Experimental hint of the genuine three-hadron interactions using femtoscopy in pp collisions with ALICE

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On behalf of the ALICE Collaboration
Technical University of Munich
PANIC2021

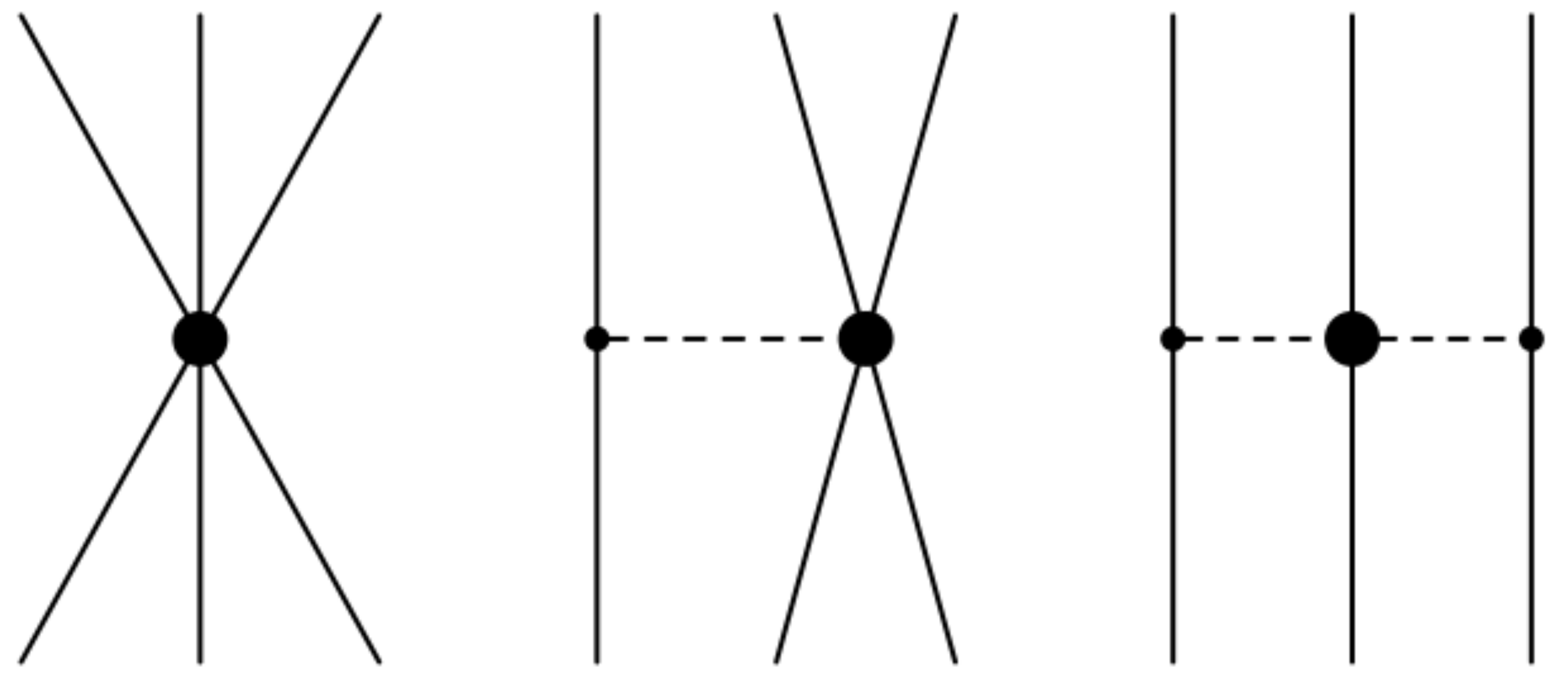
Three-body interactions

Necessary:

- to explain observed many-body systems,
- for the description of the Equation of State for neutron stars.

Three-baryon interaction diagrams in χEFTs

EPJA 56 (2020) 175



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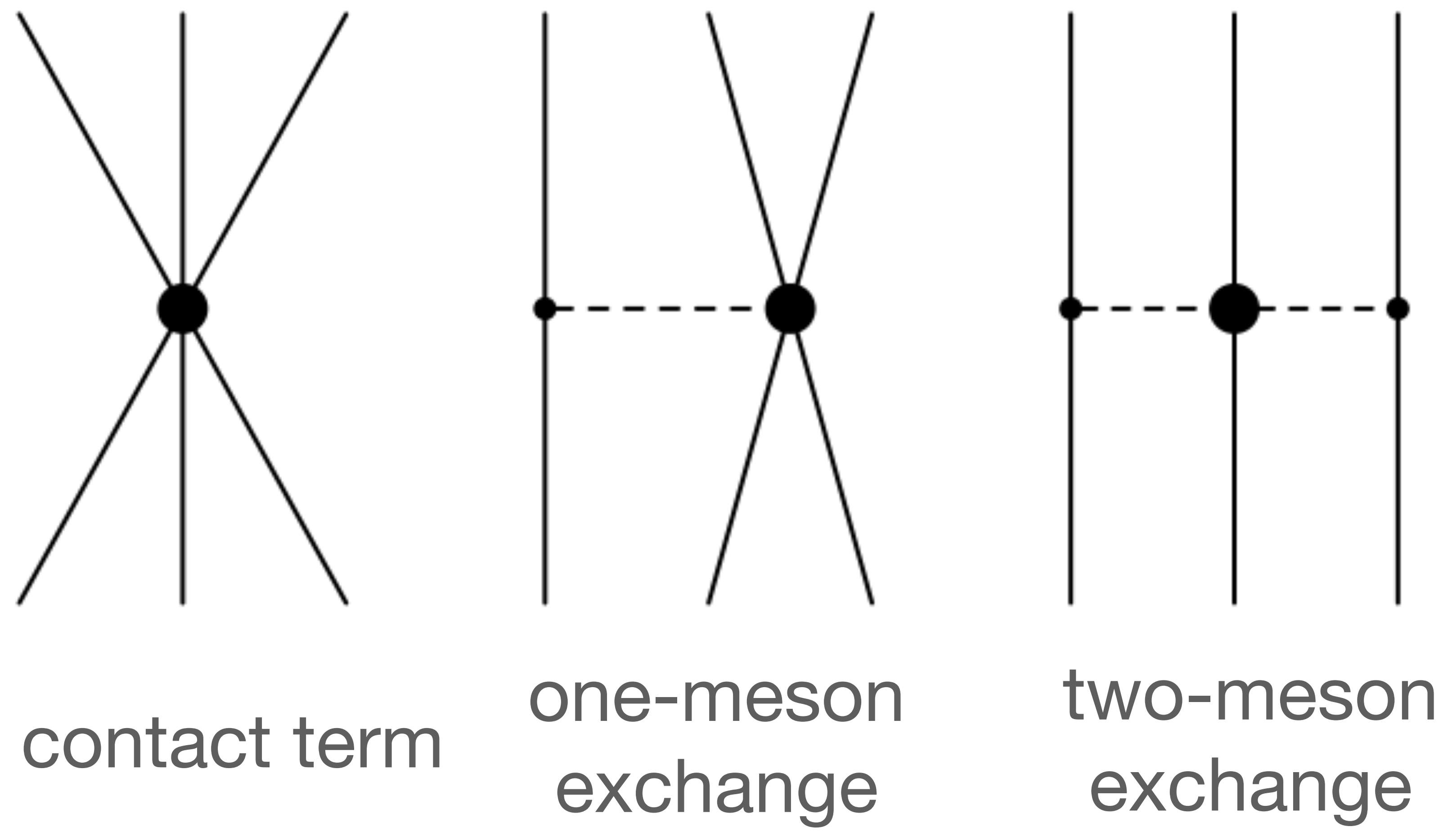

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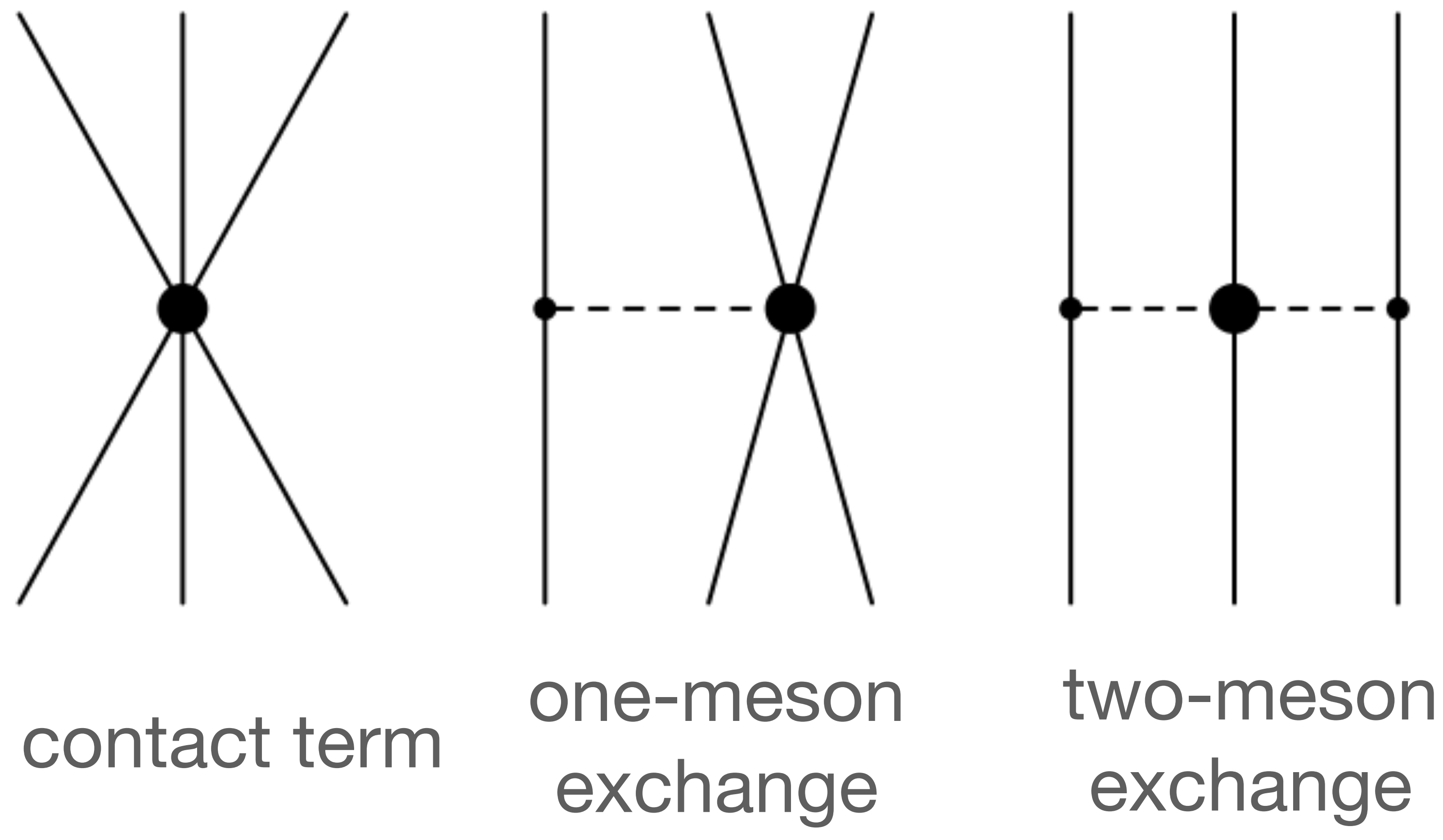


Are there any measurements to pin down many-body interactions?

Measurement of nuclei and hypernuclei binding energies, but

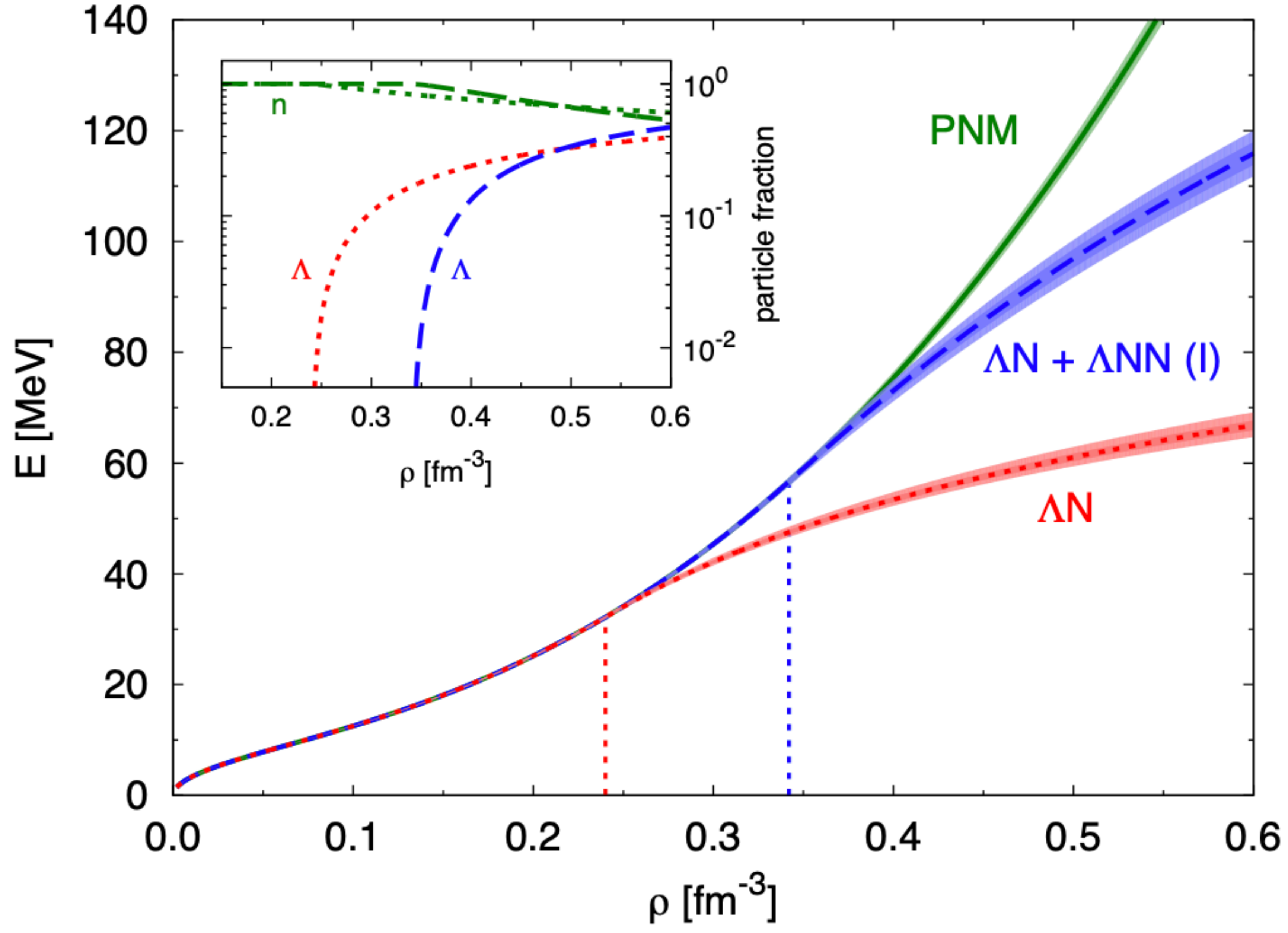
- the interaction is probed at “large” distances (around 2.2 fm in ^{12}C),
- the superposition of two- and many-body effects complicates the extraction of the genuine many-body interactions.

Three-body interactions in neutron stars

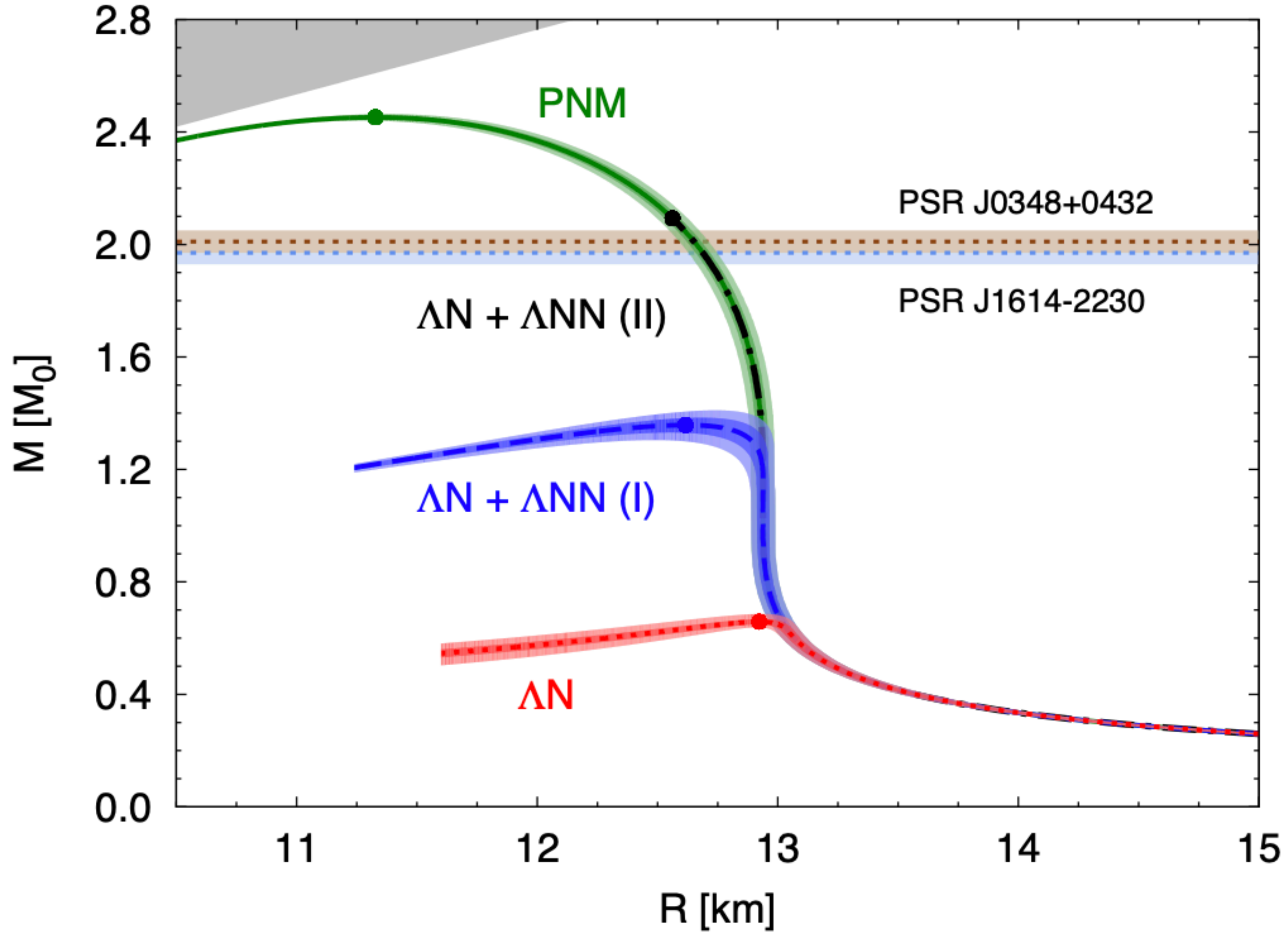
- ΛN softens the equations of state -> Only low-mass neutron stars possible.
- Observations -> Up to ~2 solar masses.
- One possible solution -> Include three body interaction.

Three-body interaction constrained using nuclei and hypernuclei data.

Phys. Rev. Lett. 114, 092301

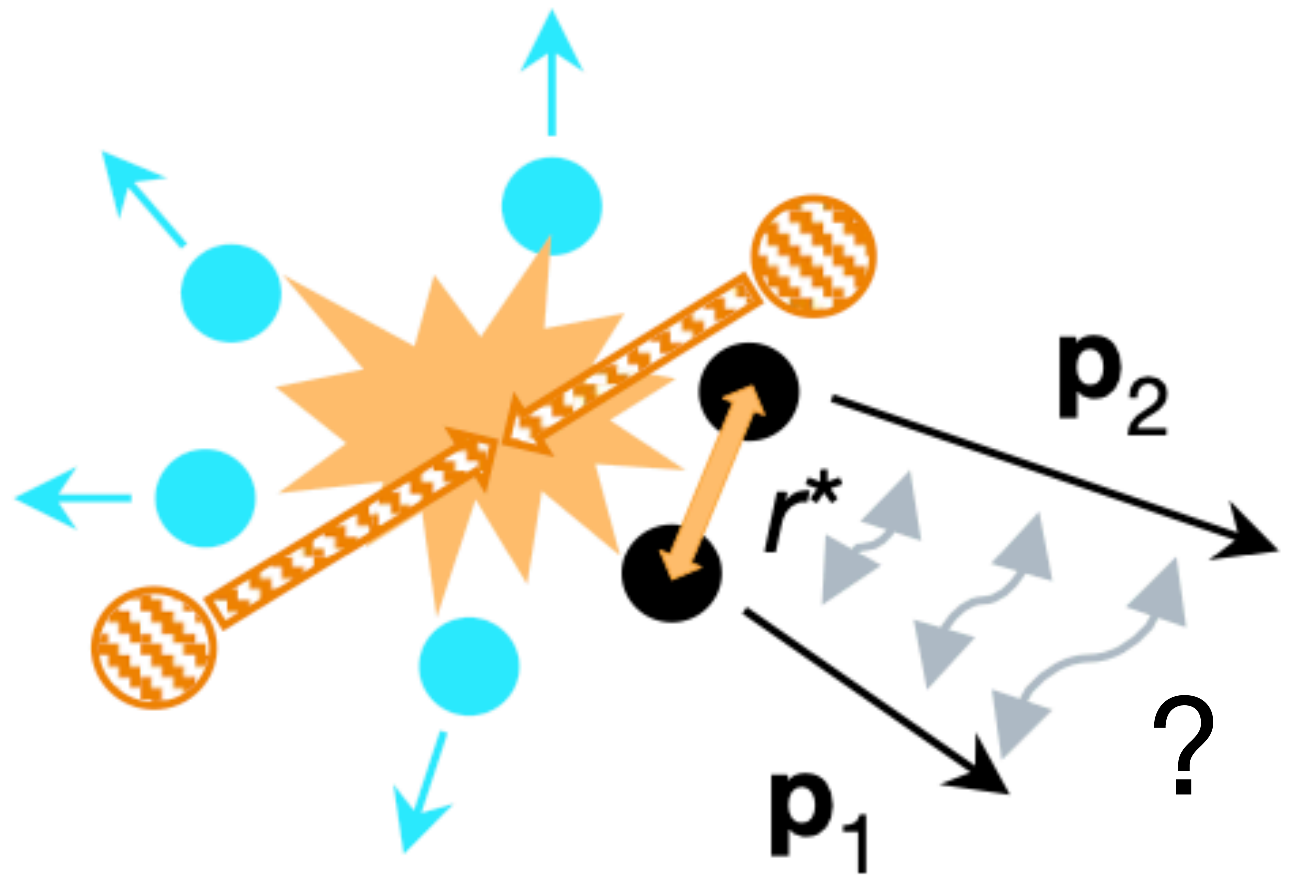


TOV equations



Are there other methods to study interaction?

