Via Piella, Bo

Accessing the three-body dynamics with multi-particle correlations at LHC

V. Mantovani Sarti (TUM)

4th Workshop on Anti-Matter, Hyper-Matter and Exotica Production at the LHC

15.02.2023

valentina.mantovani-sarti@tum.de

Many-body dynamics in nuclear physics

1. Properties of nuclei and hypernuclei cannot be described satisfactorily with two-body forces only.
   L.E. Marcucci et al., Front. Phys. 8:69 (2020)
   Hypernuclei session Tue. 14.02

2. Many-body scattering requires three-body calculations (e.g. neutron-deuteron).
   L. Girlanda et al., PRC 102, 064003 (2020)

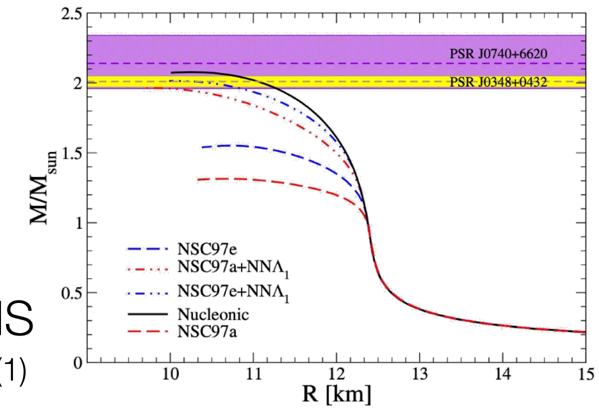
ρ_0

ρ (fm^{-3})

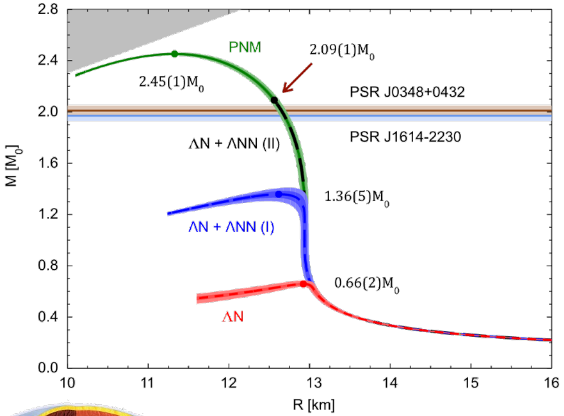
Many-body dynamics in astrophysics

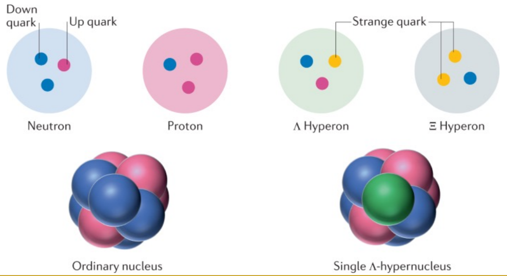
3. Equation of state of matter inside neutron stars
   - Production of hyperons energetically favourable around 2-3 ρ_0
   - Only two-body ΛN
     → Too soft EoS, incompatible with measured heavy NS
     → Large improvement in 2-body YN with femtoscopy(1)
   - Introduction of three-body ΛNN forces
     → Stiffens EoS, model-dependent(2)
     → Need for additional experimental constraints

D. Logoteta et al., Eur.Phys.J.A 55 (2019)

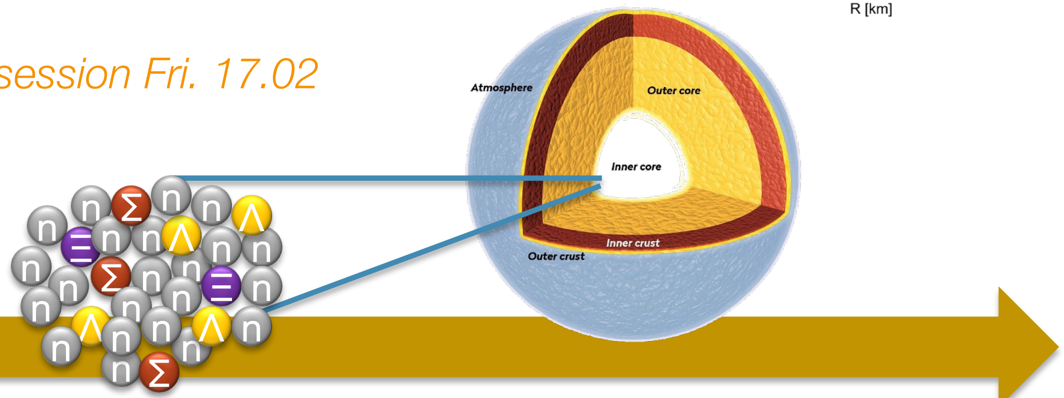


D. Lonardoni et al., PRL 114 (2019)





NS session Fri. 17.02



ρ_0 $\sim 3\ \rho_0$ ρ (fm^{-3})

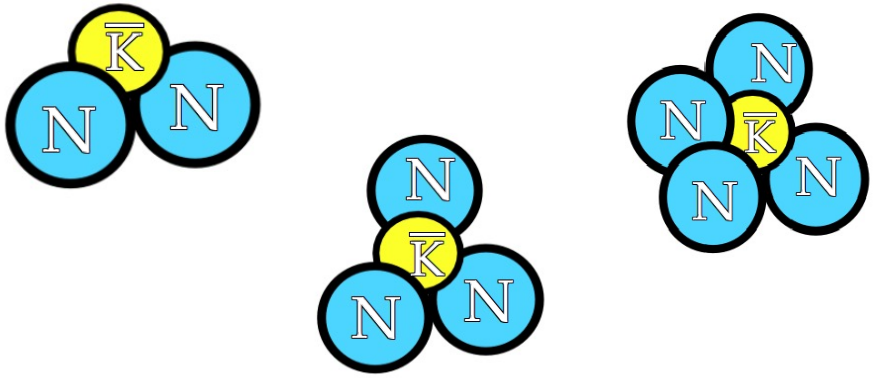
(1) *ALICE Coll. PLB 833 (2022)*
ALICE Coll. Nature 588 (2020)
L. Fabbietti et al. Ann.Rev.Nucl.Part.Sci. 71 (2021)

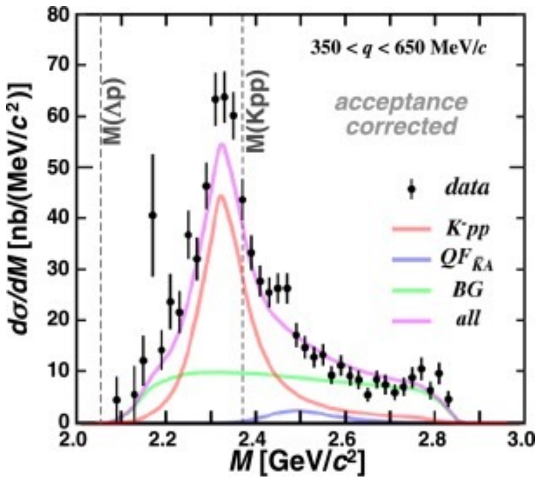
(2) *D. Logoteta et al., Eur.Phys.J.A 55 (2019)*
D. Gerstung et al., Eur.Phys.J.A 56 (2020)
D. Lonardoni et al., PRL 114 (2019)

Many-body dynamics with mesons and bound states

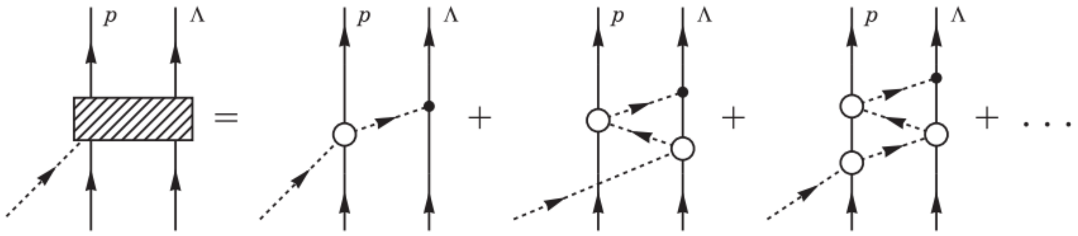
- Exotic bound states of antikaons with nucleons due to the strongly attractive KN interaction in I = 0 channel
  S. Wycech, NPA 450 (1986); Y. Akaishi, T. Yamazaki, PRC 65 (2002)

- First experimental evidence of the p-p-K- bound state by the E15 Collaboration. *E15 Coll., PLB 789 (2019) 620*





Kaonic bound state formation mechanism

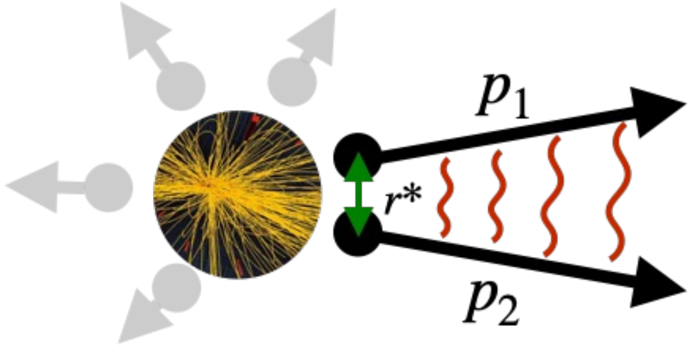


$K^{-}pp$

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

Next experimental challenge: genuine three-body interaction measurements

Two-body femtoscopy at LHC



Emission source S(r*)

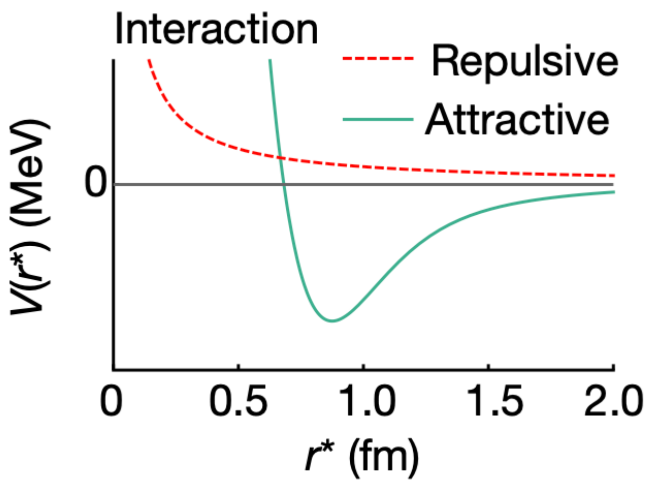
ALICE Coll. PLB 811 (2020) 135849

ALICE Collaboration
pΛ: PLB 833 (2022), 137272
pΣ⁰: PLB 805 (2020) 135419
pΞ/pΩ: Nature 588 (2020) 232-238
pϕ: PRL 127 (2021), 172301
Kp: PRL 124 (2020) 09230,
PLB 822 (2021) 136708
arXiv: 2205.15176 [nucl-ex]
and many more:
PRC 99 (2019) 2, 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRC 103 (2021) 5, 055201
PLB 829 (2022), 137060
arXiv: 2201.05352 [nucl-ex]
arXiv: 2204.10258 [nucl-ex]

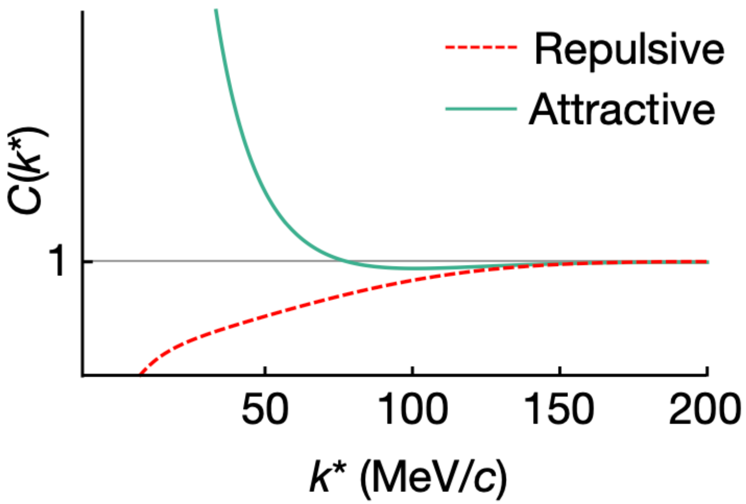
- Two-particle correlation function *Today session*

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

- Measurements in small colliding systems (~1-2 fm)
  → Access to the strong interaction and short-range dynamics

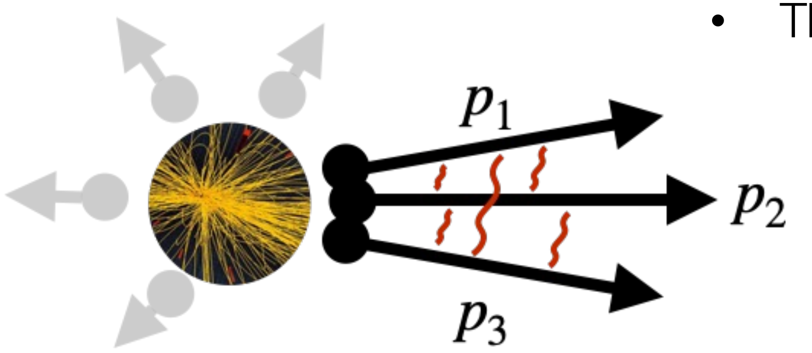


Schrödinger equation
Two-particle wave function
$|\psi(k^*, r^*)|$



Correlation function C(k*)

Three-body femtoscopy at LHC



- Three-particle correlation function

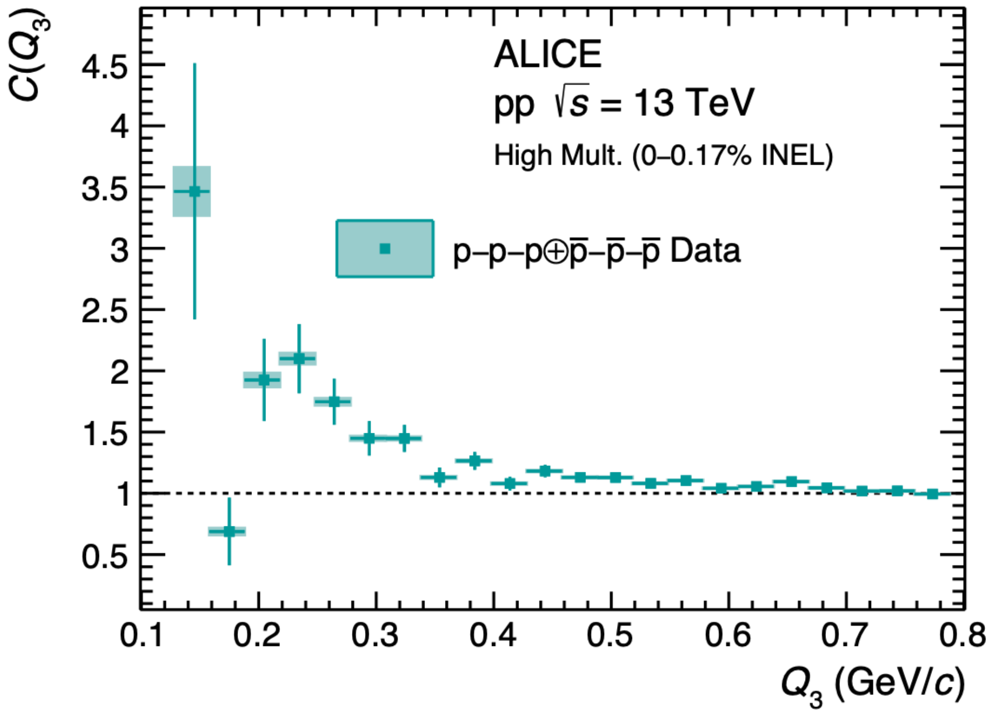
$$C(\boldsymbol{p}_1, \boldsymbol{p}_2, \boldsymbol{p}_3) \equiv \frac{P(\boldsymbol{p}_1, \boldsymbol{p}_2, \boldsymbol{p}_3)}{P(\boldsymbol{p}_1)P(\boldsymbol{p}_2)P(\boldsymbol{p}_3)} = \mathcal{N}\frac{N_{\mathrm{same}}(Q_3)}{N_{\mathrm{mixed}}(Q_3)}$$

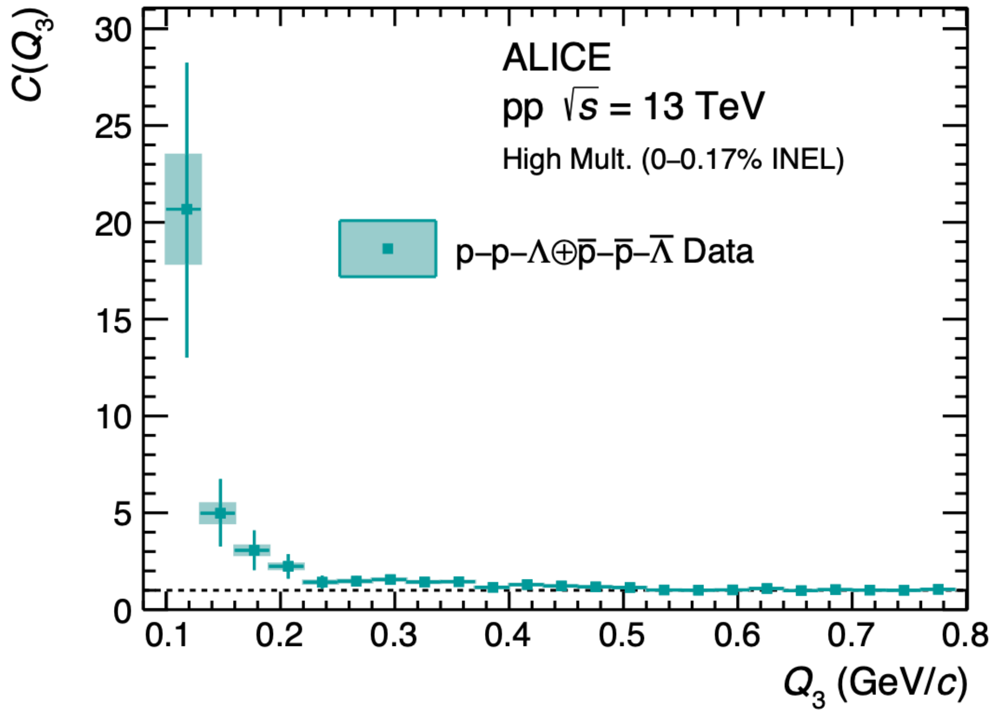
$$Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - -q_{ki}^2}$$

- Applied multi-pion correlations to study coherent emission
  ALICE Coll. Phys.Rev.C 89 (2014), Phys.Rev.C 93 (2016)

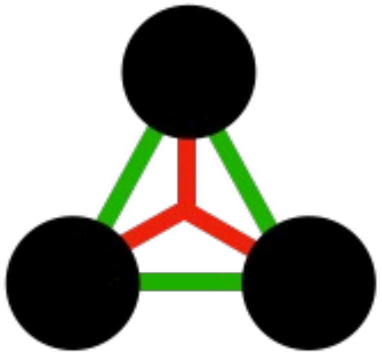
- First measurement of p-p-p and p-p-Λ correlations in high-multiplicity pp collisions 13 TeV by ALICE
  ALICE Coll. arXiv: 2206.03344 nucl-ex

Accessing the ppp and ppΛ interactions at LHC





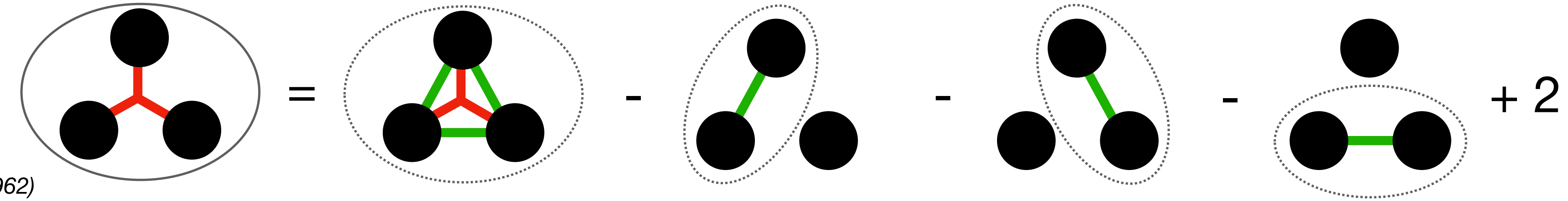
- Signal different from unity at low Q_3
- How can we interpret these three-body correlations?
  → Two-body interactions
  → Three-body interactions



