Warsaw University of Technology

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Two-particle correlations at the BES program

.. and what can we learn about EoS?

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Introduction
- *QCD phase diagram*
- *Femtoscopy*

Results
- *BES program*
- *Interactions*

Conclusions

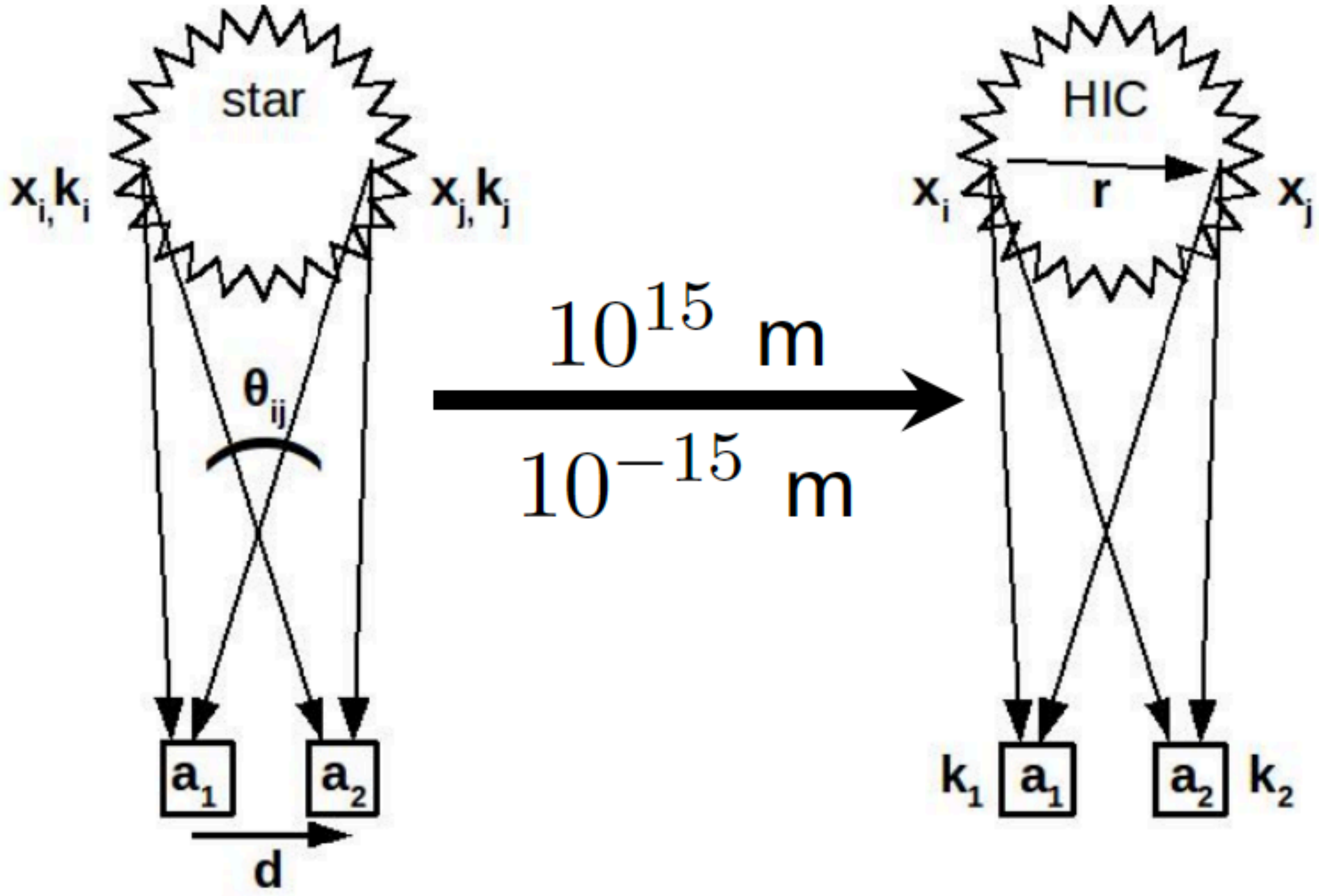
Dense Nuclear Matter Equation of State from Heavy-Ion Collisions,
INT 22-84W Workshop, UW, December 5-9 2022

Introduction

Correlation femtoscopy

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

Impossible
to measure directly!



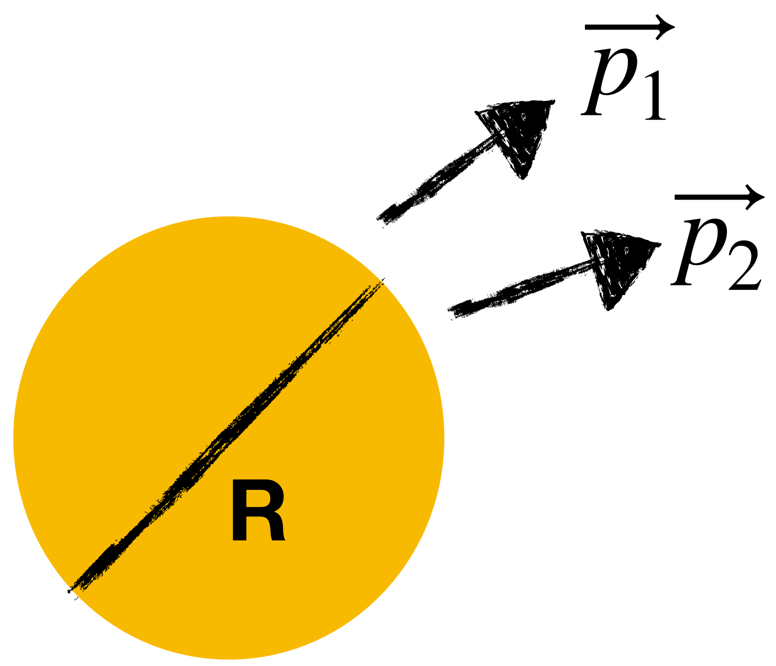
Femtoscopy (HIC) inspired by Hanbury Brown and Twiss interferometry method (Astronomy)

but!

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

Traditional and non-traditional femtoscopy

Femtoscopy (originating from 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 correlations that arise due to:

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

Final State Interactions (Coulomb, strong)

determined | assumed | measured

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

r^* - two-particle separation
k^* - momentum of the first particle in Pair Rest Frame

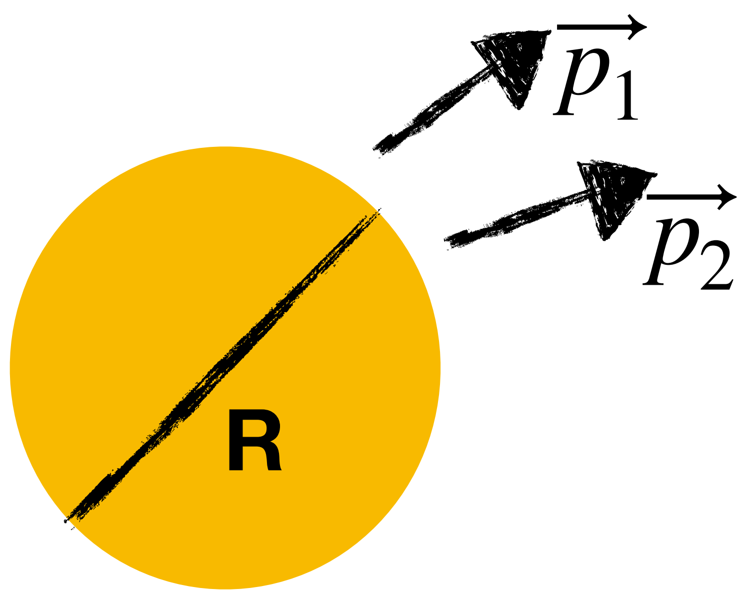
$S(r^*)$ - emission function

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

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

Traditional and non-traditional femtoscopy

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



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

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

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Published: 04 November 2015

Measurement of interaction between antiprotons

The STAR Collaboration

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

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.

nature

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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

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

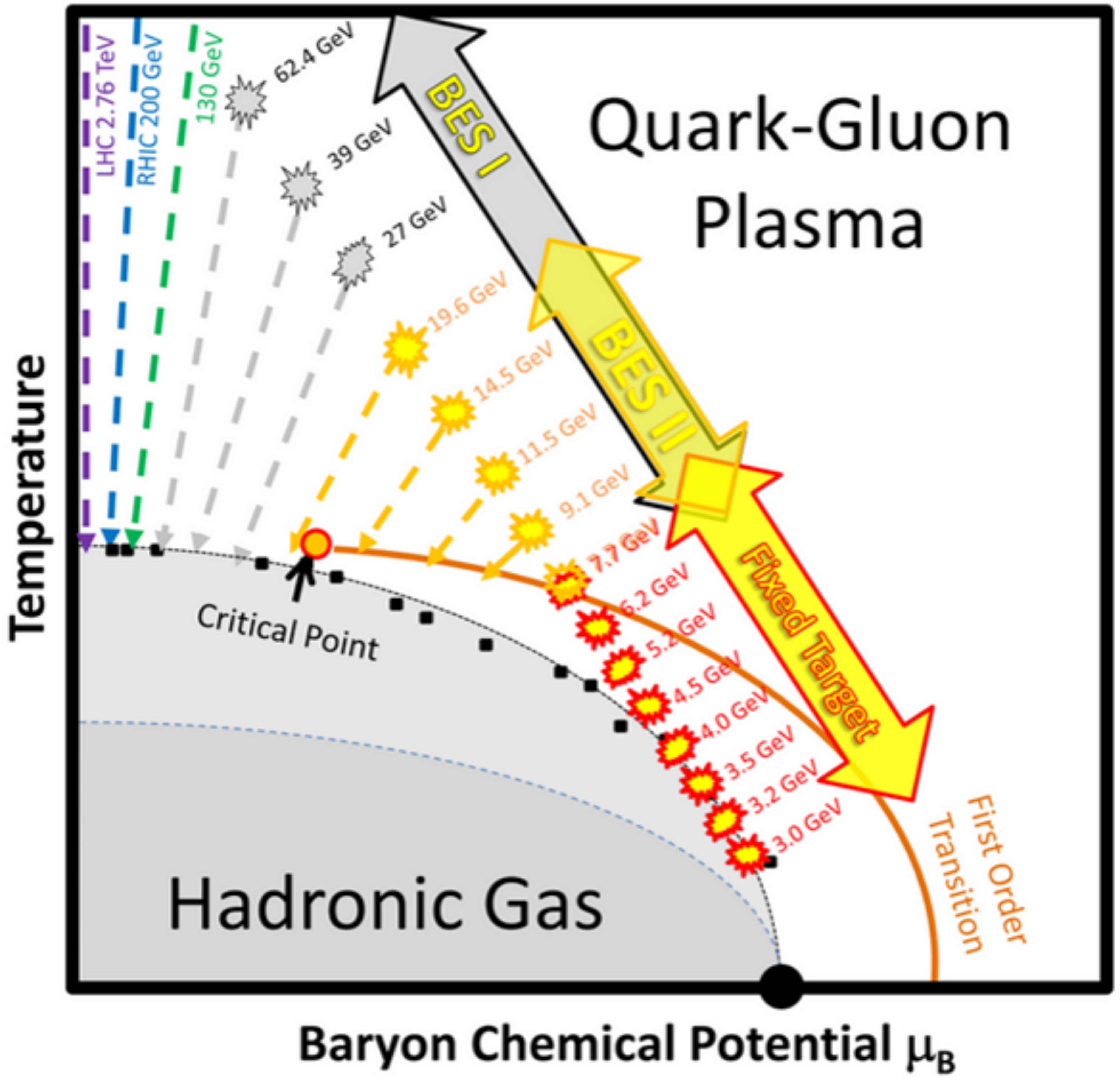
This article has been updated

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.

Results

I) Program Beam Energy Scan



RHIC Top Energy: 200 GeV
p+p, p+Al, p+Au, d+Au, 3He+Au, Cu+Cu, Cu+Au, Ru+Ru, Zr+Zr, Au+Au, U+U

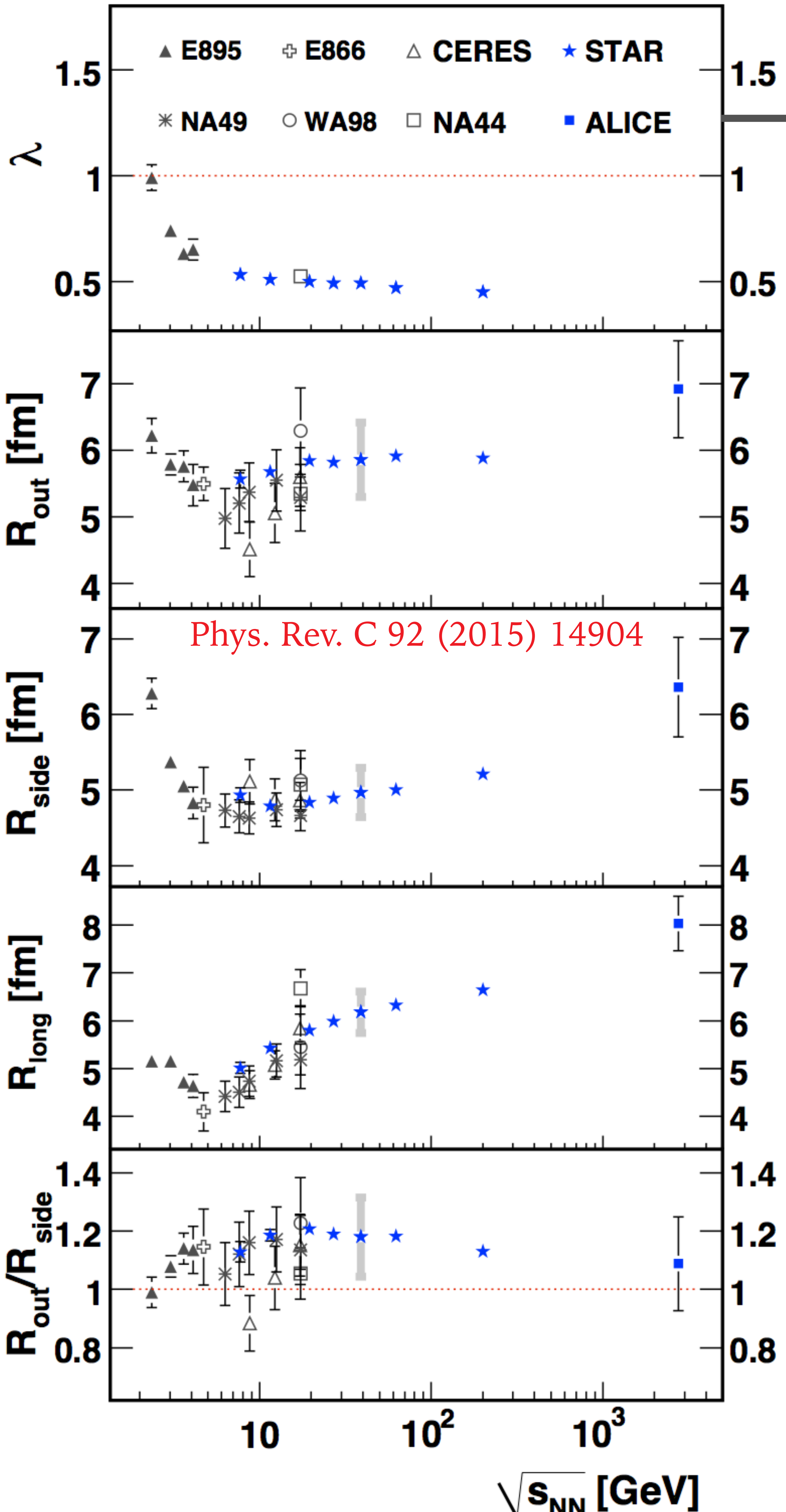
1. QCD at high energy density/temperature
2. Properties of QGP, EoS

Beam Energy Scan: Au+Au 7.7-62 GeV

1. Search for **turn-off** of **QGP** signatures
2. Search for signals of the **first-order phase transition**
3. Search for QCD **critical point**
4. Search for signals of **Chiral symmetry restoration**