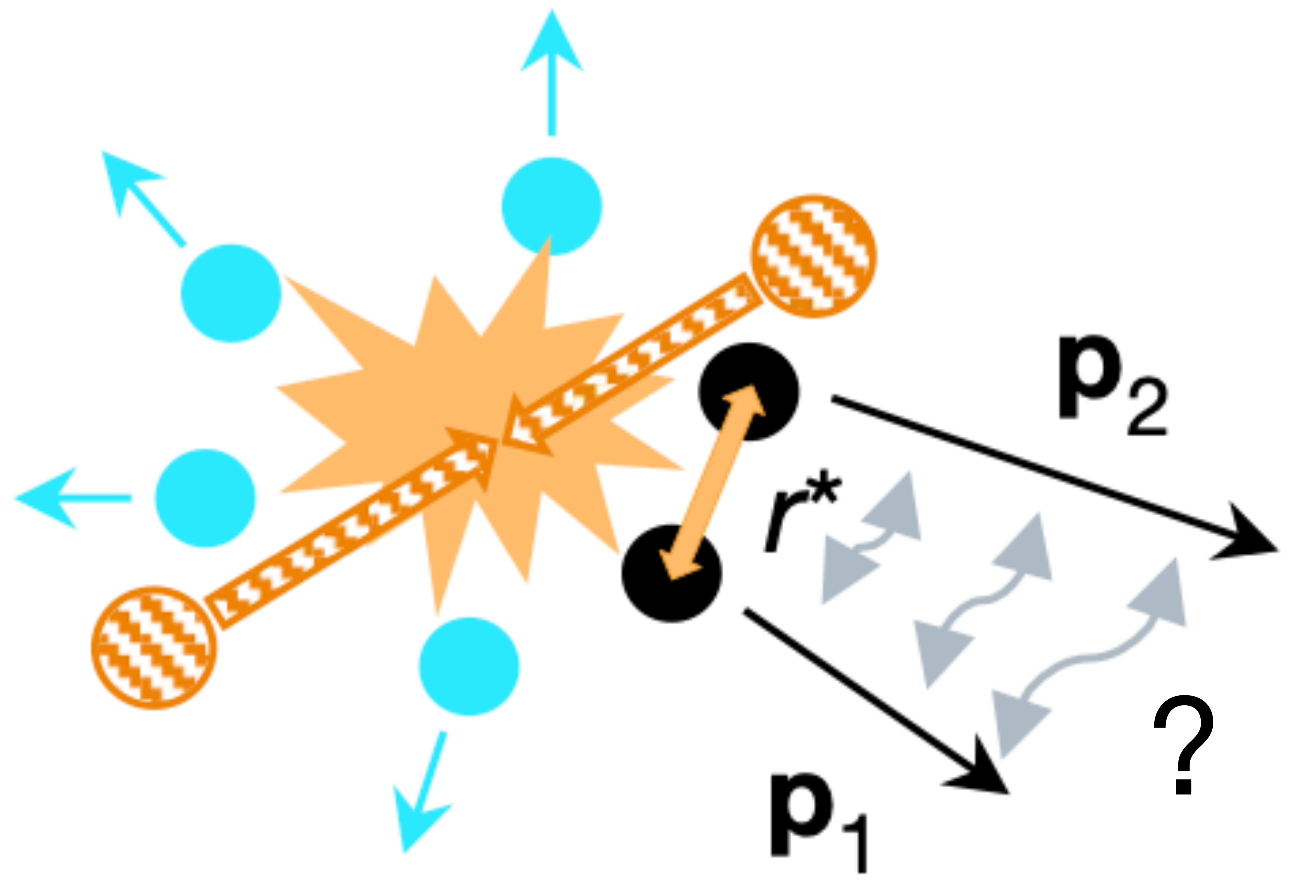
Femtoscopy technique

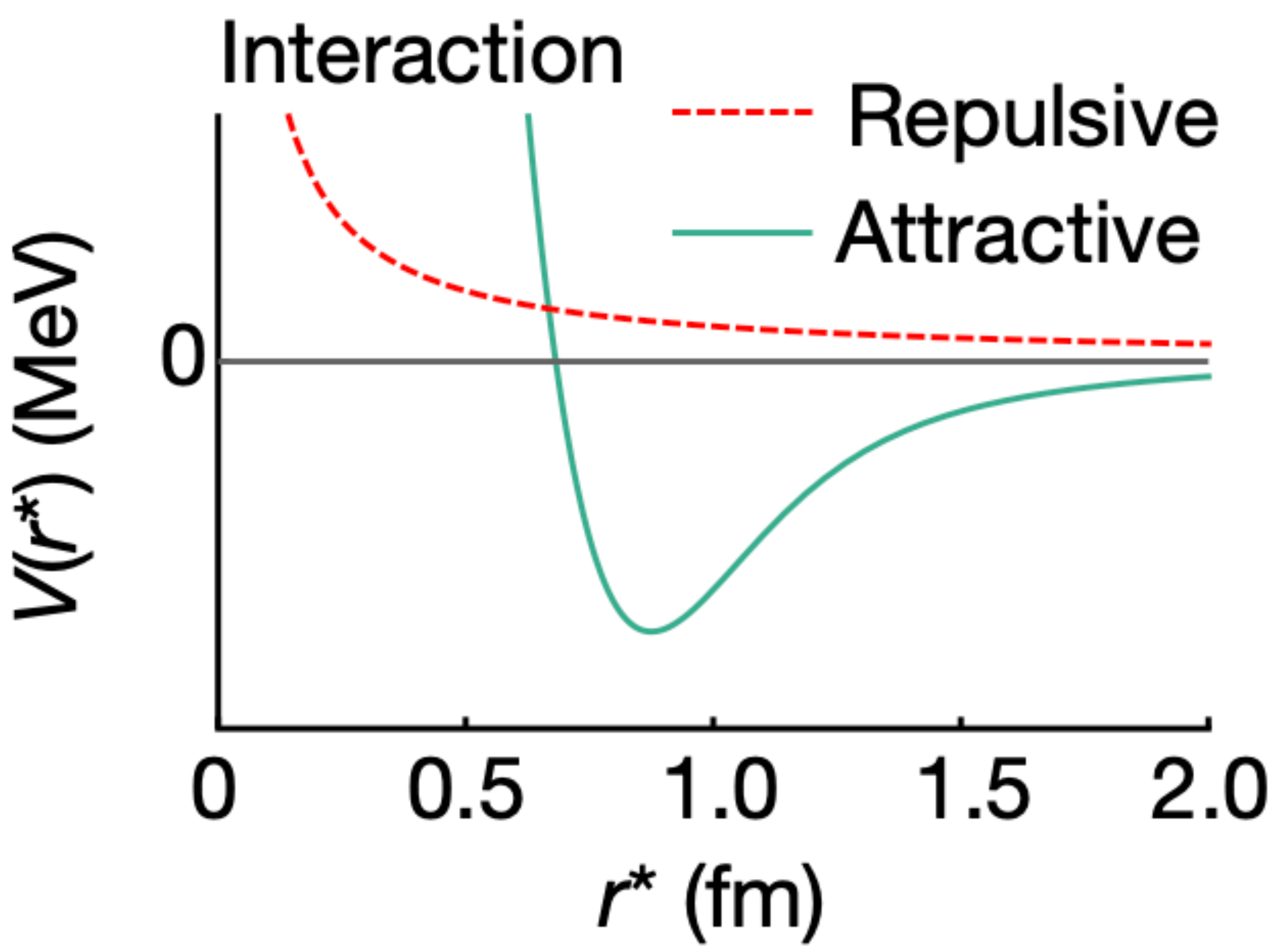


Emission source $S(r^*)$

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

Femtoscopy technique





Emission source *S(r*)*

Schrödinger equation
Two-particle wave function
$$\left|\psi(\mathbf{k}^*, \mathbf{r}^*)\right|$$

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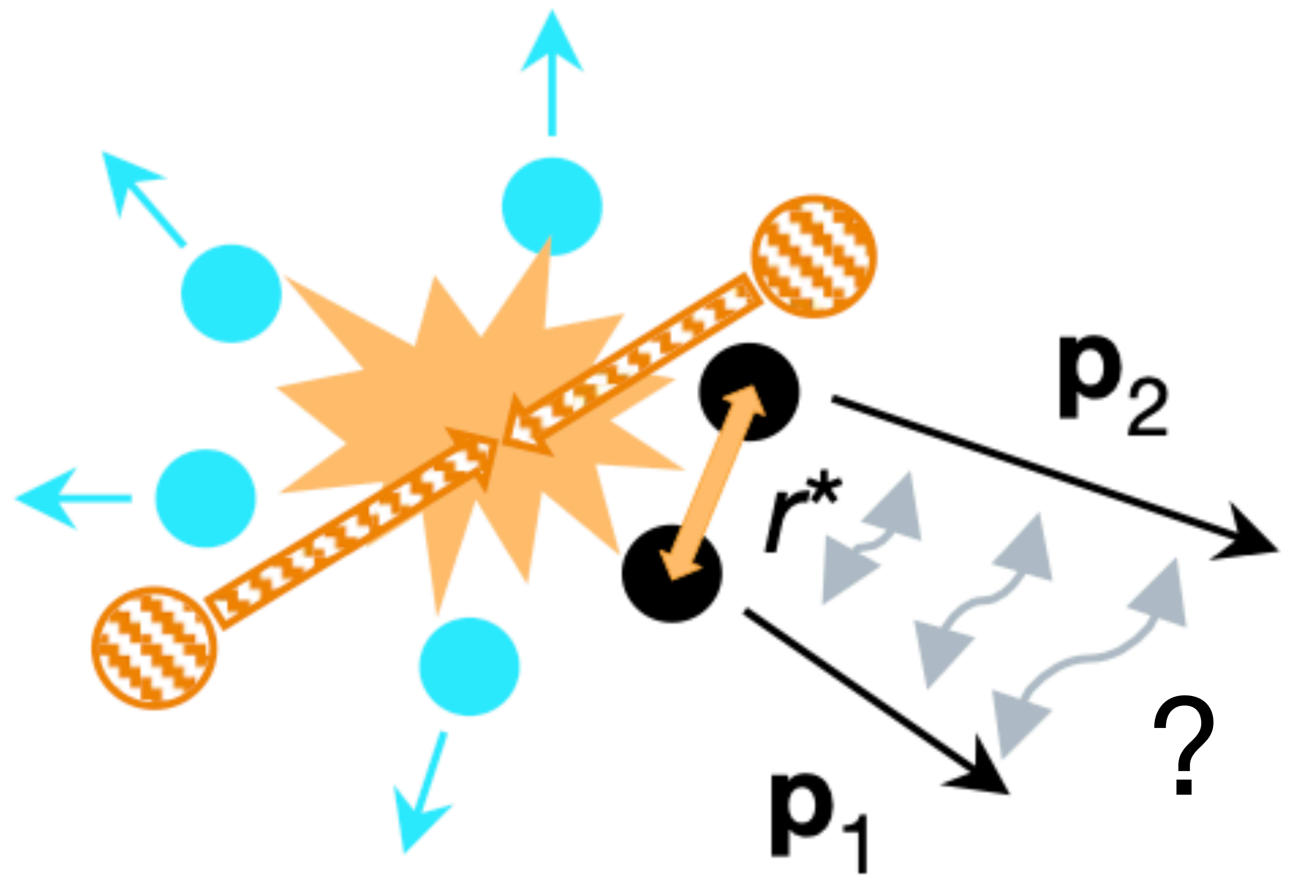

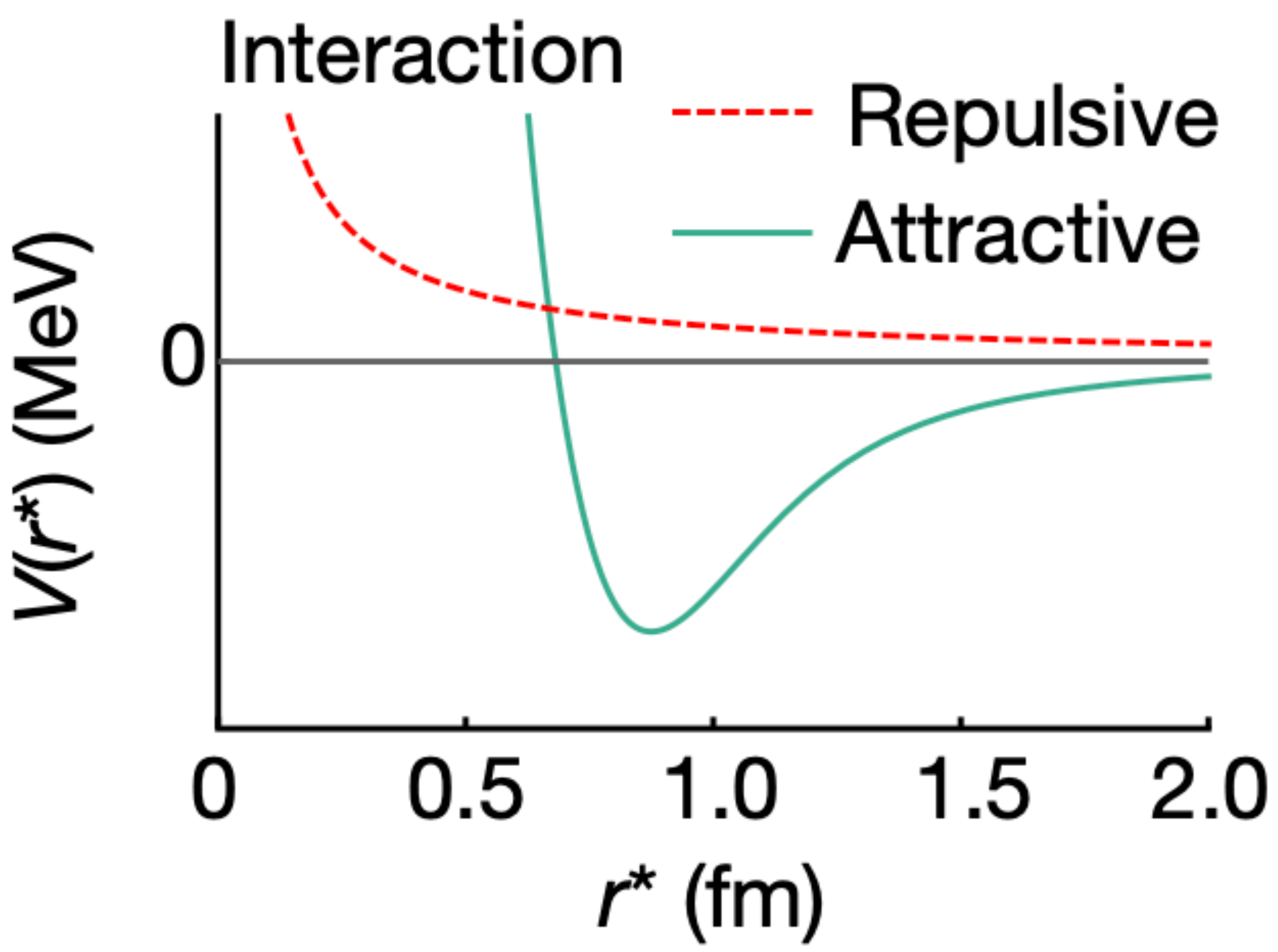

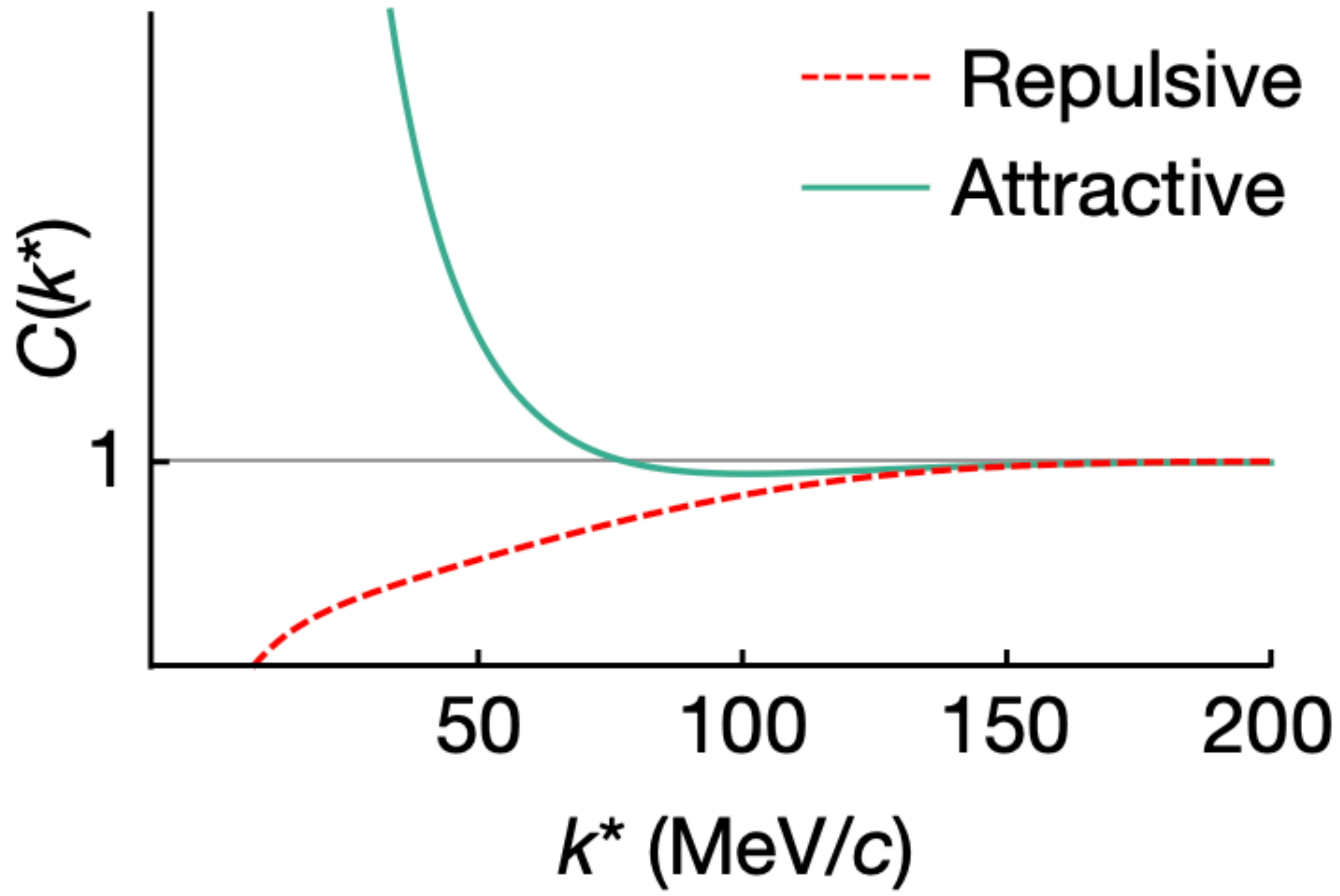

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Schrödinger equation
Two-particle wave function
$\left|\psi\left(\mathbf{k}^{*}, \mathbf{r}^{*}\right)\right|$

Correlation function *C(k*)*

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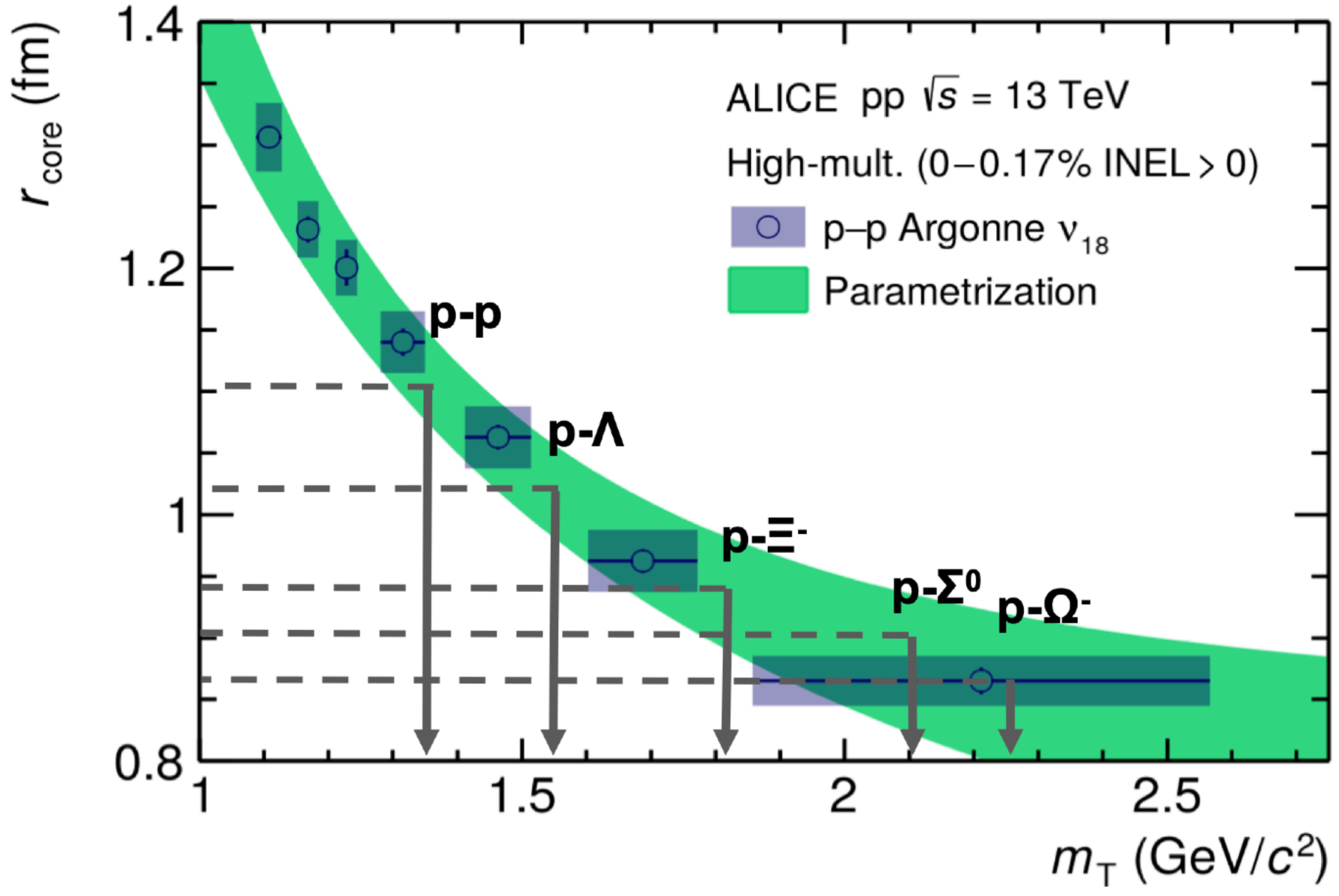
Emission source

- ALICE pp collision system has small source size!
- Two main contributions:
  - general: Collective effects result in Gaussian core;
  - specific: Decaying resonances require source correction.

