Czech
Technical
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Understanding hadronic interactions from femtoscopic correlation function measurements

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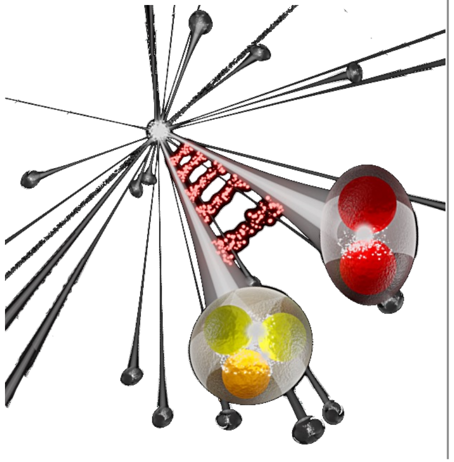
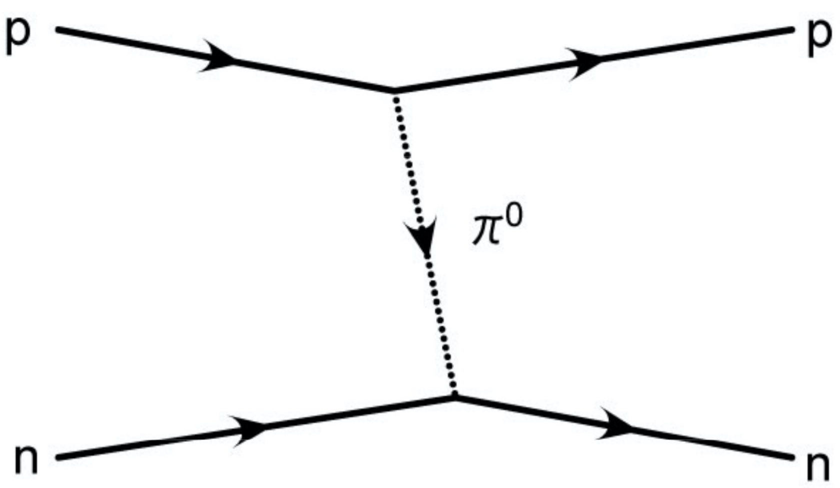
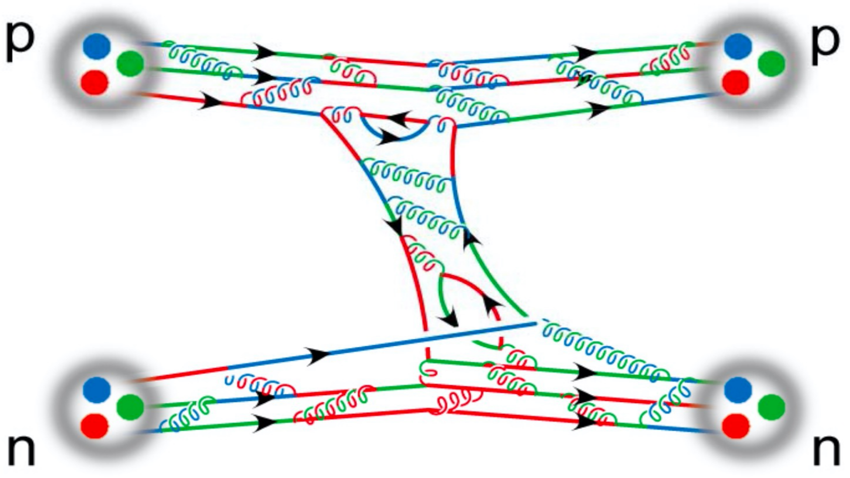


Hadronic interactions

Low energy hadronic interactions:

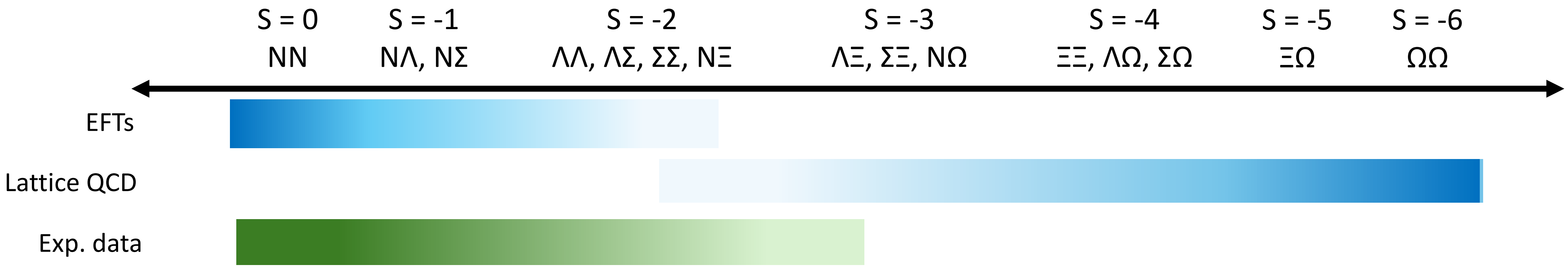


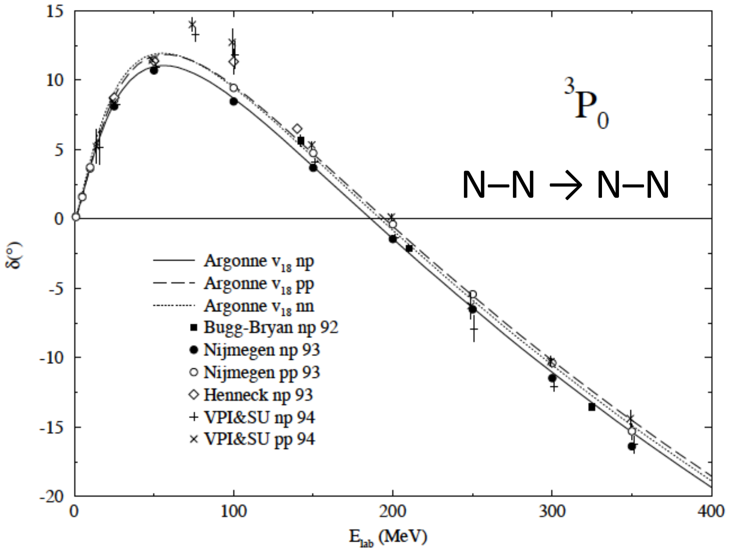


Effective Field Theories (EFT)
- hadrons as degrees of freedom
- low-energy coefficients constrained by data

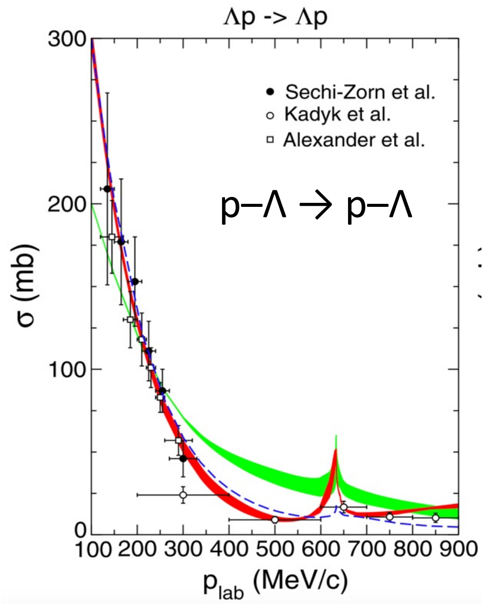
Lattice QCD
- quarks and gluons as degrees of freedom
- unstable for low mass hadrons

Theory and experimental data

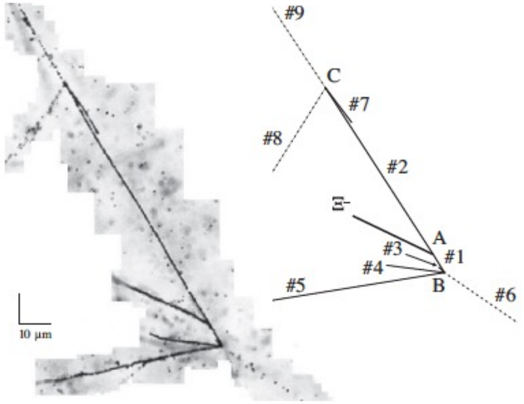




R. B. Wiringa et al. PRC 51 (1995)



J.Haidenbauer et al. NPA 915 (2013)

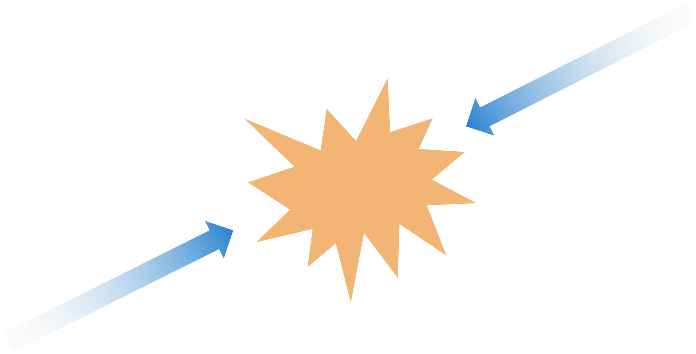


Ξ hypernucleus

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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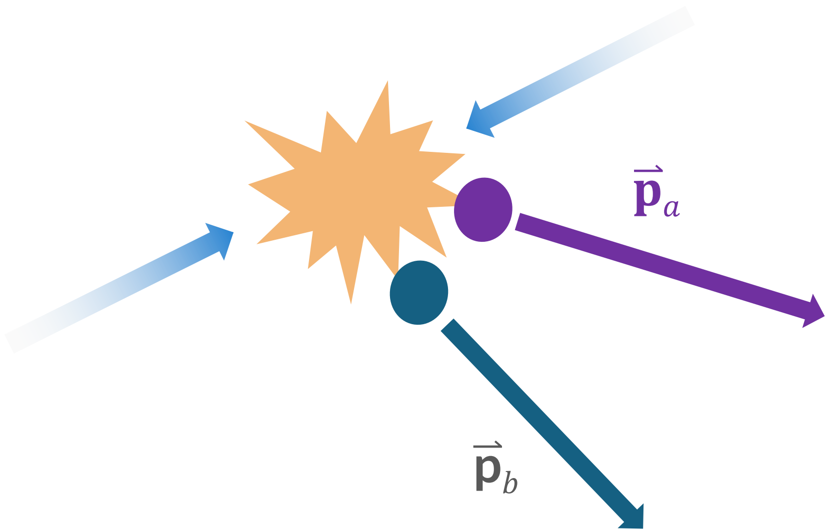

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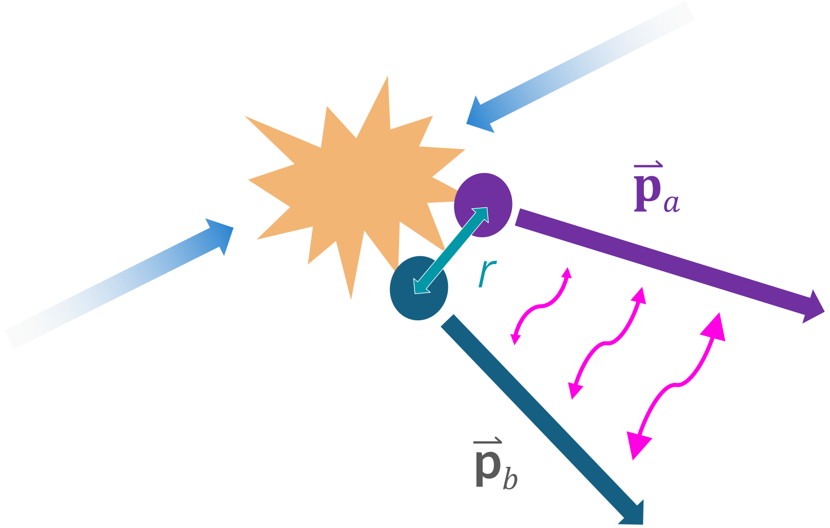

Correlation function

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

Femtoscopy technique at the Large Hadron Collider

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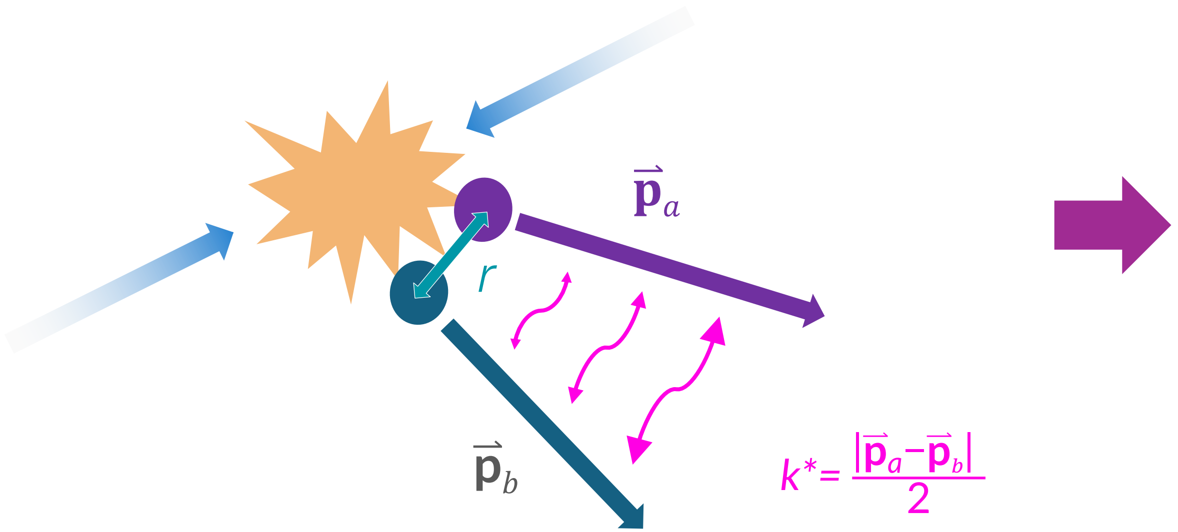


Correlation function

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

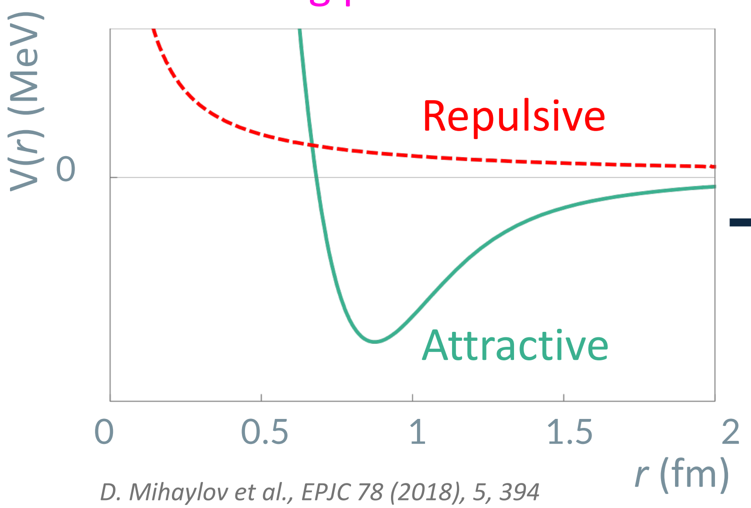
Correlation function

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

Two-particle wave function

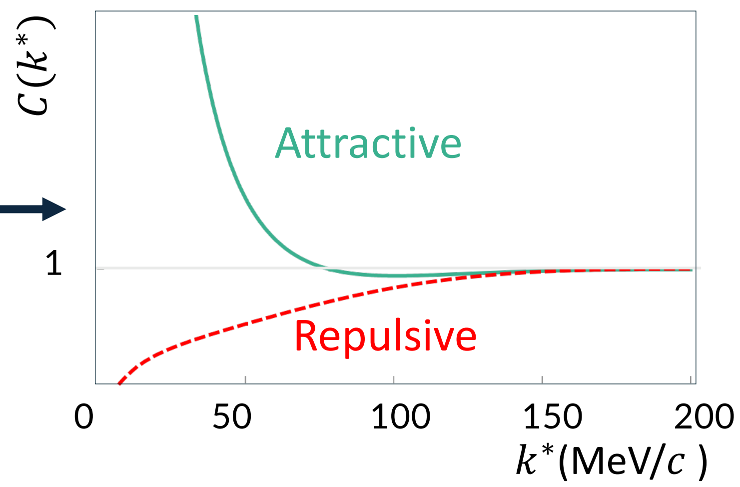
M. Lisa, S. Pratt et al., ARNPS 55 (2005), 357-402
L. Fabbietti et al., ARNPS 71 (2021), 377-402

