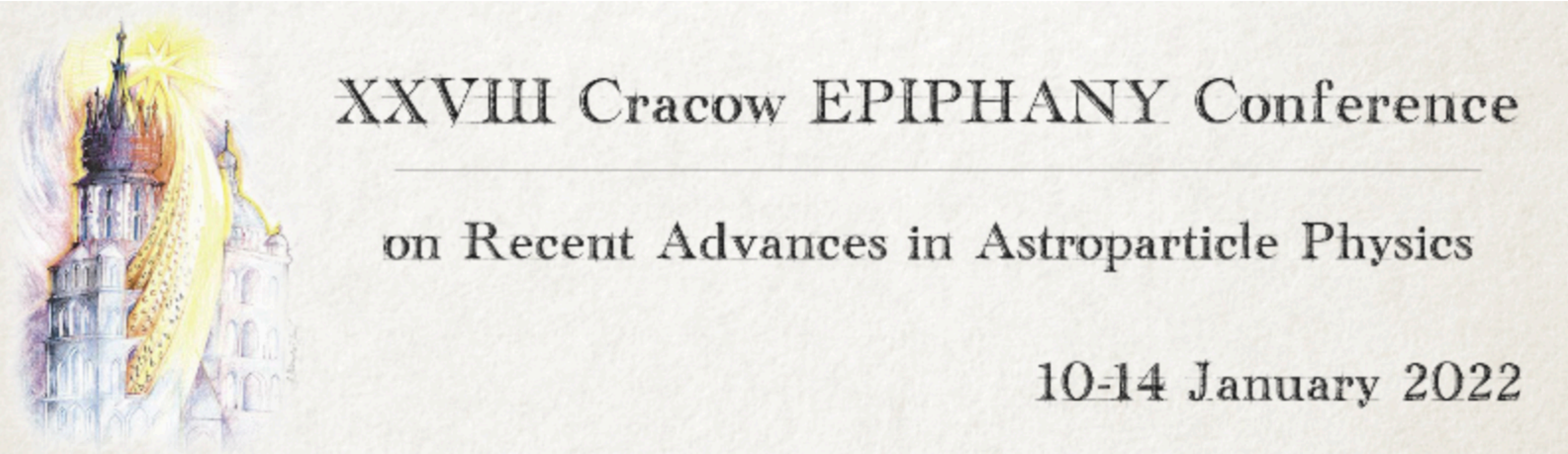
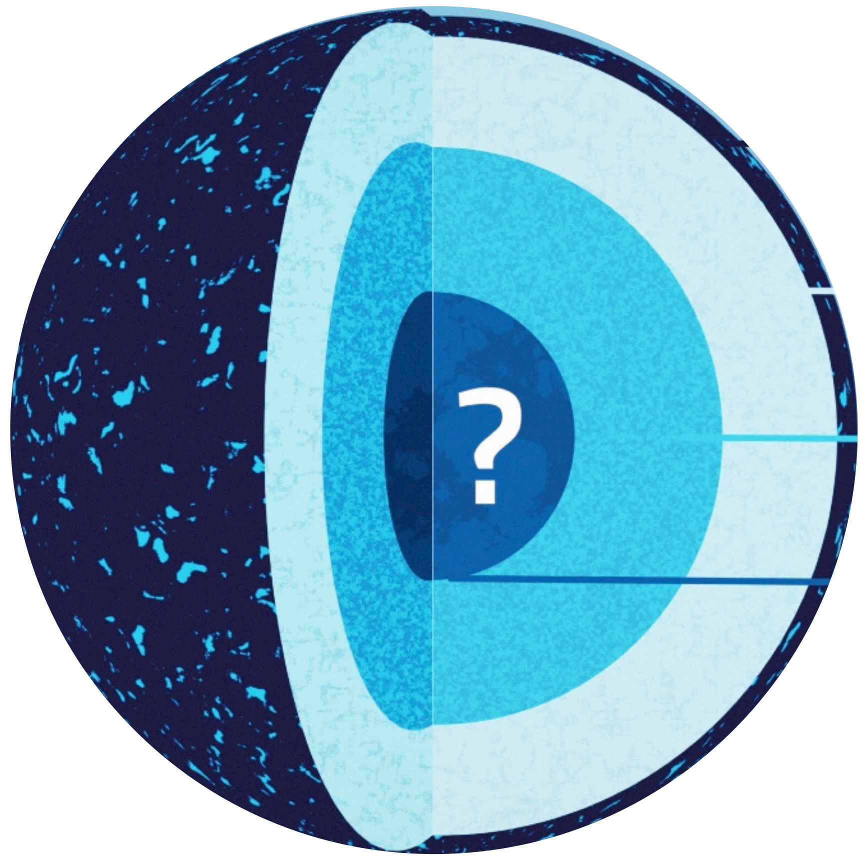
ALICE at the LHC, neutron stars and indirect dark matter searches

Laura Šerkšnytė
On behalf of the ALICE Collaboration
Technical University of Munich
EPIPHANY2022



Outline

- Part 1: Strong interaction in neutron stars and at the LHC
  - Possible hyperon presence in neutron stars
  - Necessary two- and three-body interaction measurements



