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# Strong final state interactions seen by femtoscopy

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GDR QCD Seminar, 6th October 2022

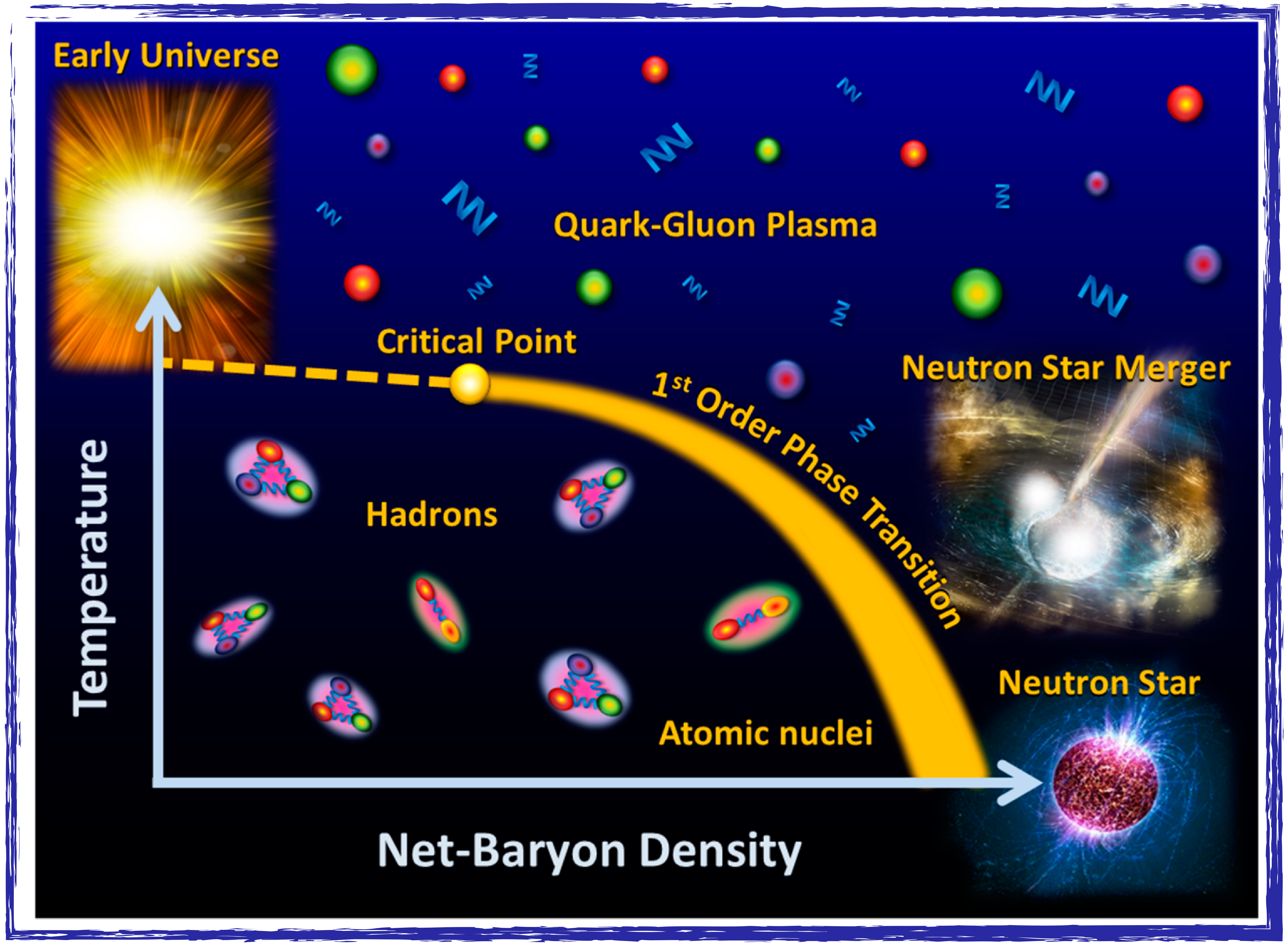
# Outline

**Introduction**

- QCD phase diagram
- HIC and femtoscopy method

**Results**

1. **Interactions**
   - 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
2. **QCD Phase diagram scan**

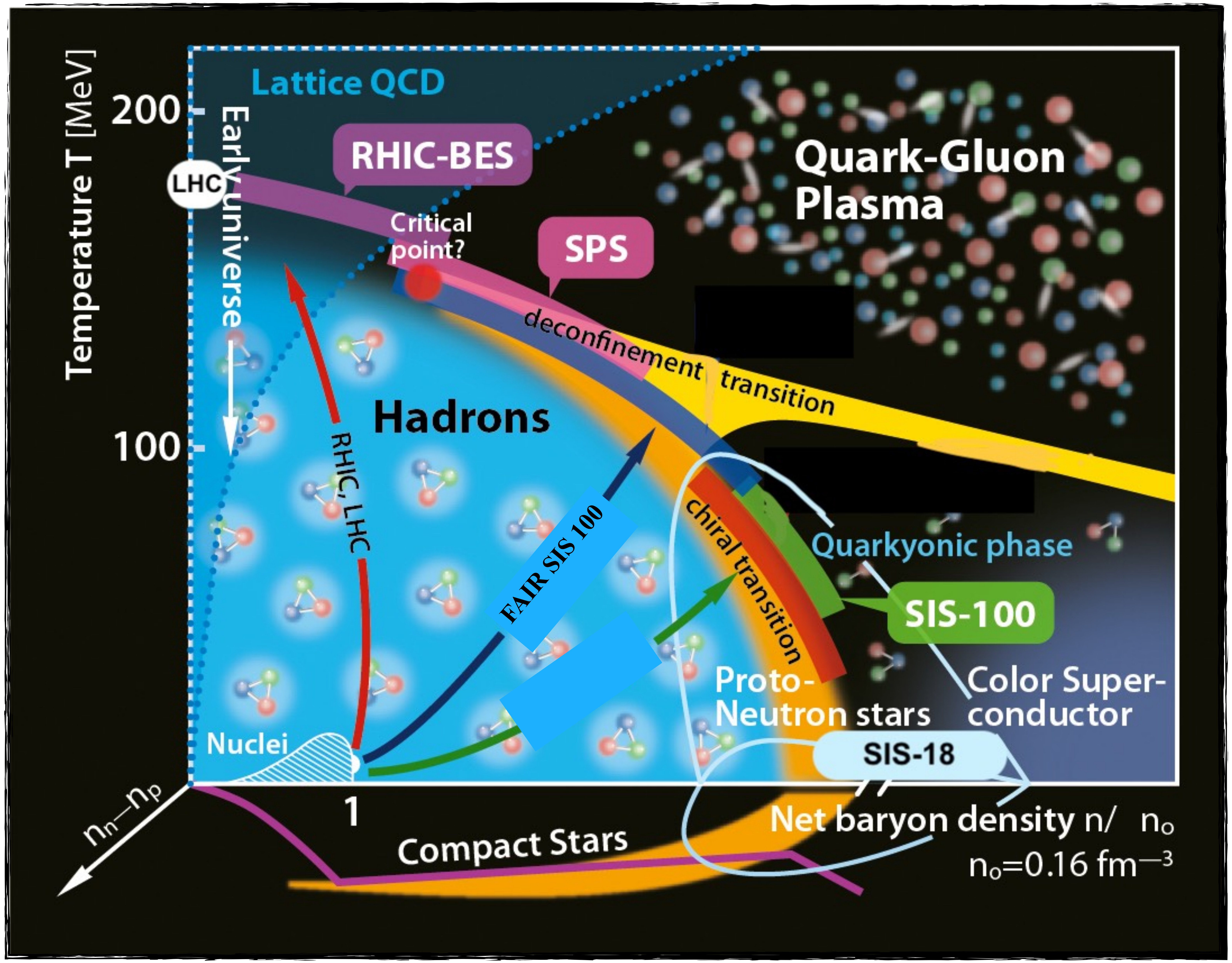


*https://www.researchgate.net/figure/Color-Online-A-schematic-of-QCD-phase-diagram_fig2_357552969*

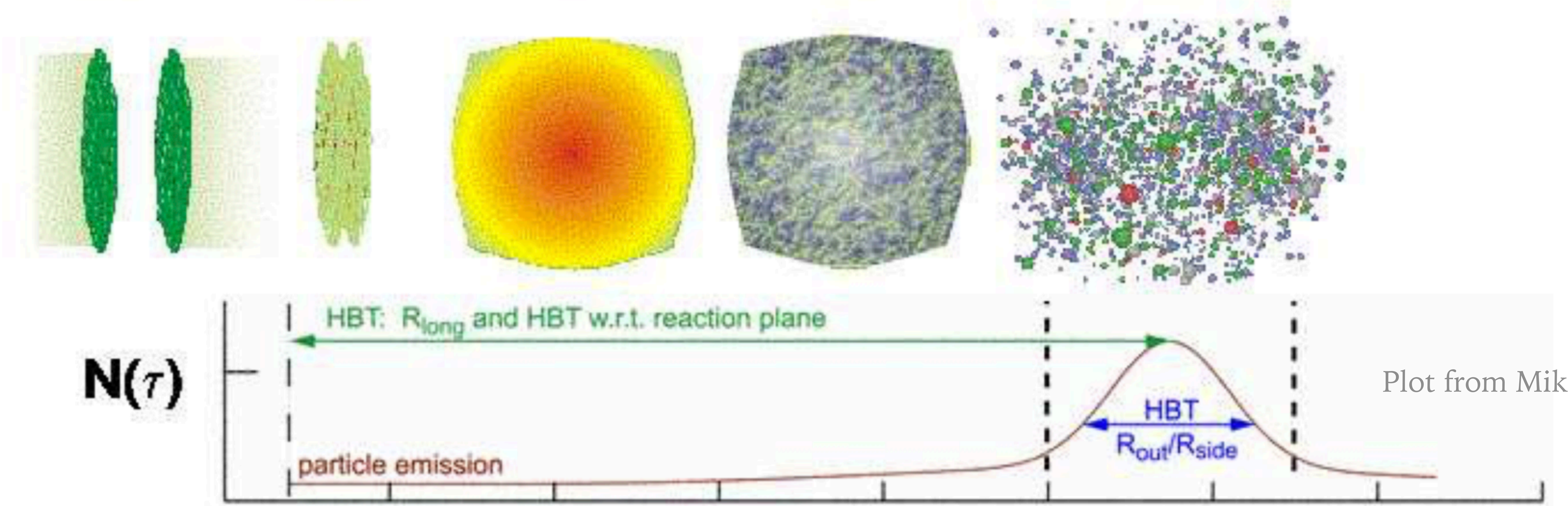
**Summary and conclusions**

# Introduction

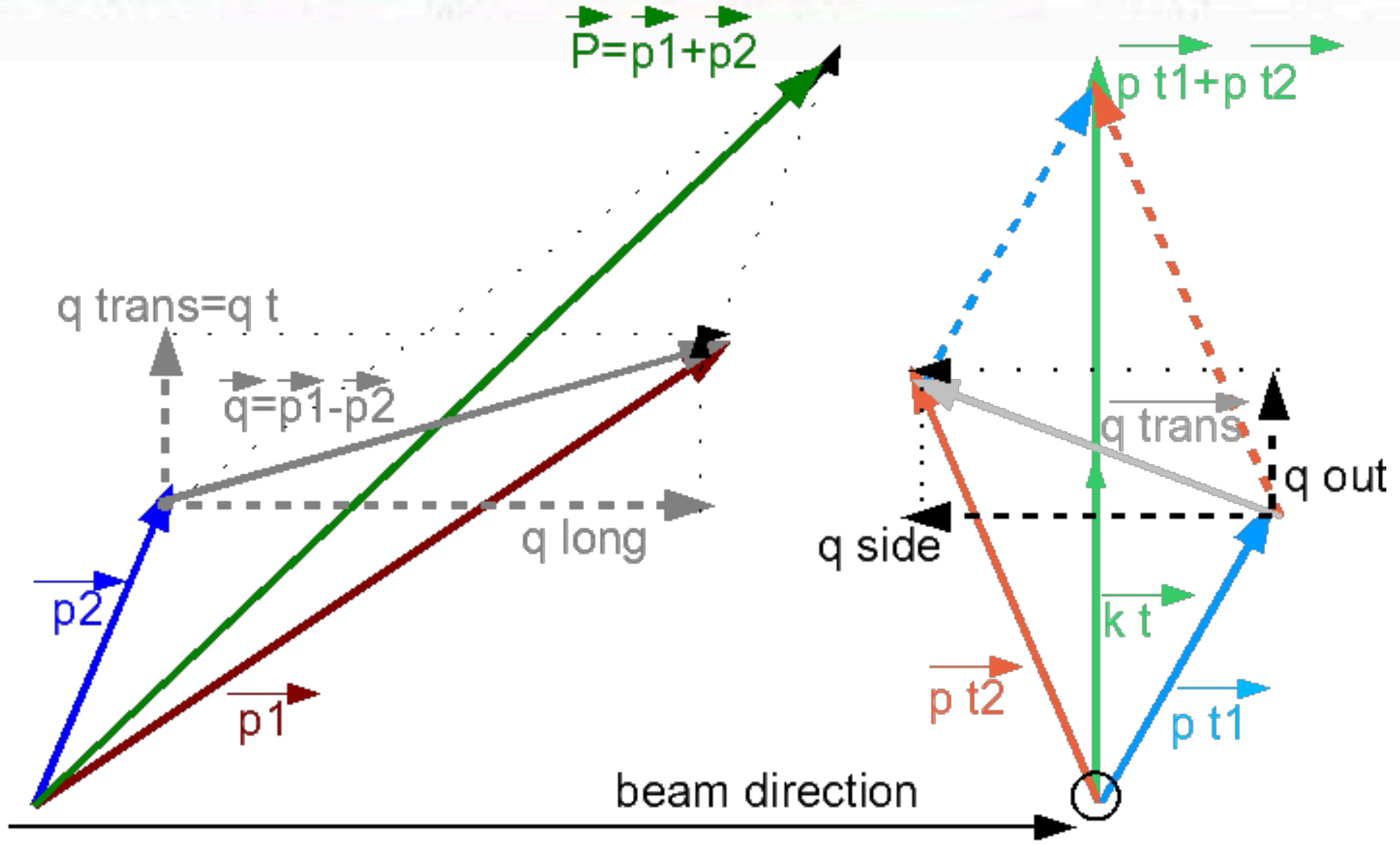
# QCD Phase diagram of strongly interacting matter



# Heavy-Ion collision and the HBT method



Plot from Mike Lisa

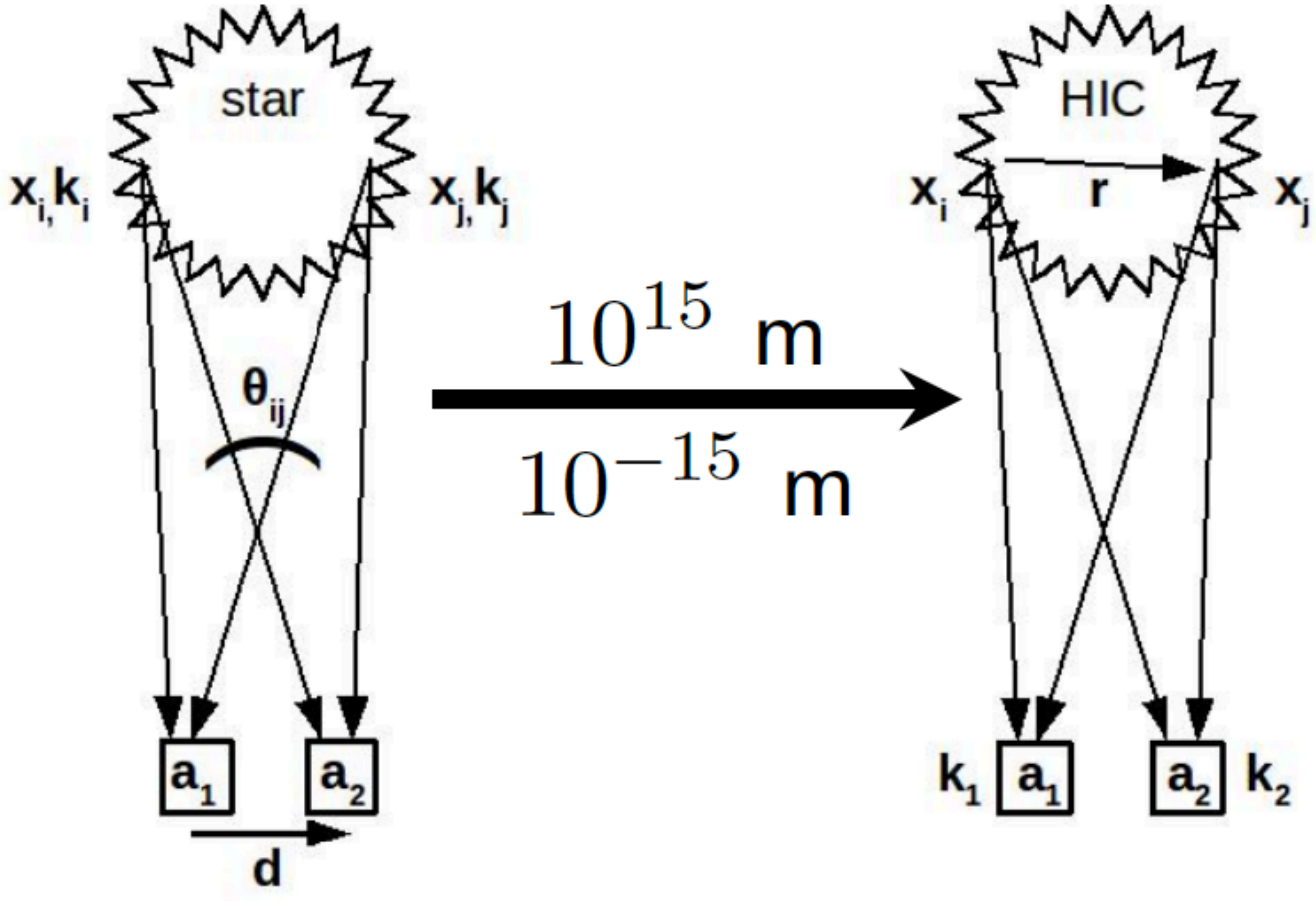


*long* - beam axis
*out* - pair transverse **p**
*side* - perpendicular to
out and long

# Correlation **femtoscopy**

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

Impossible
to measure directly!



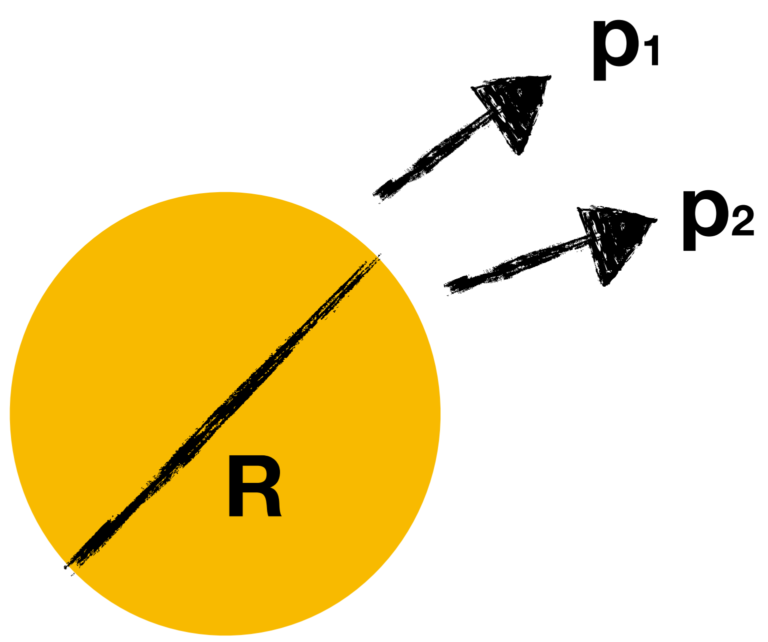
Femtoscopy (HIC) inspired by Hanbury Brown and Twiss interferometry method (Astronomy)

**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)

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

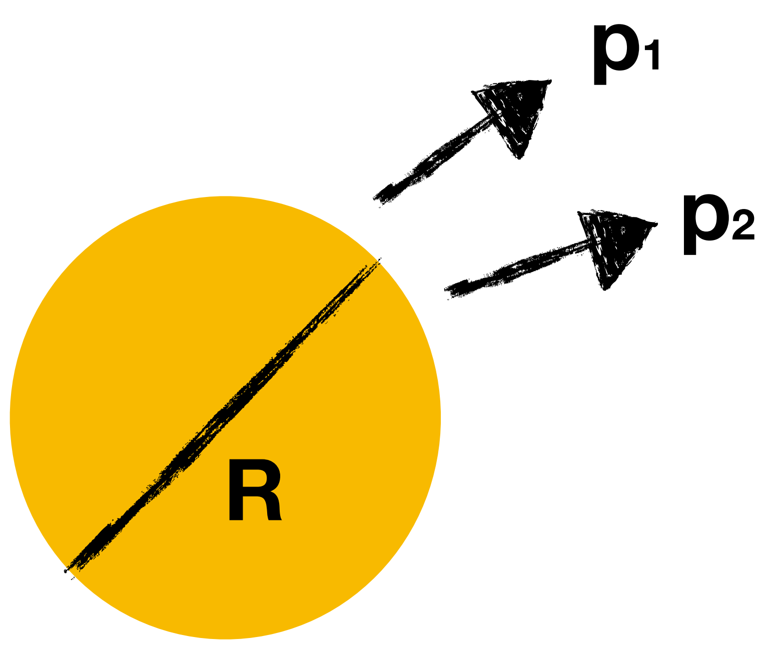
$S(r*)$ - emission function

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

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

# Traditional and non-traditional femtoscopy

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

**Final State Interactions** (Coulomb, strong)

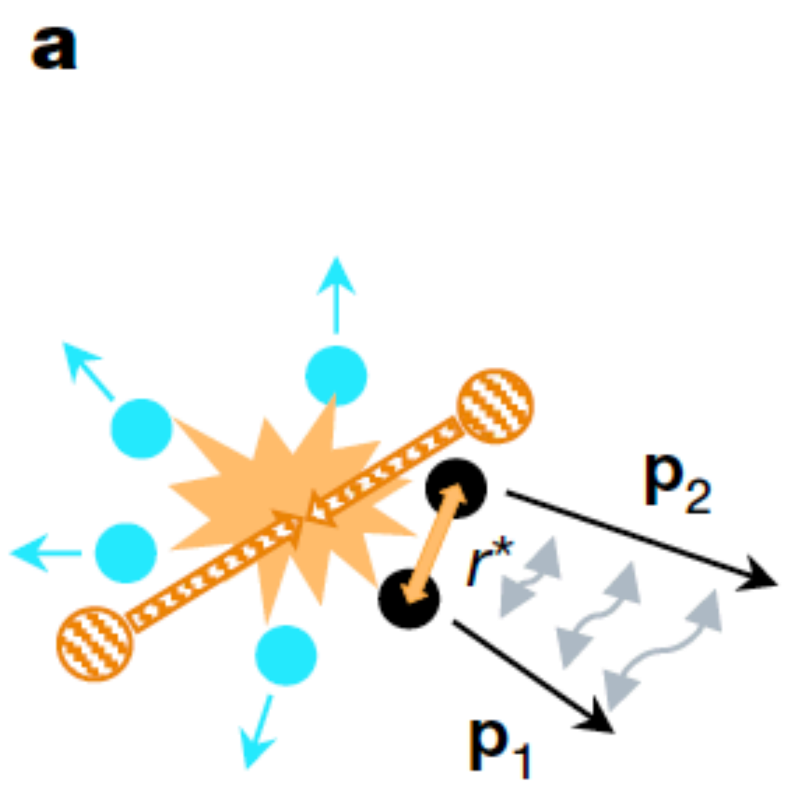
$$C(k^*, r^*) = \overset{\text{assumed}}{\int S(r^*)} \overset{\text{determined}}{|\Psi(k^*, r^*)|^2} d^3r^* = \overset{\text{measured}}{\frac{Sgnl(k^*)}{Bckg(k^*)}}$$

$S(r^*)$ - emission function

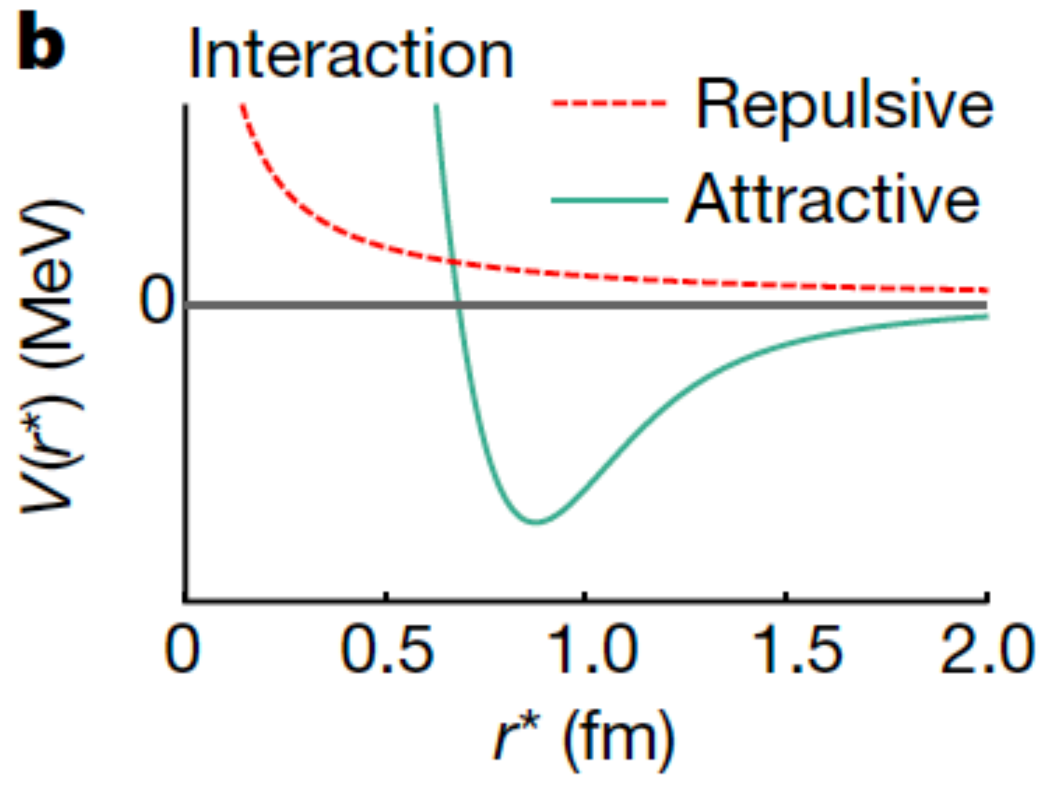
$\Psi(k^*, r^*)$ - two-particle wave function (includes e.g. FSI interactions)

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

# Traditional and non-traditional femtoscopy



Emission source *S*(*r**)

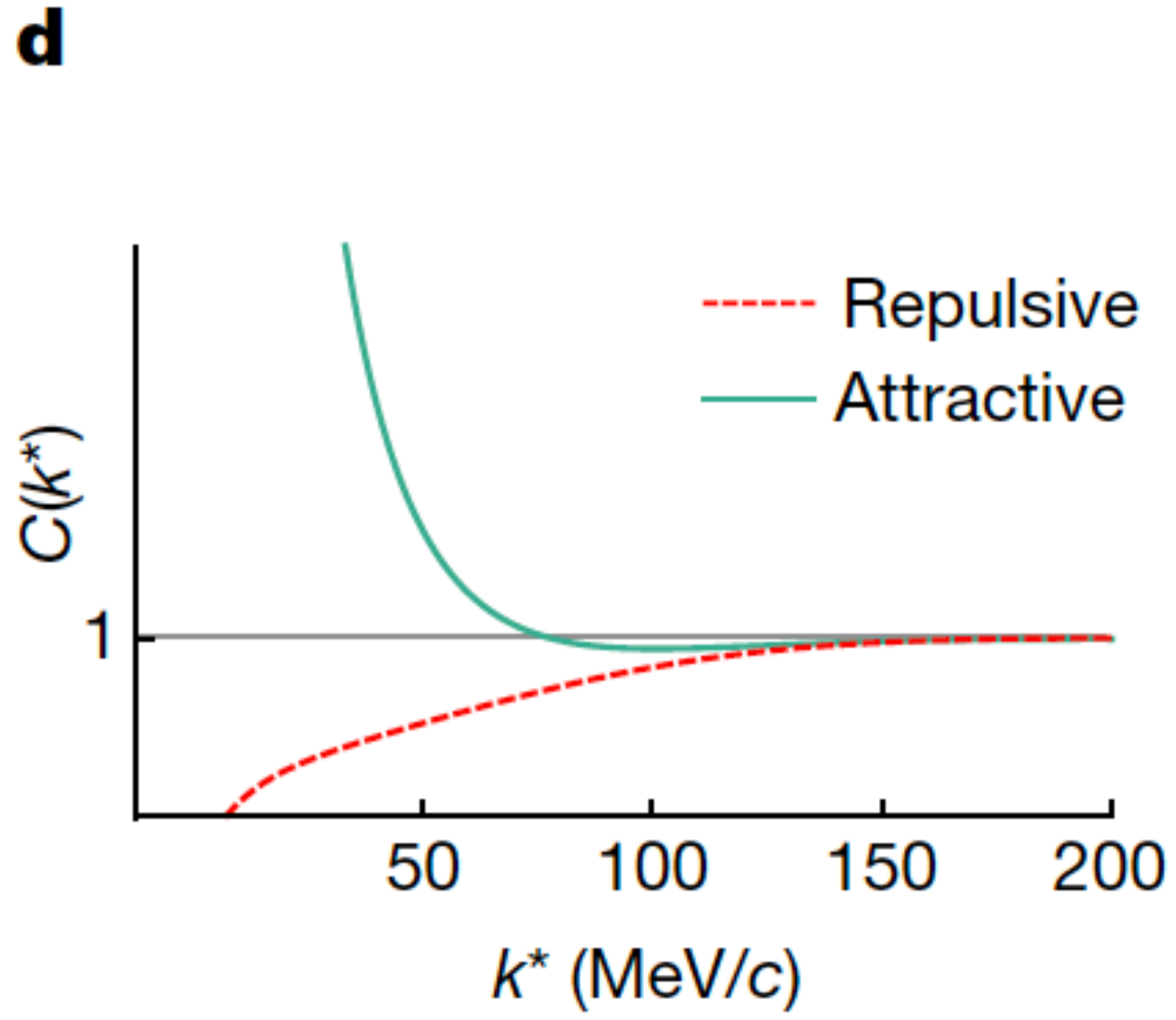


Schrödinger equation

↓

Two-particle wavefunction

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



Correlation function

**c**

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

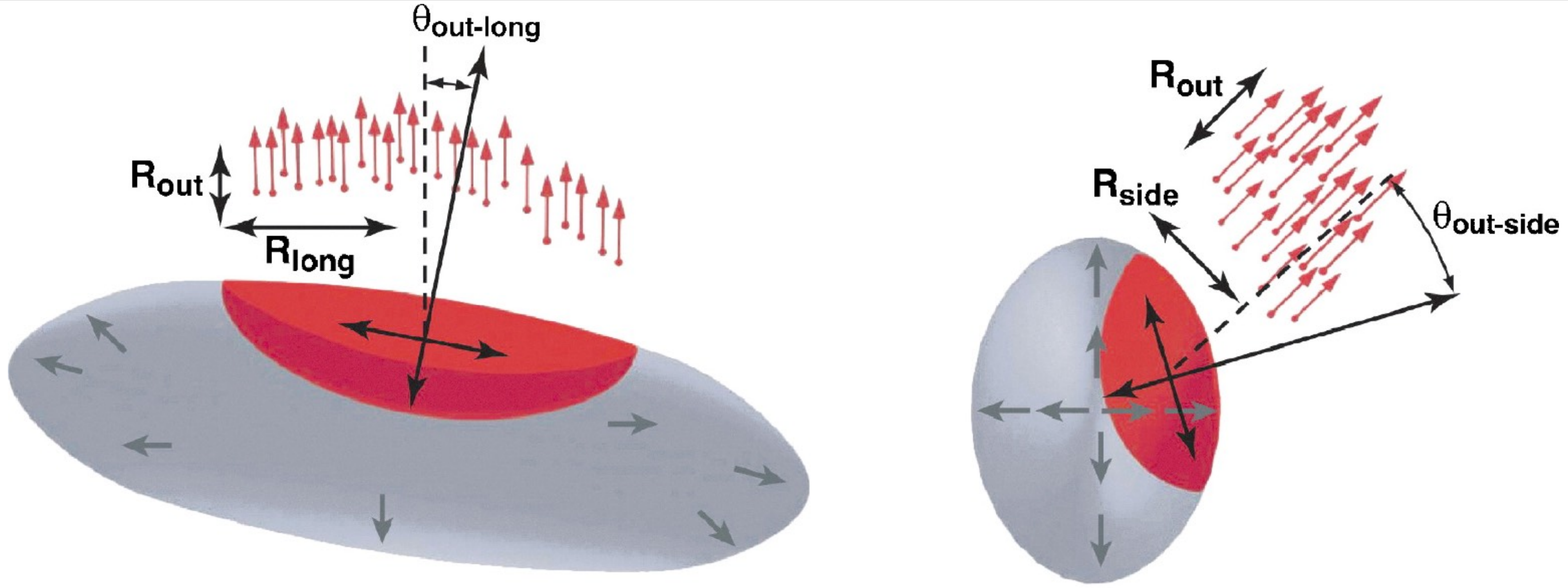
Object of study of
Traditional femtoscopy

