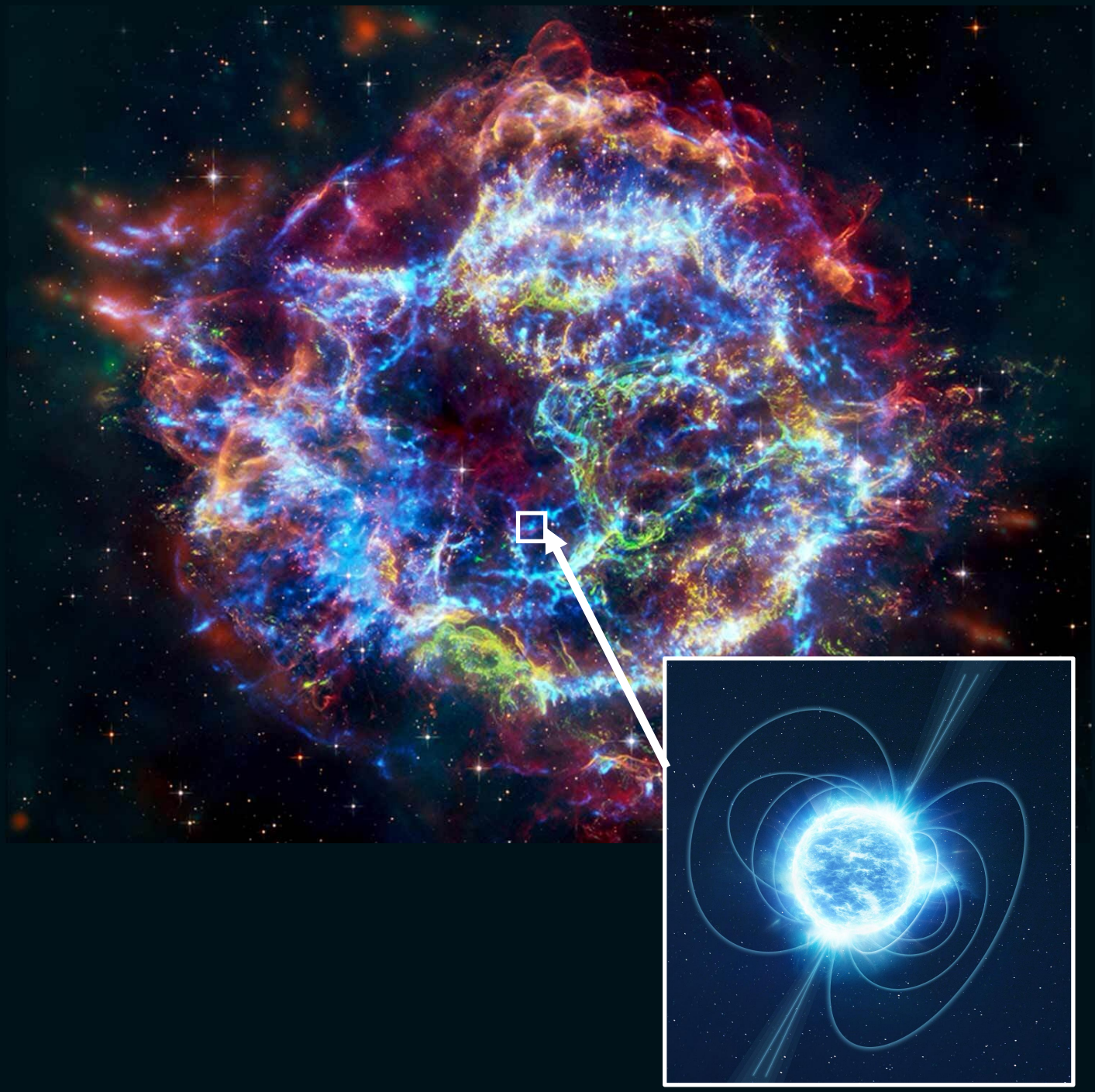
Czech Technical University in Prague

From femtoscopic measurements at the LHC to the core of Neutron Stars



Dr. Raffaele Del Grande

Czech Technical University in Prague

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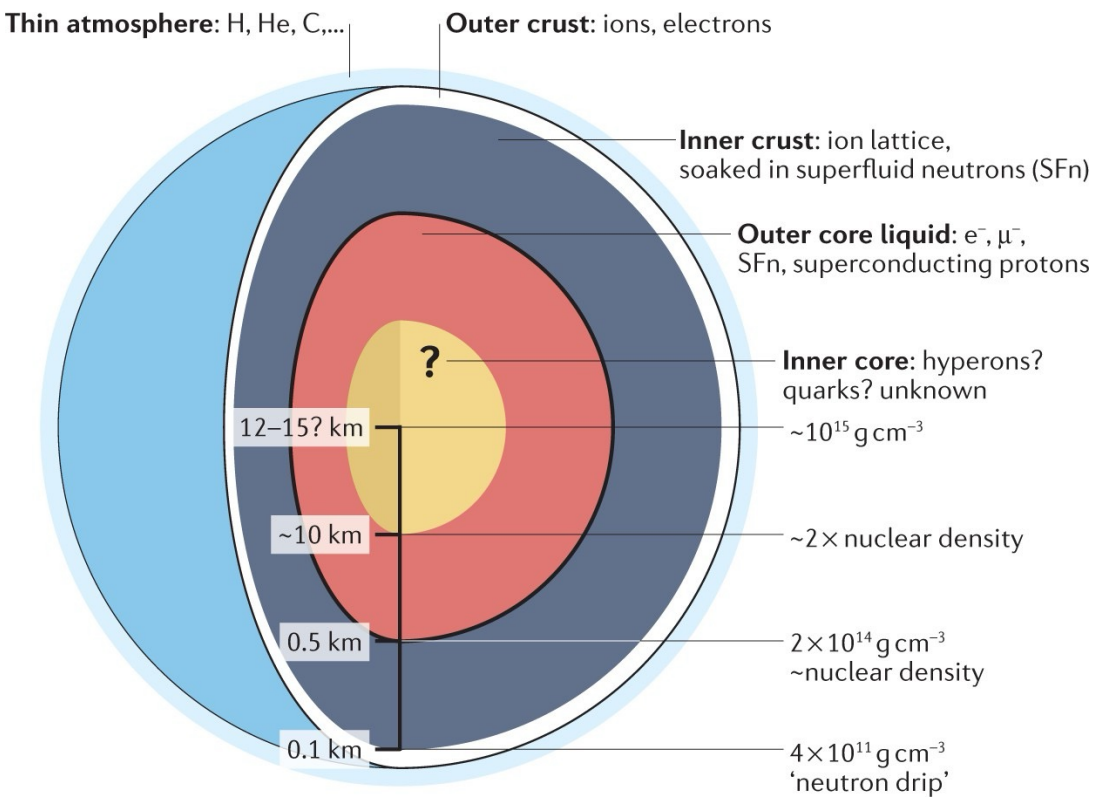
European Research Council

Neutron Stars structure

- Radius: 10 – 15 km
- Mass: 1.5 – 2.0 M_{Sun}
- High density expected in the inner core.

  $\rho = 2 – 3\ \rho_0$
- Inner core composition: **UNKNOWN!**



Nature Reviews Physics 4 (2022)
Figure adapted from NICER

Hydrostatic Equilibrium

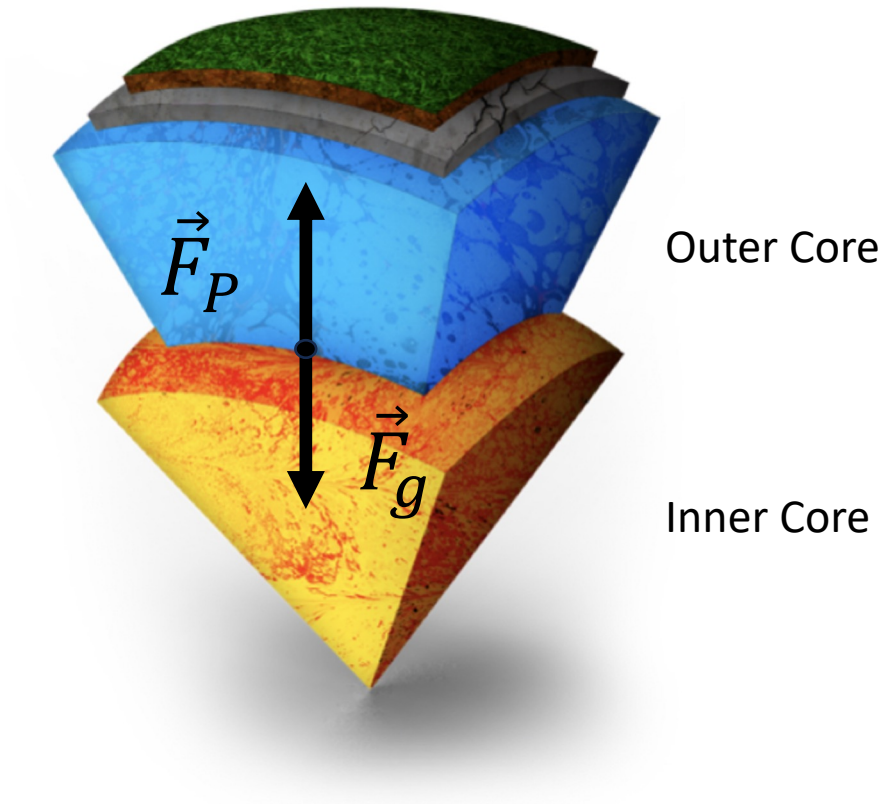
- Radius: 10 – 15 km
- Mass: 1.5 – 2.0 M_{Sun}
- High density expected in the inner core.

  $\rho = 2 - 3\ \rho_0$
- Inner core composition:
  - Make a hypothesis
  - Calculate the hydrostatic equilibrium
  - Compare with measured Mass-Radii
- Pressure of the star

$$P = \sum P_{particle\ species}$$

Hydrostatic Equilibrium

$$P_c \approx \frac{G\ M\ \bar{\rho}}{R}$$



Mass-Radius relation

- Radius: 10 – 15 km
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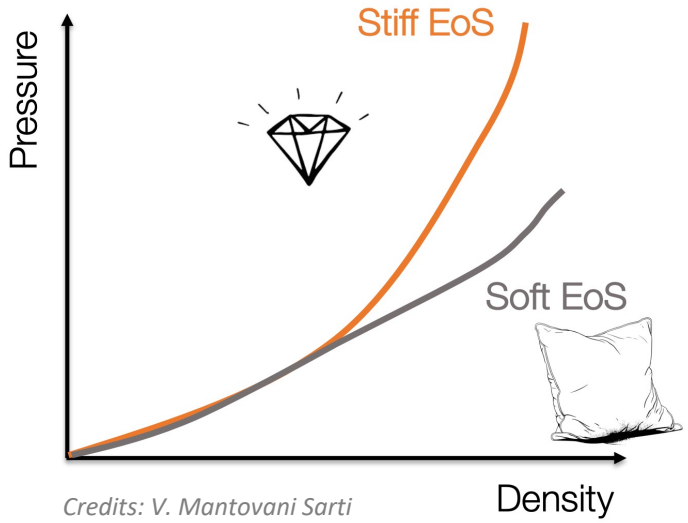
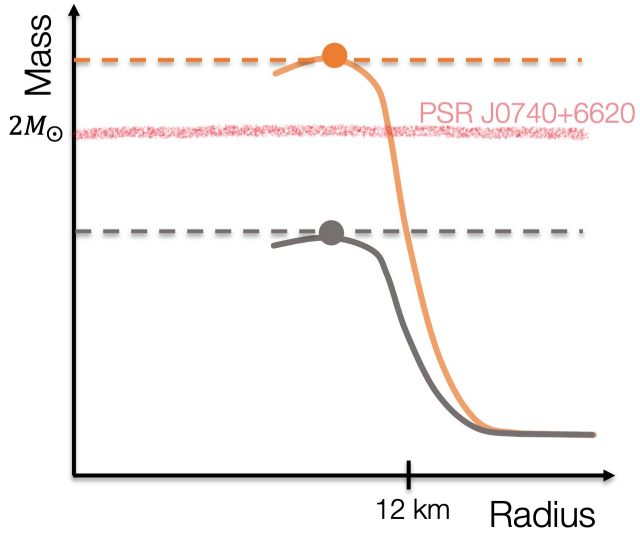


Credits: V. Mantovani Sarti



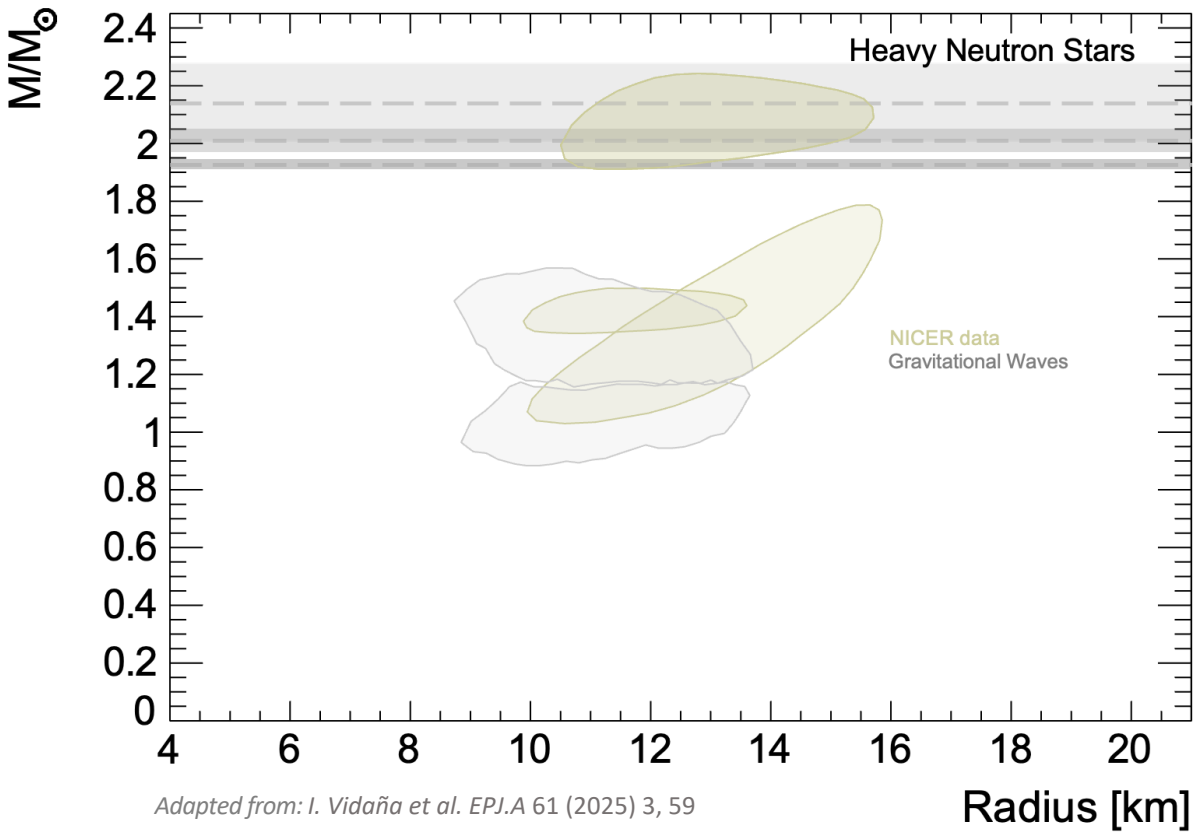
Credits: V. Mantovani Sarti

Non-interacting neutron gas

- Radius: 10 – 15 km
- Mass: 1.5 – 2.0 M_{Sun}
- High density expected in the inner core.

  $\rho = 2 – 3\ \rho_0$
- Inner core composition:
  - HYP: Non-interacting neutron gas?
  - Degenerate pressure due to the Pauli blocking
- Pressure of the star

$$P = P_{\text{free neutrons}}$$



Adapted from: I. Vidaña et al. EPJ.A 61 (2025) 3, 59

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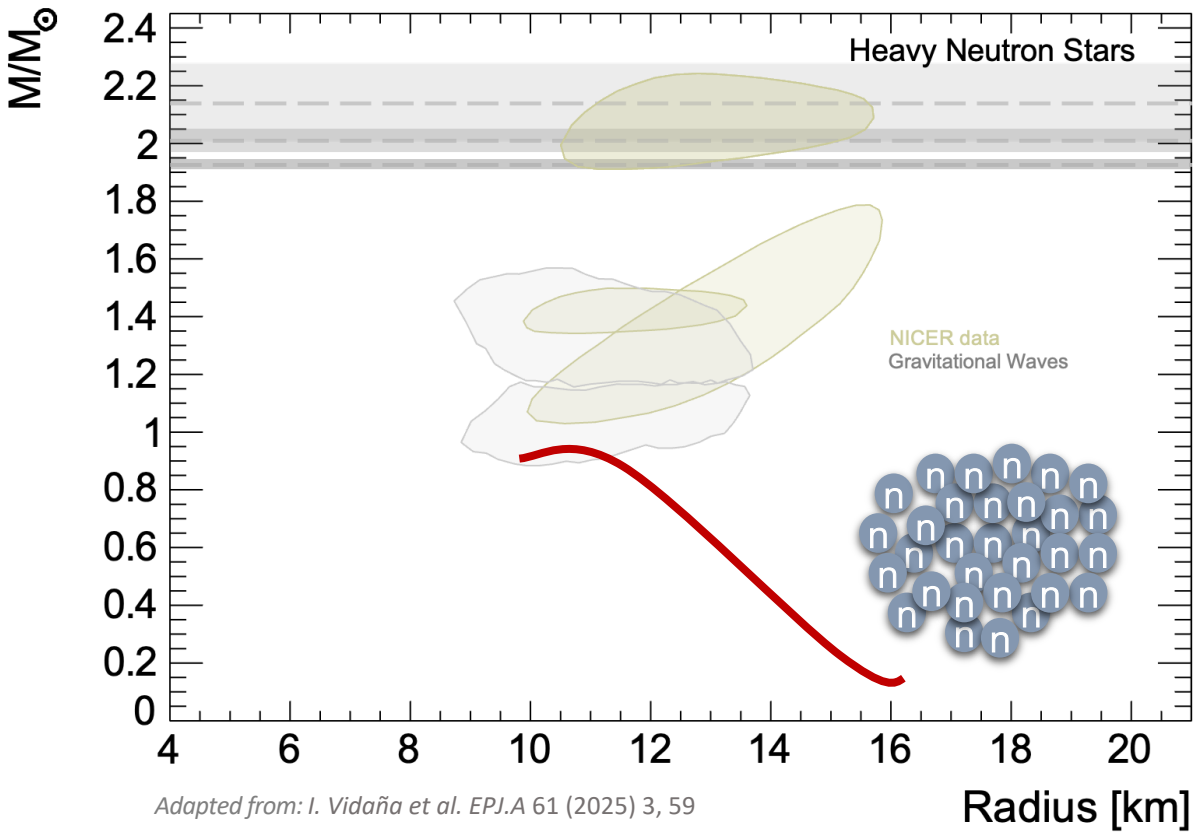
  $$P = P_{\text{free neutrons}}$$
- **Not sufficient to counterbalance the gravity in heavy neutron stars!!**



Adapted from: I. Vidaña et al. EPJ.A 61 (2025) 3, 59

Non-interacting neutron gas

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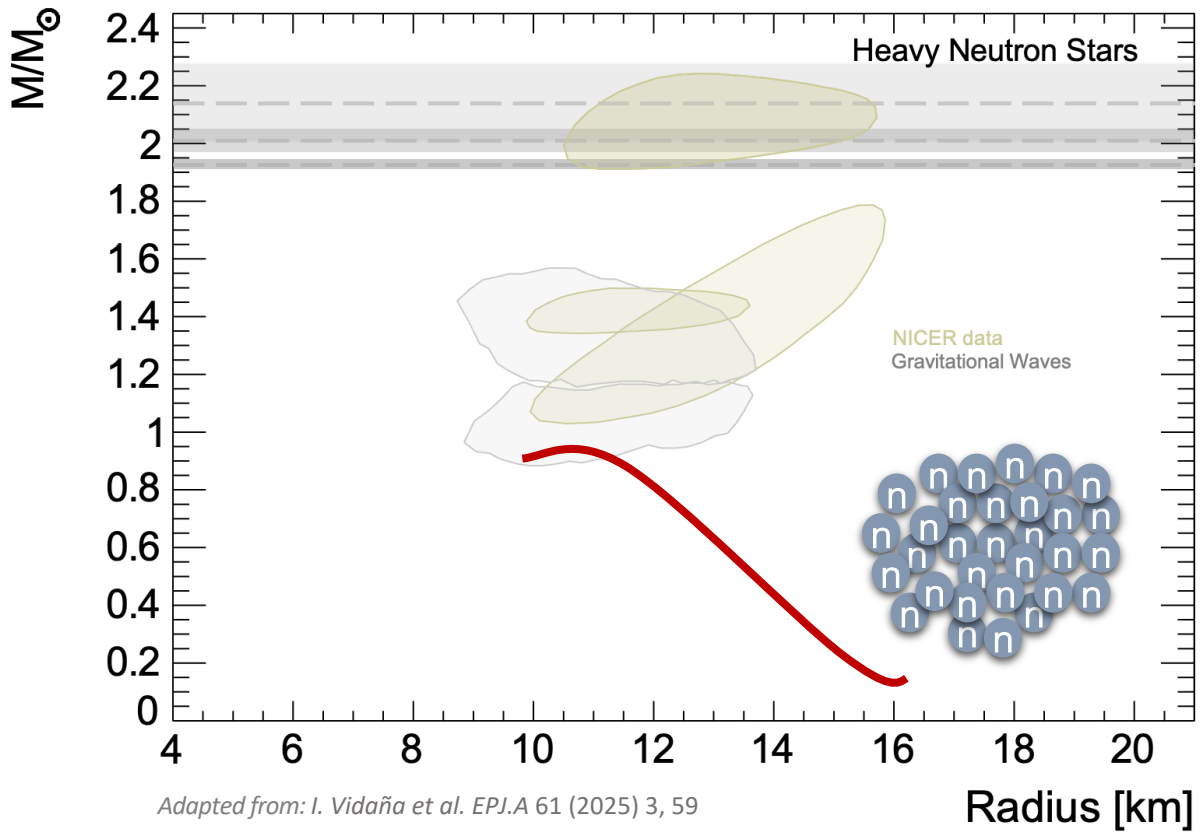
- Mass: 1.5 – 2.0 M_{Sun}
- High density expected in the inner core.

