Probing the genuine three-baryon interactions using femtoscopy in pp collisions with ALICE

Laura Šerkšnytė[1], Raffaele Del Grande[1,*]

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

On behalf of the ALICE Collaboration

HADRON 2021: 19th International Conference on Hadron Spectroscopy and Structure

27th July 2021

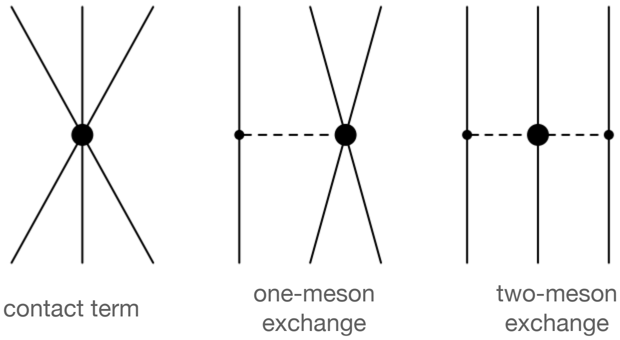
***raffaele.del-grande@tum.de**

Three-body forces

- Many-body systems **cannot be described satisfactorily** with two-body forces only.

- Fundamental ingredient for the microscopic description of the **equation of state** of neutron stars.

Three-baryon interaction diagrams in χEFTs



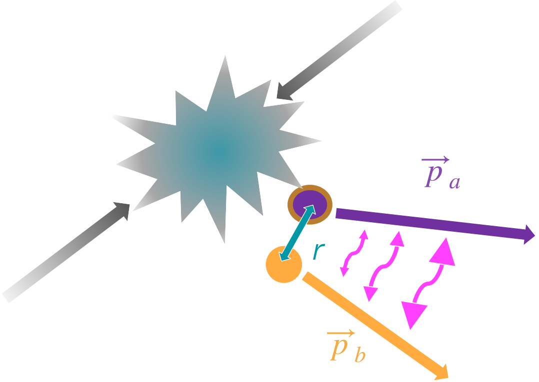
- The parameters of the models are tuned using the binding energies of nuclei and hypernuclei but…
  1. such measurements yield the **superposition of two- and many-body effects**;
  2. the interaction is tested at **“large” distances.**

     ➡ In ^{12}C the average distance among nucleons is $< d > \sim 2.2$ fm

Investigating hadronic interactions at LHC

ALICE at the LHC

Hadron-hadron strong interactions

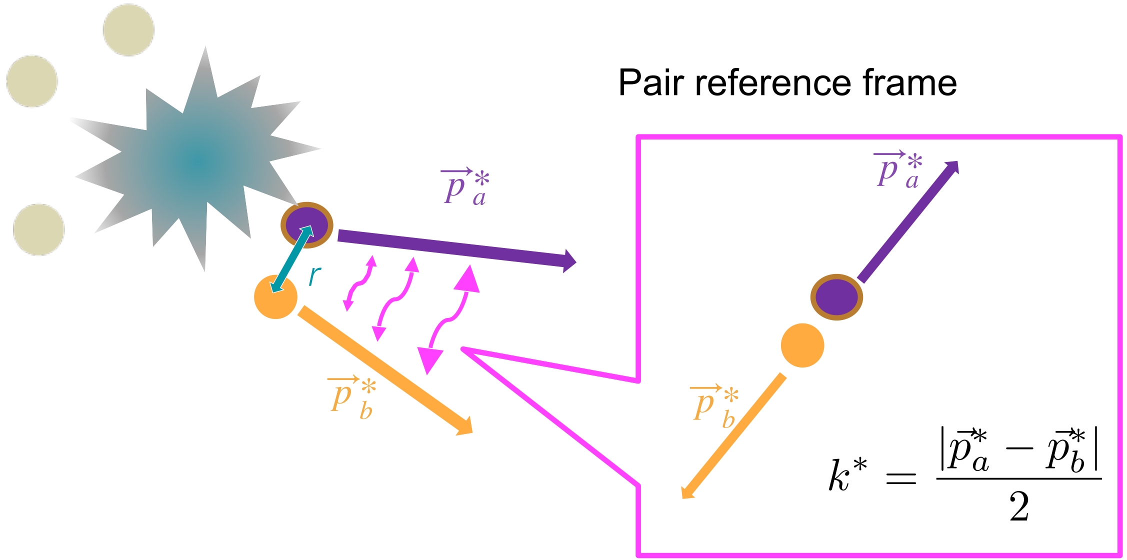


Femtoscopy technique

Two-body correlation function

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

Two-body femtoscopy



Schrödinger Equation:

V(r) -> $\left|\psi\left(k^*, r\right)\right|^2$ relative wave function for the pair

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

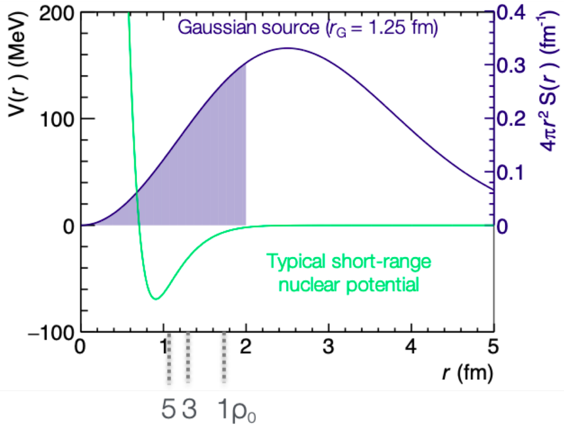
Emission source   Two-particle wave function

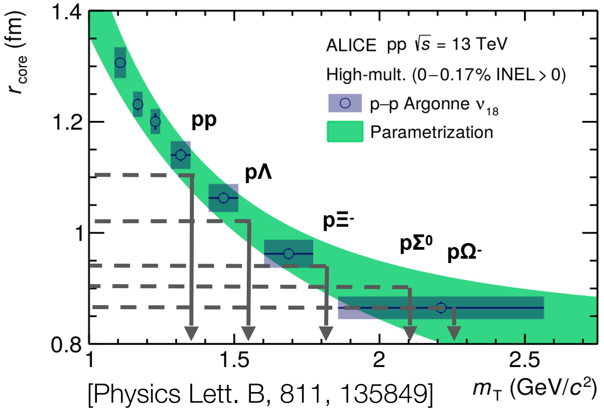
Two-body femtoscopy

Gaussian source profile

$$S(r) = (4\pi r_0^2)^{-3/2} \cdot \exp\left(-\frac{r^2}{4r_0^2}\right)$$

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





[Physics Lett. B, 811, 135849]

Schrödinger Equation:

V(*r*) -> $\left|\psi\left(k^*, r\right)\right|^2$ relative wave function for the pair

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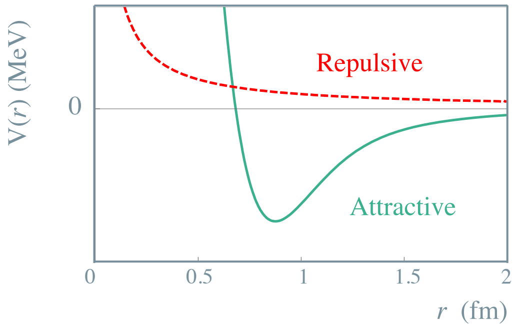
Emission source   Two-particle wave function

