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Technical
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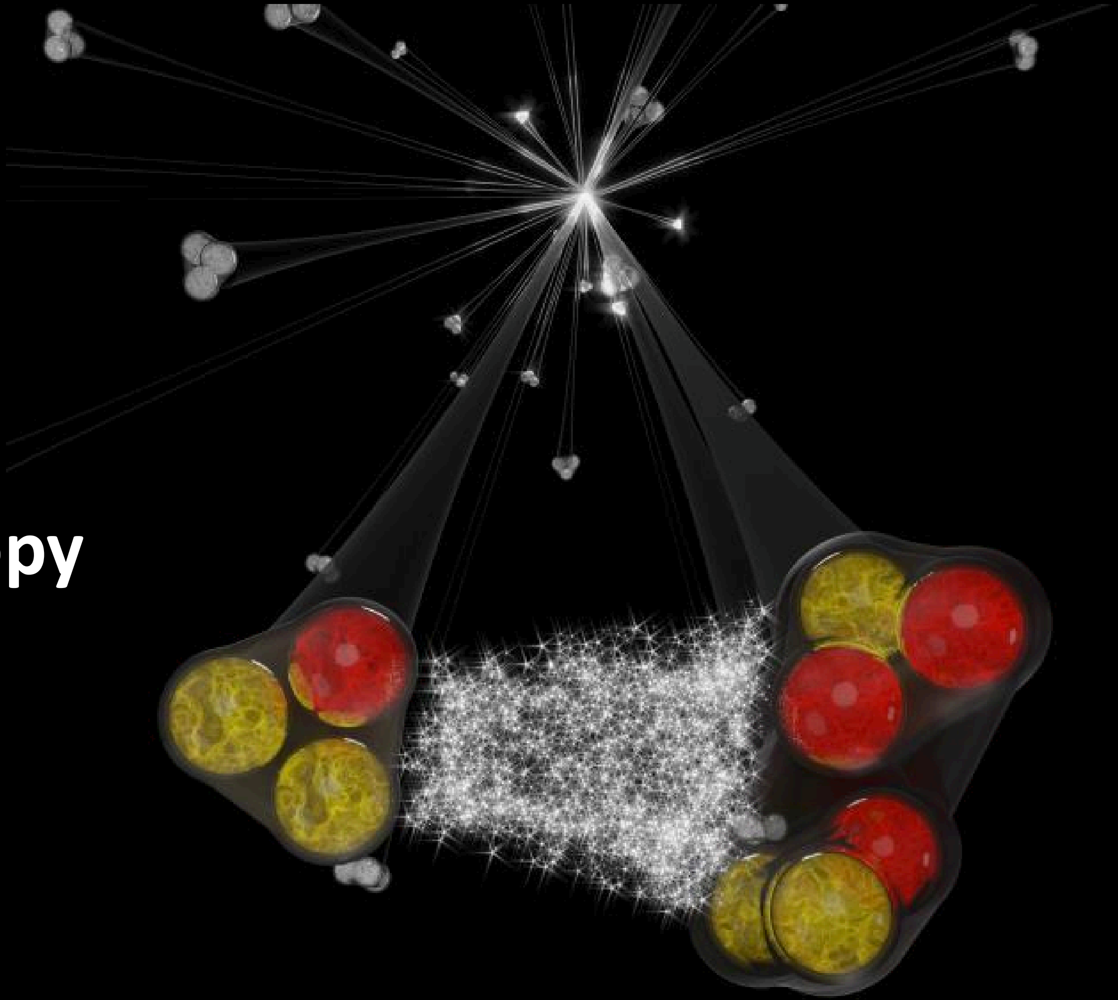

Understanding two- and three-body hadronic interactions using femtoscopy

Raffaele Del Grande

Czech Technical University in Prague
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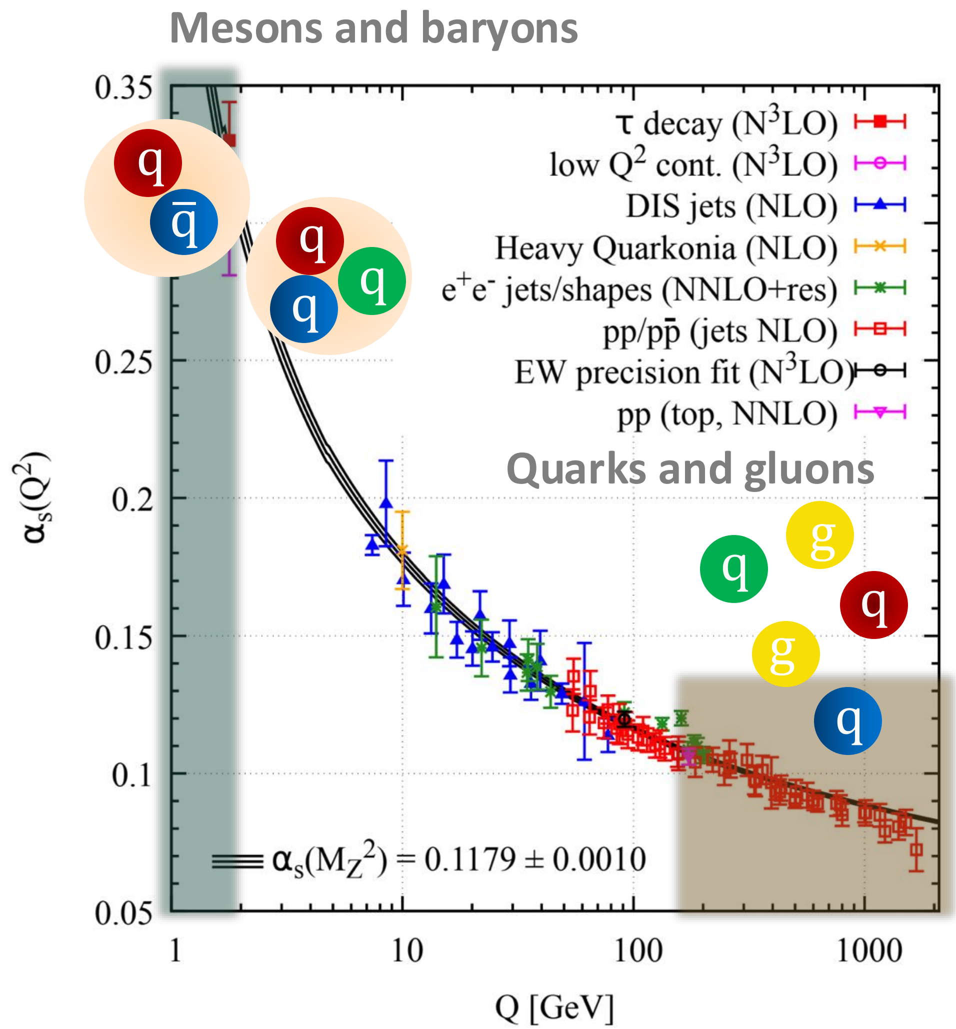
5 June 2025

HENPIC Seminar

Hadronic interactions

Understand how QCD evolves from high-energy to low-energy regime



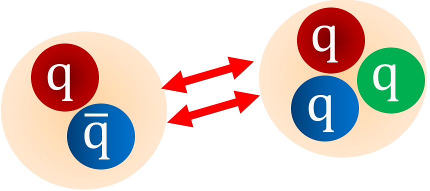
PDG, PTEP 2022, 083C01(2022)

Hadronic interactions

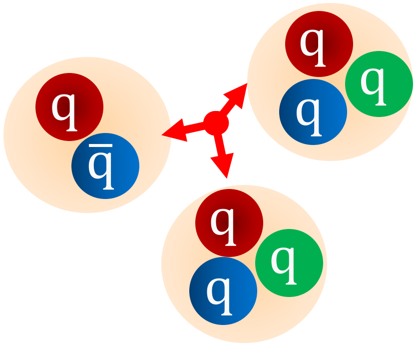
Understand how QCD evolves from high-energy to low-energy regime

How do hadrons interact?

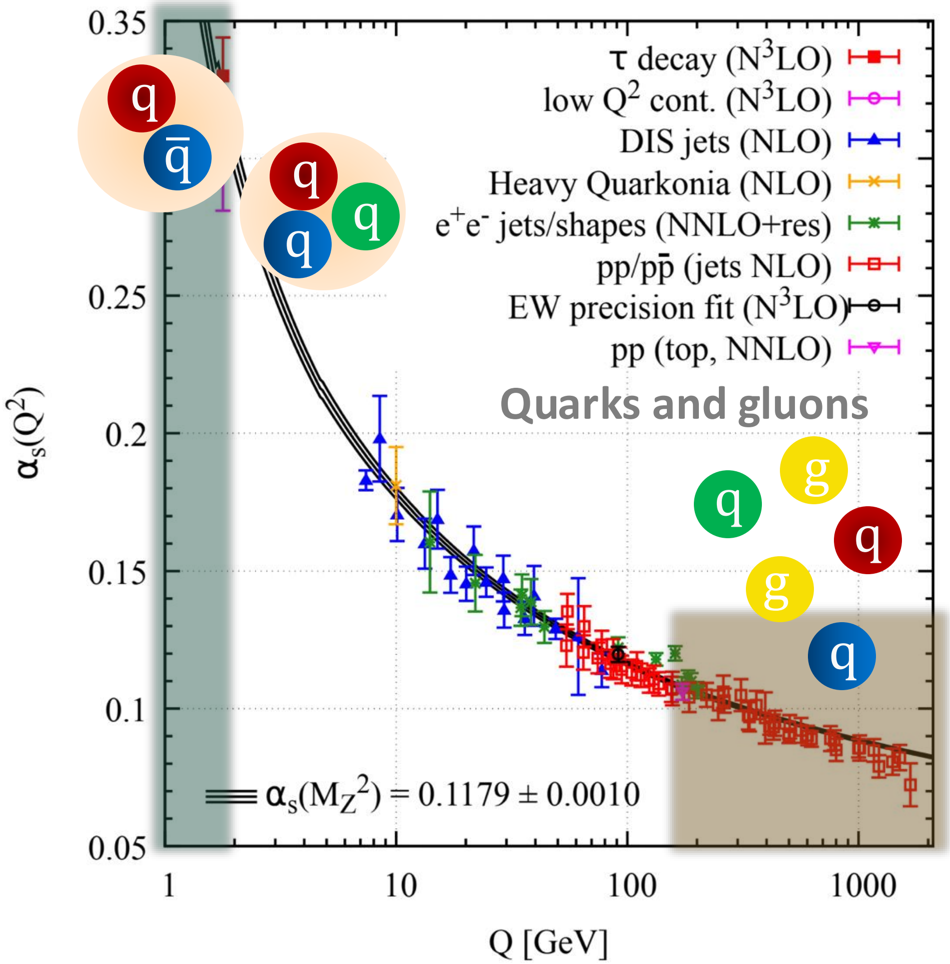
Two-body interactions



Three-body interactions



Mesons and baryons

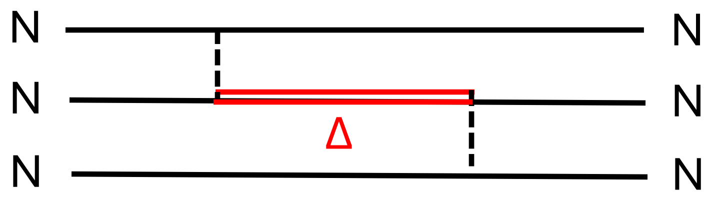


PDG, PTEP 2022, 083C01(2022)

Three-body dynamics

Dynamics of baryons involves formation of hadronic excitations

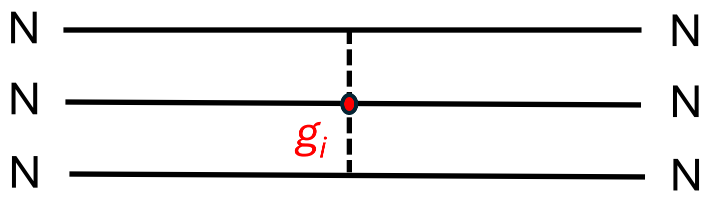
H.-W. Hammer, S. König, U. van Kolck RMP 92 (2020)



Short-range dynamics

Three-body forces in Effective Field Theories

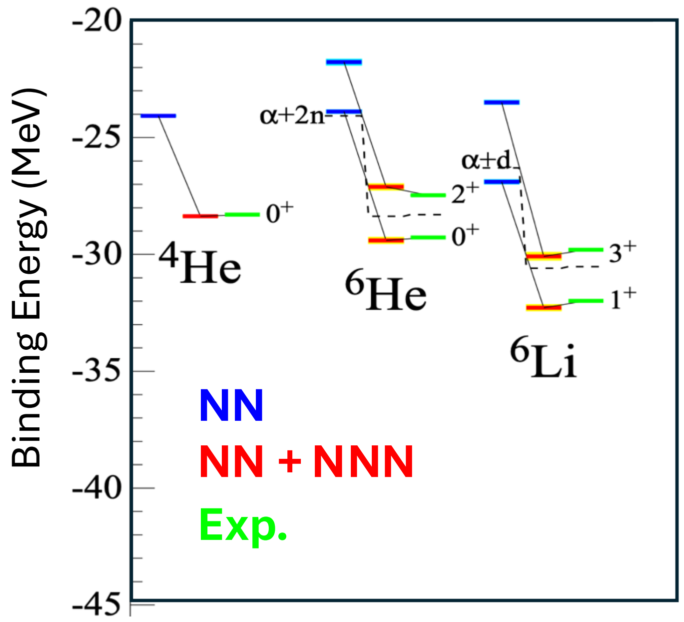
E. Epelbaum, H.-W. Hammer, U.-G. Meißner, RMP 81, 1773 (2009)



g_i constants to be fixed by the experimental data

Three-body forces

3BFs contribute 10-20% to the binding energies.



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

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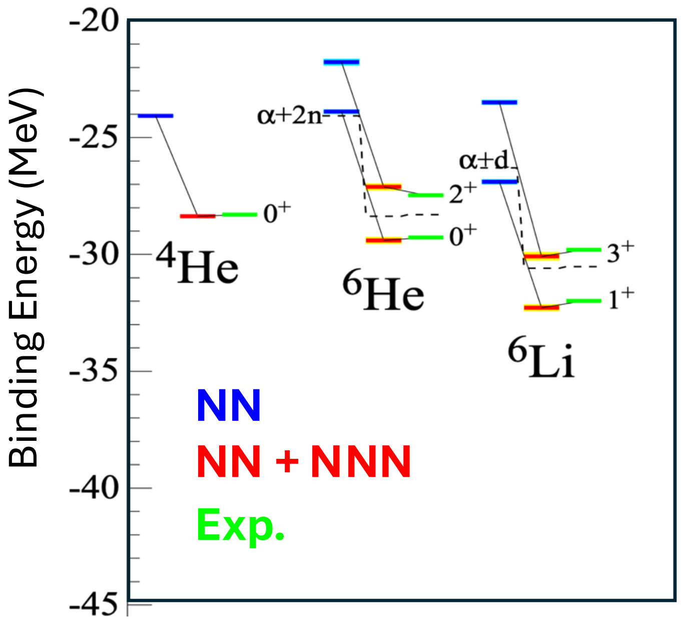
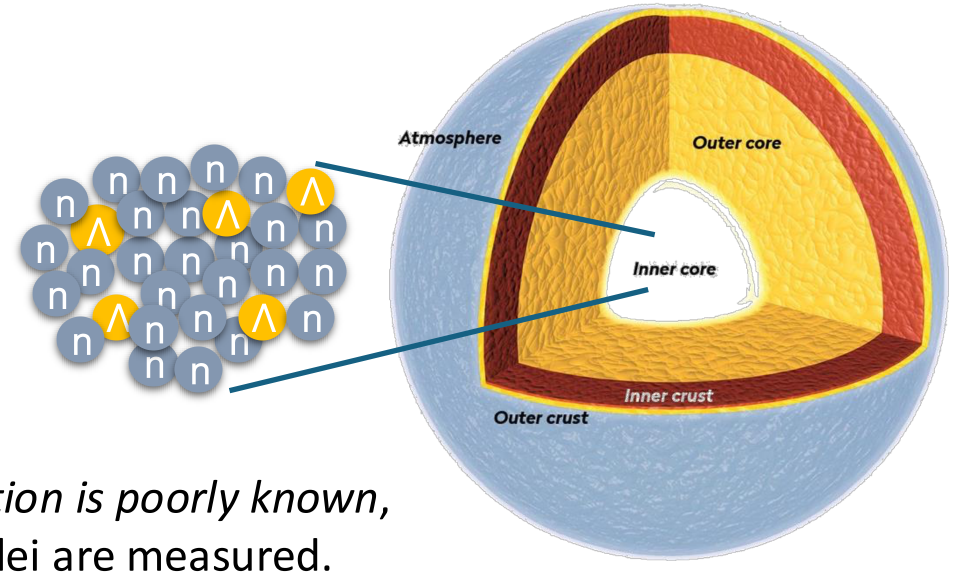


R. Navarro Perez et al., PRC 88, 024002 (2013)

Stronger impact on dense nuclear matter?

D. Lonardoni et al. PRL 114, 092301 (2015)



ΛNN interaction is poorly known,
38 hypernuclei are measured.

Nuclei

$\rho_0 = 0.16\ \text{fm}^{-3}$

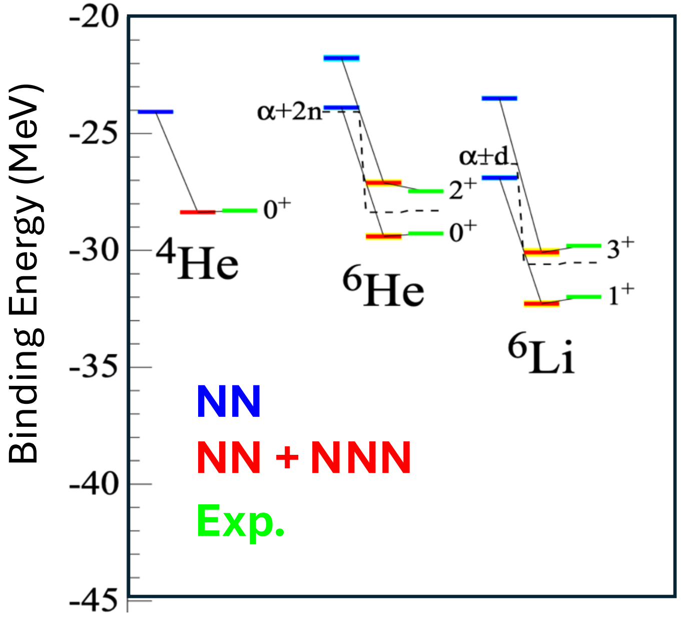
Neutron Star Core?

2-5 ρ_0

Baryon density

Three-body forces

3BFs contribute 10-20% to the binding energies.



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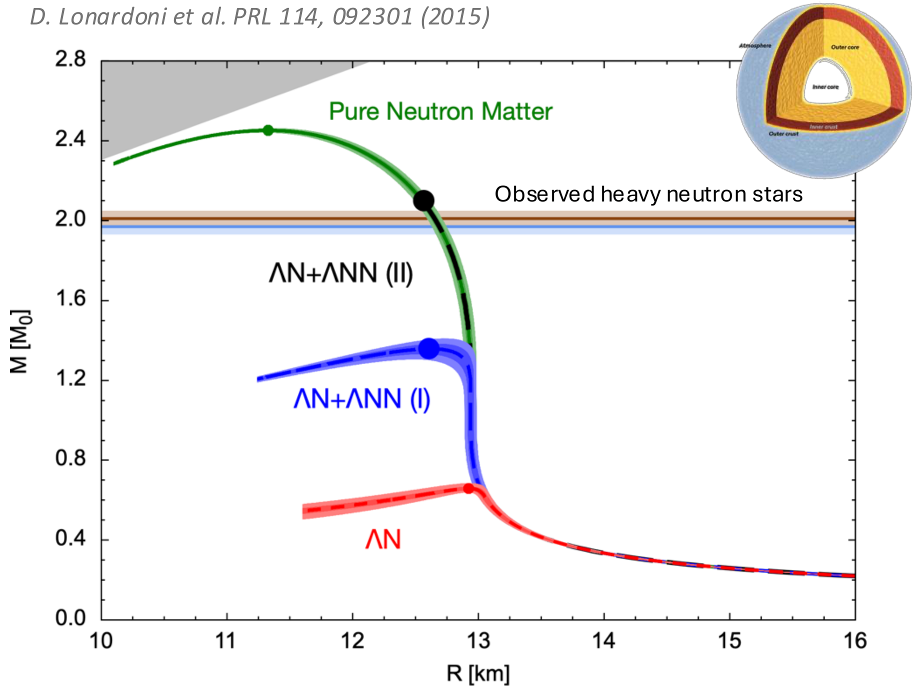

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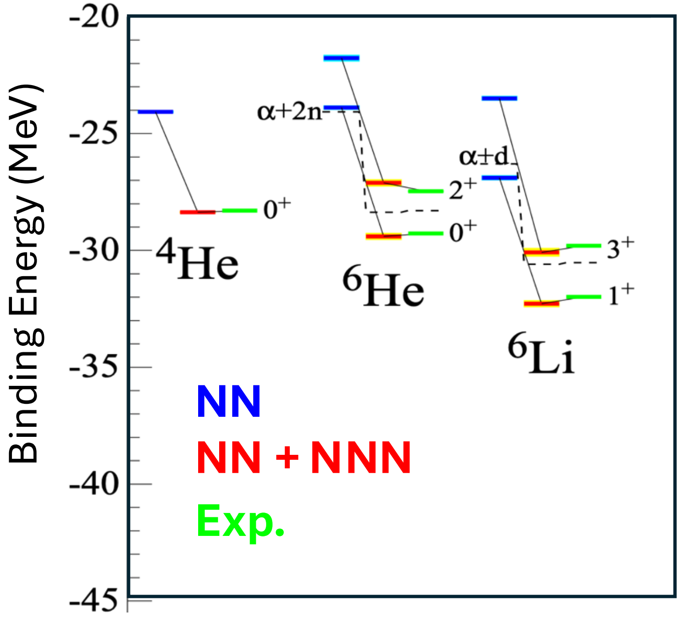

