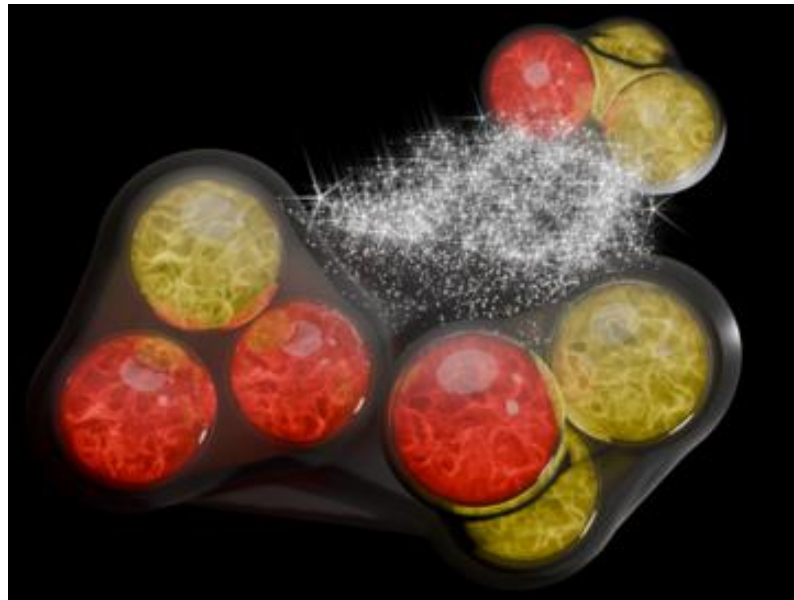# Exploring hadronic interactions in three-body systems at the LHC

Raffaele Del Grande[1,*]

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

Hadrons and Hadron Interactions in QCD 2024 (HHIQCD2024)
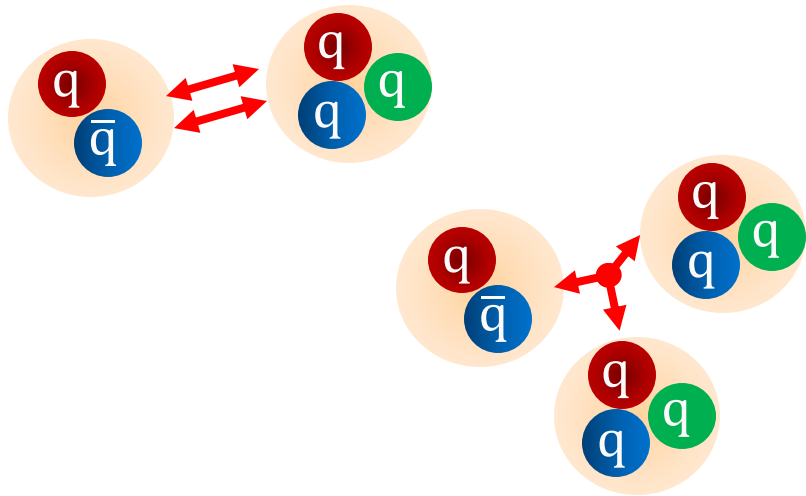
30th October 2024, Kyoto, Japan

*raffaele.del-grande@tum.de

Motivation

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

  How do hadrons interact?
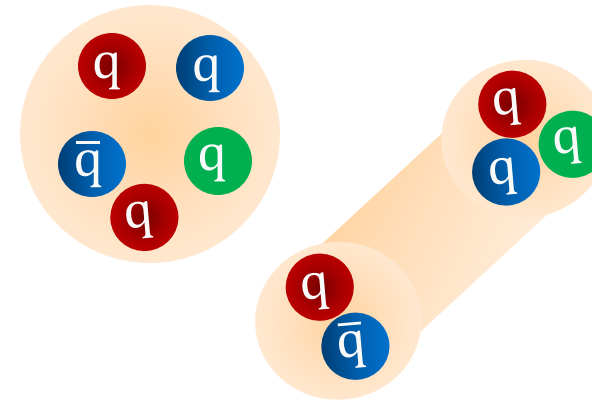 2-body and many-body interactions

- Many exotic and molecular states have been observed in experiments (e.g. BELLE, LHCb, …)
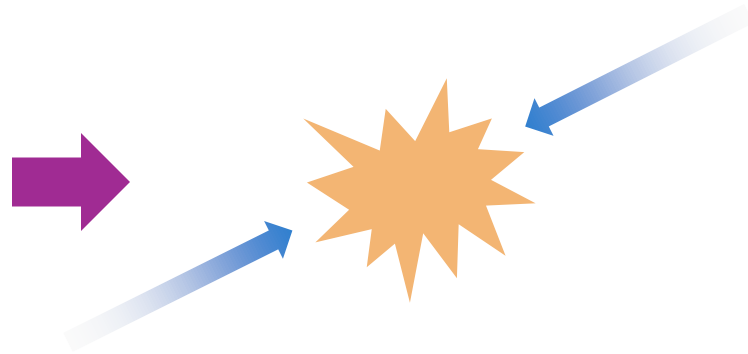
  How do hadrons emerge?
  Conventional and exotic states

Need for experimental data

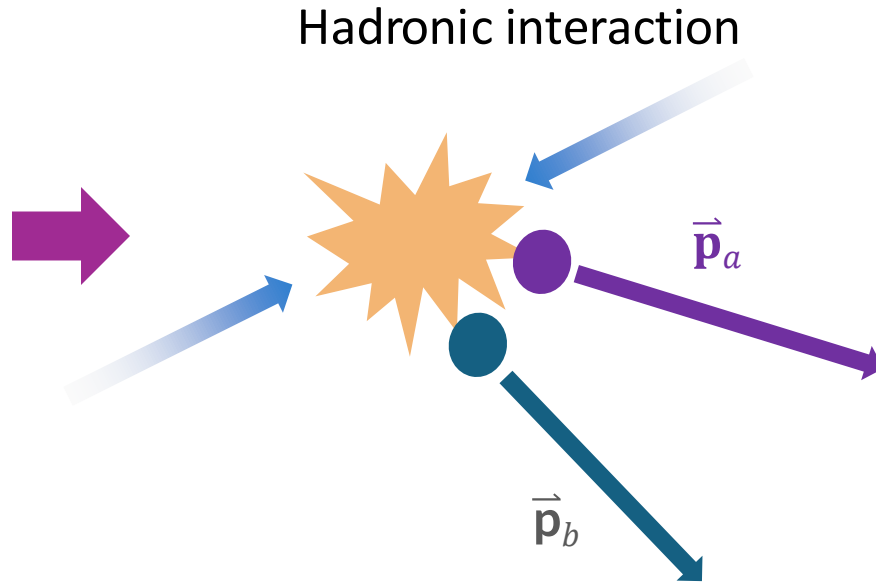# Femtoscopy technique at the Large Hadron Collider

ALICE at the LHC

Hadronic interaction

Femtoscopy technique at the Large Hadron Collider

ALICE at the LHC

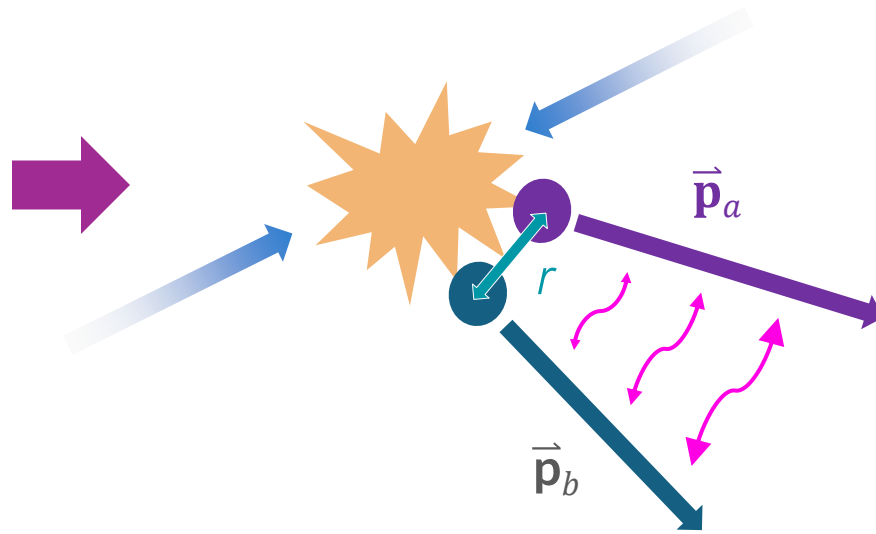Hadronic interaction

$\vec{\mathbf{p}}_a$

$\vec{\mathbf{p}}_b$

Femtoscopy technique at the Large Hadron Collider

ALICE at the LHC

Hadronic interaction

Femtoscopy technique

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

Correlation function

$\vec{\mathbf{p}}_a$

$\vec{\mathbf{p}}_b$

r
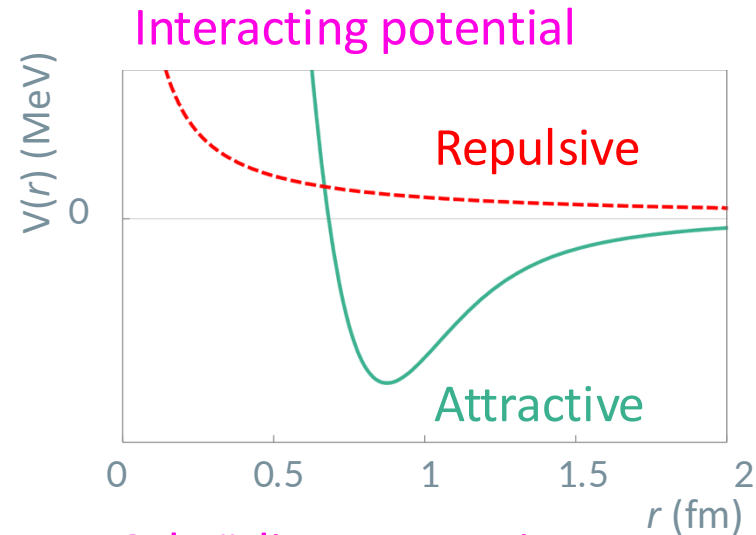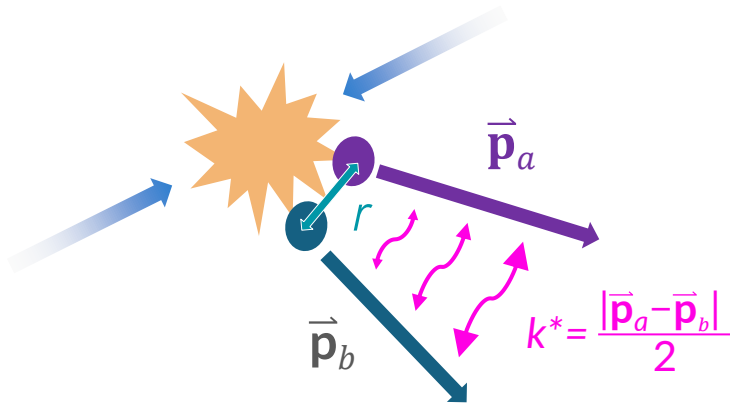
$k^* = \dfrac{|\vec{\mathbf{p}}_a - \vec{\mathbf{p}}_b|}{2}$
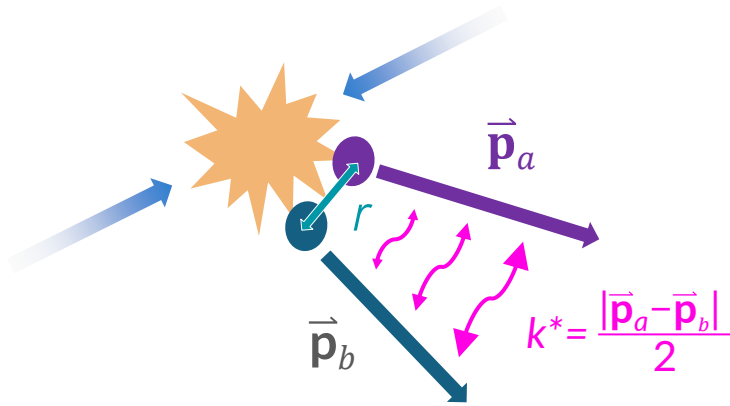
Emission source $S(\vec{r}\,)$

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

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

Correlation function

$\vec{p}_a$

$\vec{p}_b$

r

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

Repulsive

Attractive

0   0.5   1   1.5   2

r (fm)

$V(r)$ (MeV)

0

Emission source $S(\vec{r}\,)$
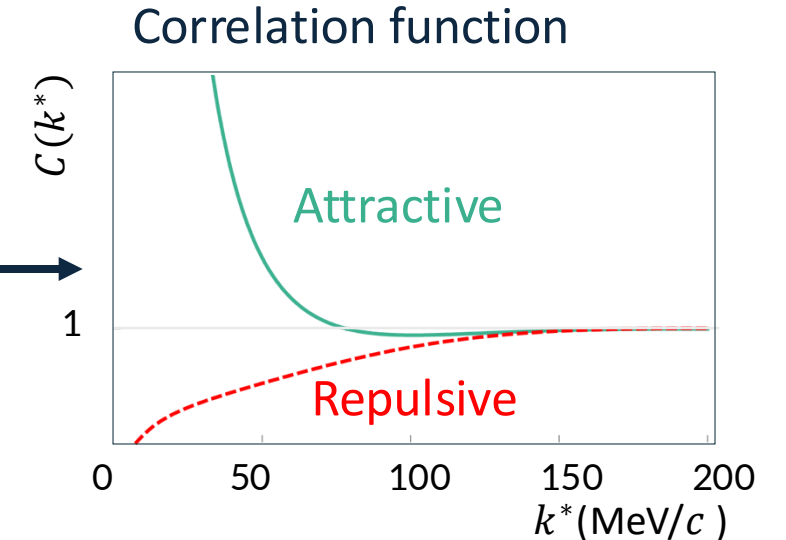
Schrödinger equation

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

Two-particle wave function

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

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

Correlation function

Interacting potential

$V(r)$ (MeV)

Repulsive

0

Attractive

0   0.5   1   1.5   2

r (fm)

Correlation function

$C(k^*)$

Attractive

1

Repulsive

0   50   100   150   200

k^*(MeV/c)

$\vec{\mathbf{p}}_a$

$\vec{\mathbf{p}}_b$

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

r

Emission source $S(\vec{r}\,)$
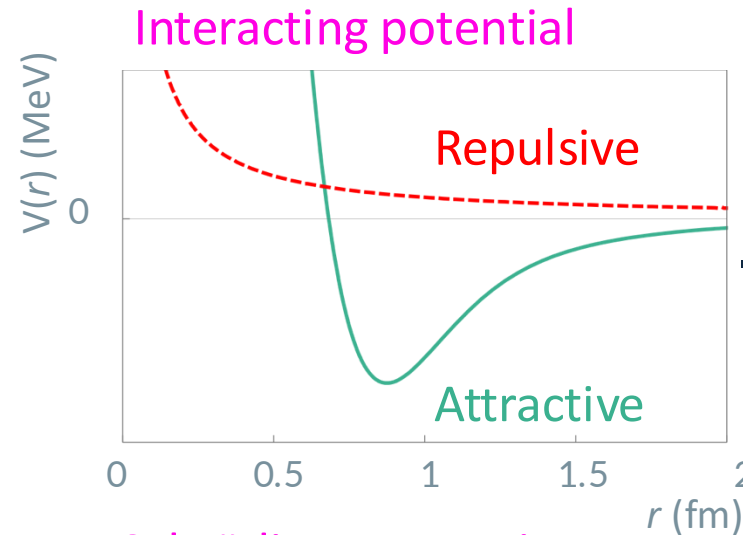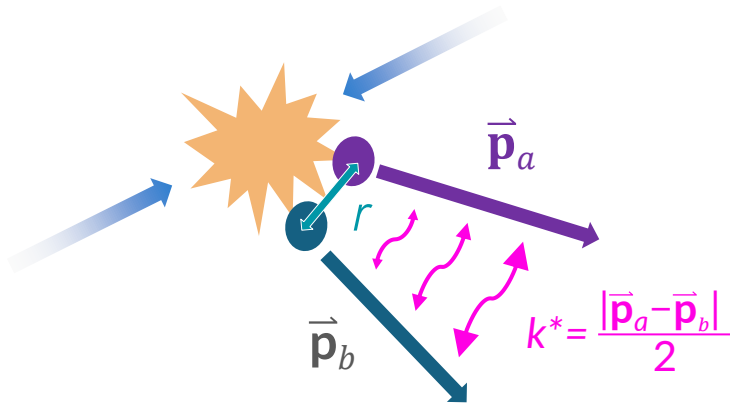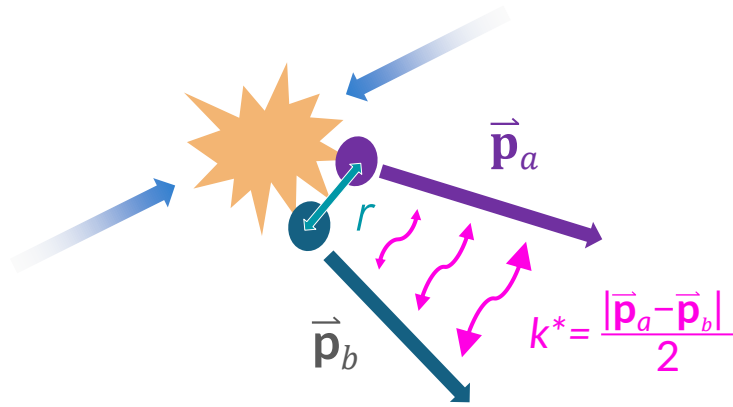
Schrödinger equation

D. Mihaylov et al., EPJC 78 (2018), 5, 394
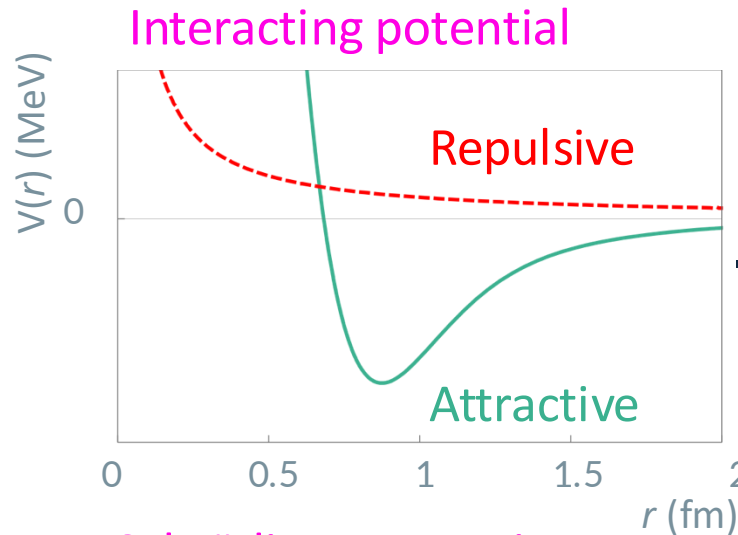
Two-particle wave function

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

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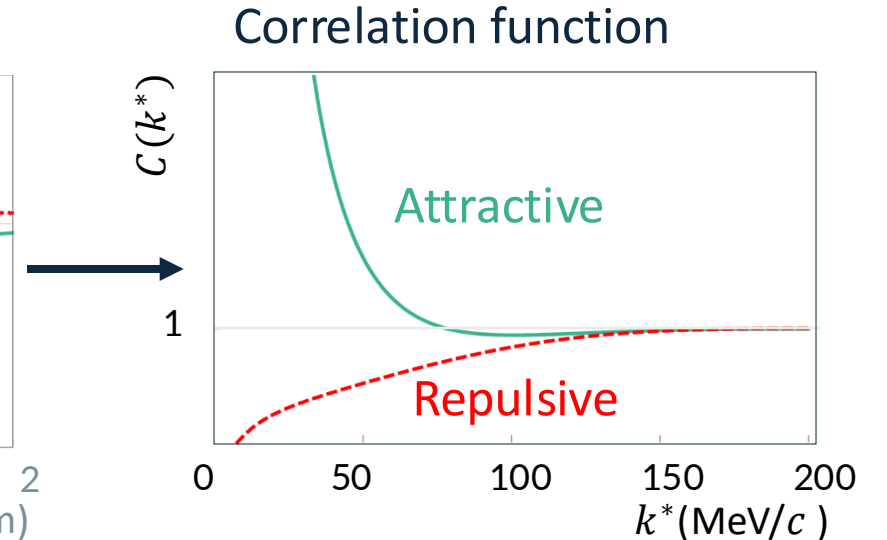*L. Fabbietti et al., ARNPS 71 (2021), 377-402*

Correlation function

Interacting potential

$V(r)$ (MeV)

Repulsive

0

Attractive

0   0.5   1   1.5   2

r (fm)

Correlation function

$C(k^*)$

Attractive

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Repulsive

0   50   100   150   200

k^*(MeV/c)

$\vec{\mathbf{p}}_a$

r

$\vec{\mathbf{p}}_b$

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

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

Schrödinger equation

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

Two-particle wave function

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

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

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

measured   known interaction

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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)

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

Source function in pp collisions at the LHC

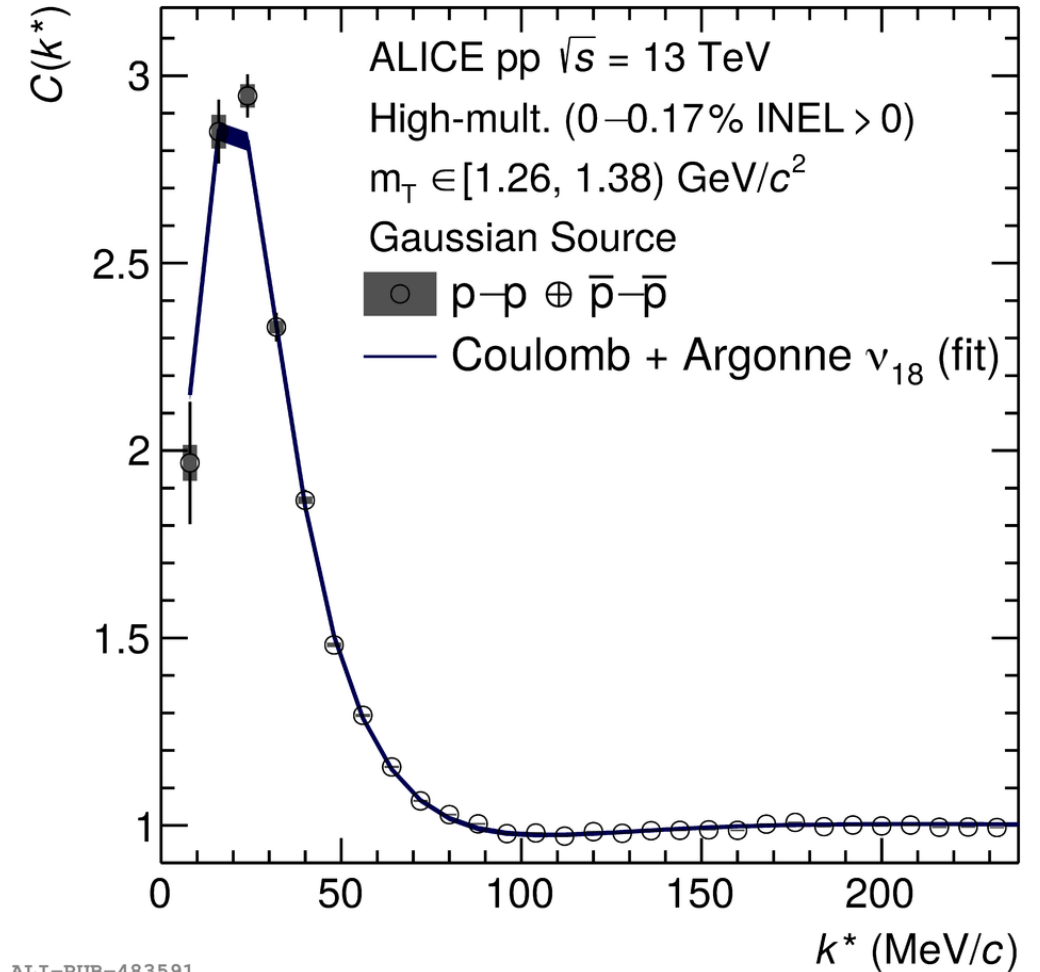- Emitting source function anchored to p-p correlation function

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

ALI−PUB−483591

ALICE Coll., PLB, 811 (2020)

Source function in pp collisions at the LHC

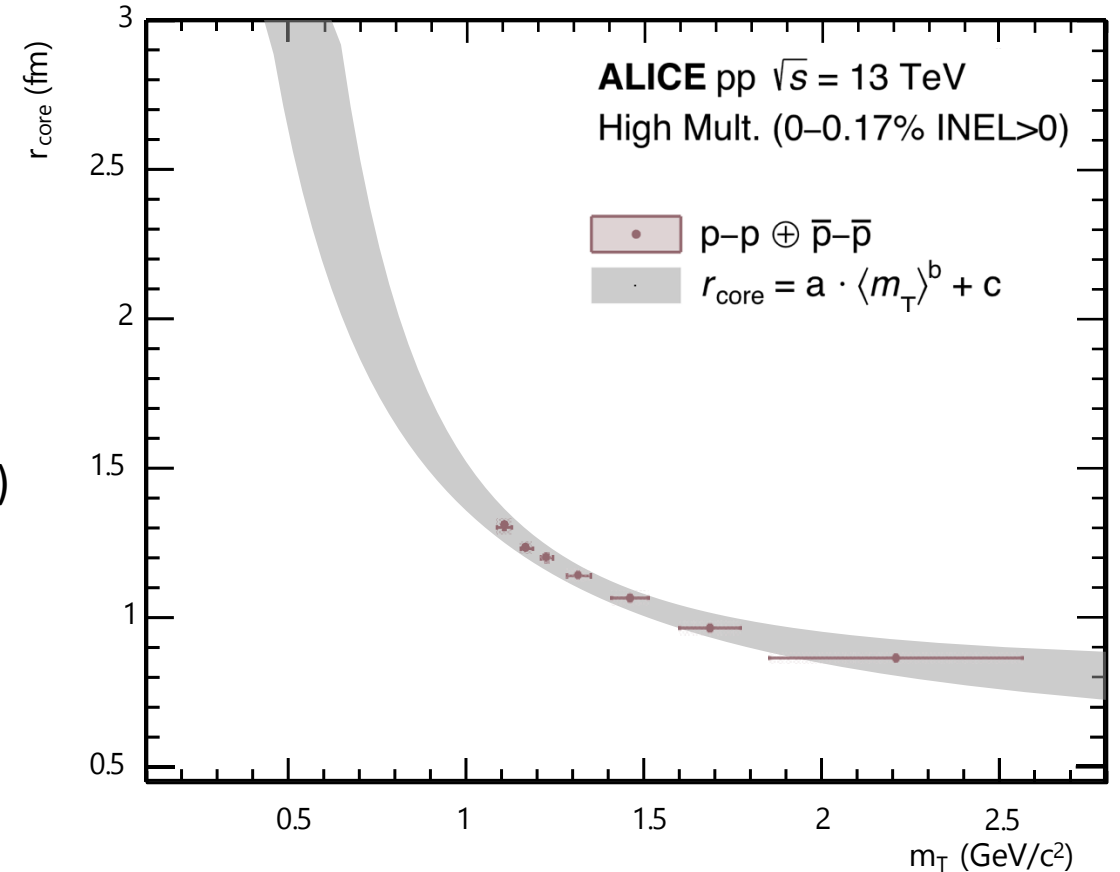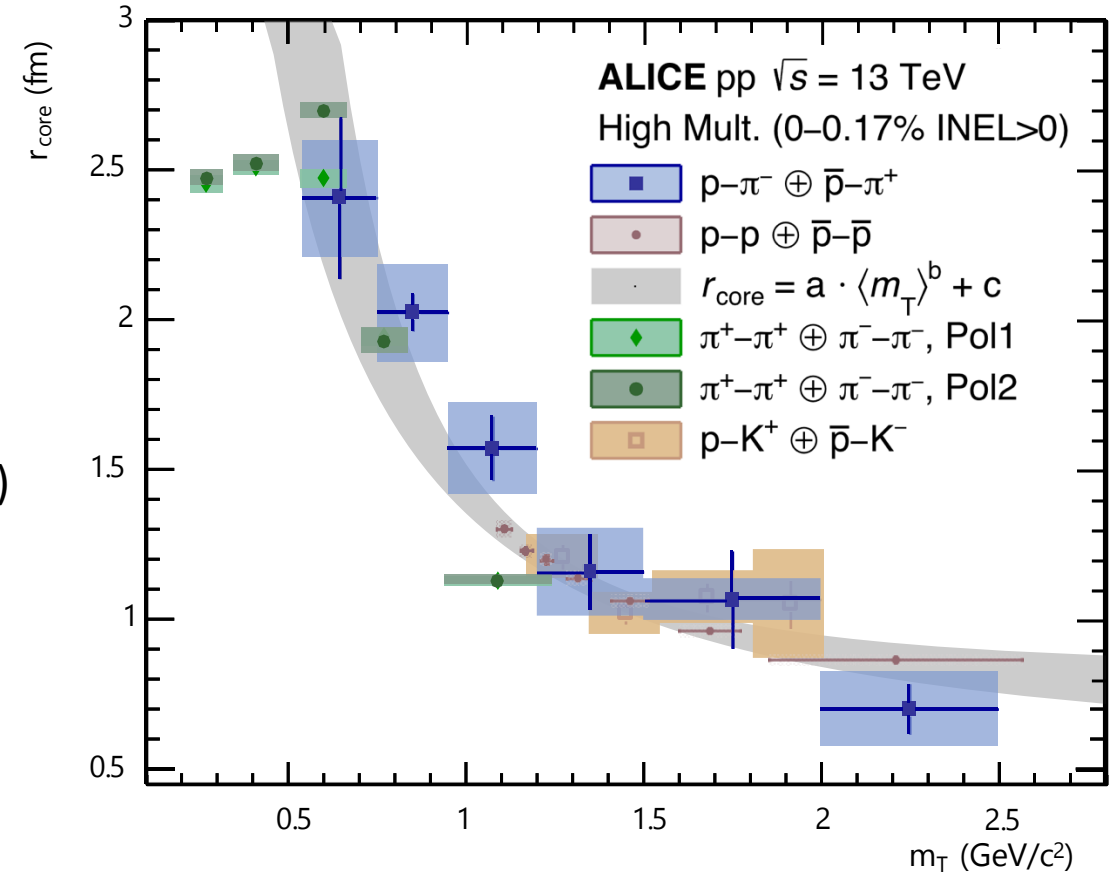- Emitting source function anchored to p-p correlation function

