Czech
Technical
University
in Prague

Exploring strange hadronic matter through femtoscopy at the LHC

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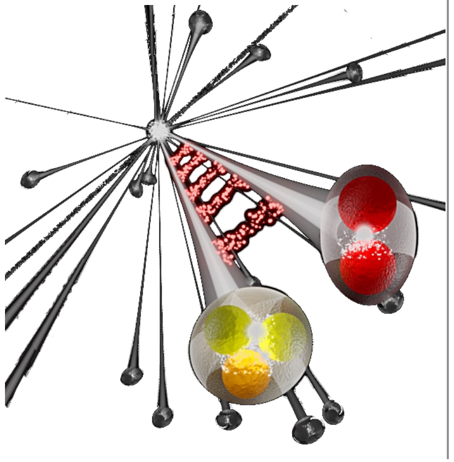
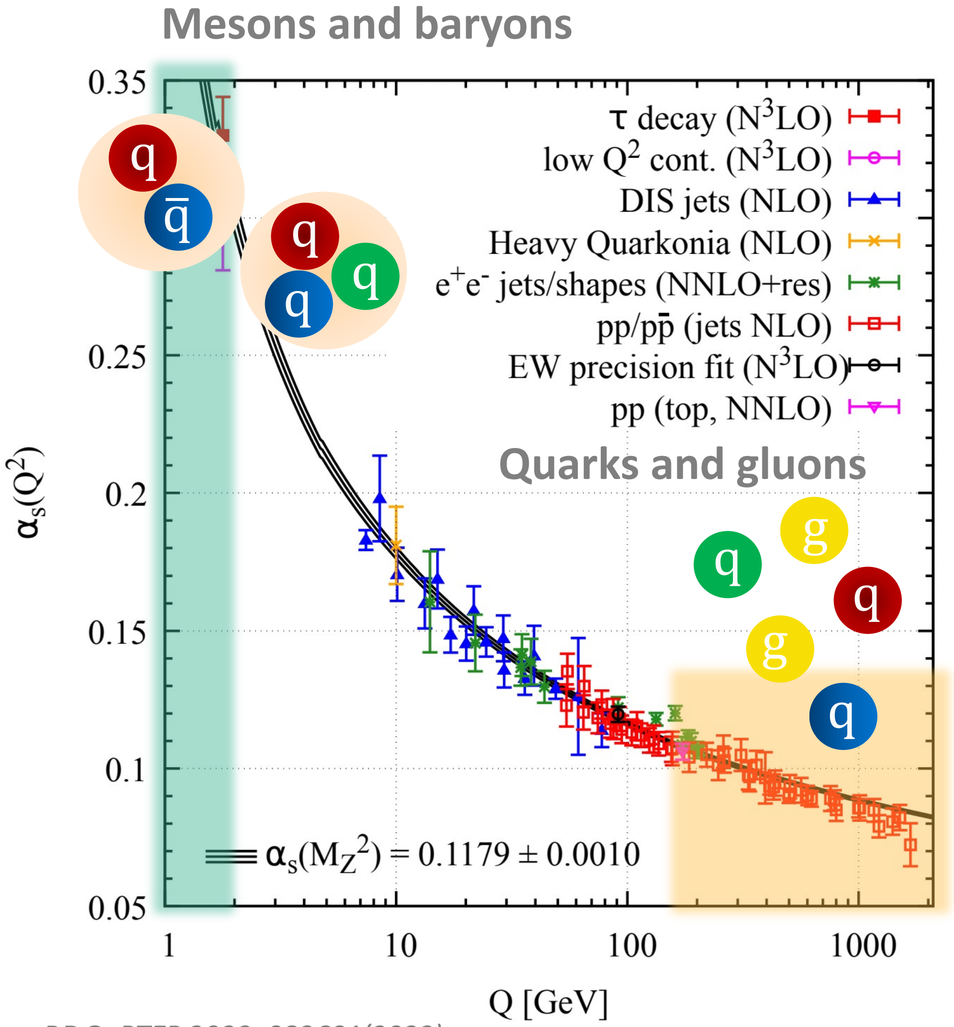


Credits to Laura Fabbietti's group at TU Munich

Hadronic interactions

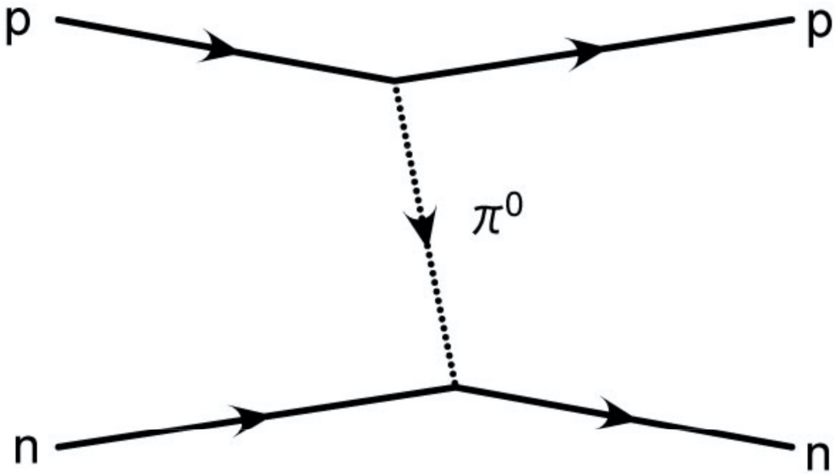
- Quantum Chromodynamics (QCD) is conceived as a theory with quarks and gluons as degrees of freedom
- High energy regime (Q >> 1 GeV):
  - Perturbation theory is applicable
  - High predictive power of the calculations
- Low-energy (Q < 1 GeV):
  - Quark confinement and emergence of hadrons
  - Very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

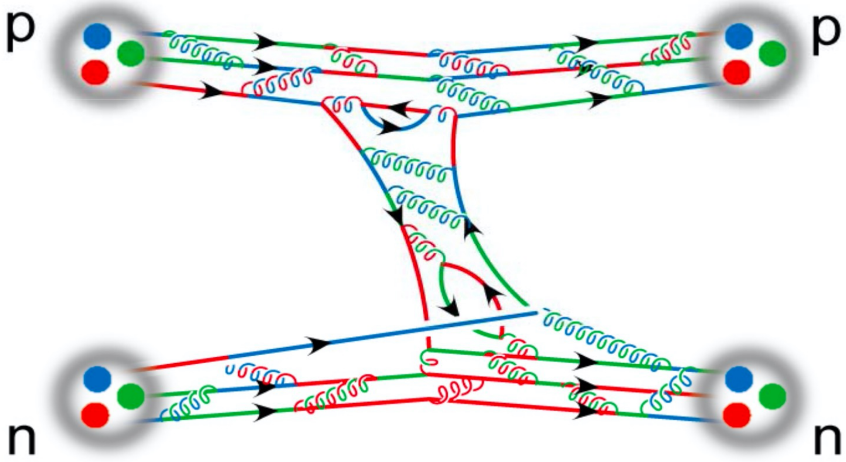


PDG, PTEP 2022, 083C01(2022)

Hadronic interactions

Low energy hadronic interactions:

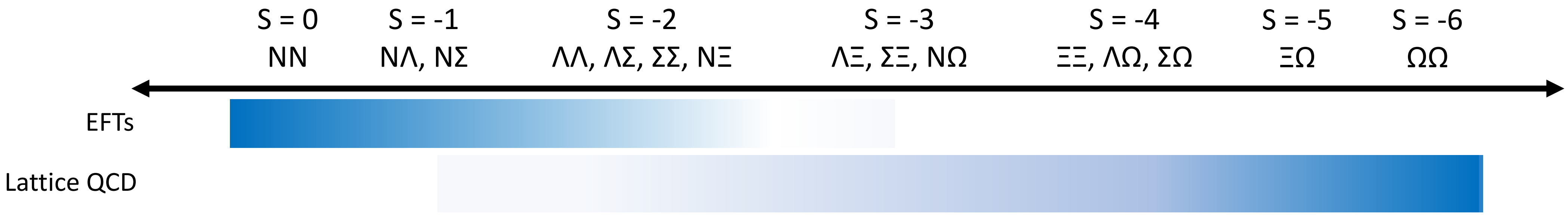




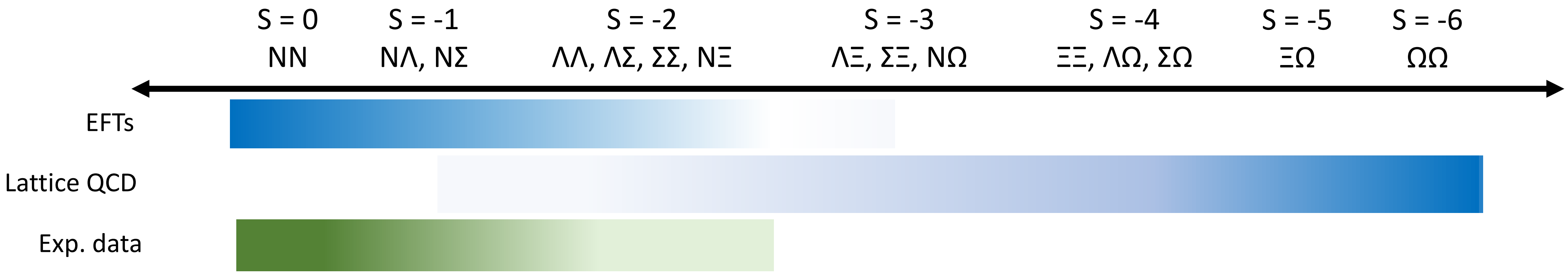
Effective Field Theories (EFT)
- hadrons as degrees of freedom
- low-energy coefficients constrained by data

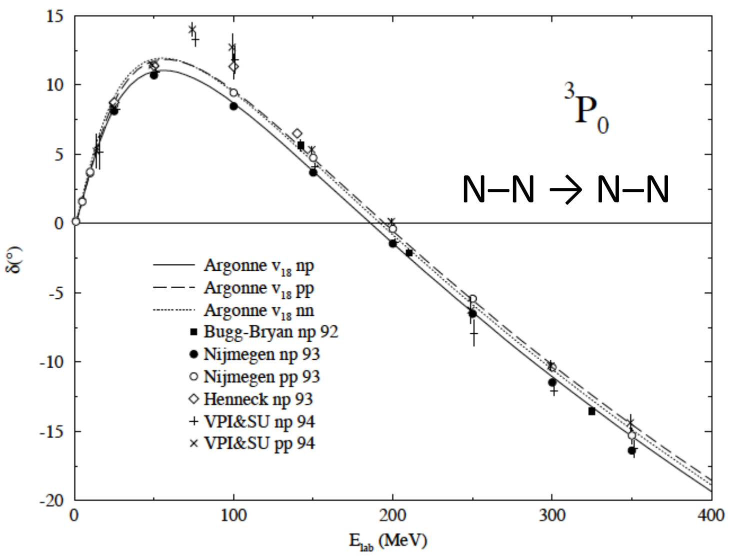
Lattice QCD
- quarks and gluons as degrees of freedom
- unstable for low mass hadrons

Theory and experimental data

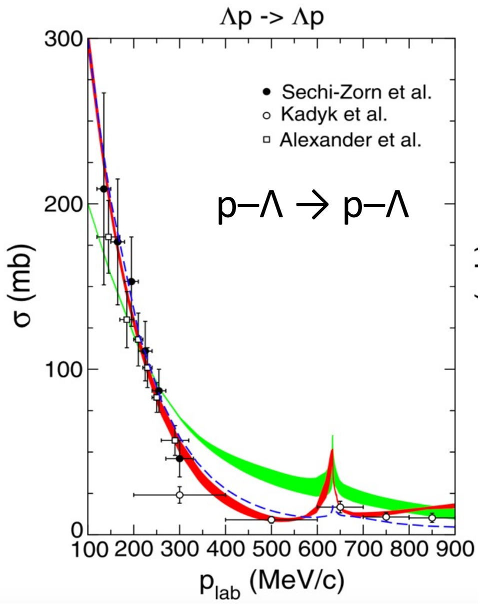


Theory and experimental data

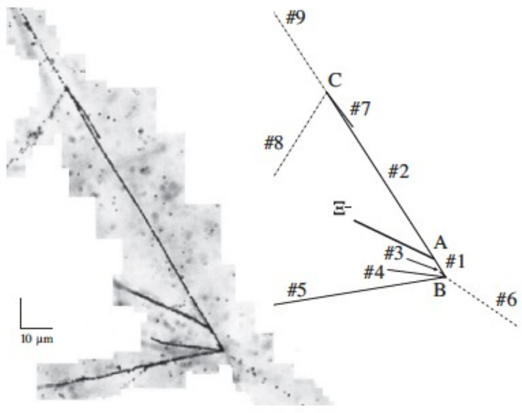




R. B. Wiringa et al. PRC 51 (1995)



J.Haidenbauer et al. NPA 915 (2013)

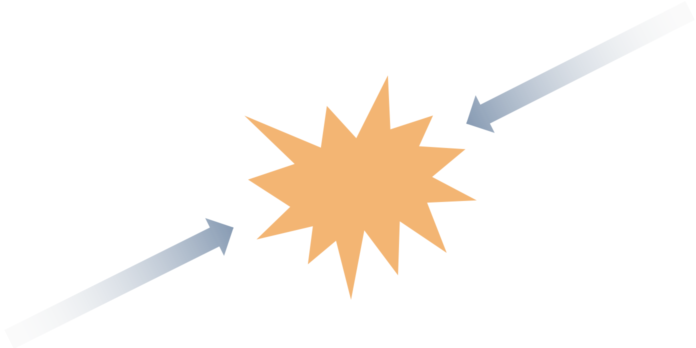


Ξ hypernucleus

J-PARC E07 Coll. PRL 126 (2021)

Femtoscopy technique at the Large Hadron Collider

High-energy collisions



Femtoscopy technique at the Large Hadron Collider

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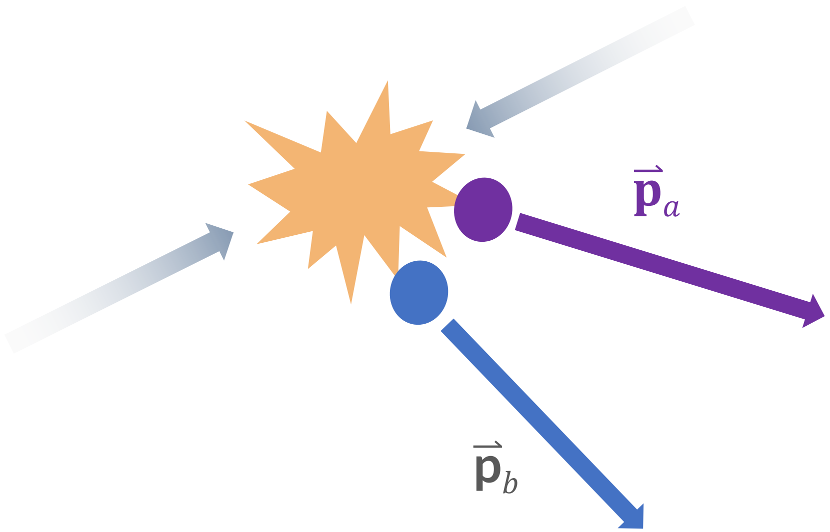

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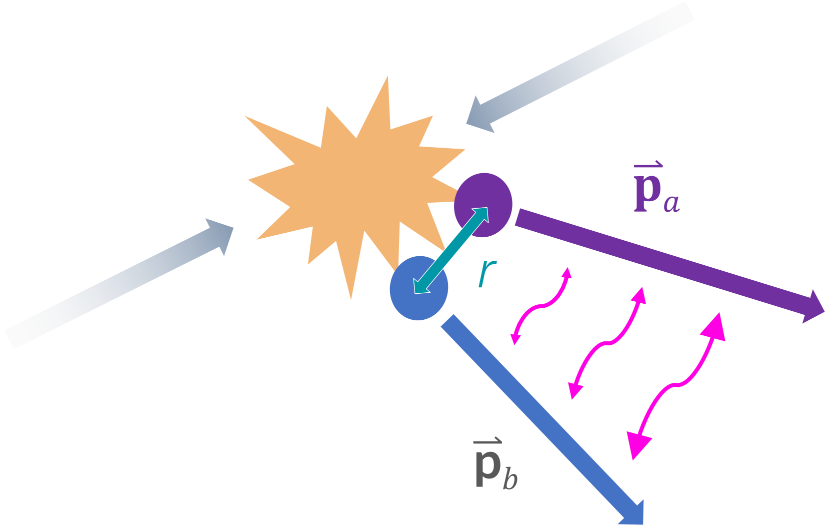
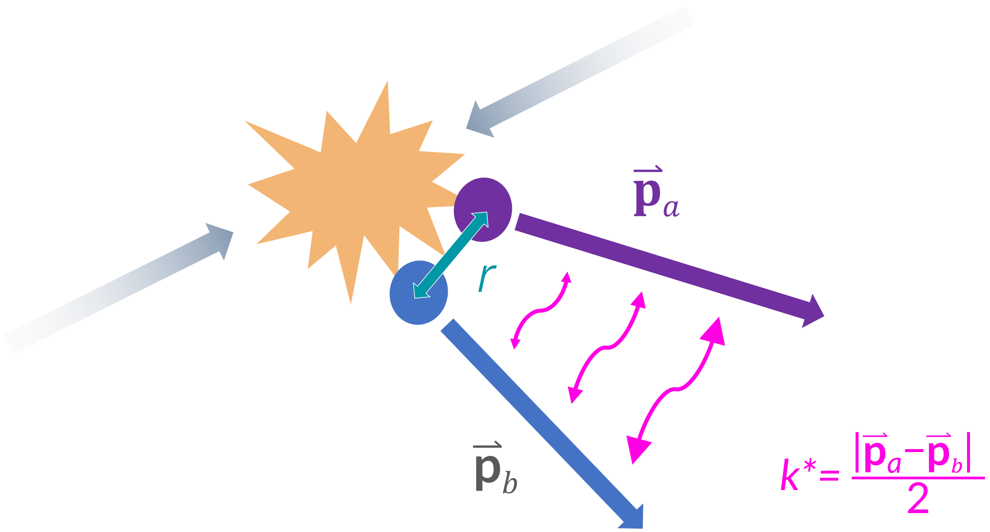


