Investigation of the three-body interactions of hadrons in pp collisions with ALICE

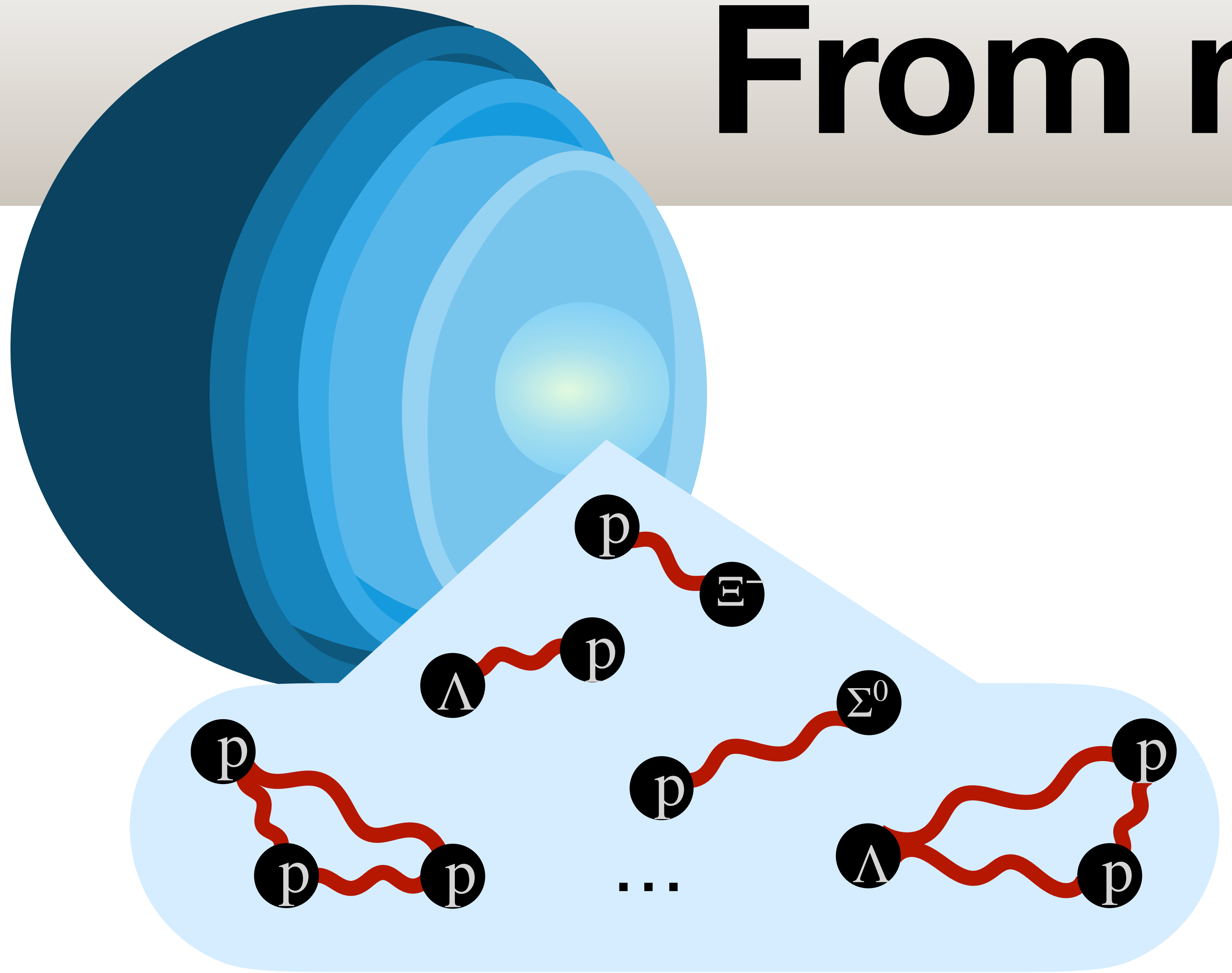
Laura Šerkšnytė on behalf of the ALICE Collaboration
Technical University of Munich

Prague, 29.06.2022

Based on: EPJC 82 2022 (TUM), arXiv:2206.03344 (ALICE) and new results!

HYP 2022 PRAGUE

From nuclear matter…

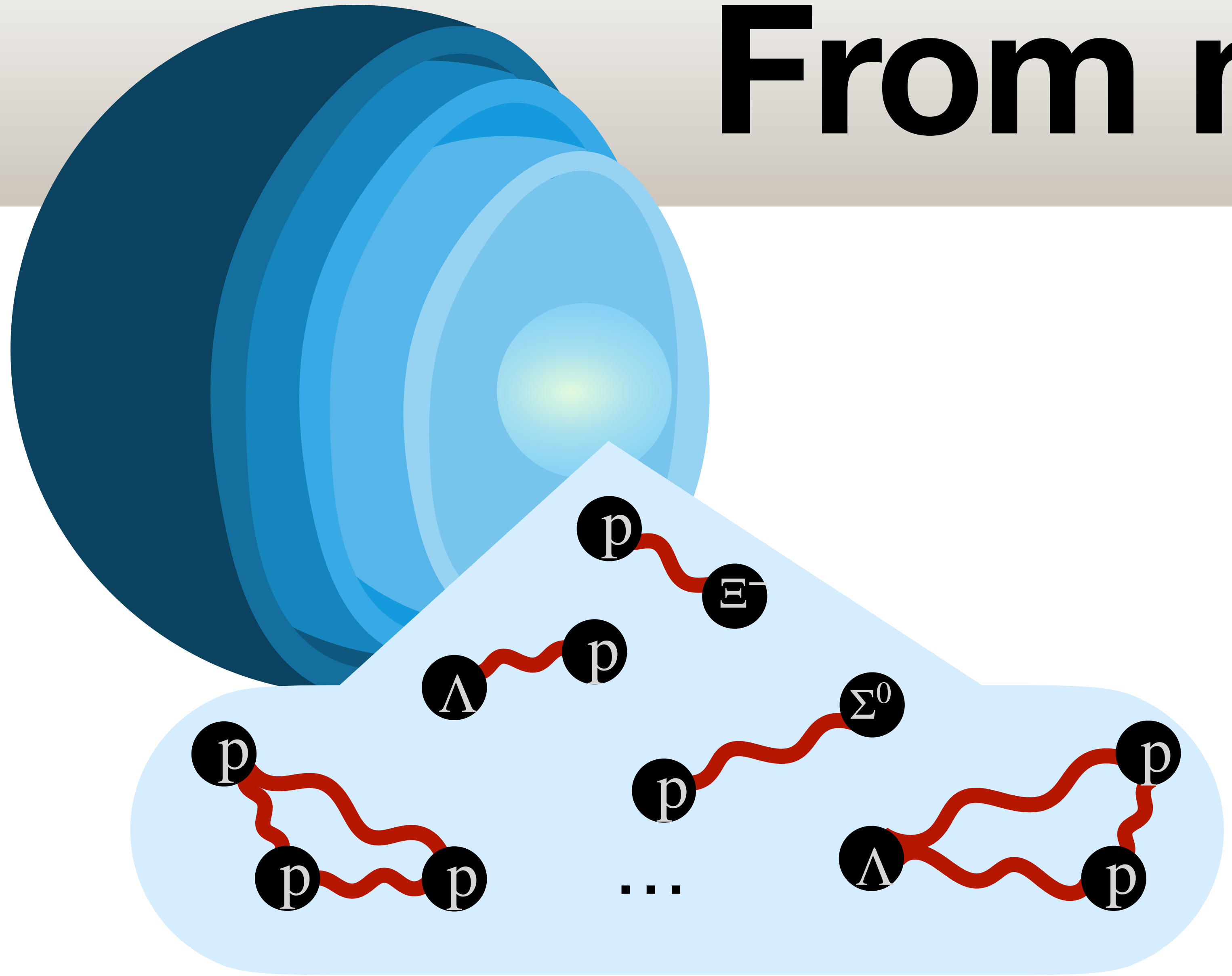


- Properties of nuclei and hypernuclei cannot be described satisfactorily with two-body forces only.
  L.E. Marcucci et al., Front. Phys. 8:69 (2020)

- 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)

Previous talks + Weise (Today 12:30) + Kochankovski (Tomorrow 11:40)

From nuclear matter…



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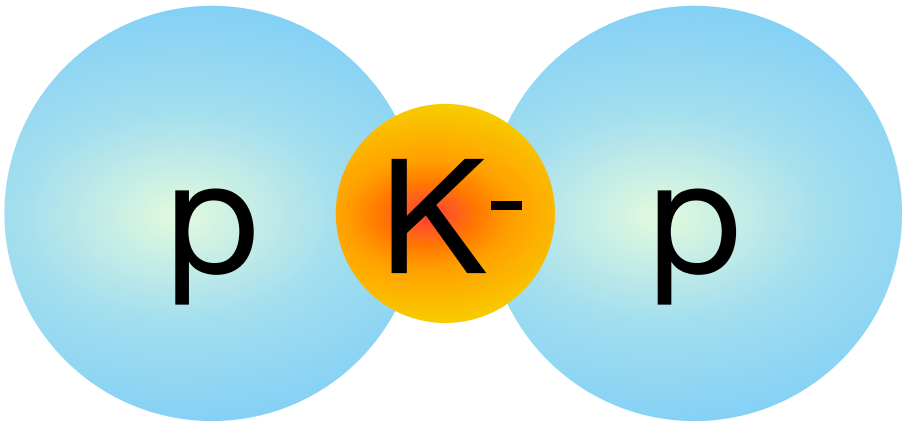
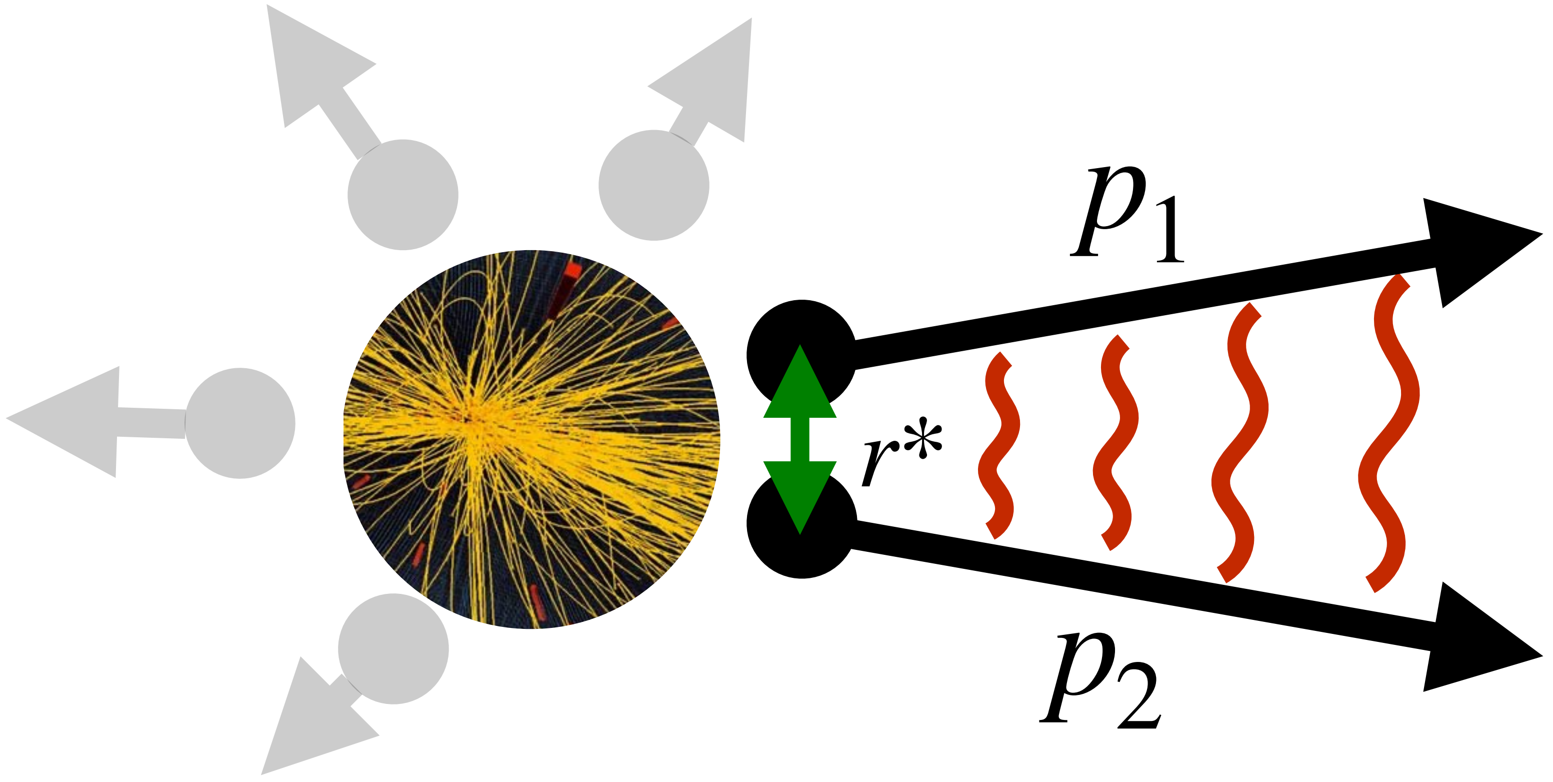
…to kaonic bound states

- $\bar{K}$-N-N: 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) 399; Y. Akaishi, T. Yamazaki, PRC 65 (2002) 044005;
  Sekihara et. al., PTEP 2016 no. 12, (2016); N. V. Shevchenko et.al., PRL 98 (2007) 082301;
  S. Wycech, A. M. Green, PRC 79 (2009) 014001; Y. Ikeda, T. Sato, PRC 76 (2007) 035203;
  N. Barnea et. al., PLB 712 (2012) 132-137
- First solid experimental evidence of the p-p-K^- bound state by the E15 Collaboration.
  E15 Coll., PLB 789 (2019) 620

Previous talks + Yamaga (Tomorrow 8:55)



Femtoscopic technique



Emission source *S(r*)*

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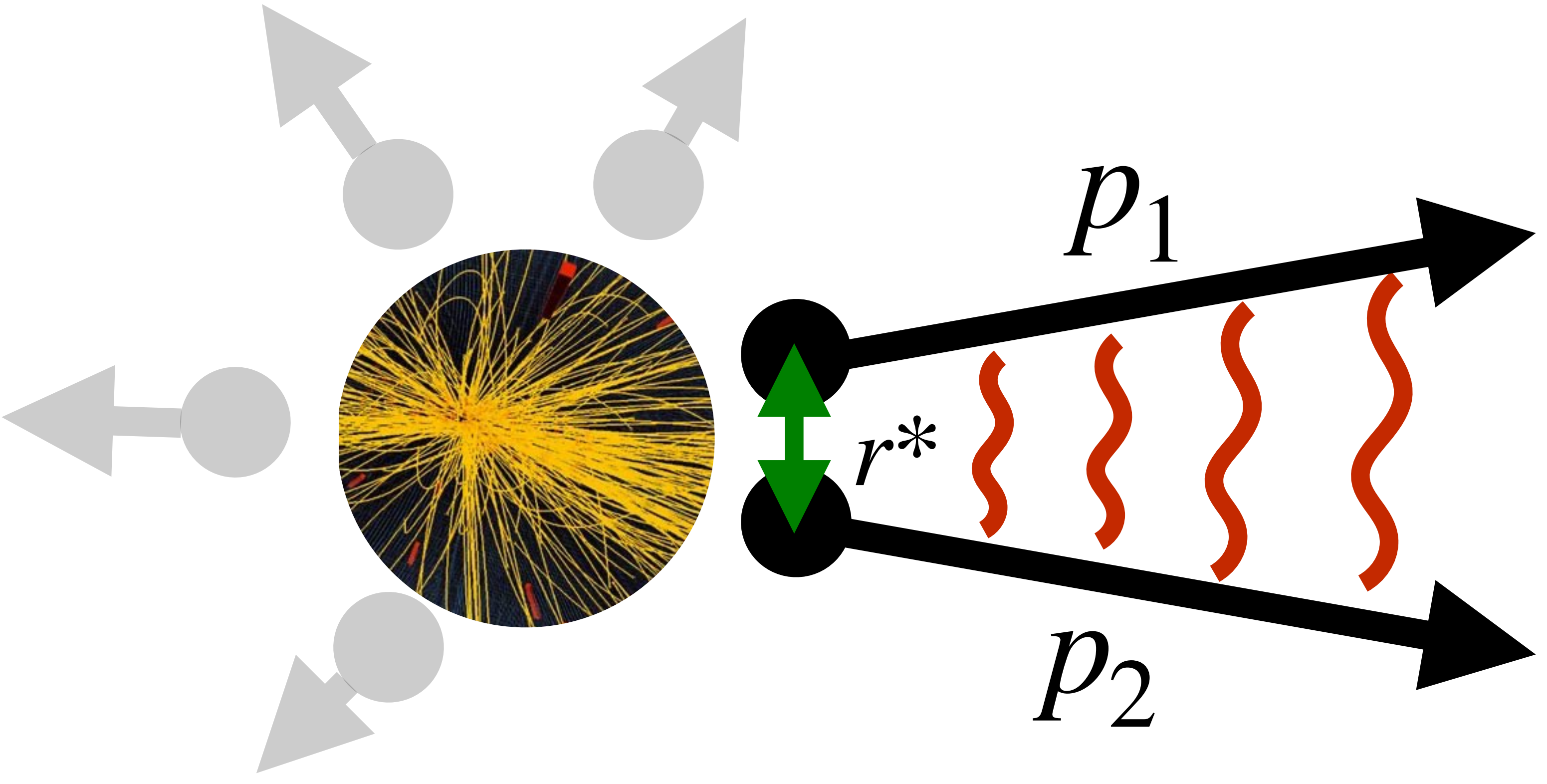
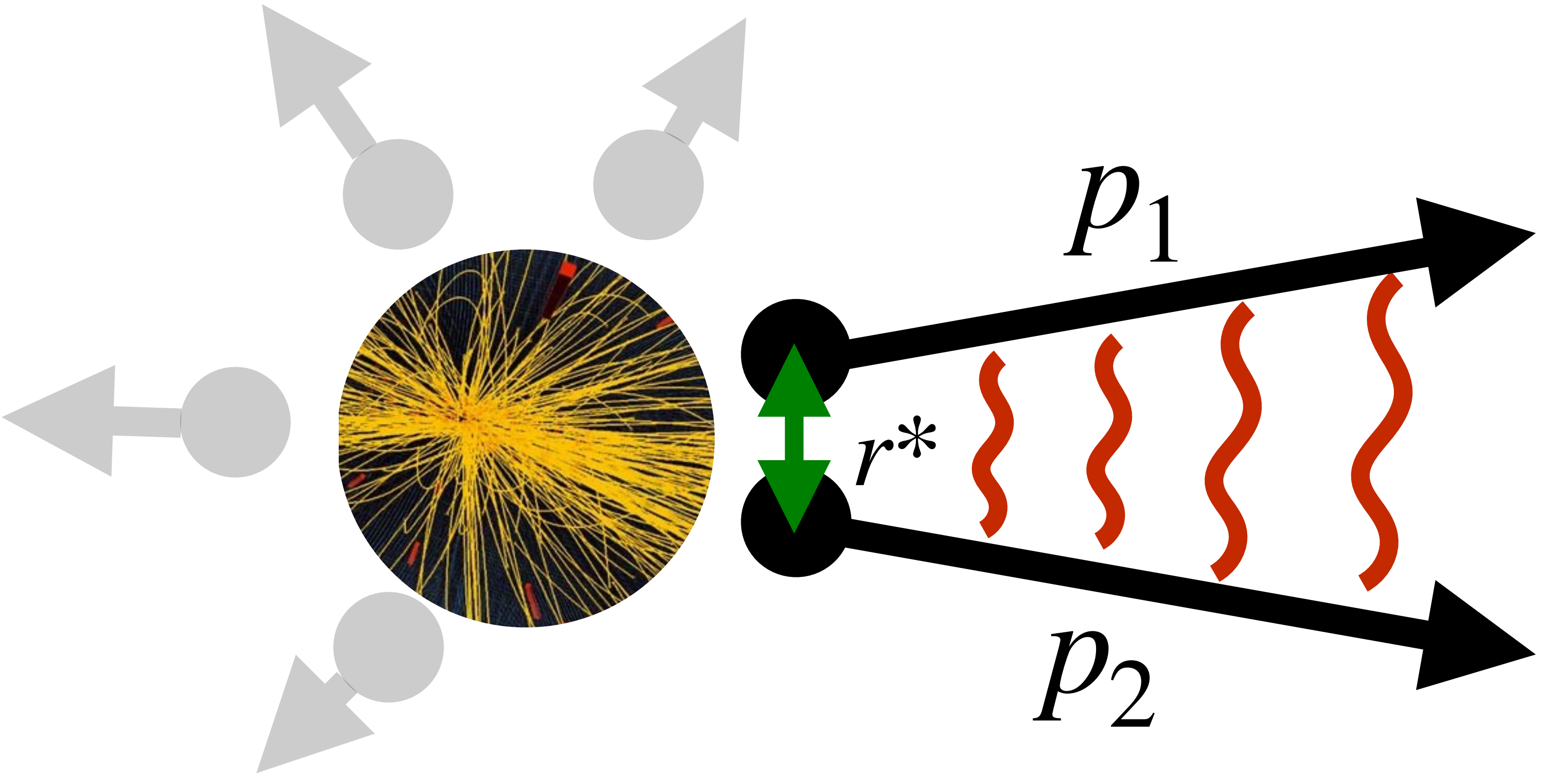
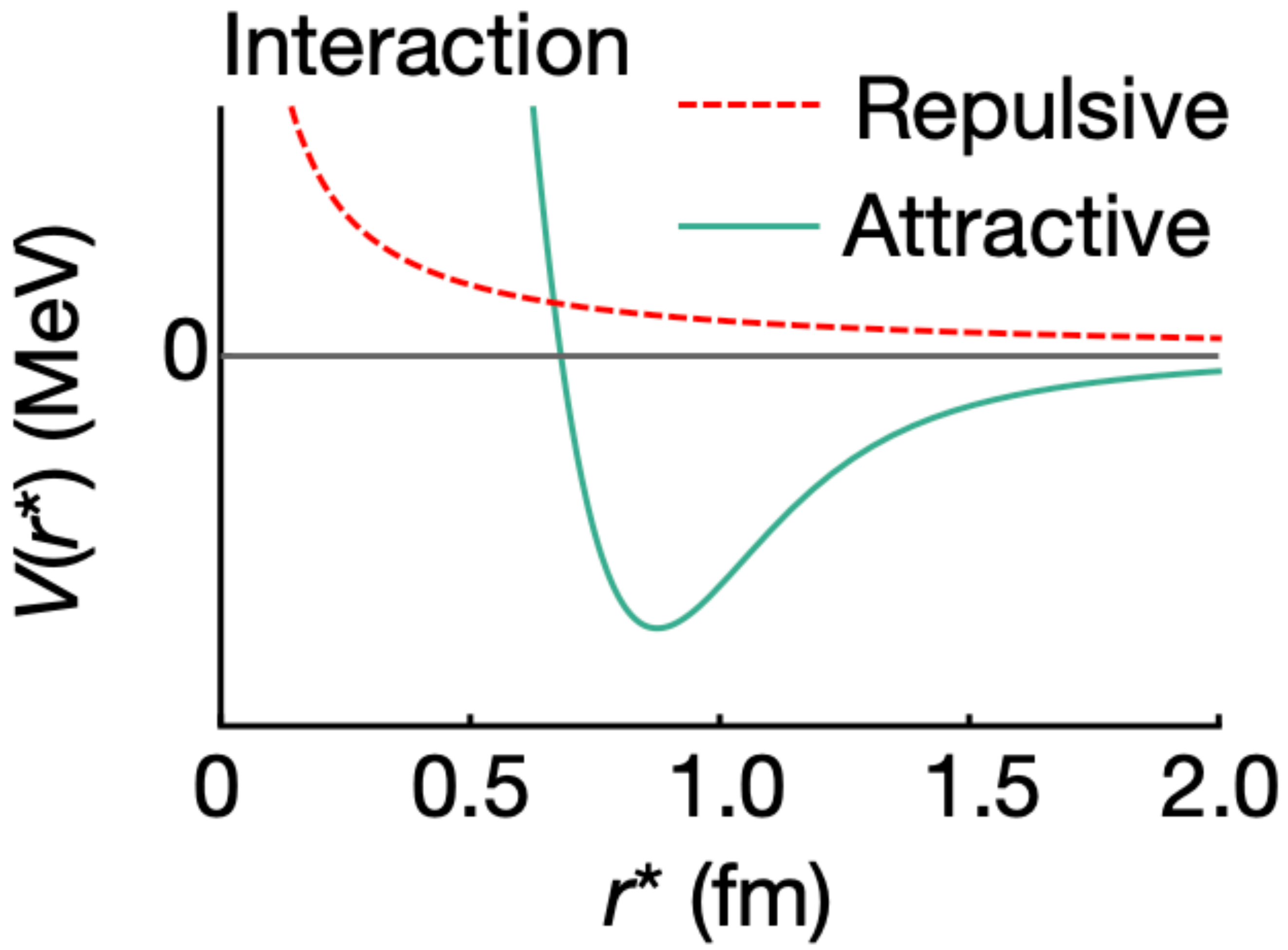


Emission source *S(r*)*

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

Femtoscopic technique





Emission source *S(r*)*

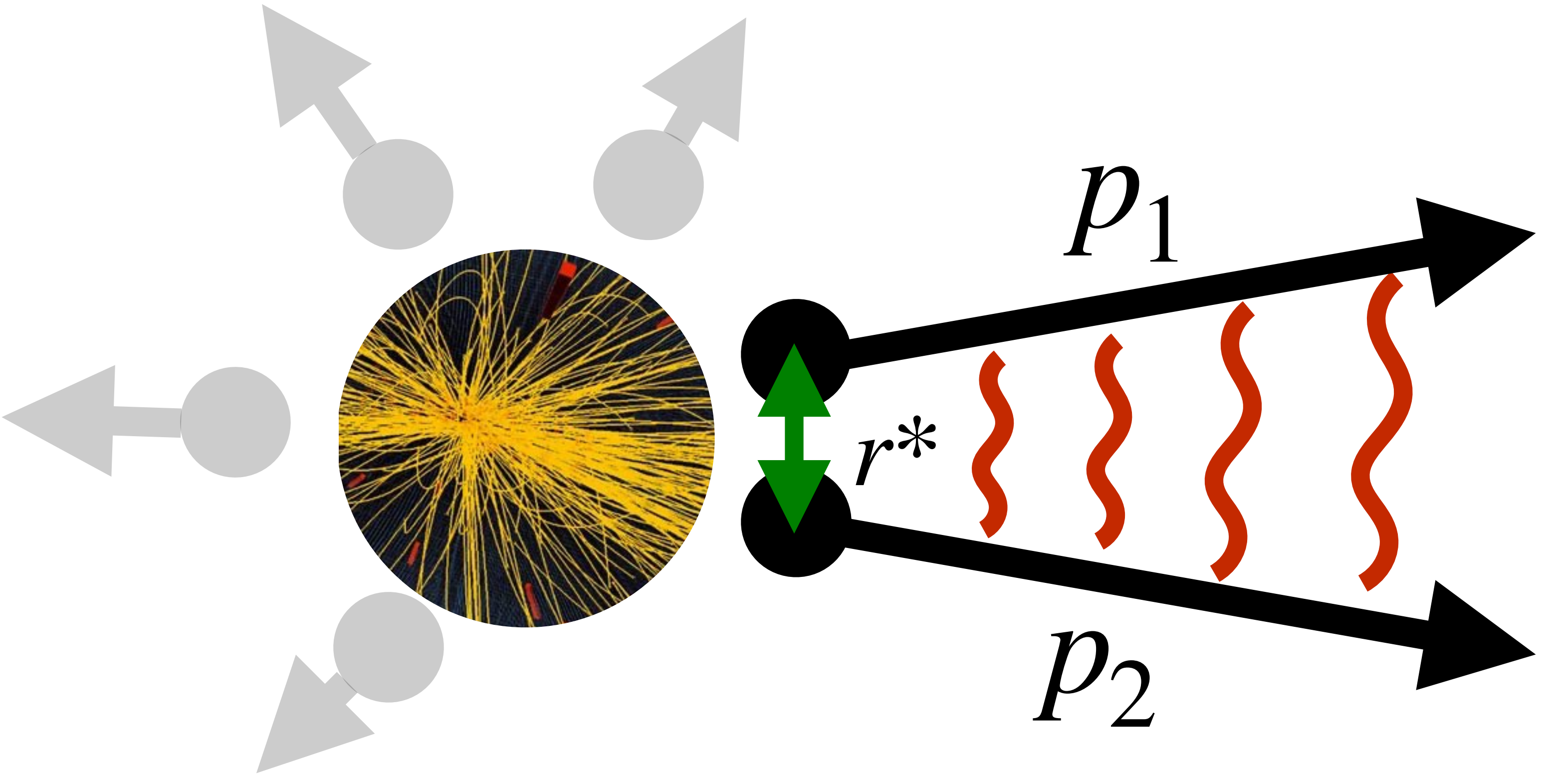
Schrödinger equation
Two-particle wave function

$$\left|\psi(\mathbf{k}^*, \mathbf{r}^*)\right|$$

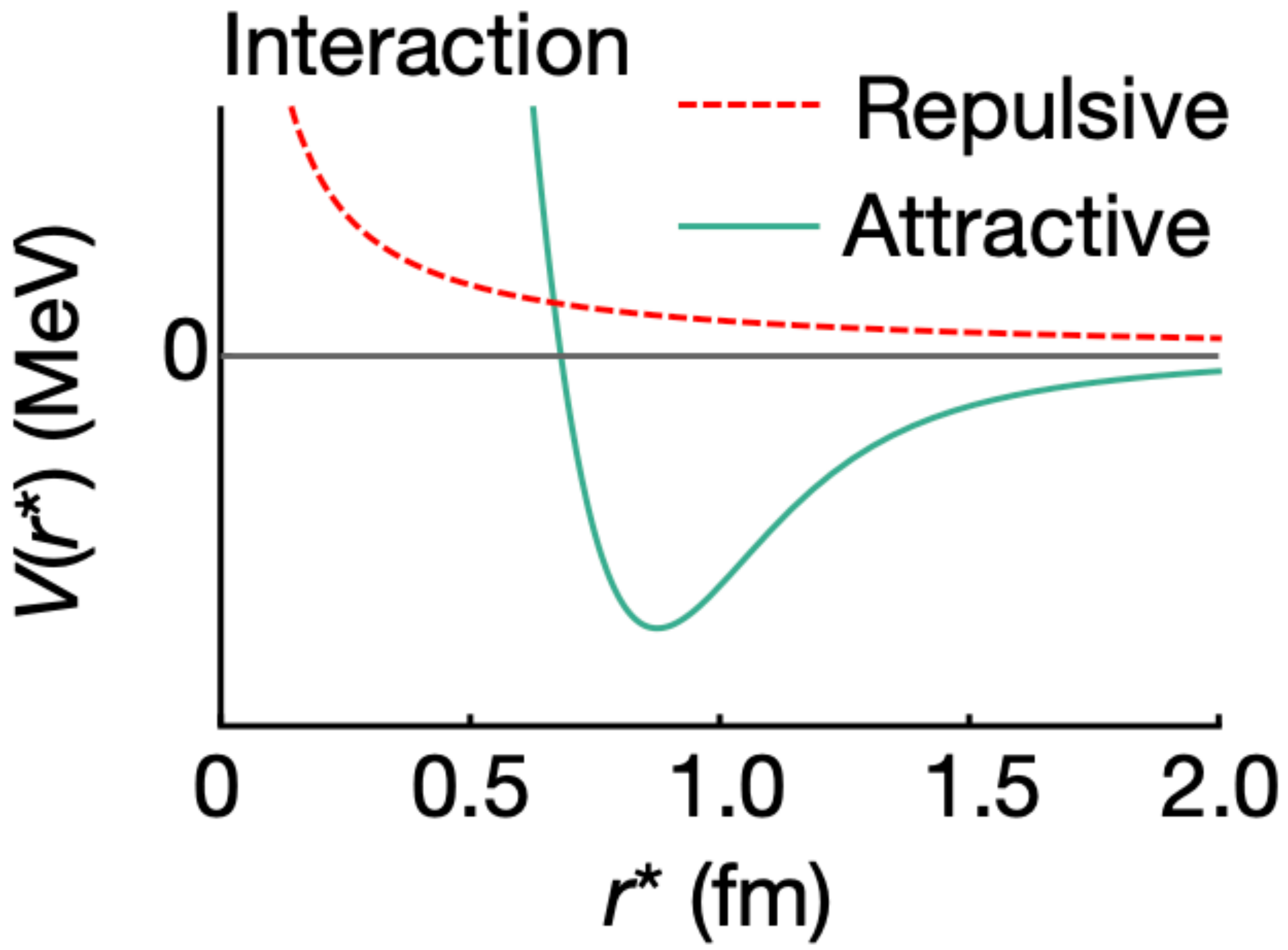
$$C(k^*) = \mathcal{N}\frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} = \int S(r^*)\left|\psi(\mathbf{k}^*, \mathbf{r}^*)\right|^2 \mathbf{d}^3 r^*$$

