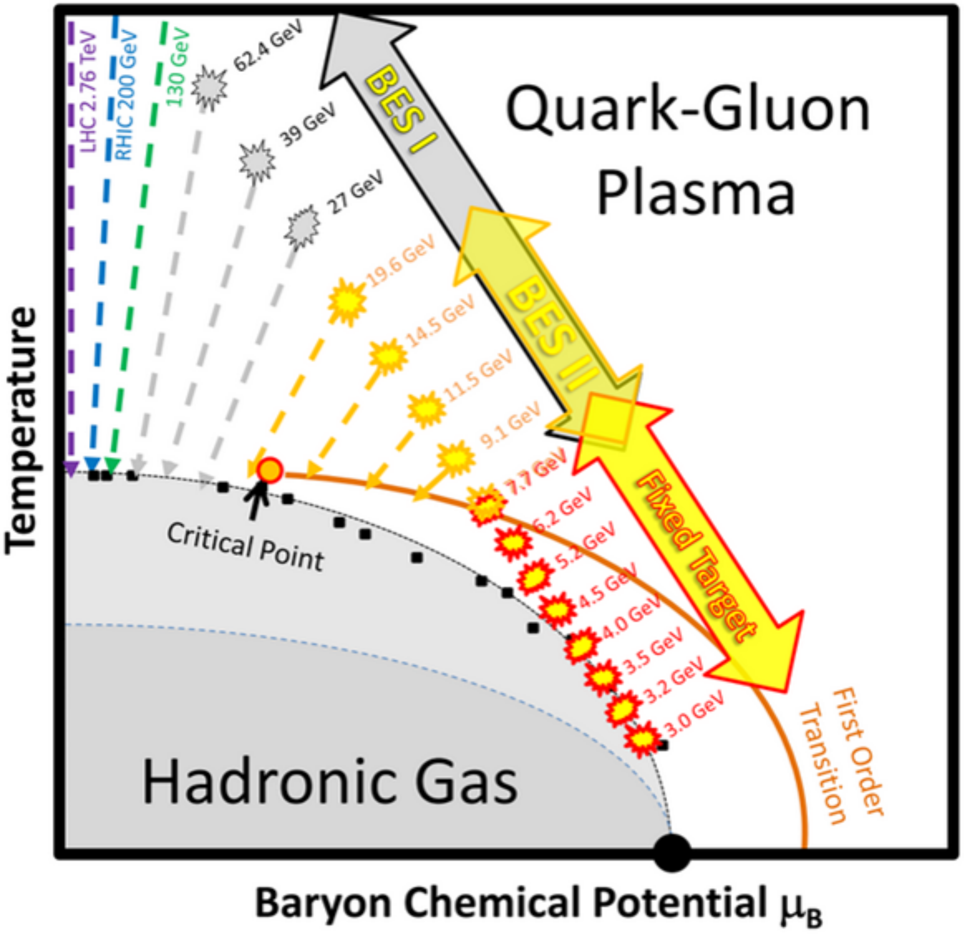
Introduction

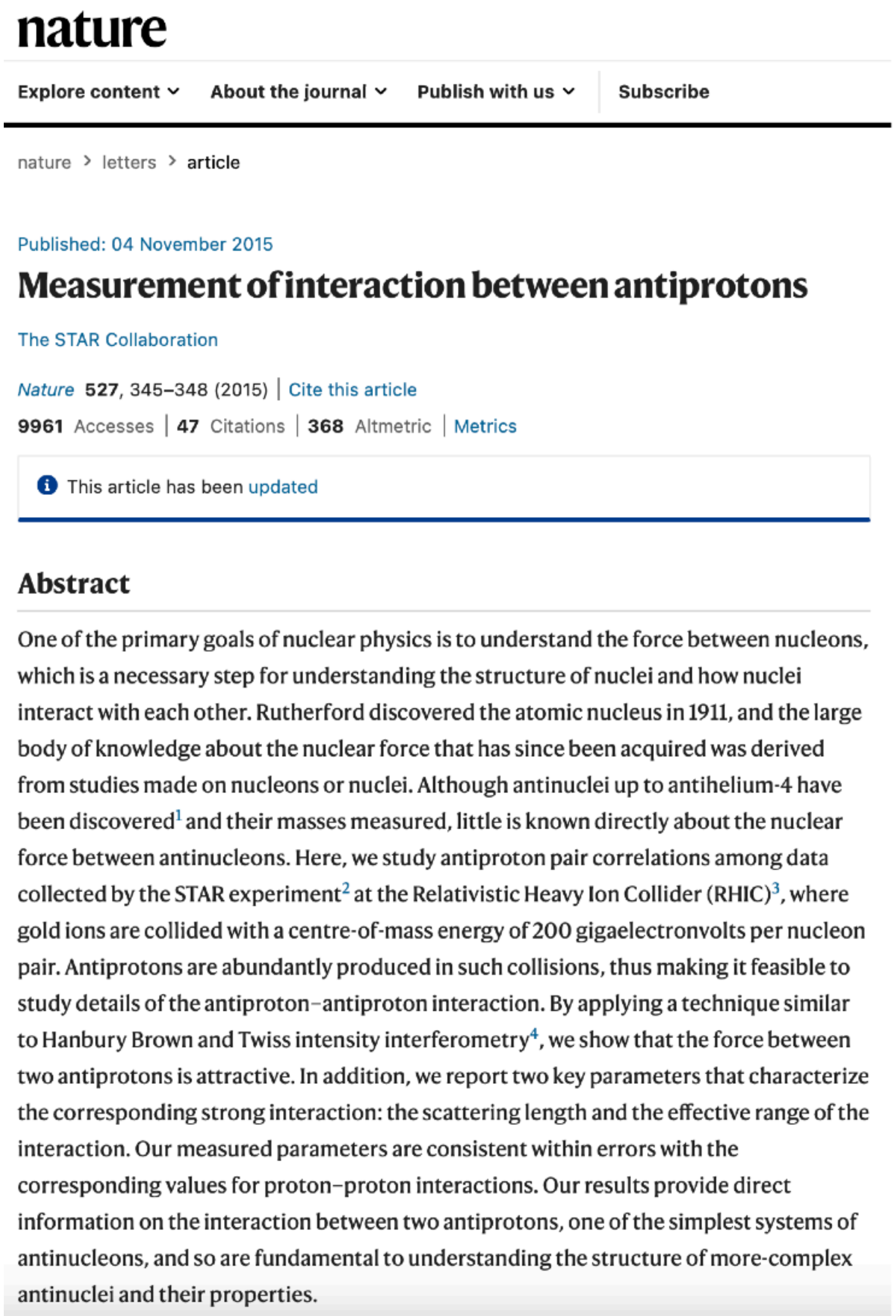
Phase diagram of strongly interacting matter



Phase diagram of strongly interacting matter







Published: 04 November 2015

Measurement of interaction between antiprotons

The STAR Collaboration

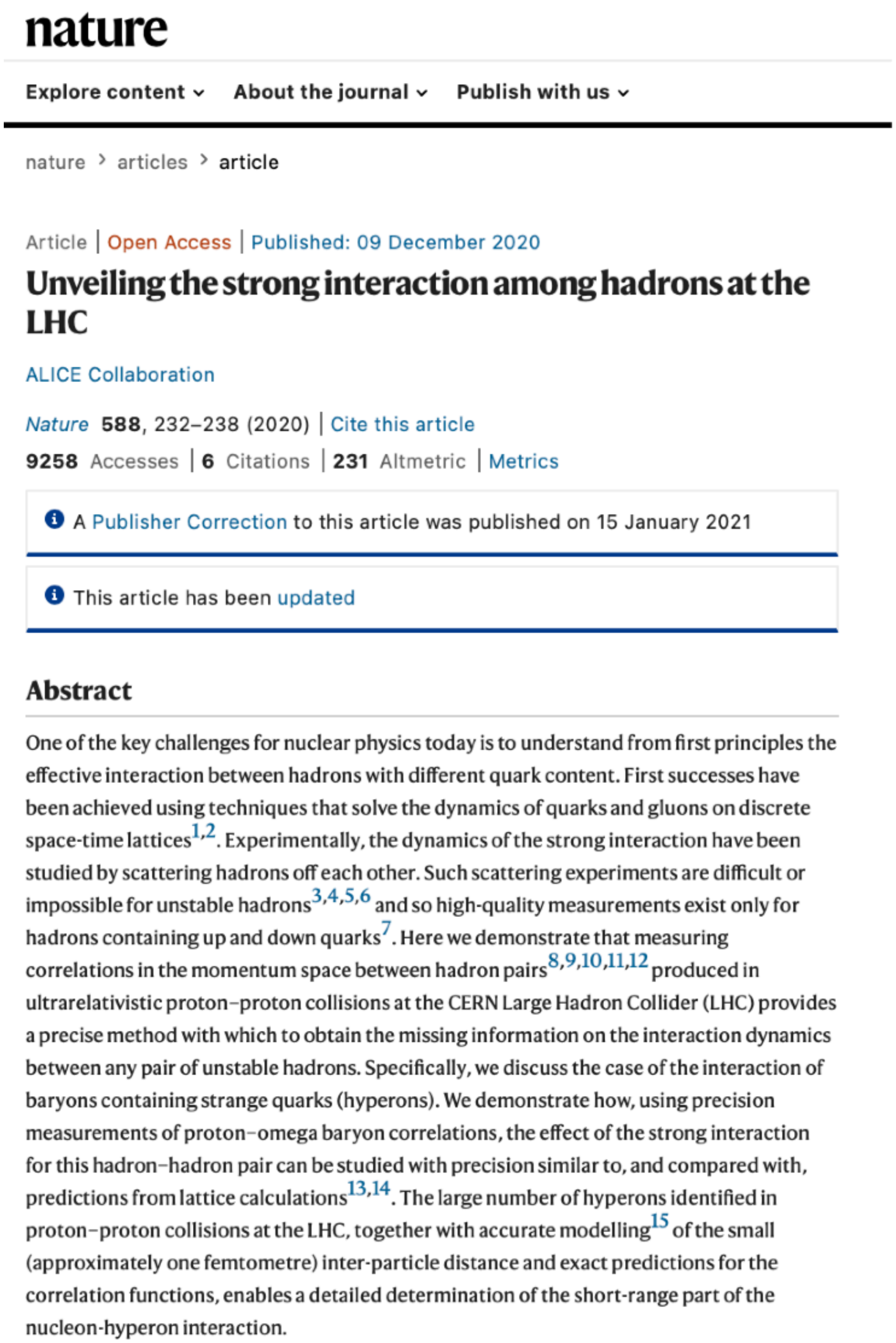
Nature **527**, 345–348 (2015) | Cite this article

9961 Accesses | **47** Citations | **368** Altmetric | Metrics

This article has been updated

Abstract

One of the primary goals of nuclear physics is to understand the force between nucleons, which is a necessary step for understanding the structure of nuclei and how nuclei interact with each other. Rutherford discovered the atomic nucleus in 1911, and the large body of knowledge about the nuclear force that has since been acquired was derived from studies made on nucleons or nuclei. Although antinuclei up to antihelium-4 have been discovered[1] and their masses measured, little is known directly about the nuclear force between antinucleons. Here, we study antiproton pair correlations among data collected by the STAR experiment[2] at the Relativistic Heavy Ion Collider (RHIC)[3], where gold ions are collided with a centre-of-mass energy of 200 gigaelectronvolts per nucleon pair. Antiprotons are abundantly produced in such collisions, thus making it feasible to study details of the antiproton–antiproton interaction. By applying a technique similar to Hanbury Brown and Twiss intensity interferometry[4], we show that the force between two antiprotons is attractive. In addition, we report two key parameters that characterize the corresponding strong interaction: the scattering length and the effective range of the interaction. Our measured parameters are consistent within errors with the corresponding values for proton–proton interactions. Our results provide direct information on the interaction between two antiprotons, one of the simplest systems of antinucleons, and so are fundamental to understanding the structure of more-complex antinuclei and their properties.