Correlation function

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

Femtoscopy technique at the Large Hadron Collider

High-energy collisions



Correlation function

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

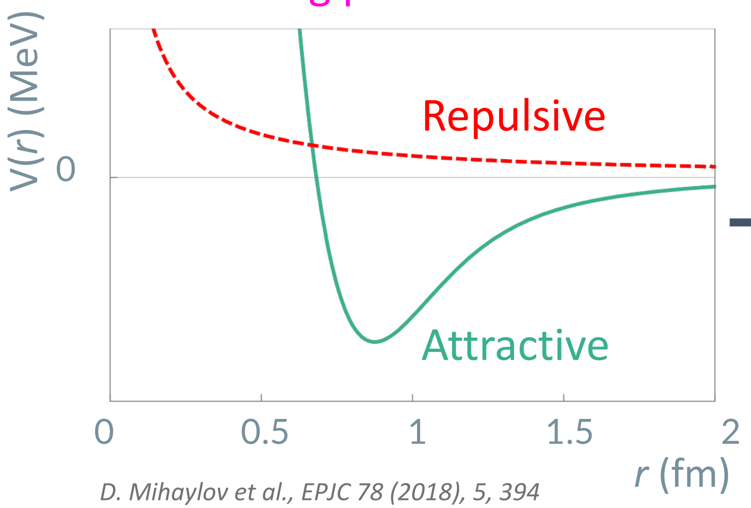
Correlation function

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

Two-particle wave function

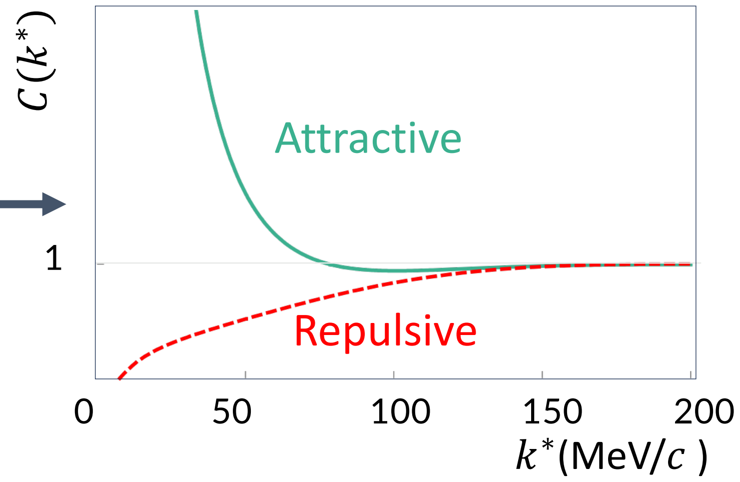
M. Lisa, S. Pratt et al., ARNPS 55 (2005), 357-402
L. Fabbietti et al., ARNPS 71 (2021), 377-402

Interacting potential



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

Correlation function



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

Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

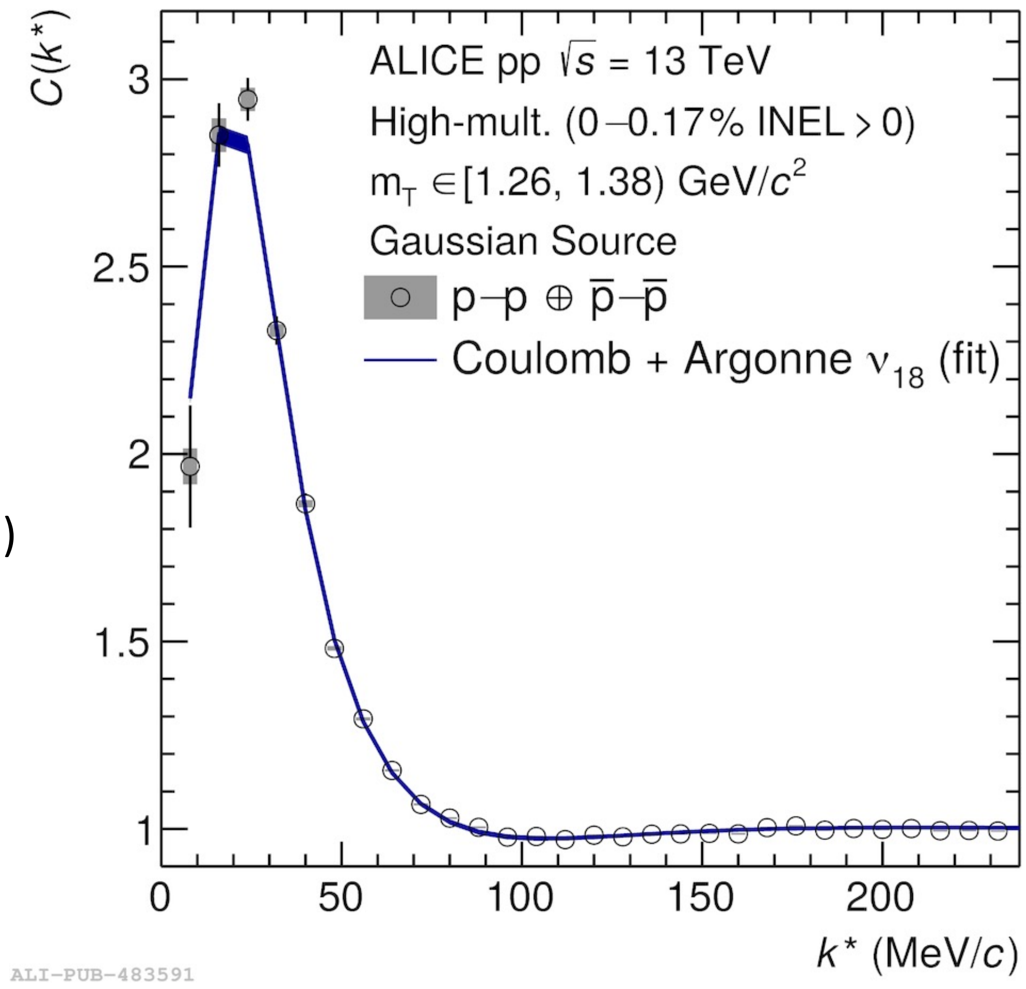
$$\underbrace{C(k^*)}_{\text{measured}} = \int S(\vec{r}\,) \underbrace{\left|\psi(\vec{k}^*, \vec{r}\,)\right|^2}_{\text{known interaction}} d^3\vec{r}$$

- Gaussian parametrization

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

Effect of short lived resonances (cτ ~ 1 fm)

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



ALICE Coll., PLB, 811 (2020)

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measured — known interaction

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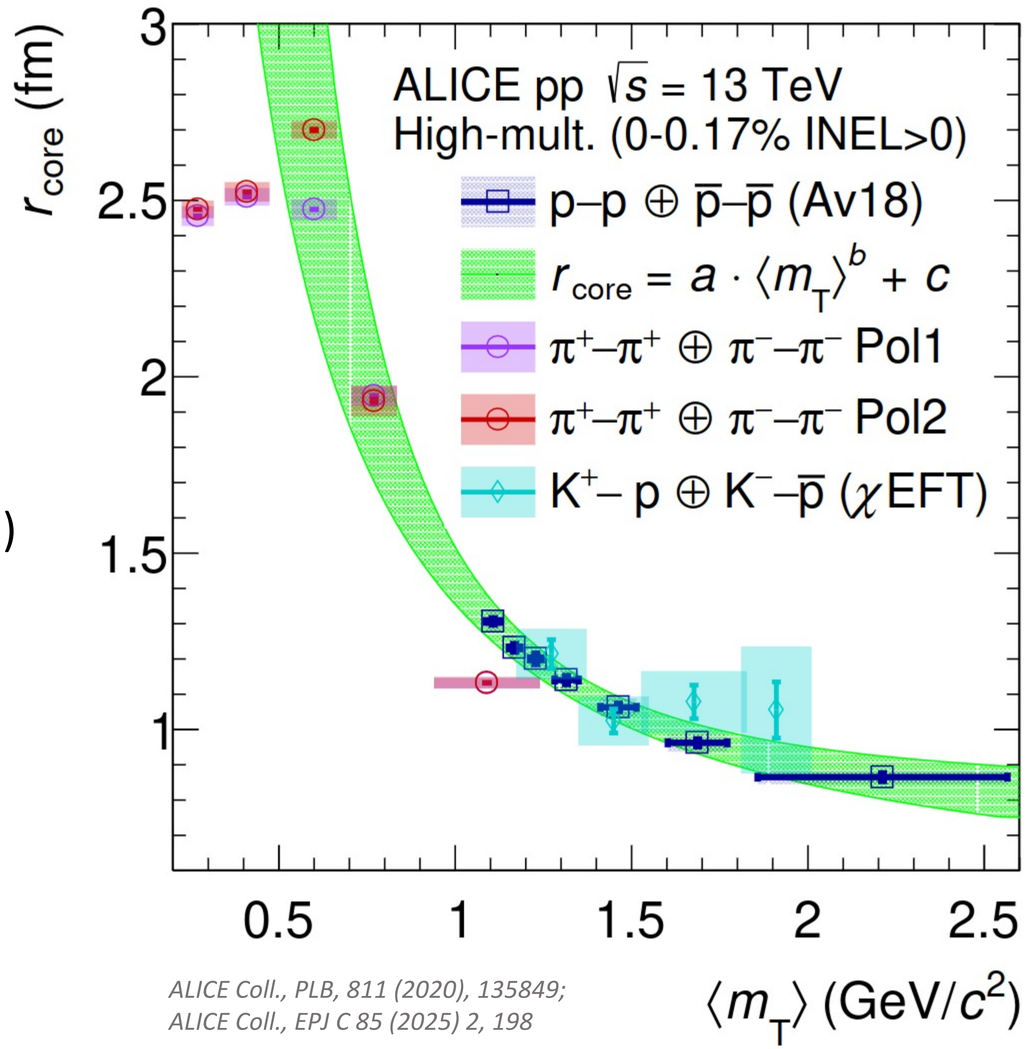
Effect of short lived resonances (cτ ~ 1 fm)

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

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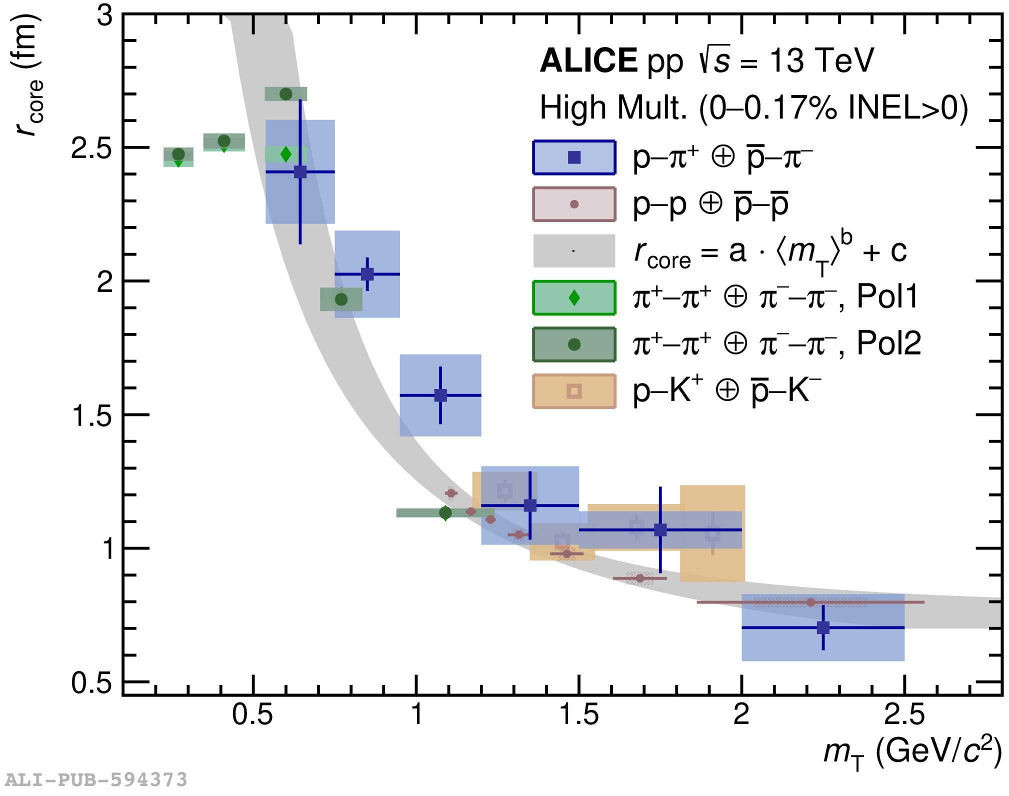

ALICE Coll., PLB, 811 (2020), 135849;
ALICE Coll., EPJ C 85 (2025) 2, 198;
ALICE Coll., EPJ A 61 (2025) 8, 194

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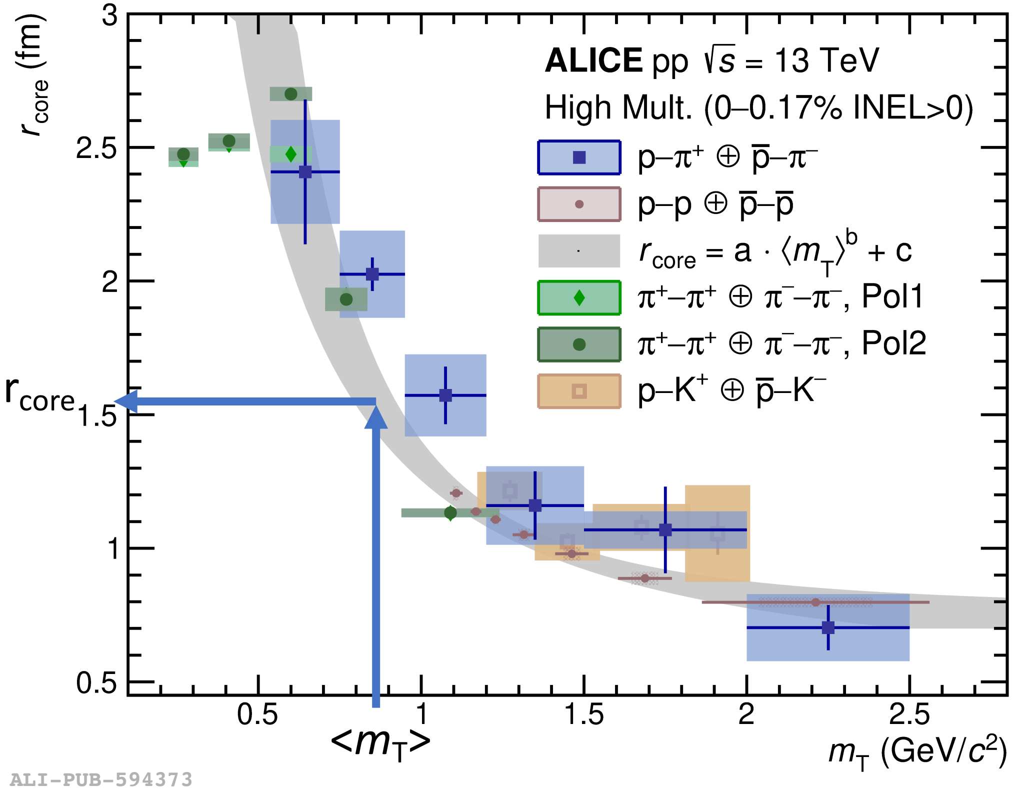
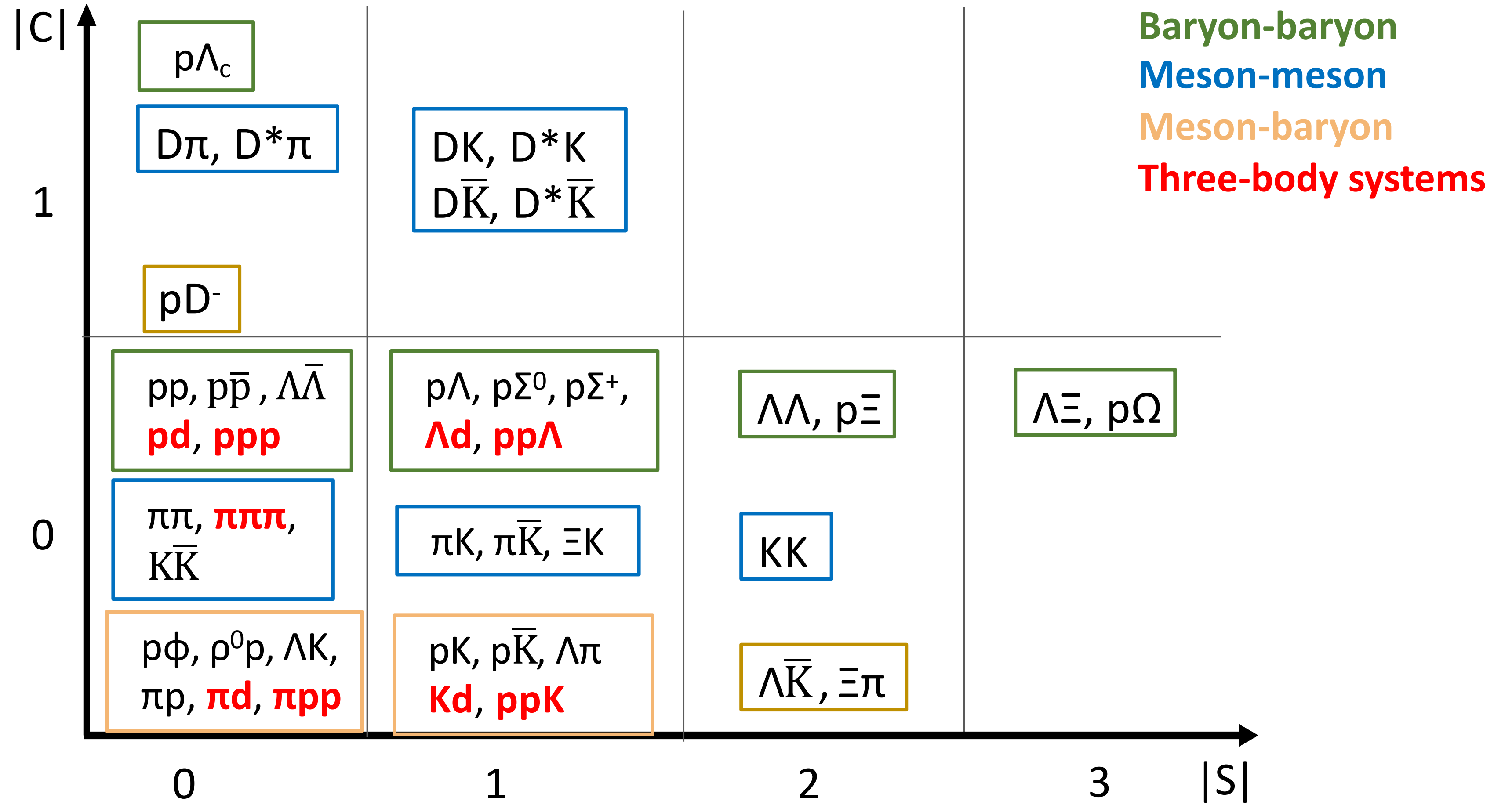


ALICE Coll., PLB, 811 (2020), 135849;
ALICE Coll., EPJ C 85 (2025) 2, 198;
ALICE Coll., EPJ A 61 (2025) 8, 194