Nature 588, 232–238 (2020)

Femtoscopic technique



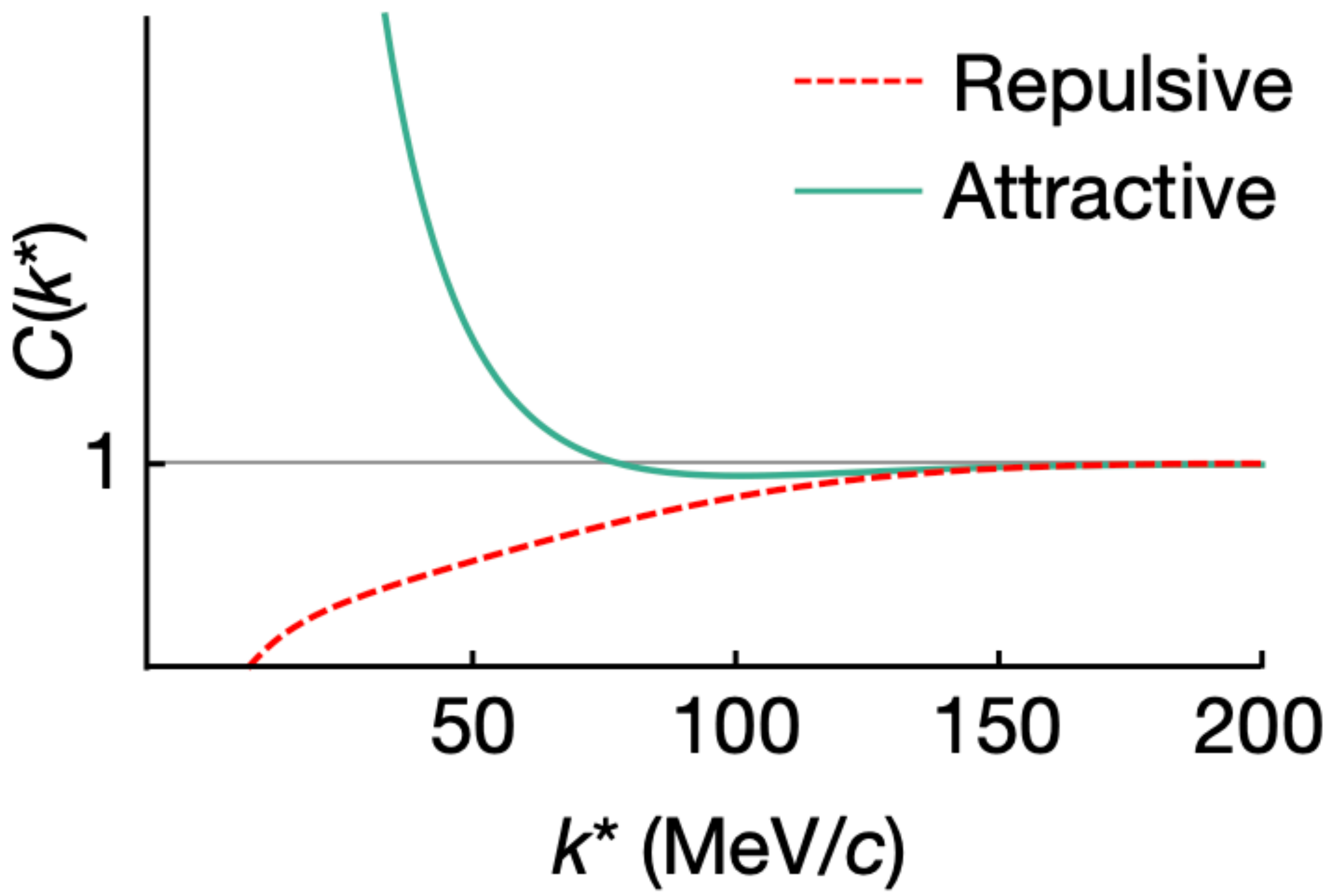
Emission source $S(r^*)$



Schrödinger equation

Two-particle wave function

$\left|\psi(\mathbf{k}^*, \mathbf{r}^*)\right|$



Correlation function $C(k^*)$

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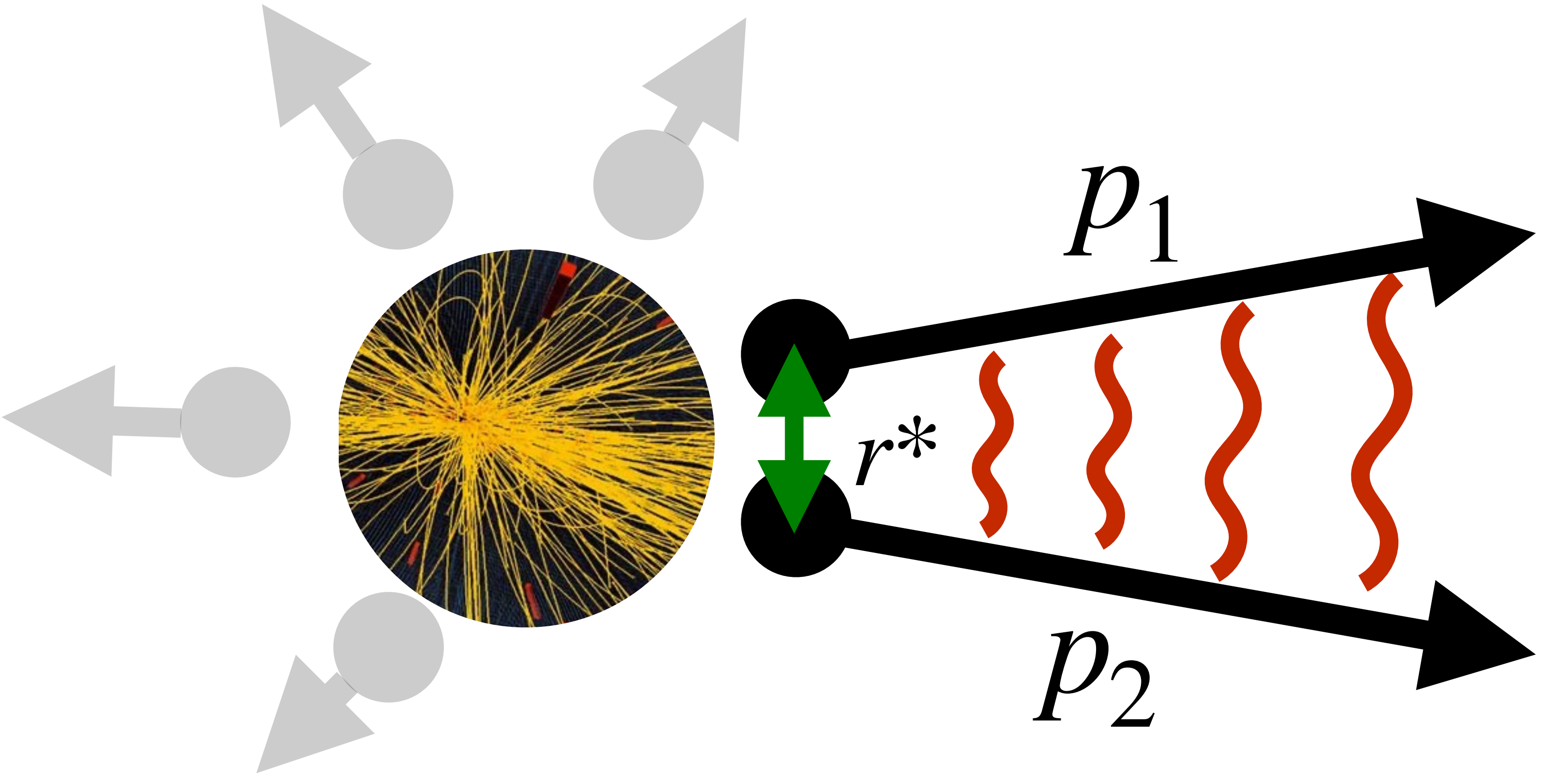
Femtoscopic technique

Talks:
Today: D. L. Mihaylov 14:30; B. Singh 15:45;
G. Mantzaridis 17:30;
R. Lea, tomorrow 9:20, O. V. Dole, Friday 09:00



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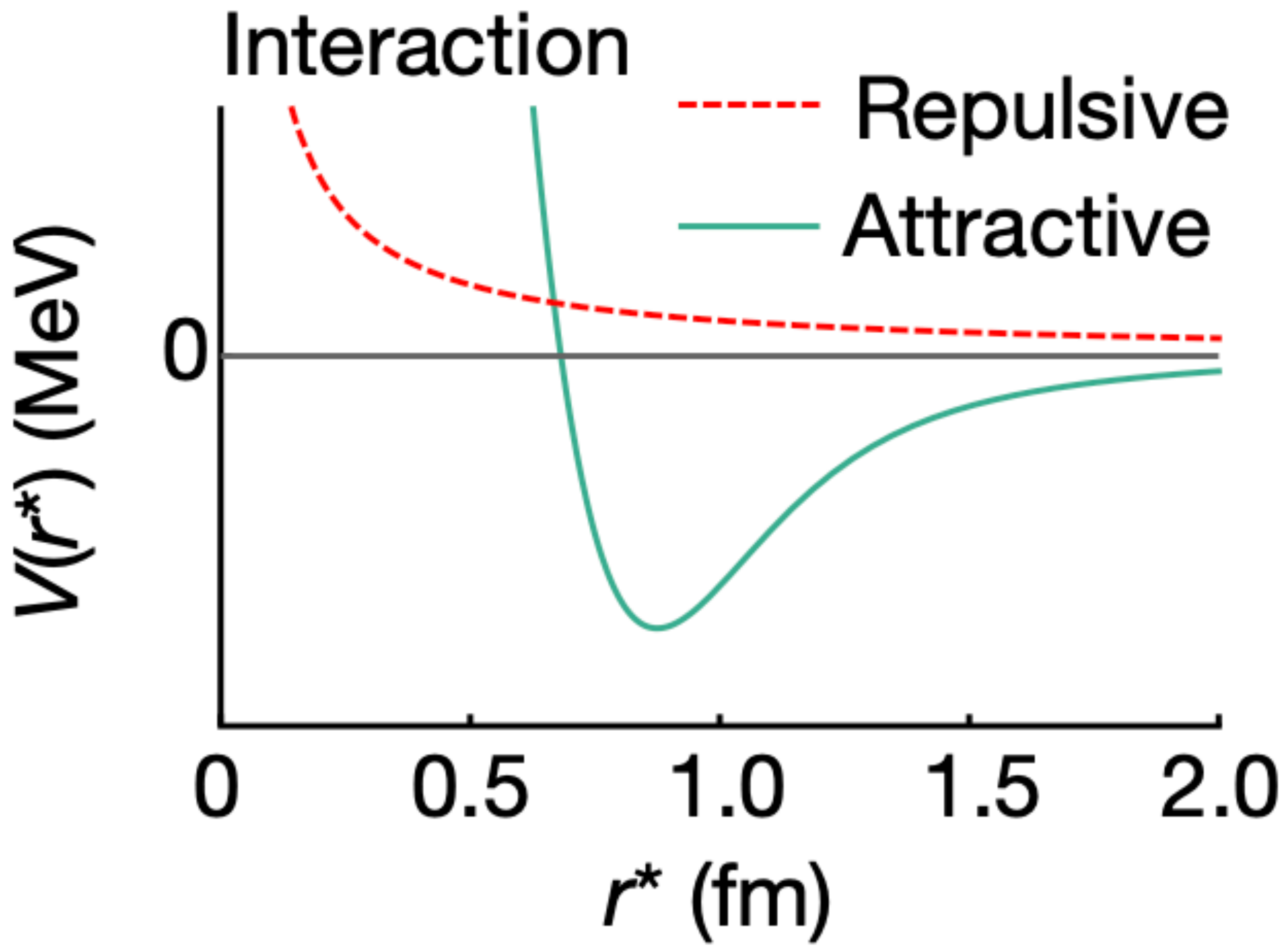

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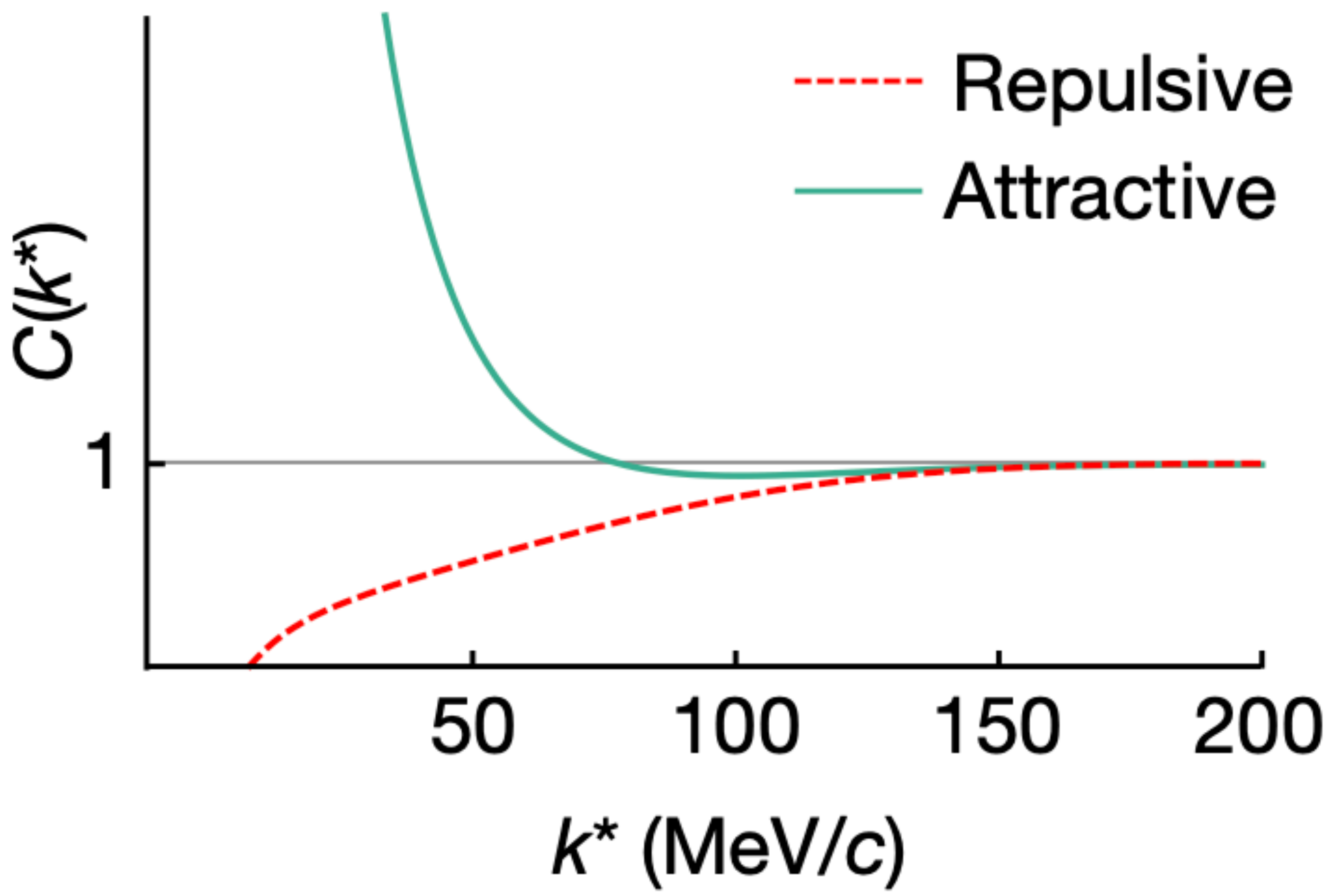

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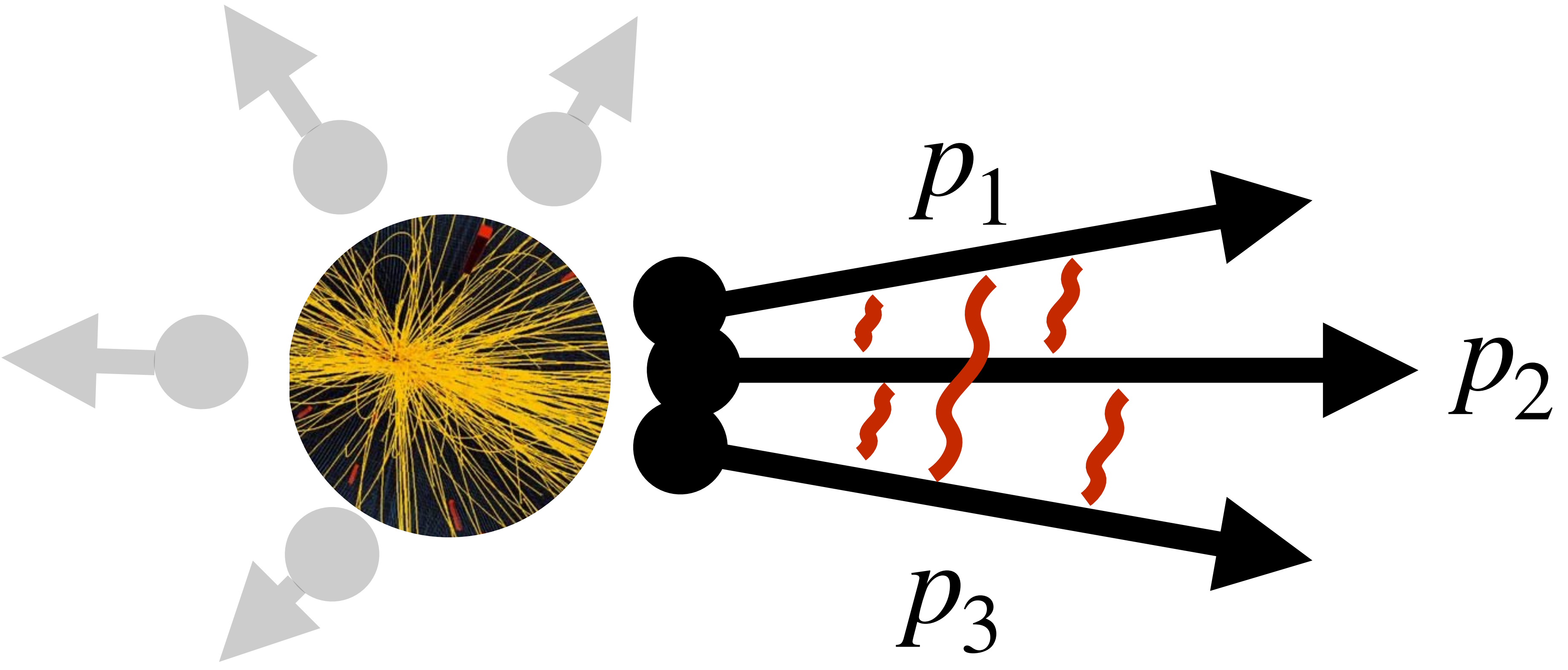
Femtoscopic technique: 3-body

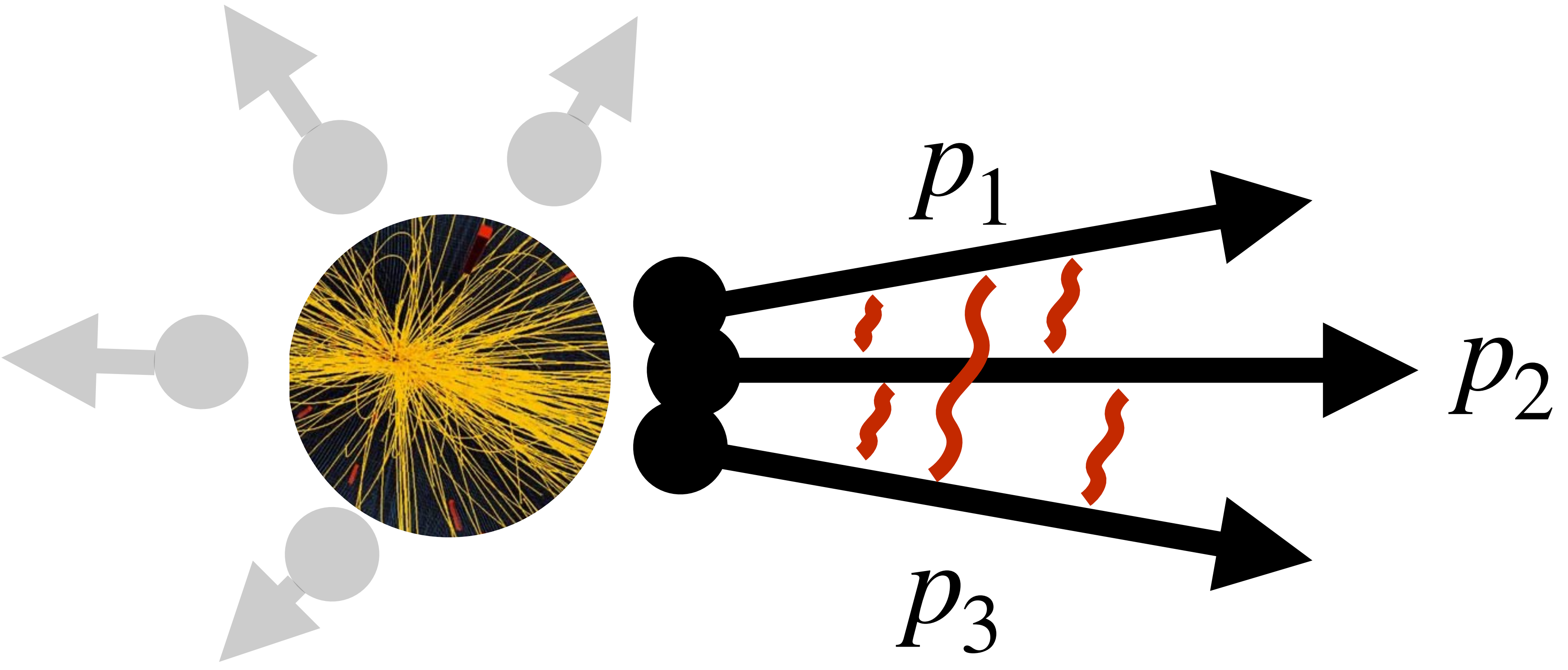


Three-particle correlation function:

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

$$Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - q_{ki}^2}$$

Femtoscopic technique: 3-body



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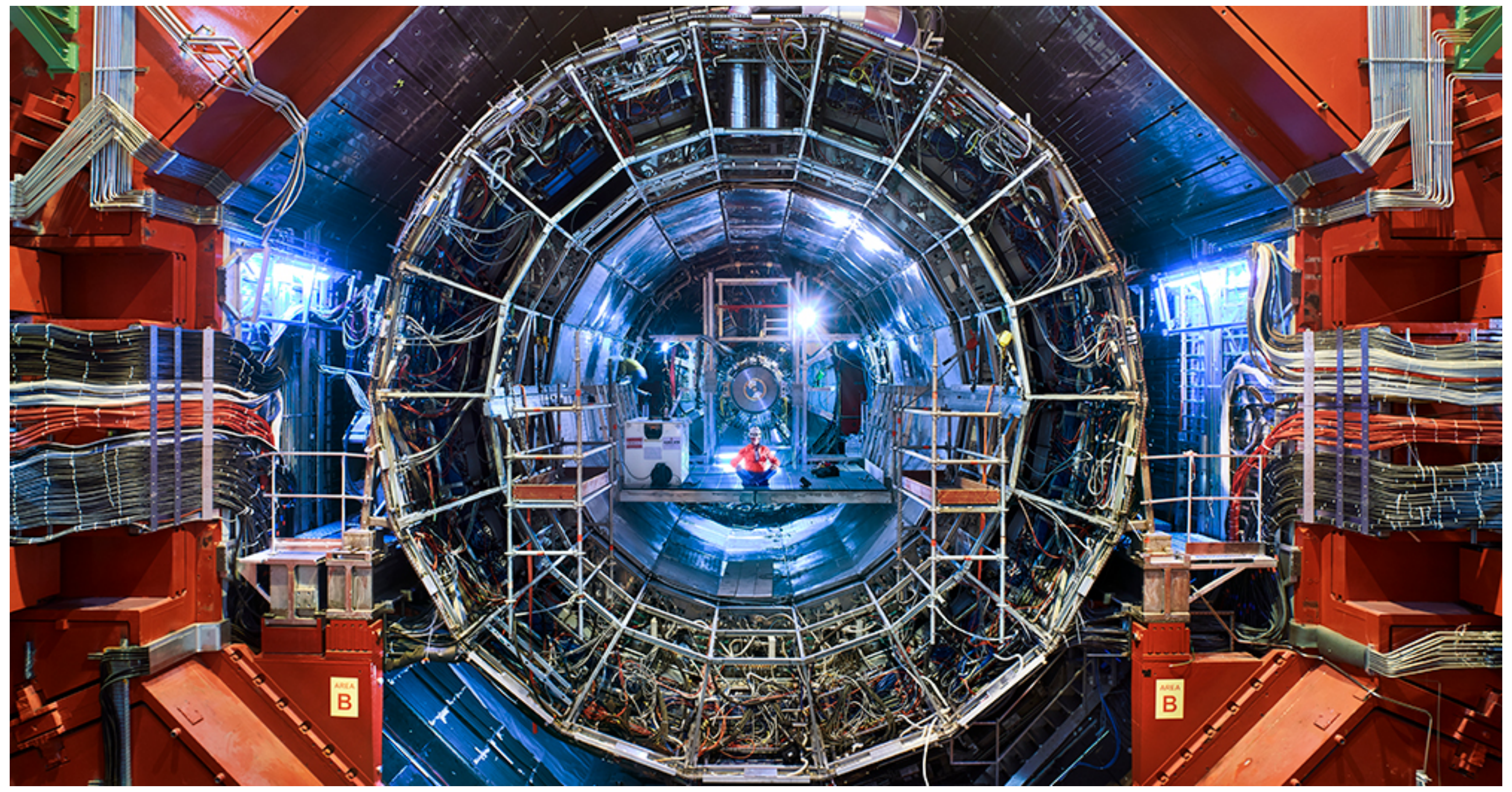
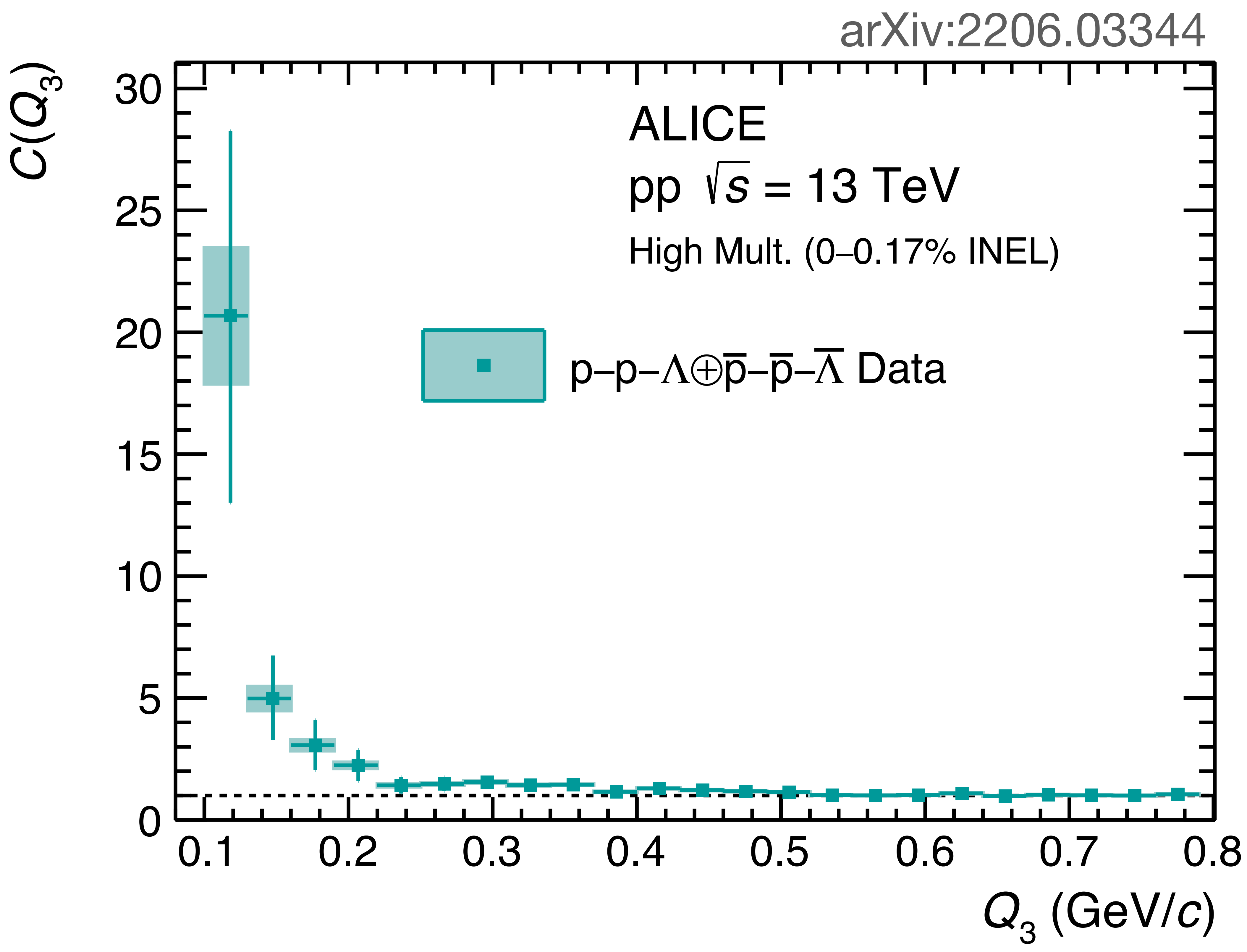
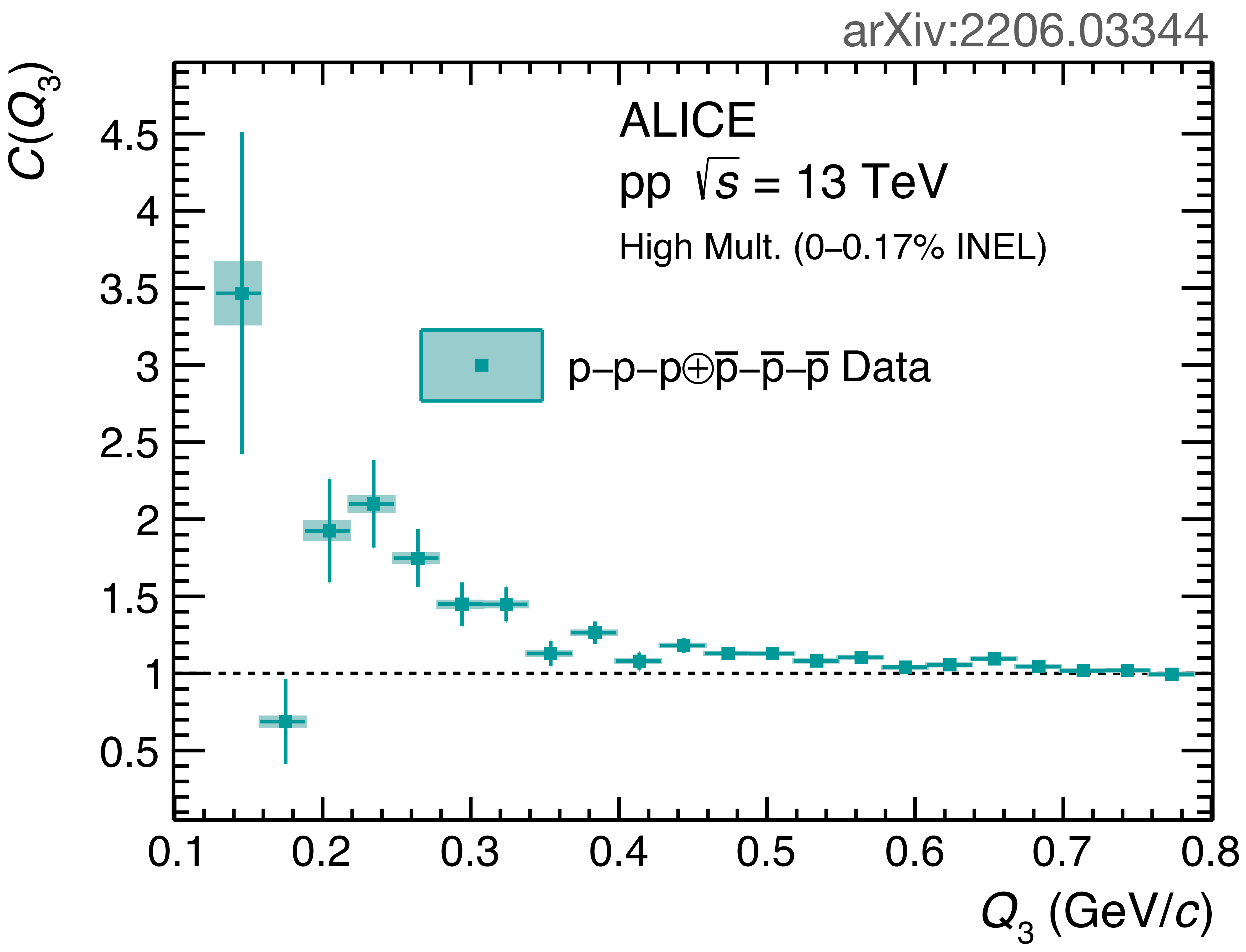
In this talk:

- Data: high-multiplicity pp @ $\sqrt{s}$ = 13 TeV events
- Analyses: p-p-p, p-p-Λ, p-p-K^+, p-p-K^-



p-p-Λ and p-p-p correlation functions





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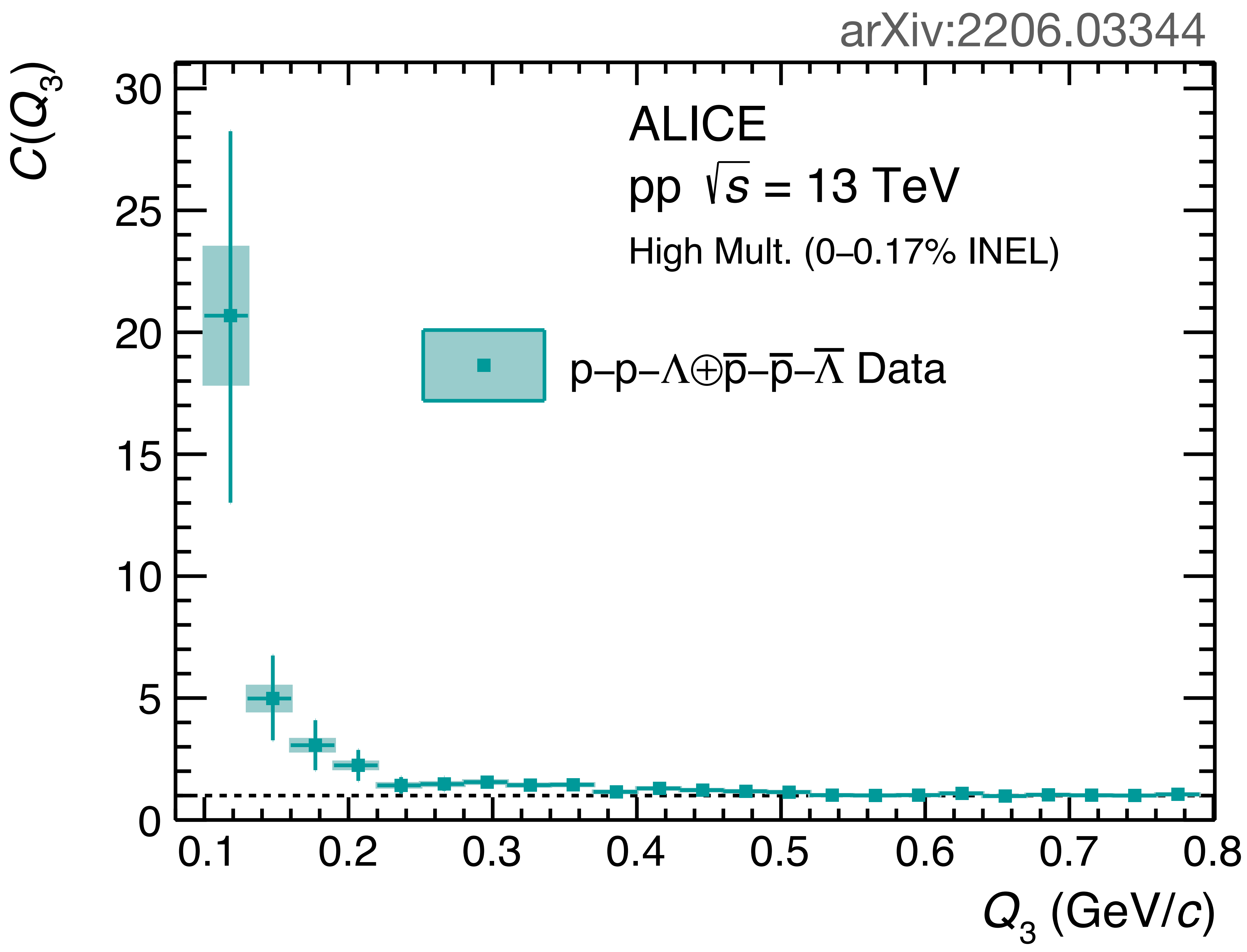
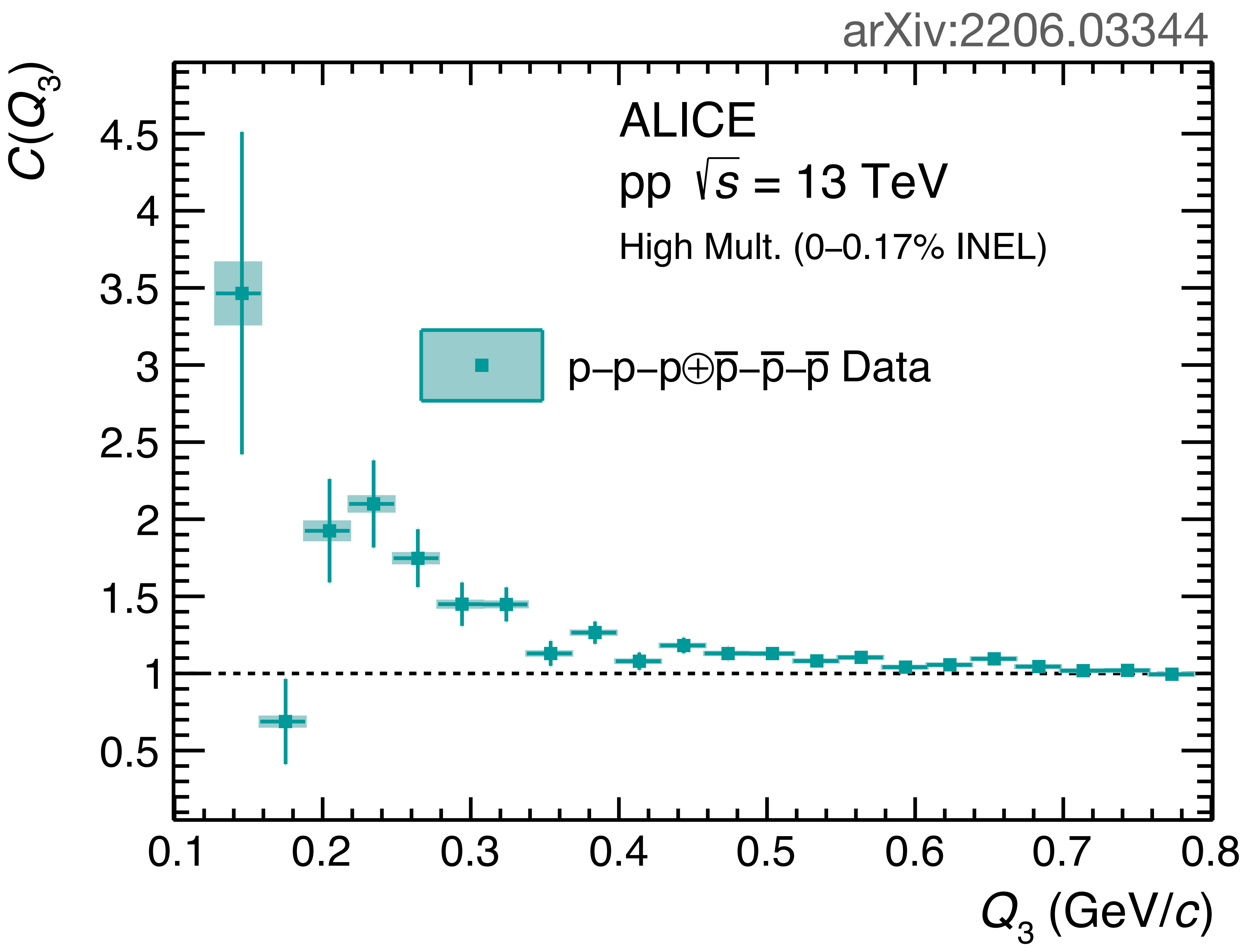
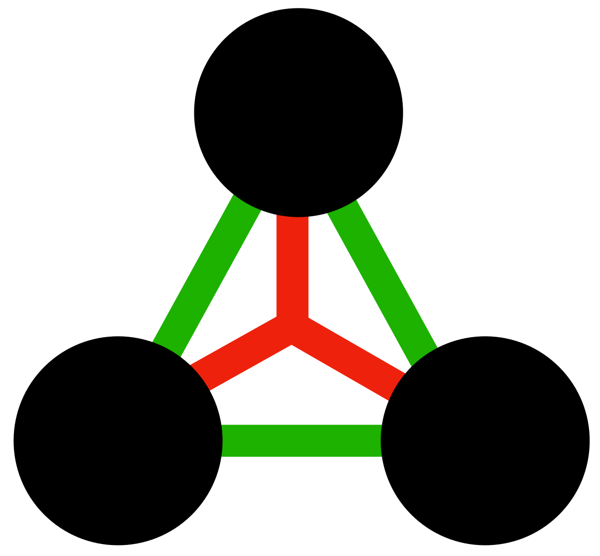




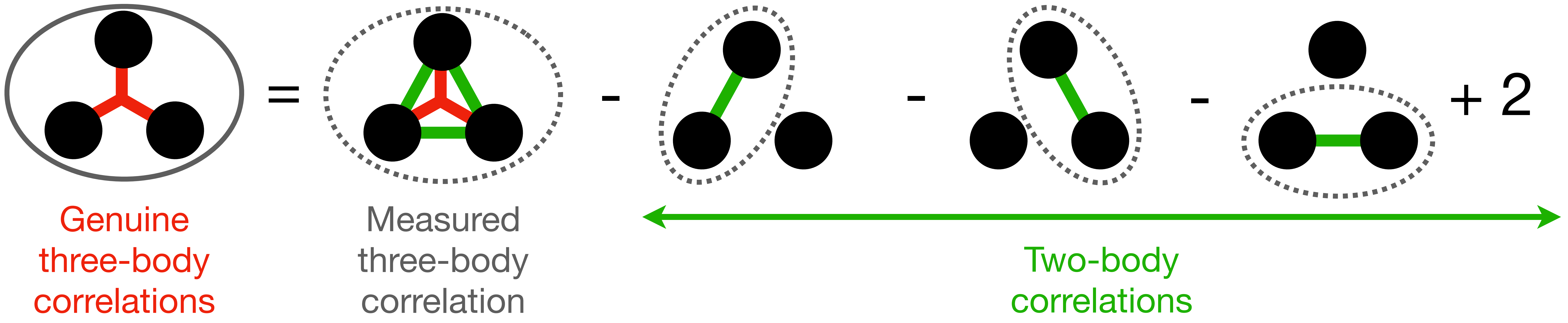
How can one interpret three-body correlation function?

- **Two-body interactions**
- **Three-body interactions**



Cumulants in femtoscopy

The total three-particle correlations can be expressed as a sum of genuine three-body correlation and the lower-order contribution employing Kubo's cumulants [1]:



In terms of correlation functions:

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

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

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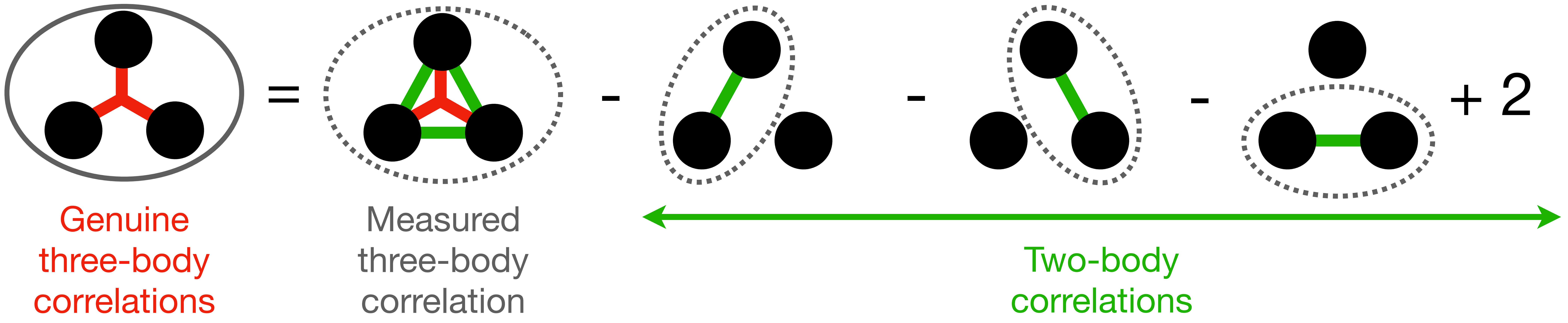

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How to estimate lower-order contributions?

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

Lower-order contributions

Data-driven method

- Use event mixing
- Two particles from the same event and one particle from another:

Lower-order contributions

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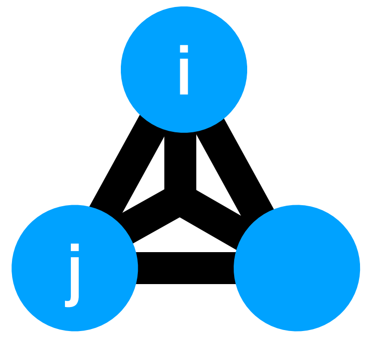
event X



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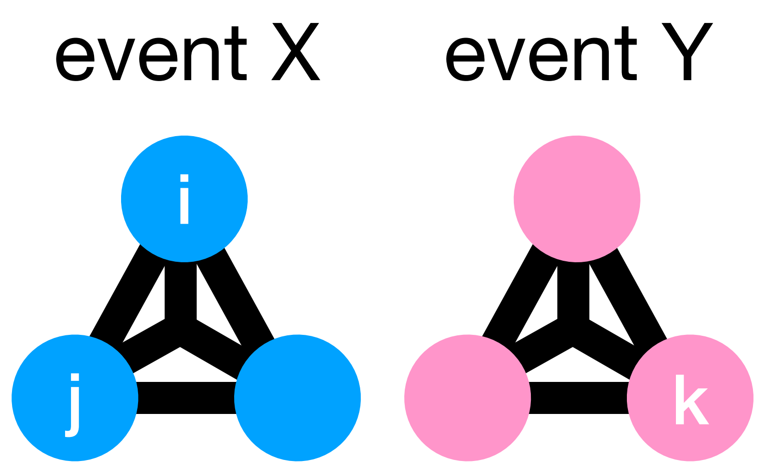

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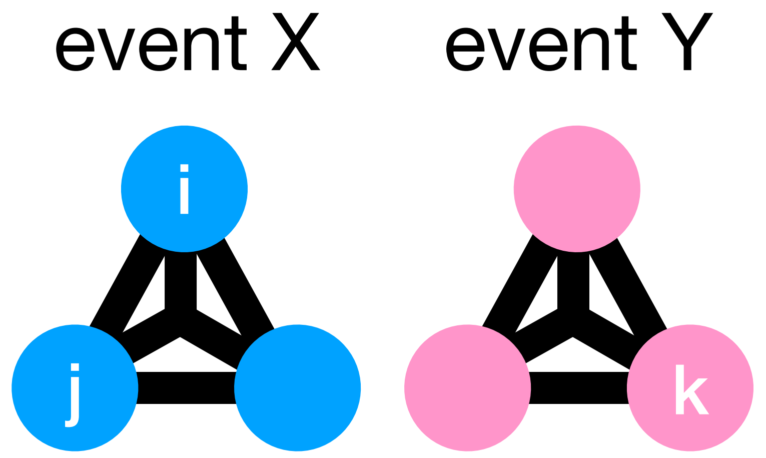

$$C_{ij}\left(\left[\mathbf{p}_i, \mathbf{p}_j\right], \mathbf{p}_k\right) = \frac{N_2\left(\mathbf{p}_i, \mathbf{p}_j\right) N_1\left(\mathbf{p}_k\right)}{N_1\left(\mathbf{p}_i\right) N_1\left(\mathbf{p}_j\right) N_1\left(\mathbf{p}_k\right)}$$

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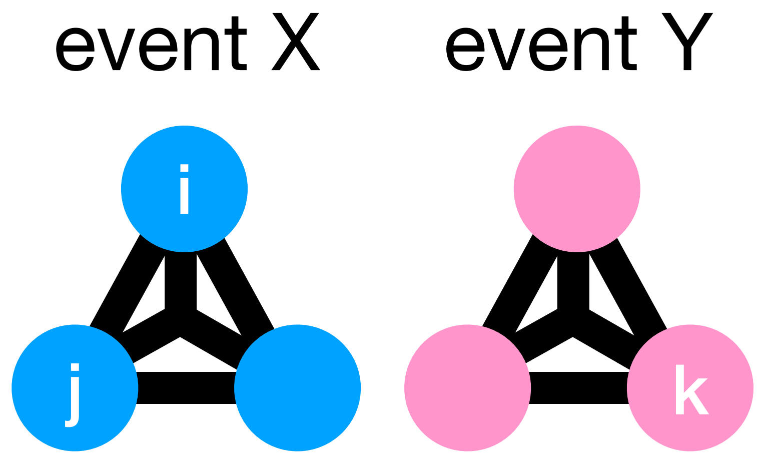

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Projector method

- Use two-particle measured or theoretical correlation function $C([\mathbf{p}_i, \mathbf{p}_j])$
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$$C_2\left(k^*_{ij}\right) \rightarrow C_{ij}\left(Q_3\right)$$

Del Grande, Šerkšnytė et al. EPJC 82 (2022) 244

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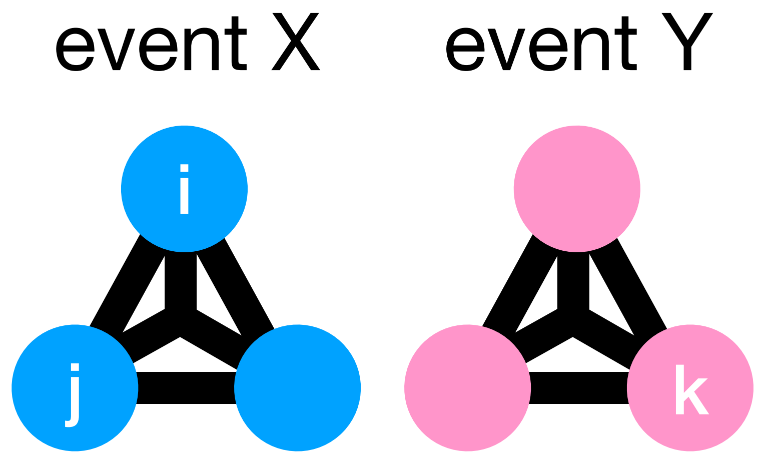

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k^*_{ij} (pair) $\rightarrow$ Q_3 (triplet)

For one Q_3 value ➡

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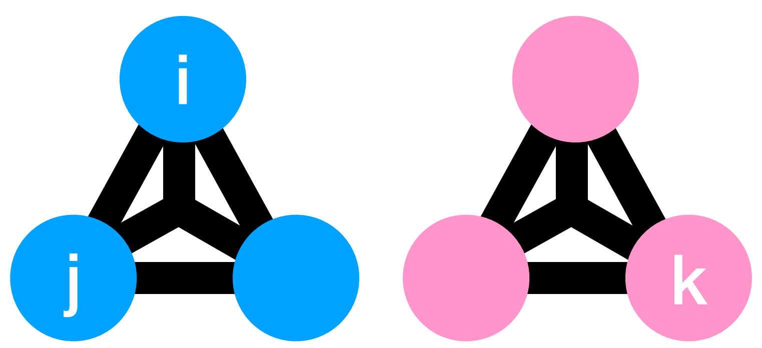

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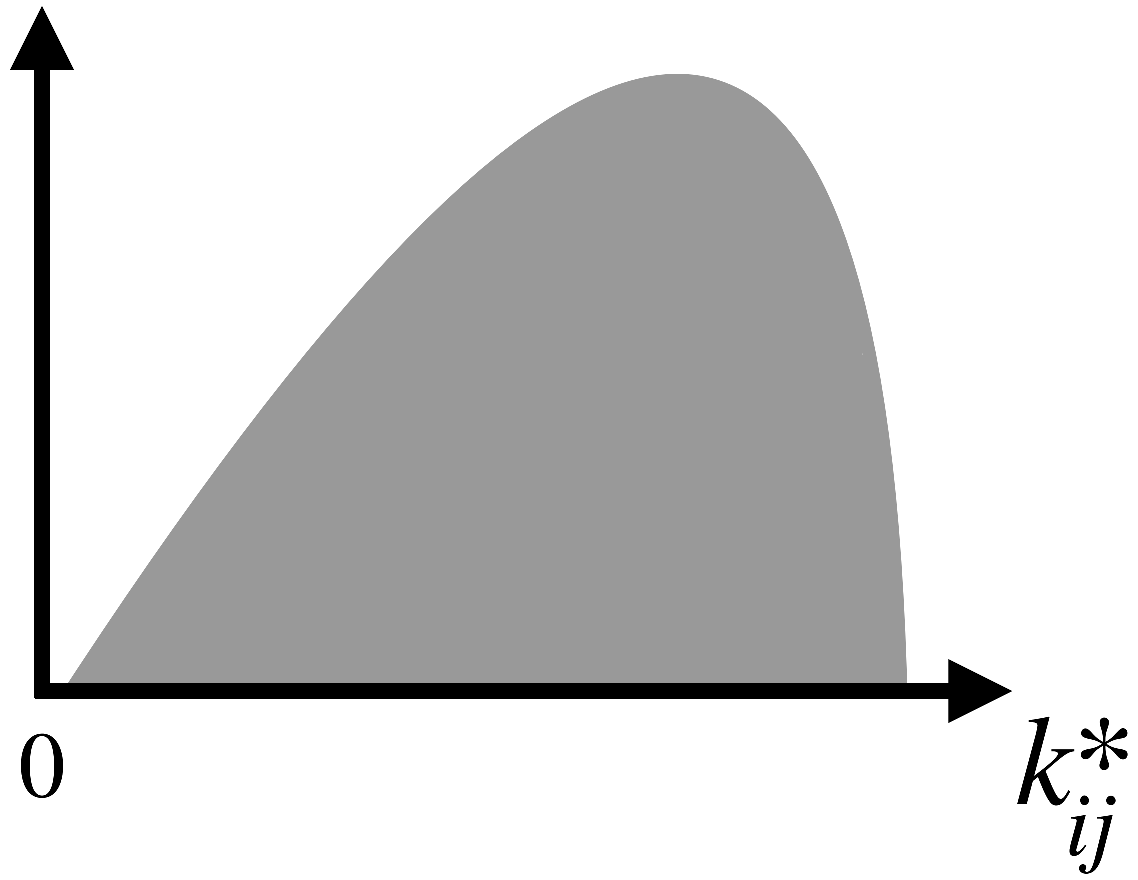

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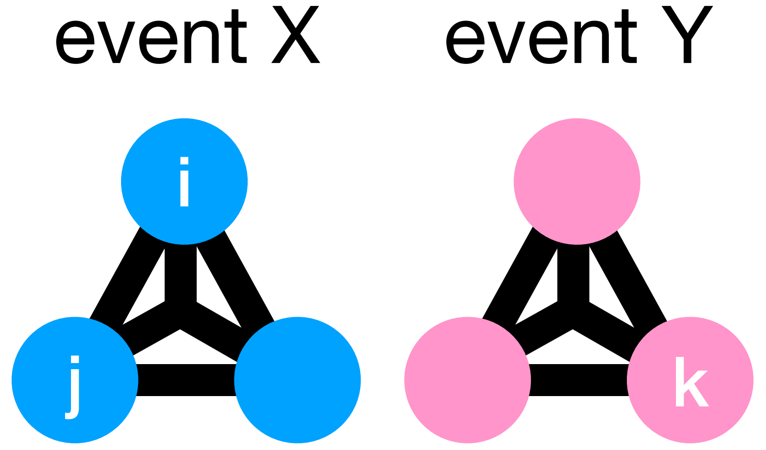

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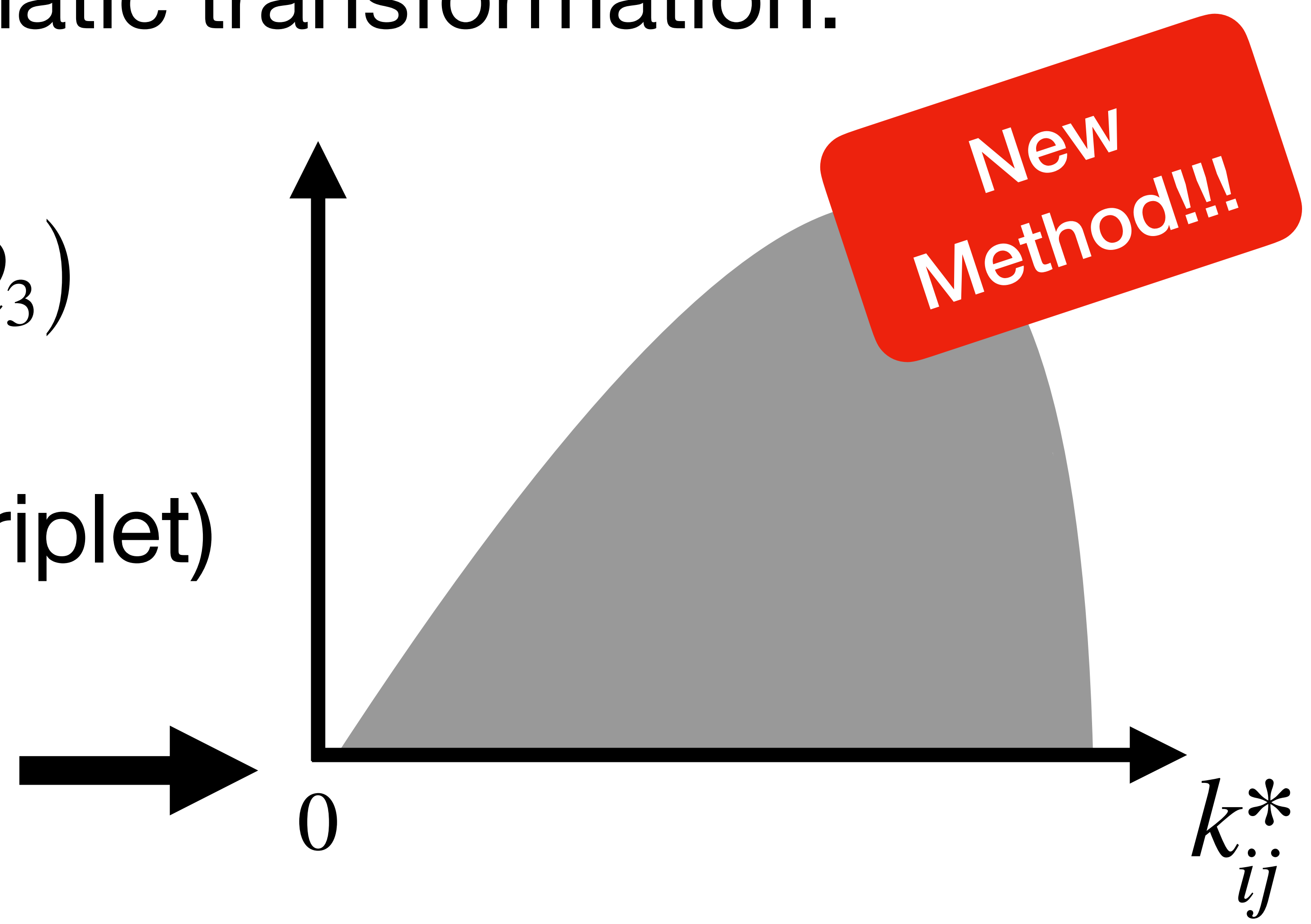