Object of study of
non-traditional femtoscopy

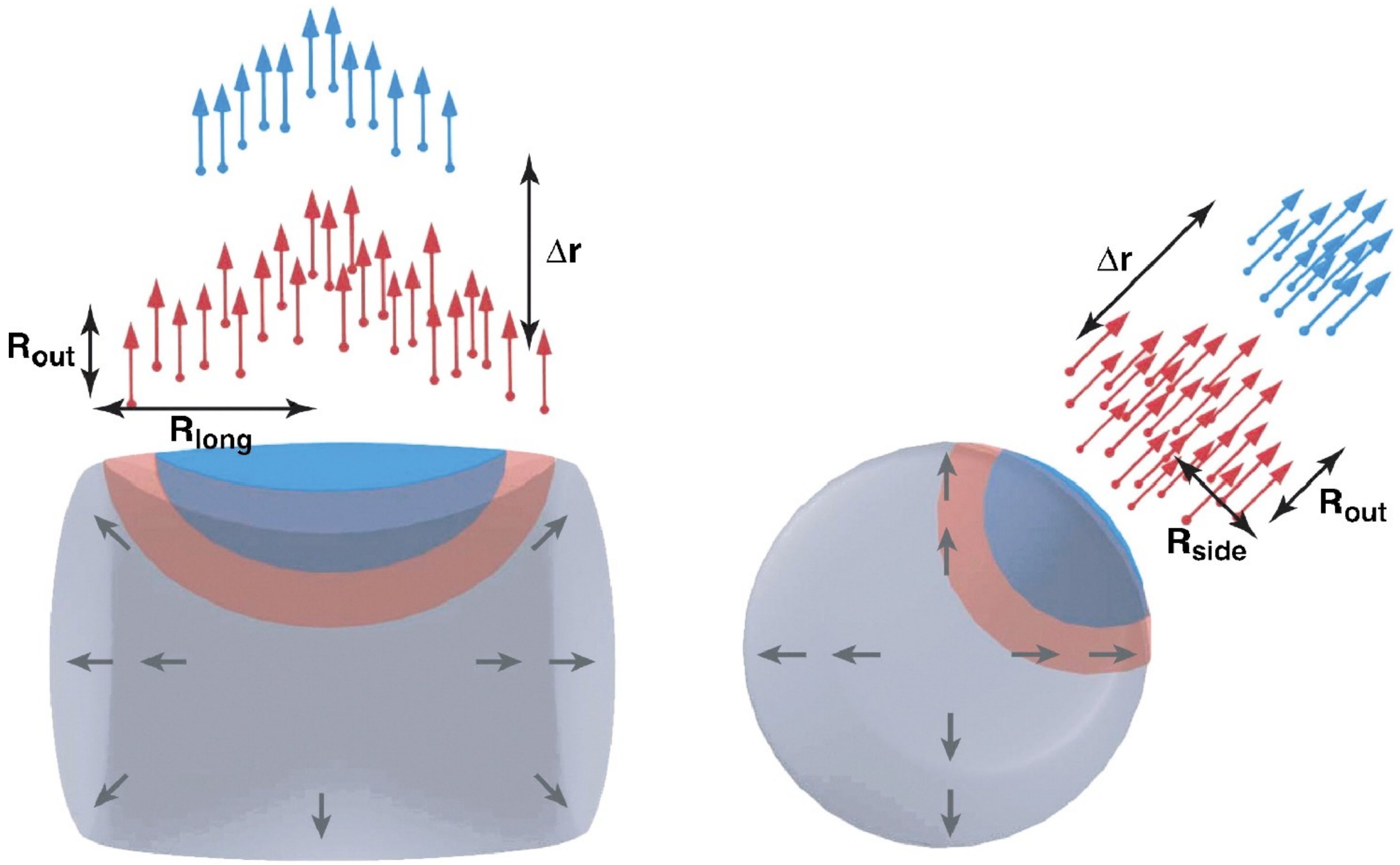
Pairs from the
same collision

Pairs from the
different collisions

# What does femtoscopy measure?



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

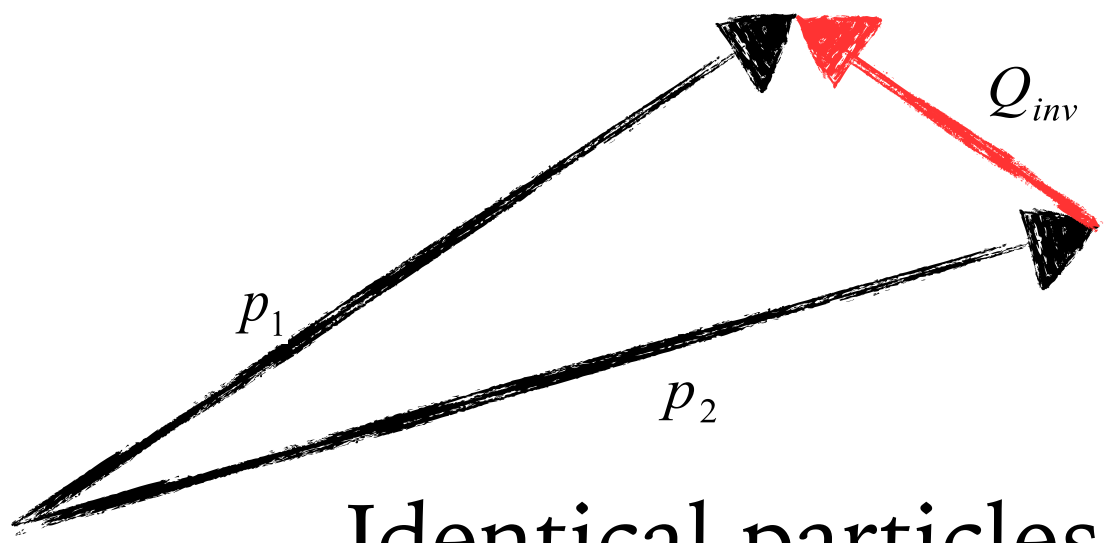


Lisa MA, et al. 2005.
Annu. Rev. Nucl. Part. Sci. 55:357–402

**Homogeneity region**

$Q_{inv}$

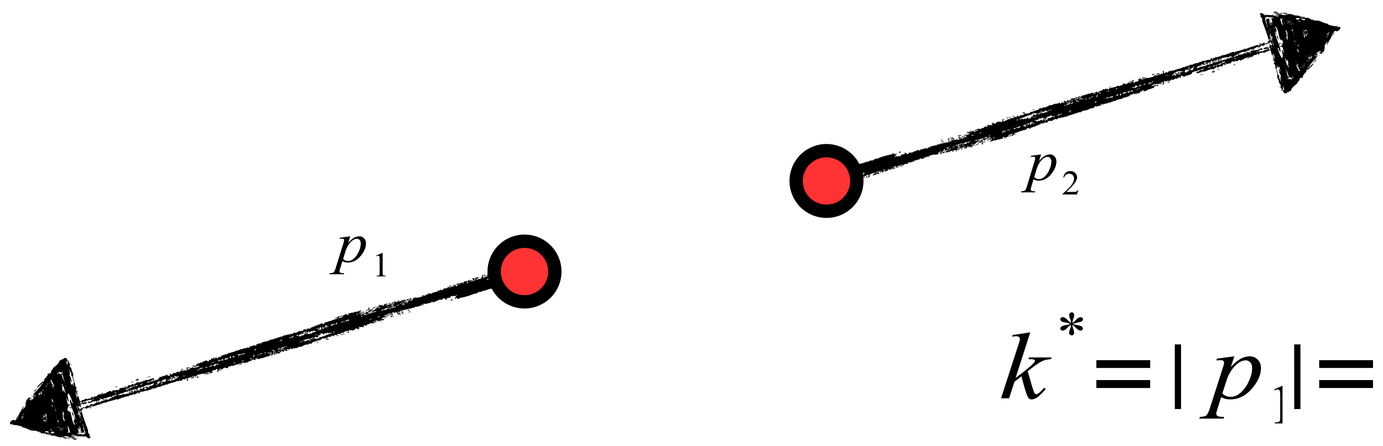
Longitudinal Co-Moving System - **LCMS**



Identical particles

$k^*$

Pair Rest Frame - **PRF**

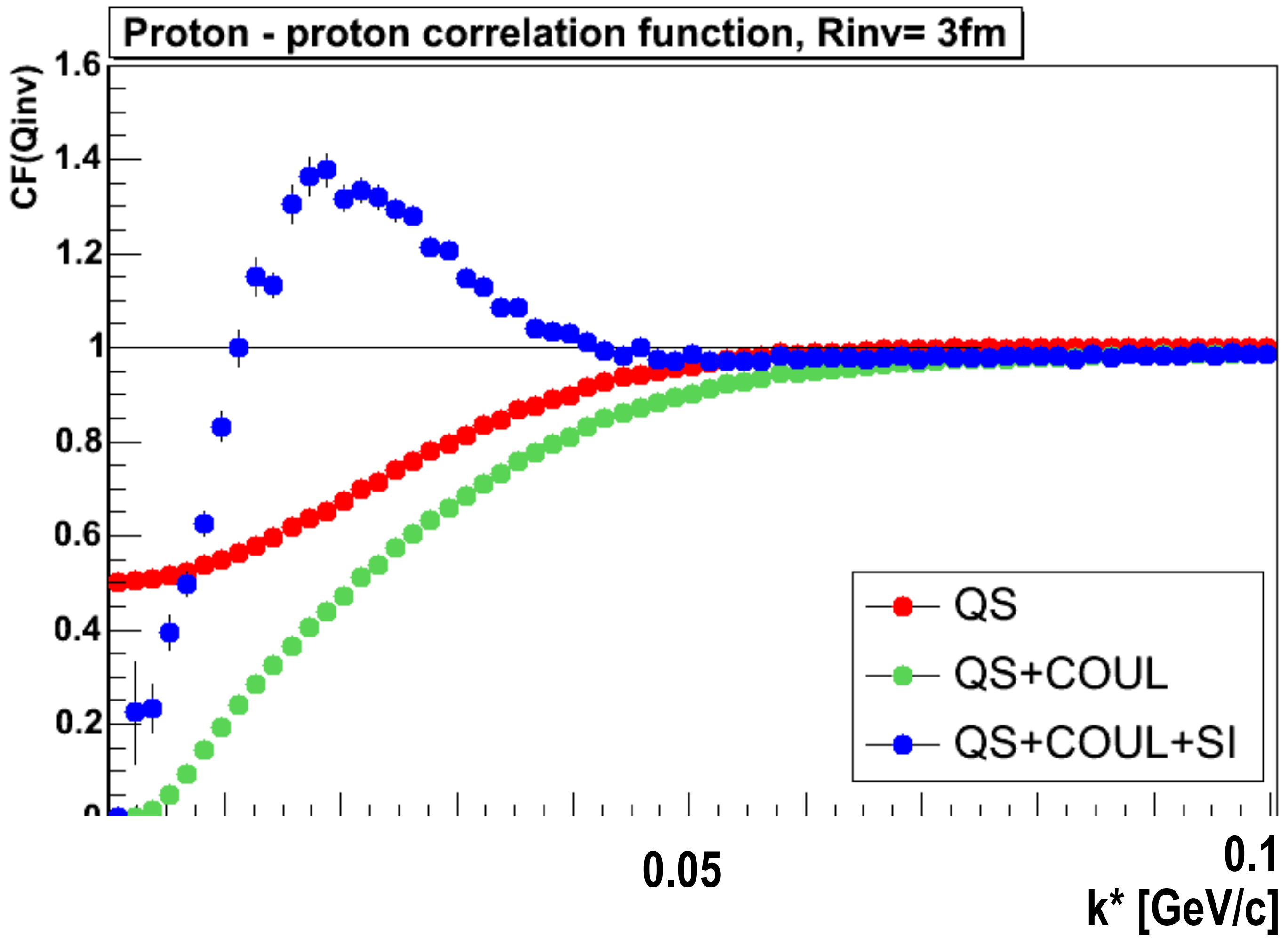


$$k^* = |p_1| = |p_2|$$

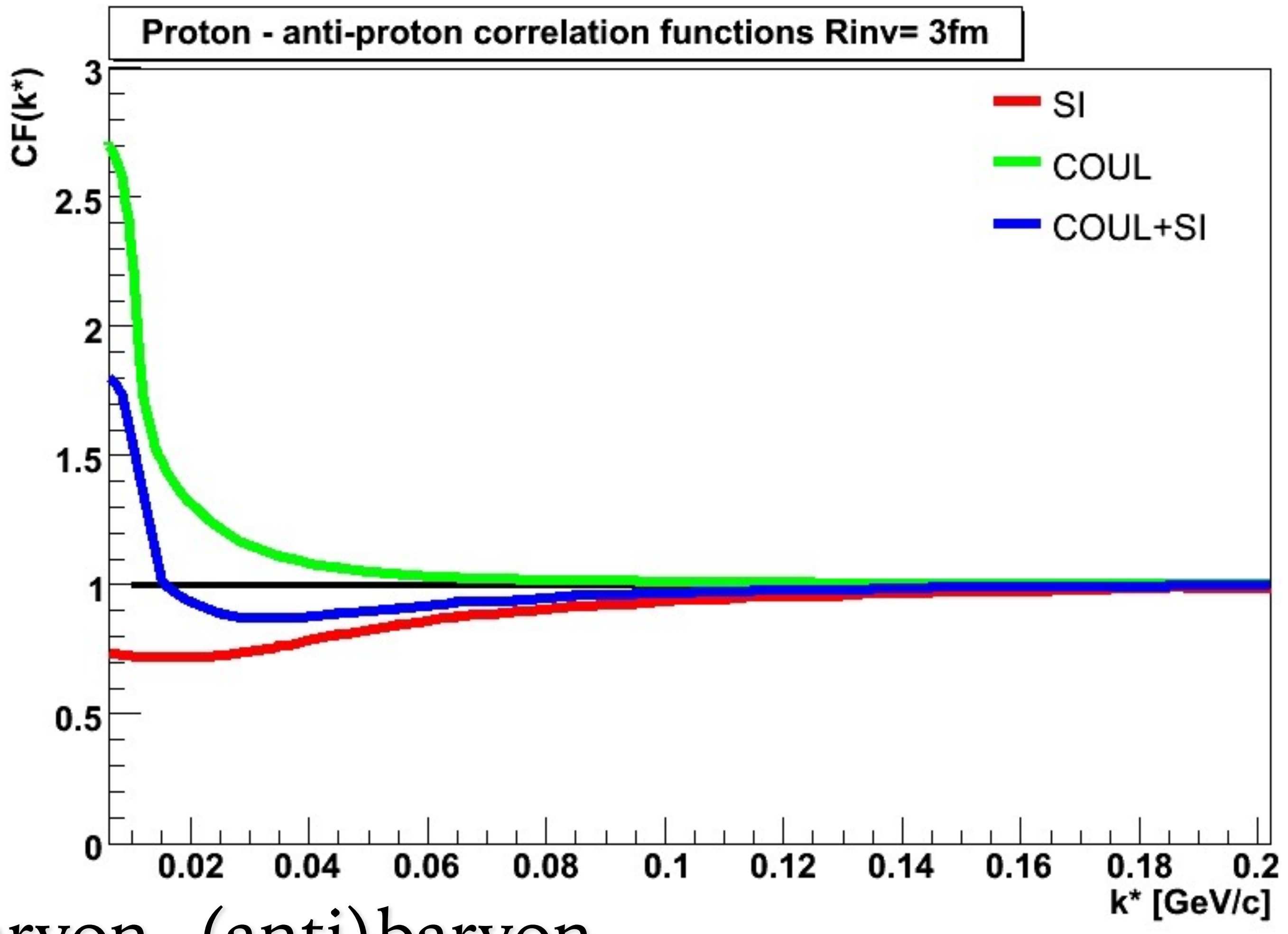
Nonidentical particles

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

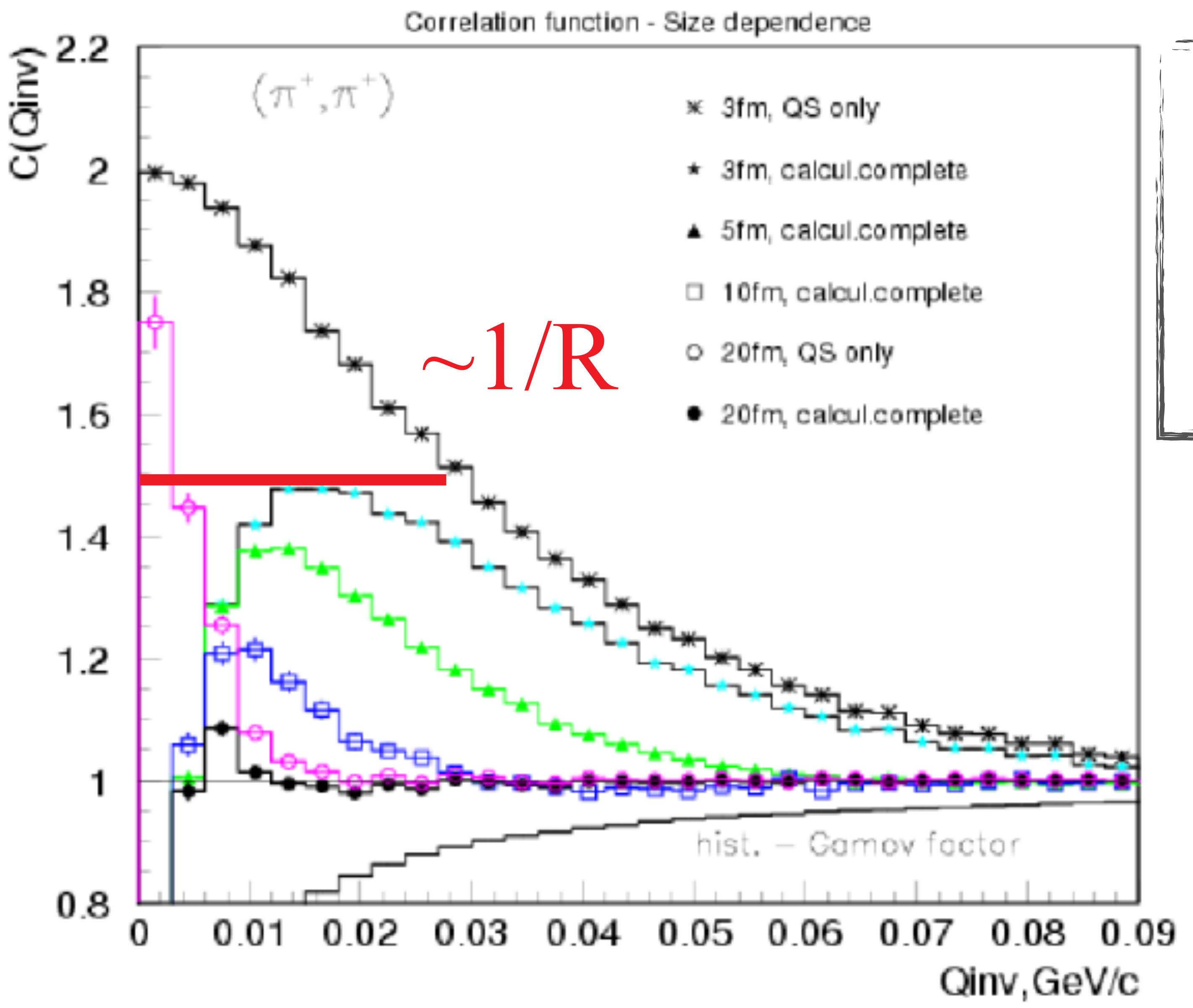
# Effects and interactions



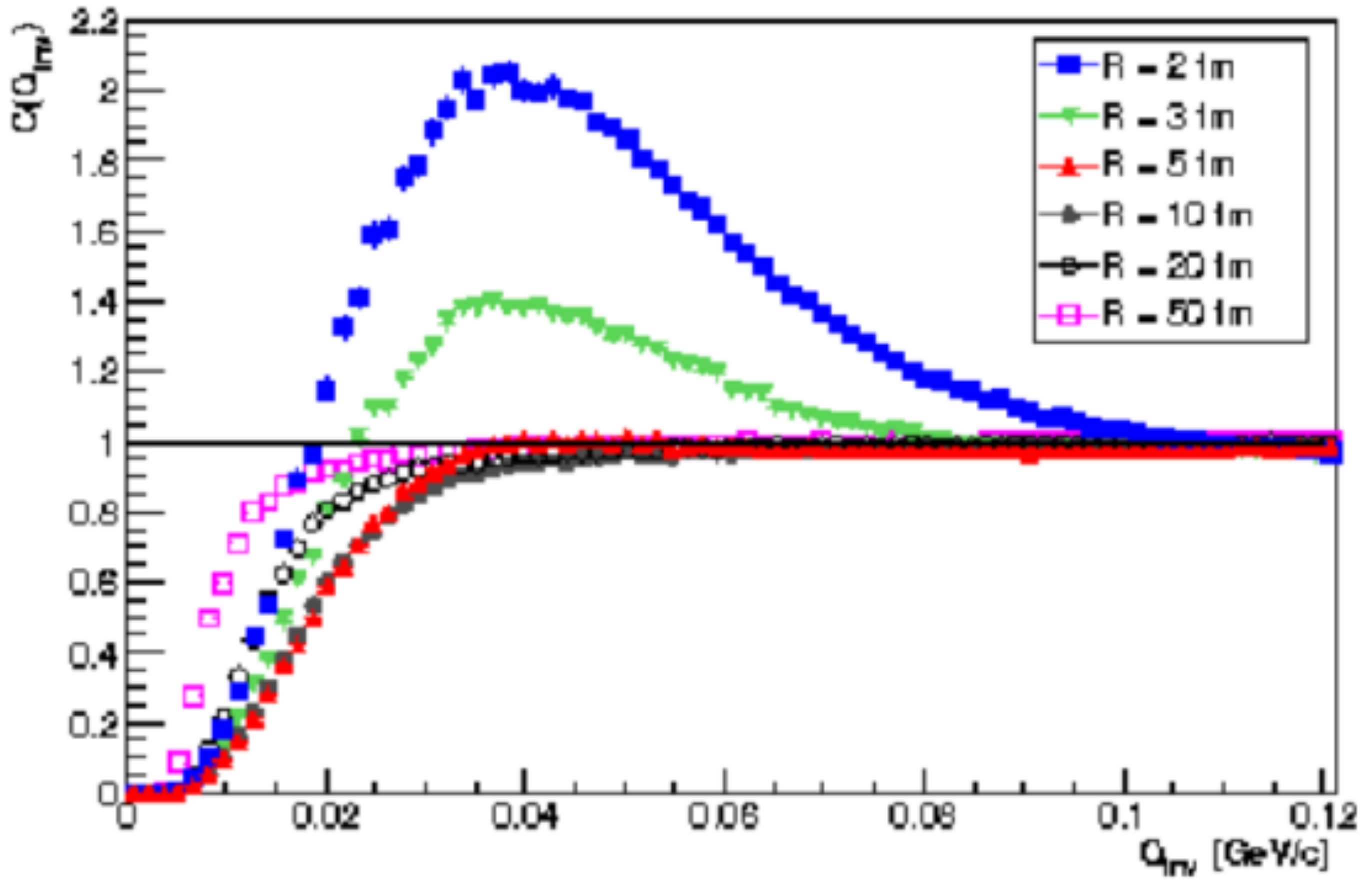
**Identical** baryon- baryon
- Quantum Statistics- **QS**
- Final State Interactions- **FSI**
  - Coulomb
  - Strong



**Non-identical** baryon- (anti)baryon
- Final State Interactions- **FSI**
  - Coulomb
  - Strong

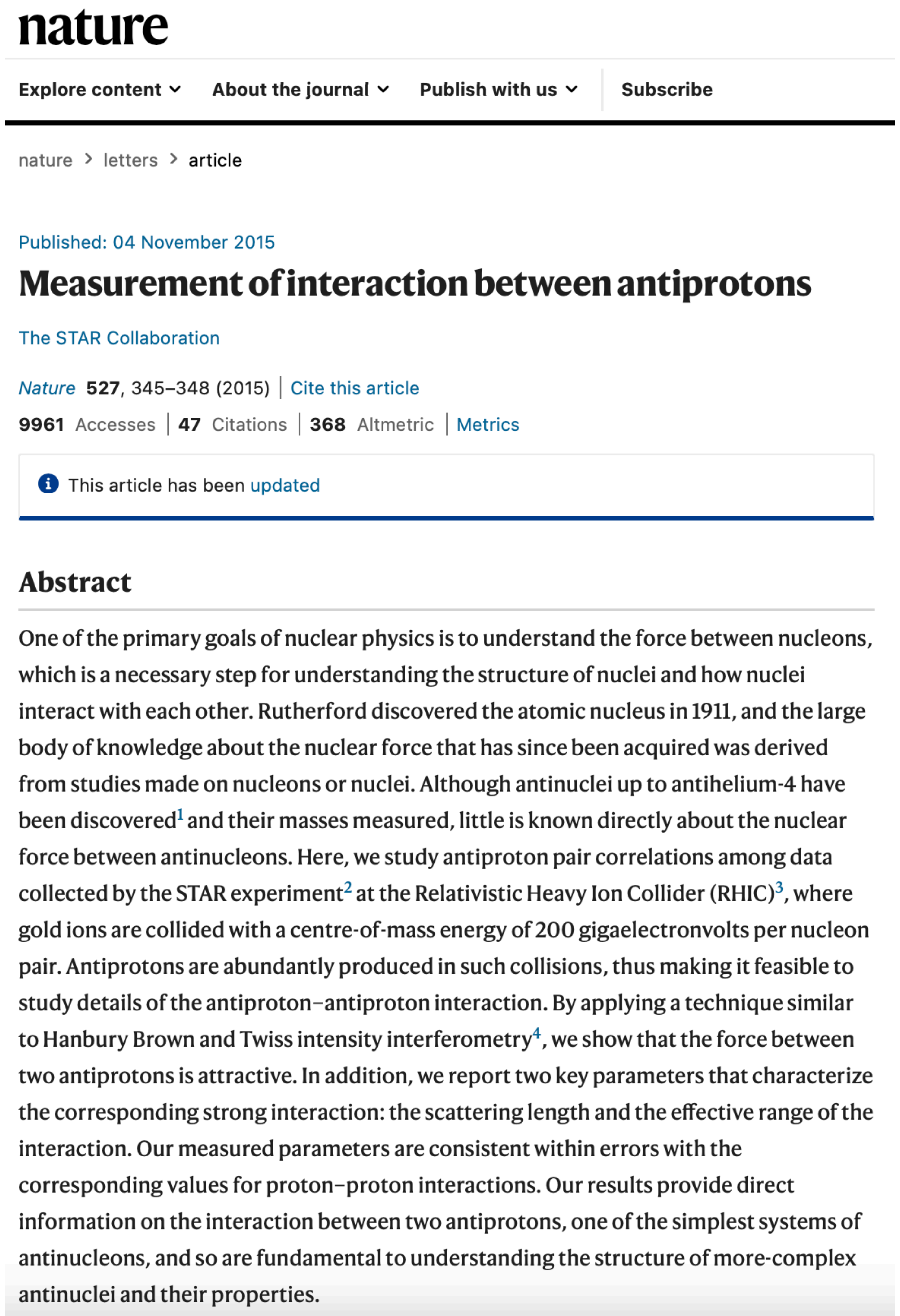


**Width** of correlation function ~ **1/R**



Bigger source and weaker correlation

# Results



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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

ℹ 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.

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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

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

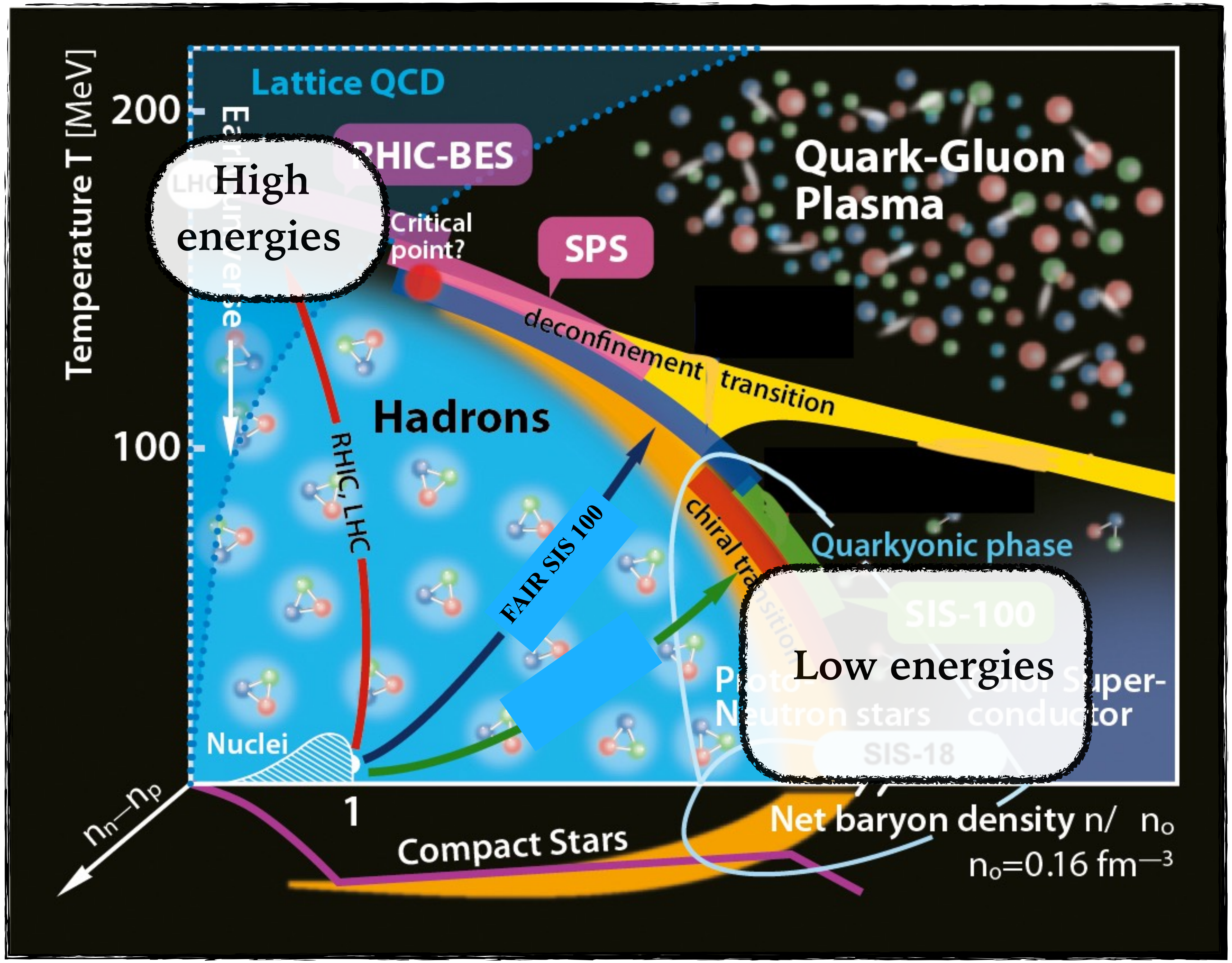
ℹ A Publisher Correction to this article was published on 15 January 2021

ℹ 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.