Femtoscopy measurements at the LHC

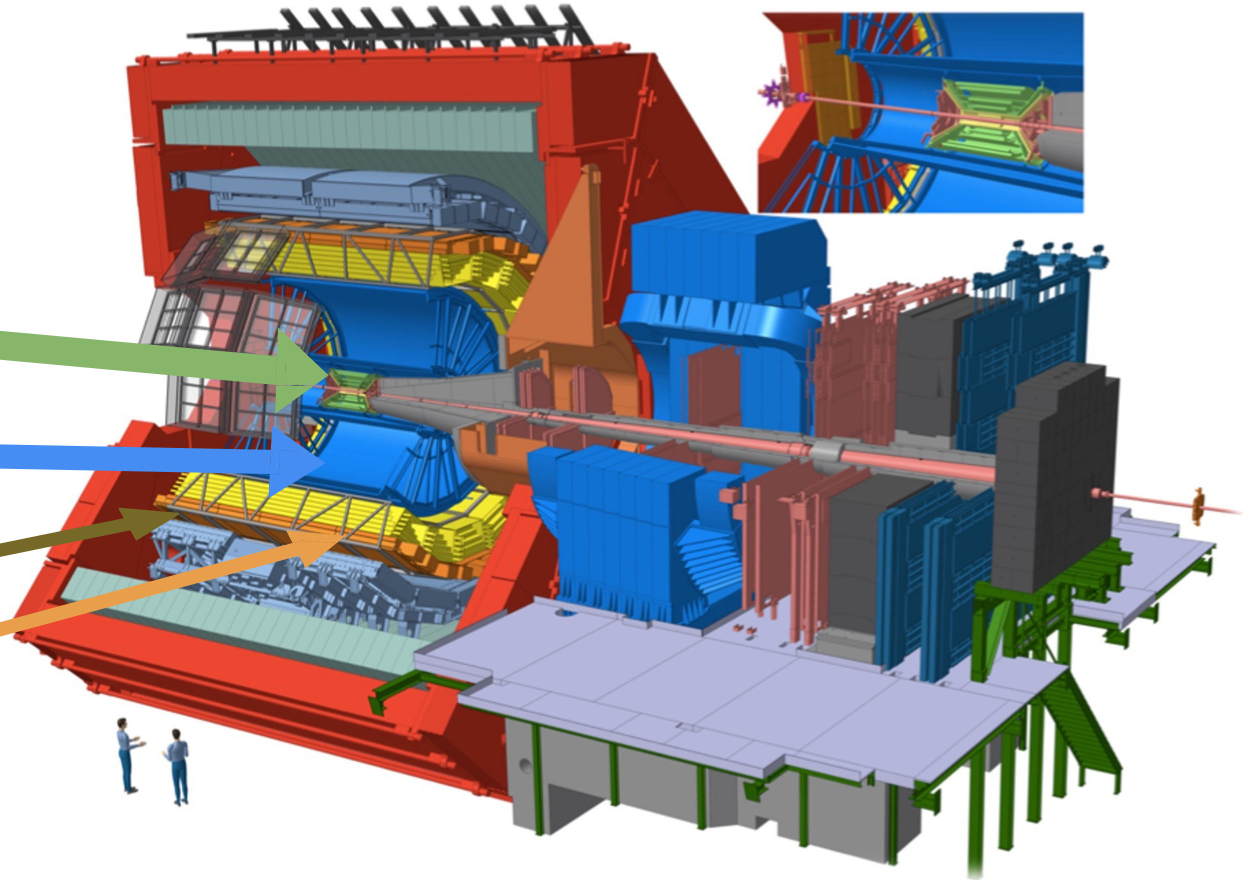


ALICE Collaboration:
PRC 99 (2019) 2, 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 09230
PLB 805 (2020) 135419
PLB 811 (2020) 135849
Nature 588 (2020) 232-238
PRL 127 (2021), 172301
PLB 822 (2021), 136708
PRC 103 (2021) 5, 055201
PLB 833 (2022), 137272
PLB 829 (2022), 137060
PRD 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
EPJ A 61 (2025) 8, 194
arXiv:2504.02333 [nucl-ex]
arXiv:2510.14448 [nucl-ex]

ALICE detector

Excellent tracking and particle identification (PID) capabilities

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



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

Time Projector Chamber
Tracking, PID (dE/dx)

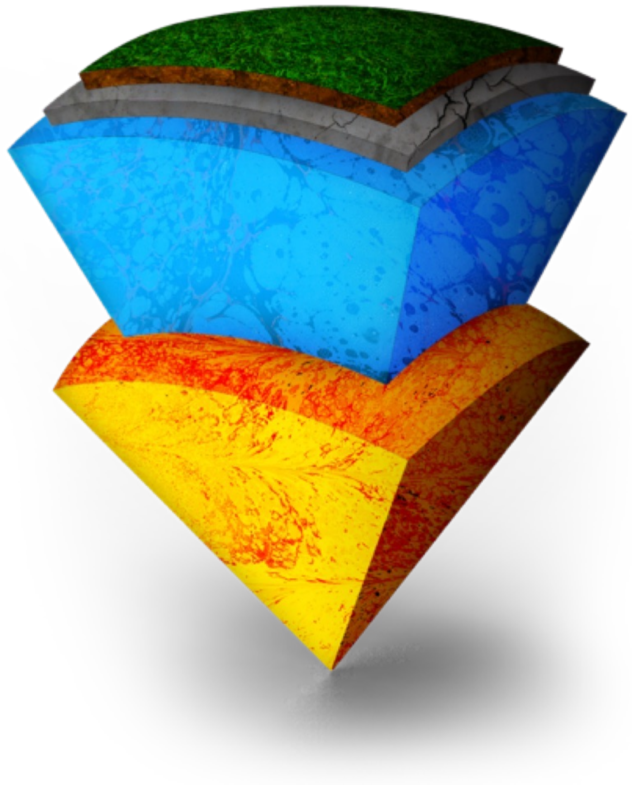
Transition Radiation Detector

Time Of Flight detector
PID (TOF measurement)

Hyperons in neutron stars?

$R \sim 10 - 15$ km

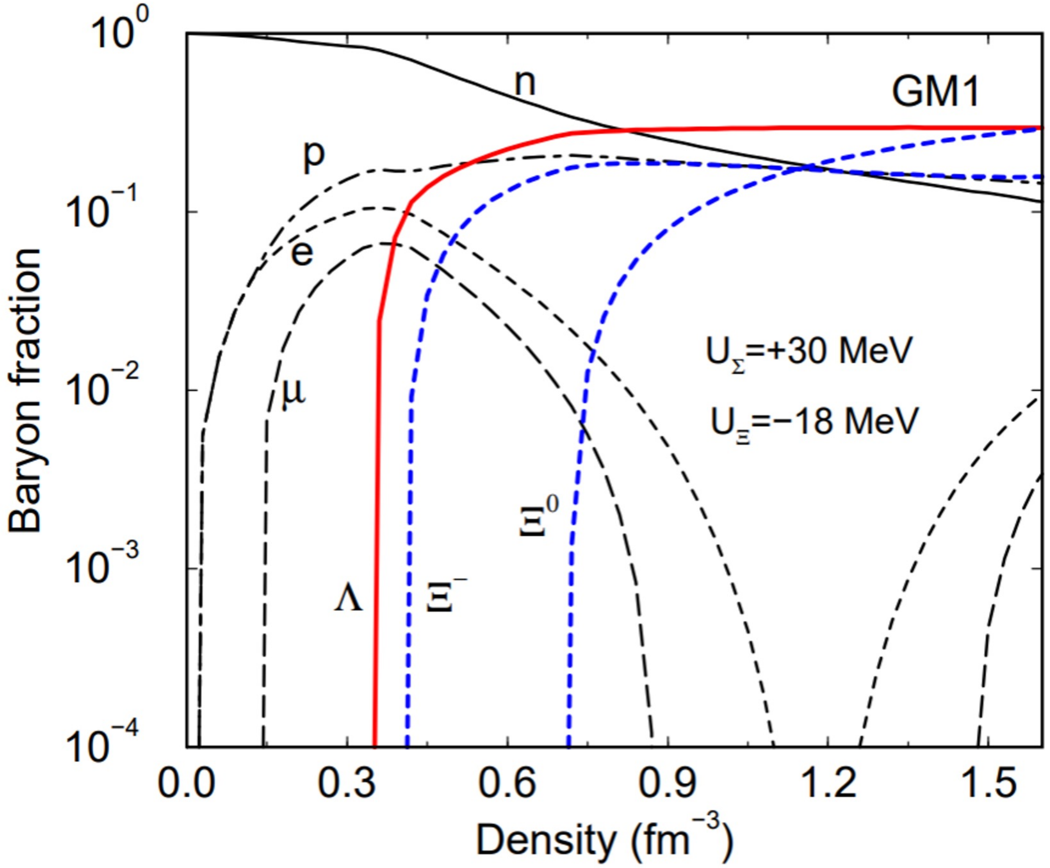
M $\sim 1.5 - 2\ M_{\odot}$



Outer crust:
Ions
Electrons
Neutrons

Inner core:
Neutrons?
Hyperons?
Quark-matter?
Axions?

With increasing gravitational pressure the density of the system rises and eventually neutron (fermions) will convert into hyperons.



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

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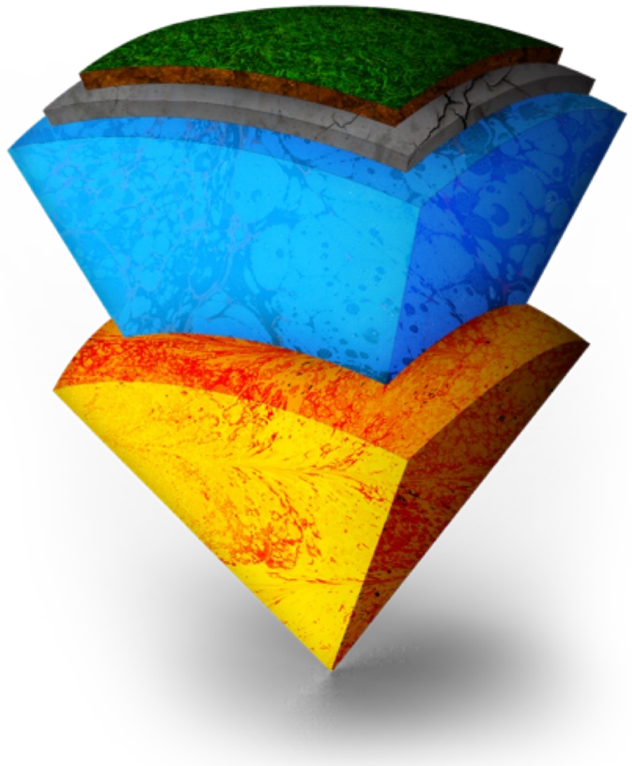

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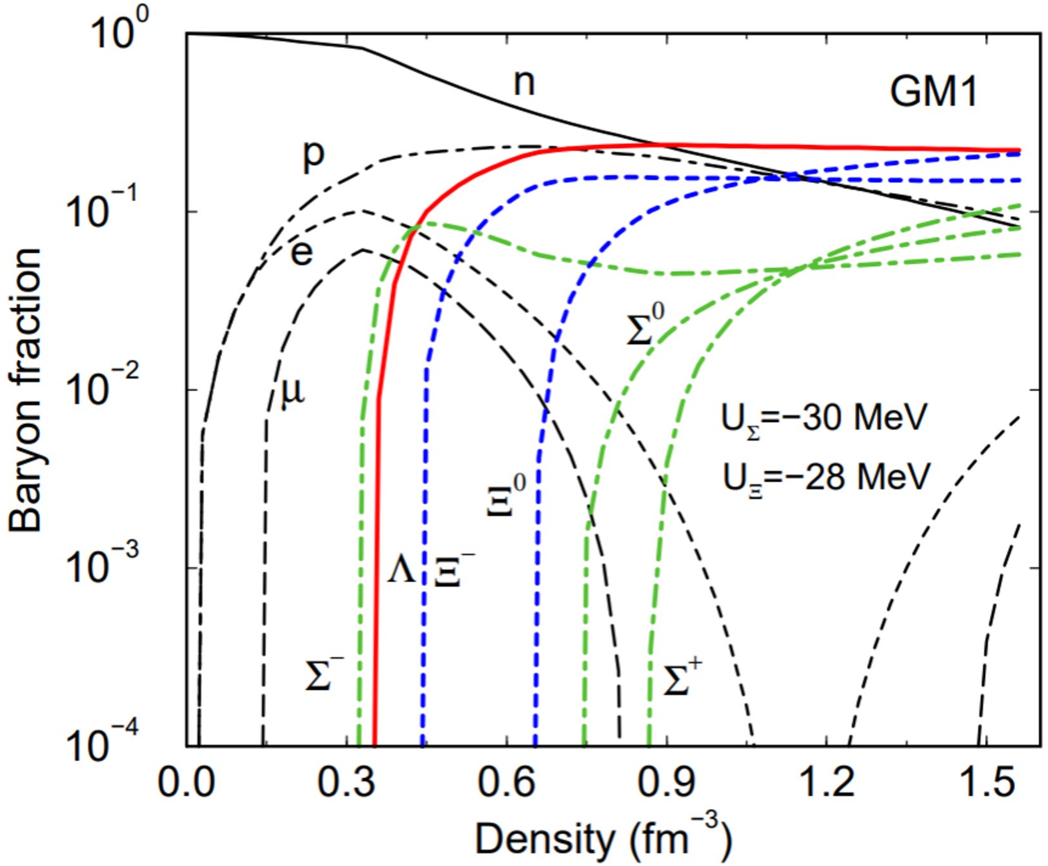
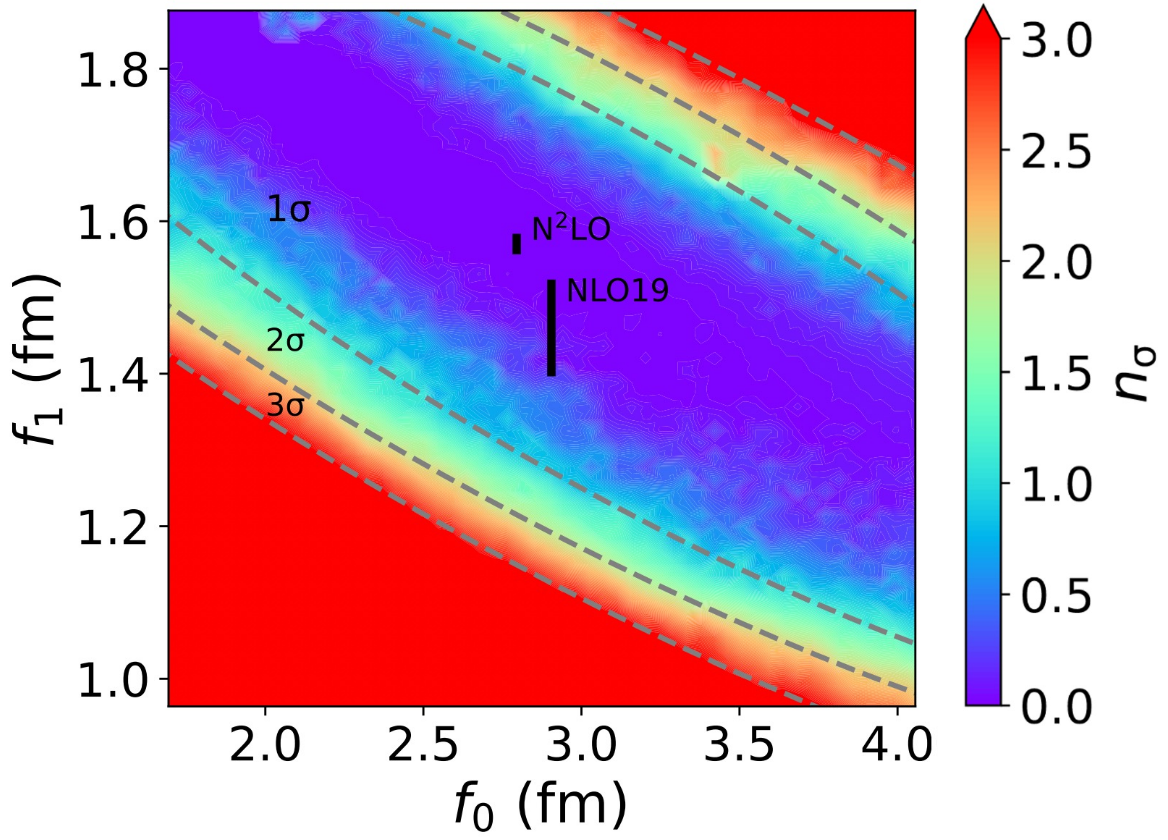


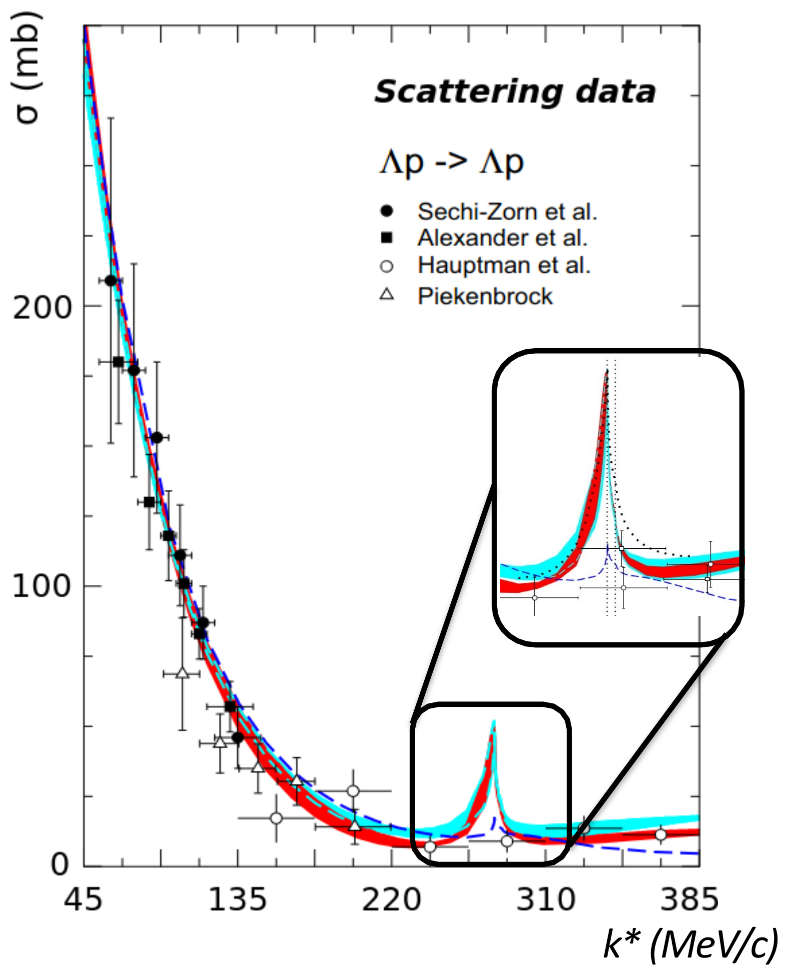
J. Schaffner-Bielich et al NPA 835 (2010)

