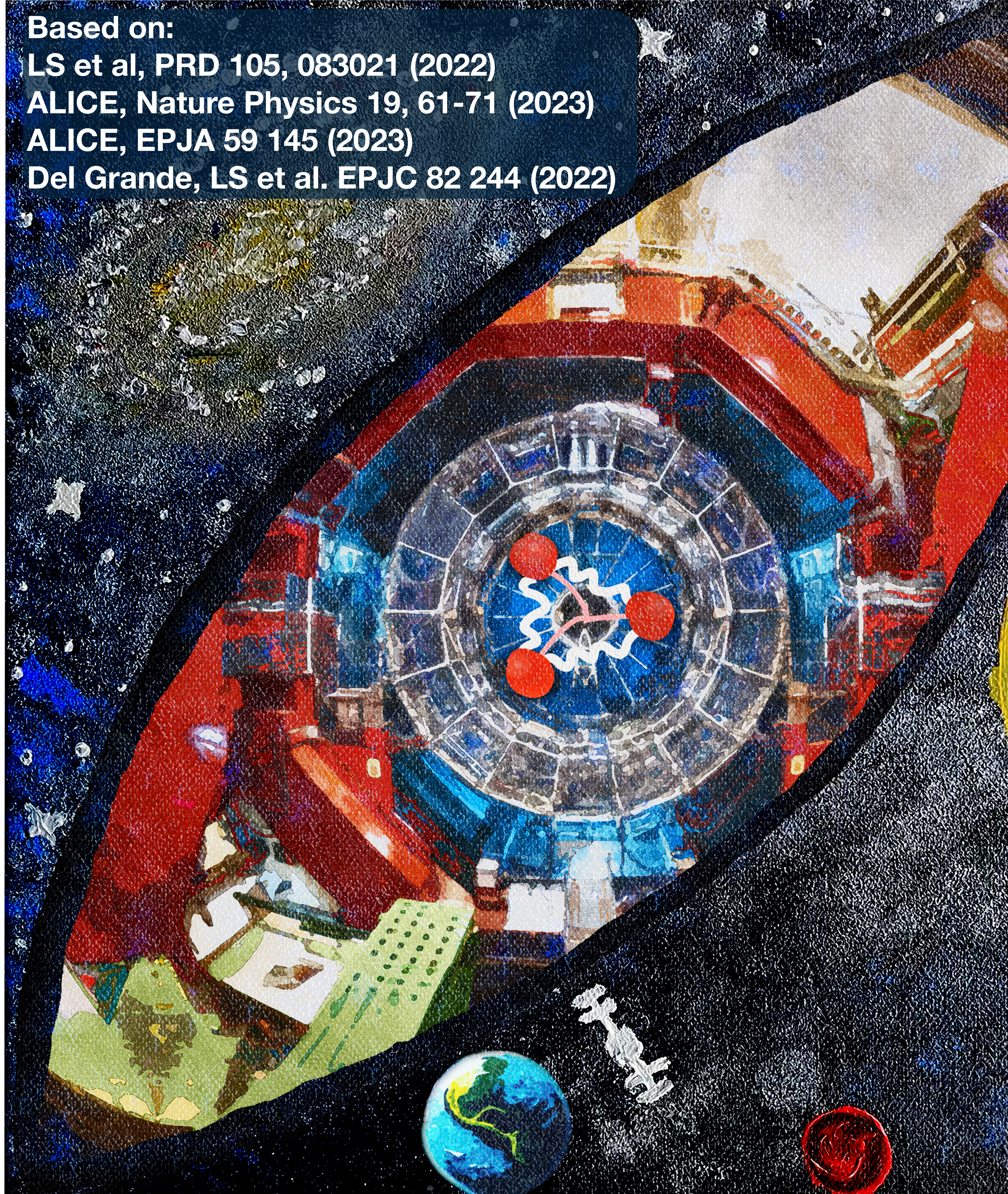
Unlocking the mysteries of nuclear interactions and their astrophysical impact

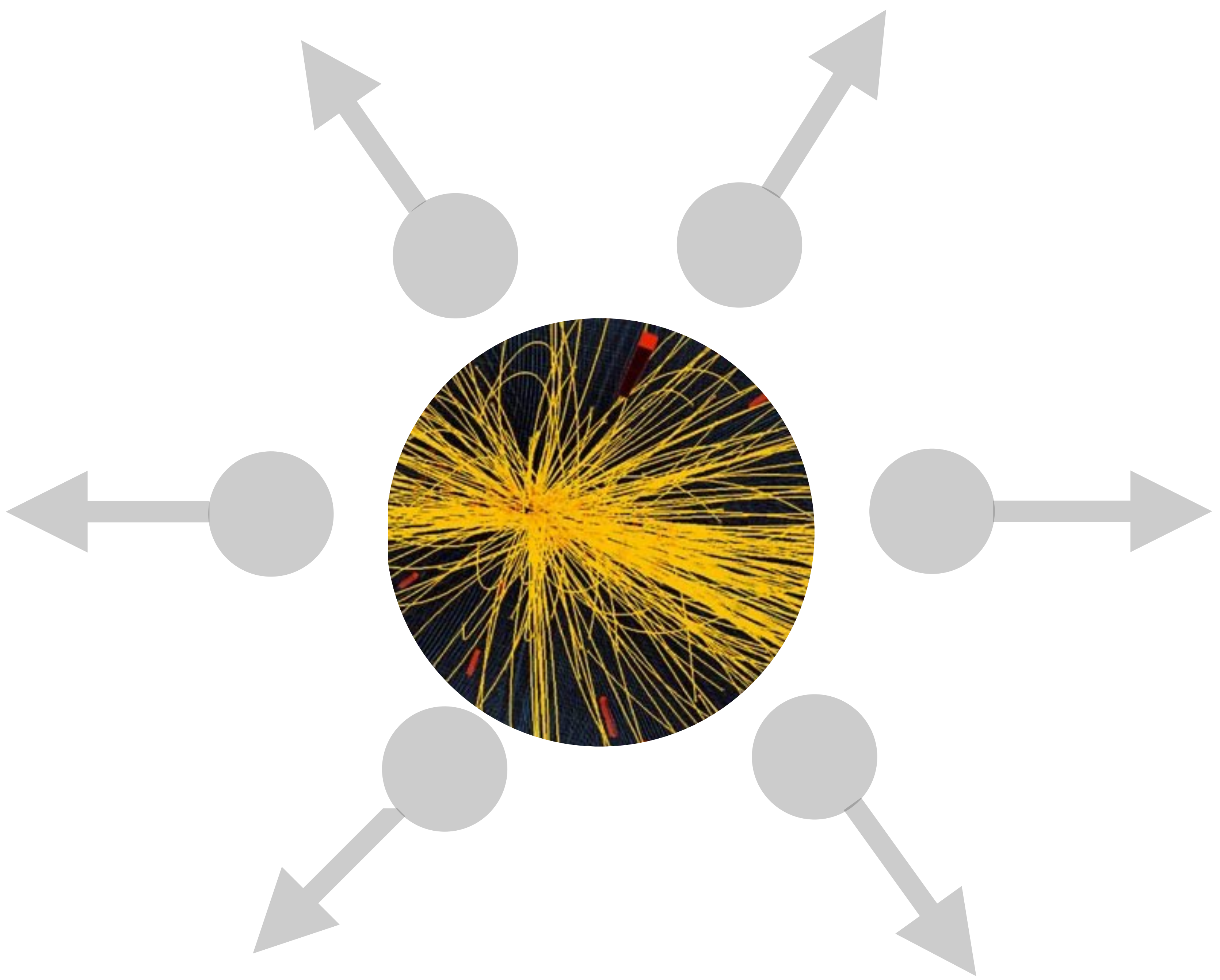
Laura Šerkšnytė
Supervisor: Prof. Dr. Laura Fabbietti
Technical University of Munich

Dissertation Prize Symposium
11th March 2024, Gießen

Based on:
LS et al, PRD 105, 083021 (2022)
ALICE, Nature Physics 19, 61-71 (2023)
ALICE, EPJA 59 145 (2023)
Del Grande, LS et al. EPJC 82 244 (2022)



Nuclear studies on Earth



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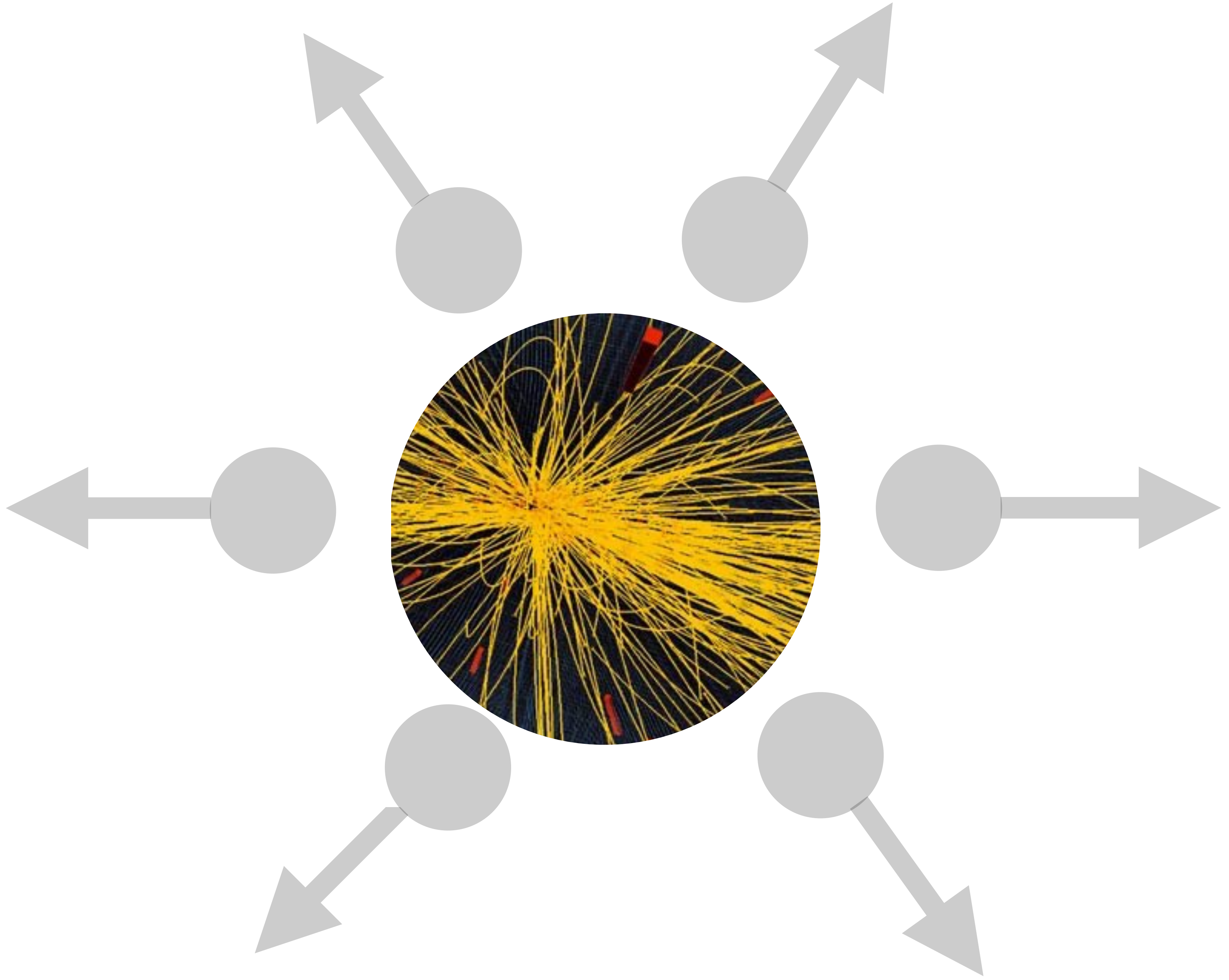
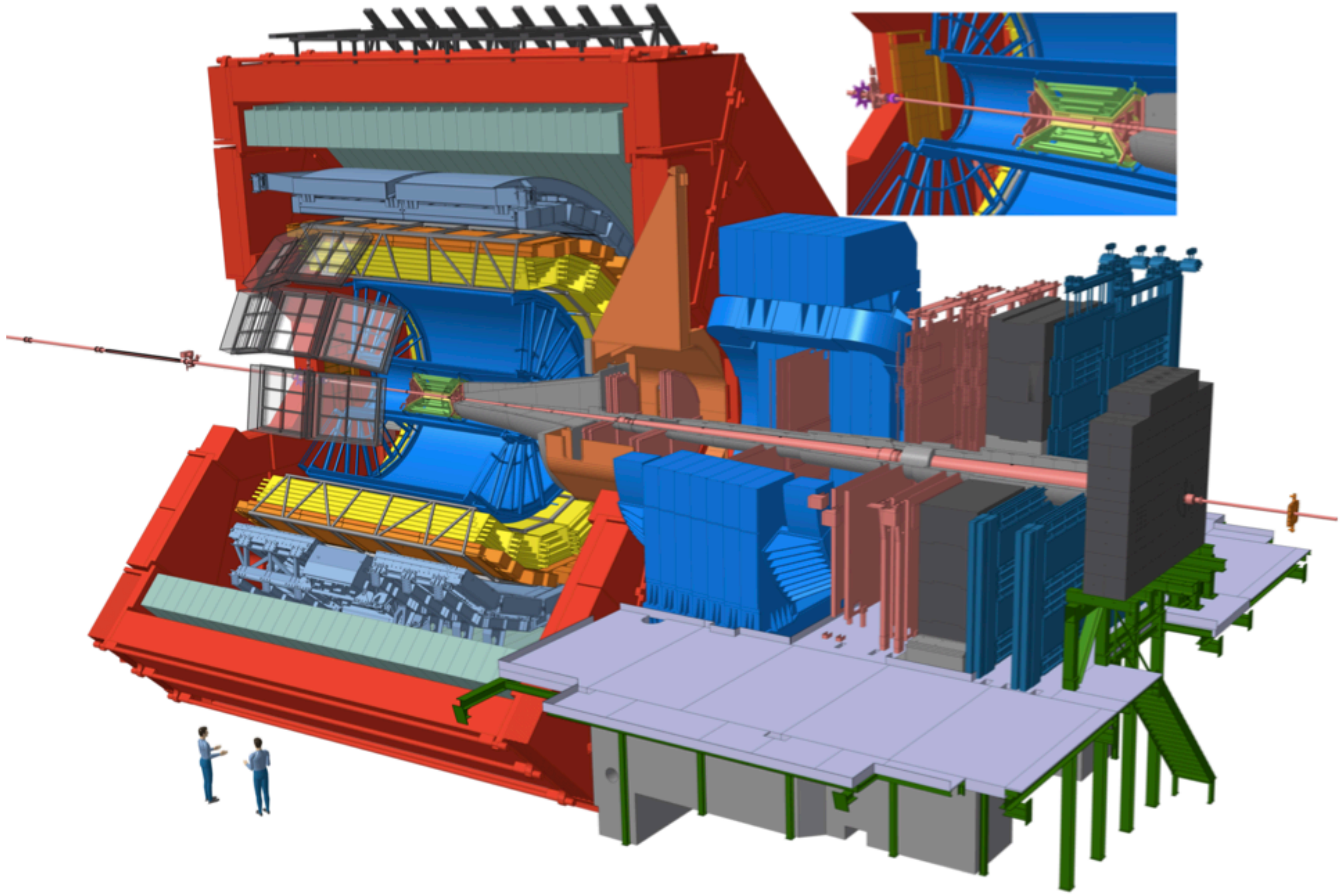


Measure: $\pi, \mathrm{K}, \mathrm{p}, \mathrm{d}, \mathrm{He} \ldots$

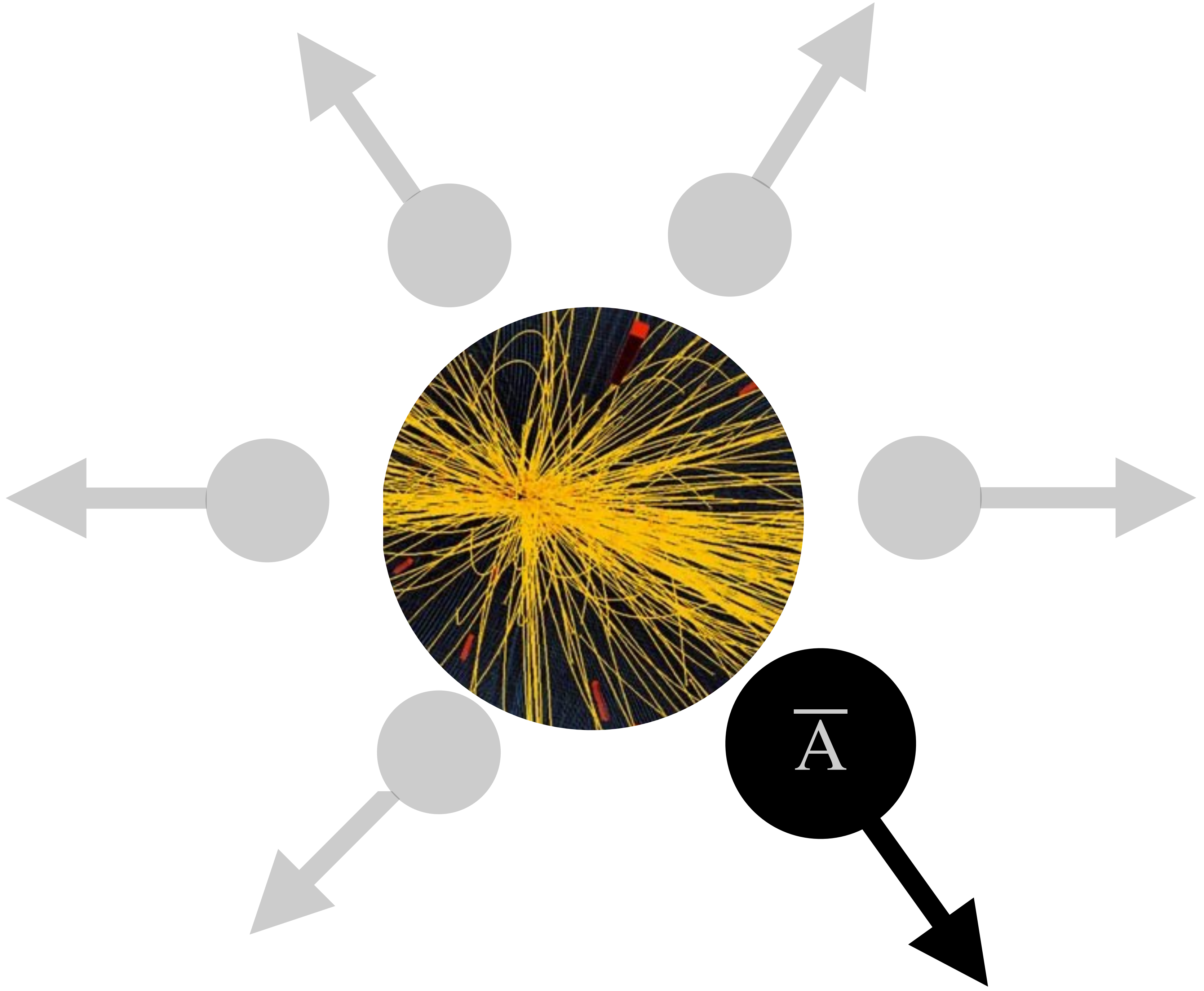
ALICE



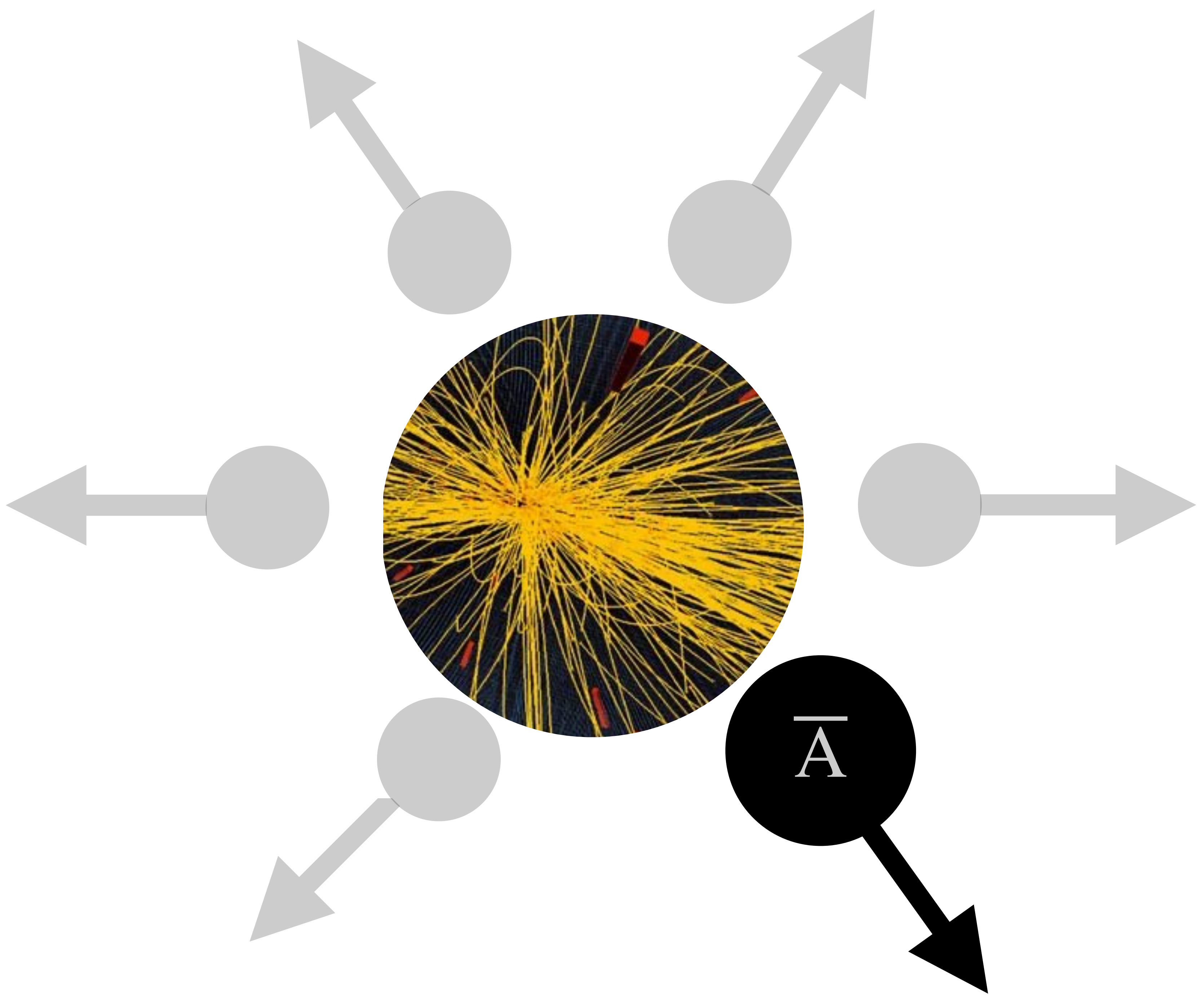
Excellent particle tracking and identification capabilities

LHC Run 2 pp @ $\sqrt{s}$ = 13 TeV: 1.2 billion events!

ALICE, Int.J.Mod.Phys.A 29 (2014) 1430044
ALICE, JINST 3 (2008) S08002



Measure: $\bar{d}$, $\overline{{}^{3}He}$



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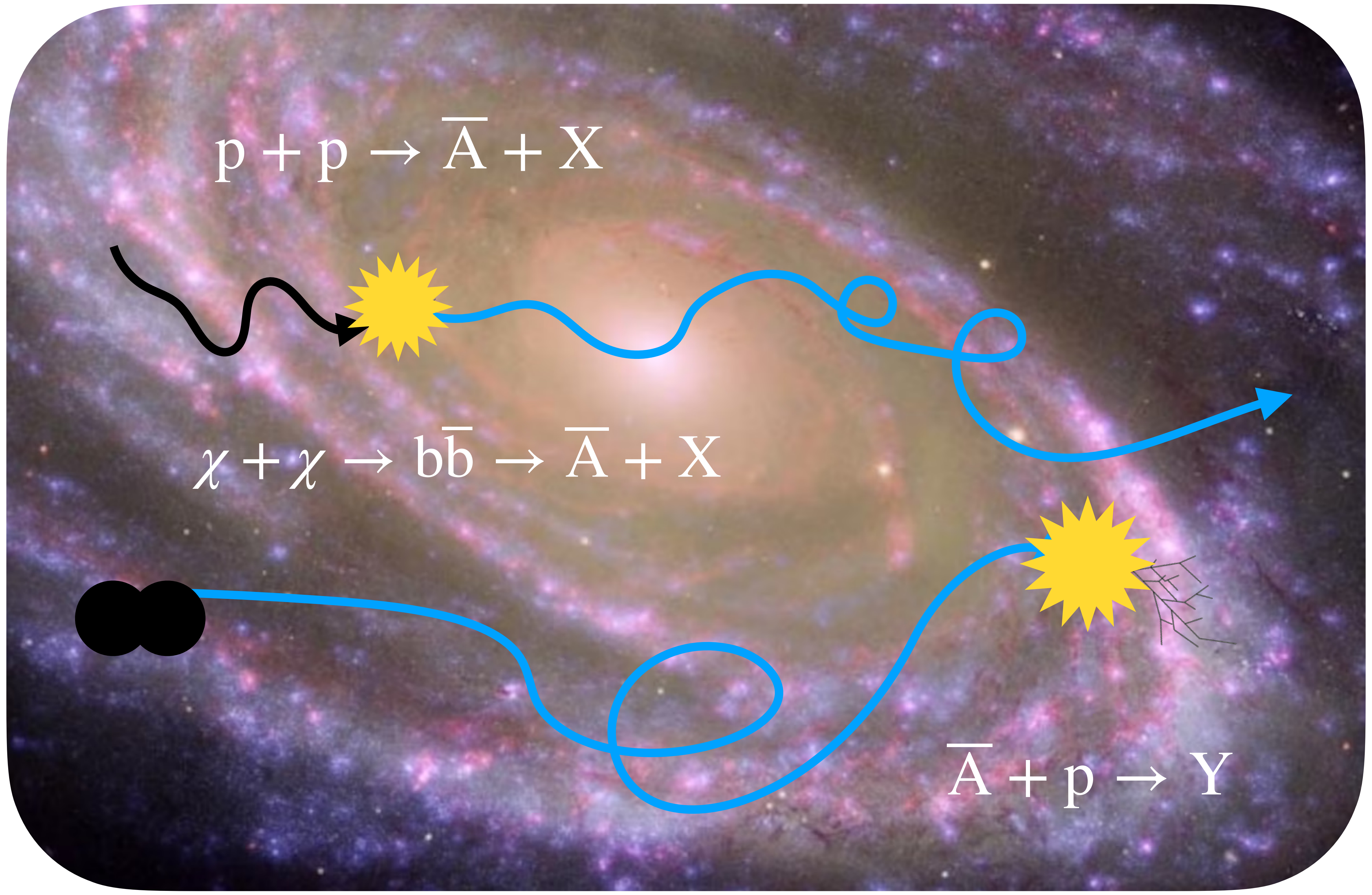

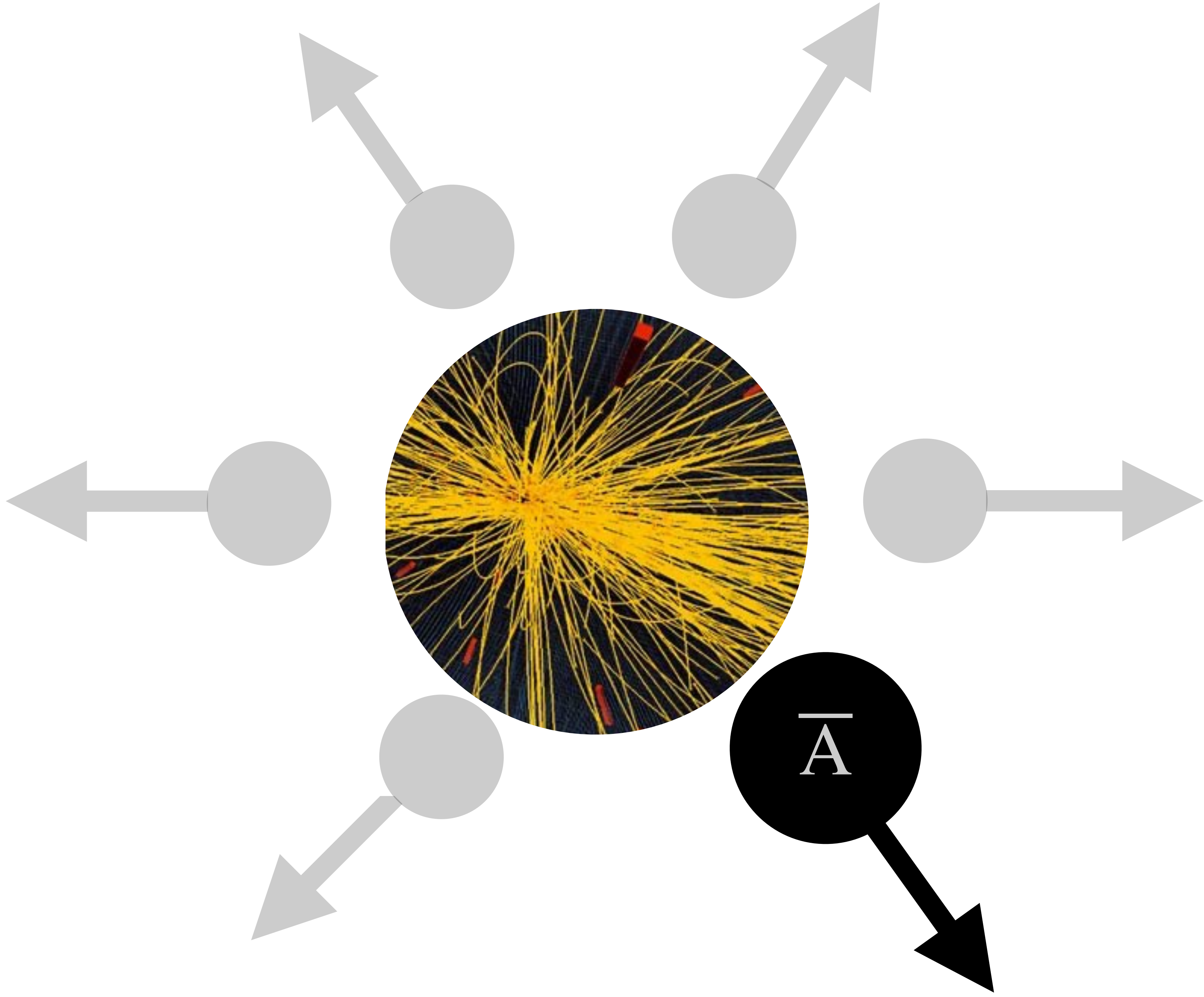

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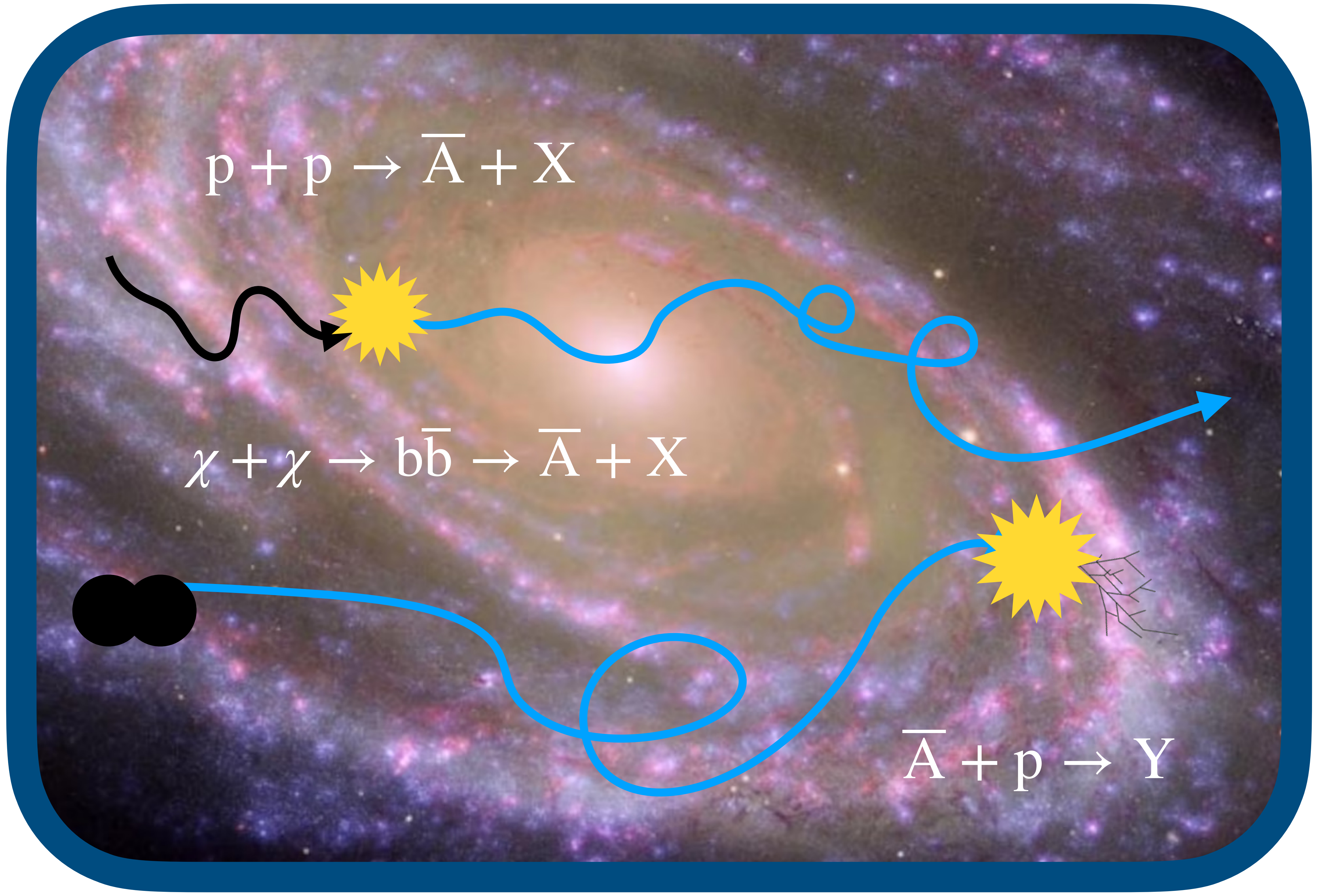
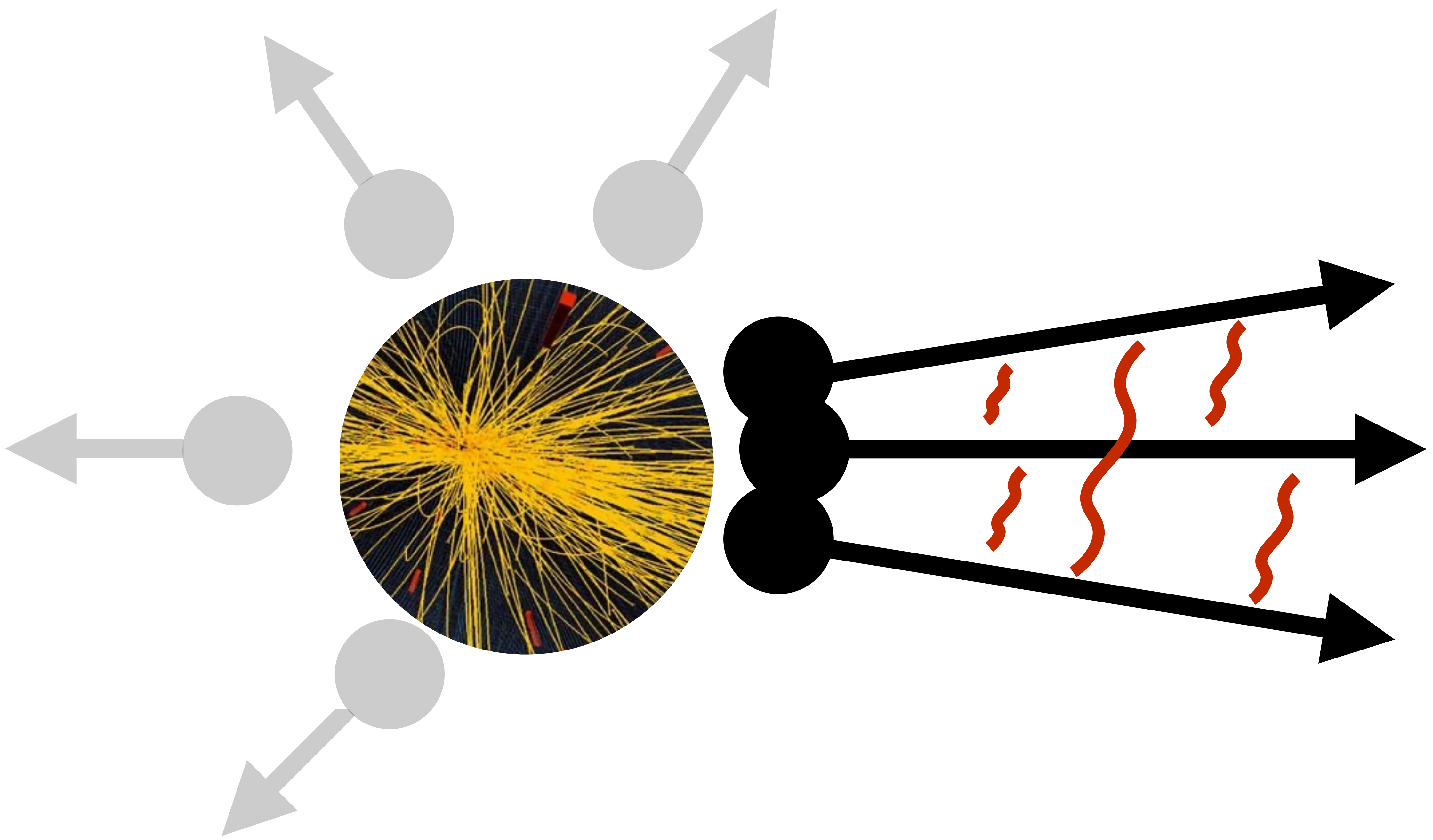
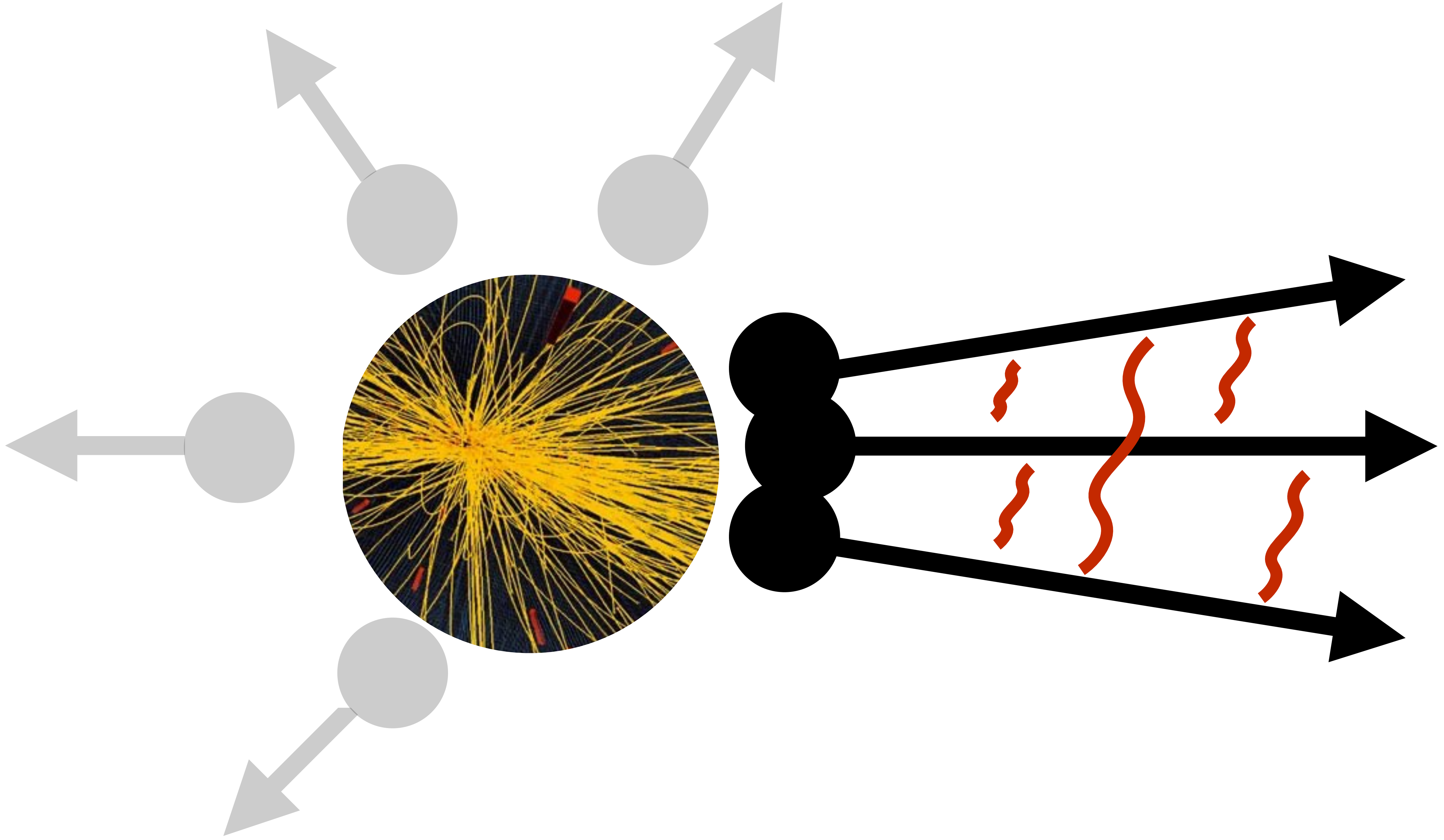




Measure: $p - p - p$, $p - p - \Lambda$



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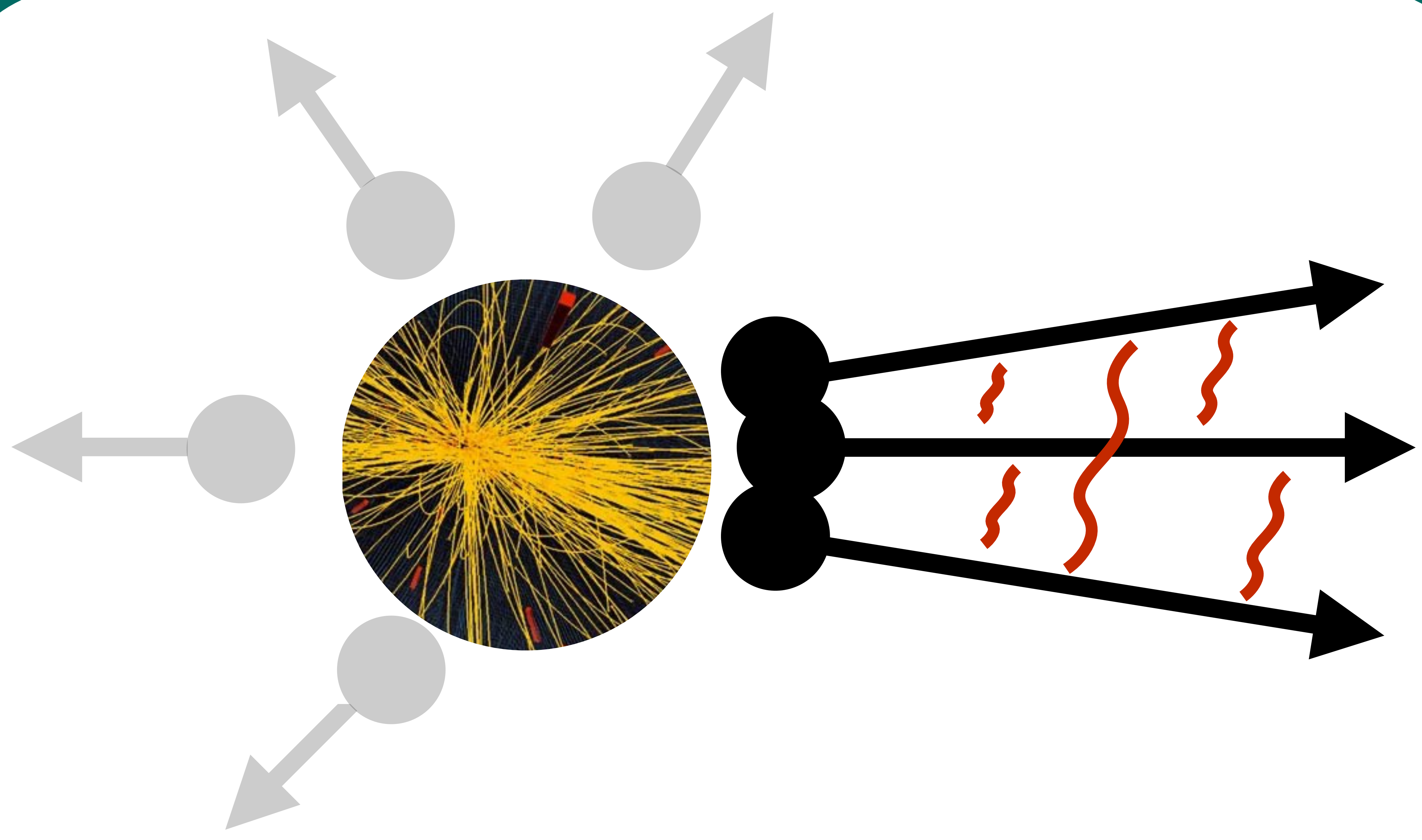