Adapted from ALICE Coll. arXiv: 2206.03344 nucl-ex

Cumulants in femtoscopy

Kubo´s rule[(1)] :



(1) *R. Kubo, J. Phys. Soc. Jpn. 177 (1962)*

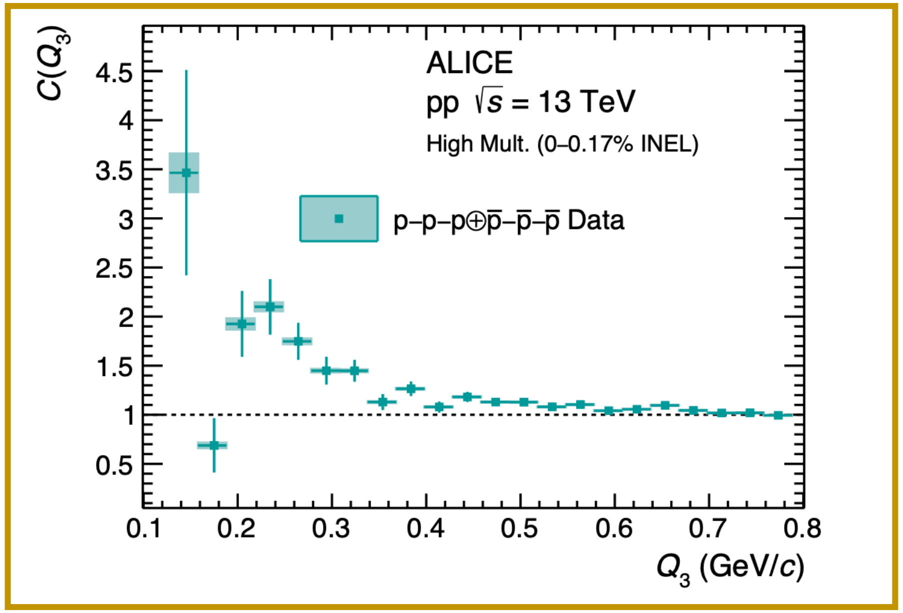
Genuine three-body correlations

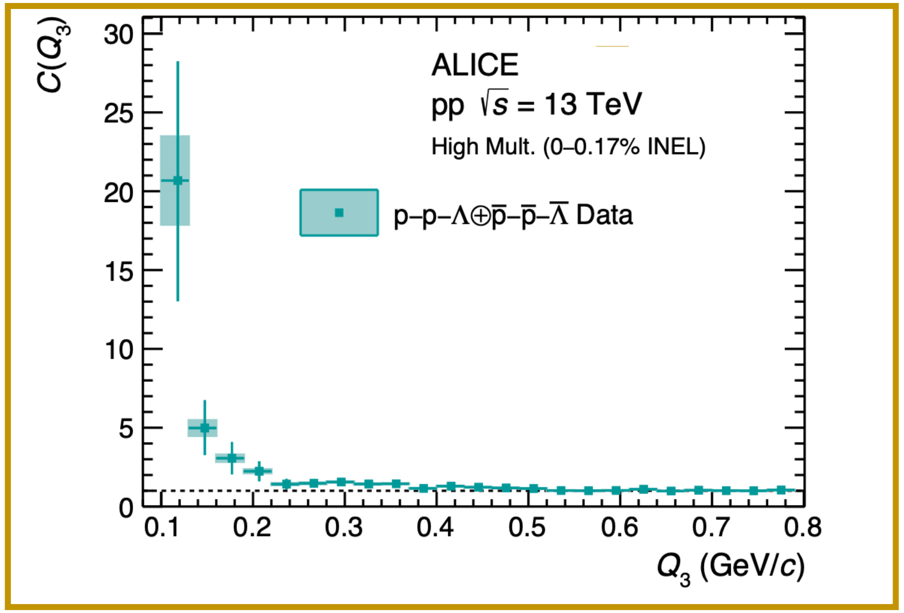
Measured three-body correlation

Two-body correlations

Correlations:

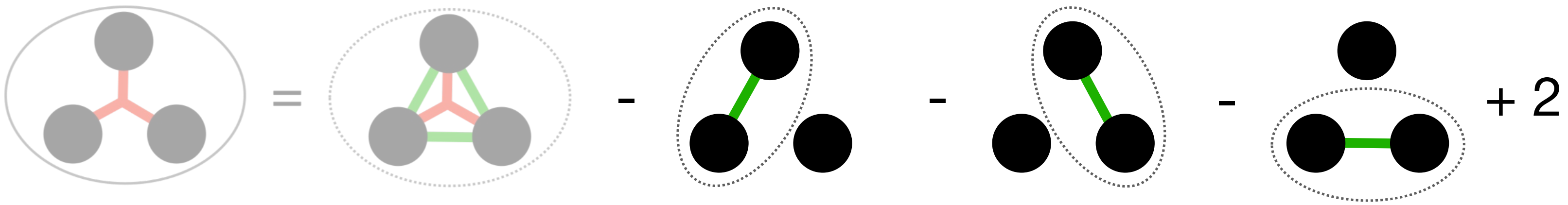
$$c_3(Q_3) = C(Q_3) - C_{12}(Q_3) - C_{23}(Q_3) - C_{31}(Q_3) + 2$$



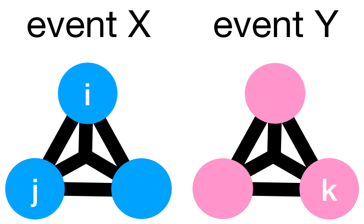


Adapted from ALICE Coll. arXiv: 2206.03344 nucl-ex

Lower order contributions: two different approaches



- Using directly the data
- Two particles from the same event and one particle from another:



$$C_{ij}([\mathbf{p}_i, \mathbf{p}_j], \mathbf{p}_k) = \frac{N_2(\mathbf{p}_i, \mathbf{p}_j) N_1(\mathbf{p}_k)}{N_1(\mathbf{p}_i) N_1(\mathbf{p}_j) N_1(\mathbf{p}_k)}$$

ALICE Coll. arXiv: 2206.03344 nucl-ex

- Projector method
- Evaluate two-body contribution in three-body correlation function
  - Two-particle measured or theoretical correlation function $C([\mathbf{p}_i, \mathbf{p}_j])$
- Kinematic transformation in phase space

two-body CF projector

$$C_{ij}(Q_3) = \int \underbrace{C(k_{ij}^*)}_{\text{two-body CF}} \underbrace{W_{ij}(k_{ij}^*, Q_3)}_{\text{projector}} dk_{ij}^*$$

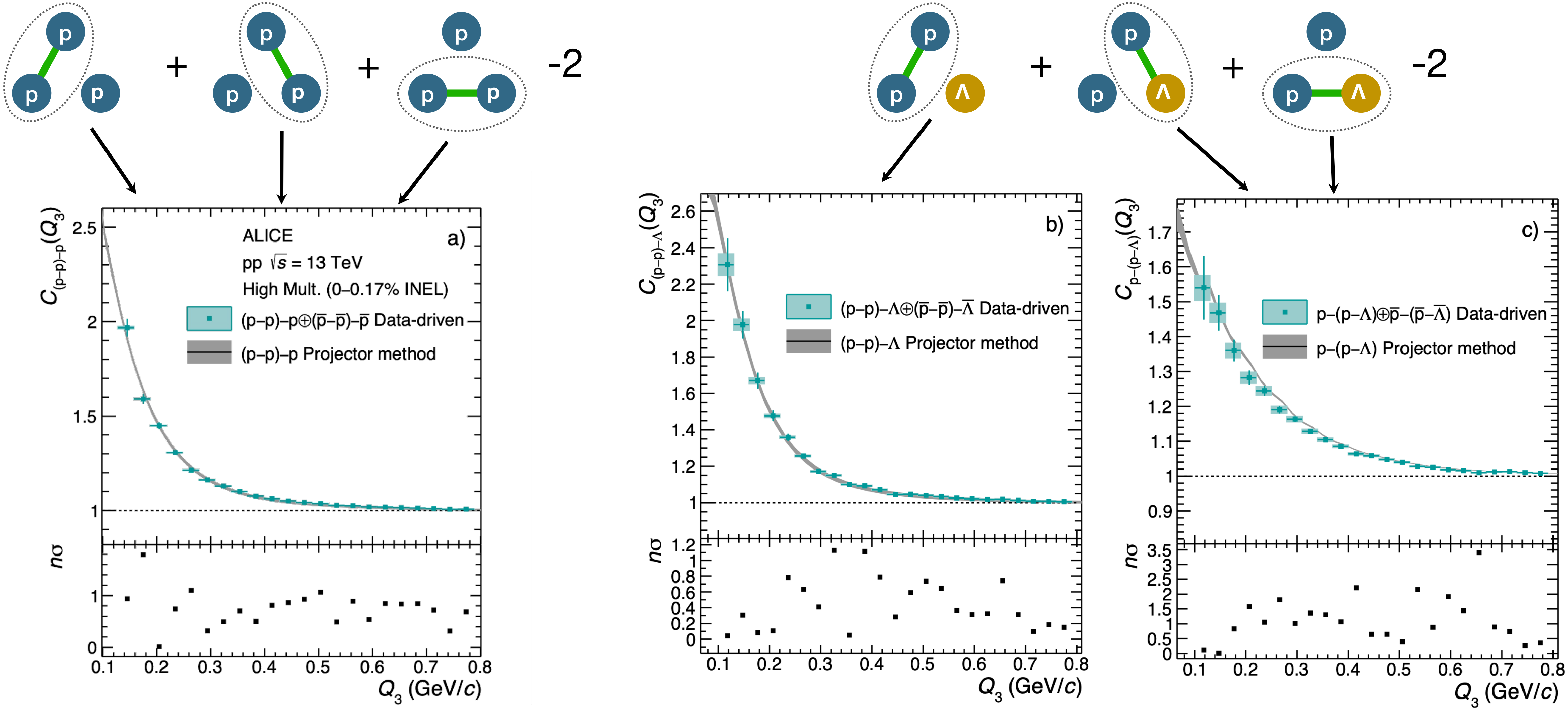
Measured/modeled 2-body correlation functions

Jacobian from 2-body to 3-body coordinates

p-p: ALICE Coll. PLB 805 (2020) 135419
pΛ: ALICE Coll. PLB 833 (2022), 137272

R. Del Grande, L.Serksnyte et al. EPJC 82 (2022)

Lower order contributions in p-p-p and p-p-Λ

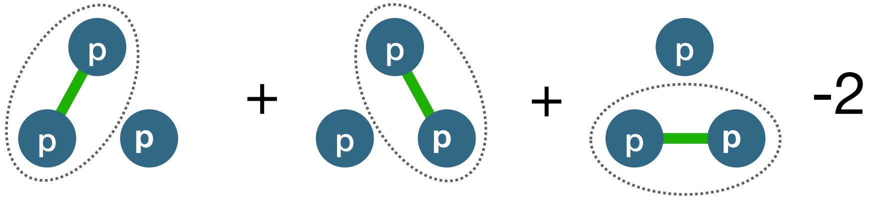


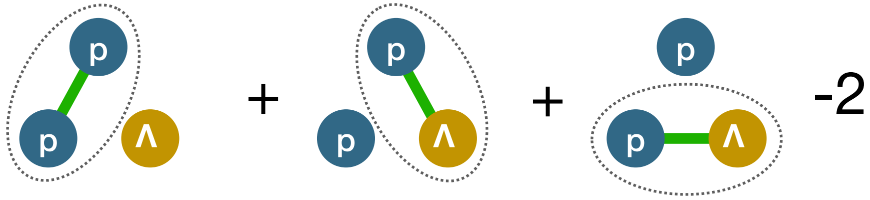
Measured p-p correlation *ALICE Coll. PLB 805 (2020) 135419*

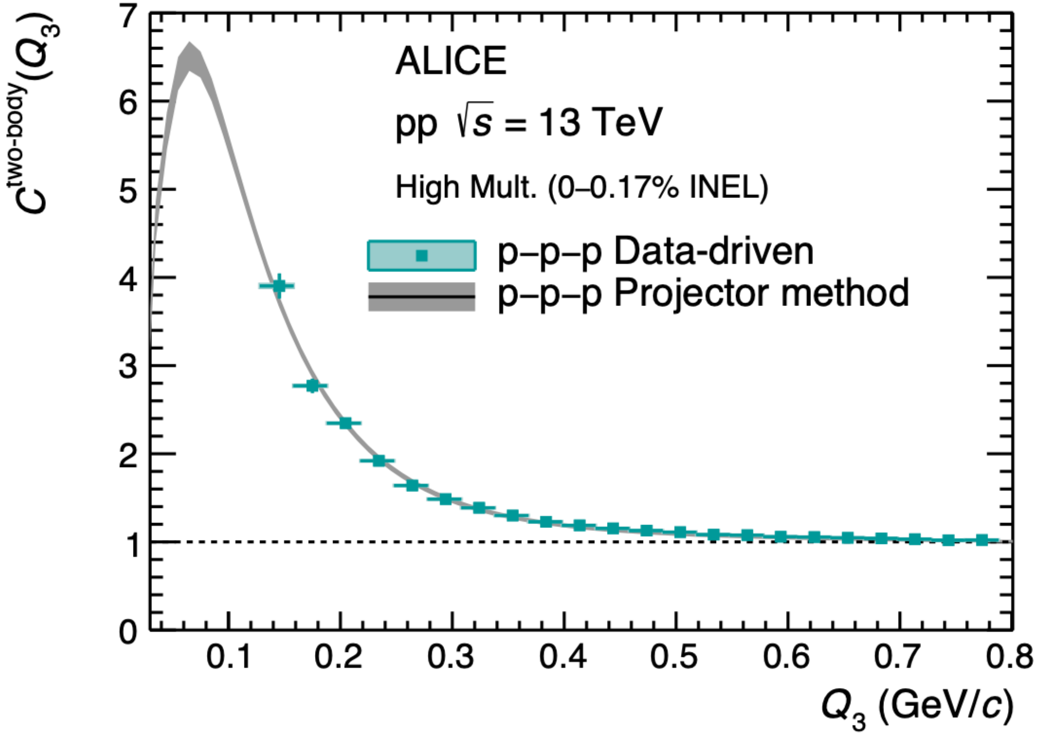
Measured p-Λ correlation *ALICE Coll. PLB 833 (2022), 137272*