Credits: NASA's Goddard Space Flight Center/Conceptual Image Lab

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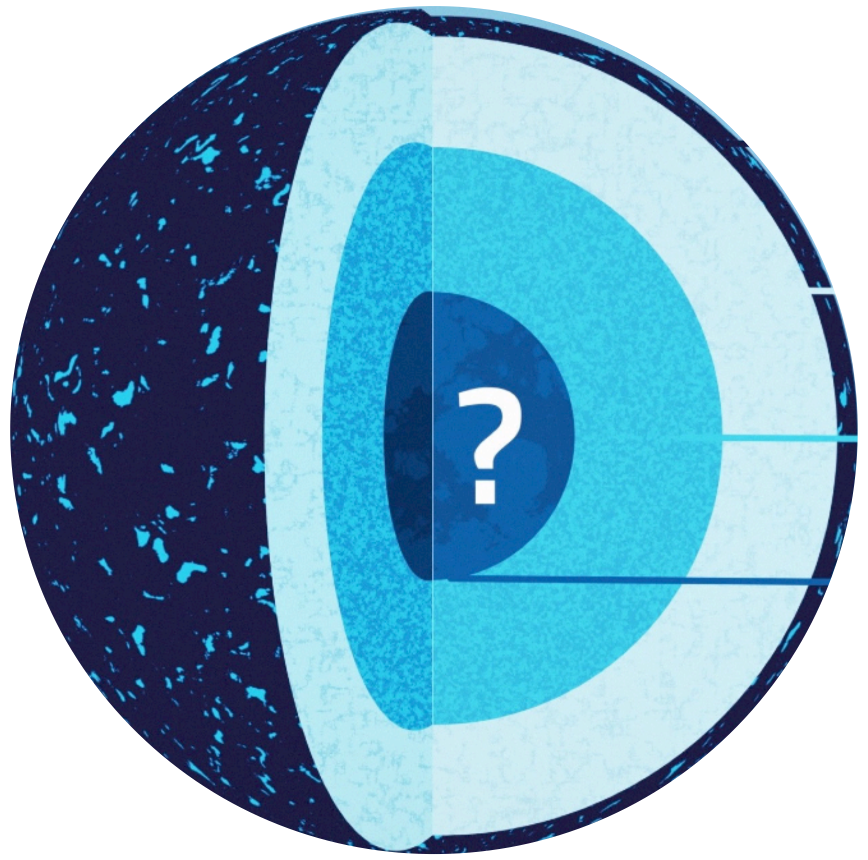

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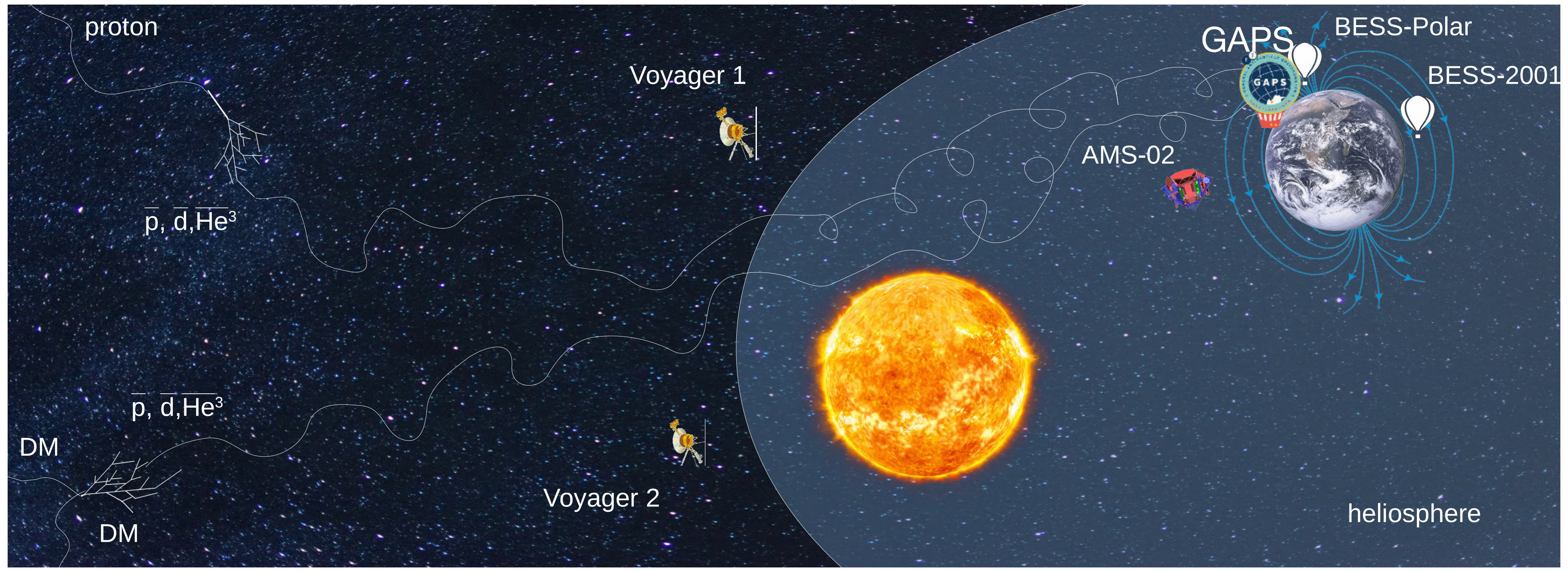
- Part 2: Light antinuclei in the galaxy and at the LHC
  - Antinuclei cosmic rays - indirect dark matter probe
  - Necessary light antinuclei production and inelastic cross section measurements