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

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

Effect of short lived resonances (cτ ~ 1 fm)

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

ALICE Coll., arXiv:2311.14527

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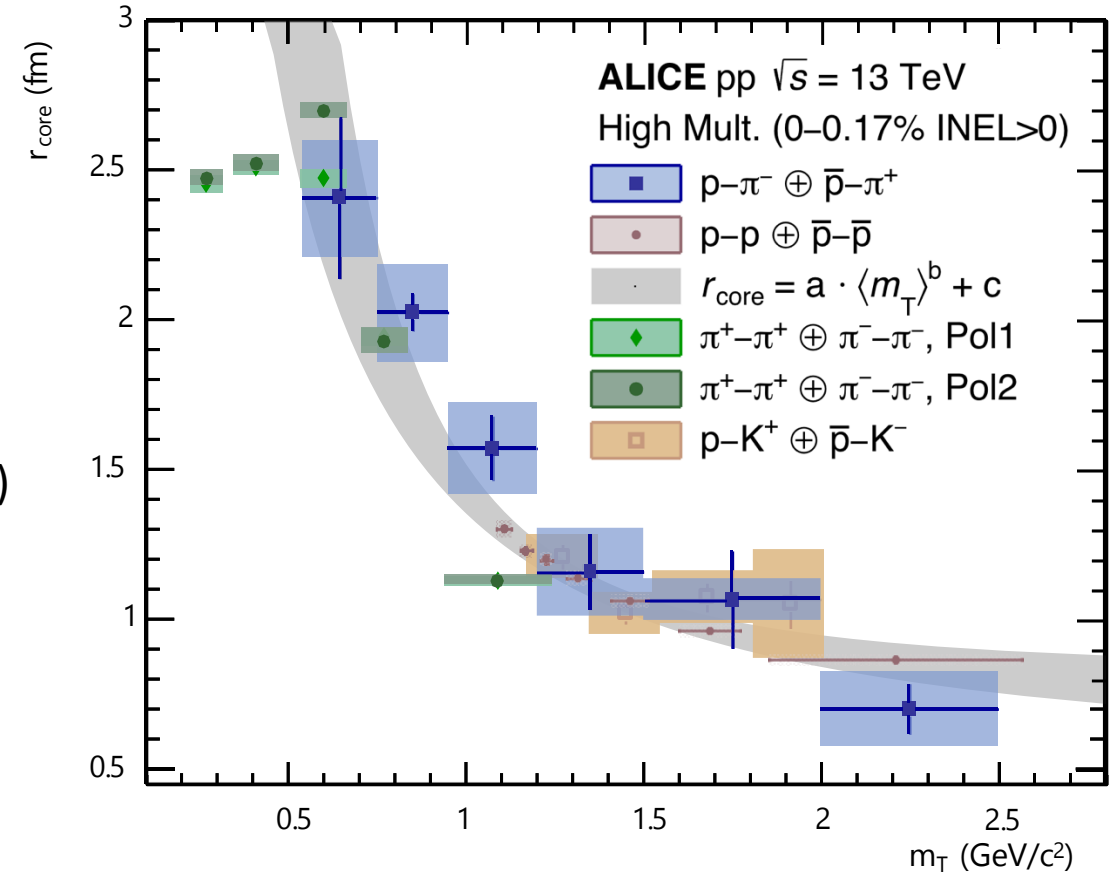$$\text{known interaction}$$

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Effect of short lived resonances (cτ ~ 1 fm)

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

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

ALICE Coll., arXiv:2311.14527

Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

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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)

- **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

Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

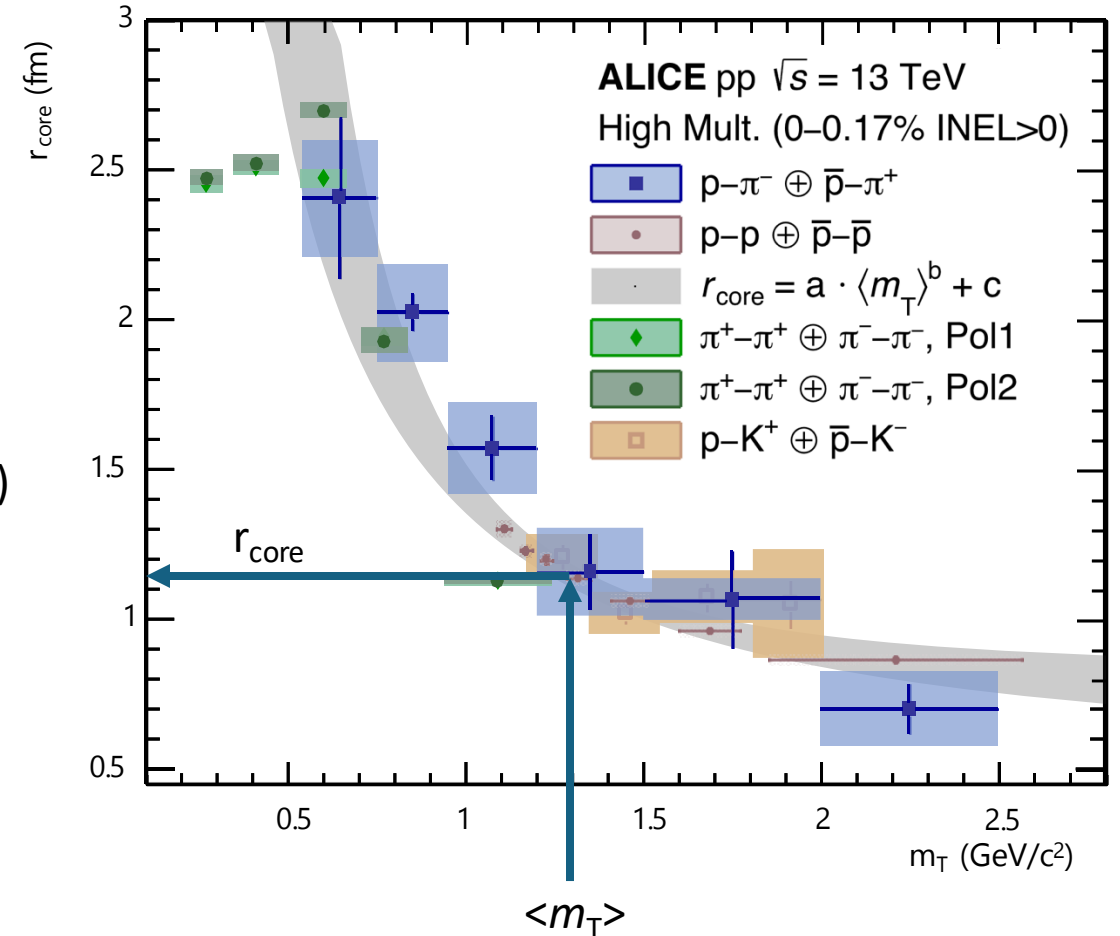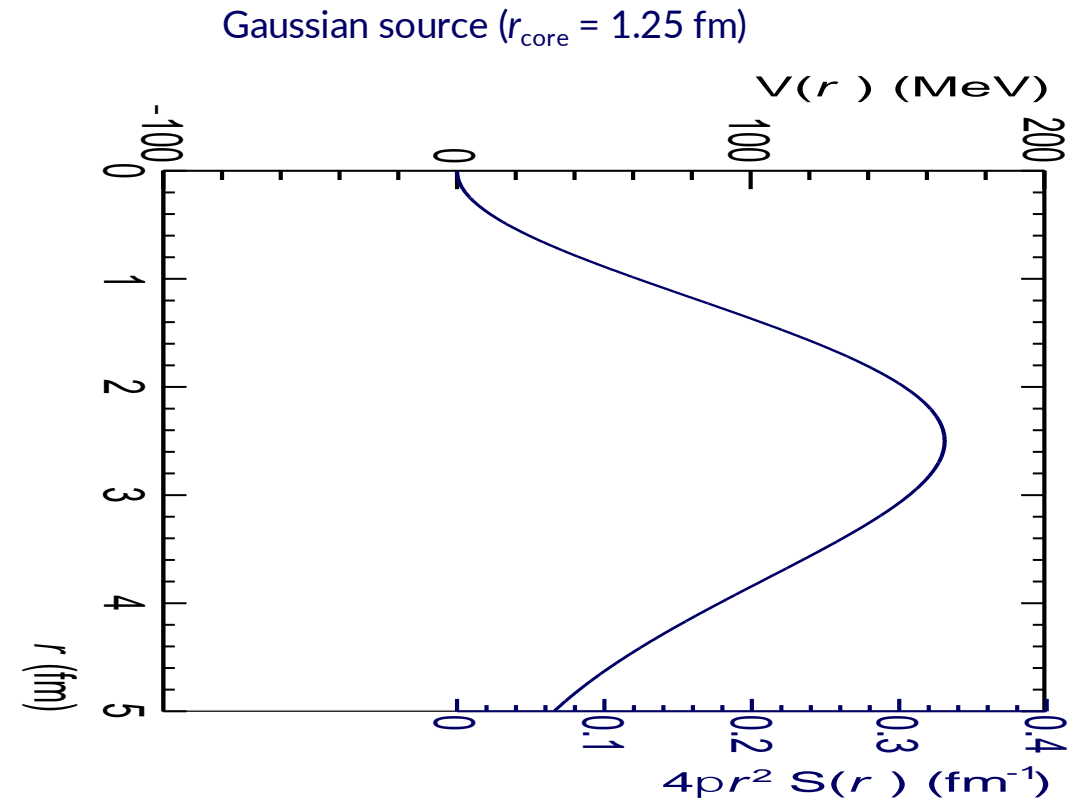$$C(k^*) = \int S(\vec{r})\left|\psi(\vec{k}^*,\vec{r})\right|^2 d^3\vec{r}$$

measured   known interaction

- Gaussian parametrization

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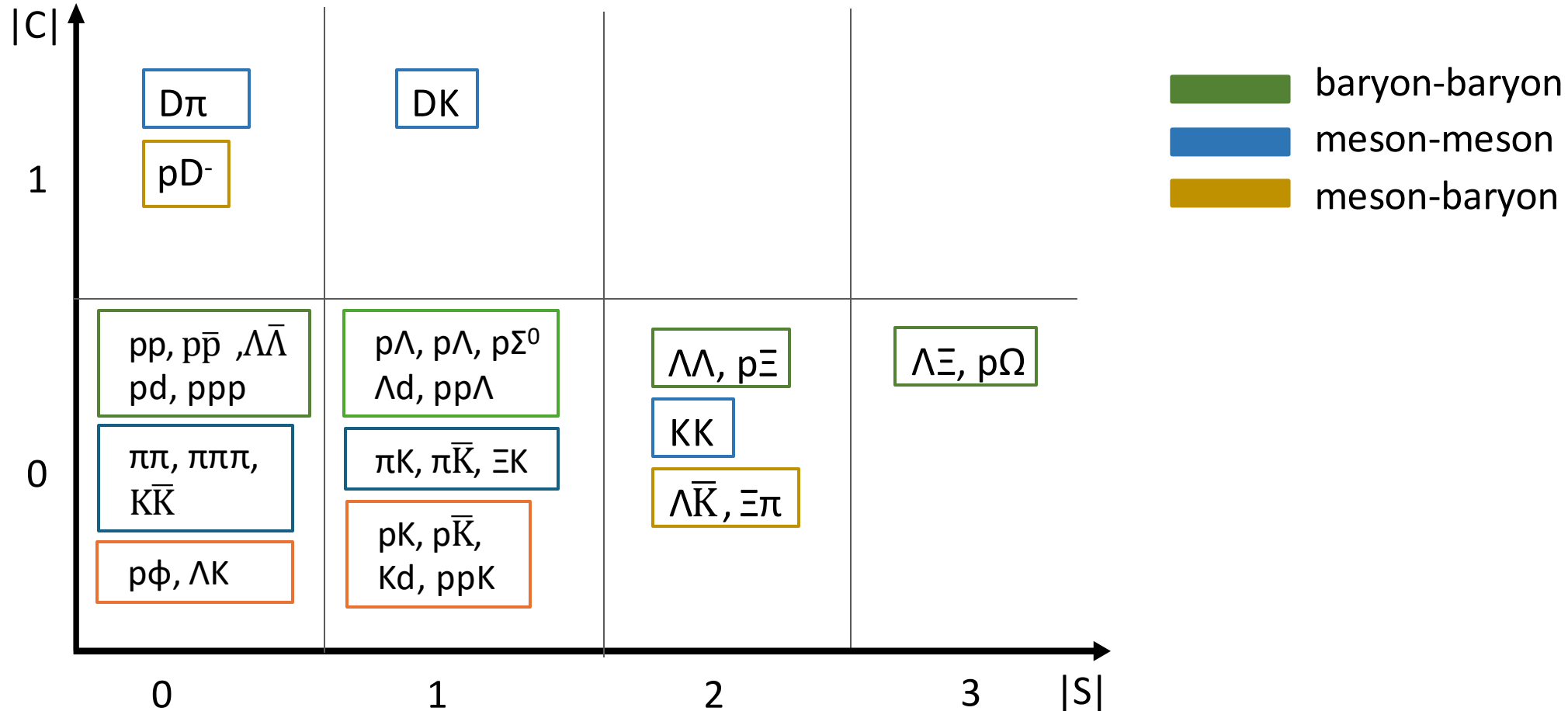
Effect of short lived resonances (cτ ~ 1 fm)

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ALICE Coll., arXiv:2311.14527

Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

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

- Gaussian parametrization

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

Effect of short lived resonances ($c\tau \sim 1$ 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., arXiv:2311.14527*
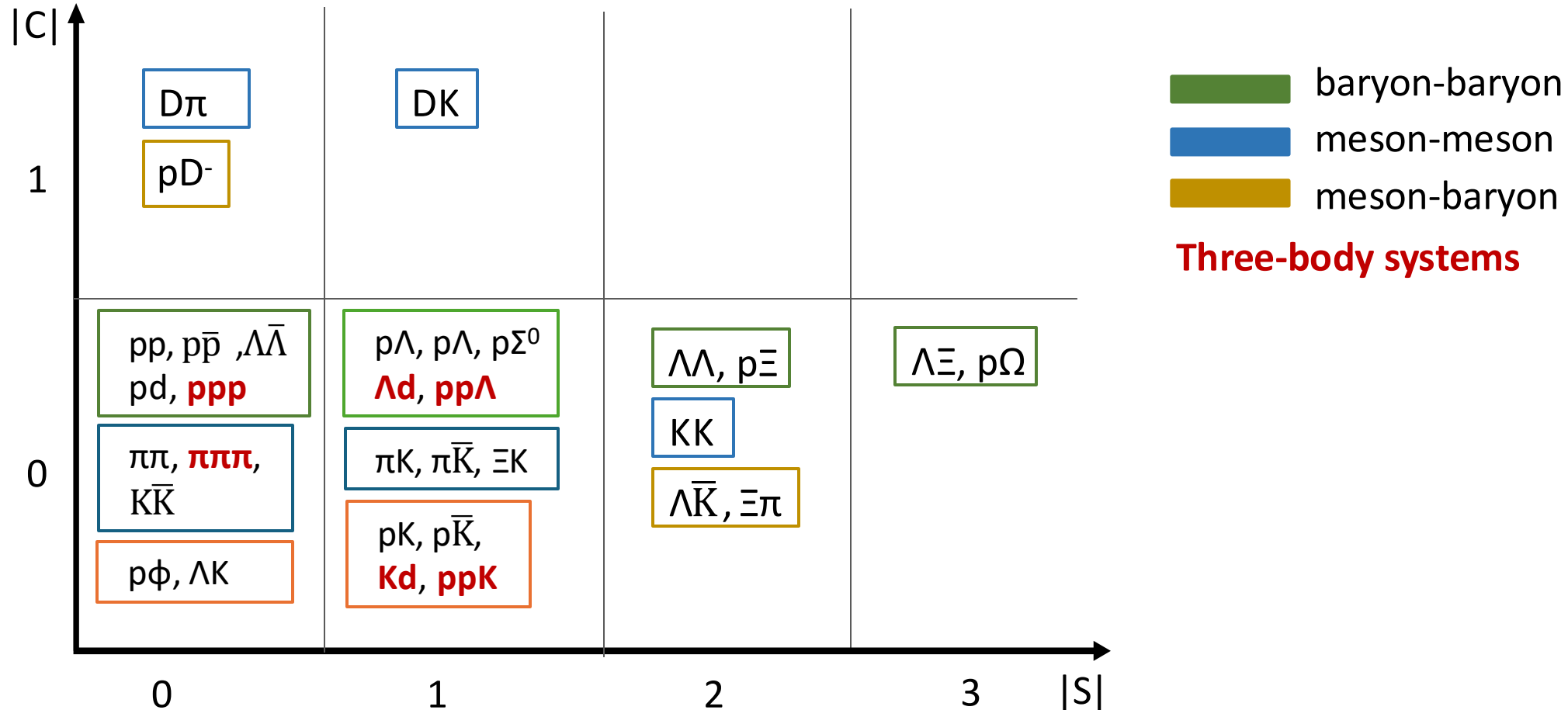
Gaussian source (r_{core} = 1.25 fm)

Femtoscopy measurements at the LHC

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

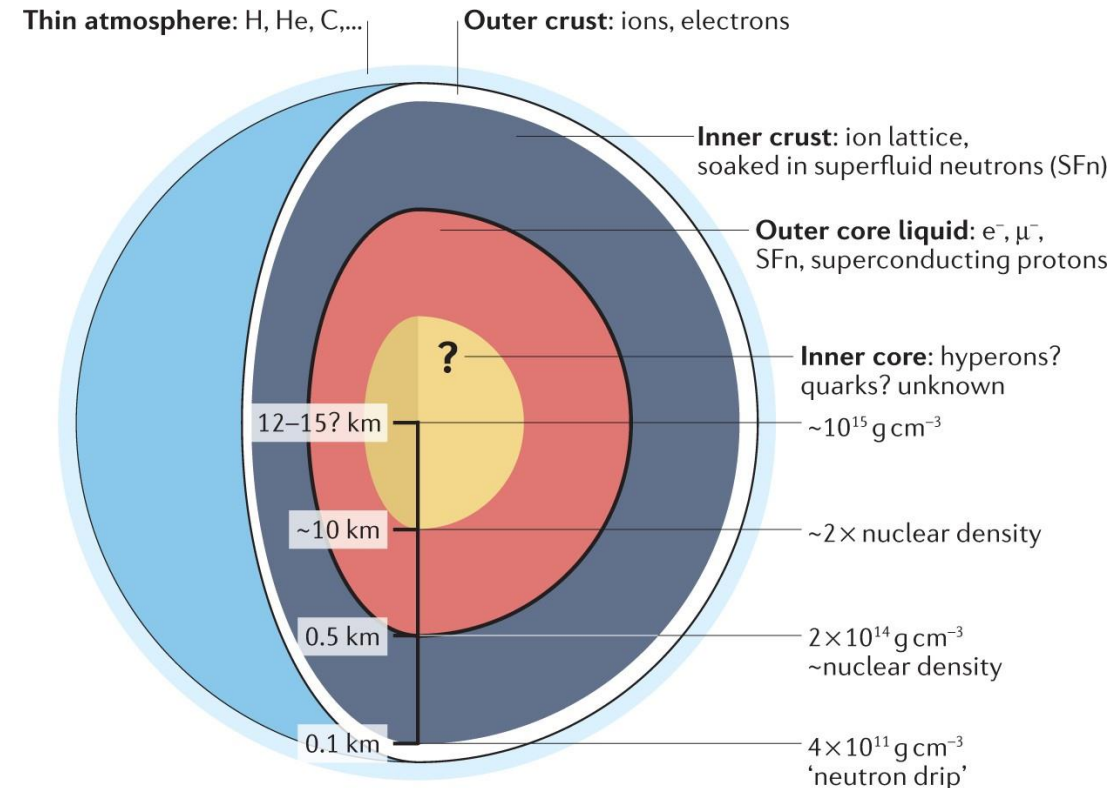# Femtoscopy measurements at the LHC

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

The NΛ and NNΛ interactions in neutron stars

- High density in the core of neutron stars
  - → Production of hyperons as Λ at ρ = 2-3ρ_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
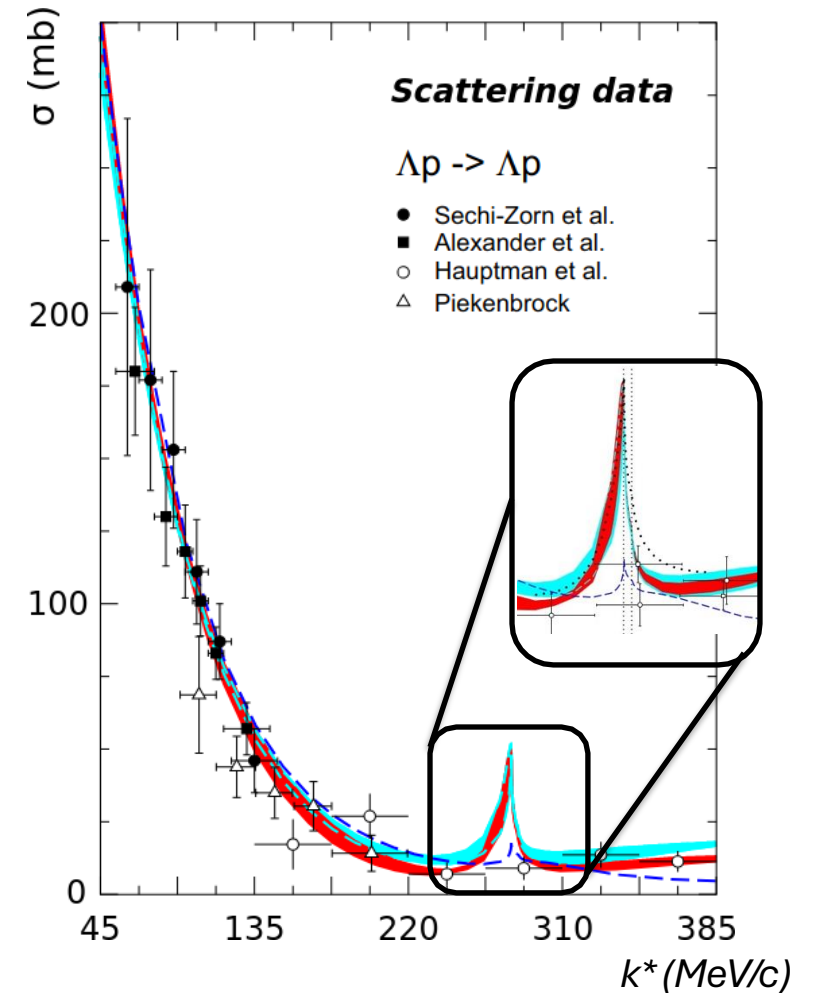 - → too repulsive YNN leads to no hyperons in the NSs

Thin atmosphere: H, He, C,...

Outer crust: ions, electrons

Inner crust: ion lattice,
soaked in superfluid neutrons (SFn)

Outer core liquid: e⁻, μ⁻,
SFn, superconducting protons

Inner core: hyperons?
quarks? unknown

$\sim 10^{15}\,\mathrm{g\,cm^{-3}}$

$\sim 2 \times$ nuclear density

$2 \times 10^{14}\,\mathrm{g\,cm^{-3}}$
~nuclear density

$4 \times 10^{11}\,\mathrm{g\,cm^{-3}}$
'neutron drip'

12–15? km

~10 km

0.5 km

0.1 km

?

Nature Reviews Physics 4 (2022)
Figure adapted from NICER

The NΛ and NNΛ interactions in neutron stars

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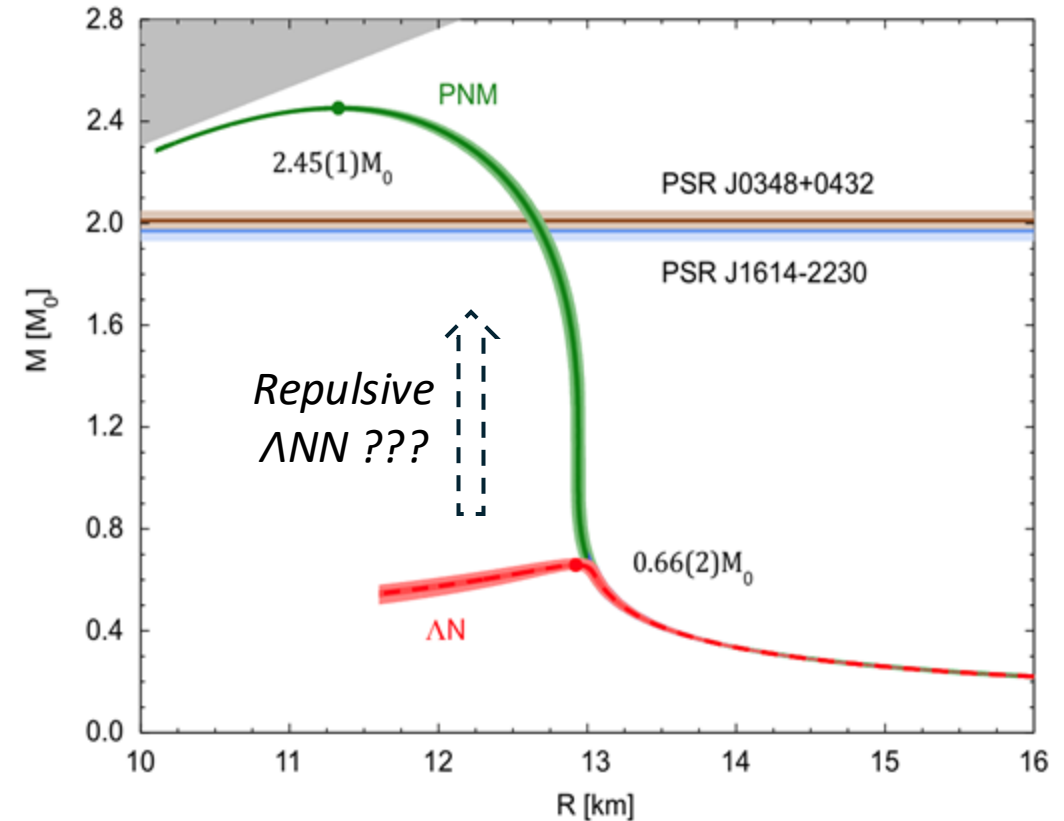
The pΛ interaction so far...