  $\rho = 2 - 3\ \rho_0$
- Inner core composition:
  - HYP: Non-interacting neutron gas? **NO!**
  - Degenerate pressure due to the Pauli blocking
- Pressure of the star

$$P = P_{\text{free neutrons}} + n\,\boldsymbol{U}\ (\boldsymbol{\rho})$$

- **Necessary to include the strong nuclear interaction!!**

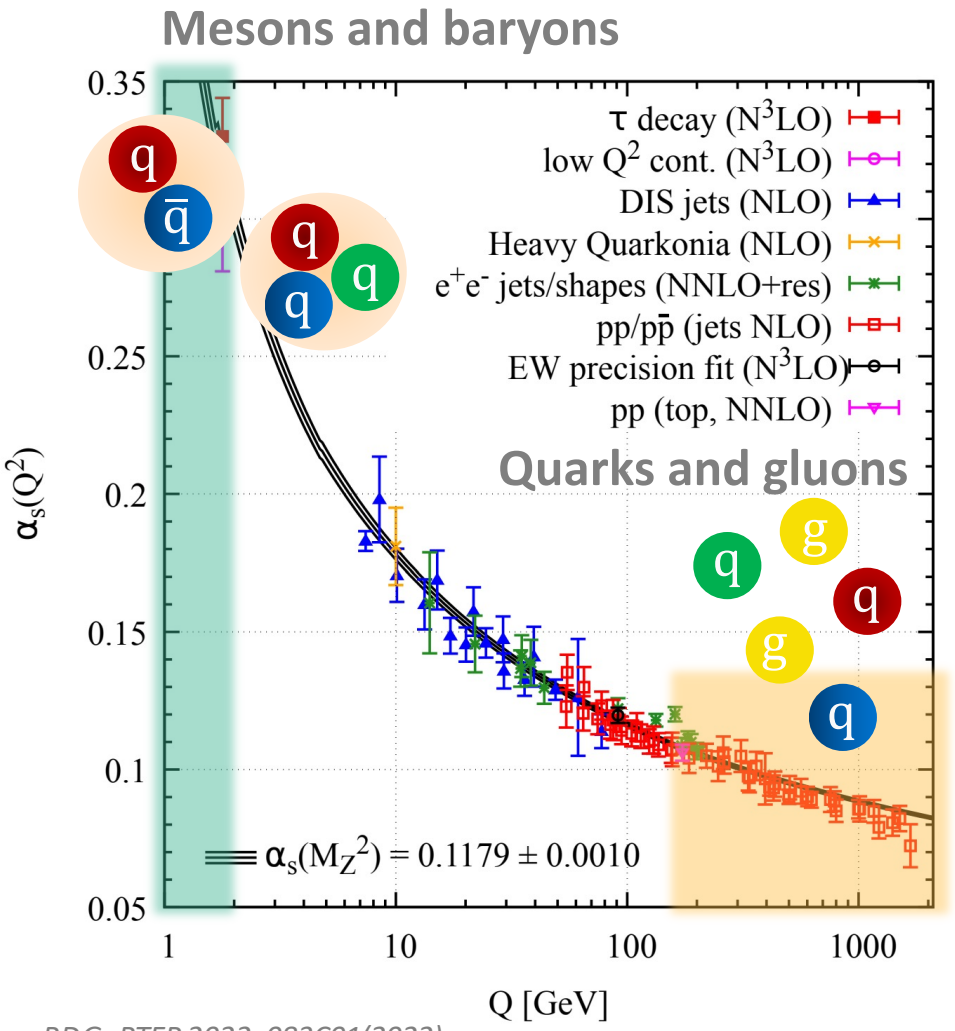


Adapted from: I. Vidaña et al. EPJ.A 61 (2025) 3, 59

Hadronic interactions

- Quantum Chromodynamics (QCD) is conceived as a theory with quarks and gluons as degrees of freedom
- High energy regime (Q >> 1 GeV):
  - Perturbation theory is applicable
  - High predictive power of the calculations
- Low-energy (Q < 1 GeV):
  - Quark confinement and emergence of hadrons
  - Very complicated calculations in QCD

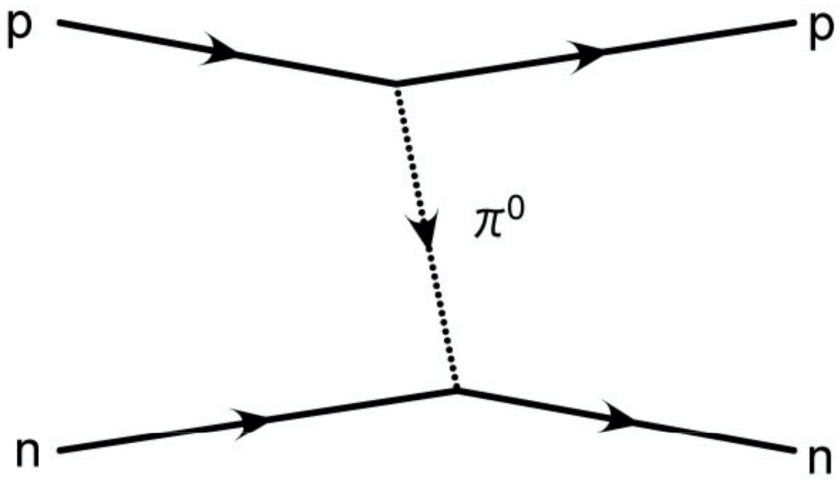
How do hadrons interact?

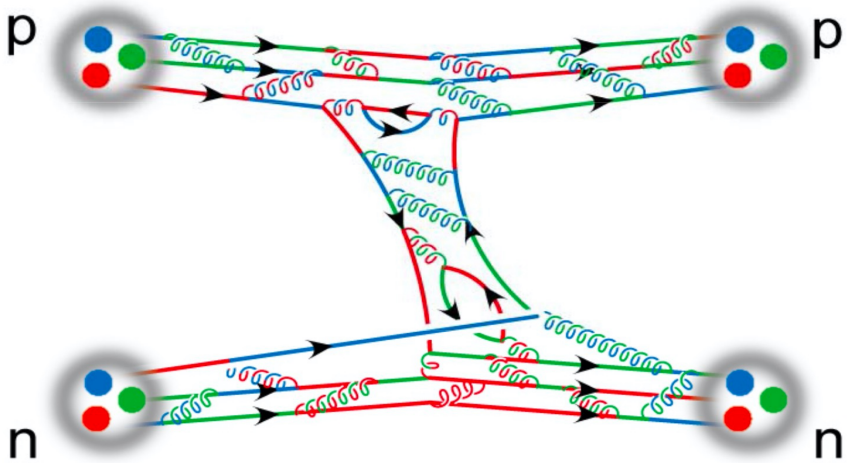


PDG, PTEP 2022, 083C01(2022)

Hadronic interactions

Low energy hadronic interactions:





Effective Field Theories (EFT)

- hadrons as degrees of freedom
- low-energy coefficients constrained by data

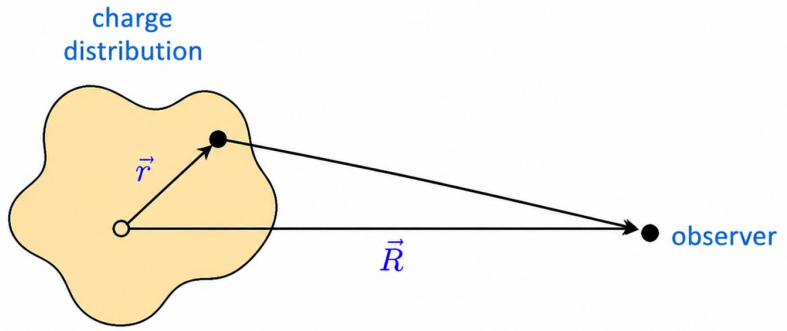
Lattice QCD

- quarks and gluons as degrees of freedom
- unstable for low mass hadrons

What is an Effective Theory?

A classical example: compute electric potential generated by a localized charge distribution $\rho(\vec{r})$.

Exact solution: $V(\vec{R}) = \frac{1}{4\pi\epsilon_0}\int d^3r \frac{\rho(\vec{r})}{|\vec{R}-\vec{r}|}$



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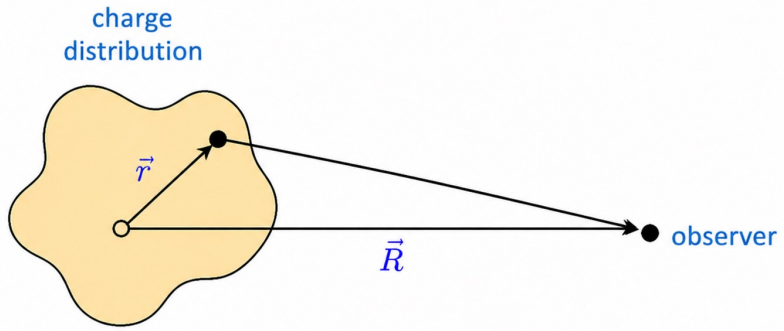


Exact solution: $V(\vec{R}) = \frac{1}{4\pi\epsilon_0}\int d^3r \frac{\rho(\vec{r})}{|\vec{R}-\vec{r}|}$

Effective solution:

$$V(\vec{R}) = \frac{1}{4\pi\epsilon_0}\int d^3r\, \rho(\vec{r})\left[\frac{1}{R} + \frac{\vec{R}\cdot\vec{r}}{R^3} + \frac{3\left(\vec{R}\cdot\vec{r}\right)^2 - R^2r^2}{2\,R^5} + \ldots\right] = \frac{1}{4\pi\epsilon_0}\left[\frac{\boldsymbol{q}}{R} + \frac{\vec{R}\cdot\boldsymbol{\vec{P}}}{R^3} + \frac{\vec{R}\cdot\boldsymbol{Q}\cdot\vec{R}}{2\,R^5} + \ldots\right]$$

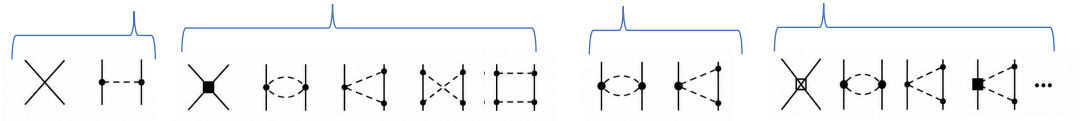
We have integrated out the short-distance physics and absorbed the unknown information in q, P, Q

$$\boldsymbol{q} = \int d^3r\, \rho(\vec{r}) \qquad \boldsymbol{\vec{P}} = \int d^3r\, \rho(\vec{r})\, \vec{r} \qquad \boldsymbol{Q_{ij}} = \int d^3r\, \rho(\vec{r})\, 3\,(r_i\, r_j - r^2\, \delta_{ij})$$

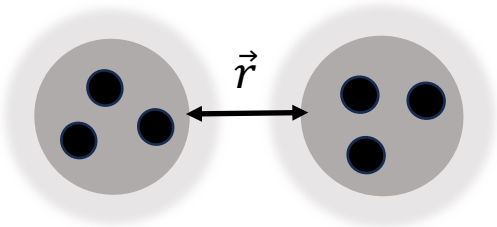
Nucleon-nucleon interaction

Expansion of the nuclear potential in effective theory

$$V_{NN}(r) = V_{LO}(r) + V_{NLO}(r) + V_{N2LO}(r) + V_{N3LO}(r) + \ \ldots$$



2 constants 7 constants 15 constants



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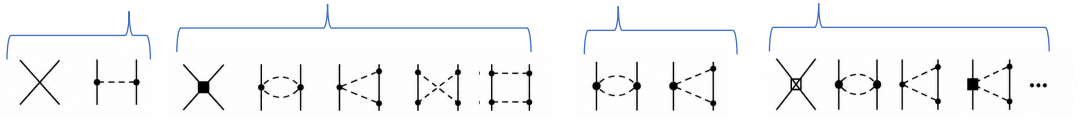

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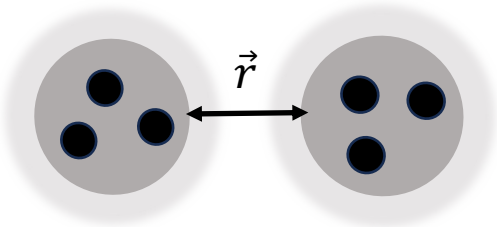
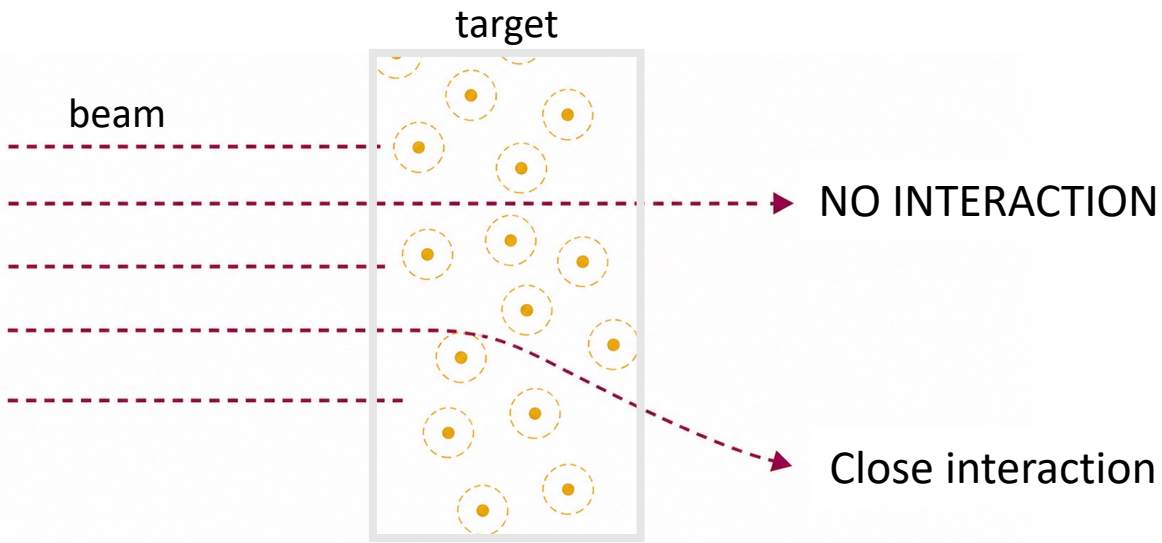
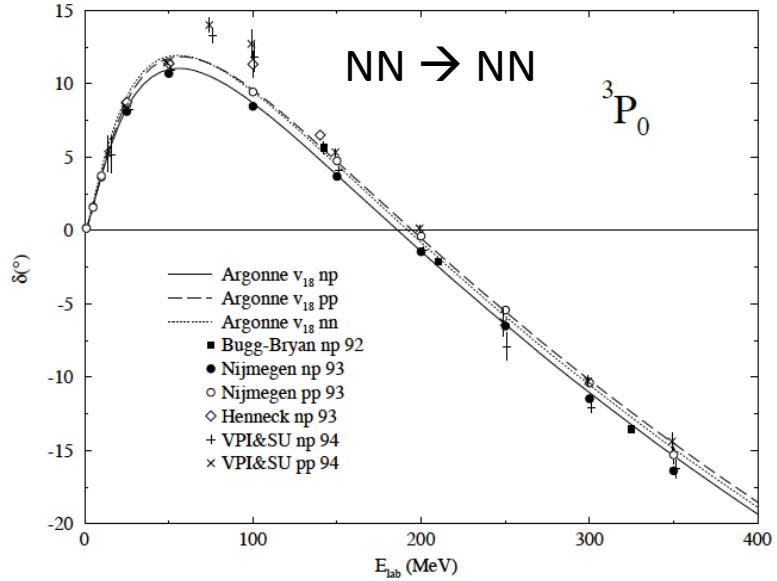


Scattering experiments



R. B. Wiringa et al. PRC 51 (1995)



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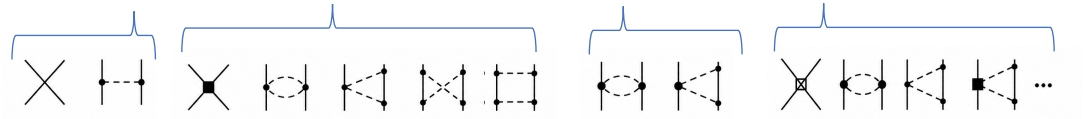

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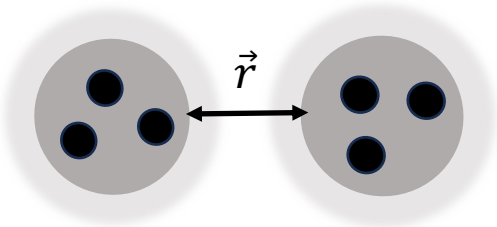
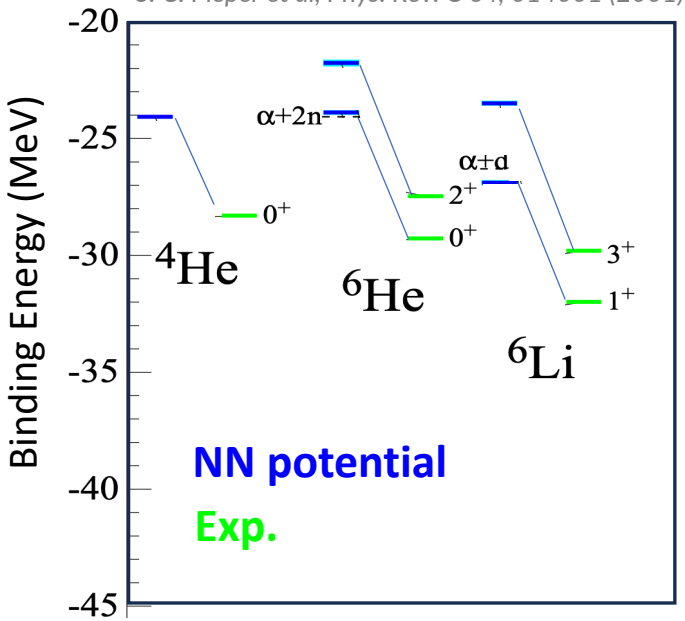


- Realistic NN interactions cannot describe many-body systems

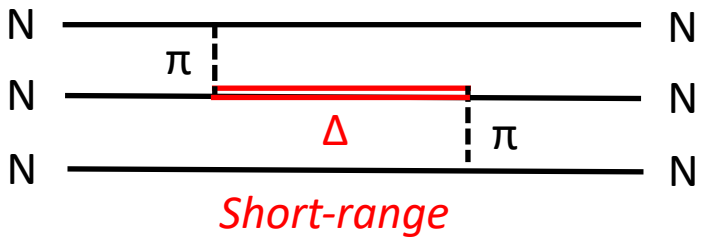
S. C. Pieper et al, Phys. Rev. C 64, 014001 (2001)



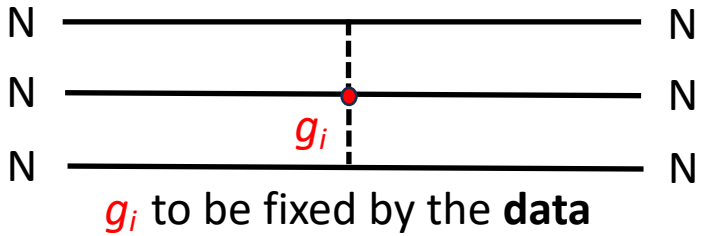
Three-nucleon interaction

Formation of hadronic excitations

H.-W. Hammer, S. König, U. van Kolck RMP 92 (2020)



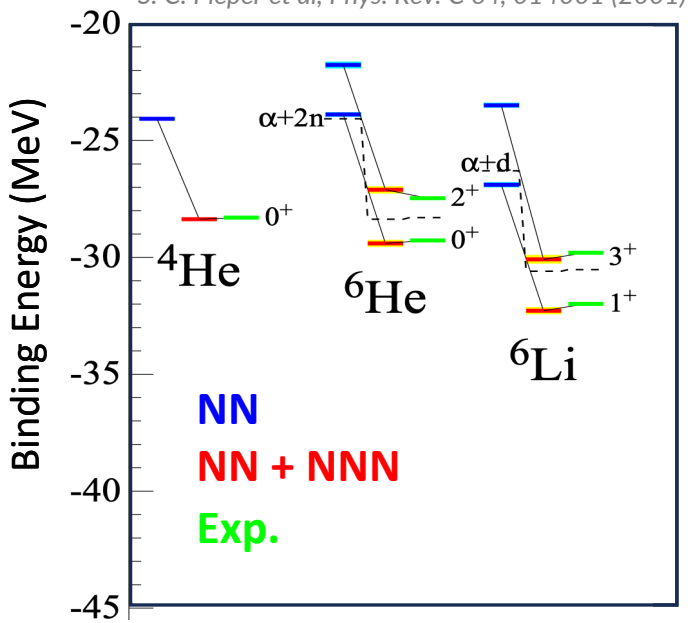
Three-body forces in EFT



g_i to be fixed by the **data**

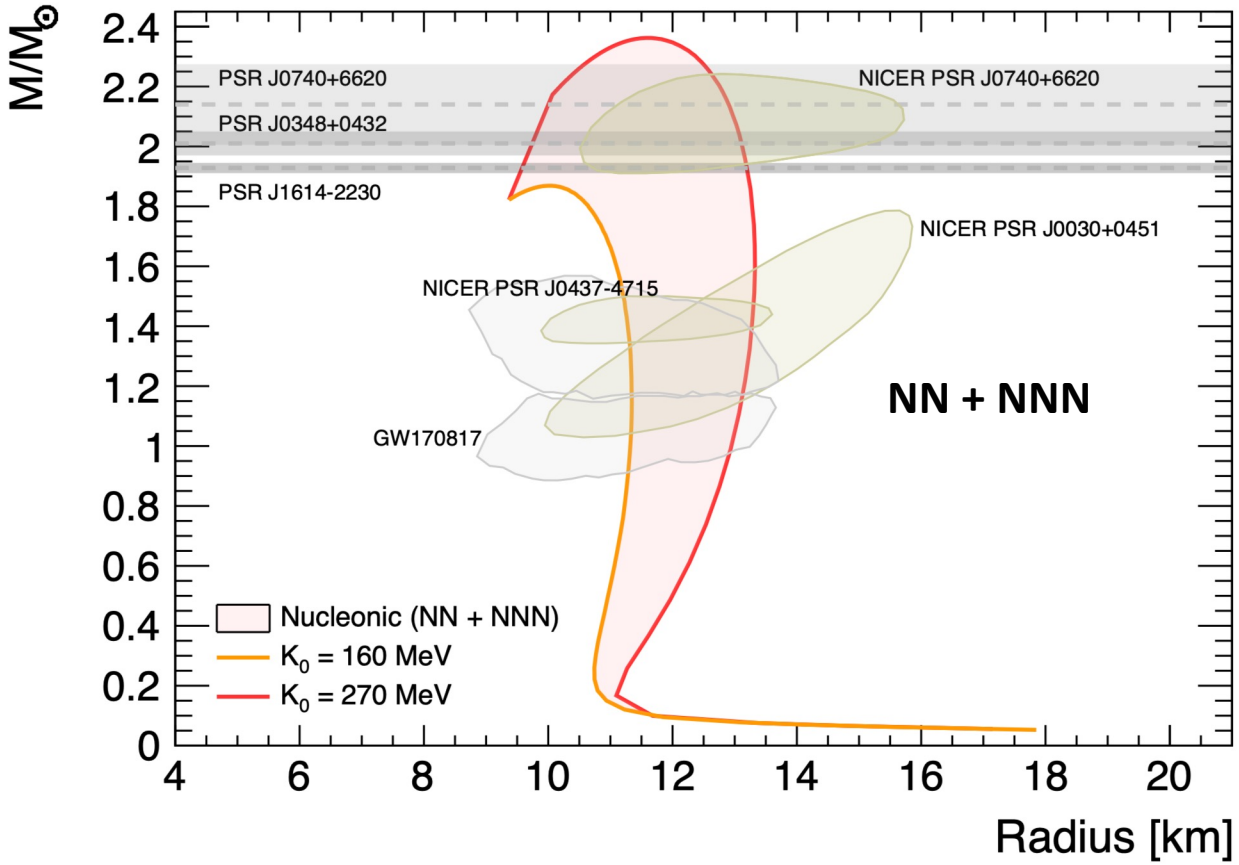
- Excellent description of nuclei.
  Contribution to B.E. → 10%
- Increasing effect with the baryons in the system.