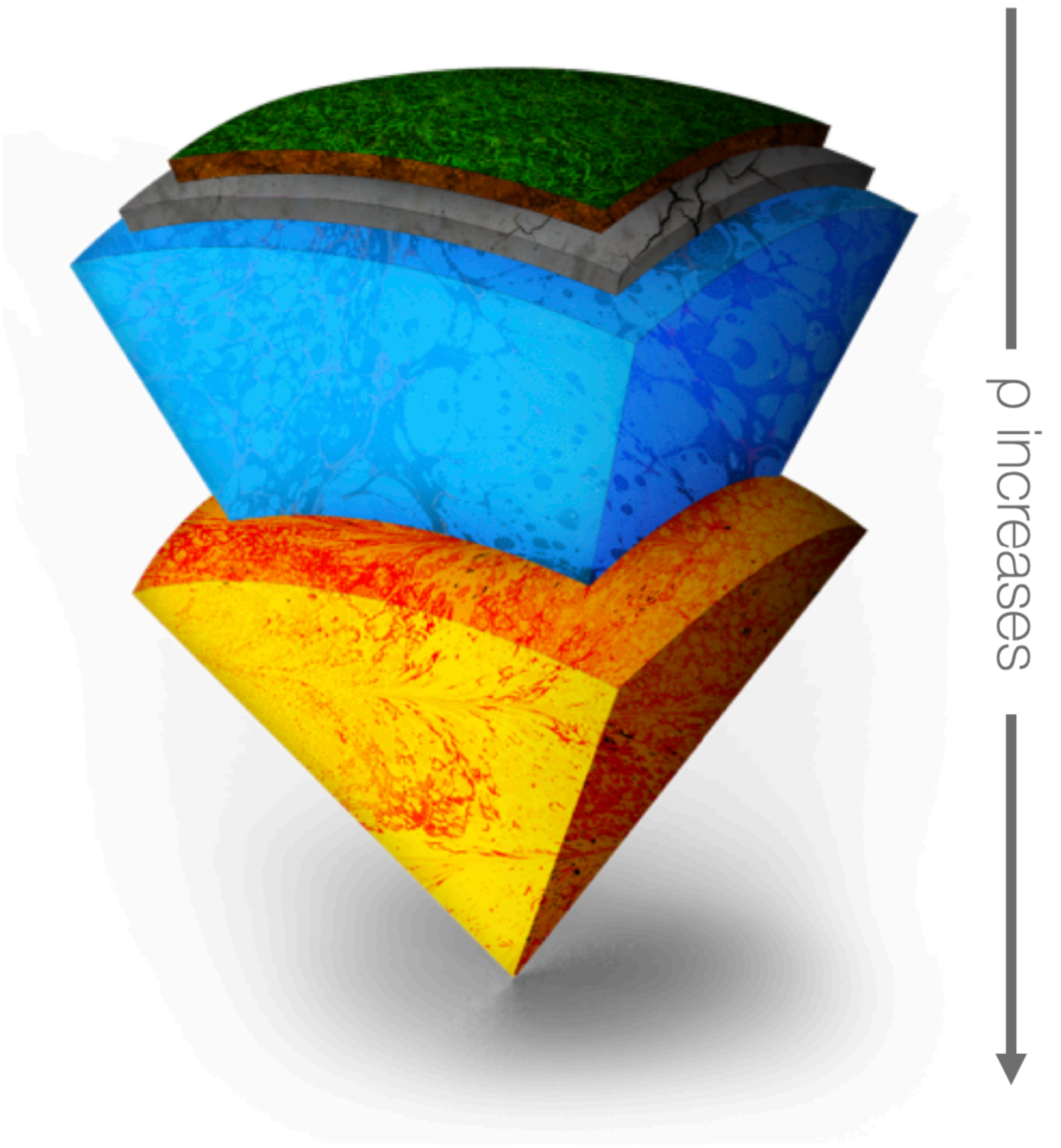
Strong interaction in neutron stars and at the LHC

Motivation: neutron stars

Dimensions
R ~ 10 – 15 km
M ~ 1.5 – 2.2 $M_{\odot}$

Outer Crust
Ions, electron gas,
Neutrons

Inner Core
Neutrons?
Protons?
Hyperons?
Kaon condensate?
Quark Matter?