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

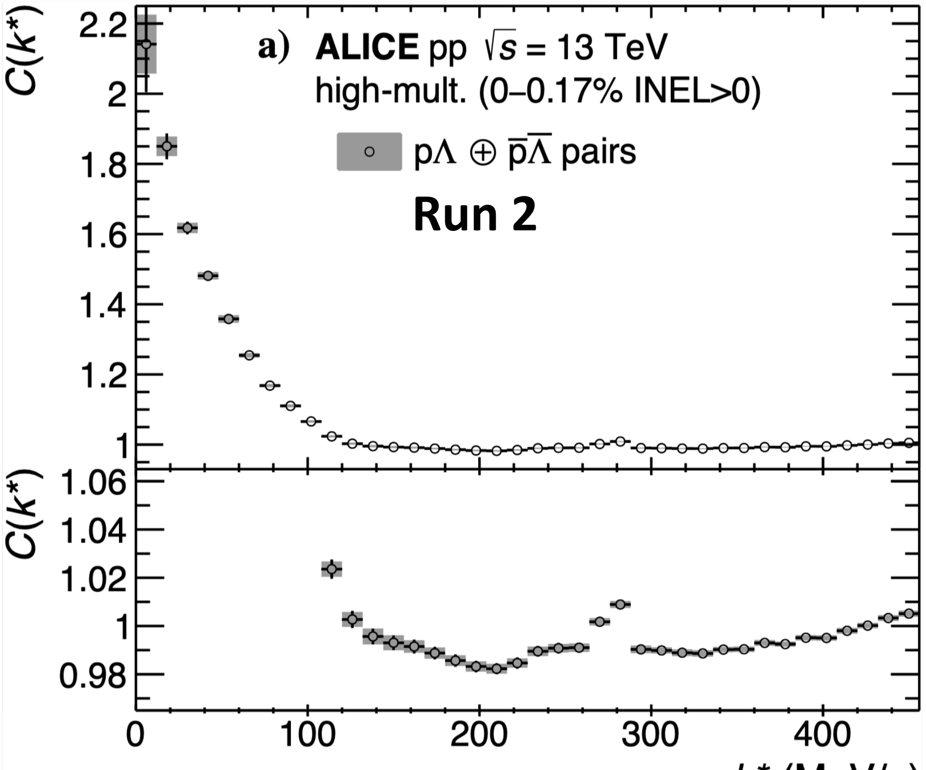




NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

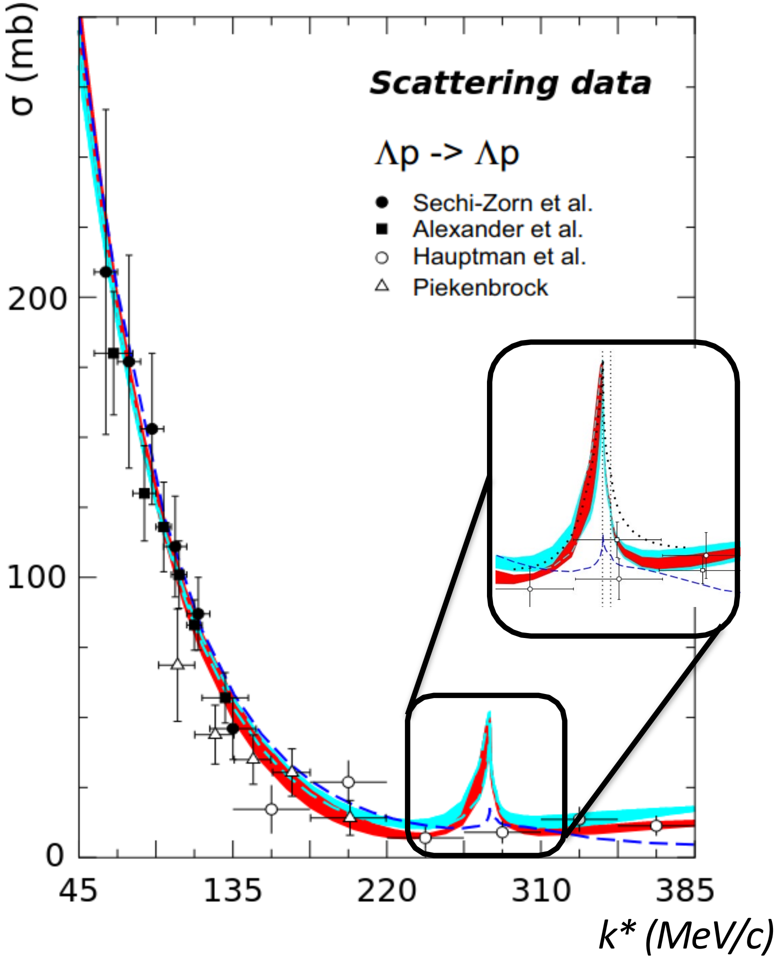
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

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



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

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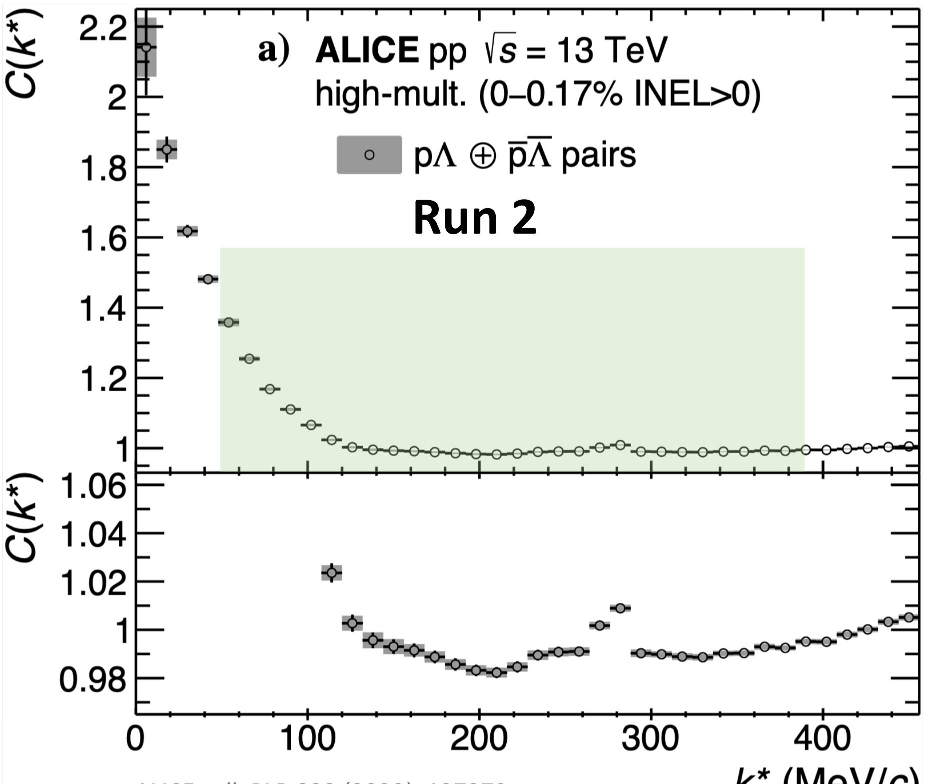

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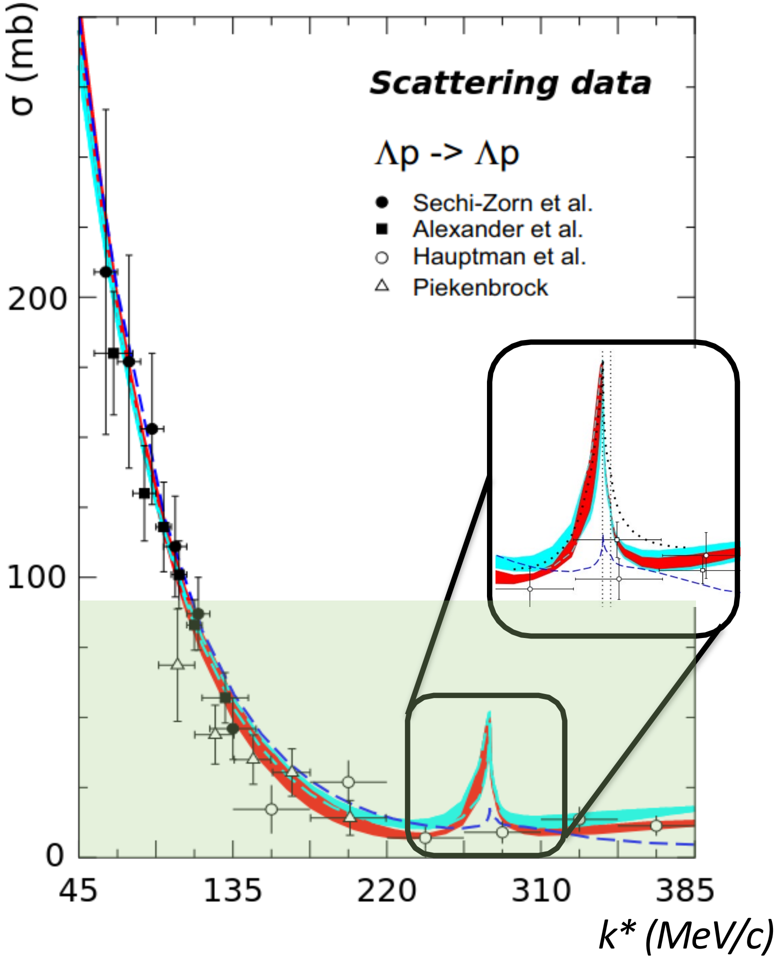
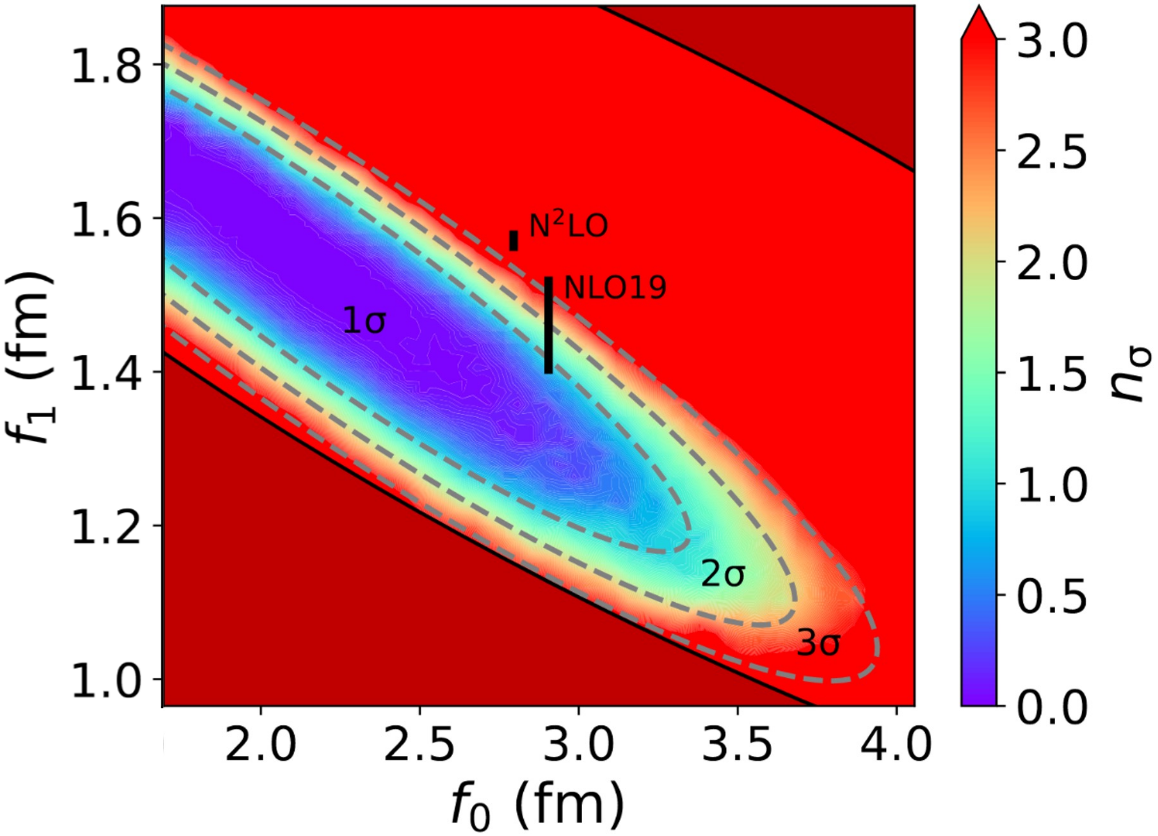


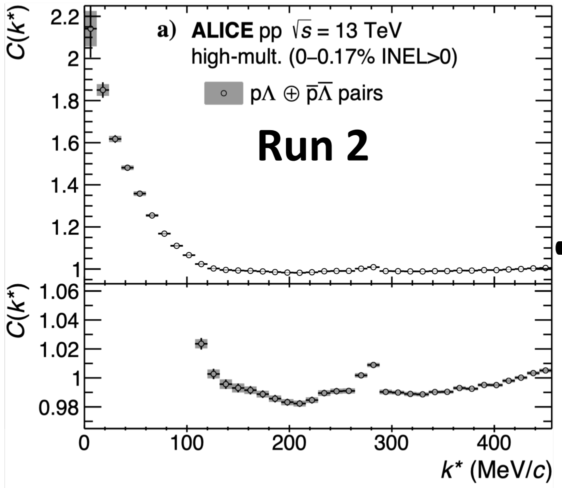
NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

The pΛ interaction in the femtoscopy era

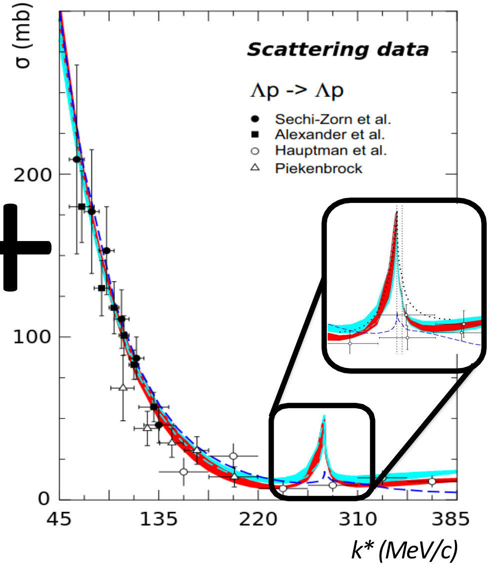
- Combined analysis of femtoscopic and scattering data

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



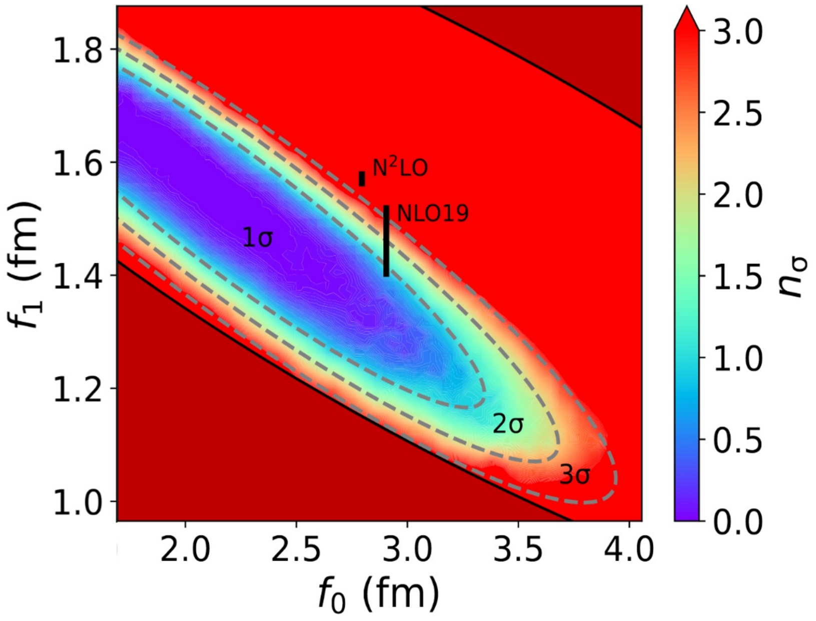


ALICE coll. PLB 833 (2022), 137272



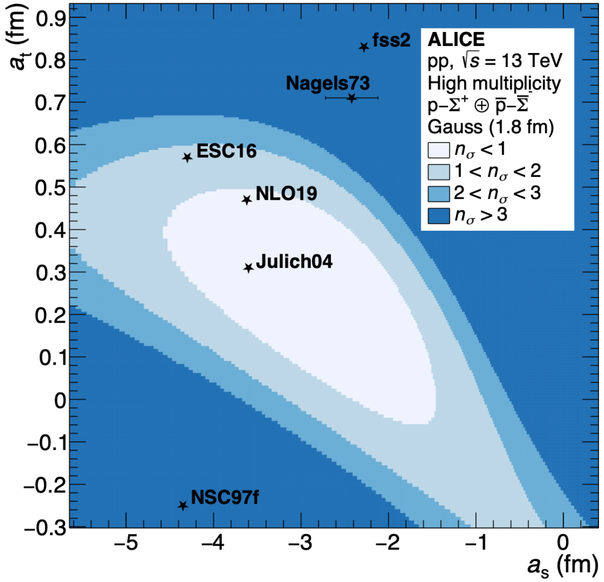
Interactions in the femtoscopy era

- Most precise measurement of the p-Λ scattering parameters



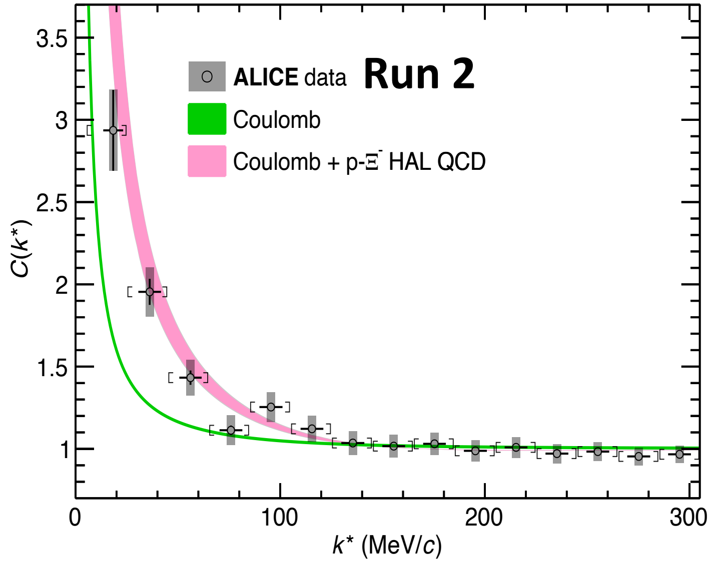
D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550

- First measurement of the p-Σ⁺ scattering parameters



ALICE Coll., arXiv:2510.14448 [nucl-ex]

- Evidence of an attractive p-Ξ⁻ interaction



ALICE Coll., Nature 588 (2020) 232

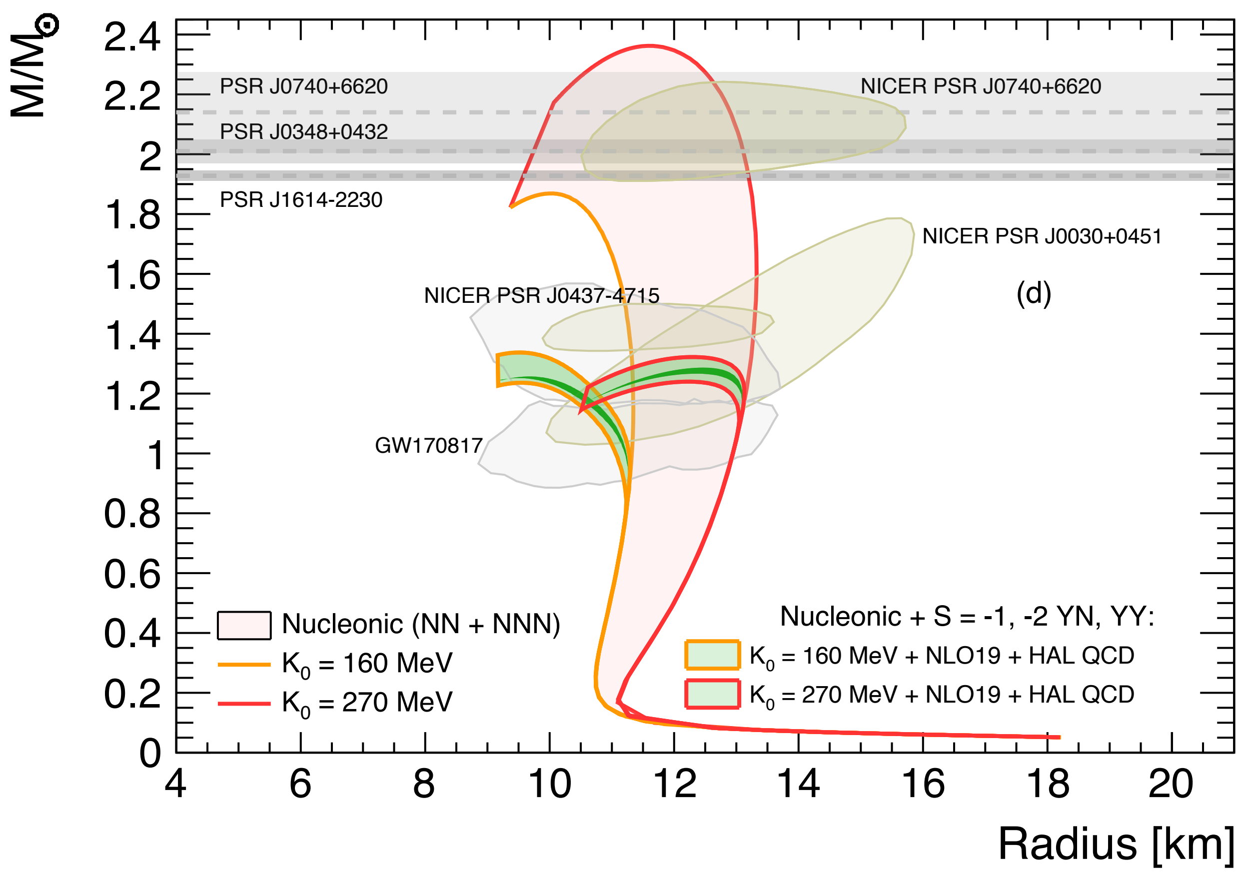
New precise experimental inputs for EFTs

