New experimental frontiers in the study of many-body nuclear interactions with ALICE at the LHC

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On behalf of the ALICE Collaboration

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Many-body systems

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

- **N-N-N and N-N-Λ interactions**: fundamental ingredients for the Equation of State (EoS) of neutron stars.
  
  D. Lonardoni et al., PRL 114, 092301 (2015)

- Many-body scatterings (e.g. proton-deuteron) and formation mechanisms of light nuclei. L. Girlanda et al., PRC 102, 064003 (2020)

- \(\bar{K}NN\): exotic bound states of antikaons with nucleons predicted twenty years ago due to the strongly attractive \(\bar{K}N\) interaction in \(I = 0\) channel. S. Wycech, NPA 450 (1986) 399c; Y. Akaishi, T. Yamazaki, PRC 65 (2002) 044005


Next experimental challenge: genuine three-body interaction measurements
IN THIS TALK:

Colliding system: \( pp \) @ \( \sqrt{s} = 13 \text{ TeV} \)
Data set: High-multiplicity events

\( p\bar{p}-p, \ p\bar{p}-\Lambda, \ p\bar{p}-K^+, \ p\bar{p}-K^-, \ p\text{-deuteron} \)

\( Q_3 \) is defined as:
\[
Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}
\]

\( q_{ij}^\mu = (p_i - p_j)^\mu - \frac{(p_i - p_j) \cdot p_{ij}}{p_{ij}^2} p_{ij}^\mu \quad P_{ij} \equiv p_i + p_j \)

Femtoscopy technique\(^(*)\)

Three-particle correlation function
\[
C(p_1, p_2, p_3) \equiv \frac{P(p_1, p_2, p_3)}{P(p_1) \cdot P(p_2) \cdot P(p_3)} = \mathcal{N} \cdot \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}
\]

The Lorentz invariant \( Q_3 \) is defined as:
\[
Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}
\]

\( q_{ij}^\mu = (p_i - p_j)^\mu - \frac{(p_i - p_j) \cdot p_{ij}}{p_{ij}^2} p_{ij}^\mu \quad P_{ij} \equiv p_i + p_j \)
p-p-p and p-p-Λ correlation functions

Measured triplets at $Q_3 < 0.4$ GeV/c $\rightarrow$ 1011 triplets

Measured triplets at $Q_3 < 0.4$ GeV/c $\rightarrow$ 496 triplets

Correlation functions include two- and three-particle correlations
In terms of correlation functions:

\[ c_3(Q_3) = C(Q_3) - C_{12}(Q_3) - C_{23}(Q_3) - C_{31}(Q_3) + 2 \]
Lower-order contributions evaluation

Data-driven approach

Using the **same** and **mixed-events** distributions:

\[ C([p_1, p_2], p_3) = \frac{N_2(p_1, p_2) N_1(p_3)}{N_1(p_1) N_1(p_2) N_1(p_3)} \]

The scalar \( Q_3 \) is calculated from the measured single-particle momenta

\[(p_1, p_2, p_3) \rightarrow Q_3\]

Projector method

Using the **two-body correlation function** of the pair (1,2).

A kinematic transformation from

\[ k_{12}^* \text{ (pair)} \rightarrow Q_3 \text{ (triplet)} \]

\[ C_2(k_{12}^*) \rightarrow C_3(Q_3) \]

is performed.

For the pair \((i, j)\) we have

\[ C_{3}^{ij}(Q_3) = \int C_2(k_{ij}^*) W_{ij}(k_{ij}^*, Q_3) \, dk_{ij}^* \]

p-p-p correlation function

Lower-order correlations

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

C($Q_3$)

$Q_3$ (GeV/c)

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C($Q_3$)

$Q_3$ (GeV/c)
p-p-p cumulant

Statistical significance:
\[ n_\sigma = 6.7 \quad \text{for} \quad Q_3 < 0.4 \text{ GeV/c} \]

Conclusion:
Presence of a genuine three-body effect in p-p-p.
Possible interpretations:
- Pauli blocking at the three-particle level
- long-range Coulomb interaction effects
- three-body strong interaction

Collaboration with A. Kievsky, L. Marcucci and M. Viviani (Pisa University - INFN) for the theoretical interpretation.
Positive cumulant for p-p-Λ.