S. C. Pieper et al, Phys. Rev. C 64, 014001 (2001)



Neutron star structure

- Solving the structure of neutron stars is a nuclear physics problem:
  - ➢ NN + NNN strong interaction needed to determine the mass



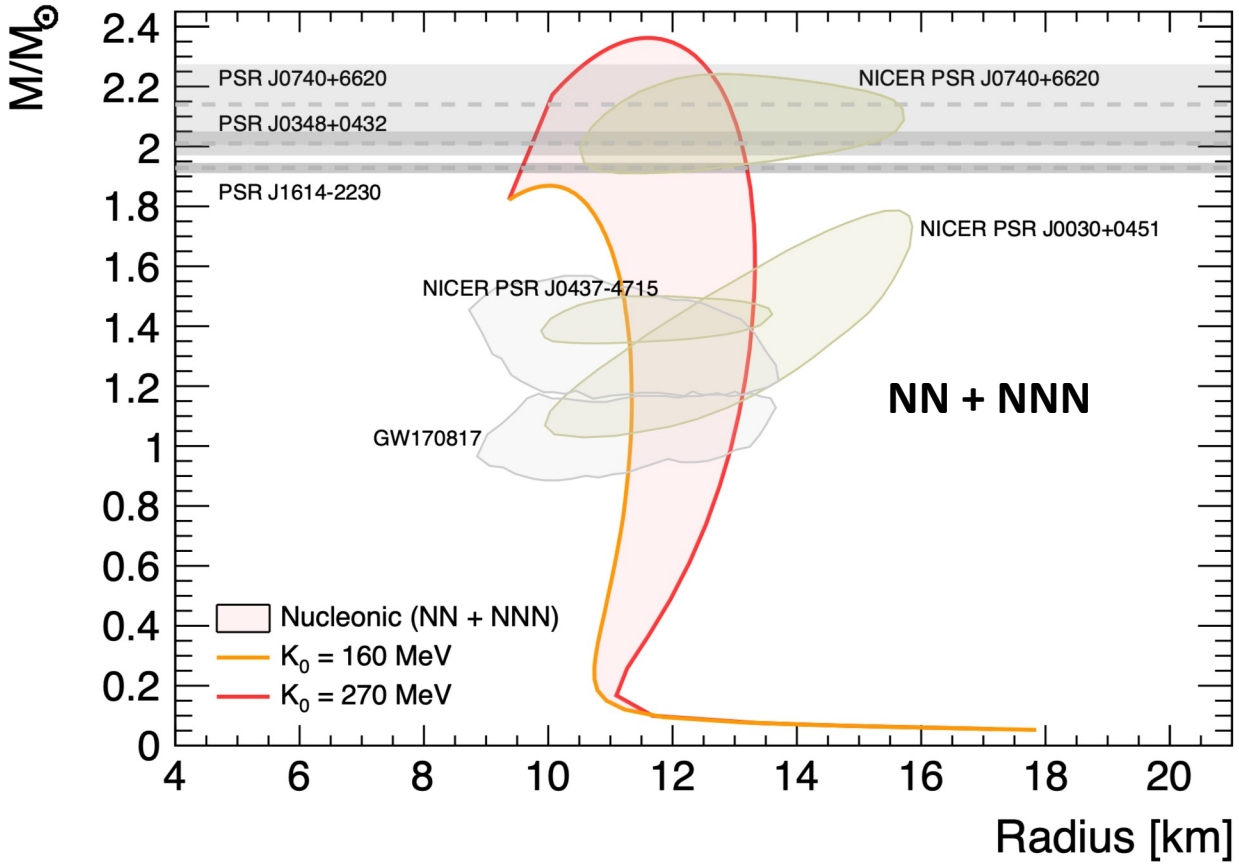
I. Vidaña, V. Mantovani Sarti, J. Haidenbauer, D. Mihaylov, L. Fabbietti, EPJ.A 61 (2025) 3, 59

Neutron star structure

- Solving the structure of neutron stars is a nuclear physics problem:
  - ➢ NN + NNN strong interaction needed to determine the mass.

- Production of hyperons is energetically possible via weak interactions, e.g.

$$n\,n \rightarrow n\,\Lambda$$
$$n\,n \rightarrow p\,\Sigma^{-}$$
$$\ldots$$



I. Vidaña, V. Mantovani Sarti, J. Haidenbauer, D. Mihaylov, L. Fabbietti, EPJ.A 61 (2025) 3, 59

Neutron stars with hyperons

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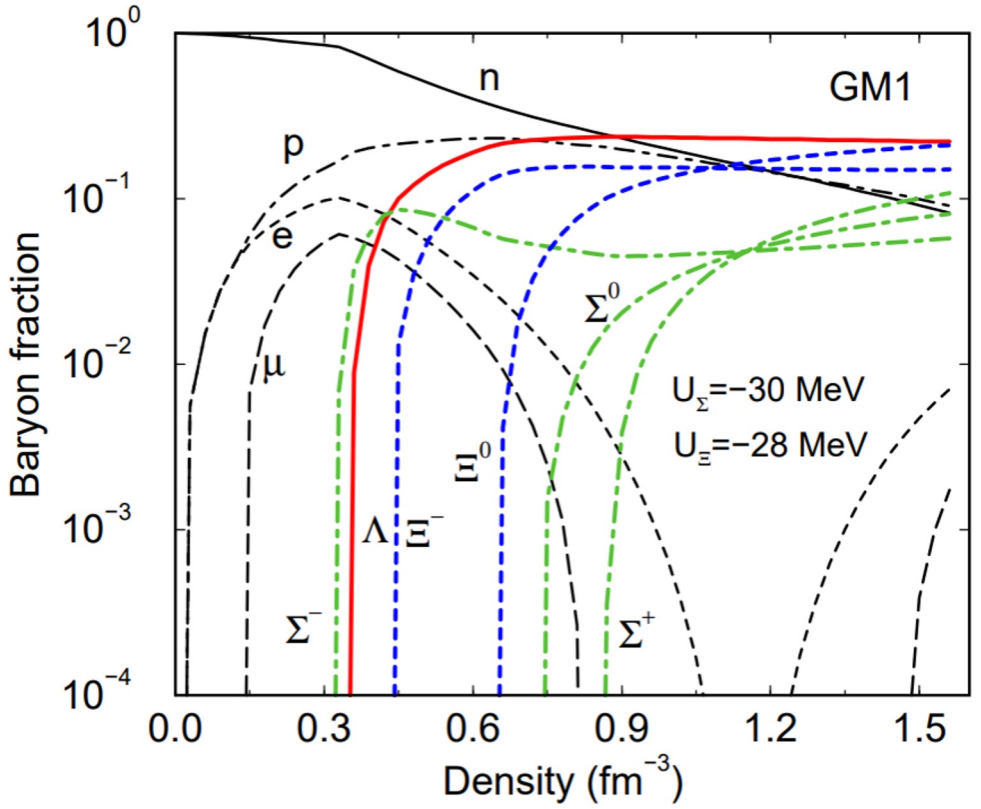
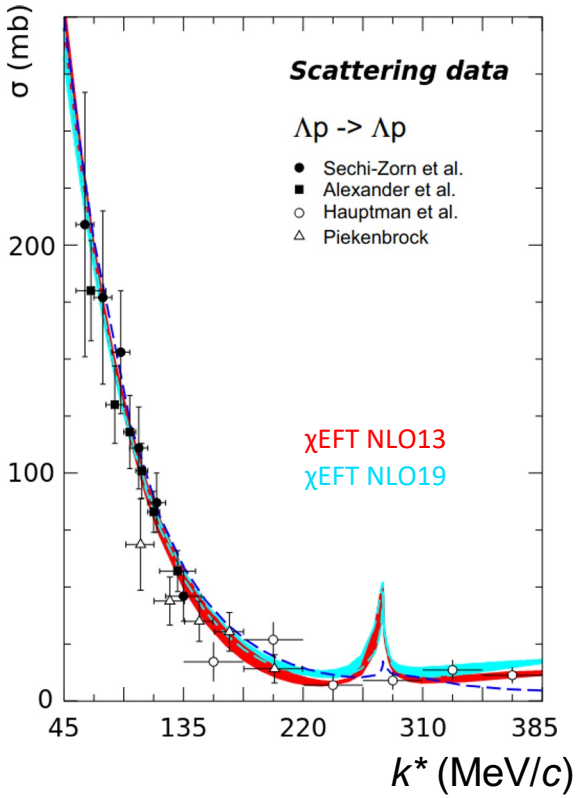


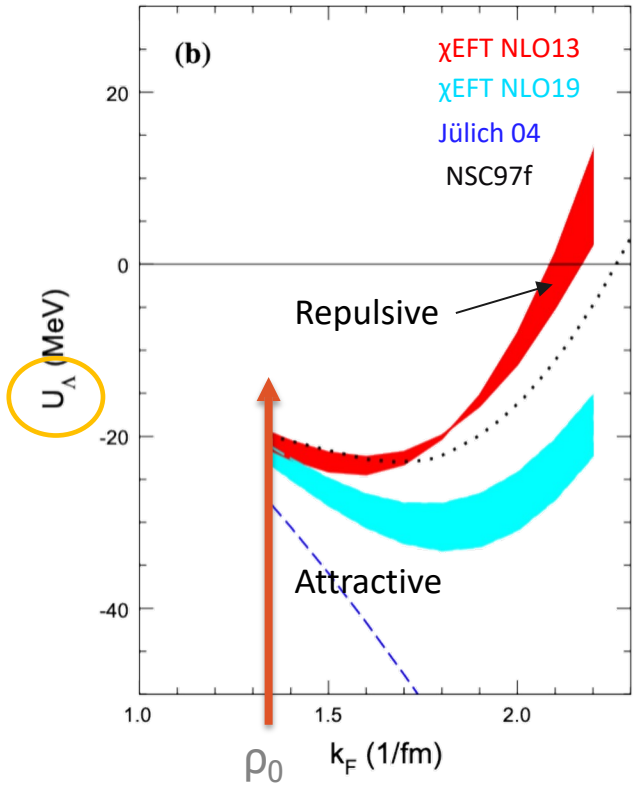
J. Schaffner-Bielich et al NPA 835 (2010)

Inclusion of the ΛN interaction

- Low statistics and not available at low momenta
- ΛN interaction is not well constrained

$$P = \sum P_{\text{free}} + \sum n_i U_i(\rho)$$





J.Haidenbauer, N.Kaiser et al. NPA 915 24 (2013)

J.Haidenbauer, U. Meißner EPJA 56 (2020)

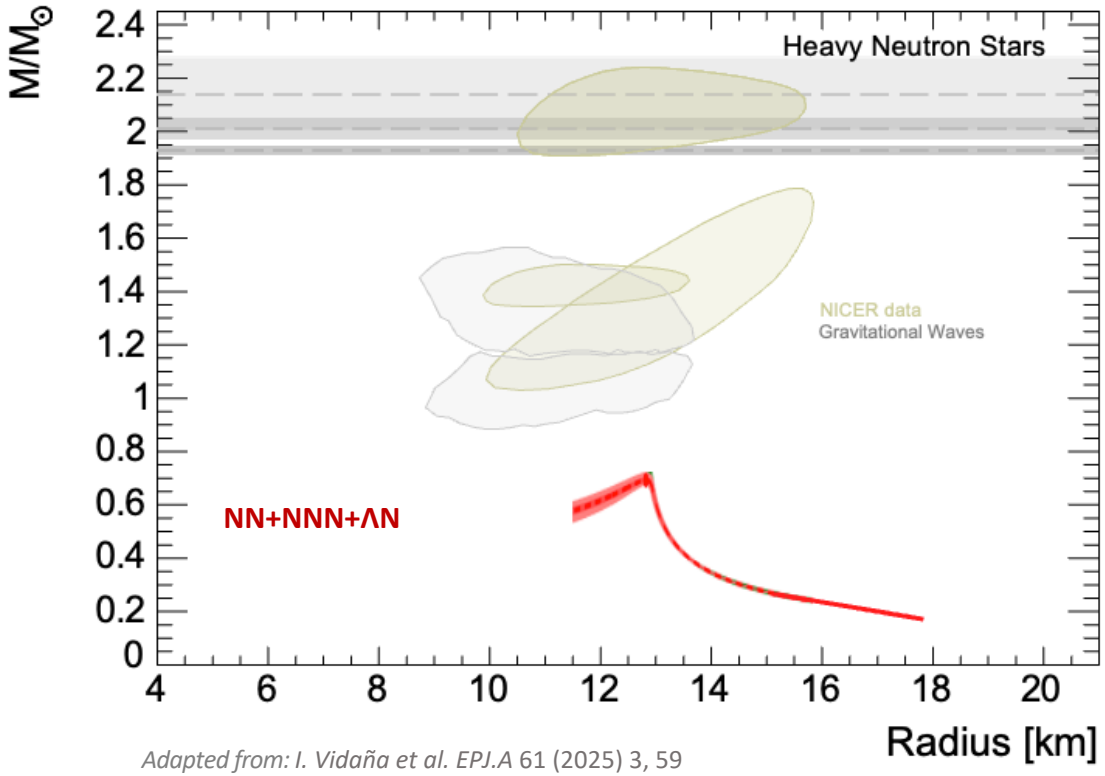
Hyperon puzzle

- The NN and NNN can stiffen the equation of state and reproduce observed heavy neutron stars

  I. Vidaña, V. Mantovani Sarti, J. Haidenbauer, D. Mihaylov, L. Fabbietti, EPJ.A 61 (2025) 3, 59

- Inclusion of Λ hyperon results in a softening of the equation of state

HYPERON PUZZLE!



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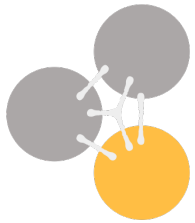
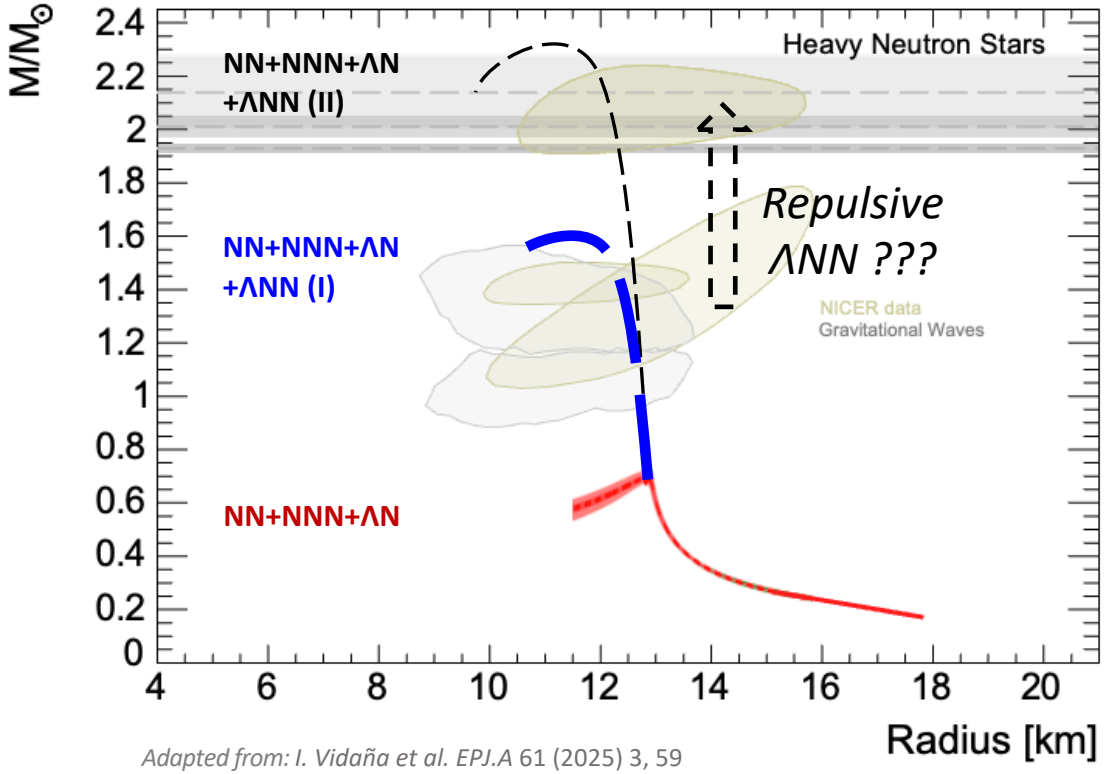
HYPERON PUZZLE!

- More precise constraints on the ΛN interaction
- Three-body forces can help but…
  … **ΛNN interaction is unknown!**

$$P = \sum P_{kin} + \sum n_i \, U_i \, (\rho) \; + \boldsymbol{U_{\Lambda NN}} \, (\boldsymbol{\rho})$$





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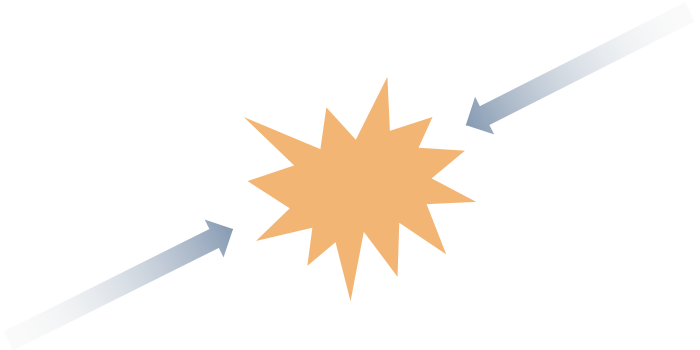
Femtoscopy technique at the Large Hadron Collider

High-energy collisions



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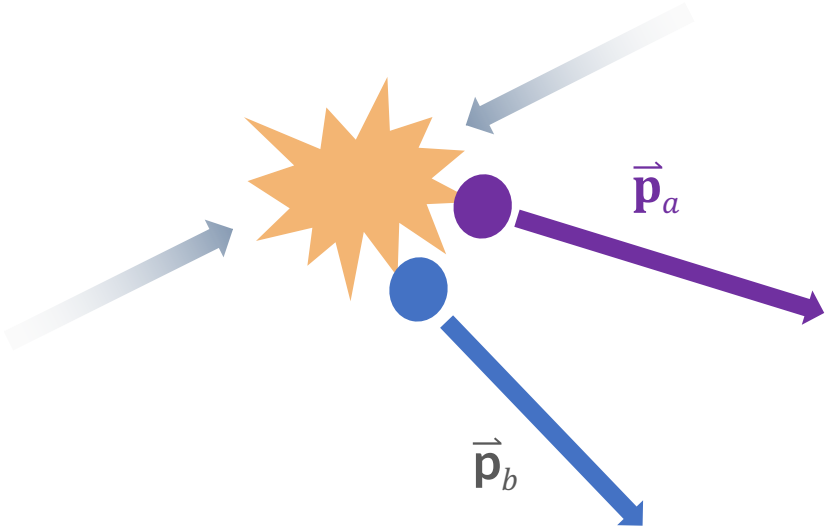

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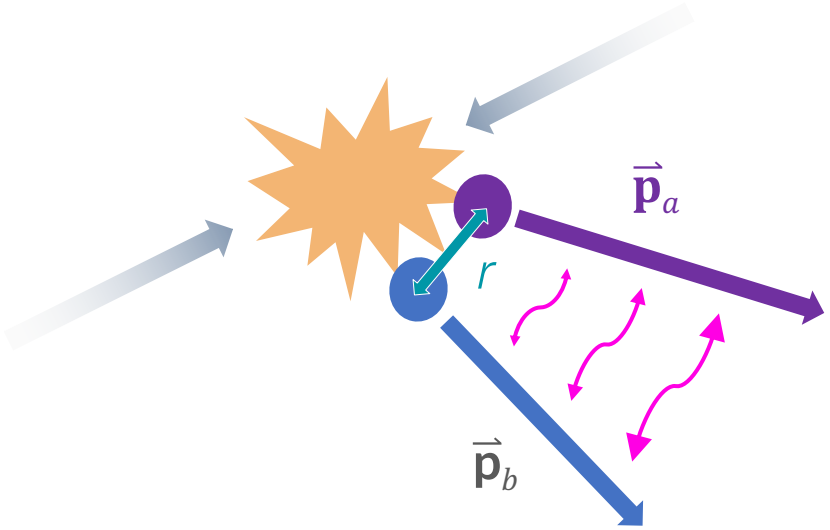

Correlation function

$$C(\vec{\mathbf{p}}_a, \vec{\mathbf{p}}_b) \equiv \frac{P(\vec{\mathbf{p}}_a, \vec{\mathbf{p}}_b)}{P(\vec{\mathbf{p}}_a)\, P(\vec{\mathbf{p}}_b)}$$

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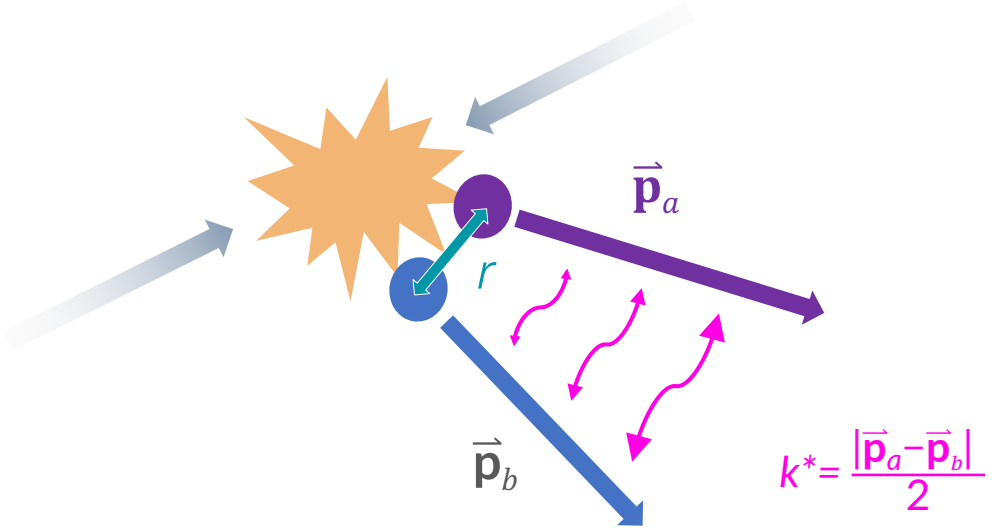
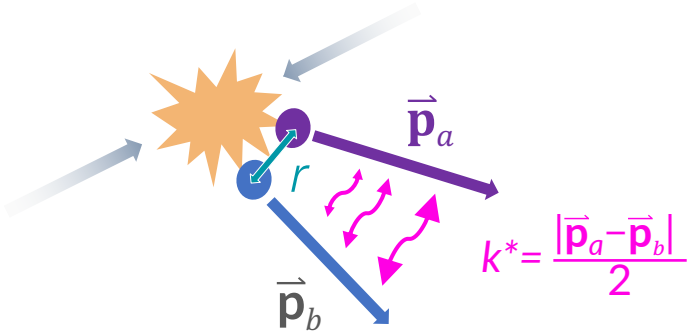