Two-body femtoscopy

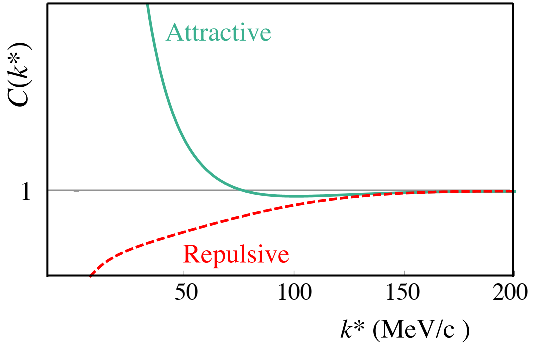
Given the source function the interaction model is tested:

Interacting potential



→

Correlation function



Schrödinger Equation:

V(*r*) -> $\left|\psi\left(k^*, r\right)\right|^2$ relative wave function for the pair

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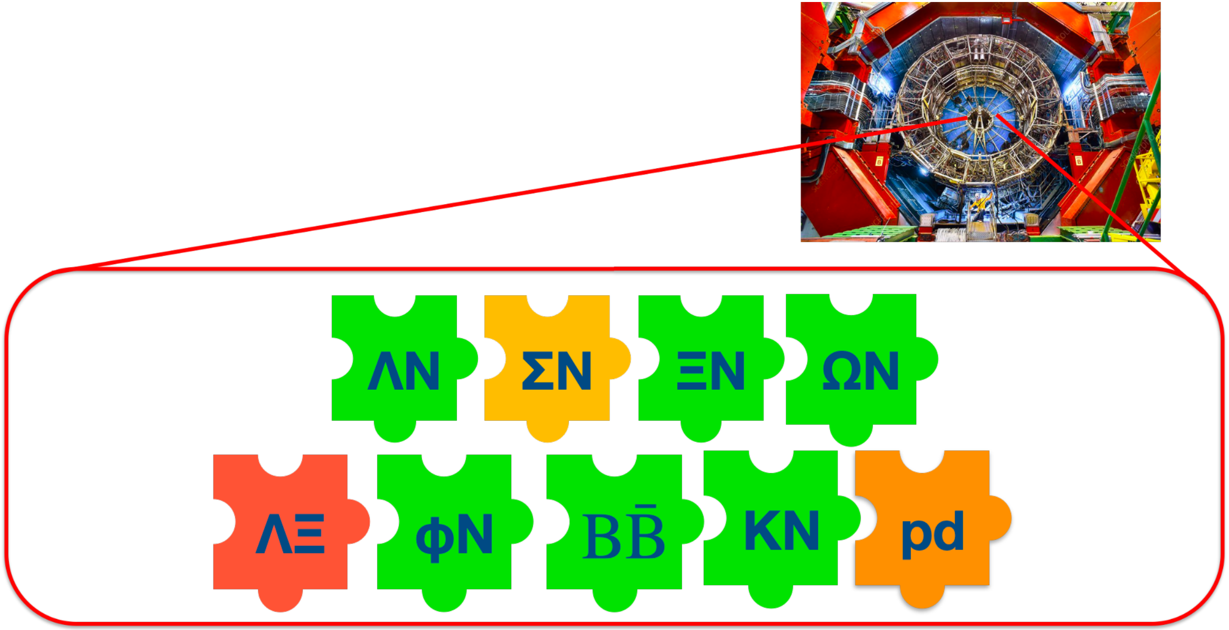
Emission source Two-particle wave function

- >1 if the interaction is attractive
- = 1 if there is no interaction
- <1 if the interaction is repulsive

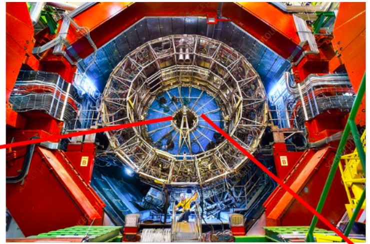
Two-body femtoscopy: achieved results

1. PRC 99 (2019) 024001
2. PLB 797 (2019) 134822
3. PRL 123 (2019) 112002
4. PRL 124 (2020) 09230
5. PLB 805 (2020) 135419
6. PLB 811 (2020) 135849
7. Nature 588 (2020) 232-238
8. ALICE Coll. arXiv:2104.04427
9. ALICE Coll. arXiv:2105.05578
10. ALICE Coll. arXiv:2105.05683
11. ALICE Coll. arXiv:2105.05190



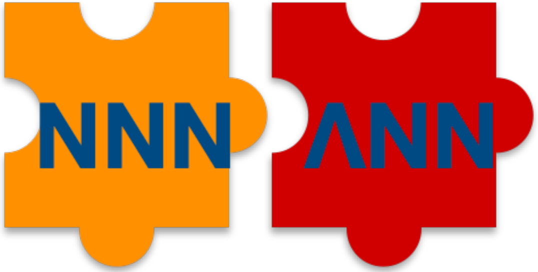
see L. Fabbietti's talk
tomorrow at 9.00 a.m.

Investigating three-body interactions at the LHC



First femtoscopic measurement of p-p-Λ and p-p-p

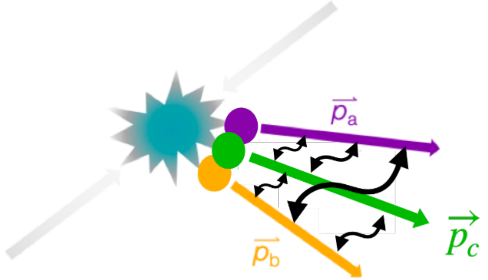
Colliding system: pp @ $\sqrt{s}$ = 13 TeV
Data set: High Multiplicity events



- purity of p: 98.3%
- purity of Λ: 95.7%

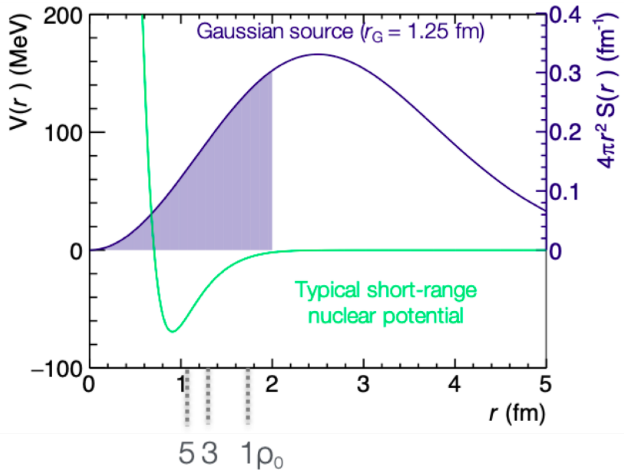
Three-body femtoscopy at the LHC

Three particles are emitted from a same common source and may undergo *final-state interactions* before the detection.