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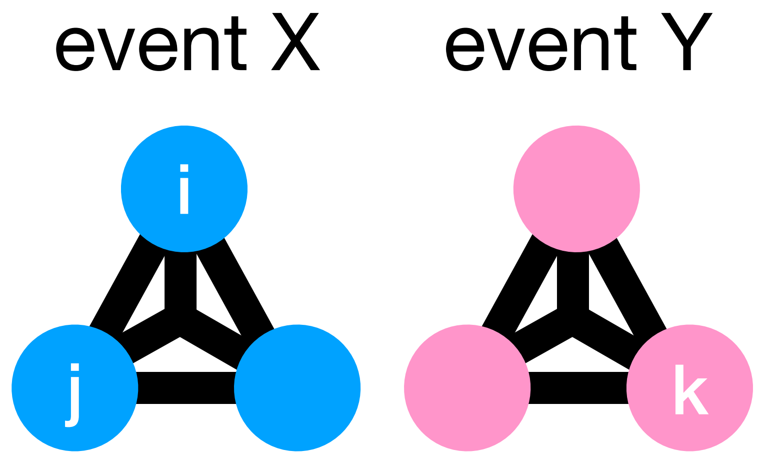

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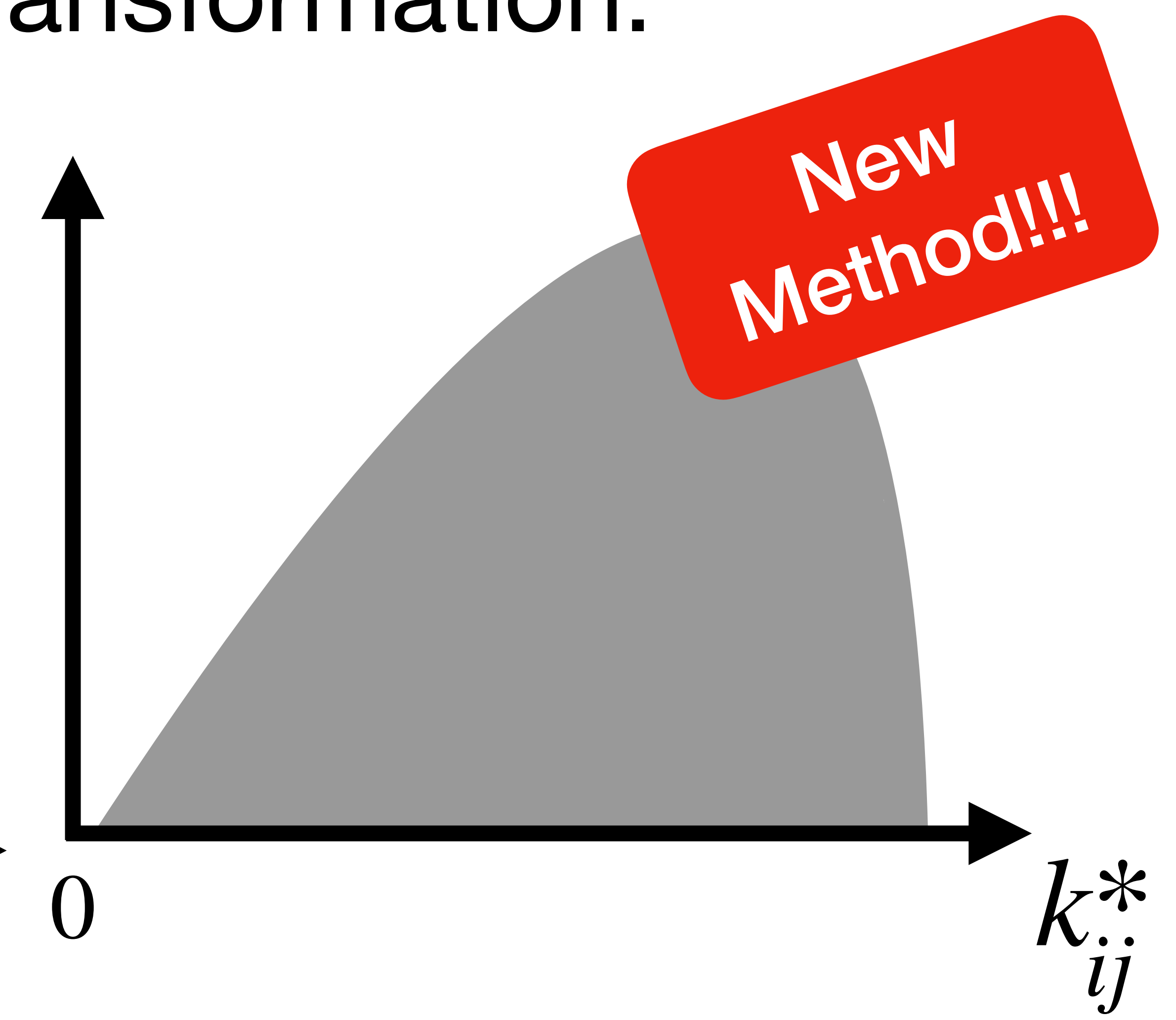

- To obtain the correlation function:

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

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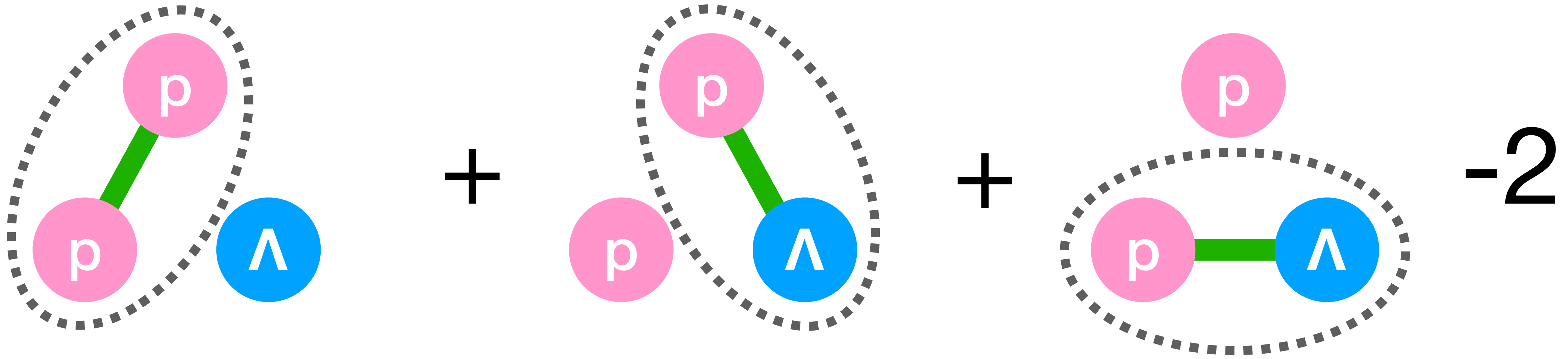
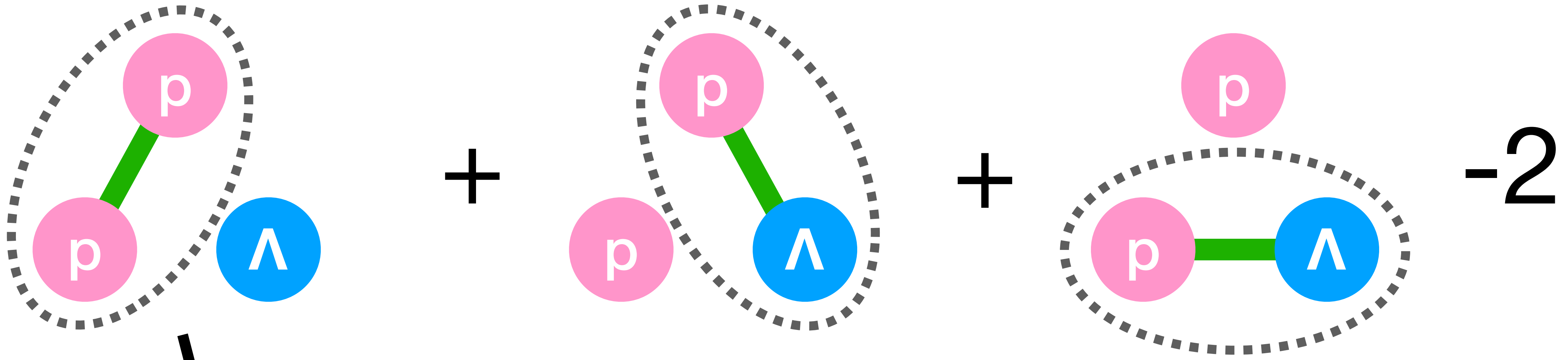
Lower order contributions : p-p-Λ



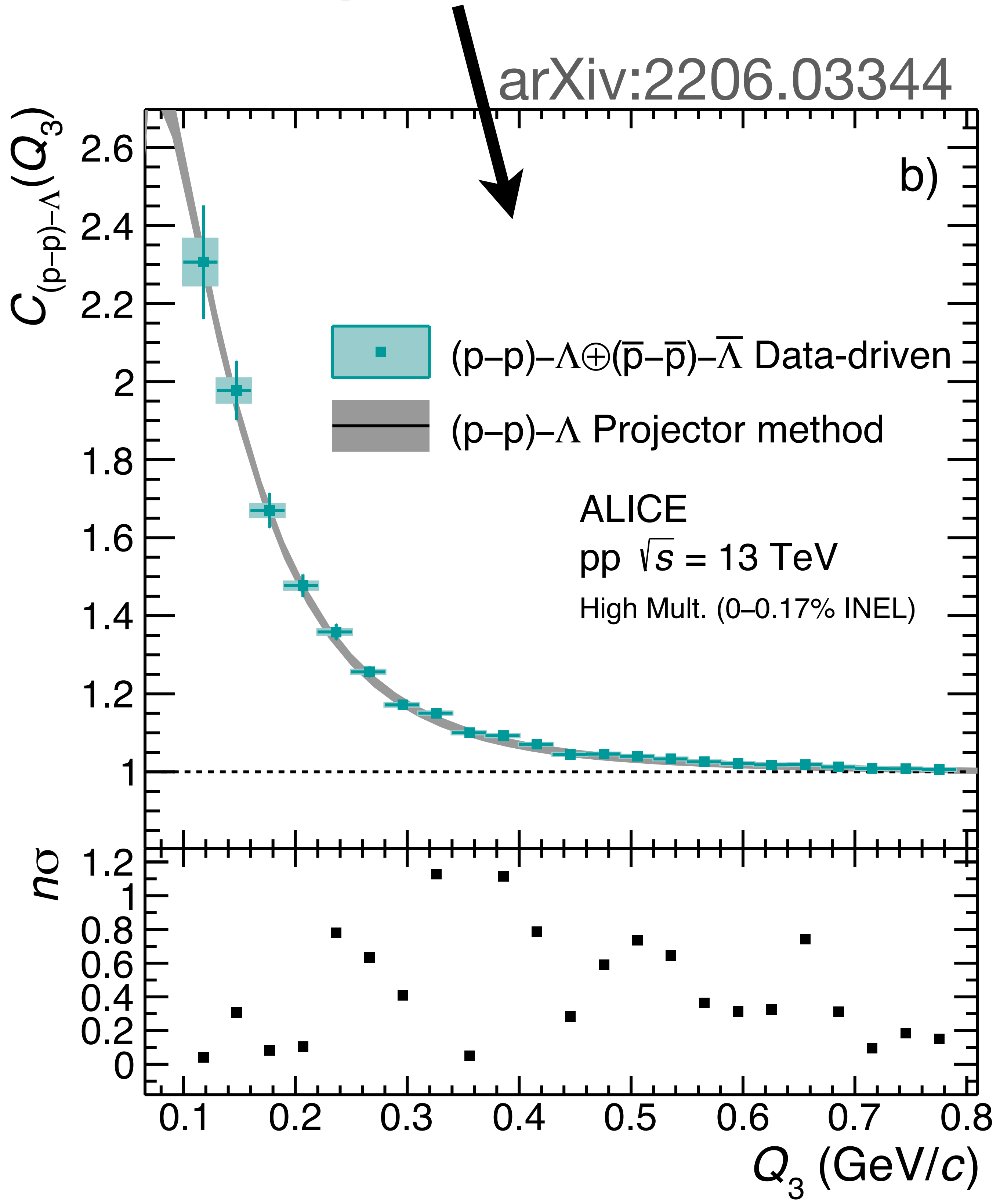
Already measured p-p [1] and p-Λ [2] correlation functions used for projection.

[1] PLB 805 (2020) 135419; [2] arXiv:2104.04427

Lower order contributions : p-p-Λ



arXiv:2206.03344



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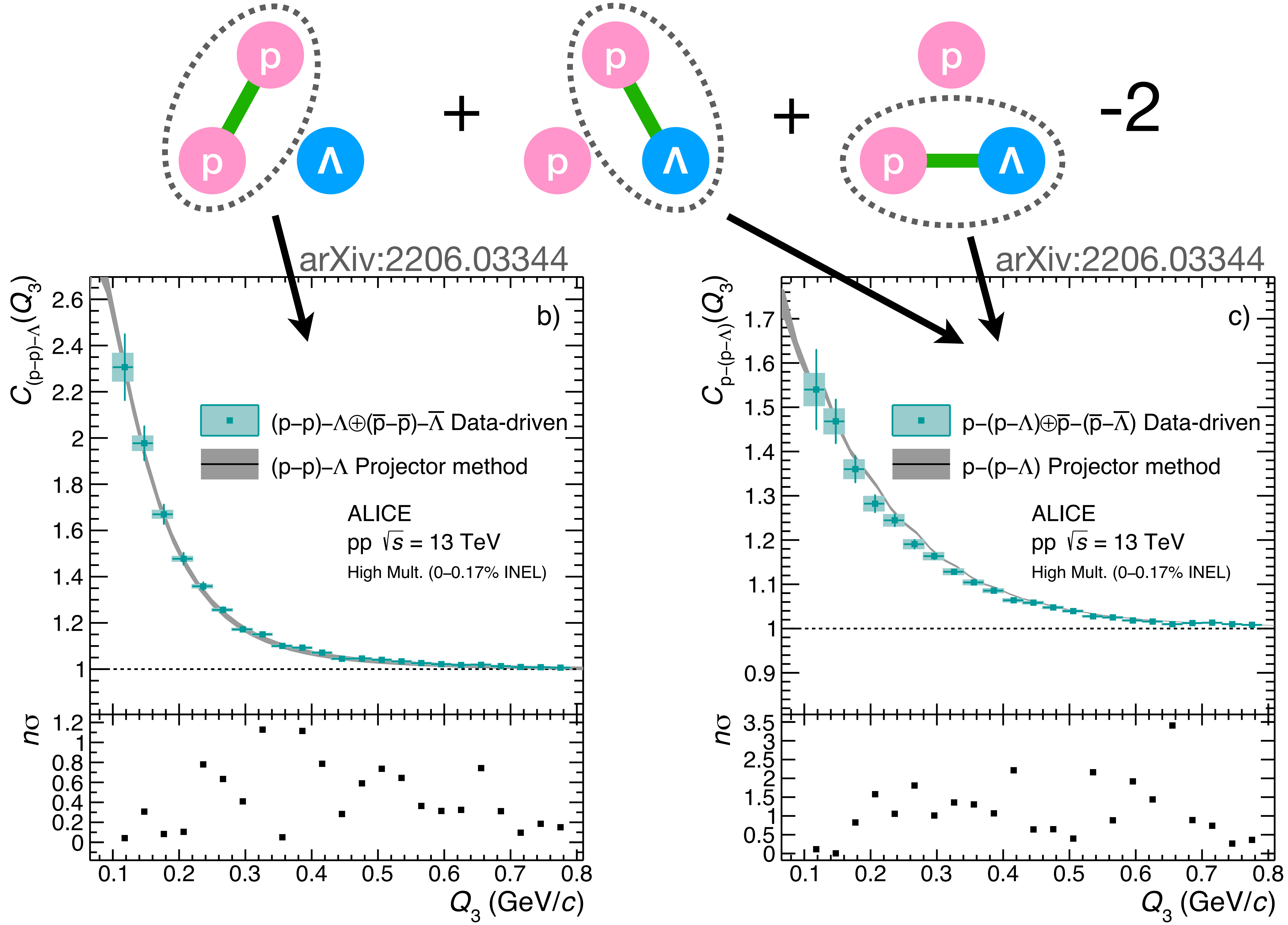

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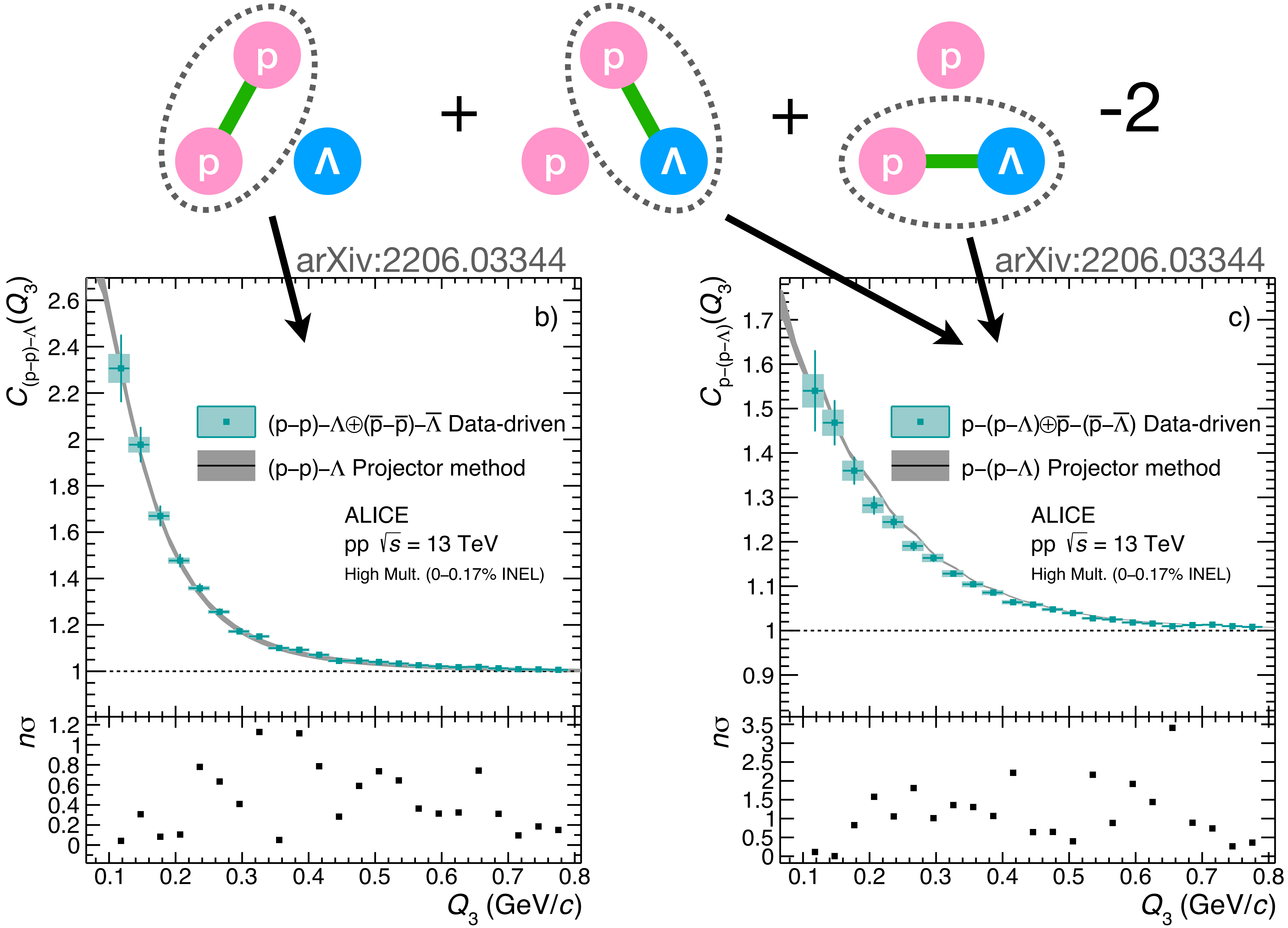
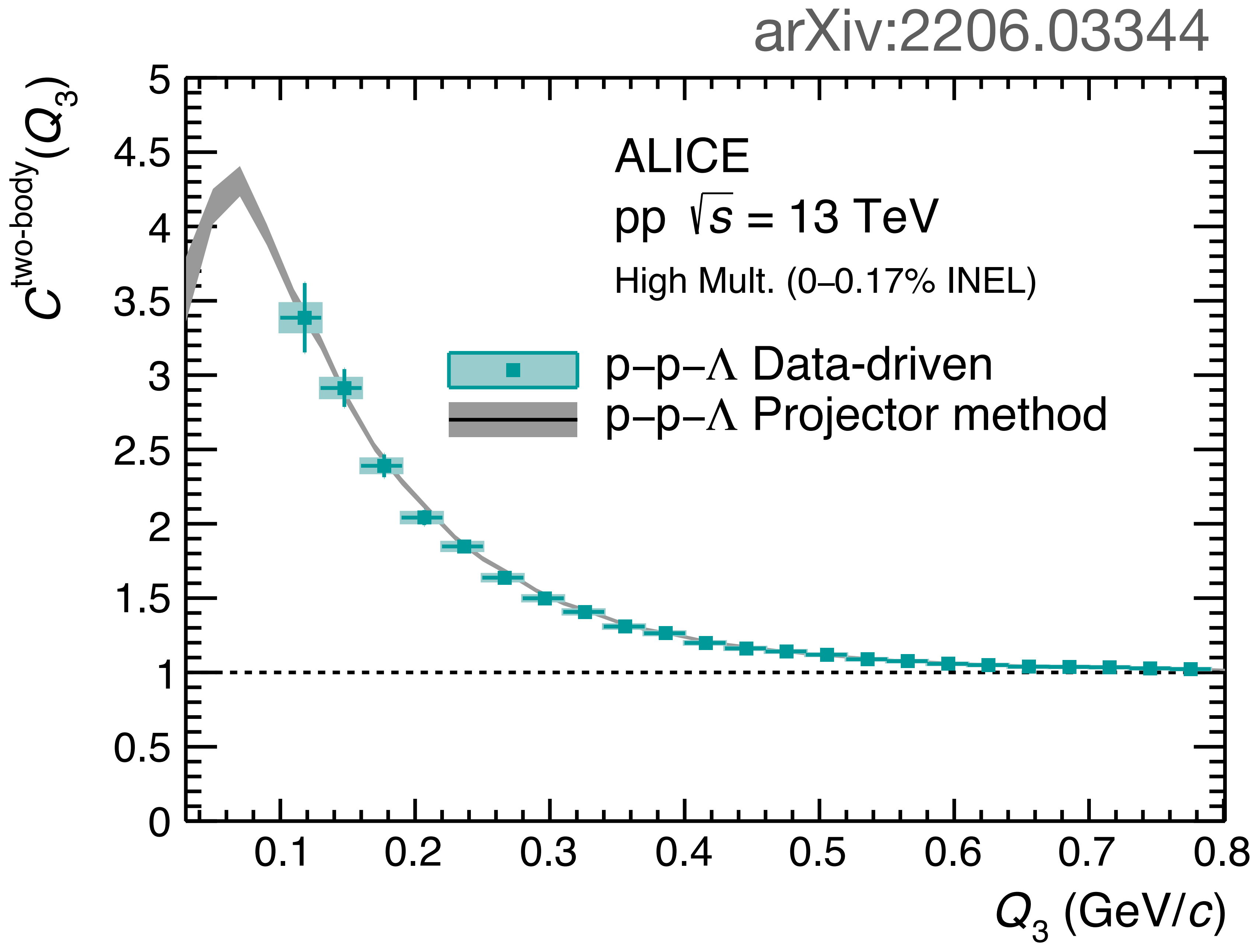


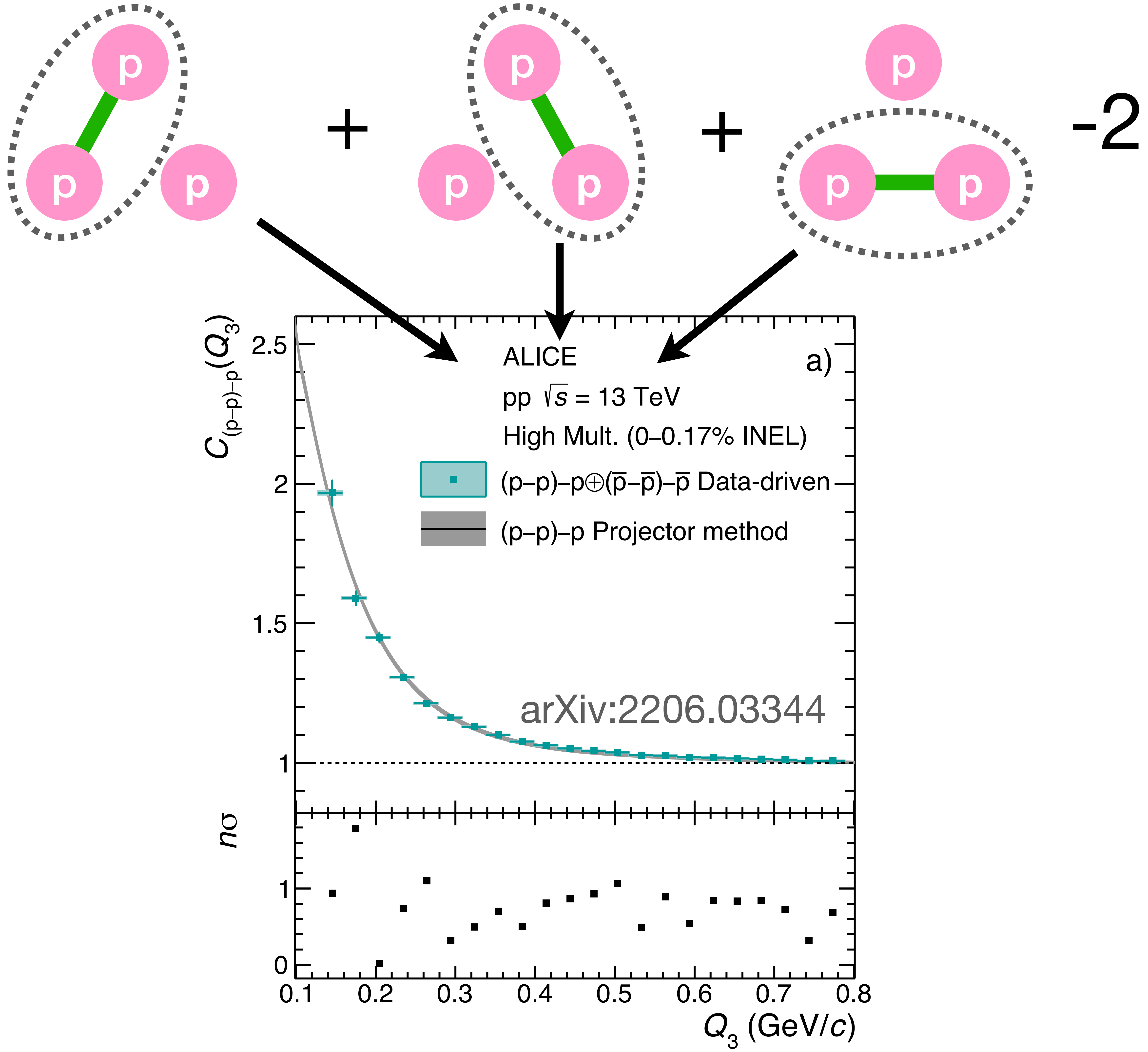
Total lower-order contributions



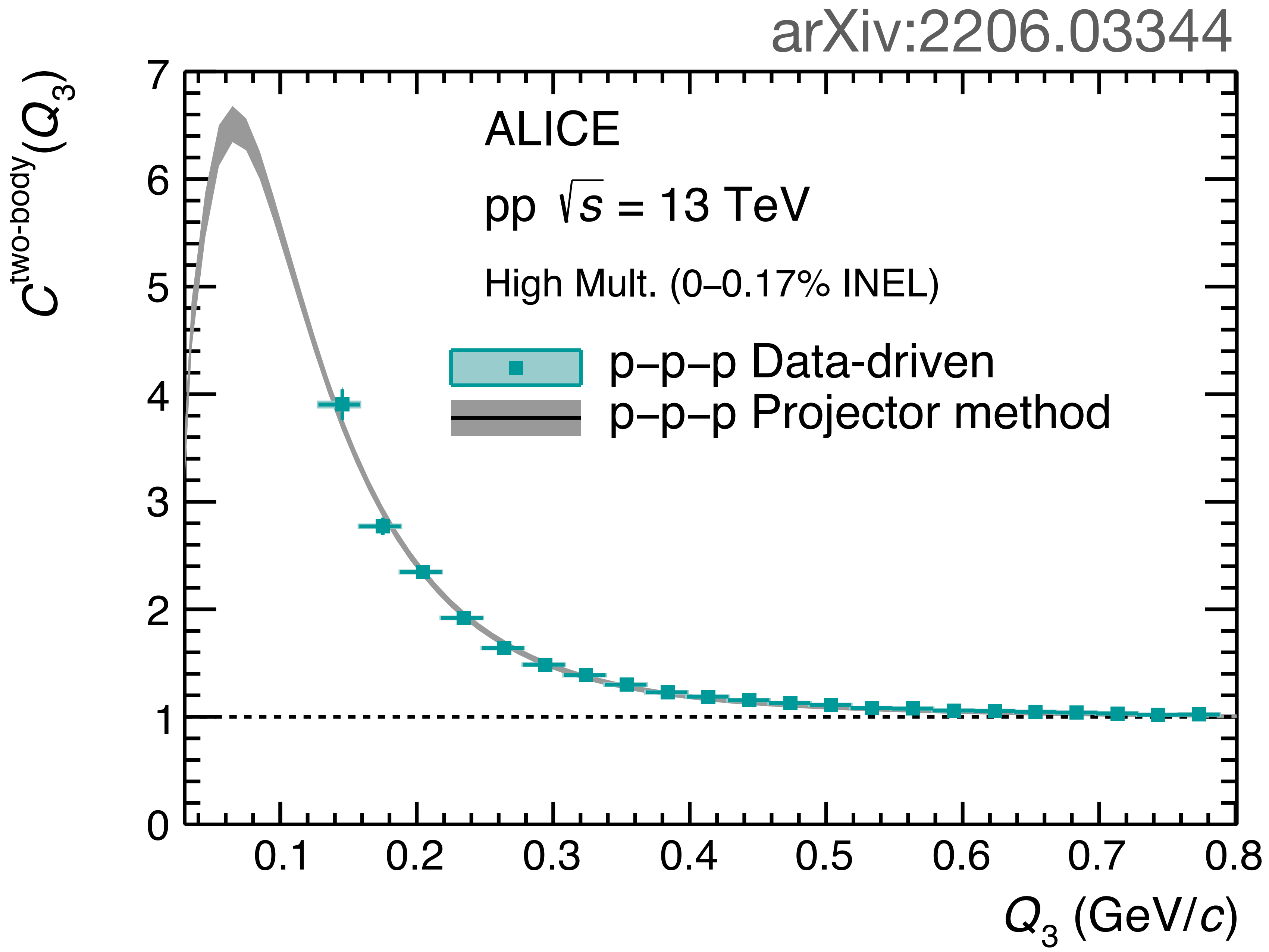
Already measured p-p [1] and p-Λ [2] correlation functions used for projection.

