Czech
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# Understanding two- and three-body hadronic interactions using femtoscopy

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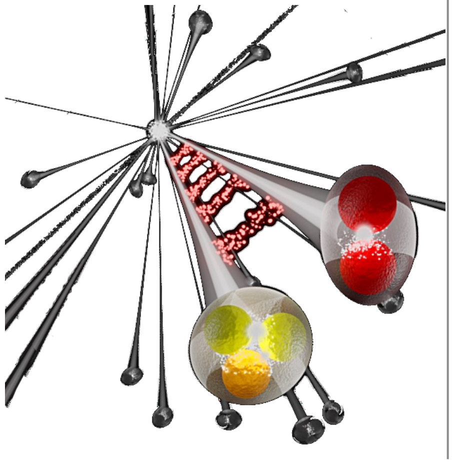
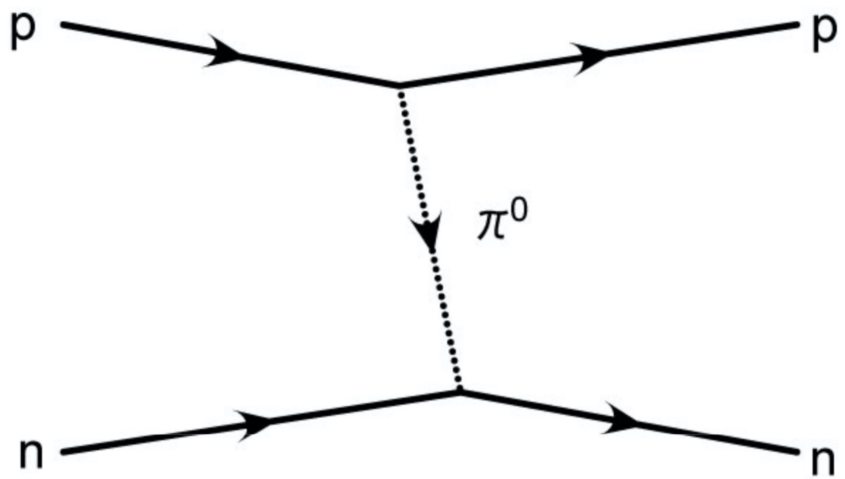
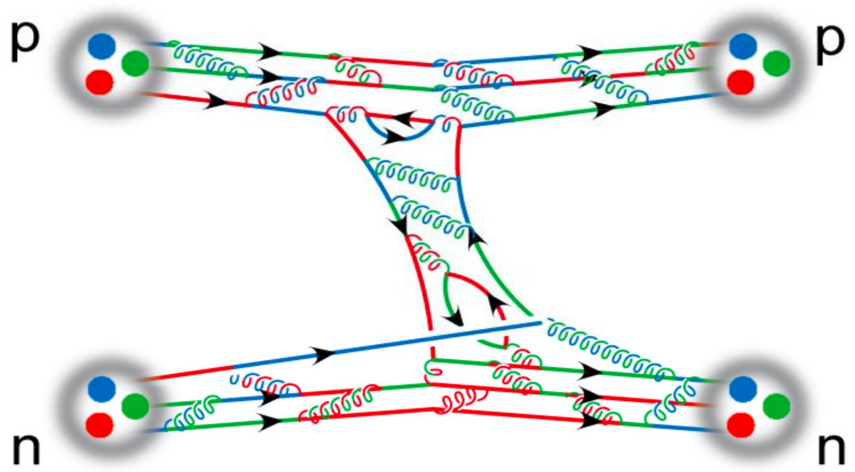


# Hadronic interactions

Low energy hadronic interactions:

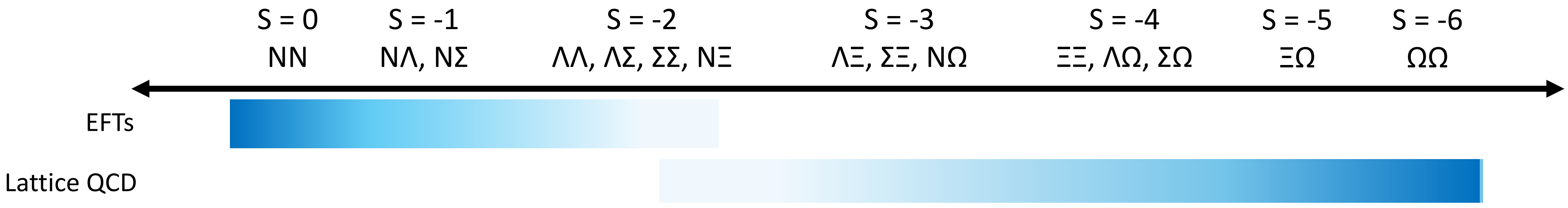


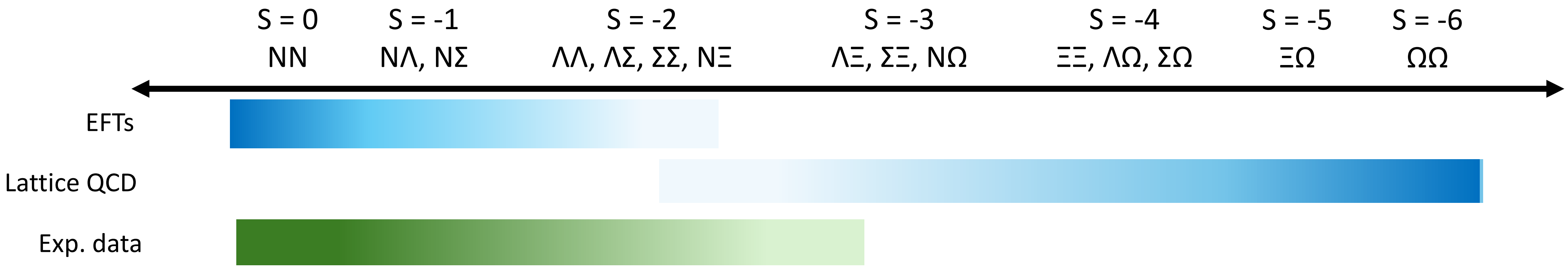

**Effective Field Theories** (EFT)
- hadrons as degrees of freedom
- low-energy coefficients constrained by data

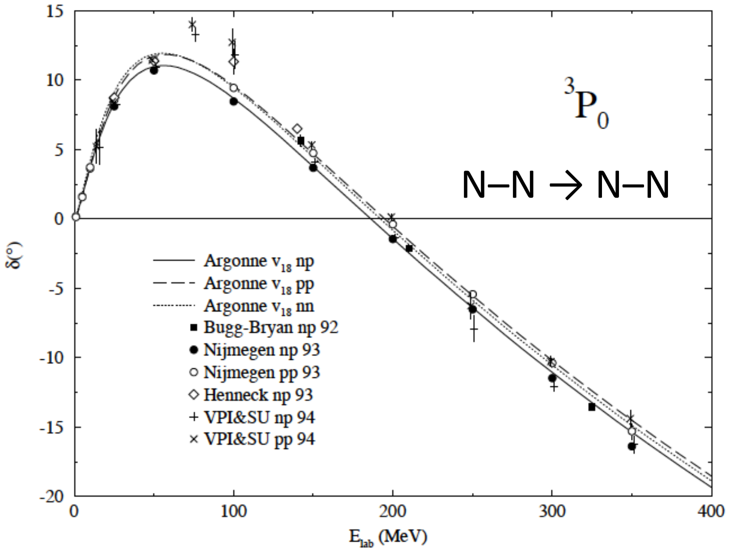
**Lattice QCD**
- quarks and gluons as degrees of freedom
- unstable for low mass hadrons