- 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

Scattering data

Λp -> Λp
- ● Sechi-Zorn et al.
- ■ Alexander et al.
- ○ Hauptman et al.
- △ Piekenbrock

$k* (MeV/c)$

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

The pΛ interaction before femtoscopy

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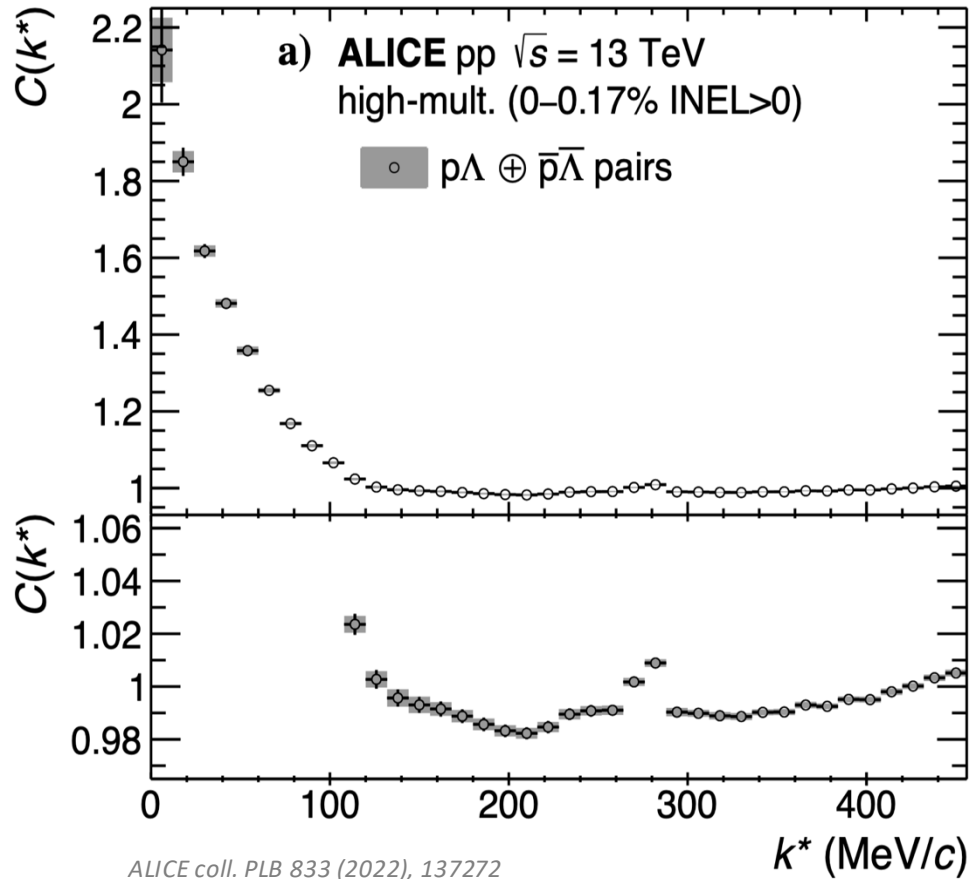- Agreement with N2LO and NLO19

D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550
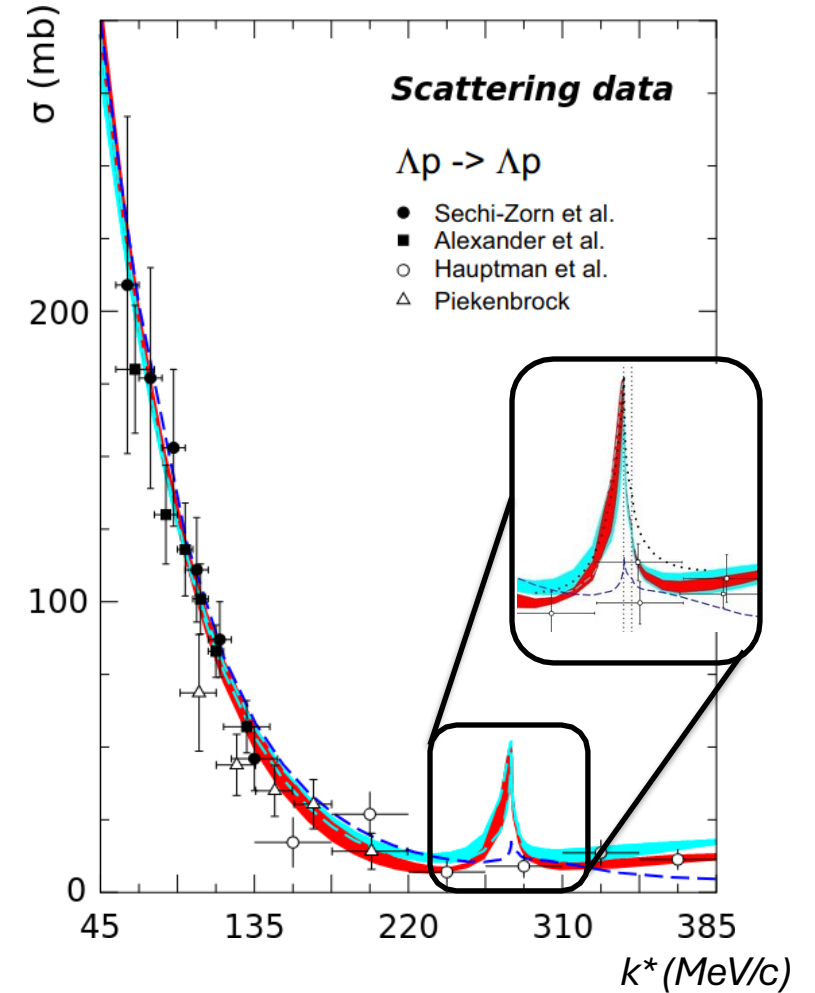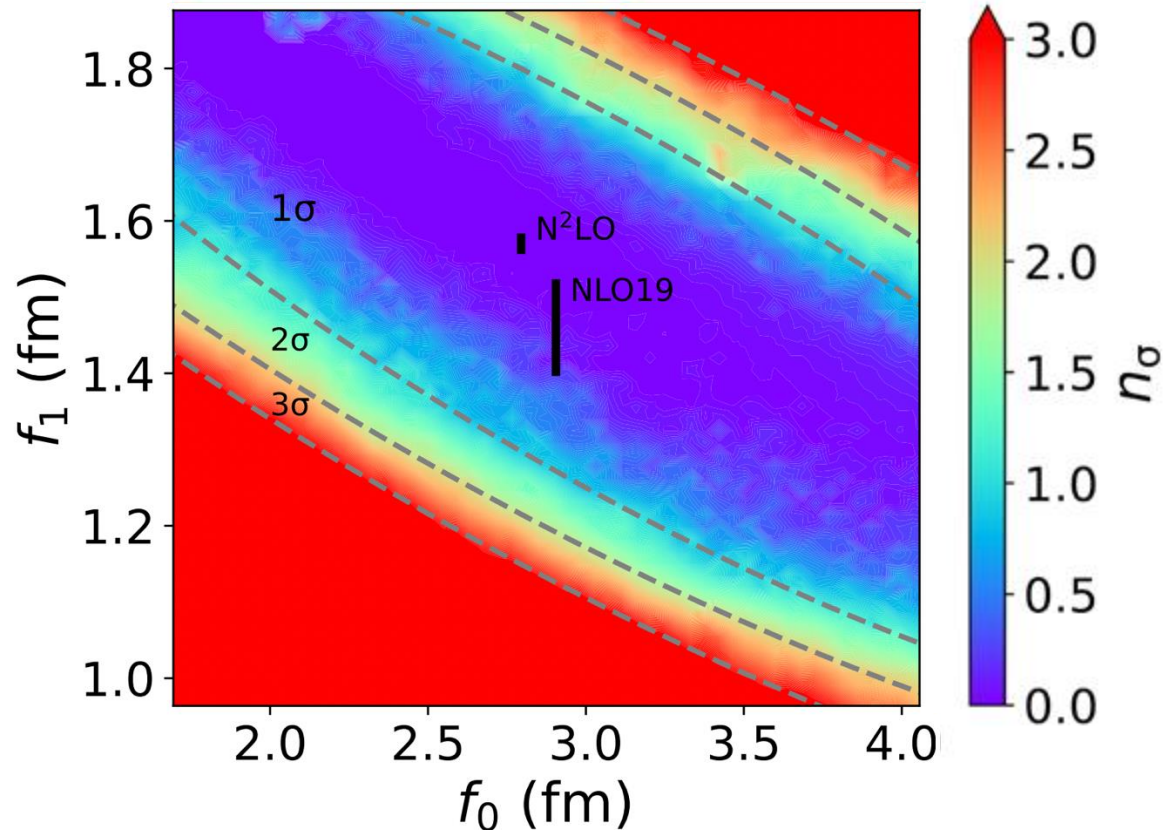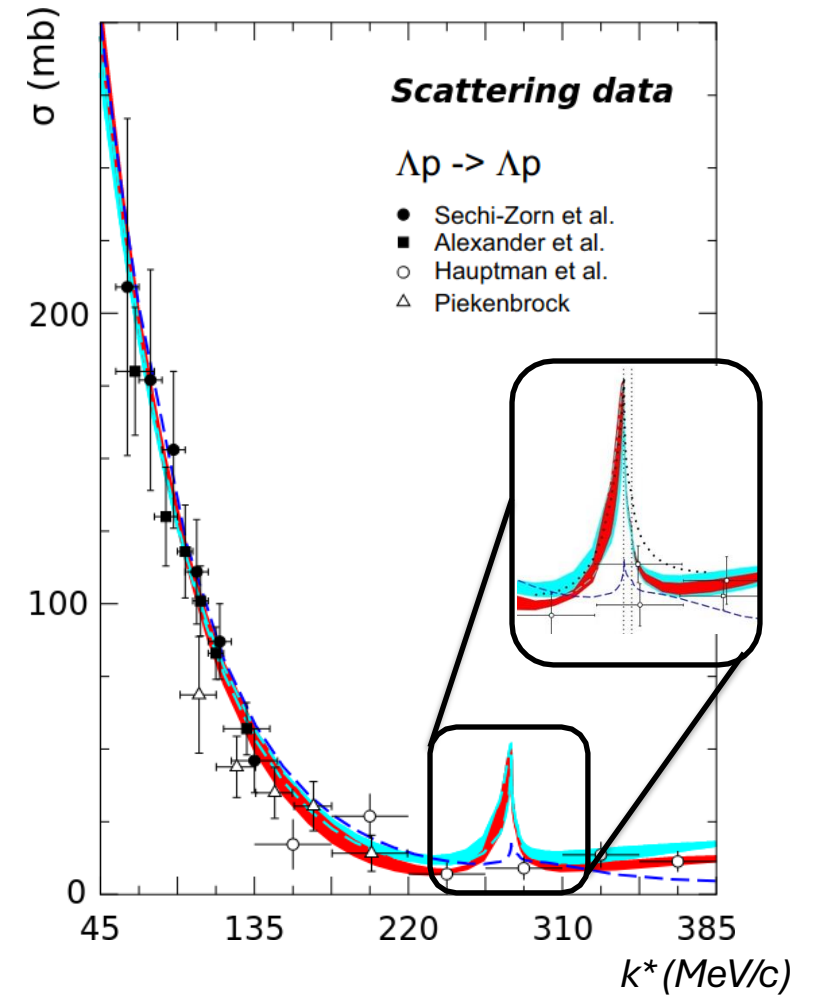
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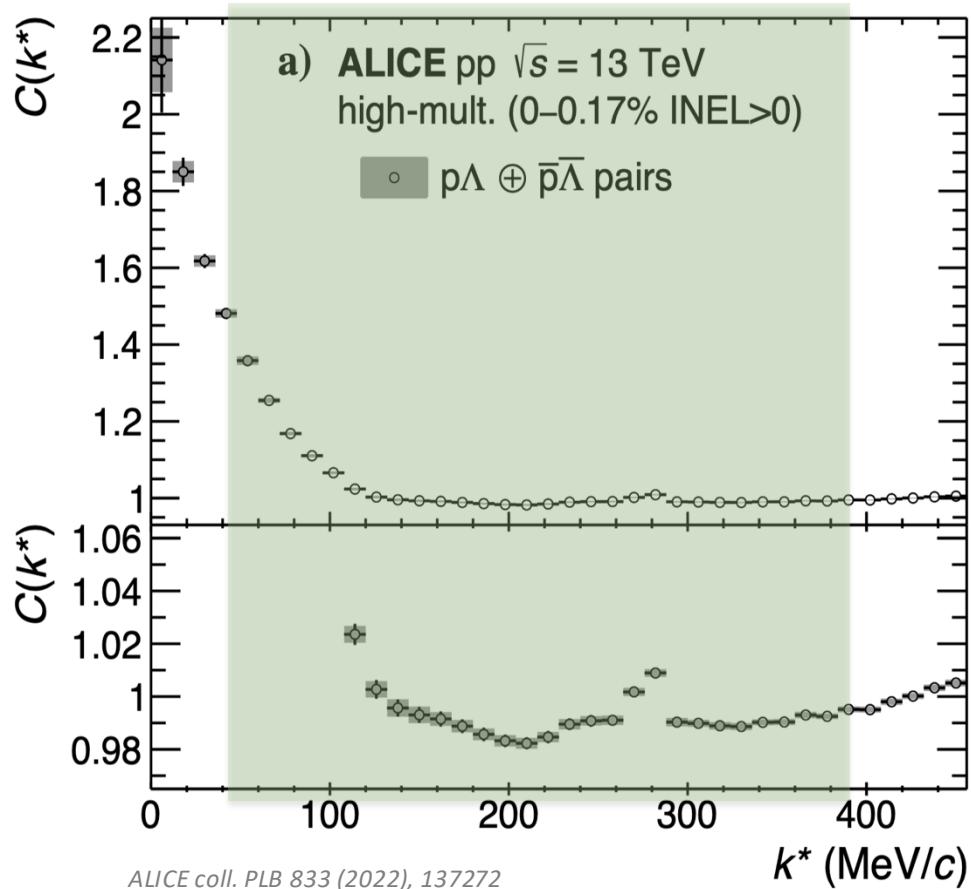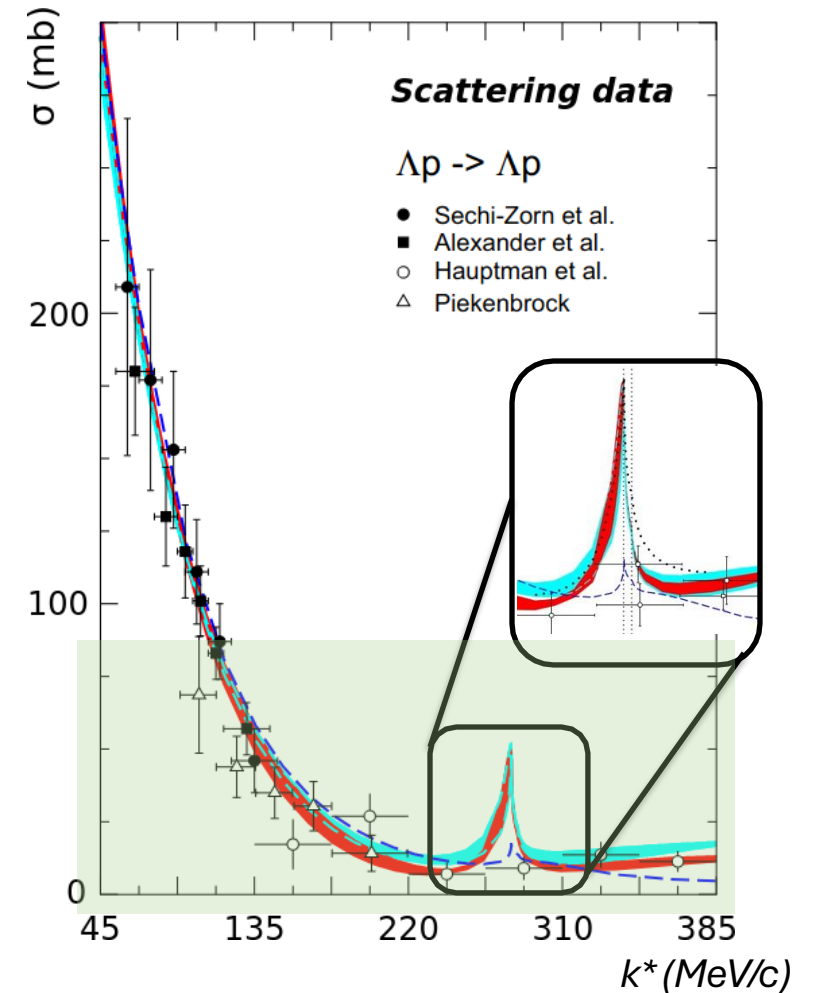
The pΛ interaction in the femtoscopy era

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)

The pΛ interaction in the femtoscopy era

a) **ALICE** pp $\sqrt{s}$ = 13 TeV
high-mult. (0–0.17% INEL>0)
pΛ ⊕ p̄Λ̄ pairs

ALICE coll. PLB 833 (2022), 137272

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The pΛ interaction in the femtoscopy era

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

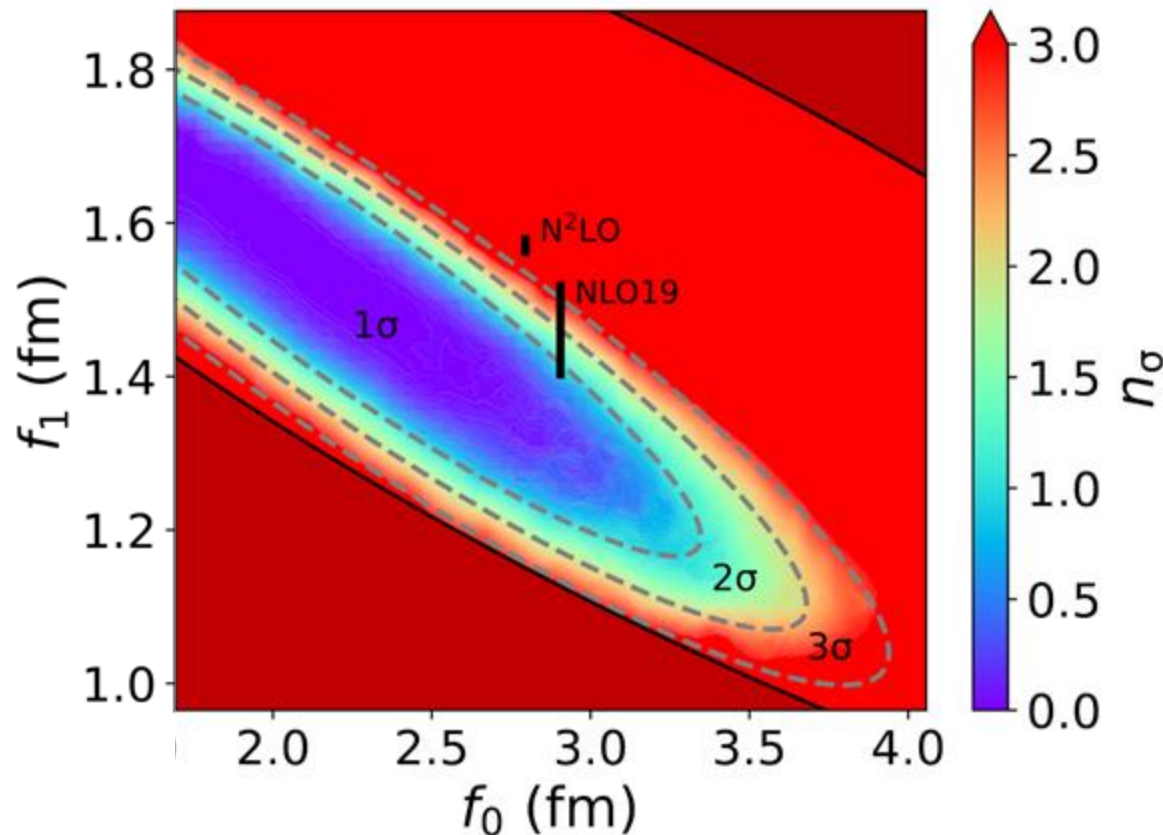 *D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550*
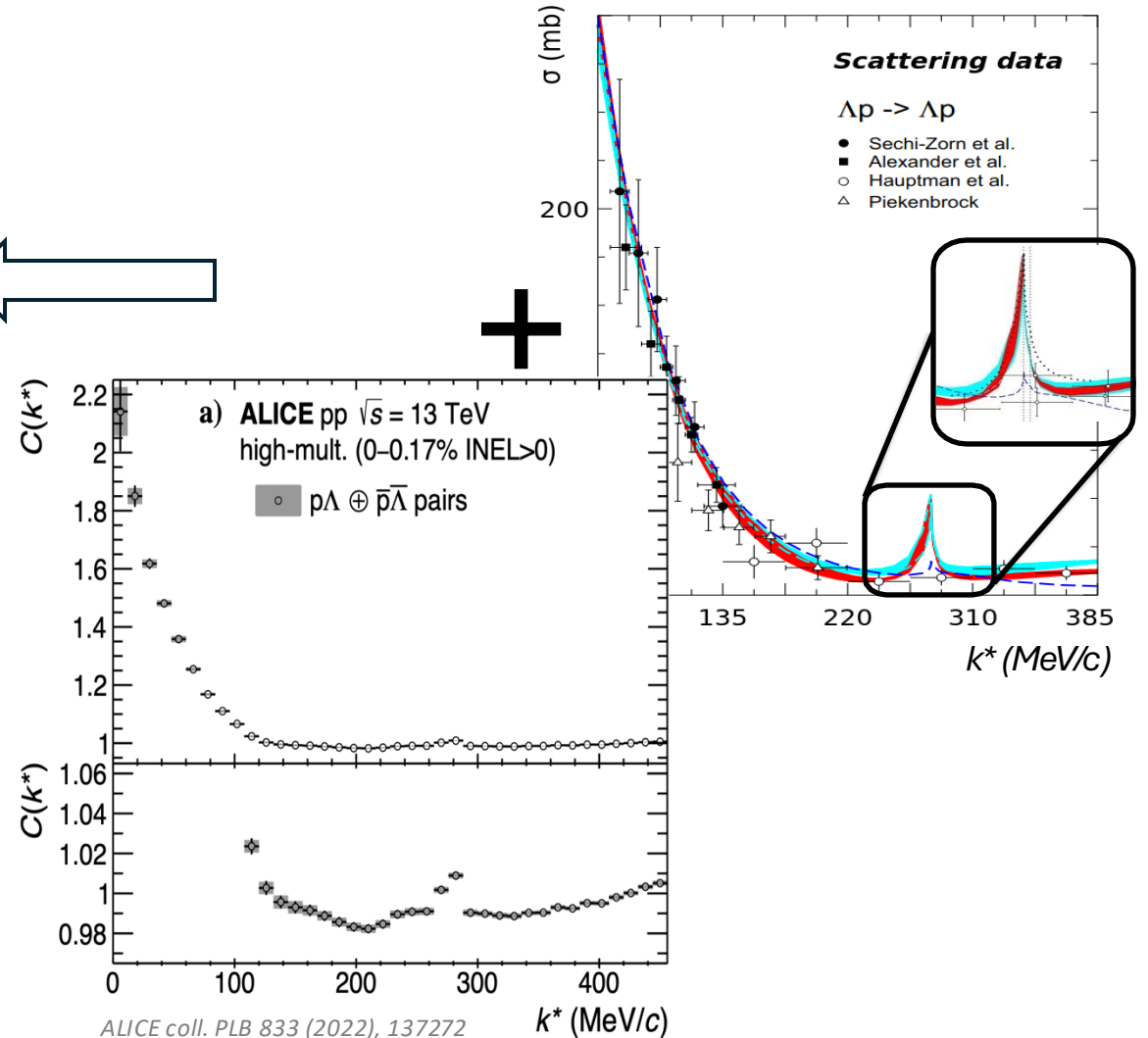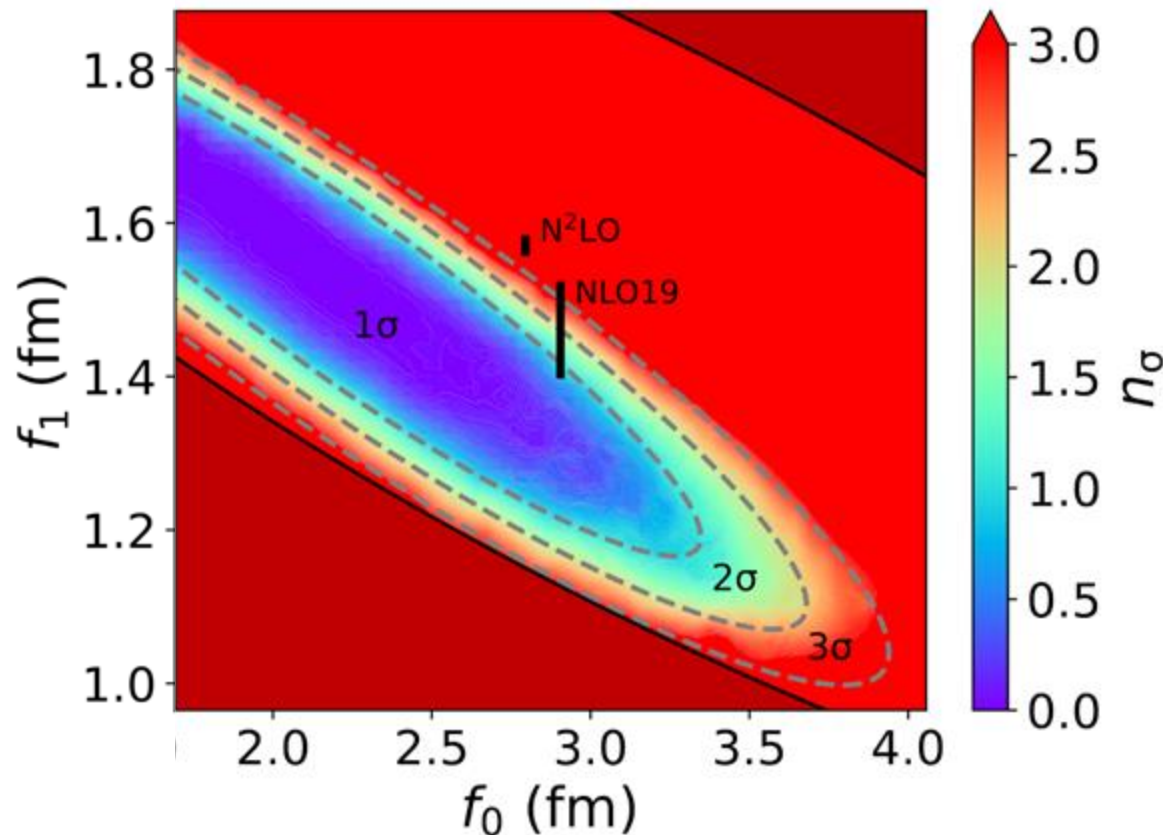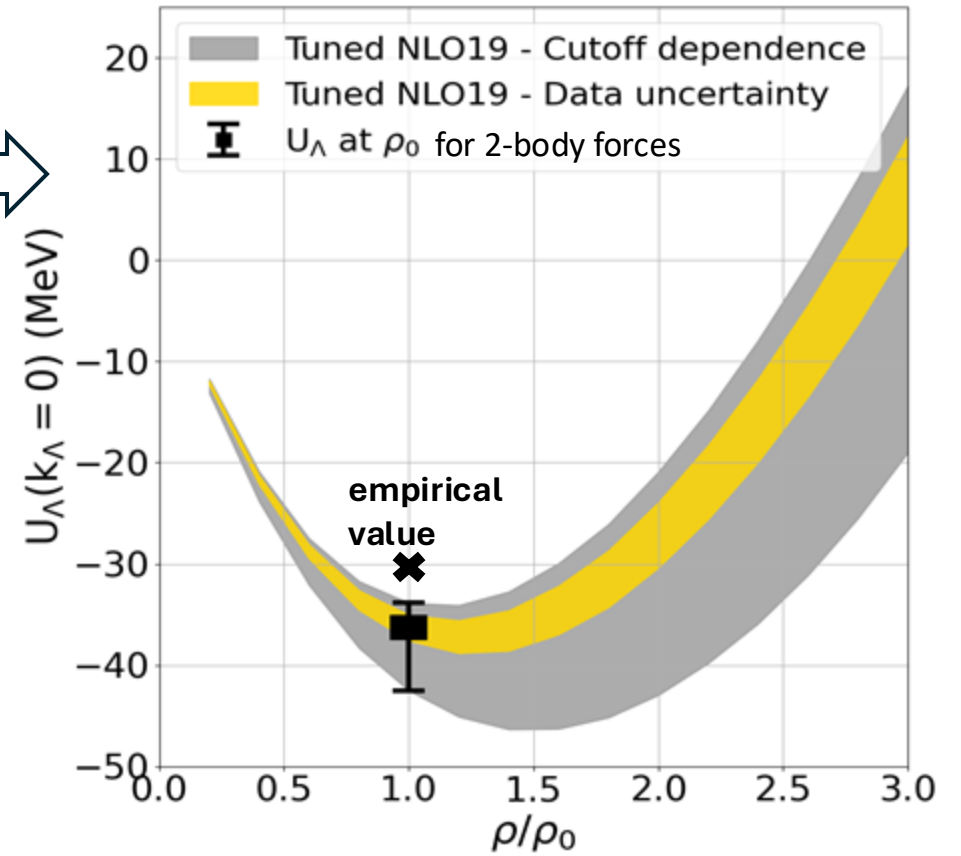

ALICE coll. PLB 833 (2022), 137272

The pΛ interaction in the femtoscopy era

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

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

New parameterizations of the χEFT Compatible with repulsive 3-body forces

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

NNN using proton-deuteron correlations
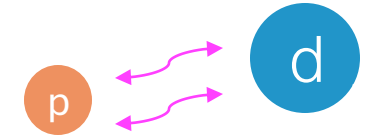
o Coulomb + strong interaction using the Lednický model

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

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

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

o 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				

o Only s-wave interaction
o 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);*

- 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
pp High-mult. $\sqrt{s}$ = 13 TeV

p–d ⊕ p̄–d̄
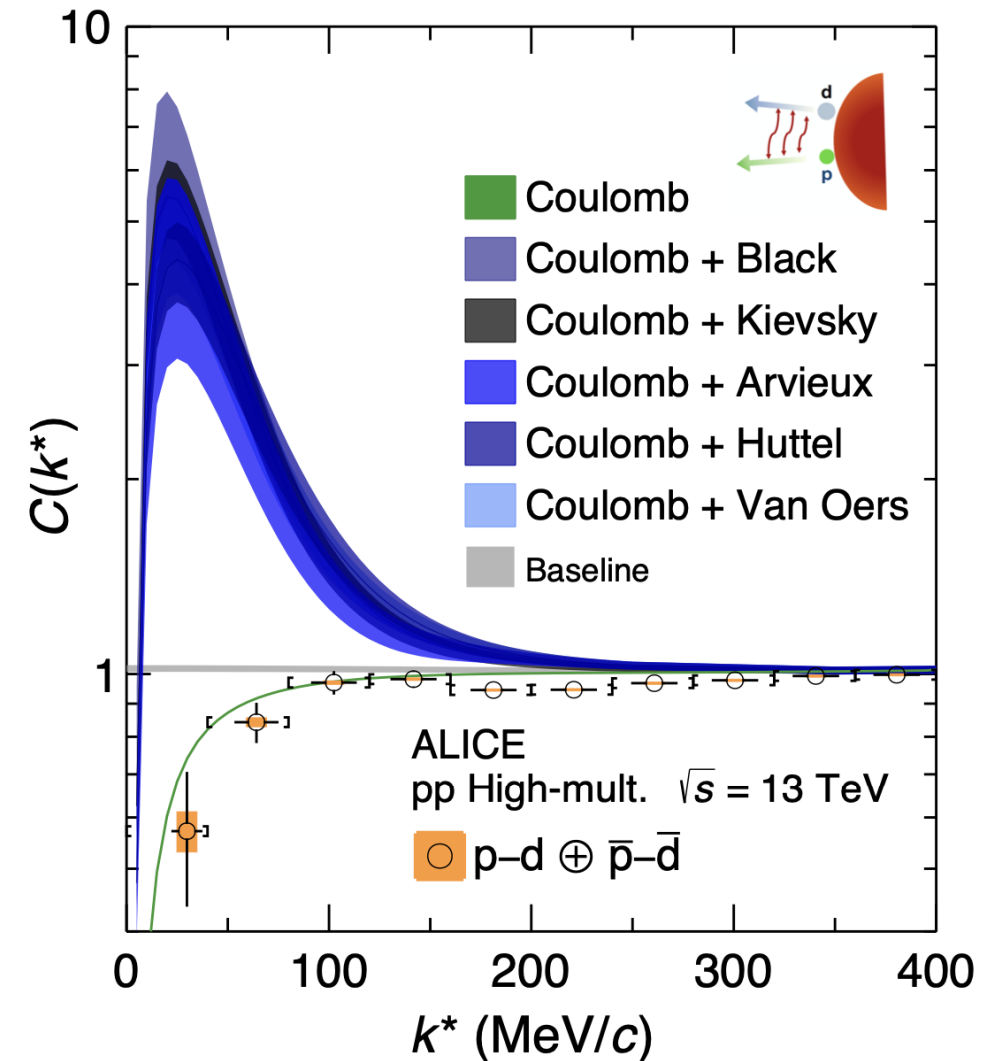
ALICE Coll. Phys. Rev. X 14, 031051 (2024)

NNN using proton-deuteron correlations
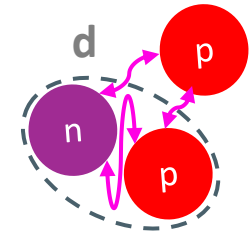
- The p–d **correlation function**, assuming that p–p–n forms p–d