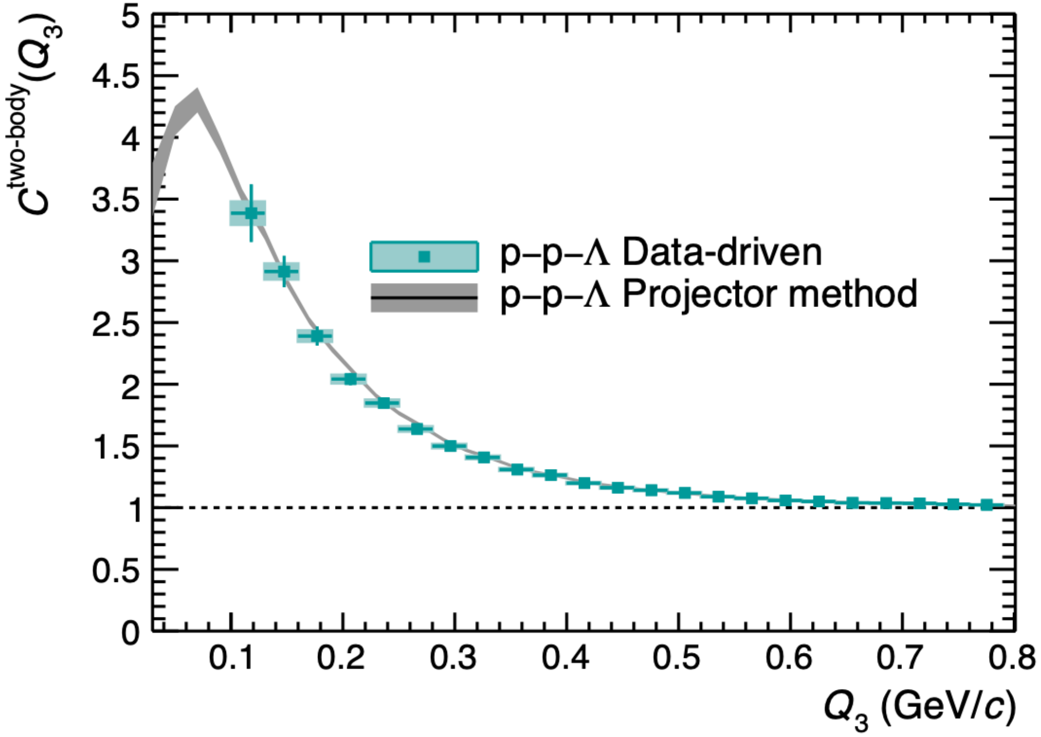
ALICE Coll. arXiv: 2206.03344 nucl-ex

Lower order contributions in p-p-p and p-p-Λ



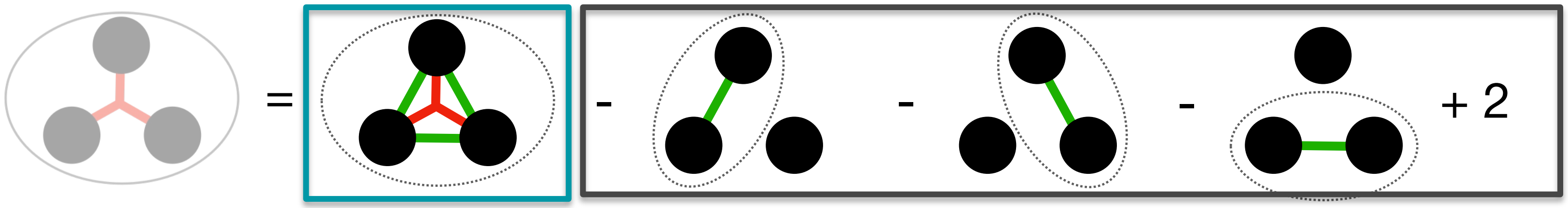


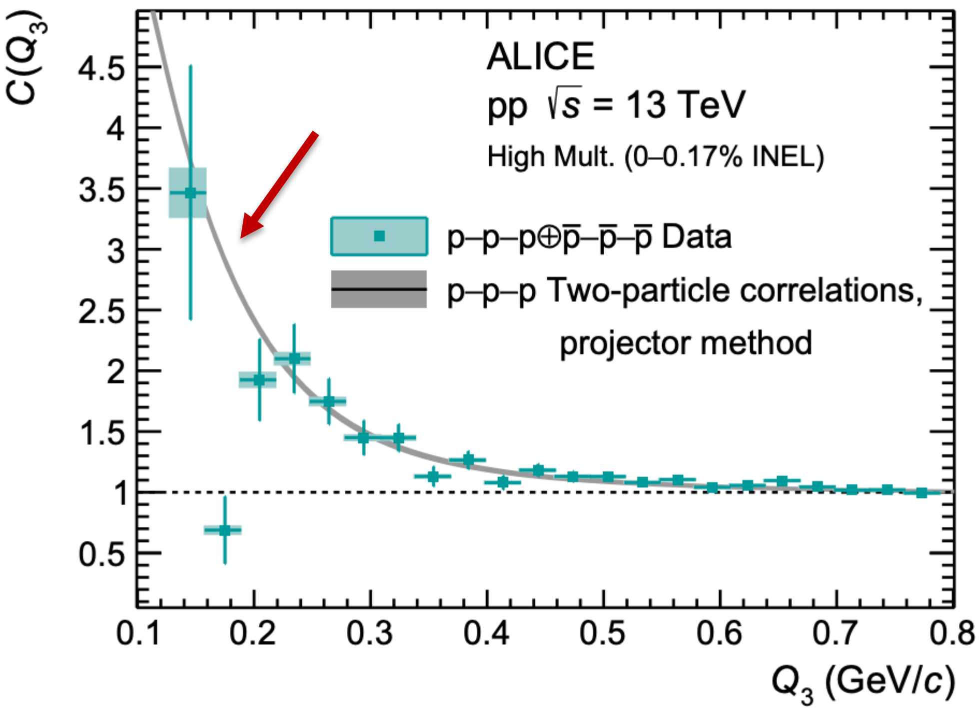


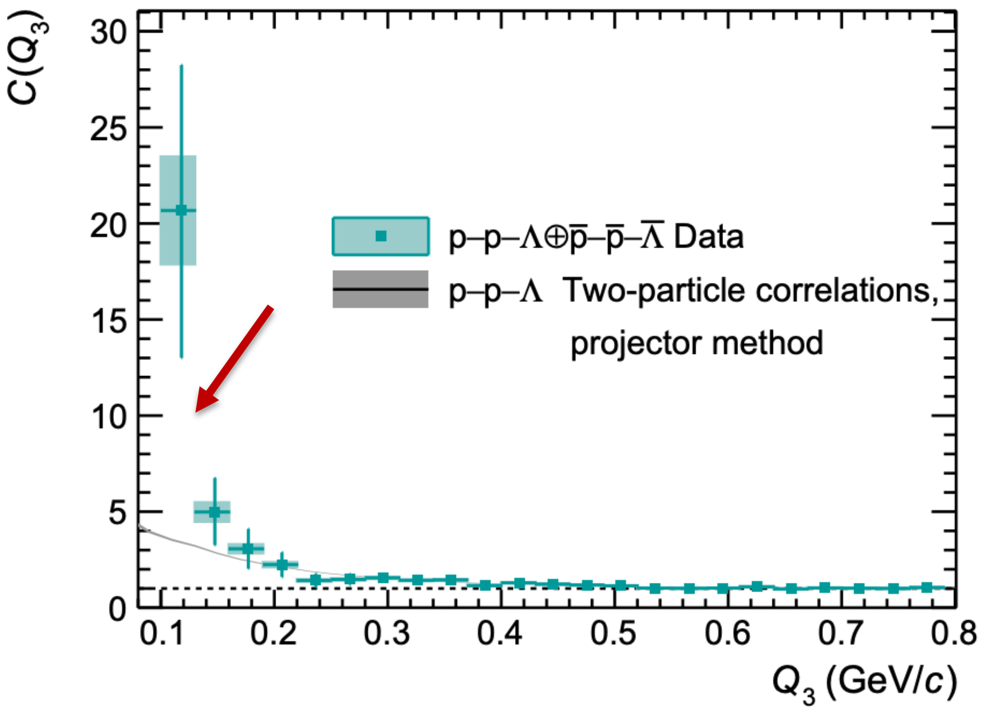


ALICE Coll. arXiv: 2206.03344 nucl-ex

Understanding the three-particle correlation functions

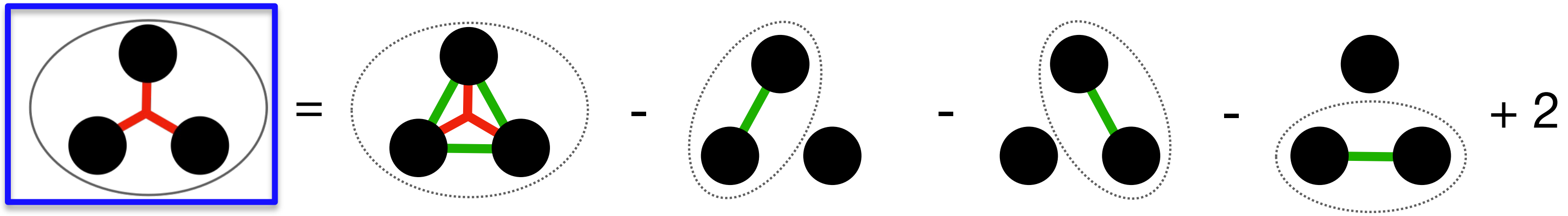


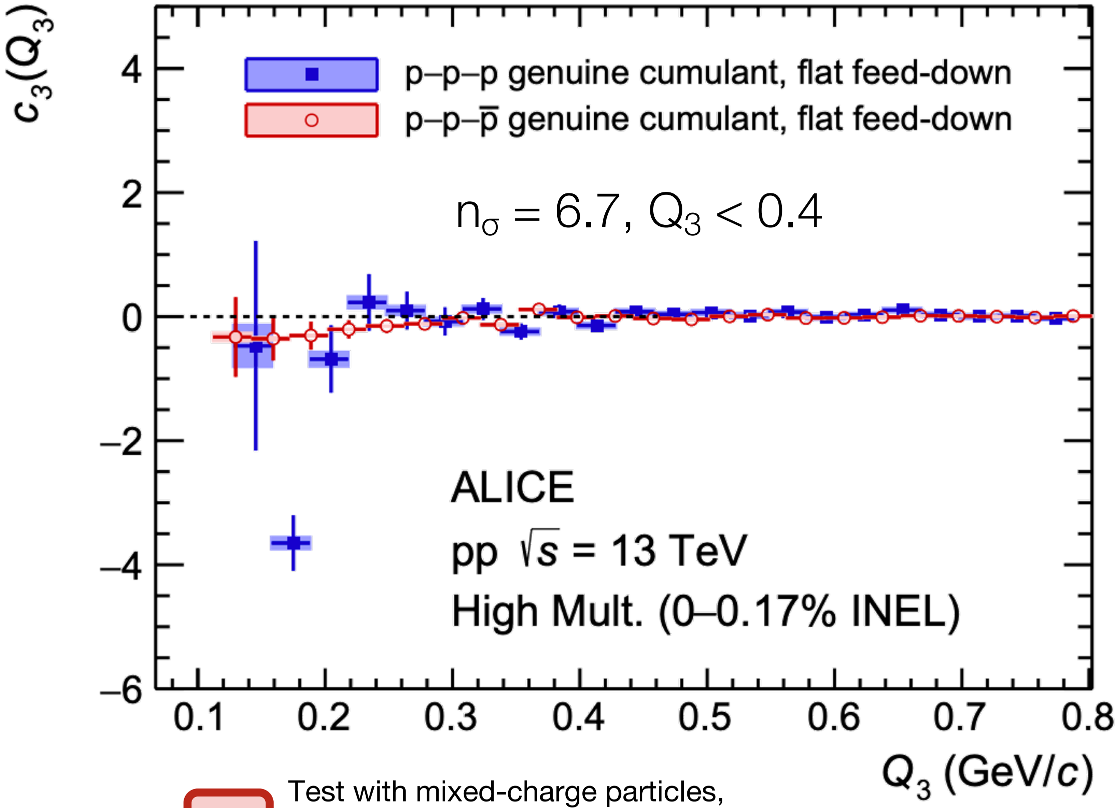




ALICE Coll. arXiv: 2206.03344 nucl-ex

p-p-p cumulant



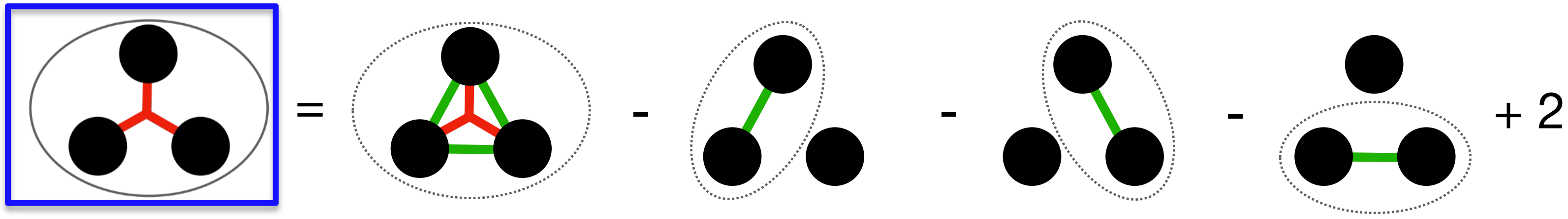


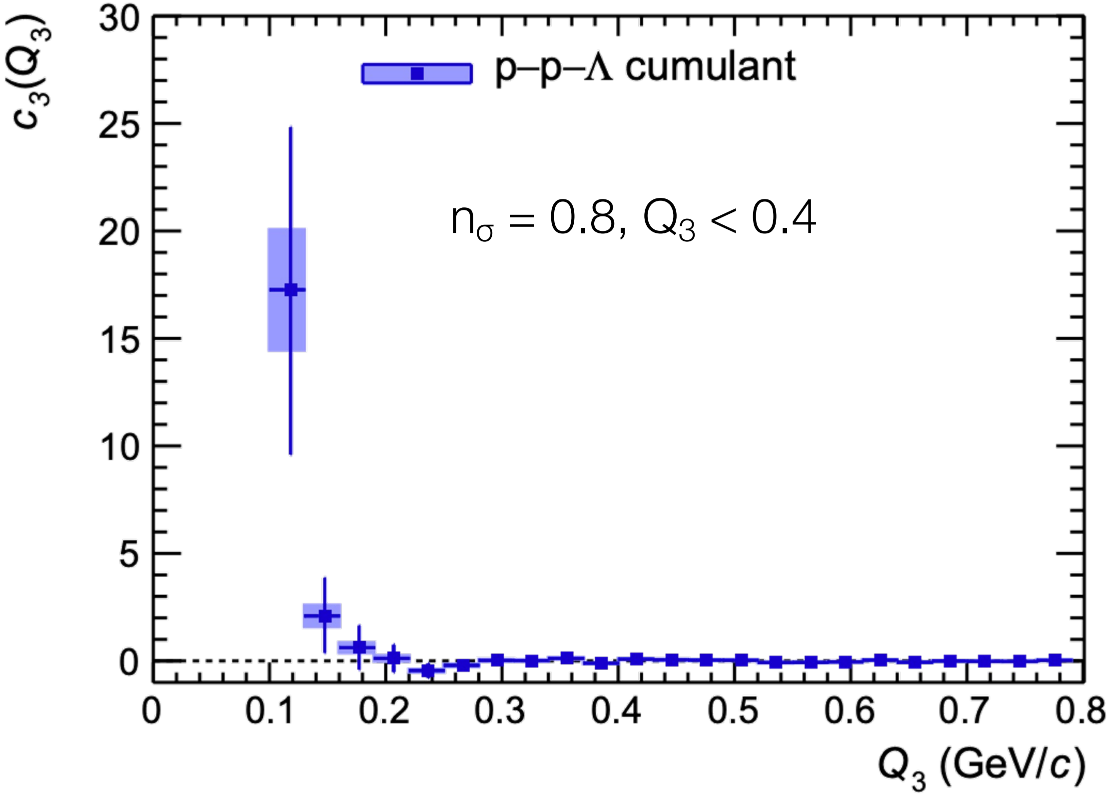
Test with mixed-charge particles, cumulant negligible.

- Negative cumulant and deviation from zero
  → Presence of a genuine 3-body effect
- Possible interpretations
  – Pauli blocking at 3-particle level
  – 3-body strong interaction
- Take-home message:
  → Significant deviation from null hypothesis
  → Ongoing collaboration with Pisa theory group
  (Prof. Kviesky, Prof. Marcucci and Dr. Viviani)

ALICE Coll. arXiv: 2206.03344 nucl-ex

p-p-Λ cumulant

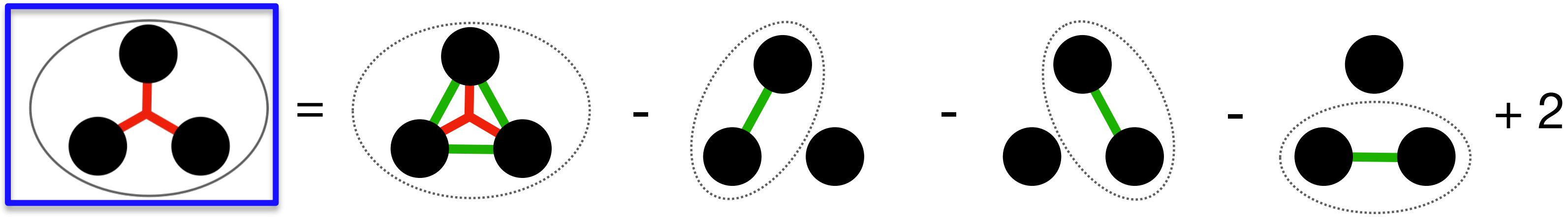


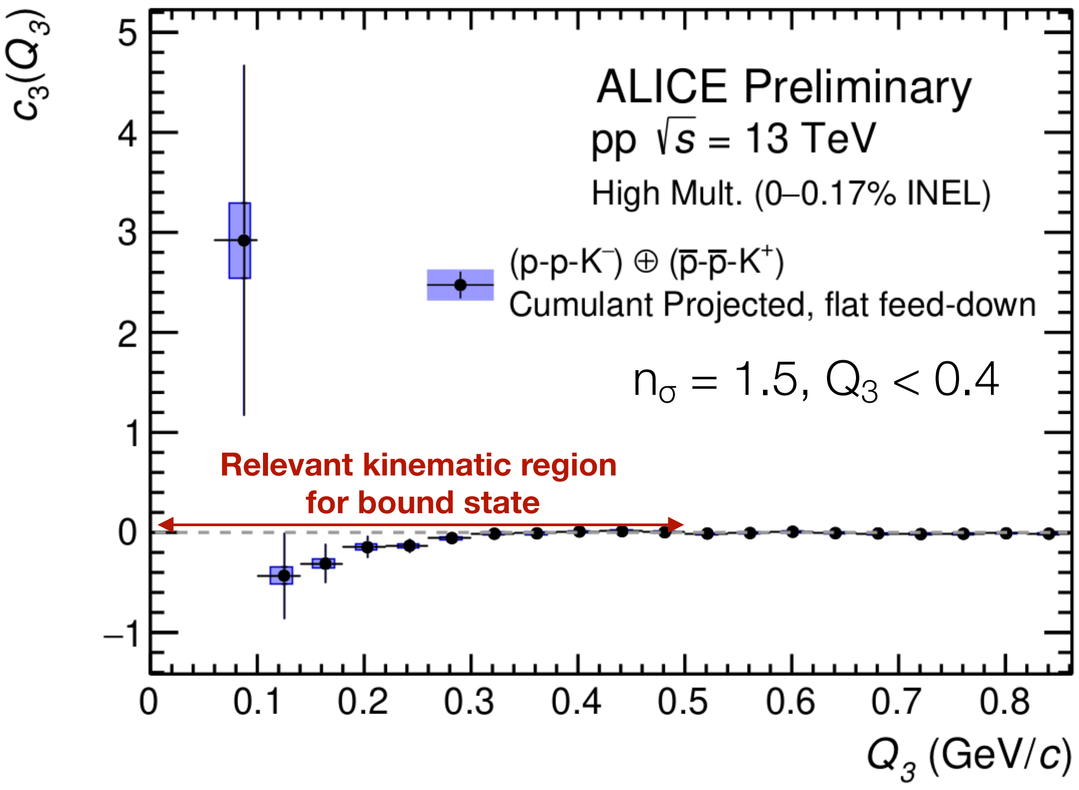


- Positive cumulant and deviation from zero
  → Presence of a genuine 3-body effect
- Main contribution from three-body strong interaction
  → Not there yet but …
- Take-home message:
  → No significant deviation from null hypothesis
  → Final answer in ongoing Run 3 and future Run 4 at LHC with enhanced statistics!

ALICE Coll. arXiv: 2206.03344 nucl-ex

In the meson sector: the p-p-K$^-$ cumulant



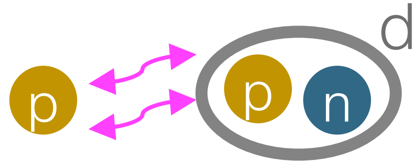


- Zero cumulant in this case
  → No three-body effect

- Take-home message:
  → Cumulant compatible with zero
  → p-p-K- dynamics dominated by two-body interactions
  → Confirming three-body strong interaction should not be relevant in the formation of exotic kaonic bound states!

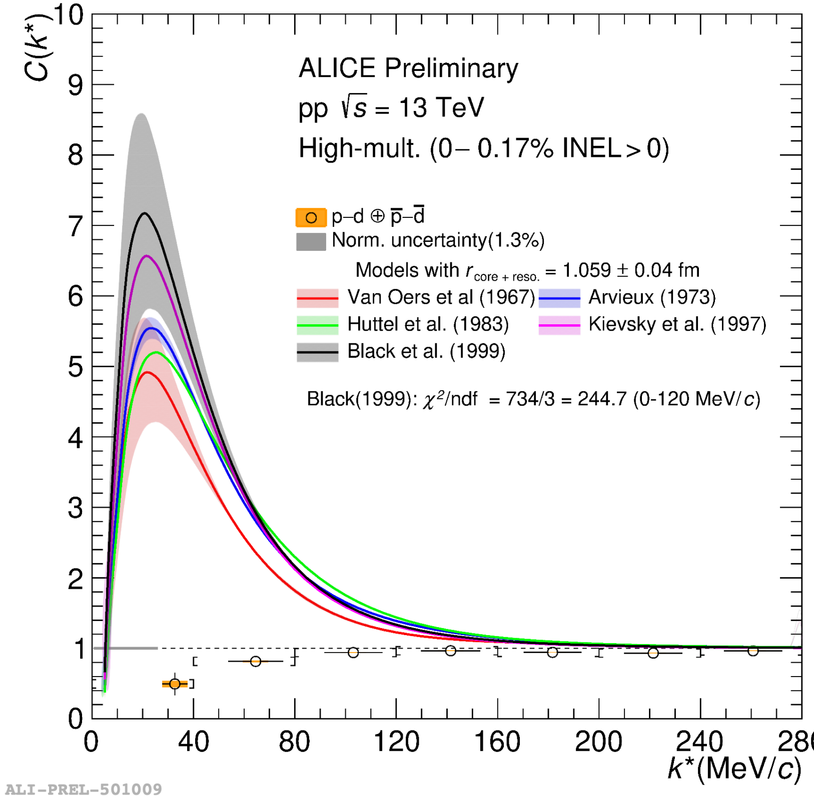
ALICE Coll. arXiv: 2206.03344 nucl-ex

Hadron-deuteron correlations



- Indirect measurements of three body forces via h-d correlations in pp collisions:
  - Presence of a composite object as the deuteron (p,n)
  - Access to spin-isospin NNN dependence
  - Large discrepancy with theoretical CF via Lednicky-Lyuboshits approach(1)
    - p and d as distinguishable point-like particles does not work!
  - Effect of three-body p-(p-n) dynamics must be included (Work in collaboration with Pisa group (2))

  - Theoretical studies in Λd correlations
    J. Haidenbauer Phys.Rev.C 102 (2020)
    - S=1/2 state related to $^3H_\Lambda$ binding energy
    - S=3/2 sensitive to spin-triplet ΛN
    - Dedicated ALICE measurements in Run 3 and 4



(1) *R. Lednicky, Phys. Part. Nuclei 40, 307–352 (2009)*
Van Oers,Brockmann et al. Nucl. Phys. A 561-583 (1967)
J.Arvieux et al. Nucl. Phys. A 221 253-268 (1973)
E.Huttel et al. Nucl. Phys. A 406 443-455 (1983)
A.Kievsky et al. PLB 406 292-296 (1997)
T.C.Black et al. PLB 471 103-107 (1999)
(2) *Kievsky et al, Phys. Rev. C 64 (2001) 024002*
Kievsky et al, Phys. Rev. C 69 (2004) 014002
Deltuva et al, Phys. Rev. C71 (2005) 064003