Only two particles are identical and charged —> Non-zero cumulant can be directly linked to the three-body strong interaction.

—> Important measurement for the physics of neutron stars.

Statistical significance:

\( n_\sigma = 0.8 \) for \( Q_3 < 0.4 \) GeV/c

Conclusion: no significant deviation observed from the null hypothesis.

A factor 500 gain in statistics is expected from Run 3 data taking.
p-p-K⁺ and p-p-K⁻ correlation functions

Correlation functions include two- and three-particle correlations

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p-p-K\(^+\) correlation function

\[
\begin{align*}
\text{pp \ $\sqrt{s} = 13$ TeV} & \\
\text{High Mult. (0–0.17\% INEL)} & \\
(p-p-K^+) \oplus (\bar{p}-\bar{p}-K^-) & \\
(p-p)-K^+ + 2 \times p-(p-K^-) - 2, \text{ Projected} & \\
\end{align*}
\]

Lower-order correlations

\[
\begin{align*}
\text{ALICE Preliminary} & \\
\text{pp \ $\sqrt{s} = 13$ TeV} & \\
\text{High Mult. (0–0.17\% INEL)} & \\
(p-p)-K^+ + 2 \times p-(p-K^-) - 2, \text{ Projected} & \\
\end{align*}
\]
p-p-K+ cumulant

Statistical significance:

\[ n_\sigma = 2.3 \quad \text{for} \quad Q_3 < 0.4 \text{ GeV/c} \]

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

Above 180 MeV/c, genuine three-body effects do not significantly contribute in the dynamics of the p-p-K+ system.
**p-p-K⁻ cumulant**

![Cumulant](image)

**Statistical significance:**

\[ n_\sigma = 0.5 \quad \text{for} \quad Q_3 < 0.4 \text{ GeV/c} \]

**Conclusion:**

The measured cumulant is compatible with zero within the uncertainties.

**Genuine three-body effects are not significant in p-p-K⁻ systems**

The measurement confirms that three-body strong interaction is not relevant in the formation of the exotic kaonic bound states.
Proton-deuteron correlations

- Indirect measurement
  - Correlations between proton and a composite object as deuteron
  - Accessing spin-isospin dependence of N-N-N
  - Formation mechanisms of light nuclei in hadron-hadron collisions
Proton-deuteron correlations

- Indirect measurement

  - Correlations between proton and a composite object as deuteron
  
  - Accessing spin-isospin dependence of N-N-N
  
  - Point-like particle models(*) constrained to scattering p-d experiments
    
    - Coulomb + strong interaction (S=1/2 and S=3/2) using the Lednický-Lyuboshitz (LL) model
      
    
    - Only s-wave interaction
    
    - Source radius: \( r_{\text{core + reso.}} = (1.059 \pm 0.040) \, \text{fm} \)

Proton-deuteron correlations

- Indirect measurement

- Discrepancy between the measured correlation function and the LL prediction for small source radii:
  
  - Increased agreement with larger source sizes

→ Compatible with the delayed formation of deuterons in hadron-hadrons collisions

Theoretical interpretation in collaboration with:
- A. Kievsky, L. Marcucci and M. Viviani (Pisa University - INFN);
- S. König (North Carolina State University).

Conclusions and Outlooks

Femtoscopy technique applied in pp collisions at the LHC to study many-body systems dynamics:

– Genuine three-body effects isolated for the first time using the Kubo's rule.

- **p-p-p**: negative cumulant with a significance of 6.7 $\sigma$.
  
  **Possible interpretations:**
  
  $\rightarrow$ Pauli blocking on three-particle level
  $\rightarrow$ long-range Coulomb interaction
  $\rightarrow$ three-body strong interaction

- **p-p-$\Lambda$**: no significant deviation from 0 in Run 2 data.

