Current status of measuring hadronic interactions in pp collisions with ALICE

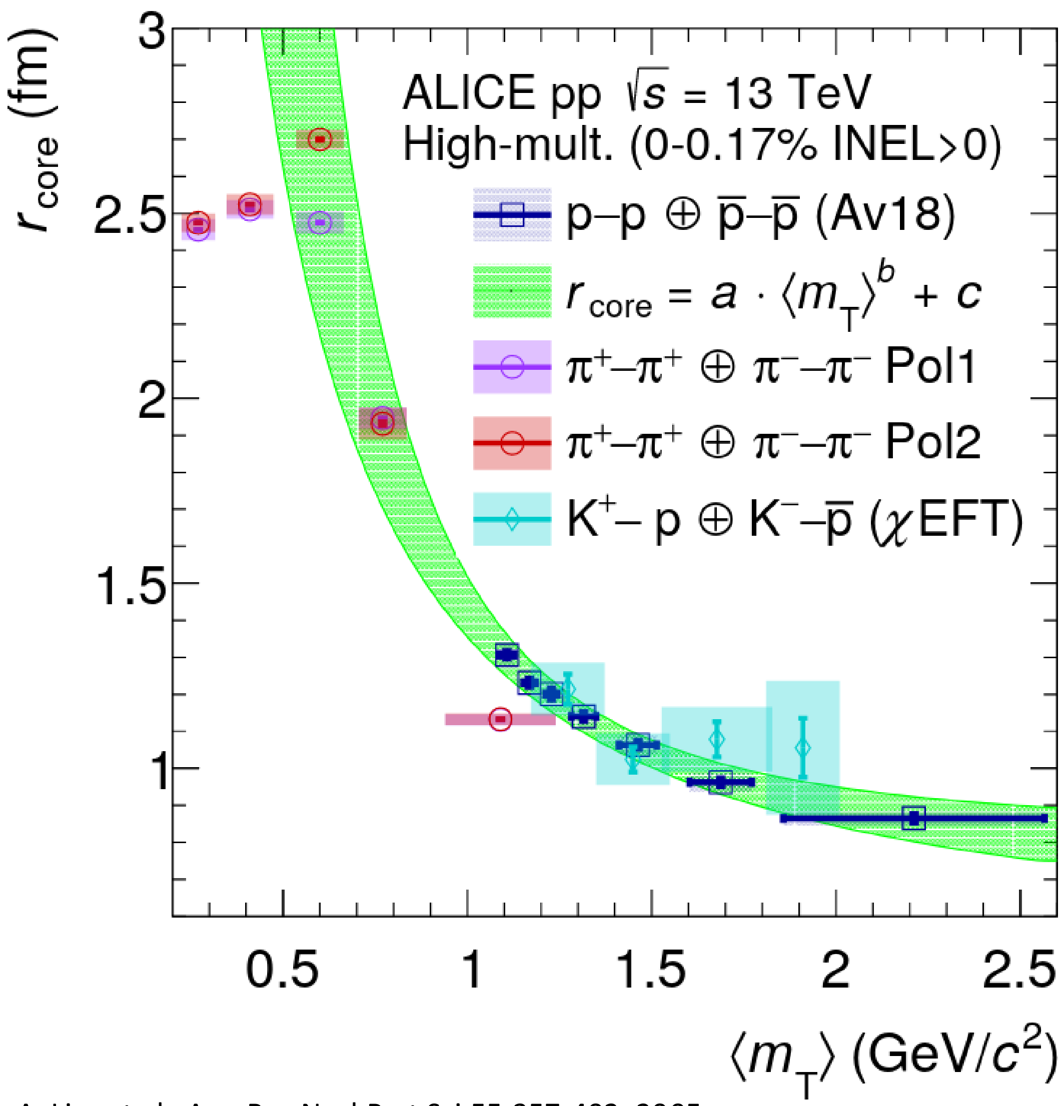
Georgios Mantzaridis

PAN-AMERICAN FEW-BODY PHYSICS BOOT CAMP: FOSTERING COLLABORATION

ECT* Trento

17.10.2025

Accessing hadronic interactions with femtoscopy

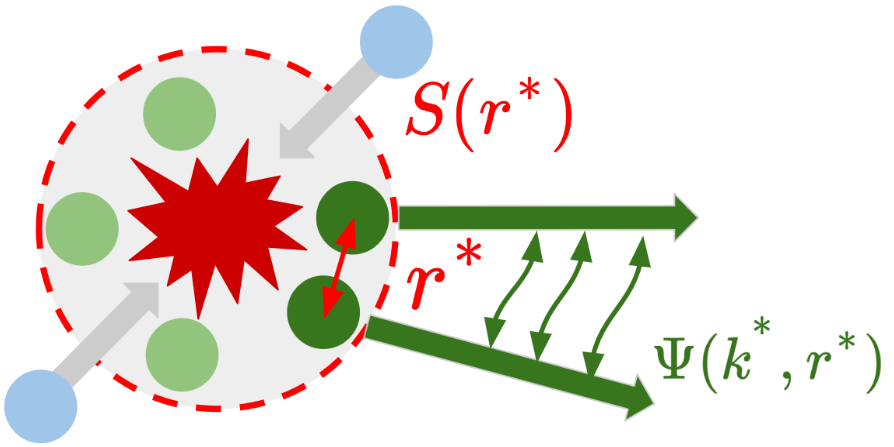


M. A. Lisa et al., Ann.Rev.Nucl.Part.Sci.55:357-402, 2005

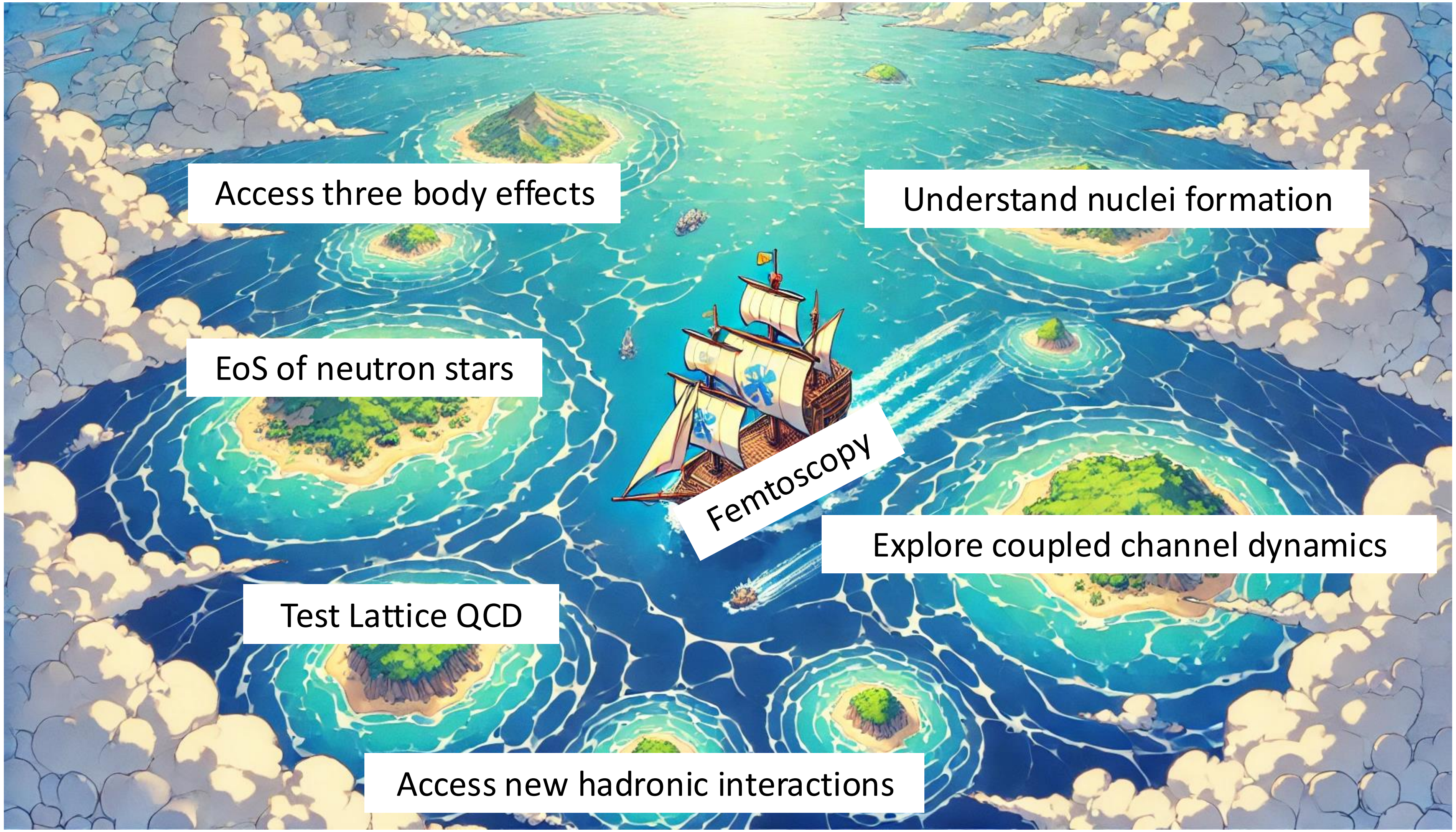
$$C(k^*) = \mathcal{N}\frac{N_{\mathrm{SE}}(k^*)}{N_{\mathrm{ME}}(k^*)} = \int S(r^*)\,|\psi(r^*,k^*)|^2\, d^3r \xrightarrow{k^*\to\infty} 1$$

Workflow for accessing interaction:

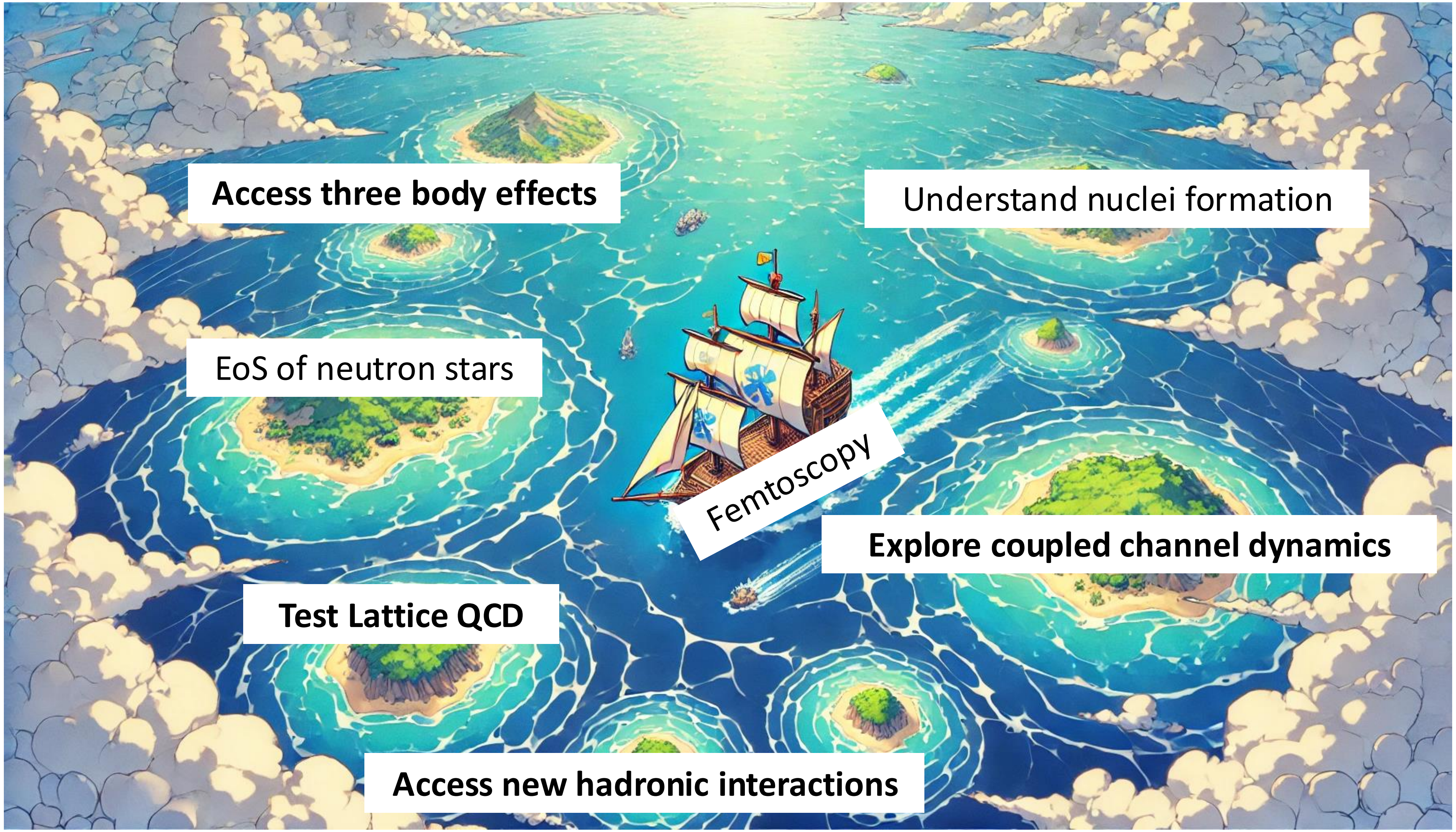
- Measure correlation function $C(k^*)$
- Fix source $S(r^*)$
- Study interaction $\psi(r^*,k^*)$



What can be studied with femtoscopy



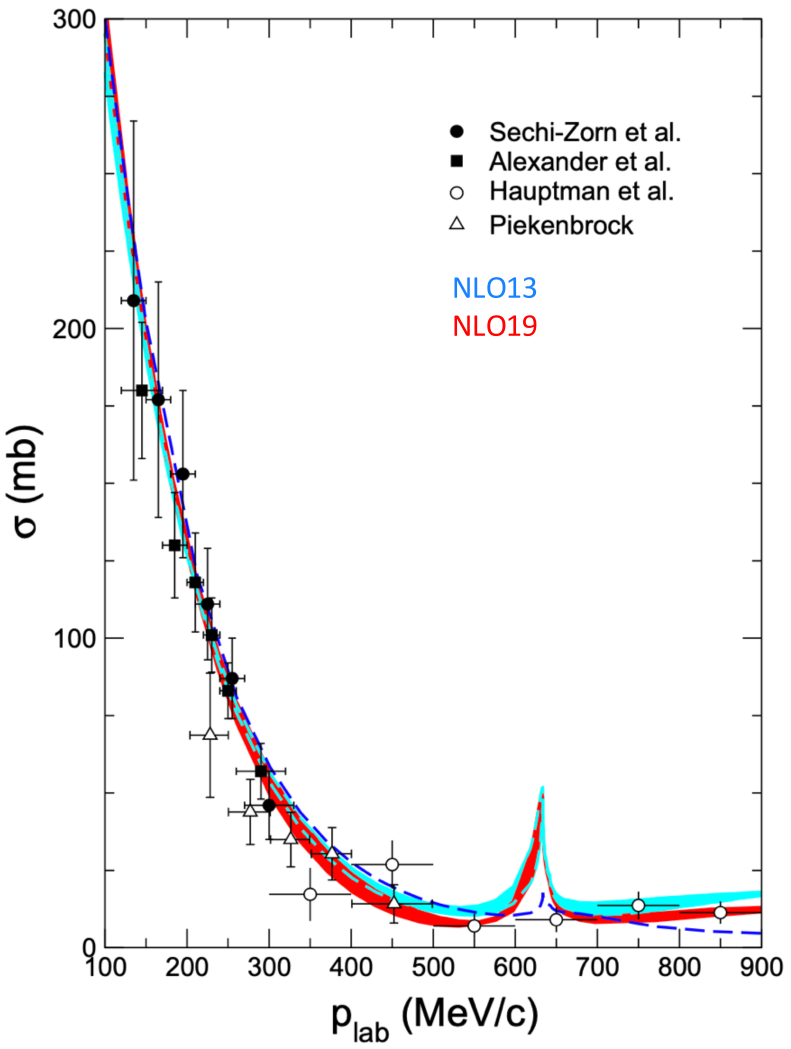
What can be studied with femtoscopy



The ΛN interaction with χEFT

- χEFT constrained to scattering and hypernuclei data
  - ➔ Difficult reach to low momenta
  - ➔ Insufficient precision to resolve the coupling cusp
- Coupling of ΛN to ΣN relevant for the EoS
- Different interactions equally reproduce the measurement
  - ➔ Different implications for 3-body interactions
  - ➔ More differential data necessary

➔ **Precise knowledge of two and three body forces in the ΛN and ΣN system necessary for the EoS**

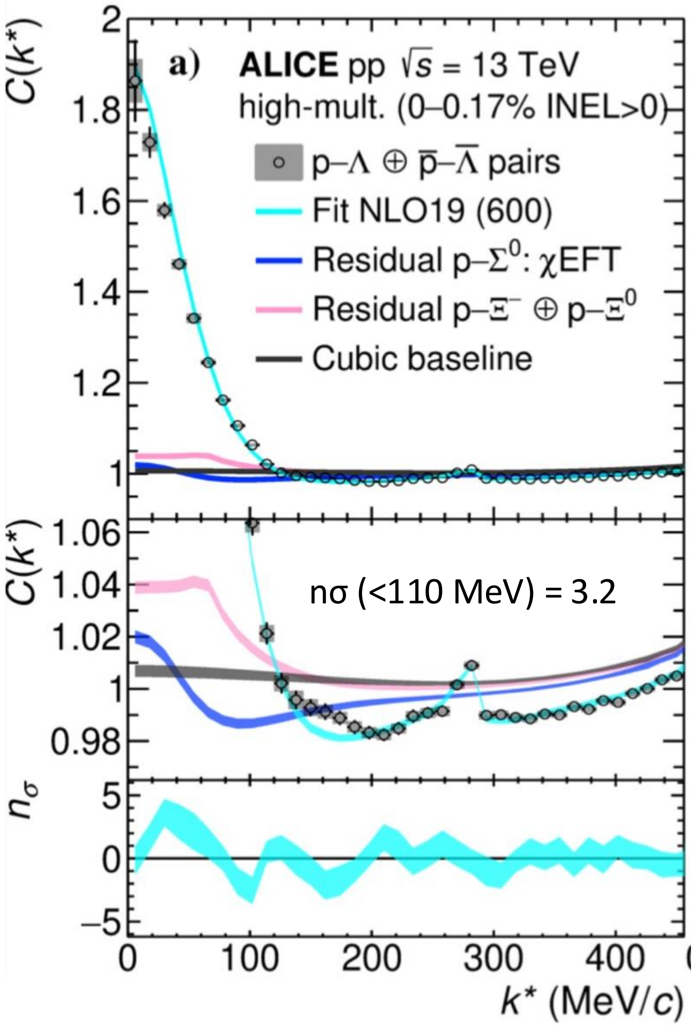


J.Haidenbauer, U. Meiβner, Eur.Phys.J.A 56 (2020)

NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)
NLO19: J.Haidenbauer, U. Meiβner, Eur.Phys.J.A 56 (2020)

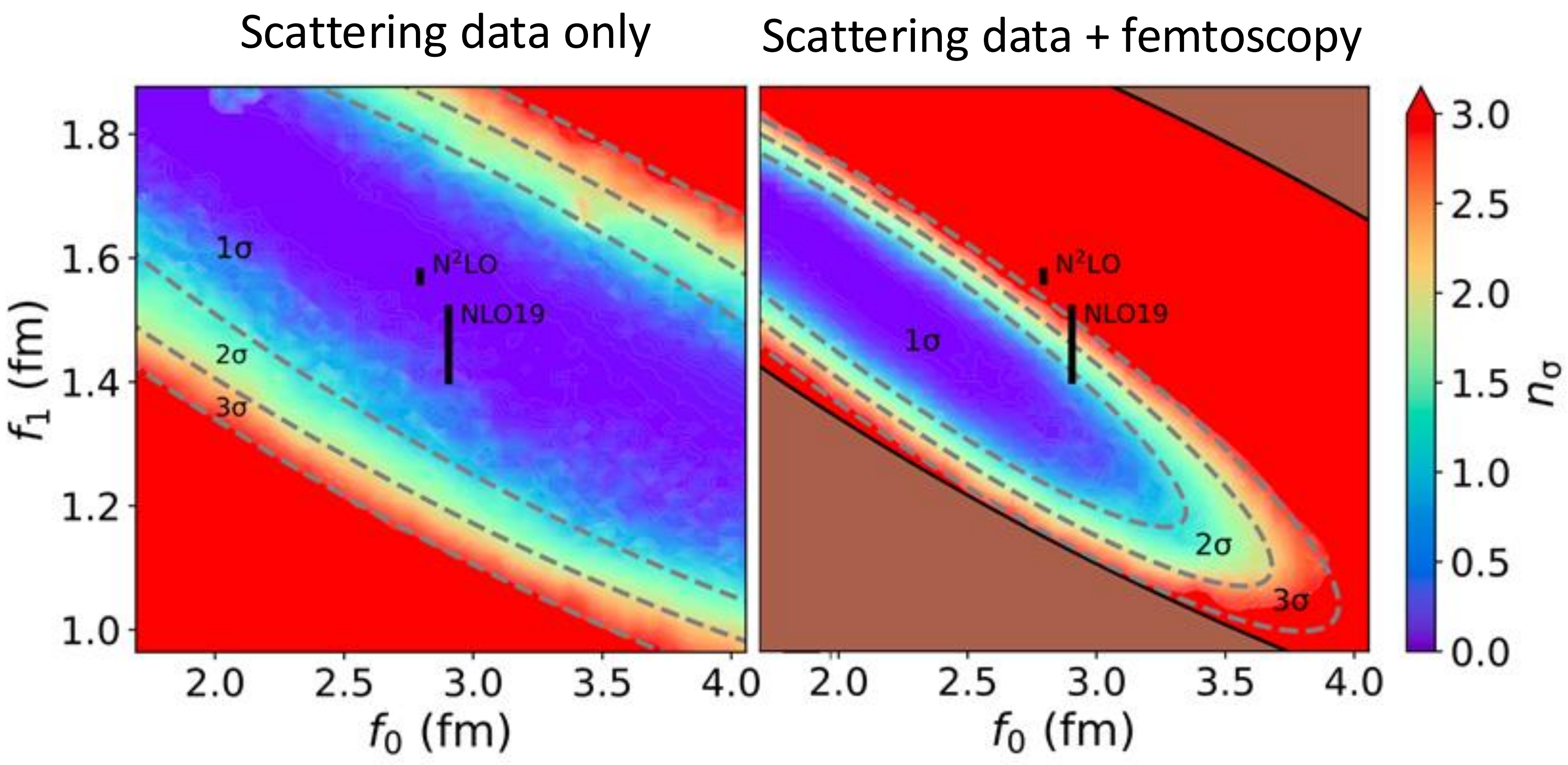
The ΛN interaction with femtoscopy

- Extended momentum range to k*≈10 MeV/*c*
- Good resolution in the cusp
- Sensitivity to different models of the ΛN interaction
  - → Best agreement with NLO19
- Some tension with the data still present
  - → Weaker p-Λ interaction?
  - → Use femtoscopy measurement to fit interaction parameters



ALICE Collaboration, Phys. Lett. B 833, 137272 (2022)

Using femtoscopic data for potential fits



- New limits for the scattering lengths:

$$f_1 \approx 2.2\text{fm} - 0.3 f_0 (\pm 0.1\text{fm})$$

➔ f_0 > 3.5 fm excluded

➔ f_0 < 2 fm: Attractive 3 body forces needed

Use new scattering length to…

- Constrain LECs in χEFT

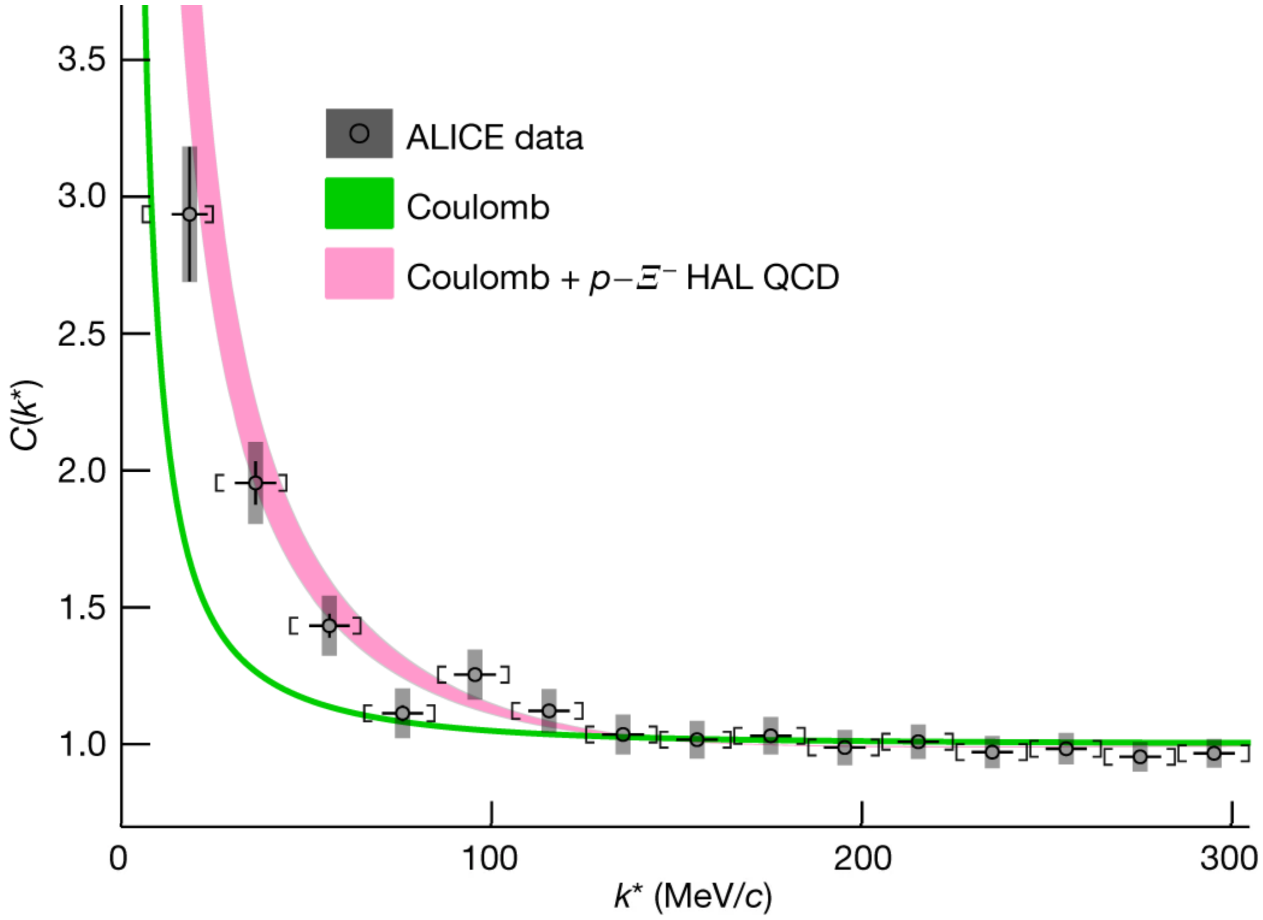
D. L. Mihaylov, J. Haidenbauer, V. Mantovani Sarti, arXiv:2312.16970

Test Lattice QCD calculations

	|S| = 0	|S| = 1	|S| = 2	|S| = 3
		Theory		
Lattice QCD				
		Experiment		
Scattering Experiments				???
Hypernuclei Experiments				
Femtoscopy	How can femtoscopy contribute?			

p-Ξ⁻ interaction with femtoscopy

- Coulomb only assumption: Missing attractive interaction to explain the data
- Good agreement using Lattice QCD potential



ALICE, Nature 588, pages 232–238 (2020)
T. Iritani et al. (HAL QCD Coll.) Phys. Lett. B792 (2019) 284

p-Ξ⁻ interaction with femtoscopy

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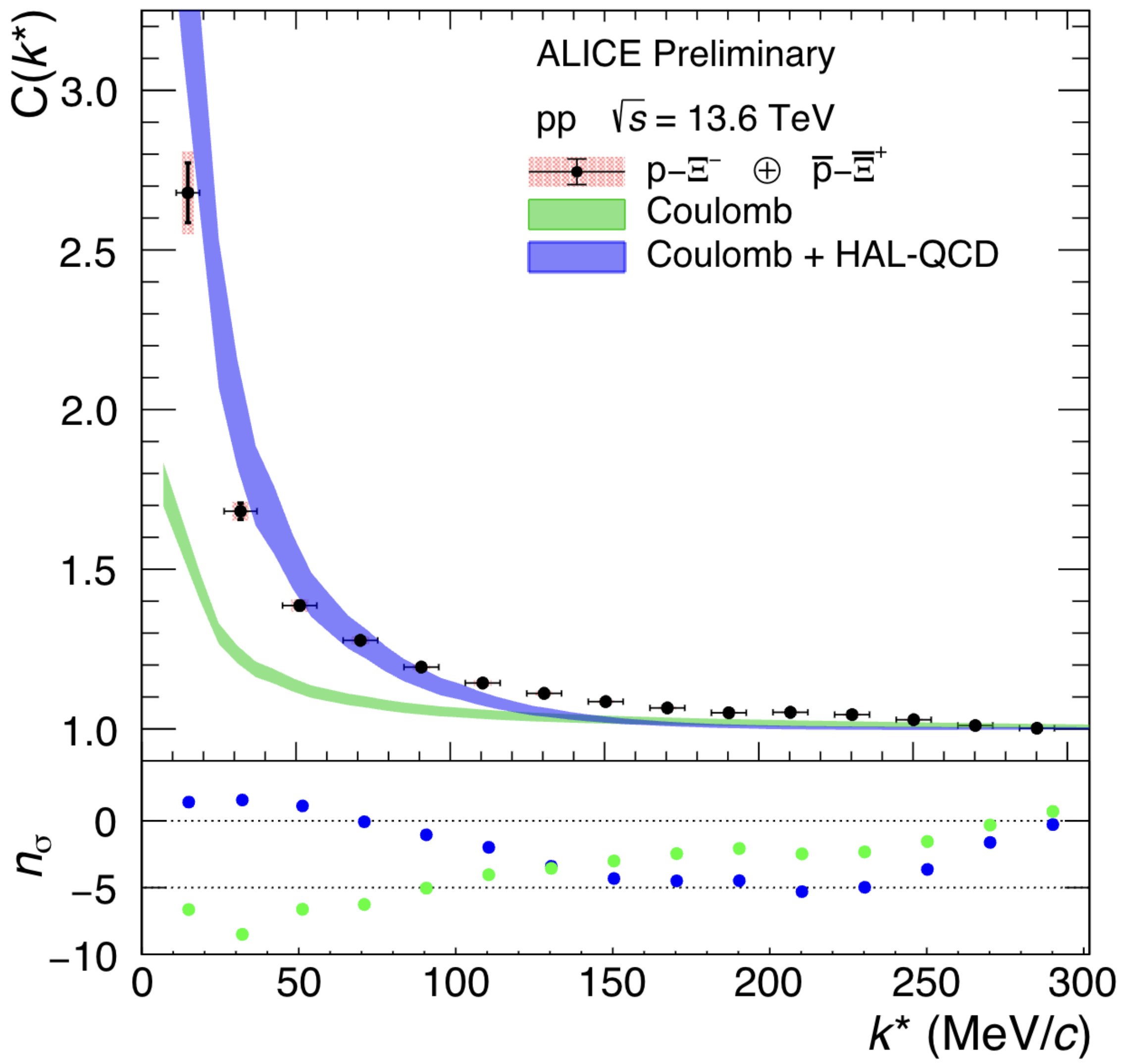
- Huge gain in statistics (~ x20) with Run 3 data



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p-Ξ⁻ interaction with femtoscopy

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- Good agreement using Lattice QCD potential
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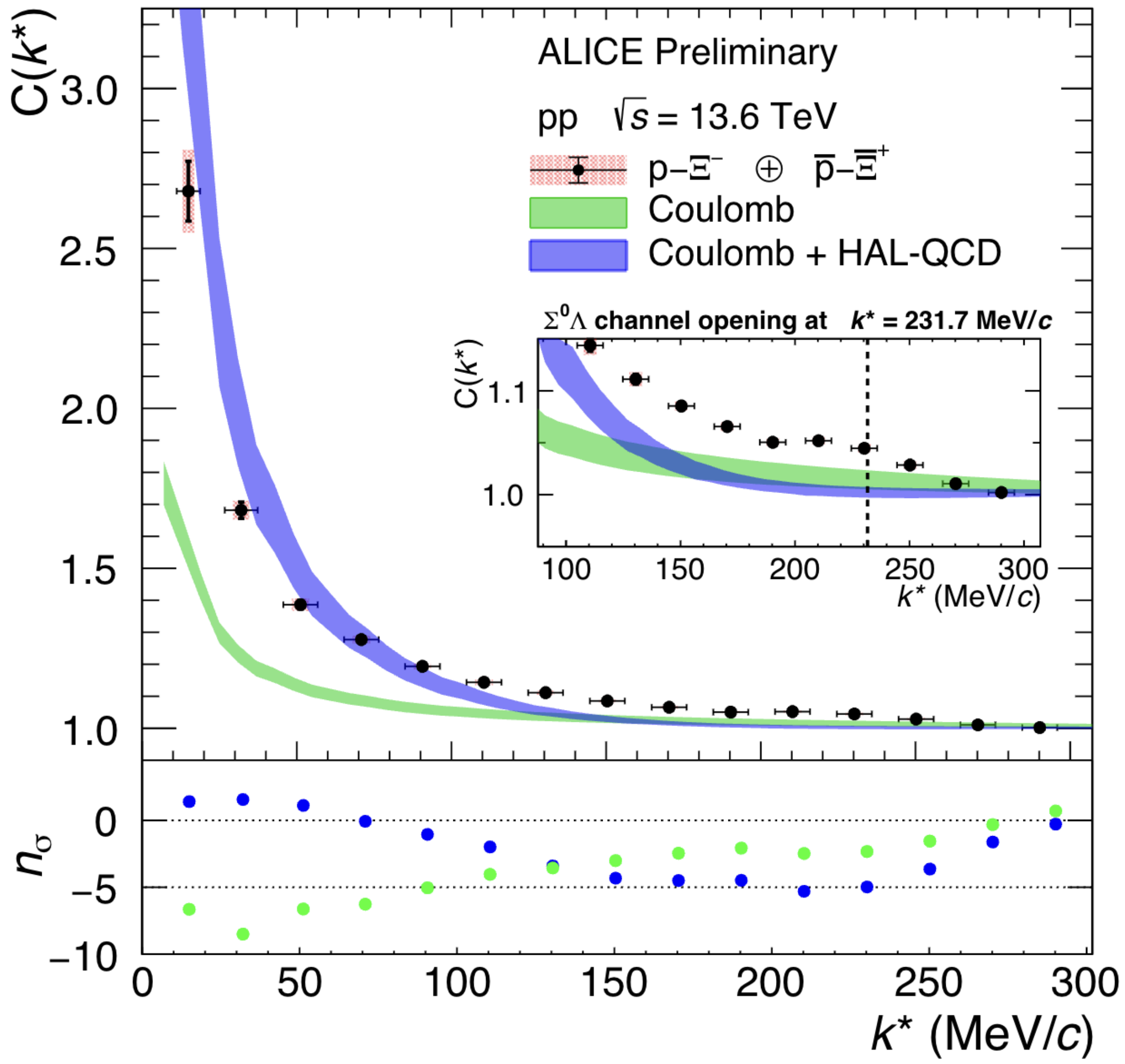
→ Signal visible at the $\Sigma^0\Lambda$ channel opening

