

Czech Technical University in Prague



European Research Council

Probing hadronic interactions with femtoscopy at the LHC

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New-EXOTICA: New Frontiers in Exotic Atoms
Trento, Italy
16 October 2026

On behalf of …

L. Fabbietti



V. Mantovani Sarti



L. Šerkšnytė



D. Mihaylov



A. Riedel



M. Korwieser



G. Mantzaridis



W. Rzesa



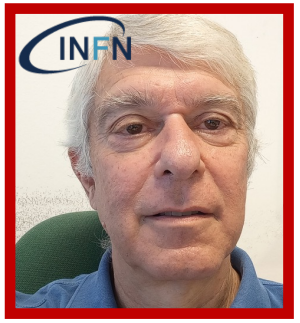
J. Haidenbauer



I. Vidaña



A. Kievsky



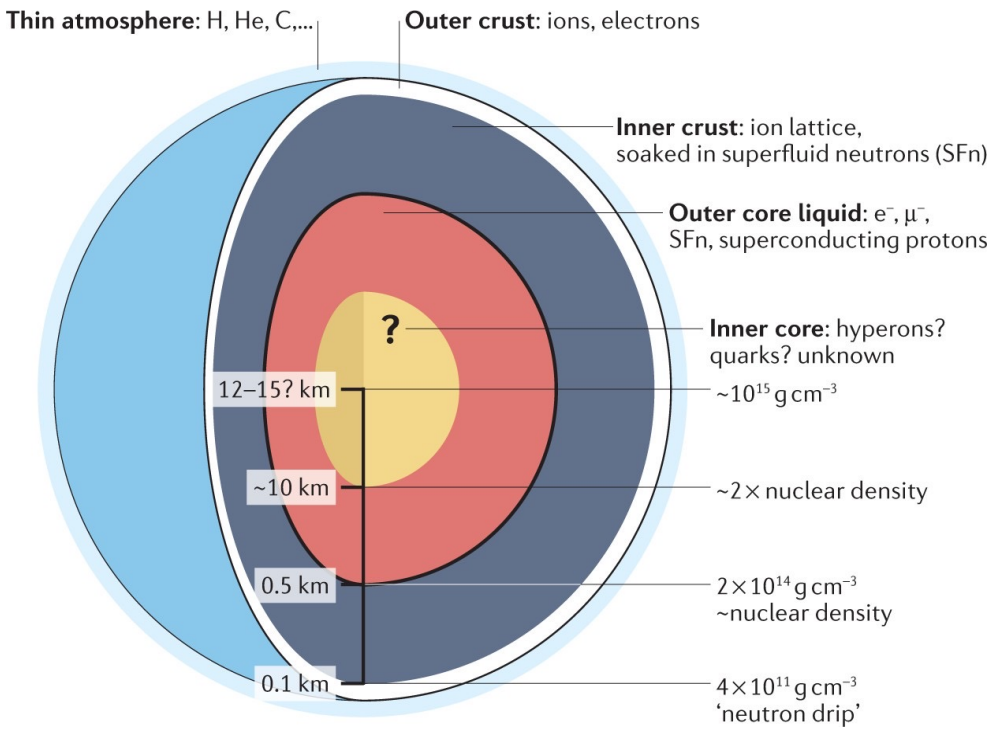
E. Garrido



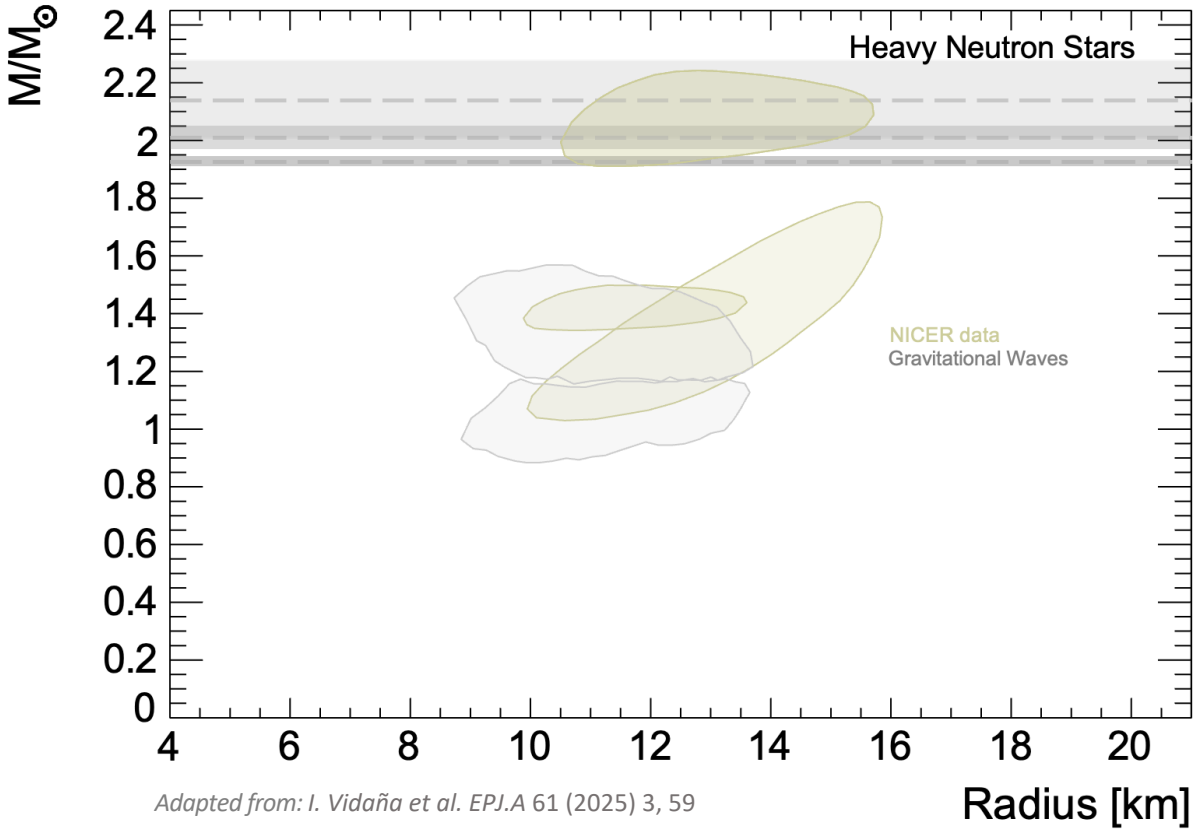
… and many others!

Neutron Stars structure

- Radius: 10 – 15 km
- Mass: 1.0 – 2.0 M_{Sun}



Nature Reviews Physics 4 (2022)
Figure adapted from NICER

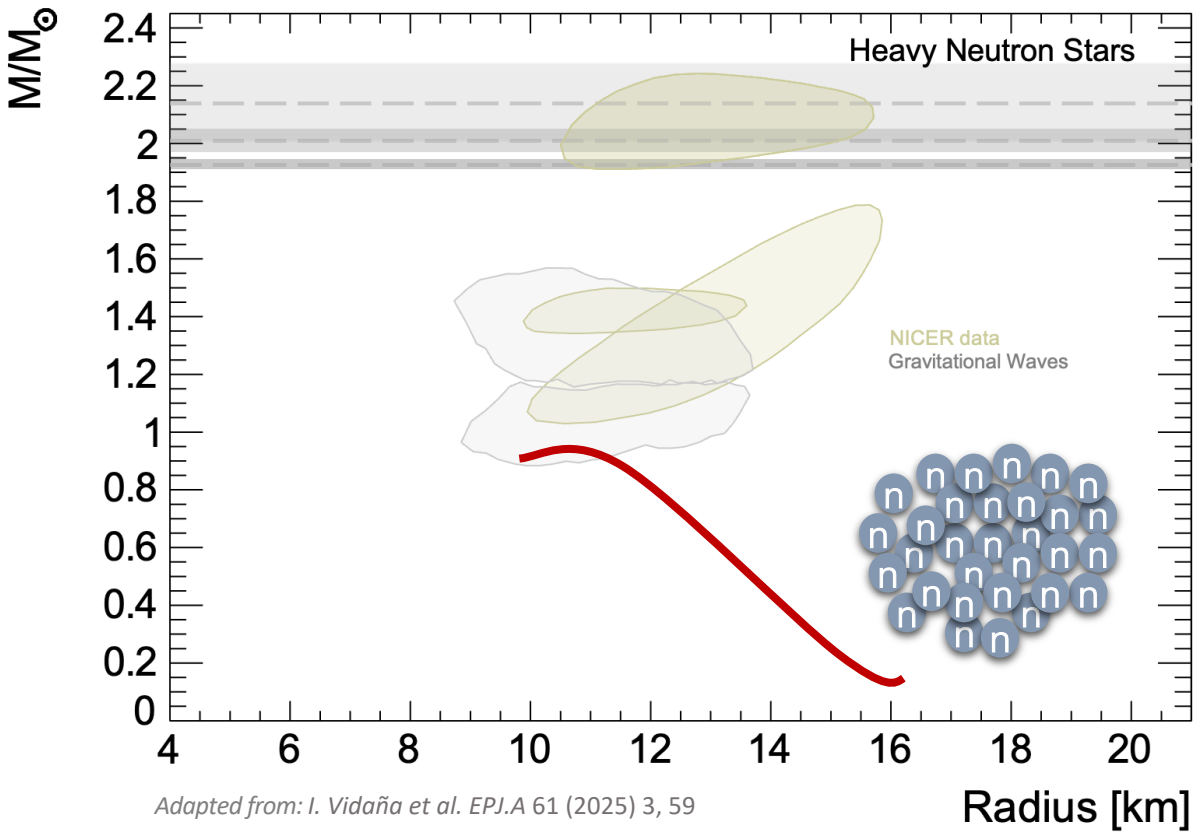


Adapted from: I. Vidaña et al. EPJ.A 61 (2025) 3, 59

Non-interacting neutron gas

- Radius: 10 – 15 km
- Mass: 1.0 – 2.0 M_{Sun}
- Inner core composition:
  - HYP: Non-interacting neutron gas?
  - Degenerate pressure due to the Pauli blocking

- **Not sufficient to counterbalance the gravity in heavy neutron stars!!**



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

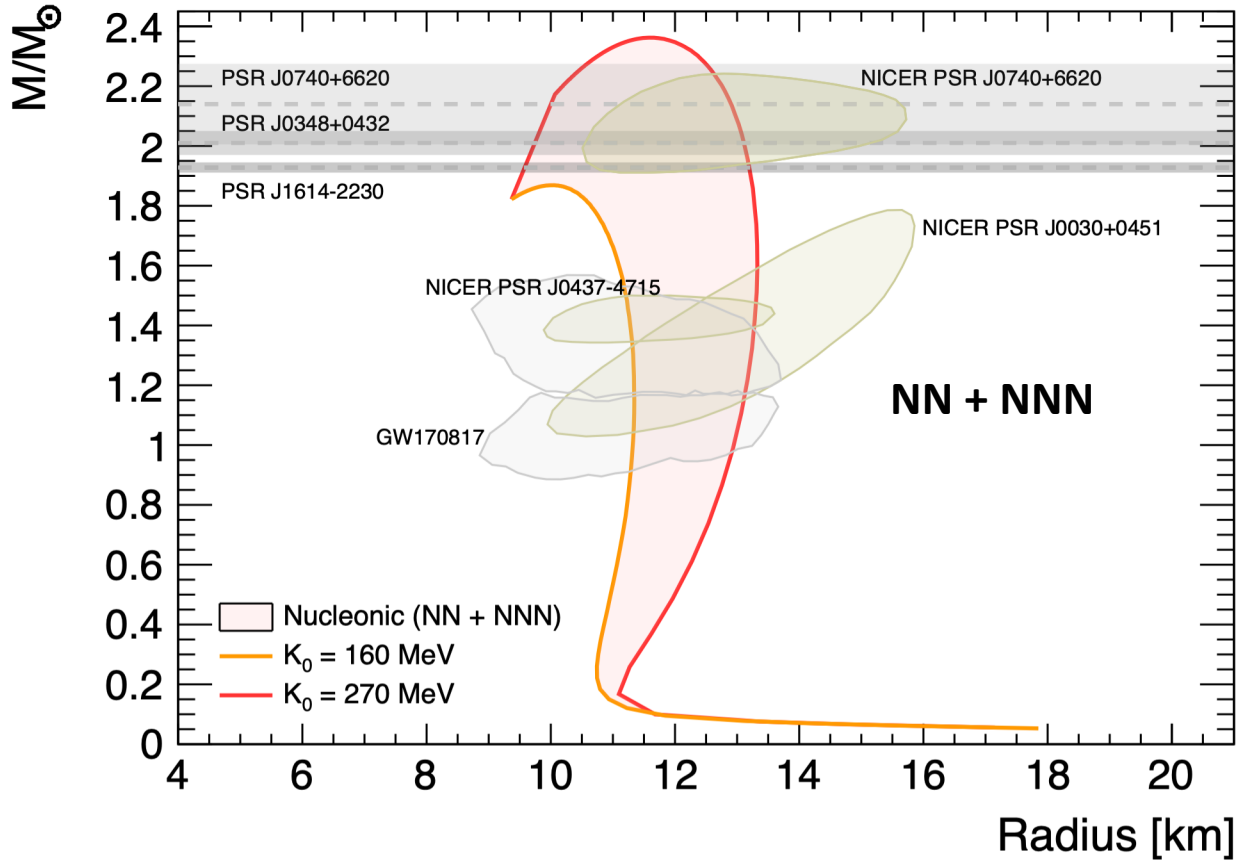
Strangeness in neutron stars

- Nuclear force contribute to guarantee the gravitational stability of the star

$$\rho_{Core} \geq 2 - 3\ \rho_0$$

- Production of hyperons is energetically possible via weak process

$$n\ n \rightarrow n\ \Lambda$$
$$n\ n \rightarrow p\ \Sigma^-$$
$$\dots$$



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

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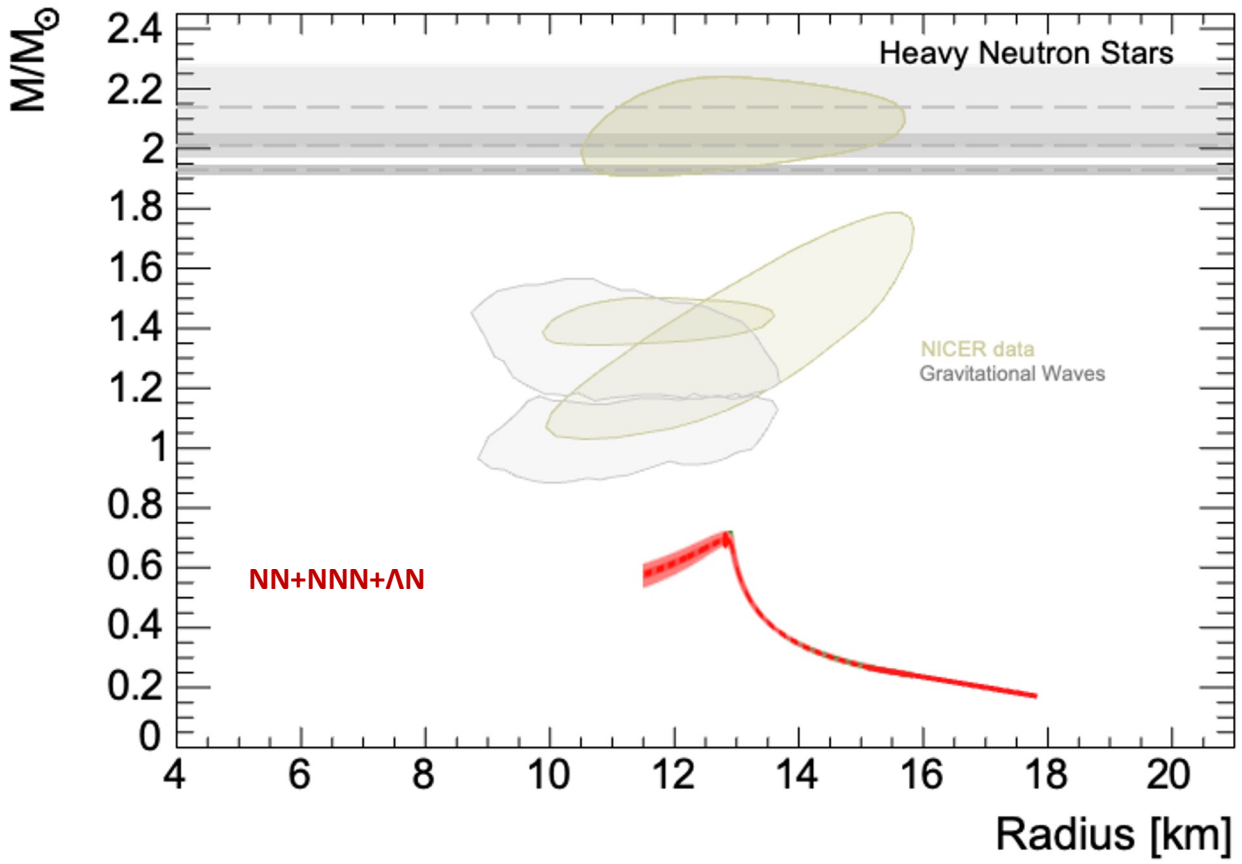
- Inclusion of hyperons results in a softening of the equation of state



Models anchored to scattering data

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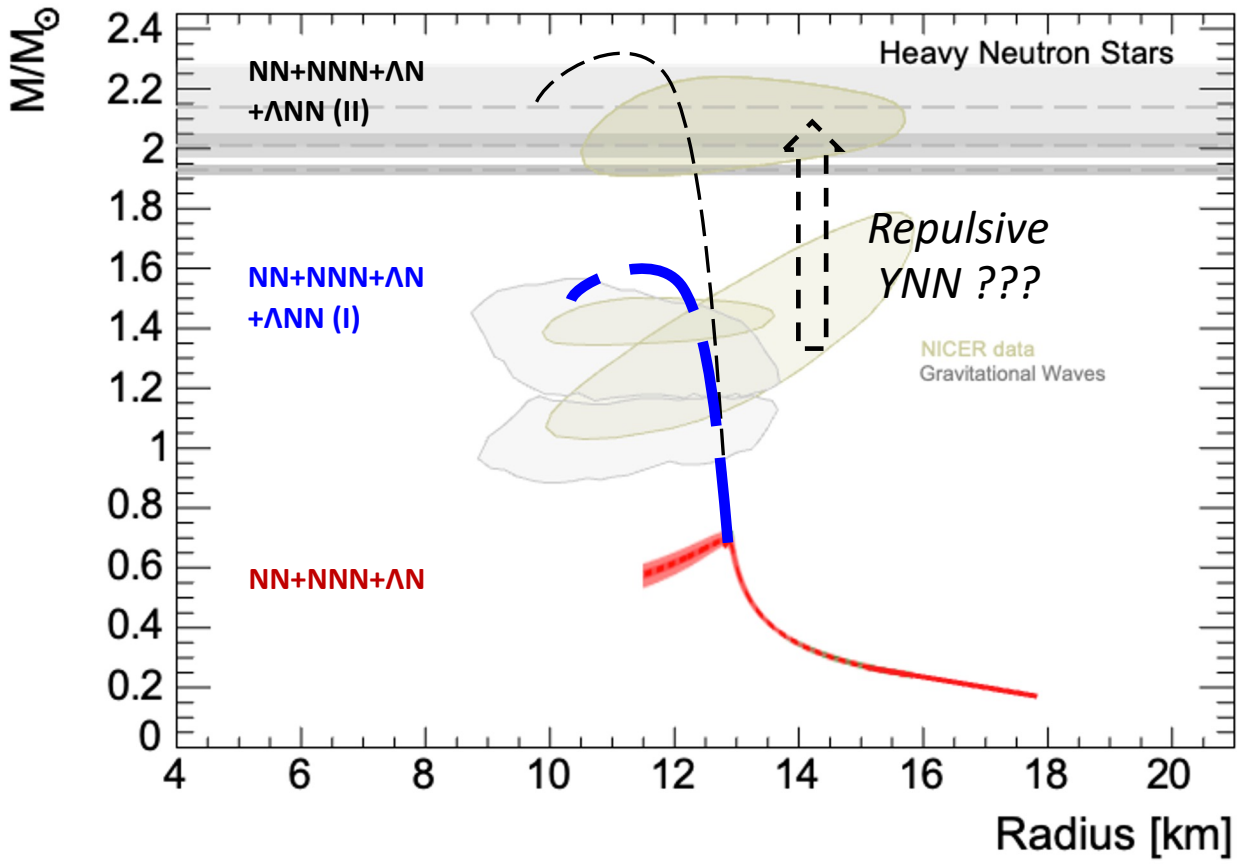
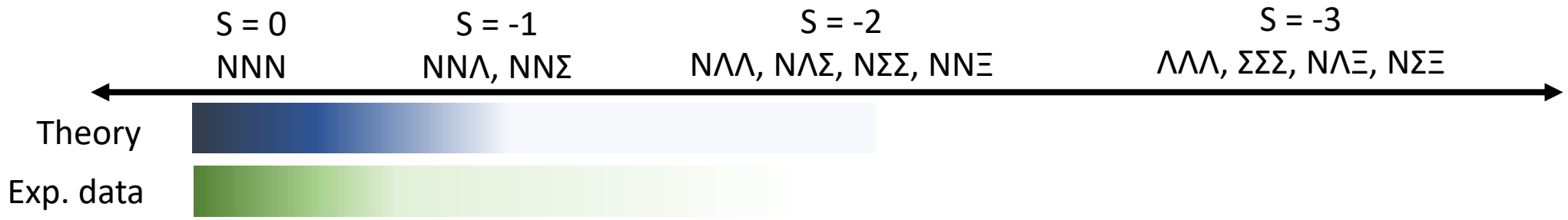
$$\dots$$

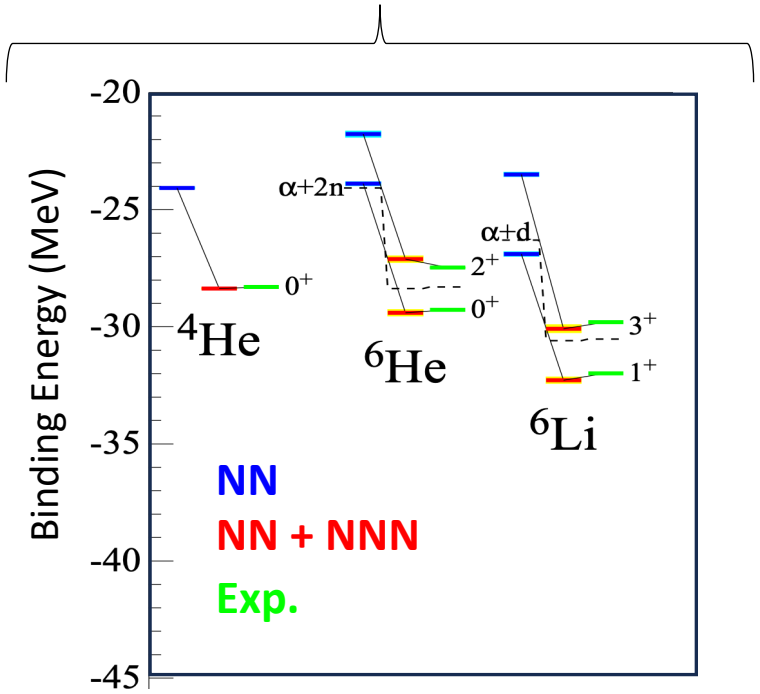
- Inclusion of hyperons results in a softening of the equation of state
- Three-body forces can help but…
  … **YNN interaction are largely unknown!**