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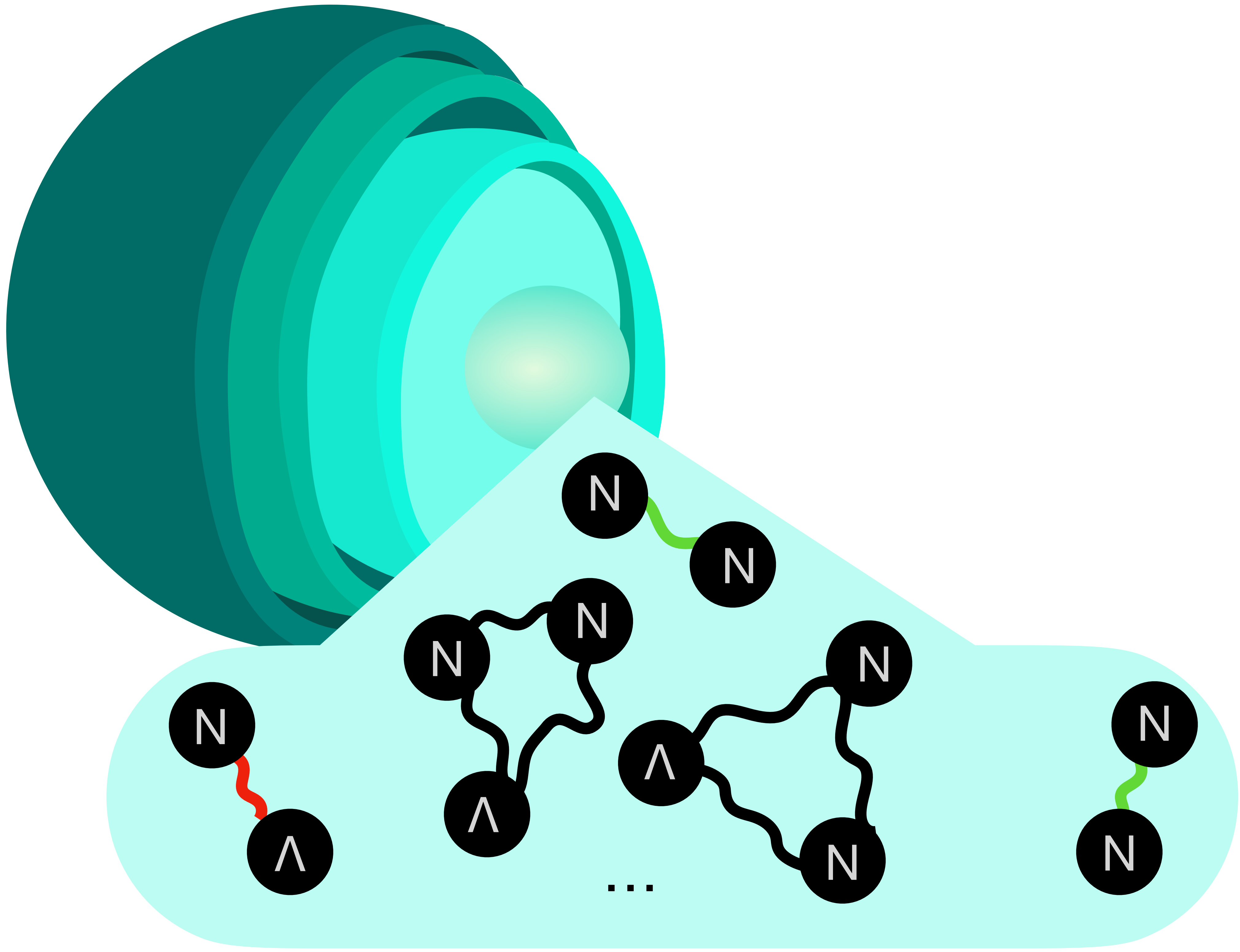
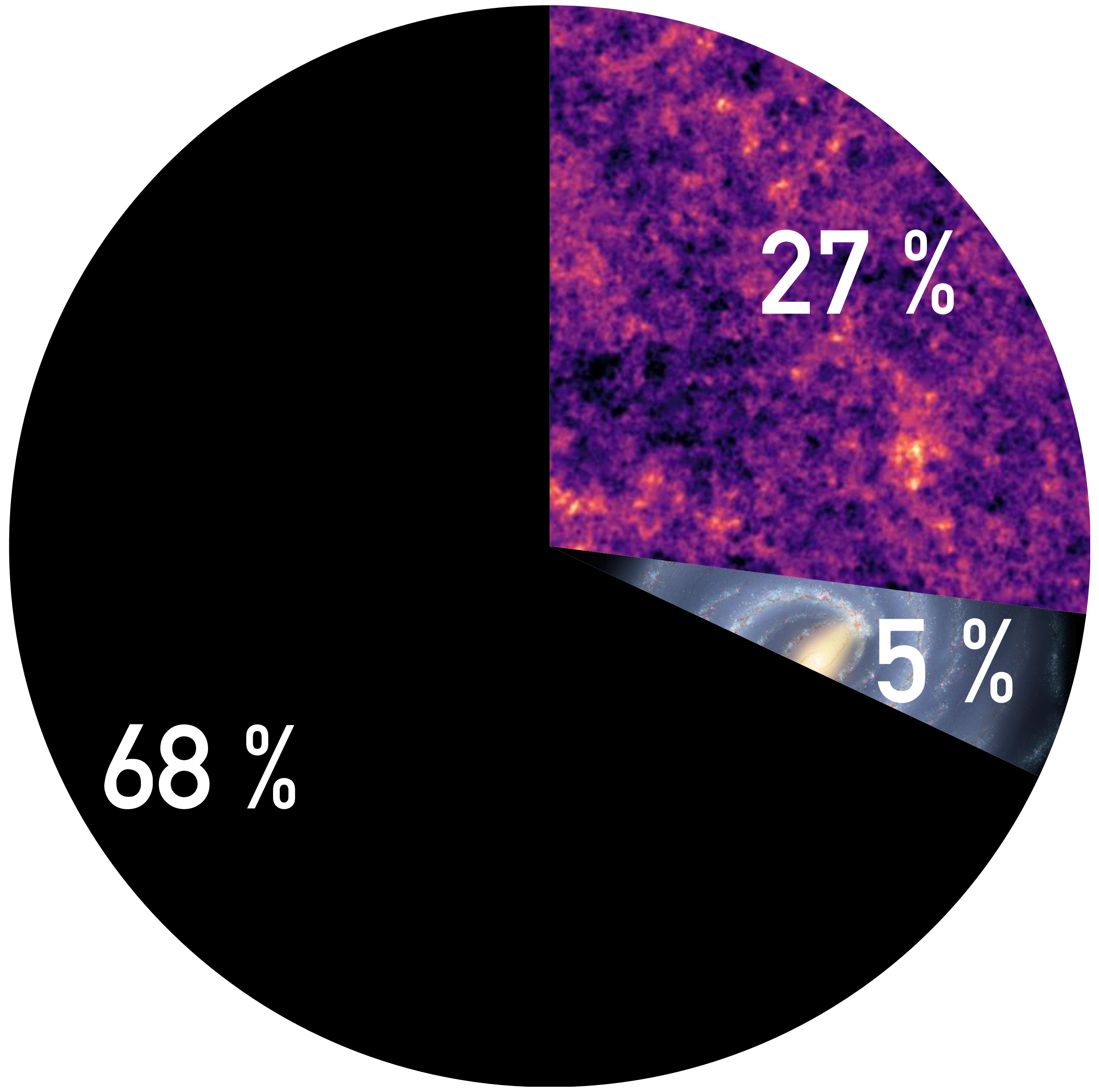


Dark matter searches

- Universe - around 27% made of dark matter



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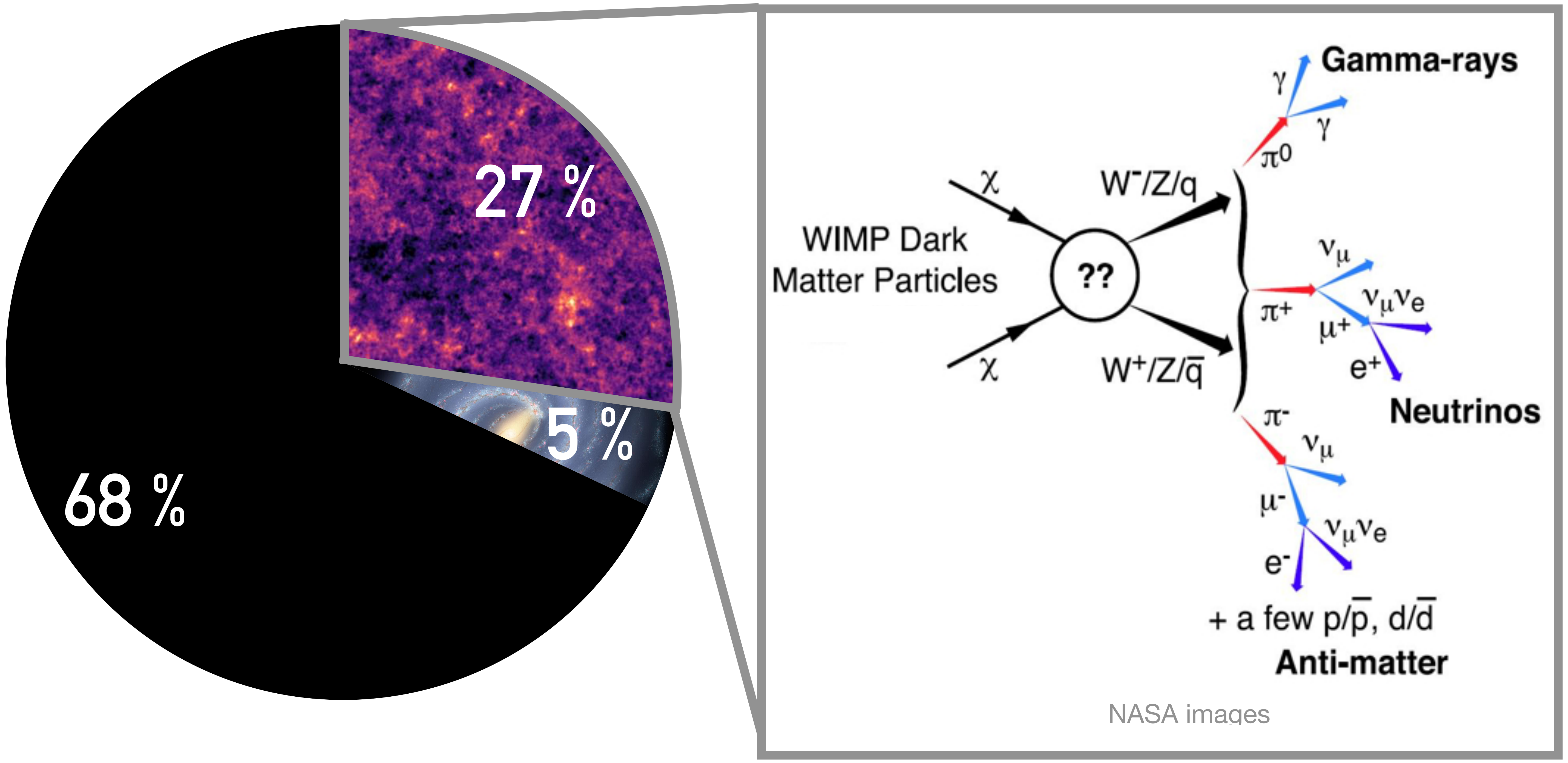
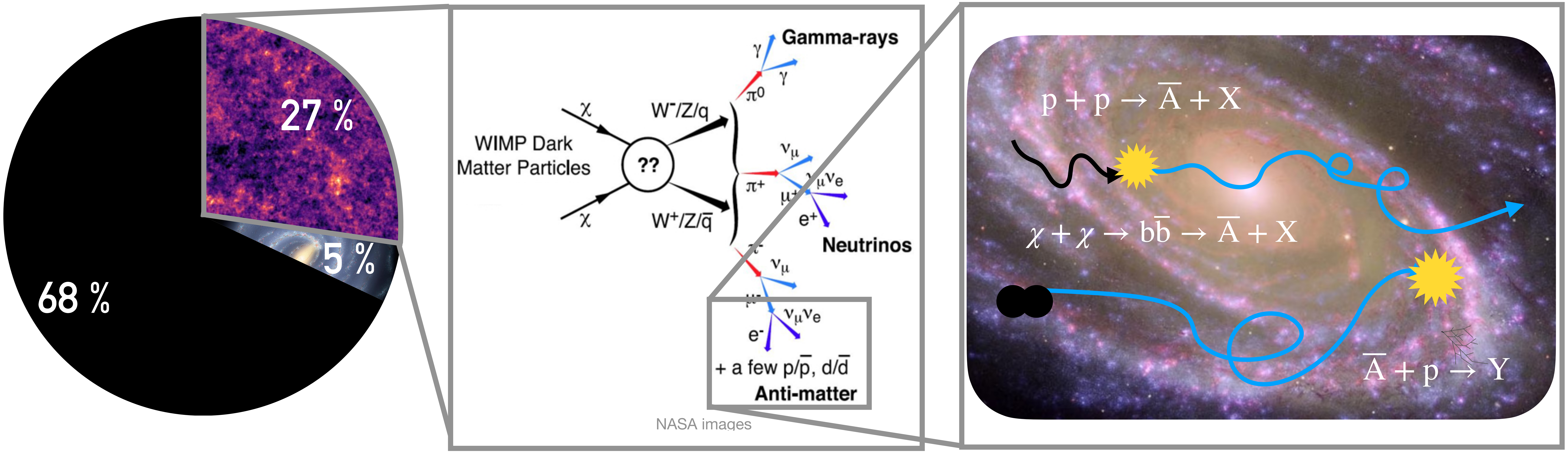


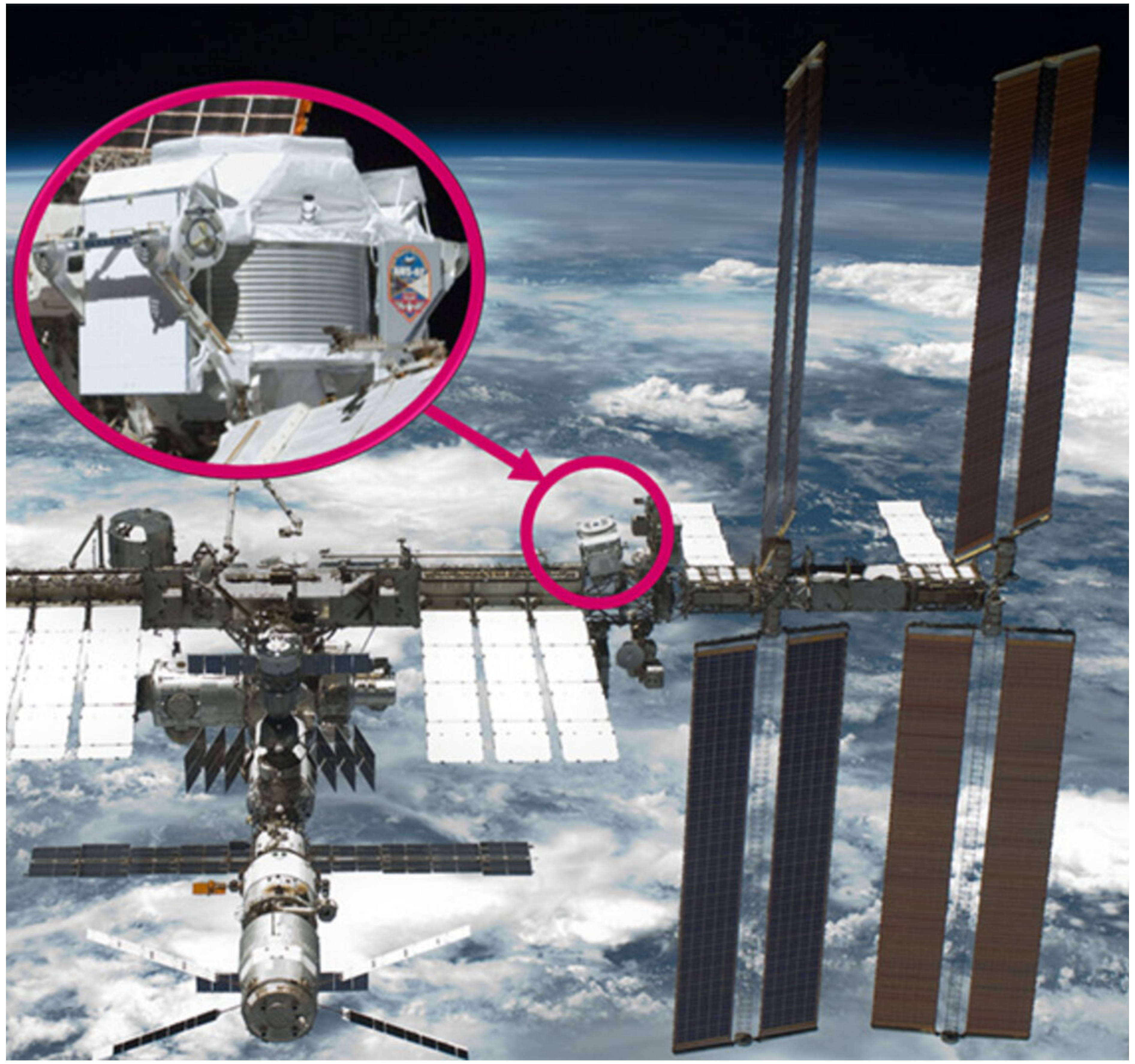
Dark matter searches

- Universe - around 27% made of dark matter
- Indirect searches - look for annihilation products
- Promising probe: cosmic ray antinuclei



Alpha magnetic spectrometer AMS-02

- 7.5 ton spectrometer on the International Space Station
- High-precision cosmic ray measurements over a large range of nuclei



ESA media

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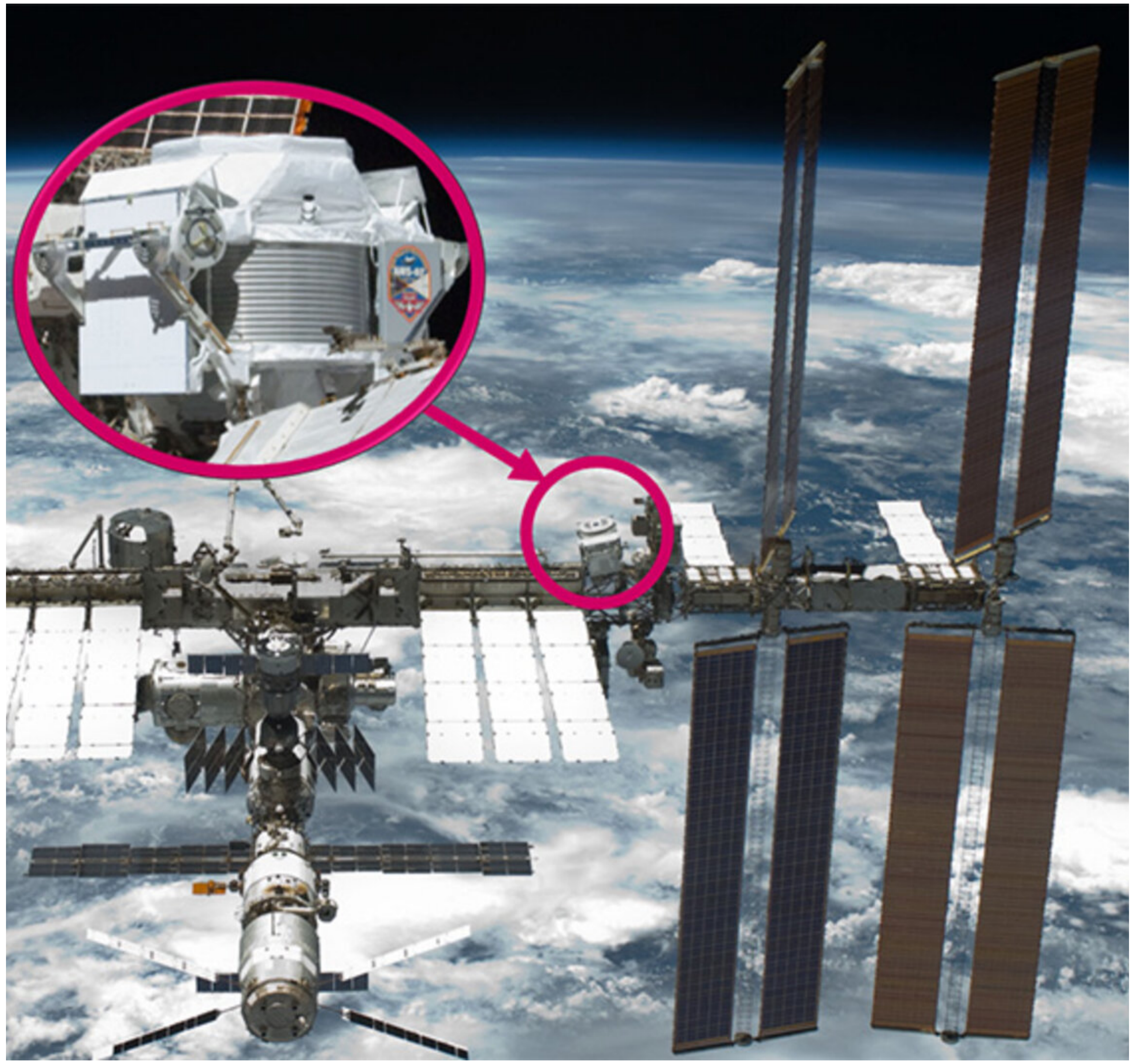

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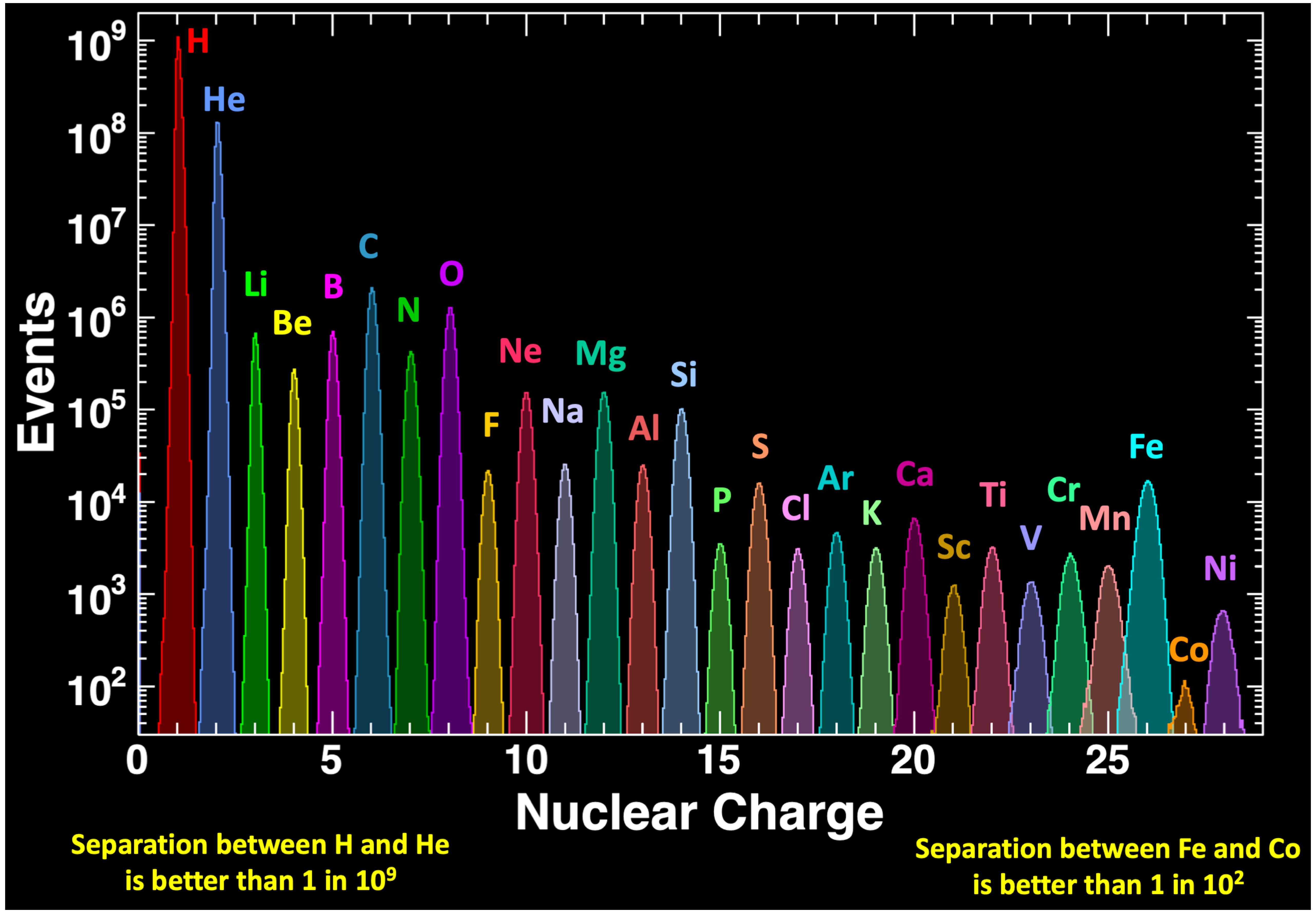

S. Ting CERN Colloquium Jun. 8th 2023

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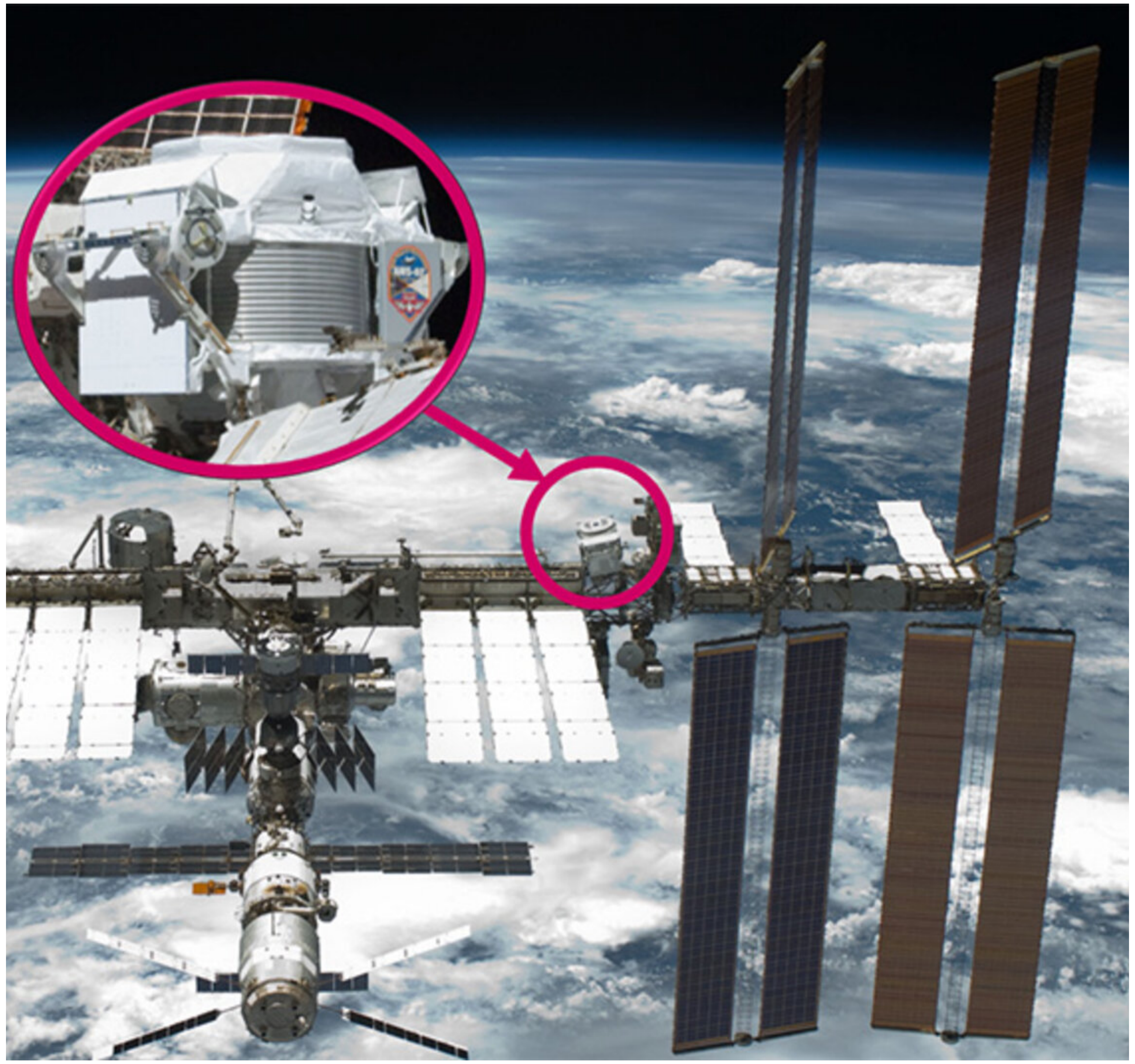

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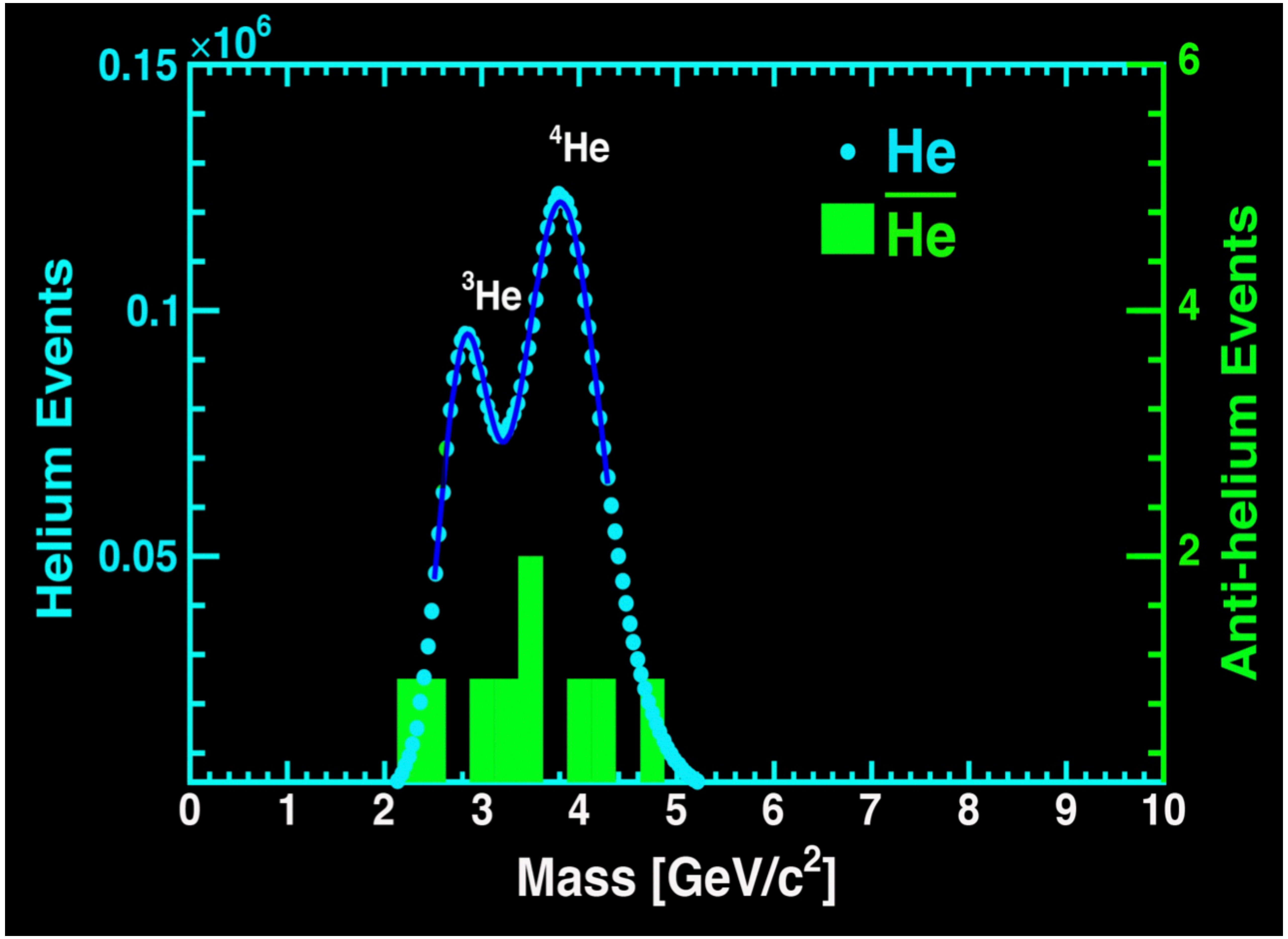
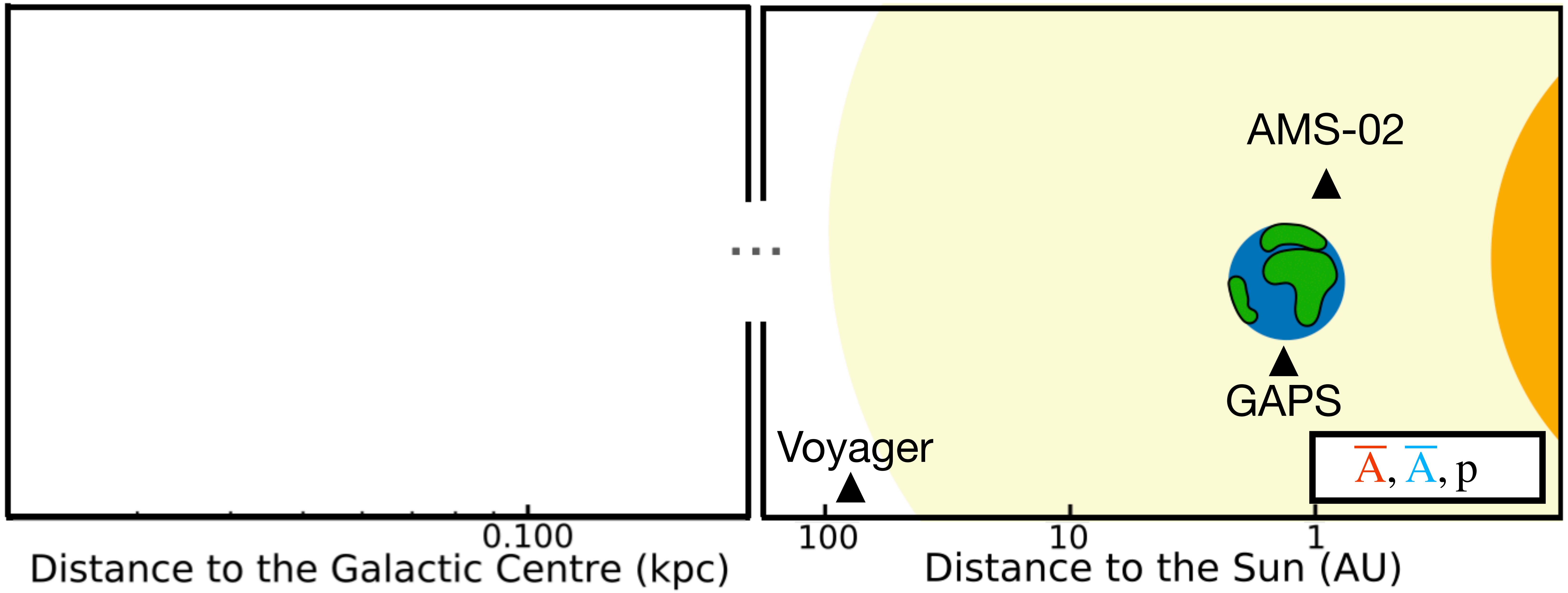


Paolo Zuccon for AMS-02 Collaboration in MIAPP22 workshop

Antinuclei flux

Transport equation

$$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \mathbf{div}(D_{xx}\mathbf{grad}\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi \frac{dp}{dt} - \frac{p}{3}(\mathbf{div} \cdot \mathbf{V})\psi\right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}$$



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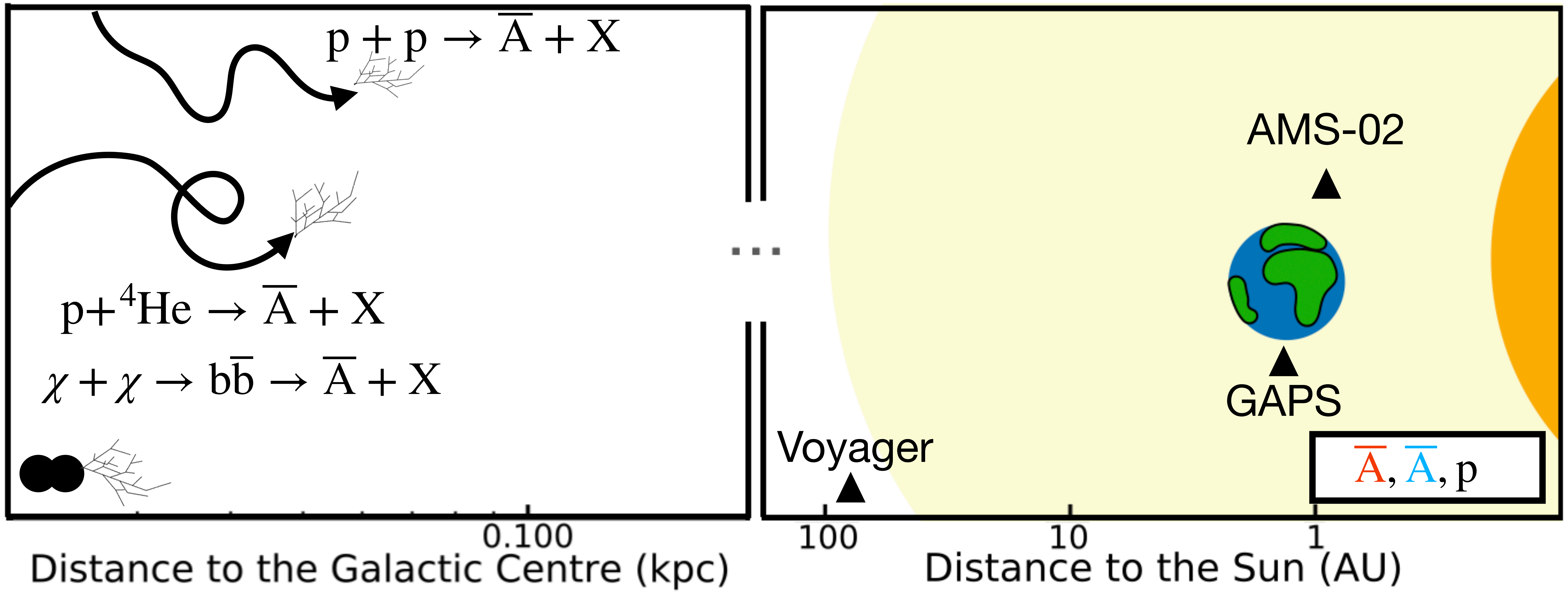
Source Function



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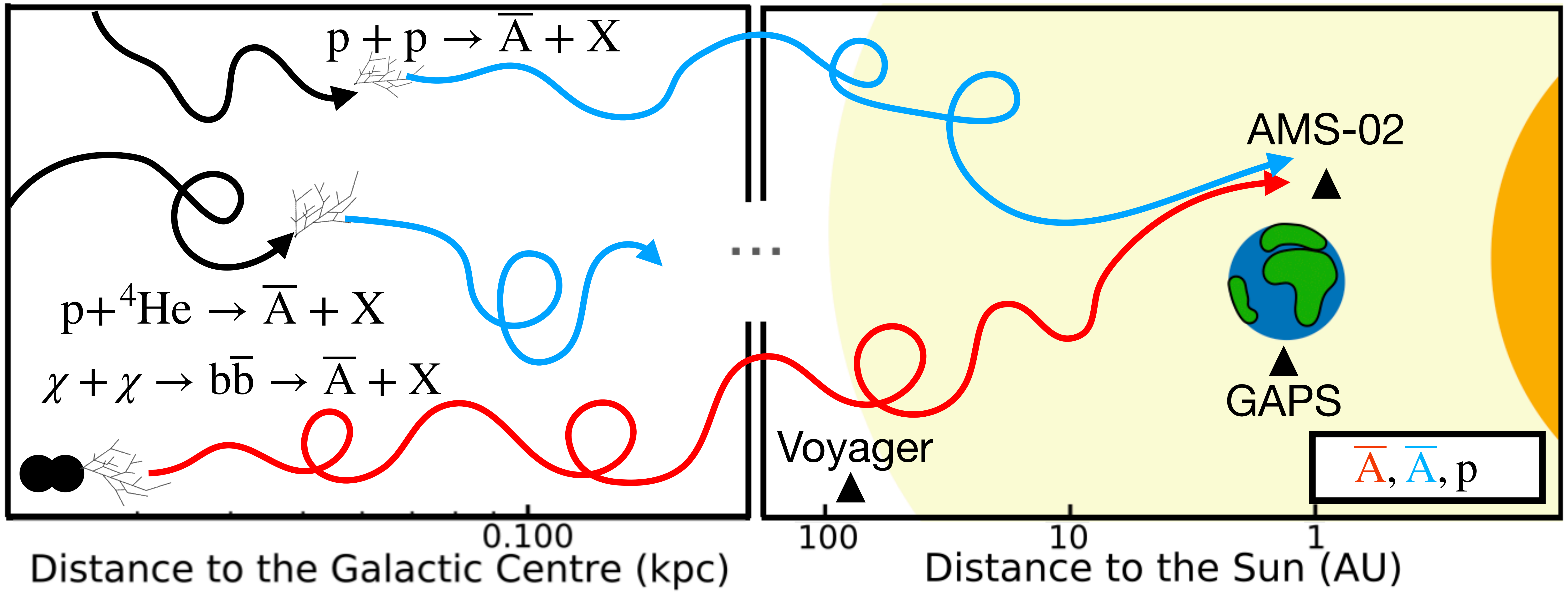
Source Function

Propagation: diffusion, convection…



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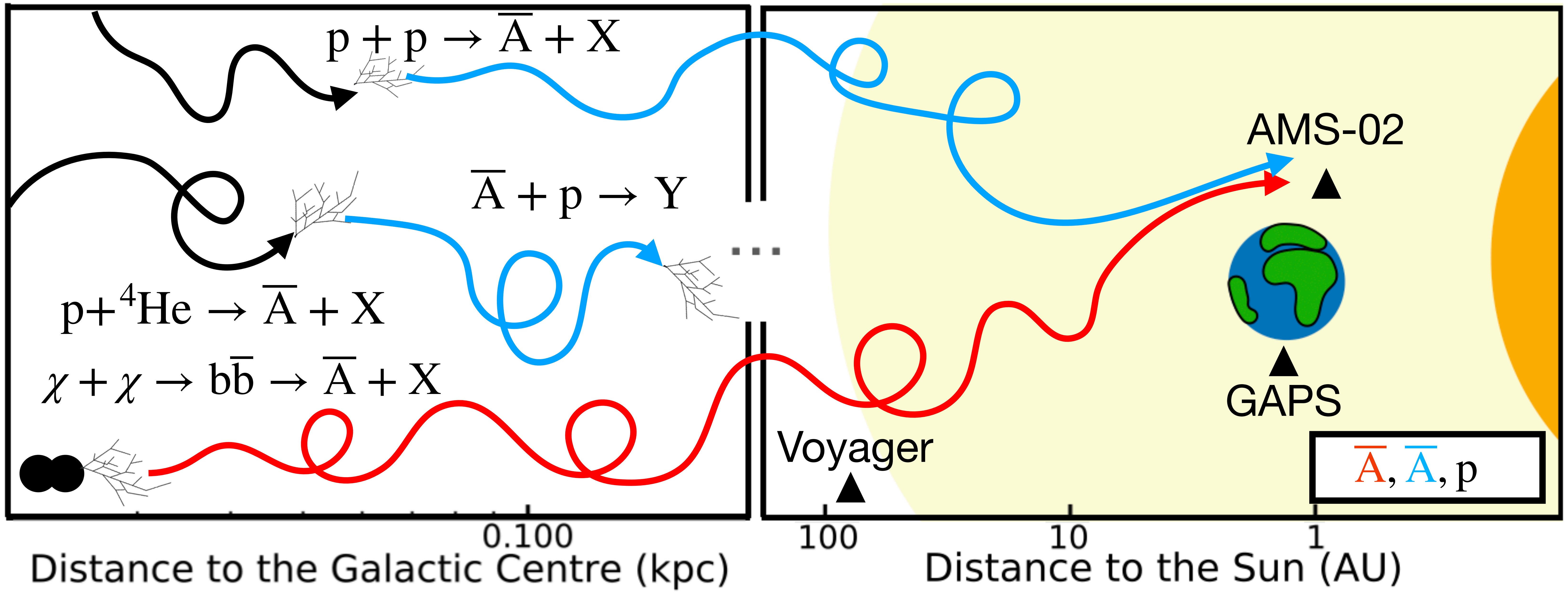
Propagation: diffusion, convection…