[1] PLB 805 (2020) 135419; [2] arXiv:2104.04427

Lower order contributions : p-p-p



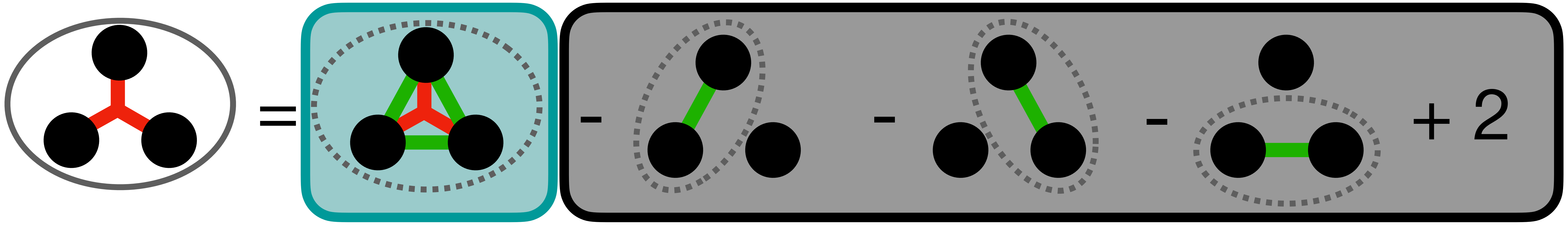
Total lower-order contributions

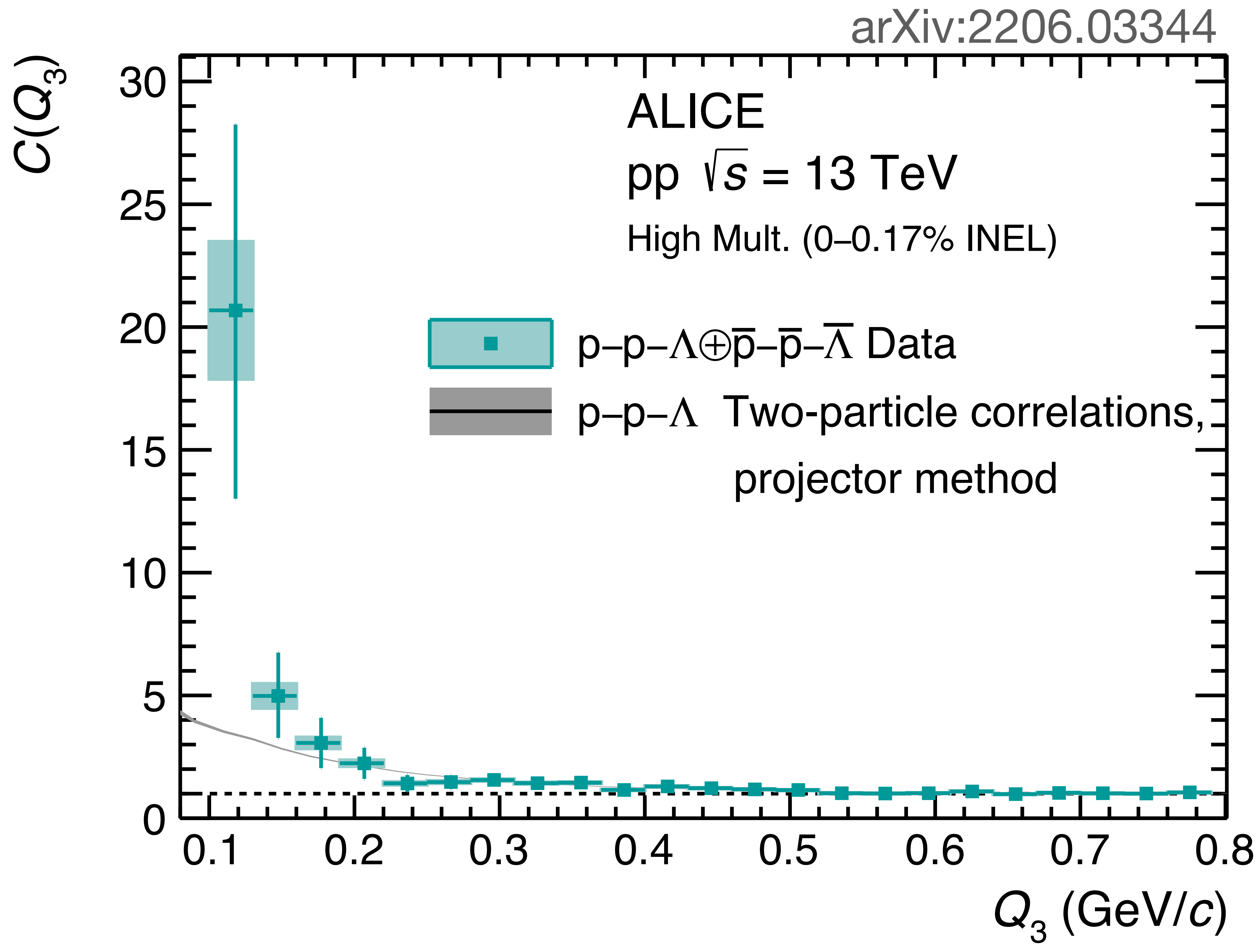


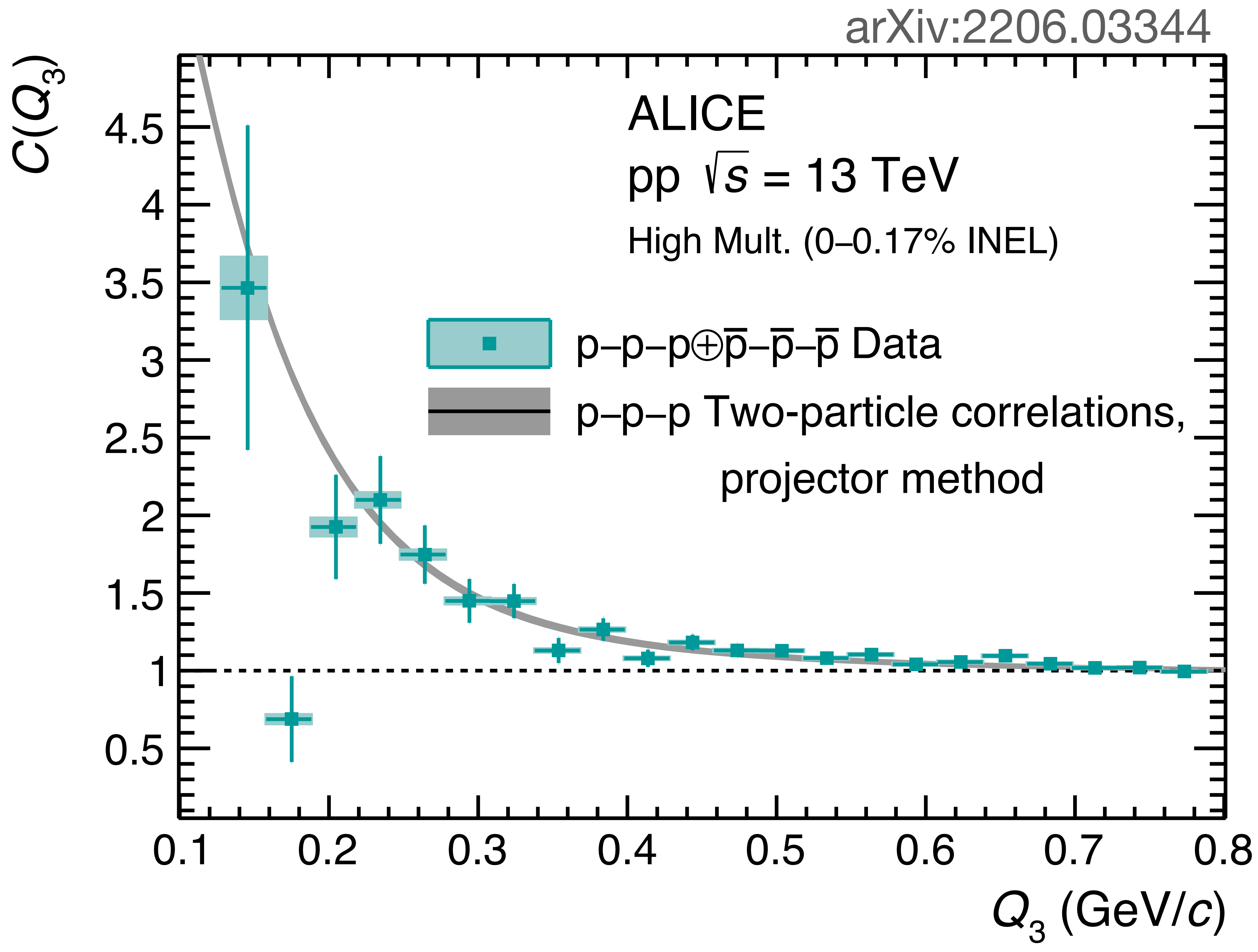
Already measured p-p [1] correlation function used for projection.

[1] PLB 805 (2020) 135419

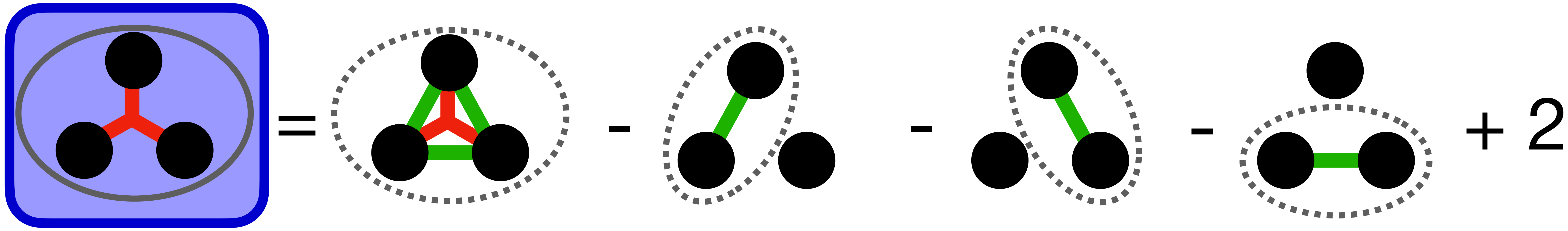
p-p-Λ and p-p-p correlation functions







p-p-Λ cumulant



Positive cumulant for p-p-Λ

- Only two identical and charged particles
  - ✓ Main expected contribution from three-body strong interaction
- Relevant measurement for equation of state of neutron stars.

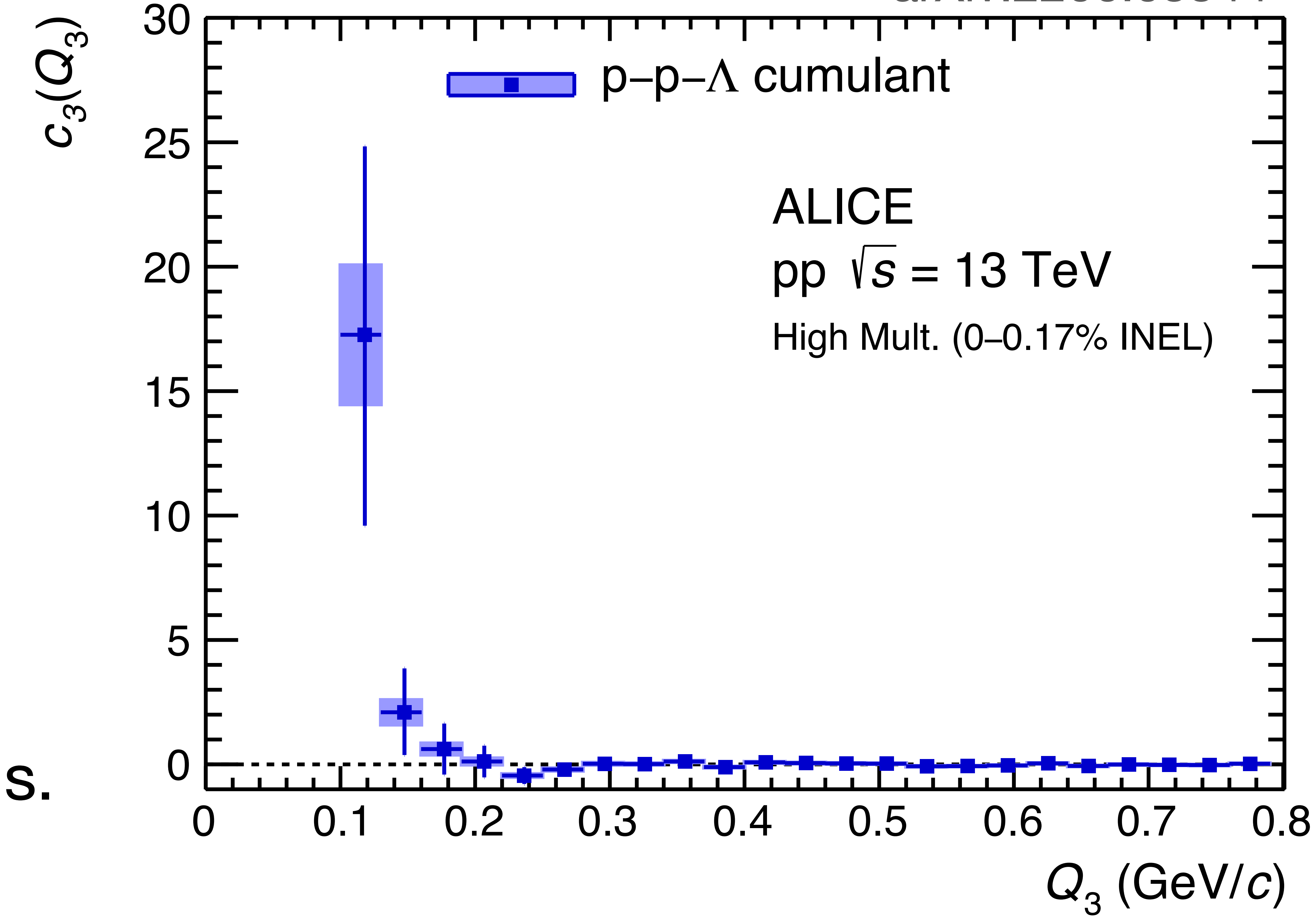
Statistical significance:

n_σ= 0.8 for Q_3 < 0.4 GeV/c

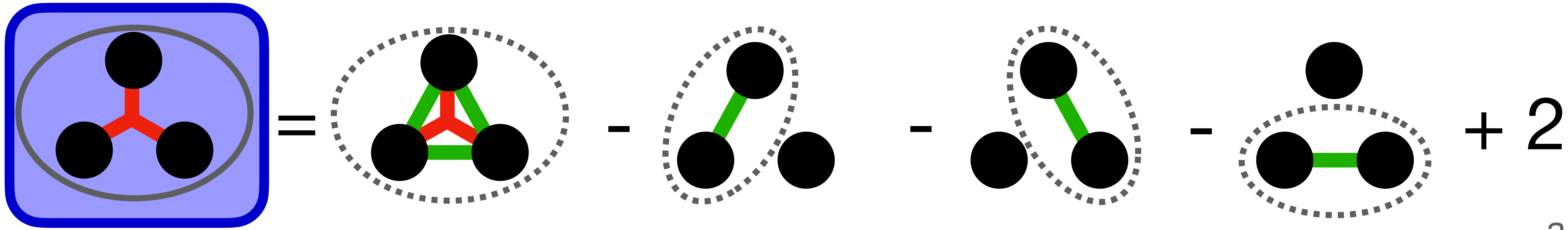
Conclusion: no significant deviation from null hypothesis.

In upcoming Run 3, two orders of magnitude gain in statistics expected!

arXiv:2206.03344



p-p-p cumulant

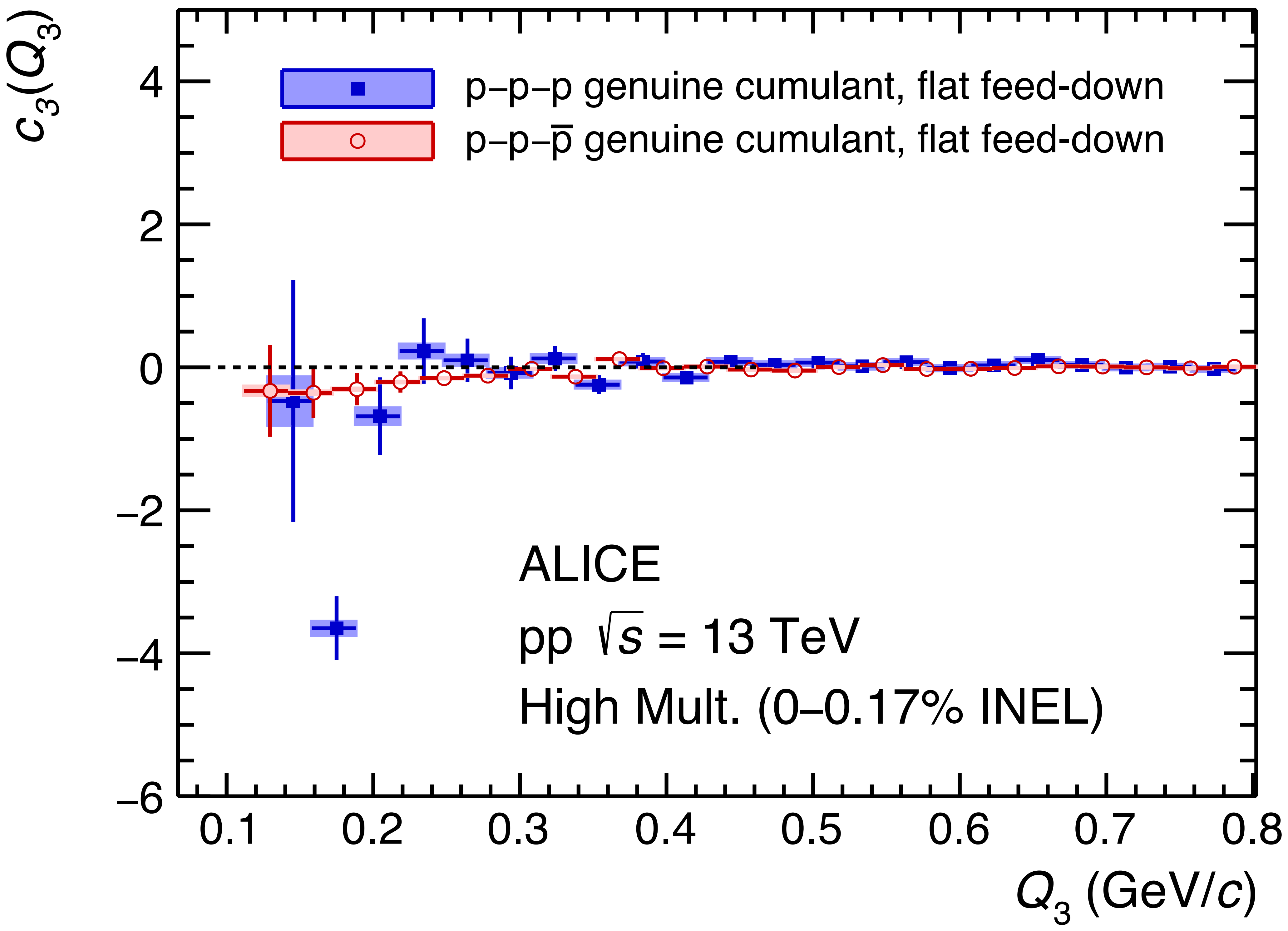


Negative cumulant for p-p-p

Possible forces at play:

- Pauli blocking at the three-particle level
- three-body strong interaction

arXiv:2206.03344



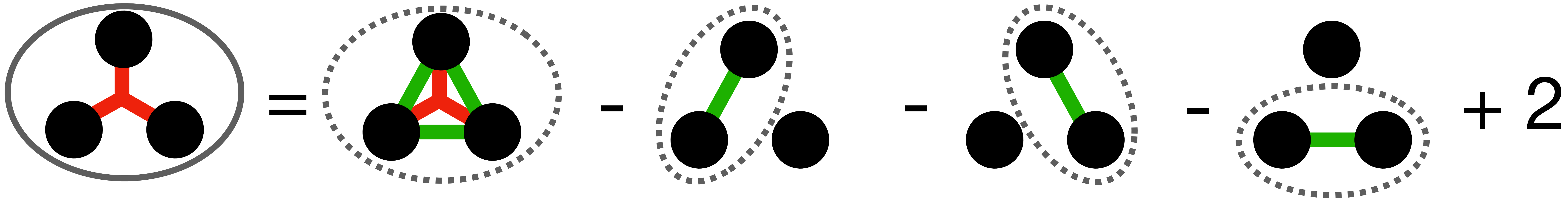
Test with mixed-charge particles, cumulant negligible.

Statistical significance:

n_σ **= 6.7 for** Q_3 **< 0.4 GeV/**c

Conclusion: significant deviation from null hypothesis; ongoing collaboration with A. Kievsky, L. Marcucci and M. Viviani (Pisa University - INFN) for the theoretical interpretation.

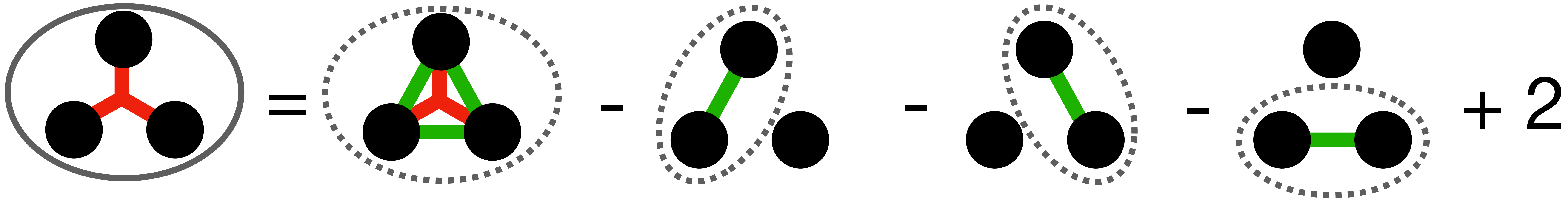
p-p-K^+ correlation function

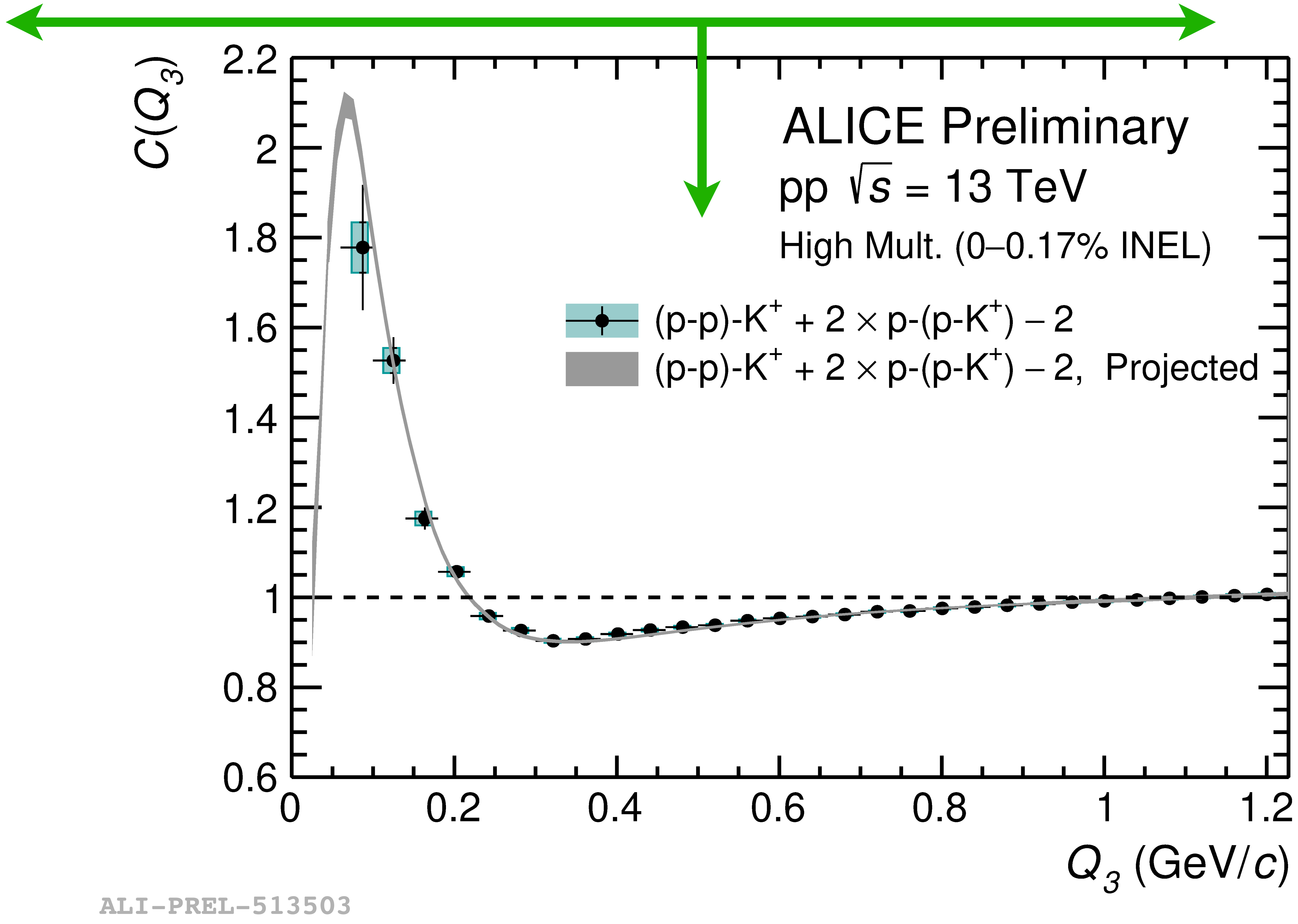


Already measured p-p [1] and newly obtained p-K^+ correlation functions used for projection.

[1] PLB 805 (2020) 135419

p-p-K+ correlation function

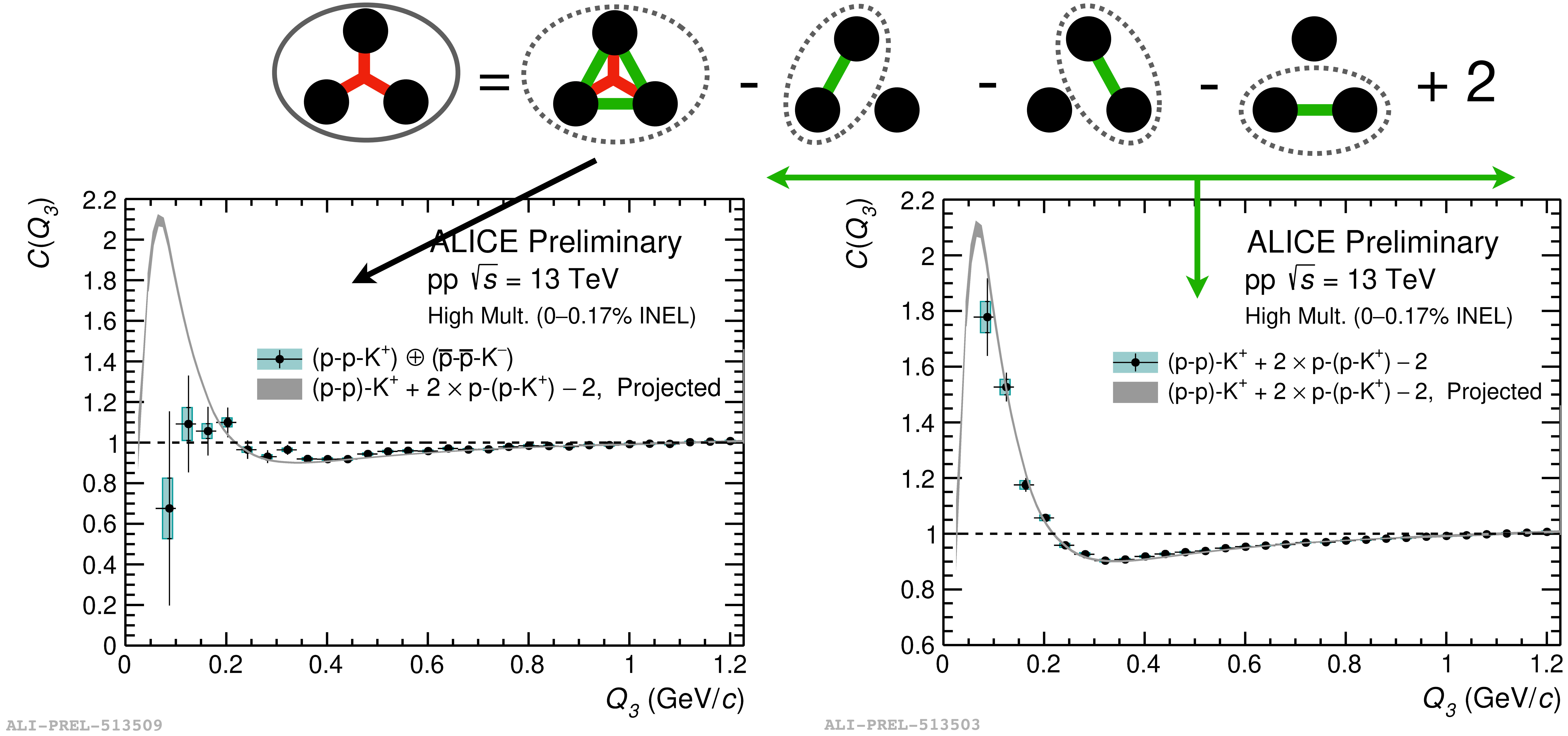




Already measured p-p [1] and newly obtained p-K+ correlation functions used for projection.