Article | Open Access | Published: 09 December 2020

Unveiling the strong interaction among hadrons at the LHC

ALICE Collaboration

Nature **588**, 232–238 (2020) | Cite this article

9258 Accesses | **6** Citations | **231** Altmetric | Metrics

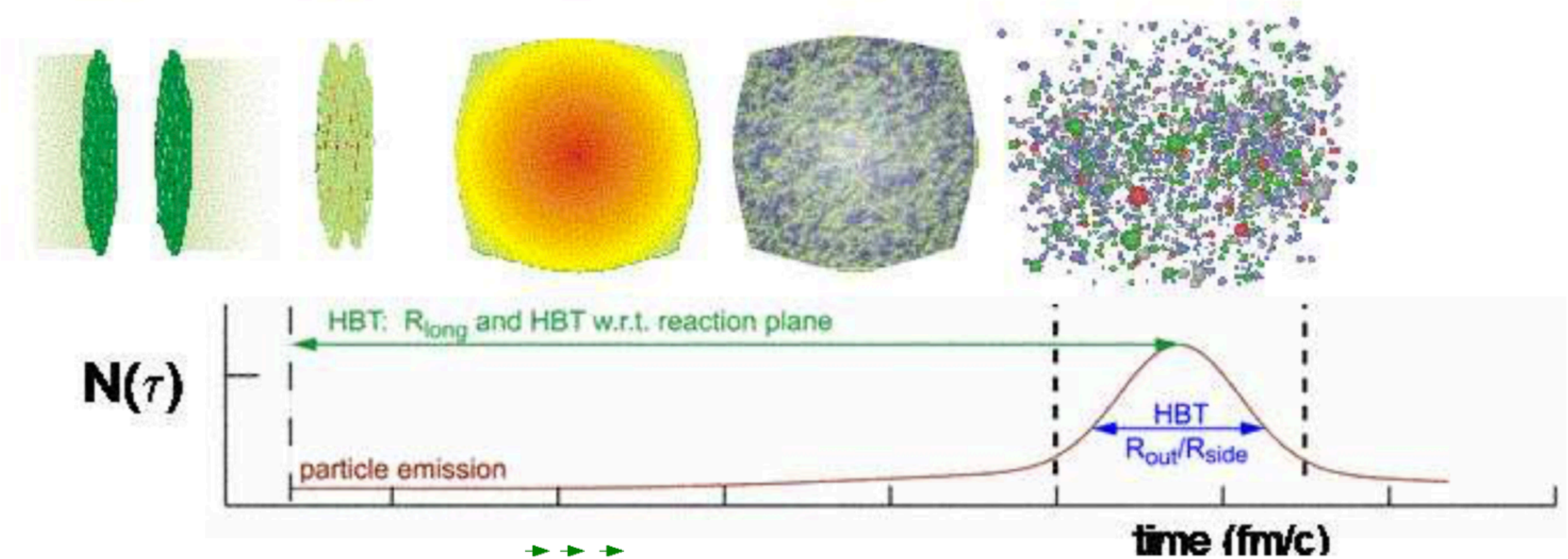
A Publisher Correction to this article was published on 15 January 2021

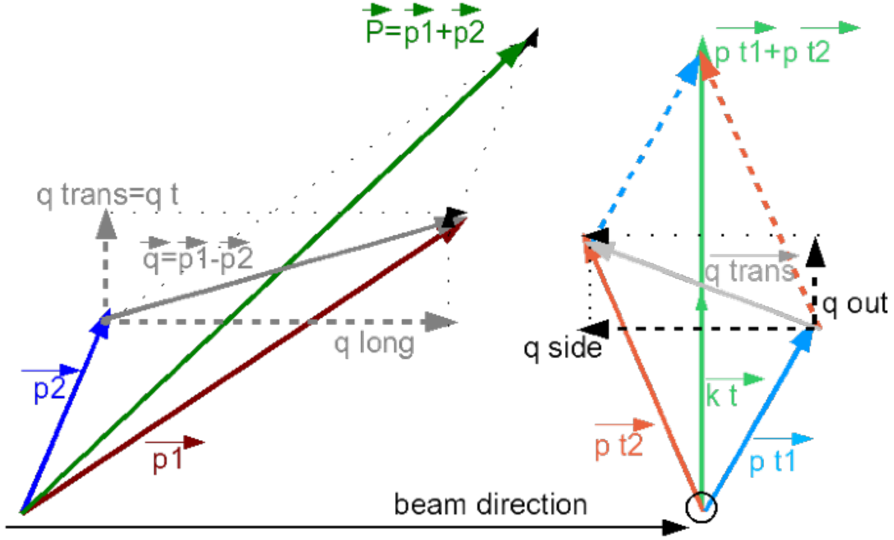
This article has been updated

Abstract

One of the key challenges for nuclear physics today is to understand from first principles the effective interaction between hadrons with different quark content. First successes have been achieved using techniques that solve the dynamics of quarks and gluons on discrete space-time lattices[1,2]. Experimentally, the dynamics of the strong interaction have been studied by scattering hadrons off each other. Such scattering experiments are difficult or impossible for unstable hadrons[3,4,5,6] and so high-quality measurements exist only for hadrons containing up and down quarks[7]. Here we demonstrate that measuring correlations in the momentum space between hadron pairs[8,9,10,11,12] produced in ultrarelativistic proton–proton collisions at the CERN Large Hadron Collider (LHC) provides a precise method with which to obtain the missing information on the interaction dynamics between any pair of unstable hadrons. Specifically, we discuss the case of the interaction of baryons containing strange quarks (hyperons). We demonstrate how, using precision measurements of proton–omega baryon correlations, the effect of the strong interaction for this hadron–hadron pair can be studied with precision similar to, and compared with, predictions from lattice calculations[13,14]. The large number of hyperons identified in proton–proton collisions at the LHC, together with accurate modelling[15] of the small (approximately one femtometre) inter-particle distance and exact predictions for the correlation functions, enables a detailed determination of the short-range part of the nucleon-hyperon interaction.

Heavy-Ion collision and the femtoscopy method





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

Correlation **femtoscopy**

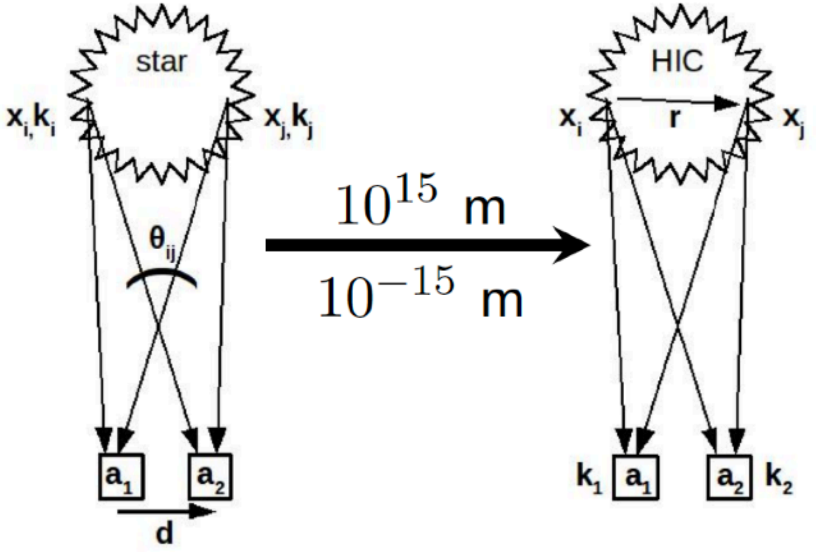
Size: $\sim 10^{-15}$ m (fm)
Time: $\sim 10^{-23}$ s

Impossible
to measure directly!

Correlation femtoscopy

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

Impossible
to measure directly!



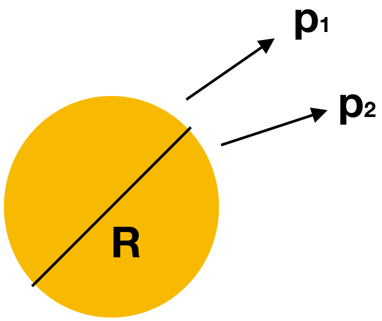
Femtoscopy (HIC) inspired by Hanbury Brown and Twiss interferometry method (Astronomy)

but!

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

Traditional and non-traditional femtoscopy

Femtoscopy (known as HBT):
the method to probe geometric and dynamic properties of the source



Space-time properties ($10^{-15}m,\ 10^{-23}s$) can be determined due to two-particle momentum correlations that arise due to:

Quantum Statistics (Fermi-Dirac, Bose-Einstein);

Final State Interactions (Coulomb, strong)

$$C(k^*, r^*) = \overset{\text{determined}}{\boxed{\int S(r^*)}}\,\overset{\text{assumed}}{\boxed{|\Psi(k^*, r^*)|}}^2 d^3r^* = \overset{\text{measured}}{\boxed{\frac{Sgnl(k^*)}{Bckg(k^*)}}}$$

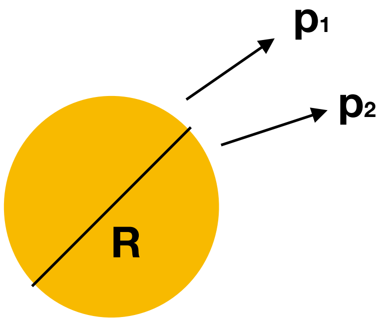
$S(r^*)$ - emission function

$\Psi(k^*, r^*)$ - two-particle wave function (includes e.g. FSI interactions)

$\dfrac{Sgnl(k^*)}{Bckg(k^*)}$ - correlation function

Traditional and non-traditional femtoscopy

If we assume we know the emission function, measured correlation function can be used to determine parameters of Final State Interactions



Space-time properties ($10^{-15}m$, $10^{-23}s$) can be determined due to two-particle momentum correlations that arise due to:

Quantum Statistics (Fermi-Dirac, Bose-Einstein);

Final State Interactions (Coulomb, strong)

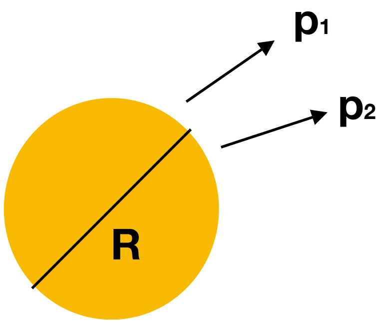
$$C(k^*, r^*) = \overset{\text{assumed}}{\int S(r^*)} \overset{\text{determined}}{|\Psi(k^*, r^*)|}^2 d^3r^* = \overset{\text{measured}}{\frac{Sgnl(k^*)}{Bckg(k^*)}}$$

$S(r^*)$ - emission function

$\Psi(k^*, r^*)$ - two-particle wave function (includes e.g. FSI interactions)

$\frac{Sgnl(k^*)}{Bckg(k^*)}$ - correlation function

Traditional and non-traditional femtoscopy

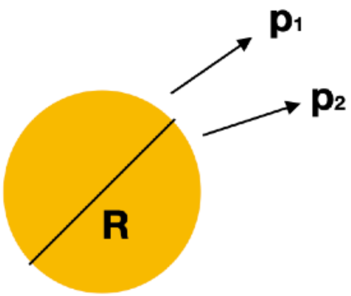


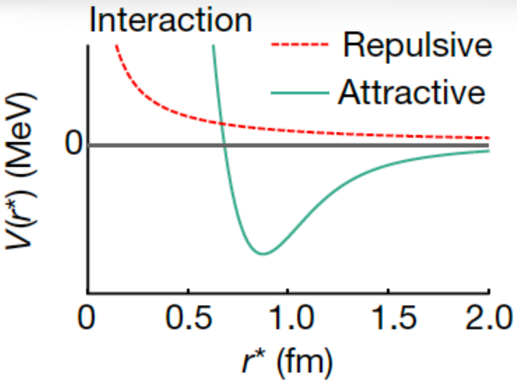
Emission source S(r*)

$$C(k^*, r^*) = \int S(r^*)\,|\Psi(k^*, r^*)|^2 \, d^3r^* = \frac{Sgnl(k^*)}{Bckg(k^*)}$$

Object of study of
traditional femtoscopy

Traditional and non-traditional femtoscopy





Emission source $S(r^*)$

Schrödinger equation

↓

Two-particle wavefunction

$|\psi(\mathbf{k}^*, \mathbf{r}^*)|$

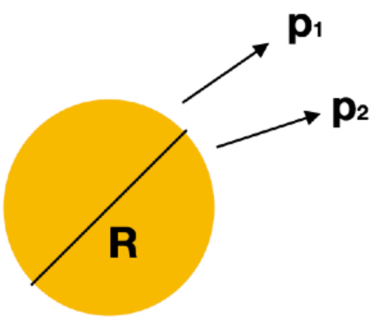
$$C(k^*, r^*) = \int S(r^*)\,|\Psi(k^*, r^*)|^2\, d^3r^* = \frac{Sgnl(k^*)}{Bckg(k^*)}$$

Object of study of traditional femtoscopy

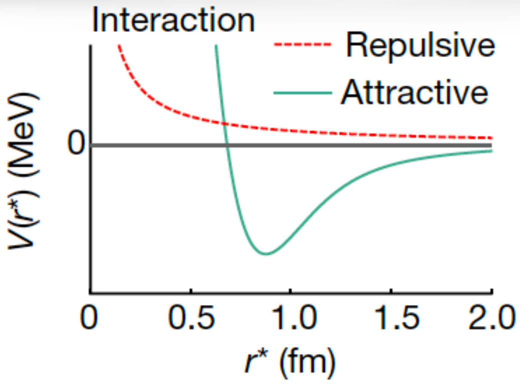
Object of study of non-traditional femtoscopy

Traditional and non-traditional femtoscopy

Nature 588, 2020, (233-238)



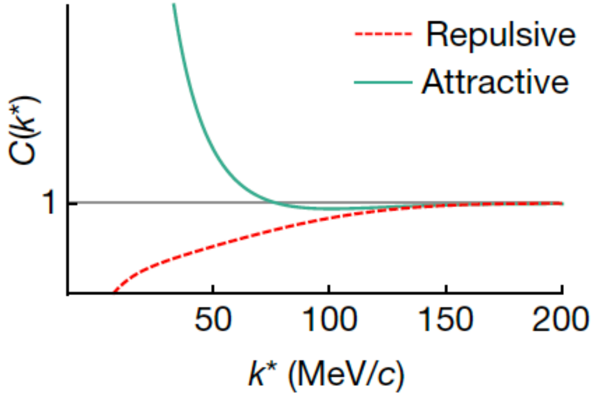
Emission source $S(r^*)$



Schrödinger equation

Two-particle wavefunction

$|\psi(\mathbf{k}^*, \mathbf{r}^*)|$



Correlation function

$$C(k^*, r^*) = \int S(r^*)\,|\Psi(k^*, r^*)|^2\, d^3r^* = \frac{Sgnl(k^*)}{Bckg(k^*)}$$