# QCD Phase diagram of strongly interacting matter



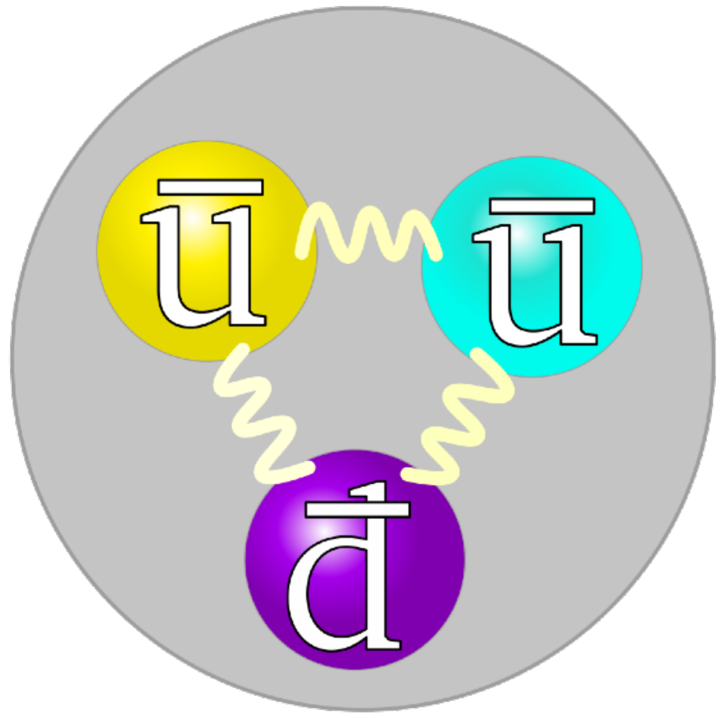
High energies

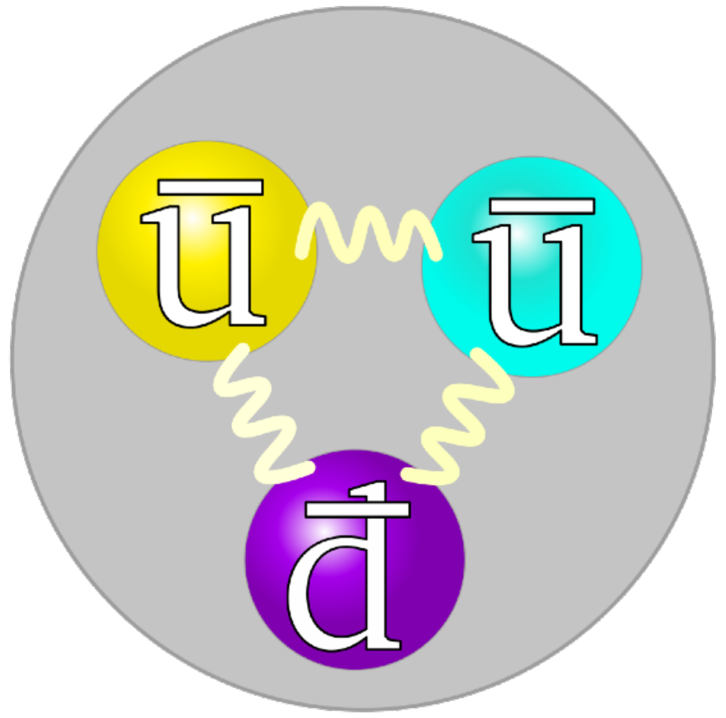
FAIR SIS 100

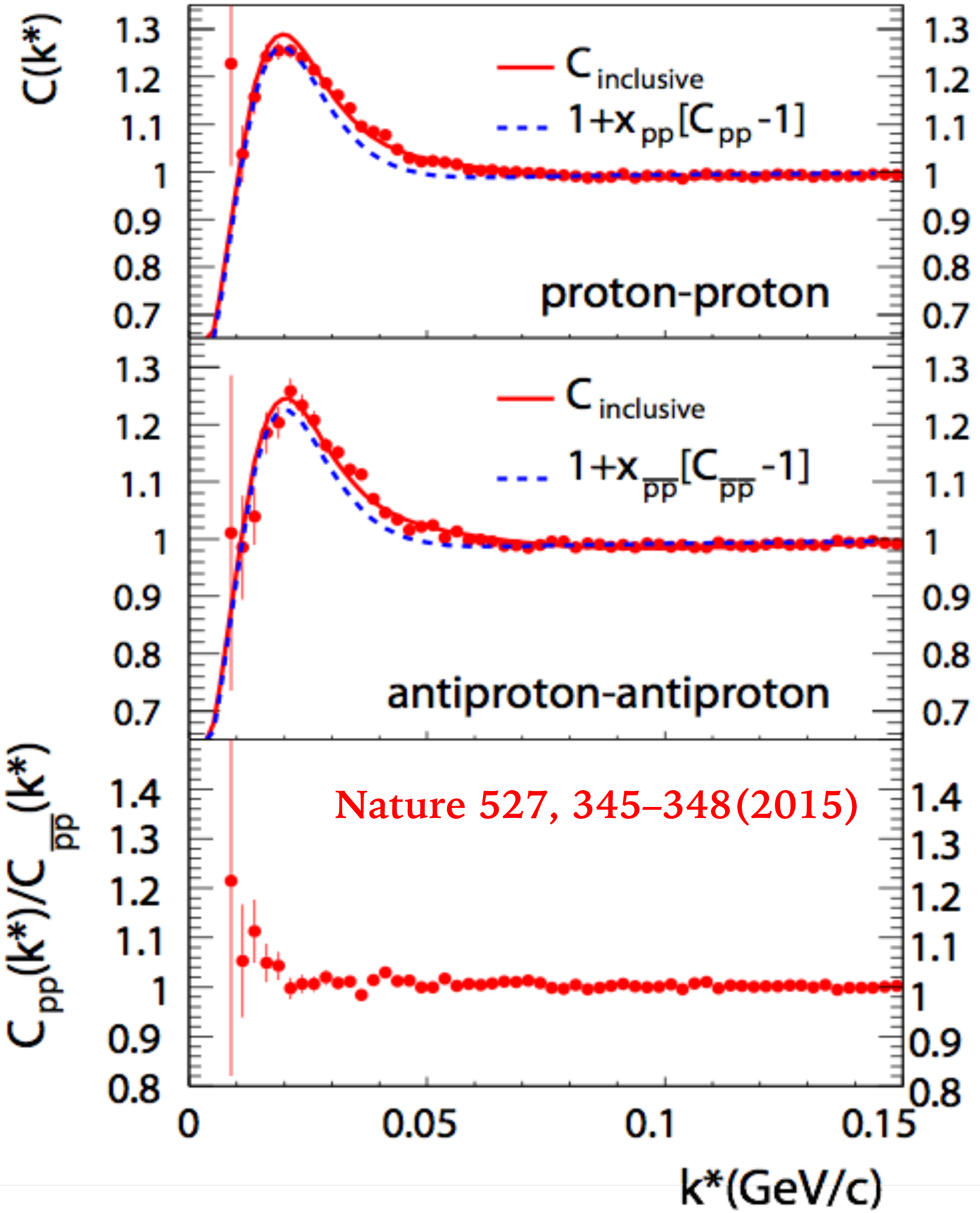
Low energies

# 1a) 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.

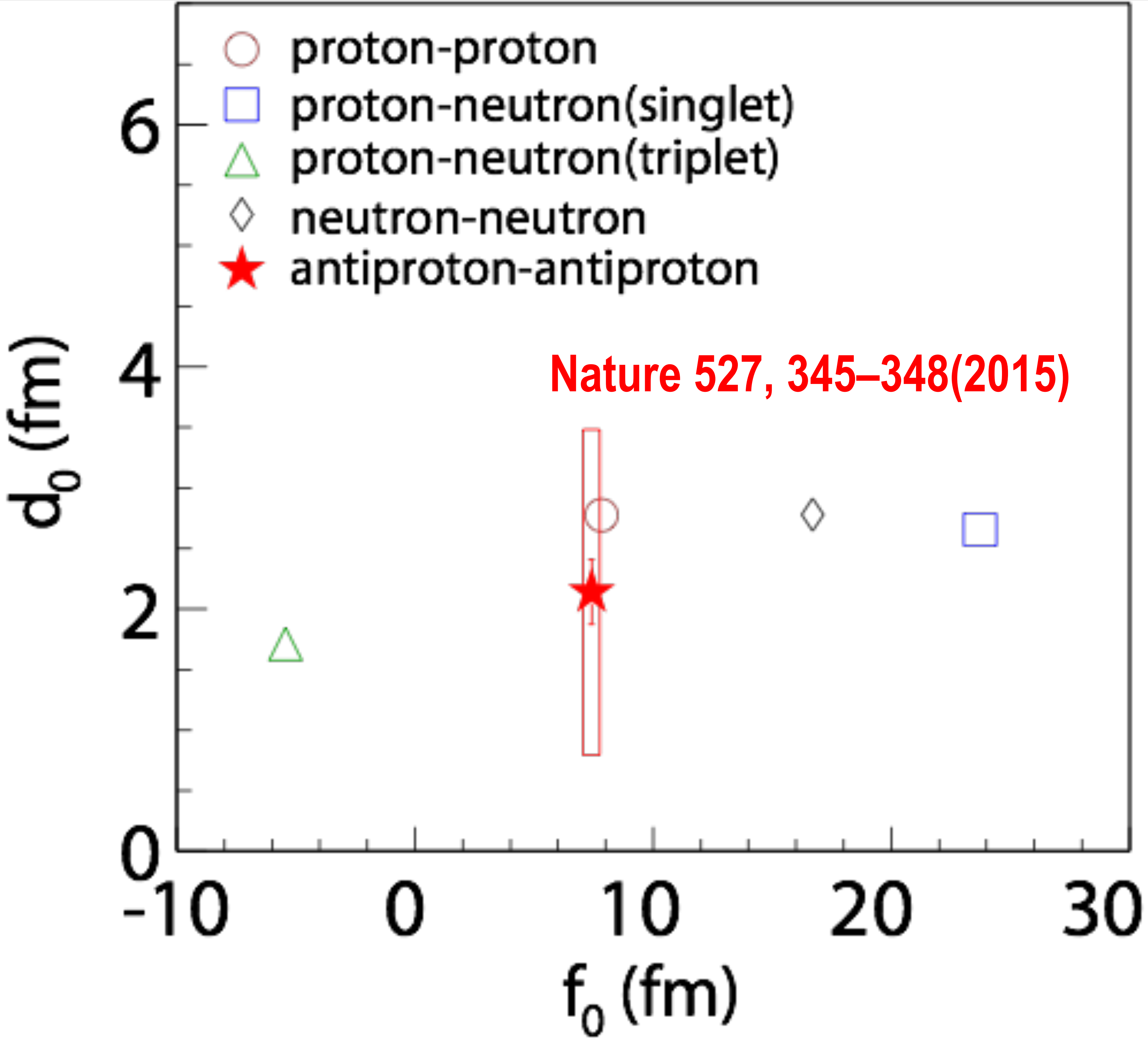






Nature 527, 345–348(2015)

# 1a) 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.

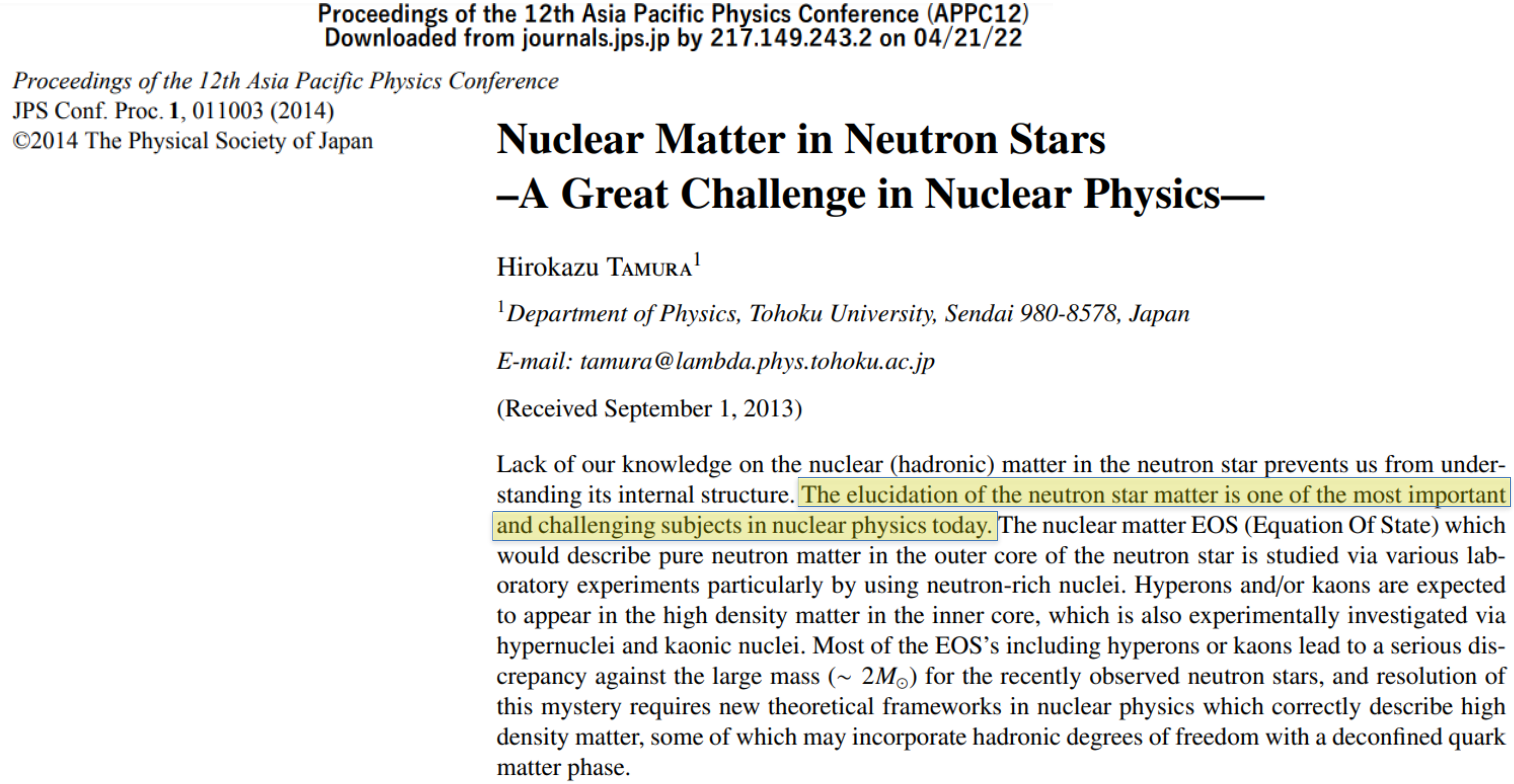
The scattering length $f_0$: determines low-energy scattering.

The elastic cross section, $\sigma_e$, (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 $d_0$.

# 1b) Inside a neutron star



*Proceedings of the 12th Asia Pacific Physics Conference*
JPS Conf. Proc. **1**, 011003 (2014)

## Nuclear Matter in Neutron Stars
## –A Great Challenge in Nuclear Physics—

Hirokazu Tamura[1]

[1] *Department of Physics, Tohoku University, Sendai 980-8578, Japan*

*E-mail: tamura@lambda.phys.tohoku.ac.jp*

(Received September 1, 2013)

Lack of our knowledge on the nuclear (hadronic) matter in the neutron star prevents us from understanding its internal structure. The elucidation of the neutron star matter is one of the most important and challenging subjects in nuclear physics today. The nuclear matter EOS (Equation Of State) which would describe pure neutron matter in the outer core of the neutron star is studied via various laboratory experiments particularly by using neutron-rich nuclei. Hyperons and/or kaons are expected to appear in the high density matter in the inner core, which is also experimentally investigated via hypernuclei and kaonic nuclei. Most of the EOS's including hyperons or kaons lead to a serious discrepancy against the large mass ($\sim 2M_{\odot}$) for the recently observed neutron stars, and resolution of this mystery requires new theoretical frameworks in nuclear physics which correctly describe high density matter, some of which may incorporate hadronic degrees of freedom with a deconfined quark matter phase.

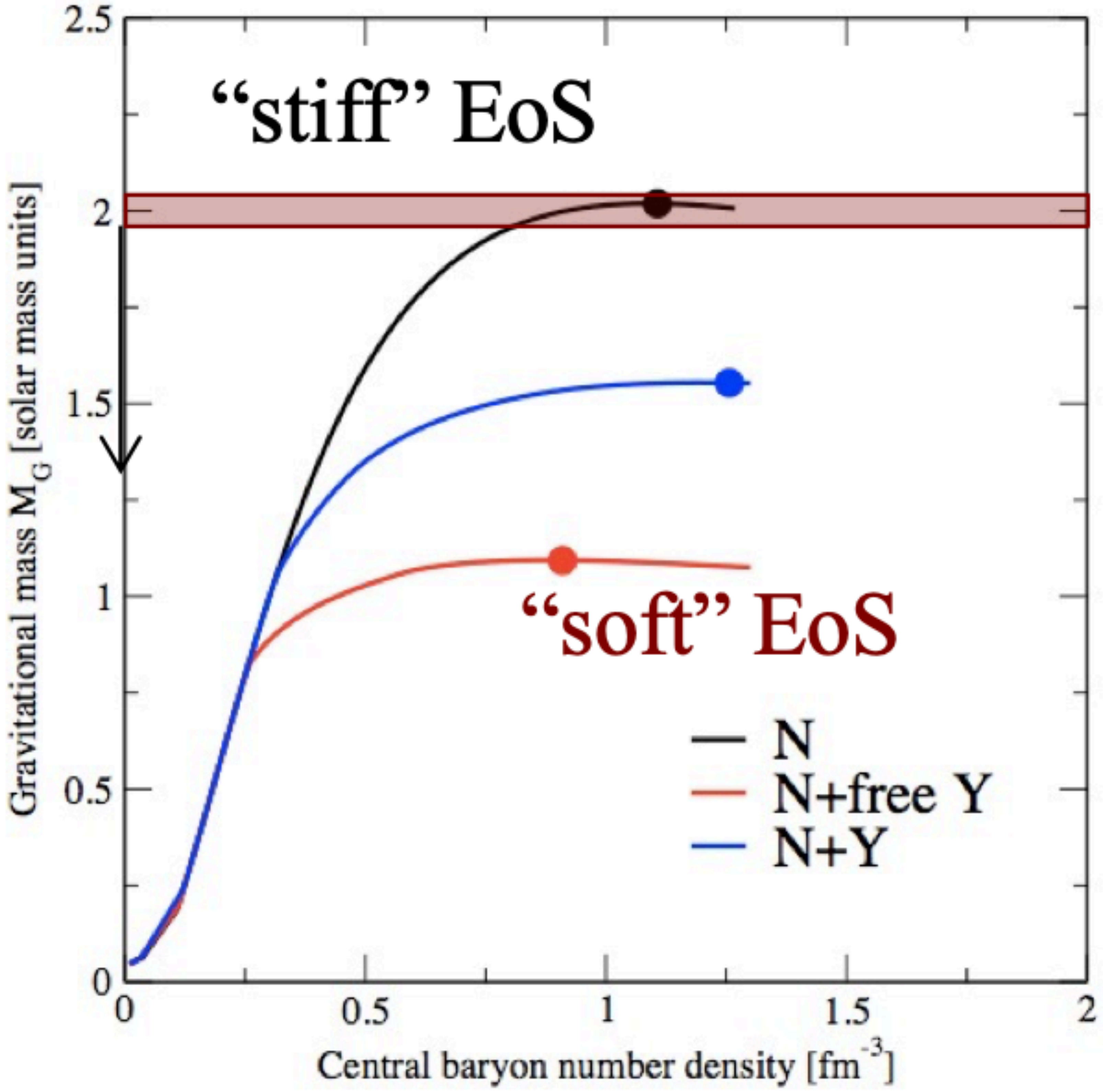
# 1b) Neutron star puzzle

- **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$^3$

# 1b) 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).**

$M_{NS} \approx 1 \div 2\ M_{\odot}$

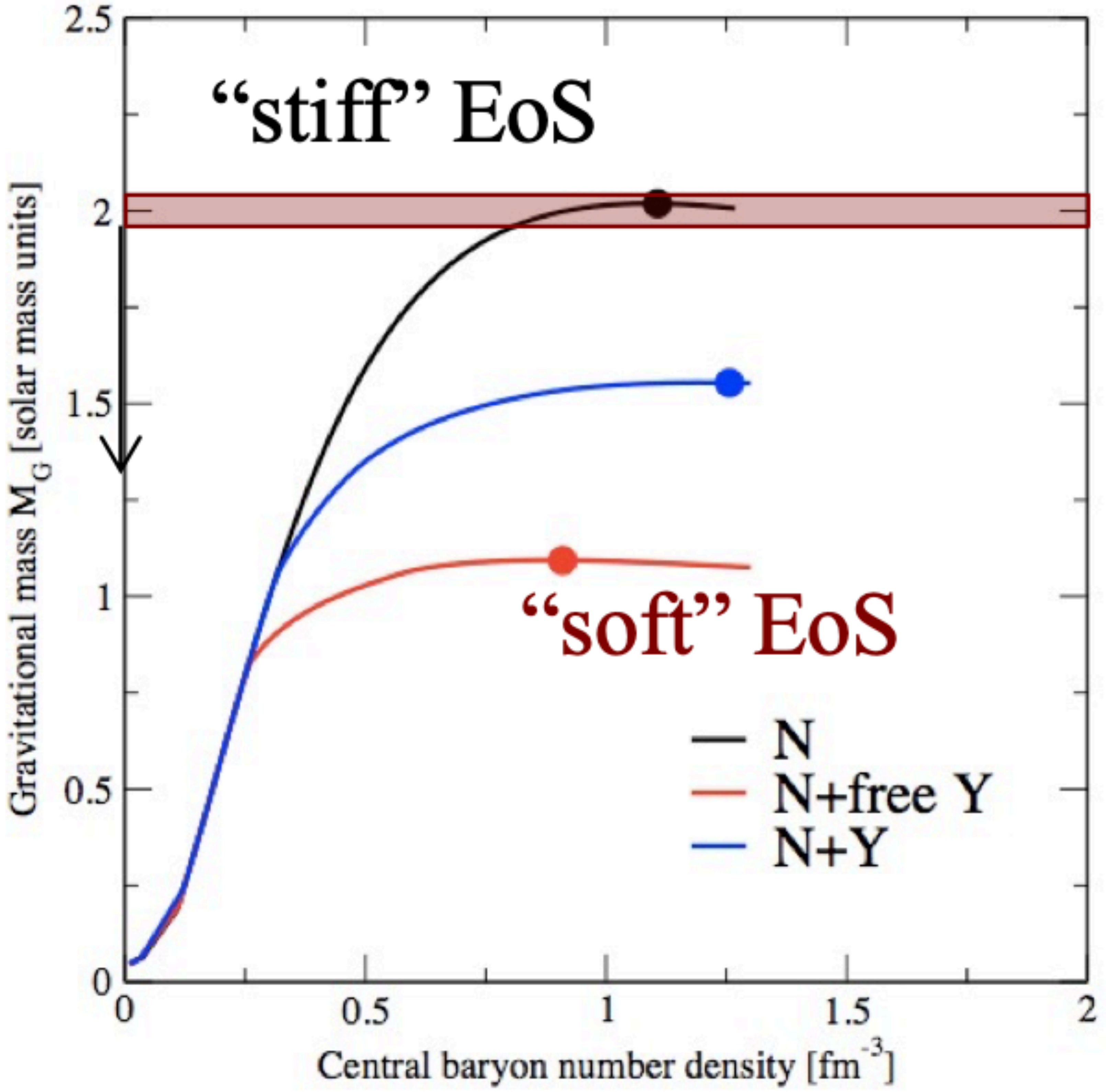
$R \approx 10\text{-}12$ km

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

The solution: a mechanism providing the **additional pressure** 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



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# 1b) 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 YN & YY interactions**
- Chiral forces
- Hyperonic Three Body Forces
- Quark Matter Core - Phase transition at densities lower than hyperon threshold

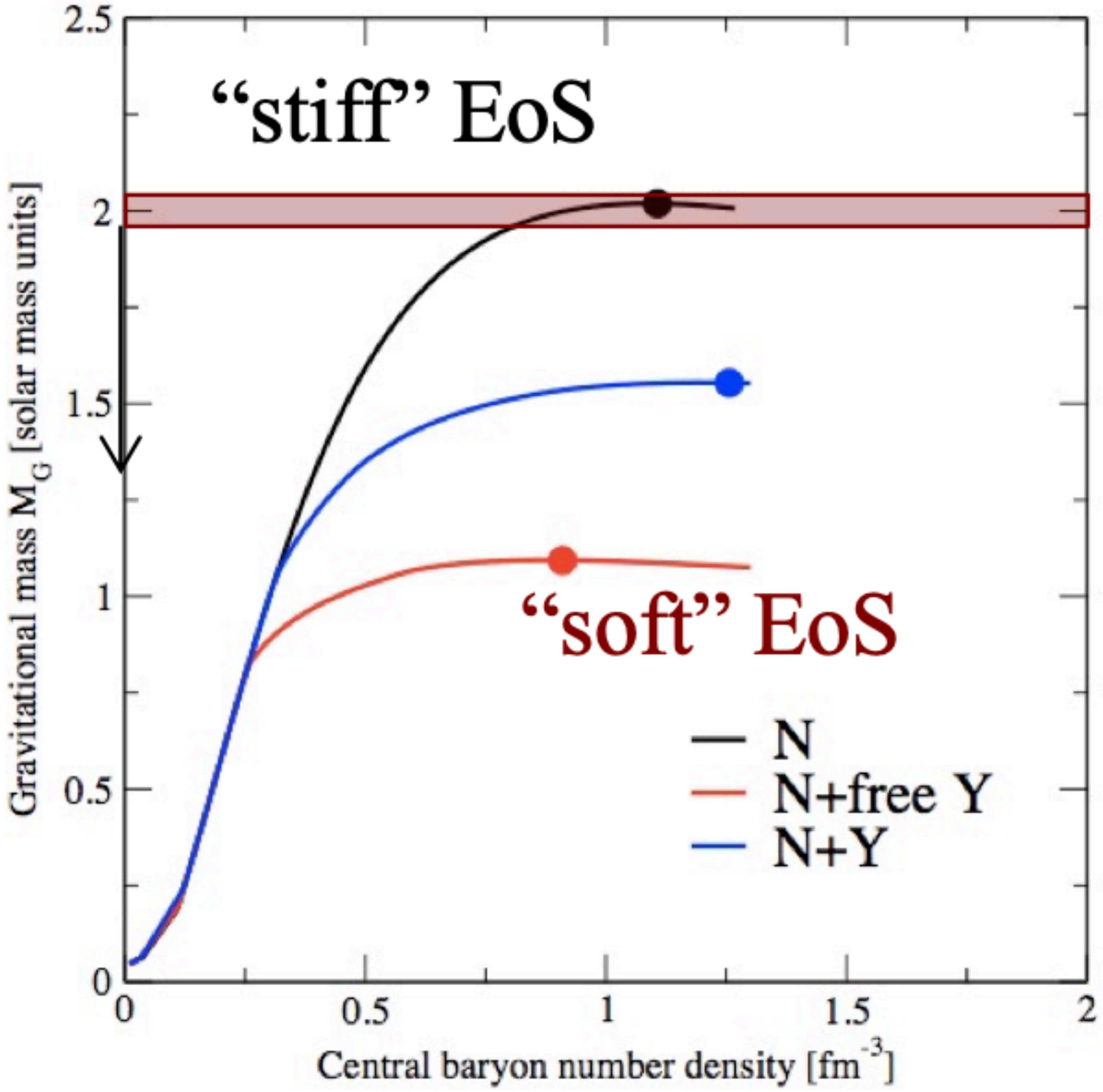
A lot of experimental and theoretical effort to understand:

- 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

$M_{NS} \approx 1 \div 2\ M_{\odot}$

$R \approx 10\text{-}12$ km

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



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

# 1b) Equation Of States for different types of baryonic matter

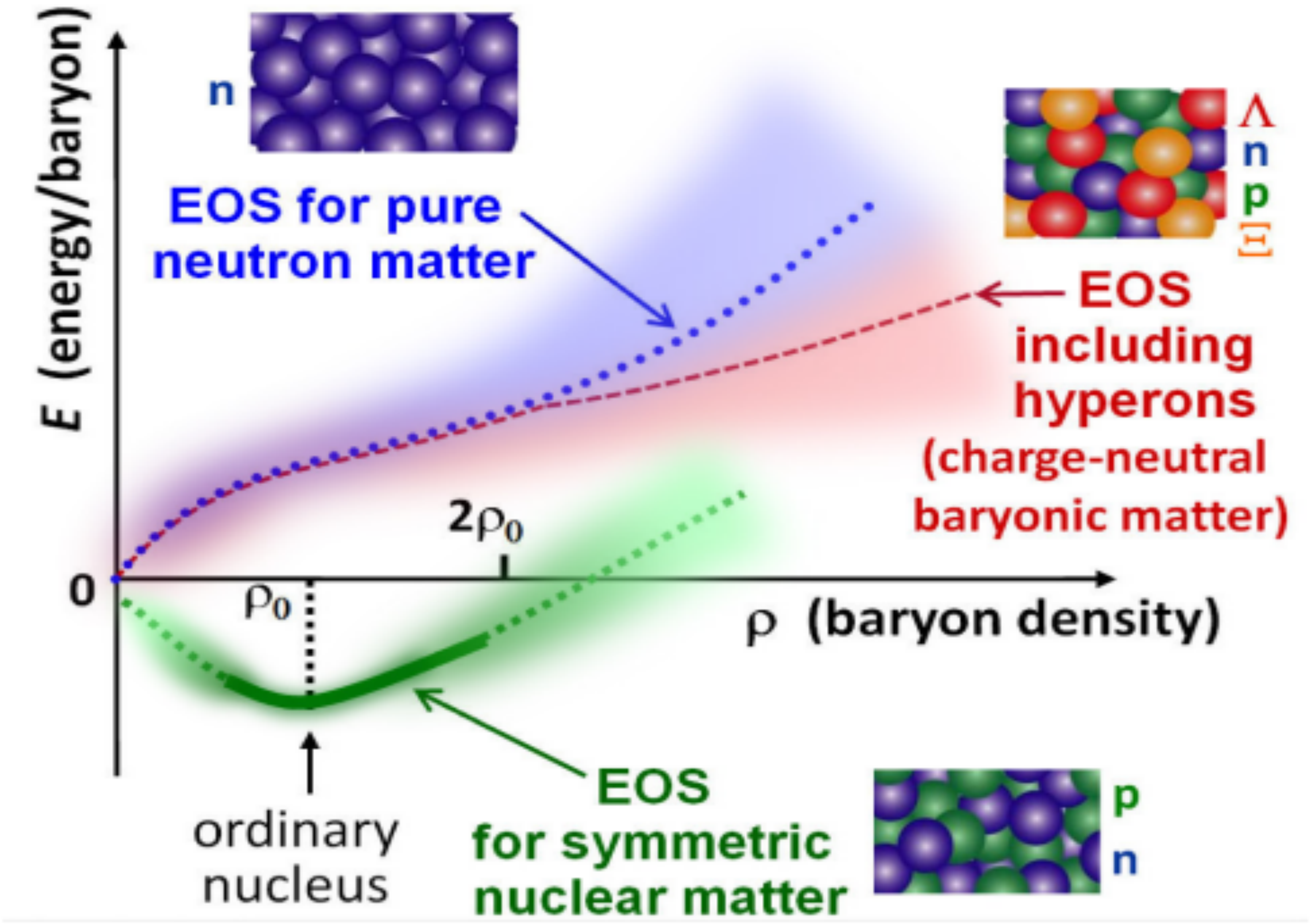


**Fig. 1.** A schematic illustration for nuclear (baryonic) matter Equation Of State (EOS) as a function of baryon density for symmetric nuclear matter, pure neutron matter, and charge-neutral baryonic matter with hyperons. The EOS is determined only for symmetric nuclear matter around $\rho \sim (0.5\text{–}2)\rho_0$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

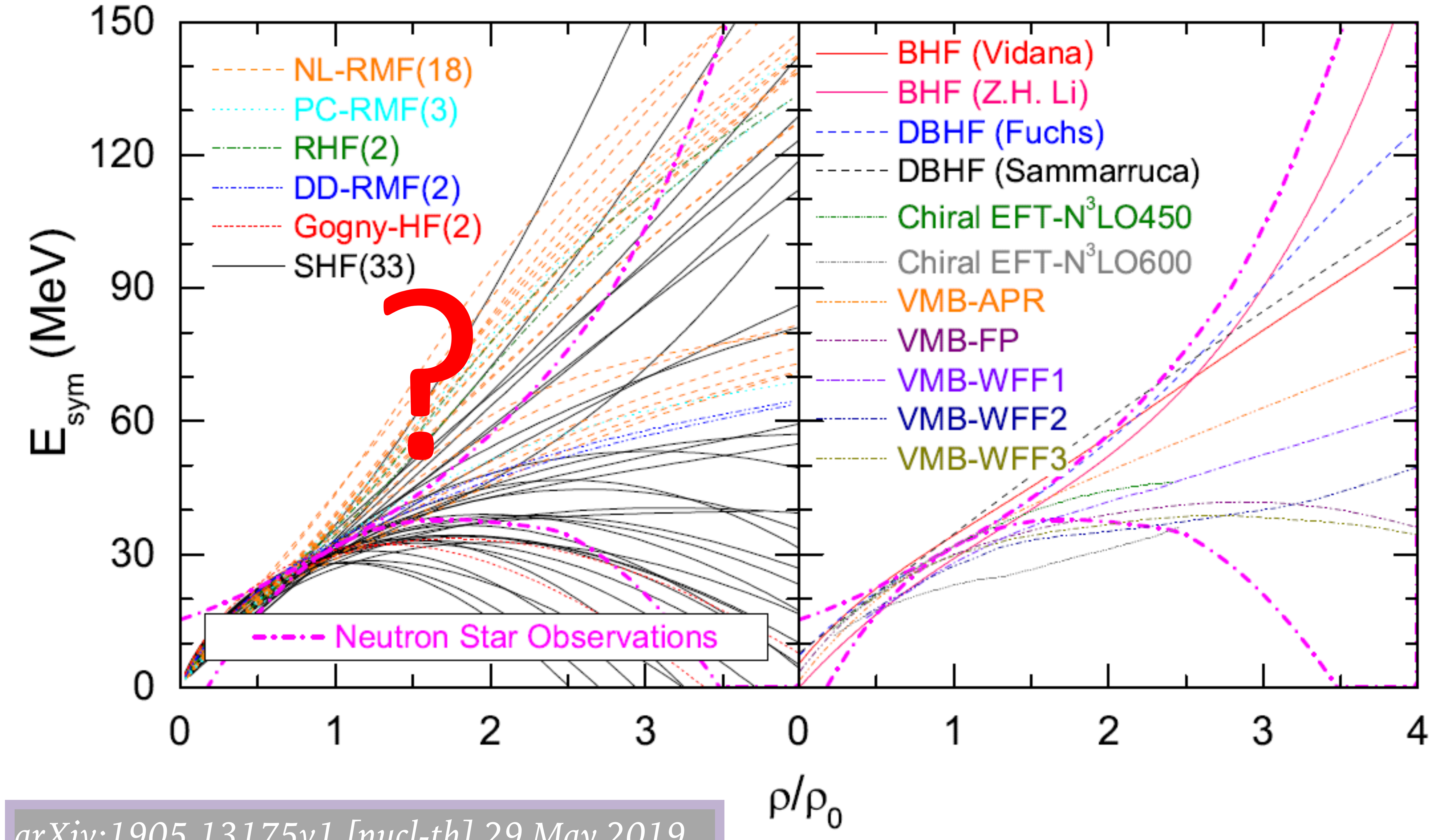
„To establish the EOS applicable to the neutron star has been one of the most important subjects in nuclear physics for a long time but has not been achieved yet.”

