Two-particle correlations at the Beam Energy Scan program

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Outline

Introduction

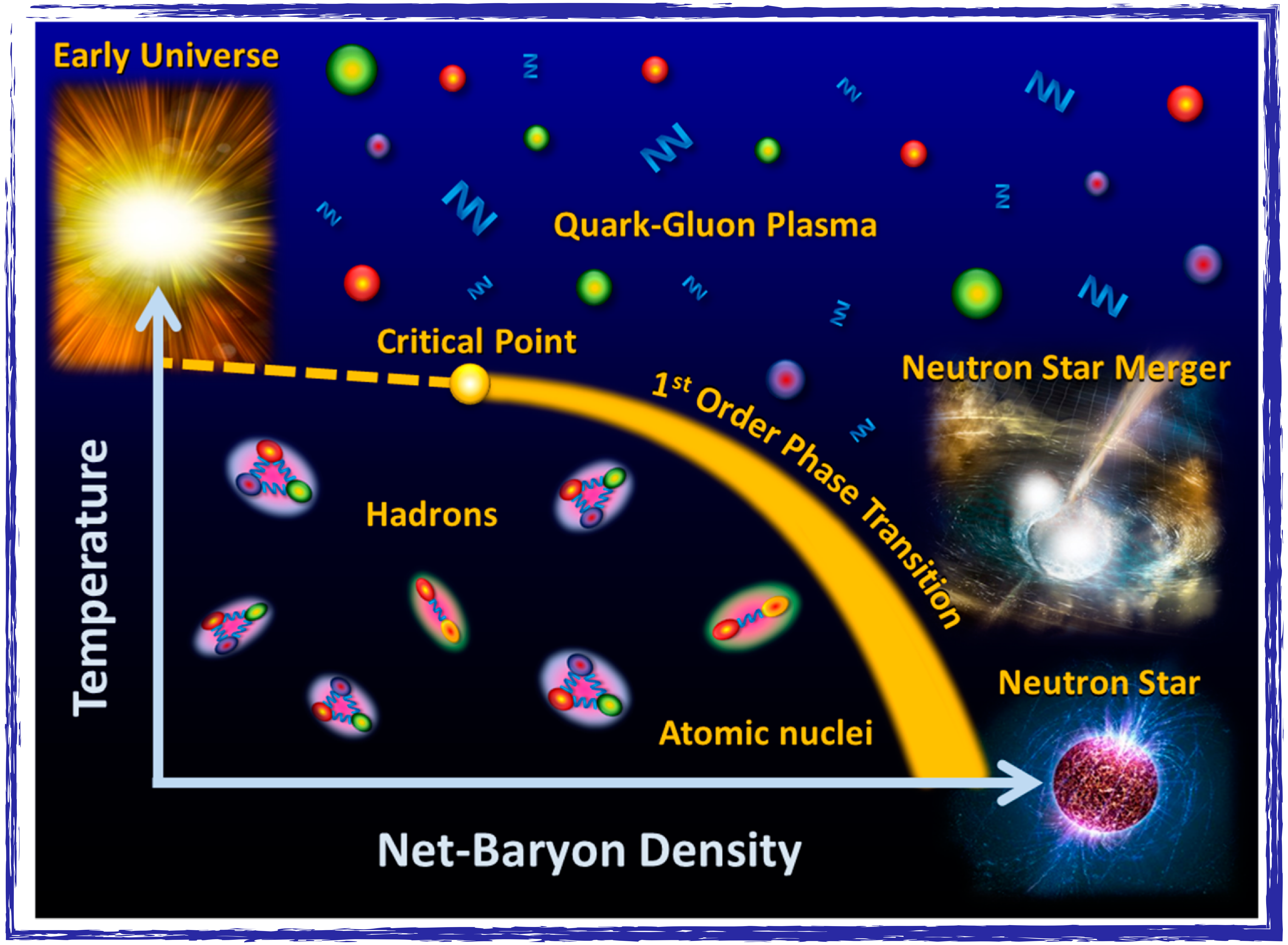
- QCD phase diagram
- Correlation femtoscopy

Results

- Final State Interactions
- Phase transition

Future

Conclusions



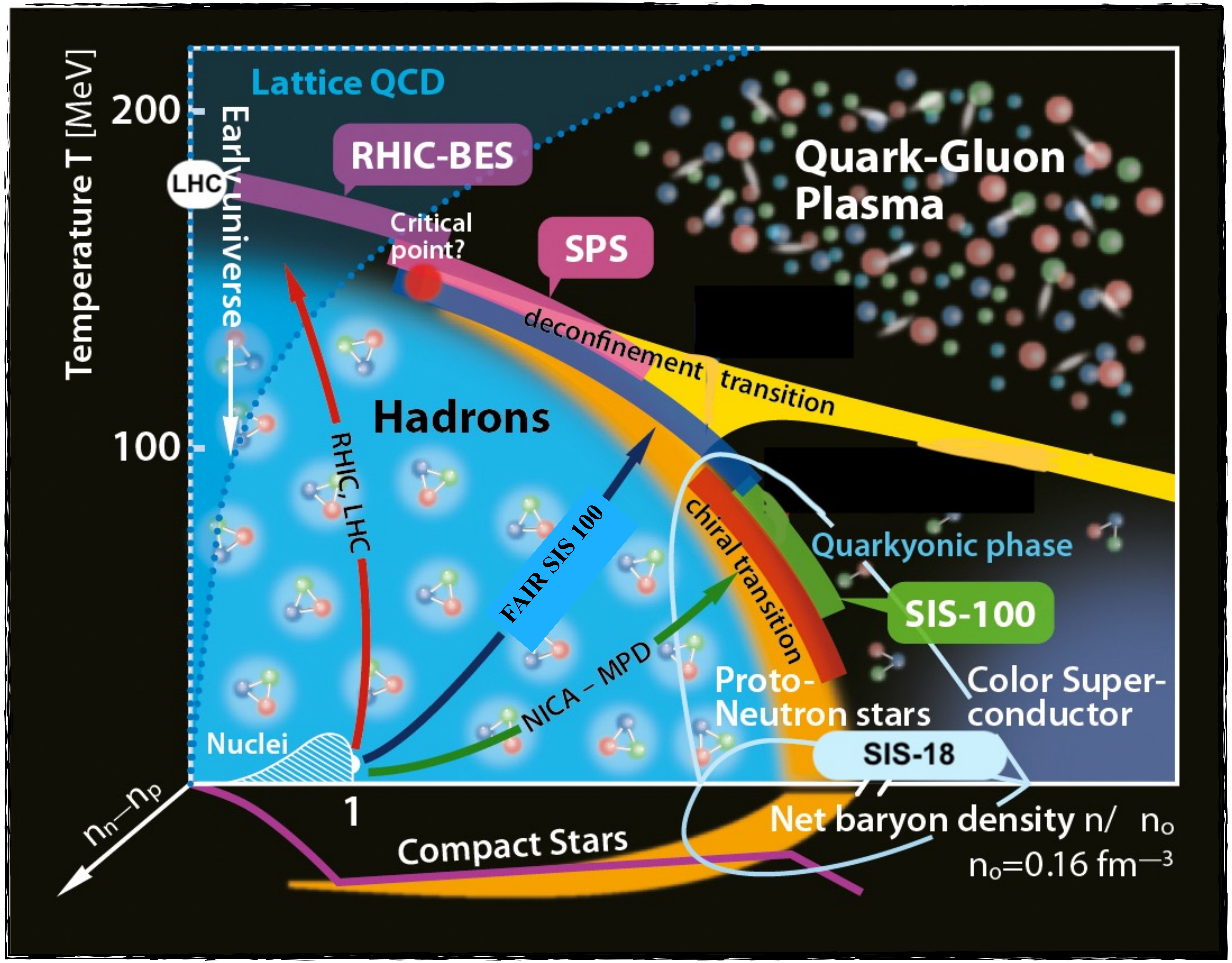
https://www.researchgate.net/figure/Color-Online-A-schematic-of-QCD-phase-diagram_fig2_357552969

Introduction

QCD phase diagram

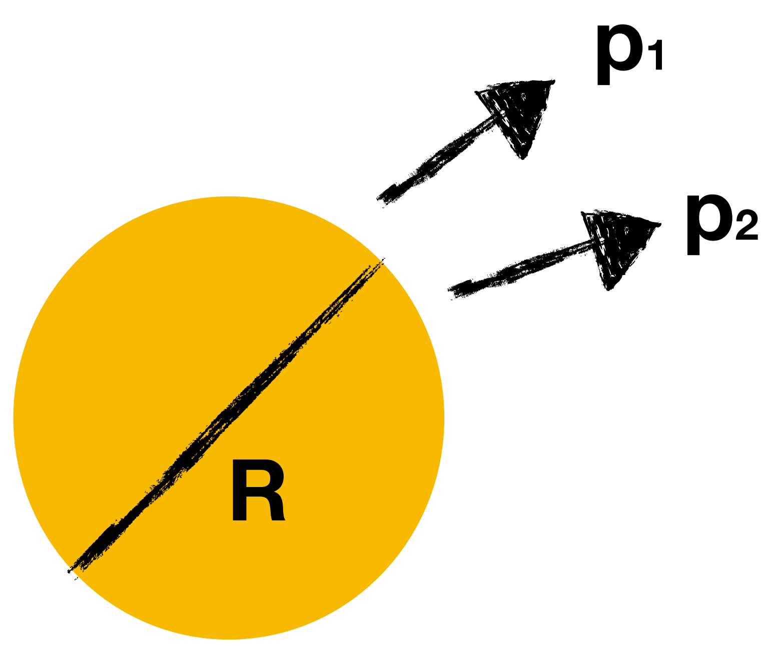
Correlation femtoscopy

QCD Phase diagram of strongly interacting matter



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

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

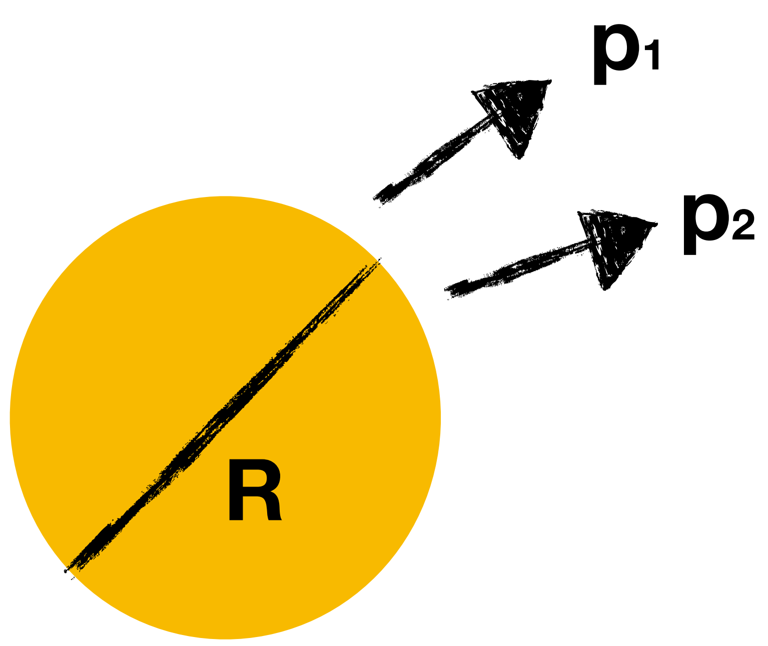
$S(r^*)$ - emission function

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

Results

Final State Interactions

Phase transition

Neutron star puzzle

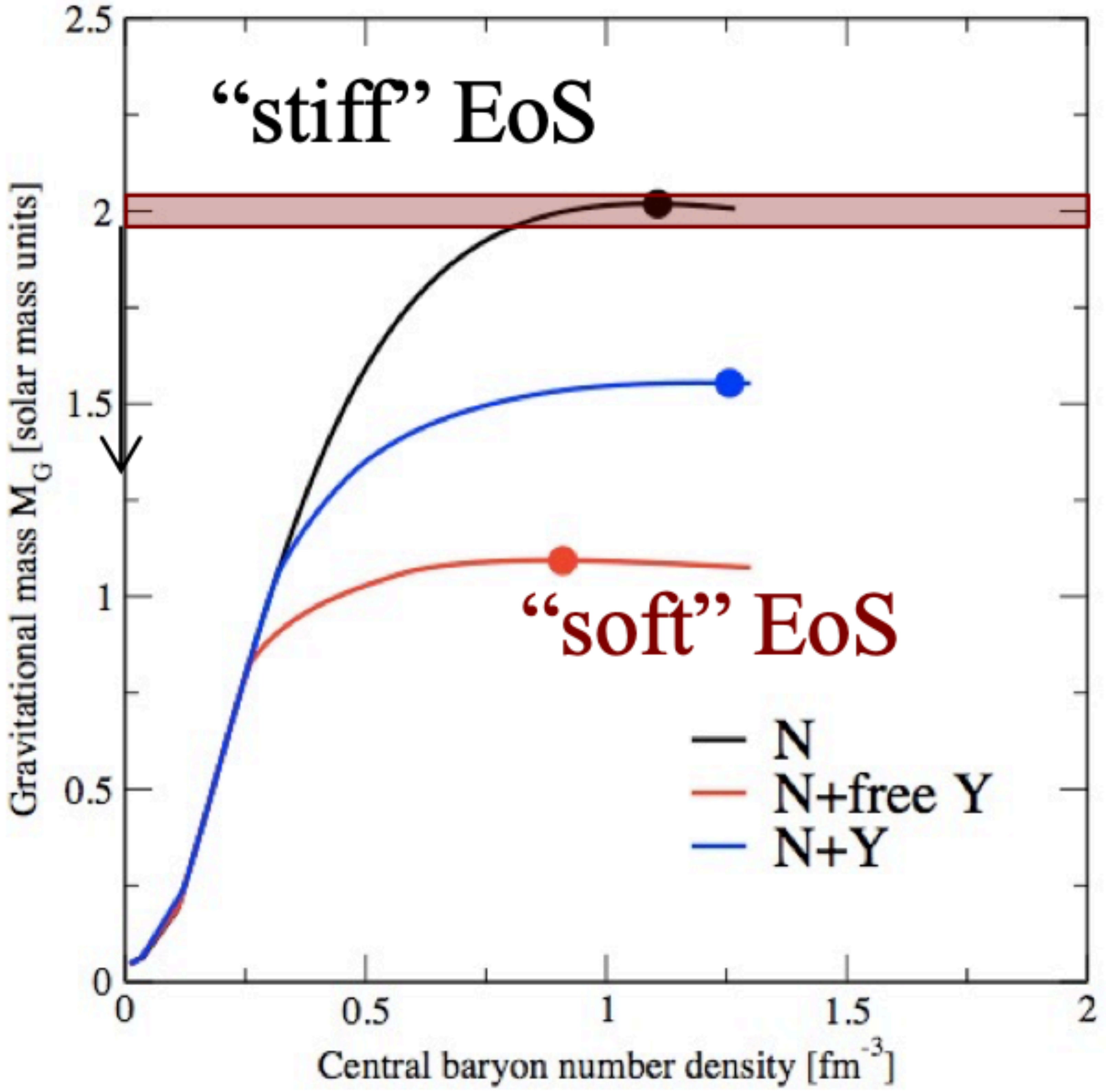
- **Hyperons**: expected in the core of neutron stars; **conversion of N into Y energetically favorable.**

- 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

$\rho \approx 3 \div 5\ \rho_0$



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

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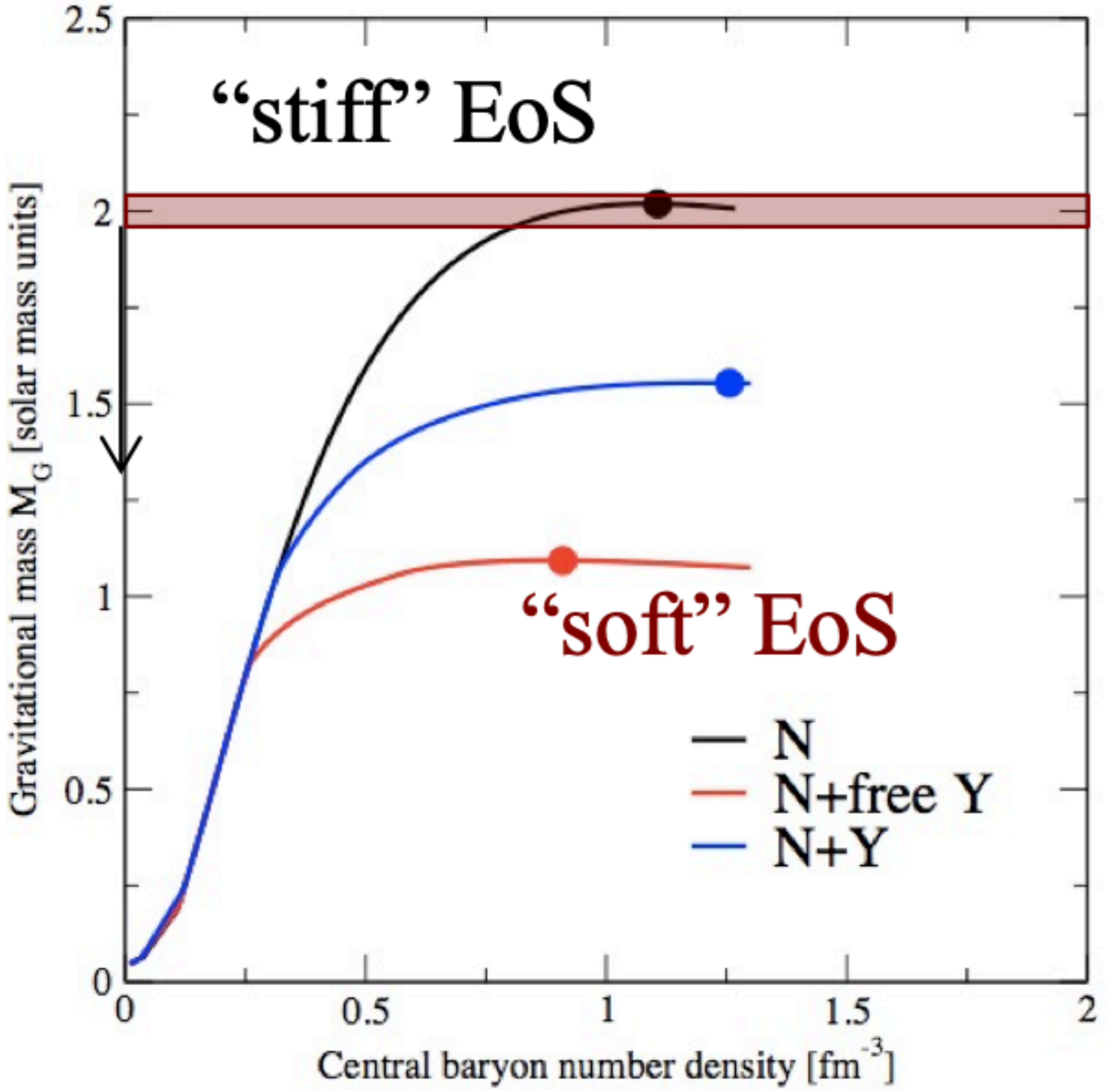
The solution: a mechanism providing the **additional pressure** to make the EoS stiffer.



Possible mechanisms:

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

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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).**

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

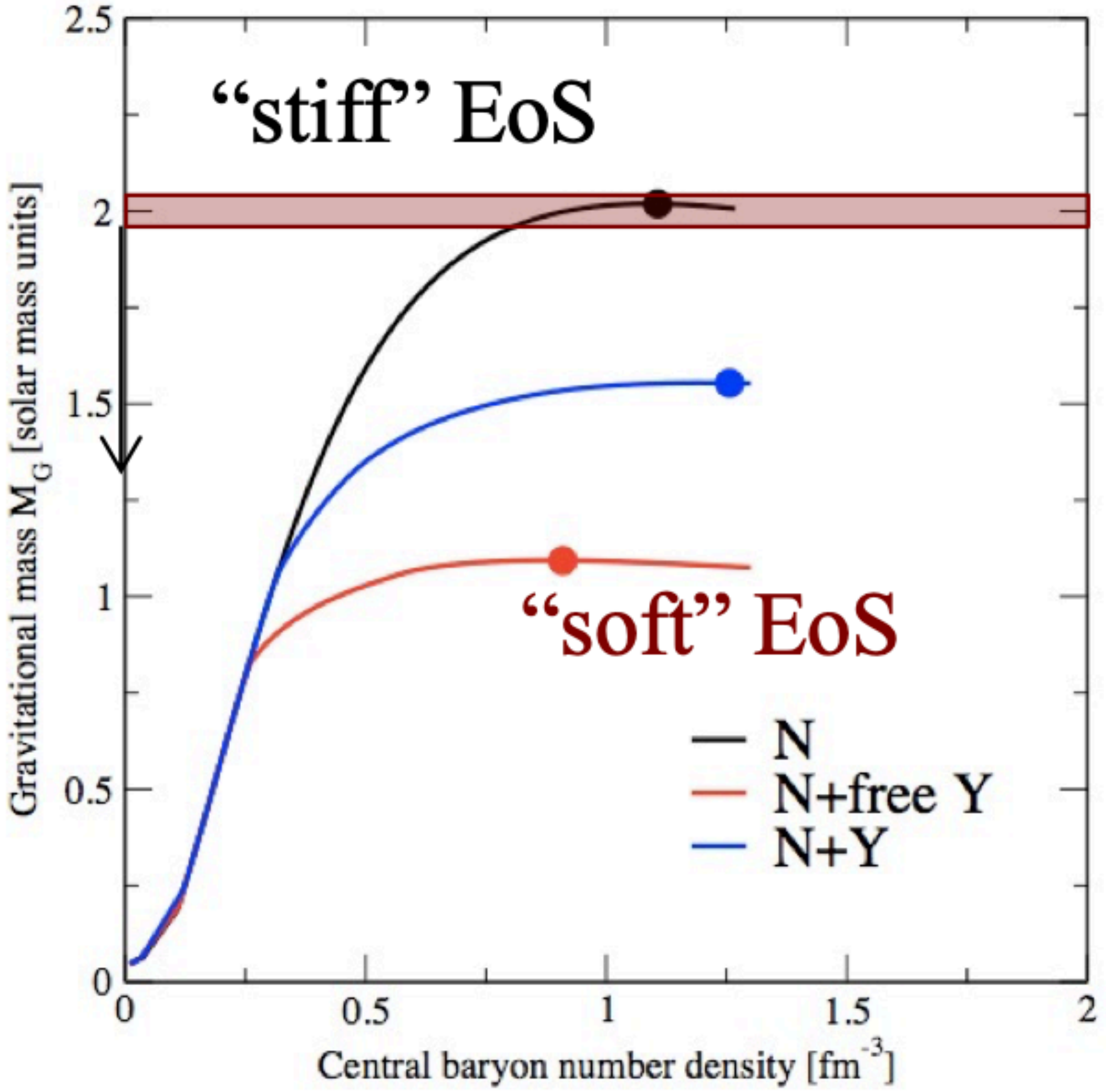
Possible mechanisms:

- **Two-body Y-N & Y-Y 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 **K-N** 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

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



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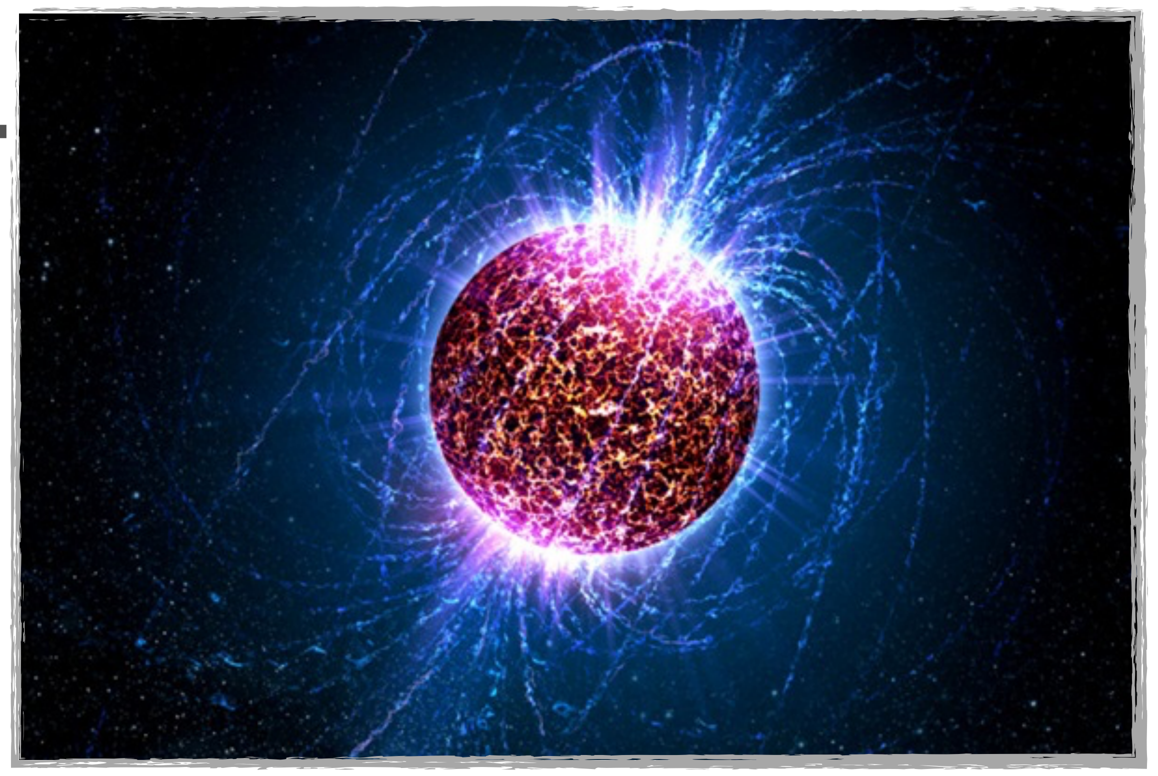
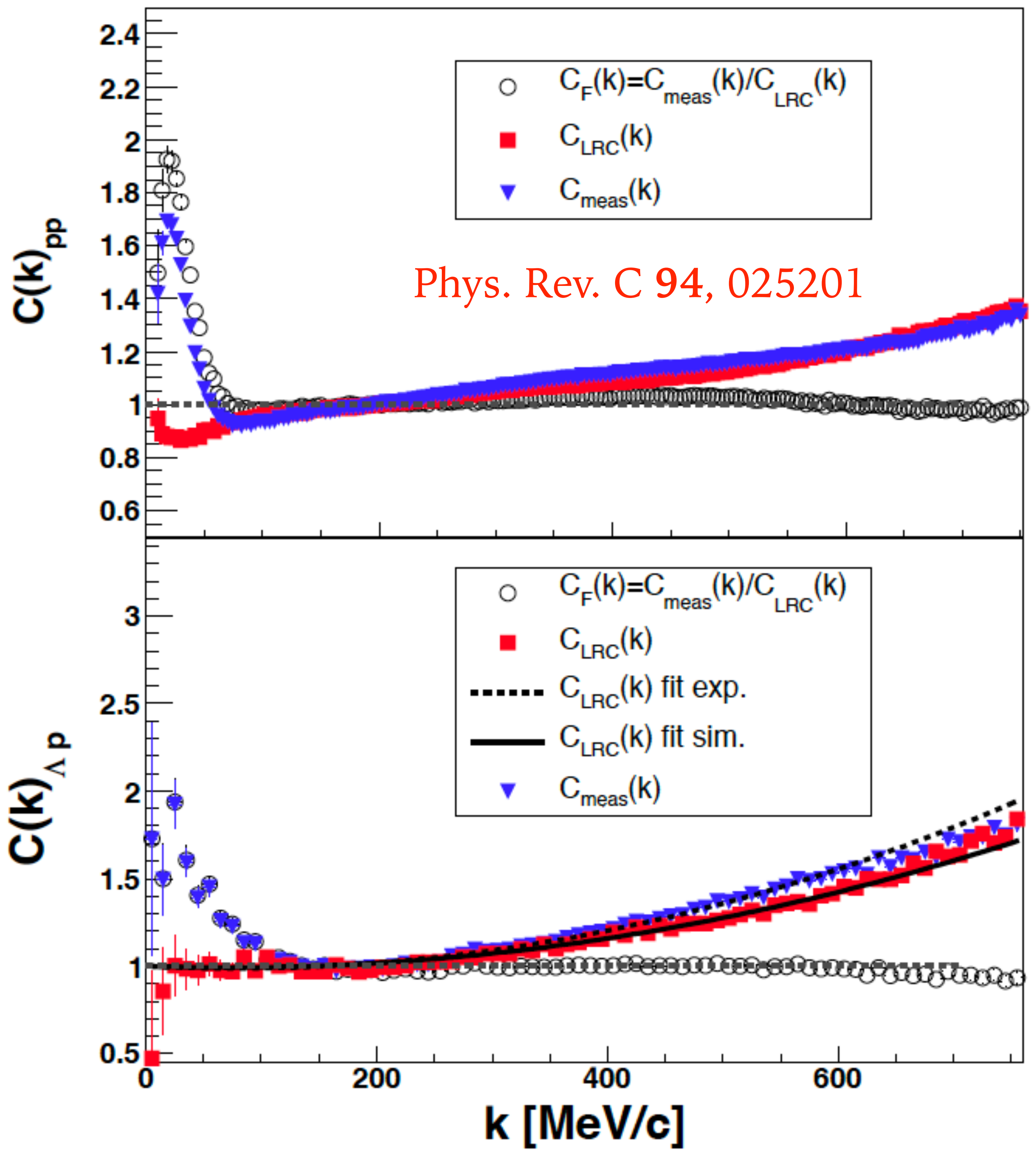
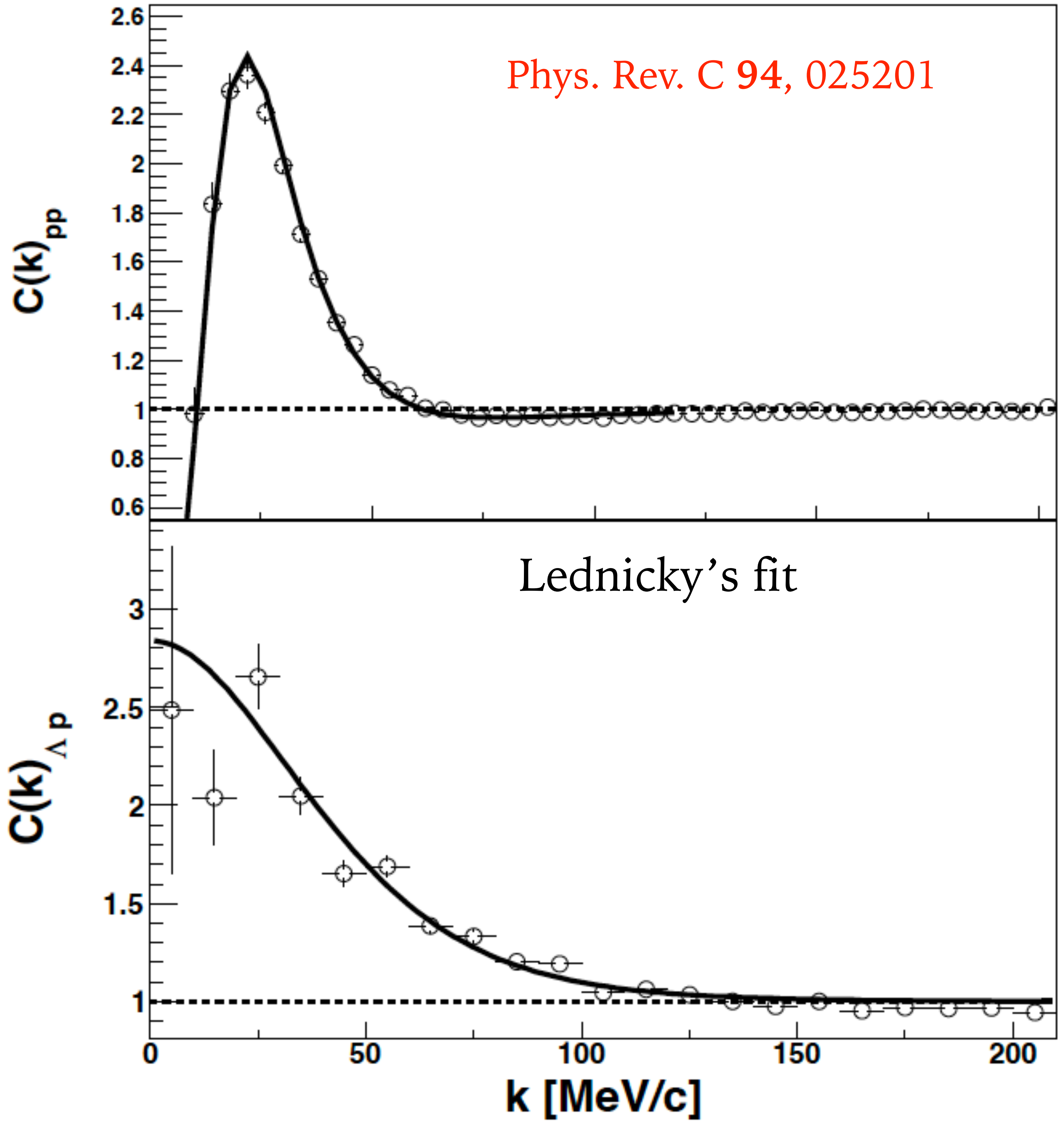
Y-N and Y-Y interactions