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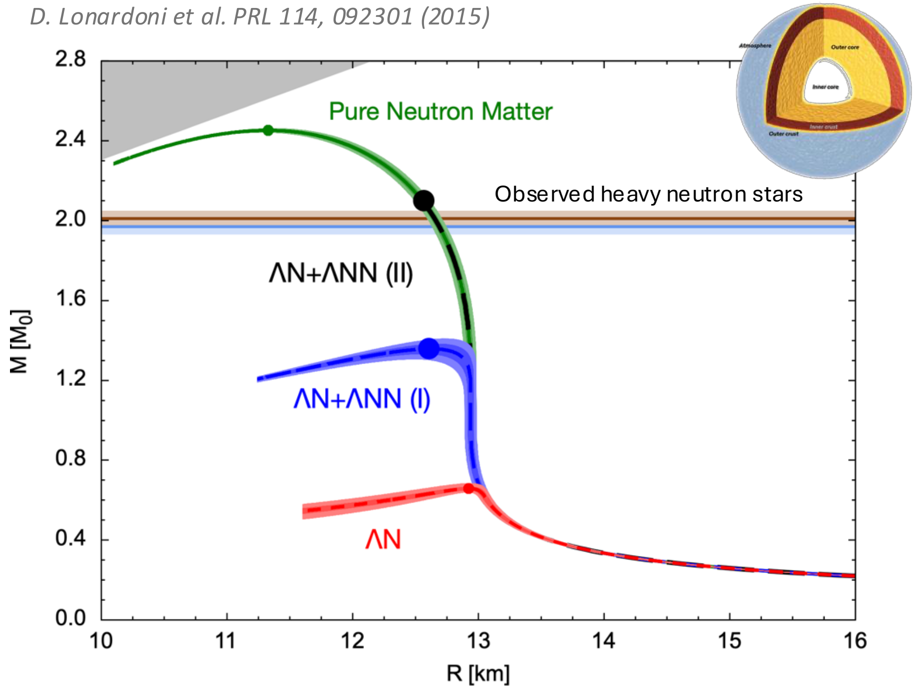
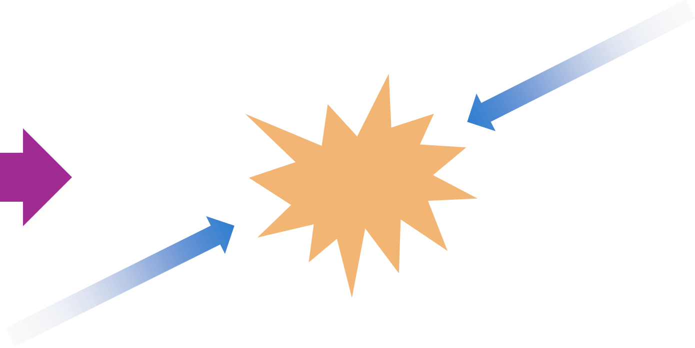


Femtoscopy technique at the Large Hadron Collider

ALICE at the LHC

Hadronic interaction



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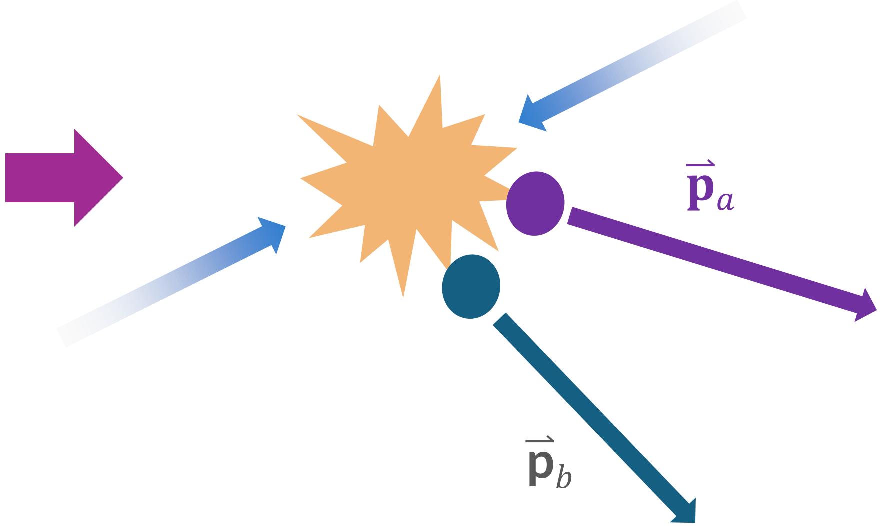

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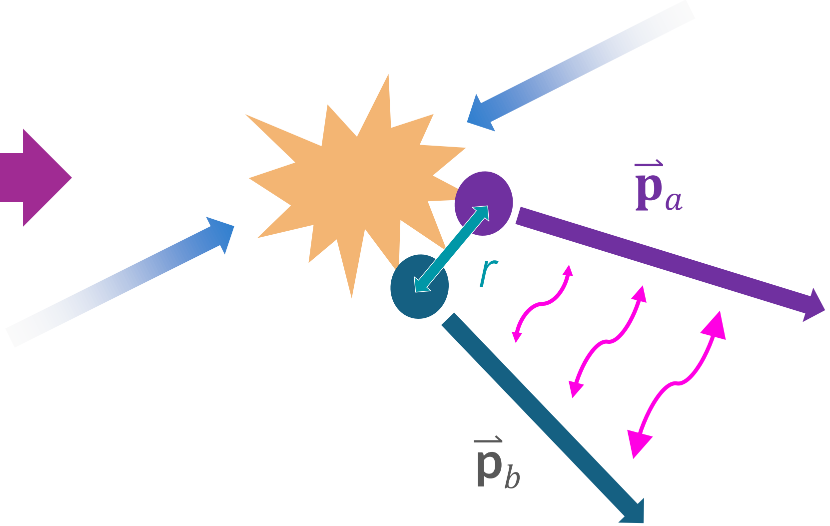
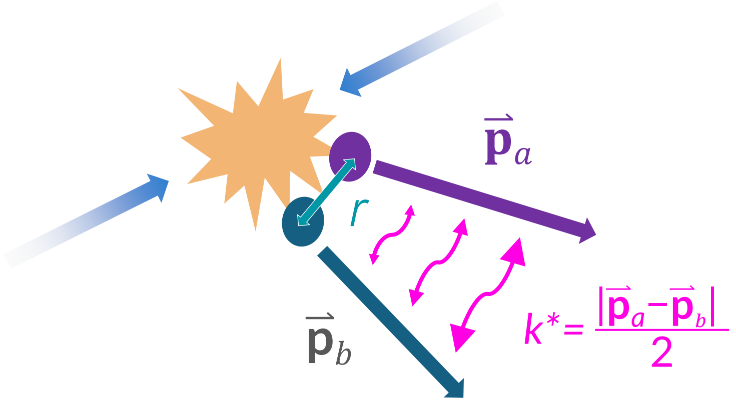


Femtoscopy technique

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

Correlation function

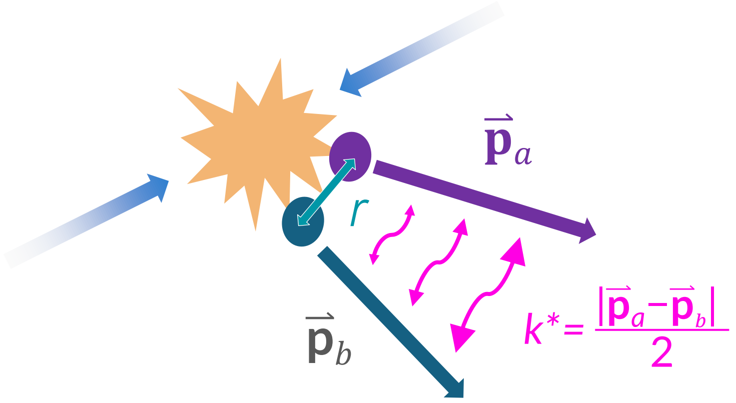


Emission source $S(\vec{r}\,)$

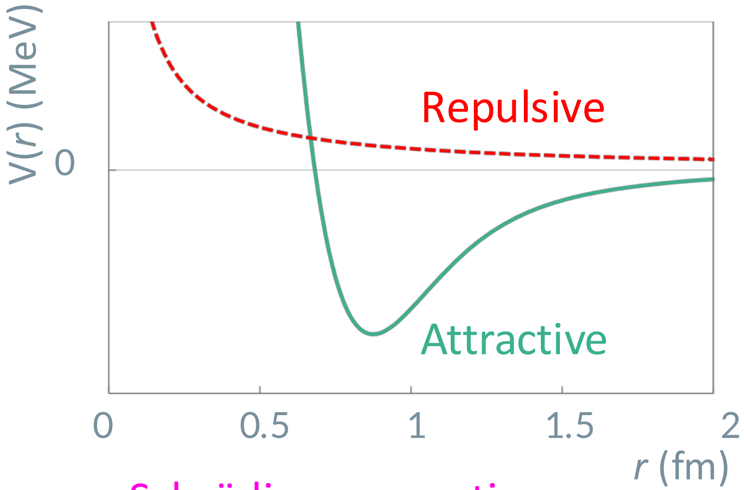
$$C(k^*) = \int \overbrace{S(\vec{r}\,)}\left|\psi(\vec{k}^*,\vec{r}\,)\right|^2 d\,\vec{r} \;= \mathcal{N}(k^*)\,\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

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

Correlation function



Interacting potential



Emission source $S(\vec{r}\,)$

Schrödinger equation

D. Mihaylov et al., EPJC 78 (2018), 5, 394

Two-particle wave function

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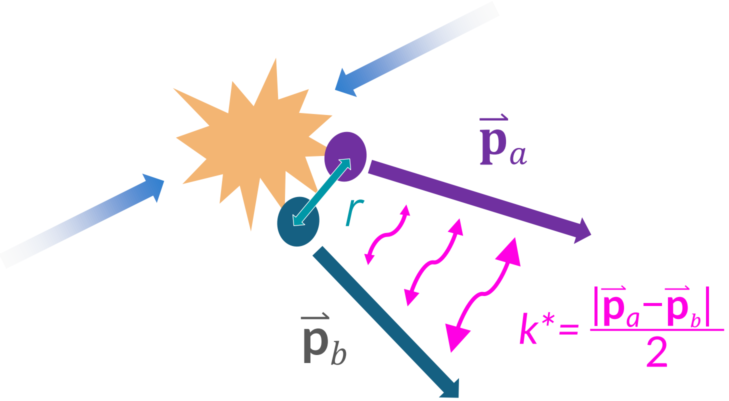

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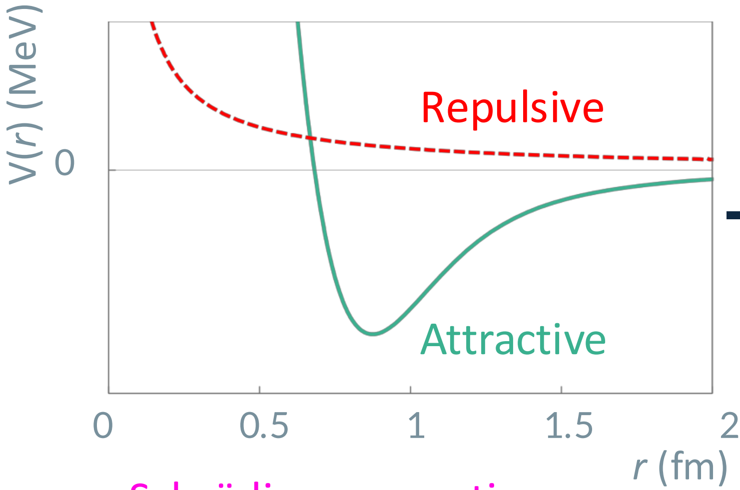

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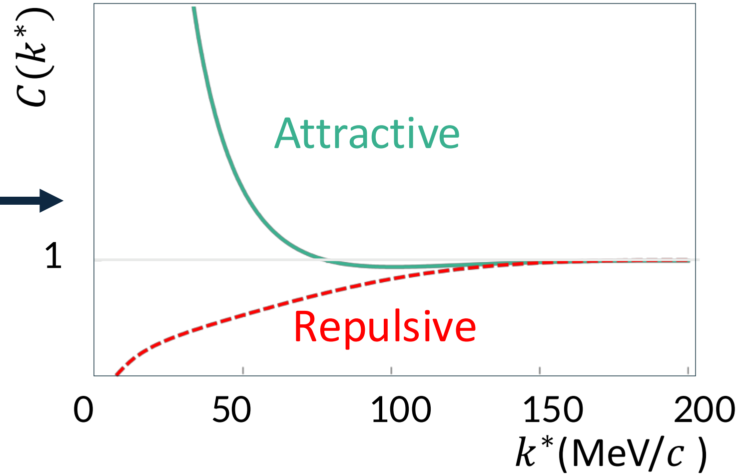

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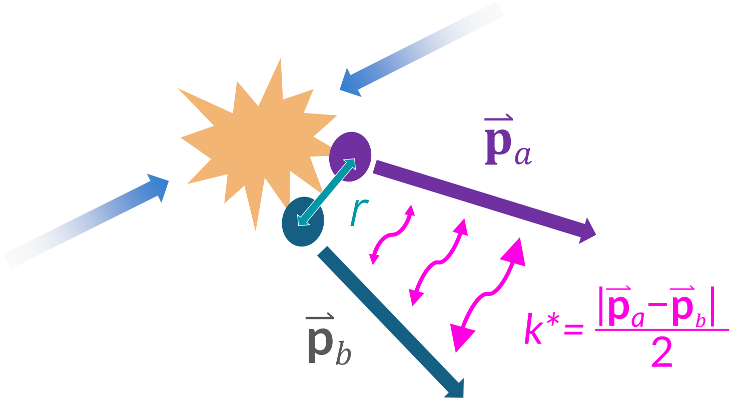

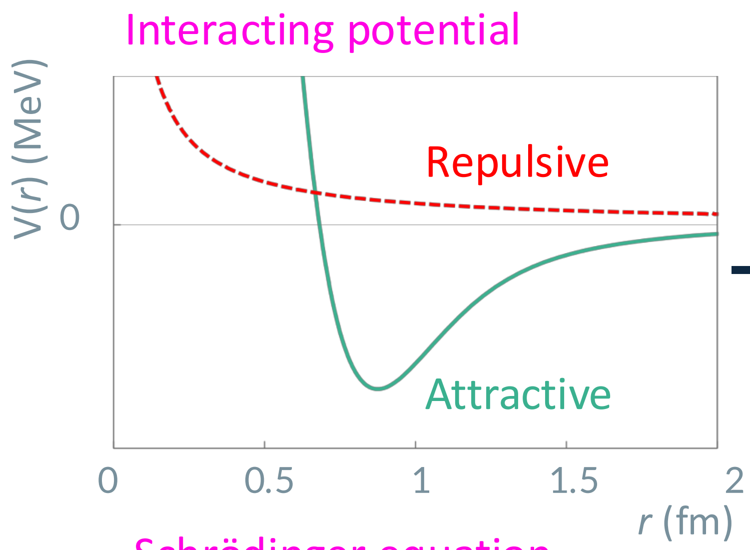

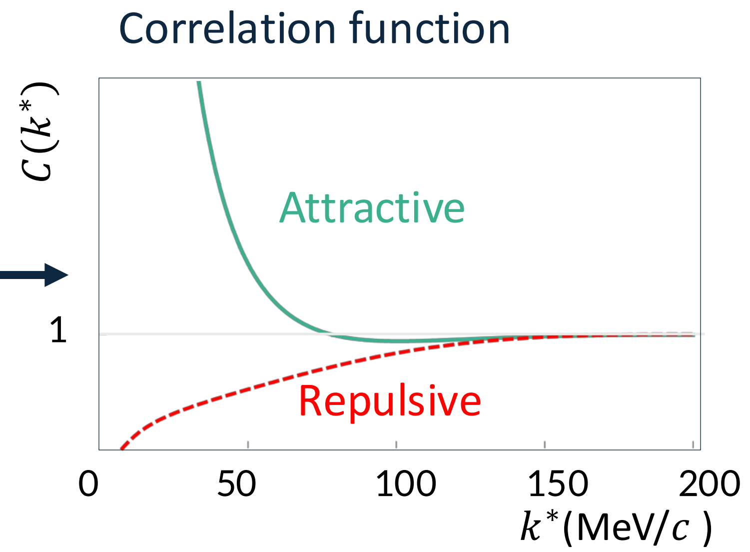

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Measuring $C(k^*)$, fixing the source $S(\vec{r}\,)$, study the interaction

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

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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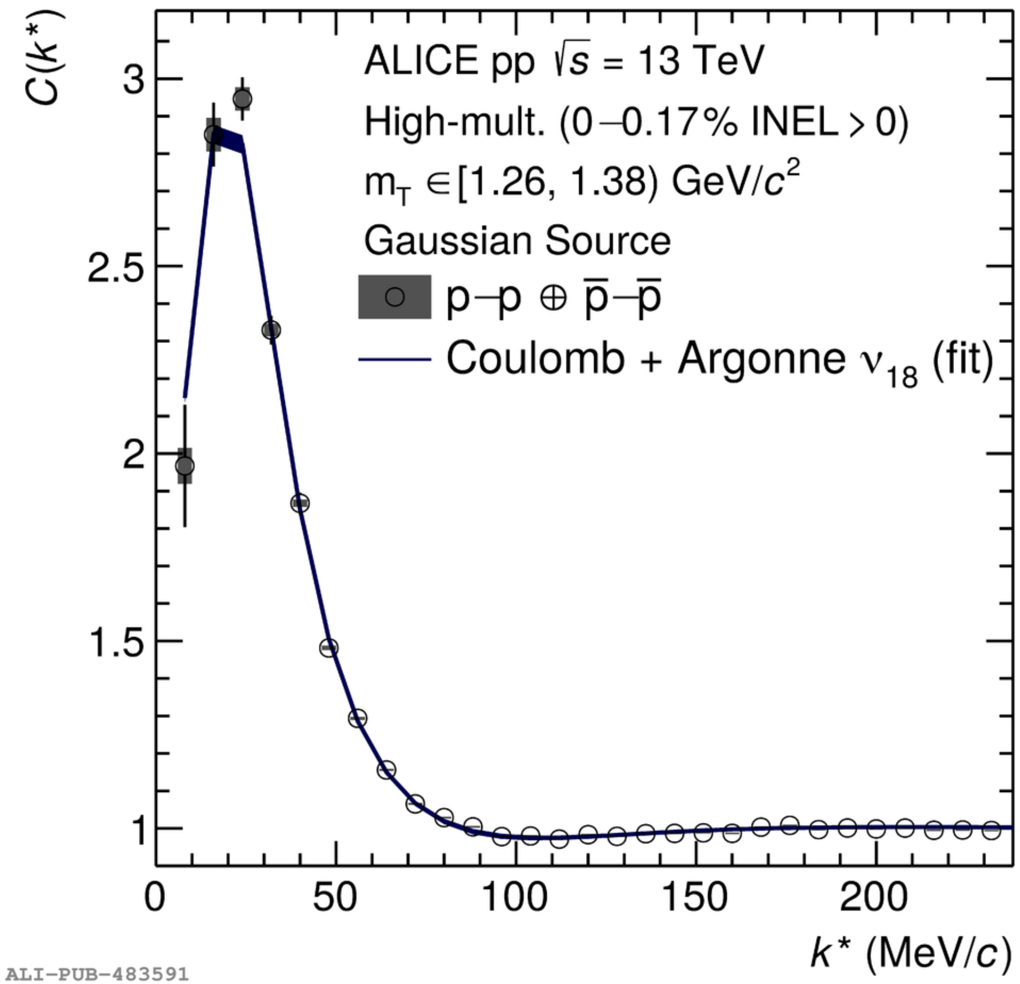

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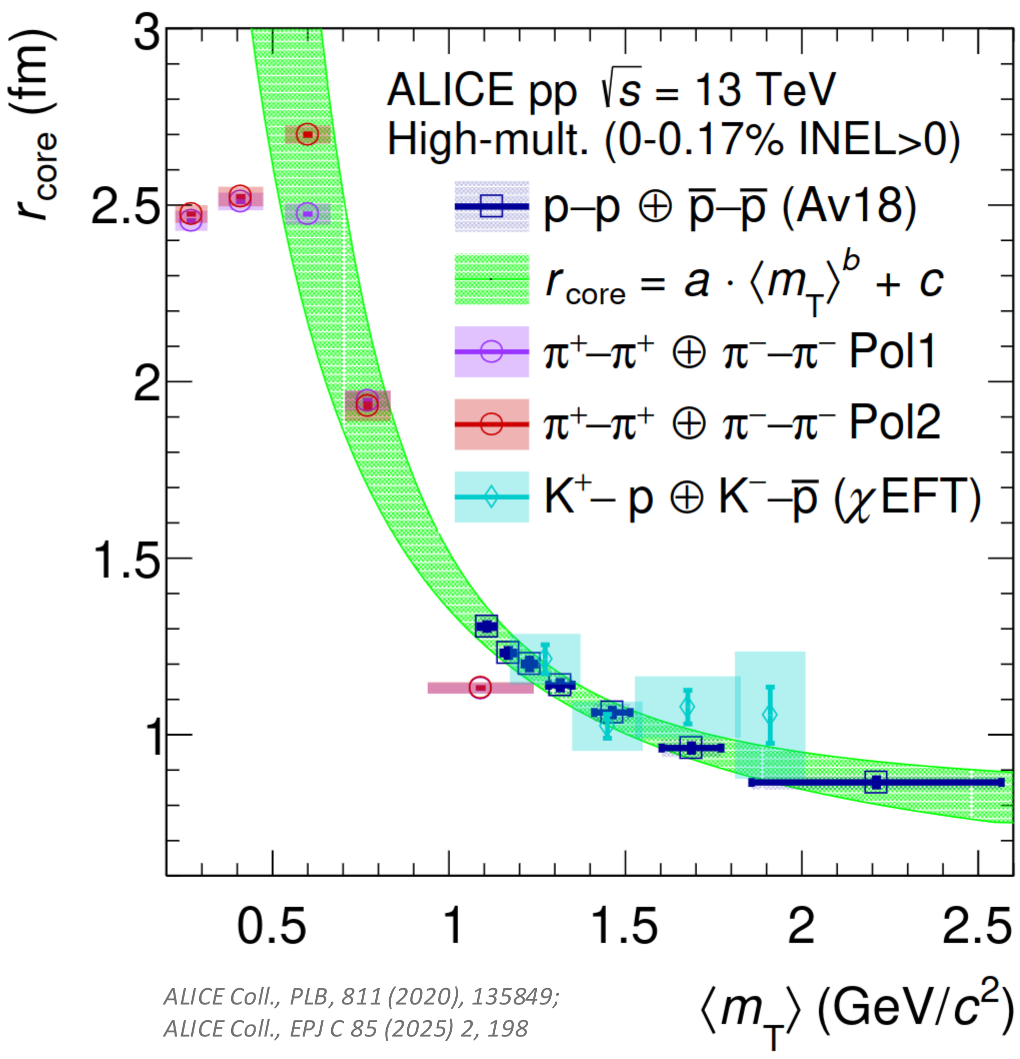
- **Small particle-emitting source created in pp collisions at the LHC**