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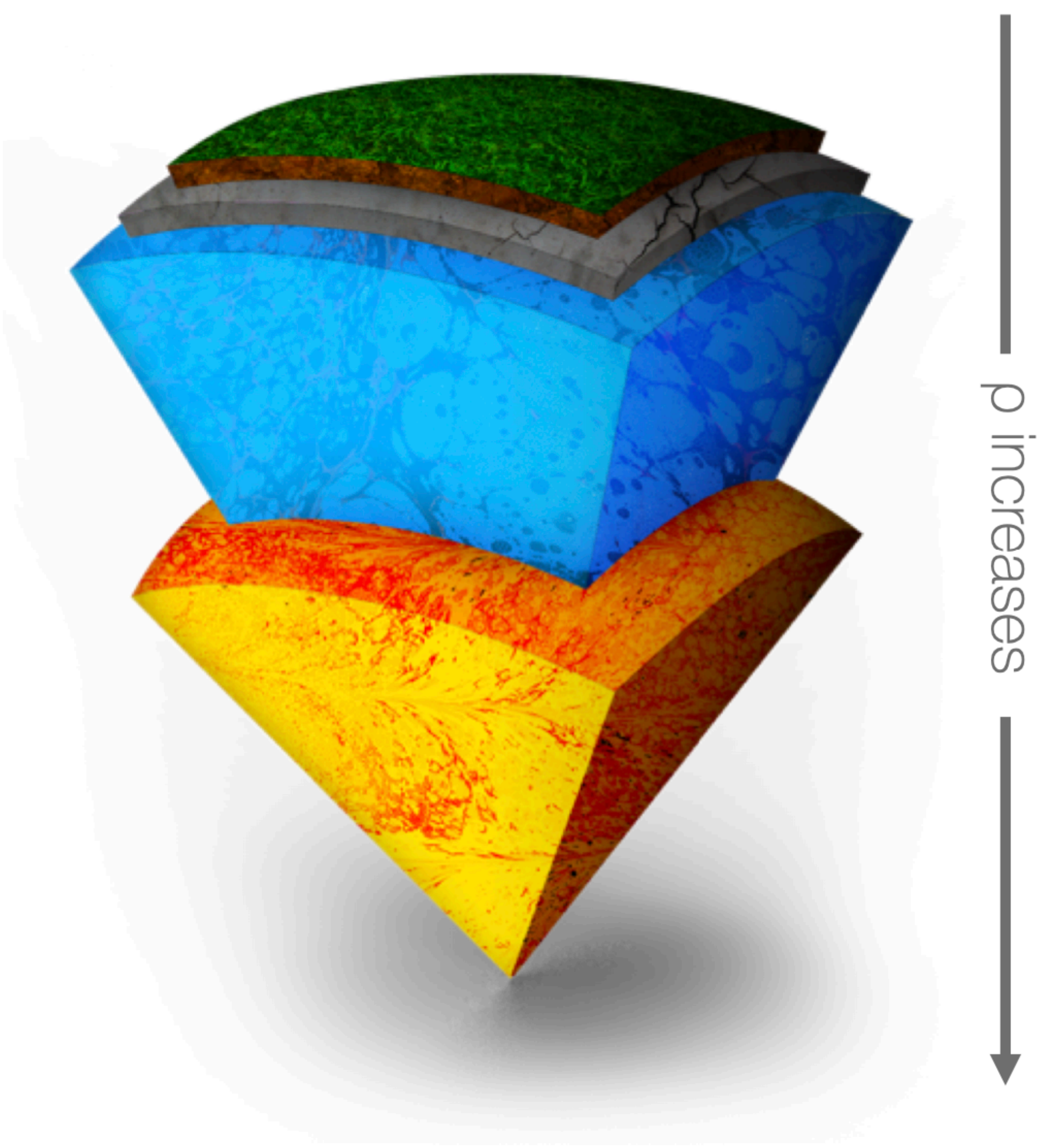
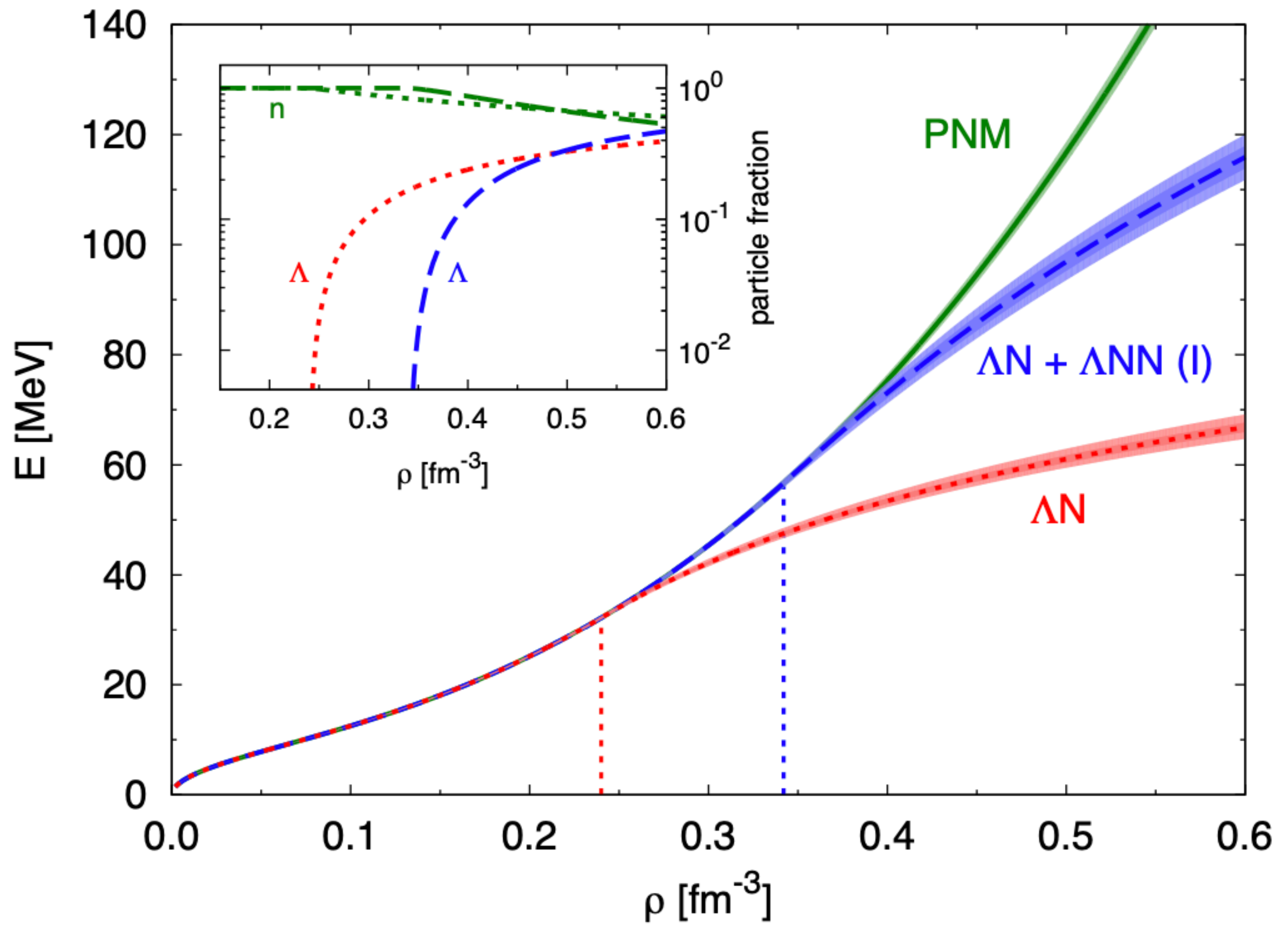