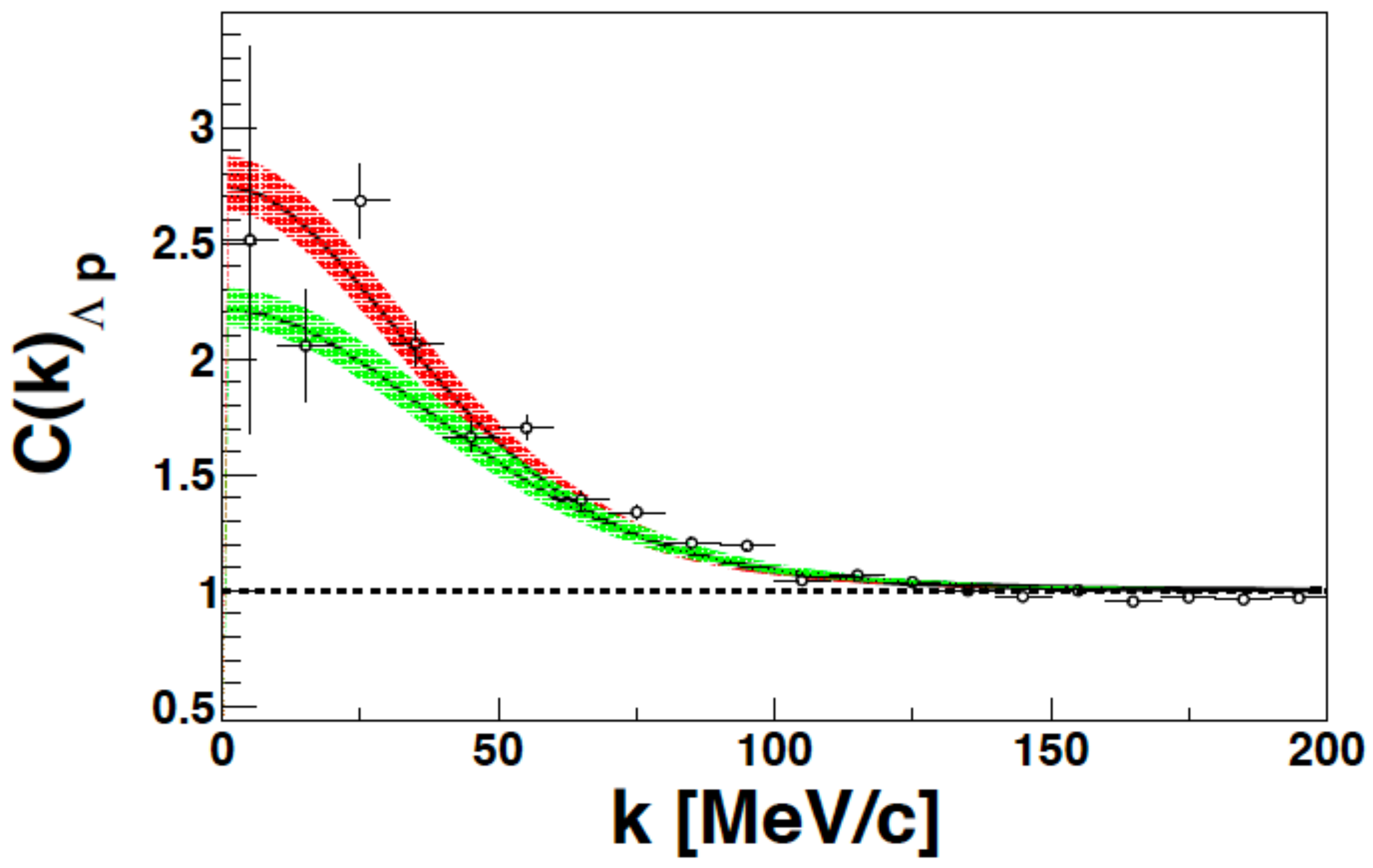


- **Experiment**: More interest about Y–N and Y–Y interactions.
- **Theory**: Major steps forward have been made (Lattice QCD).
- **Numerous theoretical predictions** exist, but no clear evidence for any such **bound states**, despite **many experimental searches**.
- The existence of **hypernuclei** (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.

Y-N interactions at HADES







NLO scattering paremeters

$$f_{0,NLO}^{S=0} = 2.91fm$$
$$d_{0,NLO}^{S=0} = 2.78fm$$
$$f_{0,NLO}^{S=1} = 1.54fm$$
$$d_{0,NLO}^{S=1} = 2.72fm$$

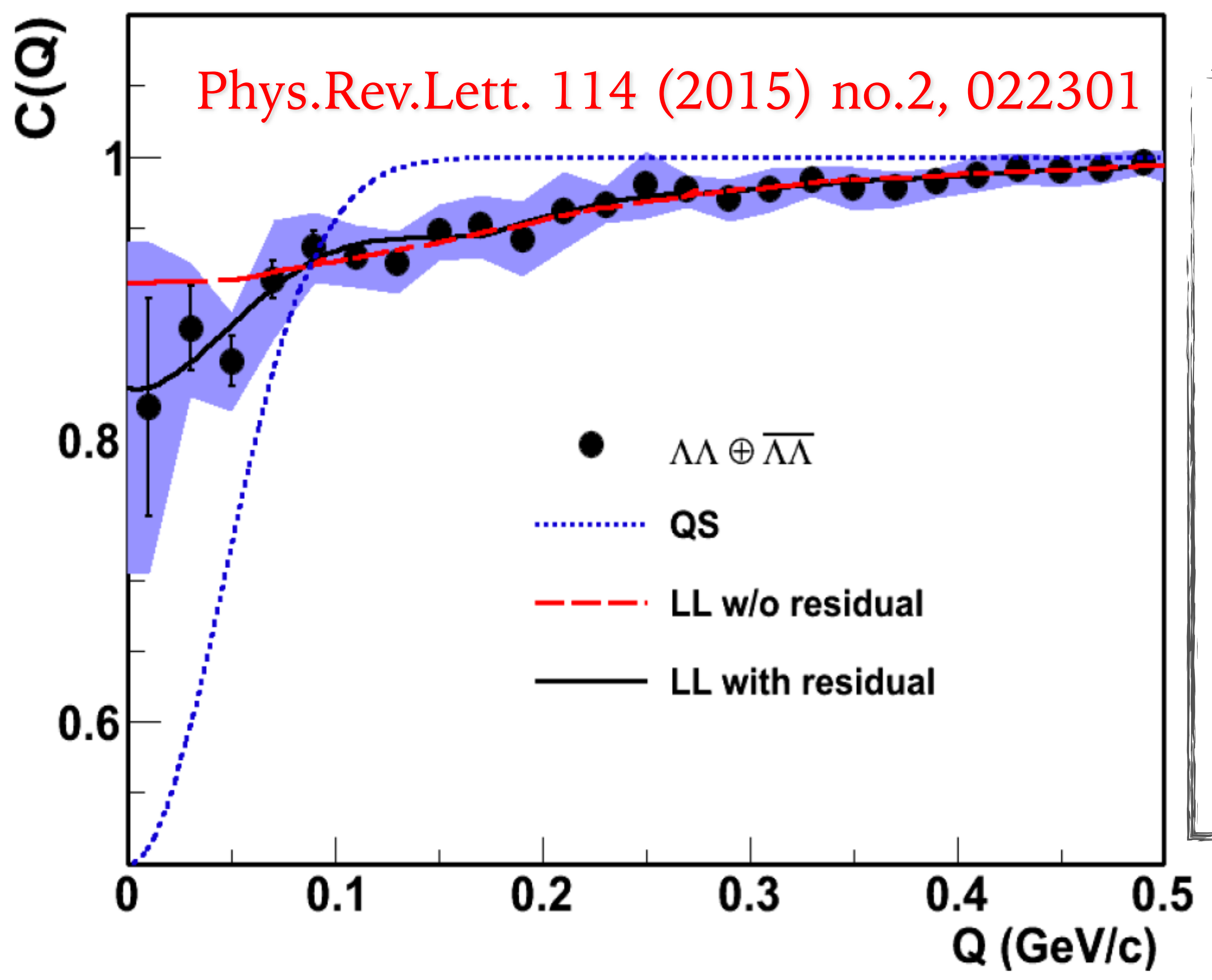
LO scattering parameters

$$f_{0,LO}^{S=0} = 1.91fm$$
$$d_{0,LO}^{S=0} = 1.40fm$$
$$f_{0,LO}^{S=1} = 1.23fm$$
$$d_{0,LO}^{S=1} = 2.13fm$$

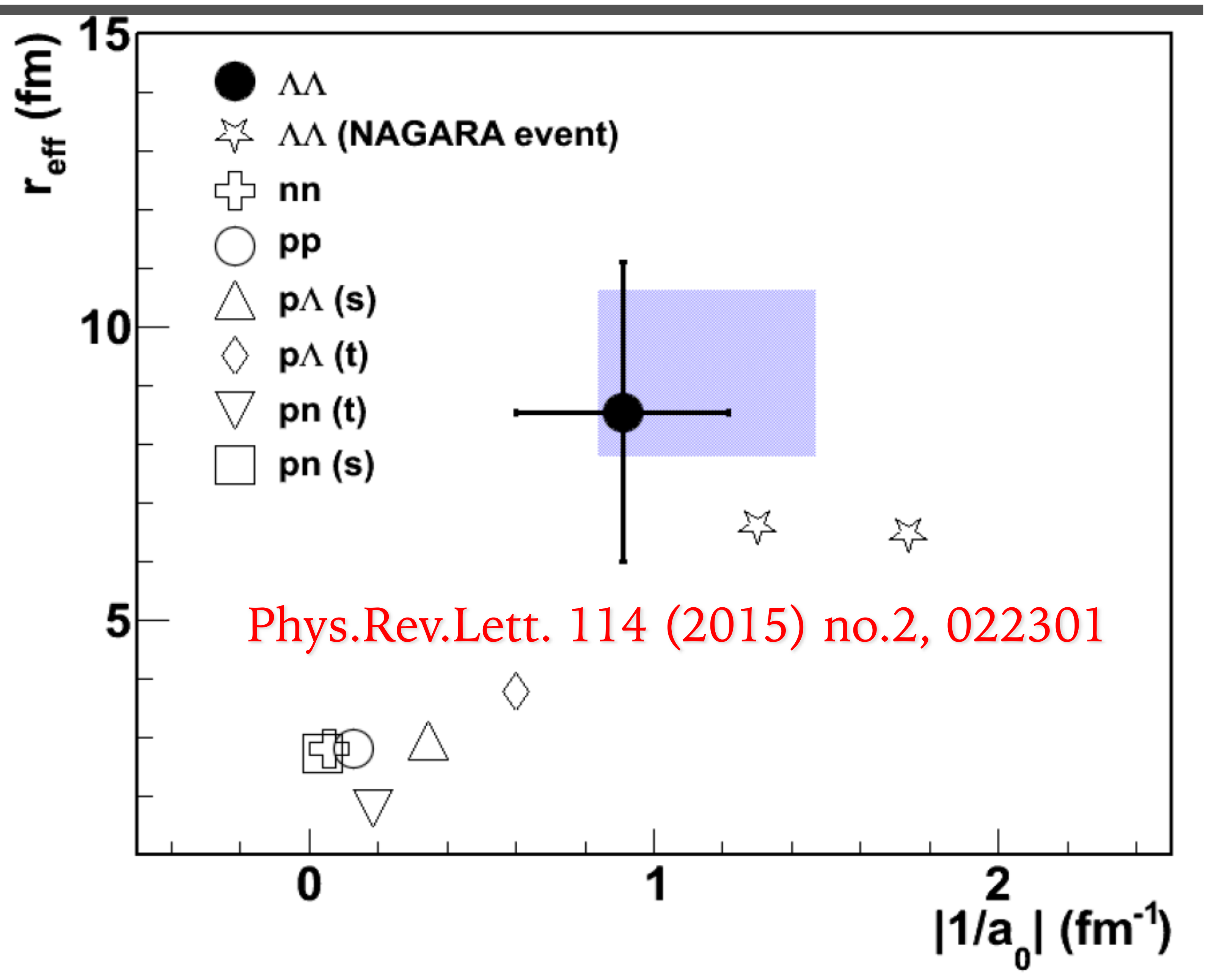
$$C_F(k) = \frac{C_{meas}(k)}{C_{LRC}(k)}$$
$$C_{LRC}(k^*) = 1 + ak + bk^2$$

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 N-Y interactions.

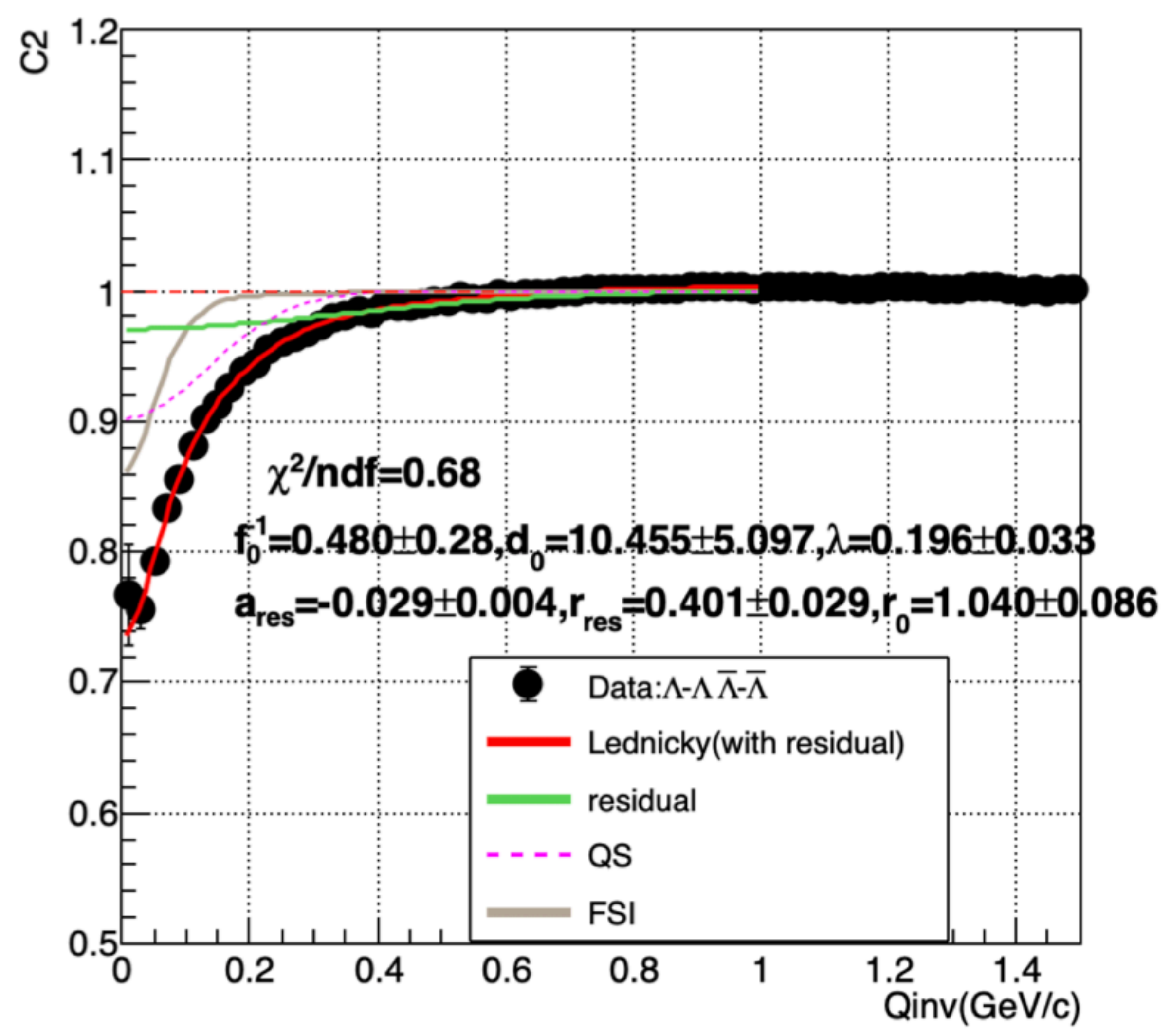
Strange Baryon Correlations (Including Λ Hyperons)



- The binding energy of Λ − Λ **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

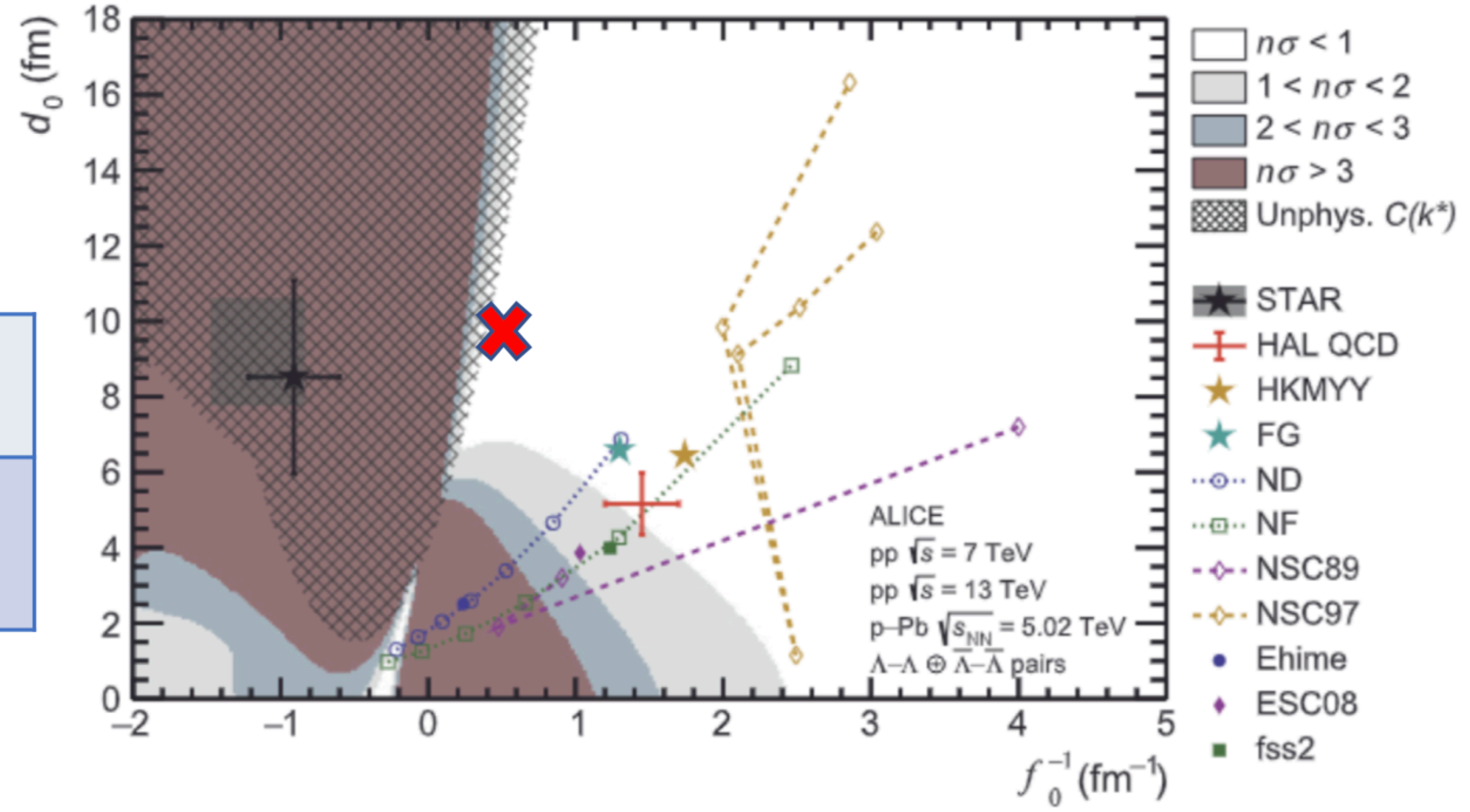


F0 became positive!!

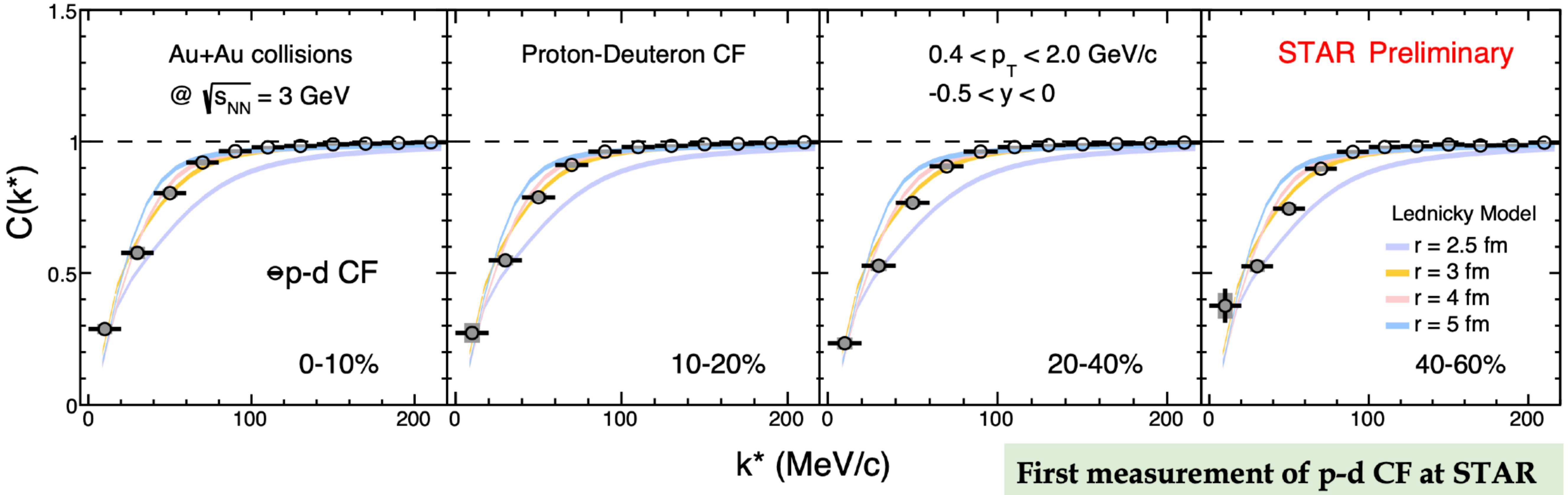
1/f0	0.480fm
d0	10.455fm

ALICE's study

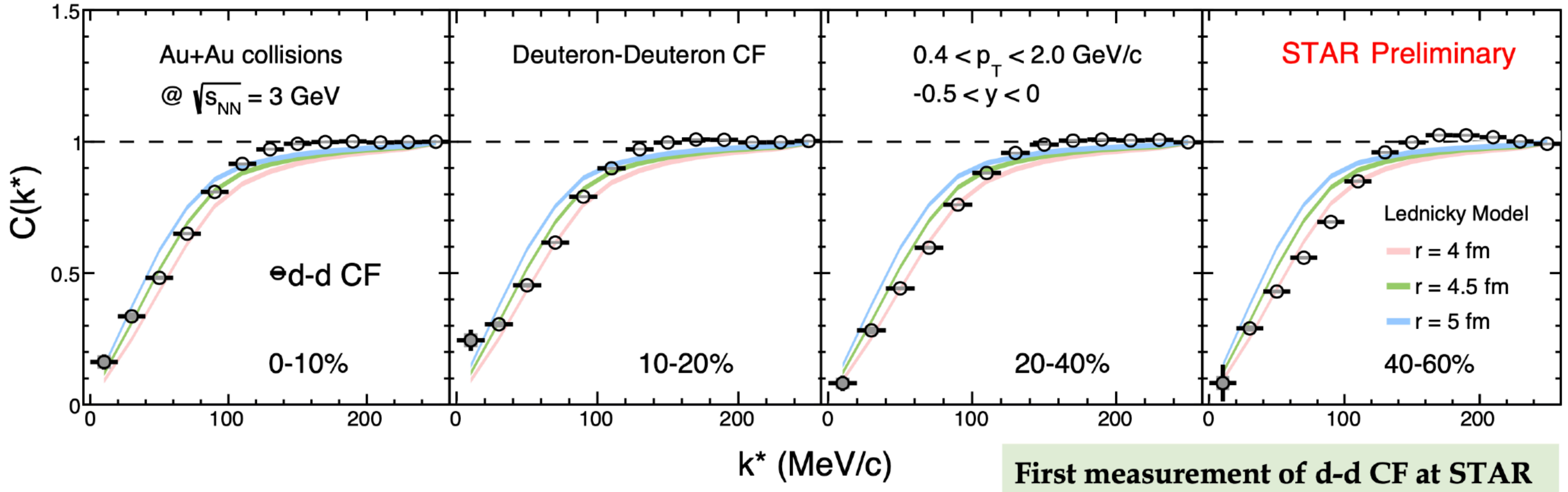
ALICE Collaboration Phys. Lett. B 797 (2019) 134822