Advantages:

- **Not affected by nuclear medium effects** which are instead present in bound objects;
- The typical source radii in two-body femtoscopy is ~1.25 fm
  → **test of the interaction at short distances**



Three-body correlation function

Two-body correlation function

$$C(\mathbf{p}_1, \mathbf{p}_2) \equiv \frac{P(\mathbf{p}_1, \mathbf{p}_2)}{P(\mathbf{p}_1) \cdot P(\mathbf{p}_2)} = \mathcal{N} \cdot \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

➡

Three-body correlation function

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

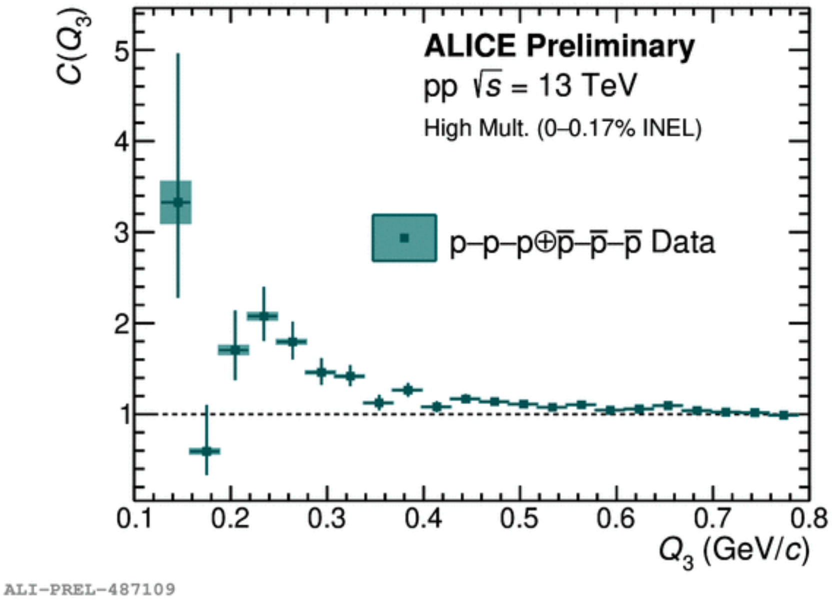
The small statistics requires to project the correlation function on **1-dimensional** observable.
The Lorentz invariant Q_3 is defined as:

$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}$$

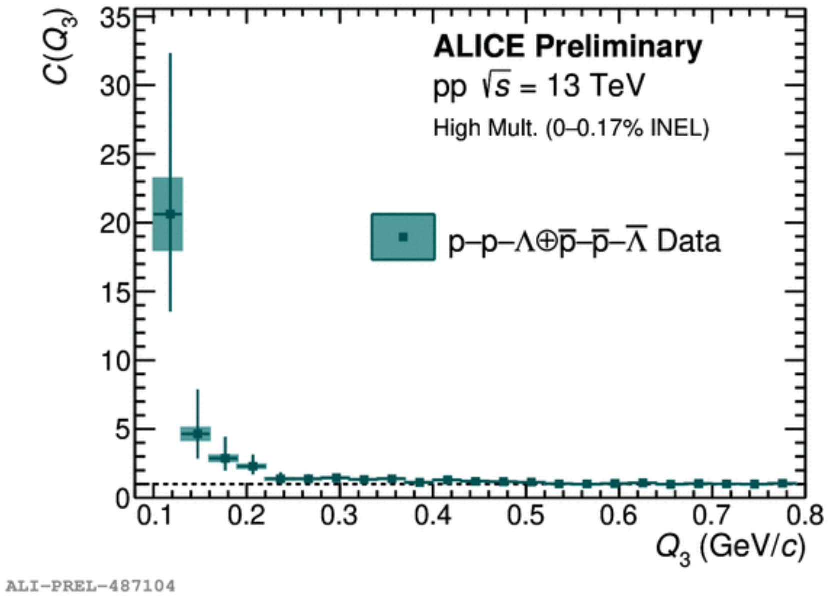
$$q^\mu = \left(p_i - p_j\right)^\mu - \frac{\left(p_i - p_j\right) \cdot P}{P^2} P^\mu \qquad P \equiv p_i + p_j$$

p-p-p and p-p-Λ Correlation Functions

Measured triplets
at $Q_3 < 0.4$ GeV/c ----> 1011 triplets



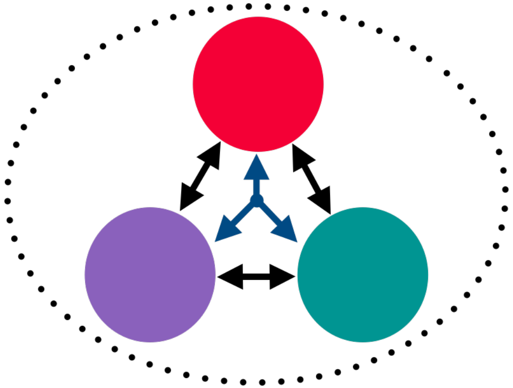
Measured triplets
at $Q_3 < 0.4$ GeV/c ----> 496 triplets



<u>These are not genuine three-body correlation functions</u>

Accessing the genuine three-body correlation

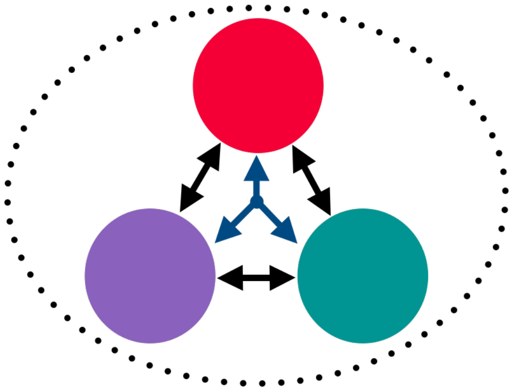
- Measured three-particle correlation function includes both two-body and genuine three-body interactions.



Accessing the genuine three-body correlation

- Measured three-particle correlation function includes both two-body and genuine three-body interactions.

- Kubo's cumulant expansion method is used and to access genuine three-body correlation.

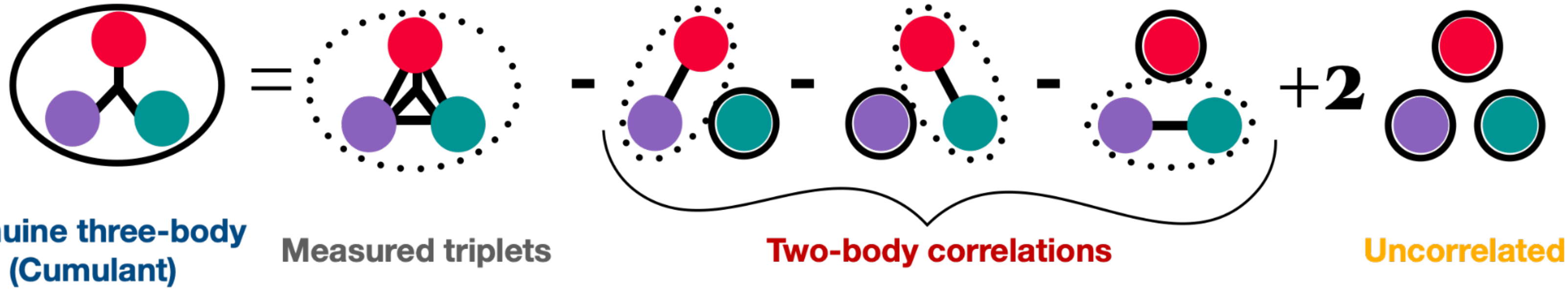


JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN, Vol. 17, No. 7, JULY 1962

Generalized Cumulant Expansion Method*

Ryogo KUBO
Department of Physics, University of Tokyo
(Received April 11, 1962)

Kubo’s cumulant expansion method



In terms of correlation functions:

$$\mathbf{c}_3\left(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3\right) = C([\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3]) - \underbrace{C([\mathbf{p}_1, \mathbf{p}_2], \mathbf{p}_3) - C(\mathbf{p}_1, [\mathbf{p}_2, \mathbf{p}_3]) - C([\mathbf{p}_1, \mathbf{p}_3], \mathbf{p}_2)} + 2$$

Genuine three-body (Cumulant) — Measured triplets — Two-body correlations — Uncorrelated

The pairs in the square brackets are correlated, the particle outside is not correlated.