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

Identical pion femtoscopy



→ R_{side} spatial source evolution in the transverse direction

→ R_{out} related to spatial and time components

→ R_{out}/R_{side} signature of phase transition

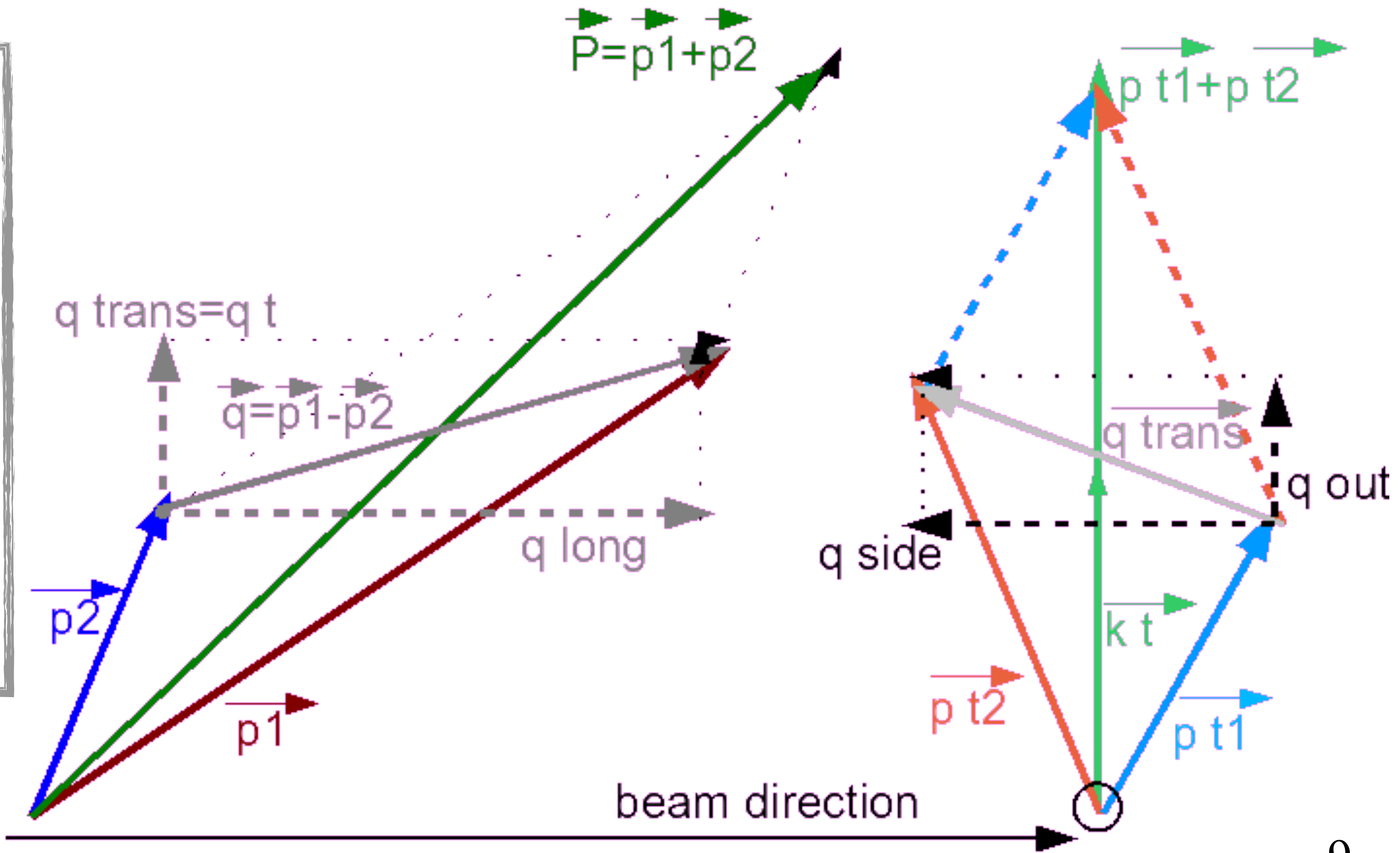
→ $R_{out}^2 - R_{side}^2 = \Delta\tau^2 \beta_t^2$; $\Delta\tau$ – emission time

→ R_{long} temperature of kinetic freeze-out and source lifetime

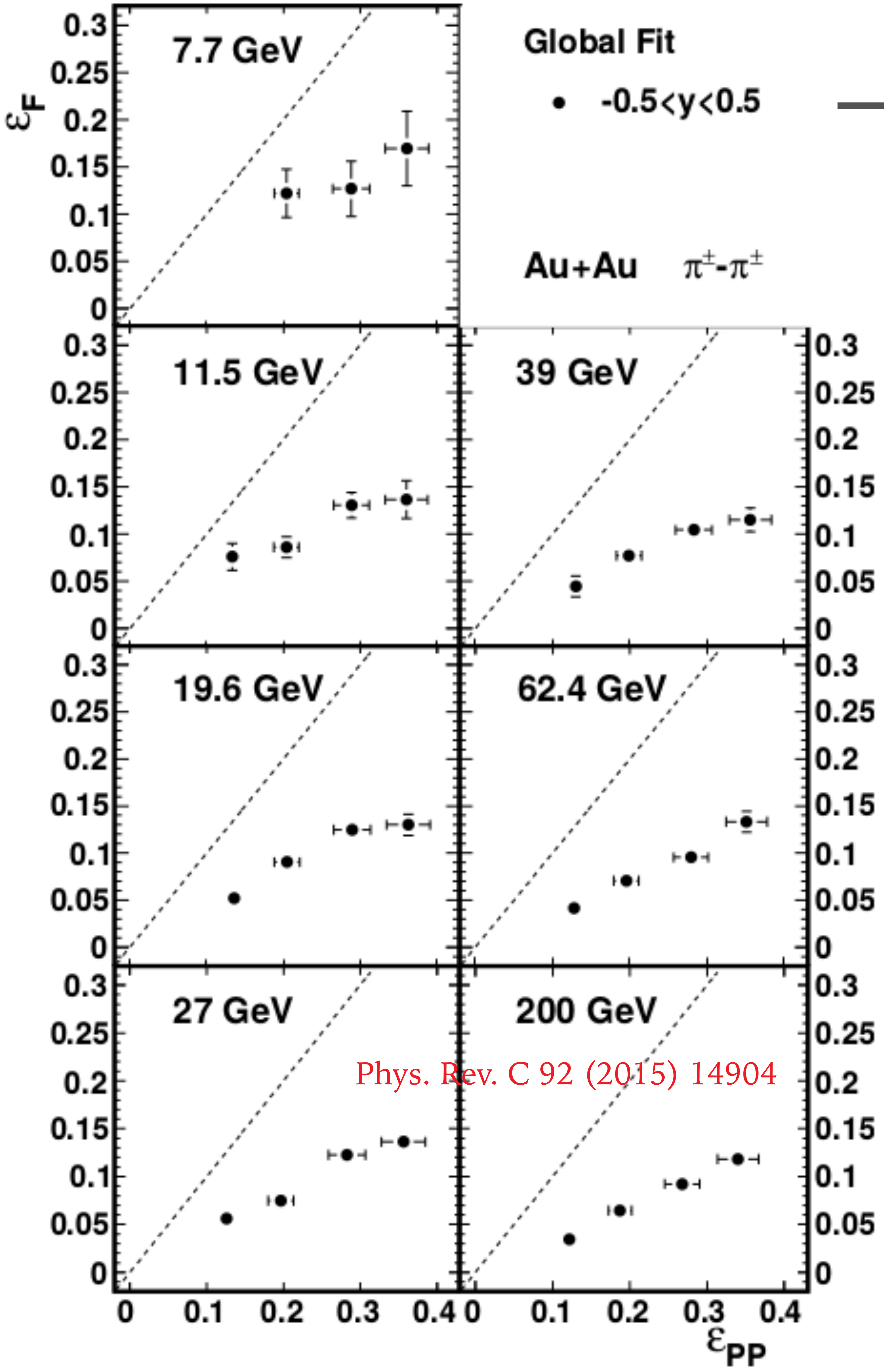
$$C(\vec{q}) = (1-\lambda) + K_{Coul}(q_{inv})\lambda \times \exp\left(-q_o^2R_o^2 - q_s^2R_s^2 - q_l^2R_l^2 - 2q_oq_sR_{os}^2 - 2q_oq_lR_{ol}^2\right)$$

HBT source sizes determined for wide range of collision energy;

Non-monotonic behavior seen in three directions



Identical pion femtoscopy



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

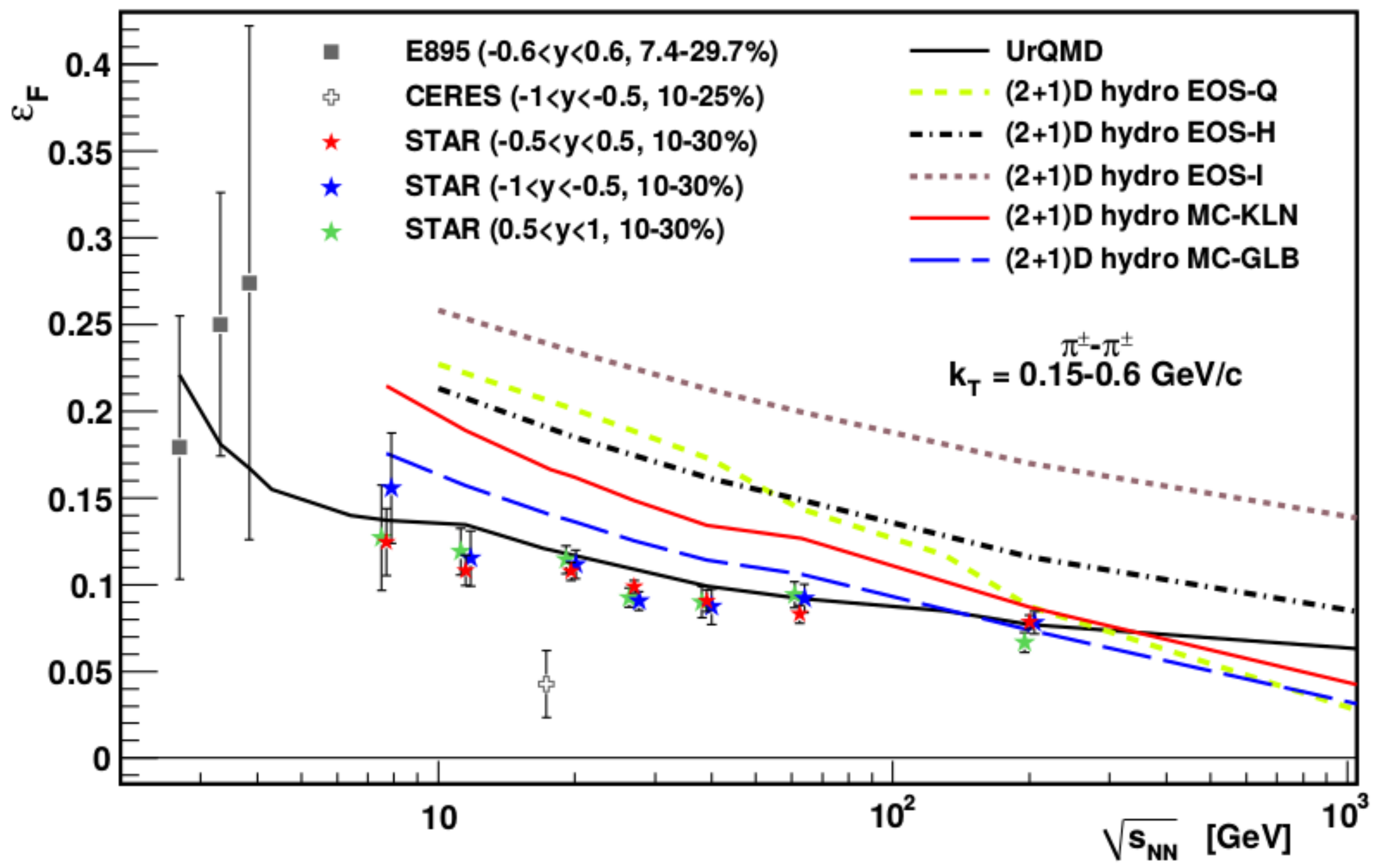
$$R^2_\mu(\Phi) = R^2_{\mu,0} + 2\sum_{n=2,4,6\ldots} R^2_{\mu,n}\sin(n\Phi) \qquad (\mu = os)$$

$$\varepsilon_{PP} = \frac{\sqrt{(\sigma_y^2-\sigma_x^2)^2+4\sigma_{xy}^2}}{\sigma_x^2+\sigma_y^2}.$$

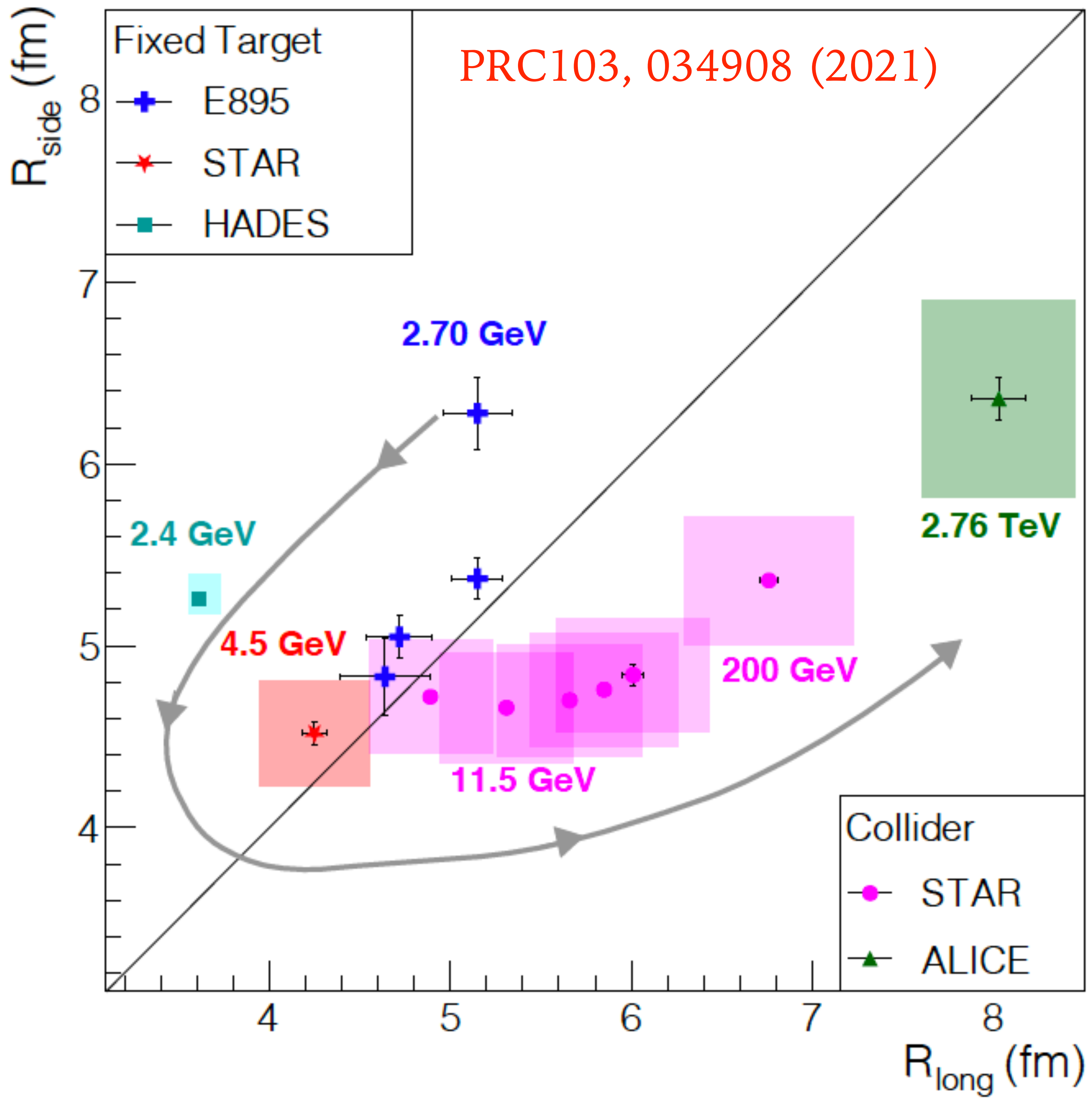
$$\varepsilon_F = \frac{\sigma_y'^2-\sigma_x'^2}{\sigma_y'^2+\sigma_x'^2} \approx 2\frac{R^2_{s,2}}{R^2_{s,0}}$$

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

System evolves faster in the reaction plane



Identical pion femtoscopy



- 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.