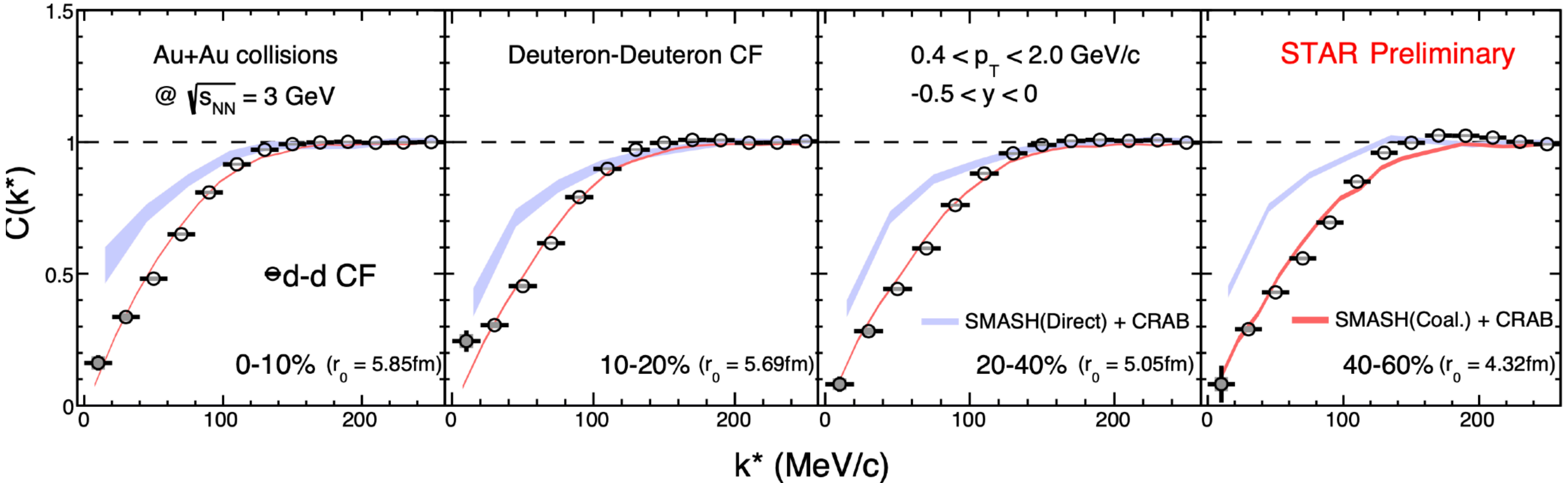
Light nuclei formation at STAR



First measurement of p-d CF at STAR



First measurement of d-d CF at STAR

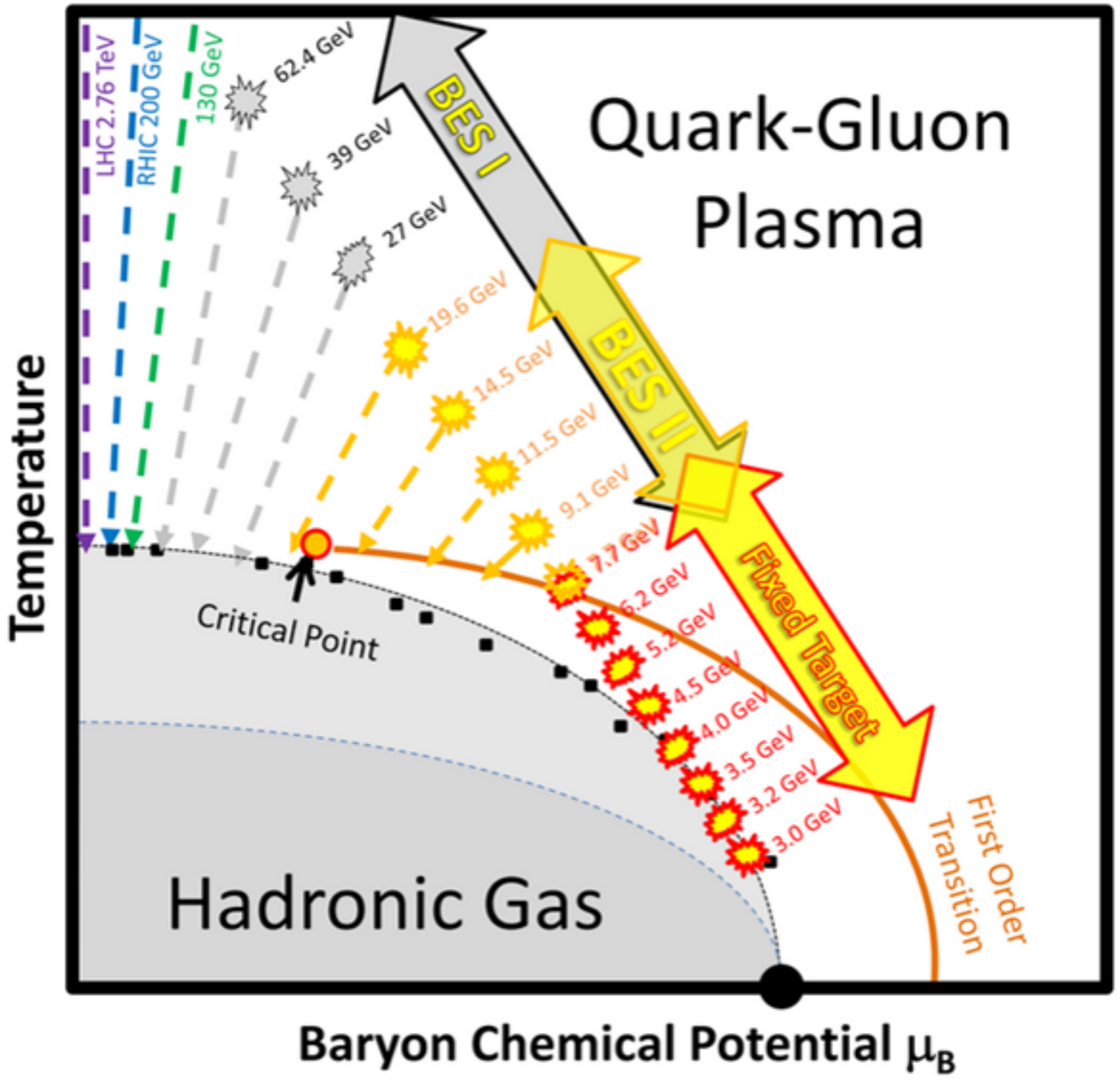


- First measurement of **proton-deuteron** and **deuteron-deuteron** correlation functions from STAR

- **Proton-deuteron** and **deuteron-deuteron** 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.

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

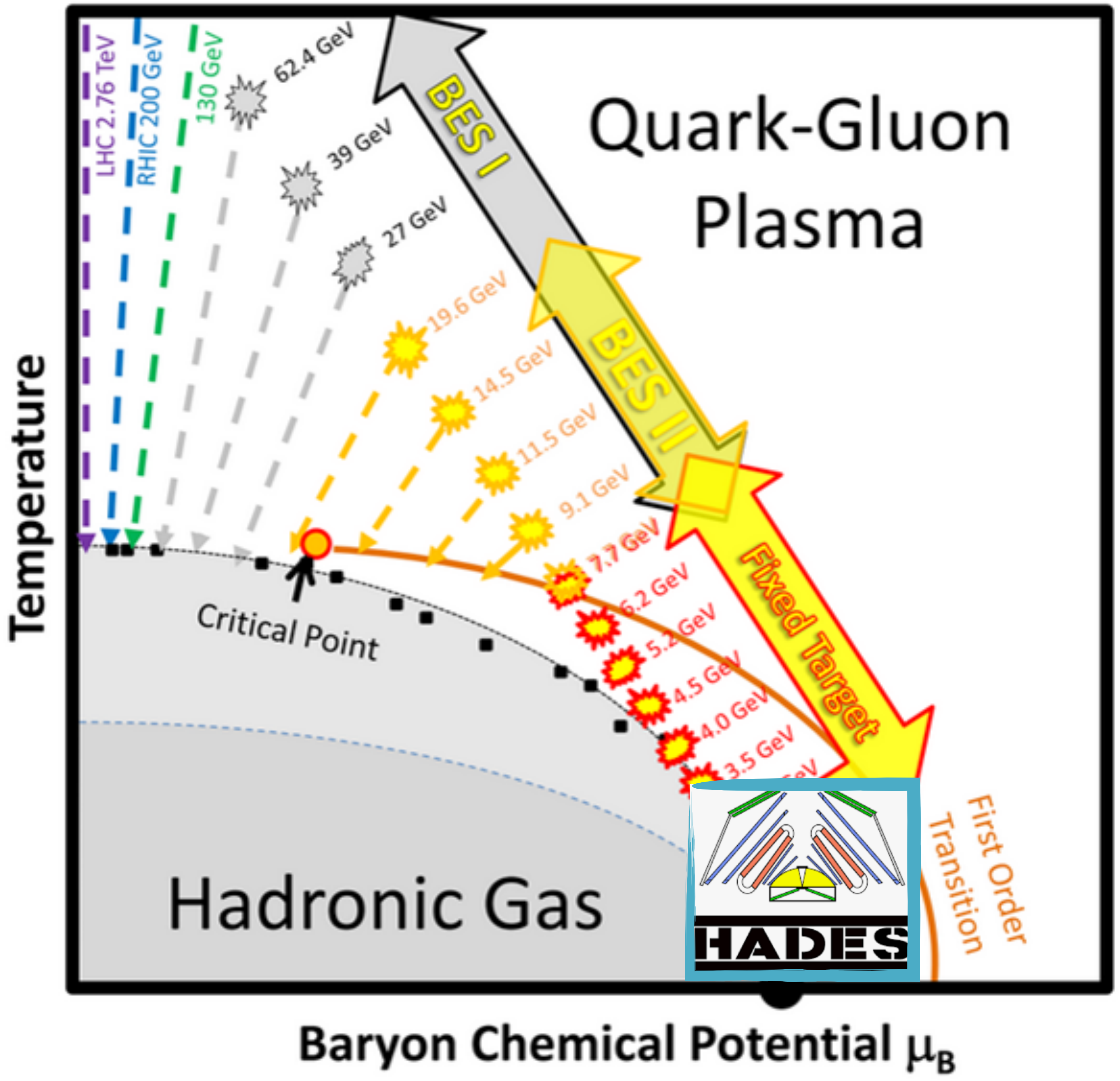
1. QCD at high energy density/temperature
2. Properties of QGP, EoS

Beam Energy Scan: Au+Au 3-62 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 =3-7.7 GeV
High baryon density regime with 420-720 MeV

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



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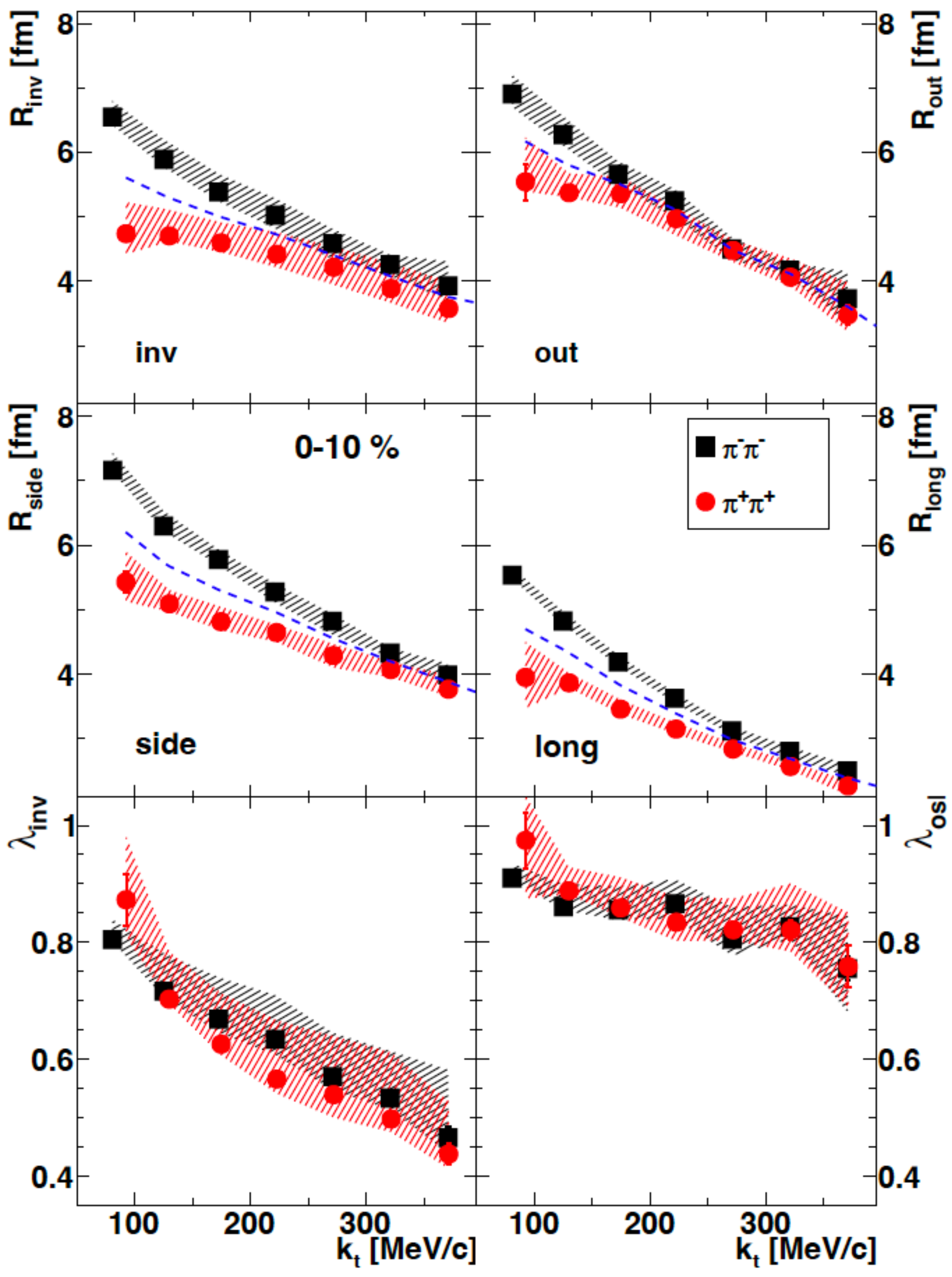
High baryon density regime with 420-720 MeV

1-2 GeV/nucleon:

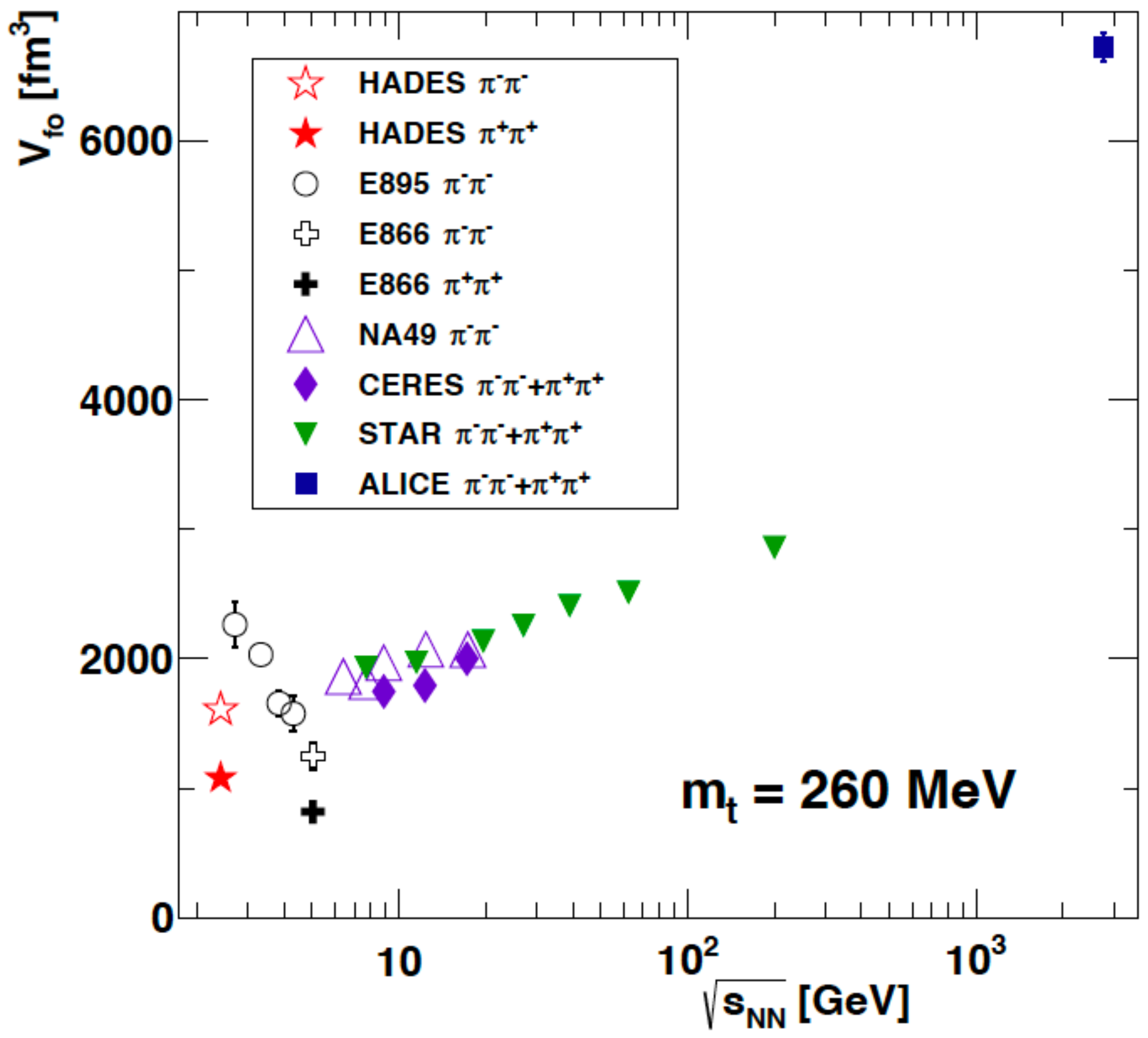
C+C, Ar+KCl, p+p, d+p and p+Nb

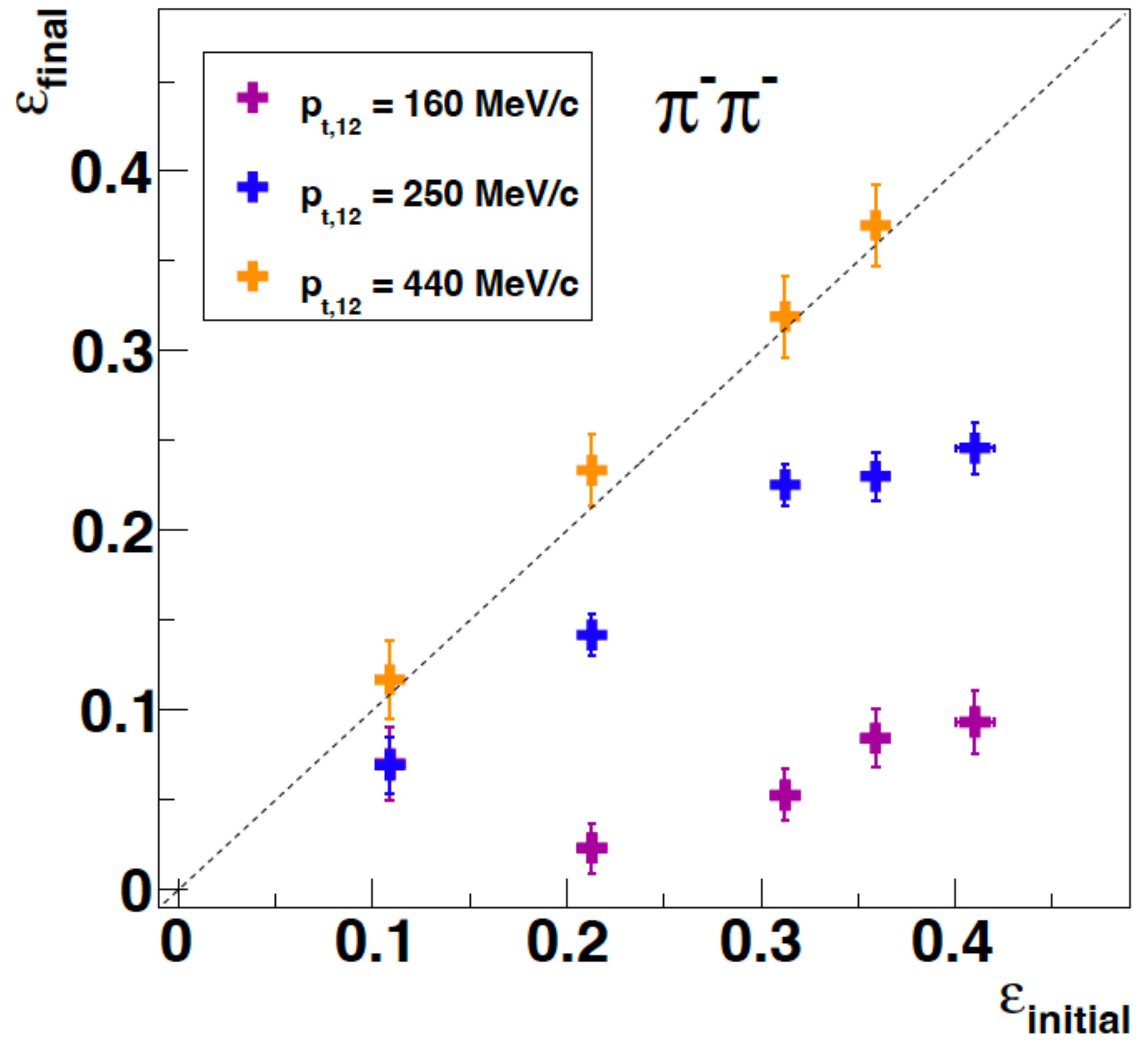
3-5 GeV/nucleon: p+p

Identical pion correlations at HADES

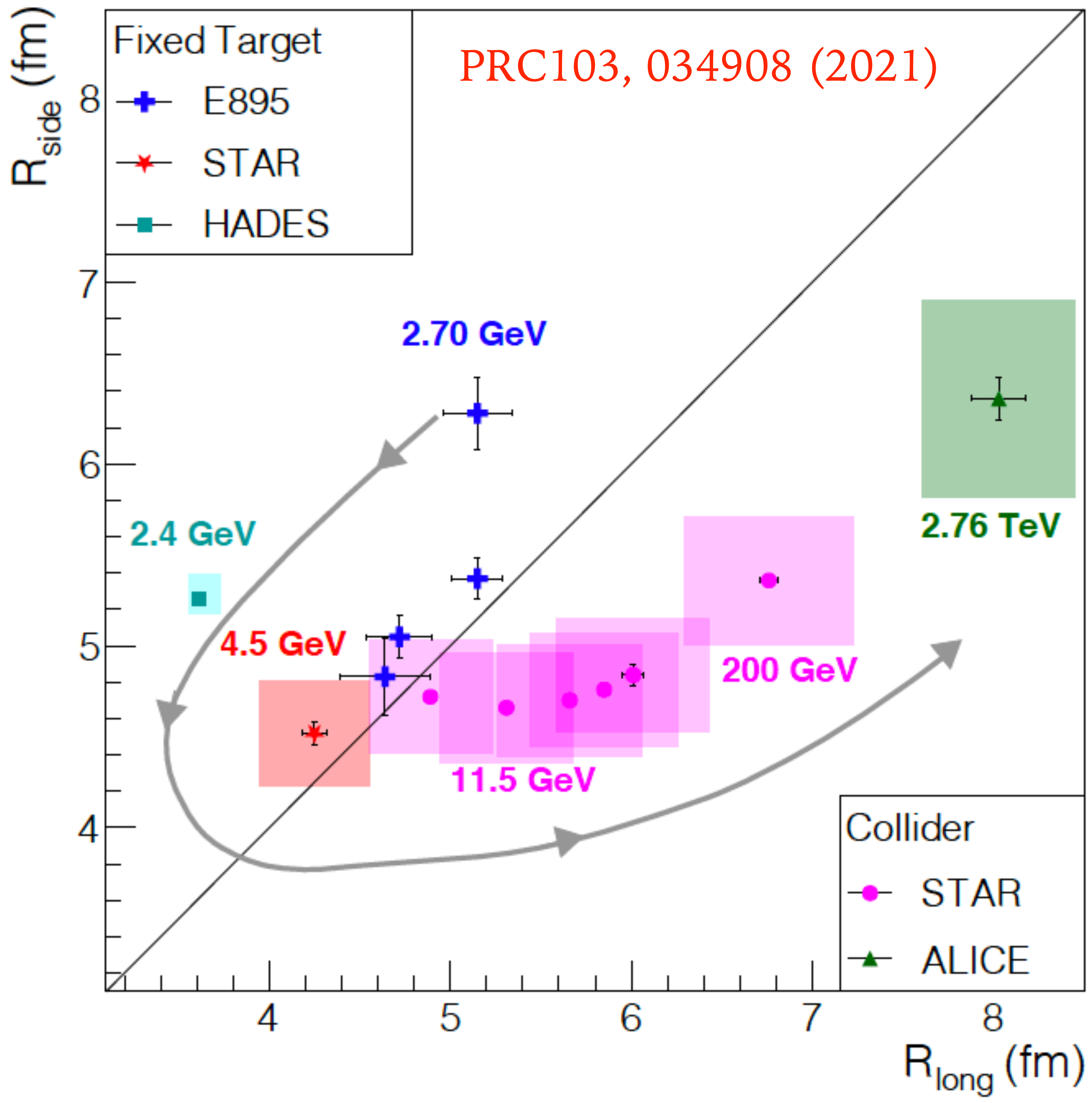


- **Differences** of the **radii** for pairs of $\pi^-$and π^+
- $R_{long} < R_{out} \simeq R_{side}$
- **Small variation of the freeze-out volume** $V_{fo} = (2\pi)^{3/2} R_{side}^2 R_{long}$
- **The final eccentricity recovers the initial eccentricity** for large p_T.





Identical pion correlations



- 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.

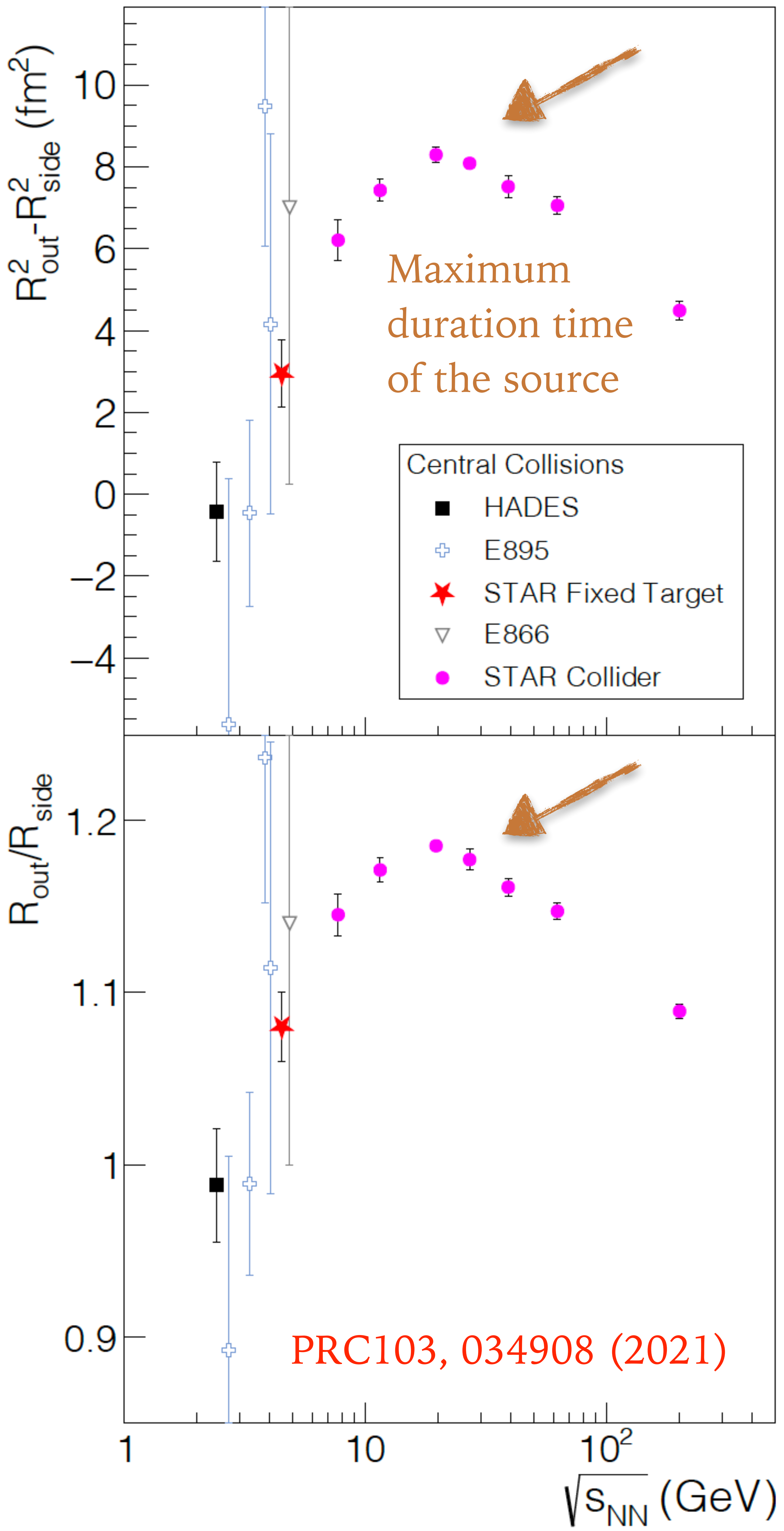
How to measure a phase transition?