Object of study of Traditional femtoscopy

Object of study of non-traditional femtoscopy

Pairs from the same collision

Pairs from the different collisions

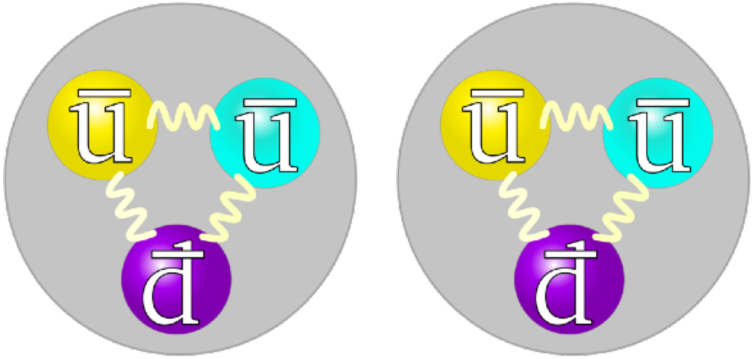
Results

a) Proton Femtoscopy @200 GeV

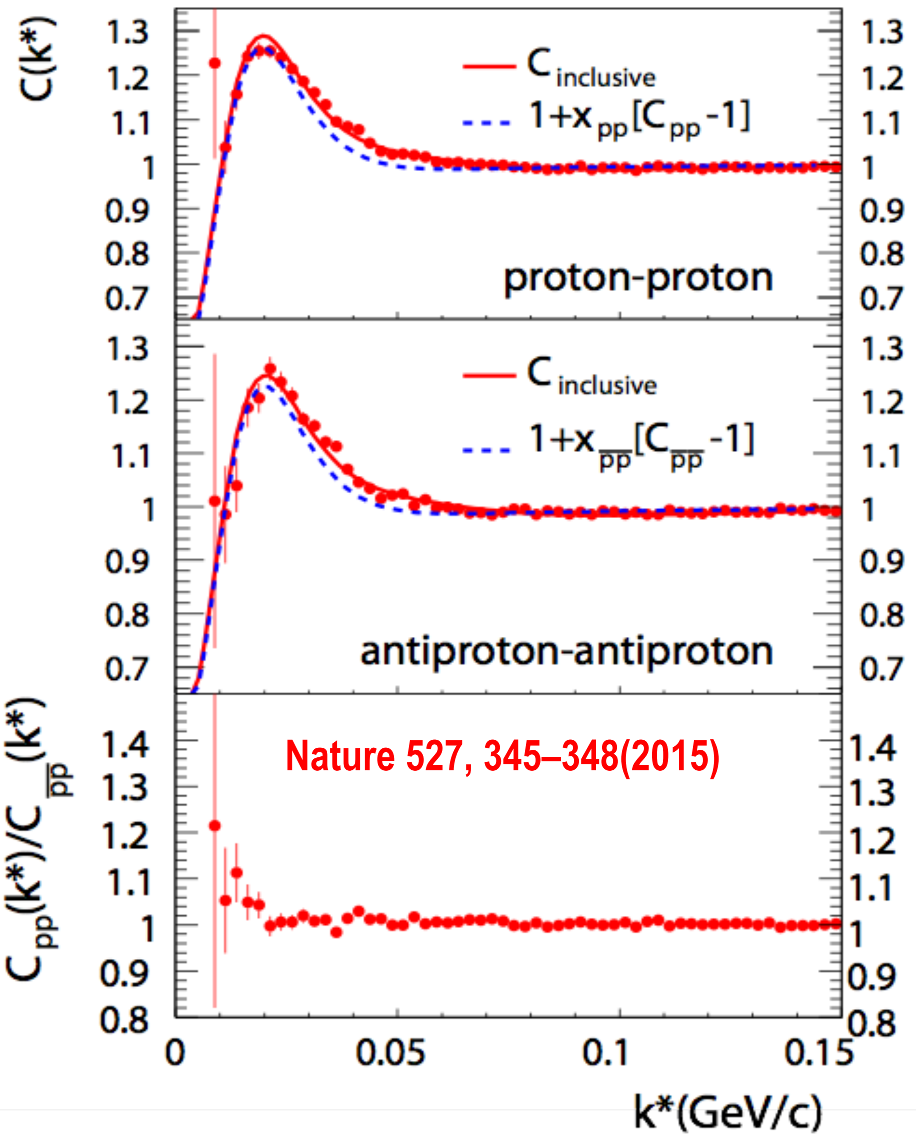
So far, the knowledge on **nuclear force** was derived from studies made on **nucleon** or / and **nuclei**.

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:

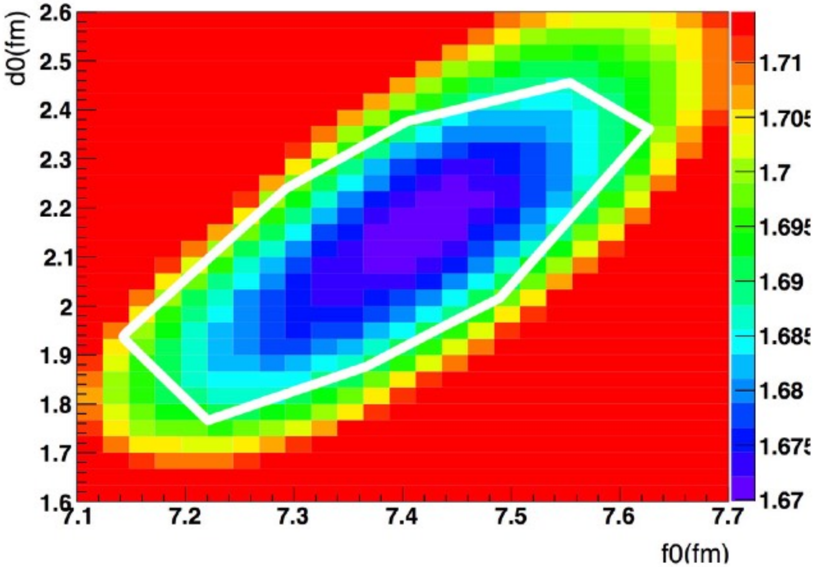
p-p CF,

R=2.75±0.01fm; χ^2/NDF = 1.66;

antiproton-antiproton CF,

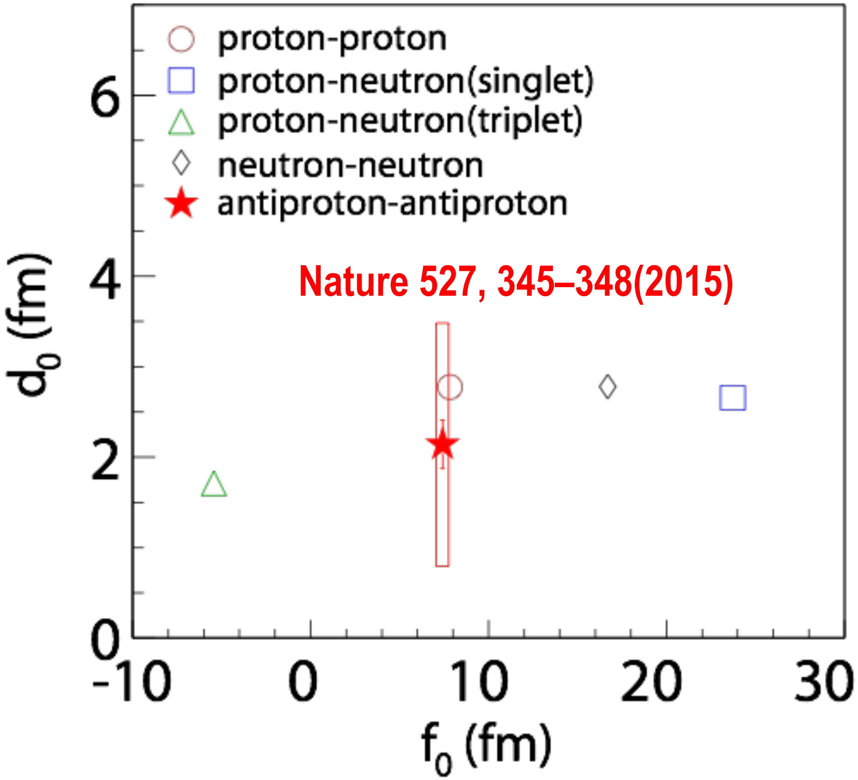
R=2.80±0.02fm , f_0=7.41±0.19fm,

d_0=2.14±0.27fm; x2/NDF=1.61



x^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, $\lim_{k \to 0} \sigma_e = 4\pi f_0^2$

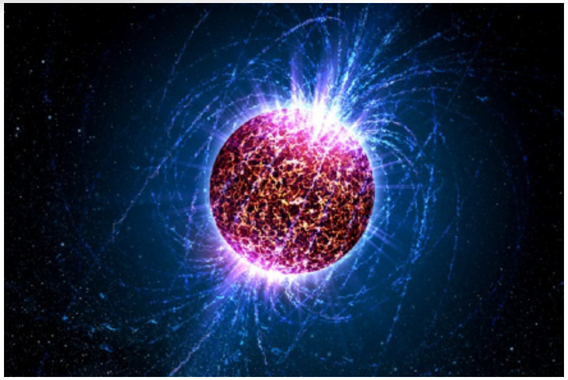
d_0 - the effective range of strong interaction between two particles.

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) Y-N and Y-Y interactions



Experiment: Studies Y–N and Y–Y interactions in progress

Theory: Major steps forward have been made (Lattice QCD).

Numerous theoretical predictions exist, but no clear evidence for any such bound states, despite many experimental searches.

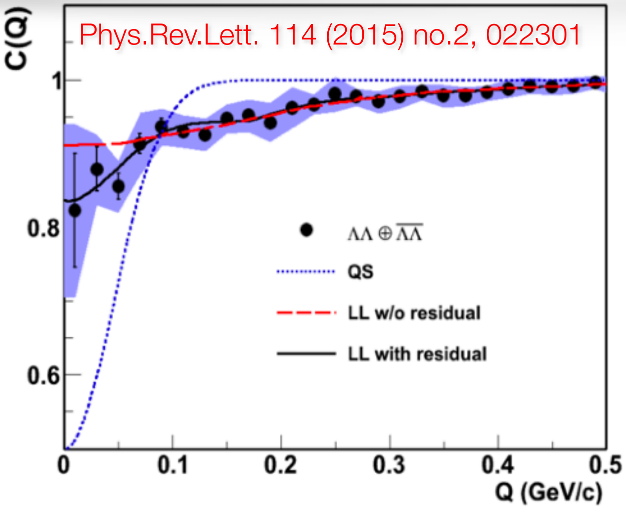
The existence of hypernuclei is confirmed by attractive strong Y–N interaction -> indicates the possibility to bind Y to a nucleus.

The measurement of the Y–N and Y–Y interactions leads to important implications for the possible formation of Y–N or Y–Y bound states.

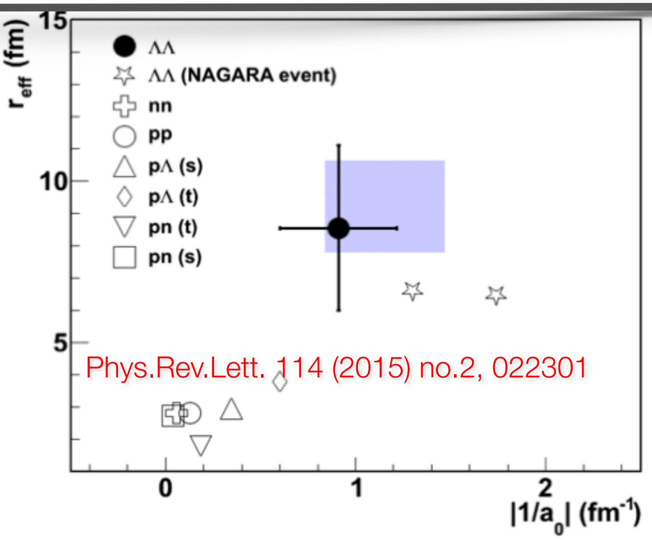
A precise knowledge of these interactions will have impact to the physics of neutron stars.

The structure of the neutron stars cores is still unknown, hyperons can appear there depending on the Y–N and Y–Y interactions.

c) Strange Baryon Correlations (Including Λ Hyperons)



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



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

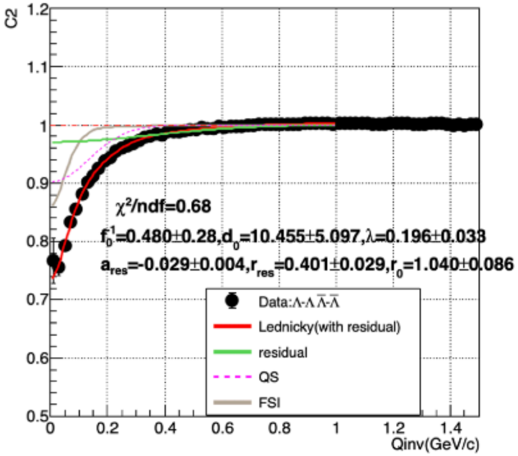
The data are compatible with hypernuclei results and lattice computations.

The binding energy of the possible Lambda–Lambda bound state is estimated within an effective-range expansion approach

N	lambda	r0	1/f0	d0	ares	rres
1.0	0.5	2.0 fm	1.0 fm	3.0 fm	-0.04	0.05 fm

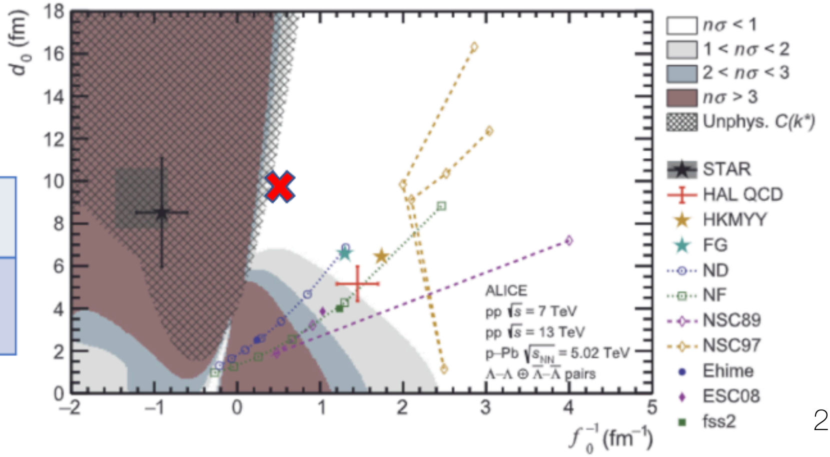
ALICE's study

ALICE Collaboration Phys. Lett. B 797 (2019) 134822

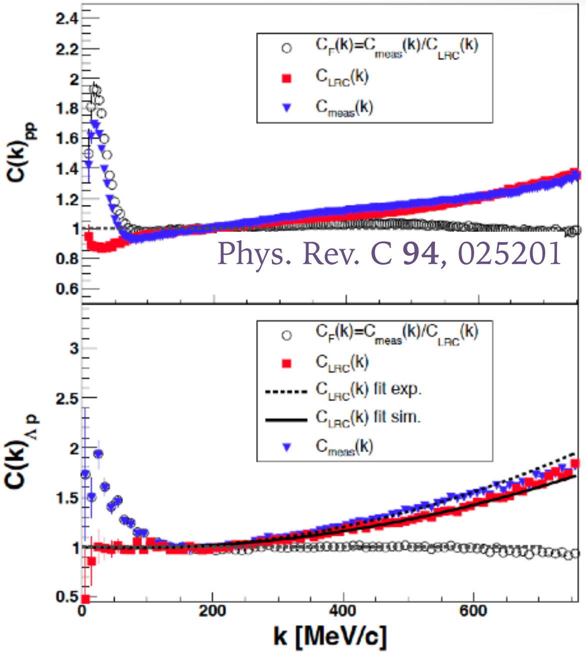


F0 became positive!!