- **p-p-$K^+$ and p-p-$K^-$**: cumulants compatible with 0, no evidence of a genuine three-body force
  
  $\rightarrow$ kaonic bound state formation driven by two-body forces.

– Formation mechanism of light nuclei in hadron-hadron collisions.

- **proton-deuteron**: discrepancy between the measured correlation function and the LL prediction for small source radii.
  
  **Possible interpretation** $\rightarrow$ compatible with late formation of the deuterons

– More precision studies within reach with the large data samples collected in Run 3 & 4.
Thank You
Backup
Femtoscopy used in the “traditional” way: known interaction $\rightarrow$ source determination

Determined using:
- p-p interaction: Argonne v18
- crosscheck using p-$\Lambda$ ($\chi$EFT LO and NLO)

Exponential tail is included to account for the effect due to the short lived strongly-decaying resonances

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

Gaussian source profile

Exponential tail (for the resonances)

Common universal core source for baryons

Fix the source at $< m_T >$ of the hadron-hadron pair under study
Two-body femtoscopy

\[ S(r) = (4\pi r_{\text{core}}^2)^{-3/2} \cdot \exp \left( -\frac{r^2}{4r_{\text{core}}^2} \right) \otimes \frac{1}{s} \exp \left( -\frac{r}{s} \right), \quad s = \beta \gamma \tau_{\text{res}} = \frac{p_{\text{res}}}{M_{\text{res}}} \tau_{\text{res}} \]

Gaussian source profile

Exponential tail added to account for the effect due to strong short-lived resonances

Small particle-emitting source created in pp and p–Pb collisions at the LHC.

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

Emission source Two-particle wave function
Detector Effects

$\Delta\eta$- $\Delta\phi$ distribution (same event normalised to mixed event distributions), averaged over the TPC radii. Triplets are rejected if track merging and track splitting effects are visible at small $\Delta\eta$-$\Delta\phi$.

DATA $\rightarrow$

MC $\rightarrow$
Delayed formation of the deuteron

- Source size increases due to \textit{late formation} of deuteron
  - As a result the measured interaction between proton and deuteron weakens

Case I: p and d are formed at the same time

Case II: delayed formation of d

\[ r_a = 1.059 \pm 0.04 \text{ fm} \]

\[ r_c = \text{larger source size } \approx 5 \text{ fm} \]
p-d correlation function


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Projector method

\[ C_{3}^{ij}(Q_{3}) = \int C_{2}(k_{ij}^{*}) W_{ij}(k_{ij}^{*}, Q_{3}) \, dk_{ij}^{*} \]

Input:
(proton-proton)

Outputs:
(proton-proton)-proton
(proton-proton)-Λ

\[ C(Q_{3}) \]

[ALICE Collaboration / Physics Letters B 805 (2020) 135419]
Projector method

\[ C_{3ij}(Q_3) = \int C_2(k^*) W_{ij}(k^*, Q_3) \, dk^* \]

Inputs:
- (proton-proton)-proton
- (proton-proton)-\( \Lambda \)

Outputs:
- Data-driven approach VS Projector method

[ALICE Collaboration / Physics Letters B 805 (2020) 135419]
Projector method

\[ C_{ij}^{\alpha}(Q_3) = \int C_2(k^*) W_{ij}(k^*, Q_3) \, dk^* \]

**Input:** proton-\(\Lambda\)

**Outputs:**

(proton-\(\Lambda\))-proton

---

**Projector method**

\[
C_{ij}^{ij}(Q_3) = \int C_2(k_{ij}^*) W_{ij}(k_{ij}^*, Q_3) \, dk_{ij}^*
\]

**Outputs:**
(proton-Λ)-proton

**Data-driven approach VS Projector method**

Projector method

\[ C_{ij}^{ij}(Q_3) = \int C_2(k^*) W_{ij}(k^*, Q_3) \, dk^*_ij \]

Output:
(proton-K⁺)-proton

Input:
proton-K⁺

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

\((p-K^+) \oplus (\bar{p}-K^-)\) Projected

NEW

\[ C(Q_3) \]

\[ C(k^*) \]