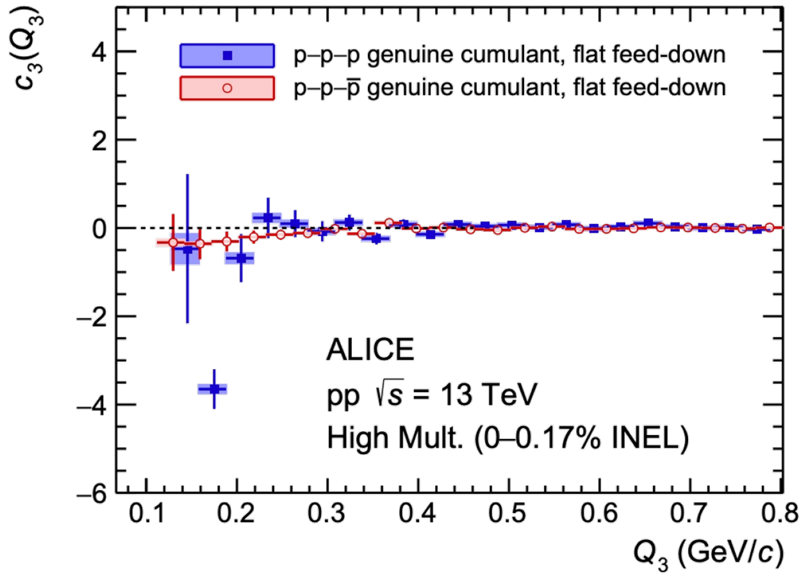
Conclusions and outlooks

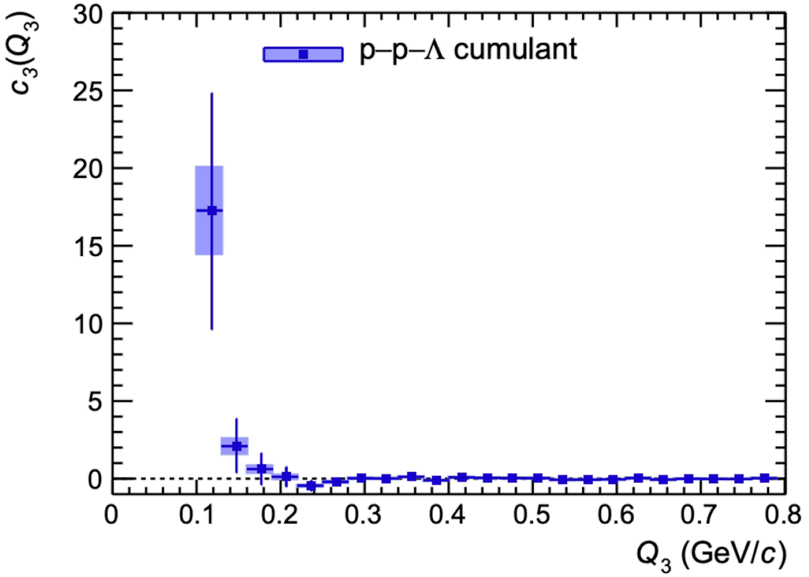
1. Femtoscopy in pp collisions at the LHC applied to triplets
   – Genuine three-body cumulants isolated for the first time using the Kubo's rule

2. p-p-p and p-p-Λ cumulants
   – p-p-p statistically significant negative cumulant, ongoing work for the theoretical interpretation and modeling
   – p-p-Λ not significant yet, Run 3 statistics will determine the nature of the interaction
   – Important ingredient for the physics of neutron stars

3. Similar technique applied to p-p-K$^{\pm}$
   – Kaonic bound state dynamics dominated by 2-body

4. Indirect access to three-body dynamics via hadron-deuteron correlations (p-d,Λ-d) and extension to



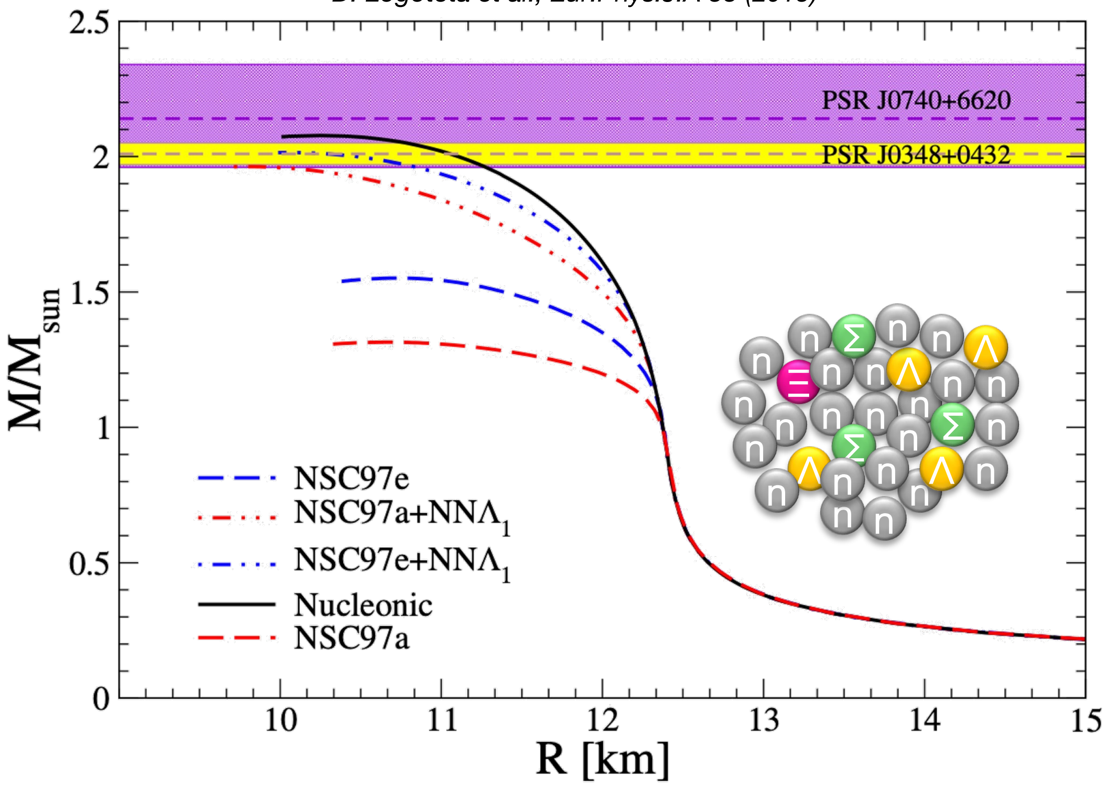


Additional slides

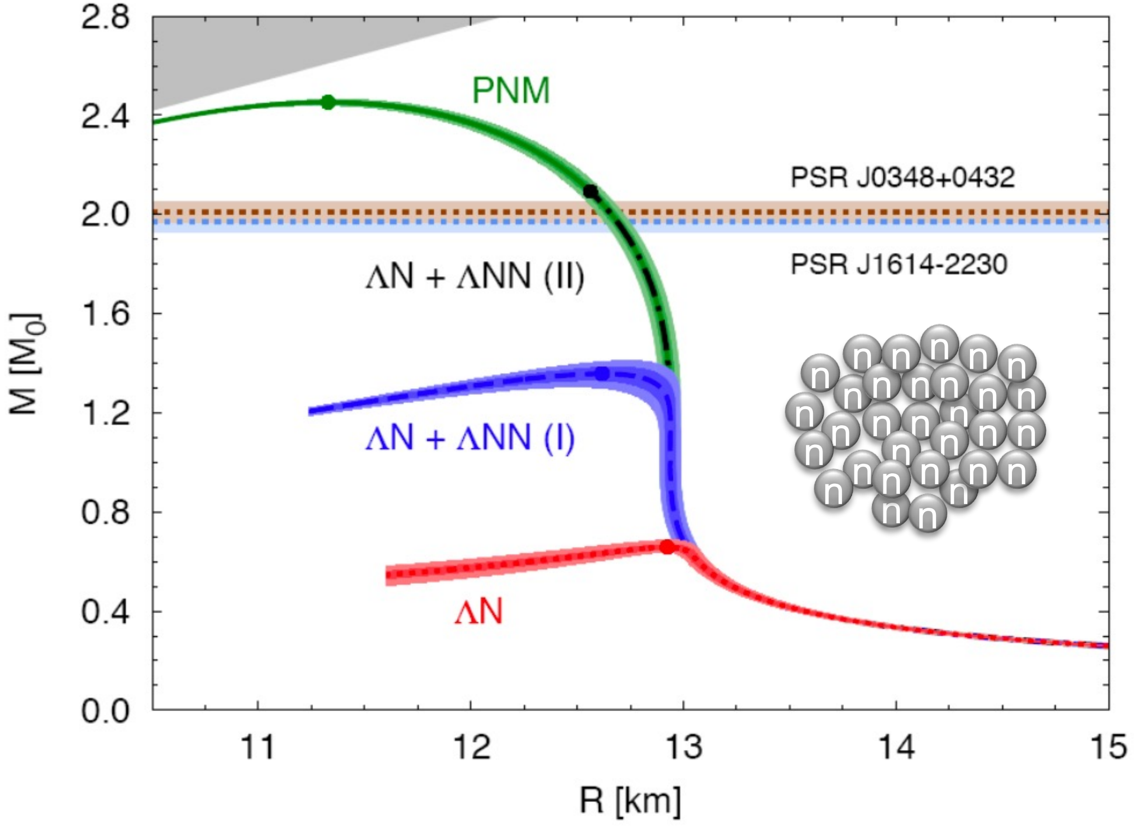
Hyperonic three-body interactions in different EoS

- 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 NS

D. Logoteta et al., Eur.Phys.J.A 55 (2019)



D. Lonardoni et al., PRL 114 (2019)



Hyperonic three-body interactions in different EoS

- Repulsive 3-body ΛNN interaction can stiffen the EoS….but:
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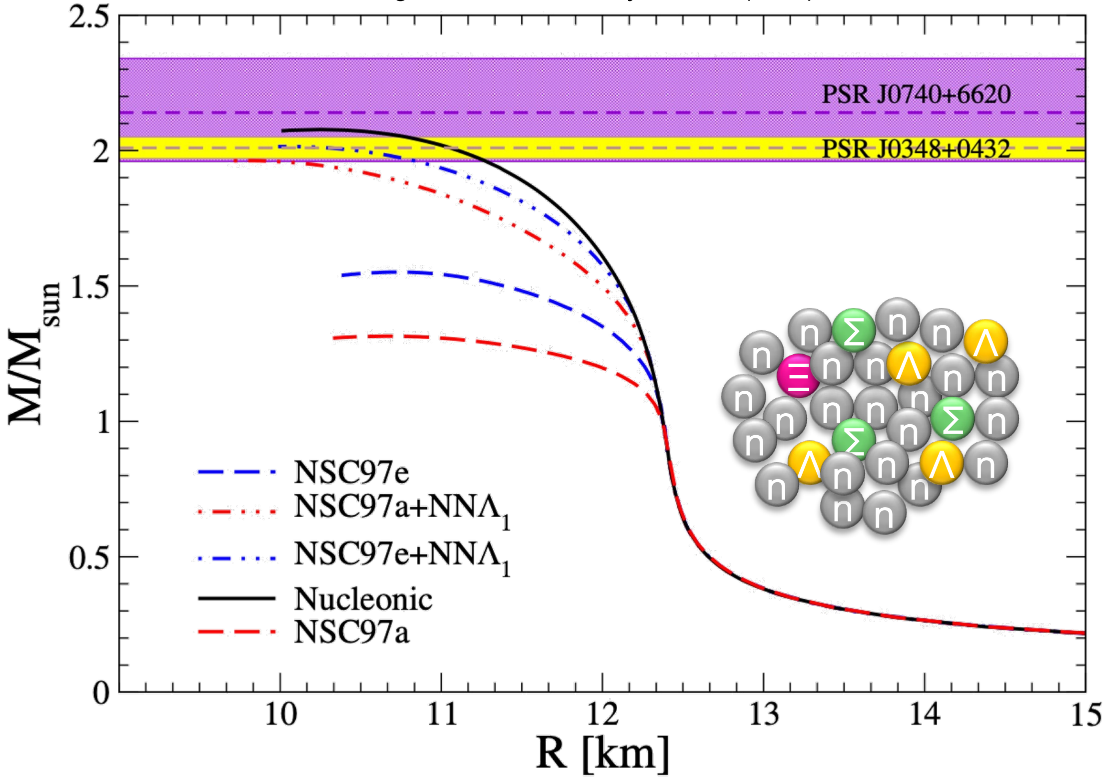
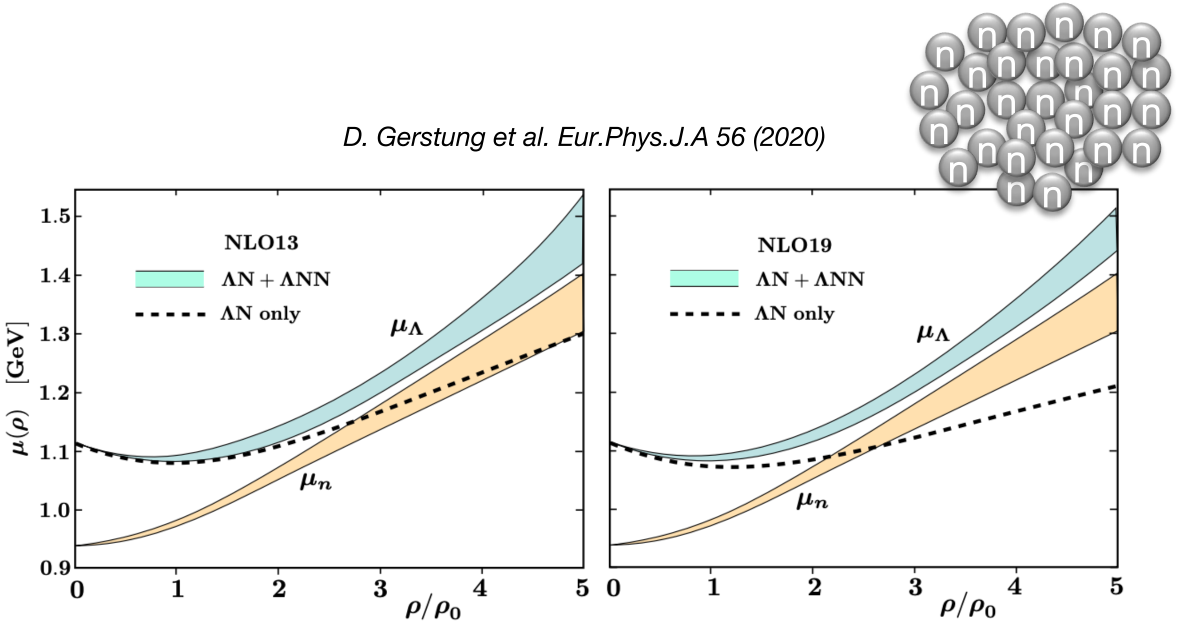
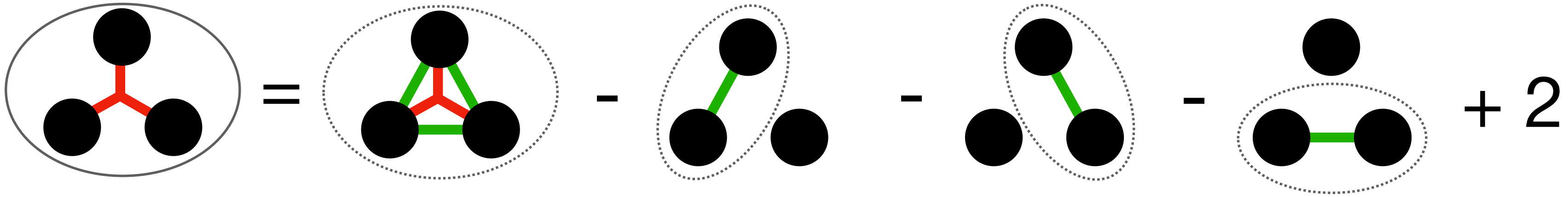
D. Logoteta et al., Eur.Phys.J.A 55 (2019)

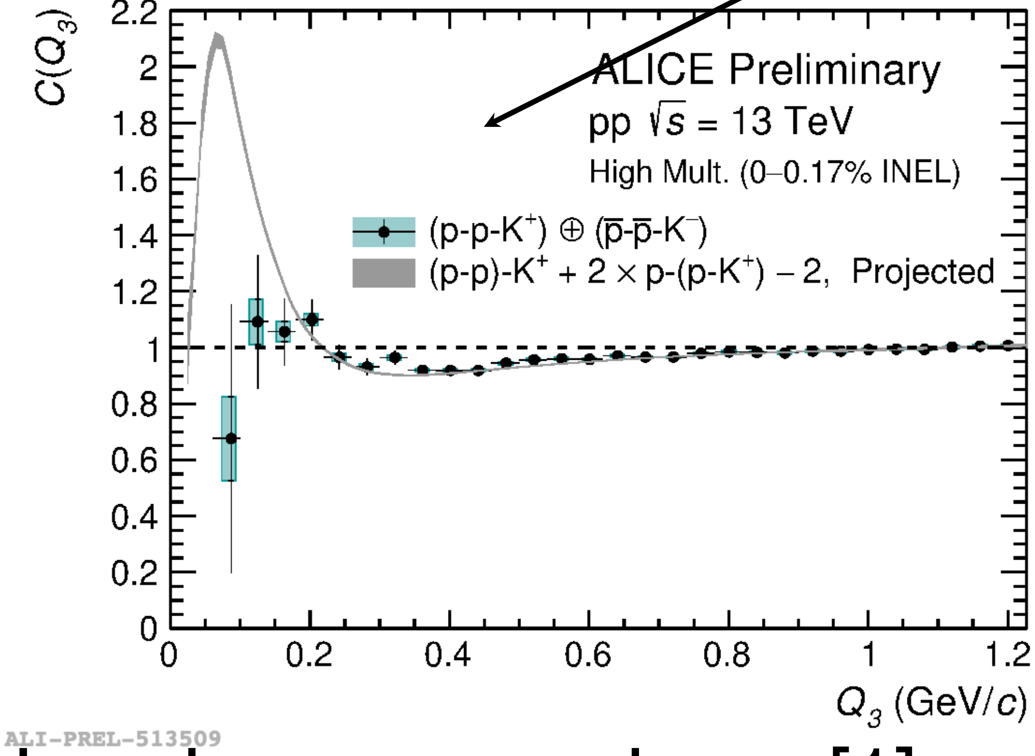


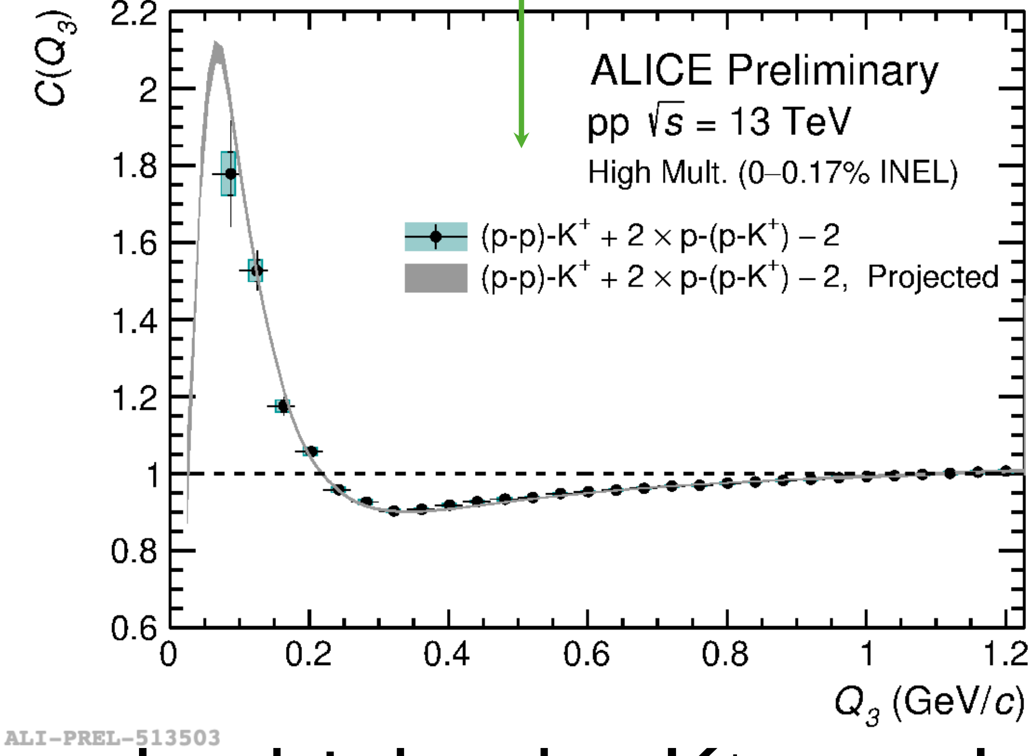
D. Gerstung et al. Eur.Phys.J.A 56 (2020)



p-p-K+ correlation function





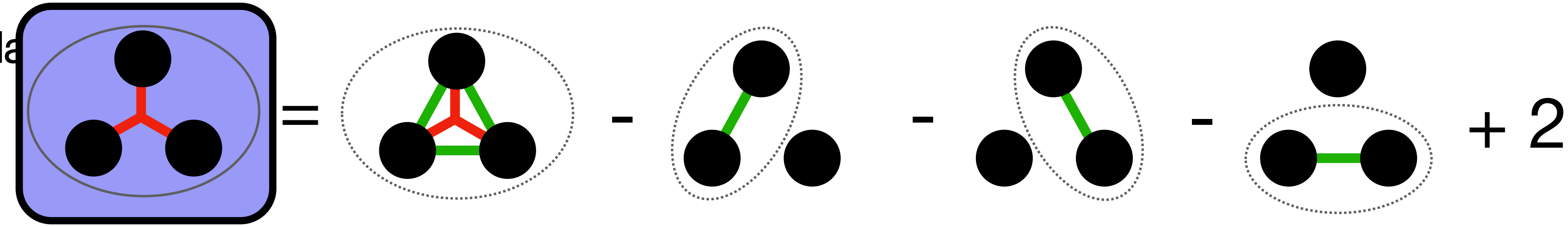


Already measured p-p [1] and newly obtained p-K$^+$ correlation functions used for projection.