# Theory and experimental data

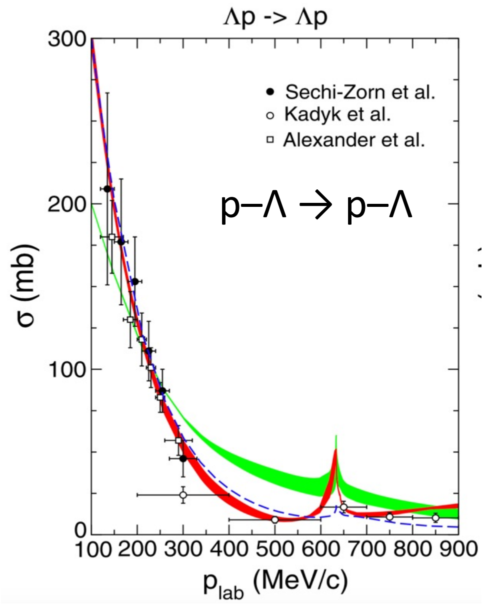


# Theory and experimental data

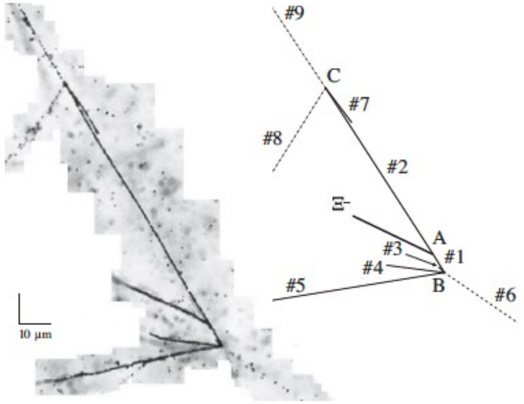



*R. B. Wiringa et al. PRC 51 (1995)*



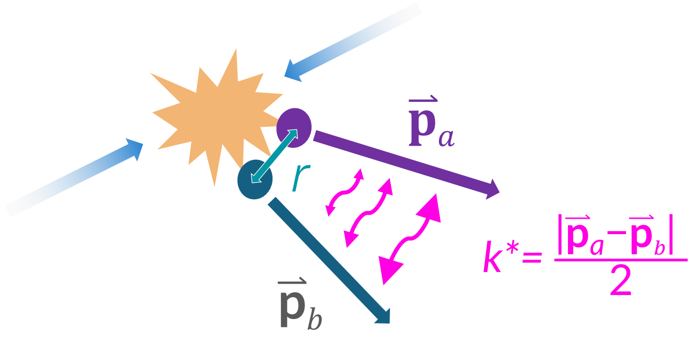

*J.Haidenbauer et al. NPA 915 (2013)*



Ξ hypernucleus

*J-PARC E07 Coll. PRL 126 (2021)*

# Femtoscopy for interactions



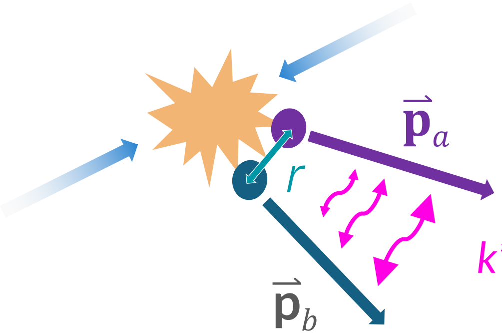

$$C(k^*) = \int S(\vec{r}\,)\left|\psi(\vec{k}^*, \vec{r}\,)\right|^2 d\,\vec{r} \;= \mathcal{N}(k^*)\,\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

Two-particle wave function

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

*Plenary talk*
*V. Mantovani Sarti*

# Femtoscopy for interactions




$k^* = \frac{|\vec{\mathbf{p}}_a - \vec{\mathbf{p}}_b|}{2}$

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

Two-particle wave function

M. Lisa, S. Pratt et al., ARNPS 55 (2005), 357-402
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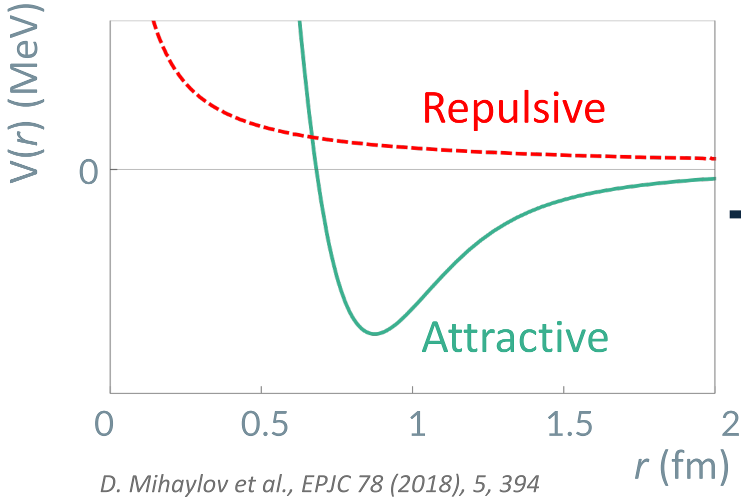
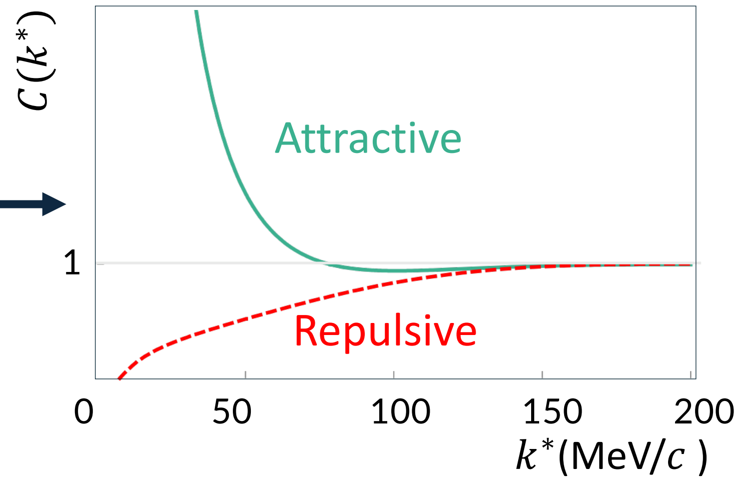
Interacting potential




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

Correlation function

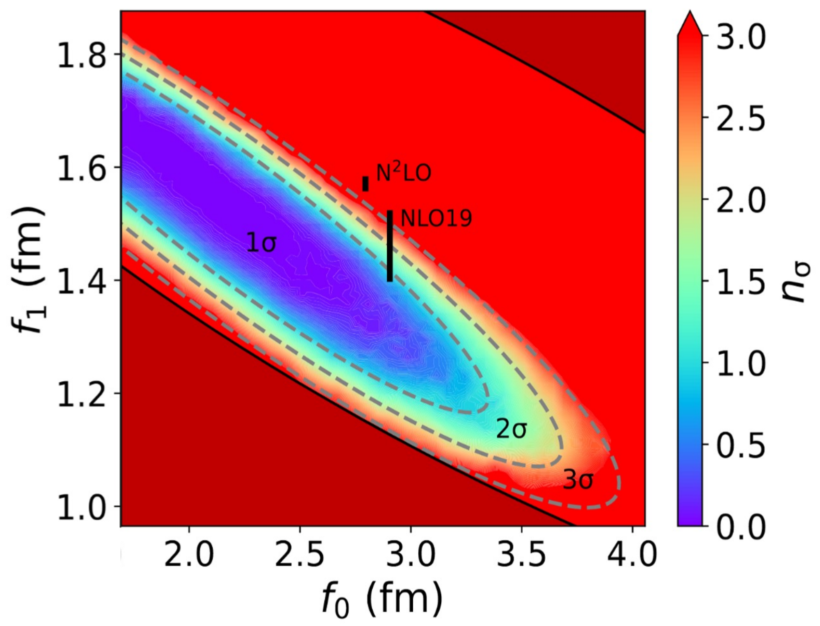



*Plenary talk*
*V. Mantovani Sarti*

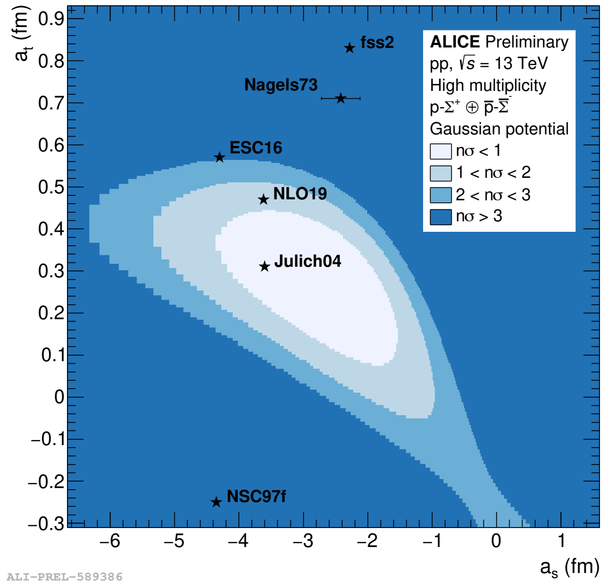
Measuring $C(k^*)$ → fixing the source $S(\vec{r}\,)$ → study the interaction

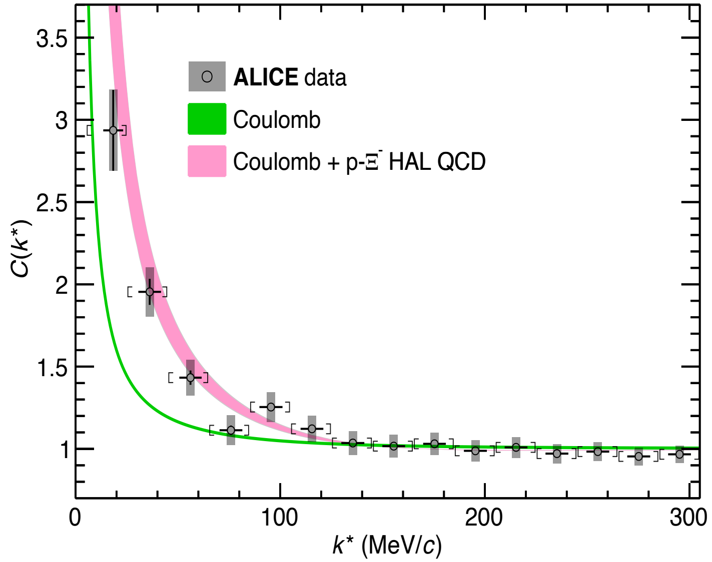
# Interactions in the femtoscopy era

- Most precise measurement of the p-Λ scattering parameters
- First measurement of the p-$\Sigma^+$ scattering parameters
- Evidence of an attractive p-$\Xi^-$ interaction