Models anchored to scattering data and hypernuclei

Three-body interactions

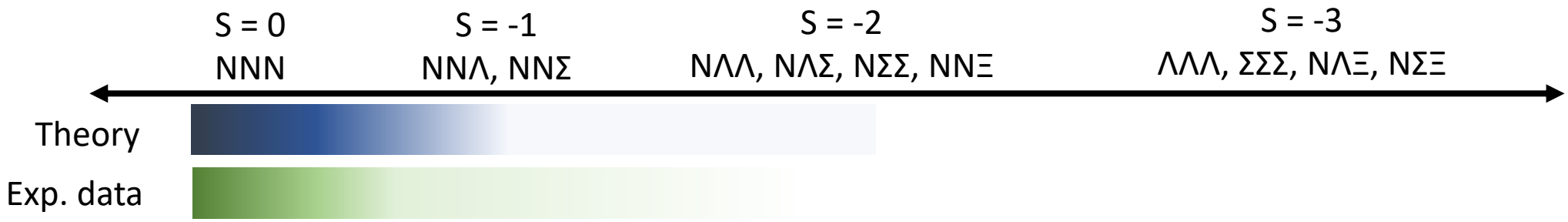




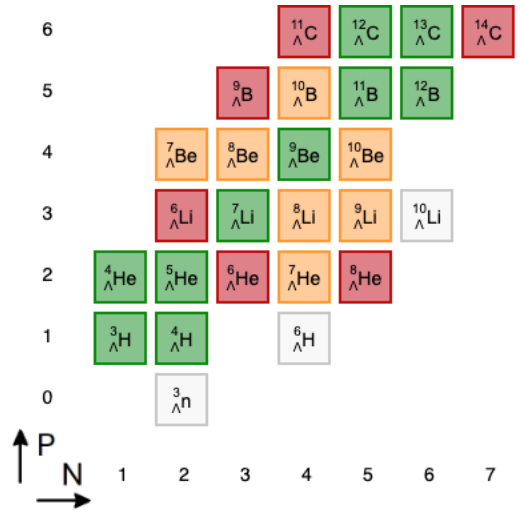
- Precisely constrained from nuclei (10% contribution to the binding energy)

R. Navarro Perez et al., PRC 88, 024002 (2013)

Three-body interactions

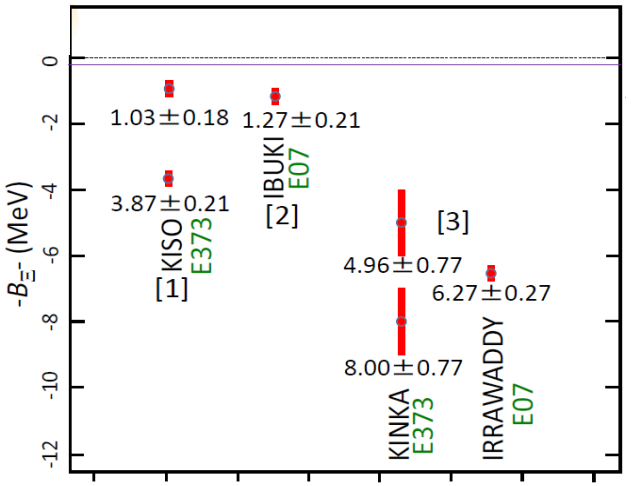


Λ-hypernuclei: *38 hypernuclei*



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

Ξ-hypernuclei: only *4 events*

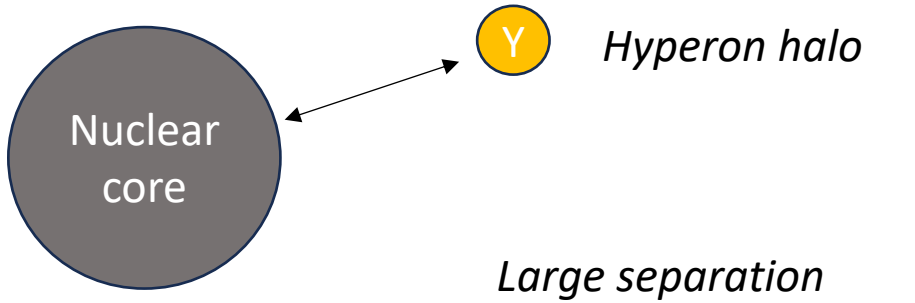


Scarce data with hyperons!
YNN not constrained

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

Average distances with baryon density

- Naïve representation of a hypernucleus



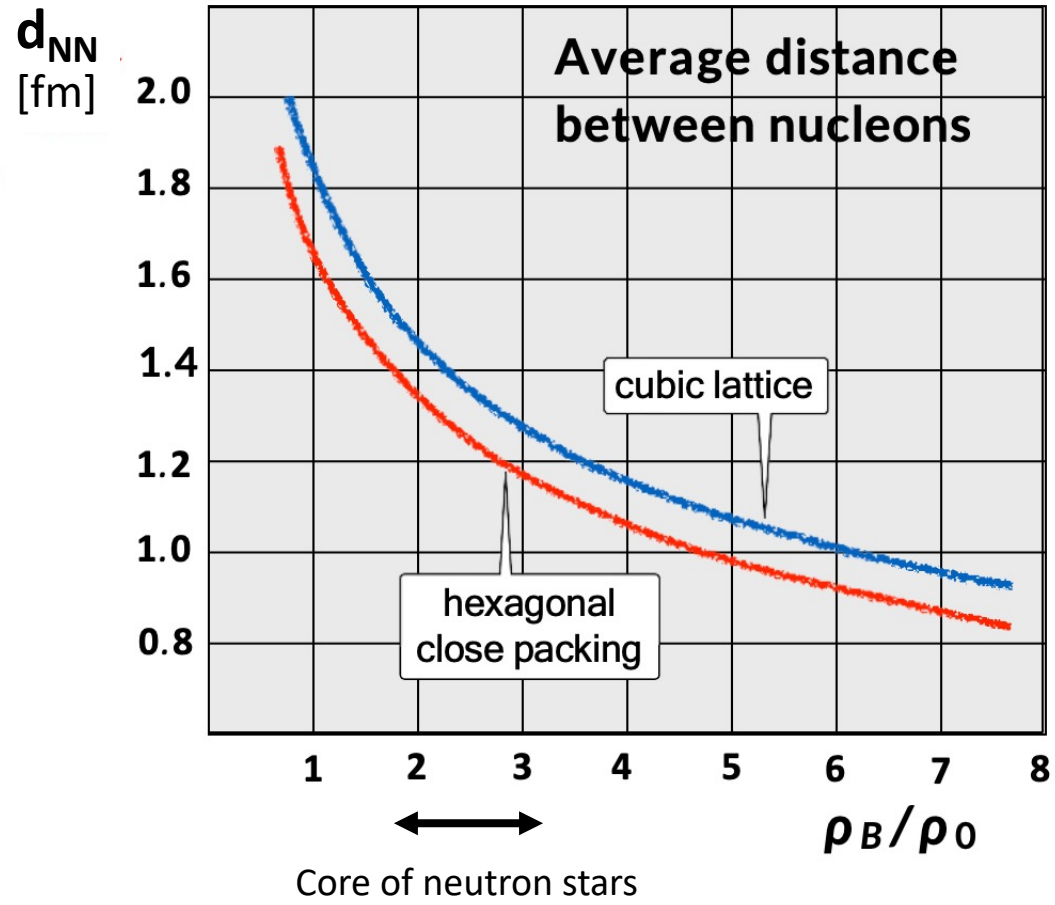
Large separation
(e.g. 10 fm in hypertriton)

ALICE Coll., Phys. Rev. Lett. 131, 102302

- How the YNN interaction evolves to the smaller scales?

Necessary to control the size of the system

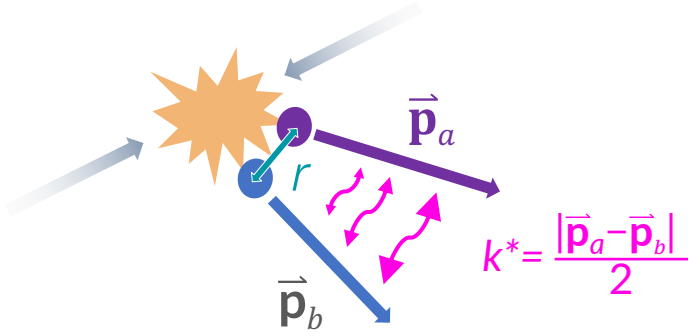
Plot credits: W. Weise



Core of neutron stars

Femtoscopy technique at the Large Hadron Collider

High-energy collisions



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

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

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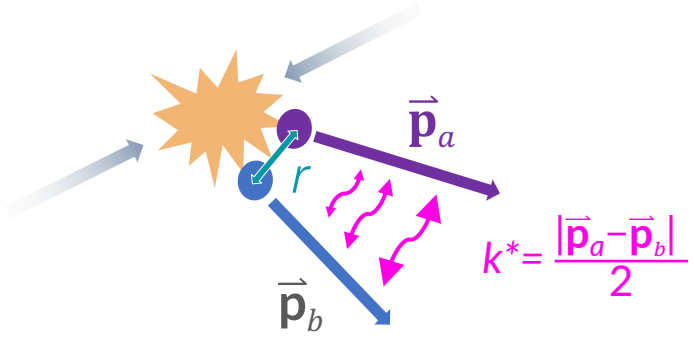

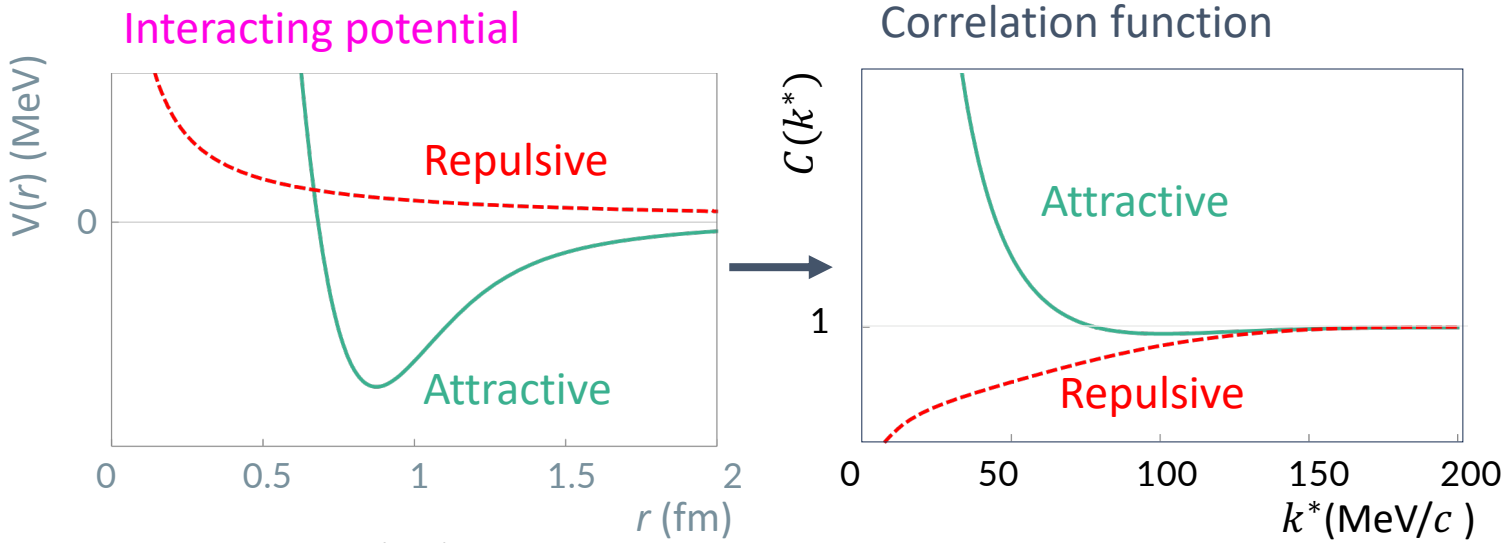

ALICE Coll., Nature 588 (2020) 232-238

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Source function in pp collisions at the LHC

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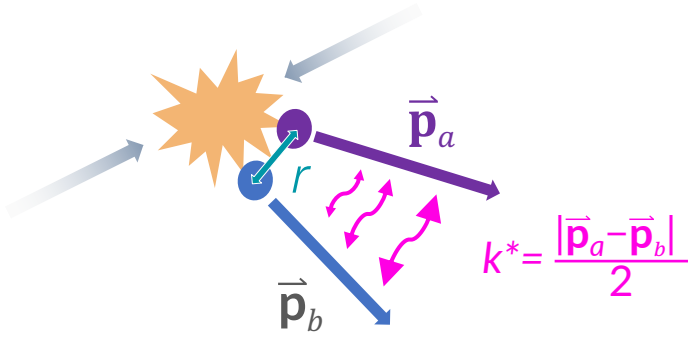
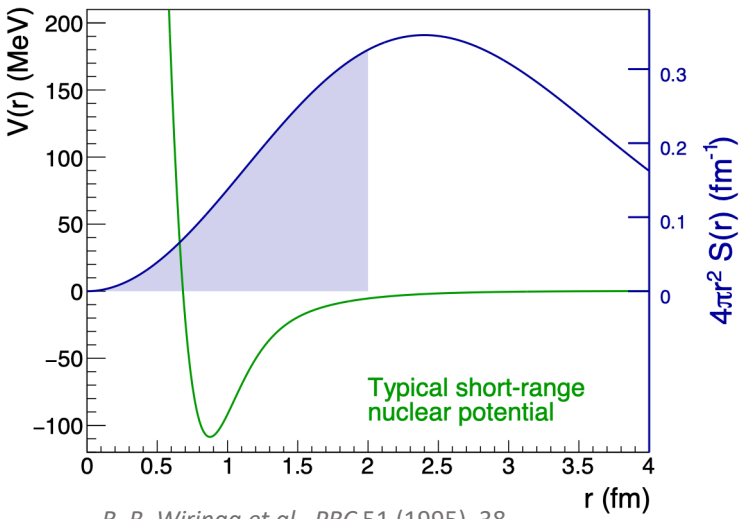
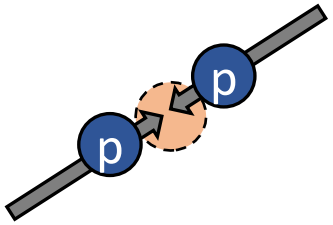


Source function



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



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., arXiv:2606.28098

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p-p correlation function

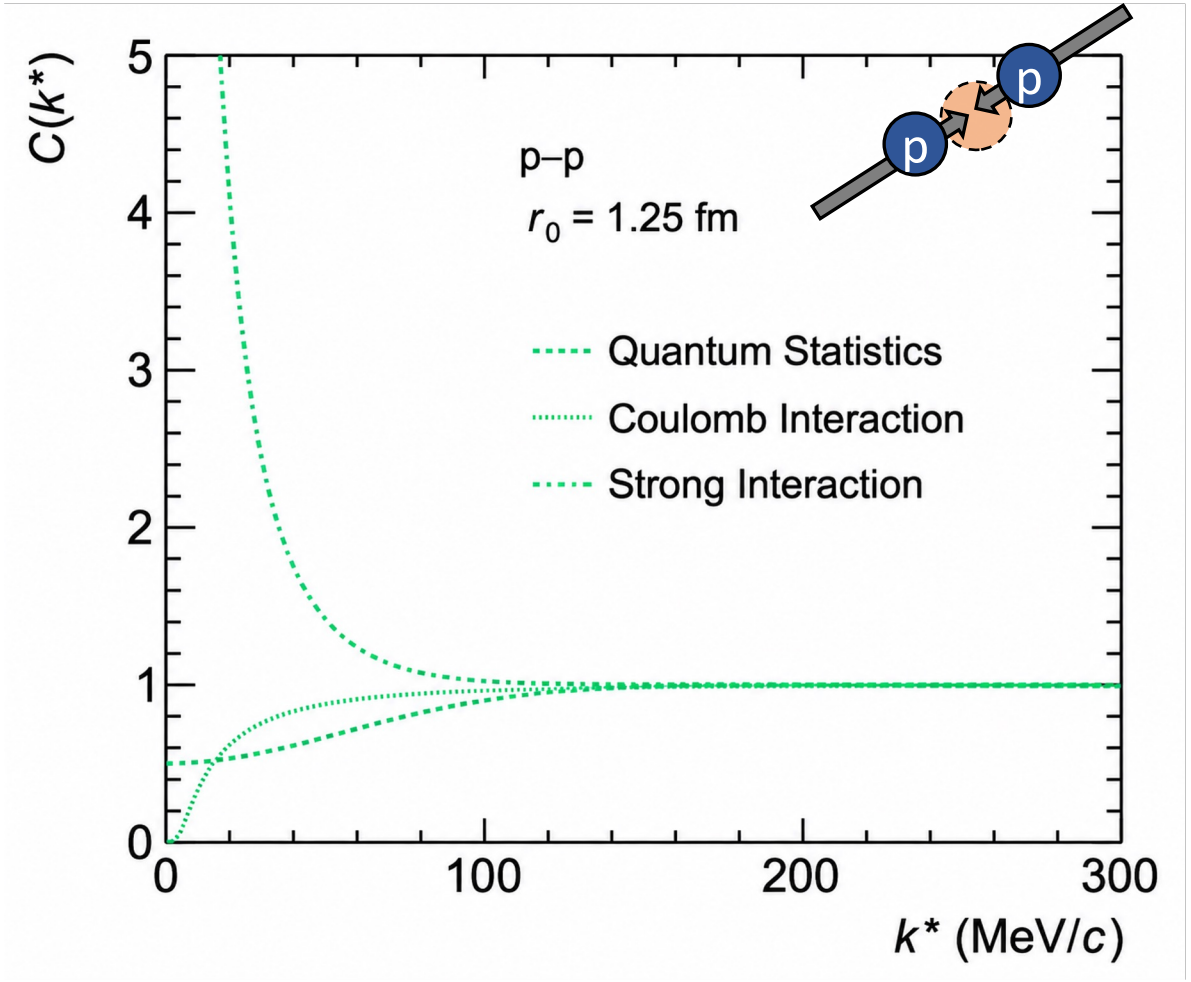
Correlation signal originates from the combination of three distinct effects:

Repulsive contributions

1. Quantum statistics (Fermi-Dirac)
2. Coulomb interaction

Attractive contributions

3. Strong interaction



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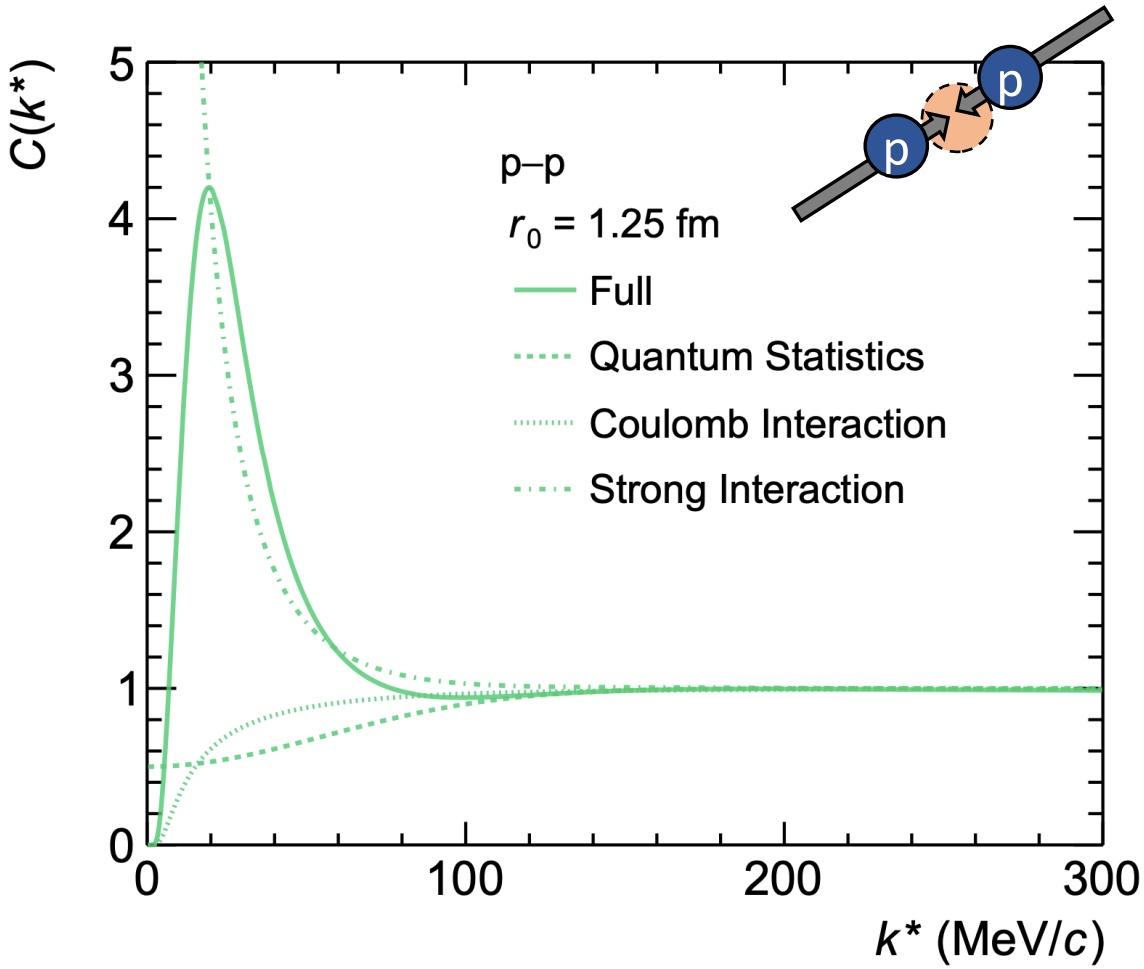
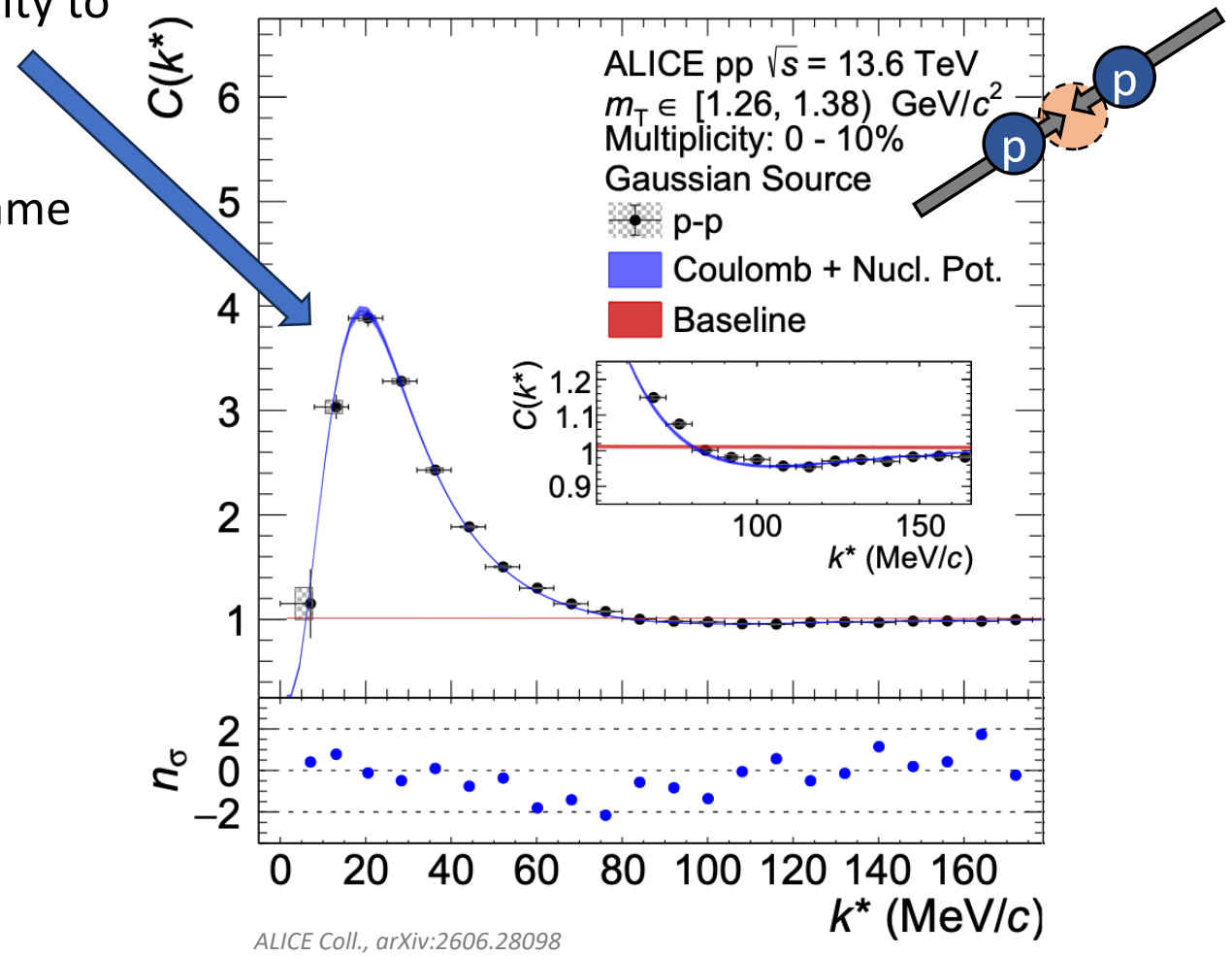
Full correlation function exhibits a pronounced peak at low relative momenta



p-p correlation function

- Low-energy peak visible in the data, sensitivity to the strong interaction
- Agreement with the theory
  - ➢ p-p correlation function captures the same dynamics of scattering data

