Accessing the genuine three-baryon interactions via femtoscopic studies in pp collisions at $\sqrt{s}$ = 13 TeV with ALICE

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On behalf of the ALICE Collaboration
Technical University of Munich
NUCLEUS2021

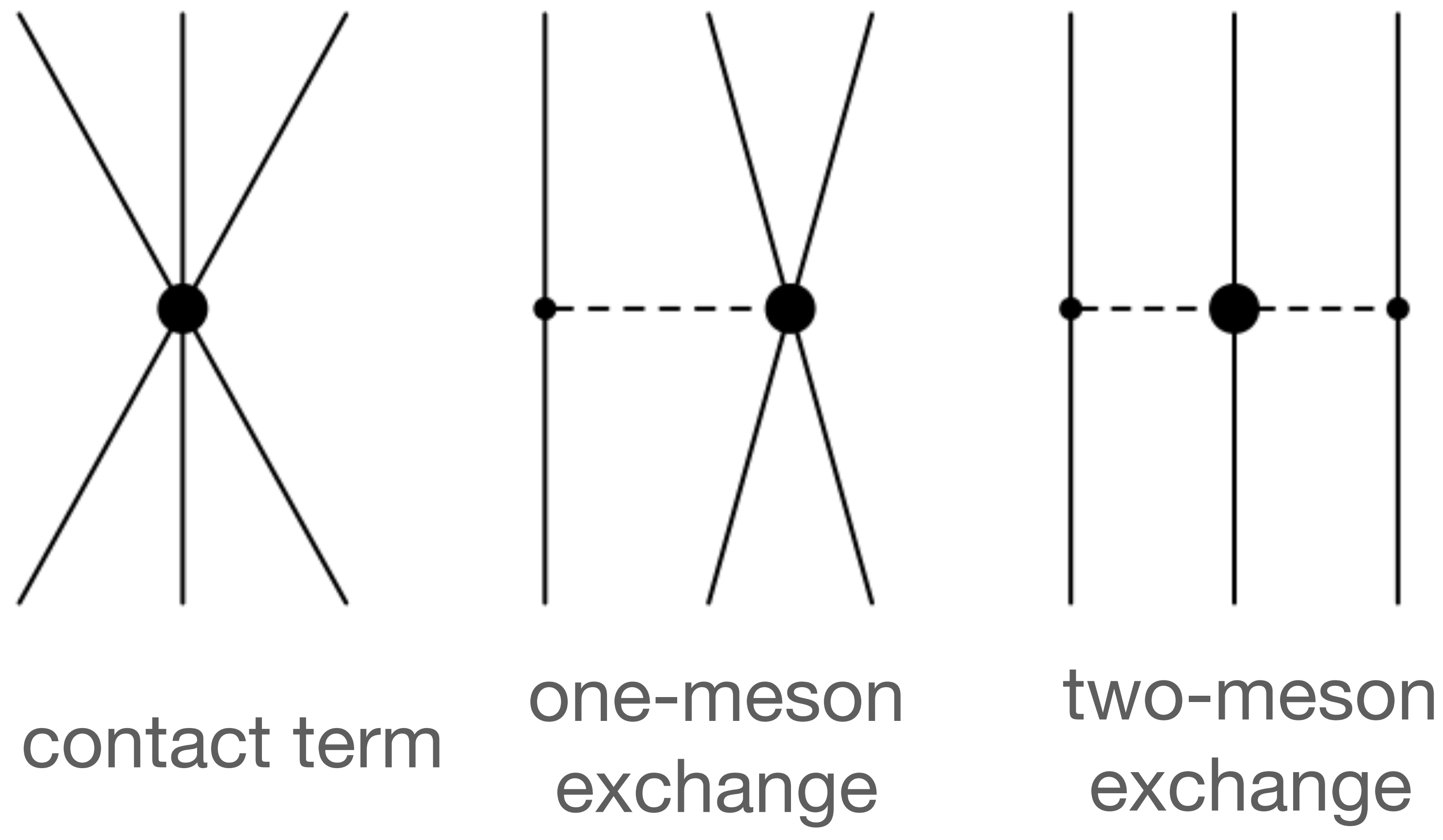
Three-body interactions

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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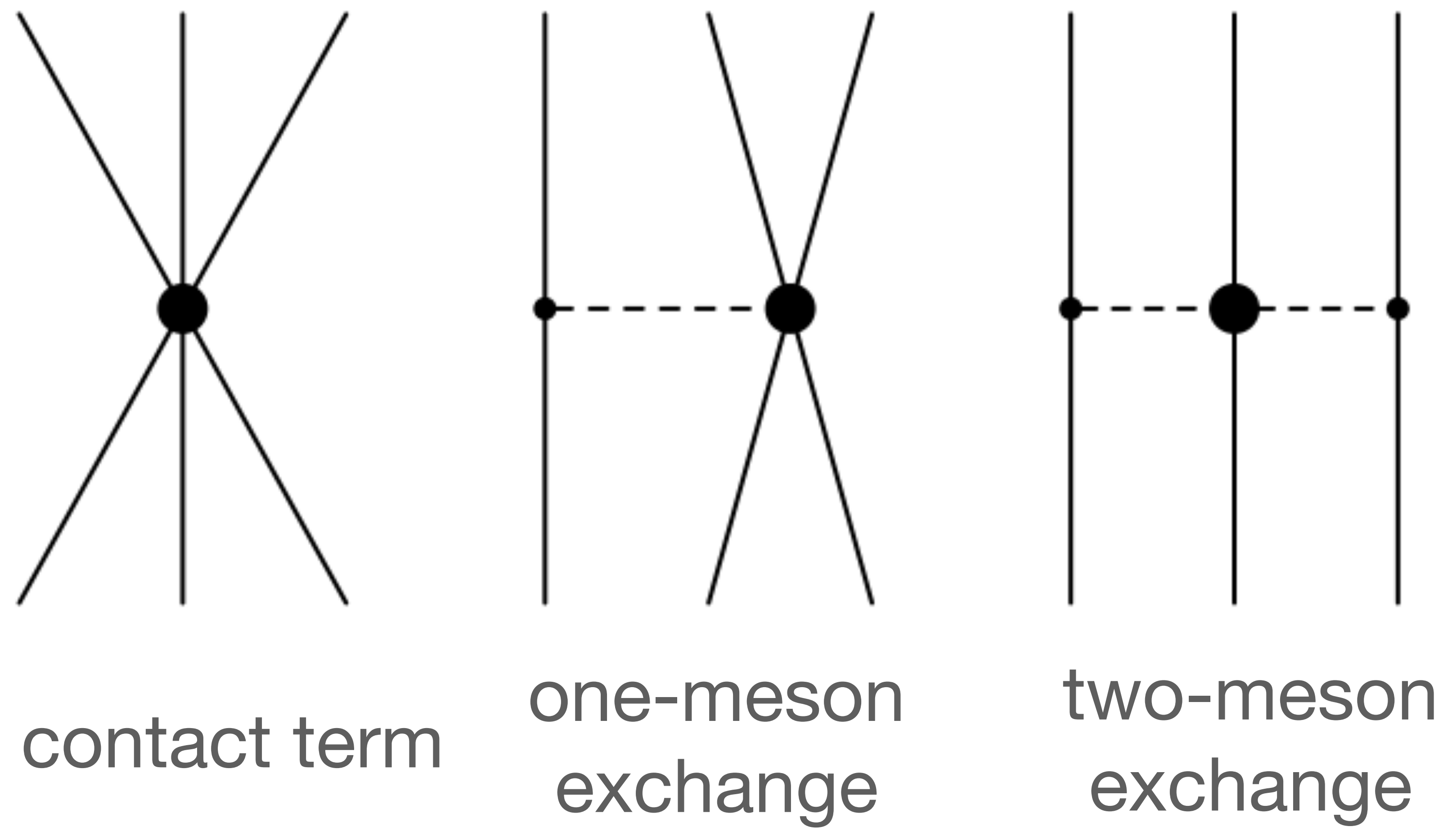

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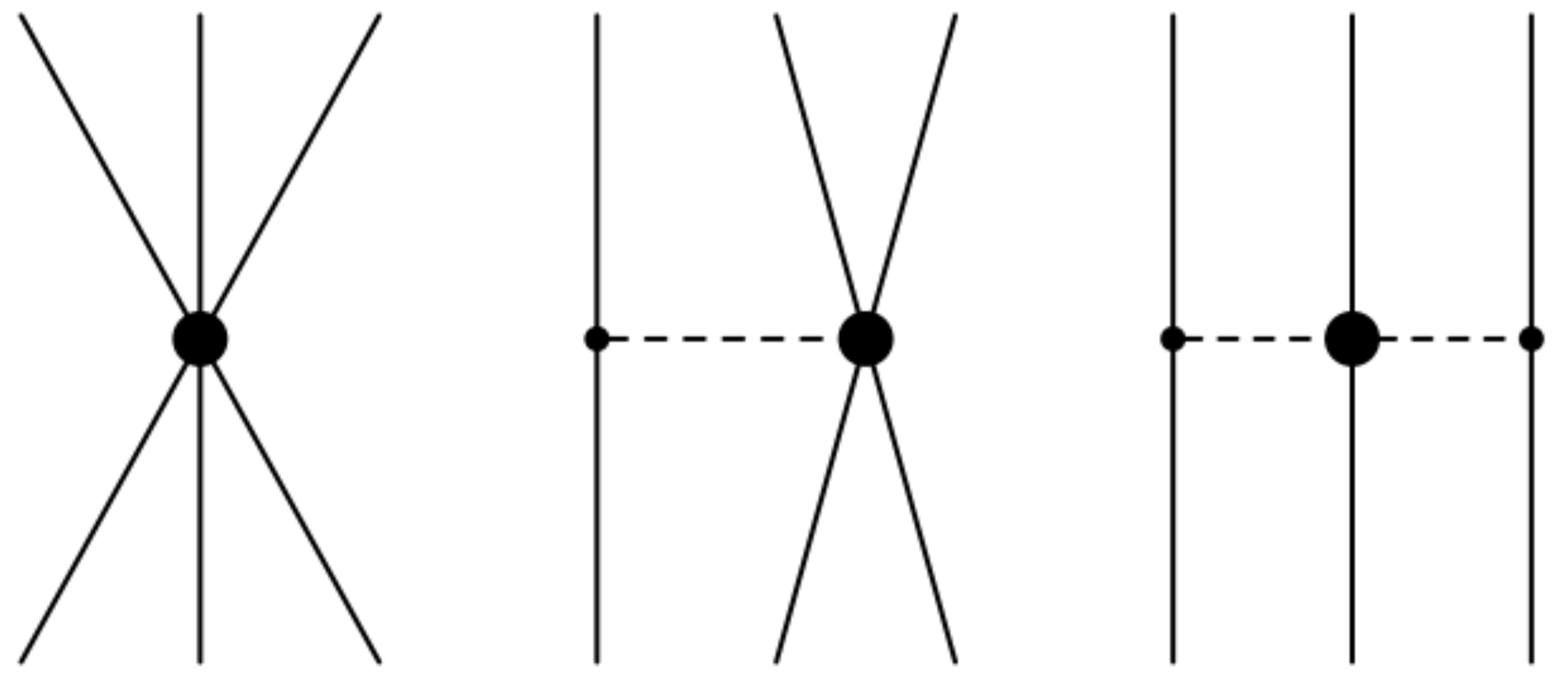


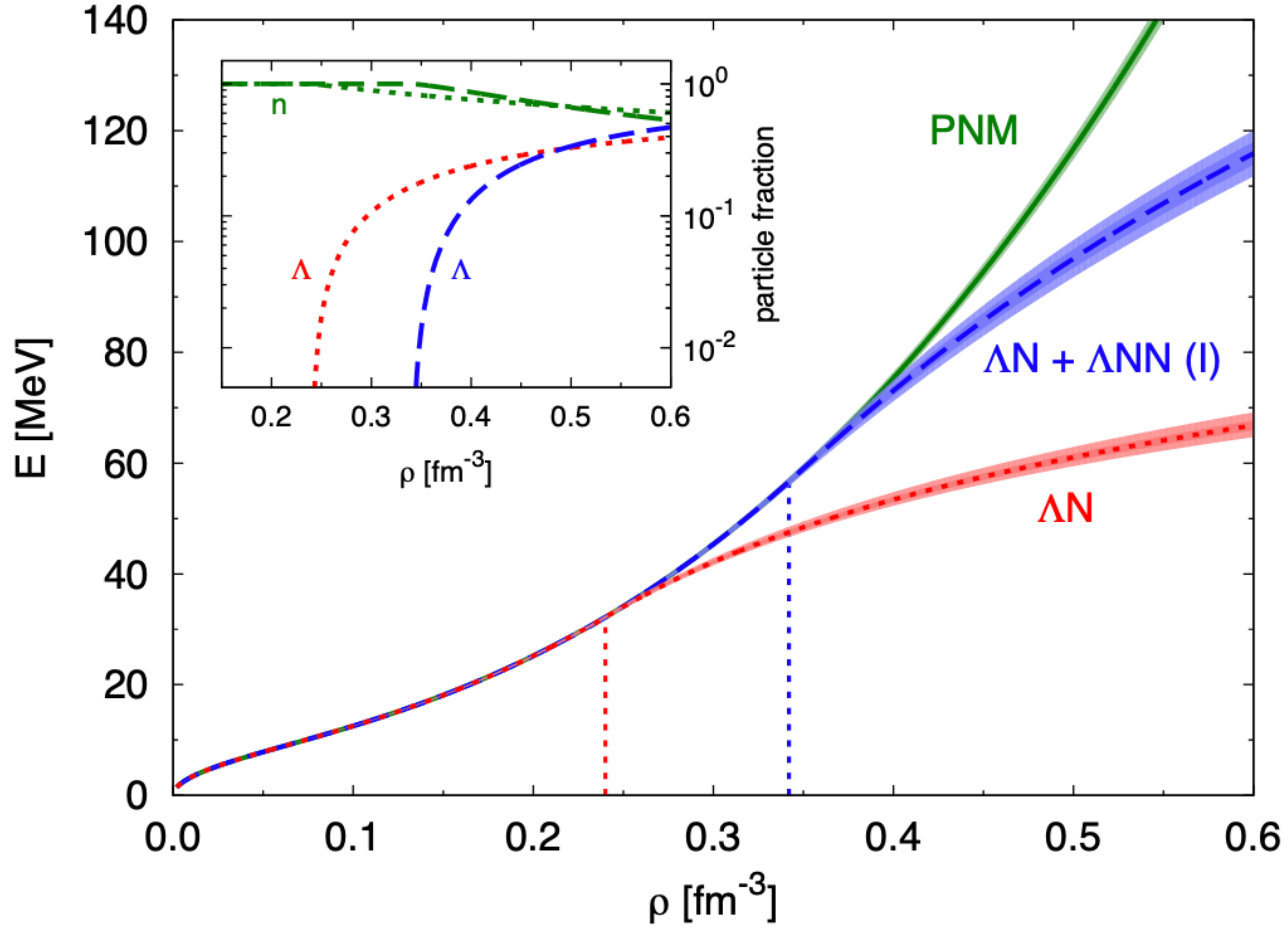
Measurement of nuclei and hypernuclei binding energies, but

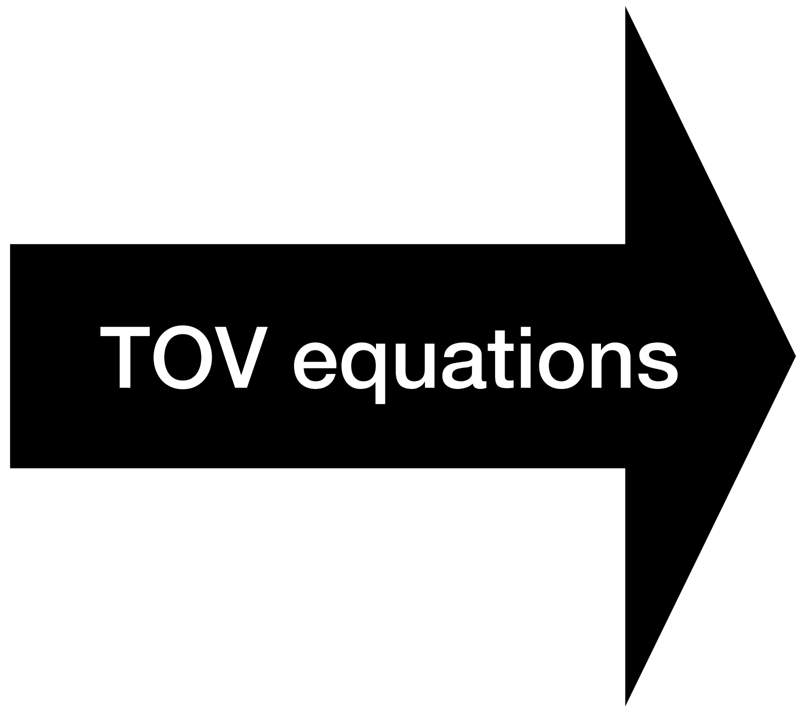
- the interaction is probed at "large" distances (around 2.2 fm in ^{12}C),
- the superposition of two- and many-body effects complicates the extraction of the genuine three-body interactions.

Three-body interactions in neutron stars

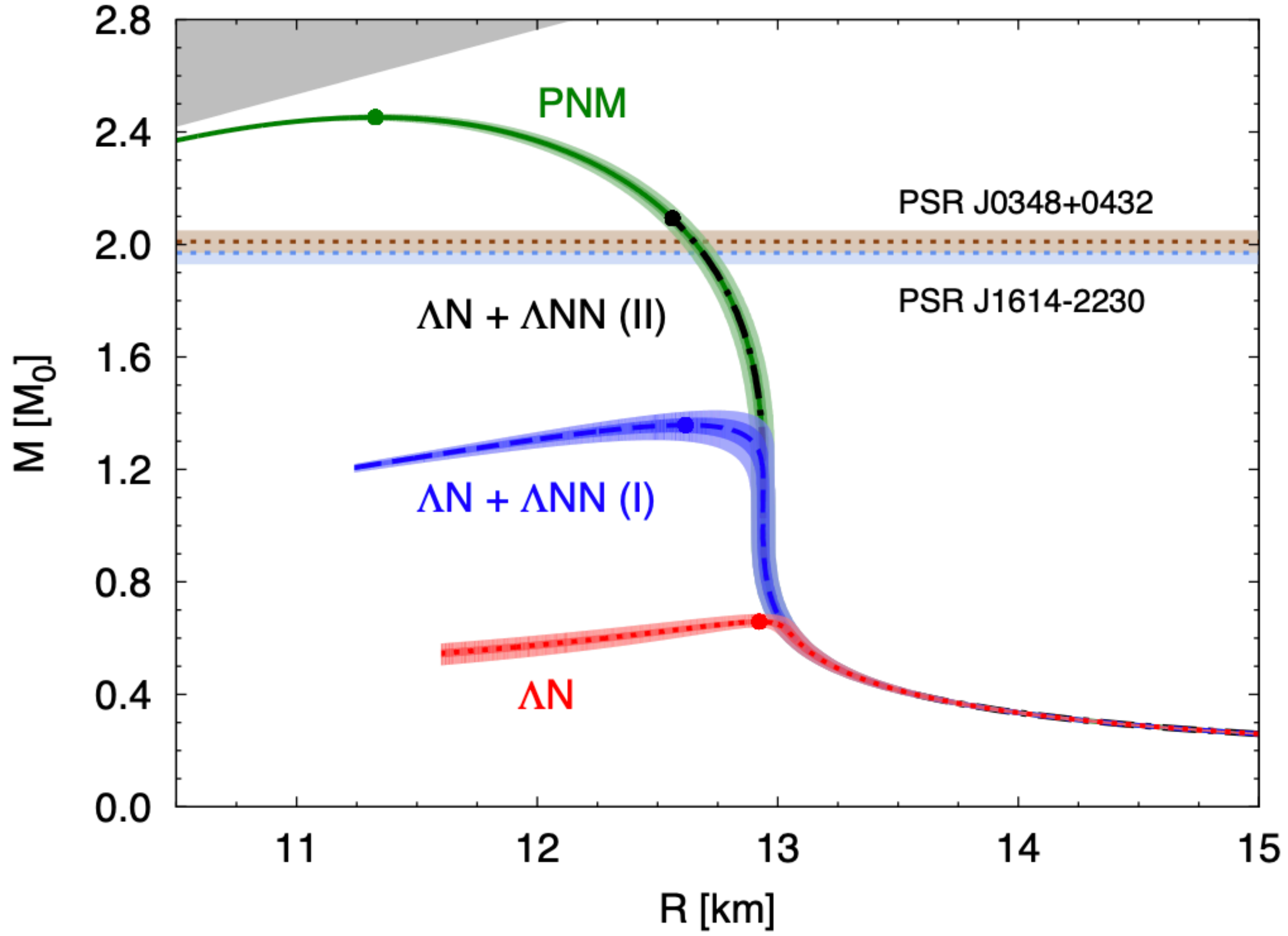
- ΛN softens the equations of state -> Only low-mass neutron stars possible.
- Observations -> Up to ~2 solar masses.
- One possible solution -> Include three-body interaction.

Three-body interaction constrained using hypernuclei data.



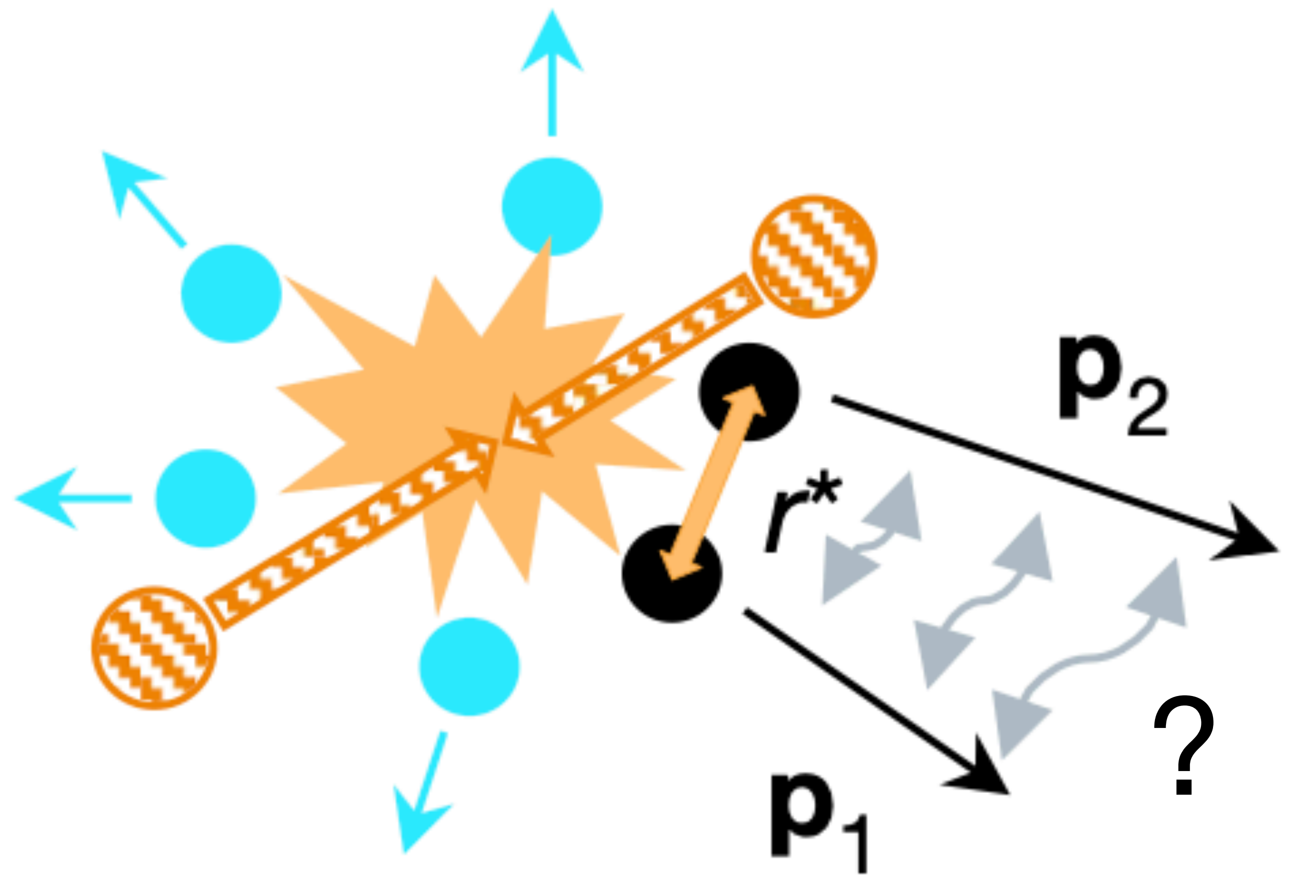


Phys. Rev. Lett. 114, 092301



Are there other methods to study interaction?