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

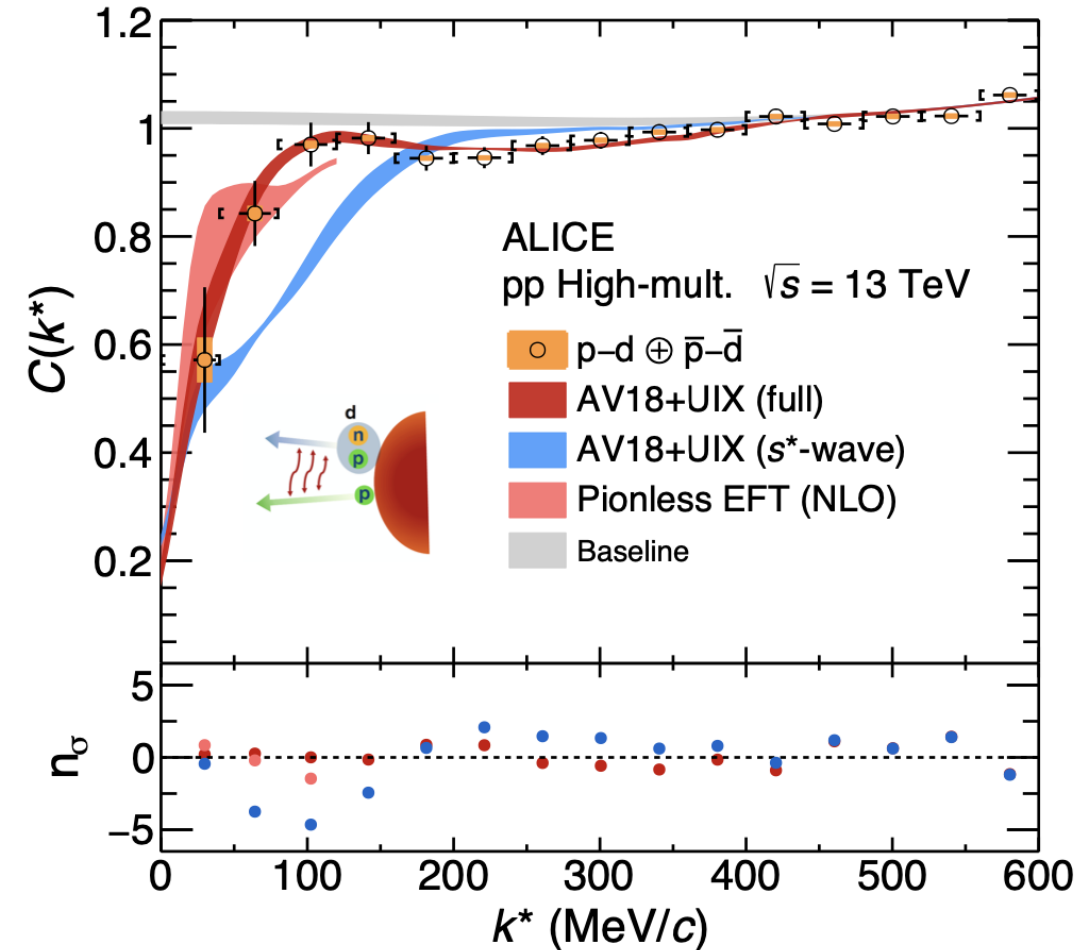where $S_1(r)$ is a single-particle Gaussian source and A_d is the formation probability of a deuteron

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

$$\Psi_{m_2,m_1}(x,y) = \Psi_{m_2,m_1}^{free} + \sum_{LSJ}^{J\leq\bar{J}}\sqrt{4\pi}\ i^L\sqrt{2L+1}\ e^{i\sigma_L}\left(1m_2\frac{1}{2}m_1\Big|SJ_z\right)(L0SJ_z|JJ_z)\widetilde{\Psi}_{LSJJ_z}$$

Asymptotic solution   Three-body dynamics

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

ALICE
pp High-mult. $\sqrt{s} = 13$ TeV
- p–d $\oplus$ $\bar{\text{p}}$–$\bar{\text{d}}$
- AV18+UIX (full)
- AV18+UIX (s^*-wave)
- Pionless EFT (NLO)
- Baseline

$C(k^*)$

n_σ

k^* (MeV/c)

ALICE Coll. Phys. Rev. X 14, 031051 (2024)
M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002
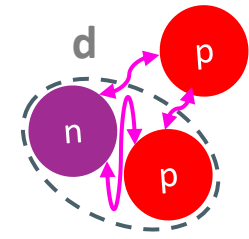
NNN using proton-deuteron correlations

- Full three-body calculations are required
  (NN + NNN + Quantum Statistics)

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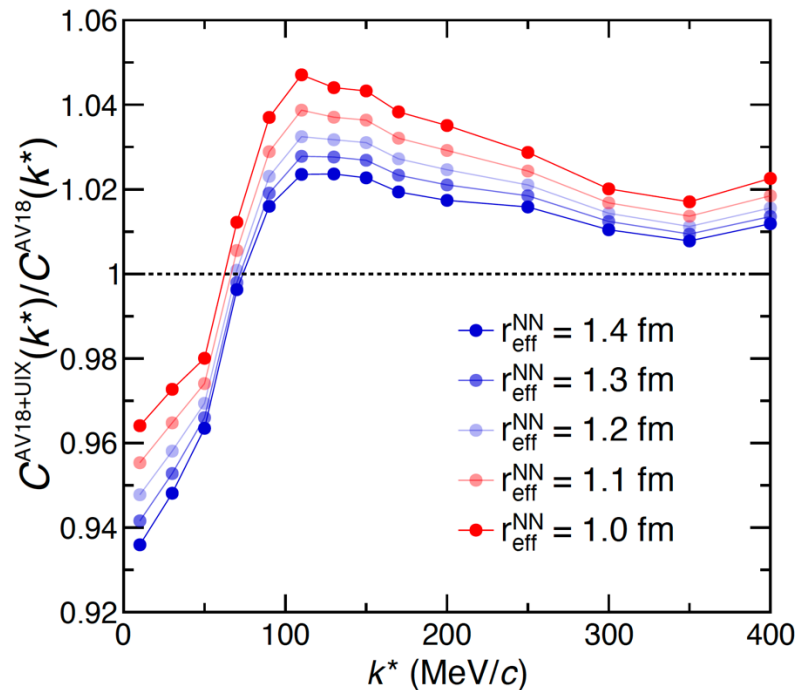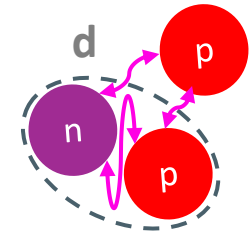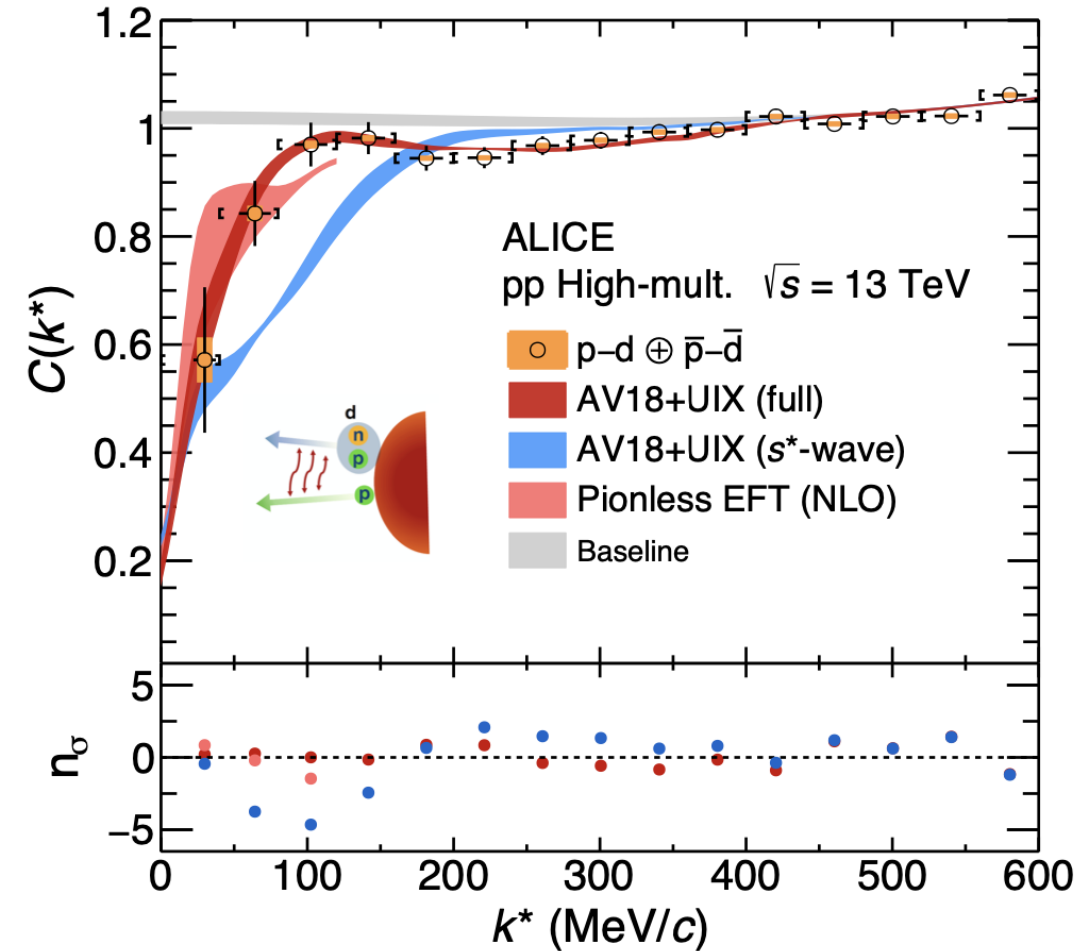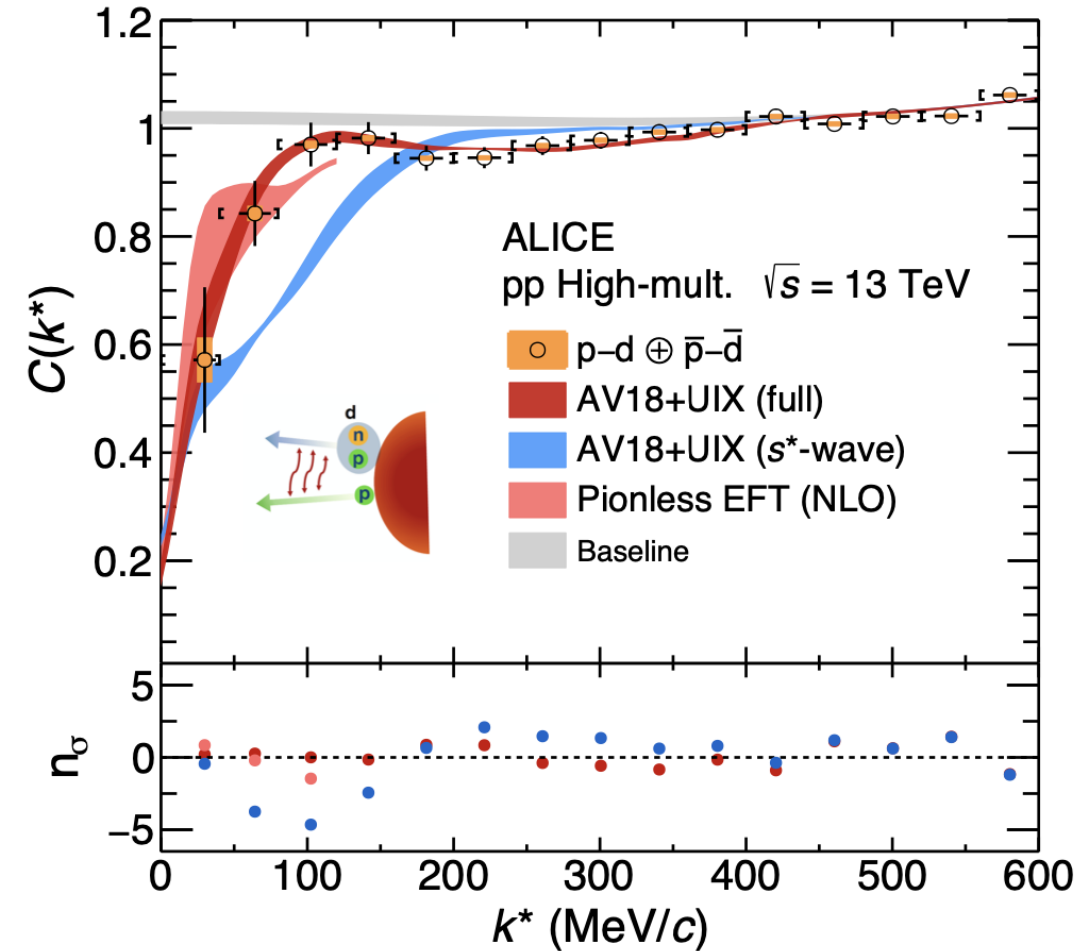 many-body dynamics

ALICE Coll. Phys. Rev. X 14, 031051 (2024)
M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002
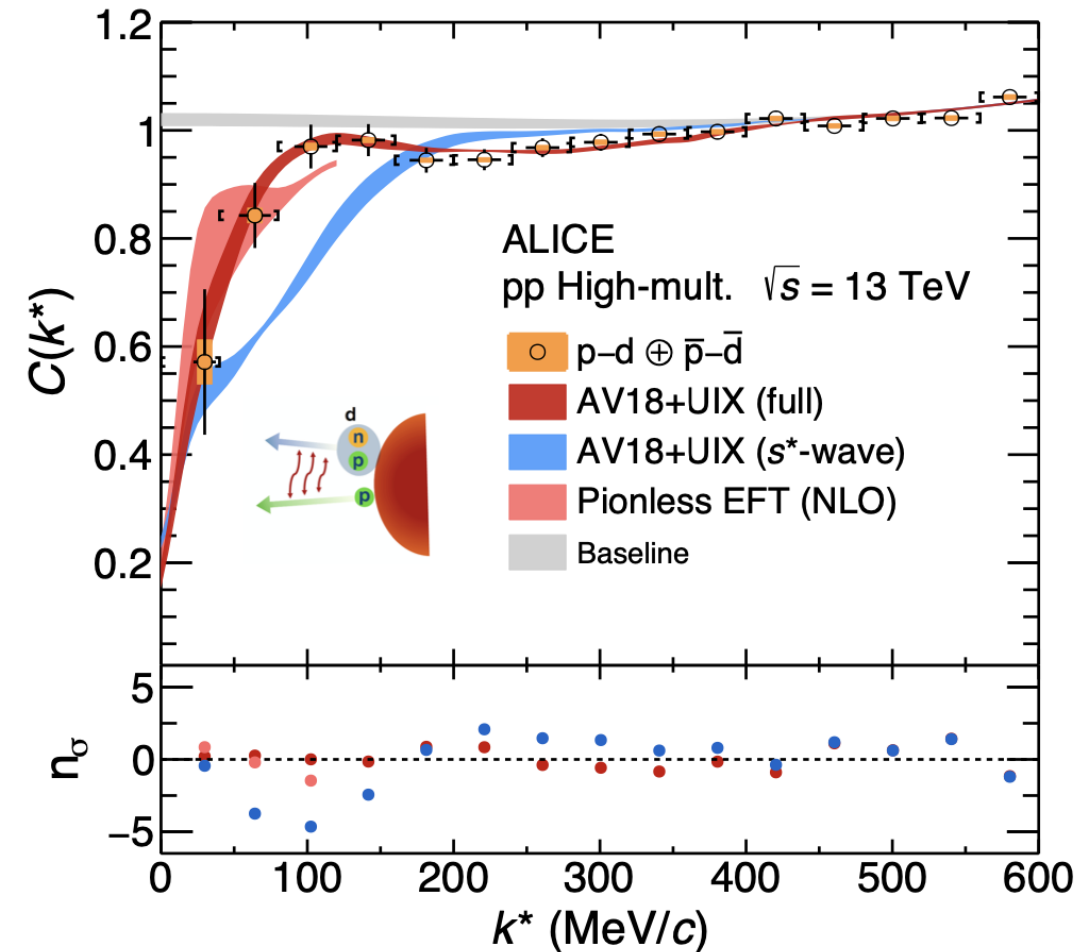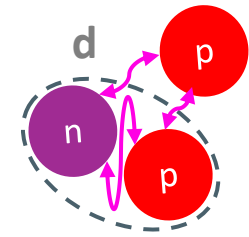
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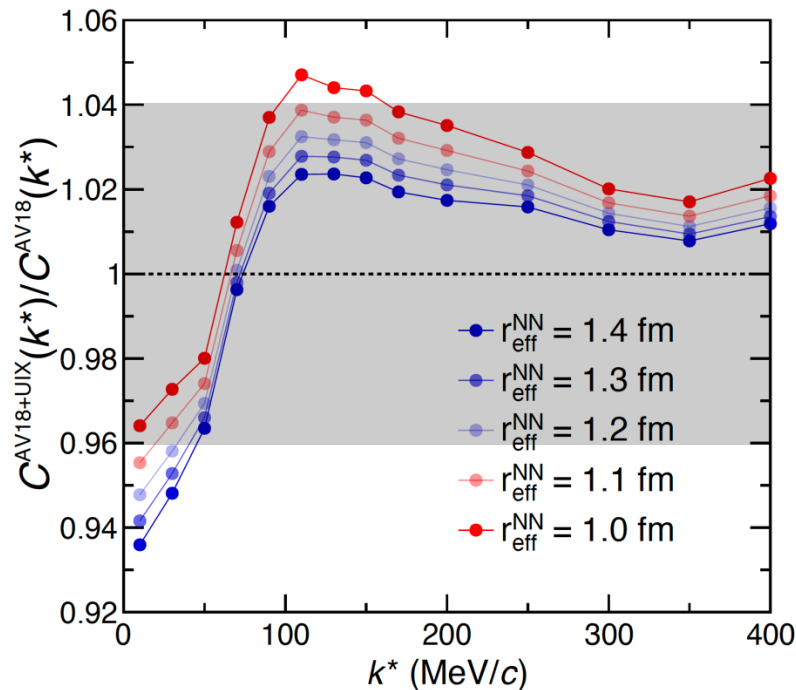
- Sensitivity to three-body forces up to 5%

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

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ALICE
pp High-mult. $\sqrt{s}$ = 13 TeV

- p–d ⊕ p̄–d̄
- AV18+UIX (full)
- AV18+UIX (s^*-wave)
- Pionless EFT (NLO)
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ALICE Coll. Phys. Rev. X 14, 031051 (2024)
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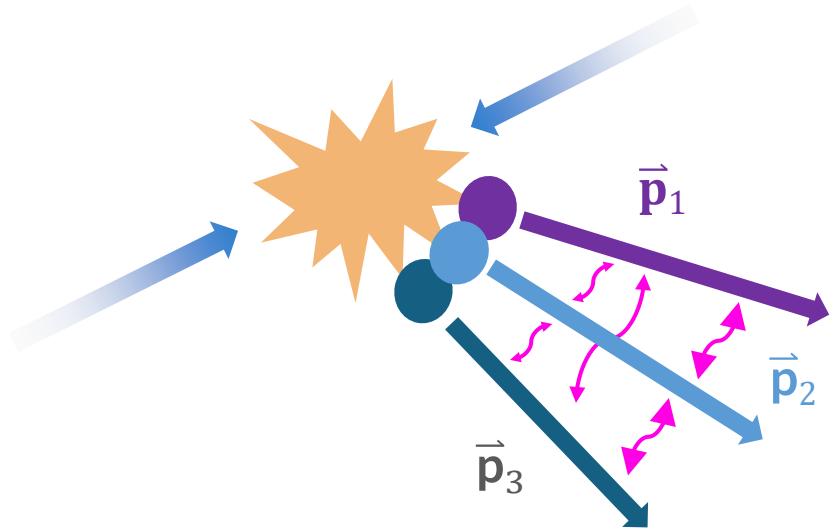
NNN using proton-deuteron correlations
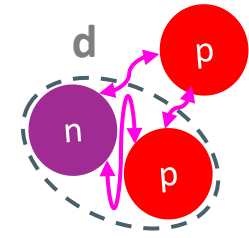
- Full three-body calculations are required (NN + NNN + Quantum Statistics)

- Run 3 data from 2022 already analysed and results are promising!

- In Run 3 expected uncertainty of 1%
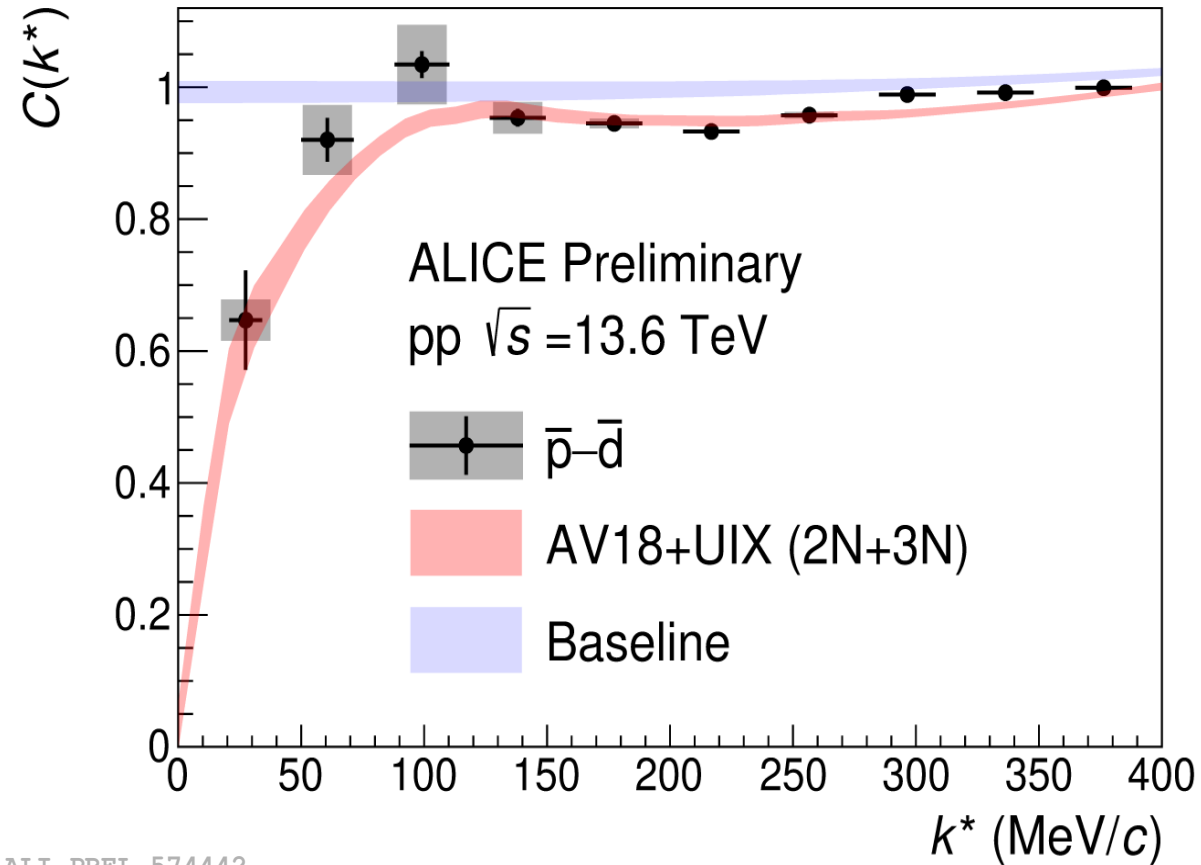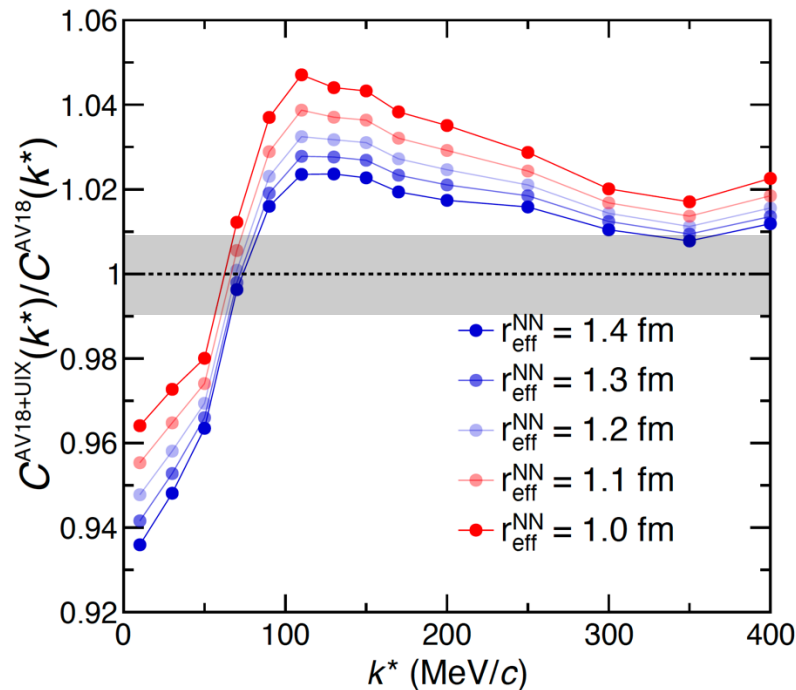
ALI-PREL-574442

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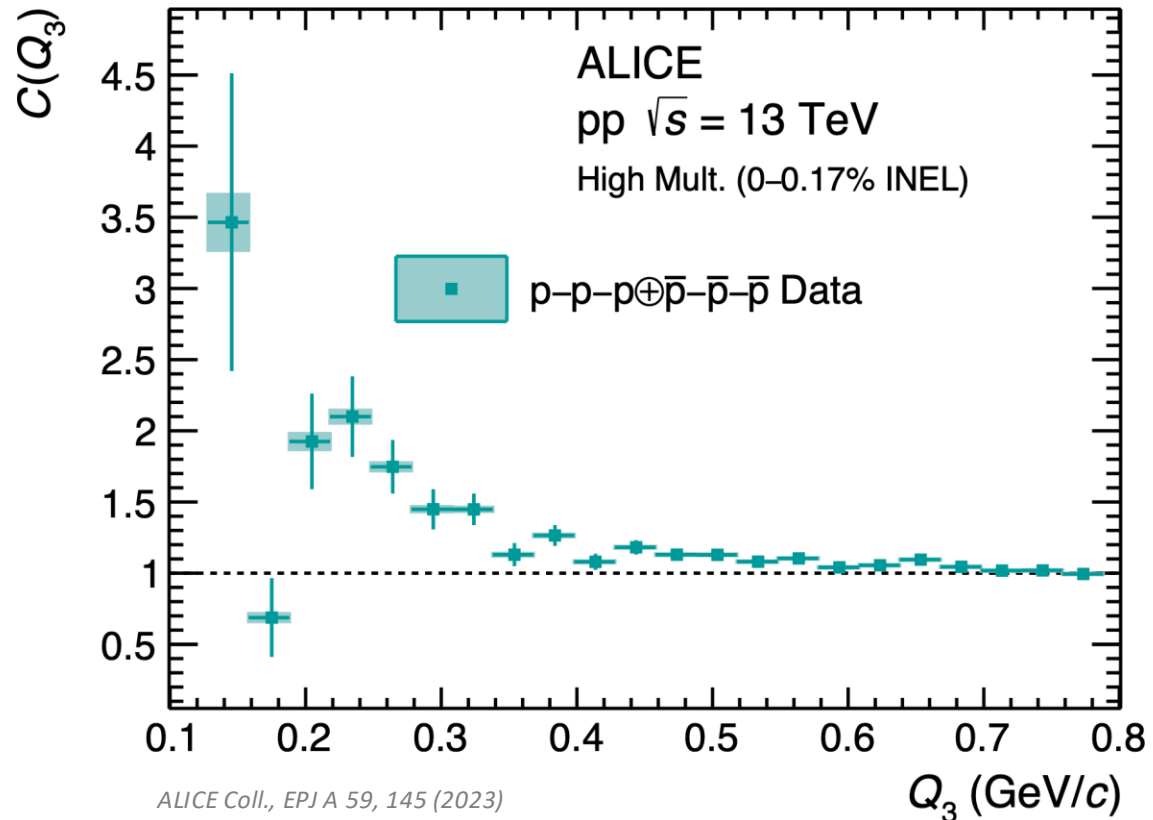*ALICE Coll., EPJ A 59, 145 (2023)*

Hyper-radius:

$$\rho = 2\sqrt{r_{12}^2 + r_{23}^2 + r_{31}^2}$$
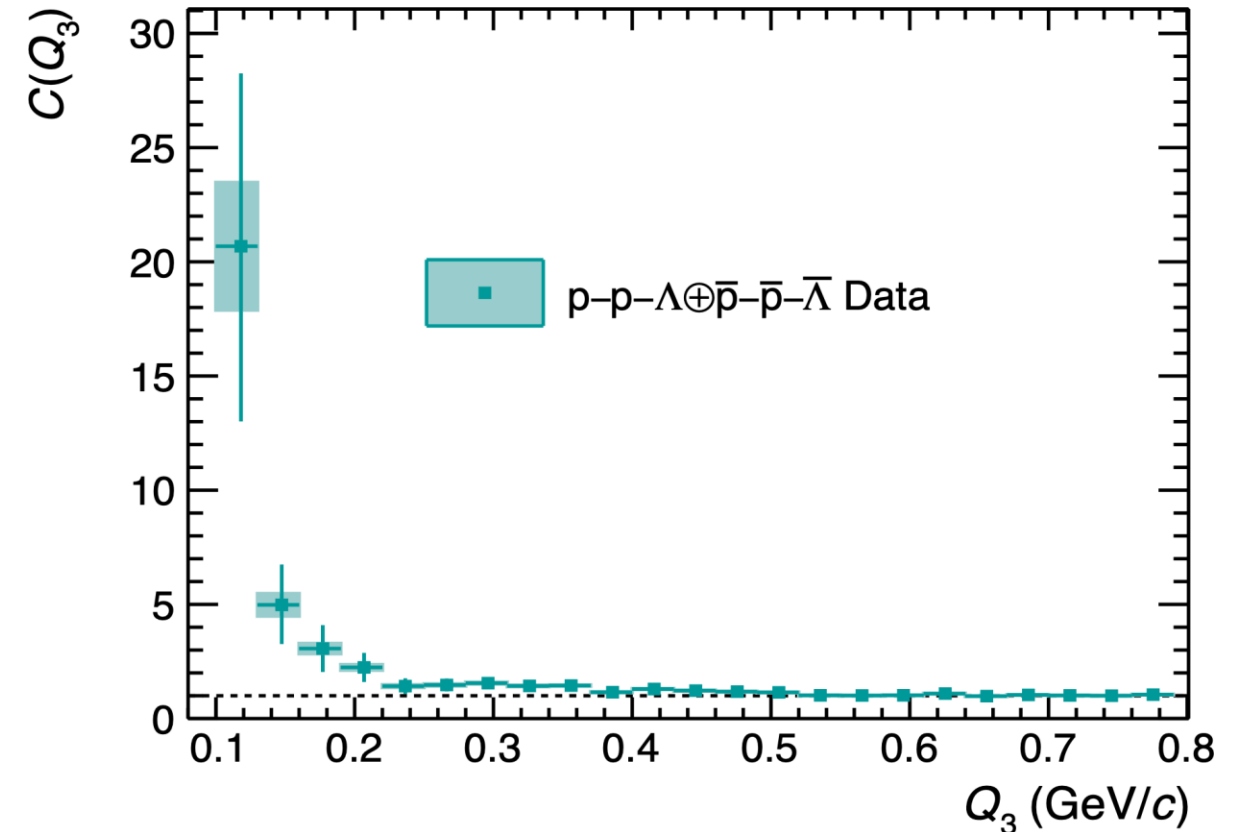
L. E. Marcucci et al., Front. in Phys. 8, 69 (2020).