[1] PLB 805 (2020) 135419

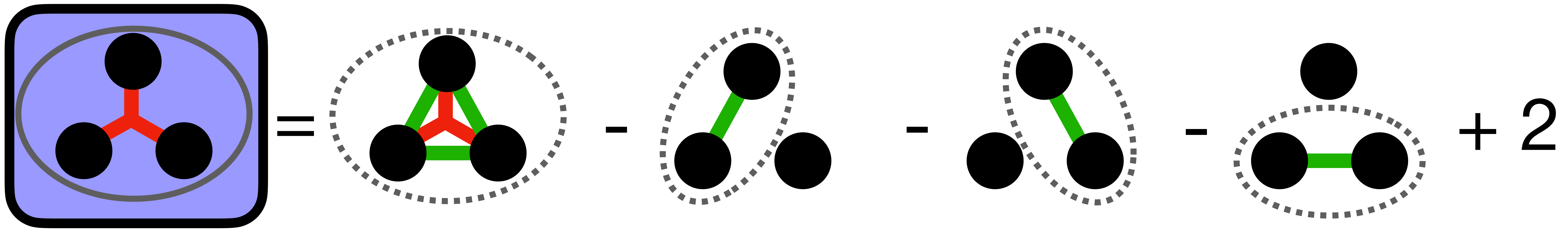
p-p-K+ correlation function



Already measured p-p [1] and newly obtained p-K+ correlation functions used for projection.

[1] PLB 805 (2020) 135419

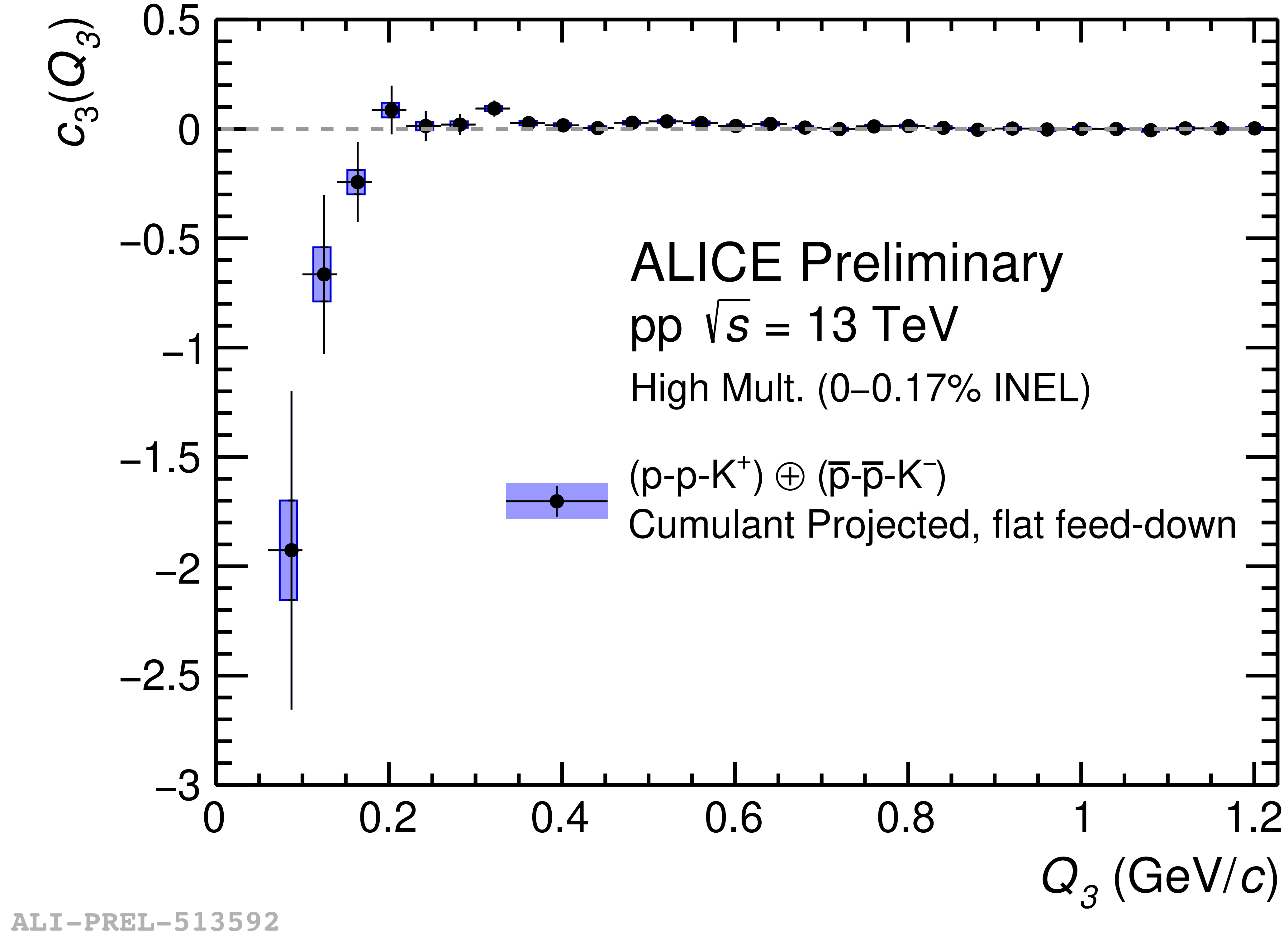
p-p-K+ cumulant



Negative cumulant for p-p-K+

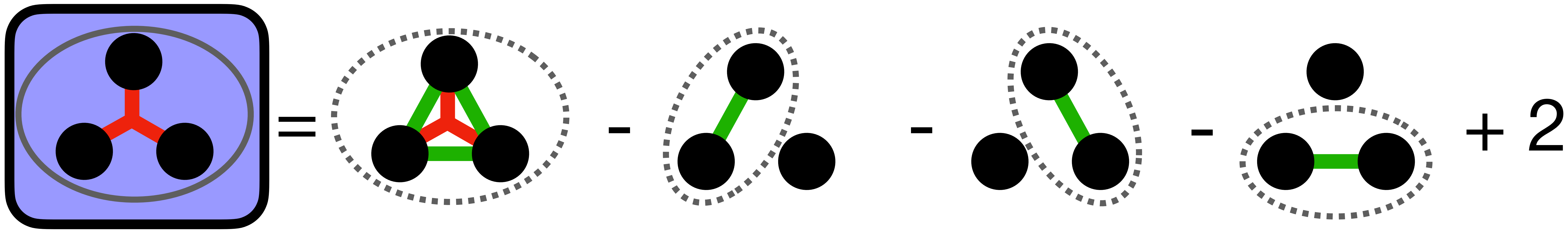
Statistical significance:

n_σ**= 2.3 for** Q_3 **< 0.4 GeV/**c



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

p-p-K$^-$ cumulant



Zero cumulant for p-p-K$^-$

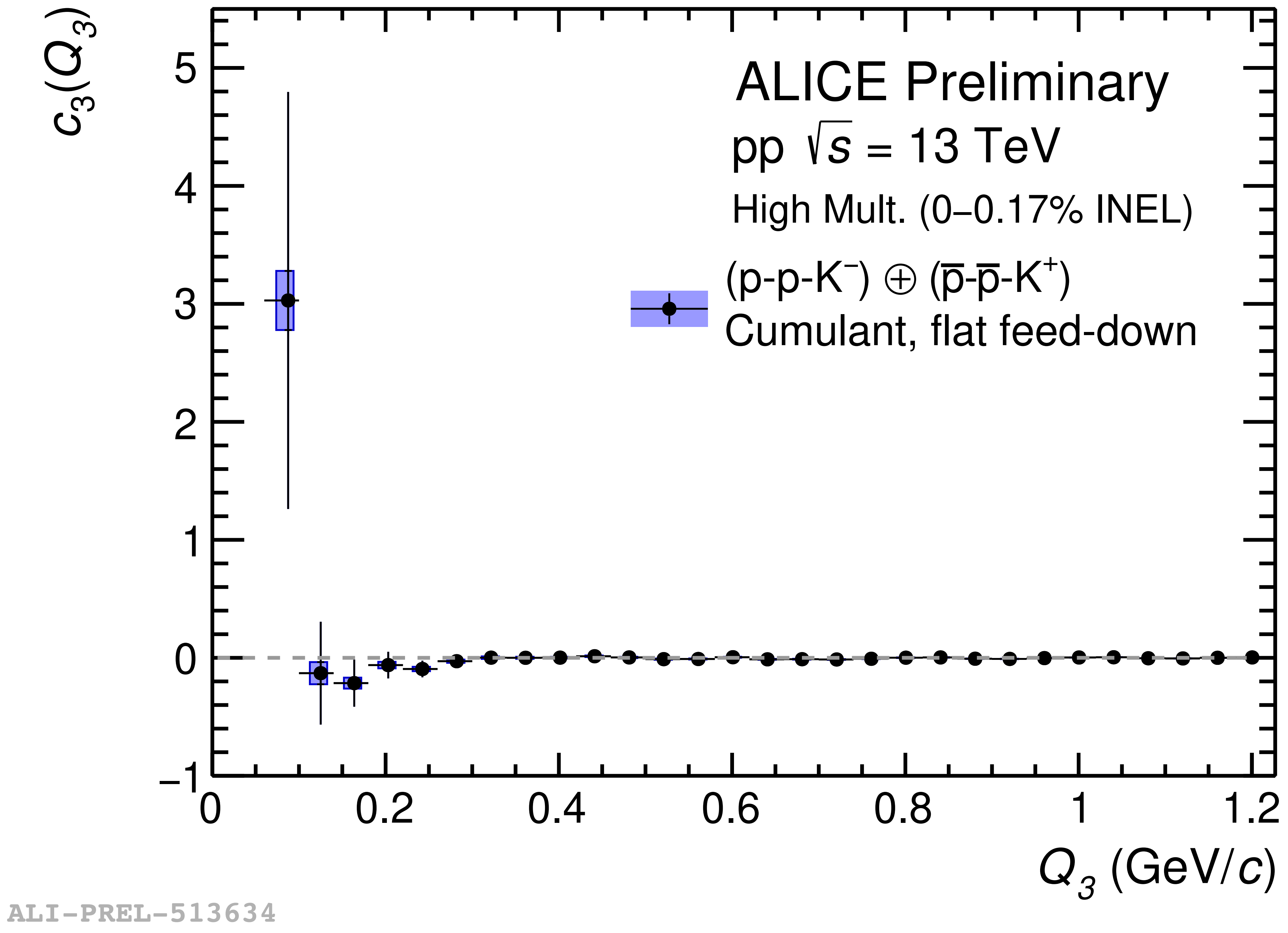
Statistical significance:

n_σ= 0.5 for Q_3 < 0.4 GeV/c

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

p-p-K$^-$ system shows only two-body interactions.

✓ The measurement confirms that three-body strong interaction should not be relevant in the formation of exotic kaonic bound states!

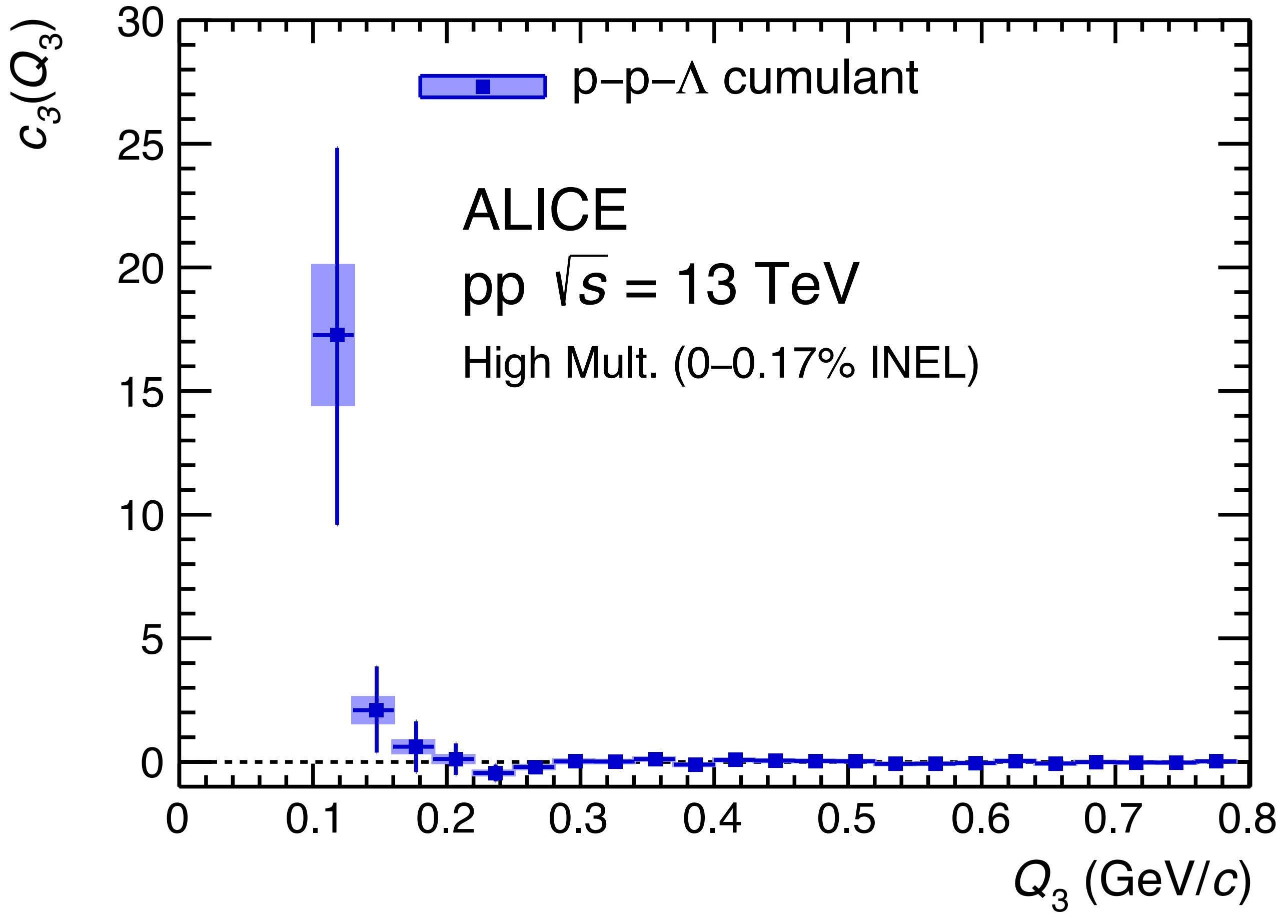


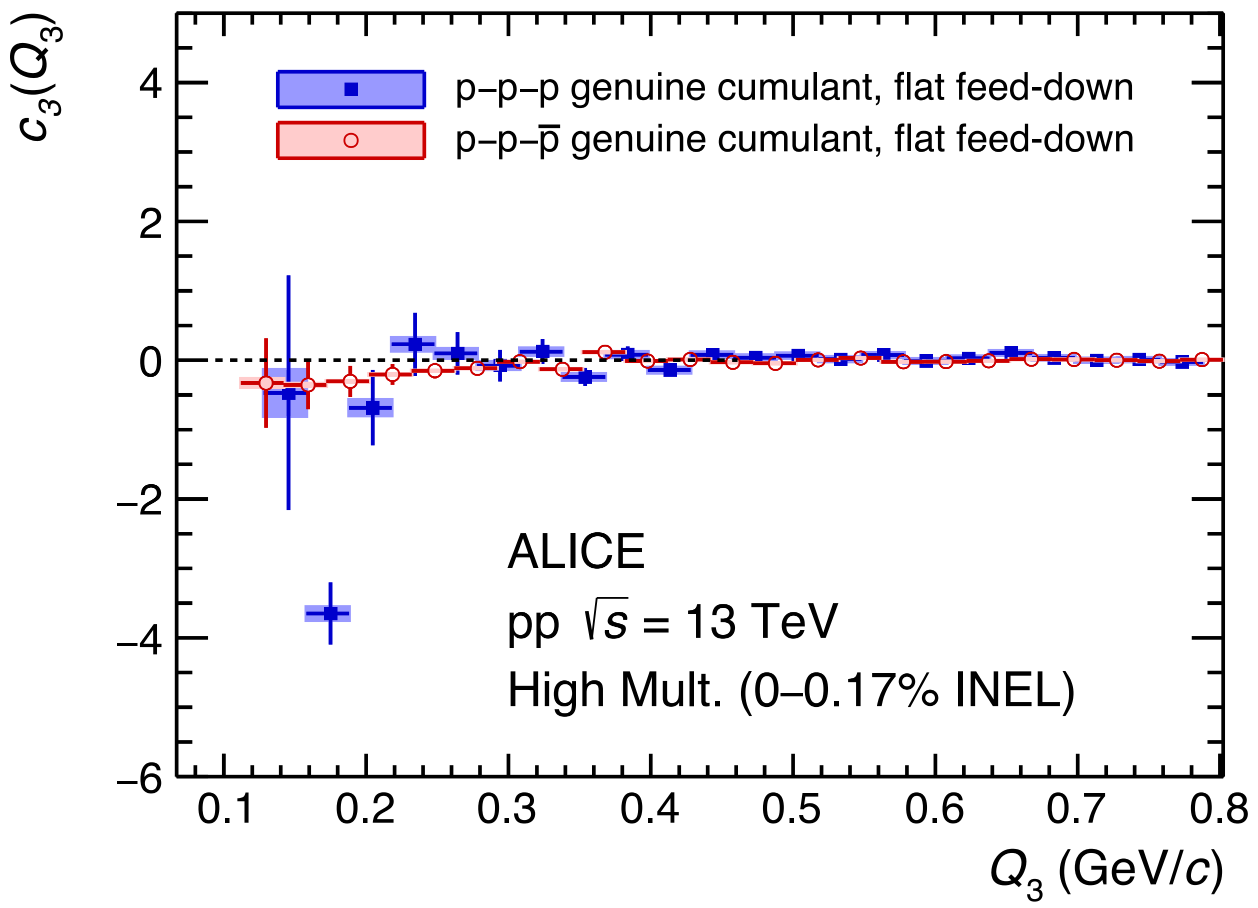
Conclusion

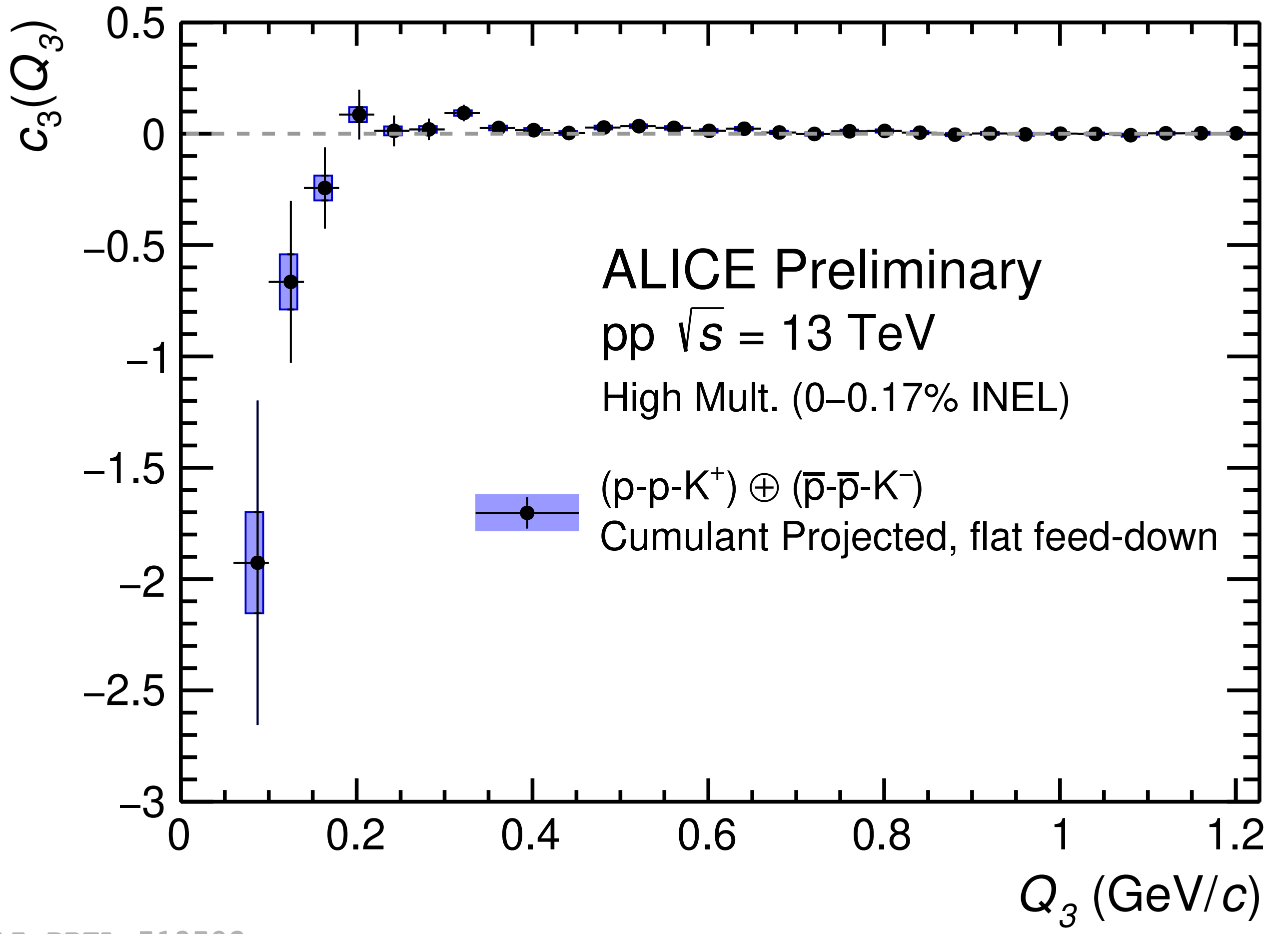
First measurements tackling the problem of genuine three-body interactions using femtoscopy!

- p-p-Λ: no significant deviation from 0 in Run 2 data
- p-p-p: negative cumulant with a significance of 6.7σ
- p-p-K^+ and p-p-K^-: cumulants compatible with 0, no evidence of a genuine three-body force

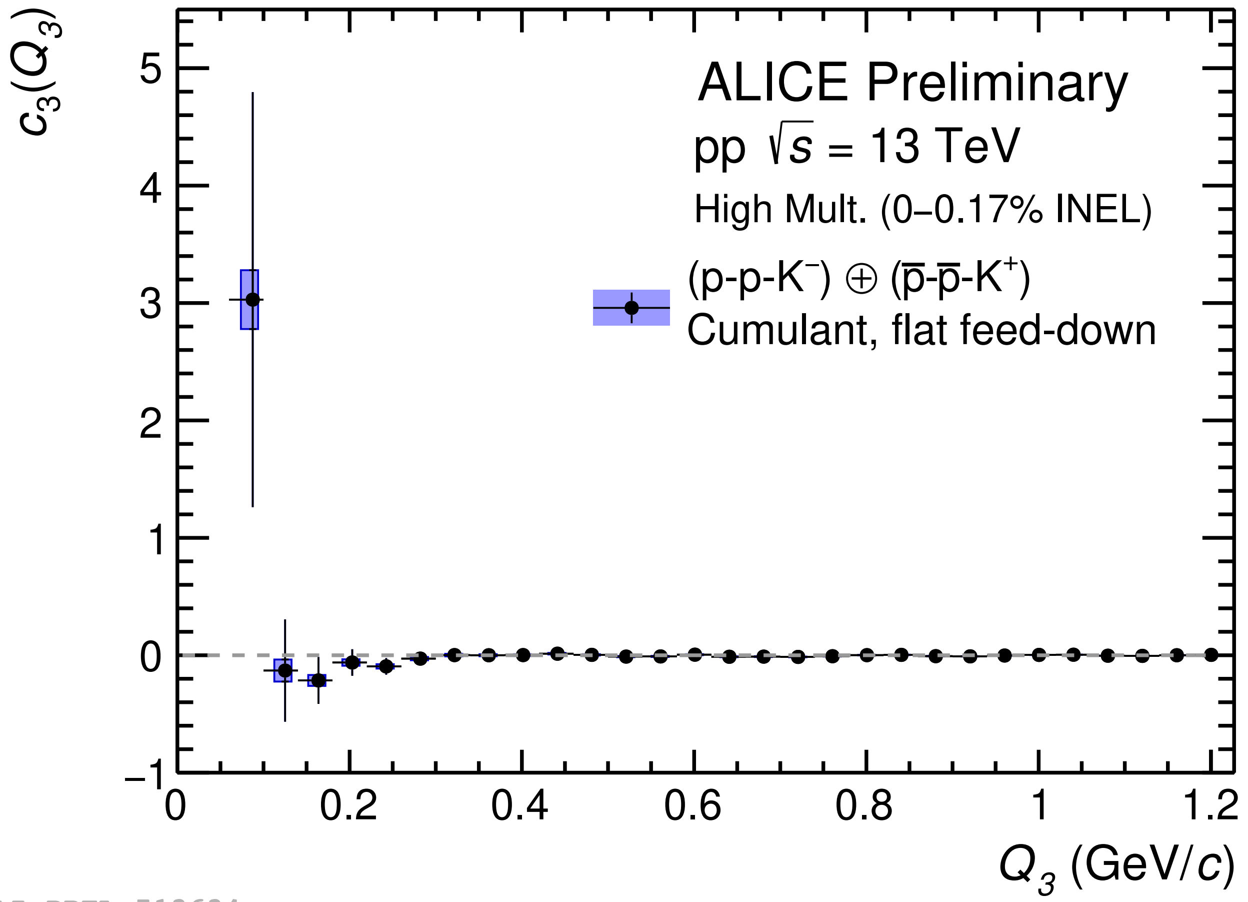
Run 3 will provide us with data to study the genuine three-body interactions!







ALI-PREL-513592



ALI-PREL-513634

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European Commission | Horizon 2020 European Union funding for Research & Innovation

HIM HELMHOLTZ Helmholtz-Institut Mainz

ALICE detector

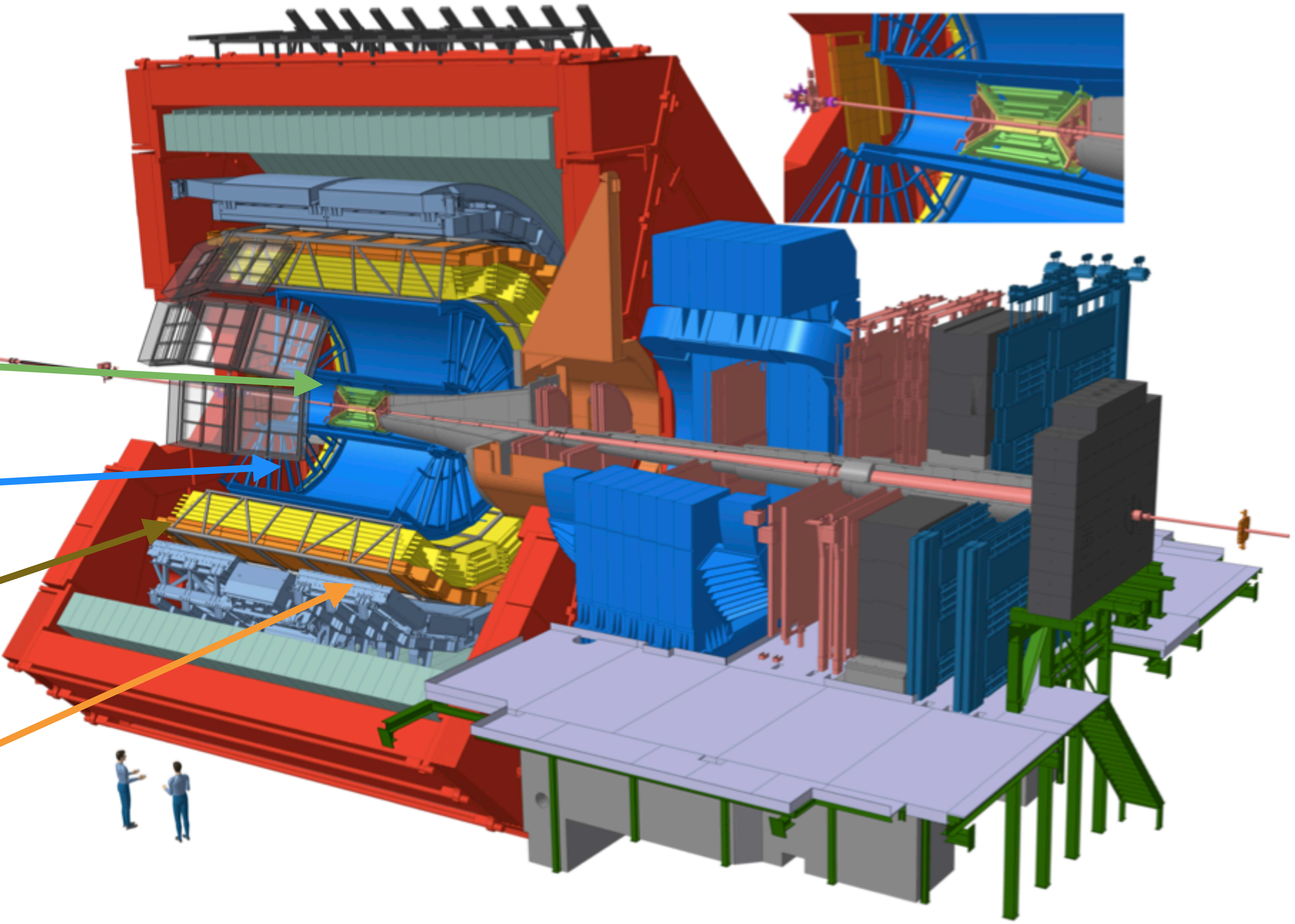
- Excellent tracking and particle identification (PID) capabilities
- Most suitable detector at the LHC to study (anti-)nuclei production and annihilation