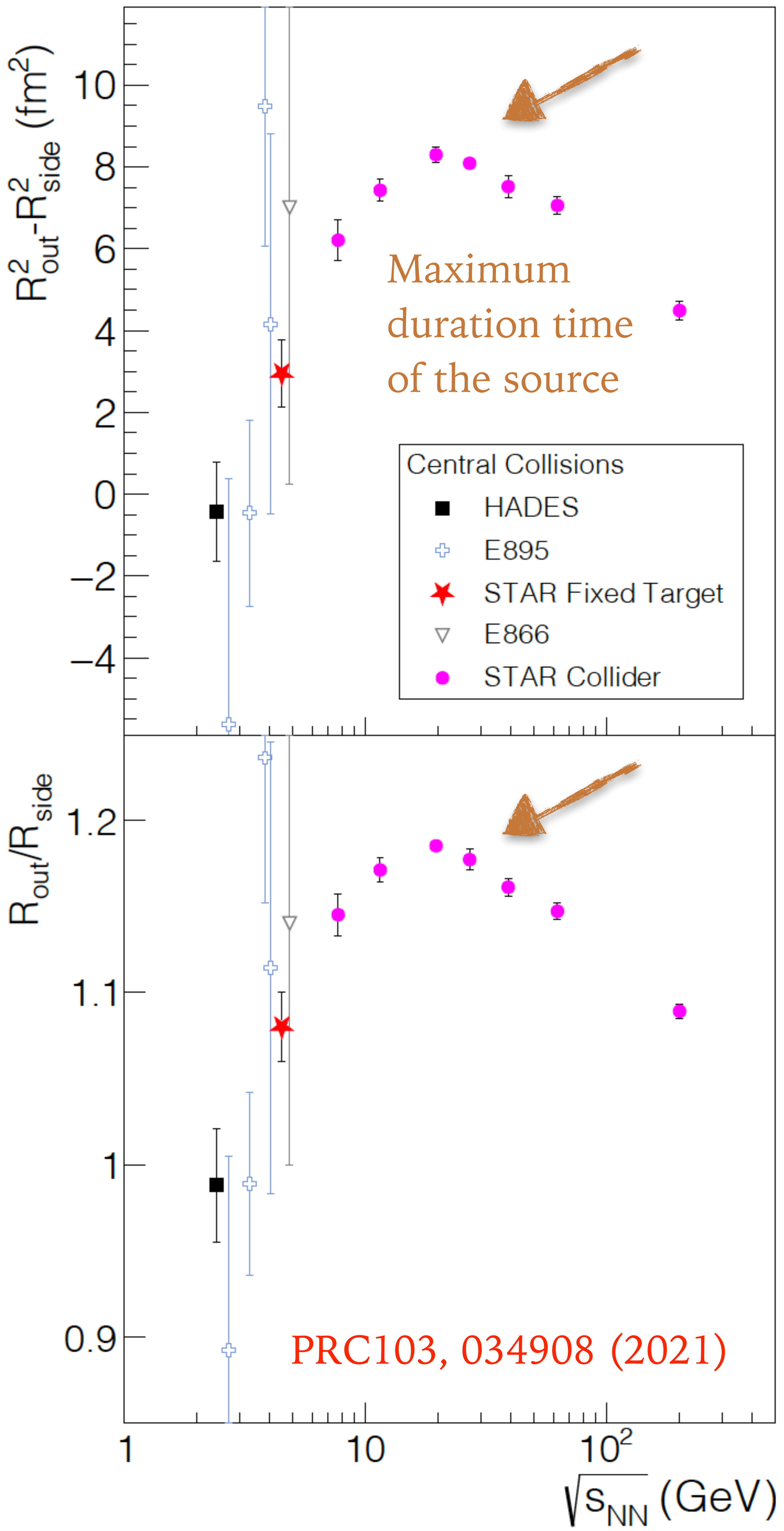
How to measure a phase transition?

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

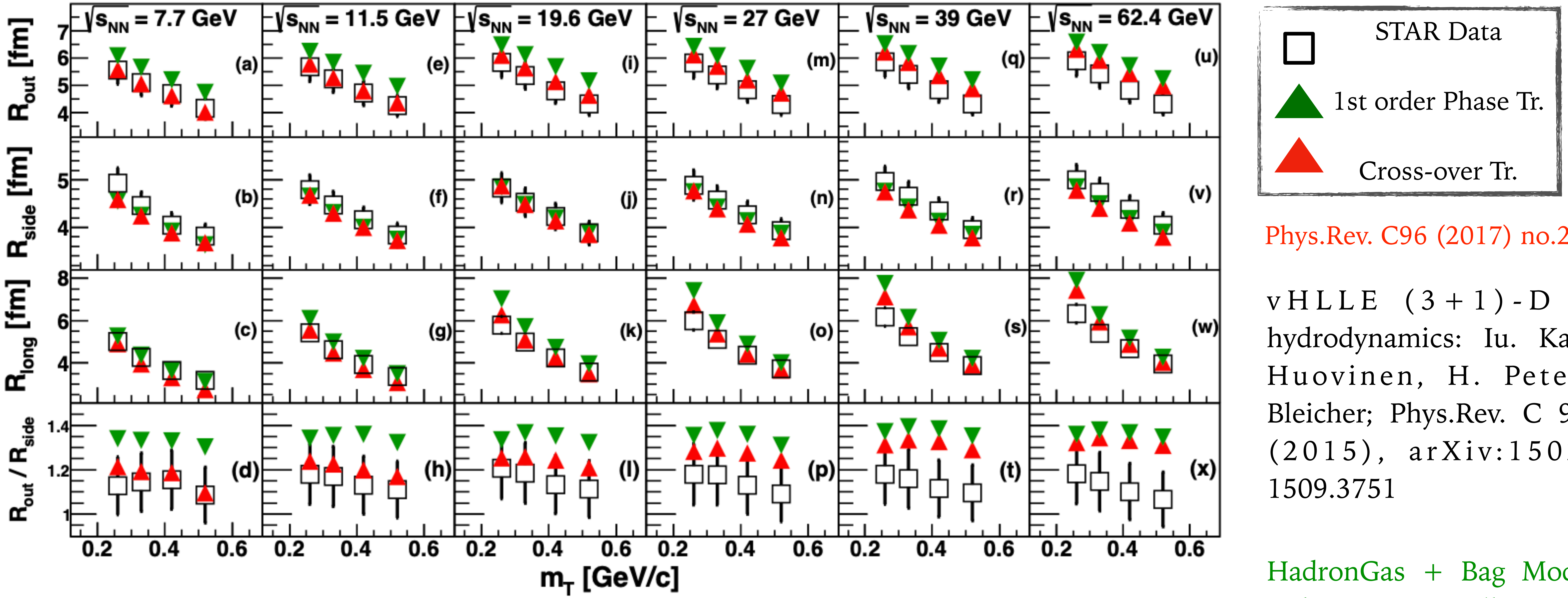
Visible peak in $\frac{R_{out}}{R_{side}}(\sqrt{s_{NN}})$ near the $\sqrt{s_{NN}} \simeq 20$ GeV

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

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

HadronGas + Bag Model → 1st 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)

Pre-thermal phase → Hydrodynamical phase → Hydronic cascades

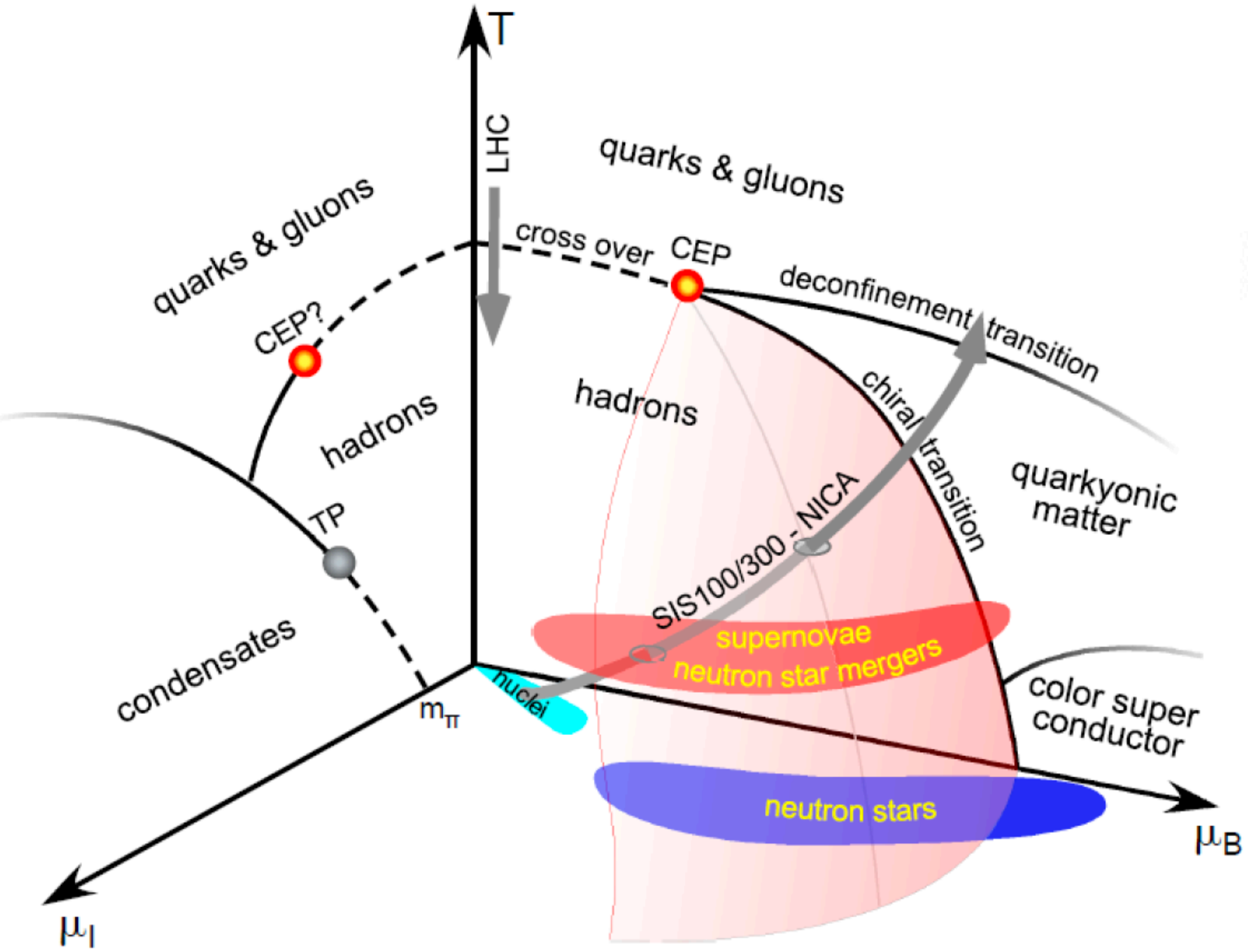
UrQMD — vHLEE — UrQMD

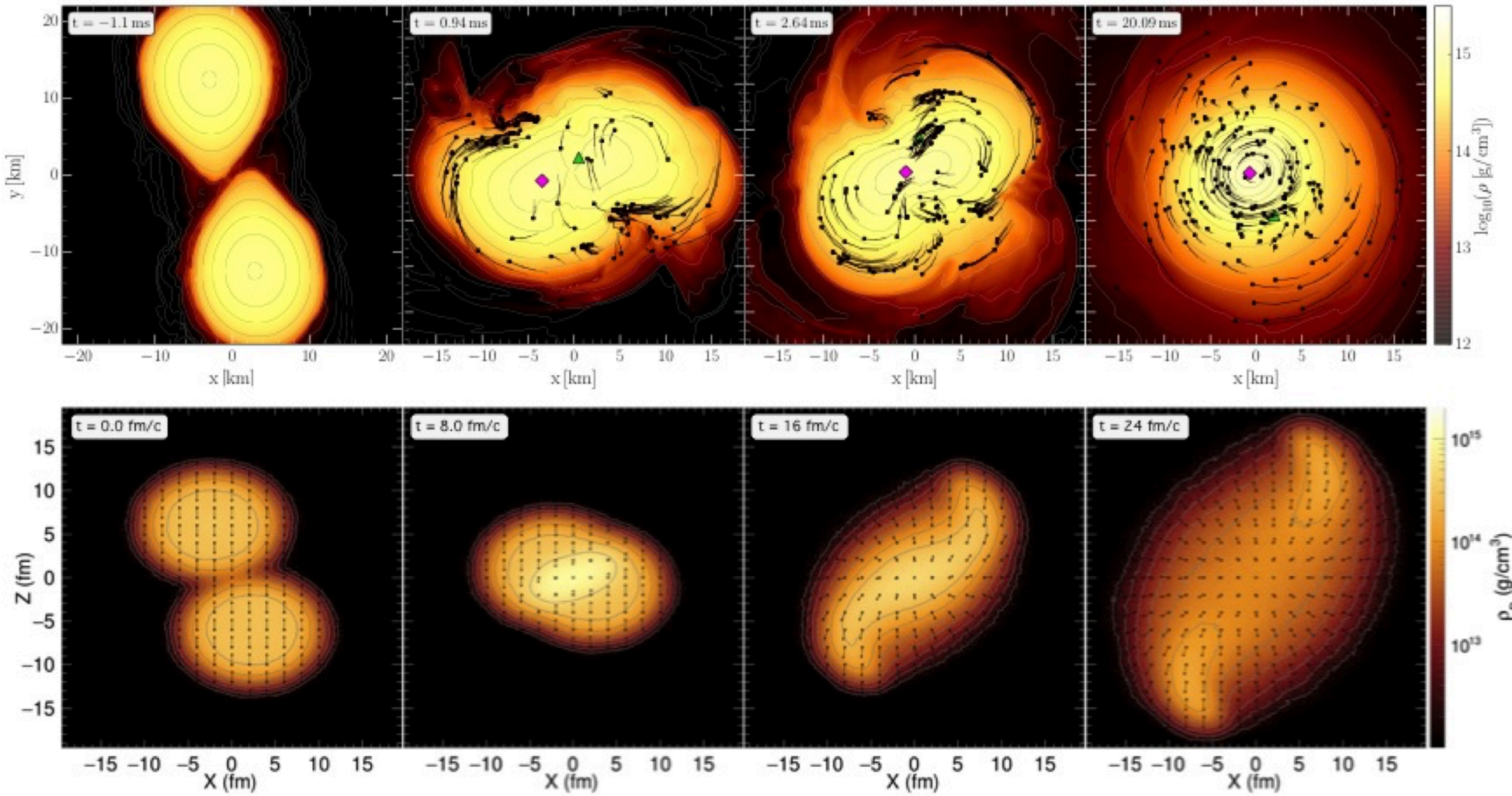
vHLEE+UrQMD model verify **sensitivity of HBT measurements to the first-order phase transition**

II) Investigation of the strong interactions

$M_{NS} \approx 1 \div 2\ M_{\odot}$
$R \approx 10\text{-}12$ km
$\rho \approx 3 \div 5\ \rho_0$

$\rho_0 \approx 2.8 \times 10^{14}\ g/cm^3$





HADES, Nature Phys. 15 (2019) 10, 1040-1045

NUPECC Long Range Plan 2017

Strange hadronic matter in the inner core

The inner core of the neutron star is totally unknown.

Hyperons appear at a density larger than (2–3) ρ_0

Λ hyperons (free from Pauli exclusion principle by n) - allowed to stay at the bottom of the nuclear potential made by n.

When the neutron's KE on the Fermi surface of the neutron matter exceeds Λ-n mass difference (176 MeV), n converts into Λ.