Fragmentation, annihilation



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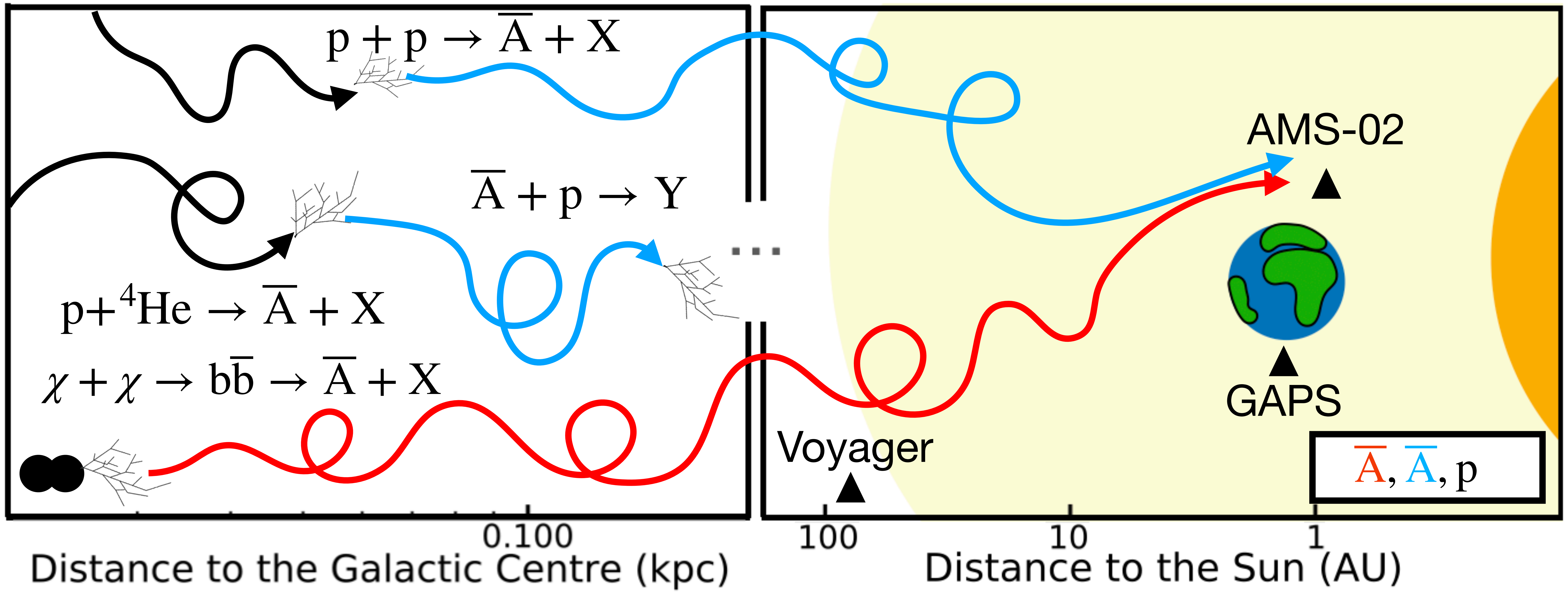
Can be numerically solved using the GALPROP code

A. W. Strong and I. V. Moskalenko, ApJ 509 212 (1998)



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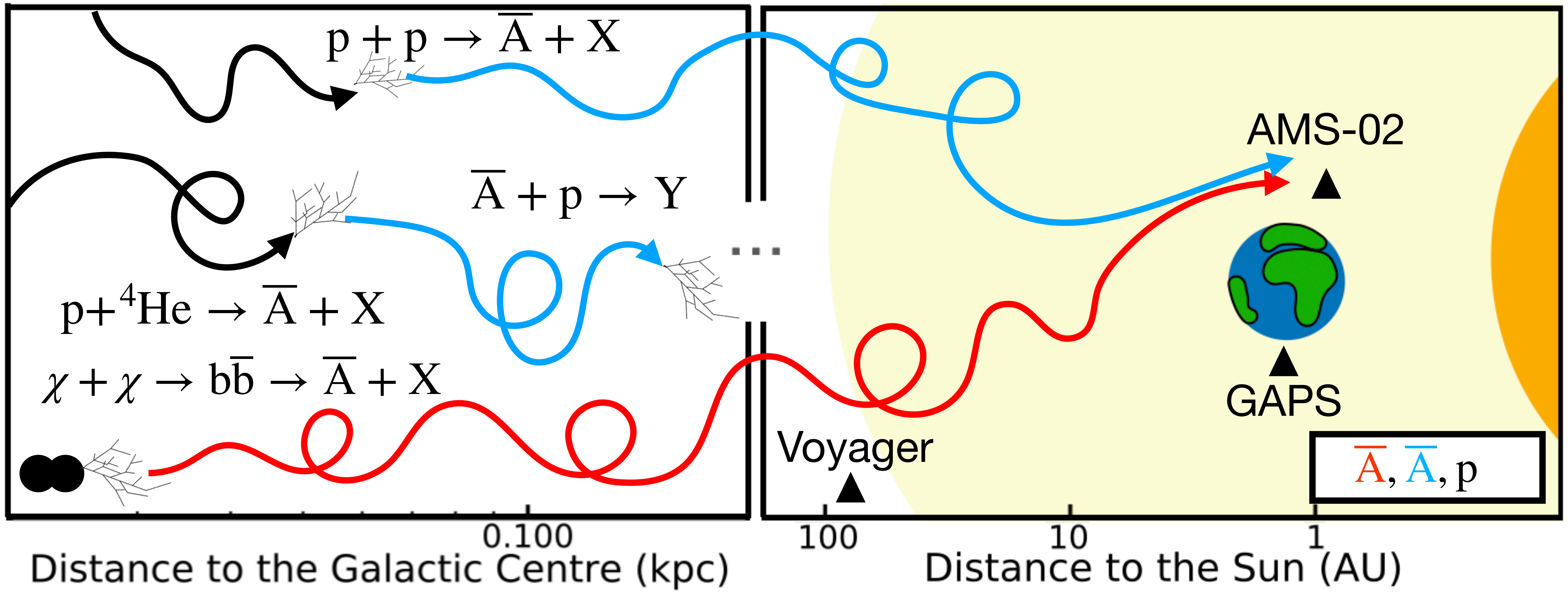

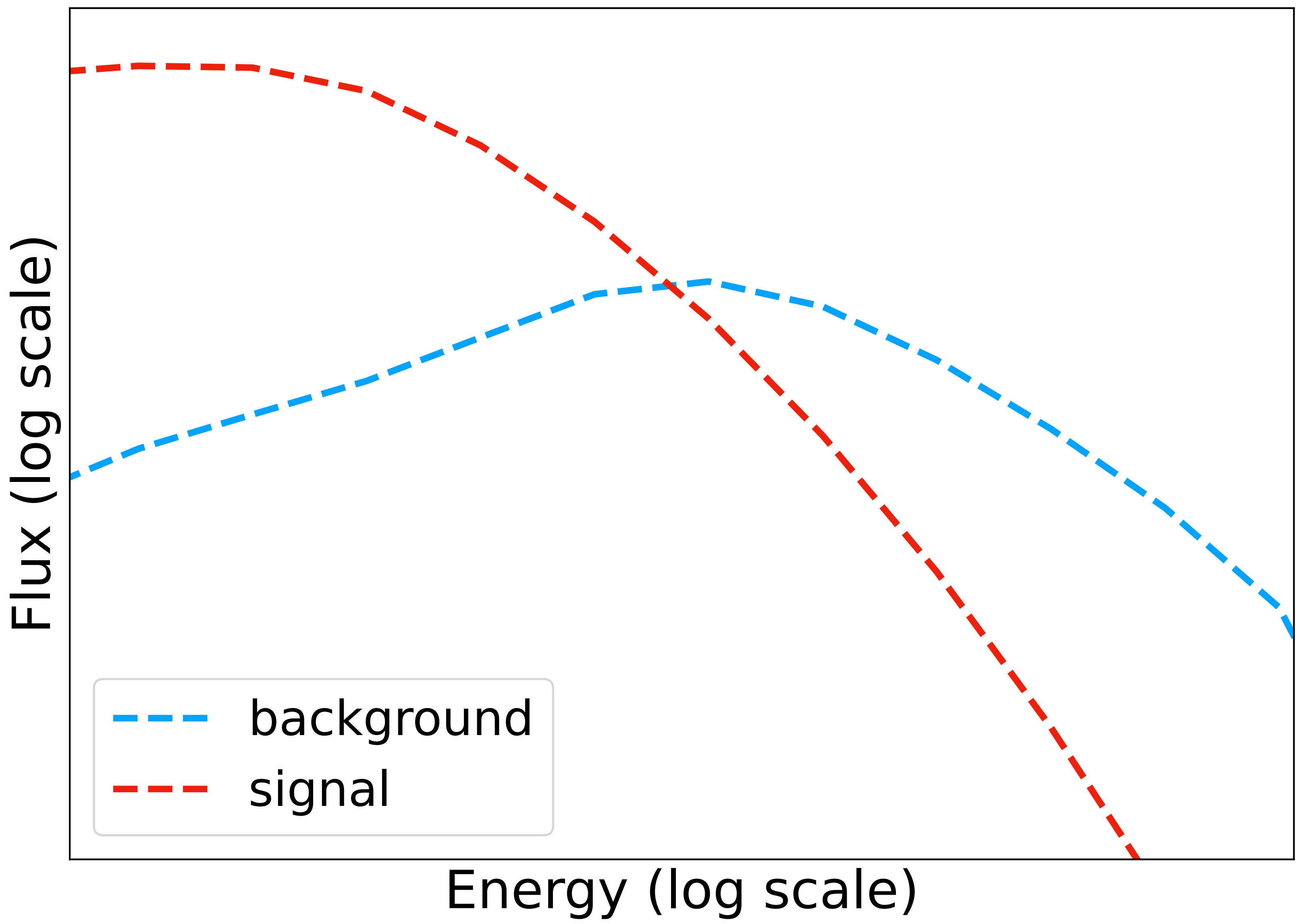

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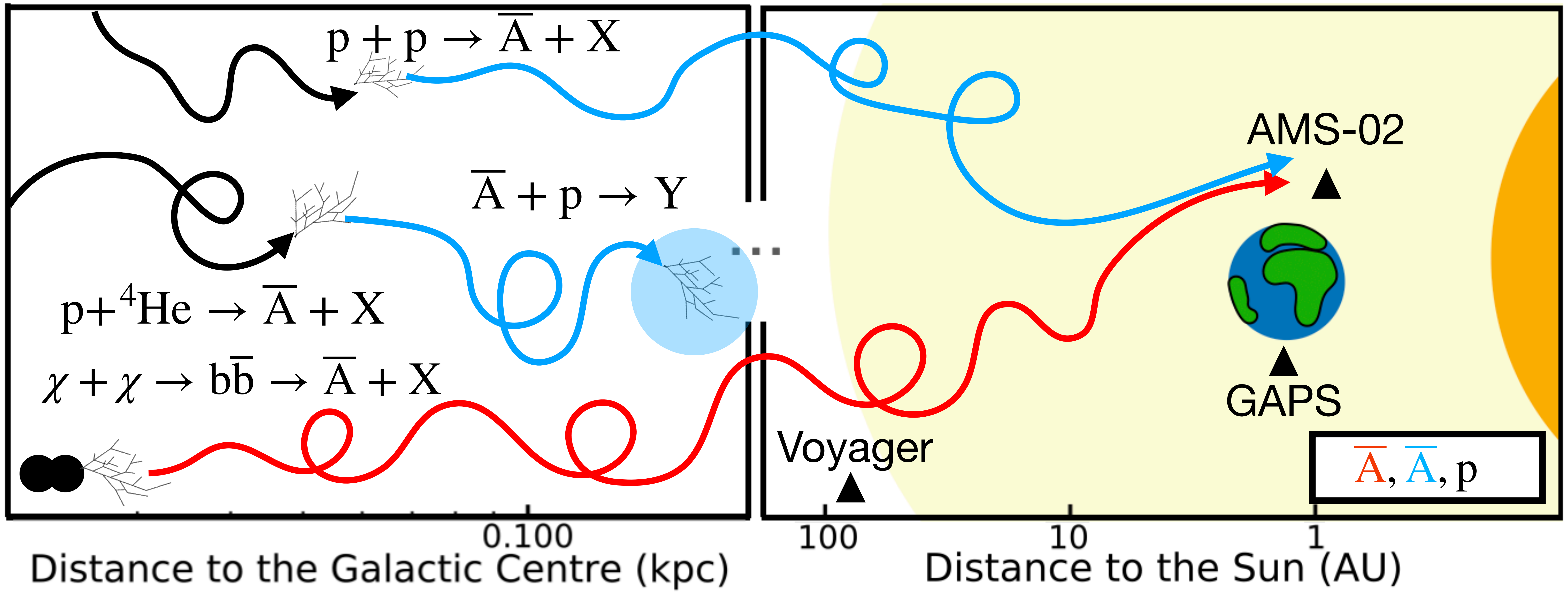

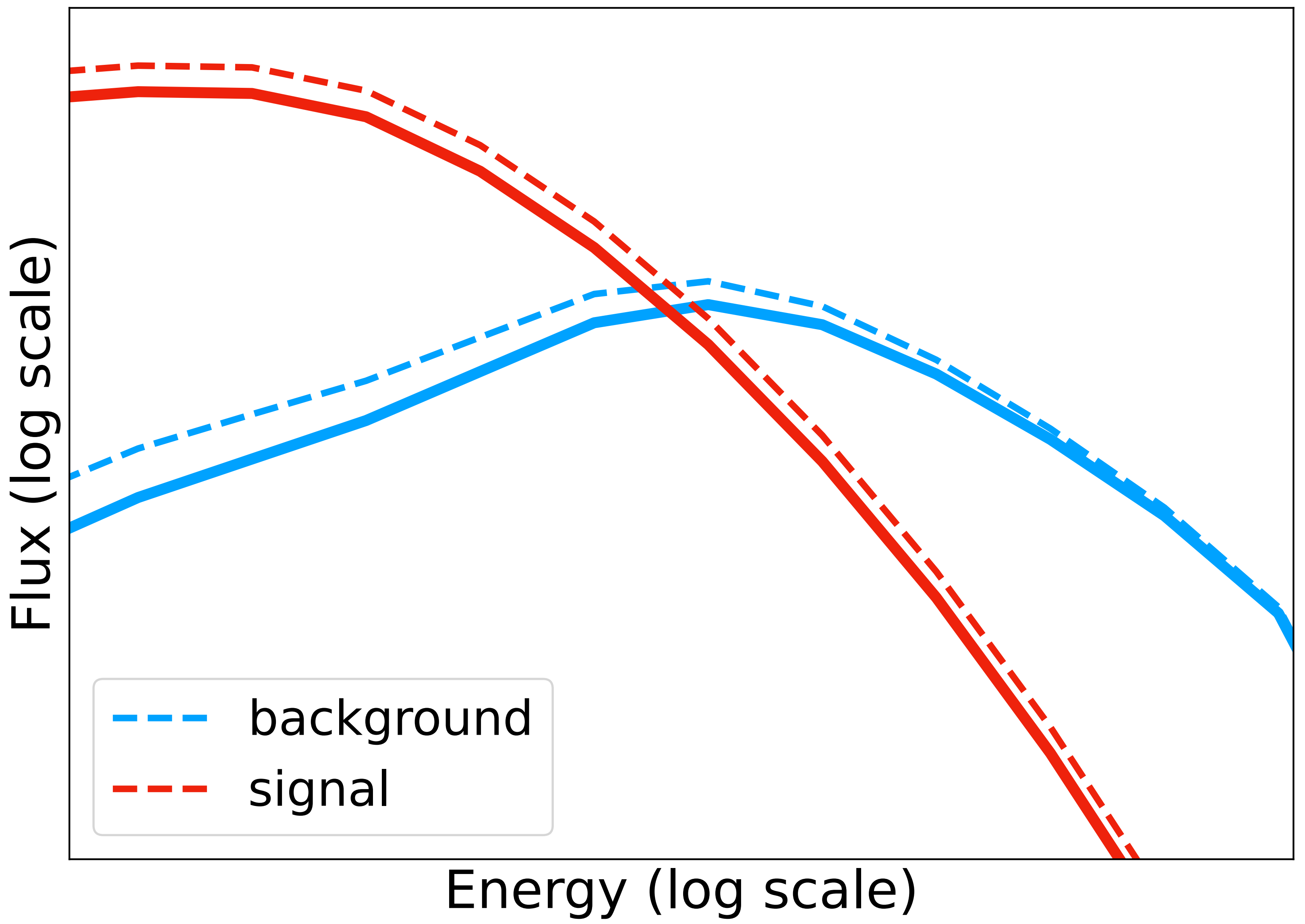

Inelastic antihelium cross-section

- Series of inelastic cross section measurements on heavy target material $\langle A \rangle = 34.7$
  - antideuterons, antitriton and antihelium-3

ALICE: PRL 125, 162001; PLB 848, 138337 (2024); Nature Physics 19, 61-71 (2023)

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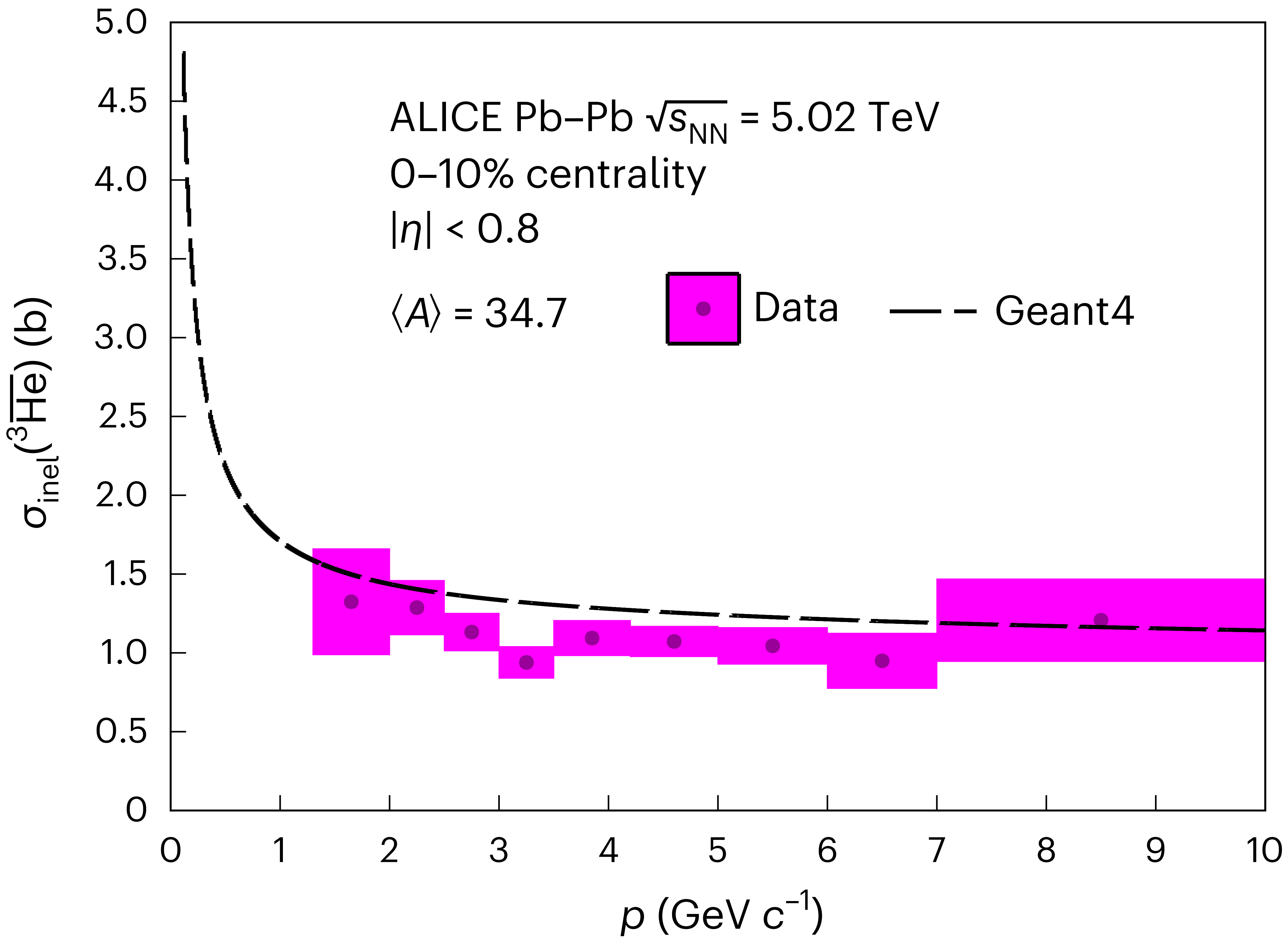

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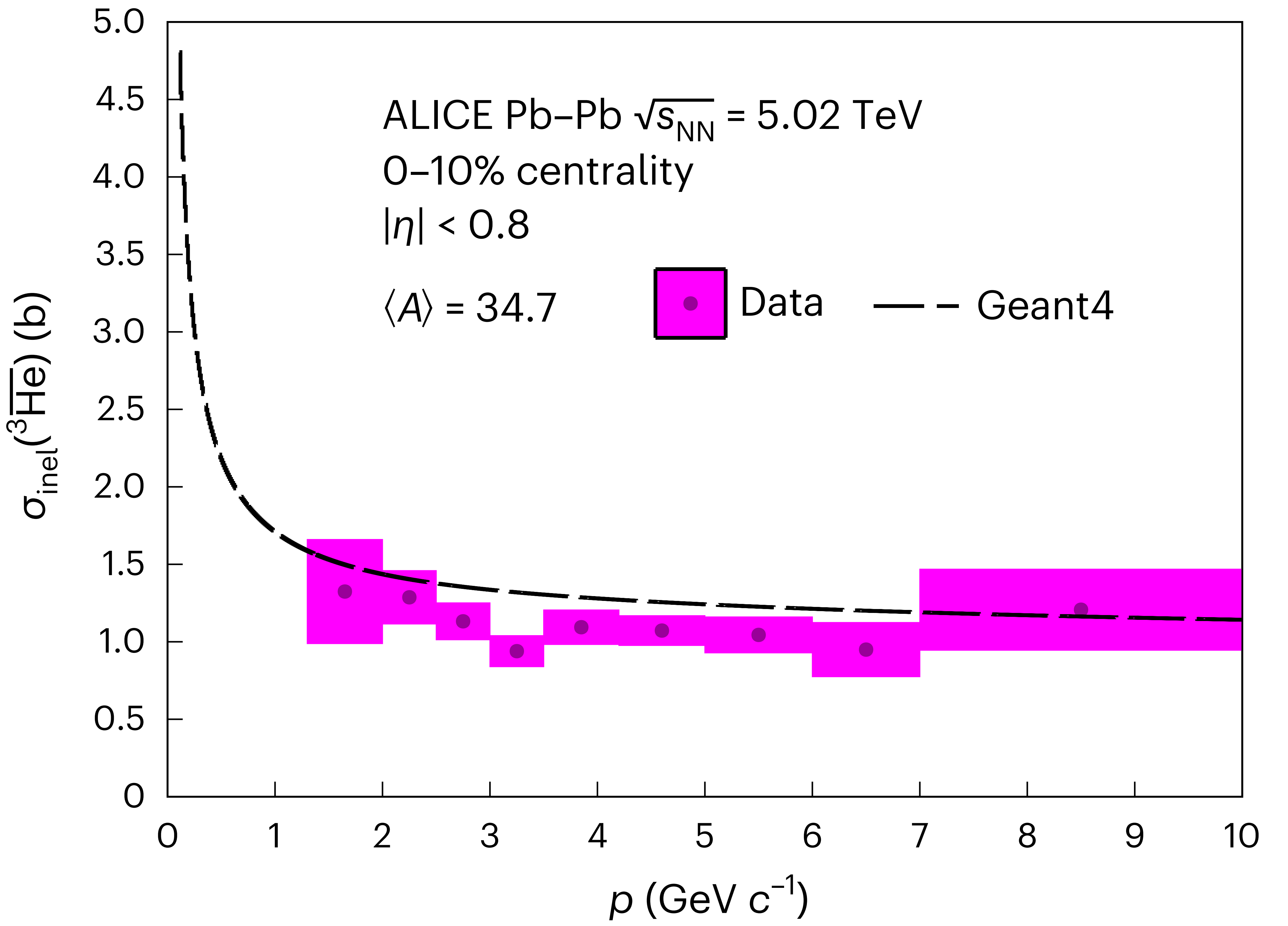
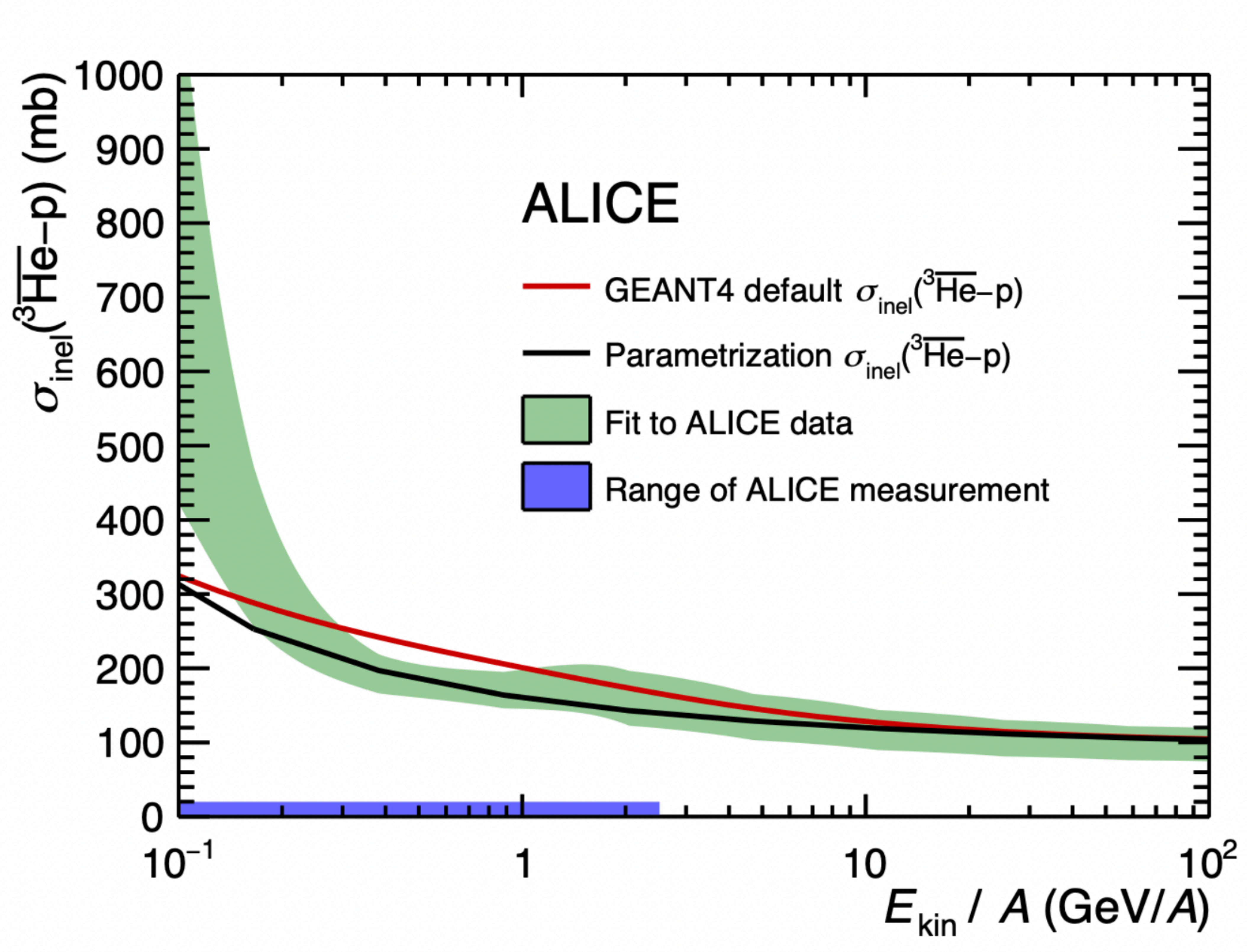
- Estimate for proton and helium targets at low energies

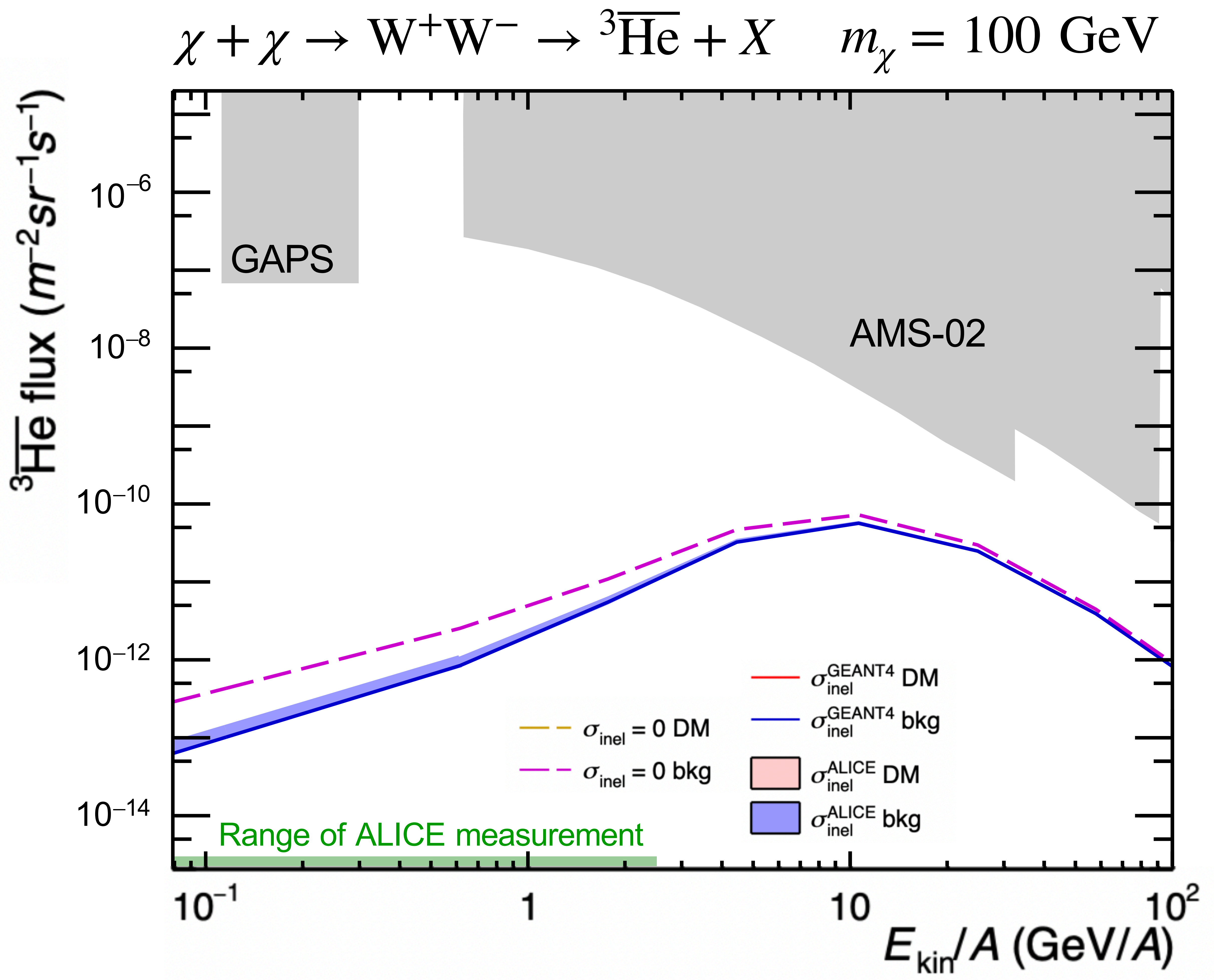


$$corr = \frac{\sigma_{ALICE}}{\sigma_{Geant4}}$$



Cosmic ray antihelium-3 at Earth

ALICE, Nature Physics 19, 61-71 (2023)



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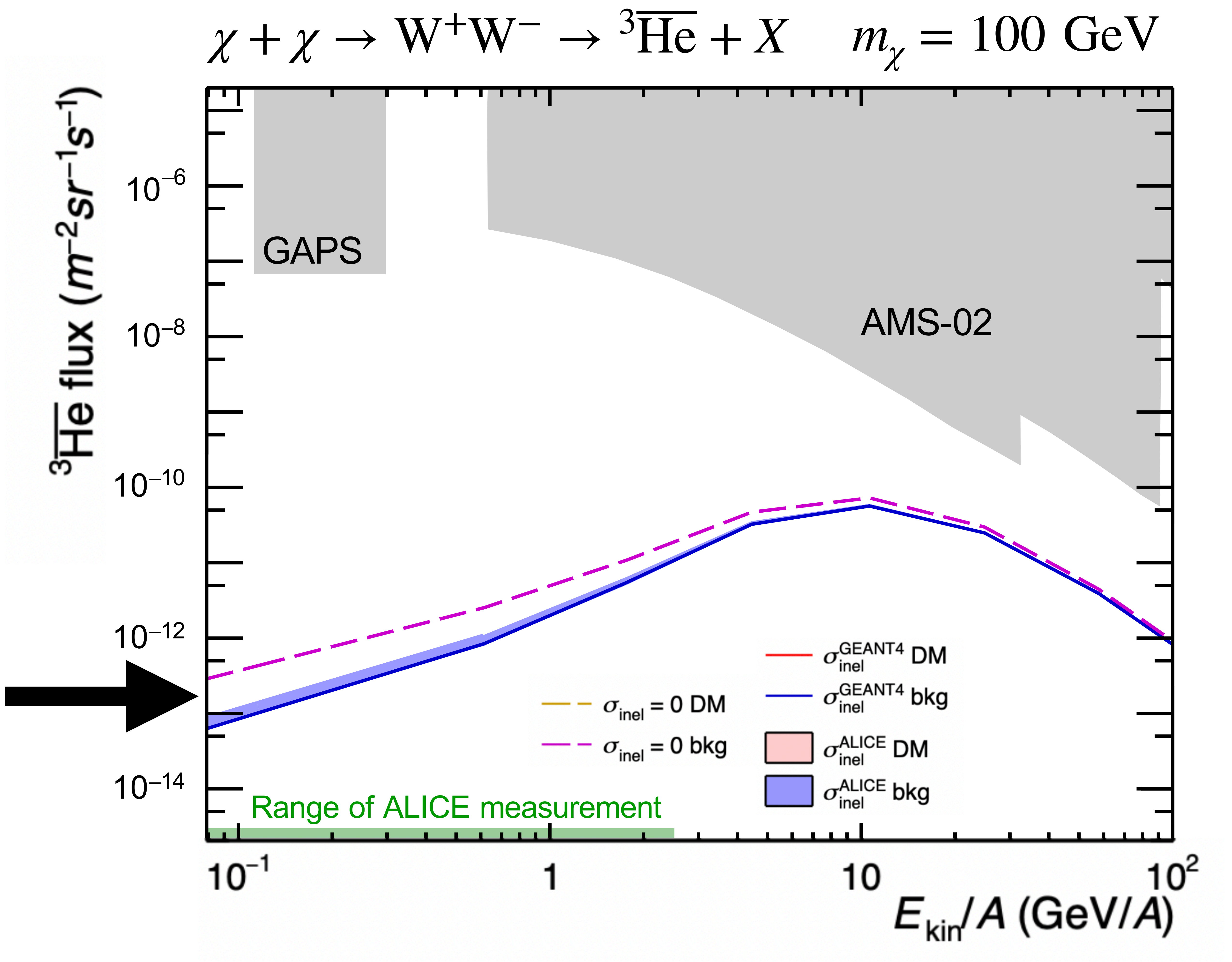
Inelastic interaction effect



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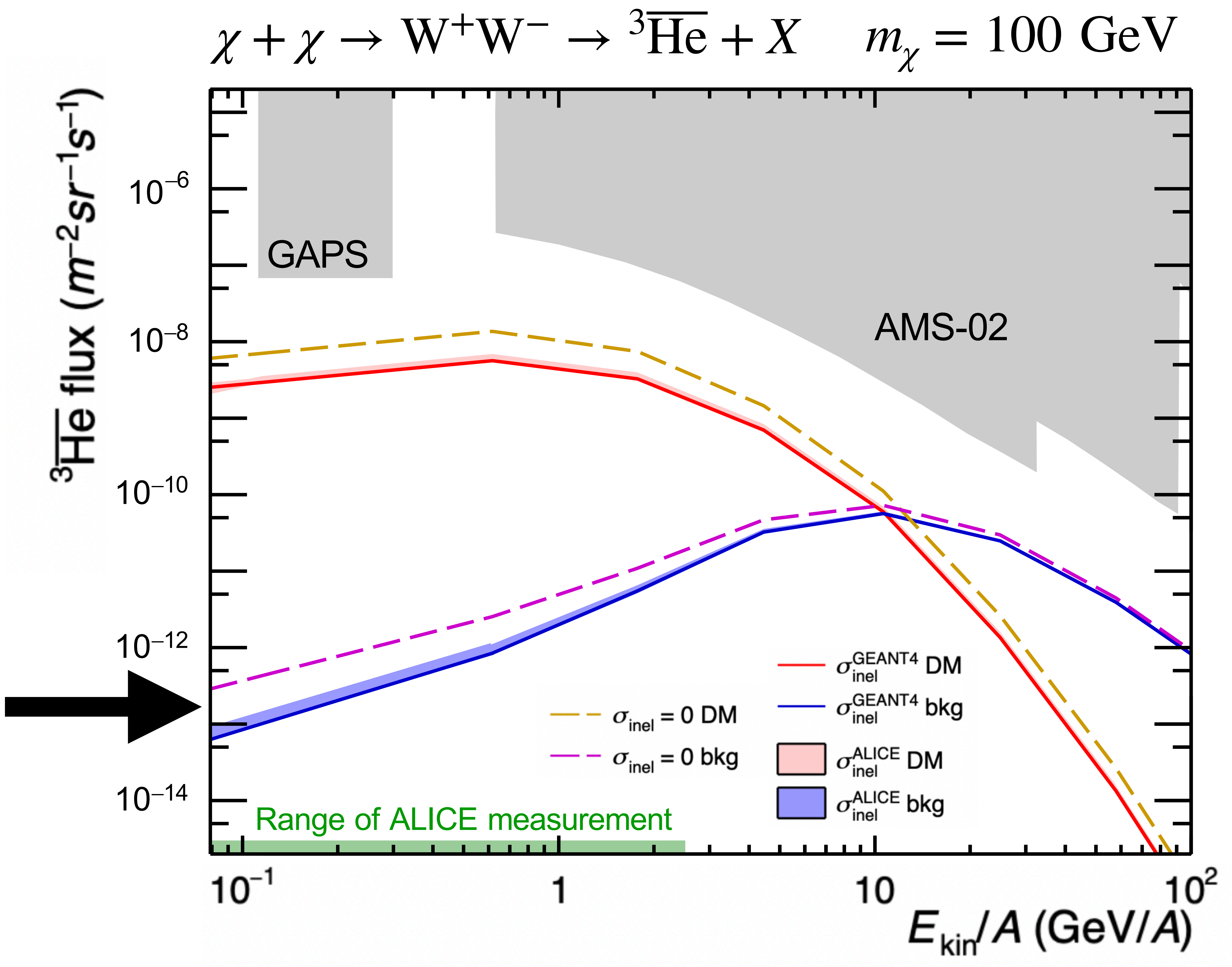

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Cosmic-ray antinuclei

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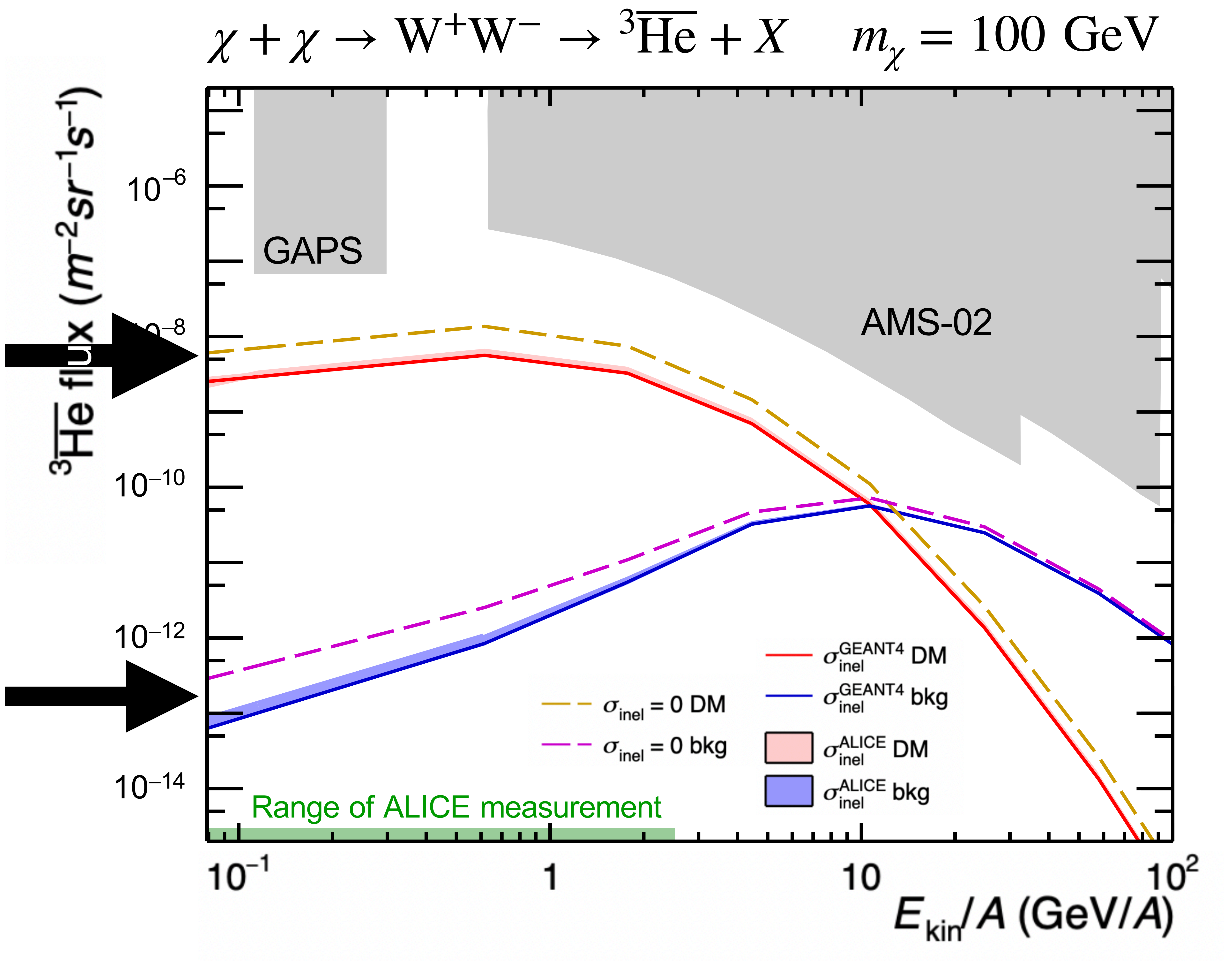