ALICE Coll. PLB 811 (2020) 135849



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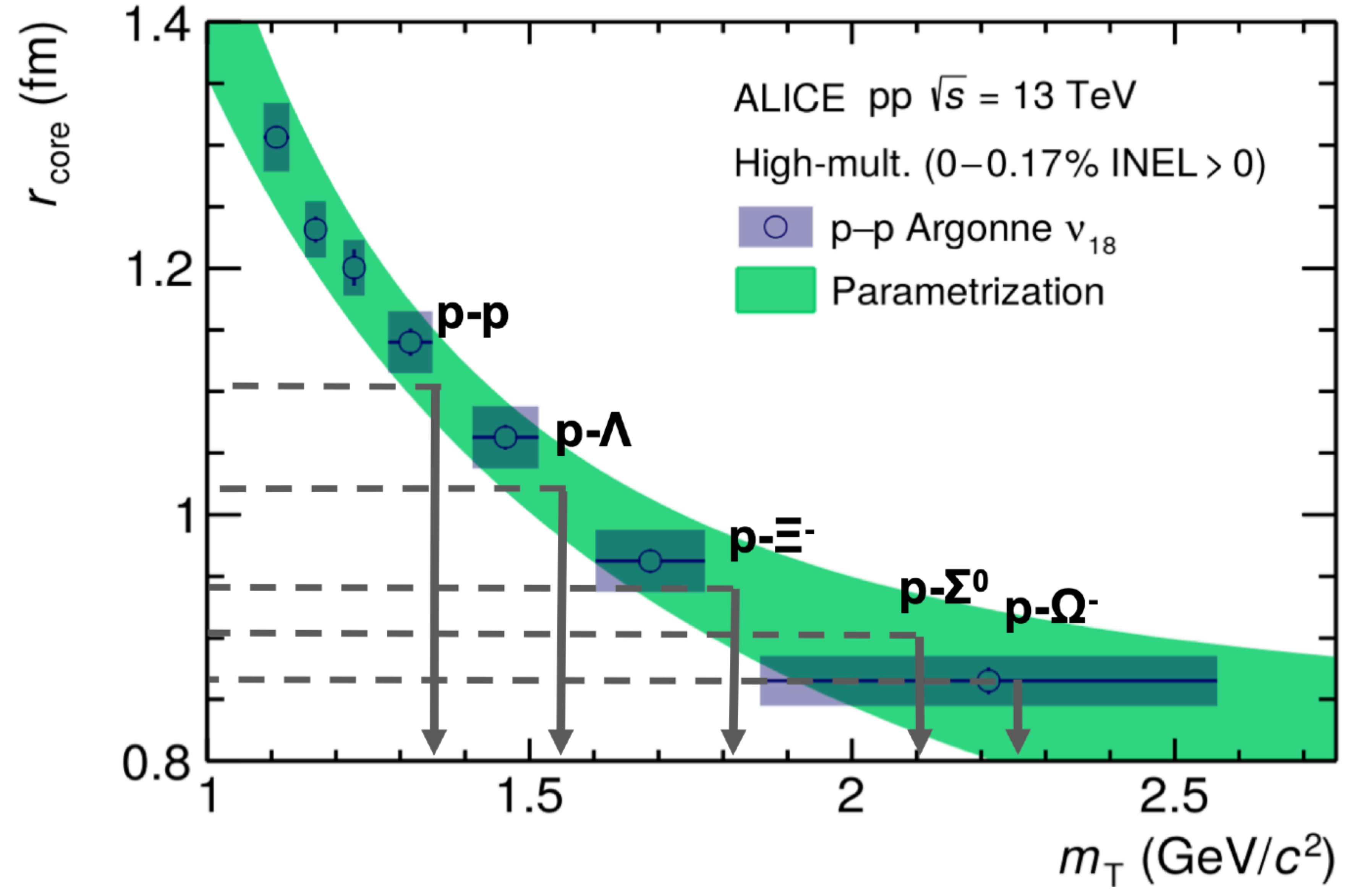

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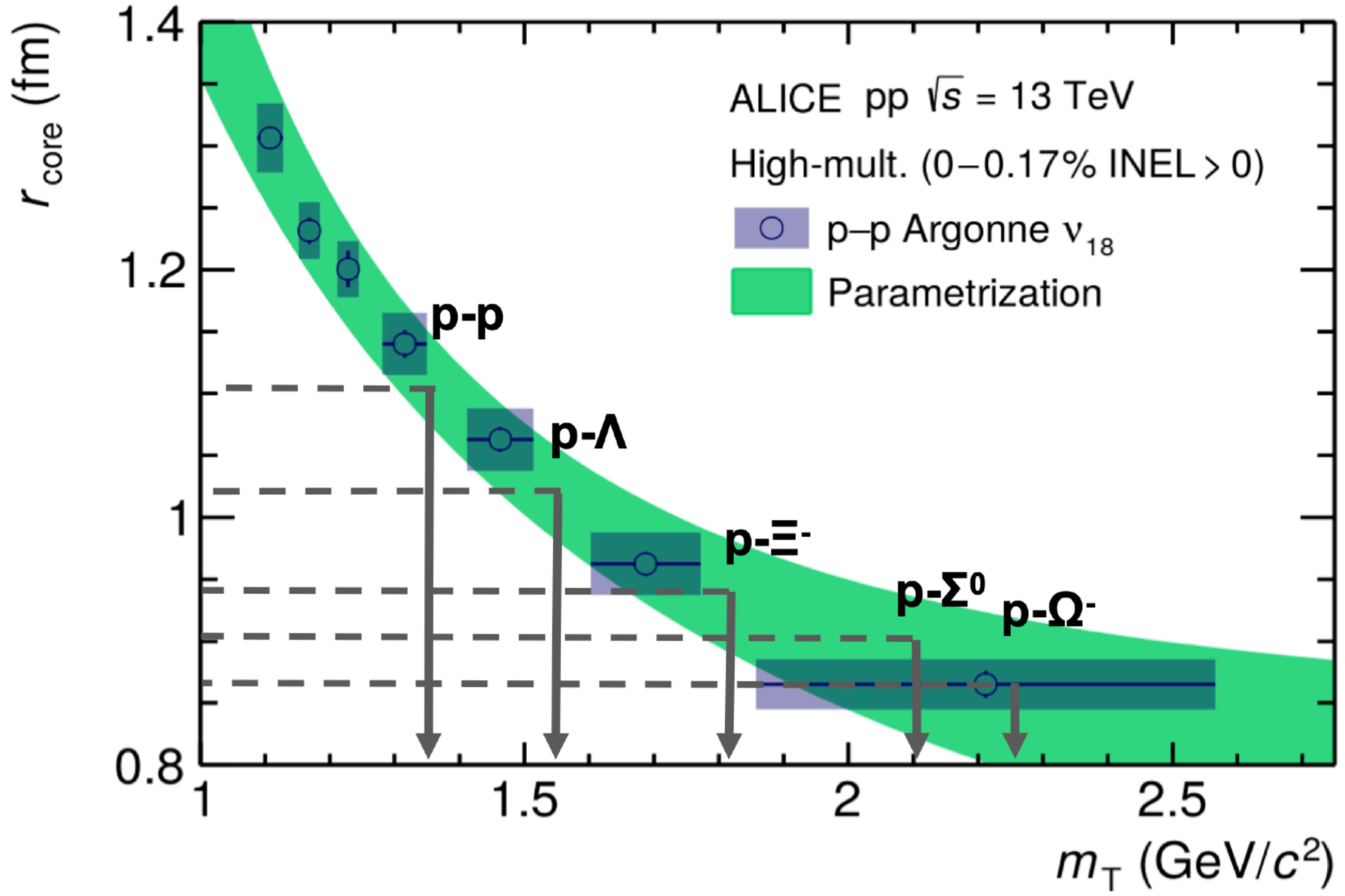
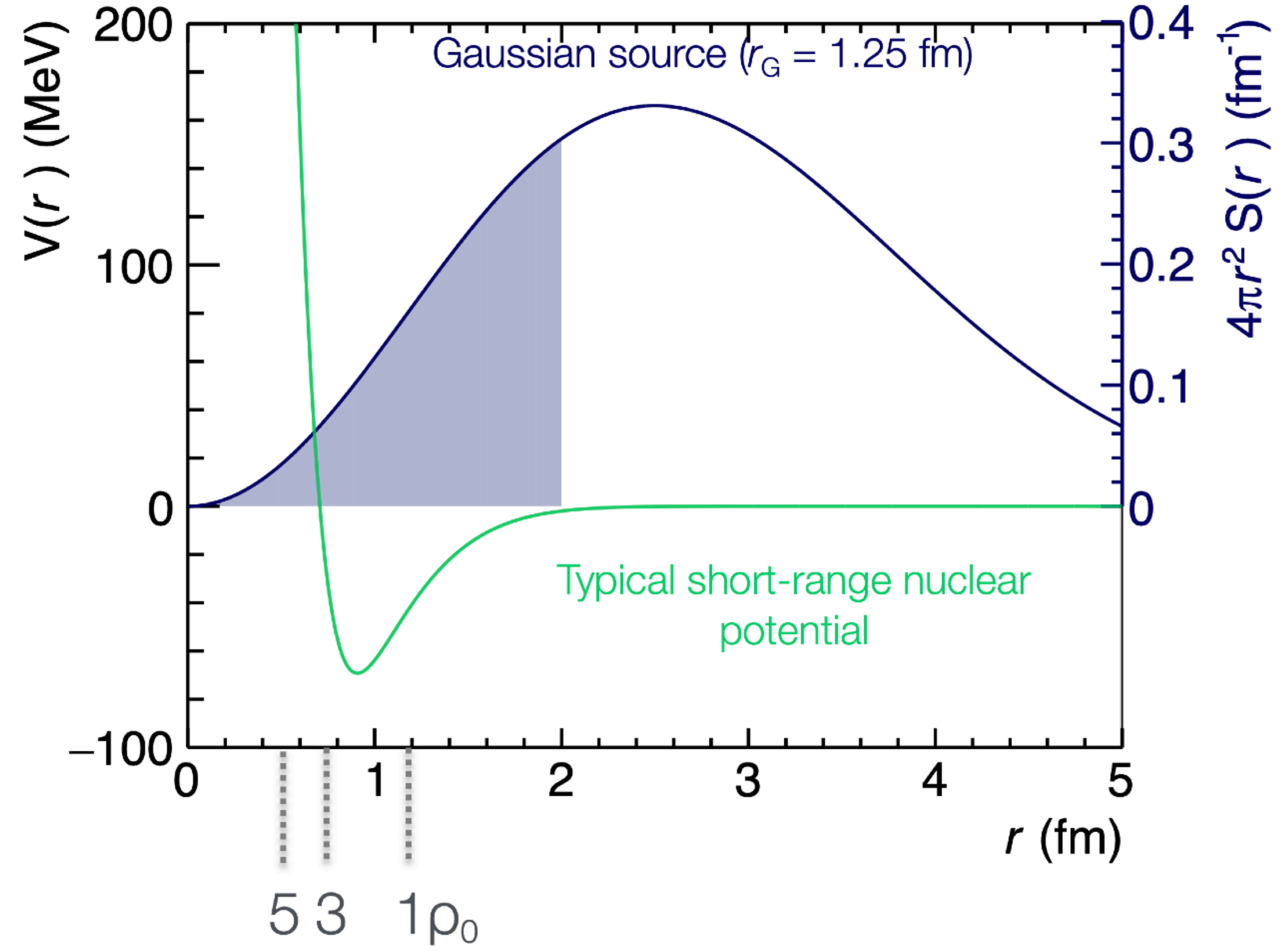


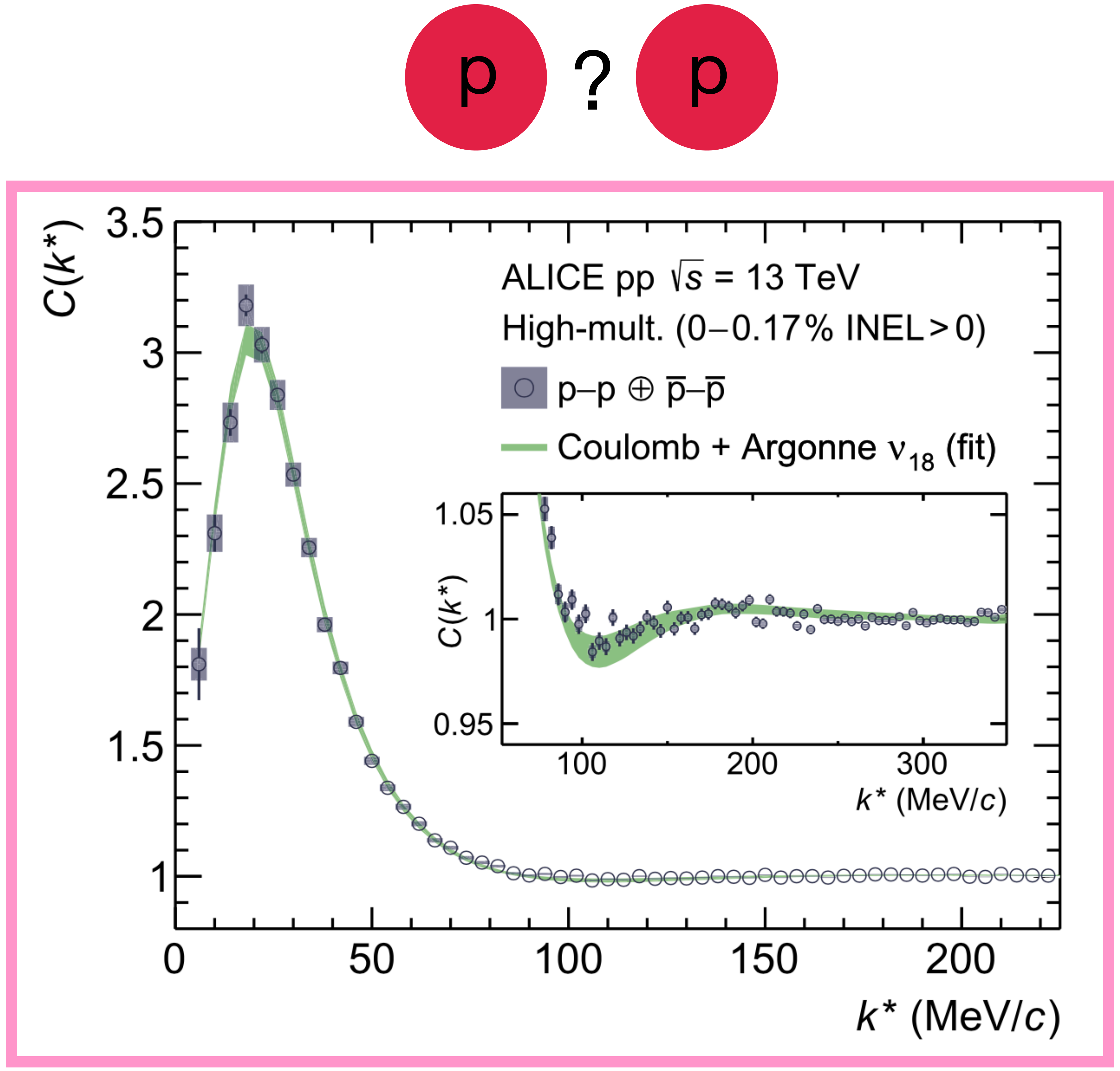
So what interaction distances are probed by femtoscopy?

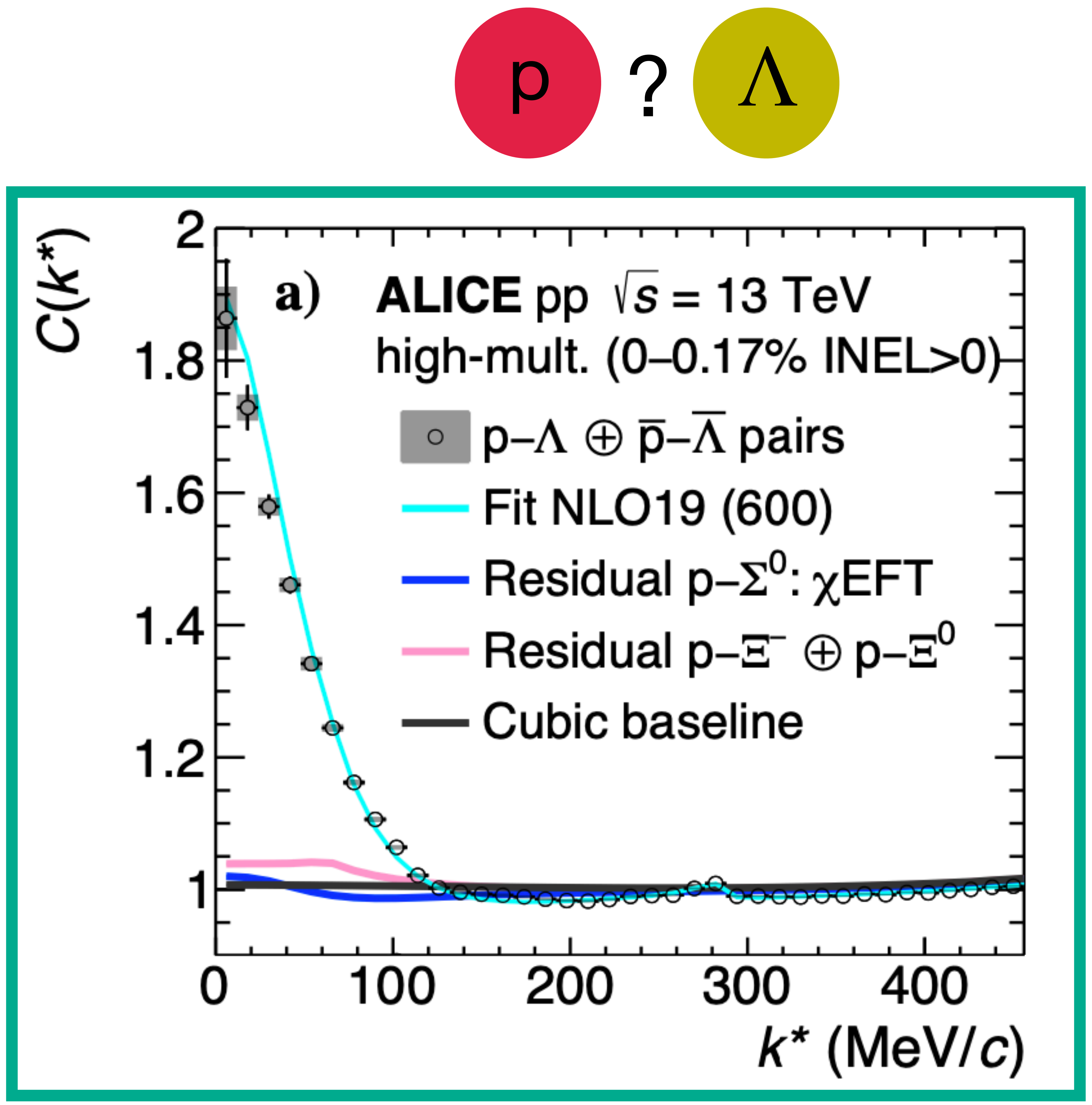
- Interaction measured down to very small distances.
- Mimics large densities which are important for neutron stars.



Two-body measurements

- Many different two-body interactions measured successfully!





TUM Group:
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ALICE:
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Talk:
V. Mantovani Sarti
08.09 (Thursday) at 17:20

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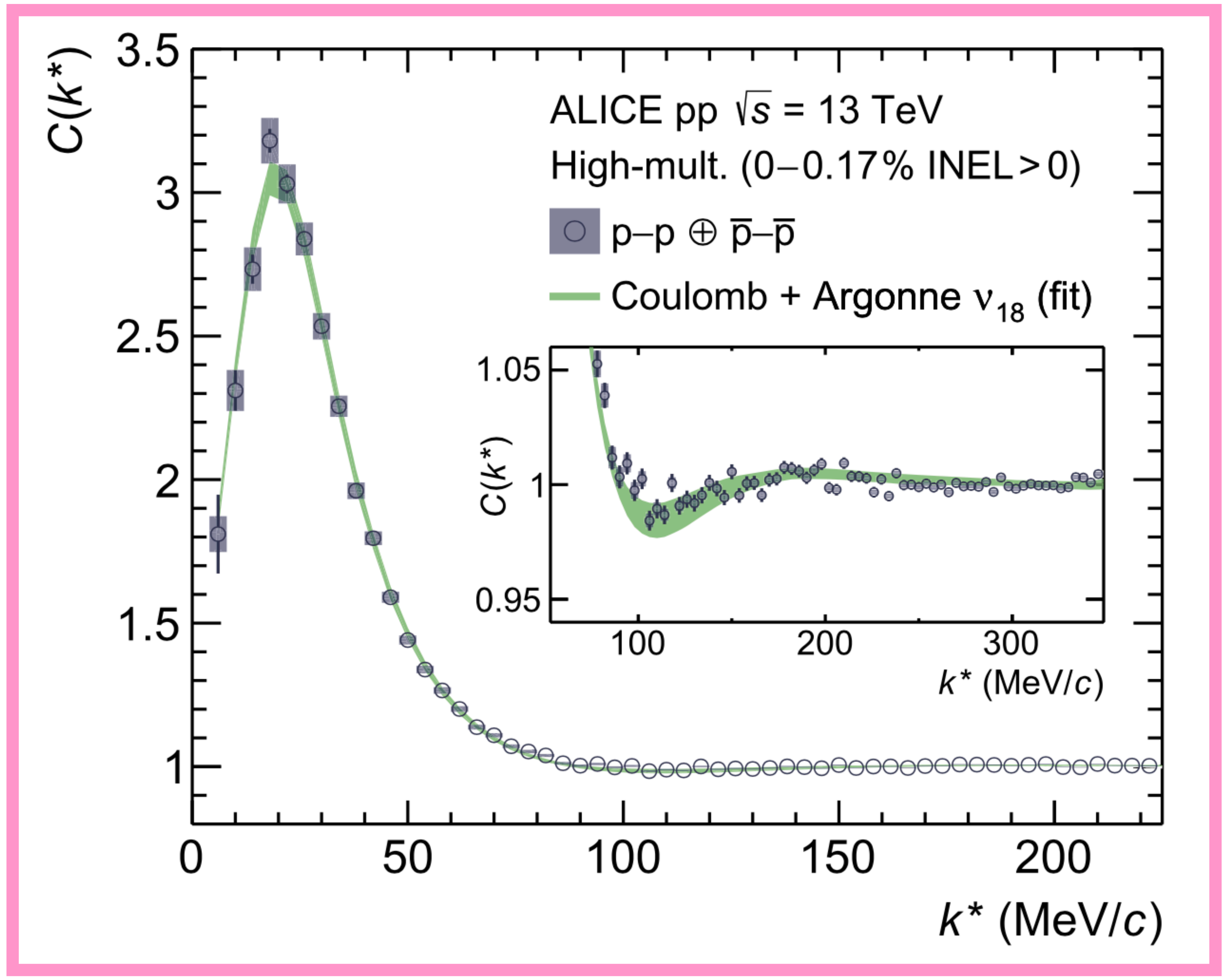
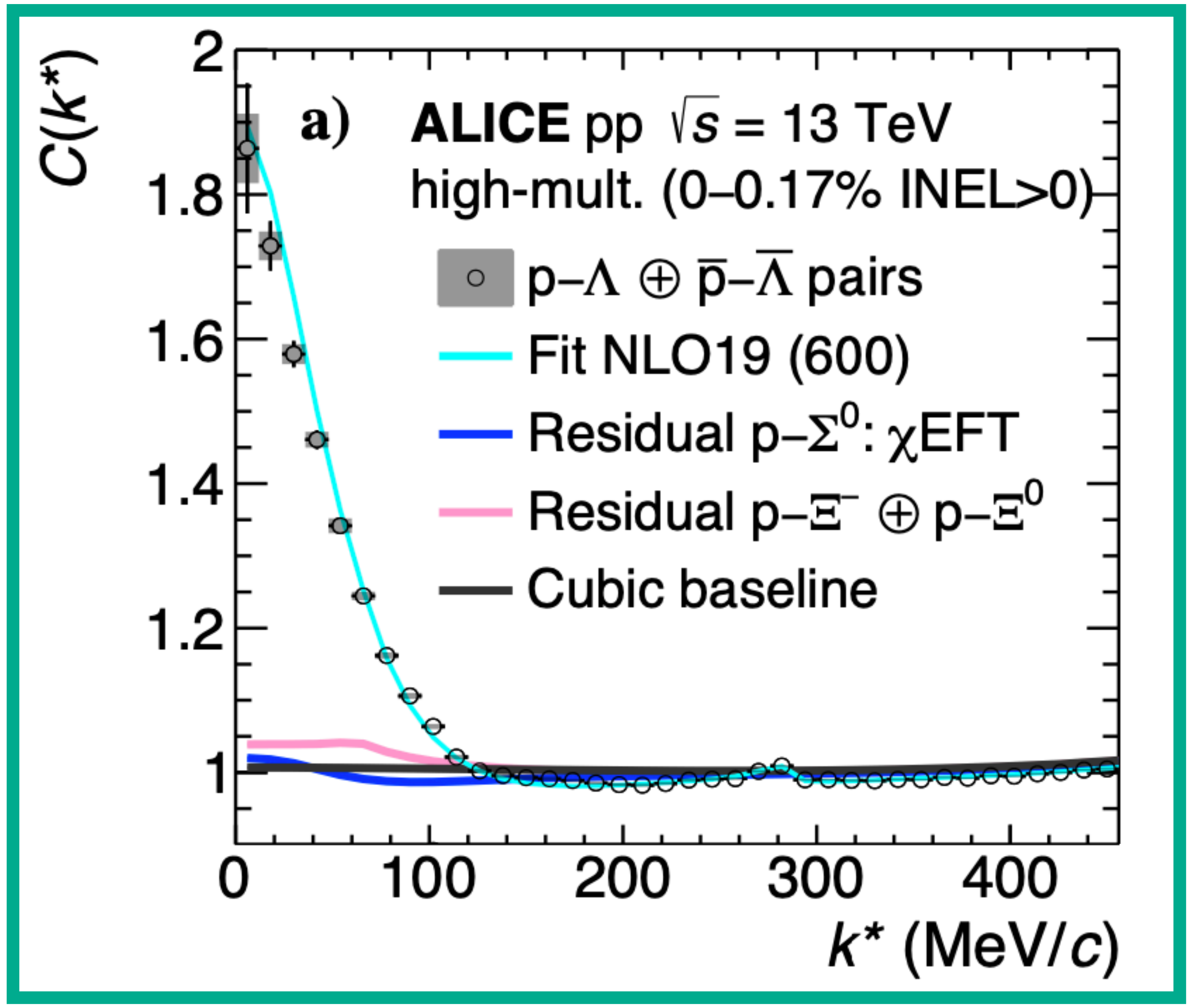
p ? p



p ? Λ



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Can one use this method to pin down the three-body interactions?