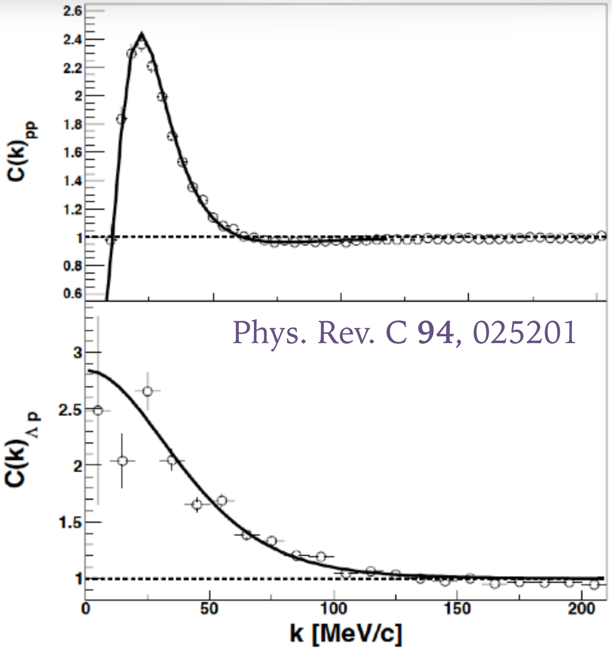
1/f0	0.480fm
d0	10.455fm



c) Strange Baryon (Λ) Correlations at HADES



Phys. Rev. C **94**, 025201



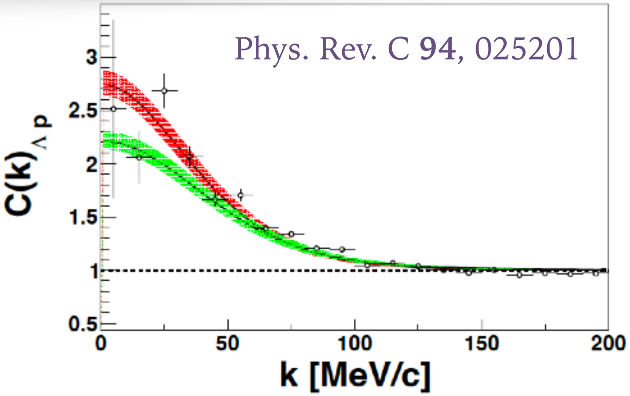
Phys. Rev. C **94**, 025201

Lednicky’s fit

$$C_F(k) = \frac{C_{meas}(k)}{C_{LRC}(k)}$$

$$C_{LRC}(k^*) = 1 + ak + bk^2$$

The femtoscopy technique to study interactions between particles can be applied to many colliding systems at very different energies, which can help to improve the understanding of hyperon-nucleon interactions.



Phys. Rev. C **94**, 025201

LO scattering parameters

NLO scattering paremeters

SI parameters:

$f_{0,NLO}^{S=0} = 2.91fm$

$d_{0,NLO}^{S=0} = 2.78fm$

$f_{0,NLO}^{S=1} = 1.54fm$

$d_{0,NLO}^{S=1} = 2.72fm$

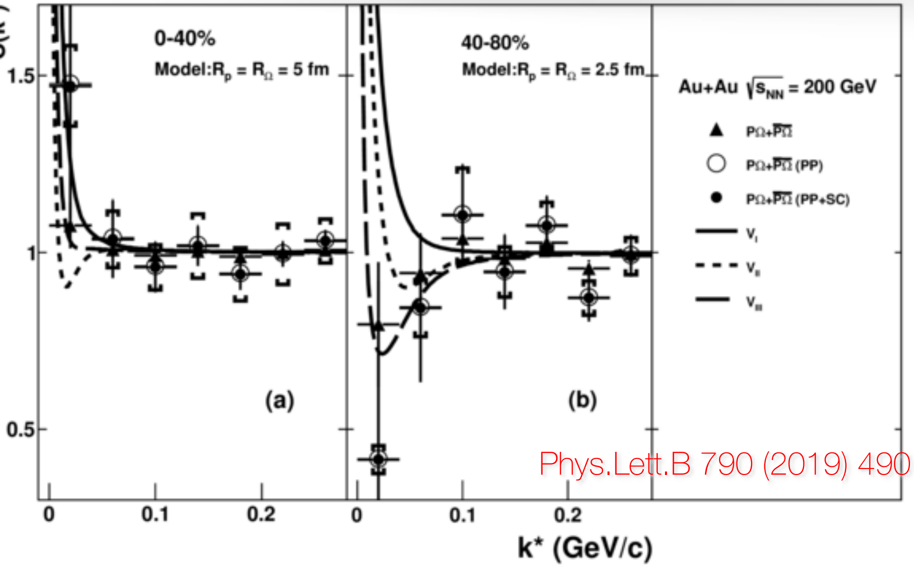
$f_{0,LO}^{S=0} = 1.91fm$

$d_{0,LO}^{S=0} = 1.40fm$

$f_{0,LO}^{S=1} = 1.23fm$

$d_{0,LO}^{S=1} = 2.13fm$

c) Strange Baryon Correlations (including p-Ω)

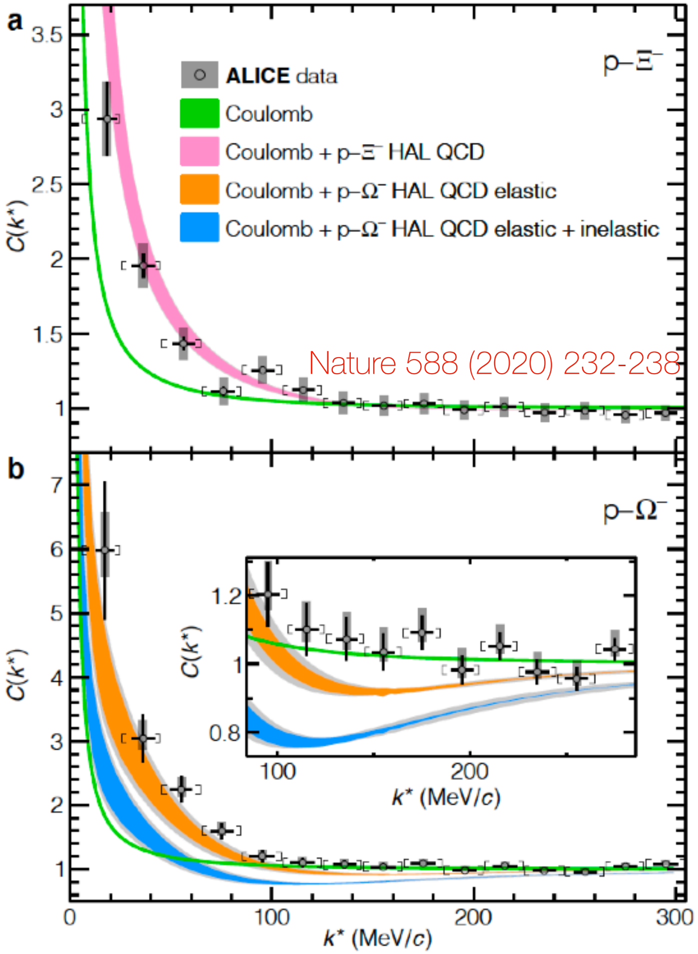


Phys.Lett.B 790 (2019) 490

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

Scattering length is positive and favor p-Ω bound state hypothesis

	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



Nature 588 (2020) 232-238

c) Strange Baryon Correlations (including p-Ξ)

First measurement of p-Ξ correlation in Au+Au collisions at RHIC

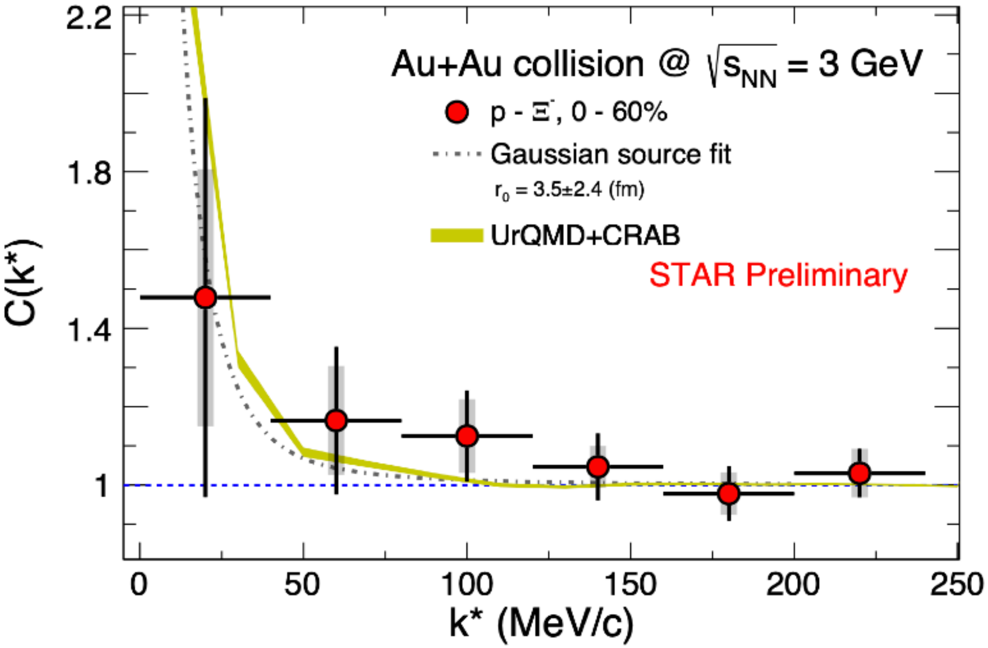
Feed-down correction not included yet.

p-Ξ correlation shows enhancement above Coulomb interaction

Large uncertainties due to limited proton-Ξ pairs at low energy

Modeled by hadronic transport model UrQMD + an afterburner, model results

Au+Au collisions @ 3 GeV; 0 - 60% centrality



c) Strange Baryon Correlations (Including Ξ Hyperons)

First measurement of Ξ-Ξ correlation in Au+Au collisions.

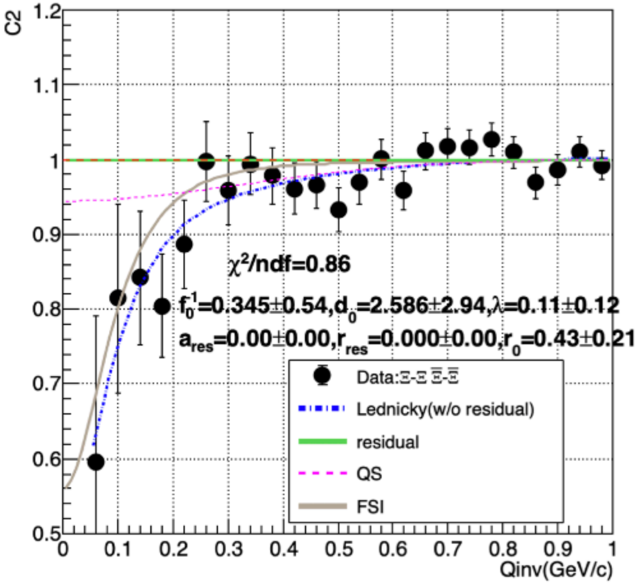
Lattice QCD/chiral EFT calculations indicate an attractive interaction, but not strong enough to form a bound state

The result shows anti-correlation at Q < 0.25 GeV/c.

Combination of quantum statistics, strong interaction, and Coulomb interaction.

Feed-down and Coulomb effects need to be evaluated for further discussion.

N	lambda	r0	1/f0	d0
1.0	0.5	1.5fm	1.0 fm	5.0 fm



F0 became positive!!