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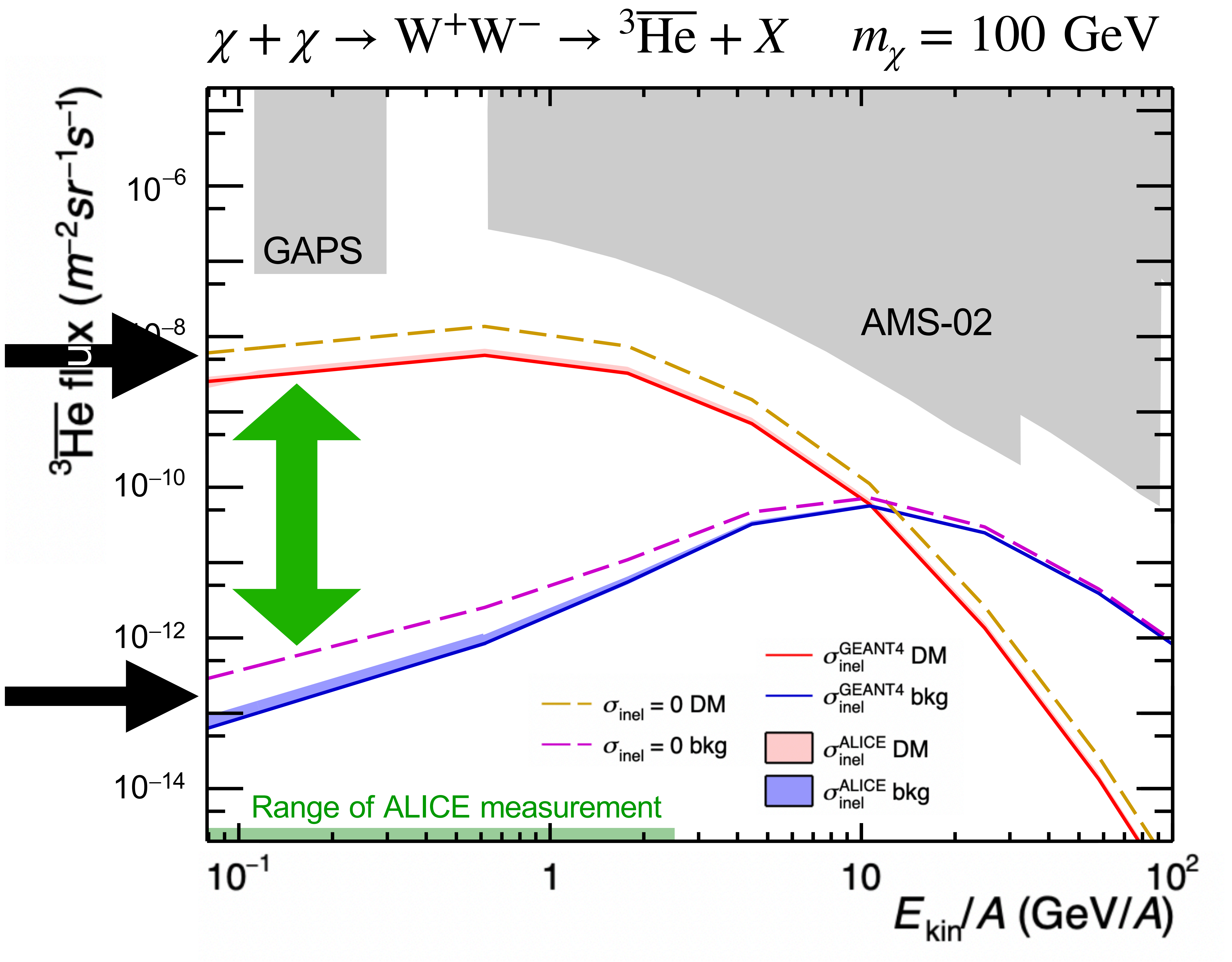
Good S/B



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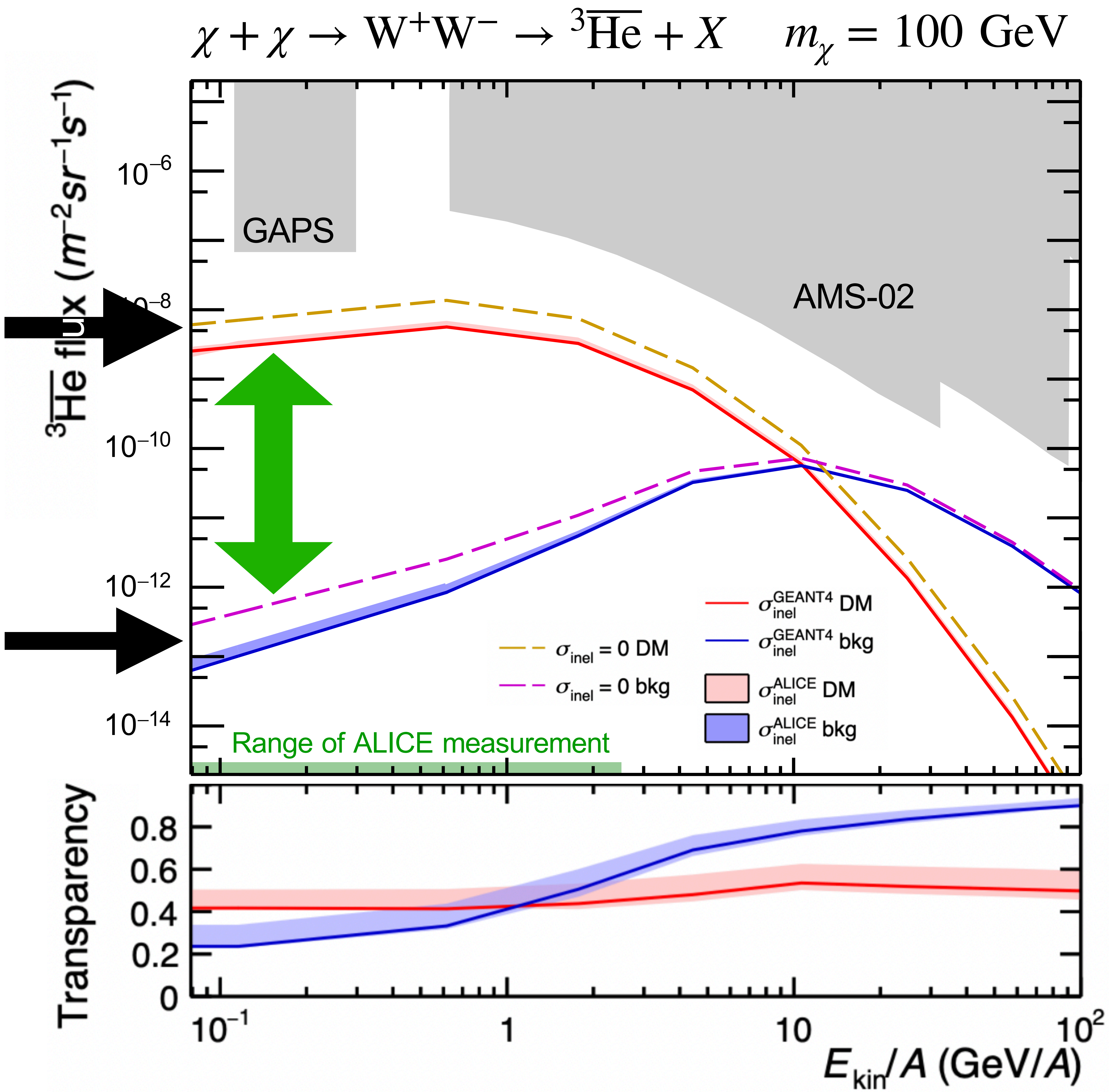

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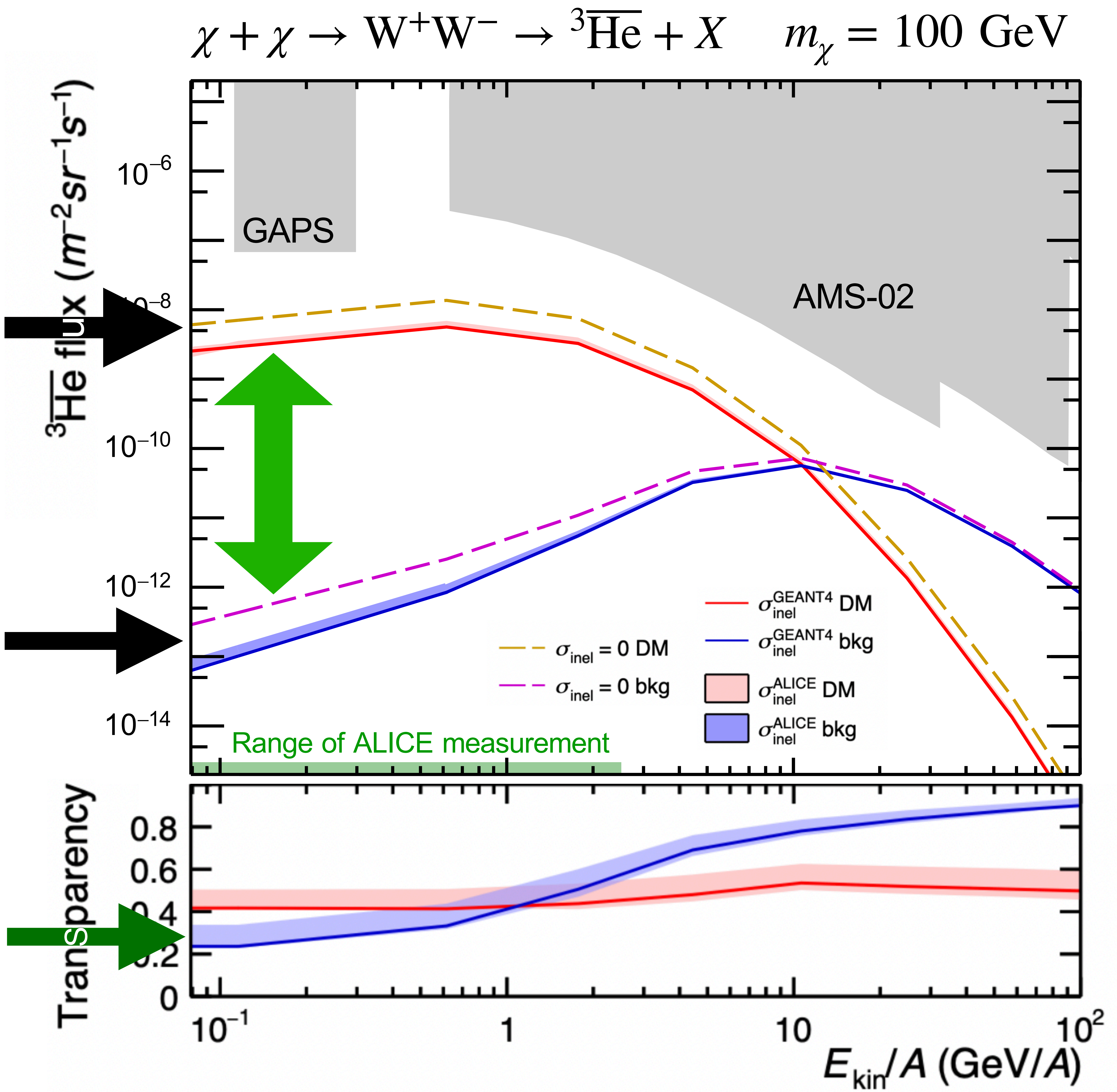
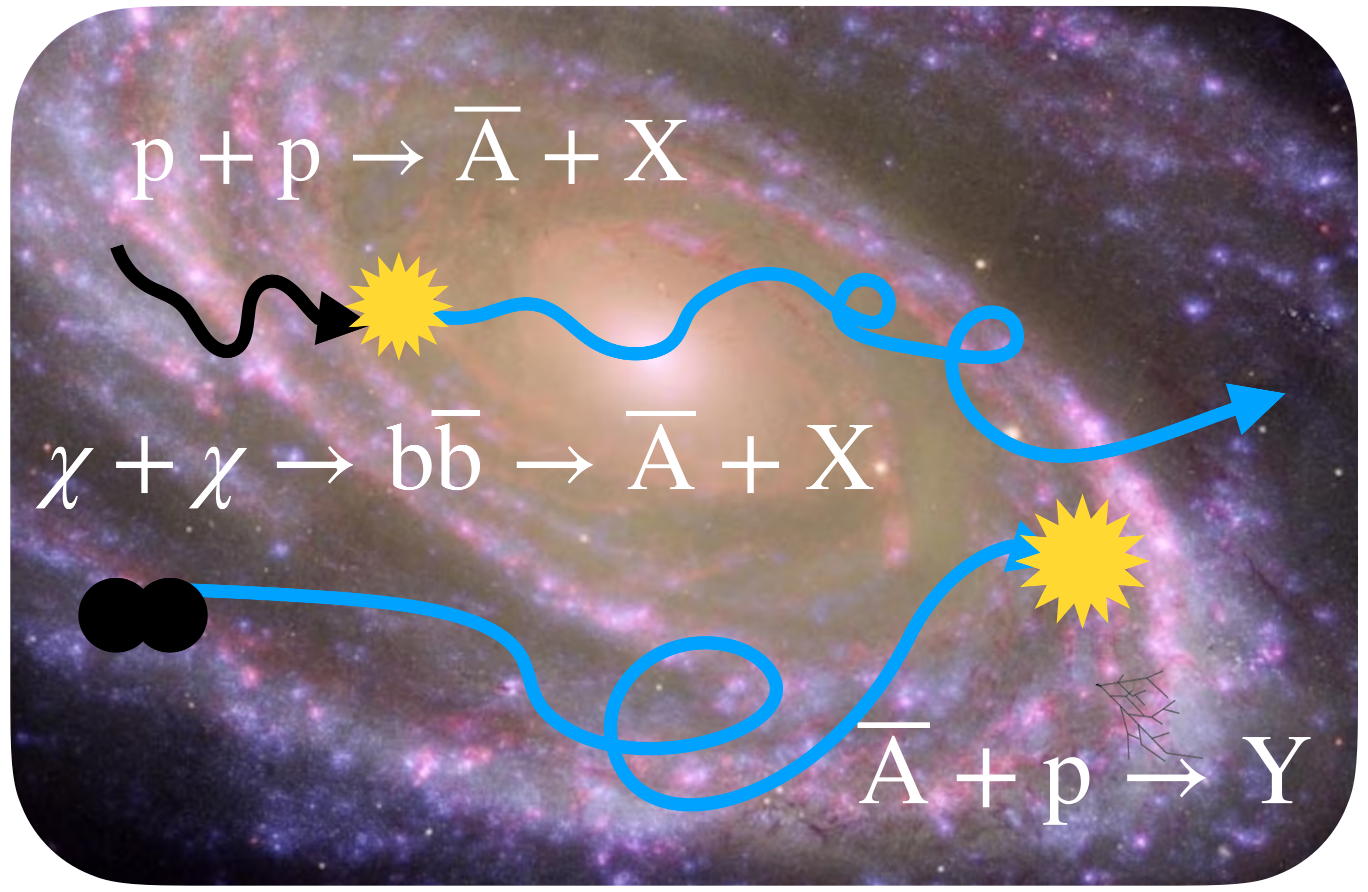
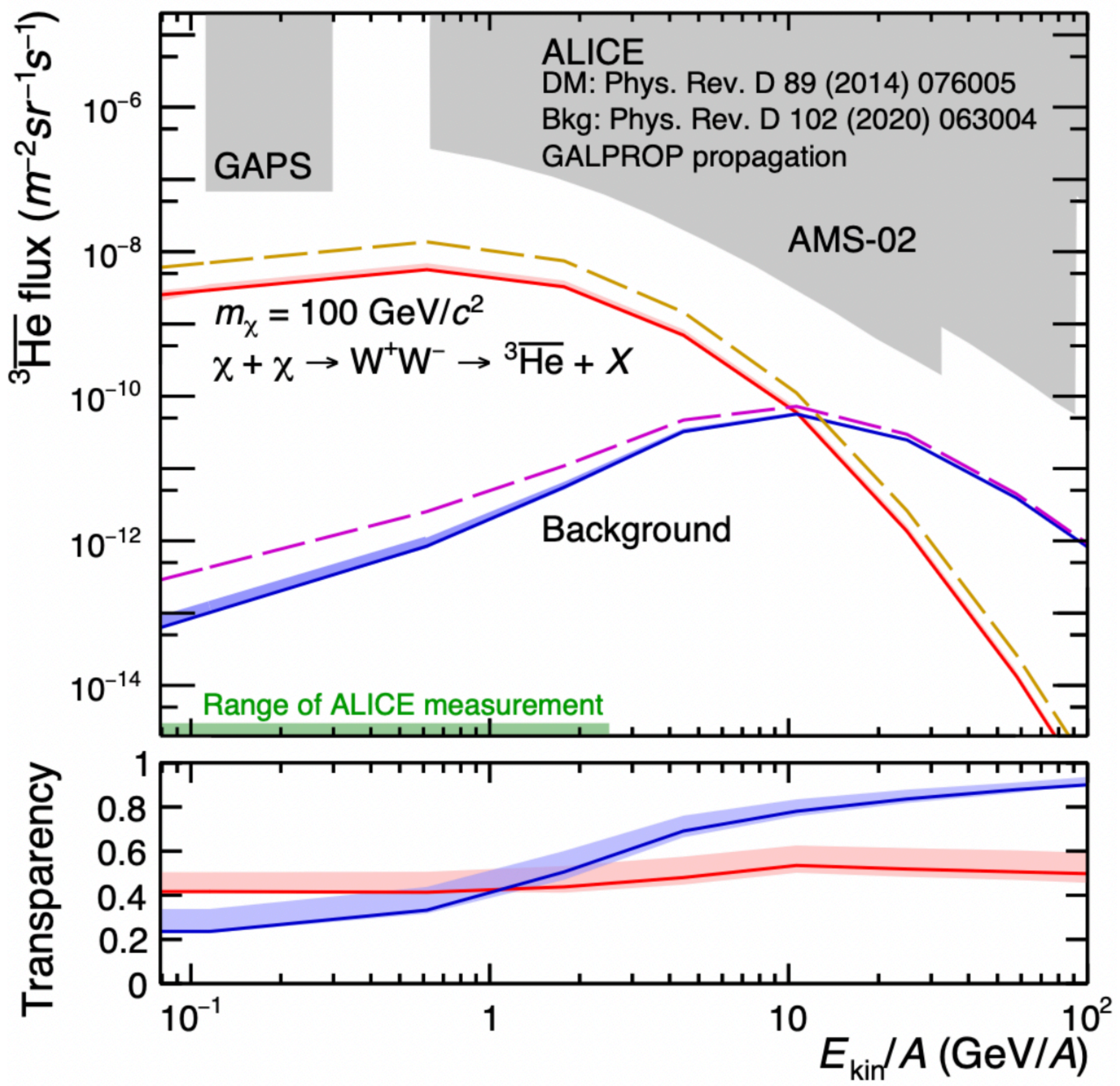


Cosmic-ray antinuclei

Three-baryon correlations



Our Galaxy is transparent to the propagation of antinuclei



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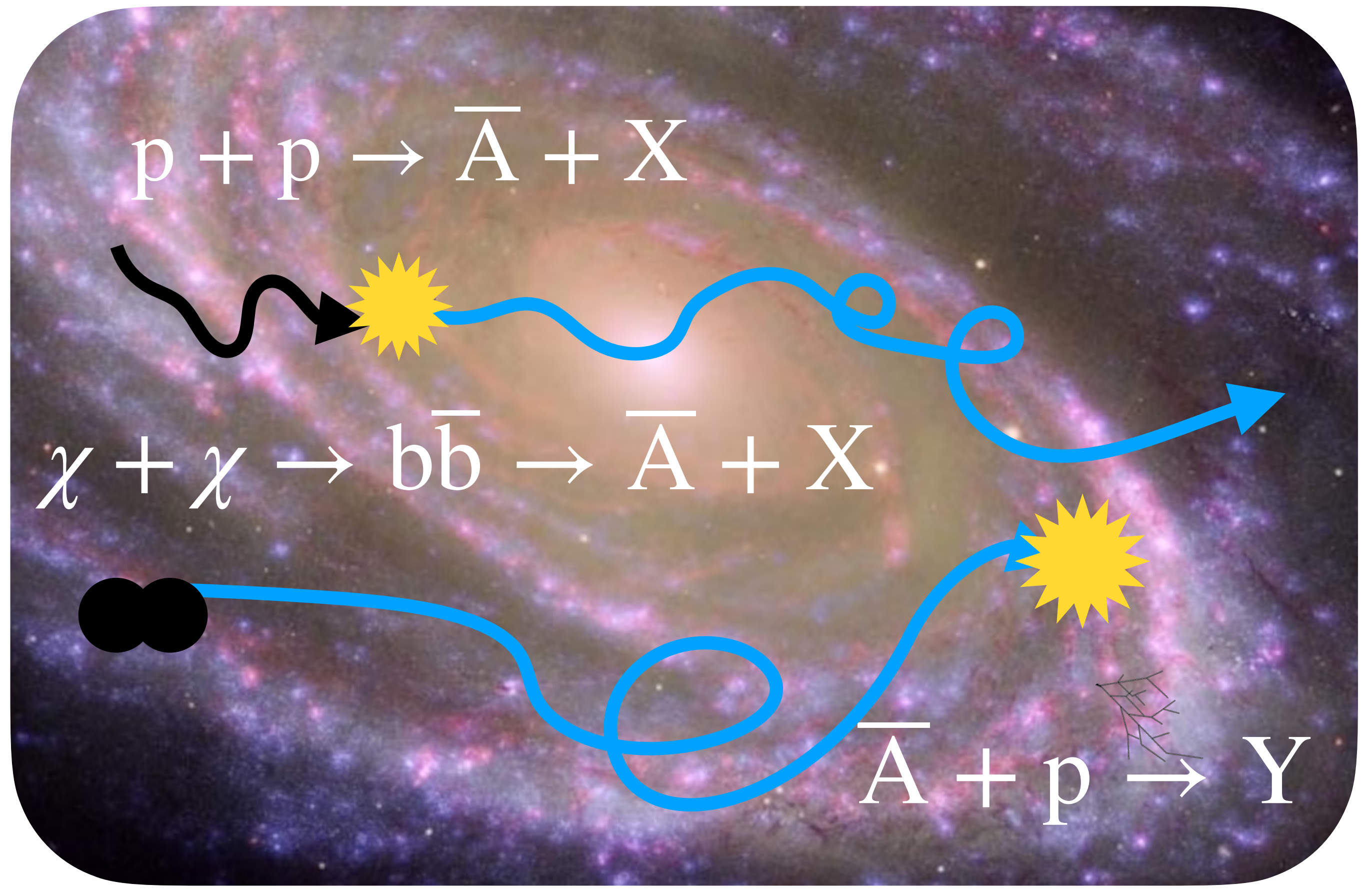

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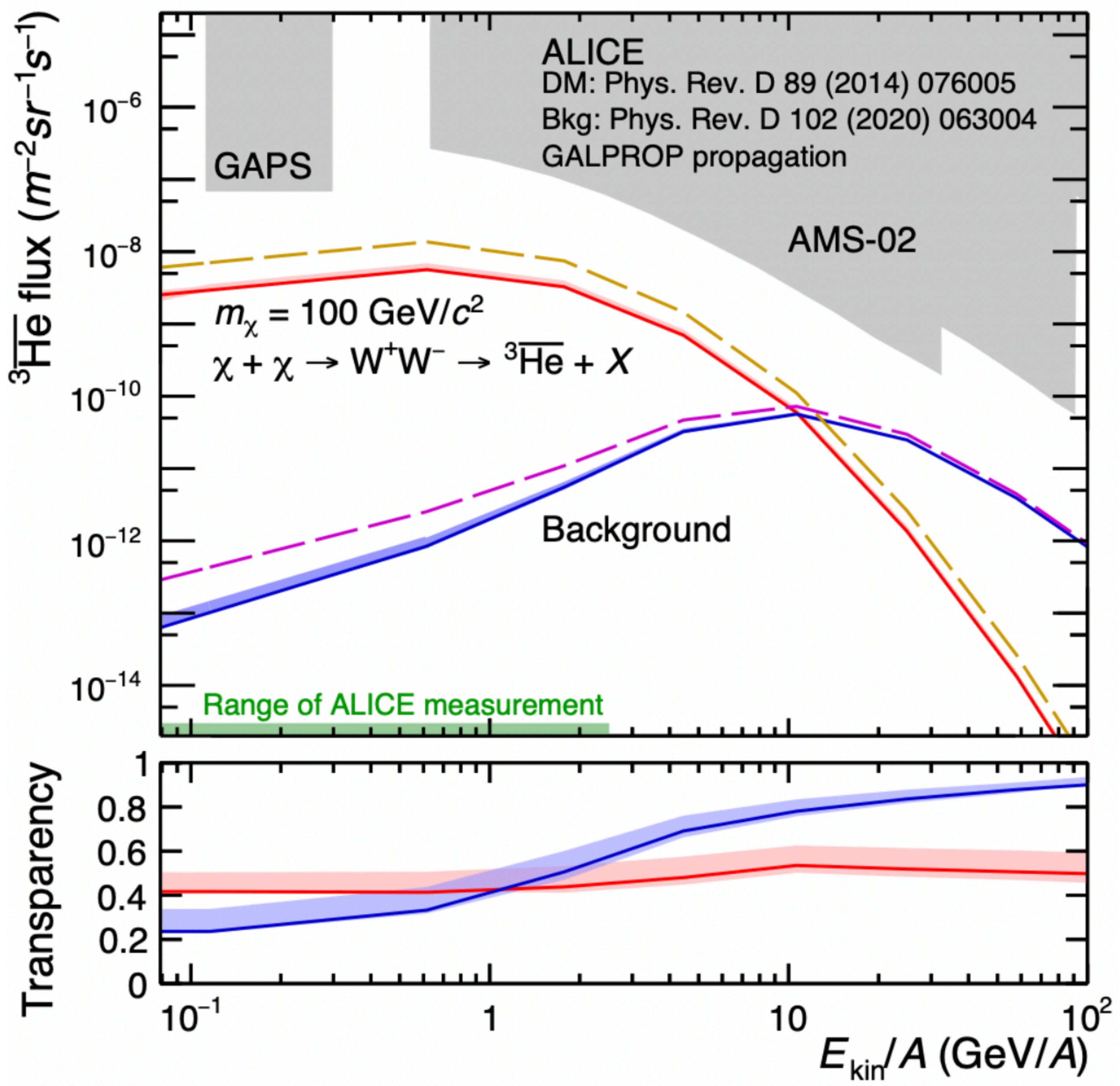

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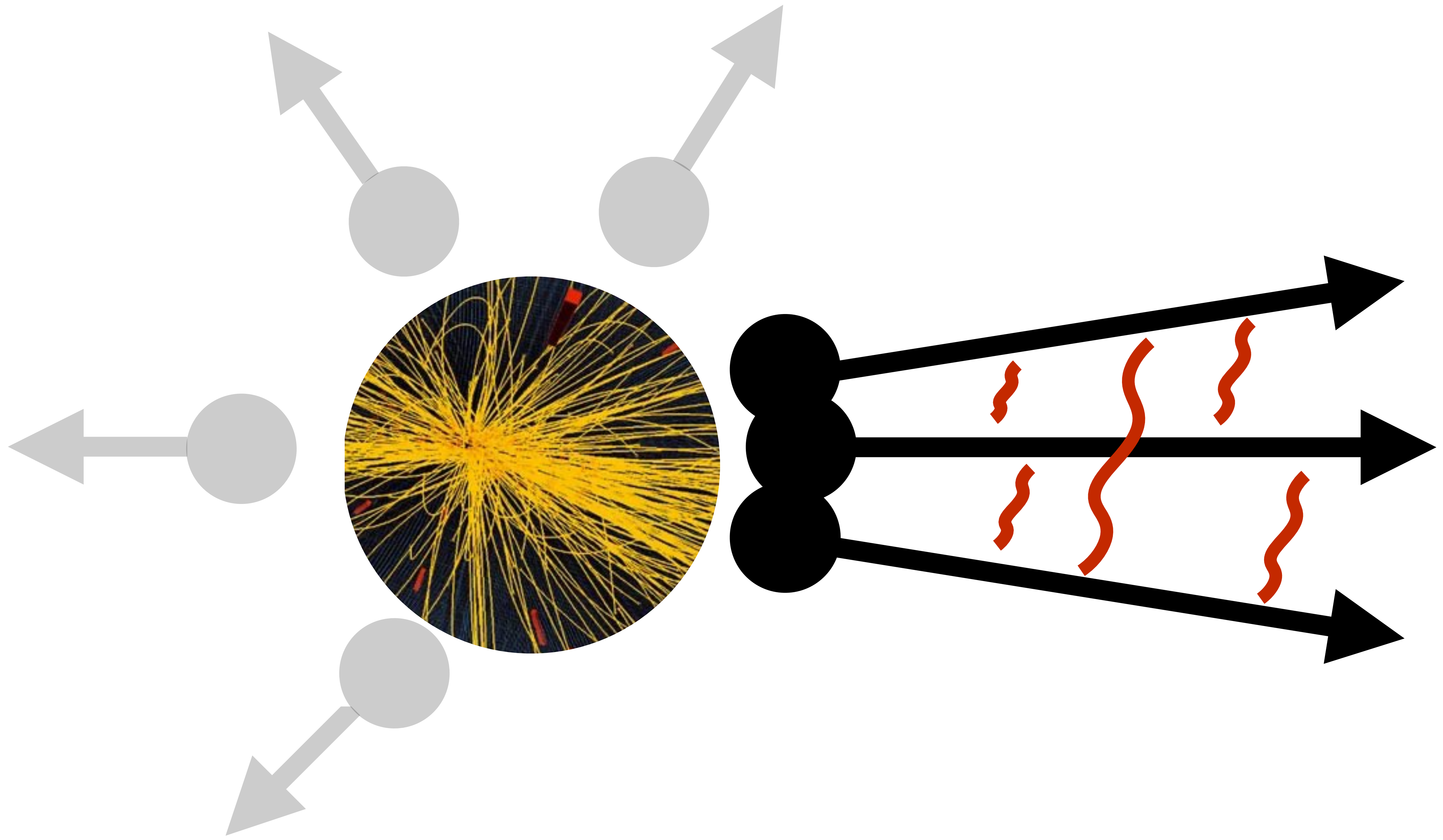
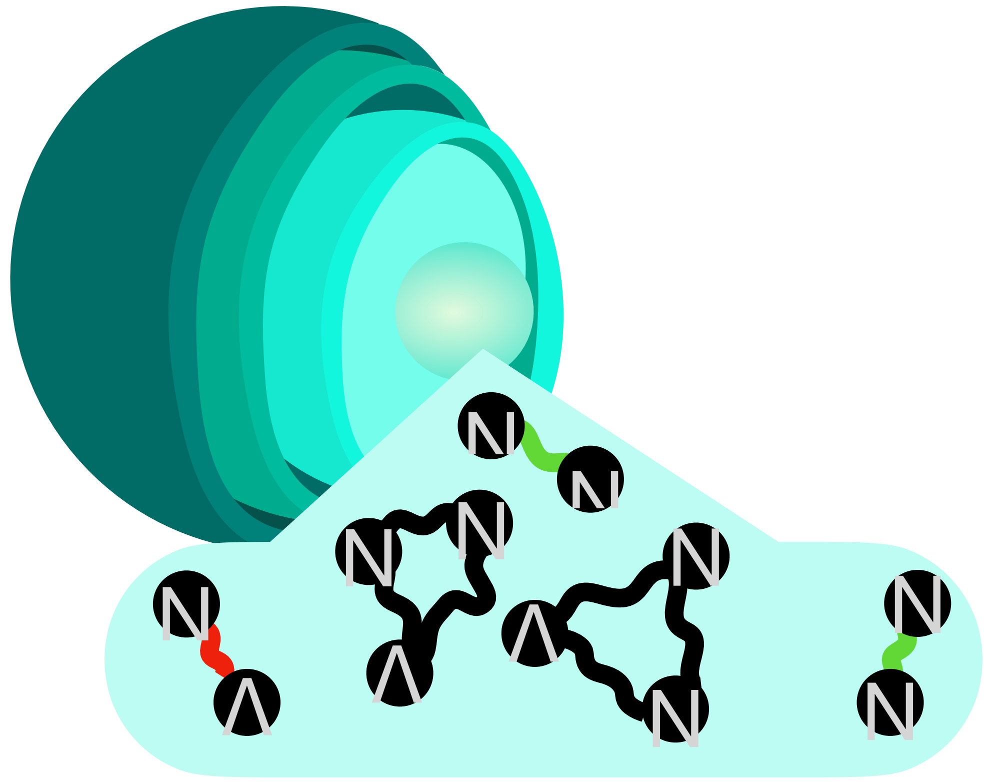
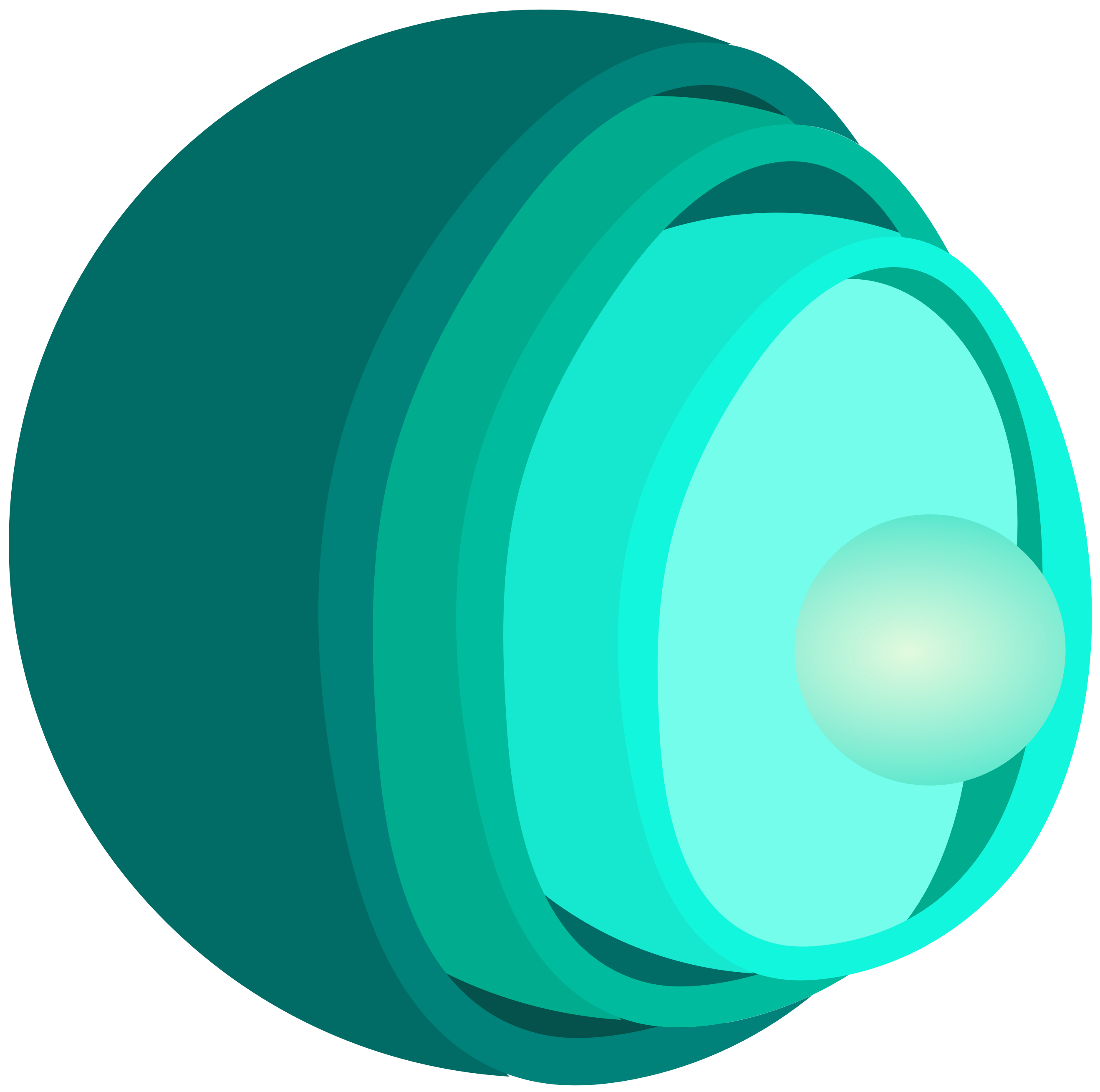




Neutron stars



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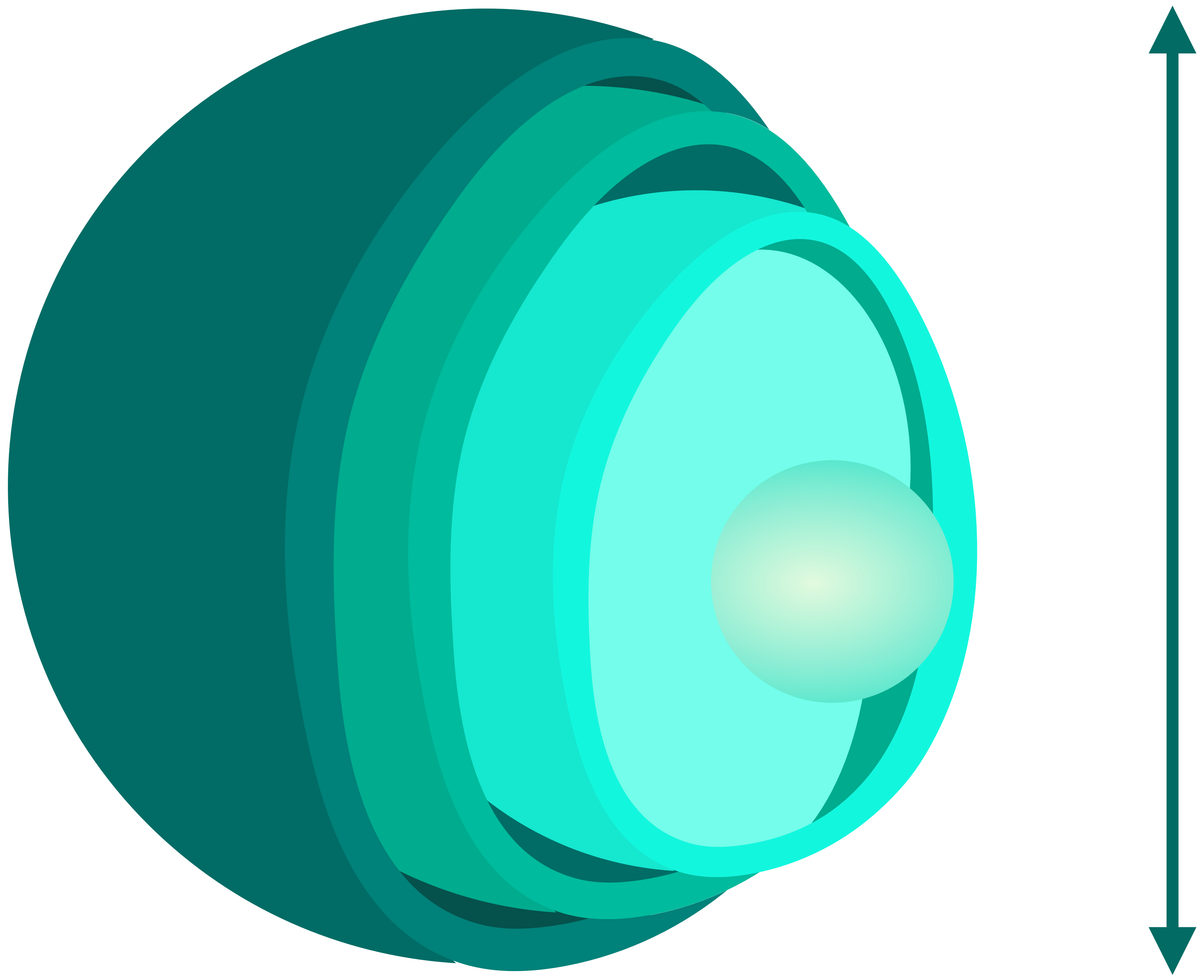

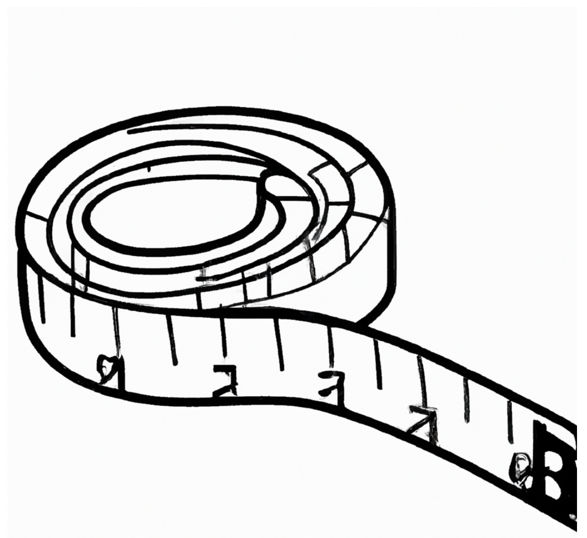

10 - 20 km

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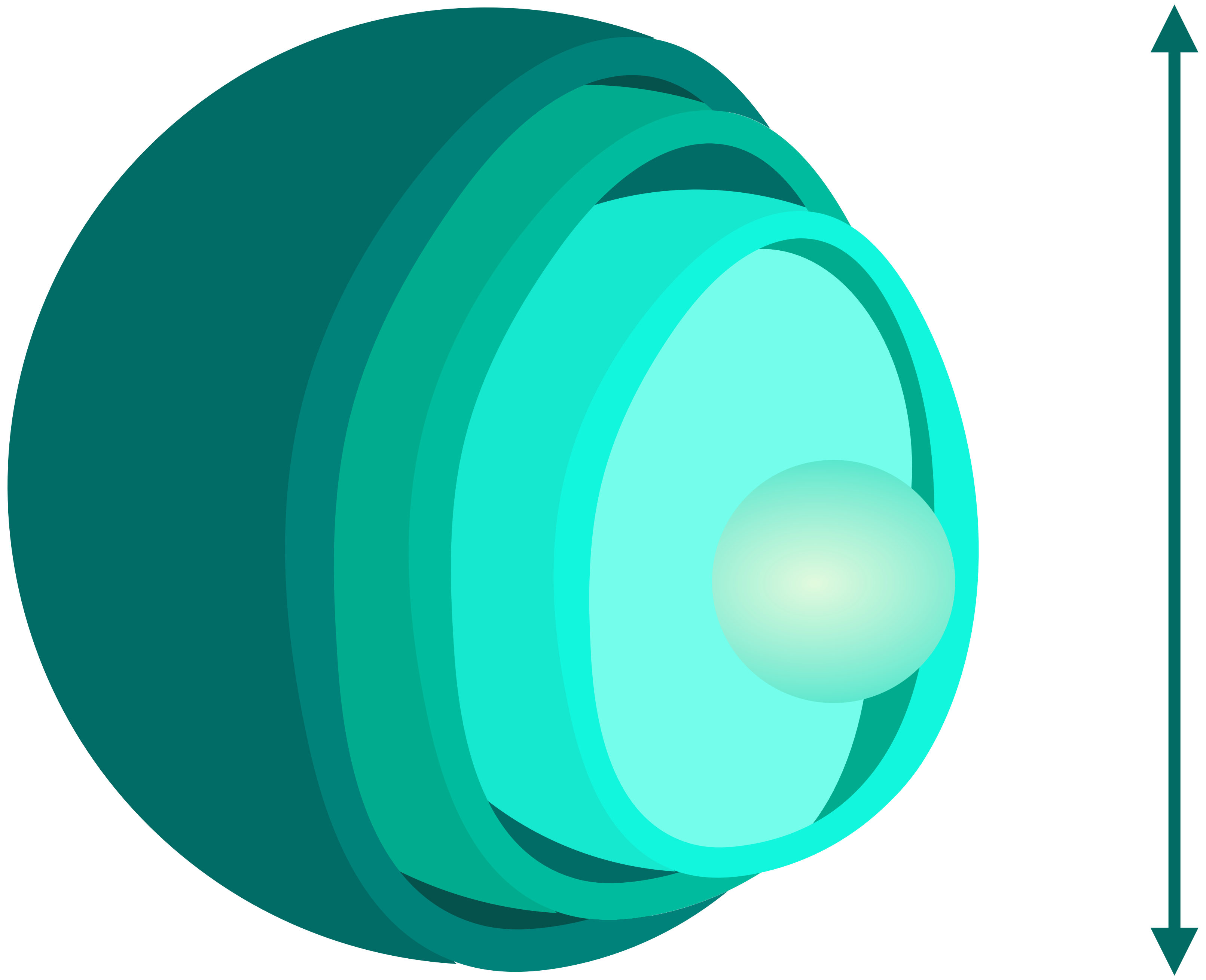