→ $\Sigma^0\Lambda$ coupled channel not included in the HAL QCD potentials



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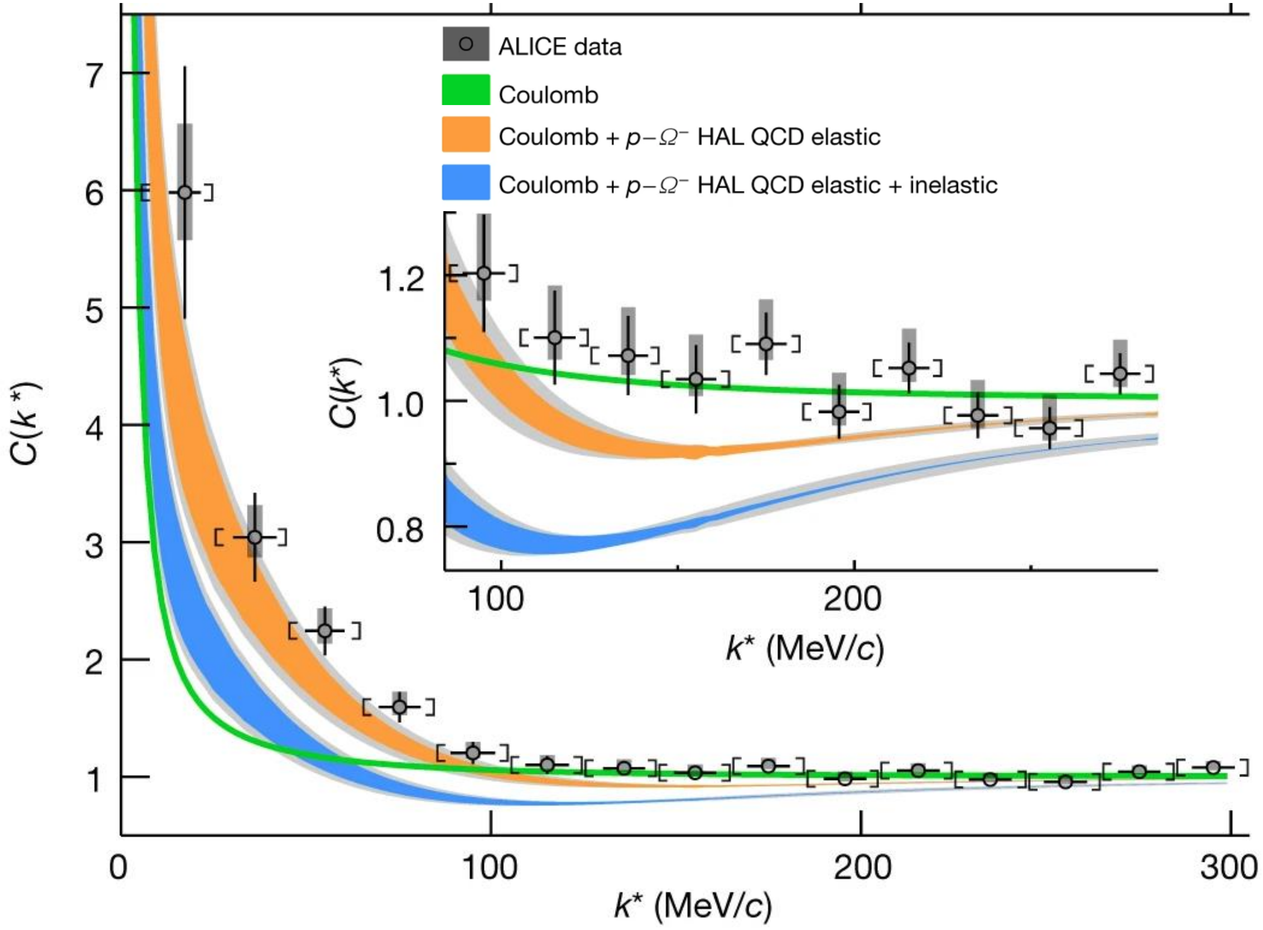
p-Ω⁻ interaction with femtoscopy

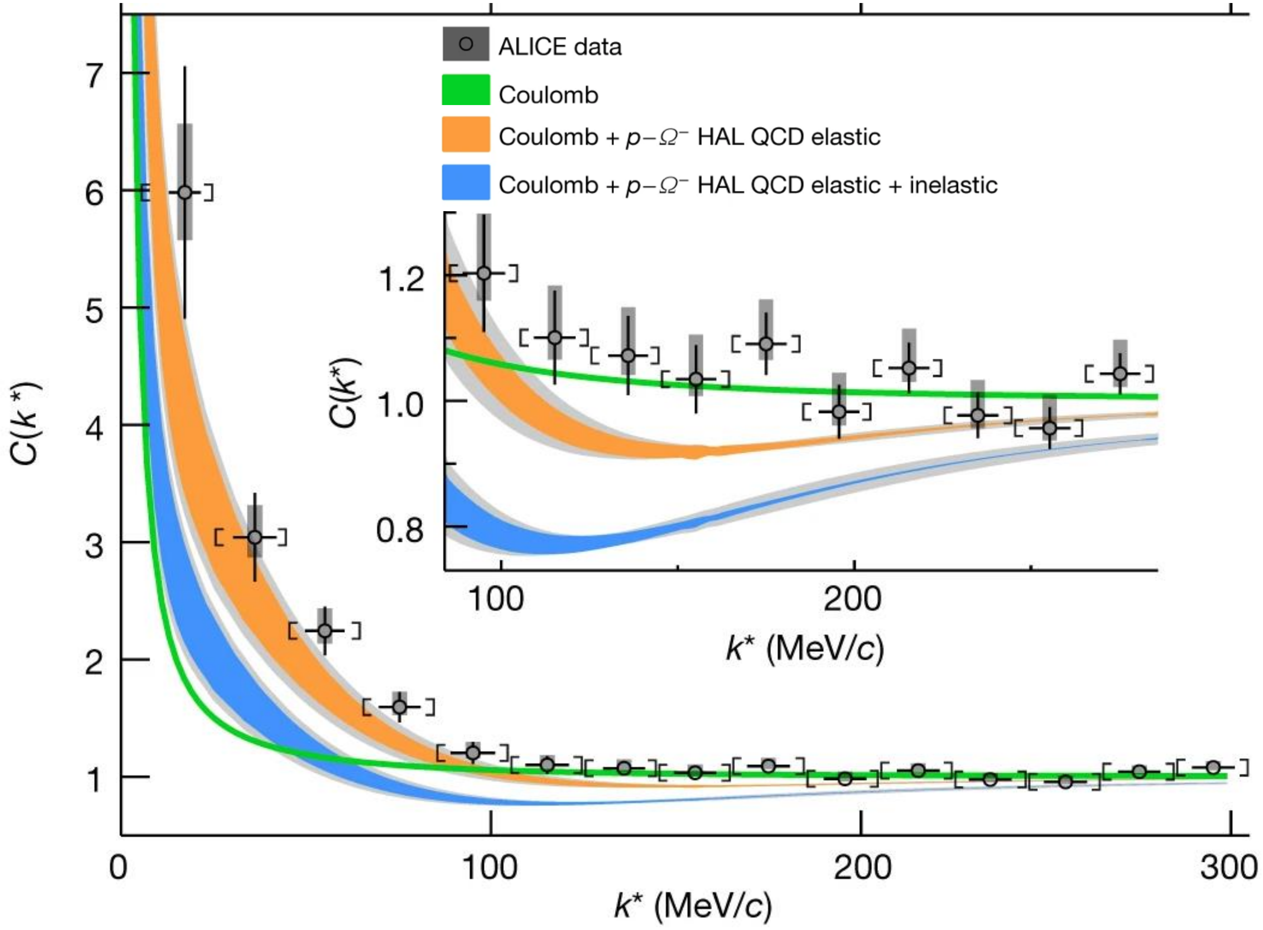
- $^5S_2$ state: Fully calculated
- $^3S_1$ state: Unkown coupling to $\Lambda\Xi^-$
  a) Negligible coupling
  b) Dominant coupling



ALICE, Nature 588, pages 232–238 (2020)
T. Iritani et al. (HAL QCD Coll.) Phys. Lett. B792 (2019) 284

p-Ω^- interaction with femtoscopy

- $^5S_2$ state: Fully calculated
- $^3S_1$ state: Unkown coupling to $\Lambda\Xi^-$
  a) Negligible coupling
  b) Dominant coupling
- Higher accuracy in the data then in the theoretical calculation
- Coulomb only assumption: Missing attractive interaction
- Best agreement: Negligible coupling to $\Lambda\Xi^-$
- Prediction of a bound state with binding energy 2.5 MeV
  ➔ not reproduced by the data



ALICE, Nature 588, pages 232–238 (2020)
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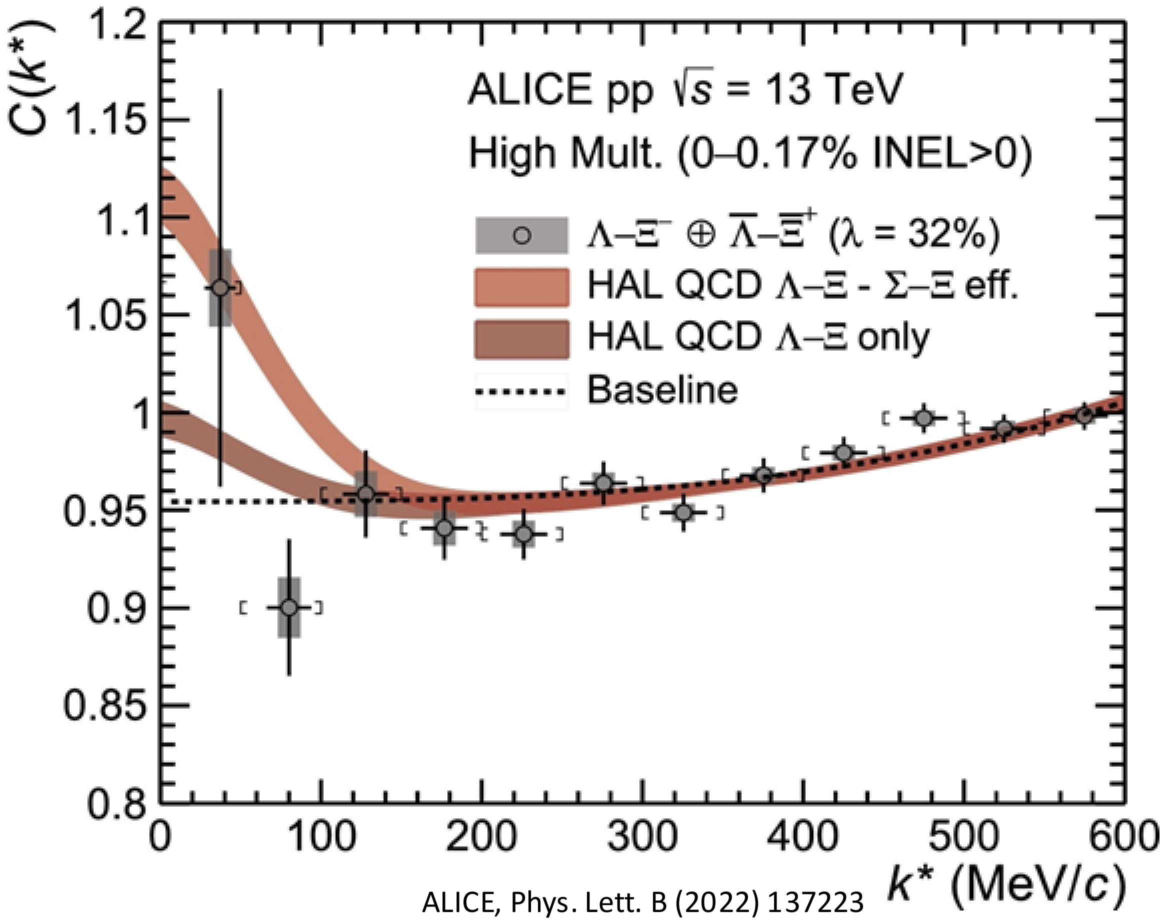
Λ-Ξ^- interaction with femtoscopy

- Measured correlation function compatible with the baseline (nσ = 0.76)
- Indication of a shallow ΛΞ^- interaction
- No cusp visible
  - ➔ Negligible coupling to p-Ω^-
- Compatible with Lattice QCD calculations
- Sizable statistical uncertainties

➔ **Run 3 for better statistical precision**

# pairs (k*< 200 MeV/c):	$5.0 \cdot 10^3$
$\lambda_{genuine}$:	32 %

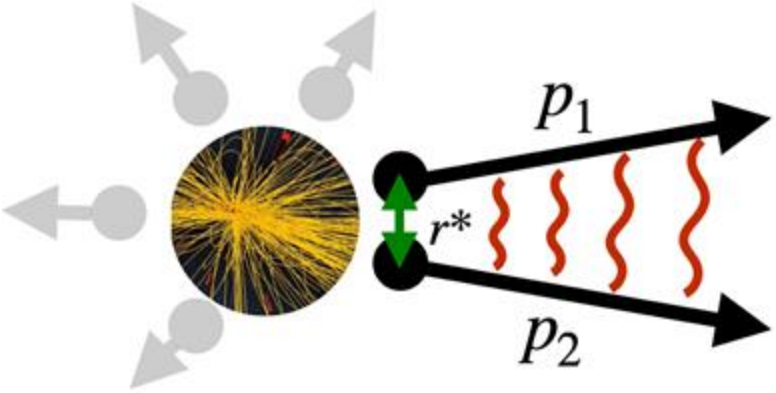


ALICE, Phys. Lett. B (2022) 137223

Three body correlations with femtoscopy

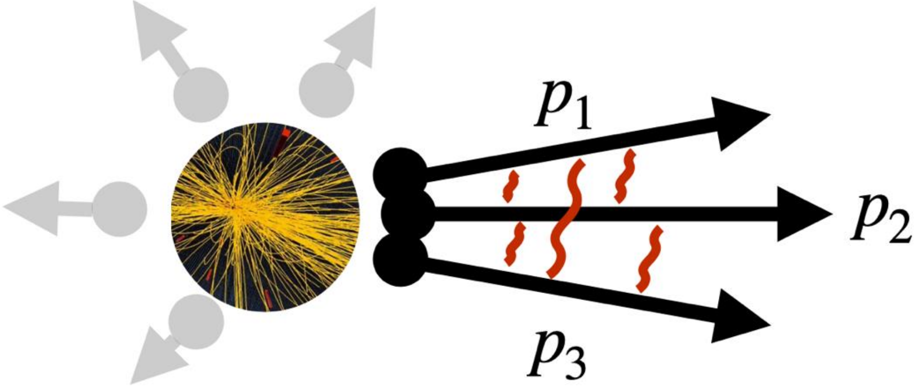
(a) Indirect Access

Measure correlations including e.g. the deuteron



(b) Direct Access

Extend femtoscopy formalism to 3-body systems



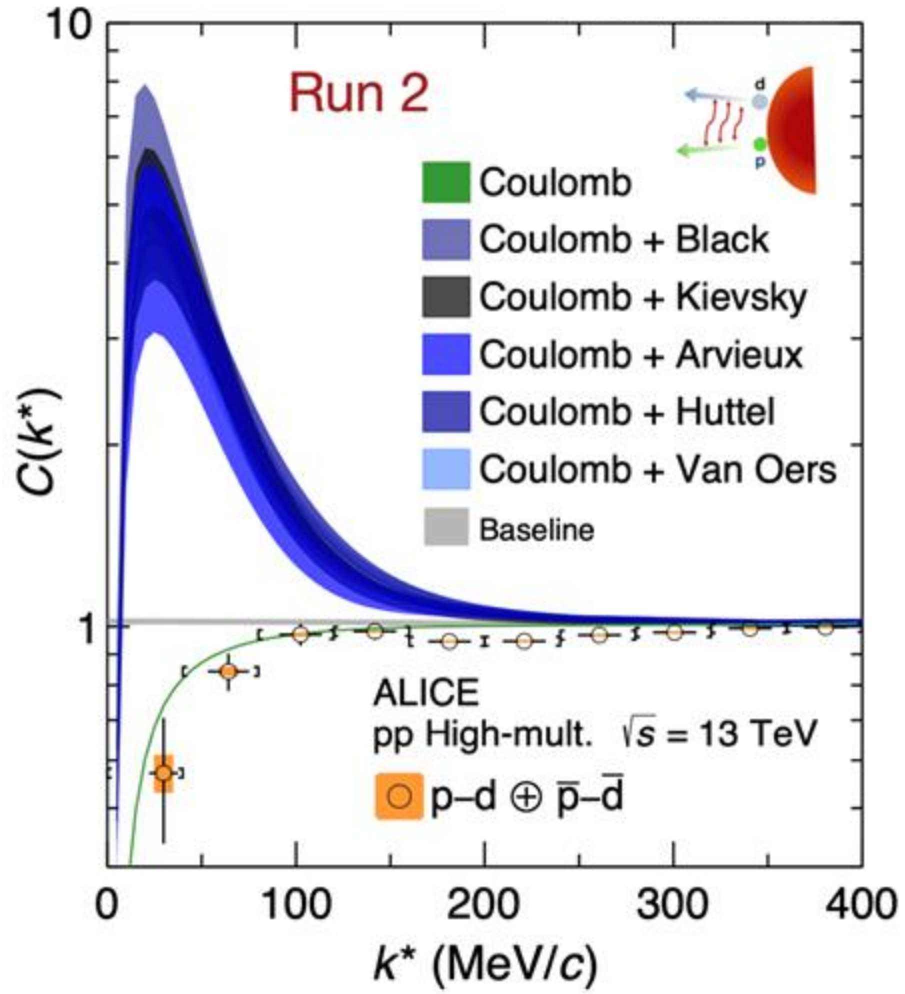
Indirect access of three-body correlations

Proton-deuteron correlation function

- Modelling: Lednický-Lyuboshits approach (effective two body system)
- Input: Available scattering data
- Source size: Extracted with from the common m_T scaling

➔ $r_{\mathrm{eff}}^{\mathrm{pd}} = 1.08^{+0.006}_{-0.006}\,\mathrm{fm}$

- Bad agreement with the data
  ➔ Inclusion of Pauli Repulsion effects necessary!



ALICE, arXiv:2308.16120

Indirect access of three-body correlations

Proton-deuteron correlation with full 3 body calculation

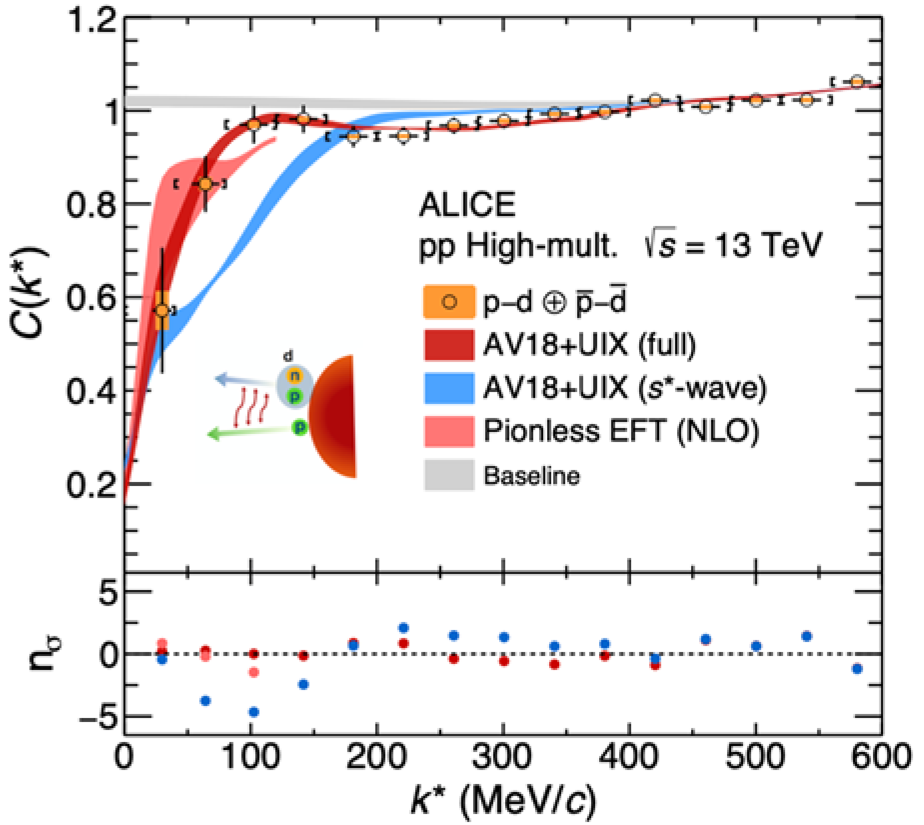
$$C_{pd}(k^*) = \frac{1}{16A_d}\int S(\rho, R_M)|\Psi(k^*,\rho)|^2 \rho^5 d\rho d\Omega$$

Wavefunction:

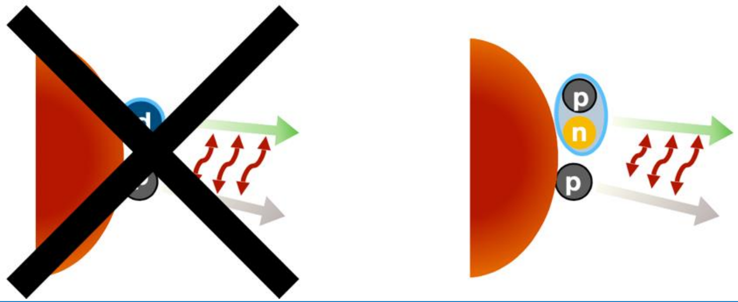
➢Hyperspherical harmonic (HH) approach with Argonne V18 (AV18) + Urbana IX (UIX) potentials

➢Pionless EFT NLO

➔Sensitivity to three-body effects!