Lower order contributions evaluation

Data-driven approach

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

$$C([\mathbf{p}_1, \mathbf{p}_2], \mathbf{p}_3) = \frac{N_2(\mathbf{p}_1, \mathbf{p}_2)\ N_1(\mathbf{p}_3)}{N_1(\mathbf{p}_1)\ N_1(\mathbf{p}_2)\ N_1(\mathbf{p}_3)}$$

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

$$(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \rightarrow Q_3$$

Projector method

[R. Del Grande, L. Šerkšnytė et al, arXiv:2107.10227v1 (2021)]

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

A kinematic transformation from

$$k^*_{12}\ \text{(pair)} \rightarrow Q_3\ \text{(triplet)}$$

$$C(k^*_{12}) \rightarrow C(Q_3)$$

is performed.

For the pair i-j we have

$$C_3^{ij}(Q_3) = \int C_2(k^*_{ij})\ W_{ij}(k^*_{ij}, Q_3)\ dk^*_{ij}$$

two-body correlation function

projector

Lower order contributions evaluation

Data-driven approach

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

$$C([\mathbf{p}_1,\mathbf{p}_2],\mathbf{p}_3) = \frac{N_2(\mathbf{p}_1,\mathbf{p}_2)\ N_1(\mathbf{p}_3)}{N_1(\mathbf{p}_1)\ N_1(\mathbf{p}_2)\ N_1(\mathbf{p}_3)}$$

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For the pair i-j we have

$$C_3^{ij}(Q_3) = \int \underbrace{C_2(k^*_{ij})}_{\text{two-body correlation function}} \underbrace{W_{ij}(k^*_{ij}, Q_3)}_{\text{projector}}\ dk^*_{ij}$$

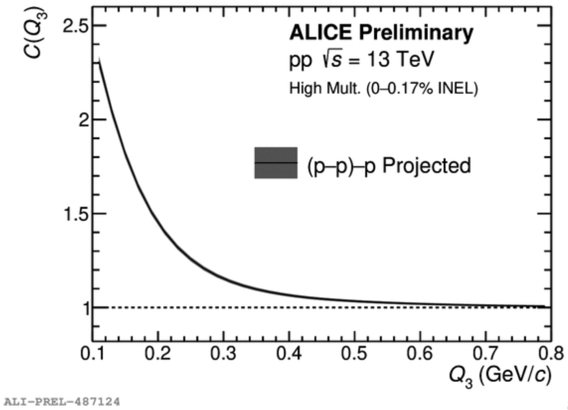
Two-body correlations

$$C_{ij}(Q_3) = \int C_{ij}(k^*) \cdot W_{ij}(k^*, Q_3)\; dk^*$$

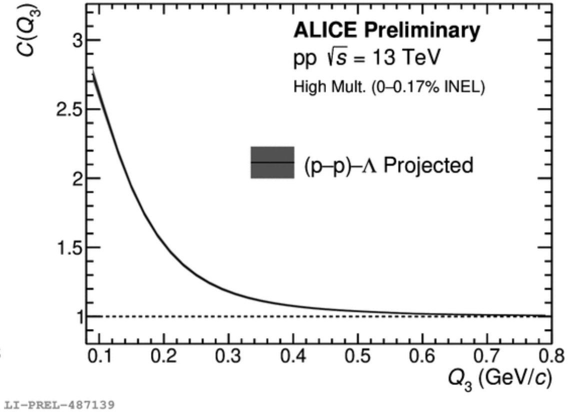
Outputs:

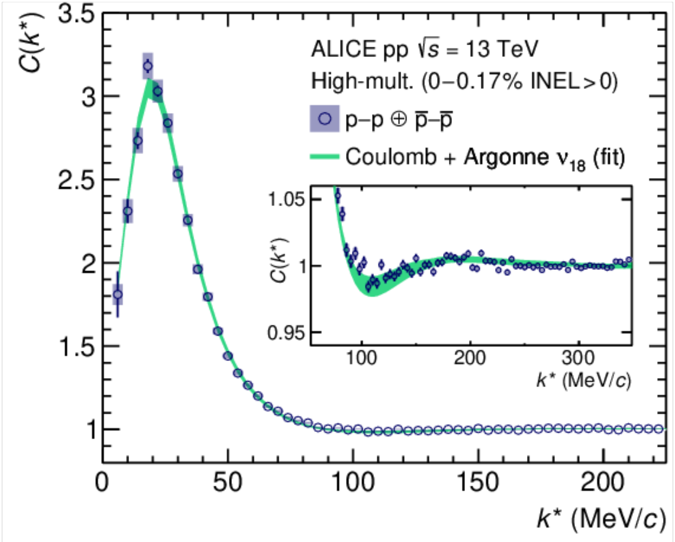
Input:
proton-proton

(proton-proton)-proton



(proton-proton)-Λ





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

Two-body correlations

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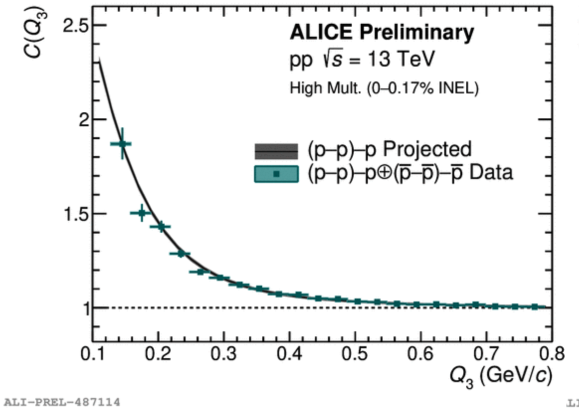
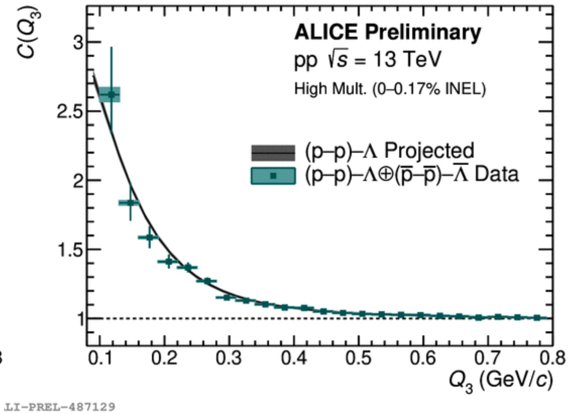
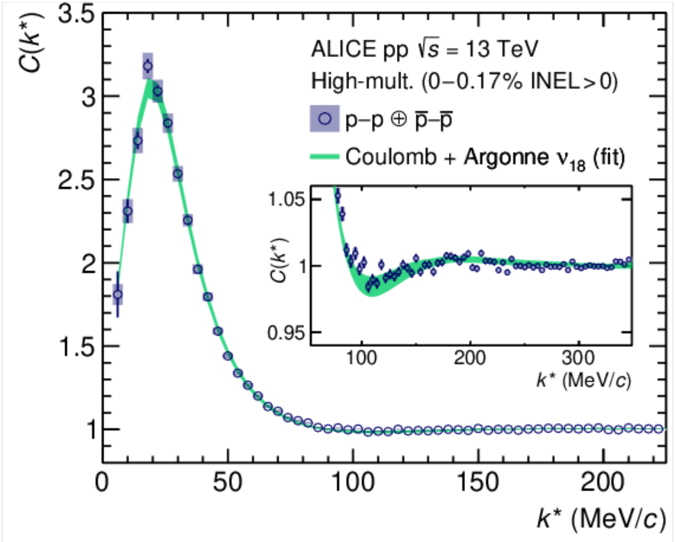


(proton-proton)-Λ





Data-driven approach VS **Projector method**

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

Two-body correlations

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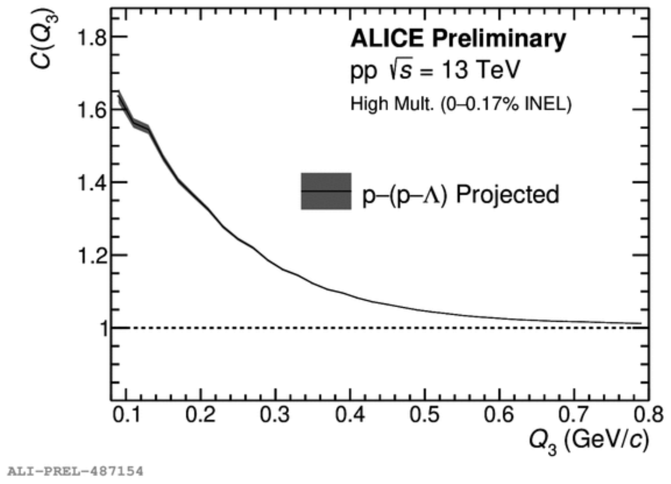
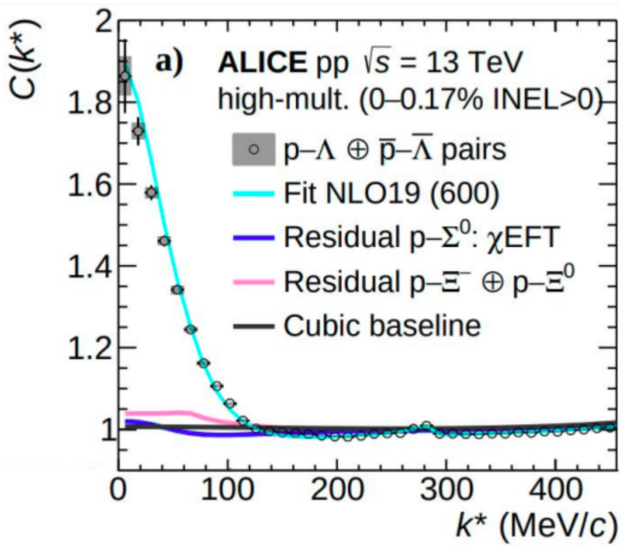
Output:

(proton-Λ)-proton



Input:

proton-Λ



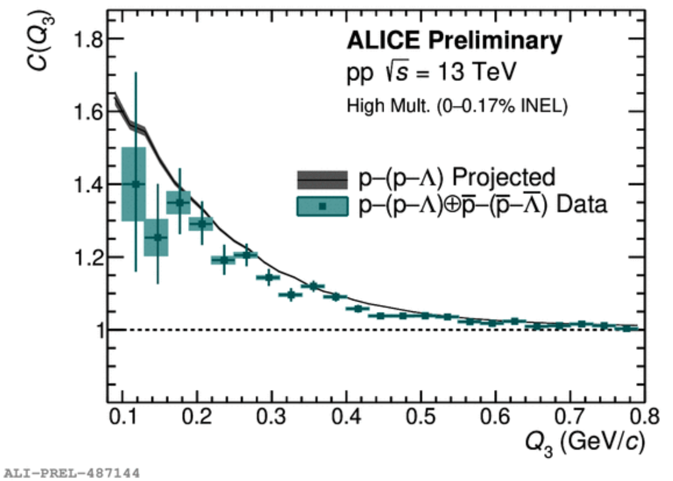
[ALICE Collaboration / arXiv:2104.04427 (submitted to PRL)]

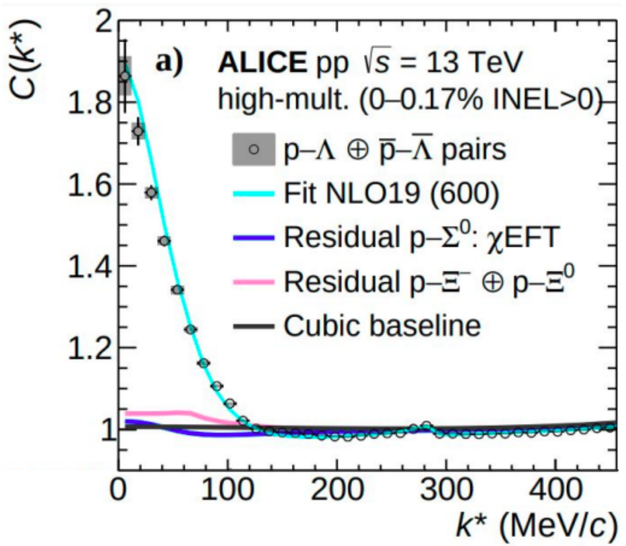
Two-body correlations

$$C_{ij}(Q_3) = \int C_{ij}(k^*) \cdot W_{ij}(k^*, Q_3)\ dk^*$$

Output:
(proton-Λ)-proton

Input:
proton-Λ





Data-driven approach VS **Projector method**

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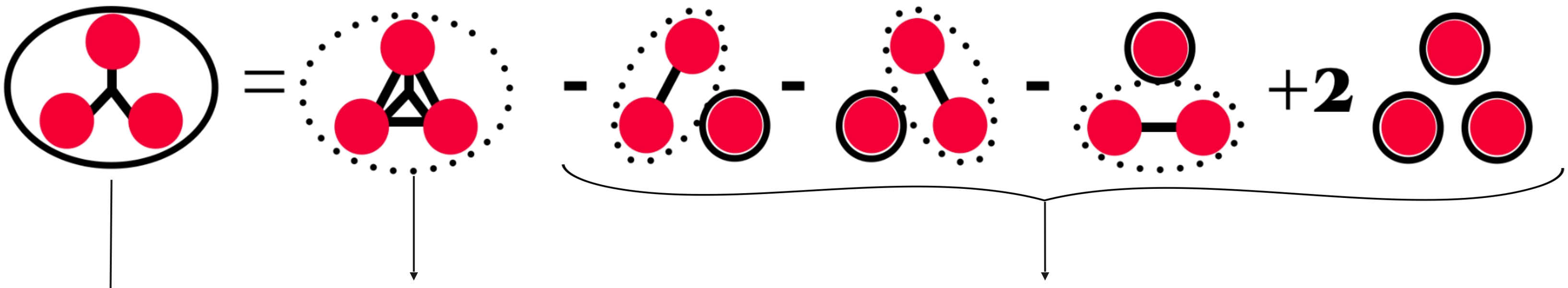
Kubo's Cumulant expansion method