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

# 1b) Equation Of States for different types of baryonic matter

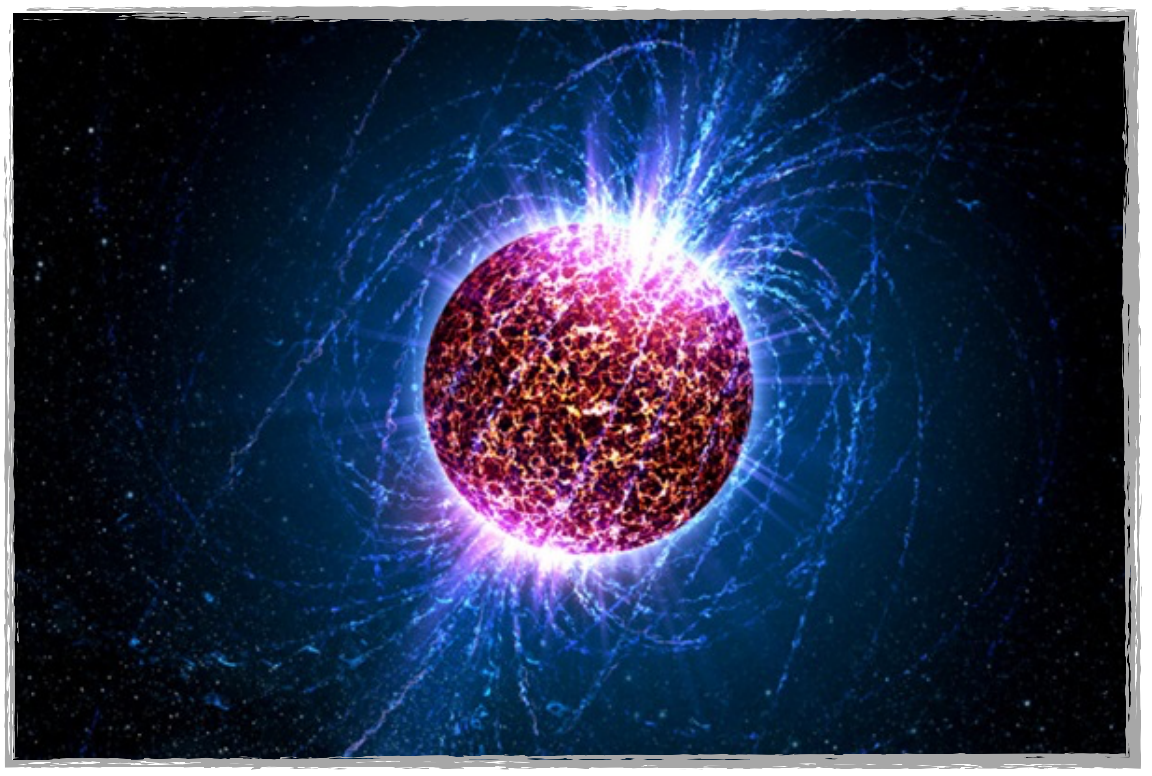
Determining the Equation of State (EOS) of dense neutron-rich nuclear matter is a shared goal of both nuclear physics and astrophysics. Except possible phase transitions, the density dependence of **nuclear symmetry Esym(ρ) is the most uncertain part of the EOS of neutron-rich nucleonic matter especially at supra-saturation densities.**

„The Energy per nucleon **E(ρ, δ)** in nuclear matter at **density ρ** and **isospin asymmetry** $\delta = (\rho_n - \rho_p)/\rho$ is the most basic input for calculating the EOS of neutron star matter regardless of the models used."



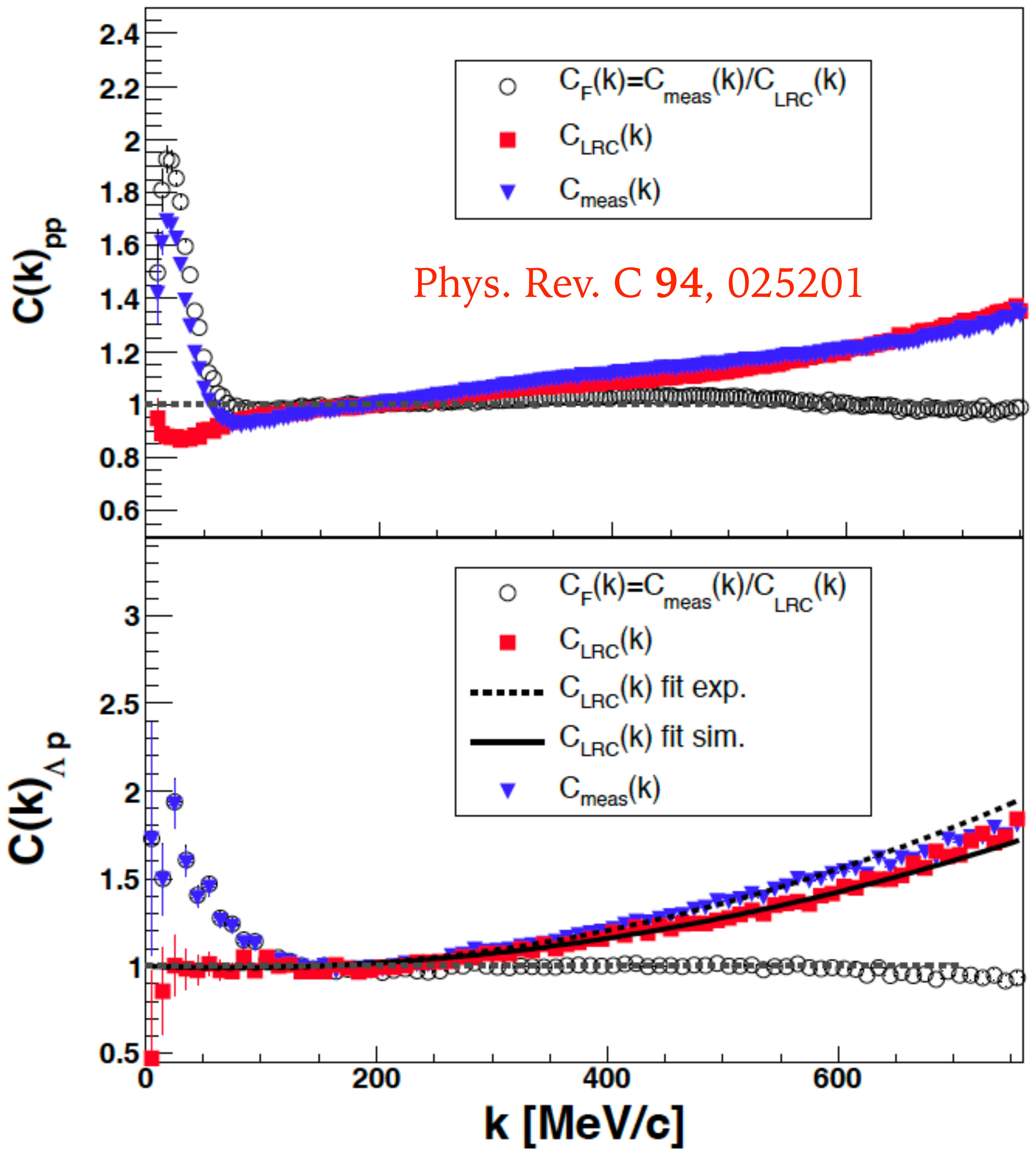
*arXiv:1905.13175v1 [nucl-th] 29 May 2019*

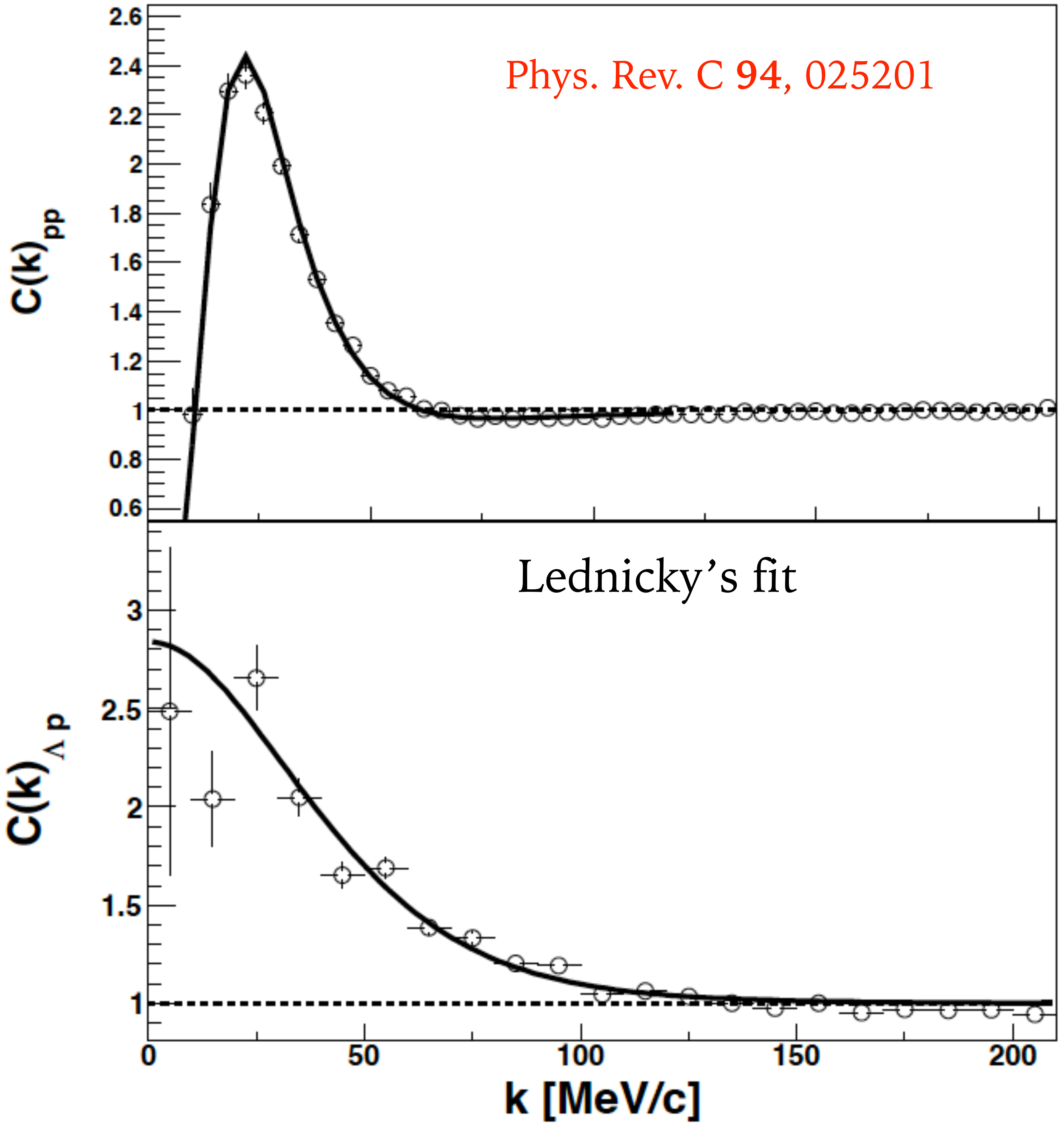
# 1b) Y-N and Y-Y interactions

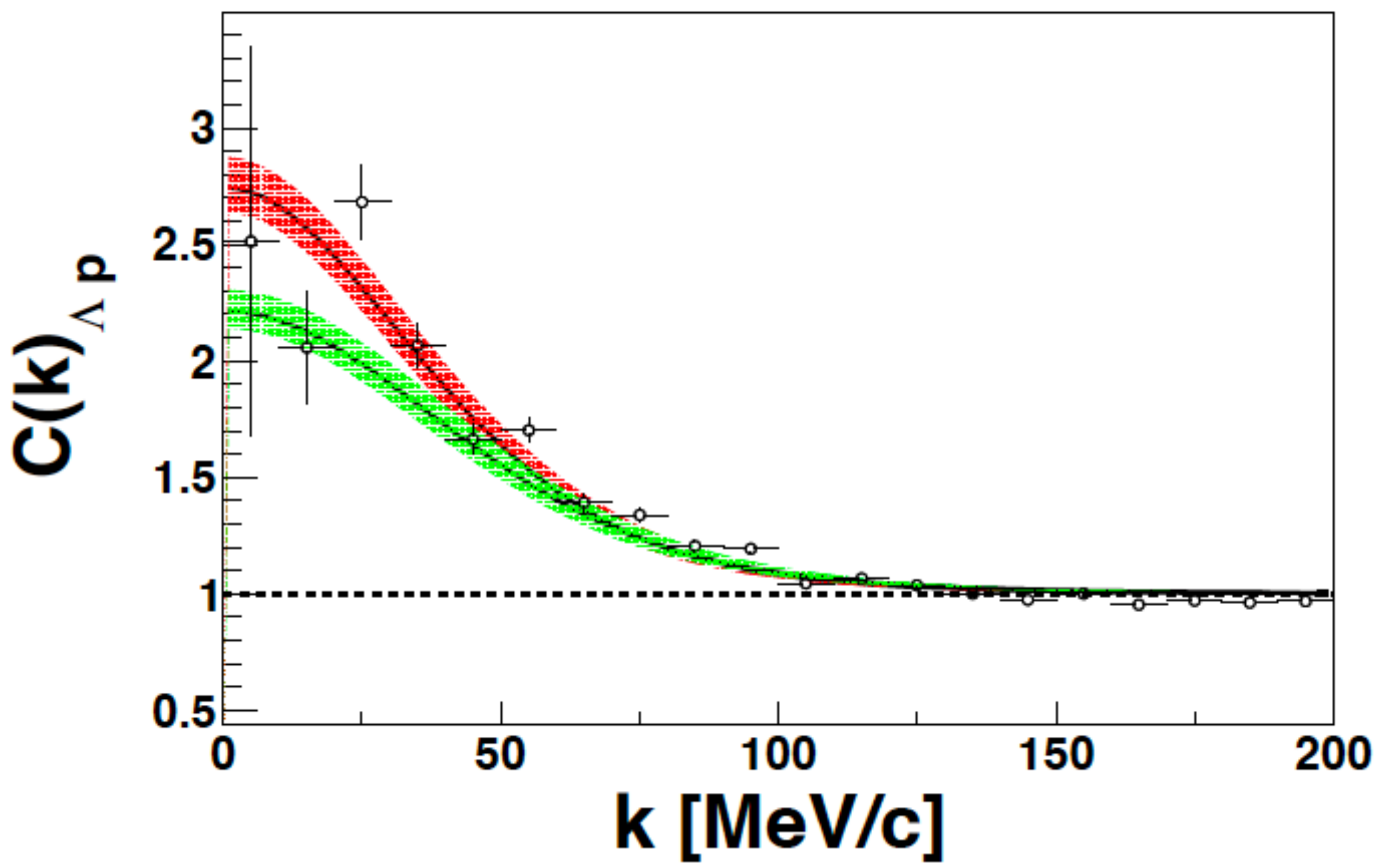


- **Experiment**: More interest about Y–N and Y–Y interactions.
- **Theory**: Major steps forward have been made (Lattice QCD).
- **Numerous theoretical predictions** exist, but no clear evidence for any such **bound states**, despite **many experimental searches**.
- The existence of **hypernuclei**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

# 1c) YN interactions at HADES







NLO scattering paremeters

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

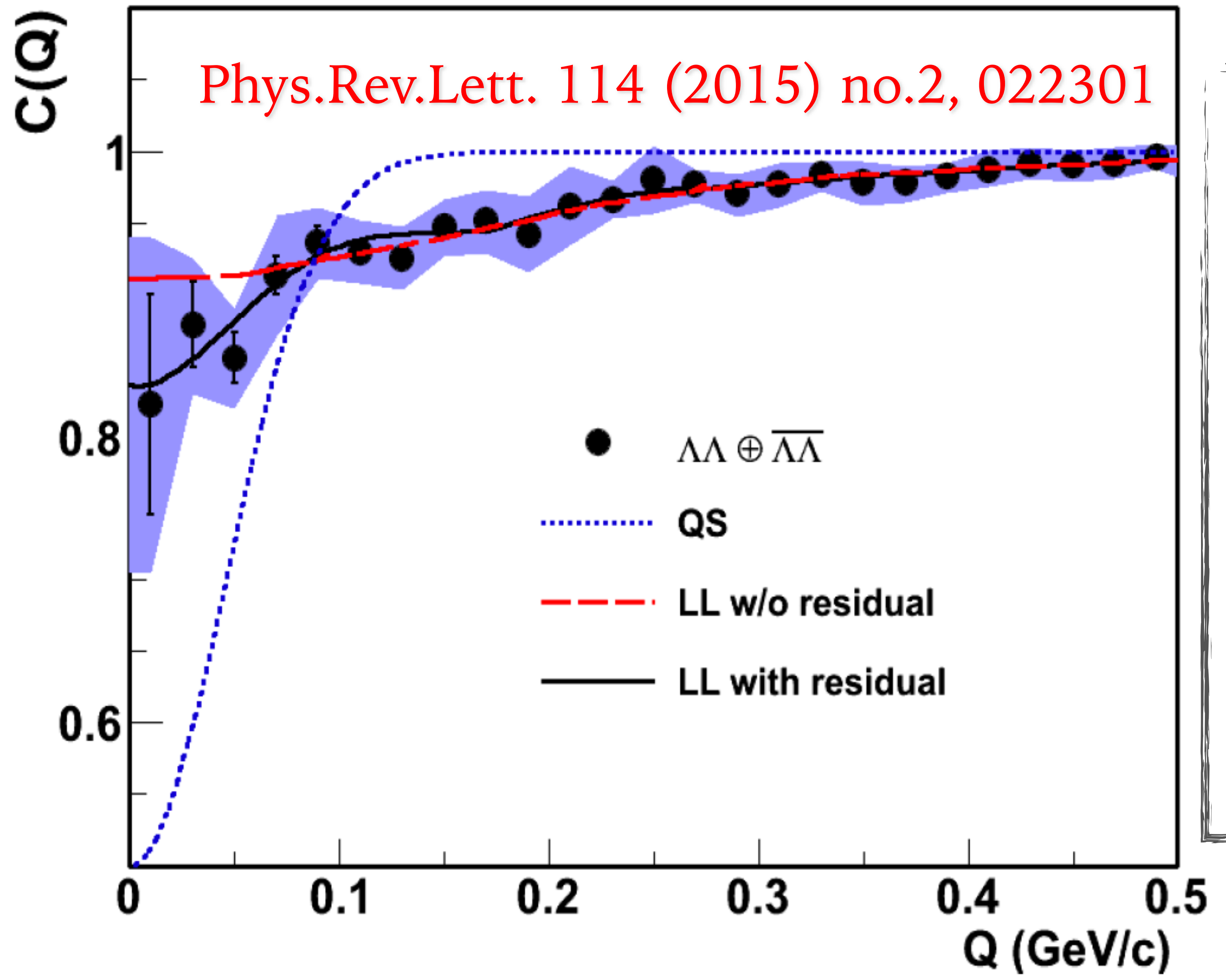
$$C_F(k) = \frac{C_{meas}(k)}{C_{LRC}(k)}$$
$$C_{LRC}(k^*) = 1 + ak + bk^2$$

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.

LO scattering parameters

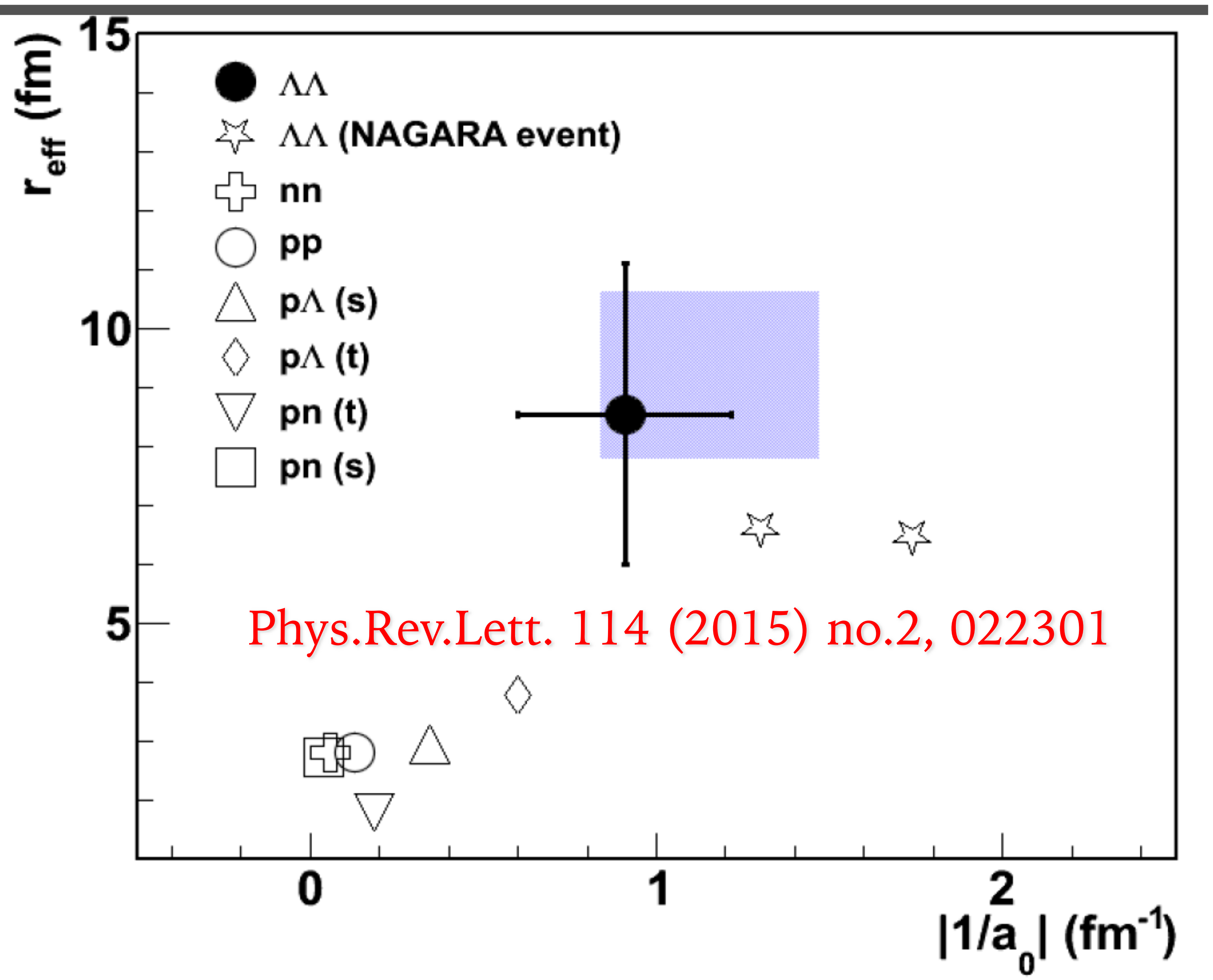
$$f_{0,LO}^{S=0} = 1.91fm$$
$$d_{0,LO}^{S=0} = 1.40fm$$
$$f_{0,LO}^{S=1} = 1.23fm$$
$$d_{0,LO}^{S=1} = 2.13fm$$

# 1c) Strange Baryon Correlations (Including Λ Hyperons)



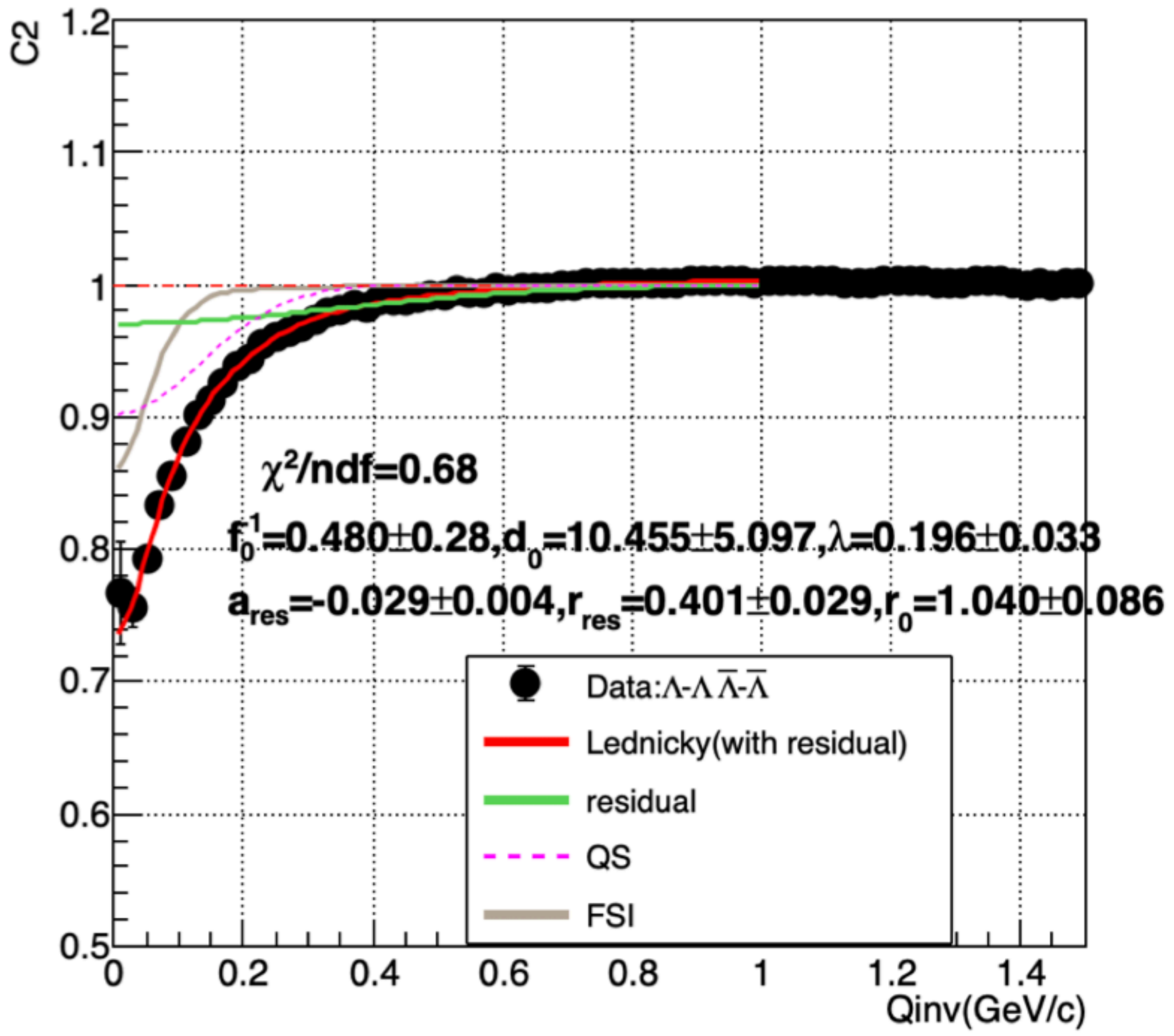
Phys.Rev.Lett. 114 (2015) no.2, 022301

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



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

| 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 |

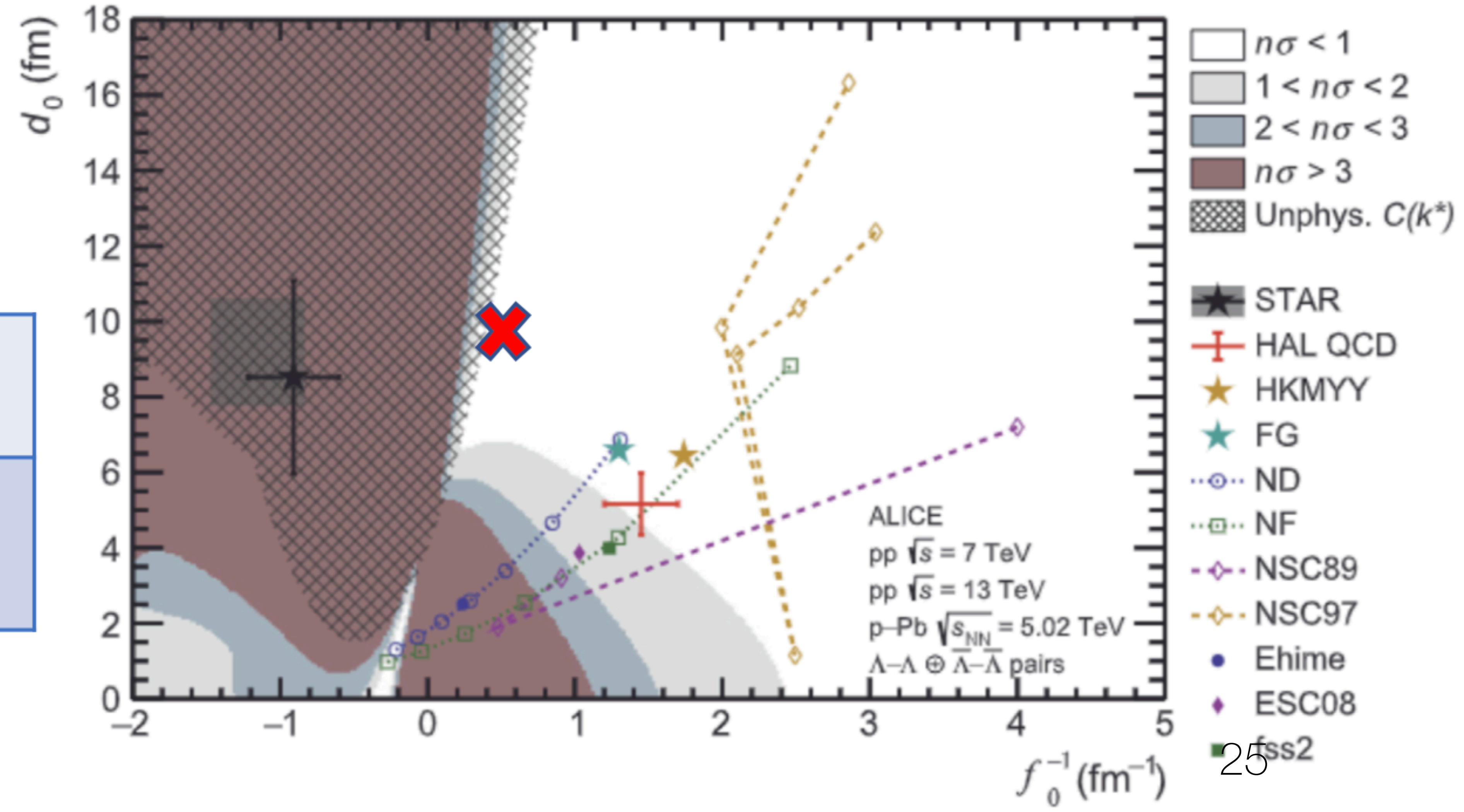


F0 became positive!!

