Experimental access to the three-body forces between hadrons with ALICE

Otón Vázquez Doce (LNF-INFN)
on behalf of the ALICE Collaboration

EuNPC2022, Santiago de Compostela, October 25, 2022

Fellini
Fellowship for Innovation at INFN

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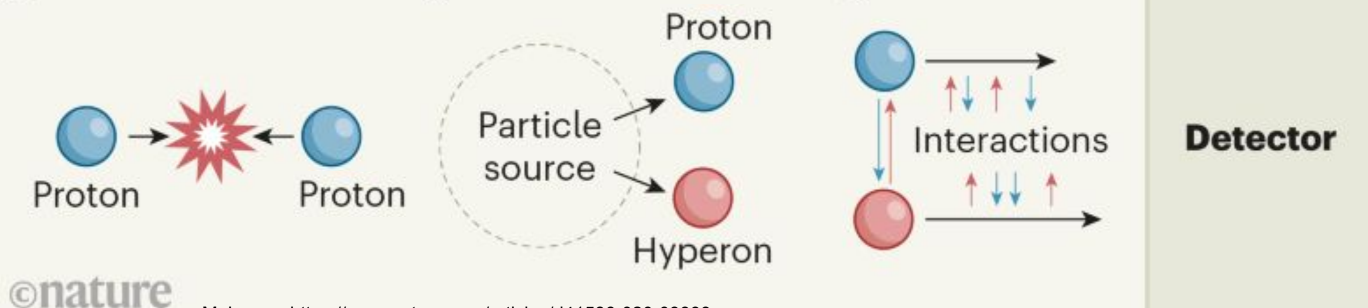
Hadron-hadron interactions via femtoscopy

Nucleus-Nucleus collisions at the LHC recorded by ALICE



M. Lorenz https://www.nature.com/articles/d41586-020-03393-z

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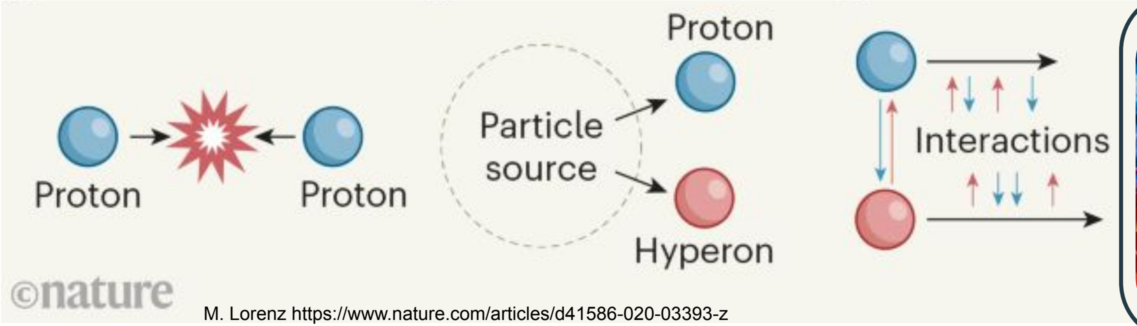

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- Charged particle tracking and PID
- Reconstruction of hyperons via weak decay

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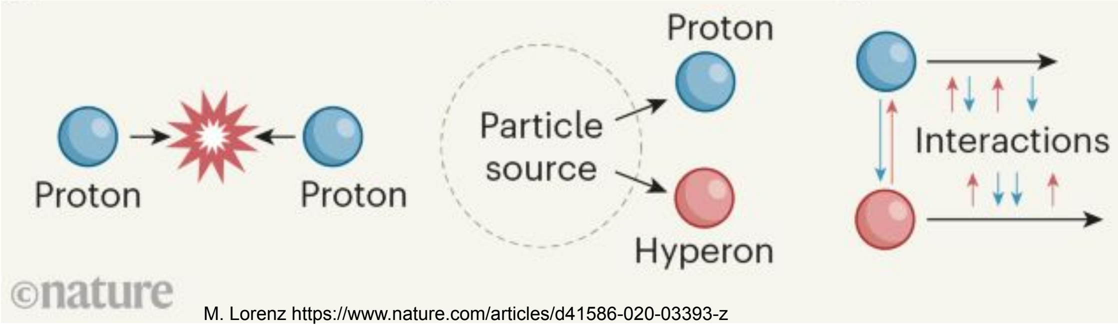

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Experimental observable: Correlation function of two final-state particles

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

→ Pairs of particles from same collison

→ Particles produced in different collisions

$$k^* = \frac{|\vec{p_a^*} - \vec{p_b^*}|}{2}$$

relative momentum in pair rest frame

Theoretical correlation function

$$C(k^*) = \int \underbrace{S(\boldsymbol{r}^*)}_{\text{source}} \underbrace{|\psi(\boldsymbol{k}^*, \boldsymbol{r}^*)|^2}_{\text{wave function}} \, \mathrm{d}^3\boldsymbol{r}^*$$

Lisa, Pratt, Wiedemann, Solz, Ann. Rev. Nucl. Part. Sci. 55 (2005) 357

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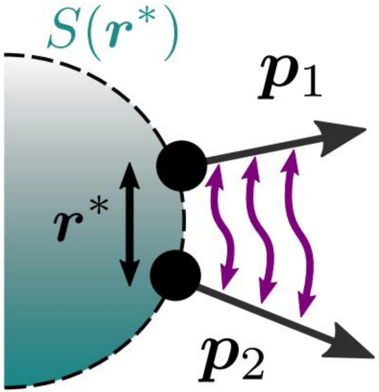

pp, p–Pb: r*~1fm
Pb–Pb: r*~3-10fm

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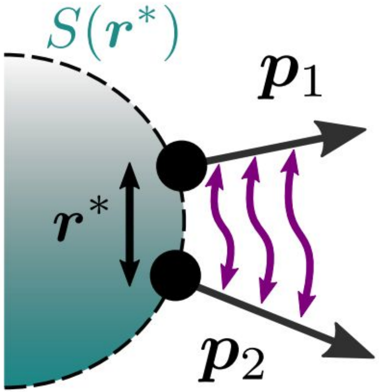
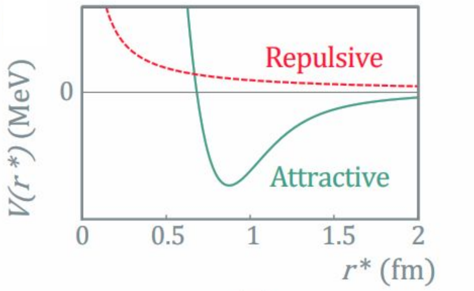


Interaction



Schrödinger equation

Two-particle wave function

$\psi(k^*, r^*)$

pp, p–Pb: r*~1fm
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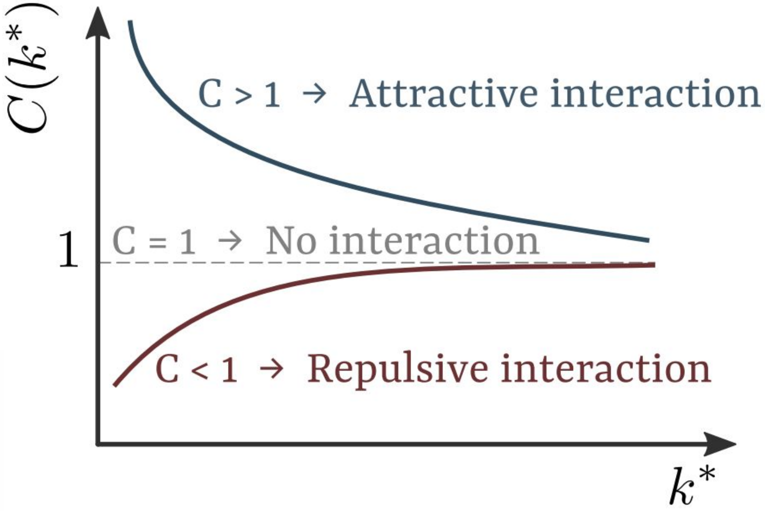