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



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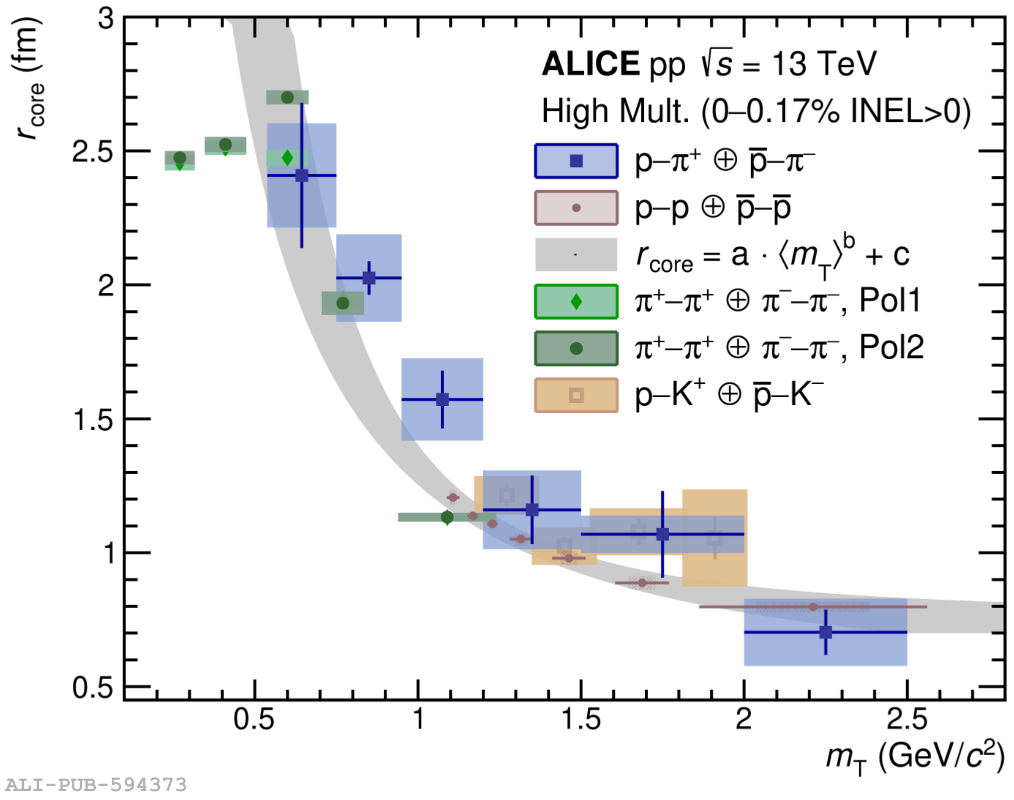

ALICE Coll., PLB, 811 (2020), 135849;
ALICE Coll., EPJ C 85 (2025) 2, 198;
ALICE Coll., arXiv:2502.20200 (2025)

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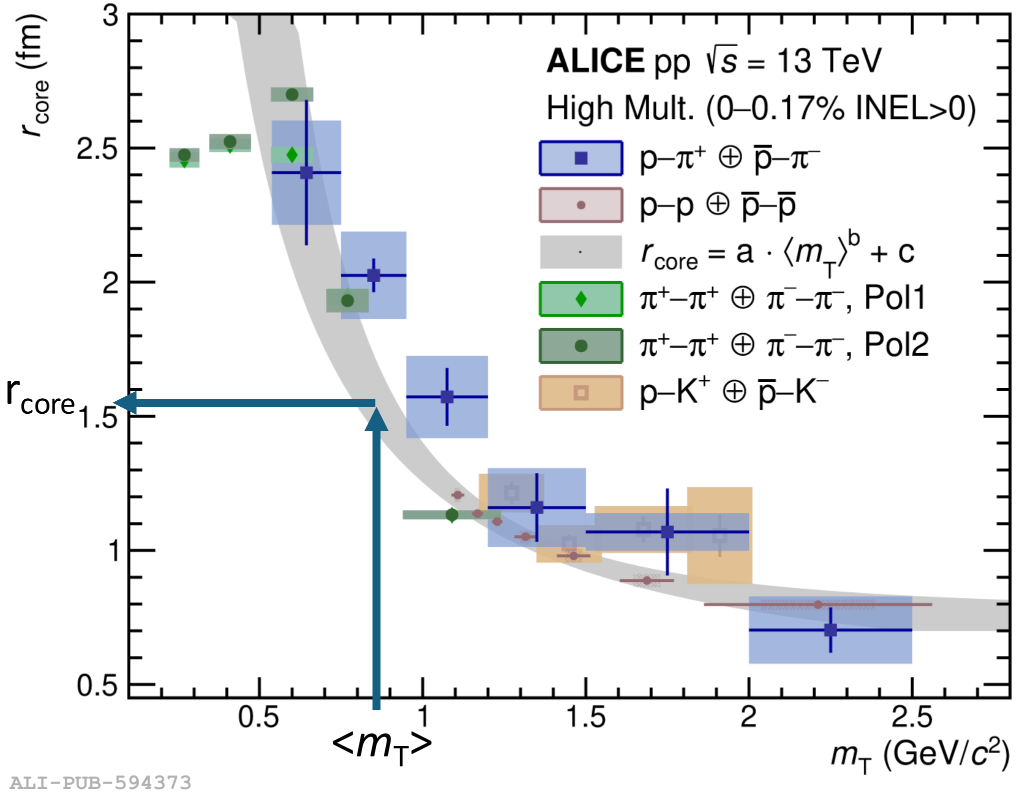
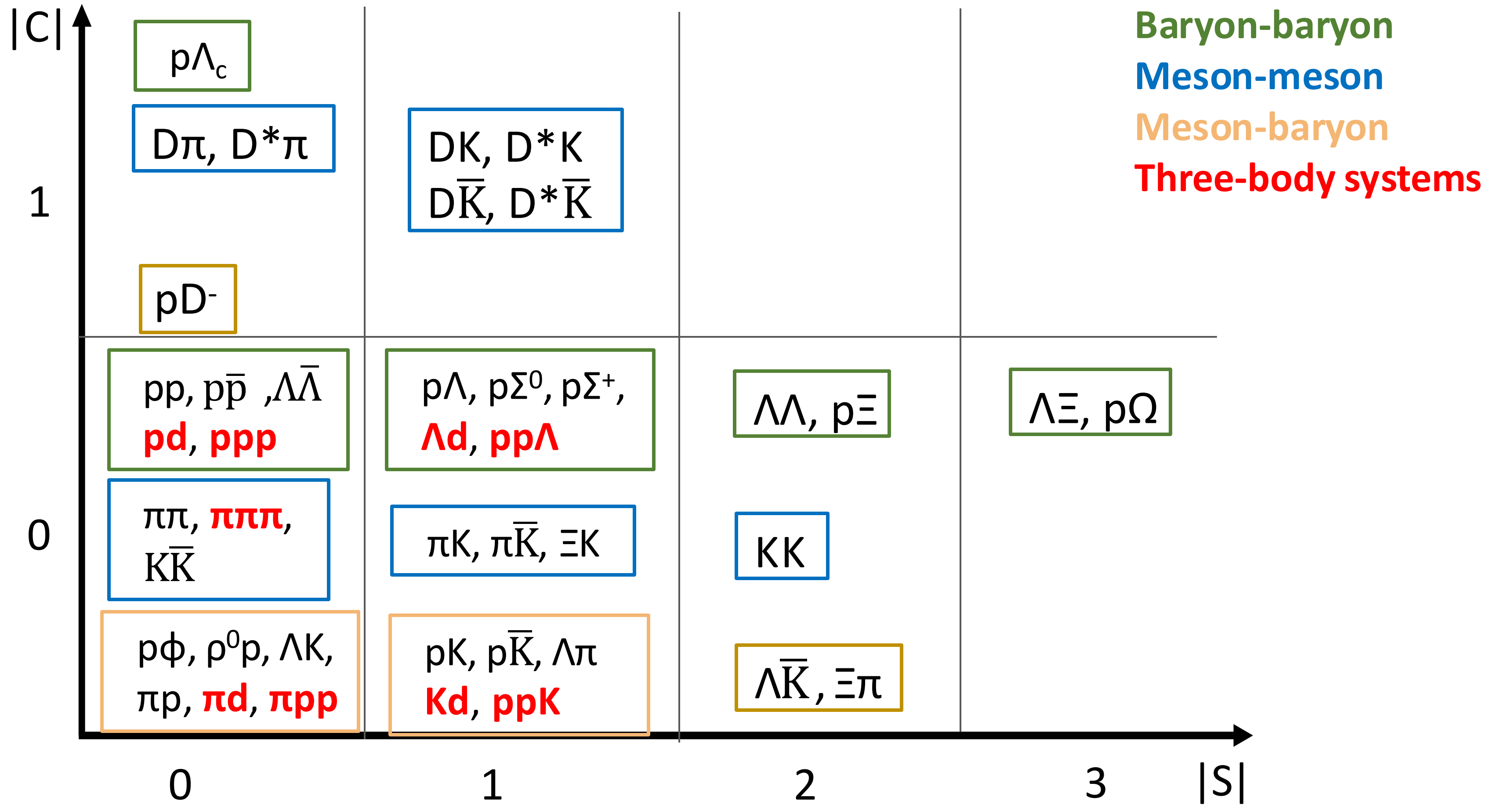


ALICE Coll., PLB, 811 (2020), 135849;
ALICE Coll., EPJ C 85 (2025) 2, 198;
ALICE Coll., arXiv:2502.20200 (2025)

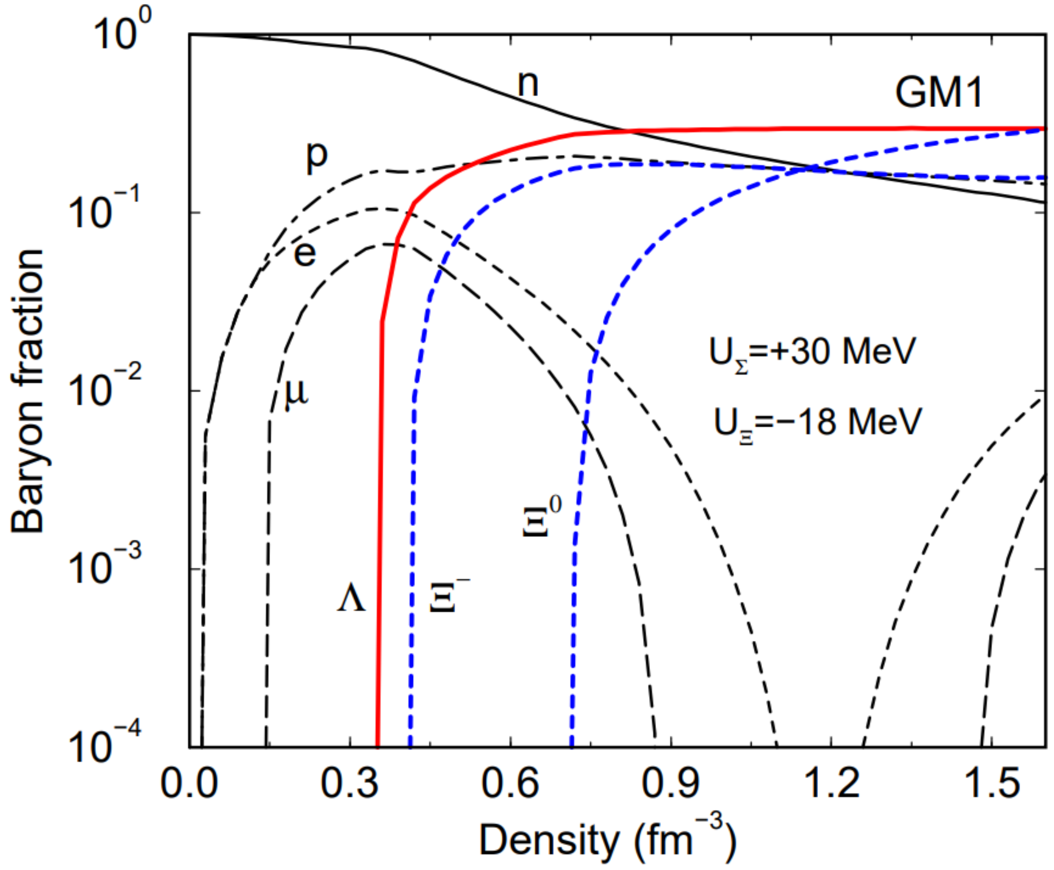
Femtoscopy measurements at the LHC

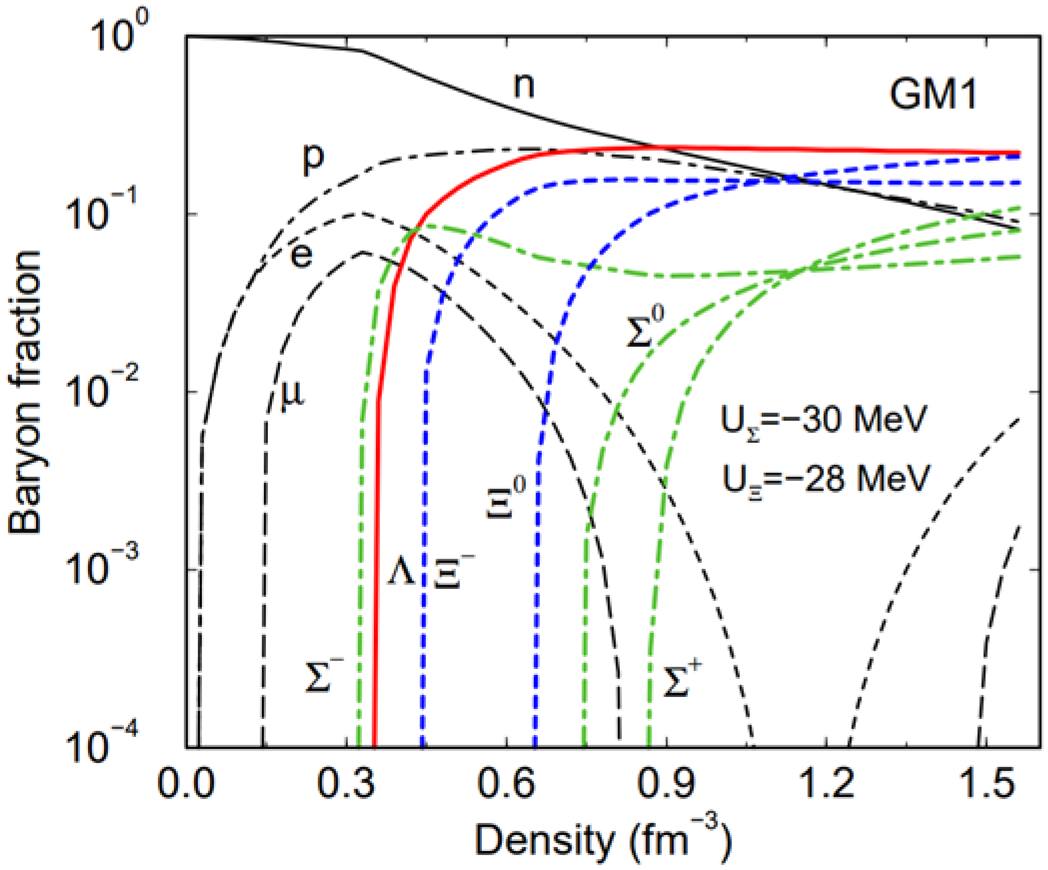


ALICE Collaboration:
PRC 99 (2019) 2, 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 09230
PLB 805 (2020) 135419
PLB 811 (2020) 135849
Nature 588 (2020) 232-238
PRL 127 (2021), 172301
PLB 822 (2021), 136708
PRC 103 (2021) 5, 055201
PLB 833 (2022), 137272
PLB 829 (2022), 137060
PRD 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
arXiv:2502.20200 [nucl-ex]
arXiv:2504.02333 [nucl-ex]

Hyperons in neutron stars

- Exact composition strongly depends on constituent interactions and couplings!



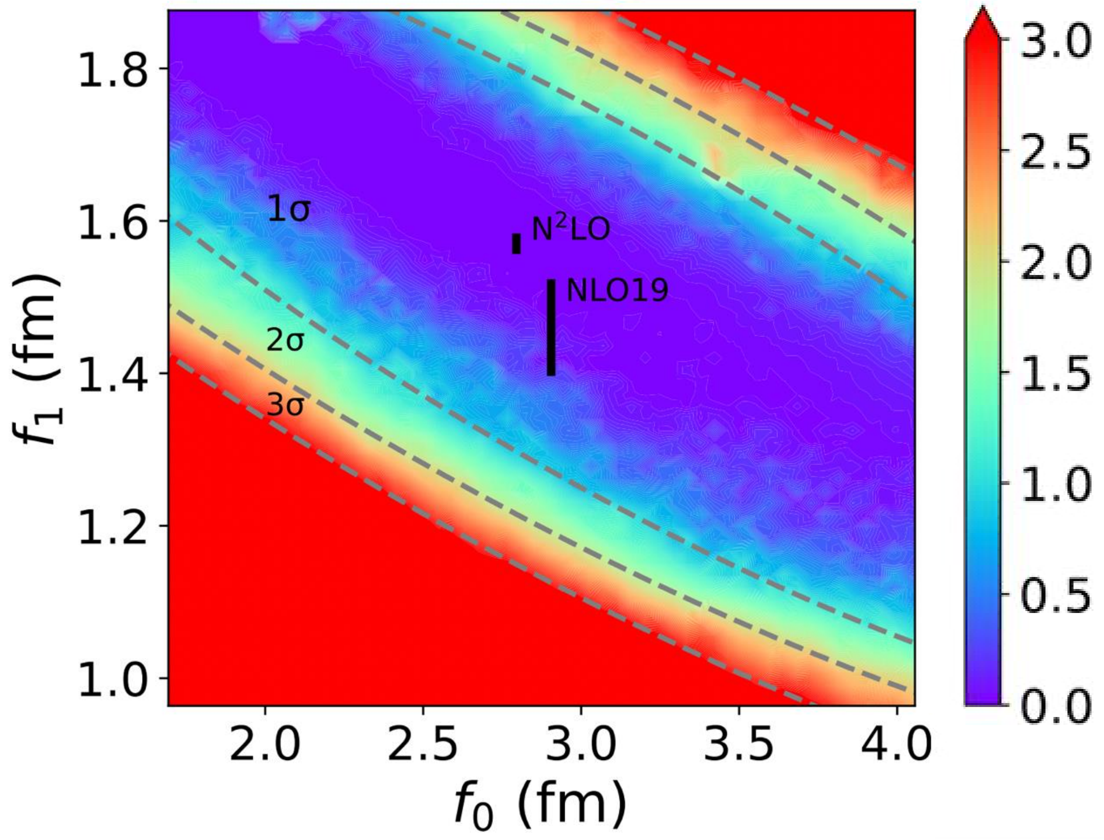


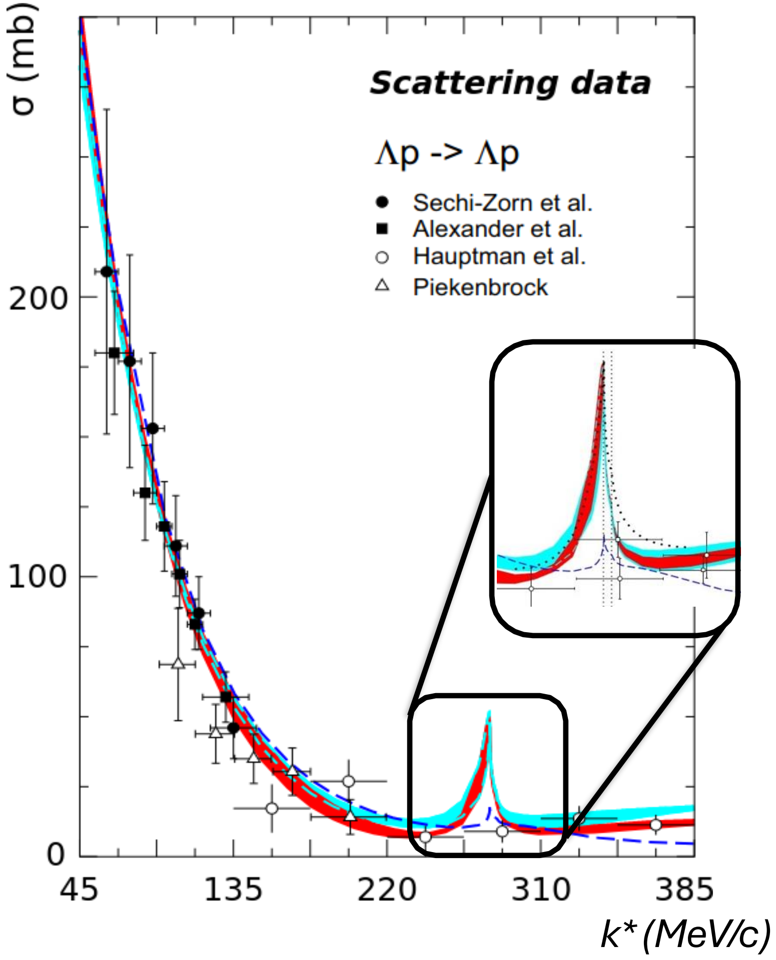
J. Schaffner-Bielich et al NPA 835 (2010)