Femtoscopy technique



Emission source *S(r*)*

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

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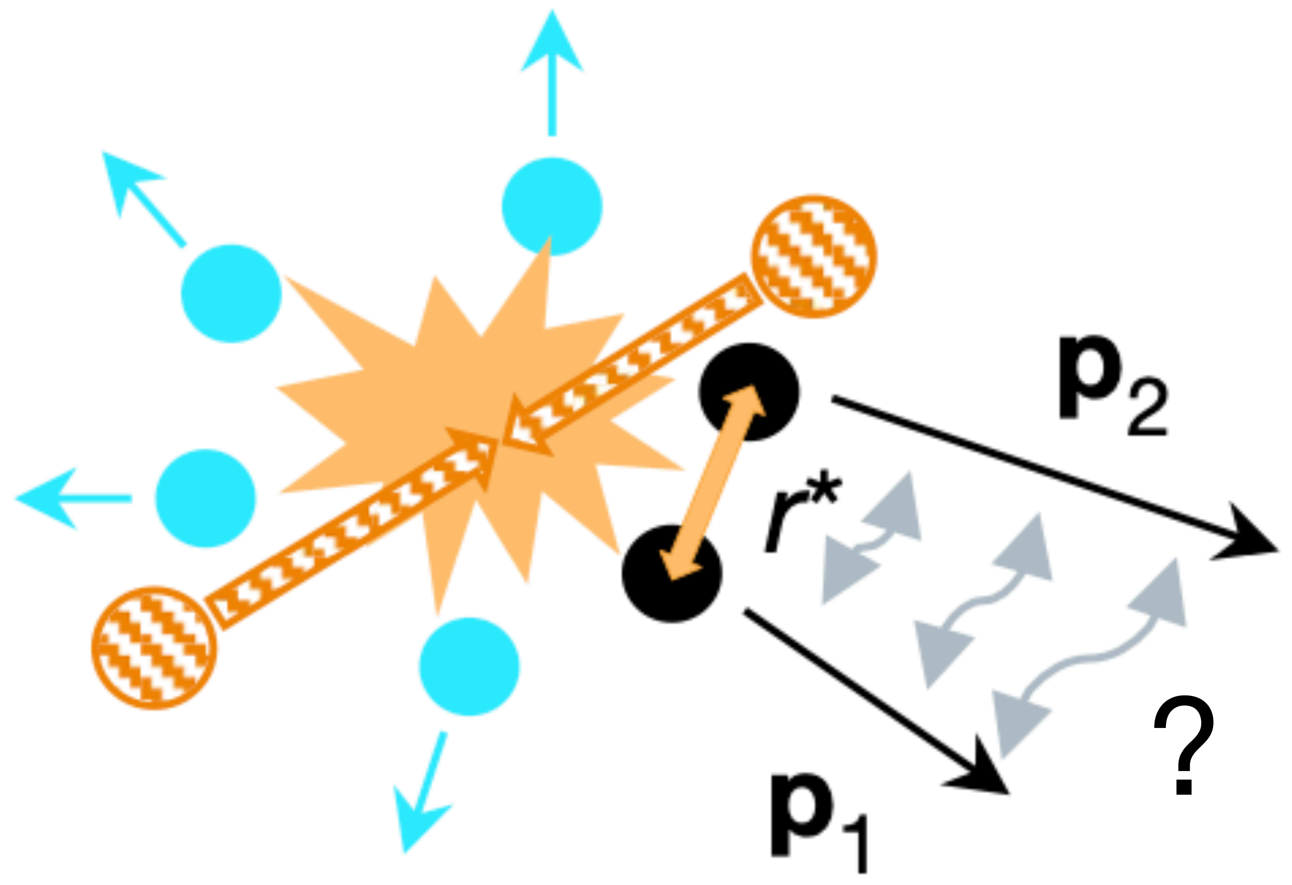

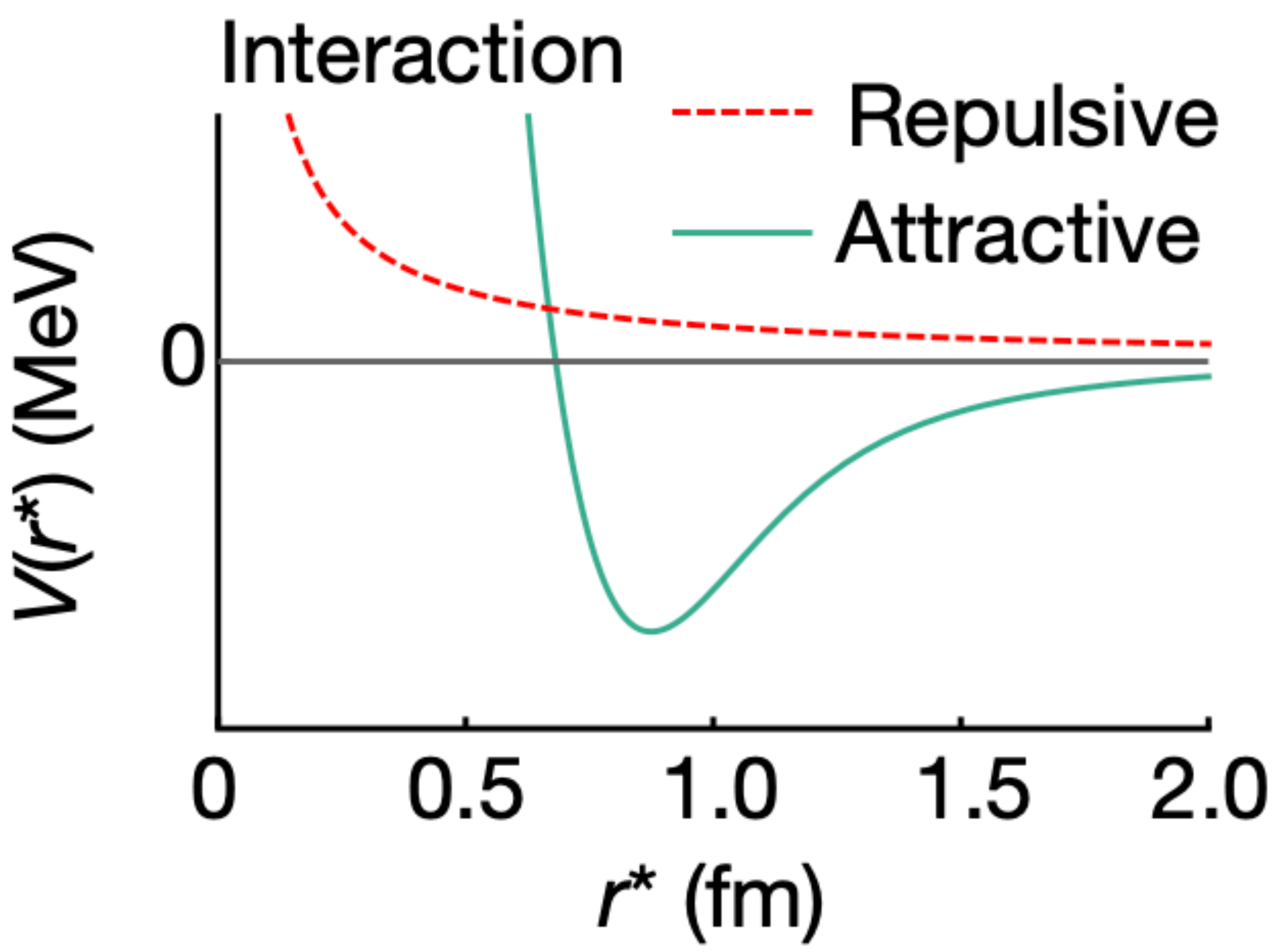

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Schrödinger equation
Two-particle wave function
$\left|\psi\left(\mathbf{k}^*, \mathbf{r}^*\right)\right|$

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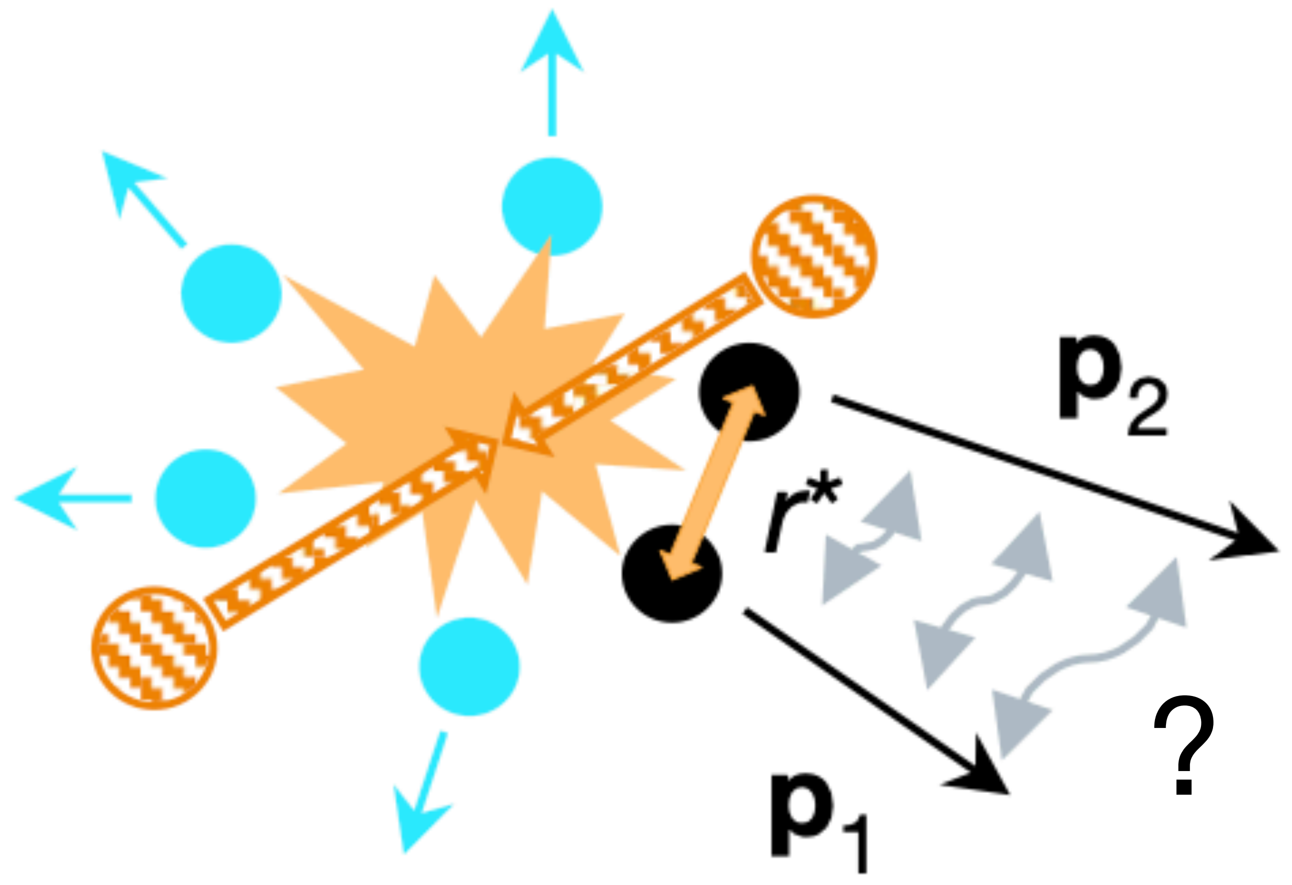

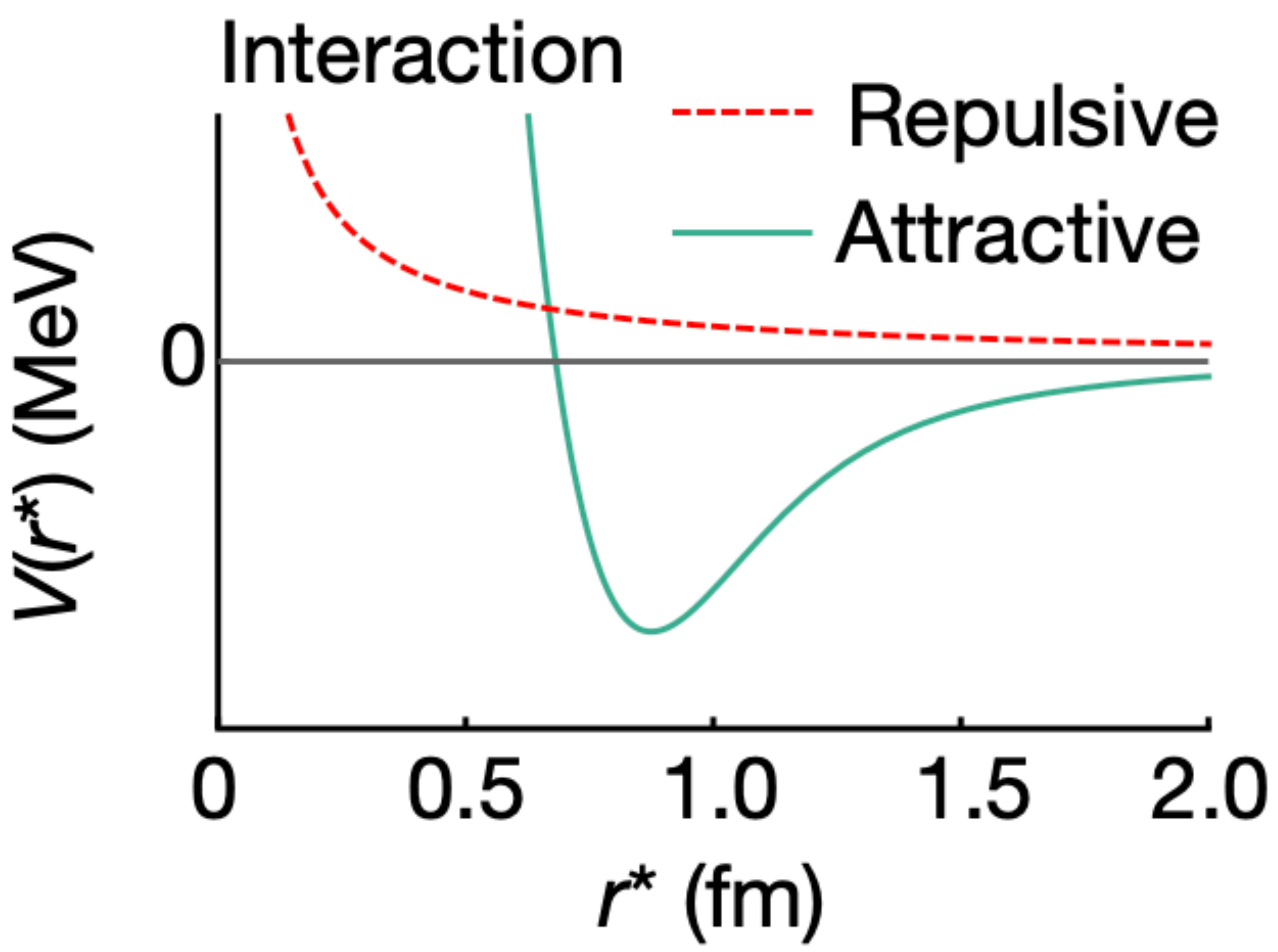

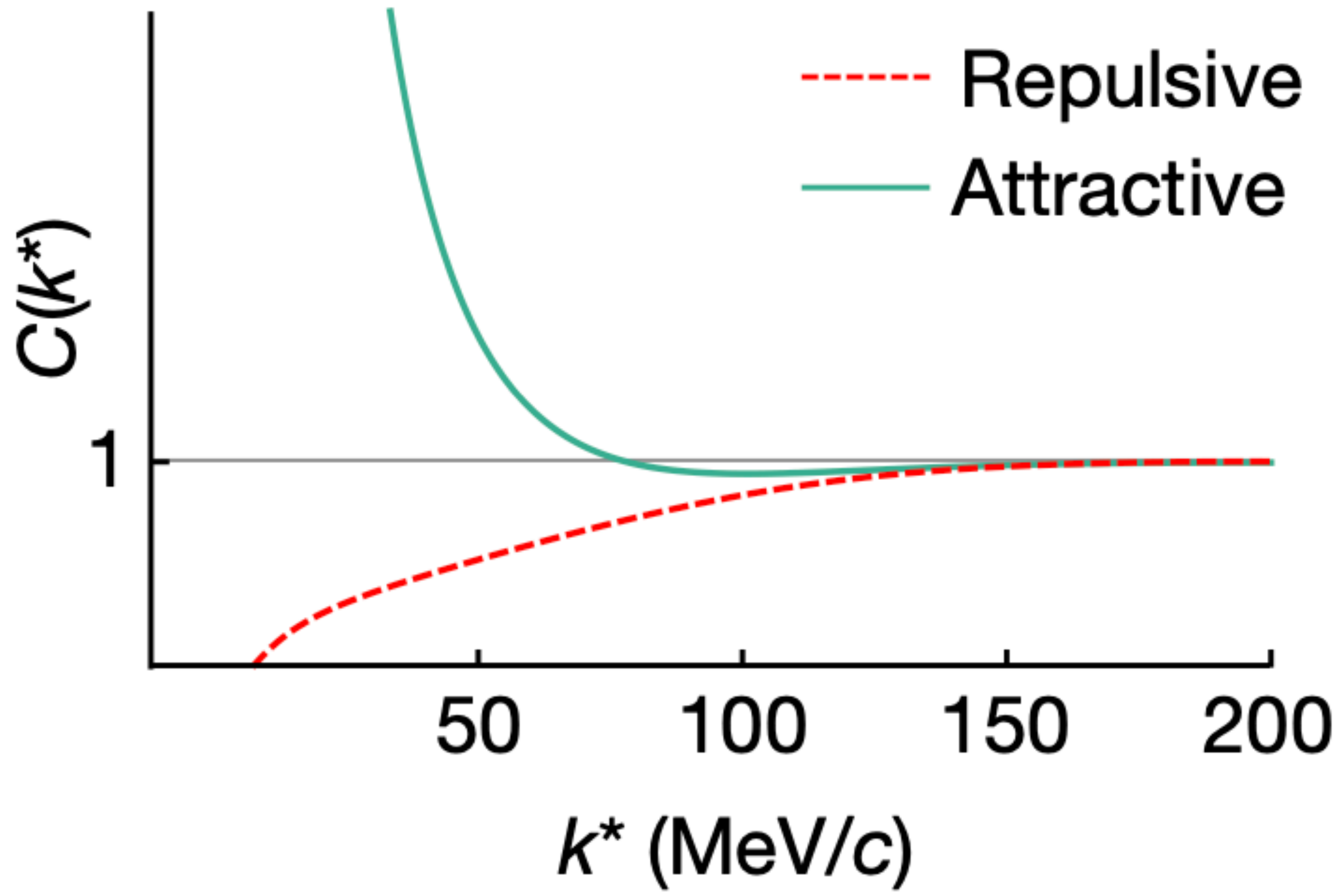

Emission source $S(r^*)$

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Two-particle wave function
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Correlation function $C(k^*)$

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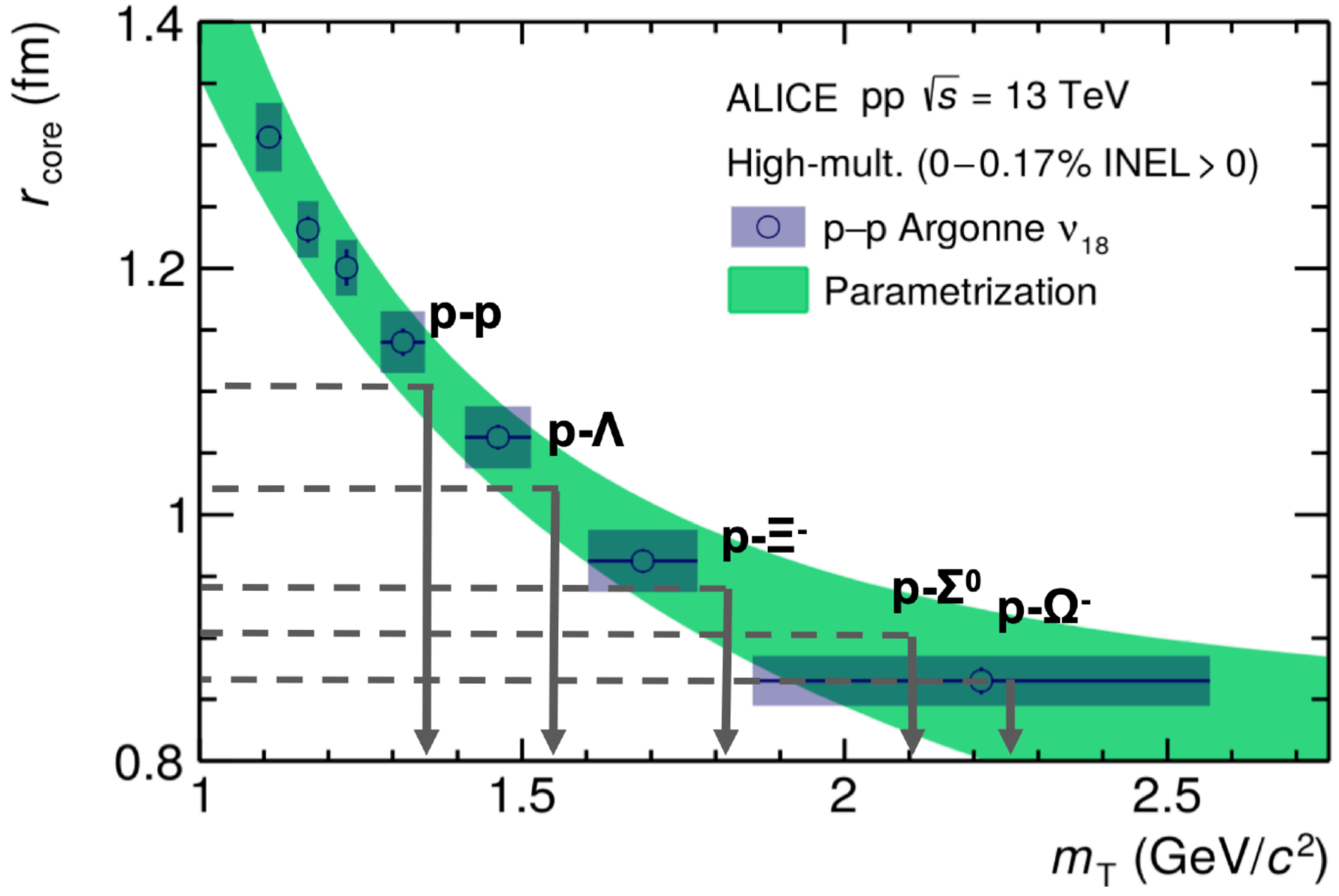
Emission source

ALICE Coll. PLB 811 (2020) 135849

- pp collisions in ALICE at $\sqrt{s}$ = 13 TeV have small source size!
- Two main contributions:
  - general: Collective effects result in Gaussian core;
  - specific: Decaying resonances require source correction.