Energetically favourable to produce new degrees of freedom: ***hyperon puzzle***

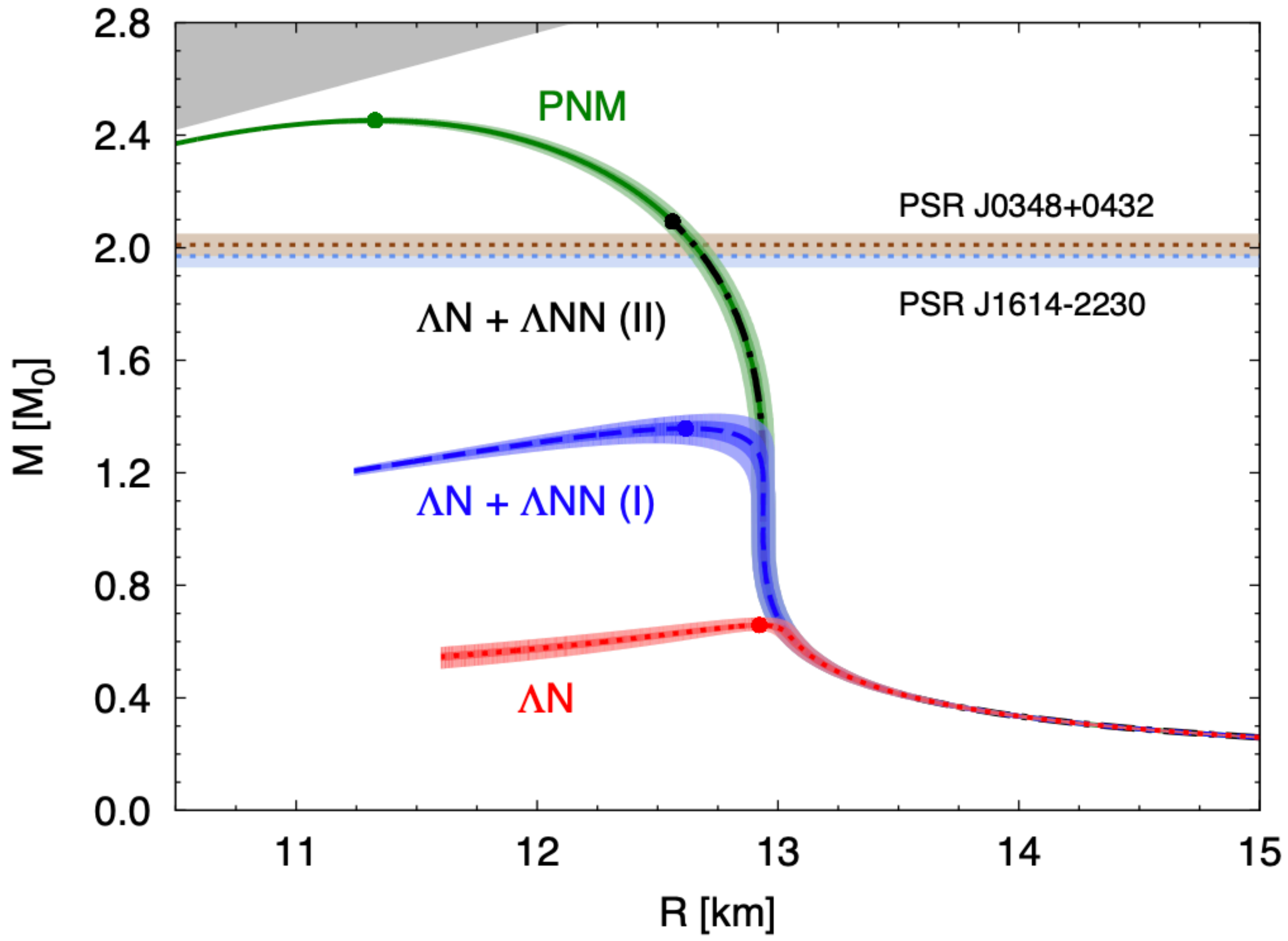
Beautiful short video about neutron stars and strong interaction studies by TUM ALICE group: https://youtu.be/u8uL2pA3tuI