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

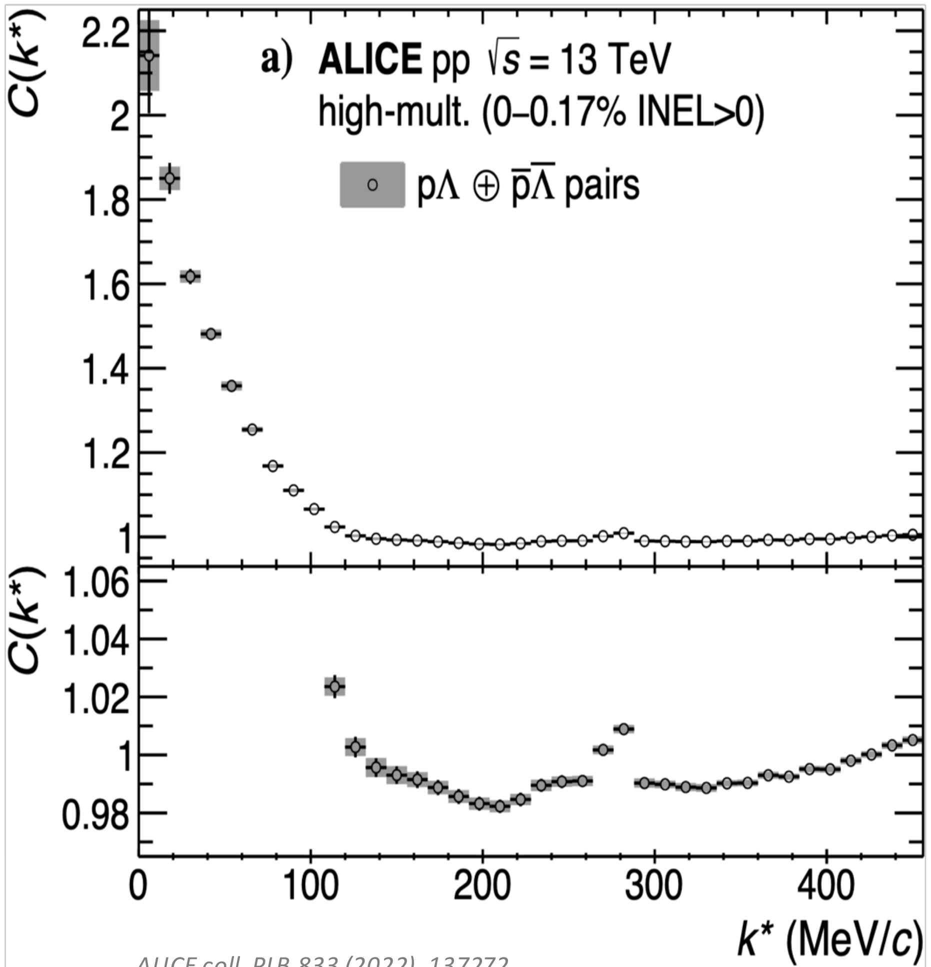




NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

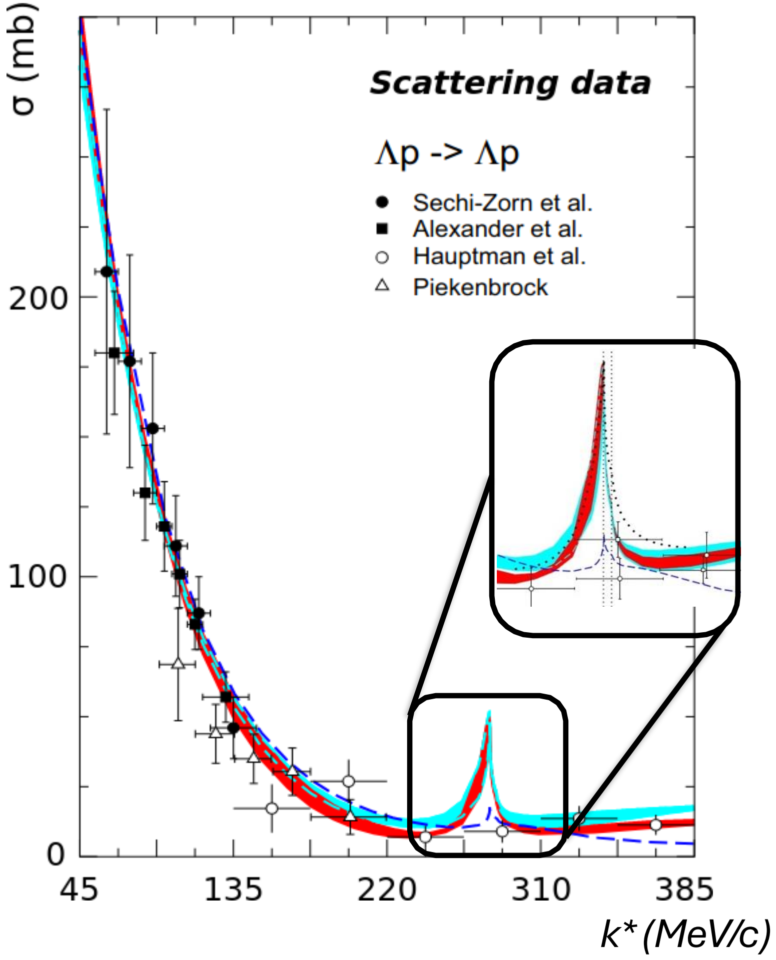
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

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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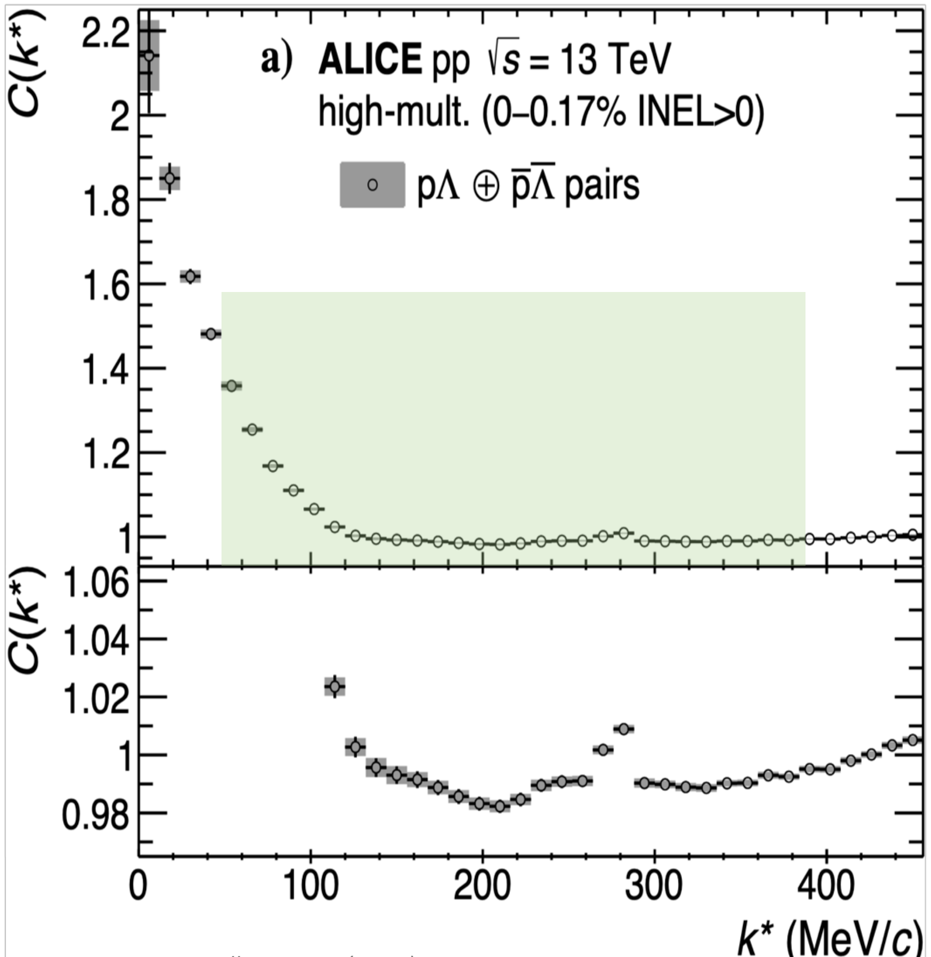

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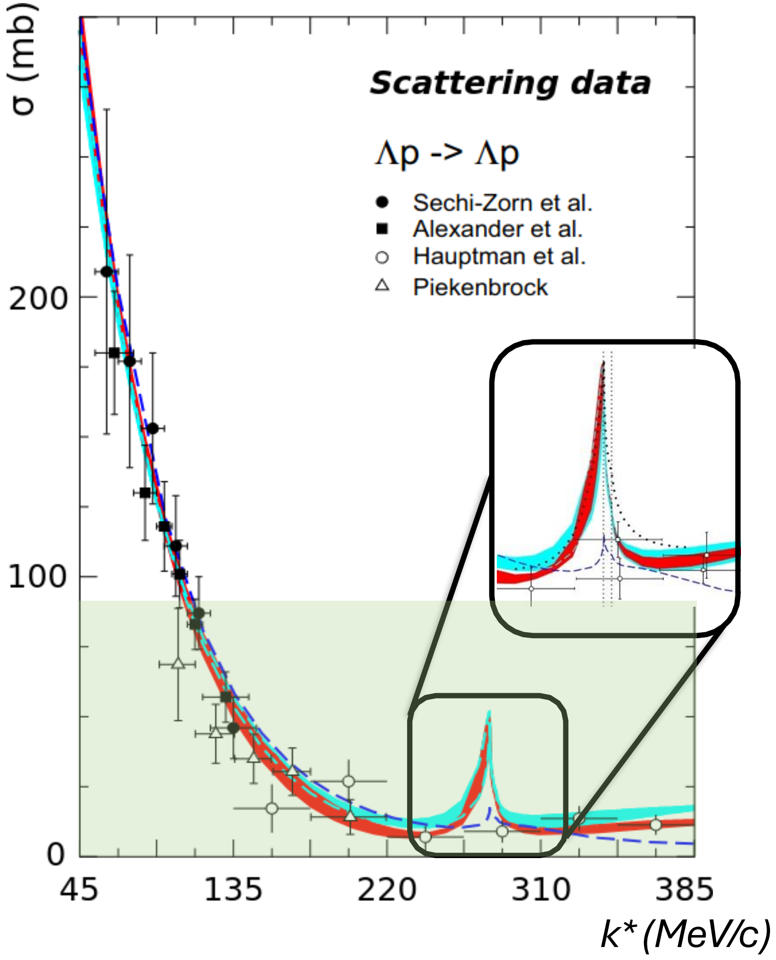

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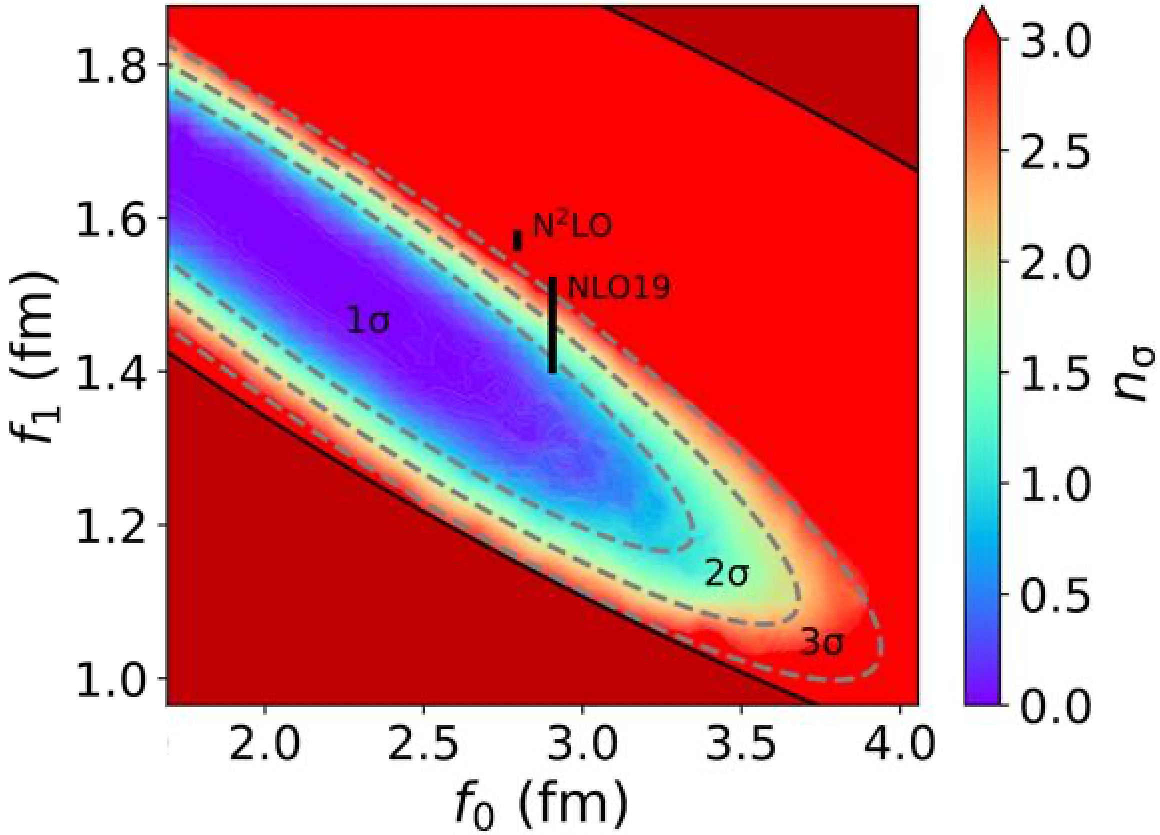
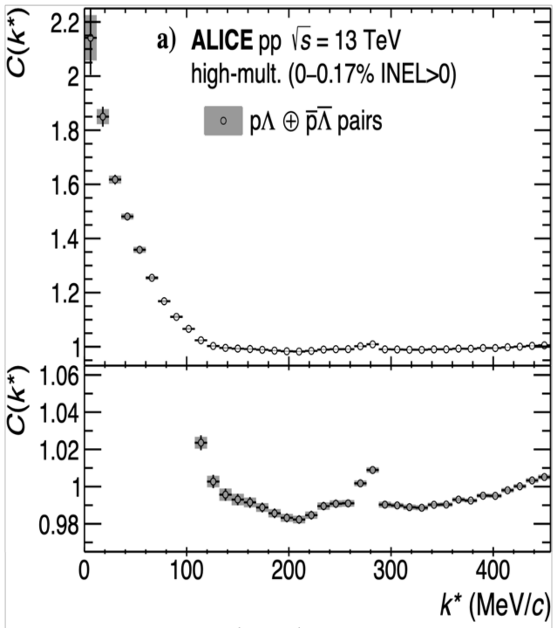
The pΛ interaction in the femtoscopy era

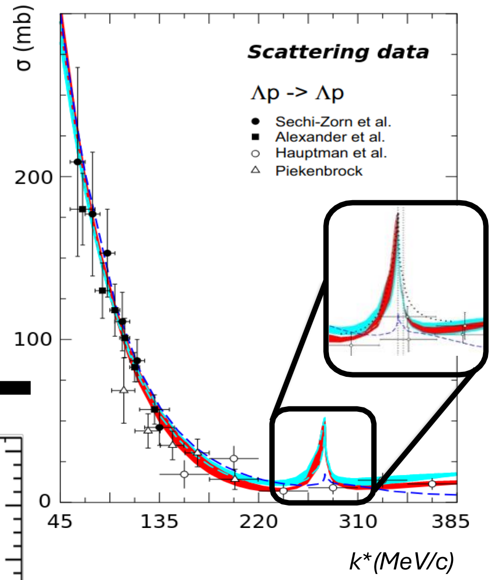
- Combined analysis of femtoscopic and scattering data

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



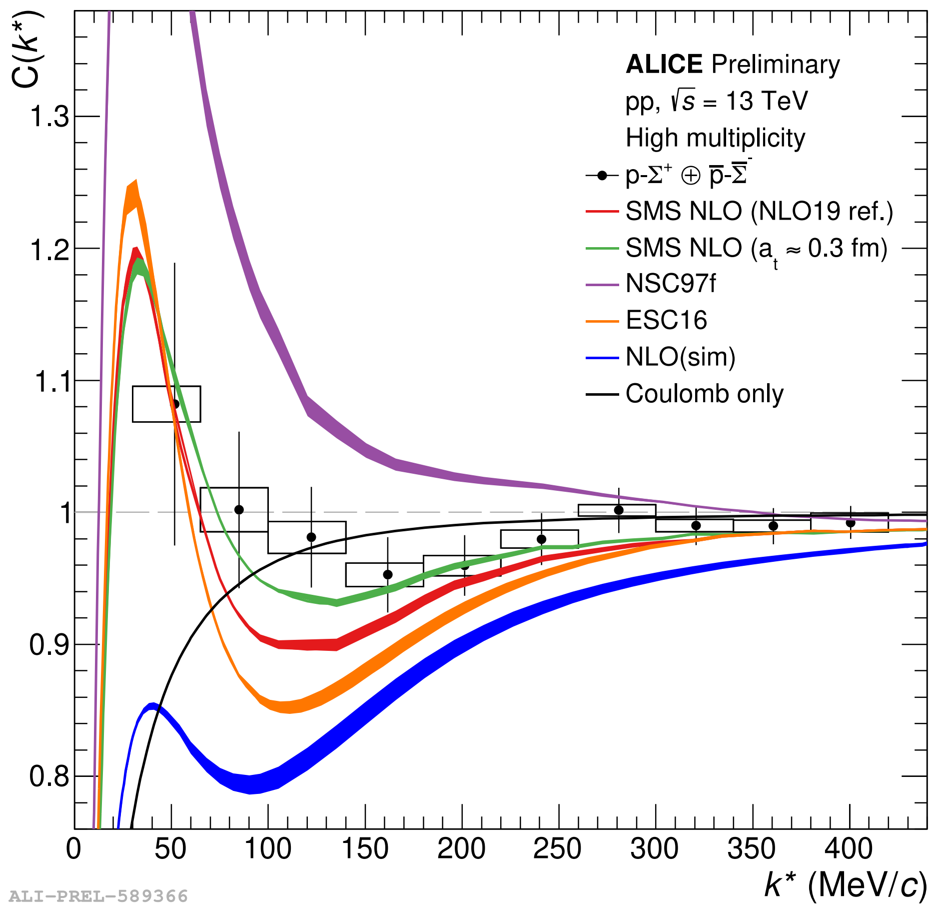


ALICE coll. PLB 833 (2022), 137272

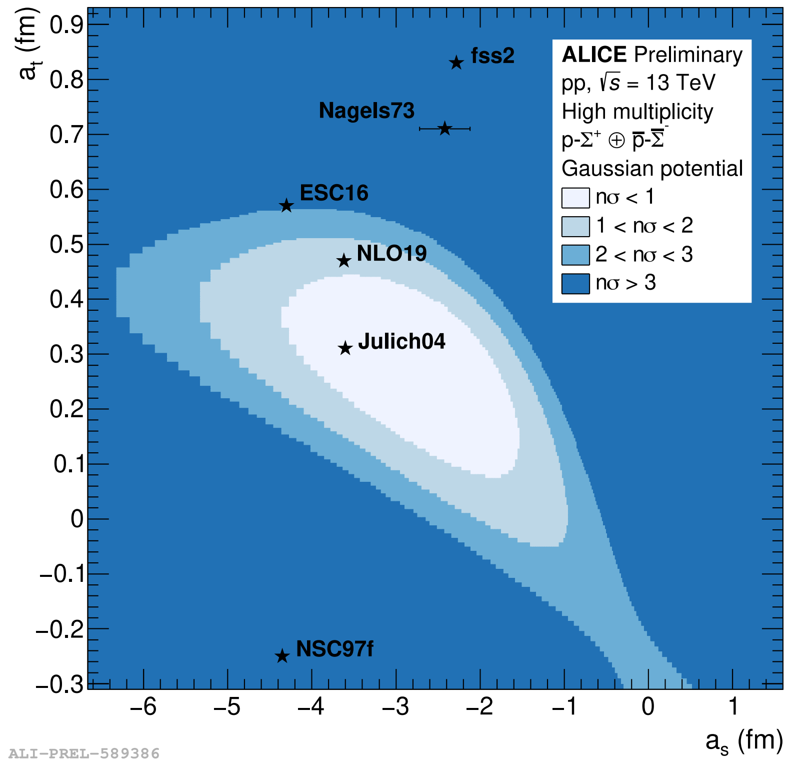


The pΣ^+ interaction

- Data sensitive to the triplet channel



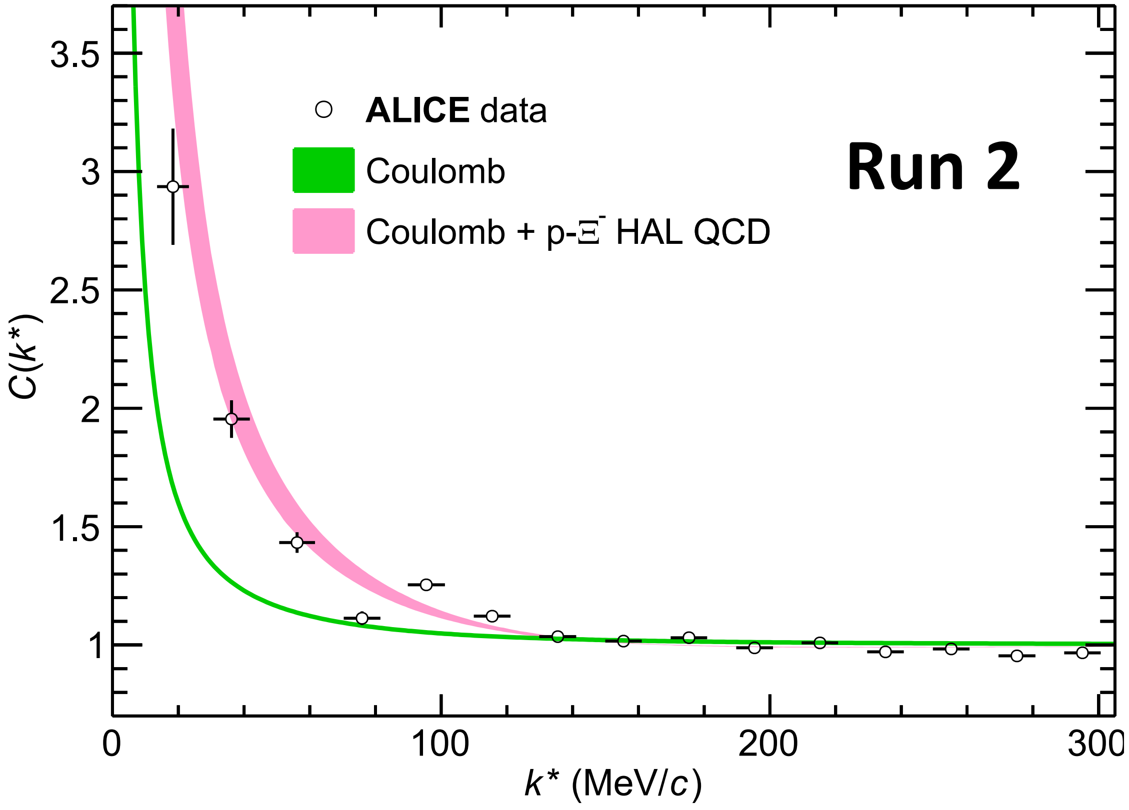
- Fit with Gaussian + Coulomb
- Shallow repulsion in triplet channel



B. Heybeck in collaboration with Y. Kamiya

The pΞ⁻ interaction

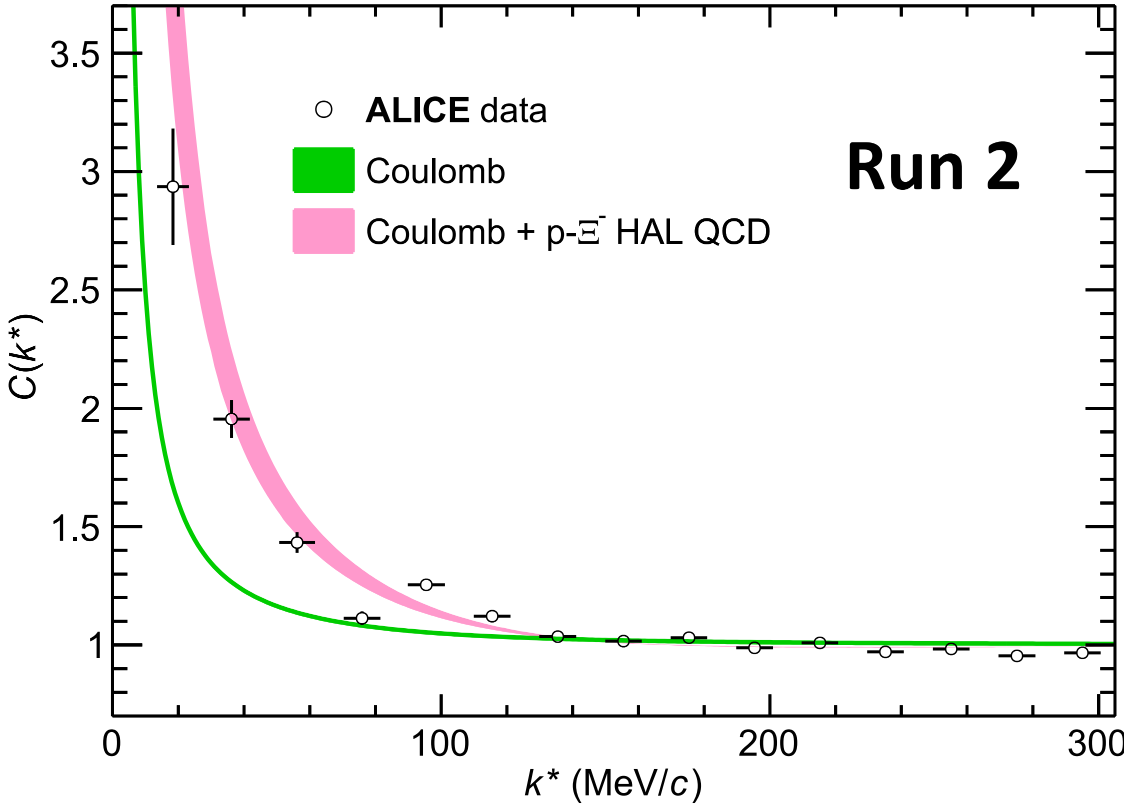
- Evidence of the attractive strong interaction