Three-body femtoscopy

Two-body correlation function

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

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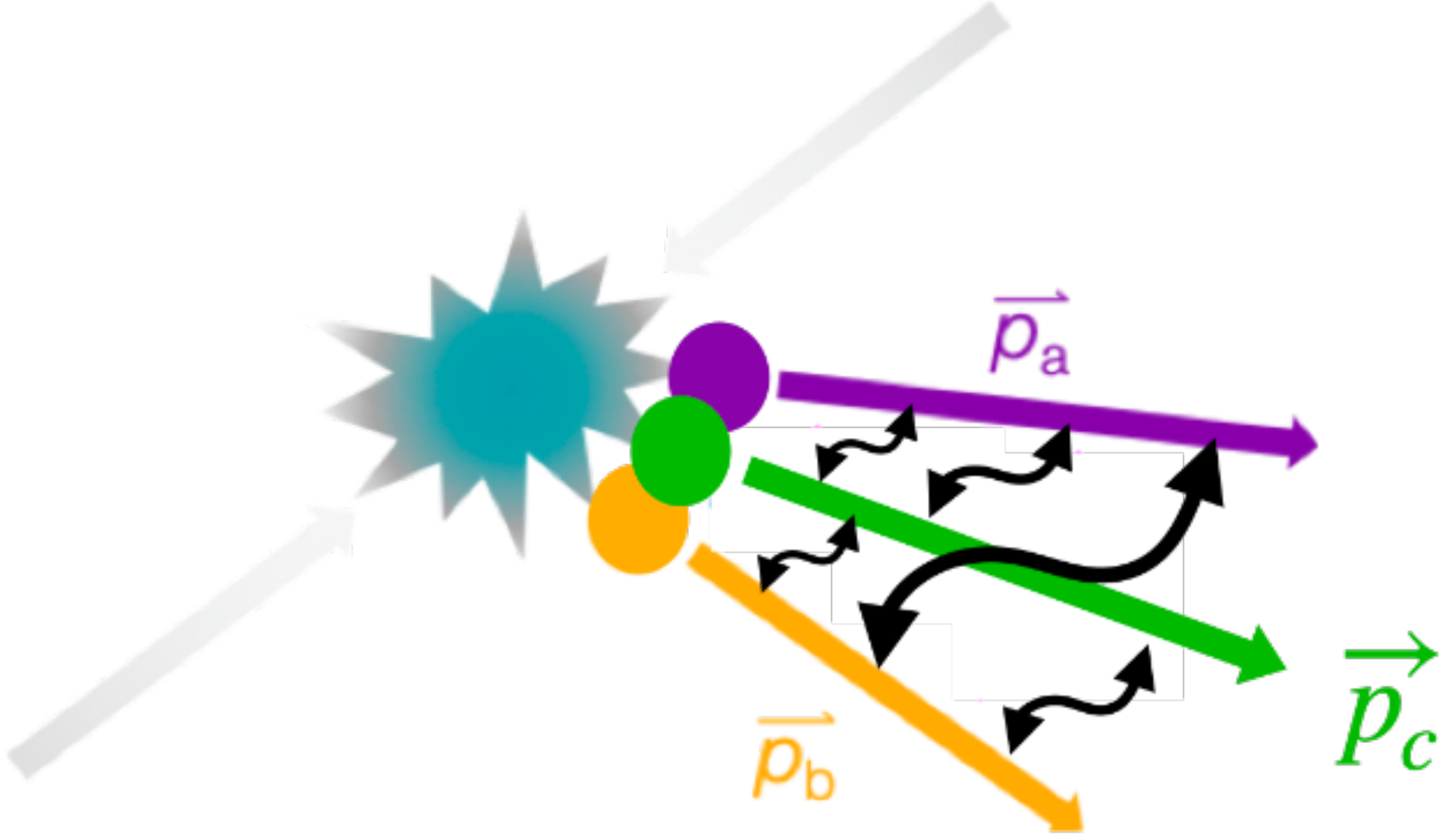
Experimentally studying three-body correlations, the small statistics requires to project the correlation function on **1-dimensional** observable Q_3.

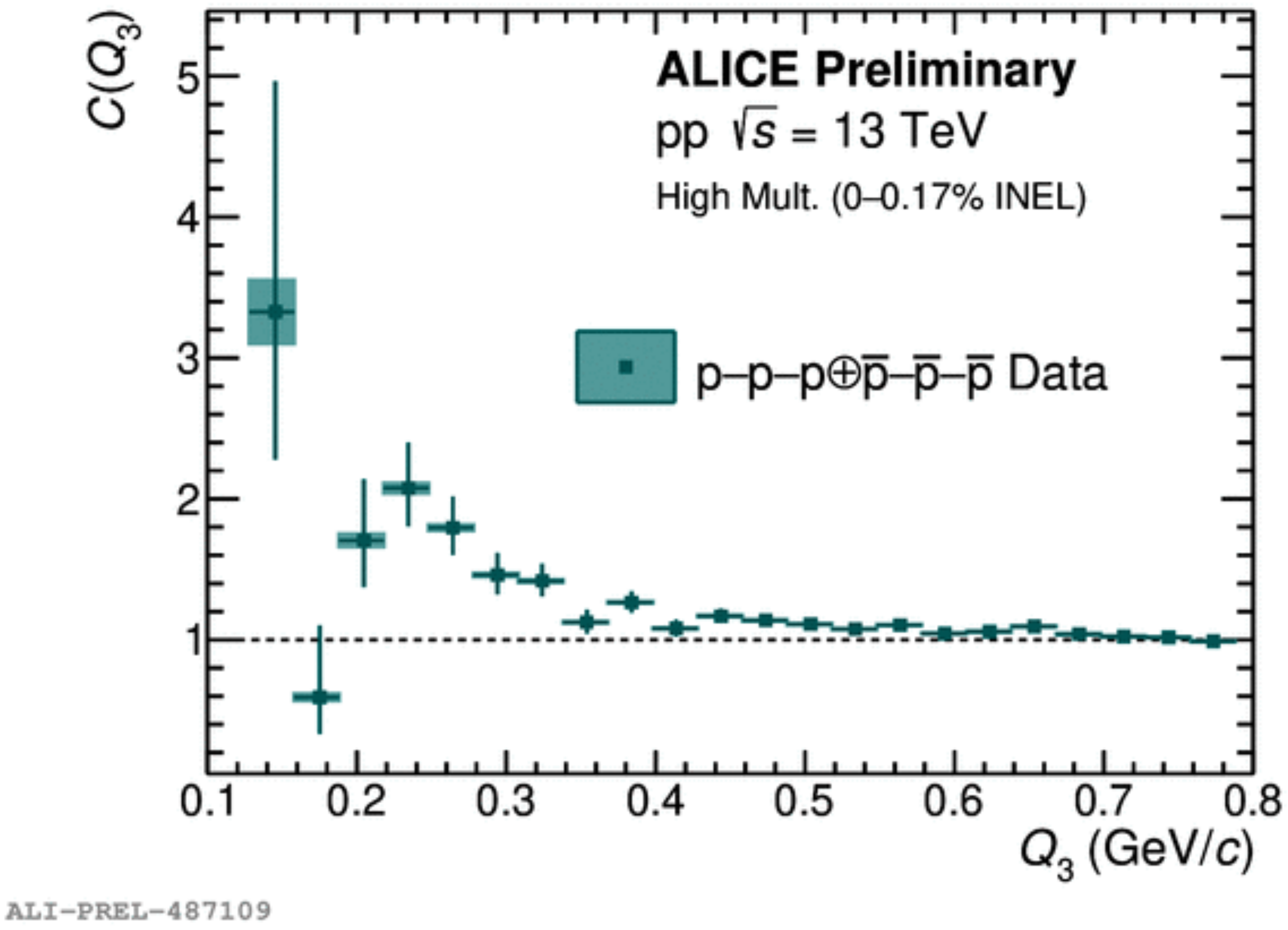
$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}$$

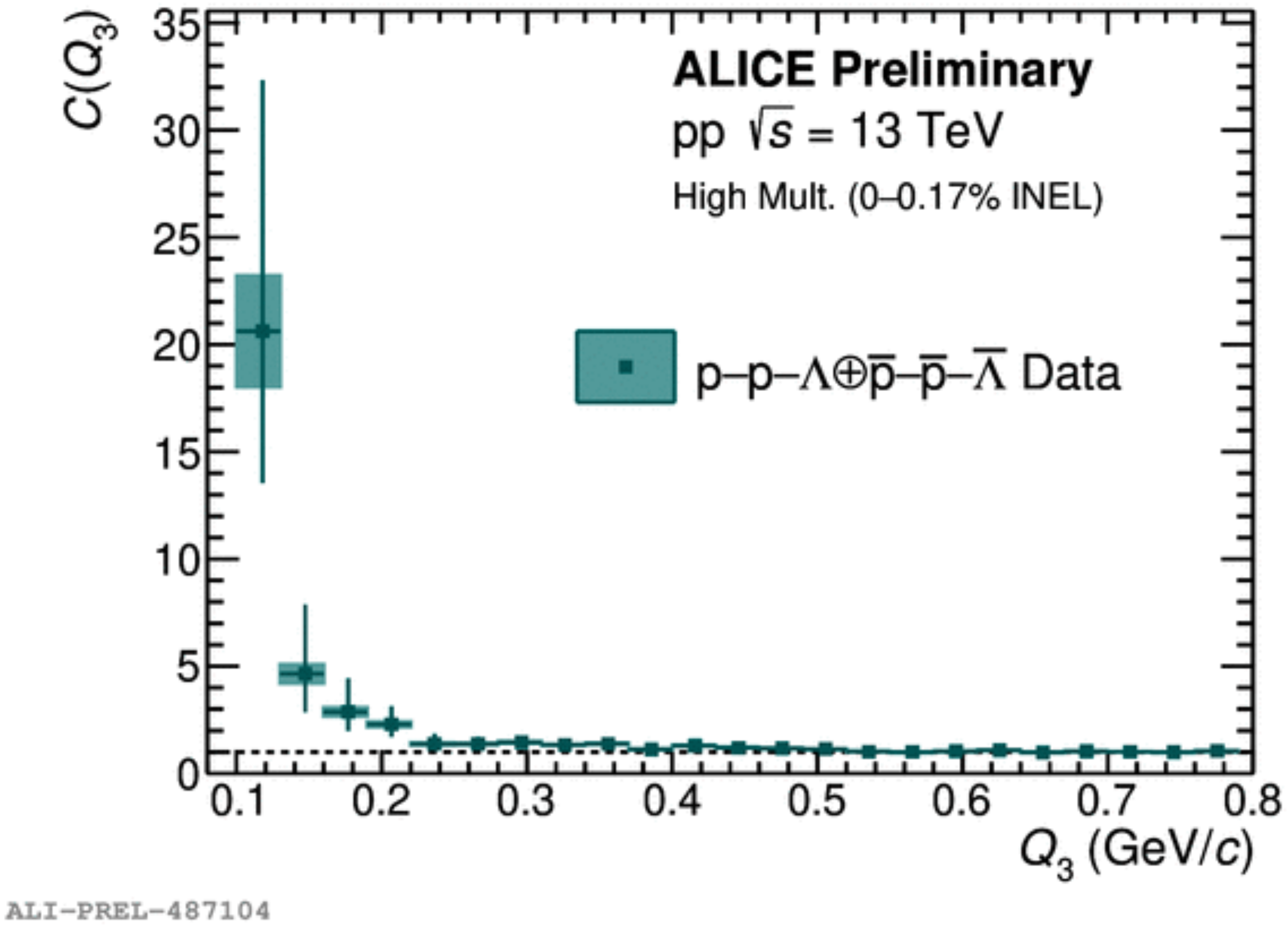
$$q^\mu = \left(p_i - p_j\right)^\mu - \frac{\left(p_i - p_j\right) \cdot P}{P^2} P^\mu$$

$$P \equiv p_i + p_j$$



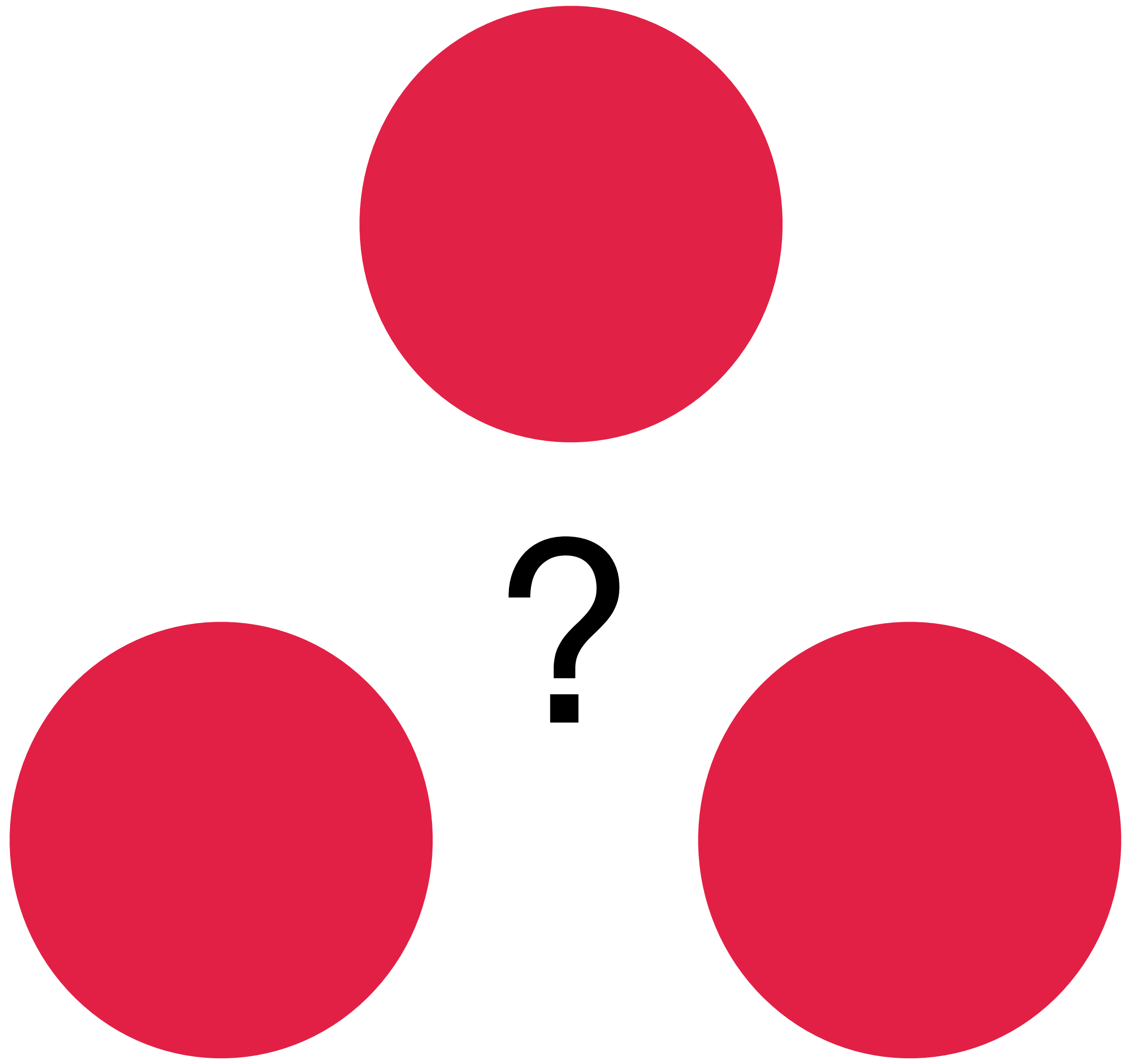
Measurement in pp collisions at $\sqrt{s}$ = 13 TeV





How can we understand and interpret these results?

Accessing genuine three-body interaction



Measured correlation function includes:

- pairwise particle interactions,
- genuine three-particle interaction.

[1] J. Phys. Soc. Jpn. 17, pp. 1100–1120 (1962)

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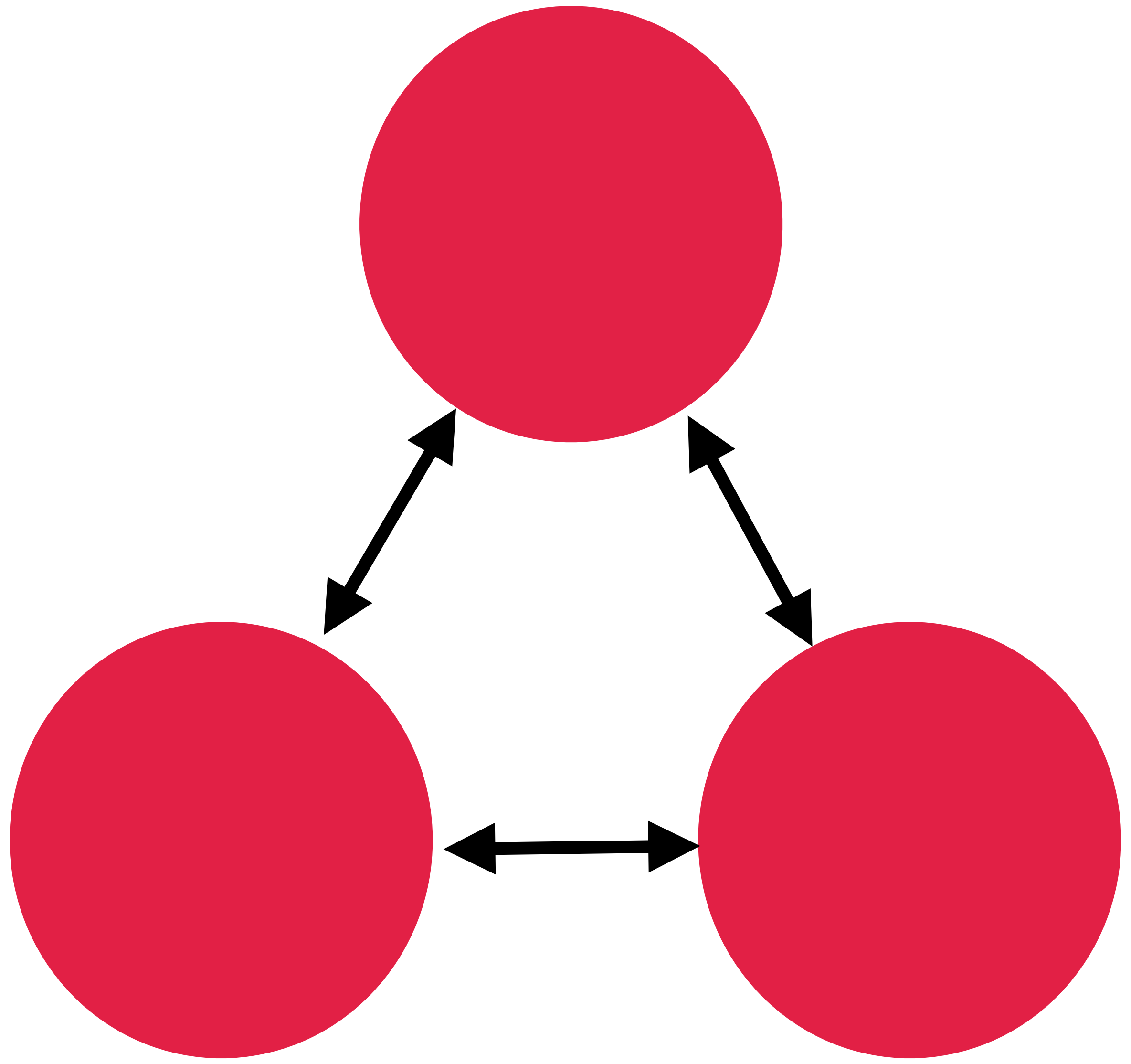

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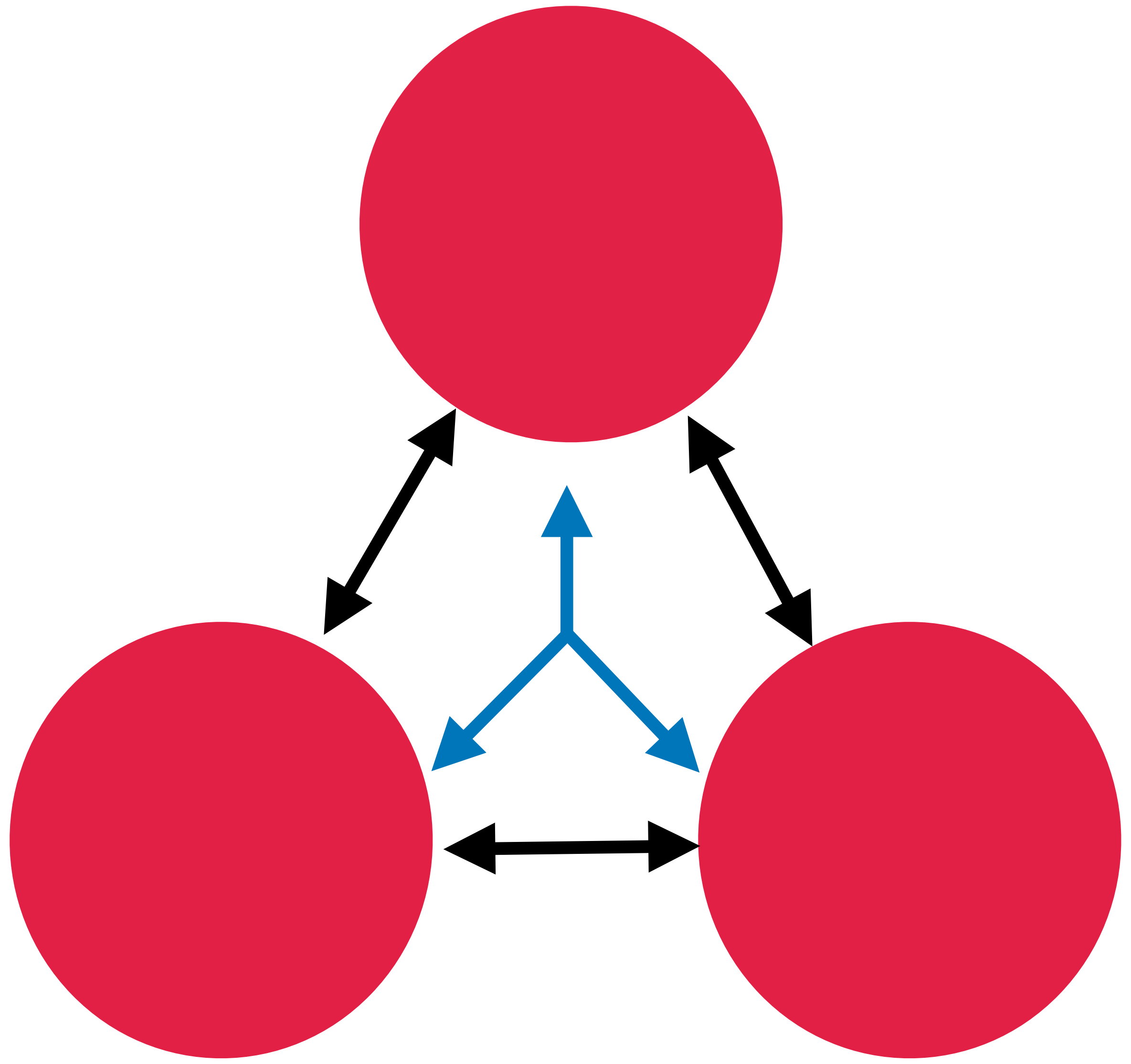