Hyperons in neutron stars

- Results in softening of equation of state (EoS). But it strongly depends on:
    - Y-N and Y-Y interactions included,
    - three-body interactions.



TOV equations



Lonardoni et al., Phys. Rev. Lett. 114, 092301 (2015)

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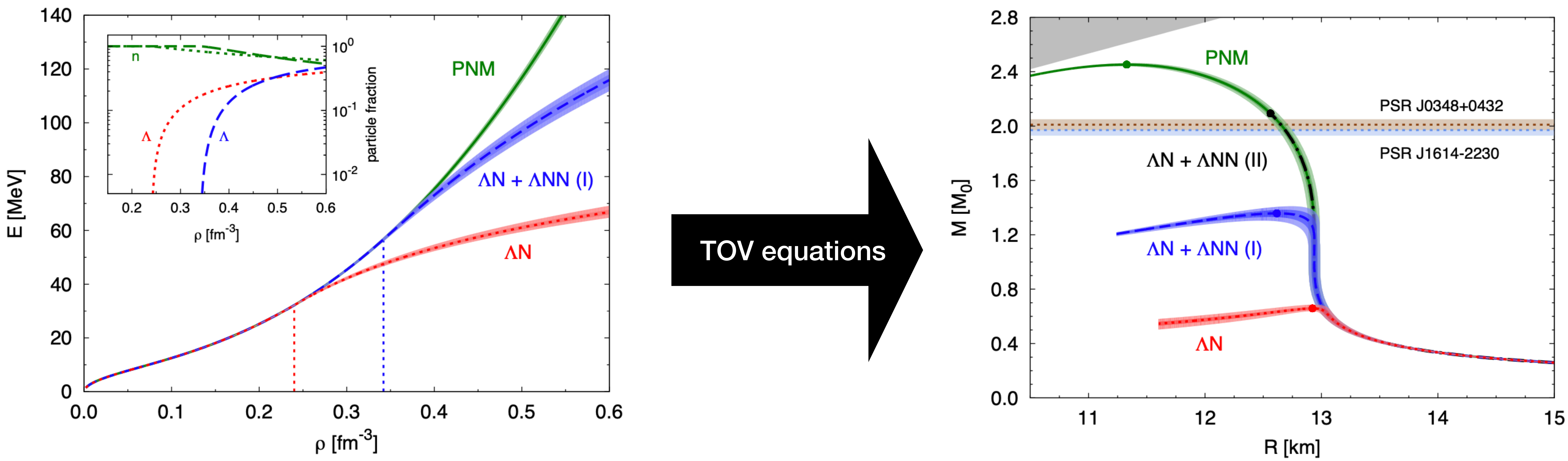
Study at the LHC