ALICE Coll., Nature 588 (2020) 232

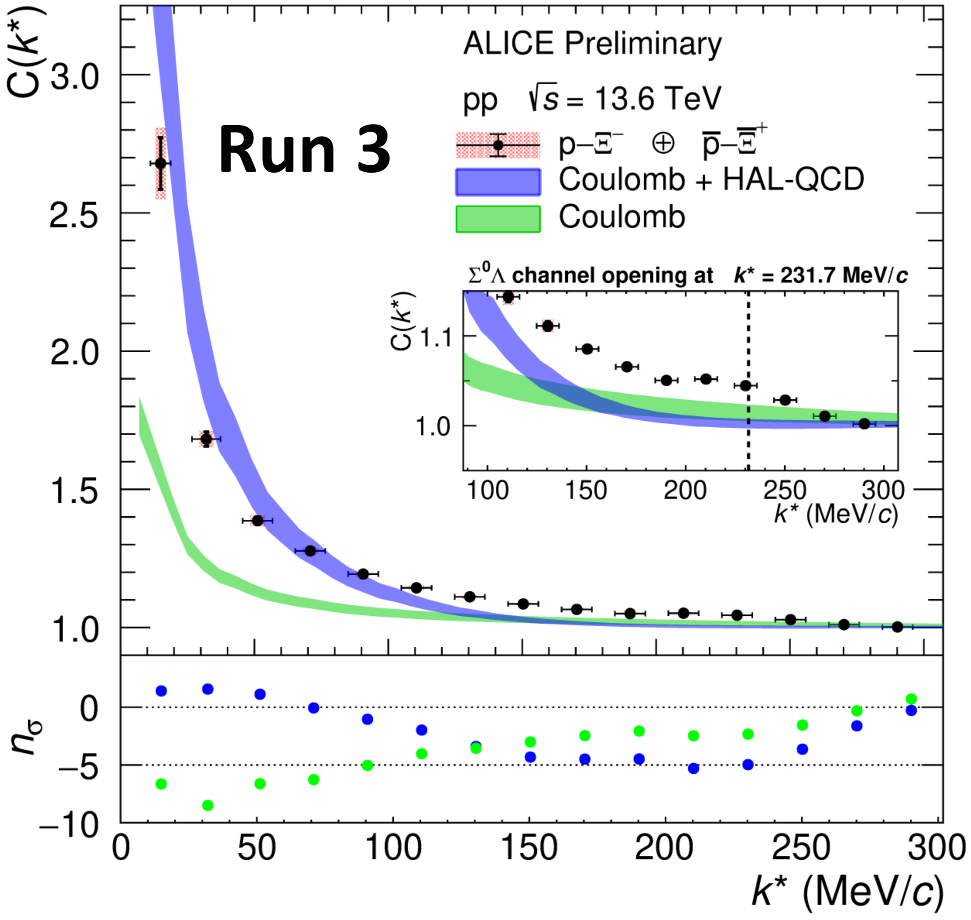
The pΞ^- interaction

- Evidence of the attractive strong interaction



ALICE Coll., Nature 588 (2020) 232

- Opening of the pΞ → $\Lambda\Sigma^0$ channel

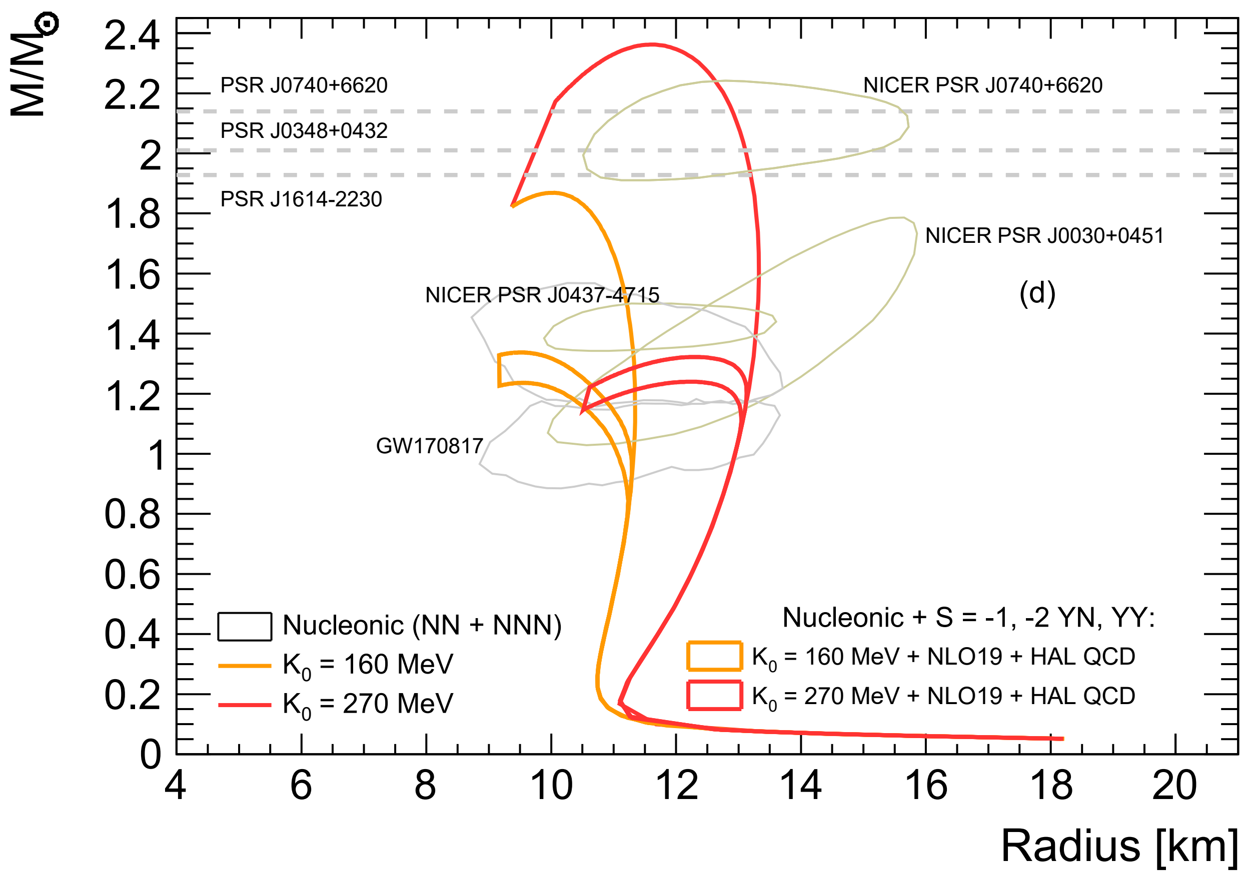


ALI-PREL-603893

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, arXiv: 2412.12729 (2024)



Towards a realistic equation of state of neutron stars

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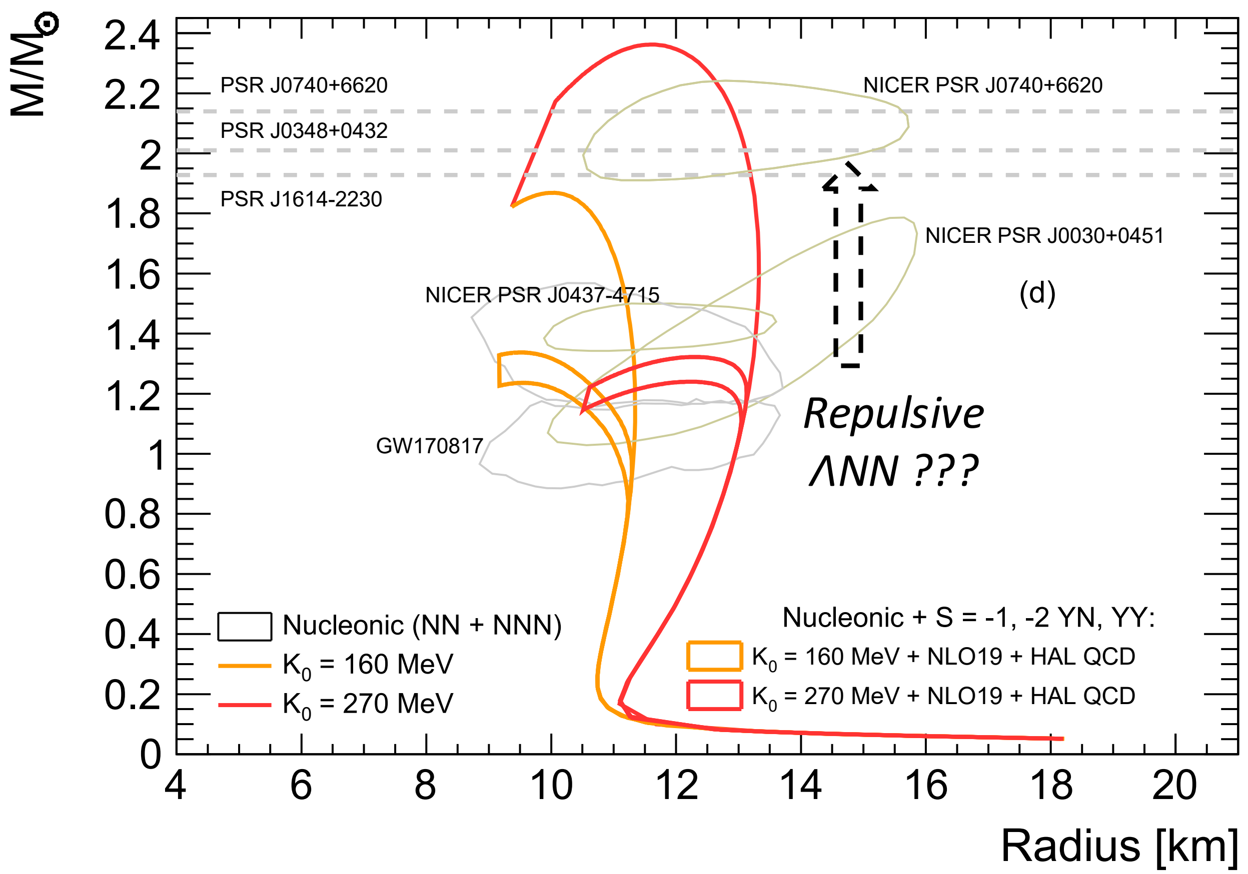
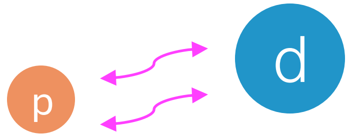
- Next step → inclusion of three body interaction involving hyperons

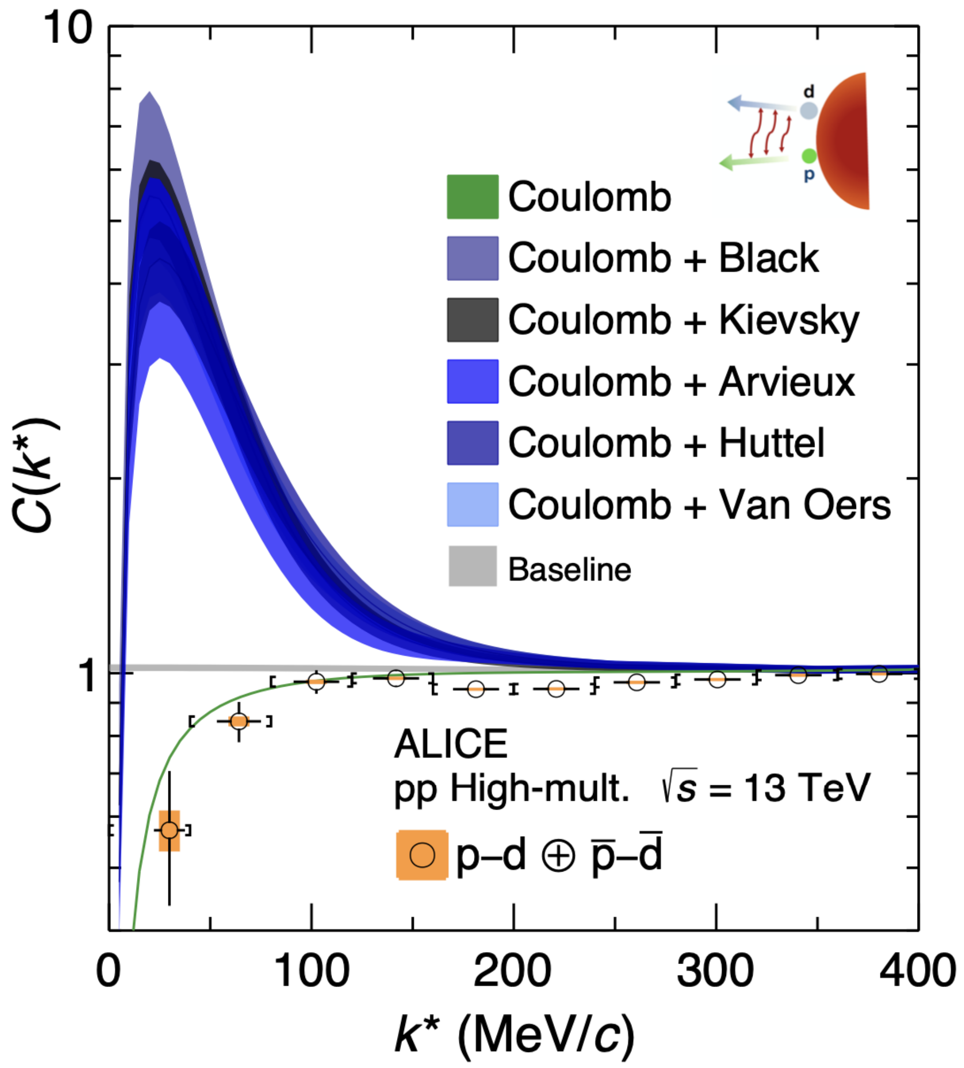


NNN using proton-deuteron correlations



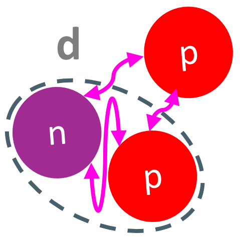
- Point-like particle models anchored to scattering experiments
  W. T. H. Van Oers et al., NPA 561 (1967);
  J. Arvieux et al., NPA 221 (1973); E. Huttel et al., NPA 406 (1983);
  A. Kievsky et al., PLB 406 (1997); T. C. Black et al., PLB 471 (1999);
- Coulomb + strong interaction using Lednický model
  Lednický, R. Phys. Part. Nuclei 40, 307–352 (2009)
- Only s-wave interaction
- Source radius evaluated using the universal m_T scaling

Point-like particle description doesn't work for p-d



ALICE Coll. Phys. Rev. X 14, 031051 (2024)

NNN using proton-deuteron correlations



- The p-d **correlation function**, assuming that p-p-n forms p-d

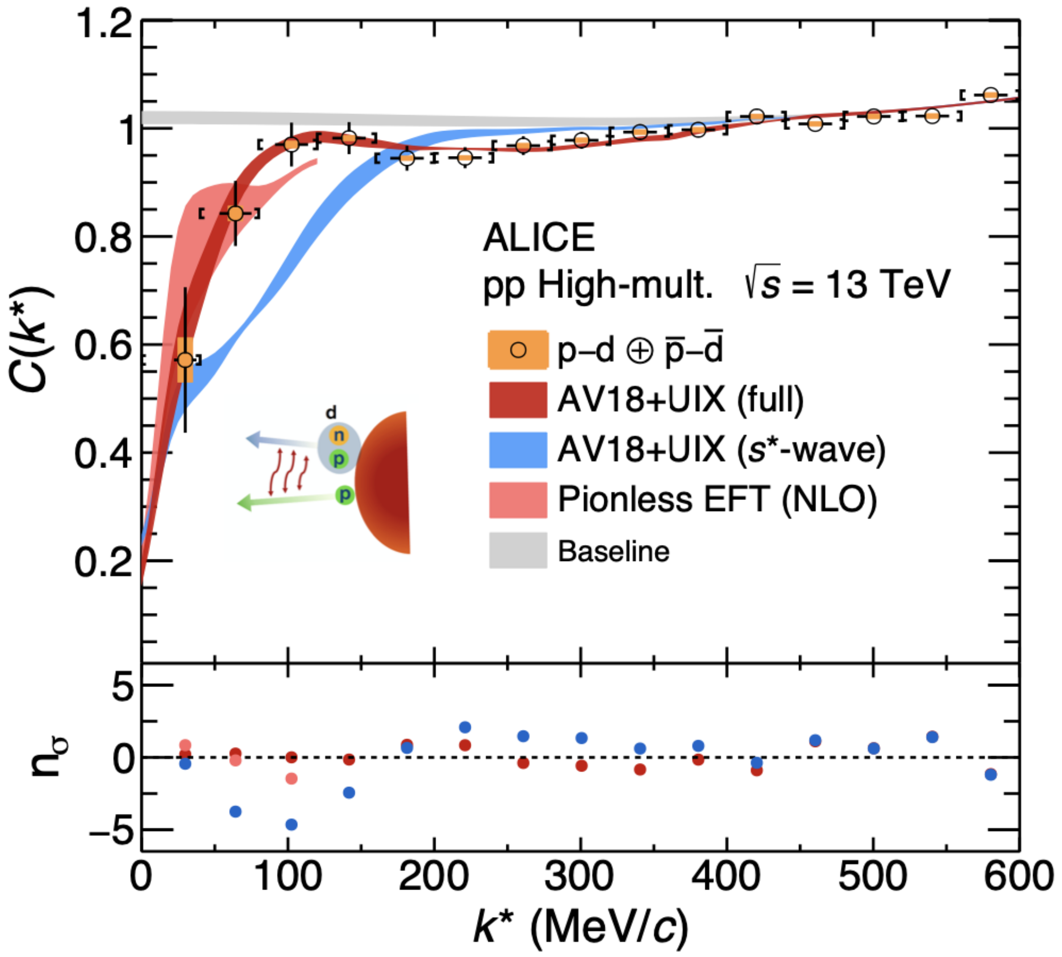
$$C_{pd}(k) = \frac{1}{A_d}\frac{1}{6}\sum_{m_1,m_2} \int d^3r_1 d^3r_2 d^3r_3 S_1(r_1) S_1(r_2) S_1(r_3) \left|\Psi_{m_1,m_2}\right|^2$$

where $S_1(r)$ is a single-particle Gaussian source and A_d is the formation probability of a deuteron

- The **three-body wavefunction** of the p–d System

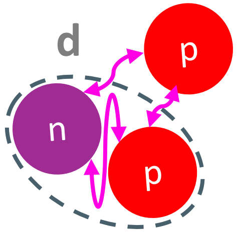
$$\Psi_{m_2,m_1}(x,y) = \underbrace{\Psi^{free}_{m_2,m_1}}_{\text{Asymptotic solution}} + \underbrace{\sum_{LSJ}^{J\leq\bar{J}} \sqrt{4\pi}\; i^L \sqrt{2L+1}\, e^{i\sigma_L} \left(1 m_2 \tfrac{1}{2} m_1 \middle| S J_z\right) (\mathrm{L0SJ_z|JJ_z}) \tilde{\Psi}_{LSJJ_z}}_{\text{Three-body dynamics}}$$

- **Hadron-nuclei correlations at the LHC can be used to study many-body dynamics**

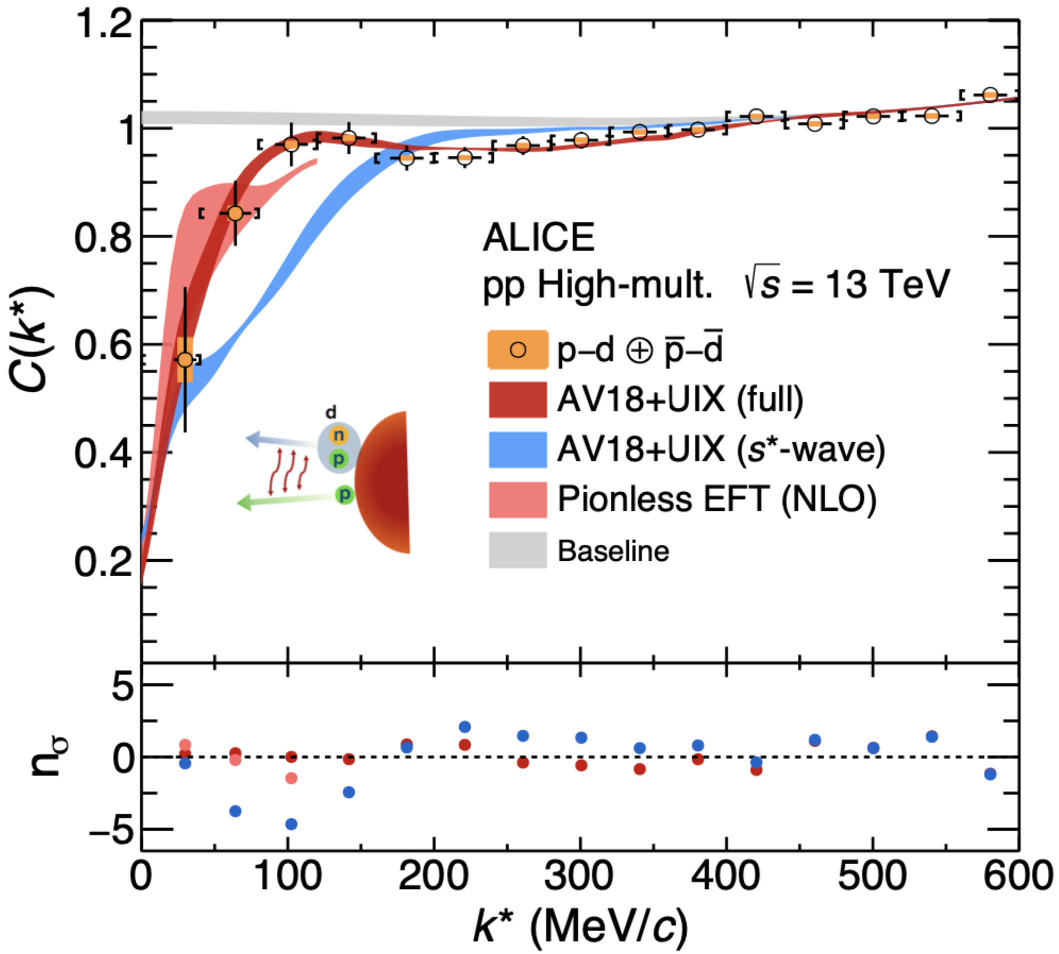


ALICE Coll. Phys. Rev. X 14, 031051 (2024)
M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002

