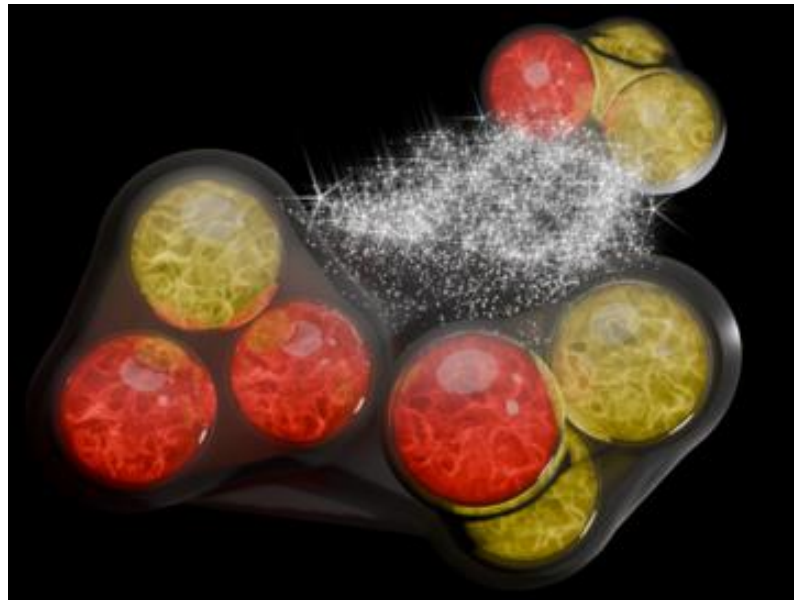


Exploring hadronic interactions in three-body systems at the LHC

Raffaele Del Grande^{1,*}

¹Physik Department E62, Technische Universität München, 85748 Garching, Germany



Hadrons and Hadron Interactions in QCD 2024 (HHIQCD2024)

30th October 2024, Kyoto, Japan

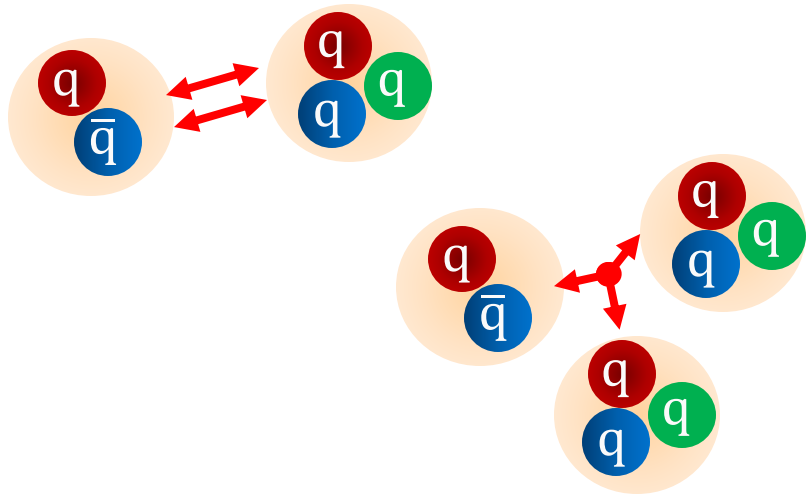
*raffaele.del-grande@tum.de

Motivation

- Hadronic interactions are poorly known in the strange and charm sectors

How do hadrons interact?

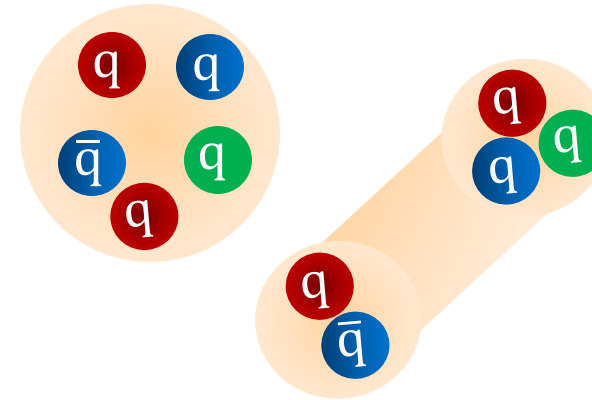
2-body and many-body interactions



- Many exotic and molecular states have been observed in experiments (e.g. BELLE, LHCb, ...)

How do hadrons emerge?

Conventional and exotic states



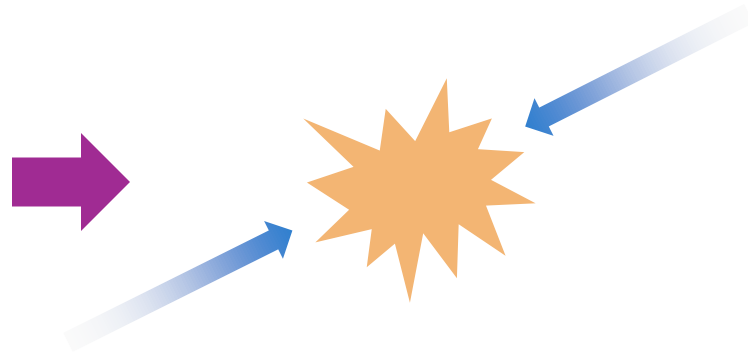
Need for experimental data

Femtoscscopy technique at the Large Hadron Collider

ALICE at the LHC

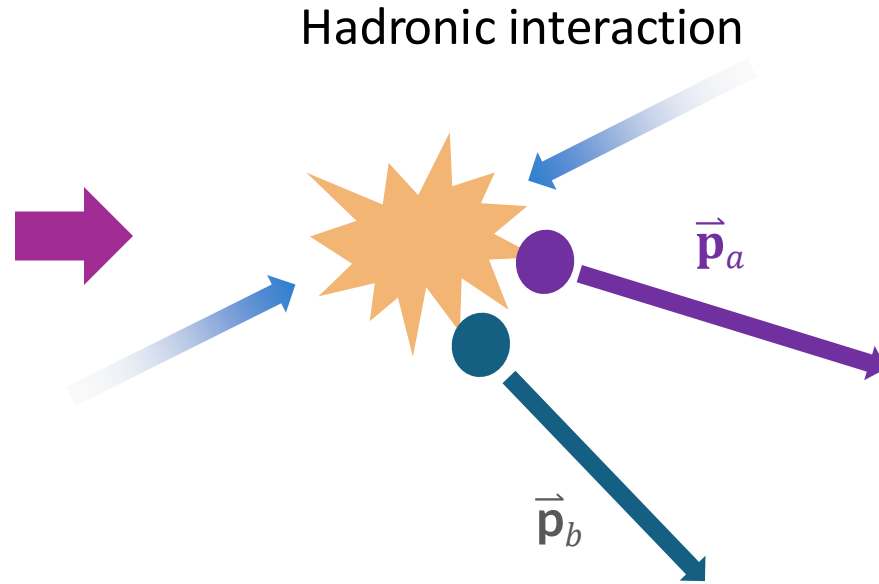


Hadronic interaction



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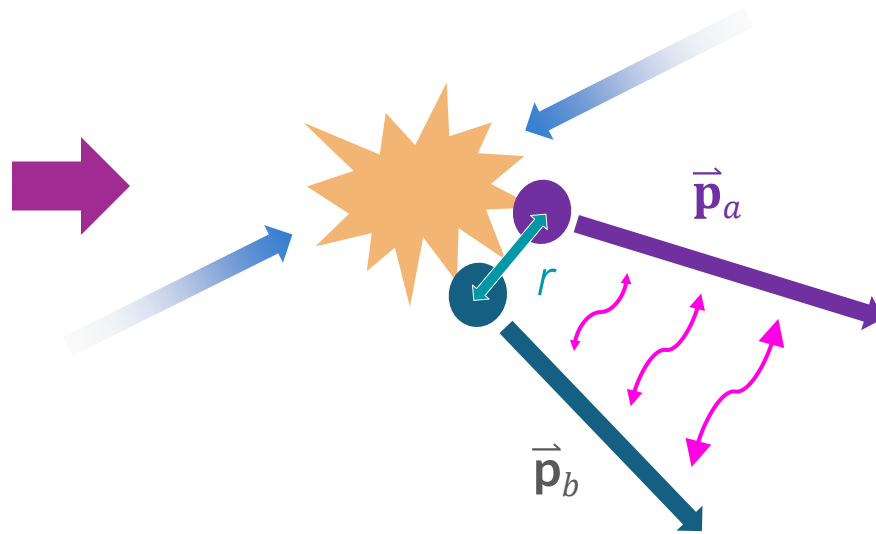


Femtoscscopy technique at the Large Hadron Collider

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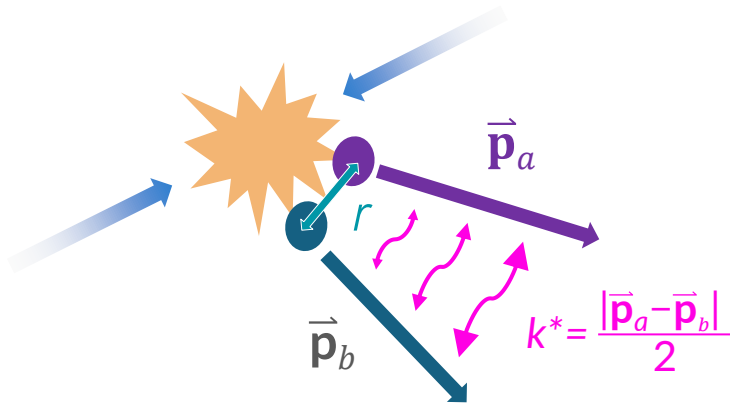
Hadronic interaction



Femtoscscopy technique

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

Correlation function

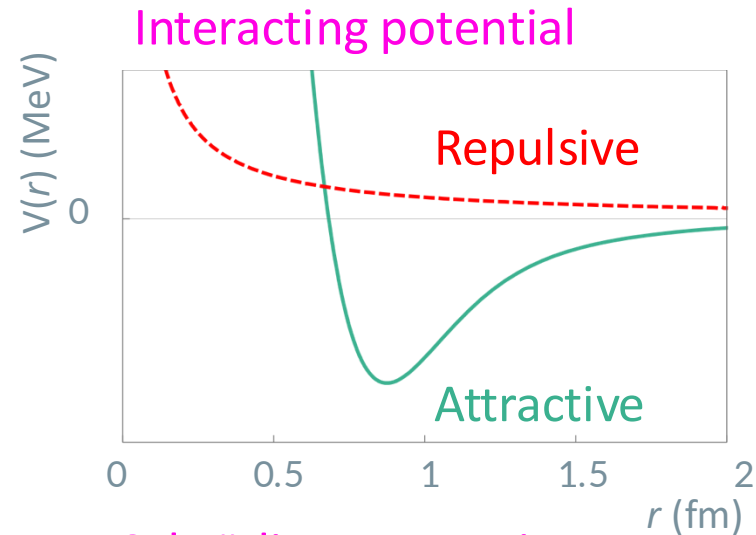
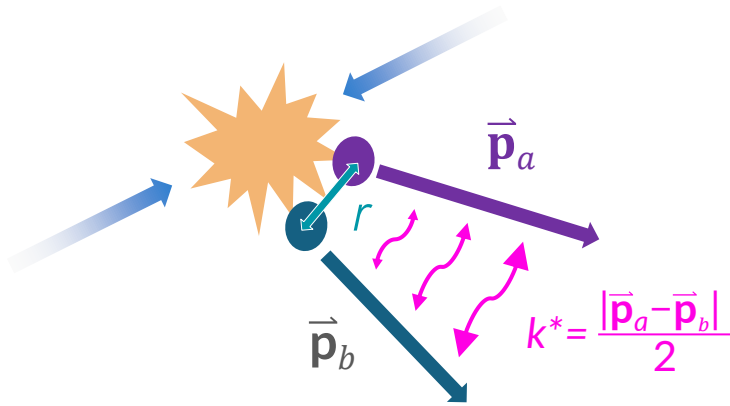


Emission source $S(\vec{r})$

$$C(k^*) = \int \overbrace{S(\vec{r})} \left| \psi(\vec{k}^*, \vec{r}) \right|^2 d^3\vec{r} = \mathcal{N}(k^*) \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

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

Correlation function



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

Schrödinger equation

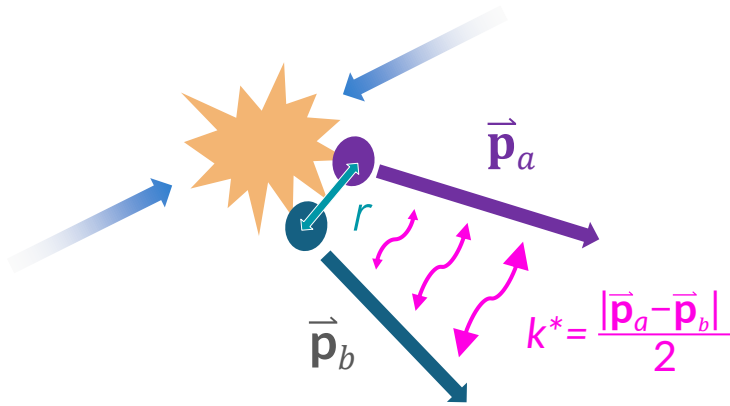
D. Mihaylov et al., EPJC 78 (2018), 5, 394

Two-particle wave function

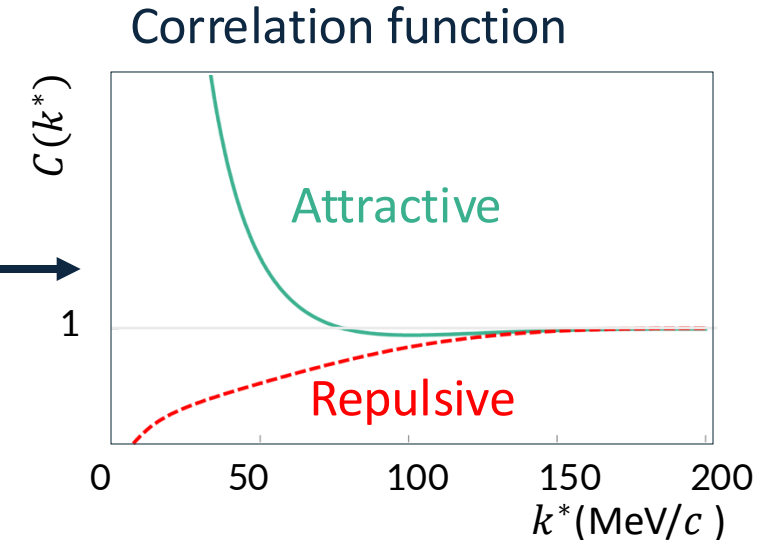
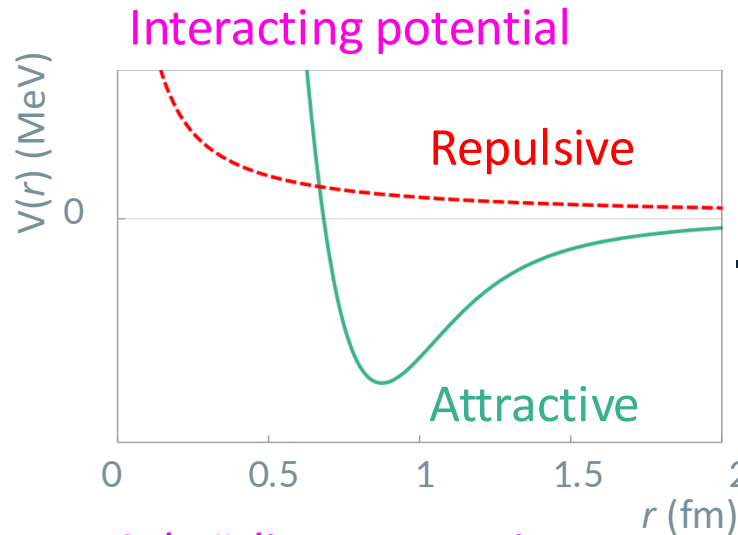
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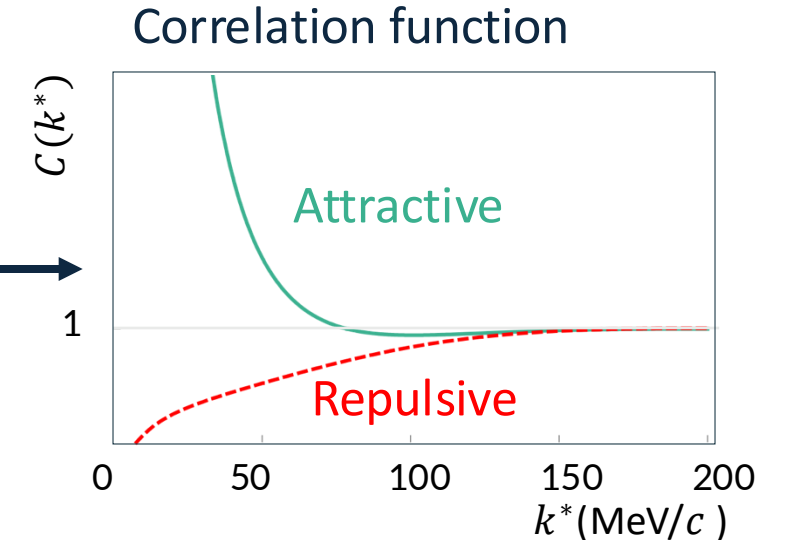
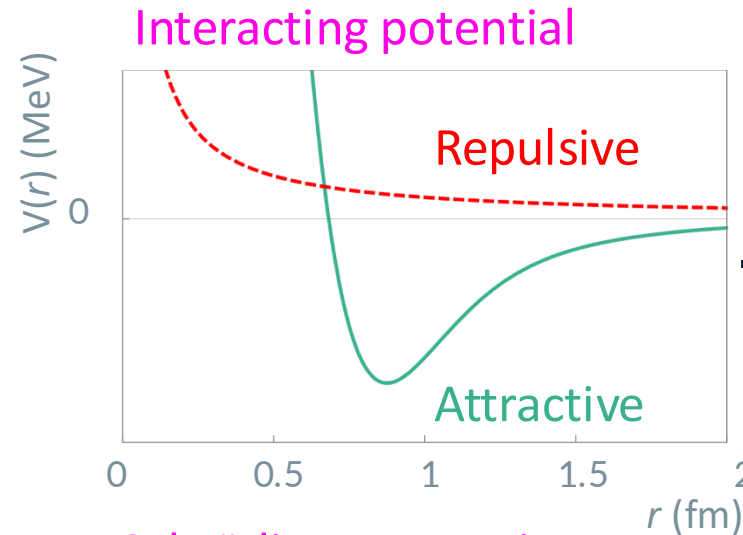
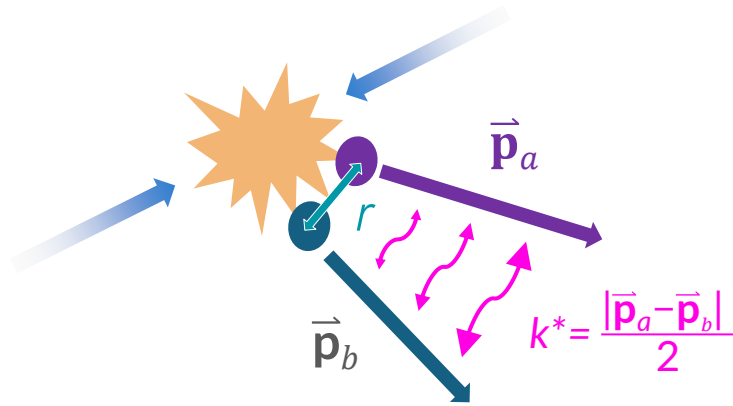
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Measuring $C(k^*)$, fixing the source $S(\vec{r})$, study the interaction

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

Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

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

Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

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

known interaction

- Gaussian parametrization

$$S(r) = \frac{1}{(4\pi r_{\text{core}}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{\text{core}}^2}\right) \times \text{Effect of short lived resonances } (c\tau \sim 1 \text{ fm})$$

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

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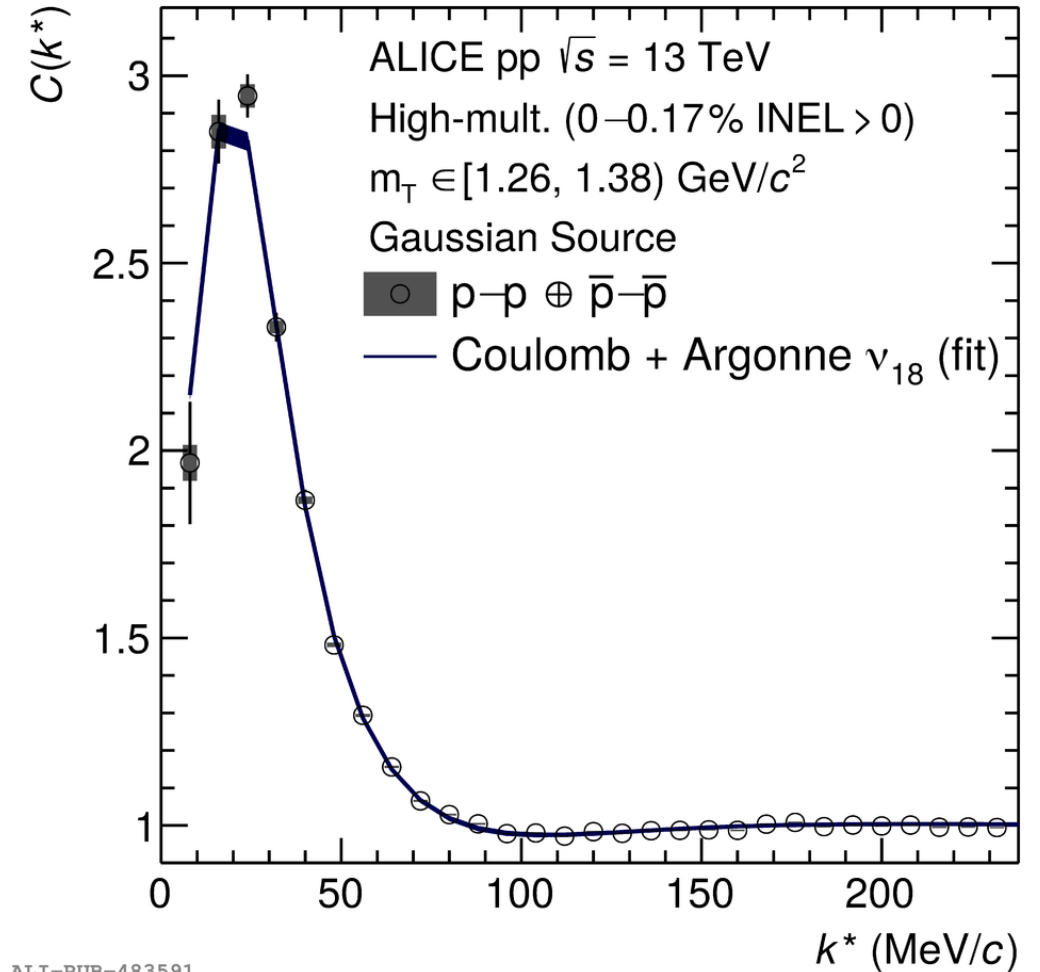
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measured
known interaction

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



ALI-PUB-483591

ALICE Coll., PLB, 811 (2020)

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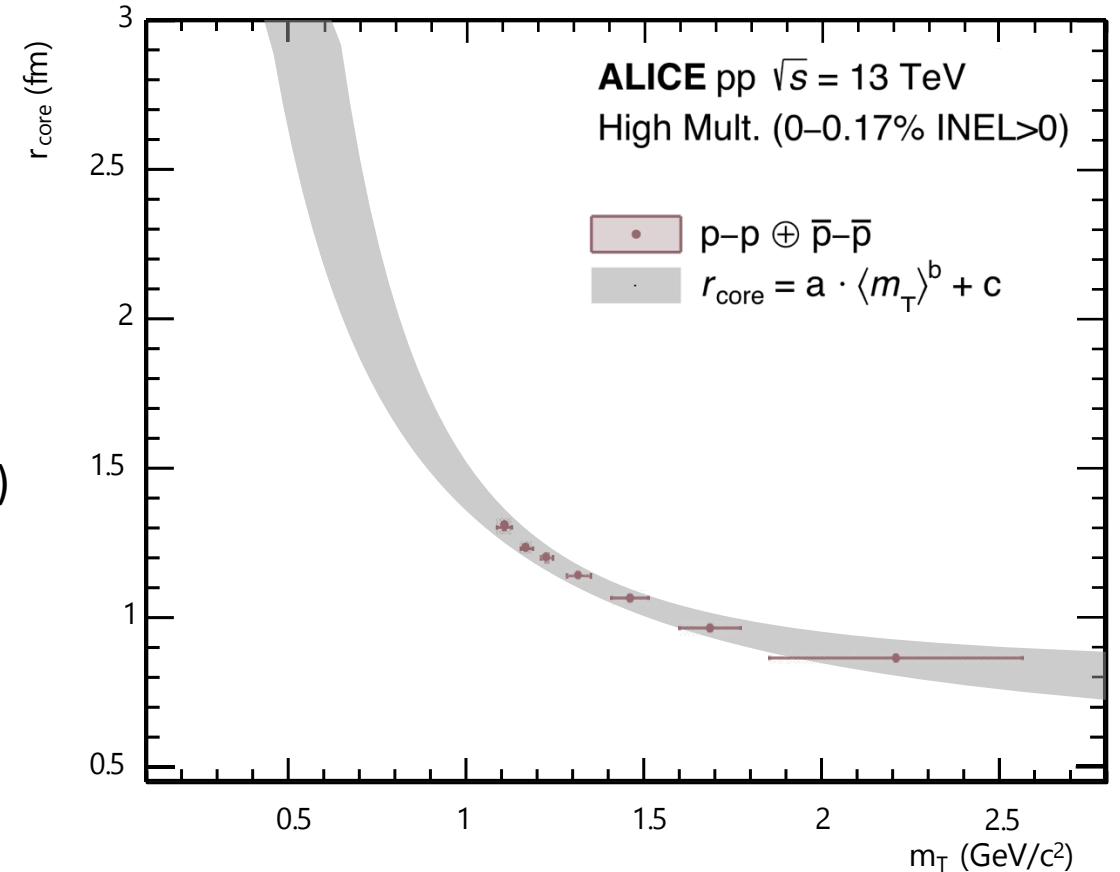
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ALICE Coll., PLB, 811 (2020), 135849



ALICE Coll., arXiv:2311.14527

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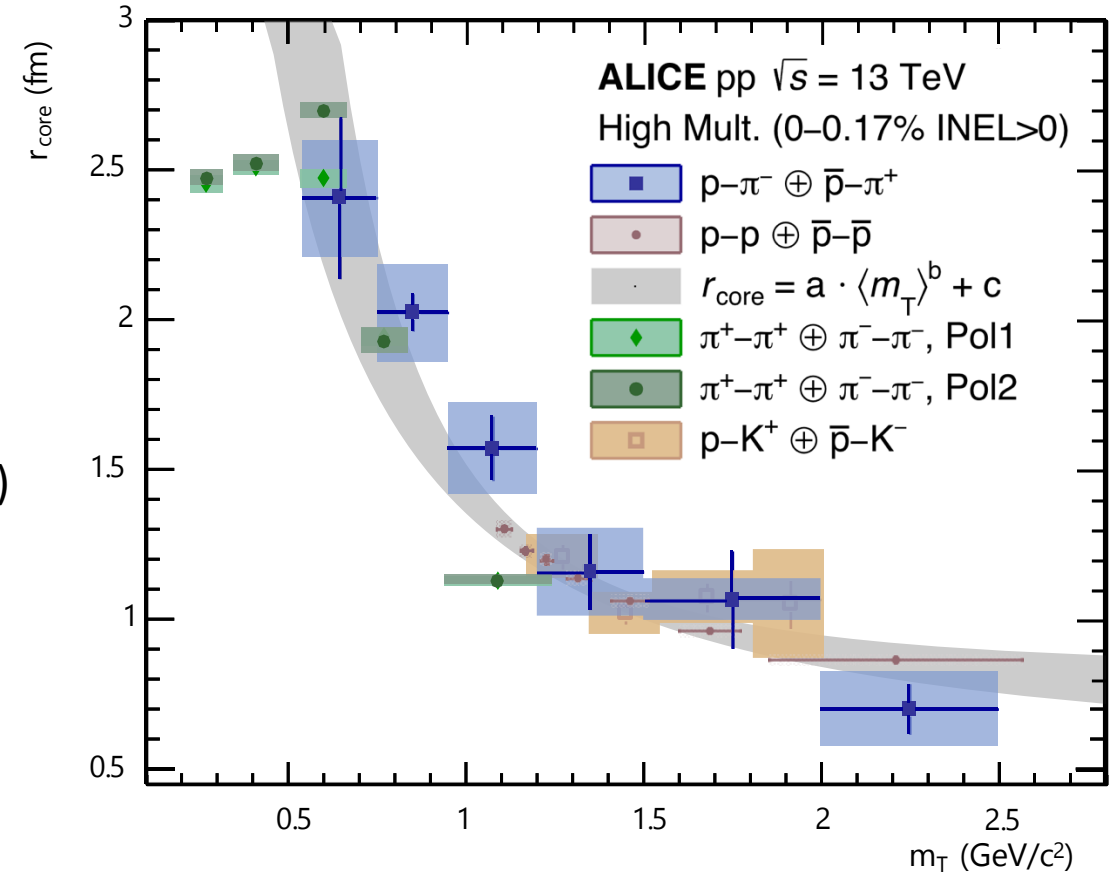
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ALICE Coll., PLB, 811 (2020), 135849

- One universal source for all hadrons (cross-check with K^+ -p, π - π , p- Λ , p- π)