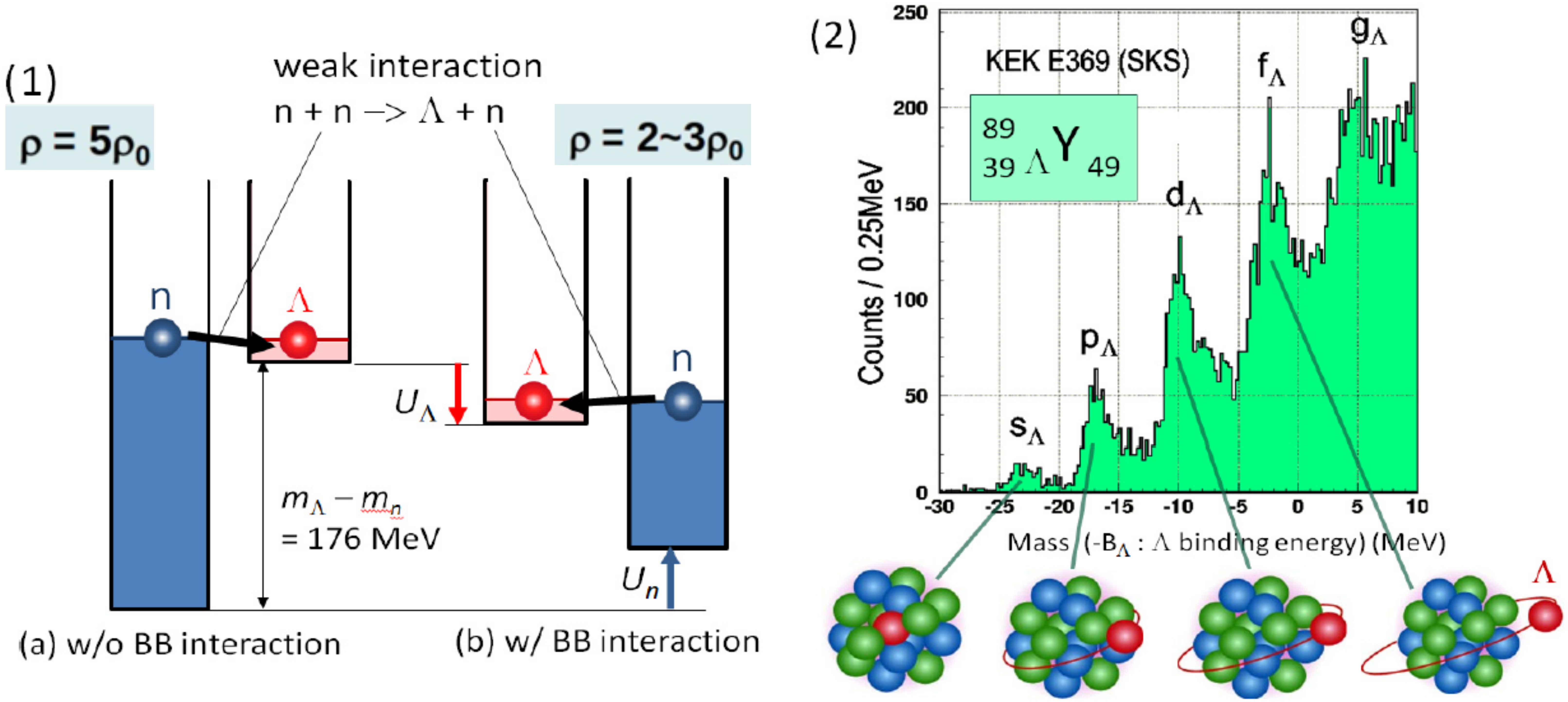


Fig. 3. (1) Energies of neutrons and Λ hyperons in high density neutron matter confined in the potential made by gravity. See text for details. (2) Excitation spectrum of a Λ hypernucleus $^{89}_{\Lambda}$Y via the (π^+, K^+) reaction on ^{89}Y target [6].

H. Tamura, JPS Conf Proc. 1, 011003 (2014)

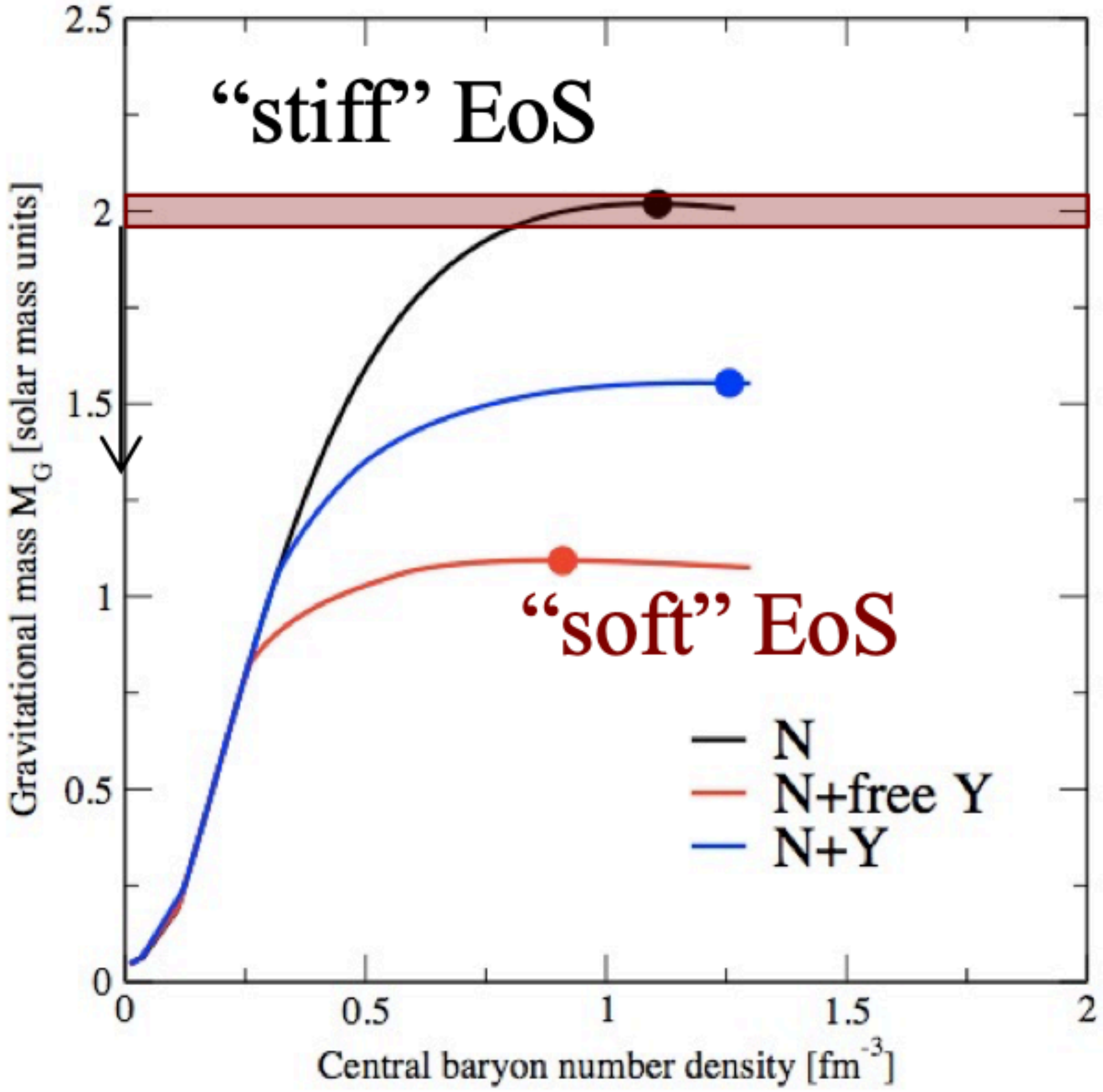
Neutron star puzzle

- **Hyperons**: expected in the core of neutron stars; **conversion of N into Y energetically favorable.**

- Appearance of Y: The relieve of Fermi pressure → **softer EoS** → **mass reduction (incompatible with observation).**

$M_{NS} \approx 1 \div 2\ M_{\odot}$
$R \approx 10\text{-}12$ km
$\rho \approx 3 \div 5\ \rho_0$

The solution requires a mechanism that could provide the **additional pressure** at high densities needed to make the EoS stiffer.



Possible mechanisms:

- **Two-body YN & YY interactions**
- Chiral forces
- Hyperonic Three Body Forces
- Quark Matter Core - Phase transition at densities lower than hyperon threshold

A lot of experimental and theoretical effort to understand:

- The **KN** interaction, governed by the presence of **Λ(1405)**
- The nature of **Λ(1405)**, the consequences of **KNN** formation
- **K** and $\bar{K}$ investigated to understand kaon condensation

$\rho_0 \approx 2.8 \times 10^{14}$ g/cm^3

Eqution Of States for different types of baryonic matter

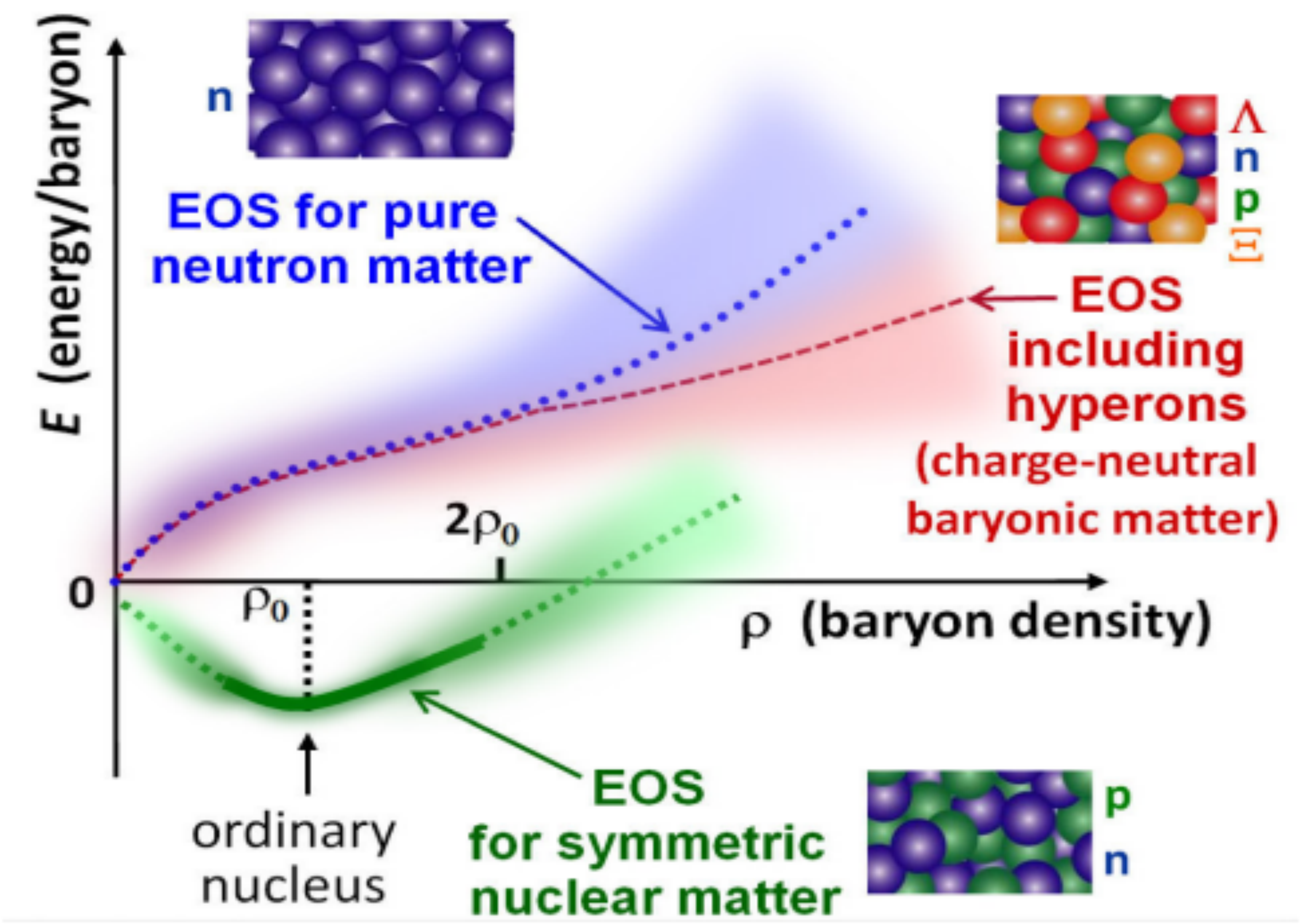
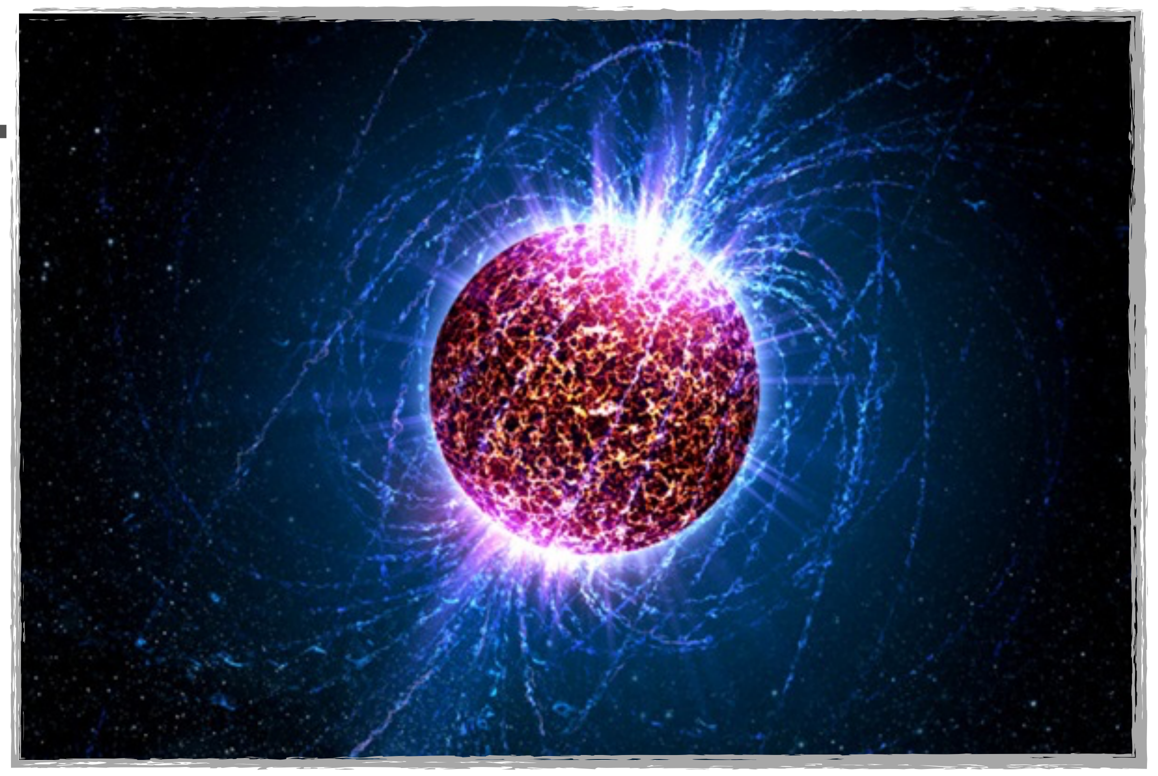


Fig. 1. A schematic illustration for nuclear (baryonic) matter Equation Of State (EOS) as a function of baryon density for symmetric nuclear matter, pure neutron matter, and charge-neutral baryonic matter with hyperons. The EOS is determined only for symmetric nuclear matter around $\rho \sim (0.5\text{–}2)\rho_0$ and has large uncertainties particularly for pure neutron matter, as symbolically shown in the figure.

„To establish the EOS applicable to the neutron star has been one of the most important subjects in nuclear physics for a long time but has not been achieved yet."