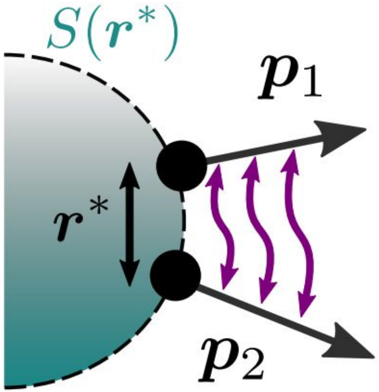

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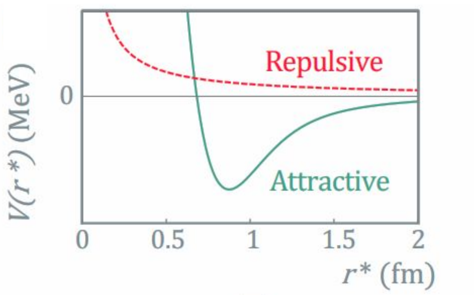

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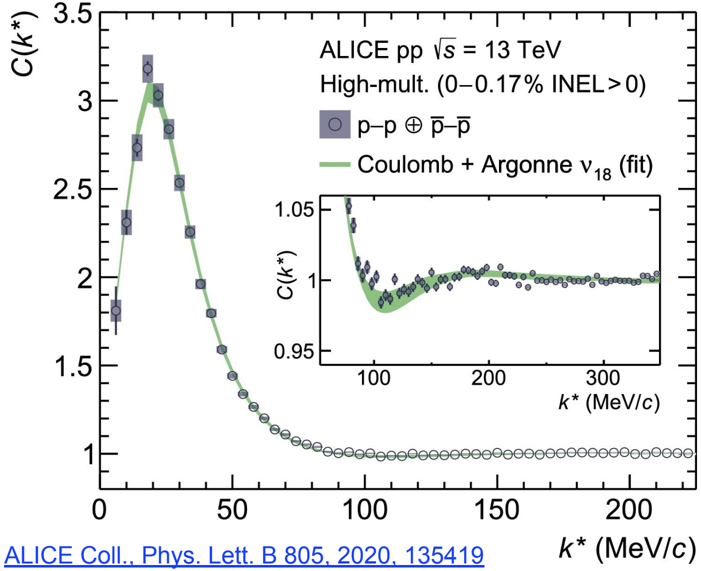
Determination of the source size

Source size determined via traditional femtoscopy analysis (known interaction)

- fit p-p correlation function ⇒ extract gaussian source radius



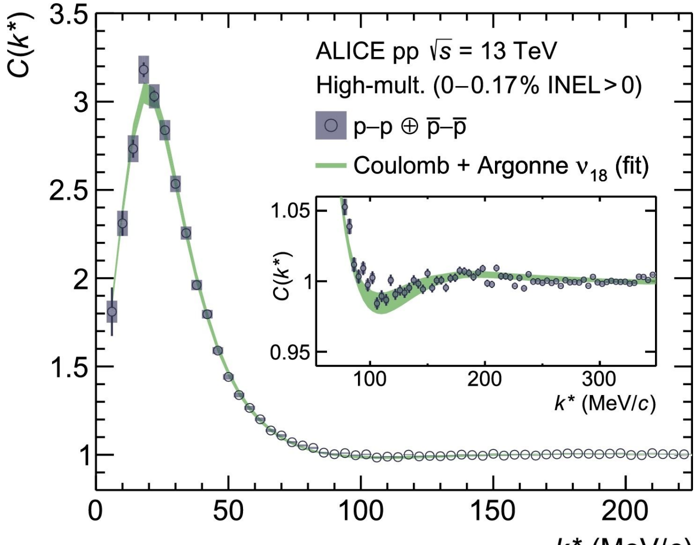
ALICE Coll., Phys. Lett. B 805, 2020, 135419

Determination of the source size

Source size determined via traditional femtoscopy analysis (known interaction)

- fit p-p correlation function ⇒ extract gaussian source radius
- differential <m_T> fit ⇒ "map" of source size
  - take into account effect of strong decaying resonances

ALICE Coll., Phys. Lett. B 811 (2020) 135849



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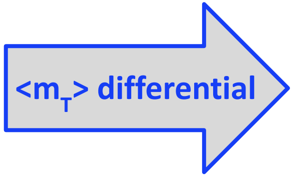
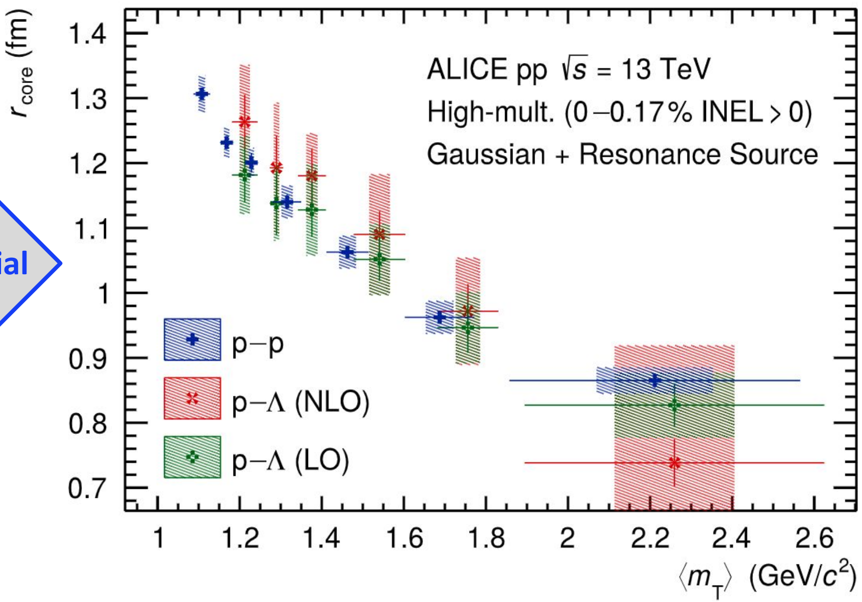
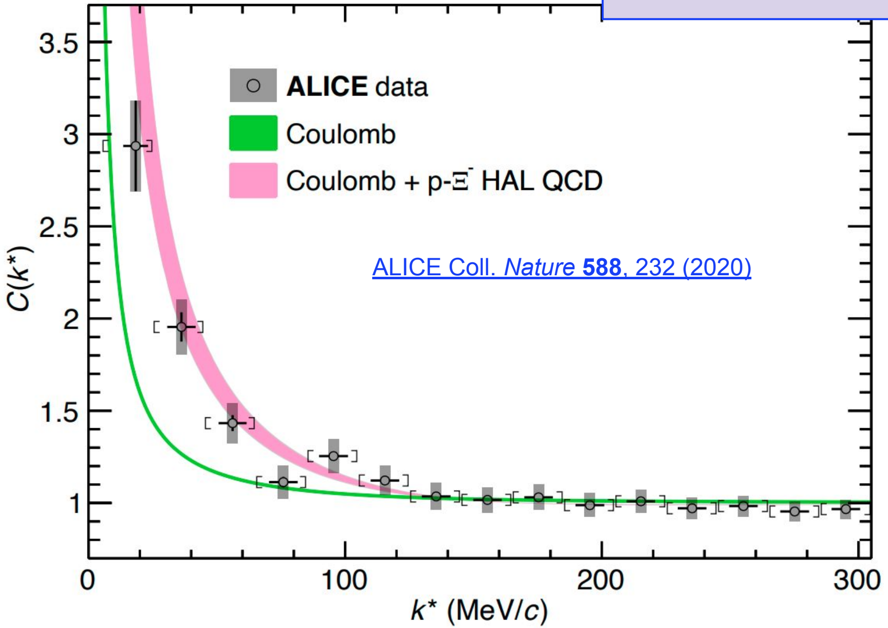