ALICE Coll., arXiv:2311.14527

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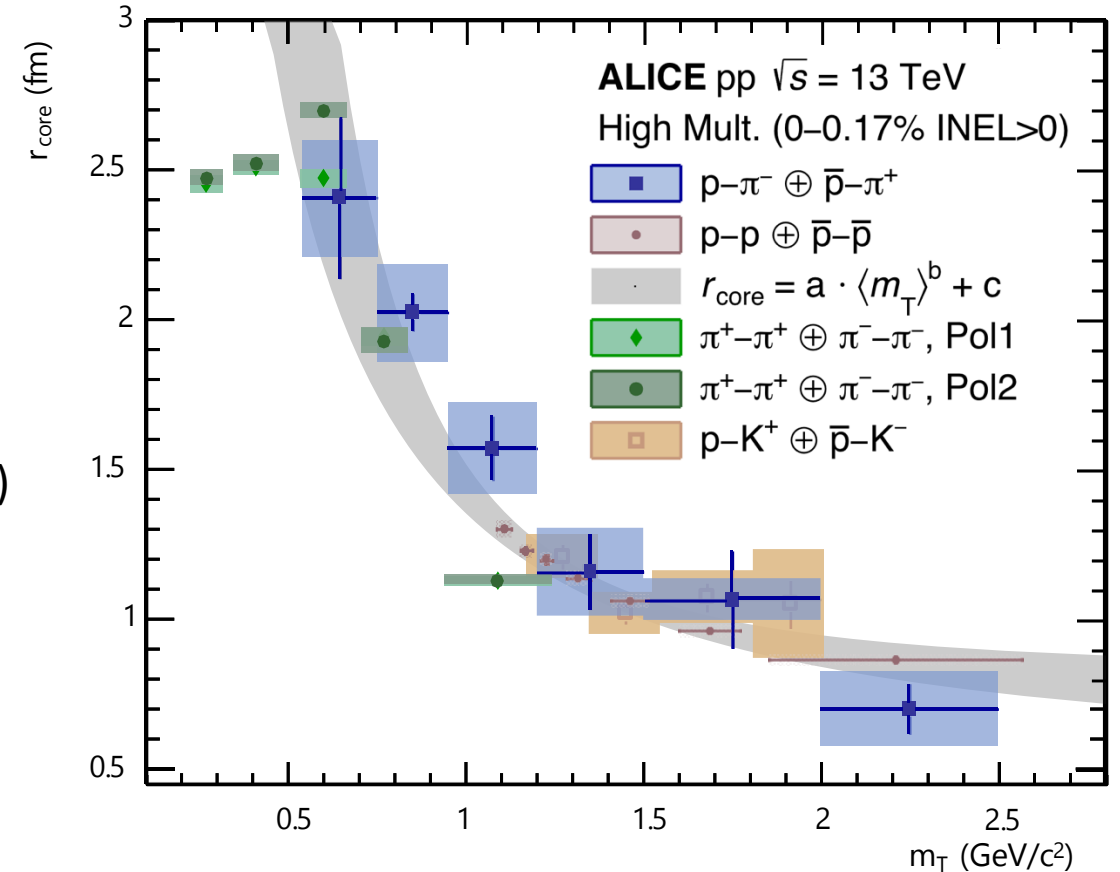
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ALICE Coll., PLB, 811 (2020), 135849

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- **Small particle-emitting source created in pp collisions at the LHC** ALICE Coll., PLB, 811 (2020), 135849; ALICE Coll., arXiv:2311.14527



ALICE Coll., arXiv:2311.14527

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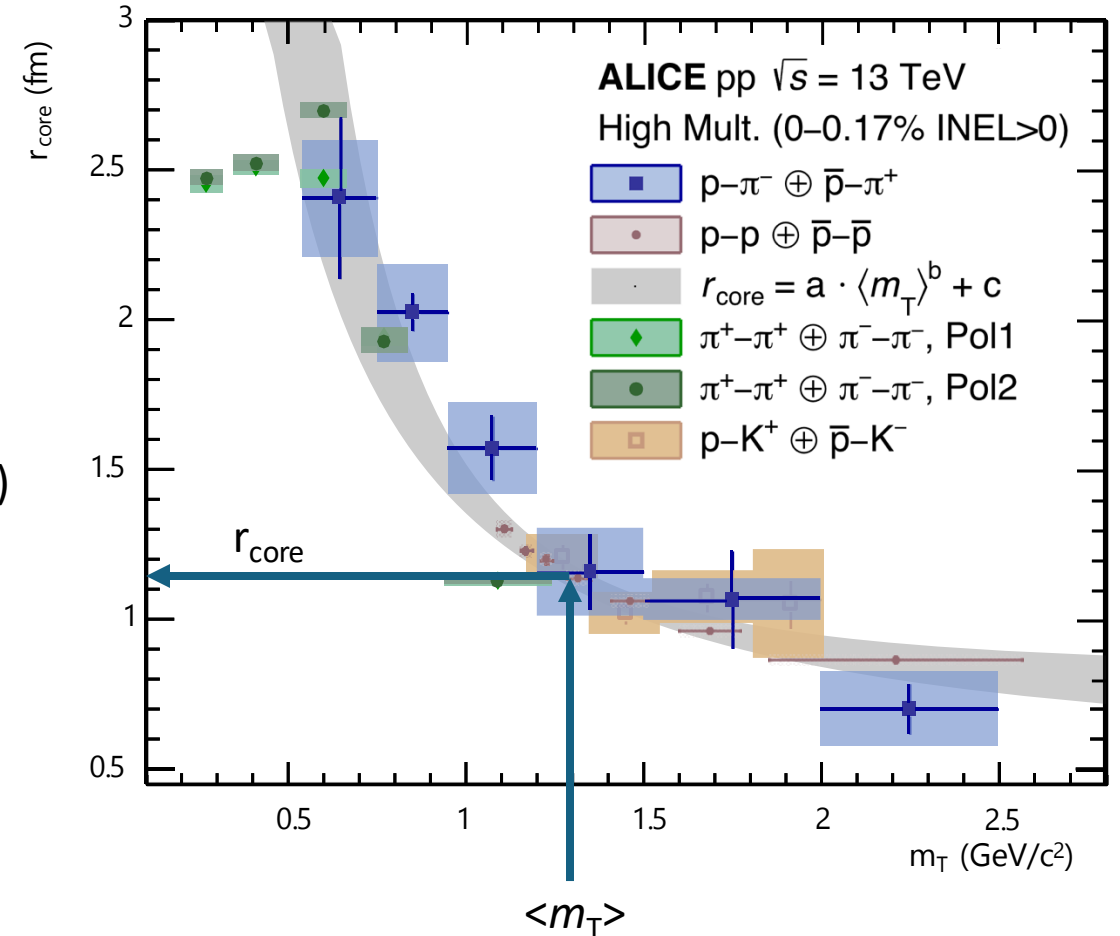
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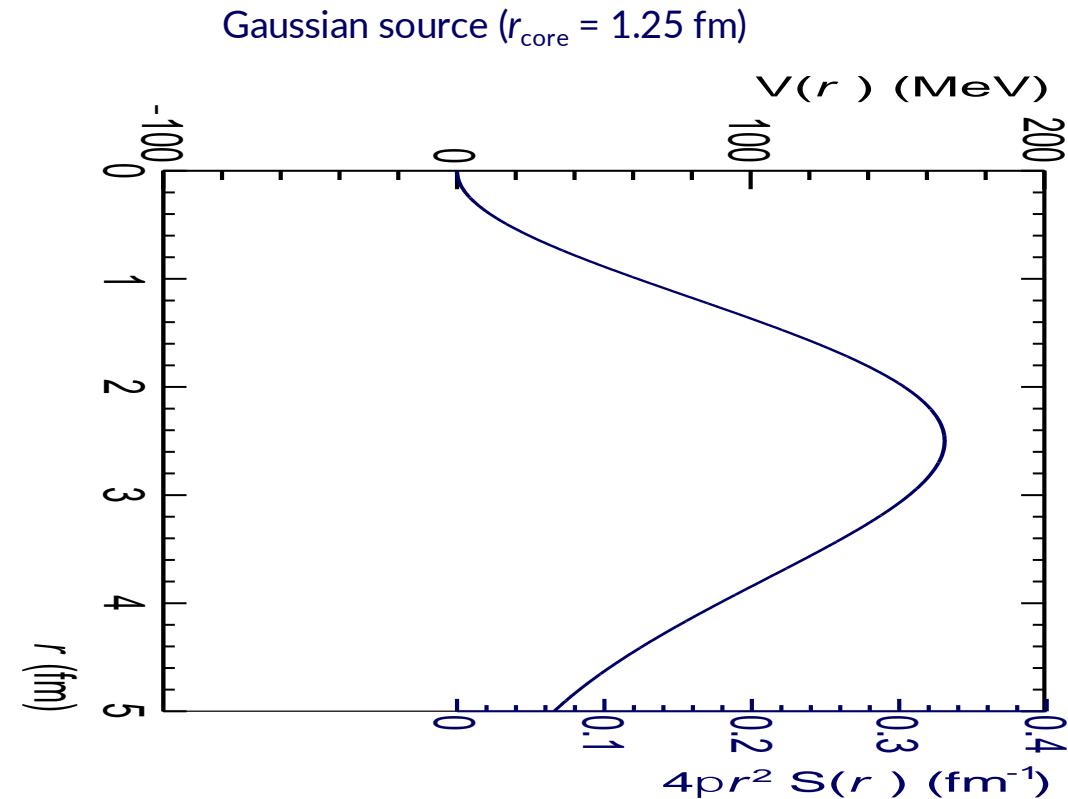
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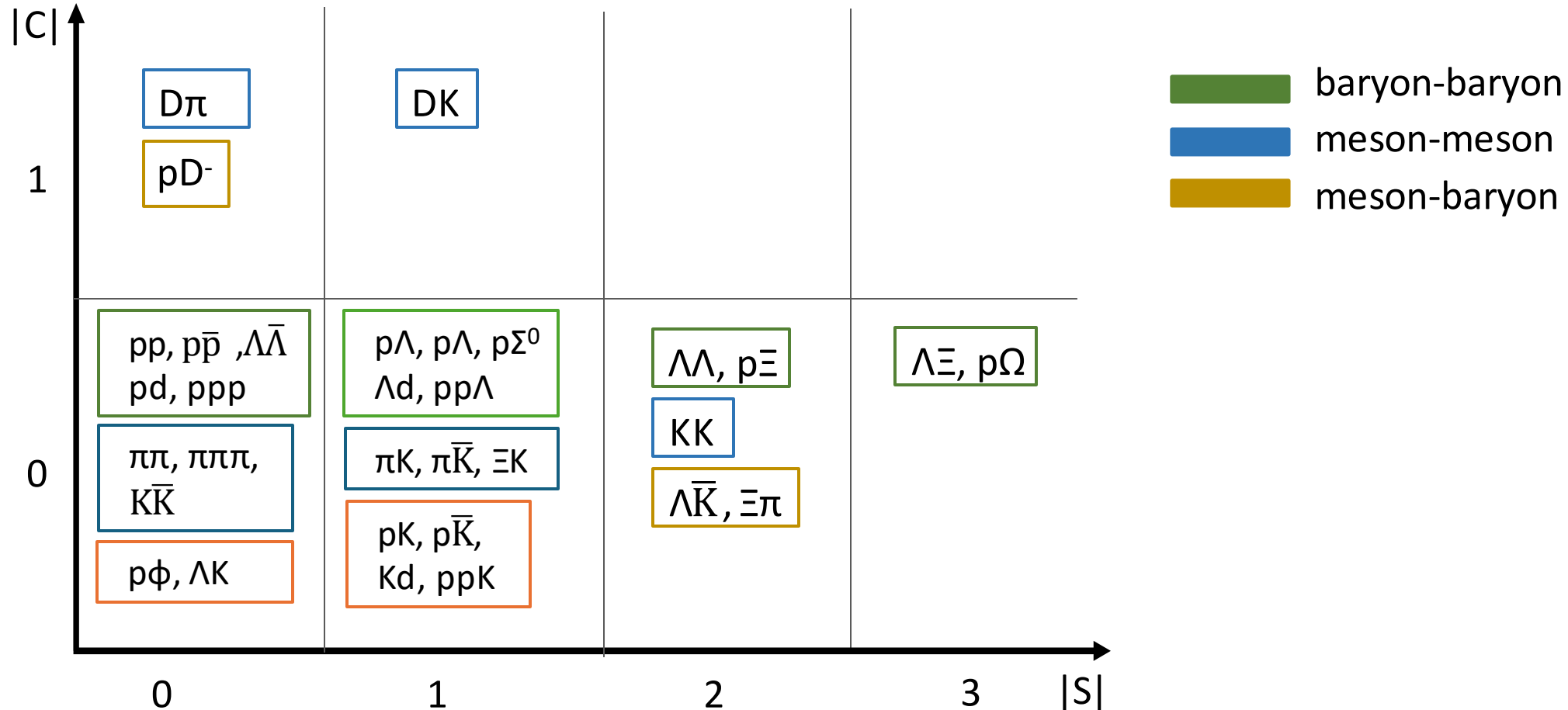
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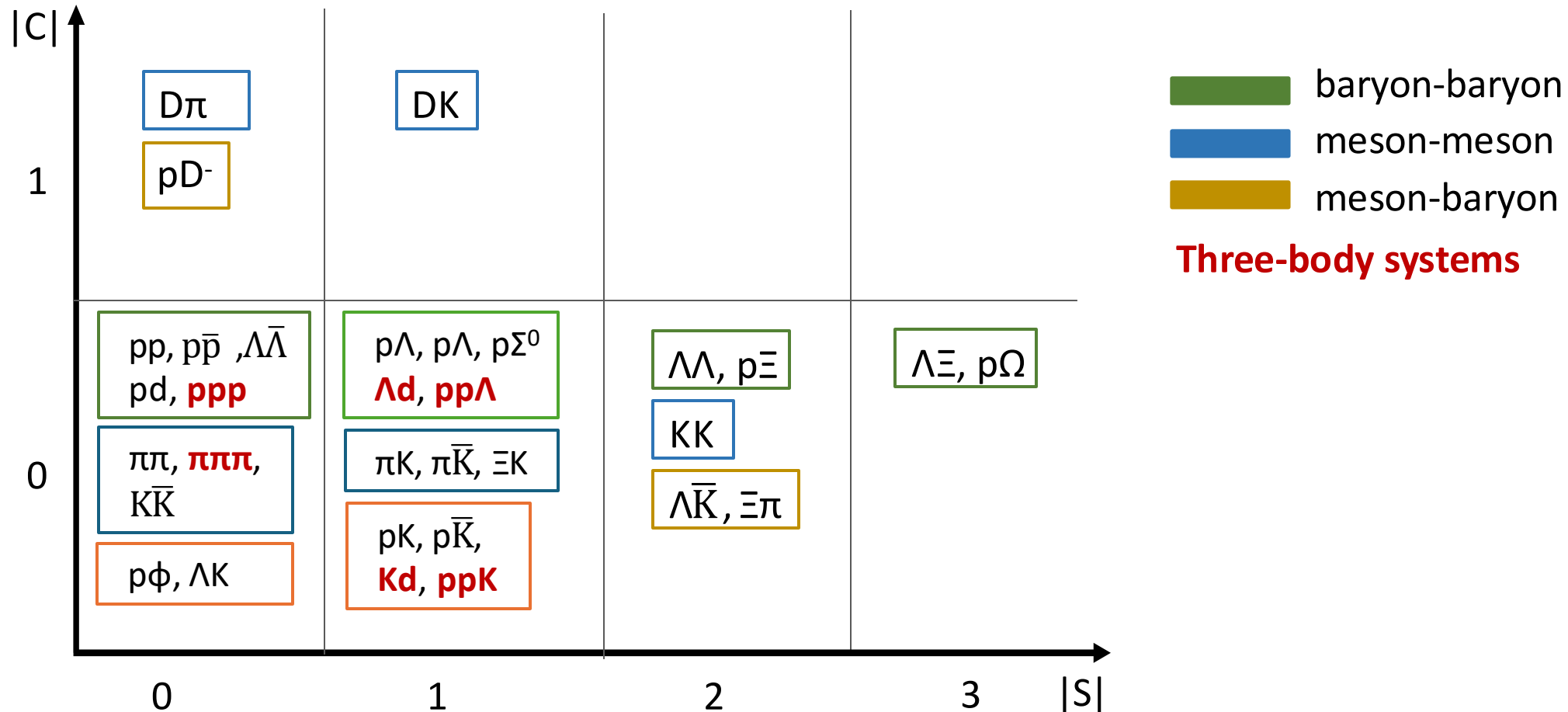
Femtosceny measurements at the LHC

ALICE provided unprecedented precision input in the study of the hadronic interactions



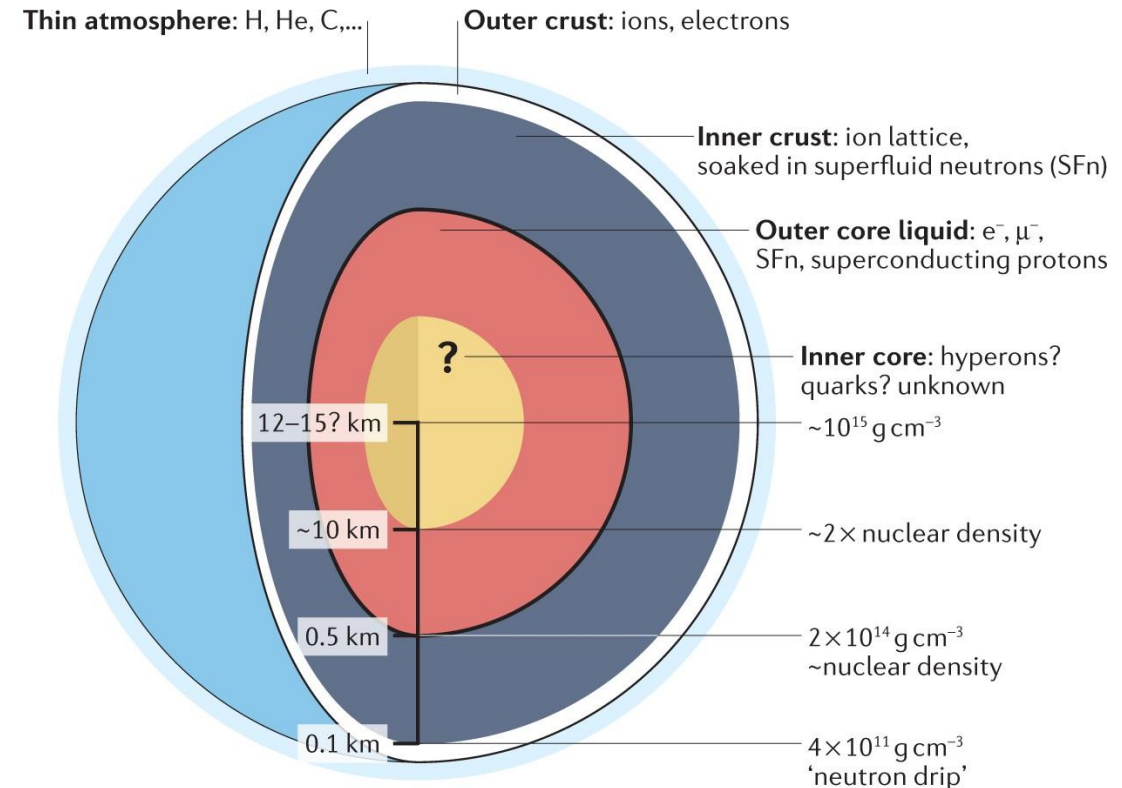
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The $N\Lambda$ and NNA interactions in neutron stars

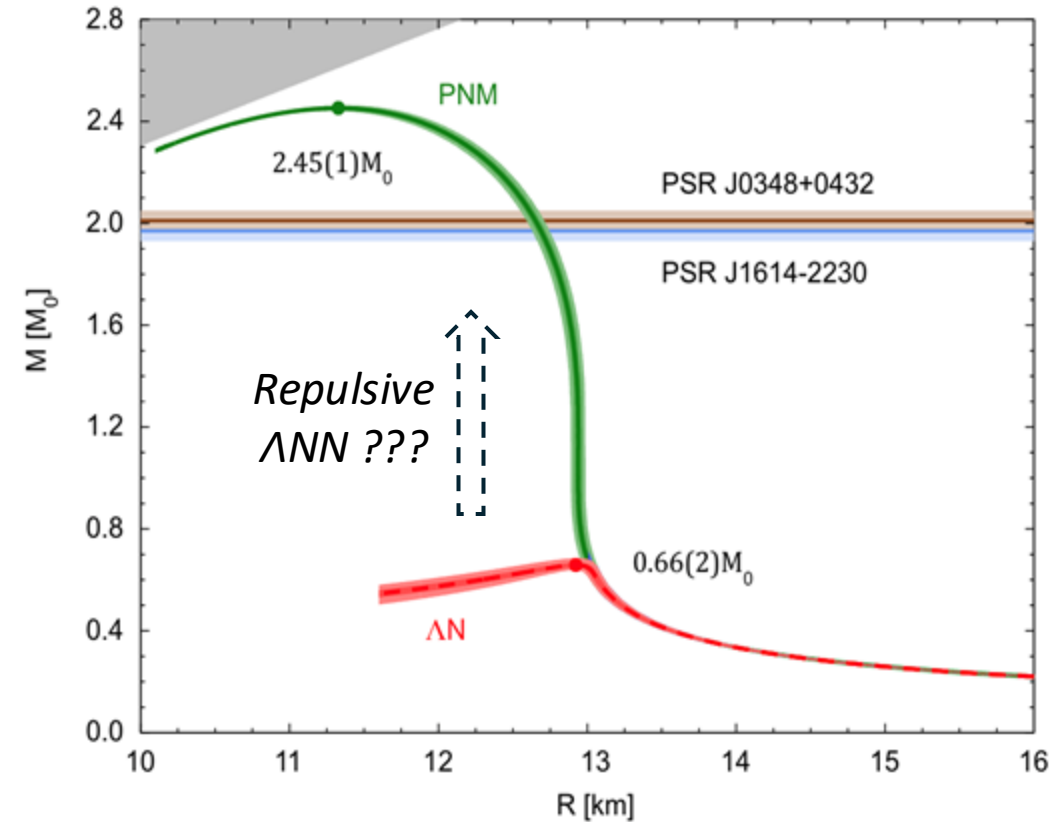
- High density in the core of neutron stars
 - Production of hyperons as Λ at $\rho = 2-3\rho_0$ and softening of the equation of state
 - Incompatibility with astrophysical measurements of $M_{NS} \gtrsim 2 M_{\odot}$
 - Long-standing hyperon puzzle
- Repulsive 3-body ΛNN interaction can stiffen the EoS but:
 - Effect on EoS largely model dependent
 - too repulsive YNN leads to no hyperons in the NSs



Nature Reviews Physics 4 (2022)
Figure adapted from NICER

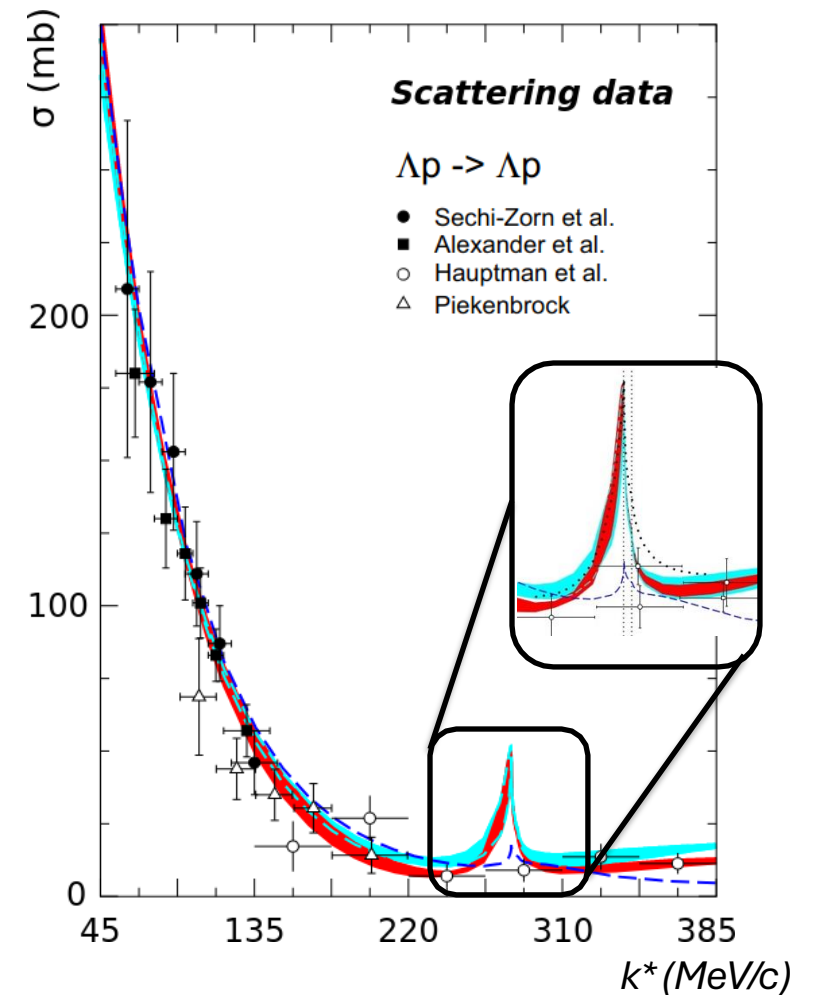
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The $p\Lambda$ interaction so far...

- Mainly investigated with scattering data
 - High-precision results by CLAS at large momenta
CLAS coll. PRL 127 (2021), 27, 27230
 - Large uncertainties at low momenta and not available down to threshold
- Cusp structure at ΣN opening
 - Coupling ΛN - ΣN driving the behaviour of Λ at finite ρ
D. Gerstung et al. Eur.Phys.J.A 56 (2020), 6, 175; J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91
 - State-of-art chiral potentials with different ΛN - ΣN strength



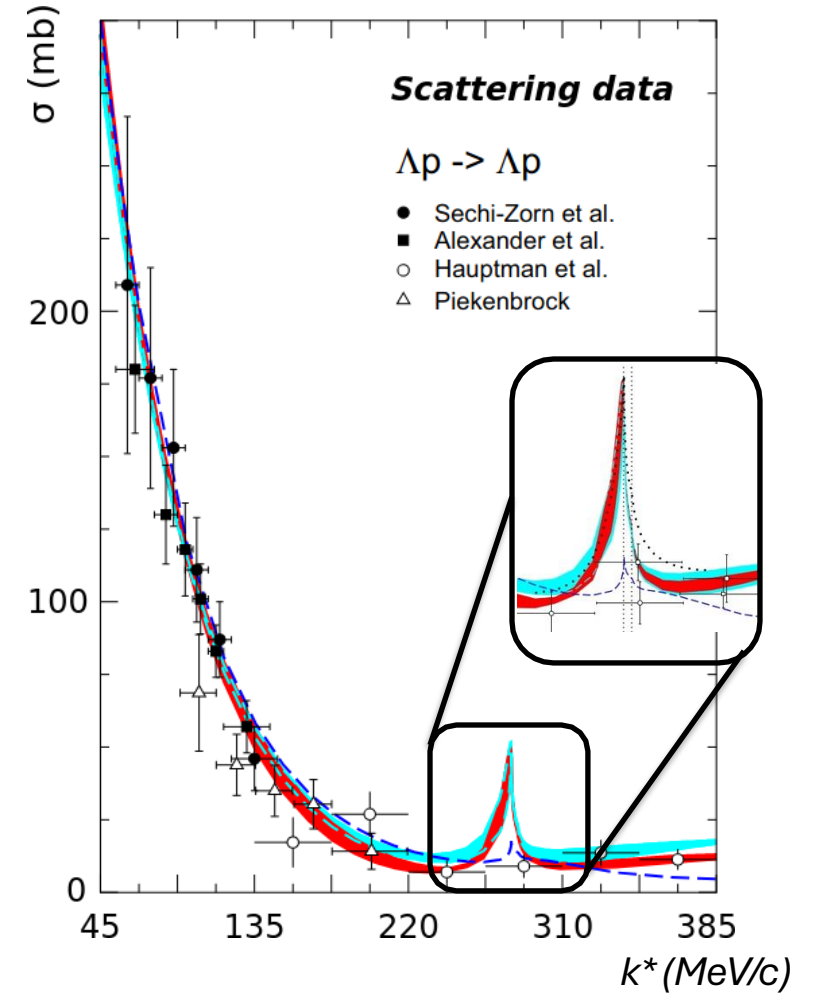
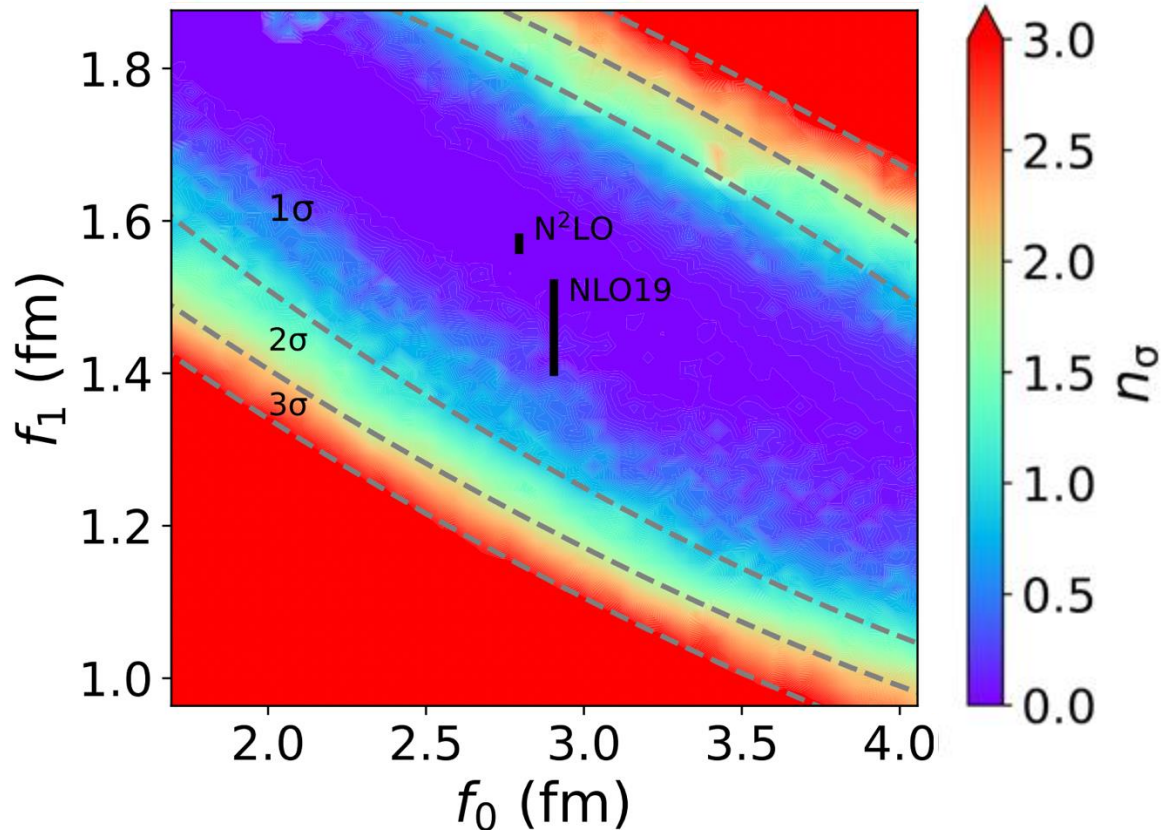
NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