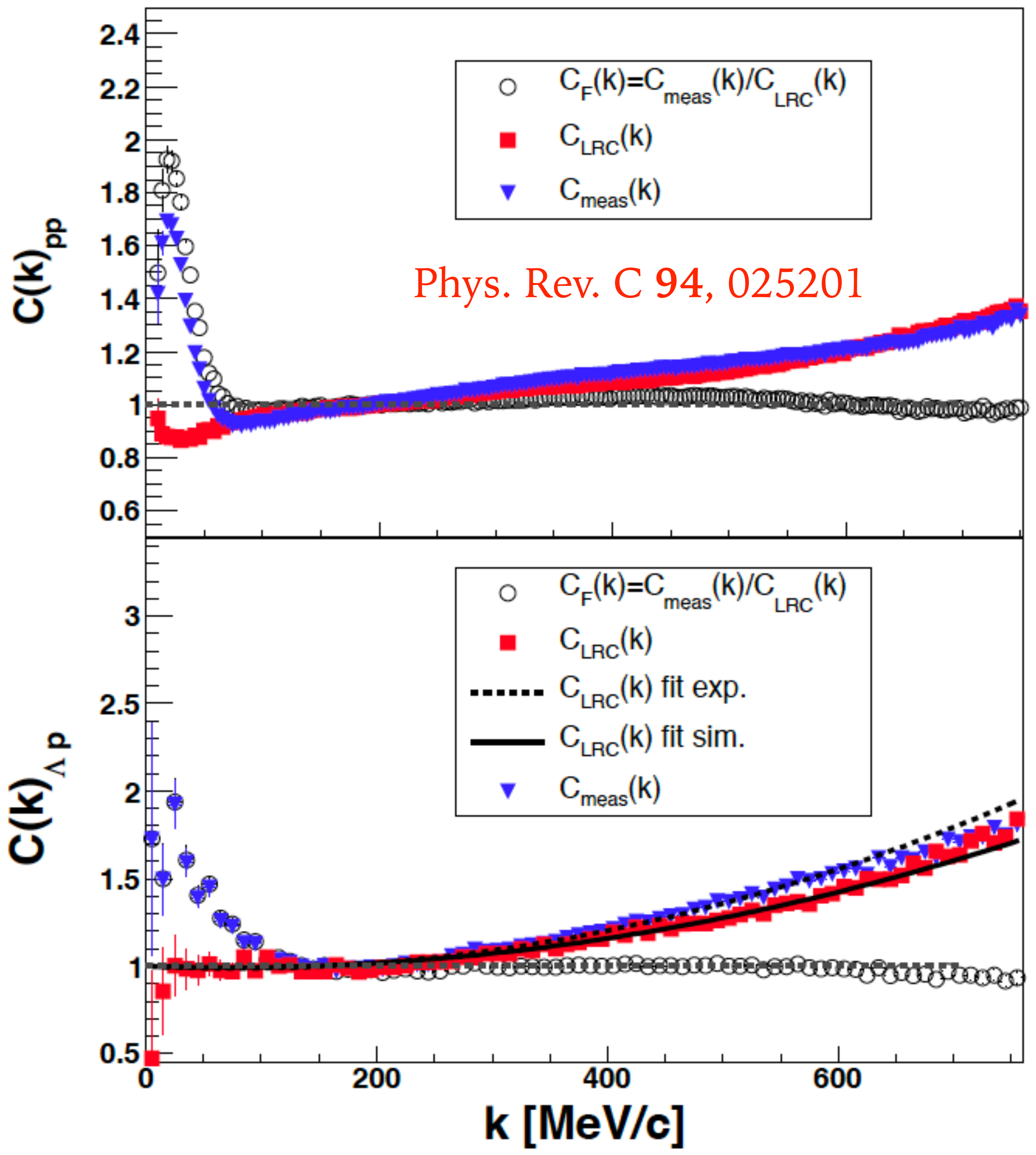
H.Tamura, JPS Conf. Proc. , 011003 (2014)

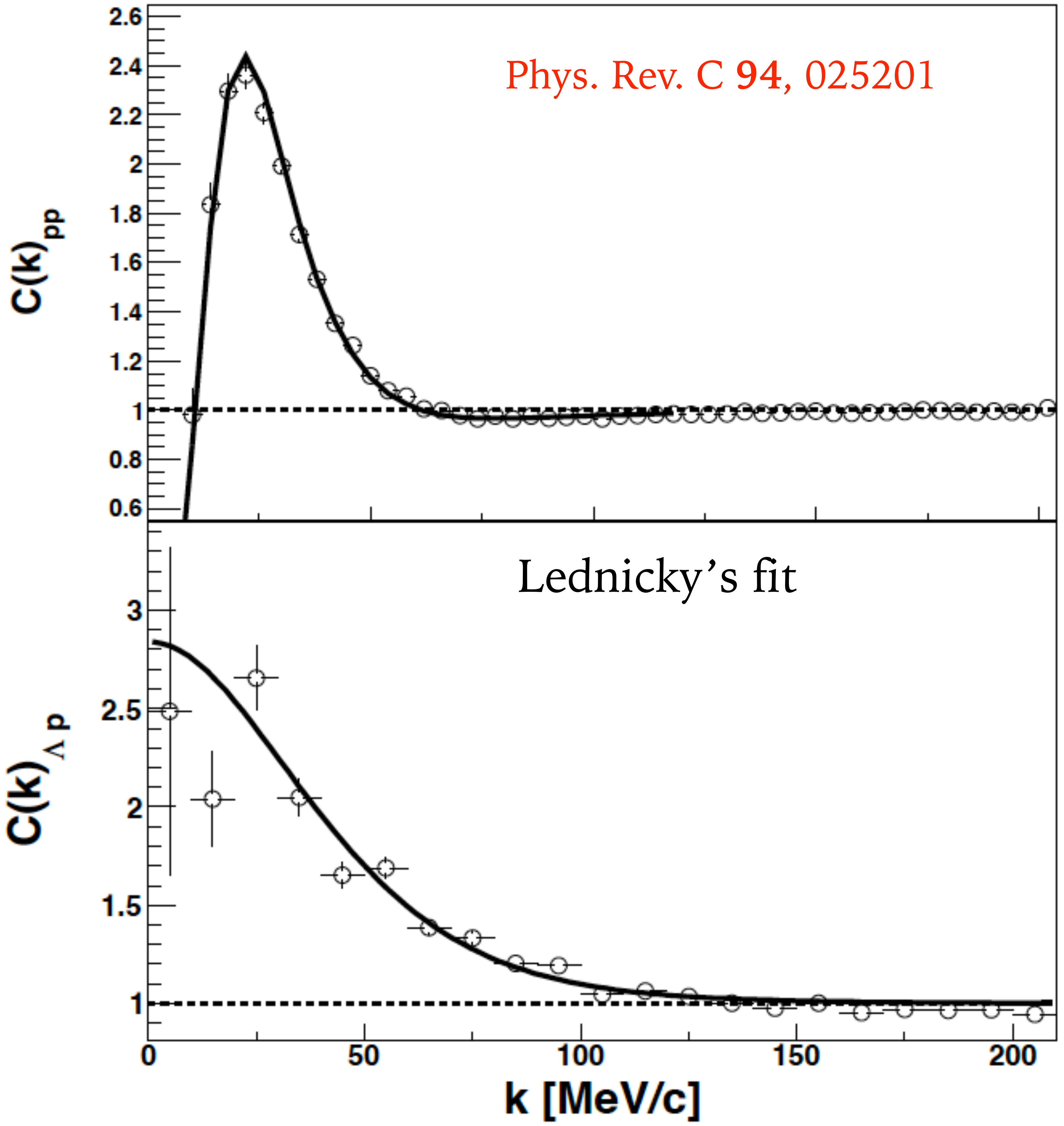
N-Y and Y-Y interactions

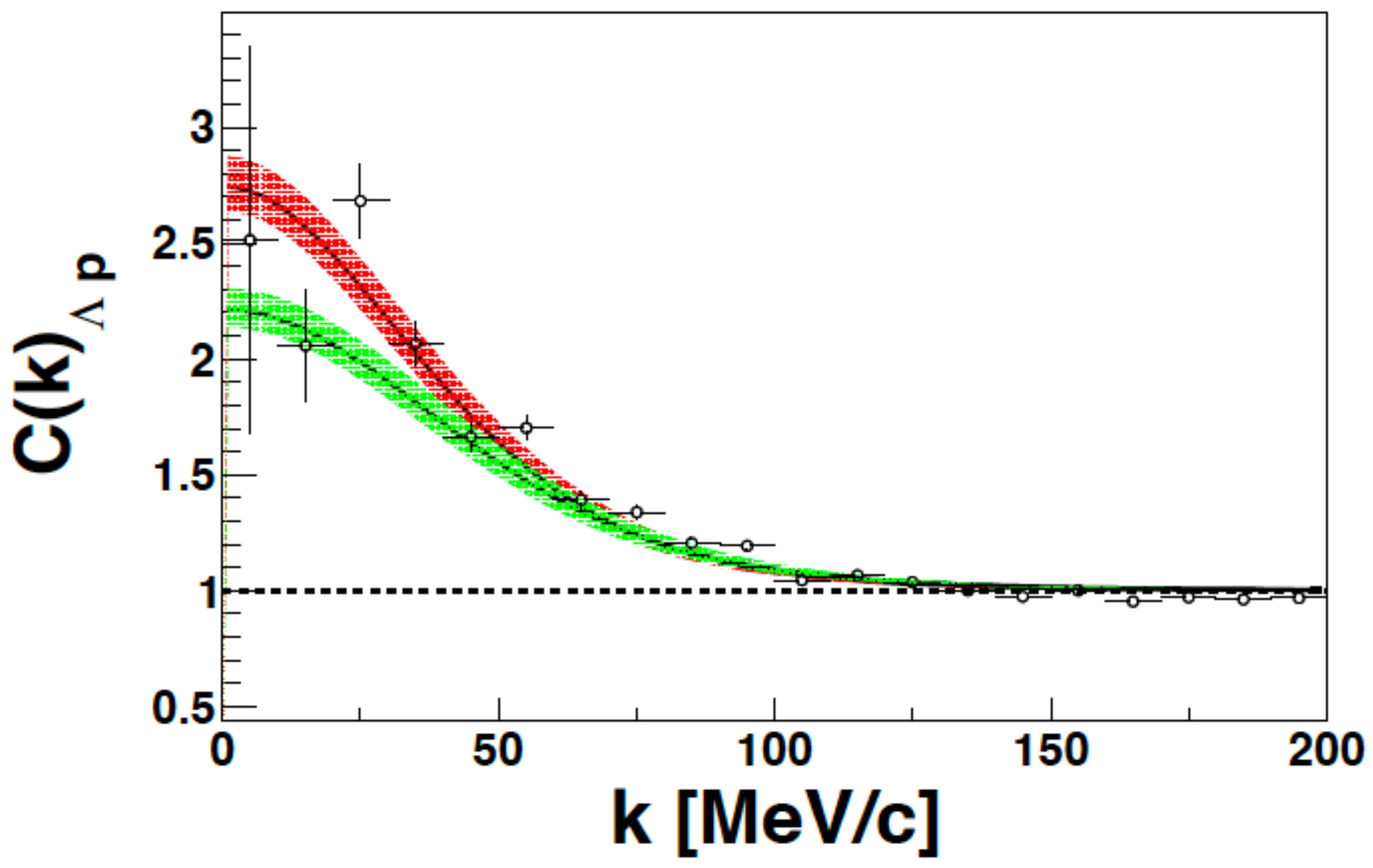


- **Experiment**: More interest about N-Y and Y–Y interactions (femtoscopy).
- **Theory**: Major steps forward have been made (Lattice QCD).
- **Numerous theoretical predictions** exist, but no clear evidence for any such **bound states**, despite **many experimental searches**.
- The existence of **hypernuclei** (confirmed by attractive Y–N interaction) → indicates the possibility to bind Y to N.
- 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 help to explore unknown structure of neutron stars.