1/f0	0.345fm
d0	2.586fm

d) Neutral kaons

See D. Pawłowska talk

Kaon correlation functions are sensitive to:

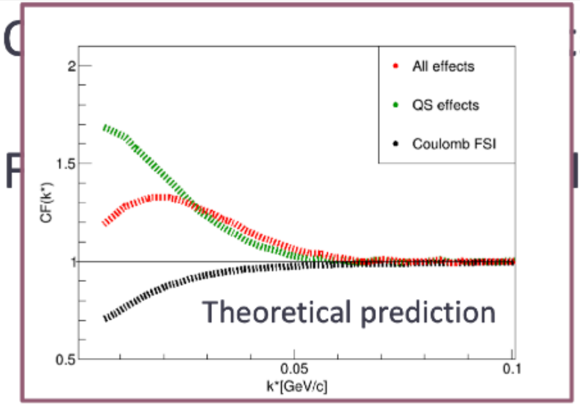
$K^{\pm}K^{\pm}$	$K_s^0K_s^0$	$K_s^0K^{\pm}$
Quantum Statistical effects (QS) Final State Interaction (FSI) - Coulomb interaction (COUL)	Quantum Statistical effects (QS) Final State Interaction (FSI) - strong interaction (SI)	Final State Interaction (FSI) - strong interaction (SI)

d) Neutral kaons

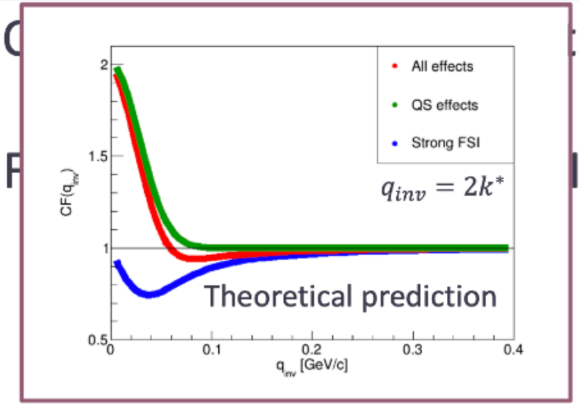
See D. Pawłowska talk

Kaon correlation functions are sensitive to:

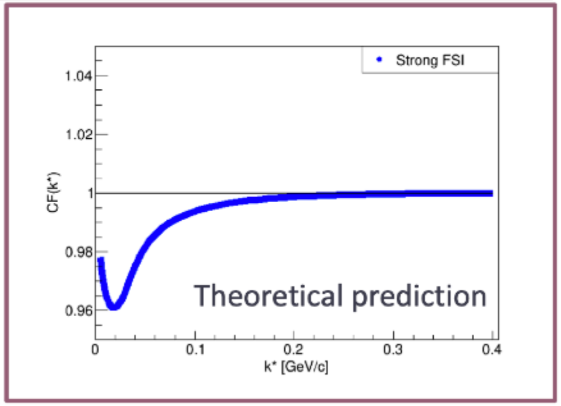
$K^{\pm}K^{\pm}$



$K^0_sK^0_s$



$K^0_sK^{\pm}$

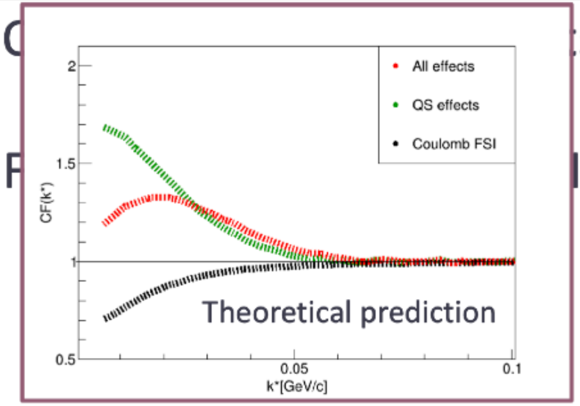


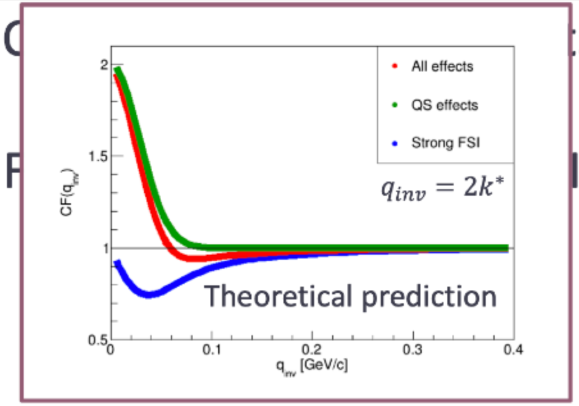
d) Neutral kaons

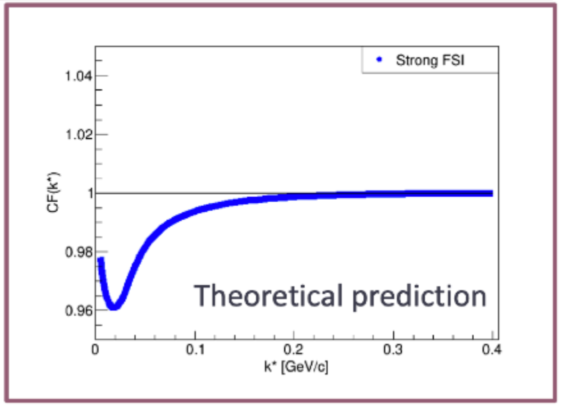
See D. Pawłowska talk

Kaon correlation functions are sensitive to:

$K^{\pm}K^{\pm}$	$K^0_sK^0_s$	$K^0_sK^{\pm}$







Kaons can provide complementary information to pions: contain strange quarks (larger production of strange particles is one of the signatures of QGP)

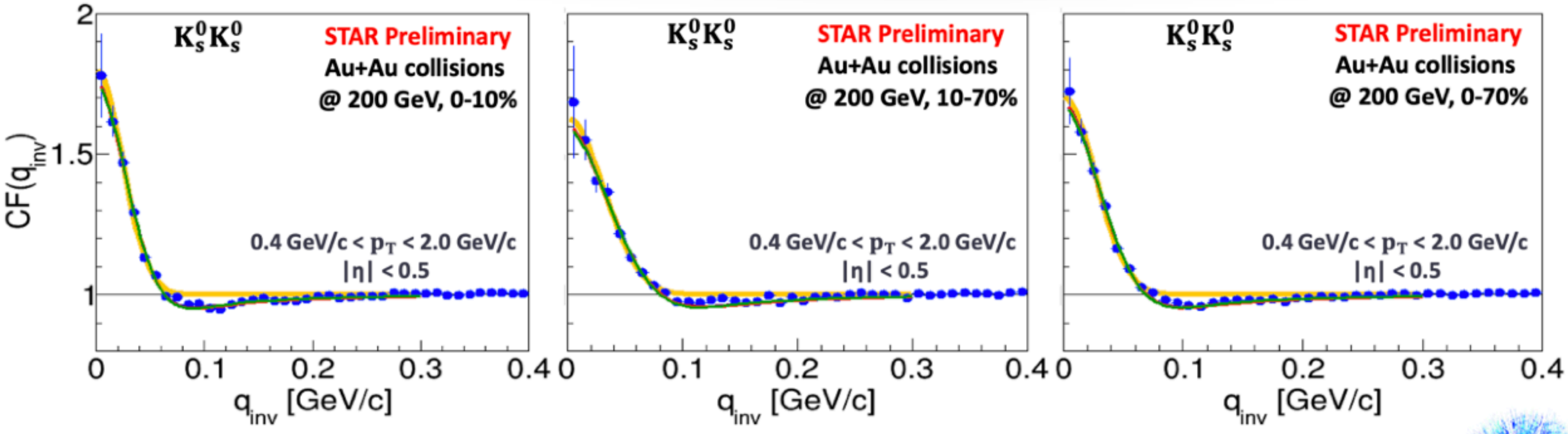
- less affected by the feed-down from resonance decays
- smaller cross section on reaction with the hadronic matter

Very interesting:

- compare femtoscopic results for all possible kaon combination $(K^{\pm} - K^{\pm}, K^0_S - K^0_S, K^0_S - K^{\pm})$;
- K^0_S **could be a 4-quark state**

d) Neutral kaons

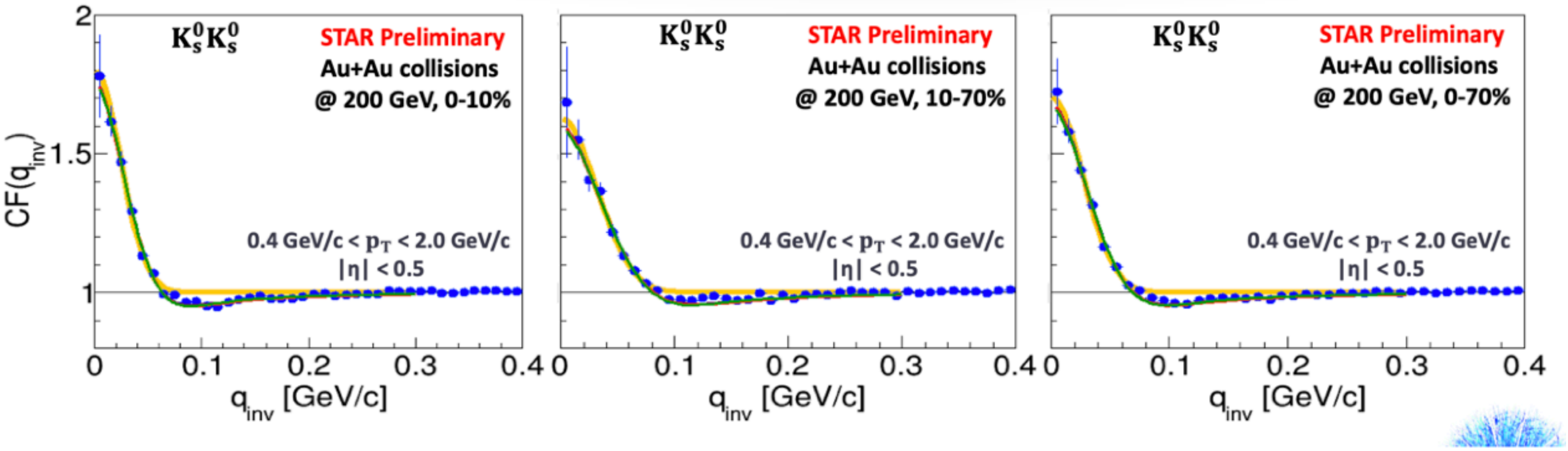
See D. Pawłowska talk

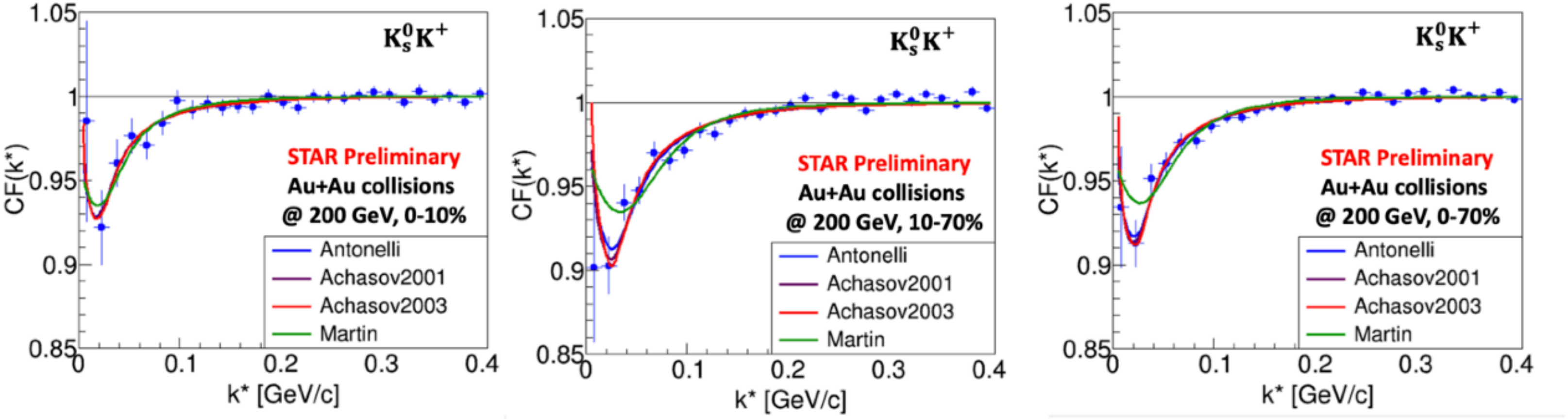


The strong final-state interaction has a significant effect on the neutral kaons correlation due to the near-threshold $f_0(980)$ and $a_0(980)$ resonances

d) Neutral kaons

See D. Pawłowska talk





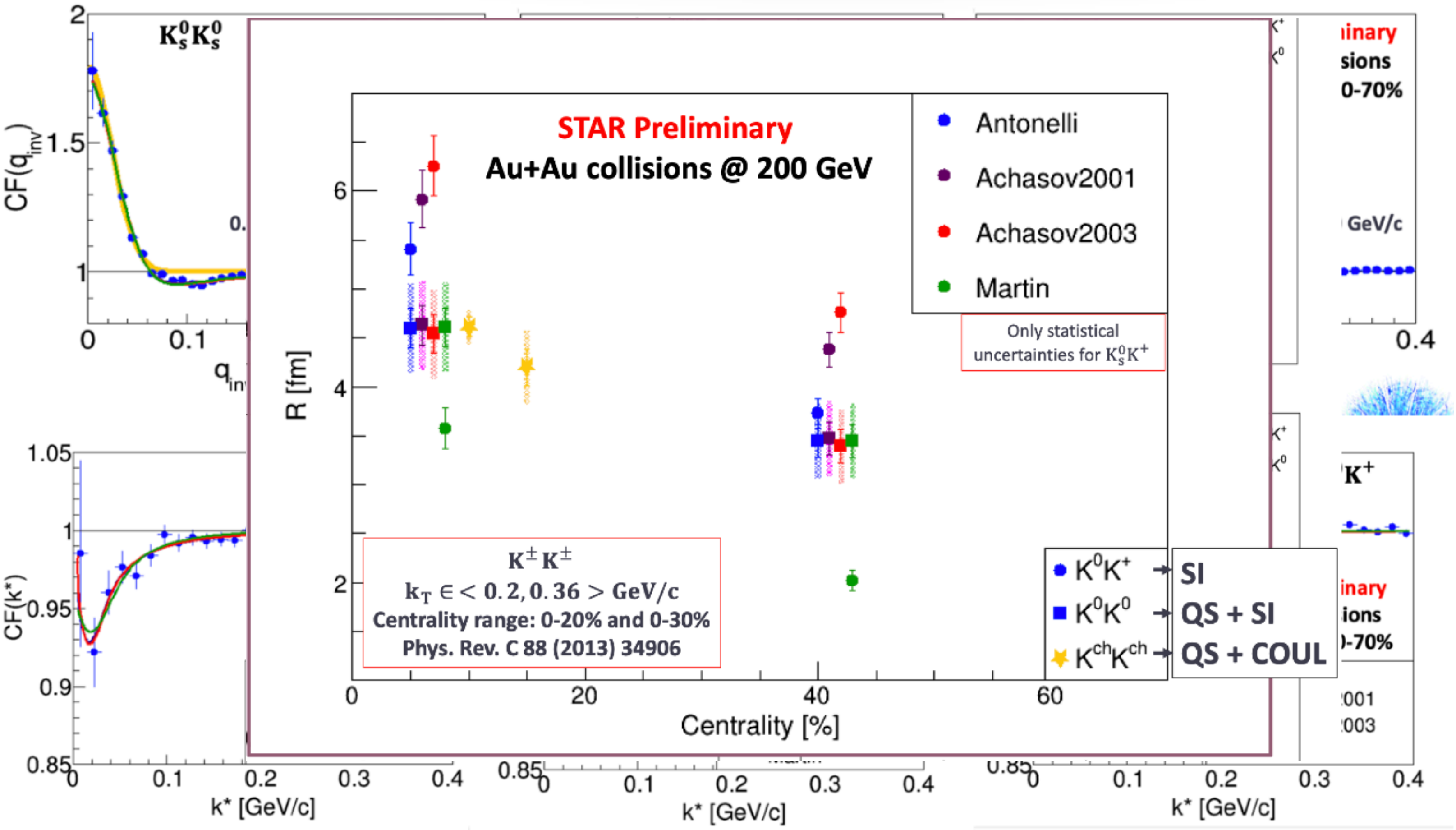
The $a_0(980)$ FSI parametrization gives very good representation of the shape of the signal region in CF