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

The $p\Lambda$ interaction before femtoscopy

- Spin-0 and Spin-1 scattering length from scattering data
- Agreement with N²LO and NLO19

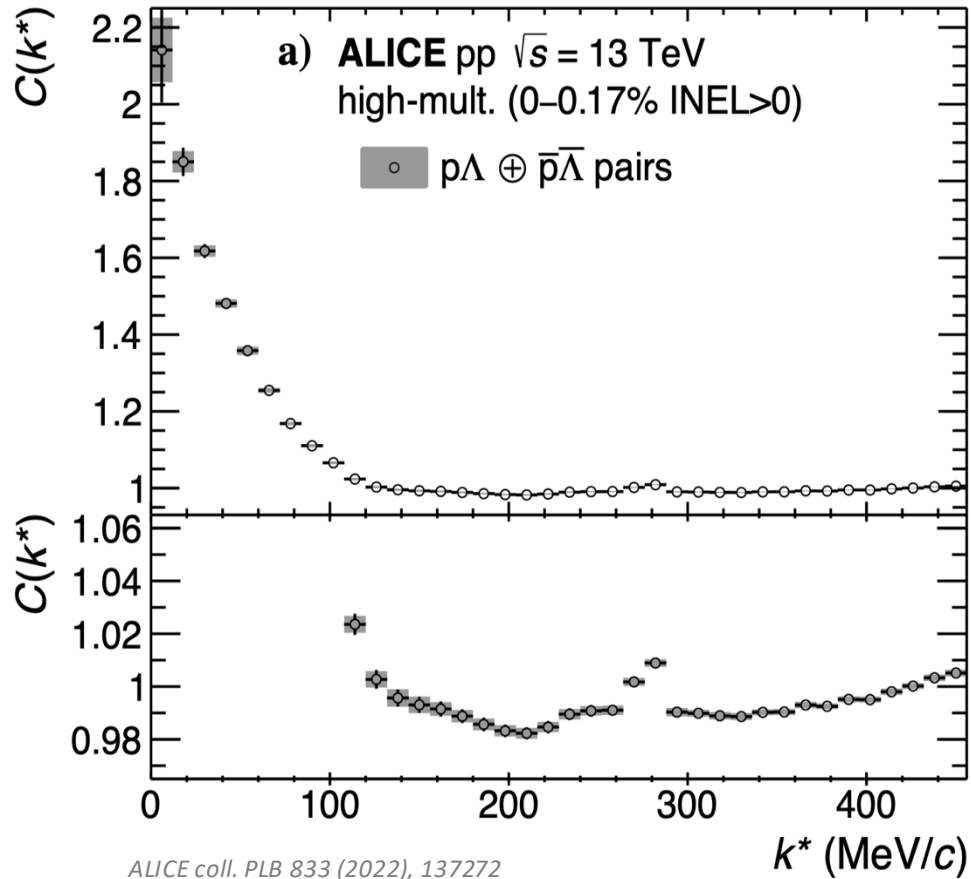
D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550



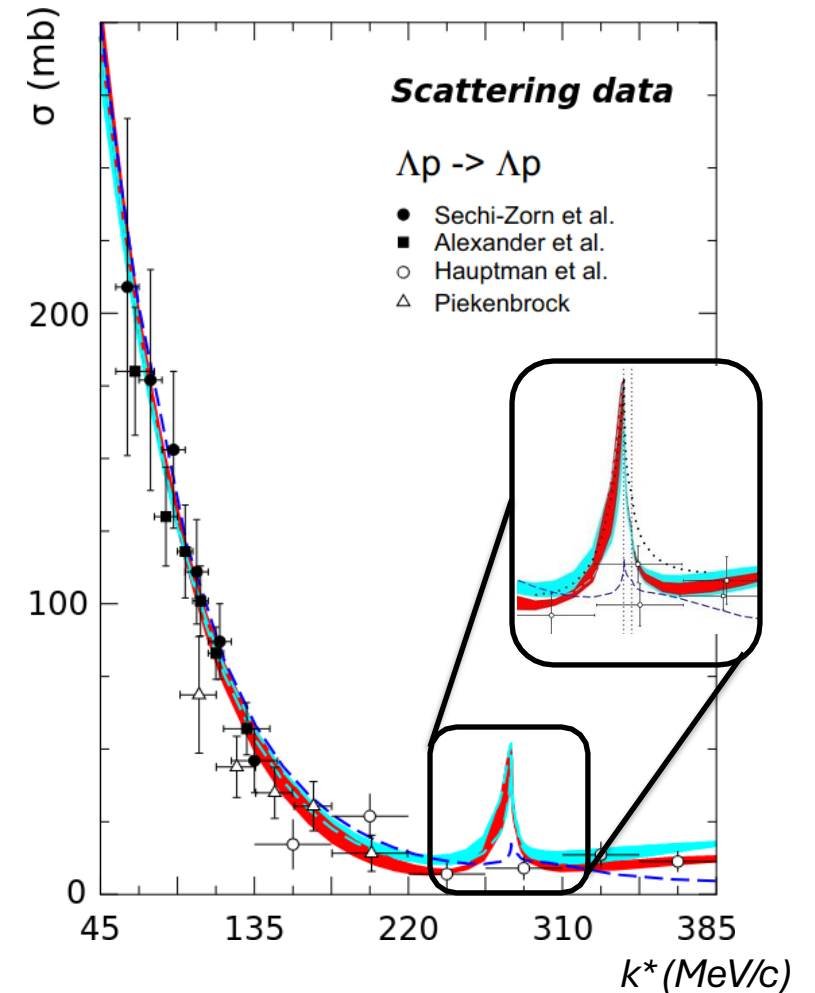
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The $p\Lambda$ interaction in the femtoscopy era



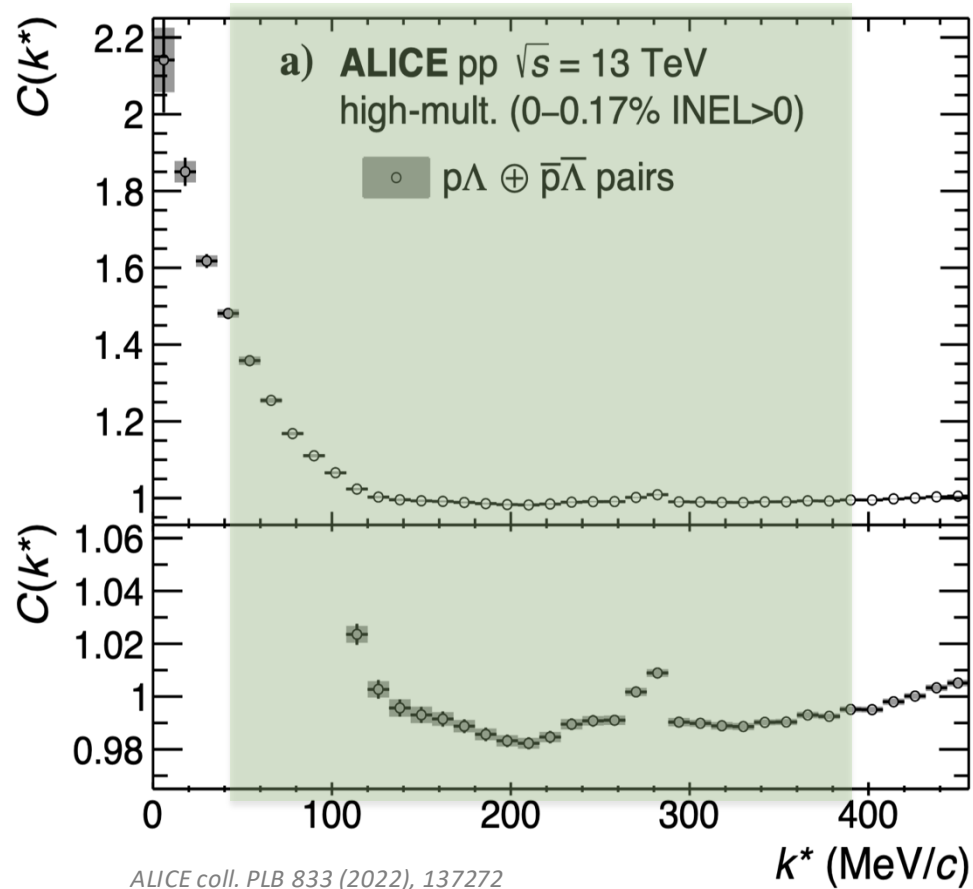
- Measurement down to zero momentum
- Factor 20 improved precision (<1%)
- First experimental evidence of ΛN - ΣN opening in 2-body channel



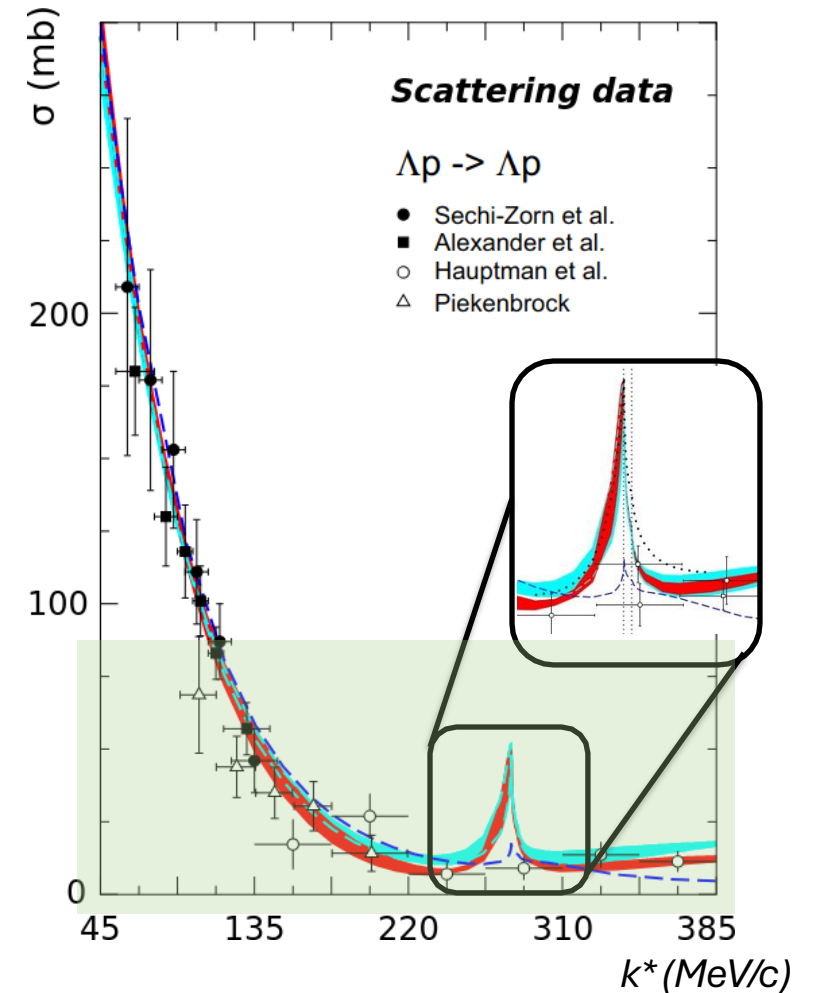
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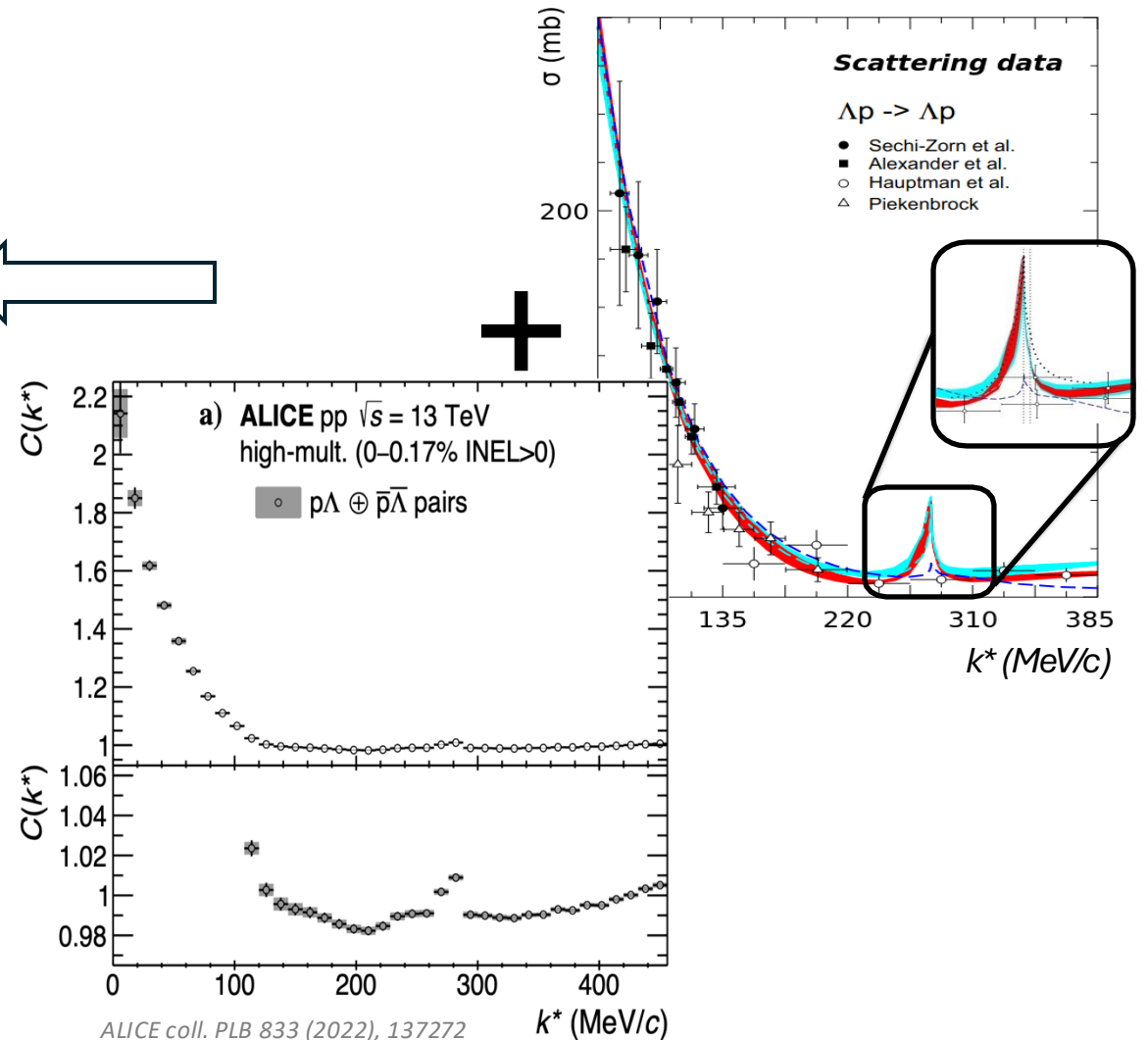
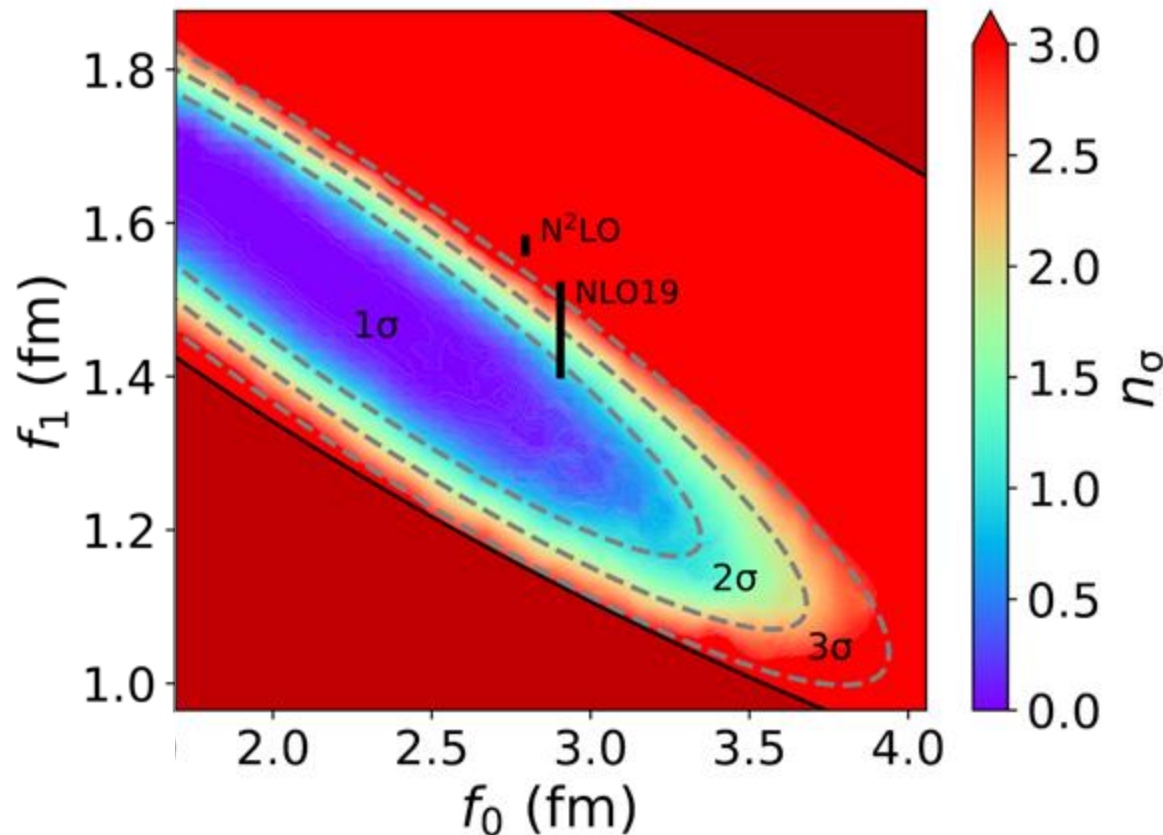
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- **NEW**: combined analysis of femtoscopic and scattering data

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

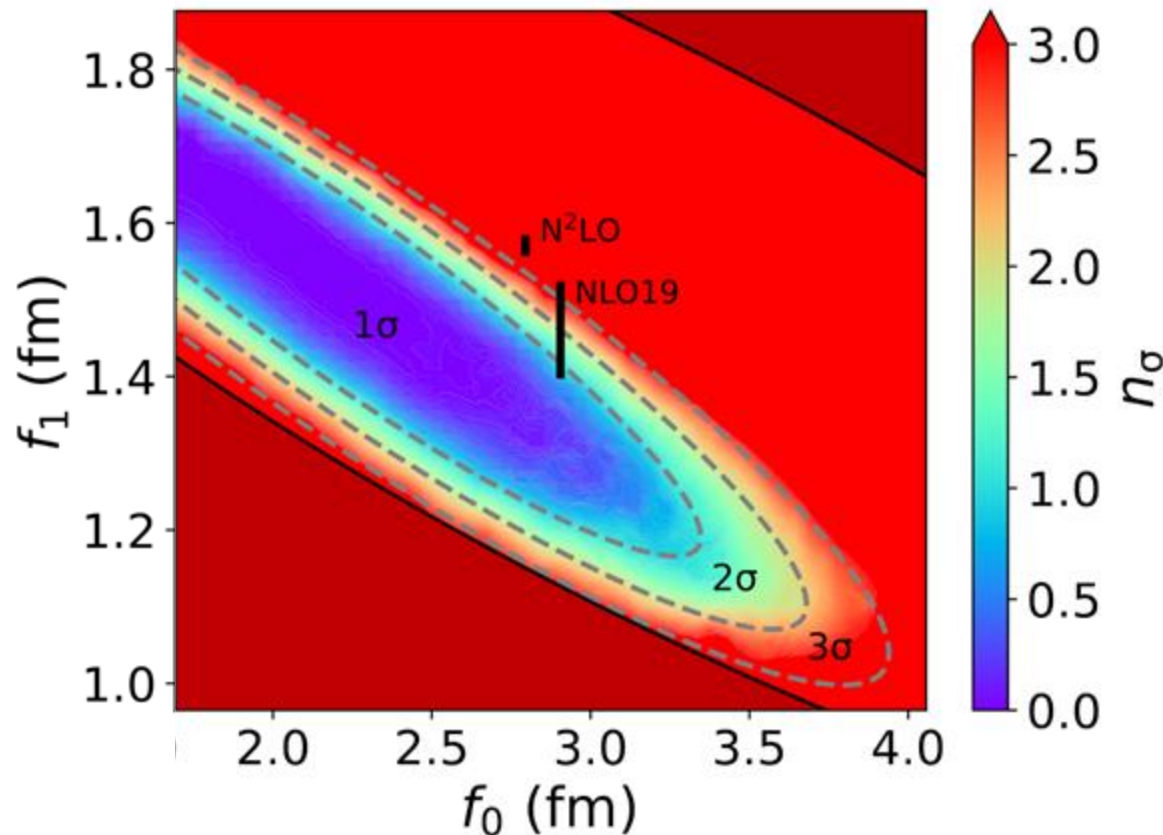


ALICE coll. PLB 833 (2022), 137272

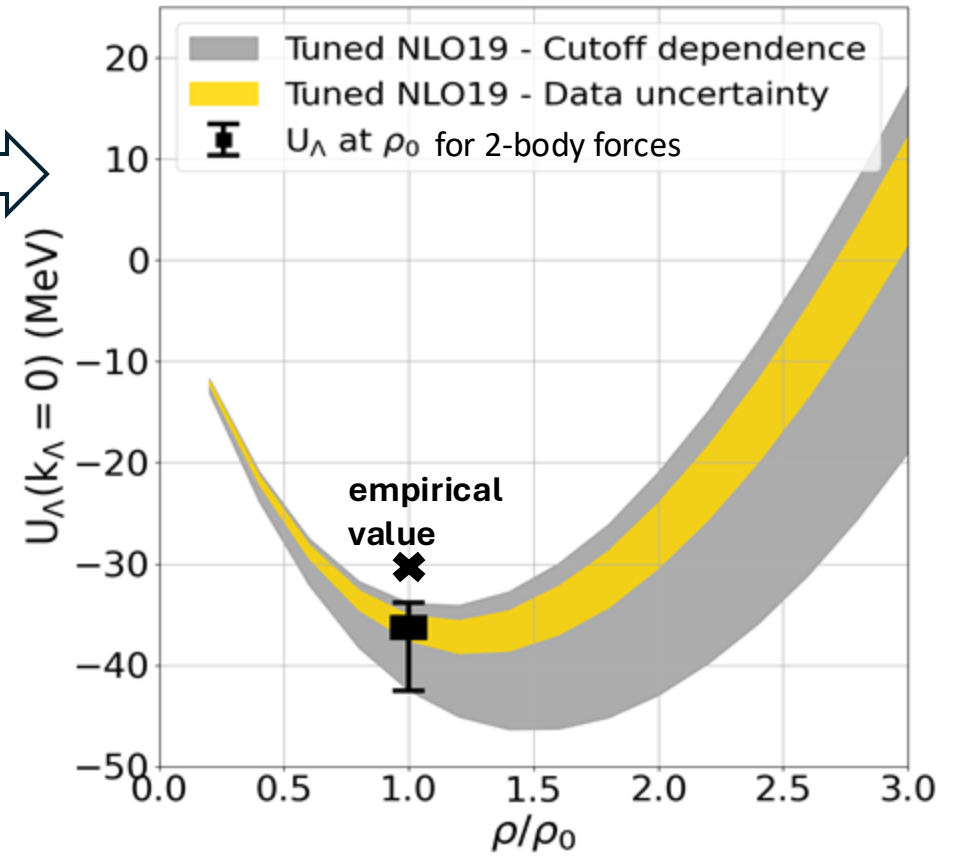
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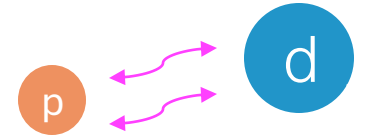


**New parameterizations of the χ EFT
Compatible with repulsive 3-body forces**



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

NNN using proton-deuteron correlations



- Coulomb + strong interaction using the Lednický model

$$\psi(\vec{k}^*, \vec{r}^*) = e^{i\delta_c} \sqrt{A_c(\eta)} \left[e^{-i\vec{k}^* \cdot \vec{r}^*} F(-i\eta, 1, i\xi) + f_C(k^*) \frac{\tilde{G}(\rho, \eta)}{r^*} \right]$$

$$f_C(k^*) = \left(\frac{1}{f_0} + \frac{d_0 \cdot k^{*2}}{2} - \frac{2h(k^*)}{a_c} - ik^* A_C(k^*) \right)^{-1}$$

Lednický, R. Phys. Part. Nuclei 40, 307–352 (2009)

- Point-like particle models anchored to scattering experiments

System	Spin averaged		S = 1/2		S = 3/2	
	f ₀ (fm)	d ₀ (fm)	f ₀ (fm)	d ₀ (fm)	f ₀ (fm)	d ₀ (fm)
p-d			-1.30 ^{+0.20} _{-0.20}	—	-11.40 ^{+1.20} _{-1.80}	2.05 ^{+0.25} _{-0.25}
			-2.73 ^{+0.10} _{-0.10}	2.27 ^{+0.12} _{-0.12}	-11.88 ^{+0.10} _{-0.40}	2.63 ^{+0.01} _{-0.02}
			-4.0	—	-11.1	—
			-0.024	—	-13.7	—
			0.13 ^{+0.04} _{-0.04}	—	-14.70 ^{+2.30} _{-2.30}	—
K ⁺ -d	-0.470	1.75				
	-0.540	0.0				

- Only s-wave interaction
- Source radius evaluated using the hadron-hadron universal m_T scaling

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

NNN using proton-deuteron correlations

- Point-like particle models anchored to scattering experiments

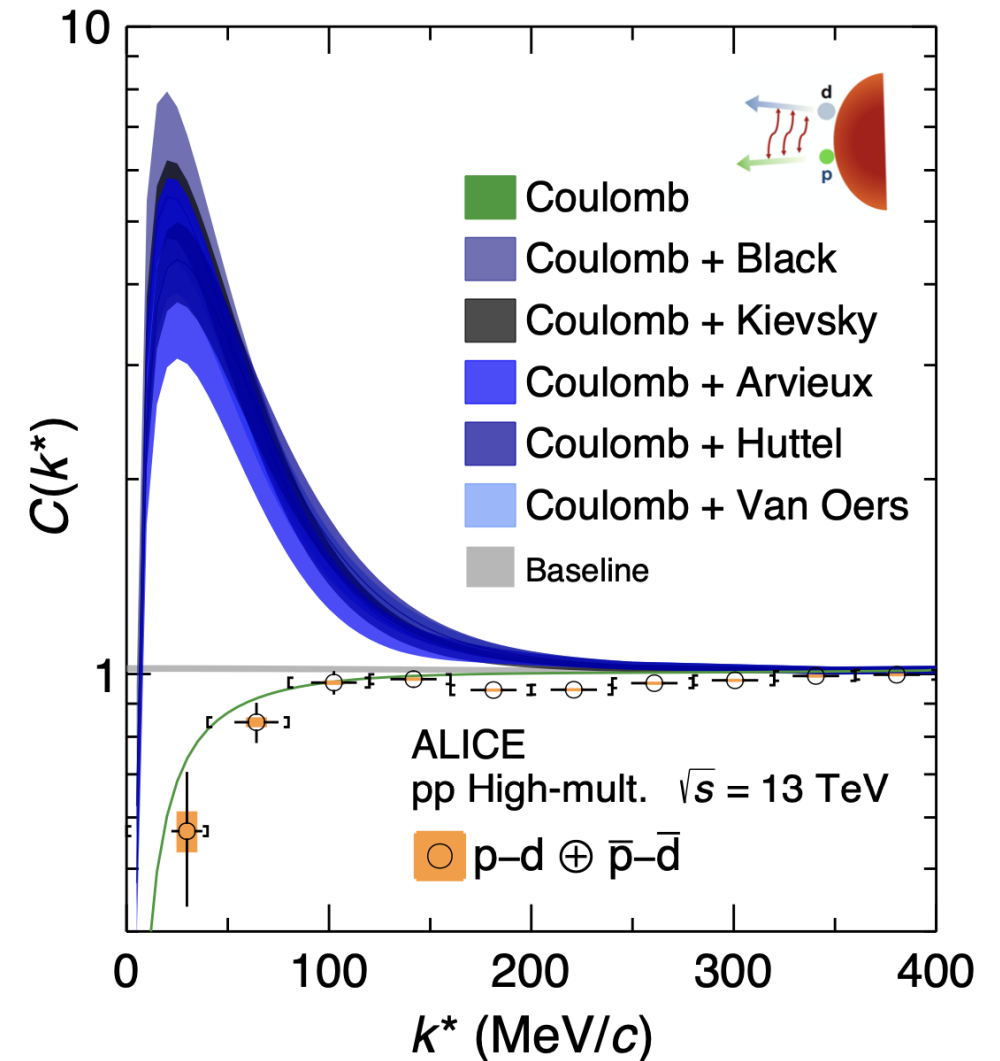
W. T. H. Van Oers et al., NPA 561 (1967);

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);

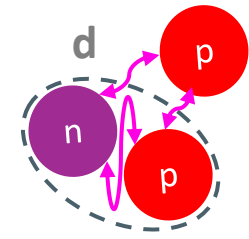
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Point-like particle description doesn't work for p-d