[1] PLB 805 (2020) 135419

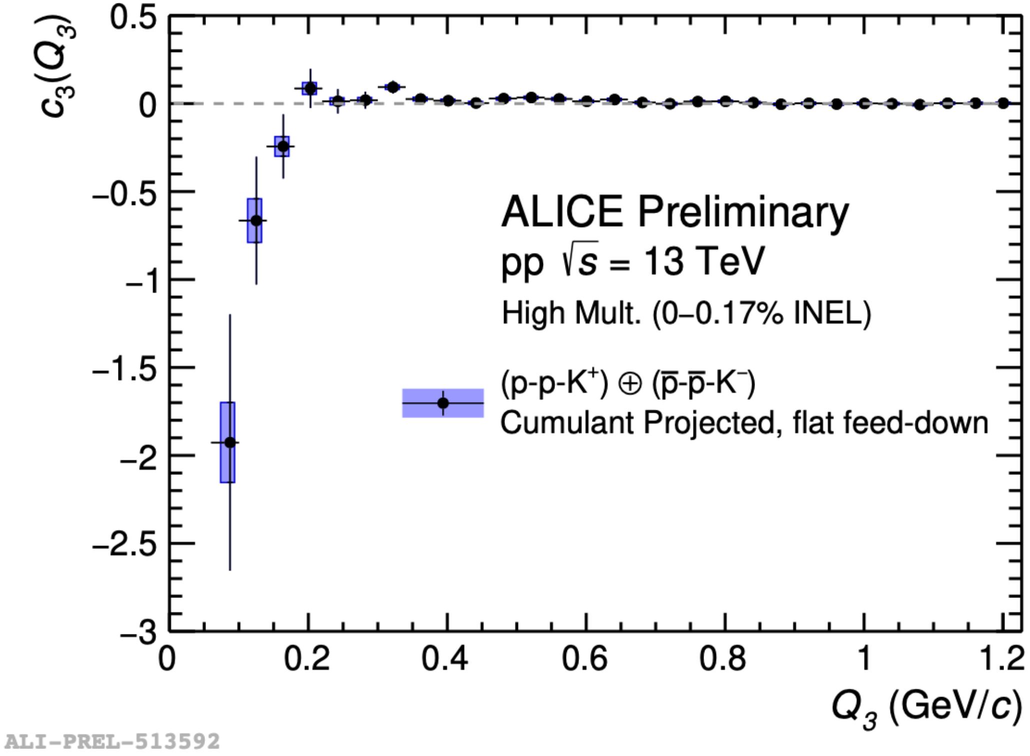
p-p-K$^+$ cumulant

Negative cumula



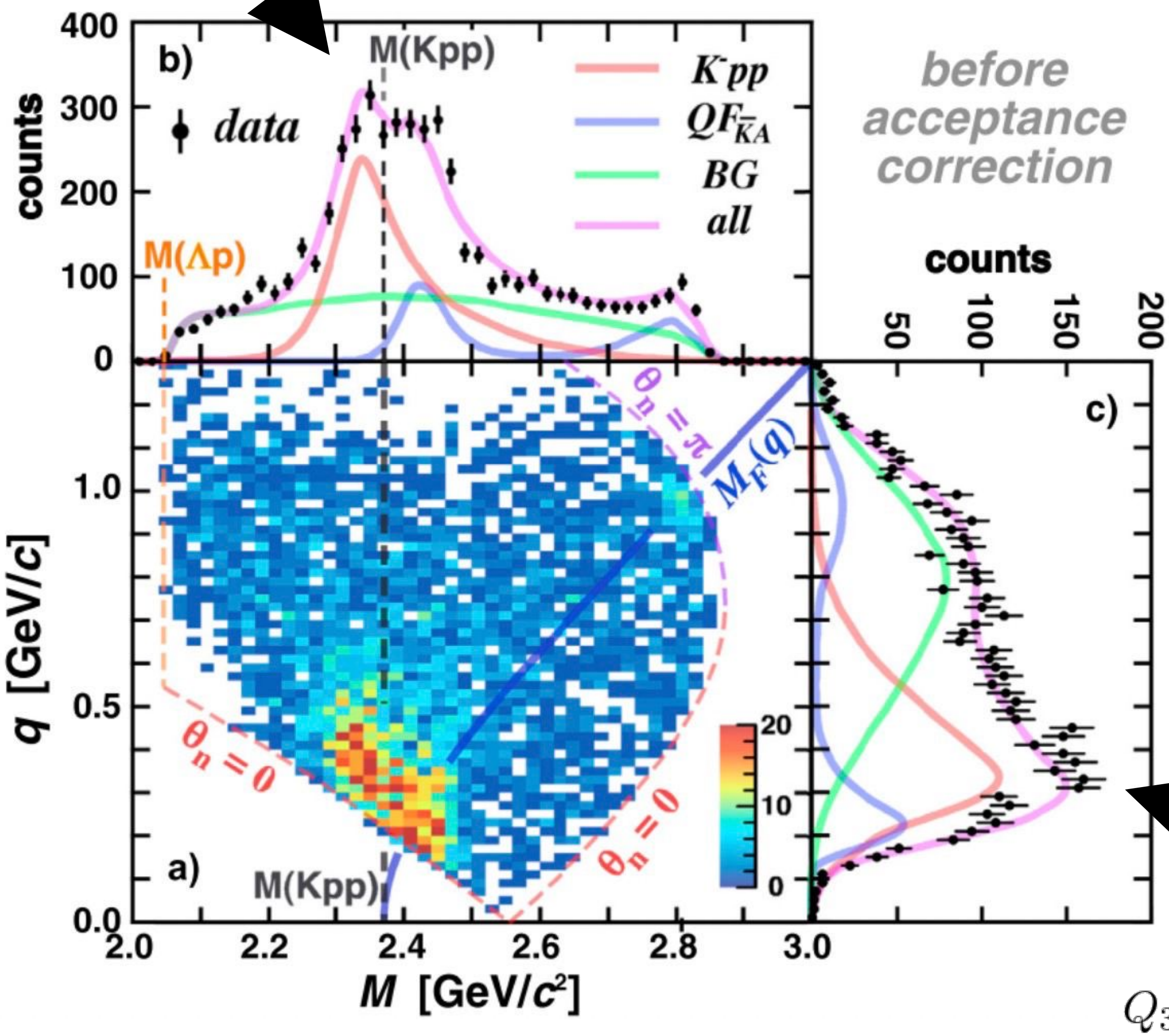
Statistical significance:
n_σ= 2.3 for Q_3 < 0.4 GeV/c

Conclusion: the measured cumulant is compatible with zero within the uncertainties.



Kaonic bound state measured by E15

E15 Coll., PLB 789 (2019) 620



The E15 collaboration measured the bound state via the following decay:

$$K^- + p + p \rightarrow \Lambda + p$$

The Λp momentum distribution has a peak at

$$q = p_\Lambda + p_p \approx 0.35\ \mathrm{GeV}/c$$

Using the momentum conservation:

$$p_{K^-} + p_p + p_p \approx 0.35\ \mathrm{GeV}/c$$

The protons are at-rest → $p_K \approx 0.35$ GeV/c

In terms of Q_3 we have

$$Q_3 = 2\sqrt{k_{\mathrm{pK}}^2 + k_{\mathrm{pK}}^2 + k_{\mathrm{pp}}^2} = 2\sqrt{2}\,k_{\mathrm{pK}} = 4/3\sqrt{2}\,p_K < 0.5\,\mathrm{GeV}/c$$

Lednický model: pointlike deuterons

- For distinguishable pointlike particles
  - Starting from the scattering parameters ⇒ define the s-wave two-particle relative wave function
  - Considers Coulomb effects
  - Assumption: p and d are pointlike particles!

⇒ **p–d scattering parameters** from fits to p–d scattering data

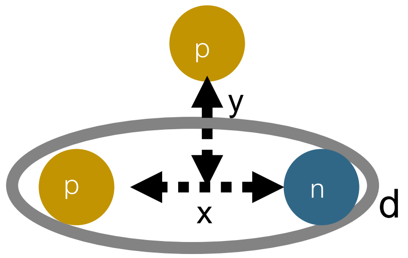
$S = 1/2$		$S = 3/4$		References
f_0(fm)	r_0(fm)	f_0(fm)	r_0(fm)	
$-1.30^{+0.20}_{-0.20}$	—	$-11.40^{+1.80}_{-1.20}$	$2.05^{+0.25}_{-0.25}$	Van Oers et al. [15]
$-2.73^{+0.10}_{-0.10}$	$2.27^{+0.12}_{-0.12}$	$-11.88^{+0.40}_{-0.10}$	$2.63^{+0.01}_{-0.02}$	Arvieux et al. [16]
-4.0	—	-11.1	—	Huttel et al. [17]
-0.024	—	-13.7	—	Kievsky et al. [18]
$0.13^{+0.04}_{-0.04}$	—	$-14.70^{+2.30}_{-2.30}$	—	Black et al. [19]

Convention sign: In this presentation positive (negative) f_0 means attractive (repulsive) interaction

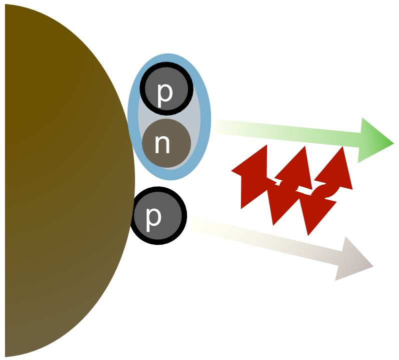
p–d correlation with d as composite object

The three body wave function with proper treatment of 2N and 3N interaction at very short distances goes to a p–d state.

- **Three–body wavefunction for p–d:** $\Psi_{m_2,m_1}(x,y)$ describing three-body dynamics, anchored to p–d scattering observables.
  - x = distance of p-n system within the deuteron
  - y = p-d distance
  - m2 and m1 deuteron and proton spin



- $\Psi_{m_2,m_1}(x,y)$ three-nucleon wave function asymptotically behaves as p–d state:



$$\Psi_{m_2,m_1}(\boldsymbol{x},\boldsymbol{y}) = \underbrace{\Psi^{(\mathrm{free})}_{m_2,m_1}}_{\text{Asymptotic form}} + \underbrace{\sum_{LSJ}^{J\leq\bar{J}} \sqrt{4\pi} i^L \sqrt{2L+1} e^{i\sigma_L} (1 m_2 \tfrac{1}{2} m_1 | S J_z)(L 0 S J_z | J J_z) \widetilde{\Psi}_{LSJJ_z}}_{\text{Strong three-body interaction}} .$$

Asymptotic form Strong three-body interaction

$\tilde{\Psi}_{LSJJ_Z}$ describe the configurations where the three particles are close to each other

$\Psi^{(\mathrm{free})}_{m_1,m_2}$ an asymptotic form of p-d wave function

Kievsky et al, Phys. Rev. C 64 (2001) 024002
Kievsky et al, Phys. Rev. C 69 (2004) 014002
Deltuva et al, Phys. Rev. C71 (2005) 064003

p–d correlation with d as composite object

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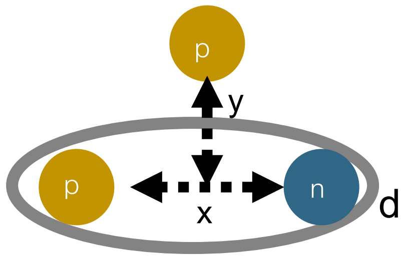
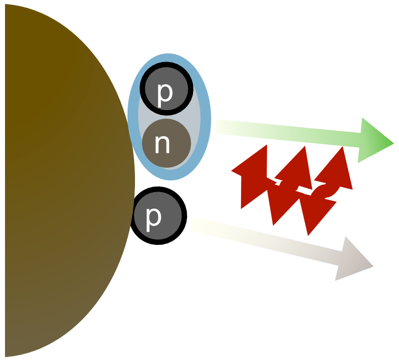


- $\Psi_{m_2,m_1}(x,y)$ three-nucleon wave function asymptotically behaves as p–d state:

$$\Psi_{m_2,m_1}(\boldsymbol{x},\boldsymbol{y}) = \Psi^{(\text{free})}_{m_2,m_1} + \sum_{LSJ}^{J\leq\bar{J}} \sqrt{4\pi}\, i^L \sqrt{2L+1}\, e^{i\sigma_L} (1 m_2 \tfrac{1}{2} m_1 | S J_z)(L 0 S J_z | J J_z) \widetilde{\Psi}_{LSJJ_z} \, .$$

Asymptotic form Strong three-body interaction



$\rightarrow \tilde{\Psi}_{LSJJ_Z}$ describe the configurations where the three particles are close to each other

$\rightarrow \Psi^{(\text{free})}_{m_1,m_2}$ an asymptotic form of p-d wave function

Kievsky et al, Phys. Rev. C 64 (2001) 024002
Kievsky et al, Phys. Rev. C 69 (2004) 014002
Deltuva et al, Phys. Rev. C71 (2005) 064003

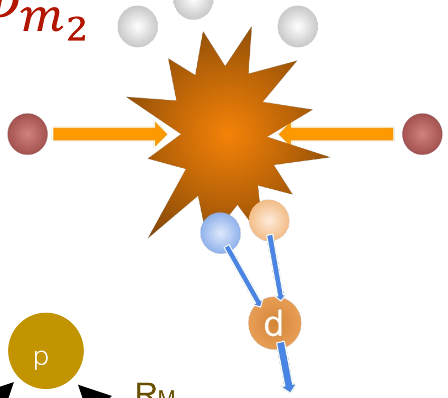
The correlation function

- **Starting with the PPN state that goes into pd state**:
  - Nucleons with the Gaussian sources distributions

Single-particle Gaussian emission source

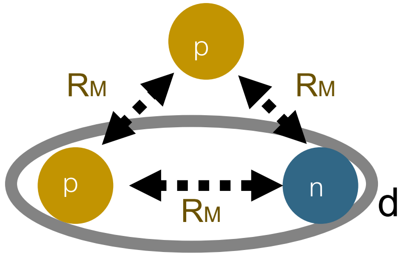
$$A_d C_{pd}(k) = \frac{1}{6} \sum_{m_2,m_1} \int d^3r_1 d^3r_2 d^3r_3 \, S_1(r_1) S_1(r_2) S_1(r_3) |\Psi_{m_2,m_1}|^2 \, ,$$

  - Where A_d is the deuteron formation probability using deuteron wavefunction ϕ_{m_2}



$$A_d = \frac{1}{3} \sum_{m_2} \int d^3r_1 d^3r_2 \, S_1(r_1) S_1(r_2) |\phi_{m_2}|^2 \, ,$$

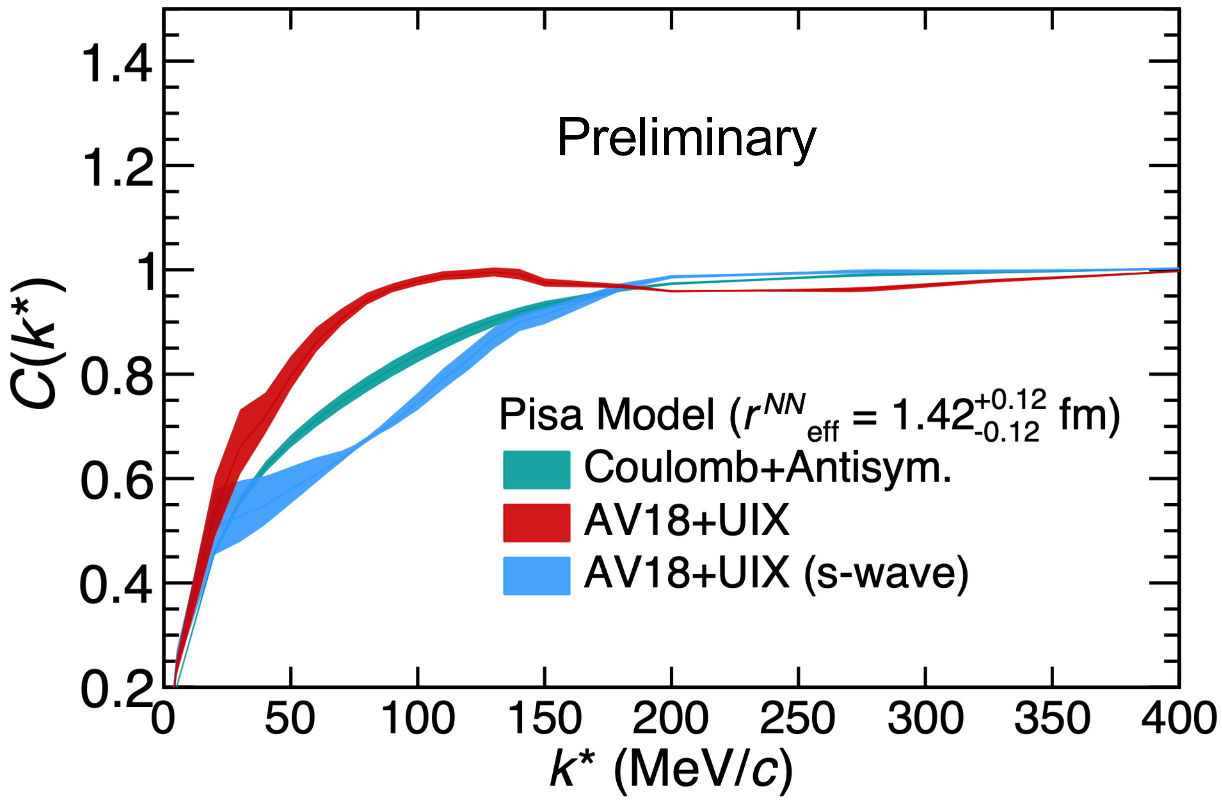
  - Final definition of the correlation with p–p source size R_M :



$$A_d C_{pd}(k) = \frac{1}{6} \sum_{m_2,m_1} \int \rho^5 d\rho d\Omega \, \frac{e^{-\rho^2/4R_M^2}}{(4\pi R_M^2)^3} |\Psi_{m_2,m_1}|^2 \, .$$