First tests 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

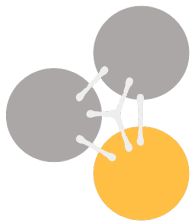


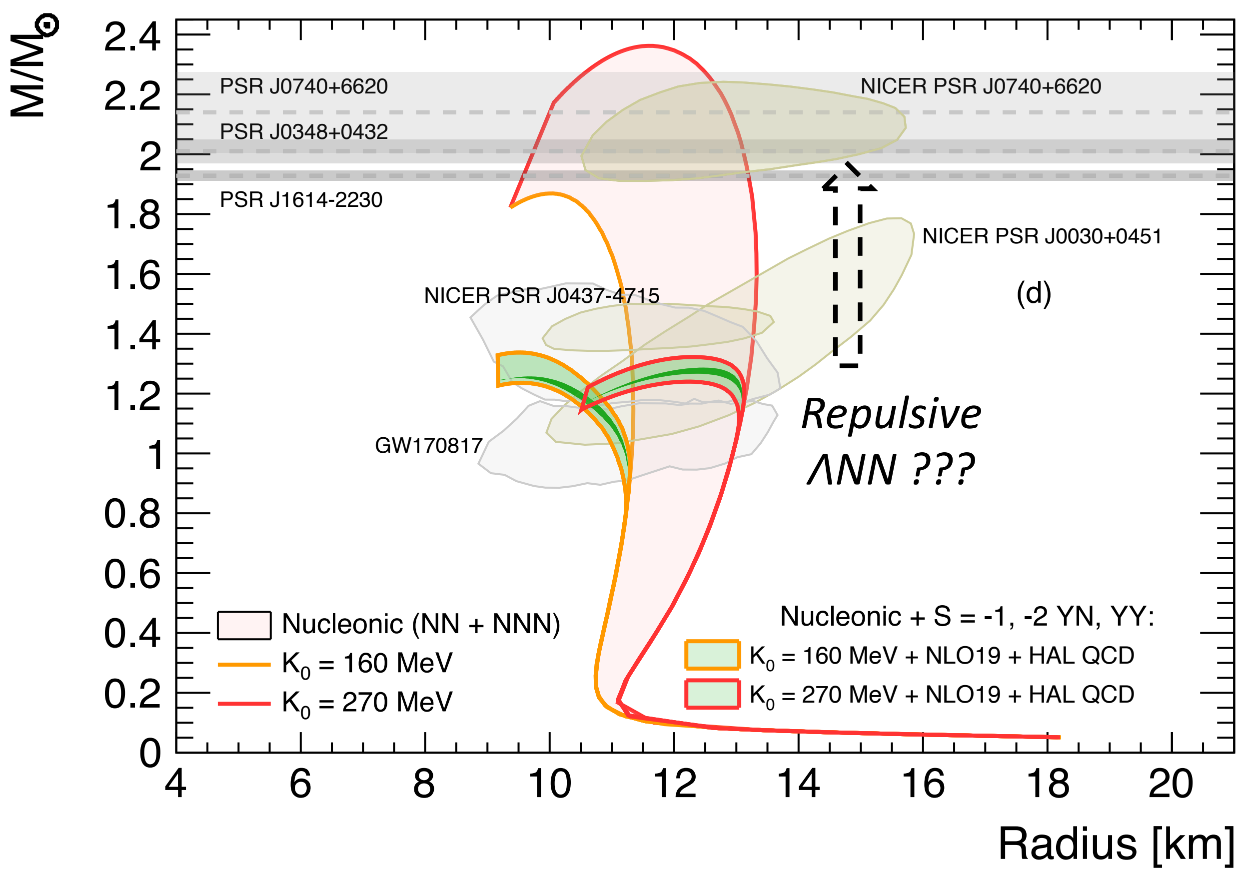
I. Vidaña, V. Mantovani Sarti, J. Haidenbauer, D. Mihaylov, L. Fabbietti, EPJ.A 61 (2025) 3, 59

Towards a realistic equation of state of neutron stars

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

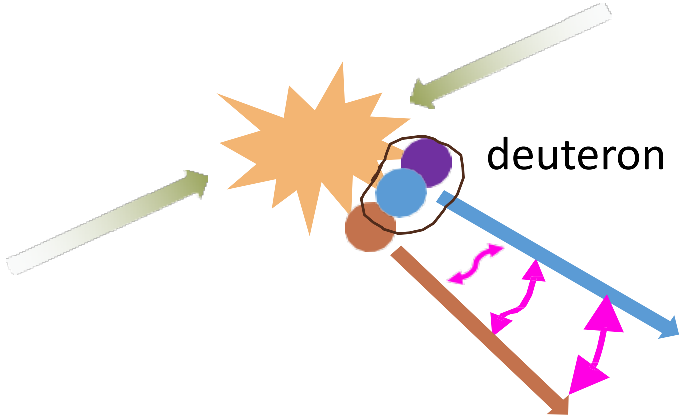
  … ΛNN interaction is not well known!!





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

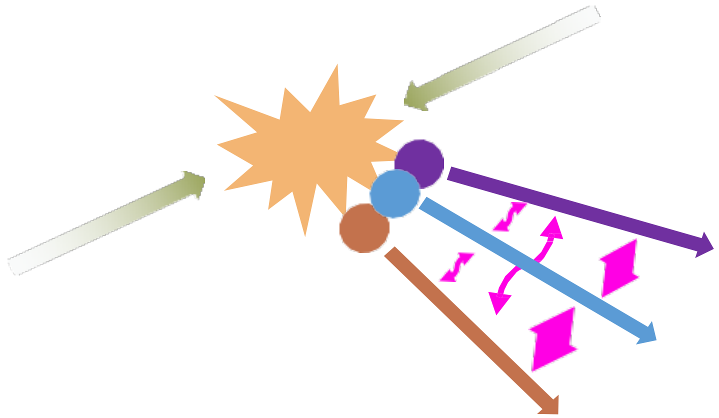
Three-body femtoscopy at the LHC



Hadron-deuteron correlations:

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

Hadron-deuteron scattering wave function



Three particle correlations:

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

Three-body scattering wave function

Hypermomentum:

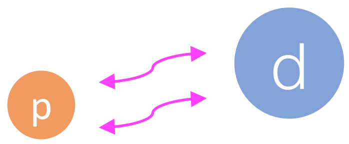
$$Q_3 = 2\sqrt{k_{12}^2 + k_{23}^2 + k_{31}^2}$$

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

***R. Del Grande** et al. EPJC 82 (2022) 244*

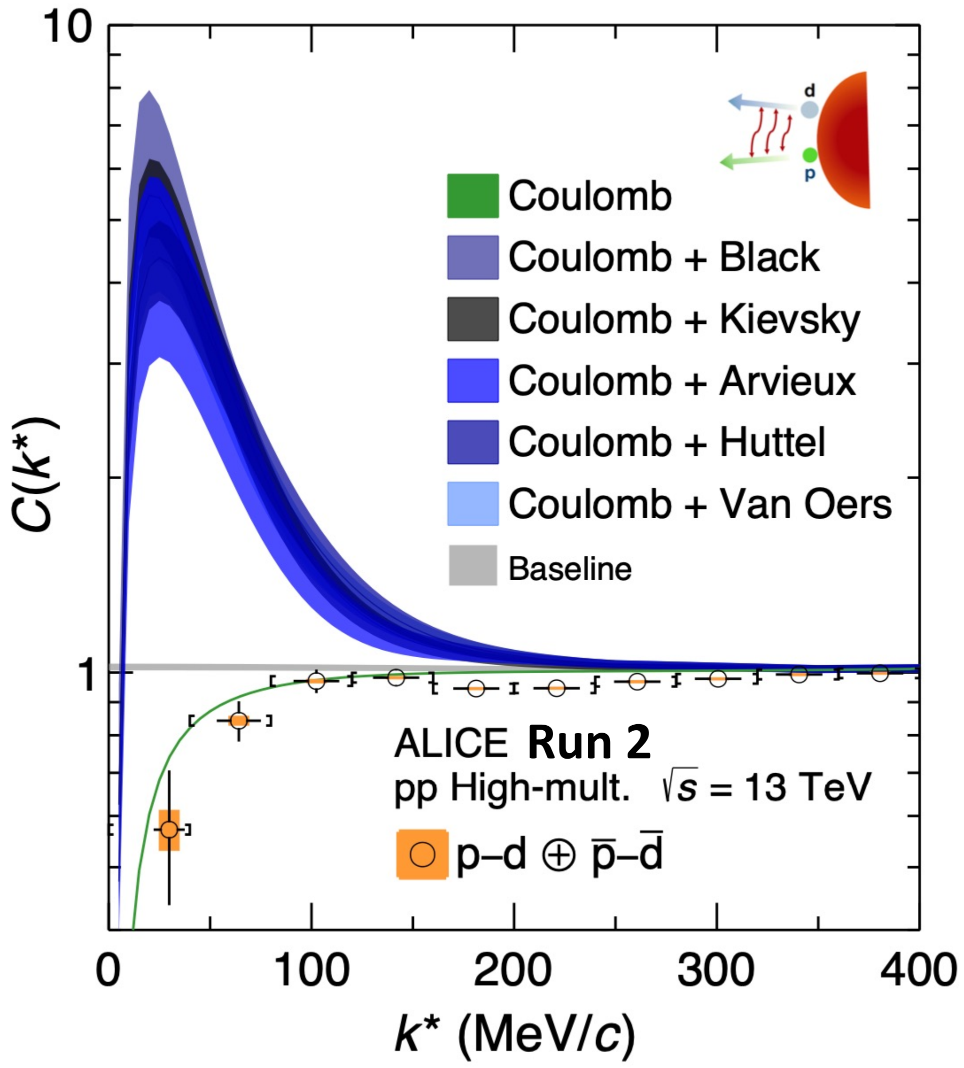
ALICE Coll., EPJ A 59, 145 (2023)

NNN using proton-deuteron correlations



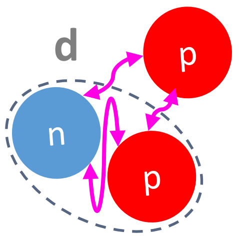
- Point-like particle models anchored to scattering experiments
  W. T. H. Van Oers et al., NPA 561 (1967);
  J. Arvieux et al., NPA 221 (1973); E. Huttel et al., NPA 406 (1983);
  A. Kievsky et al., PLB 406 (1997); T. C. Black et al., PLB 471 (1999);
- Coulomb + strong interaction using Lednický model
  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

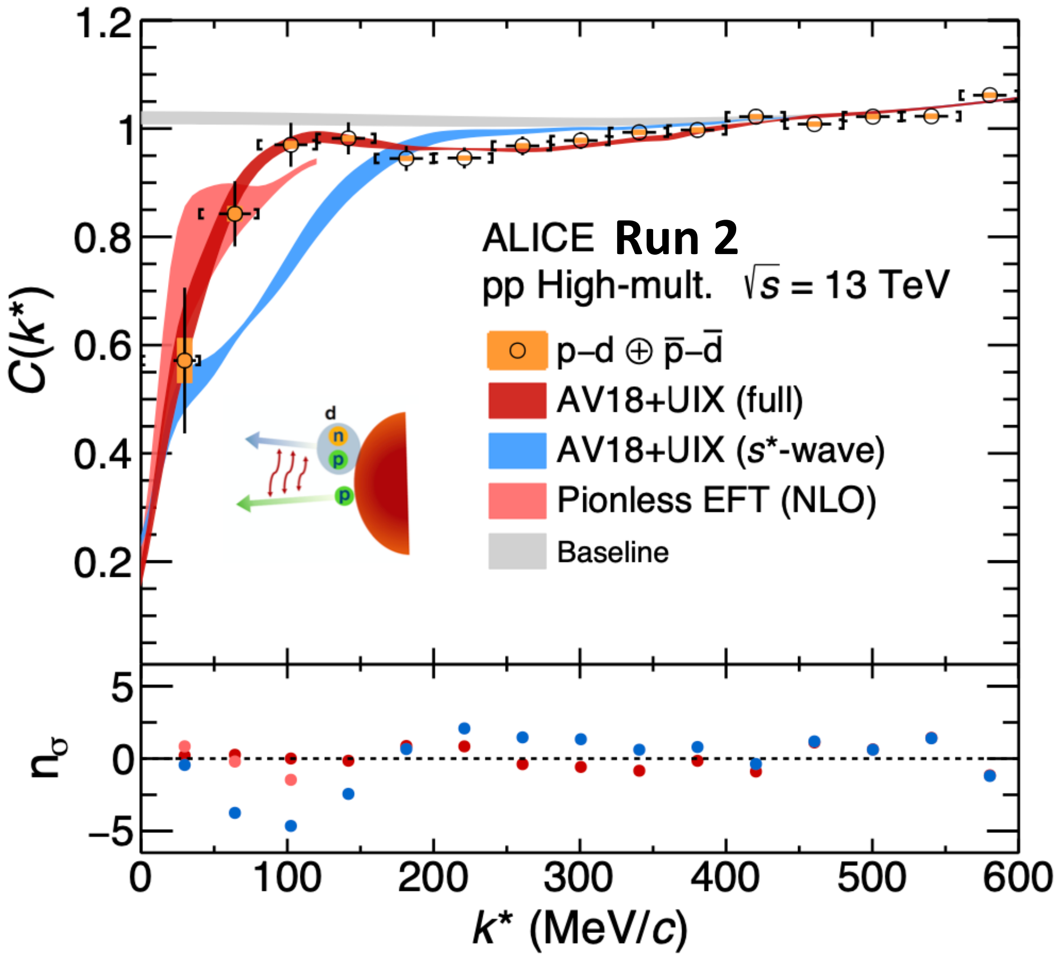


ALICE Coll. Phys. Rev. X 14, 031051 (2024)

NNN using proton-deuteron correlations



- Full three-body calculations are required (NN + NNN + Quantum Stat.)
- **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

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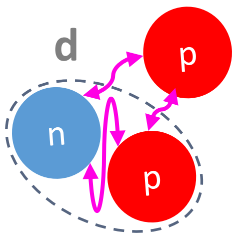

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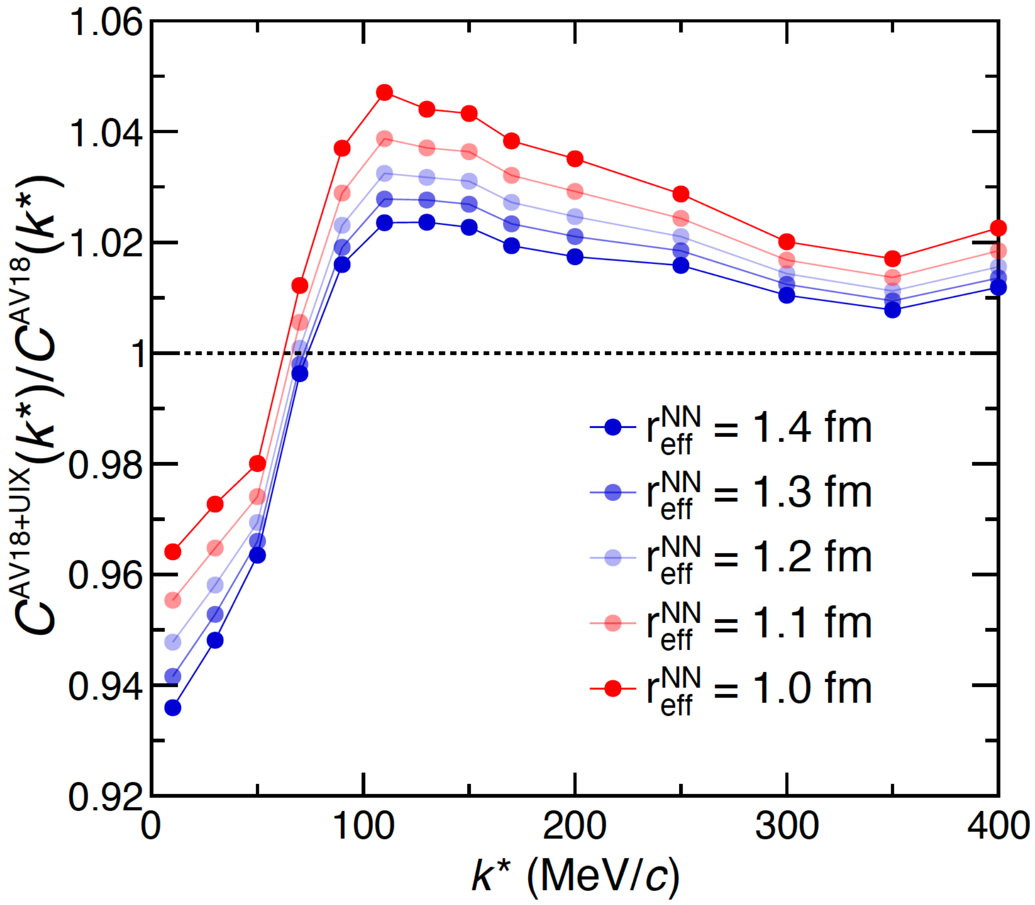
- Sensitivity to three-body forces up to 5%



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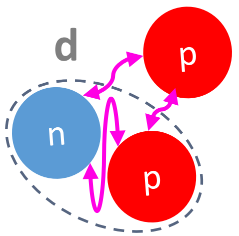