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

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

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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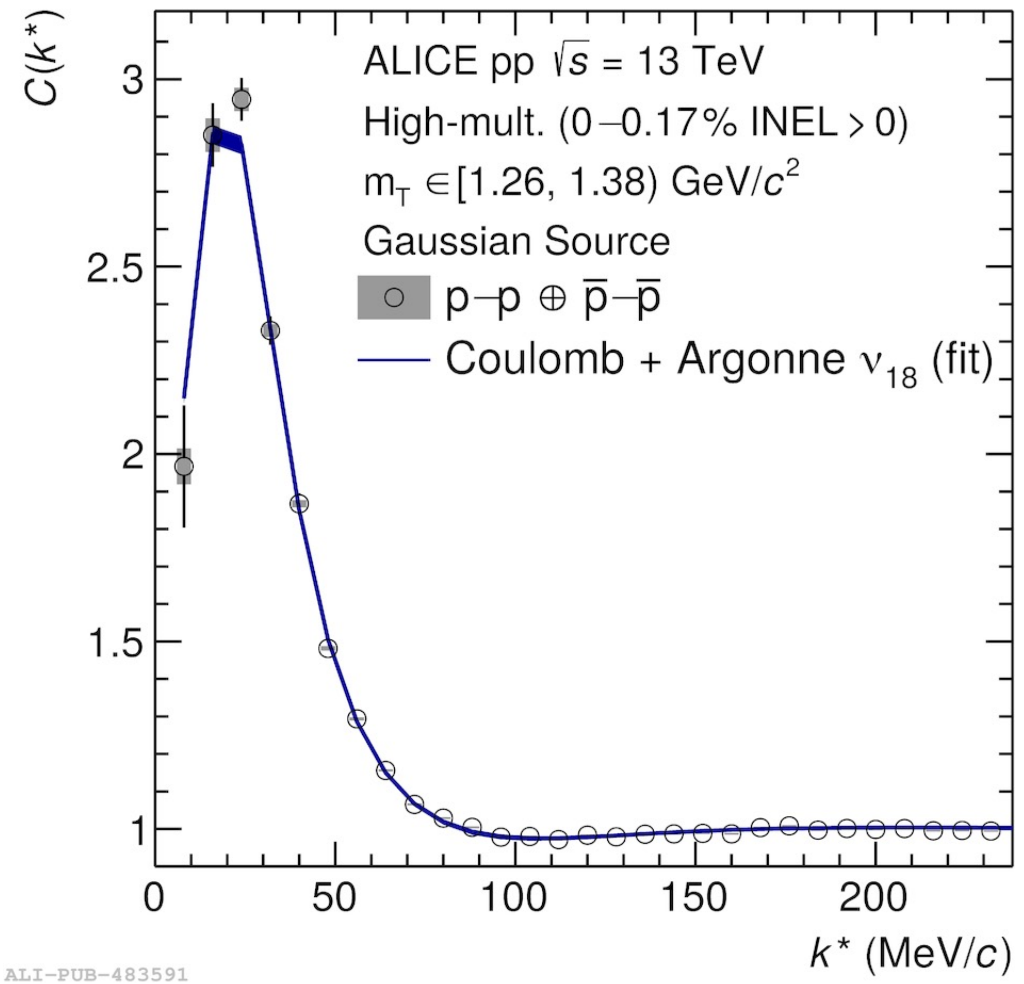
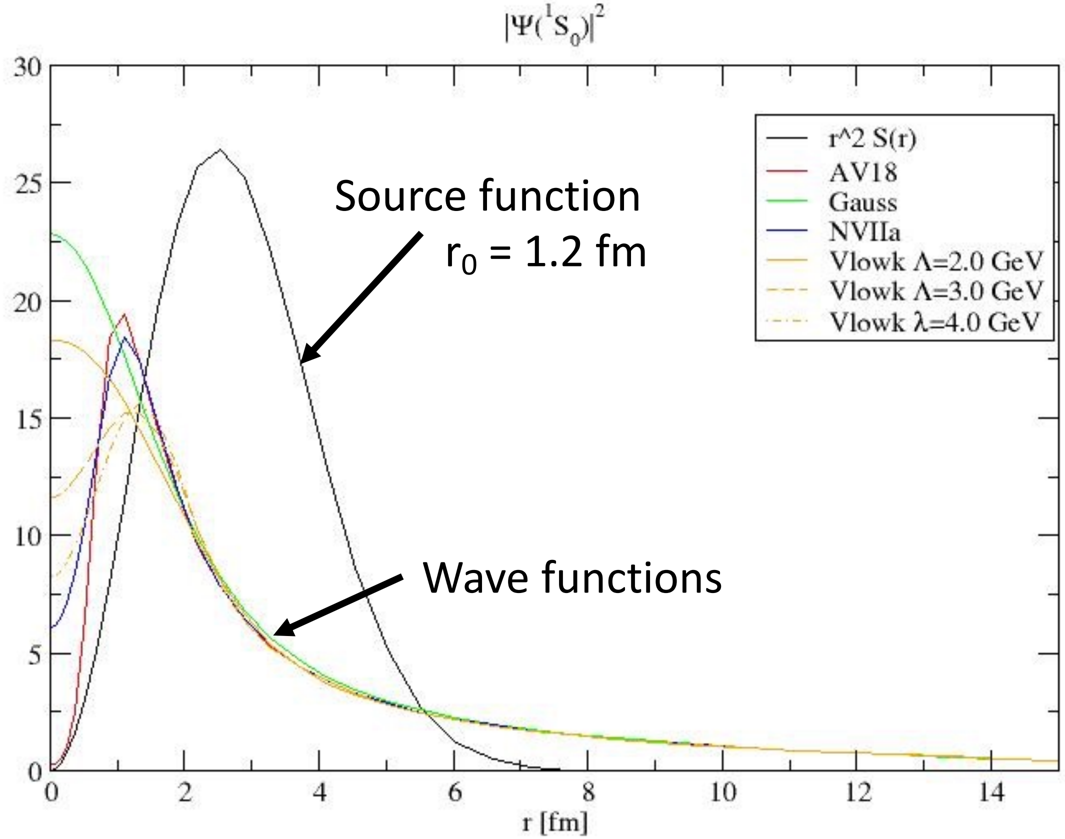
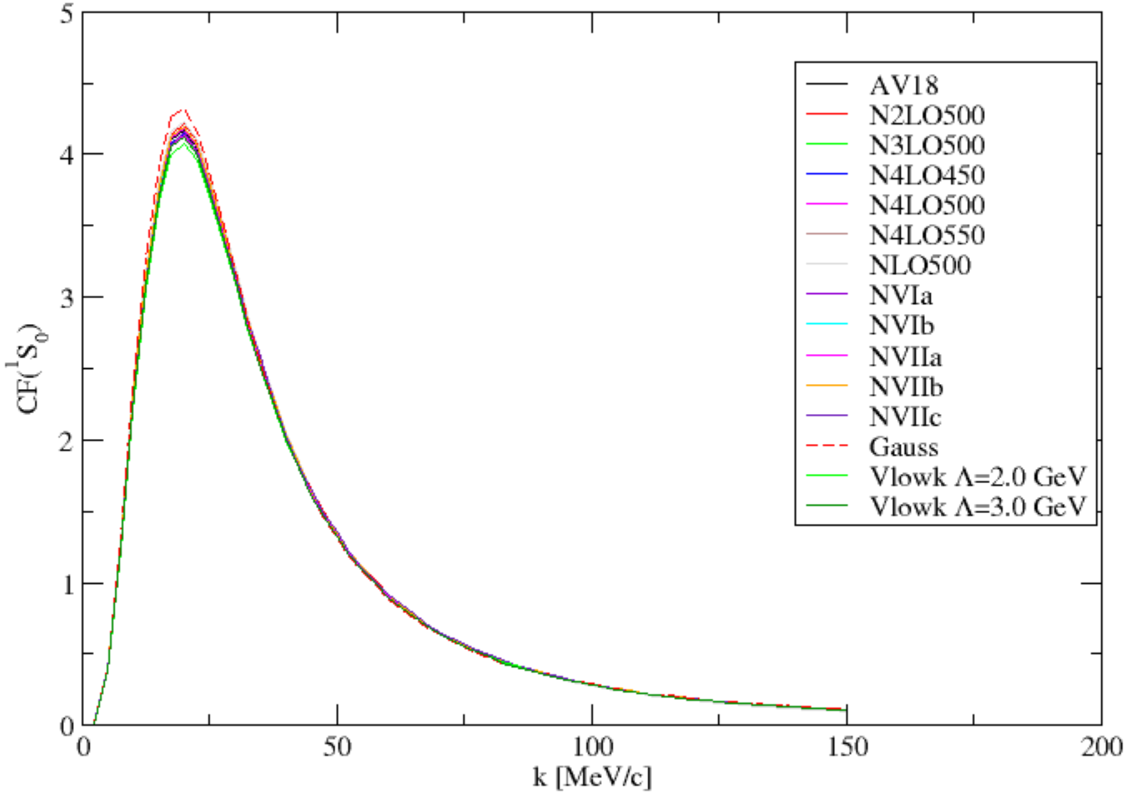


ALICE Coll., PLB, 811 (2020)

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

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

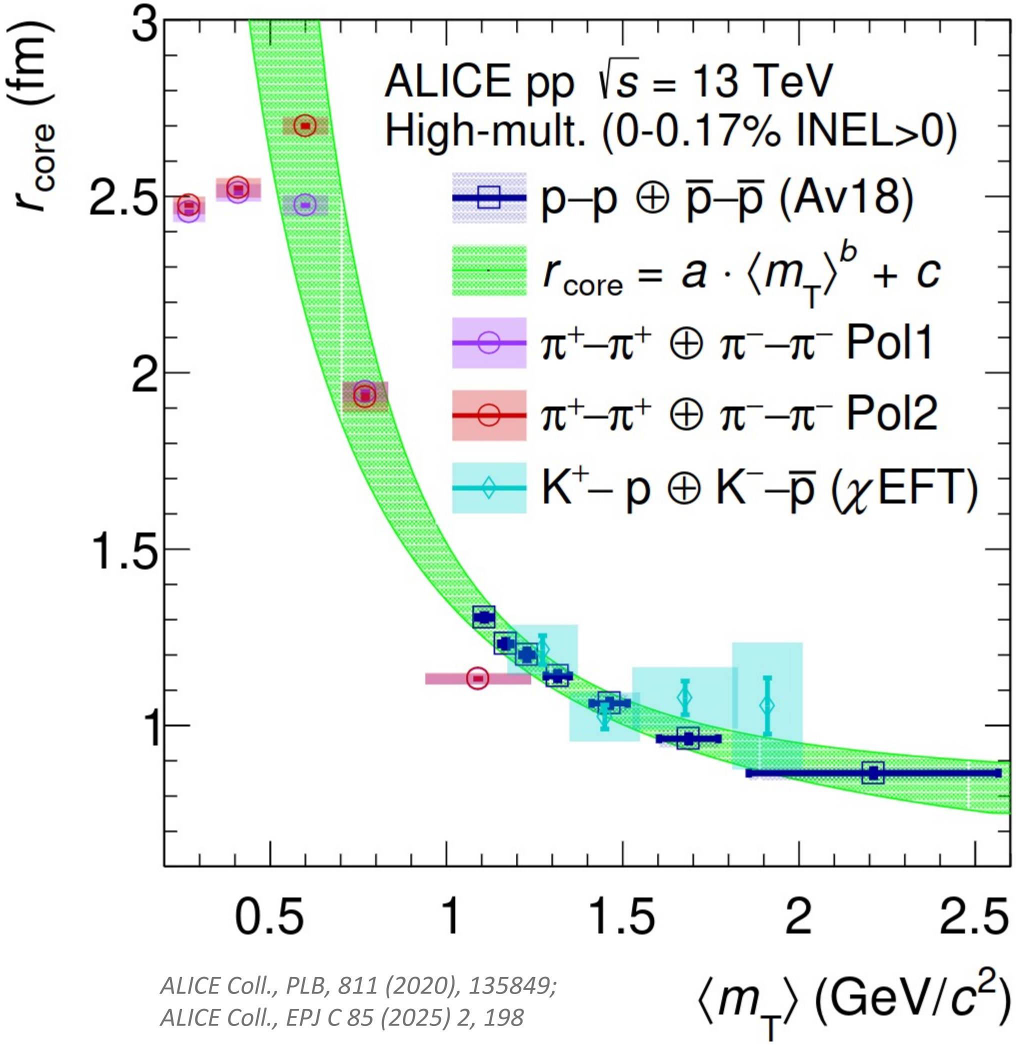
$$S(r) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{core}^2}\right) \times$$

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

Source function in pp collisions at the LHC

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

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)

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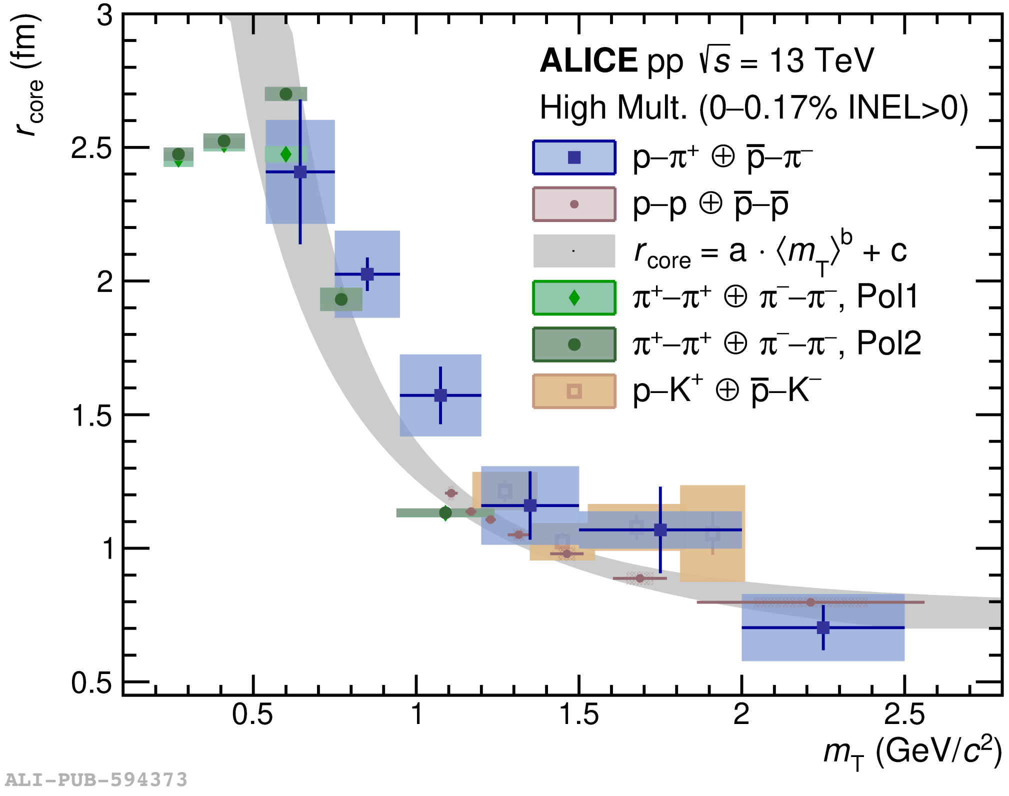

ALICE Coll., PLB, 811 (2020), 135849;
ALICE Coll., EPJ C 85 (2025) 2, 198;
ALICE Coll., arXiv:2502.20200 (2025)

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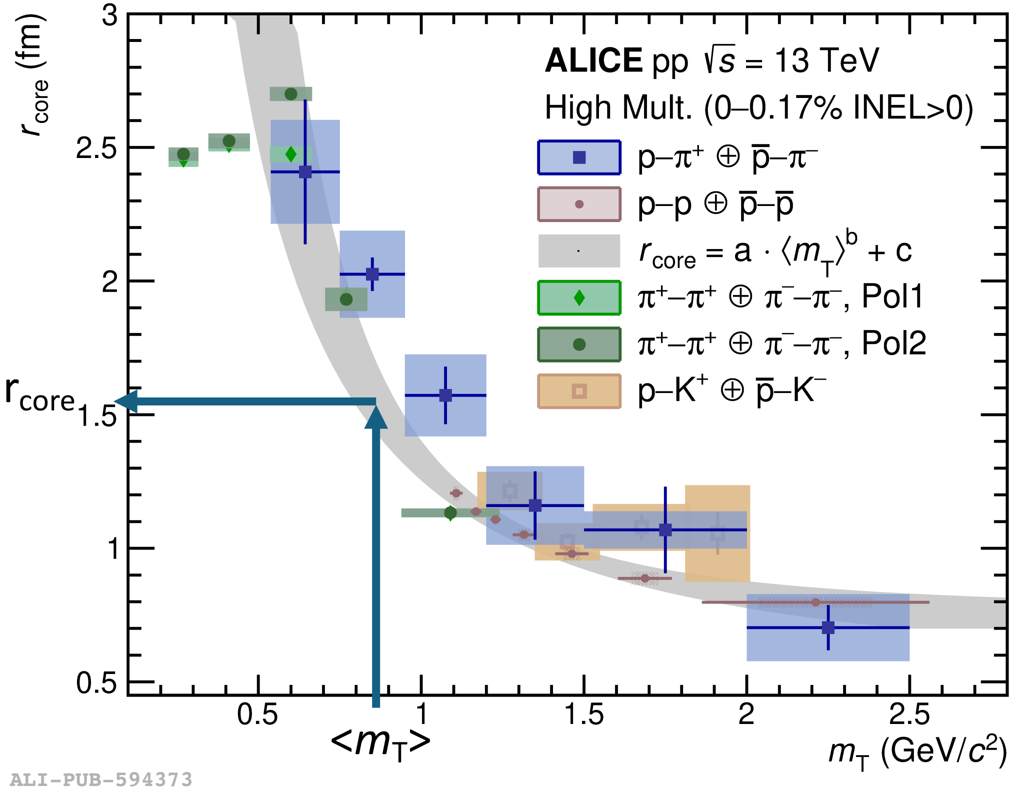
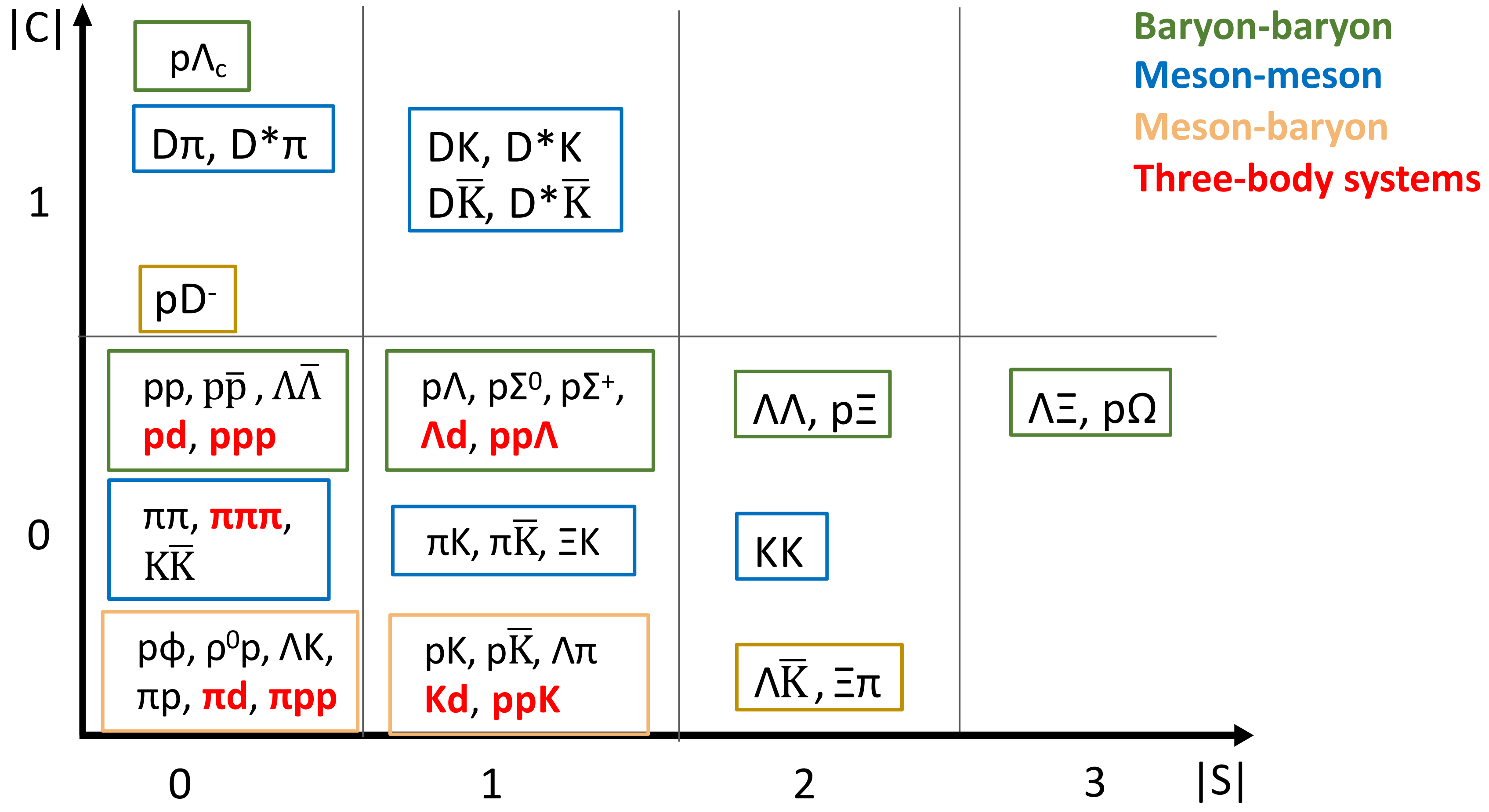


ALICE Coll., PLB, 811 (2020), 135849;
ALICE Coll., EPJ C 85 (2025) 2, 198;
ALICE Coll., arXiv:2502.20200 (2025)

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]