Correlation function

$$C(k^*) = \mathcal{N}(k^*)\frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

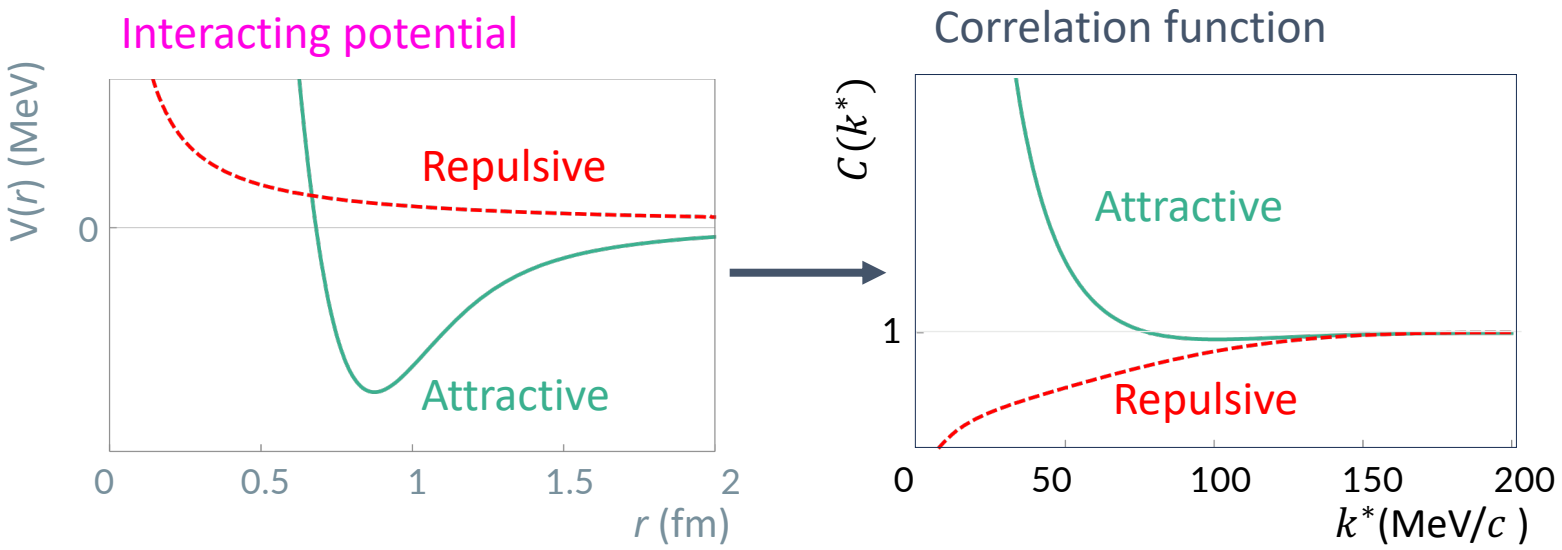
Femtoscopy for interactions



$$C(k^*) = \int S(\vec{r}\,)\left|\psi(\vec{k}^*, \vec{r}\,)\right|^2 d\,\vec{r} = \mathcal{N}(k^*)\frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

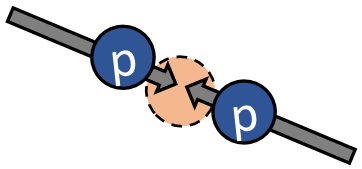
Two-particle wave function

M. Lisa, S. Pratt et al., ARNPS 55 (2005), 357-402
L. Fabbietti et al., ARNPS 71 (2021), 377-402
D. Mihaylov et al., EPJC 78 (2018), 5, 394



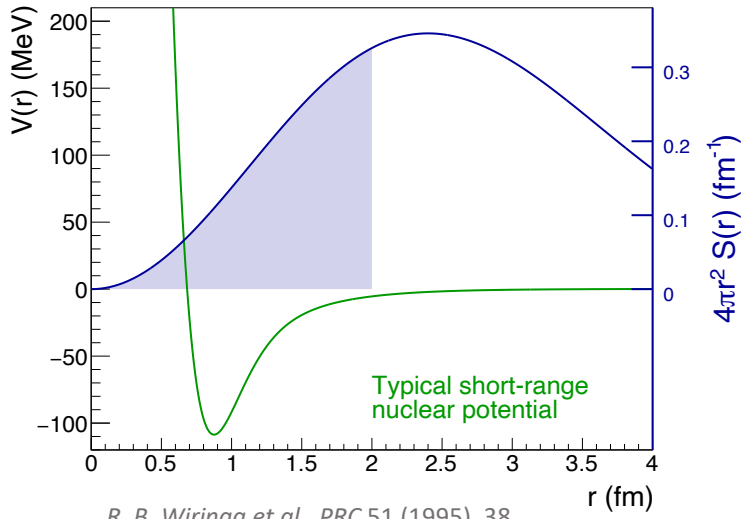
Measuring $C(k^*)$ → **constraining the source $S(\vec{r}\,)$** → study the interaction

Small and large colliding systems at LHC: from pp to Pb-Pb



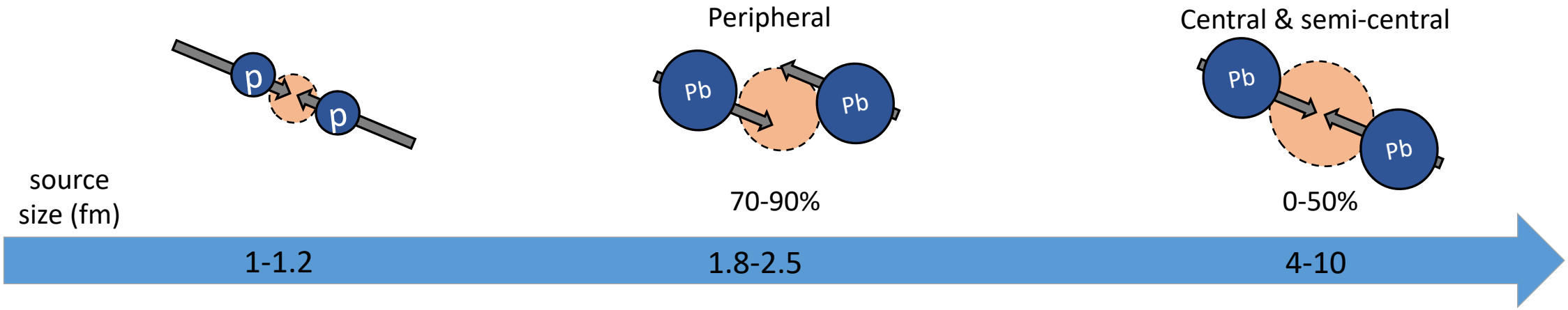
source size (fm)

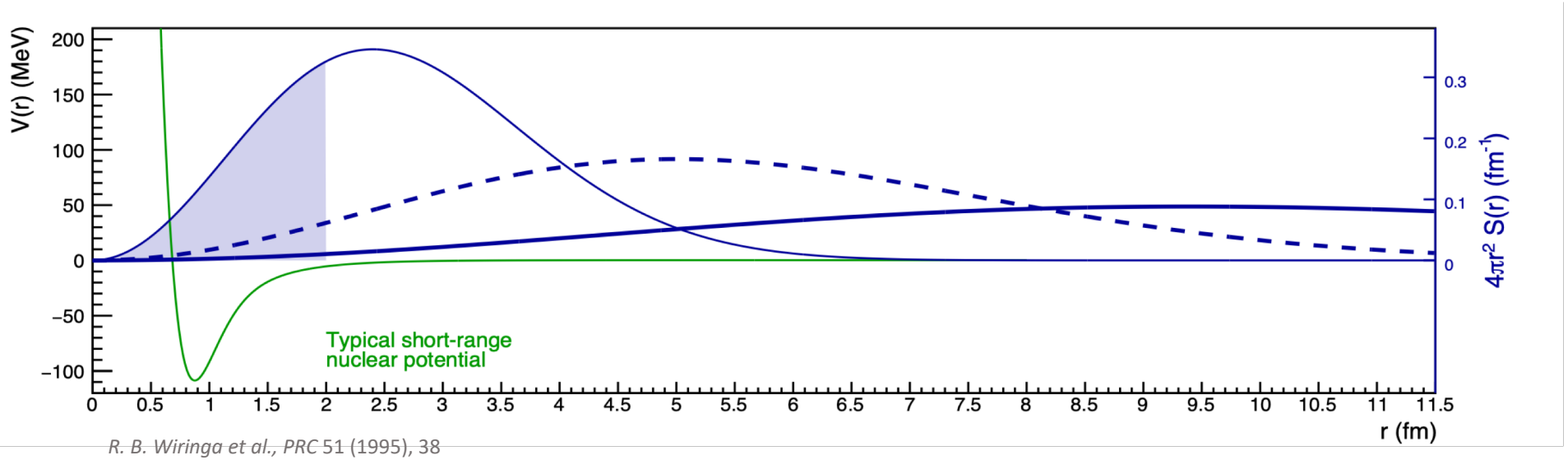
1-1.2



R. B. Wiringa et al., PRC 51 (1995), 38

Small and large colliding systems at LHC: from pp to Pb-Pb





R. B. Wiringa et al., PRC 51 (1995), 38

ALICE detector

Excellent tracking and particle identification (PID) capabilities

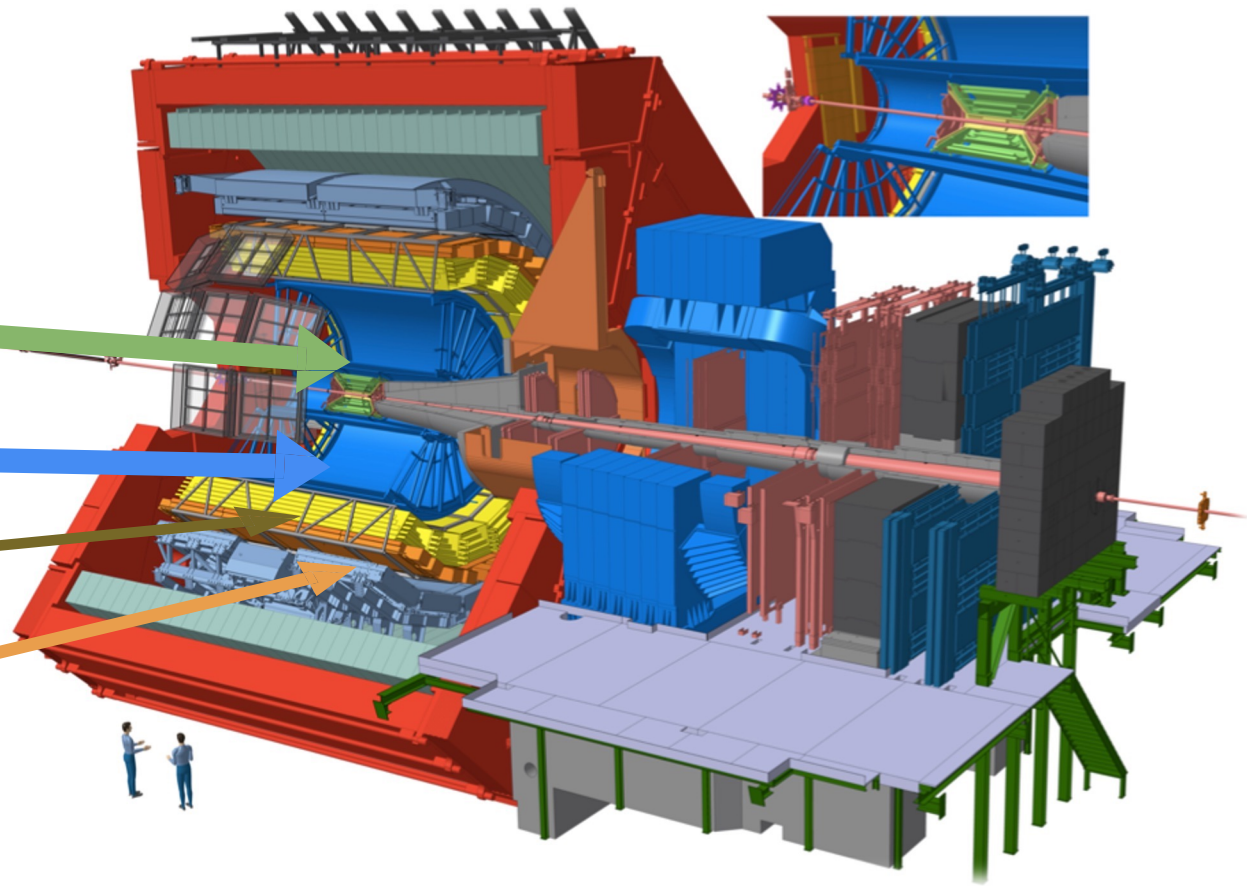
- Run 2 data: 2015 – 2018
- Run 3 data: 2022 – 2026

Inner Tracking System
Tracking, vertex, PID (dE/dx)

Time Projector Chamber
Tracking, PID (dE/dx)

Transition Radiation Detector

Time Of Flight detector
PID (TOF measurement)



Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

$$C(k^*) = \int S(\vec{r}\,) \left|\psi(\vec{k}^*, \vec{r}\,)\right|^2 d^3\vec{r}$$

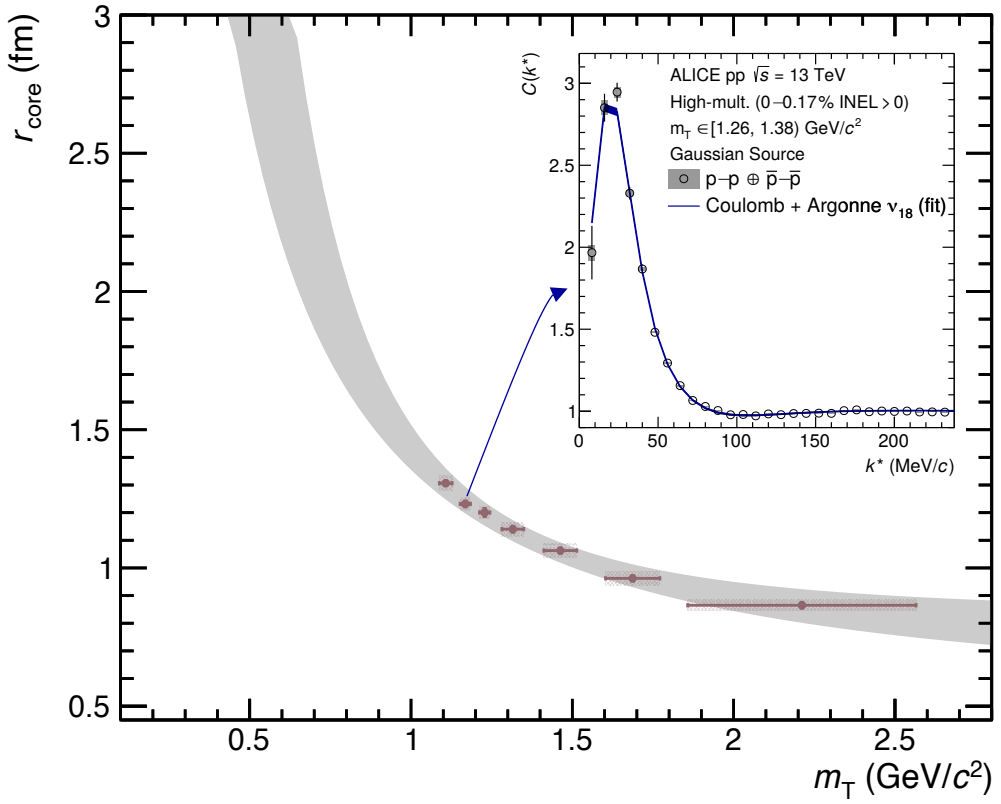
measured — known interaction

- Gaussian parametrization

$$S(r) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{core}^2}\right) \times$$

Effect of short lived resonances (cτ ~ 1 fm)

ALICE Coll., PLB, 811 (2020), 135849



ALICE Coll., PLB, 811 (2020), 135849;
ALICE Coll., EPJ C 85 (2025) 2, 198;
ALICE Coll., EPJ A 61 (2025 8, 194

Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

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measured — known interaction

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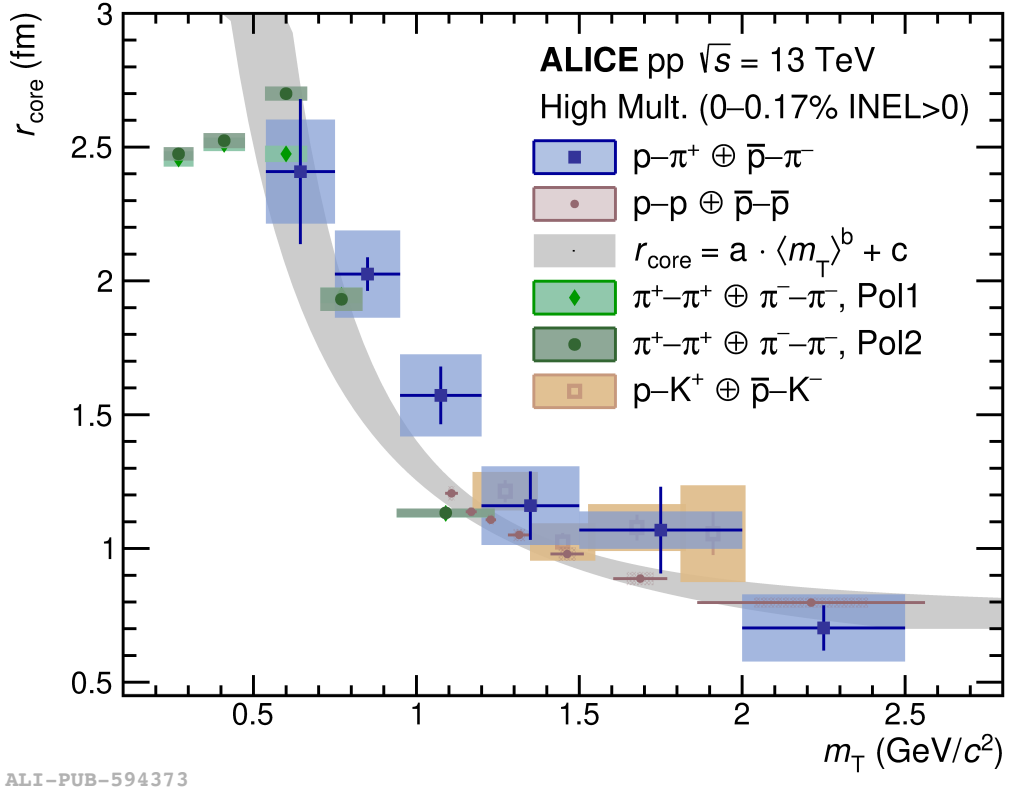
Effect of short lived resonances (cτ ~ 1 fm)

ALICE Coll., PLB, 811 (2020), 135849

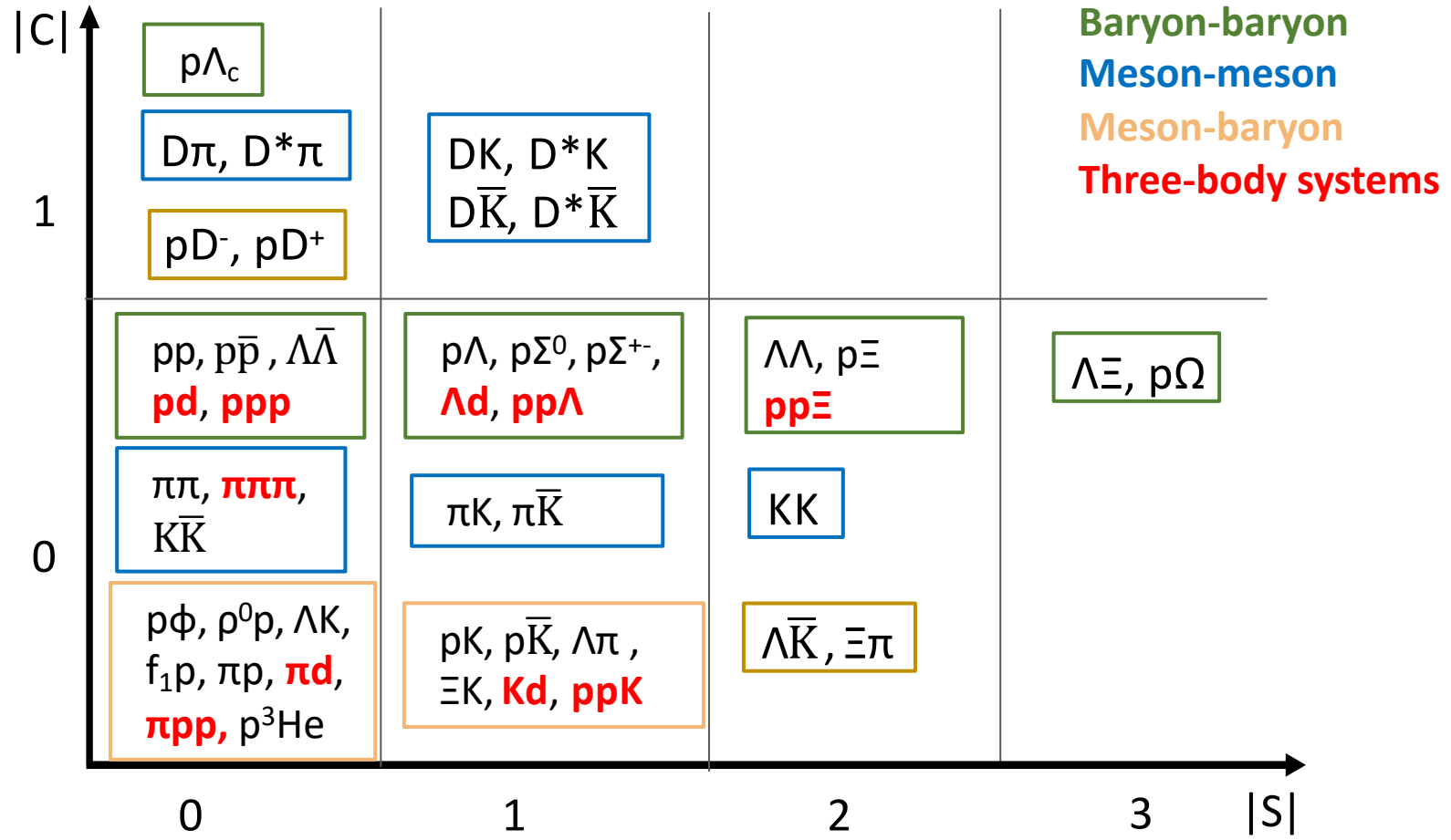
- One universal source for all hadrons (cross-check with K^+-p, π-π, p-Λ, p-π)
- **Small particle-emitting source created in pp collisions at the LHC** *ALICE Coll., PLB, 811 (2020), 135849; ALICE Coll., EPJ C 85 (2025) 2, 198; ALICE Coll., EPJ A 61 (2025 8, 194*