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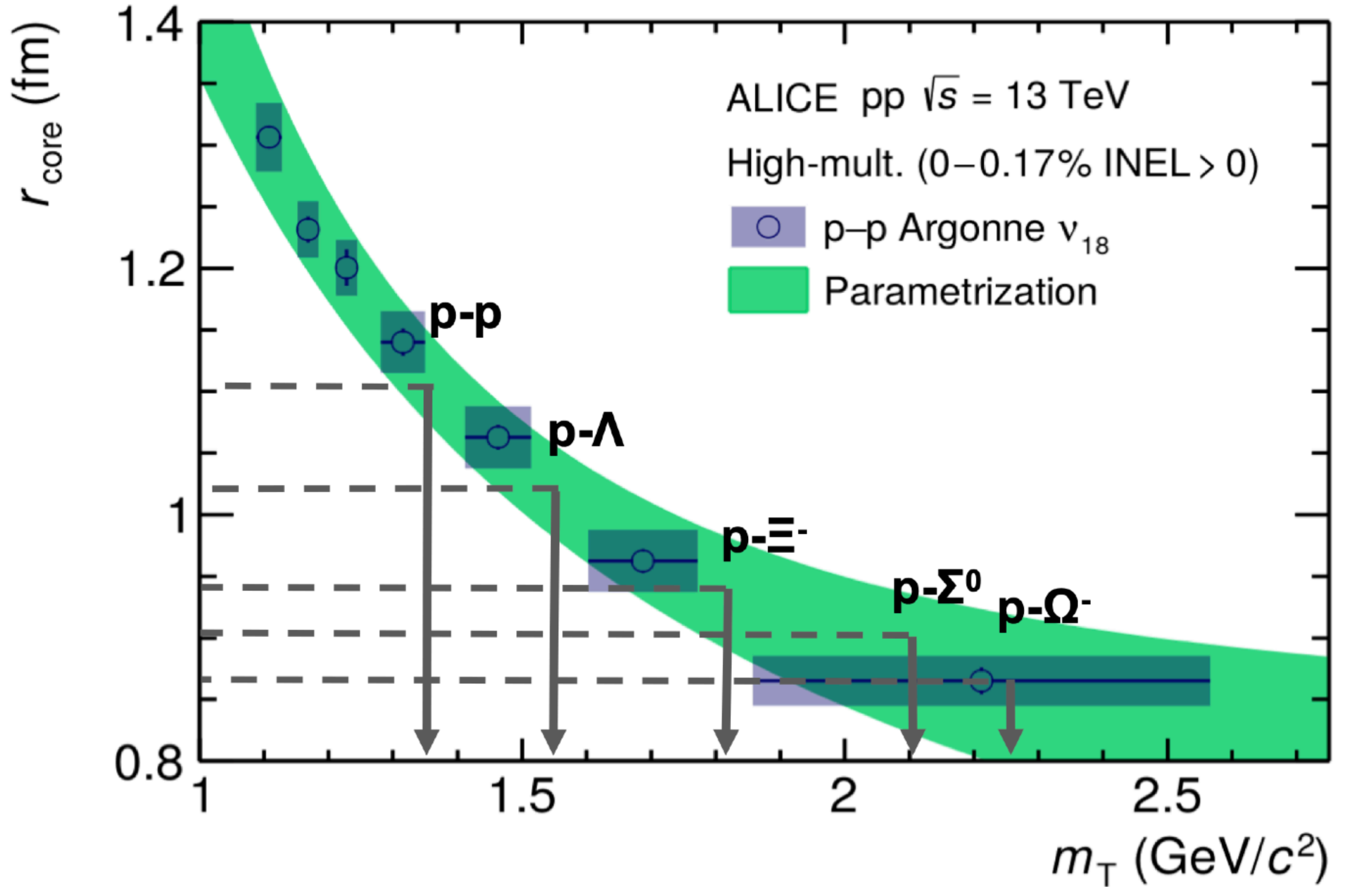

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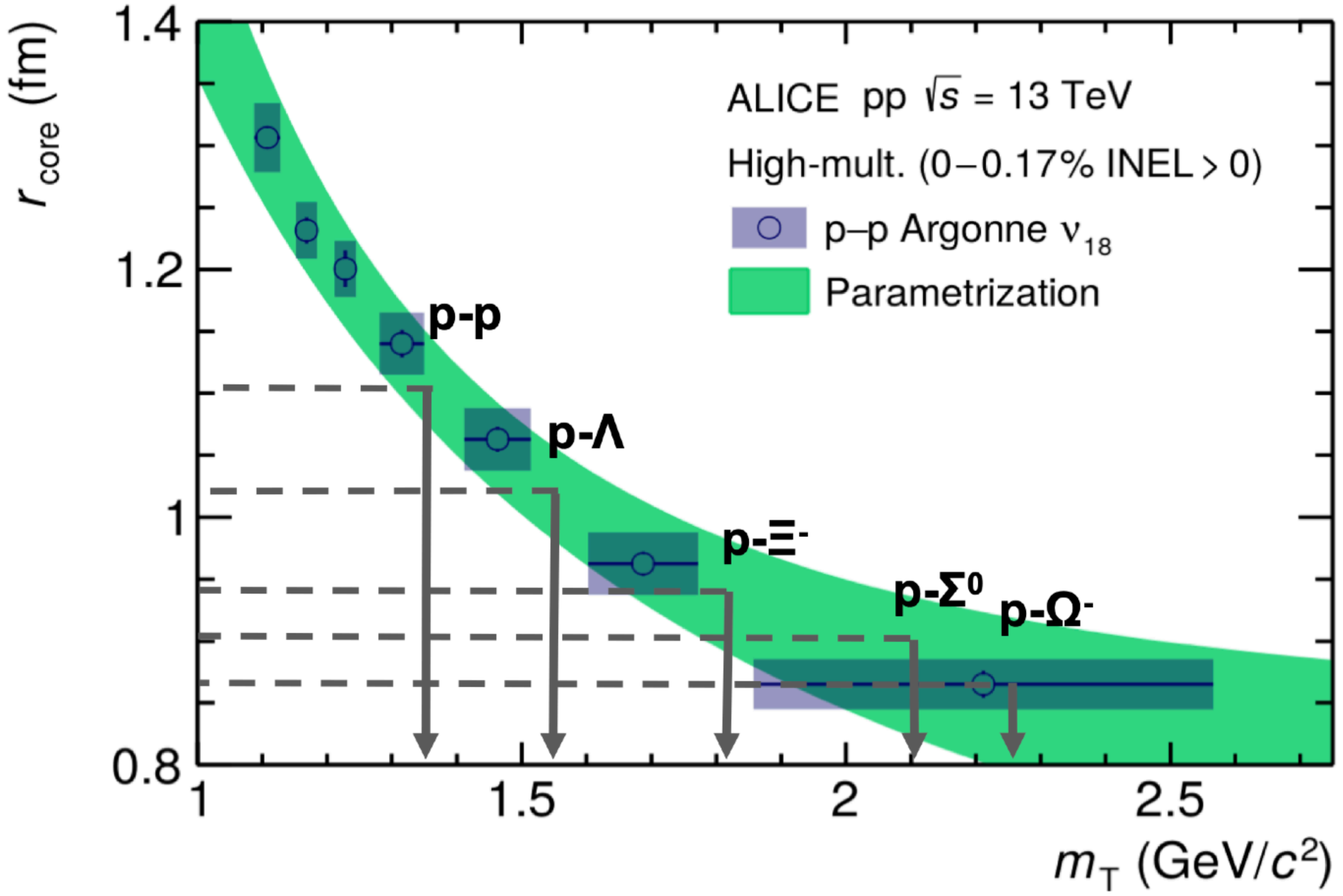

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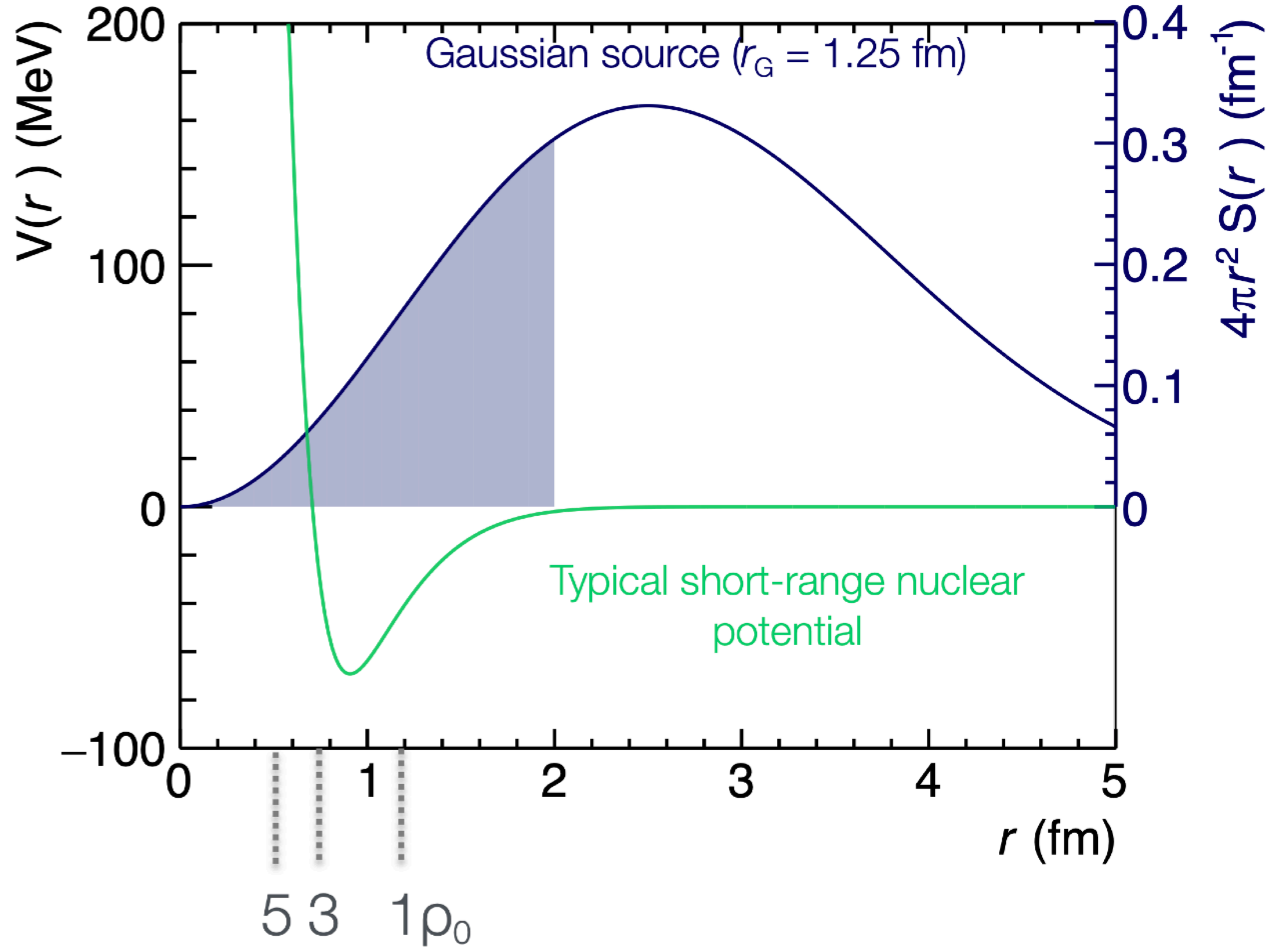
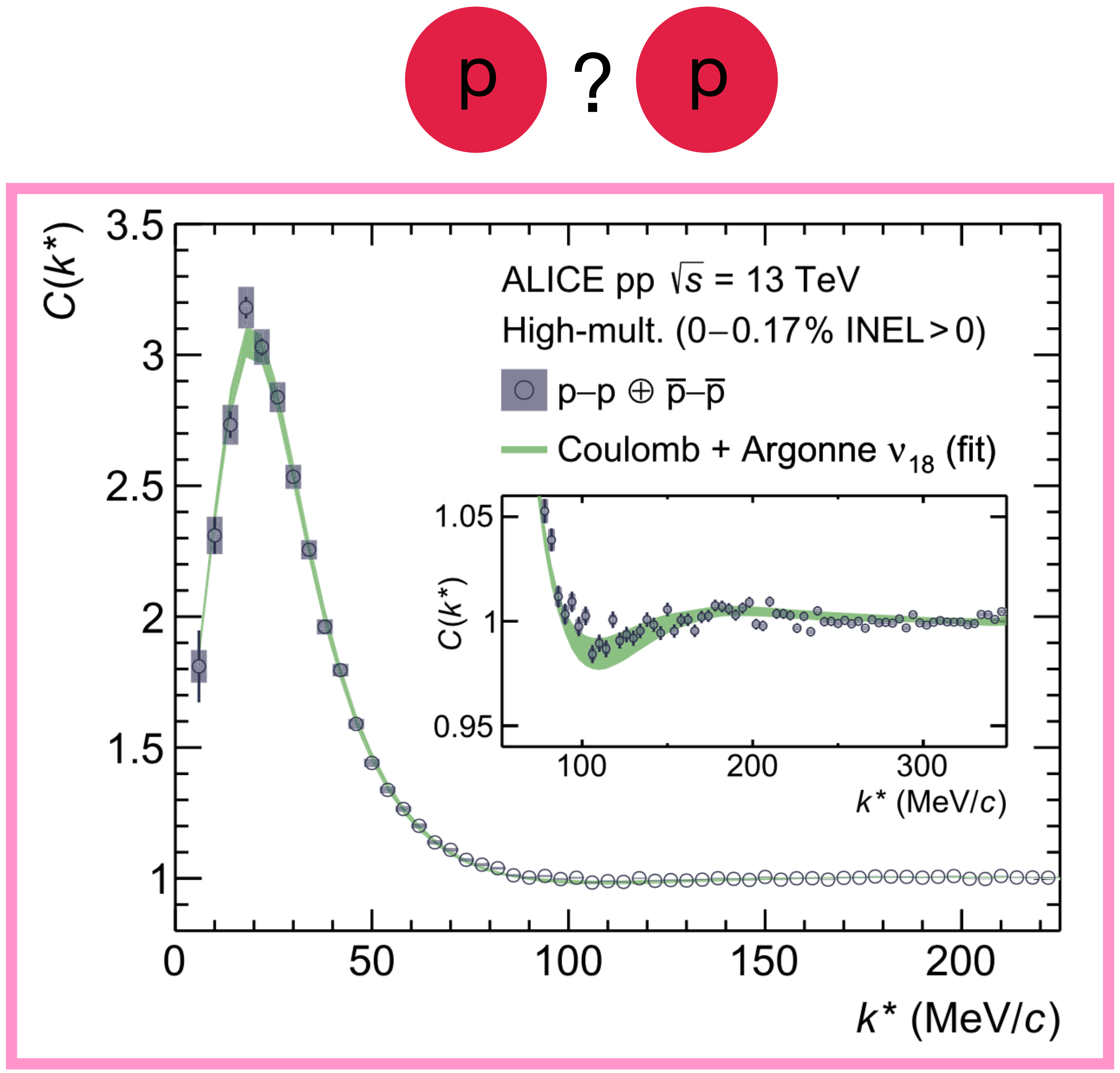
So what interaction distances are probed by femtoscopy?

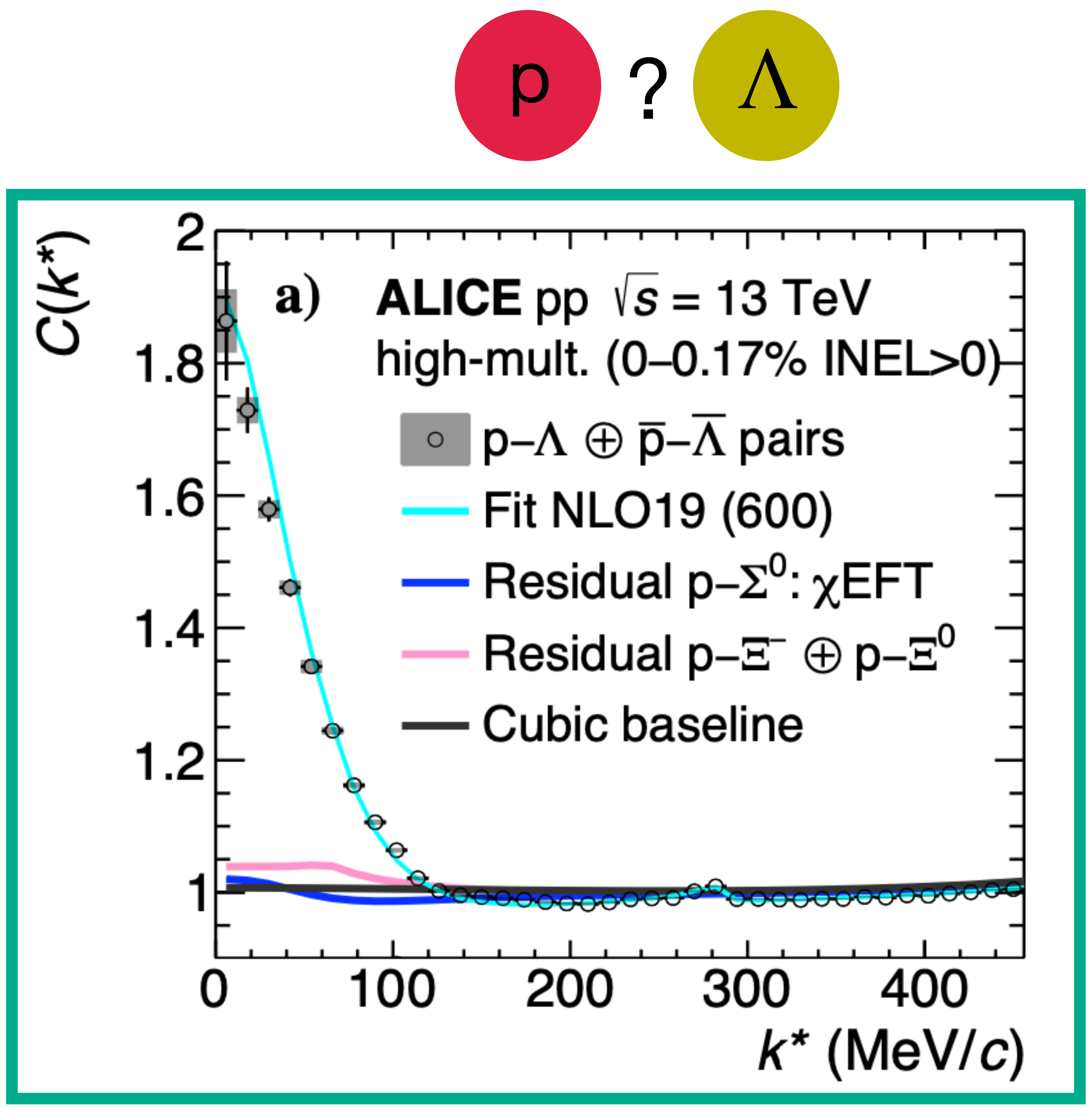
- Interaction measured down to very small distances.
- Mimics large densities which are important for neutron stars.



Two-body measurements

- Many different two-body interactions measured successfully!





TUM Group:
EPJC 78 (2018) 394
arXiv:2107.10227

ALICE:
PRC 99 (2019) 024001
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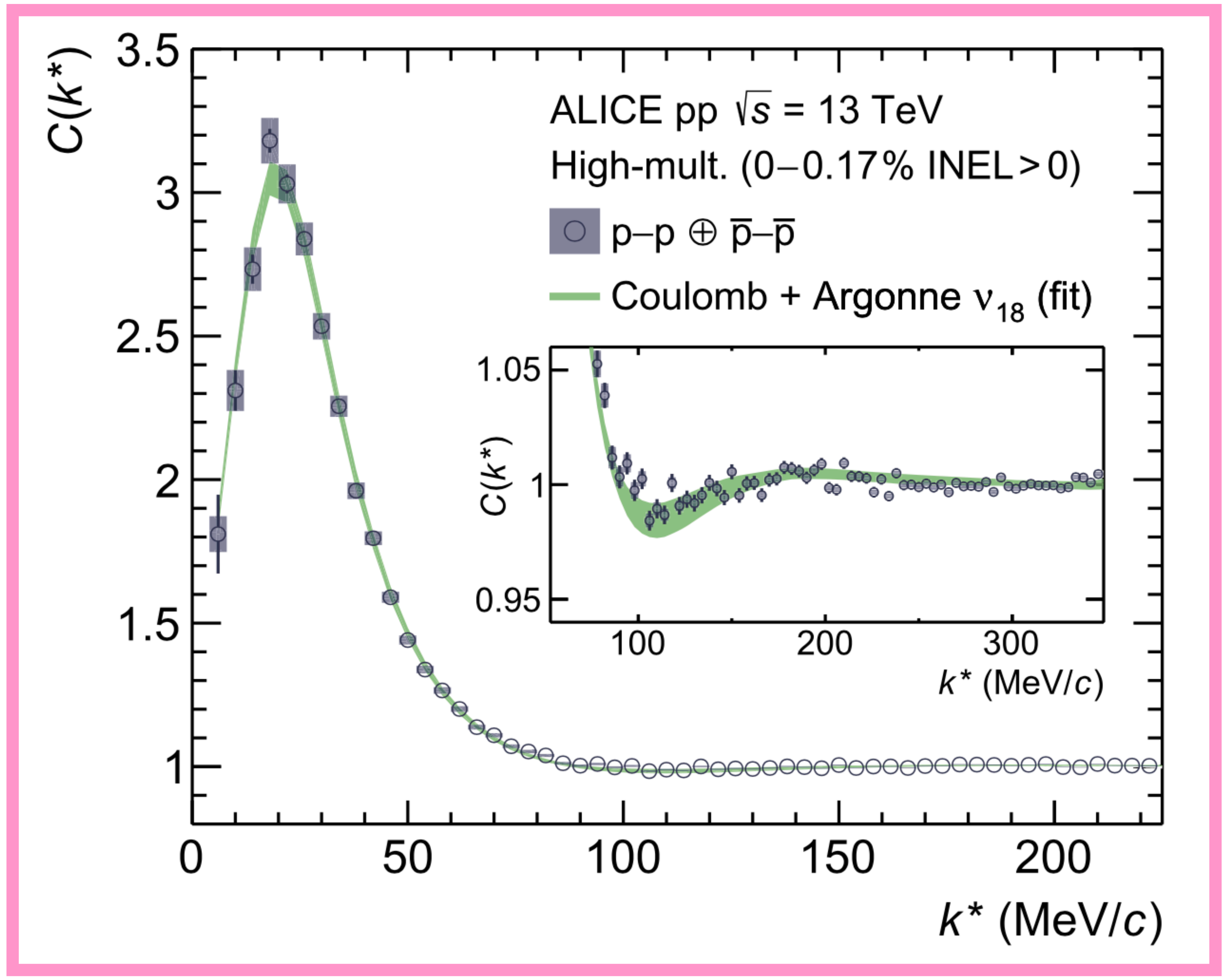