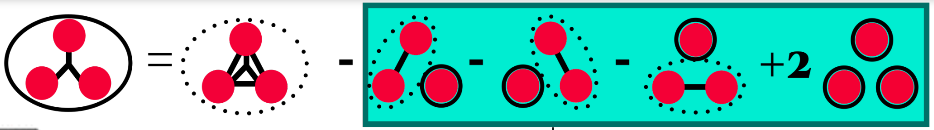


Measured correlation function

Lower-order correlations

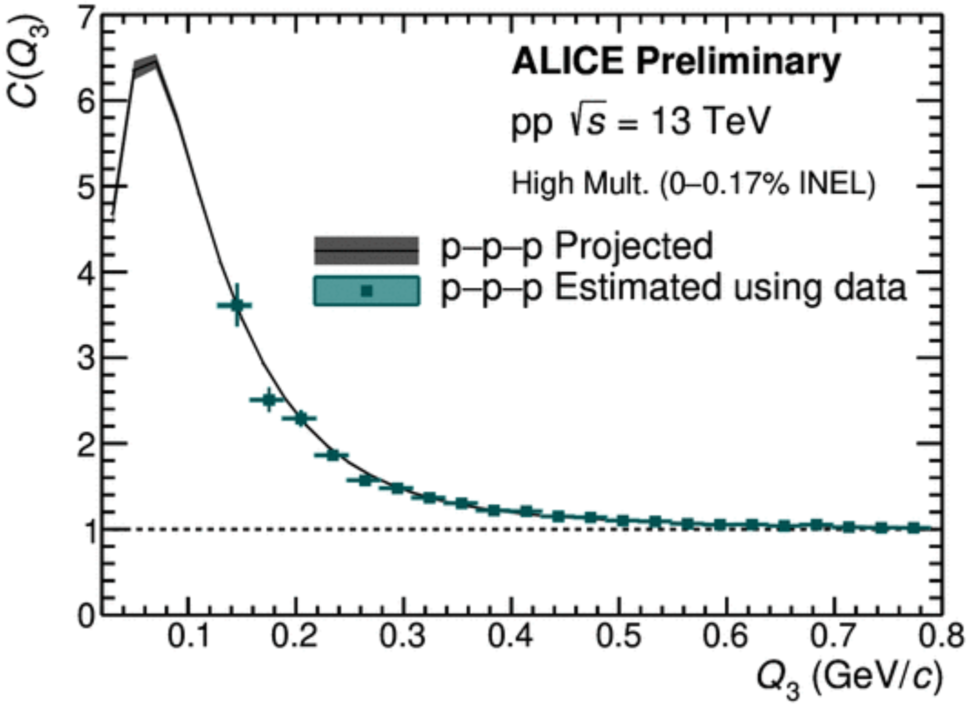
Three-body cumulant
(to be extracted)

p-p-p: two-body CF projected onto Q_3



Lower-order contributions to the three-body cumulant

$$C_{ppp}^{\text{two-body}}(Q_3) = 3\ C_3^{pp}(Q_3) - 2$$

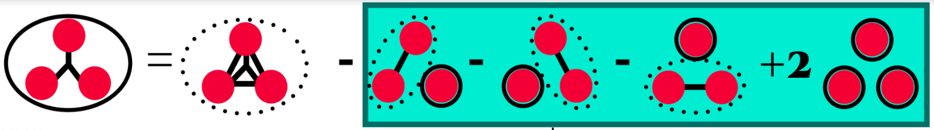


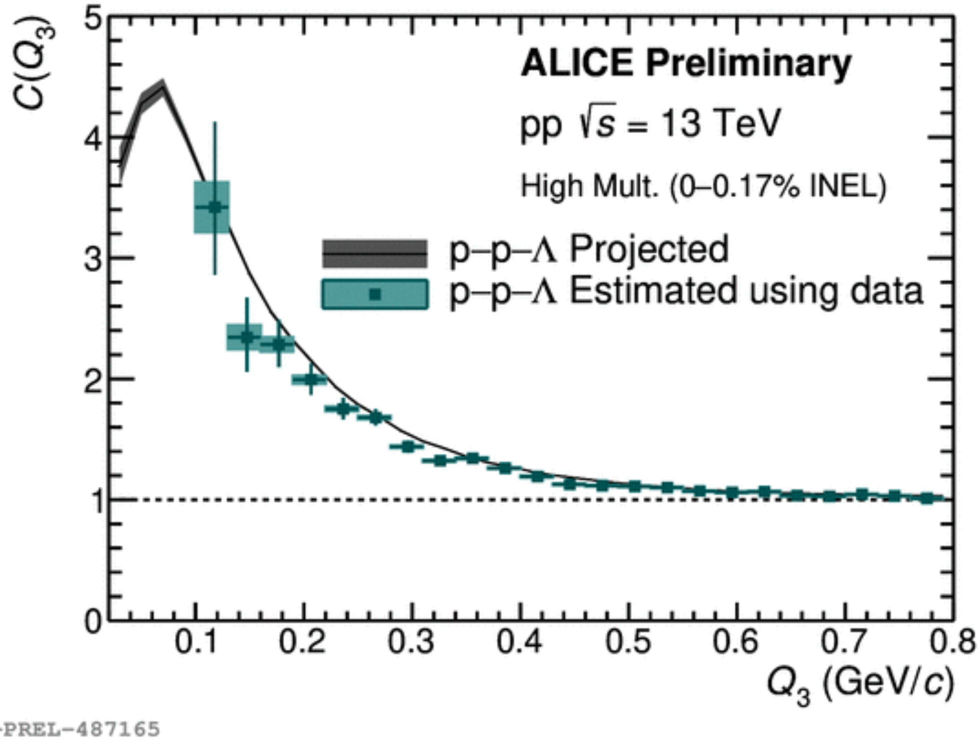
ALI-PREL-487159

Comparison:

- **Data-driven approach**
- **Projector method**

p-p-Λ: two-body CF projected onto Q_3





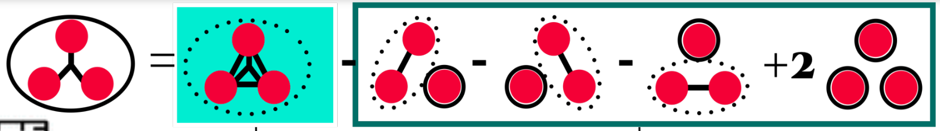
Lower-order contributions to the three-body cumulant

$$C_{pp\Lambda}^{\mathrm{two-body}}(Q_3) = C_3^{pp}(Q_3) + 2\ C_3^{p\Lambda}(Q_3) - 2$$