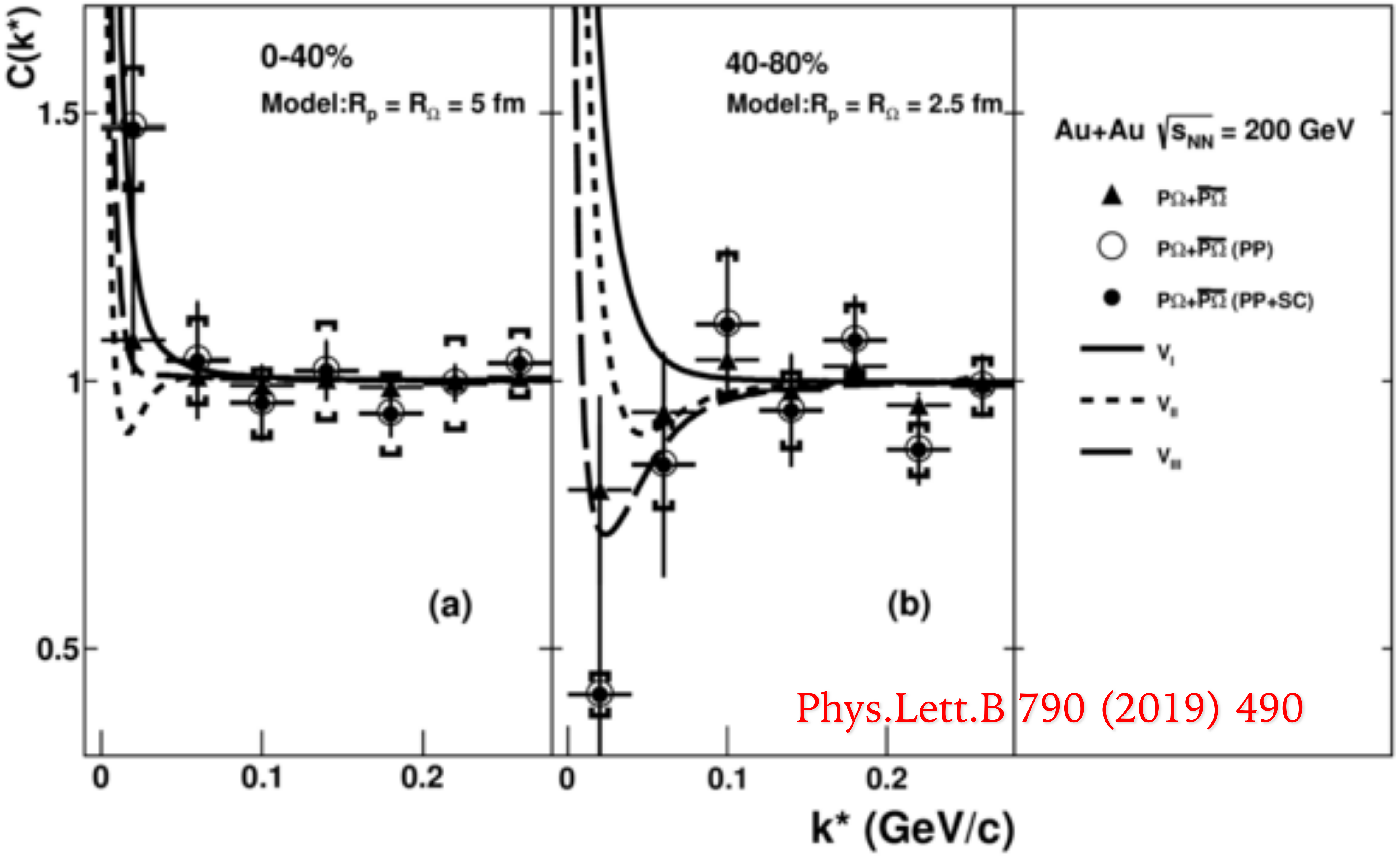
| 1/f0 | 0.480fm |
|---|---|
| d0 | 10.455fm |

ALICE's study

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

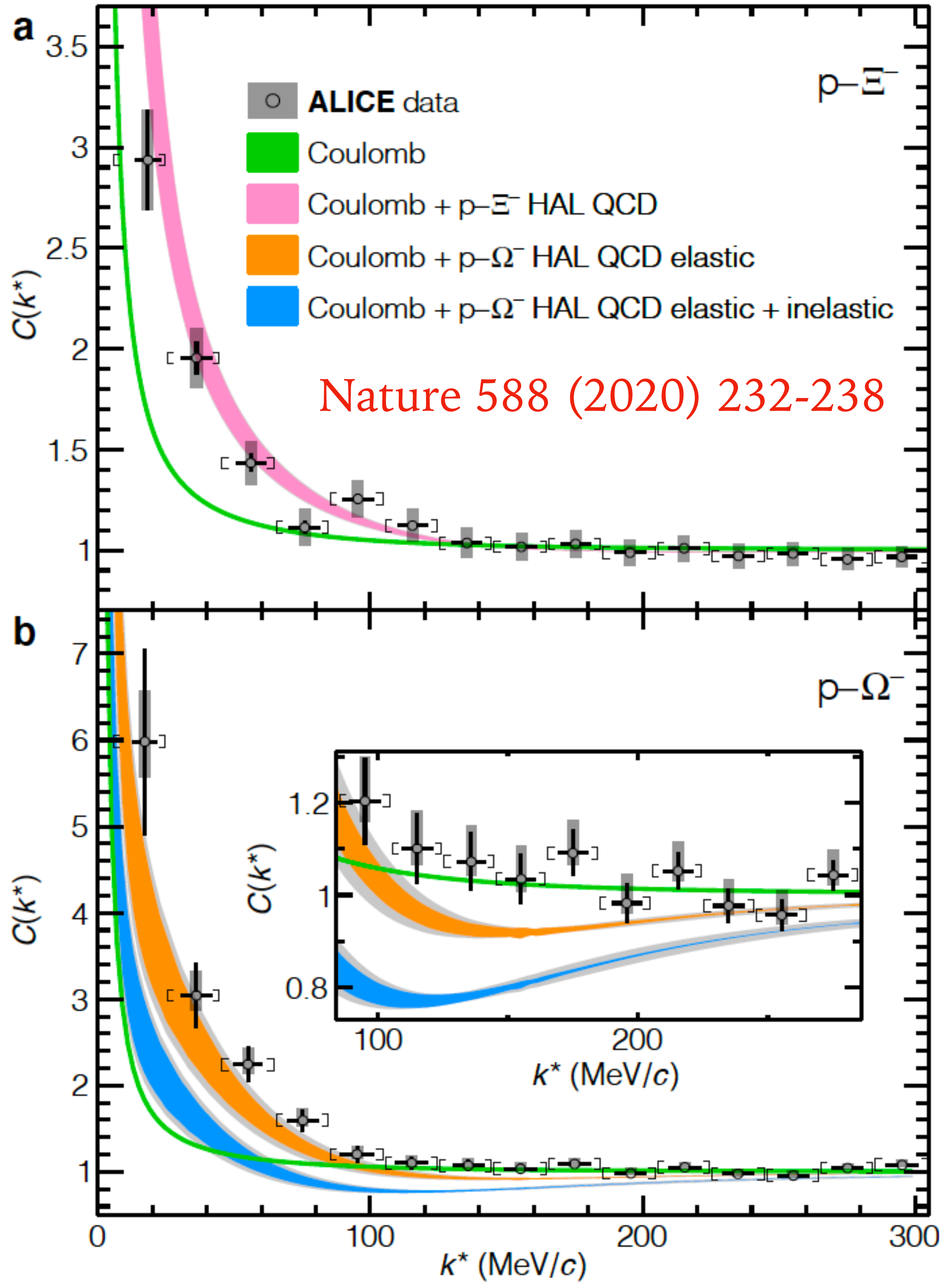


# 1d) Strange Baryon Correlations (including p-Ω)



Phys.Lett.B 790 (2019) 490

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



Nature 588 (2020) 232-238

| | **V₁** | **V₂** | **V₃** |
|---|---|---|---|
| **$E_{bin}$ [MeV]** | - | 6.3 | 26.9 |
| **$a_0$ [MeV]** | -1.12 | 5.79 | 1.29 |
| **$r_{eff}$ [MeV]** | -1.16 | 0.96 | 0.65 |

# 1d) Strange Baryon Correlations (Including Ξ Hyperons)

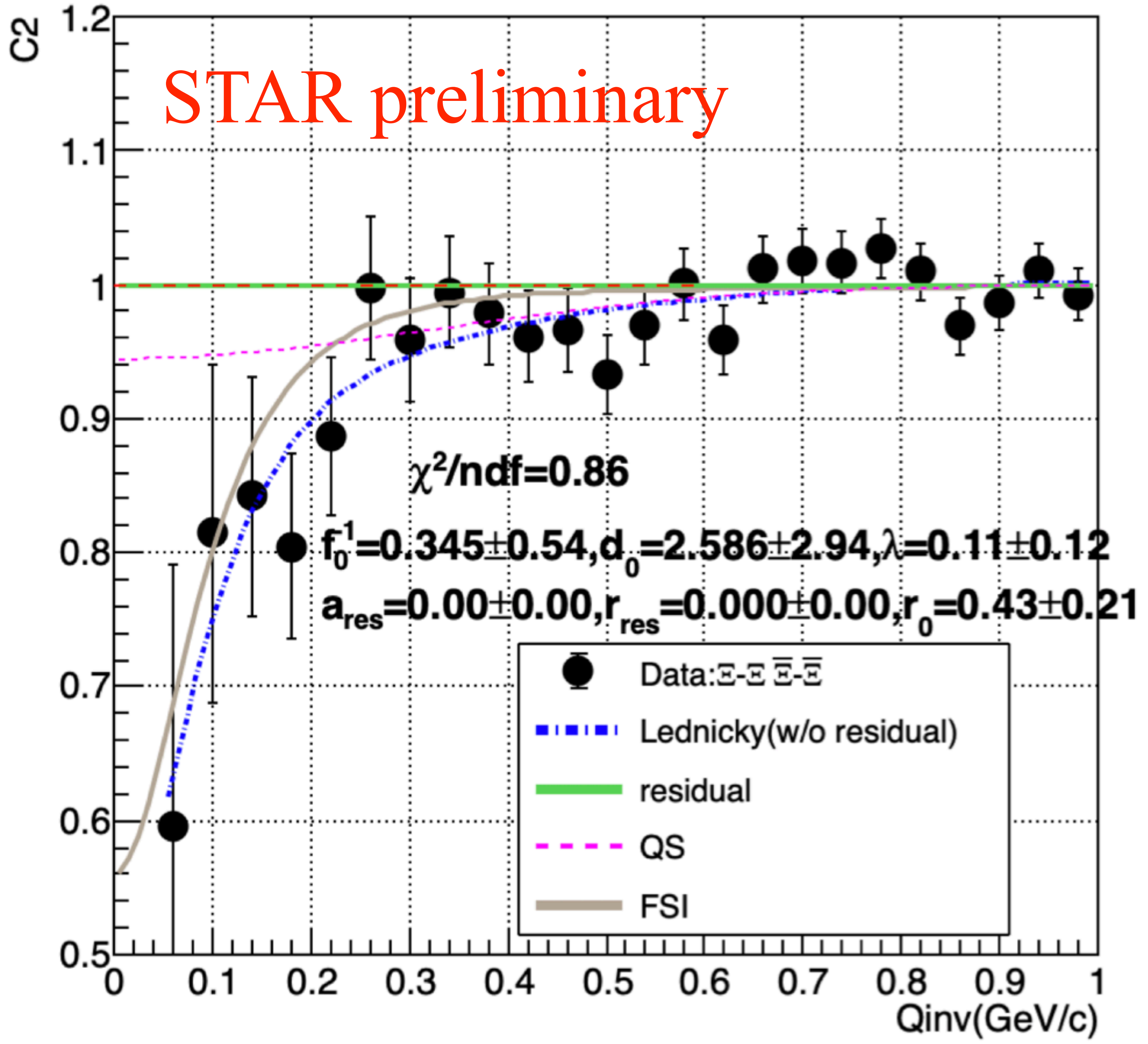
**First measurement** of Ξ-Ξ correlation at RHIC

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

Anti-correlation at Q < 0.25 GeV/c.

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

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

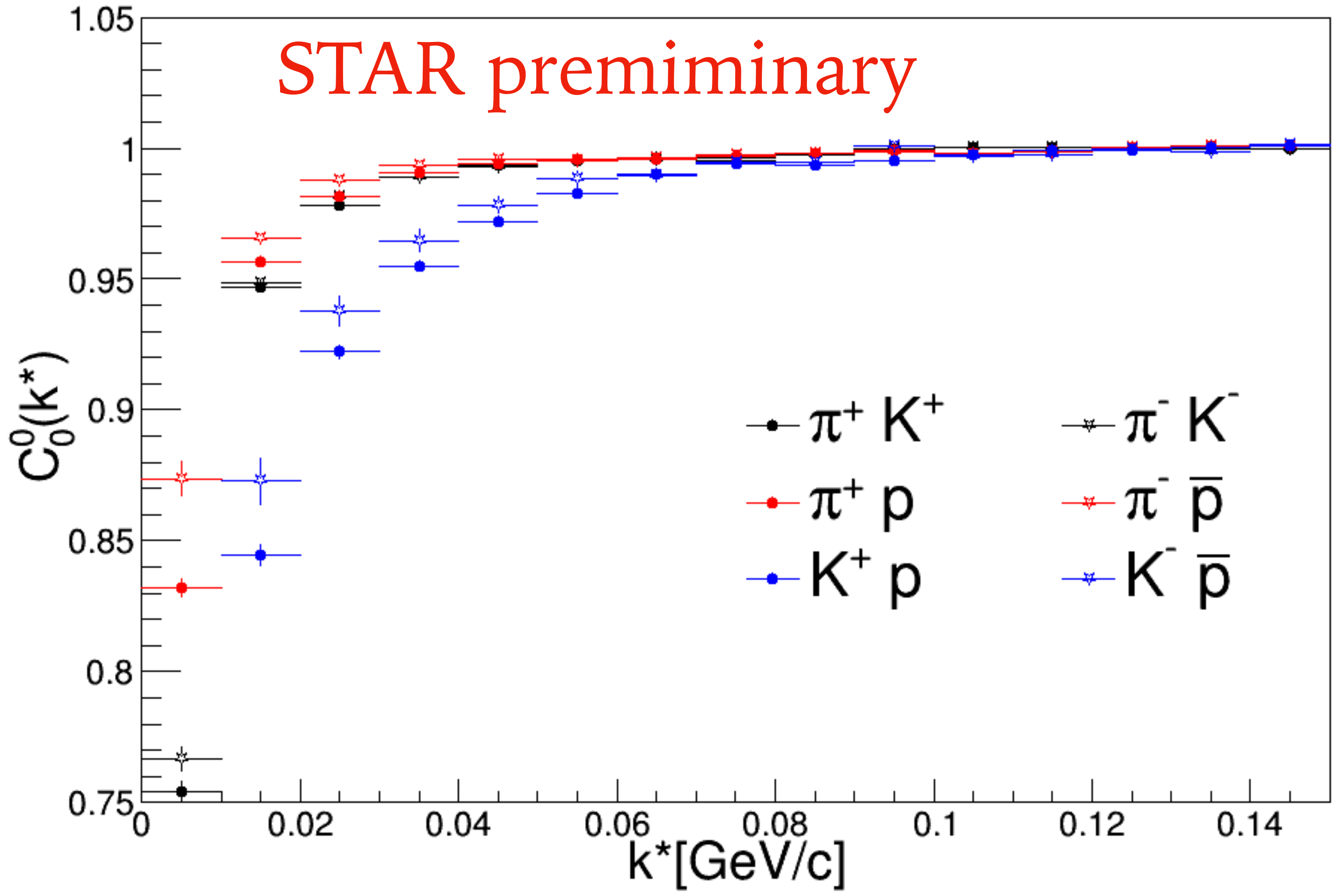


F0 became positive!!

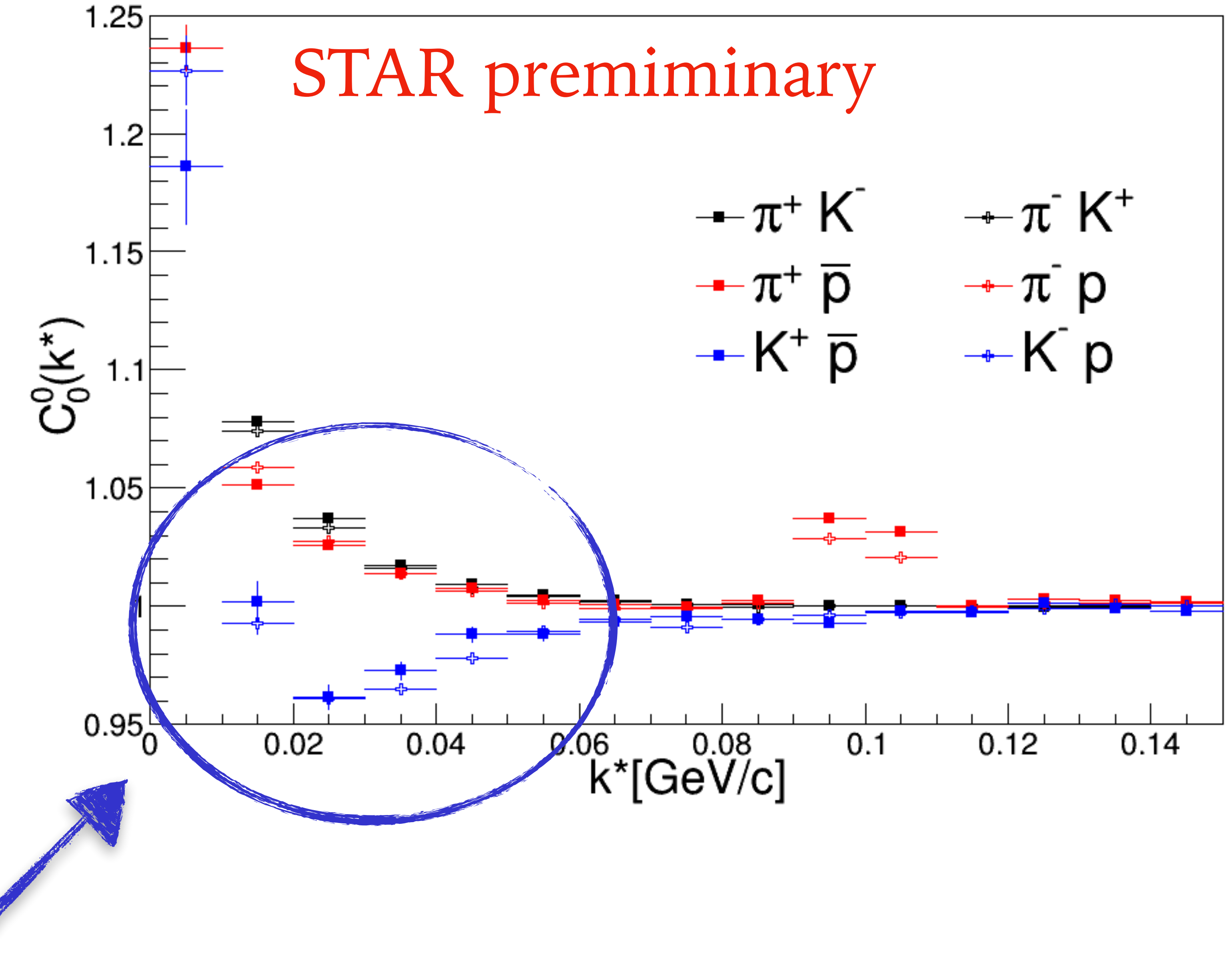
| 1/f0 | 0.345fm |
|---|---|
| d0 | 2.586fm |

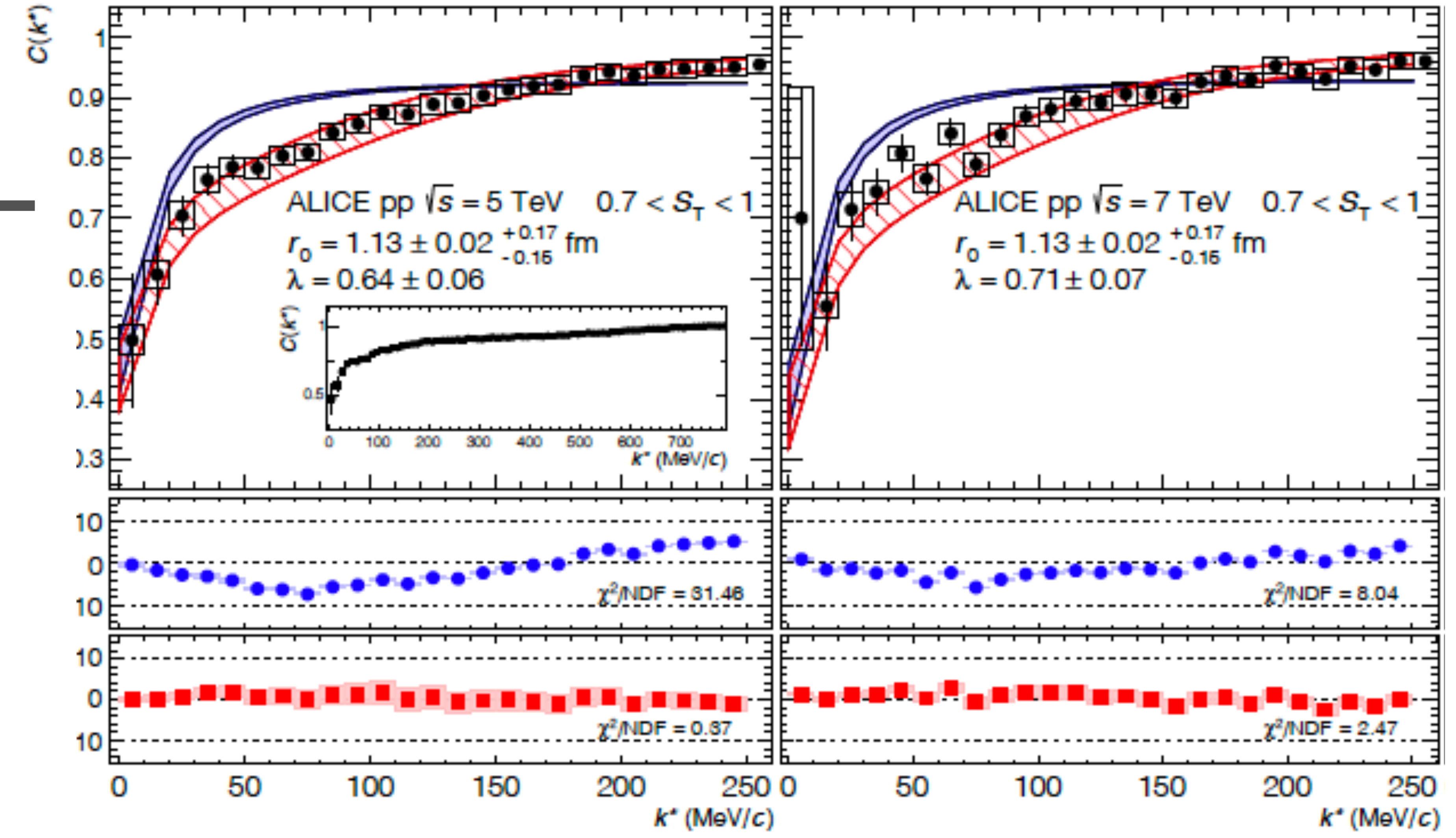
# 1d) Proton-kaon (bound state?)

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

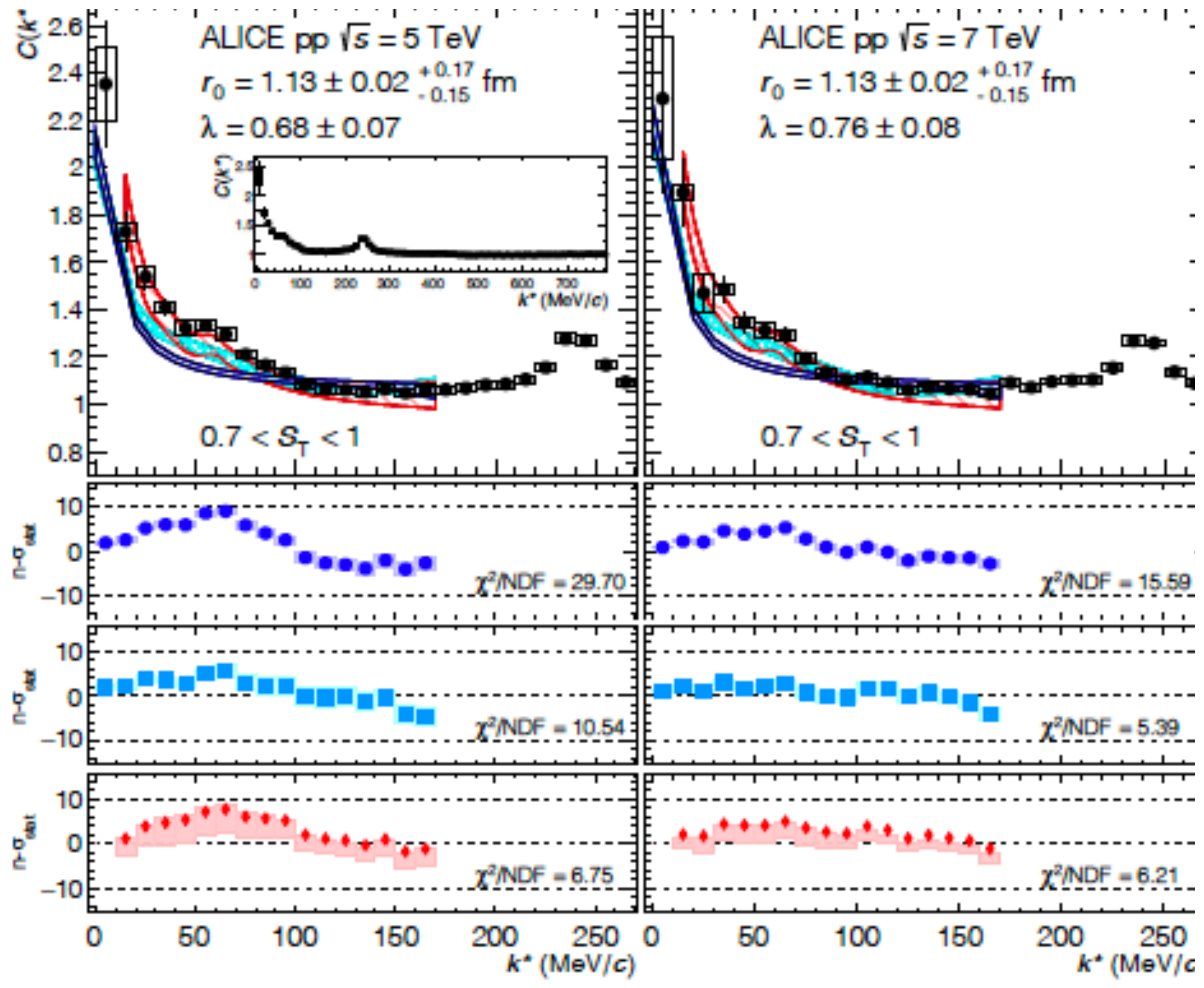


Opposite charges 0-10% @ Au+Au 39 GeV





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.

# 1d) Neutral kaons

## Parametrization - $K_s^0 K_s^0$

**Gaussian density distribution** (includes only **QS effects**): $CF(q_{inv}) = 1 + \lambda e^{[-R_{inv}^2 q_{inv}^2]}$

$\lambda$ - the correlation strength, $R_{inv}$ - the size of the particle-emitting source.