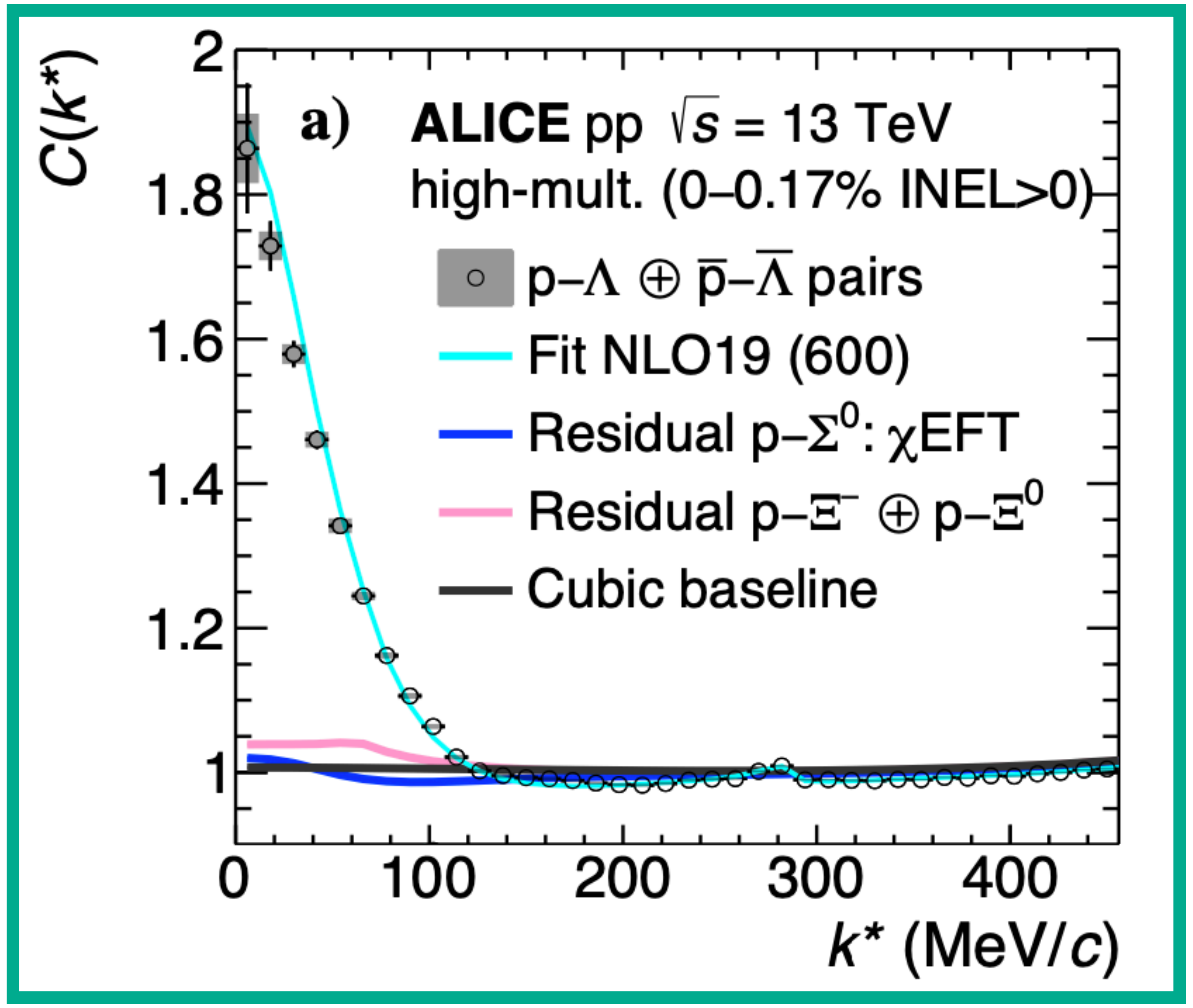

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Can one use this method to pin down the three-body interactions?

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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Three-body correlation function

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

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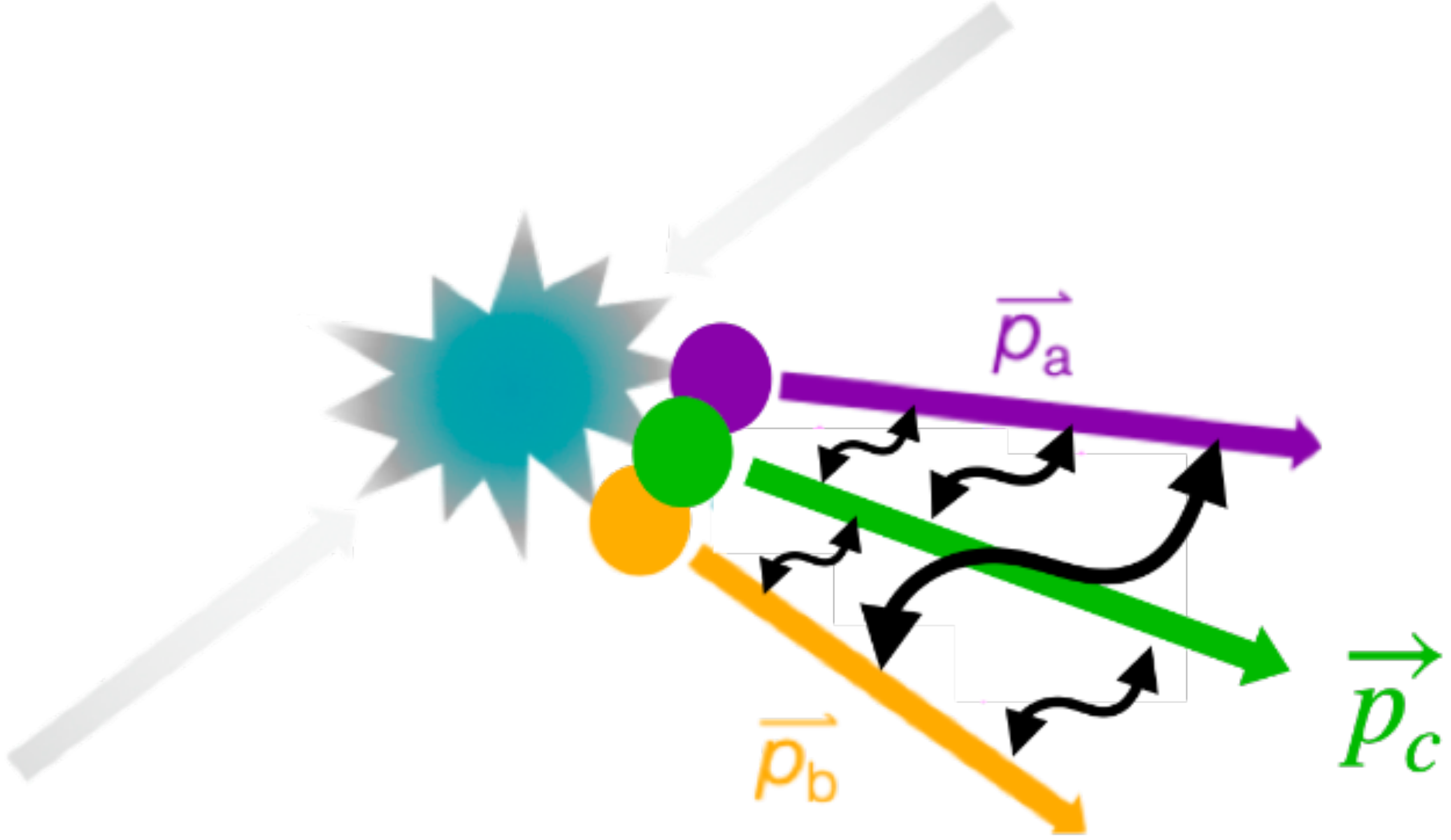
Experimentally studying three-body correlations, the small statistics requires to project the correlation function on **1-dimensional** observable Q_3.

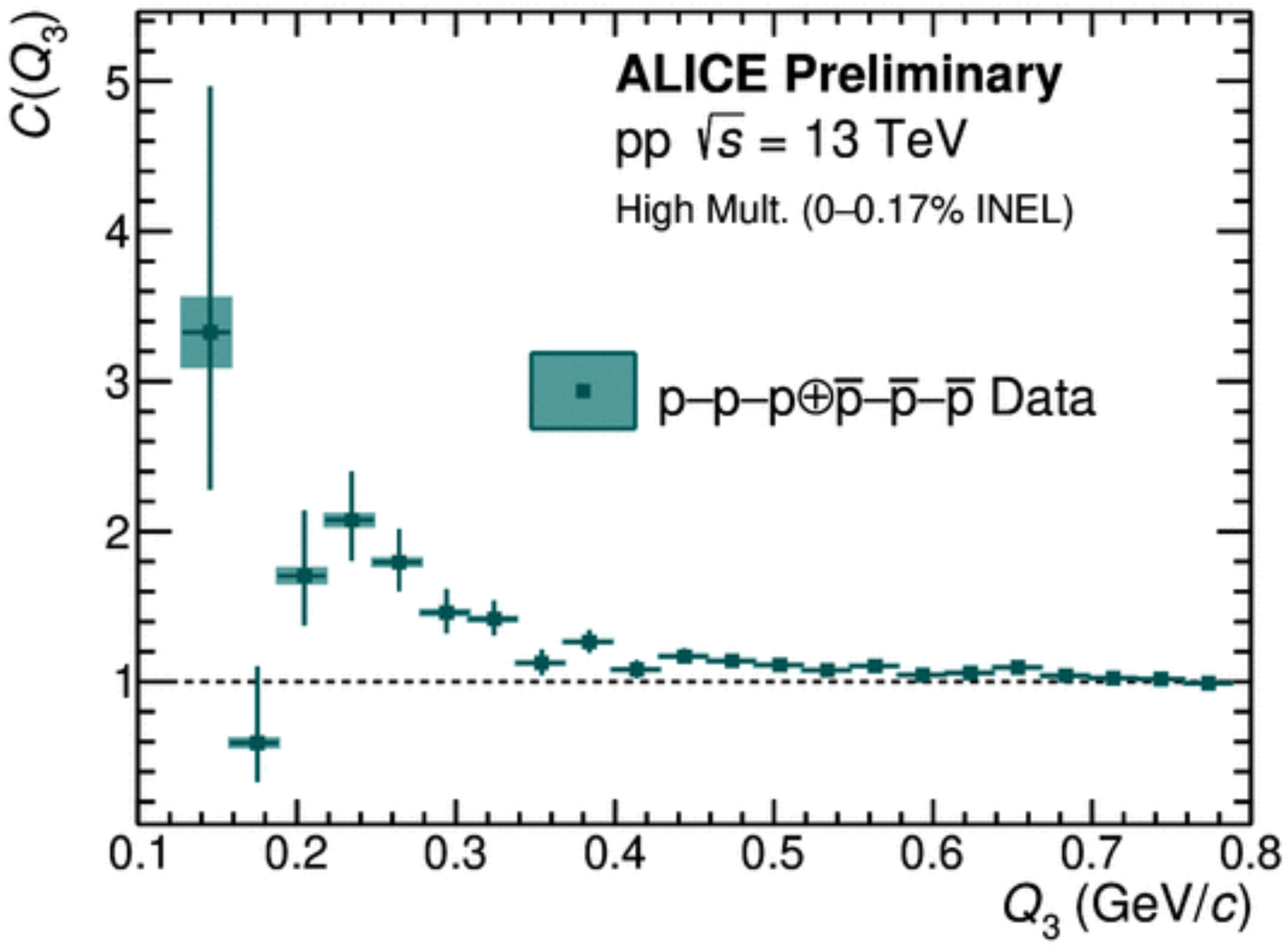
$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}$$

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

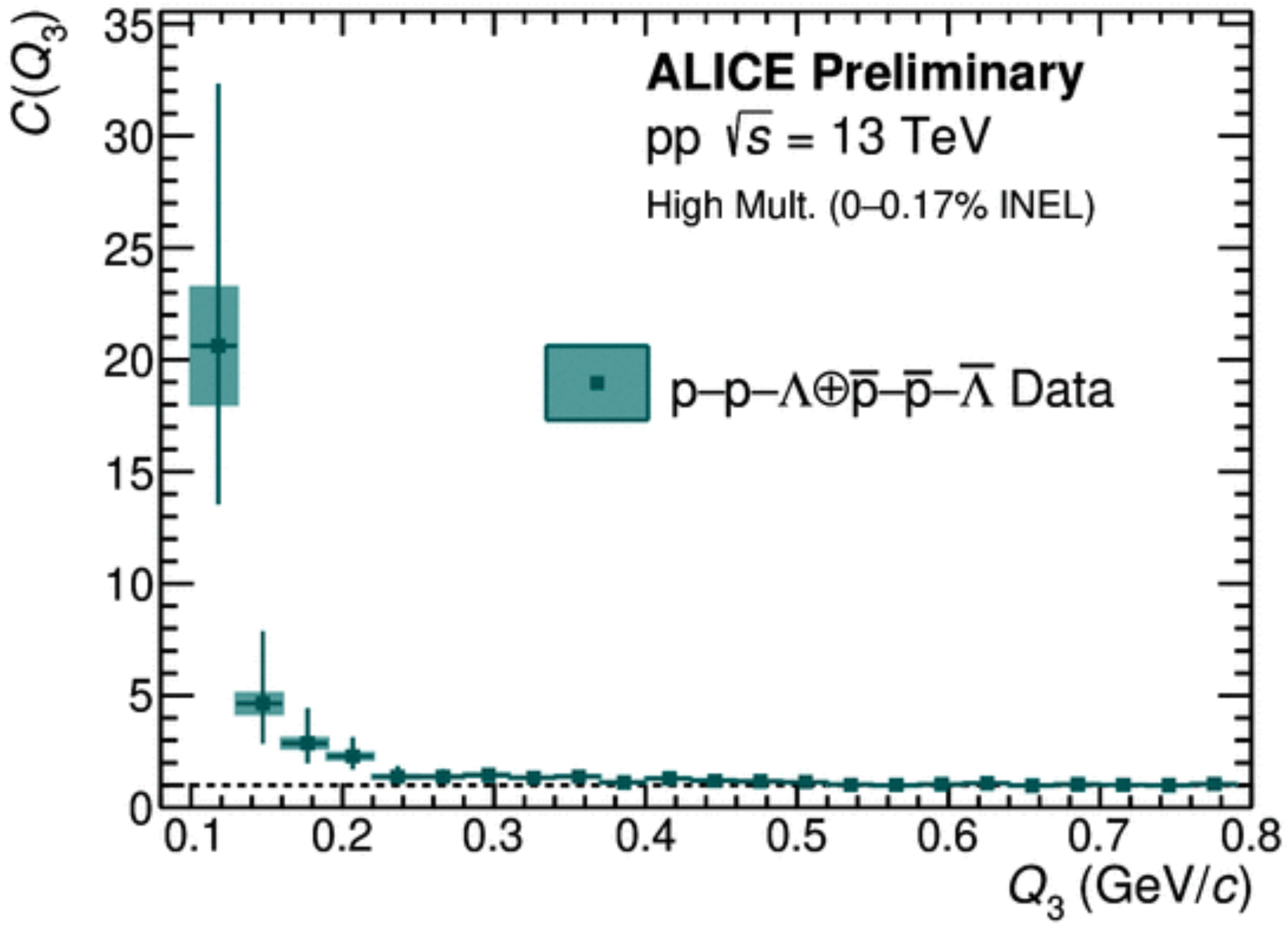
$$P \equiv p_i + p_j$$



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



ALI-PREL-487109



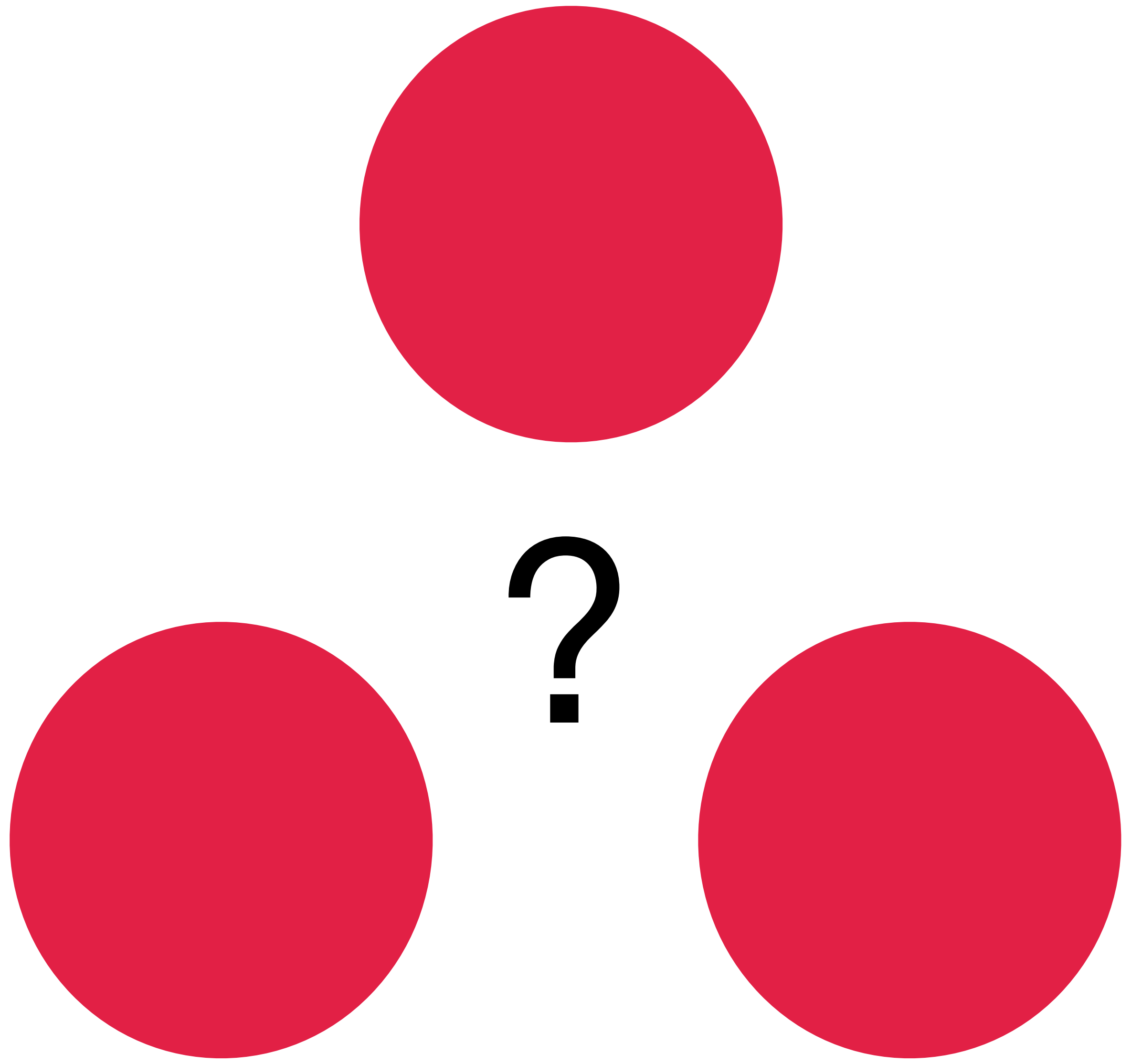
ALI-PREL-487104

How can we understand and interpret these results?

Accessing genuine three-body interaction

Measured correlation function includes:

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



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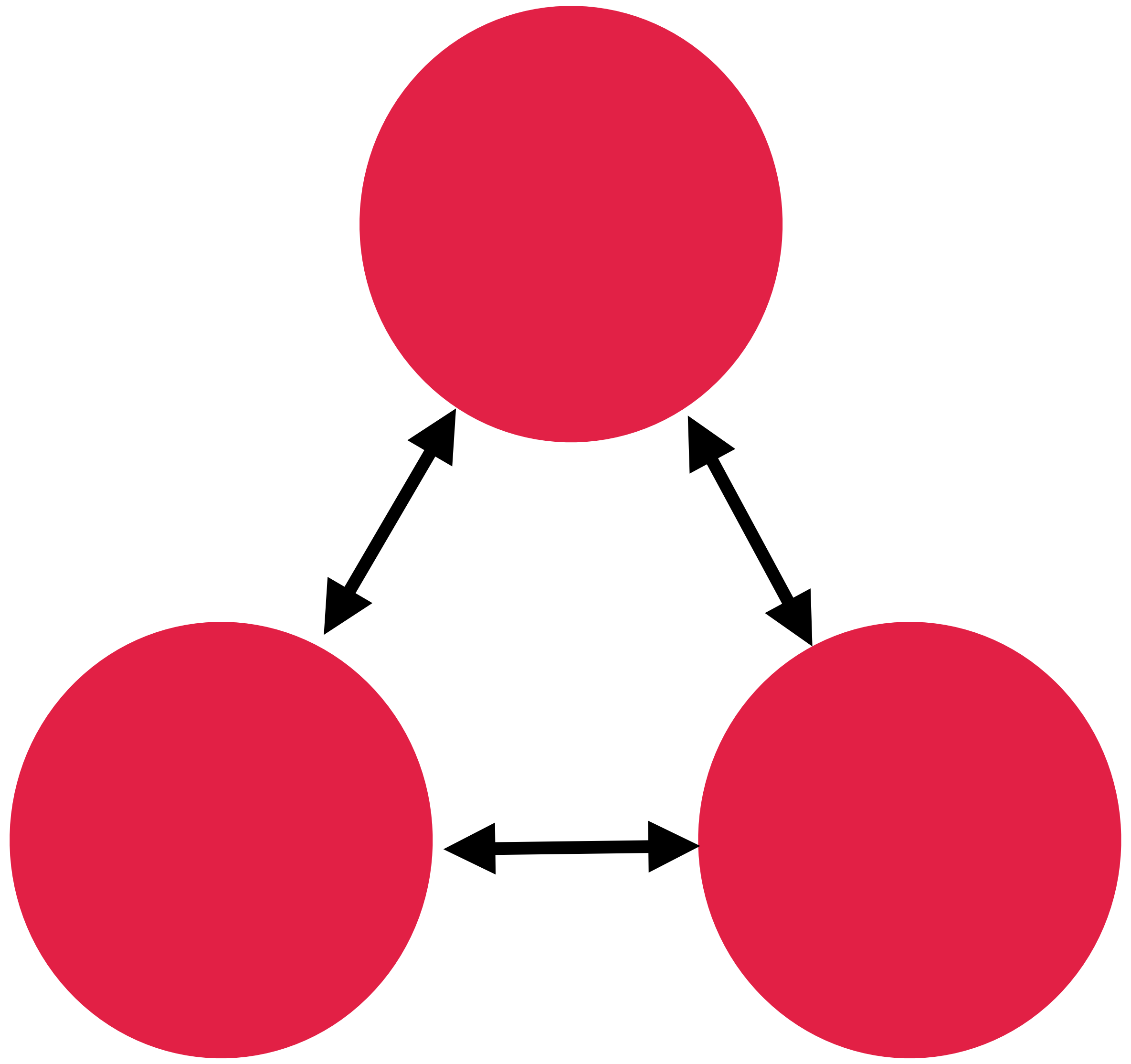