The parametrization with the larger $a_0(980)$ mass and decay coupling gives larger size of the source

Antonelli parametrization favors $a_0(980)$ resonance as a tetraquark

d) Neutral kaons

See D. Pawłowska talk

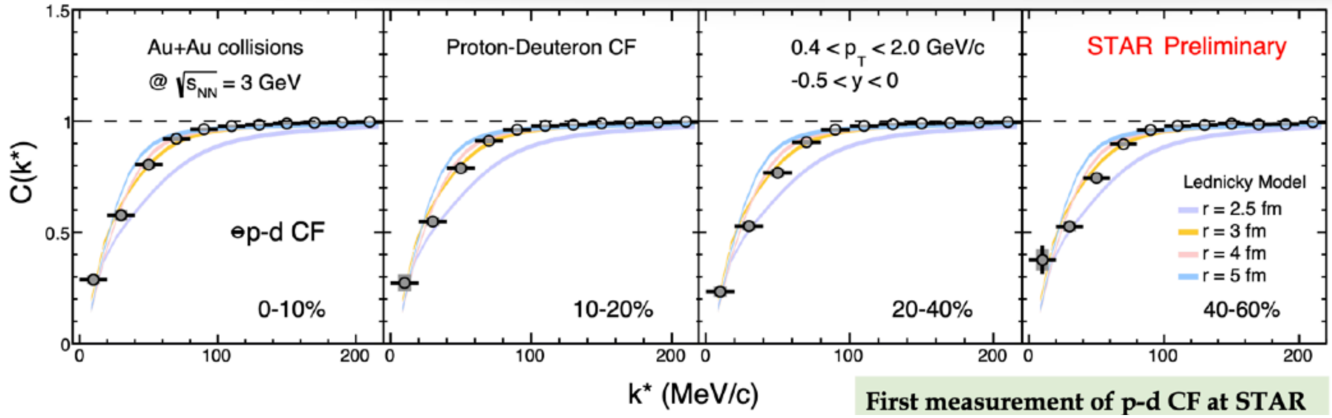


The a_0(980) FSI parametrization gives very good representation of the shape of the signal region in CF

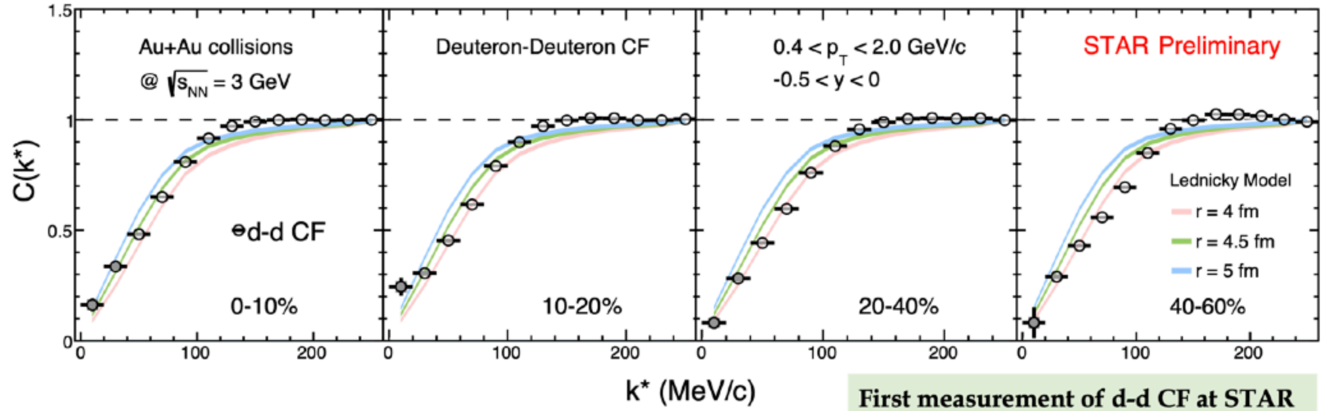
The parametrization with the larger a_0(980) mass and decay coupling gives larger size of the source

Antonelli parametrization favors a_0(980) resonance as a tetraquark

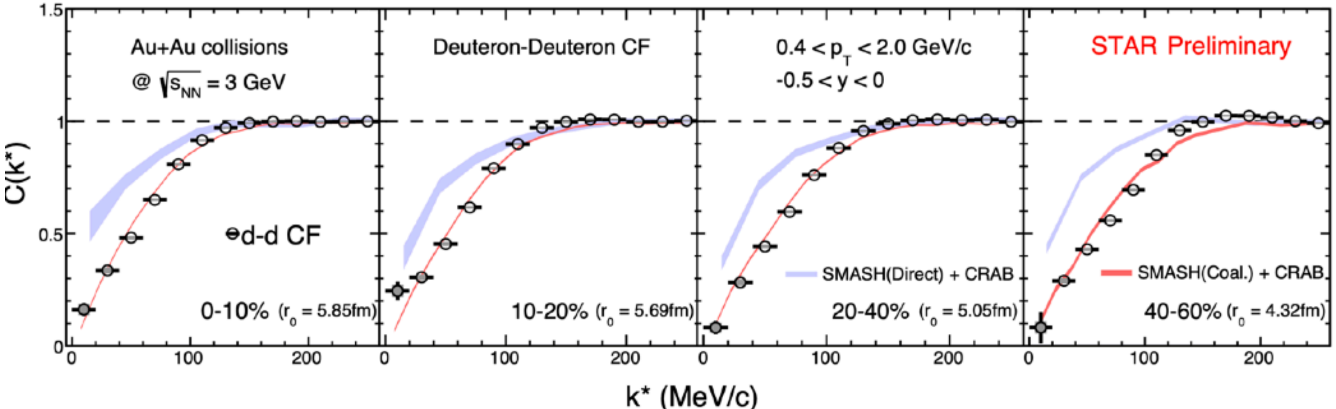
e) Light nuclei formation at $\sqrt{s_{NN}} = 3$ GeV



First measurement of p-d CF at STAR



First measurement of d-d CF at STAR



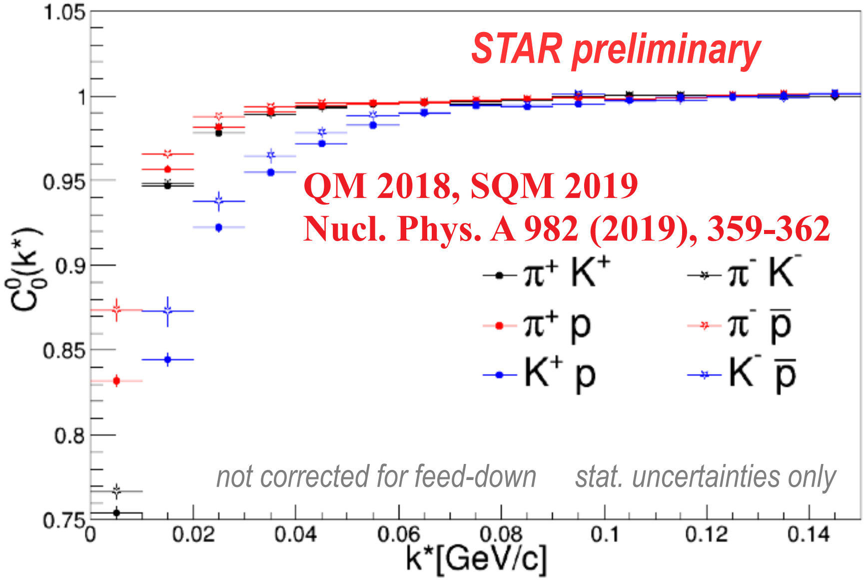
- First measurement of proton-deuteron and deuteron-deuteron correlation functions from STAR

- Proton-deuteron and deuteron-deuteron CF qualitatively described by L&L model -> deuteron-deuteron has larger emission source size than proton-deuteron

- Deuteron-deuteron CF described better by the model including coalescence. Light nuclei are likely to be formed via coalescence.

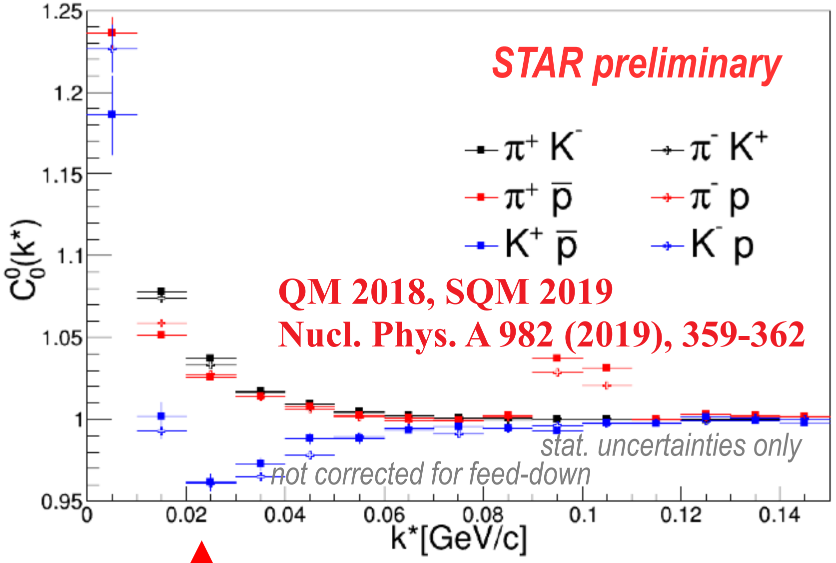
f) Nonidentical particle correlations

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



Determined by **Coulomb** Interactions

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



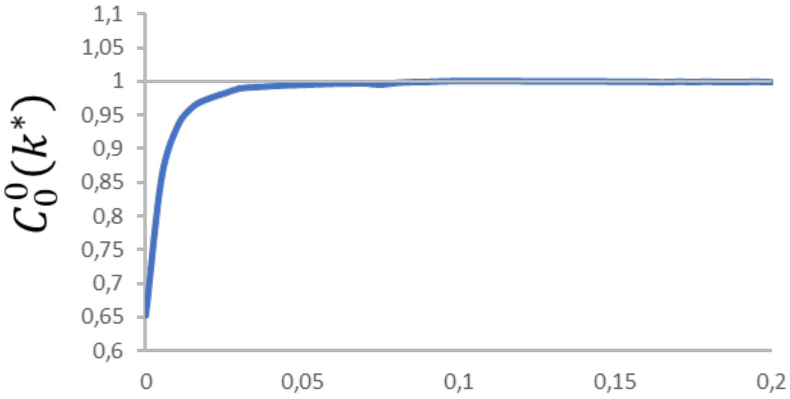
$C_0^0(K-p)$ different shape due to strong interaction

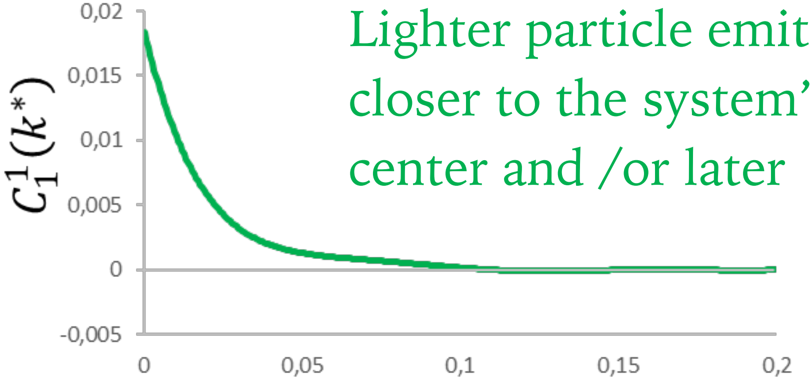
Determined by full **FSI**: **Coulomb** and **Strong** interactions (kaon-proton)

See P. Szymański poster

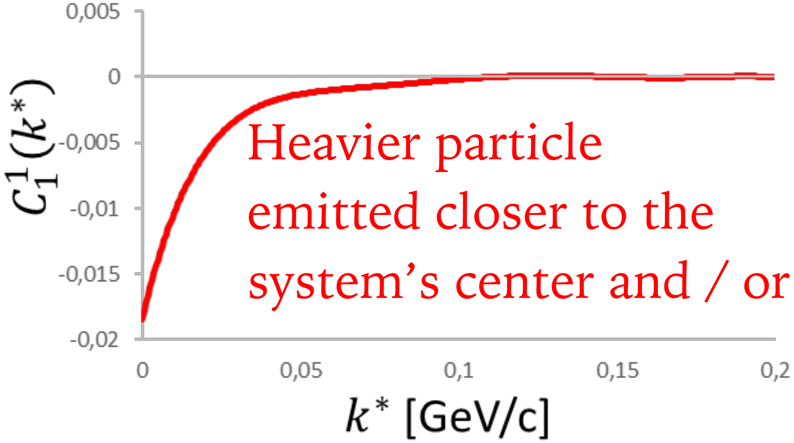
e) Nonidentical particles - emission asymmetry