ALICE, arXiv:2308.16120



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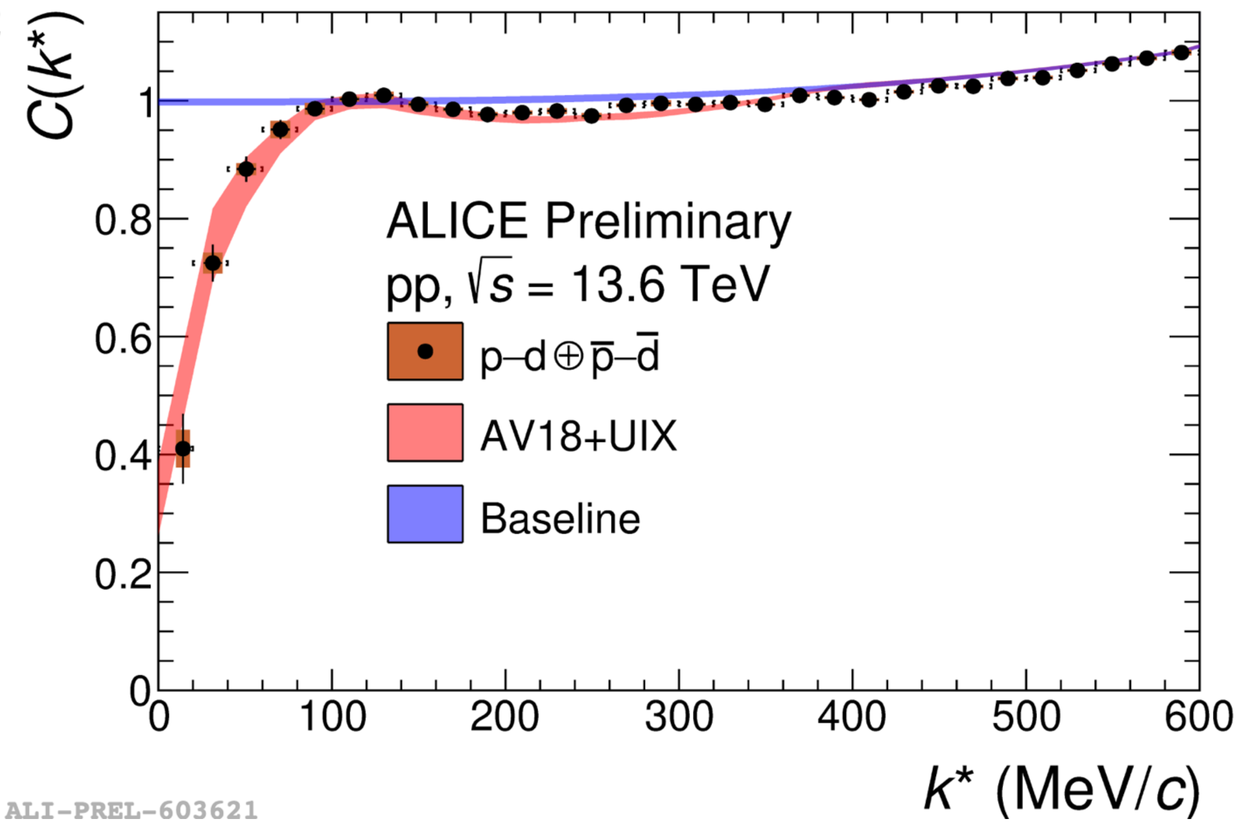
- ➢Pionless EFT NLO

➔Sensitivity to three-body effects!

➔Run 2 precision not sufficient for genuine there-body interaction

➔5% accuracy in the data needed

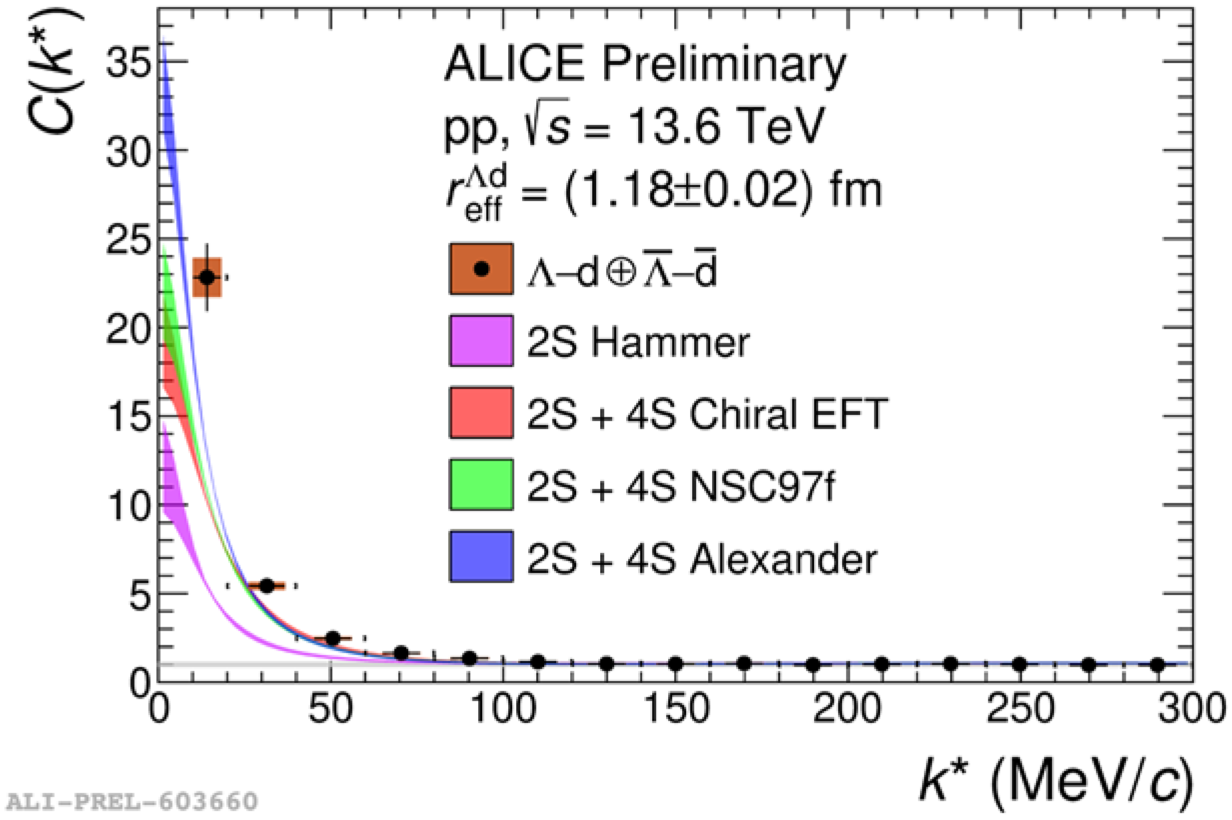
Run 3 Preliminary



Preliminary Result for Λ-d

- Modelled as an effective two-body system employing Lednický-Lyuboshits approach
- Scattering parameters available in the literature do not describe the data well
- Next steps:
  - Extract Λ-d scattering parameters
  - Model with 3-body calculations
- study three-body force effects

Run 3 Preliminary



Direct access of the three-body correlations

(a) Indirect Access

Measure correlations including e.g. the deuteron

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

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

(b) Direct Access

Direct access of the three-body correlations

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(b) Direct Access

Extend femtoscopy formalism to 3-body systems

$$Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - q_{ki}^2}$$

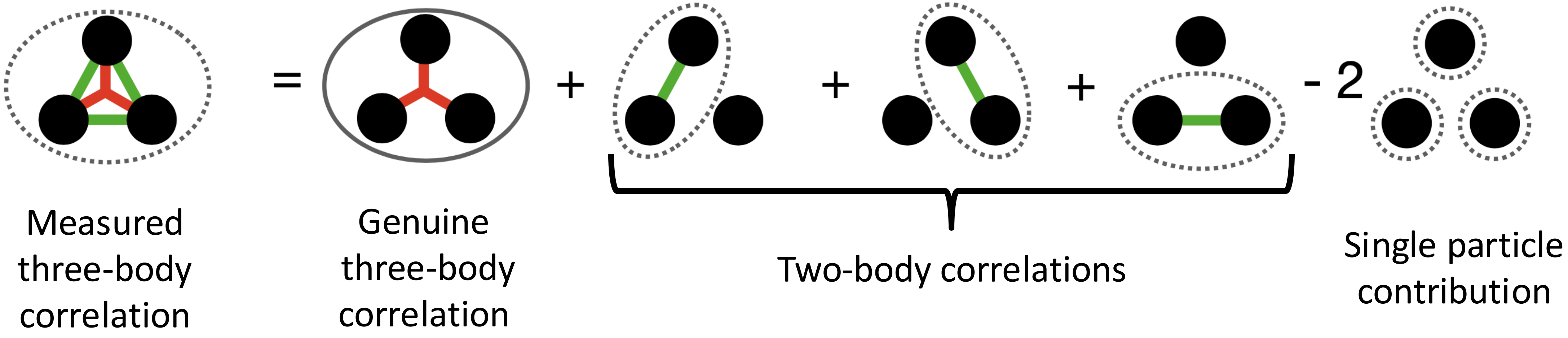
$$C(Q_3) = \mathcal{N} \frac{N_{\mathrm{same}}(Q_3)}{N_{\mathrm{mixed}}(Q_3)}$$

Direct access of the three-body correlations

- Theoretical correlation function:

$$C_3(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) = \iiint S_3(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3) |\Psi(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, \mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)|^2 d^3\mathbf{r}_1 d^3\mathbf{r}_2 d^3\mathbf{r}_3$$

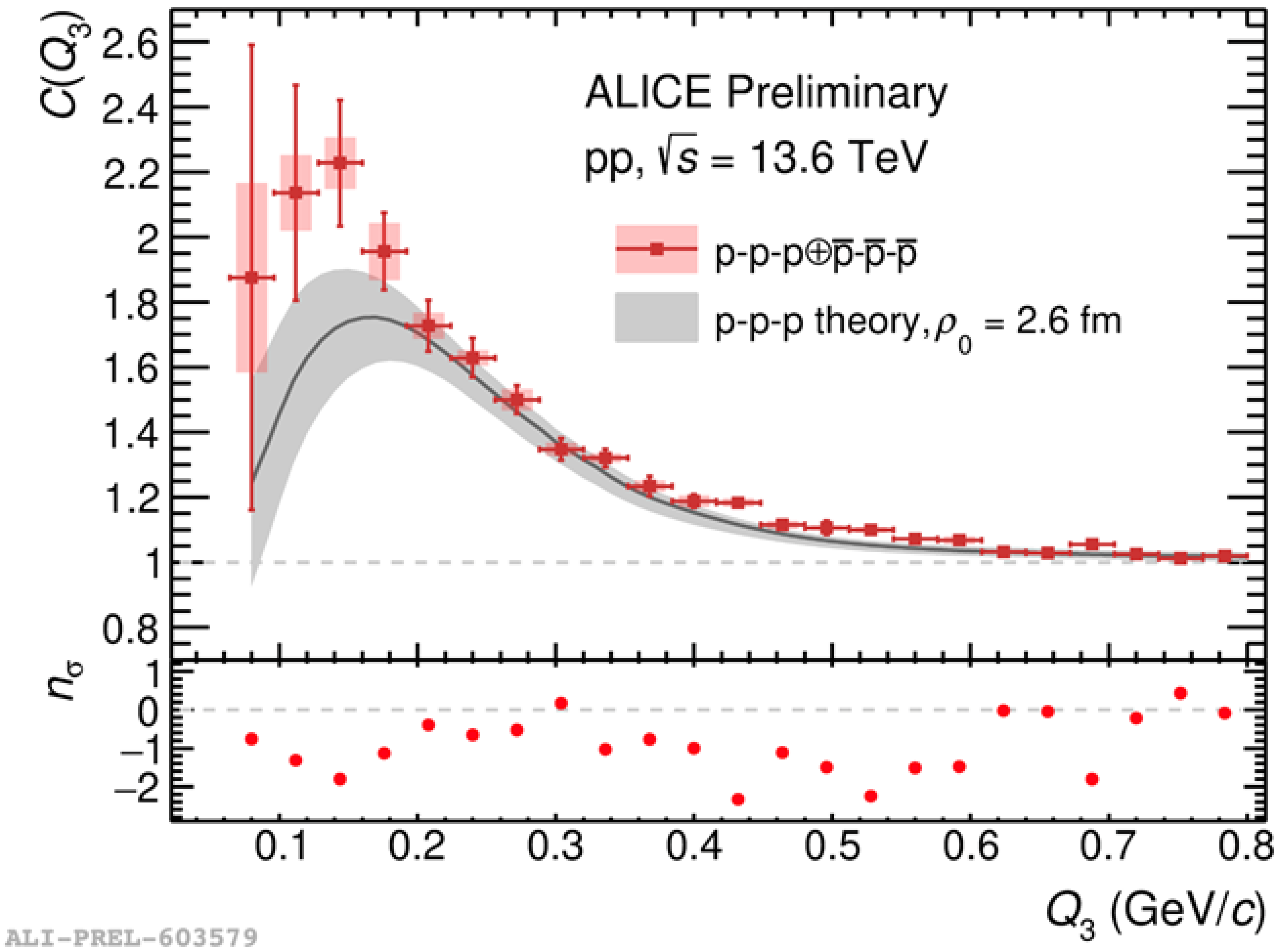
- Isolate the genuine three body correlations with Kubo's cumulant method:



R. Kubo, J. Phys. Soc. Jpn. 17, 1100-1120 (1962)
Del Grande, L. Šerkšnytė et al. EPJC 82 (2022) 244

Direct access of p-p-p correlations

- Latest Run 3 result obtained with data from 2024
- Theoretical modeling: Wavefunction from Hyperspherical Harmonics[1]
  - AV18
  - Three body Coulomb
  - Quantum Statistics
- Agreement with data: 1.67σ
- Contribution from three body UIX potential negligable

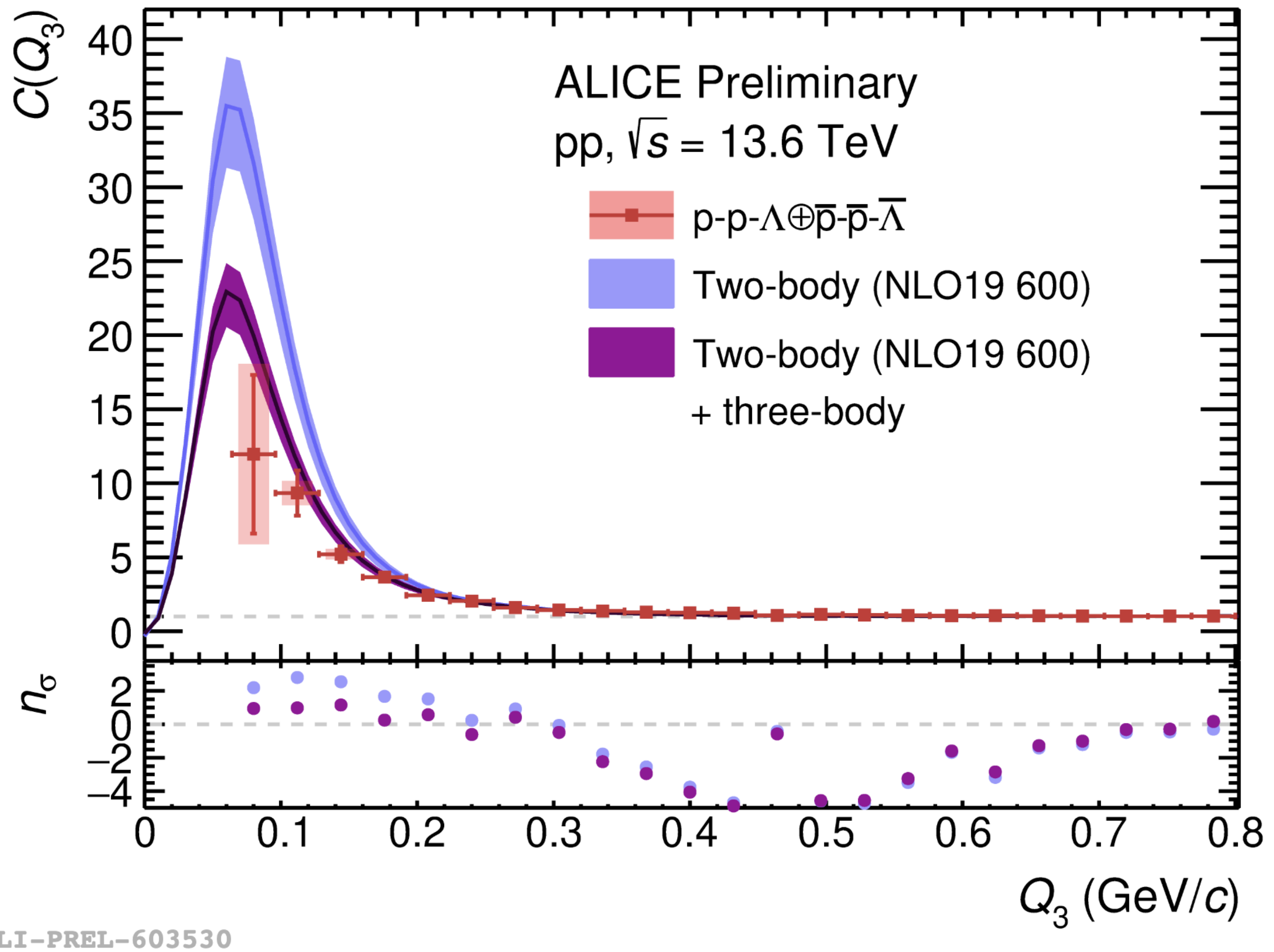


[1] A. Kievsky, LS, et al., Phys.Rev.C 109 (2024) 3, 034006

Direct access of p-p-Λ correlations

- Two body interaction only:
  - Scattering parameters based on NLO19 600
  - 3.7σ compatability up to Q_3=0.2 GeV/c
- Including three body interactions:
  - WF via hyperspherical harmonics
  - 0.7σ compatability up to Q_3=0.2 GeV/c
  - Preliminary calculations: Inclusion of higher partial waves missing