ALICE detector

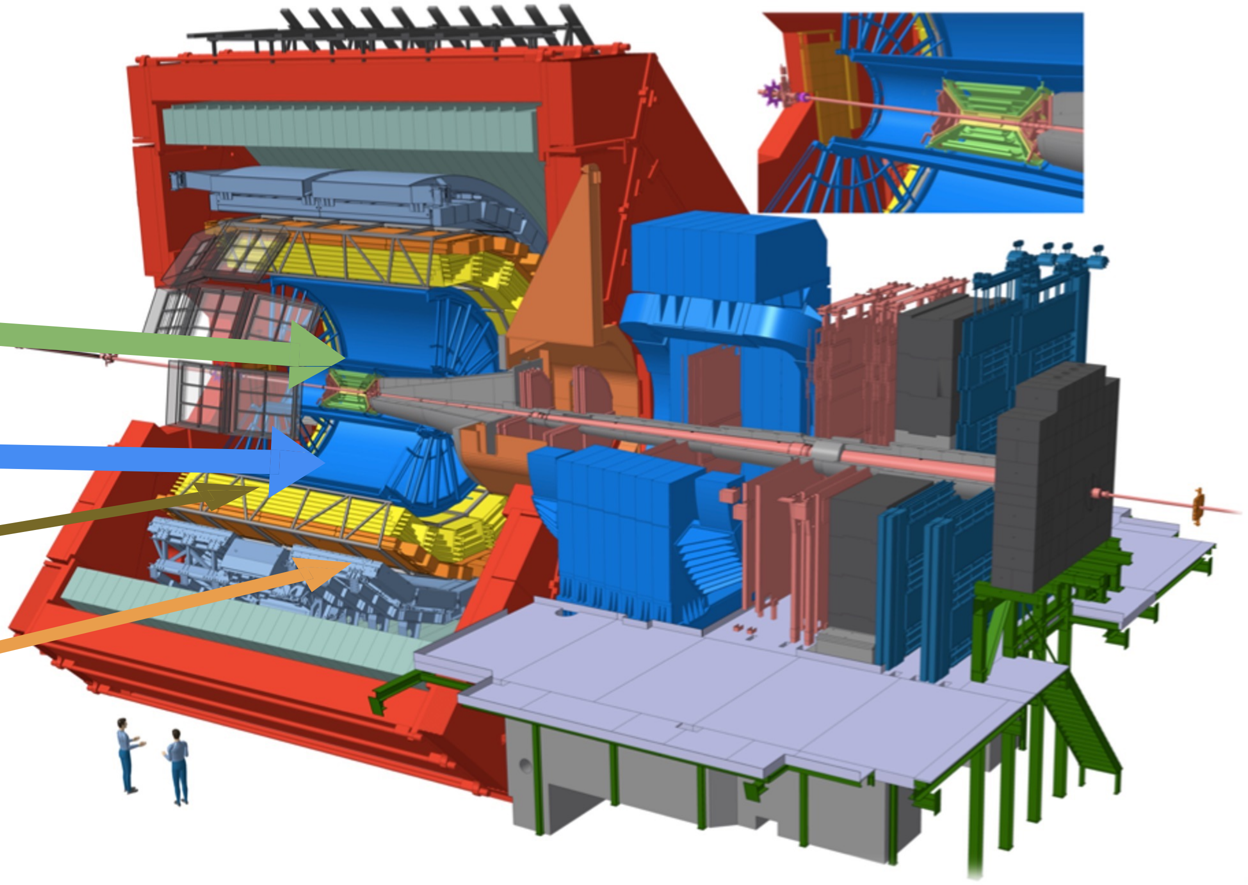
- Excellent tracking and particle identification (PID) capabilities
- Run 2 data: 2015 – 2018
- Run 3 data: 2022 – present

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

Time Projector Chamber
Tracking, PID (dE/dx)

Transition Radiation Detector

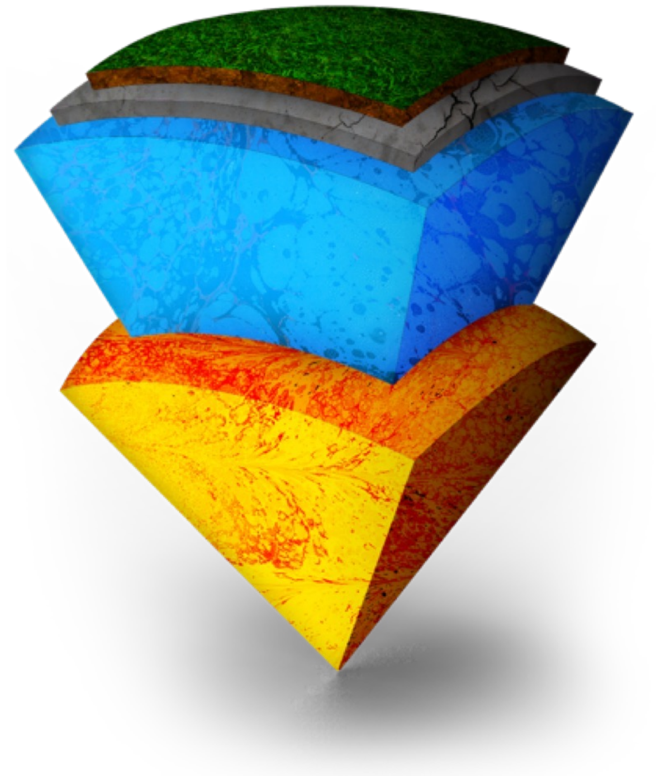
Time Of Flight detector
PID (TOF measurement)



Hyperons in neutron stars?

$R \sim 10 - 15$ km

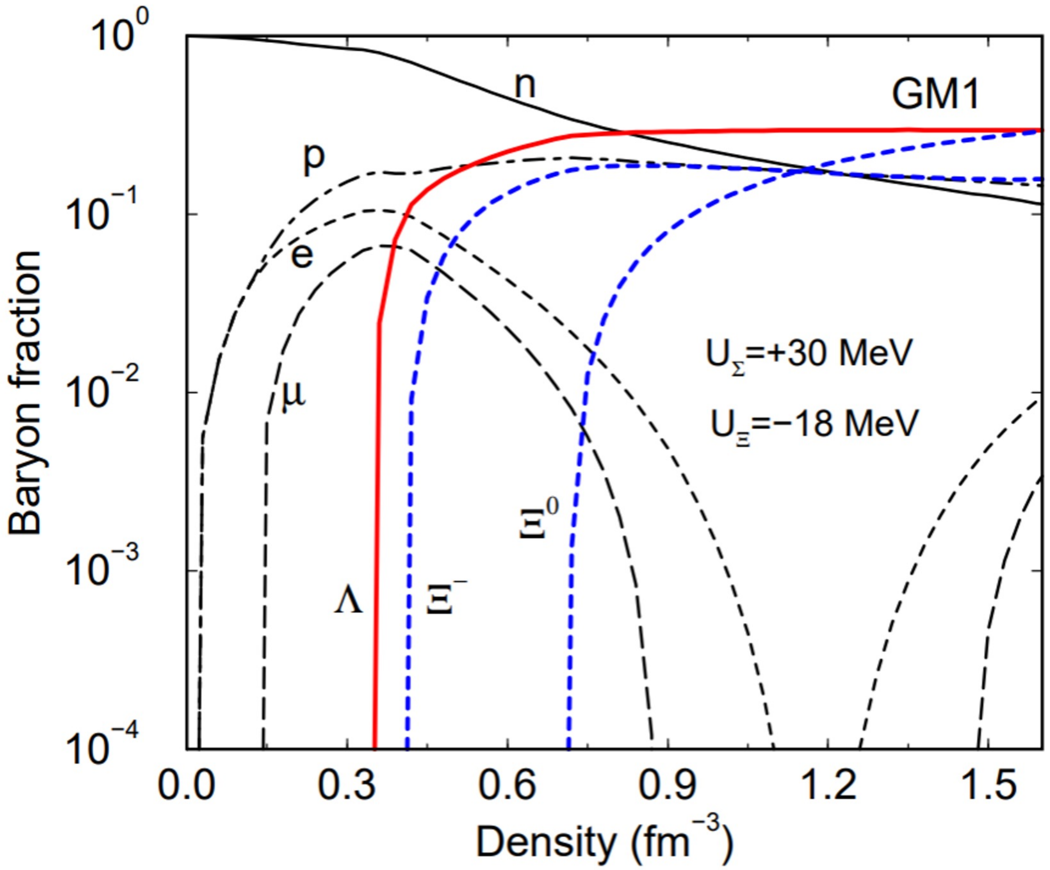
M $\sim 1.5 - 2\ M_{\odot}$



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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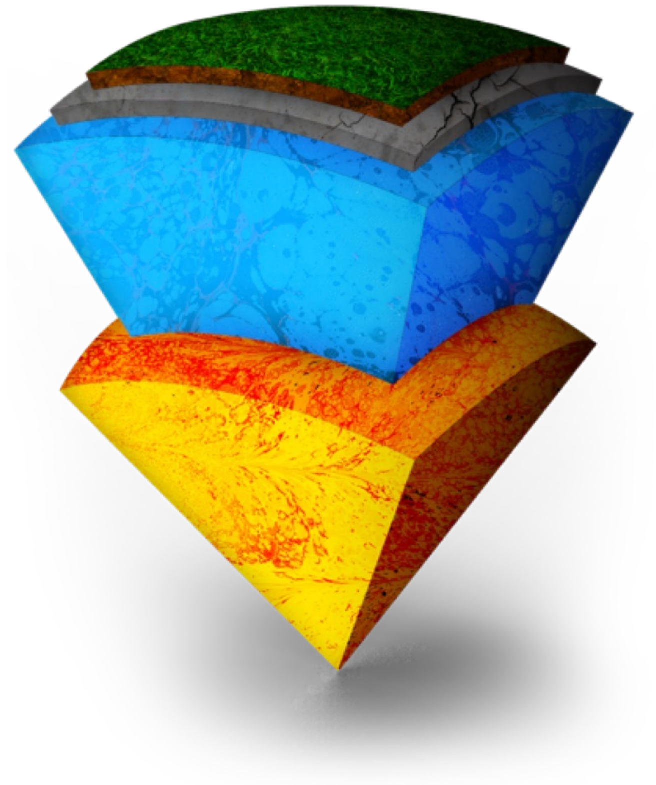

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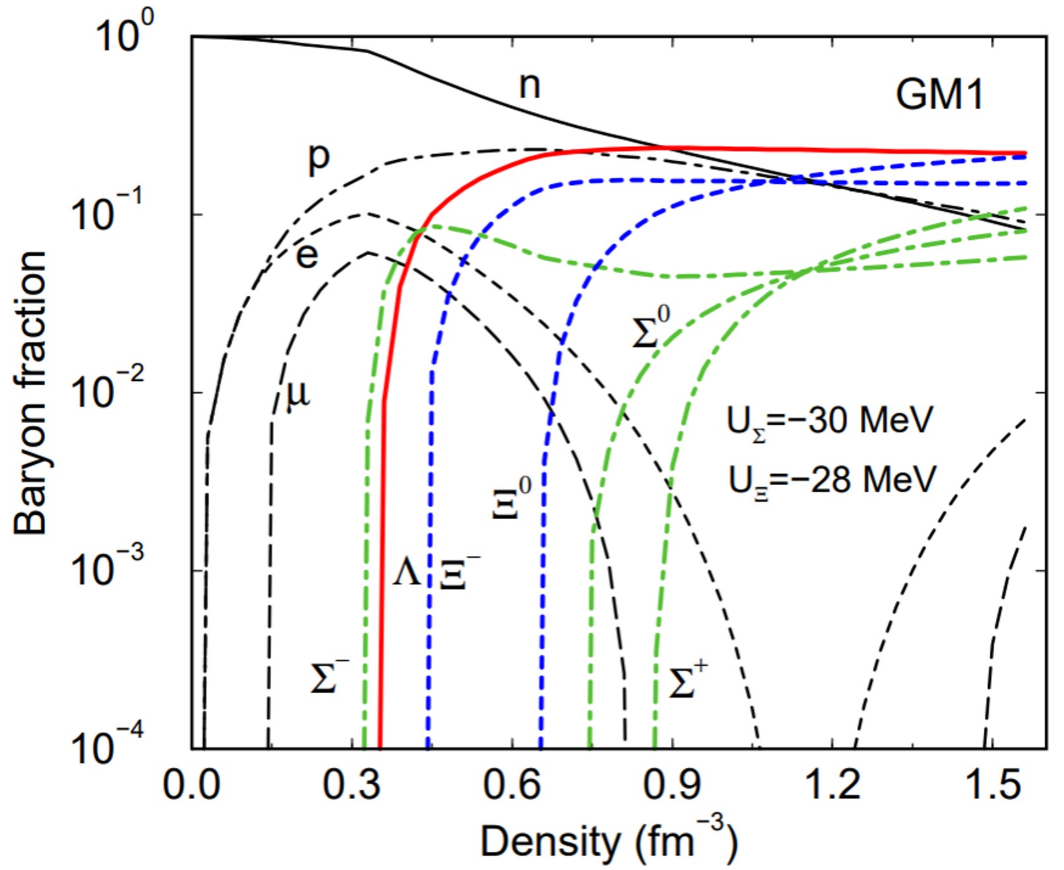
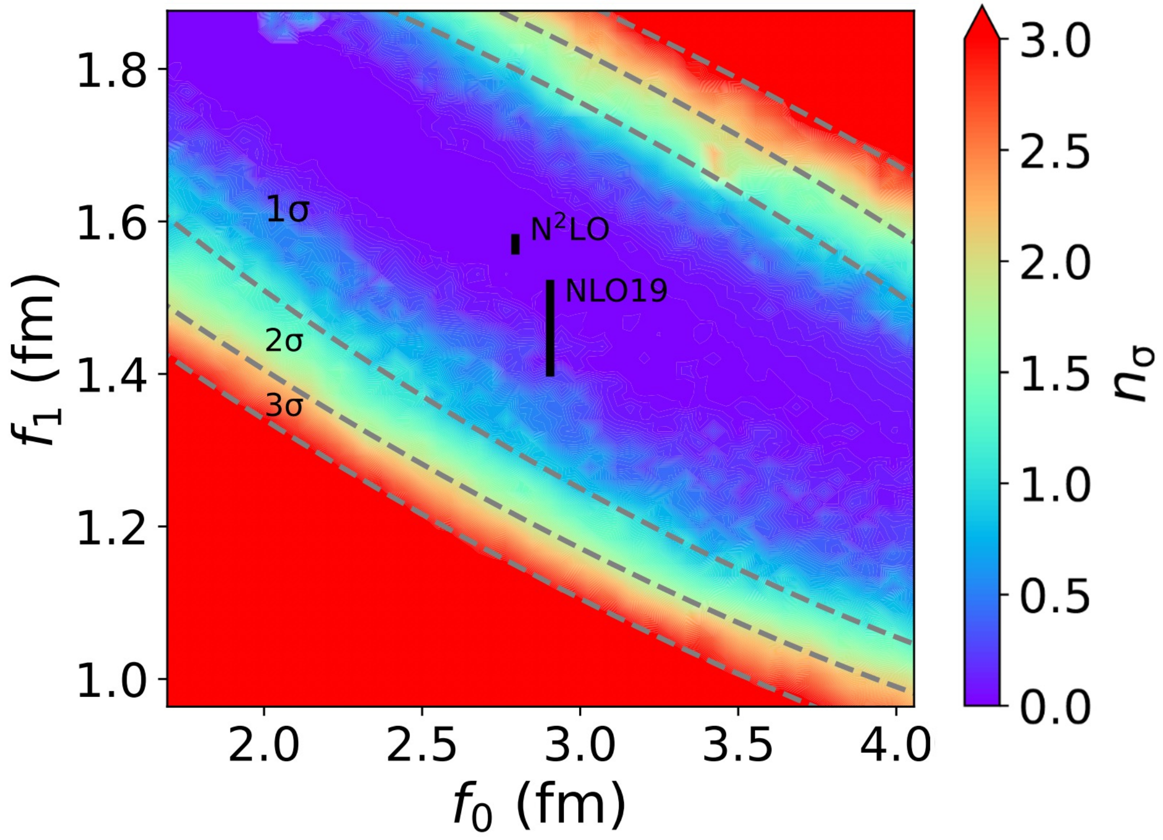


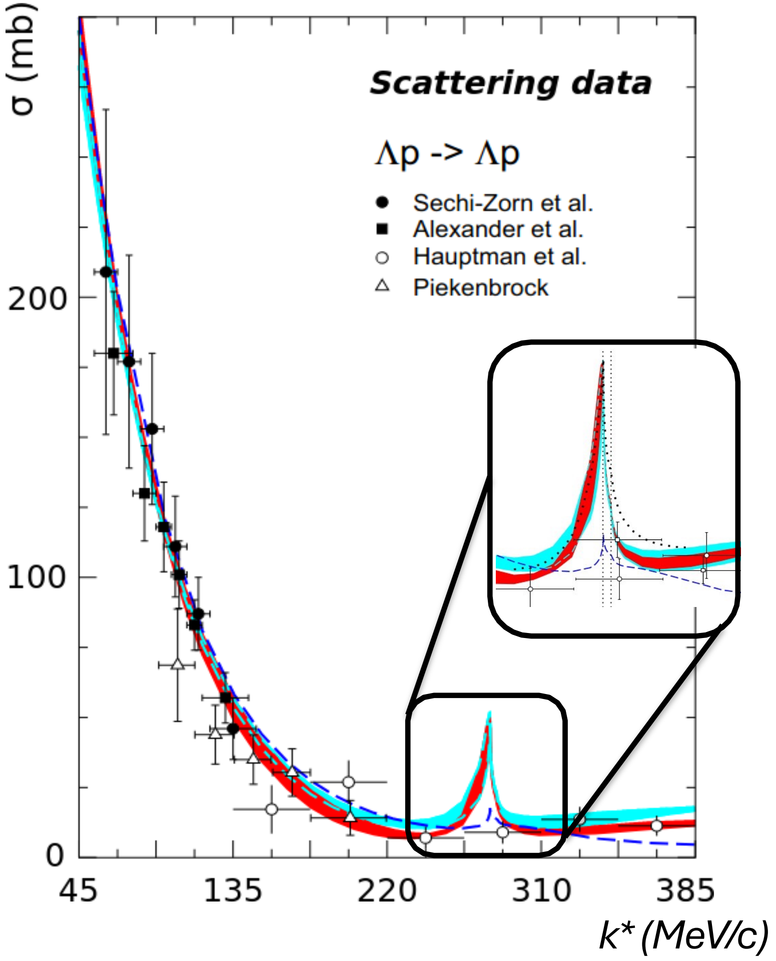
J. Schaffner-Bielich et al NPA 835 (2010)