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



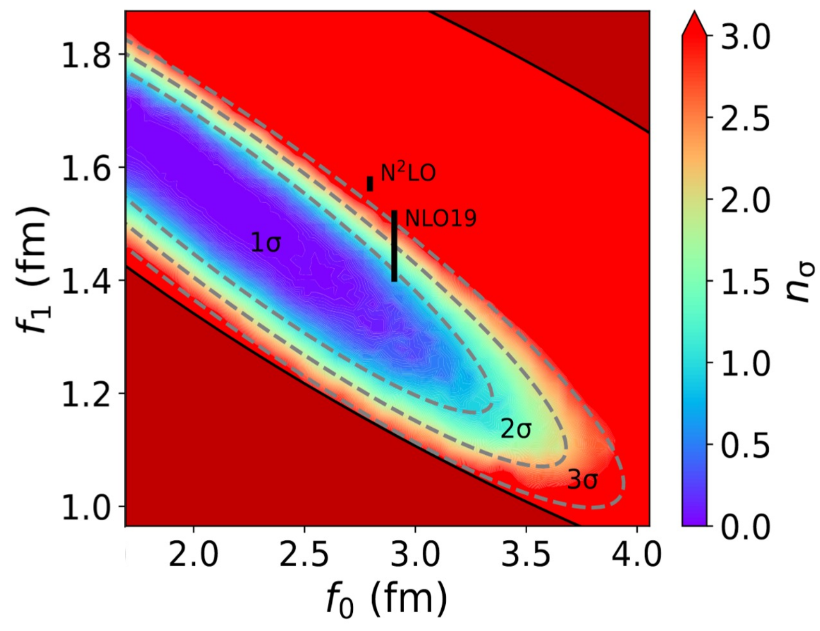

ALICE Coll., Nature 588 (2020) 232

New precise experimental inputs for EFTs

First tests of Lattice QCD

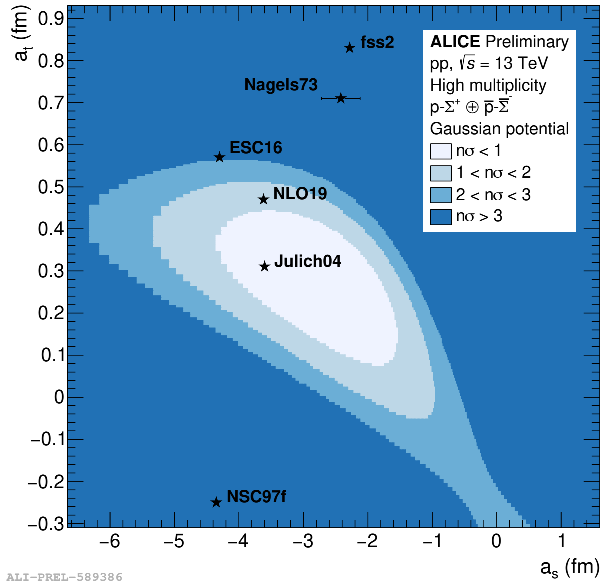
# Interactions in the femtoscopy era

- Most precise measurement of the p-Λ scattering parameters

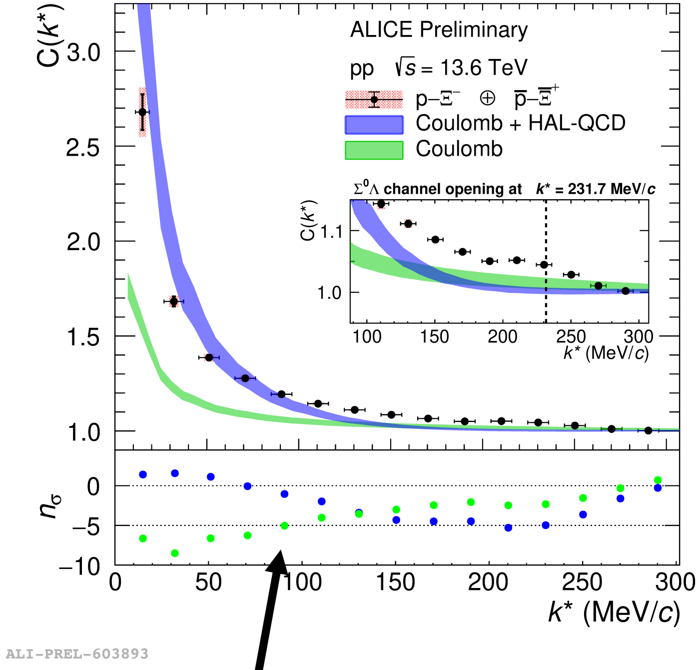



*D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550*

- First measurement of the p-$\Sigma^+$ scattering parameters




- Evidence of an attractive p-$\Xi^-$ interaction
- Opening of the p$\Xi$ → $\Lambda\Sigma^0$ channel