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

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



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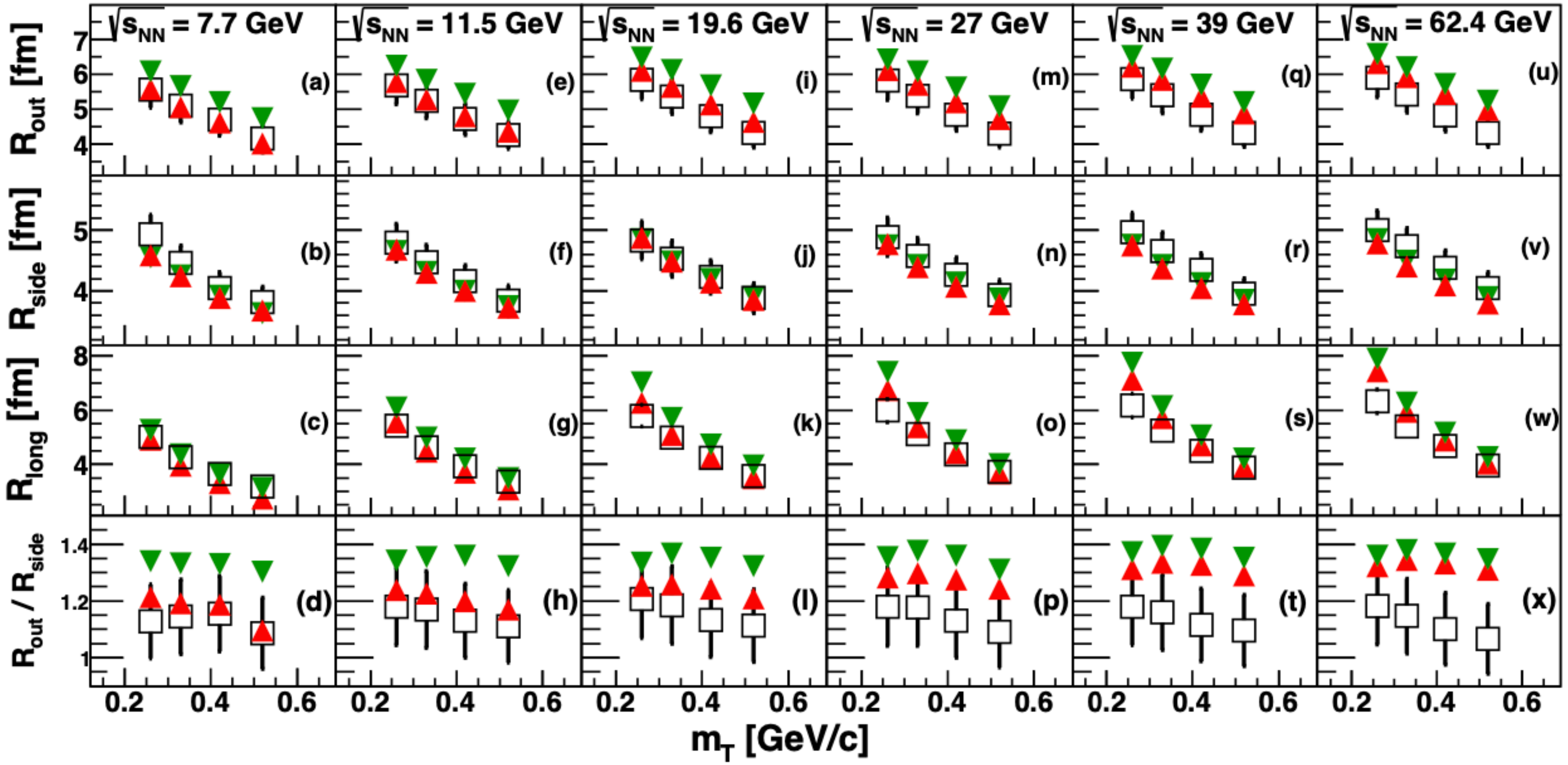
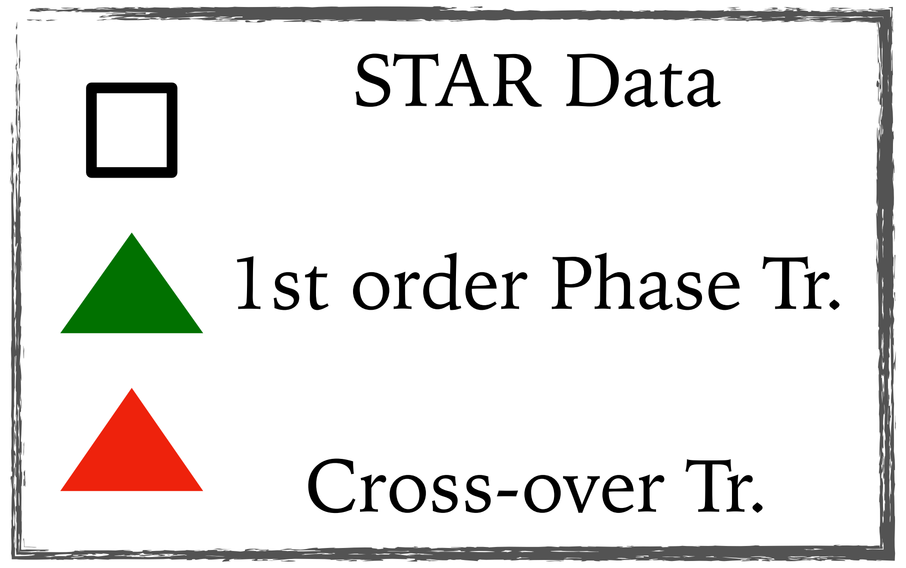




Phys.Rev. C96 (2017) no.2, 024911

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

Pre-thermal phase → Hydrodynamical phase → Hydronic cascades

UrQMD　　vHLEE　　UrQMD

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)

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

Future

CBM (and HADES) challenges

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

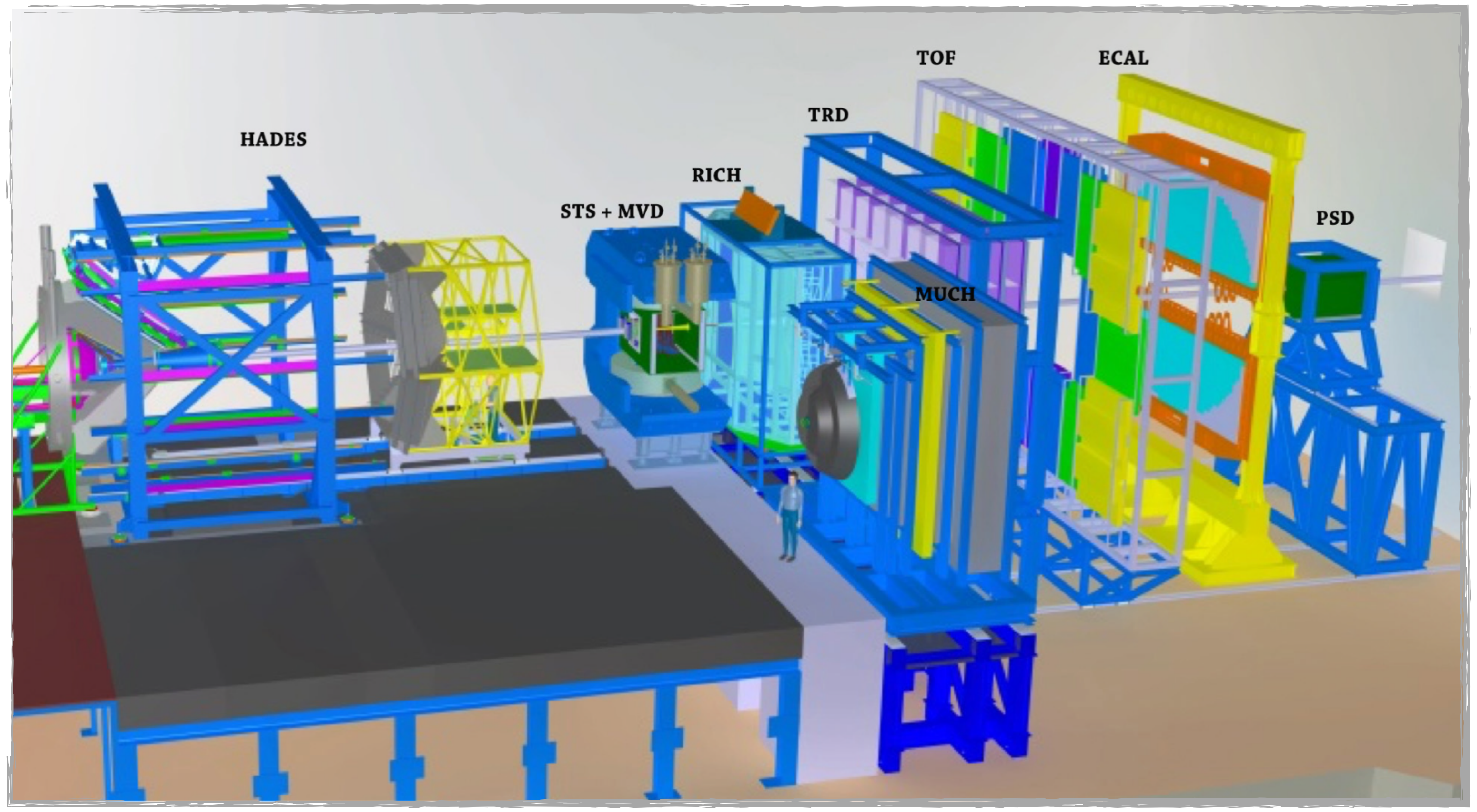
Challenges in QCD matter physics –
The scientific programme of the Compressed Baryonic Matter experiment at FAIR

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.

QCD Phase Structure and Interactions at High Baryon Density:
Completion of BES Physics Program with CBM at FAIR

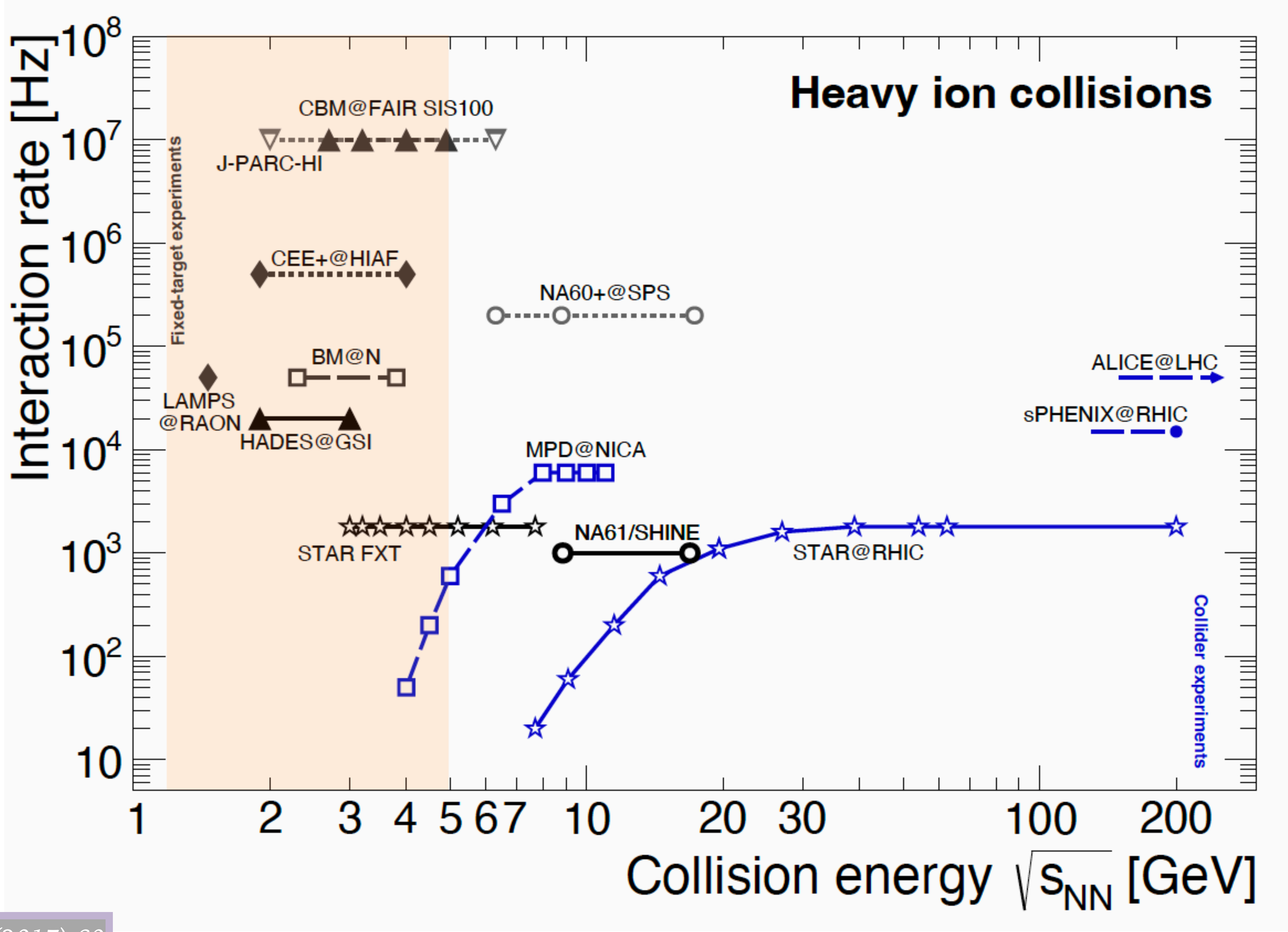
the nature (attractive or repulsive) of some hyperon interactions. The high baryon density and large number of hyperons produced in nucleus-nucleus collisions at FAIR energies will put CBM in a unique position to measure those interactions with unprecedented precision. Unlike at RHIC and LHC, the collision dynamics at the relatively low center-of-mass energy of FAIR are less explosive, allowing hyperons and nucleons to interact over a longer duration during the collision evolution, yielding stronger correlations. The CBM experiment will carry out a program to measure the correlations of Λ-N, Ξ-N, Ω-N, Λ-Λ, Λ-Ξ, and possibly Ξ-Ξ.

arXiiv:2209.05009 [nucl-ex]12 Sept 2022



The CBM experimental setup together with the HADES detector

Bright future



CBM, EPJA 53 3 (2017) 60

Summary

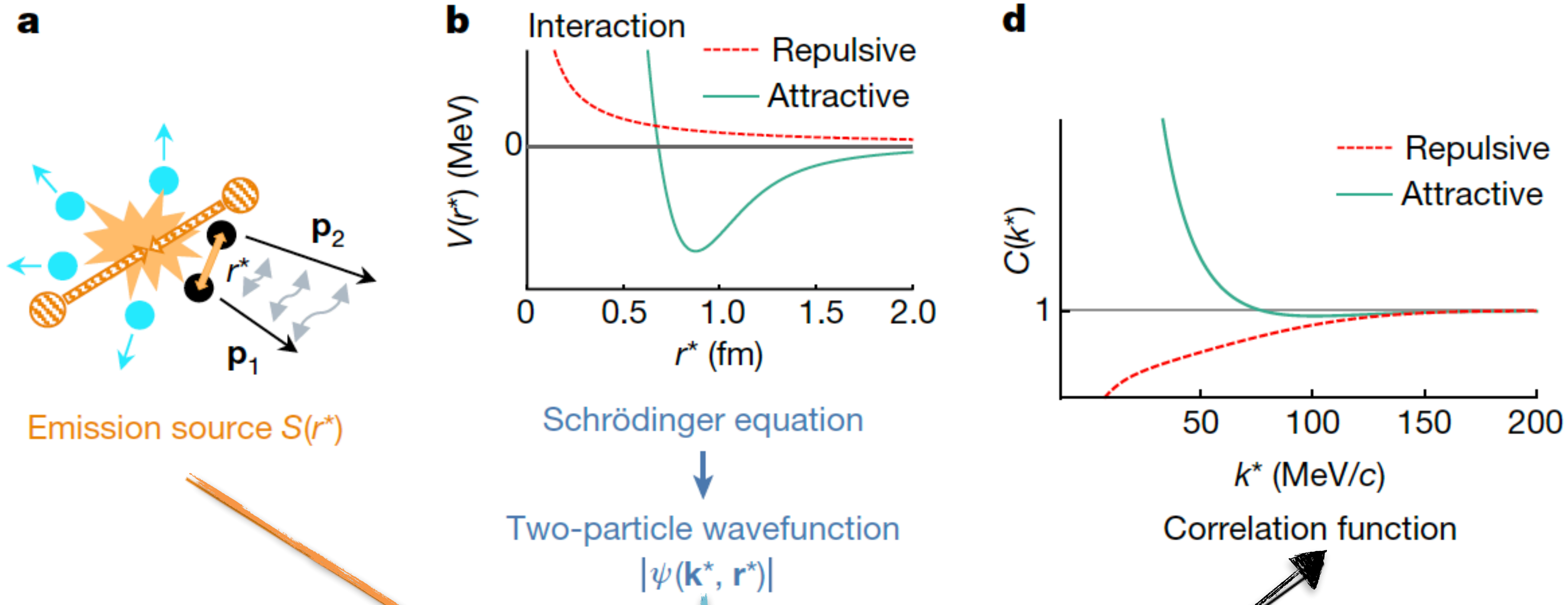
Summary

Energy Scan Programs give un access to:

- **Low energy** gives a real access to the area of **Neutron Stars**
- **Intermediate energies** can help to search for the signatures of the **phase transition** between hadron and quark matter
- **All energies** help a lot to study **strong interactions at the final state**

Back-up slides

Traditional and non-traditional femtoscopy



c

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

Pairs from the same collision

Pairs from the different collisions

Object of study of Traditional femtoscopy

Object of study of non-traditional femtoscopy

Published: 04 November 2015

Measurement of interaction between antiprotons

The STAR Collaboration

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

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

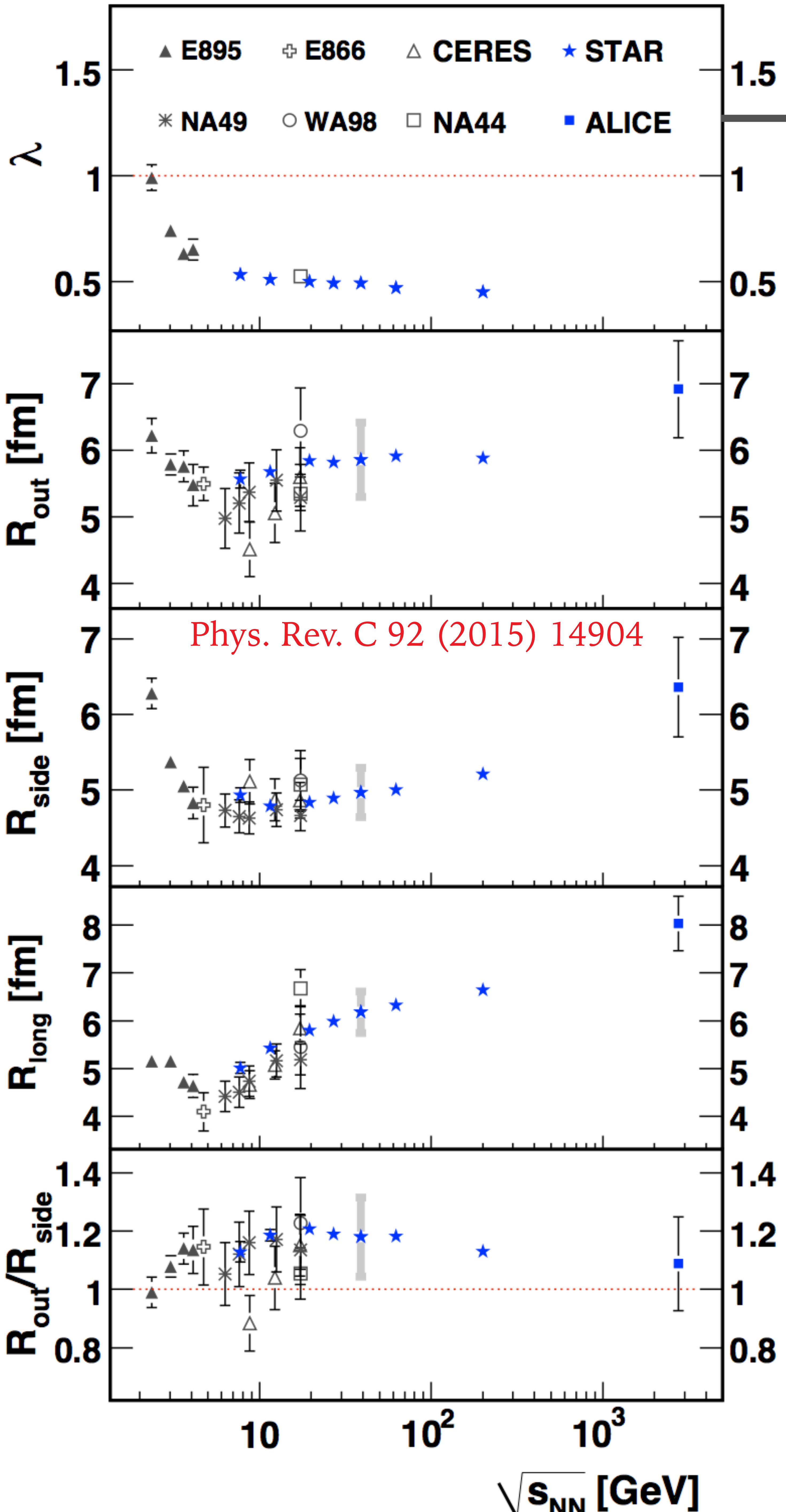
ALICE Collaboration

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

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.

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

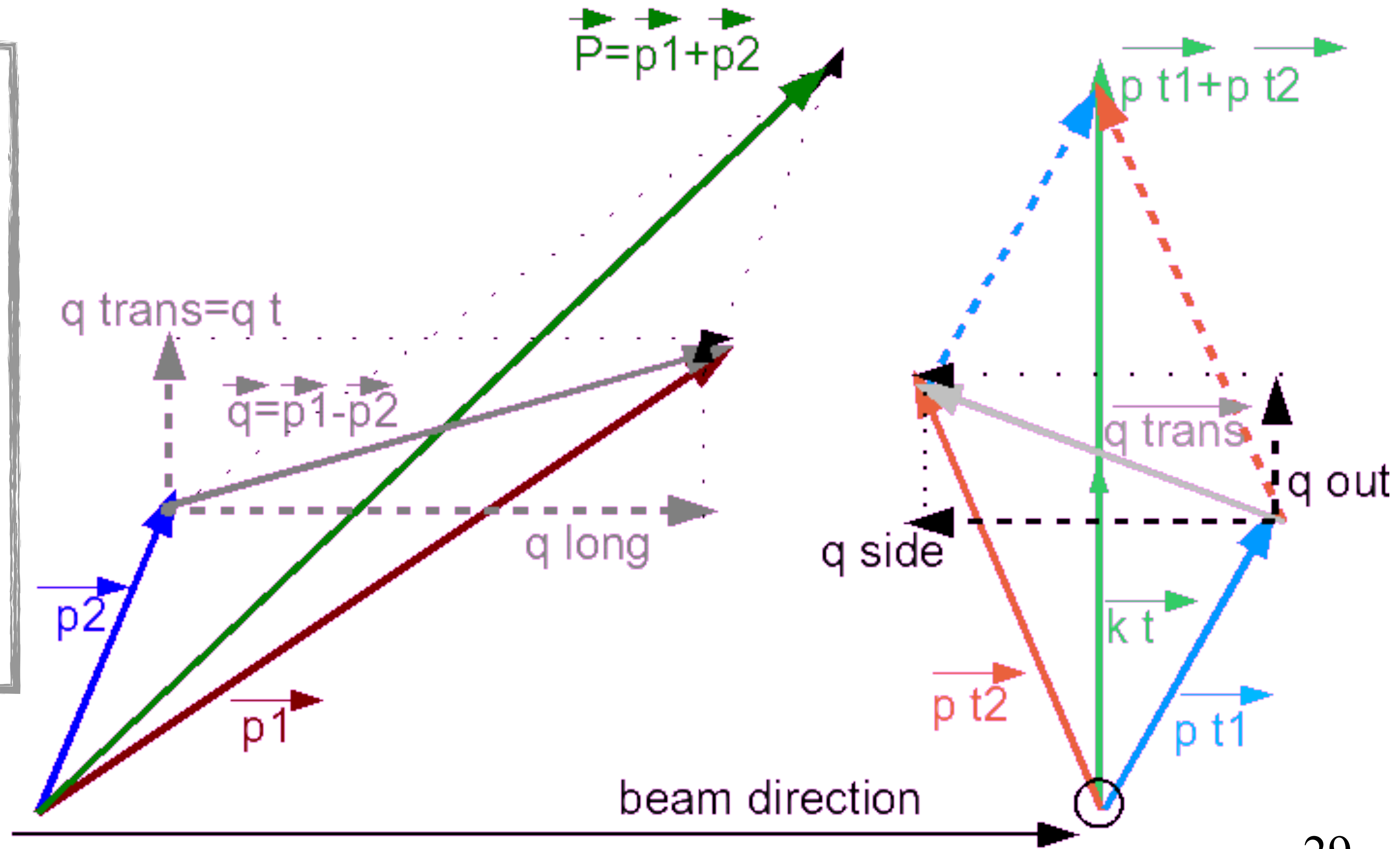
→ $R_{out}{}^2$- $R_{side}{}^2 = \Delta\tau^2\ \beta_t{}^2$; $\Delta\tau$ – emission time