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

ALICE
pp $\sqrt{s}$ = 13 TeV
High Mult. (0–0.17% INEL)

p–p–p$\oplus\bar{p}$–$\bar{p}$–$\bar{p}$ Data

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

p-p-Λ

p–p–Λ$\oplus\bar{p}$–$\bar{p}$–$\bar{\Lambda}$ Data

p-p-p correlation function

- First ever full three-body correlation function calculations

three-proton wave function

$$C(Q_3) = \int \rho^5 d\rho\, S(\rho, \rho_0) |\Psi(\rho, Q_3)|^2$$
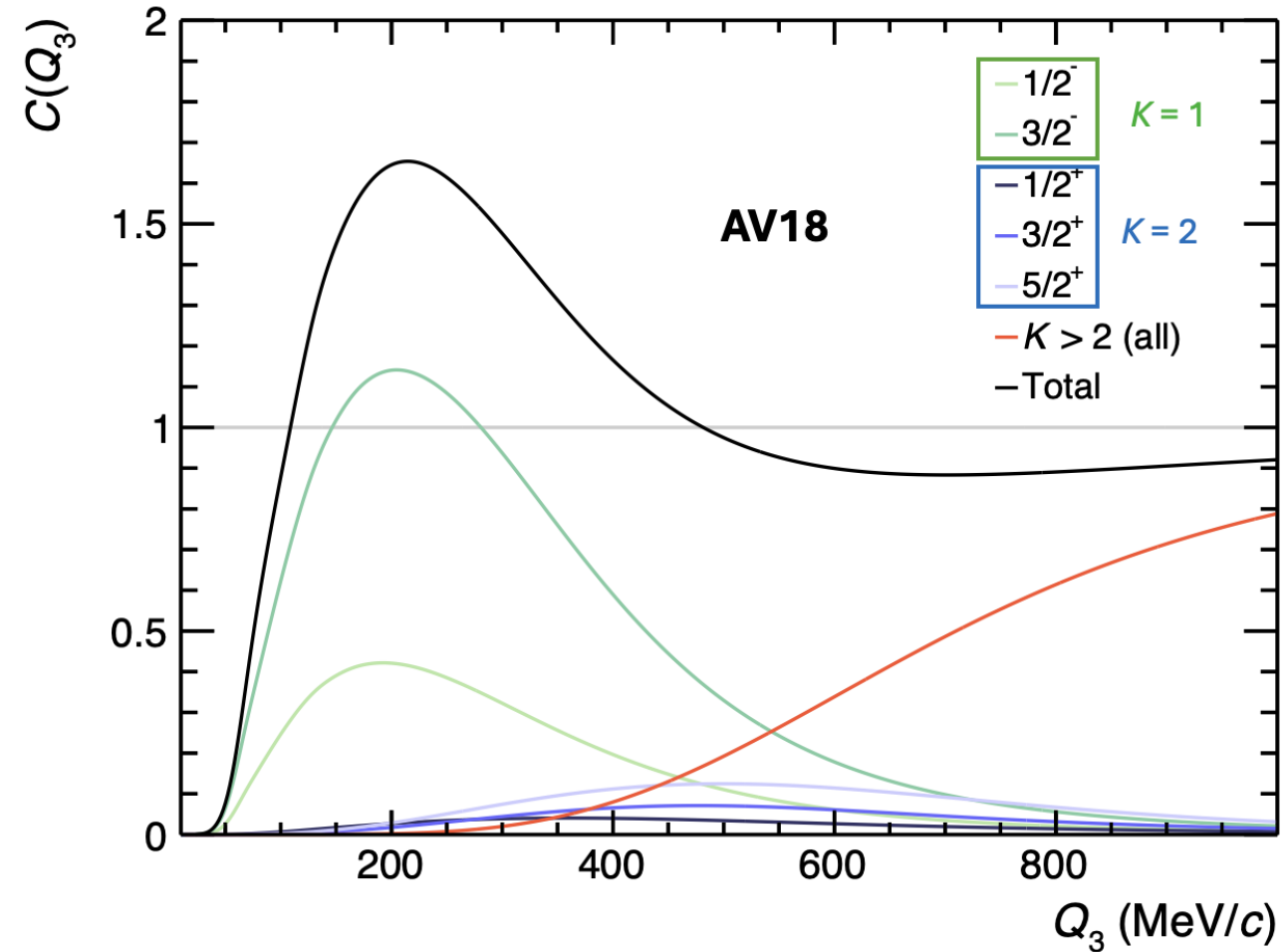
hyperradius

- Wave function in hyperspherical harmonics

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

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

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

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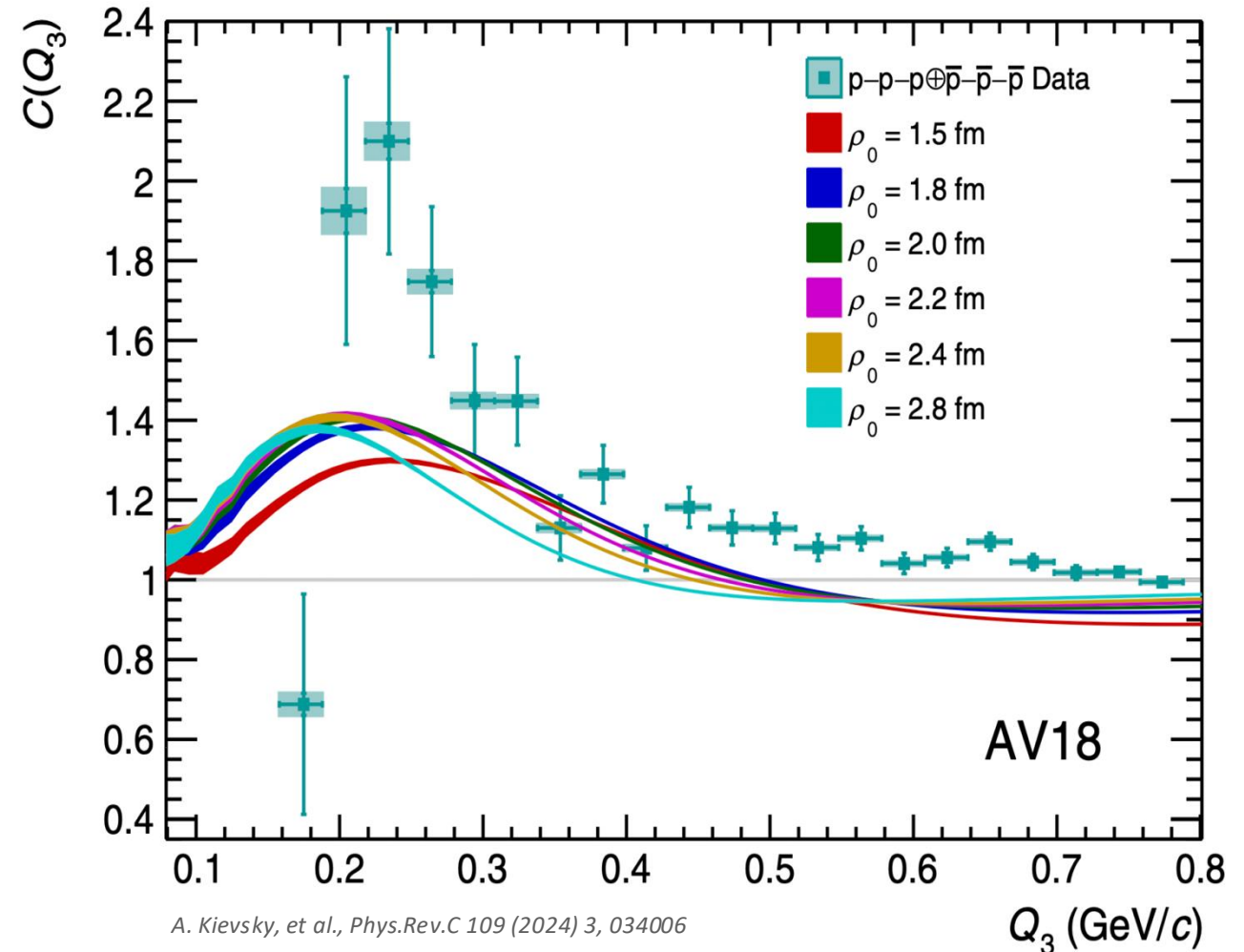 superposition of many partial waves

A. Kievsky, 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

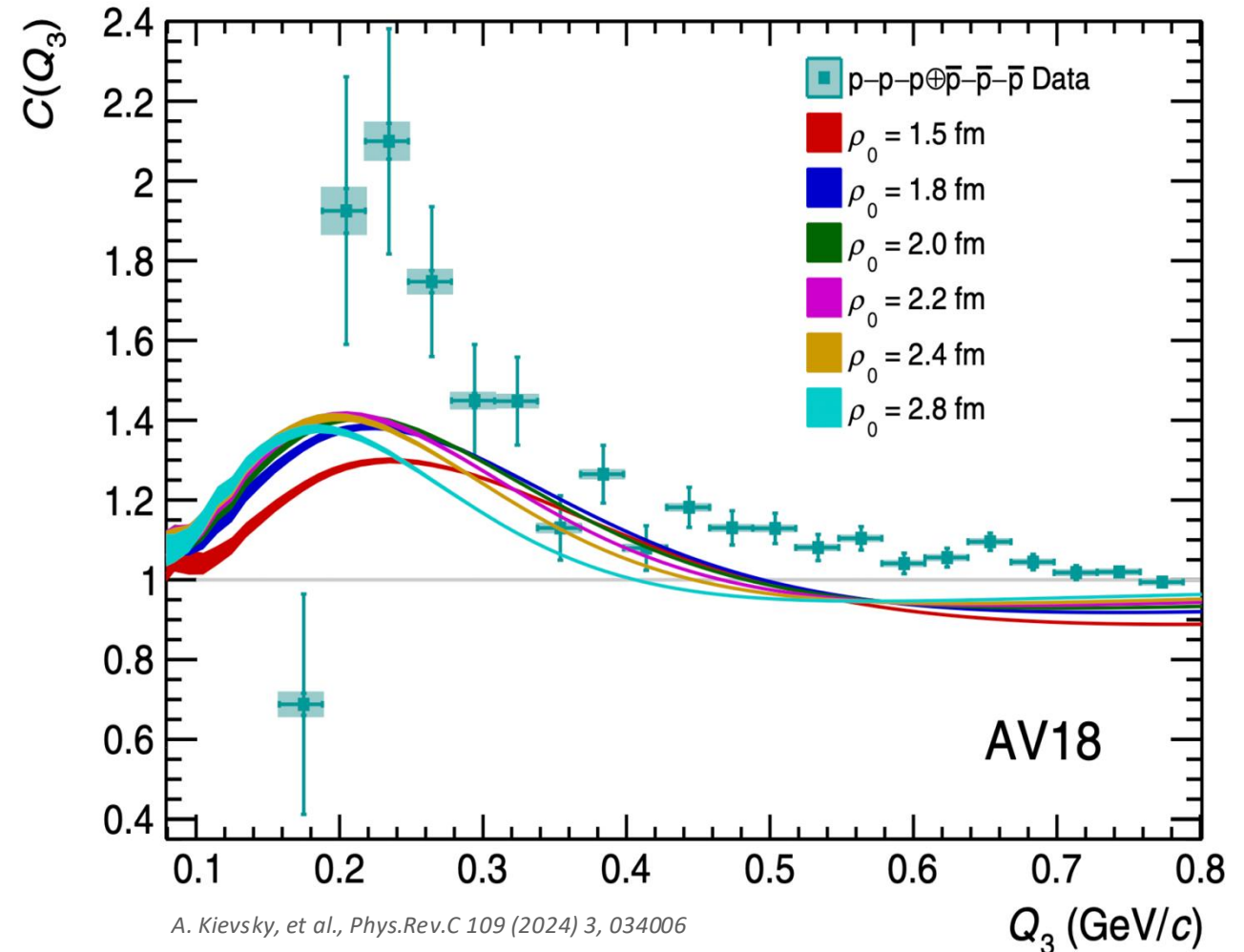*A. Kievsky, et al., Phys.Rev.C 109 (2024) 3, 034006*

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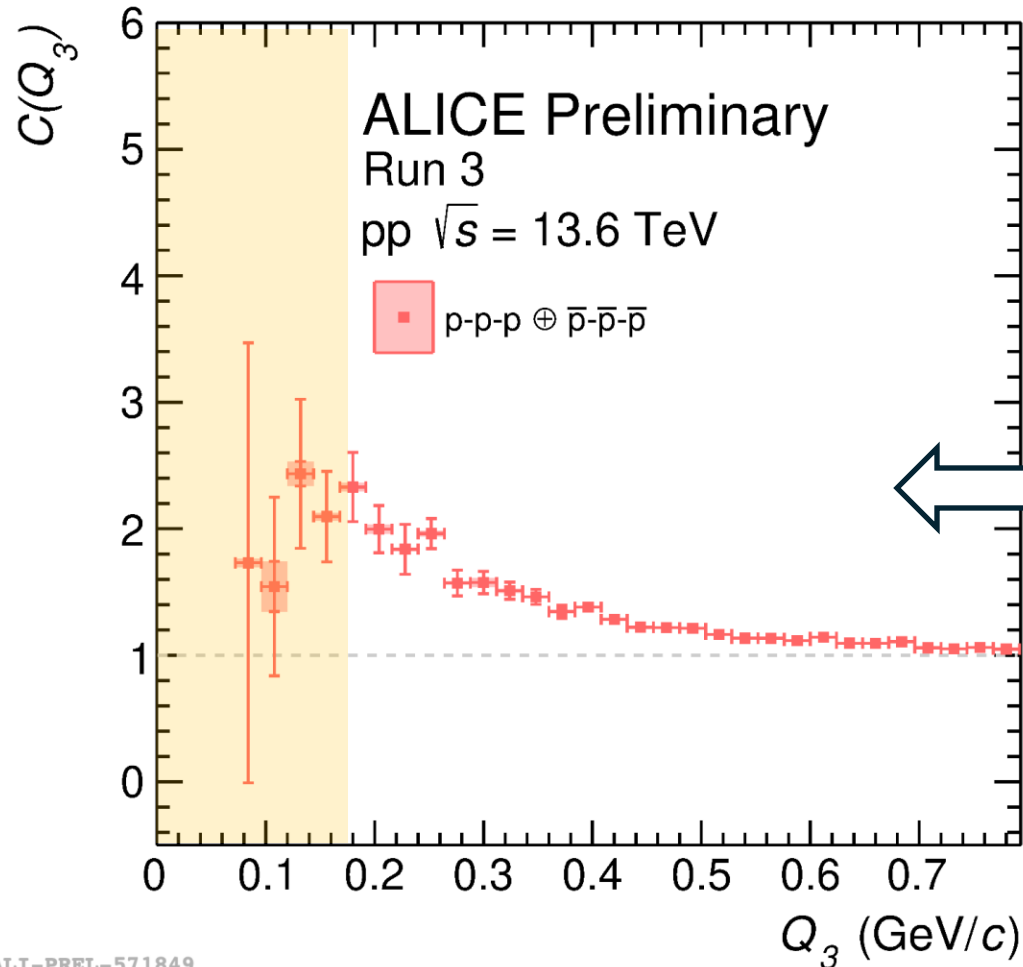
Required improvements:

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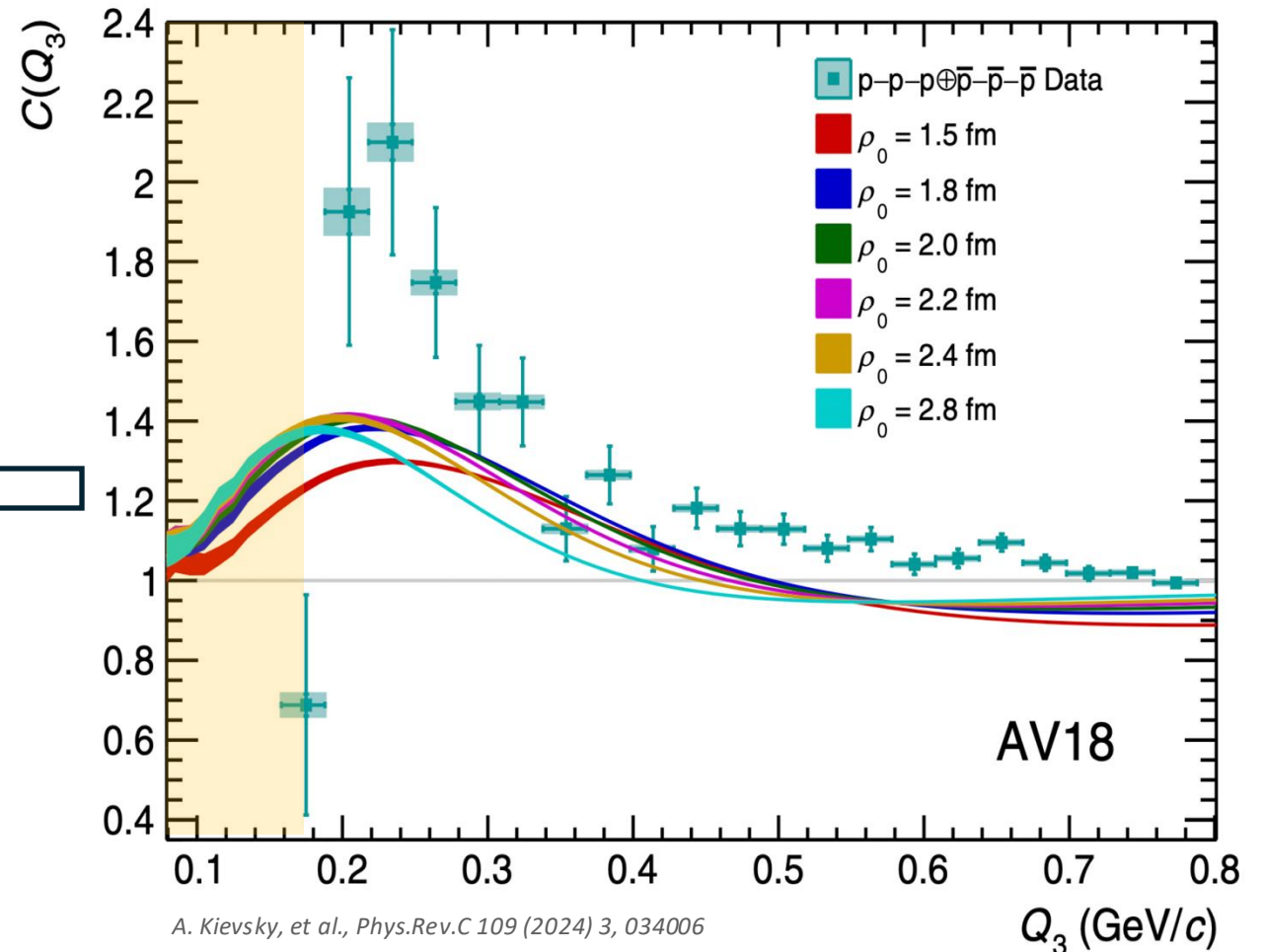- Asymptotic behaviour of the wave function for three charged particles

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!
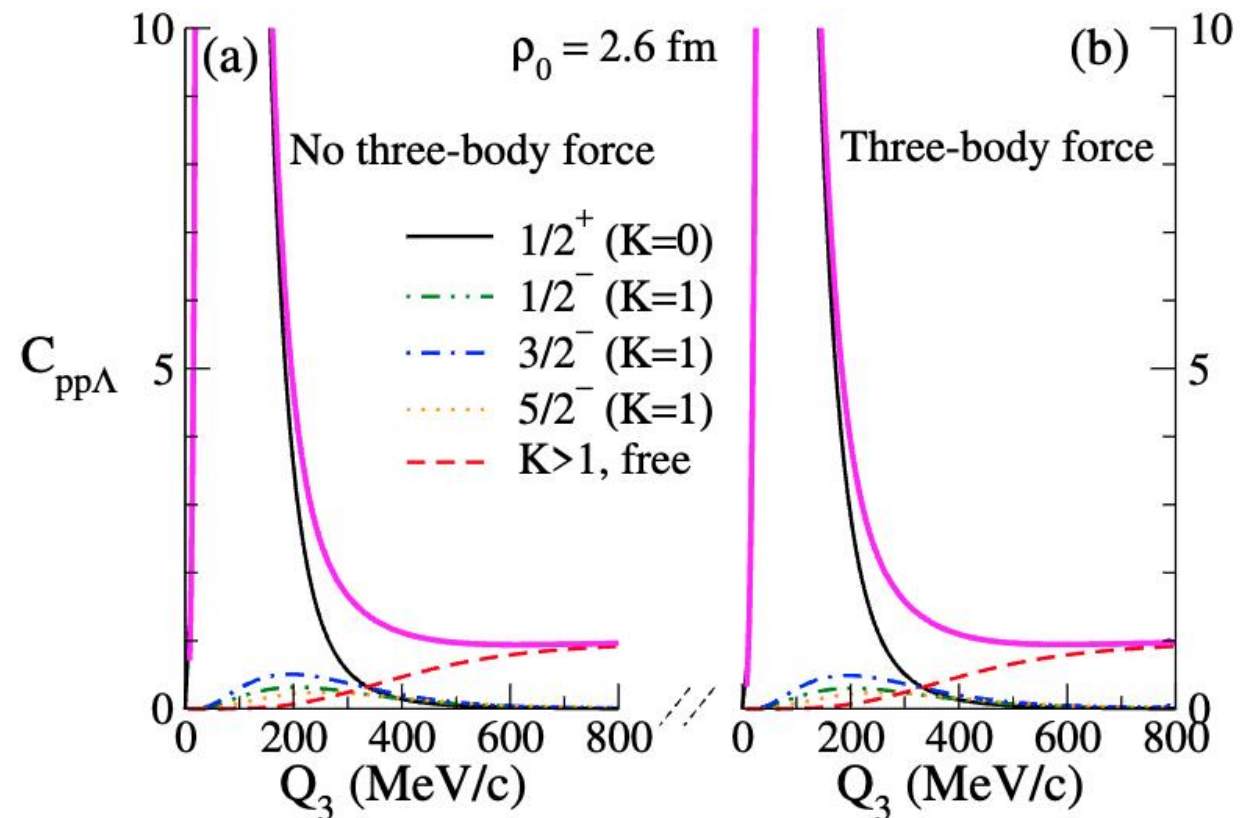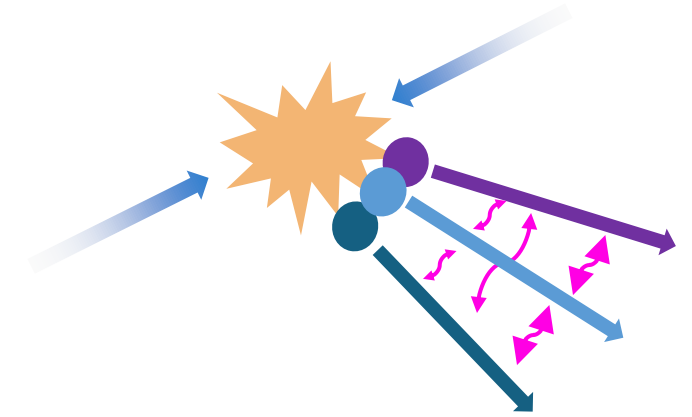
- ALICE Run-2 (2015-2018)

ALICE Preliminary
Run 3
pp $\sqrt{s}$ = 13.6 TeV

p-p-p $\oplus$ $\bar{p}$-$\bar{p}$-$\bar{p}$

p–p–p$\oplus$$\bar{p}$–$\bar{p}$–$\bar{p}$ Data
ρ_0 = 1.5 fm
ρ_0 = 1.8 fm
ρ_0 = 2.0 fm
ρ_0 = 2.2 fm
ρ_0 = 2.4 fm
ρ_0 = 2.8 fm

AV18

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

p-p-Λ correlation function

- First ever full three-body correlation function calculations

three-proton wave function

$$C(Q_3) = \int \rho^5 d\rho \, S(\rho, \rho_0) |\Psi(\rho, Q_3)|^2$$

hyperradius

- Wave function 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

$\rho_0 = 2.6$ fm

(a) No three-body force
(b) Three-body force

- —— $1/2^+$ (K=0)
- —·—·— $1/2^-$ (K=1)
- —·— $3/2^-$ (K=1)
- ········· $5/2^-$ (K=1)
- – – – K>1, free
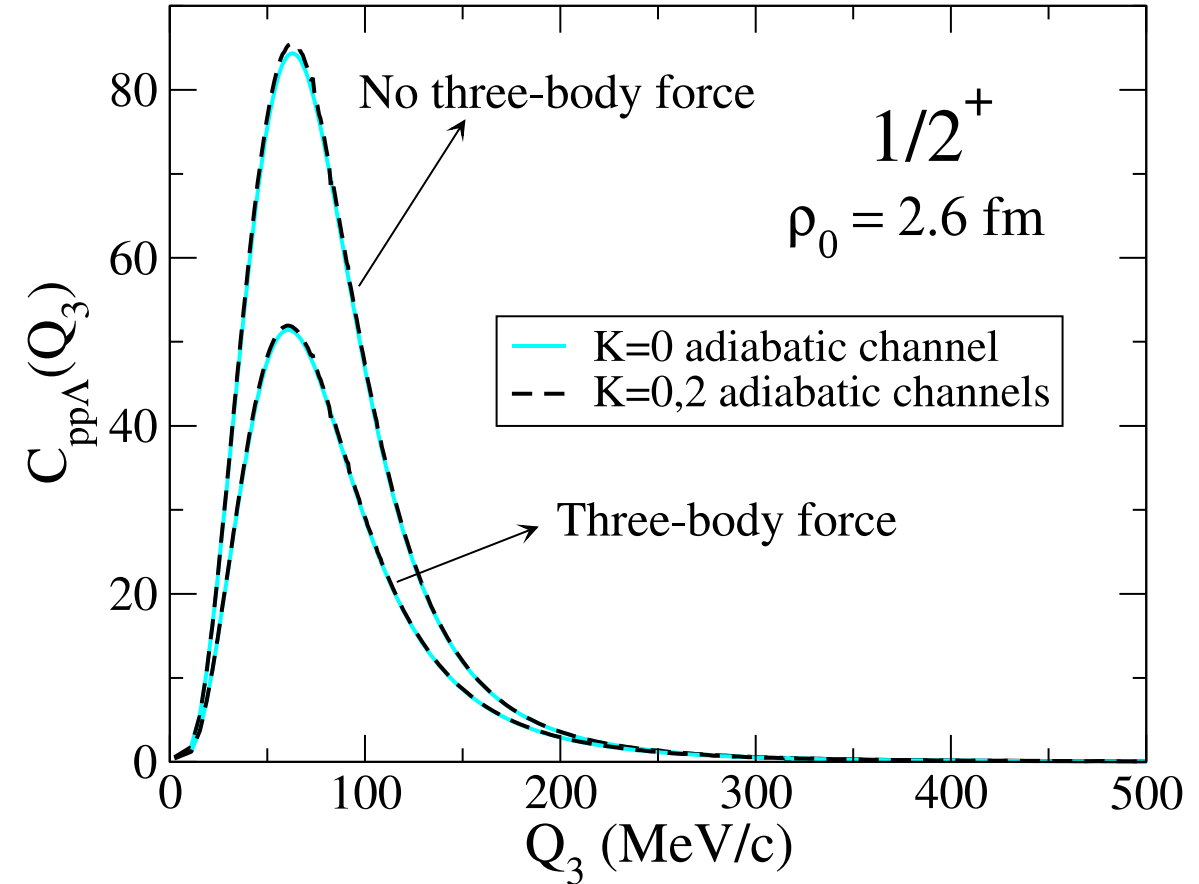
$C_{pp\Lambda}$

Q_3 (MeV/c)

p-p-Λ correlation function

- Reference calculations:
  → two-body NN and ΛN interactions provide an overbinding of the hypertriton