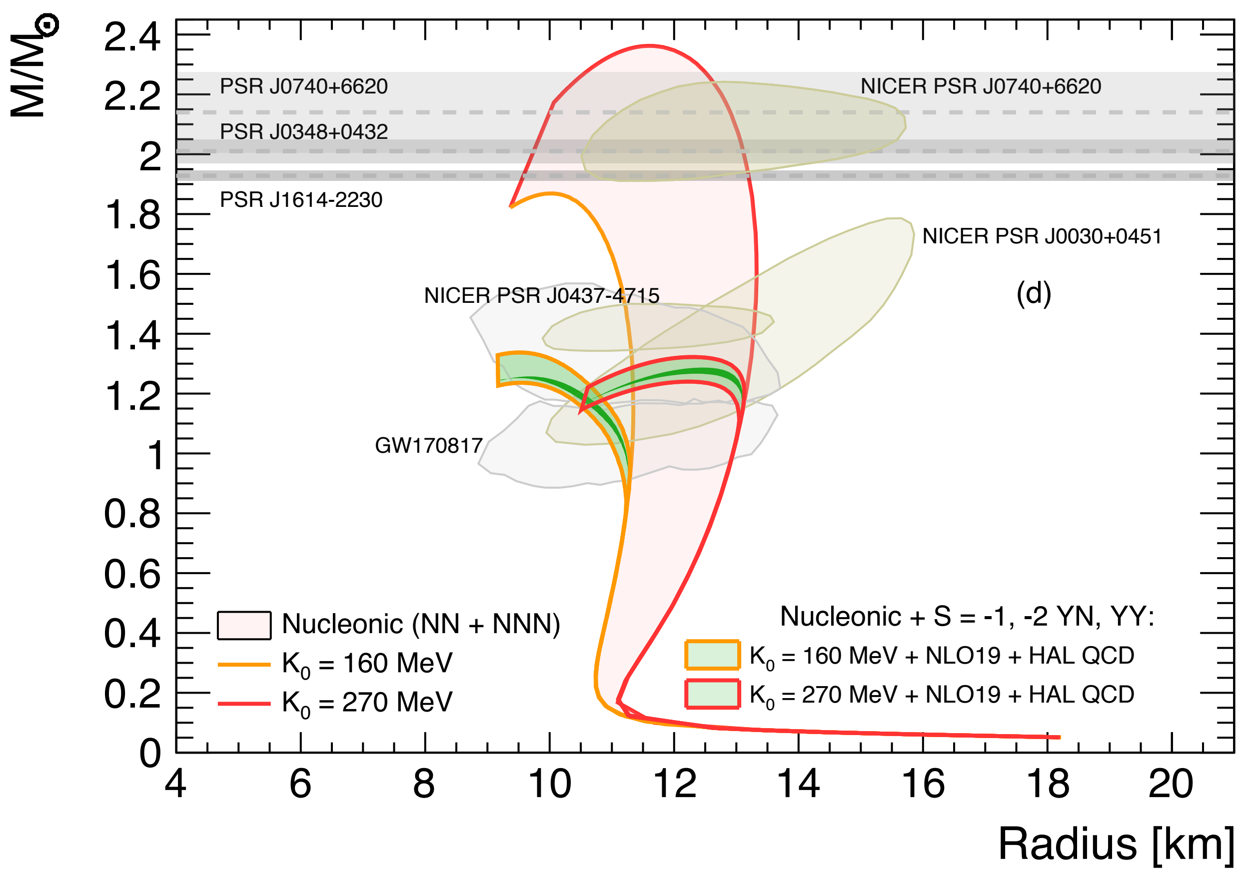

**New exciting results expected from Run 3**

# 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

*Plenary talk*
*V. Mantovani Sarti*



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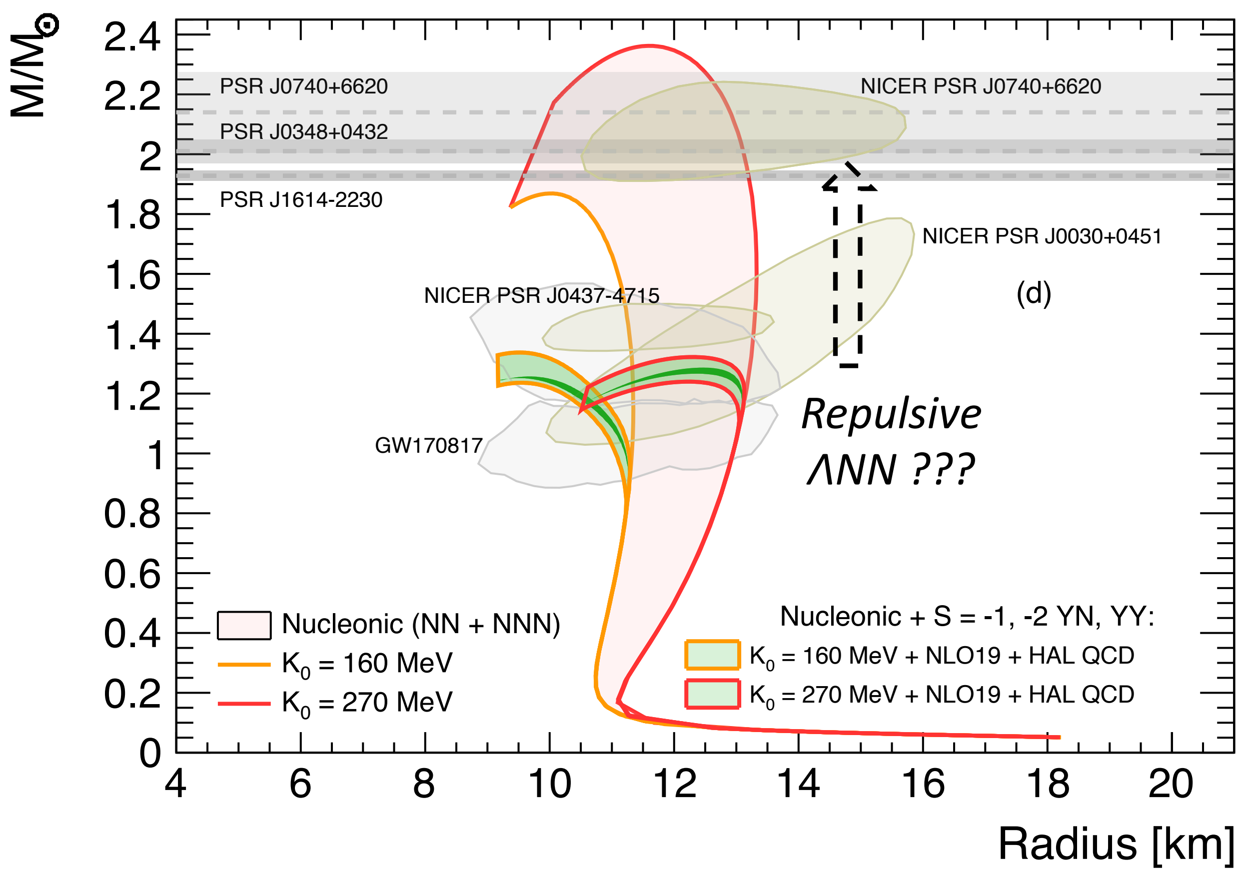
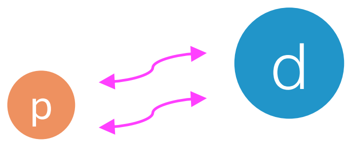
*Plenary talk*
*V. Mantovani Sarti*

- Next step → inclusion of three body interaction involving hyperons

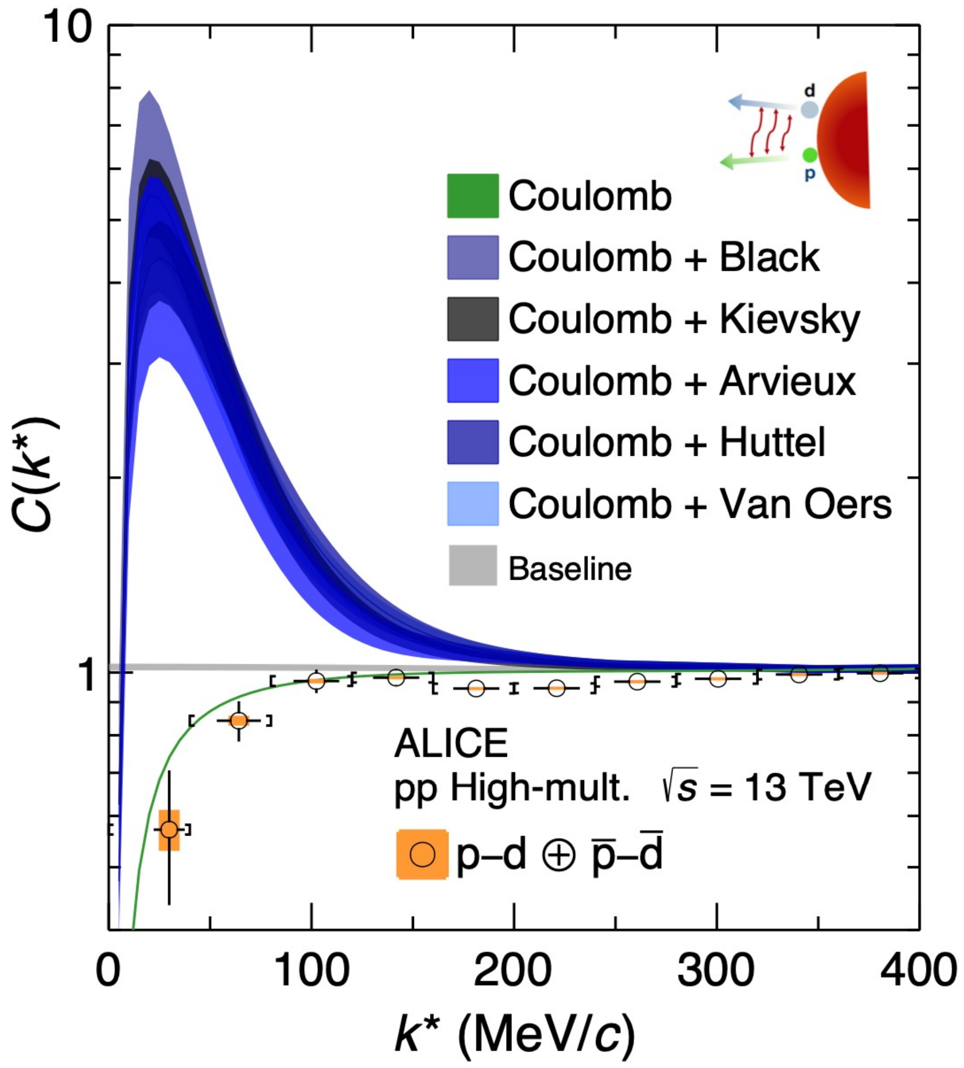


# NNN using proton-deuteron correlations



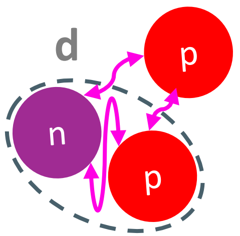

- Point-like particle models anchored to scattering experiments
  - *W. T. H. Van Oers et al., NPA 561 (1967);*
  - *J. Arvieux et al., NPA 221 (1973); E. Huttel et al., NPA 406 (1983);*
  - *A. Kievsky et al., PLB 406 (1997); T. C. Black et al., PLB 471 (1999);*
- Coulomb + strong interaction using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



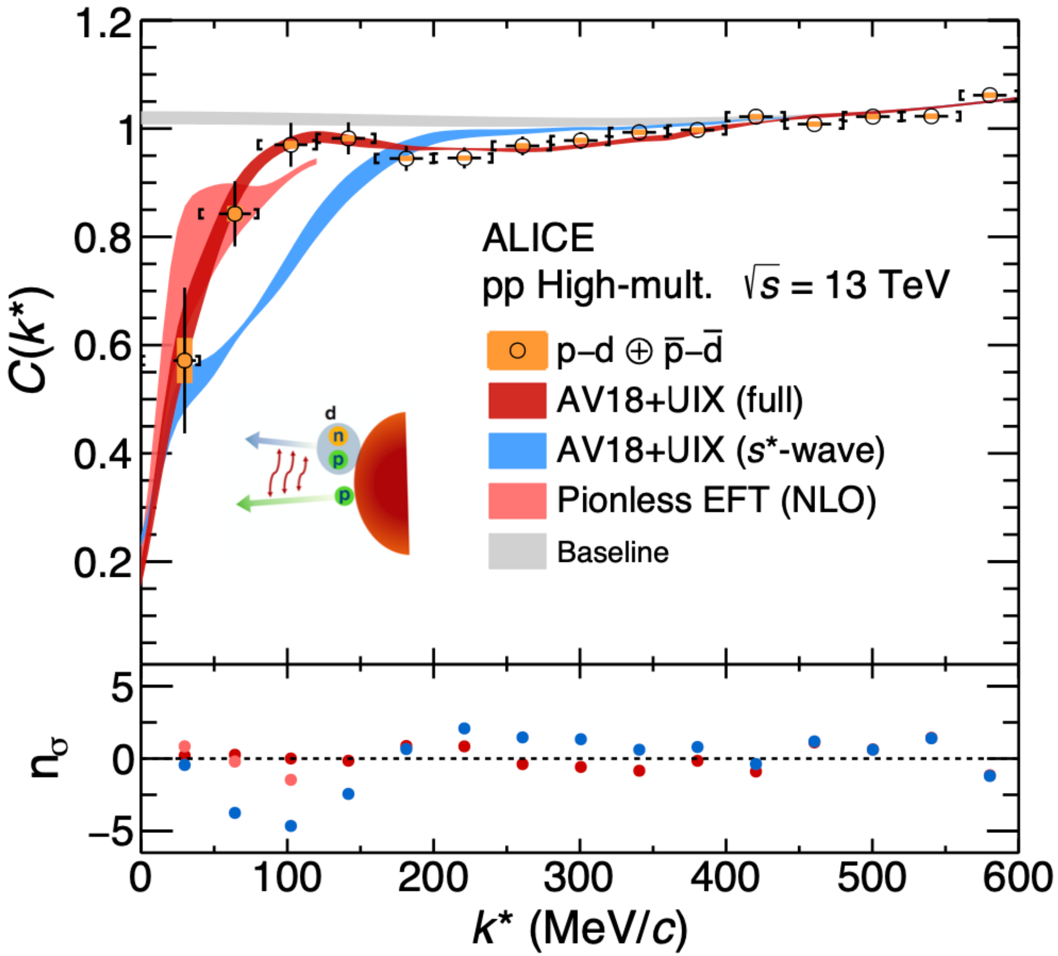

*ALICE Coll. Phys. Rev. X 14, 031051 (2024)*

# NNN using proton-deuteron correlations



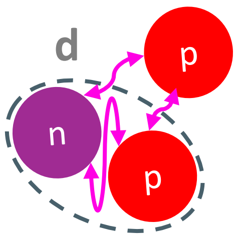

- Full three-body calculations are required (NN + NNN + Quantum Stat.)
- **Hadron-nuclei correlations at the LHC can be used to study many-body dynamics**