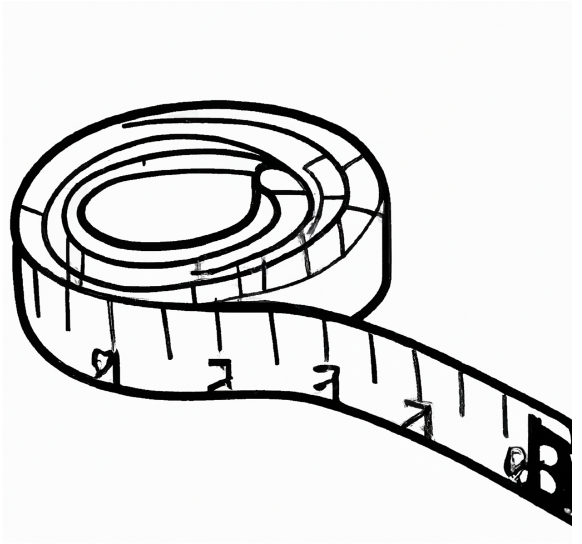

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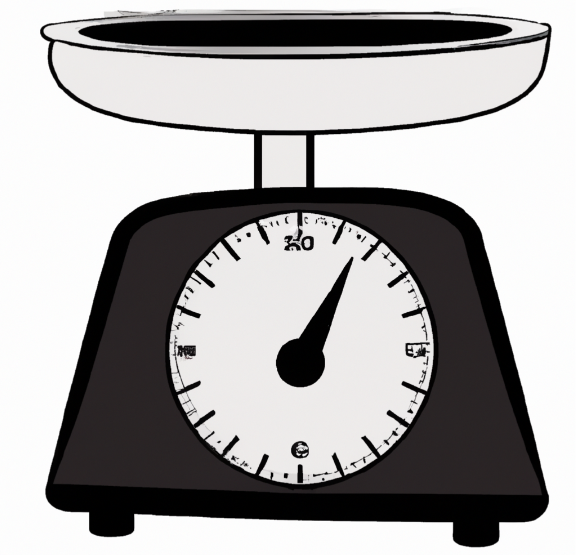
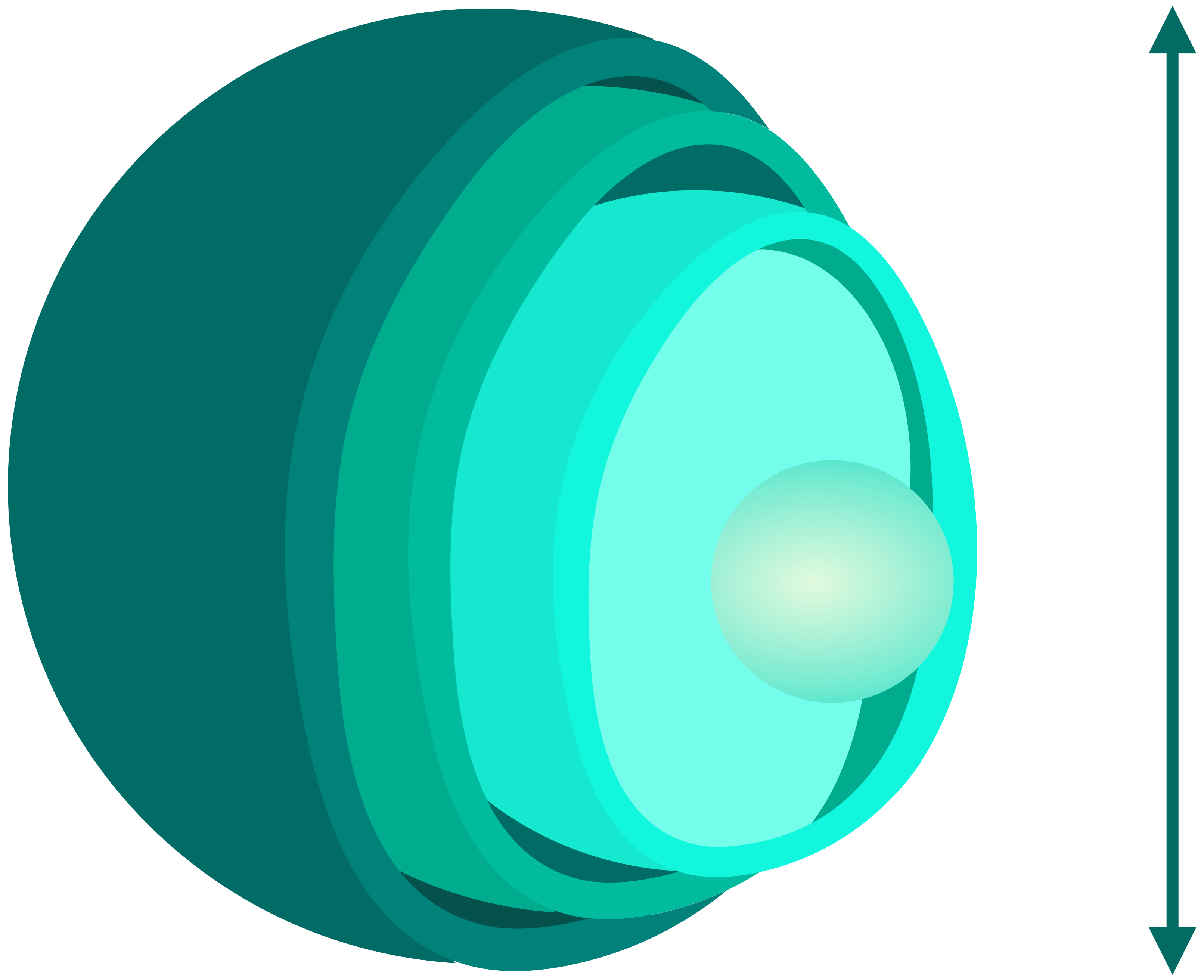
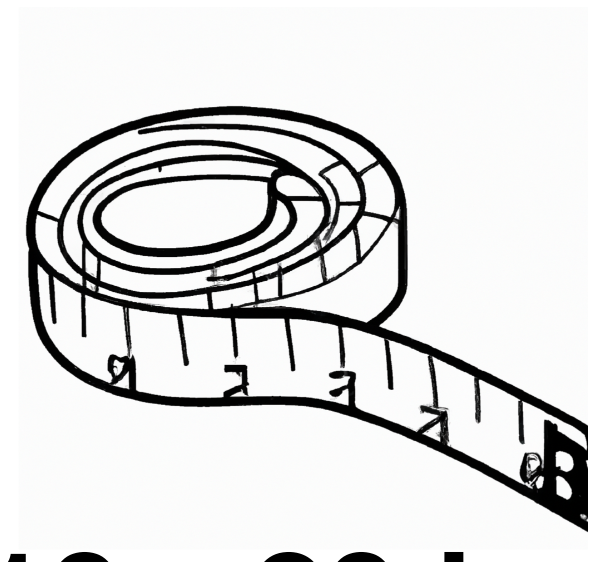


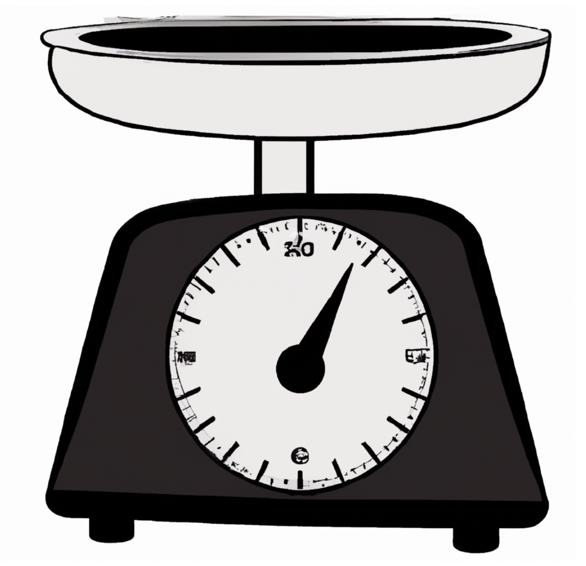
1 - 2 M_{sun}

Neutron stars





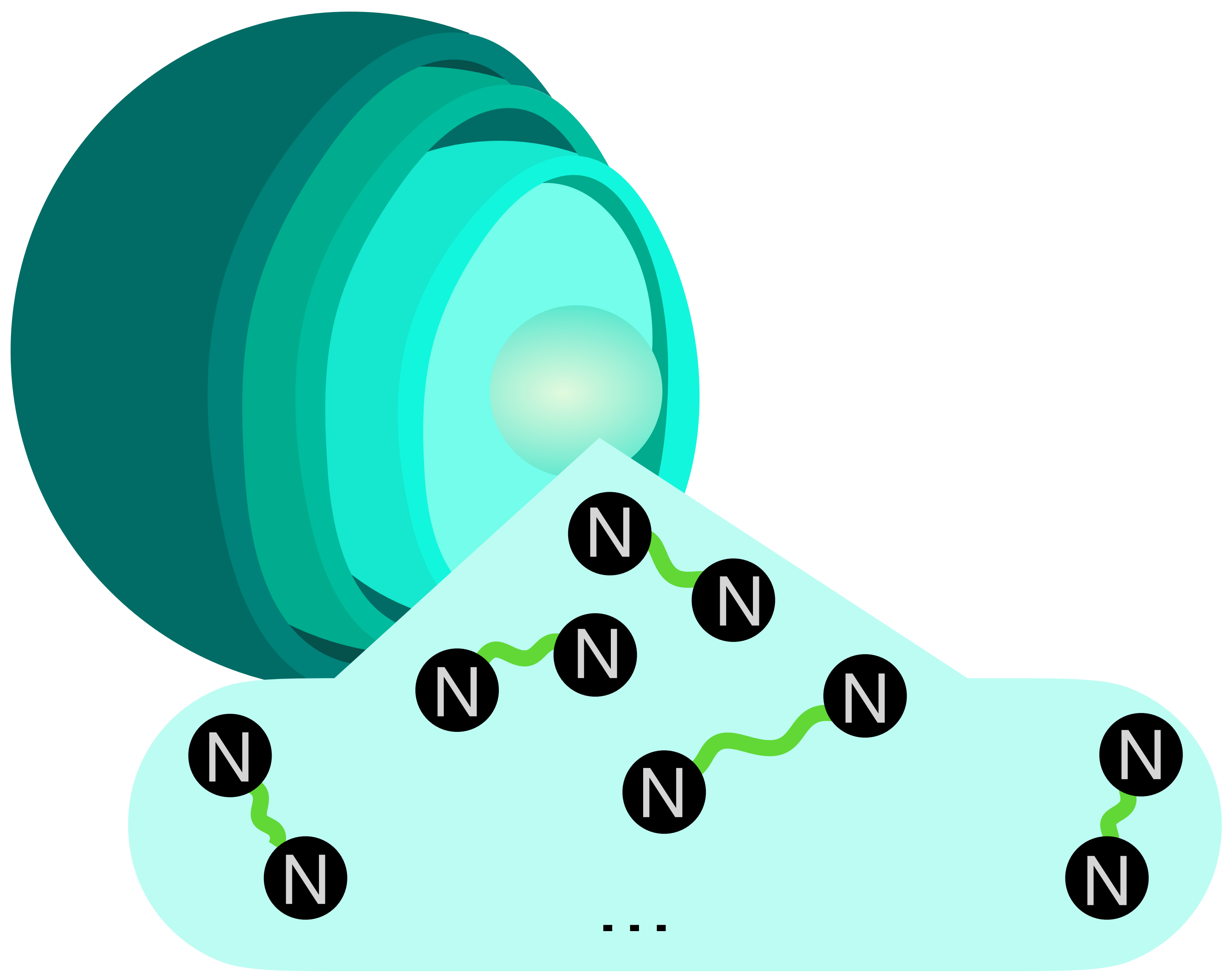
10 - 20 km



1 - 2 M_{sun}

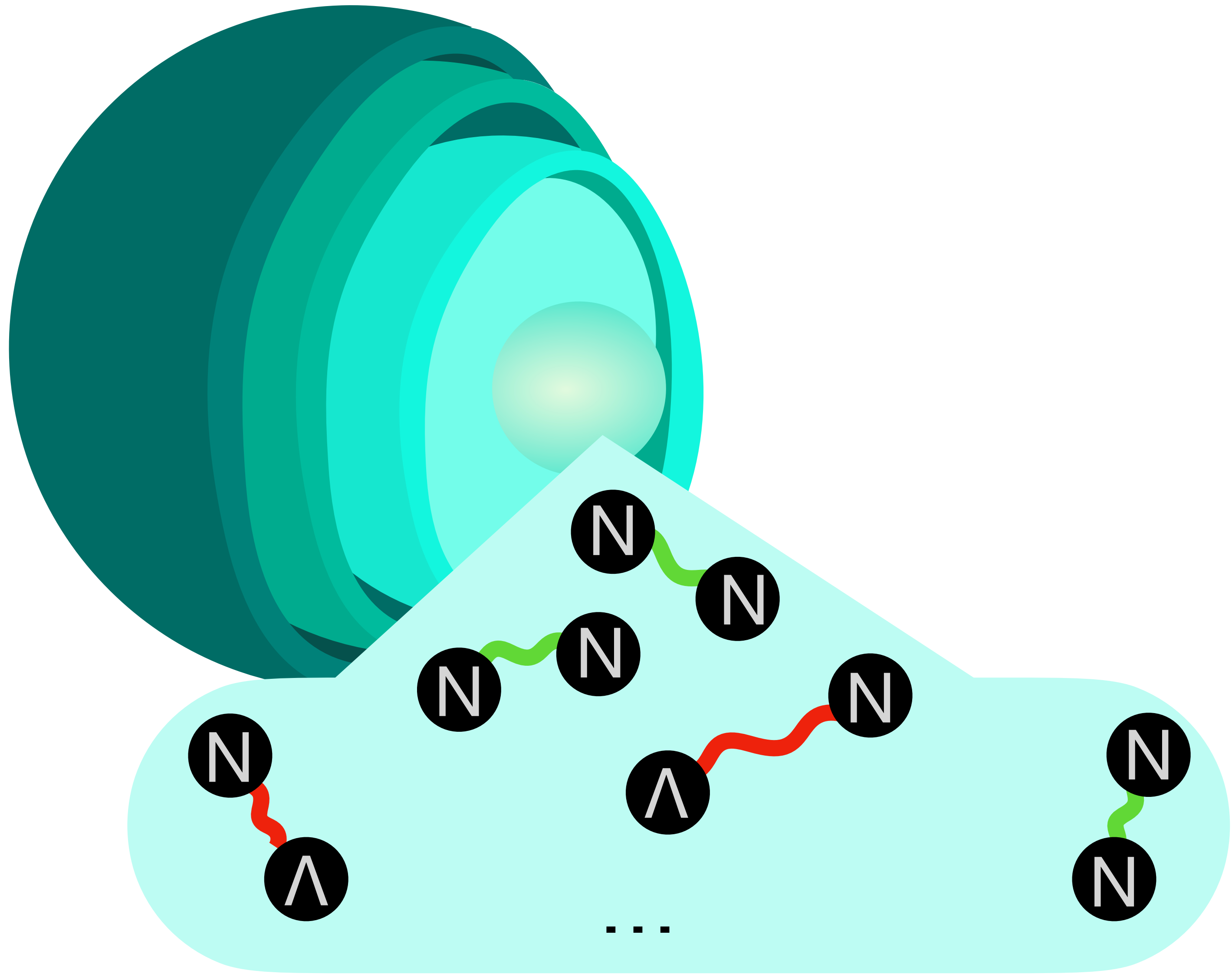
Neutron stars and three-body forces

- Neutron star density > $2\rho_0$



Neutron stars and three-body forces

- Neutron star density $> 2\rho_0$
- Strange hadrons might appear in the system



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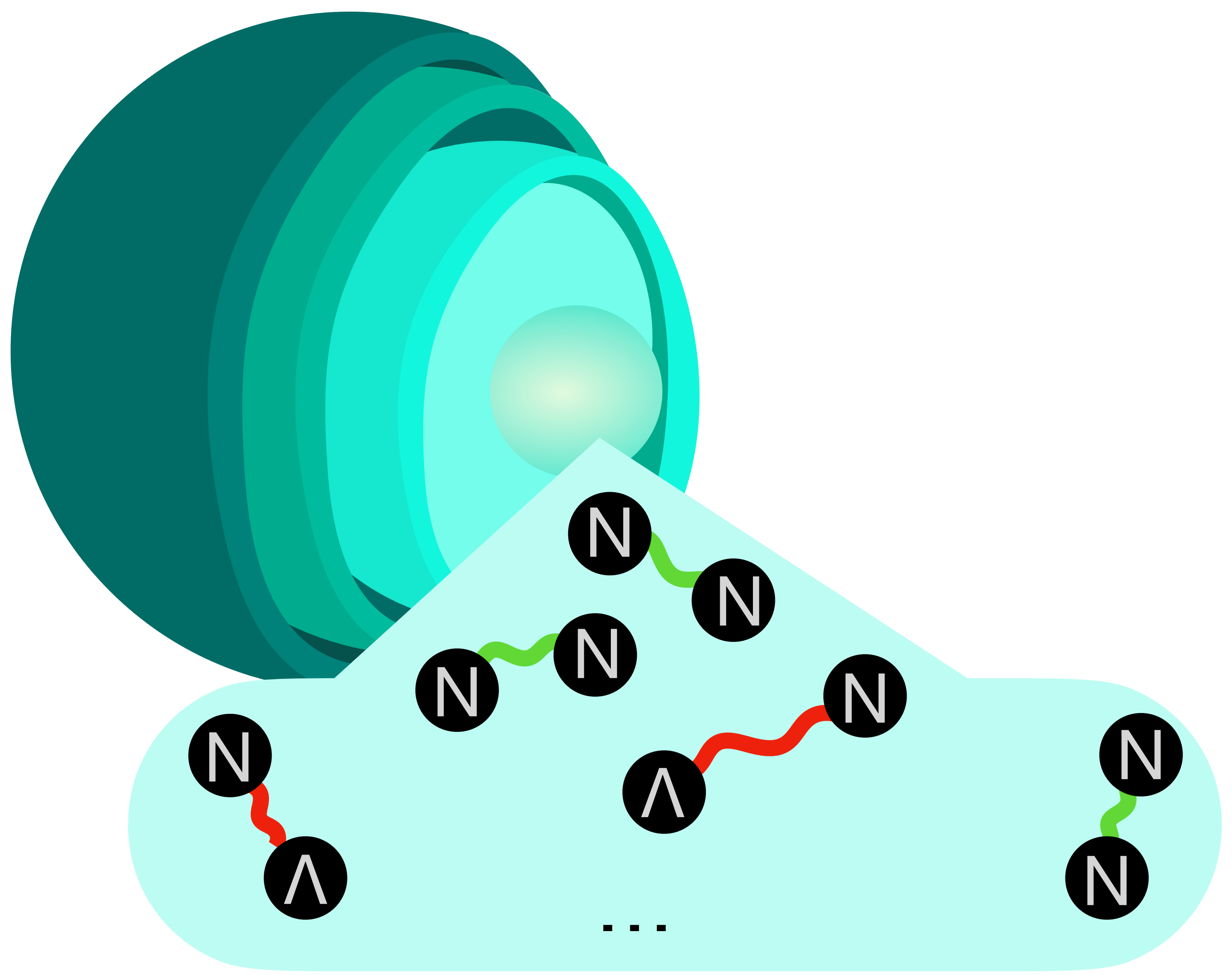

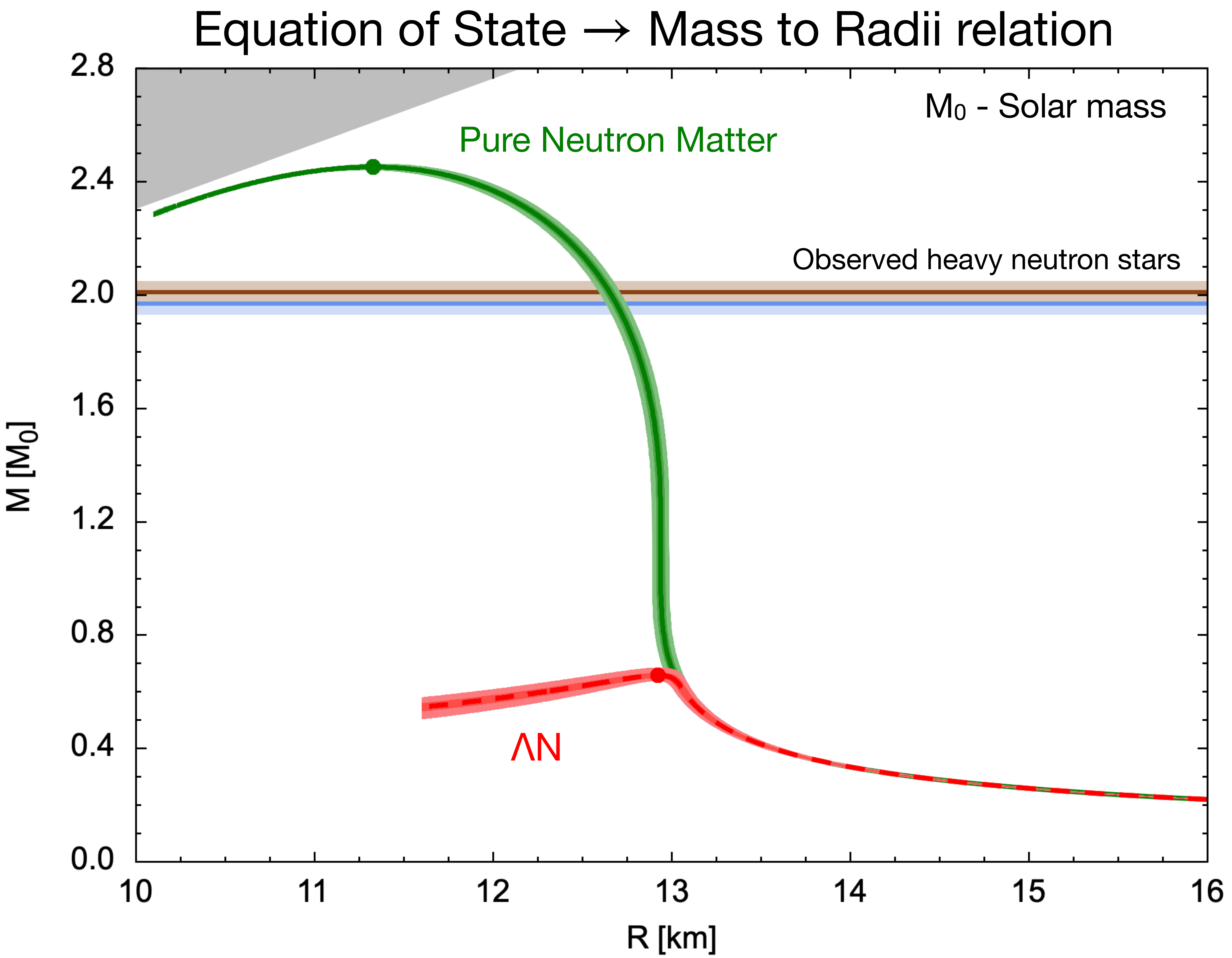

Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)

Neutron stars and three-body forces

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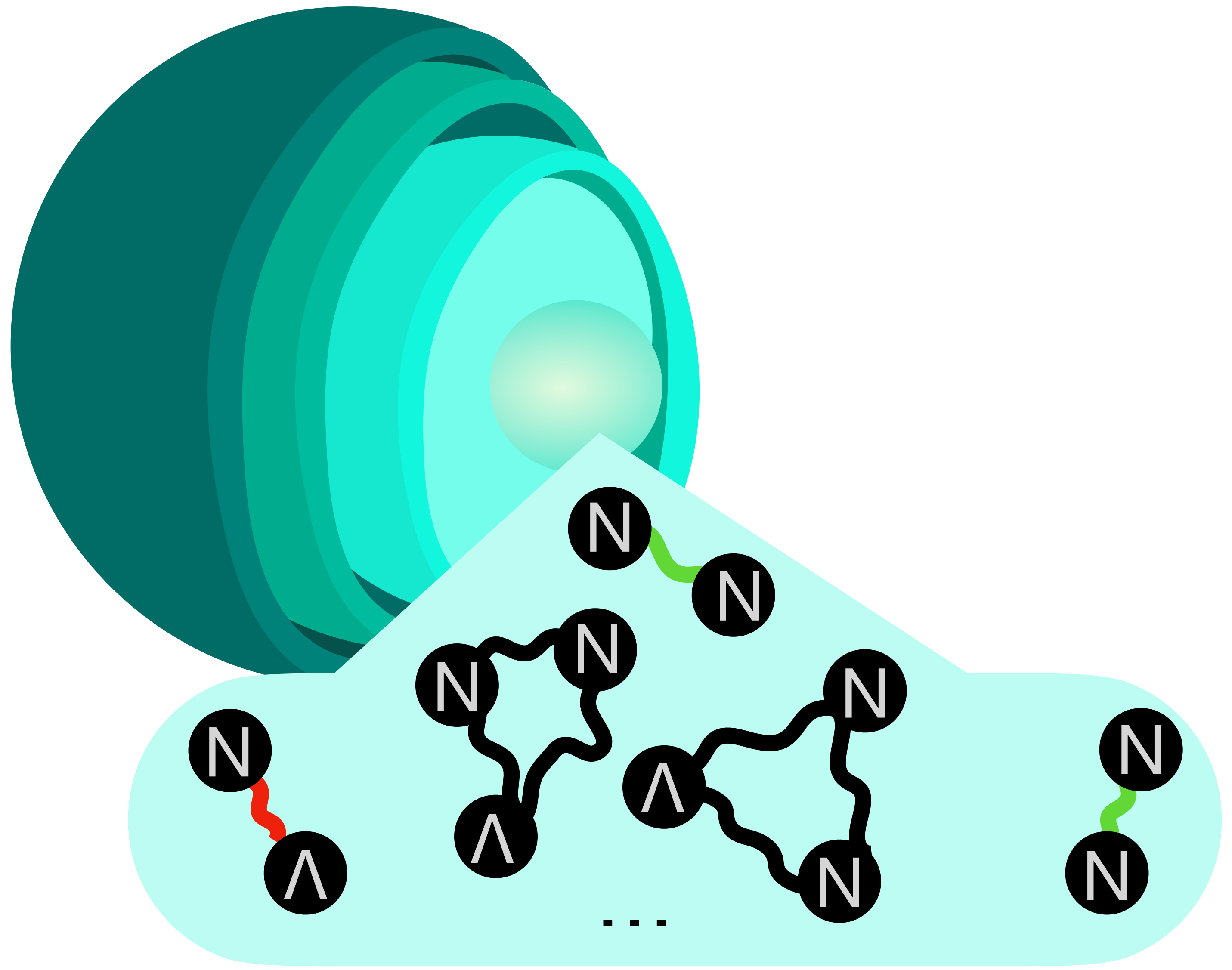
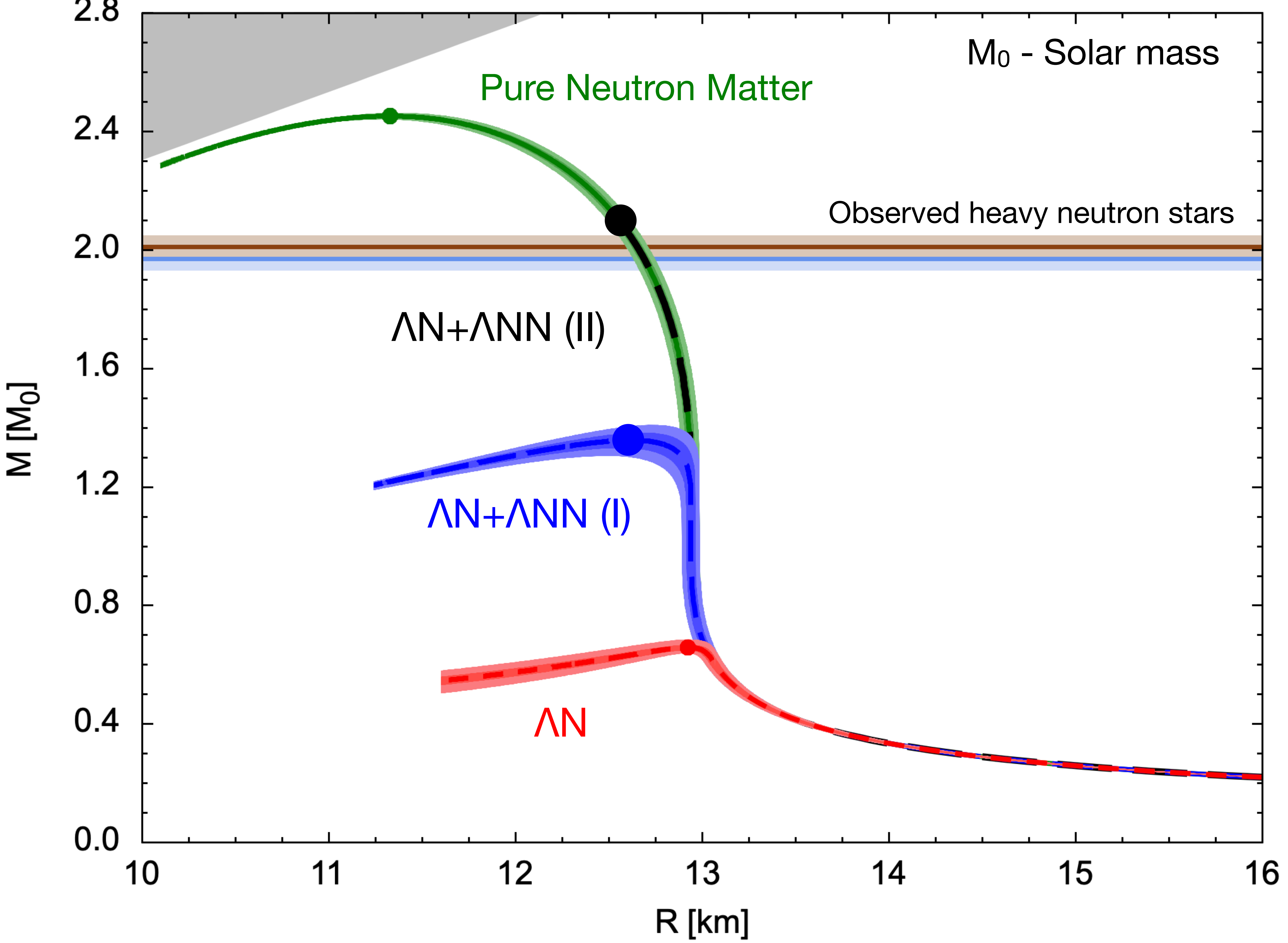


Equation of State → Mass to Radii relation



Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)

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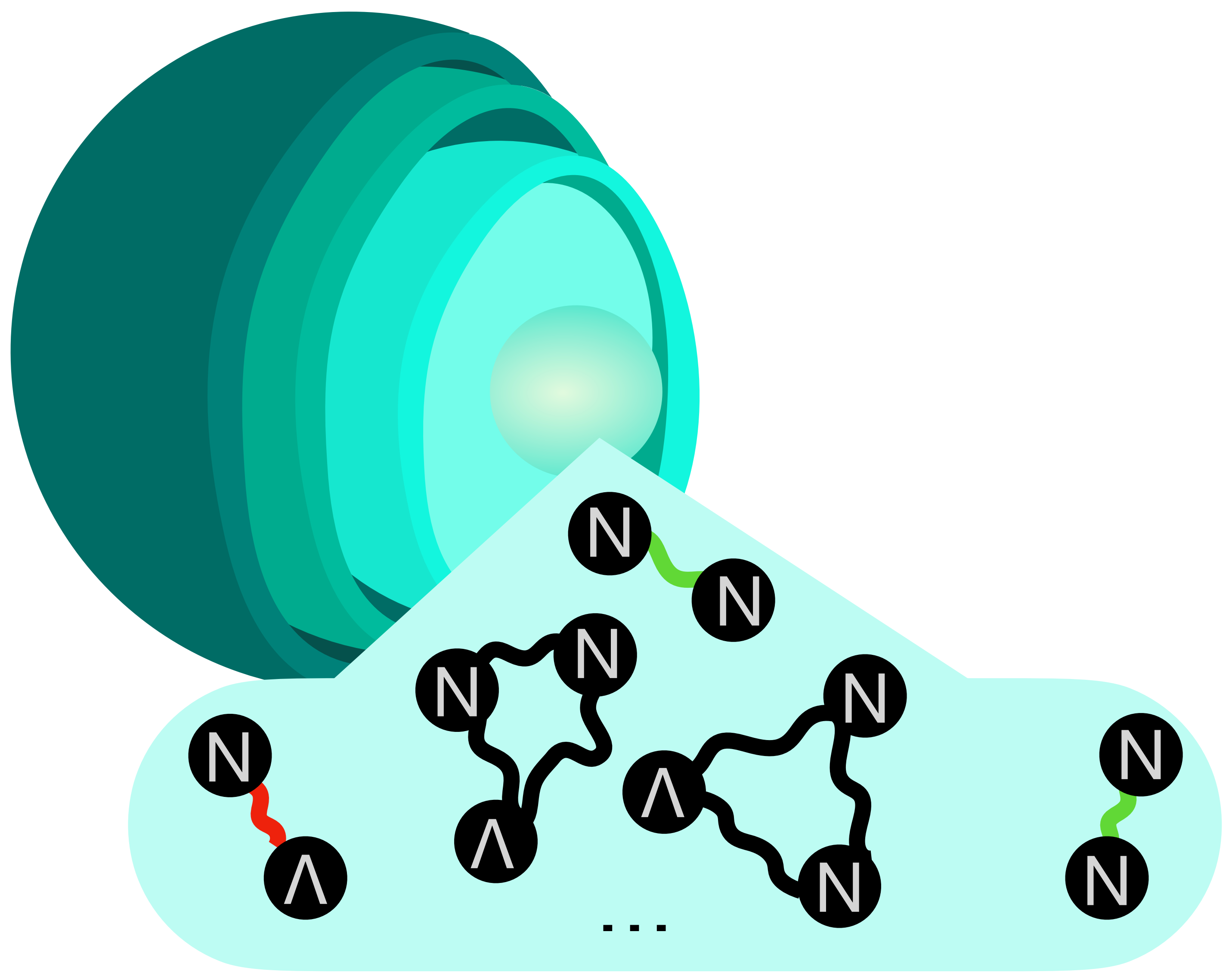
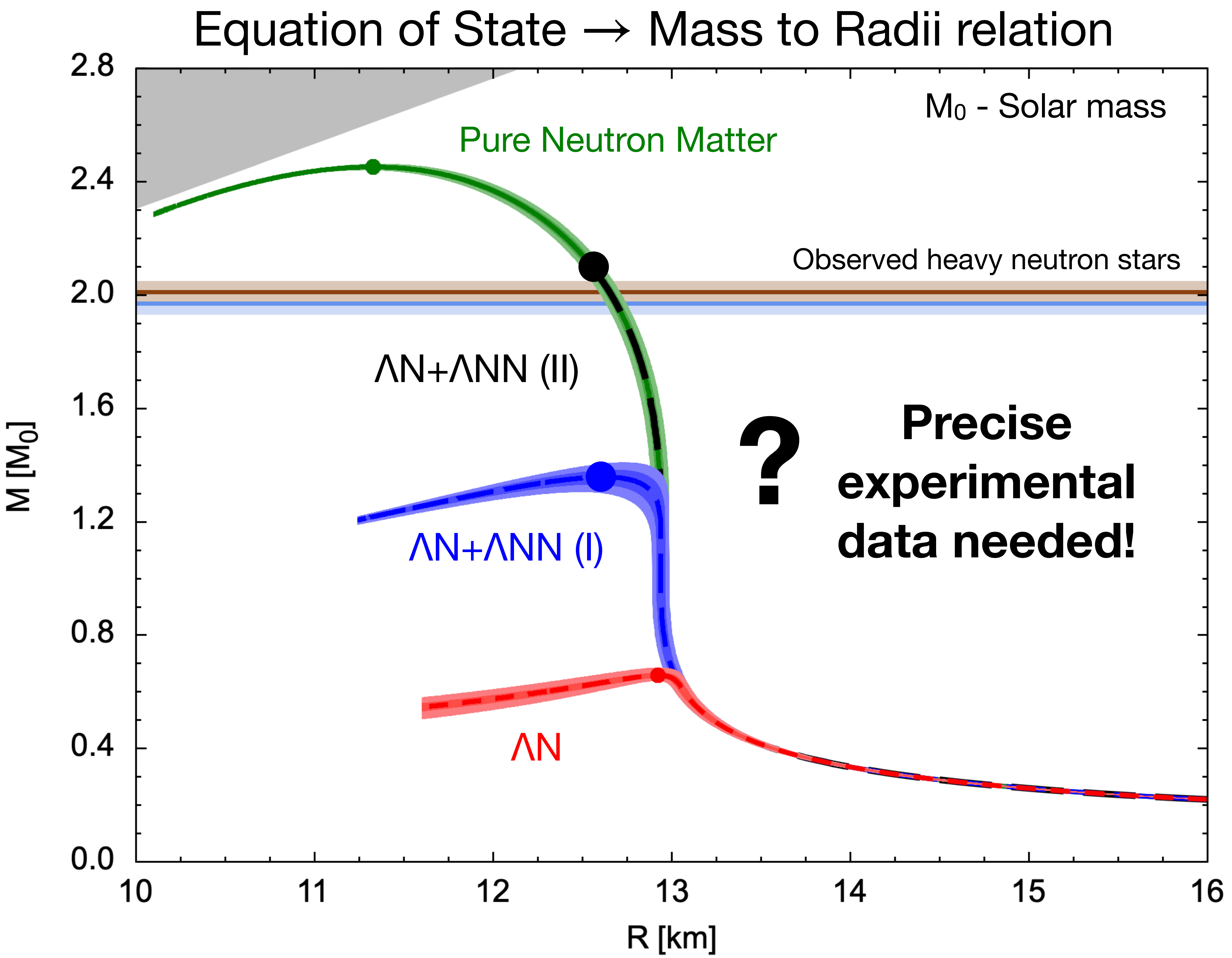
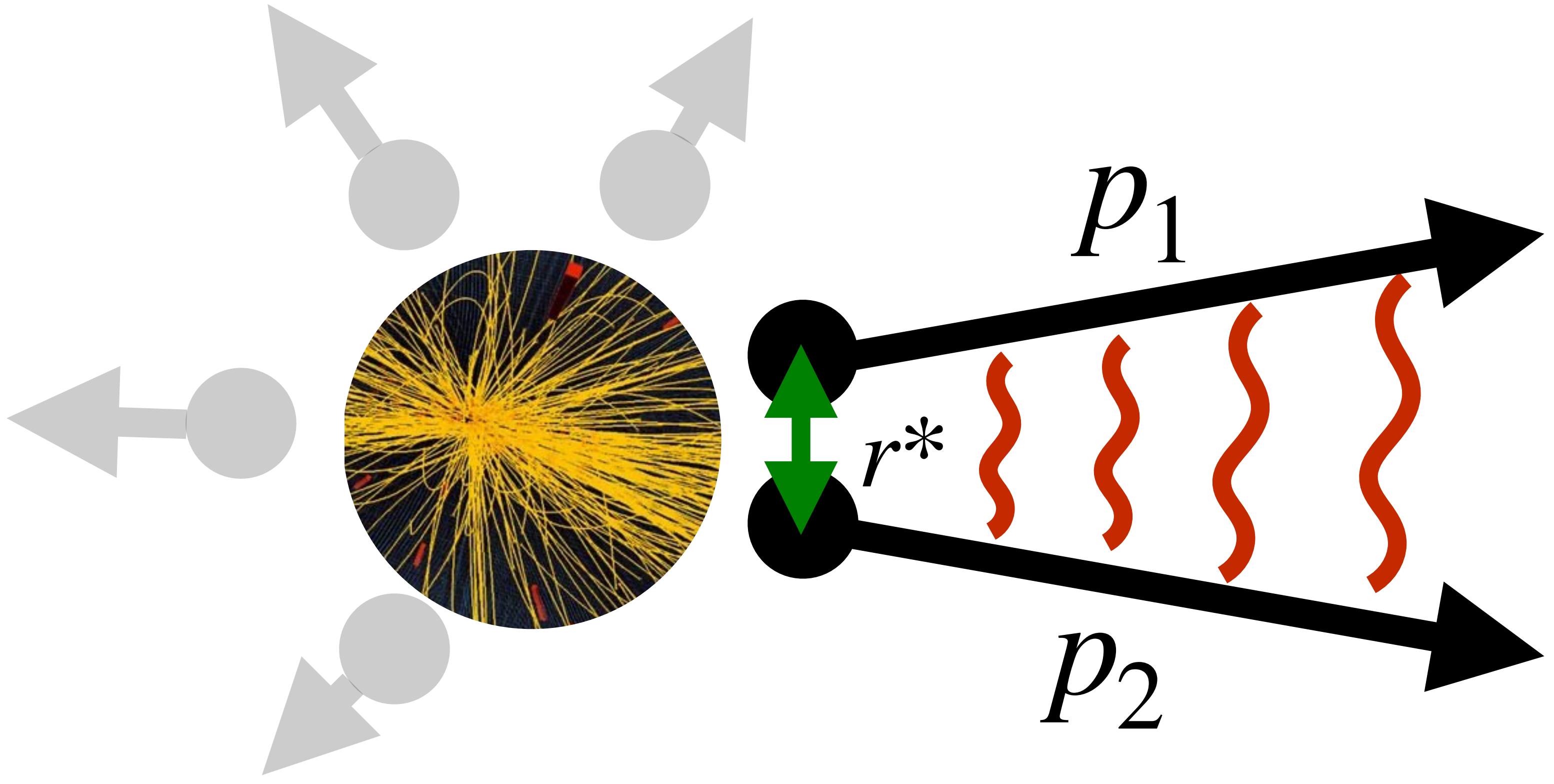




Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)