ALICE Coll., PLB, 811 (2020), 135849;
ALICE Coll., EPJ C 85 (2025) 2, 198;
ALICE Coll., EPJ A 61 (2025 8, 194

Femtoscopy measurements with ALICE

Credits: V. Mantovani Sarti



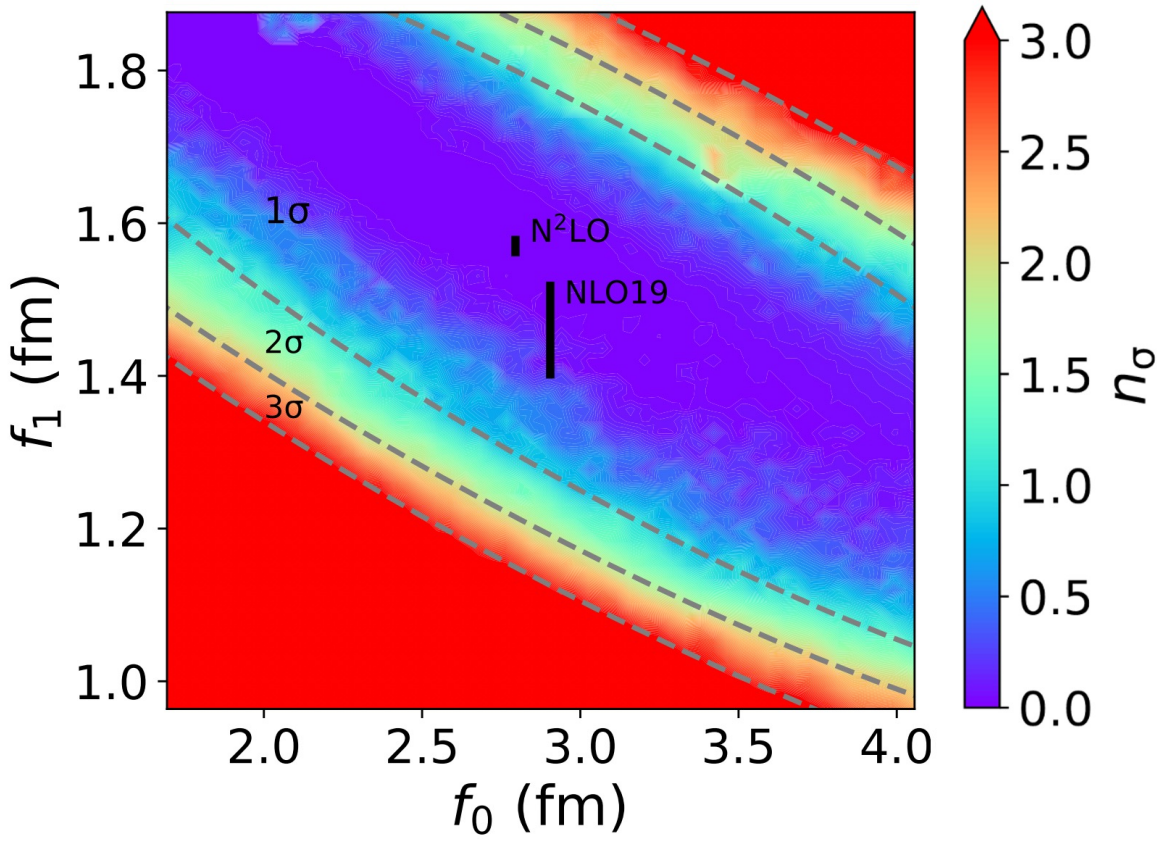
ALICE Collaboration:

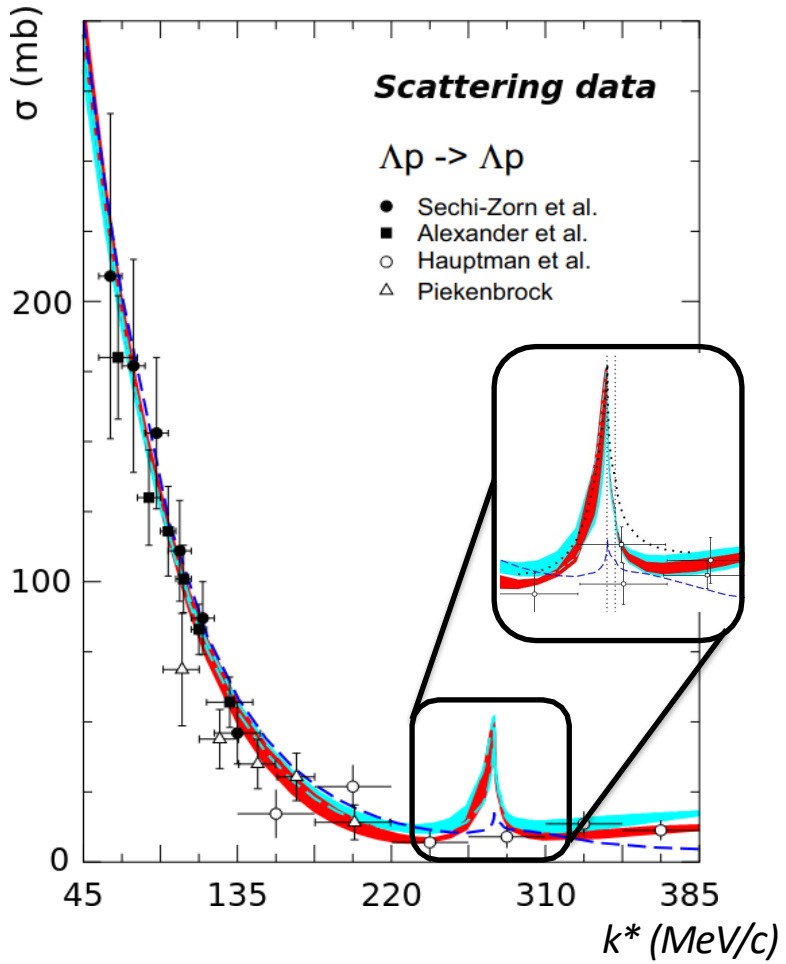
PRC 99 (2019) 2, 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 09230
PLB 805 (2020) 135419
PLB 811 (2020) 135849
Nature 588 (2020) 232-238
PRL 127 (2021), 172301
PLB 822 (2021), 136708
PRC 103 (2021) 5, 055201
PLB 833 (2022), 137272
PLB 829 (2022), 137060
PRD 106 (2022), 5, 05201
PL B 844 (2023) 137223
EPJA 59 (2023) 145
EPJC 83 (2023) 4, 340
PLB 845 (2023) 138145
EPJA (2023) 59:298
PRD 110 (2024) 3, 032004
PRX 14 (2024) 3, 031051
PLB 856 (2024) 138915
PRC 109, 024915 (2024)
EPJC 85 (2025) 2, 198
EPJ A 61 (2025) 8, 194
PRC 112 (2025) 6, 064003
PLB 874 (2026) 140252
Nature 648 (2025) 306-311
arXiv:2508.09867

The pΛ interaction before femtoscopy

- Spin-0 and Spin-1 scattering length from scattering data
- Agreement with N2LO and NLO19

D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550

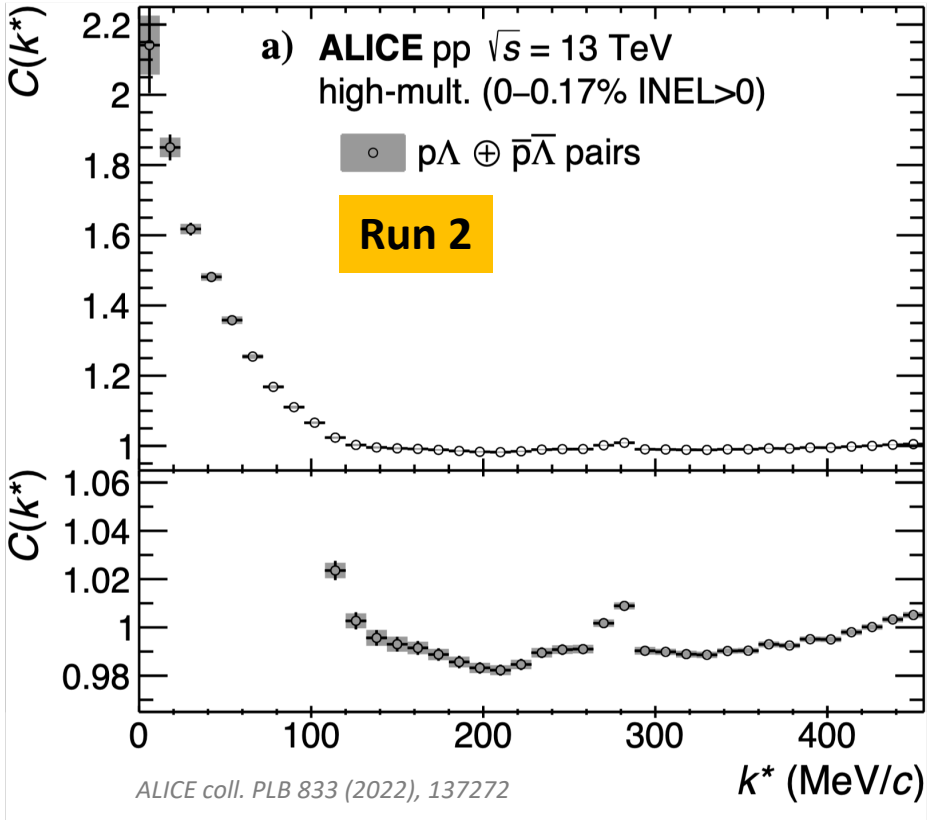




NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

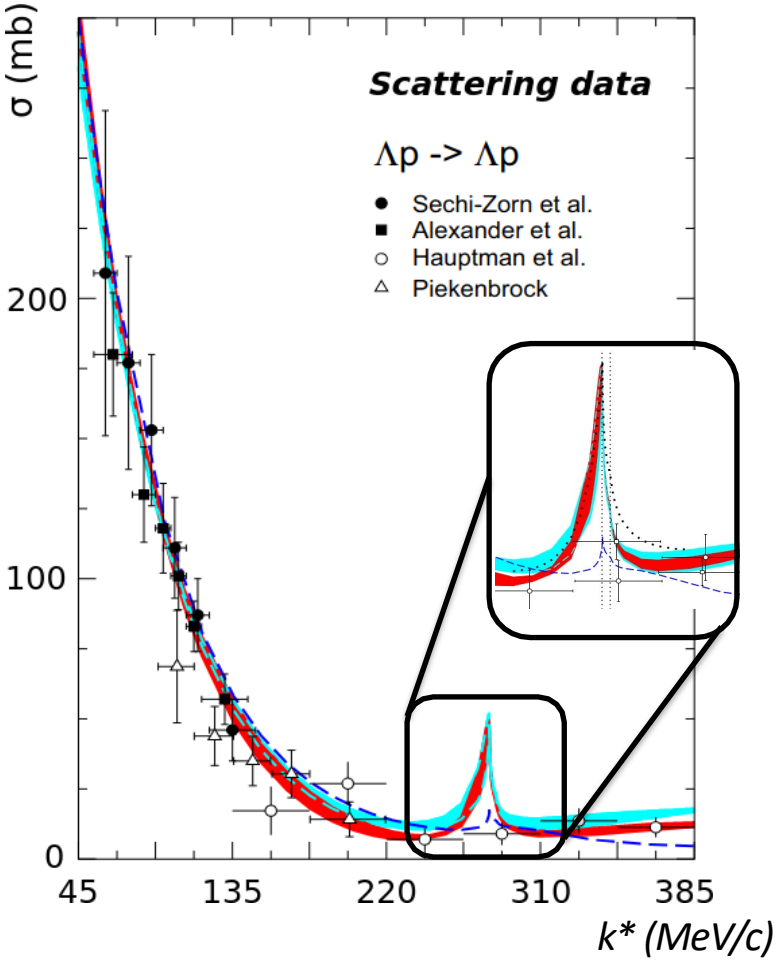
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

The pΛ interaction in the femtoscopy era



ALICE coll. PLB 833 (2022), 137272

- Measurement down to zero momentum
- Factor 20 improved precision (<1%)
- First experimental evidence of ΛN-ΣN opening in 2-body channel



NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

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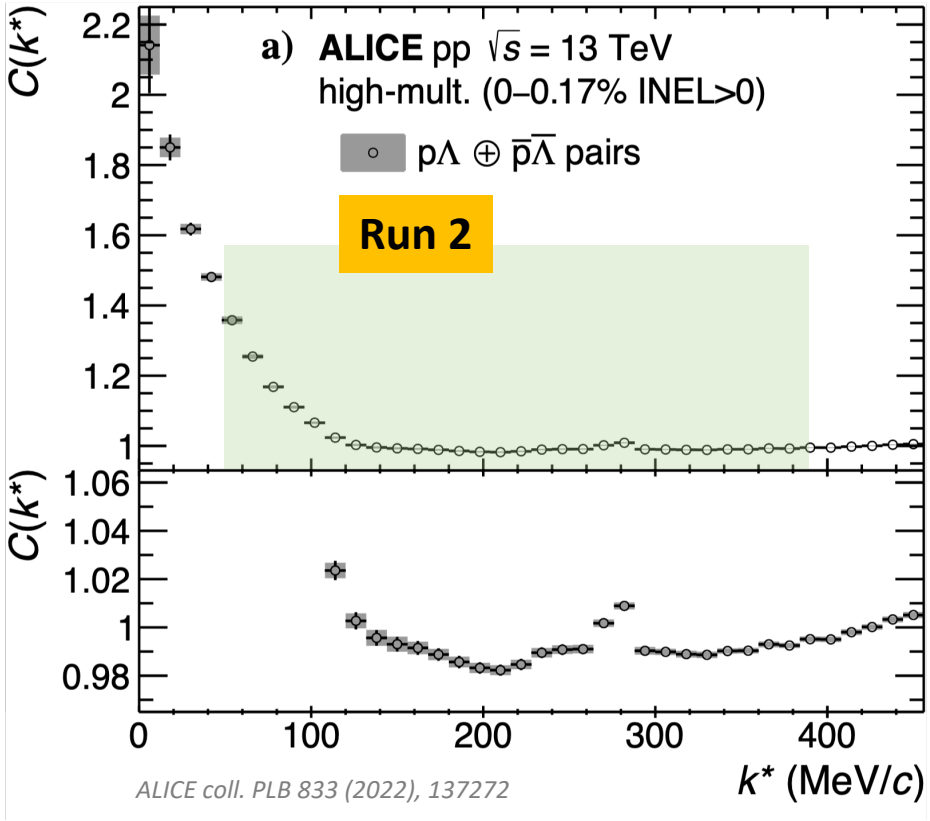
The pΛ interaction in the femtoscopy era



ALICE coll. PLB 833 (2022), 137272

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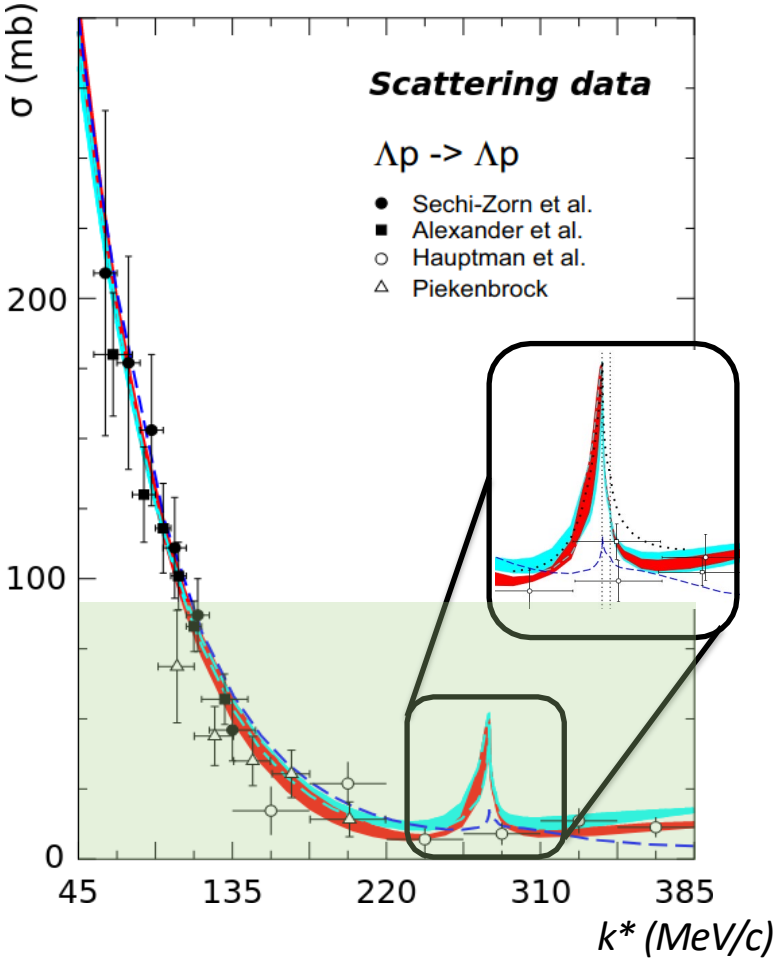


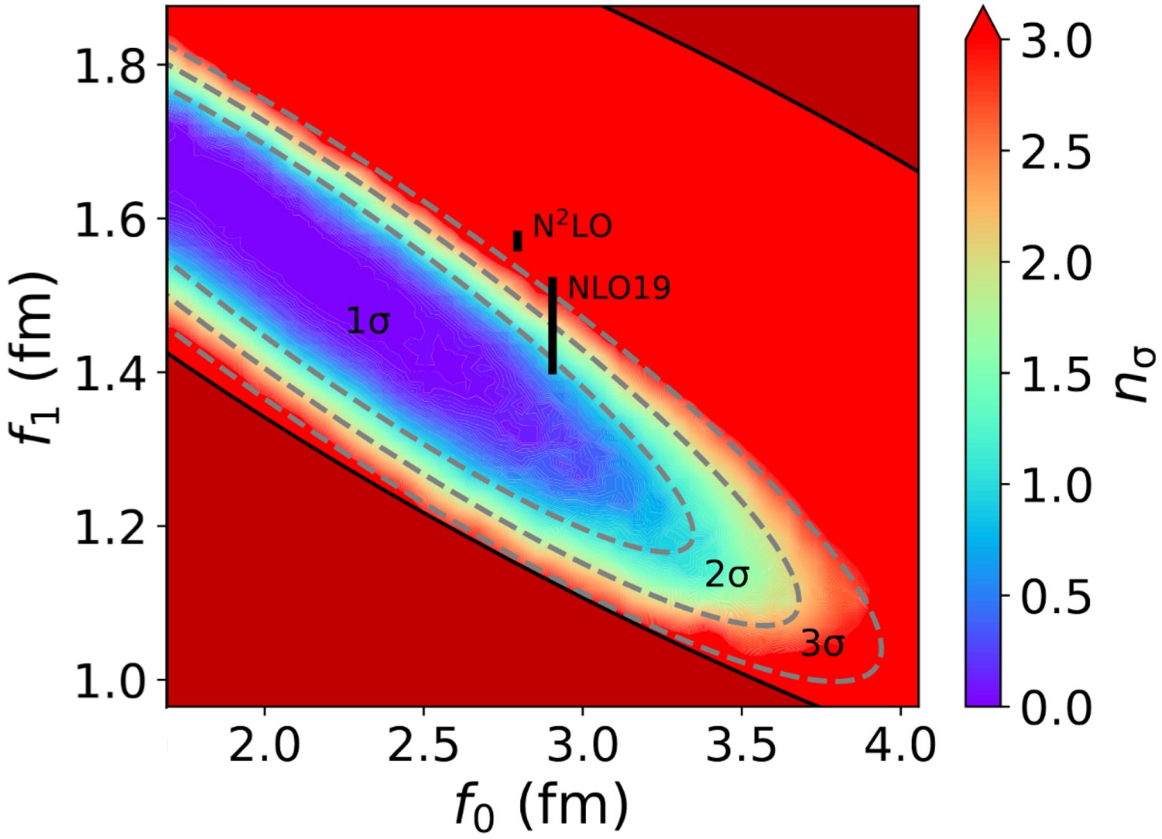
NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

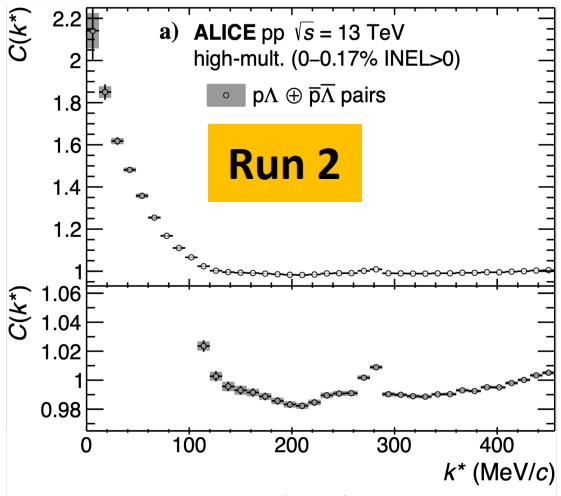
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

The pΛ interaction in the femtoscopy era

- Combined analysis of femtoscopic and scattering data

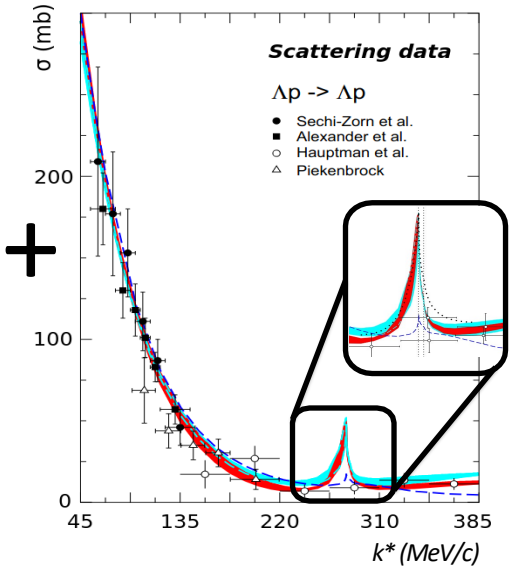
D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550