*Talk*
*A. Kievsky*




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

# NNN using proton-deuteron correlations

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*Talk*
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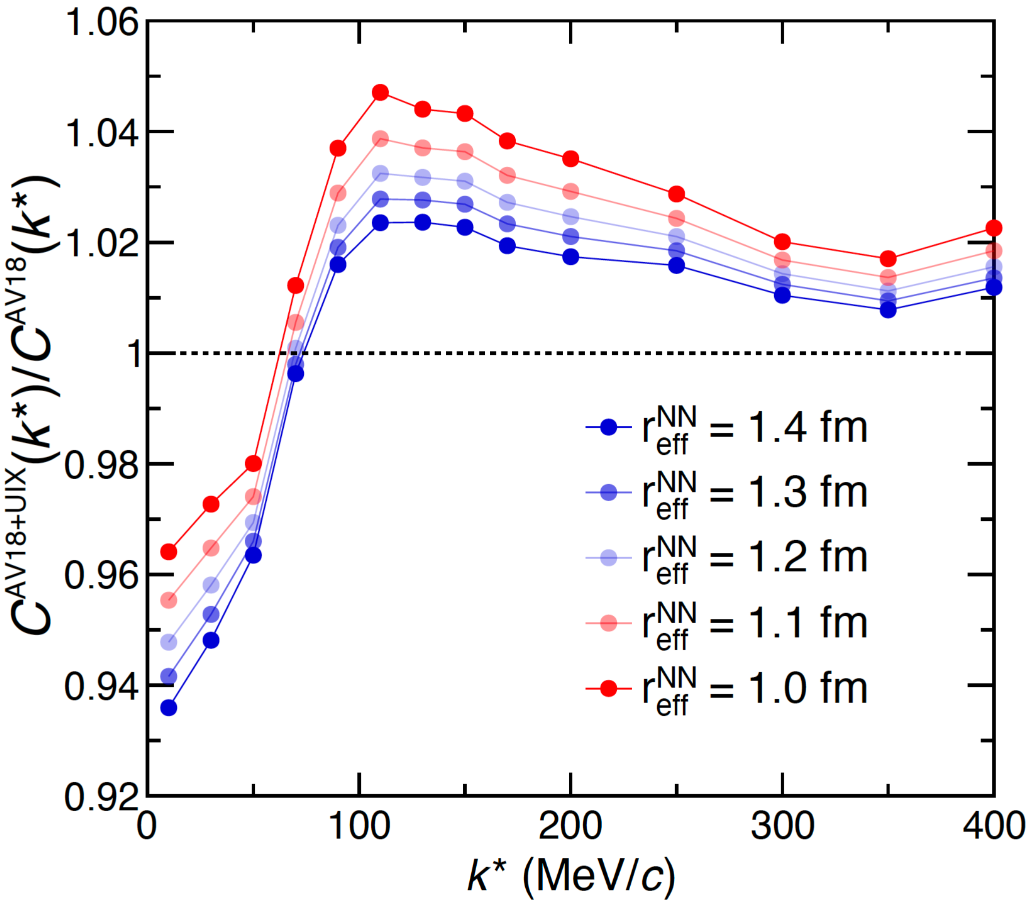
- Sensitivity to three-body forces up to 5%




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

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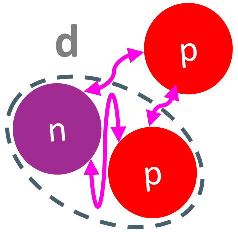


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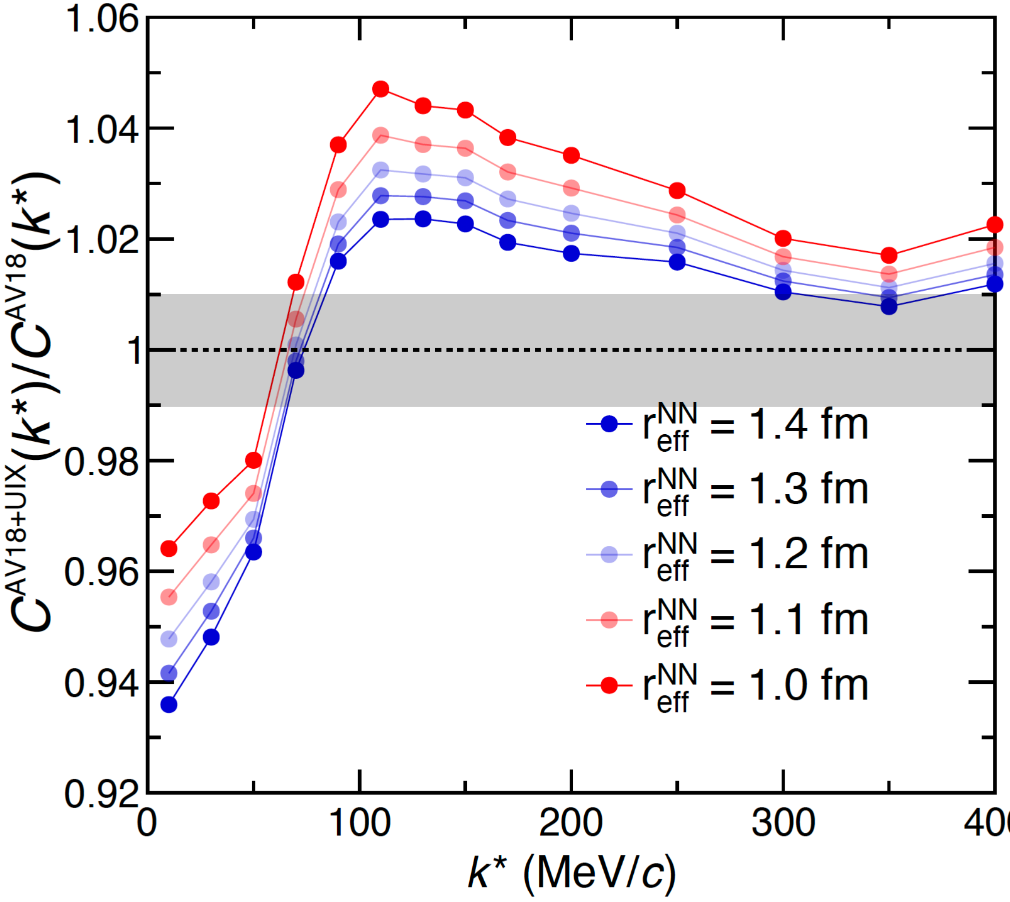
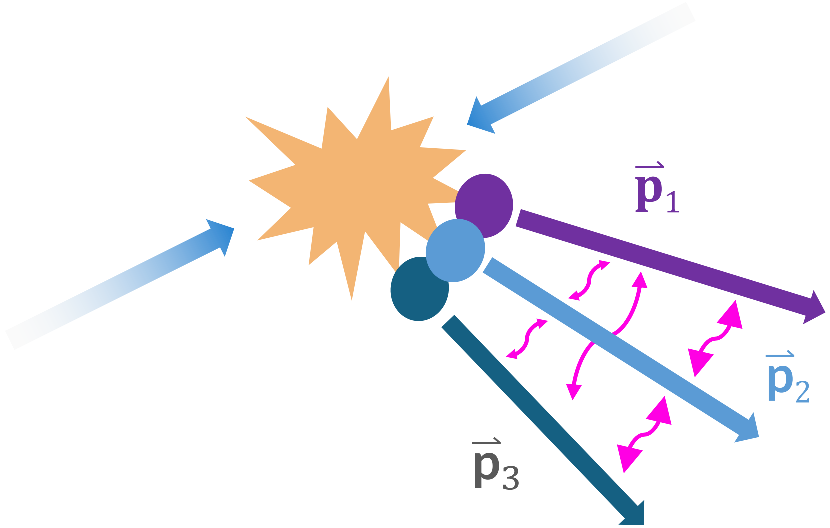
*Talk*
*A. Kievsky*