Same charges



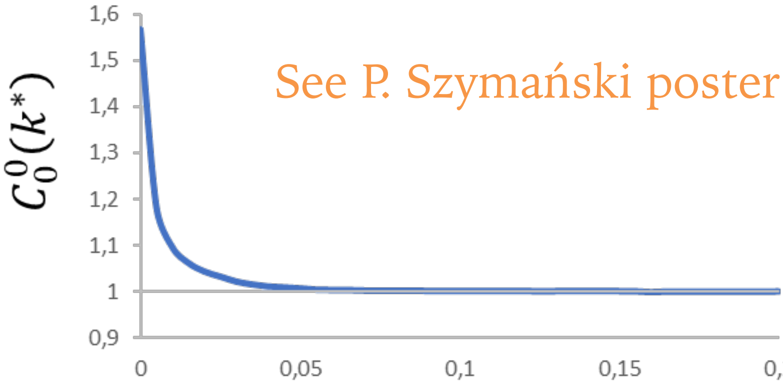


Lighter particle emitted closer to the system's center and /or later

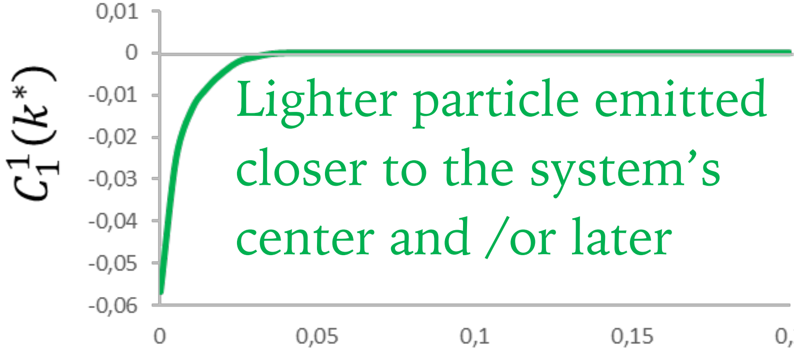


Heavier particle emitted closer to the system's center and / or later

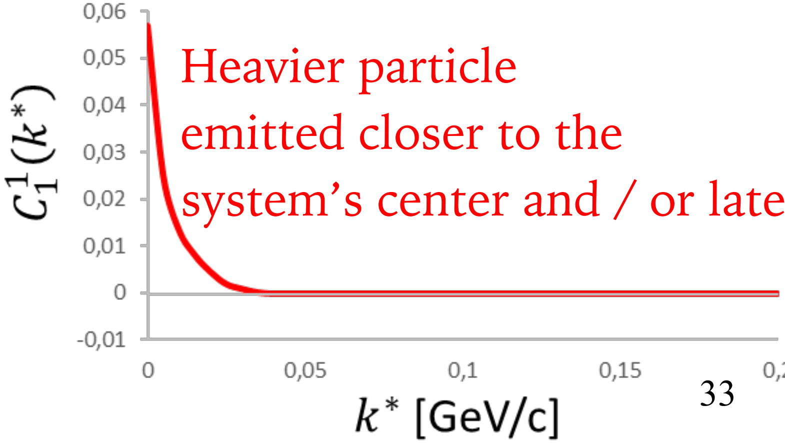
Opposite charges



See P. Szymański poster



Lighter particle emitted closer to the system's center and /or later

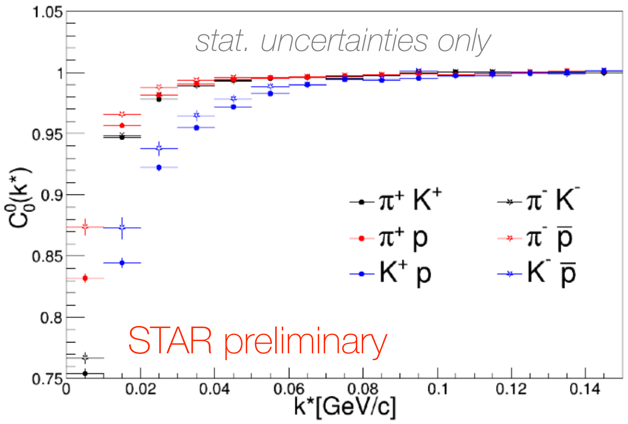


Heavier particle emitted closer to the system's center and / or later

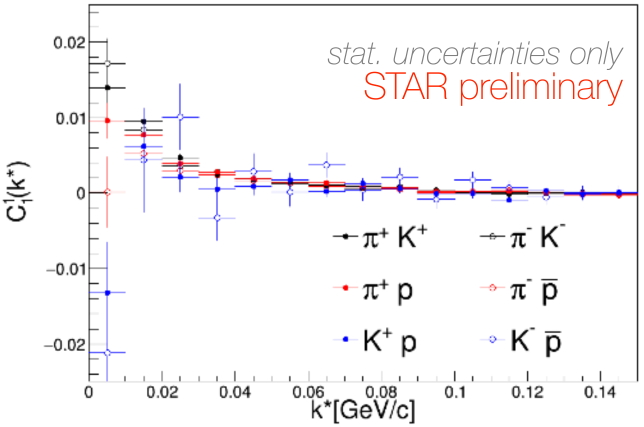
e) Nonidentical particle correlations

See P. Szymański poster

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

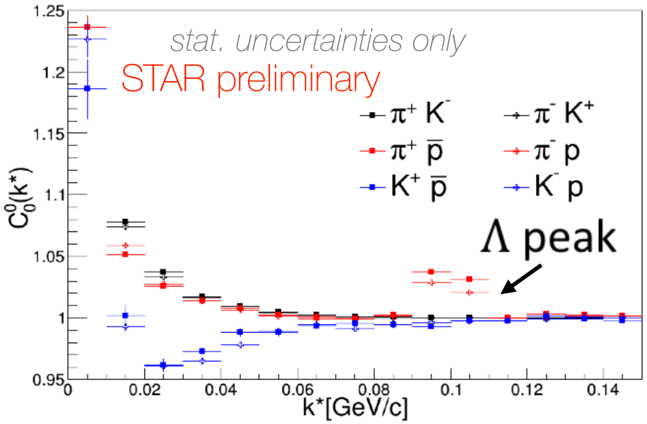


Determined by Coulomb Interactions

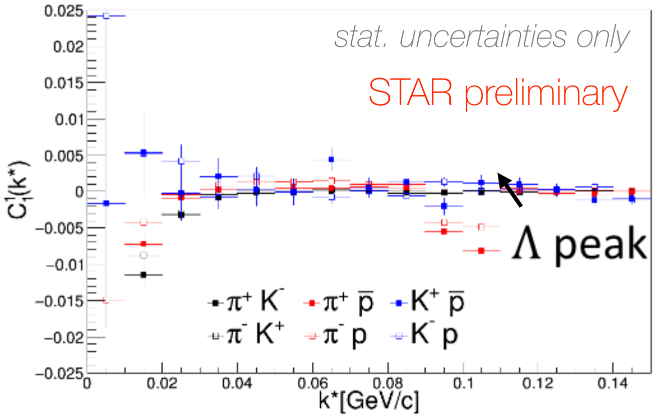


Nucl. Phys. A 982 (2019), 359-362

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



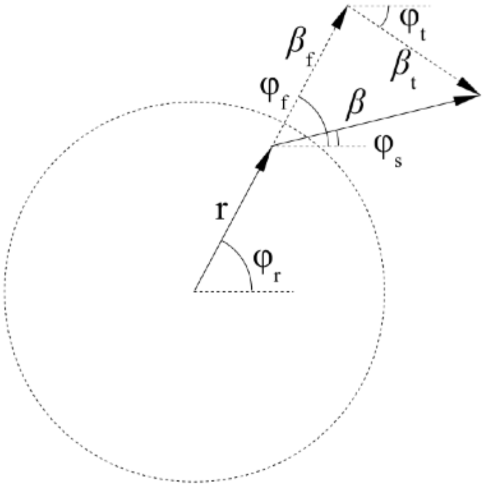
Determined by full FSI: Coulomb and Strong interactions (kaon-proton)



Heavier directed towards edge of the source.

Heavier particles freeze-out earlier

Phys. Rev. C81:064906 2010



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

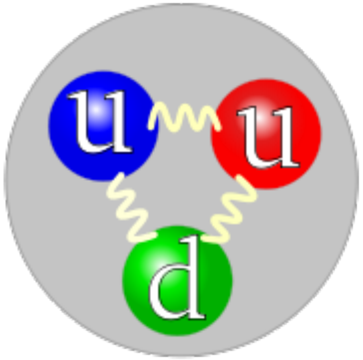
β_f - the same for both particles

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

Conclusions & Summary

Summary

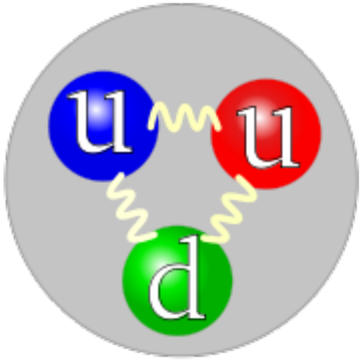
- Descriptions of the interaction among antimatter (based on the simplest systems of anti-nucleons) determined.
- A quantitative verification of matter-antimatter symmetry in context of the forces responsible for the binding of (anti)nuclei.
- Scattering length is positive and favor $\Lambda - \Lambda$ bound state hypothesis
- Scattering length is positive and favor $p - \Omega$ bound state hypothesis
- Searched for $\Xi - \Xi$ bounds states have started
- Antonelli parametrization of $K_S^0 - K^{\pm}$ strong interactions favors $a_0(980)$ resonance as a tetraquark
- d-d CF described better by the model including coalescence
- Light nuclei are likely to be formed via coalescence
- Heavier directed towards edge of the source and /or …
- Heavier particles freeze-out earlier



Summary

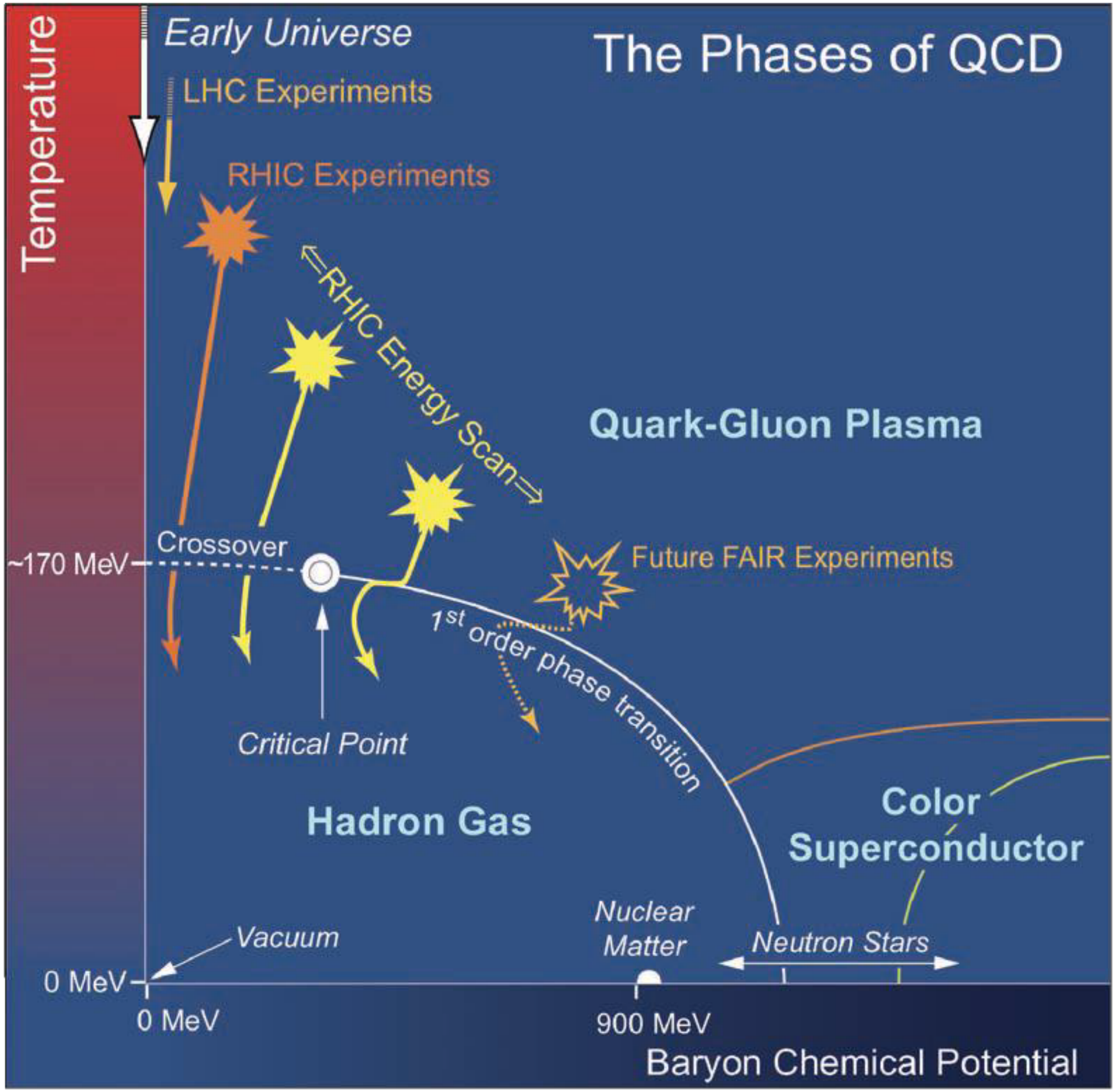
- Descriptions of the interaction among antimatter (based on the simplest systems of anti-nucleons) determined.
- A quantitative verification of matter-antimatter symmetry in context of the forces responsible for the binding of (anti)nuclei.
- Scattering length is positive and favor $\Lambda - \Lambda$ bound state hypothesis
- Scattering length is positive and favor $p - \Omega$ bound state hypothesis
- Searched for $\Xi - \Xi$ bounds states have started
- Antonelli parametrization of $K_S^0 - K^{\pm}$ strong interactions favors $a_0(980)$ resonance as a tetraquark
- d-d CF described better by the model including coalescence
- Light nuclei are likely to be formed via coalescence
- Heavier directed towards edge of the source and /or …
- Heavier particles freeze-out earlier