NNN using proton-deuteron correlations



- Full three-body calculations are required (NN + NNN + Quantum Statistics)
- Hadron-nuclei correlations at the LHC can be used to study many-body dynamics



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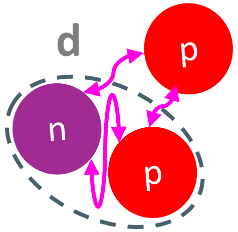
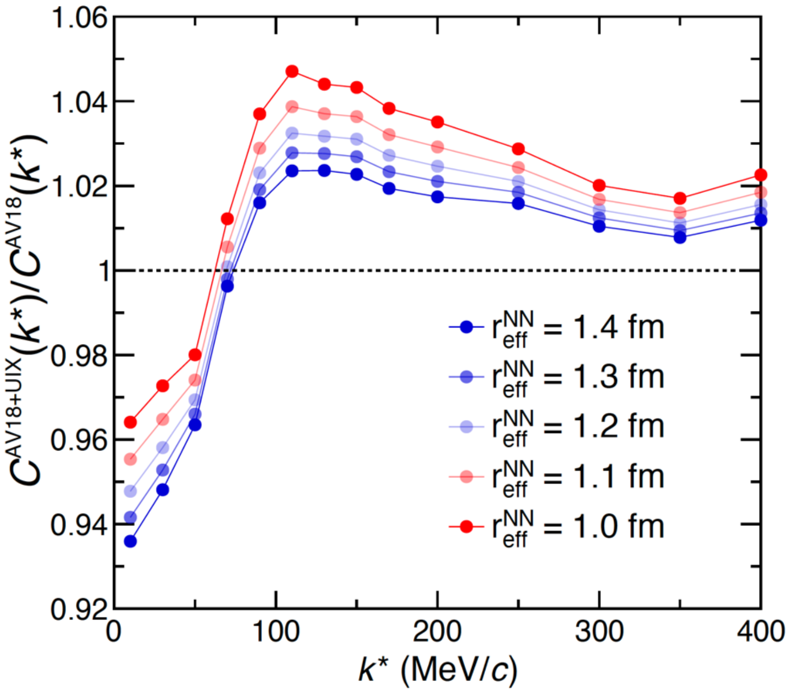
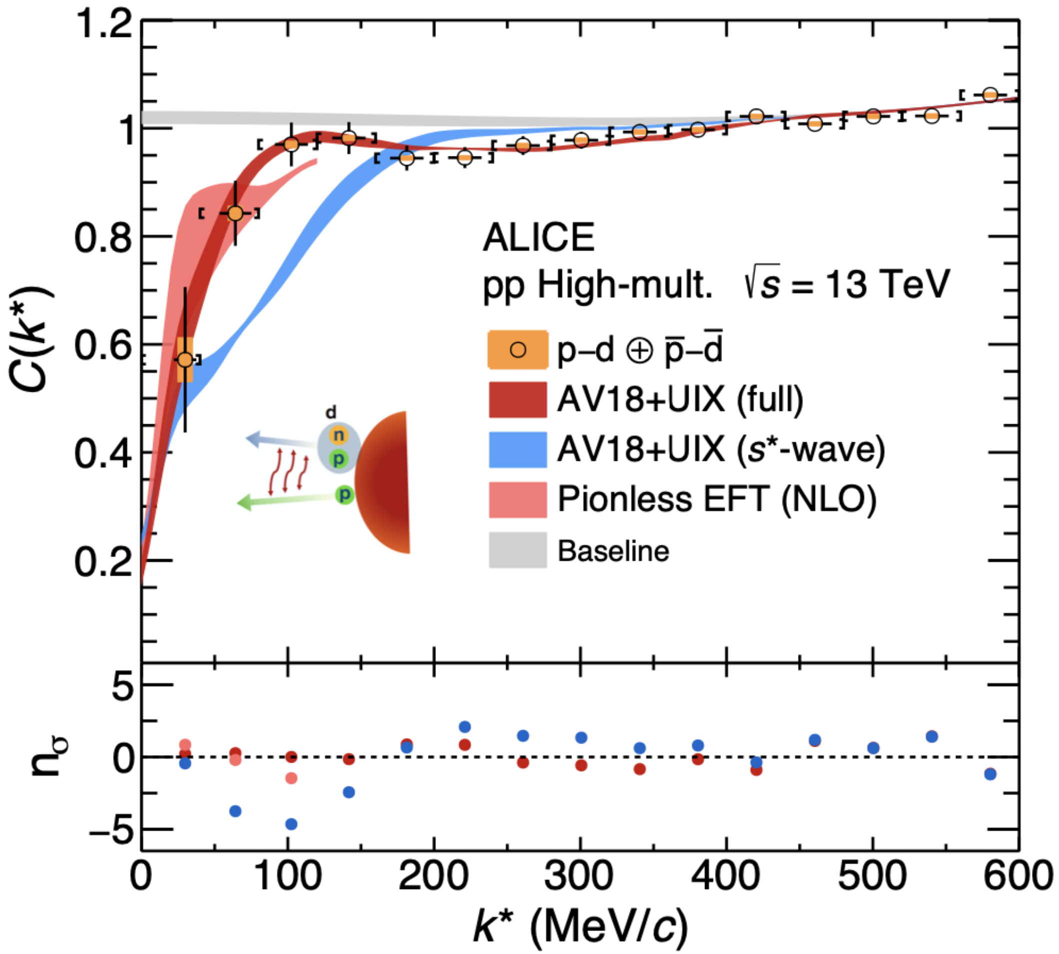


- Full three-body calculations are required (NN + NNN + Quantum Statistics)
- Hadron-nuclei correlations at the LHC can be used to study many-body dynamics
- Sensitivity to three-body forces up to 5%





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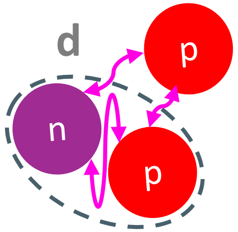

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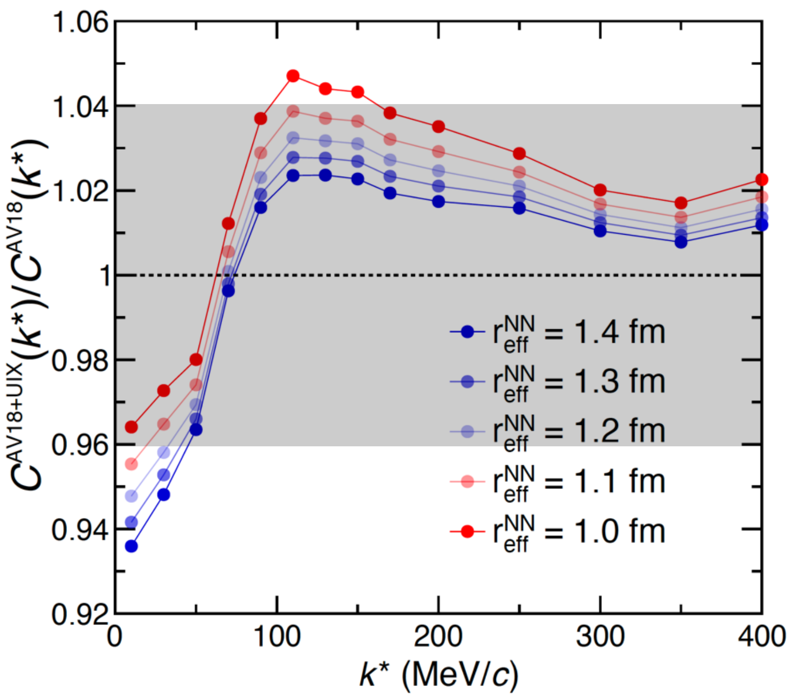

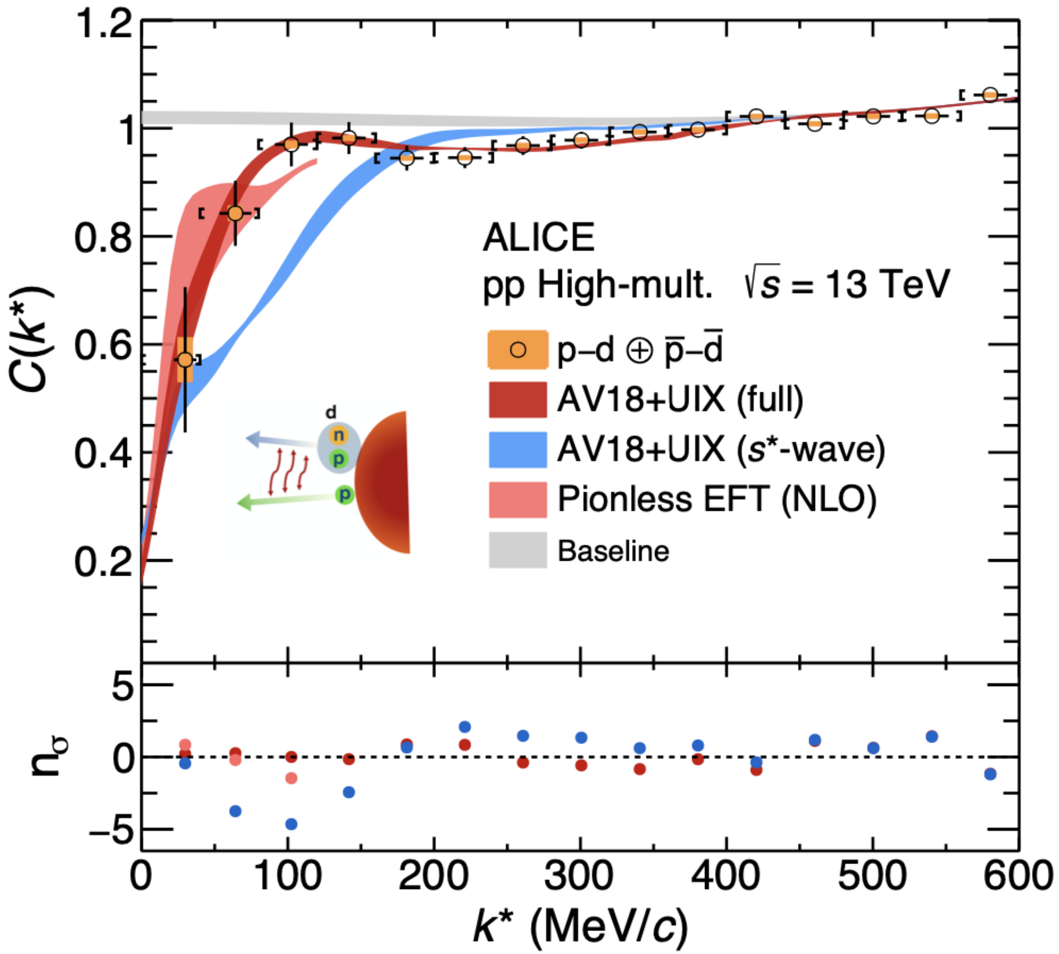

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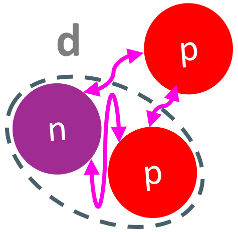
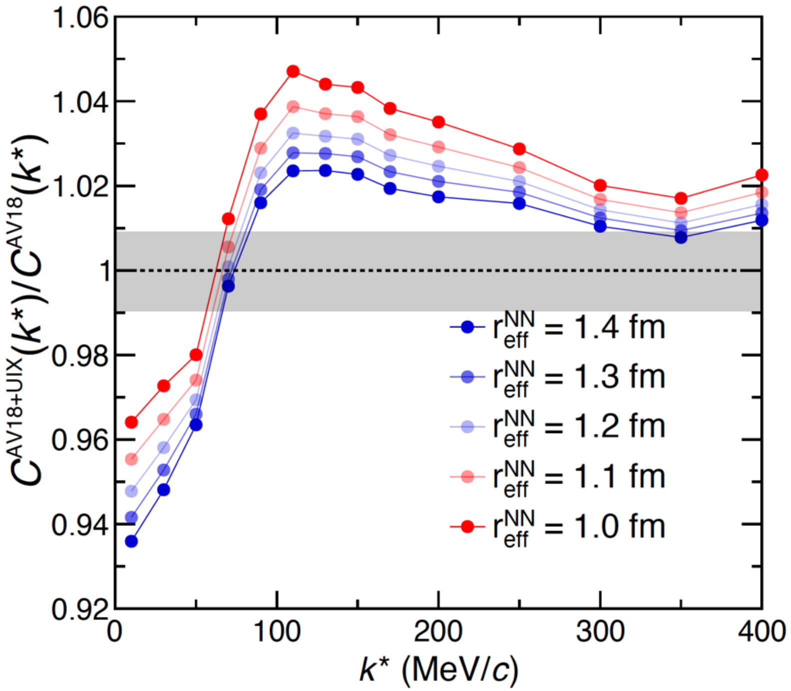
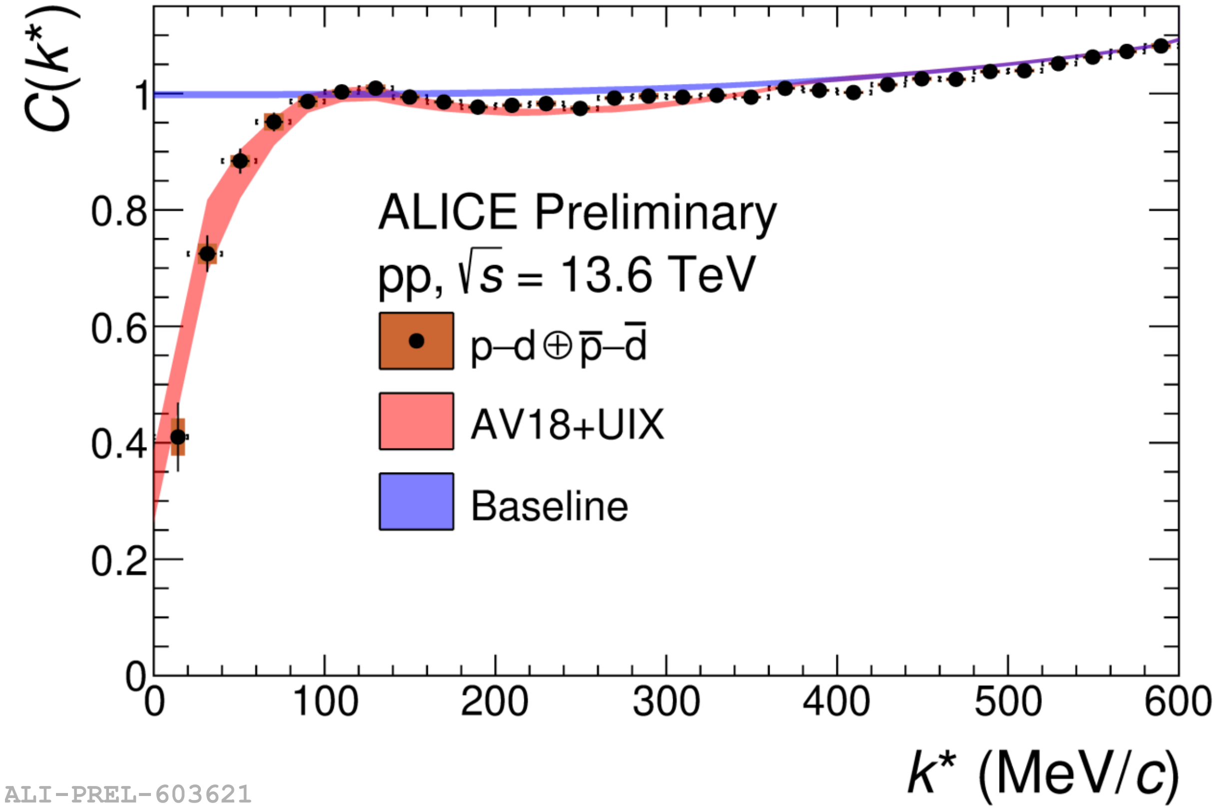
NNN using proton-deuteron correlations



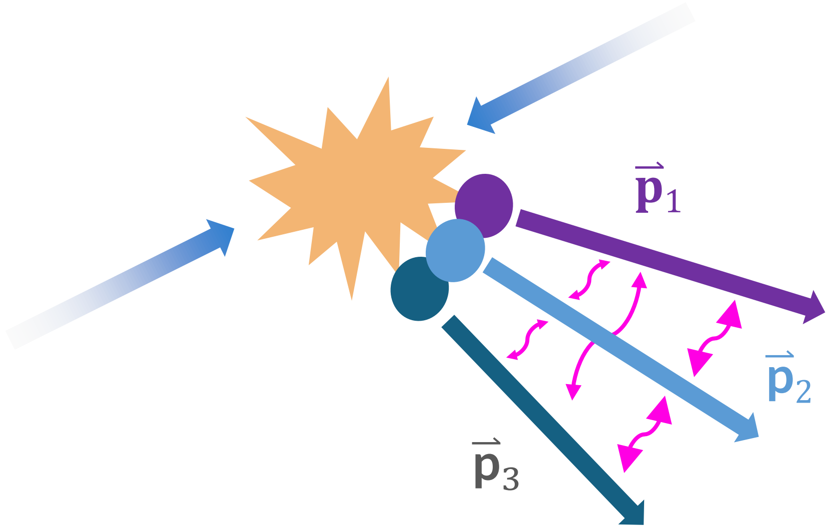
- Full three-body calculations are required (NN + NNN + Quantum Statistics)
- Results from Run 3 are promising!
- In Run 3 expected uncertainty of 1%





M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002

Three-body femtoscopy in pp collisions



Correlation function:

$$C(Q_3) = \int S(\rho)|\psi\,(Q_3,\rho\,)|^2\,\rho^5\,d\rho$$

Three-body scattering wave function

Hyper-momentum:

$$Q_3 = 2\sqrt{k_{12}^2 + k_{23}^2 + k_{31}^2}$$

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

Hyper-radius:

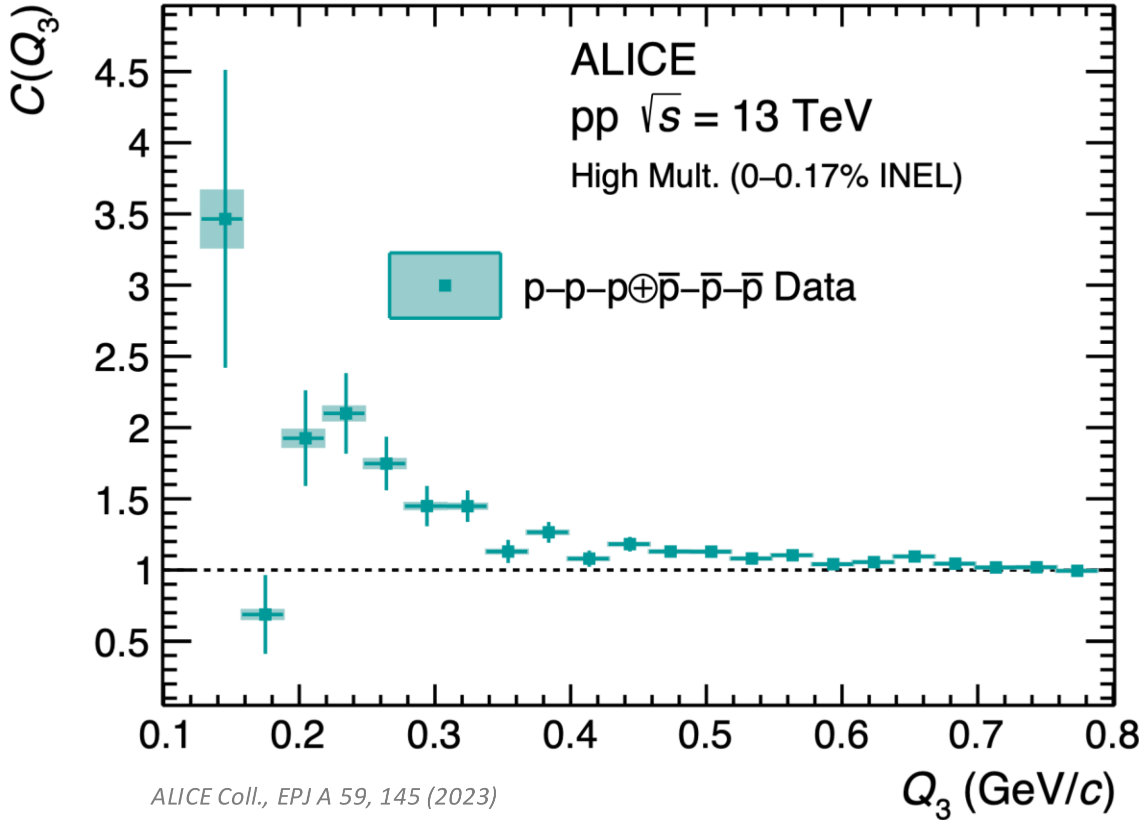
$$\rho = 2\sqrt{r_{12}^2 + r_{23}^2 + r_{31}^2}$$