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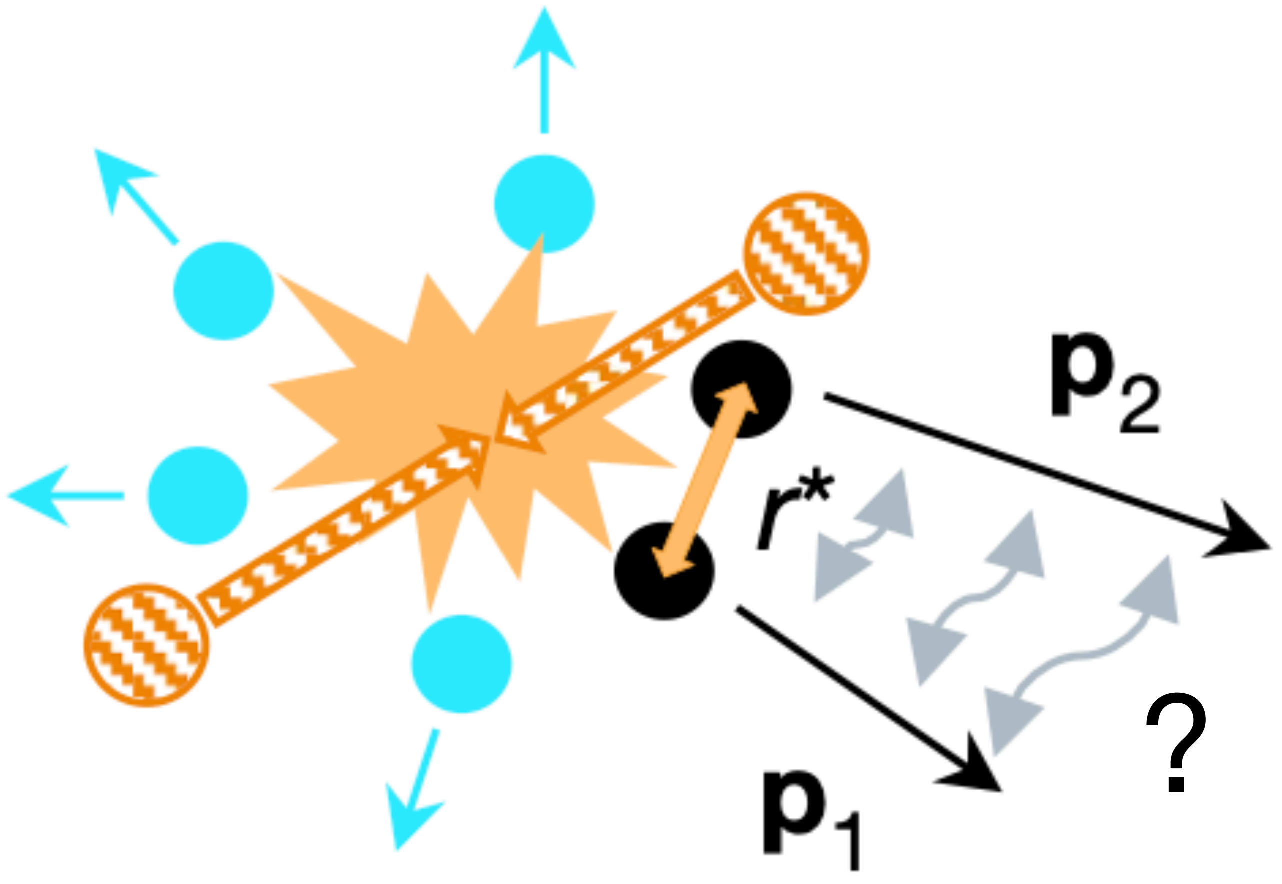
Femtoscopy technique



Emission source *S(r*)*

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

Illustrations: ALICE Coll., Nature 588, 232–238 (2020)
CATS Framework: D. Mihaylov et al., Eur. Phys. J. C78, 394 (2018)

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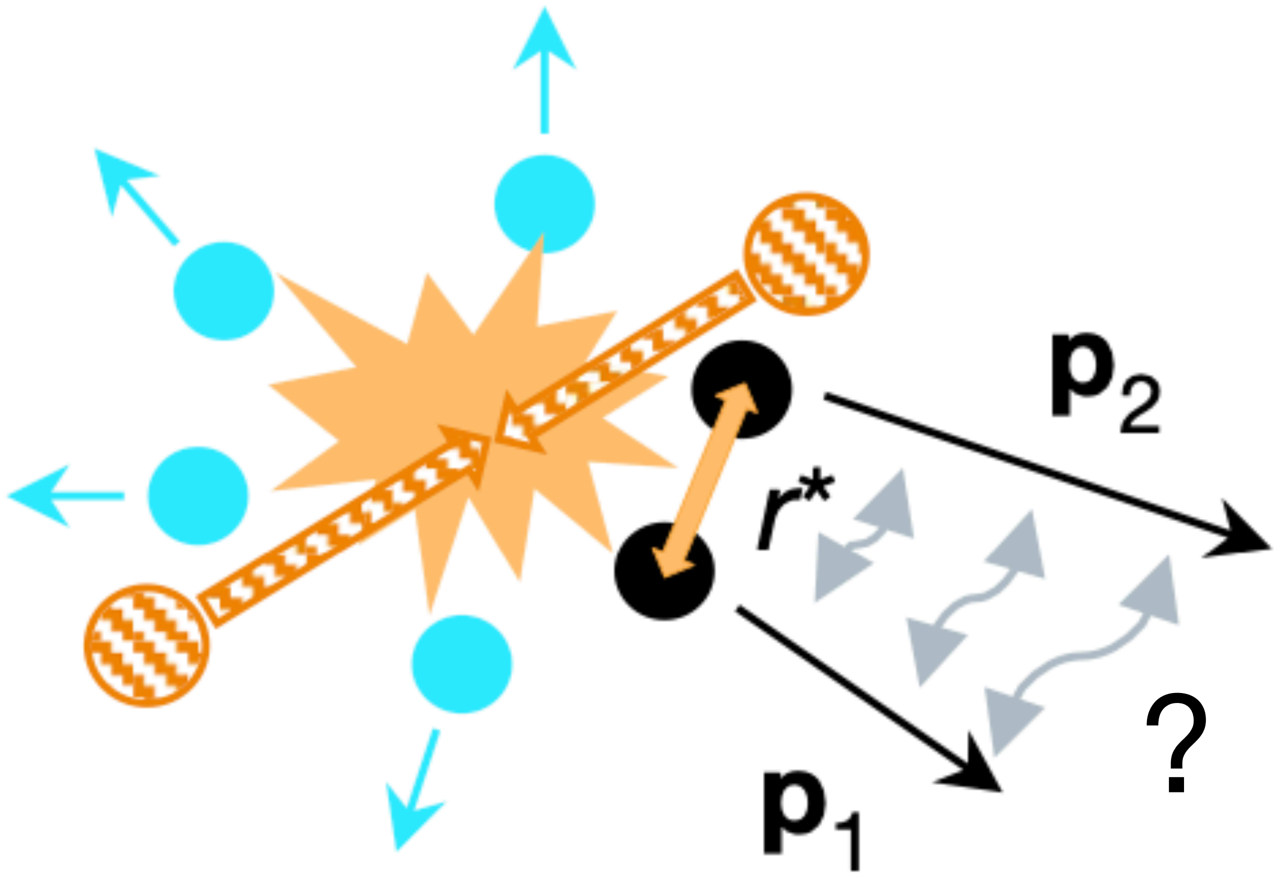