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

  E. Garrido et al., arXiv: 2408.01750 (2024)   *Binding energy from:*
  https://hypernuclei.kph.uni-mainz.de

  → three-body ΛNN interaction

$1/2^+$

ρ_0 = 2.6 fm

No three-body force

Three-body force

— K=0 adiabatic channel
- - - K=0,2 adiabatic channels

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

p-p-Λ correlation function

- Reference calculations:
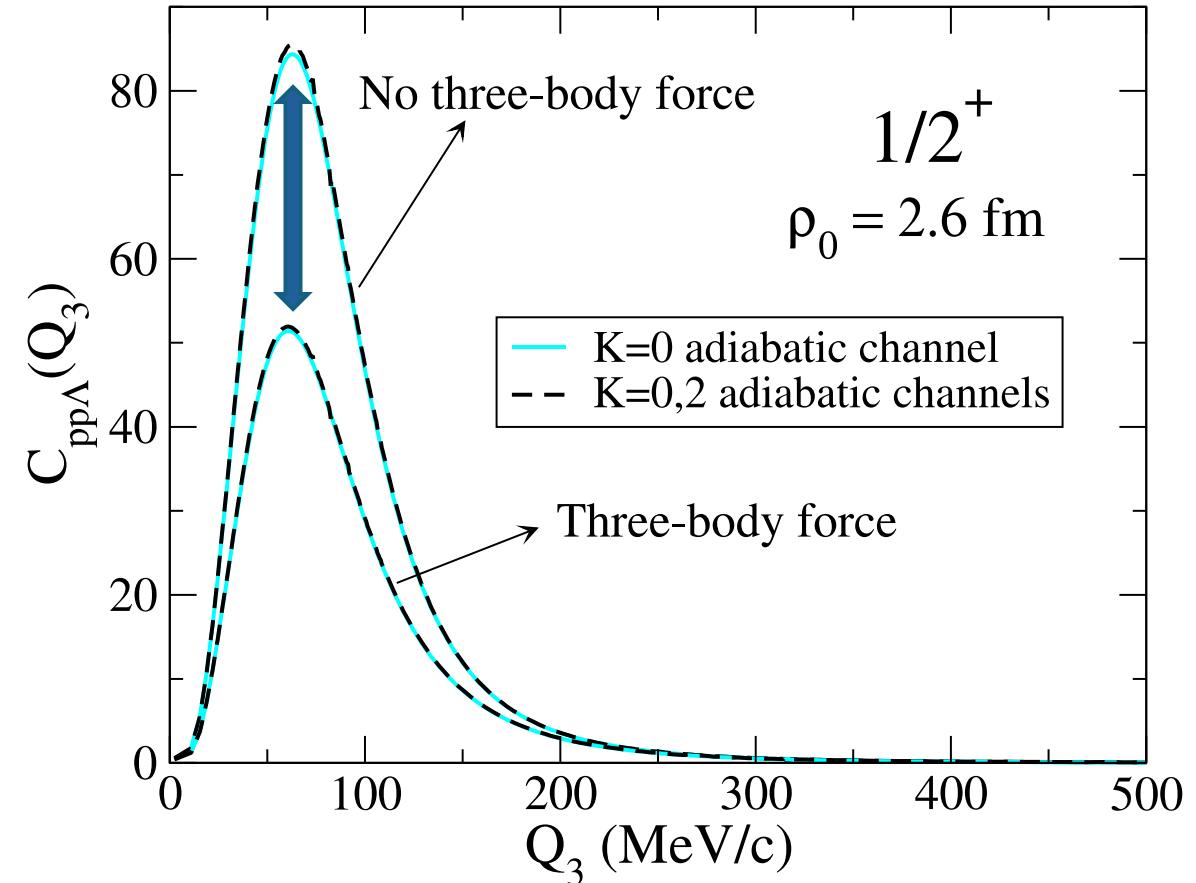 - → two-body NN and ΛN interactions provide an overbinding of the hypertriton

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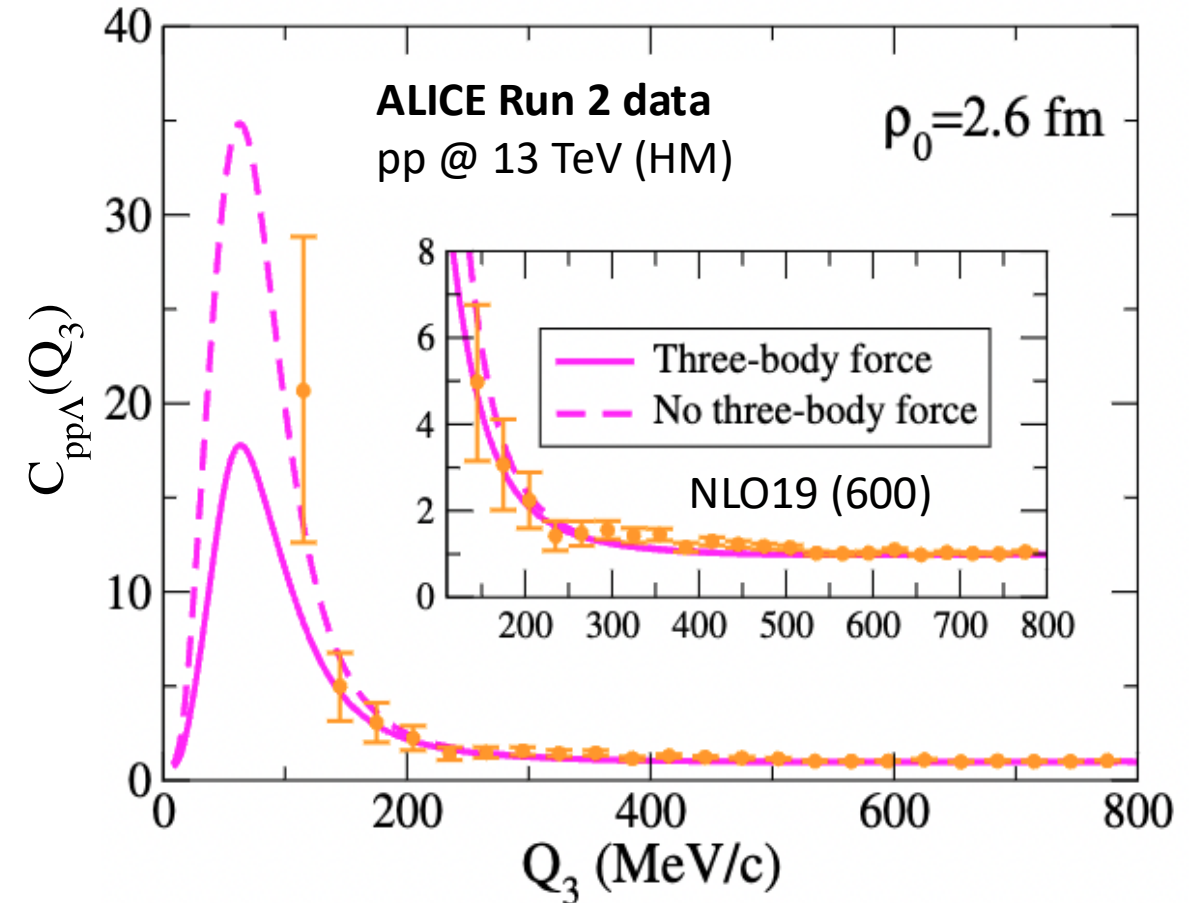 *https://hypernuclei.kph.uni-mainz.de*

  - → three-body ΛNN interaction

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

No three-body force

$1/2^+$

$\rho_0 = 2.6$ fm

— K=0 adiabatic channel
- - - K=0,2 adiabatic channels

Three-body force

$C_{pp\Lambda}(Q_3)$

Q_3 (MeV/c)

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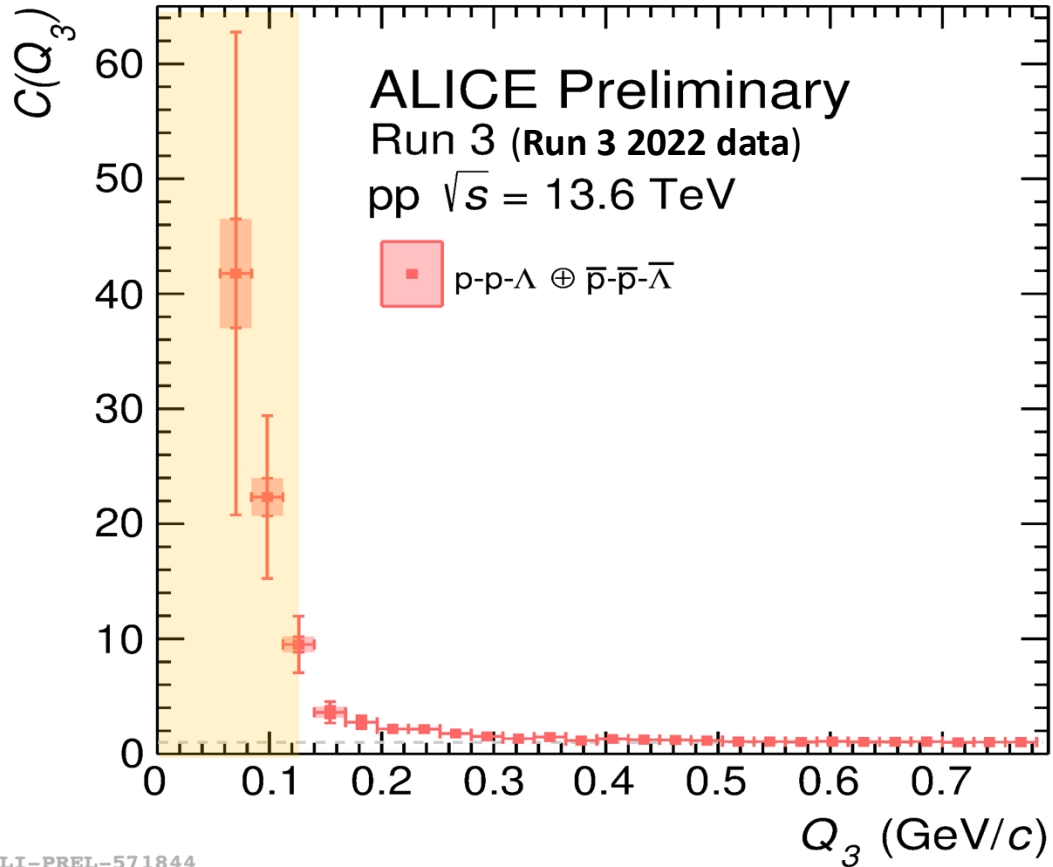*E. Garrido et al., arXiv: 2408.01750 (2024), accepted by PRC*

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

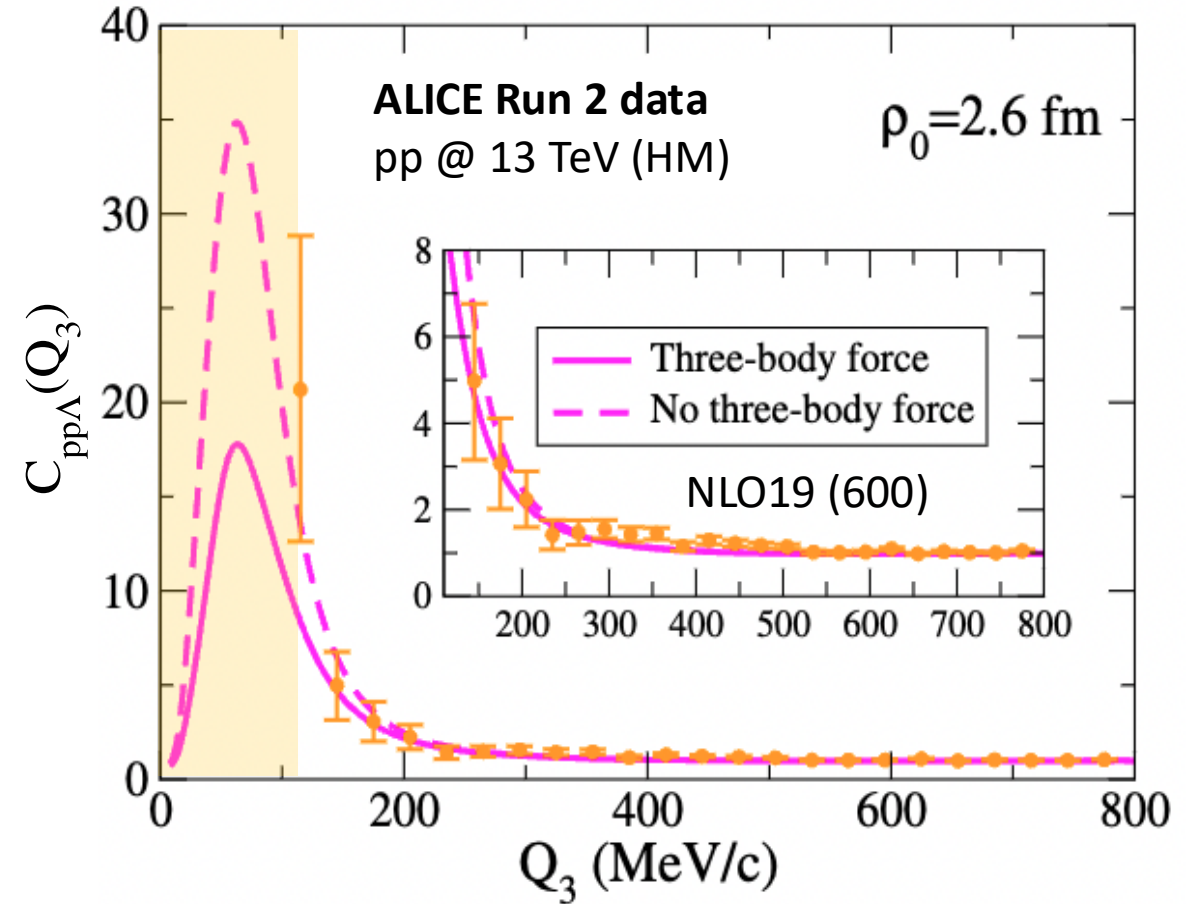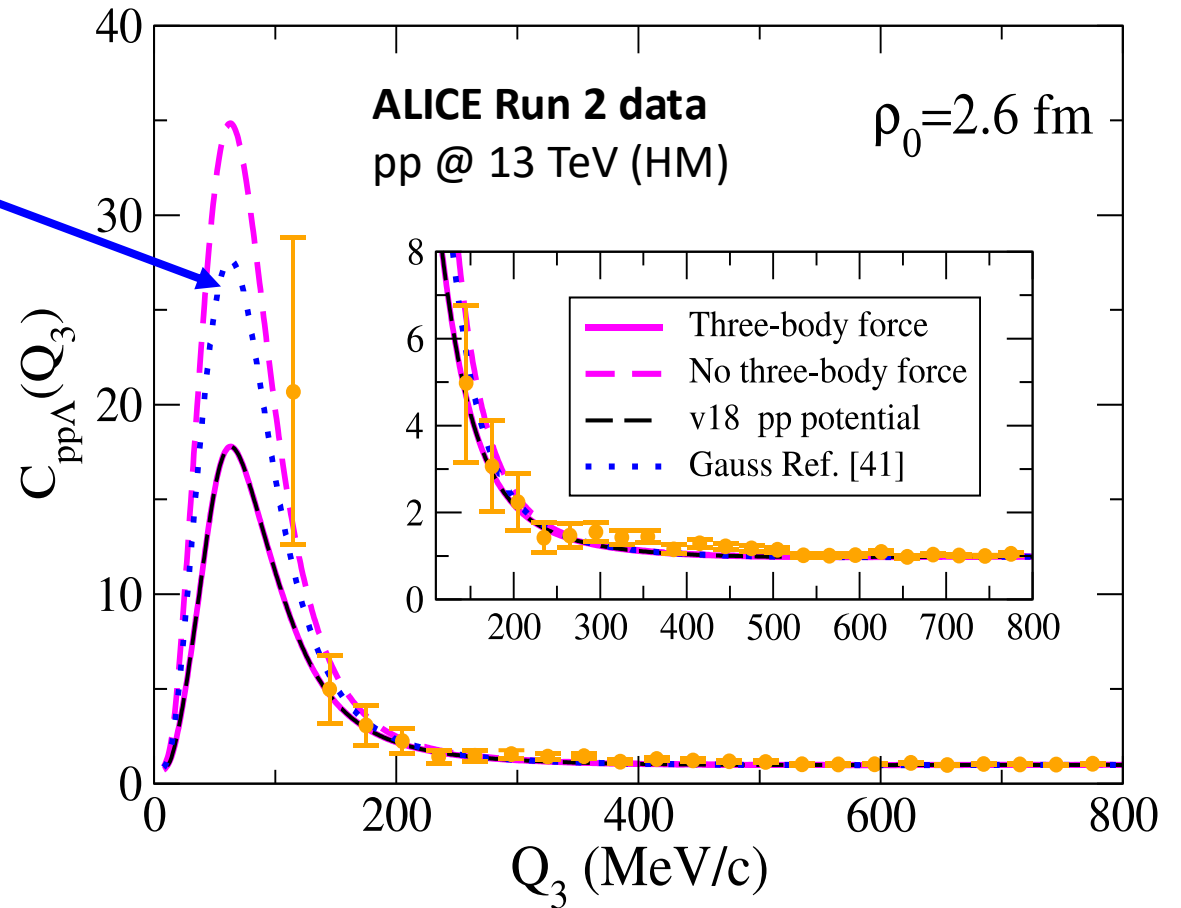- Run-2 data: one data point in the region of the maximum

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!
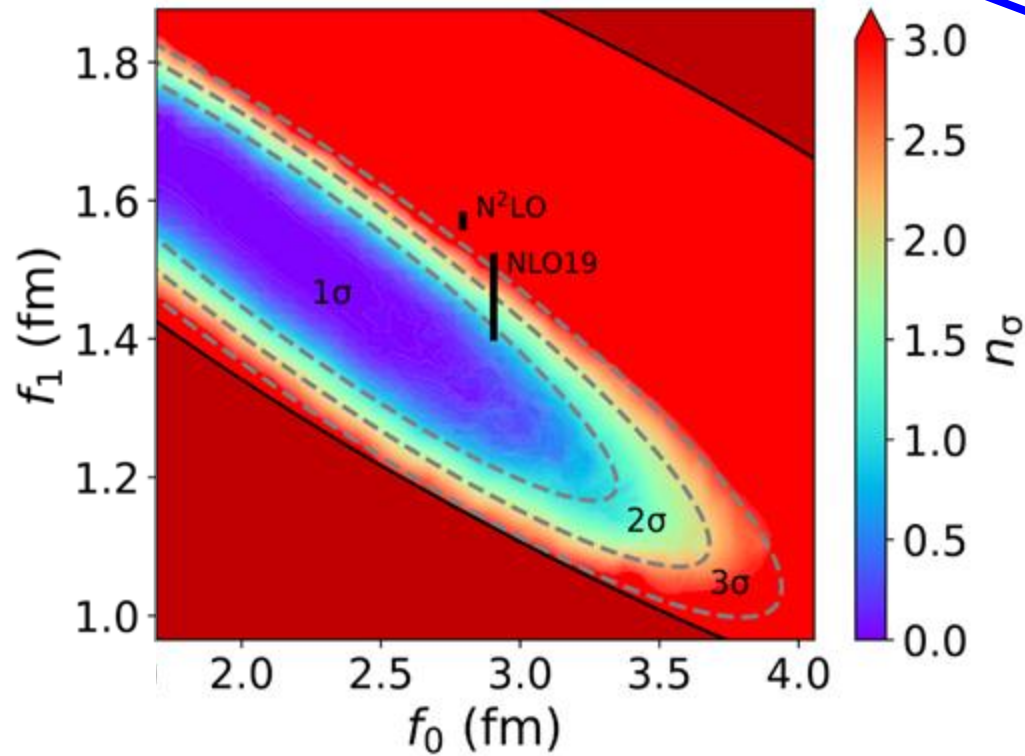
p-p-Λ correlation function

- **pΛ interaction**: scattering + femto

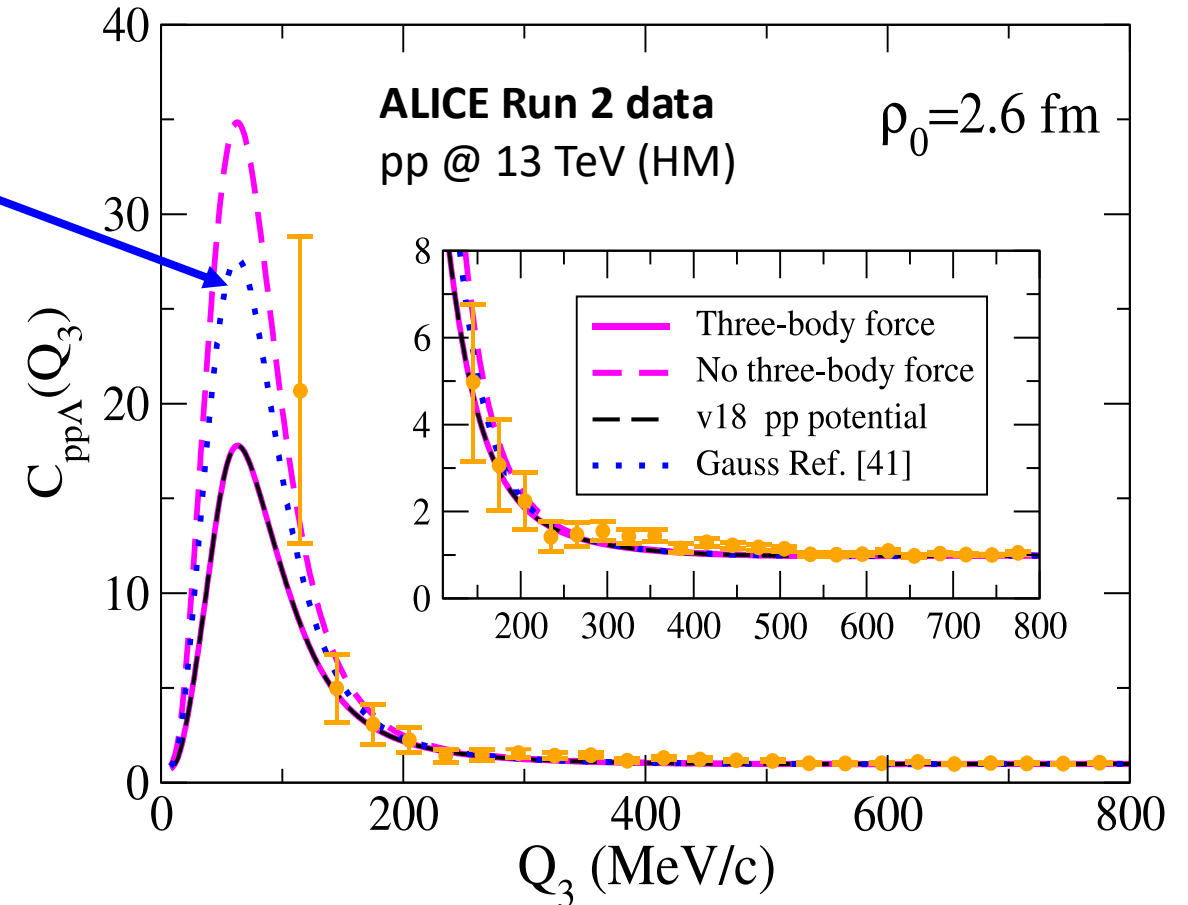 *D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550*

ALICE Run 2 data
pp @ 13 TeV (HM)

ρ_0=2.6 fm

Legend:
- Three-body force
- No three-body force
- v18 pp potential
- Gauss Ref. [41]

$C_{pp\Lambda}(Q_3)$

Q_3 (MeV/c)

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

p-p-Λ correlation function

- **pΛ interaction**: scattering + femto

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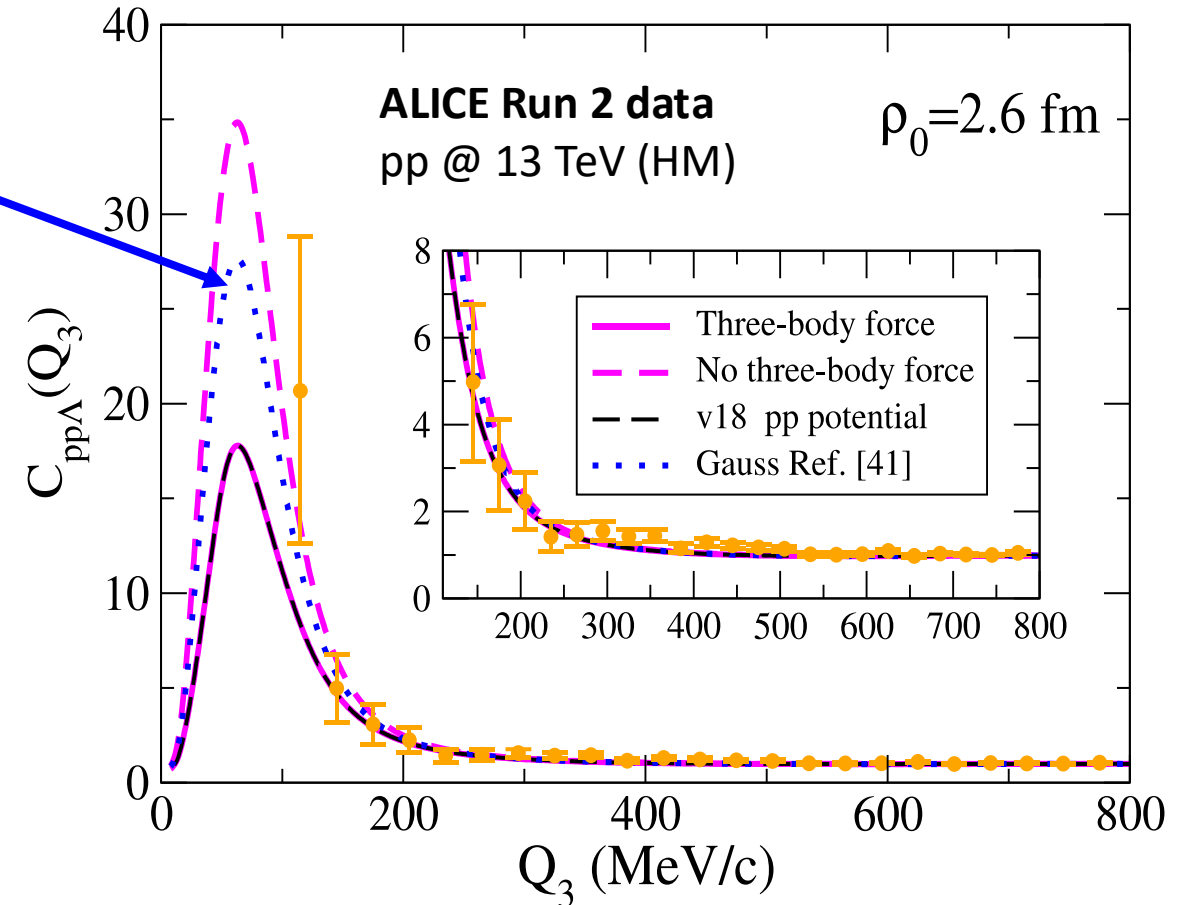- Hypertriton binding energy can be reproduced using ONLY ΛN interaction

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

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

ALICE Run 2 data
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Three-body force
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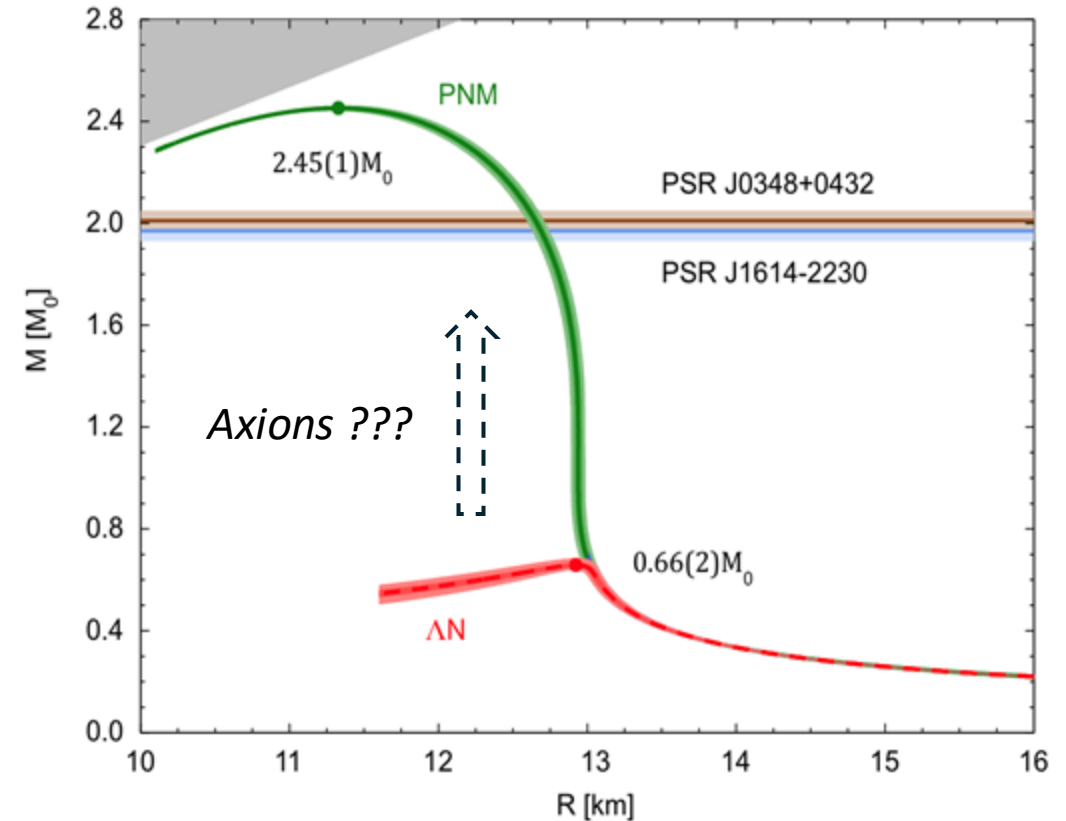v18 pp potential
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*Private comunication A. Kievsky and E. Garrido

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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 ($_{\Lambda}^{4}$H)**
  exp: 10.064 MeV ($_{\Lambda}^{4}$He)

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

ALICE Run 2 data
pp @ 13 TeV (HM) $\rho_0 = 2.6$ fm

Legend:
— Three-body force
‑ ‑ No three-body force
‑ ‑ v18 pp potential
···· Gauss Ref. [41]

$C_{pp\Lambda}(Q_3)$

Q_3 (MeV/c)

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

Private comunication A. Kievsky and E. Garrido

Raffaele Del Grande

48

Axions in neutron stars

- High density in the core of neutron stars
  - → Production of hyperons as Λ at ρ = 2-3ρ_0 and softening of the equation of state
  - → Incompatibility with astrophysical measurements of $M_{NS} \gtrsim 2\ M_\odot$
  - → Long-standing hyperon puzzle