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

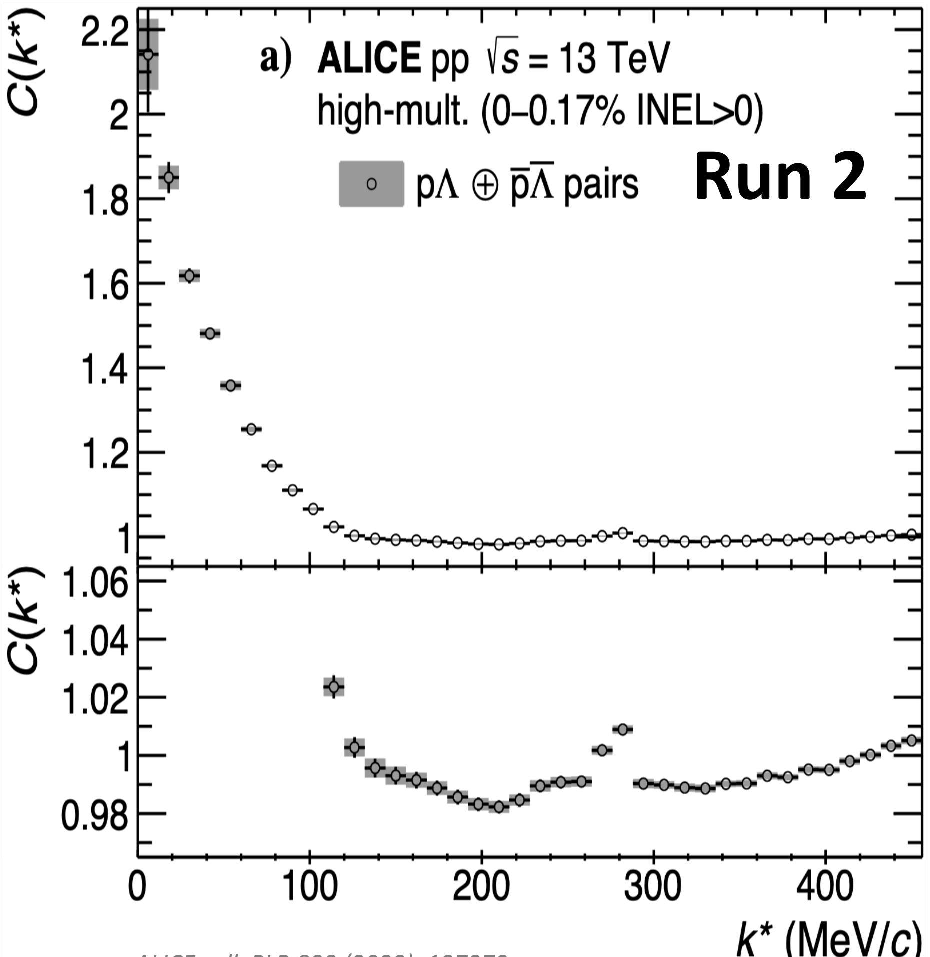




NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

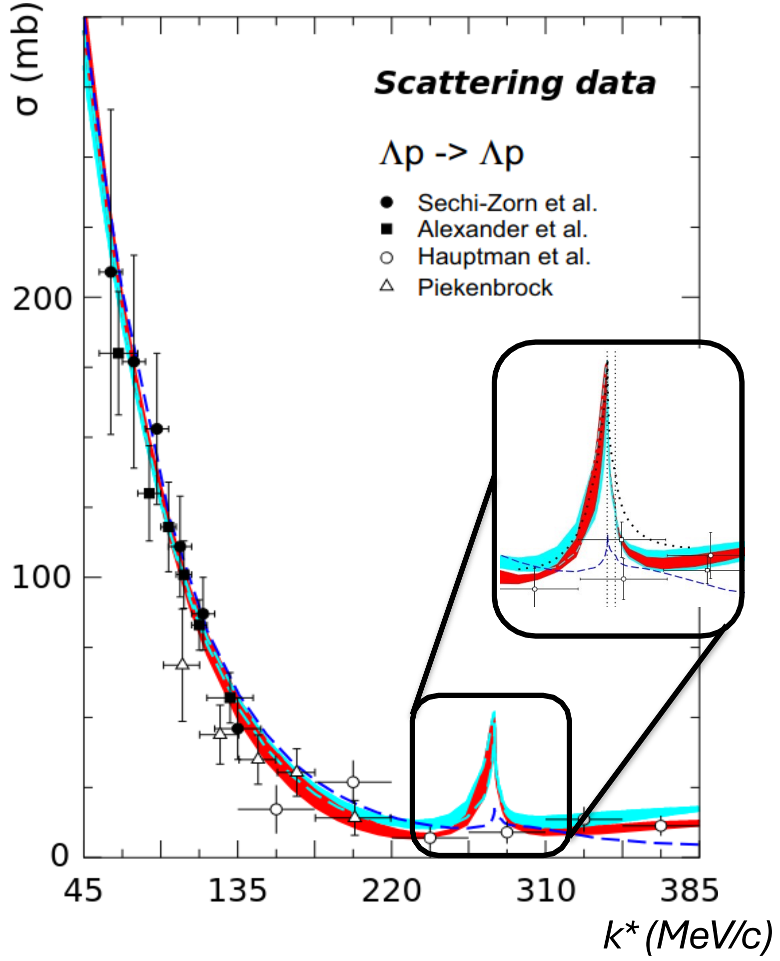
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

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

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

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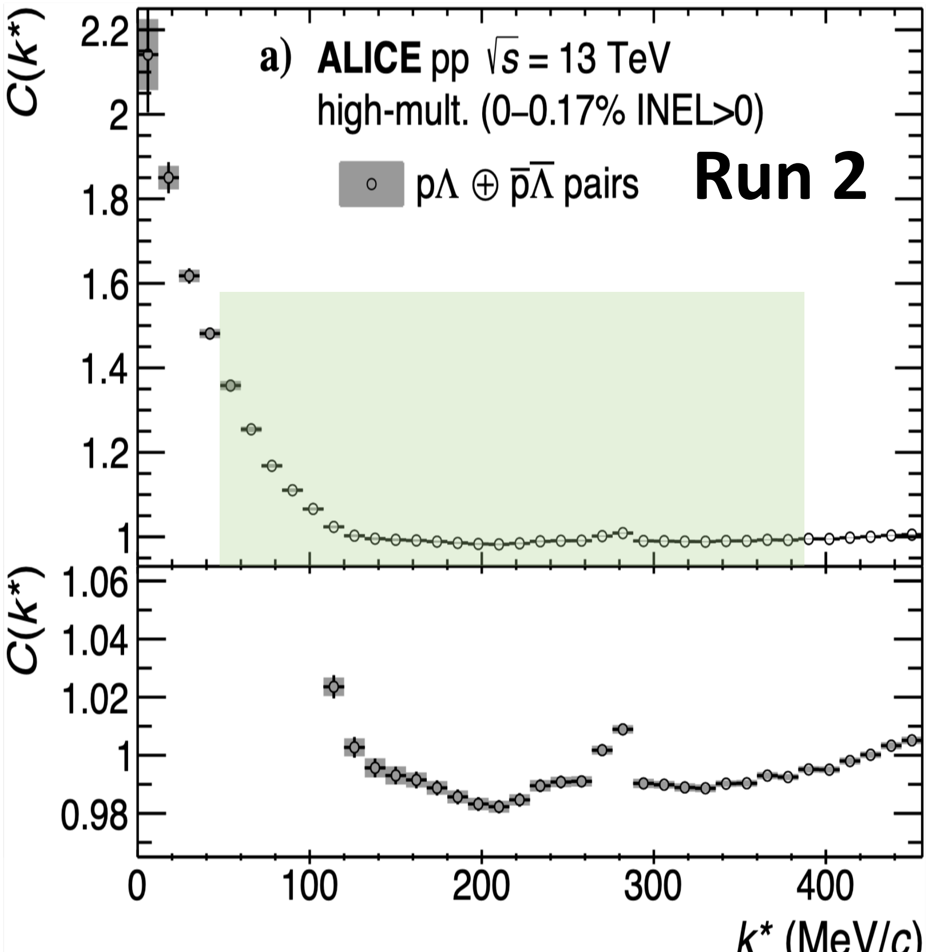

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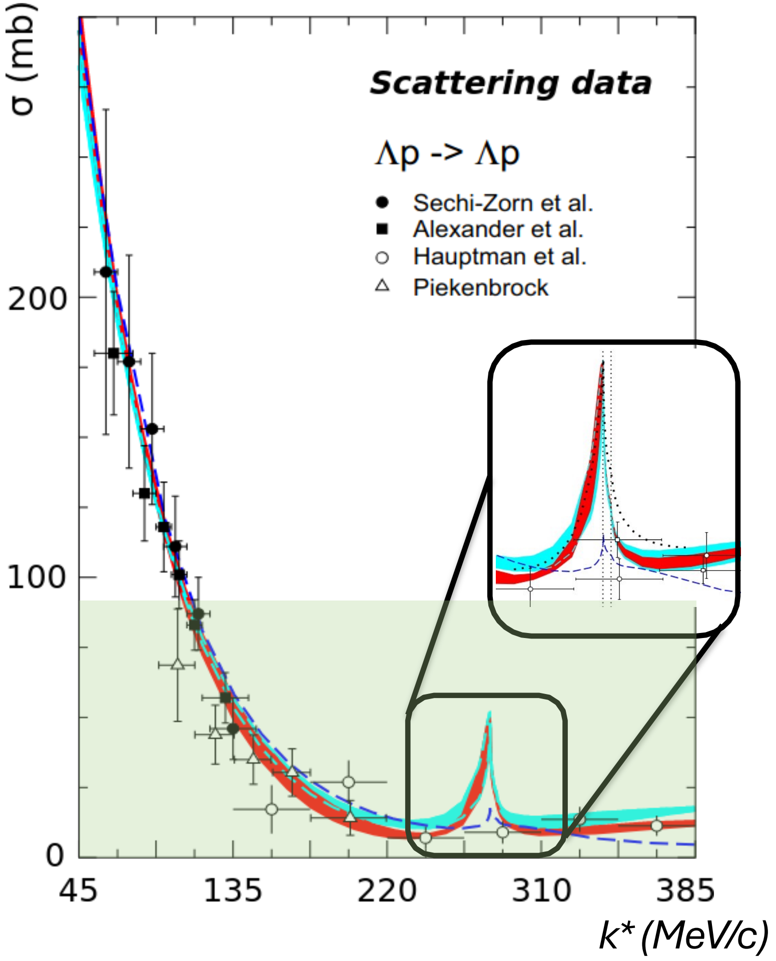


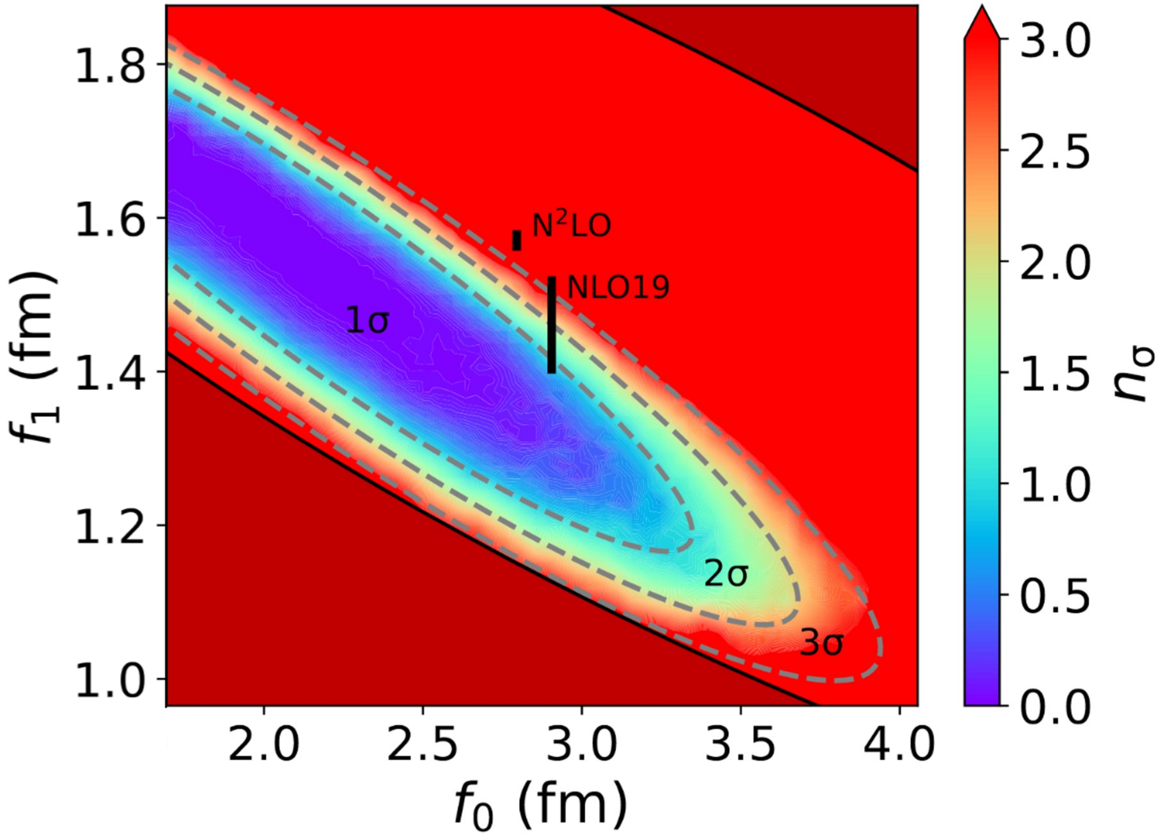
NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

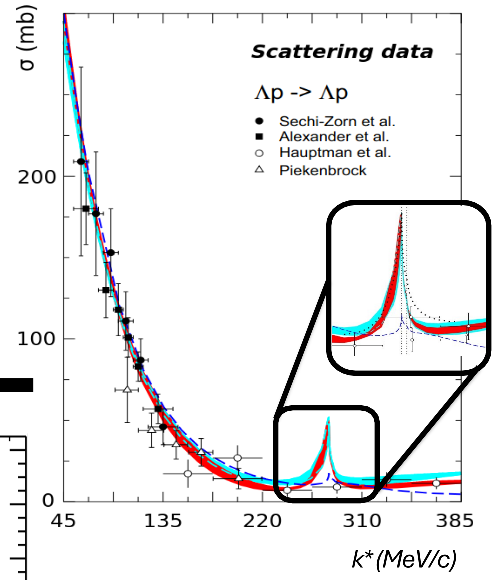
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

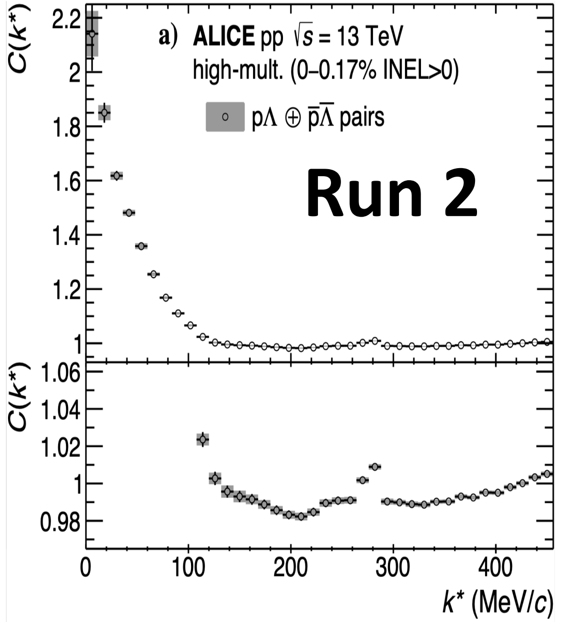
The pΛ interaction in the femtoscopy era