ALICE coll. PLB 833 (2022), 137272

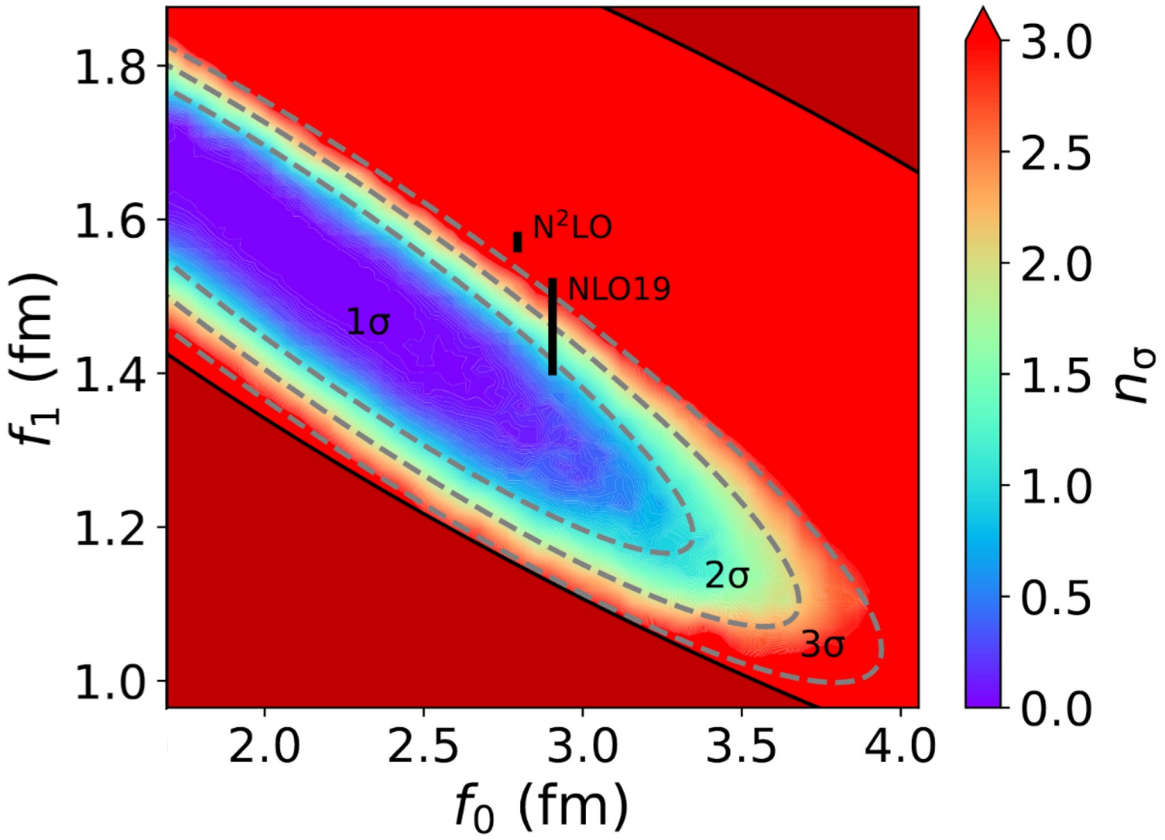
+



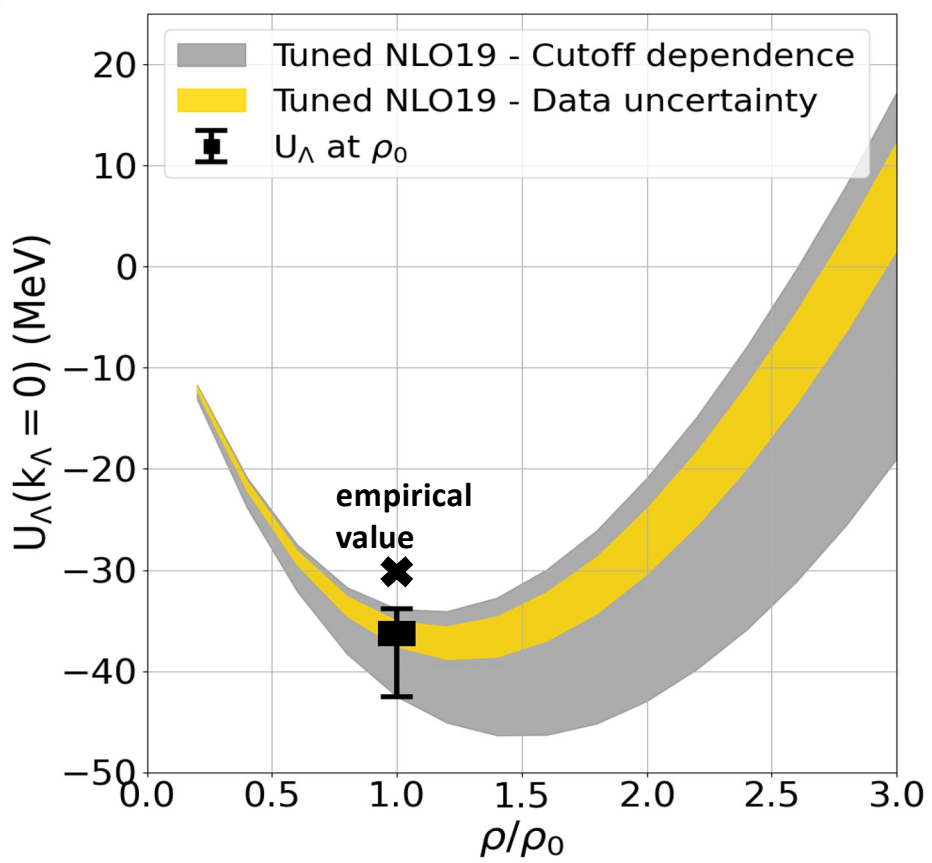
The pΛ interaction in the femtoscopy era

- Combined analysis of femtoscopic and scattering data

D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550



New parameterizations of the χEFT
Compatible with repulsive 3-body forces



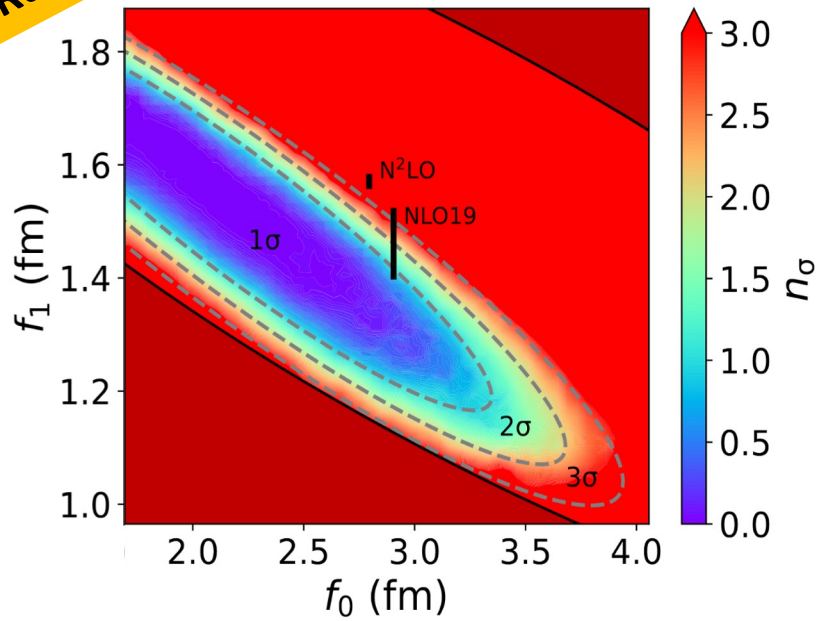
D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550

Selected results with strange hadrons

- Most precise measurement of the p-Λ scattering parameters

Run 2

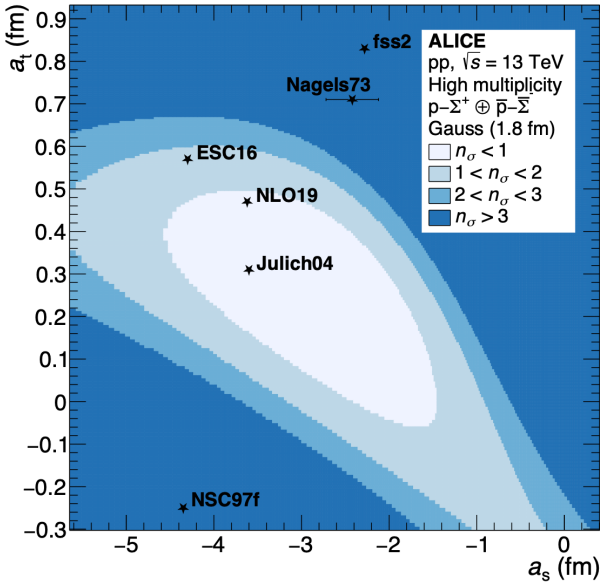
Scattering + femtoscopy



D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550

- First measurement of the p-Σ⁺ scattering parameters

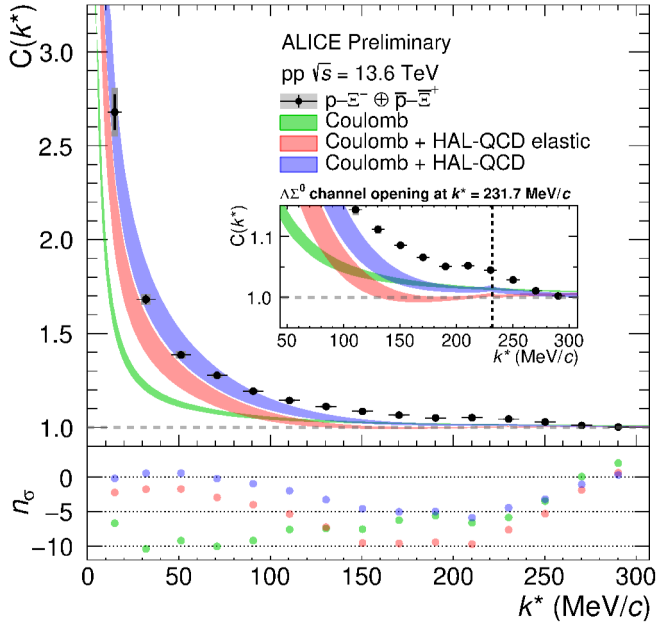
Run 2



ALICE Coll., PLB 874 (2026) 140252

- Evidence of an attractive p-Ξ⁻ interaction

Run 3



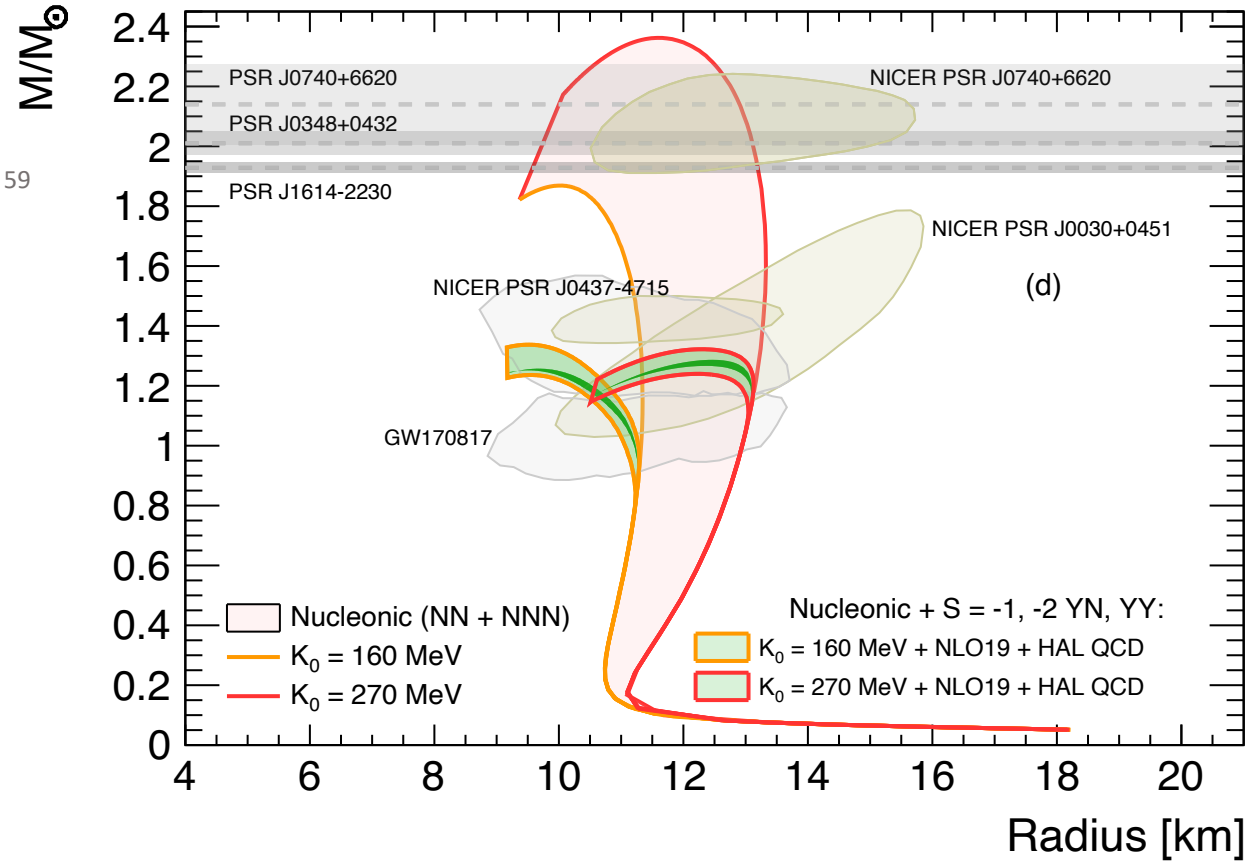
New precise experimental inputs for EFTs

Test of Lattice QCD

Towards a realistic equation of state of neutron stars

- *State-of-the-art interactions* for NN, NNN, YN (S=-1 and S=-2) and YY fail to reproduce observed heavy neutron stars

I. Vidaña, V. Mantovani Sarti, J. Haidenbauer, D. Mihaylov, L. Fabbietti, EPJ.A 61 (2025) 3, 59

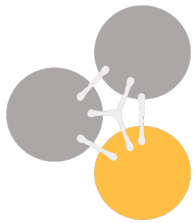


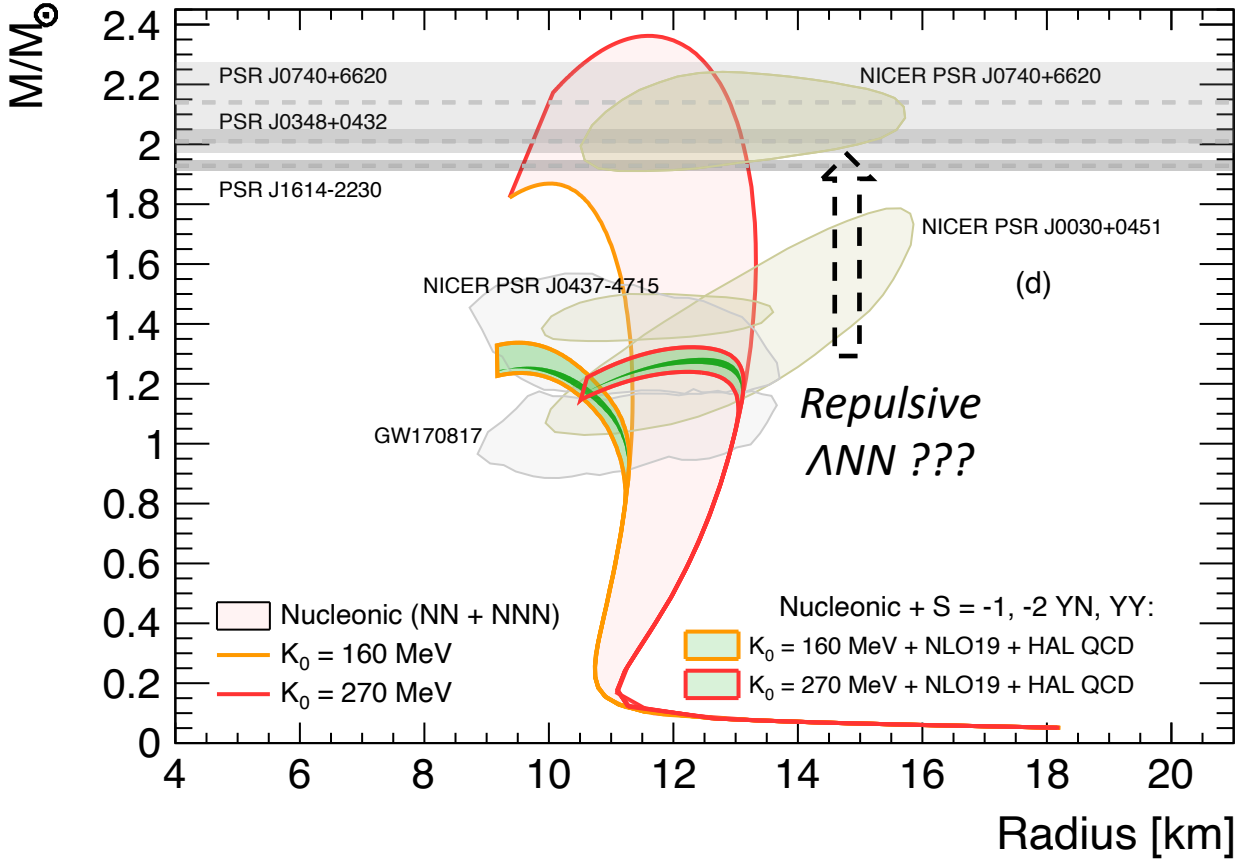
Towards a realistic equation of state of neutron stars

- Repulsive three-body forces can solve the problem but…

  … ΛNN interaction is unknown.

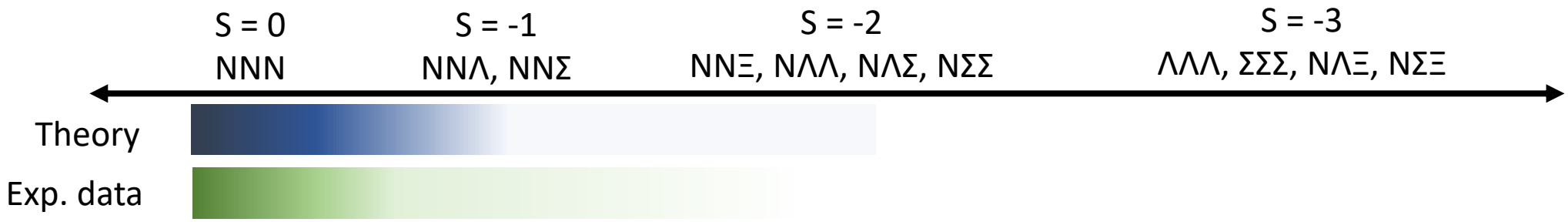
$$P = \sum P_{kin} + \sum n_i \, U_i \, (\rho) \; + \boldsymbol{U_{\Lambda NN}} \, (\boldsymbol{\rho})$$



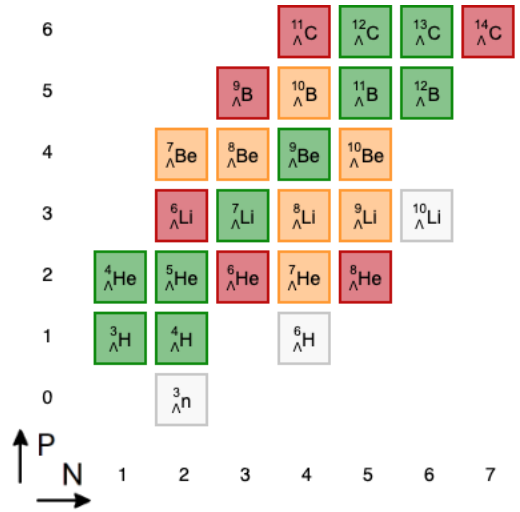


I. Vidaña, V. Mantovani Sarti, J. Haidenbauer, D. Mihaylov, L. Fabbietti, EPJ.A 61 (2025) 3, 59

Three-body interactions

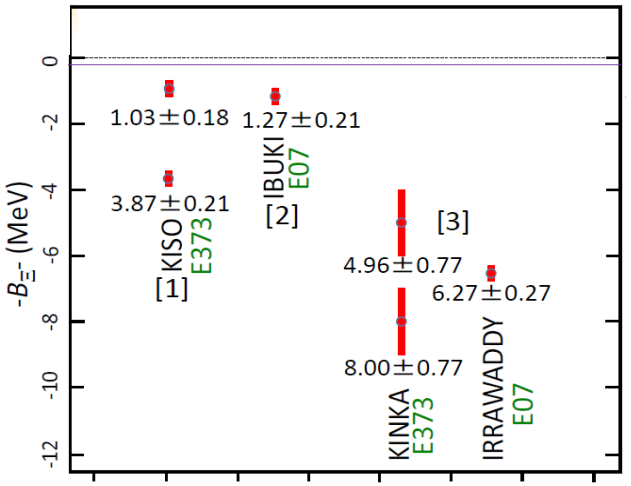


Λ-hypernuclei: *38 hypernuclei*



Mainz data base: https://hypernuclei.kph.uni-mainz.de/

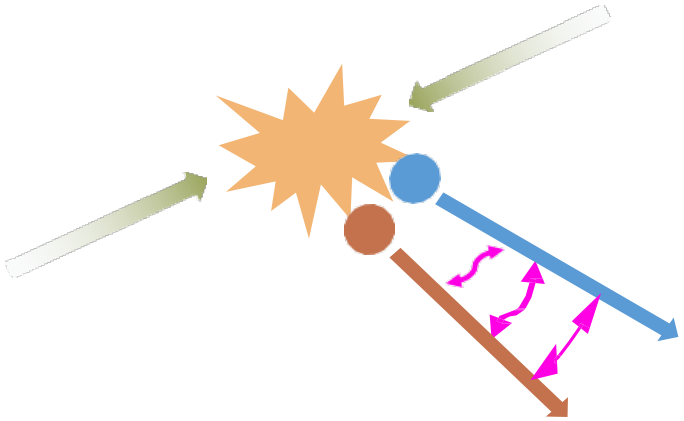
Ξ-hypernuclei: only *4 events*



Challenging measurements! YNN not sufficiently constrained

[1] K. Nakazawa, PTEP 2015, 033D02 (2015)
[2] S. H. Hayakawa, PRL 126, 062501 (2021)
[3] M. Yoshimoto, PTEP 2021, 073D02 (2021)

Femtoscopy: from two- to three-particle correlations

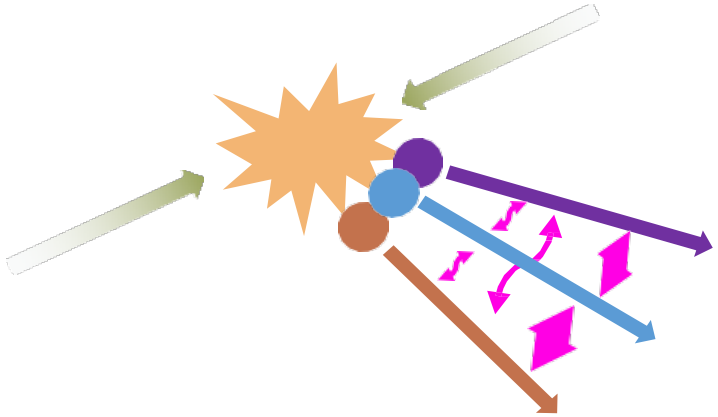


Two-particle correlations:

$$C(k^*) = \frac{N_{same}(k^*)}{N_{mixed}(k^*)} = \int S(\vec{r}\,)\left|\psi(\vec{k}^*, \vec{r}\,)\right|^2 d\,\vec{r}$$

Scattering wave function

M. Lisa, S. Pratt et al., ARNPS 55 (2005), 357-402
L. Fabbietti et al., ARNPS 71 (2021), 377-402

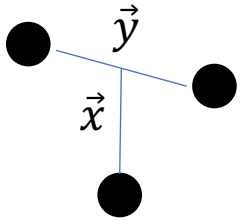


Three-particle correlations:

$$C(Q_3) = \frac{N_{same}(Q_3)}{N_{mixed}(Q_3)} = \int S(\rho)|\psi\,(Q_3, \rho\,)|^2\,\rho^5\,d\rho$$