- 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*

# 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:

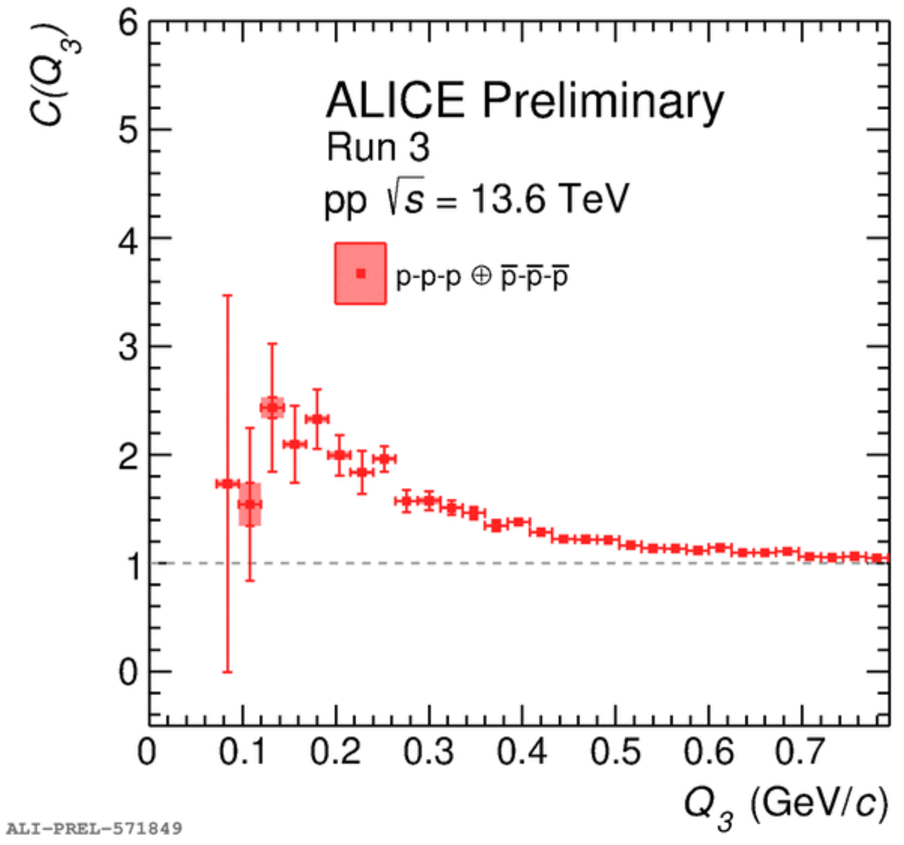
$$Q_3 = 2\sqrt{k_{12}^2 + k_{23}^2 + k_{31}^2}$$

*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)*

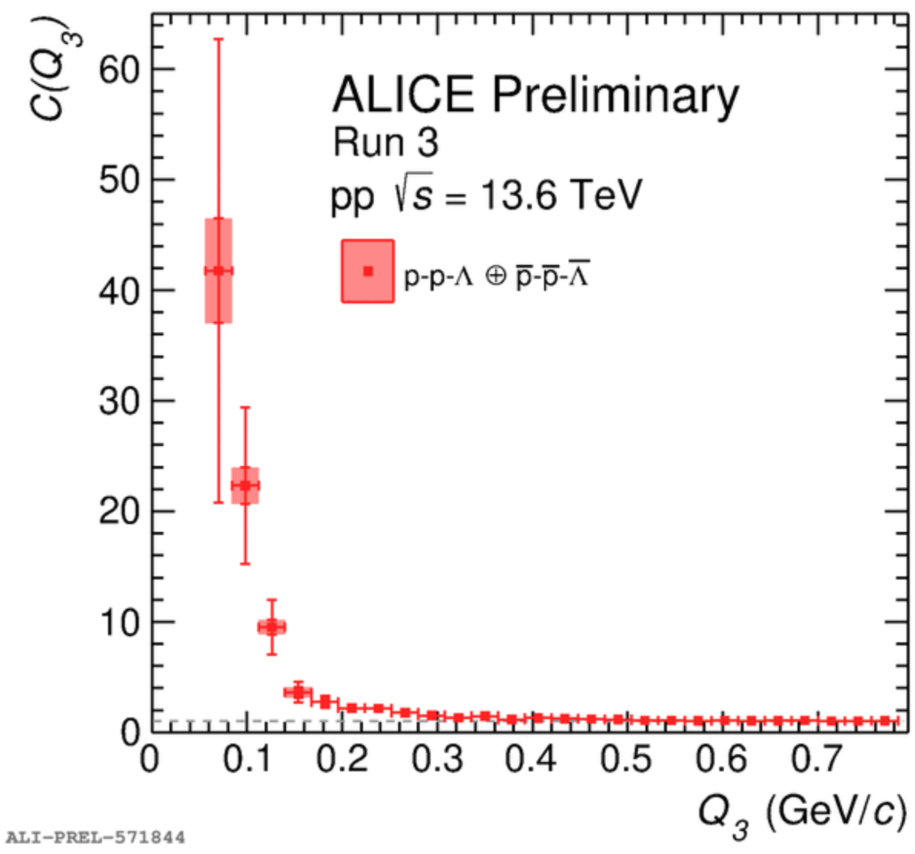
# Extension to three-particle system

- 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**




**p-p-Λ**



# p-p-p correlation function

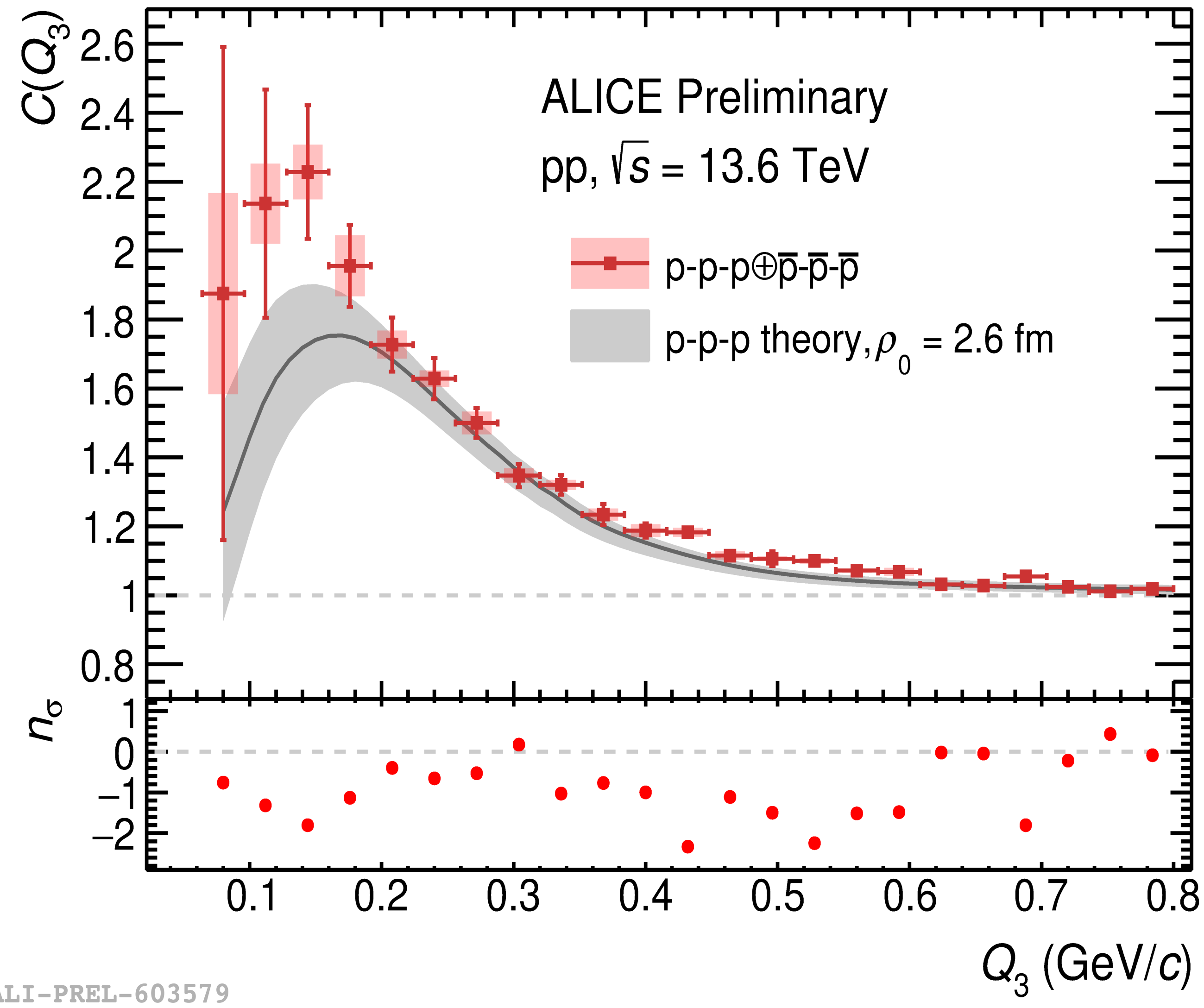
Comparison with the ALICE measurement:

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

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

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

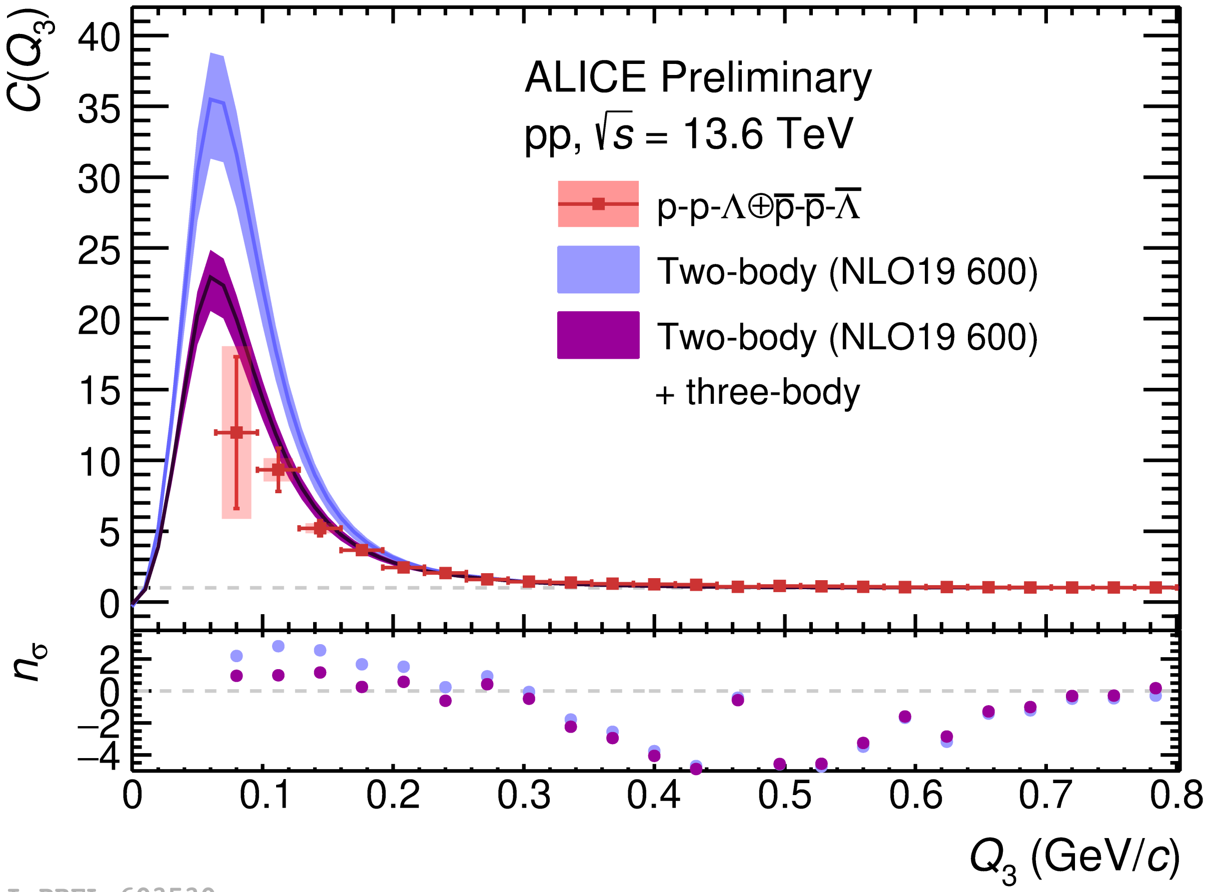
*Talk*
*A. Kievsky*



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

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

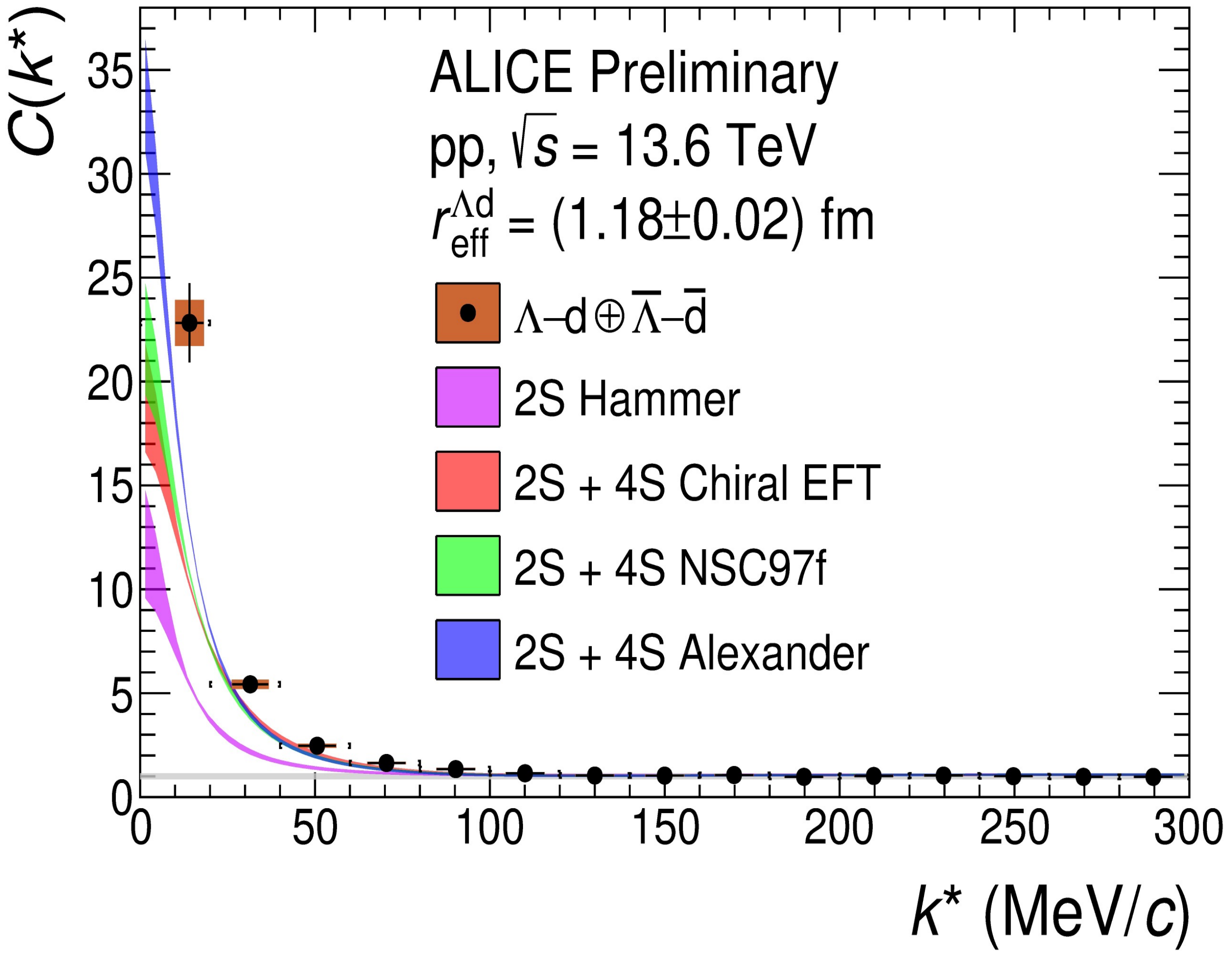



ALI-PREL-603530

# 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 hadronic interactions in the strangeness sector
  - Most precise p-Λ data at low momenta → precise extraction of the p-Λ scattering parameters using femtoscopy and scattering data
  - Shallow repulsion in the p-$\Sigma^+$ interaction in the triplet channel
  - Evidence of the attractive p-$\Xi^-$ strong interaction and ppening of the p$\Xi^-$ → $\Lambda\Sigma^0$ channel
  - First measurements of three-particle correlation functions
    - NNN interaction: up to 5% effect in p-d and negligible in the p-p-p measurement
    - NNΛ interaction: up to 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

# Thank you for your attention

# Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

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

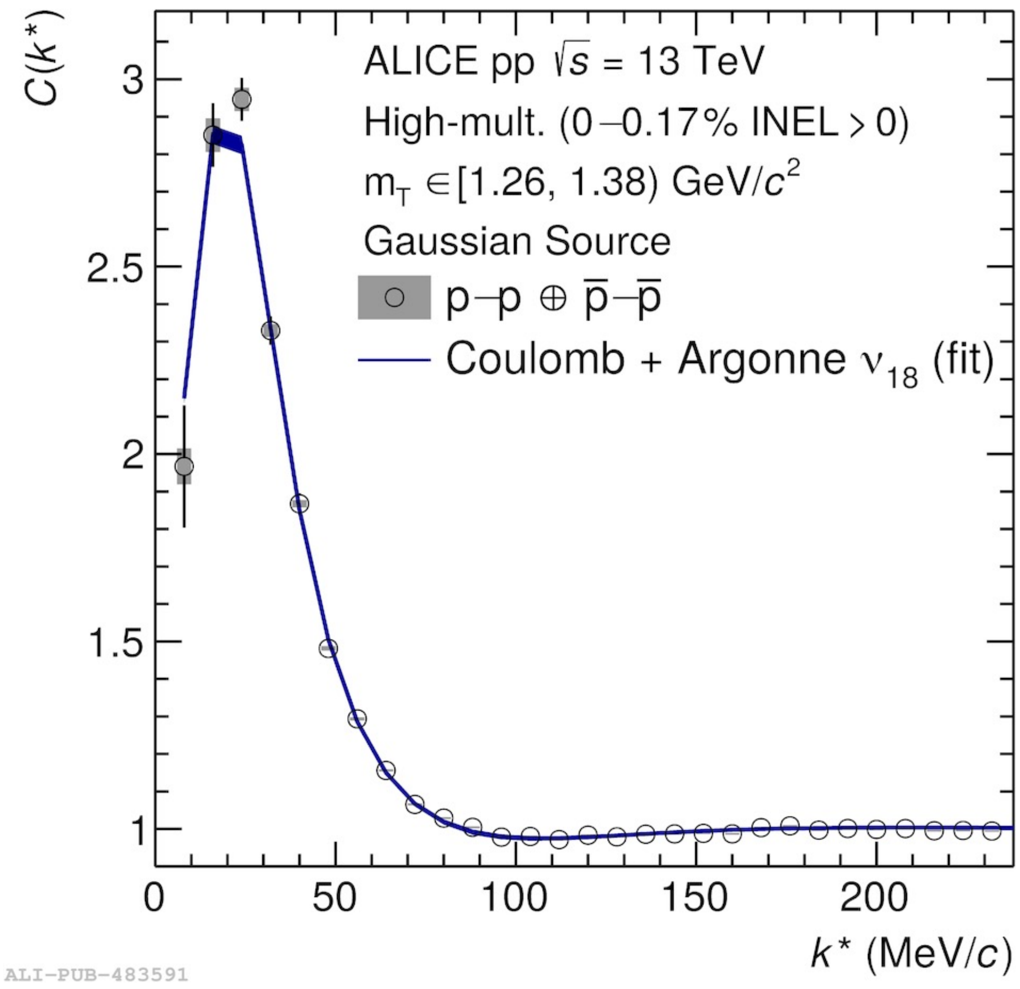
measured known interaction

- Gaussian parametrization

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

Effect of short lived resonances (cτ ~ 1 fm)