Mrówczyński et al *Eur. Phys. J. Special Topics 229, 3559 (2020)*

PISA model: theoretical p-d correlation



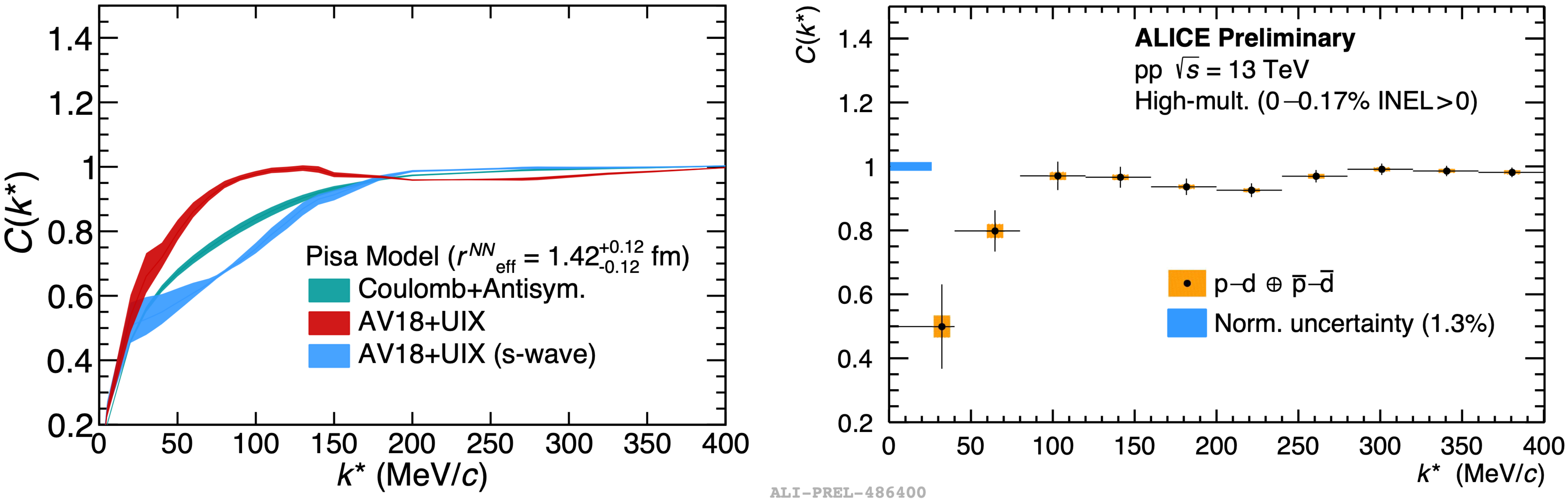
Calculation by Michele Viviani

Model including NN and NNN interactions in s+d-wave

- Coulomb interaction not enough
- Coulomb +s+p+d wave:

Source size = 1.08±0.06 fm ⇒ 1.42±0.12 fm of pp source size

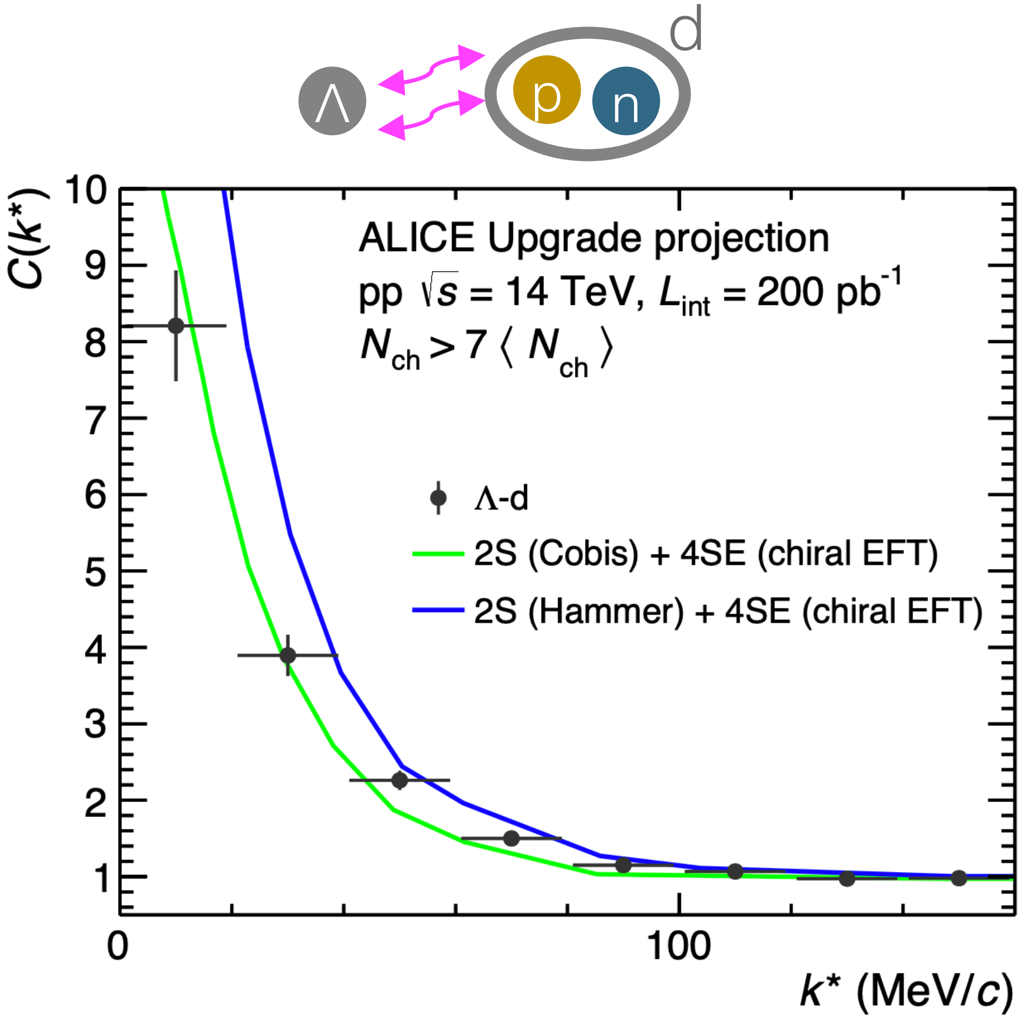
PISA model: theoretical p-d correlation



- Model calculation qualitatively reproduces the data
- The p-d correlation is affected by two + three-body p-p-n interactions!

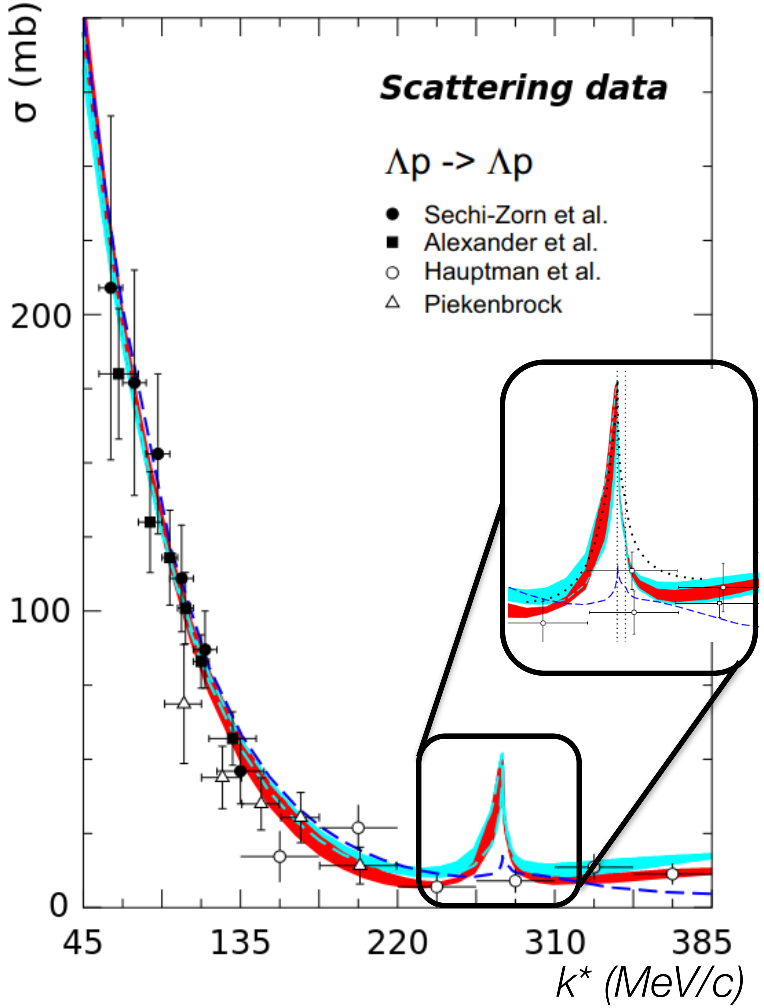
Deuteron–Λ correlations

- Explorative theoretical studies by J. Haidenbauer, arXiv:2005.05012
- Scattering parameters of the doublet state can be related to hypertriton $^3H_\Lambda$ binding energy
  - Synergy with direct hypertriton measurements
- Quartet state depends on the spin triplet Λ–N interaction
  - No experimental information on the spin dependence of the Λ-N interaction
  - Quartet becomes dominant for large source sizes
- Measurement in Run 2 ongoing, improved precision beyond!



ALICE Collab., Physics motivations for a high energy pp programme in ALICE after LS2
A. Cobis *et al.*, J. Phys. G 23 (1997) 401
H. Hammer, Nucl. Phys. A 705 (2002) 173
J. Haidenbauer, arXiv:2005.05012

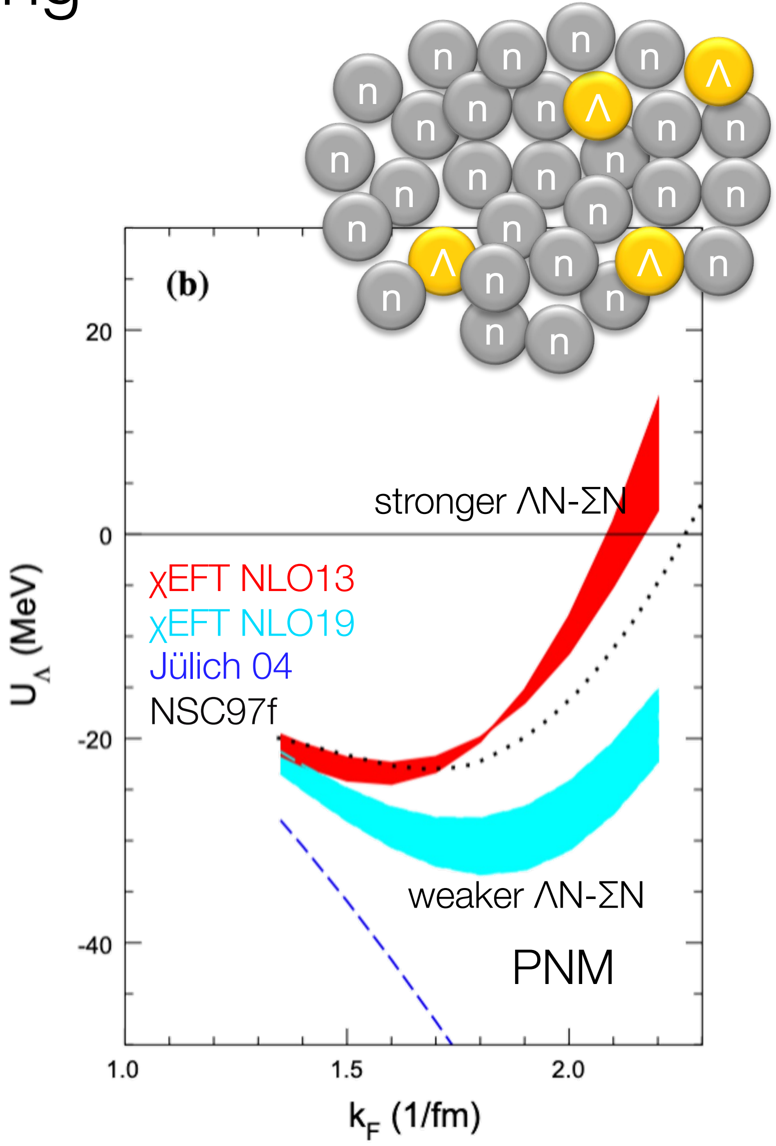
The ΛN interaction and the role of ΣN coupling



- ΣN coupling strength relevant for EoS

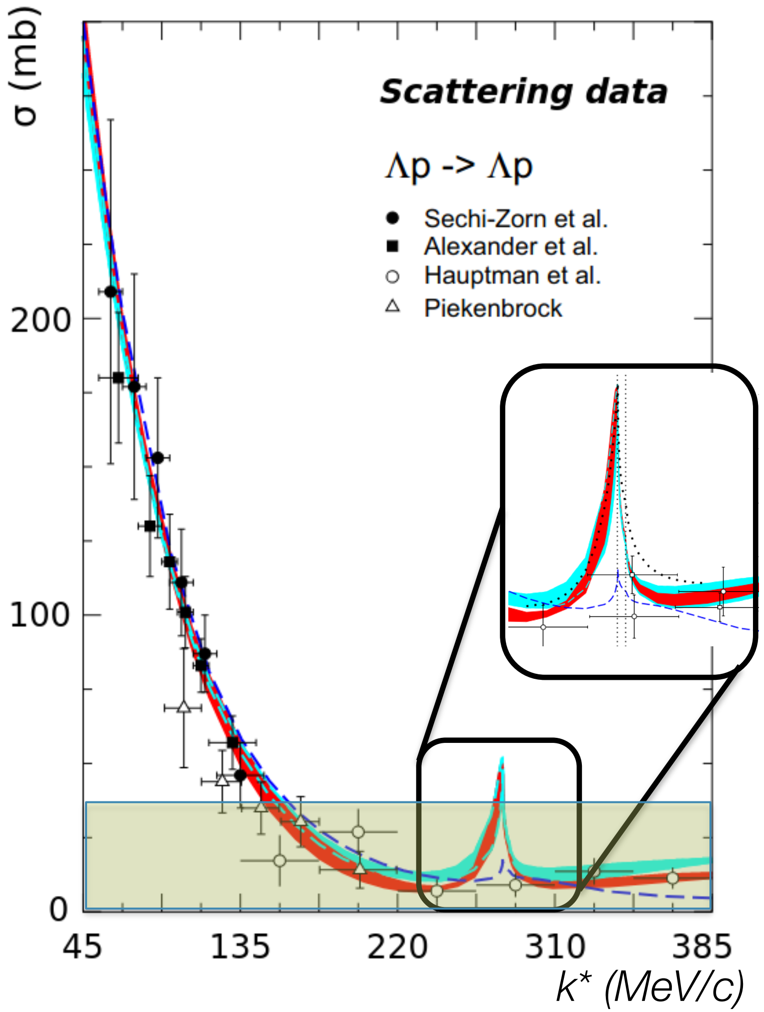
  →deeply affects the behaviour of Λ at finite density

  →implications for 3-body interactions[(*)]

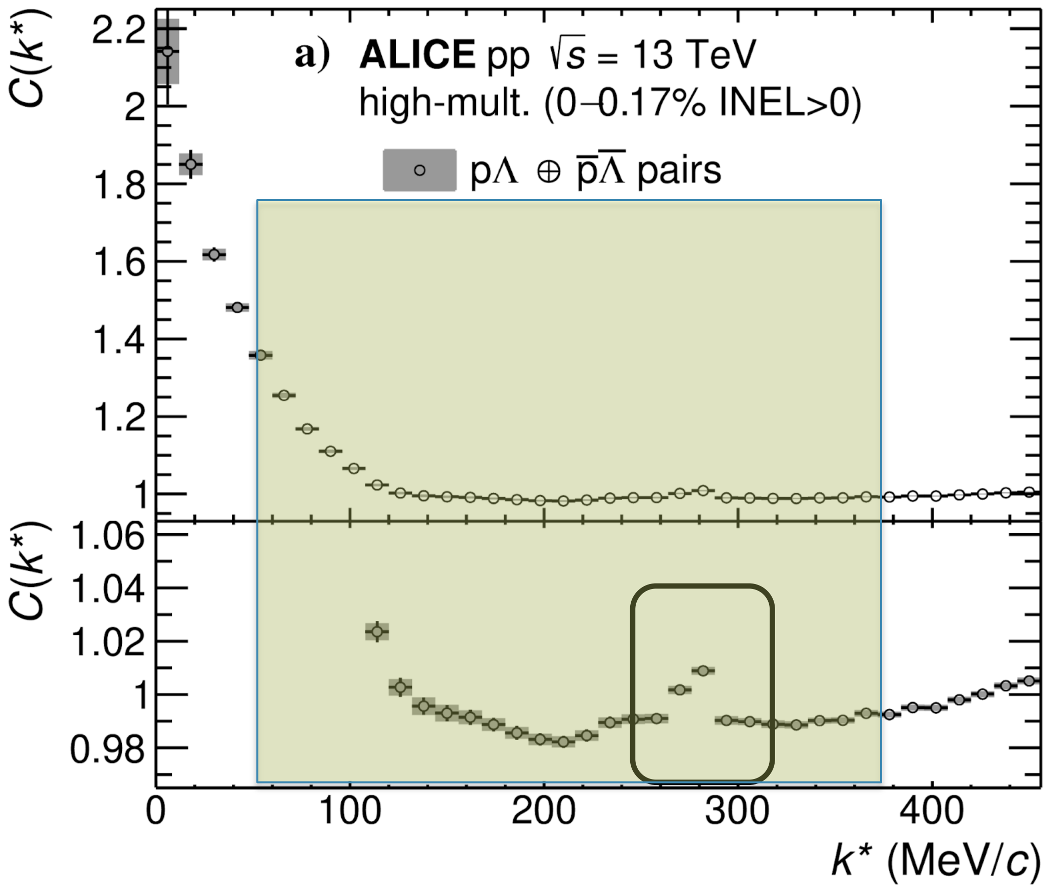


NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)
NLO19: J.Haidenbauer, U. Meißner, Eur.Phys.J.A 56 (2020)
(*)D. Gerstung et al. Eur.Phys.J.A 56 (2020) 6, 175

High-precision data on ΛN-ΣN interaction at LHC



- Extension of kinematic range
- Measurement down to zero momentum
- Factor 20 improved precision in data (<1%)
- First experimental evidence of ΣN cusp in 2-body channel



NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)
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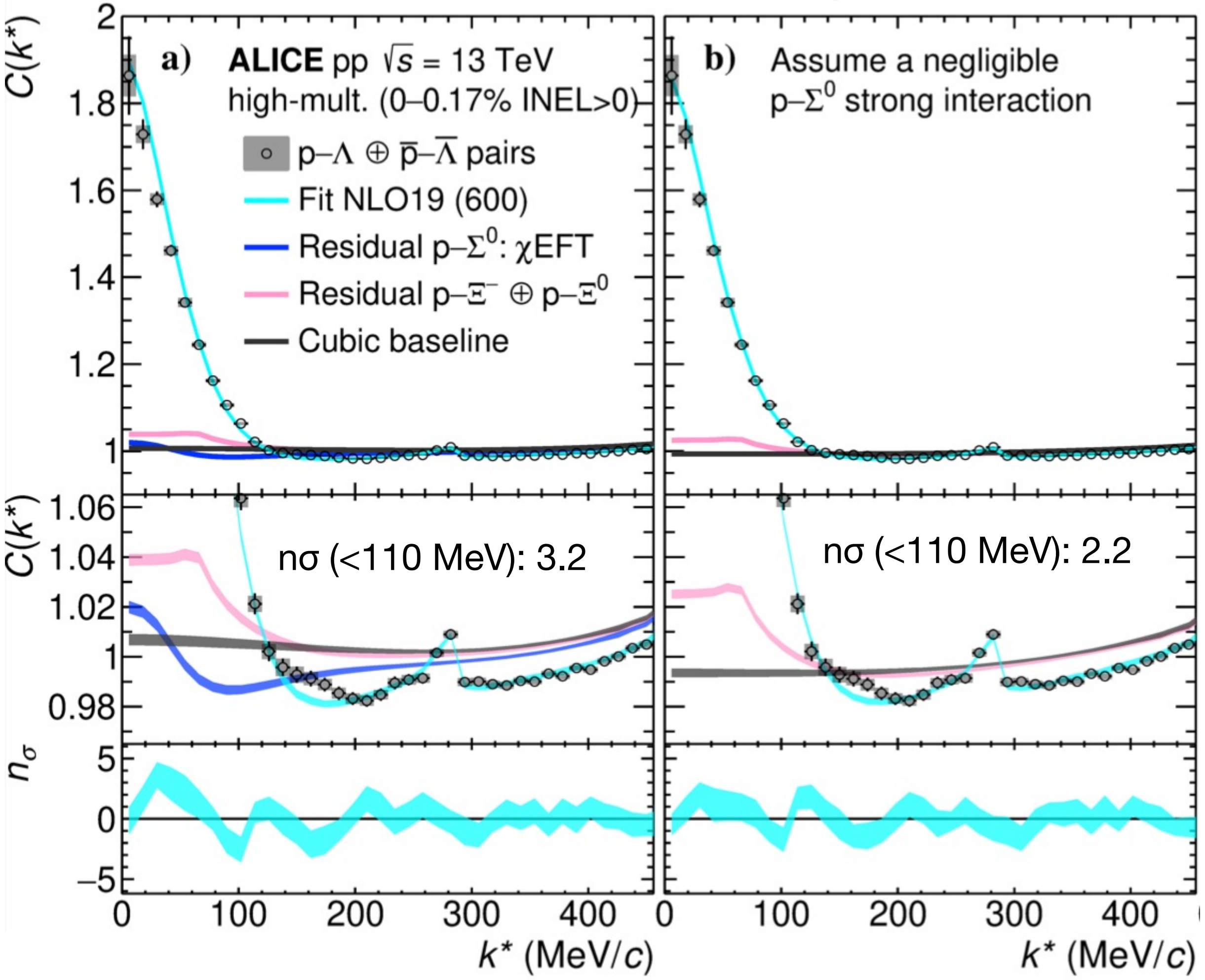
(*)D. Gerstung et al. Eur.Phys.J.A 56 (2020) 6, 175

High-precision data on ΛN-ΣN interaction at LHC

- New scenario arising for ΛN-ΣN interaction
  - NLO19 potentials favoured
    →weaker ΛN-ΣN coupling
    →large attraction of Λ at large densities
    → ΛNN large repulsion needed: no hyperons![1]
  - shallow p-Σ^0 interaction favoured, in agreement with measured p-Σ^0 correlation[2]
  - Future useful measurements:
    →pΣ^0, p$\Sigma^{+,-}$[3], Λd correlations in LHC Run 3 and Run 4
    →p$\Sigma^{+,-}$ scattering data J-PARC E40

What about more strange hyperons?