**Lednicky & Lyuboshitz model** includes **strong FSI:** [Sov.J.Nucl.Phys. 35, 770 (1982)]

$$CF(q_{inv}) = 1 + \lambda\left(\underbrace{e^{[-R_{inv}^2 q_{inv}^2]}}_{\text{QS effect}} + \underbrace{\frac{1}{2}\left[\left|\frac{f(k^*)}{R_{inv}}\right|^2 + \frac{4\Re f(k^*)}{\sqrt{\pi}R_{inv}} F_1(q_{inv}R_{inv}) - \frac{2\Im f(k^*)}{\sqrt{\pi}R_{inv}} F_2(q_{inv}R_{inv})\right]}_{\text{strong FSI through the } f_0(980) \text{ and } a_0(980) \text{ resonances}}\right)$$

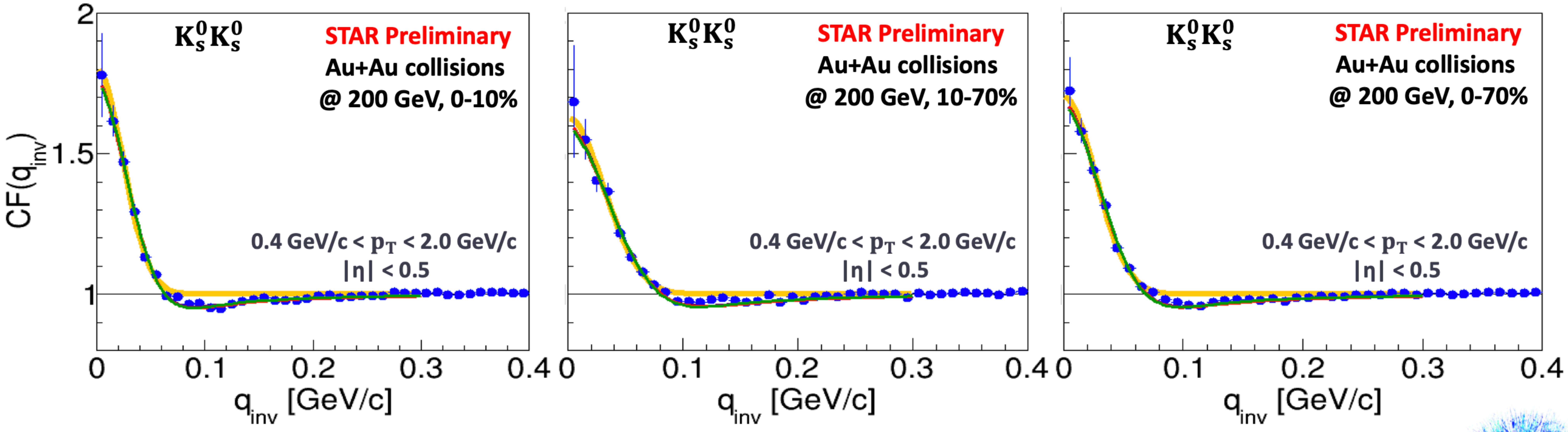
$$F_1(z) = \int_0^z dx \frac{e^{x^2} - x^2}{z},\ F_2(z) = \frac{1 - e^{x^2}}{z}$$

$$f(k^*) = \frac{1}{2}[f_0(k^*) + f_1(k^*)], \quad f_I(k^*) = \frac{\gamma_r}{m_r - s - i\gamma_r k^* - i\gamma_r' k_r'}, \quad s = 4\left(m_K^2 + k^{*2}\right)$$

| | $m_{f_0}\left[\frac{GeV}{c^2}\right]$ | $\gamma_{f_0 K\bar{K}}$ | $\gamma_{f_0 \pi\pi}$ | $m_{a_0}\left[\frac{GeV}{c^2}\right]$ | $\gamma_{a_0 K\bar{K}}$ | $\gamma_{a_0 \pi\pi}$ |
|---|---|---|---|---|---|---|
| Antonelli [1] | 0.973 | 2.763 | 0.5283 | 0.985 | 0.4038 | 0.3711 |
| Achasov2001 [2] | 0.996 | 1.305 | 0.2684 | 0.992 | 0.5555 | 0.4401 |
| Achasov2003 [3] | 0.996 | 1.305 | 0.2684 | 1.003 | 0.8365 | 0.4580 |
| Martin [4] | 0.978 | 0.792 | 0.1990 | 0.974 | 0.3330 | 0.2220 |

[1] eConf C020620, THAT06 (2002), [2] Phys. Rev. D 63, 094007 (2001)
[3] Phys. Rev. D 68, 014006 (2003), [4] Nucl. Phys. B 121, 514–530 (1977)

# 1d) 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

# 1d) Neutral kaons

## Parametrization - $K^0_S K^{\pm}$

**Lednicky & Lyuboshitz model** includes strong FSI: [Sov.J.Nucl.Phys. 35, 770 (1982)]

$$CF(k^*) = 1 + \underbrace{\frac{\lambda}{4}\left[\left|\frac{f(k^*)}{R}\right|^2 + \frac{4\Re f(k^*)}{\sqrt{\pi}R}F_1(2k^*R) - \frac{2\Im f(k^*)}{\sqrt{\pi}R}F_2(2k^*R)\right]}_{\text{strong FSI through the } a_0(980) \text{ resonance}}$$

$$F_1(z) = \int_0^z dx\,\frac{e^{x^2}-x^2}{z},\; F_2(z) = \frac{1-e^{x^2}}{z}$$

$$f\,(k^*) = \frac{\gamma_r}{m_r - s - i\gamma_r k^* - i\gamma'_r k'_r}, \qquad s = 4\left(m_K^2 + k^{*2}\right)$$

| | $m_{a_0}\left[\frac{GeV}{c^2}\right]$ | $\gamma_{a_0K\bar{K}}$ | $\gamma_{a_0\pi\eta}$ |
|---|---|---|---|
| Antonelli [1] | 0.985 | 0.4038 | 0.3711 |
| Achasov2001 [2] | 0.992 | 0.5555 | 0.4401 |
| Achasov2003 [3] | 1.003 | 0.8365 | 0.4580 |
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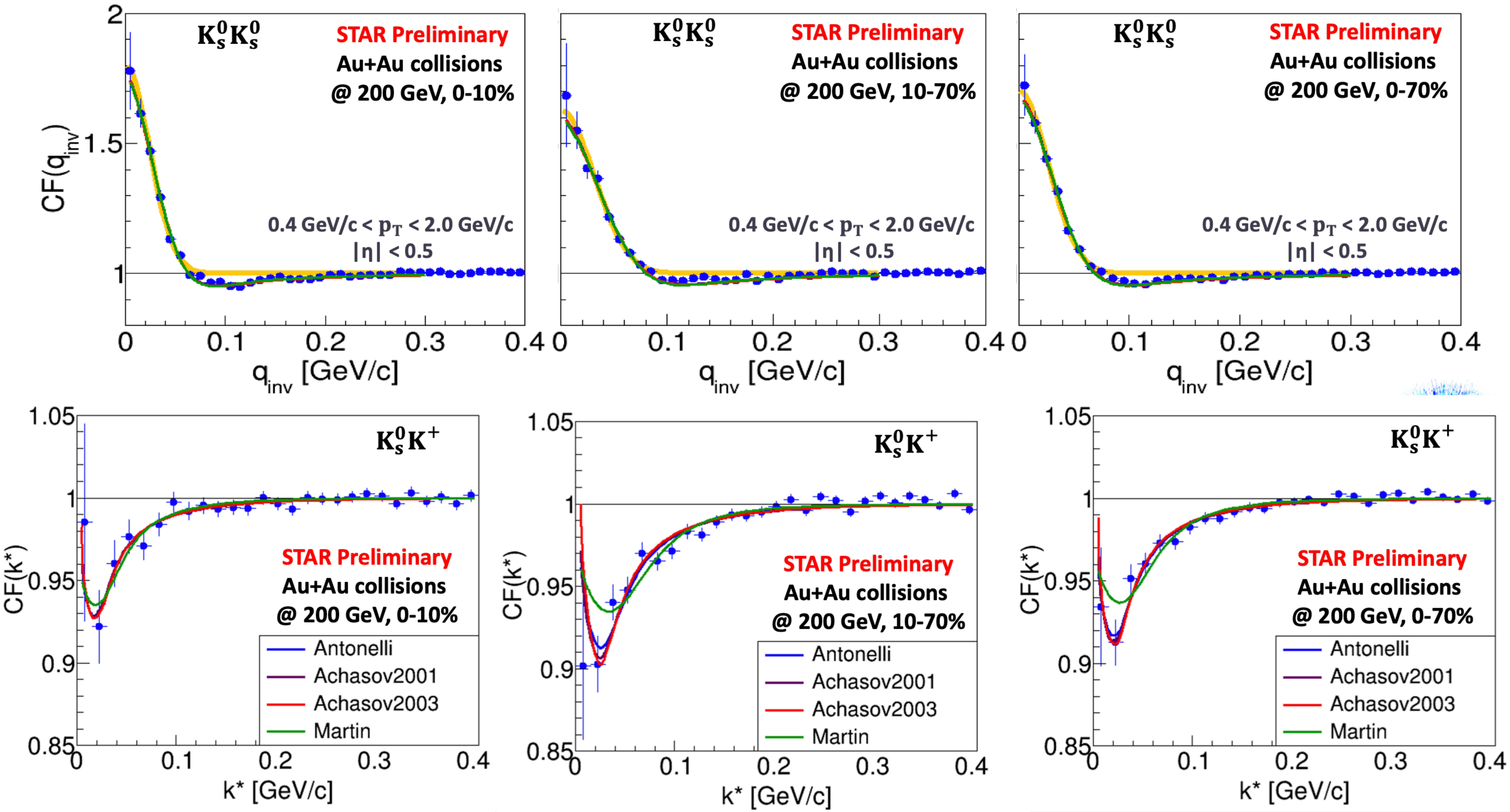
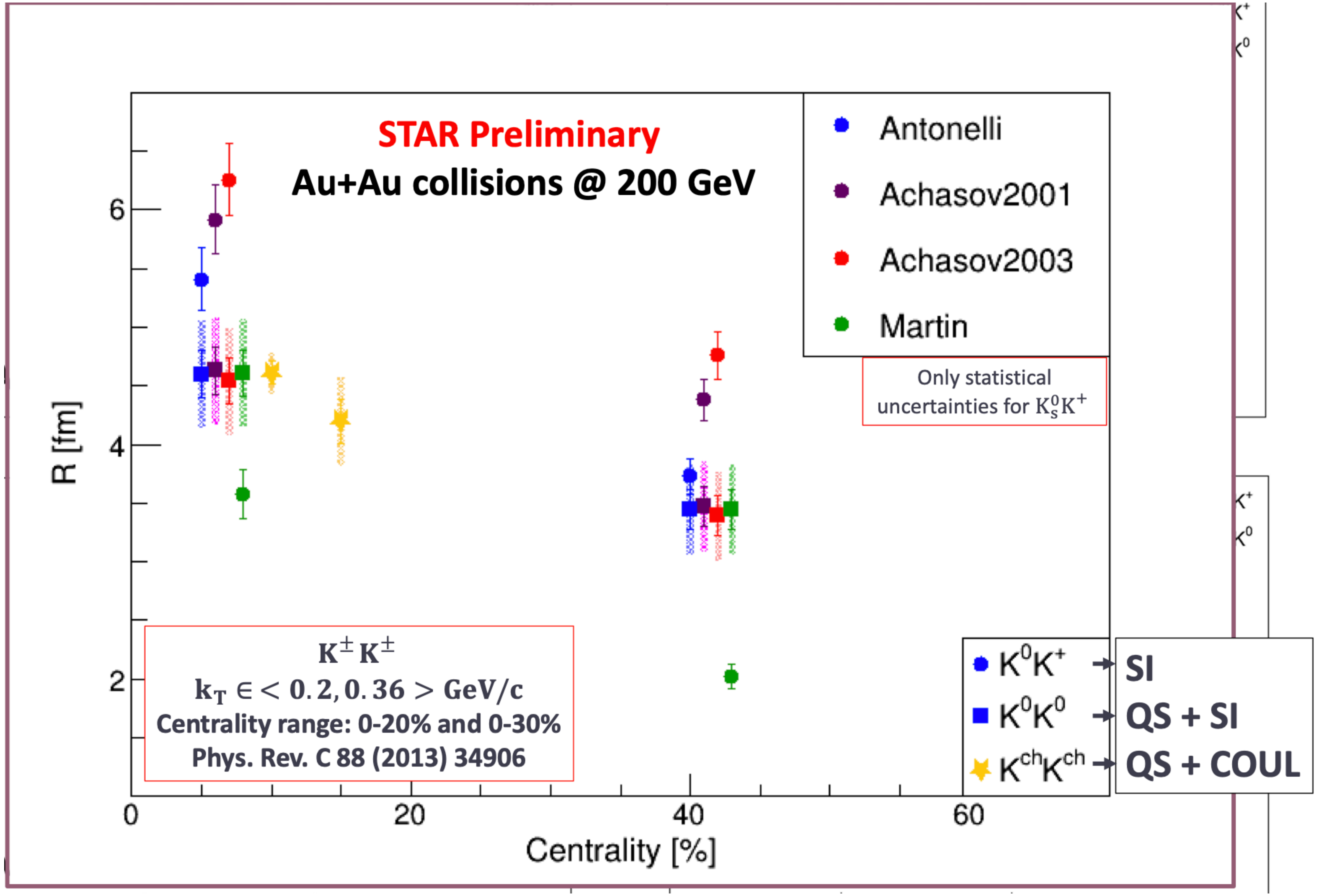
[3] Phys. Rev. D 68, 014006 (2003), [4] Nucl. Phys. B 121, 514–530 (1977)

# 1d) Neutral kaons



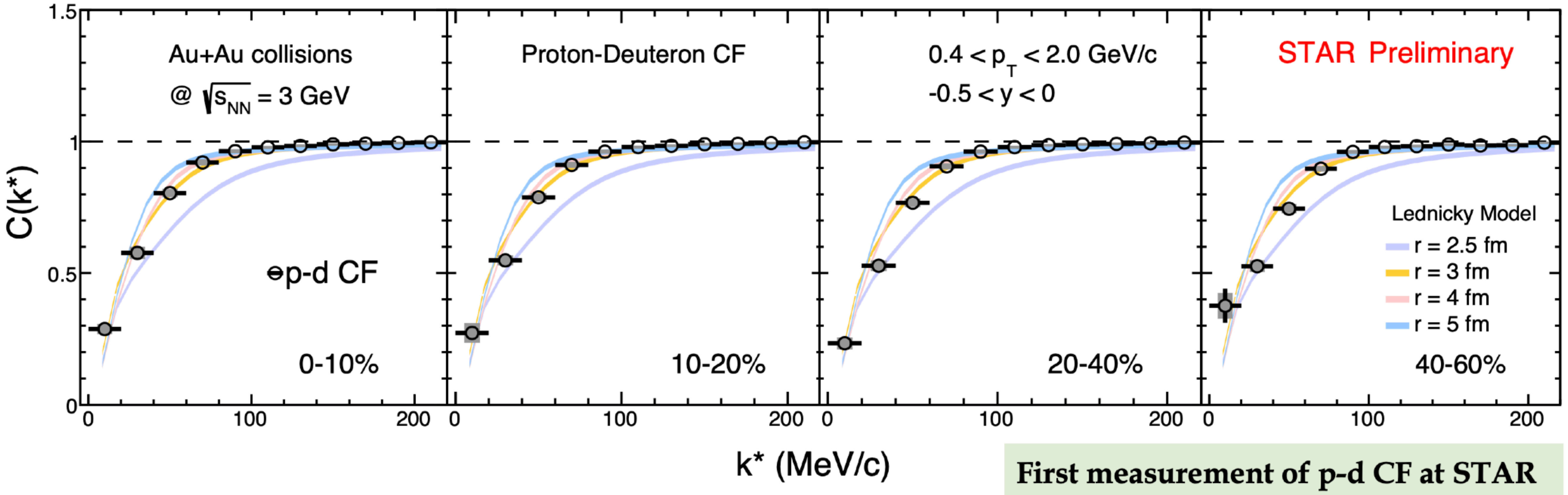
The $a_0(980)$ FSI parametrization gives very good representation of the shape of the signal region in CF; the parametrization with the larger $a_0(980)$ mass and decay coupling gives larger size of the source; **Antonelli parametrization favors $a_0(980)$ resonance as a tetraquark**

# 1d) Neutral kaons

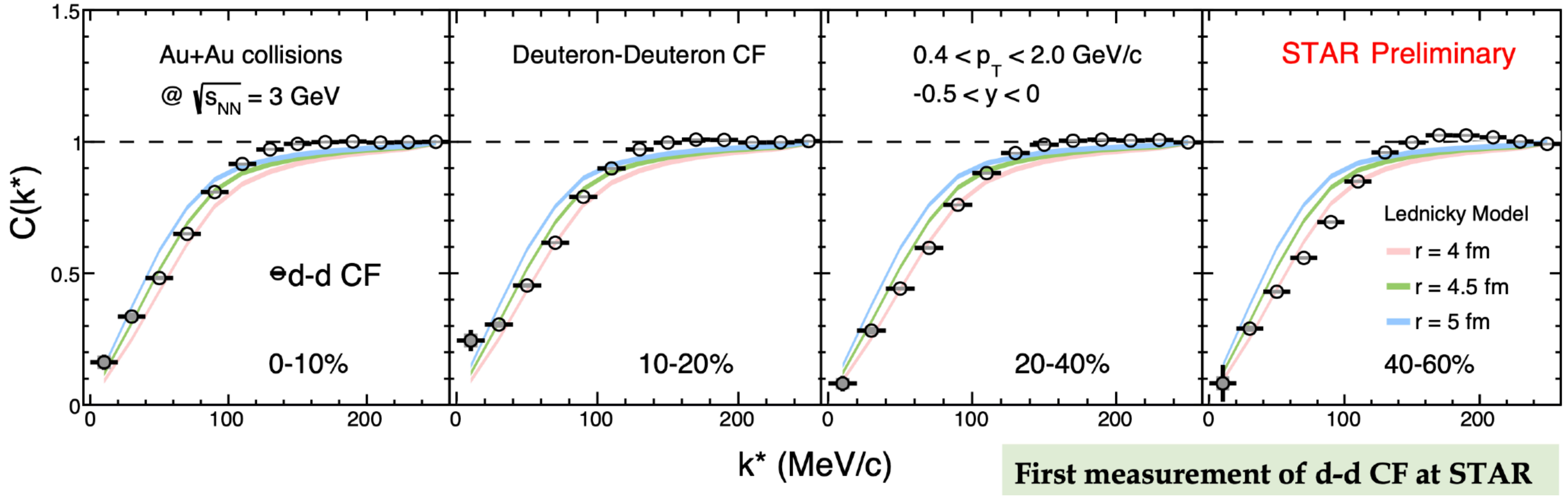


The $a_0(980)$ FSI parametrization gives very good representation of the shape of the signal region in CF; the parametrization with the larger $a_0(980)$ mass and decay coupling gives larger size of the source; **Antonelli parametrization favors $a_0(980)$ resonance as a tetraquark**

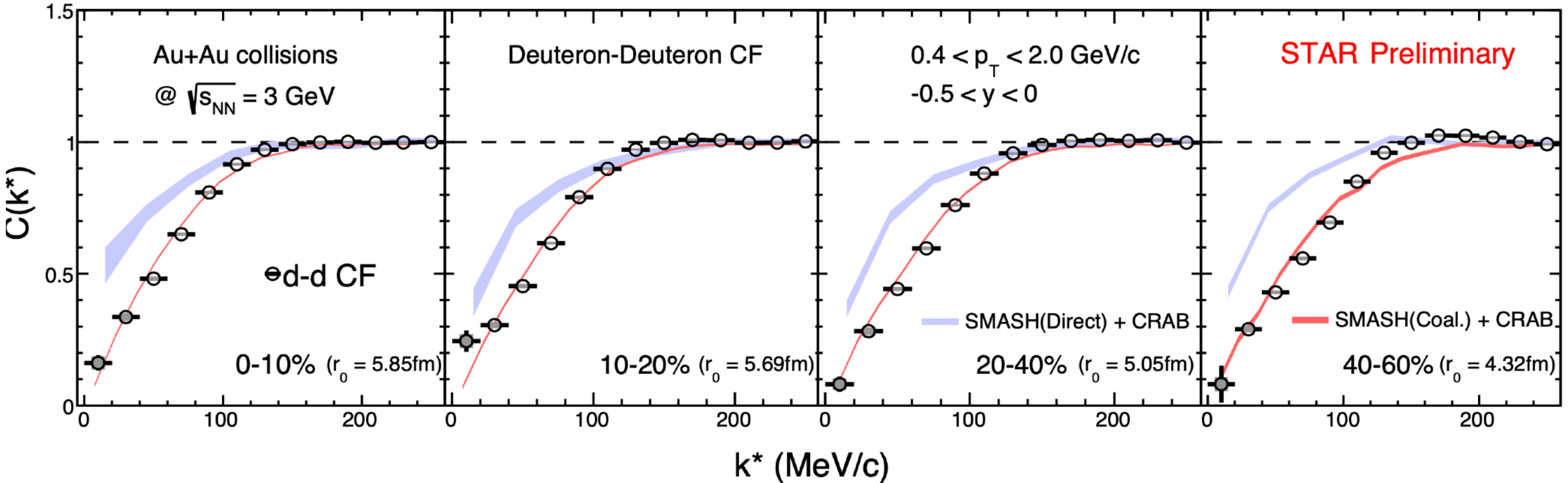
# 1e) Light nuclei formation at STAR



**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.

# 1f) Kaon-Lambda

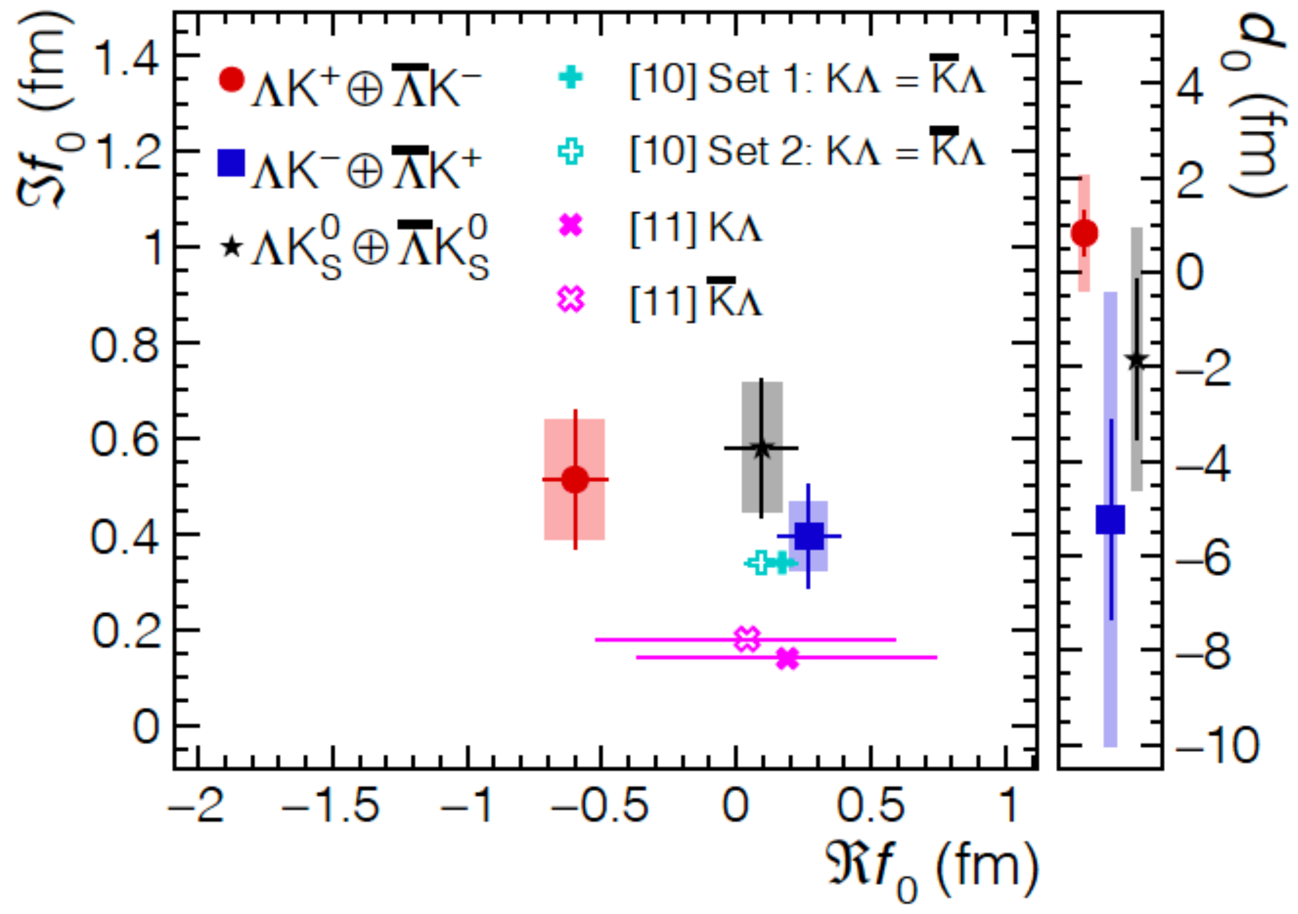
To measure scattering parameters of $\Lambda - K$ pairs in all three charge combinations $\Lambda - K^+$, $\Lambda - K^-$ and $\Lambda - K^0_S$.

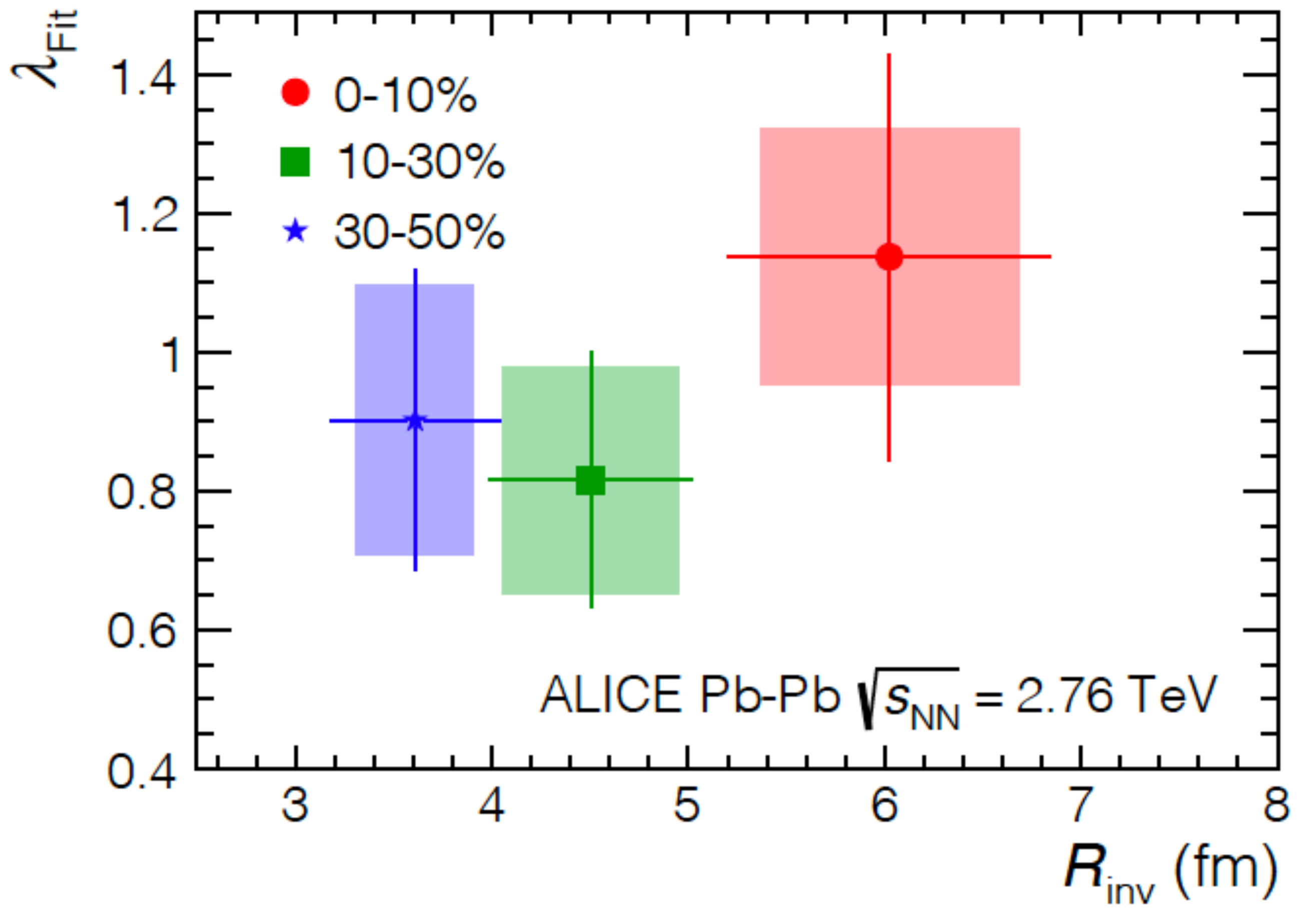
**Strong** force is **repulsive** in the $\Lambda - K^+$ interaction and **attractive** in the $\Lambda - K^-$ and $\Lambda - K^0_S$ interactions.

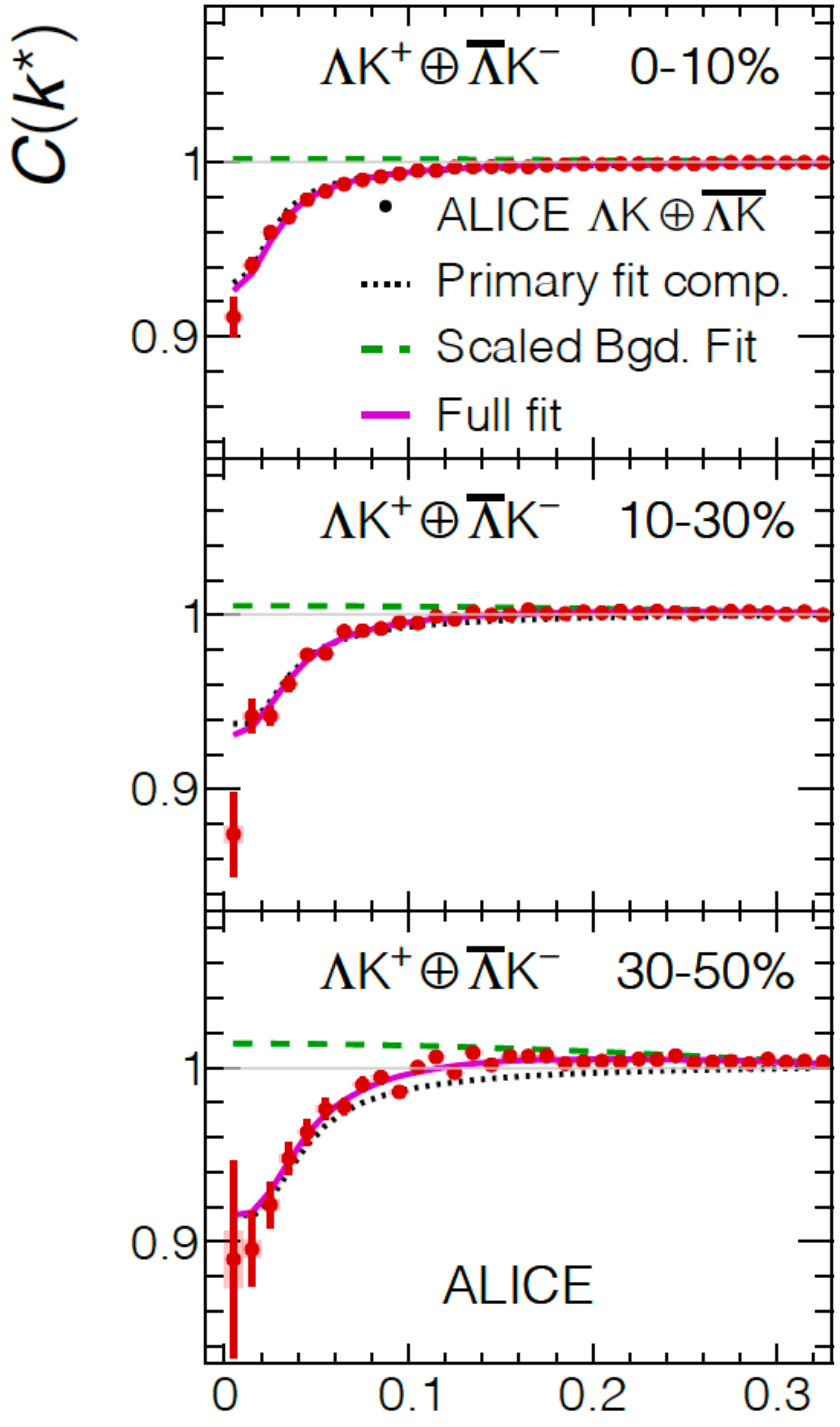
Different $q - \bar{q}$ interactions between the pairs ($s - \bar{s}$ in $\Lambda - K^+$ and $\Lambda - K^0_S$ and $u - \bar{u}$ in $\Lambda - K^-$)

Different net-strangeness for each system (S=0 for $\Lambda - K^+$, and S=-2 for $\Lambda - K^-$).