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

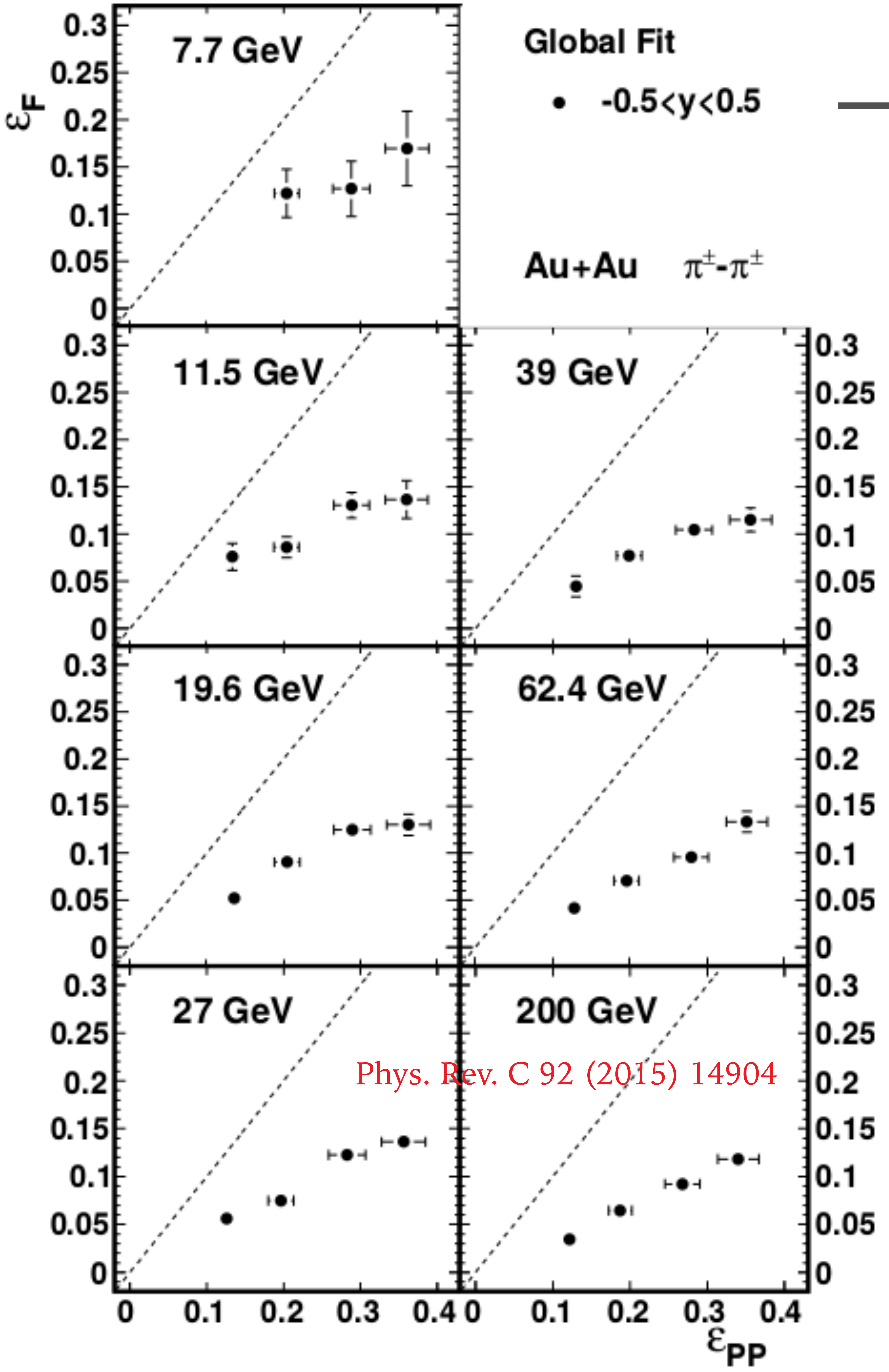
$$C(\vec{q}) = (1-\lambda) + K_{\text{Coul}}(q_{\text{inv}})\lambda$$
$$\times \exp\left(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2 - 2q_o q_s R_{os}^2 - 2q_o q_l R_{ol}^2\right)$$

HBT source sizes determined for wide range of collision energy;

Non-monotonic behavior seen in three directions



Identical pion femtoscopy



Phys. Rev. C 92 (2015) 14904

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

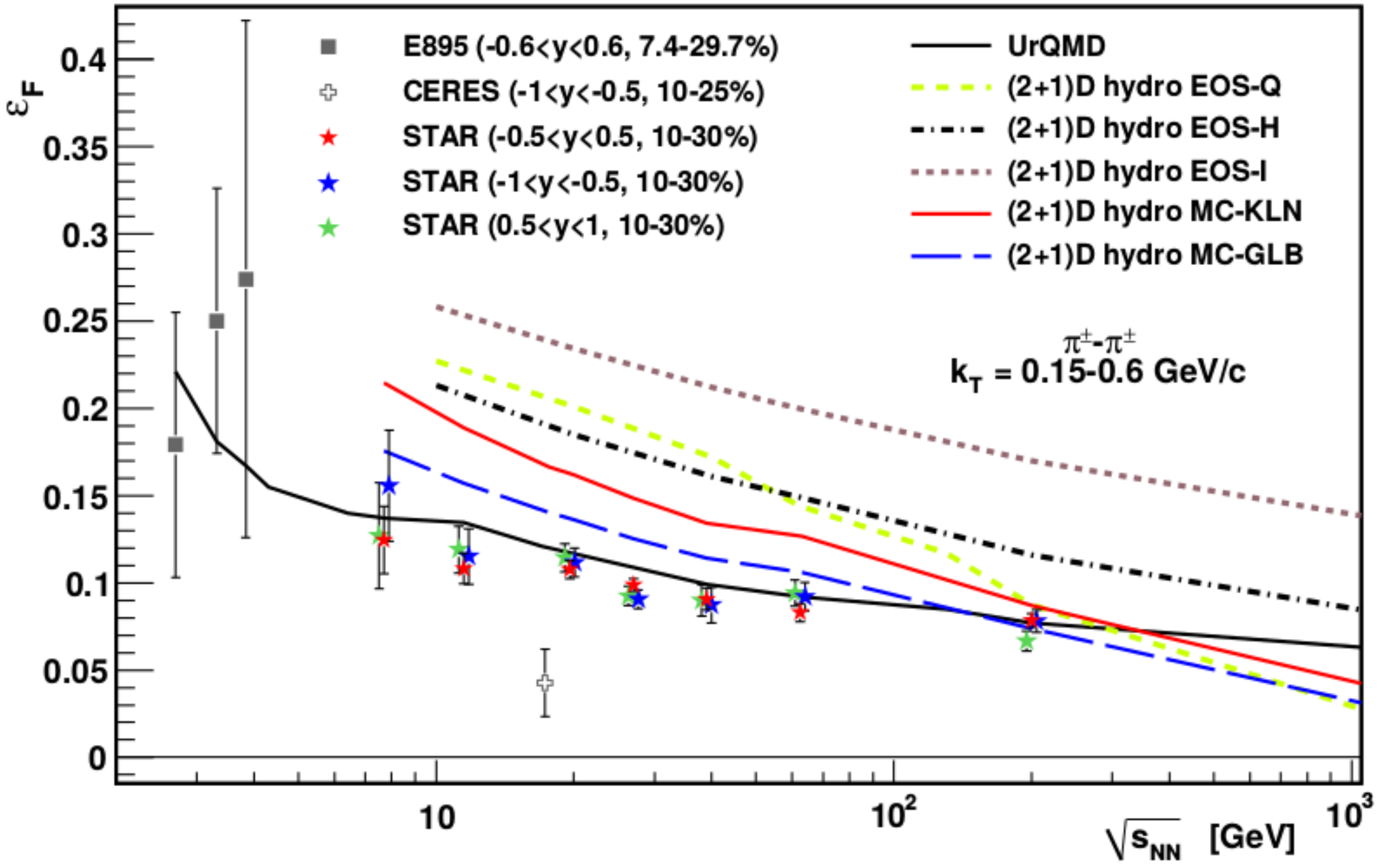
$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2\sum_{n=2,4,6\ldots} R_{\mu,n}^2 \sin(n\Phi) \qquad (\mu = os)$$

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

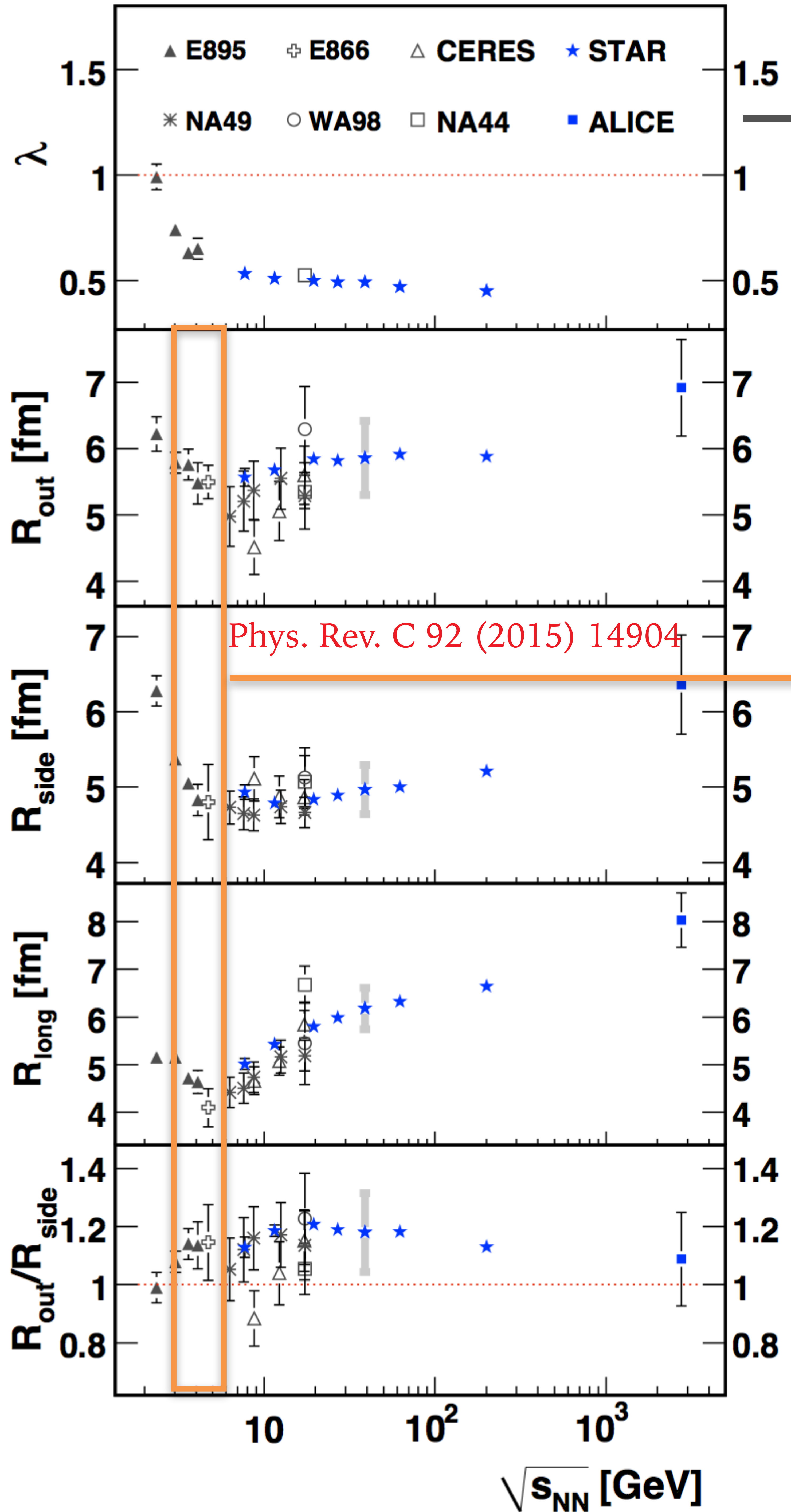
$$\varepsilon_F = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} \approx 2\frac{R_{s,2}^2}{R_{s,0}^2}$$

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

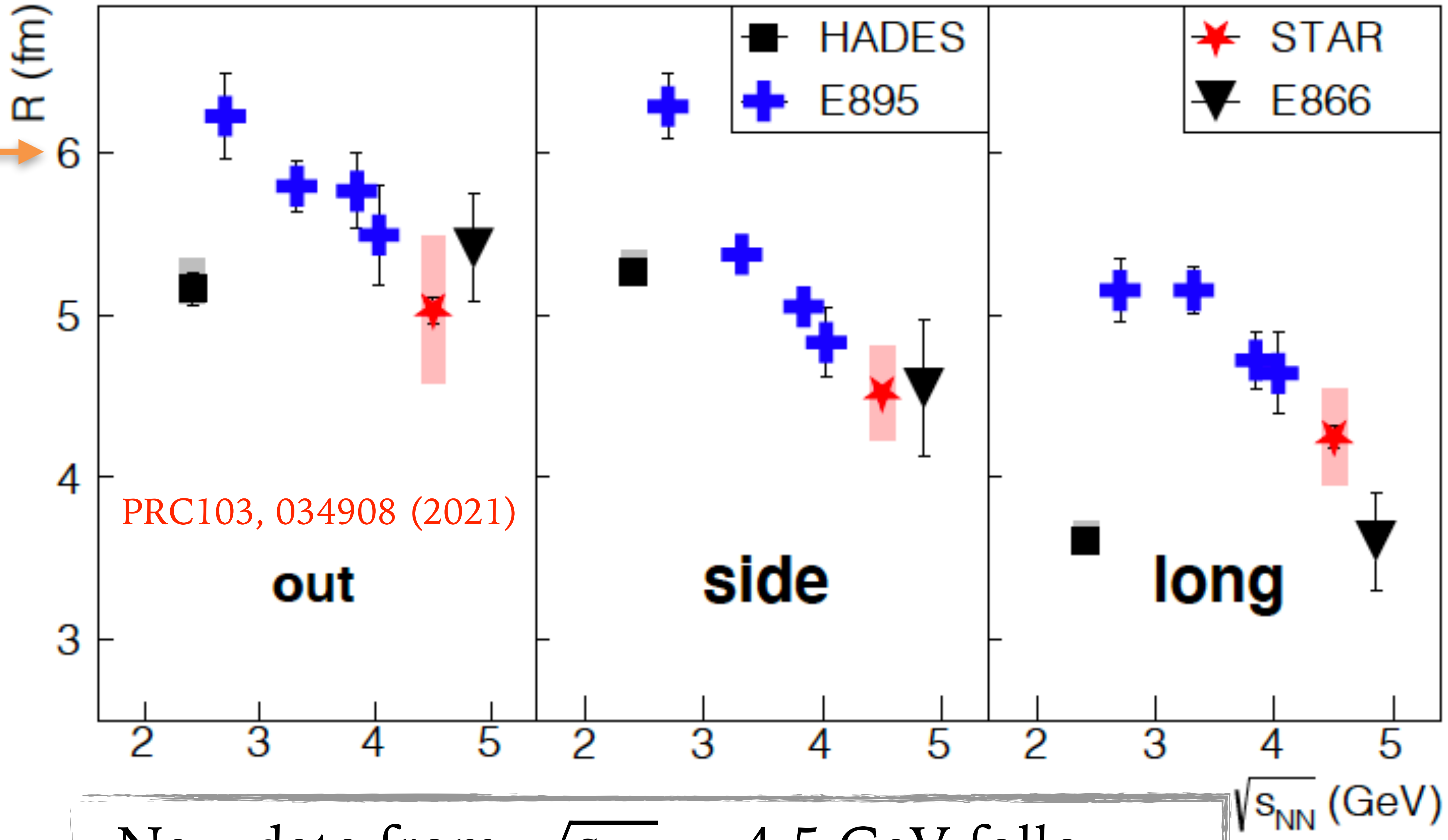
System evolves faster in the reaction plane



Identical pion femtoscopy

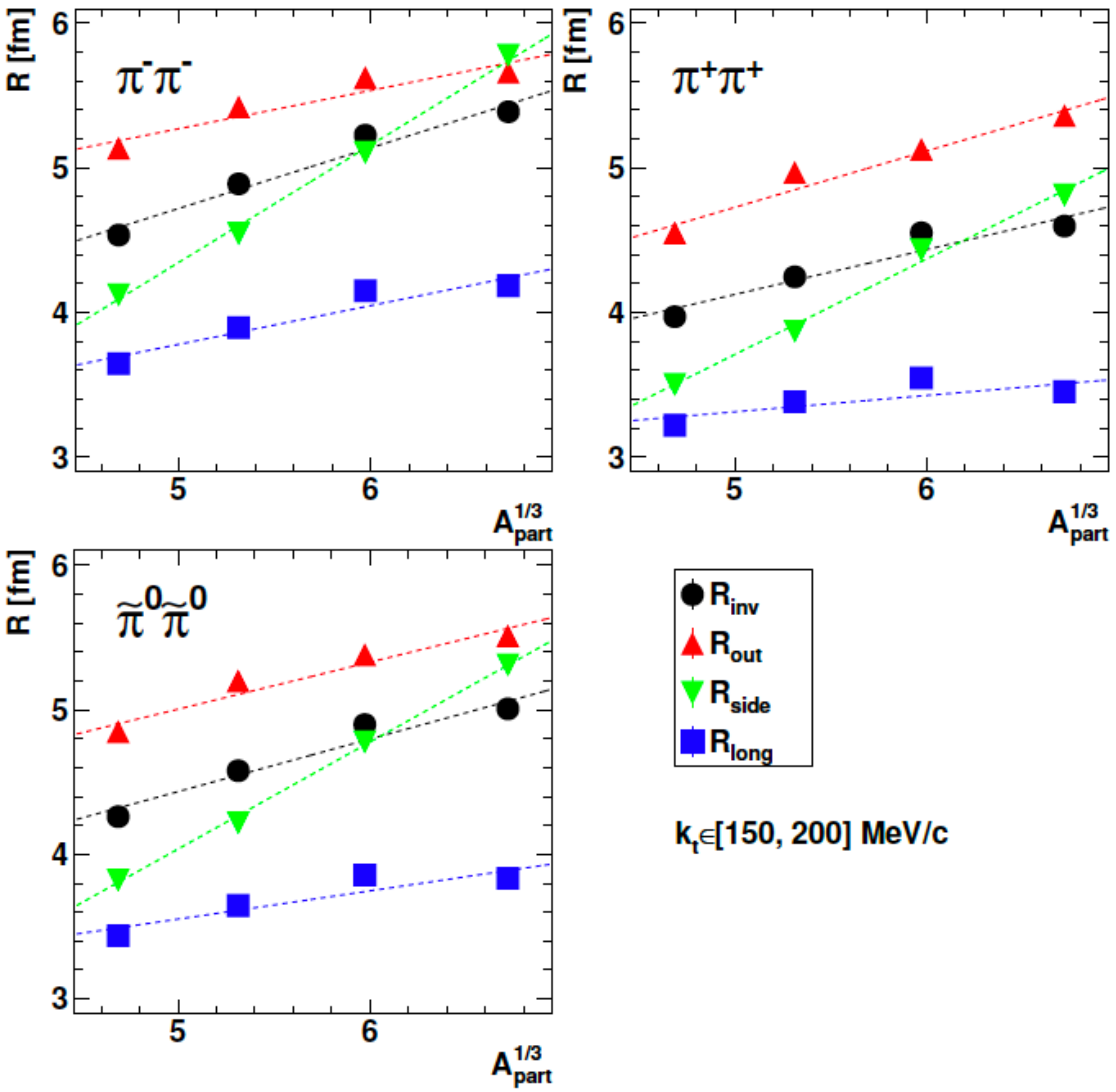


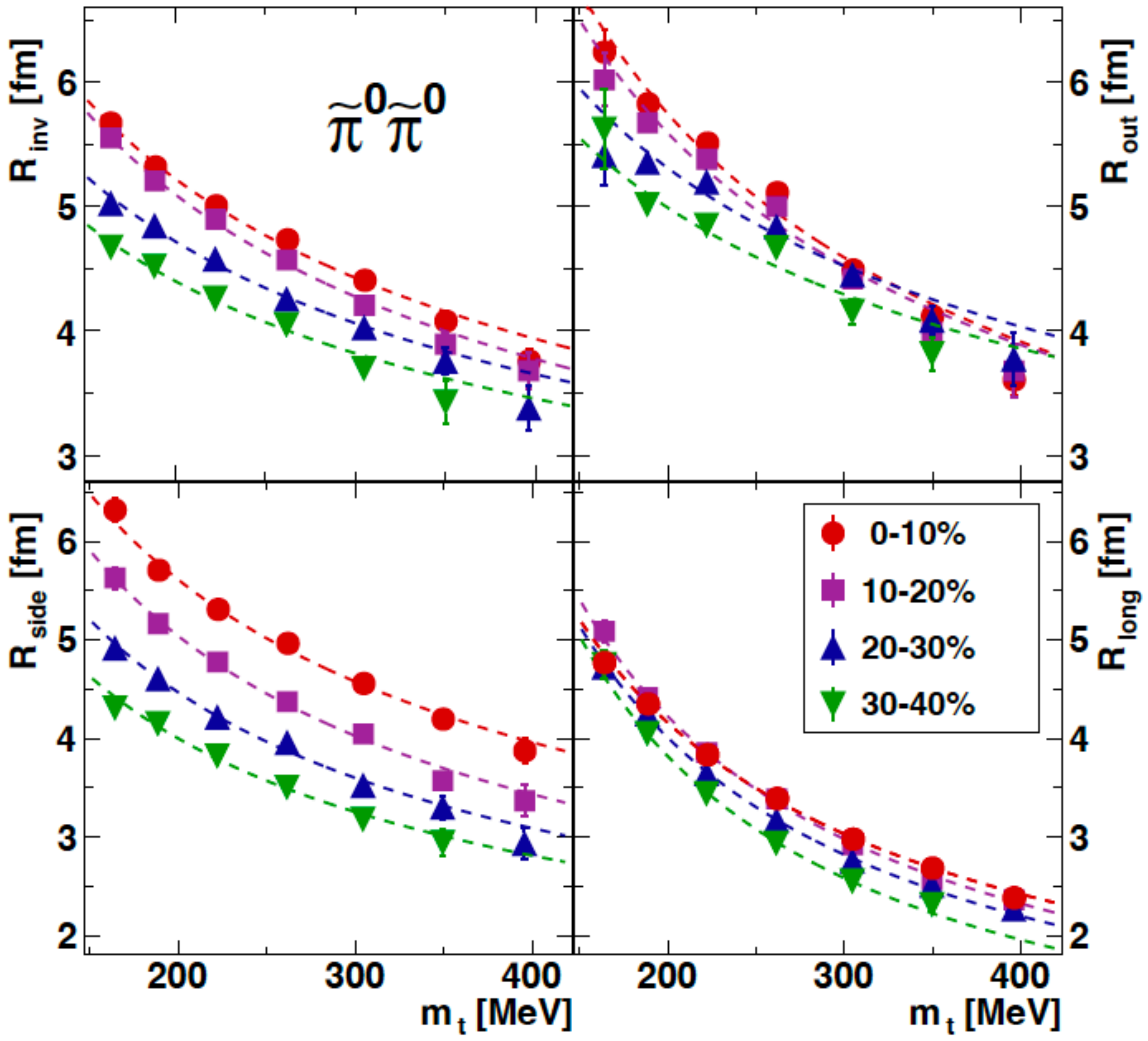
- → R_{side} spatial source evolution in the transverse direction
- → R_{out} related to spatial and time components
- → R_{out}/R_{side} signature of phase transition
- → $R_{out}^2 - R_{side}^2 = \Delta\tau^2 \beta_t^2$; $\Delta\tau$ – emission time
- → R_{long} temperature of kinetic freeze-out and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



New data from $\sqrt{s_{NN}}$ = 4.5 GeV follow trend observed for low collision energies

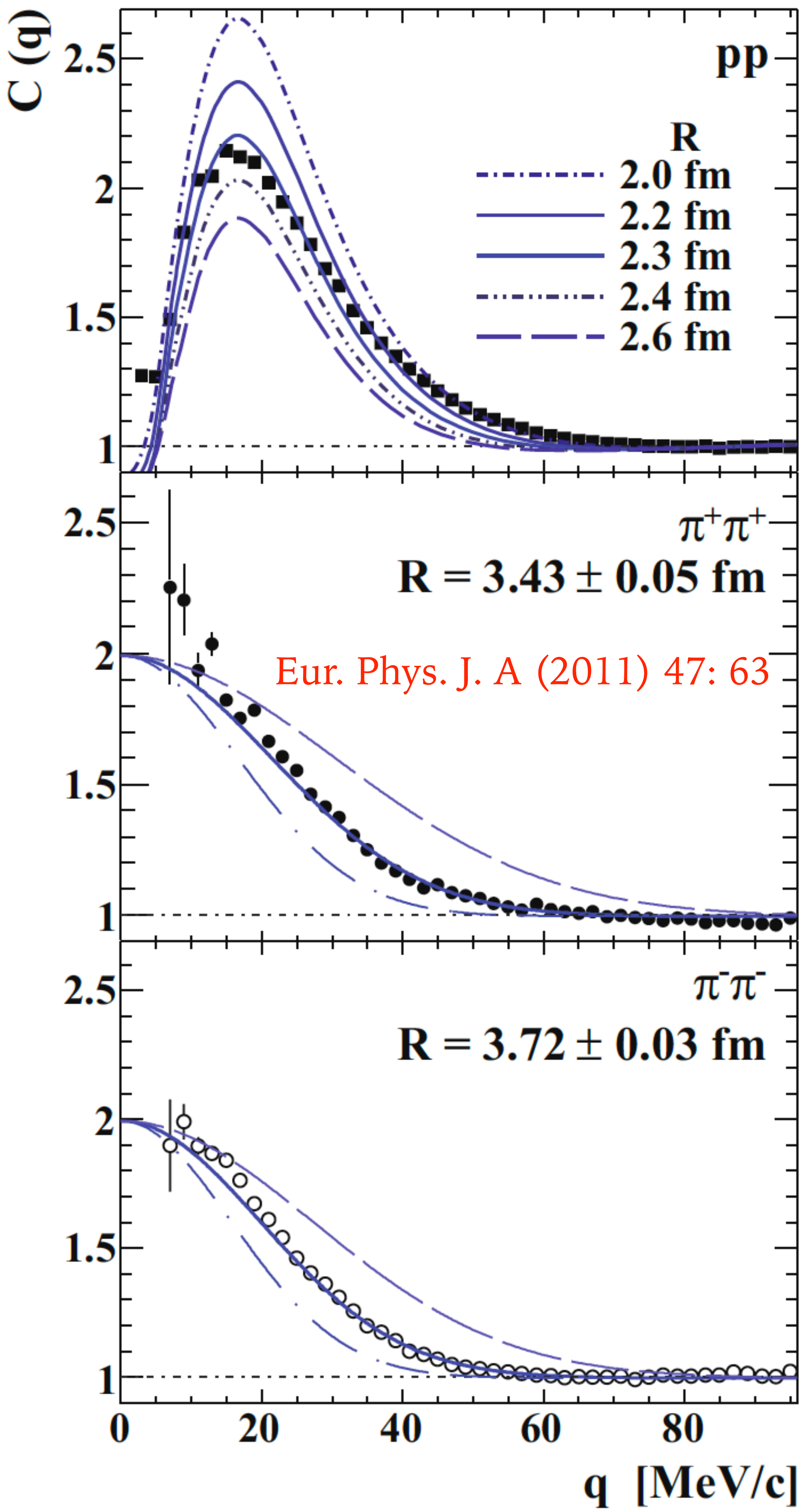
Correlations at HADES at $\sqrt{s_{NN}}$=2.4 GeV





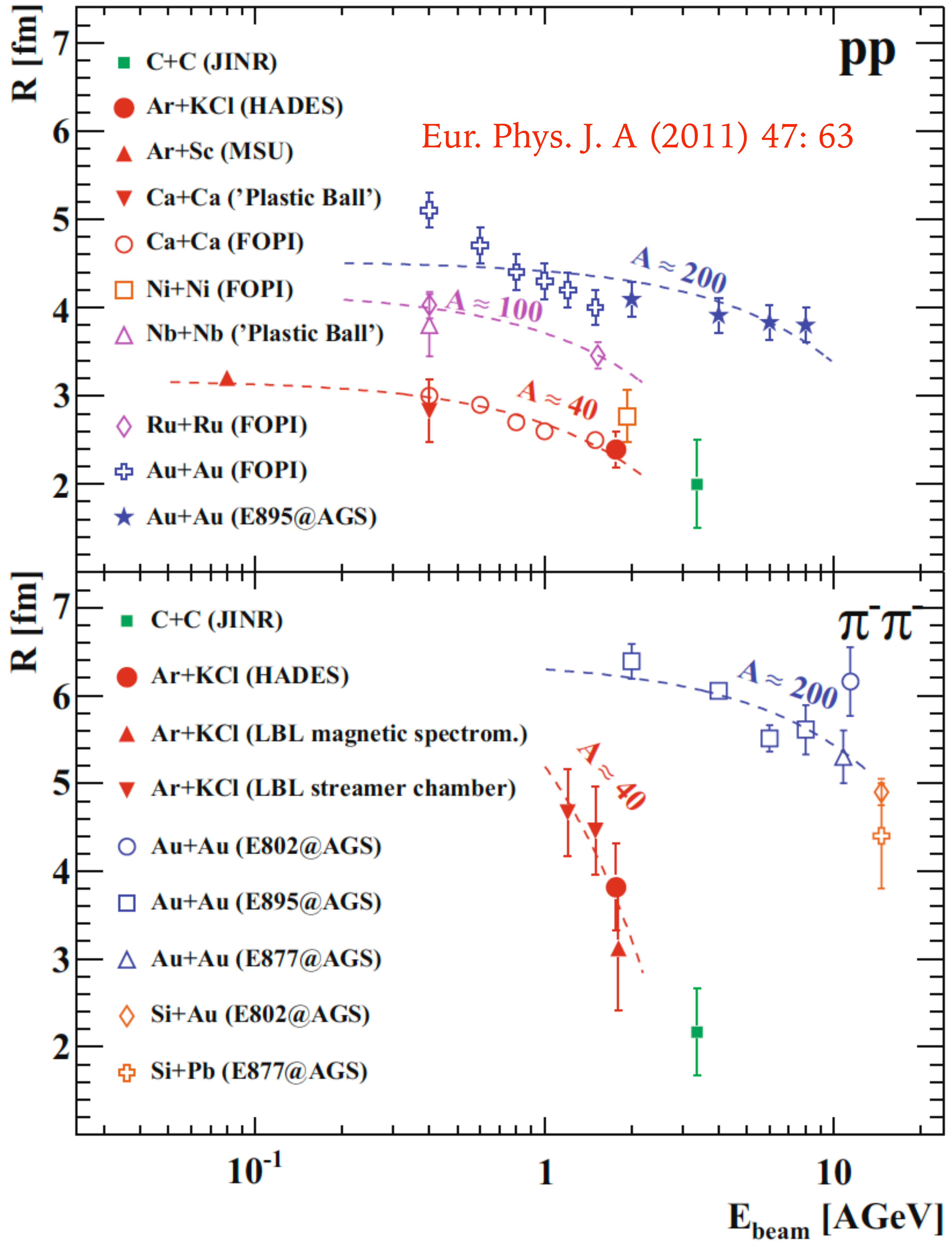
- Differences of the radii for pairs of $\pi^-$and π^+ are found (low transverse momenta).
- $R_{long} < R_{out} \simeq R_{side}$
- Data fit with $R = R_0(m_t/m_\pi)^\alpha$