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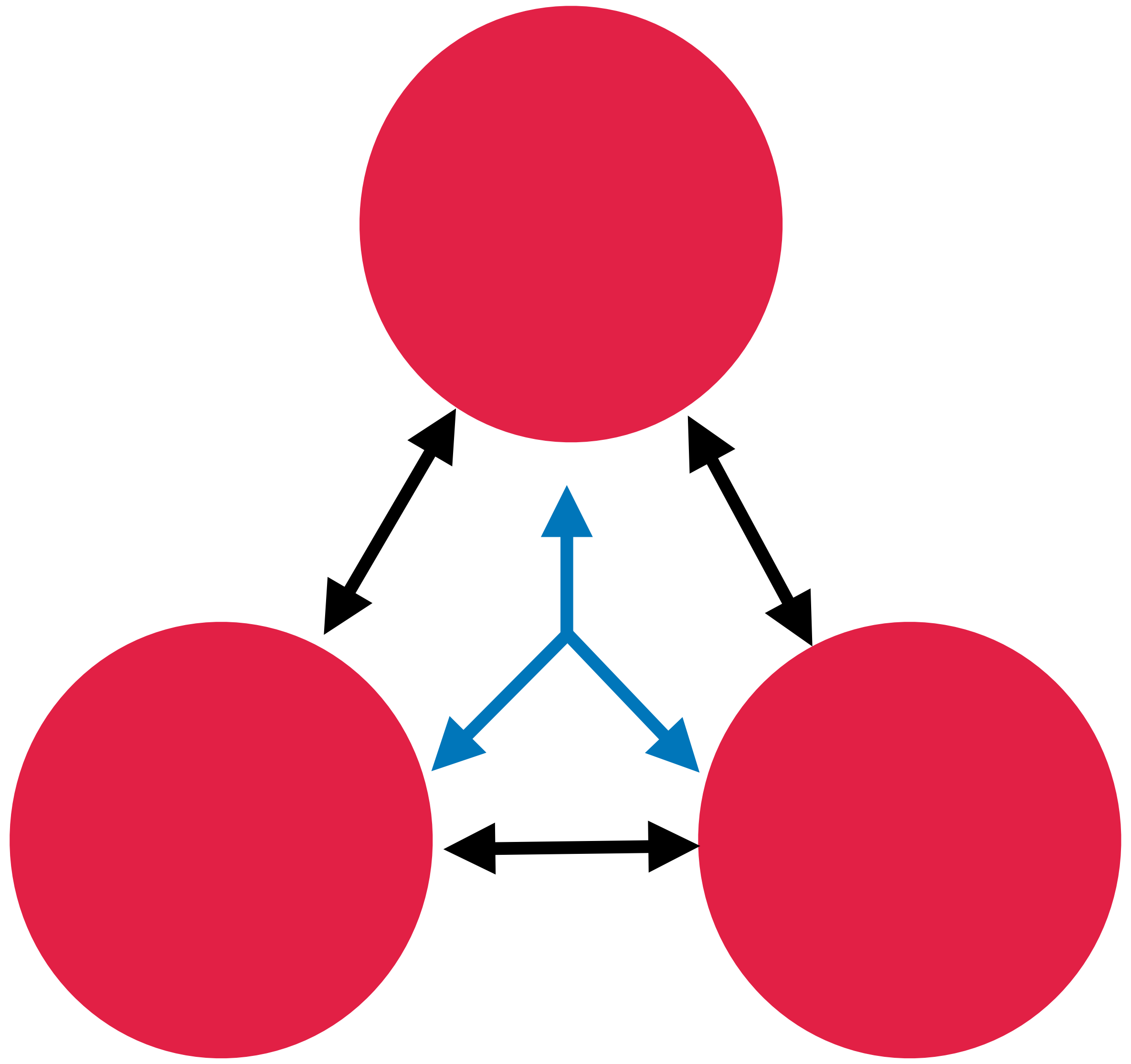

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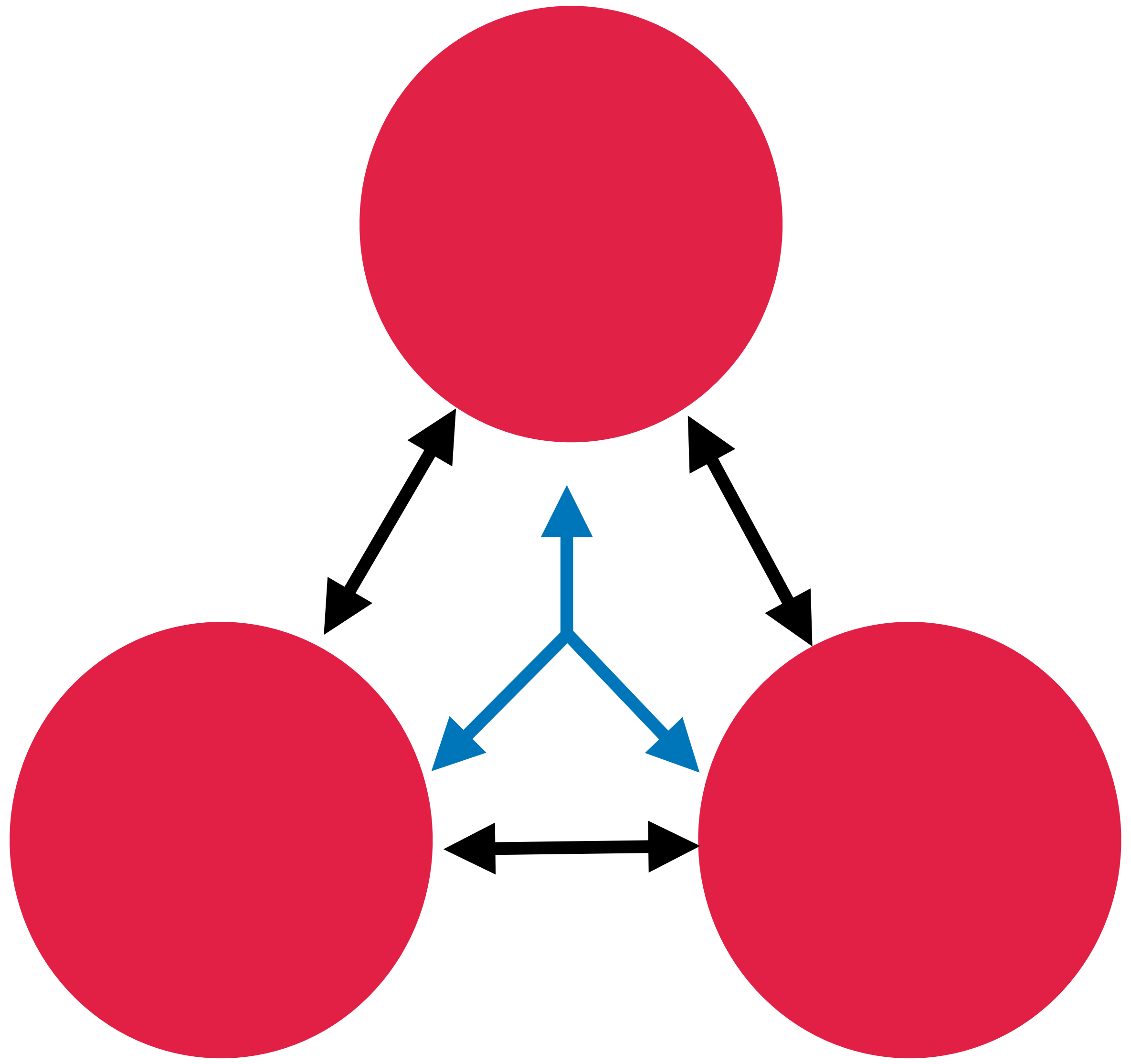

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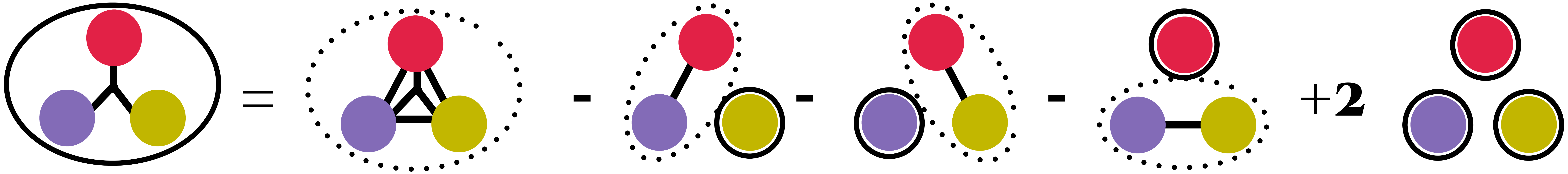
Use Kubo's cumulant expansion method [1] to extract the genuine three-body interaction.



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

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

Two-body interactions in three-body system

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

$$C([\mathbf{p}_1, \mathbf{p}_2], \mathbf{p}_3) \equiv \frac{N_2(\mathbf{p}_1, \mathbf{p}_2) \cdot N_1(\mathbf{p}_3)}{N_1(\mathbf{p}_1) \cdot N_1(\mathbf{p}_2) \cdot N_1(\mathbf{p}_3)} = \frac{N_{12,3}(Q_3)}{N_{mixed}(Q_3)}$$

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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

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

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

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

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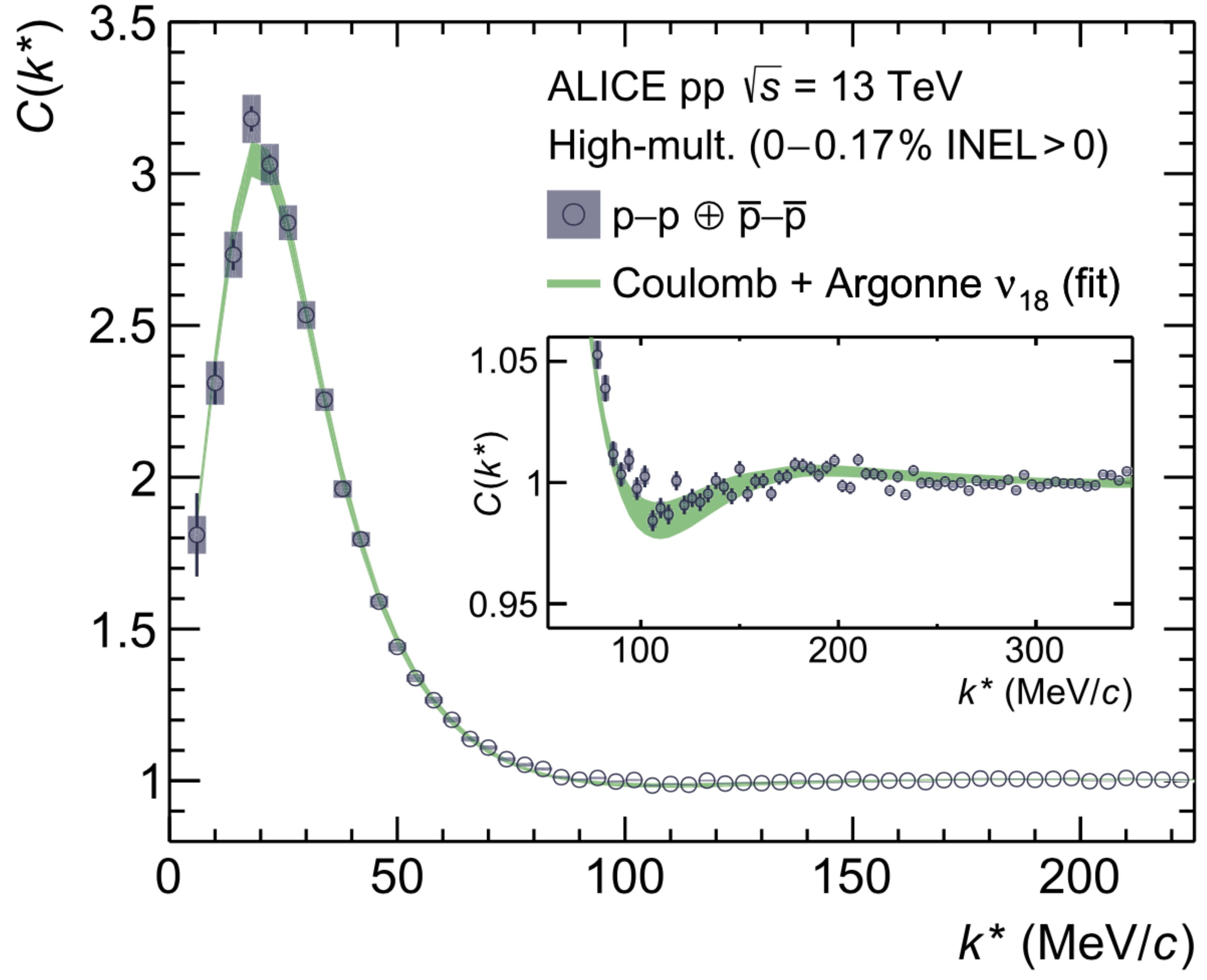
ALICE Coll. PLB 805 (2020) 135419



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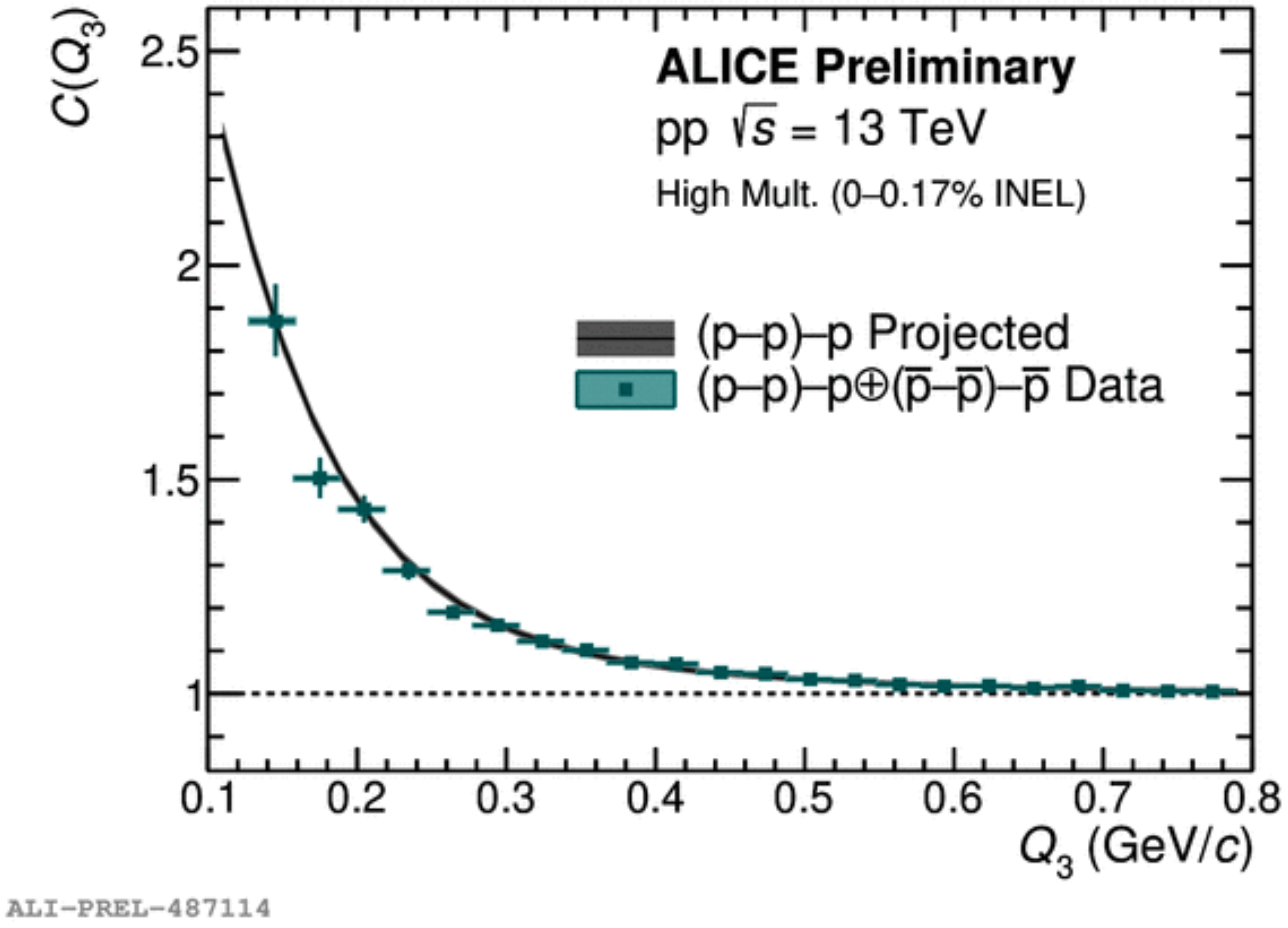
Output: (p-p)-p

Input



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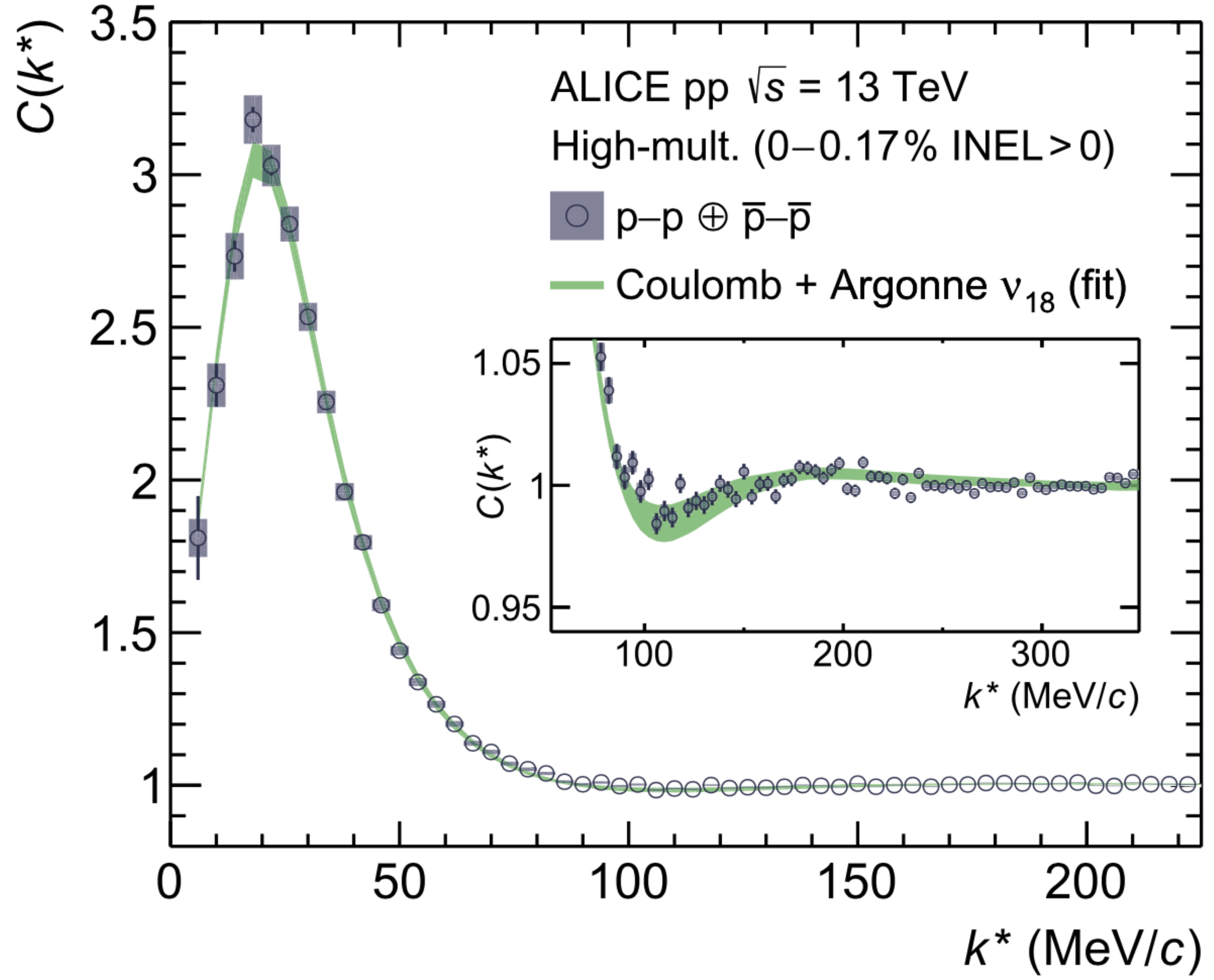

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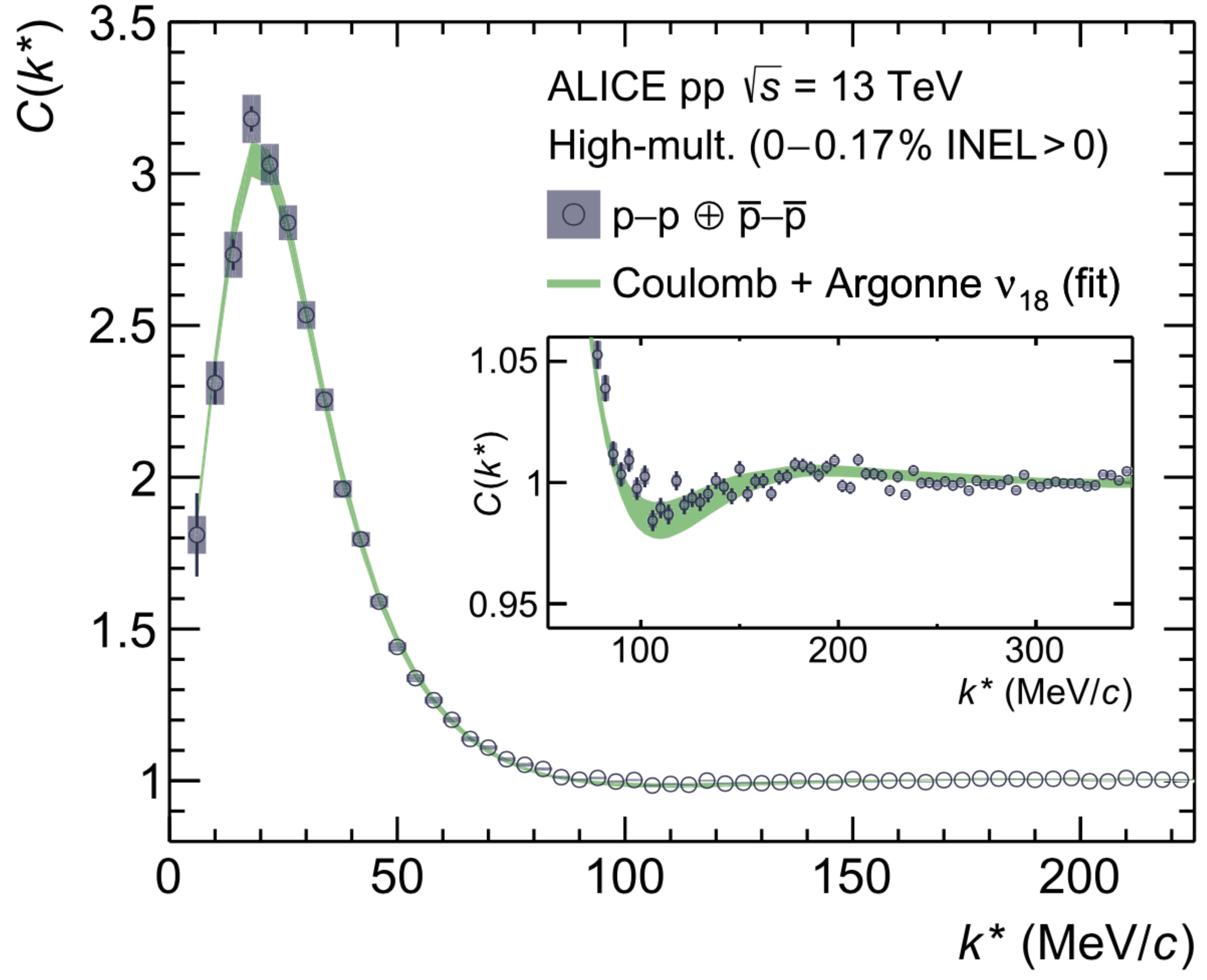