N-Y (p-Λ) interactions at HADES







NLO scattering paremeters

$f^{S=0}_{0,NLO} = 2.91 fm$

$d^{S=0}_{0,NLO} = 2.78 fm$

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

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

LO scattering parameters

$f^{S=0}_{0,LO} = 1.91 fm$

$d^{S=0}_{0,LO} = 1.40 fm$

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

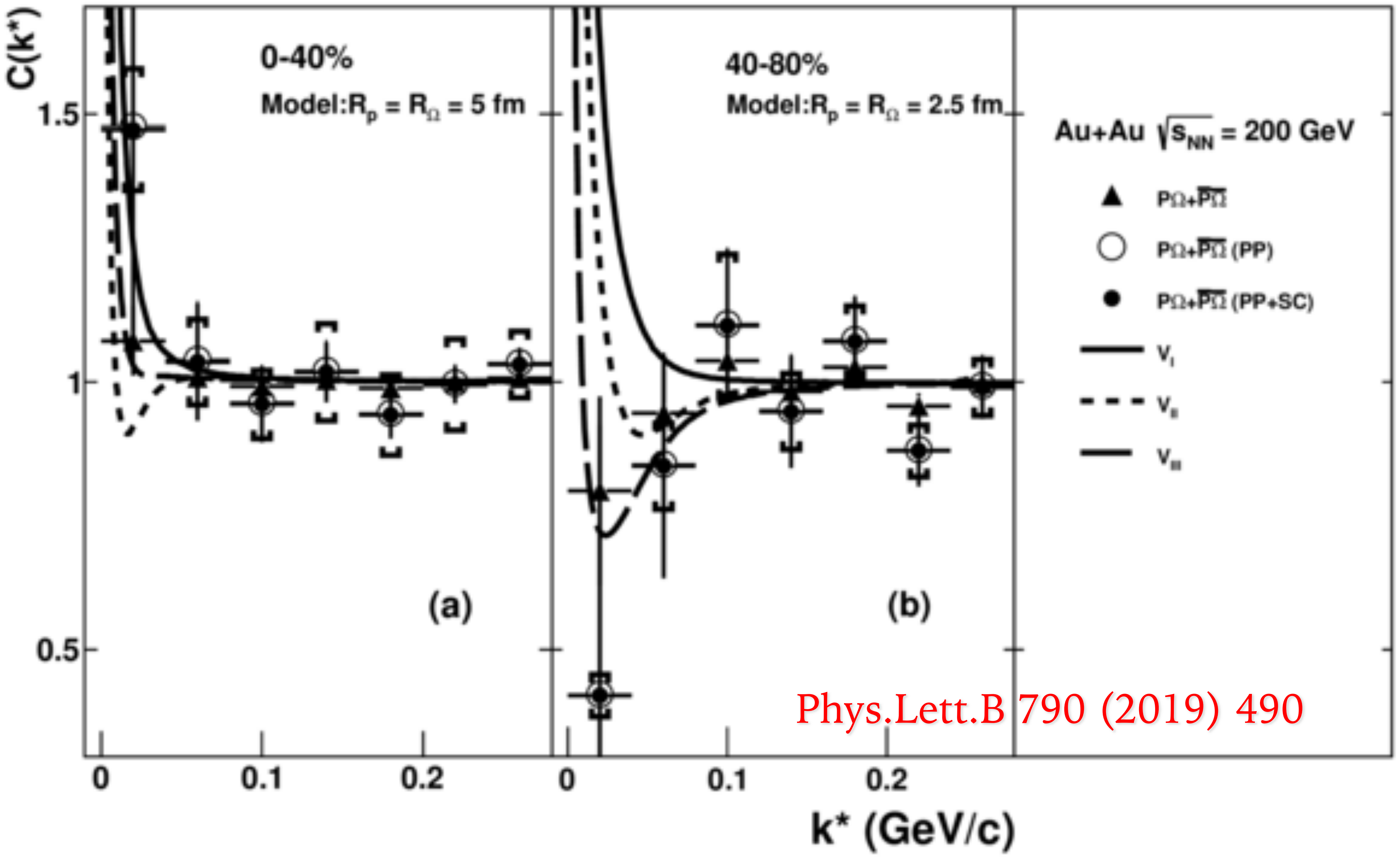
$d^{S=1}_{0,LO} = 2.13 fm$

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

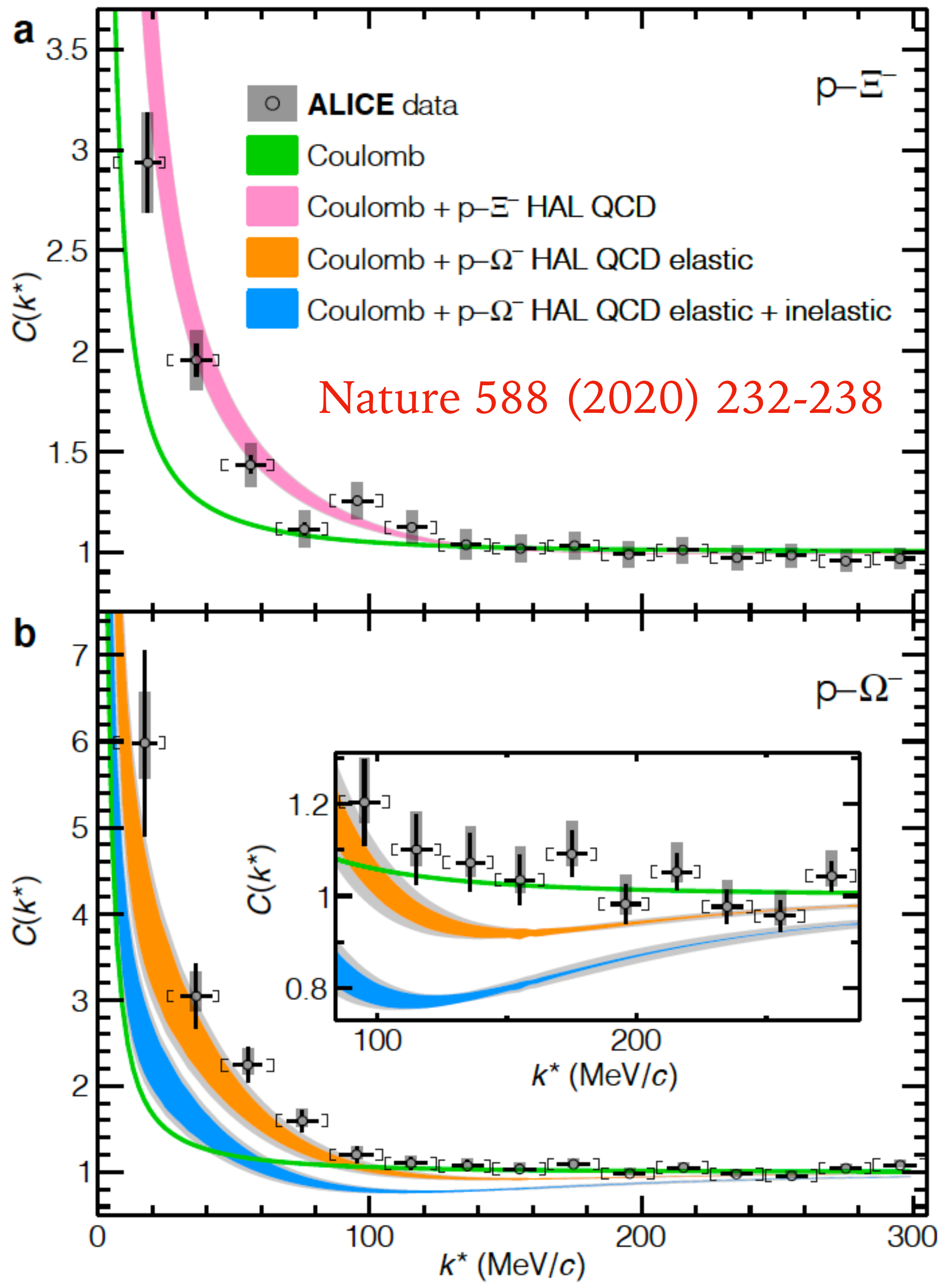
$$C_{LRC}(k^*) = 1 + ak + bk^2$$

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 H-Y interactions.

N-Y (p-Ω) interactions

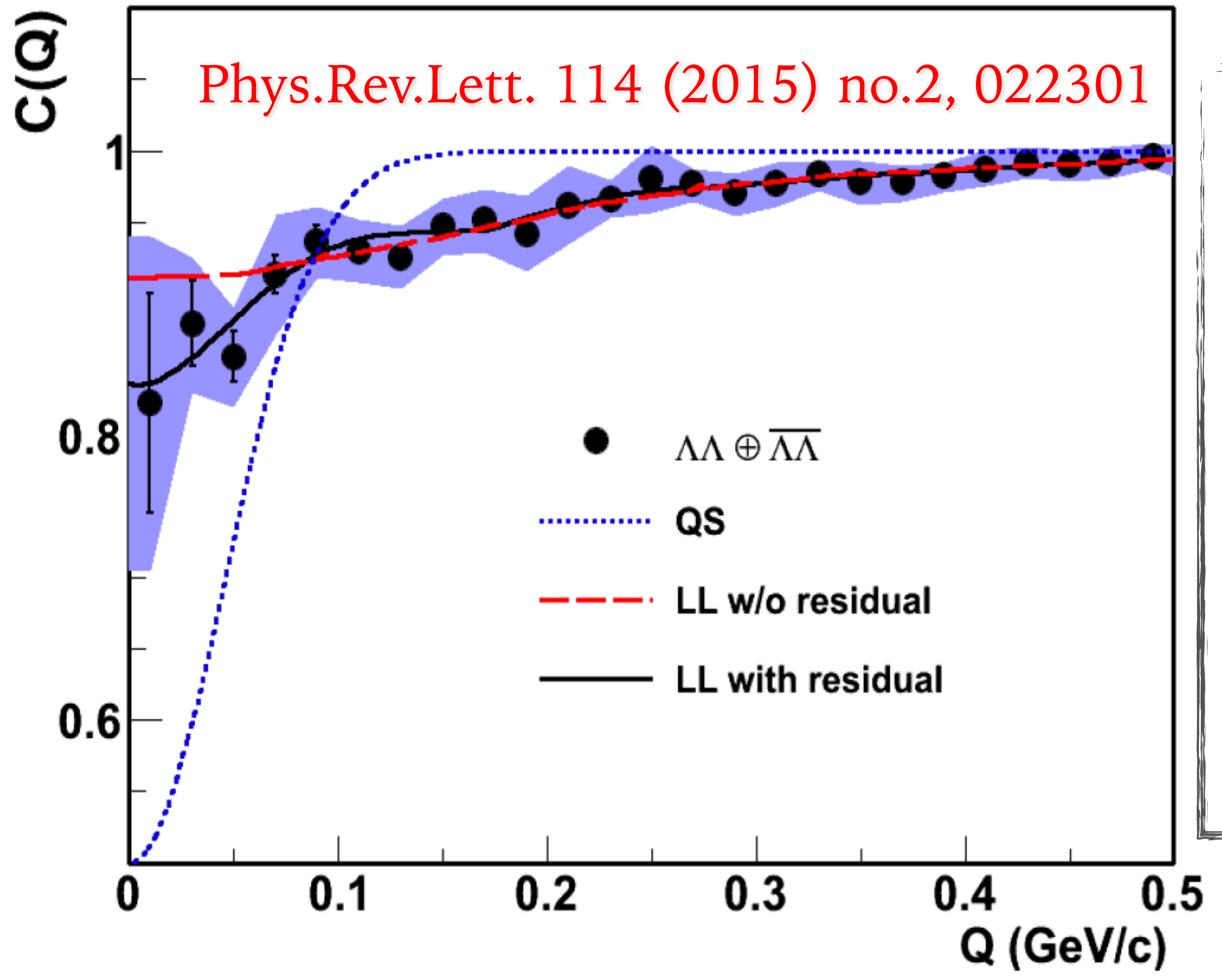


Scattering lenght positive, favor the hypothesis of pΩ bound state

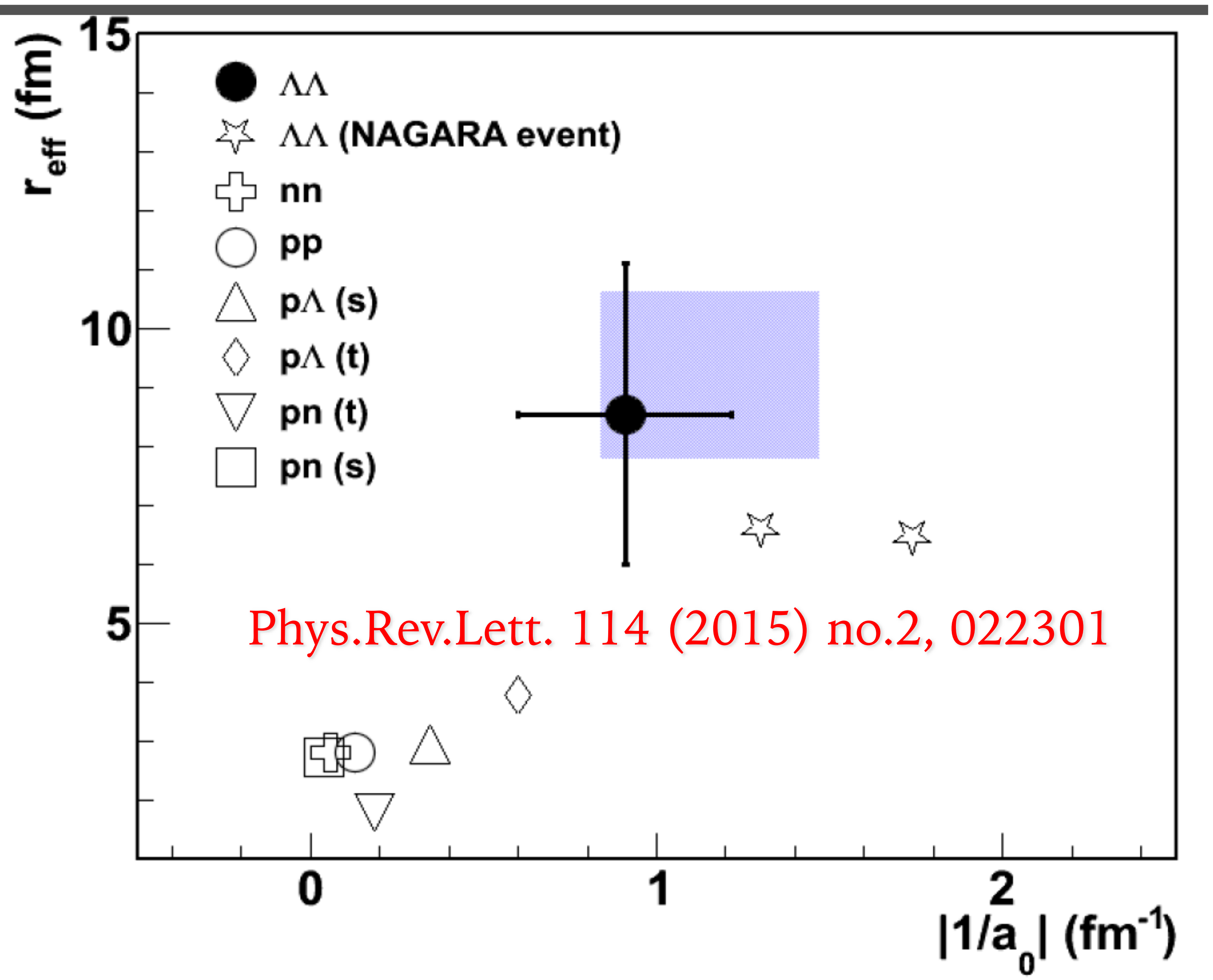


	V_1	V_2	V_3
E_{bin} [MeV]	-	6.3	26.9
a_0 [MeV]	-1.12	5.79	1.29
r_{eff} [MeV]	-1.16	0.96	0.65

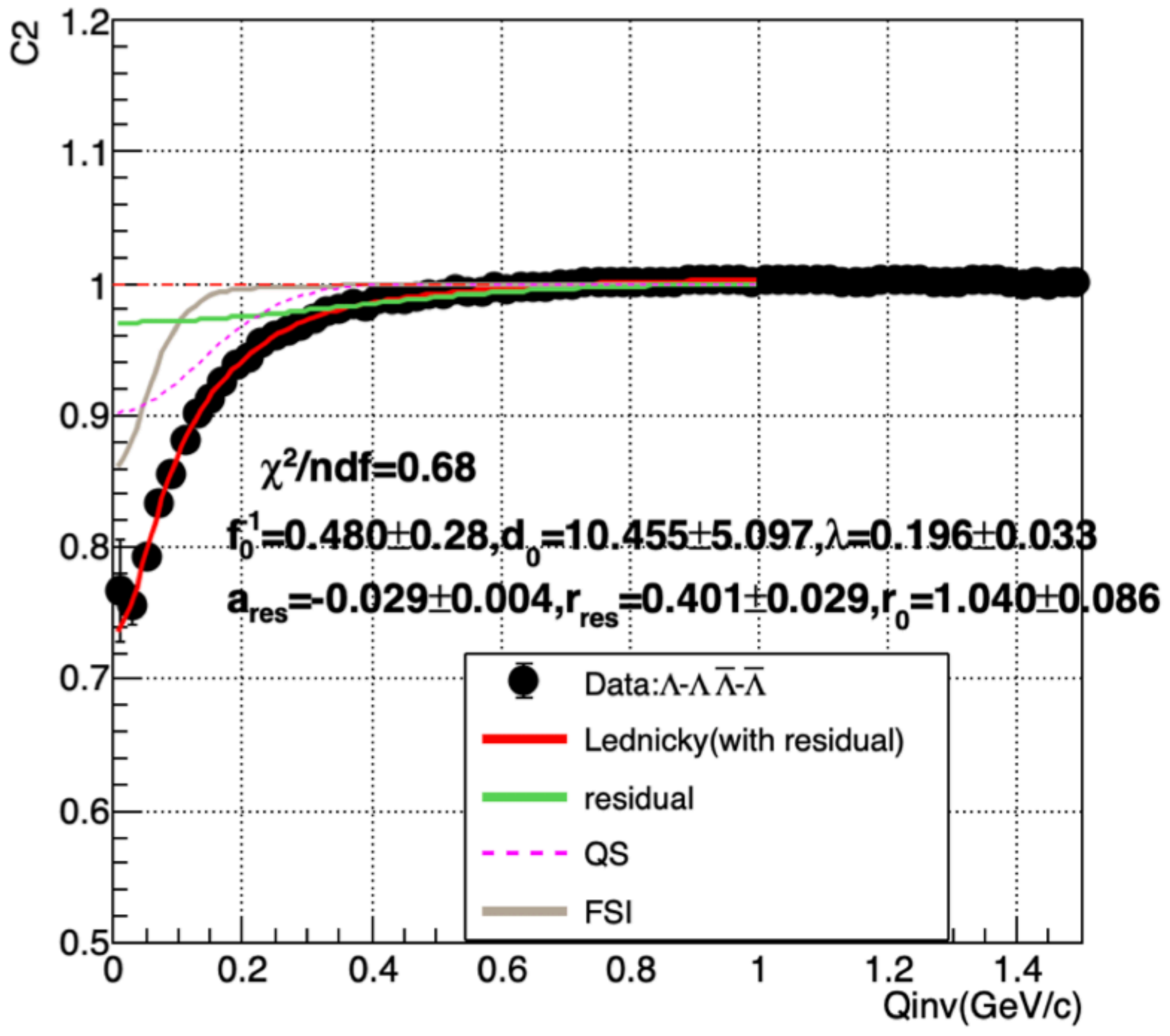
Y-Y (Λ-Λ) interactions



- The binding energy of $\Lambda-\Lambda$ **bound state** estimated within an effective-range expansion approach.
- Search go **H-dibaryon** not completed.