M. Göbel, A. Kievsky, Phys. Lett. B 869 (2025) 139835



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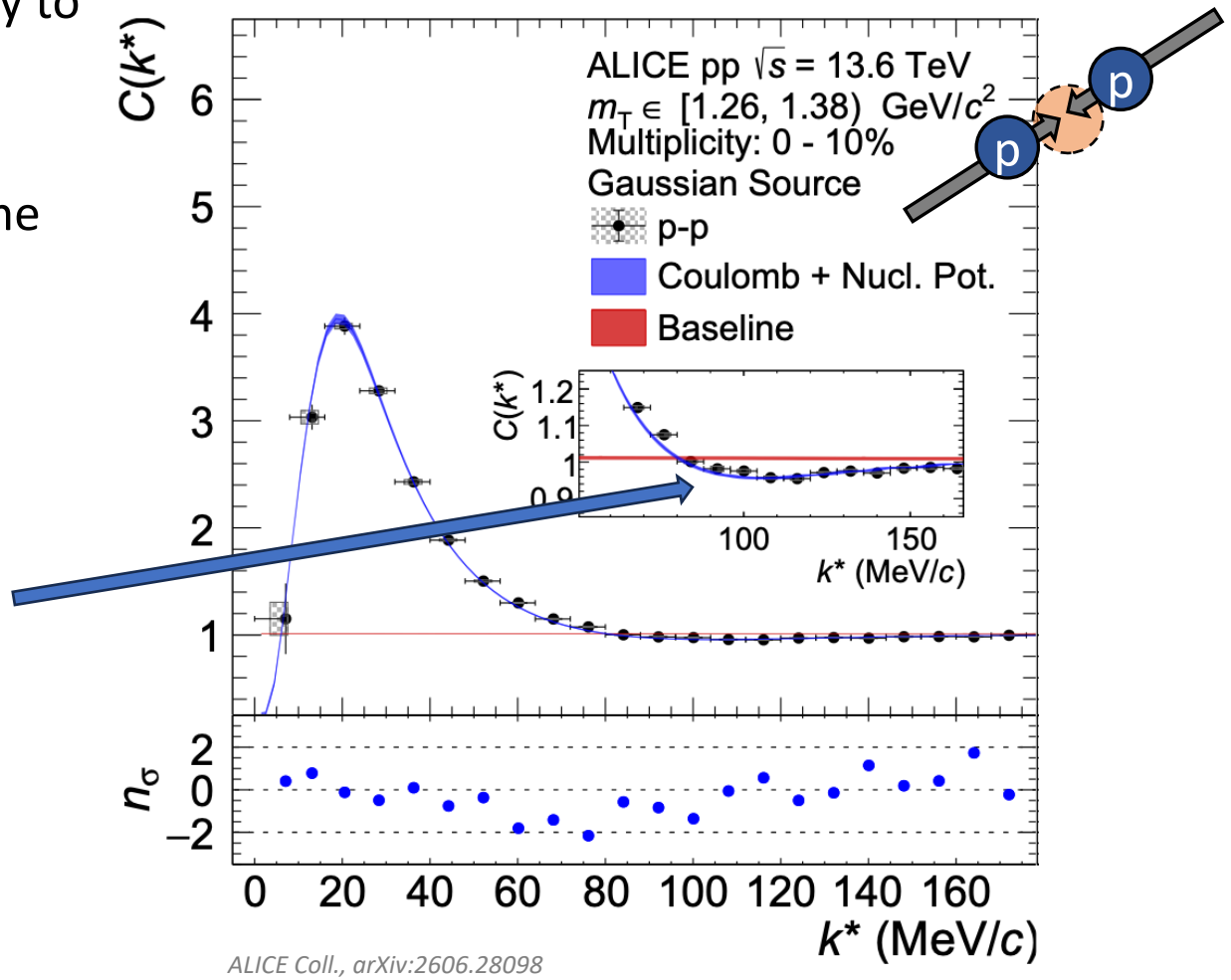
- At high *k** convergence to unity from below (repulsive long-range Coulomb interaction)



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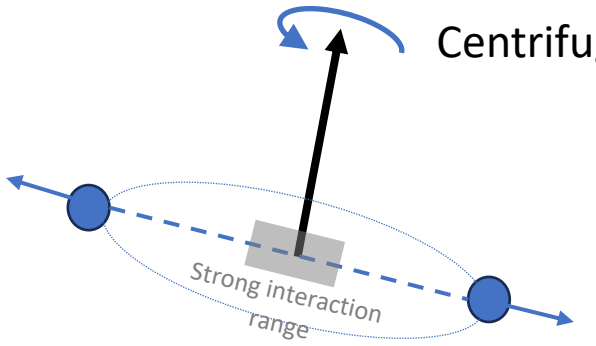
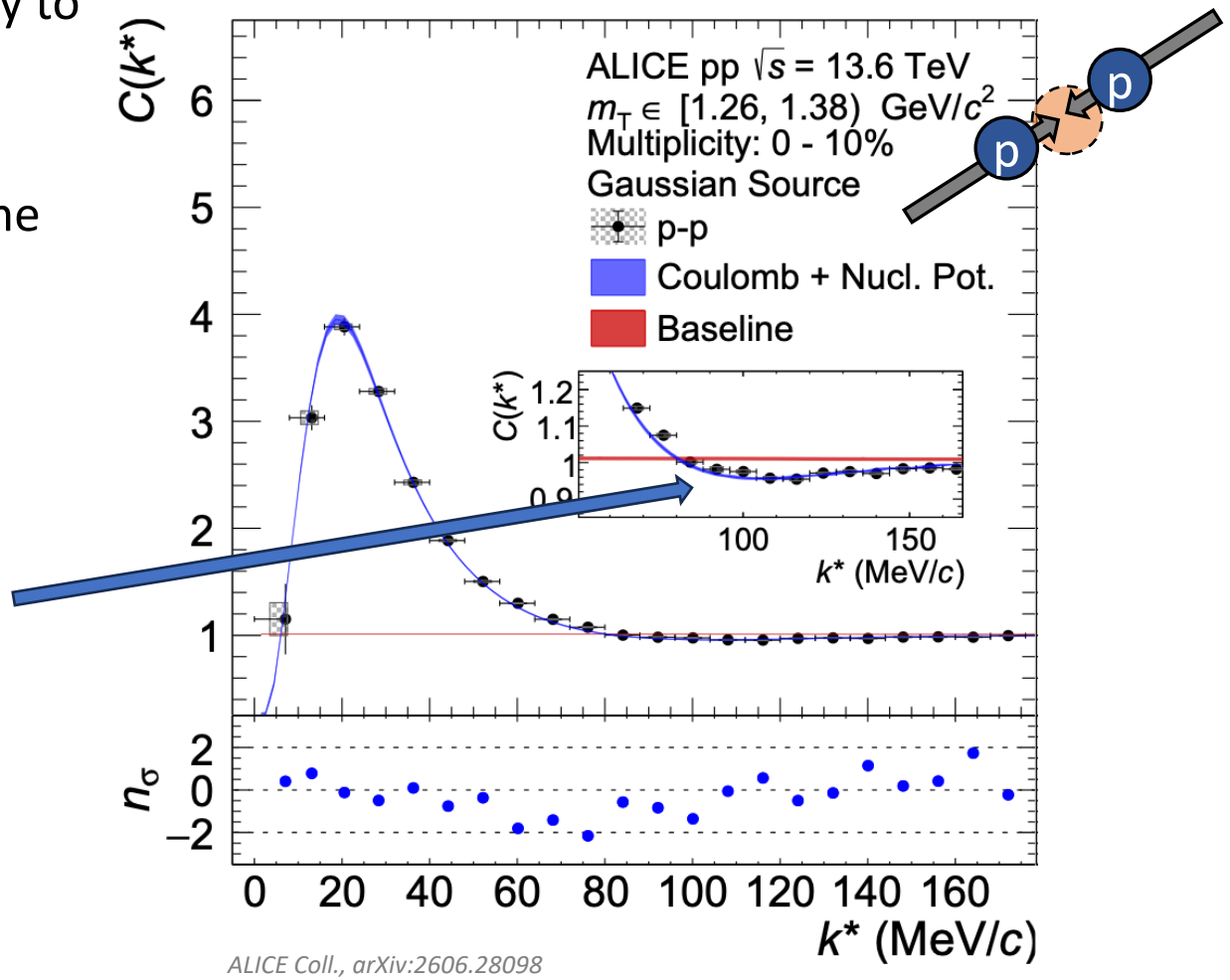
M. Göbel, A. Kievsky, Phys. Lett. B 869 (2025) 139835

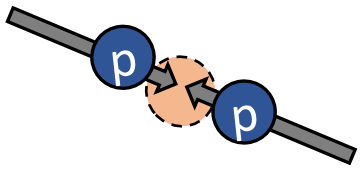
- Centrifugal barrier brings protons out of the short-range interacting region
  - ➢ **Only long-range Coulomb repulsion**



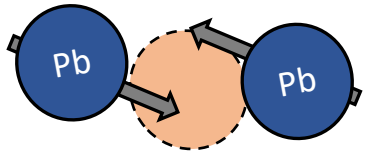


ALICE Coll., arXiv:2606.28098

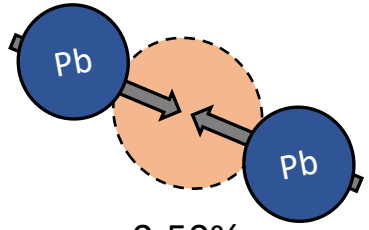
Small and large colliding systems at LHC: from pp to Pb-Pb



Peripheral



Central & semi-central



Gaussian source size (fm)

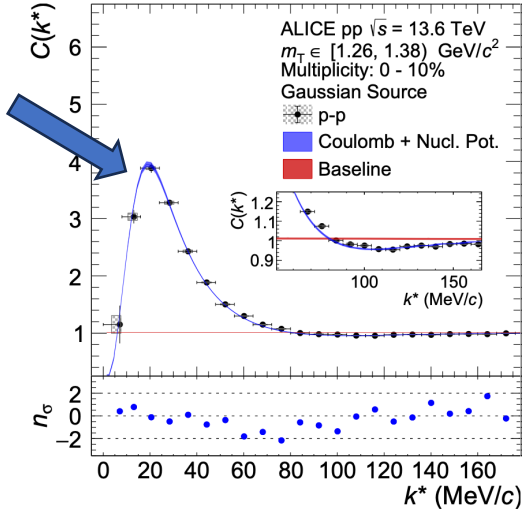
70-90%

0-50%

1-1.2 | 1.8-2.5 | 4-10

p-p correlation function

More pronounced



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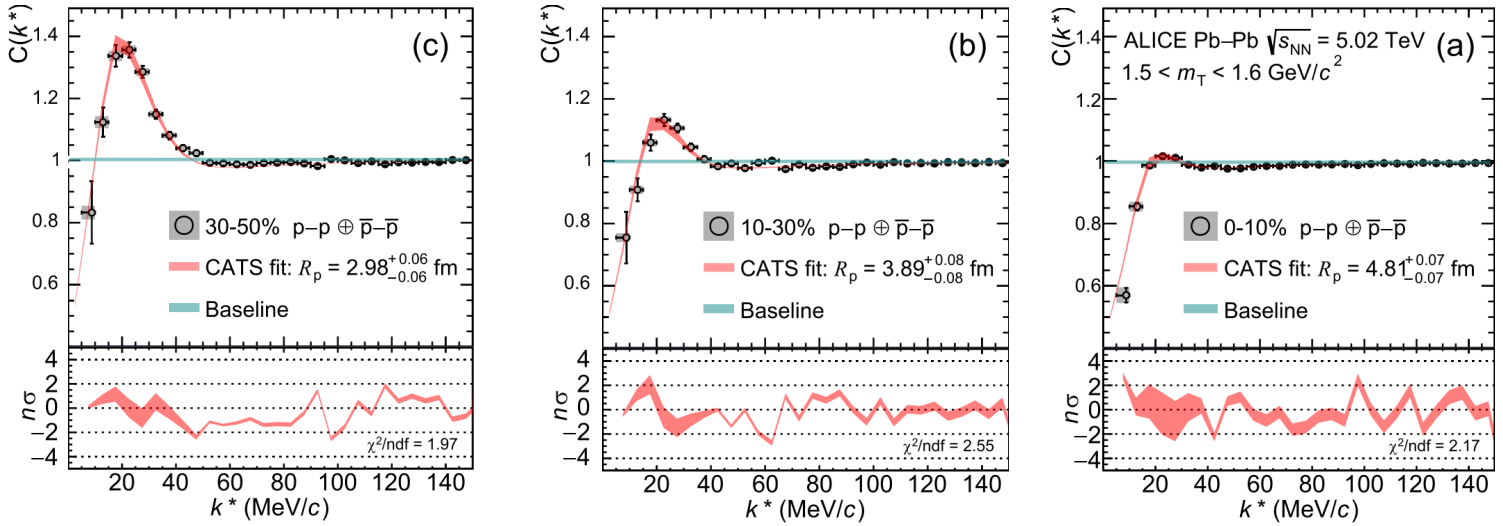


ALICE Coll. Phys.Lett.B 871 (2025) 139921

Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

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

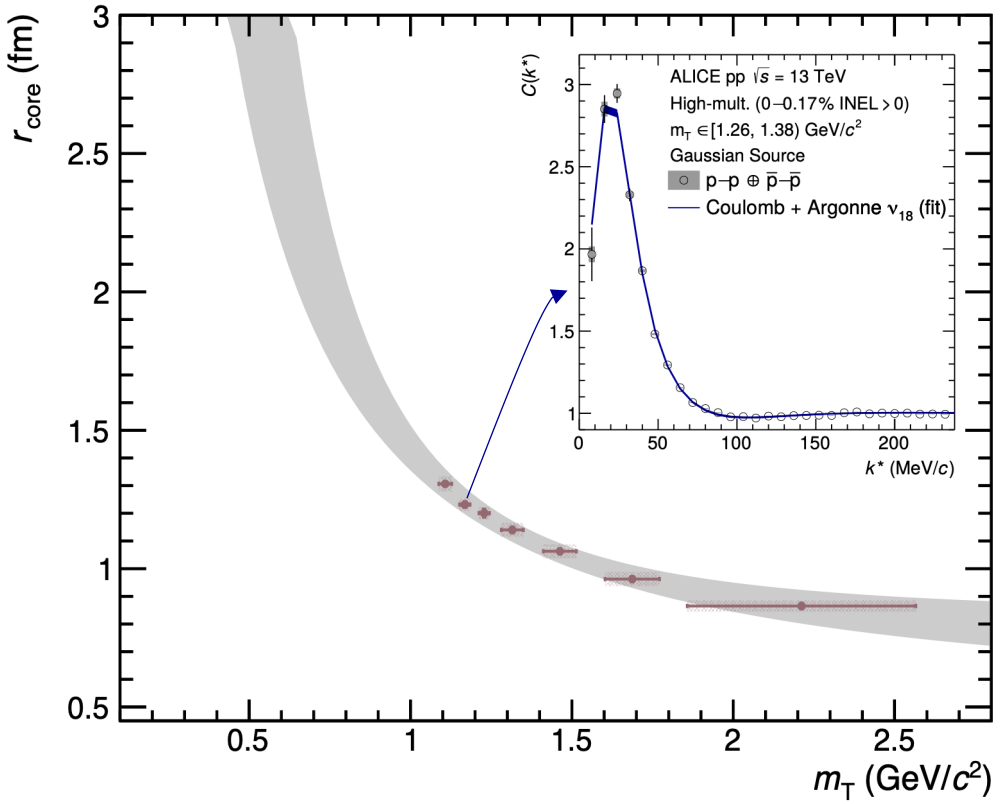
measured — known interaction

- 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



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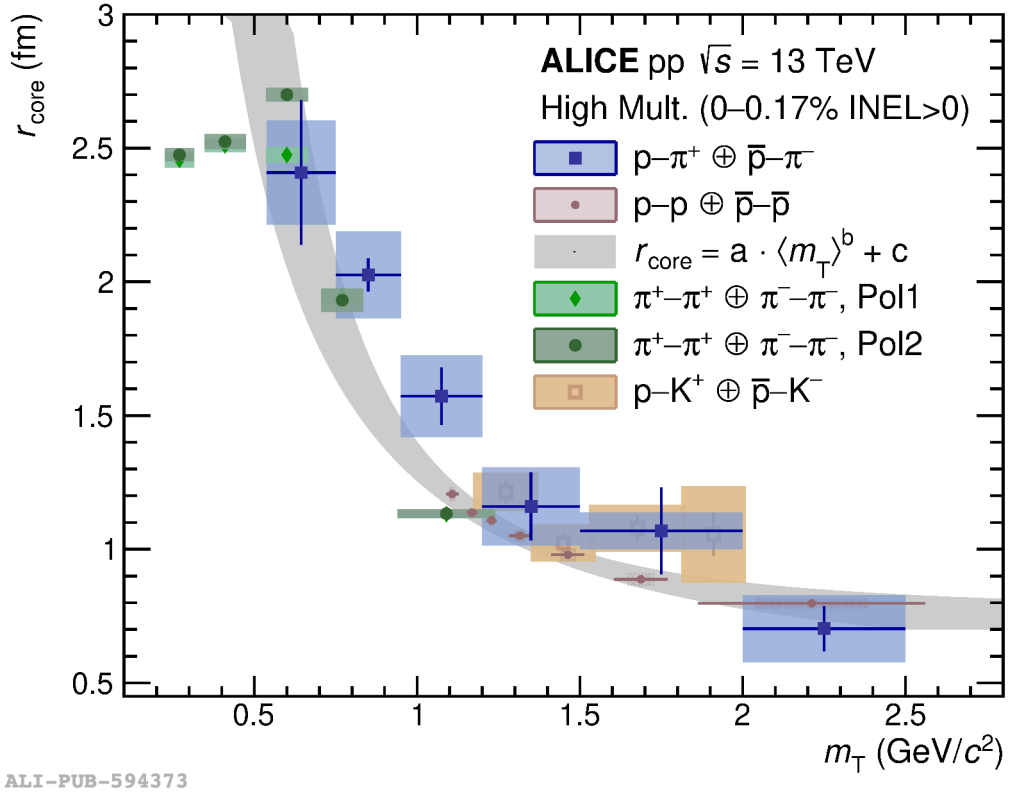
ALICE Coll., PLB, 811 (2020), 135849

- One common 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

ALICE detector

Excellent tracking and particle identification (PID) capabilities

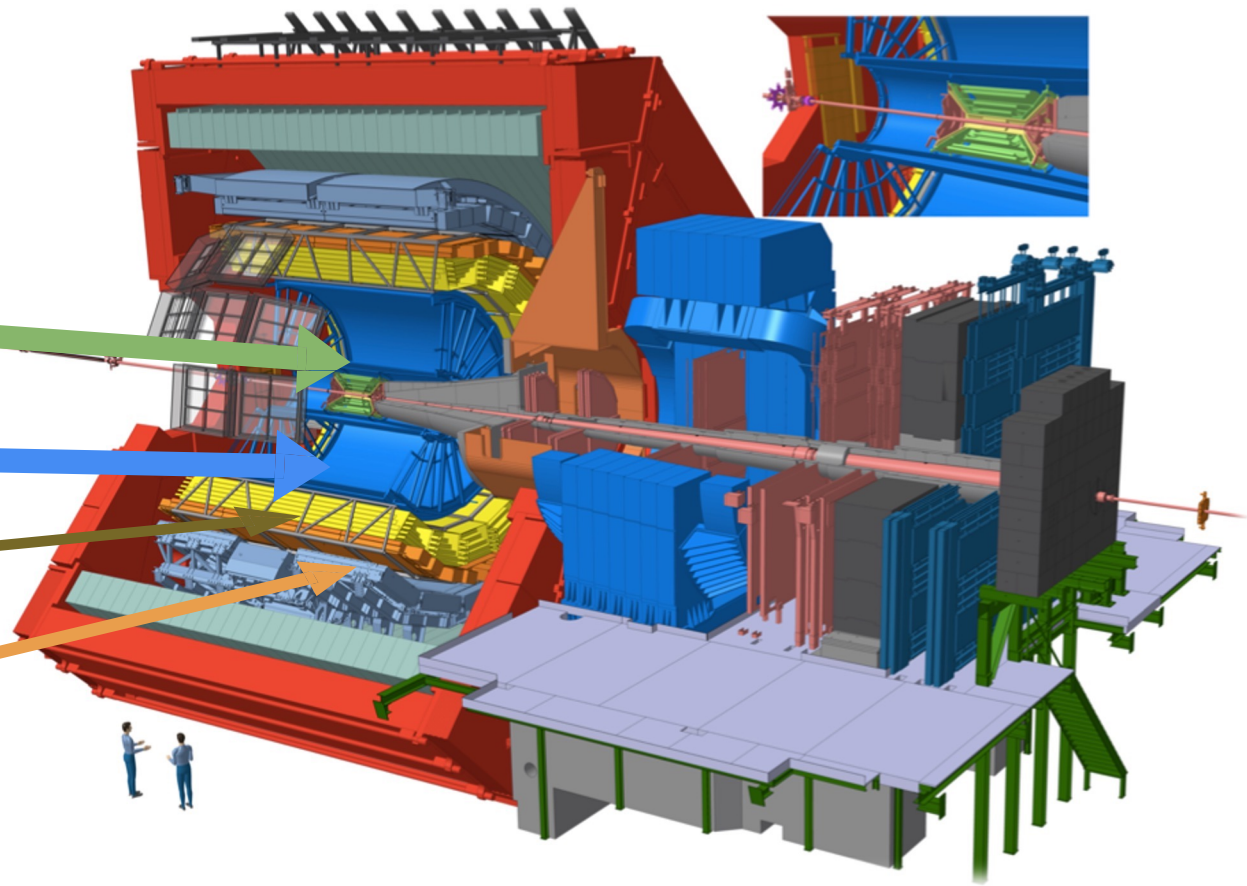
- Run 2 data: 2015 – 2018
- Run 3 data: 2022 – 2026