A practical example: p–Ξ⁻ correlation

see Talk by R. del Grande P7 session



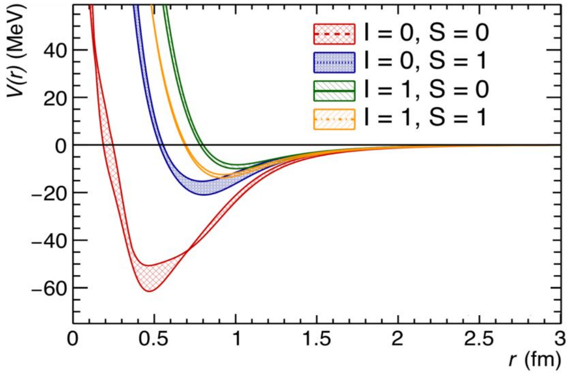
- Observation of the **attractive strong interaction**

A practical example: p–Ξ⁻ correlation

Source

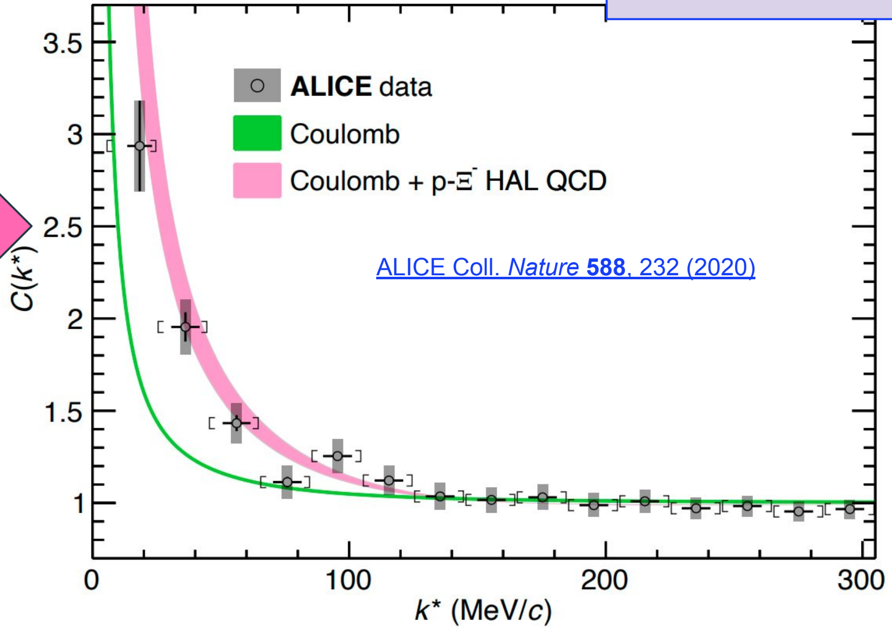
Given pair $<m_T>$=1.9 GeV/c^2 and effect of strong resonances
⇒ r_{eff} = 1.02 ± 0.05 fm

Interaction



Lattice QCD p-Ξ⁻ potential
K. Sasaki et al. (HAL QCD), Nucl. Phys. A330, 998 (2020)

see Talk by R. del Grande P7 session



- Observation of the **attractive strong interaction**
- **Described by Lattice QCD potential**
  ⇒ Implications for the EoS of NS

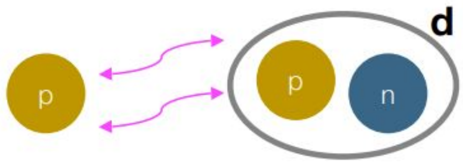
Accessing three-body forces with femtoscopy

Three-body forces

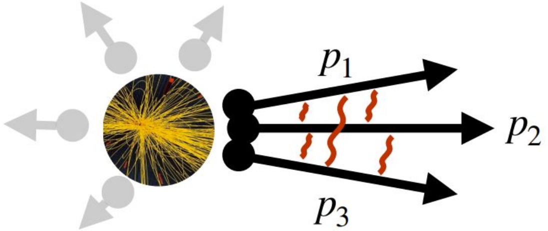
- Fundamental to **explain the nuclear structure**
  - contribute to 10–15% of nuclear binding energy at normal nuclear density
  - might become more important at higher densities
- Fundamental **ingredients for the Equation of State (EoS) of dense nuclear matter**
- Theory currently anchored to properties of nuclei, hypernuclei and scattering data

Now femtoscopy studies enable access to three-body forces:

p-d correlations



three-body correlation function



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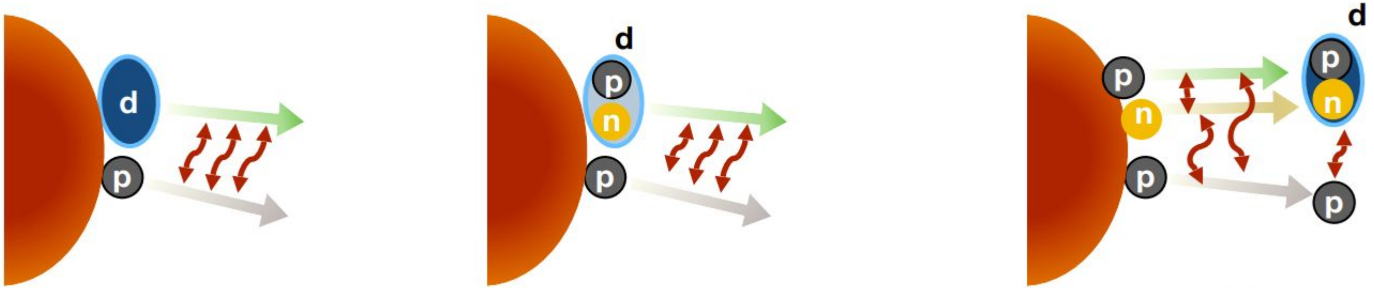
Proton-deuteron femtoscopy

- Proton-deuteron (p-d) **interaction constrained from the scattering experiments**
- **Production mechanism** of light nuclei **not understood**
  Models: Statistical Hadronisation[1,2] or Coalescence[3]



[1]J. Cleymans et al, Phys. Rev. C 74, 034903 (2006)
[2]J. Cleymans et al, Z. Phys. C 57, 135–147 (1993)
[3]K. Blum et al, Phys. Rev. C 99, 04491(2019)

p-d correlations in pp collisions at the LHC

⇒ Final-state interaction can help the study of the formation time of deuterons (antideuterons)