➔ Sensitivity to the three body p-p-Λ repulsive interaction



Summary

Access coupled channel dynamics

- NΛ and NΣ coupled channel dynamics
- Refitting of χEFT using femtoscopic data

Test Lattice QCD

- Comparison of p-Ω and ΛΞ interactions with LQCD calculations
- Signal at Σ0Λ channel opening which is not included in the LQCD potential

Access three body effects

- Indirectly via p-d correlations
- Directly via p-p-p and p-p-Λ correlations

Backup

The Lednický-Lyuboshits model

Analytical approach to model CF for strong final state interactions with the scattering amplitude f_0

$$C\left(k^*\right)_{\text{Lednicky}} = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f\left(k^*\right)^S}{r_0} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} r_0} \right) + \frac{2\Re f\left(k^*\right)^S}{\sqrt{\pi} r_0} F_1\left(2k^* r_0\right) - \frac{\Im f\left(k^*\right)^S}{r_0} F_2\left(2k^* r_0\right) \right]$$

d_0: effective range

f_0: scattering length

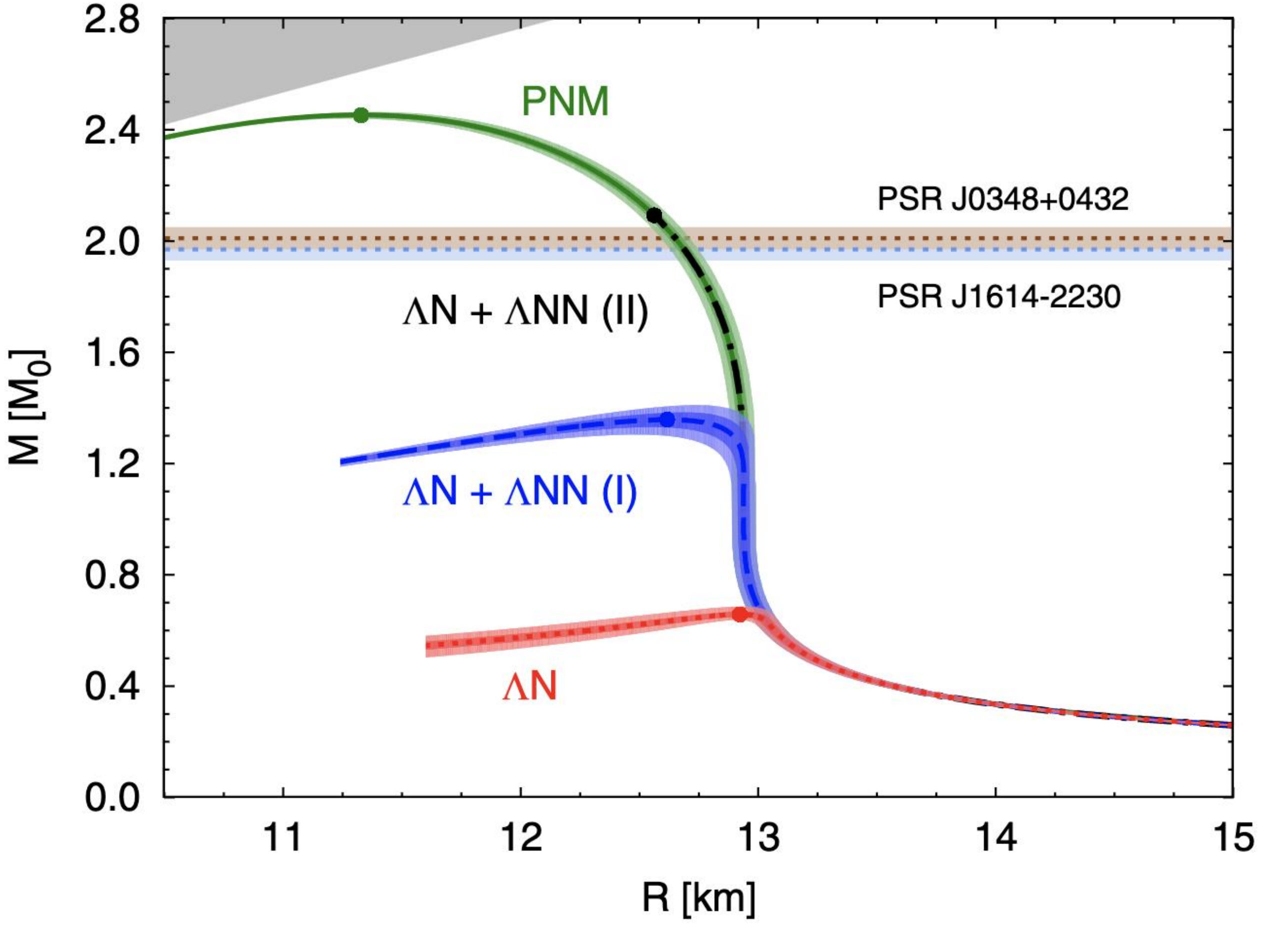
$$f\left(k^*\right) = \left(\frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - i k^* \right)^{-1}$$

EoS of neutron stars

- Large densities in neutron stars (up to $2\rho_0$)
  ➔ hyperons as new degrees of freedom expected

- EoS dependent on hyperon-nucleon interaction
  ➔ ΛN two-body effects
  ➔ ΛNN three-body effects

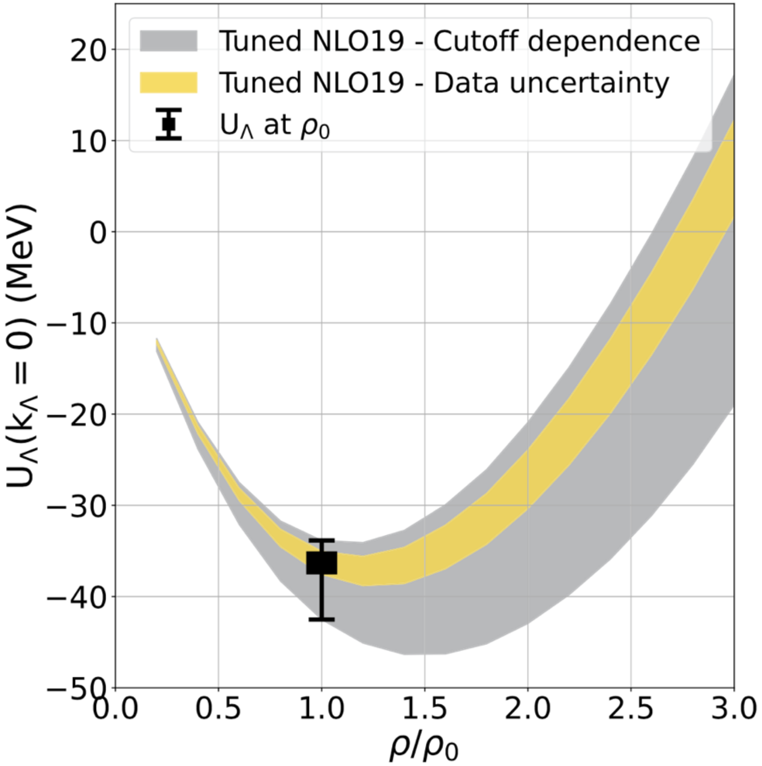
- Precise experimental measurements needed to disentangle two- and three body effects



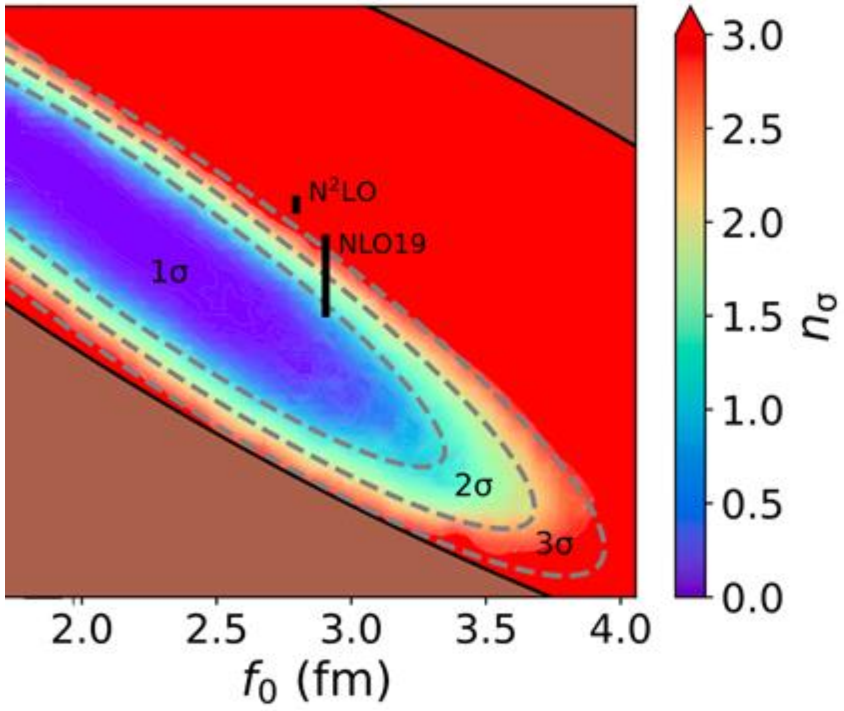
D. Lonardoni et al., PRL 114 (2015)

Using femtoscopic data for potential fits

In medium $U_\Lambda(\rho)$ potential



Scattering data + femtoscopy



D. L. Mihaylov, J. Haidenbauer, V. Mantovani Sarti, arXiv:2312.16970

- New limits for the scattering lengths:

$$f_1 \approx 2.2\mathrm{fm} - 0.3 f_0 (\pm 0.1\mathrm{fm})$$

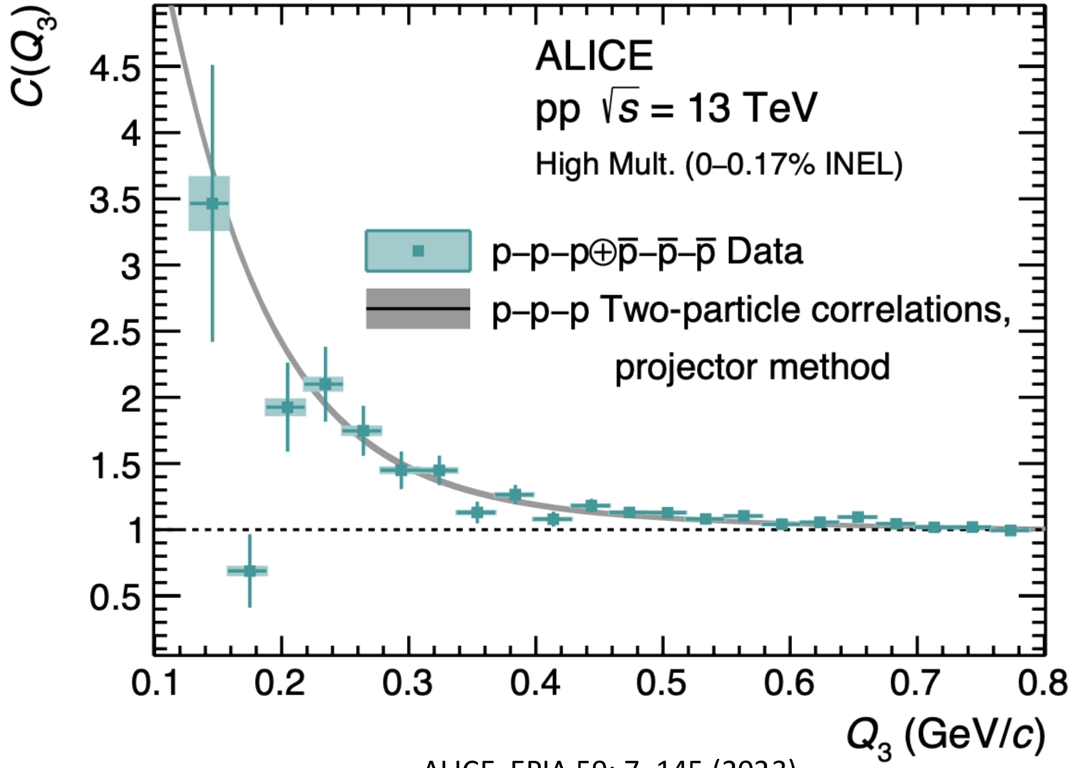
- ➔ f_0 > 3.5 fm excluded
- ➔ f_0 < 2 fm: Attractive 3 body forces needed

Use new scattering length to…

- Constrain LECs in χEFT
- Evaluate in medium Λ potential
- ➔ New $U_\Lambda(\rho_0)$ = -36 MeV (semi-empirical value at -30 MeV)
- ➔ Compatible with repulsive 3-body forces

Direct access of p-p-p correlations

- Deviation from lower order contribution: nσ = 6.7
- Theoretical predictions necessary to understand the origin of the deviation



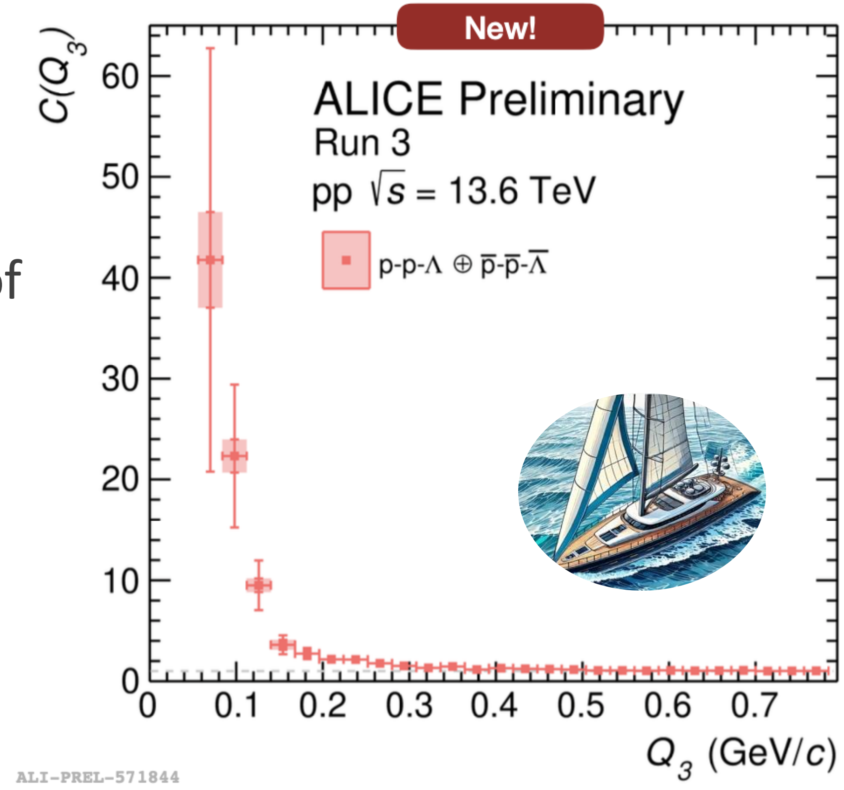
ALICE, EPJA 59; 7, 145 (2023)

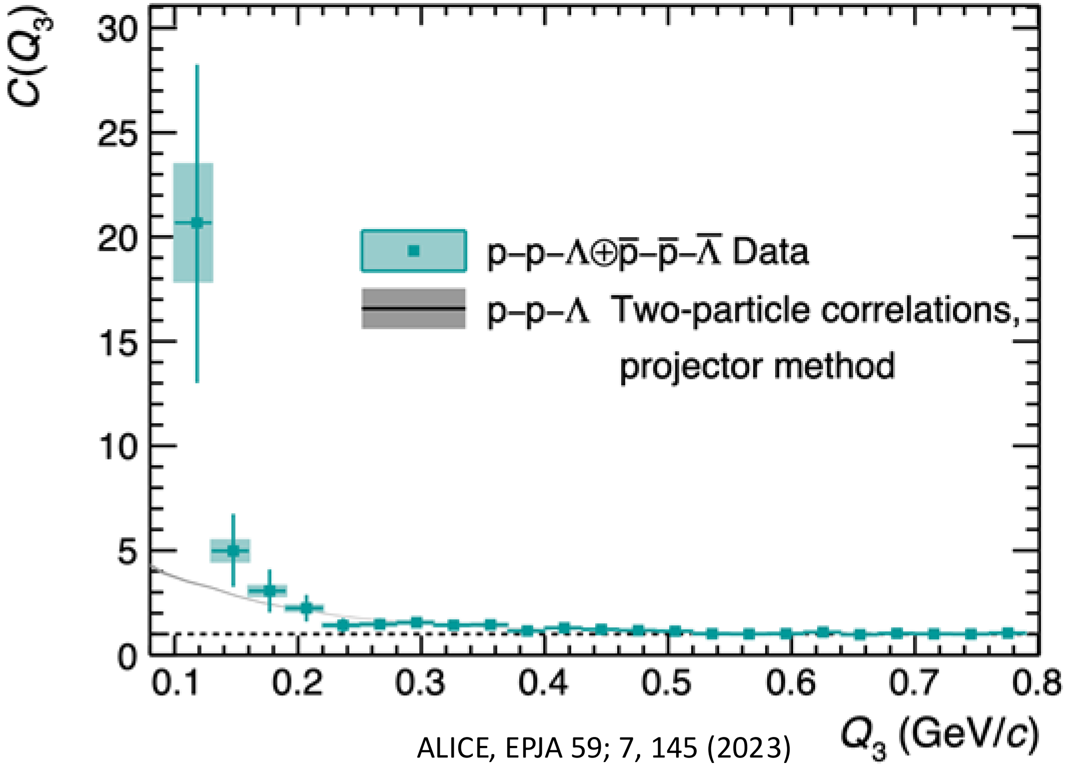
Direct access of p-p-Λ correlations

- Compatible with lower order contributions (but large statistical uncertainties)
- Awaiting first theoretical predictions to interpret the available and future data

First Run 3 Results:

- 150 times more statistcs by the end of Run
- First p-p-Λ calculations in preperation