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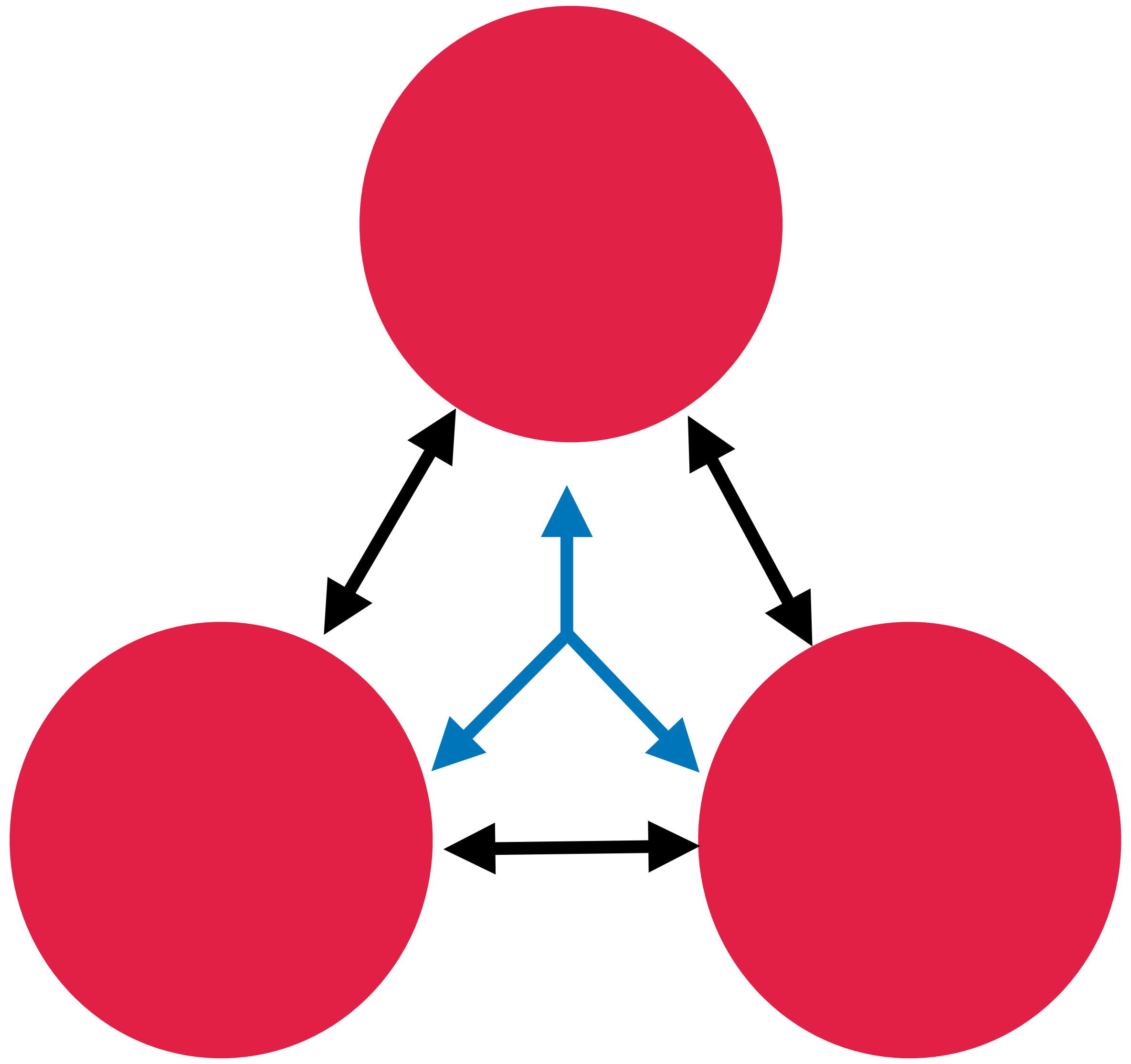

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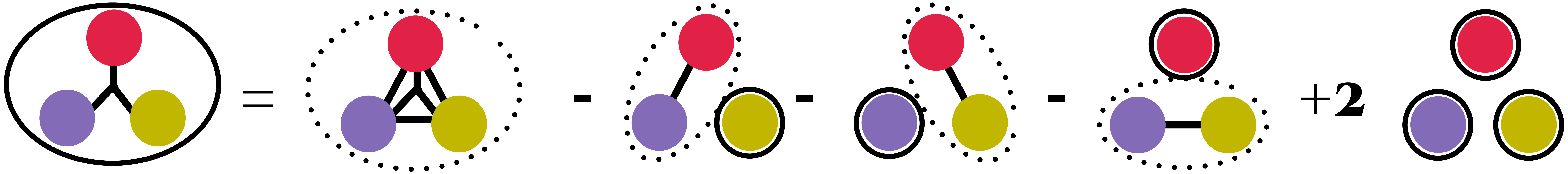
Use Kubo's cumulant expansion method [1] to extract the genuine three-body interaction.



$$c_3\left(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3\right) = C([\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3]) - C([\mathbf{p}_1, \mathbf{p}_2], \mathbf{p}_3) - C(\mathbf{p}_1, [\mathbf{p}_2, \mathbf{p}_3]) - C([\mathbf{p}_1, \mathbf{p}_3], \mathbf{p}_2) + 2$$

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Two-body interactions in three-body system

1. Data-driven method using mixed-event technique:

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

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2. Projector method using measured or theoretical two-body correlation function:

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

$$C(Q_3) = \iiint_{Q_3=\text{constant}} C([\mathbf{p}_i,\mathbf{p}_j],\mathbf{p}_k)\ d^3\mathbf{p}_i\ d^3\mathbf{p}_j\ d^3\mathbf{p}_k \quad = \quad \int C_2(k^*_{ij})\ W_{ij}(k^*_{ij},Q_3)\ dk^*_{ij}$$

$$W_{ij}(k^*_{ij},Q_3) = \frac{16(\alpha\gamma-\beta^2)^{3/2}k^{*2}_{ij}}{\pi\gamma^2 {Q_3}^4}\sqrt{\gamma {Q_3}^2-(\alpha\gamma-\beta^2)k^{*2}_{ij}}$$

The α,β,γ depend only on the masses of the three particles.

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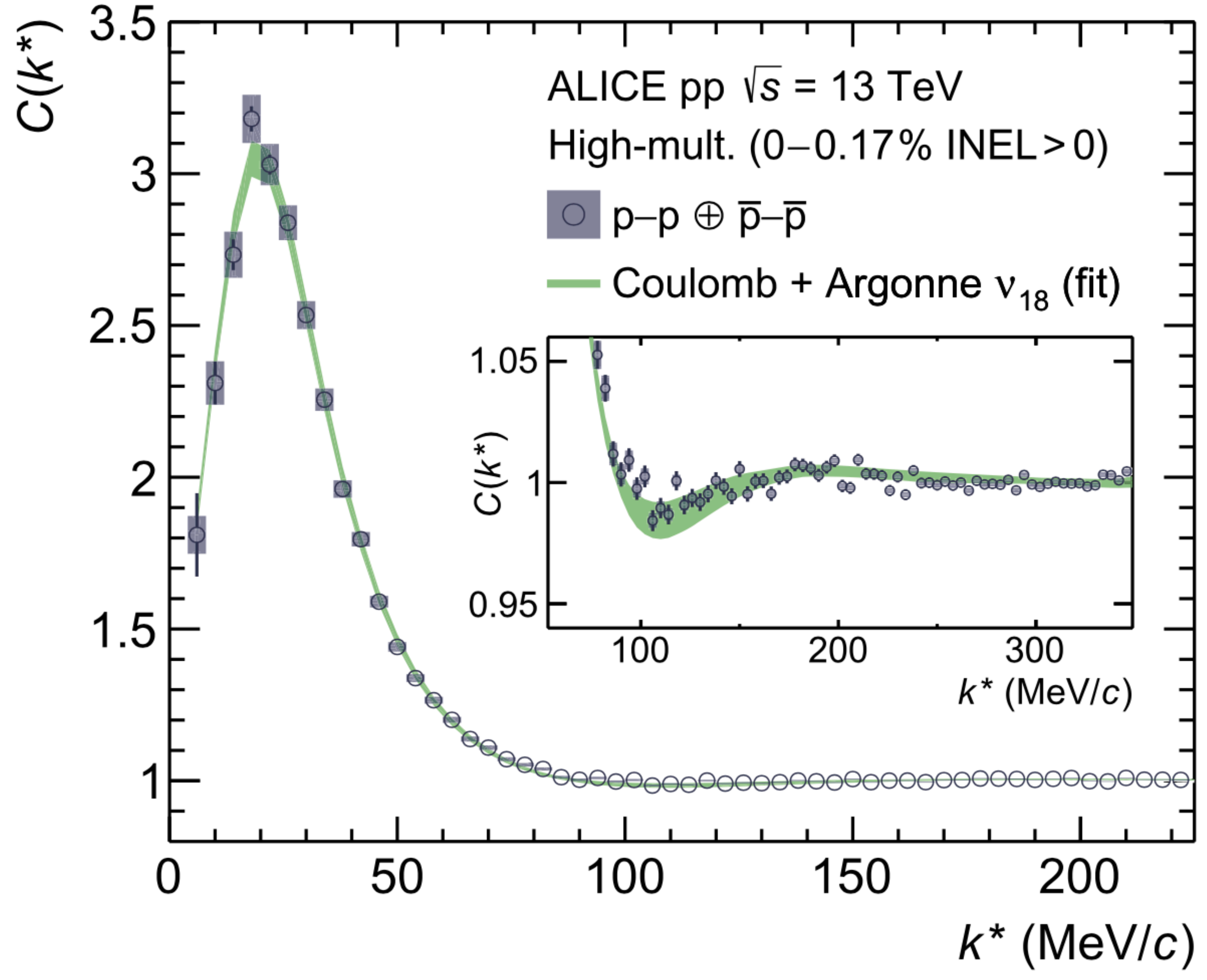
ALICE Coll. PLB 805 (2020) 135419



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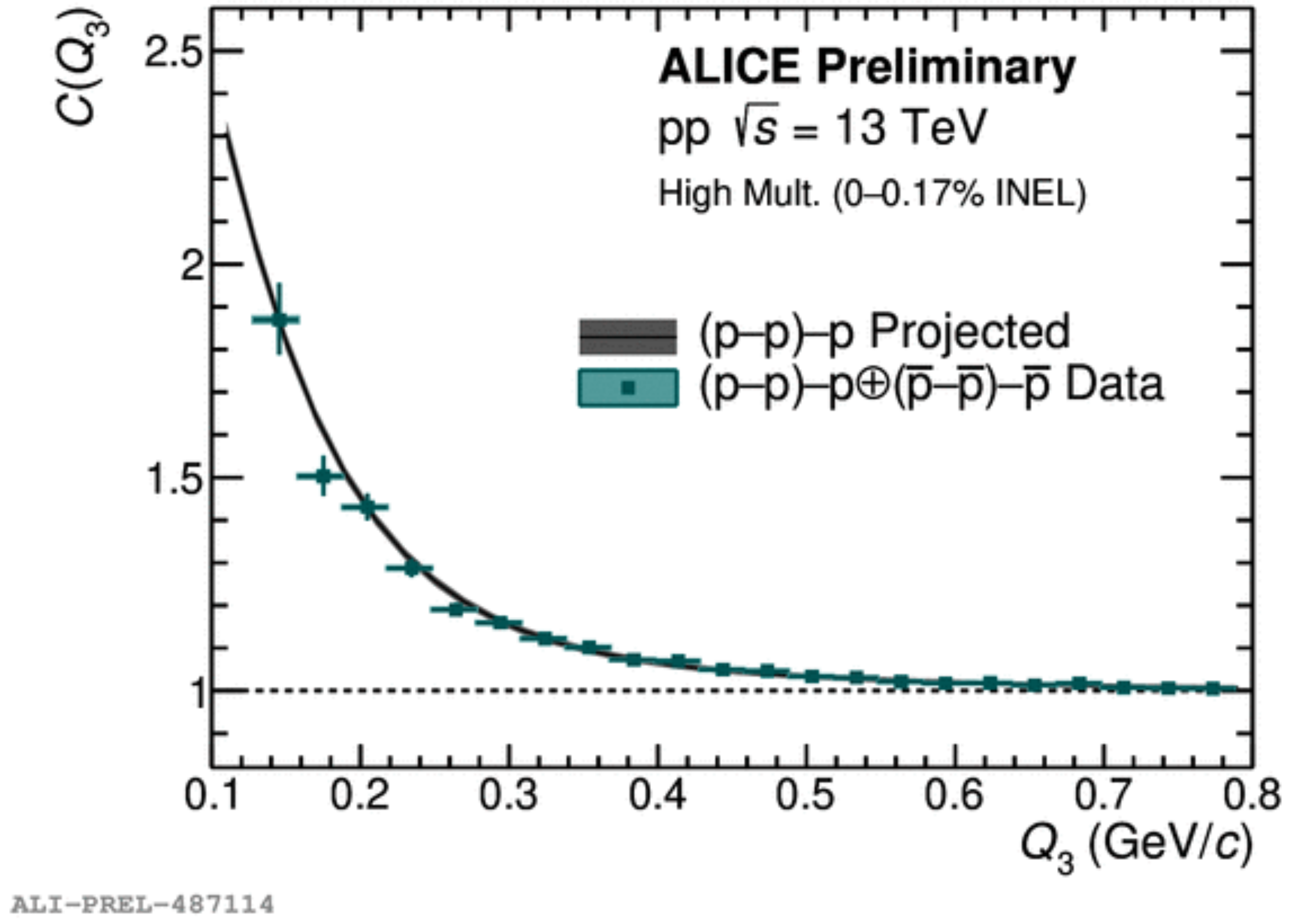
Output: (p-p)-p

Input



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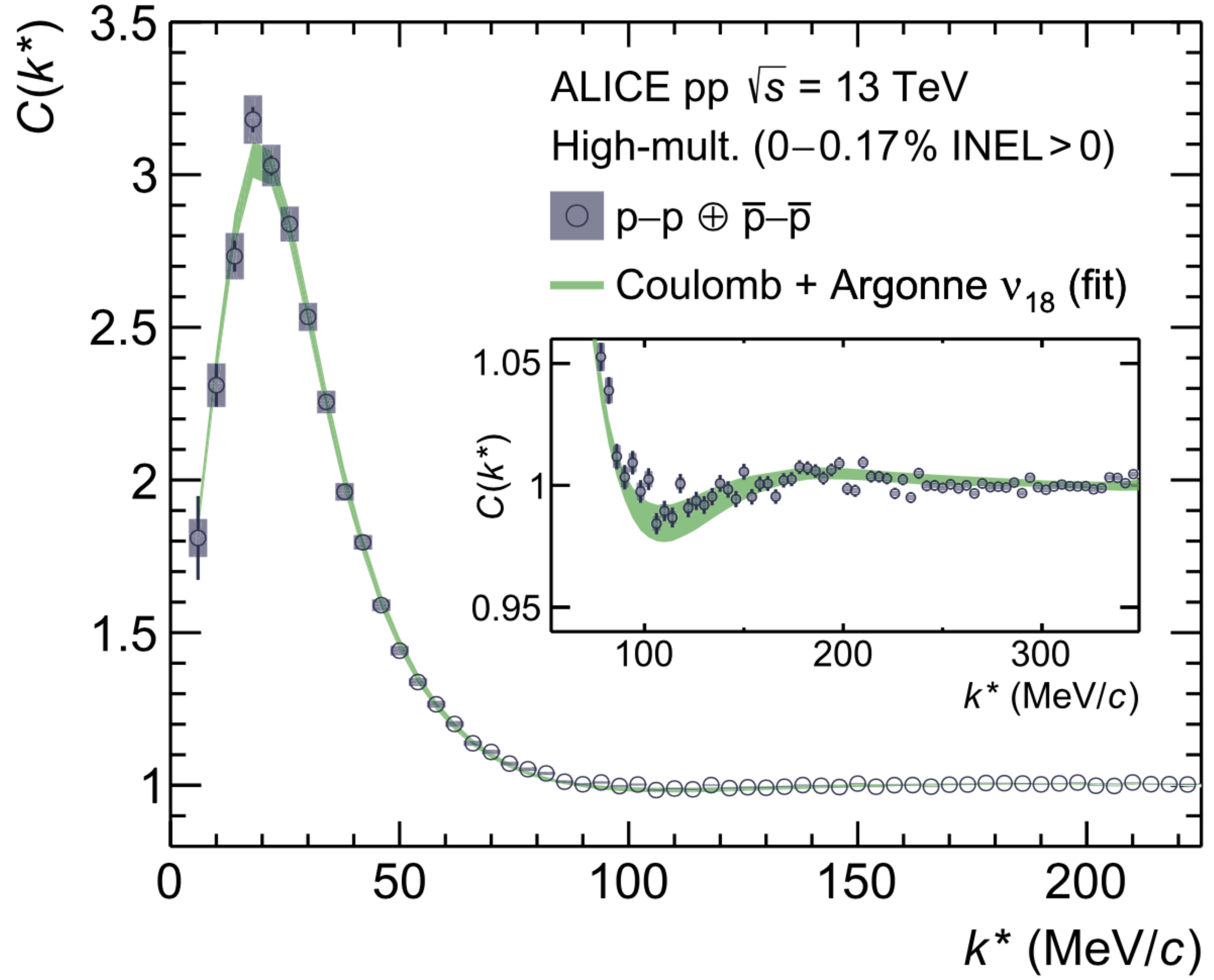

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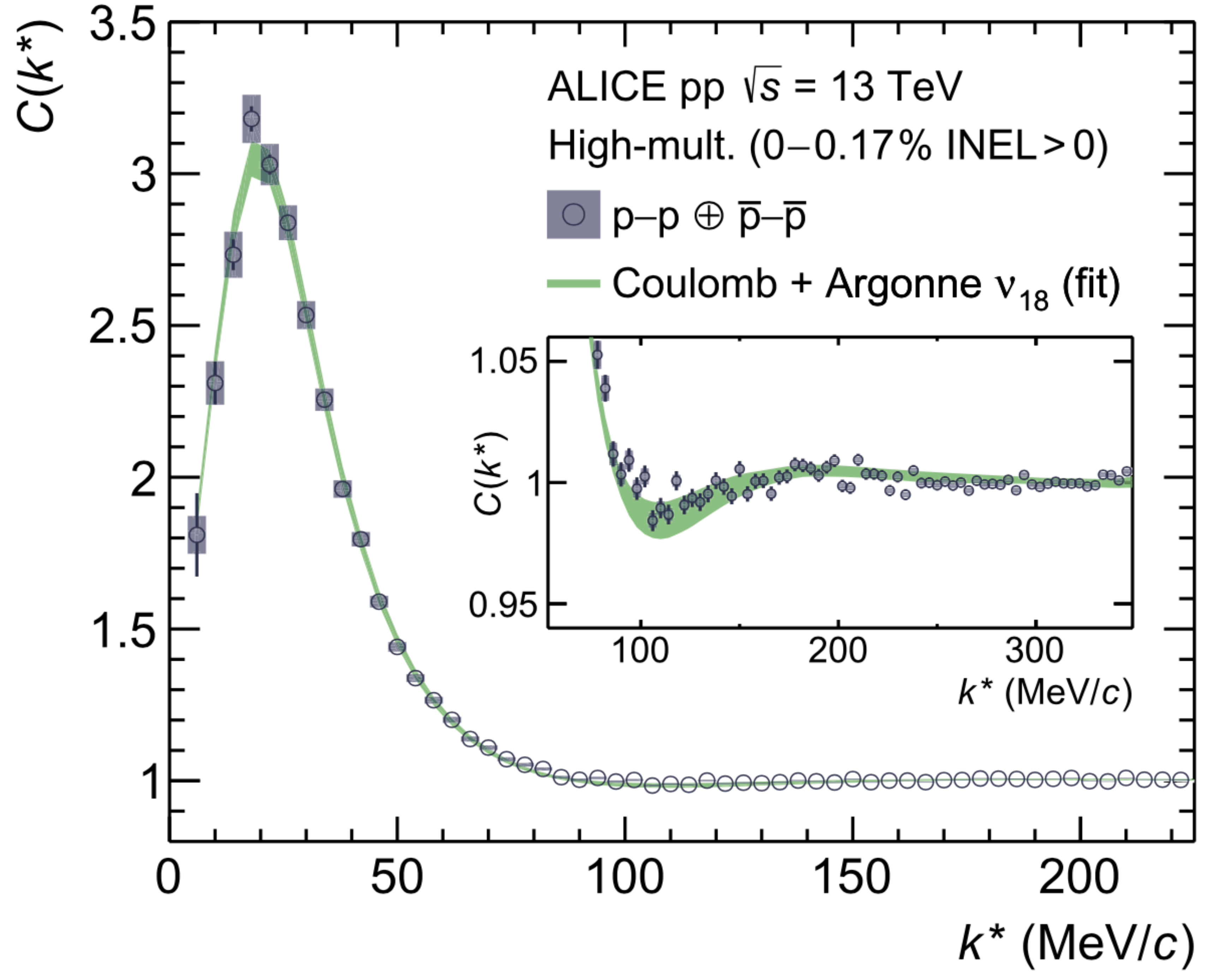