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

Time Projector Chamber
Tracking, PID (dE/dx)

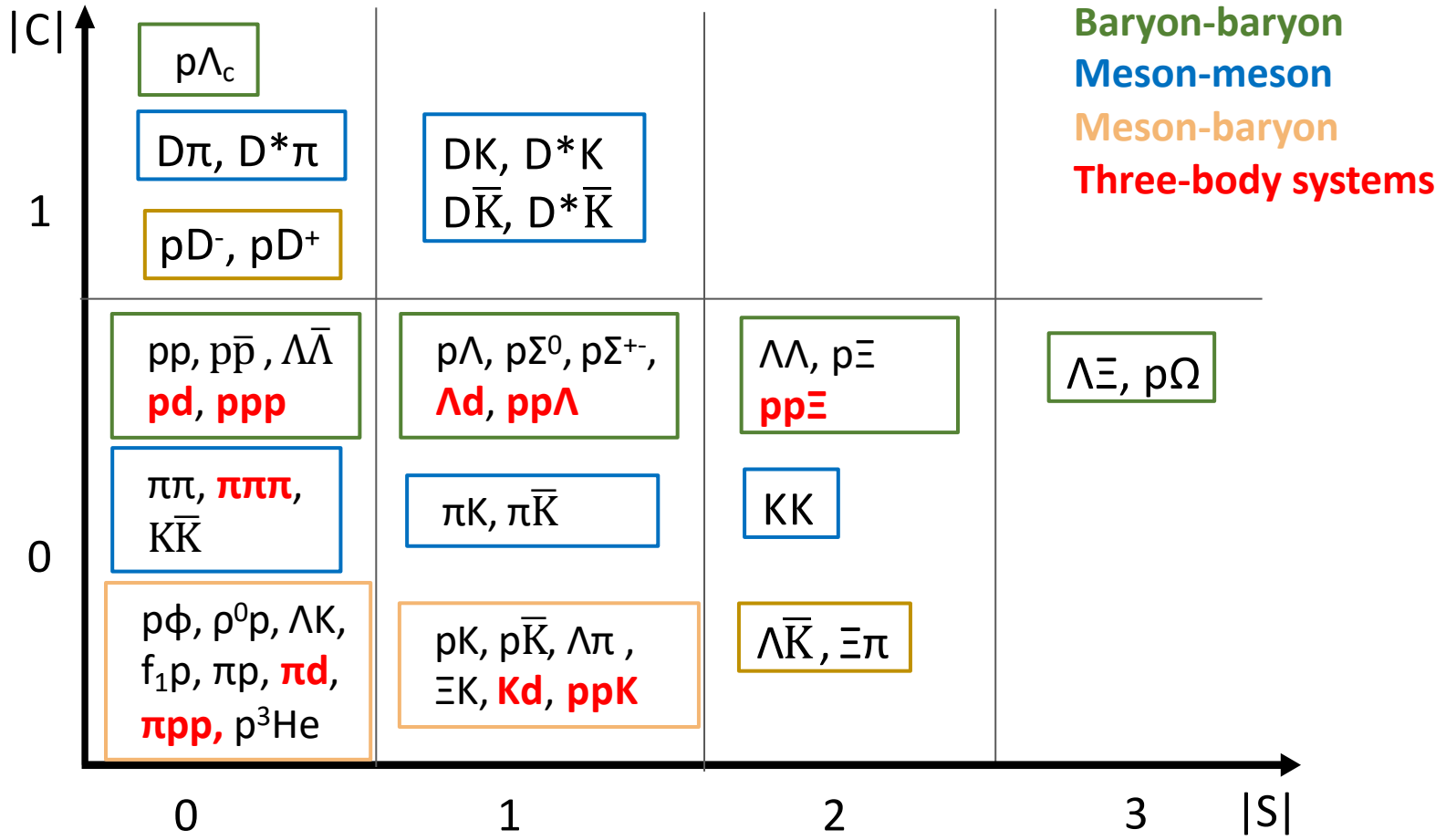
Transition Radiation Detector

Time Of Flight detector
PID (TOF measurement)



Femtoscopy measurements at the LHC

Credits: V. Mantovani Sarti



ALICE Collaboration:

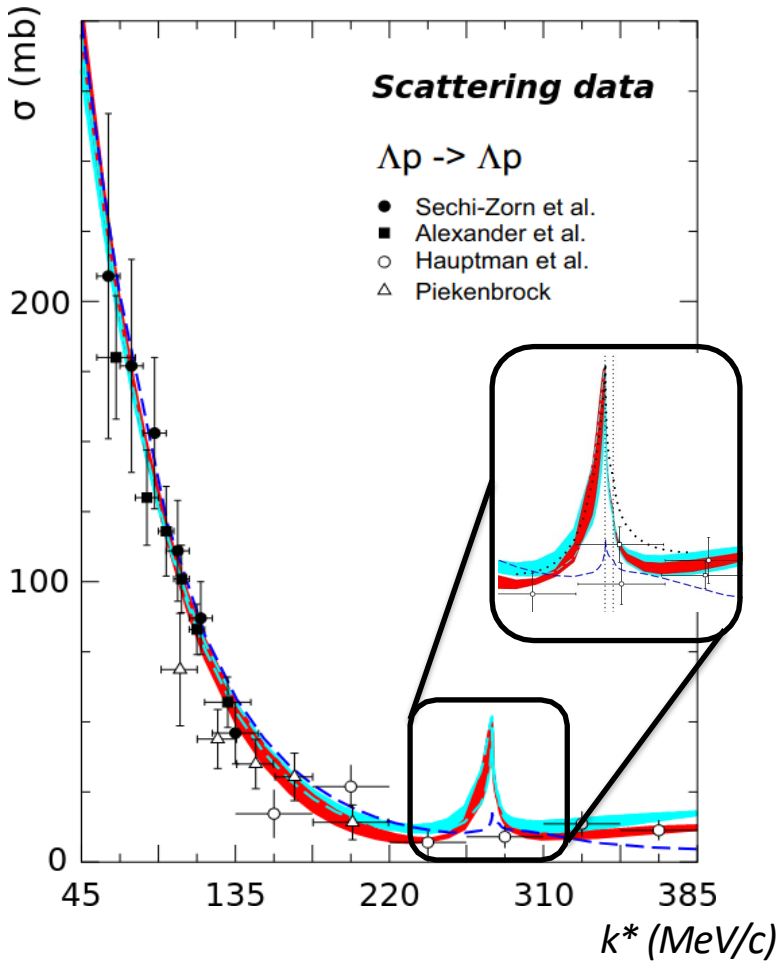
PRC 99 (2019) 2, 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 09230
PLB 805 (2020) 135419
PLB 811 (2020) 135849
Nature 588 (2020) 232-238
PRL 127 (2021), 172301
PLB 822 (2021), 136708
PRC 103 (2021) 5, 055201
PLB 833 (2022), 137272
PLB 829 (2022), 137060
PRD 106 (2022), 5, 05201
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

- Hyperons are much more challenging to study
  → they must be produced first
  → short lifetimes limits the beam luminosity

Λ	→	$p + \pi^-$	$c\tau \approx 7.8$ cm
Σ	→	$N + \pi$	$c\tau \approx 2.4 - 4.4$ cm
Ξ	→	$N + \pi$	$c\tau \approx 4.9 - 8.7$ cm
Σ^0	→	$\Lambda + \gamma$	$c\tau \approx 2.2 \times 10^{-9}$ cm

- Scattering data suffers severe limitations:
  - does not reach $k^*=0$
  - does not resolve the ΣN cusp
  - large uncertainties

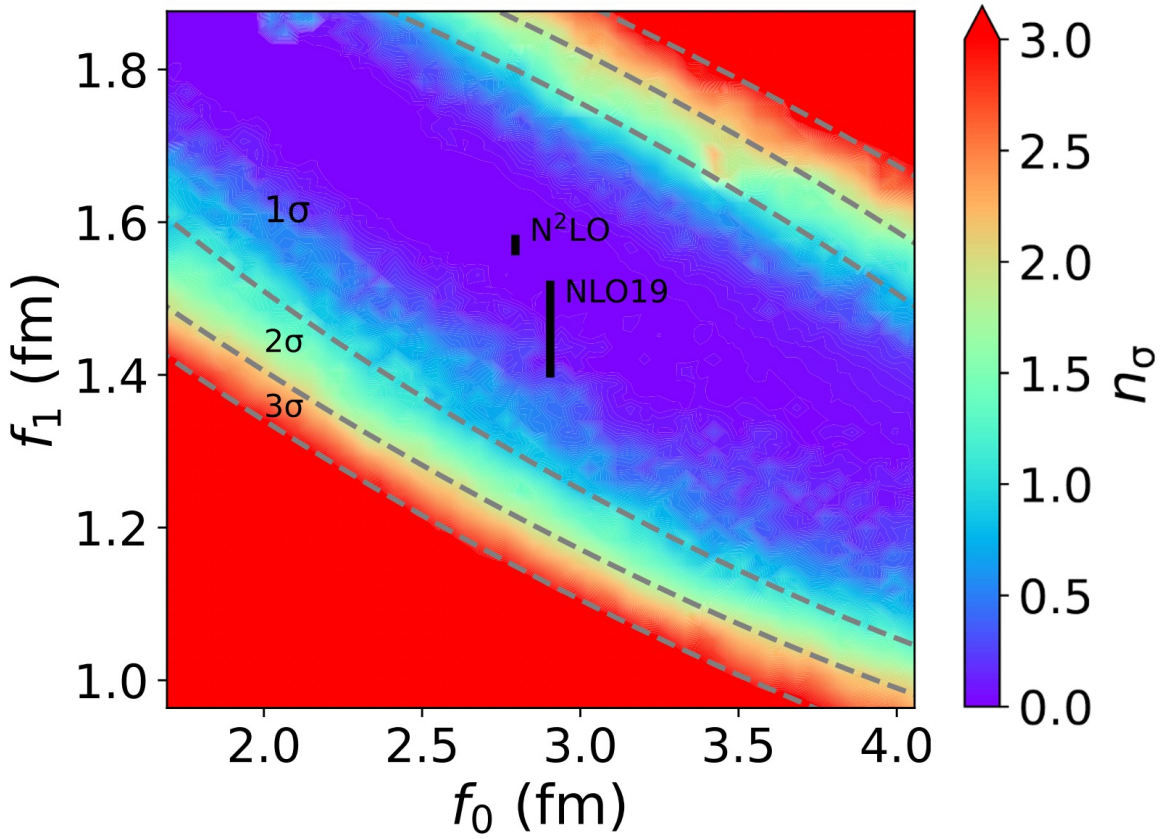


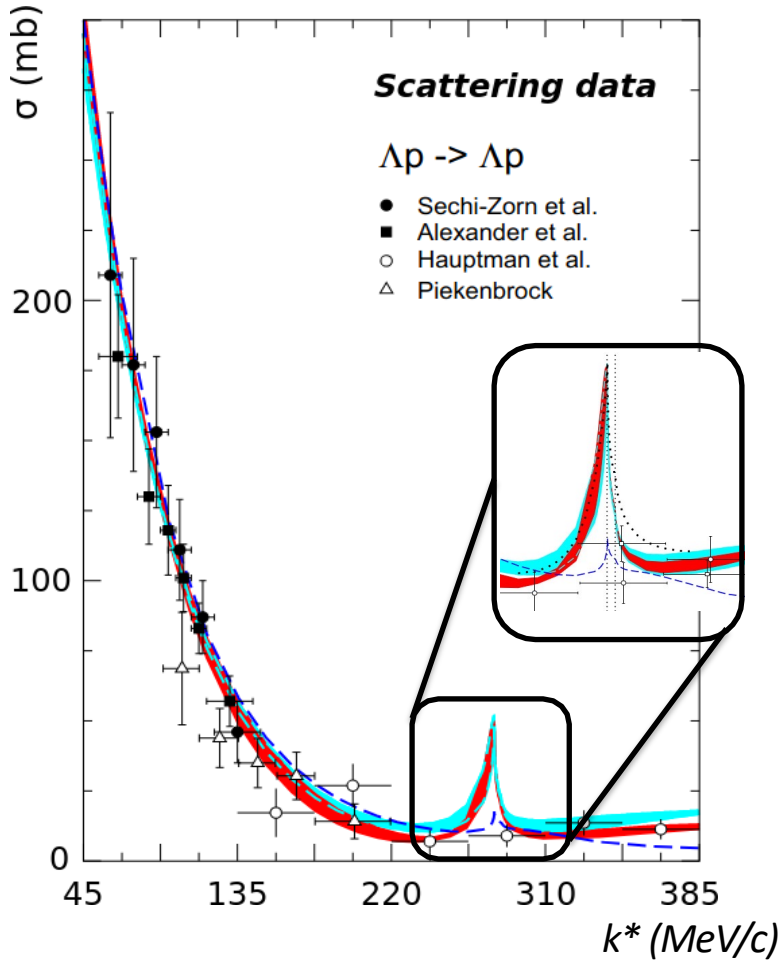
NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

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

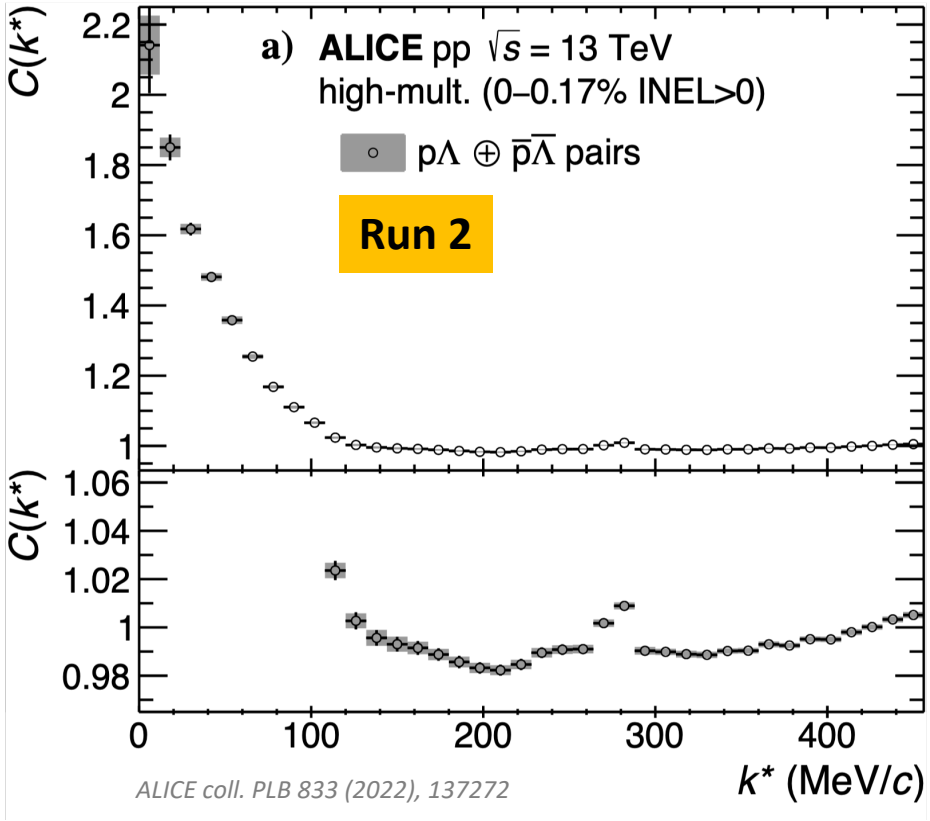




NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

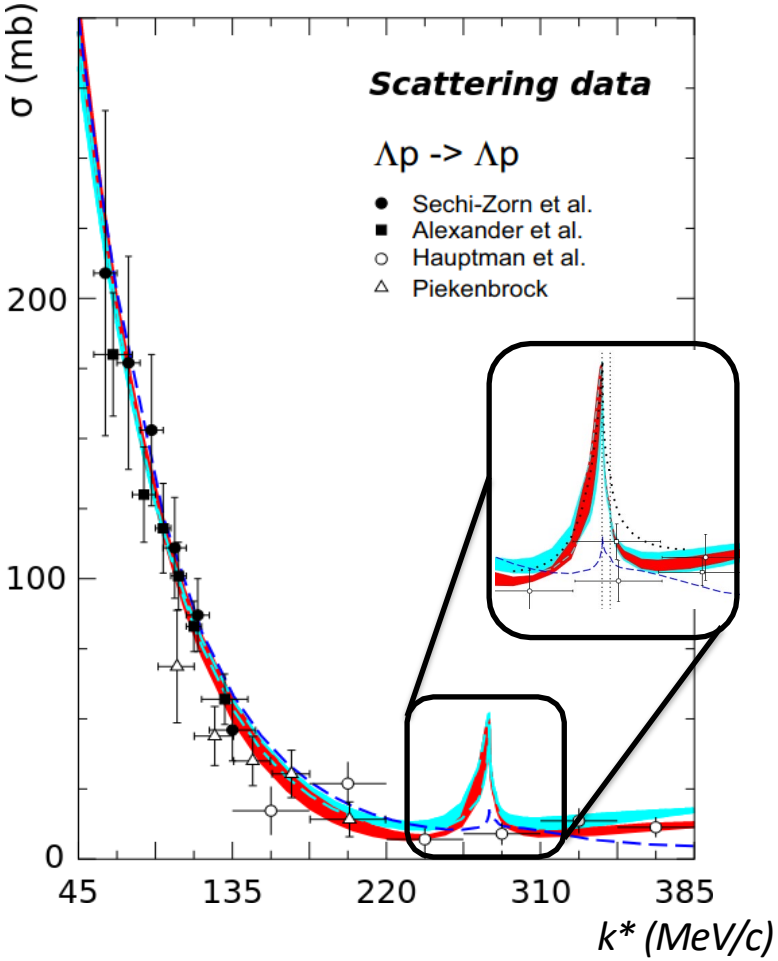
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

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



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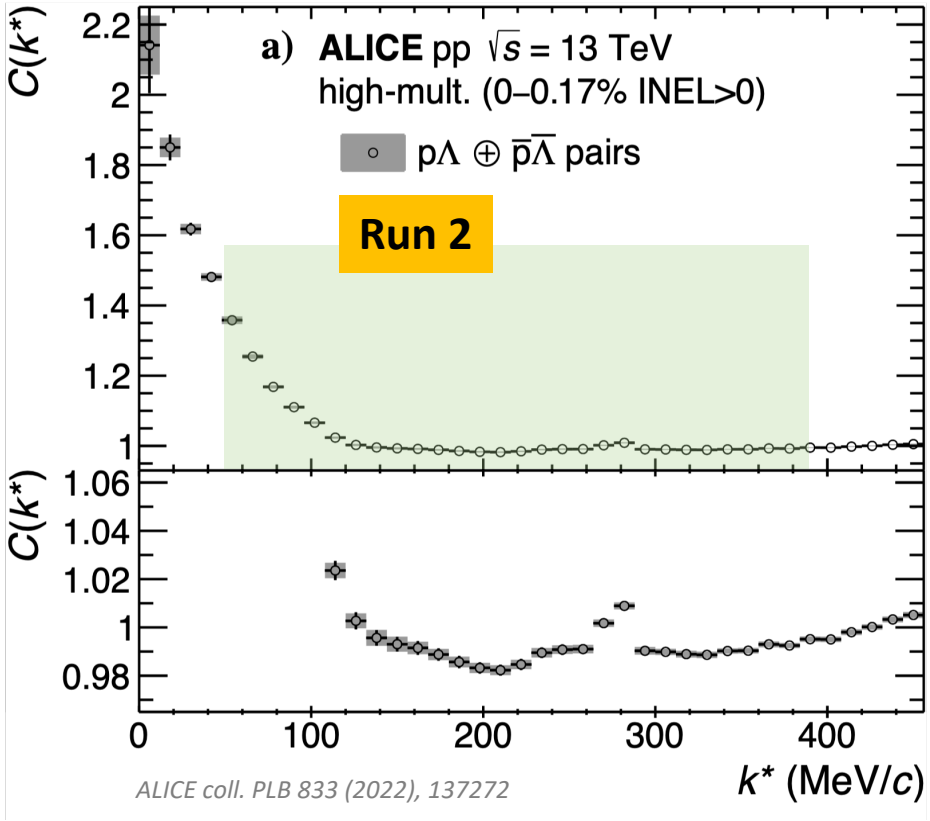

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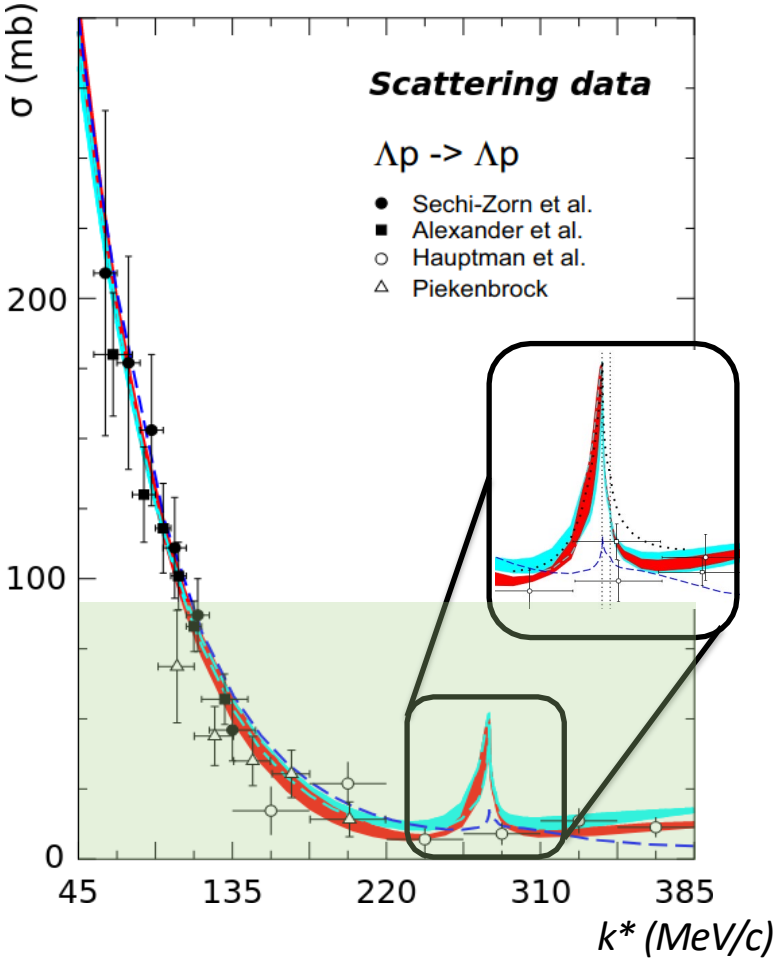