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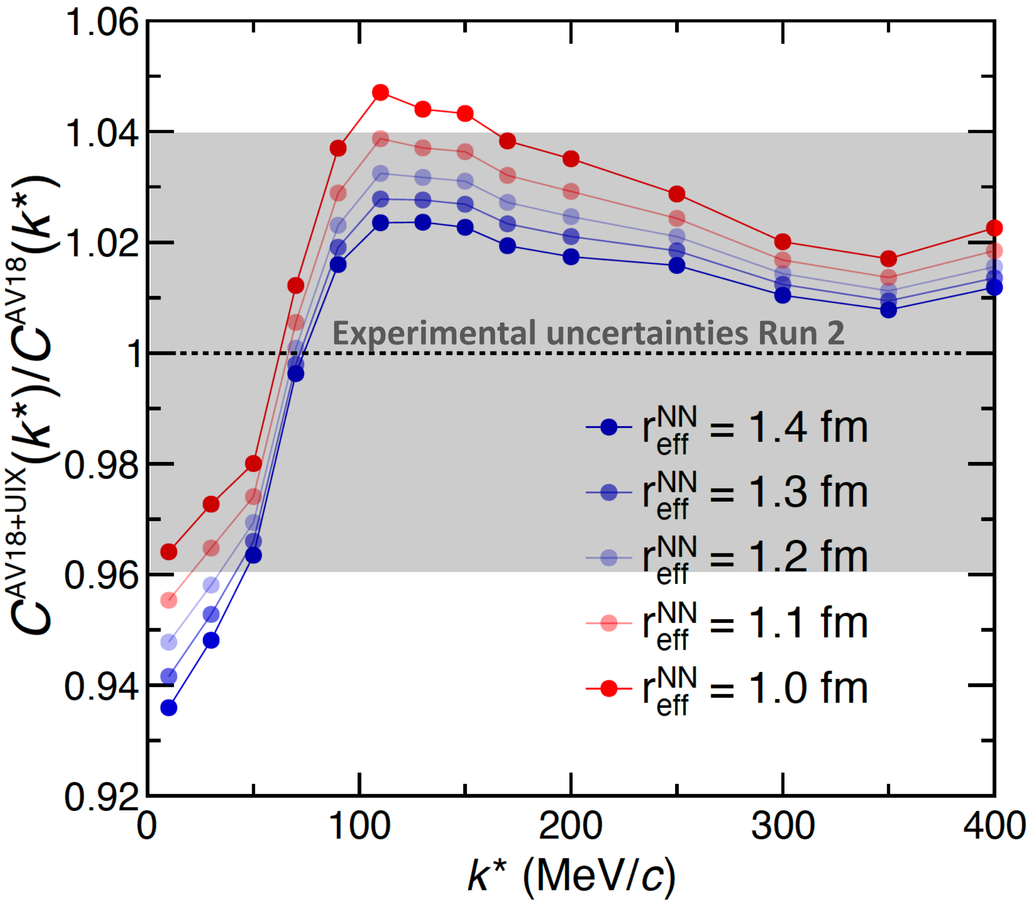

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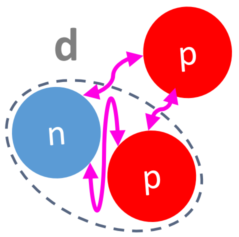
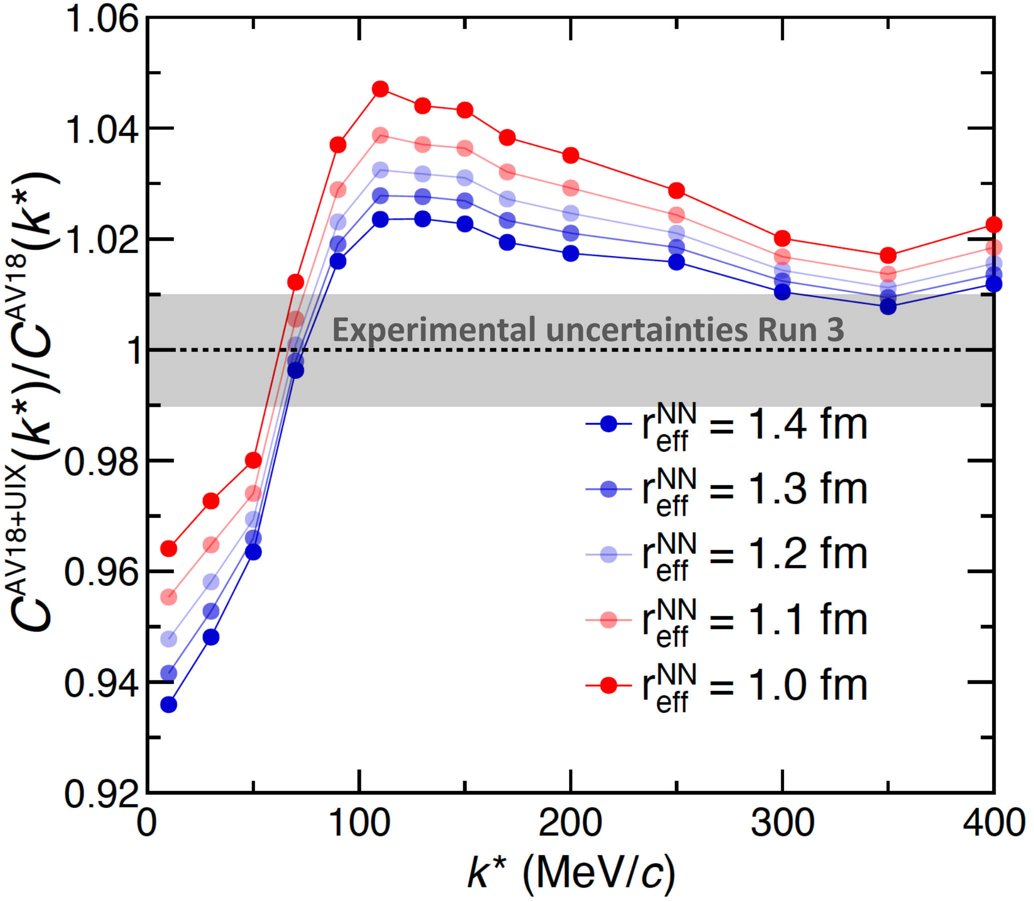
NNN using proton-deuteron correlations



- Full three-body calculations are required (NN + NNN + Quantum Stat.)
- **Hadron-nuclei correlations at the LHC can be used to study many-body dynamics**
- Sensitivity to three-body forces up to 5%
- **At the end of Run 3 expected uncertainty of 1% in ALICE measurement**

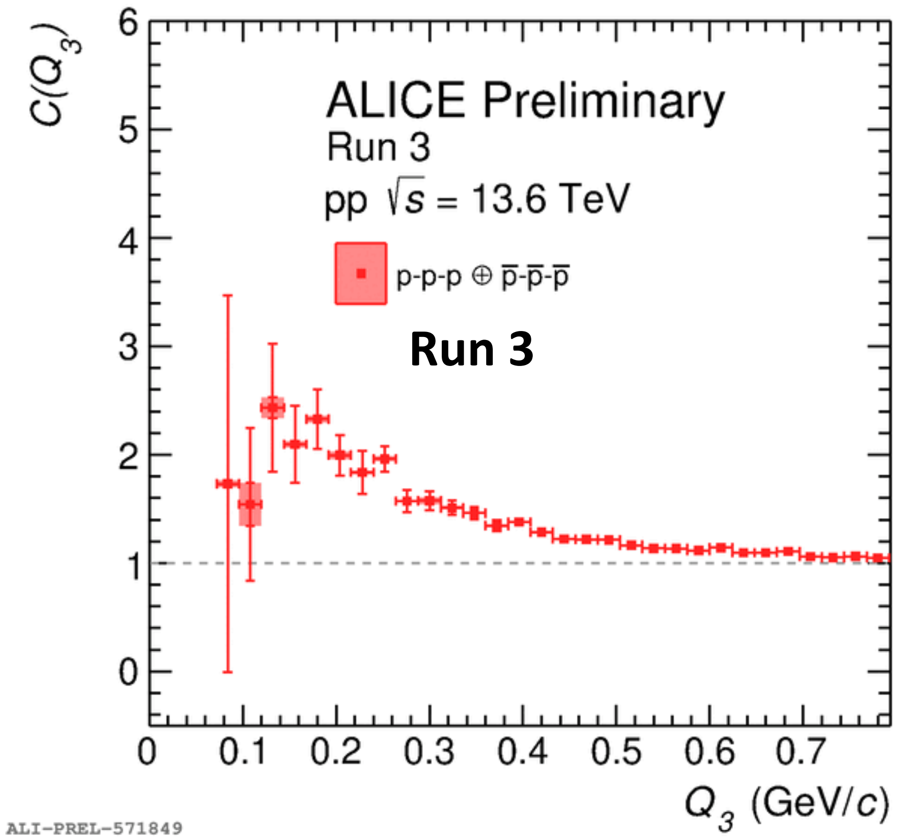


ALICE Coll. Phys. Rev. X 14, 031051 (2024)
M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002

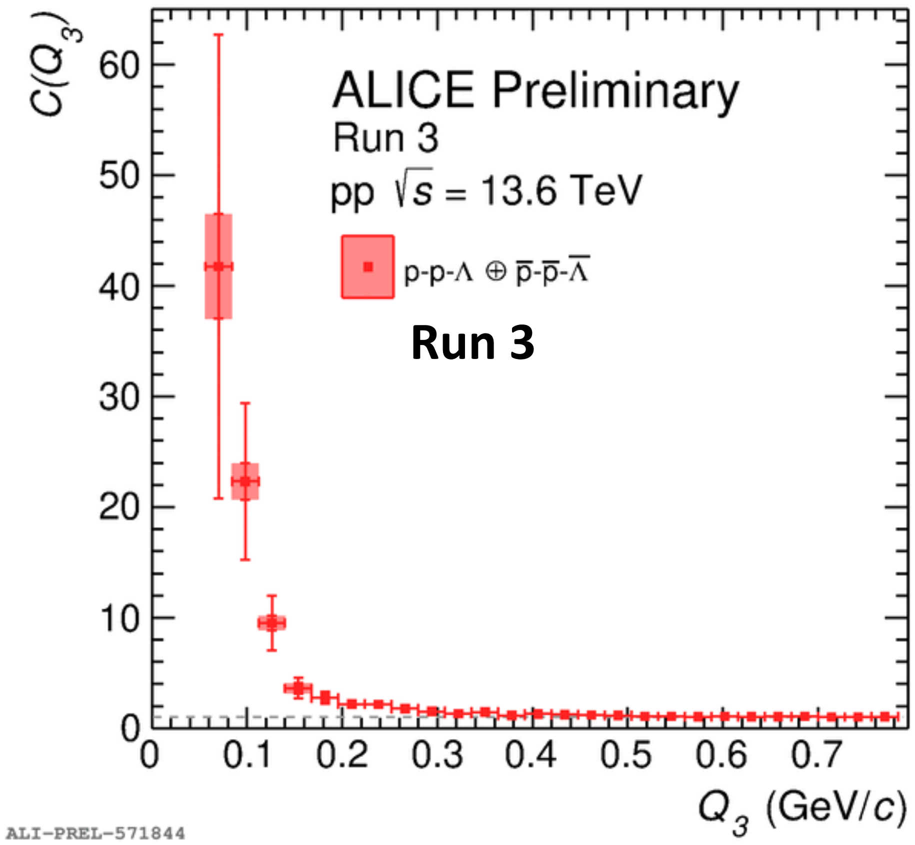
p-p-p and p-p-Λ correlation functions

- 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

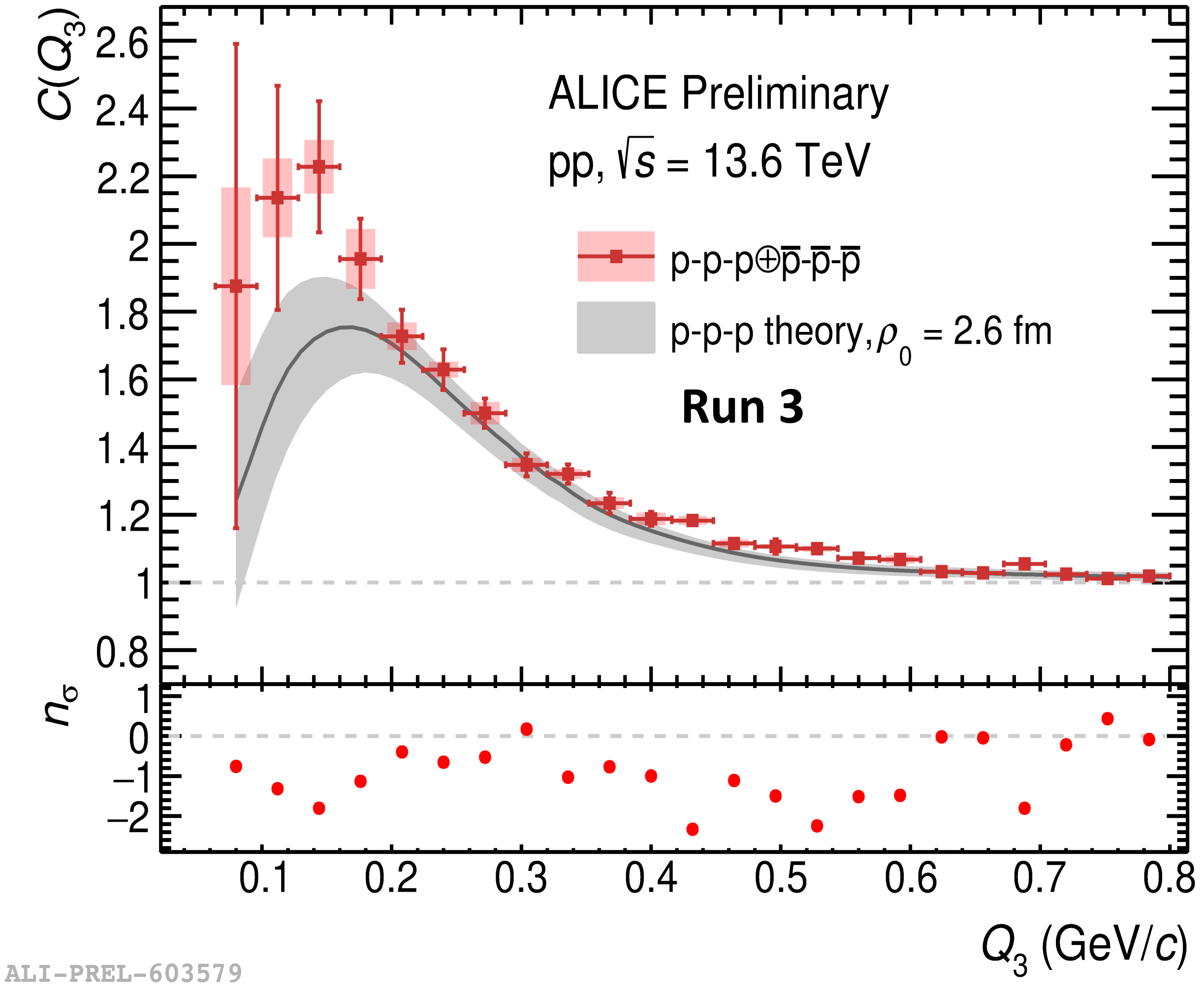


p-p-Λ



p-p-p correlation function

- First ever full three-body correlation function calculations
- Interactions:
  - pp strong interaction (AV18)
  - Coulomb
  - **Negligible three-body interactions**
- Calculations can describe the the data within 1.67σ

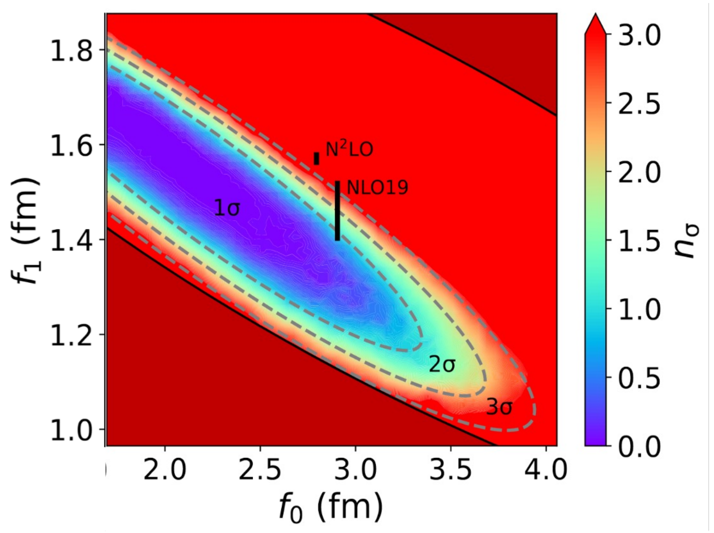


E. Garrido, A. Kievsky, R. Del Grande, L. Serksnyte, M. Viviani, L.E. Marcucci, Phys.Lett.B 868 (2025) 139731

p-p-Λ correlation function

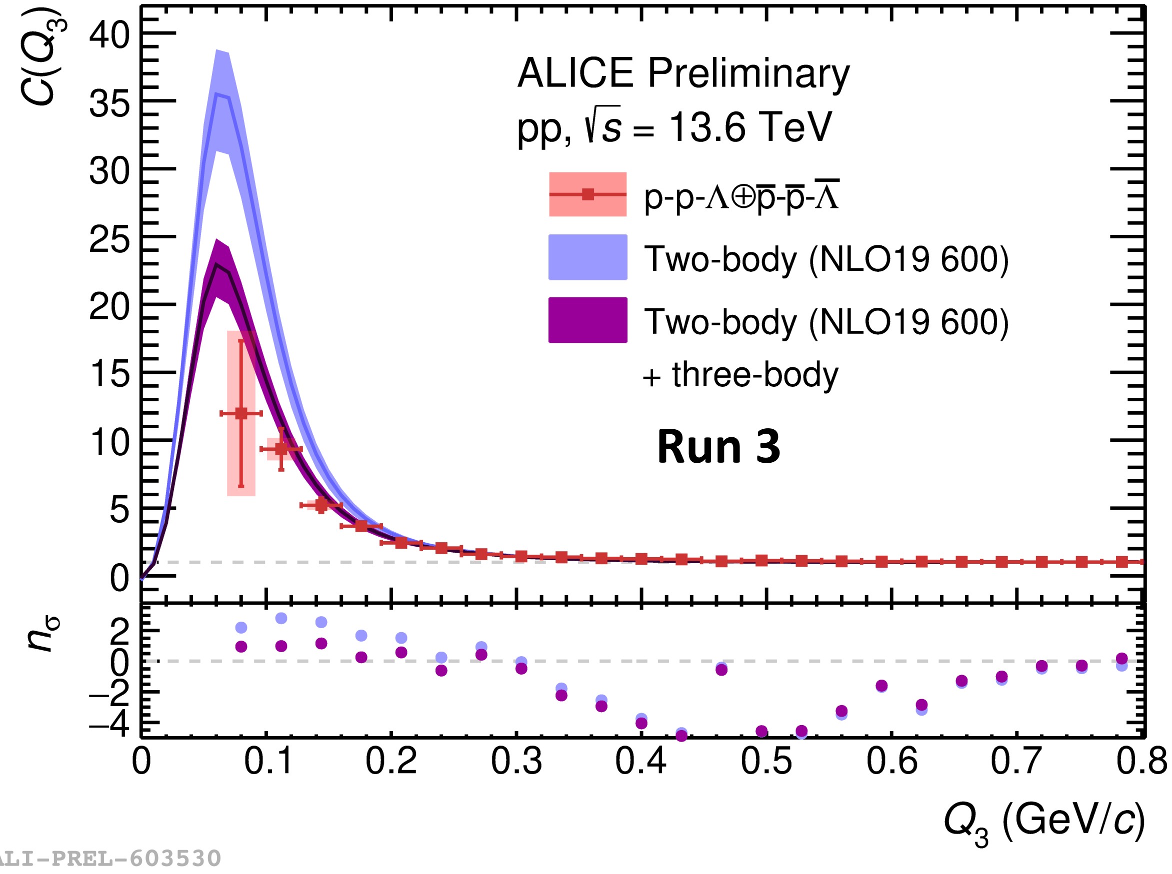
- NLO19 (600) is used to describe the pΛ interaction