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Output: (p-p)-Λ

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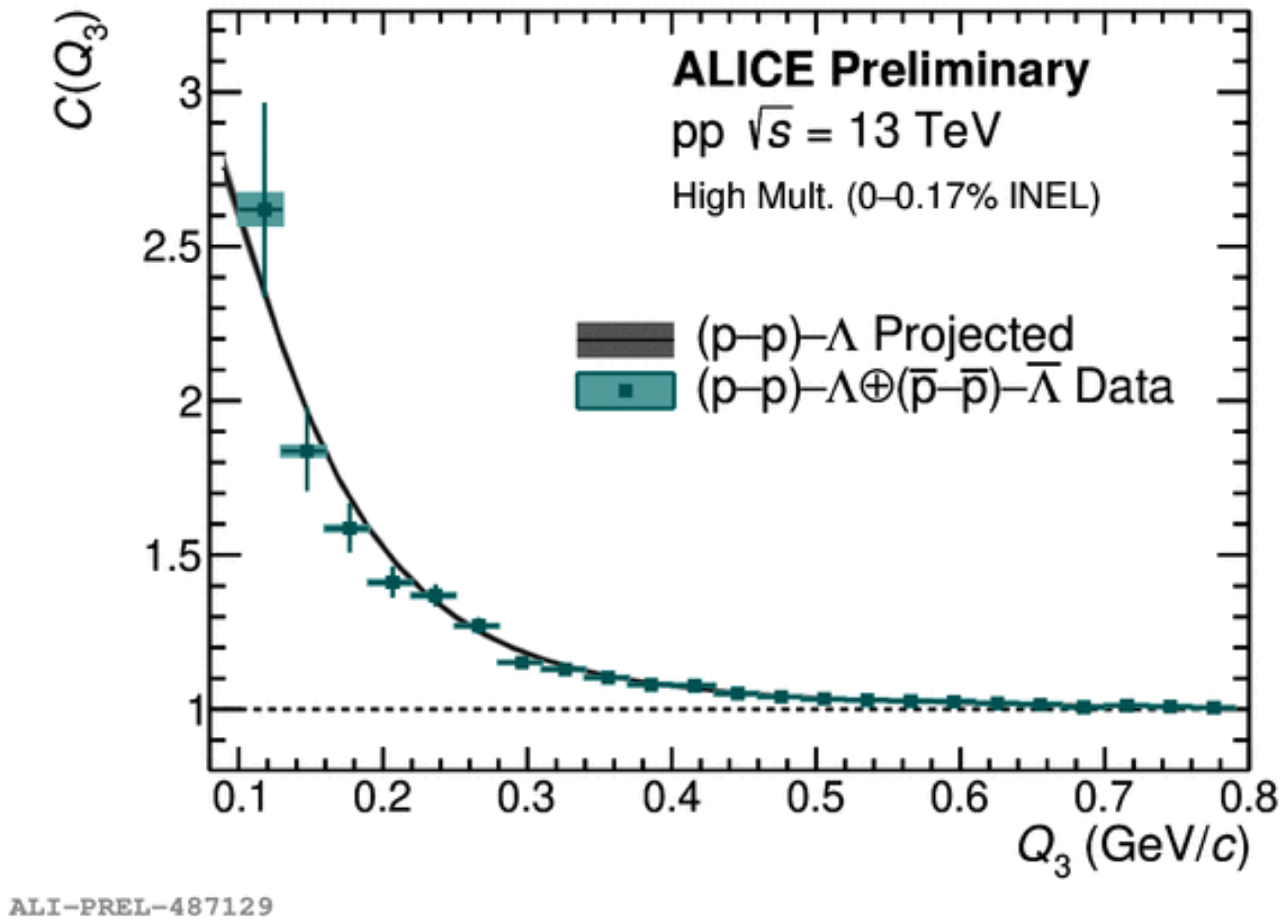

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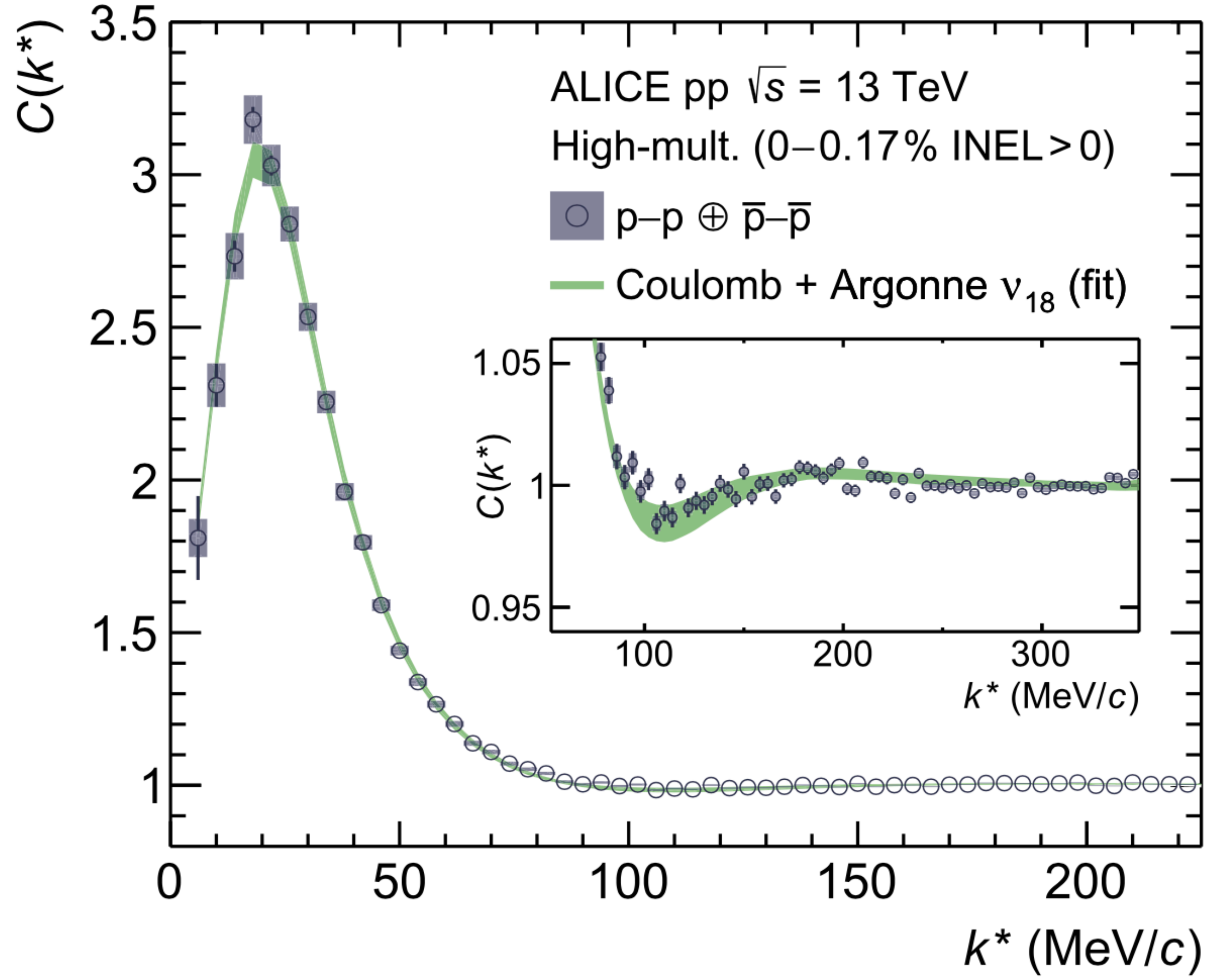

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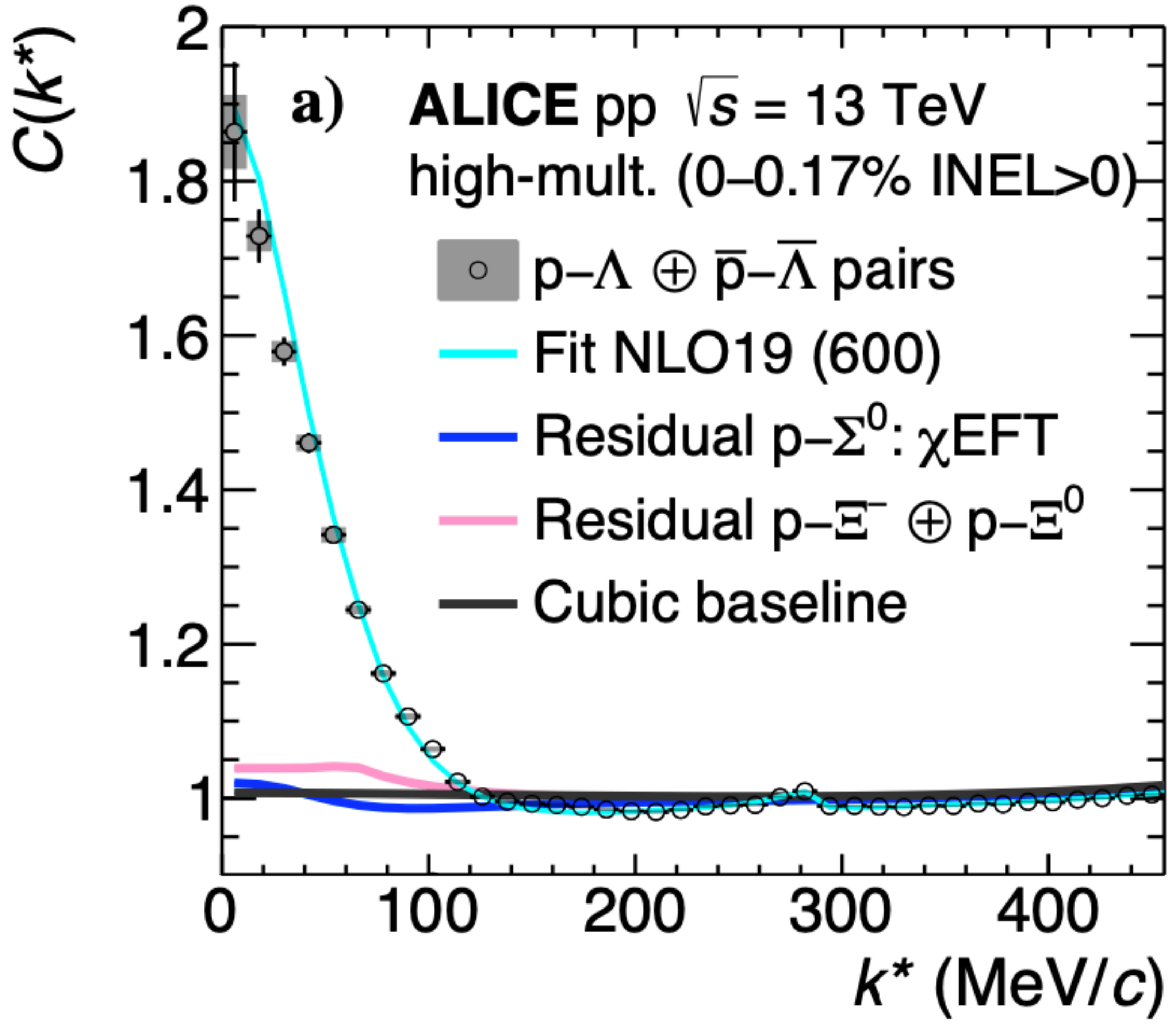
ALICE Coll. arXiv:2104.04427



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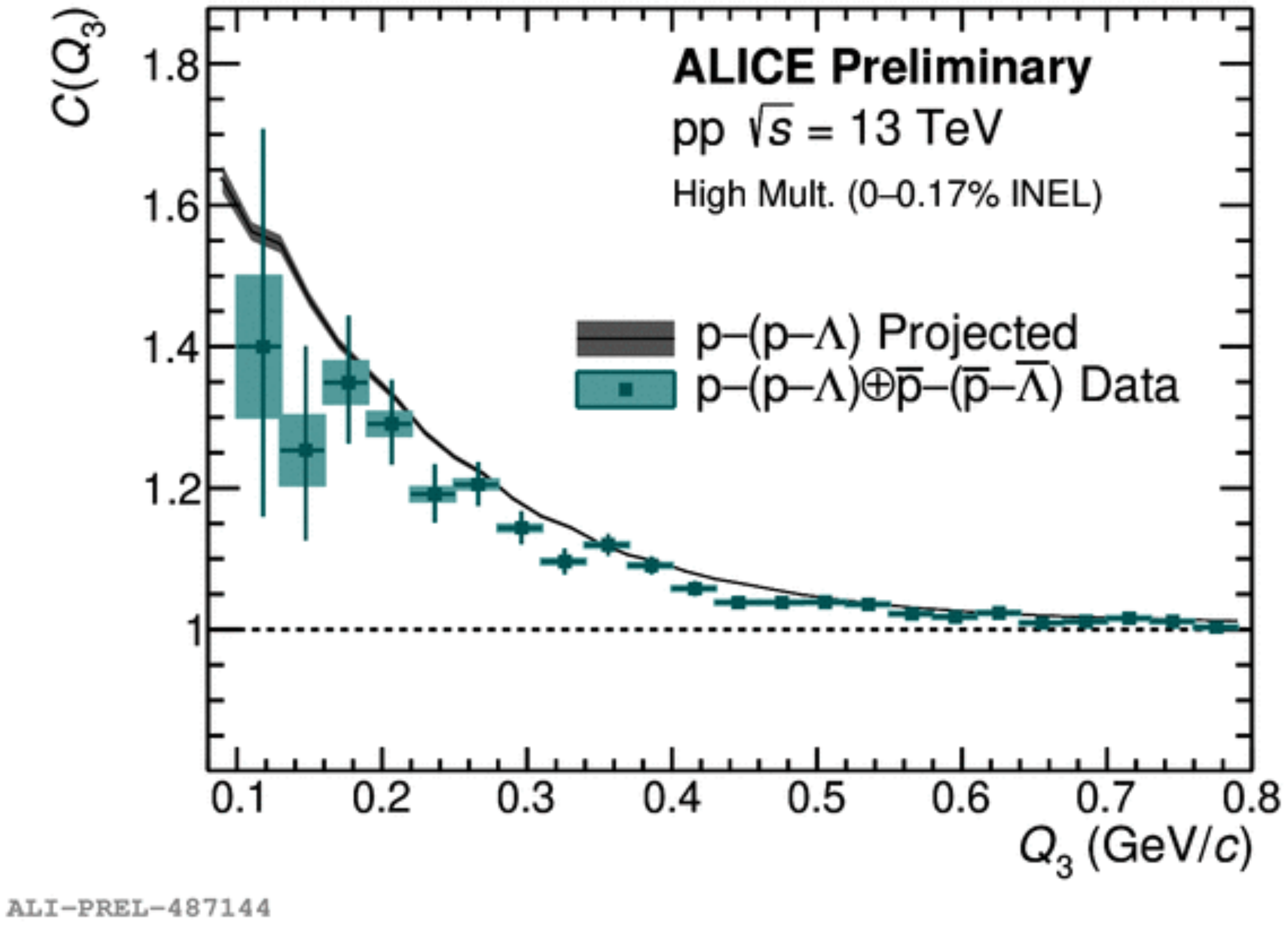

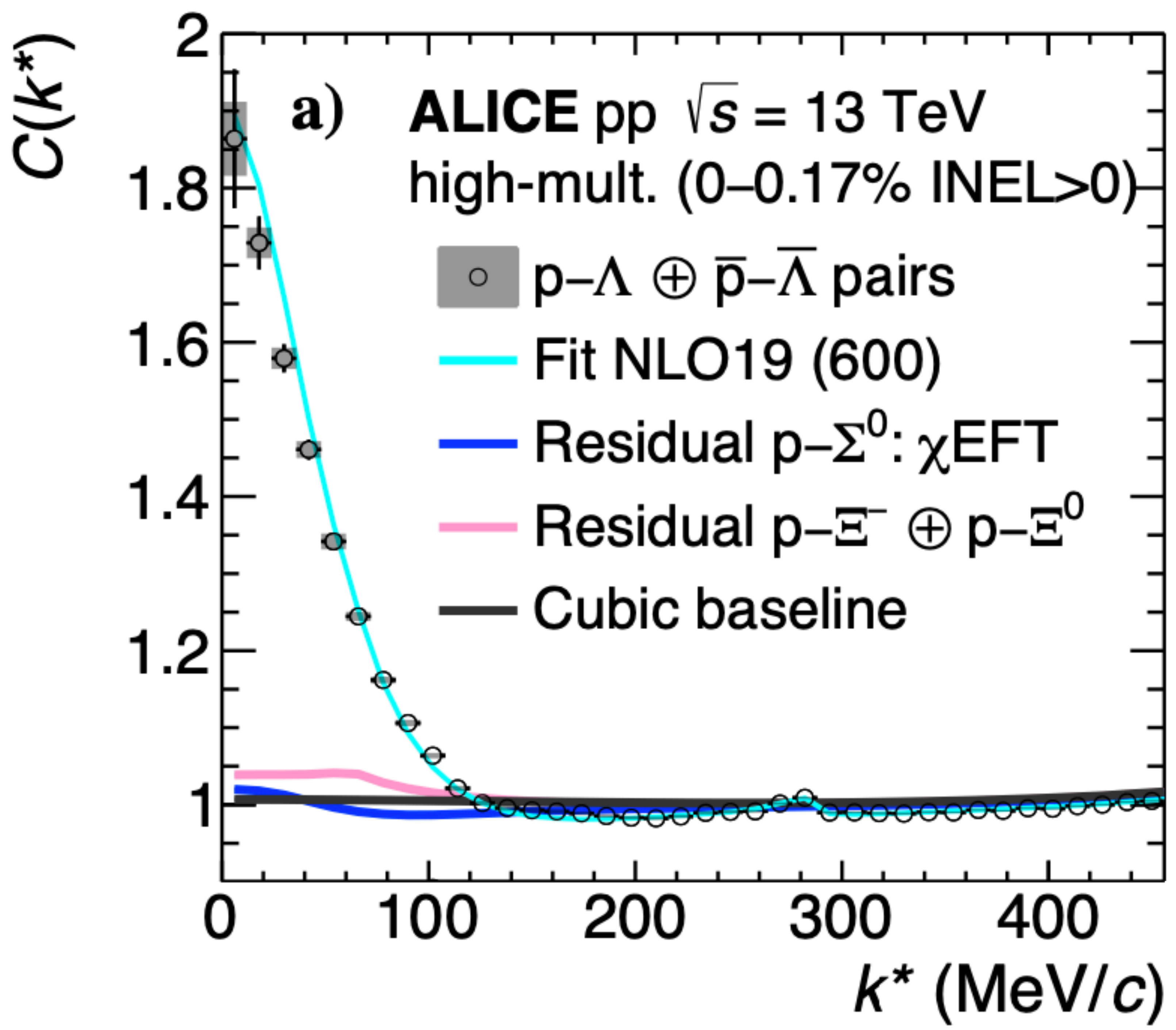

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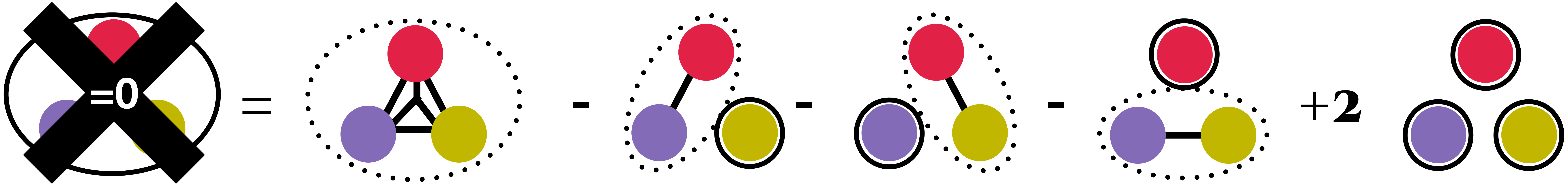
Three-body correlations: only two-body effects

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



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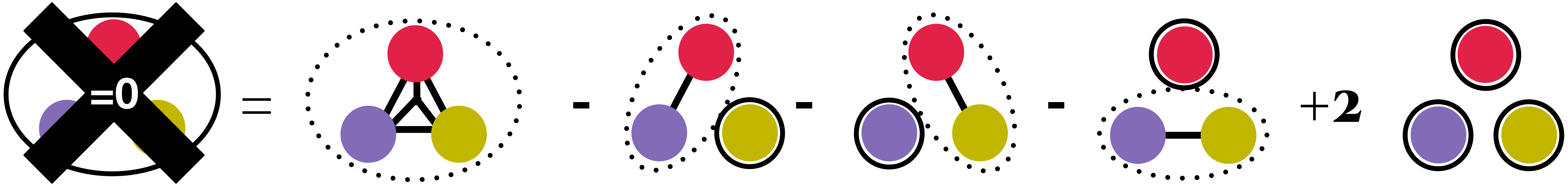