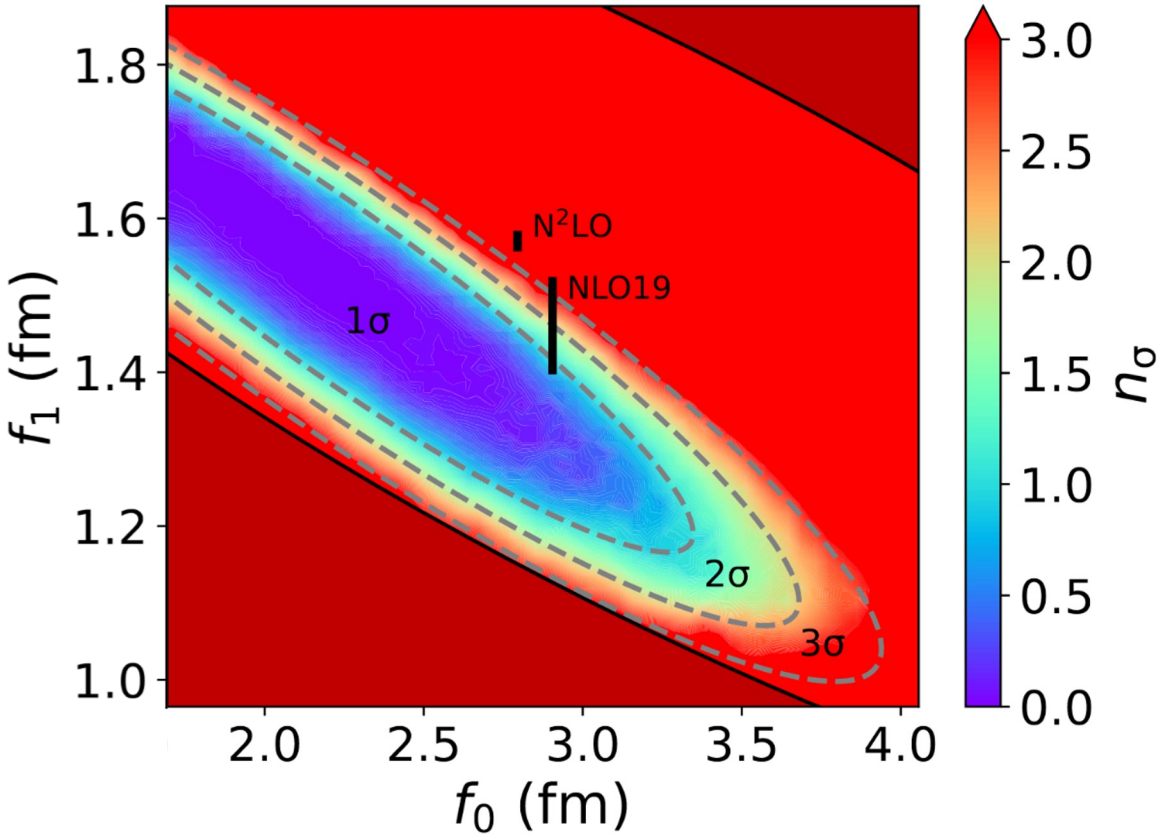
NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

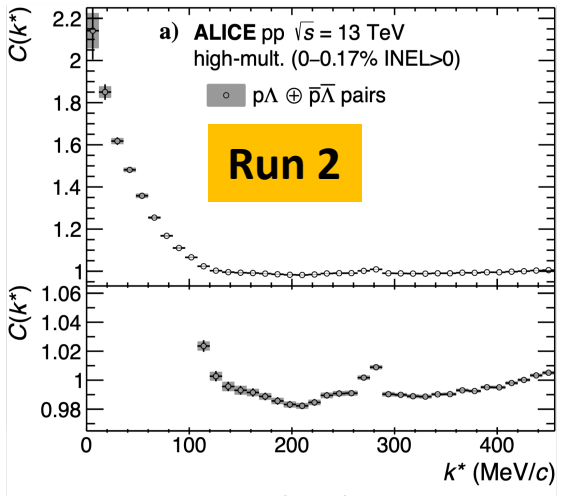
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

The pΛ interaction in the femtoscopy era

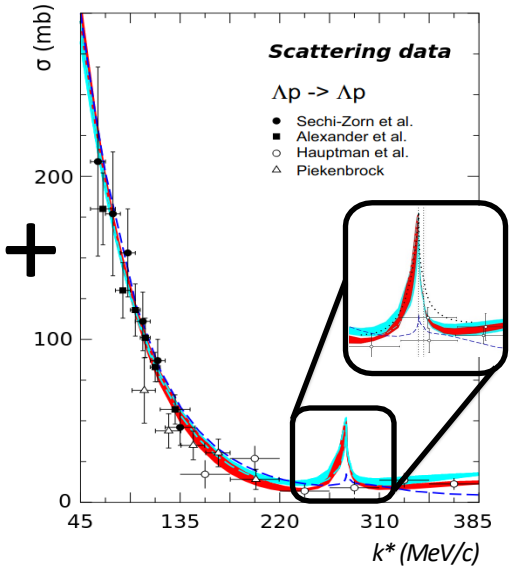
- Combined analysis of femtoscopic and scattering data

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





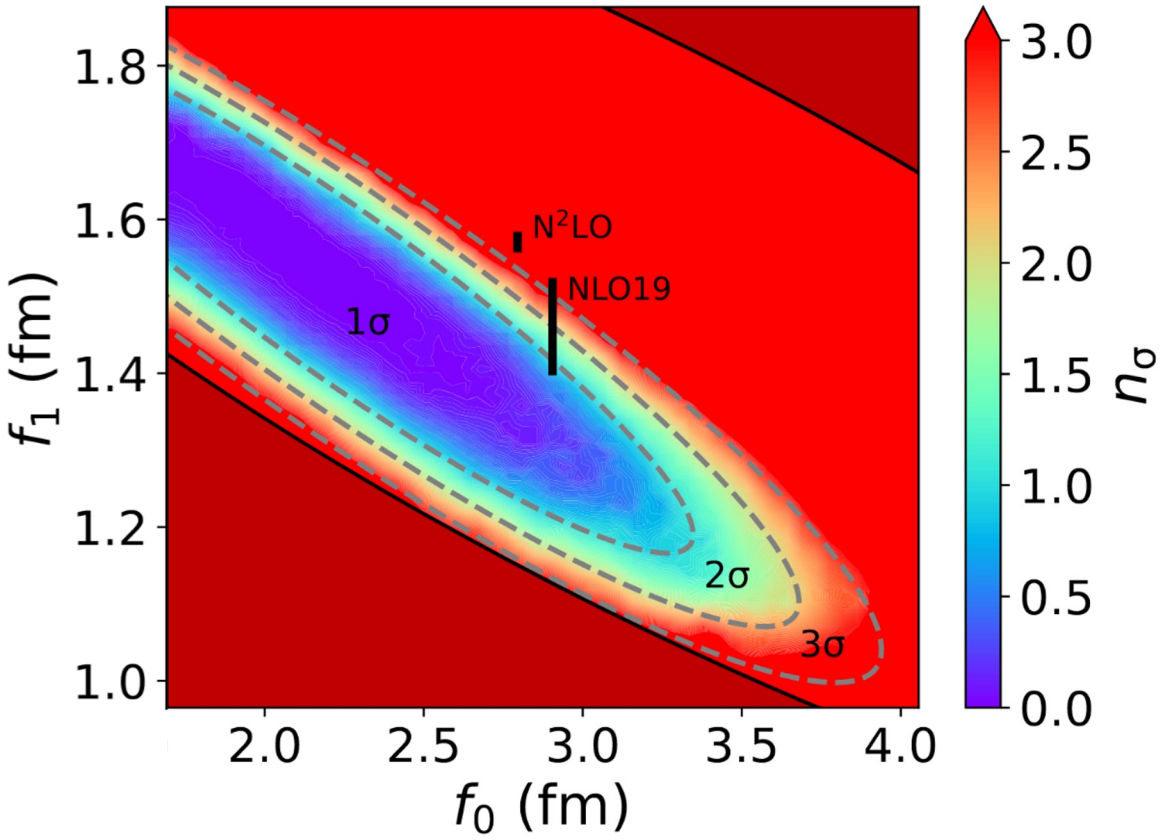
ALICE coll. PLB 833 (2022), 137272



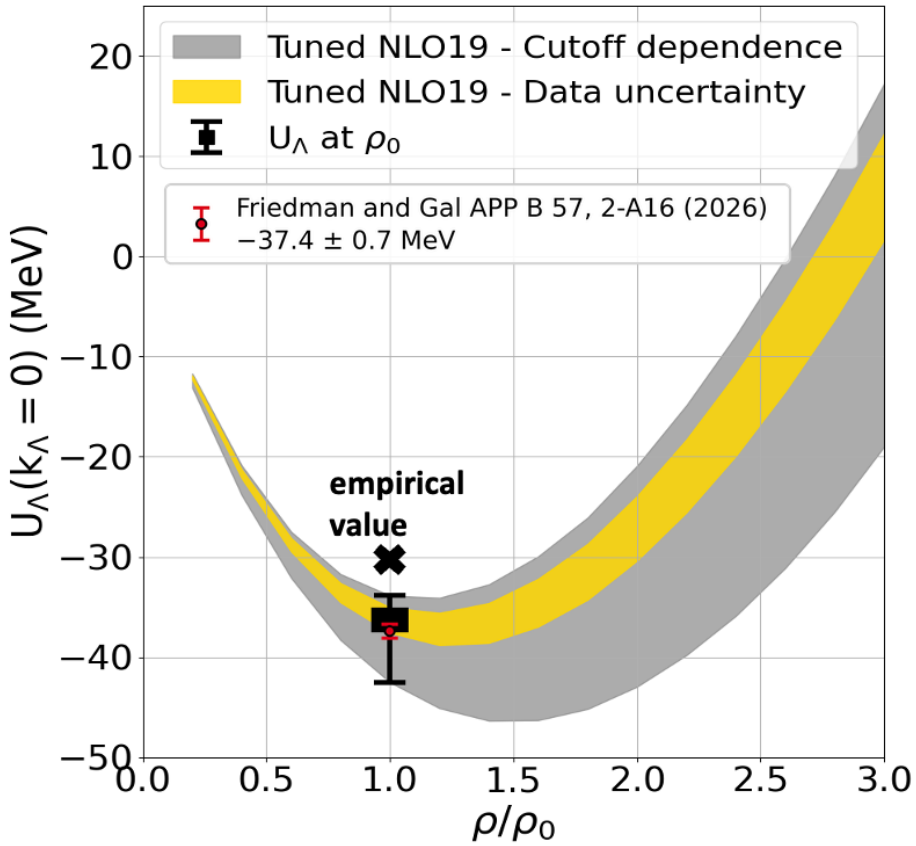
The pΛ interaction in the femtoscopy era

- 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



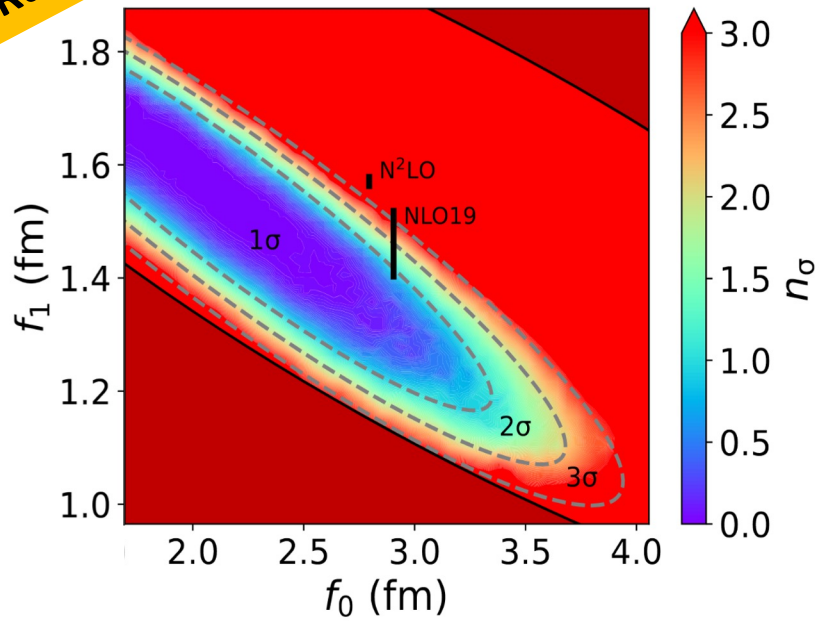
D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550

Selected results with strange hadrons

- Most precise measurement of the p-Λ scattering parameters

Run 2

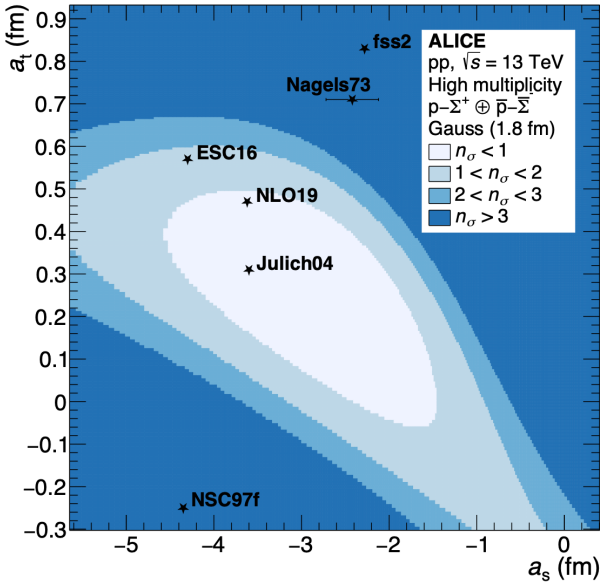
Scattering + femtoscopy



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

- First measurement of the p-Σ⁺ scattering parameters

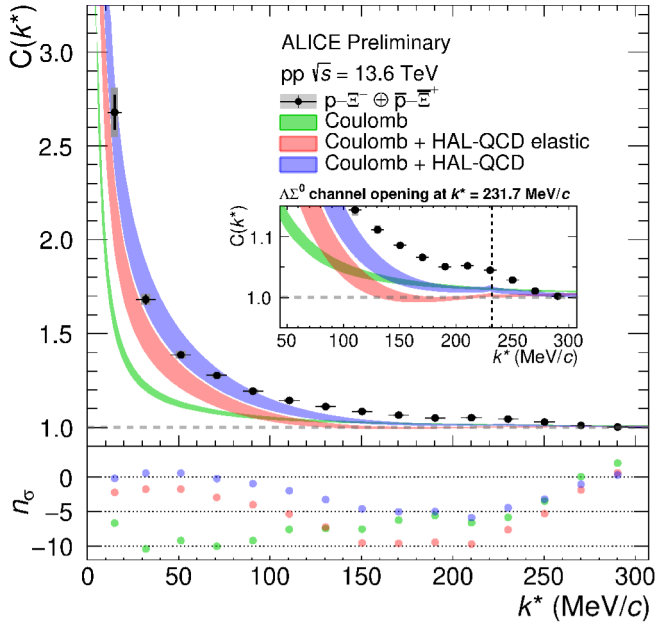
Run 2



ALICE Coll., PLB 874 (2026) 140252

- Evidence of an attractive p-Ξ⁻ interaction

Run 3



ALI-PREL-624087

New precise experimental inputs for EFTs

Test of Lattice QCD

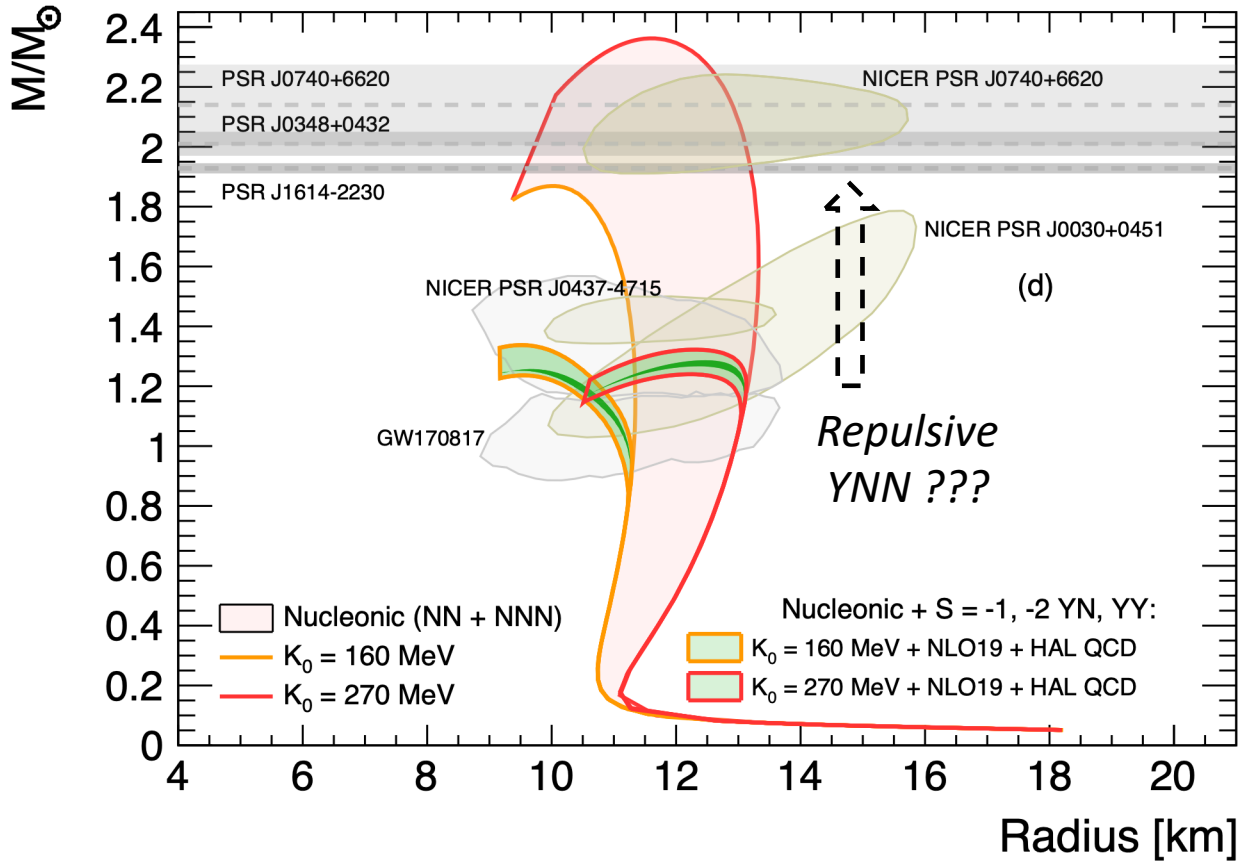
Strangeness in neutron stars

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

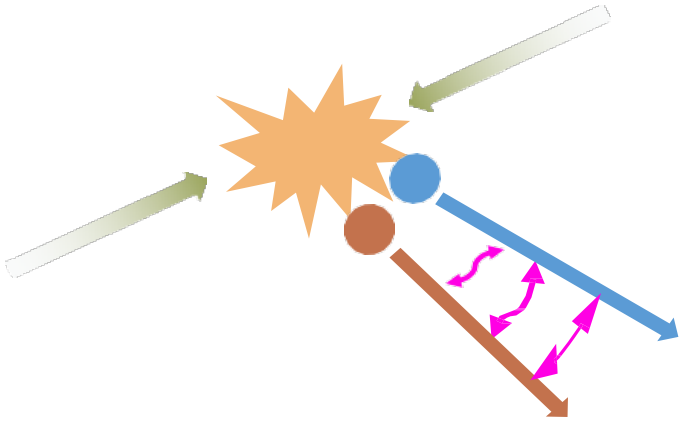
  I. Vidaña, V. Mantovani Sarti, J. Haidenbauer, D. Mihaylov, L. Fabbietti, EPJ.A 61 (2025) 3, 59

- Next step: inclusion of three body interaction involving hyperons

Can we provide precise information from femtoscopy measurements?



Femtoscopy: from two- to three-particle correlations

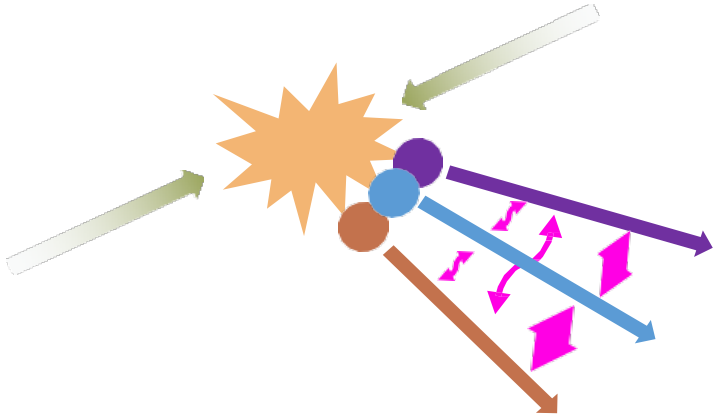


Two-particle correlations:

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

Scattering wave function

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

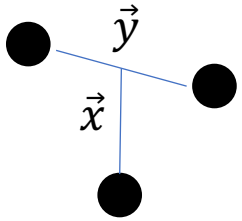


Three-particle correlations:

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

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)

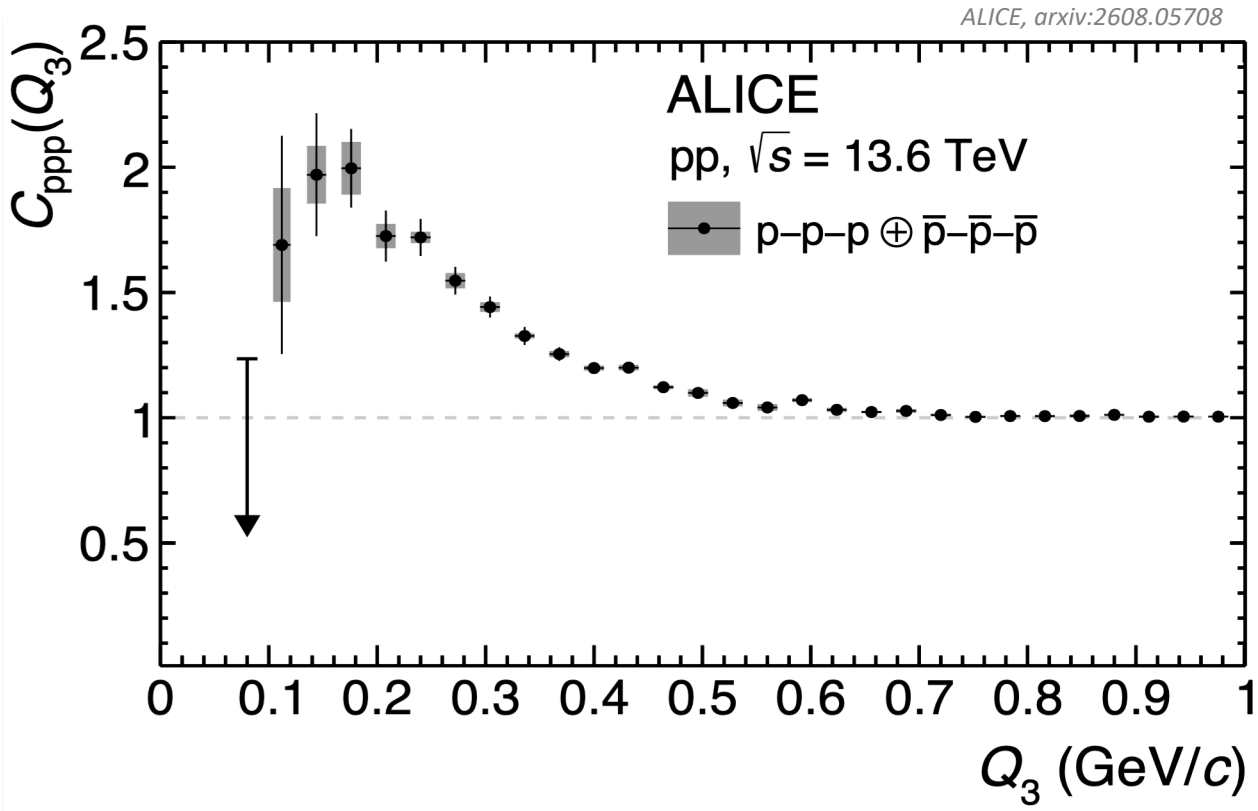
Hypermomentum

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

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

Genuine p-p-p correlation function

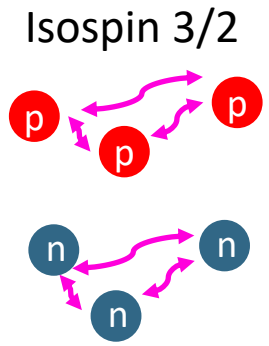
- Genuine correlation function obtained after correcting for all background channels