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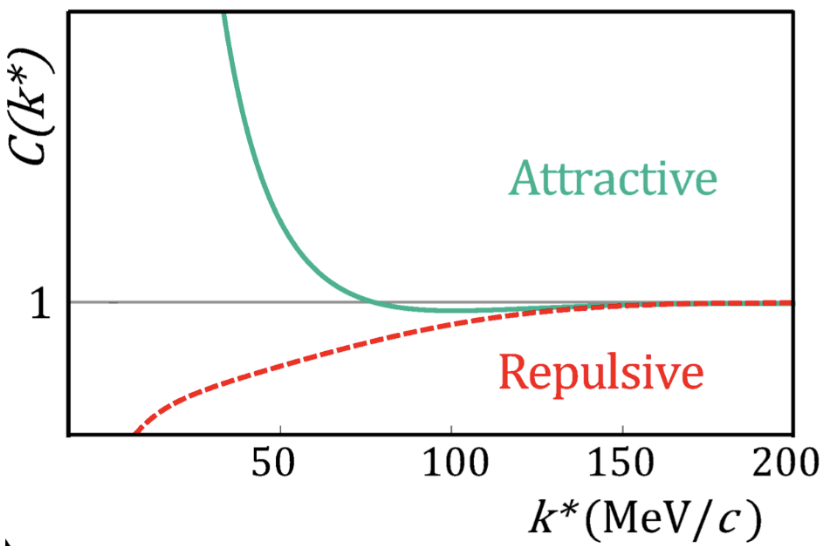
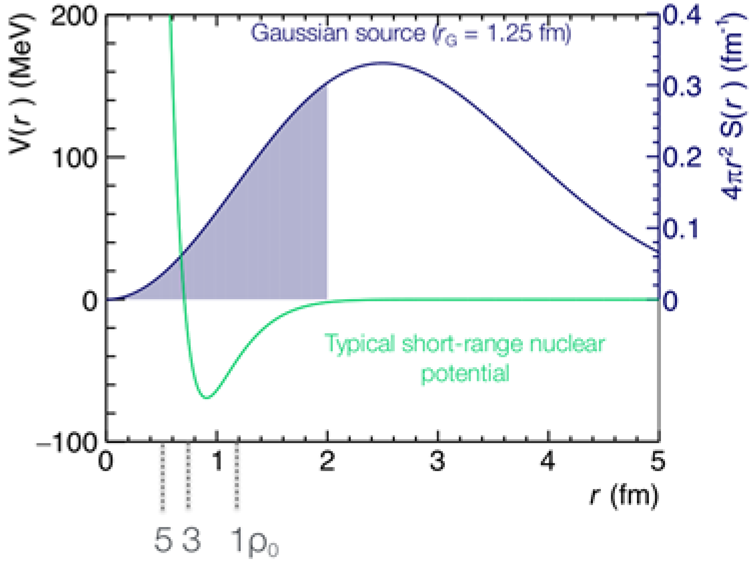
Correlation function





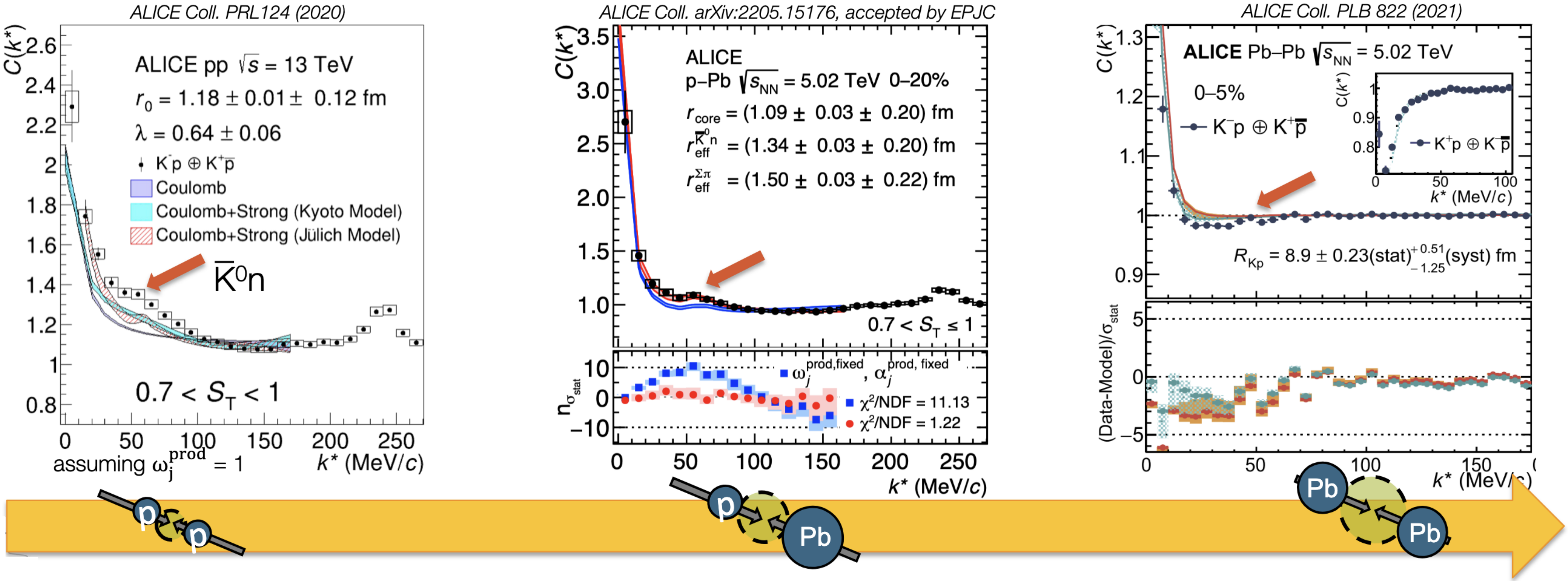
M. A. Lisa et al., Ann.Rev.Nucl.Part.Sci.55:357-402, 2005

Beyond strangeness: Charm femtoscopy

	$\|S\| = 0$	$\|S\| = 1$	$\|S\| = 2$	$\|S\| = 3$	$\|C\| \neq 0$
Theory					
Lattice QCD					
χEFT					
Experiment					
Scattering Experiments				???	
Hypernuclei Experiments					
Femtoscopy				ALICE, Nature 588 (2020) 232-238 ALICE, PLB (2022), 137223	

K^-p Femtoscopy

- Coupling to K^0n observed at k* ~ 60 MeV/c
- Interplay between coupling strength and collisions size



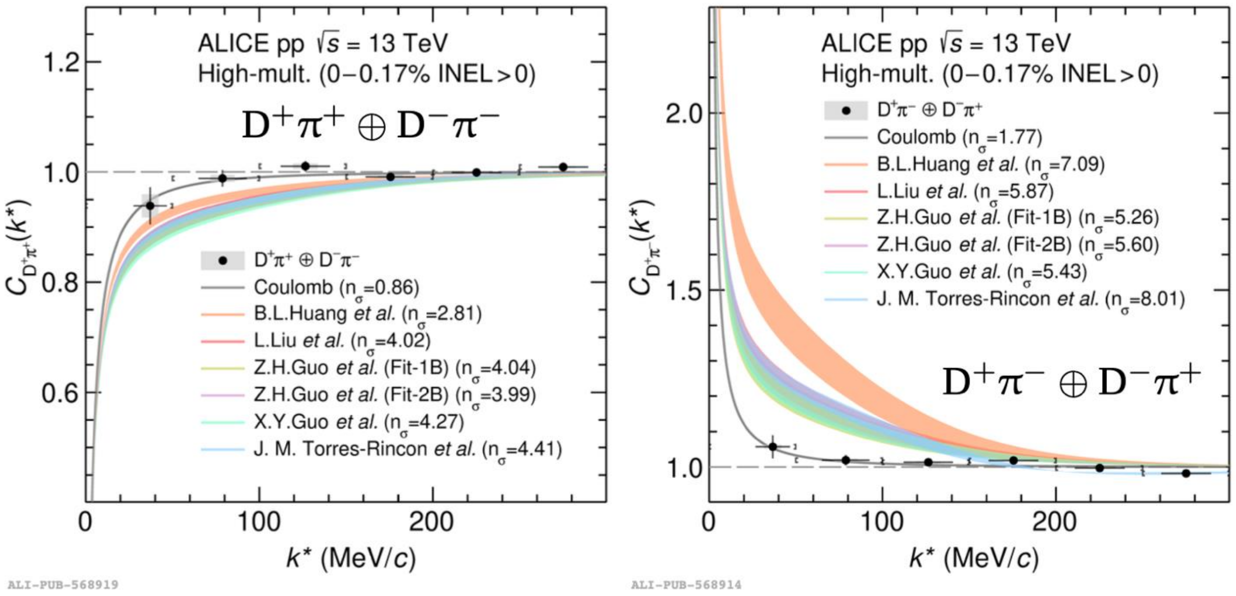
D-π femtoscopy

- ➢Tension with models for all correlation functions
- ➢Compatible with Coulomb-only assumption
- ➢Impoved statistical uncertainty in ongoing Run 3
- ➢ALICE 3 upgrade dedicated for charm hadron studies

D-meson

same charge

opposite charge



ALICE, arXiv:2401.13541

D-π and D*-π femtoscopy

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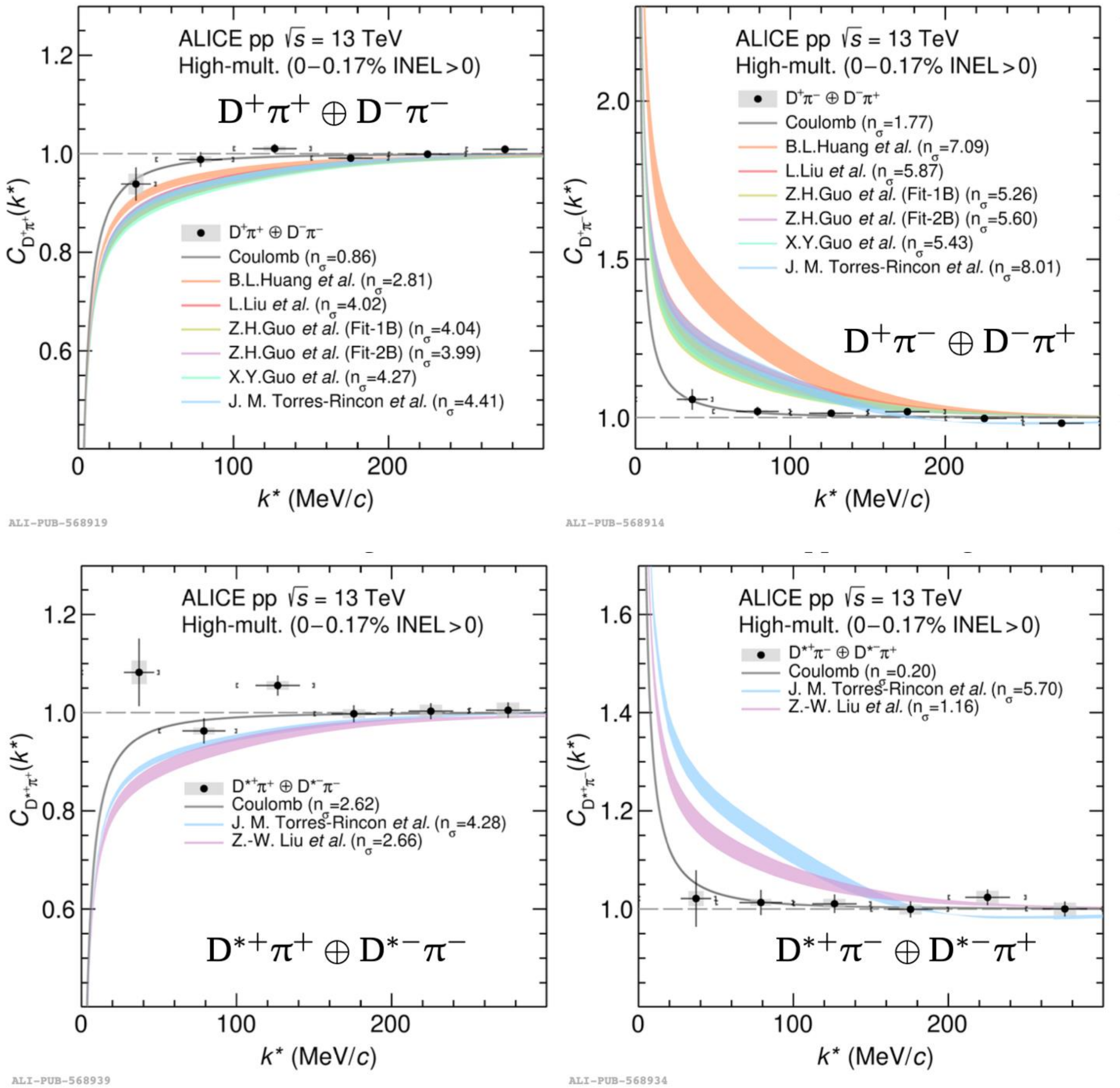
same charge

opposite charge

D-meson

D*-meson



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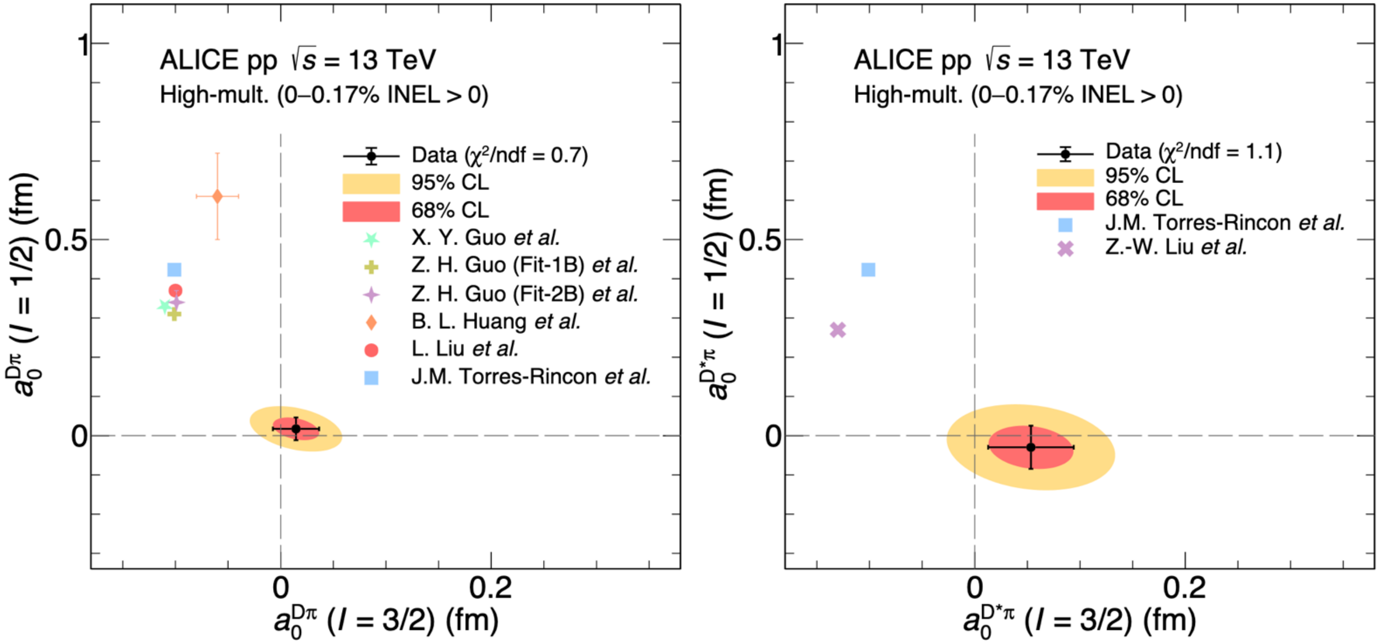


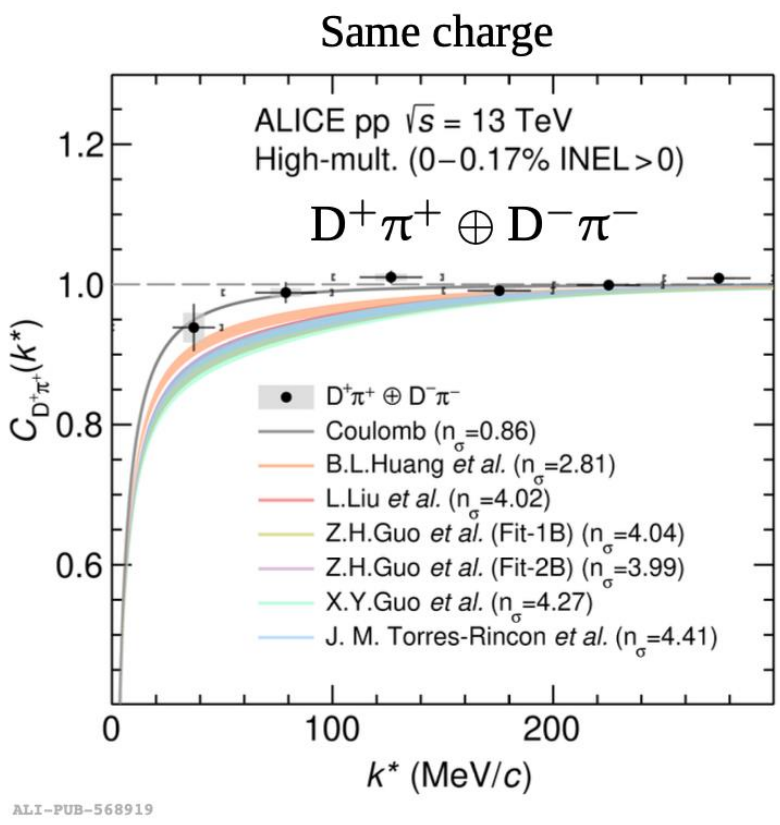
- Extraction of scattering parameters for the same charged pairs
  ➔ Small scattering parameters
  ➔ Hint to heavy quark spin symmetry

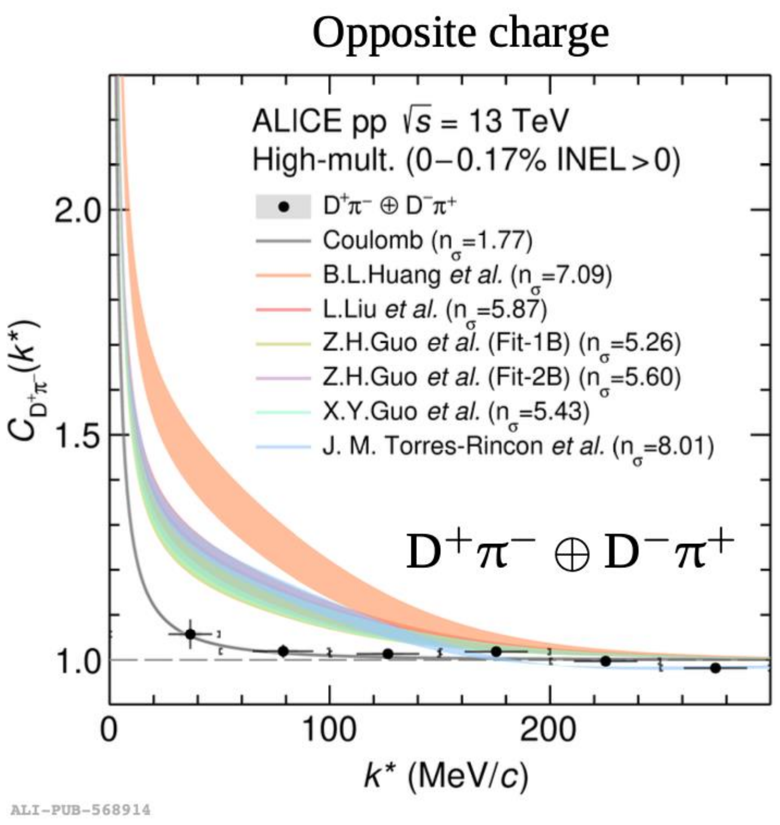
ALICE, arXiv:2401.13541

Beyond strangeness: Charm femtoscopy

	$\lvert S\rvert = 0$	$\lvert S\rvert = 1$	$\lvert S\rvert = 2$	$\lvert S\rvert = 3$	$\lvert C\rvert \neq 0$
Theory					
Lattice QCD					
χEFT					
Experiment					
Scattering Experiments				???	
Hypernuclei Experiments					
Femtoscopy		PLB 833 (2022), 137272 (p-Λ) arXiv:2312.16970		ALICE, Nature 588 (2020) 232-238 ALICE, PLB (2022), 137223	arXiv:2401.13541