L. E. Marcucci et al., Front. in Phys. 8, 69 (2020).

Extension to three-particle system

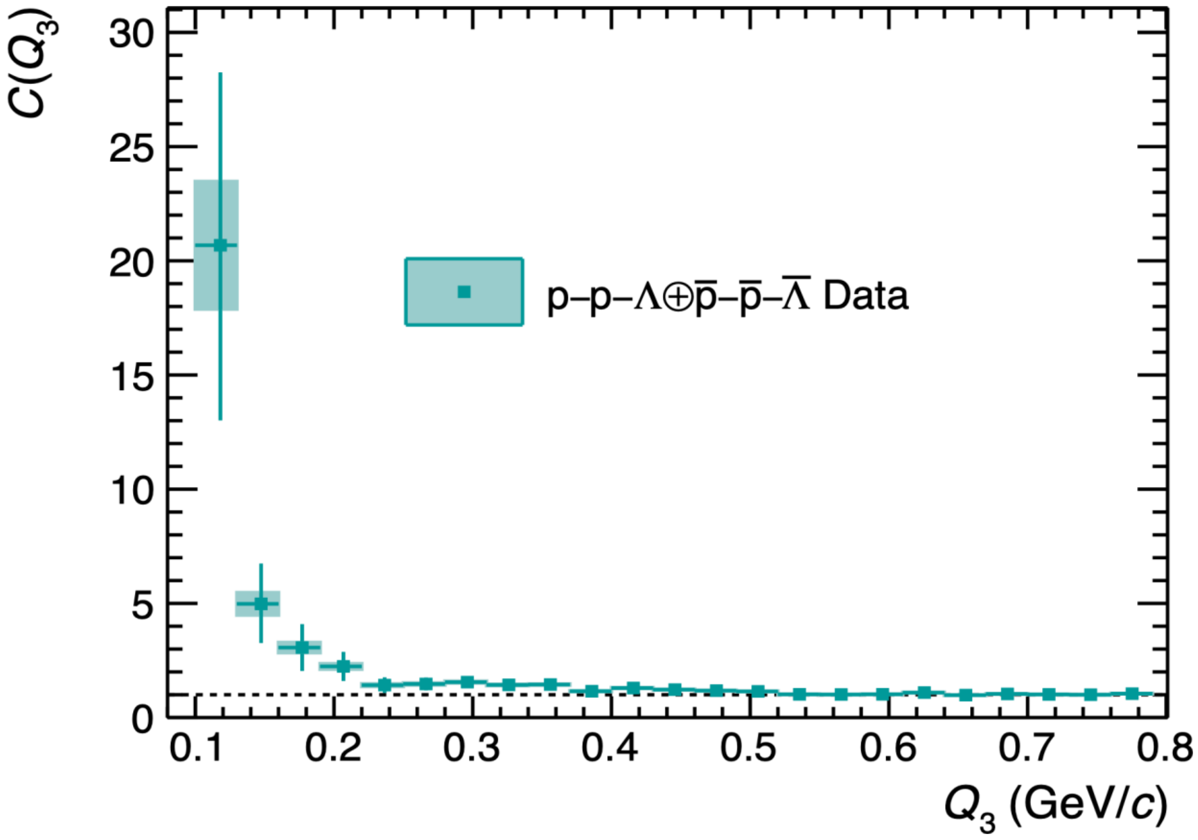
- First measurement of the free scattering of three hadrons
- Deviation from unity in p-p-p and p-p-Λ correlation functions

p-p-p



ALICE Coll., EPJ A 59, 145 (2023)

p-p-Λ



p-p-p correlation function

- First ever full three-body correlation function calculations

three-proton wave function

$$C(Q_3) = \int \rho^5 d\rho\, S(\rho, \rho_0) |\Psi(\rho, Q_3)|^2$$

hyperradius

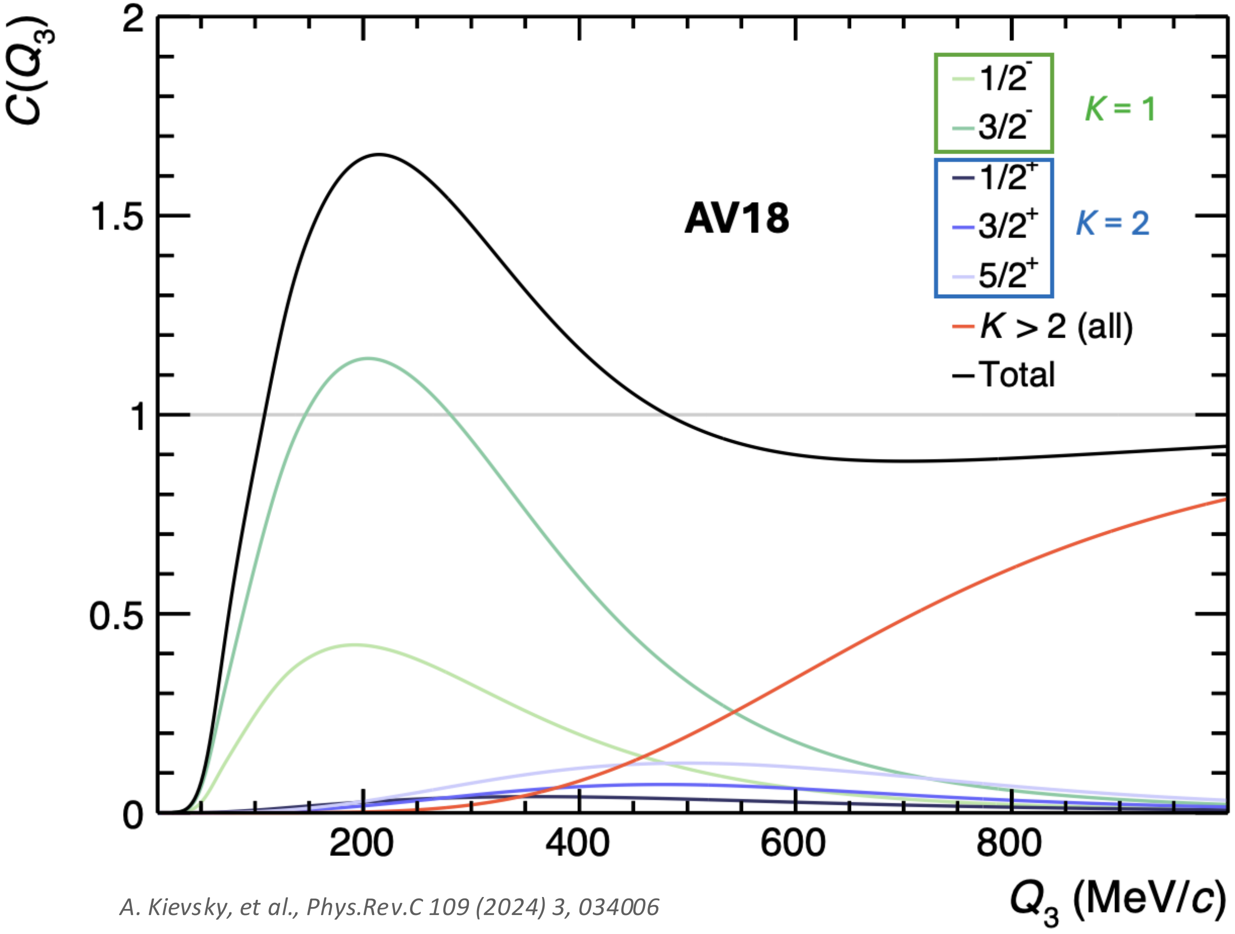
- Wave function in hyperspherical harmonics

$$\Psi(\rho, Q_3) = \sum_K R_K(\rho) Y_K(\Omega)$$

- Interactions:
  - pp strong interaction (AV18)
  - Coulomb
  - No three-body forces

A. Kievsky, et al., Phys.Rev.C 109 (2024) 3, 034006

- p-p-p correlation function: superposition of many partial waves

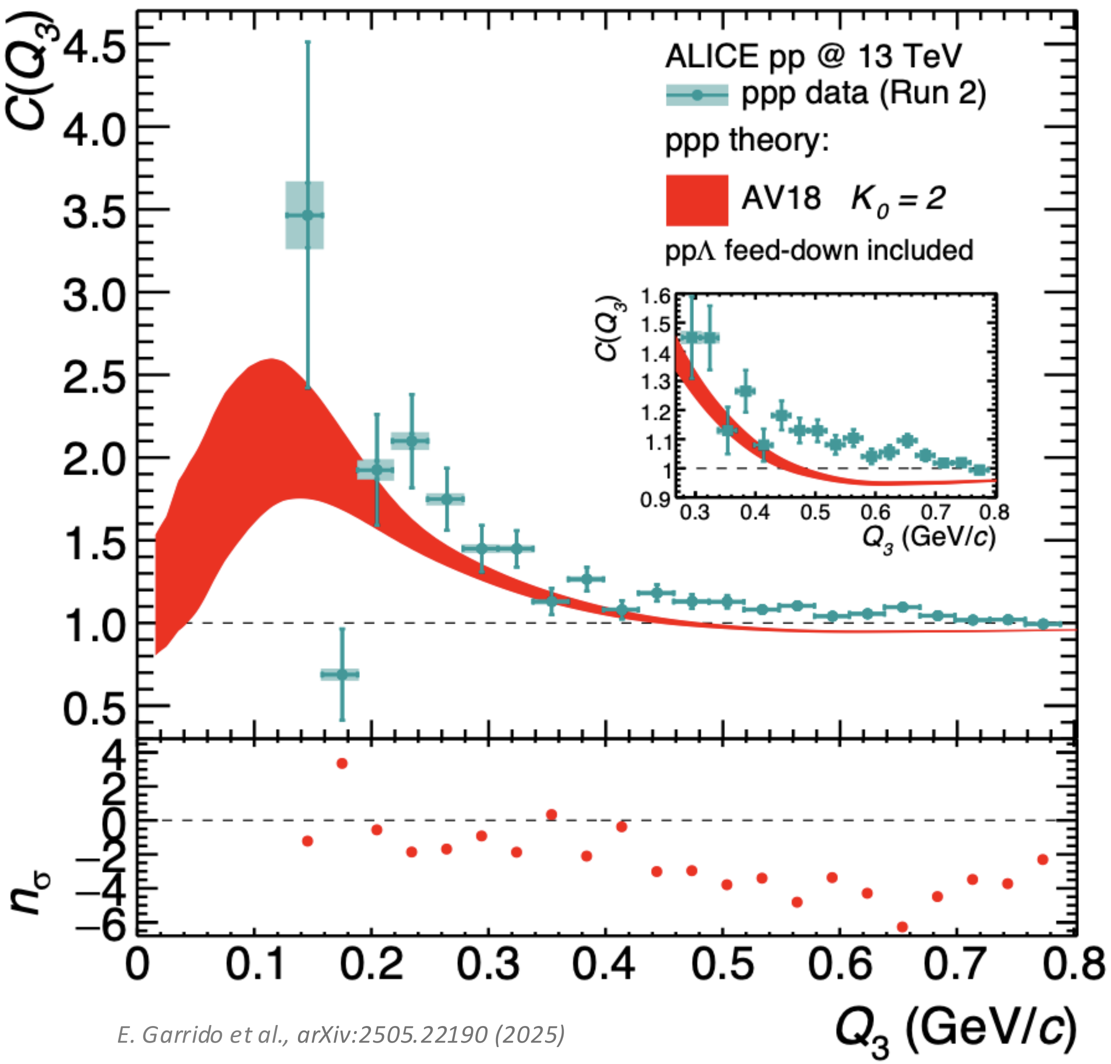


A. Kievsky, et al., Phys.Rev.C 109 (2024) 3, 034006

Comparison Run-2 data

Comparison with the ALICE Run-2 measurement:

- calculations can describe the shape observed in the data
- tension at large values of Q_3



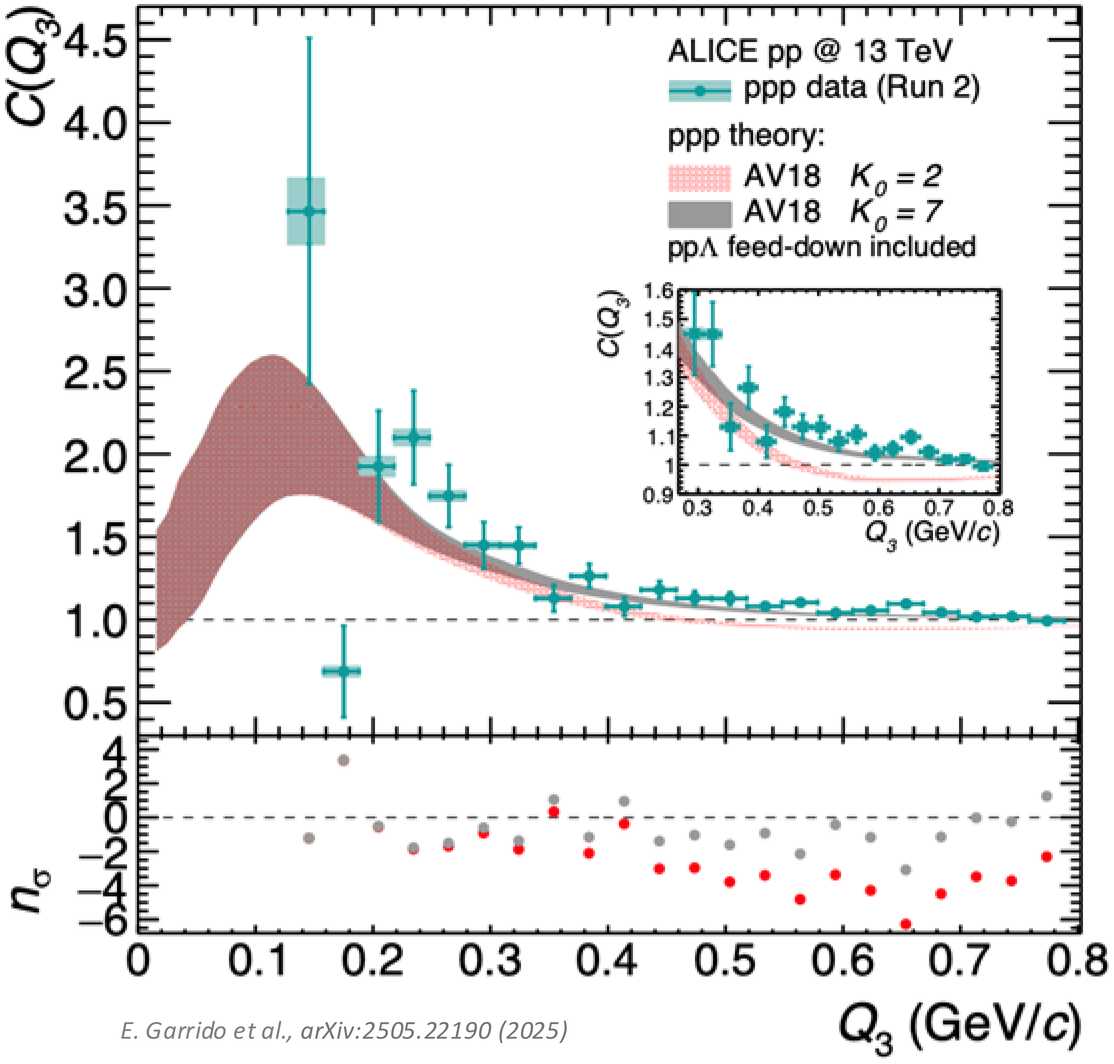
E. Garrido et al., arXiv:2505.22190 (2025)

Comparison Run-2 data

Comparison with the ALICE Run-2 measurement:

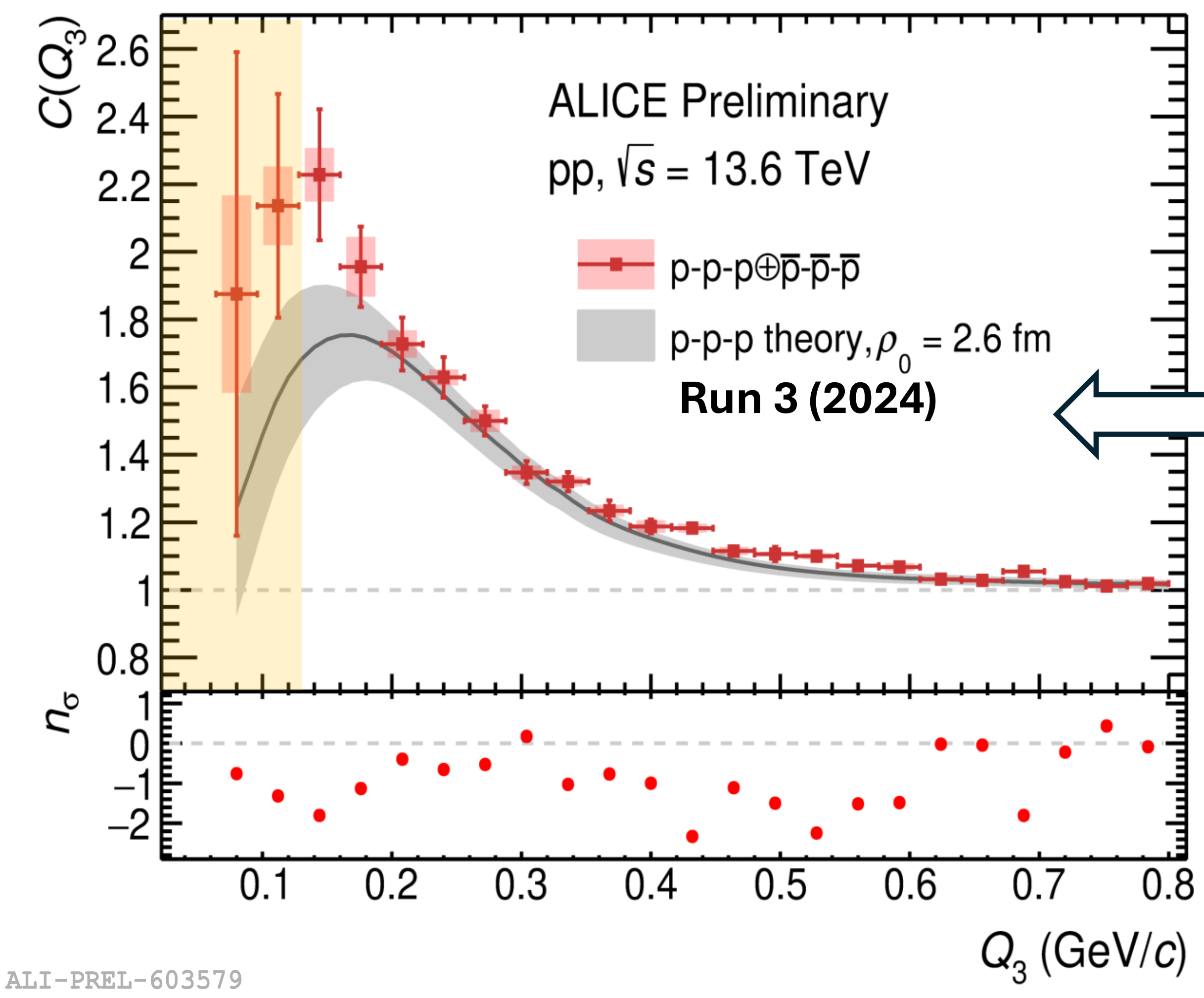
- calculations can describe the shape observed in the data
- interaction at higher partial waves (K<= 7) must be included in the calculations
- missing data in the low-energy region

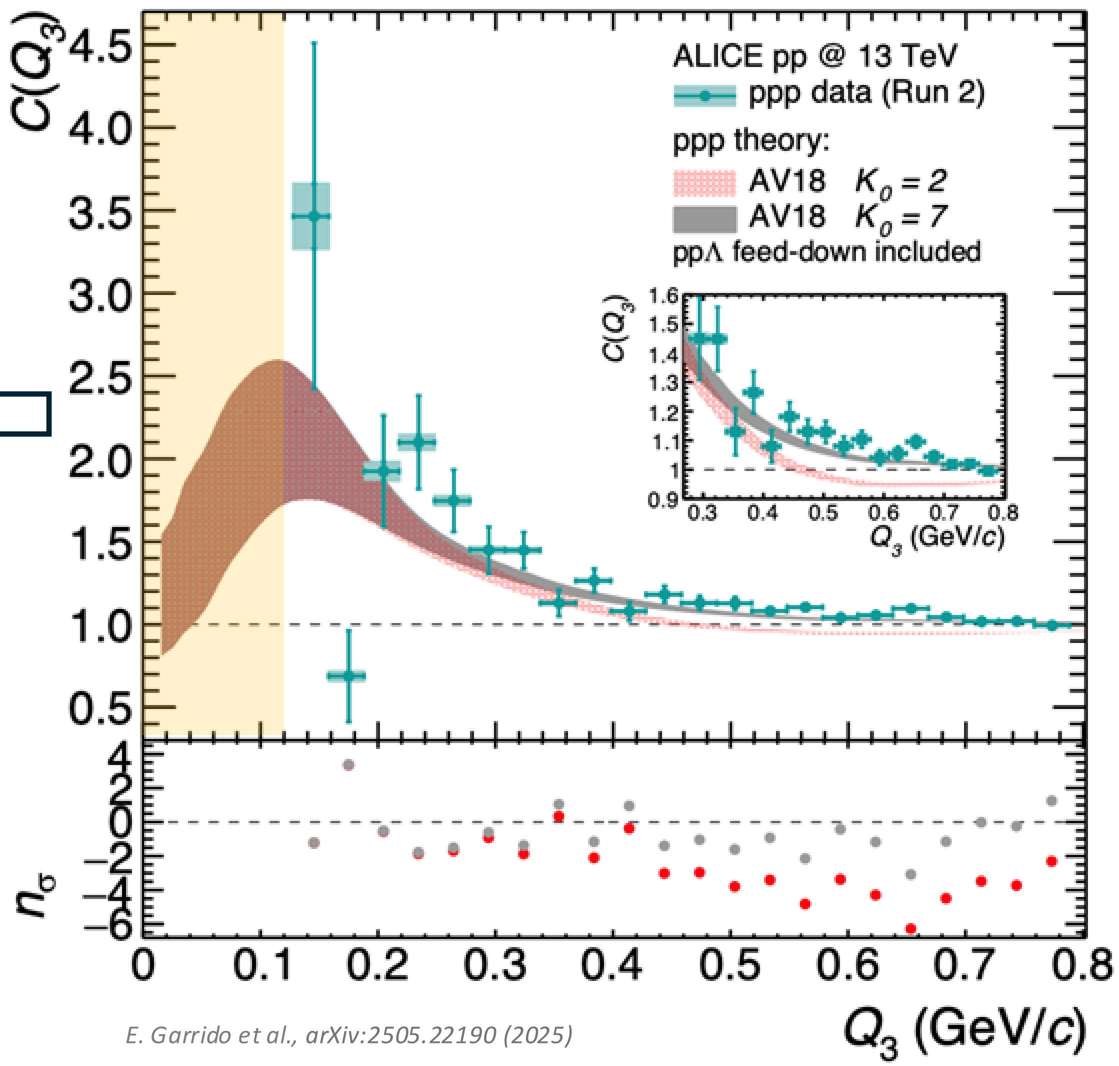
Negligible three-body interactions in p-p-p.