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

NNN using proton-deuteron correlations



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

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

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

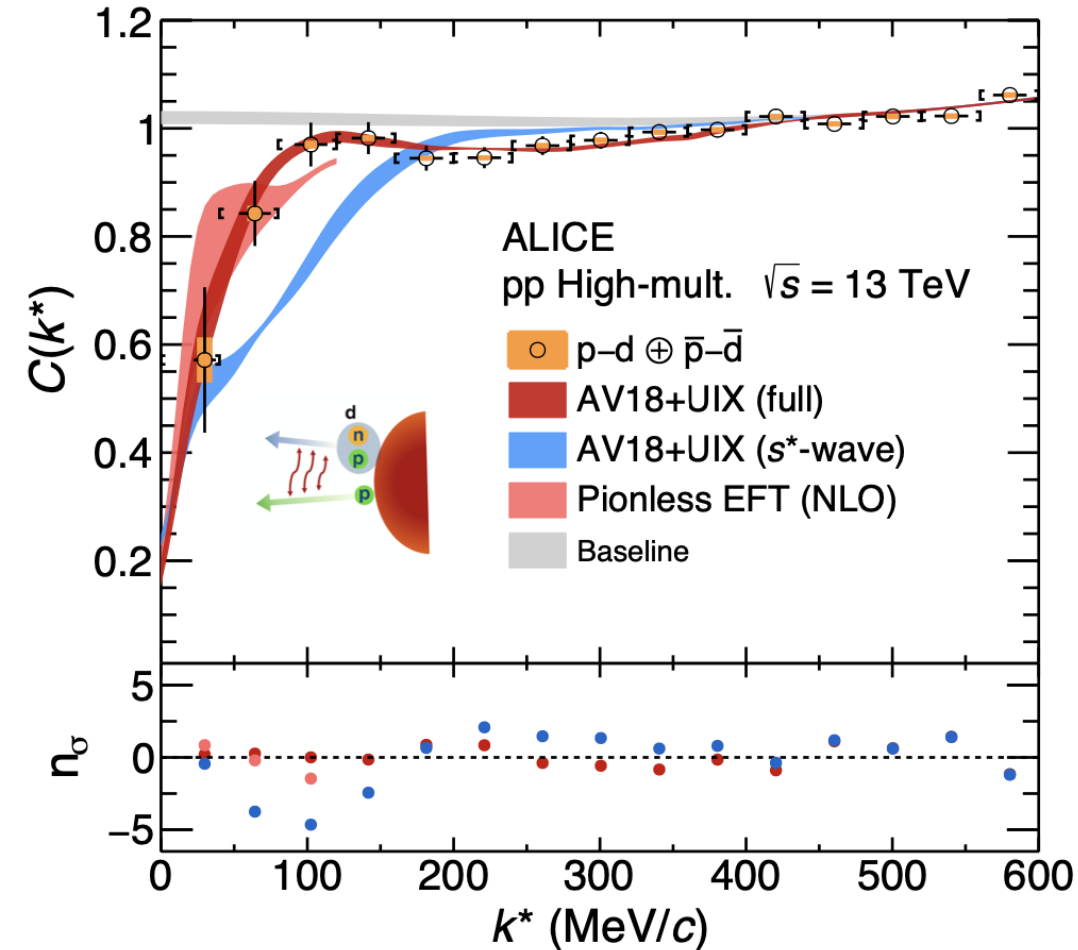
- The **three-body wavefunction** of the p-d System

$$\Psi_{m_2, m_1}(x, y) = \underbrace{\Psi_{m_2, m_1}^{free}}_{\text{Asymptotic solution}} + \underbrace{\sum_{LSJ} \sqrt{4\pi} i^L \sqrt{2L+1} e^{i\sigma_L} \left(1m_2 \frac{1}{2} m_1 \middle| SJ_z\right) (LOSJ_z | JJ_z) \tilde{\Psi}_{LSJJ_z}}_{\text{Three-body dynamics}}$$

Asymptotic solution

Three-body dynamics

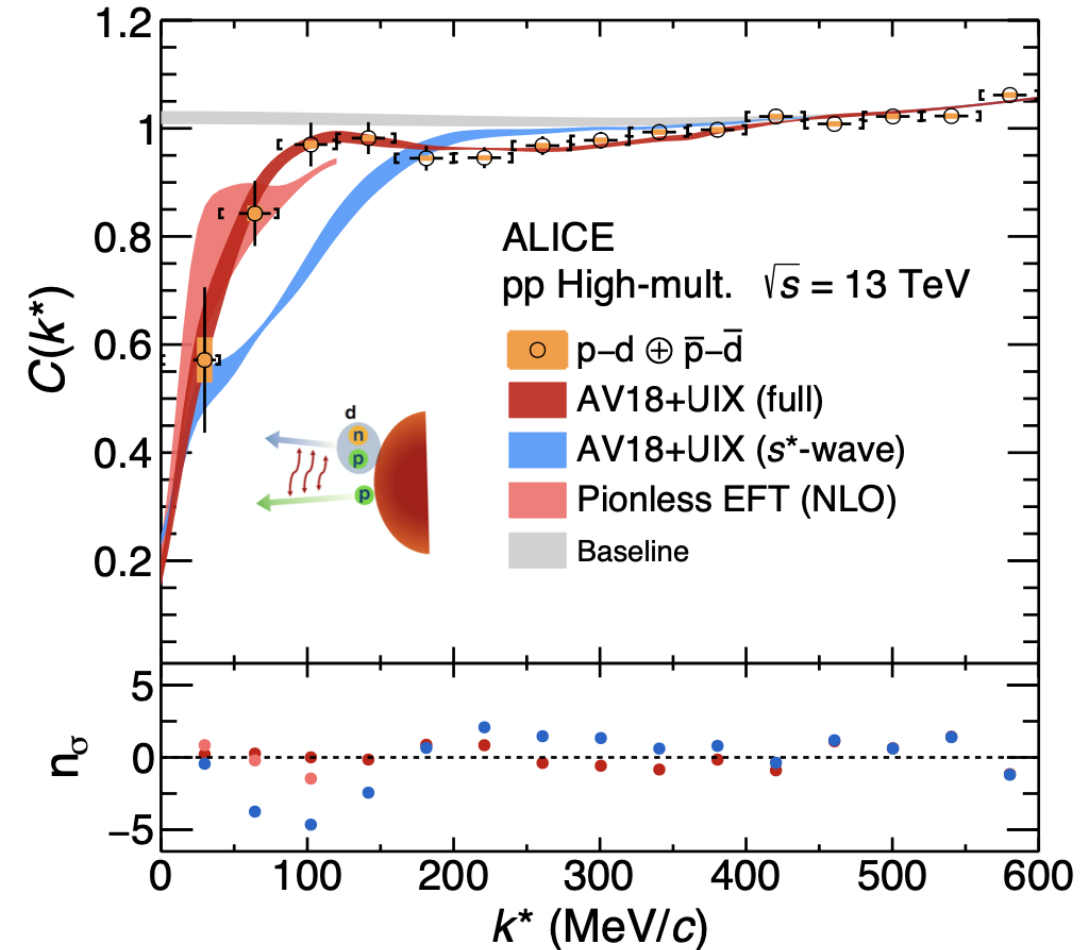
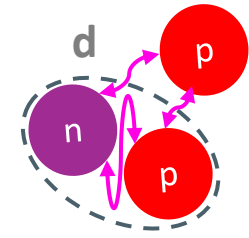
- Hadron-nuclei correlations at the LHC can be used to study many-body dynamics**



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

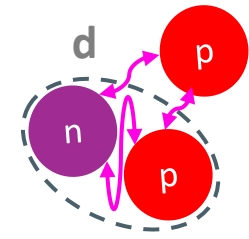
NNN using proton-deuteron correlations

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

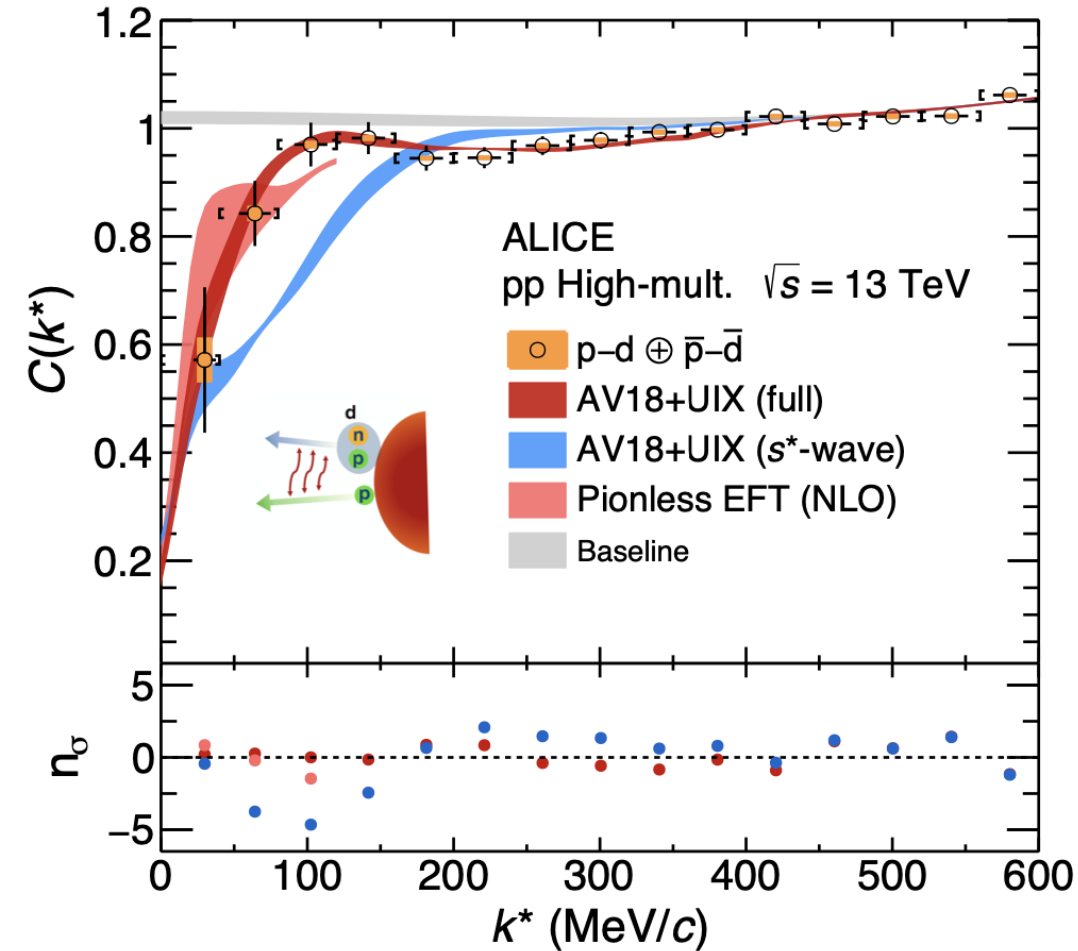
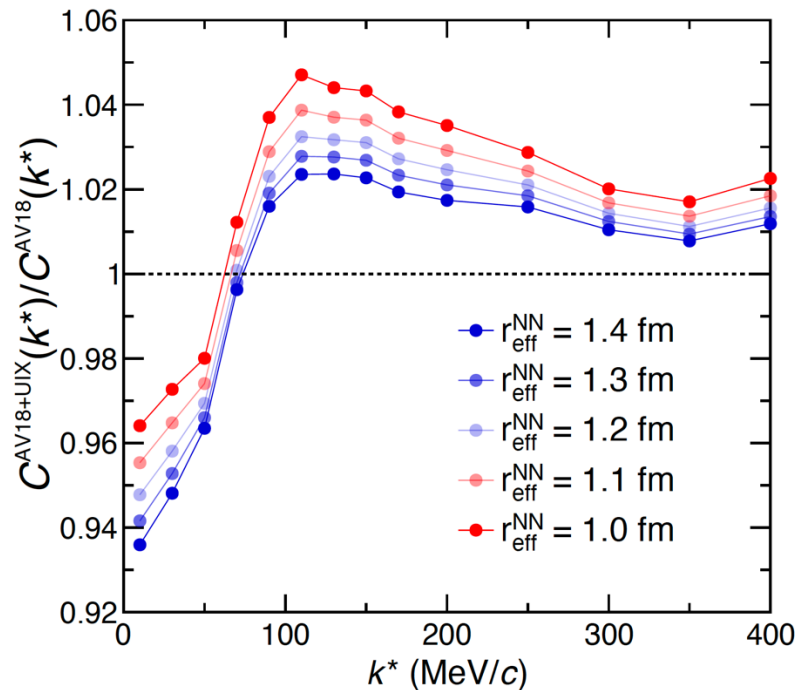


ALICE Coll. Phys. Rev. X 14, 031051 (2024)
M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002

NNN using proton-deuteron correlations

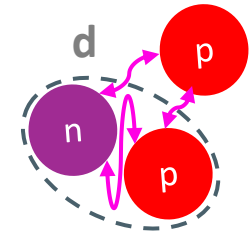


- Full three-body calculations are required (NN + NNN + Quantum Statistics)
- Hadron-nuclei correlations at the LHC can be used to study many-body dynamics
- Sensitivity to three-body forces up to 5%

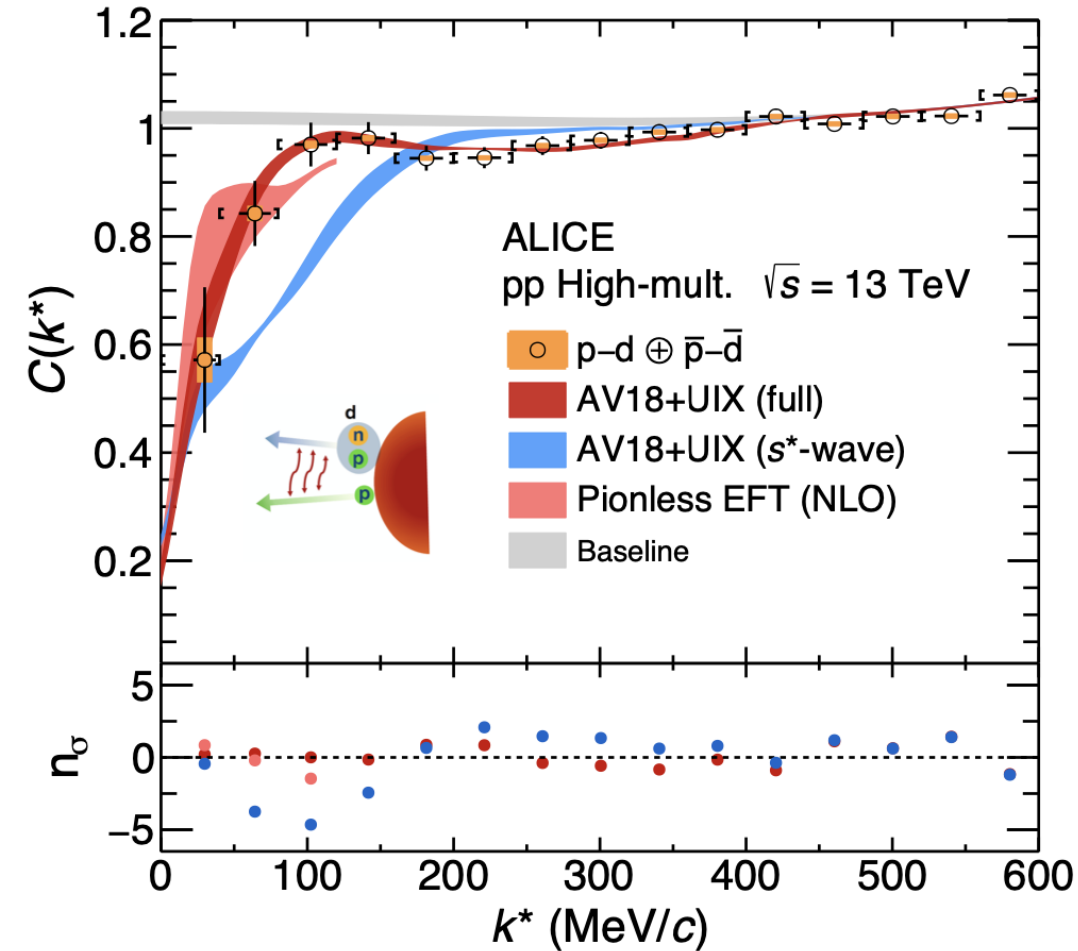
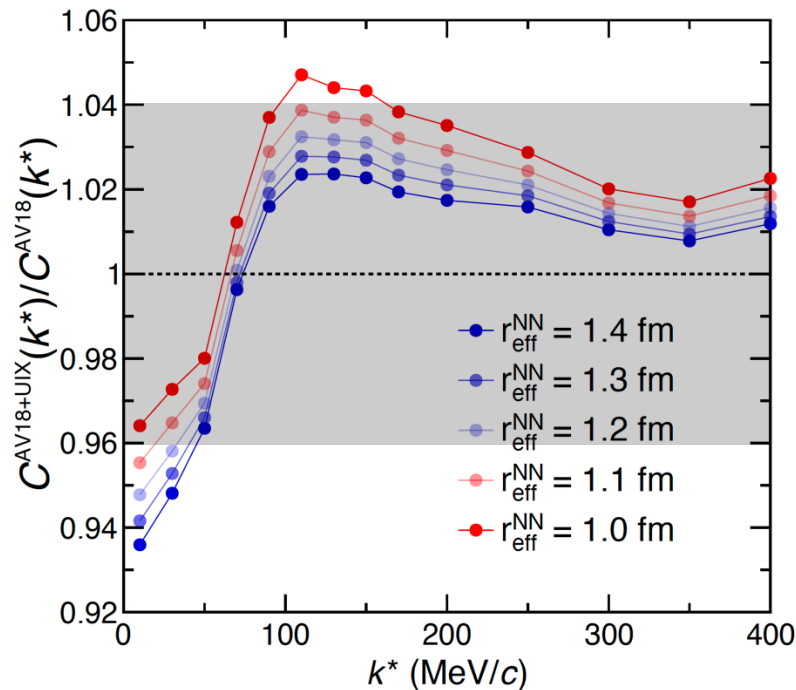


ALICE Coll. Phys. Rev. X 14, 031051 (2024)
M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002

NNN using proton-deuteron correlations

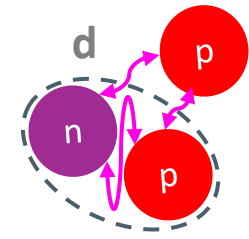


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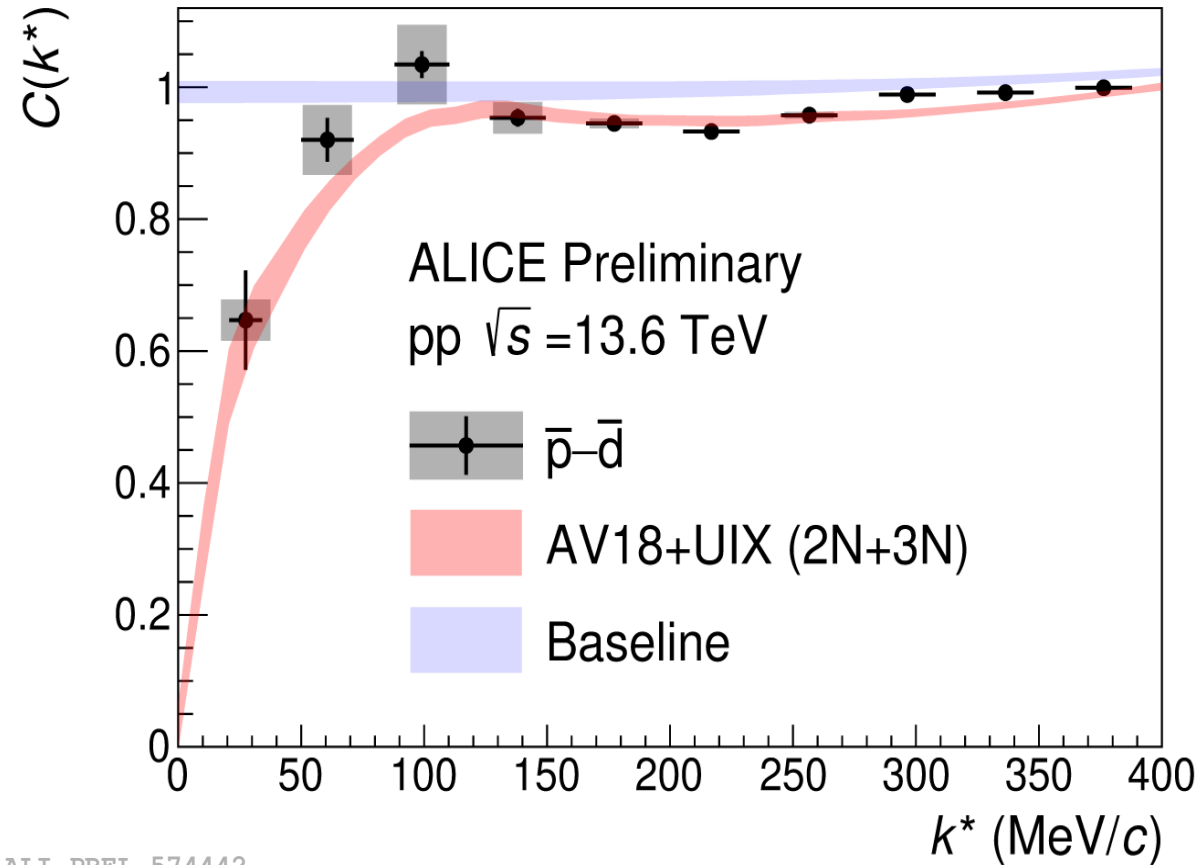
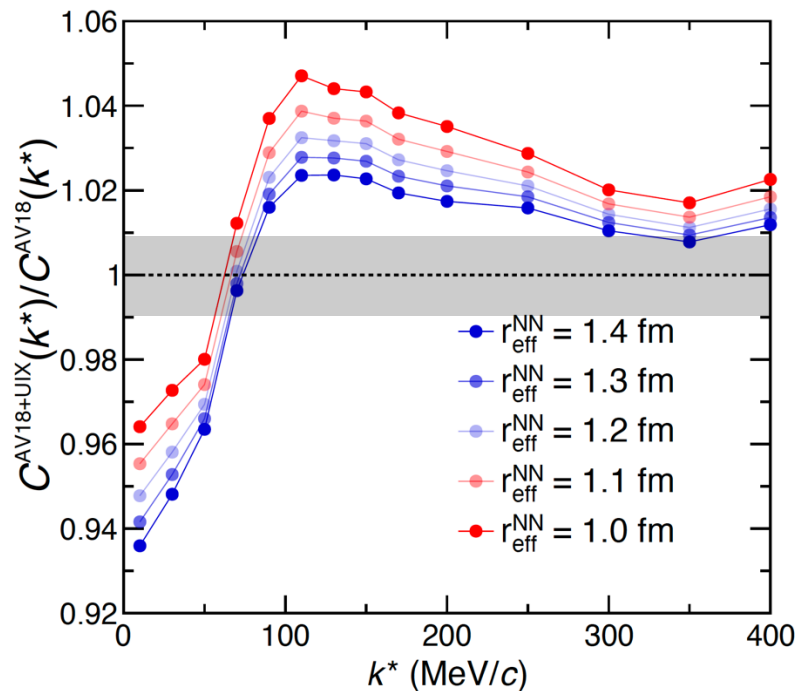


ALICE Coll. Phys. Rev. X 14, 031051 (2024)
M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002

NNN using proton-deuteron correlations

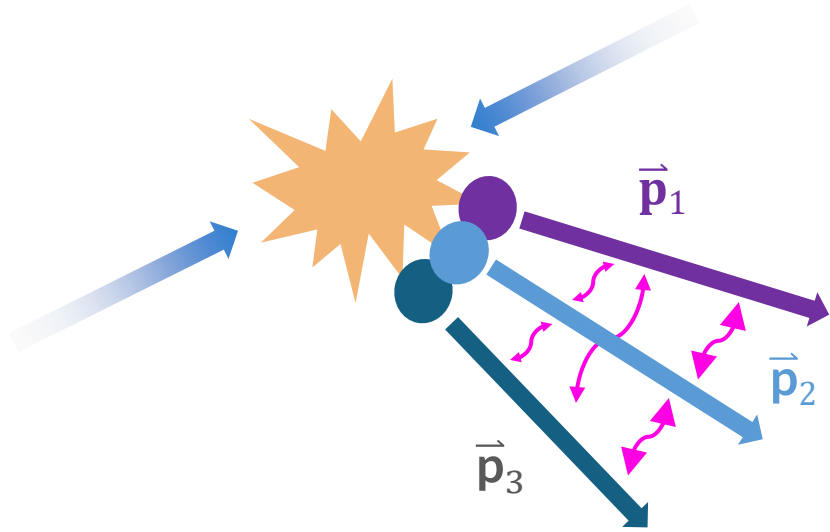


- Full three-body calculations are required (NN + NNN + Quantum Statistics)
- Run 3 data from 2022 already analysed and results are promising!
- In Run 3 expected uncertainty of 1%



ALI-PREL-574442

Three-body femtoscopy in pp collisions



Correlation function:

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

Three-body scattering wave function

Hyper-momentum:

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

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

Hyper-radius:

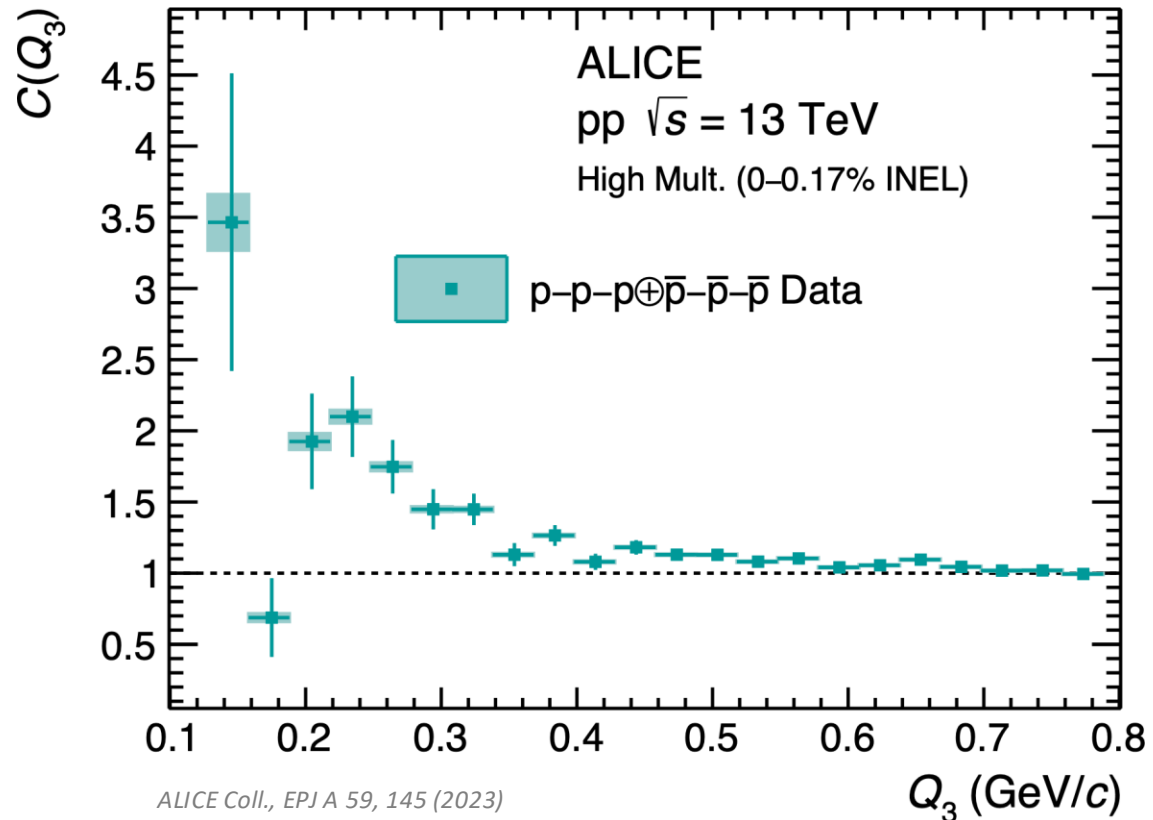
$$\rho = 2\sqrt{r_{12}^2 + r_{23}^2 + r_{31}^2}$$

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

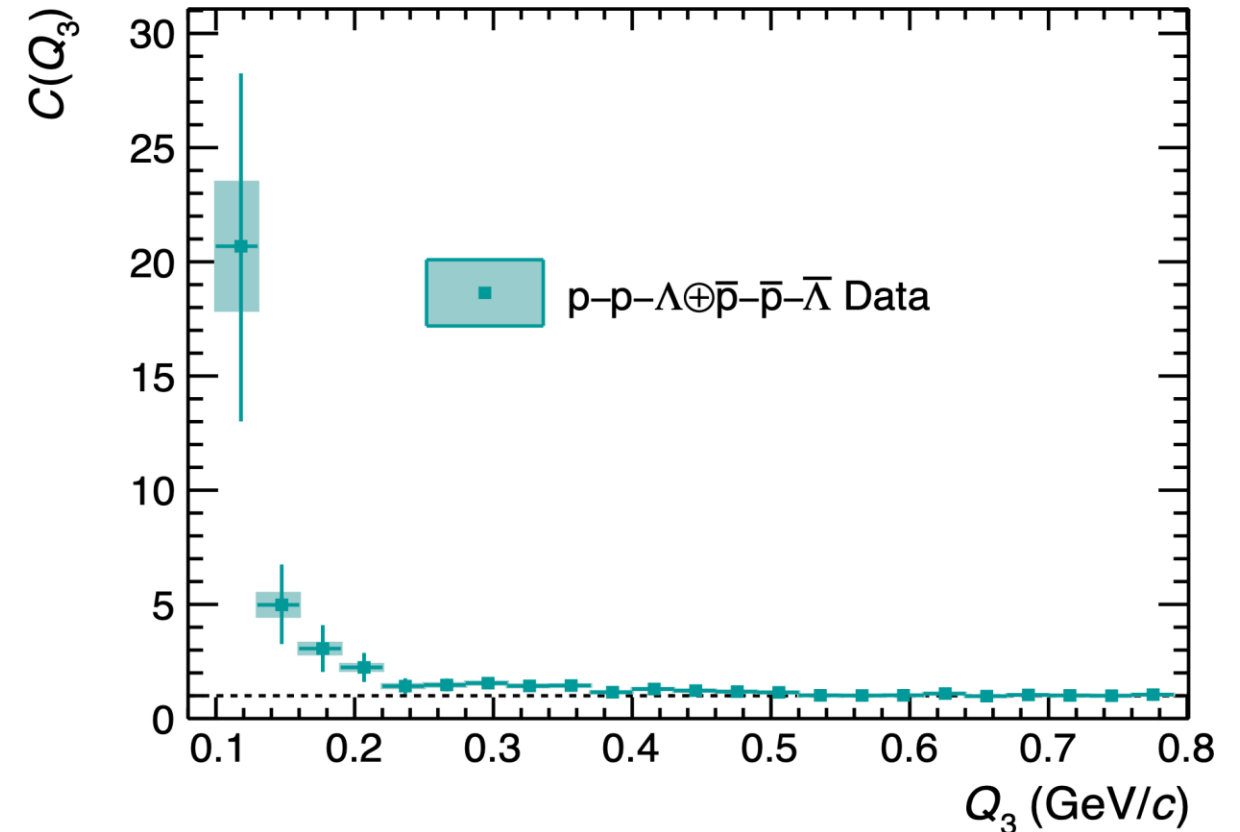
Extension to three-particle system

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

p-p-p



p-p- Λ



p-p-p correlation function

- First ever full three-body correlation function calculations

$$C(Q_3) = \int \rho^5 d\rho \underset{\text{hyperradius}}{S(\rho, \rho_0)} \overset{\text{three-proton wave function}}{|\Psi(\rho, Q_3)|^2}$$