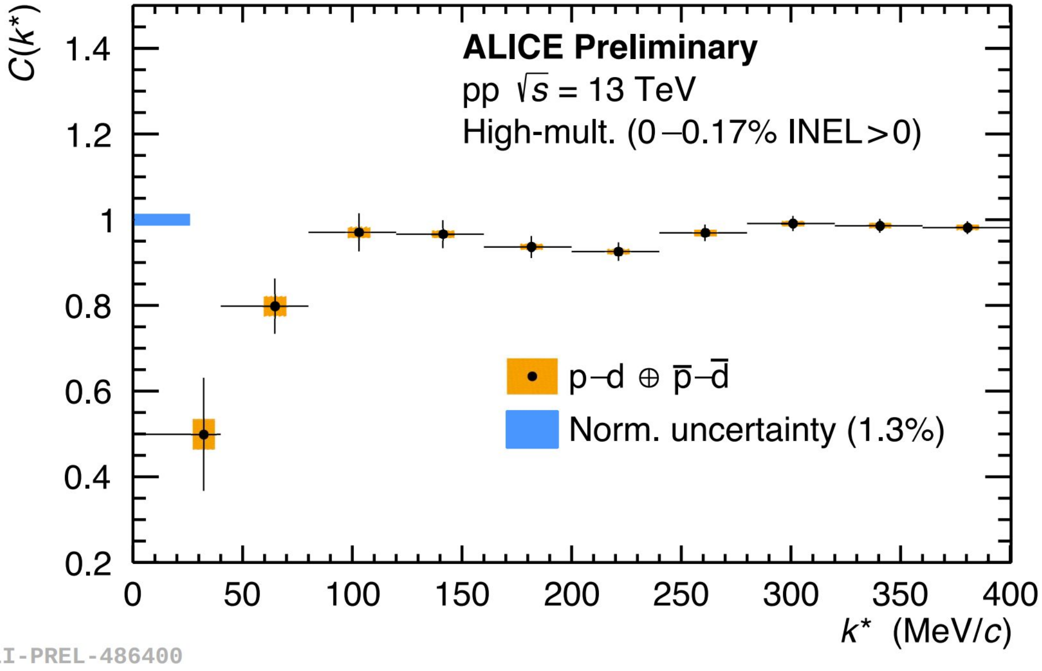
p-d correlation function

p-d correlation function in pp collisions at the LHC

Data sample:

- pp 13 TeV Run 2 High-Multiplicity trigger
- 1x10^9 events
- 3000 p-d ⊕ pbar-dbar pairs at k*< 200 MeV/c

Data shows **clear depletion at low k***
⇒ Repulsive type of interaction



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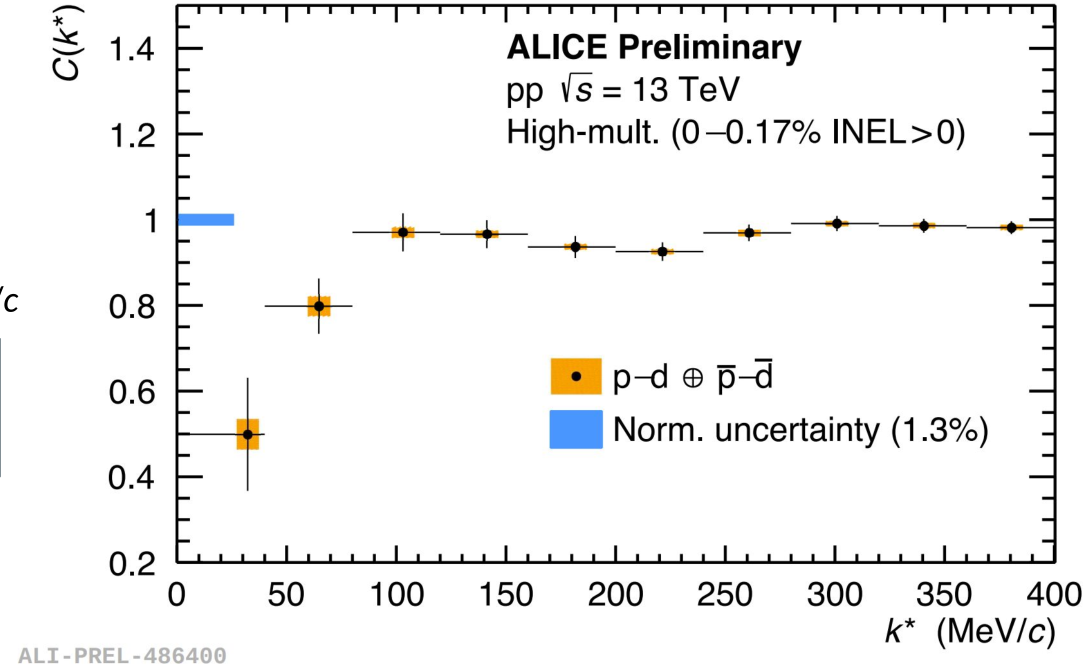
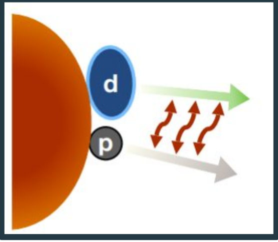
⇒ Repulsive type of interaction

Source size for p-d pairs

Given pair $\langle m_T \rangle = 1.65$ GeV/c^2 and effect of Δ-resonances
⇒ $\boldsymbol{r_{\mathrm{eff}} = 1.06 \pm 0.04}$ **fm**



p-d as two-body problem



Theoretical model constrained to scattering p-d experiments

$S=1/2$ f_0(fm)	$S=1/2$ r_0(fm)	$S=3/2$ f_0(fm)	$S=3/2$ 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. Nucl. Phys. A 561 (1967)
$-2.73^{+0.10}_{-0.10}$	$2.27^{+0.12}_{-0.12}$	$-11.88^{+0.40}_{-0.10}$	$2.63^{+0.01}_{-0.02}$	J.Arvieux et al. Nucl. Phys. A92 221 (1973)
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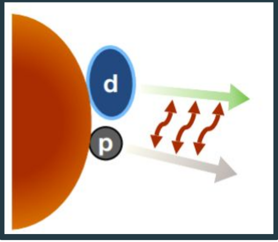
Lednický model for distinguishable particles Phys. Part. Nucl. 40 (2009) 307

- Define the s-wave **two-particle relative wave-function starting from the scattering parameters**
- Assumptions: deuteron as point-like particle

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

p-d as two-body problem



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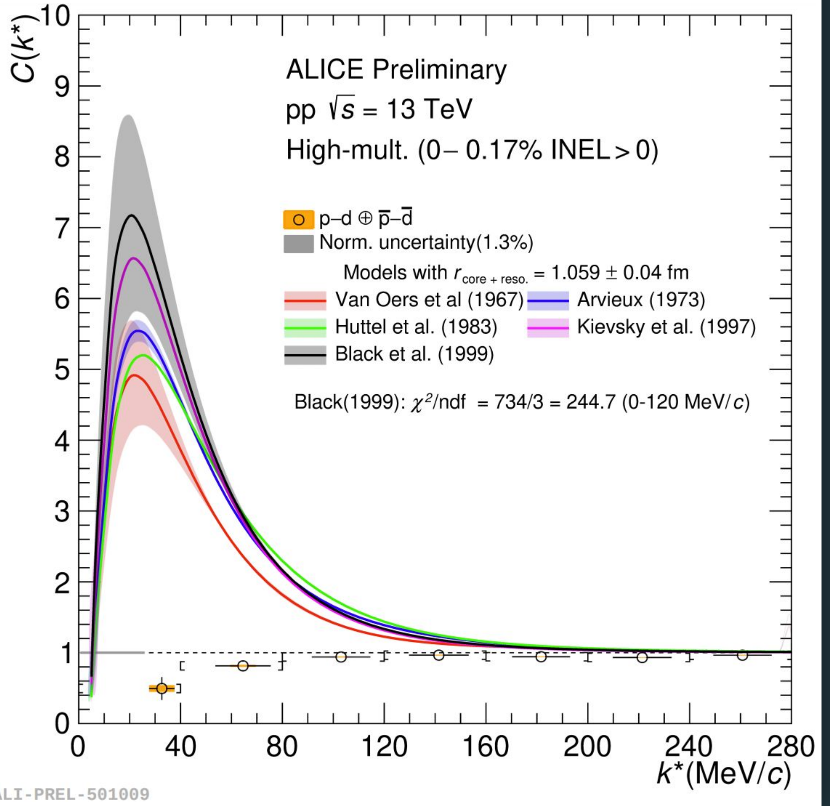
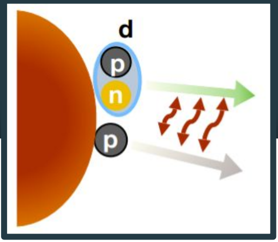
Model and data disagree for source size = 1.06±0.04 fm
➡ Model does not account for p-(p-n) interaction