Three-body wave function

Jacobi coordinates



Hyperradius

$$\rho = \sqrt{x^2 + y^2}$$

L. E. Marcucci et al., FP. 8, 69 (2020).
RDG et al. EPJC 82 (2022) 244
ALICE Coll., EPJ A 59, 145 (2023)

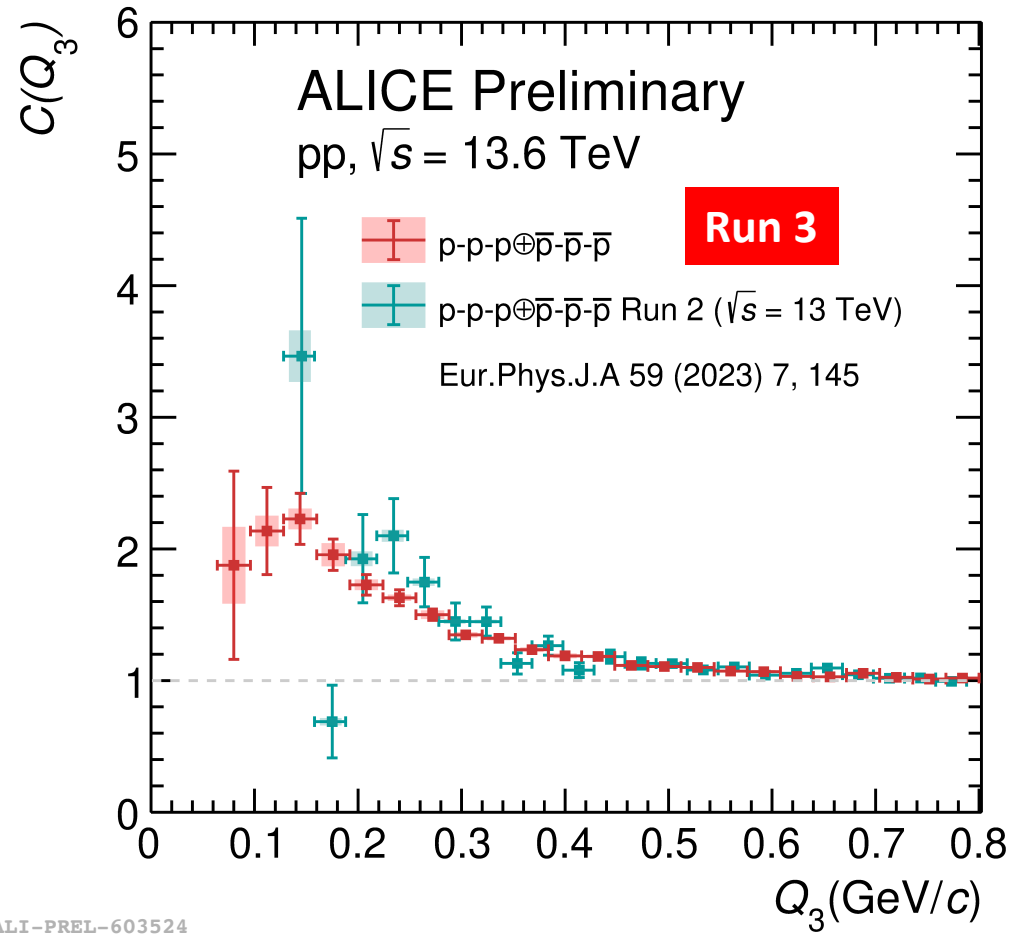
Hypermomentum

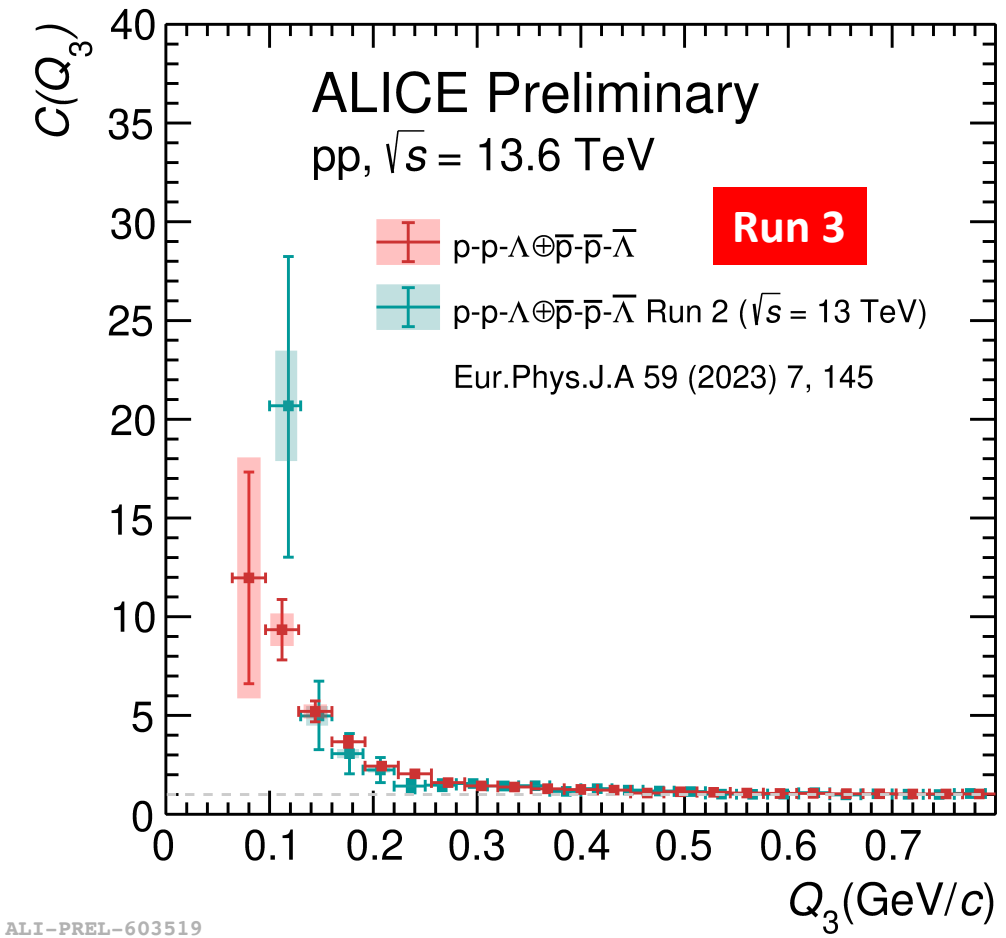
$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}$$

RDG et al. EPJC 82 (2022) 244
ALICE Coll., EPJ A 59, 145 (2023)

p-p-p and p-p-Λ correlation functions in Run 3

- New Run 3 results by ALICE: significant improvement in statistics and more data in the low Q_3 region

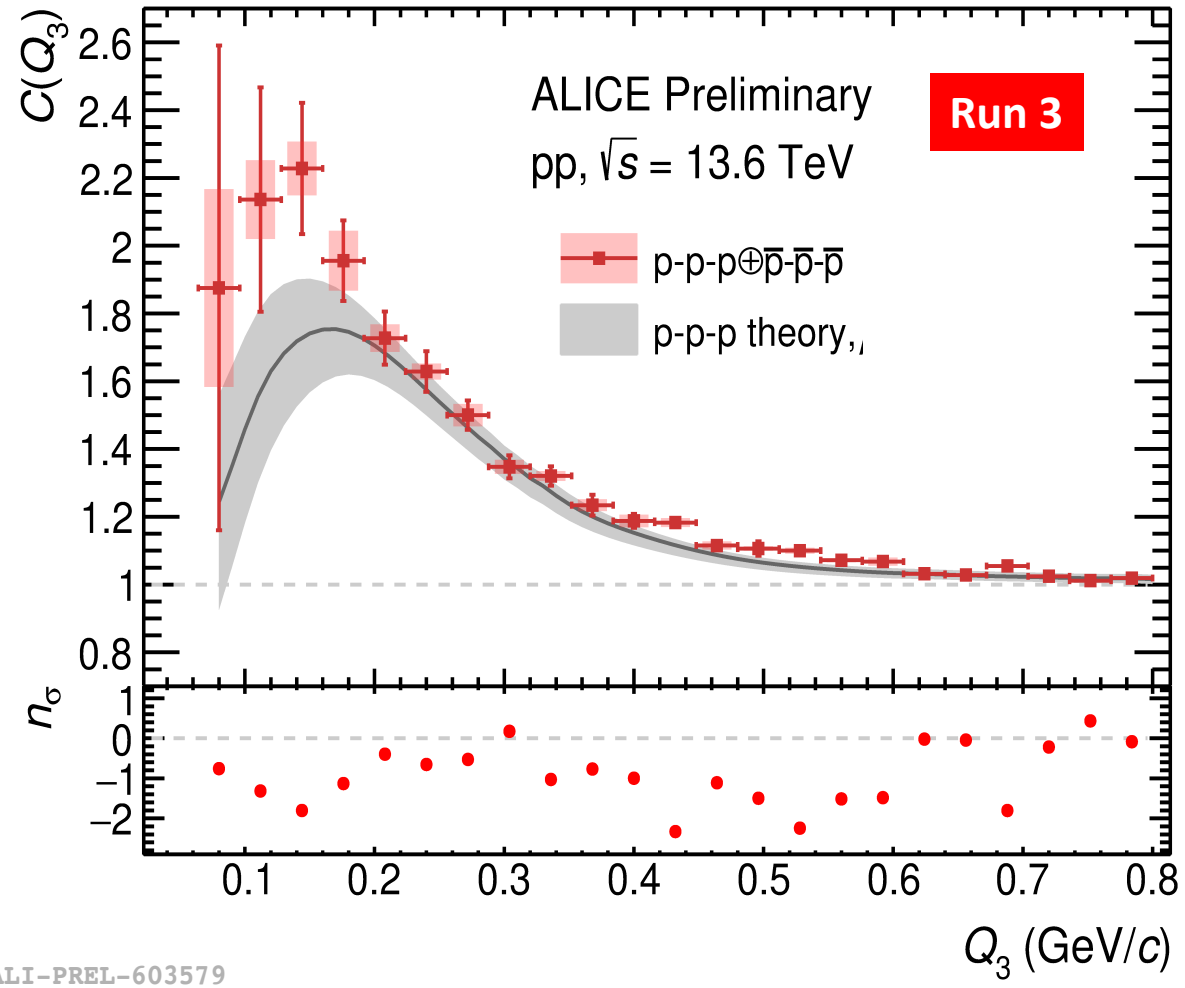




p-p-p correlation function

- First ever full description of three-body correlation function with free hadrons
- Calculations can describe the the data within 1.67σ

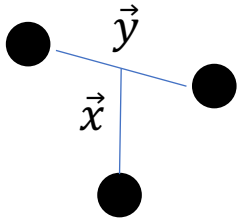
Novel way to study many-body interactions via three free baryon scattering 3->3



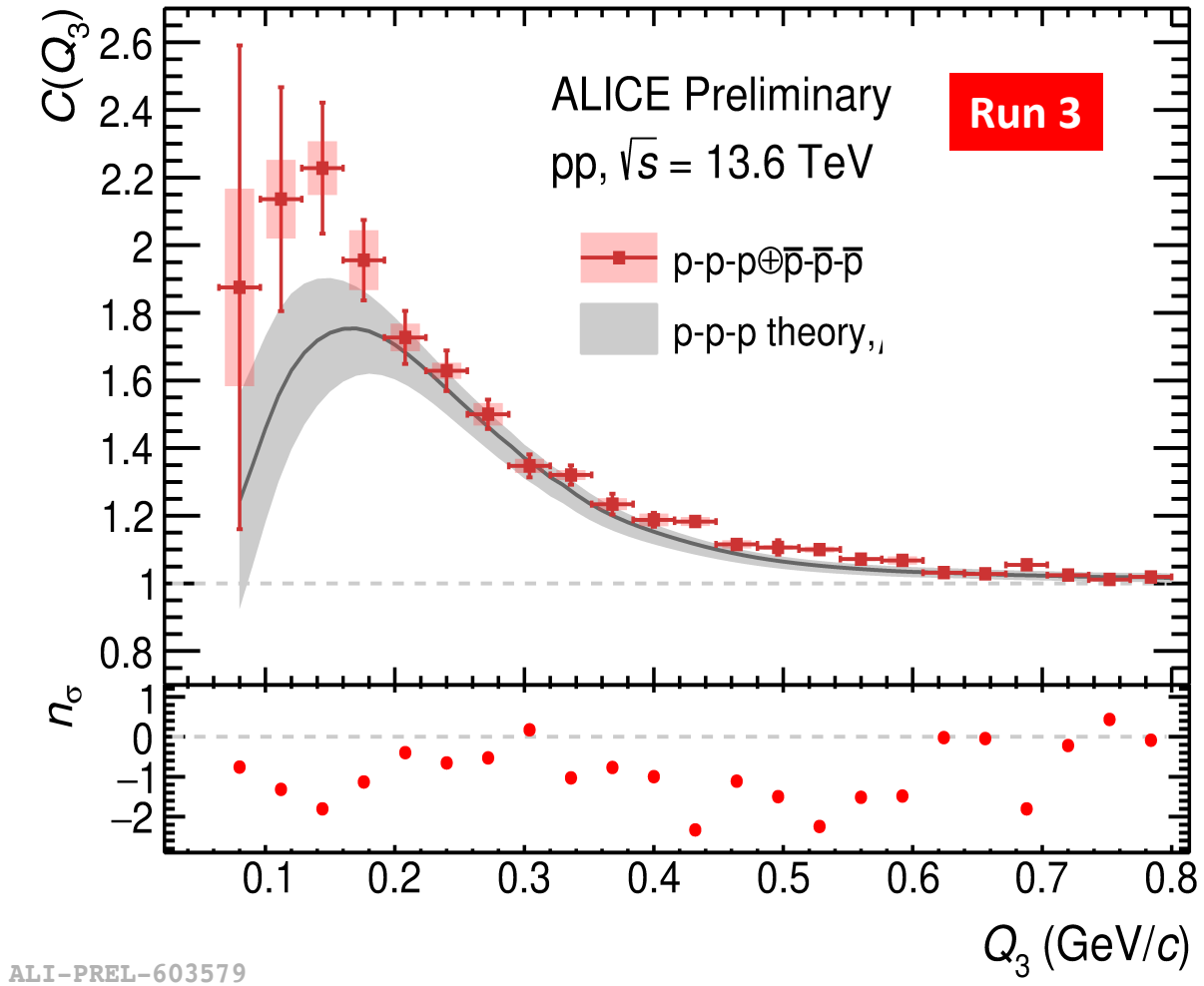
E. Garrido et al., Phys.Lett.B 868 (2025) 139731

p-p-p correlation function

- First ever full description of three-body correlation function with free hadrons
- Calculations can describe the the data within 1.67σ
- **Data converge from unity from above, strong interaction is not negligible at high energies**



New paper soon on the arXiv!



E. Garrido et al., Phys.Lett.B 868 (2025) 139731

p-p-Λ correlation function

- Reference calculations:
  → two-body NN and ΛN interactions provide an overbinding of the hypertriton

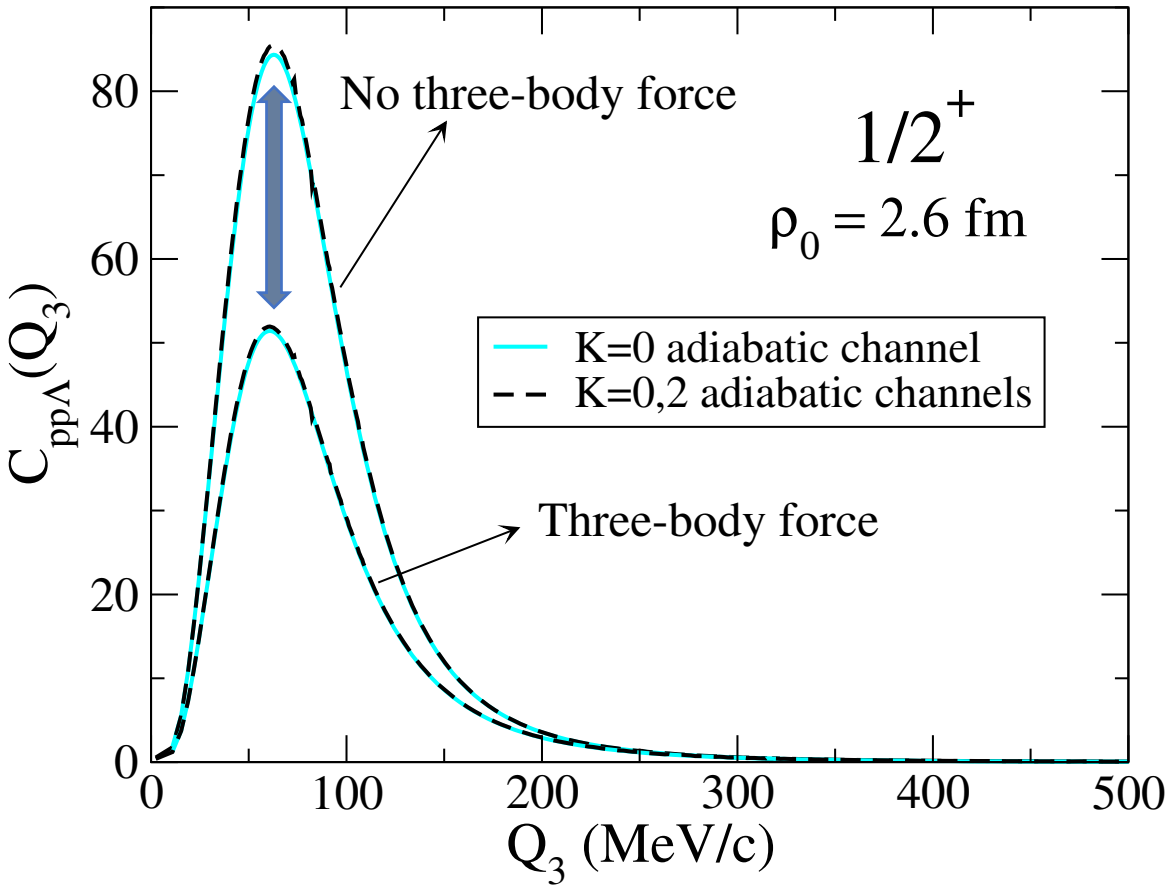
  BE($^{3}_{\Lambda}$H) = 2.904 MeV exp: 2.39 MeV

  *E. Garrido, **RDG, L. Fabbietti** et al., PRC 110 (2024) 5, 054004*

  Binding energy from: https://hypernuclei.kph.uni-mainz.de

  → three-body ΛNN interaction

- **ΛNN interaction gives 40% effect**:
  only one partial wave (K=0) significantly contributes



E. Garrido et al., PRC 110 (2024) 5, 054004

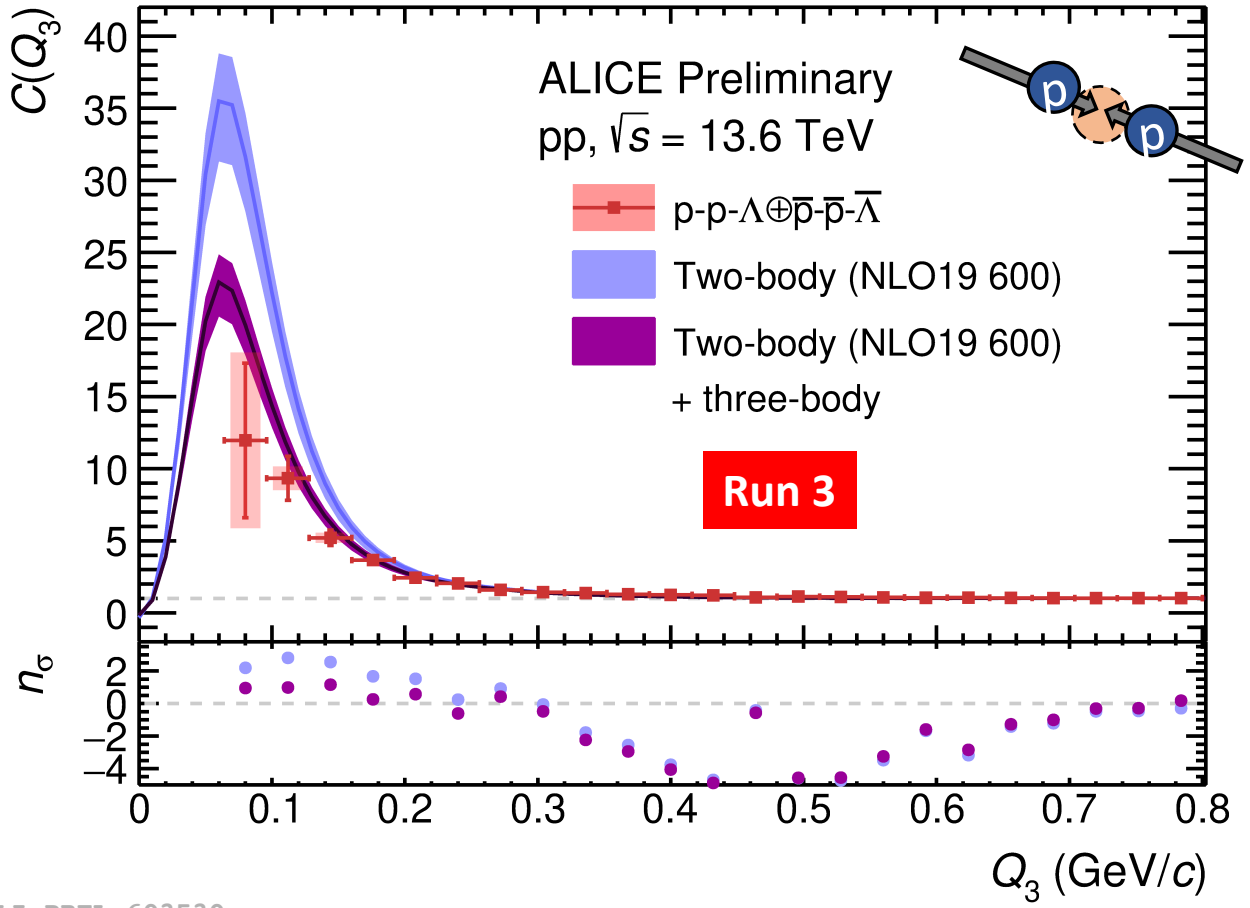
p-p-Λ correlation function in pp collisions

- Significant deviation from the absence of three-body interaction: **3.7σ at Q_3 < 0.2 GeV/*c***
- Three-body force constrained to the hypertriton binding energy

  *E. Garrido, **RDG, L. Fabbietti** et al., PRC 110 (2024) 5, 054004*

  0.7σ agreement with the data at Q_3 < 0.2 GeV/*c*

Ongoing analysis with full Run 3 data!!