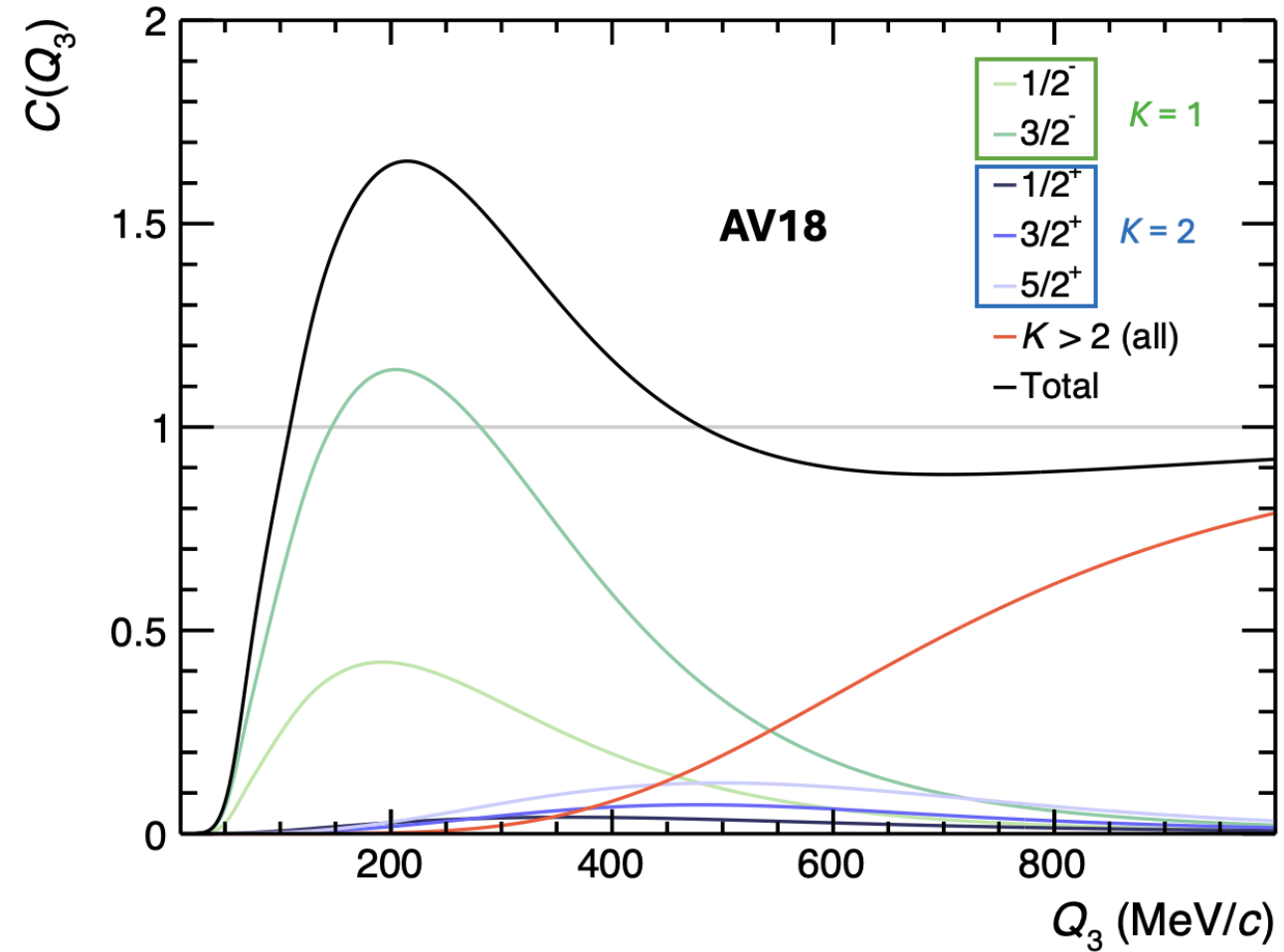
- Wave function in hyperspherical harmonics

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

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

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

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

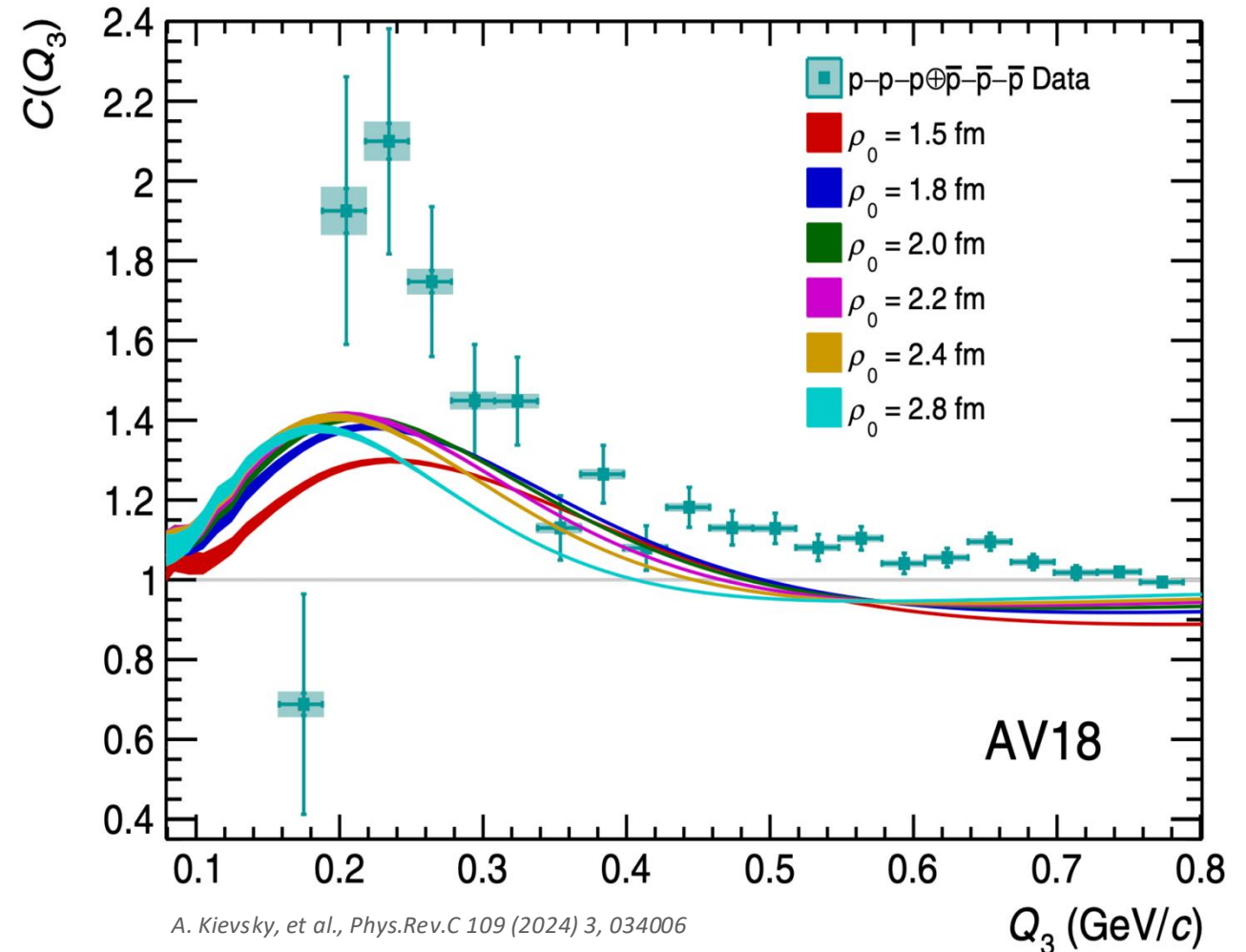


A. Kievsky, et al., Phys.Rev.C 109 (2024) 3, 034006

Comparison Run-2 data

Comparison with the ALICE Run-2 measurement:

- calculations can describe the shape observed in the data



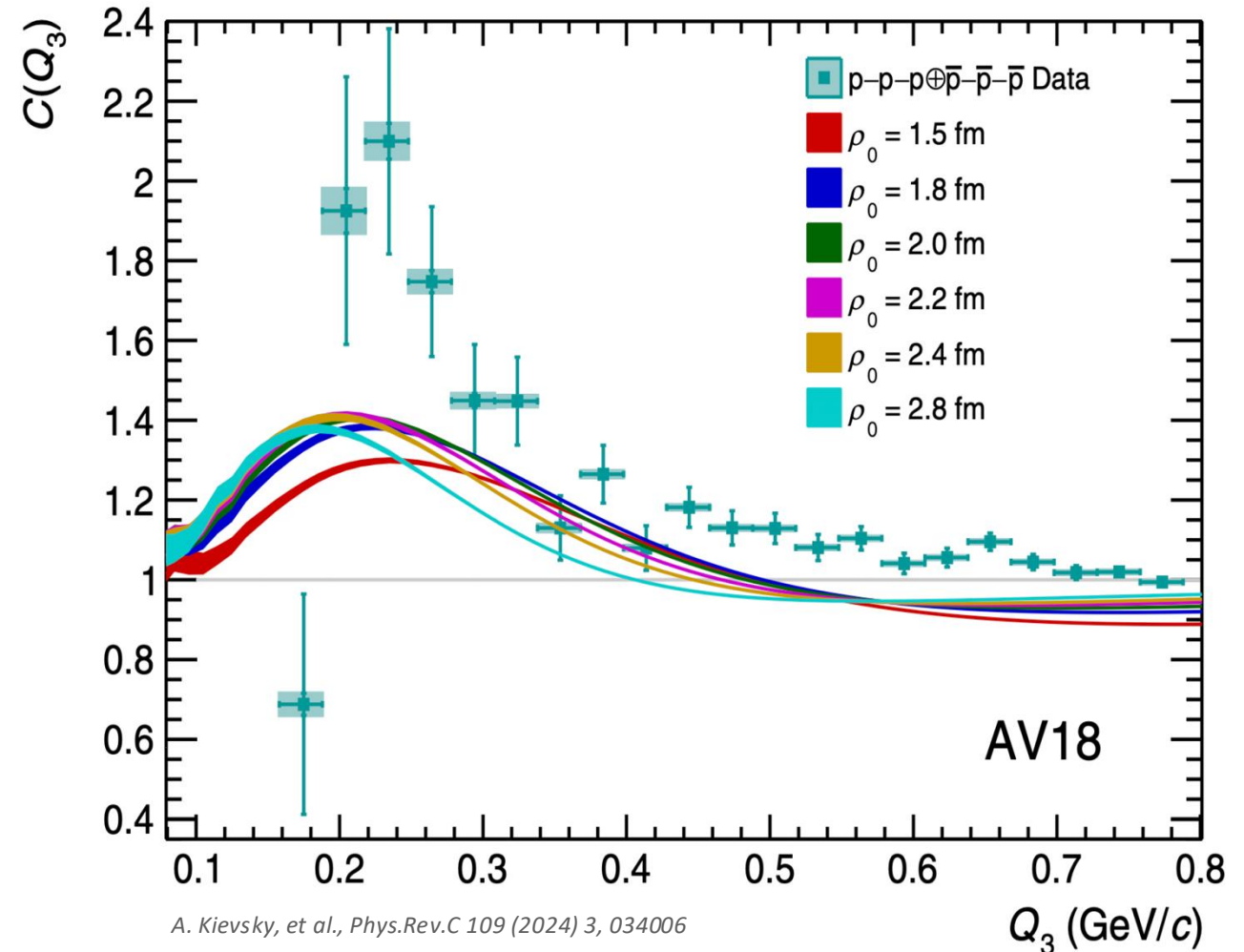
Comparison Run-2 data

Comparison with the ALICE Run-2 measurement:

- calculations can describe the shape observed in the data

Required improvements:

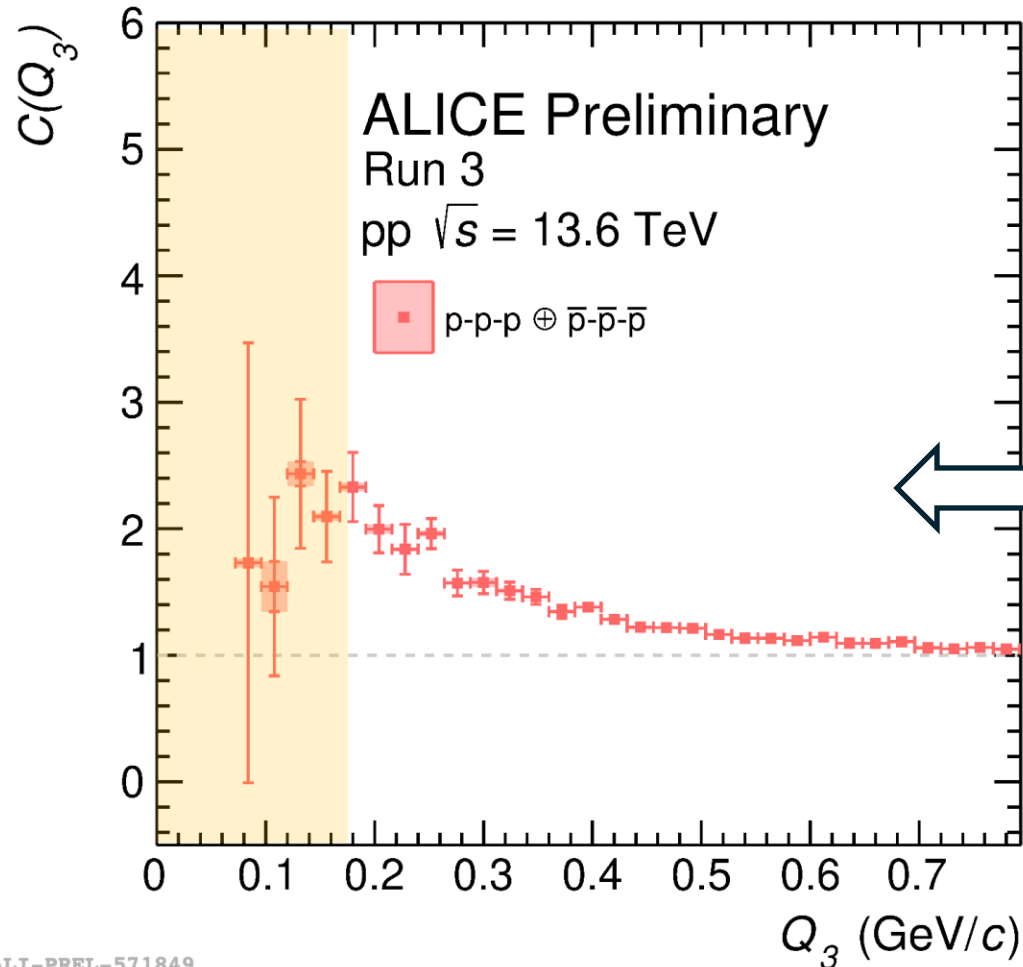
- More precision in the data is required
- Asymptotic behaviour of the wave function for three charged particles



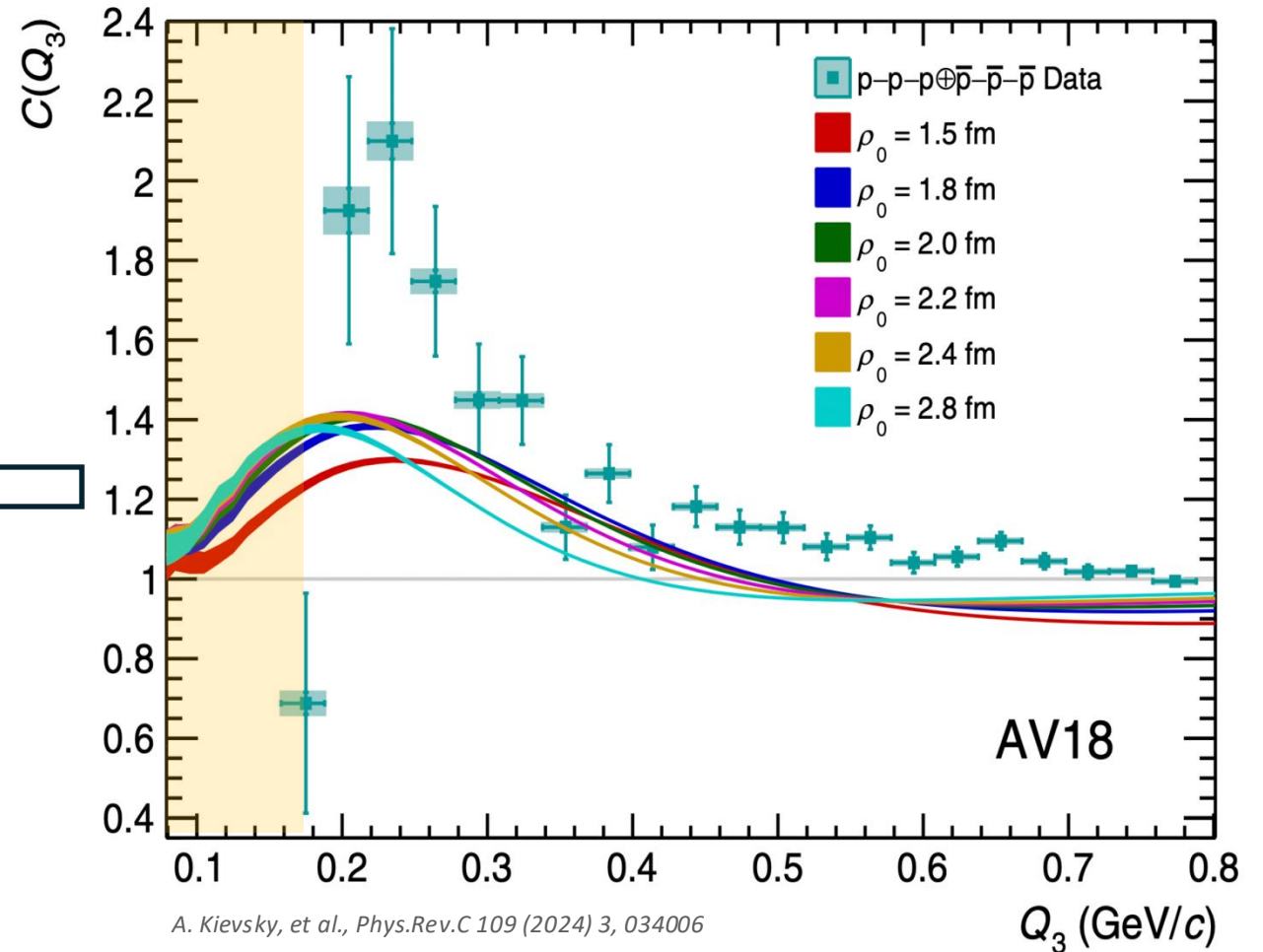
A. Kievsky, et al., Phys.Rev.C 109 (2024) 3, 034006

p-p-p correlation function in Run-3

- ALICE Run 3 data from 2022 are promising!



- ALICE Run-2 (2015-2018)



ALI-PREL-571849

p-p- Λ correlation function

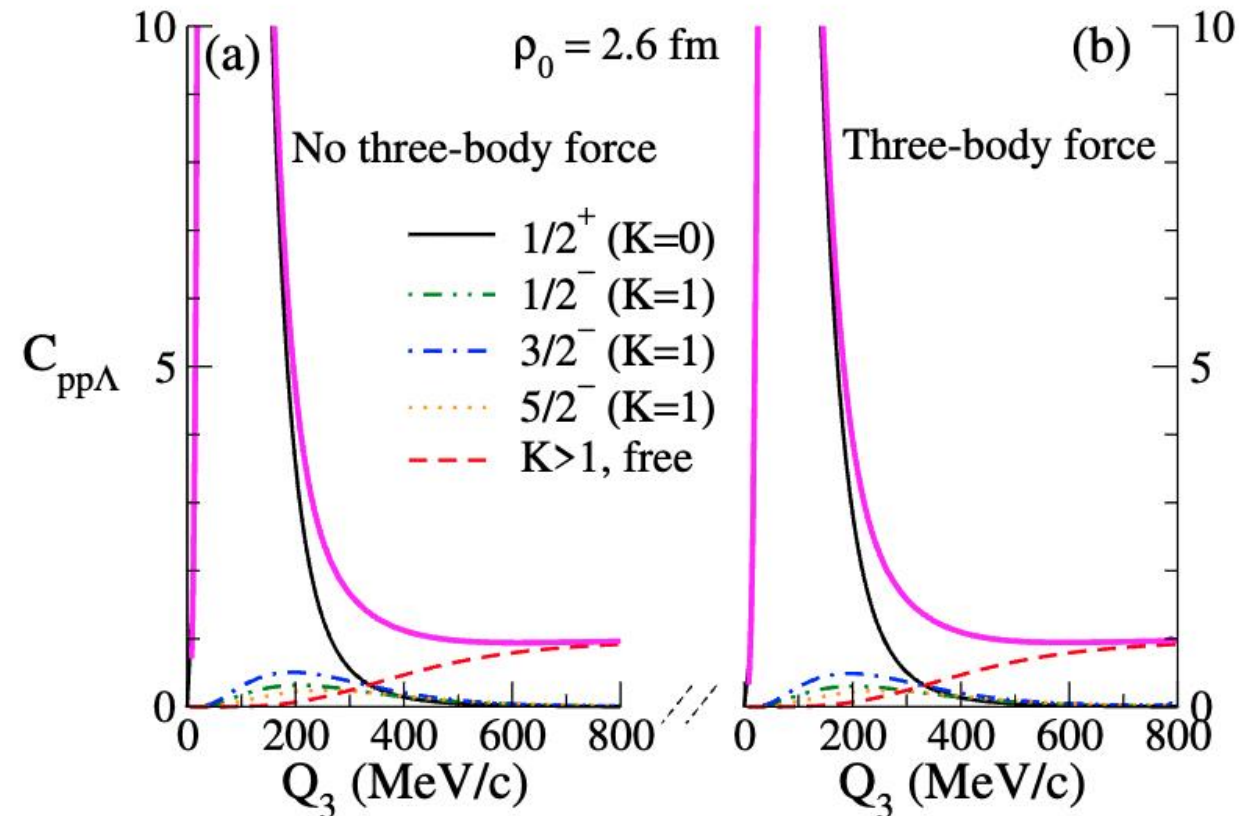
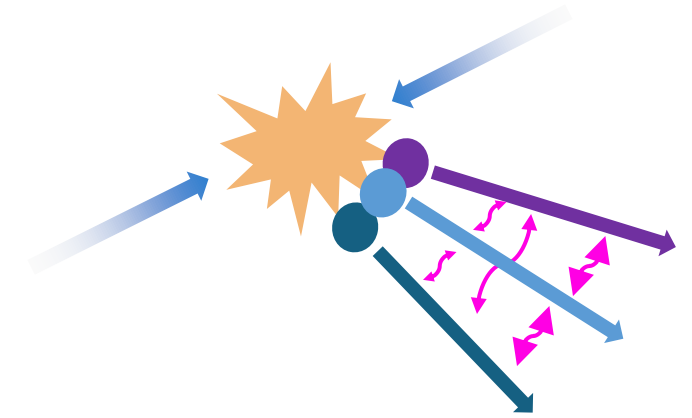
- First ever full three-body correlation function calculations

$$C(Q_3) = \int \rho^5 d\rho \underset{\text{hyperradius}}{S(\rho, \rho_0)} \overset{\text{three-proton wave function}}{|\Psi(\rho, Q_3)|^2}$$

- Wave function via HH:
 - NLO19 (600)
 - Quantum statistics
 - Three-body force constrained to the hypertriton binding energy
- Only one partial wave contributes

Results from recent paper:

E. Garrido et al., arXiv: 2408.01750 (2024), accepted by PRC



p-p- Λ correlation function

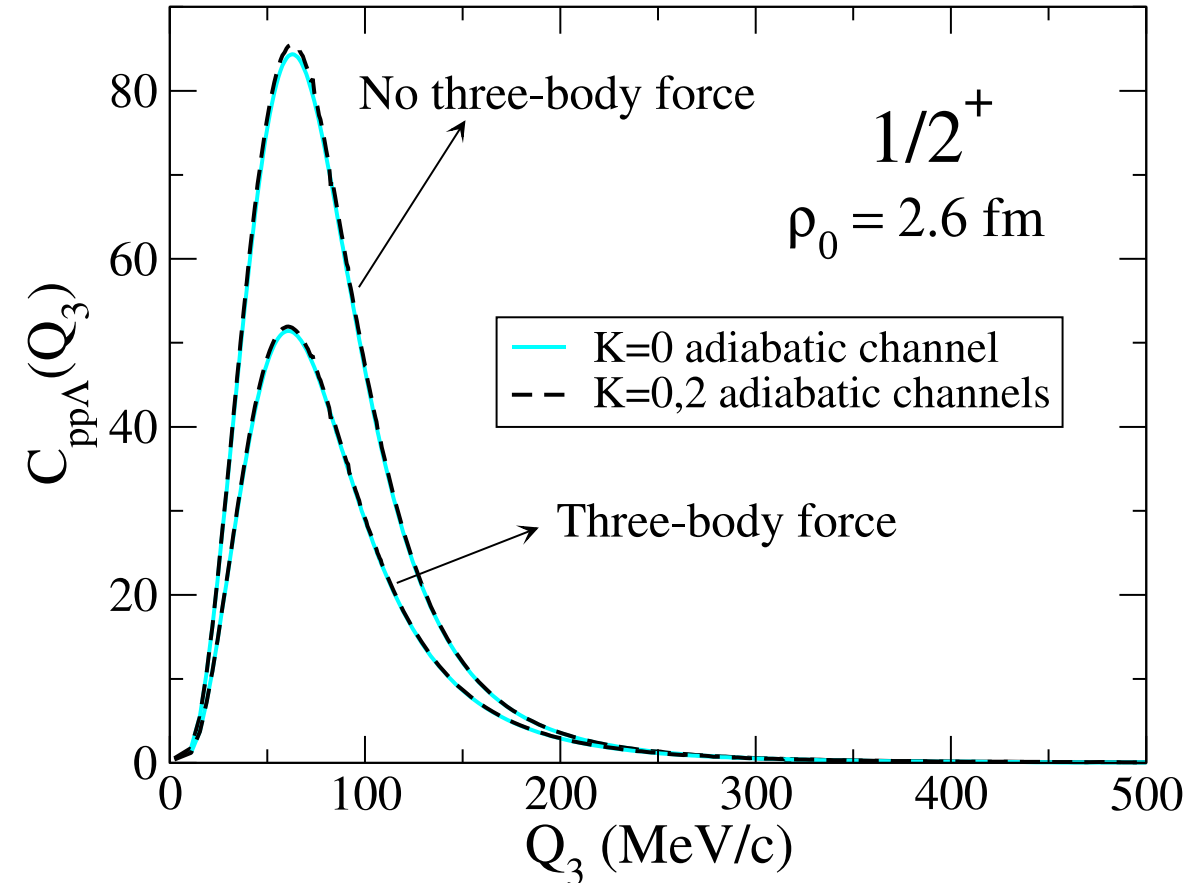
- Reference calculations:
 - two-body NN and Λ N interactions provide an overbinding of the hypertriton

$$BE({}^3_{\Lambda}\text{H}) = 2.904 \text{ MeV} \quad \text{exp: } 2.39 \text{ MeV}$$