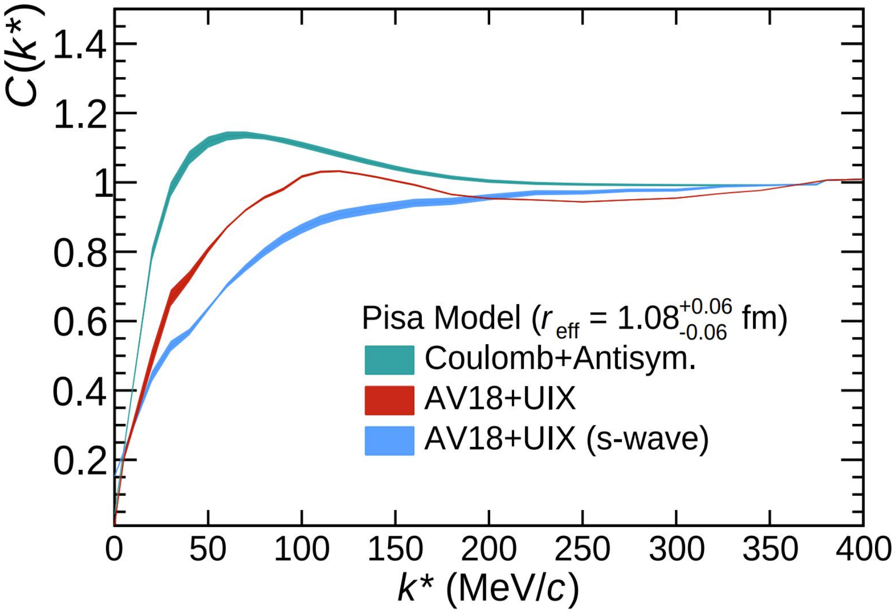
p-d as a three-body problem



Full calculation of a three-body p-p-n system projected into the p-d final state

<u>Model under construction</u> by PISA theory group (M. Viviani, A. Kievsky, L. Marcucci) qualitatively reproduces the data

- **Two-body interaction** Argonne V18 potential
- **Three-body interaction** Urbana XI potential
- **Deuteron wave-function** from AV18 NN interaction
- Deuteron is formed at the same time as the proton



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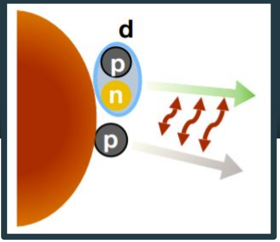

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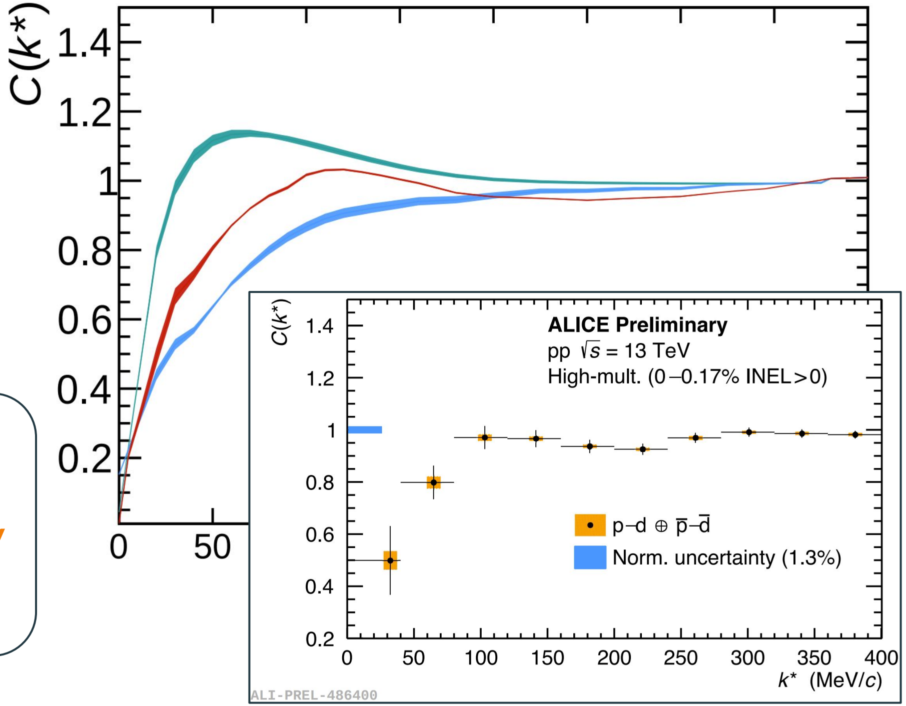


p-d correlation

- affected by two- and three-body p-p-n interactions

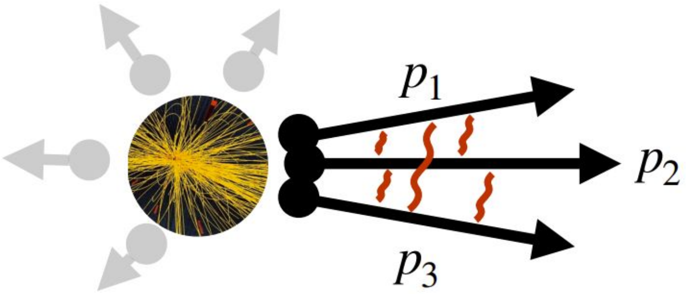
⇒ new way to explore the interaction of the three-body system at short distances

Three-body femtoscopy

Study of three-particle correlations
⇒ Direct access to the genuine three-body forces

Three-particle correlation function:

$$C(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \equiv \frac{P(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)}{P(\mathbf{p}_1)\, P(\mathbf{p}_2)\, P(\mathbf{p}_3)} = \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}$$



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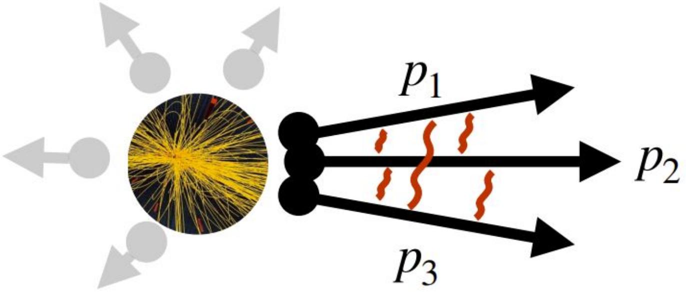

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The Lorentz invariant Q_3 is defined as:

$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2} \qquad q_{ij}^{\mu} = (p_i - p_j)^{\mu} - \frac{(p_i - p_j) \cdot P_{ij}}{P_{ij}^2} P_{ij}^{\mu} \qquad P_{ij} \equiv p_i + p_j$$