Comparison:

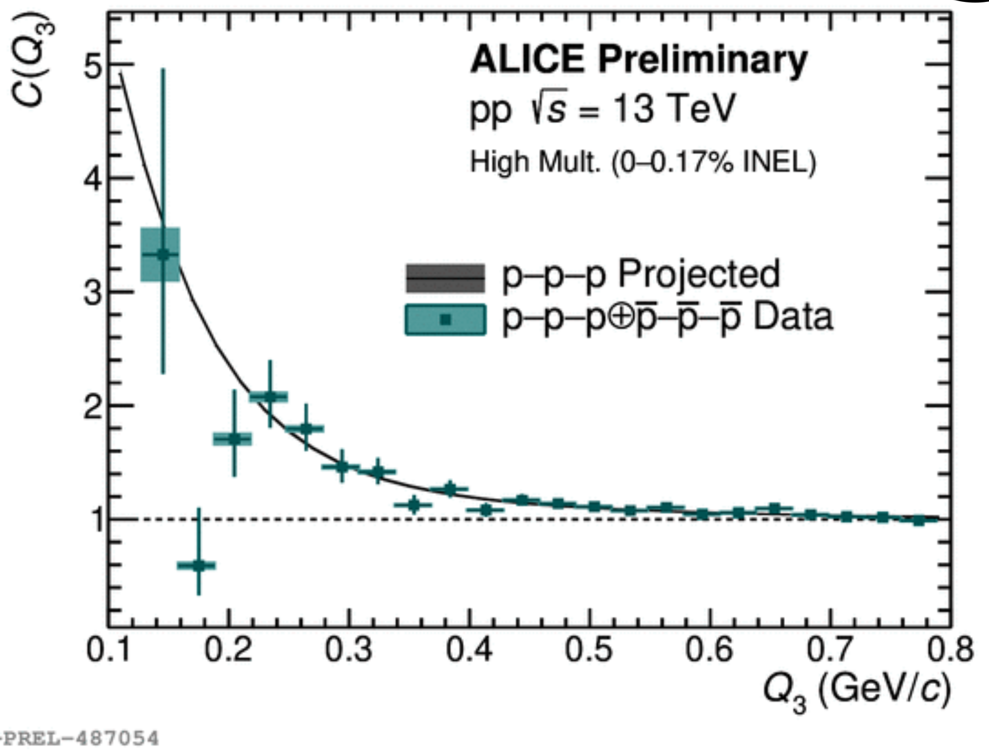
- **Data-driven approach**
- **Projector method**

p-p-p Correlation Function



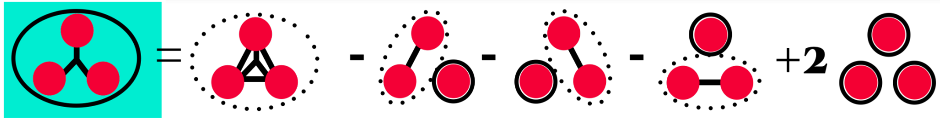
The measured p-p-p correlation function

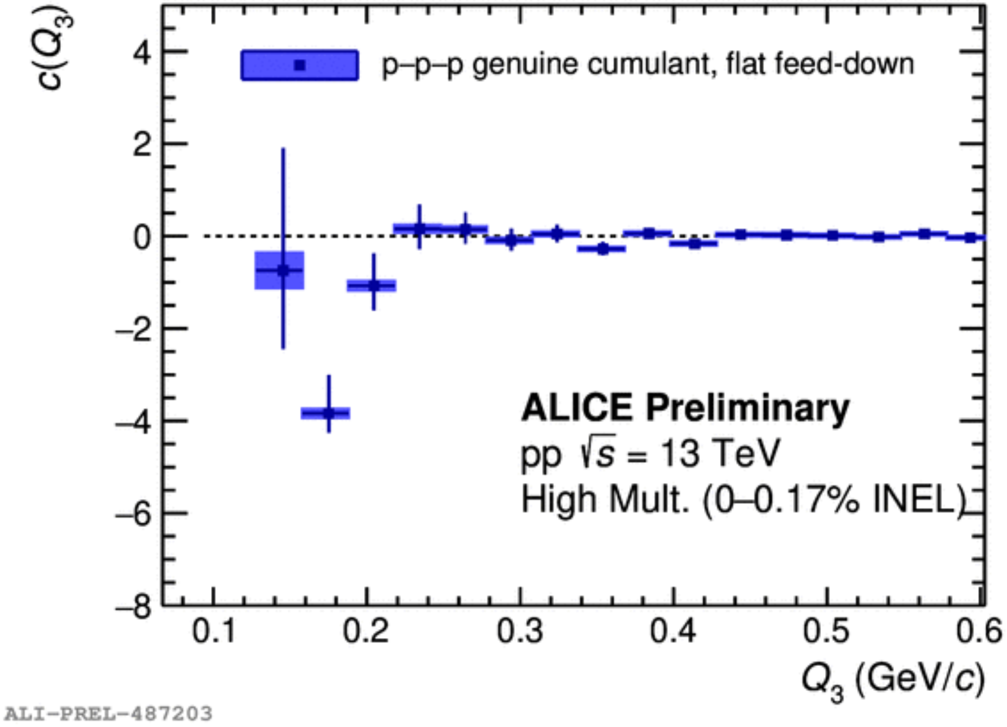
Lower-order contributions calculated with the projector method



Significant deviation of the measured correlation function from the two-body correlations projected onto Q_3 (gray curve).

p-p-p Cumulant





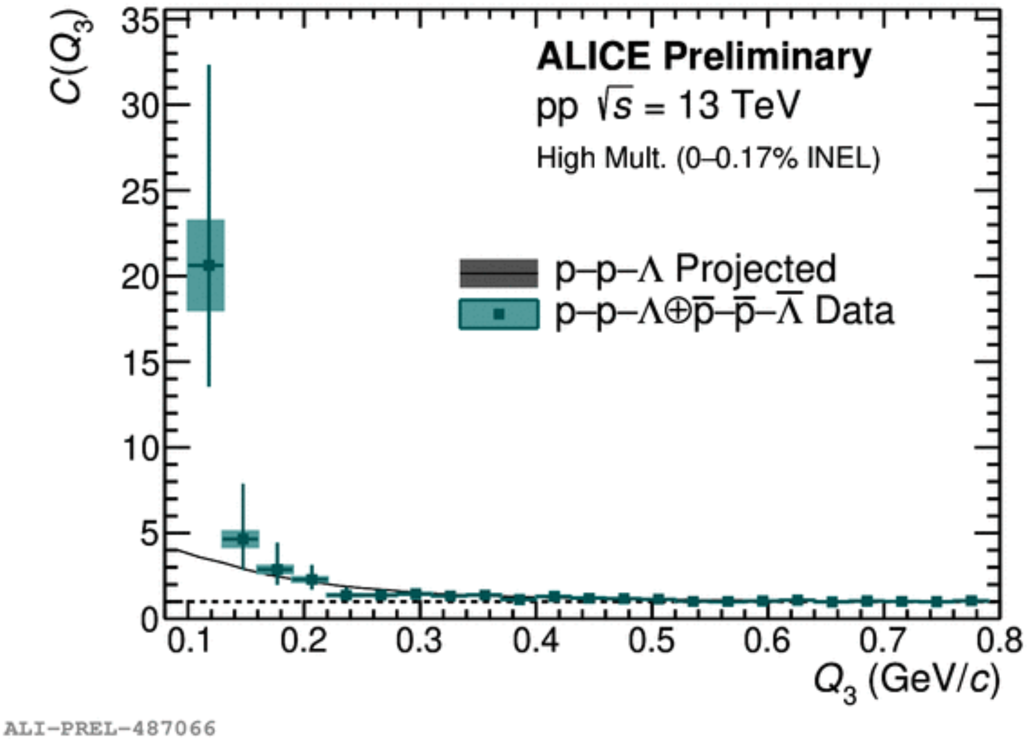
Cumulant extracted. The feed-down from the resonances is also considered.