E. Garrido et al., arXiv: 2408.01750 (2024)

Binding energy from:
<https://hypernuclei.kph.uni-mainz.de>

- three-body Λ NN interaction



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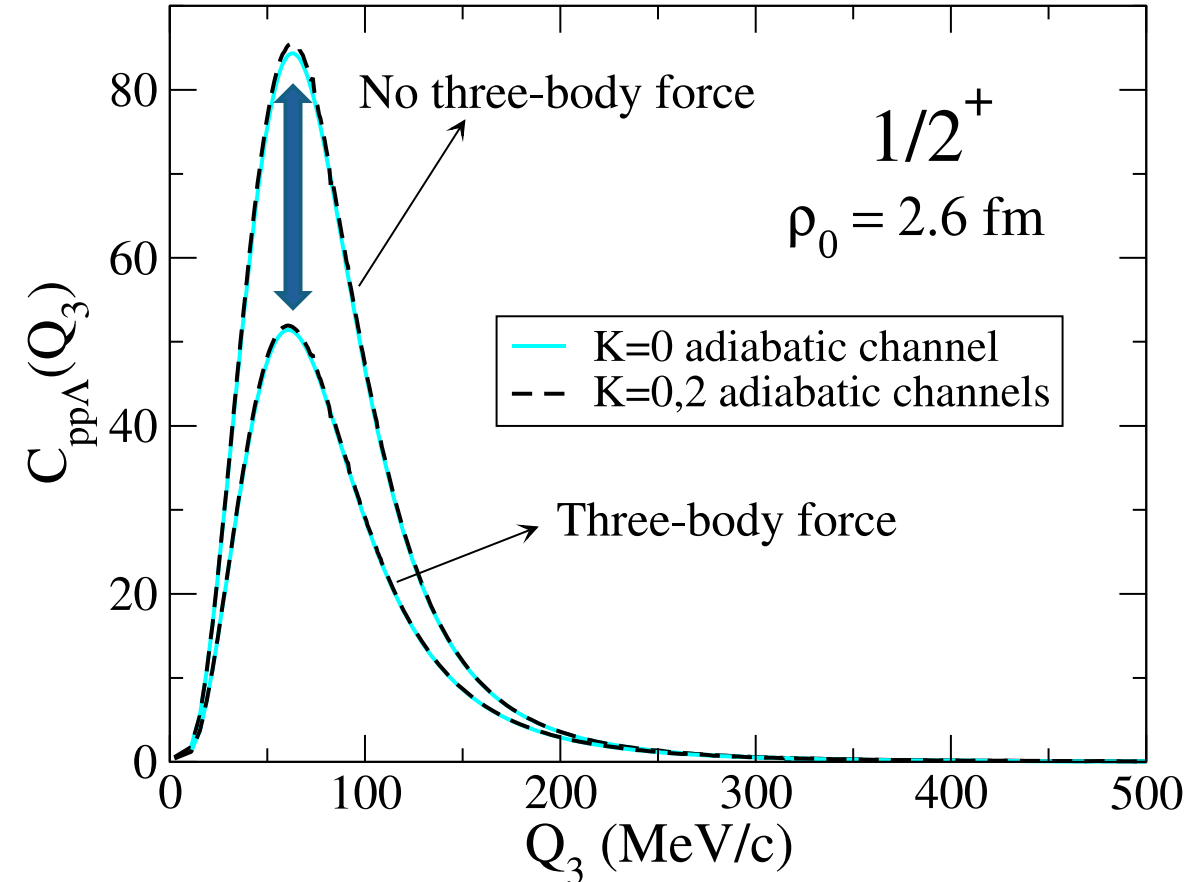
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Binding energy from:
<https://hypernuclei.kph.uni-mainz.de>

→ three-body Λ NN interaction

- **Λ NN interaction gives 40% effect:**
only one partial wave (K=0) significantly contributes

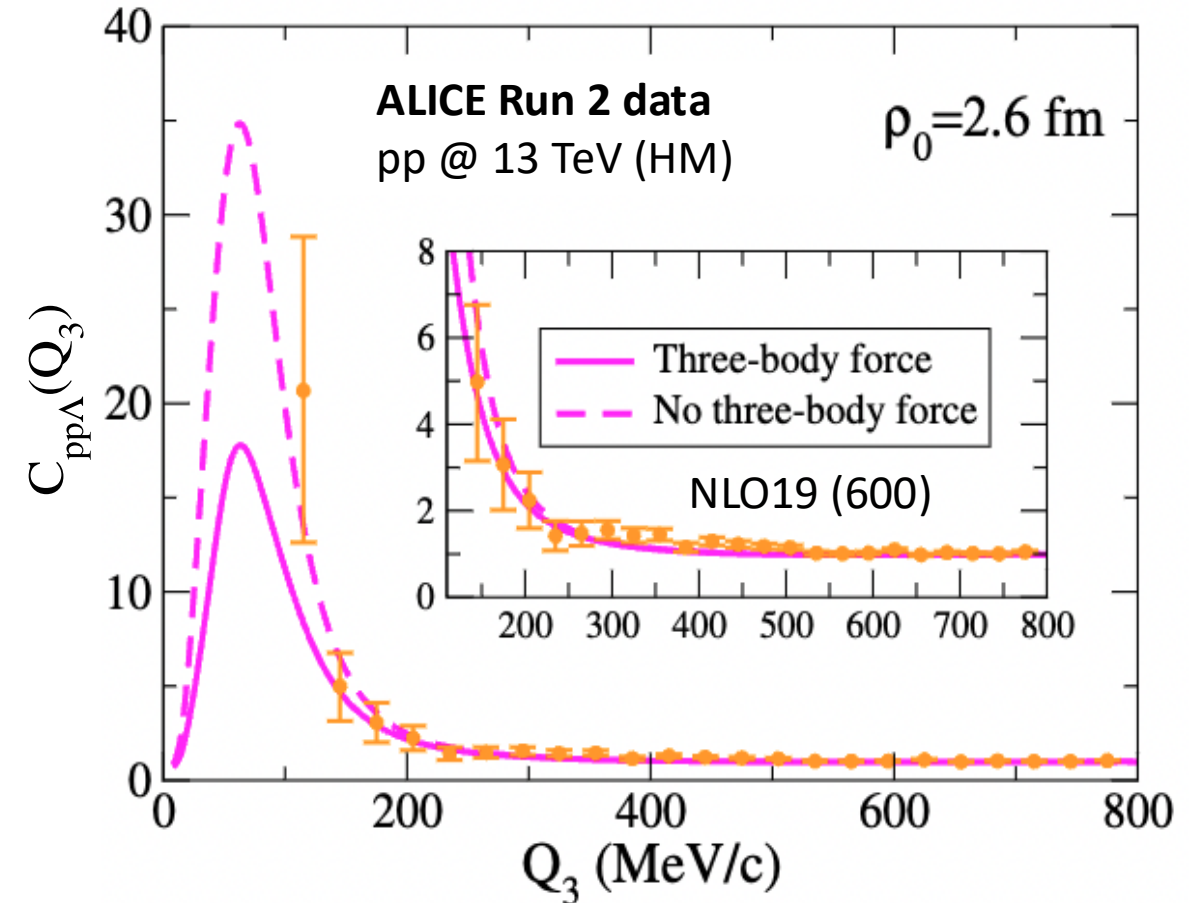


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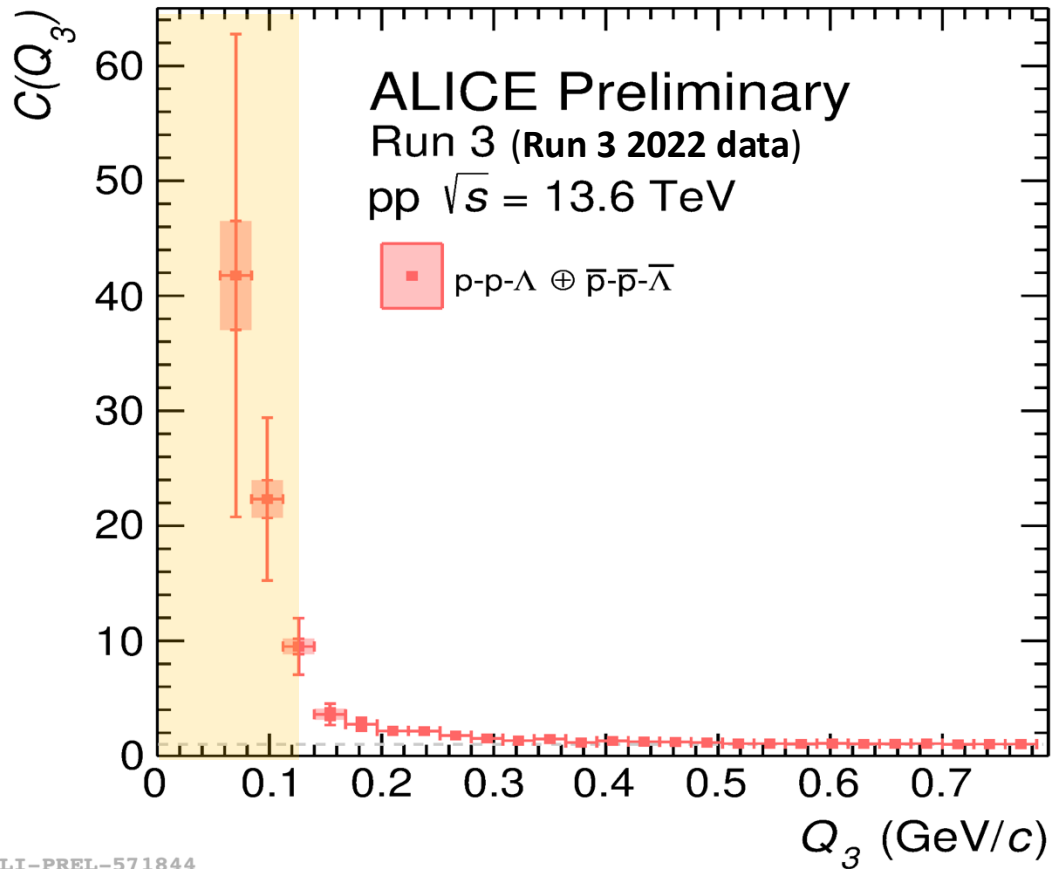
p-p- Λ correlation function

- Experimental corrections applied to the theory (feed-down from resonances and misidentifications)
- Gauss NLO19 (600): 40% effect of three-body interactions
- Run-2 data: one data point in the region of the maximum



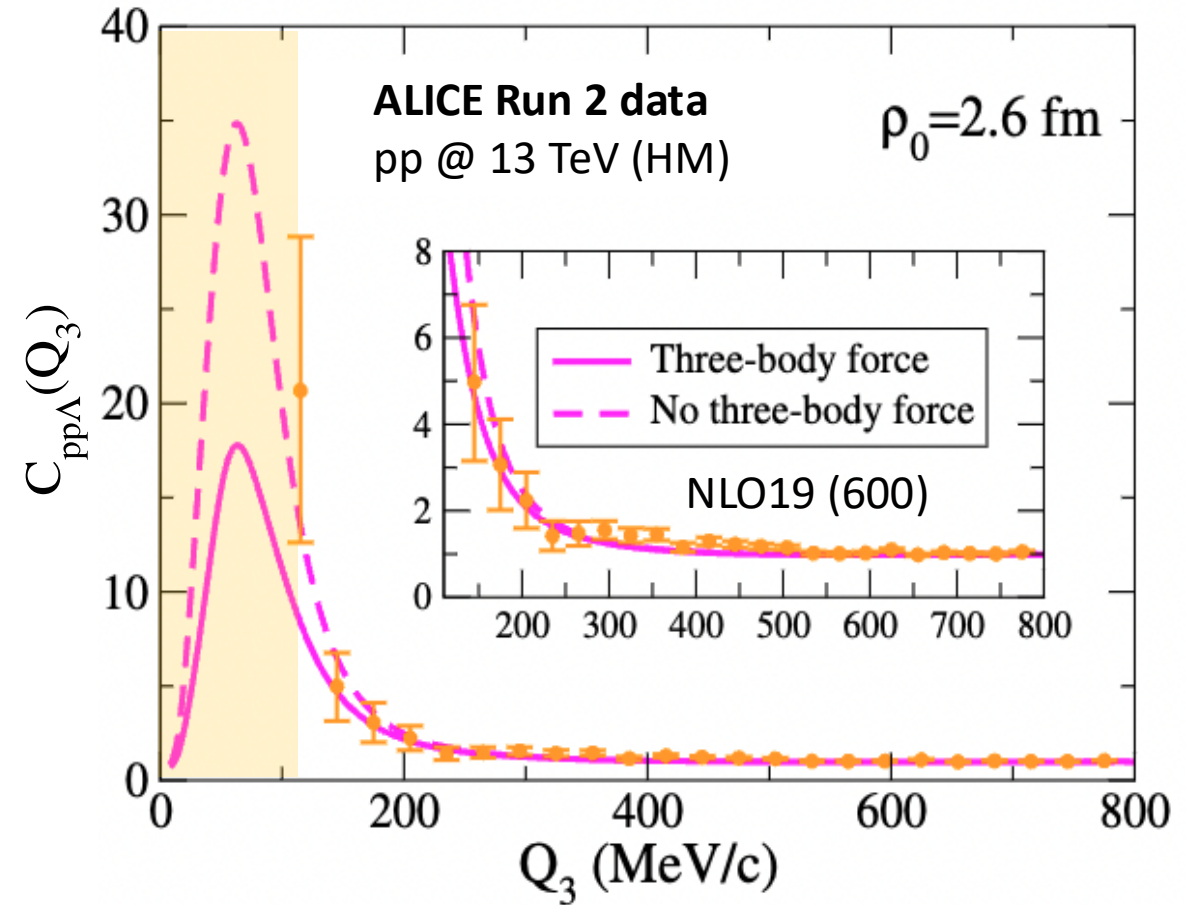
Results from recent paper:
E. Garrido et al., arXiv: 2408.01750 (2024), accepted by PRC

p-p- Λ correlation function



ALI-PREL-571844

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



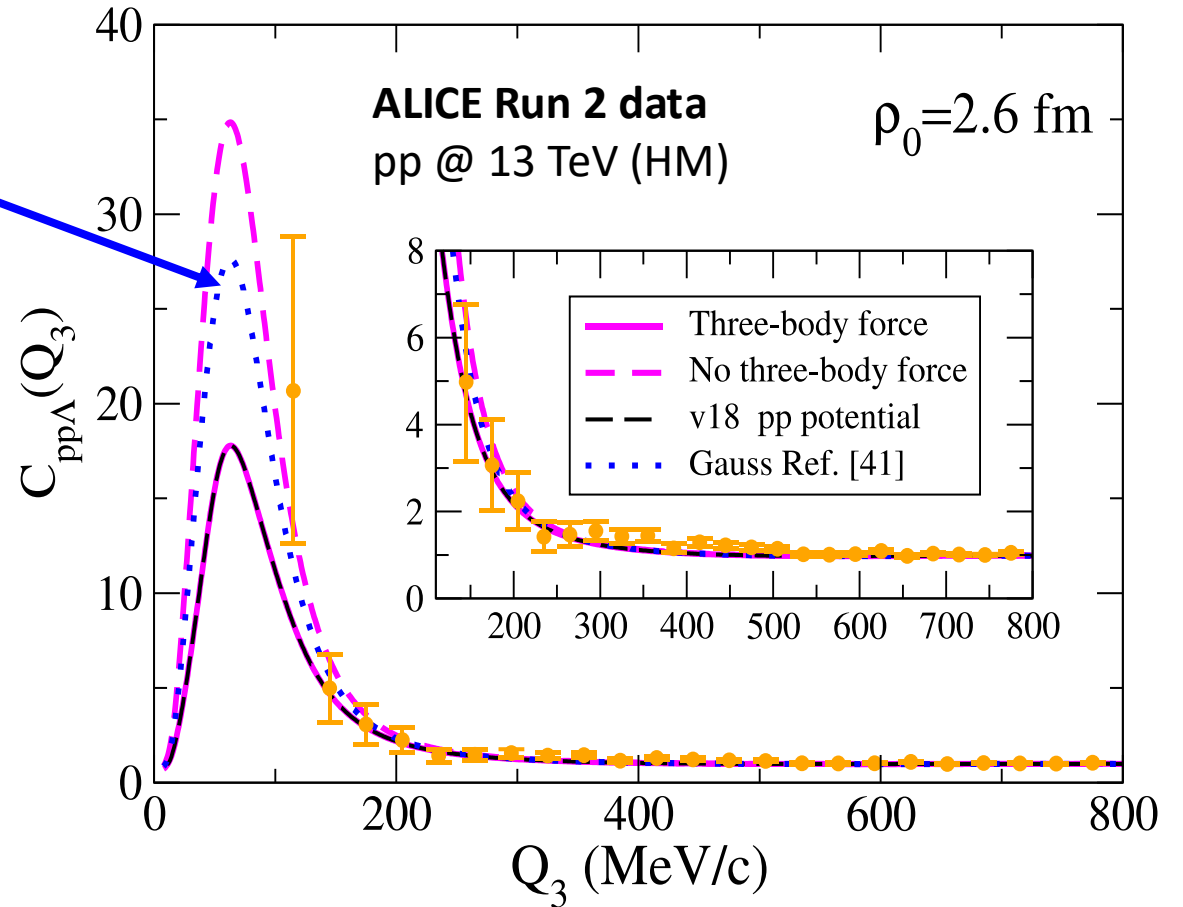
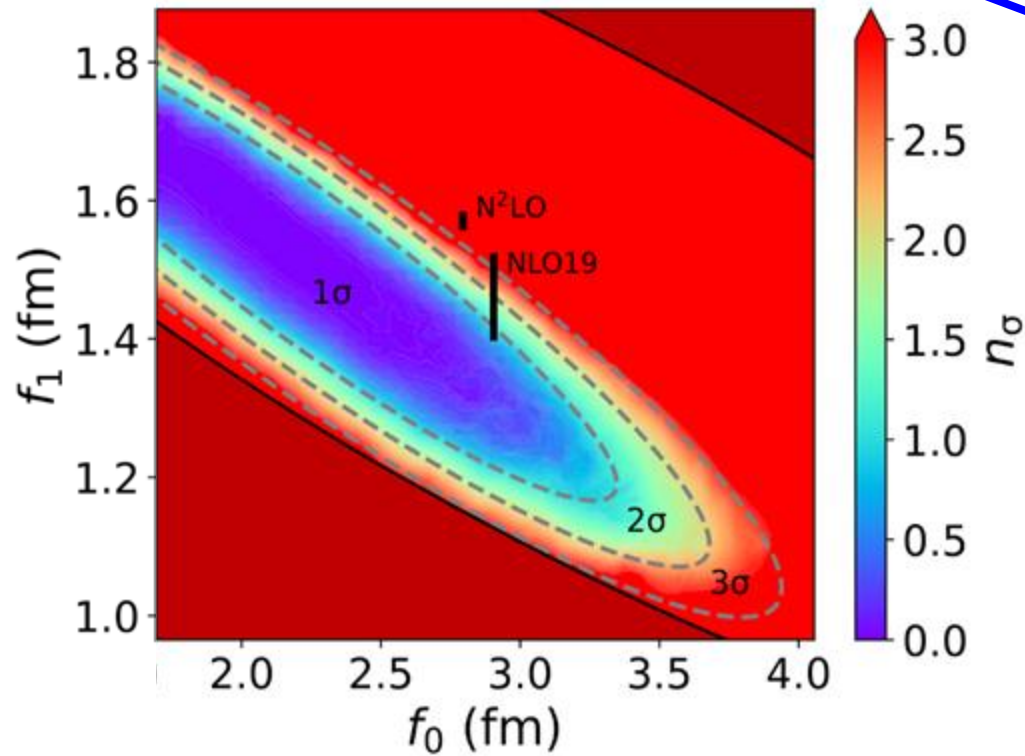
Results from recent paper:

E. Garrido et al., arXiv: 2408.01750 (2024), accepted by PRC

p-p- Λ correlation function

- **p Λ interaction**: scattering + femto

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



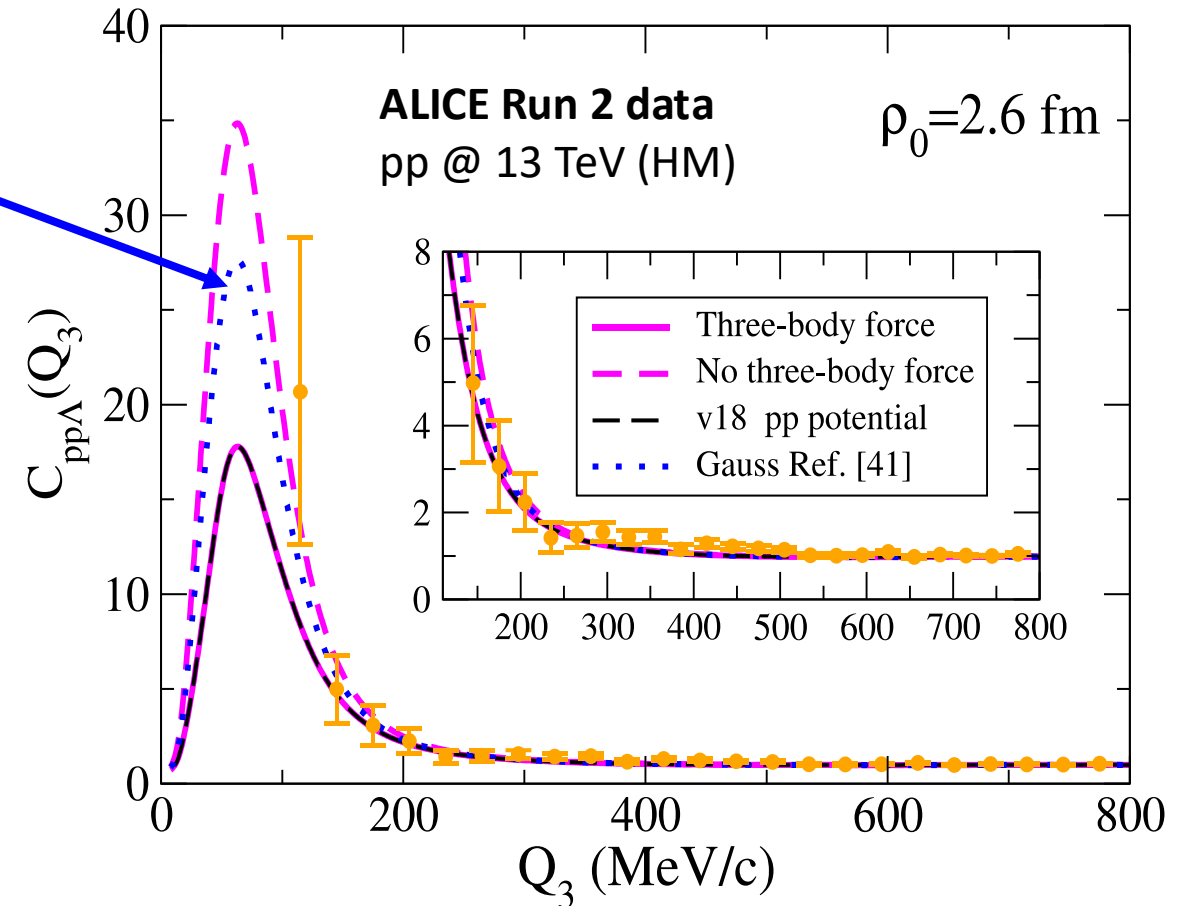
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p-p- Λ correlation function

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D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550
- Hypertriton binding energy can be reproduced using ONLY ΛN interaction

BE = 2.41 MeV **exp: 2.39 MeV**

E. Garrido et al., arXiv: 2408.01750 (2024), accepted by PRC



Results from recent paper:

E. Garrido et al., arXiv: 2408.01750 (2024), accepted by PRC

*Private communication A. Kievsky and E. Garrido

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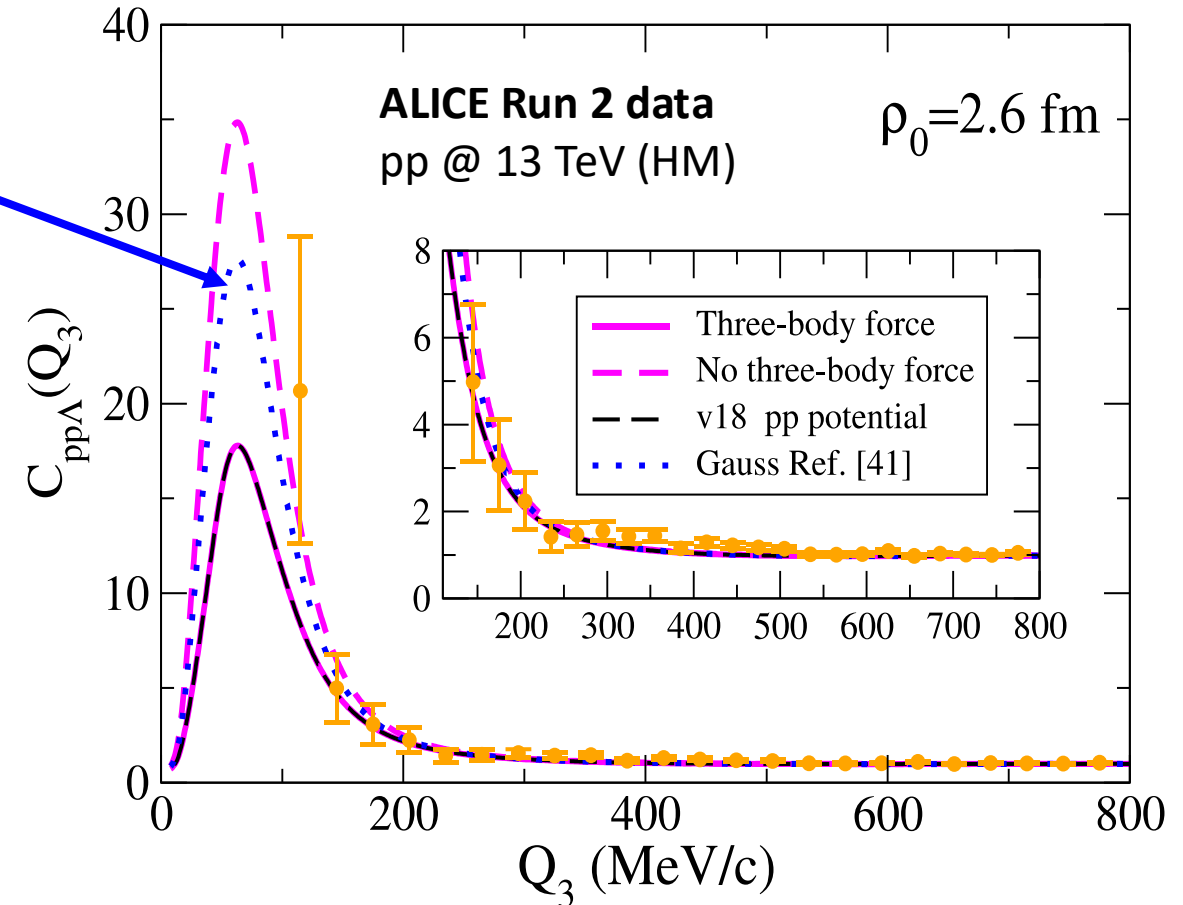
BE = 2.41 MeV **exp: 2.39 MeV**

E. Garrido et al., arXiv: 2408.01750 (2024), accepted by PRC

- Four-body systems:

BE = 13.37 MeV* **exp: 10.651 MeV** (${}^4_{\Lambda}\text{H}$)
 exp: 10.064 MeV (${}^4_{\Lambda}\text{He}$)

- Future:
Combined analysis of scattering data + hypernuclei + femtoscopy data



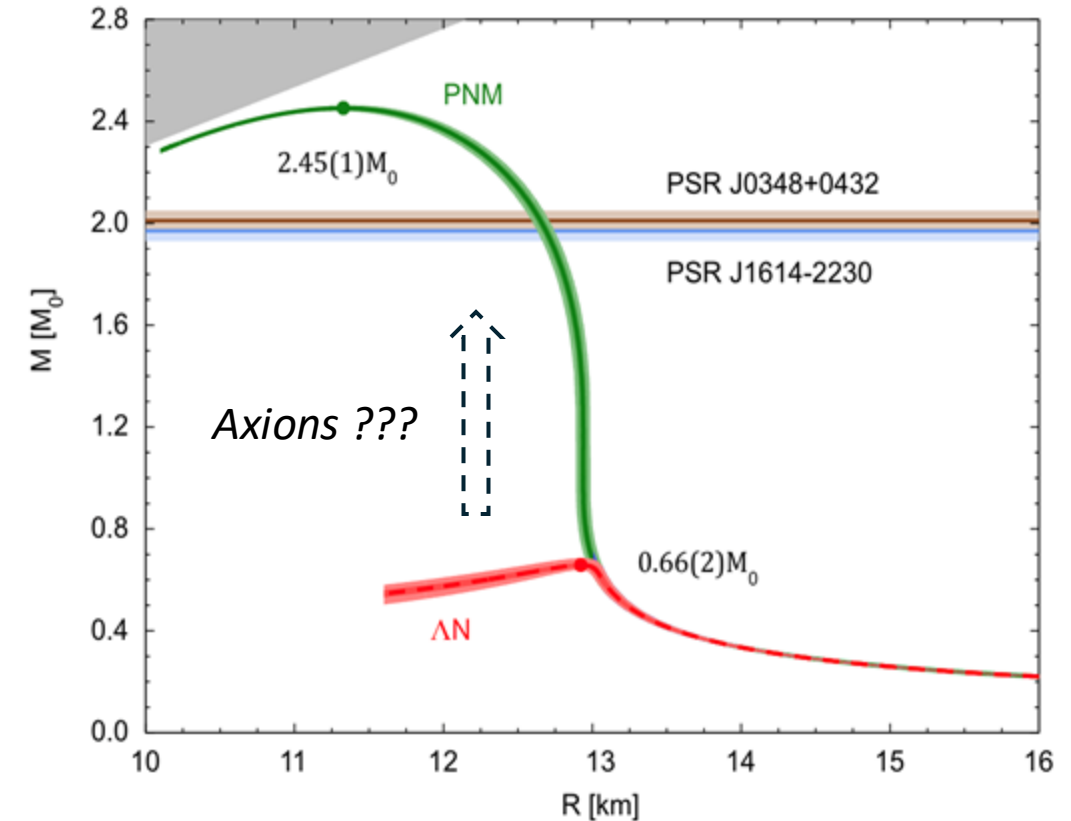
*Results from recent paper:
E. Garrido et al., arXiv: 2408.01750 (2024), Accepted by PRC*

*Private communication A. Kievsky and E. Garrido

Axions in neutron stars

- High density in the core of neutron stars
 - Production of hyperons as Λ at $\rho = 2-3\rho_0$ and softening of the equation of state
 - Incompatibility with astrophysical measurements of $M_{NS} \gtrsim 2 M_{\odot}$
 - Long-standing hyperon puzzle
- Impact of QCD axions on the equation of state (EoS)
 - Can lead to stiffer EoS