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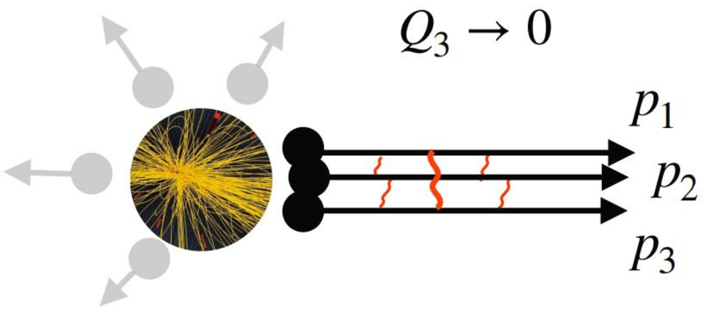

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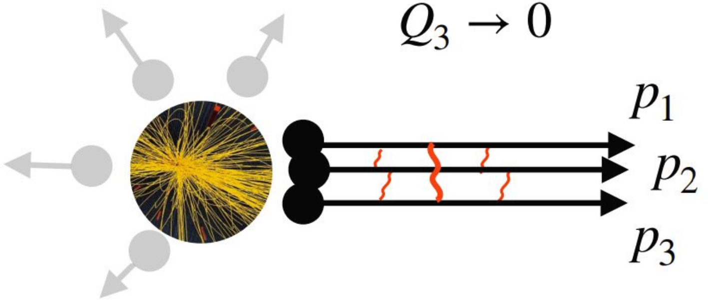

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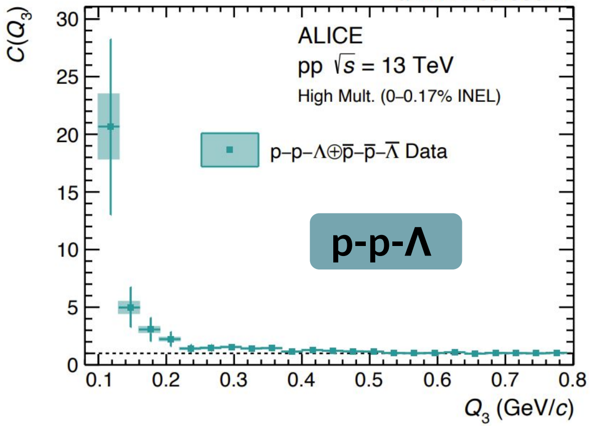
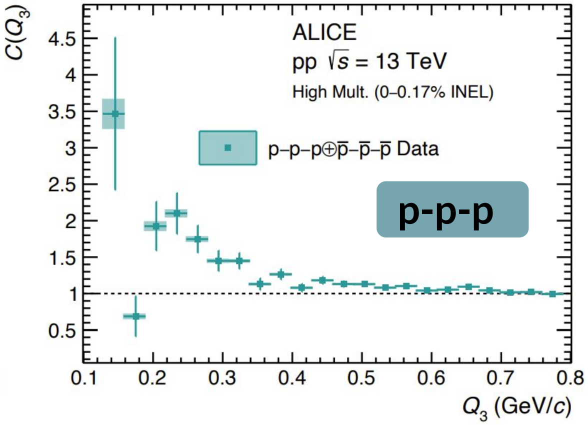
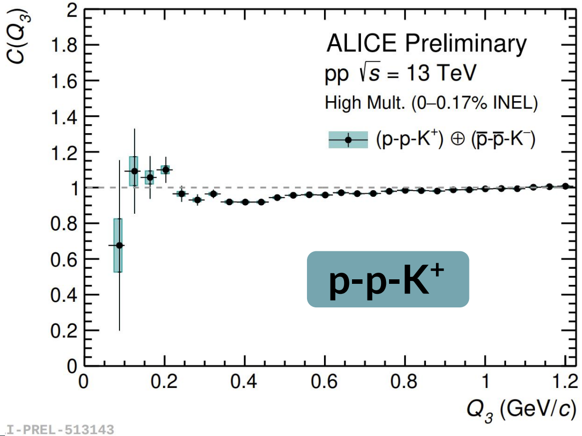
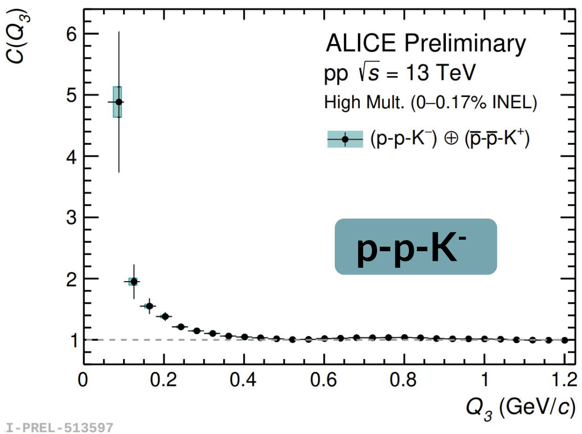
⇒ System studied: **p-p-Λ, p-p-p, p-p-K$^+$, p-p-K$^-$**

Three-body correlation function









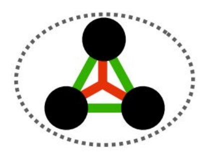
ALICE Coll. arXiv:2206.03344 EPJA in press

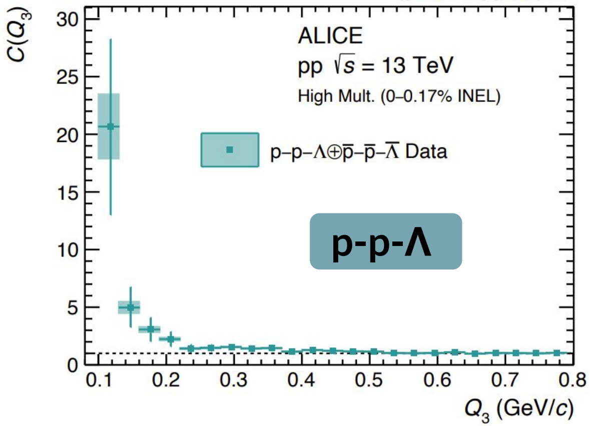
Data sample: pp 13 TeV Run 2
High-Multiplicity trigger

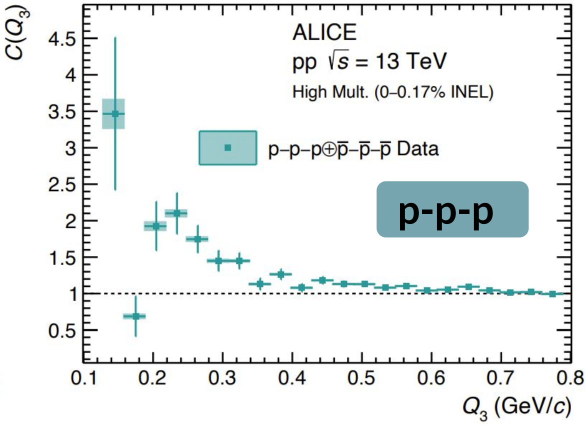
Three-body correlation function:
Full calculations of a three-body system are necessary to interpret the data

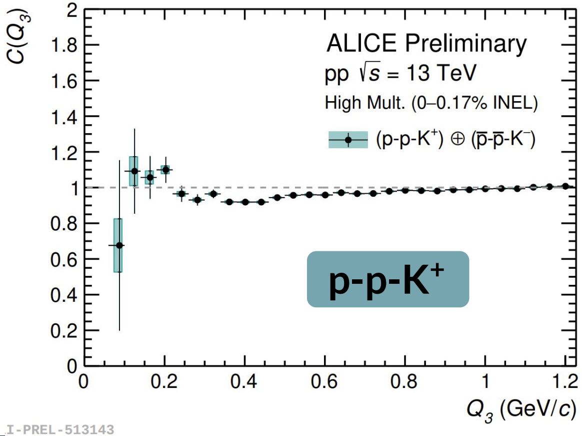
→ First preliminary calculations available motivated by ALICE data
A. Kievsy @ EXOTICO workshop