Thank you for Your attention



Back-up slides

e) Program Beam Energy Scan

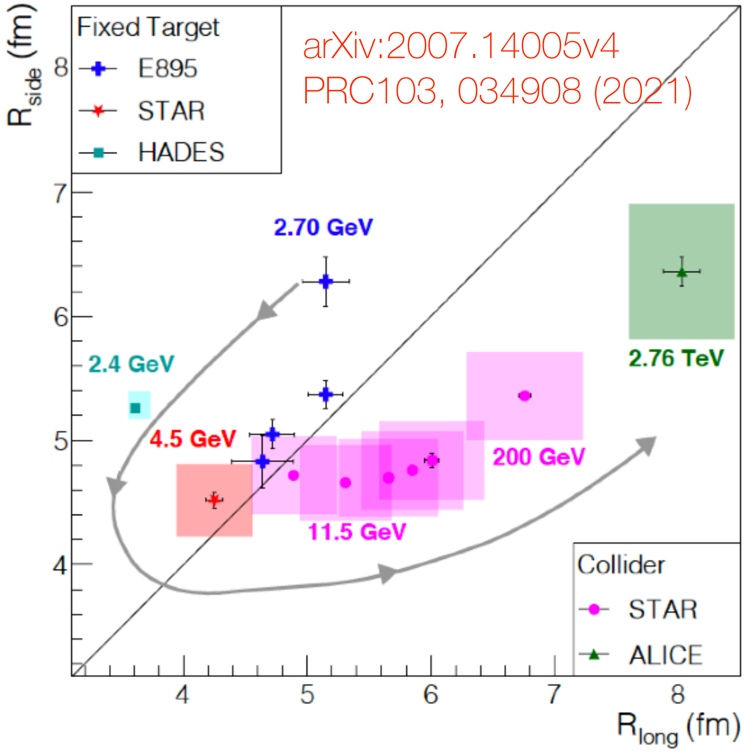


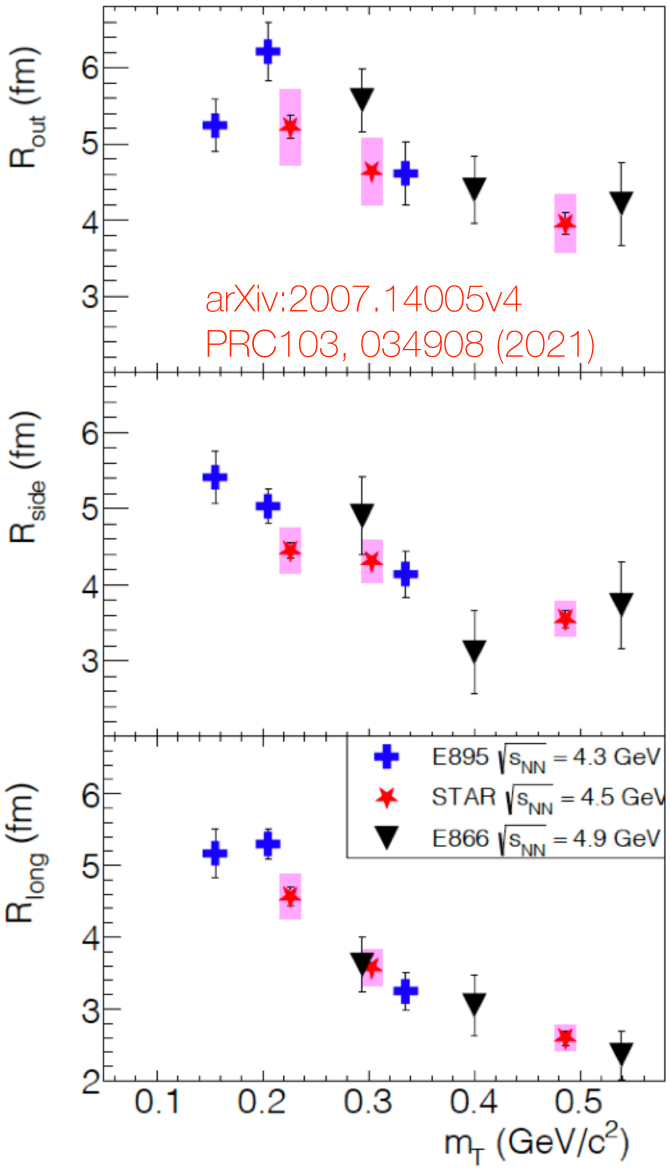
RHIC Top Energy
p+p, p+Al, p+Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, Ru+Ru, Zr+Zr, Au+Au, U+U
QCD at high energy density/temperature
Properties of QGP, EoS

Beam Energy Scan
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

How to measure a phase transition?


arXiv:2007.14005v4
PRC103, 034908 (2021)


arXiv:2007.14005v4
PRC103, 034908 (2021)

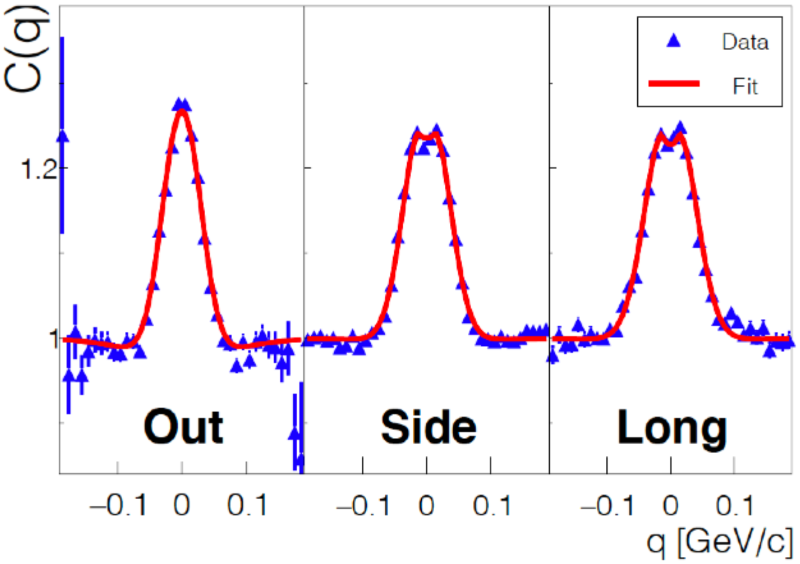
Clear evolution in the freeze-out shape indicated

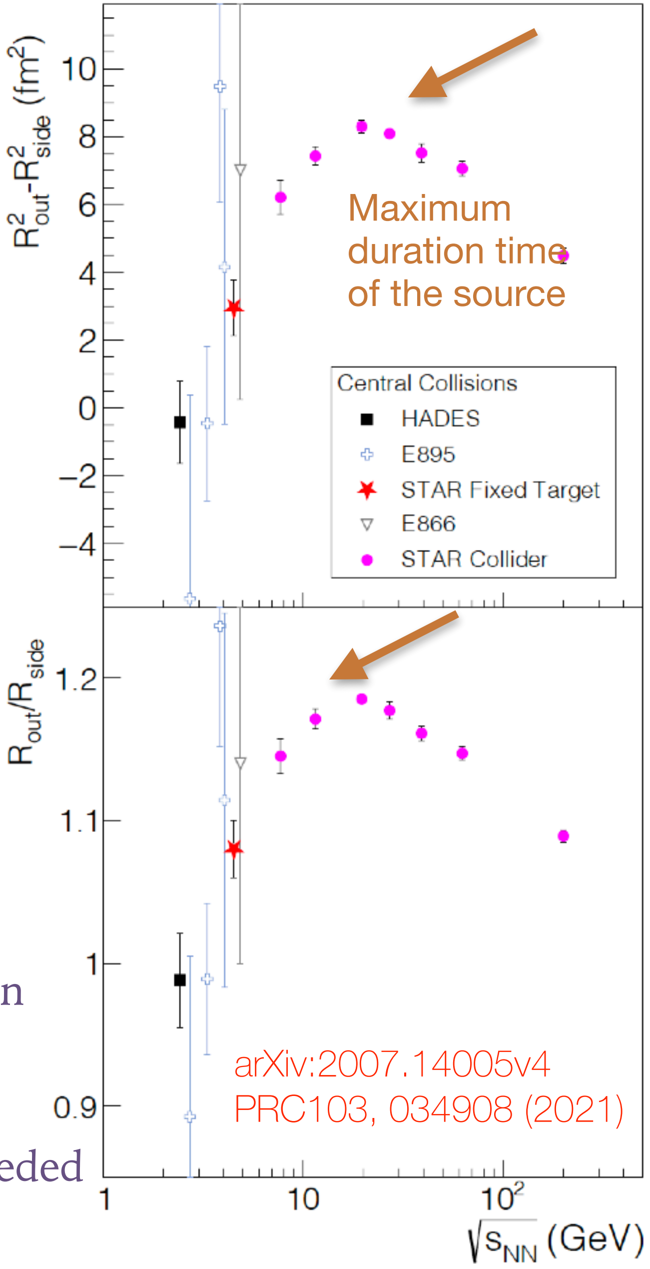
Lower energies: system more oblate ($R_{side} > R_{long}$)
Higher energies: system more prolate ($R_{side} < R_{long}$)
$\sqrt{s_{NN}}$ = 4.5 GeV: round system ($R_{side} \simeq R_{long}$)

Transition region between dynamics dominated by stopping and boost-invariant dynamics.

How to measure a phase transition?

arXiv:2007.14005v4; PRC103, 034908 (2021)





Maximum duration time of the source

arXiv:2007.14005v4
PRC103, 034908 (2021)

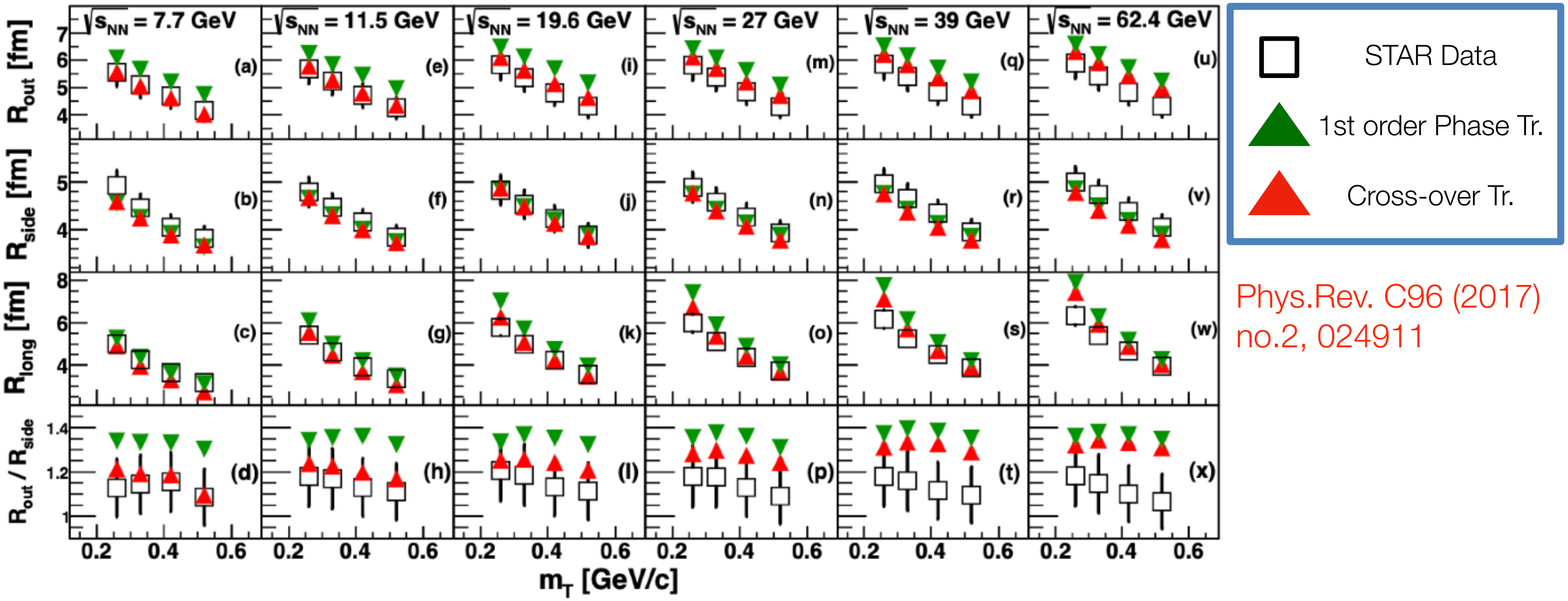
$$R^2_{out} - R^2_{side} = \beta_t^2 \Delta\tau^2$$

Visible peak in $\frac{R_{out}}{R_{side}}(\sqrt{s_{NN}})$ near the $\sqrt{s_{NN}} \simeq 20$ GeV

QCD calculations predict a peak near to the QGP transition threshold - signature of first-order phase transition?

Theoretical attention from hydro and transport models needed

How to measure a phase transition?



Phys.Rev. C96 (2017) no.2, 024911

Pre-thermal phase → **Hydrodynamical phase** → **Hydronic cascades**

UrQMD

vHLEE

UrQMD

vHLLE (3+1)-D viscous hydrodynamics
Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher
Phys.Rev. C 91, 064901 (2015), arXiv:1502.01978,1509.3751

vHLEE+UrQMD model verify sensitivity of HBT measurements to the first-order phase transition

HadronGas + Bag Model → 1^{st} order PT

P.F. Kolb, et al, PR C 62, 054909 (2000)

Chiral EoS → crossover PT (XPT)
J. Steinheimer, et al, J. Phys. G 38, 035001 (2011)

b) Strange Baryon Correlations (Including Λ Hyperons)

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

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

HZ, A. Kisiel, M. Szymański

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