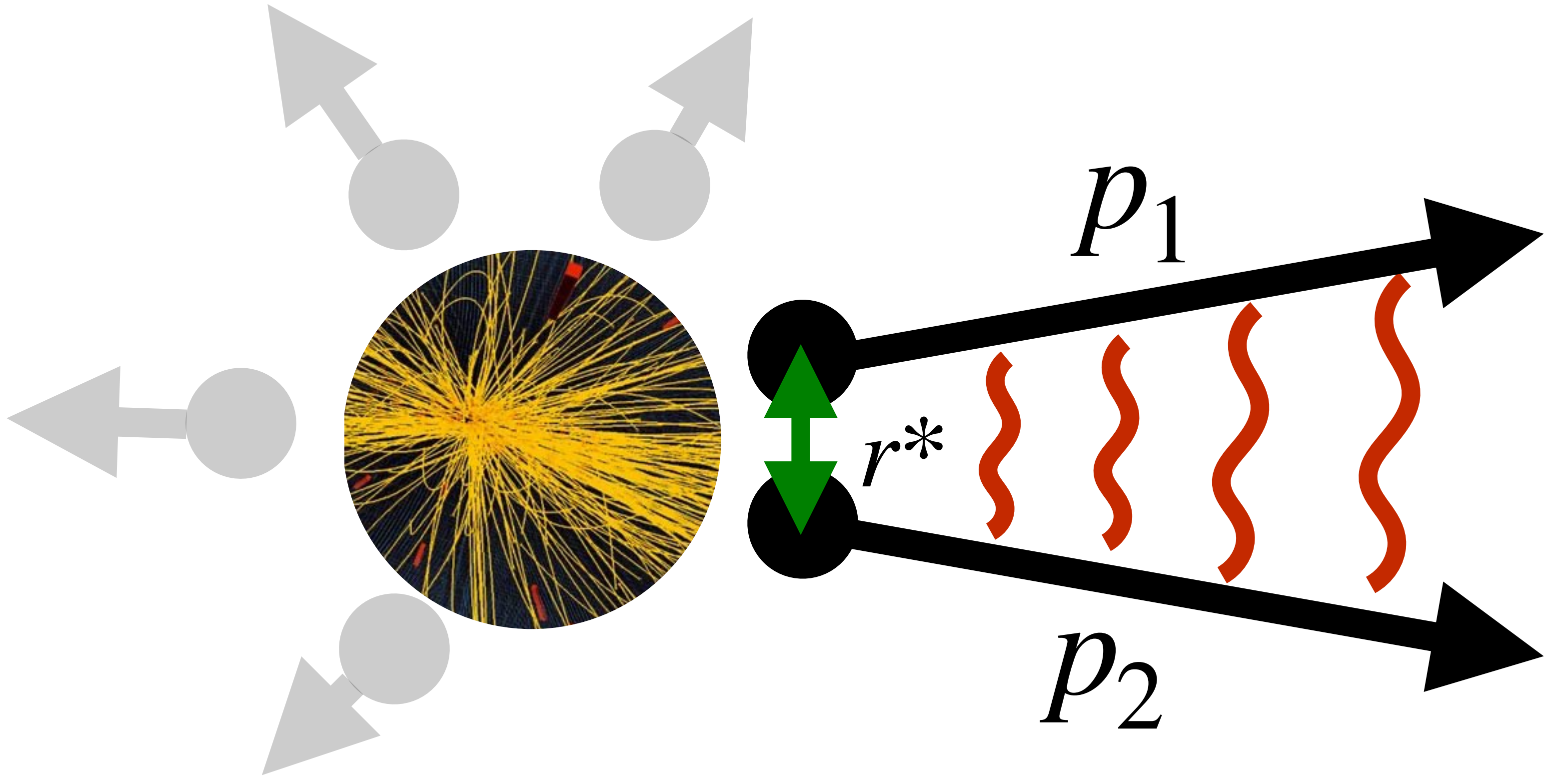
Femtoscopy technique



Femtoscopy technique

Three-baryon correlations

S.E. Koonin PLB 70 43 (1977)
D. Mihaylov et al., EPJ. C78 (2018) 394



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

k^* - relative momentum in the pair rest frame

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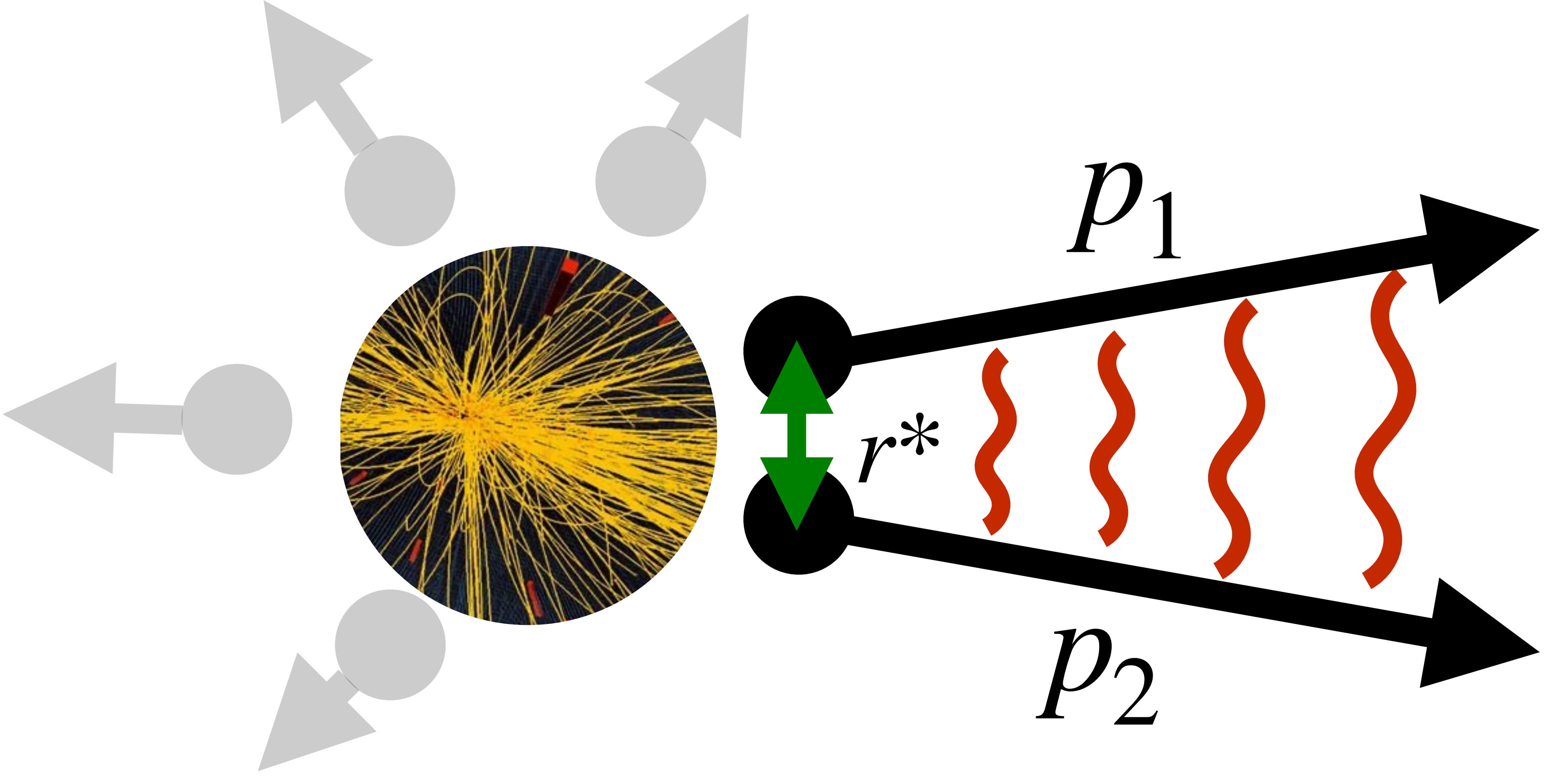

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Typical 1 fm relative distance in pp collisions → study short-range nuclear interaction

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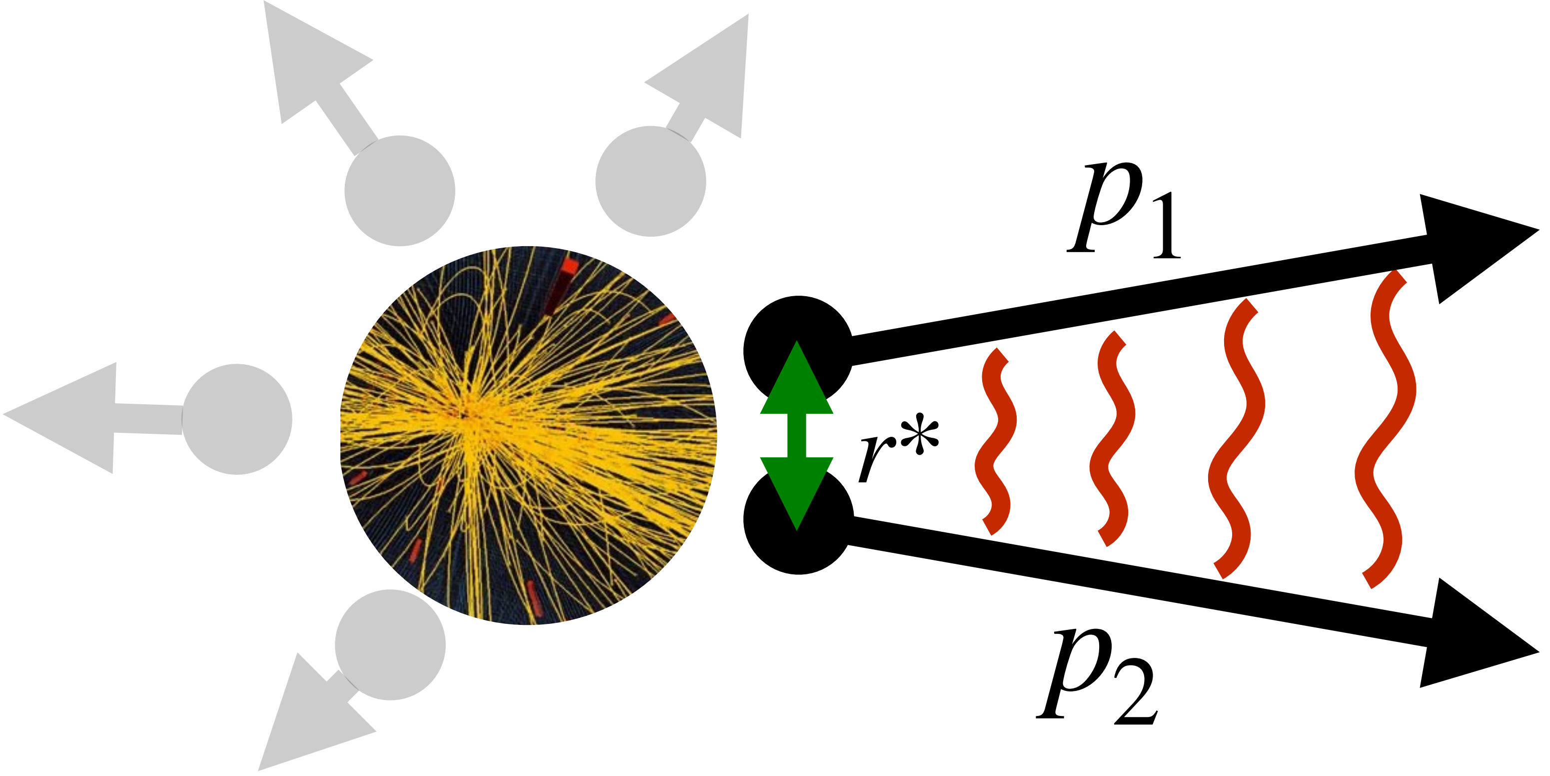

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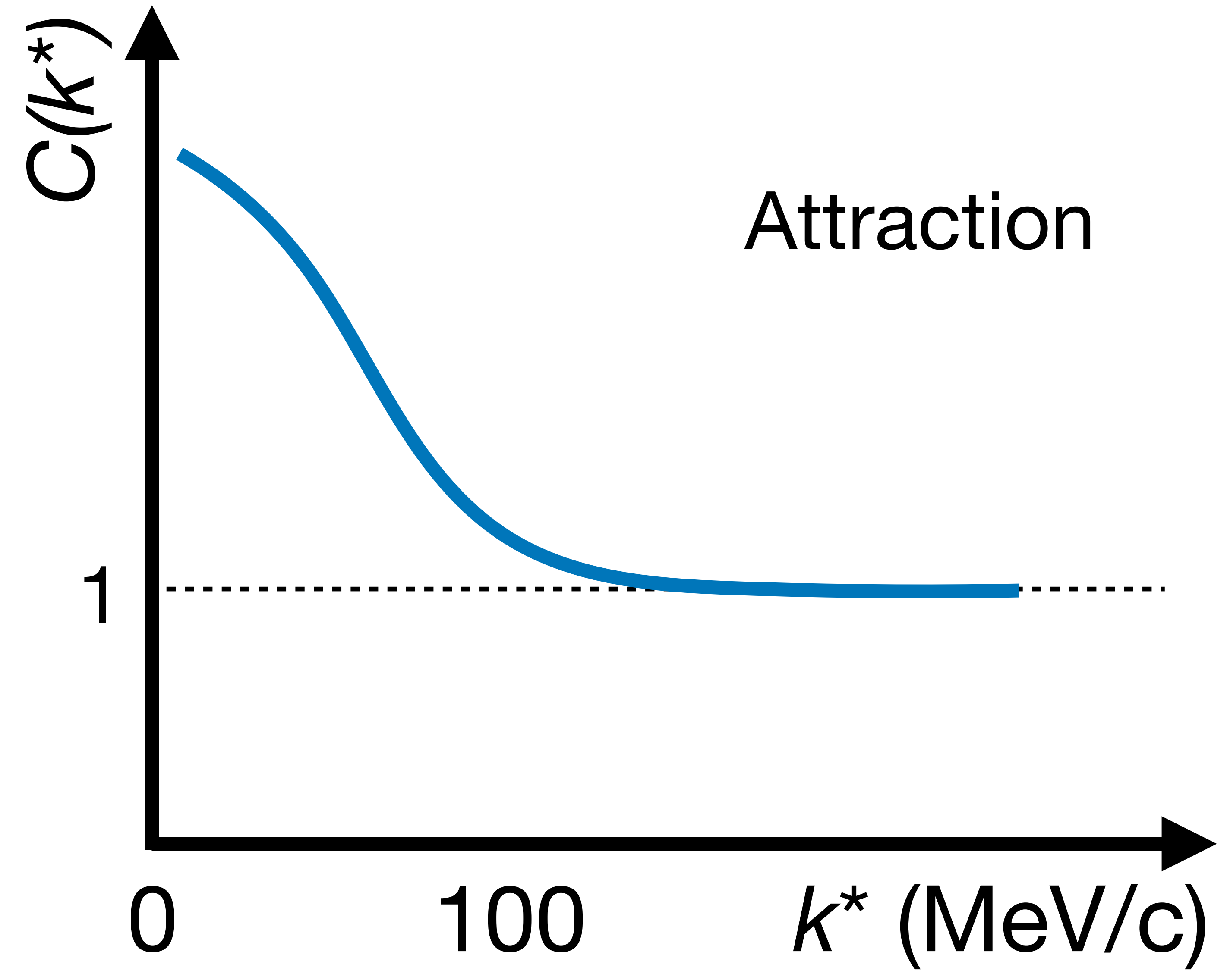

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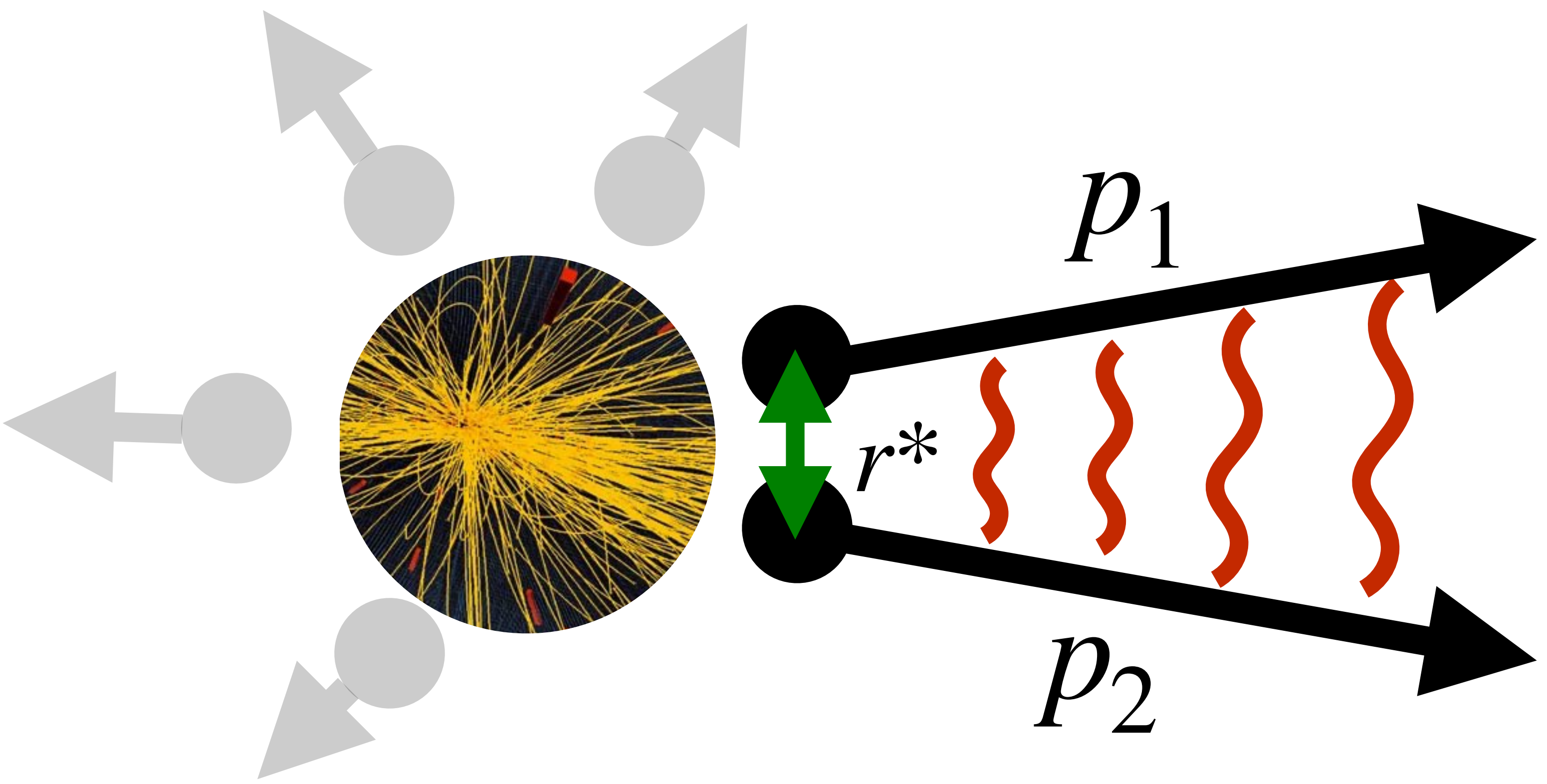

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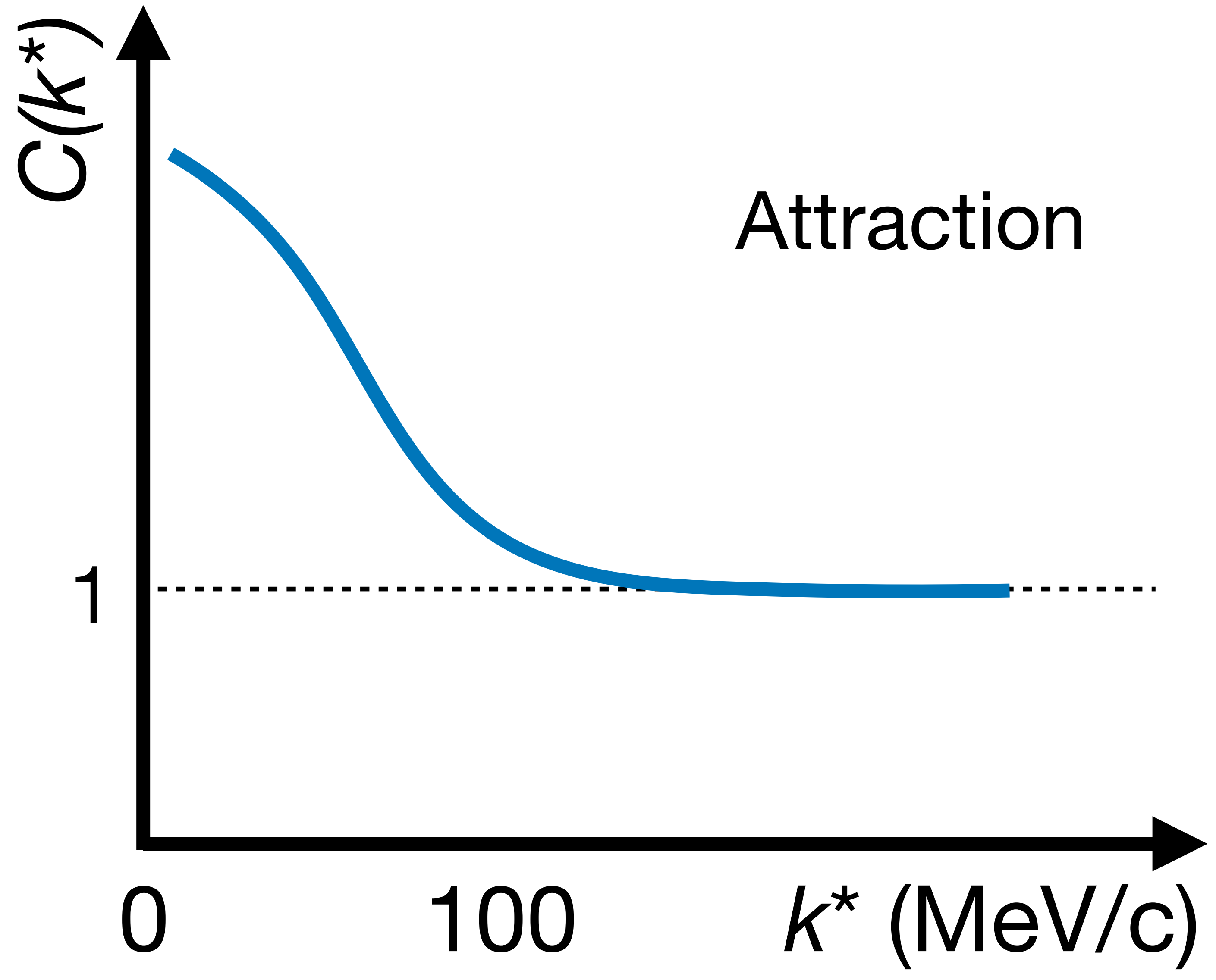

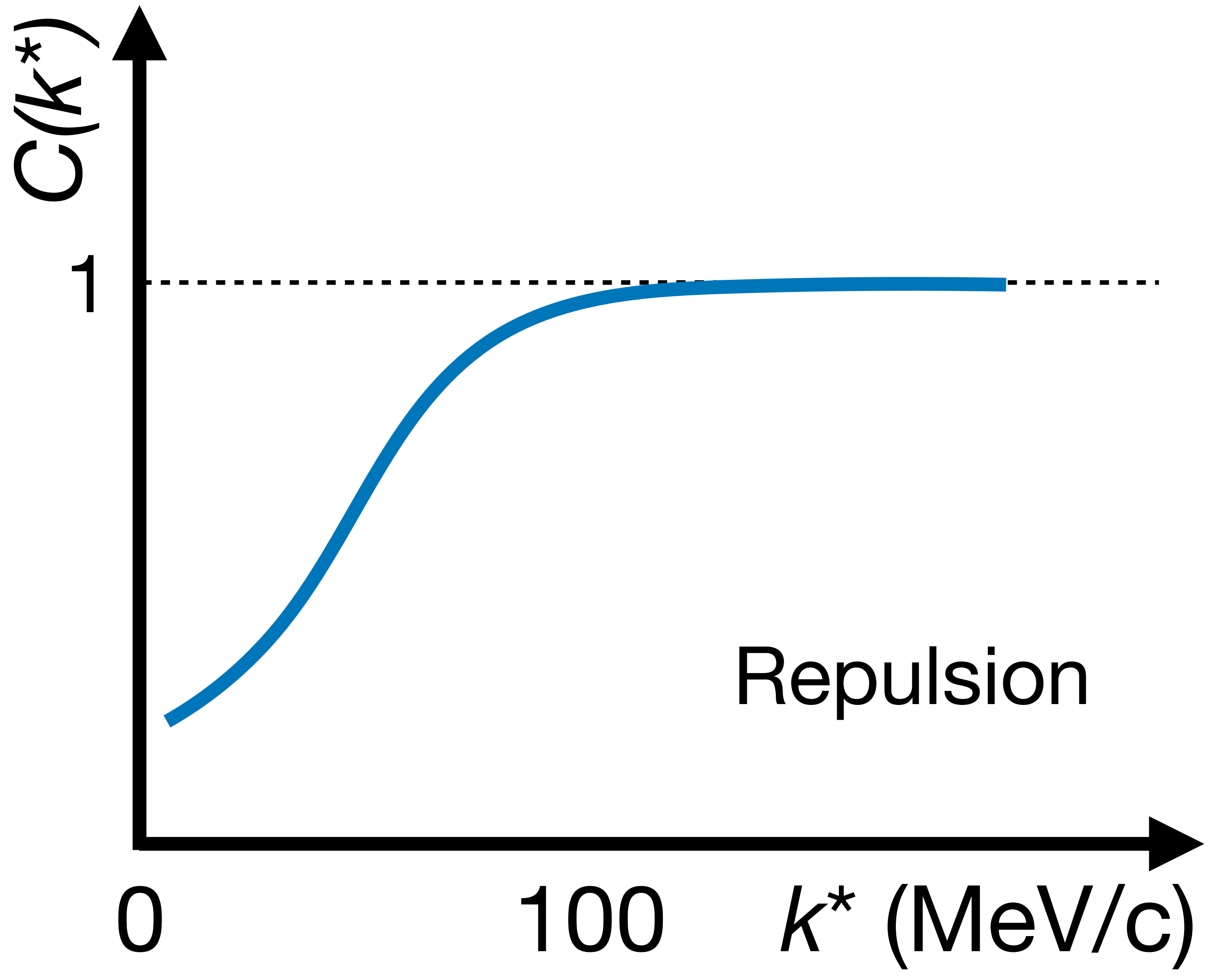

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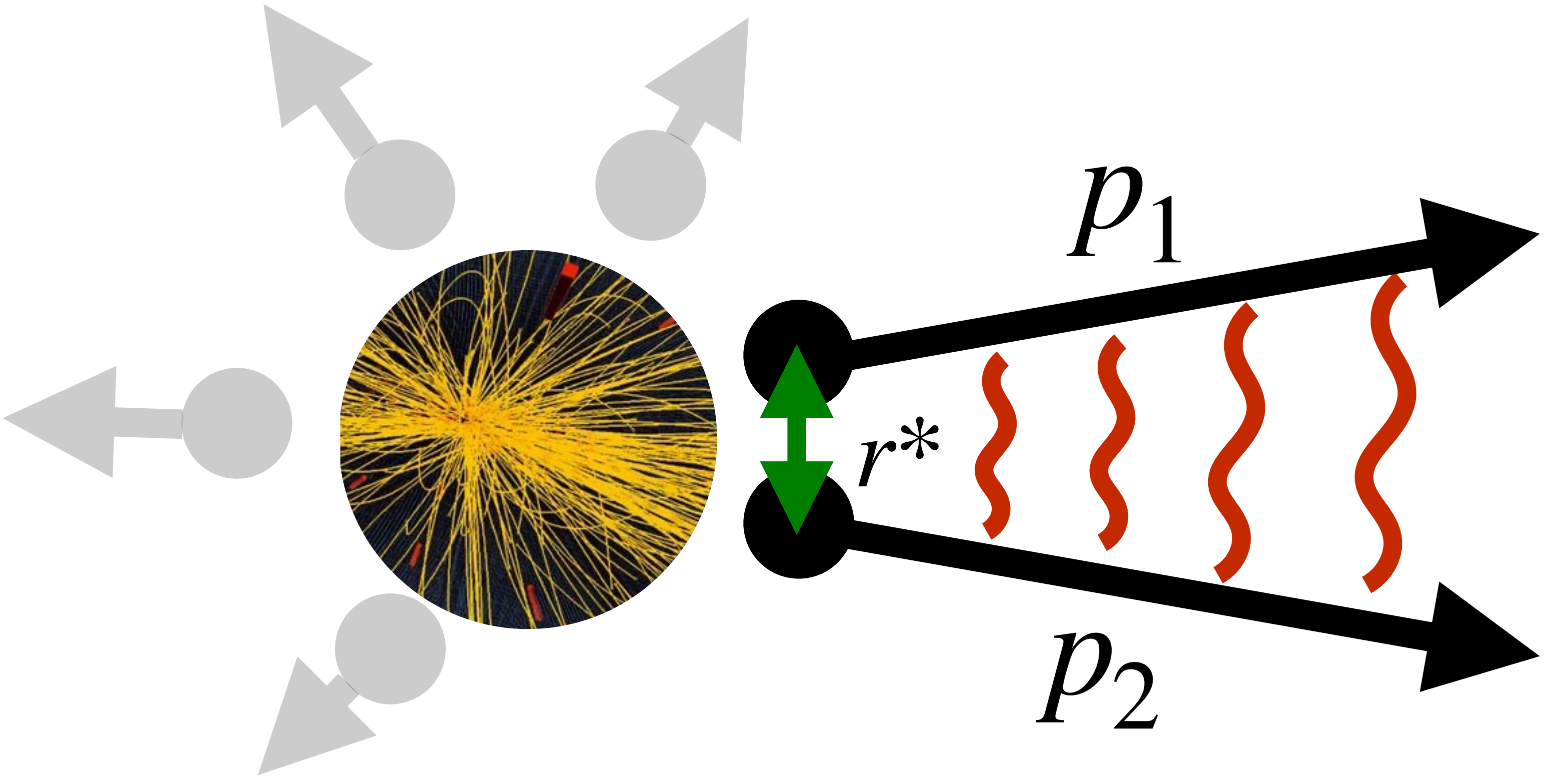

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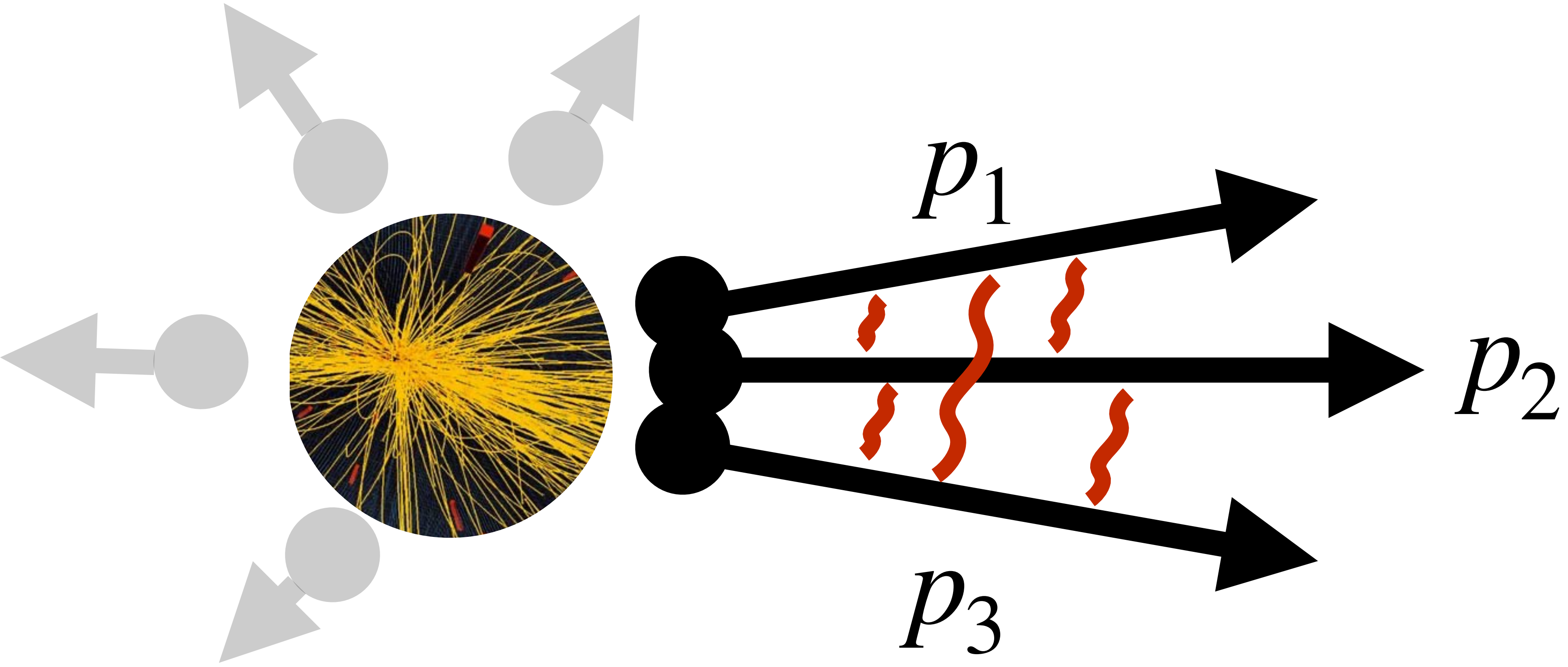


$$C(Q_3) = \mathcal{N}\frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}$$

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

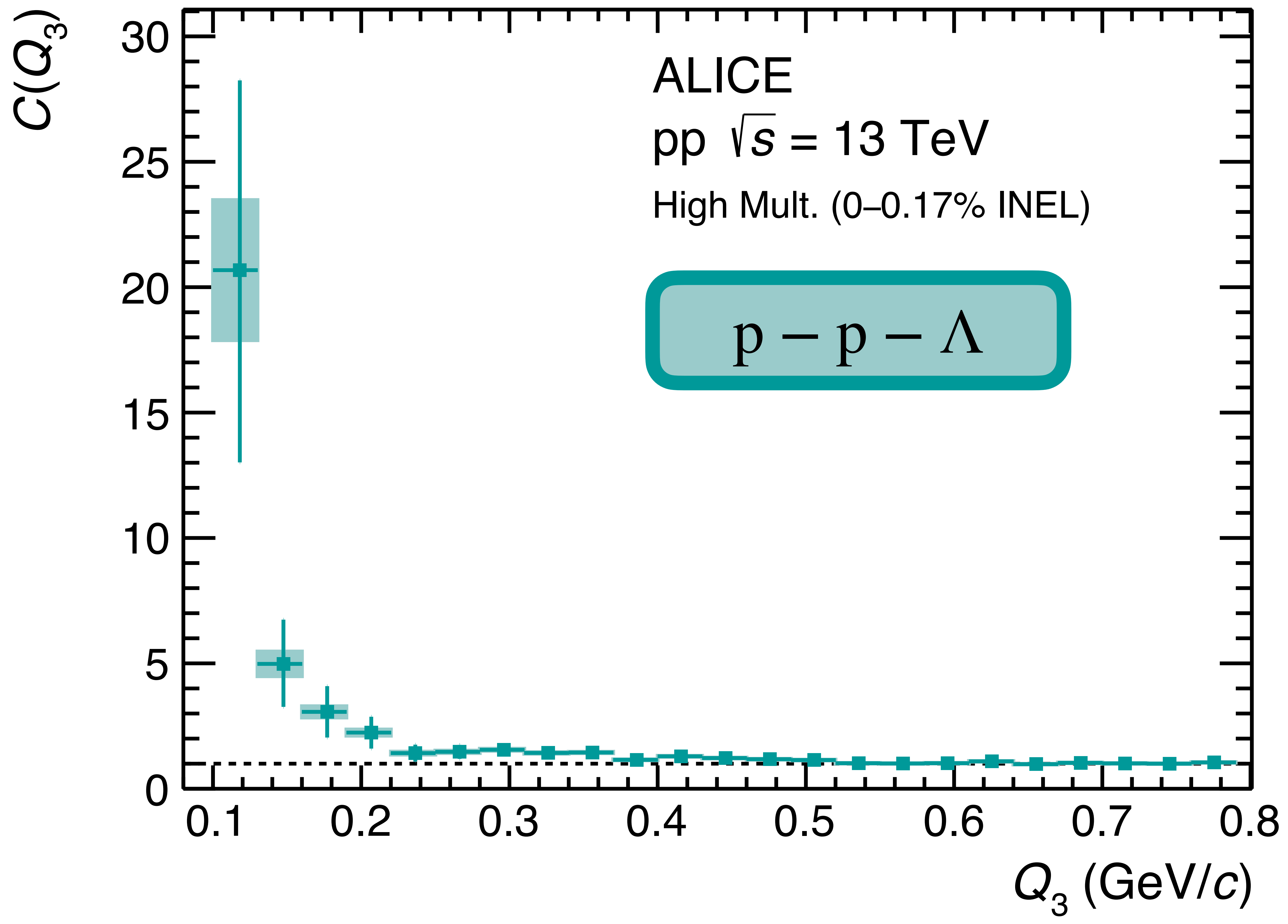
q_{ij} - relative momentum in the pair rest frame

Measured correlation functions

ALICE, EPJA 59 145 (2023)

Measured correlation functions

ALICE, EPJA 59 145 (2023)



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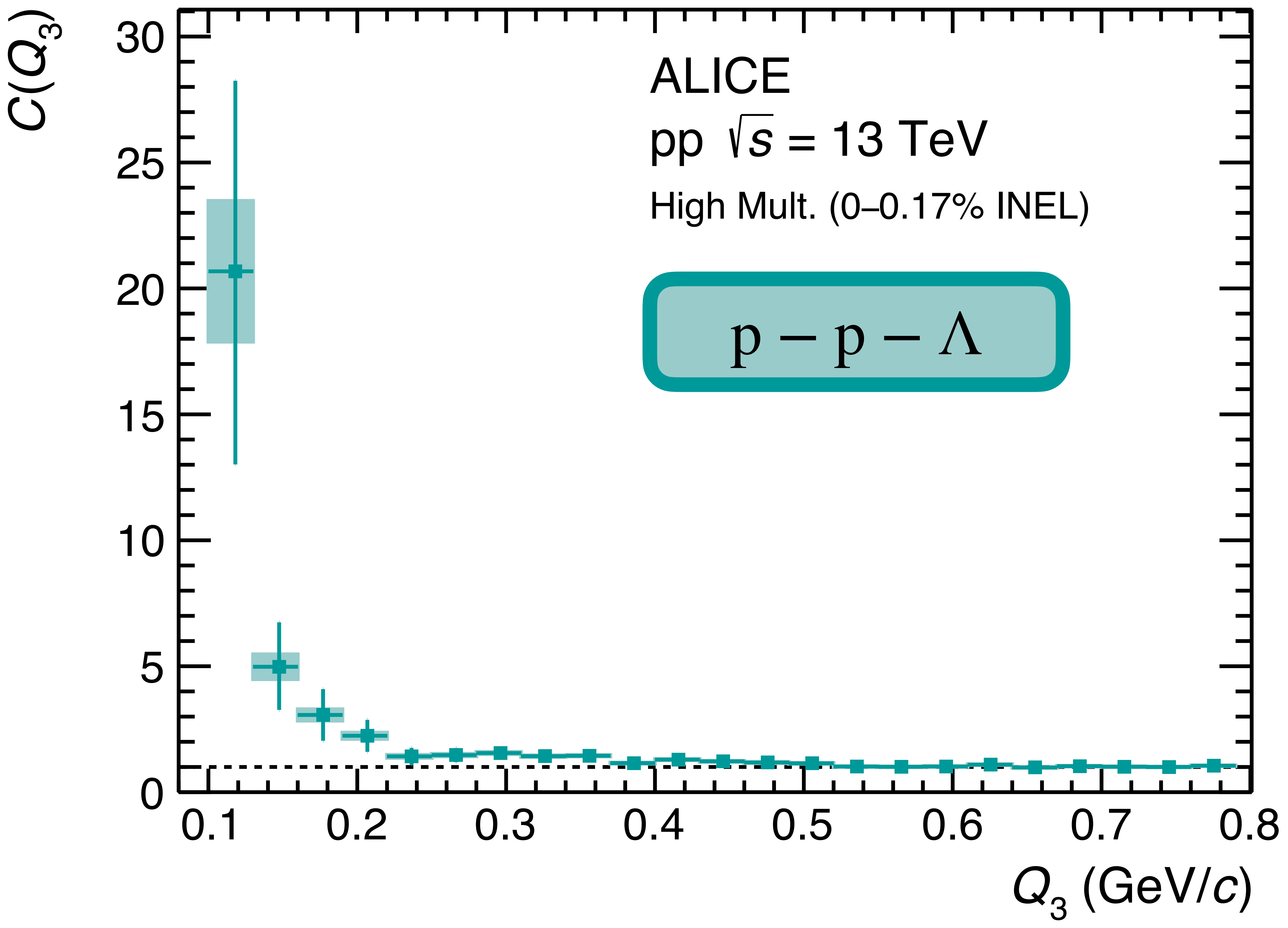
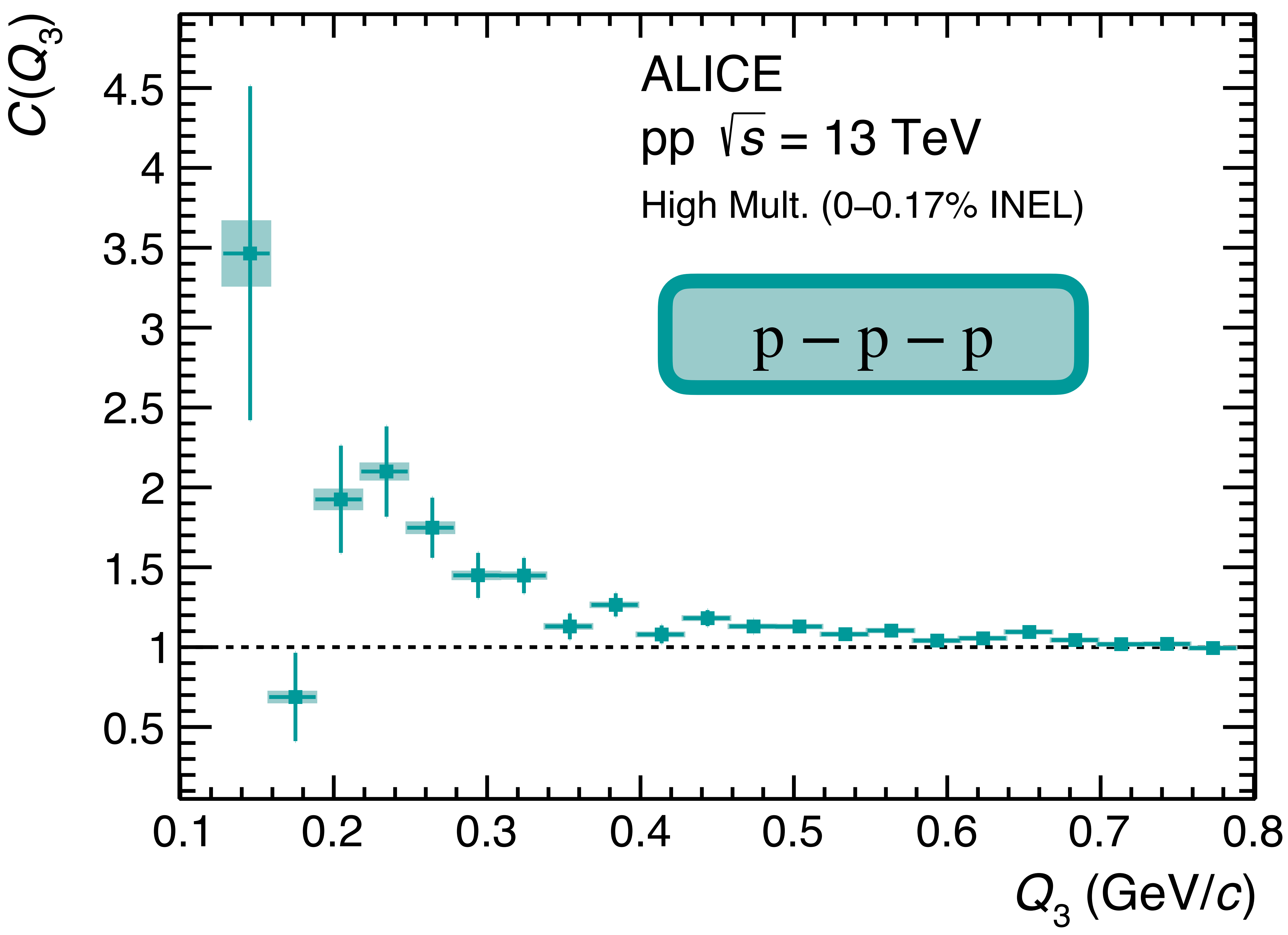