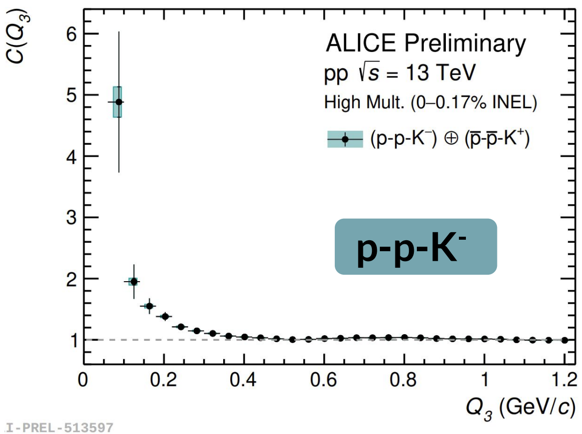
Three-body correlation function









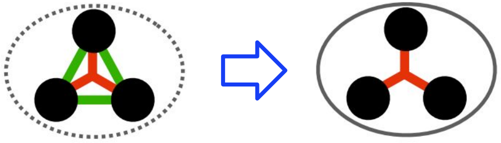


ALICE Coll. arXiv:2206.03344 EPJA in press

Data sample: pp 13 TeV Run 2
High-Multiplicity trigger

Three-body correlation function:
Full calculations of a three-body system are necessary to interpret the data

→ First preliminary calculations available motivated by ALICE data
A. Kievsy @ EXOTICO workshop



two-body
tree-body

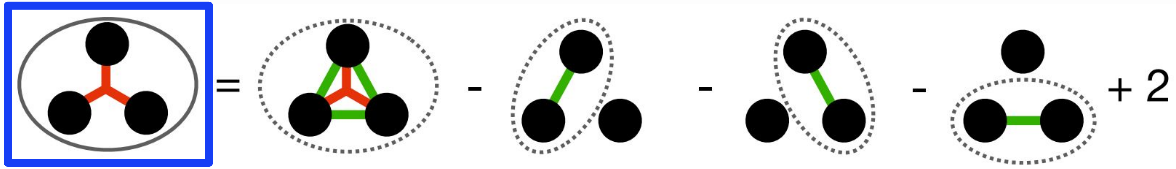
three-body

Isolation of three-body effect: Cumulant

Genuine three-body correlations (cumulant) | Measured three-body correlation function | Lower-order correlations

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

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



Isolation of three-body effect: Cumulant

Genuine three-body correlations (cumulant) | **Measured three-body correlation function** | **Lower-order correlations**

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

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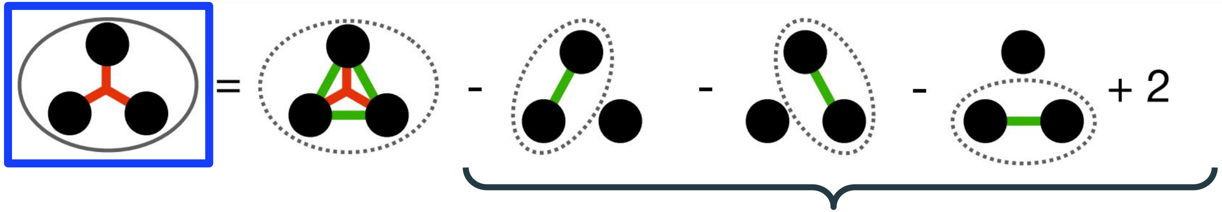

Two alternative methods to **obtain the lower-order correlations**

- Projector method: Project into Q_3 via kinematic transformation the measured/theoretical two-particle correlation function Del Grande, Šerkšnytė et al. EPJC 82 (2022) 244
  - measured two-body correlations used for projection
- Data driven approach validates the projector method
  - use of mixed events: two particles from the same event and one particle from a different event

otonvd@cern.ch

Isolation of three-body effect: Cumulant

Genuine three-body correlations (cumulant) — Measured three-body correlation function — Lower-order correlations

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

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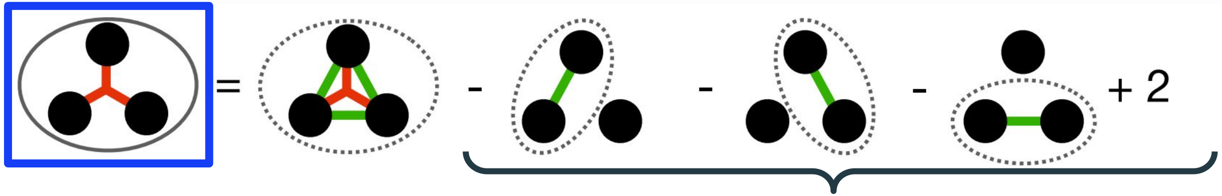

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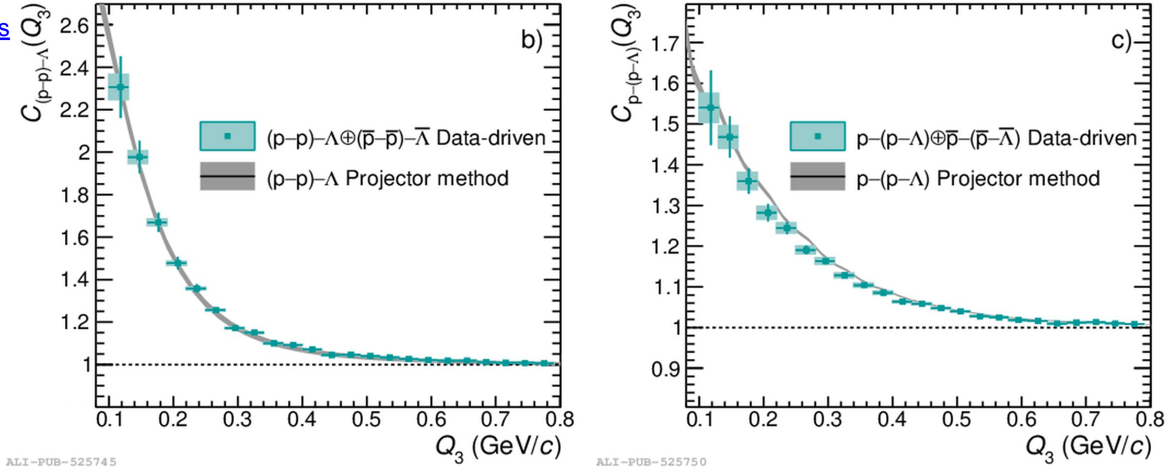


p-p-Λ cumulant

Only two identical and charged particles

- Main expected contribution from three-body strong interaction
- **Relevant measurement for EoS of NS**