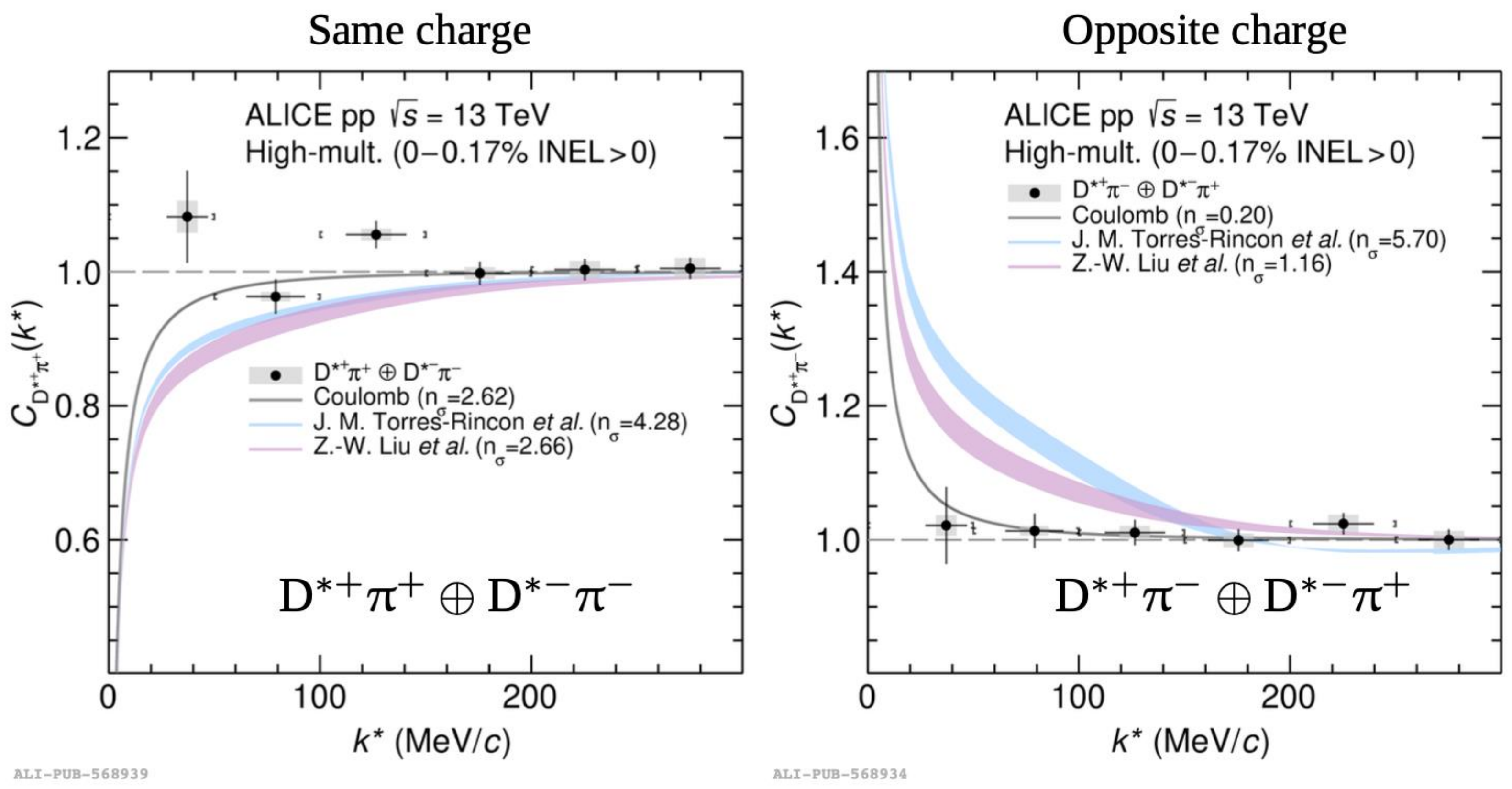
D-meson π femtoscopy





- Tension with models
- Compatible with Coulomb-only assumption

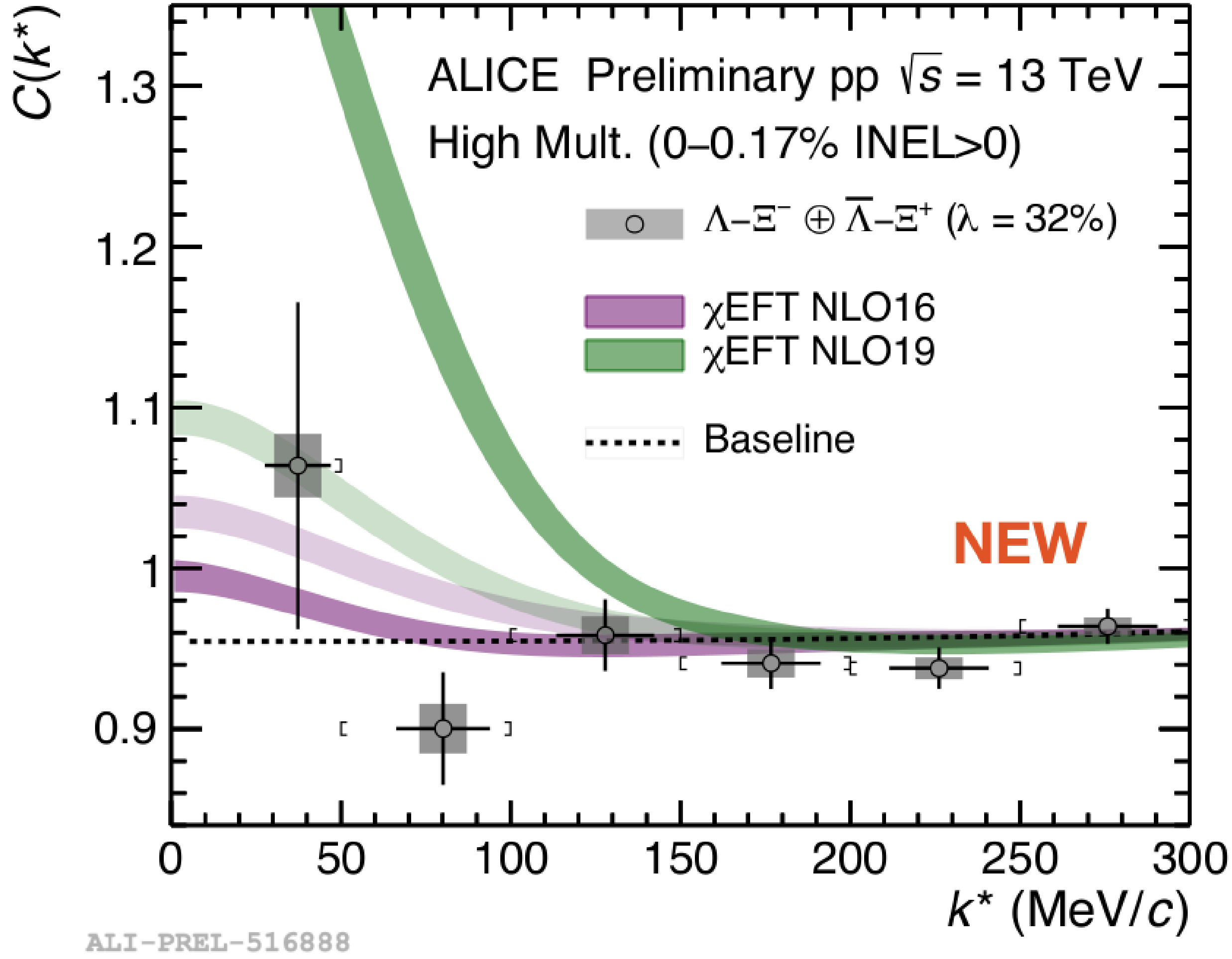
D*-meson π femtoscopy



- Tension with models
- Compatible with Coulomb-only assumption

Λ—Ξ interaction with femtoscopy

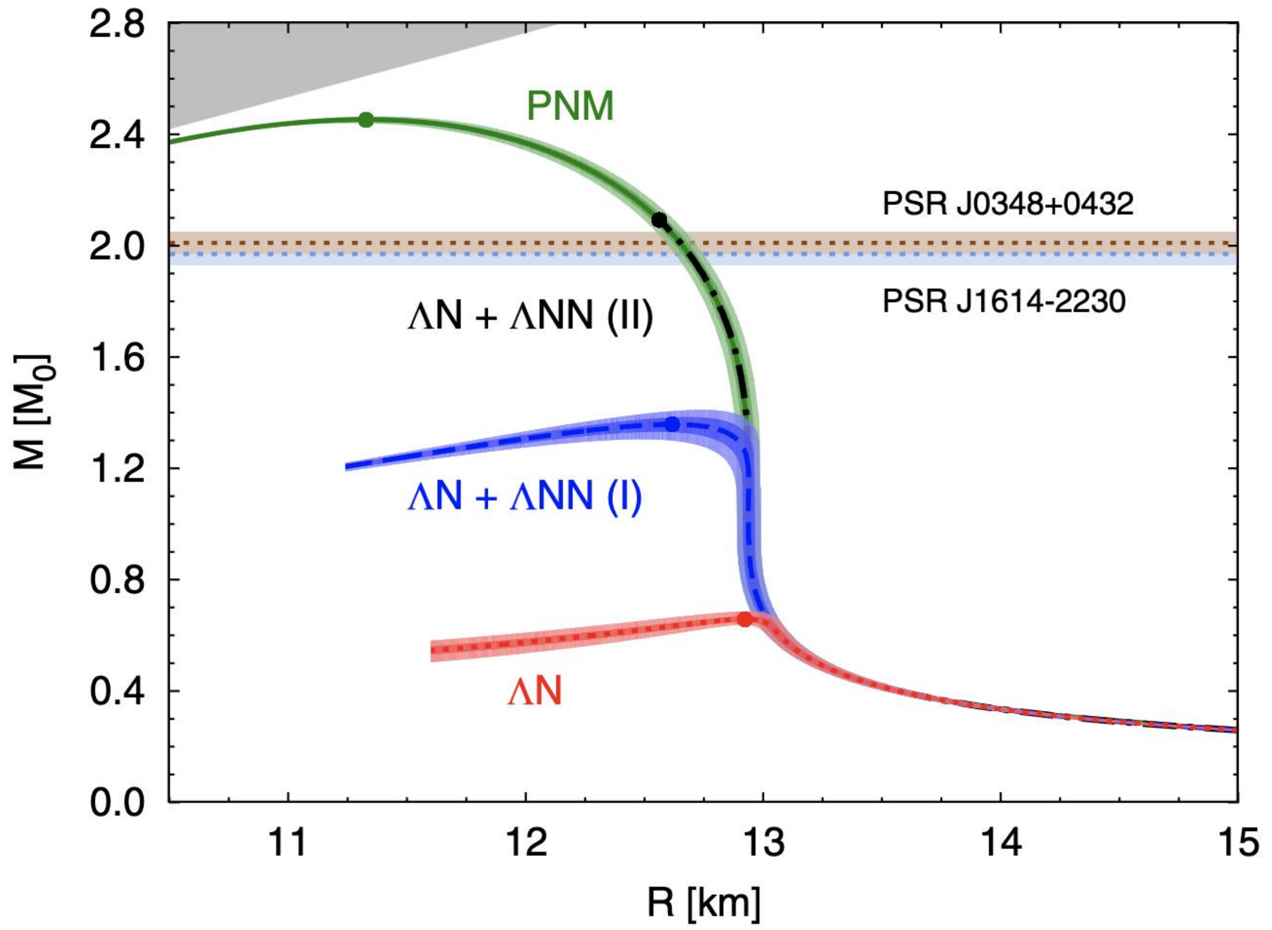
- Bla bla



EoS of neutron stars

- Large densities in neutron stars (up to 2ρ0)
  ➔ hyperons as new degrees of freedom expected
- EoS dependent on hyperon-nucleon interaction
  ➔ ΛN two-body interaction
  ➔ ΛNN three-body interaction
- Precise experimental measurement needed

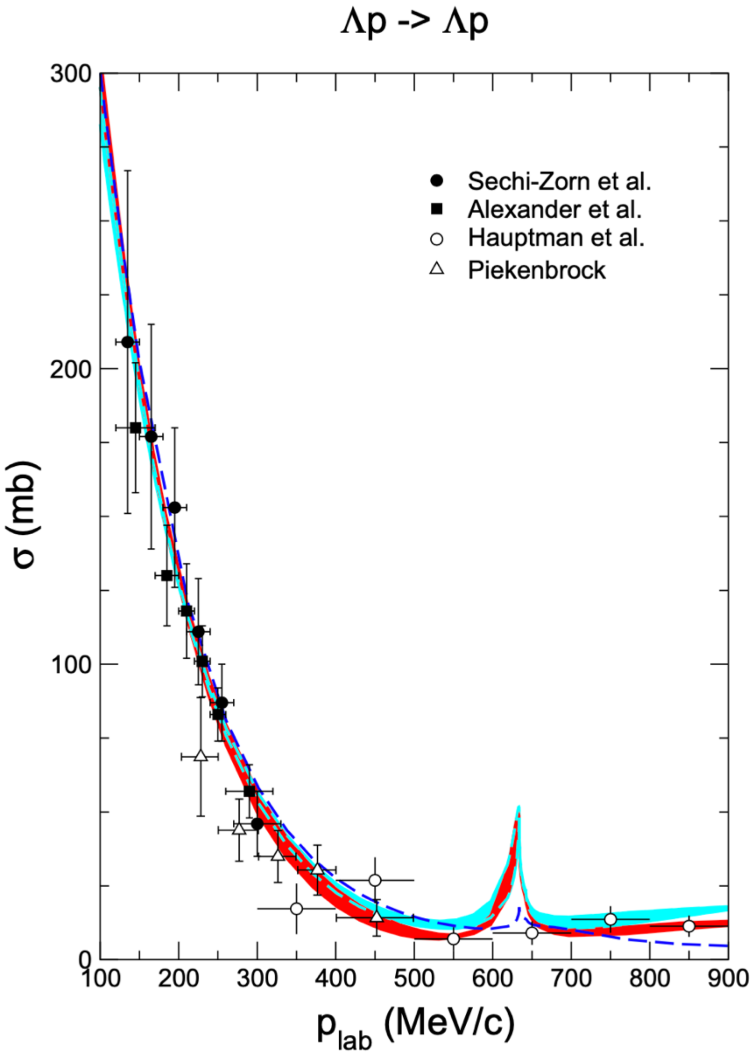
Femtoscopy can help also here!
➔ Also in the case of 3 body interactions!

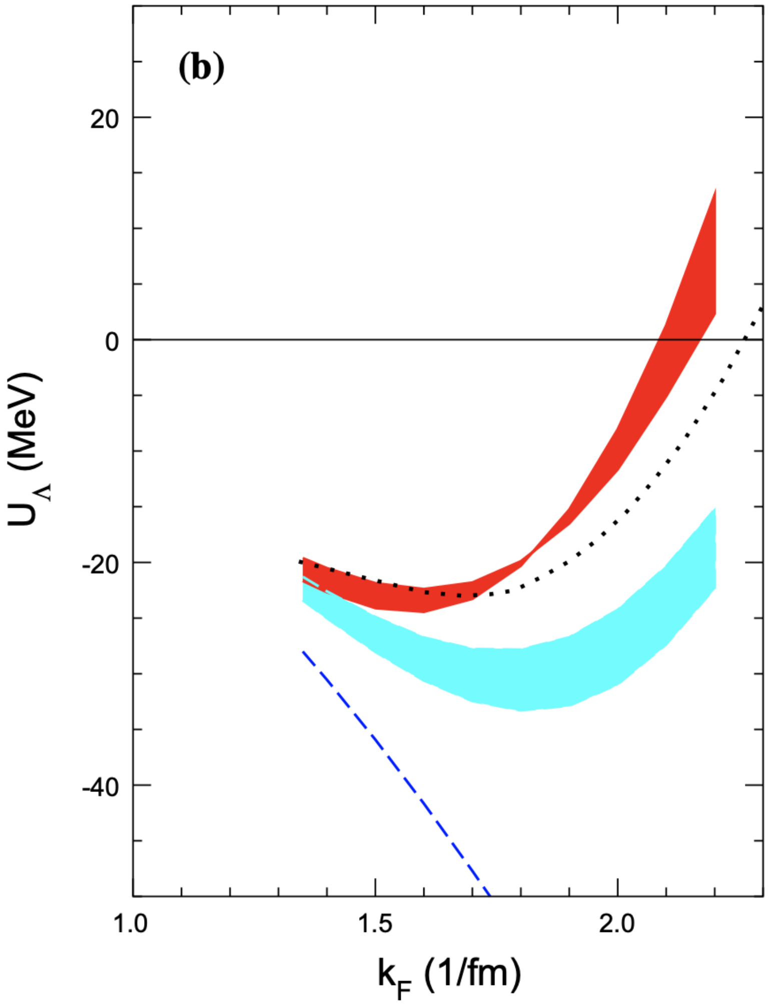


D. Lonardoni et al., PRL 114 (2015)

The ΛN interaction

- Coupling of ΛN to ΣN relevant for the EoS
- χEFT constrained to scattering and hypernuclei data
  ➔ Difficult reach to low momenta
  ➔ Insufficient precision to resolve the coupling cusp
- Different interactions equally reproduce the measurement
  ➔ Different inelastic contributions and implications for 3-body interactions
  ➔ More differential data necessary