- Combined analysis of femtoscopic and scattering data

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



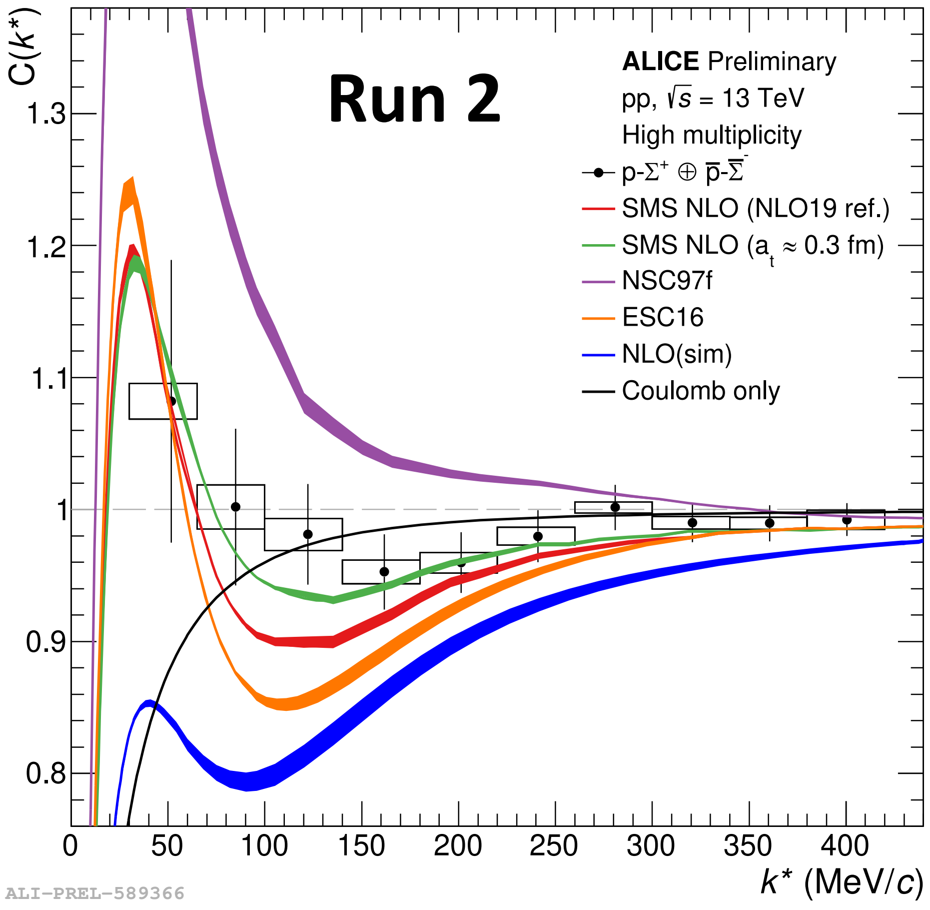




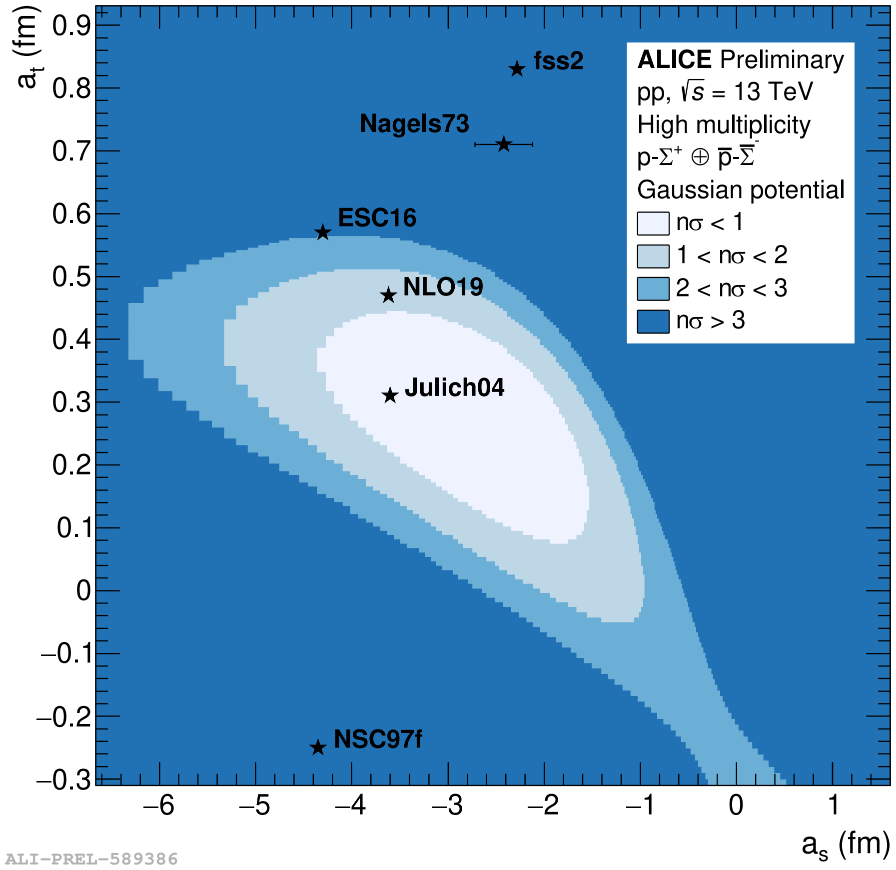
ALICE coll. PLB 833 (2022), 137272

The pΣ^+ interaction

- Data sensitive to the triplet channel

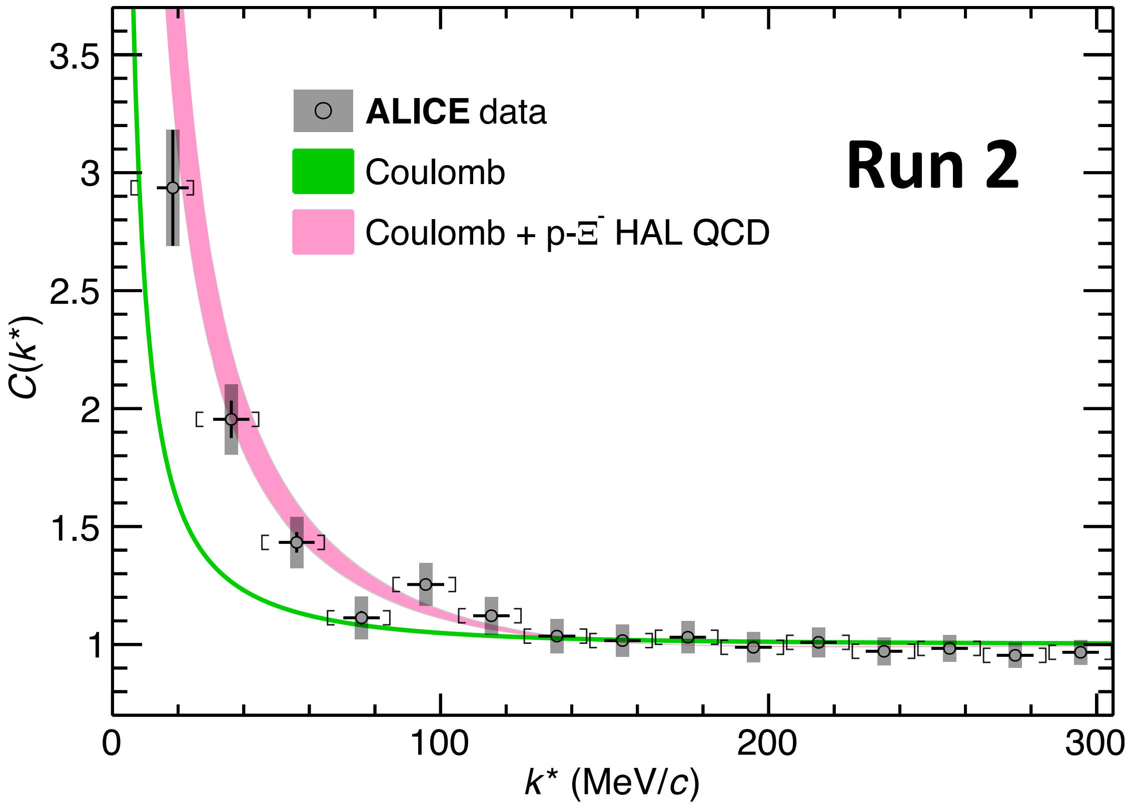


- Fit with Gaussian + Coulomb
- Shallow repulsion in triplet channel



The pΞ^- interaction

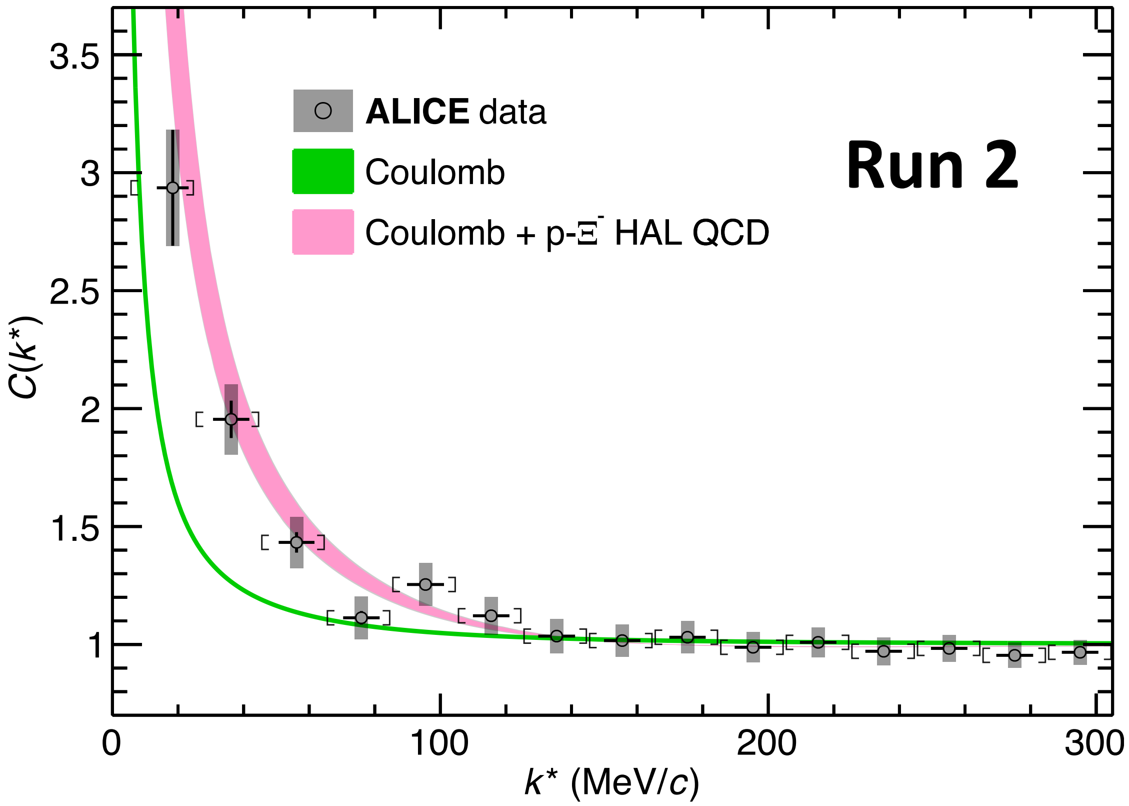
- Evidence of the attractive strong interaction



ALICE Coll., Nature 588 (2020) 232

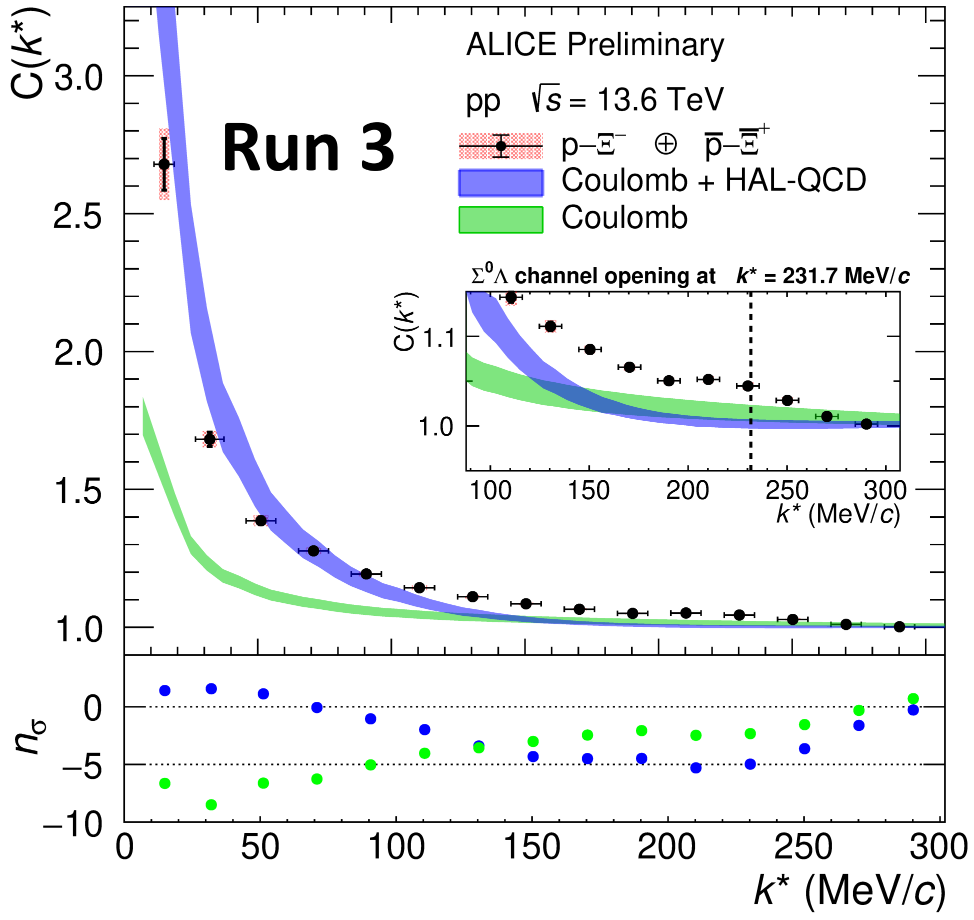
The pΞ⁻ interaction

- Evidence of the attractive strong interaction



ALICE Coll., Nature 588 (2020) 232

- Opening of the pΞ → ΛΣ⁰ channel

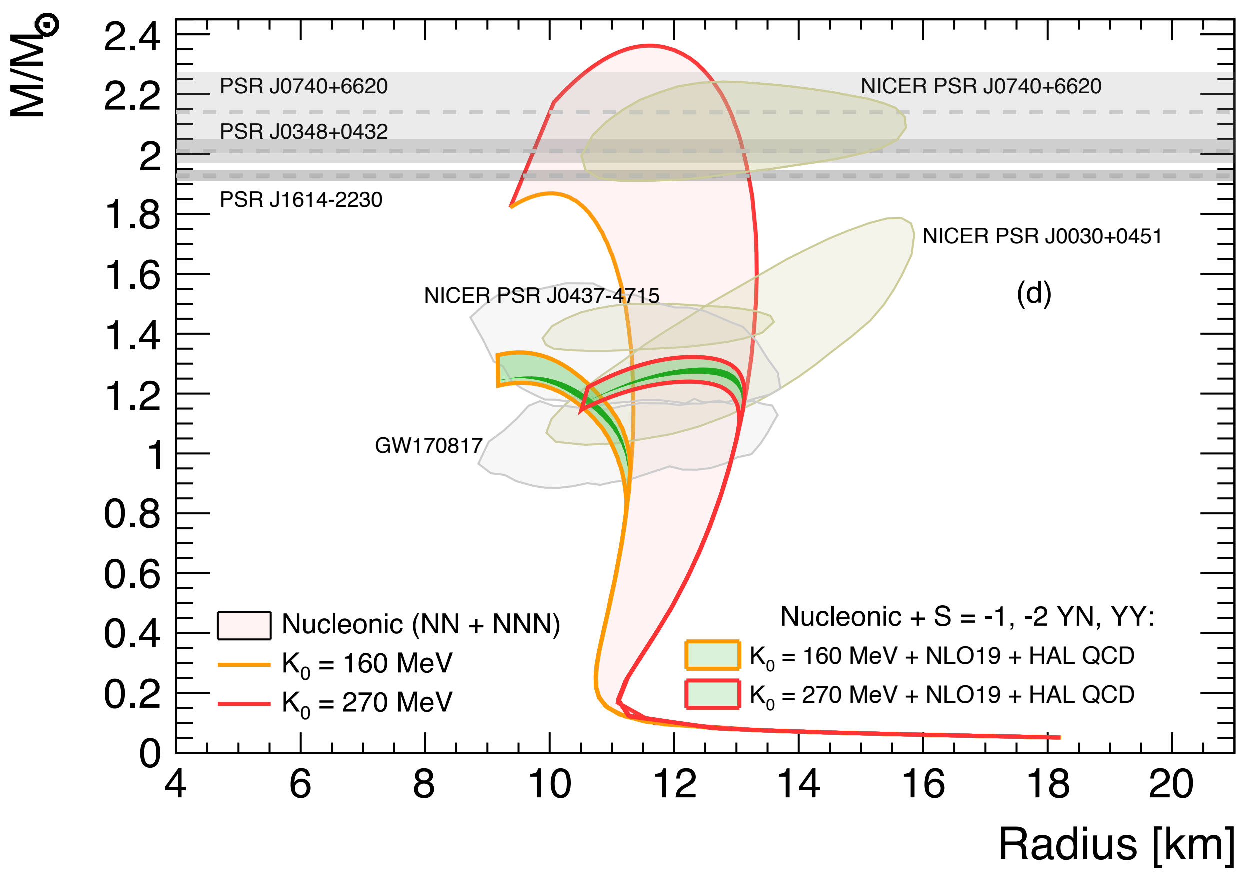


ALI-PREL-603893

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, EPJ.A 61 (2025) 3, 59



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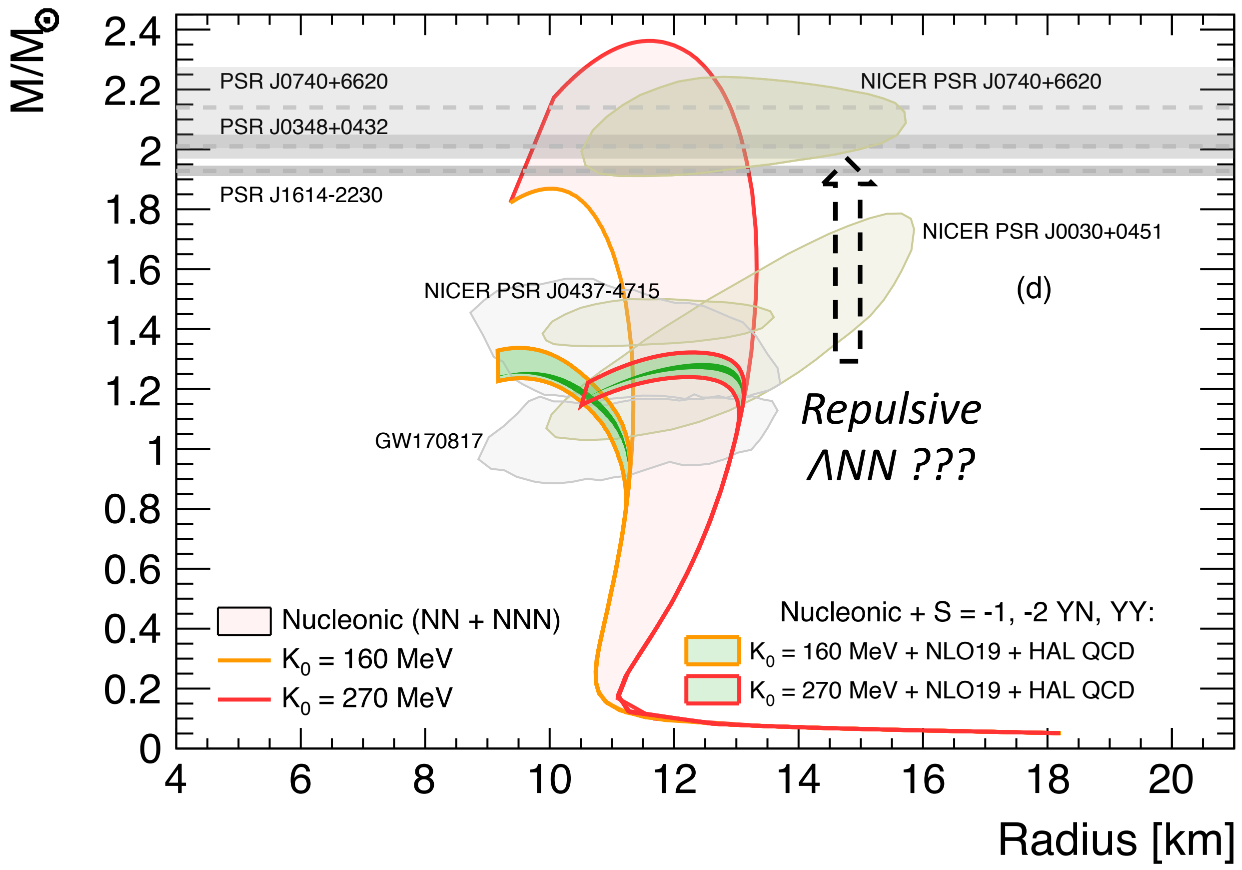
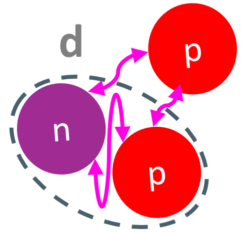
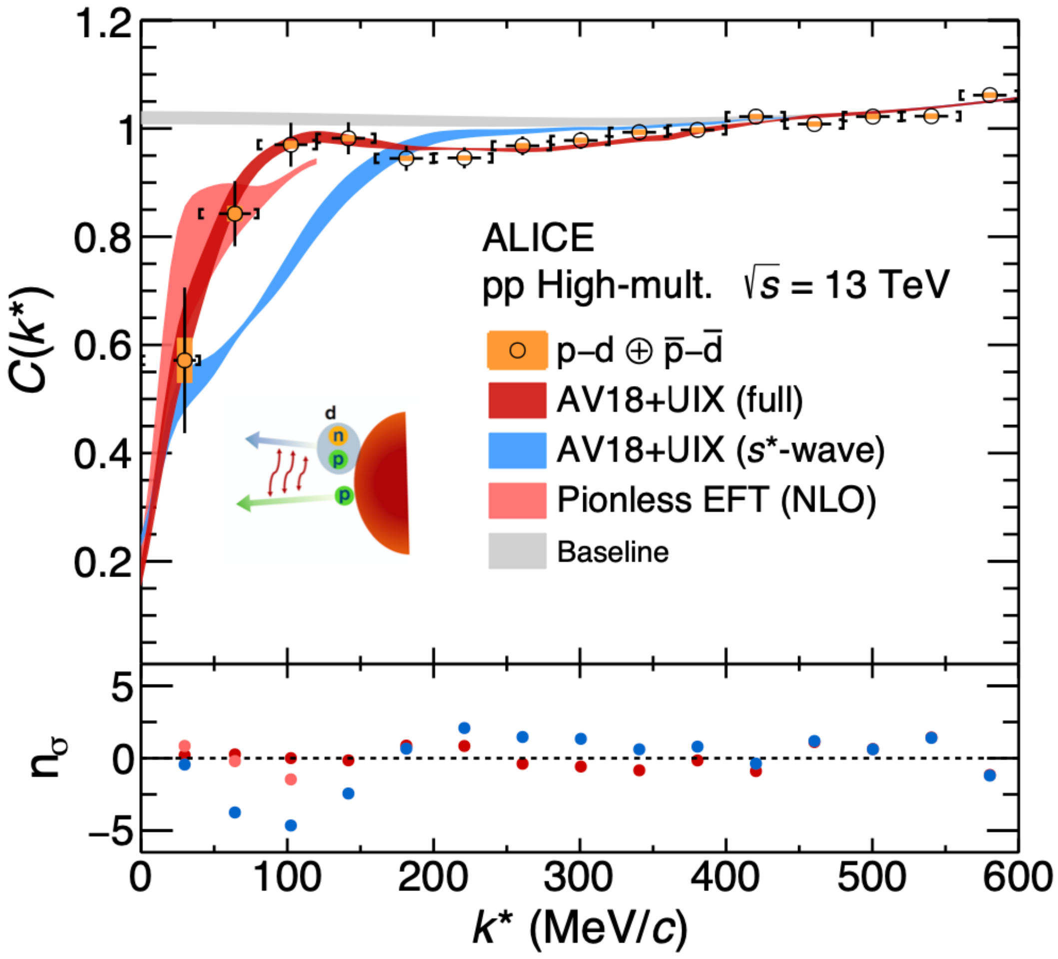
- Next step → inclusion of three body interaction involving hyperons



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



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

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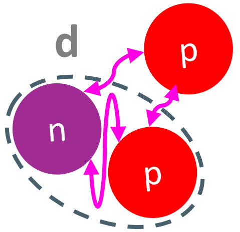