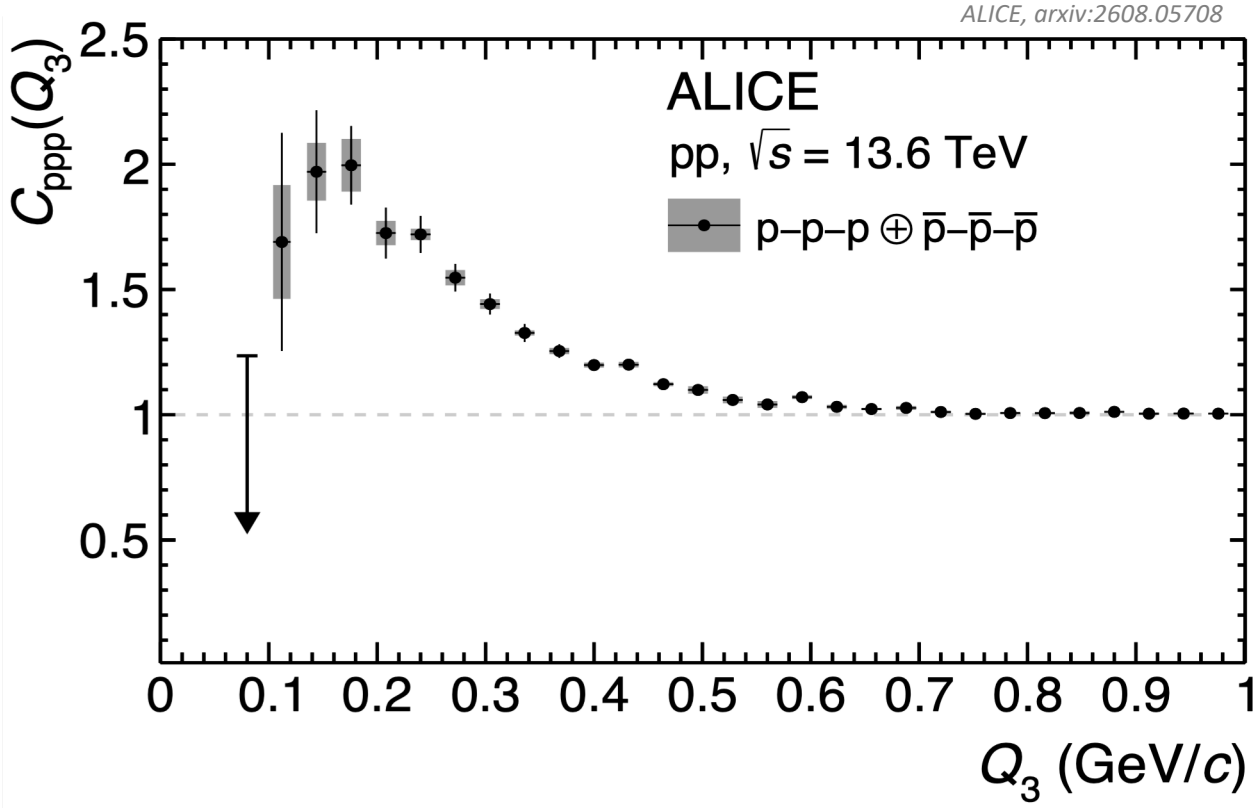
Genuine p-p-p correlation function

- Genuine correlation function obtained after correcting for all background channels
- **First direct measurement of Isospin 3/2 three-nucleon system**

Many-body systems with neutrons

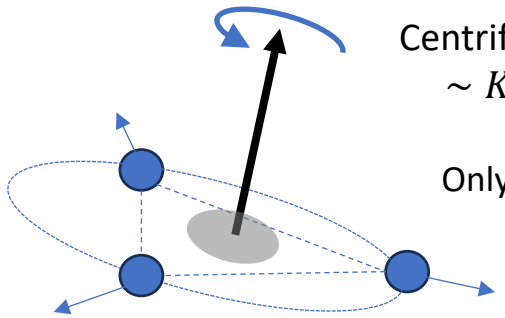


ALICE, arxiv:2608.05708



Genuine p-p-p correlation function

- Genuine correlation function obtained after correcting for all background channels
- **Inclusion of the strong interaction in the lower terms of the expansion $(K_{\max}= 2)$ indicates a repulsive-type convergence (from below 1).**
- Centrifugal barrier at high Q_3 should bring protons outside the range of the attractive strong interaction

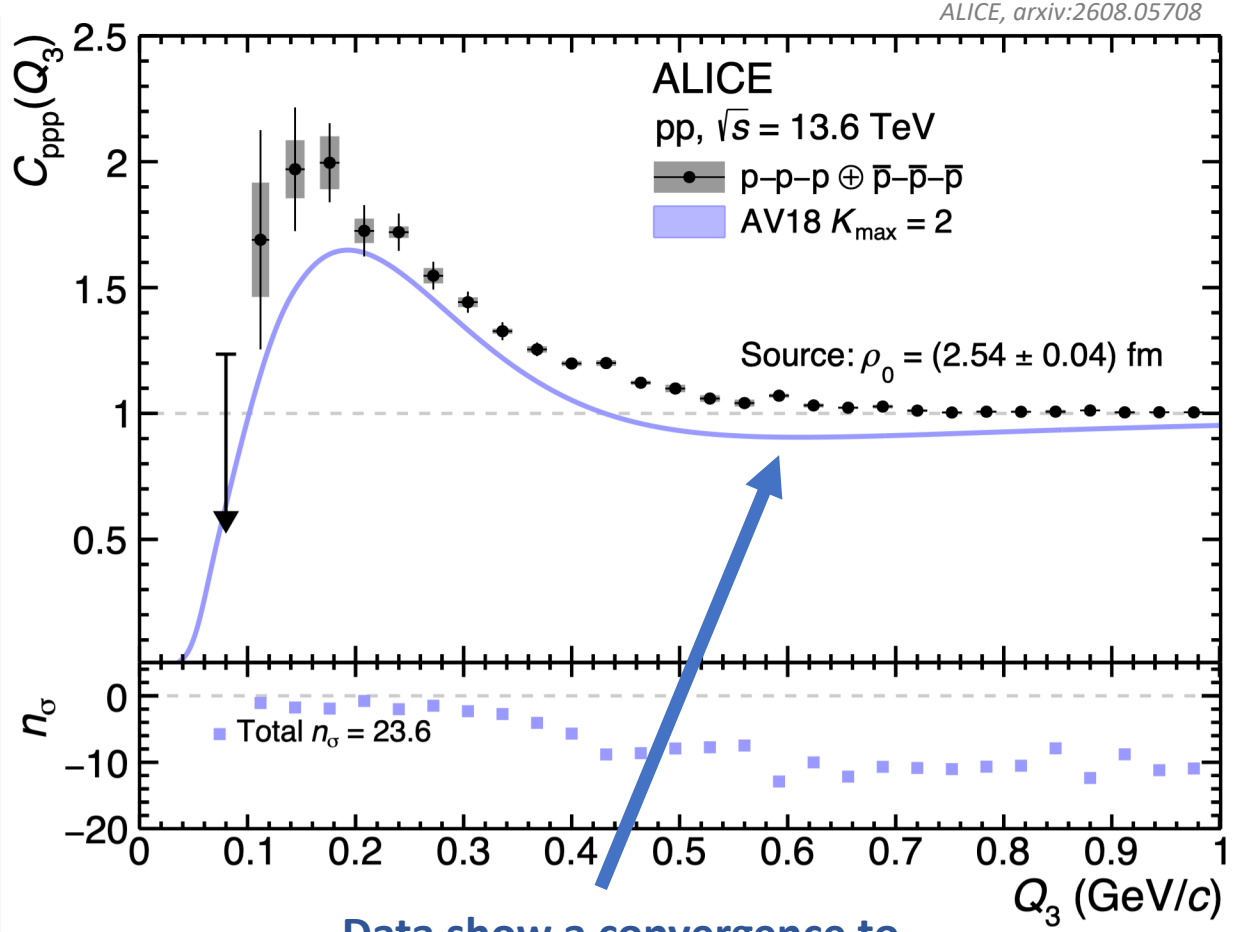


Strong interaction range

Centrifugal barrier
$\sim K\,(K+4)$

Only **long-range Coulomb repulsion**

ALICE, arxiv:2608.05708



Data show a convergence to unity from above unity!

Genuine p-p-p correlation function

- Genuine correlation function obtained after correcting for all background channels
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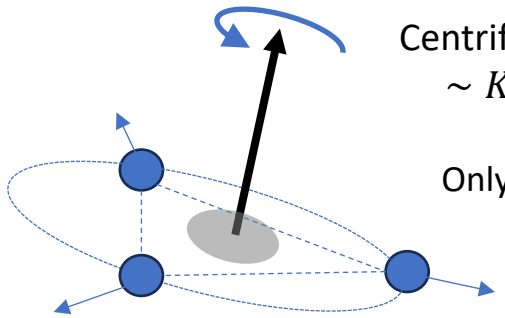

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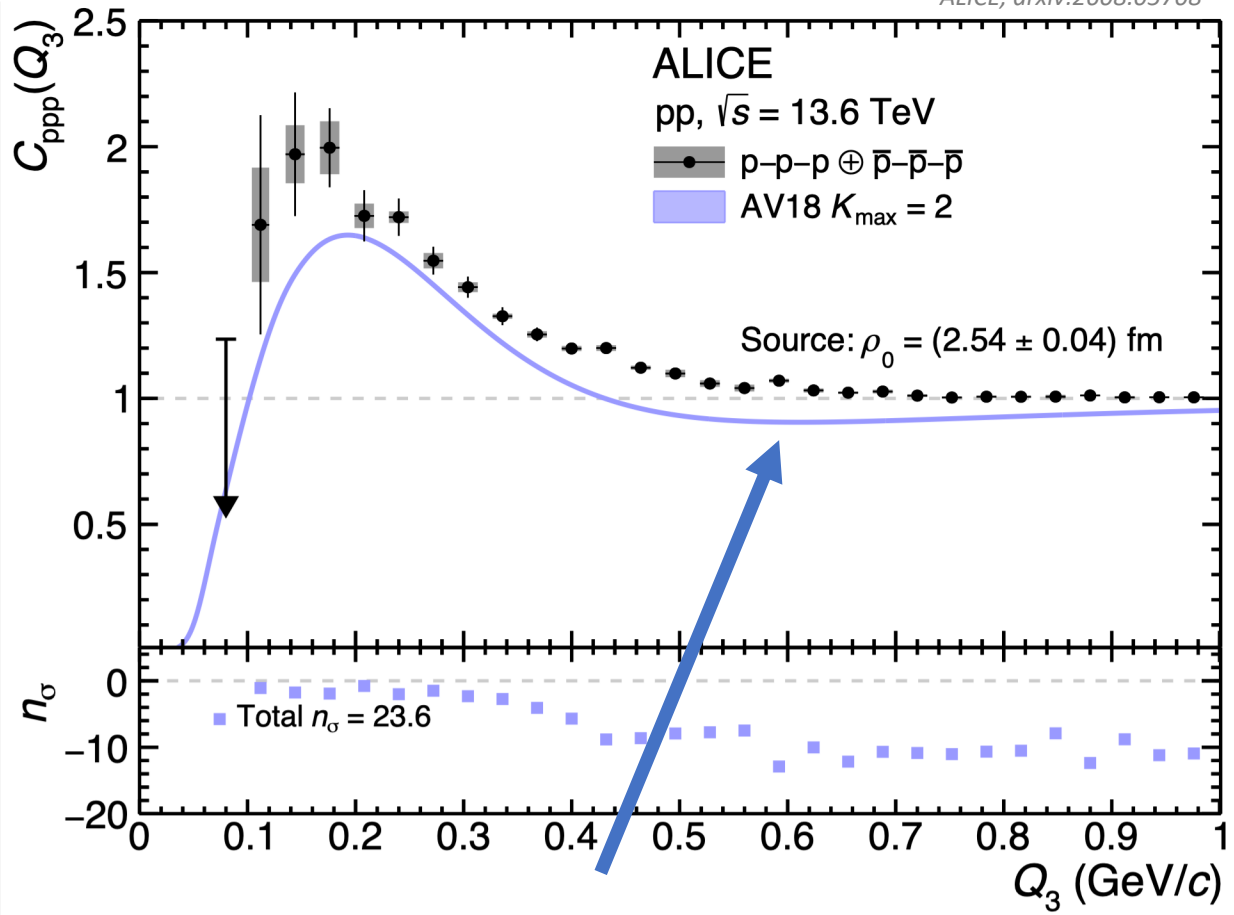
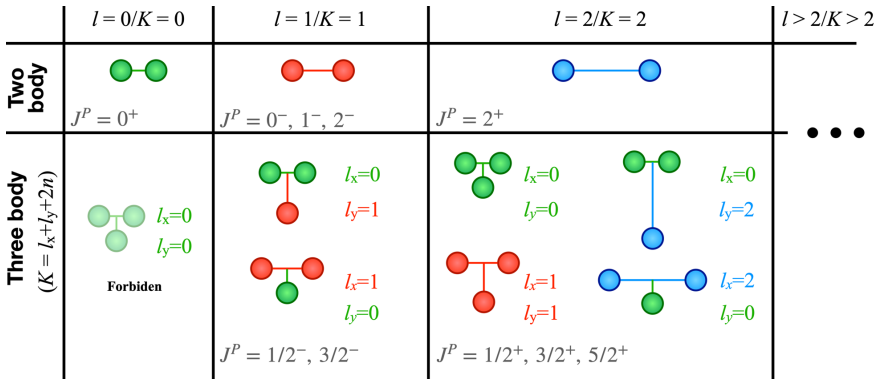
ALICE, arxiv:2608.05708



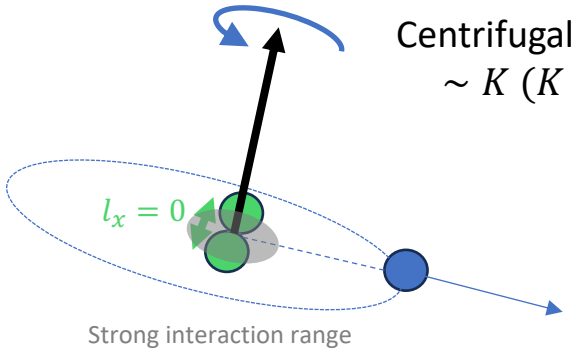
Attractive contribution observed in the data
HOW CAN THE STRONG FORCE ACT AT HIGH ENERGY?

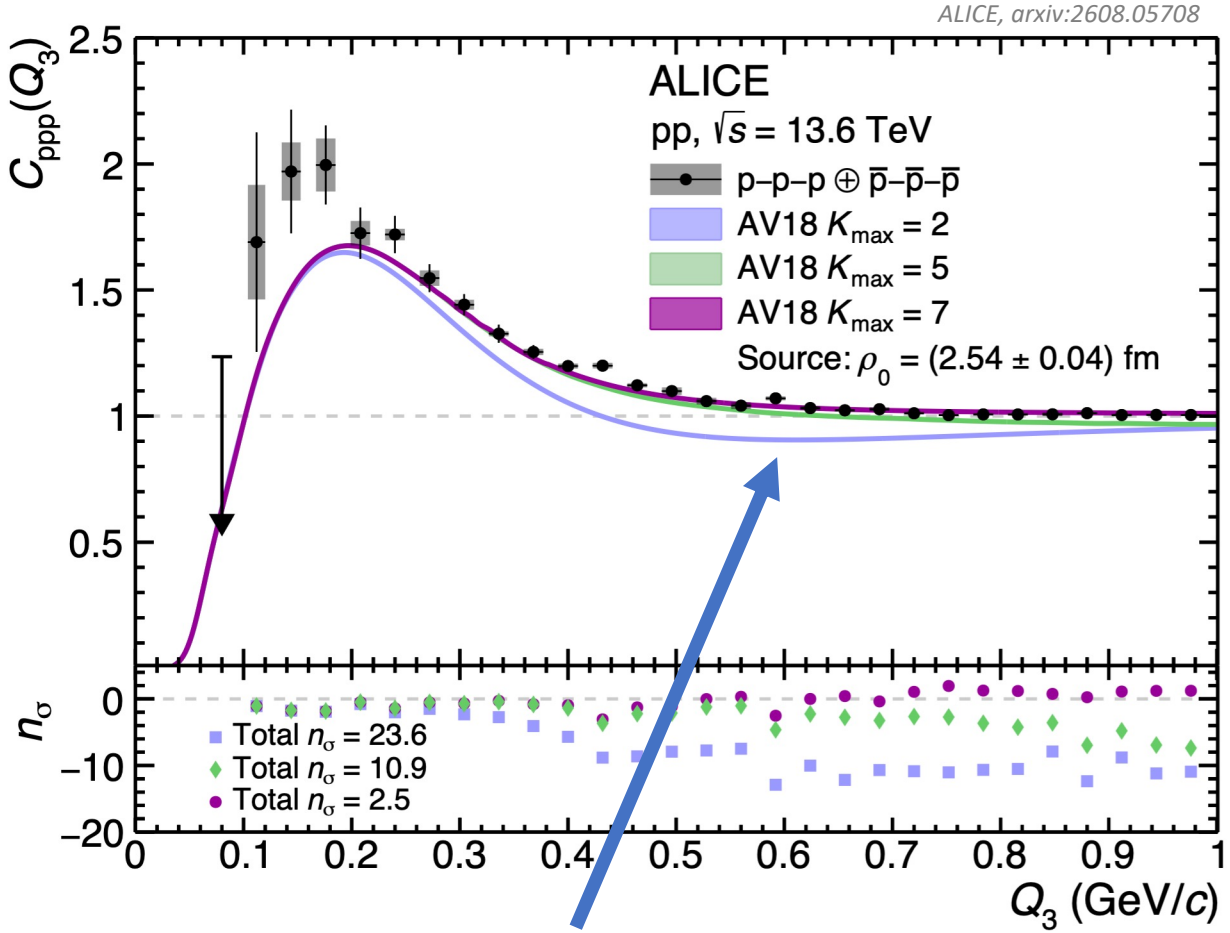
Genuine p-p-p correlation function

- Expansion in K allows two protons to always interact in $l_x = 0$



- Three-body dynamics: **strong interaction always active, event at large energy!**



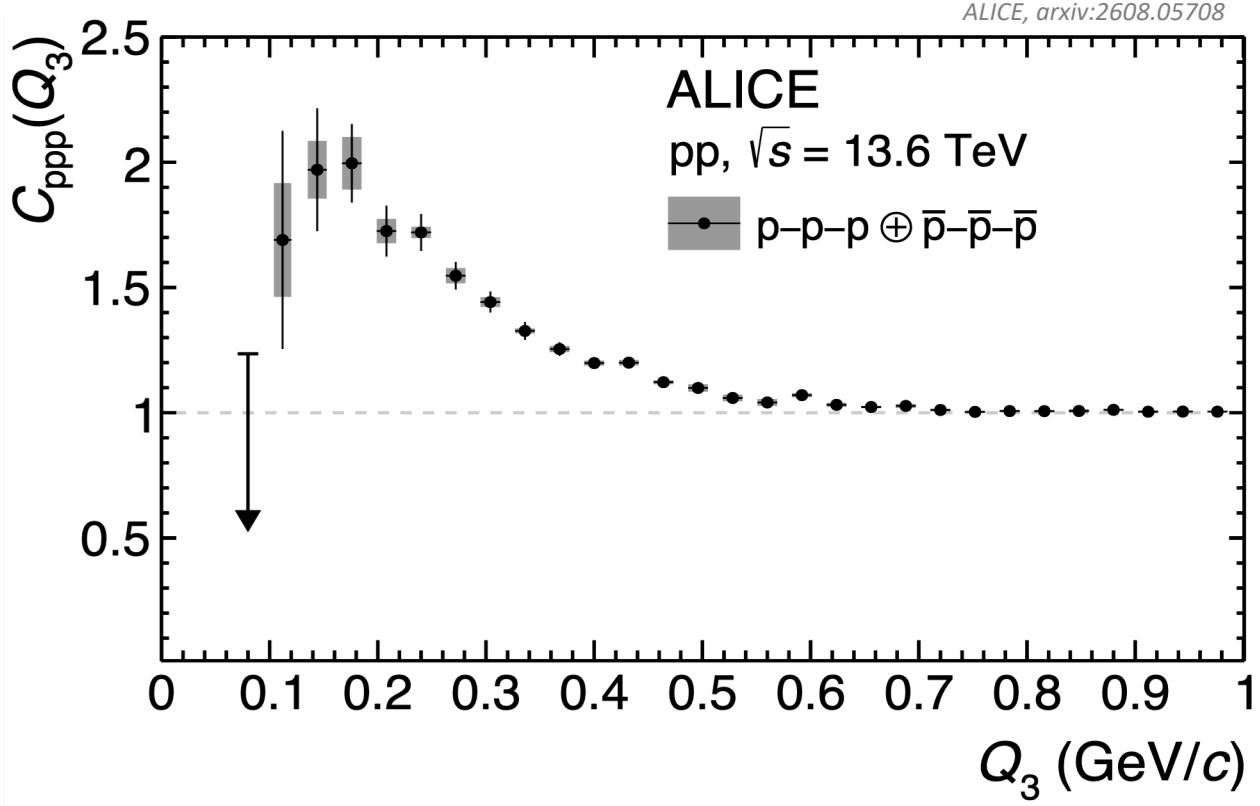


Observation of a long-range attraction!

Genuine p-p-p correlation function

Is the correlation function sensitive to the partial-wave structure of the pp interaction?