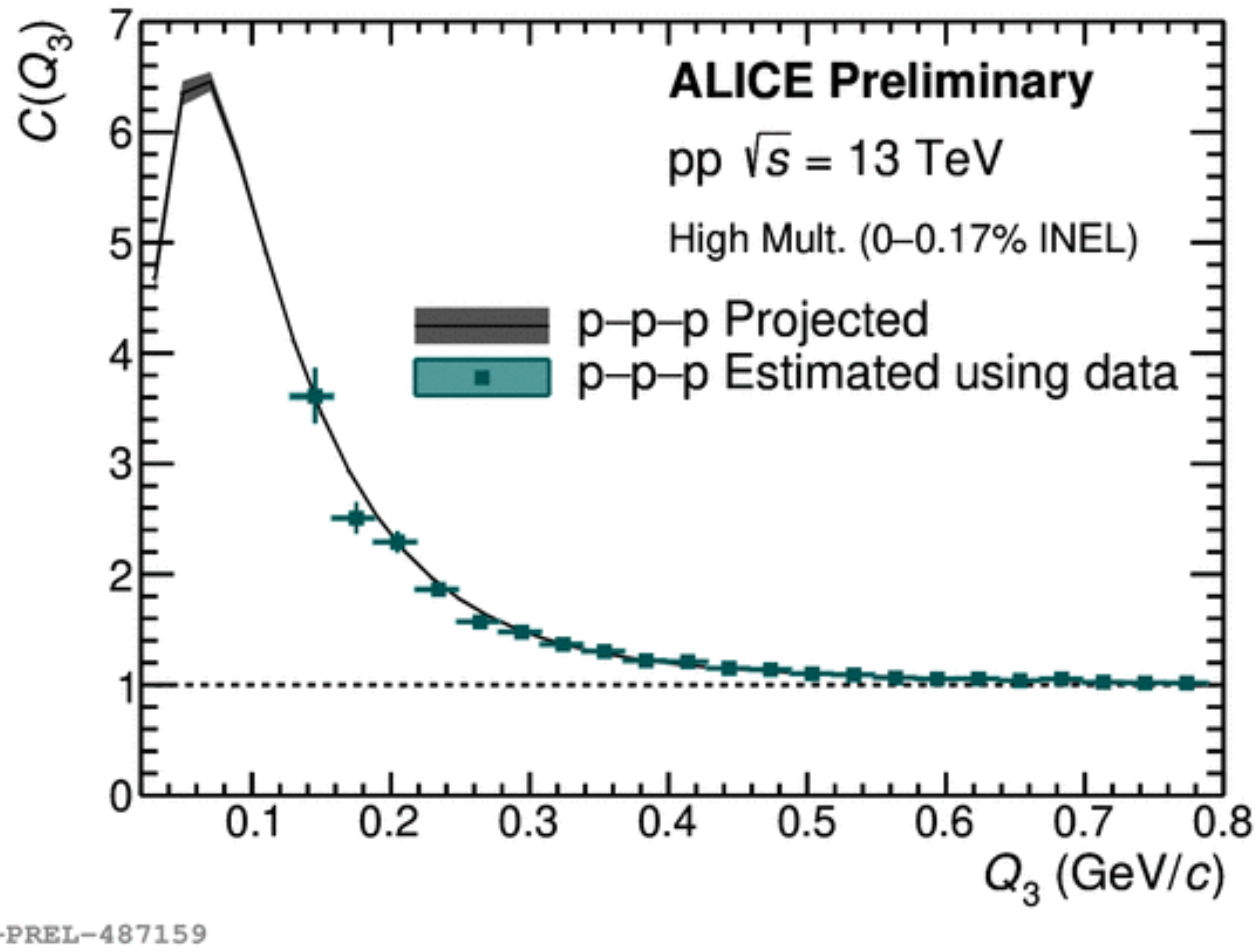

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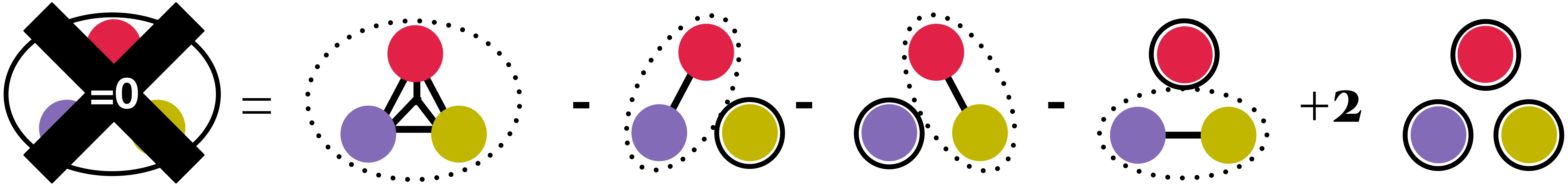
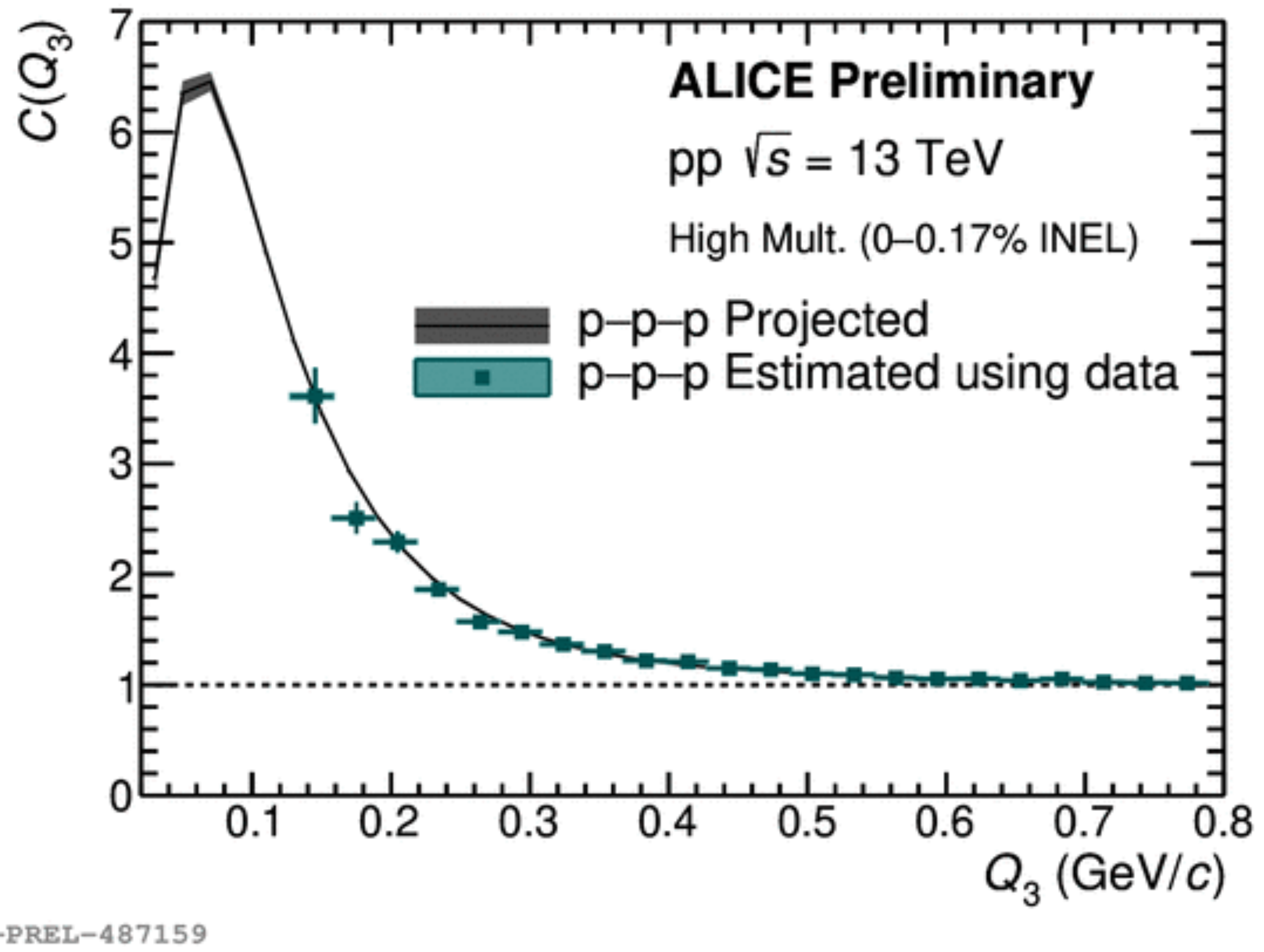
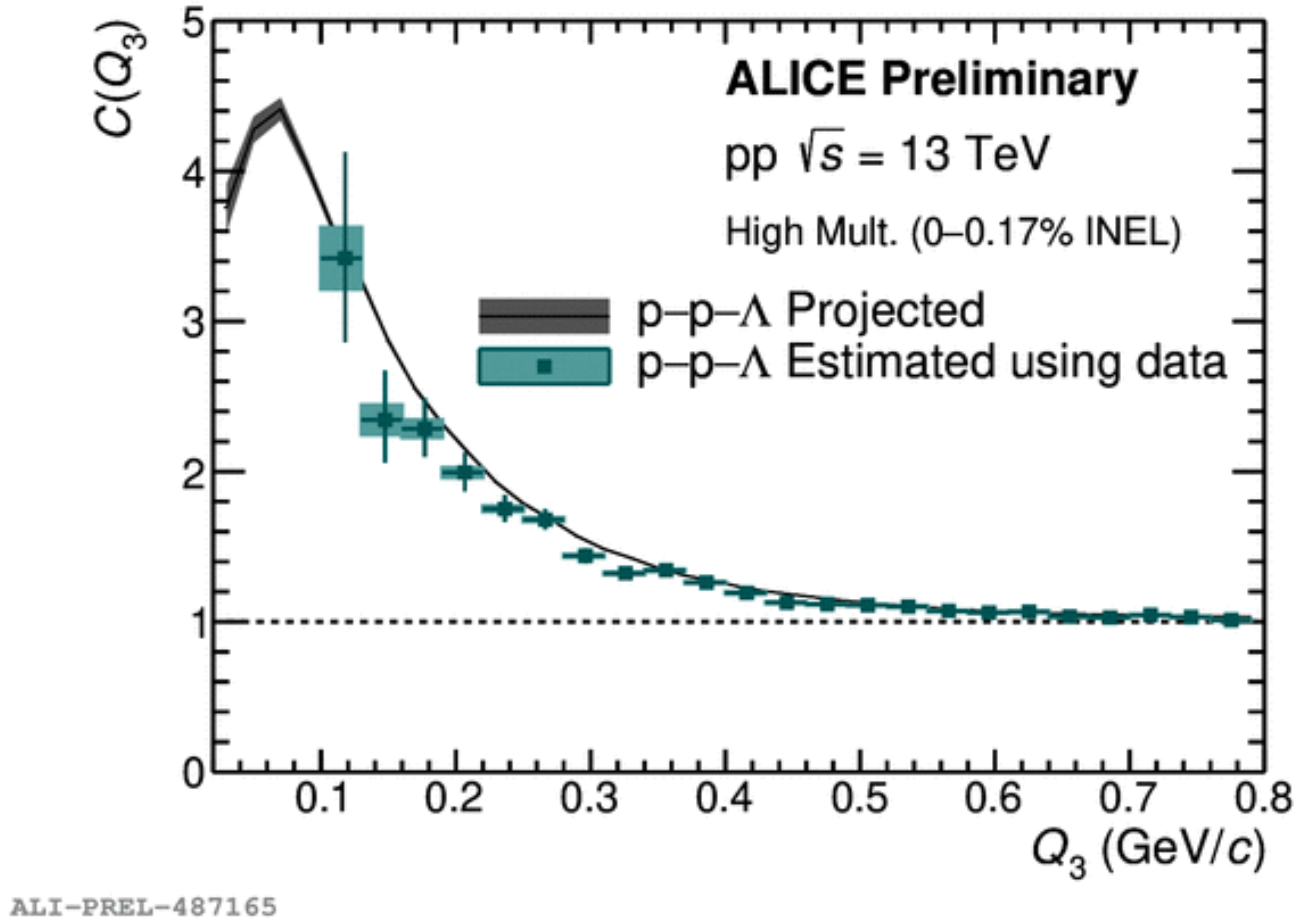
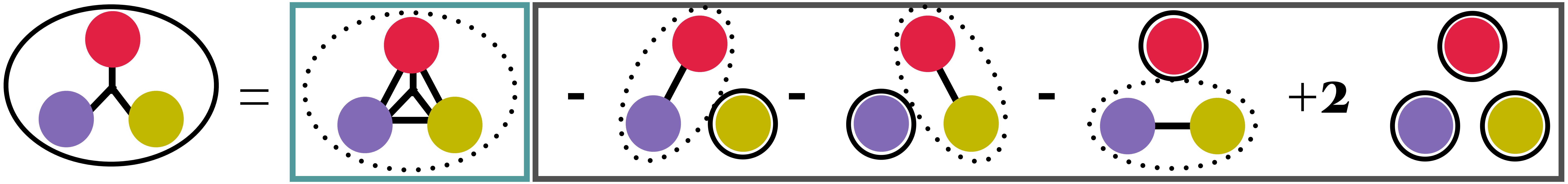






Three-body correlations

- Measured three-body correlation and lower order contribution using Kubo's cumulant.



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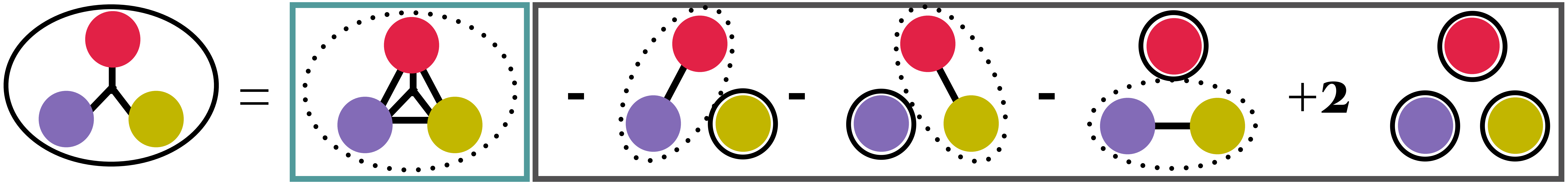

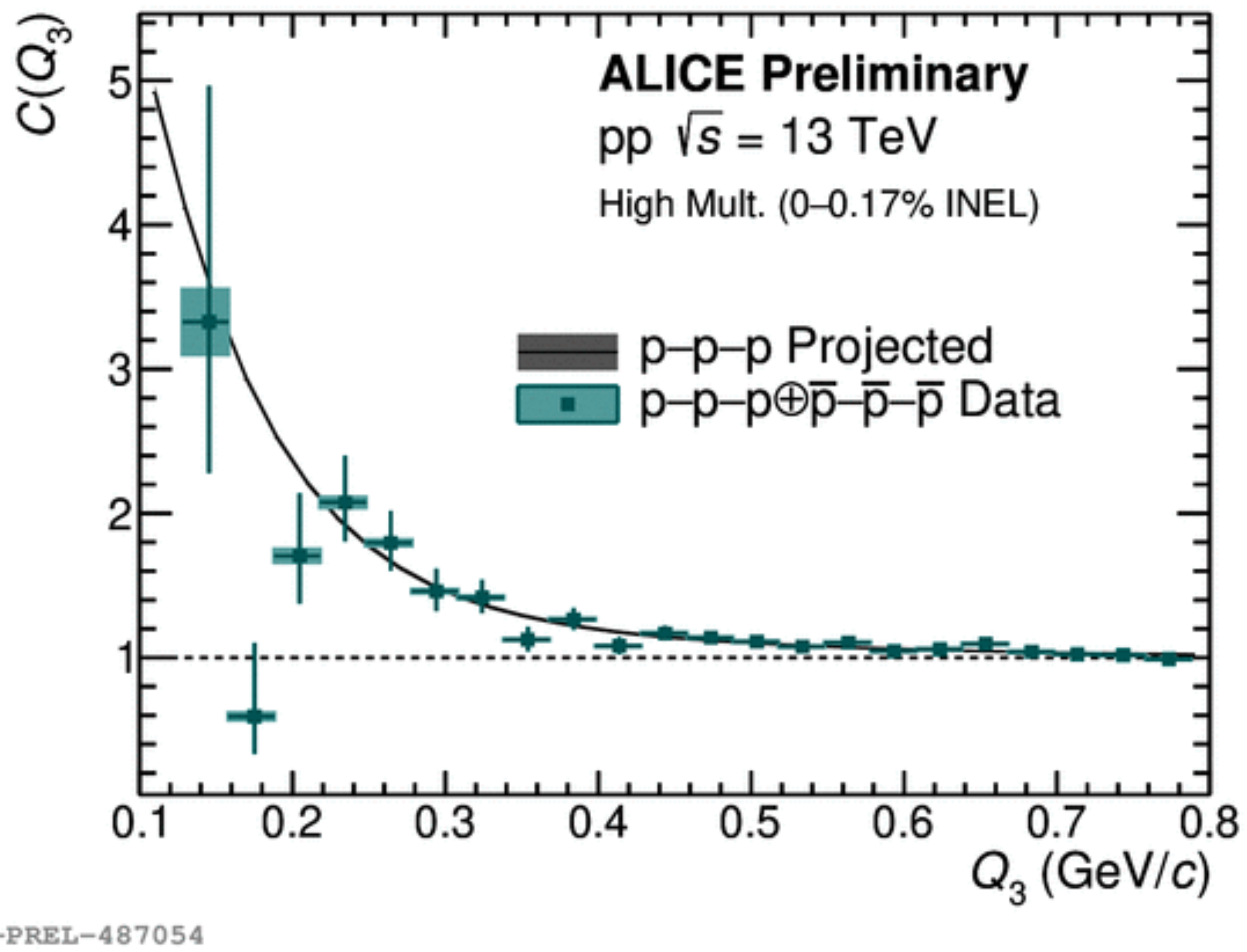

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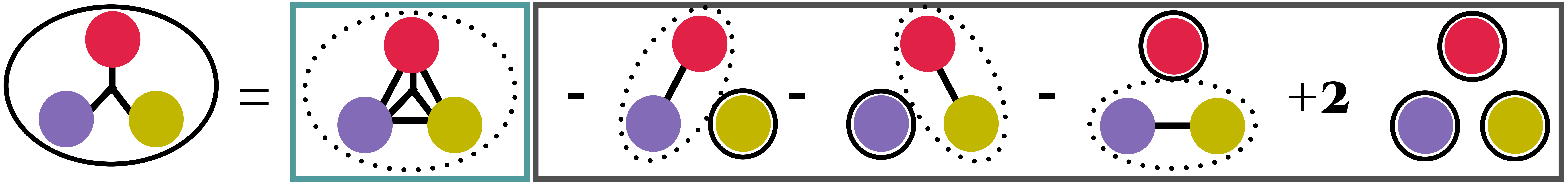

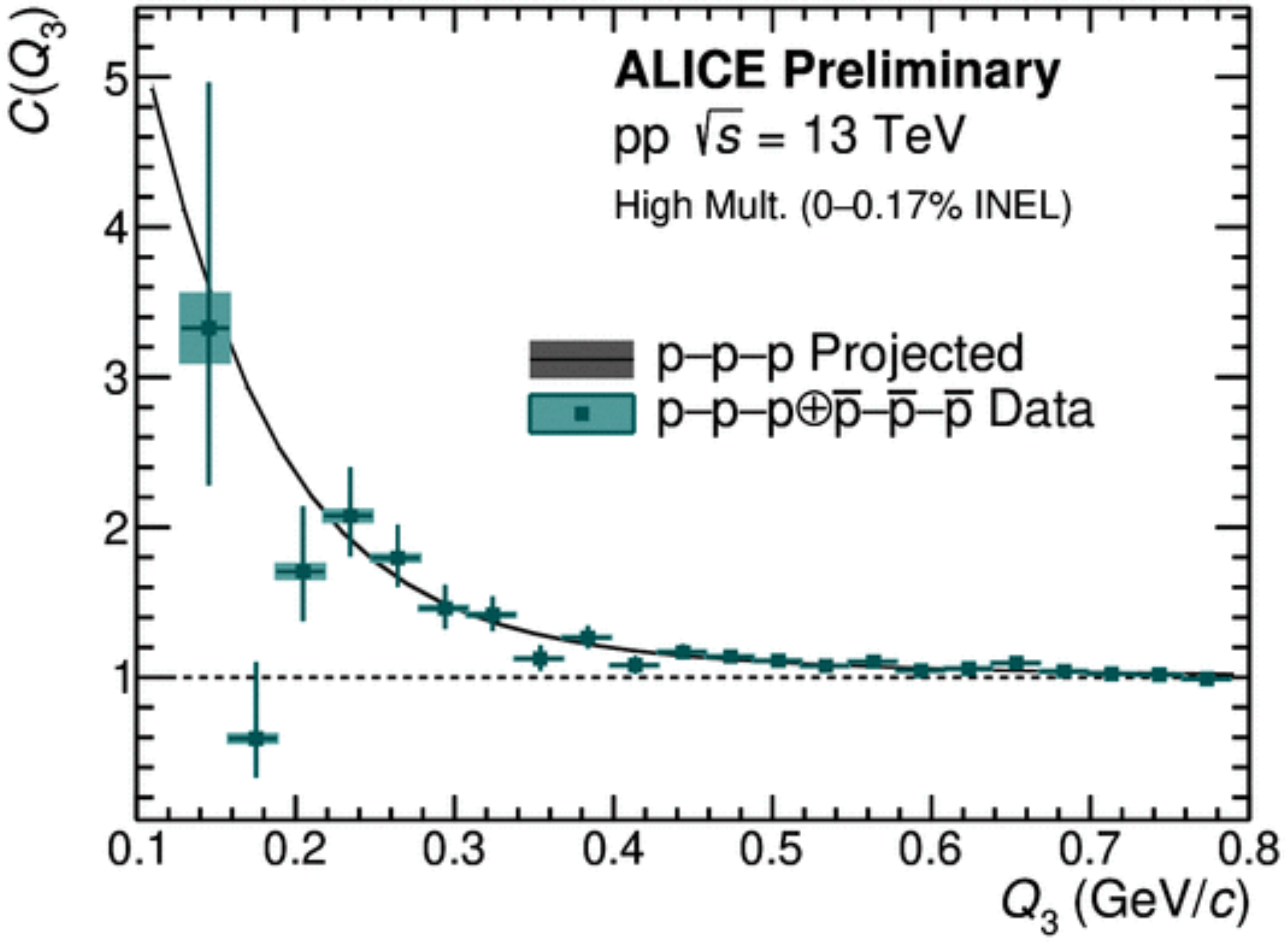

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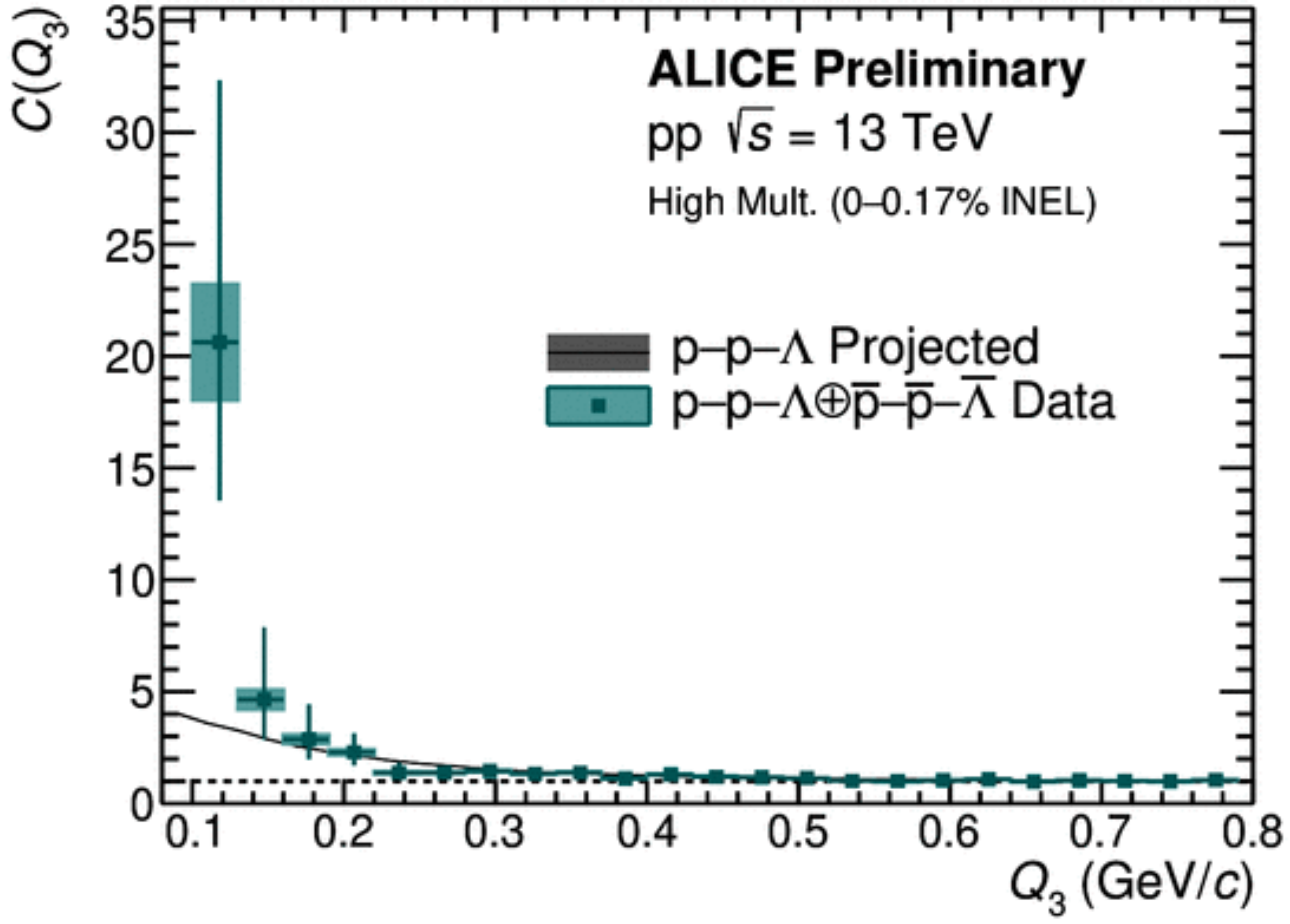