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Projector method

\[ C_{ij}^{ij}(Q_3) = \int C_{2}(k^*) W_{ij}(k^*, Q_3) \, dk^* \]

**Input:** proton-K⁺

**Output:** (proton-K⁺)-proton

Data-driven approach VS Projector method
p-p-Λ Correlation Function

p-p-Λ correlation function

Lower-order correlations

**ALICE Preliminary**

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

C($Q_3$) vs. $Q_3$ (GeV/c)
p-p-K⁻ Correlation Function

**p-p-K⁻ correlation function**

**Lower-order correlations**

**NEW**

ALICE Preliminary

pp \( \sqrt{s} = 13 \) TeV

High Mult. (0–0.17% INEL)

\( (p\cdot p\cdot K^-) \oplus (\bar{p}\cdot \bar{p}\cdot K^+) \)

\( (p\cdot p\cdot K^-) + 2 \times p\cdot(p\cdot K^-) - 2 \)

\( \Lambda(1520) \)

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ALI-PREL-513629

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The measured correlation function includes also misidentified particles and and feed-down particles coming from decays of resonances. Total measured function thus is:

\[ C(XYZ) = \sum_{i,j,k} \lambda_{i,j,k}(XYZ)C_{i,j,k}(XYZ) = \lambda_{X_0,Y_0,Z_0}(XYZ)C_{X_0,Y_0,Z_0}(XYZ) + \sum_{ijk\neq X_0Y_0Z_0} \lambda_{i,j,k}(XYZ)C_{i,j,k}(XYZ) \]

- The cumulant is calculated with the measured correlation functions not accounting for the \( \lambda \) parameters.

\[ \lambda_{i,j,k}(XYZ) = \mathcal{P}(X_i)f(X_i)\mathcal{P}(Y_j)f(Y_j)\mathcal{P}(Z_k)f(Z_k) \]

\( c(XYZ) = \sum_{i,j,k} \lambda_{i,j,k}(XYZ)c(X_iY_jZ_k) = \lambda_{X_0,Y_0,Z_0}(XYZ)c(X_0Y_0Z_0) + \sum_{i,j,k\neq (X_0Y_0Z_0)} \lambda_{i,j,k}(XYZ)c(X_iY_jZ_k) \)

- The genuine three body interaction for the feed-down and misidentified particle contributions is currently not known.
● The $\lambda$ parameters requires purity and the secondary fraction evaluation.
● The average $\Lambda$ purity is 95.57% and for protons the purity is 98.34%.
● The fractions of secondaries are estimated using Monte Carlo simulations.

Some of the contributions with highest lambda parameters:

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p-p-p$</td>
<td>61.8%</td>
</tr>
<tr>
<td>$p-p-p_\Lambda \times 3$</td>
<td>19.6%</td>
</tr>
<tr>
<td>$p-p-p_\Sigma \times 3$</td>
<td>8.5%</td>
</tr>
<tr>
<td>$p-p_\Lambda-p_\Lambda \times 3$</td>
<td>0.69%</td>
</tr>
<tr>
<td>$p-p_\Lambda-p_\Sigma \times 3$</td>
<td>0.3%</td>
</tr>
<tr>
<td>$p-p_\Sigma^- p_\Sigma^+ \times 3$</td>
<td>0.13%</td>
</tr>
<tr>
<td>$p-p-\Lambda$</td>
<td>40.5%</td>
</tr>
<tr>
<td>$p-p-\Lambda_{\Sigma^0}$</td>
<td>13.5%</td>
</tr>
<tr>
<td>$p-p-\Lambda_{\Xi^0}$</td>
<td>7.56%</td>
</tr>
<tr>
<td>$p-p-\Lambda_{\Xi^-}$</td>
<td>7.56%</td>
</tr>
<tr>
<td>$p-p_\Lambda-\Lambda \times 2$</td>
<td>8.56%</td>
</tr>
<tr>
<td>$p-p_\Sigma^- - \Lambda \times 2$</td>
<td>3.7%</td>
</tr>
</tbody>
</table>