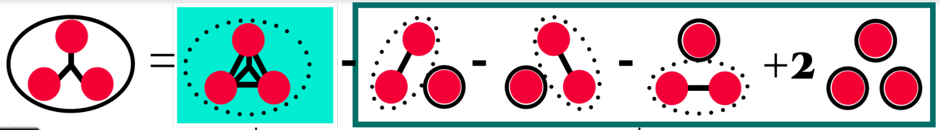
The statistical significance for the measured deviation is:

$n_\sigma = 2.9$ in the first 9 bins

Theoretical calculations of the three-body scattering are needed to interpret the data

p-p-Λ Correlation Function



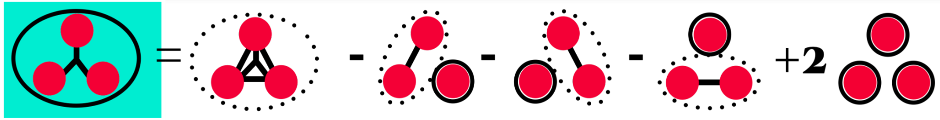


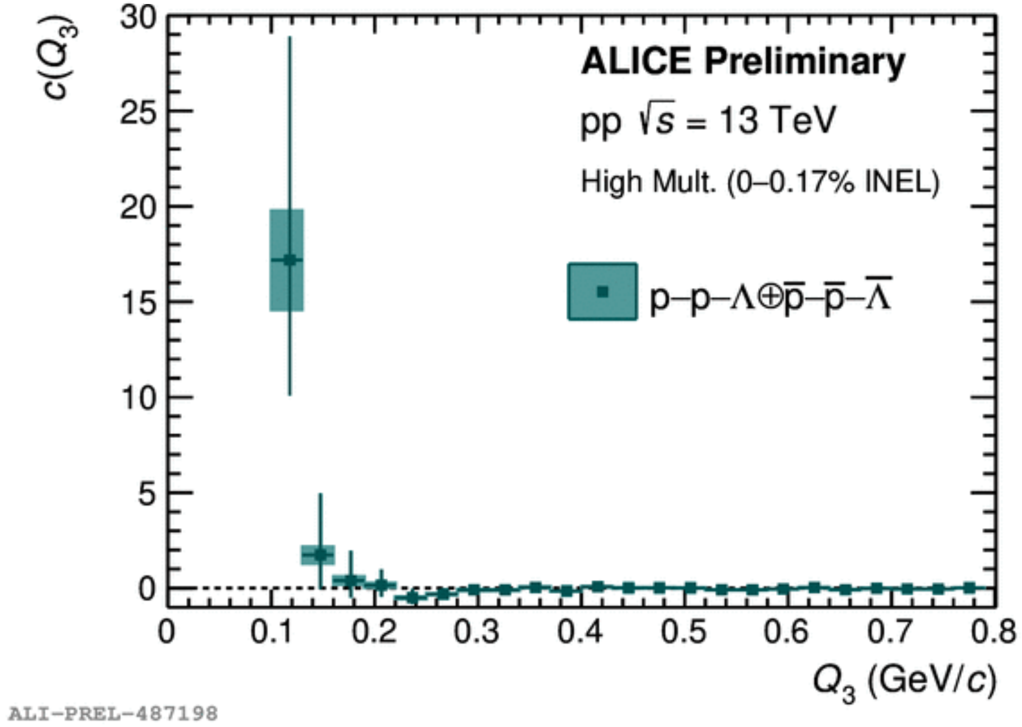
The measured p-p-Λ correlation function

Lower-order contributions calculated with the projector method

The shape deviates from the two-body correlations projected onto Q_3 (gray curve).

p-p-Λ Cumulant

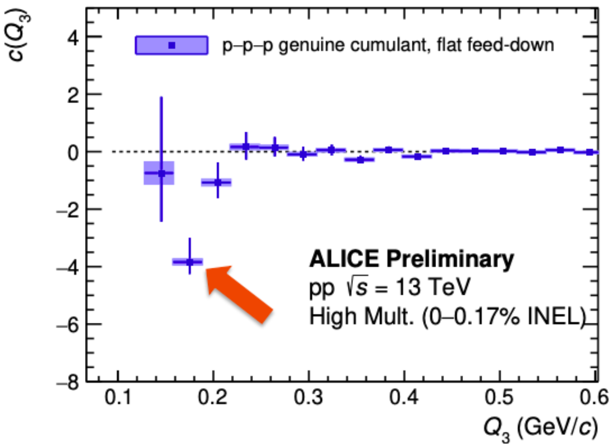


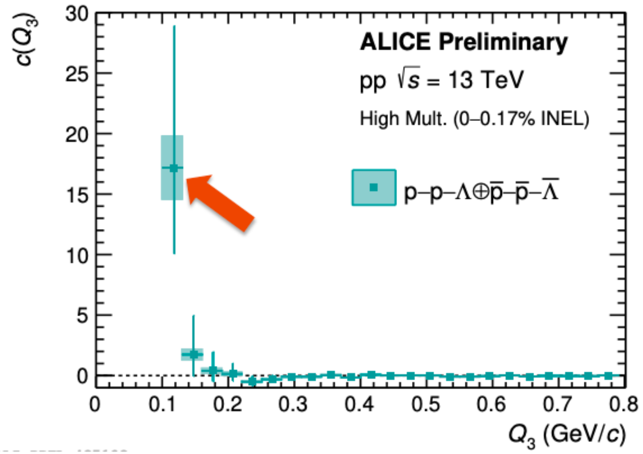


Positive cumulant for p-p-Λ

Summary

- First measurement of three-baryon correlation functions
- Cumulants for p-p-p and p-p-Λ extracted with the Kubo's method





- **p-p-p:** significant deviation (**n_σ = 2.9** in the first 9 bins)
  → FIRST HINT of genuine p-p-p correlation
- **p-p-Λ:** positive cumulant → ALICE Run 3 data should provide statistically significant result
- Calculations for the three-body scattering are needed

Thank You