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Output: (p-p)-Λ

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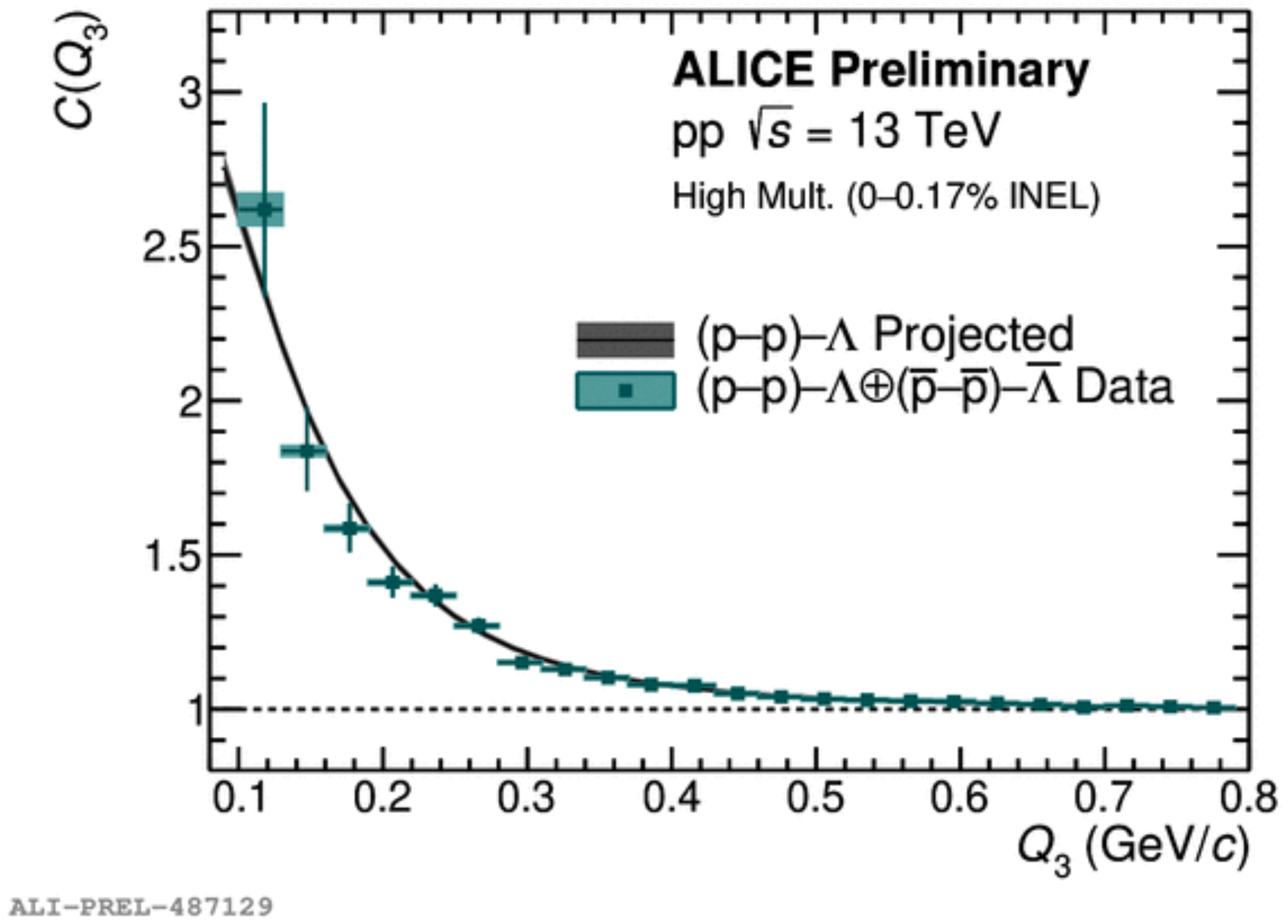

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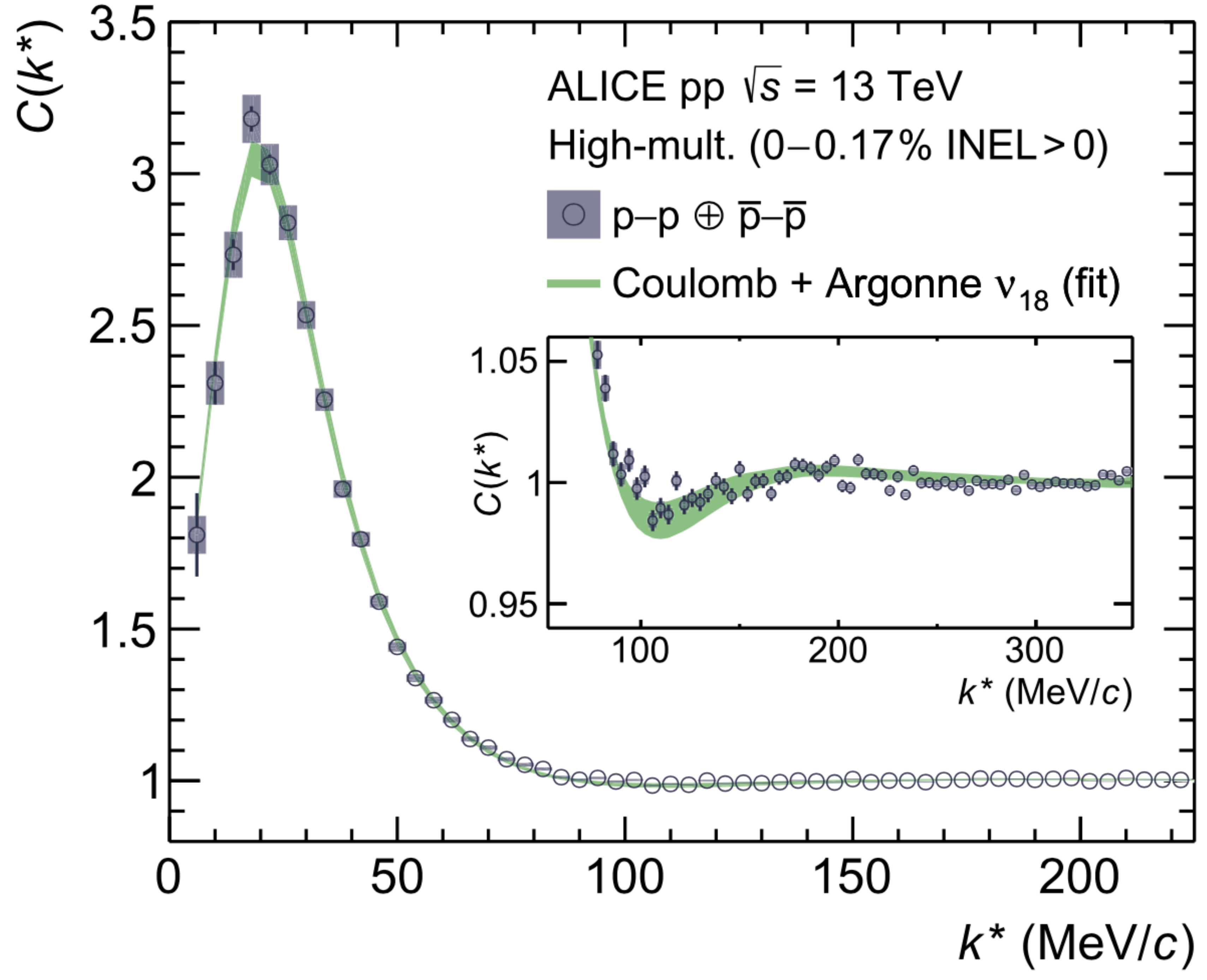

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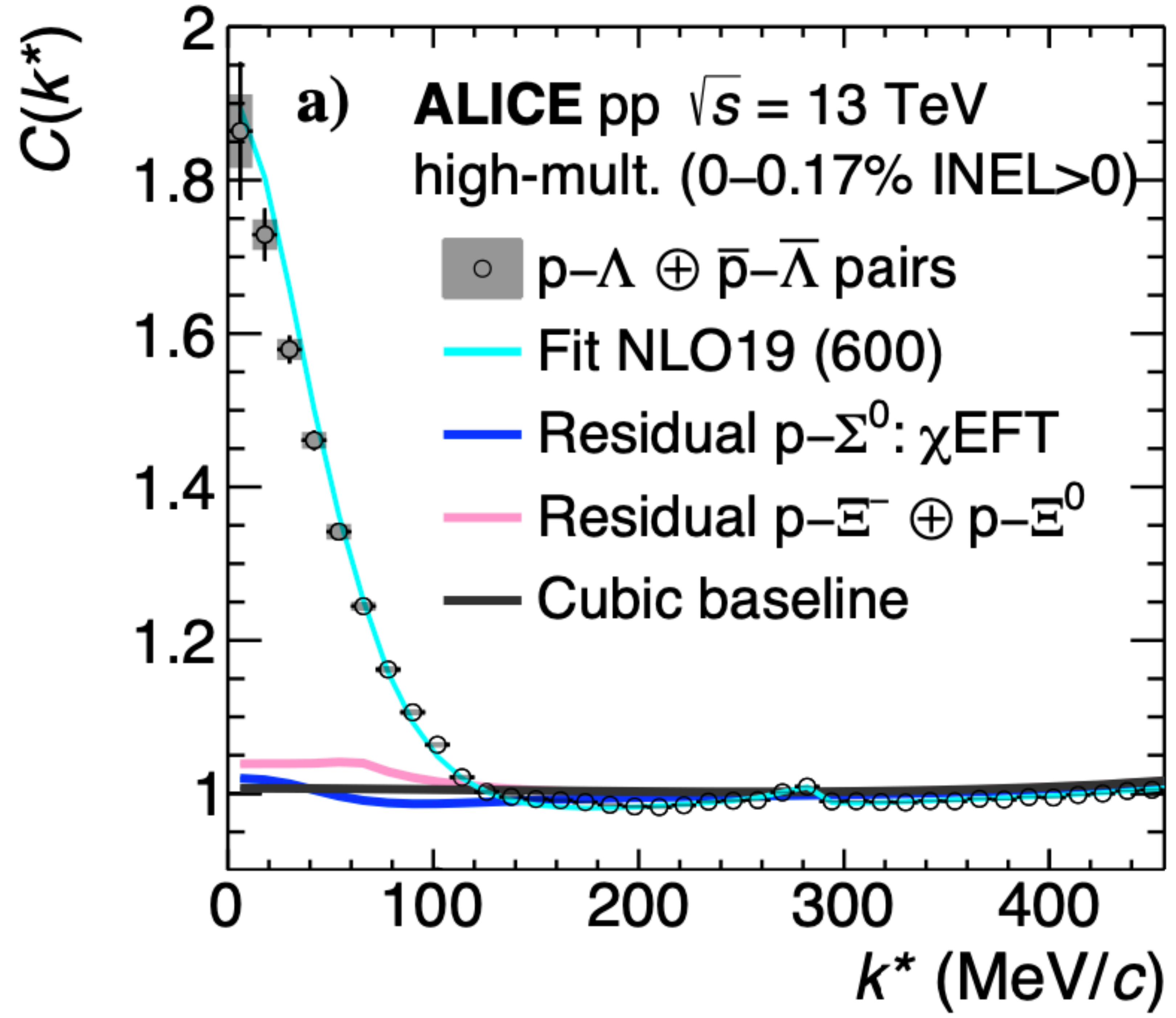
ALICE Coll. arXiv:2104.04427



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Output: p-(p-Λ)

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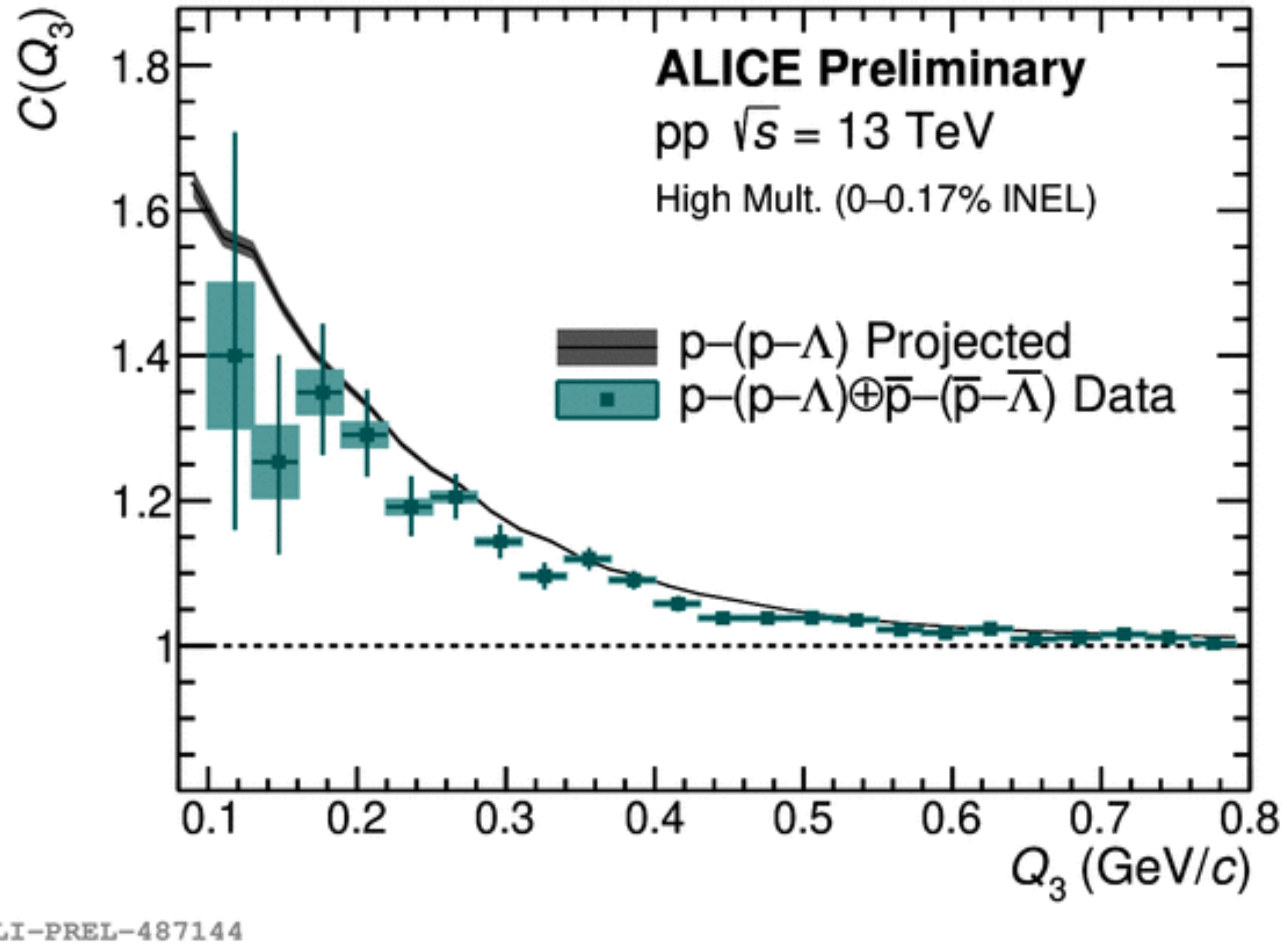

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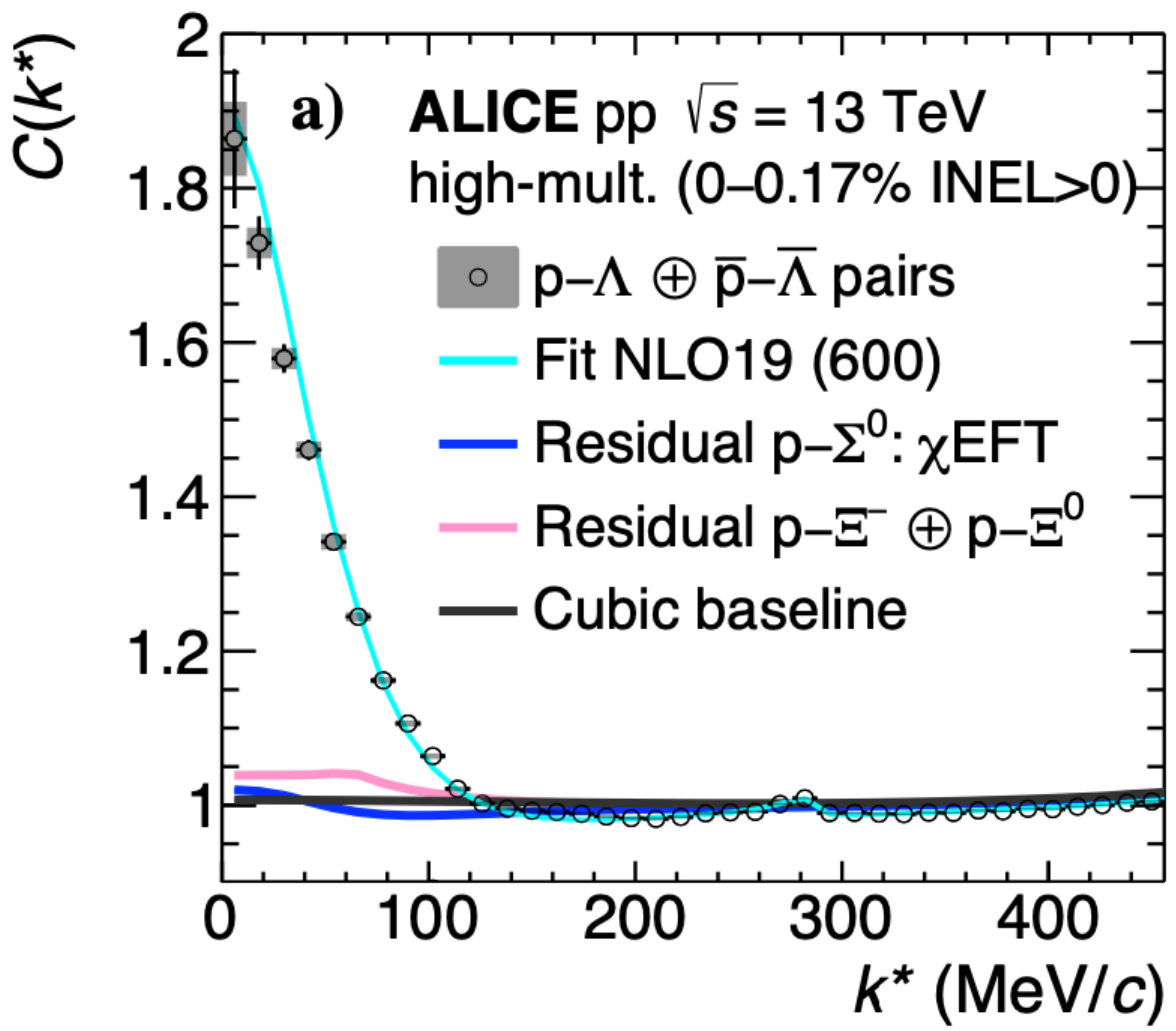

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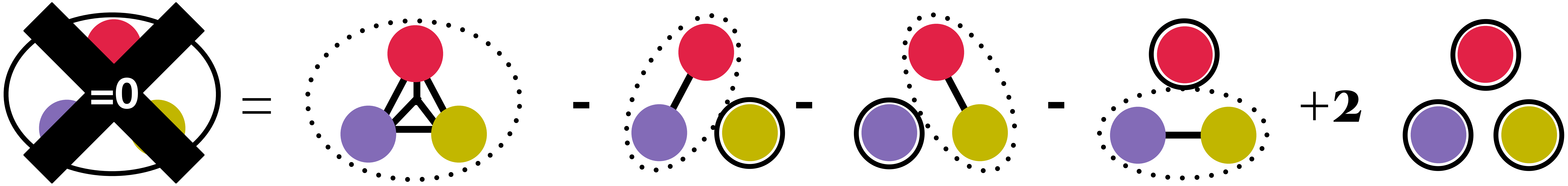
Three-body correlation: only two-body effects

- Using Kubo's cumulants and including only two-body interactions.



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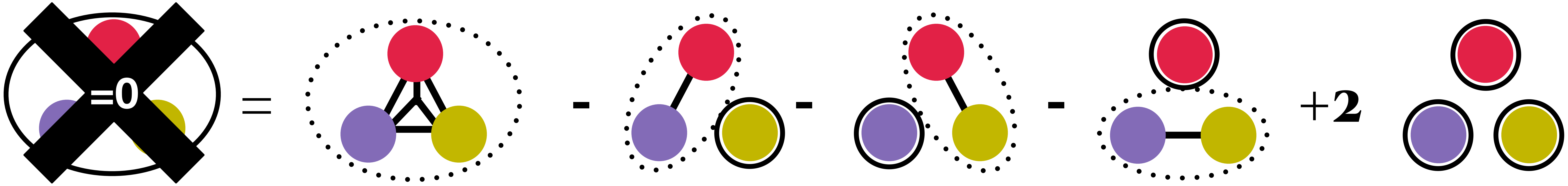