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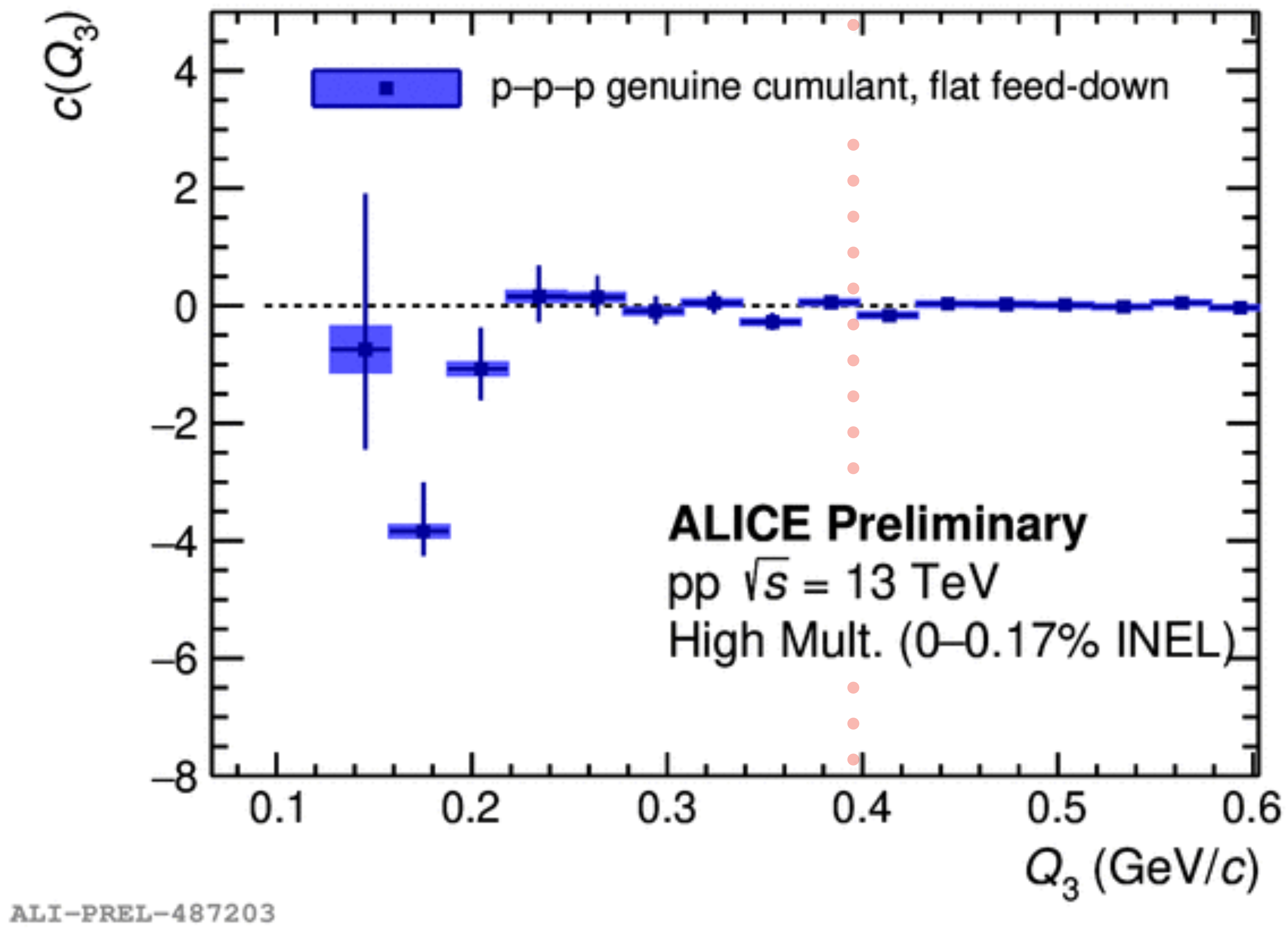
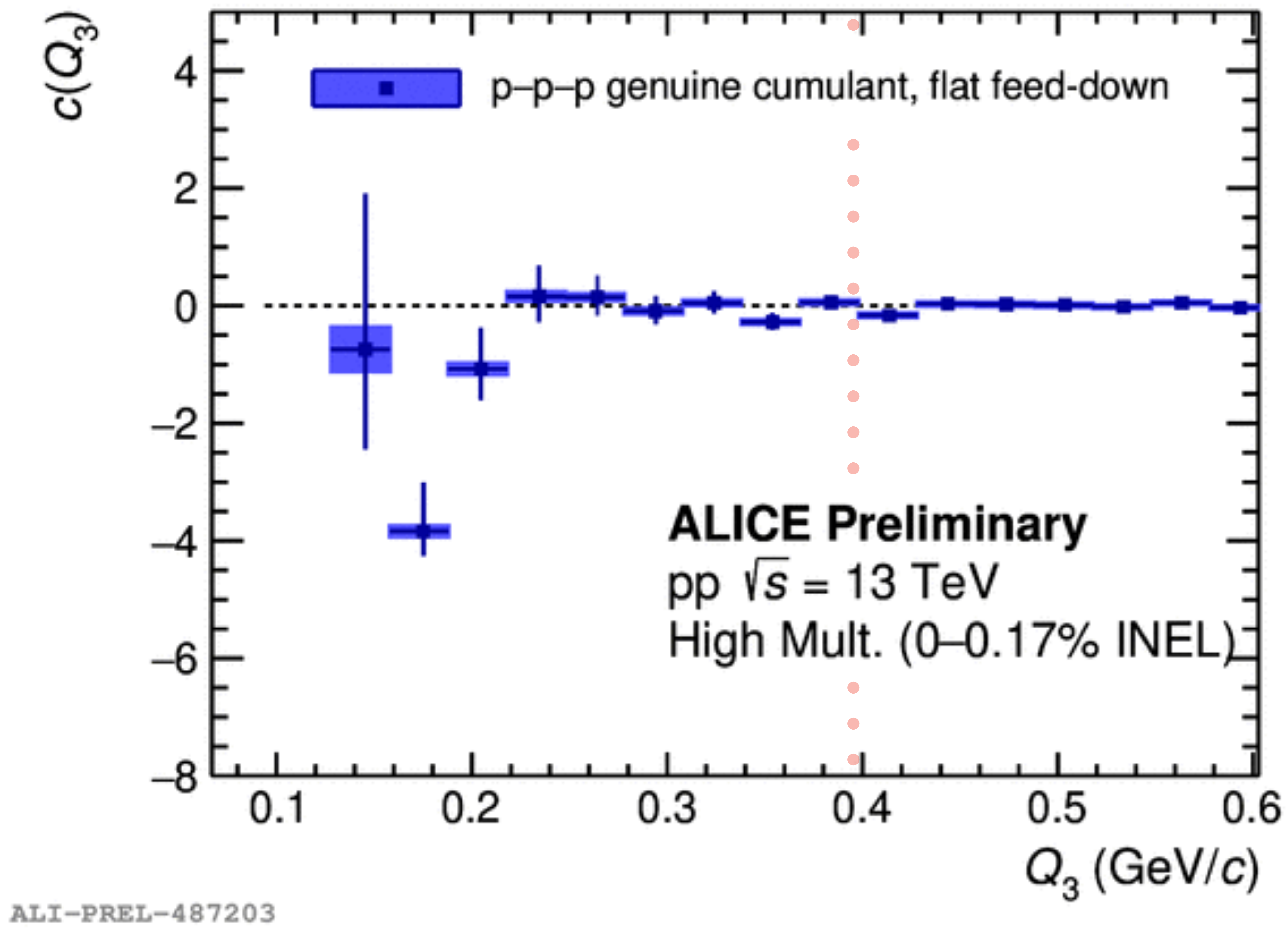
Three-body cumulants

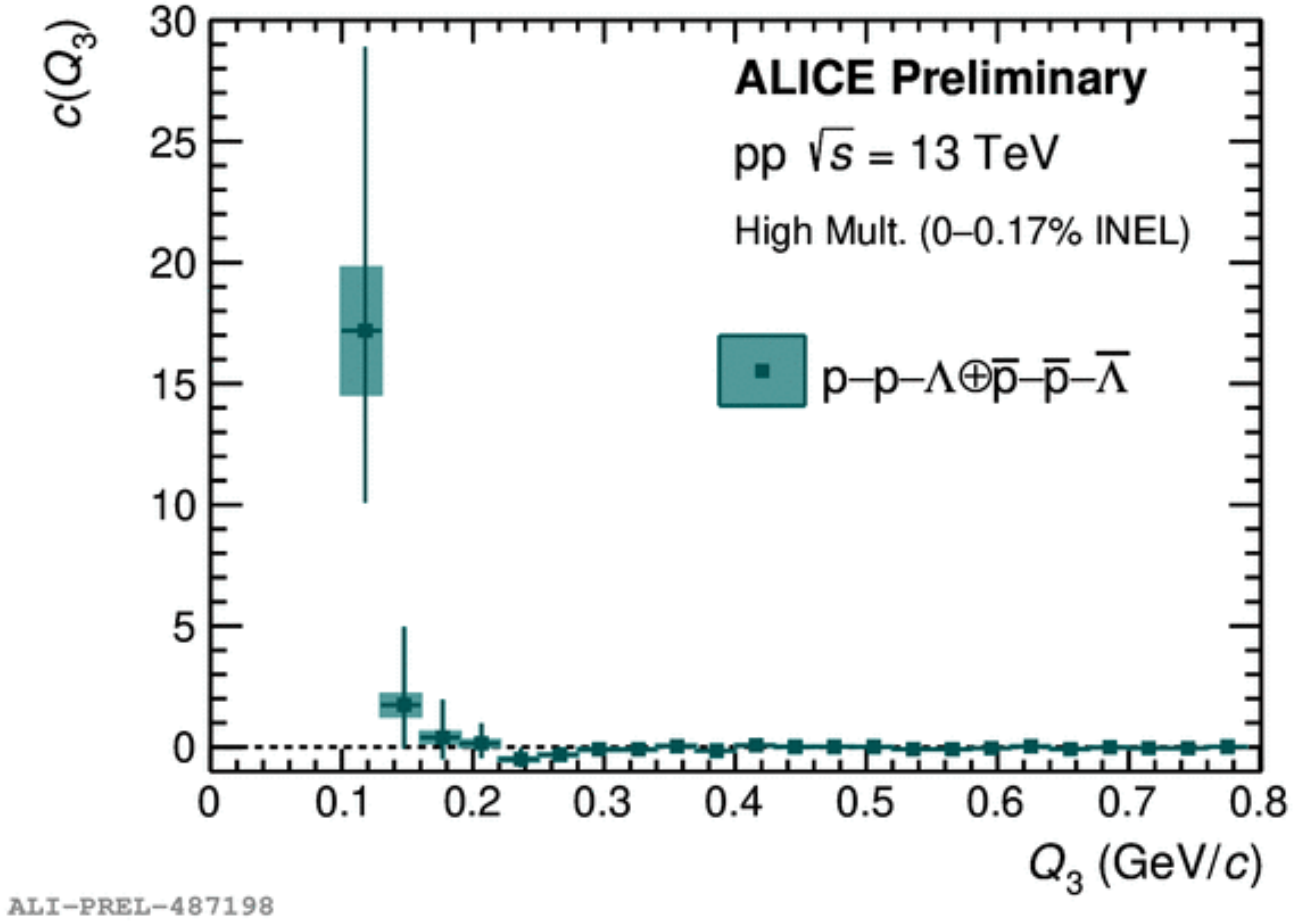


Statistical significance in the range up to 0.4 GeV/c: $n_\sigma = 2.9$

Theoretical calculations are needed to interpret the data.

Three-body cumulants





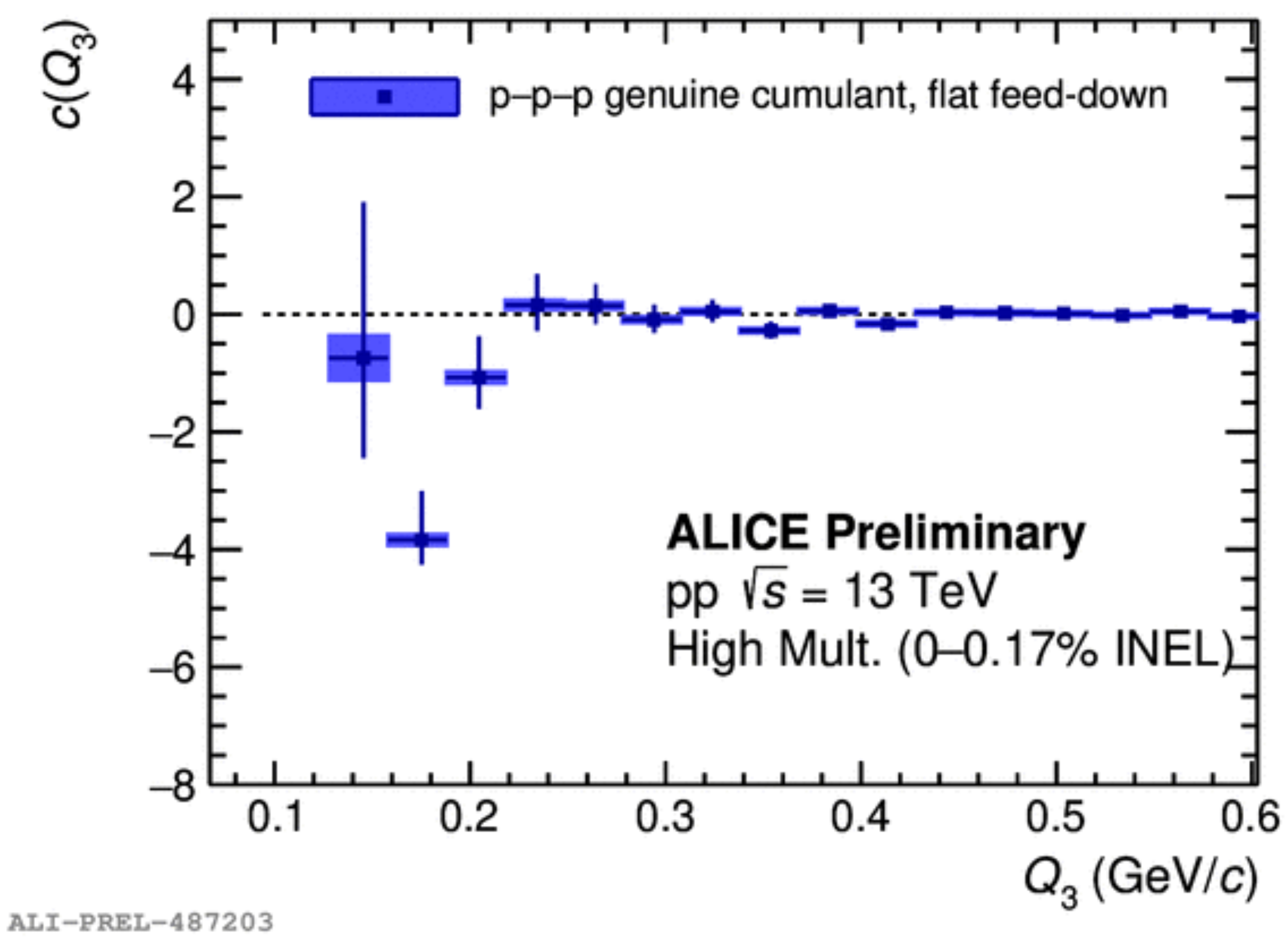
Statistical significance in the range up to 0.4 GeV/c: $n_\sigma = 2.9$

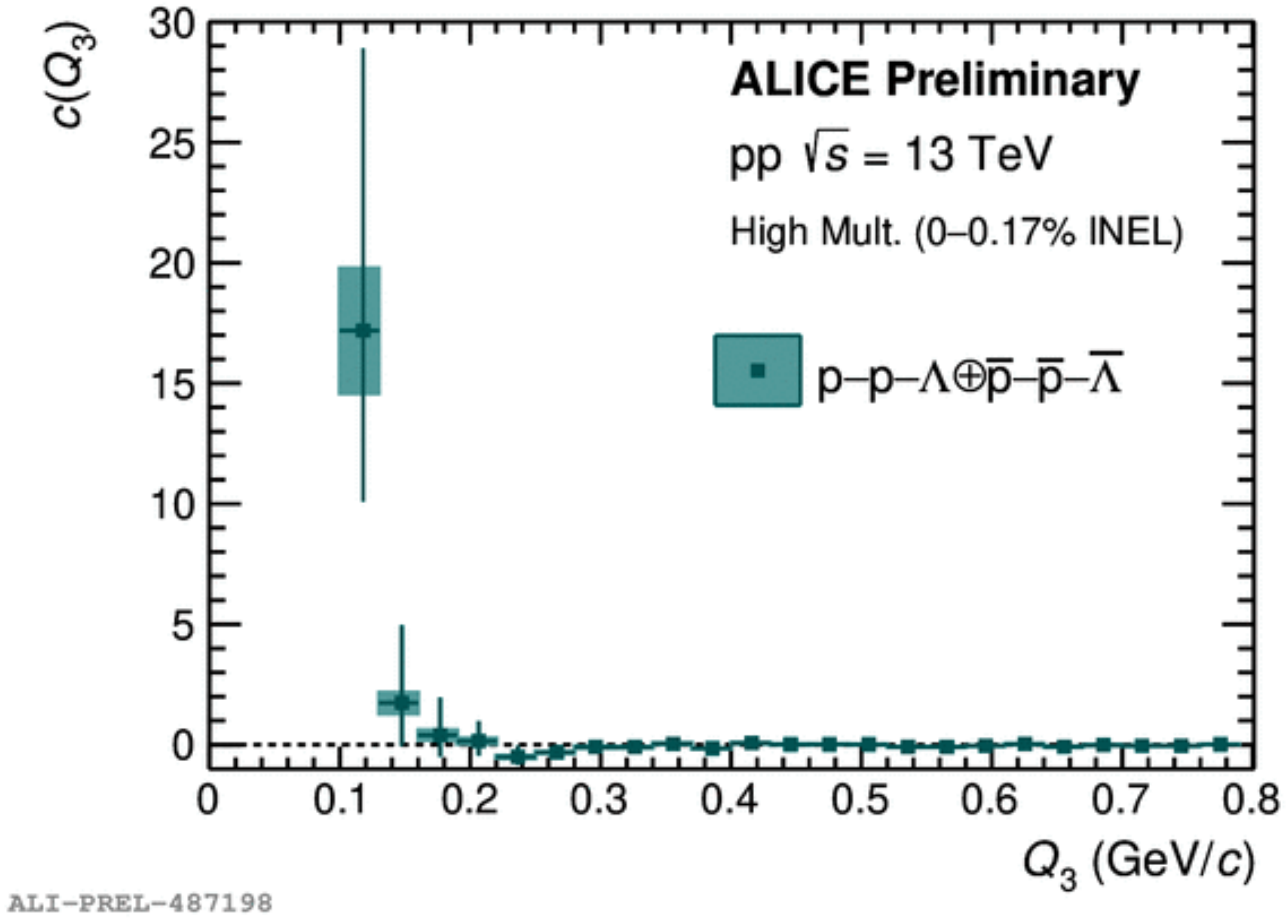
Theoretical calculations are needed to interpret the data.

Positive cumulant observed in the first bins.

Summary and outlook

- First direct measurements 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_σ = 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

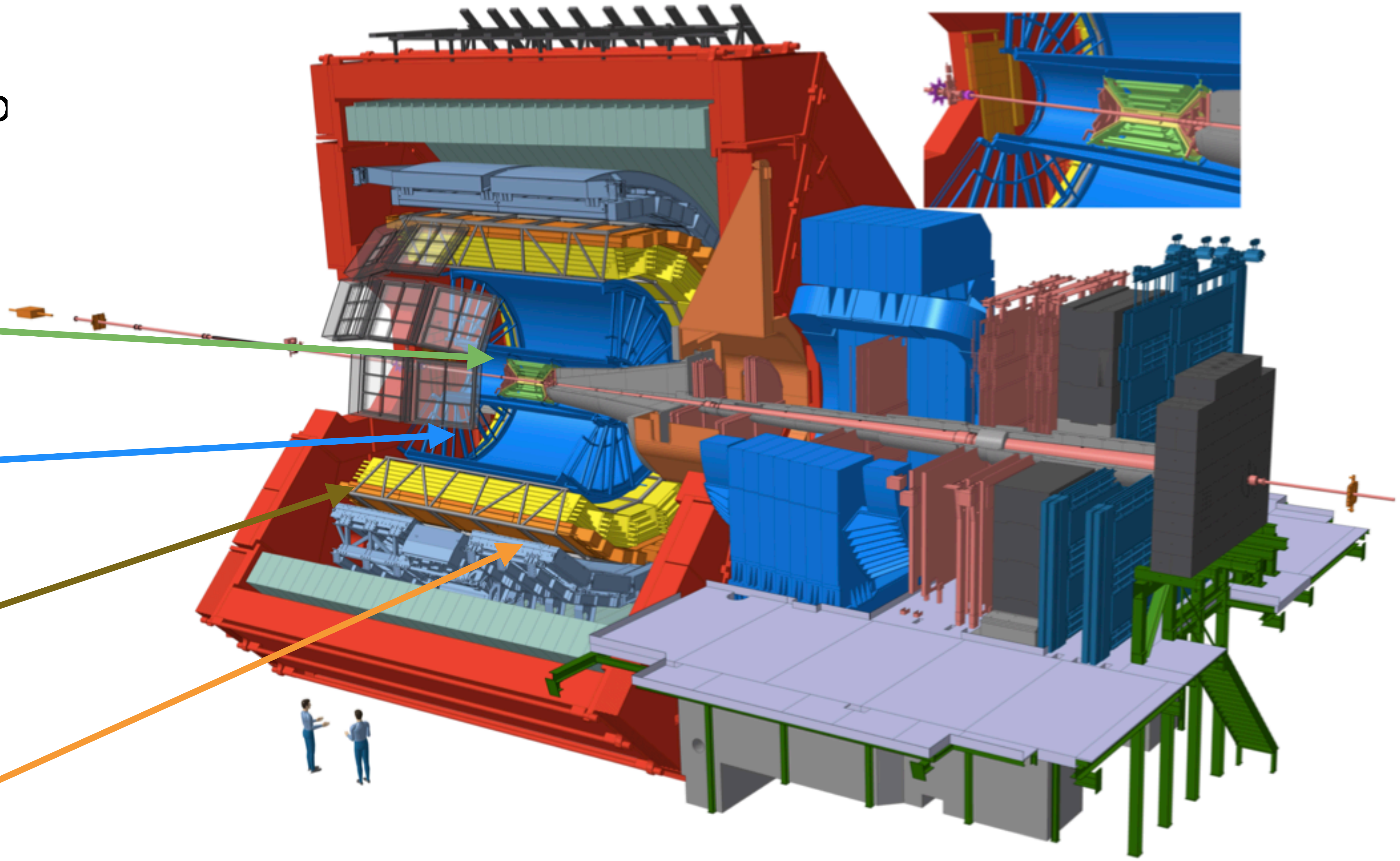
- Excellent tracking and particle identification (PID) capabilities
- Most suitable detector at the LHC to study (anti-)nuclei production and annihilation

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

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

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

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