E. Garrido et al., arXiv:2505.22190 (2025)

p-p-p correlation function in Run-3



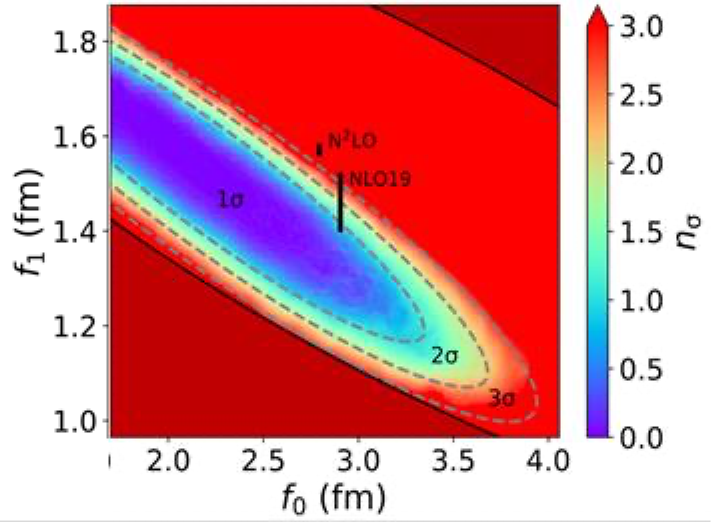


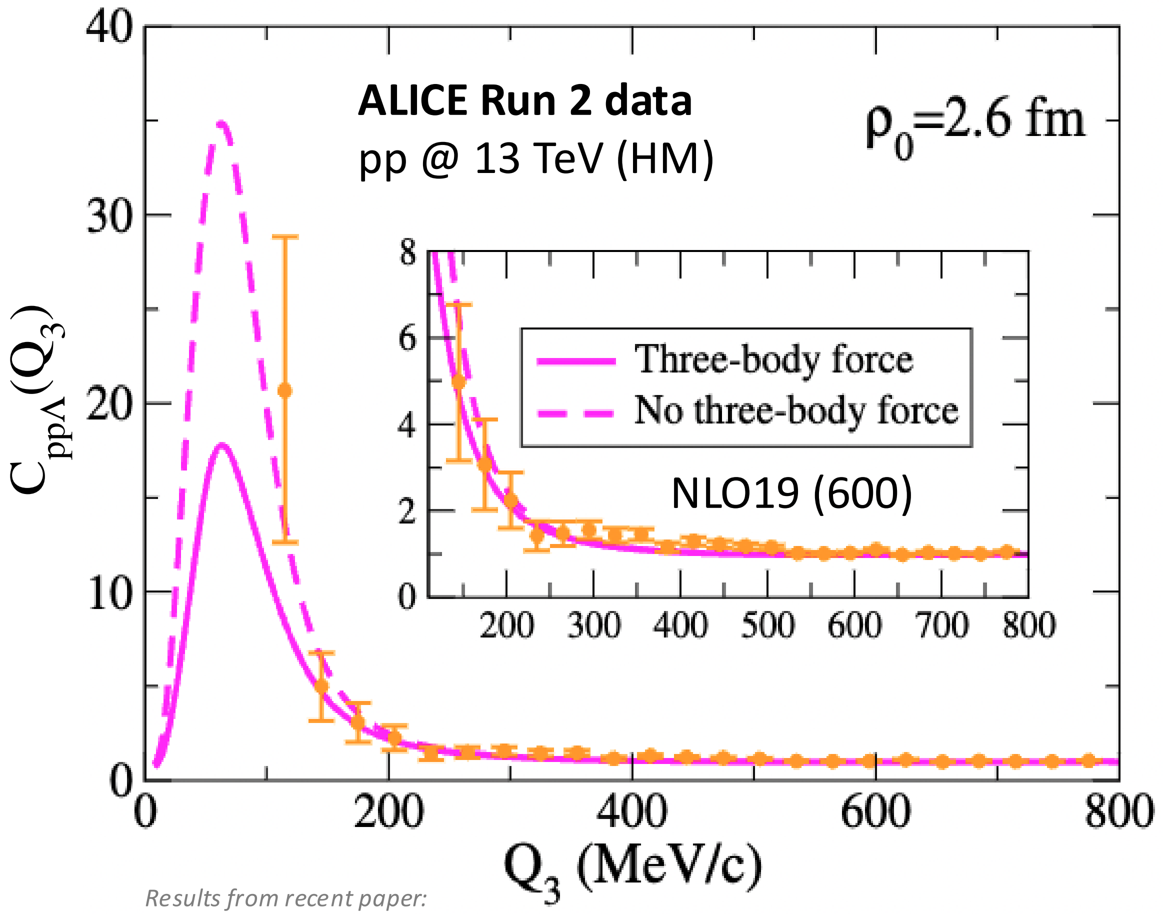
E. Garrido et al., arXiv:2505.22190 (2025)

p-p-Λ correlation function

- NLO19 (600) is used to describe the pΛ interaction

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





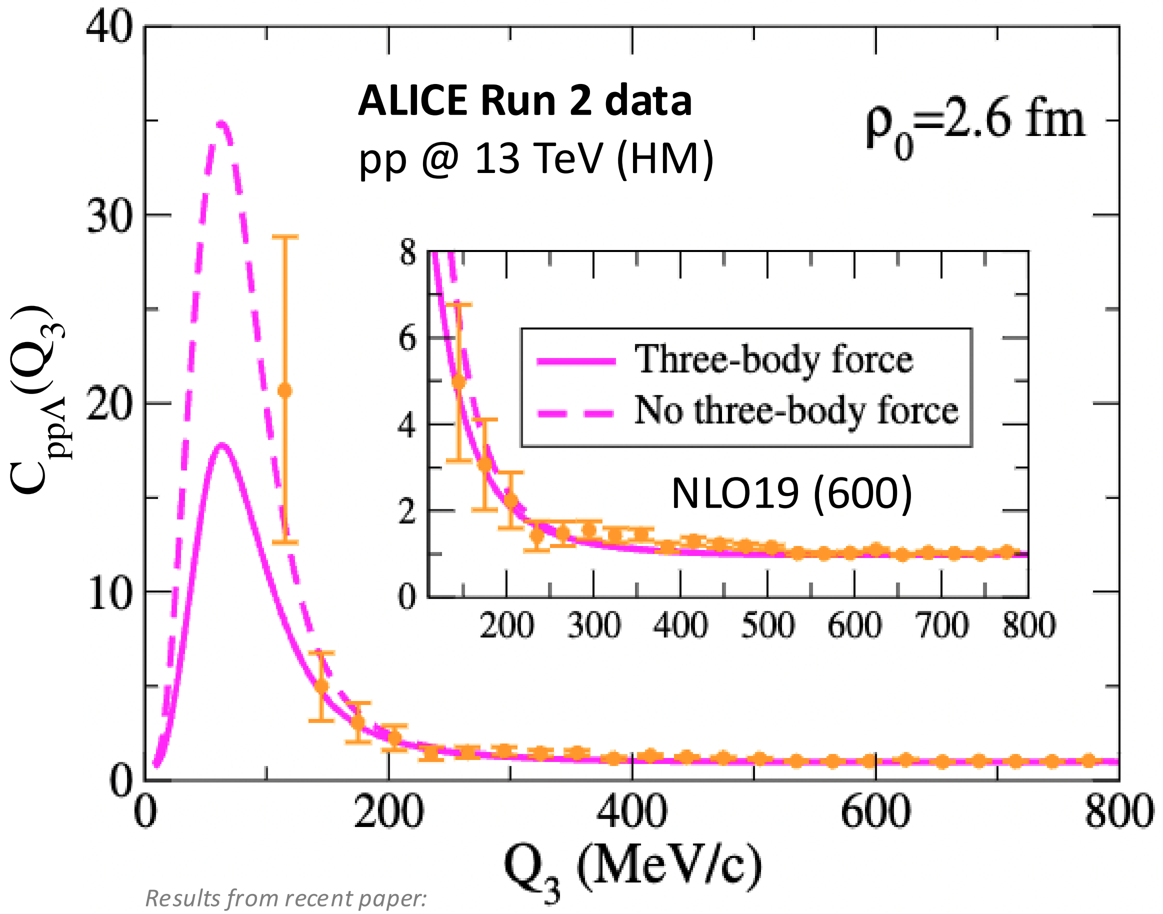
Results from recent paper:
E. Garrido et al., PRC 110 (2024) 5, 054004

- Three-body force constrained to the hypertriton binding energy

	NLO19				N2LO			Exp.
cutoff (MeV)	500	550	600	650	500	550	600	
$B(^3_\Lambda\mathrm{H})$ (MeV)	2.792	2.839	2.904	3.255	2.819	2.799	2.878	2.39

p-p-Λ correlation function

- NLO19 (600) is used to describe the pΛ interaction
  D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550
- Three-body force constrained to the hypertriton binding energy
- 40% effect of three-body interactions
- Run-2 data: one data point in the region of the maximum

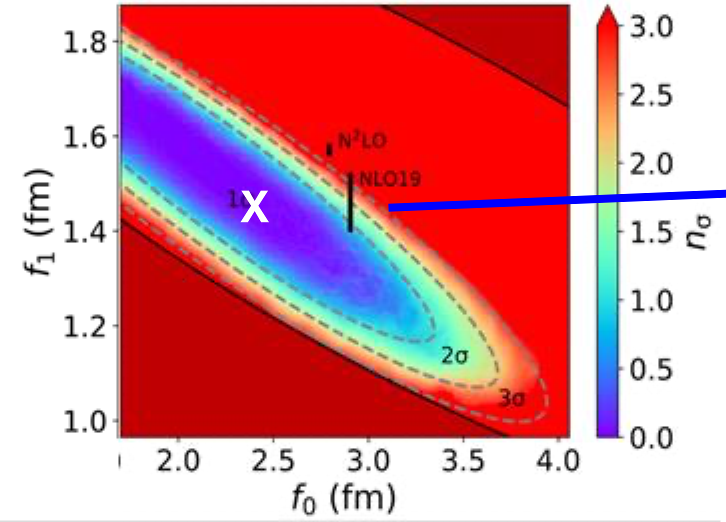


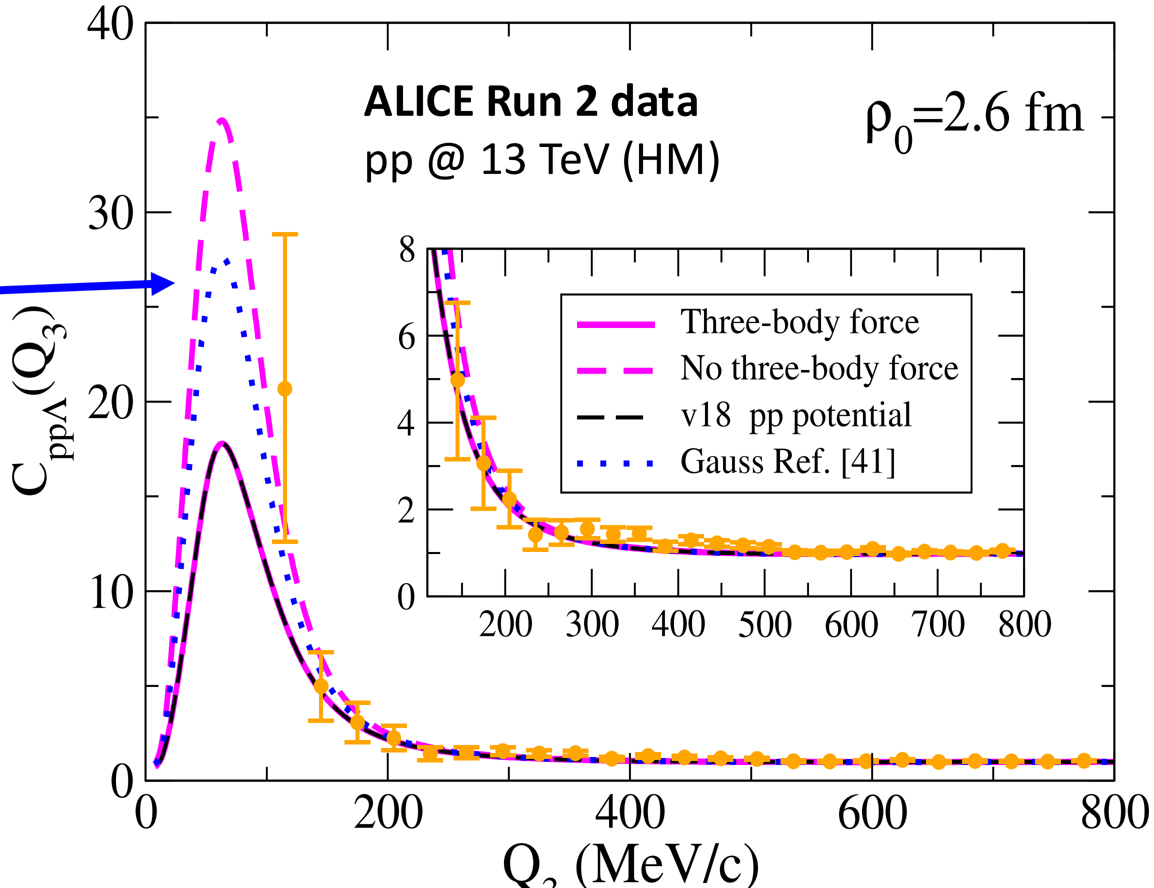
Results from recent paper:
E. Garrido et al., PRC 110 (2024) 5, 054004

p-p-Λ correlation function

- pΛ interaction from best fit of femto+scattering

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



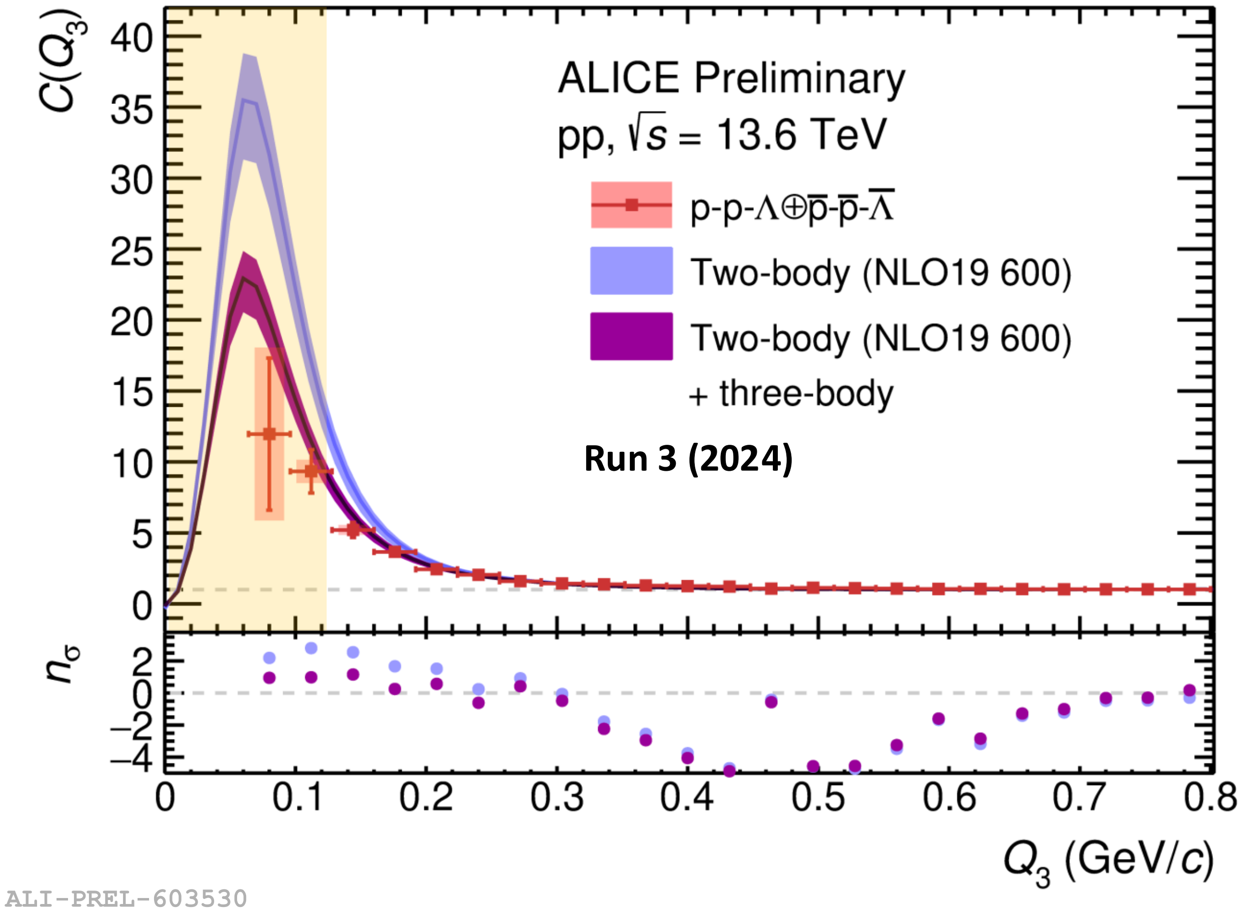


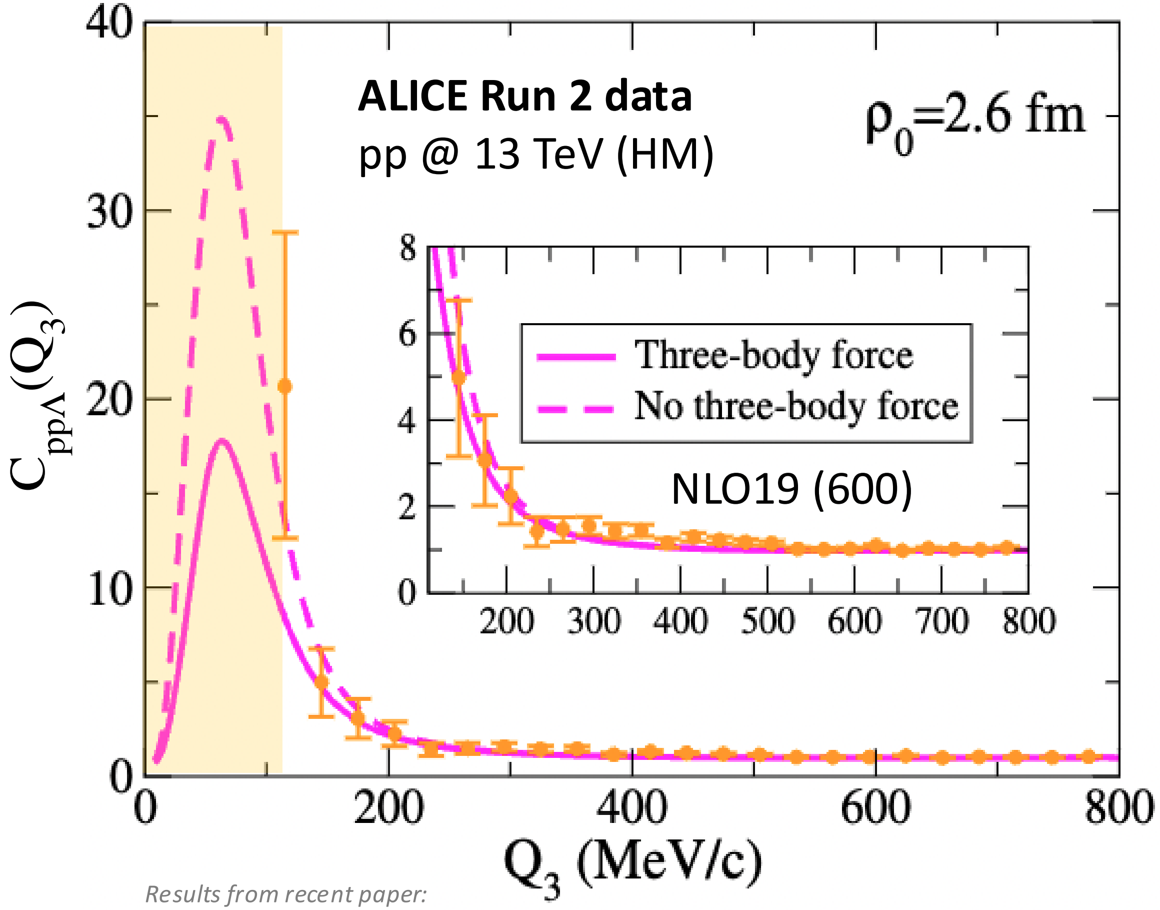
Results from recent paper:
E. Garrido et al., PRC 110 (2024) 5, 054004

- **Hypertriton binding energy well described without the need of a three-body force**

	femto+scatt.	Exp.
$B(^3_\Lambda\mathrm{H})$ (MeV)	2.41	2.39

p-p-Λ correlation function





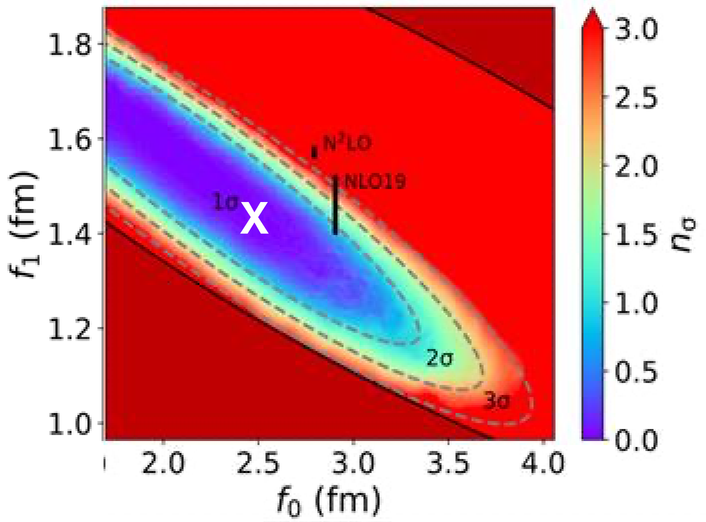
Results from recent paper:
E. Garrido et al., PRC 110 (2024) 5, 054004

By the end of Run 3: 100 times larger statistical triplets sample expected compared to Run 2 due to developed software triggers!

The future of hadron physics

1) Two-body forces from femtoscopy + scattering data

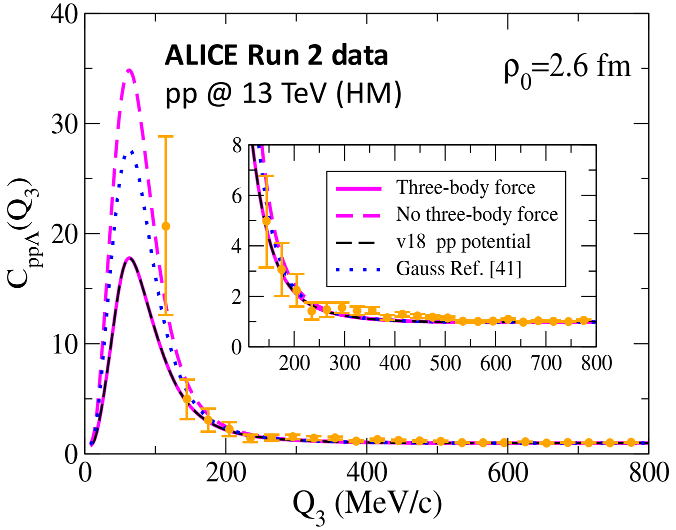
Λ N



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

2) Three-body femtoscopy to constrain three-body forces

Λ N N

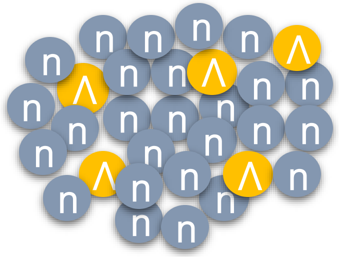


Results from recent paper:
E. Garrido et al., Phys. Rev. C 110 (2024) 5, 054004

3) Four-body systems to construct realistic potentials

Λ N N N

4) Heavier nuclei
5) Neutron stars



Conclusions and Outlook

- Exciting results from femtoscopy
  → Important experimental input to understand the many facets of QCD in strange sector
  - Most precise p-Λ data at low momenta
  - First extraction of the p-Λ scattering parameters using femtoscopy and scattering data
  - Shallow repulsion in the p-Σ^{+} interaction in the triplet channel
  - Evidence of the attractive p-Ξ^{-} strong interaction
  - Opening of the pΞ^{-} → $\Lambda\Sigma^{0}$ channel
  - First measurements of three-particle correlation functions
    - NNN interaction: up to 5% in p-d and negligible in the p-p-p measurement
    - NNΛ interaction: 40% effect in the correlation function

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