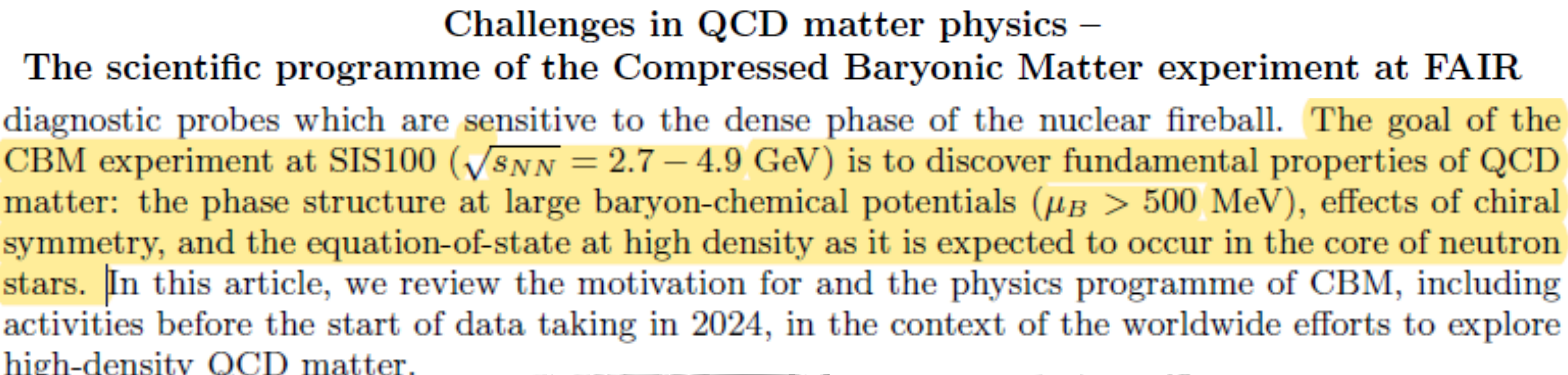
Source radii larger than expected from extrapolation from identical particle femtoscopic studies, due to separation in space–time of the single-particle Λ and K source distributions.







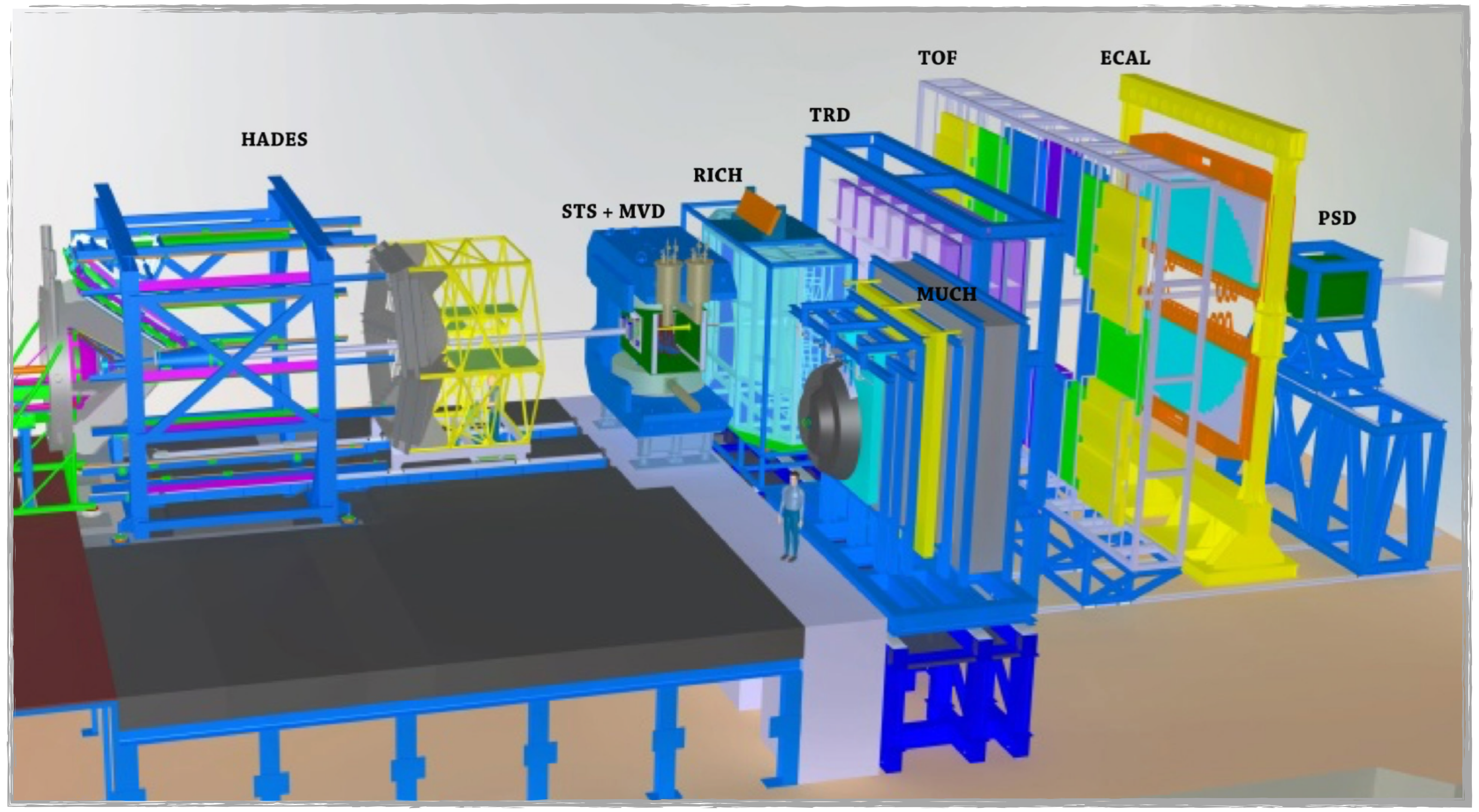
# CBM (and HADES) challenges



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

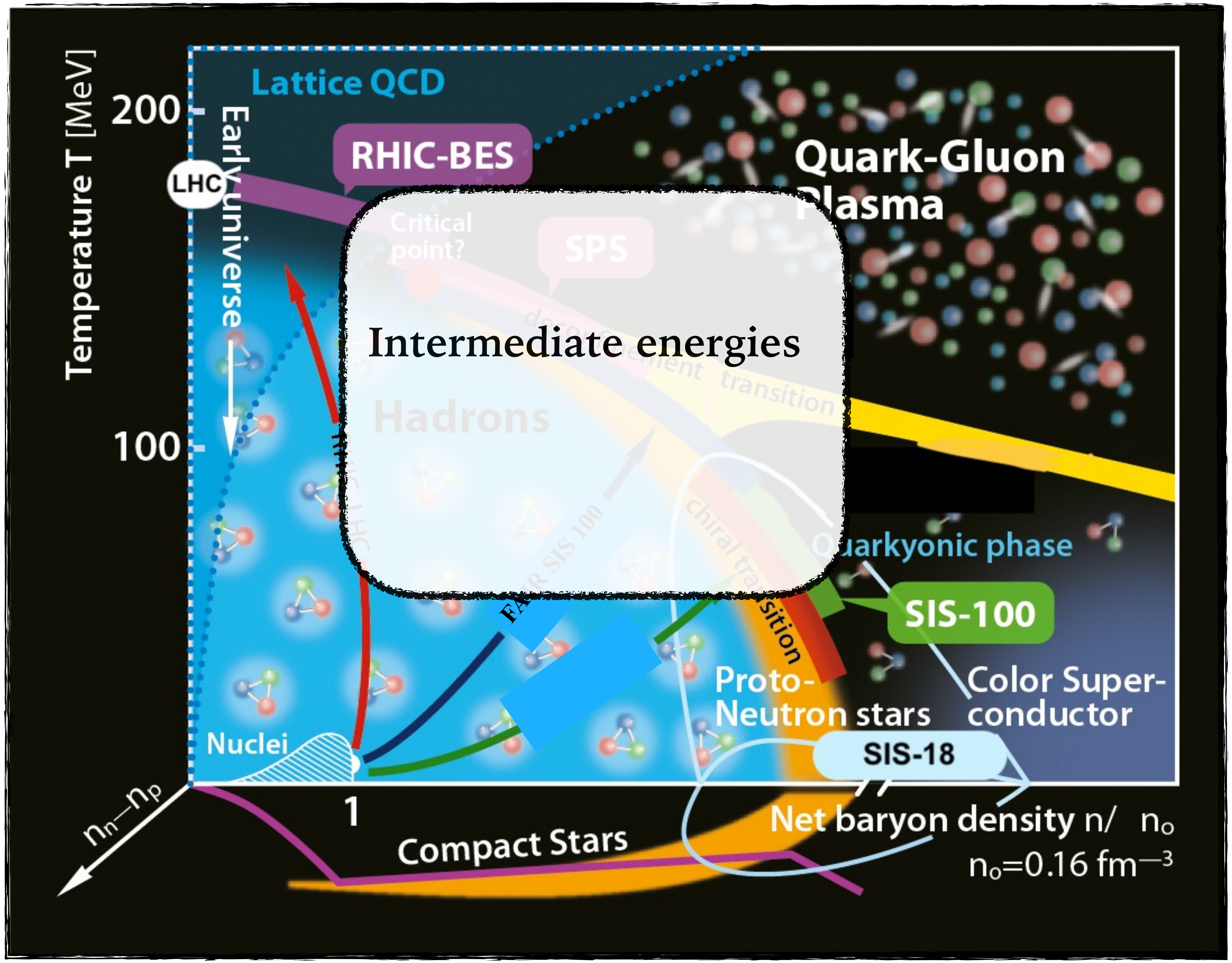
diagnostic probes which are sensitive to the dense phase of the nuclear fireball. The goal of the CBM experiment at SIS100 ($\sqrt{s_{NN}} = 2.7 - 4.9$ GeV) is to discover fundamental properties of QCD matter: the phase structure at large baryon-chemical potentials ($\mu_B > 500$ MeV), effects of chiral 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.

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



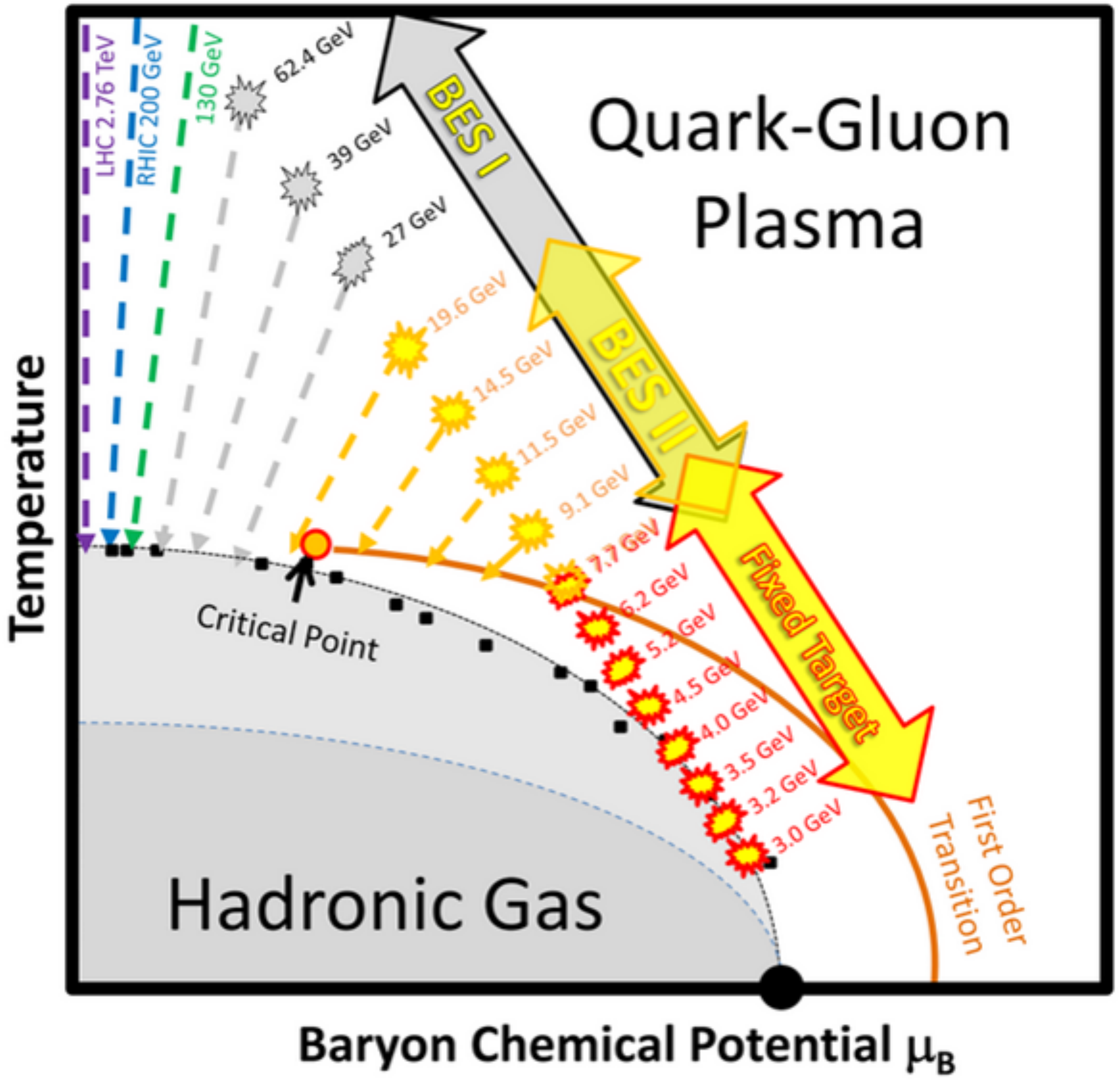
The CBM experimental setup together with the HADES detector

# QCD Phase diagram of strongly interacting matter - intermediate energies



Intermediate energies

# 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

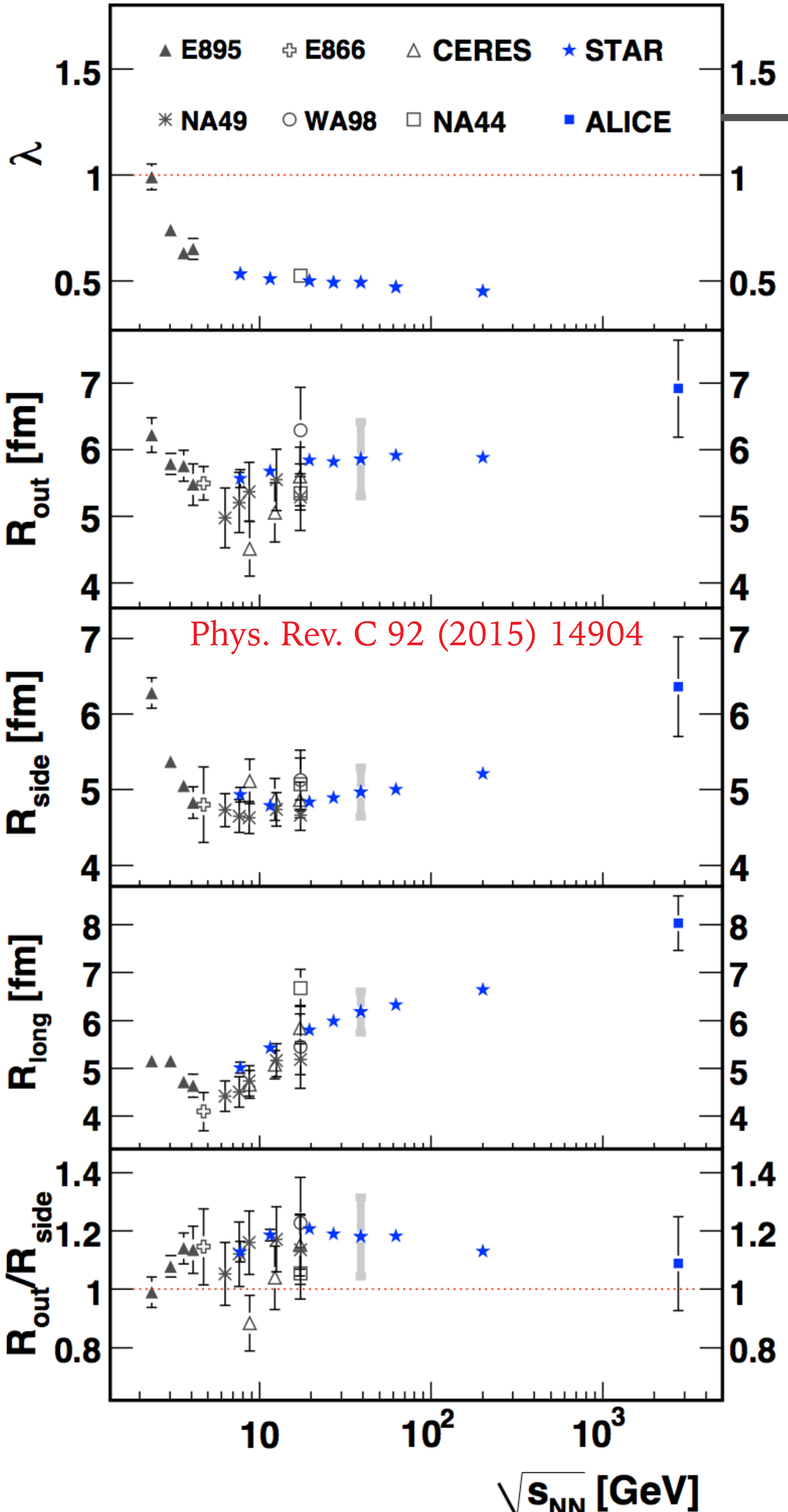
1. QCD at high energy density/temperature
2. Properties of QGP, EoS

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



Phys. Rev. C 92 (2015) 14904

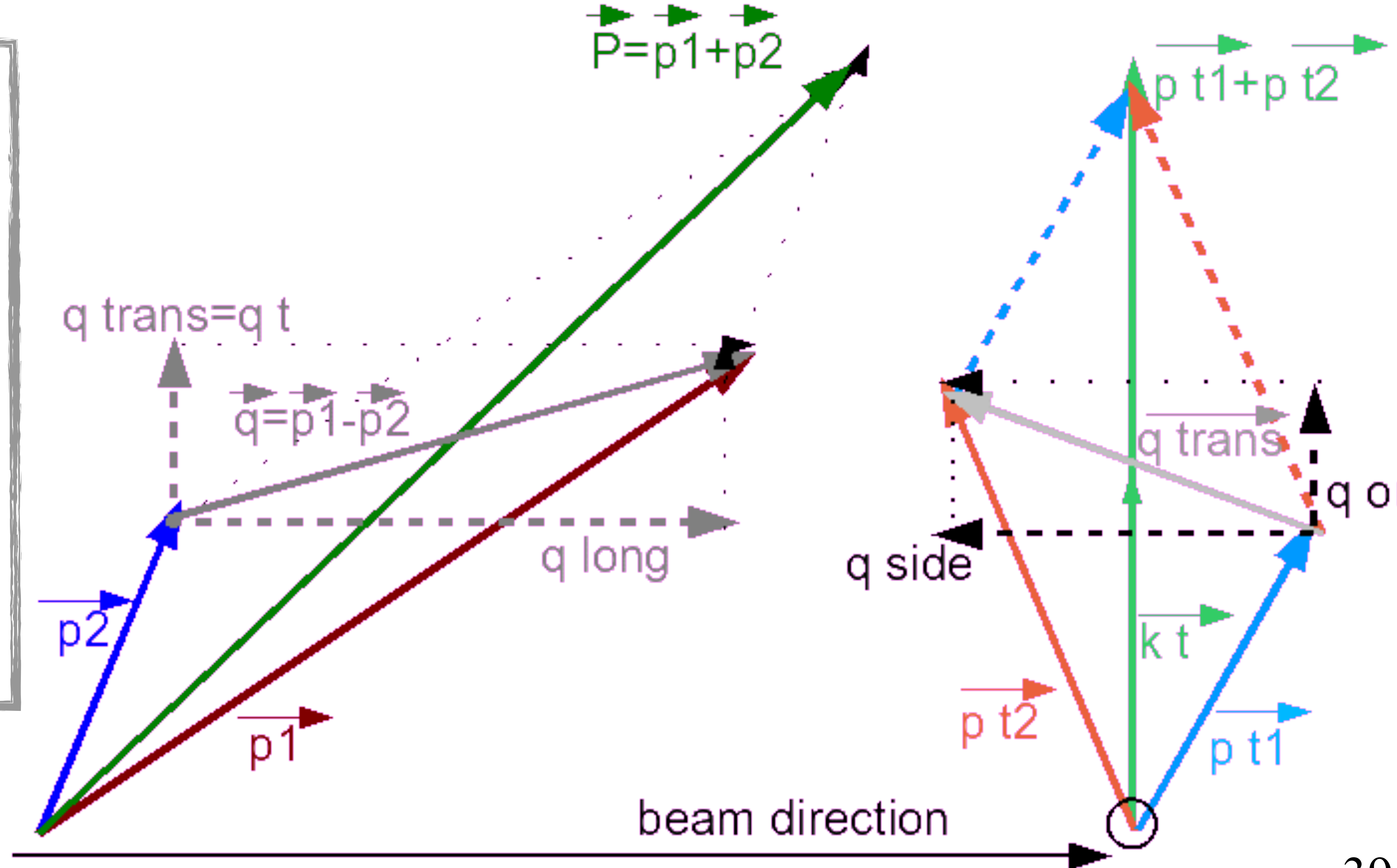
# Identical pion femtoscopy

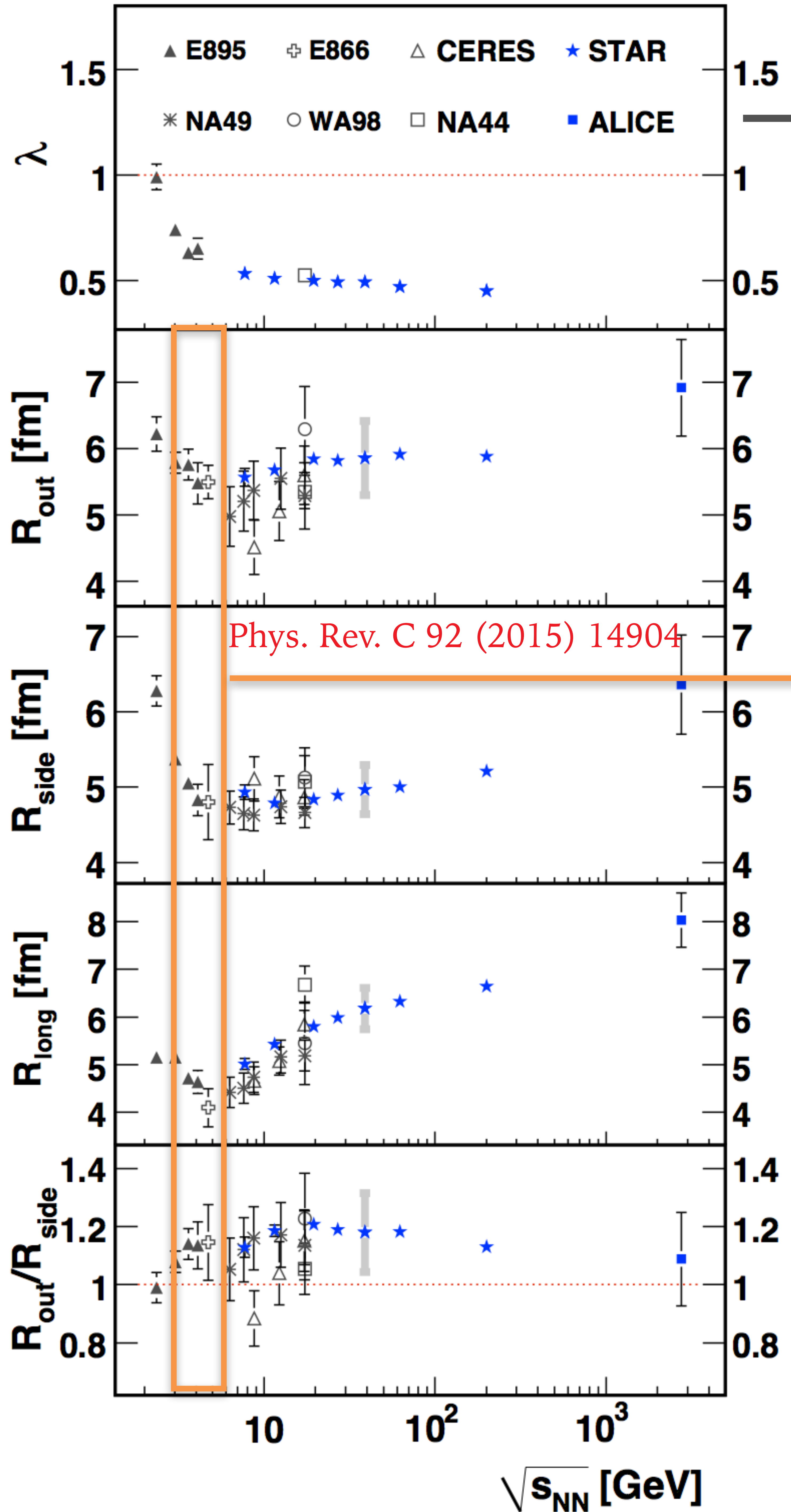
- → $R_{side}$ spatial source evolution in the transverse direction
- → $R_{out}$ related to spatial and time components
- → $R_{out}/R_{side}$ signature of phase transition
- → $R_{out}{}^2$- $R_{side}{}^2 = \Delta\tau^2\ \beta_t{}^2$; $\Delta\tau$ – emission time
- → $R_{long}$ temperature of kinetic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

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

HBT source sizes determined for wide range of collision energy;

Non-monotonic behavior seen in three directions





Phys. Rev. C 92 (2015) 14904

# Identical pion femtoscopy

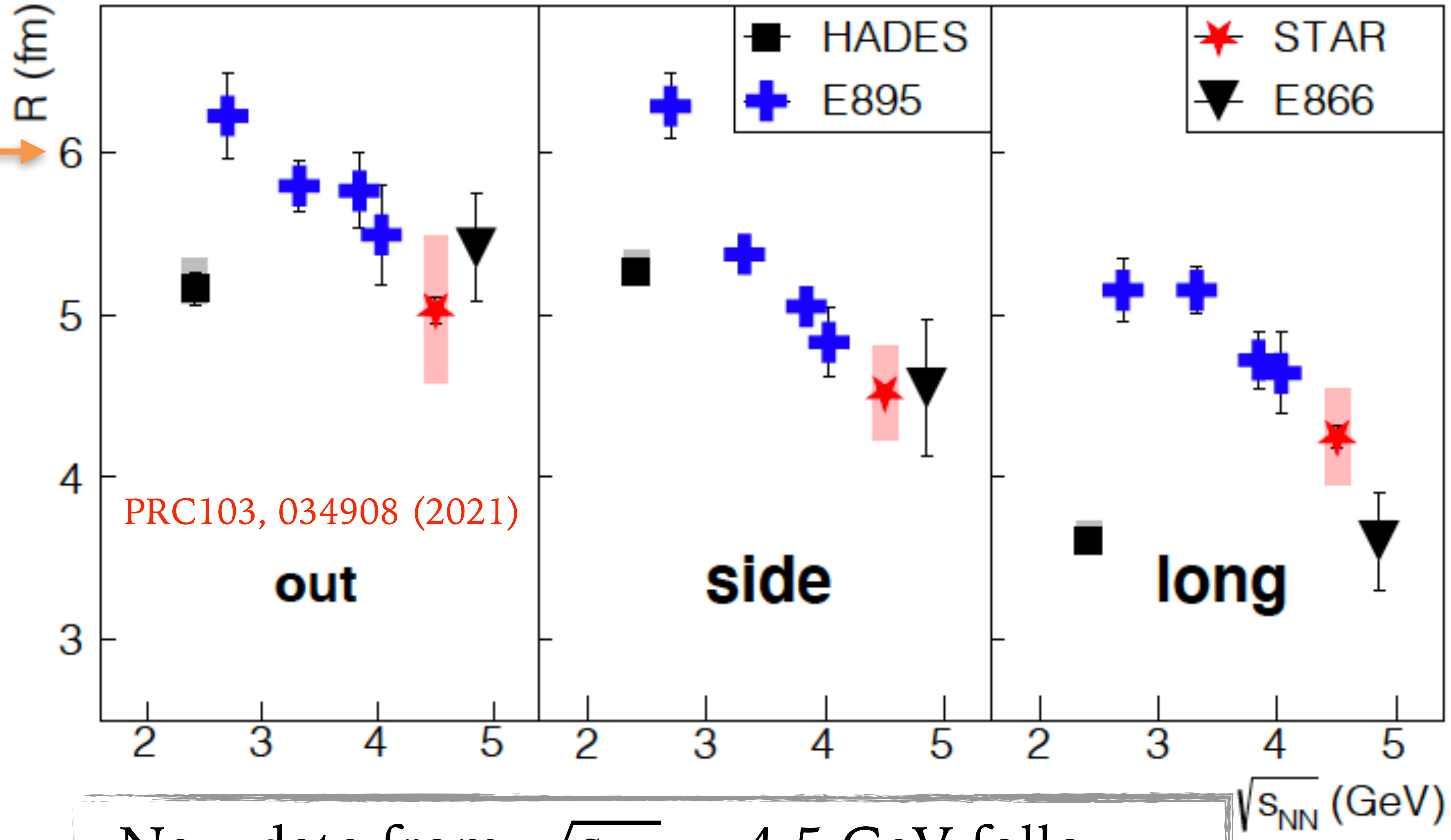
→ $R_{side}$ spatial source evolution in the transverse direction

→ $R_{out}$ 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



PRC103, 034908 (2021)

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

# Identical pion femtoscopy

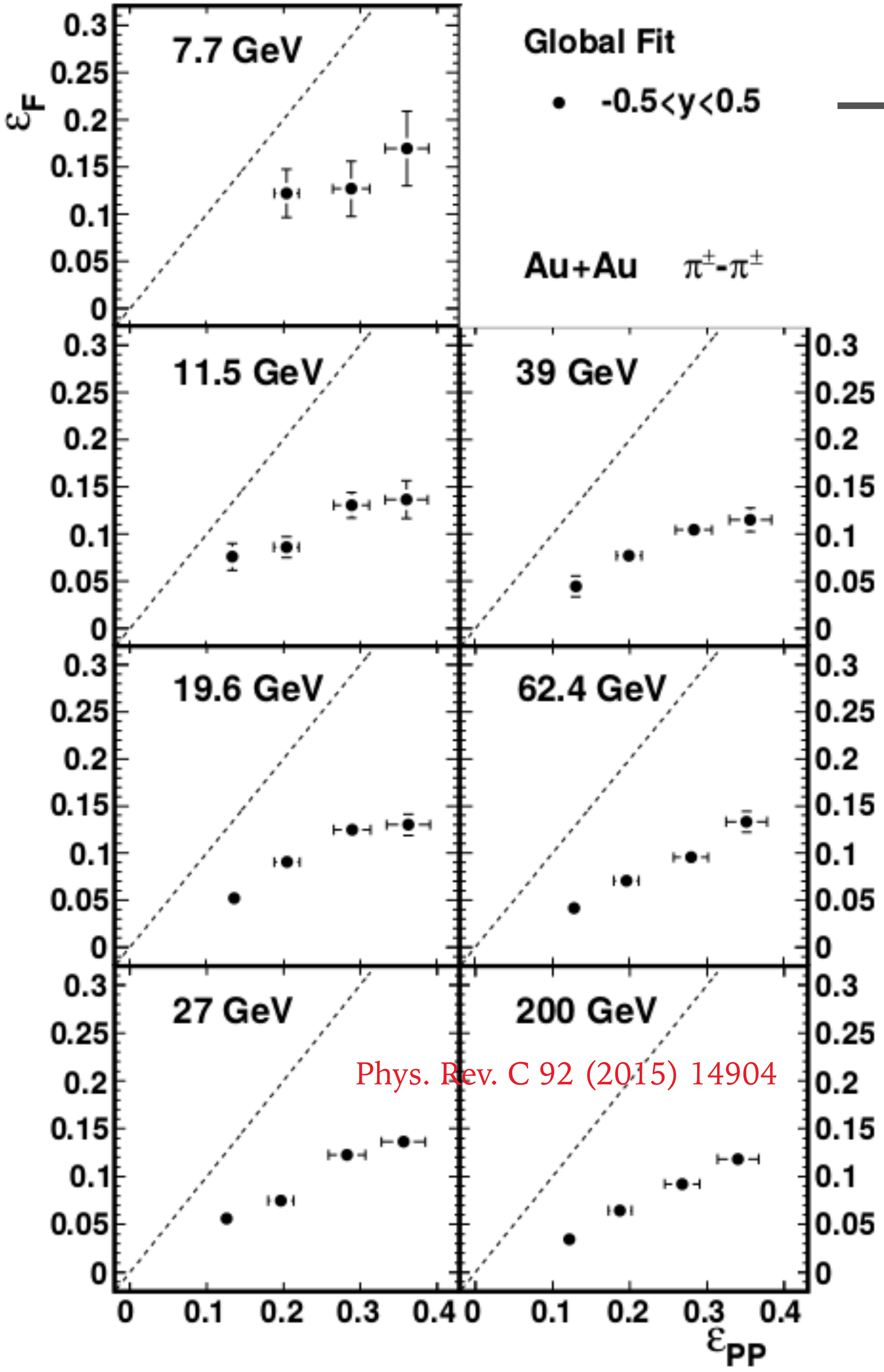
$$R^2_\mu(\Phi) = R^2_{\mu,0} + 2 \sum_{n=2,4,6\ldots} R^2_{\mu,n} \cos(n\Phi) \qquad (\mu = o,s,l,ol)$$