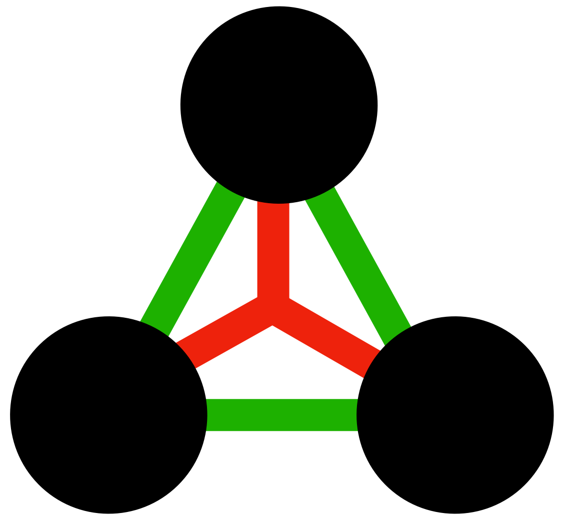


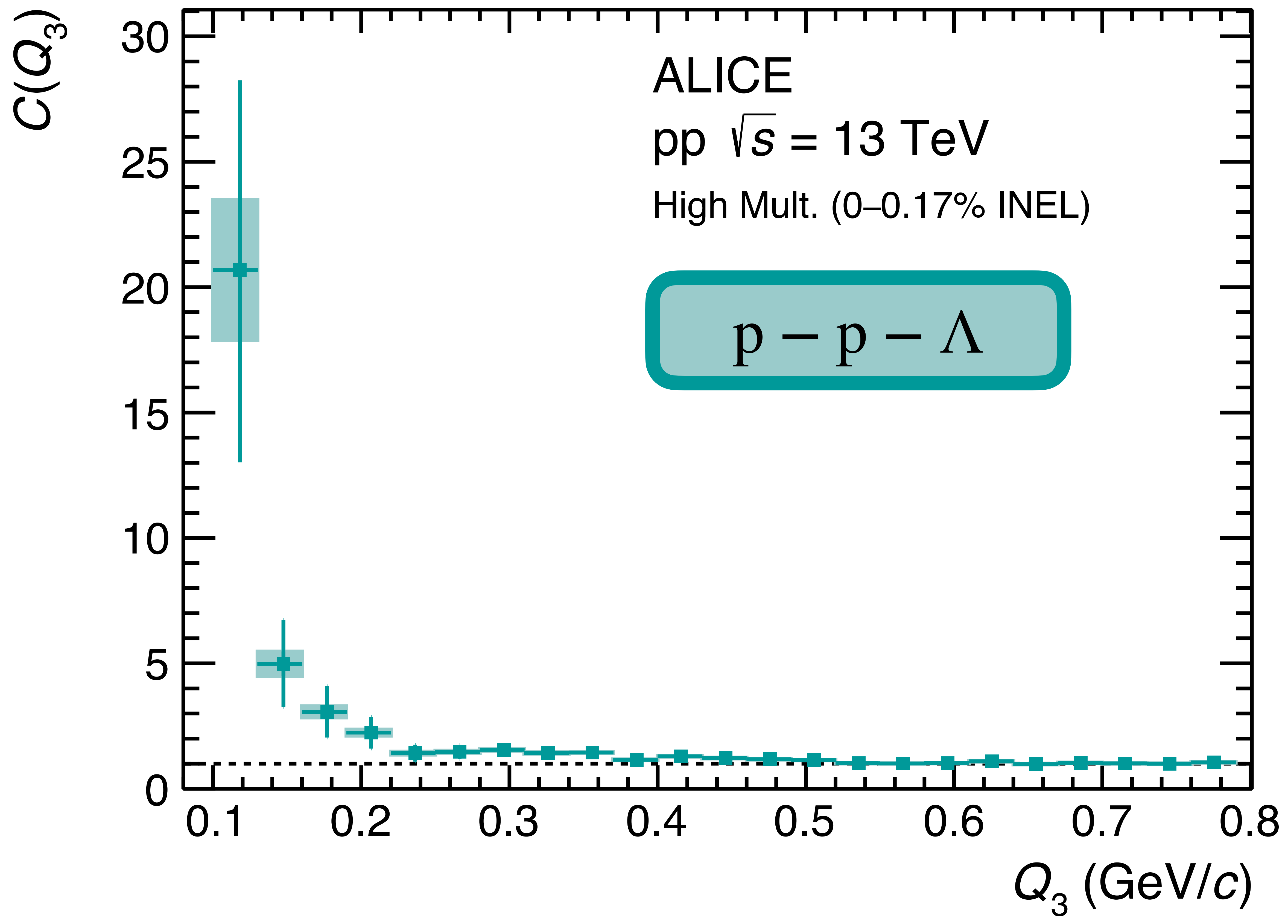
Measured correlation functions

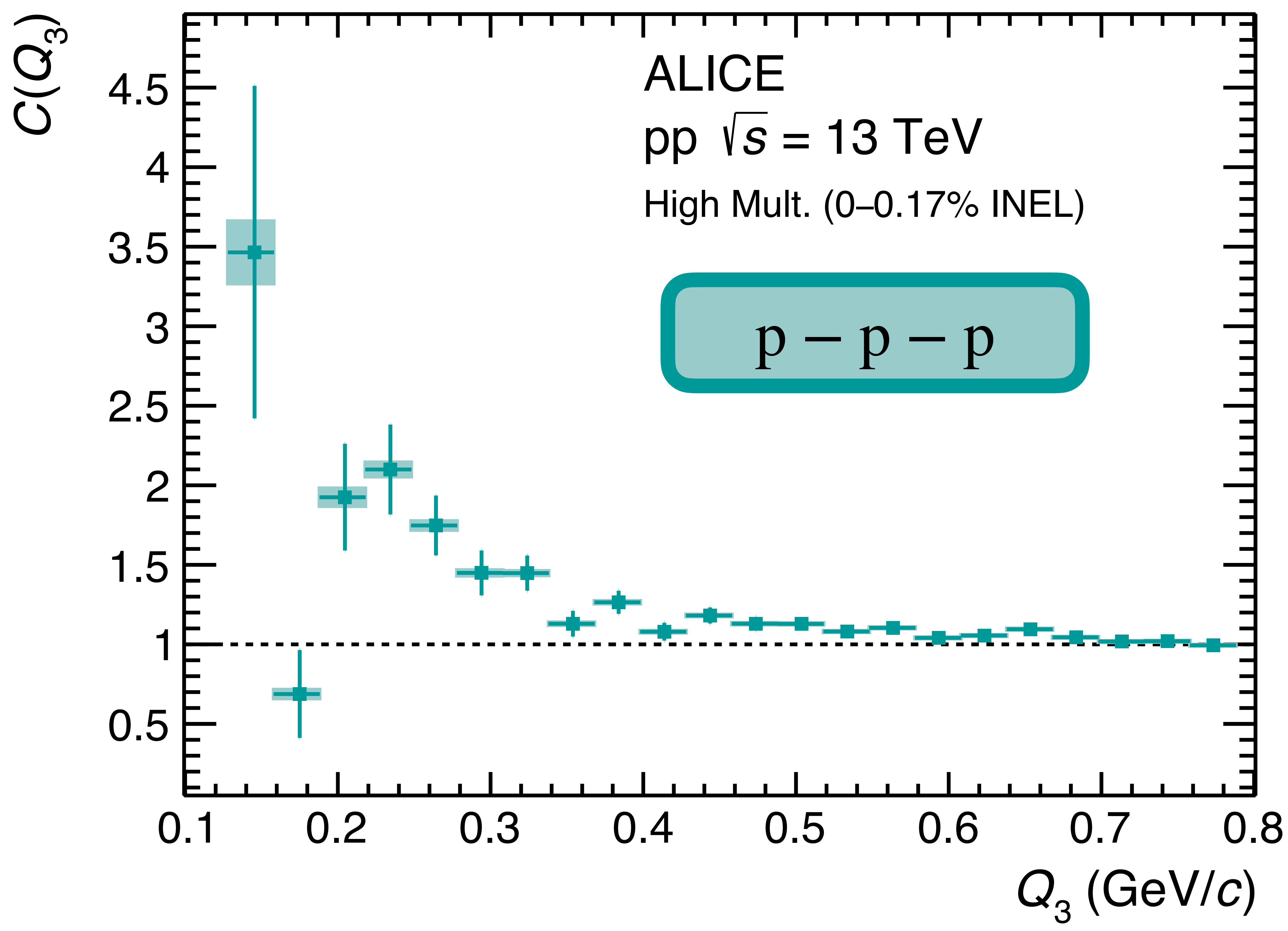
ALICE, EPJA 59 145 (2023)

Three-particle correlation function

- two-body interactions
- three-body interaction

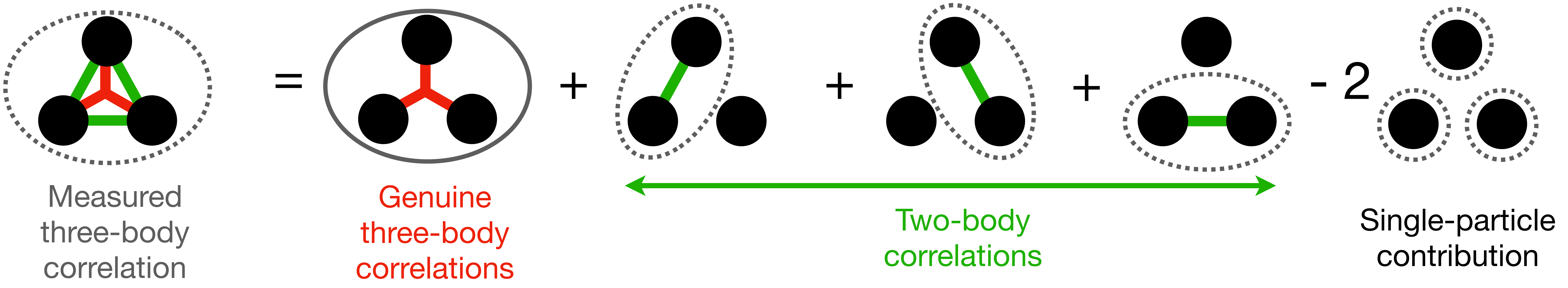






Cumulants in femtoscopy

Access genuine three-body correlations employing Kubo’s cumulants [1]:



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

Cumulants in femtoscopy

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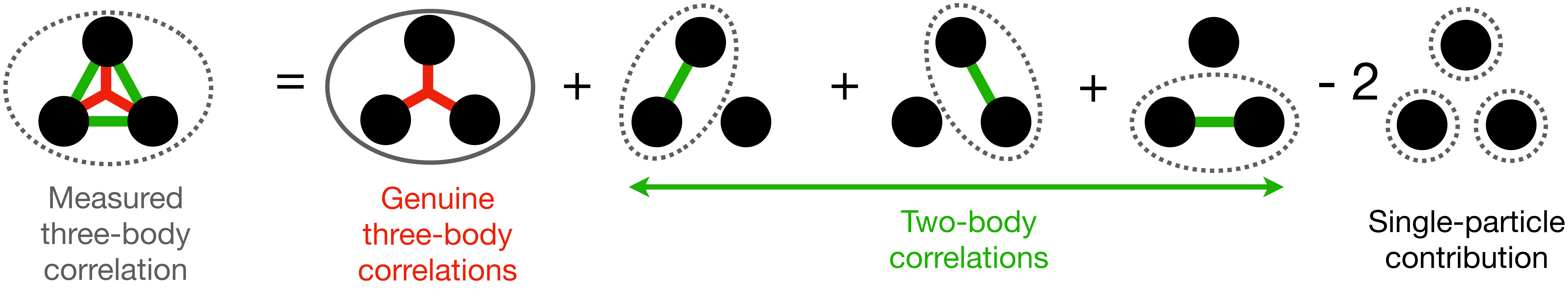

In terms of correlation functions:

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

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

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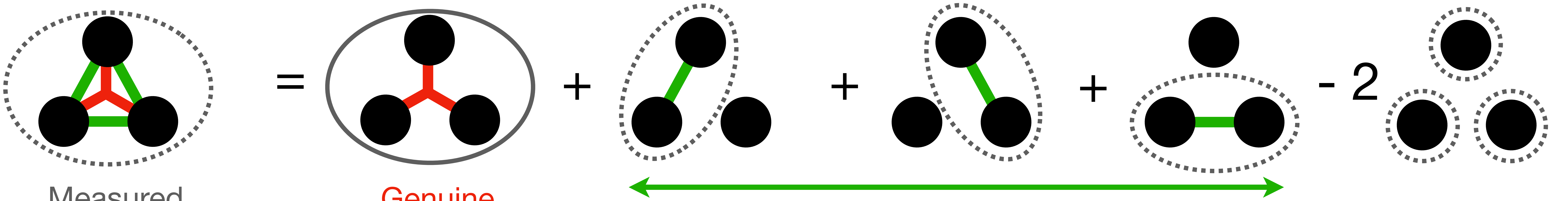

In terms of correlation functions:

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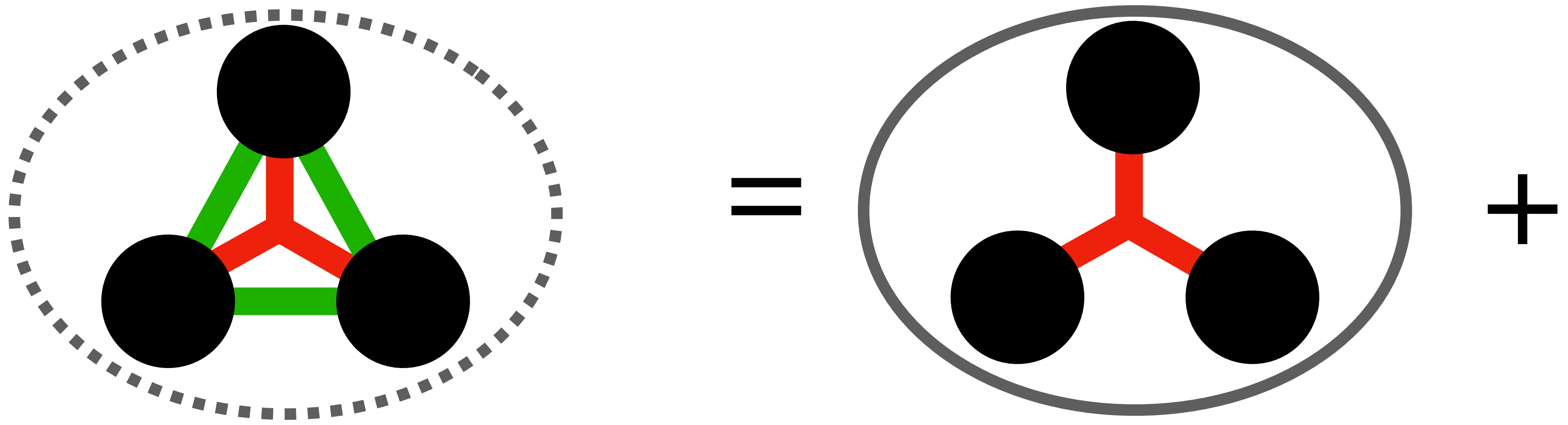
Lower-order contributions

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

Cumulants in femtoscopy

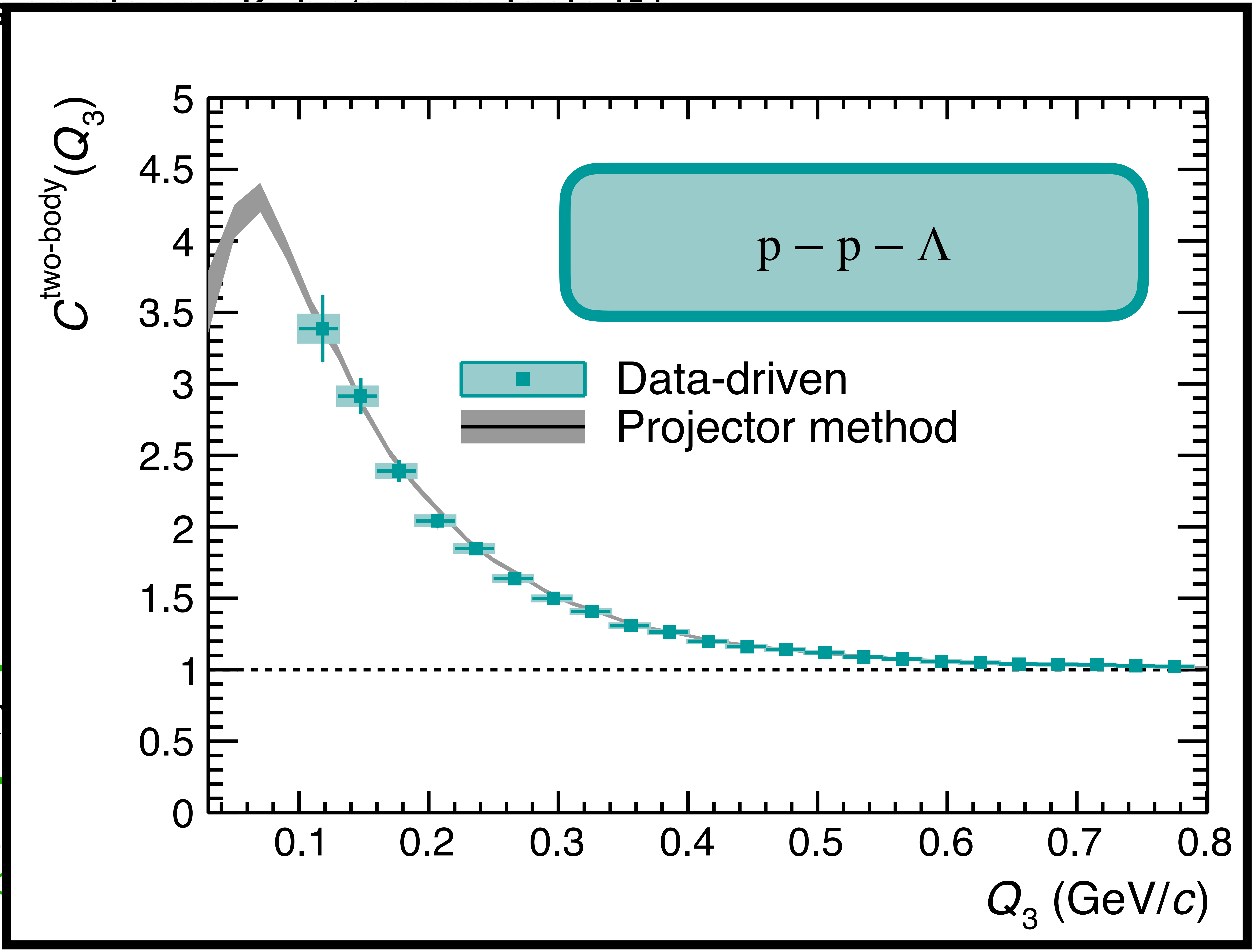
ALICE, EPJA 59 145 (2023)
Del Grande, LS et al. EPJC 82 244 (2022)

Access genuine three-body correlations



In terms of correlation functions:

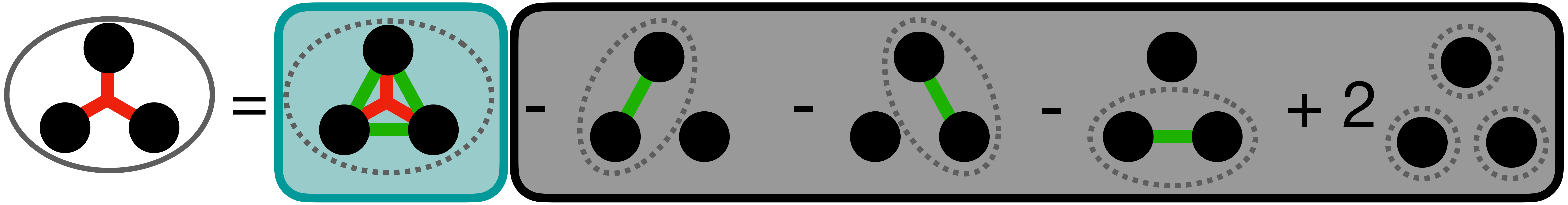
$$c_3(Q_3) = C(Q_3) - C_{12}(Q_3) - C$$

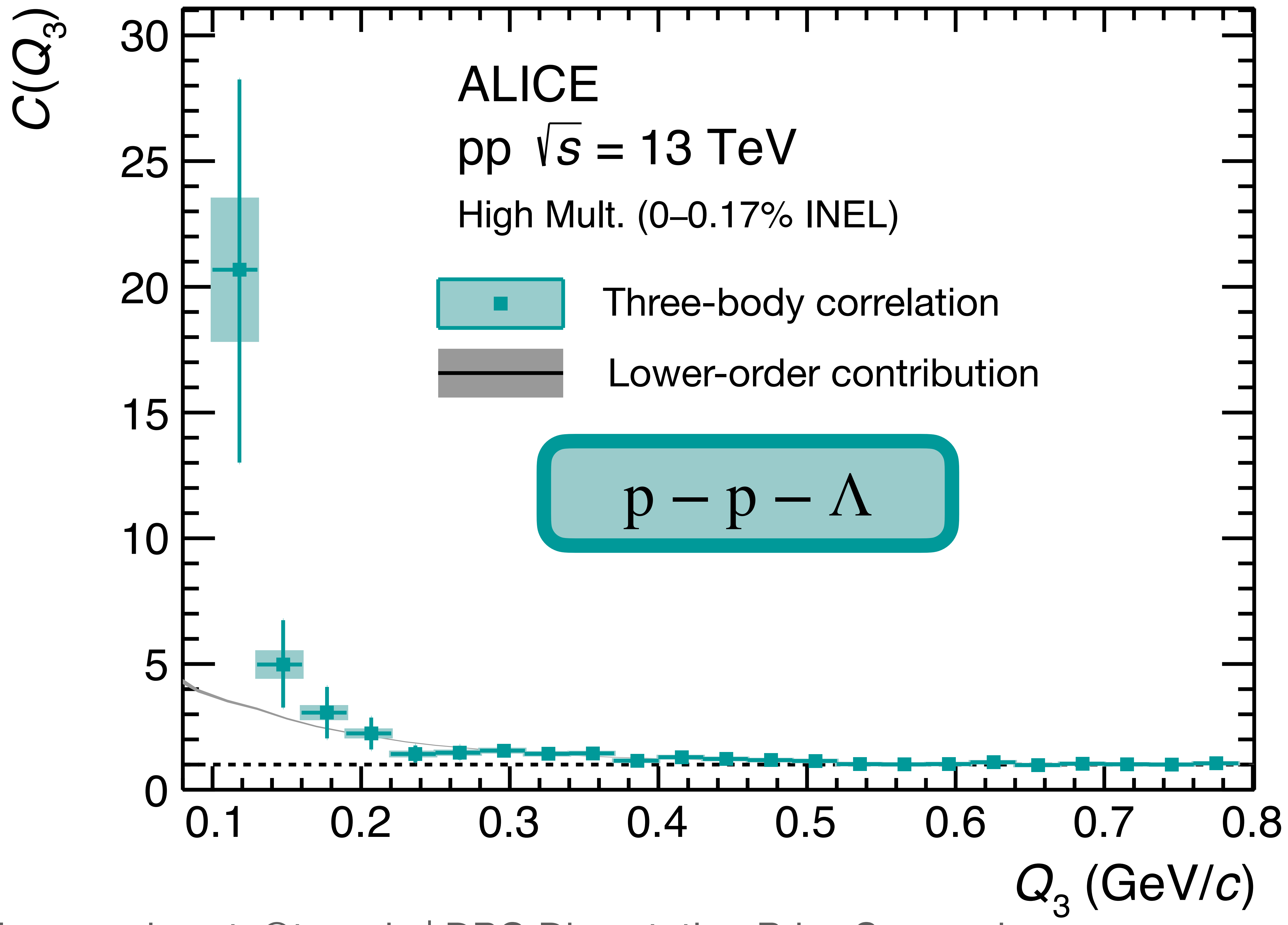


[1] R. Kubo, J. Phys. Soc. Jpn. 17, 1100-1120 (1962)

Measured correlation functions

ALICE, EPJA 59 145 (2023)

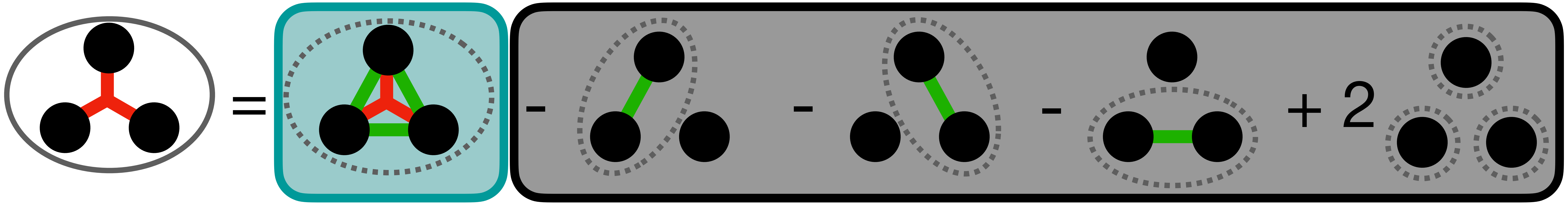


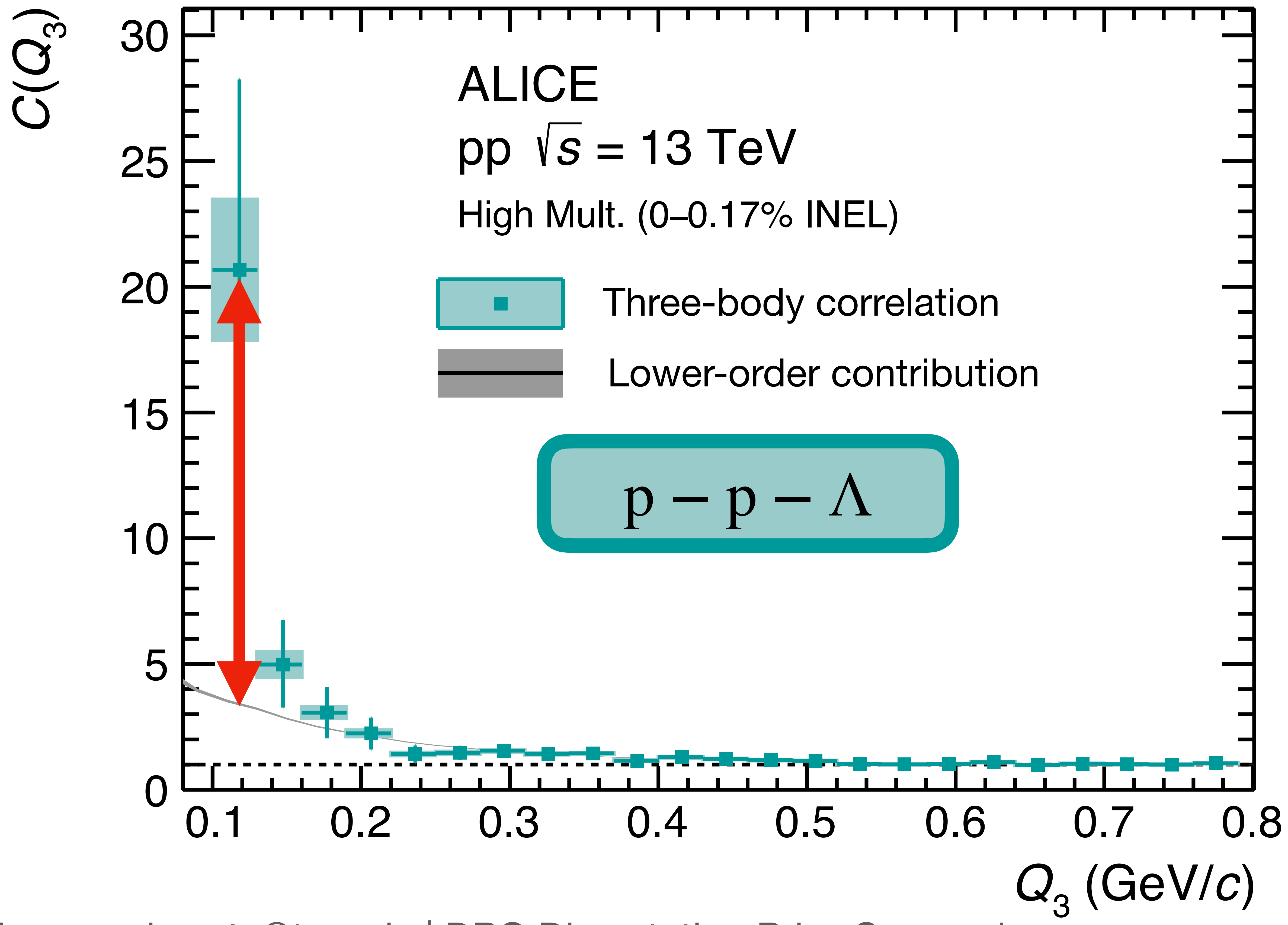


Measured correlation functions

ALICE, EPJA 59 145 (2023)

Three-baryon correlations





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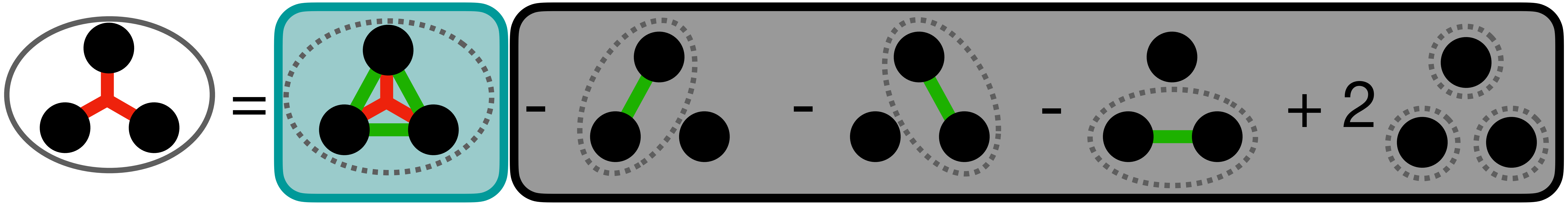

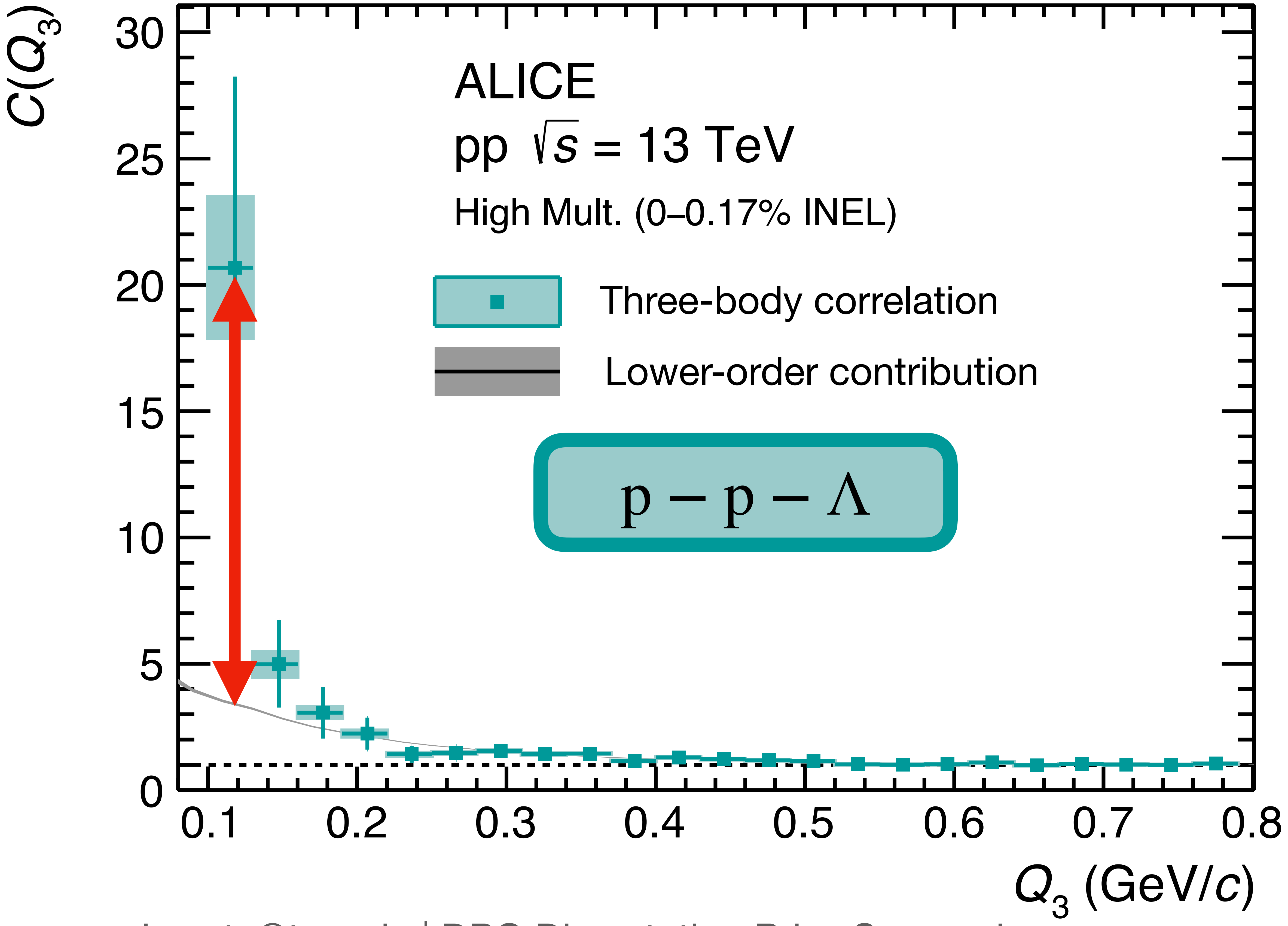

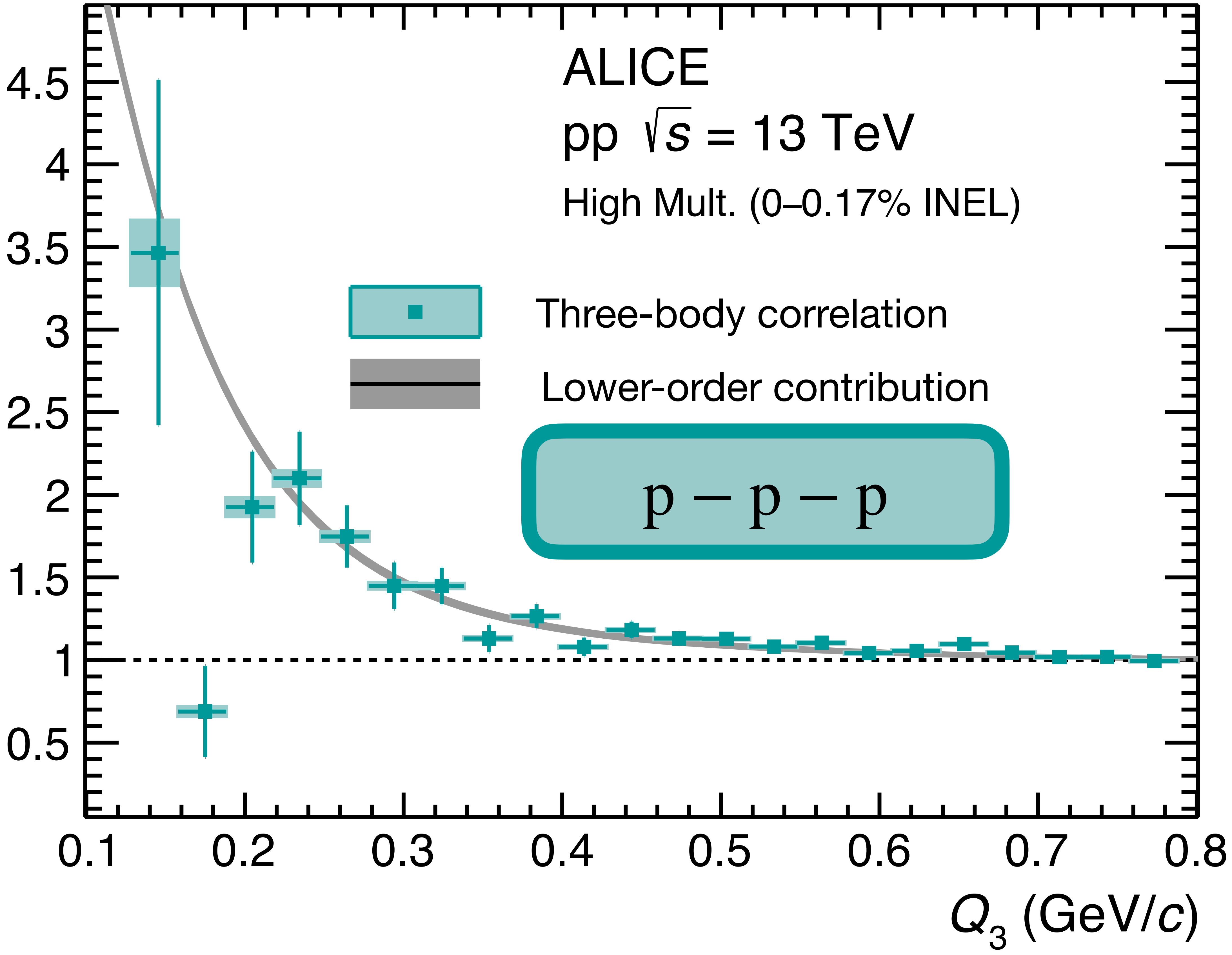

Three-baryon correlations

Measured correlation functions

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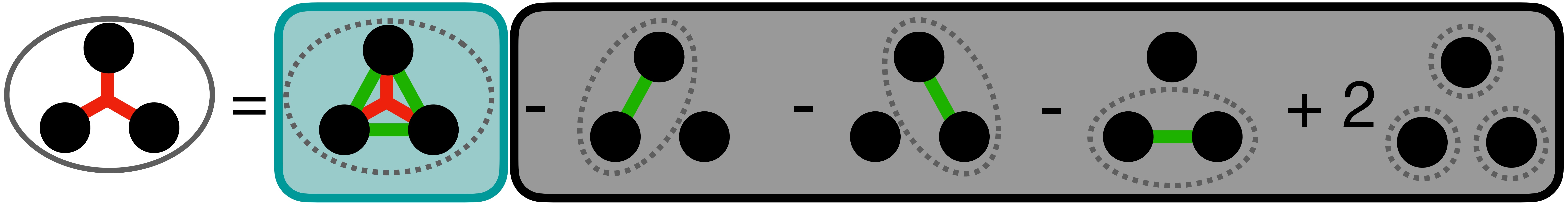