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



- Three-body force constrained to the hypertriton binding energy

	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



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

p-p-Λ correlation function

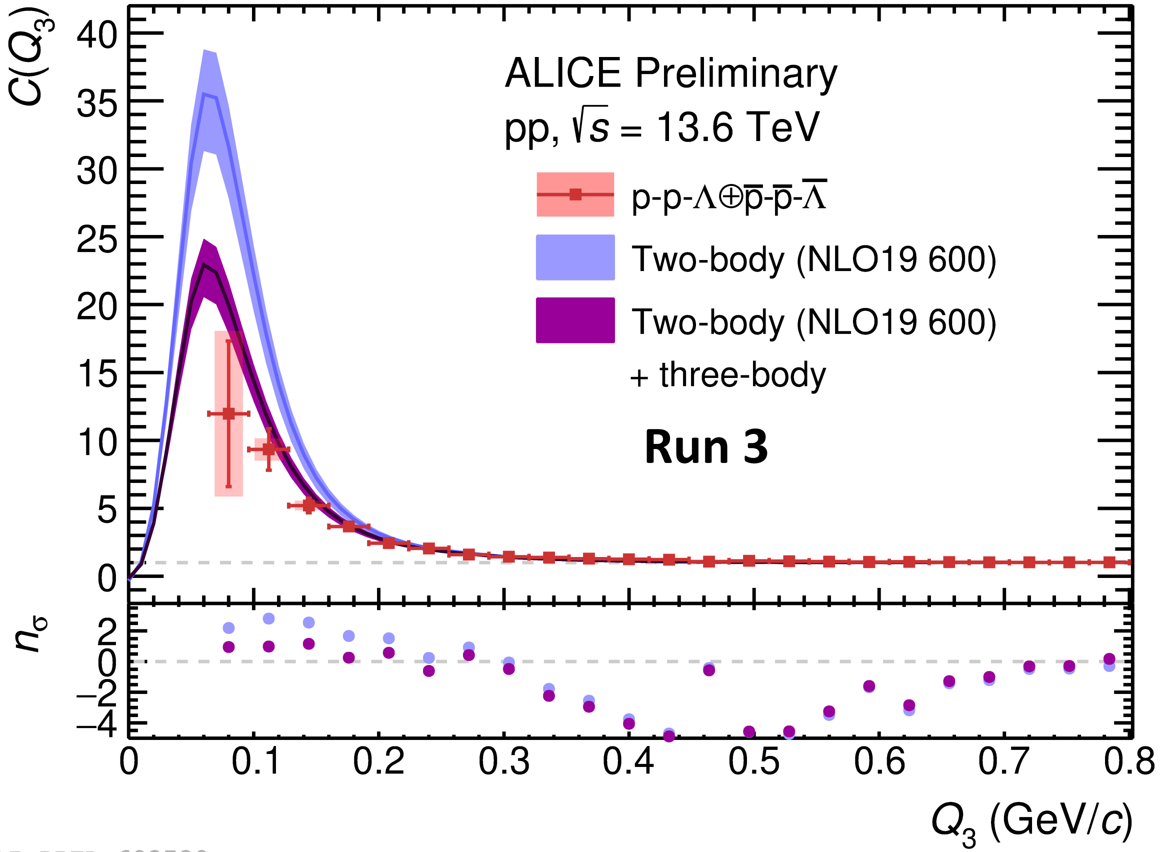
- NLO19 (600) is used to describe the pΛ interaction

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

- Three-body force constrained to the hypertriton binding energy

- Significant effect of three-body interactions

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



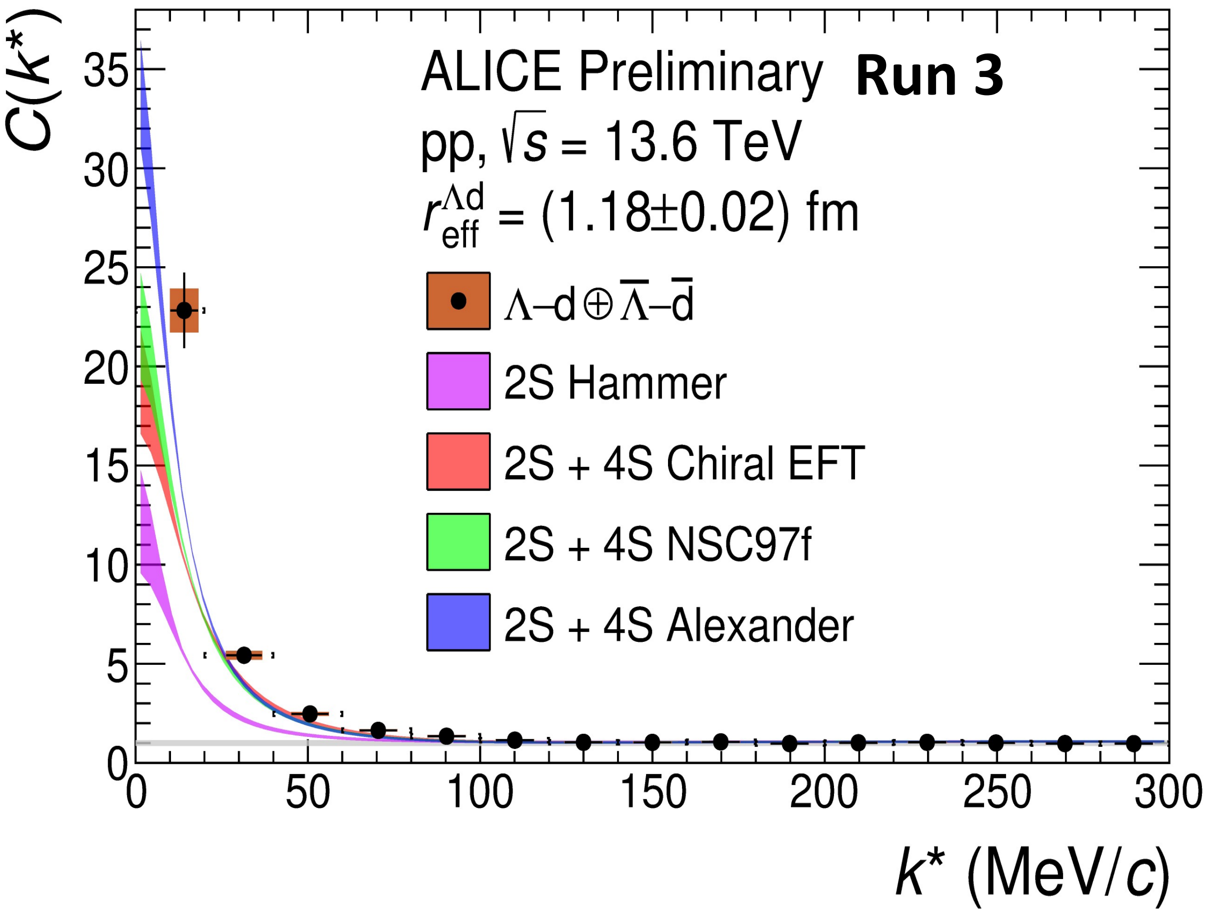
ALI-PREL-603530

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

Λ-d correlation function

- Dedicated three body triggers for pp collisions in 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



Conclusions and Outlook

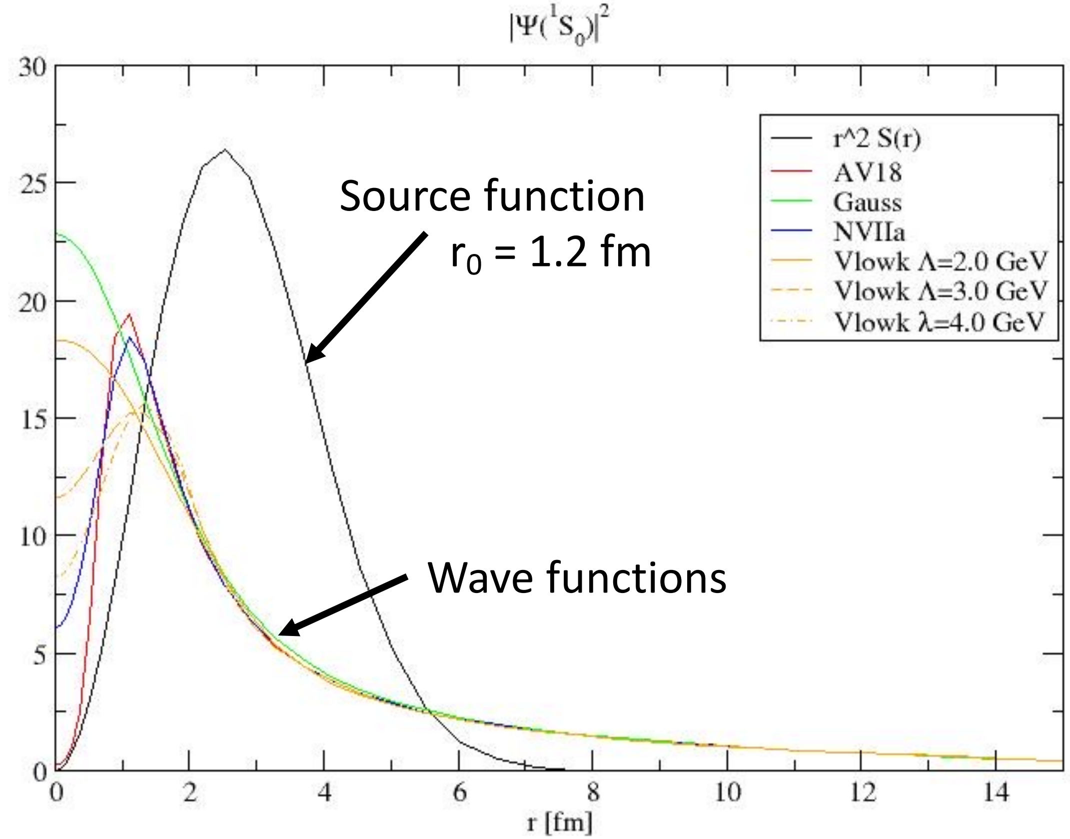
- Exciting results from femtoscopy
  → Important experimental input to understand the many facets of QCD in strange sector
  - Most precise p-Λ data at low momenta
  - First extraction of the p-Λ scattering parameters using femtoscopy and scattering data
  - Shallow repulsion in the p-Σ^{+} interaction in the triplet channel
  - Evidence of the attractive p-Ξ^{-} strong interaction
  - 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: significant effect in the correlation function

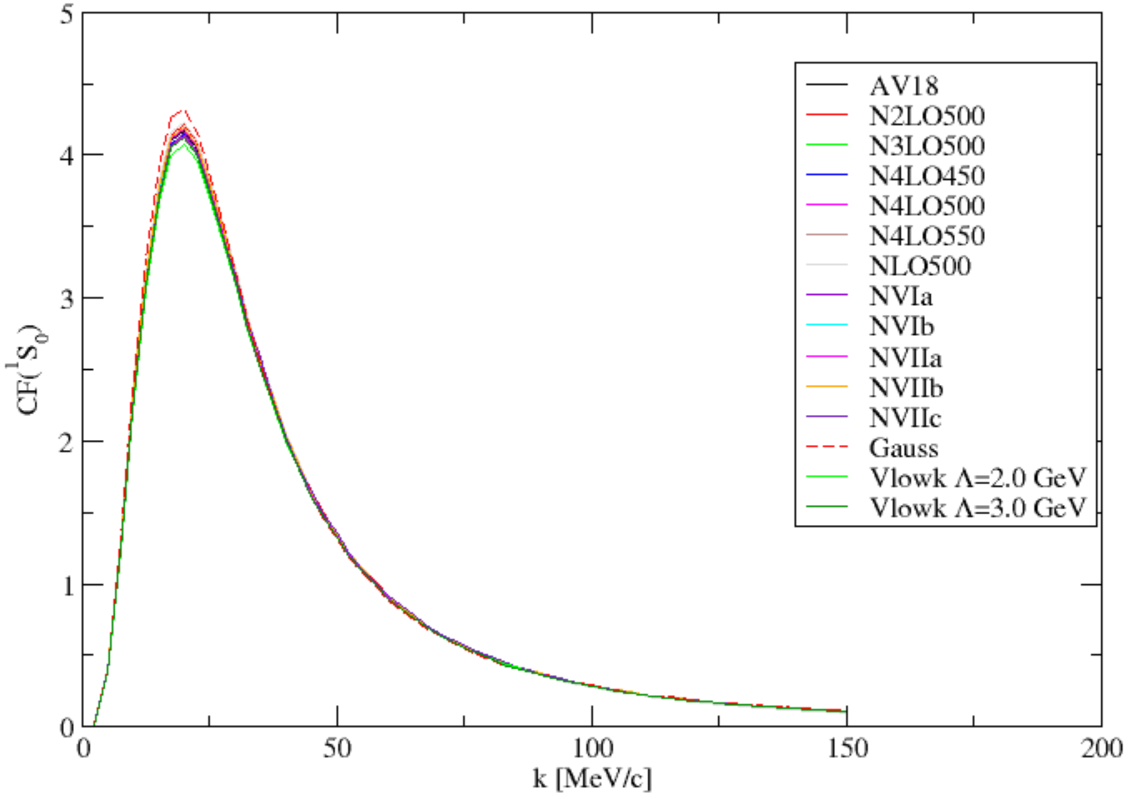
- On-going Run 3 and future Run 4
  - Access to precise data on three-particle interactions
  - Sensitivity to the effect of three-body forces in the correlation functions

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, arXiv:2505.13433v1

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

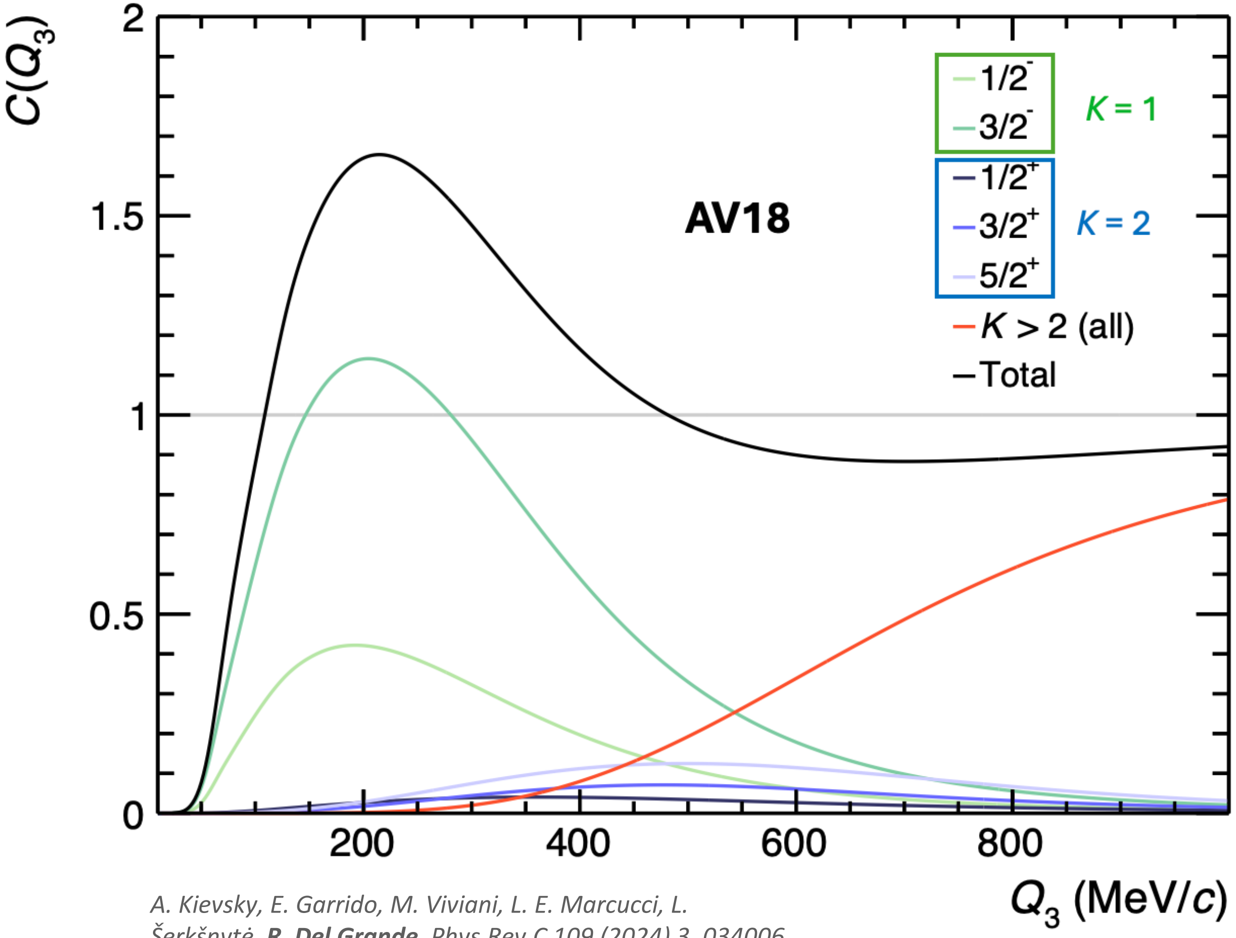
- Wave function in hyperspherical harmonics

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

- 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

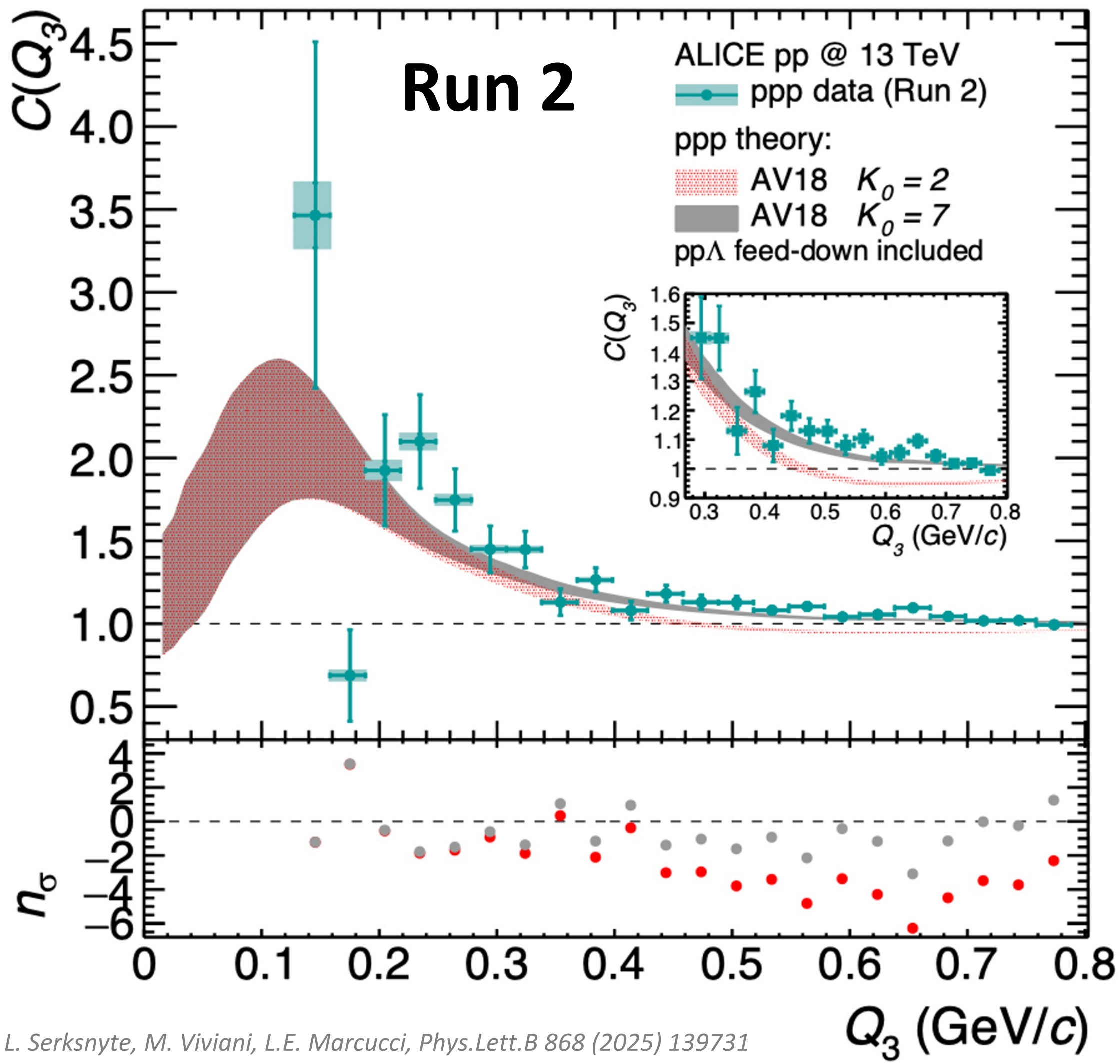


*A. Kievsky, E. Garrido, M. Viviani, L. E. Marcucci, L. Šerkšnytė, **R. Del Grande**, Phys.Rev.C 109 (2024) 3, 034006*