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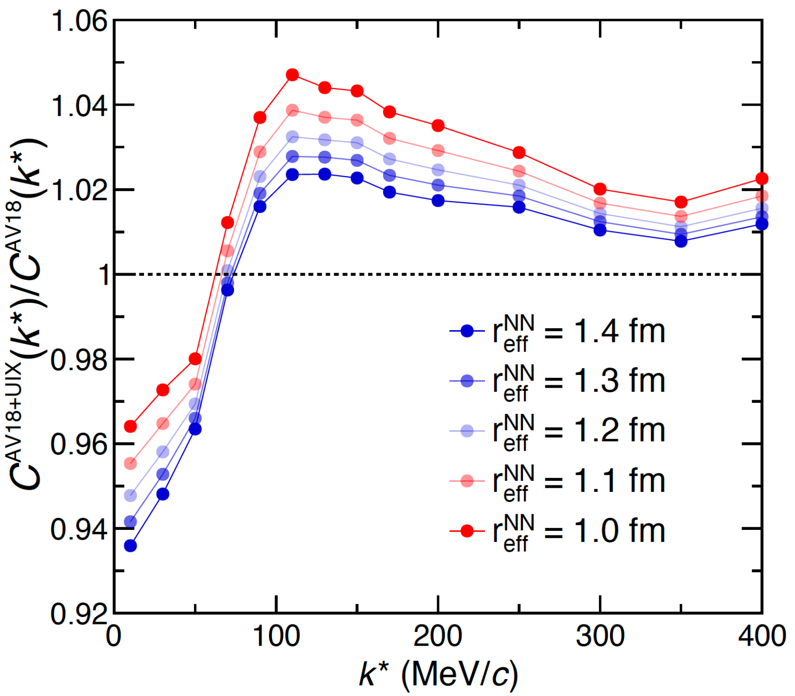
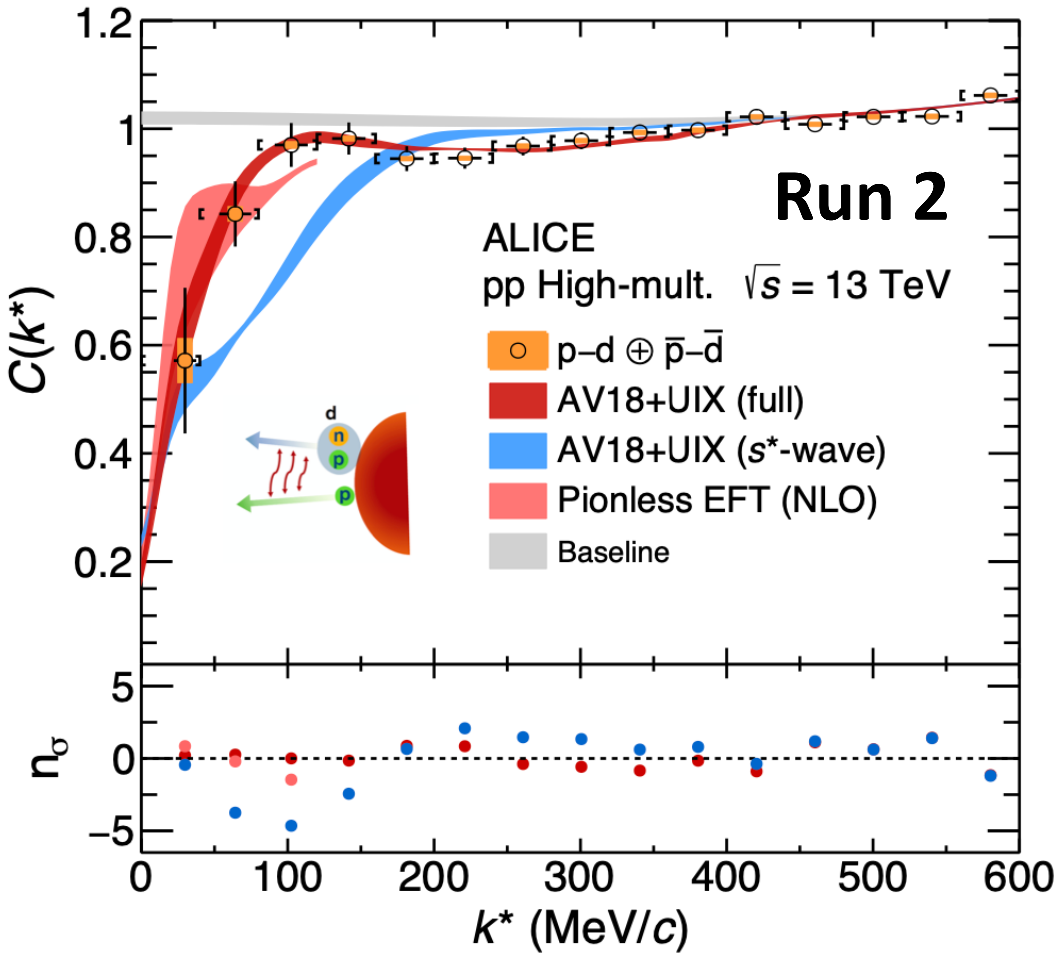
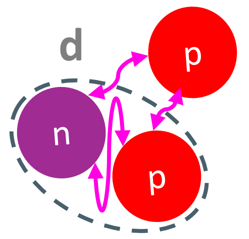
- Hadron-nuclei correlations at the LHC can be used to study many-body dynamics
- Sensitivity to three-body forces up to 5%



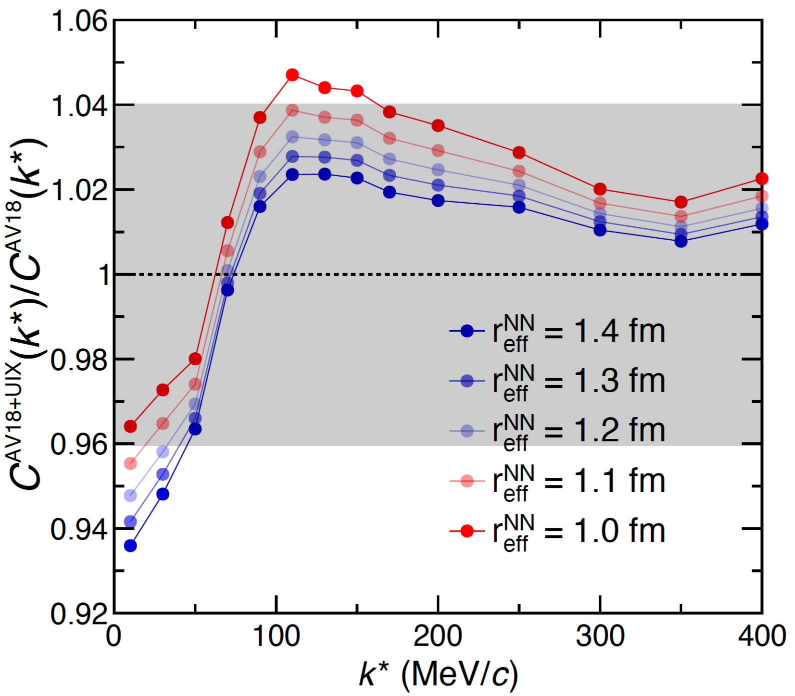


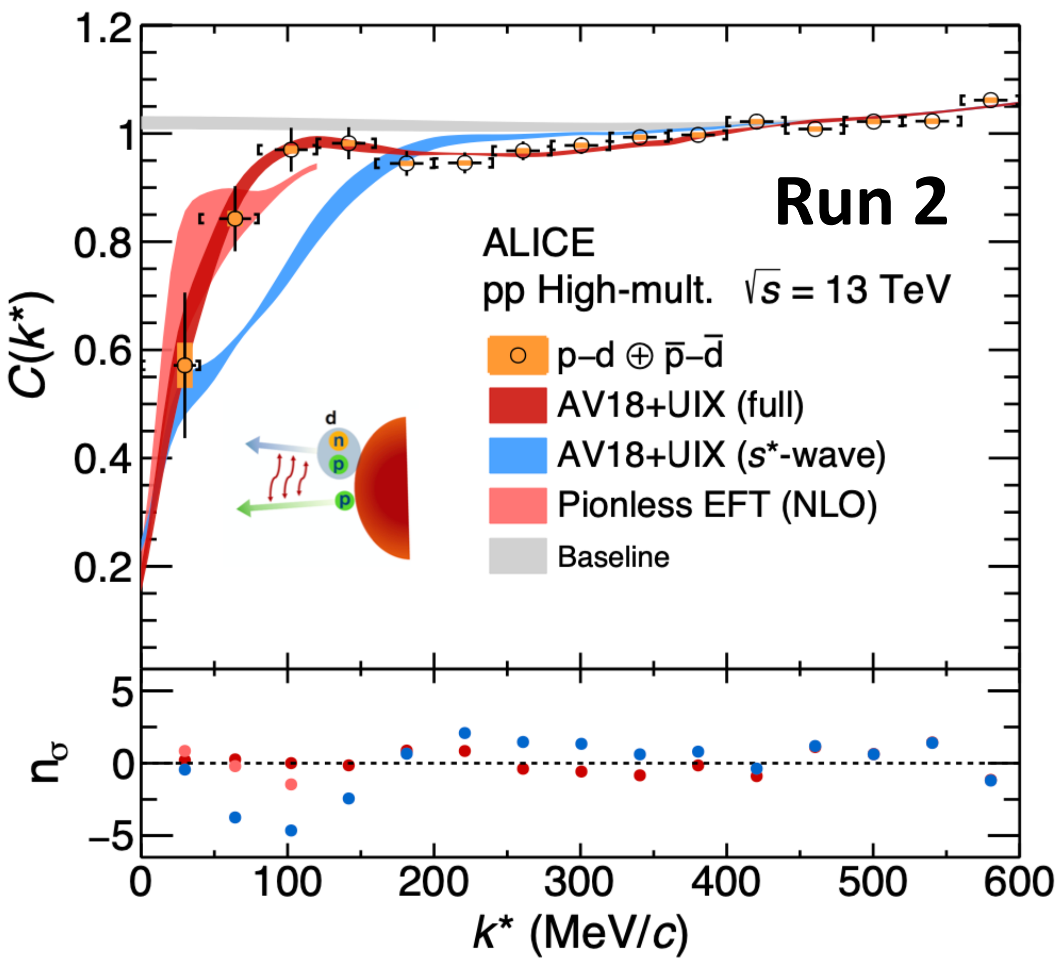
ALICE Coll. Phys. Rev. X 14, 031051 (2024)
M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002

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
- Sensitivity to three-body forces up to 5%





ALICE Coll. Phys. Rev. X 14, 031051 (2024)
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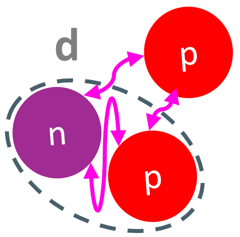
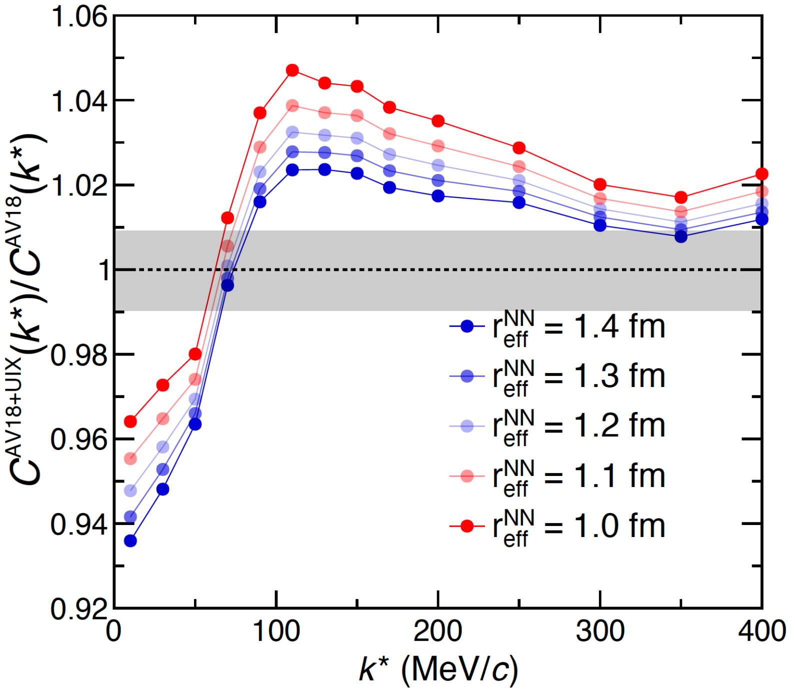
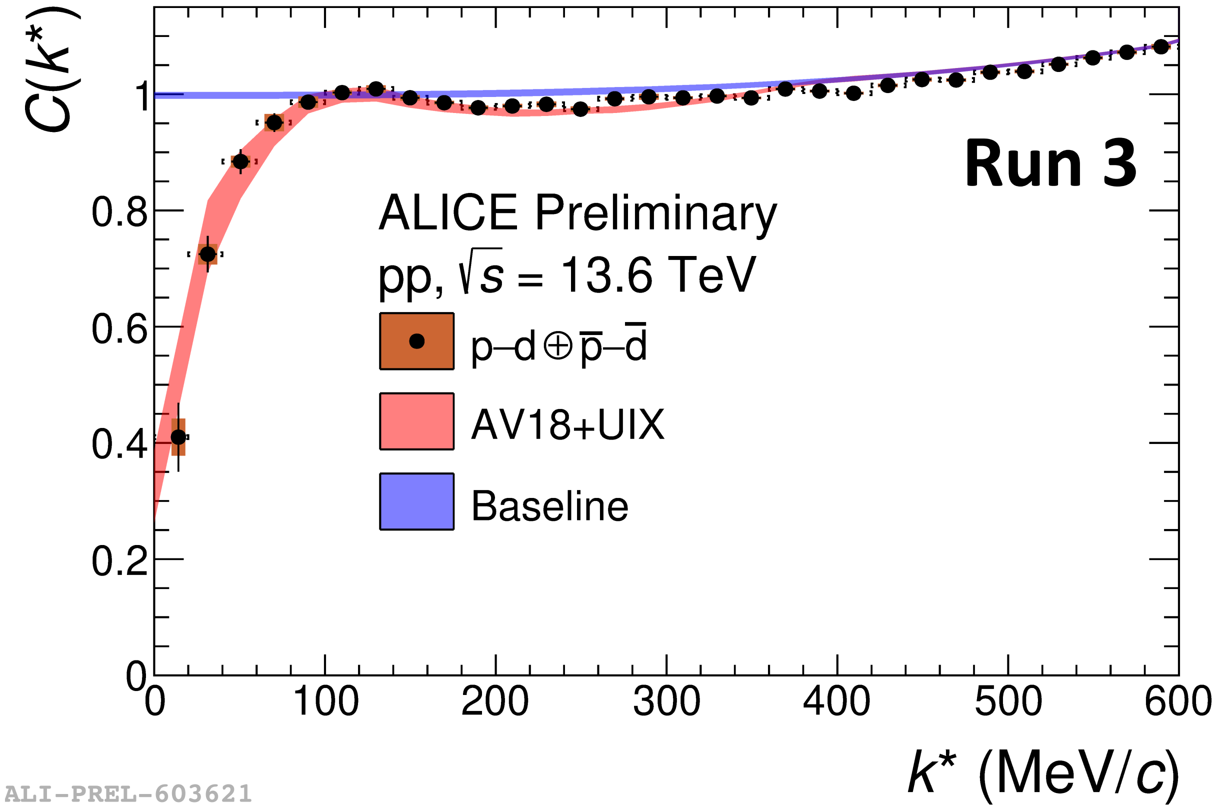
NNN using proton-deuteron correlations



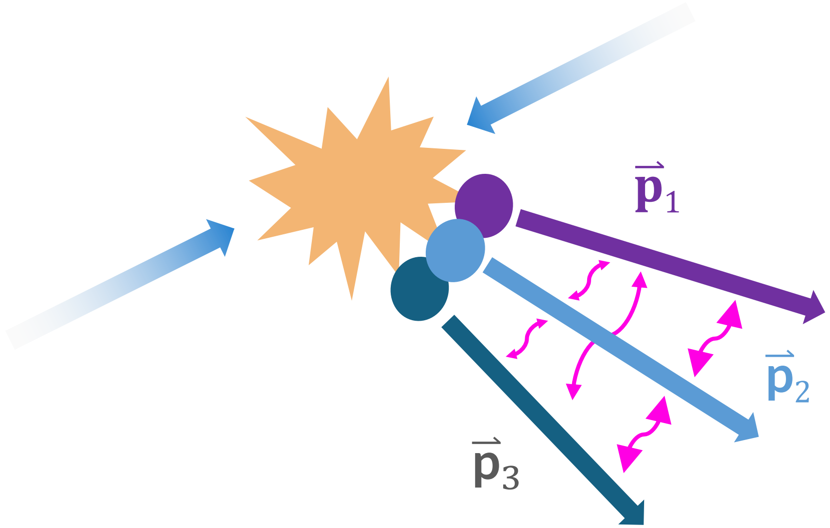
- Full three-body calculations are required (NN + NNN + Quantum Statistics)
- Results from Run 3 are promising!
- In Run 3 expected uncertainty of 1%





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

Hypermomentum:

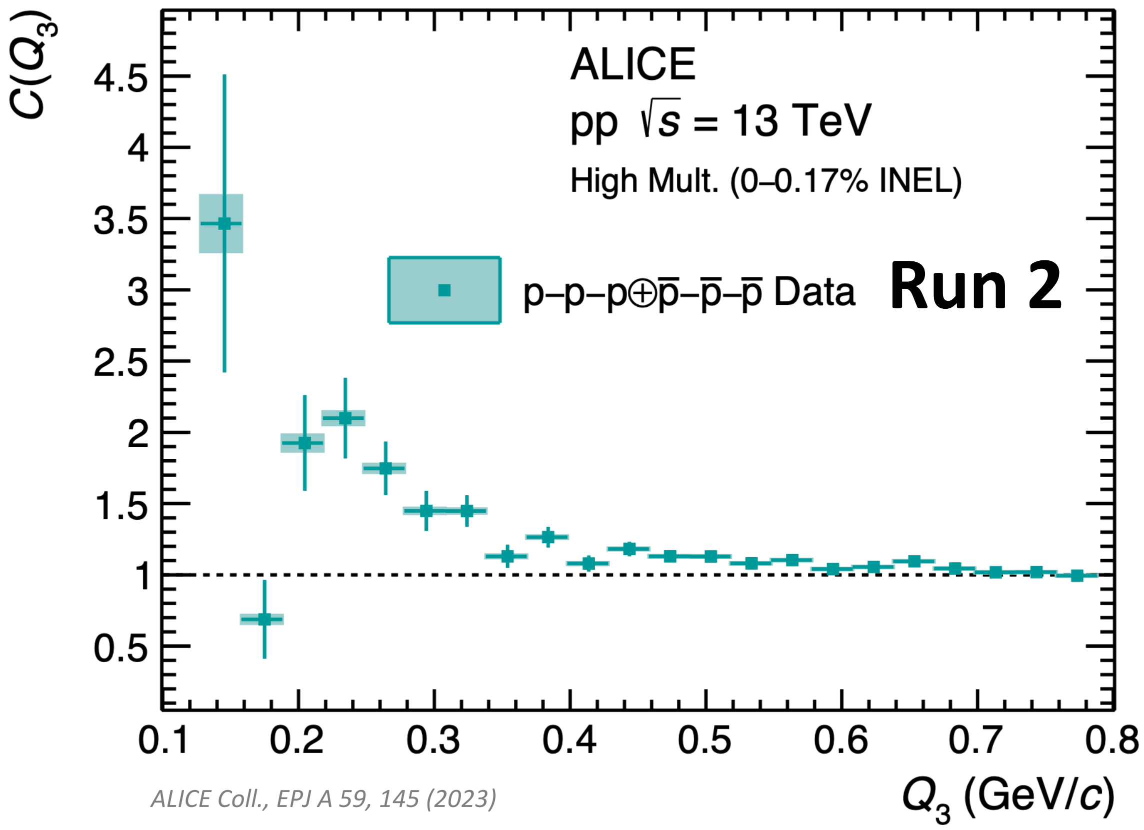
$$Q_3 = 2\sqrt{k_{12}^2 + k_{23}^2 + k_{31}^2}$$