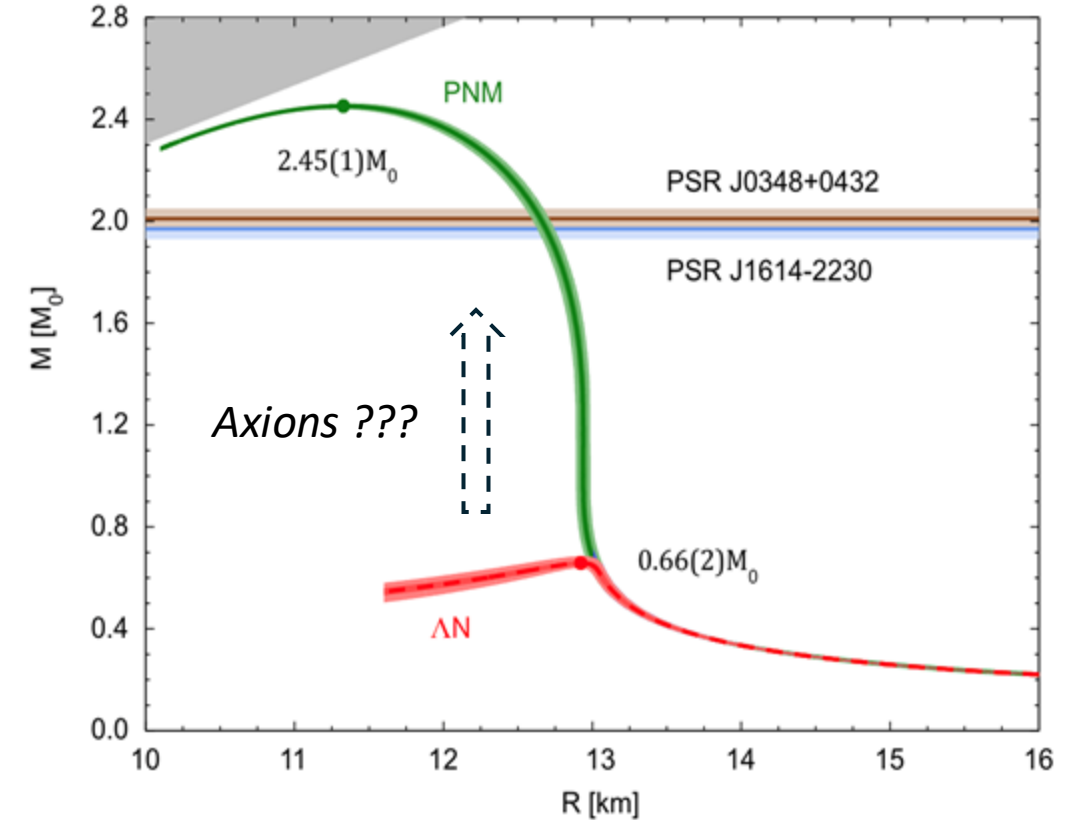
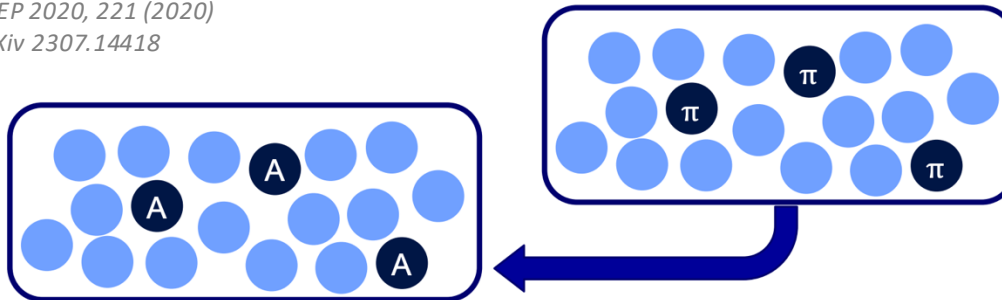
R. Balkin et al., JHEP 2020, 221 (2020)
R. Balkin et al., arXiv 2307.14418



Axions in neutron stars

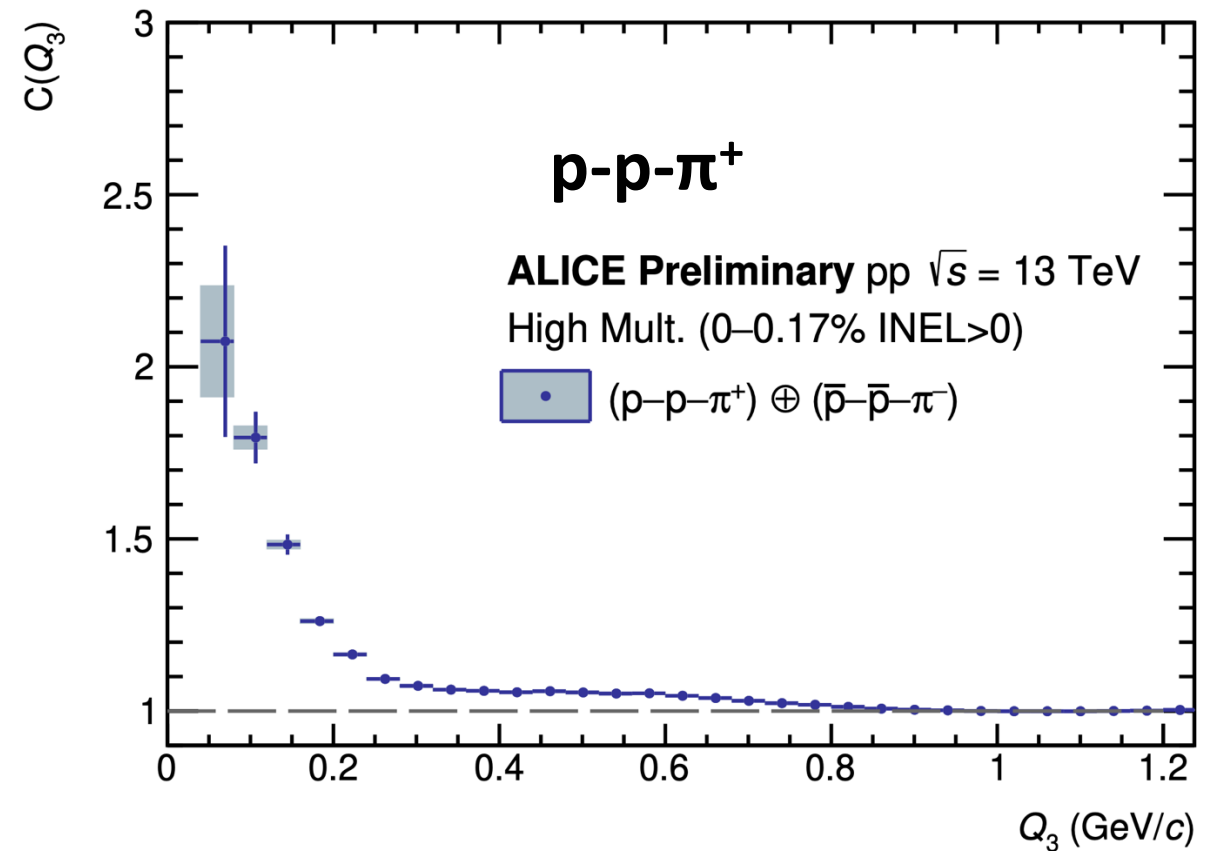
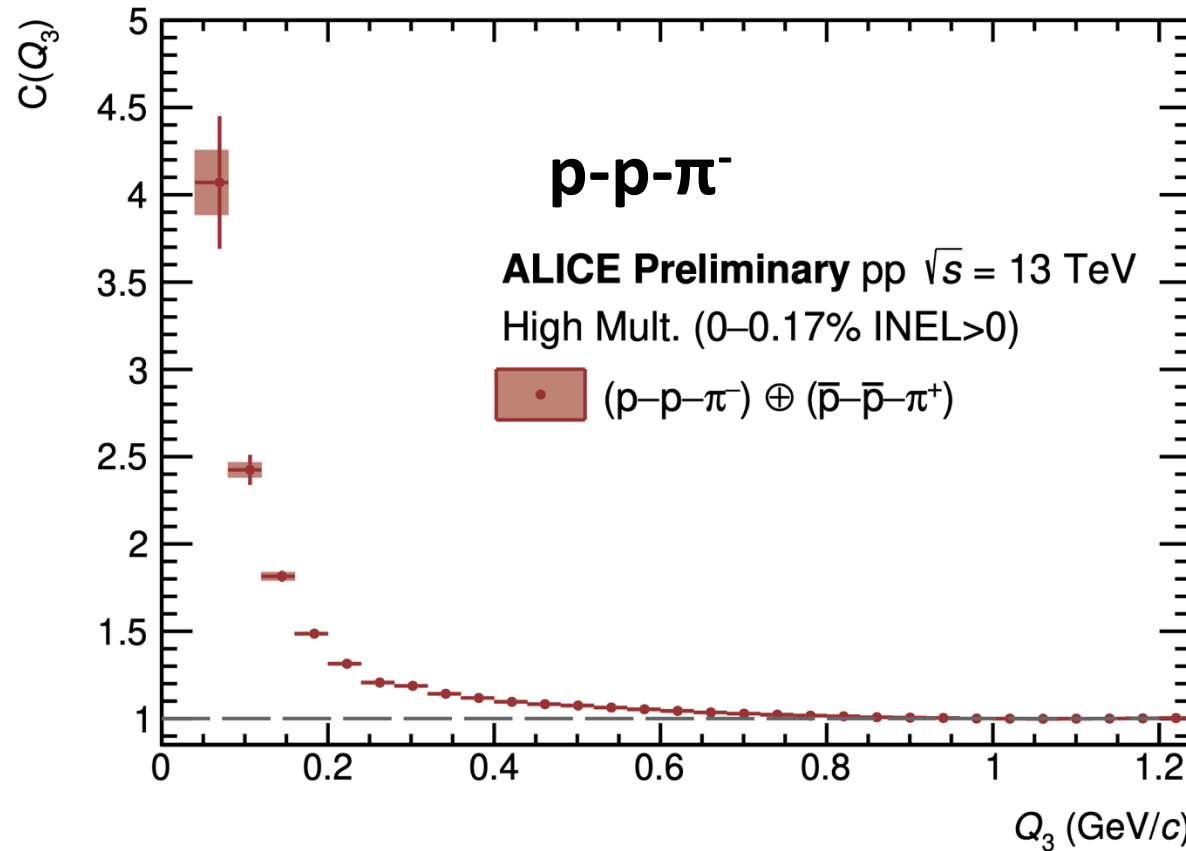
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- Impact of QCD axions on the equation of state (EoS)
 - Can lead to stiffer EoS
- Link to the in-medium interaction of pions and nucleons

R. Balkin et al., JHEP 2020, 221 (2020)
 R. Balkin et al., arXiv 2307.14418



Three-pion correlation functions

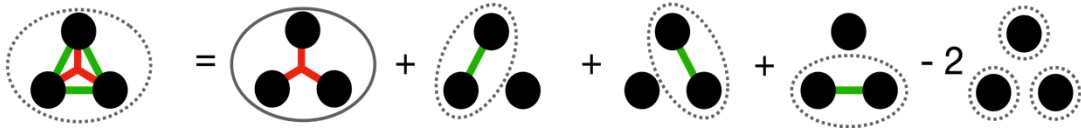
- Deviation from unity in the correlation functions



- Do we have sensitivity to genuine three-body effects?

Three-pion correlation functions

- Deviation from unity in the correlation functions
- Cumulant decomposition:

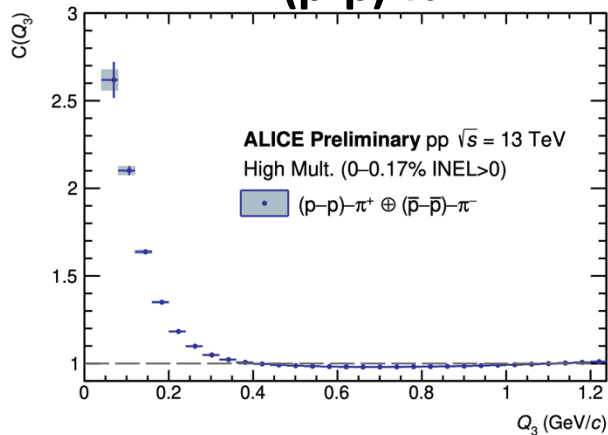


R. Kubo, J. Phys. Soc. Jpn. 17, 1100-1120 (1962)

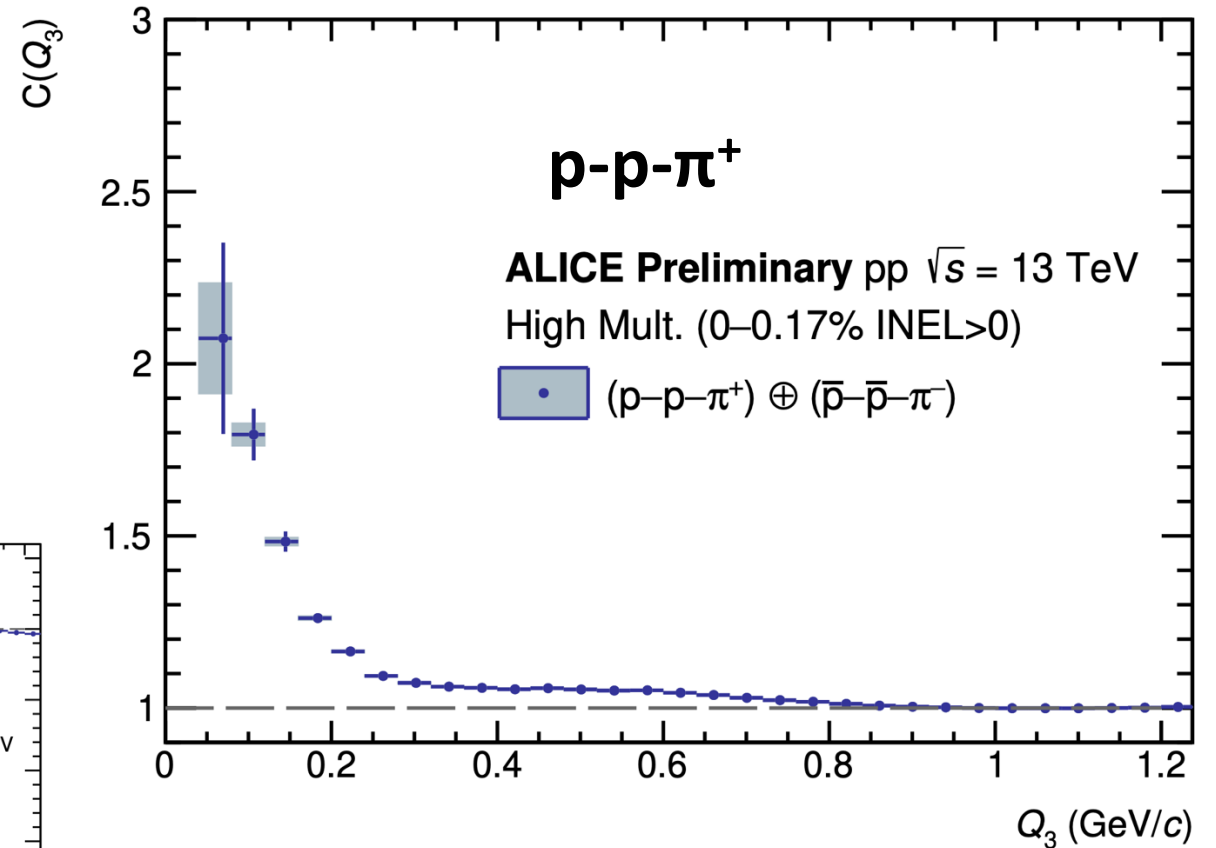
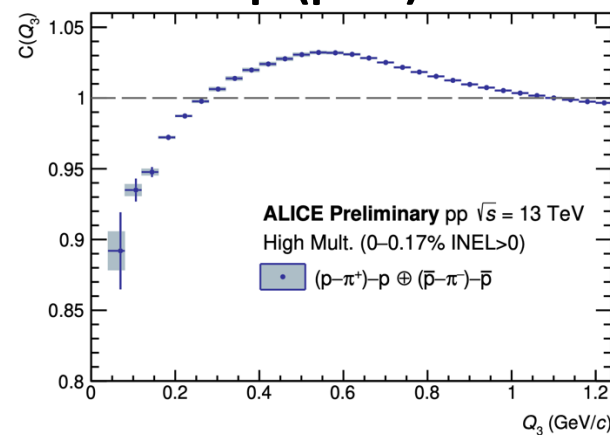
R. Del Grande et al. EPJC 82 (2022) 244

$$C(Q_3) = c_3(Q_3) + C_{pp}(Q_3) + 2 C_{p\pi}(Q_3) - 2$$

(p-p)- π^+

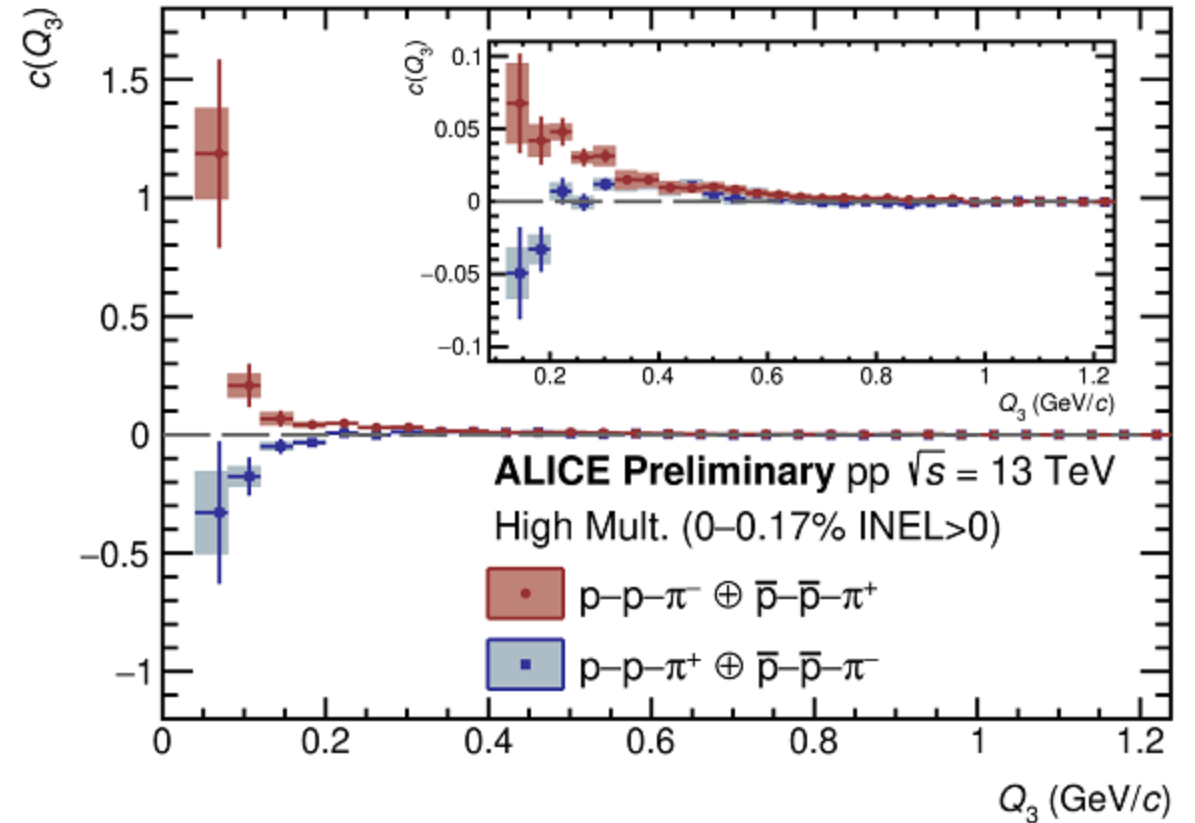


p-(p-pi+)



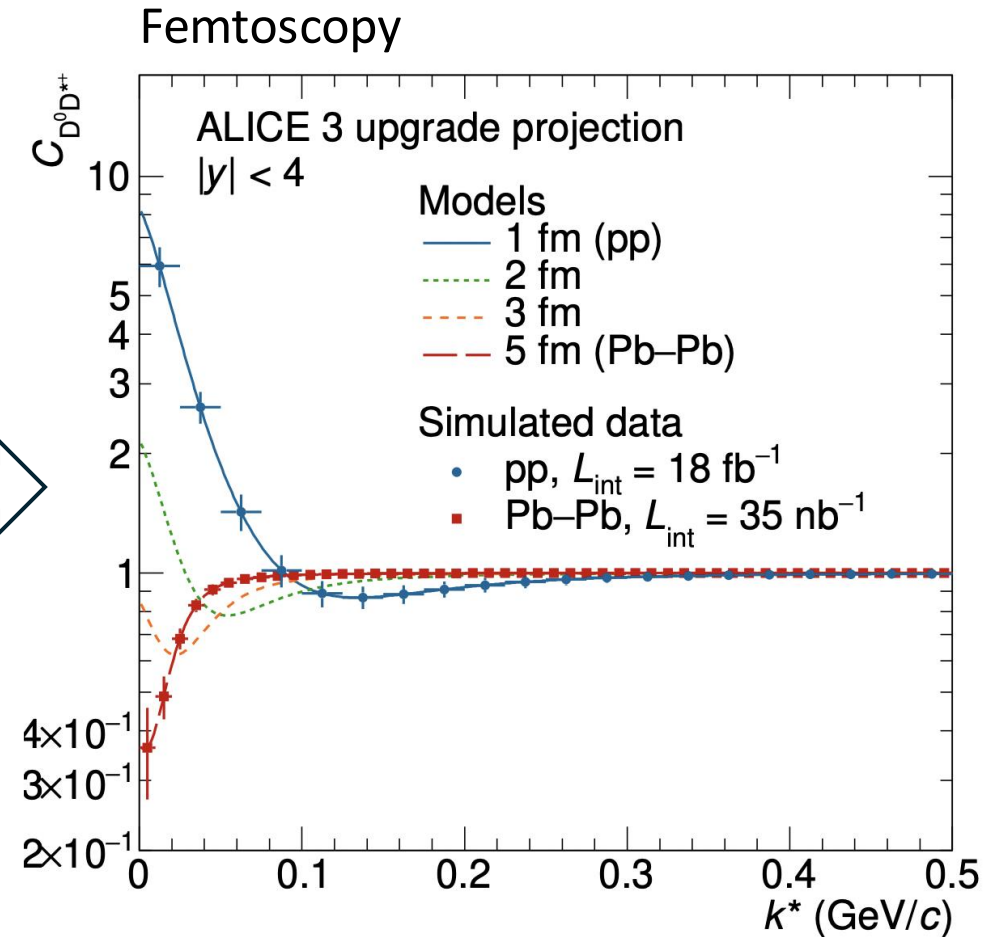
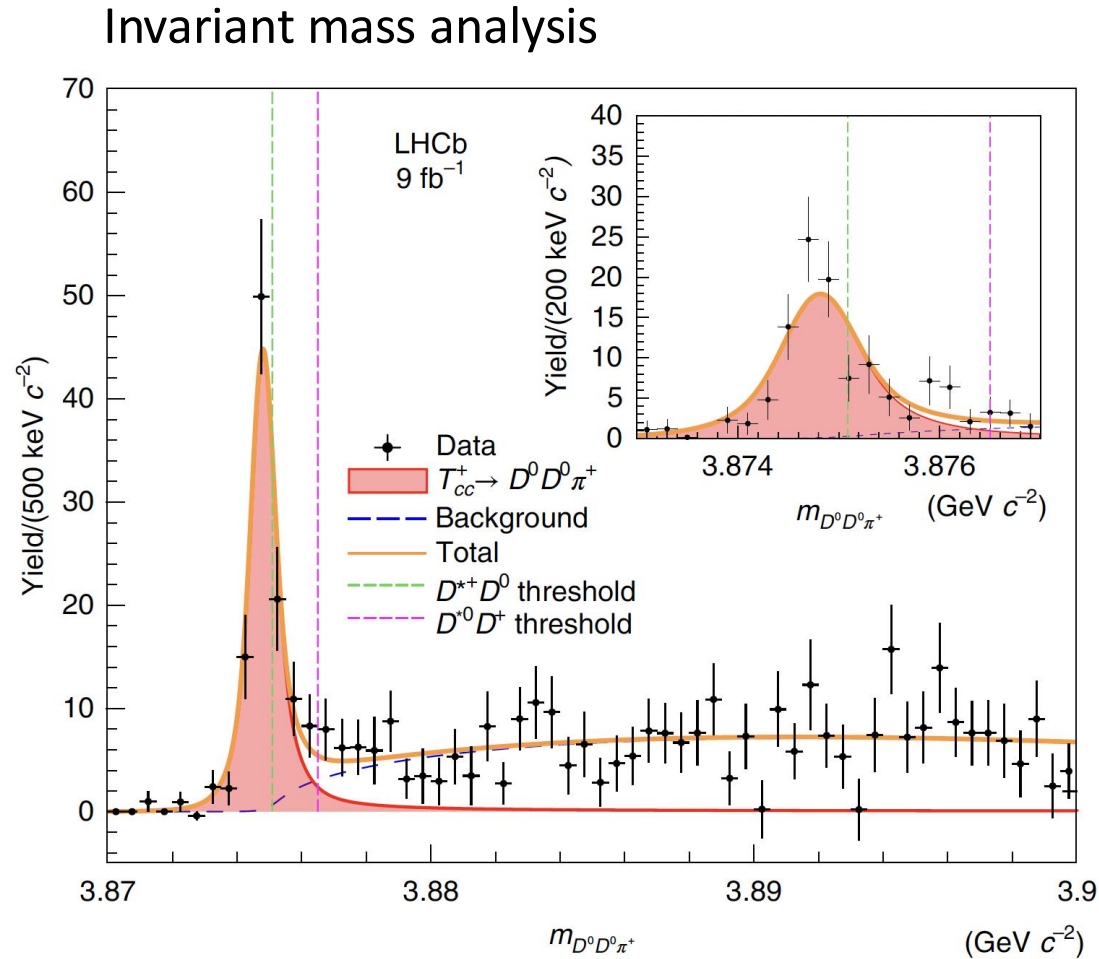
Three-pion correlation functions

- In both cases cumulant compatible with zero for large $Q_3 \rightarrow$ No three-body effects
- Three-body effects for small $Q_3 < 200$ MeV/c
 - Repulsion for $p p \pi^-$
 - Attraction for $p p \pi^+$



ALI-PREL-576418

Femtoscscopy to study molecular and bound states

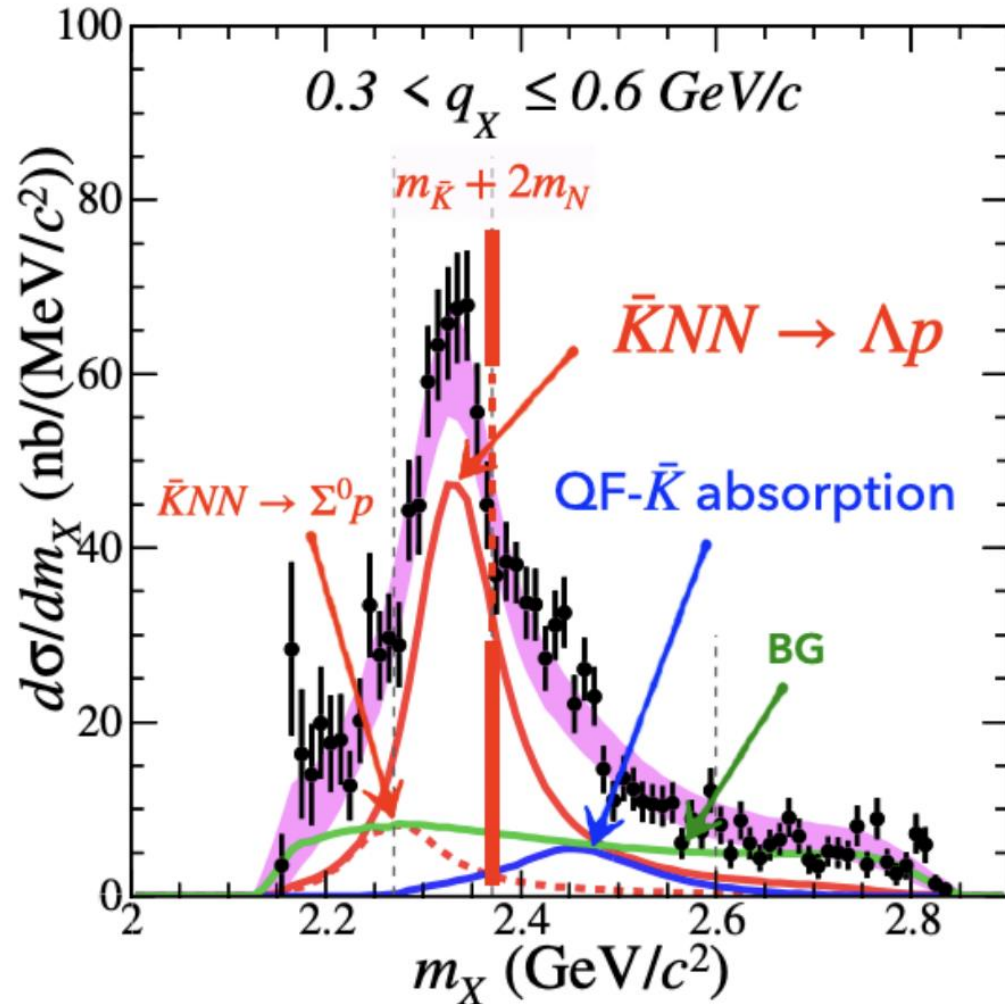


ALI-SIMUL-502575

ALICE 3 LOI, arXiv:2211.02491

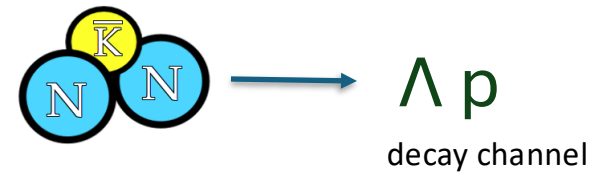
LHCb Coll. Nature Phys. (2022)

p-p-K⁻ bound state



First positive experimental evidence of the p-p-K⁻ bound state by the E15 Collaboration.