p-p-p correlation function in Run 2

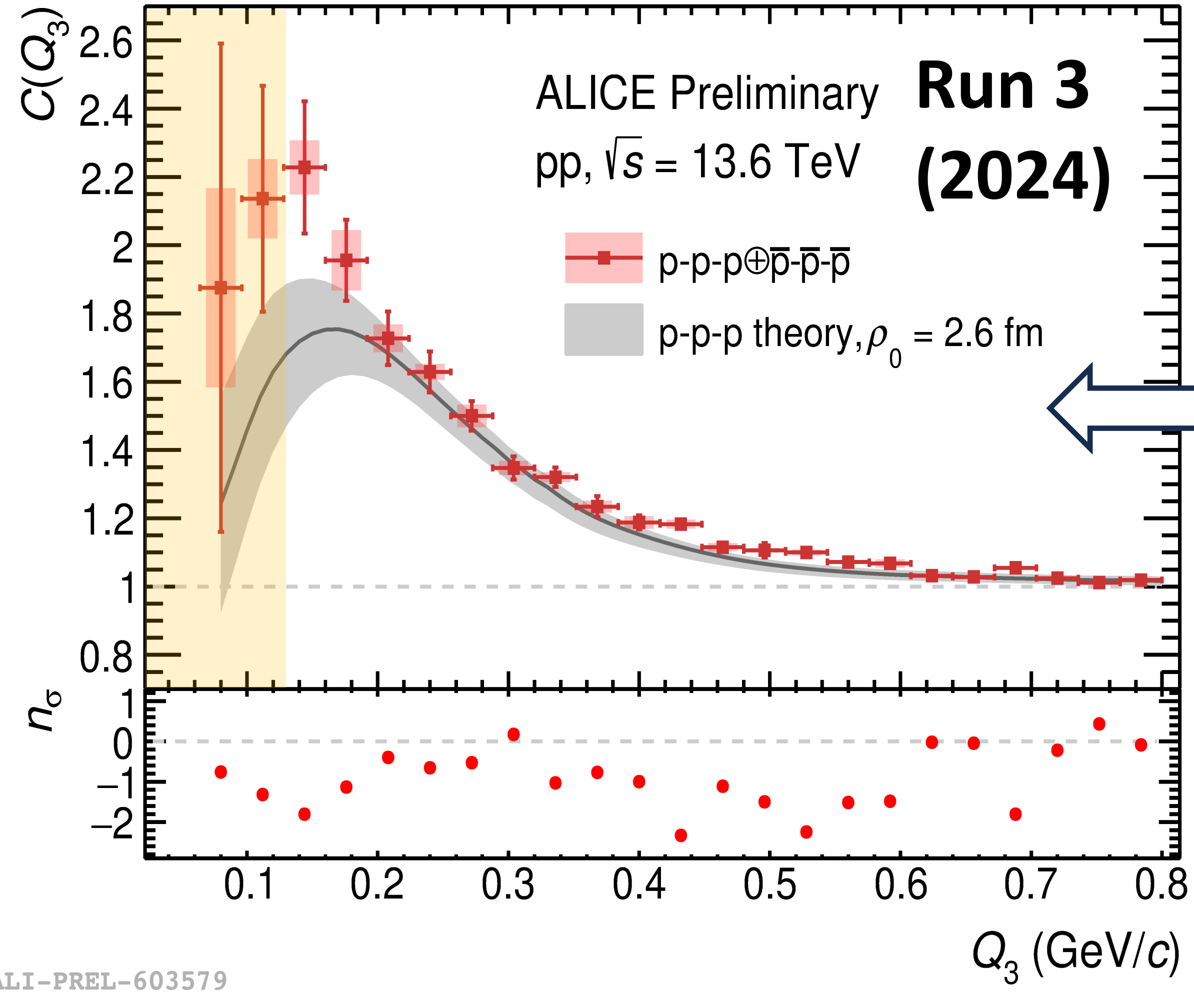
ALICE Run 2 measurement:

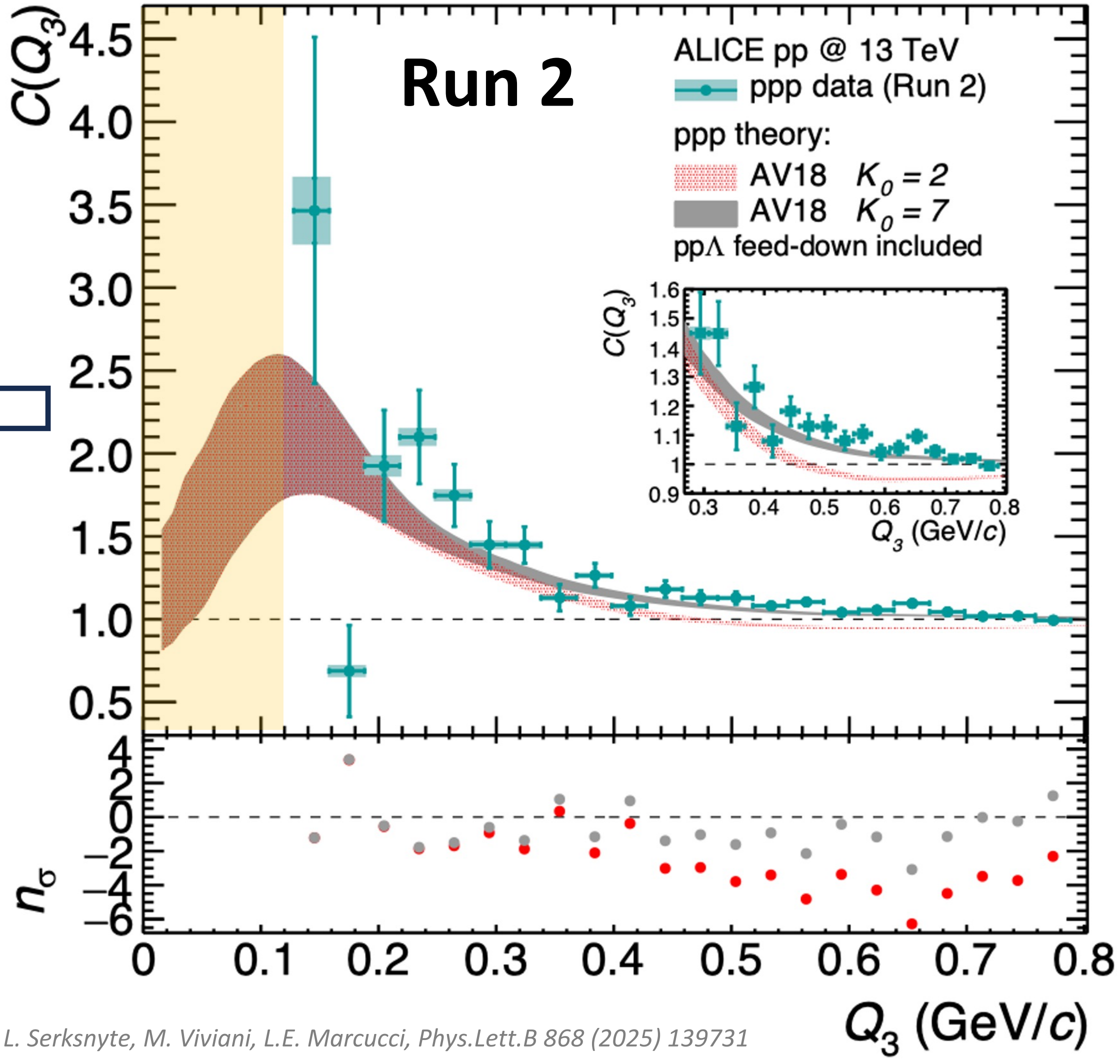
- calculations can describe the shape observed in the data
- interaction at higher partial waves (K<= 7) must be included in the calculations
- **Negligible effect from NNN interaction**
- **Missing data in the low-energy region**



*E. Garrido, A. Kievsky, **R. Del Grande**, L. Serksnyte, M. Viviani, L.E. Marcucci, Phys.Lett.B 868 (2025) 139731*

p-p-p correlation function





*E. Garrido, A. Kievsky, **R. Del Grande**, L. Serksnyte, M. Viviani, L.E. Marcucci, Phys.Lett.B 868 (2025) 139731*

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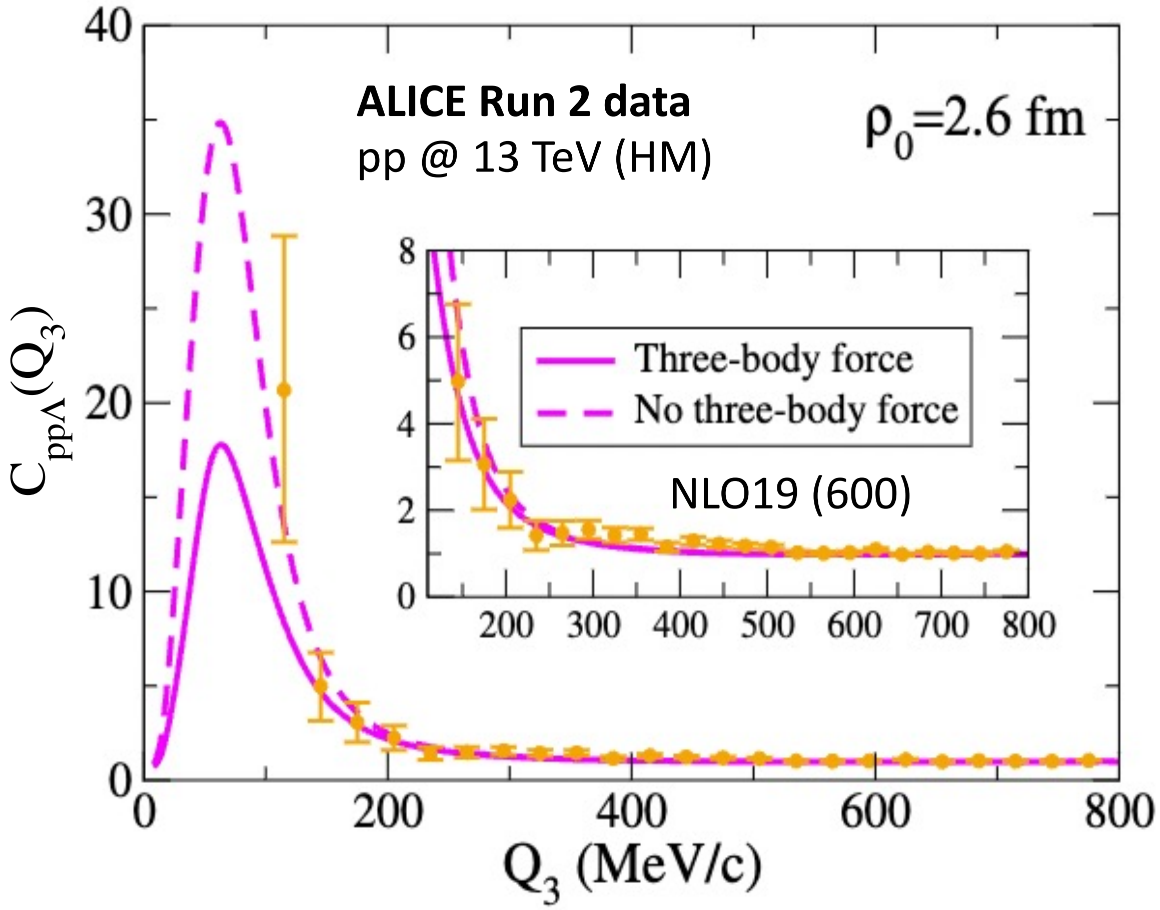
  D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550
- Three-body force constrained to the hypertriton binding energy
- 40% effect of three-body interactions
- Run-2 data: one data point in the region of the maximum



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

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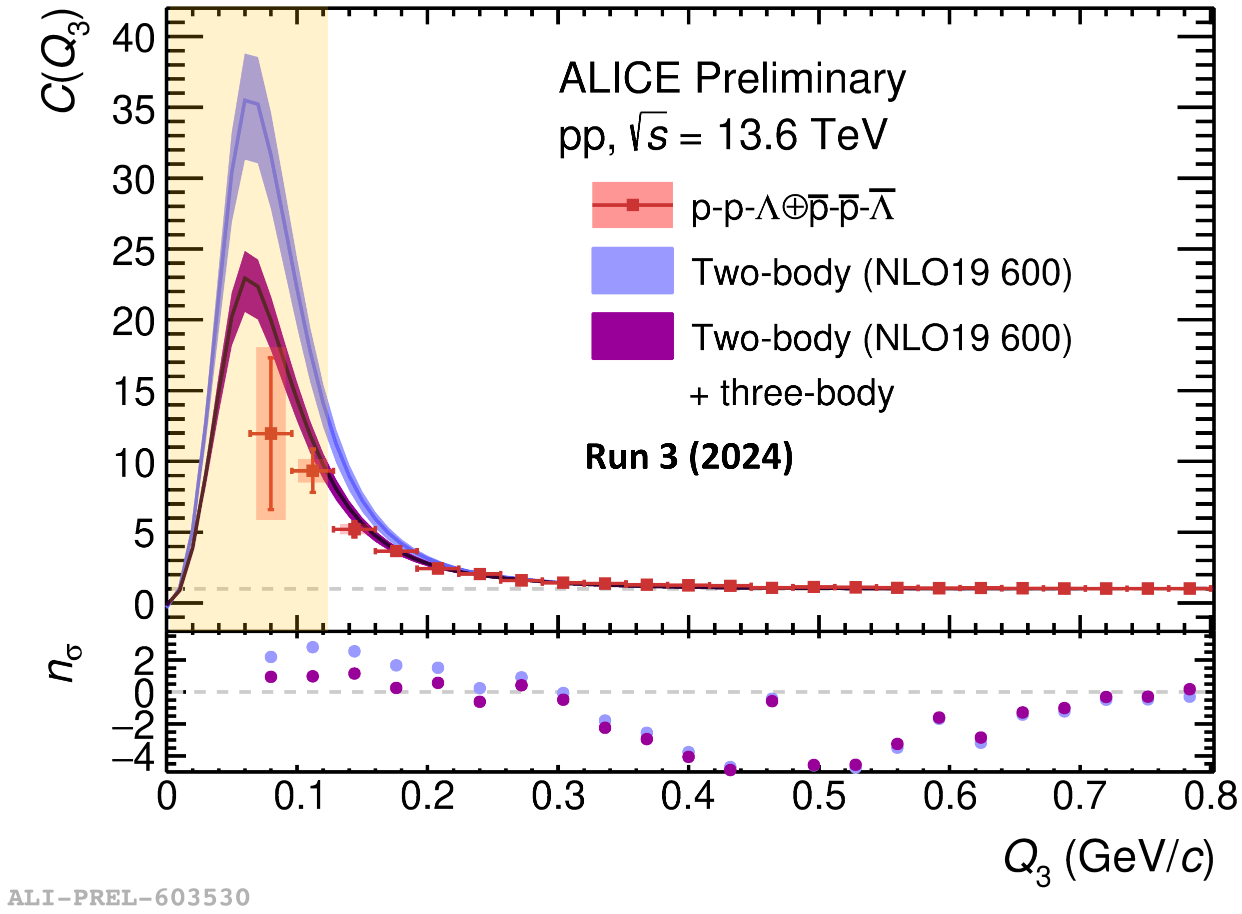

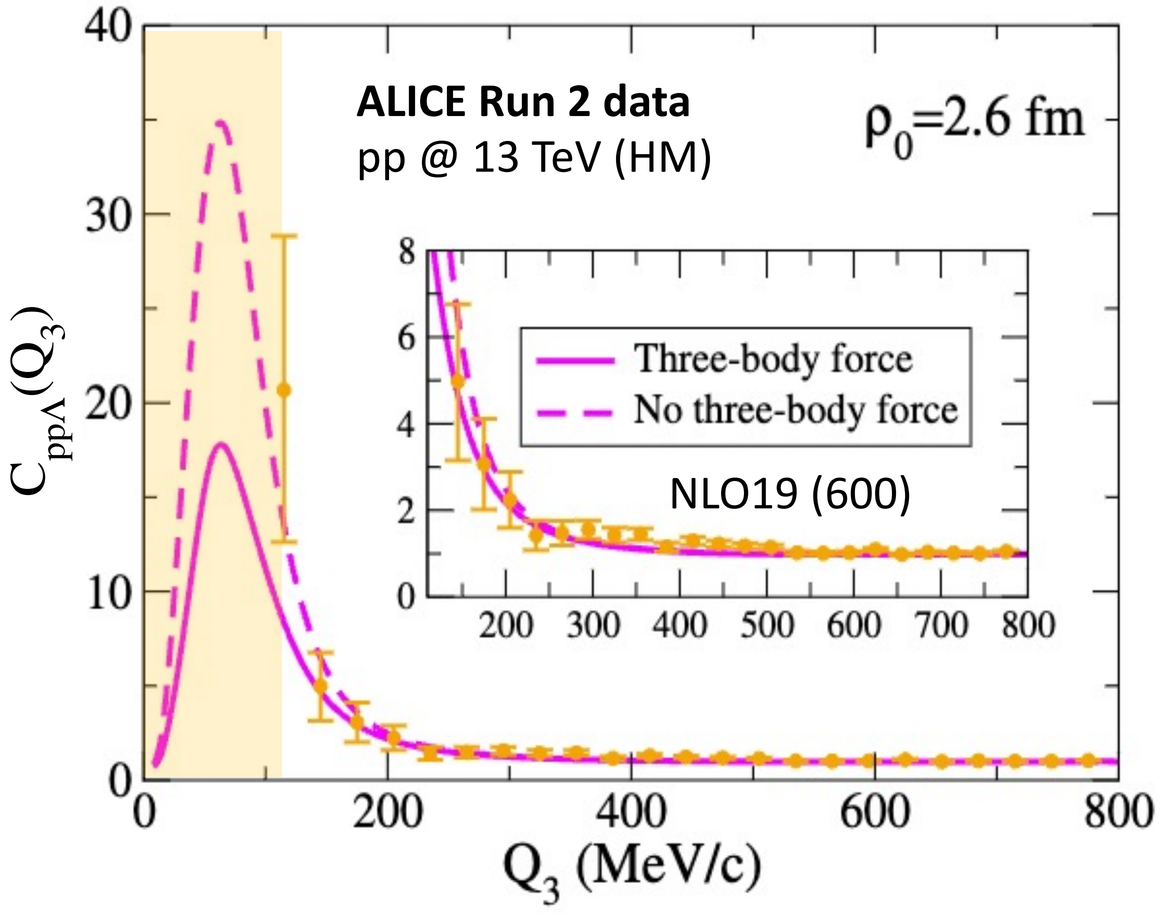

E. Garrido et al., PRC 110 (2024) 5, 054004

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