Indirect access of 3-body interaction

Kaon-deuteron correlation function

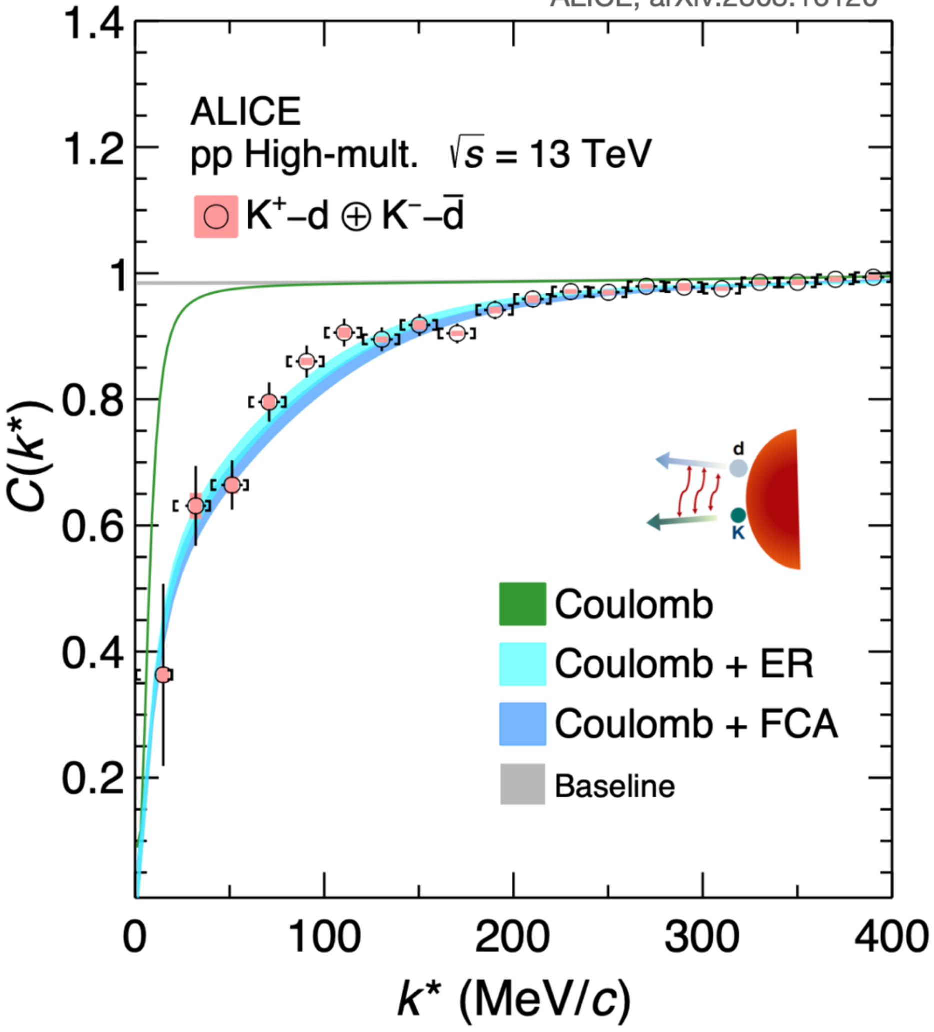
- Modelling: Lednický-Lyuboshits approach (effective two body system)
- Input: Available scattering data
- Source size: Extracted with from the common m_T scaling

➔ $r_{\mathrm{eff}}^{\mathrm{K^+d}} = 1.35^{+0.04}_{-0.05}\,\mathrm{fm}$

- Good agreement with the data

➔ Deuterons follow the common m_T scaling

ALICE, arXiv:2308.16120

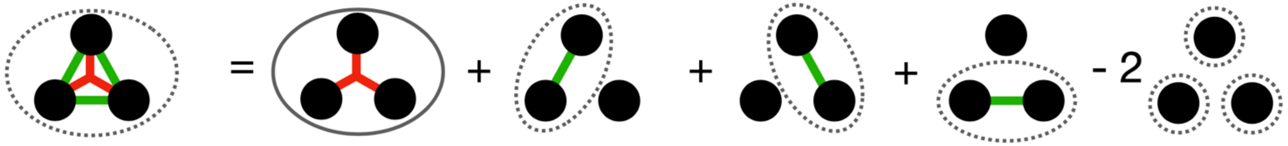


Direct access of p-p-p correlations

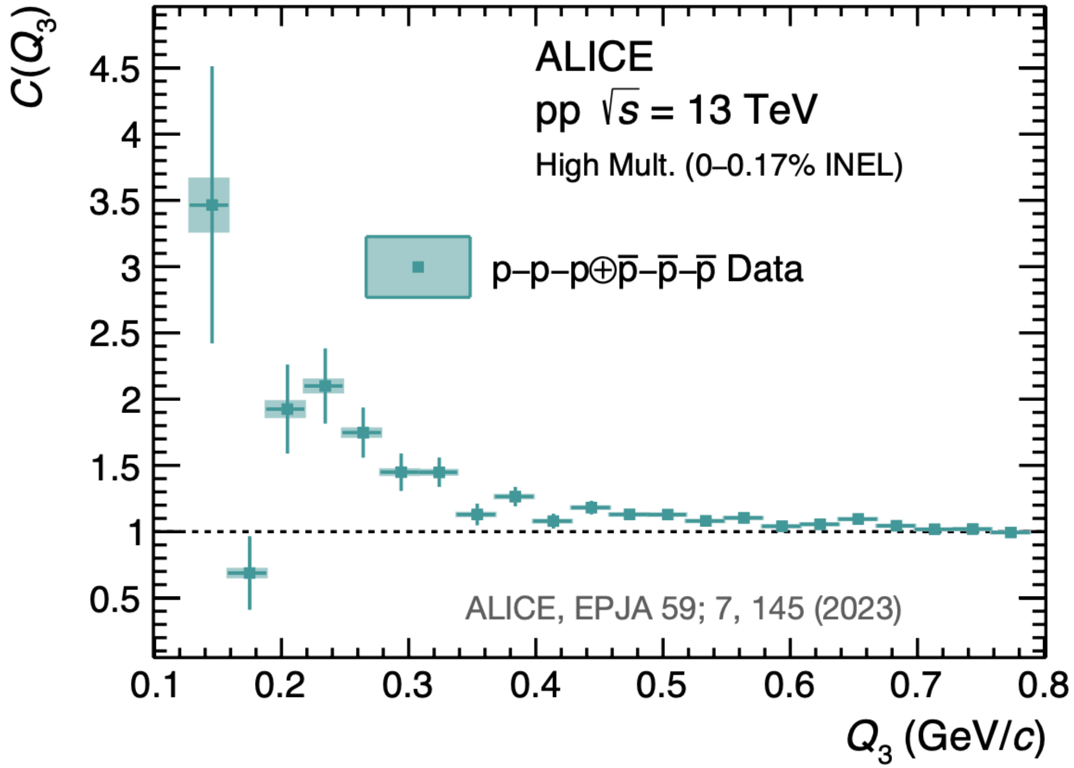
- Theoretical correlation function:

$$C_3(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3) = \iiint S_3(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)\left|\Psi(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3,\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3)\right|^2 d^3\mathbf{r}_1 d^3\mathbf{r}_2 d^3\mathbf{r}_3$$

- Isolate the genuine three body correlations with Kubo's cumulant method:



- Deviation from lower order contribution: nσ = 6.7
- Theoretical predictions necessary to understand the origin of the deviation



Indirect access of 3-body interaction

Proton-deuteron correlation with full 3 body calculation

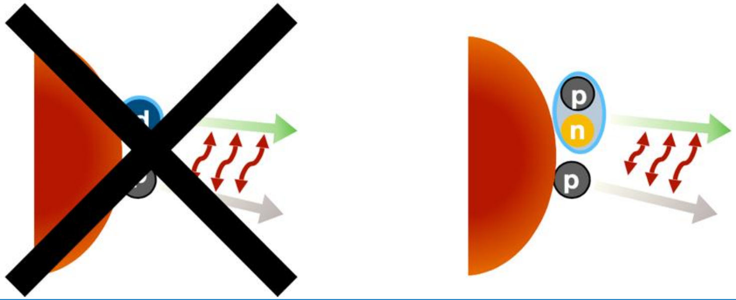
$$C_{pd}(k^*) = \frac{1}{16 A_d} \int S(\rho, R_M) |\Psi(k^*, \rho)|^2 \rho^5 d\rho d\Omega$$

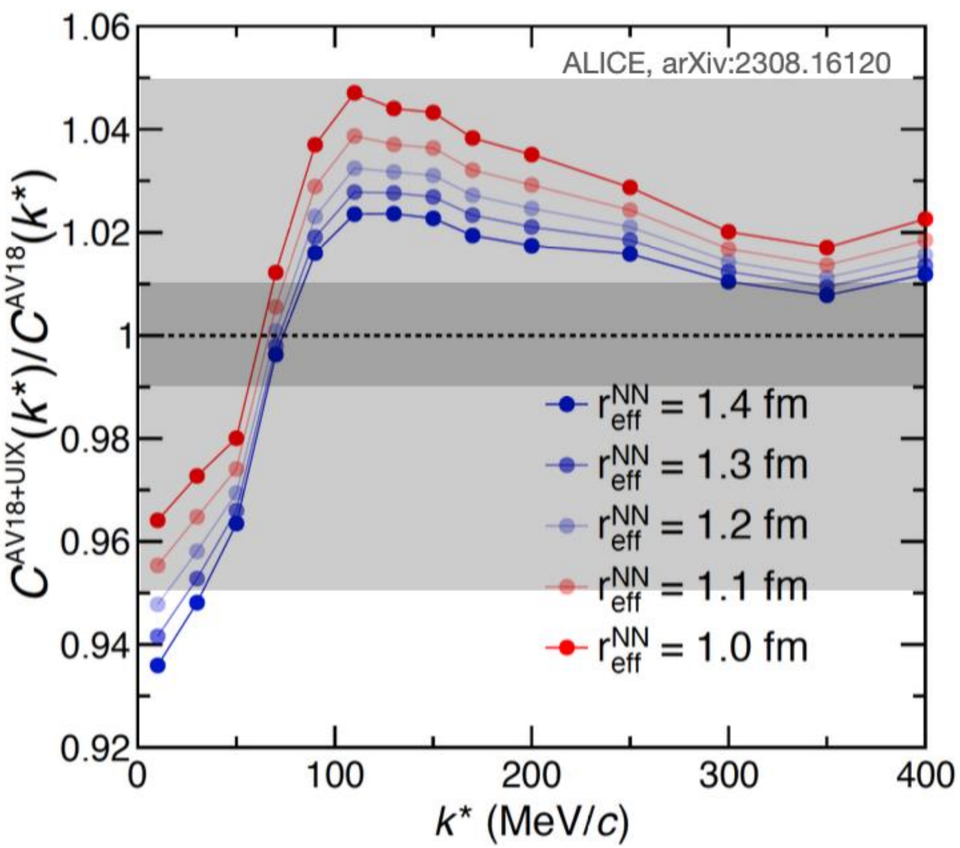
Wavefunction:

➢Hyperspherical harmonic (HH) approach with Argonne V18 (AV18) + Urbana IX (UIX) potentials

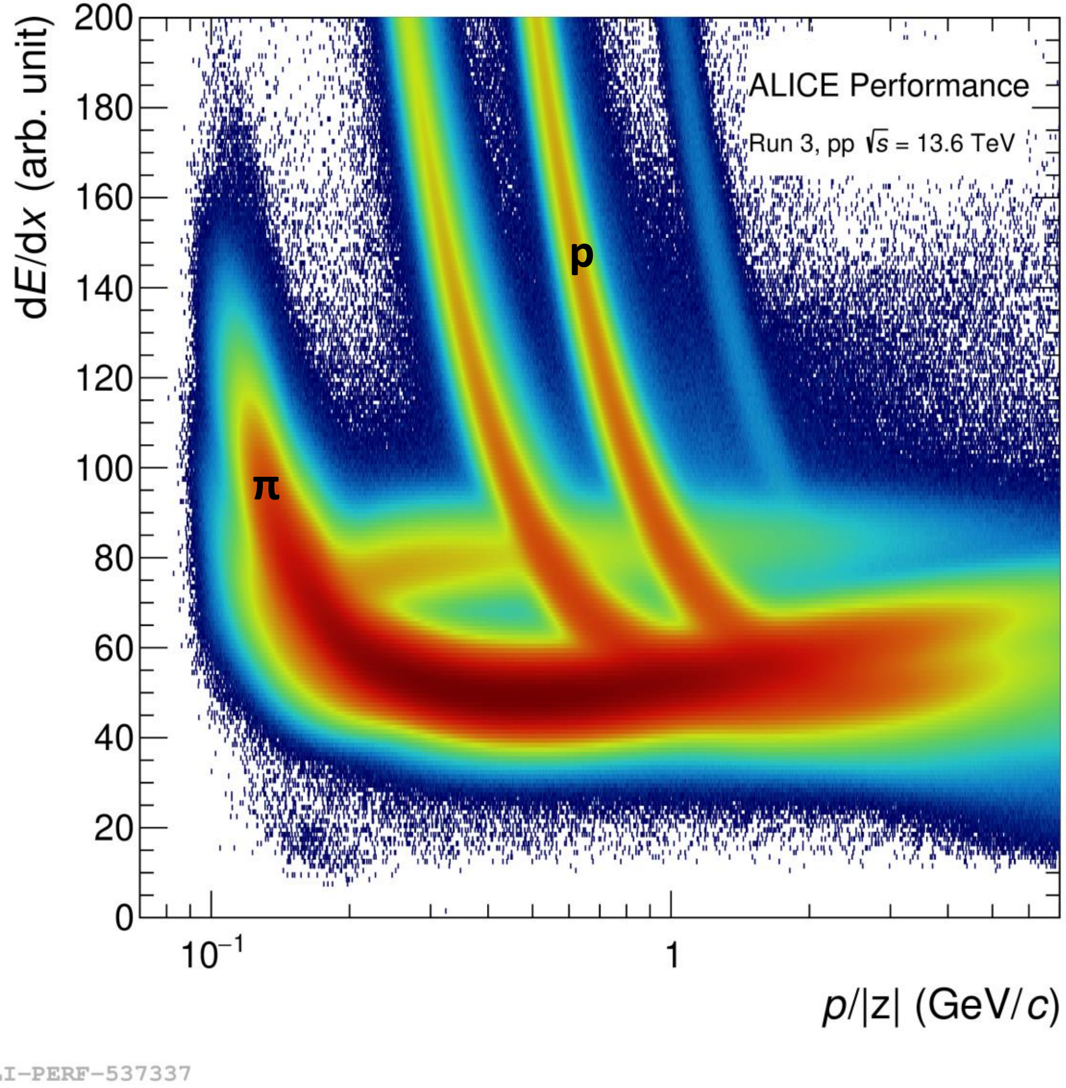
➢Pionless EFT NLO

➔ Sensitivity to 3 body effects!
(But not with the precision of Run 2 data)





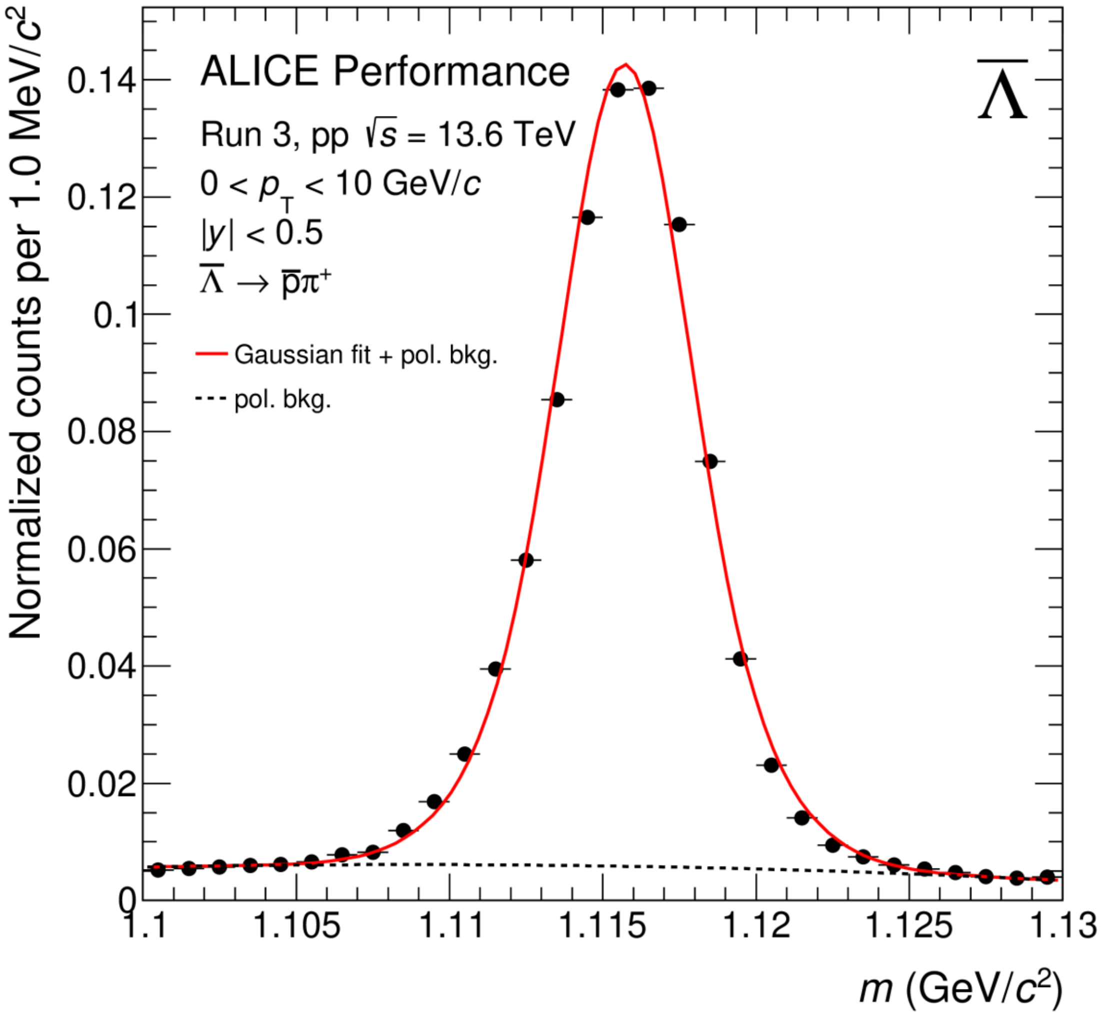
Outlook: p–Λ correlations in Run 3



Λ reconstruction: Λ → pπ

- Excellent PID and vertex finding of ALICE allows for efficient identification of Λ daughter tracks
- V0 algorithm is used to reconstruct Λ candidates

Outlook: p–Λ correlations in Run 3



ALI-PERF-529185

Λ reconstruction: Λ → pπ

- Excellent PID and vertex finding of ALICE allows for efficient identification of Λ daughter tracks
- V0 algorithm is used to construct Λ candidates

p–Λ correlation measurement:

- High purity sample necessary to extract femto signal
- Need good distinction between protons from primary collisions and Λ decays to avoid autocorrelation