ALICE Coll. PLB 833 (2022), 137272

(1) D. Gerstung et al. Eur.Phys.J.A 56 (2020) 6, 175
(2) ALICE Coll. PLB 805 (2020) 135419
(3) J. Haidenabauer, U.G. Meißner PLB 829 (2022)

Comparison with χEFT potentials

- Reduction of attraction in $^3S_1$ improve the description of the data both at low k* and in the ΣN cusp region: nσ=1.9 (negl. pΣ)
- Slight sensitivity to CSB inclusion in singlet state

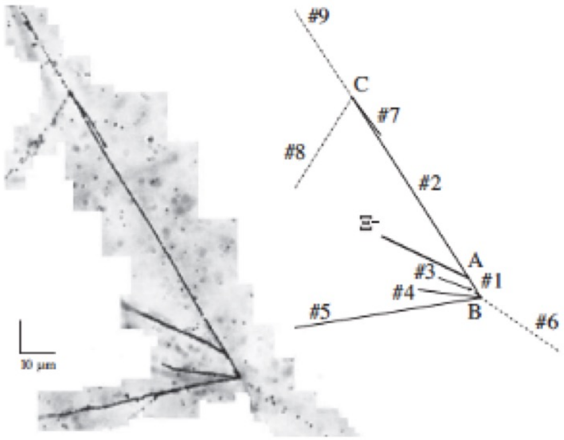
	Standard deviation (n_σ)	
p–Σ^0 (→) p–Λ (↓)	**χEFT**	Negligible FSI
LO13-600	5.6 (7.5)	10.2 (10.3)
NLO13-500	7.3 (10.3)	4.5 (5.3)
NLO13-550	4.4 (6.5)	2.1 (2.2)
NLO13-600	5.8 (5.8)	3.3 (3.6)
NLO13-650	5.5 (5.5)	4.2 (5.0)
NLO19-500	5.6 (7.2)	3.0 (3.0)
NLO19-550	4.5 (4.3)	1.8 (2.2)
NLO19-600	3.7 (3.9)	1.6 (3.0)
NLO19-650	3.7 (3.7)	2.3 (4.1)

Effect of Ξ hyperon in neutron stars

- U_Ξ plays a crucial role in the EoS of NSs
  → repulsive single-particle pot. stiffens the EoS

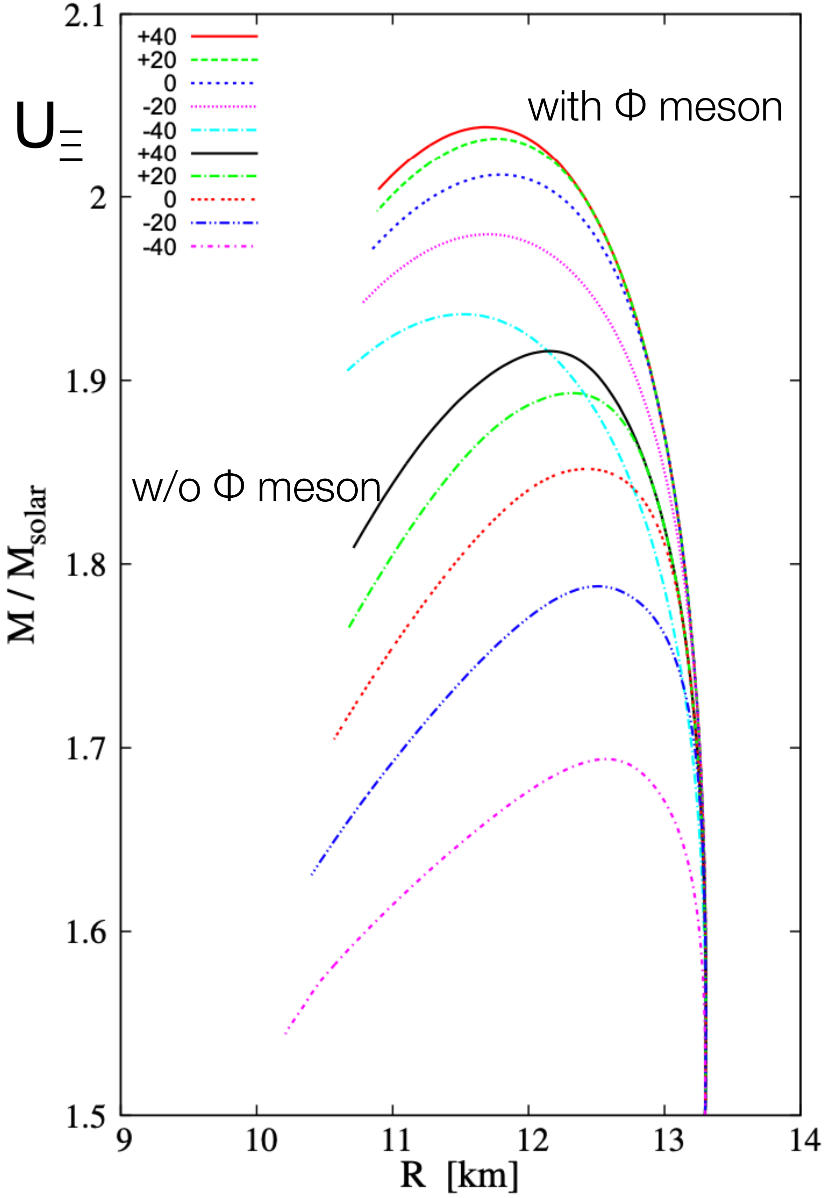
- continuous effort in hypernuclei measurements at J-PARC (E07, S-2S,)

IBUKI event



J-PARC E07 Coll. PRL 126 (2021)

- What about the NΞ interaction in vacuum?

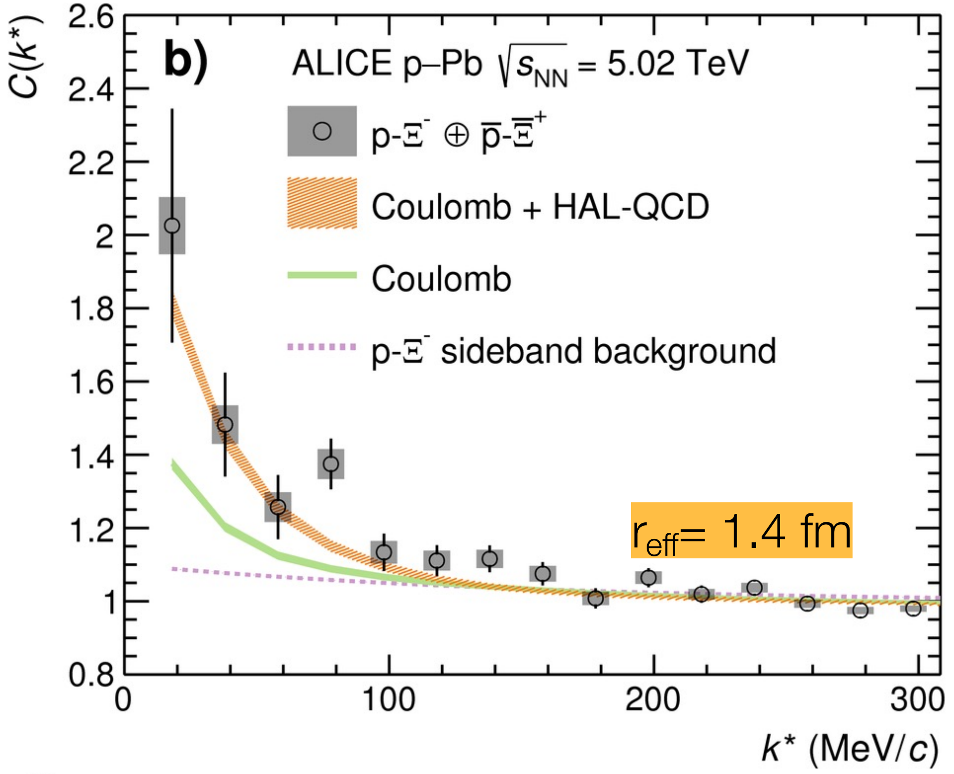


Weissenborn et al.,Nucl.Phys.A 881 (2012)

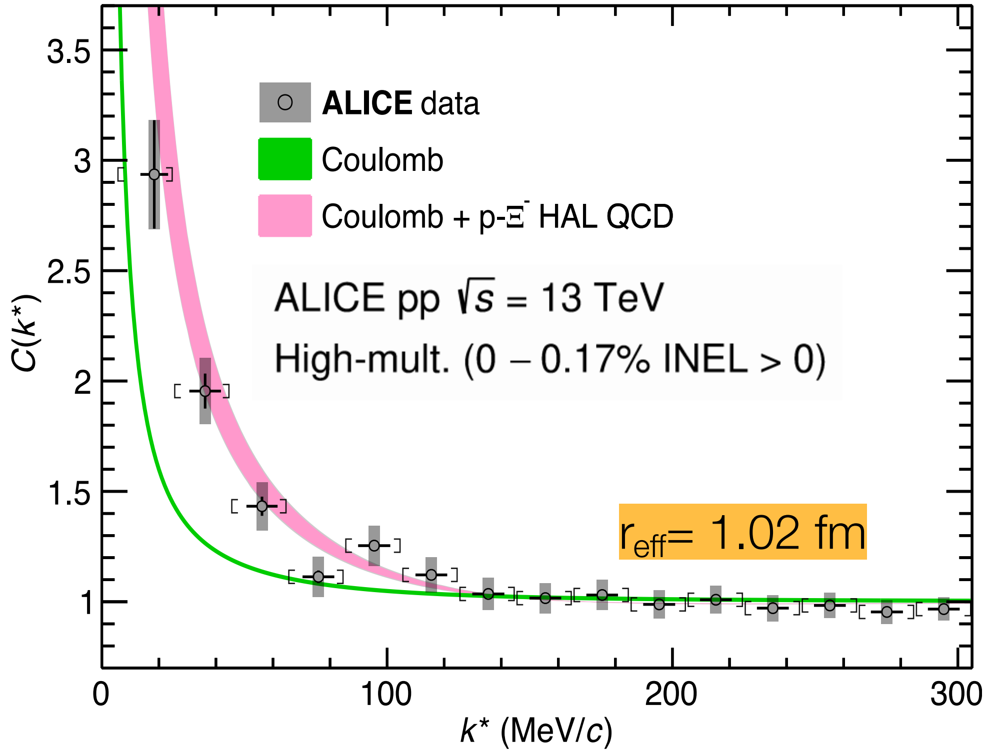
First measurements of the p-Ξ⁻ interaction at LHC

- Observation of the strong interaction beyond Coulomb
- Agreement with lattice calculations confirmed in pp and p-Pb colliding systems
- **At finite density HAL QCD potentials predict in PNM a slightly repulsive U_{Ξ} ~+6 MeV(*) → stiffening of the EoS**

ALICE Coll, Phys. Rev. Lett 123, (2019) 112002



ALICE Coll. Nature 588, 232–238 (2020)

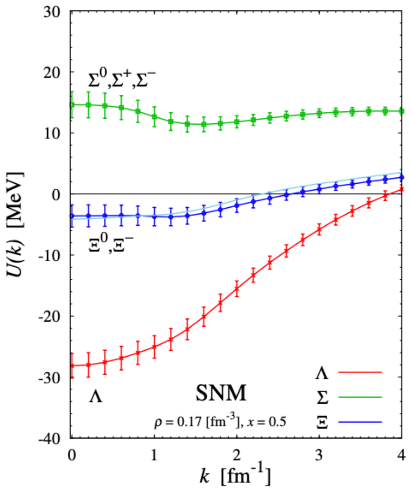


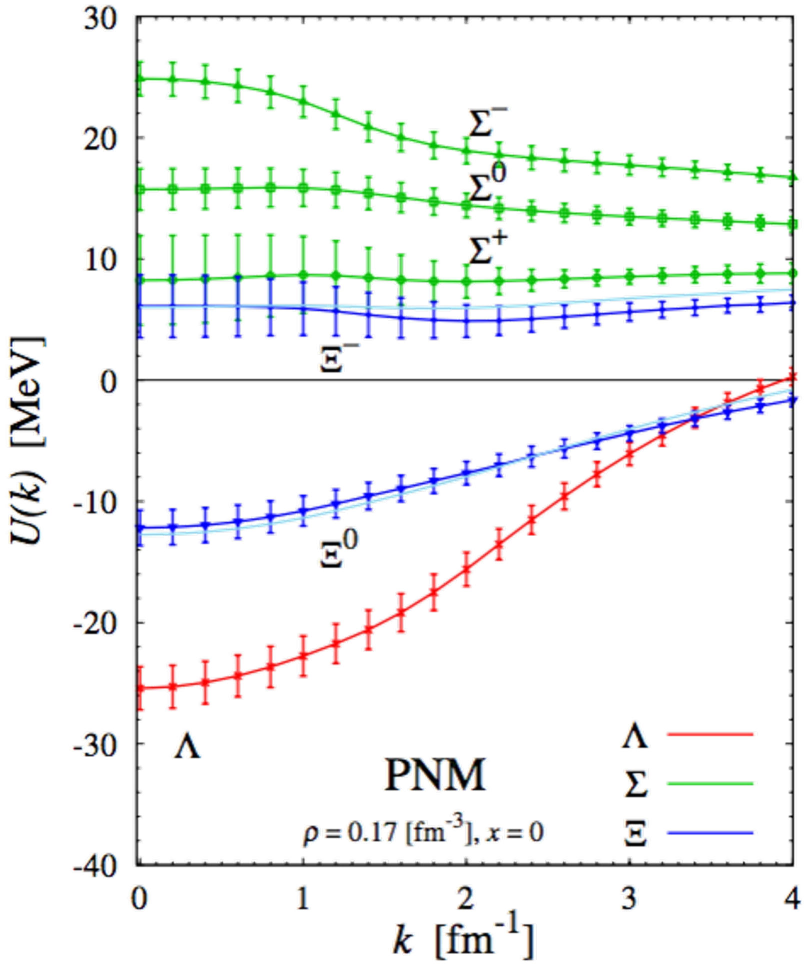
(*) HAL QCD Coll., PoS INPC2016 (2016) 277

Ξ single particle potential from HAL QCD calculations

HAL-QCD Collaboration, arXiv:1809.08932 (2018)

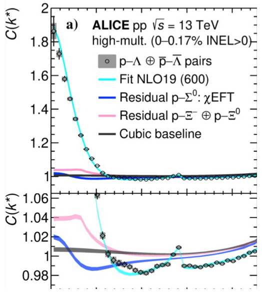
- NS environment ⇒ Pure Neutron Matter
- Tested HAL-QCD potential in vacuum with ALICE ⇒ Brueckner-Hartree-Fock many-body calculations ⇒ U_Y single-particle potential of hyperons in nucleonic matter
- At saturation density in PNM: U_{Ξ^-} slightly repulsive
- in SNM:

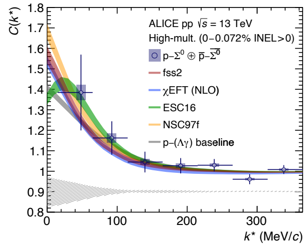


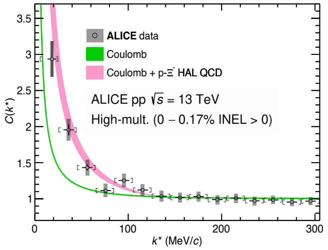


Towards a solution for the puzzle?