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

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

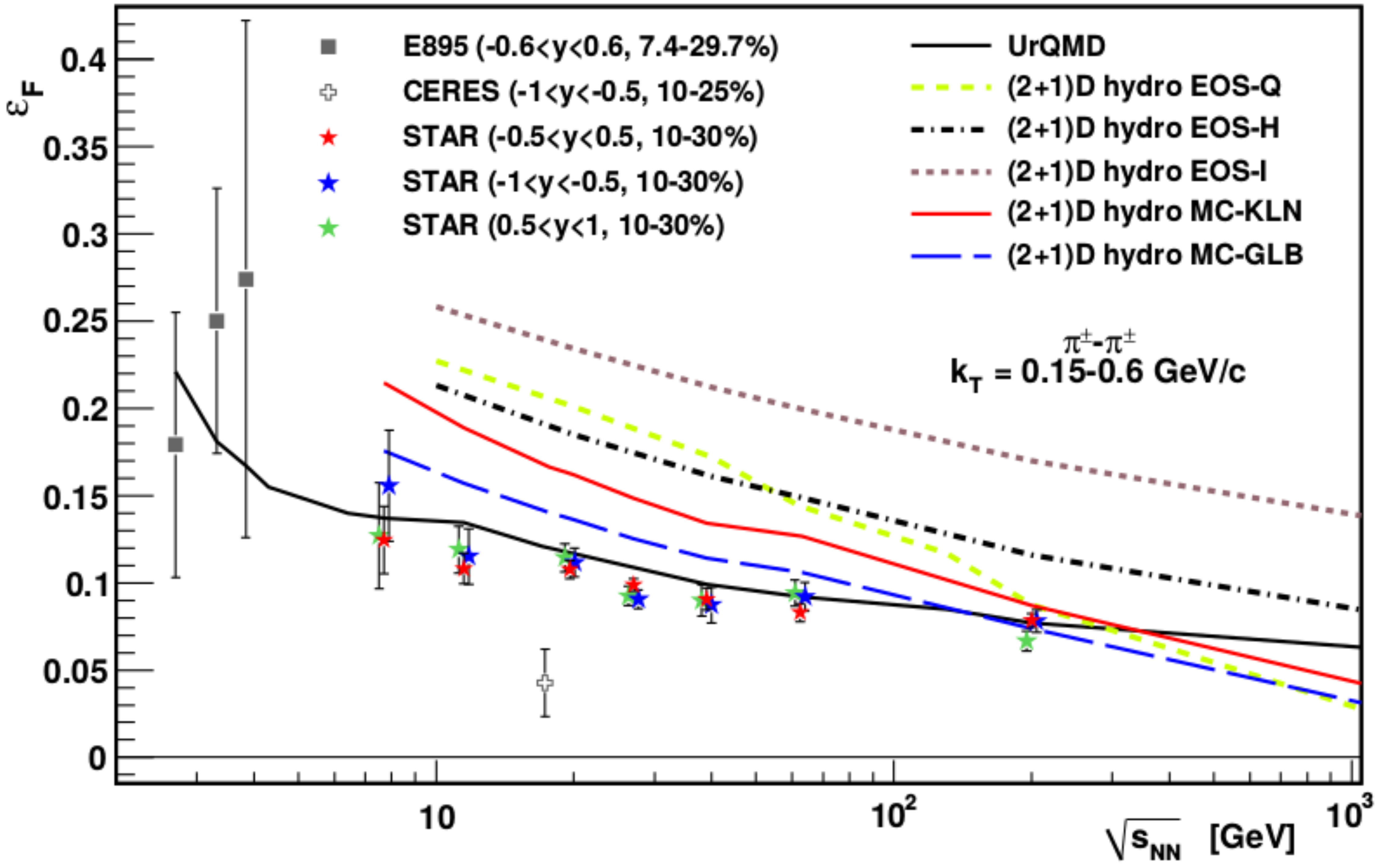
$$R^2_\mu(\Phi) = R^2_{\mu,0} + 2 \sum_{n=2,4,6\ldots} R^2_{\mu,n} \sin(n\Phi) \qquad (\mu = os)$$

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



Phys. Rev. C 92 (2015) 14904

System evolves faster in the reaction plane



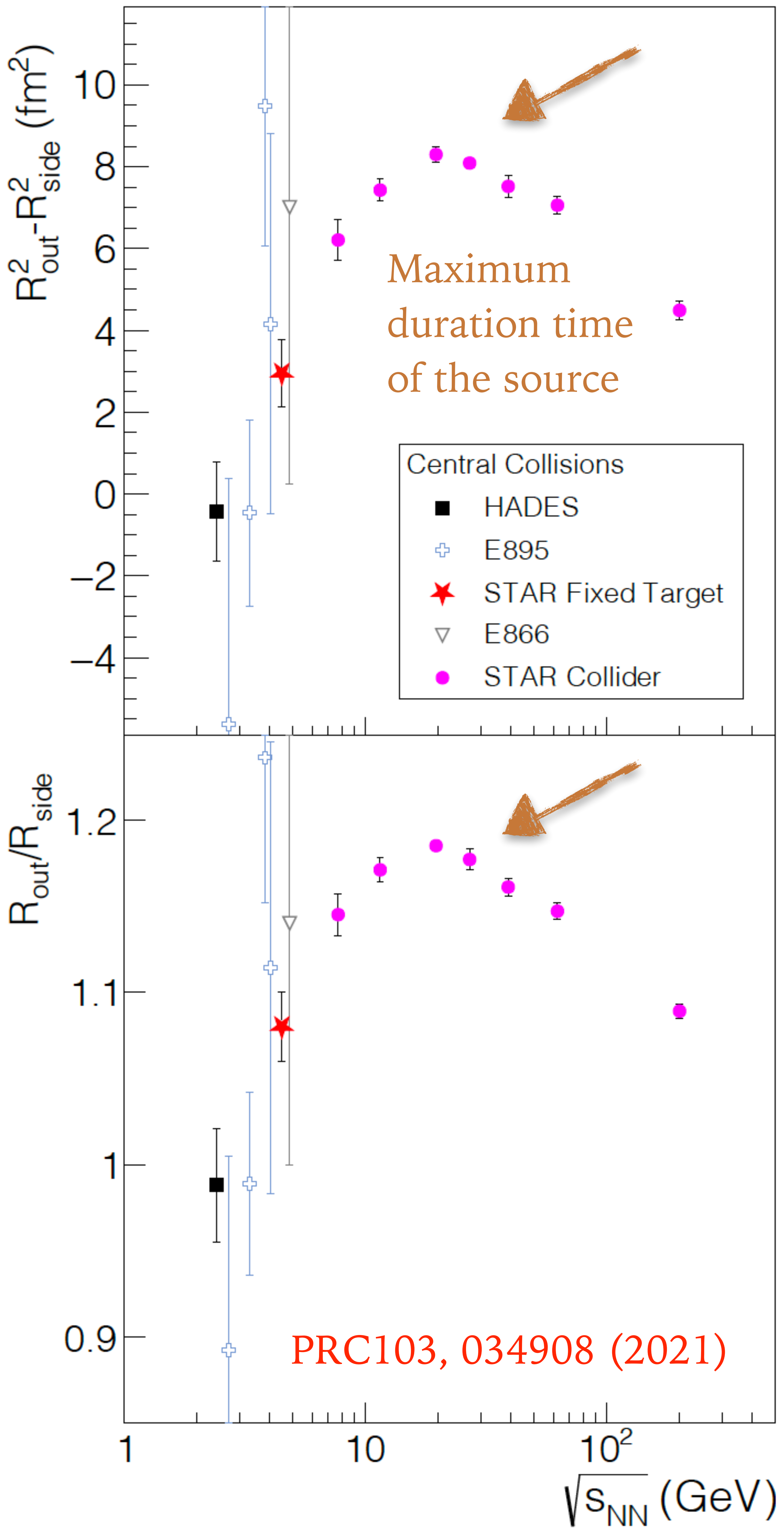
# How to measure a phase transition?

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

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?**

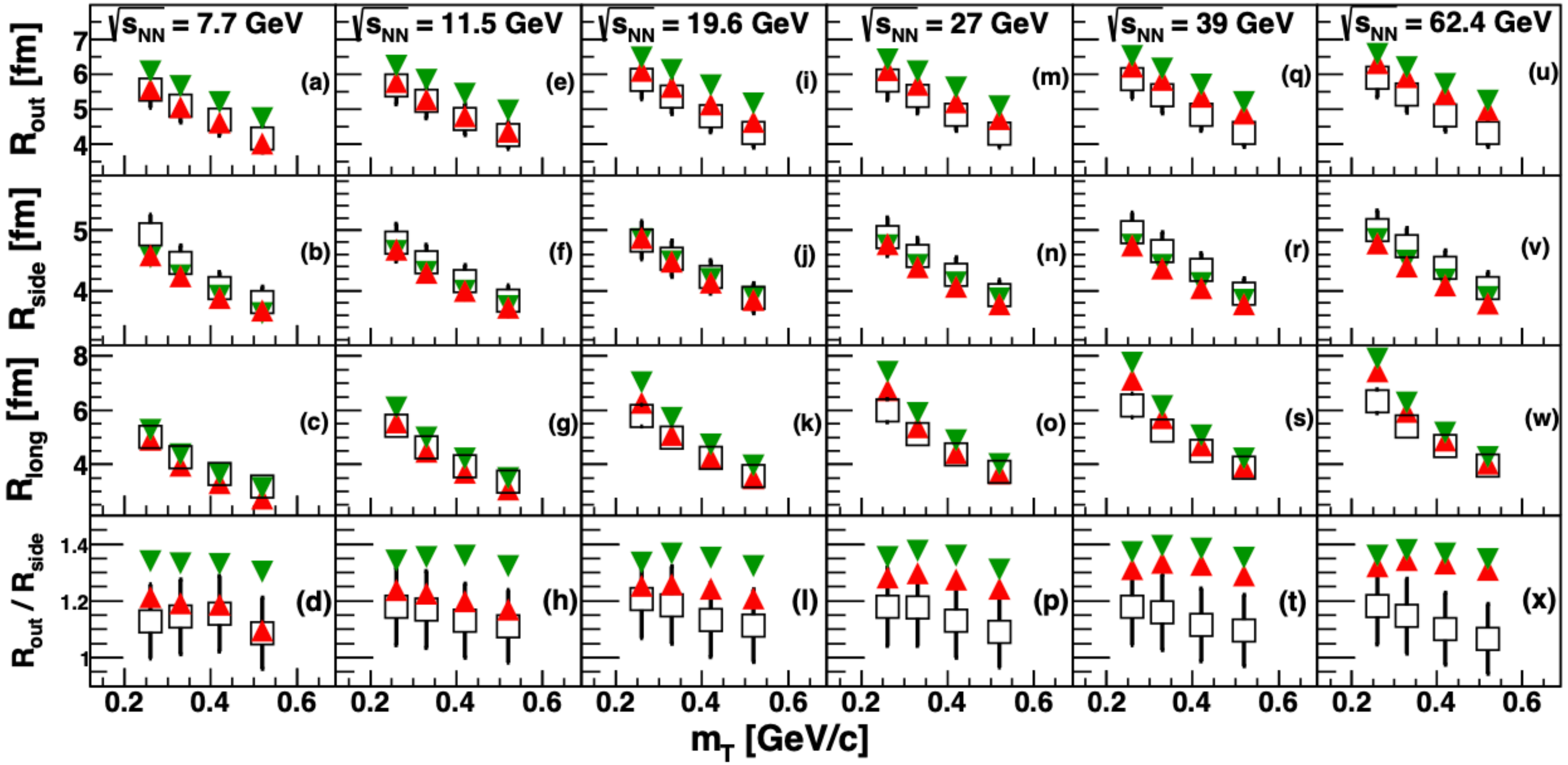
Theoretical attention from hydro and transport models needed



Maximum duration time of the source

PRC103, 034908 (2021)

# How to measure a phase transition?



☐ STAR Data

▲ 1st order Phase Tr.

▲ Cross-over Tr.

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**

# Conclusions & Summary

# Summary

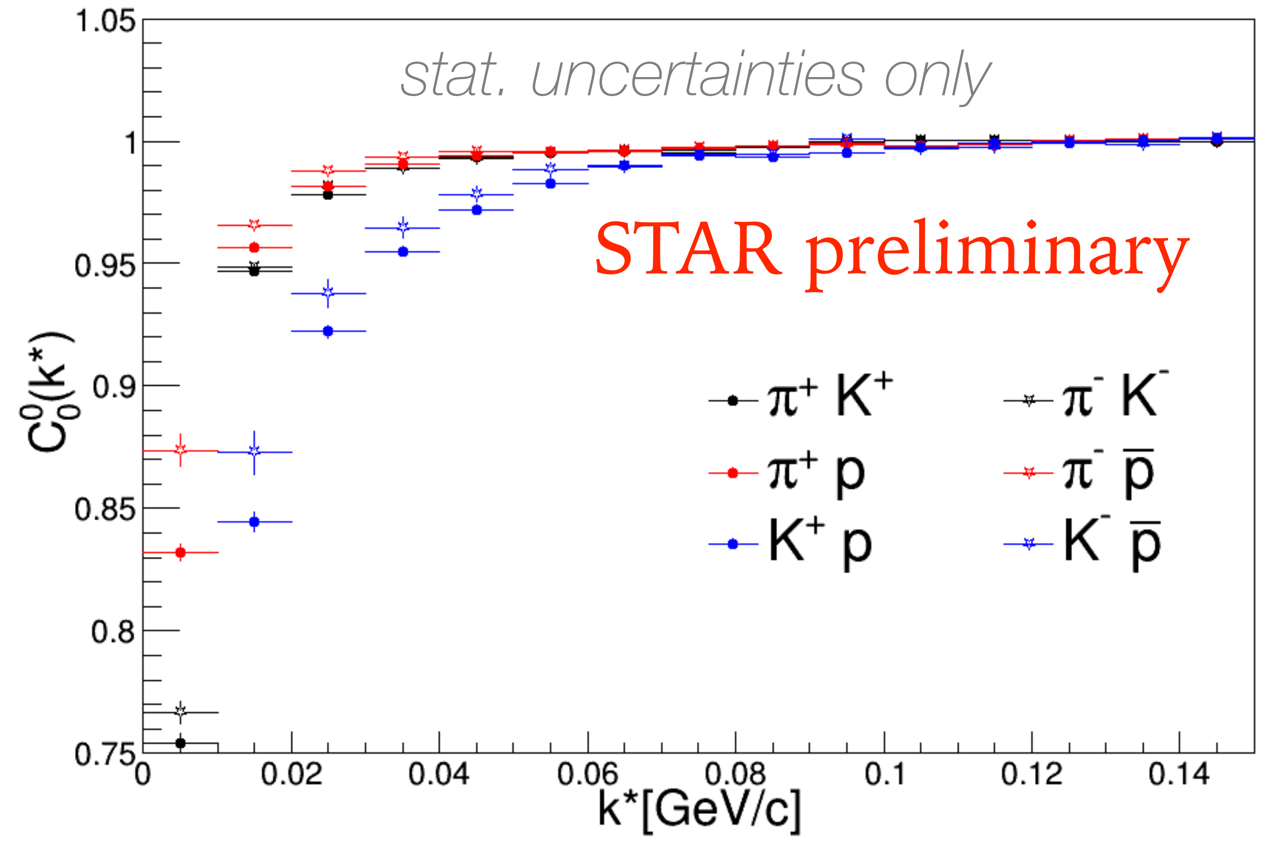
- Descriptions of the interaction among antimatter (based on the simplest systems of anti-nucleons) determined.
- A quantitative verification of matter-antimatter symmetry in context of the forces responsible for the binding of (anti)nuclei.
- Scattering length is positive and favor $\Lambda - \Lambda$ 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
- Two-particle correlations are useful tool to explore unknown QCD phase diagram area

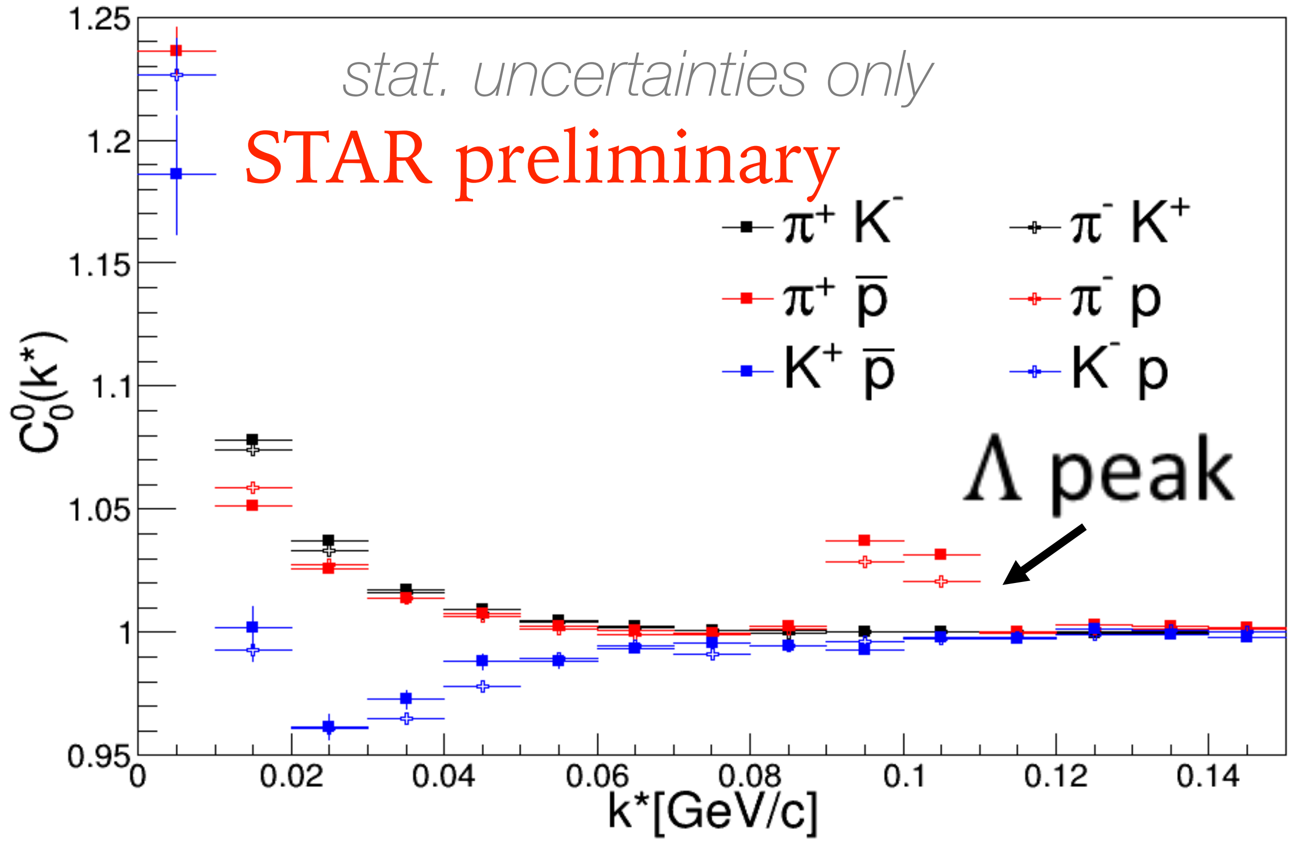
# Back-up slides

# Nonidentical particle correlations

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

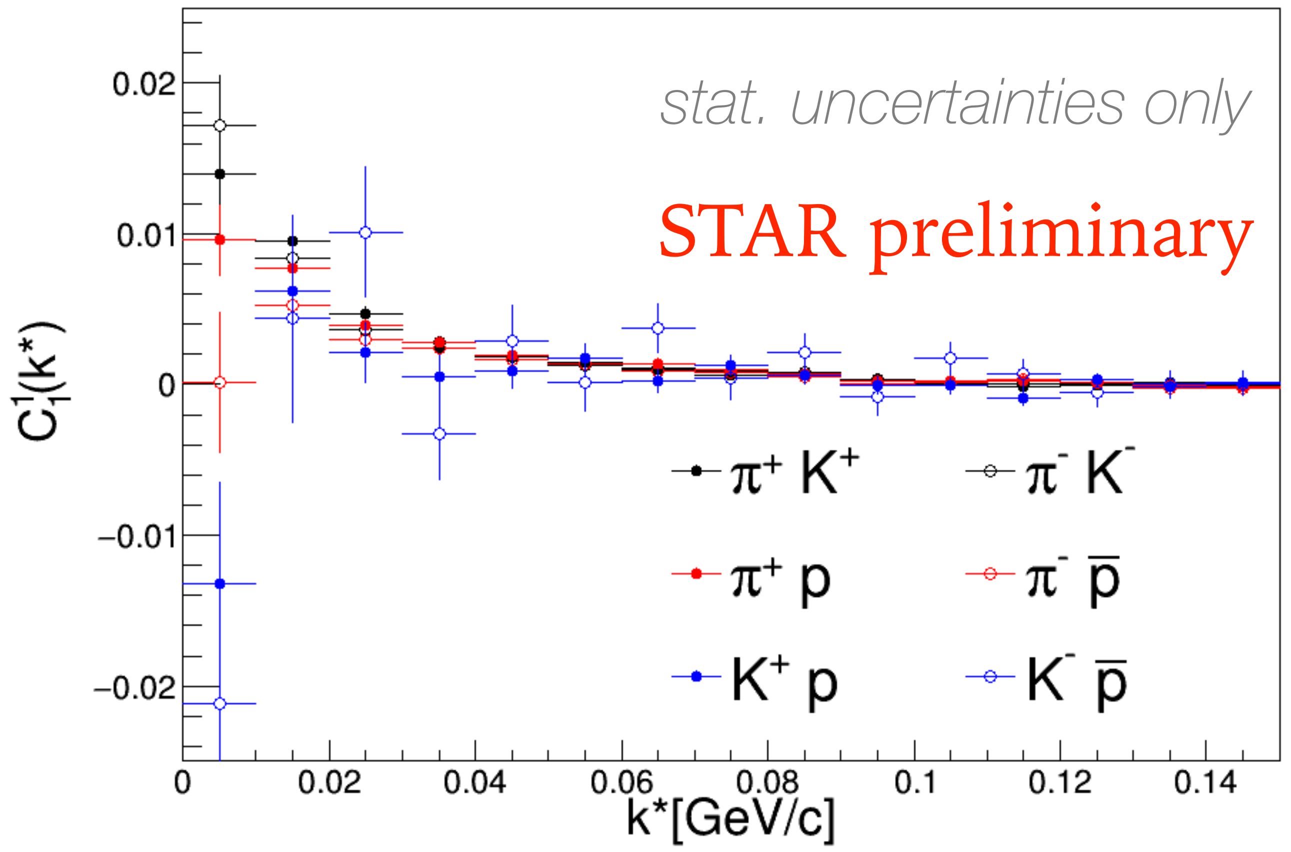
Unlike-sign 0-10% @ Au+Au 39 GeV

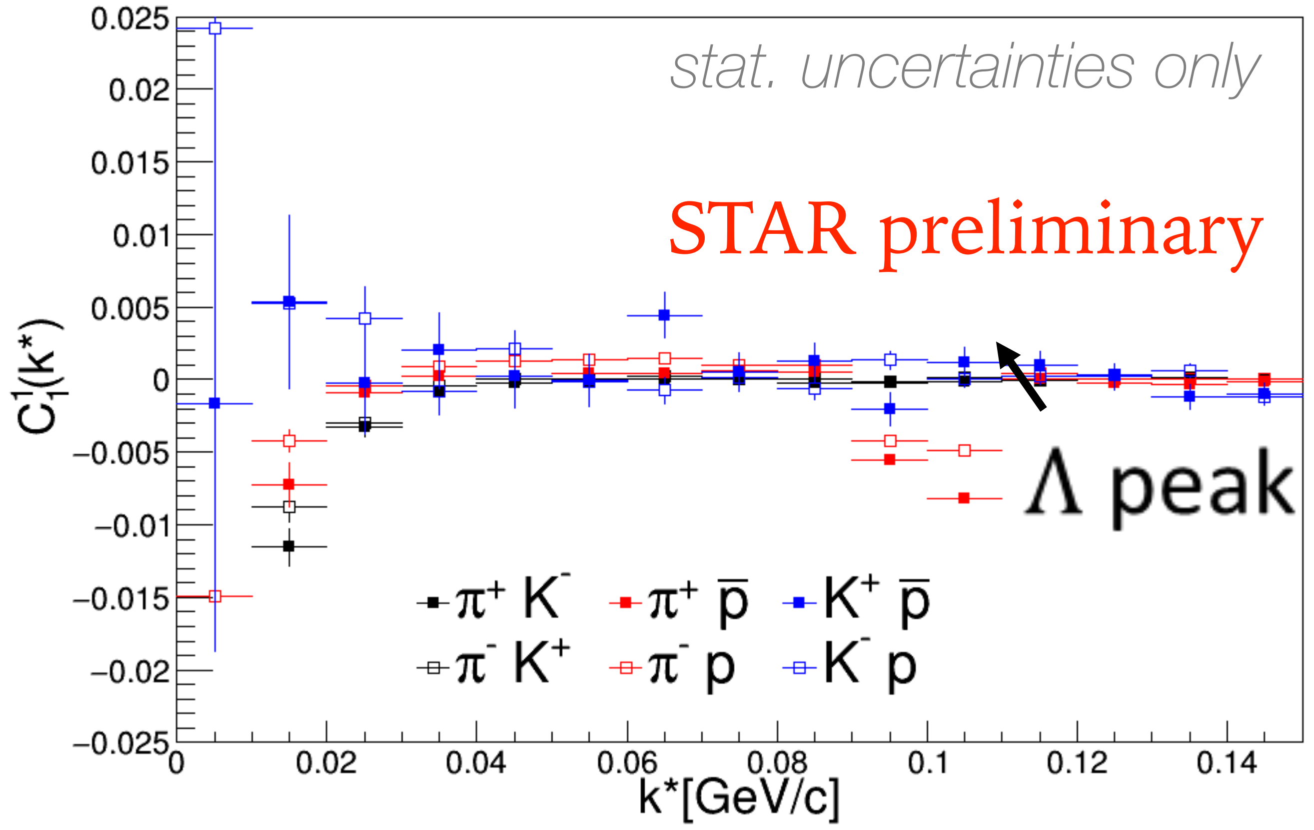




Determined by Coulomb Interactions

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

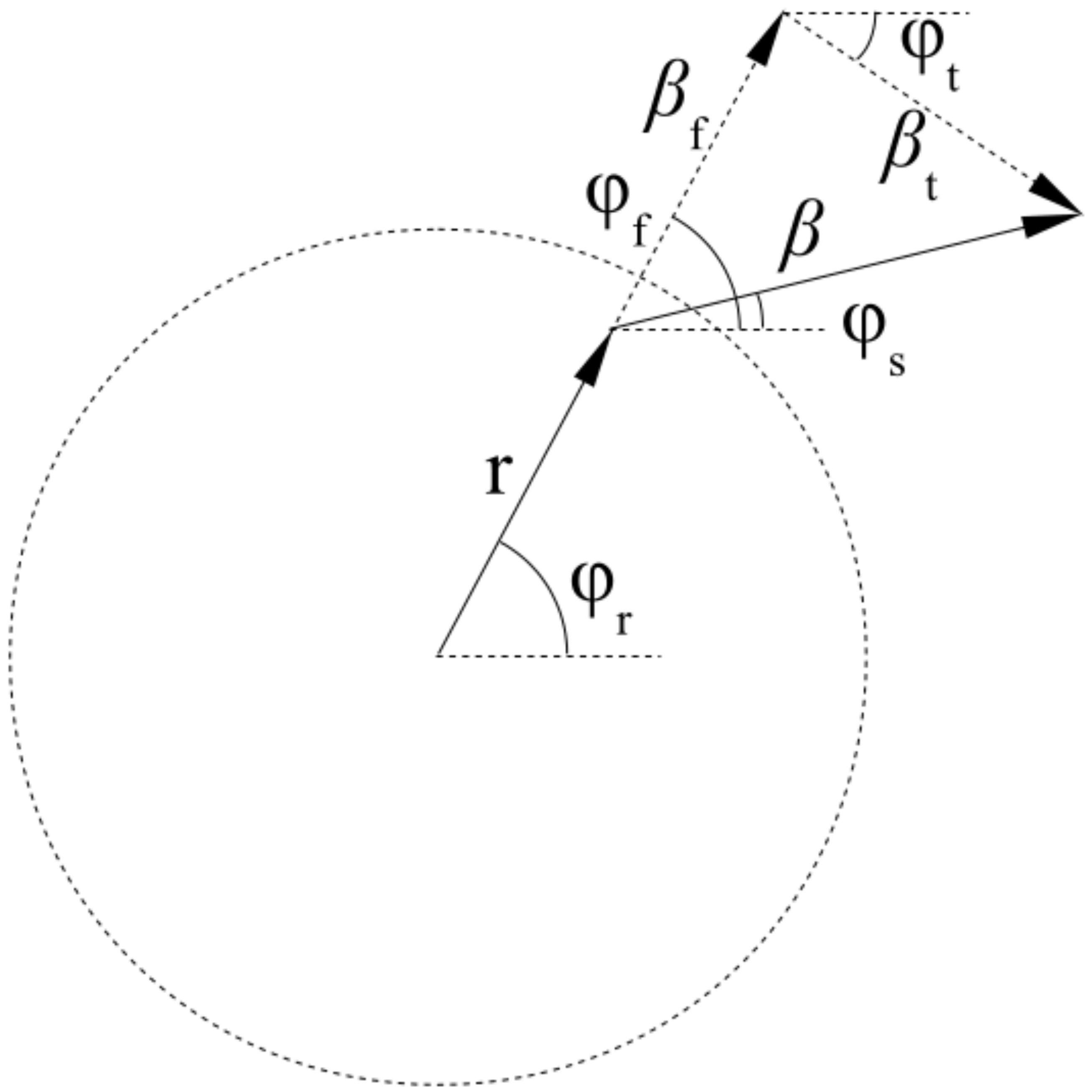




Nucl. Phys. A 982 (2019), 359-362

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