Calculations: E. Garrido et al., PRC 110 (2024) 5, 054004

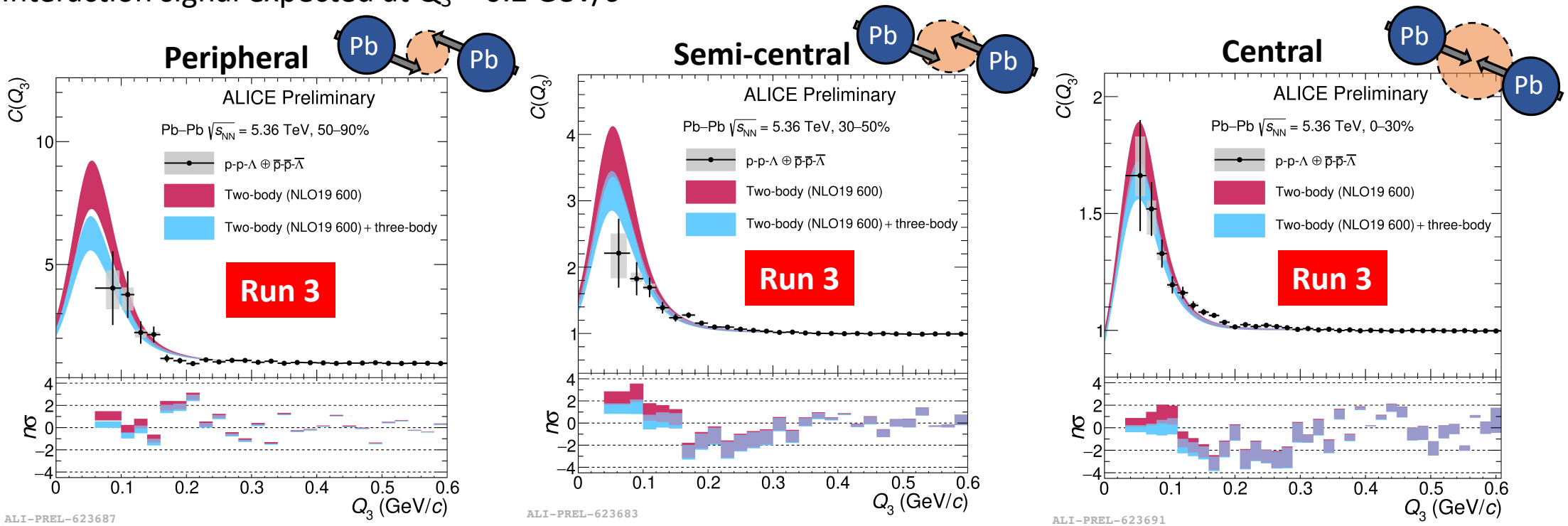
p-p-Λ correlation function in Pb–Pb collisions

Theory:

- Preliminary calculations with Gauss NLO19 (600)
  J. Haidenbauer, U.-G. Meißner, and A. Nogga, EPJ A 56, 91 (2020)
- Three-body force anchored to 3- and 4-body hypernuclei
  E. Garrido et al., PRC 110 (2024) 5, 054004
- Interaction signal expected at $Q_3 < 0.2$ GeV/c

Measurements:

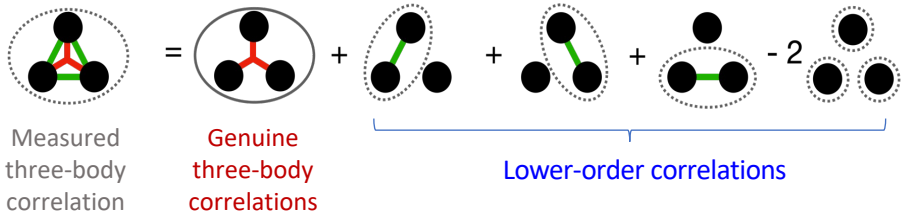
- Agreement with absence of three-body interactions in central collisions
- Deviations observed in semi-central and peripheral collisions



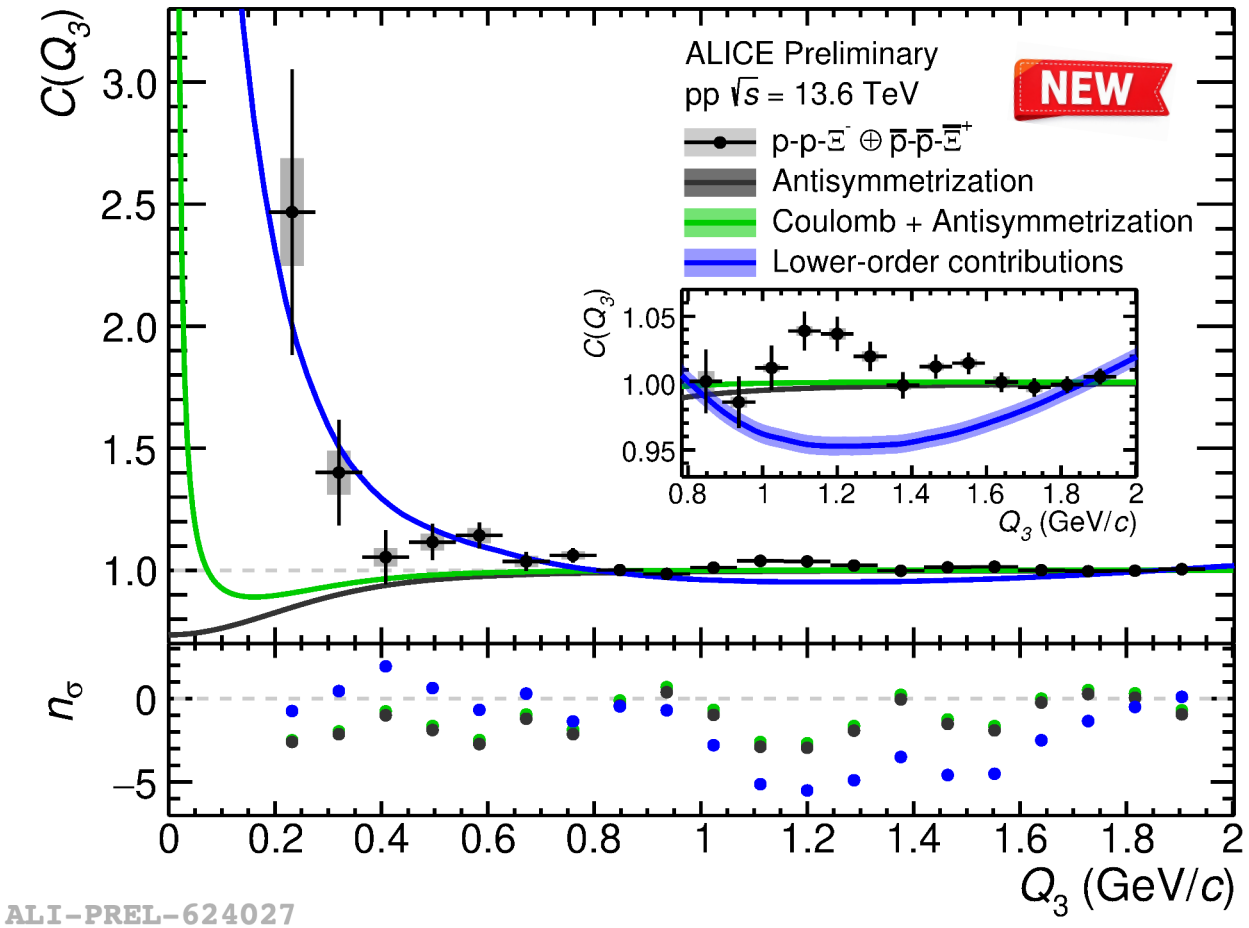
p-p-Ξ⁻ correlation function

- First measurement of p-p-Ξ⁻ final state interaction: **3.5 σ significance at Q_3 < 1 GeV/*c***
- Strong interaction with cumulant expansion method (no three-body dynamics) provides **0.6 σ agreement at Q_3 < 1 GeV/*c***

Credits: L. Šerkšnytė



- **Significant deviation observed in the range 1.0 GeV/*c* < Q_3 < 1.8 GeV/*c***



Calculations: M. Schäfer based on A. Kievsky at al., PRC 109 (2024) 3, 034006

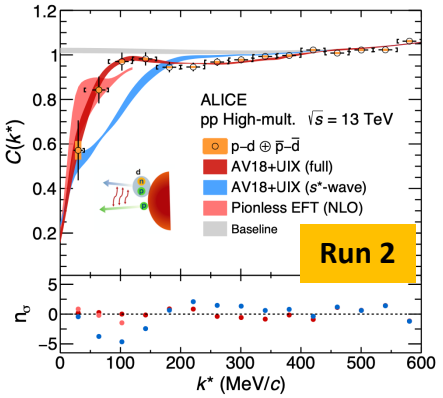
Other three-body measurements

S = 0
NNN

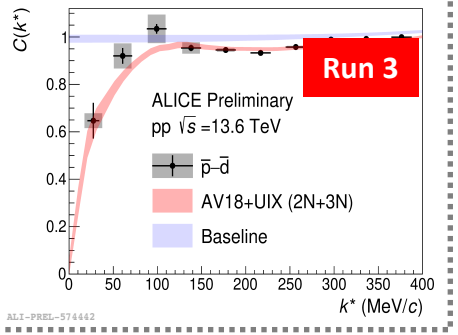
S = -1
NNΛ, KNN

S = -2
NNΞ

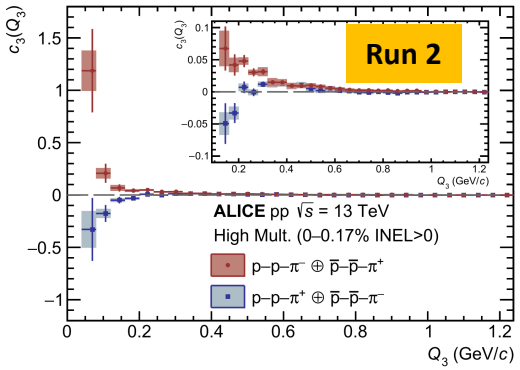
p-d



ALICE Coll., PRX 14 (2024) 3, 031051

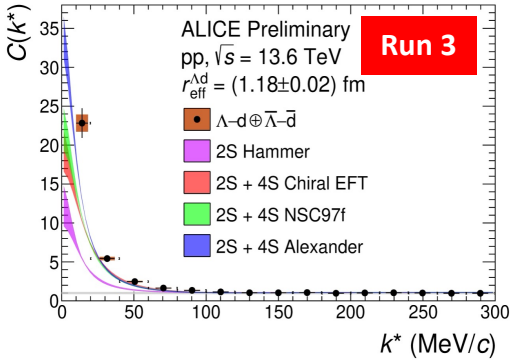


p-p-π

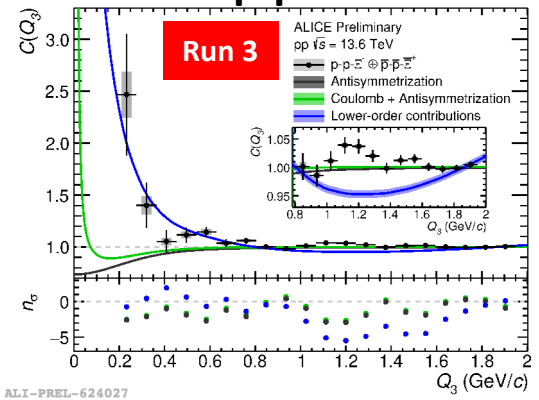


ALICE Coll., EPJ A 61 (2025) 8, 194

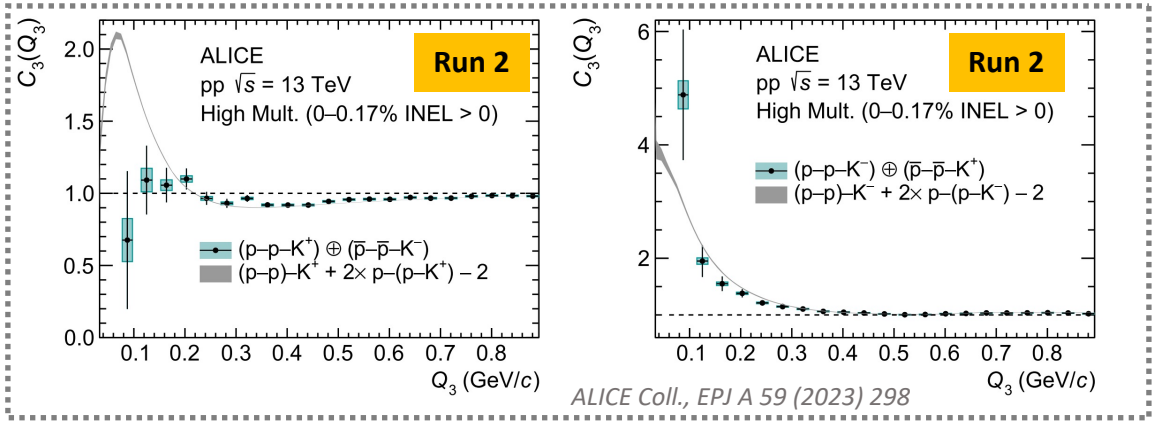
Λ-d



p-p-Ξ⁻



p-p-K



ALICE Coll., EPJ A 59 (2023) 298

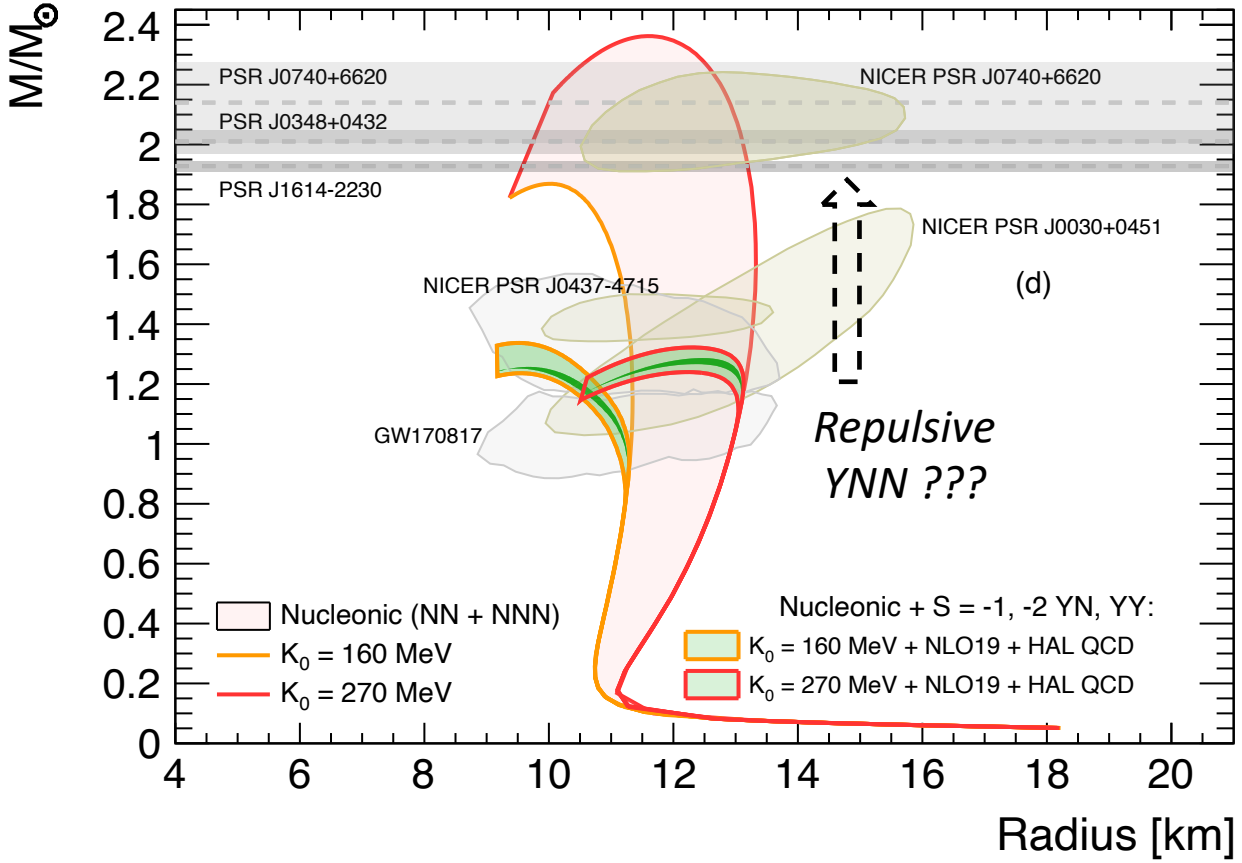
Final goal

- Constrain YNN interactions from femtoscopy data
- Derivation of realistic equation of state for hyperons and nucleons

Isaac Vidana

Valentina Mantovani Sarti

Laura Fabbietti

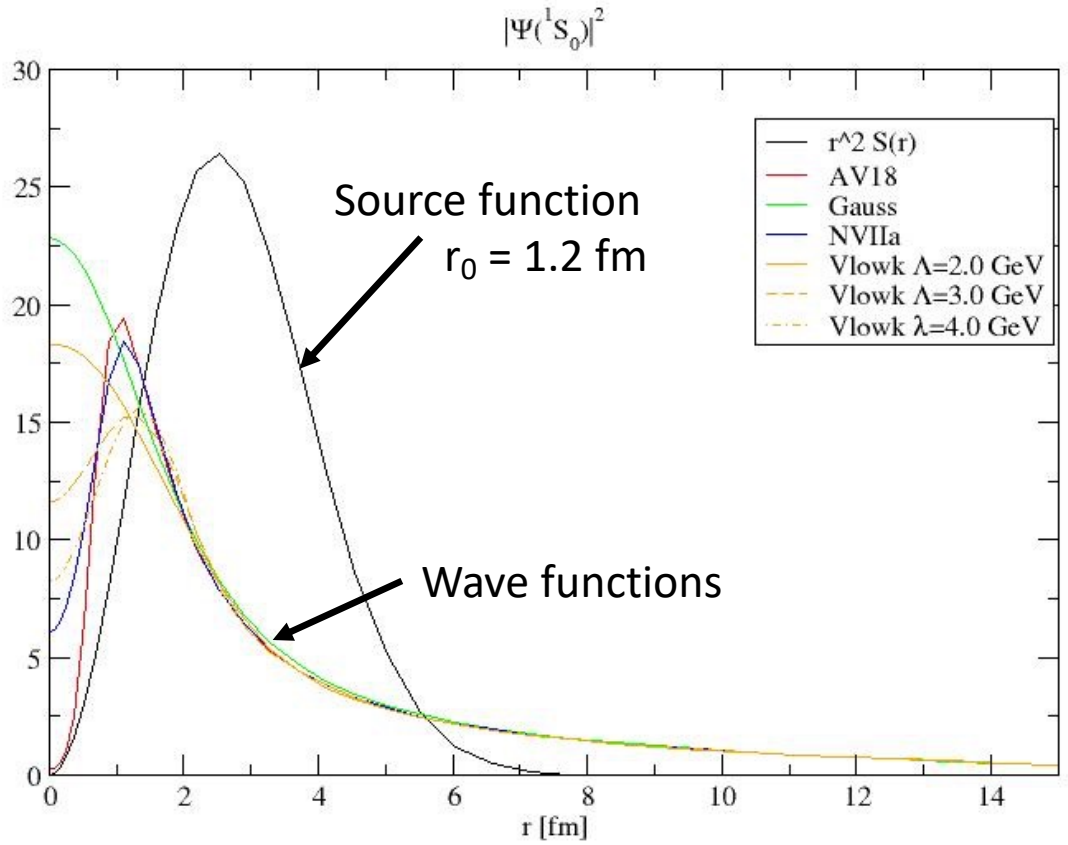


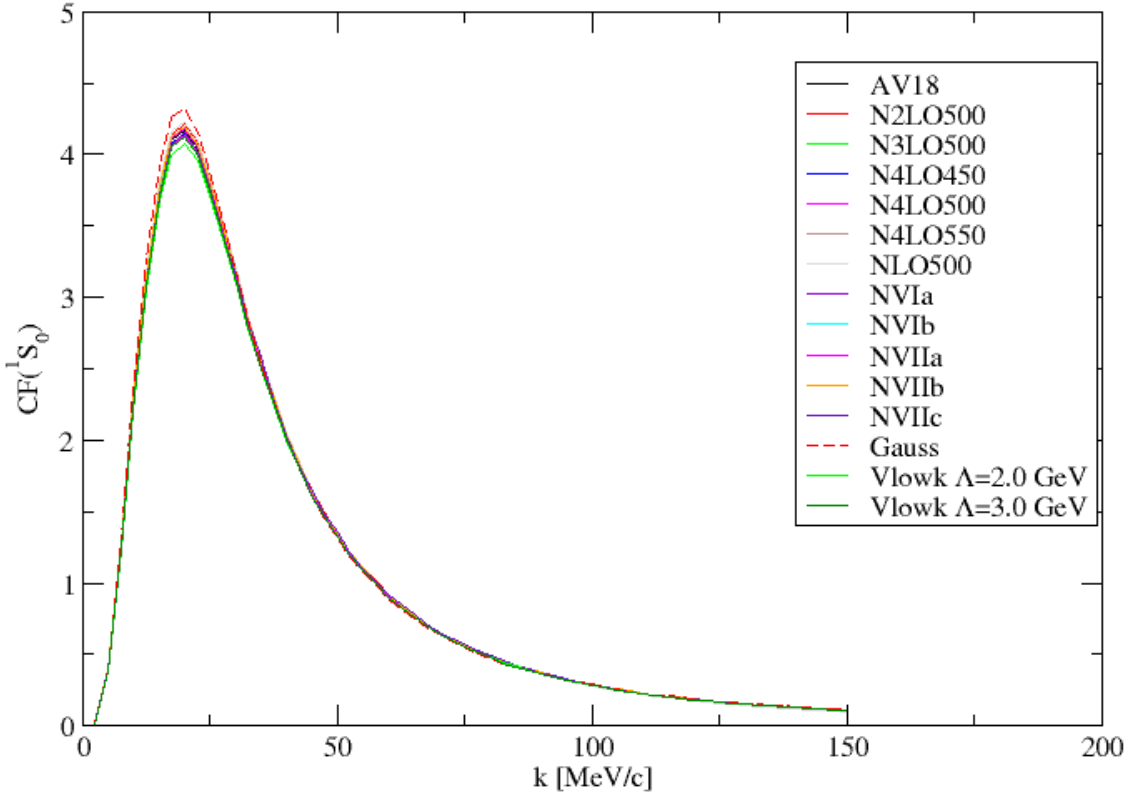
I. Vidaña, V. Mantovani Sarti, J. Haidenbauer, D. Mihaylov, L. Fabbietti, EPJ.A 61 (2025) 3, 59

Thank you for your attention

Scan of p-p wave functions

Courtesy A. Kievsky and M. Viviani





For a systematic study of the effect of different NN interaction in the correlation function see
M. Göbel, A. Kievsky, Phys.Lett.B 869 (2025) 139835

Λ-d correlation function

- Dedicated three body triggers for pp collisions at Run 3
- Λnp: Isospin 0 + Isospin 1
- Λpp: Isospin 1

Theoretical curves: Lednicky formula with scattering parameters from J. Haidenbauer *Phys.Rev. C* 102 (2020) 3, 034001

- **Point-like particle description doesn't work for Λ-d**
- **Three-body calculations are necessary**