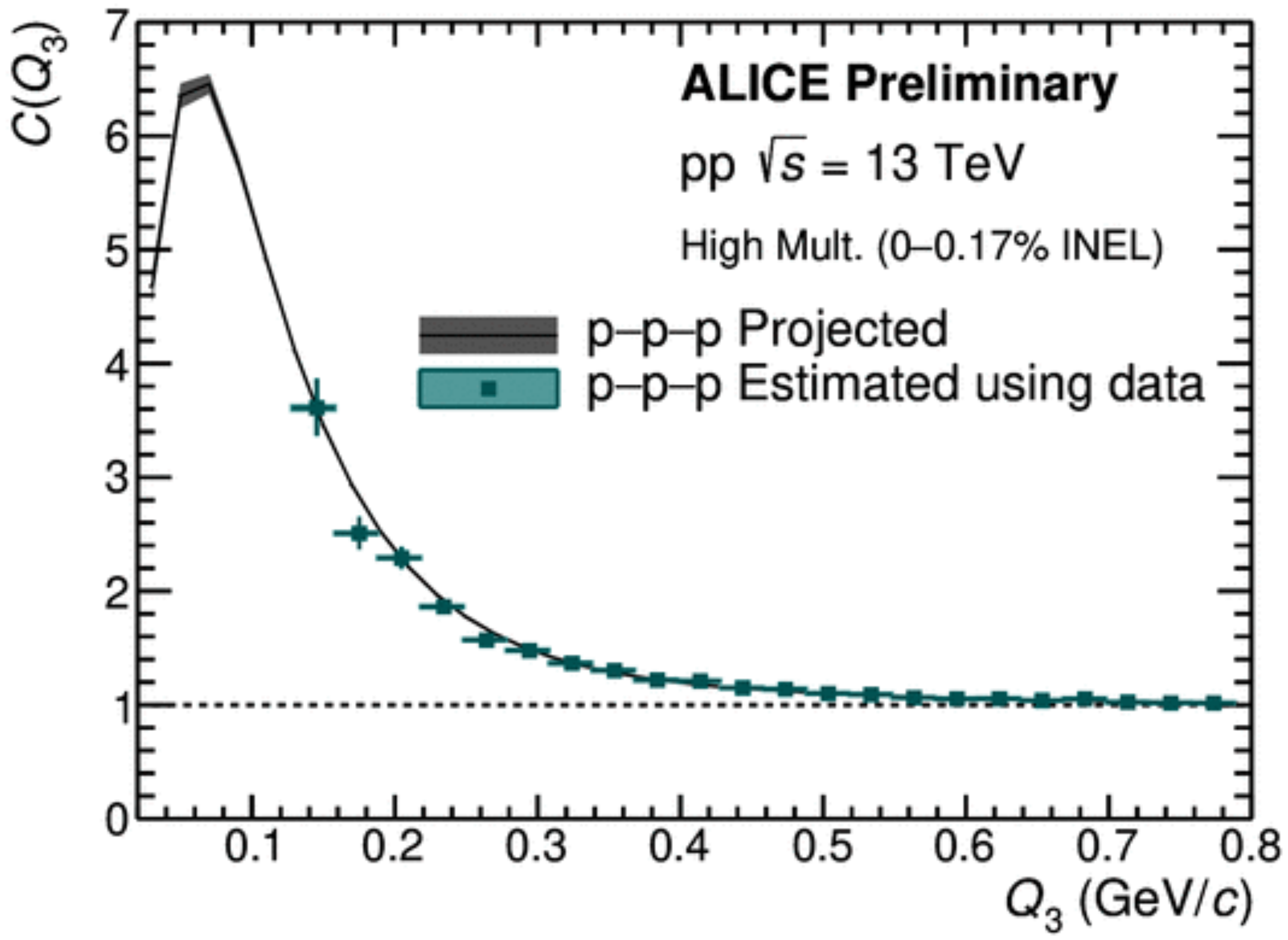

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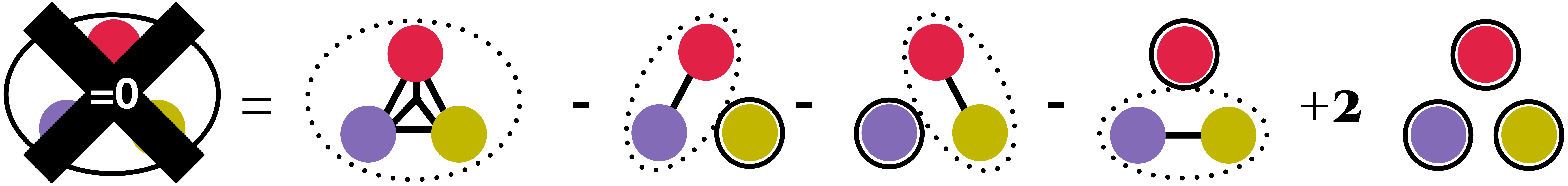
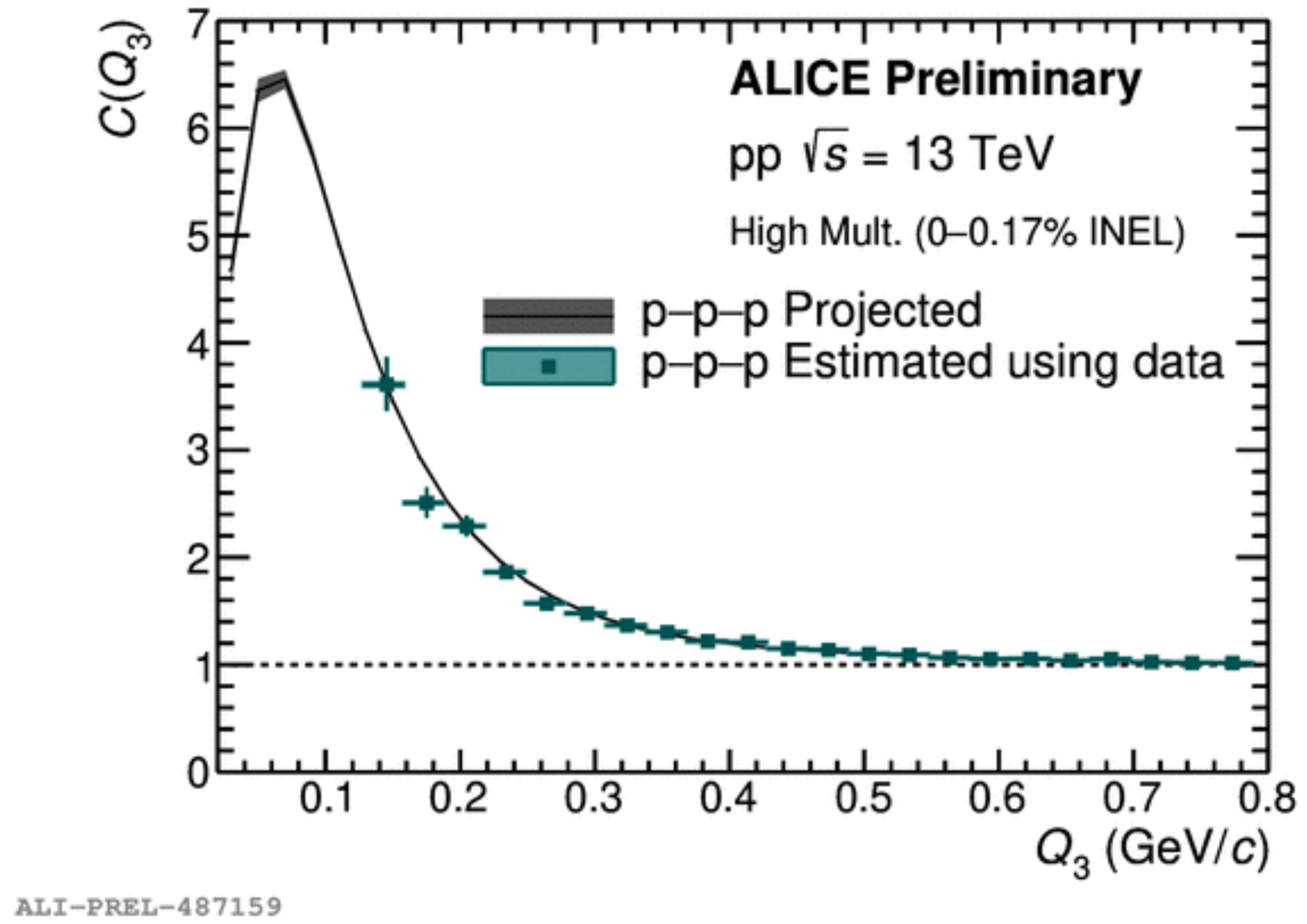
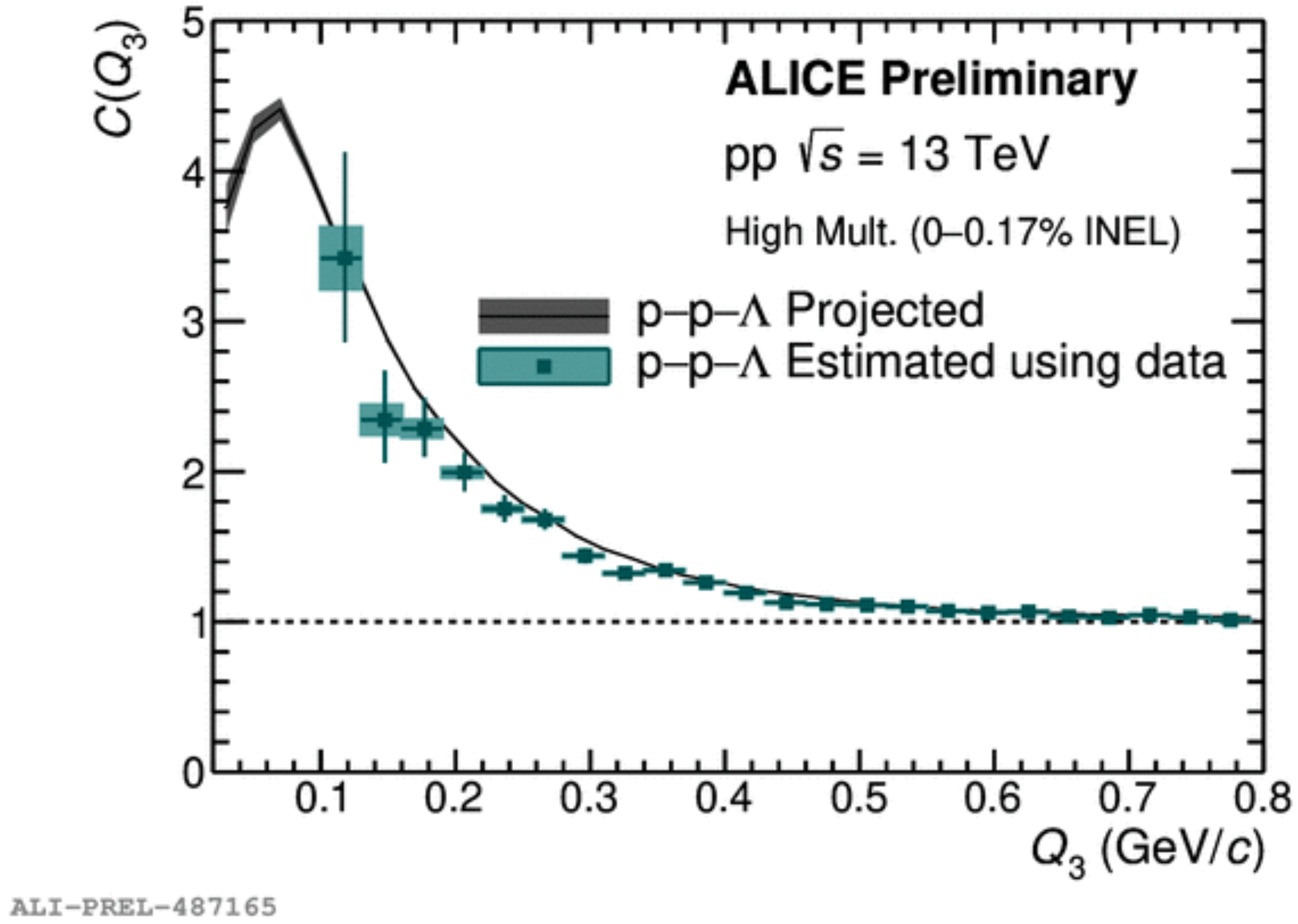
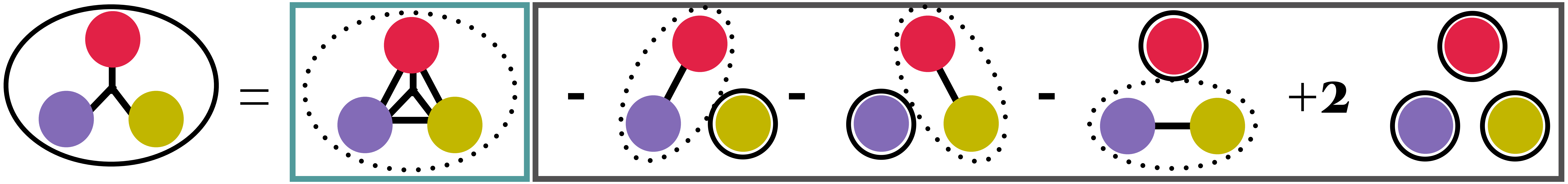






Three-body correlation

- Measured three-body and using Kubo's cumulants including only two-body interactions.



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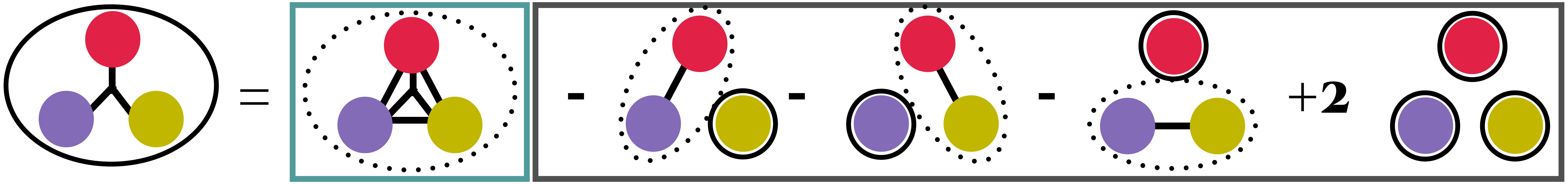

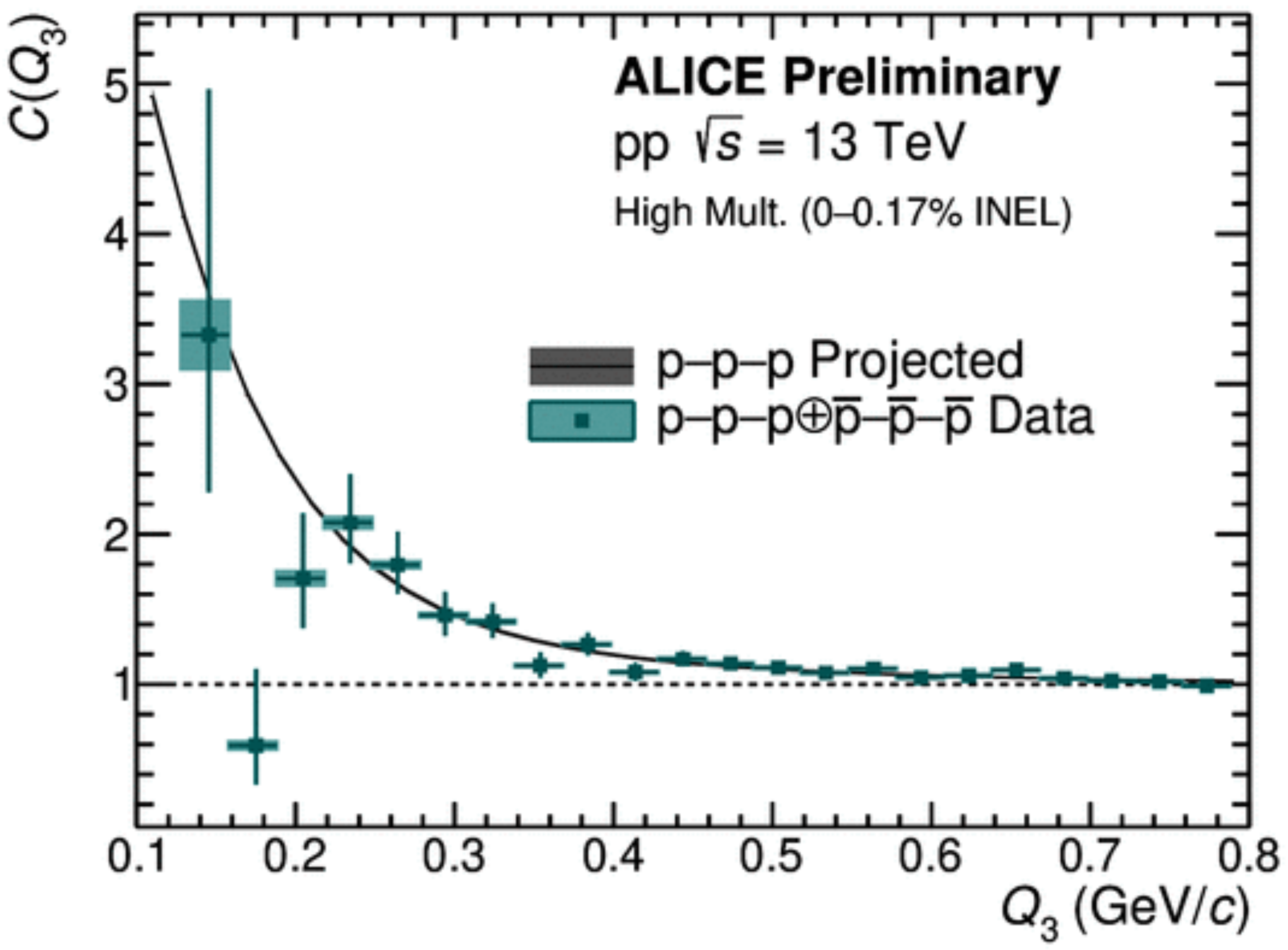

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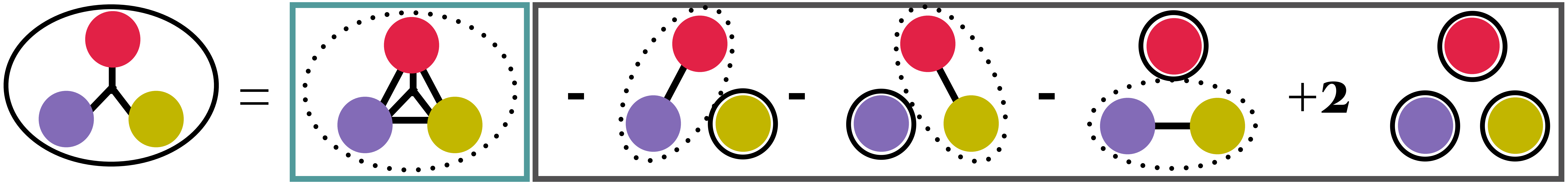
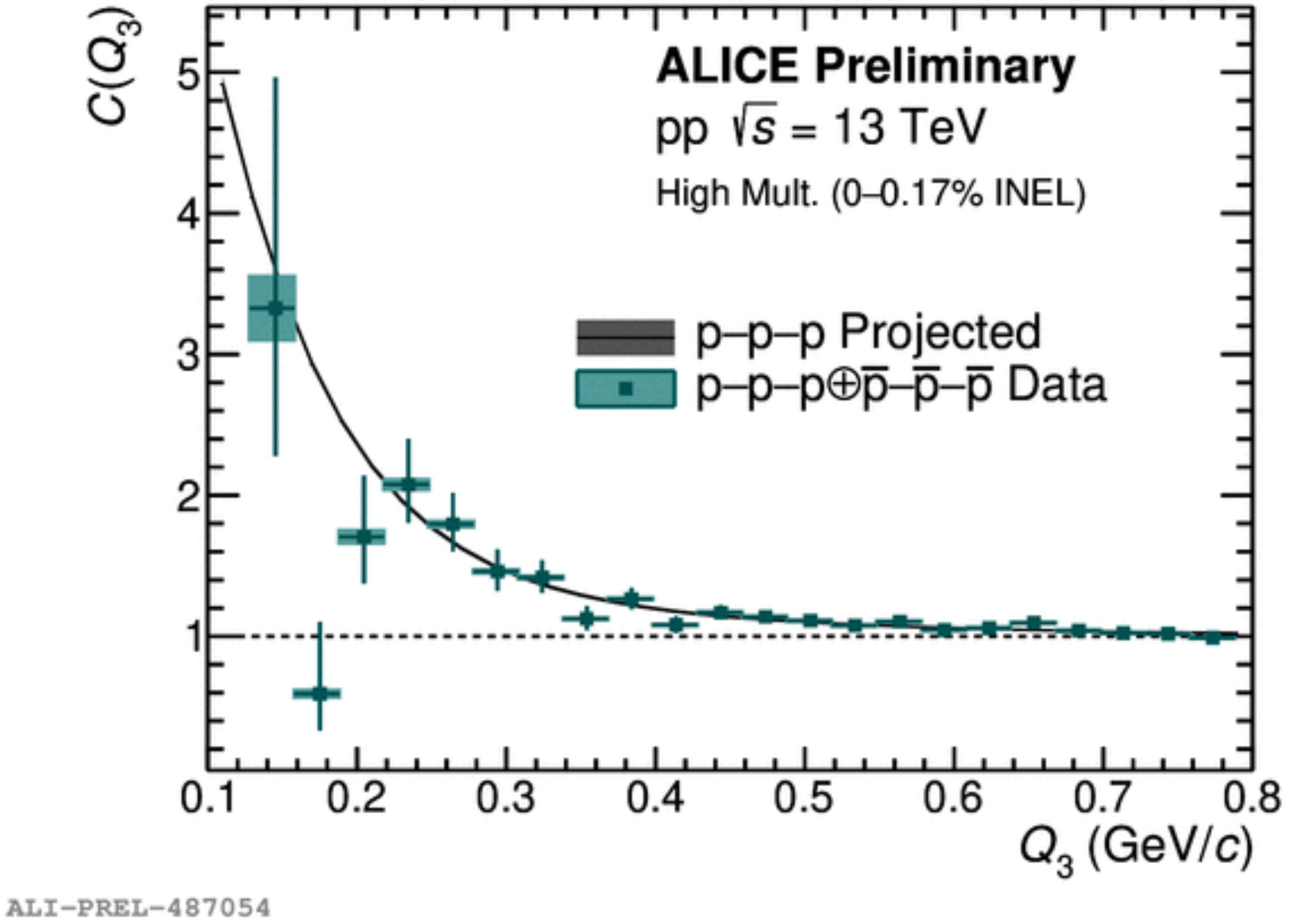
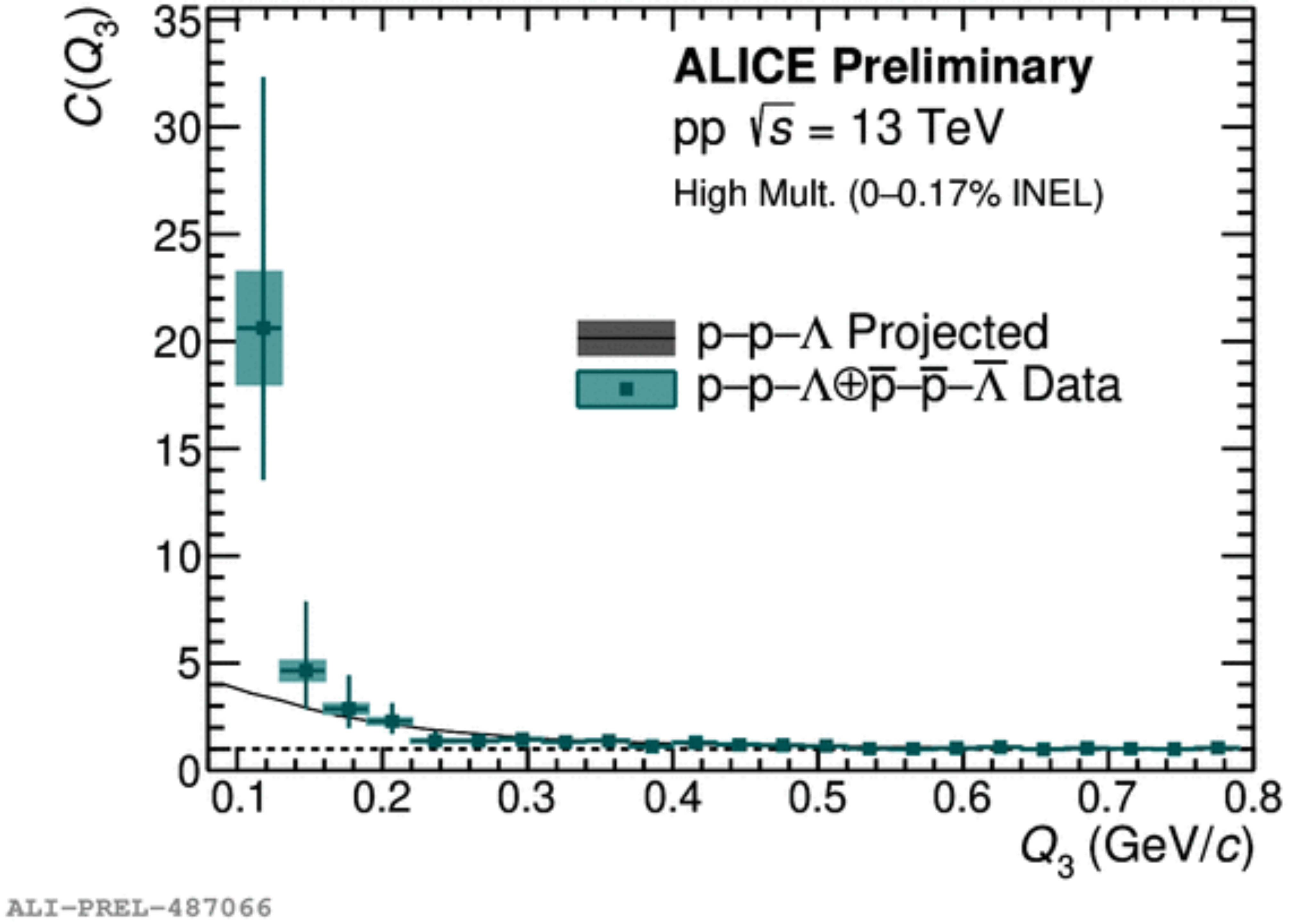
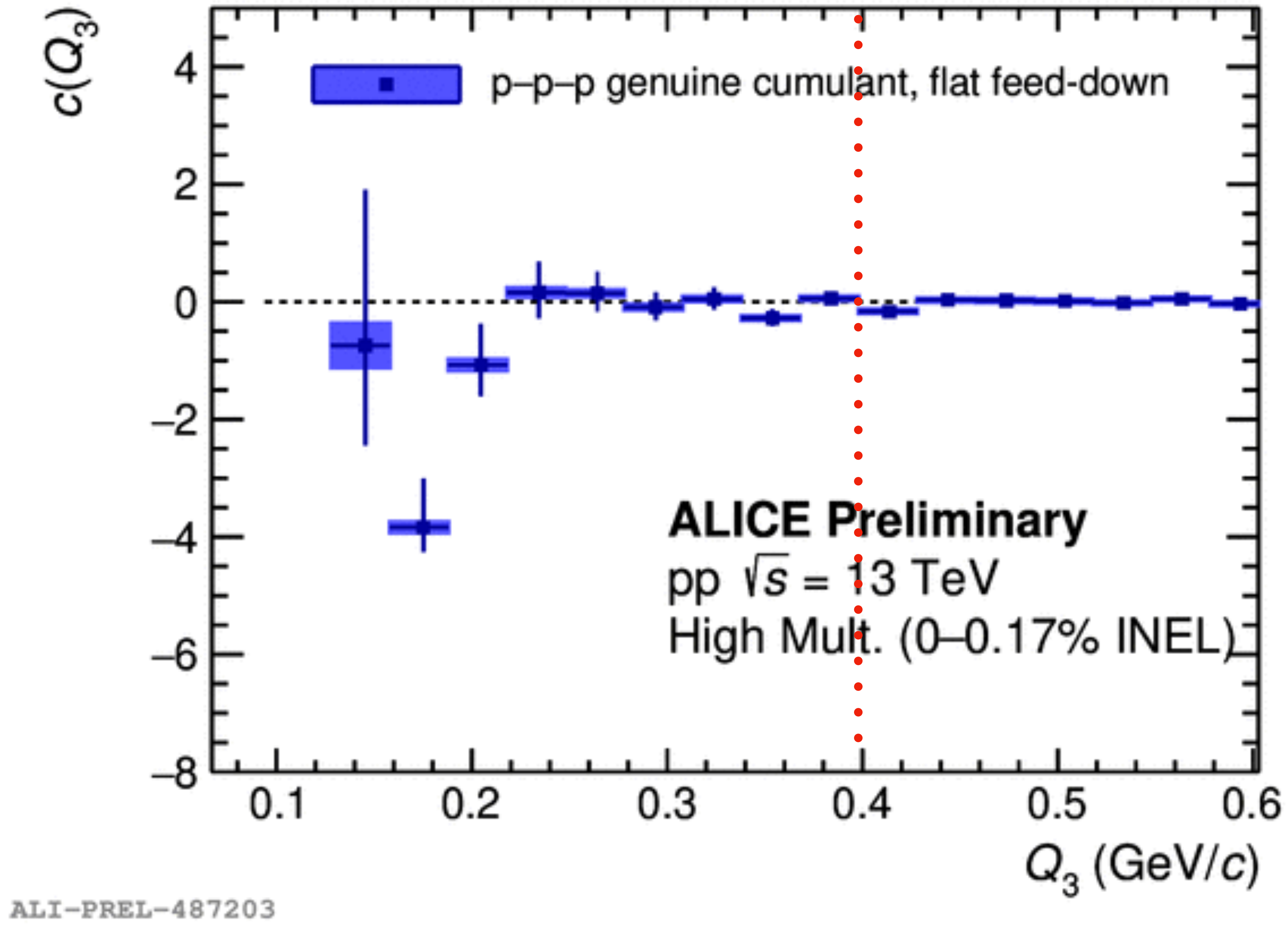