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

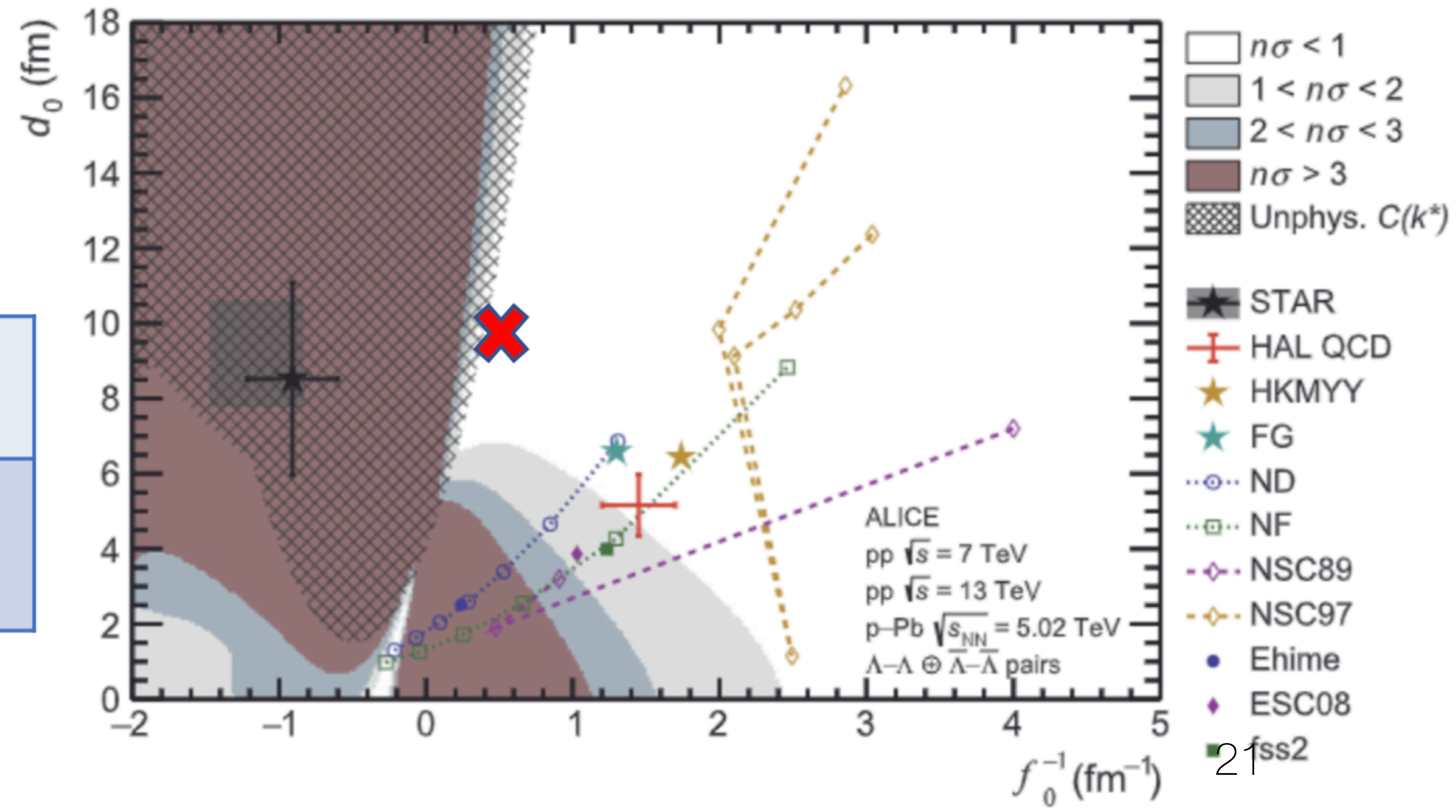


F0 became positive!!

1/f0	0.480fm
d0	10.455fm

ALICE's study

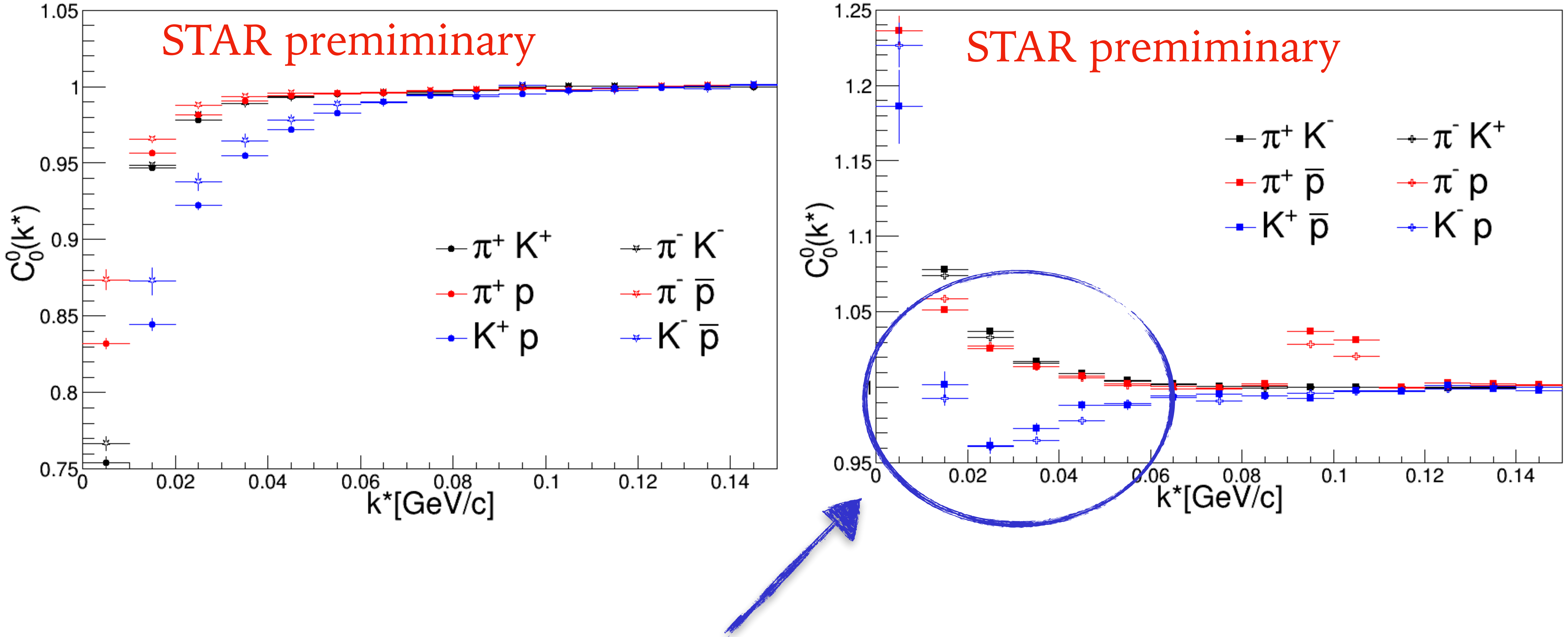
ALICE Collaboration Phys. Lett. B 797 (2019) 134822

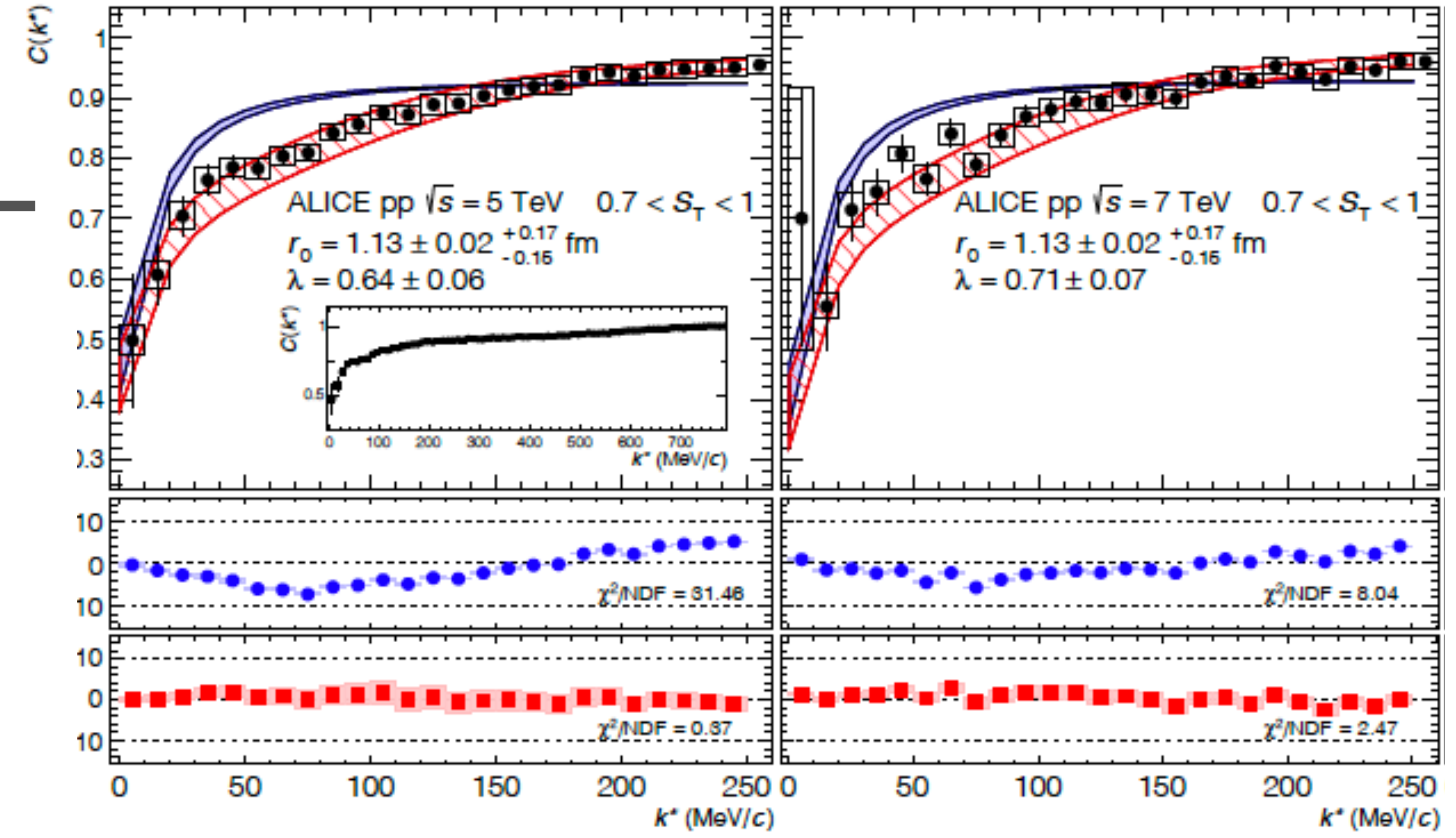


N-K (p-K) interactions (bound state?)

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

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

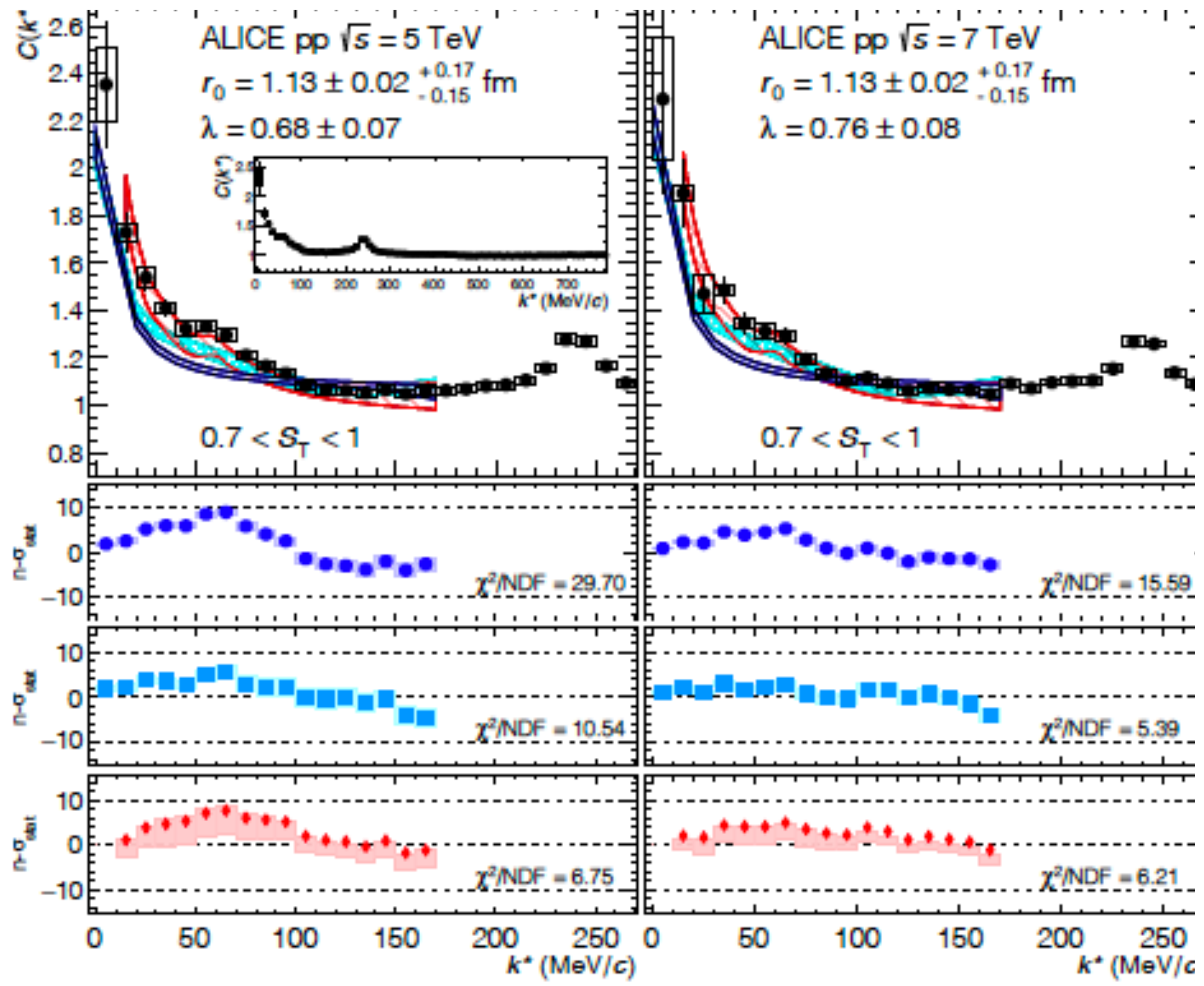




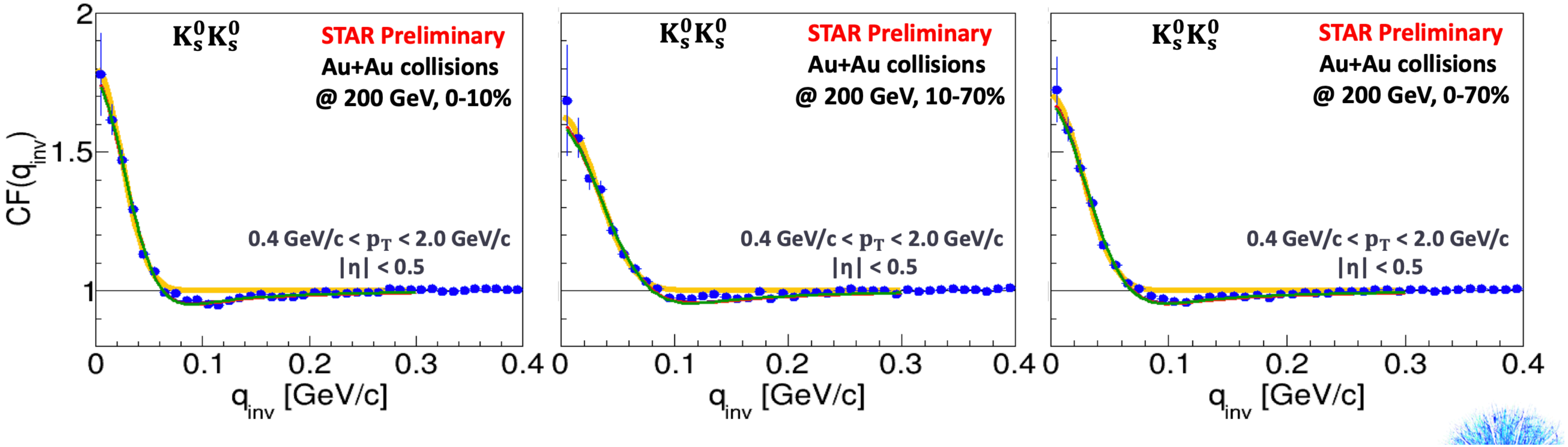
Phys.Lett.B 813 (2021) 136030

- High-precision measurement of the **strong interaction (anti-correlation)** between kaons and protons.

- A structure (ALICE in p+p collisions) observed around a relative momentum of 58 MeV/c in the measured correlation function of opposite charges in p+p collisions.