Correlation
2-body interaction
(sc. exp, hypernuclei)

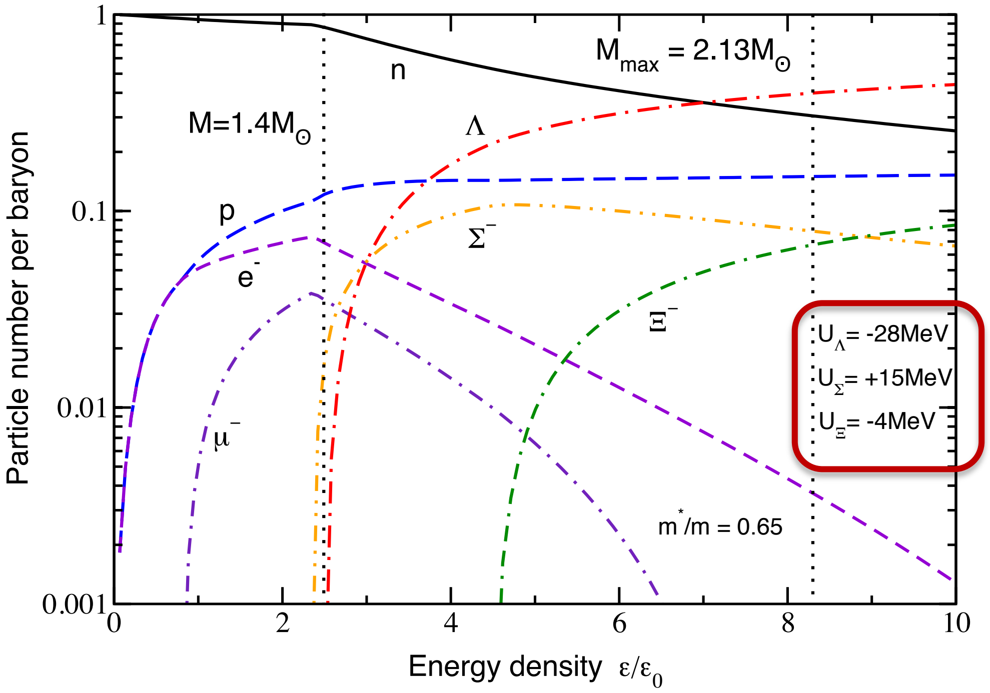






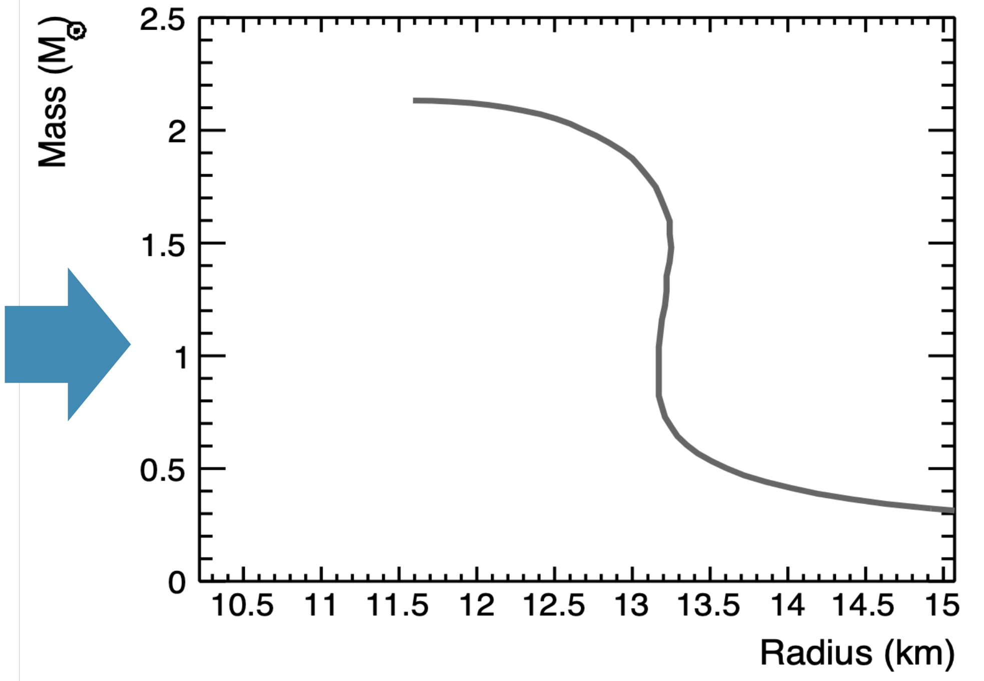
Single-partical potentials
EoS

Courtesy J. Schaffner-Bielich 2020



Mass vs Radius relation
for hyperon stars

Courtesy J. Schaffner-Bielich and B. Dönigus 2020



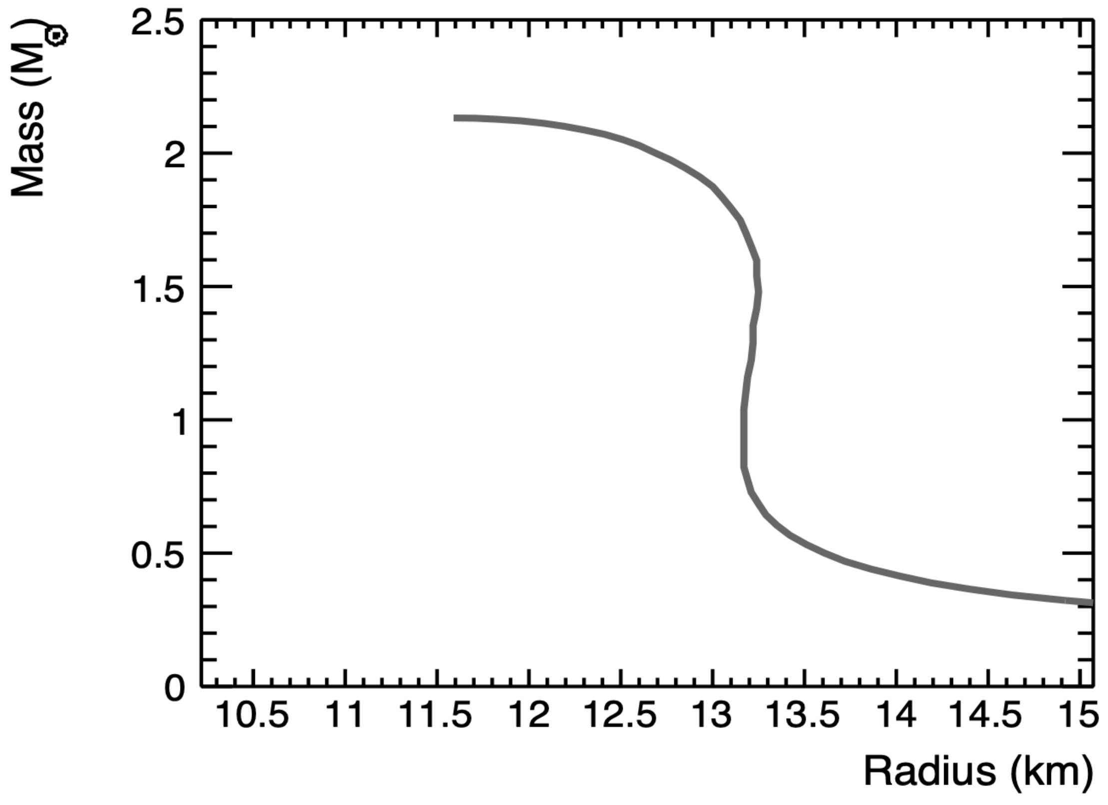
This is only an example.
Experimental uncertainties need to be propagated and some interactions are missing …

V. M. S., L. Fabbietti and O. Vazquez-Doce Ann.Rev.Nucl.Part.Sci. 71 (2021)
S. Weissenborn et al., J. NPA 881 (2012)
J. Schaffner-Bielich, I. Mishustin, PRC 53 (1996)
N. Hornick et al., PRC 98 (2018)

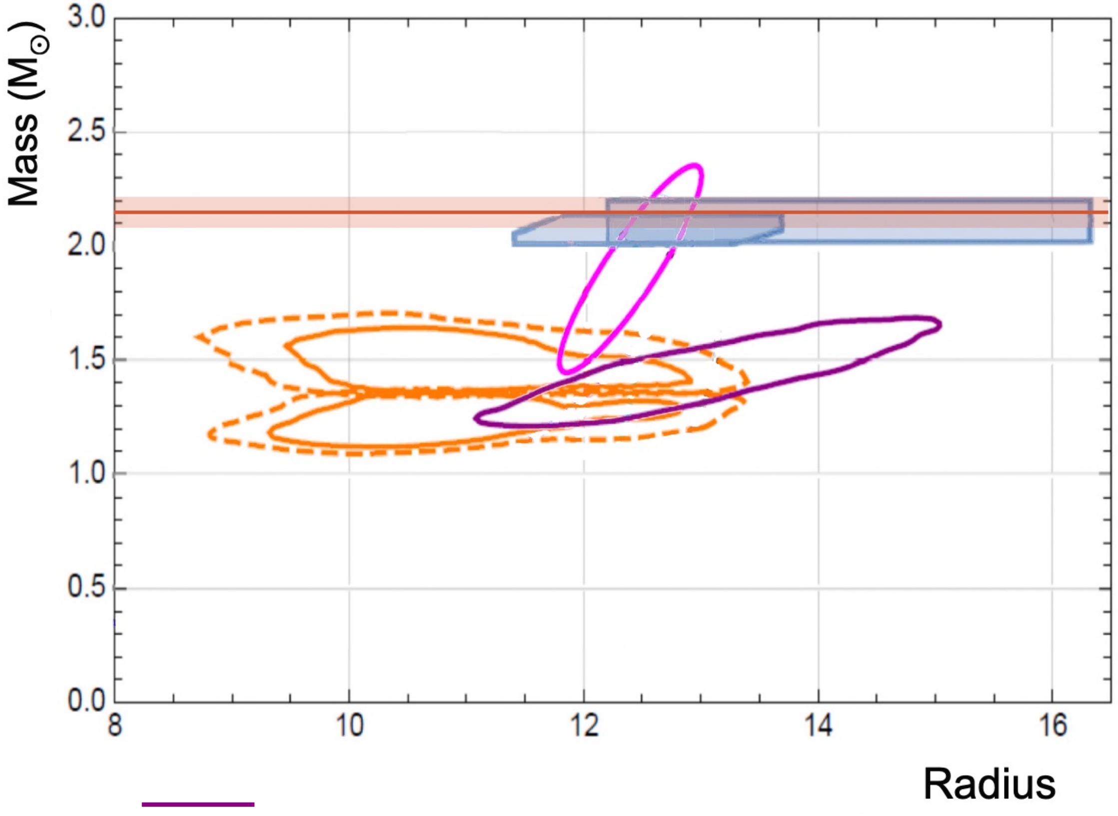
Test of the hyperon equation of state

Mass vs Radius relation
for hyperon stars

Courtesy J. Schaffner-Bielich and B. Dönigus 2020



Mass and Radius measurements
from astrophysics



NICER experiment: M.C Miller et al. AJL 918 (2021)

Mass measurement: H. T. Cromartie et al. Nature Astron. 4 (2019)

Gravitational waves data: B. P. Abbott et al. PRL 119 (2017)

First measurement of the pΣ^0 interaction

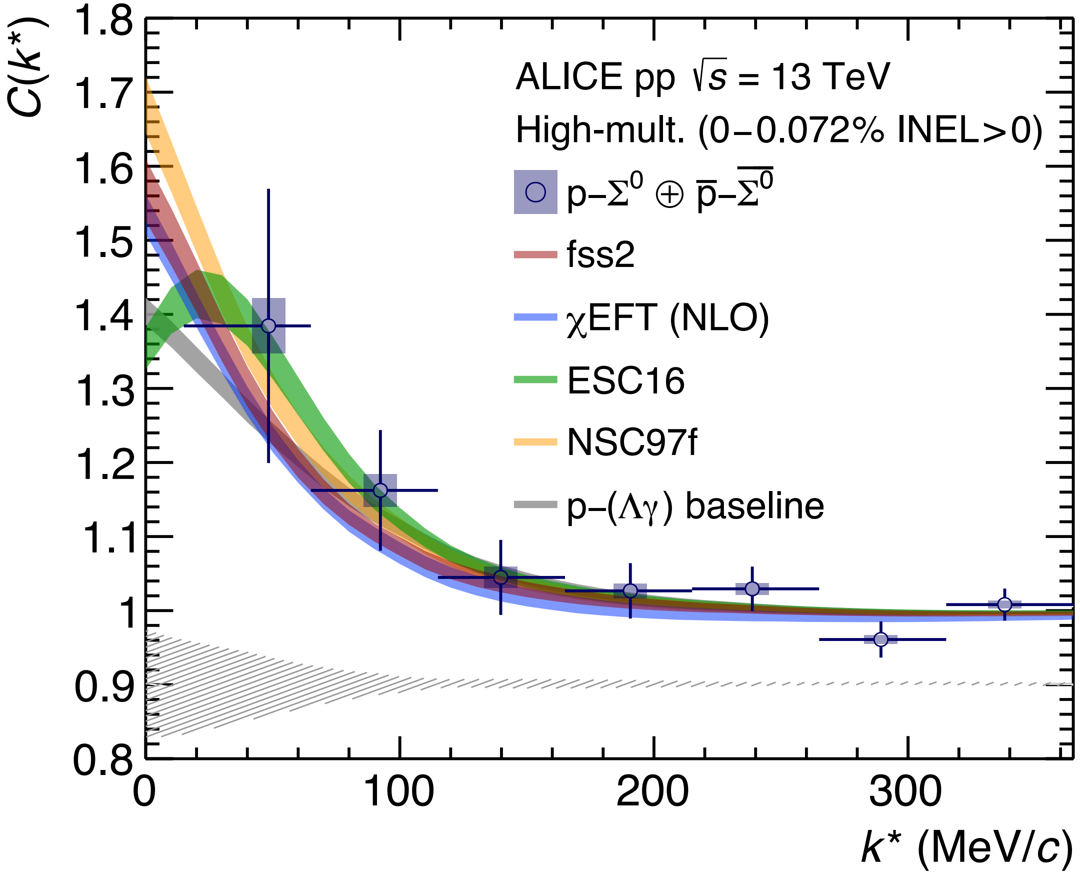
- Experimental data on hypernuclei too scarce for a final conclusion: attractive or repulsive interaction?
- Very challenging measurement via the difficult electromagnetic decay $\Sigma^0 \rightarrow \Lambda\ \gamma$

- **Correlation function is above the background ⟹ pointing to a very shallow attractive interaction**

Model	p–($\Lambda\gamma$) baseline	fss2	χEFT	NSC97f	ESC16
n_σ ($k^* < 150$ MeV/c)	0.2–0.8	0.2–0.9	0.3–1.0	0.2–0.6	0.1–0.5

- Relevant for dense neutron matter is the interaction with neutrons and the interaction of $\Sigma^{+,-}$!
  – Disentangle the different isospin contributions
- **Larger statistics in Run3 and Run4 will definitely increase the precision and constraints on the Σ-N interaction**

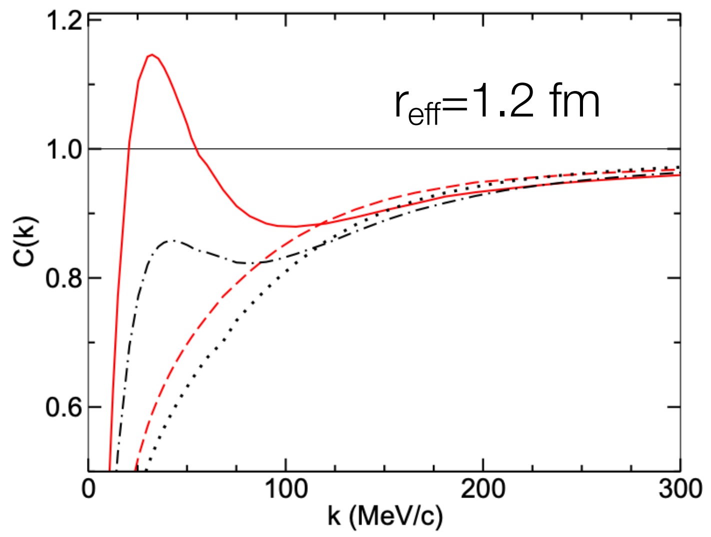
ALICE Coll. PLB 805 (2020) 135419

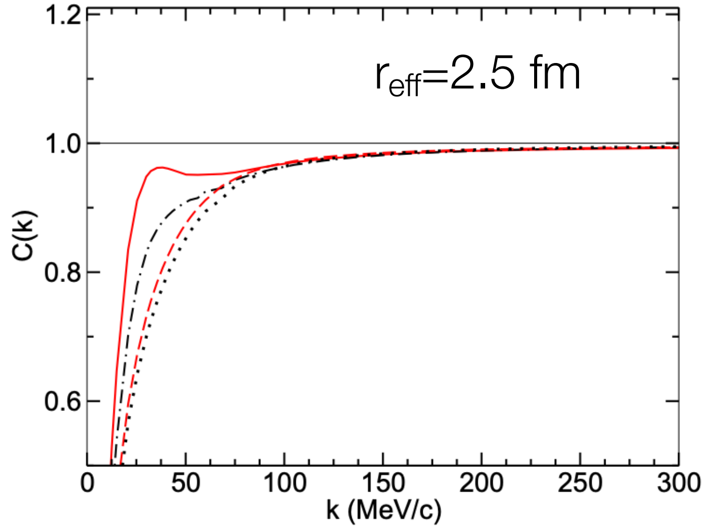


Predictions for $p\Sigma^+$ correlations from χEFT

J.Haidenbauer, U.G. Meißner Phys.Lett.B 829 (2022)

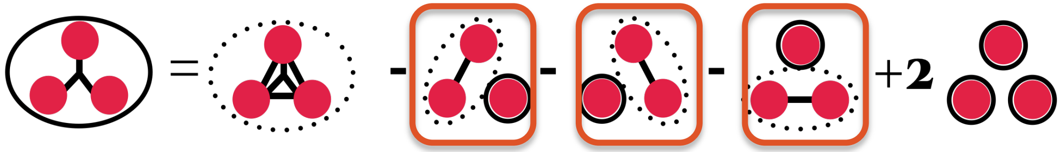
interaction	a_s^c	r_s^c	a_t^c	r_t^c
NLO13(600) [30]	−3.56	3.54	0.49	−5.08
NLO19(600) [31]	−3.62	3.50	0.47	−5.77
Jülich ’04 [32]	−3.60	3.24	0.31	−12.2
ESC16 [33]	−4.30	3.25	0.57	−3.11
Nagels ’73 [39]	−2.42 ± 0.30	3.41 ± 0.30	0.71	−0.78
fss2 [34]	−2.28	4.68	0.83	−1.52
NLO(sim)	−2.39	4.61	0.80	−1.25





The projector method

$$Q_3 = \sqrt{q_{12}^2 + q_{22}^2 + q_{31}^2}$$



- Evaluate two-body contribution in three-body correlation function
  - – With no genuine three-body correlation

$$C_3(Q_3) = C_3^{12}(Q_3) + C_3^{23}(Q_3) + C_3^{31}(Q_3) - 2$$

two-body CF   projector

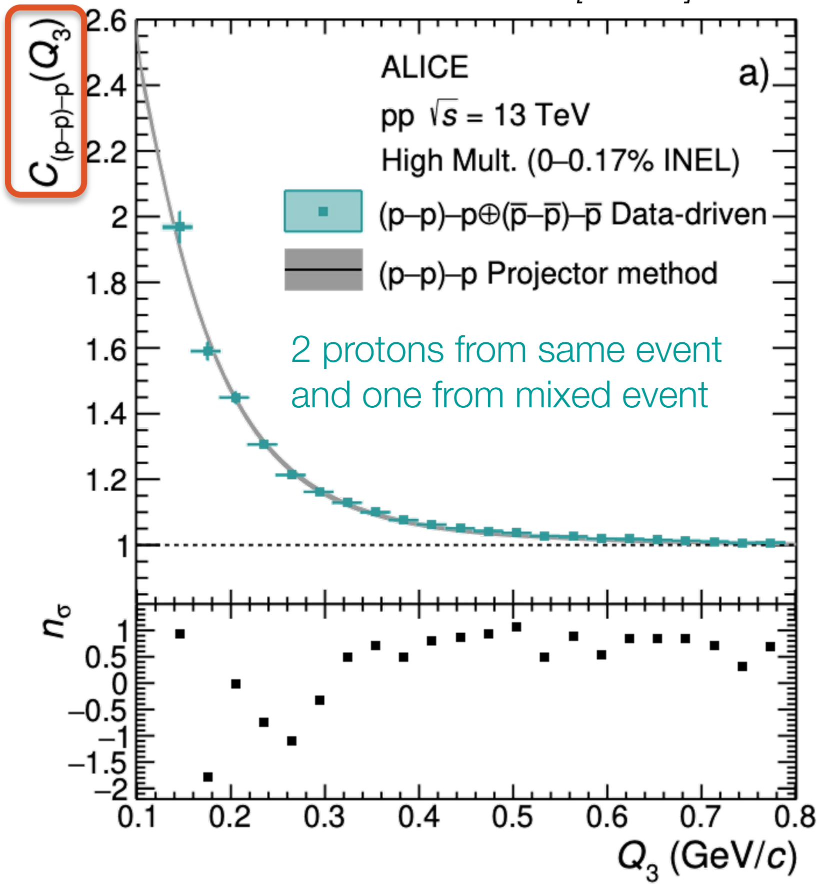
$$C_3^{ij}(Q_3) = \int C_2(k_1^{ij})\, W^{ij}(k_1^{ij}, Q_3)\, dk_1^{ij}$$

- Measured 2-body correlation functions
- same emitting source for 2-body and 3-body correlations

- Jacobian from 2-body to 3-body coordinates, integration on phase-space

- Subtract 2-body contributions with negligible uncertainties

ALICE Coll. arXiv:2206.03344 [nucl-ex]



R. Del Grande, V.M.S. et al., EPJC 82 (2022)