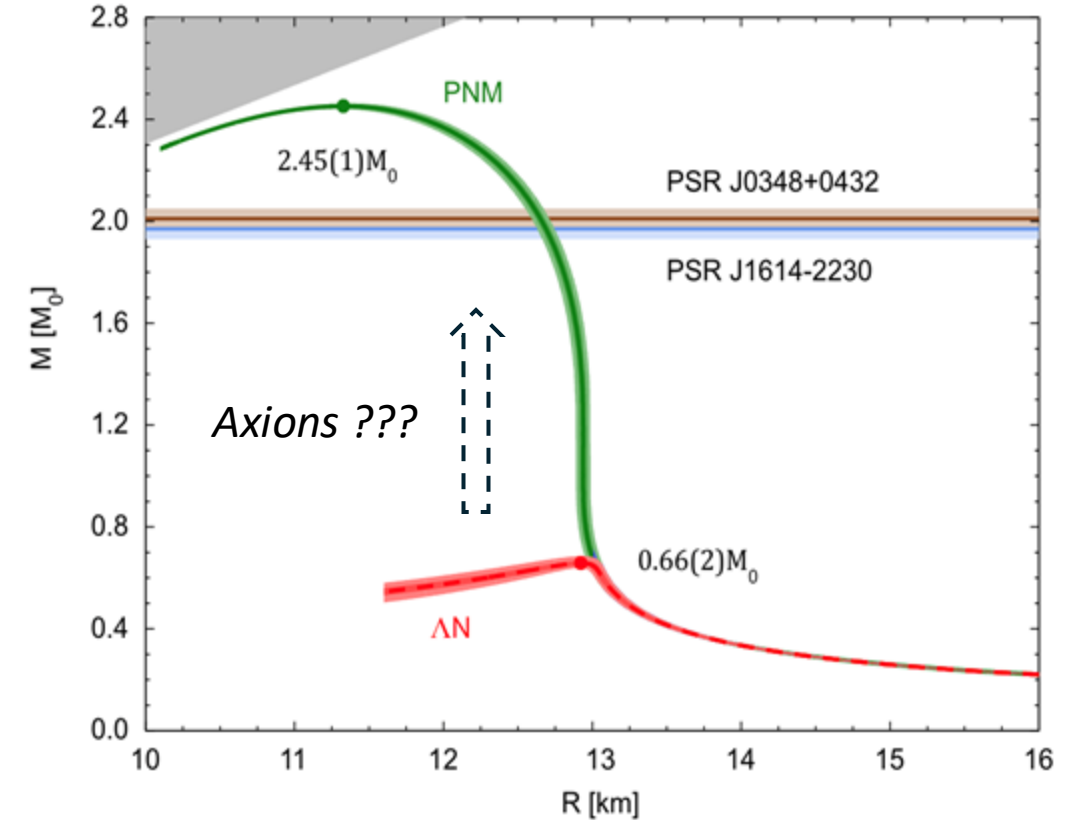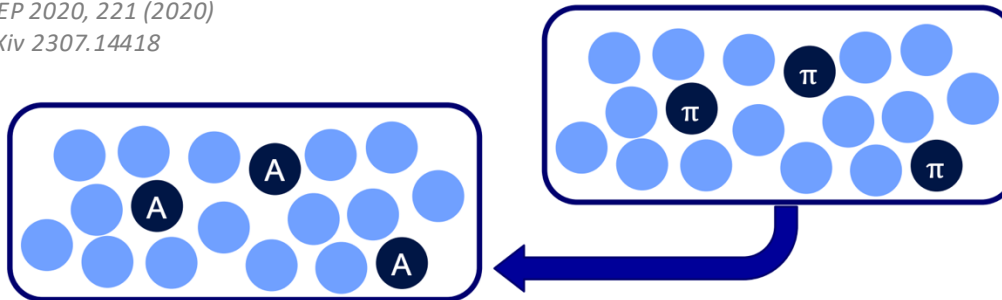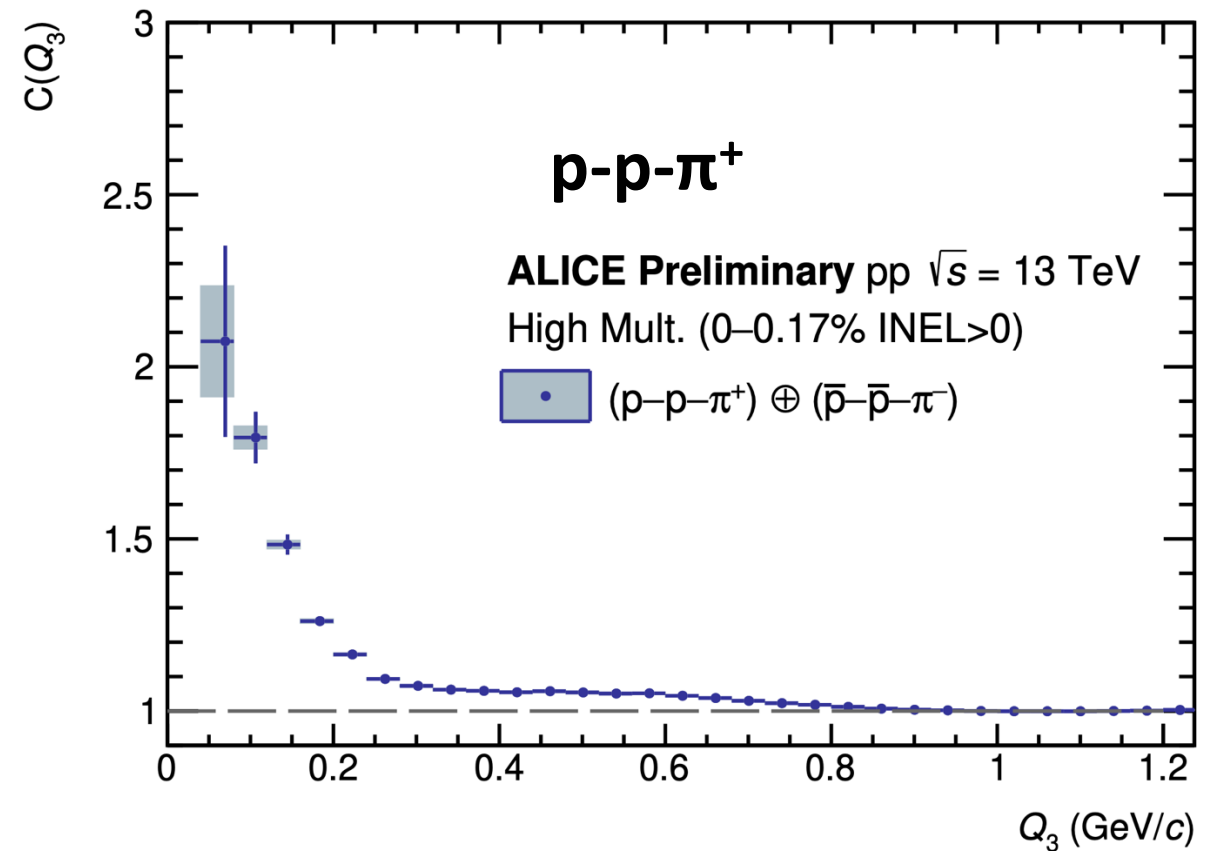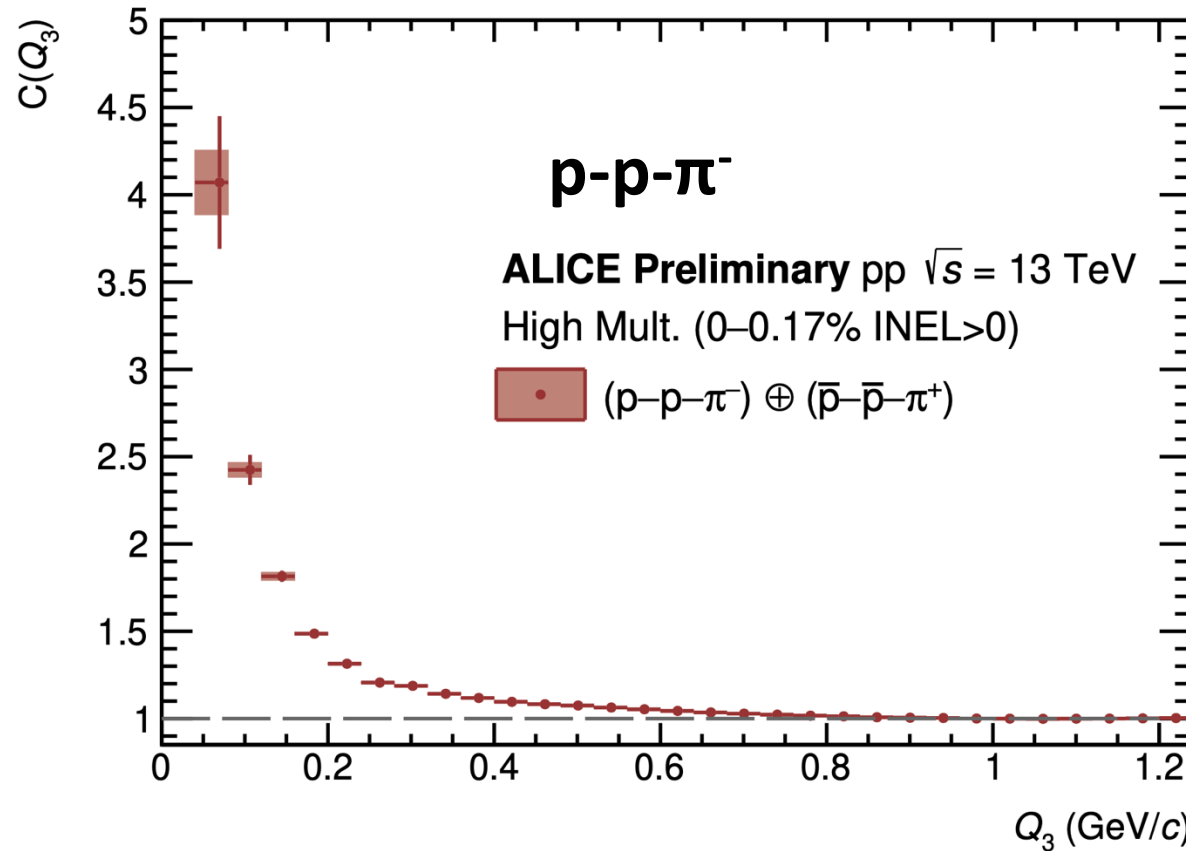- Impact of QCD axions on the equation of state (EoS)
  - → Can lead to stiffer EoS

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

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  → 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

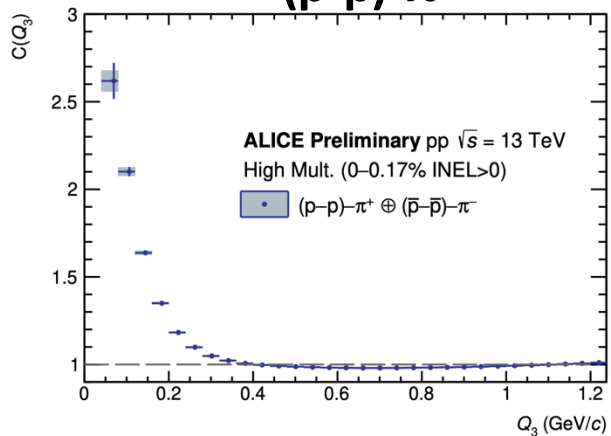- Deviation from unity in the correlation functions
- Cumulant decomposition:

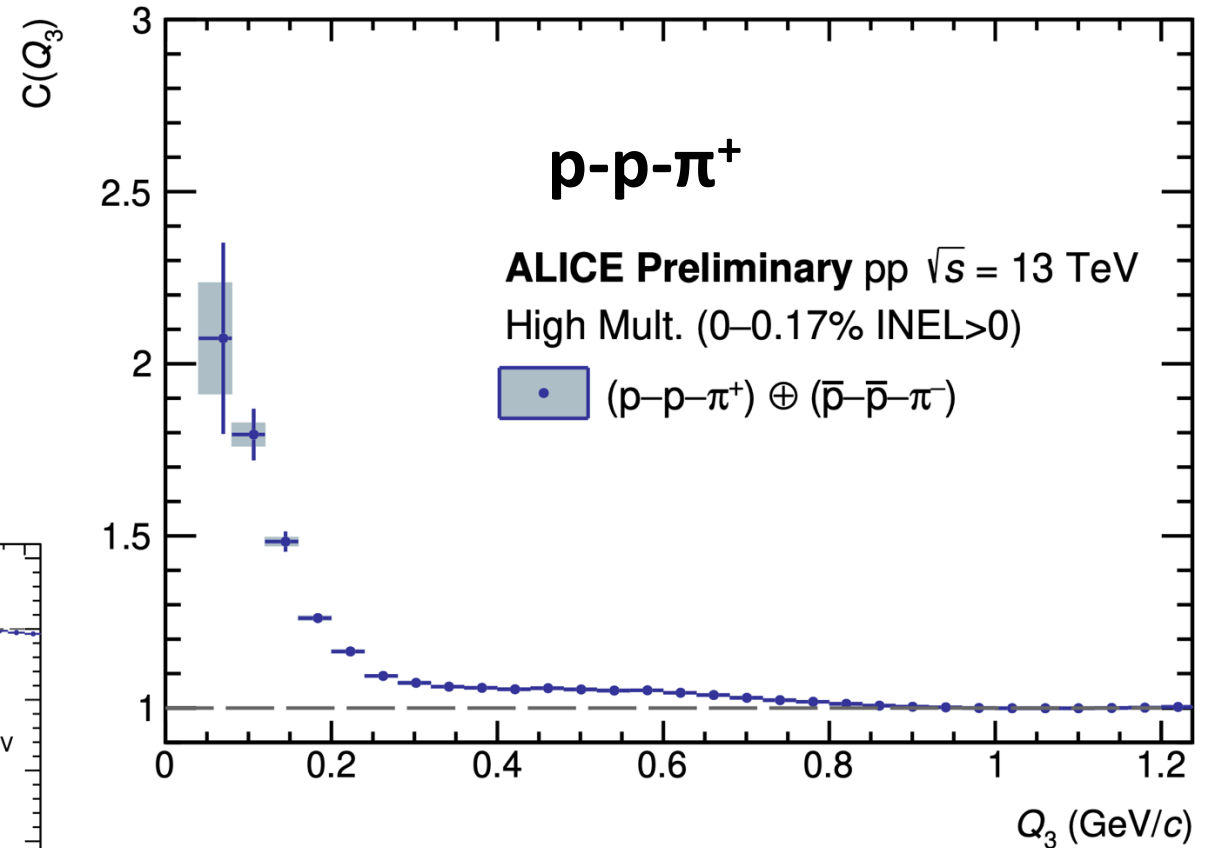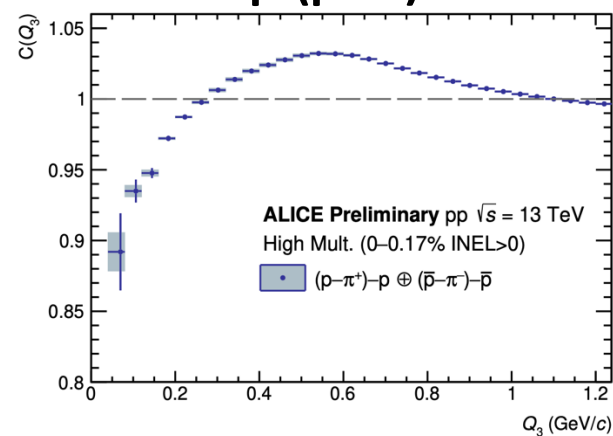*R. Kubo, J. Phys. Soc. Jpn. 17, 1100-1120 (1962)*
R. Del Grande et al. EPJC 82 (2022) 244

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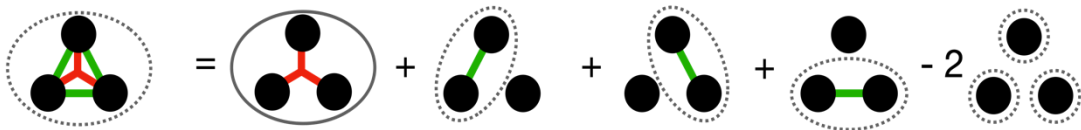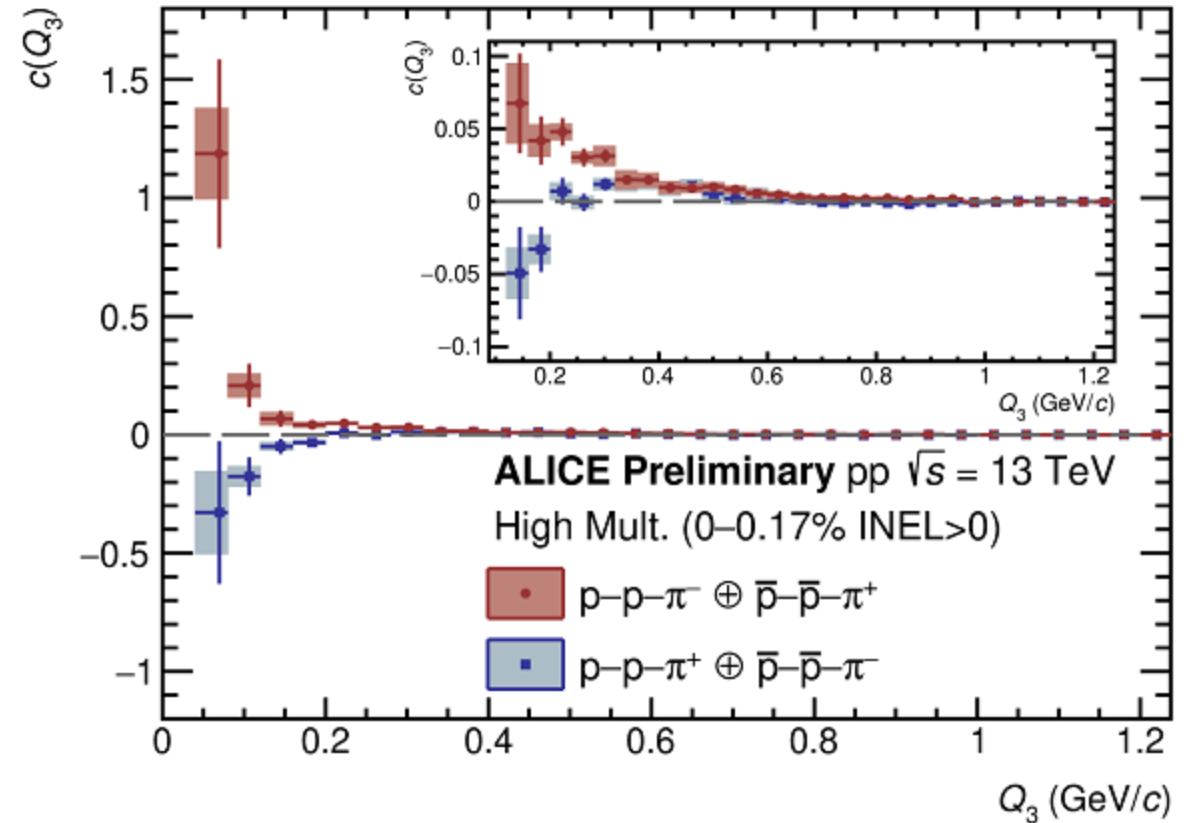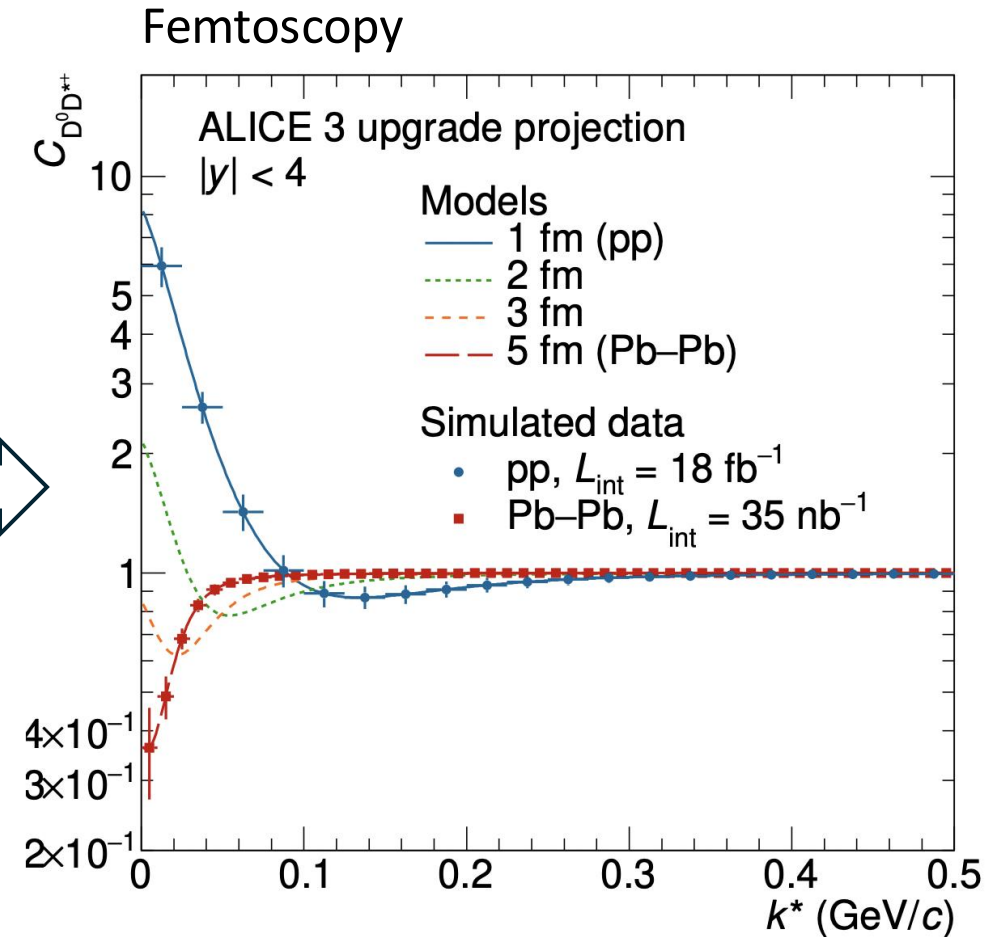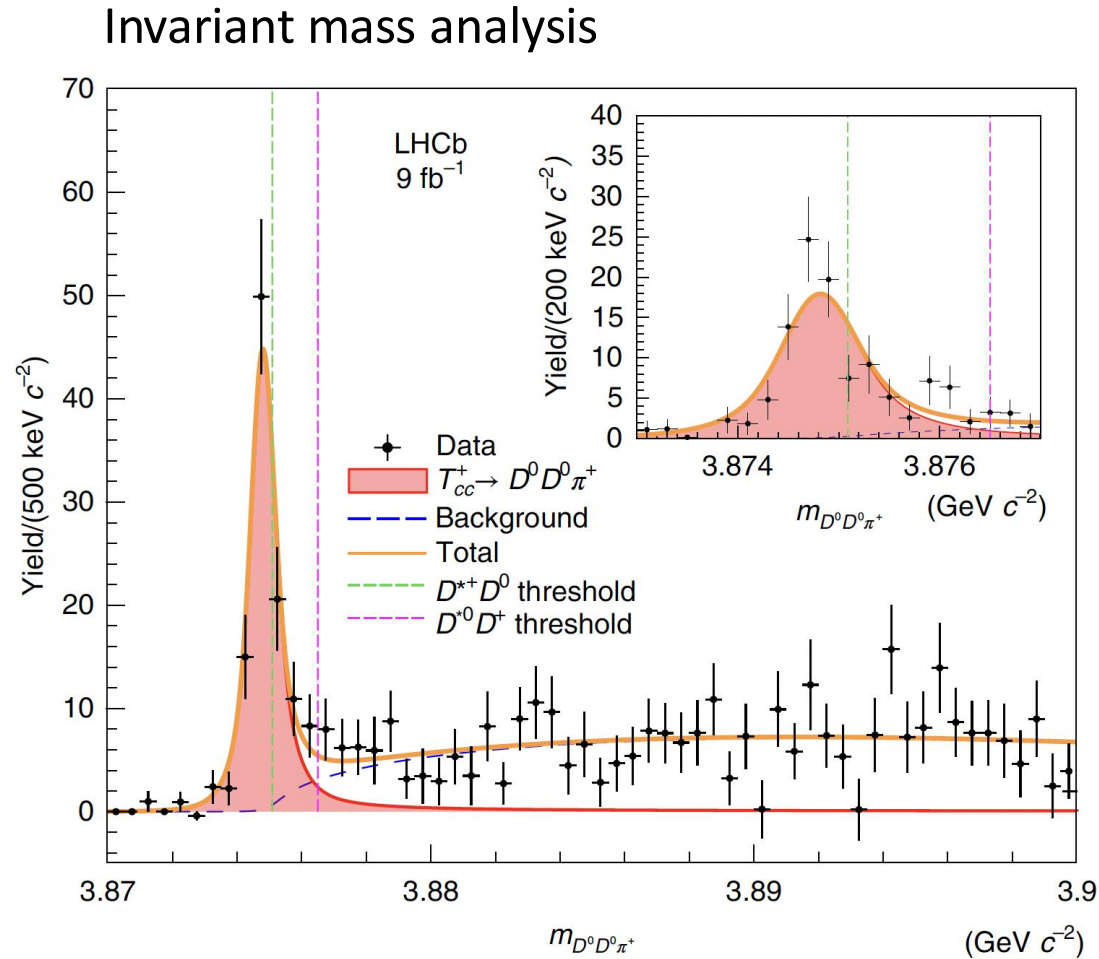
(p-p)-π⁺

p-(p-π⁺)

p-p-π⁺

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 $pp\pi^-$
  - Attraction for $pp\pi^+$

ALI-PREL-576418
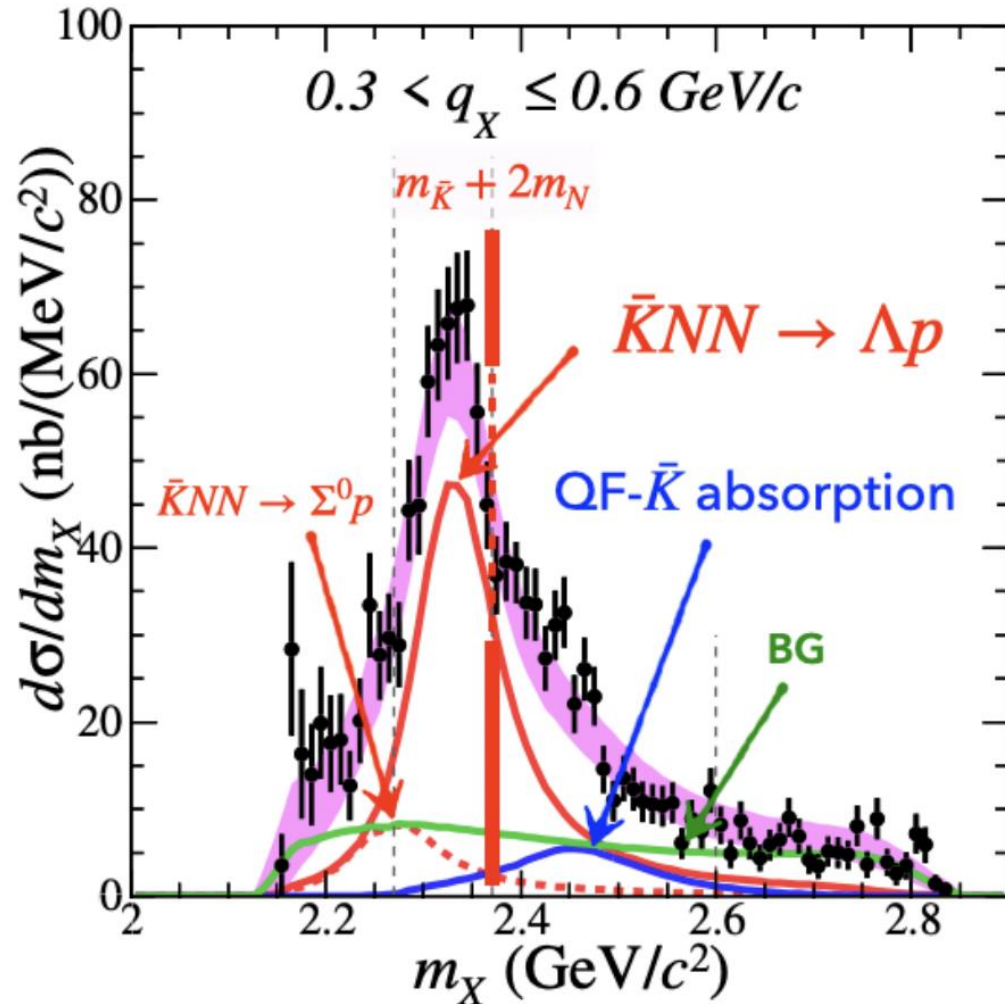
Femtoscopy to study molecular and bound states

Invariant mass analysis

LHCb Coll. Nature Phys. (2022)

Femtoscopy

ALICE 3 LOI, arXiv:2211.02491

p-p-K⁻ bound state

$0.3 < q_X \leq 0.6$ GeV/c

$m_{\bar{K}} + 2m_N$

$\bar{K}NN \to \Lambda p$

$\bar{K}NN \to \Sigma^0 p$

QF-$\bar{K}$ absorption

BG

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

Λ p

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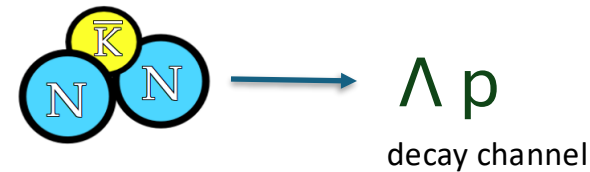
	B.E. (MeV)	Width (MeV)
Exp. (E15)	42	100
Theo.	16	72

E15 Coll., Phys.Rev.C 102 (2020) 4, 044002
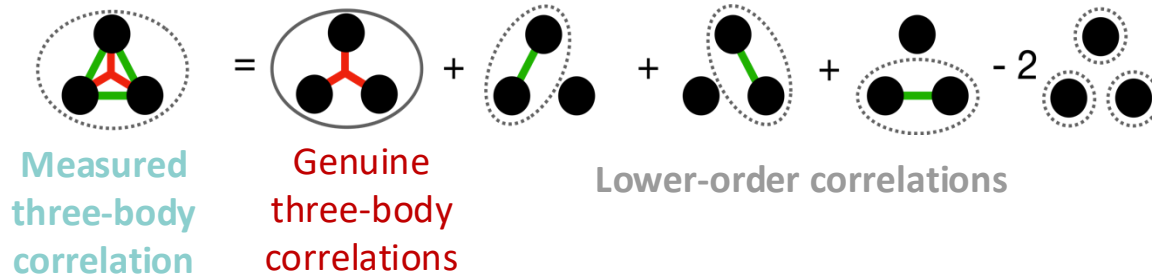*Sekihara et al., PTEP 2016 no. 12, (2016)*