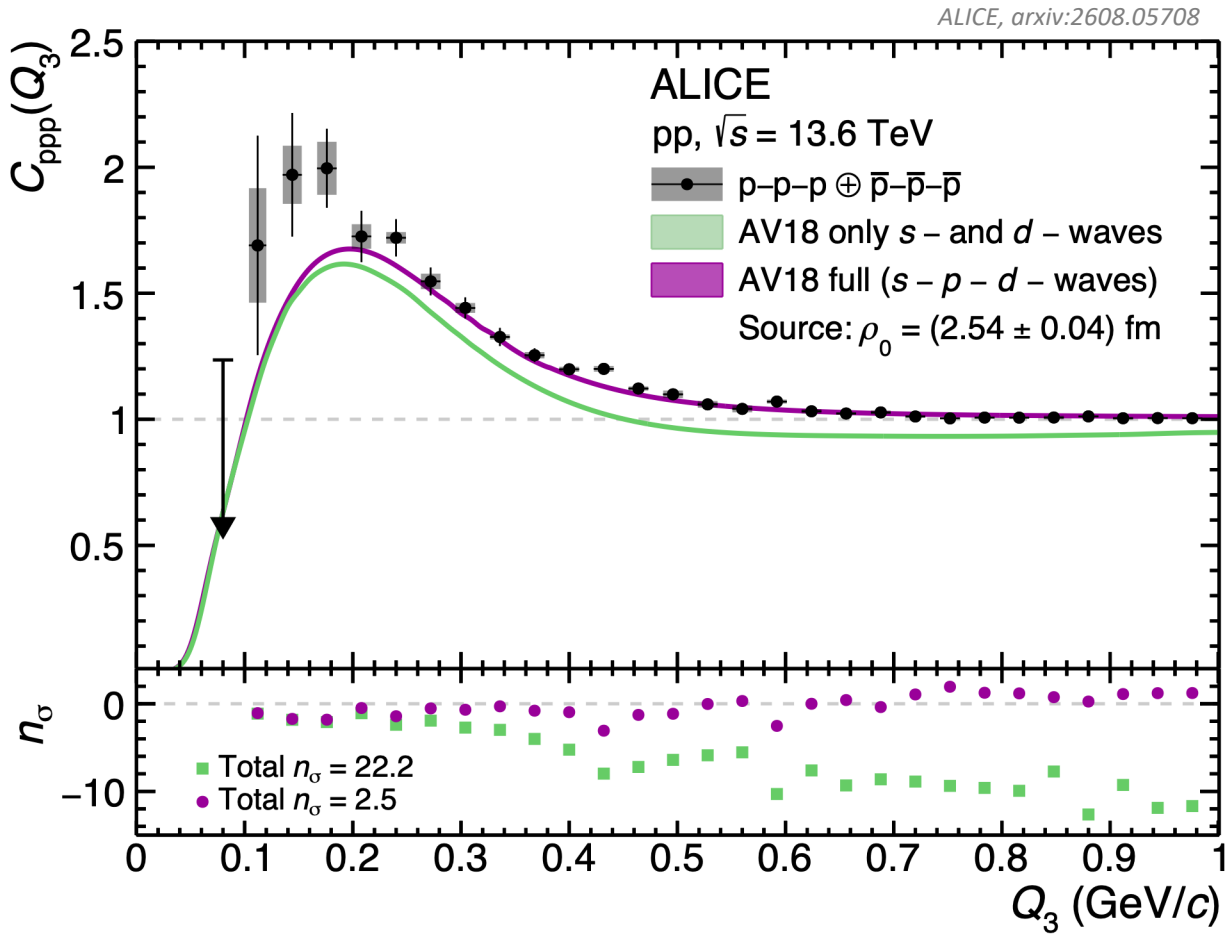
ALICE, arxiv:2608.05708



Genuine p-p-p correlation function

Is the correlation function sensitive to the partial-wave structure of the pp interaction?

- Exclusion of the interaction in p-wave results in **22.2 σ** deviation from data
- Inclusion of the interaction in all partial waves results in **2.5 σ**



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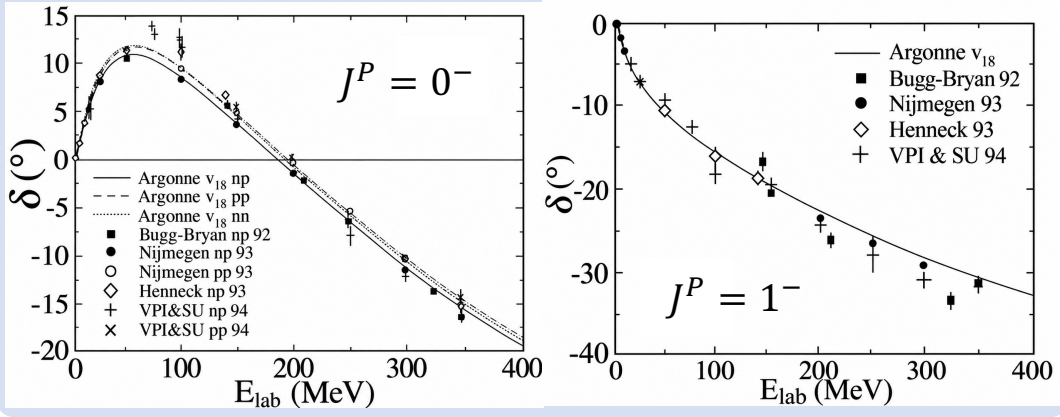
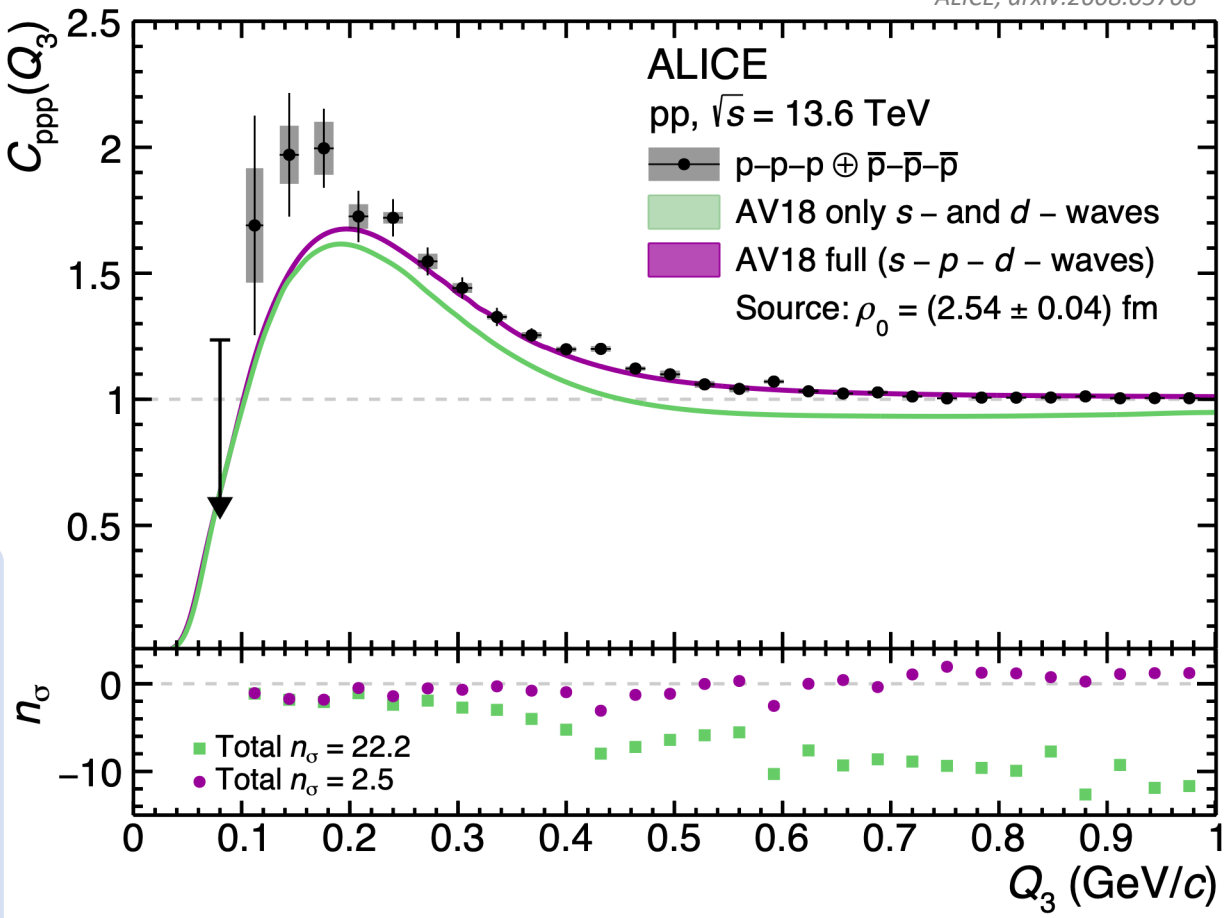
Sensitivity to the same partial-wave dynamics of the NN interaction that are constrained by scattering data

P-wave interaction (L=1)



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

ALICE, arxiv:2608.05708



What did we learn from p-p-p?

- The correlation function is sensitive to partial-wave structure constrained by scattering experiments
- The correlation function exhibits two distinctive signatures of a three-free-proton system:
  - Requires inclusion of interaction up to high grand-angular momentum values
  - Observed effective long-range attraction

This establishes three-body femtoscopy as an effective scattering experiment for 3→3 reaction inaccessible in any other experimental way!

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How about interactions with hyperons?

p-p-Λ correlation function

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

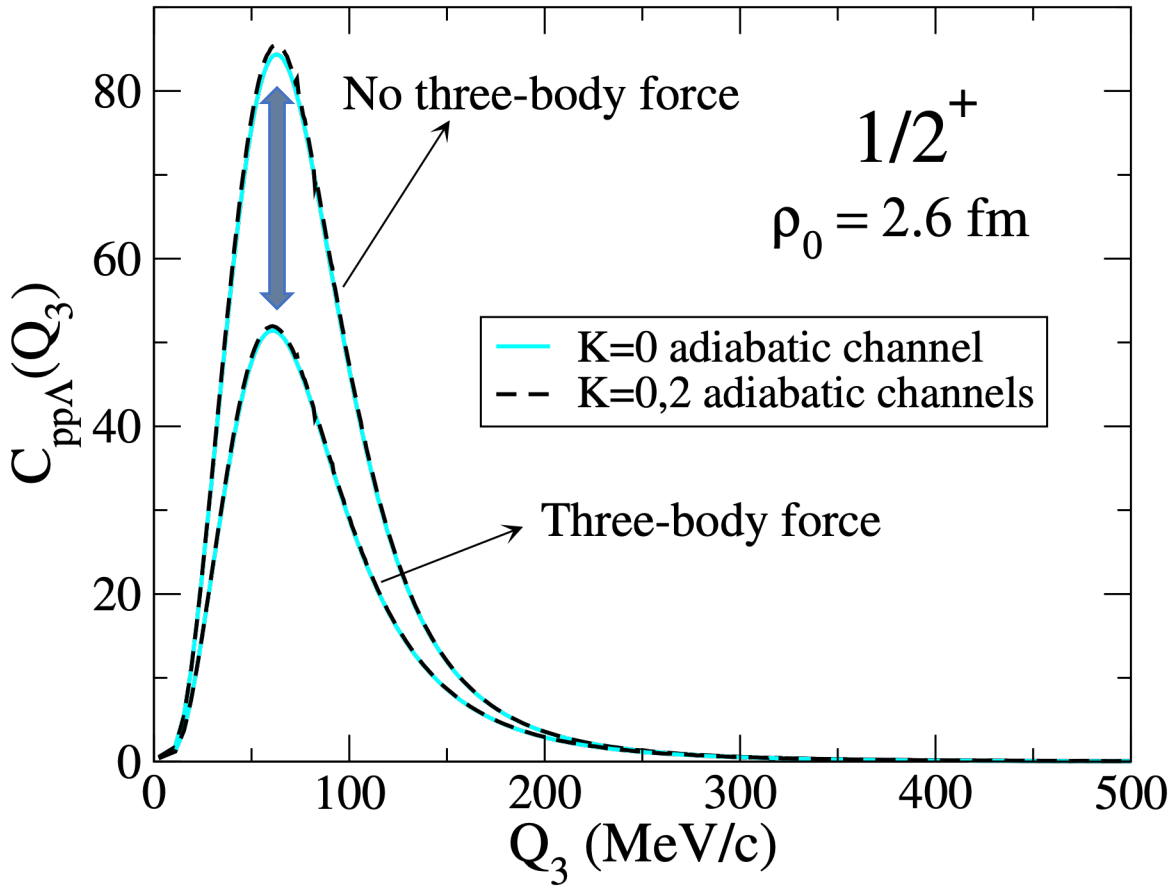
  BE($^{3}_{\Lambda}$H) = 2.904 MeV exp: 2.39 MeV

  *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

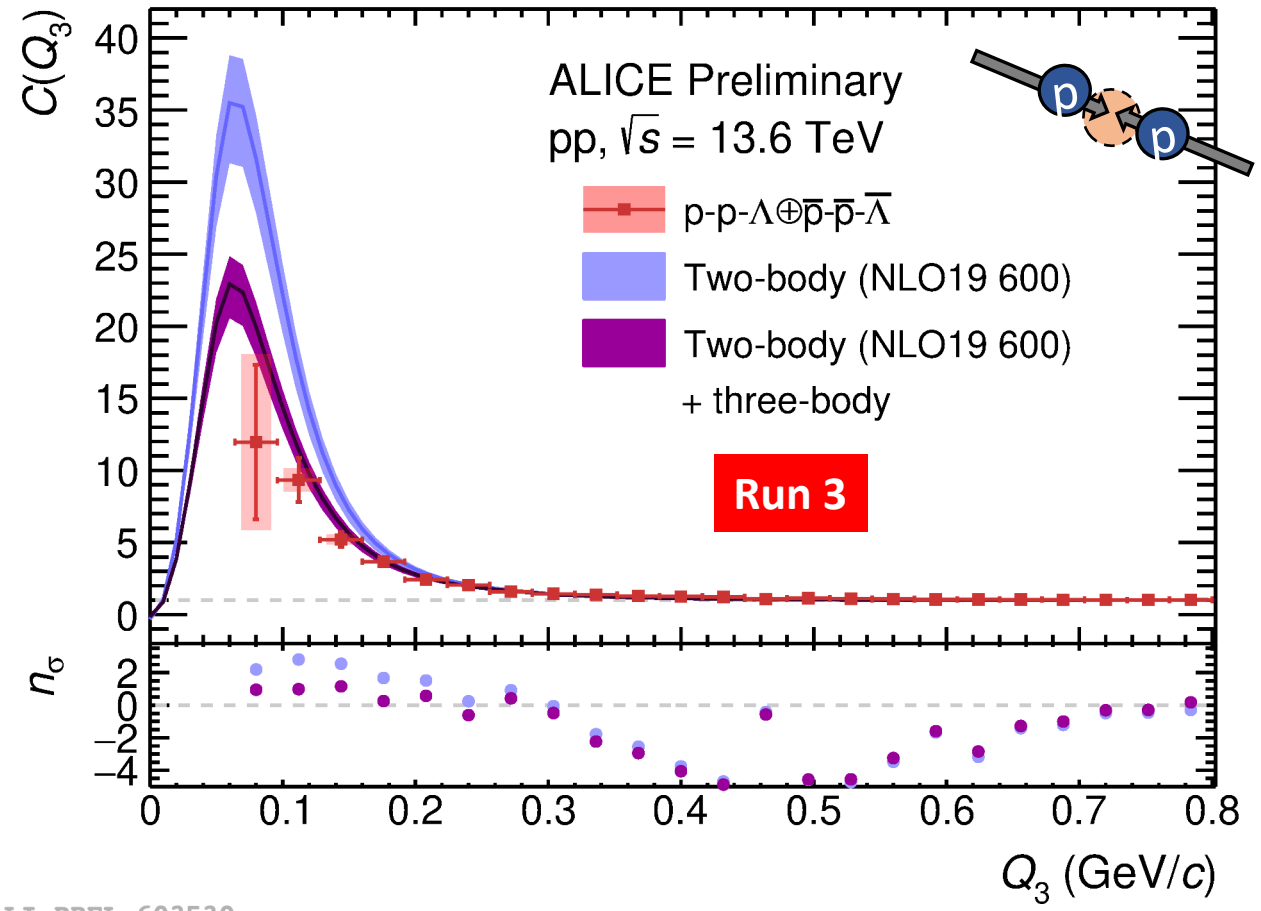
p-p-Λ correlation function in pp collisions

- 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!!



ALI-PREL-603530

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

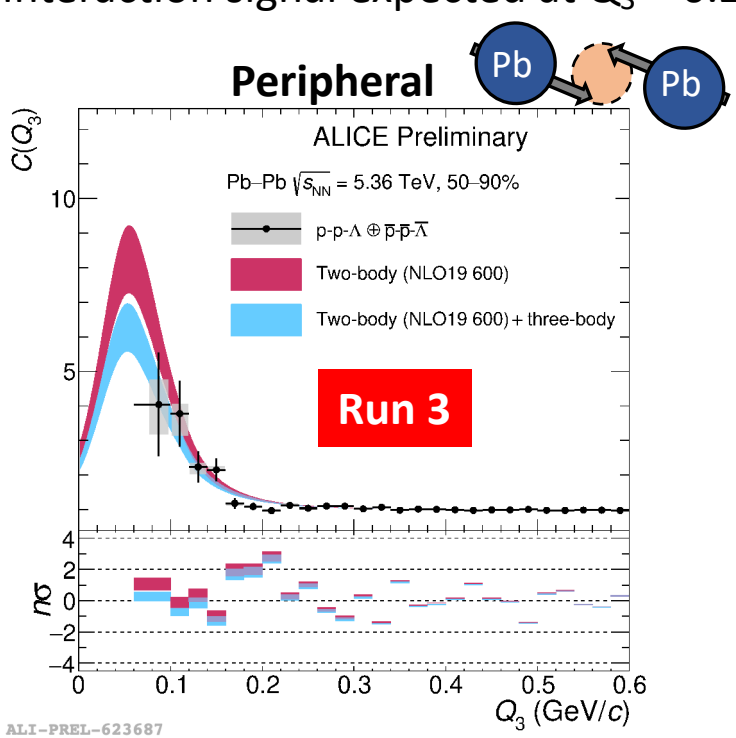
p-p-Λ correlation function in Pb–Pb collisions

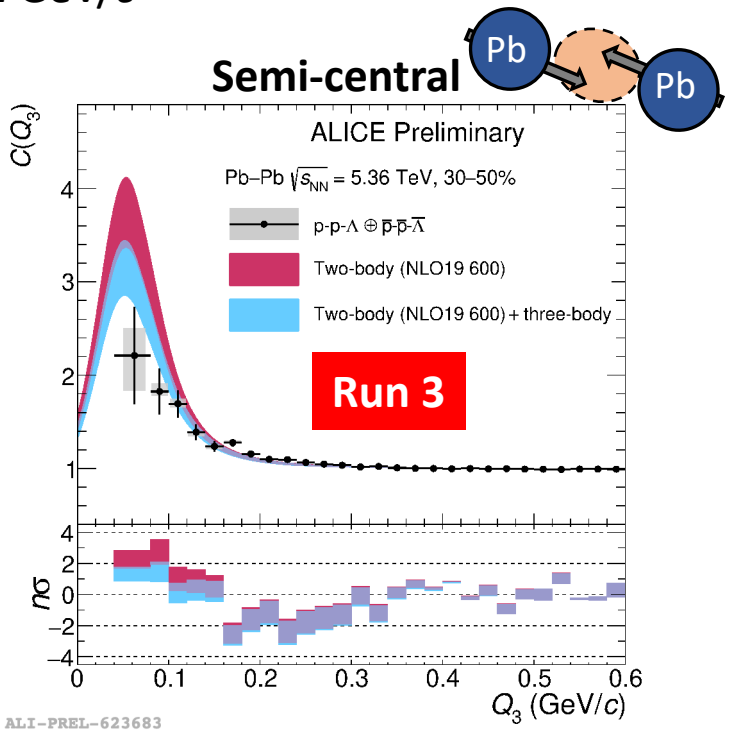
Theory:

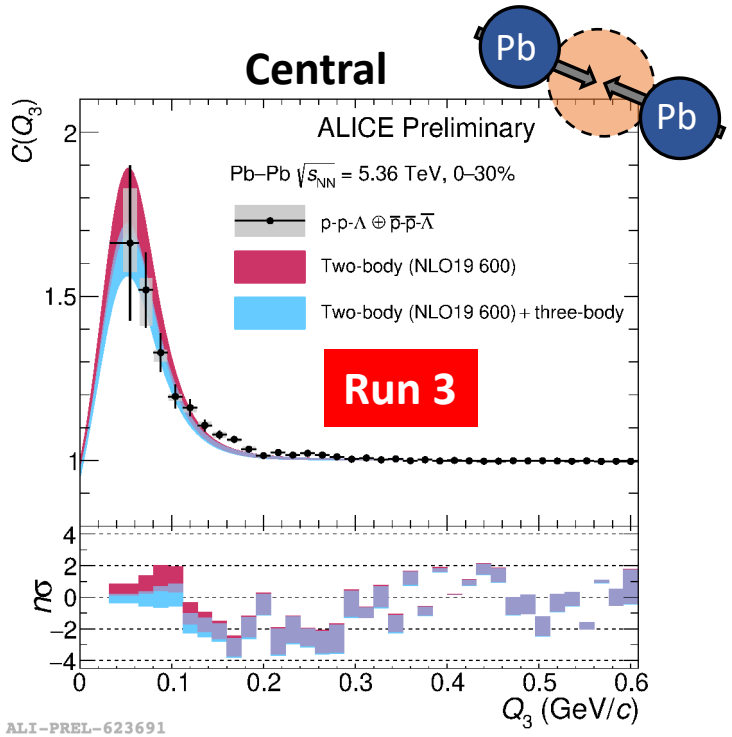
- Preliminary calculations with Gauss NLO19 (600)
  J. Haidenbauer, U.-G. Meißner, and A. Nogga, EPJ A 56, 91 (2020)
- Three-body force anchored to 3- and 4-body hypernuclei
  E. Garrido et al., PRC 110 (2024) 5, 054004
- Interaction signal expected at $Q_3 < 0.2$ GeV/c

Measurements:

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







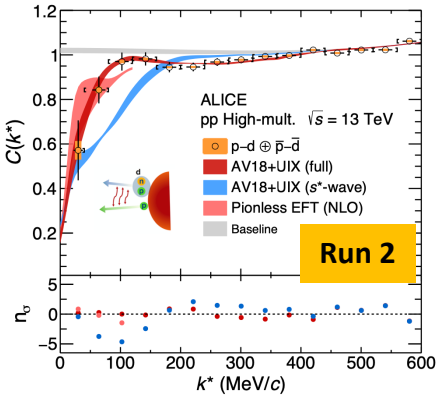
Other three-body measurements

S = 0
NNN

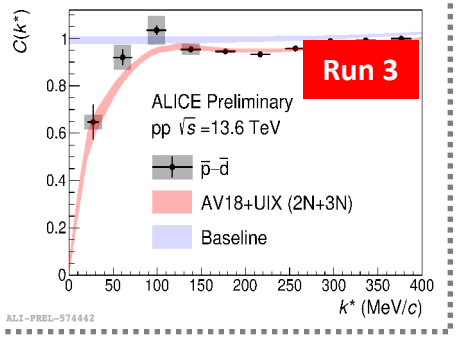
S = -1
NNΛ, KNN

S = -2
NNΞ

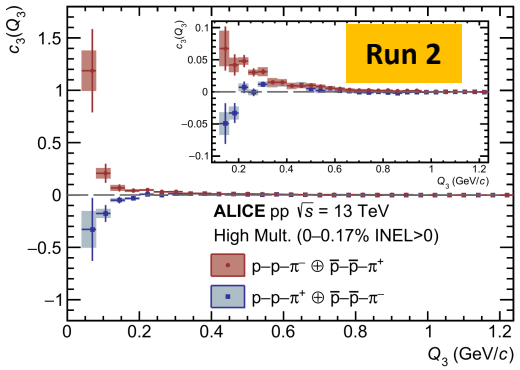
p-d



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

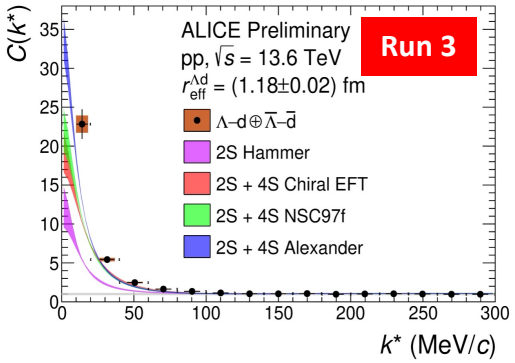


p-p-π

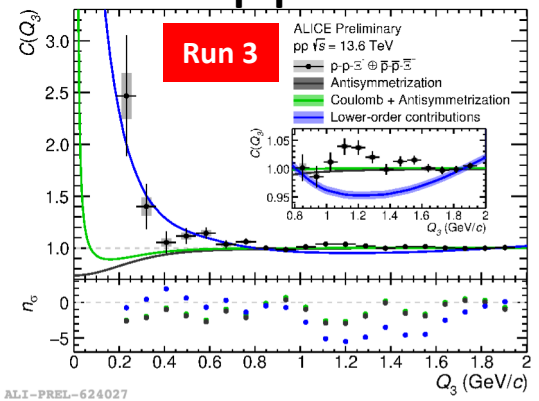


ALICE Coll., EPJ A 61 (2025) 8, 194

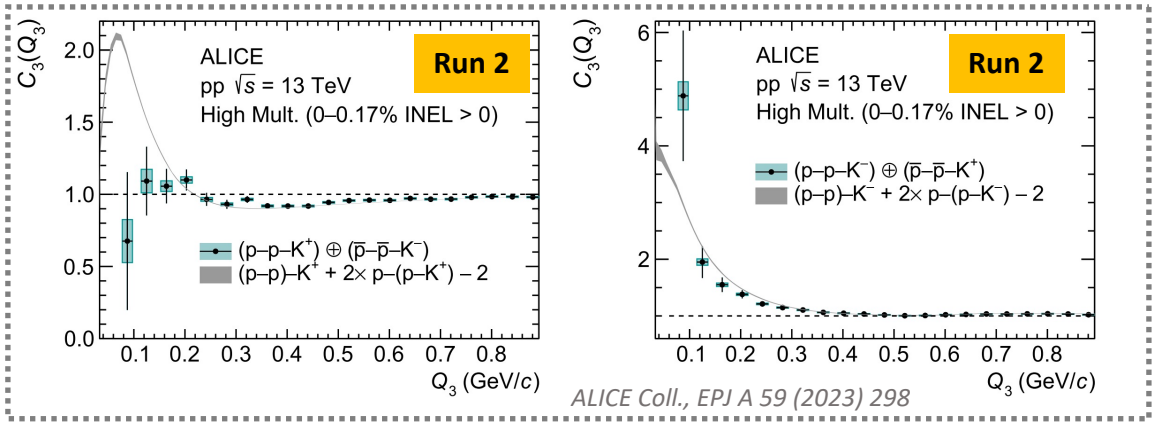
Λ-d



p-p-Ξ⁻



p-p-K



ALICE Coll., EPJ A 59 (2023) 298

Summary and Conclusions

- Feasibility of high precision measurement for hadron-hadron interactions by means of the femtoscopy technique appied to pp and Pb-Pb collisions at the LHC has been demonstrated.
- Close collaboration with theoreticians in the interpretation of the correlation functions.
- New hyperon-nucleon scattering parameters haven been extracted and a new EoS for baryonic matter containing hyperons has been calculated. Experimental uncertainties on two-body interactions are propagated.
- The largest neutron star mass obtained with such an approach is still far from the heavist masses measured.
- The feasibility of the direct measurement of three body effects by means of three baryons correlation is under study.