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

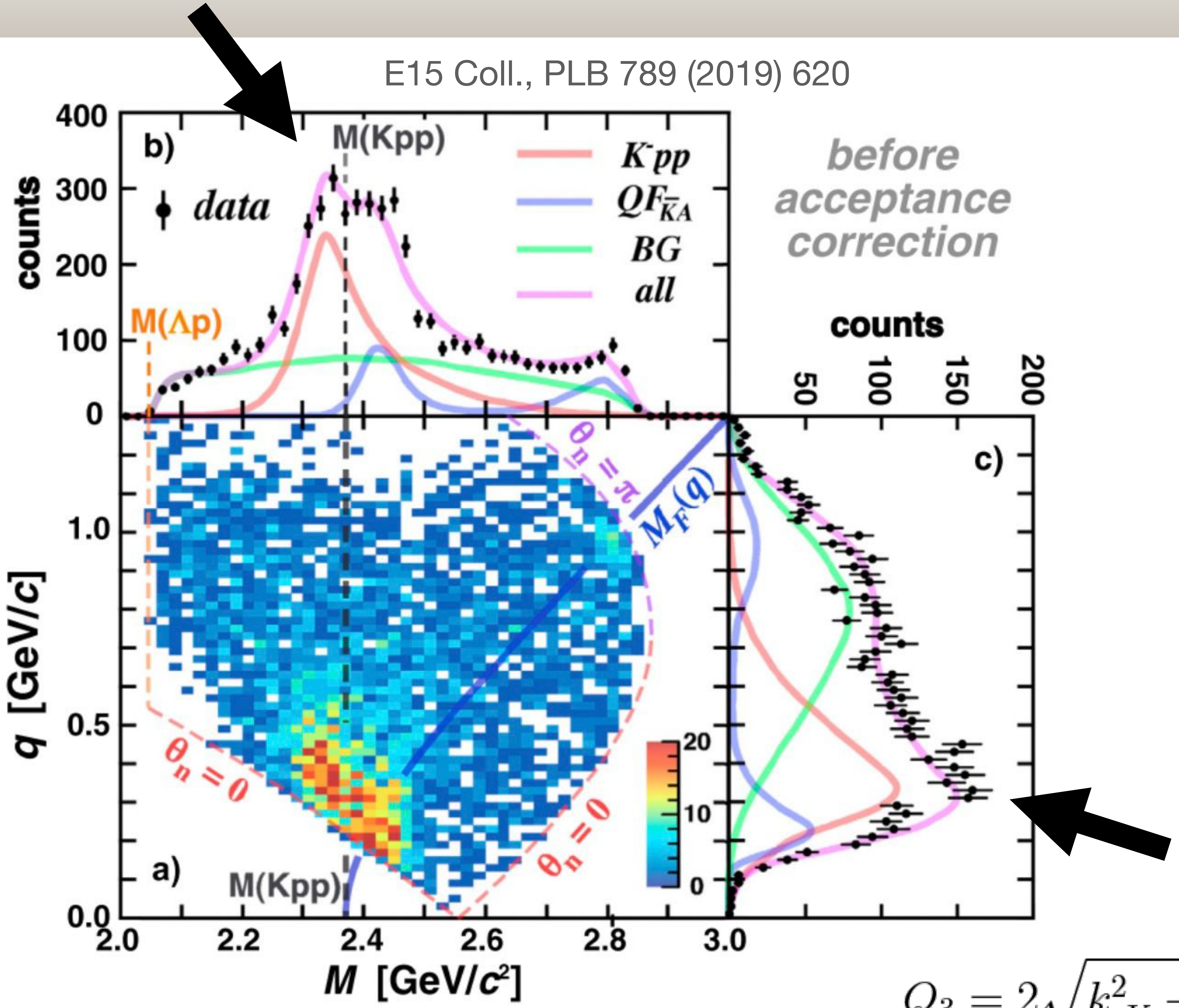
$$C(Q_3) = \iiint_{Q_3=\text{constant}} C([\mathbf{p}_i, \mathbf{p}_j], \mathbf{p}_k)\ d^3\mathbf{p}_i\ d^3\mathbf{p}_j\ d^3\mathbf{p}_k \quad = \int \quad C_2(k^*_{ij})\ W_{ij}(k^*_{ij}, Q_3)\ dk^*_{ij}$$

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

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

Kaonic bound state measured by E15

E15 Coll., PLB 789 (2019) 620



The E15 collaboration measured the bound state via the following decay:

$$K^-pp \rightarrow \Lambda p$$

The Λp momentum distribution has a peak at

$$q = p_\Lambda + p_p \approx 0.35 \text{ GeV}/c$$

Using the momentum conservation:

$$p_{K^-} + p_p + p_p \approx 0.35 \text{ GeV}/c$$

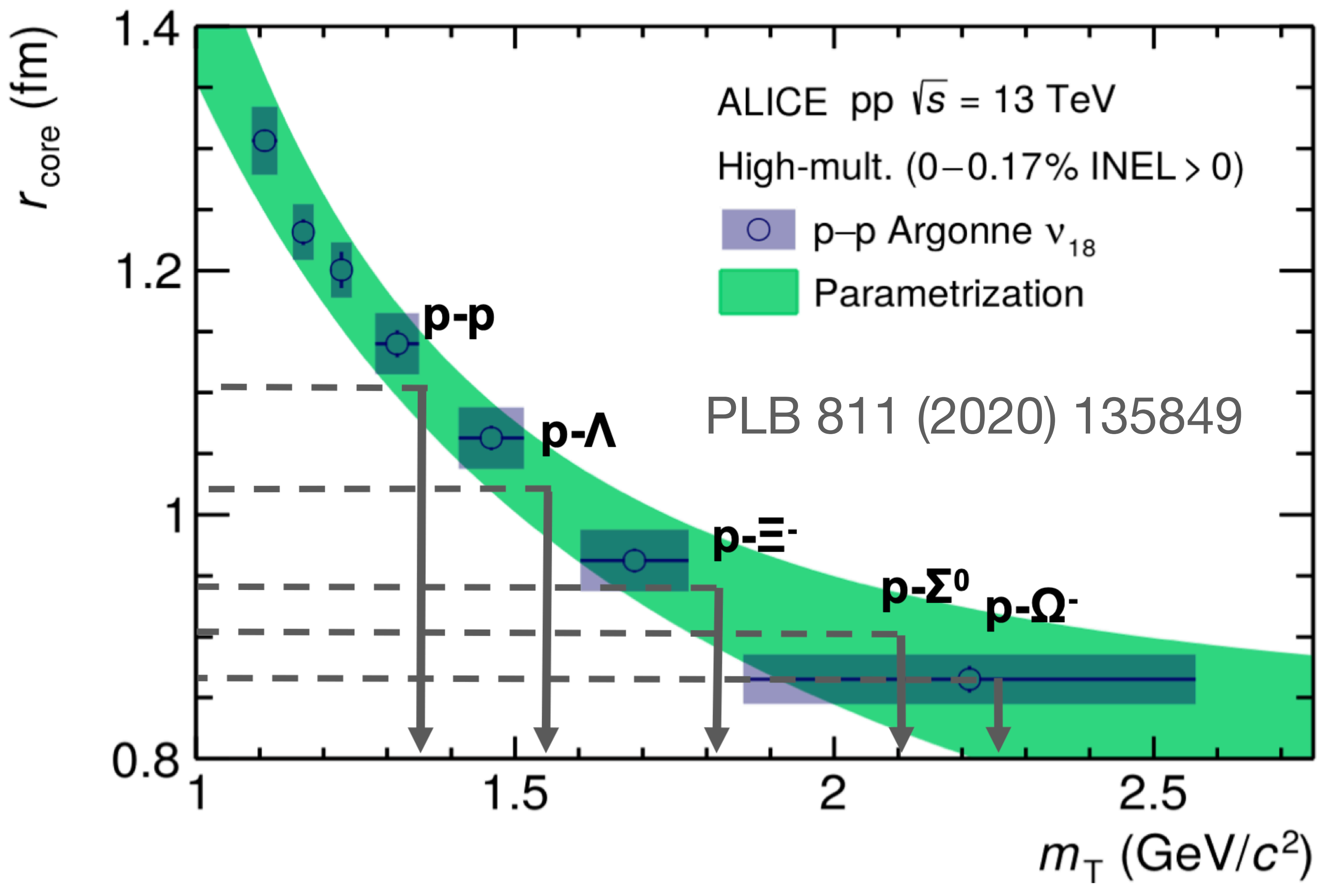
The protons are at-rest → $p_K \approx 0.35$ GeV/c

In terms of Q3 we have

$$Q_3 = 2\sqrt{k_{\rm pK}^2 + k_{\rm pK}^2 + k_{\rm pp}^2} = 2\sqrt{2}\, k_{\rm pK} = 4/3\sqrt{2}\, p_K < 0.5\,\text{GeV}/c$$

Emission source

- 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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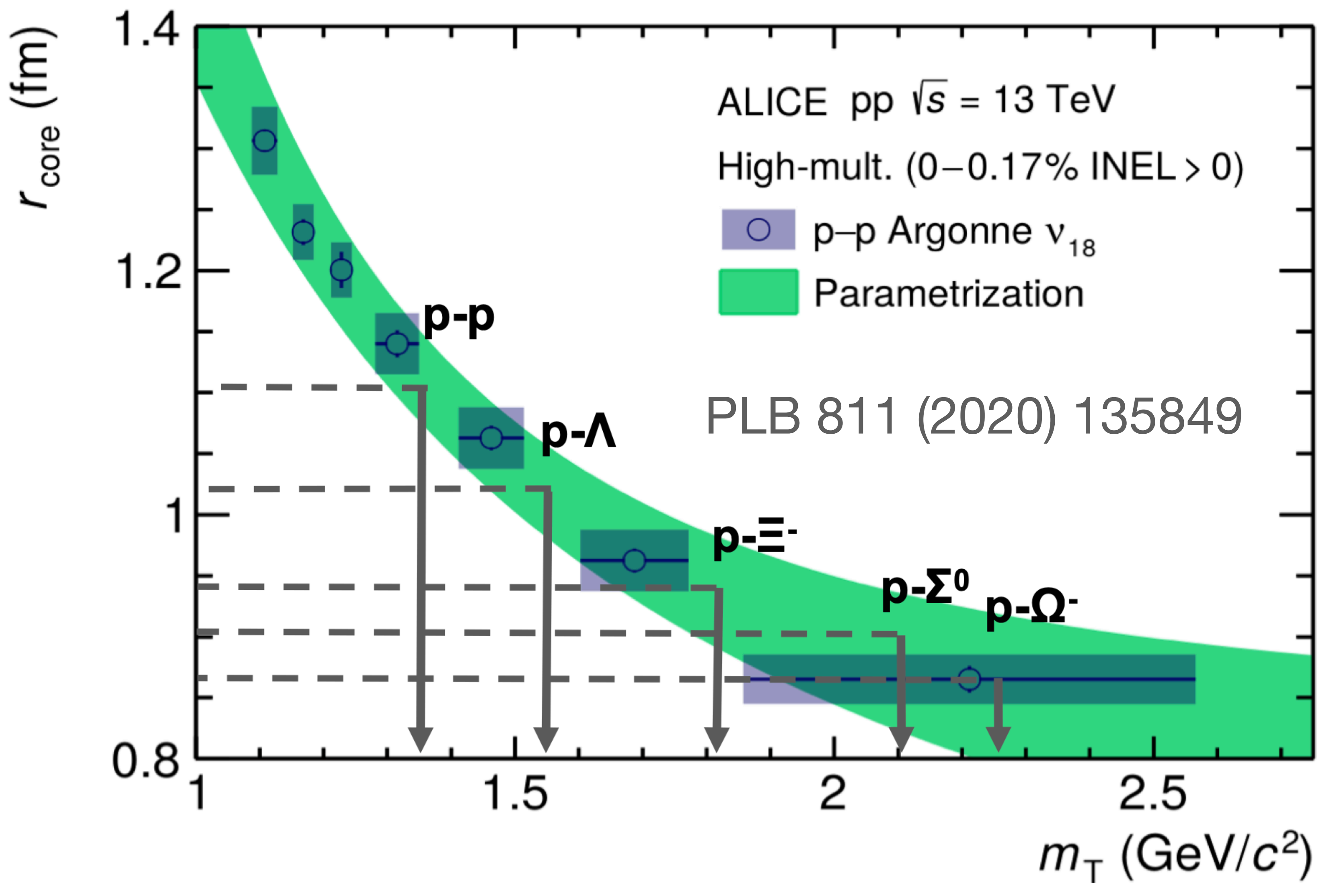
So what interaction distances are probed by femtoscopy?



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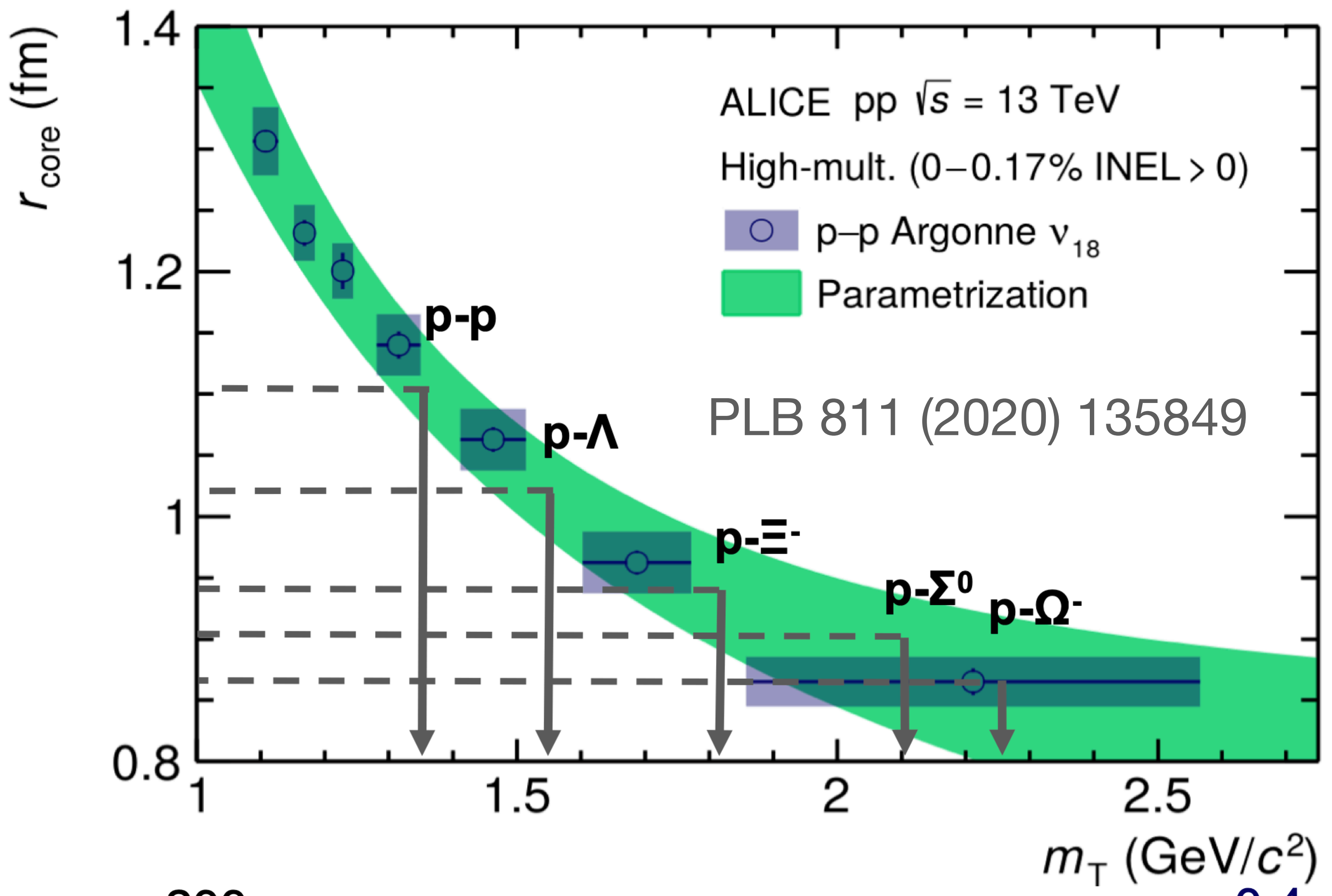
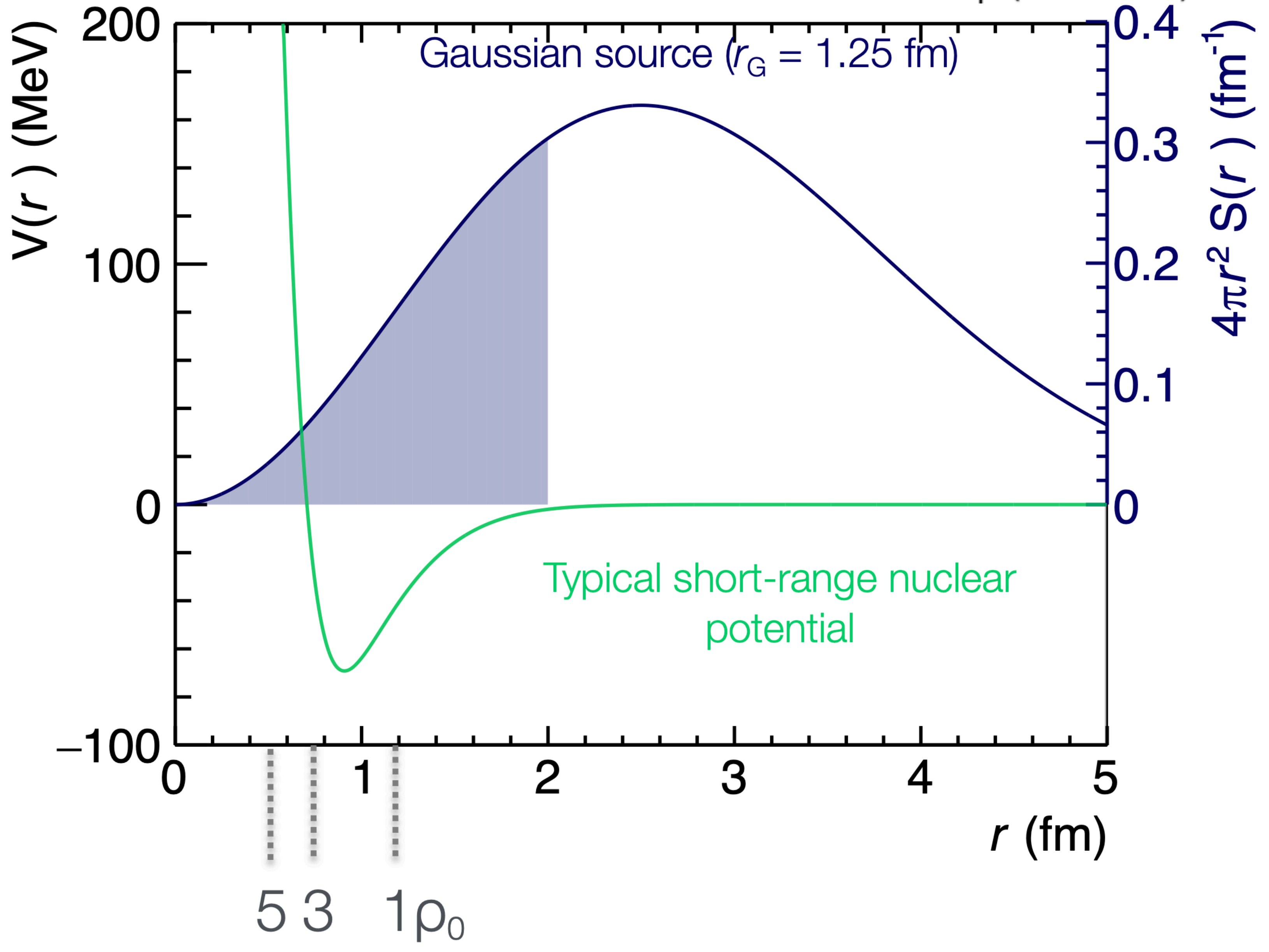
So what interaction distances are probed by femtoscopy?

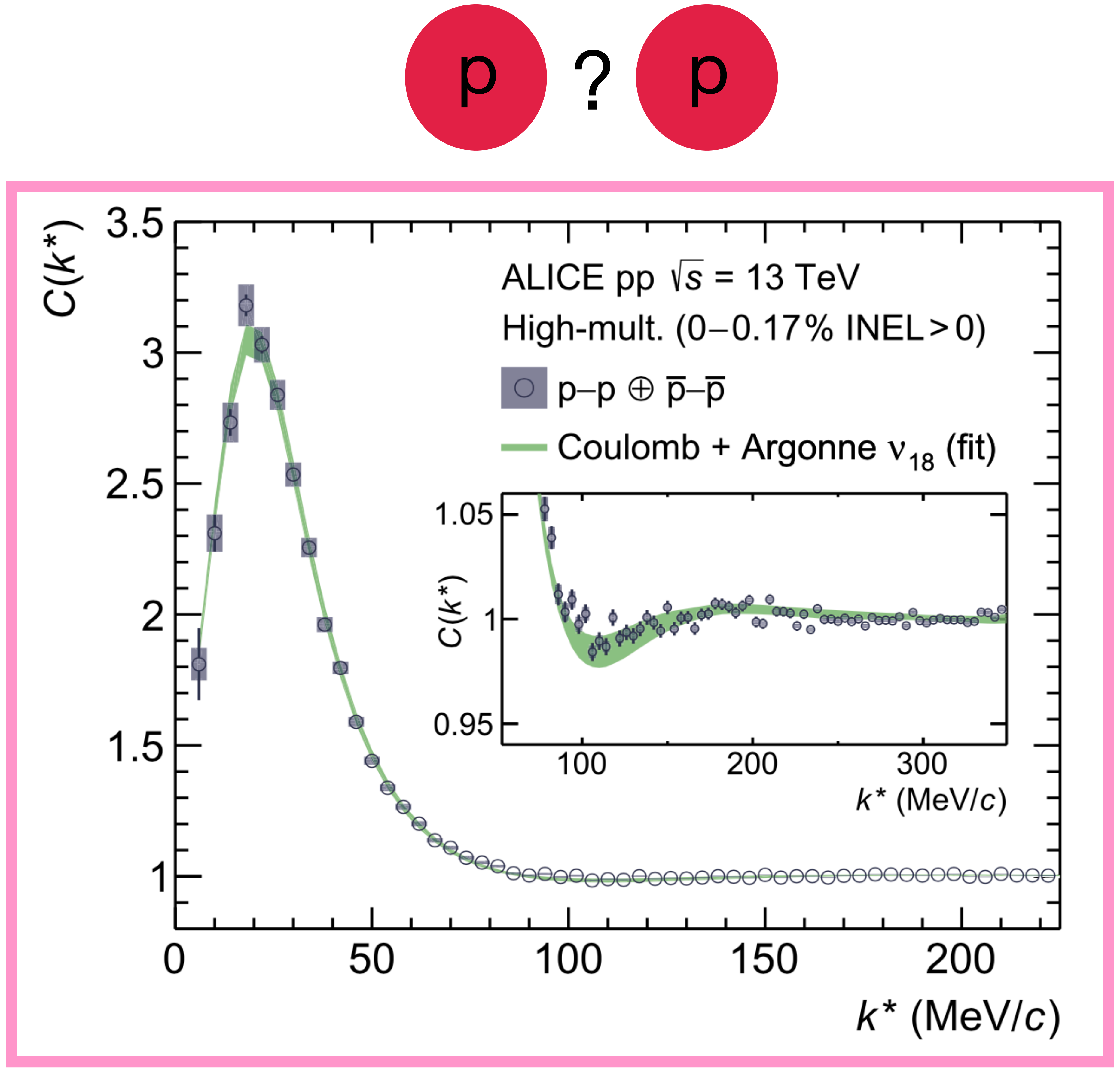
- Interaction measured down to very small distances.
- Mimics large densities which are important for neutron stars.

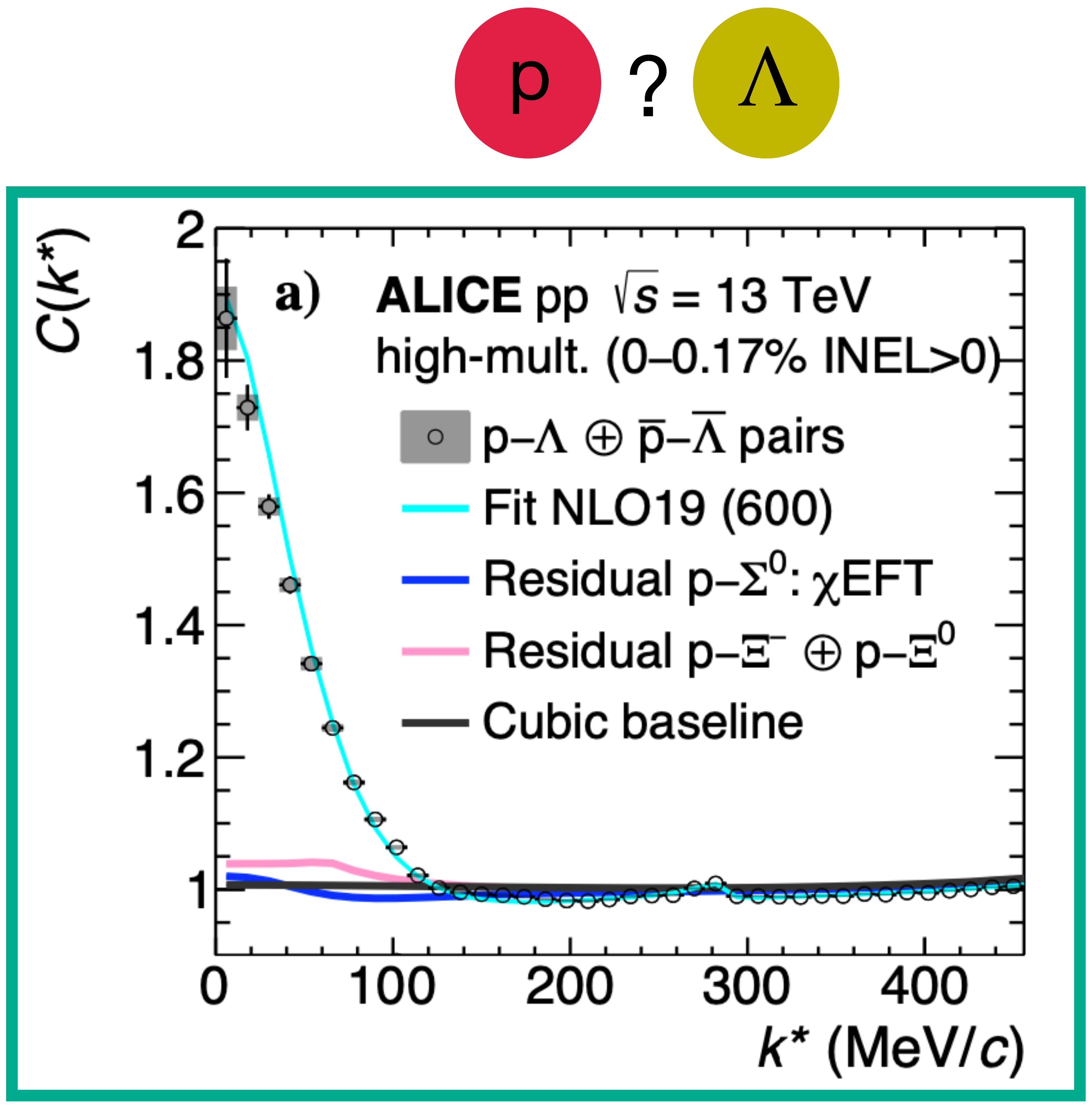




Two-body measurements

- Many different two-body interactions measured successfully!