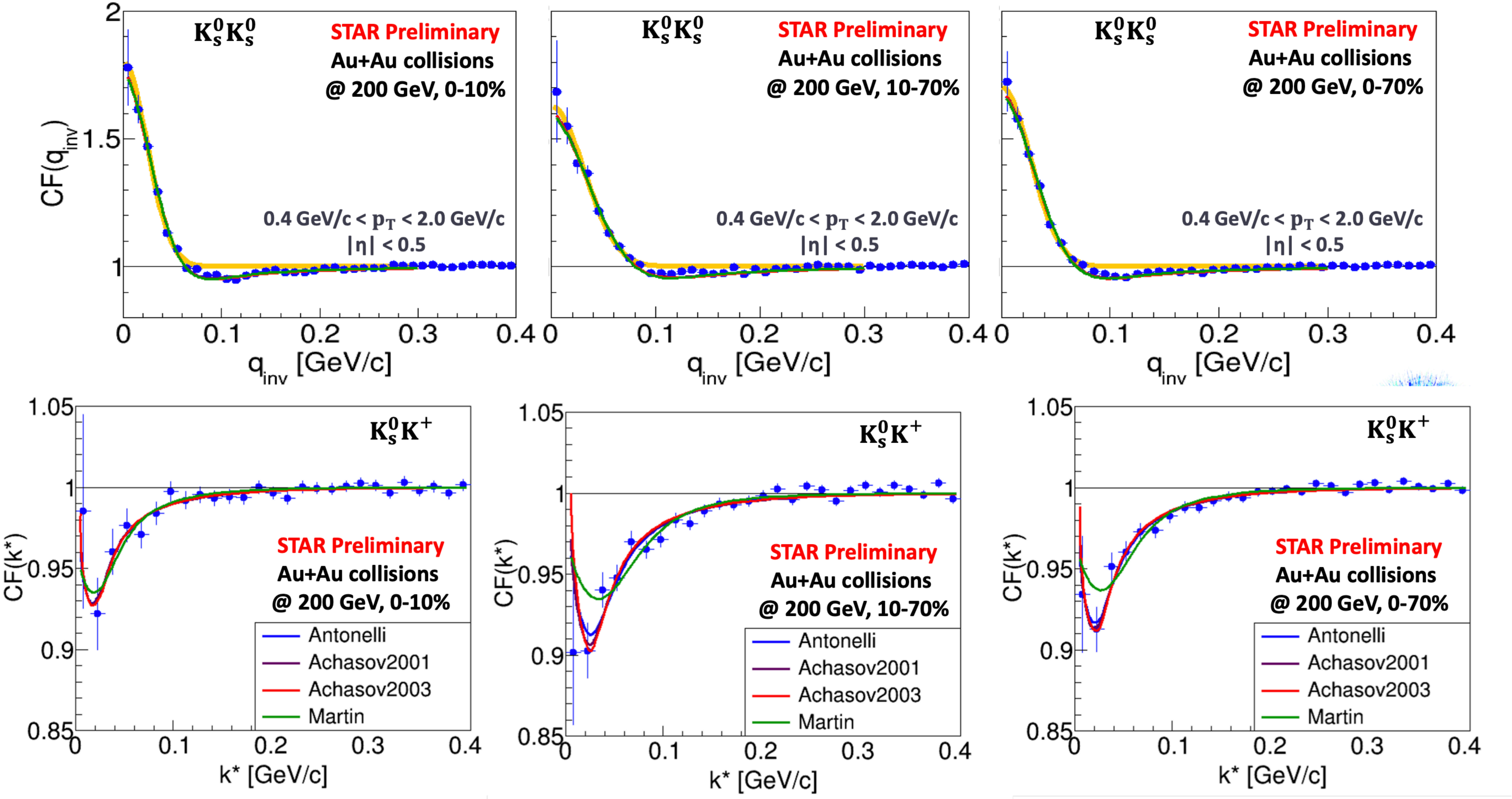
K-K (including K^0_{ch}) interactions



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

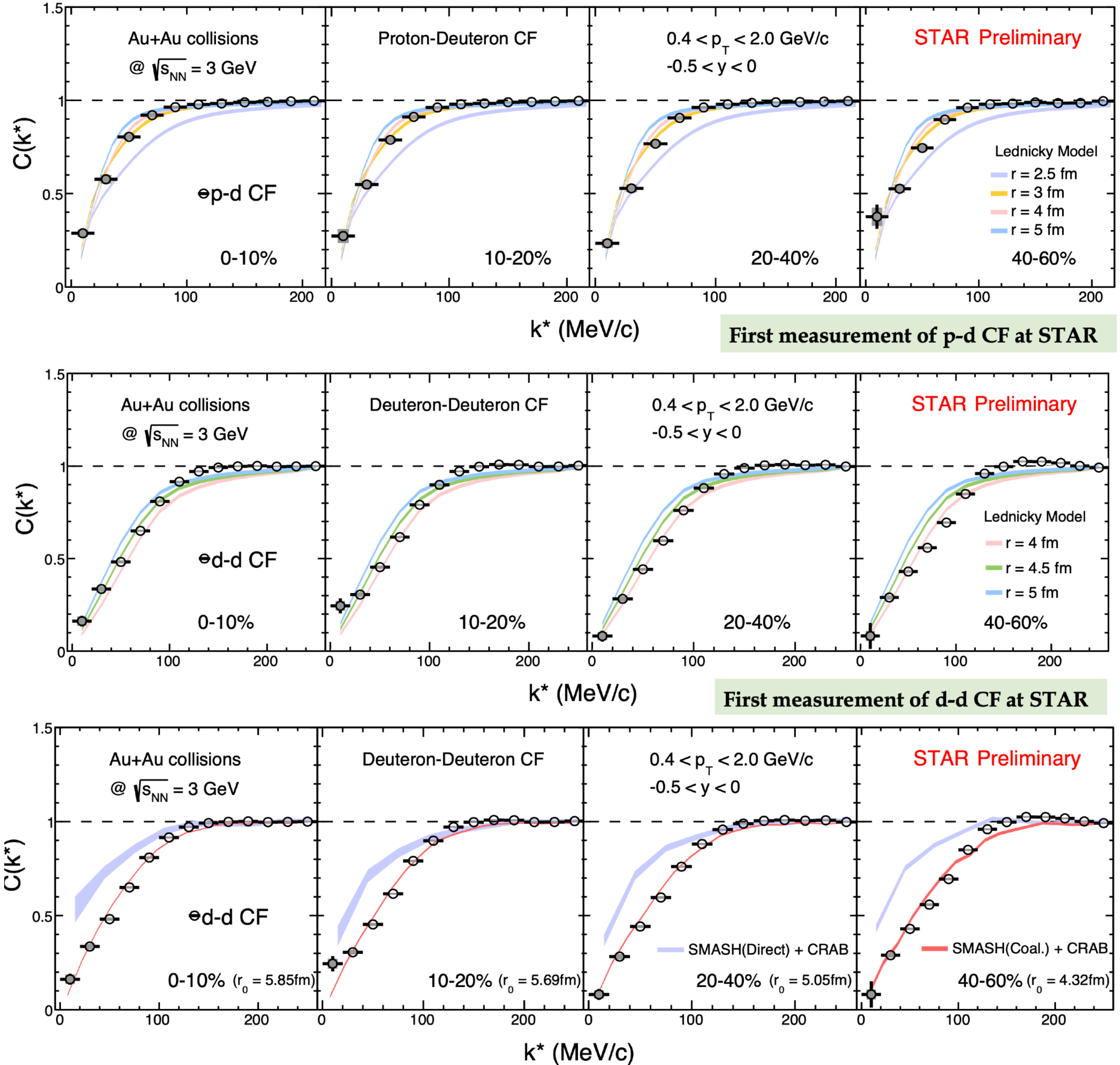
Dodaj wzór od Diany

K-K (including K^0_{ch}) interactions



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**

p-d, d-d interactions at STAR (also measured at HADES)



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

- **Proton-deuteron** and **deuteron-deuteron** correlations qualitatively described by the Lednicky-Lyuboshits model; deuteron-deuteron has larger emission source size than proton-deuteron

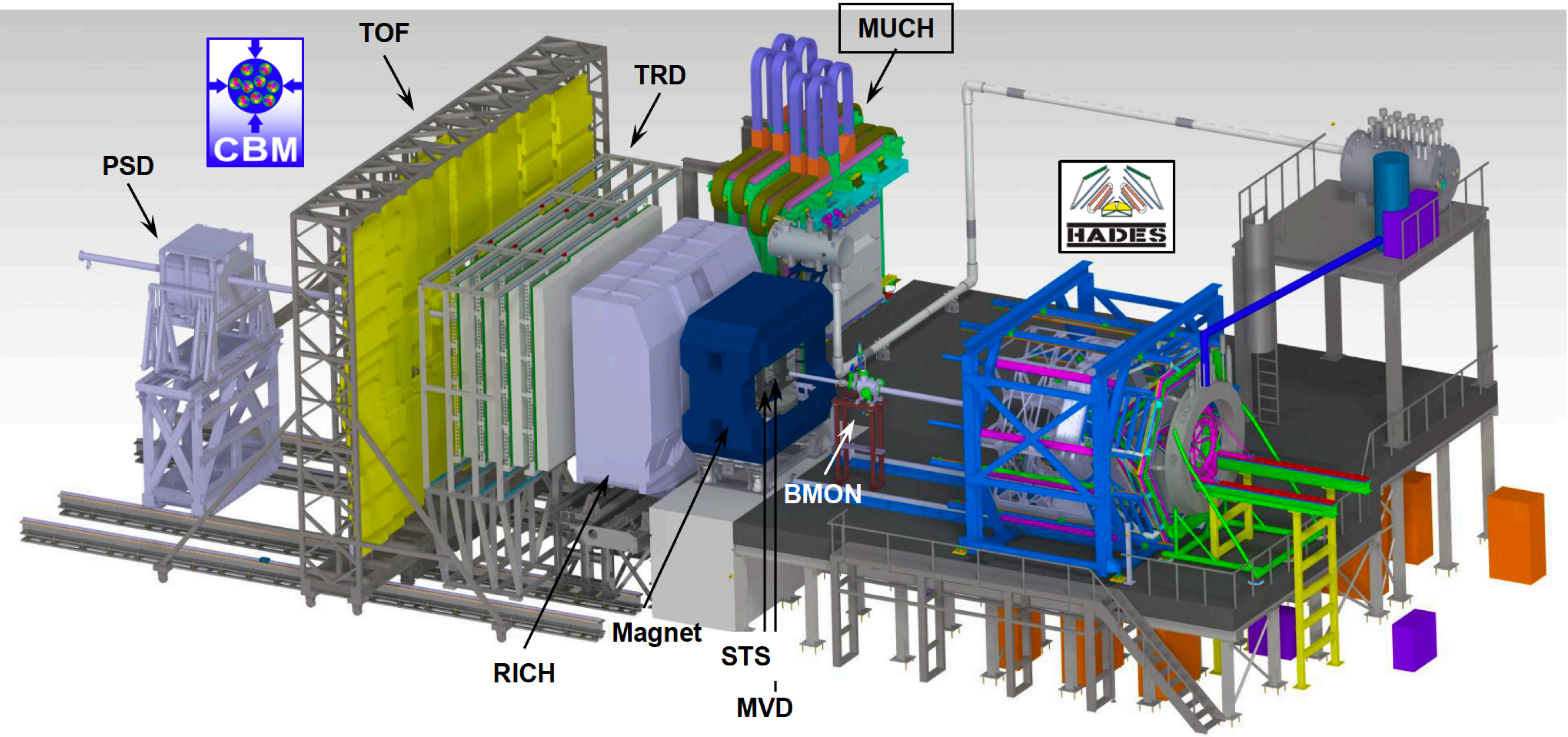
- Deuteron-deuteron correlations described better by the model including **coalescence**. Light nuclei are likely to be formed via coalescence.

(Instead of) Summary
Future

CBM and **HADES** challenges for extraction of the **EoS**

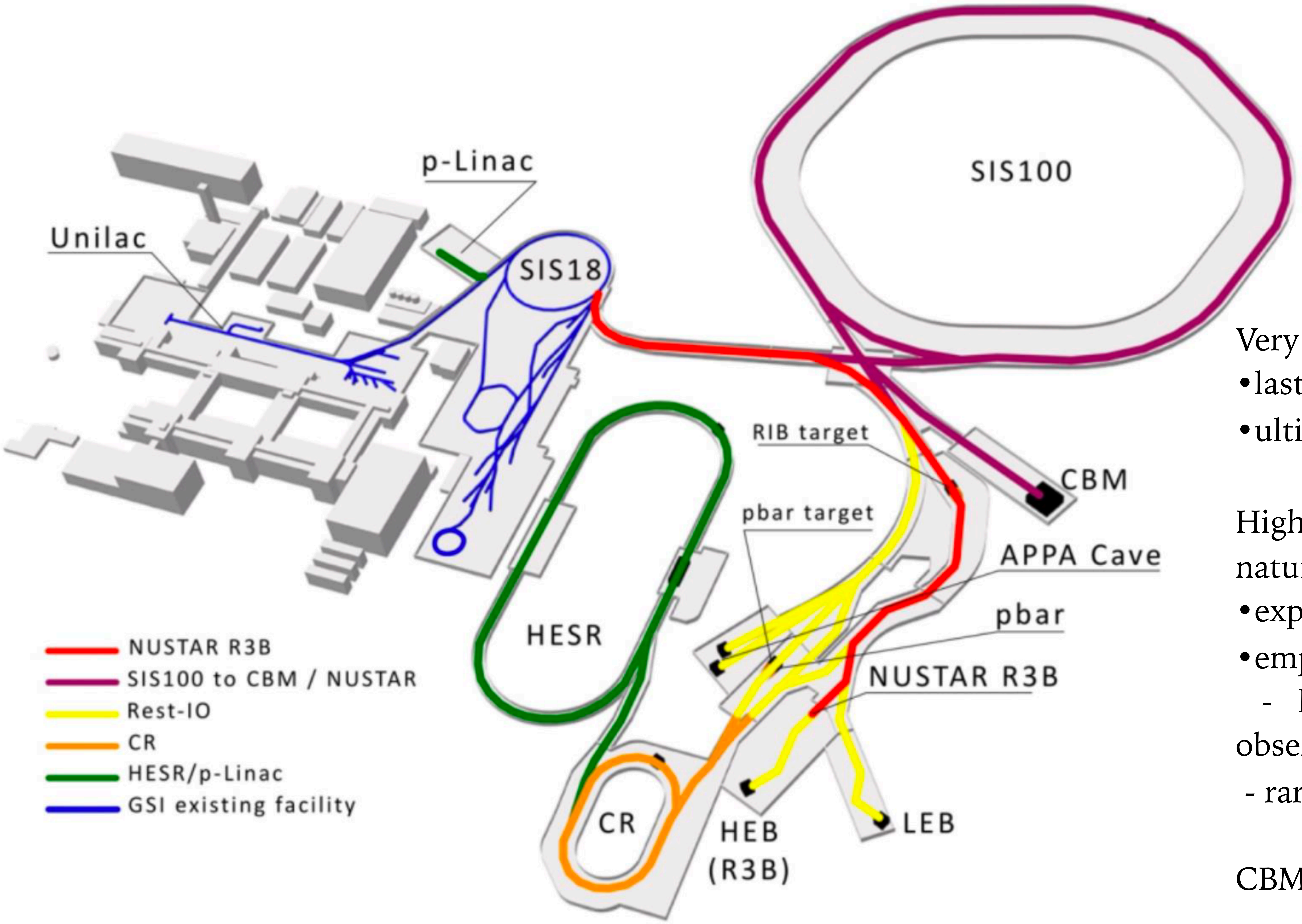
diagnostic probes which are sensitive to the dense phase of the nuclear fireball. The goal of the CBM experiment at SIS100 ($\sqrt{s_{NN}} = 2.7 - 4.9$ GeV) is to discover fundamental properties of QCD matter: the phase structure at large baryon-chemical potentials ($\mu_B > 500$ MeV), effects of chiral symmetry, and the equation-of-state at high density as it is expected to occur in the core of neutron stars. In this article, we review the motivation for and the physics programme of CBM, including activities before the start of data taking in 2024, in the context of the worldwide efforts to explore high-density QCD matter.

arXiv:1607.01487v3 [nucl-ex] 29 Mar 2017



The CBM experimental setup together with the HADES detector

CBM and **HADES** challenges for extraction of the **EoS**



Very successful STAR program is ending

- last run in 2025 (BES data all collected)
- ultimate physics goal of BES not reached yet

High μ_B program with CBM@SIS100 is natural continuation

- explore QCD matter at NS densities
- employ high statistics capability
  - high-precision of multi-differential observables
  - rare processes as sensitive probes

CBM Phase-0: HADES, mCBM

https://www.gsi.de/fileadmin/oeffentlichkeitsarbeit/fair/FAIR-report_221025.pdf

Back-up slides

CBM and **HADES** challenges for extraction of the **EoS**