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)

Extension to three-particle system

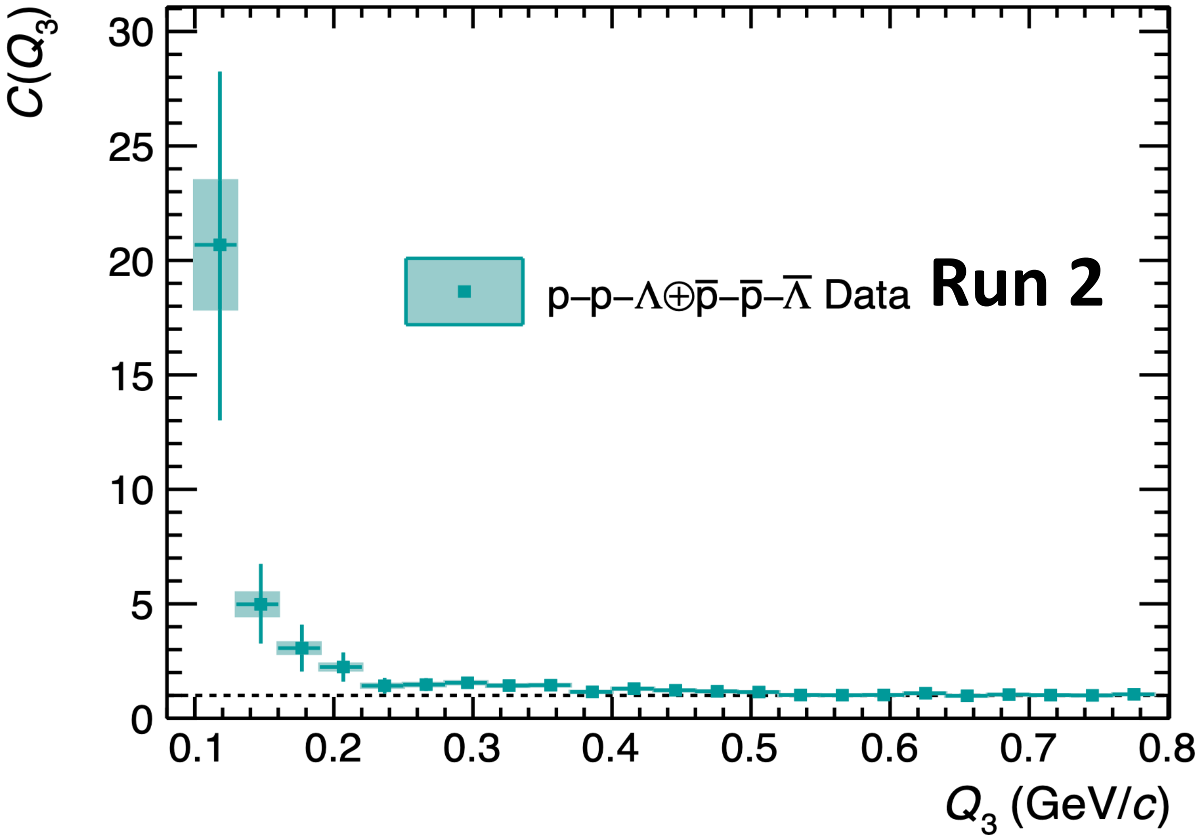
- First measurement of the free scattering of three hadrons
- Deviation from unity in p-p-p and p-p-Λ correlation functions

p-p-p



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

p-p-Λ

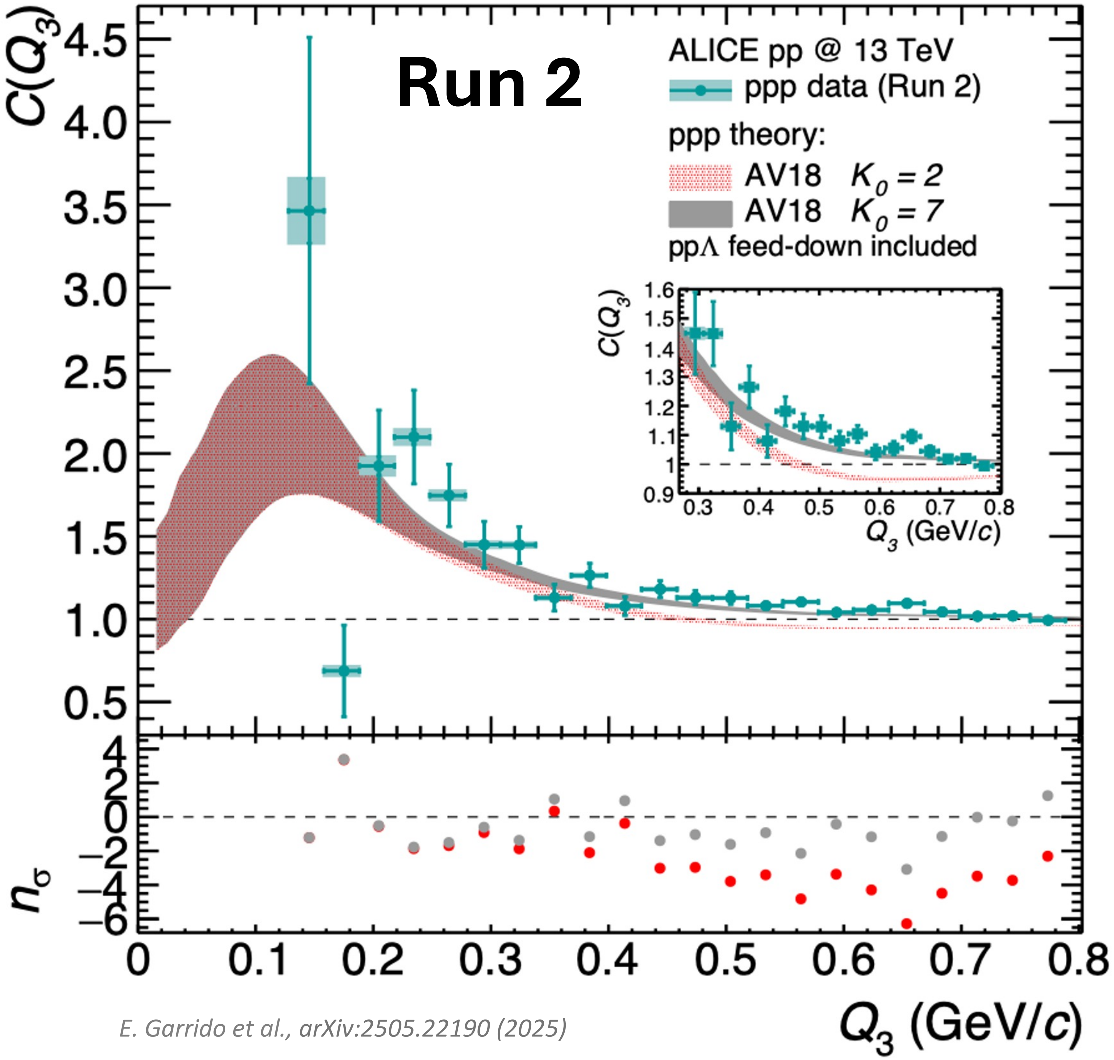


Comparison Run 2 data

Comparison with the ALICE Run 2 measurement:

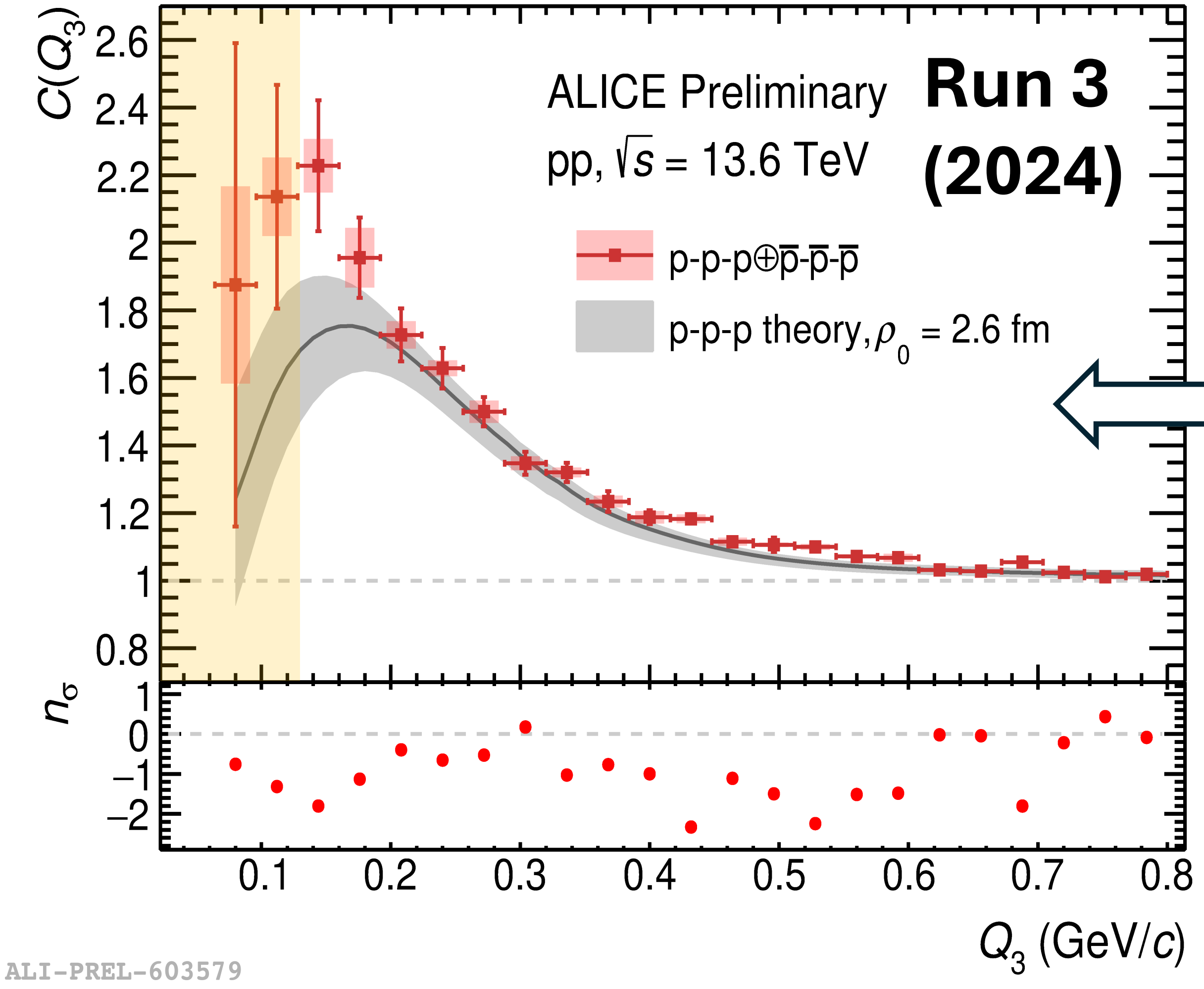
- calculations can describe the shape observed in the data
- interaction at higher partial waves (K<= 7) must be included in the calculations
- missing data in the low-energy region

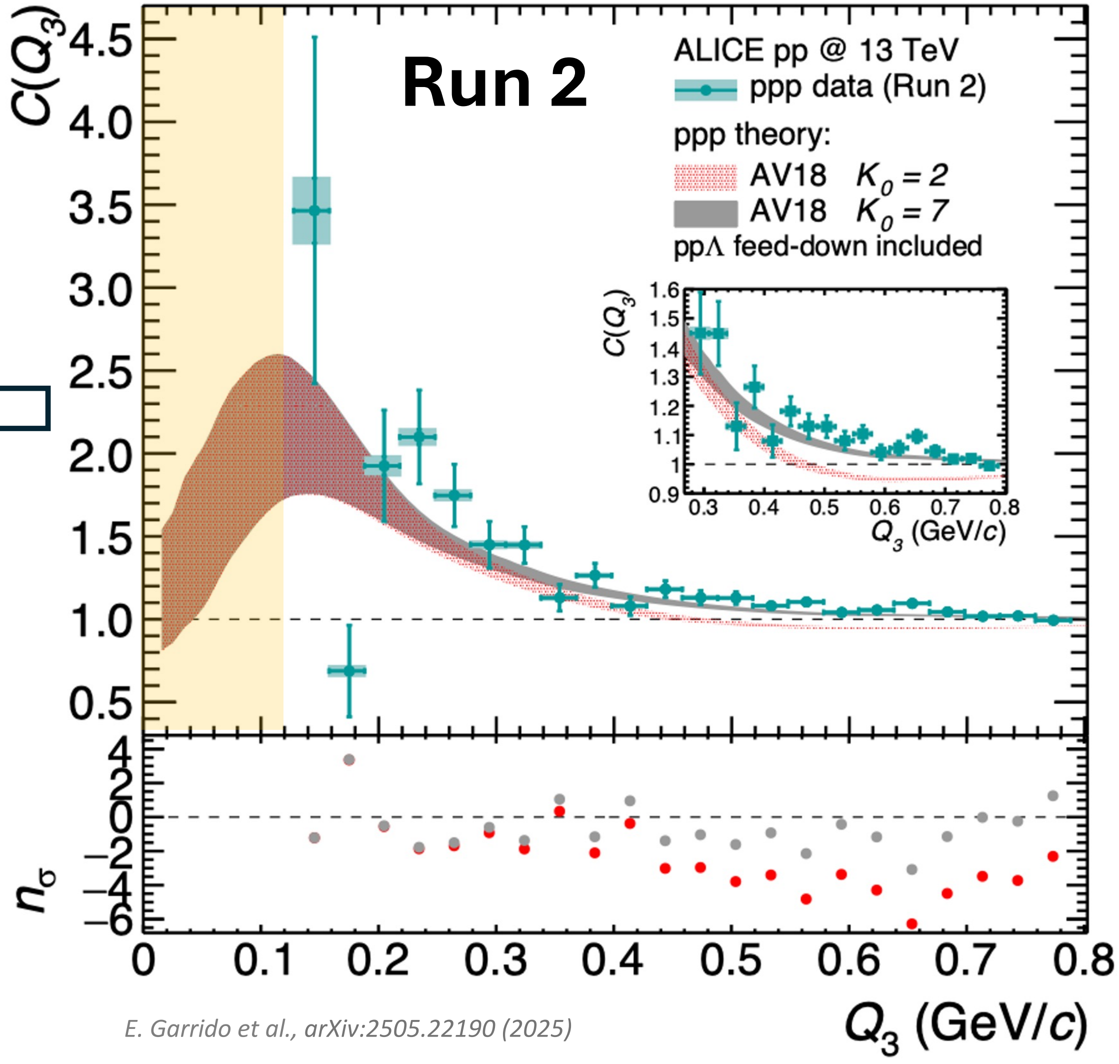
Negligible three-body interactions in p-p-p.