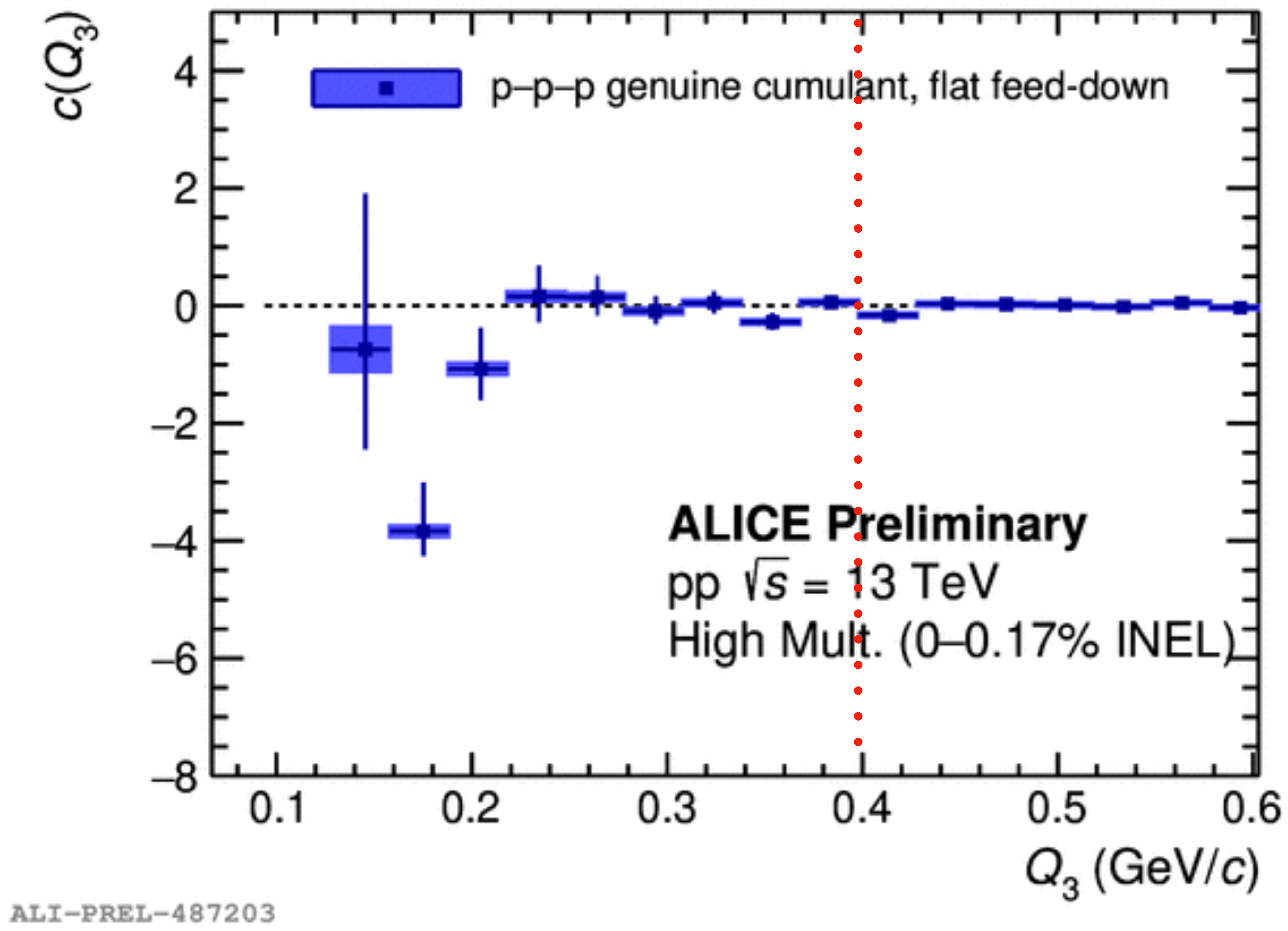
Cumulants



Statistical significance in the range up to 0.4 GeV/c: $n_\sigma = 2.9$

Theoretical calculations are needed to interpret the data.

Cumulants



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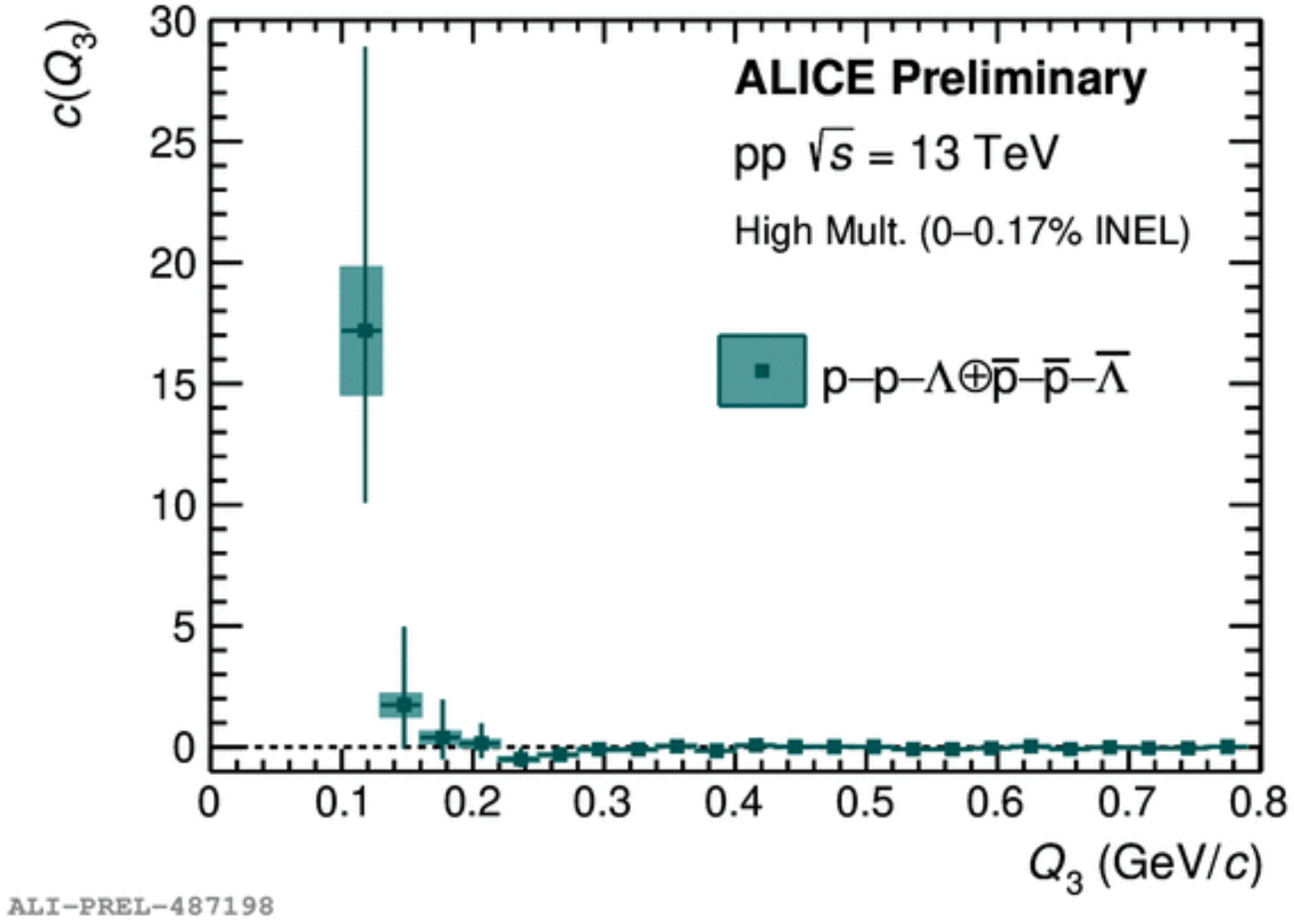
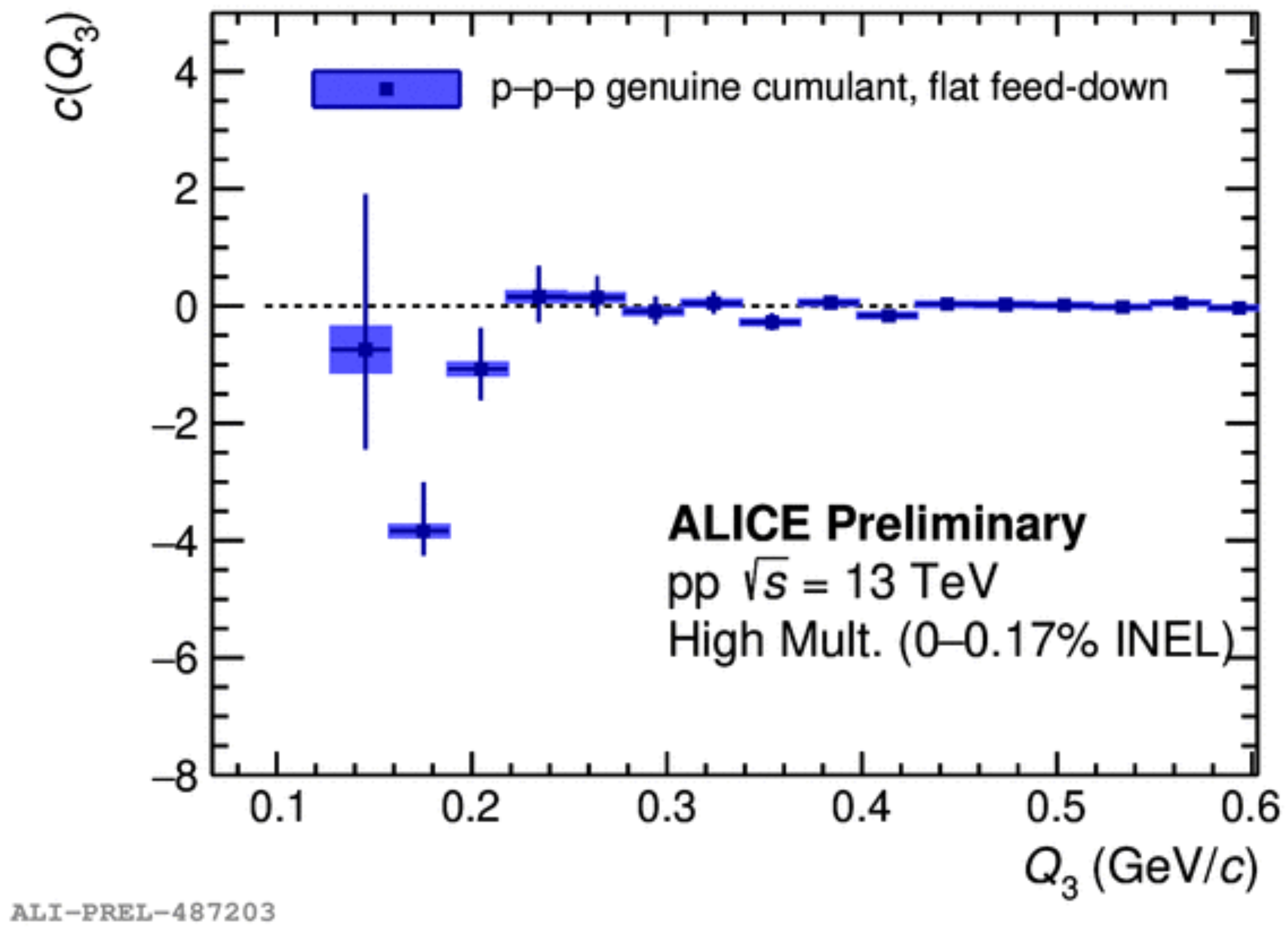
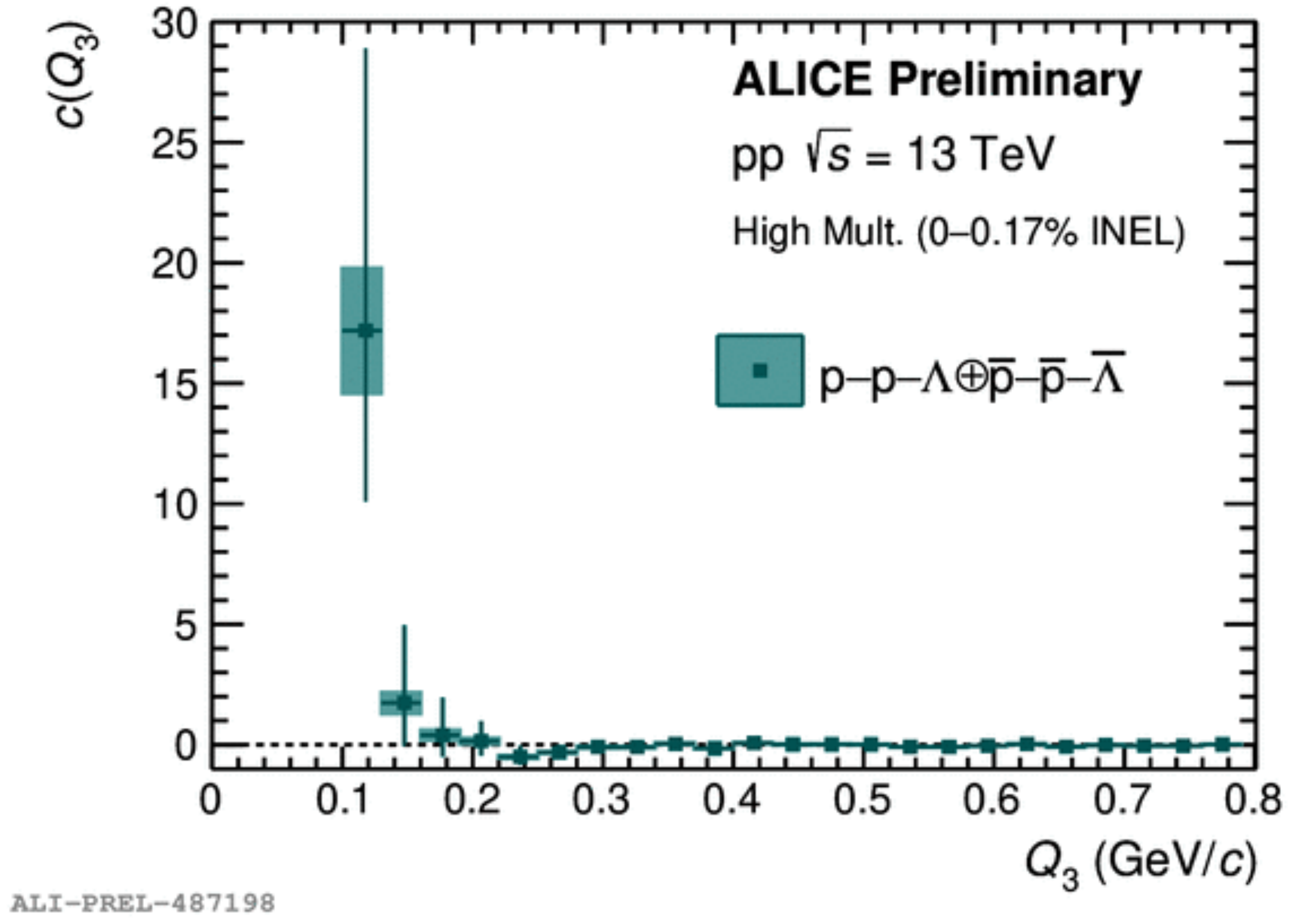


Positive cumulant observed in the first bins.

Summary and outlook

- First direct measurement performed of the three-baryon correlations in momentum space using femtoscopy method.
- Non-zero cumulant observed in both p-p-p and p-p-Λ correlations.
- First hint of genuine p-p-p interaction with significance of $n_\sigma = 2.9$ in the range up to 0.4 GeV/c.
- Much higher statistical precision will be achieved with the Run 3 data.





Back up

ALICE detector

General-purpose (heavy-ion) experiment at the Large Hadron Collider

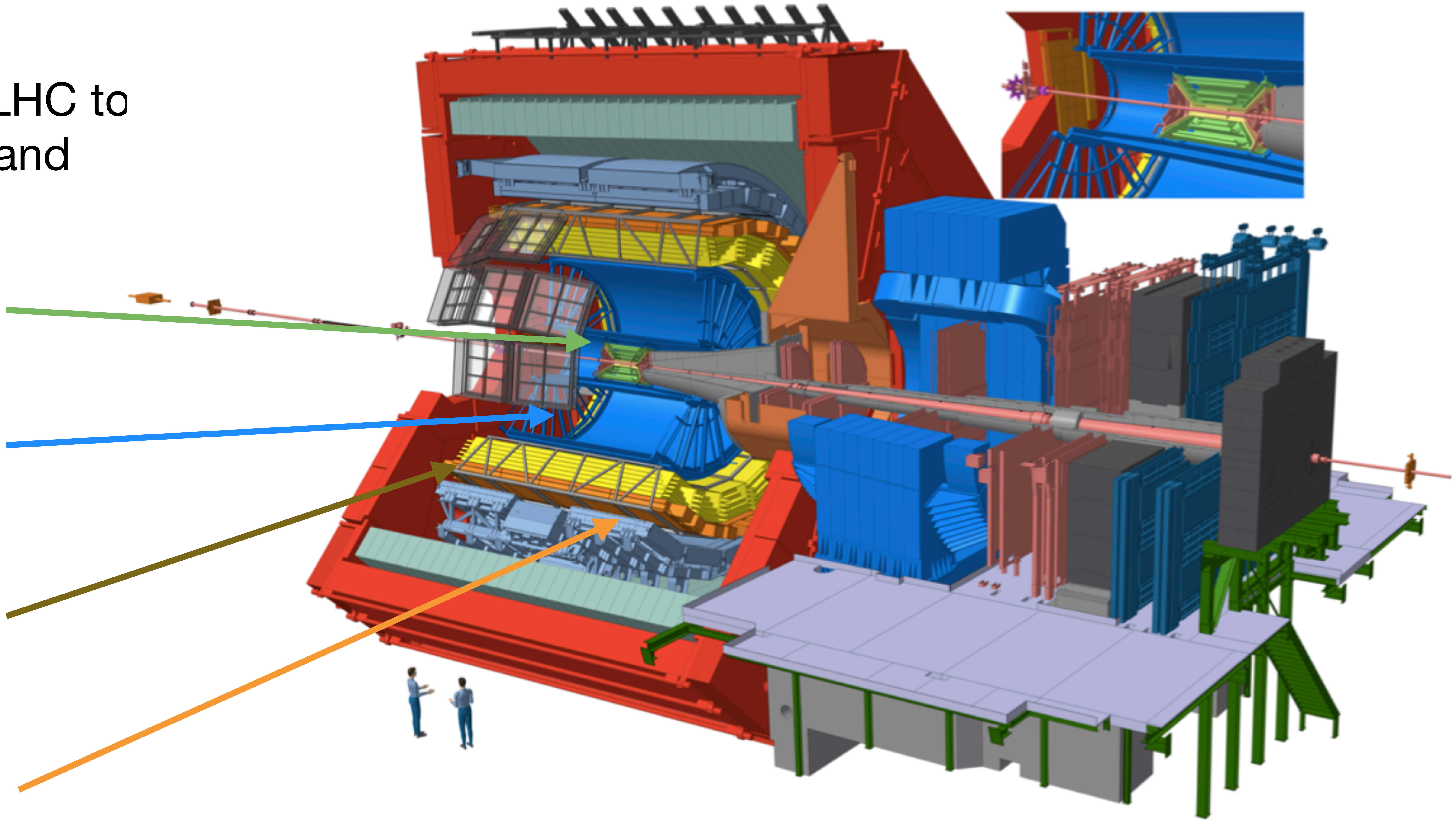
- Excellent tracking and particle identification (PID) capabilities
- Most suitable detector at the LHC to study (anti-)nuclei production and annihilation

Inner **T**racking **S**ystem
Tracking, vertex, PID (d*E*/dx)

Time **P**rojection **C**hamber
Tracking, PID (d*E*/dx)

Transition **R**adiation **D**etector

Time **O**f **F**light detector
PID (TOF measurement)



Projector

- Looking at 2-body correlation function in 3-body space requires to account for the phase-space of the particles.

- The projection onto Q_3 is performed by integrating the correlation function over all the configurations in the momentum phase space having the same value of Q_3

$$C(Q_3) = \iiint_{Q_3=\text{constant}} C([\mathbf{p}_i, \mathbf{p}_j], \mathbf{p}_k)\, d^3\mathbf{p}_i\, d^3\mathbf{p}_j\, d^3\mathbf{p}_k \quad = \quad \int C_2(k^*_{ij})\, W_{ij}(k^*_{ij}, Q_3)\, dk^*_{ij}$$

$$W_{ij}(k^*_{ij}, Q_3) = \frac{16(\alpha\gamma - \beta^2)^{3/2} {k^*_{ij}}^2}{\pi\gamma^2 {Q_3}^4} \sqrt{\gamma {Q_3}^2 - (\alpha\gamma - \beta^2){k^*_{ij}}^2}$$

- The α, β, γ depend only on the masses of the three particles.