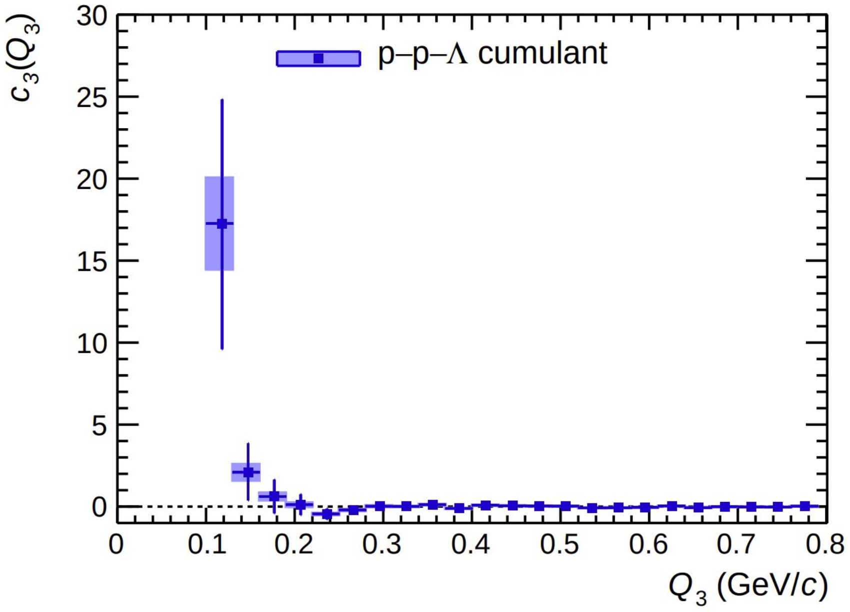
ALICE data: positive cumulant for p-p-Λ

Statistical significance: n_σ=0.8 for Q_3< 0.4 GeV/c

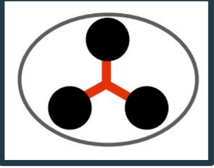
⇒ No significant deviation from null hypothesis.

Dedicated acquisition trigger in Run 3,
two orders of magnitude gain in statistics expected!

ALICE Coll. arXiv:2206.03344 EPJA in press



p-p-p cumulant

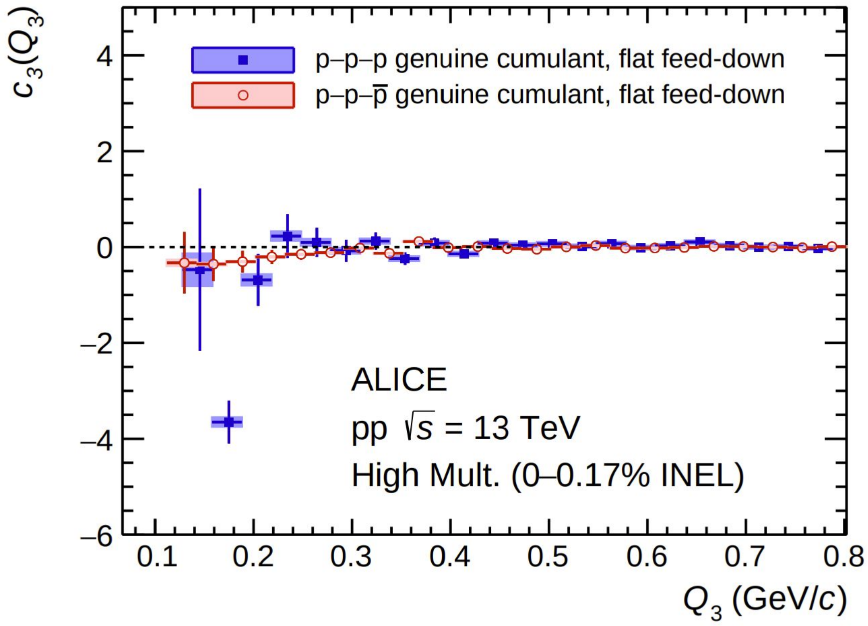


ALICE Coll. arXiv:2206.03344 EPJA in press

Negative cumulant for p-p-p

Statistical significance: n_σ=6.7 for Q_3< 0.4 GeV/c

- Test with mixed-charge particles, cumulant negligible.

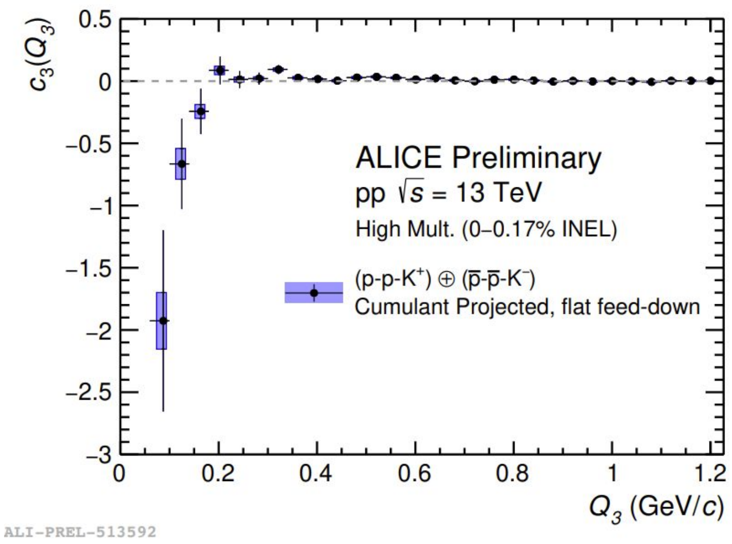


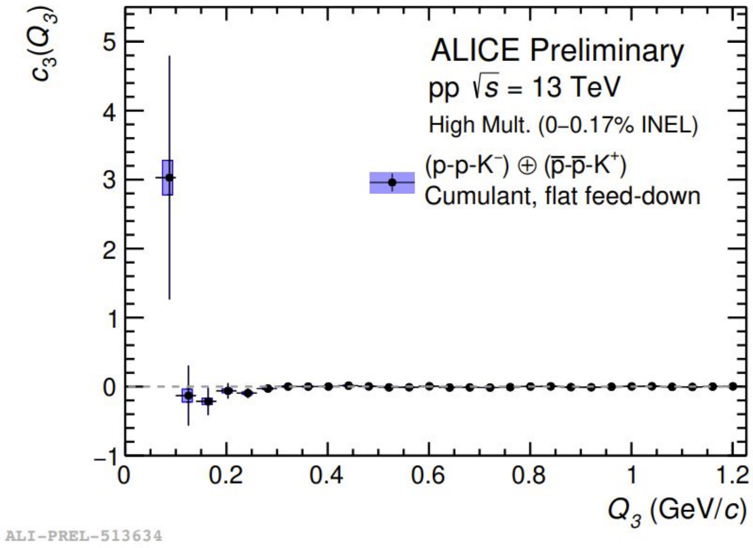
<u>Effect beyond two-body interactions</u>

Possible origin:

- Pauli blocking at the three-particle level
- three-body strong interaction
- long-range Coulomb effects

p-p-K$^+$ and p-p-K$^-$ cumulants





<u>Negative cumulant for p-p-K$^\pm$</u>

Compatible with zero within the uncertainties.

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

p-p-K$^-$ cumulant **compatible with zero within uncertainties**

⇒ **<u>p-p-K$^-$ system shows only two-body interactions</u>**

⇒ three-body strong interaction might not be relevant in the formation of KbarNN nucleus

Conclusions and outlook

Three-particle systems can be accessed and studied at the LHC in pp collisions by ALICE with a novel technique

Three-body cumulant: first direct measurement of the three-body force using femtoscopy

- p-p-p: negative cumulant with a significance of 6.7σ
- p-p-Λ, p-p-K^+, p-p-K^-: no evidence of a genuine three-body force

p-d femtoscopy: two hypotheses tested

- Data cannot be described with the assumption of point-like distinguishable particles
- Models considering three-body dynamics with a projection of p-(p-n)

to the p-d state describe qualitatively the data

⇒ Precision studies within reach with the large data samples in Run 3

More statistics = more physics. A $\langle m_T \rangle$ dependent study would enable access to shorter distances for the three-body system in the near future.