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

p-p-p correlation function in Run 3

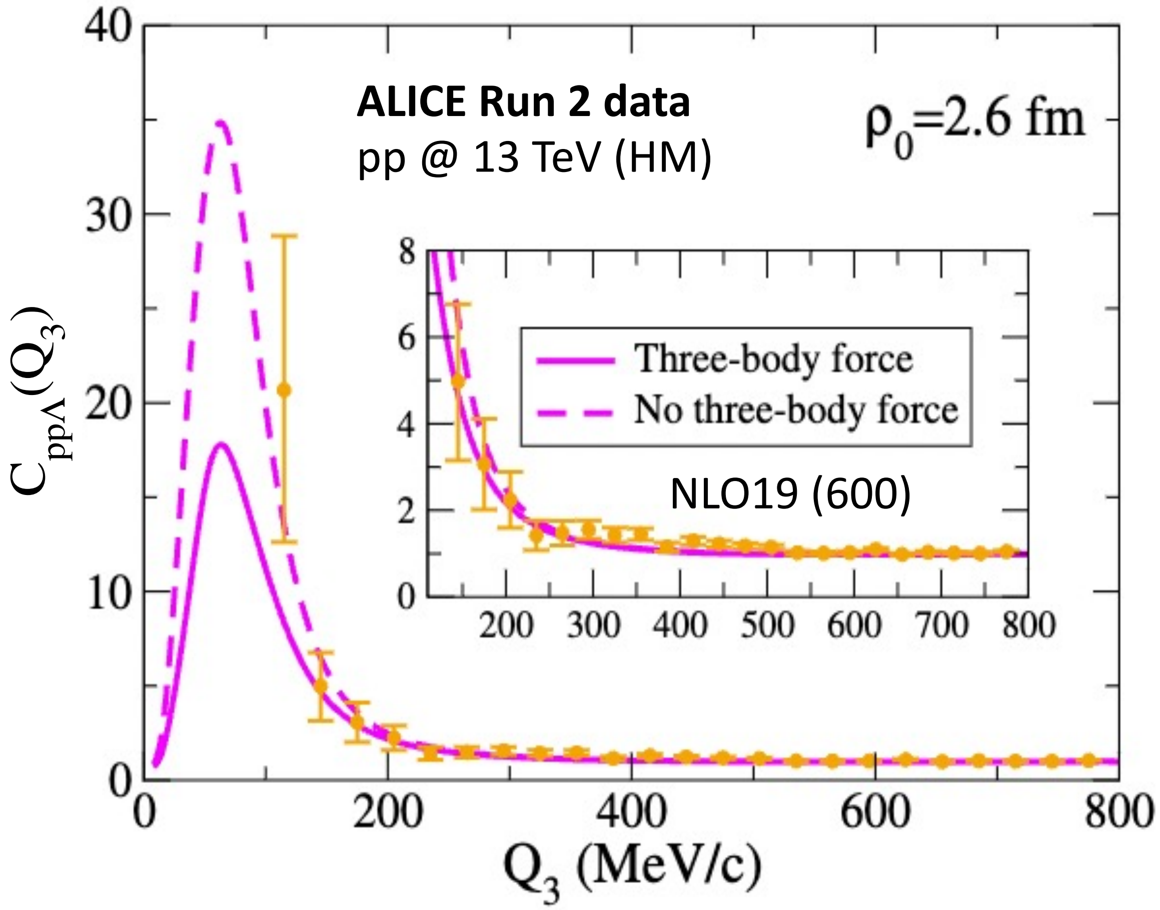




E. Garrido et al., arXiv:2505.22190 (2025)

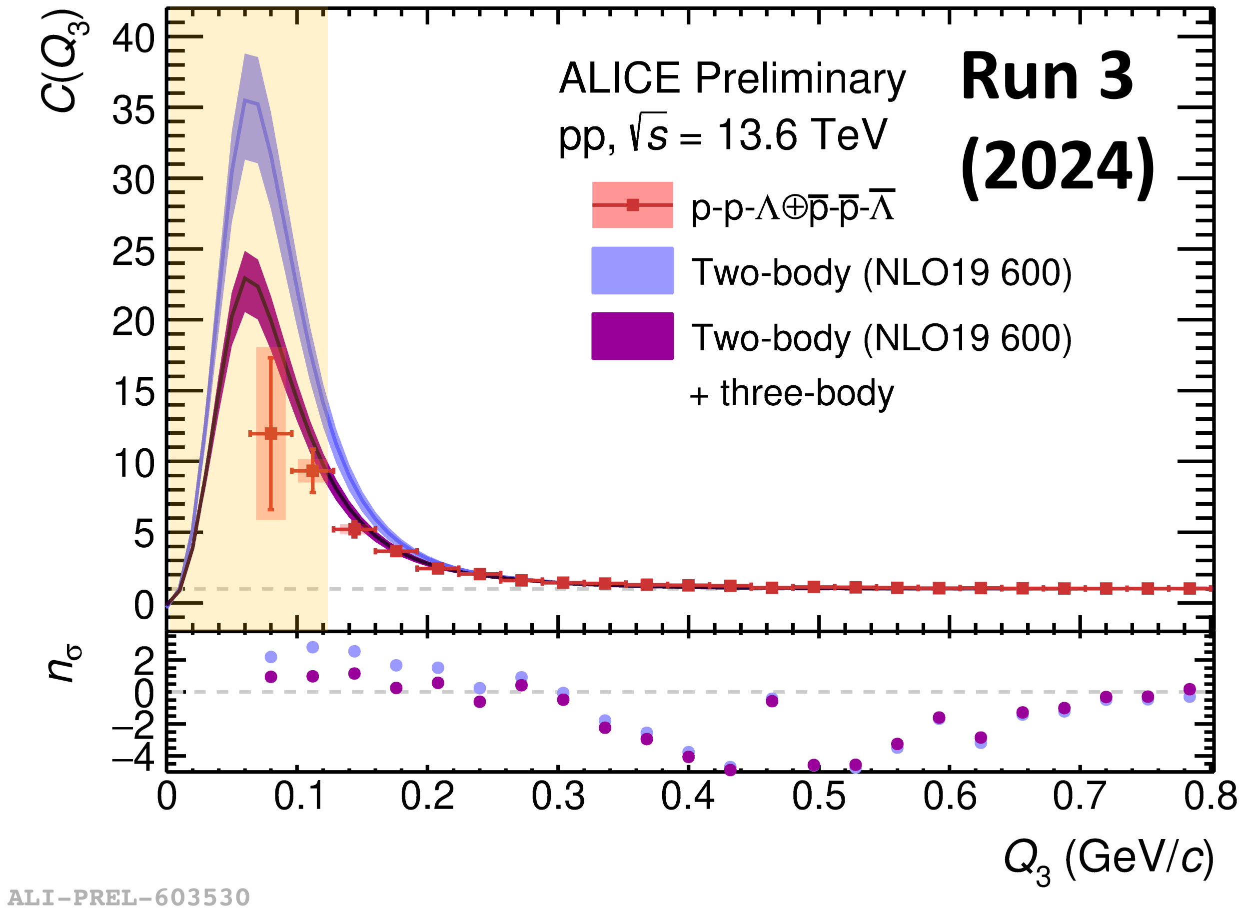
p-p-Λ correlation function

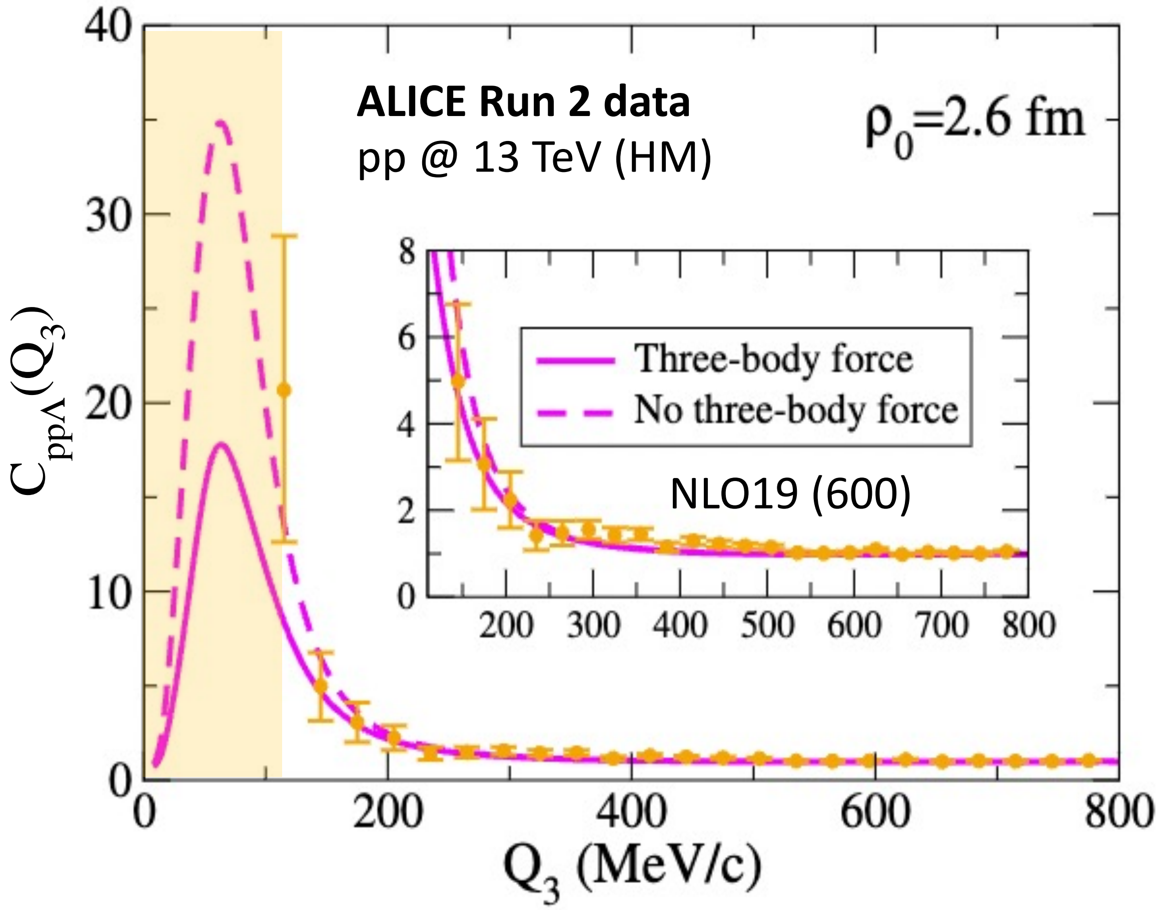
- NLO19 (600) is used to describe the pΛ interaction
  D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550
- Three-body force constrained to the hypertriton binding energy
- 40% effect of three-body interactions
- Run 2 data: one data point in the region of the maximum



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

p-p-Λ correlation function



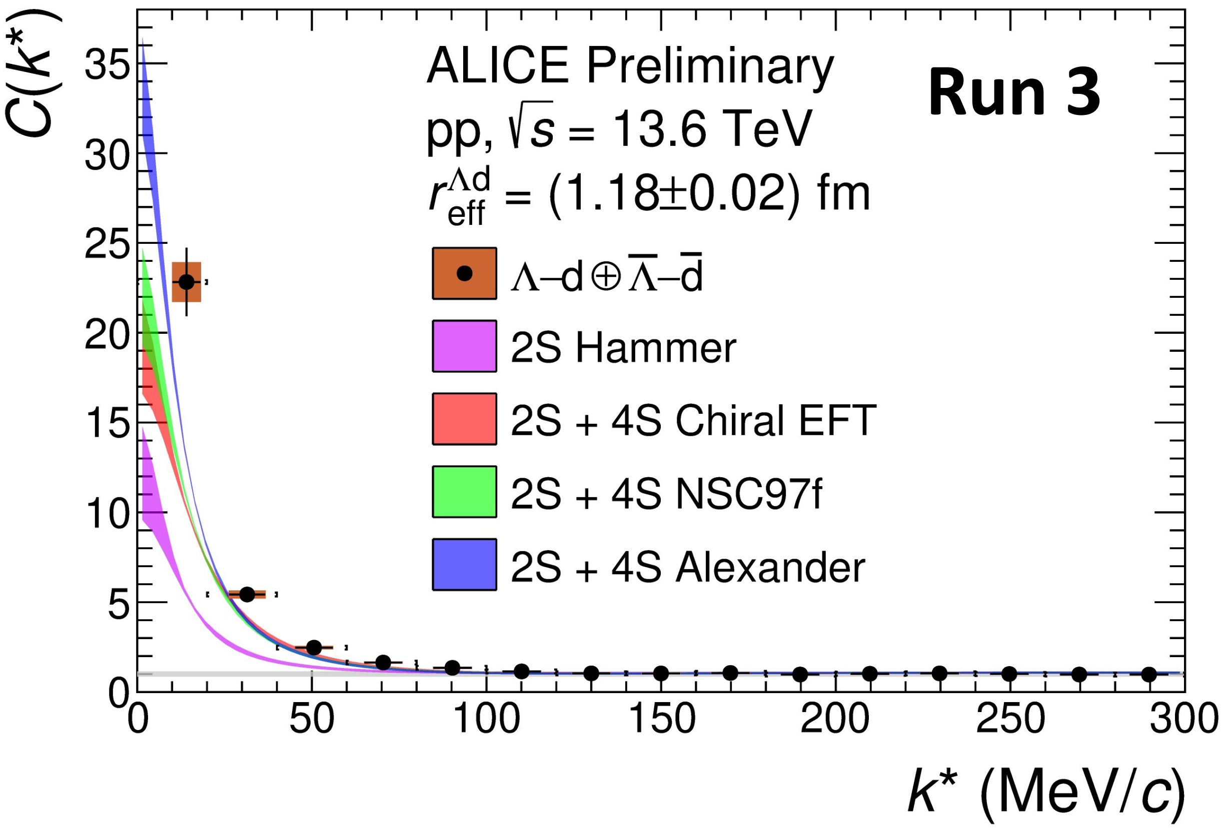


E. Garrido et al., PRC 110 (2024) 5, 054004

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

Λ-d correlation function

- Dedicated three body triggers for pp collisions at Run 3
- Λnp versus Λpp interactions !



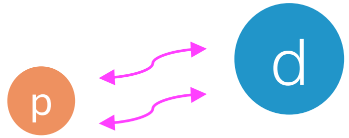
Theoretical curves: Lednicky formula with scattering parameters from J. Haidenbauer *Phys.Rev. C* 102 (2020) 3, 034001

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
  - Opening of the $p\Xi^- \rightarrow \Lambda\Sigma^0$ 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

NNN using proton-deuteron correlations

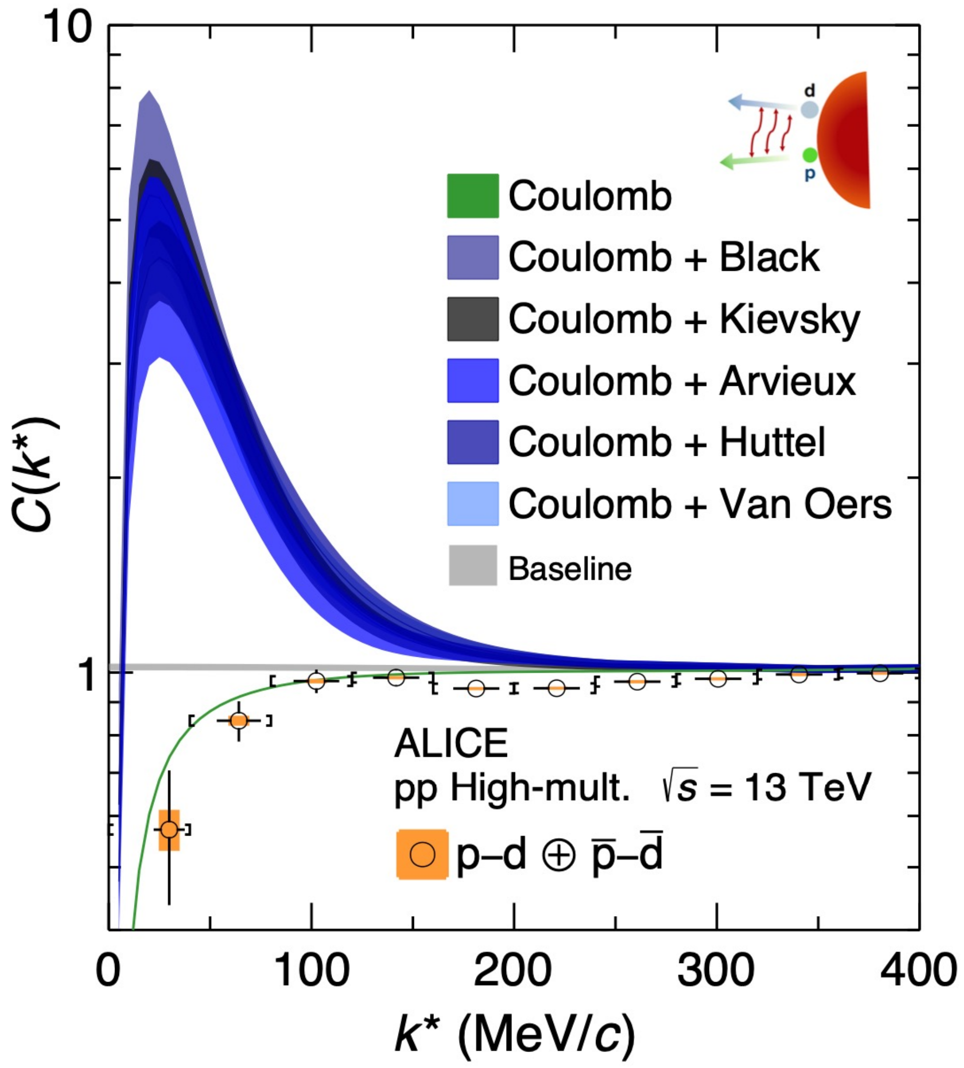


- Point-like particle models anchored to scattering experiments

  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)

Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

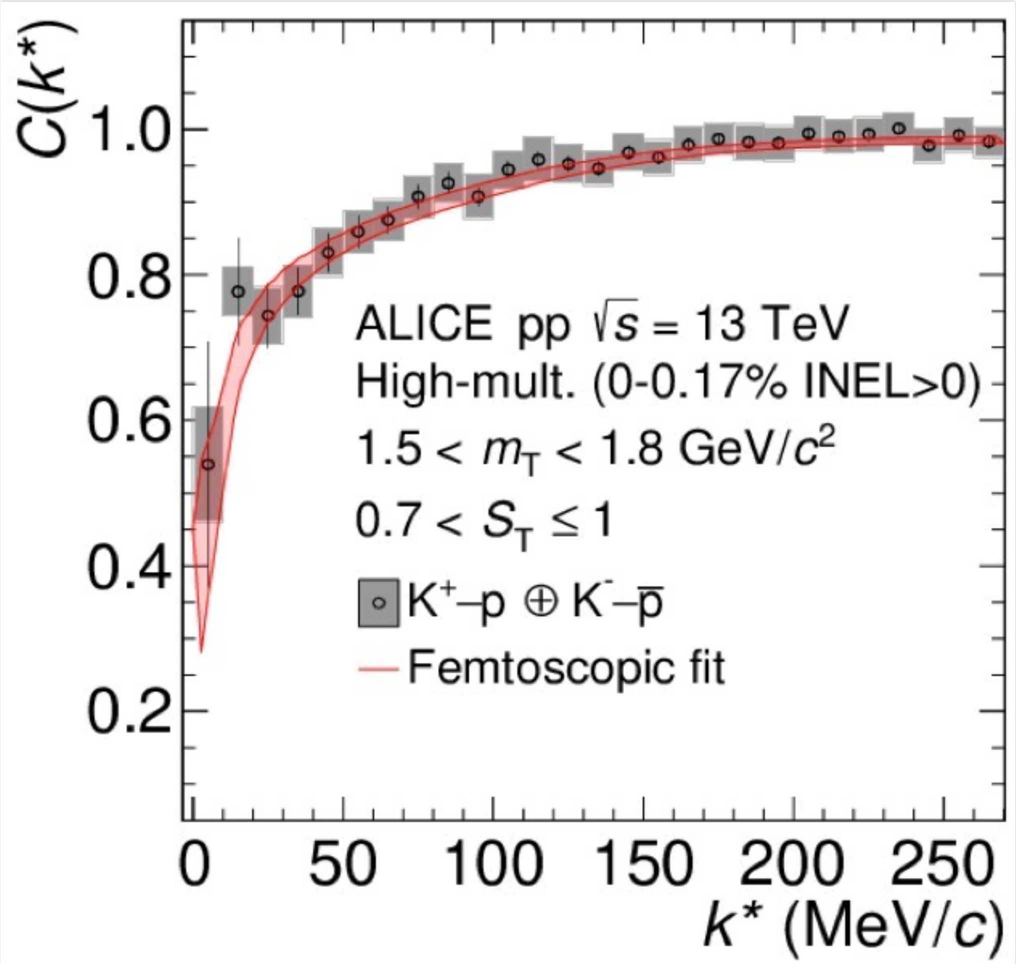
$$\underbrace{C(k^*)}_{\text{measured}} = \int S(\vec{r}\,)\underbrace{\left|\psi(\vec{k}^*,\vec{r}\,)\right|^2}_{\text{known interaction}} d^3\vec{r}$$

- Gaussian parametrization

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

Effect of short lived resonances (cτ ~ 1 fm)

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



ALICE Coll., PLB, 811 (2020)

Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

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

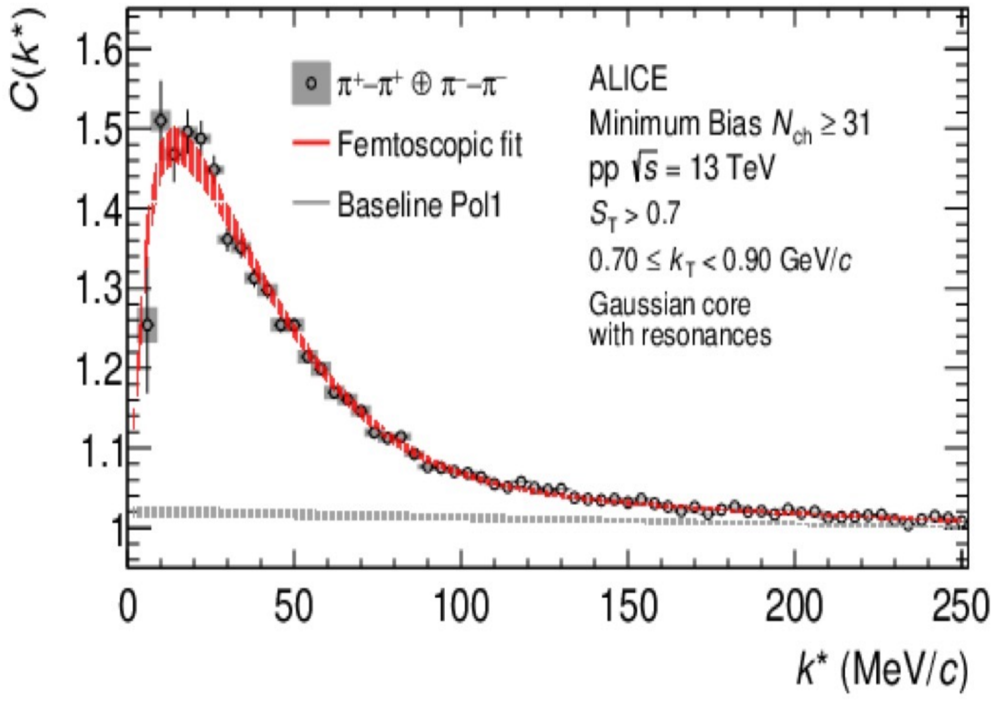
measured known interaction

- Gaussian parametrization

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

Effect of short lived resonances (cτ ~ 1 fm)

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



ALICE Coll., PLB, 811 (2020)