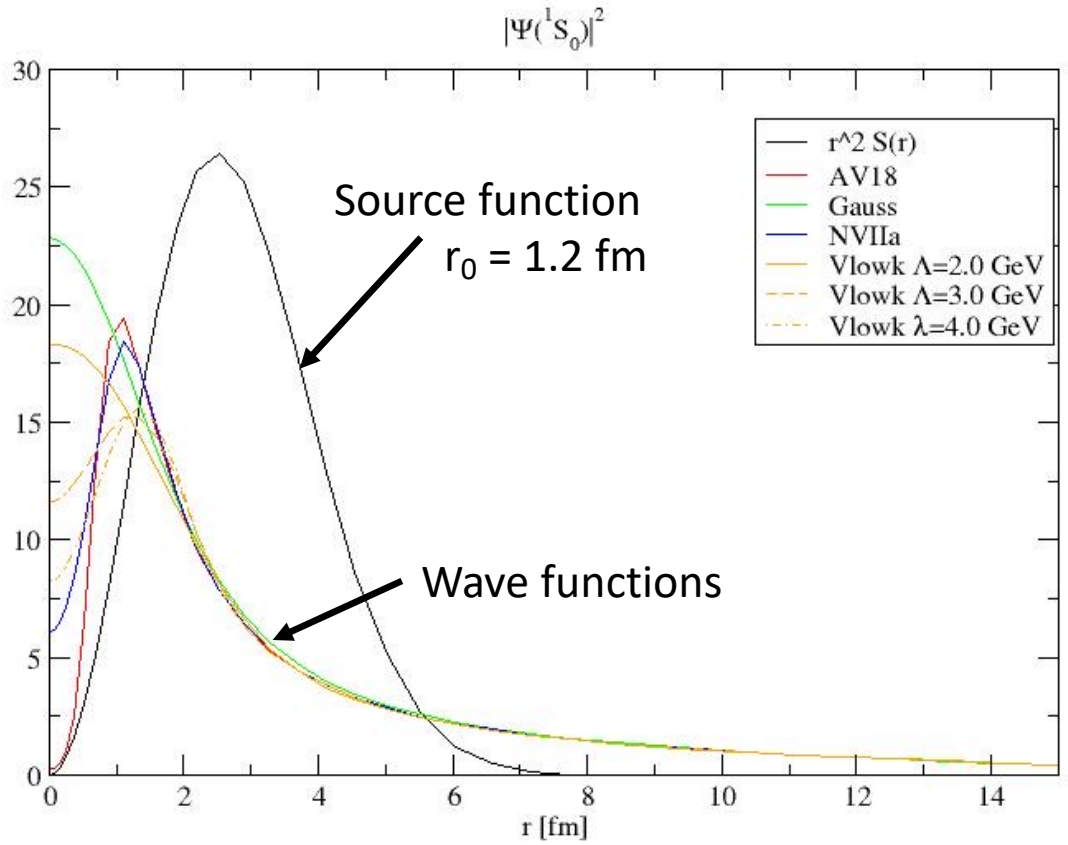
- On-going Run 3 data analysis and future Run 4
  - Access to precise data on three-particle interactions
  - Sensitivity to the effect of three-body forces in the correlation functions

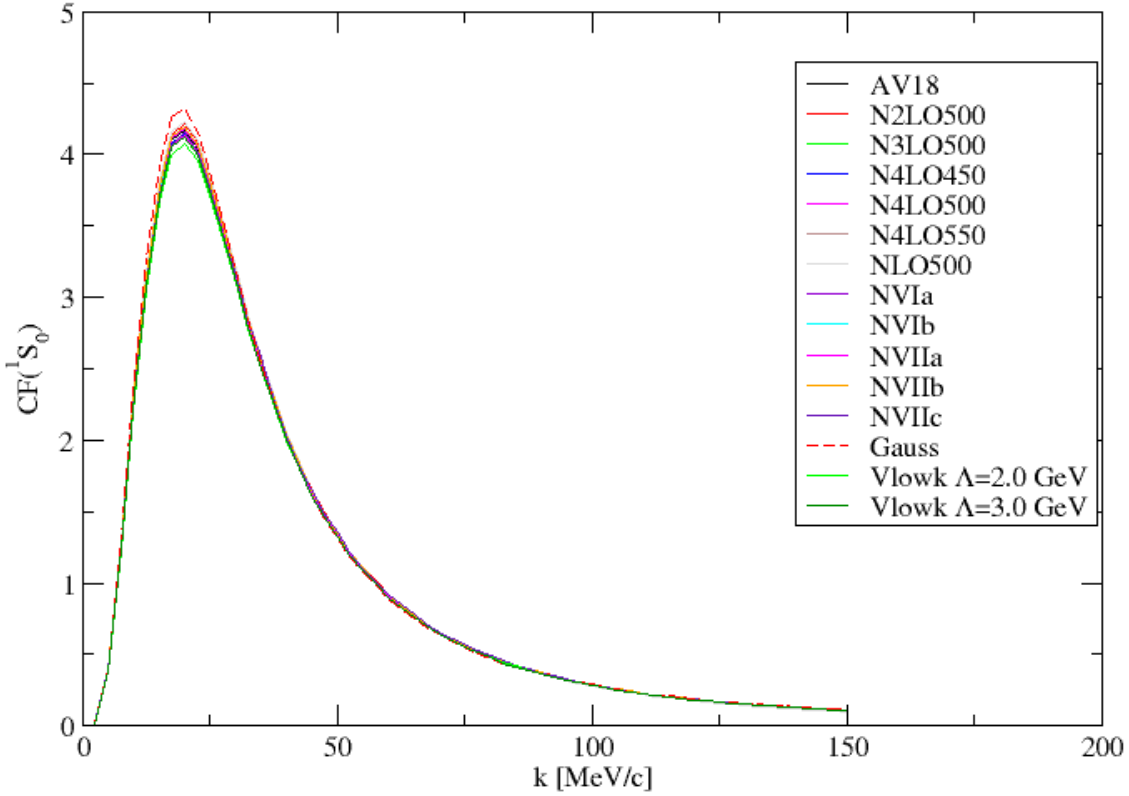
Stay tuned for much more.

Thank you for your attention

Scan of p-p wave functions

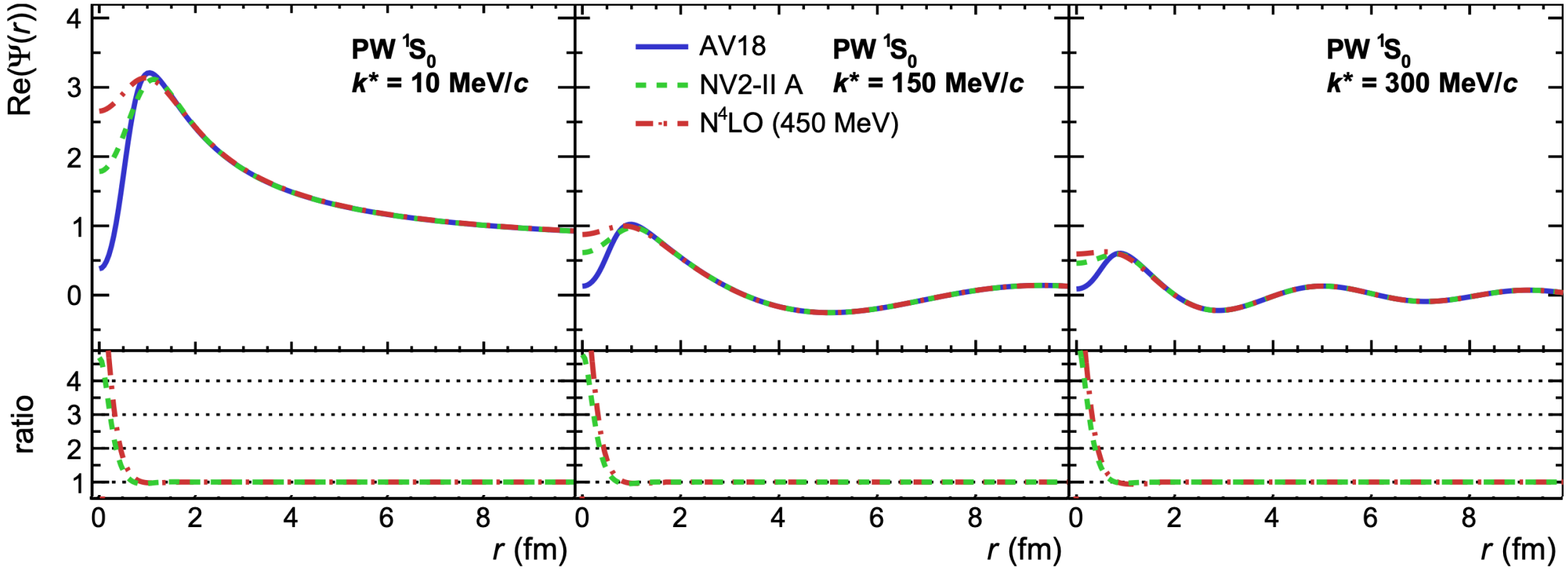
Courtesy A. Kievsky and M. Viviani





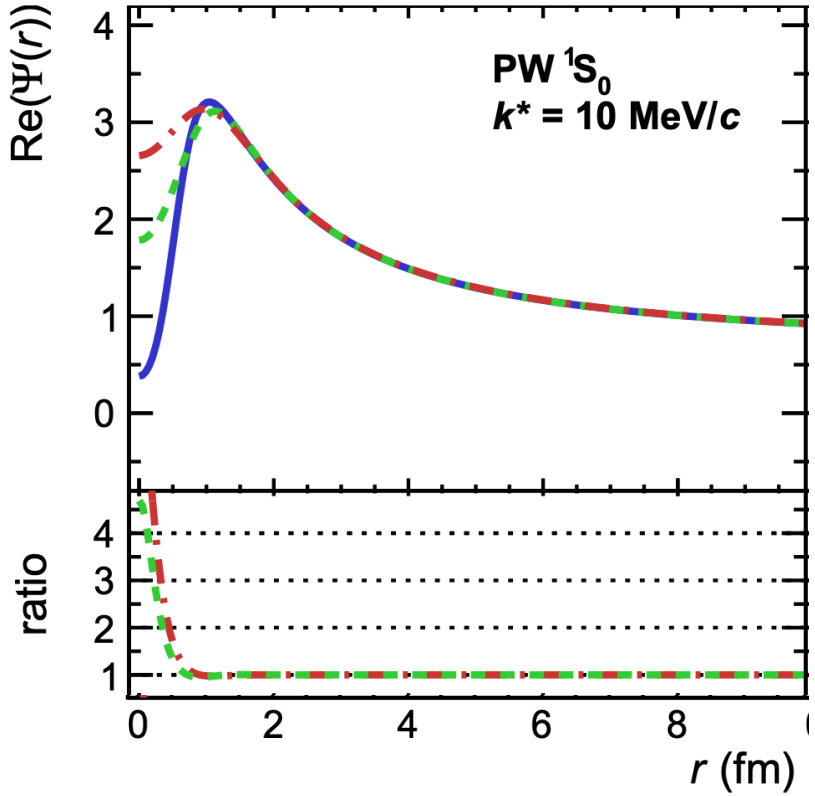
For a systematic study of the effect of different NN interaction in the correlation function see
M. Göbel, A. Kievsky, Phys.Lett.B 869 (2025) 139835

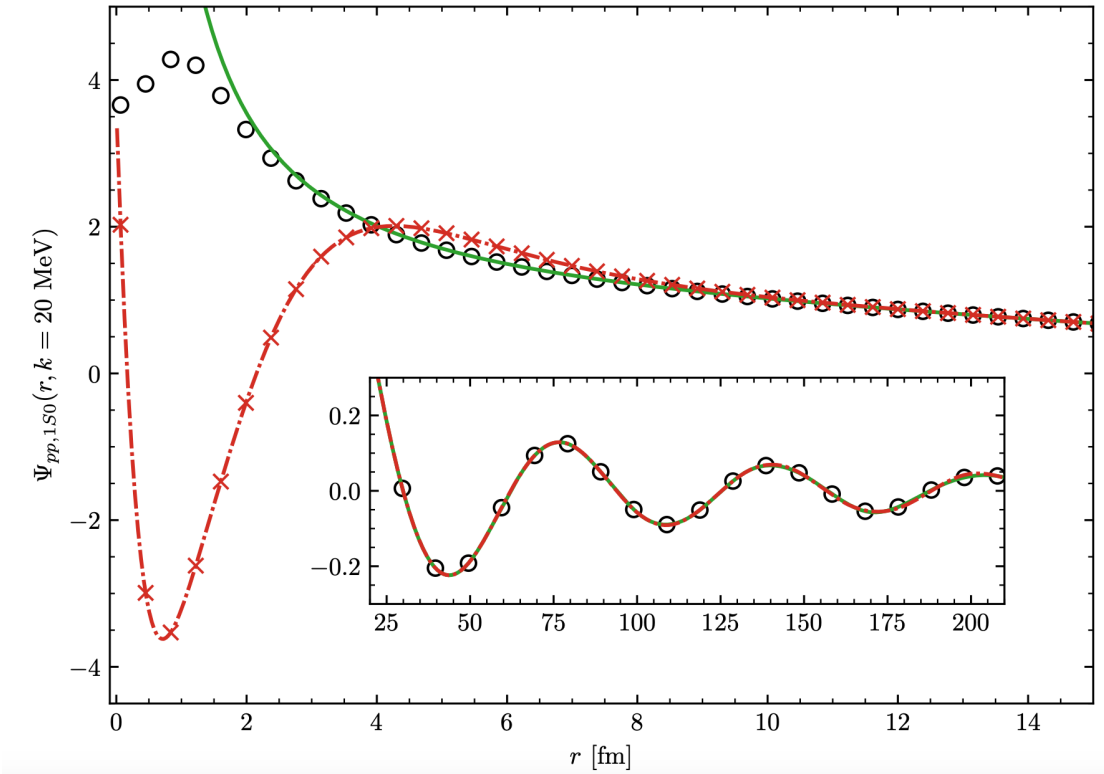
Scan of p-p wave functions



Realistic wave functions from AV18, Norfolk potentials and N^{4}LO$^+$ EFT.

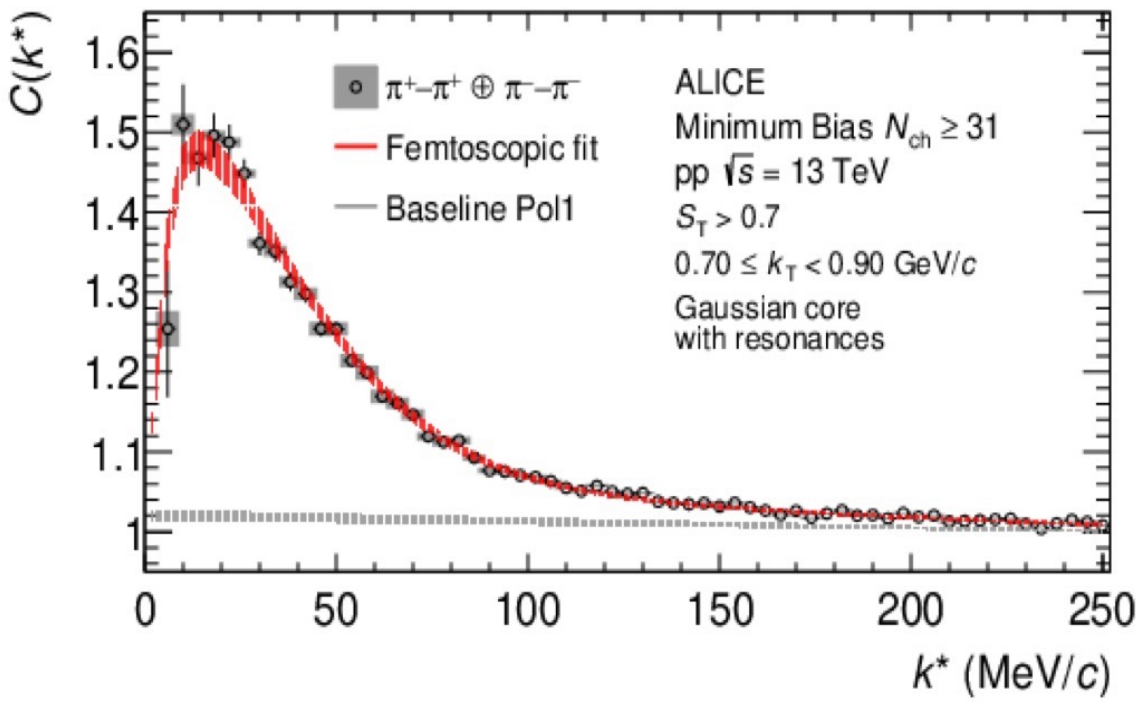
Scan of p-p wave functions



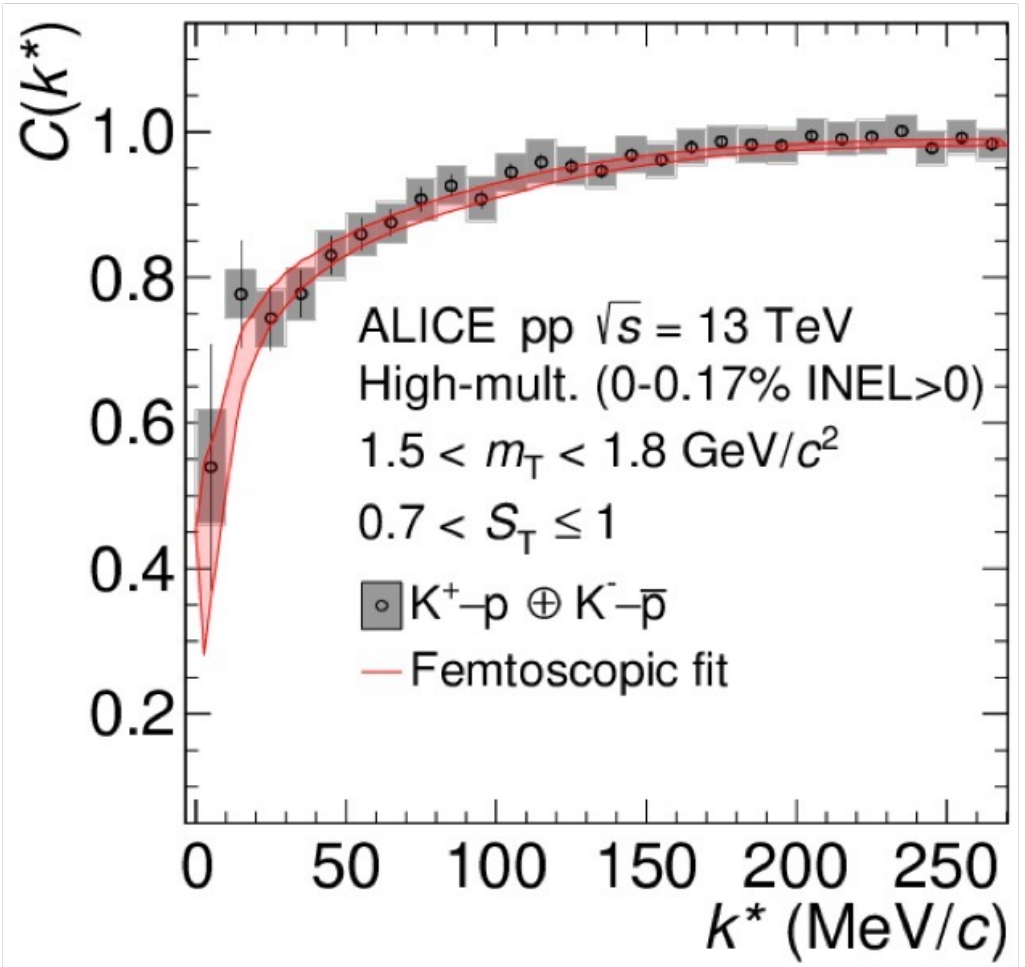


E. Epelbaum et al., Phys.Rev.Lett. 136 (2026) 21, 212301

Source function in pp collisions at the LHC



One common source for all hadrons
(cross-check with K^+-p, π-π, p-Λ, p-π)



ALICE Coll., PLB, 811 (2020)