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

ALICE:
PRC 99 (2019) 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 09230
PLB 805 (2020) 135419
PLB 811 (2020) 135849
Nature 588 (2020) 232-238
arXiv:2104.04427
arXiv:2105.05578
arXiv:2105.05683
arXiv:2105.05190

Projector method

$$C(Q_3) = \iiint_{Q_3=\text{constant}} C_2(k^*_{ij})\ W_{ij}(k^*_{ij}, Q_3)\ dk^*_{ij}$$

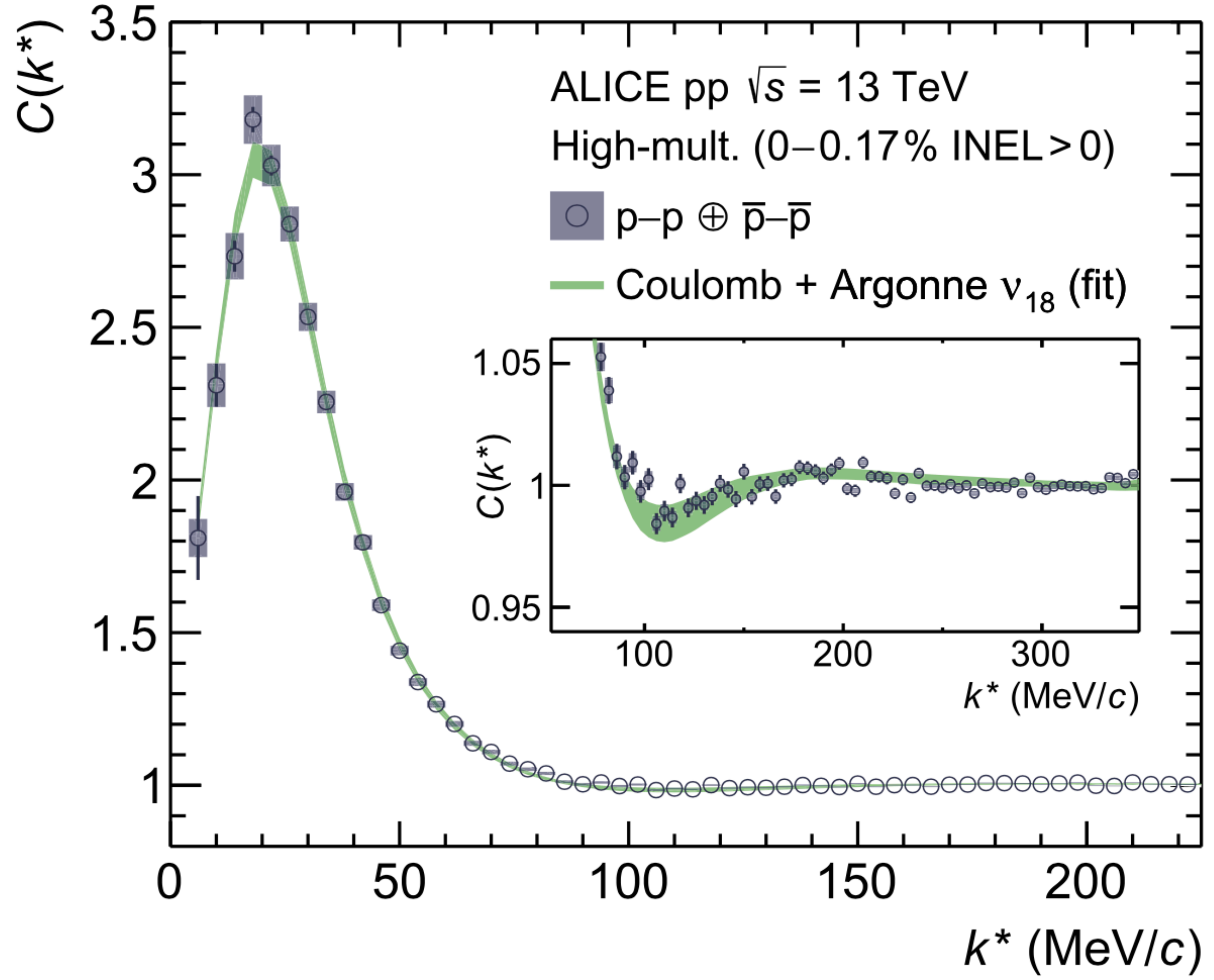
Projector method

$$C(Q_3) = \iiint_{Q_3=\text{constant}} C_2(k_{ij}^*)\ W_{ij}(k_{ij}^*, Q_3)\ dk_{ij}^*$$

Output: (p-p)-p

Input

ALICE Coll. PLB 805 (2020) 135419



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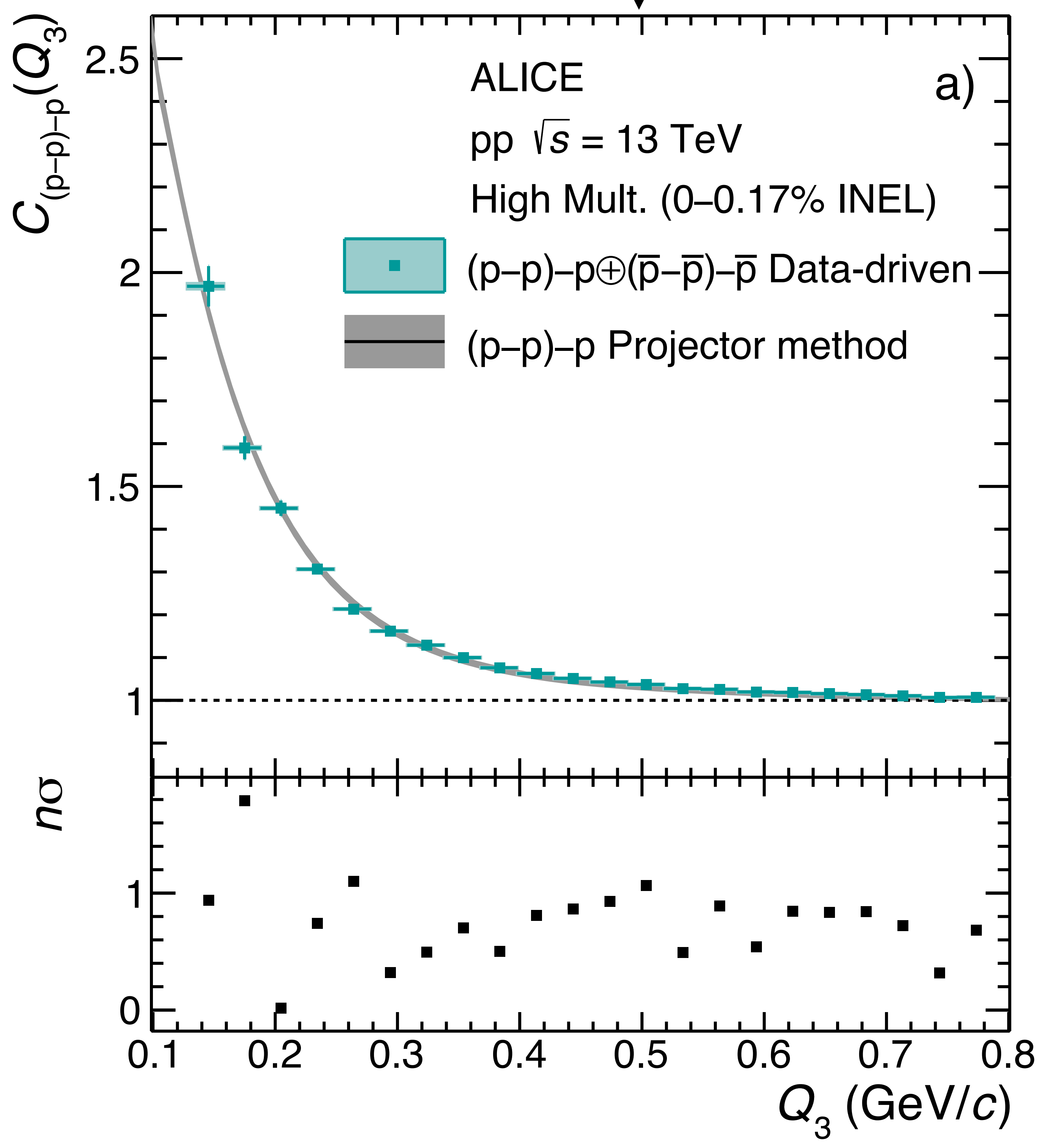
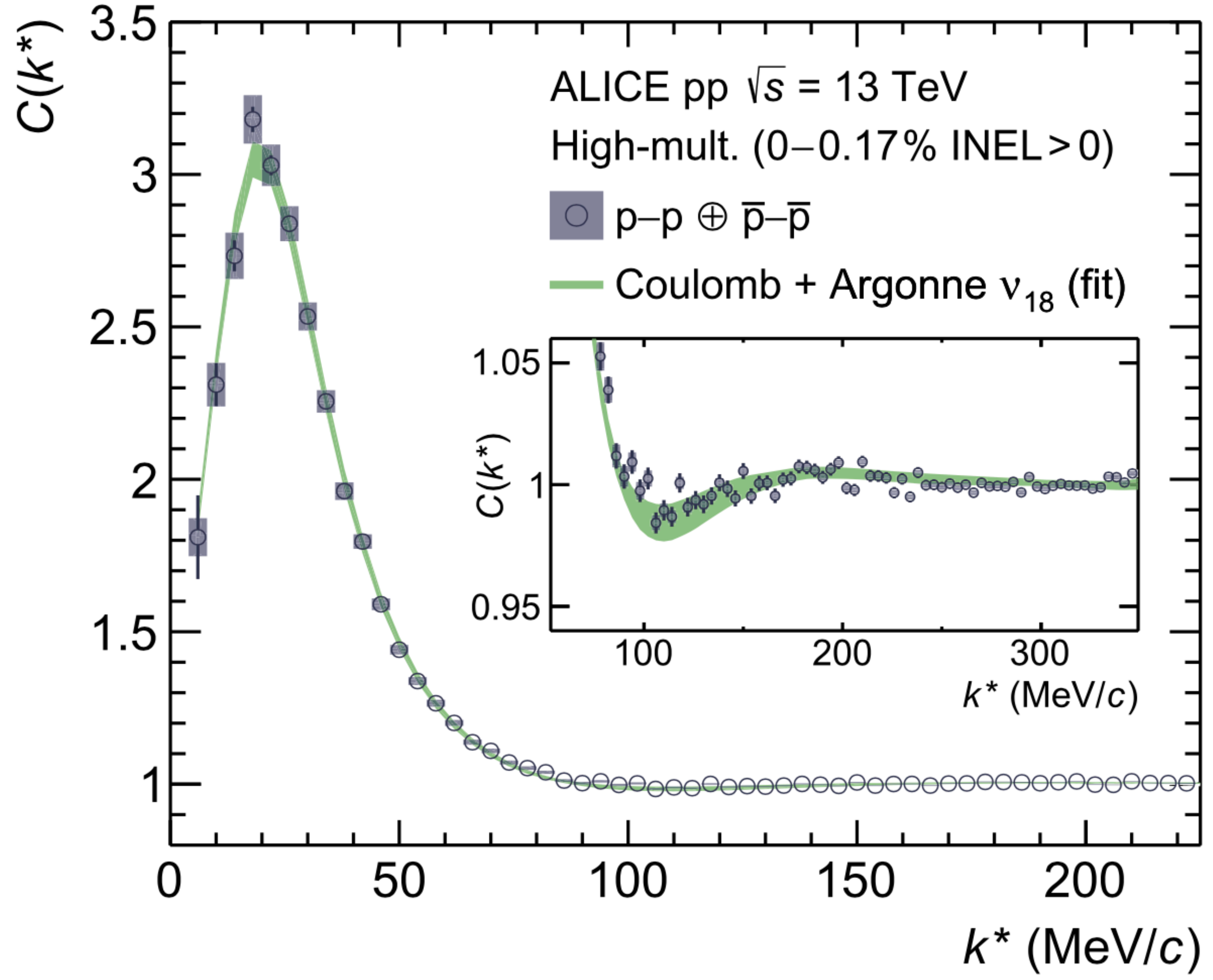


ALICE Coll. PLB 805 (2020) 135419



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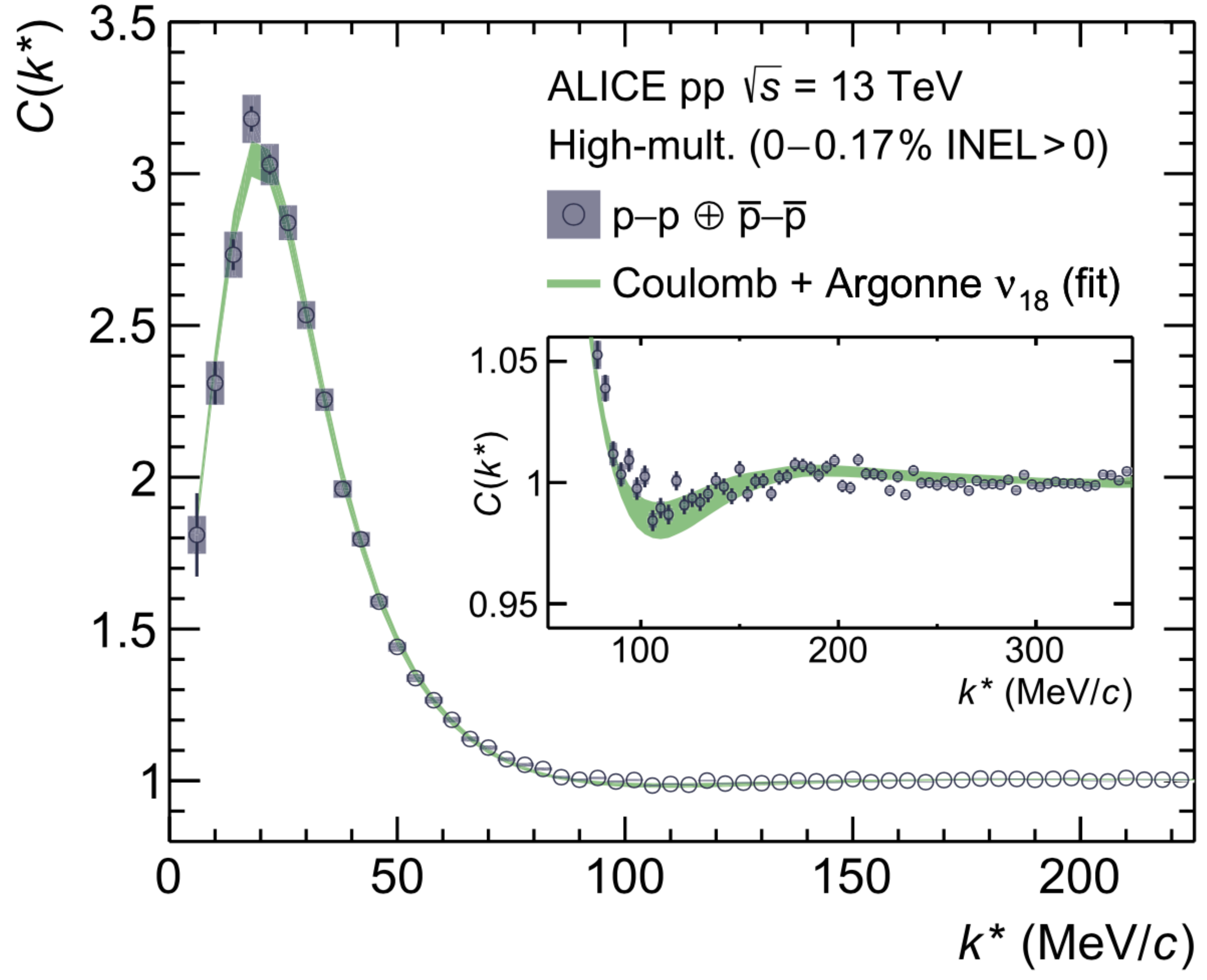
ALICE Coll. PLB 805 (2020) 135419



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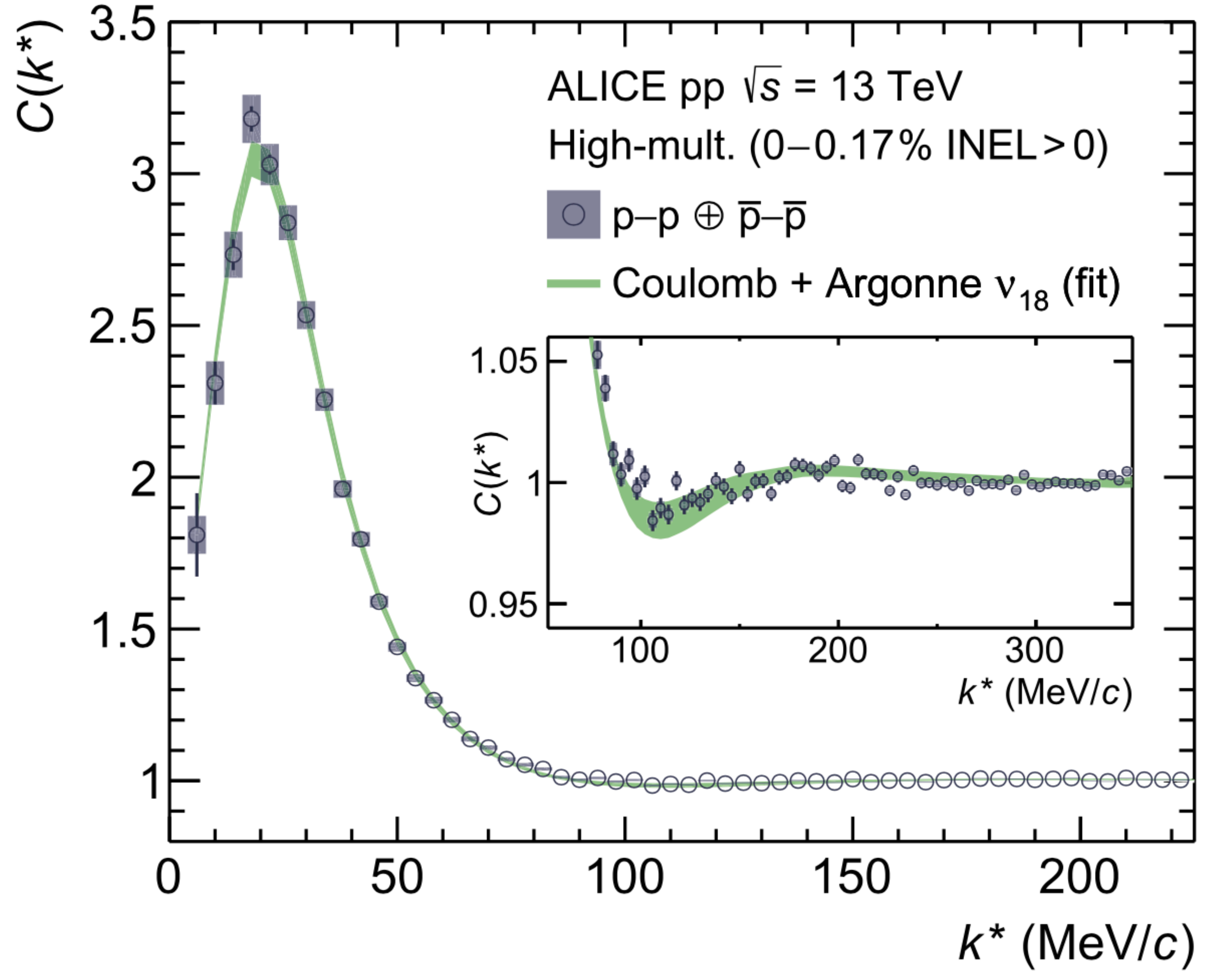
Input

ALICE Coll. PLB 805 (2020) 135419



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Output: (p-p)-Λ

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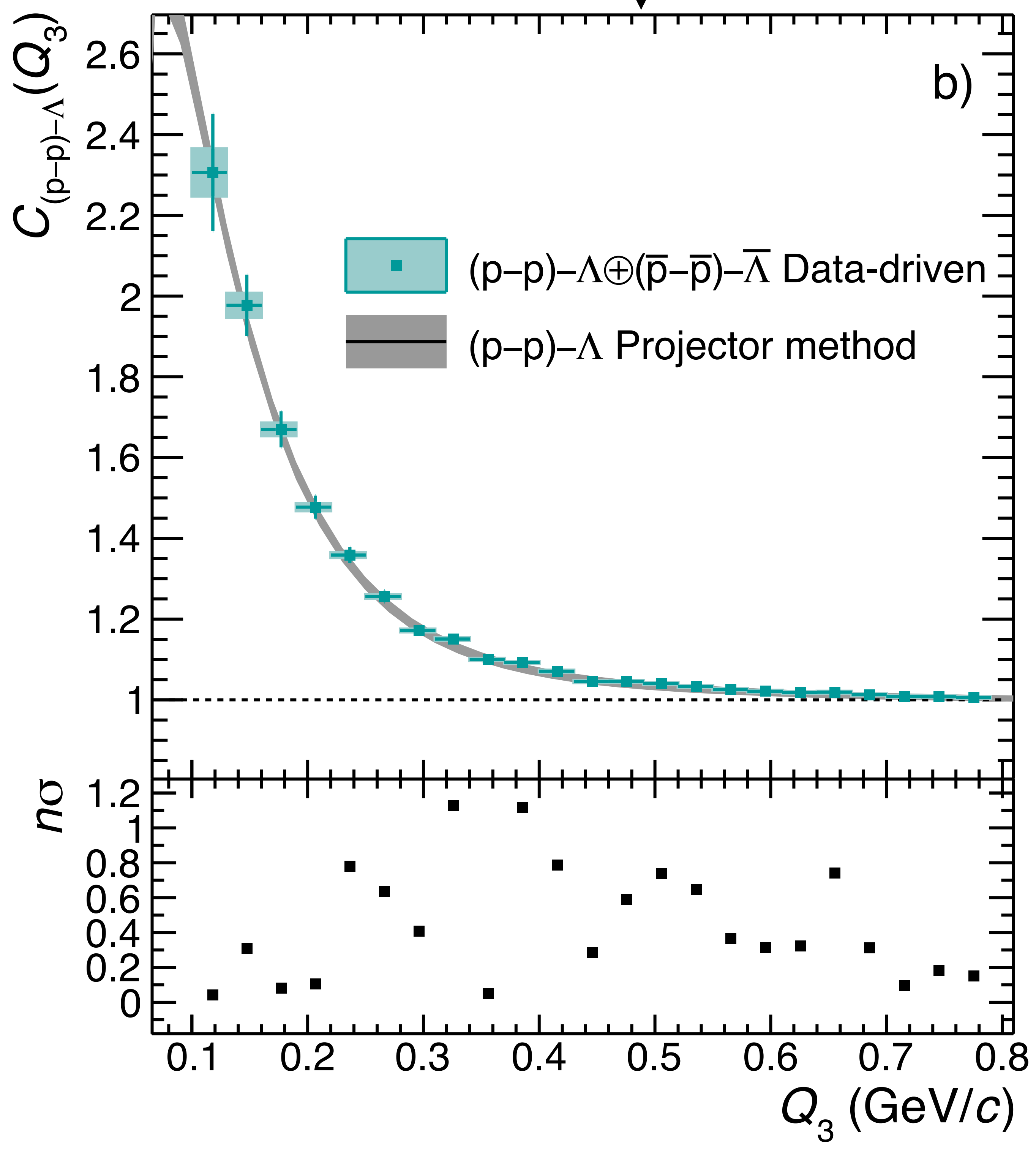
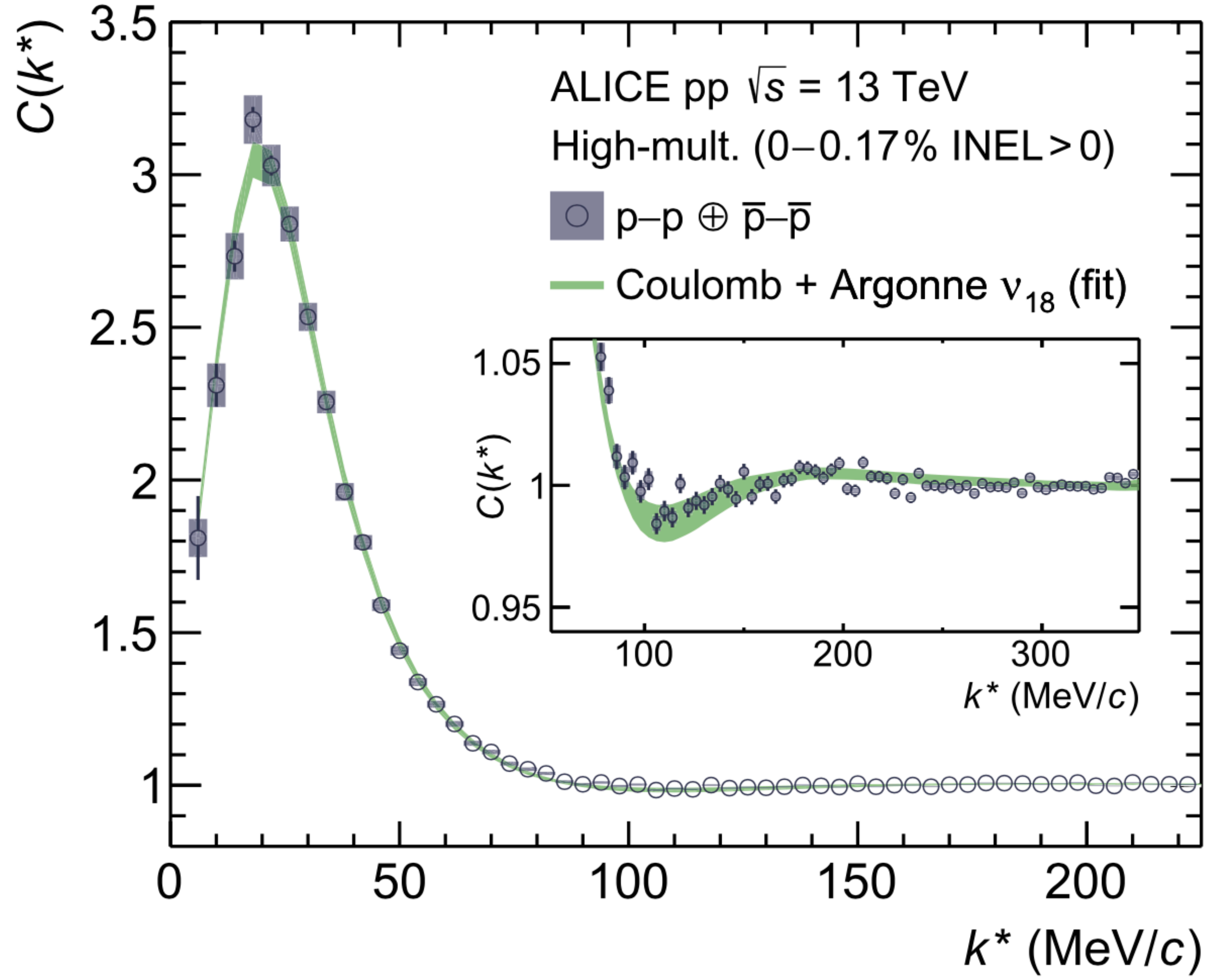


ALICE Coll. PLB 805 (2020) 135419



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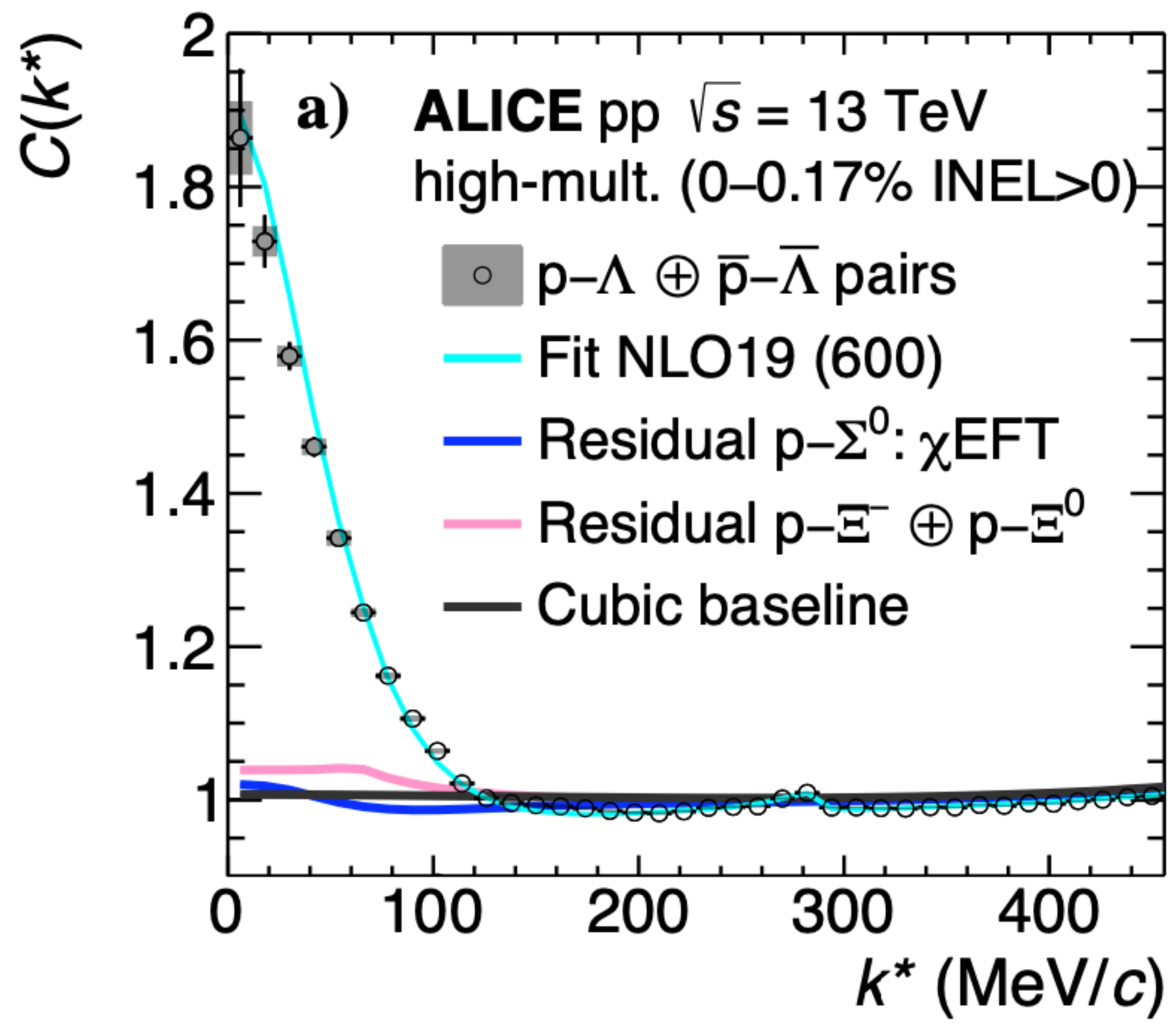
Input

ALICE Coll. arXiv:2104.04427



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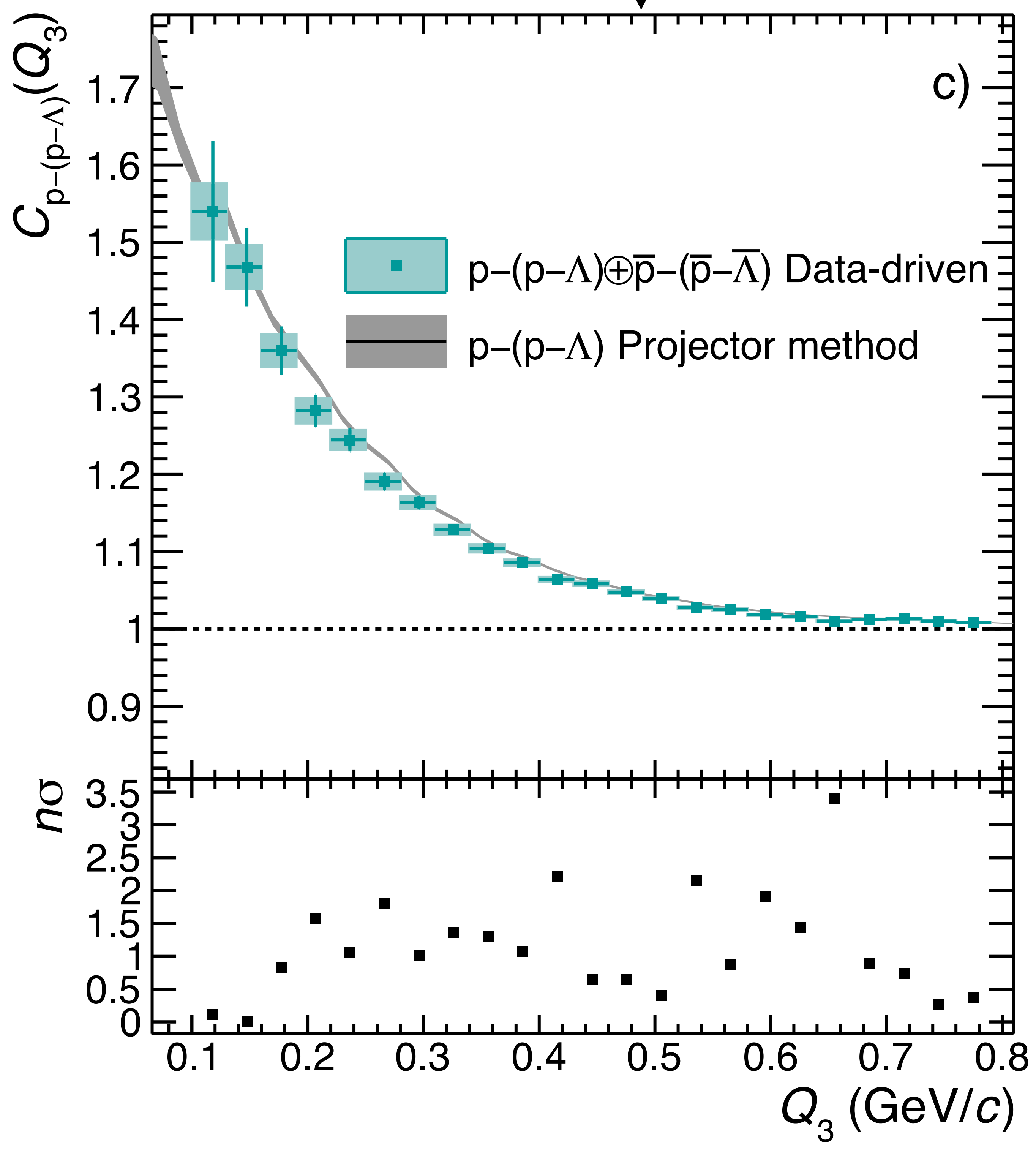

ALICE Coll. arXiv:2104.04427