Correlations at HADES at Ar+KCl

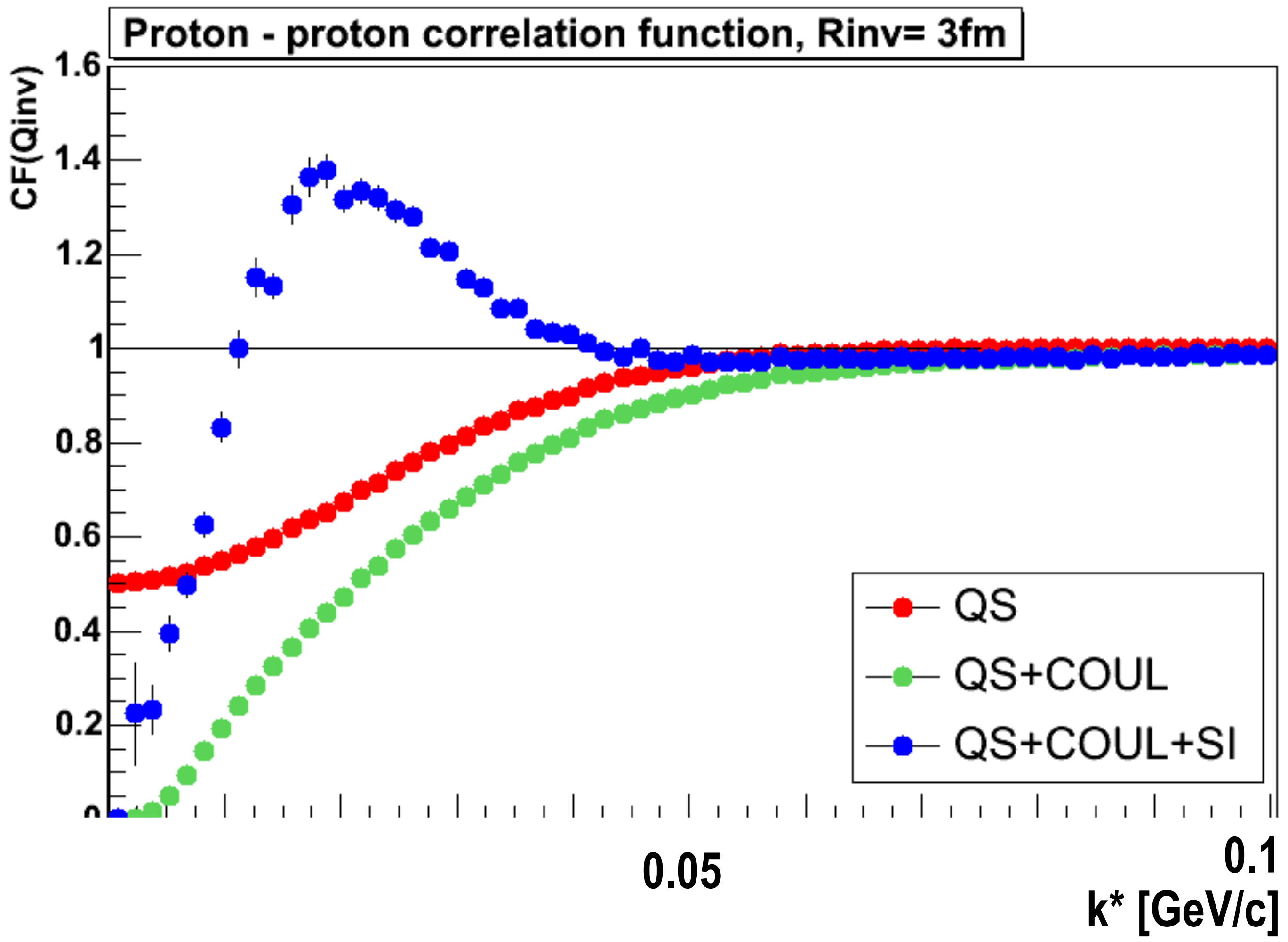


Pions emitted from bigger sources than protons

The present $p-p$ and $\pi^- - \pi^-$ radii well complement data trends in the SIS energy range.

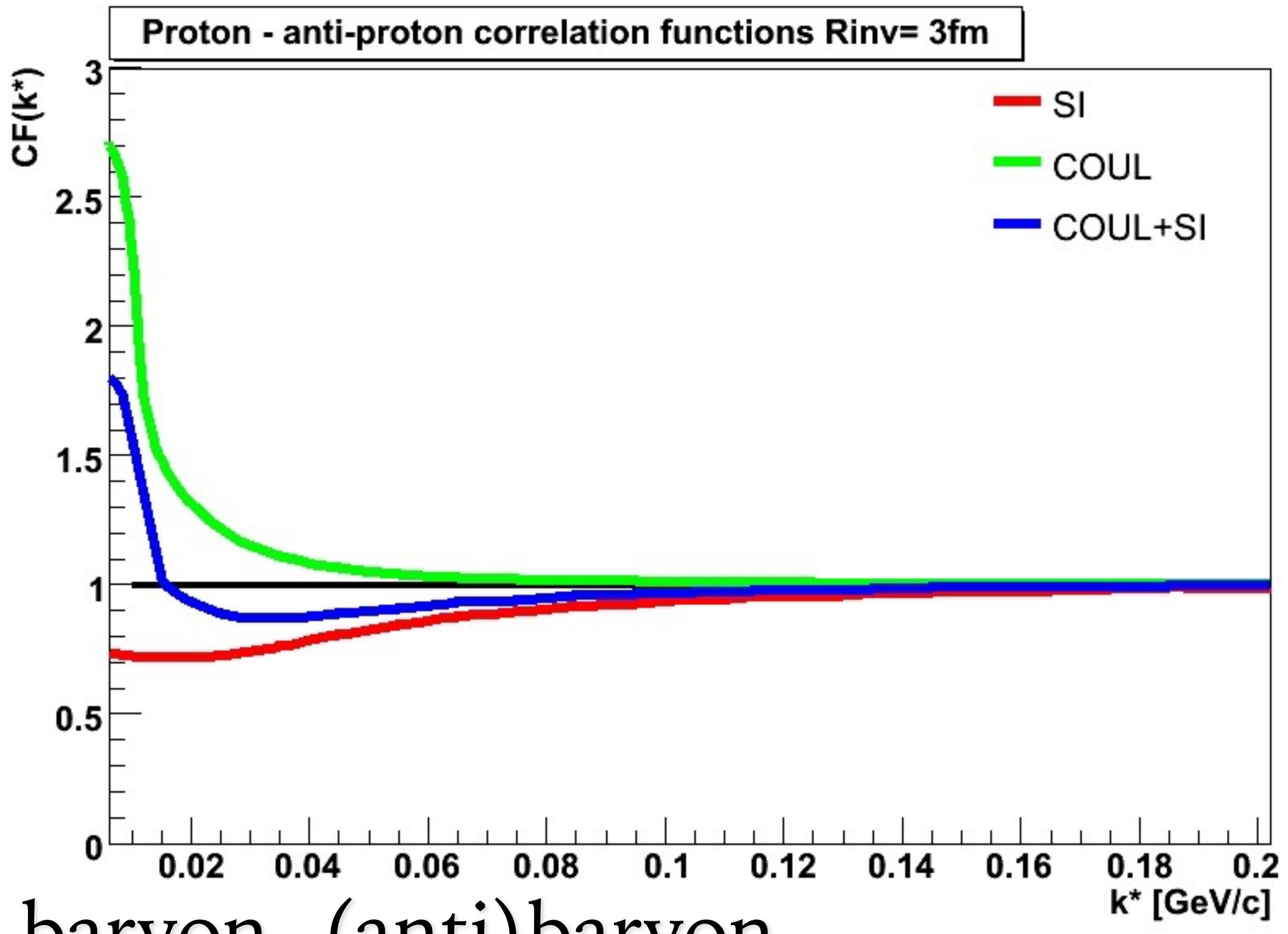


Effects and interactions



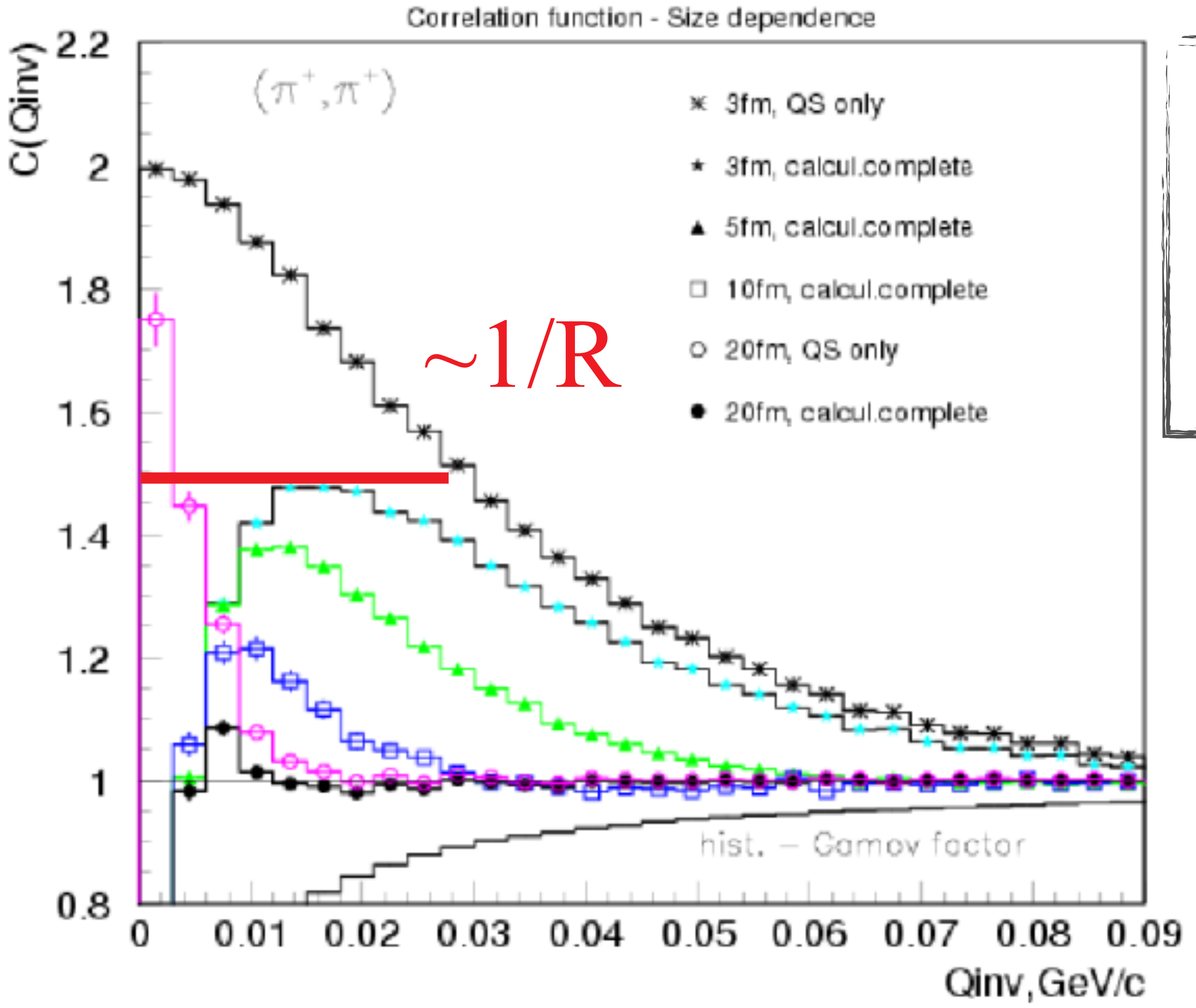
<u>Identical</u> <u>baryon- baryon</u>

- <u>Quantum Statistics- **QS**</u>
- <u>Final State Interactions- **FSI**</u>
  - <u>Coulomb</u>
  - <u>Strong</u>

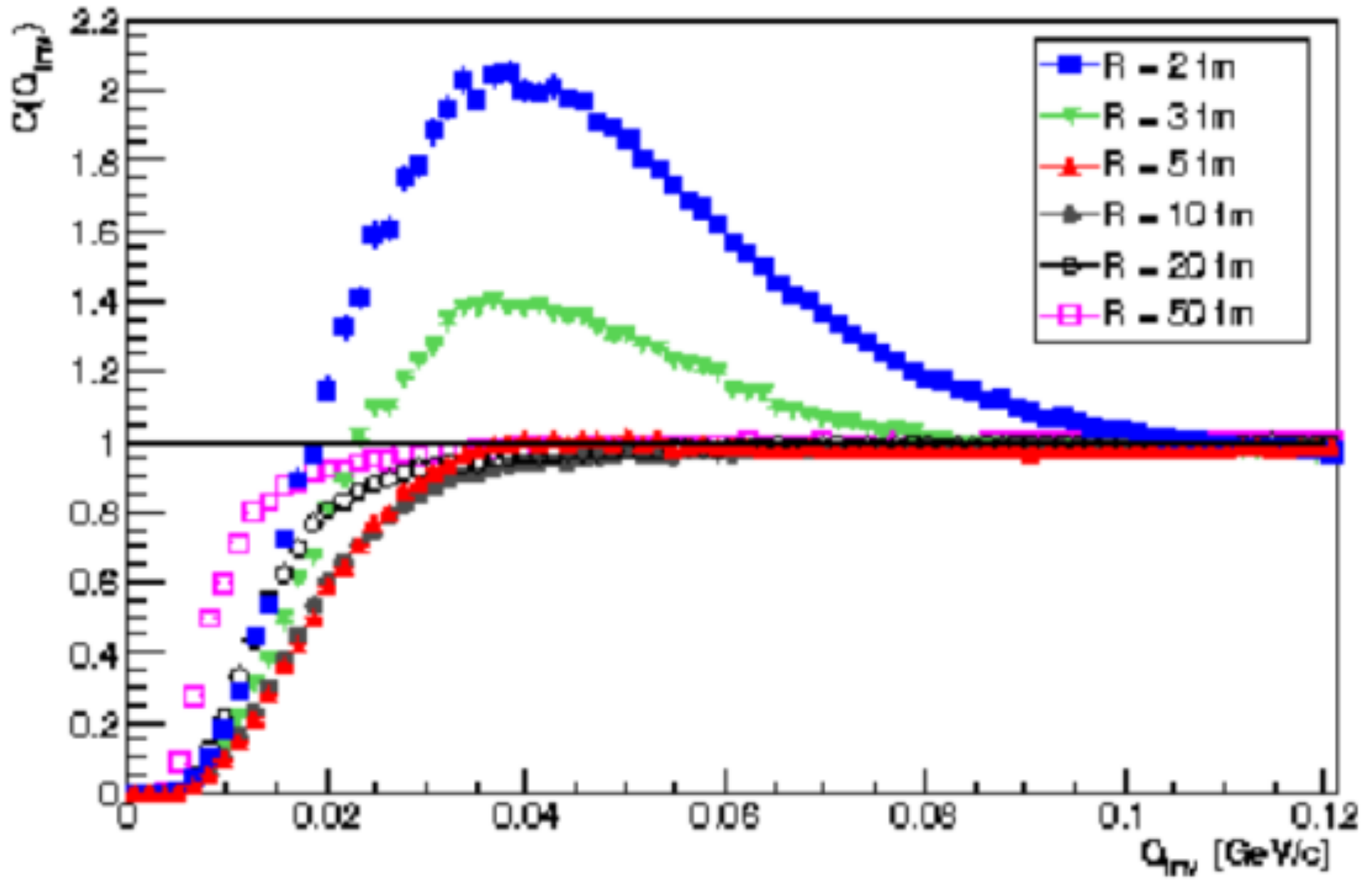


<u>Non-identical</u> <u>baryon- (anti)baryon</u>

- <u>Final State Interactions- **FSI**</u>
  - <u>Coulomb</u>
  - <u>Strong</u>



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



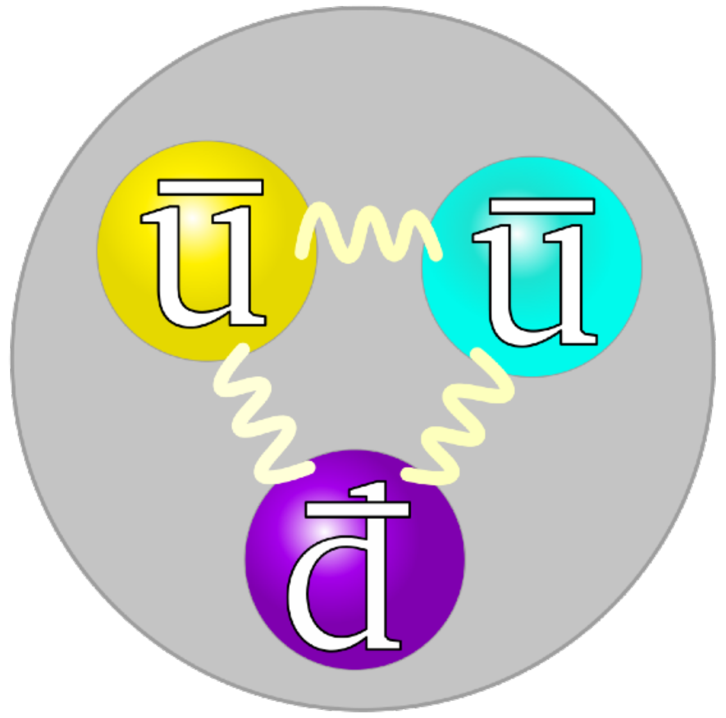
Bigger source and weaker correlation

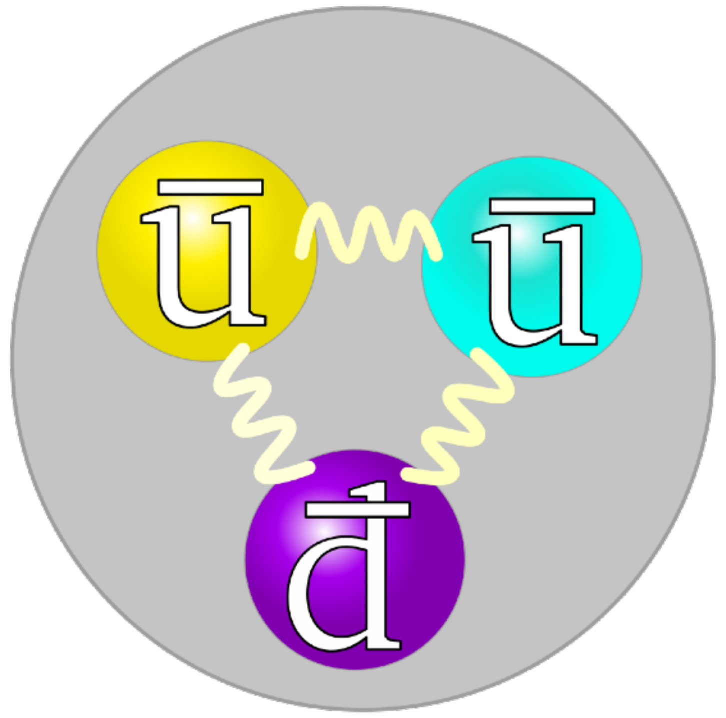
1) Strong interactions between anti-nucleons

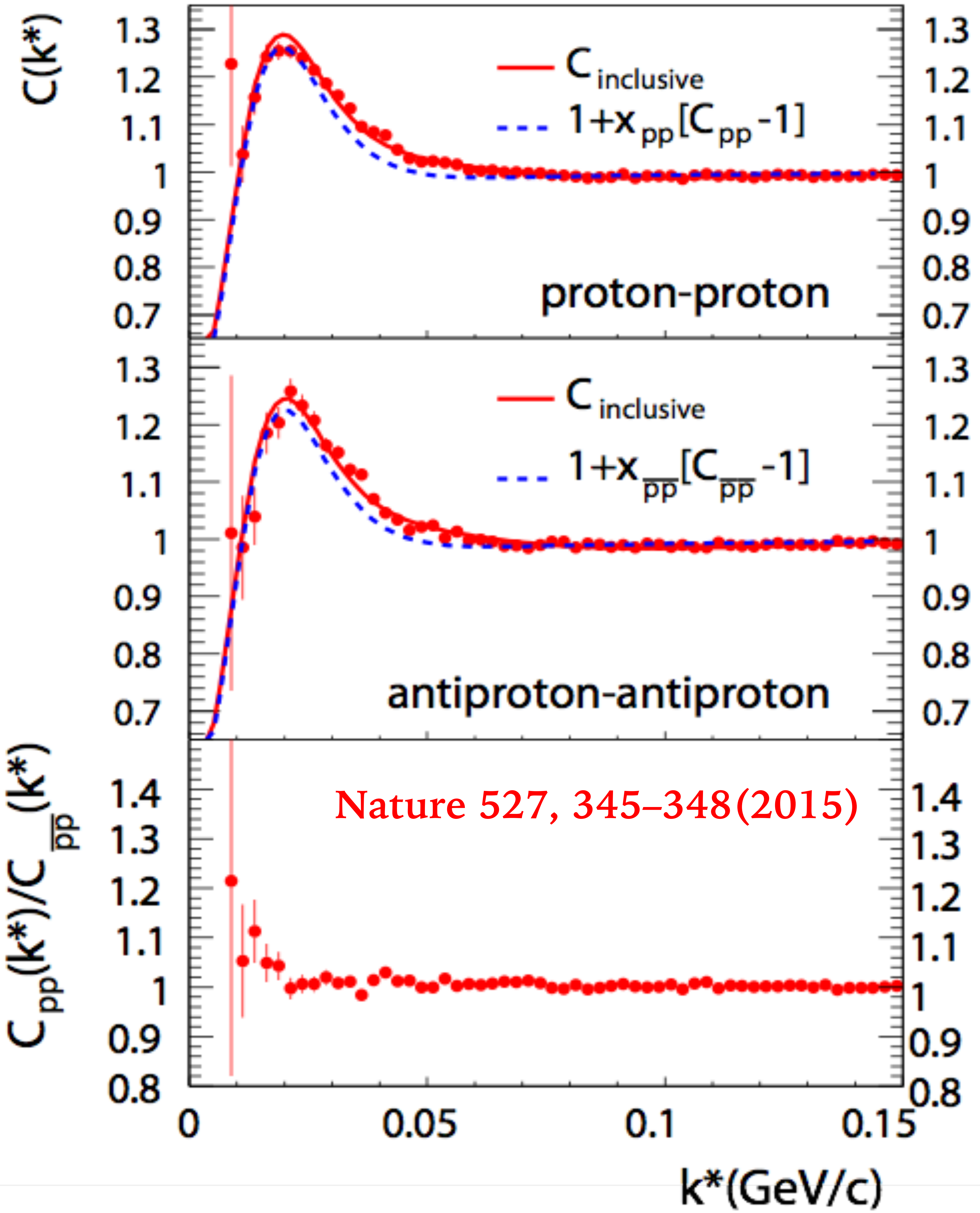
- The knowledge on **nuclear force** derived from studies of **nucleon** or / and **nuclei**.

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

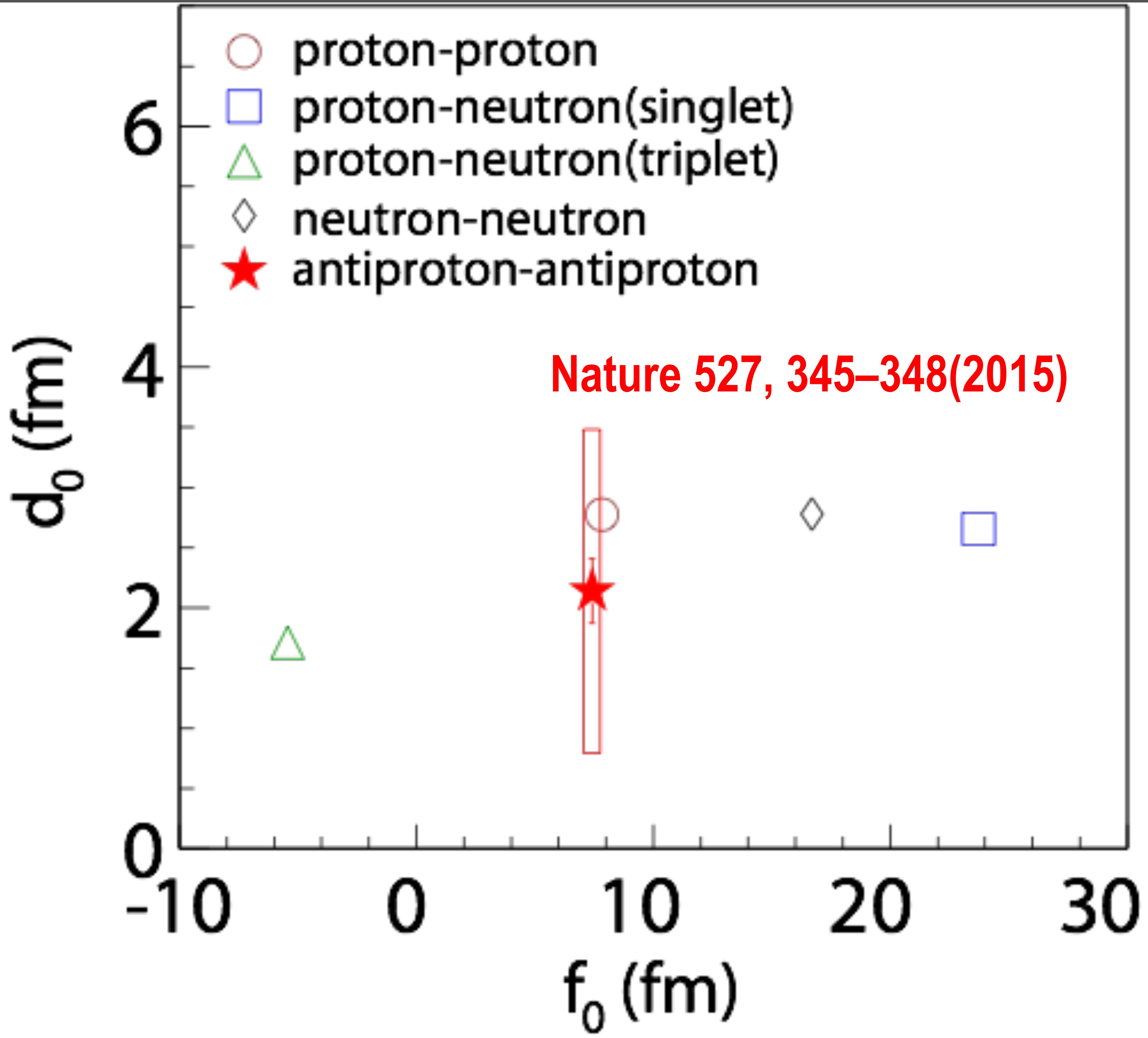
- The knowledge of **interaction** between two **anti-protons** fundamental to understand the properties of more sophisticated anti-nuclei.







1) 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.