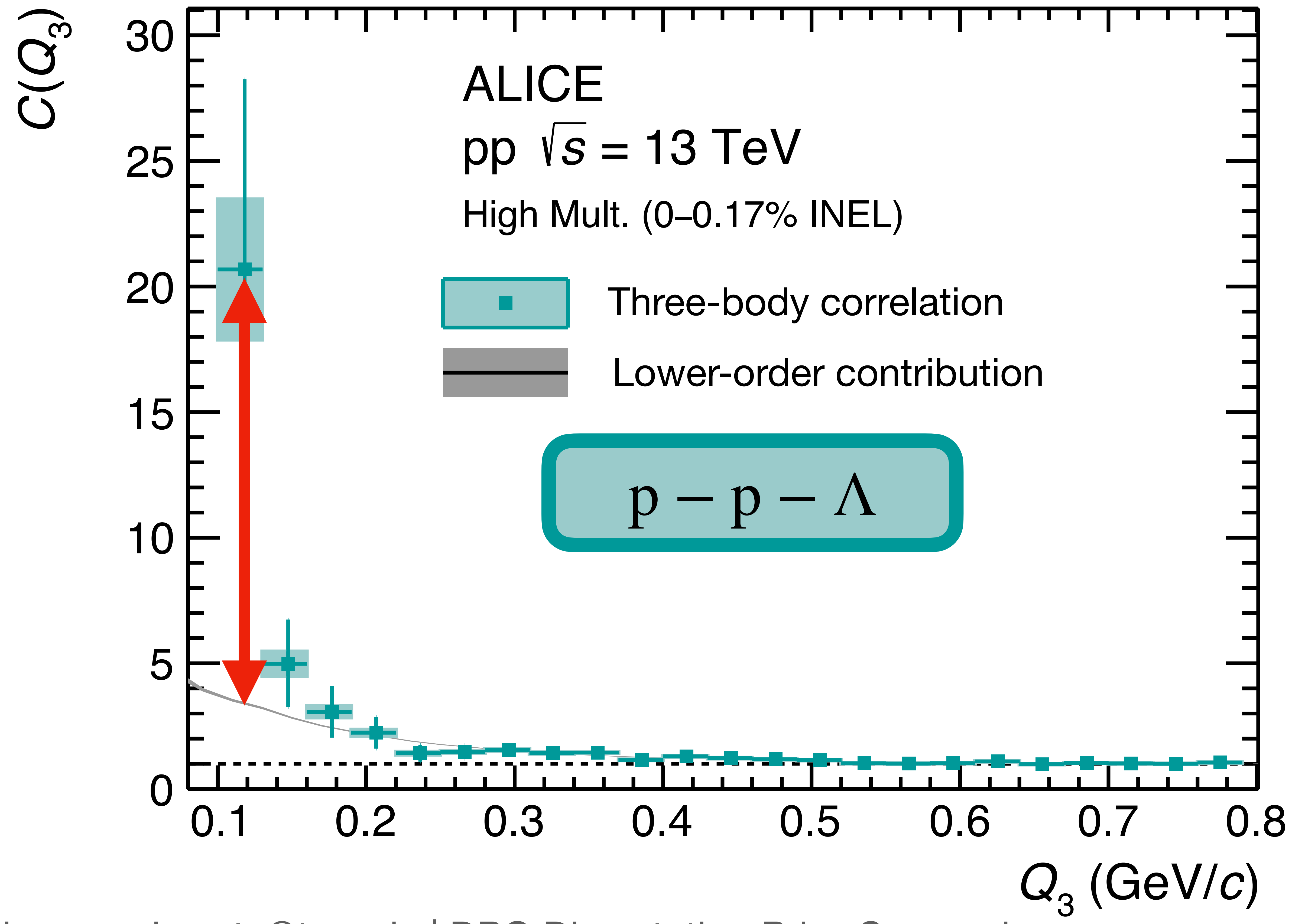

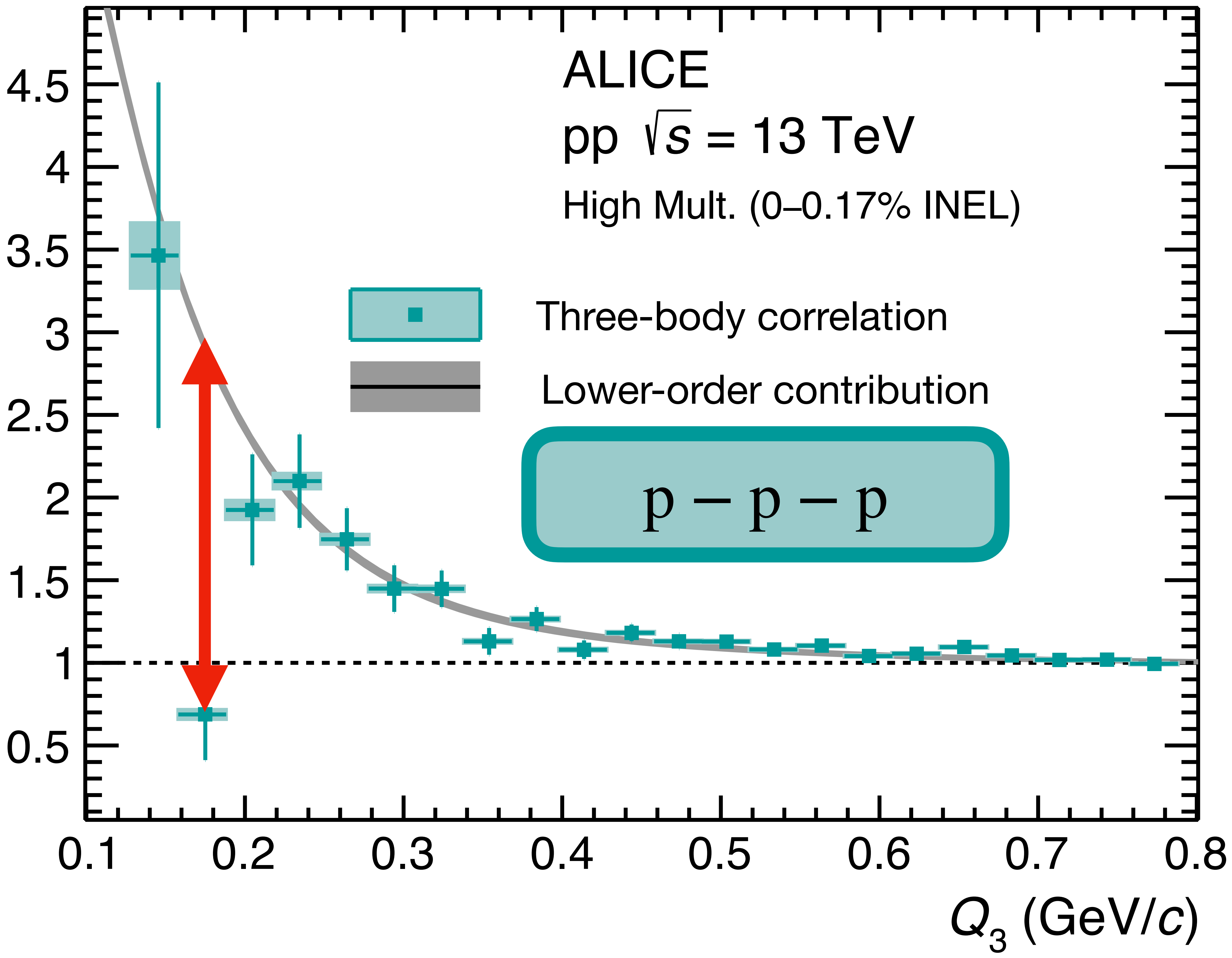

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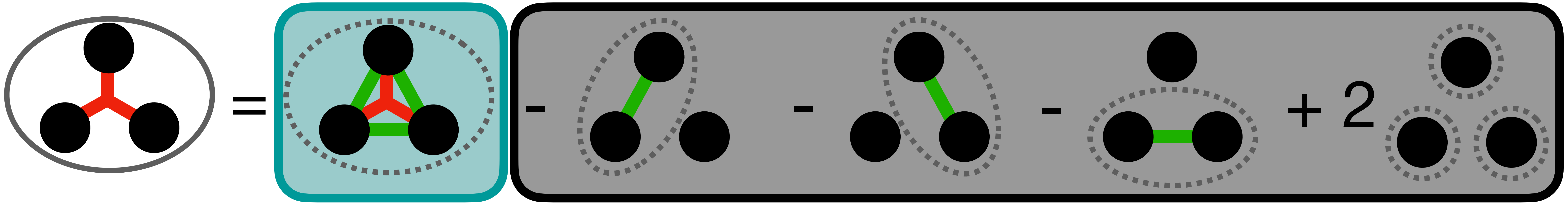
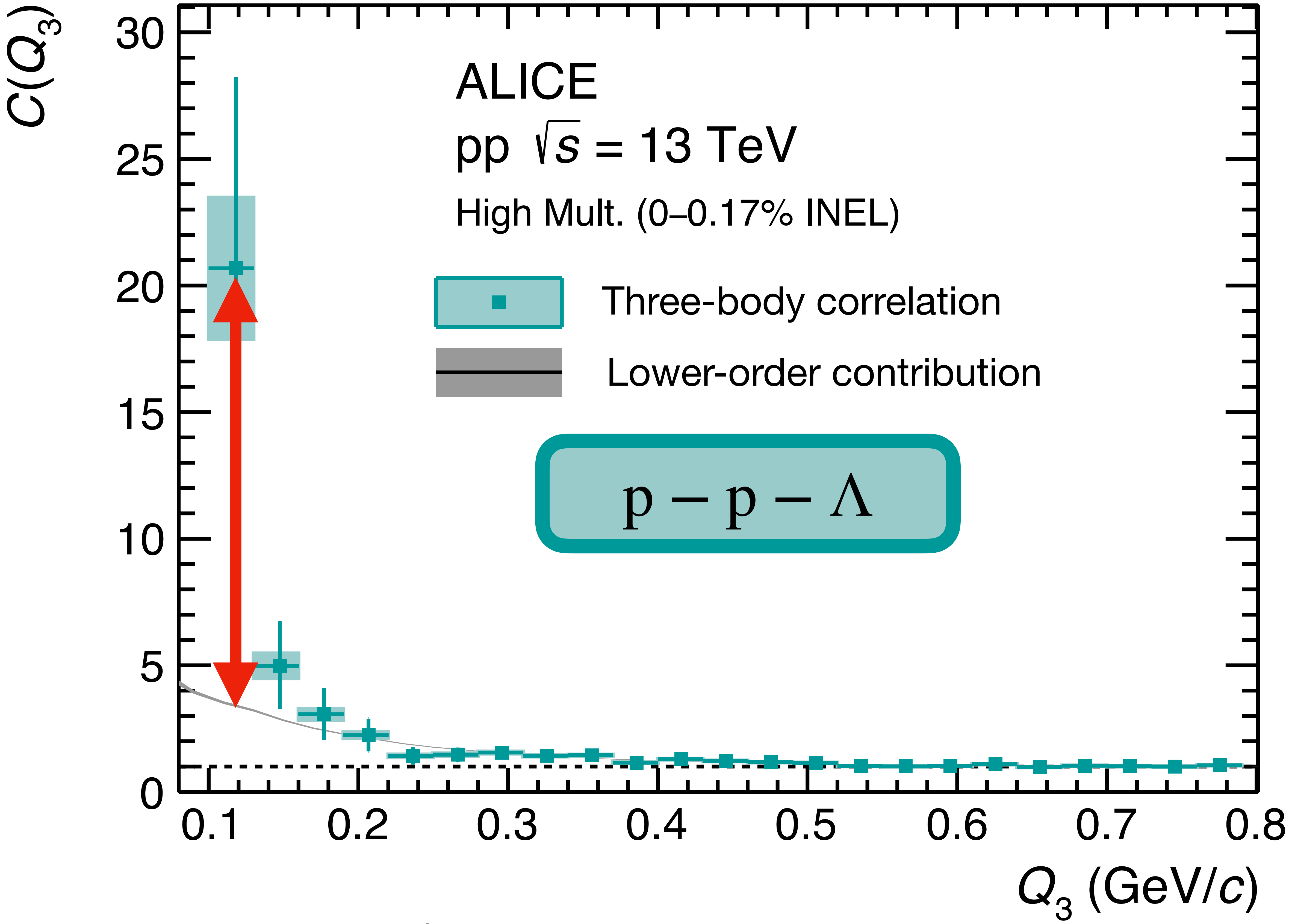
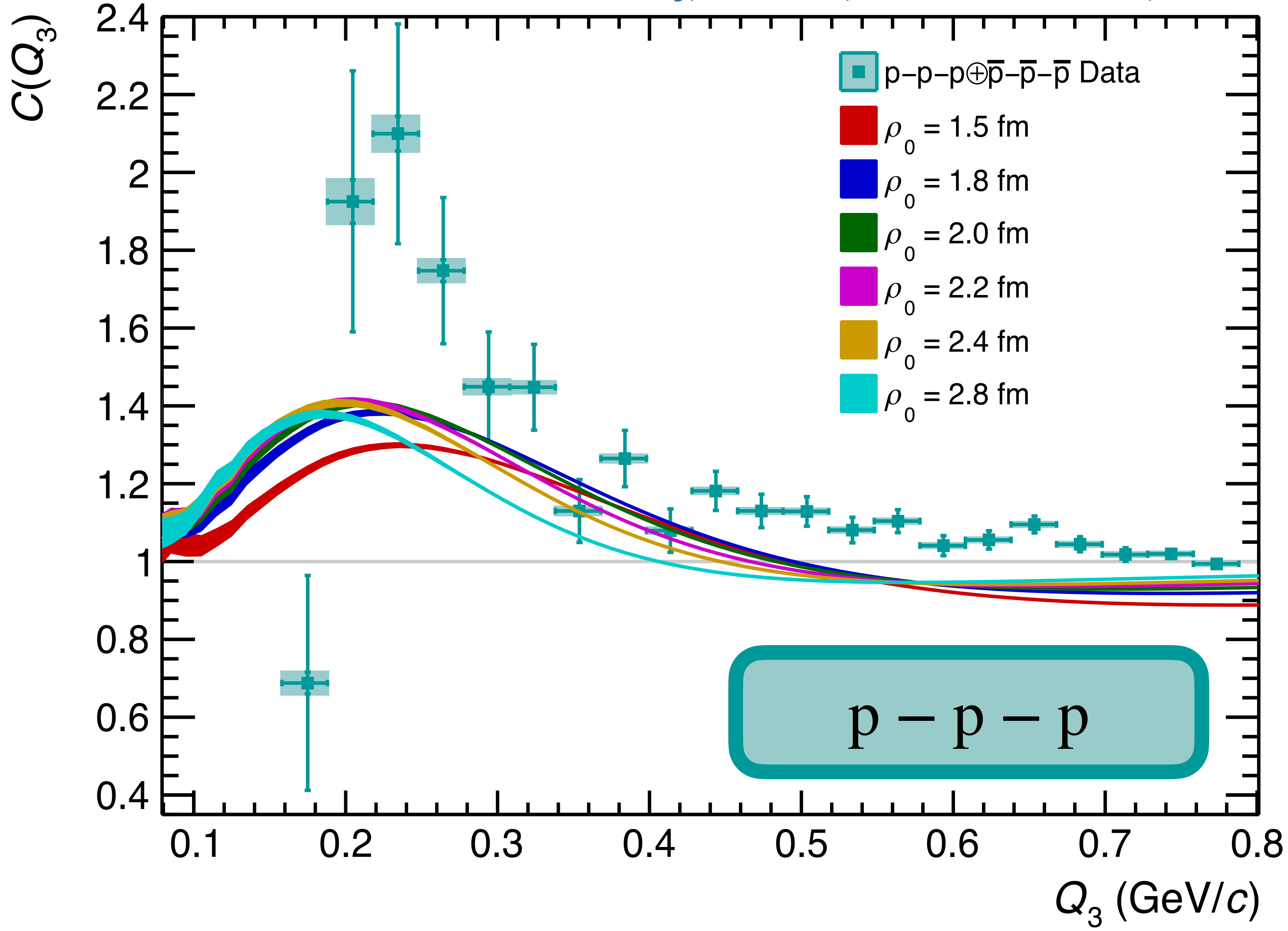


In collaboration with INFN PISA theory group

Kievsky, LS et al., arXiv:2310.10428, PRC

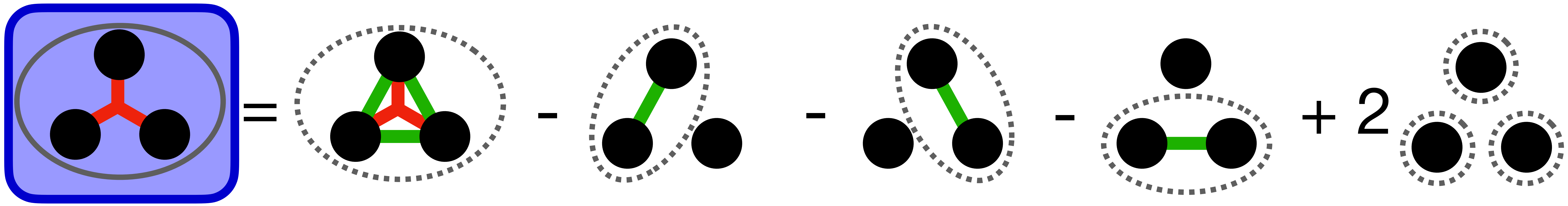




Three-baryon correlations

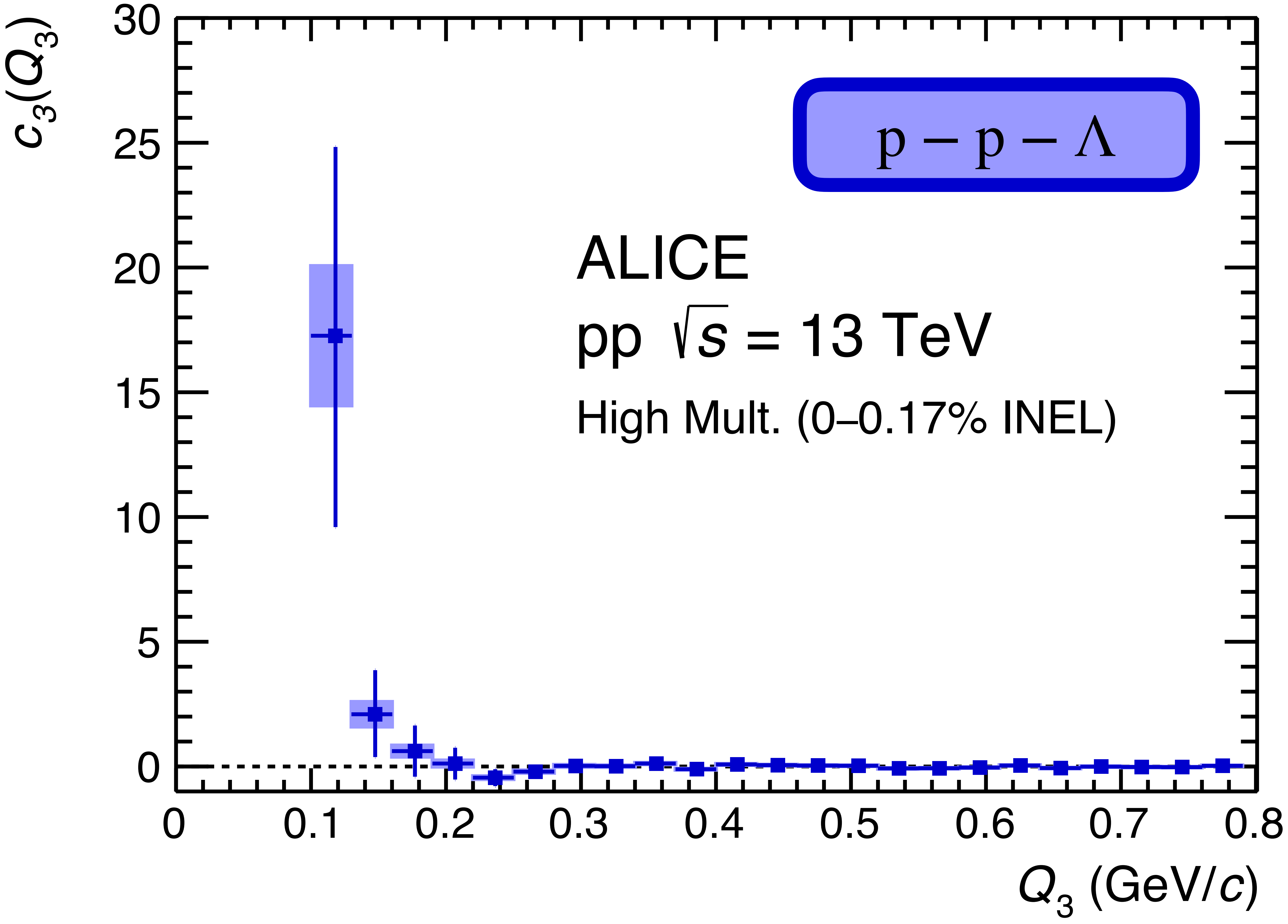
Three-body effects in p-p-Λ

ALICE, EPJA 59 145 (2023)



Hint of a attractive effects for p-p-Λ

- Only two identical and charged particles
  - ✓ Main expected contribution from three-body strong interaction



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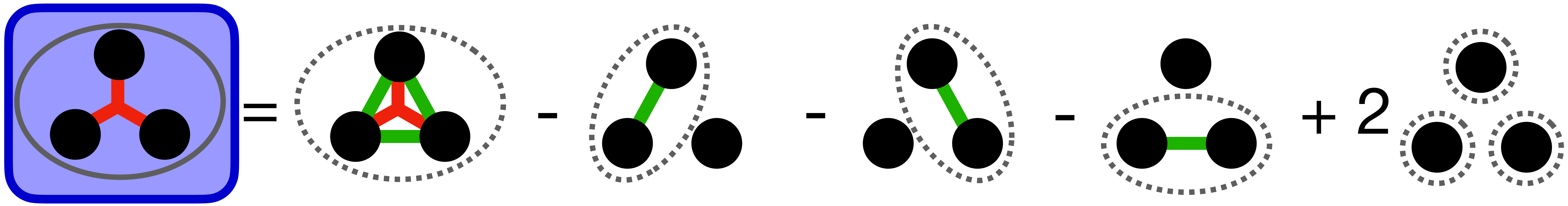

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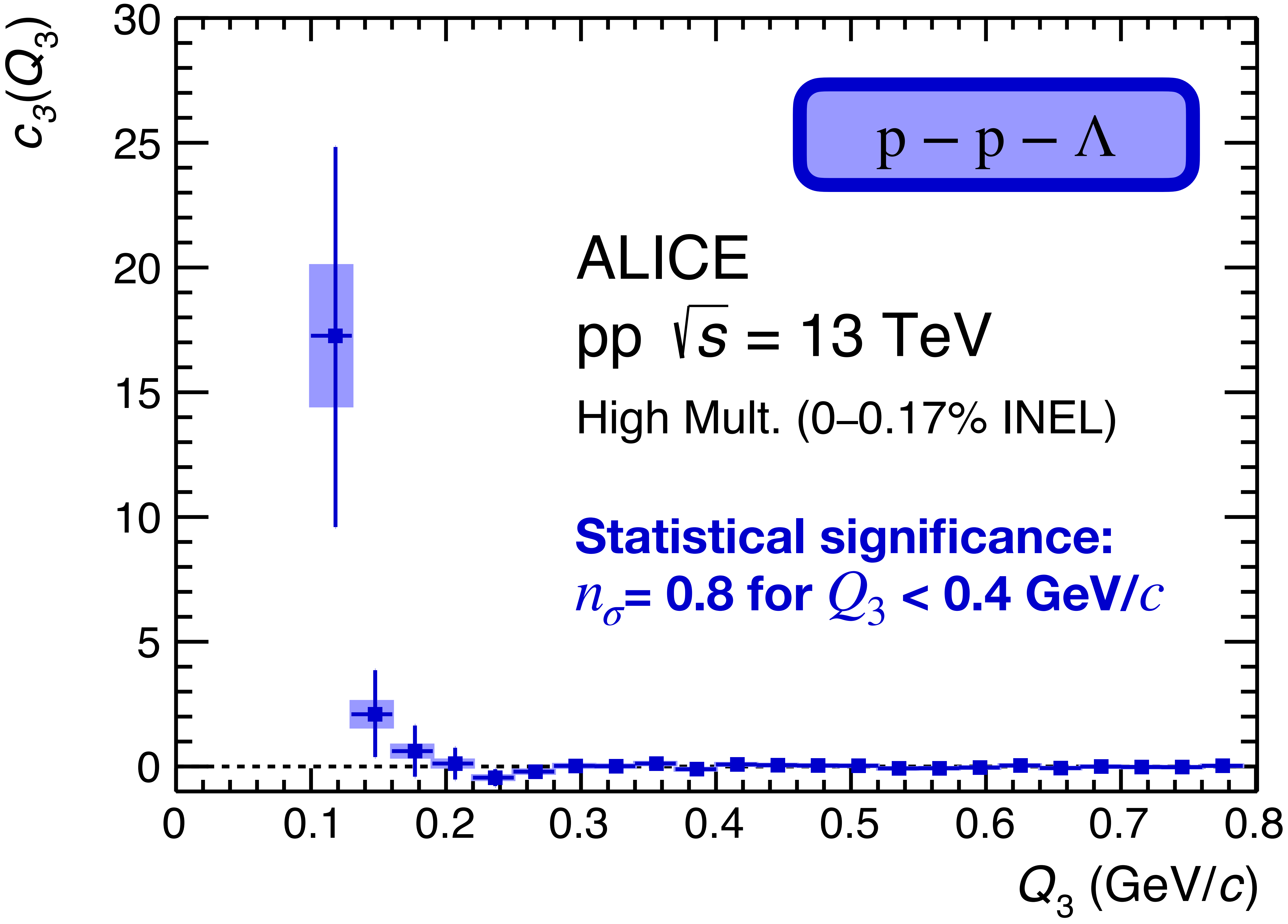

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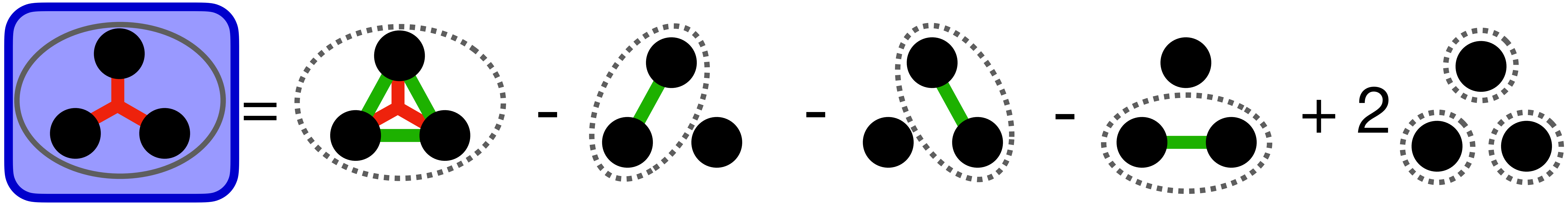
ALICE, EPJA 59 145 (2023)



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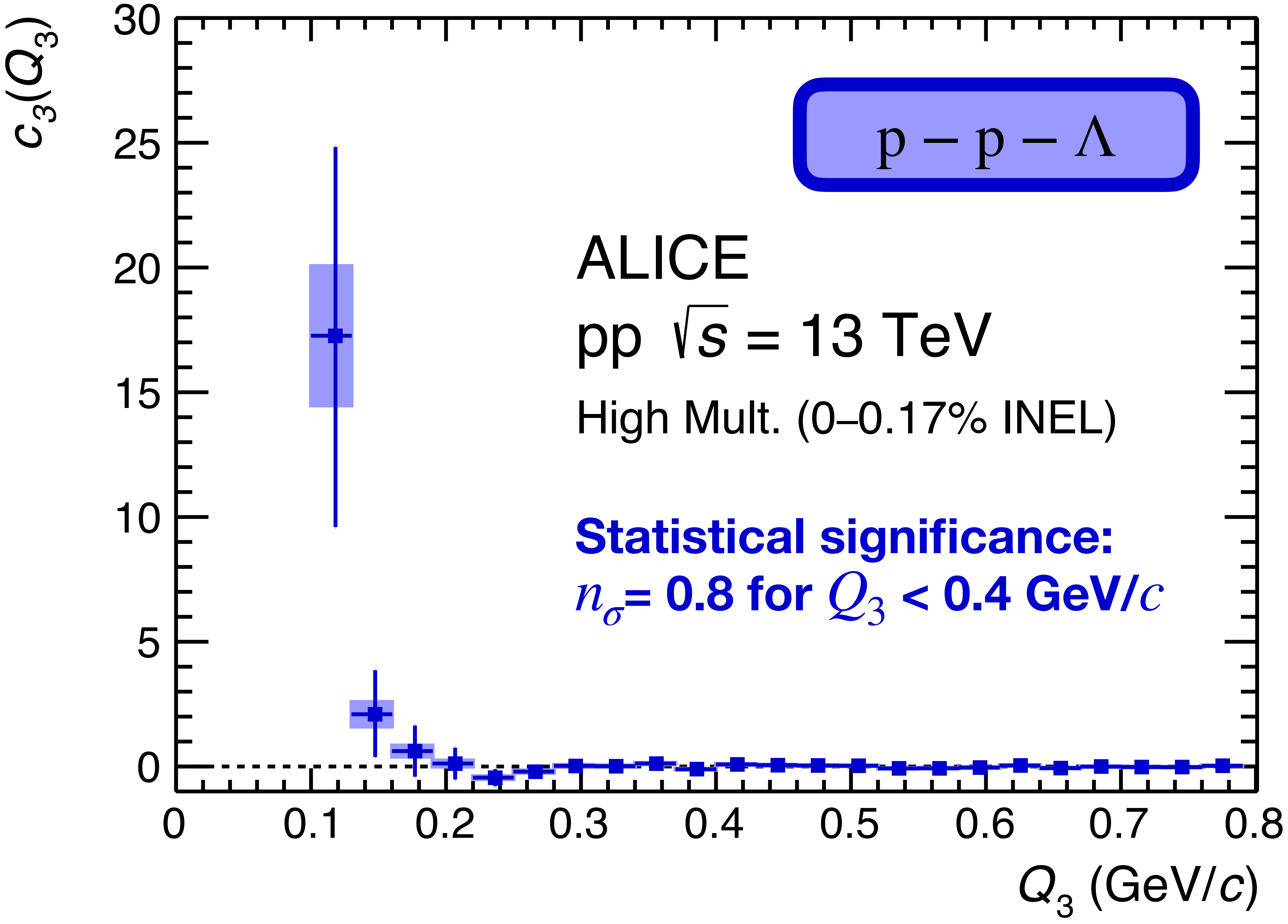
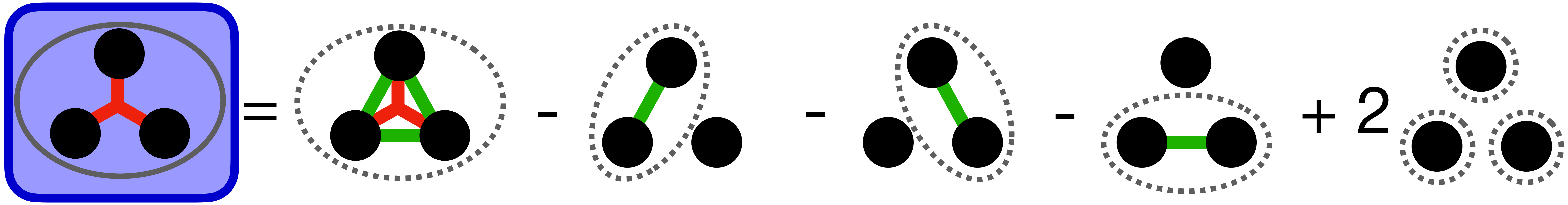


Three-baryon correlations

Three-body effects in p-p-Λ

ALICE, EPJA 59 145 (2023)



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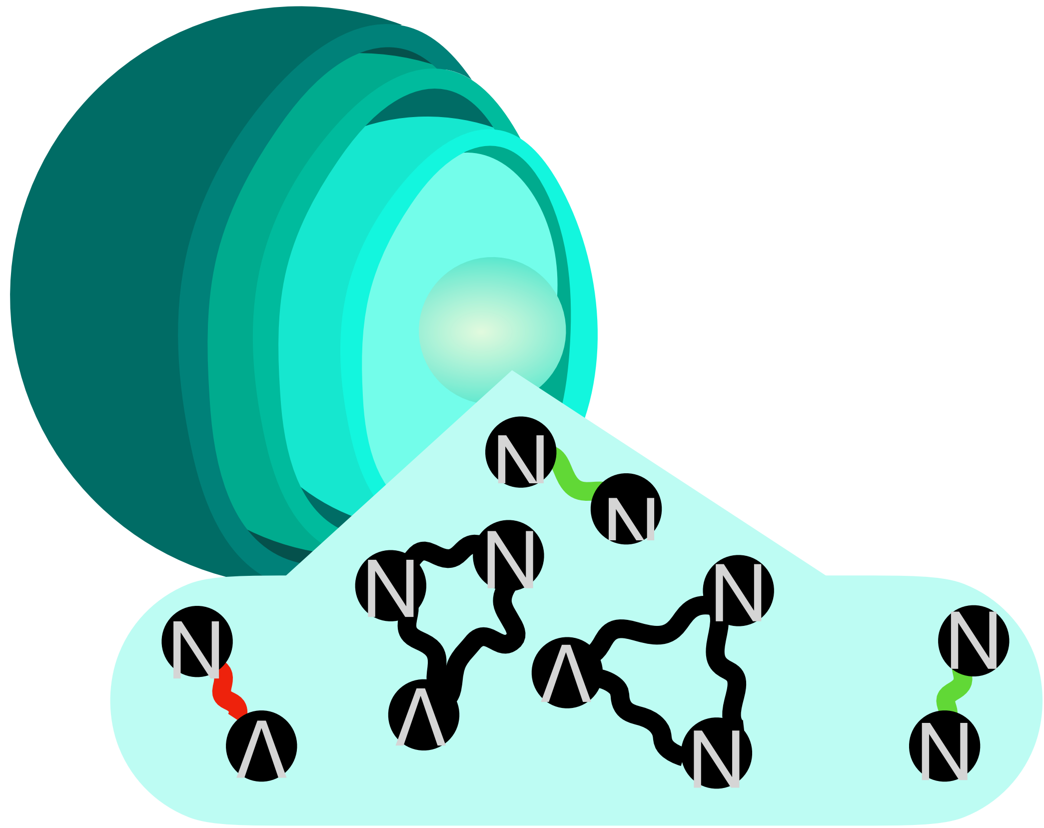
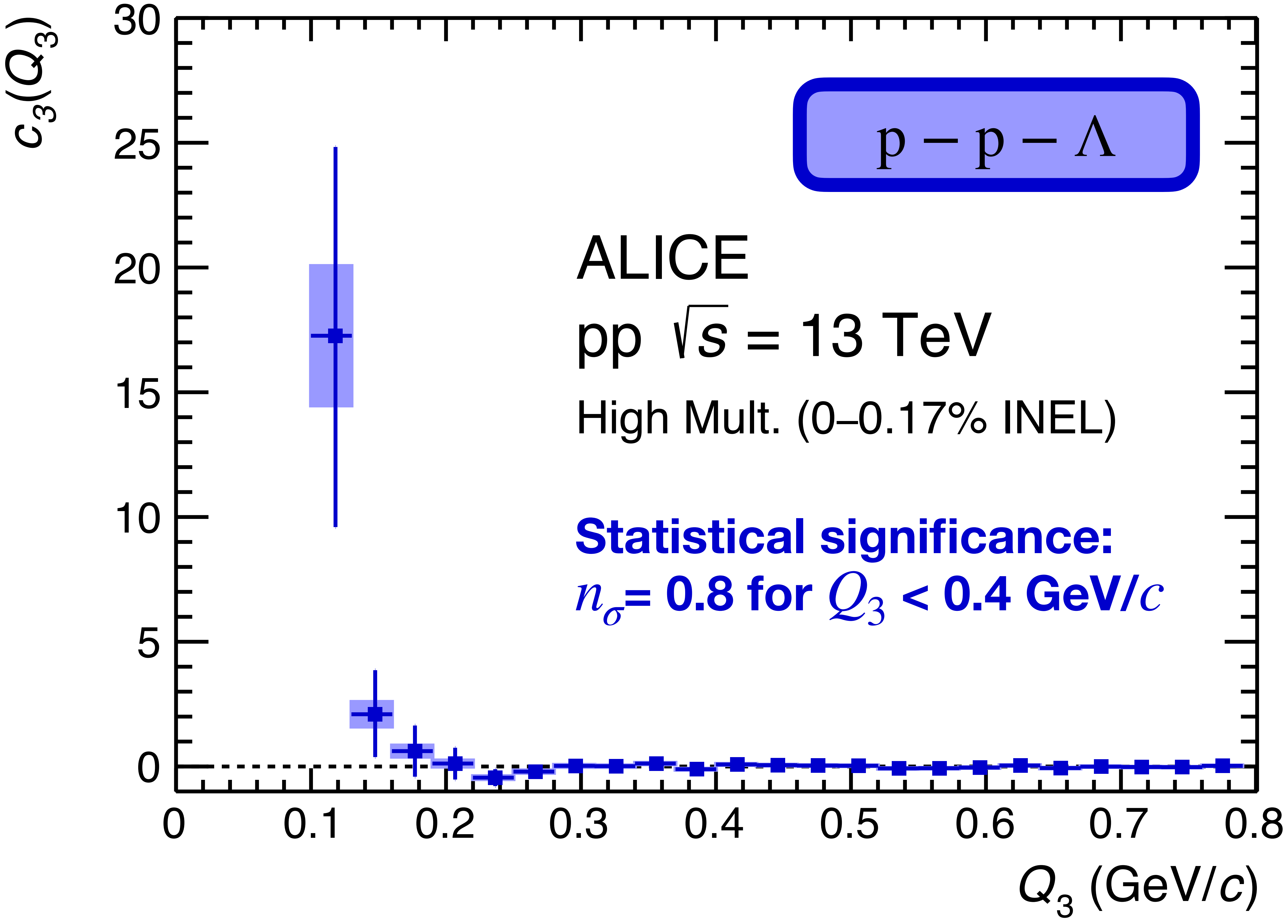
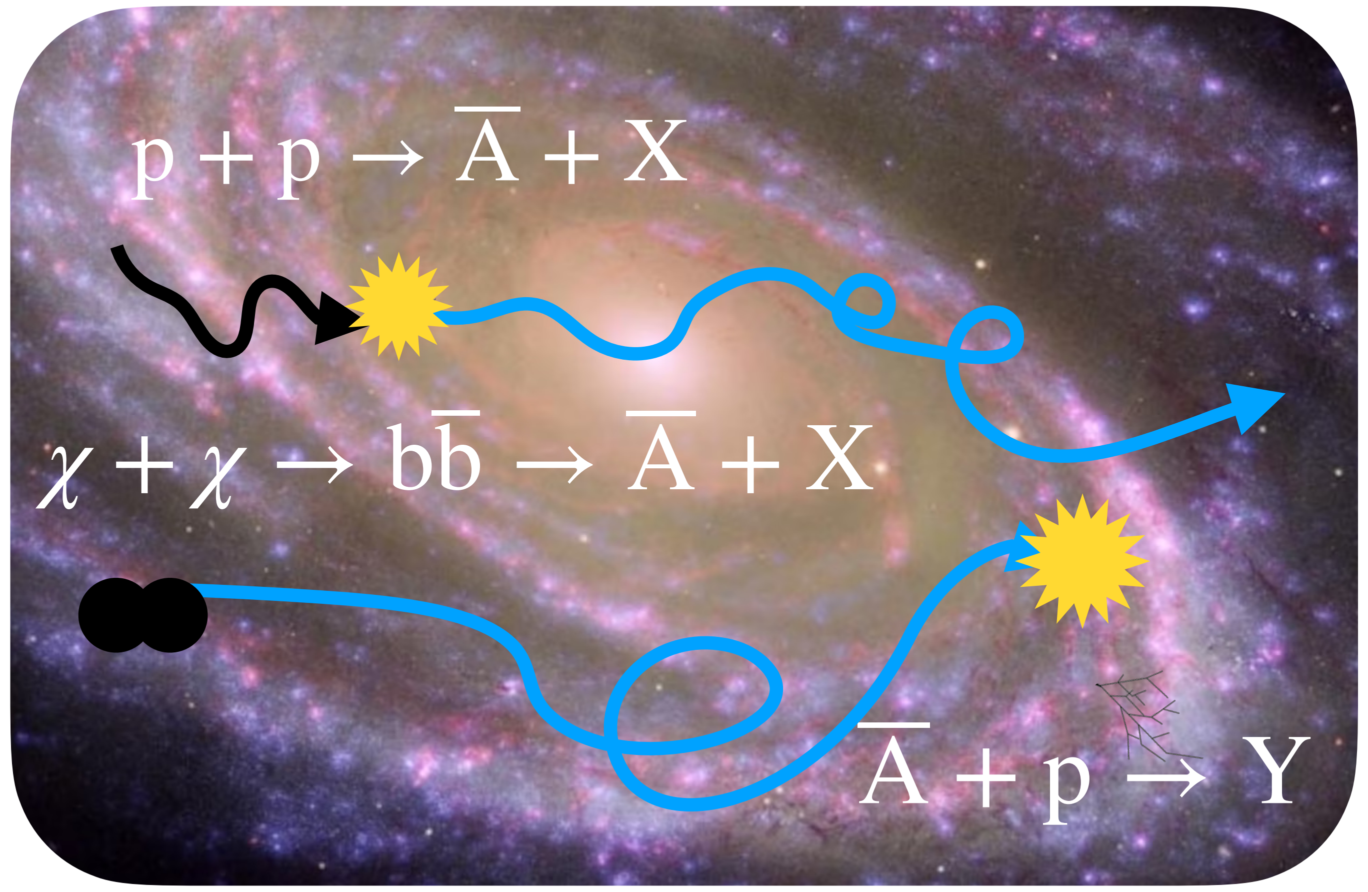
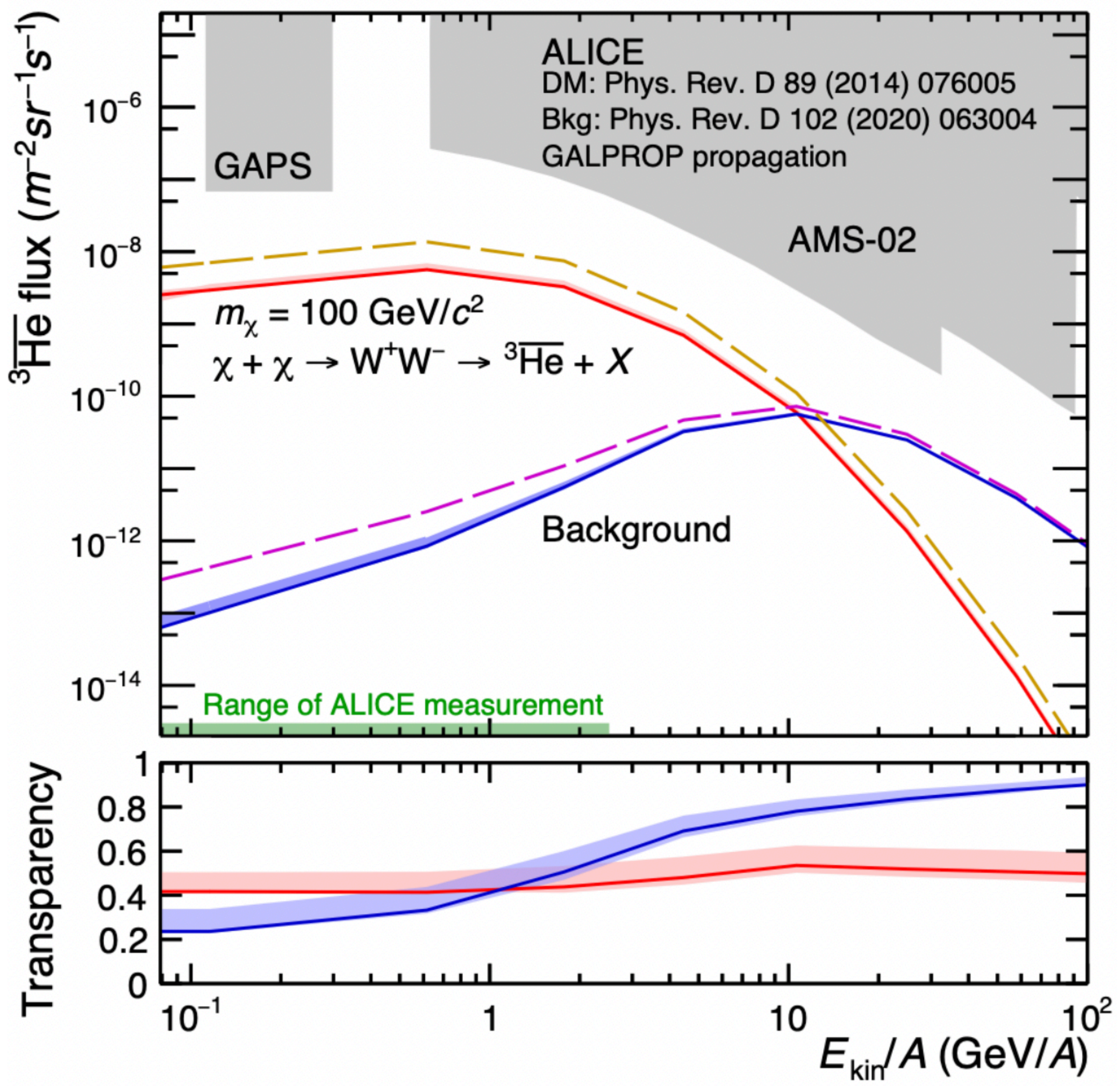




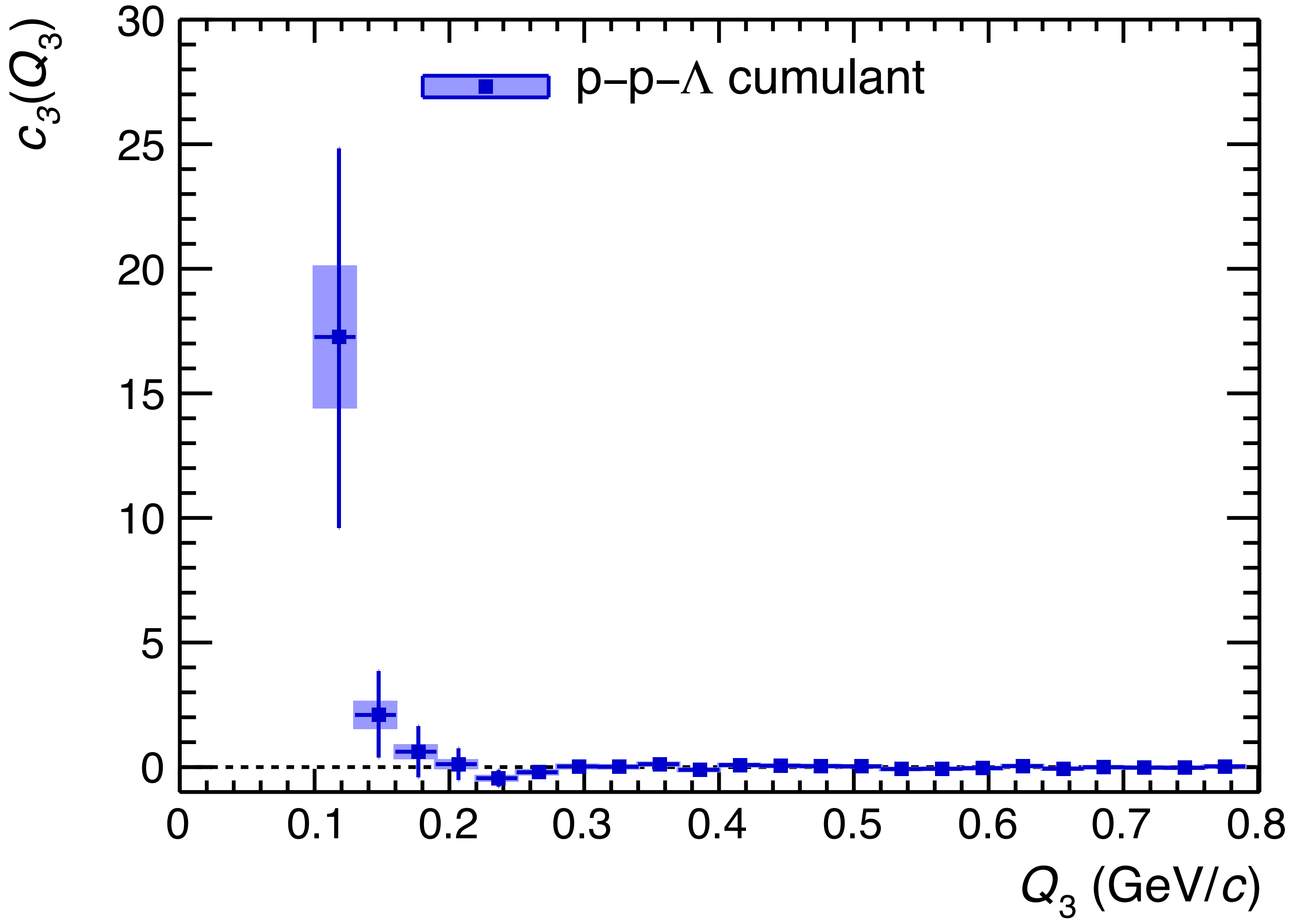
Cosmic-ray antinuclei



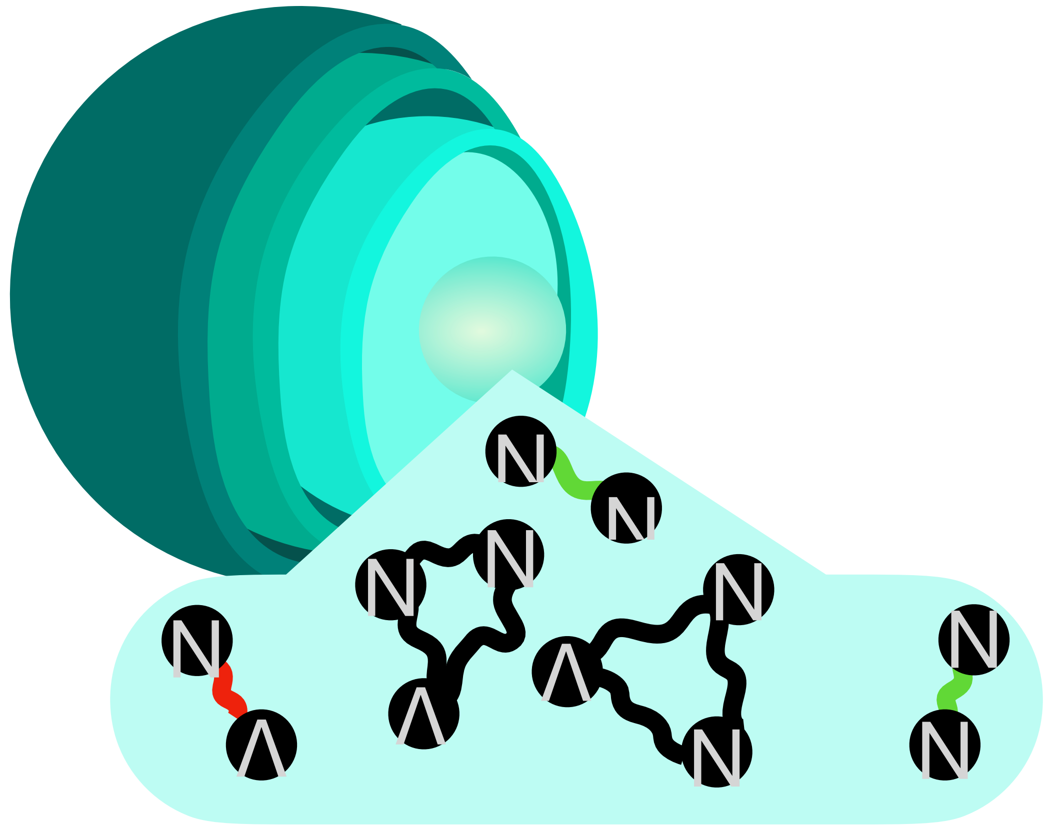
Our Galaxy is transparent to the propagation of antinuclei



Three-baryon correlations



Novel method for studies of three-body interactions



Stay tuned for LHC Run 3!

Thank you for your attention!

CR video:

Back up

Publications during PhD

- Del Grande, R., Šerkšnytė, L., Fabbietti, L., Mantovani Sarti, V., & Mihaylov, D. (2022). A method to remove lower order contributions in multi-particle femtoscopic correlation functions. The European Physical Journal C, 82(3)
- ALICE Collaboration (2022). Towards the understanding of the genuine three-body interaction for p-p-p and p-p-Λ. arXiv preprint arXiv:2206.03344 (Accepted by EPJA)
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- ALICE Collaboration (2023). Measurement of anti-3He nuclei absorption in matter and impact on their propagation in the Galaxy. Nature Physics 19 (1)
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