E15 Coll., PLB 789 (2019) 620, Phys.Rev.C 102 (2020) 4, 044002



	B.E. (MeV)	Width (MeV)
Exp. (E15)	42	100
Theo.	16	72

E15 Coll., Phys.Rev.C 102 (2020) 4, 044002

Sekihara et al., PTEP 2016 no. 12, (2016)

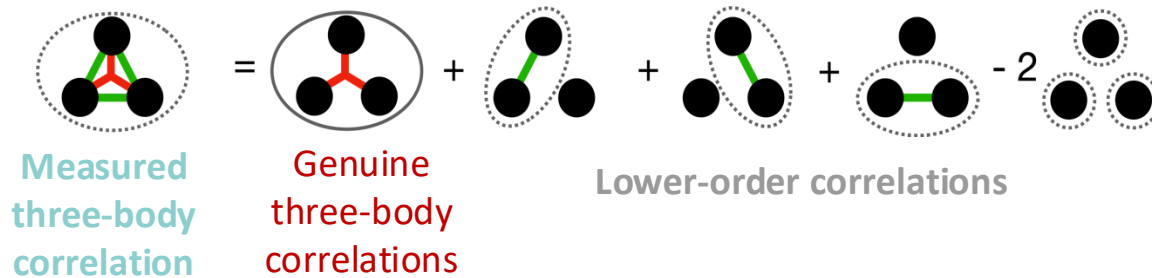
Tension between the theoretical models and experimental measurement.

p-p-K⁻ correlation function

- Cumulant used to study effects beyond two-body correlations

R. Kubo, J. Phys. Soc. Jpn. 17, 1100-1120 (1962)

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



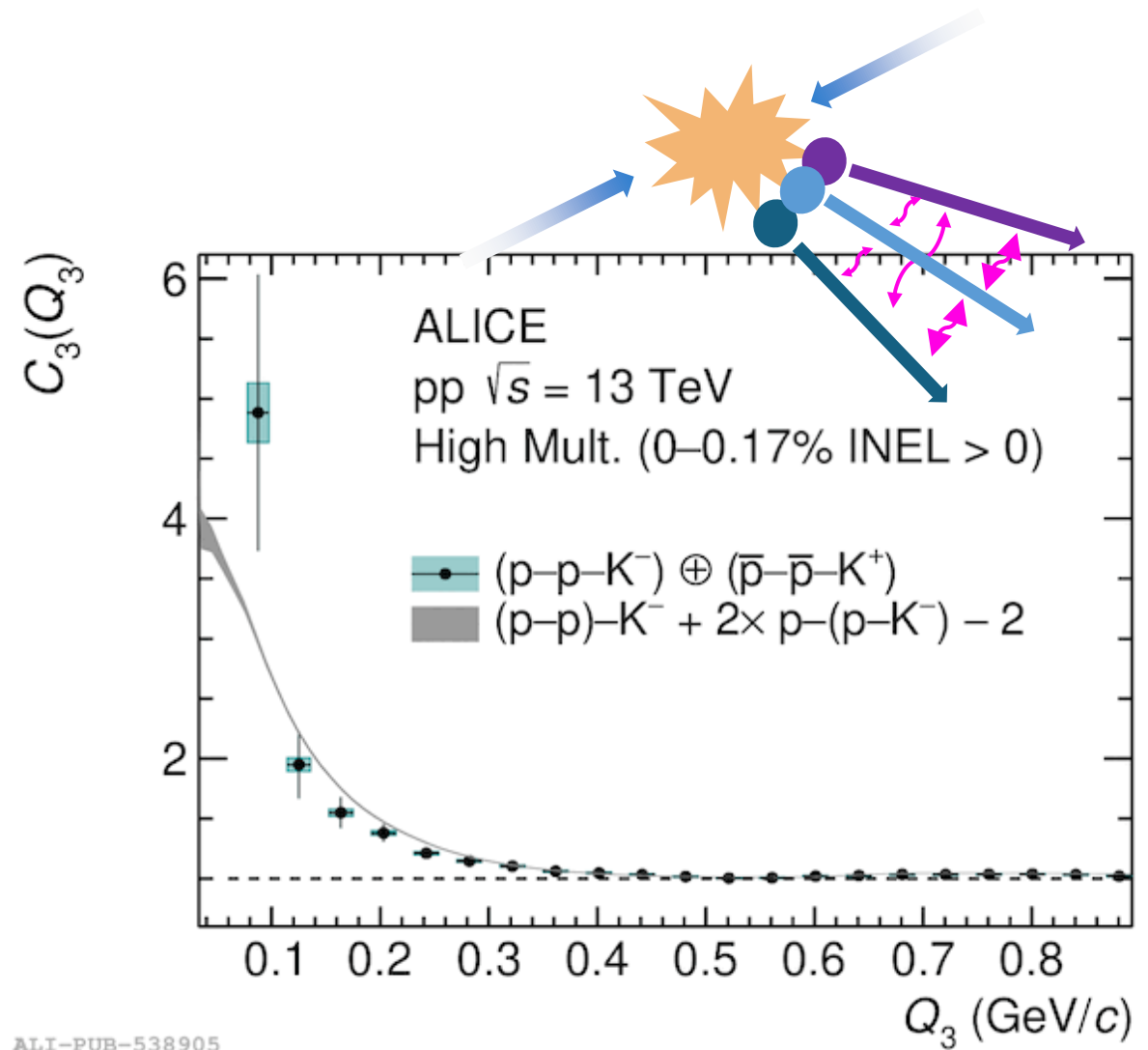
- Agreement within $n\sigma = 1.5$ with lower-order contributions

- Negligible 2NA processes: $BR(K^-d \rightarrow YN) \sim 1\%$

Katz et al., Phys. Rev. D 1 (1970) 1883-1886

- No significant effect due to bound state formation?

Future collaboration with theoreticians



ALI-PUB-538905

ALICE Coll., EPJA 59, 298 (2023)

Conclusions and Outlook

- Exciting results from femtoscopy
 - Important experimental input to understand the many facets of QCD in strange and charm sector
 - Most precise p - Λ data at low momenta
 - First extraction of the p - Λ scattering parameters using femtoscopy and scattering data
 - First measurements of three-particle correlation functions
 - NNN interaction: effect up to 5% depending on the particle distances
 - NNA interaction: 40% effect in the correlation function
 - No evidence of p - p - K bound state using correlation techniques
- On-going Run 3 and future Run 4
 - Access to precise data on three-particle interactions and interactions with charm mesons
 - Sensitivity to the effect of three-body forces in the correlation functions

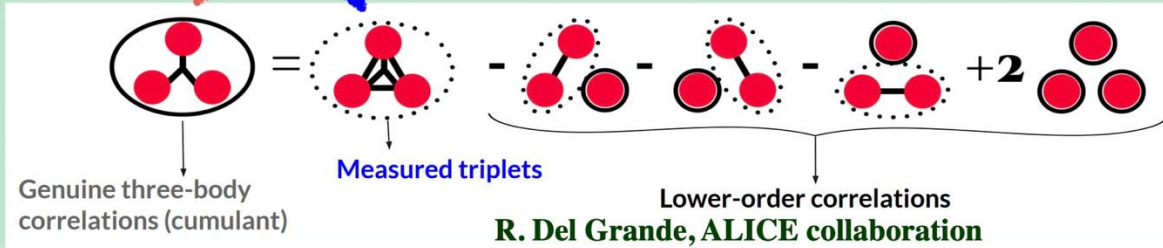
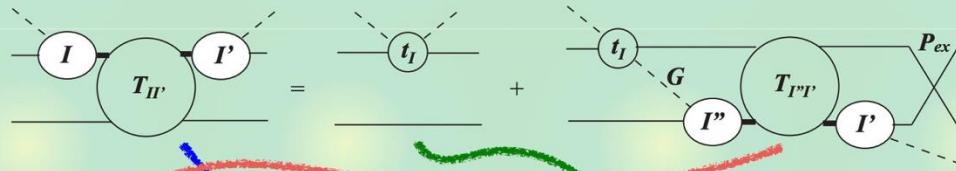
Backup

p-p-K⁻ correlation function

$\bar{K}N$ potentials and their applications

Relation to correlation functions?

3-body equation and correlation functions

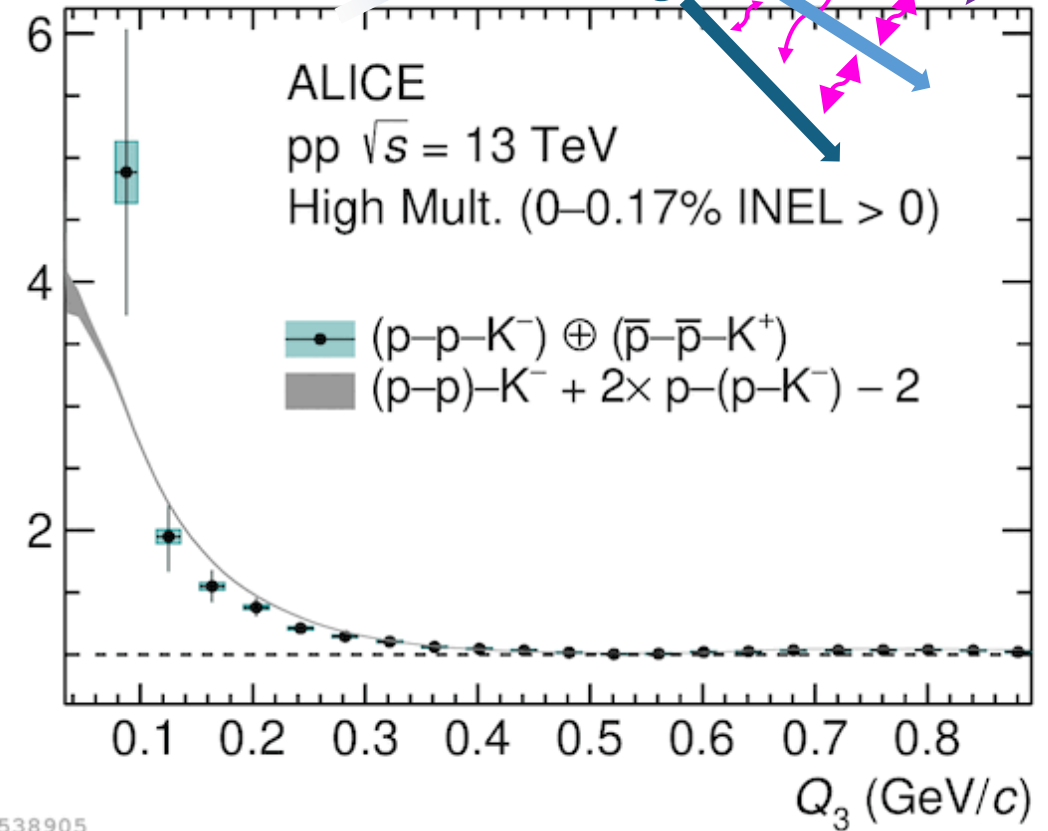


“Genuine three-body correlation”

- multiple rescattering of 2-body interaction?
- 3-body force (act only in 3-body system)?

17

$C_3(Q_3)$

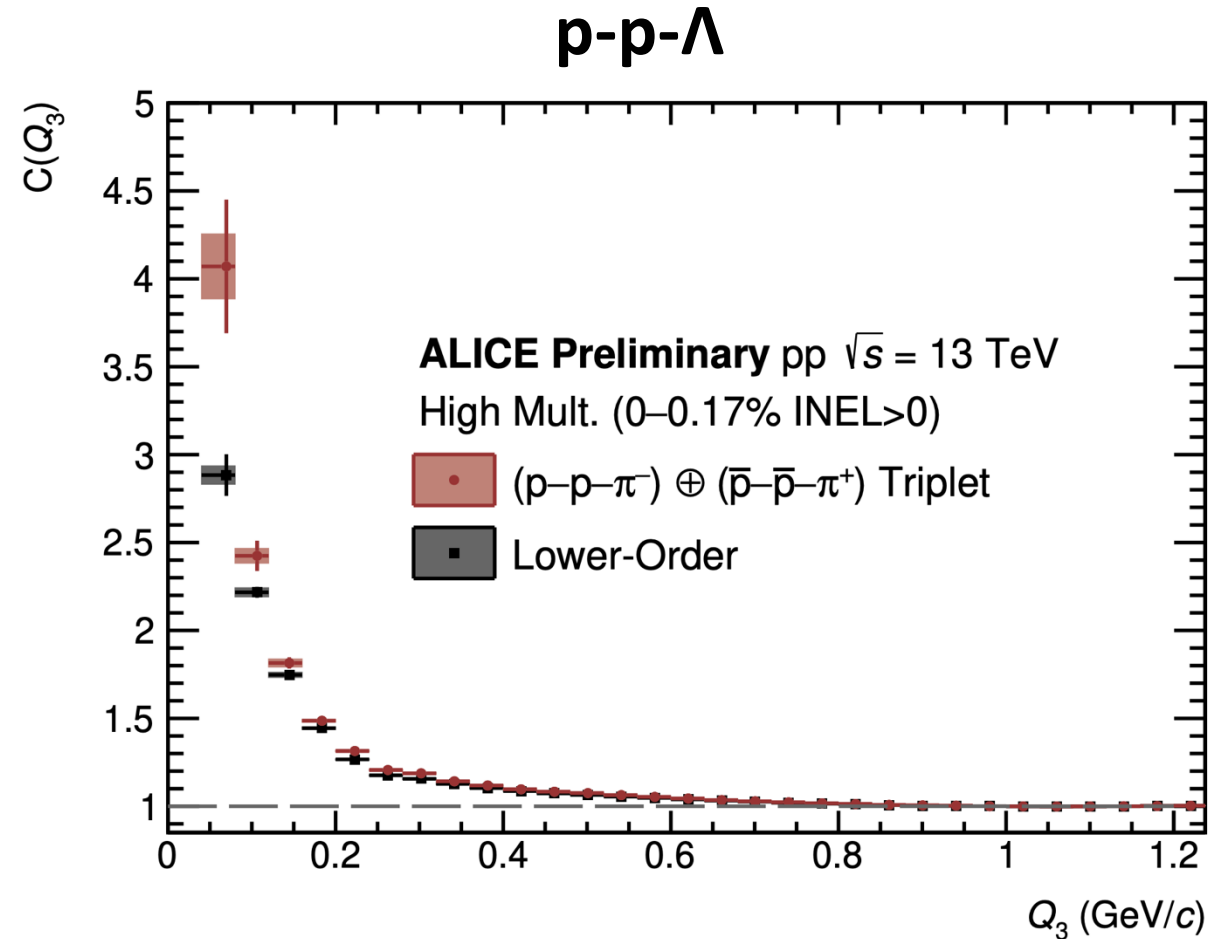
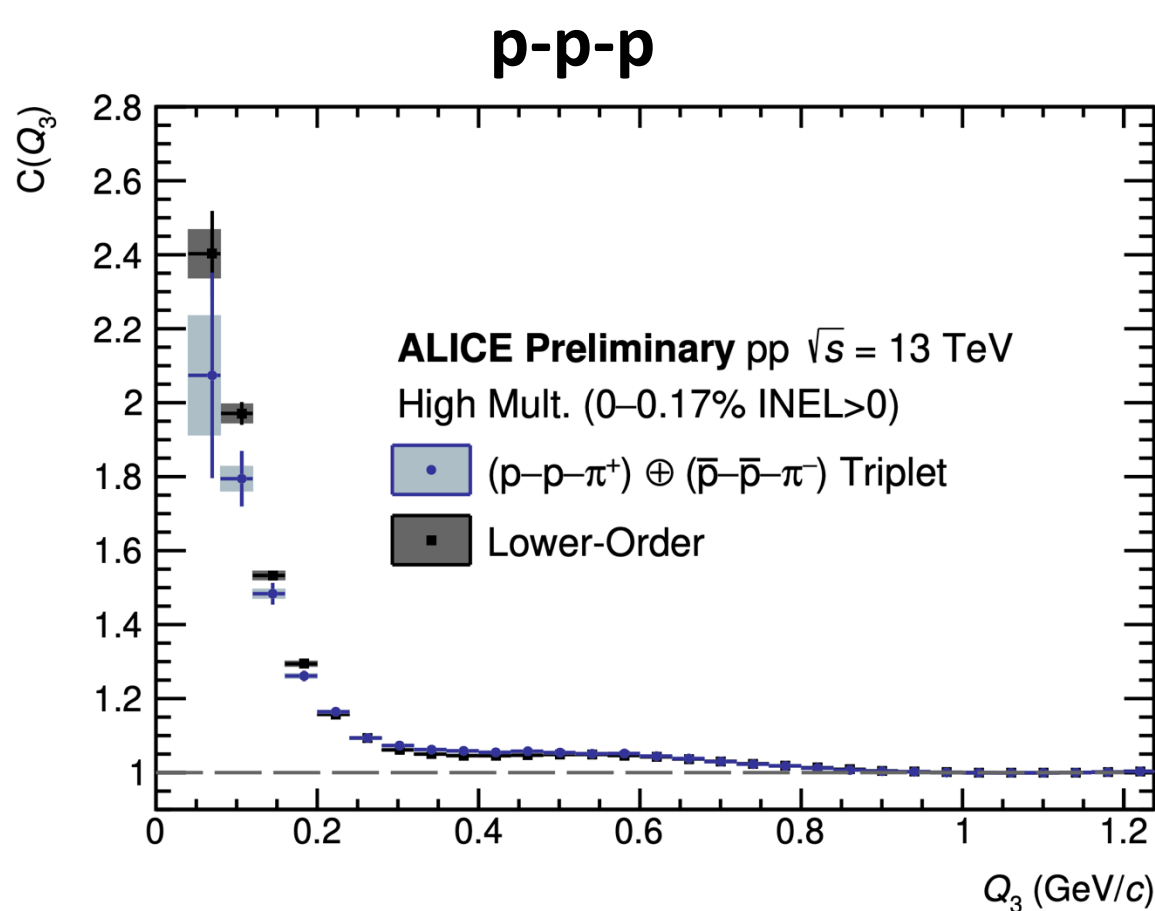


ALI-PUB-538905

ALICE Coll., EPJA 59, 298 (2023)

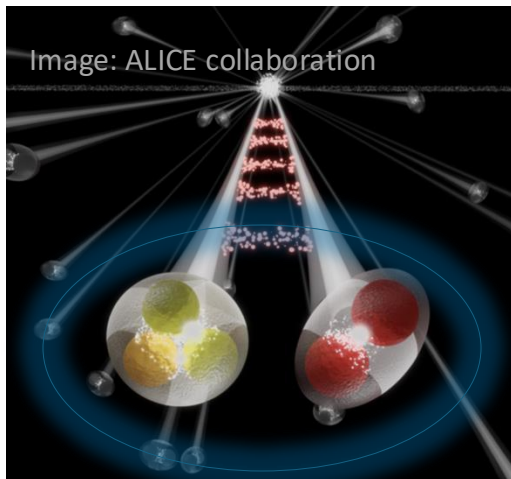
Three-pion correlation functions

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



p- ϕ bound state

- Predicted by various theoretical calculations
- No experimental evidence
 - Standart method of invariant mass measurment not yet available
- Accessible by studying **interaction** among constituents



	System	E_B [MeV]
QCD Van der Waal using Yukawa type Potential ¹	ϕ N	1.8
Chiral quark model ²	ϕ N	3.0
Monte Carlo study of ϕ photoproduction from nuclear targets ³	ϕ N	2.5
Quark delocalization color screening model ⁴	ϕ N	0.3-8.8
Unitary coupled-channel approximation anchored to ALICE p ϕ scattering data ⁵	ϕ N	9.0
Phenomenological potential+variational method ⁶	ϕ N	9.3/9.23
	ϕ NN	10.0/17.5
Phenomenological potential+variational method ⁷	ϕ N	9.5
	ϕ NN	39.8
	$\phi\phi$ NN	124.6

¹H. Gao, T.-S. H. Lee, and V. Marinov, *Phys. Rev. C* 63 (2001) 022201(R)

²F. Huang, Z.Y. Zhang, and Y.W. Yu, *Phys. Rev. C* 73 (2006) 025207

³H. Gao et al., *Phys. Rev. C* 95 (2017) 055202

⁴S. Liska, H. Gao, W. Chen, and X. Qian, *Phys. Rev. C* 75 (2007) 058201

⁵B.-X. Sun, Y.-Y. Fan, and Q.-Q. Cao, *arXiv*, 2206.02961 (2022)

⁶V. B. Belyaev, W. Sandhas, and I. I. Shlyk, *Few-Body Syst.* 44 (2008) 347

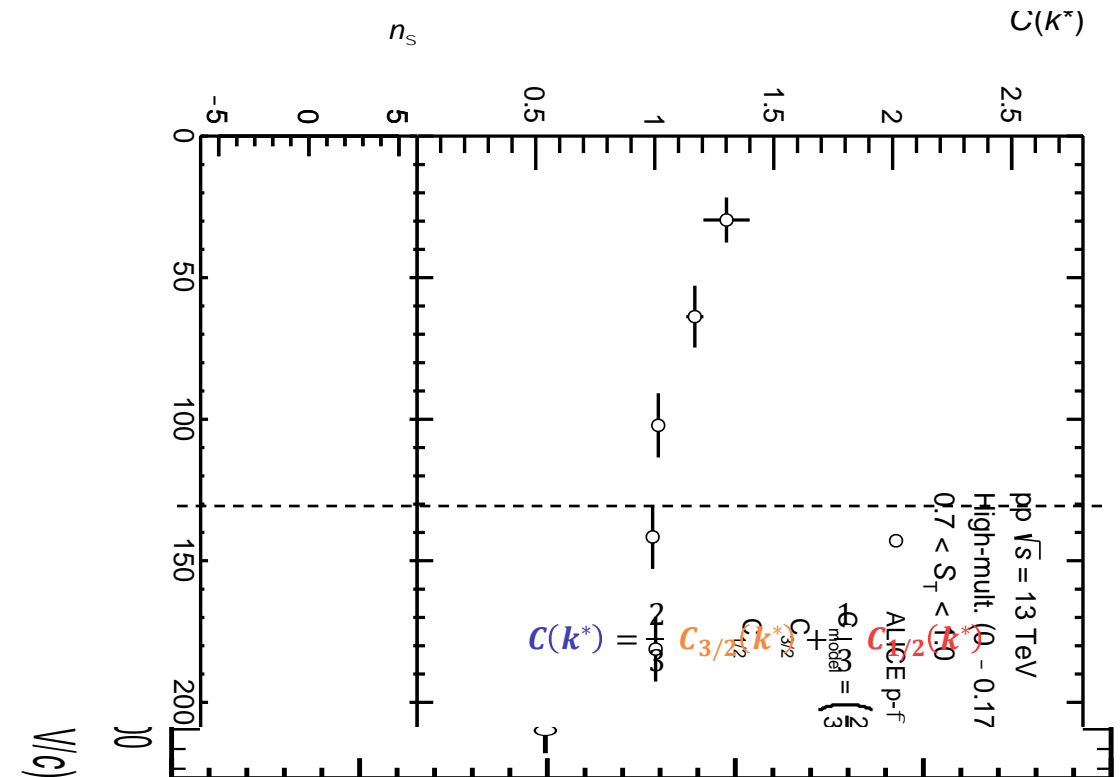
⁷S. A. Sofianos, G. J. Rampho, M. Braun, and R. M. Adam, *J. Phys. G.* 37 (2010) 085109

Femtoscscopy to study bound states

p-φ correlation function:

- Spin-3/2 interaction: elastic channel
 → Lattice QCD potentials (HAL QCD)
Yan Lyu et al., Phys. Rev. D 106 (2022) 074507
- Spin-1/2 interaction: inelastic channels
 (Nφ-ΛK, Nφ-ΣK)
 → Complex potential fitted to the data
- Attractive potential with $C(k^*) < 1$ provides
indication of a p-φ bound state
 → Binding Energy = 14.7–56.6 MeV

E. Chizzali, Y. Kamiya et al., PLB 848 (2024) 138358



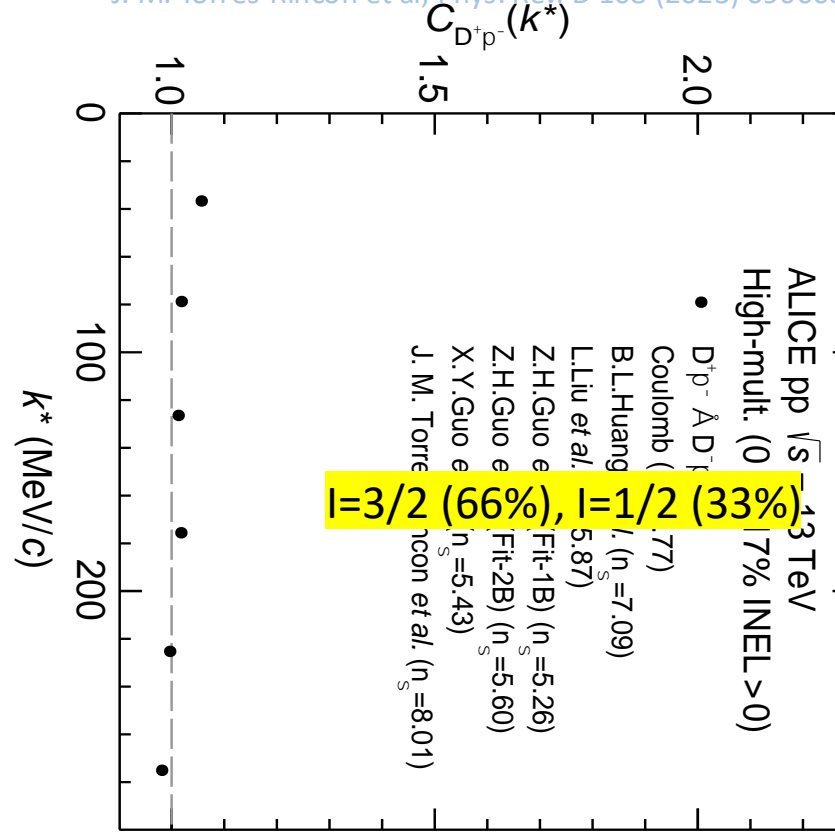
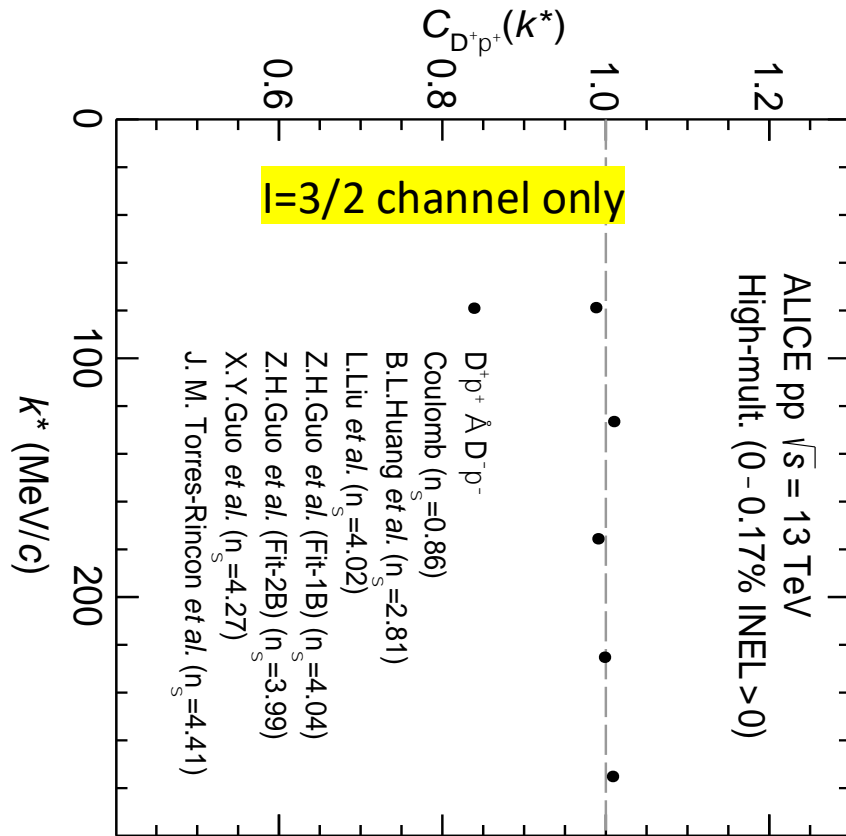
E. Chizzali, Y. Kamiya et al., PLB 848 (2024) 138358

Correlation analysis as alternative to the standard invariant mass analyses to study bound states

First measurement of $D\pi$ correlation functions

- Coulomb-only interaction favoured
- Tension with theory models

L. Liu et al, *Phys. Rev. D* 87 (2013) 014508
 X.-Y. Guo et al, *Phys. Rev. D* 98 (2018) 014510
 Z.-H. Guo et al *Eur. Phys. J. C* 79 (2019) 13
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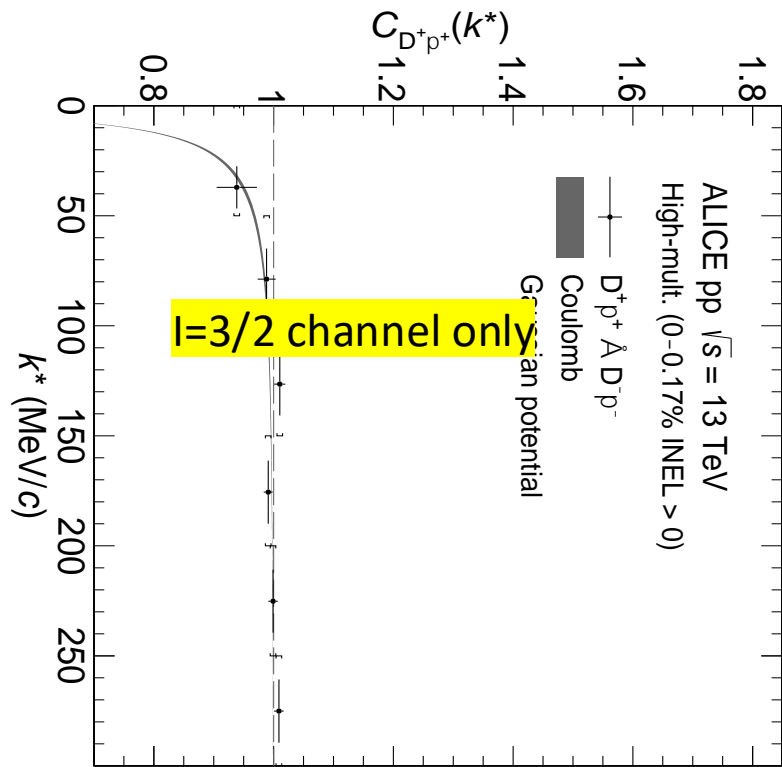


ALICE Coll., arXiv:2401.13541 (2023)



D π correlation function fit

- D π^+ and D π^- share $l=3/2$ channel \rightarrow simultaneous fit
- Vanishing scattering parameters in both isospin channels
- Tension with theory especially in $l=1/2$ channel



ALICE Coll., arXiv:2401.13541 (2023)