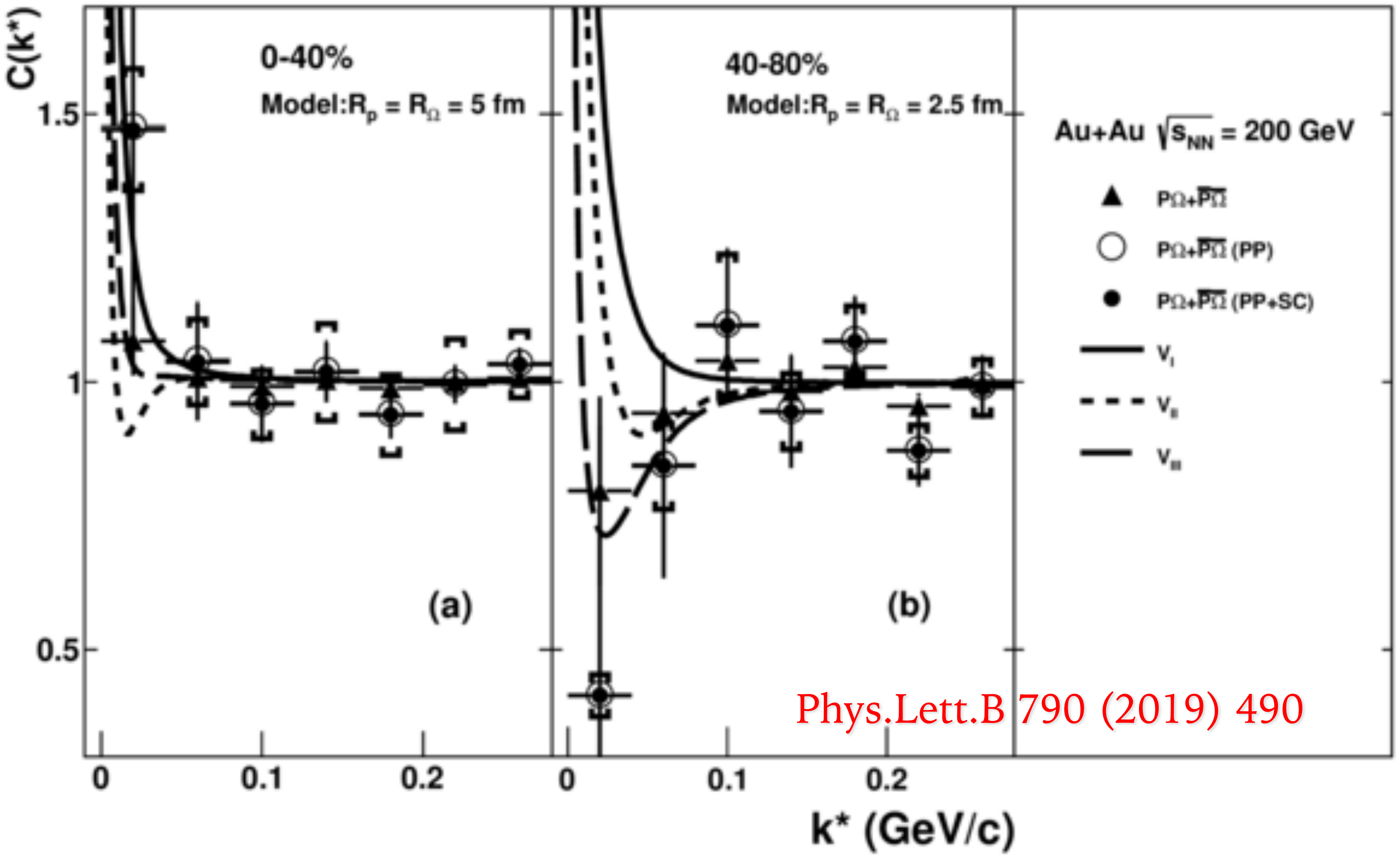
The elastic cross section, σ_e, (at low energies) determined solely by the scattering length, $\lim_{k\to 0} \sigma_e = 4\pi f_0^2$

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.

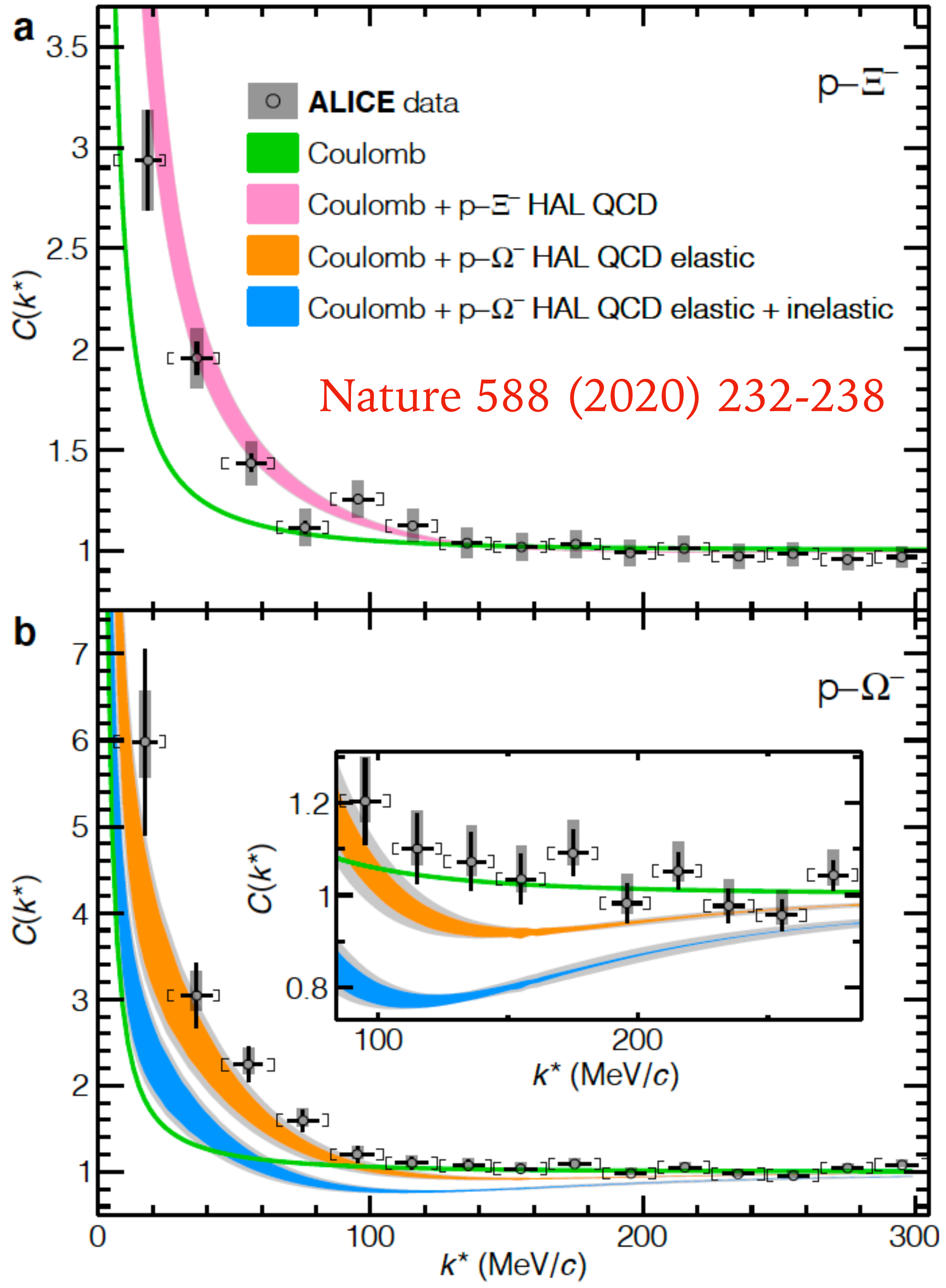
- f_0 and d_0 - two important parameters of strong interaction between two particles.
- Theoretical correlation function depends on: source size, k^*, f_0 and d_0.

Strange Baryon Correlations (including p-Ω)



Phys.Lett.B 790 (2019) 490

Scattering lenght positive, **favor the hypothesis of pΩ bound state**

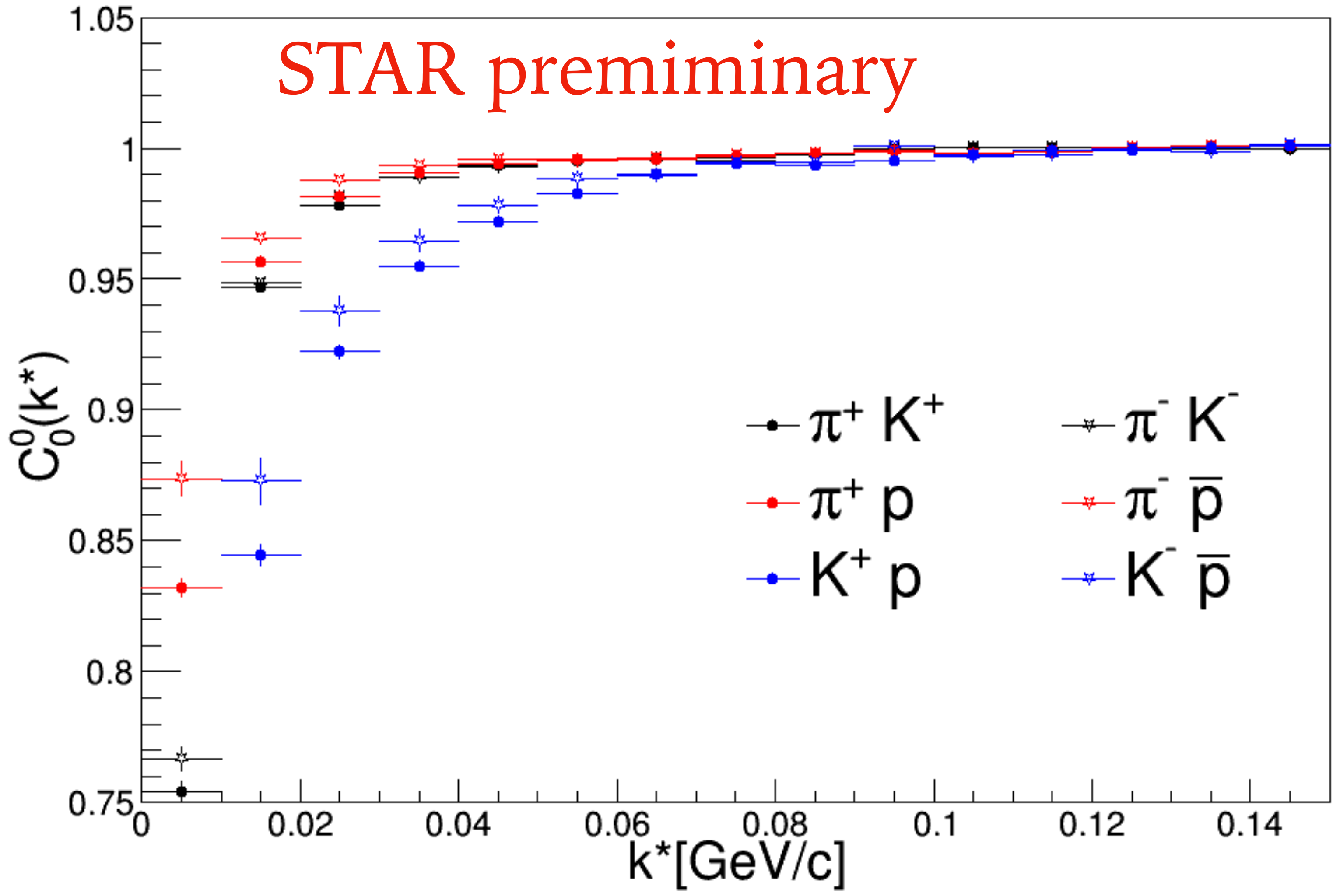


Nature 588 (2020) 232-238

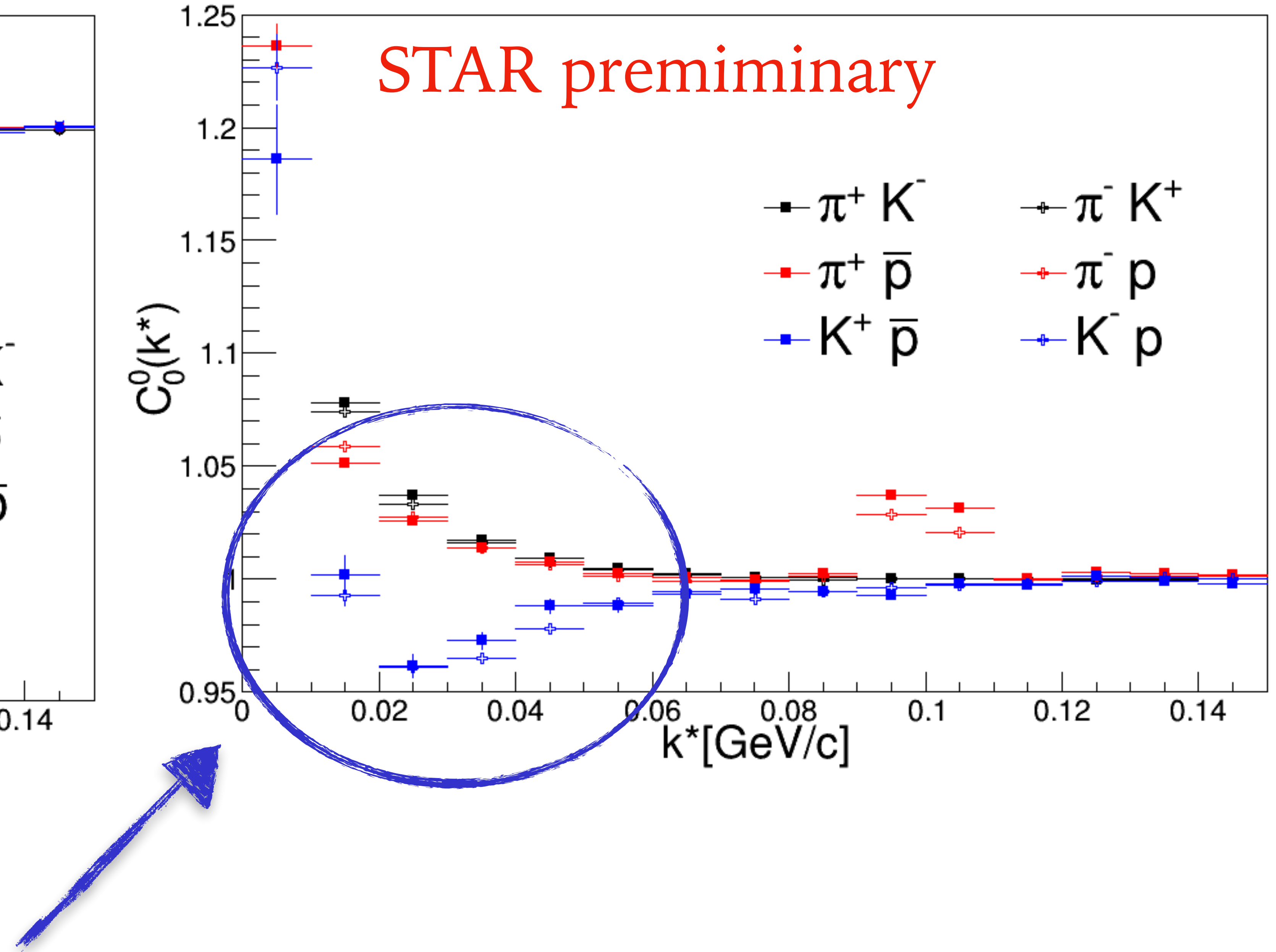
	V1	V2	V3
Ebin [MeV]	-	6.3	26.9
a0 [MeV]	-1.12	5.79	1.29
reff [MeV]	-1.16	0.96	0.65

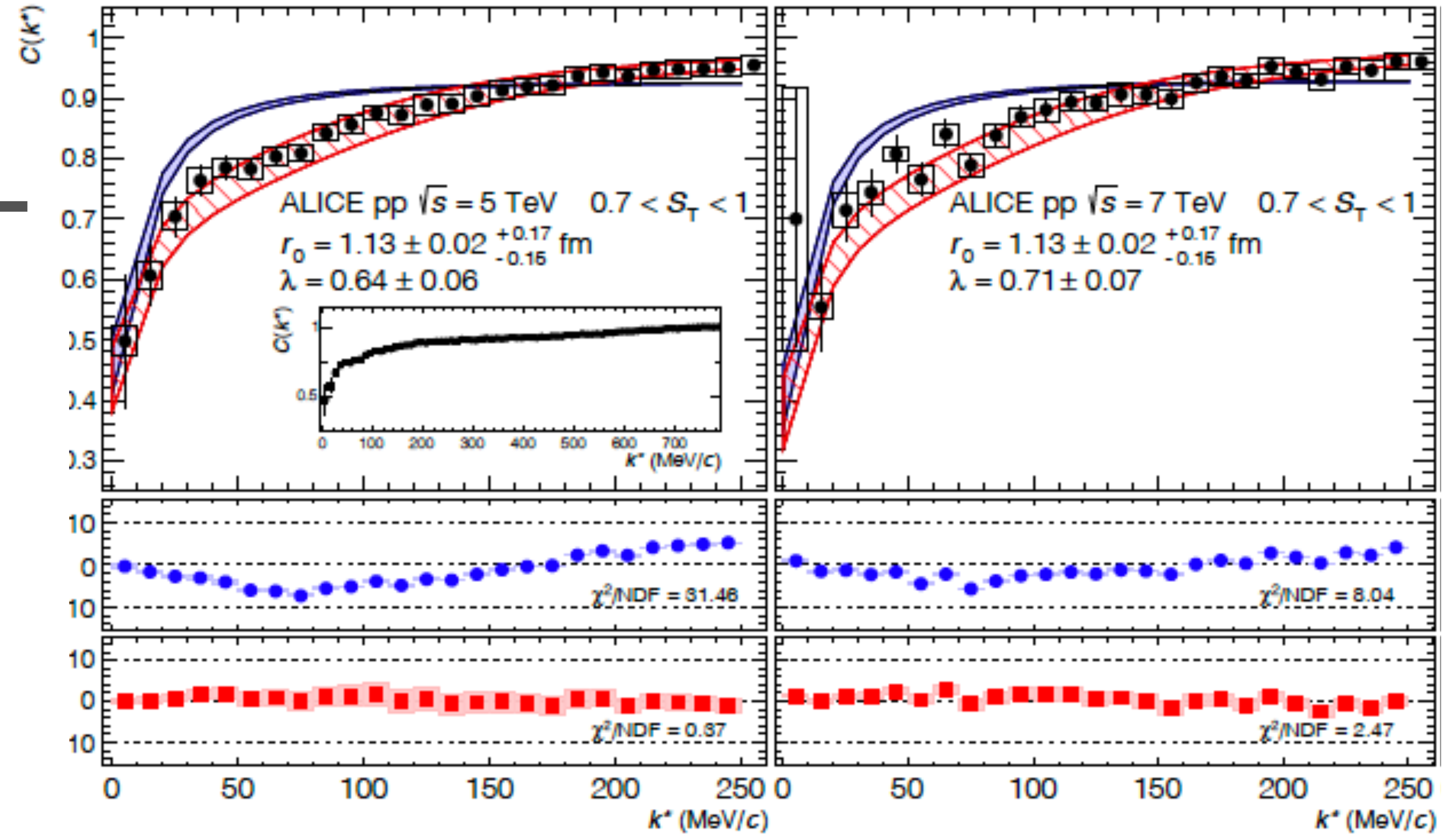
Proton-kaon (bound state?)

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



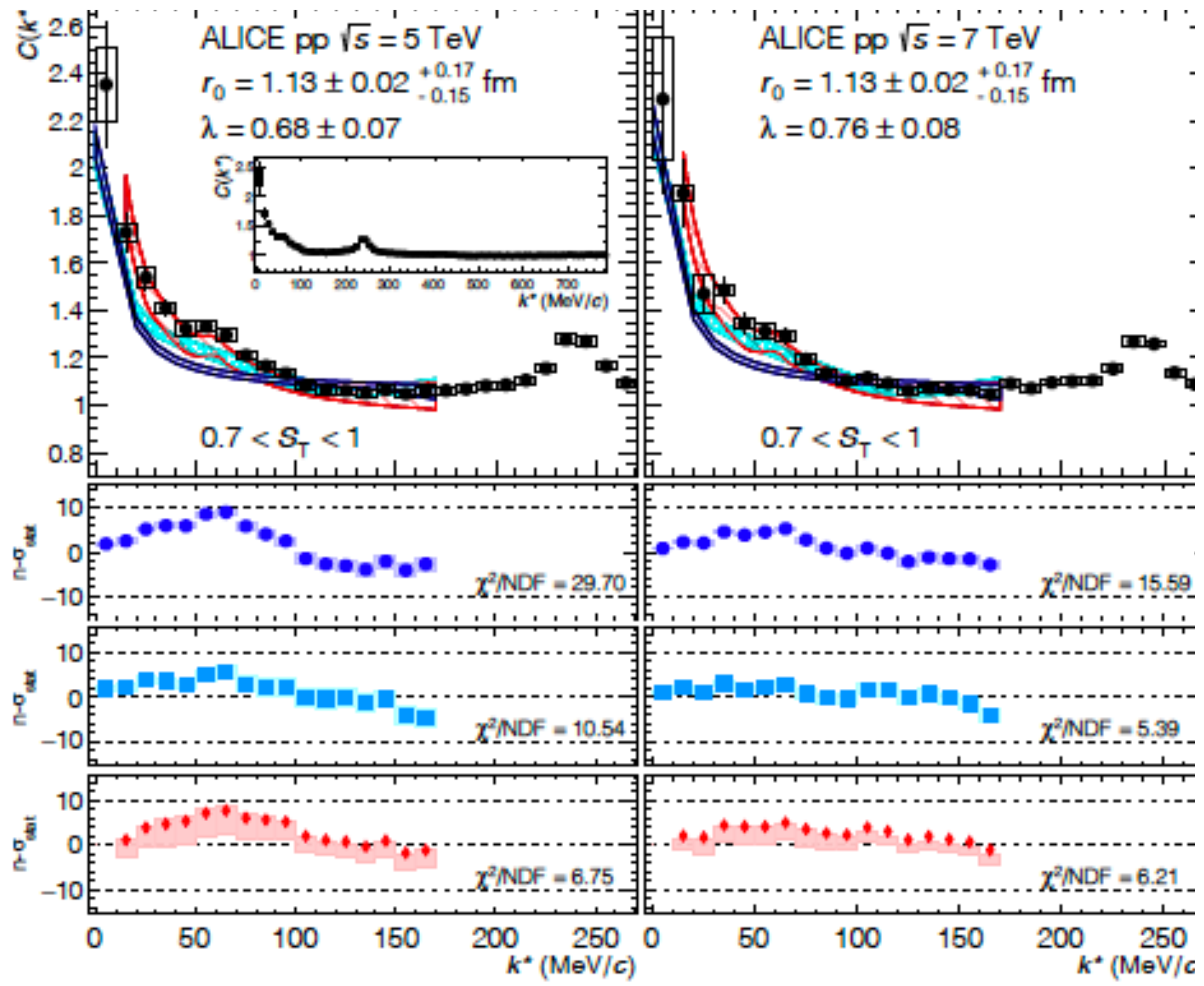
Opposite charges 0-10% @ Au+Au 39 GeV



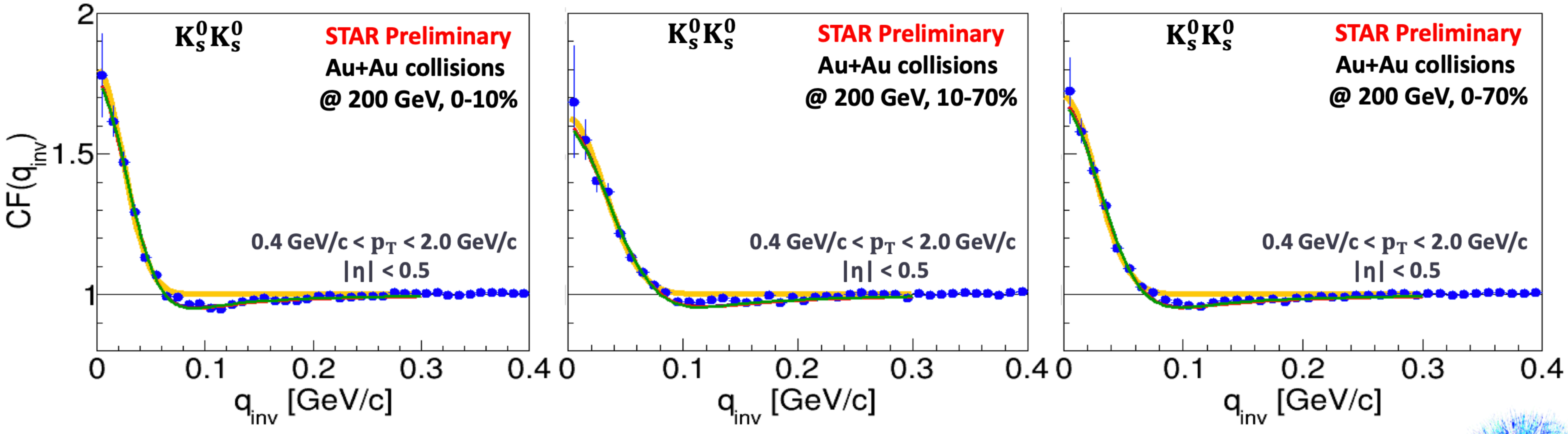


Phys.Lett.B 813 (2021) 136030

- 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.

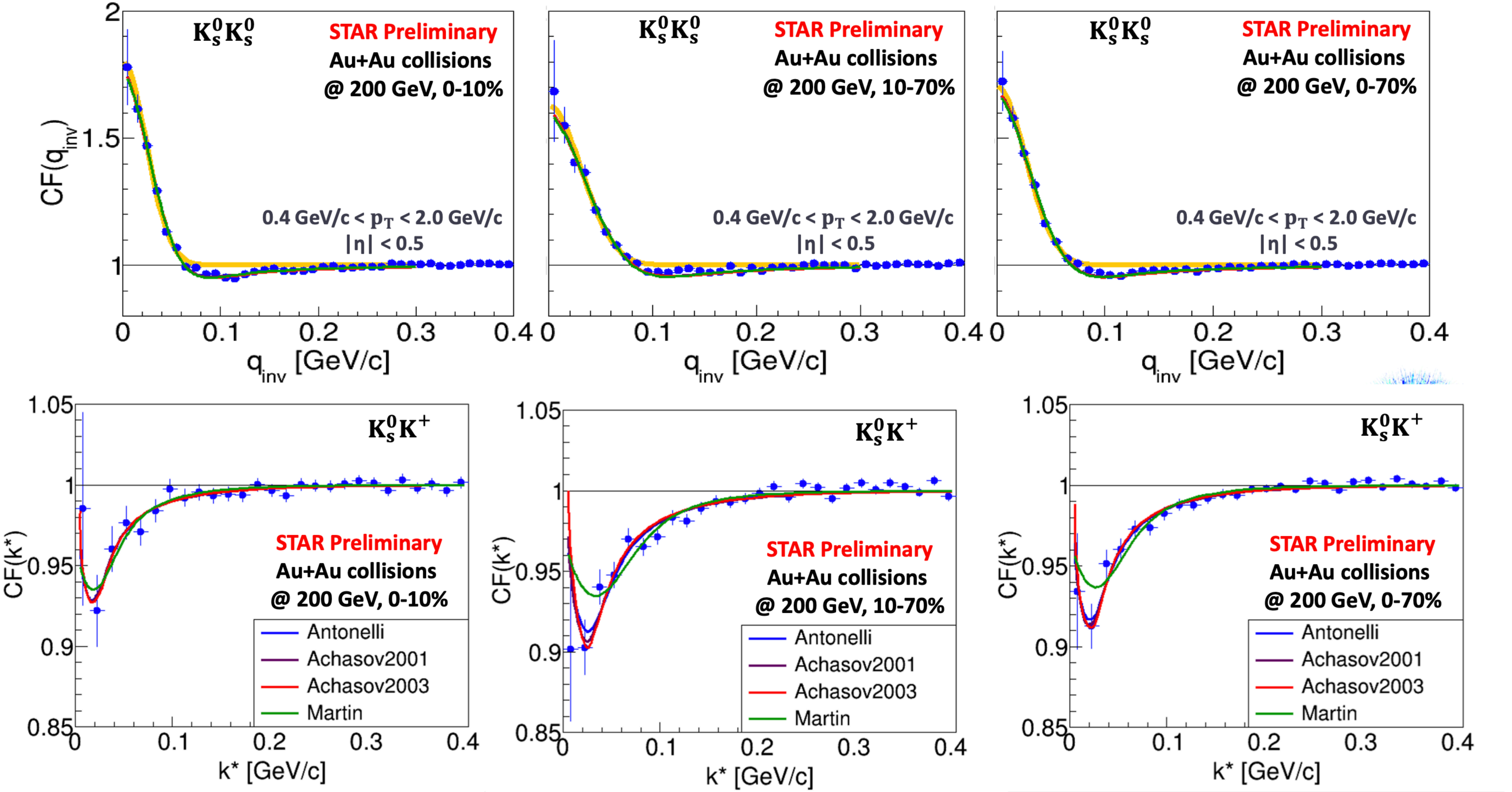


Neutral kaons



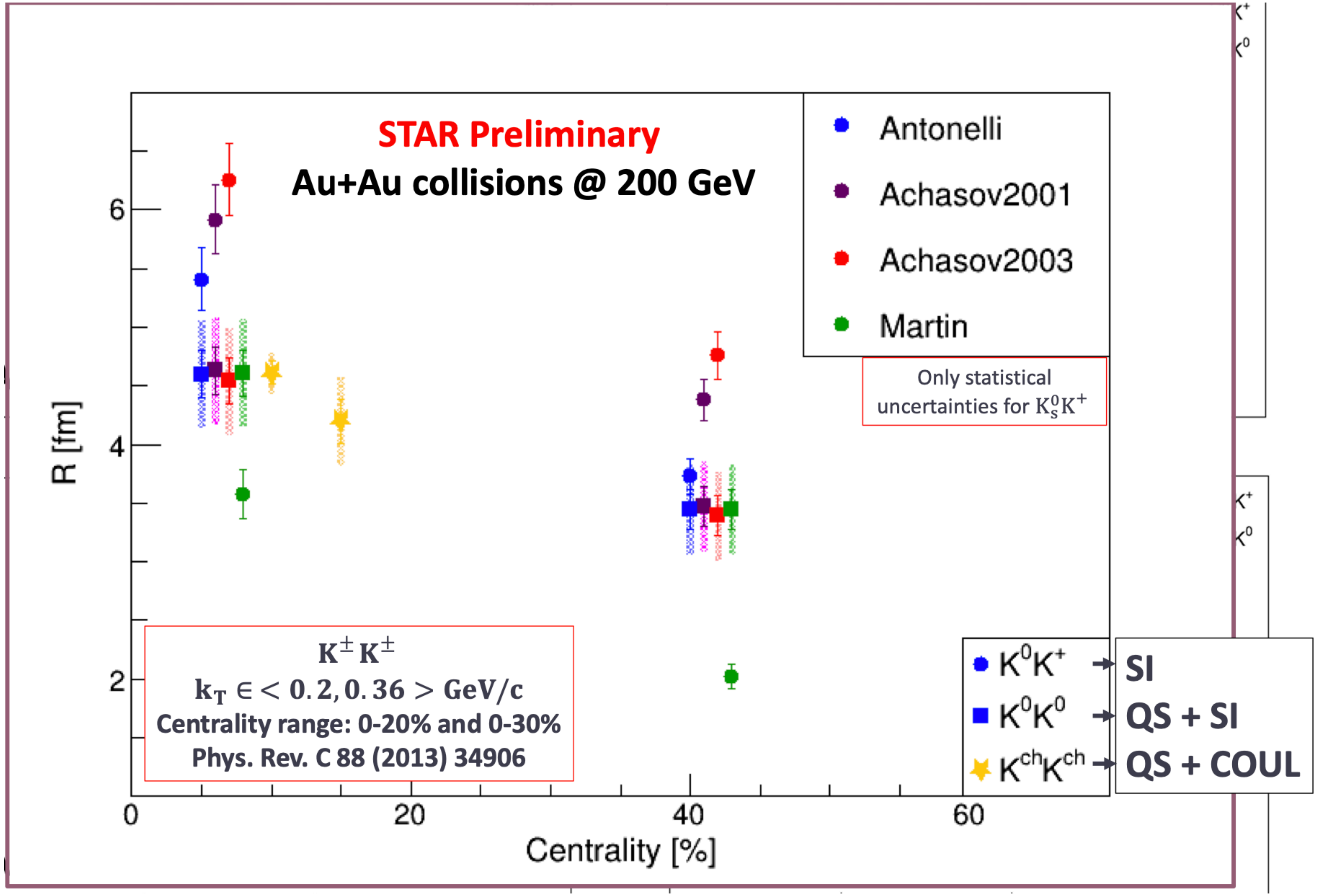
The **strong** final-state interaction has a significant effect on the **neutral kaon**s correlation due to the near-threshold $f_0(980)$ **and** $a_0(980)$ resonances