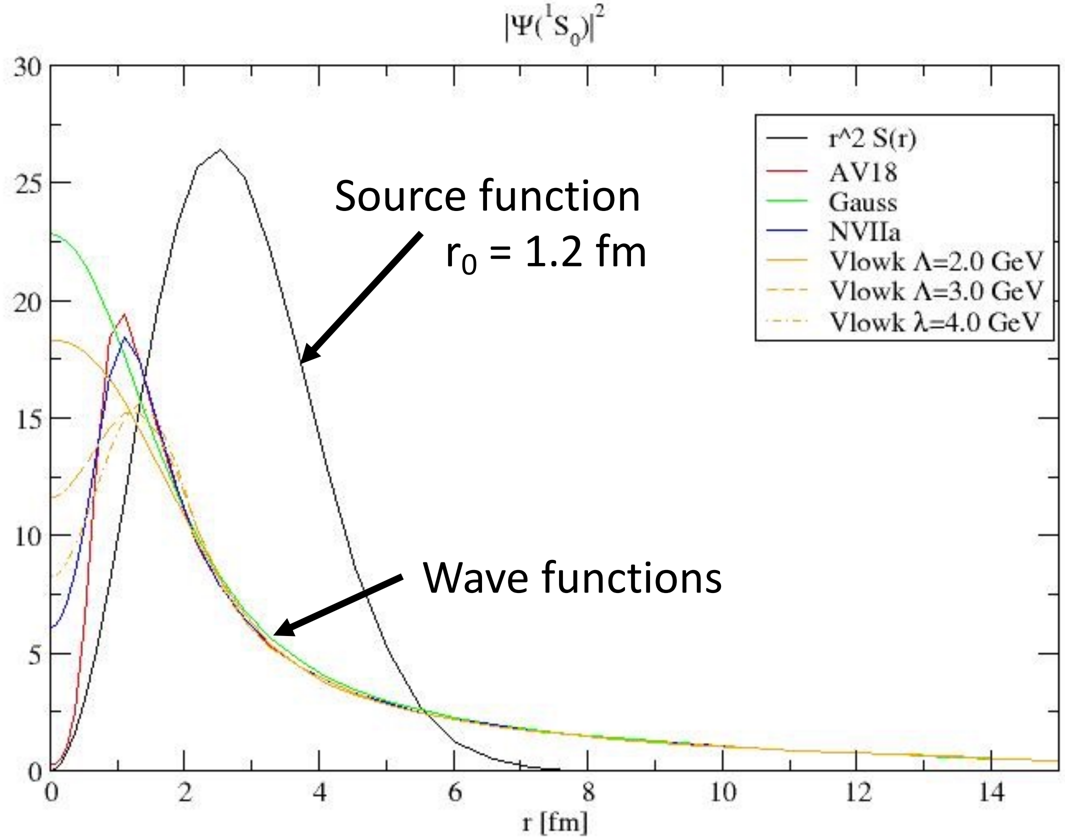
*ALICE Coll., PLB, 811 (2020), 135849*

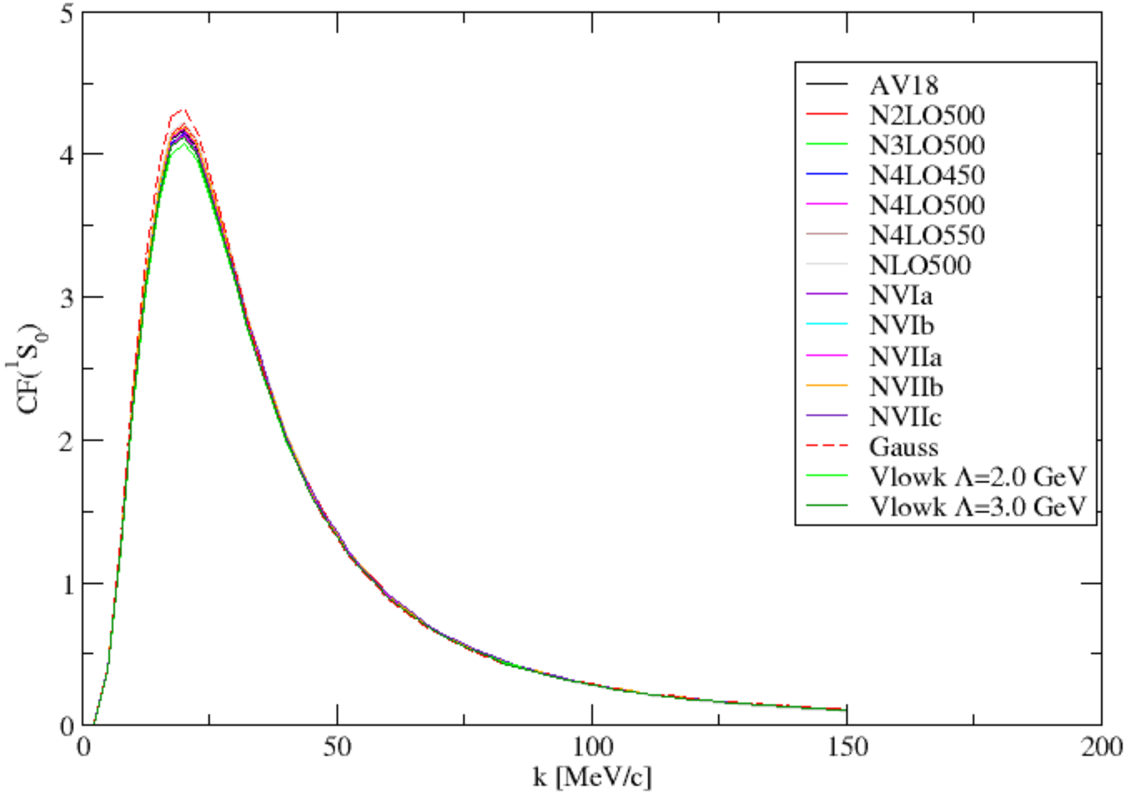



*ALICE Coll., PLB, 811 (2020)*

# 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

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

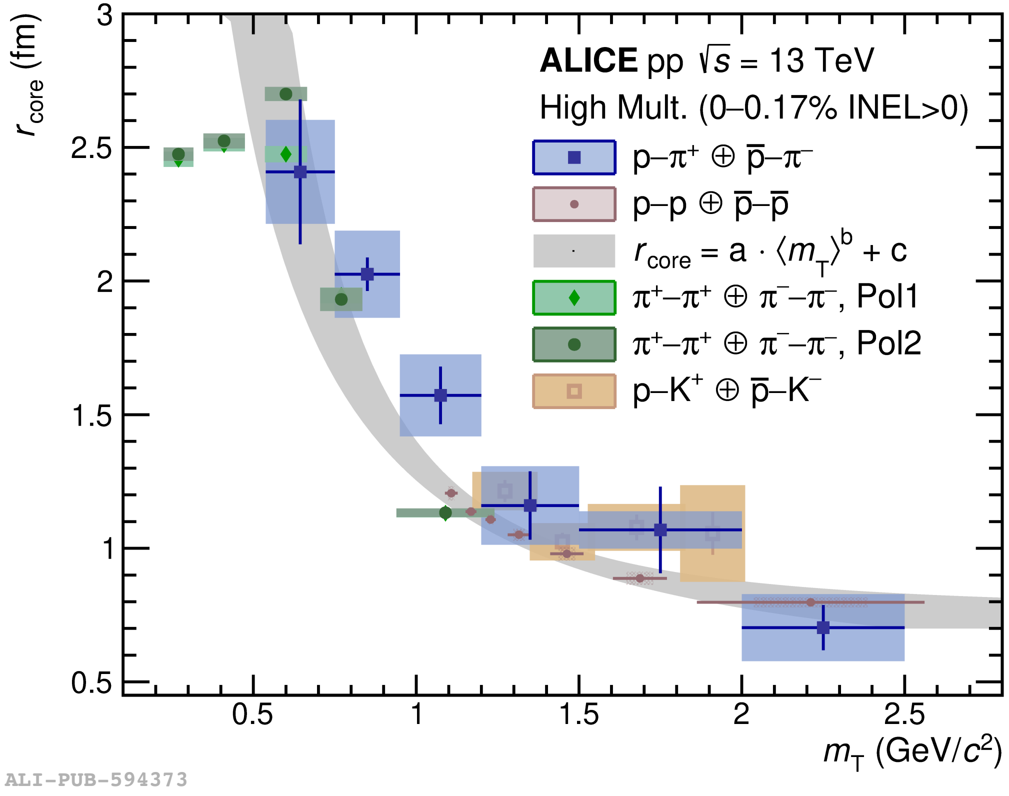
- Gaussian parametrization

$$S(r) = \frac{1}{(4\pi r_{core}^2)^{3/2}}\exp\left(-\frac{r^2}{4r_{core}^2}\right) \times$$ 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., arXiv:2502.20200 (2025)*




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