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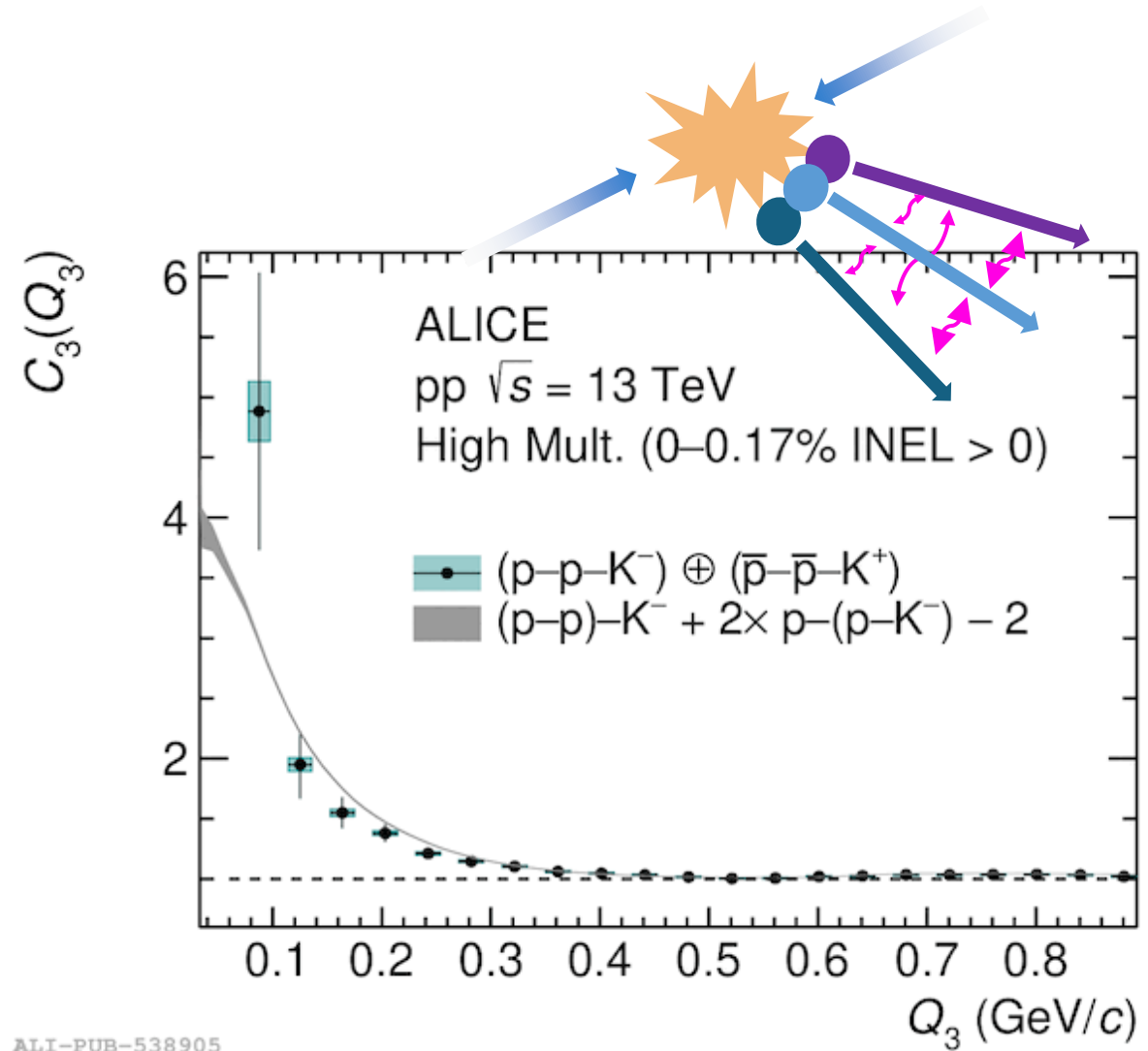 *R. Del Grande et al. EPJC 82 (2022) 244*

Measured three-body correlation = **Genuine three-body correlations** + **Lower-order correlations** - 2

- Agreement within nσ = 1.5 with lower-order contributions

  - Negligible 2NA processes: BR(K⁻d → YN) ~ 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
    - NNΛ 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

"Genuine three-body correlation"

- multiple rescattering of 2-body interaction?
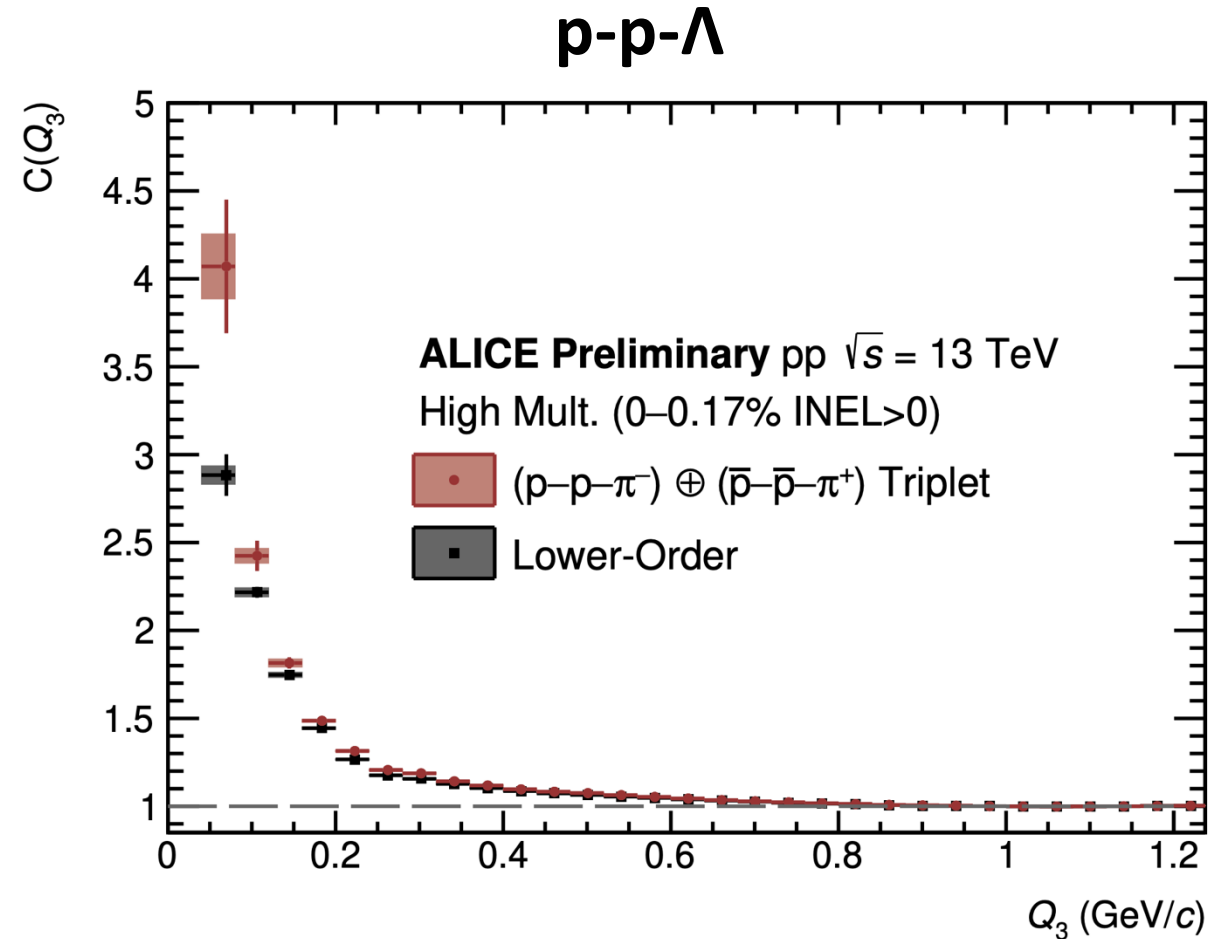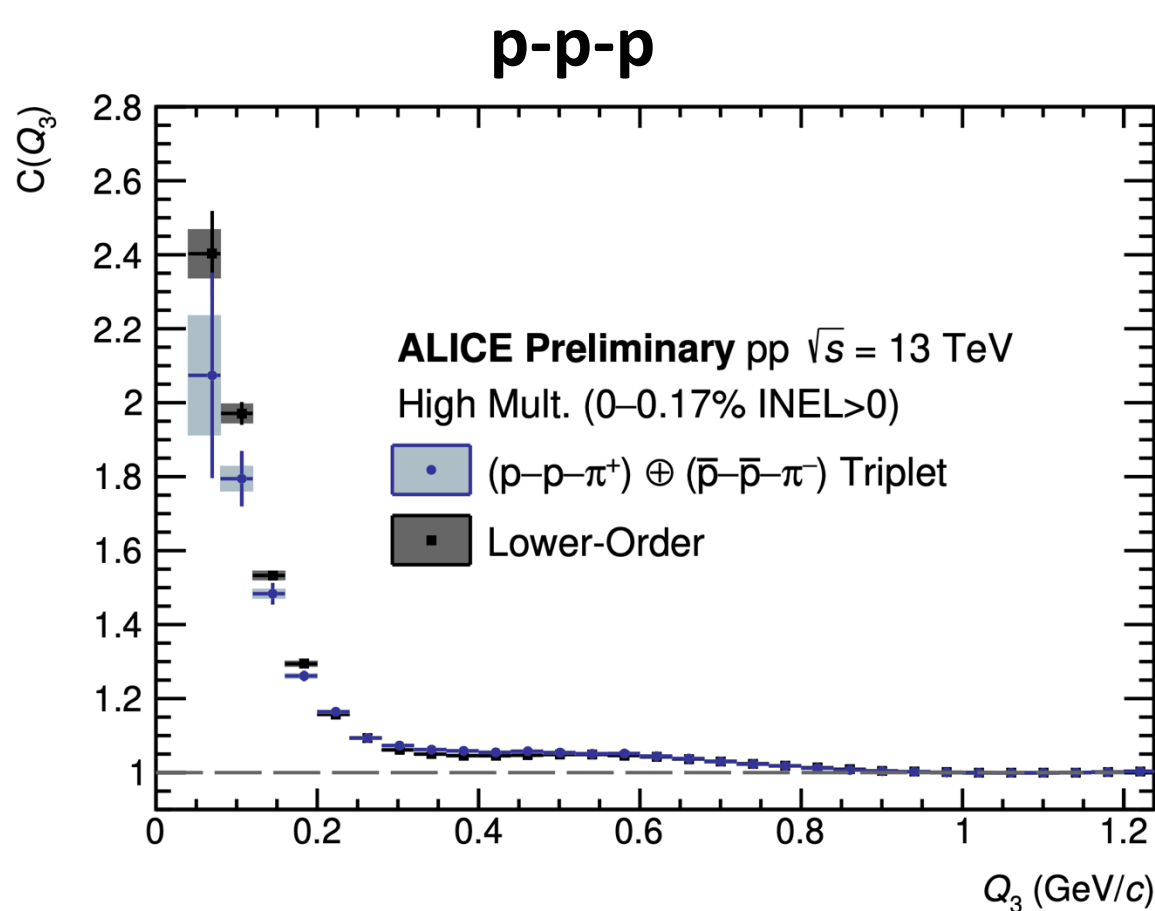- 3-body force (act only in 3-body system)?
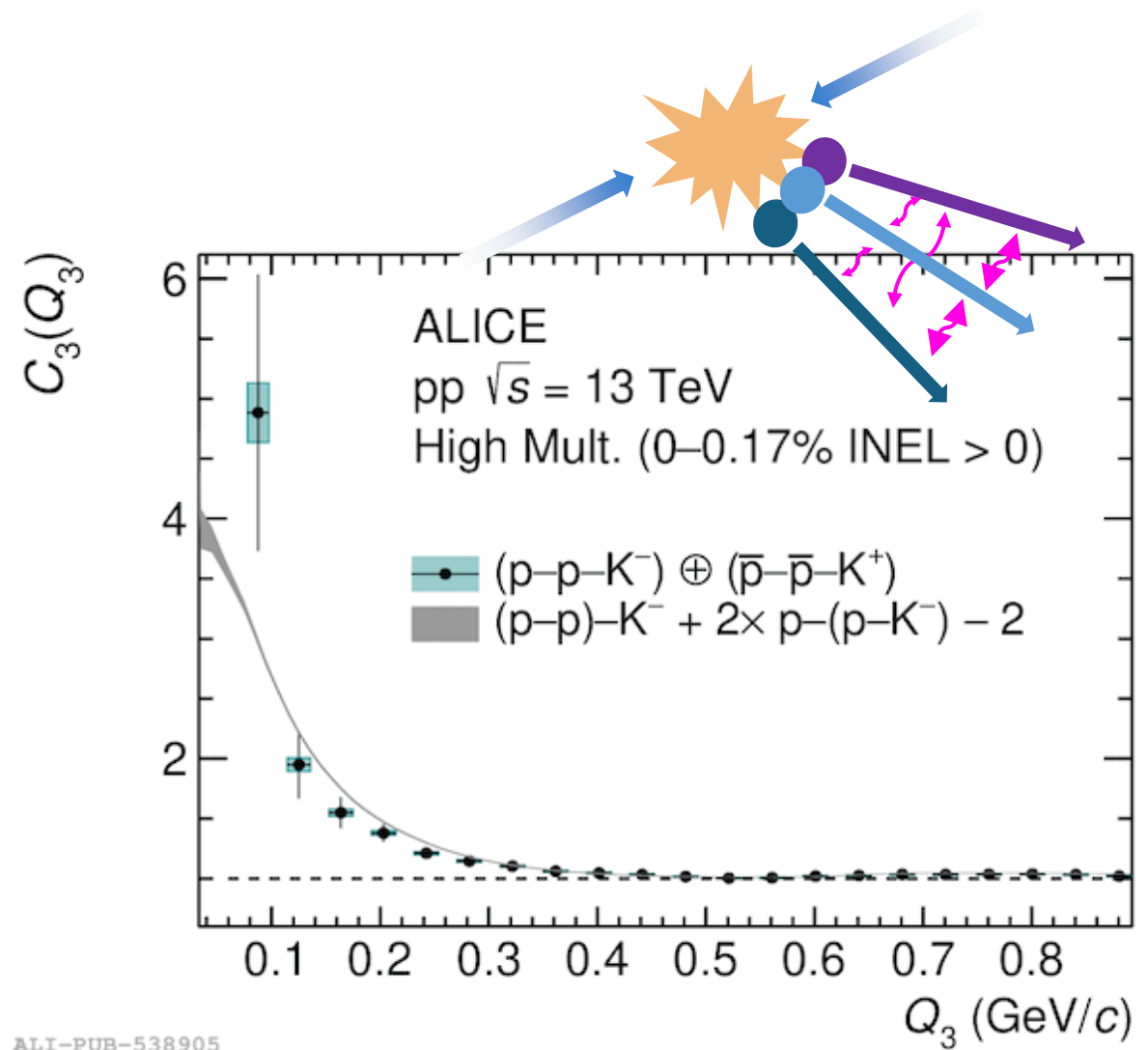
ALICE Coll., EPJA 59, 298 (2023)

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-p-p

p-p-Λ

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

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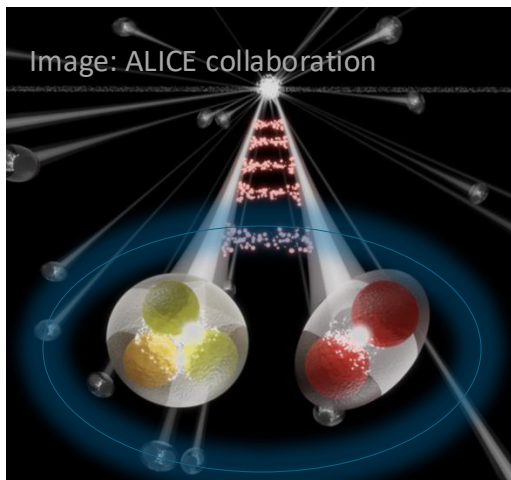
	System	E_B [MeV]
QCD Van der Waal using Yukawa type Potential[1]	φN	1.8
Chiral quark model[2]	φN	3.0
Monte Carlo study of φ photoproduction from nuclear targets[3]	φN	2.5
Quark delocalization color screening model[4]	φN	0.3-8.8
Unitary coupled-channel approximation anchored to ALICE pφ scattering data[5]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

[1]H. Gao, T.-S. H. Lee, and V. Marinov, Phys. Rev. C 63 (2001) 022201(R)
[2]F. Huang, Z.Y. Zhang, and Y.W. Yu, Phys. Rev. C 73 (2006) 025207
[3]H. Gao et al., Phys. Rev. C 95 (2017) 055202
[4]S. Liska, H. Gao, W. Chen, and X. Qian, Phys. Rev. C 75 (2007) 058201
[5]B.-X. Sun, Y.-Y. Fan, and Q.-Q. Cao, arXiv , 2206.02961 (2022)
*[6]V. B. Belyaev, W. Sandhas, and I. I. Shlyk, Few-Body Syst. 44 (2008) 347*
[7]S. A. Sofianos, G. J. Rampho, M. Braun, and R. M. Adam, J. Phys. G. 37 (2010) 085109

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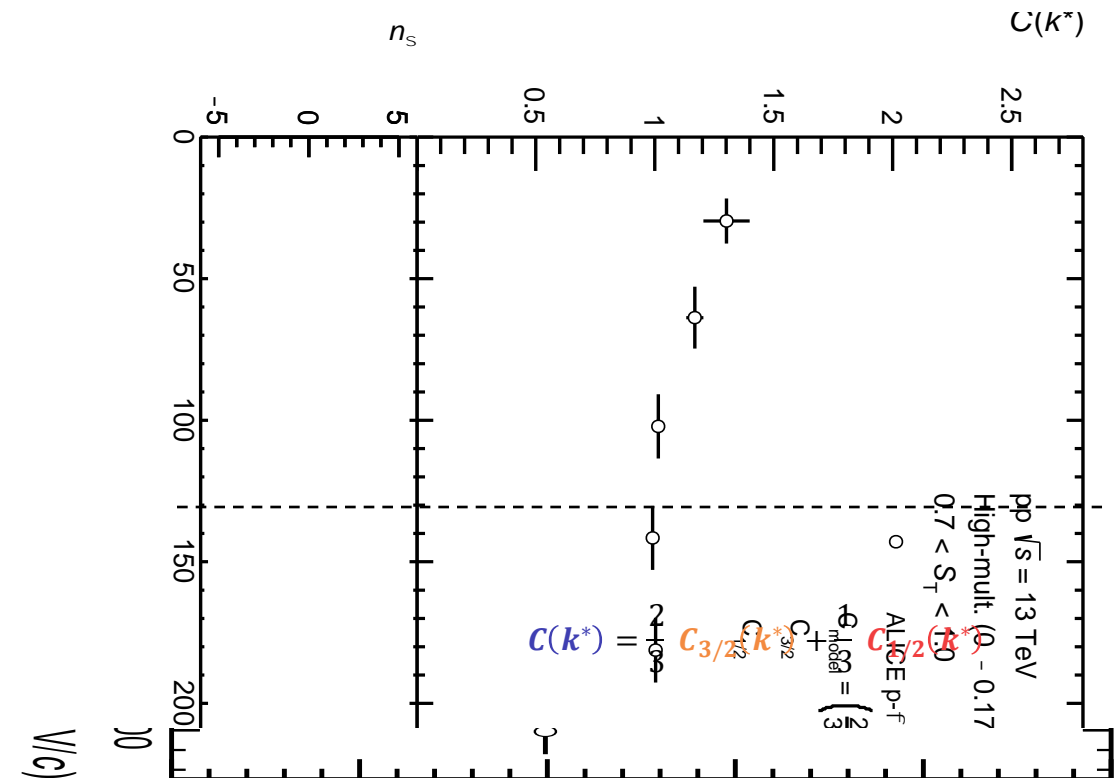
E. Chizzali, Y. Kamiya et al., PLB 848 (2024) 138358

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

$C(k^*) = \frac{2}{3}\,C_{3/2}(k^*) + \frac{1}{3}\,C_{1/2}(k^*)$

pp √s = 13 TeV
High-mult. (0 – 0.17
0.7 < S$_T$ < 1
○ ALICE p-ϕ

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

First measurement of Dπ correlation functions

- Coulomb-only interaction favoured
- Tension with theory models

L. Liu et al, Phys. Rev. D87 (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
B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
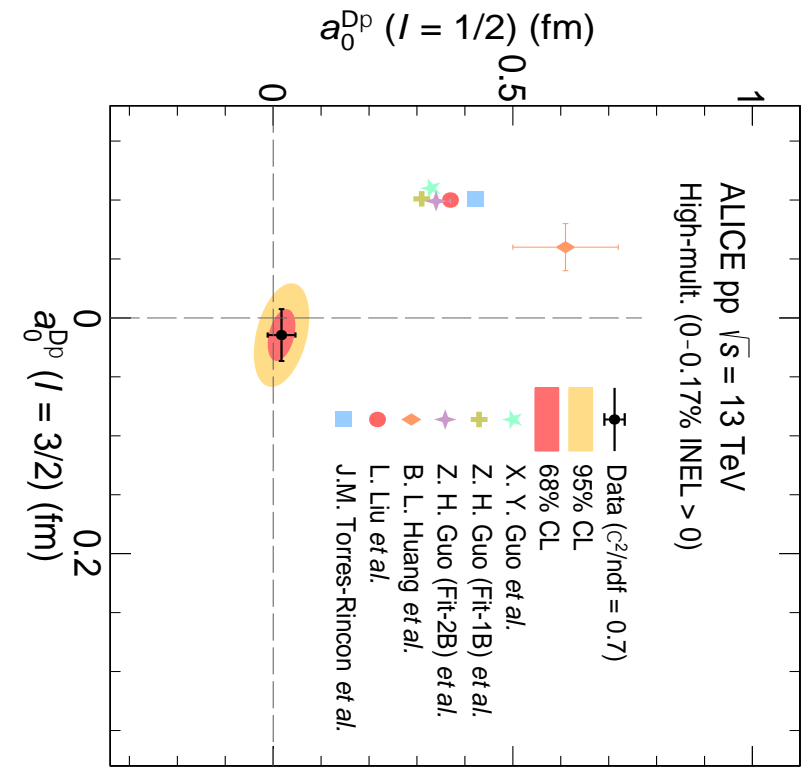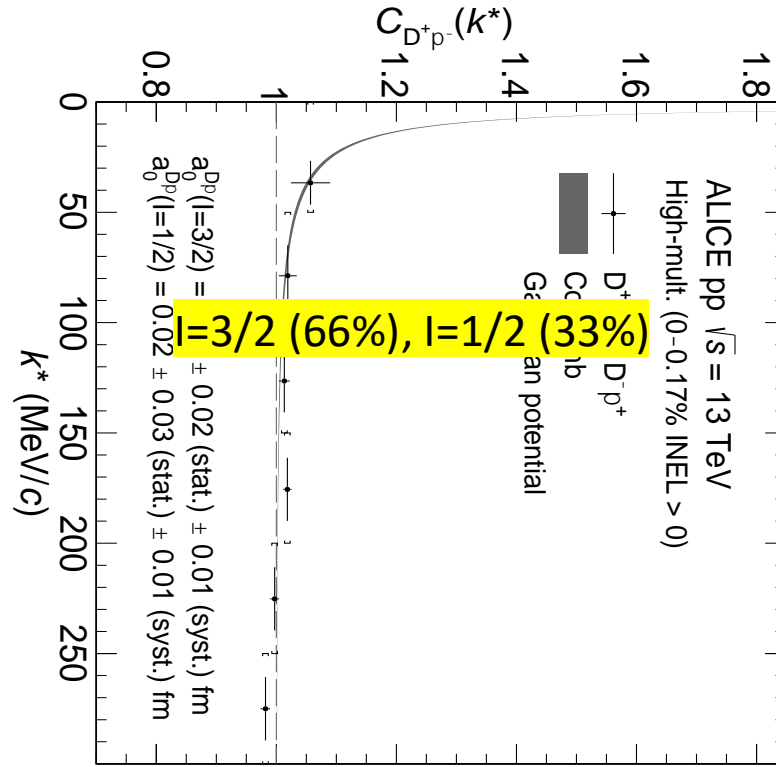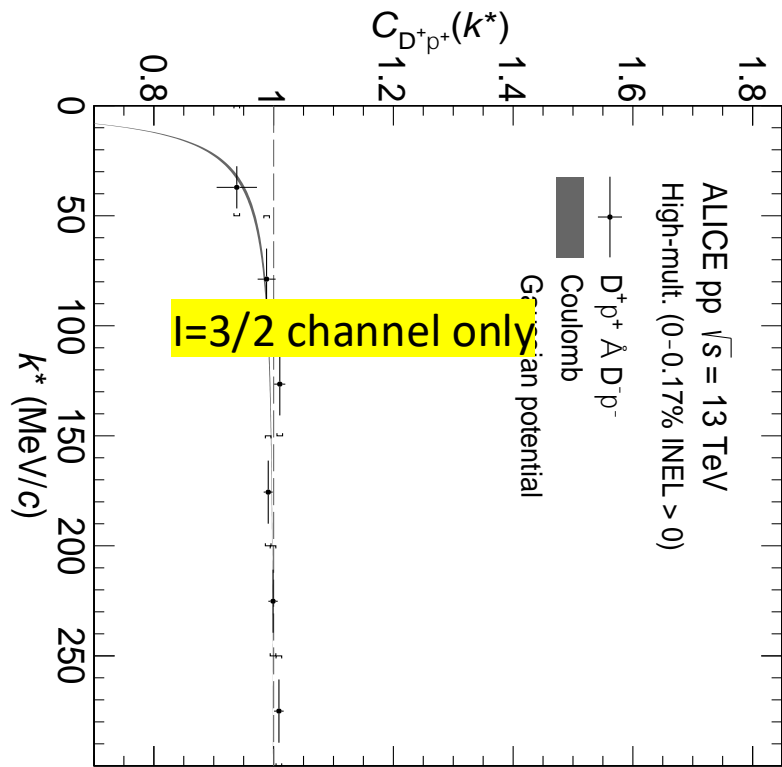J. M. Torres-Rincon et al, Phys. Rev. D 108 (2023) 096008
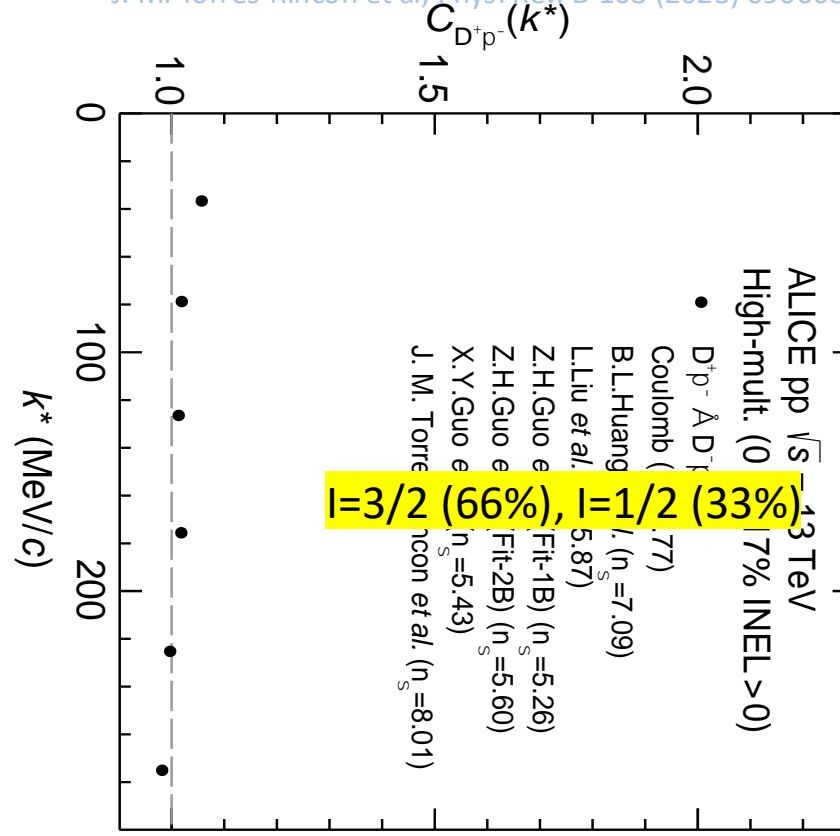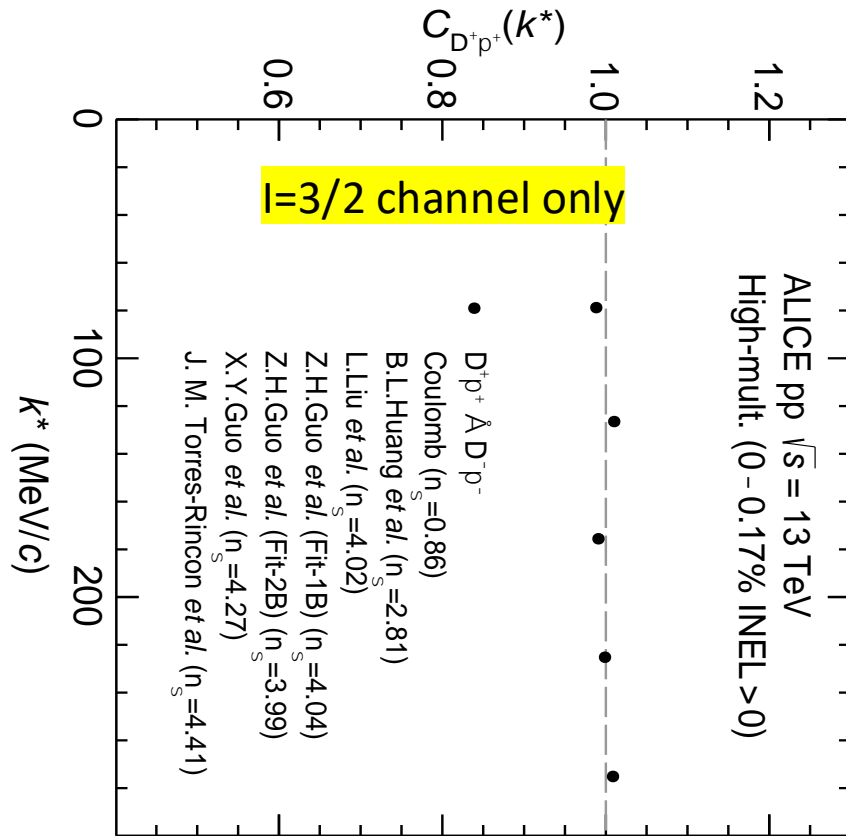
ALICE Coll., arXiv:2401.13541 (2023)

Dπ correlation function fit

- D+π+ and D+π- share I=3/2 channel→ simultaneous fit

- Vanishing scattering parameters in both isospin channels

- Tension with theory especially in I=1/2 channel

ALICE Coll., arXiv:2401.13541 (2023)