Neutral kaons



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**

Neutral kaons



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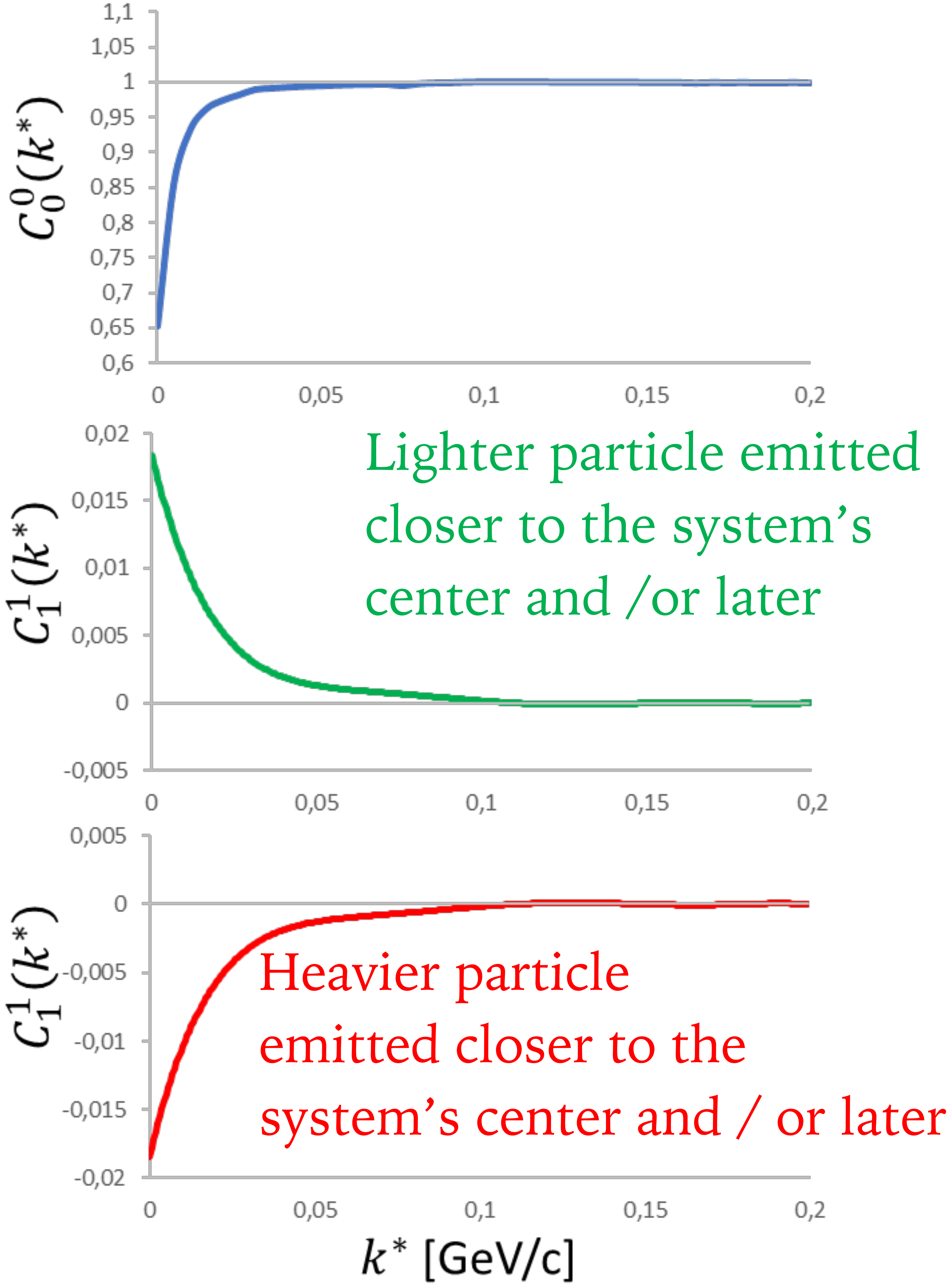
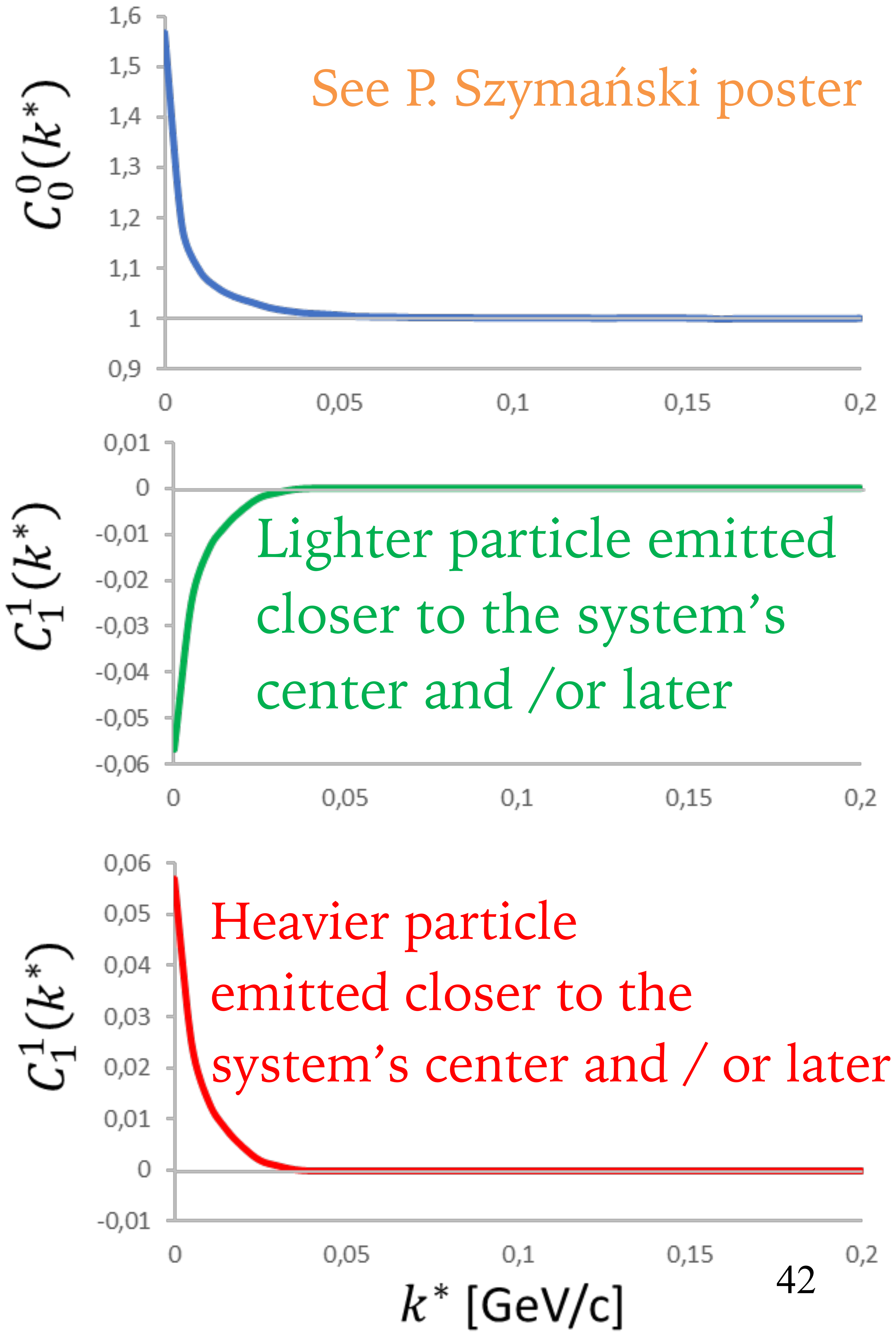
Nonidentical particles - emission asymmetry

Same charges



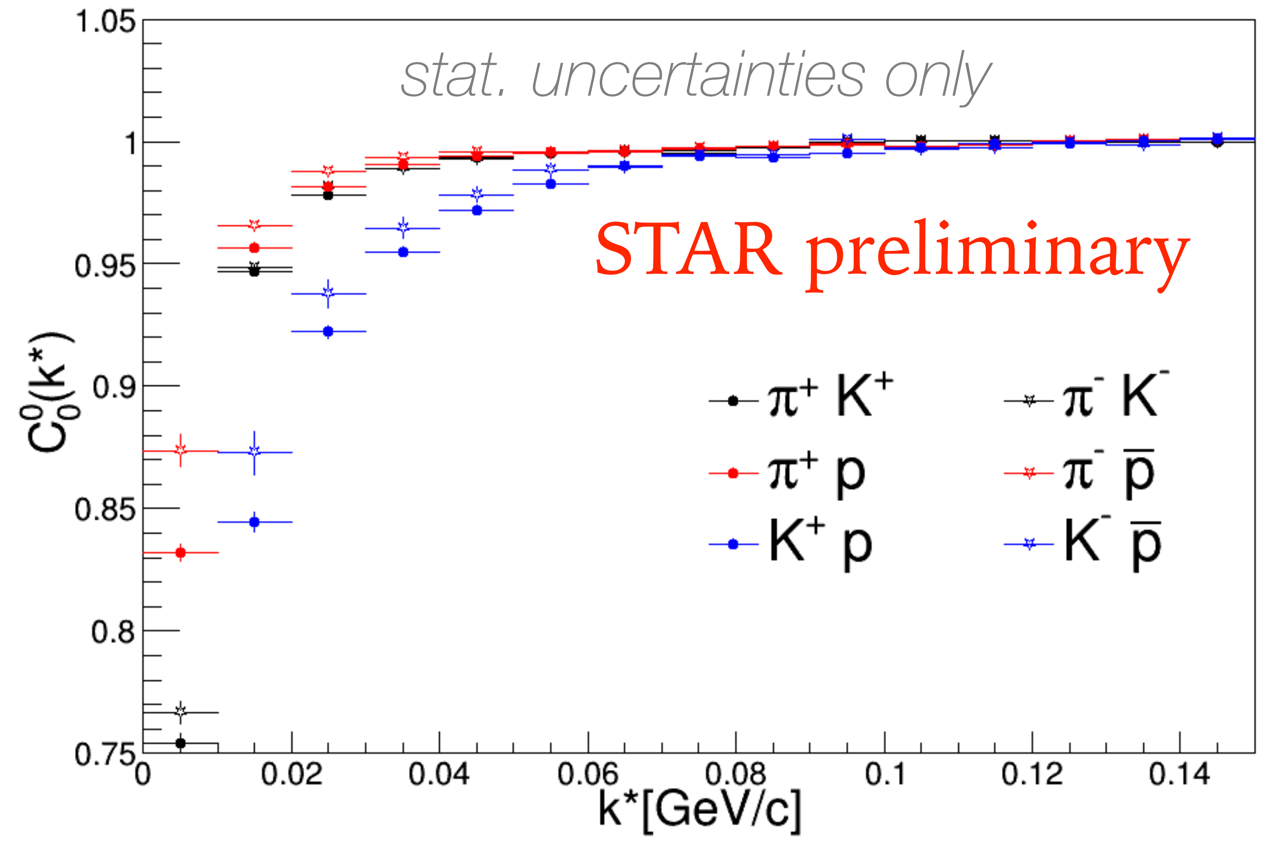
Opposite charges

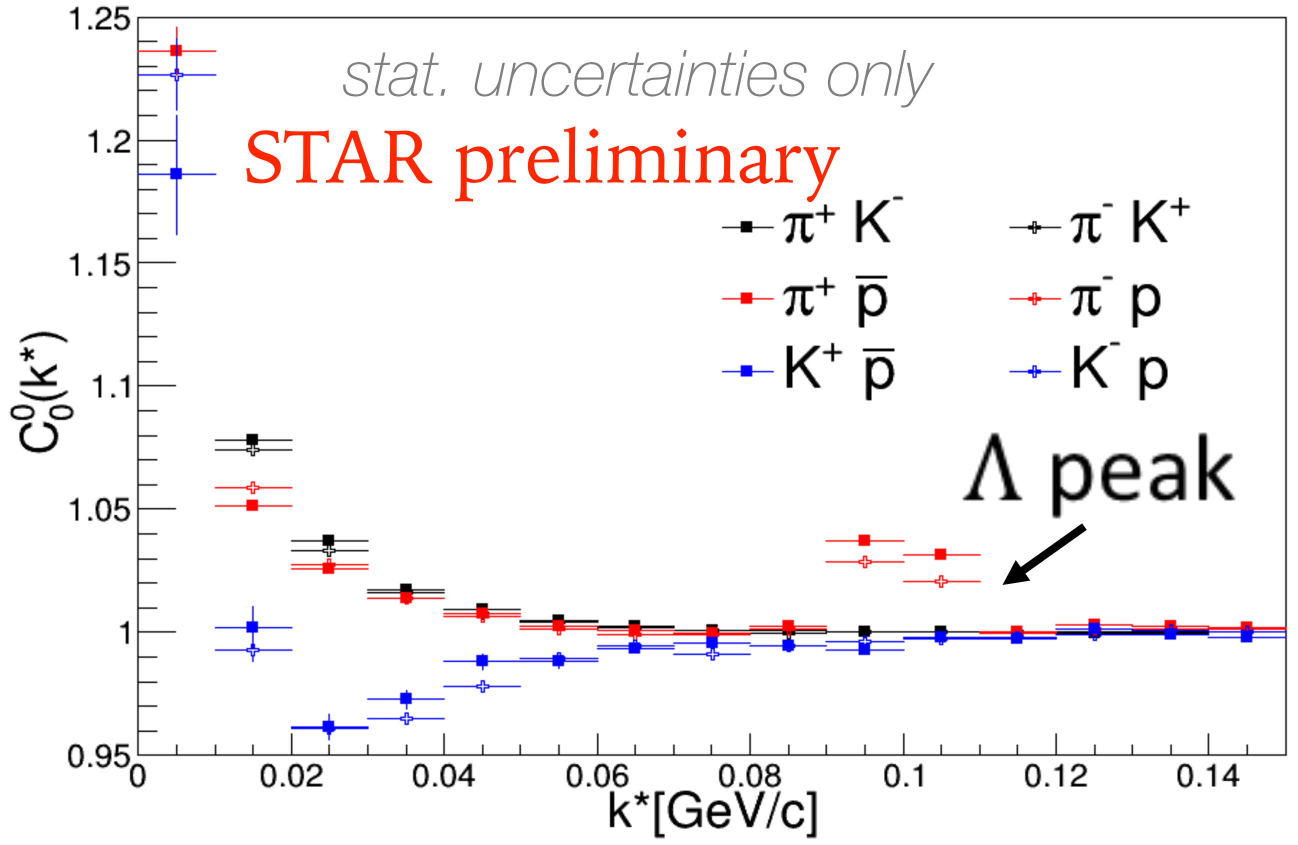


Nonidentical particle correlations

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

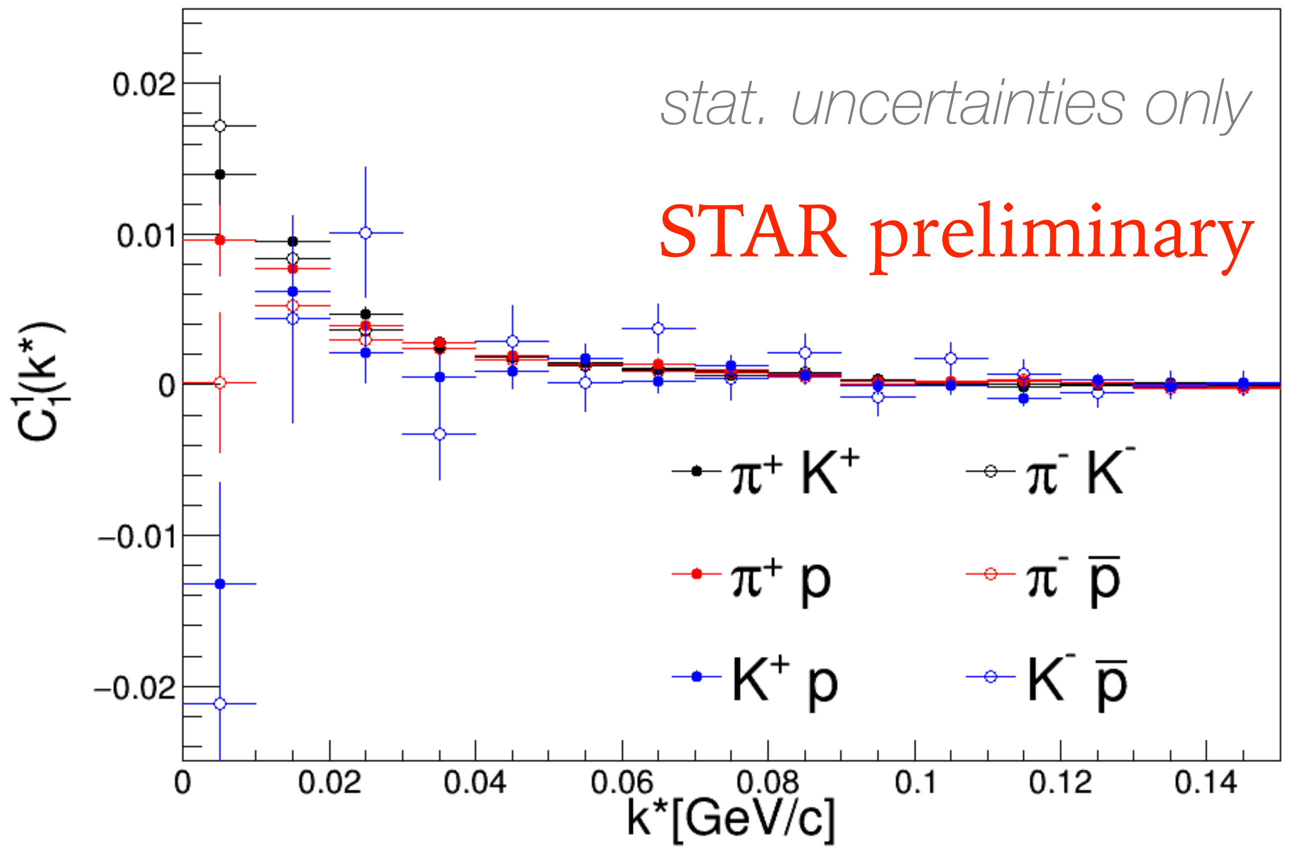
Unlike-sign 0-10% @ Au+Au 39 GeV

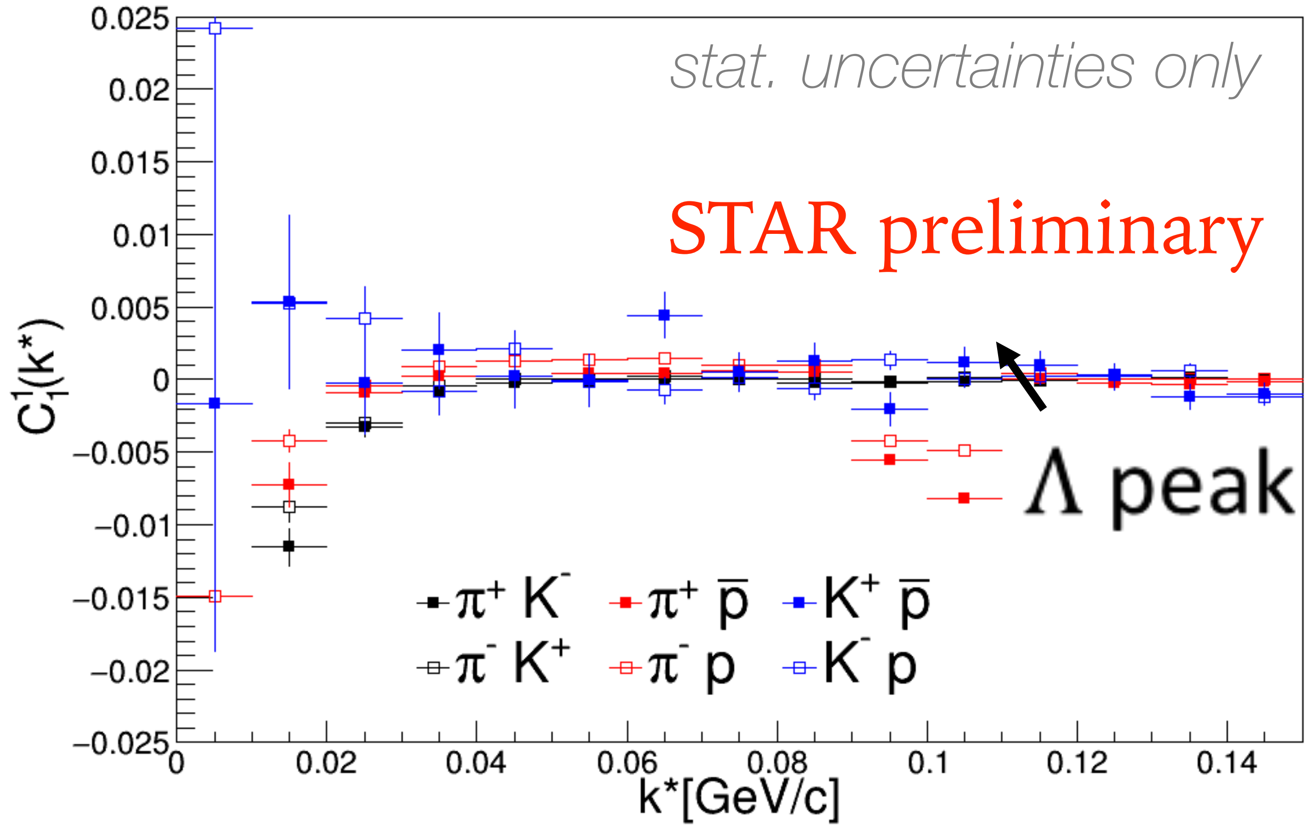




Determined by Coulomb Interactions

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

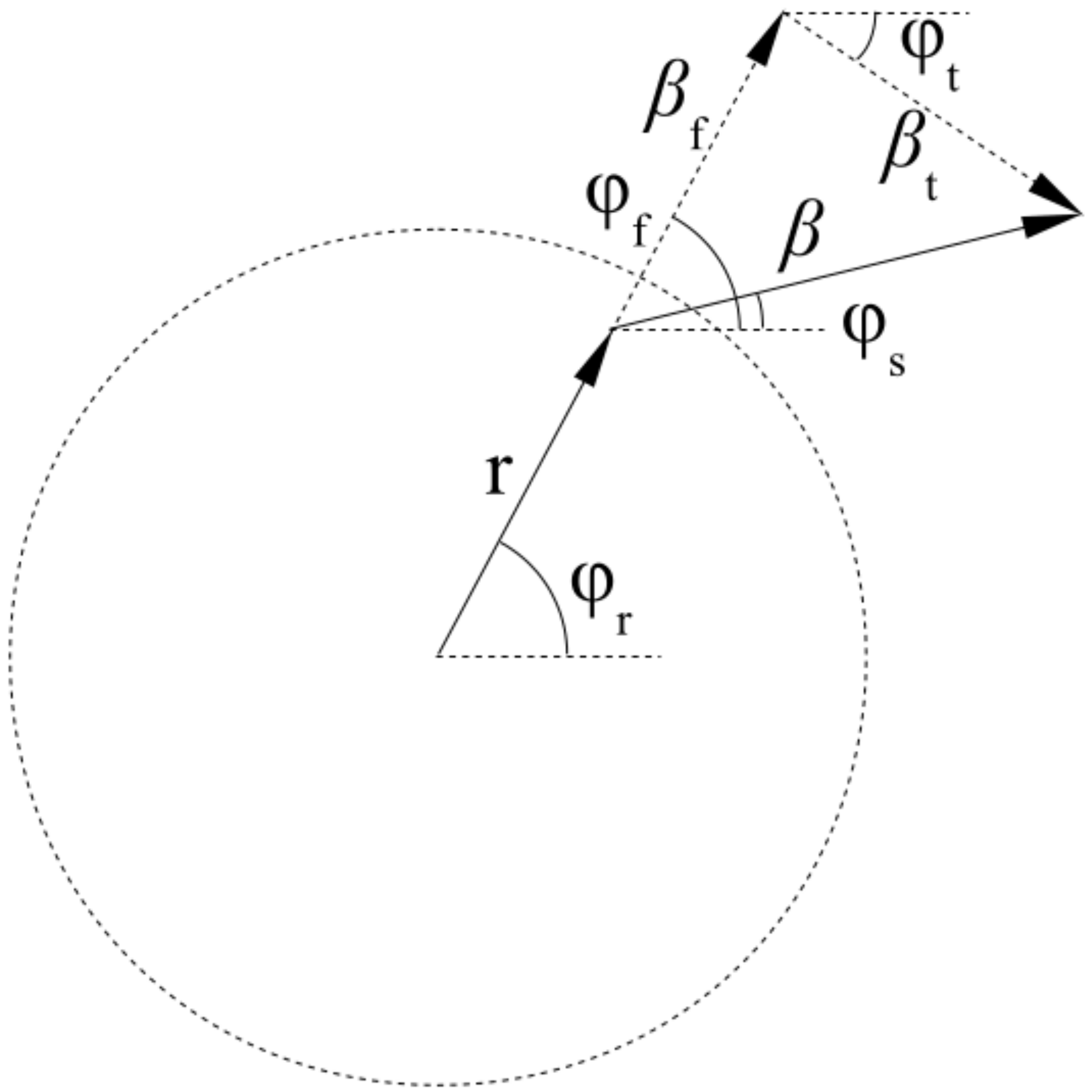




Nucl. Phys. A 982 (2019), 359-362

Heavier   directed towards edge of the source.
Heavier particles freeze-out earlier

Phys. Rev. C81:064906 2010



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

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