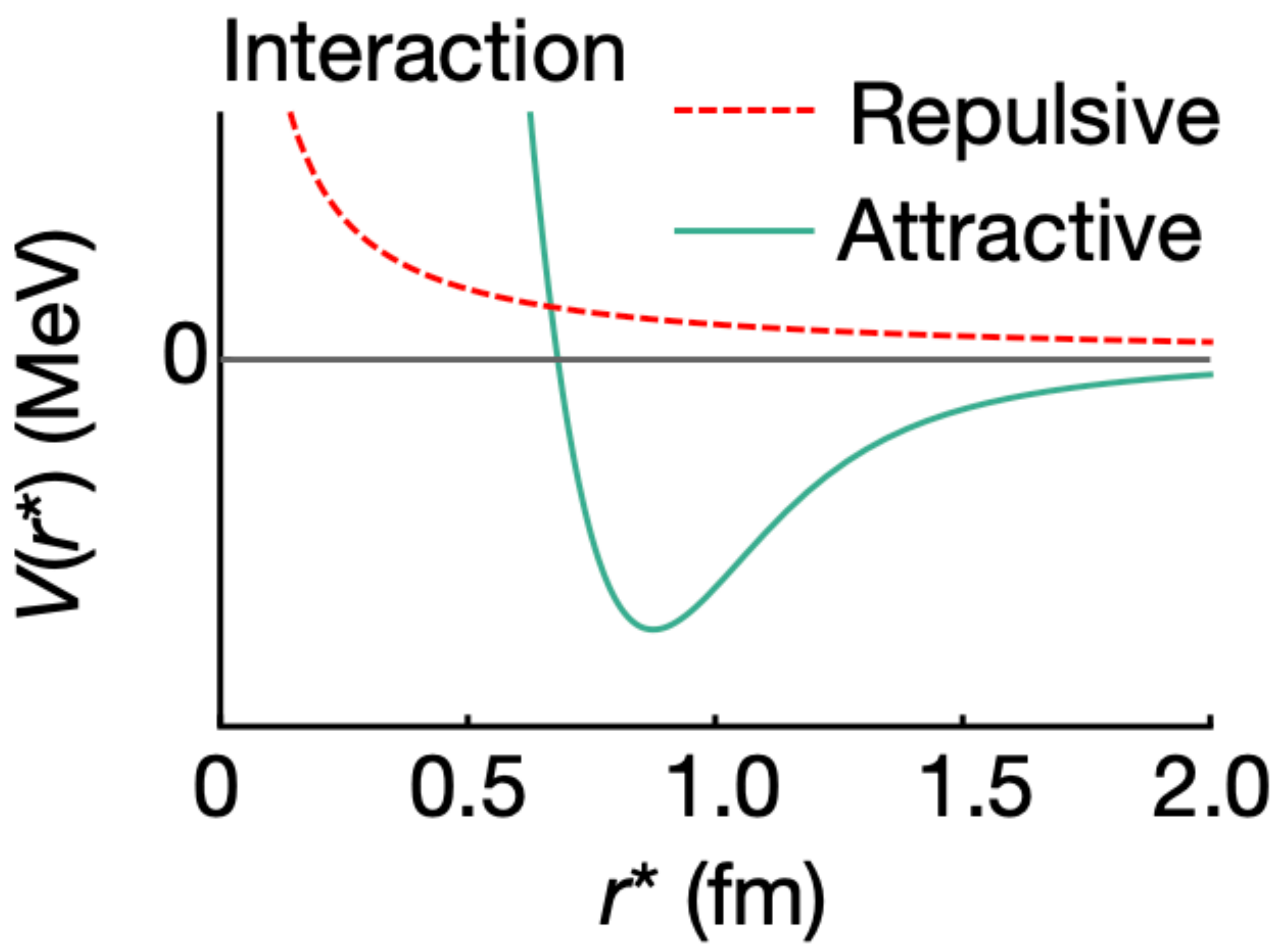

Emission source $S(r^*)$

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

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

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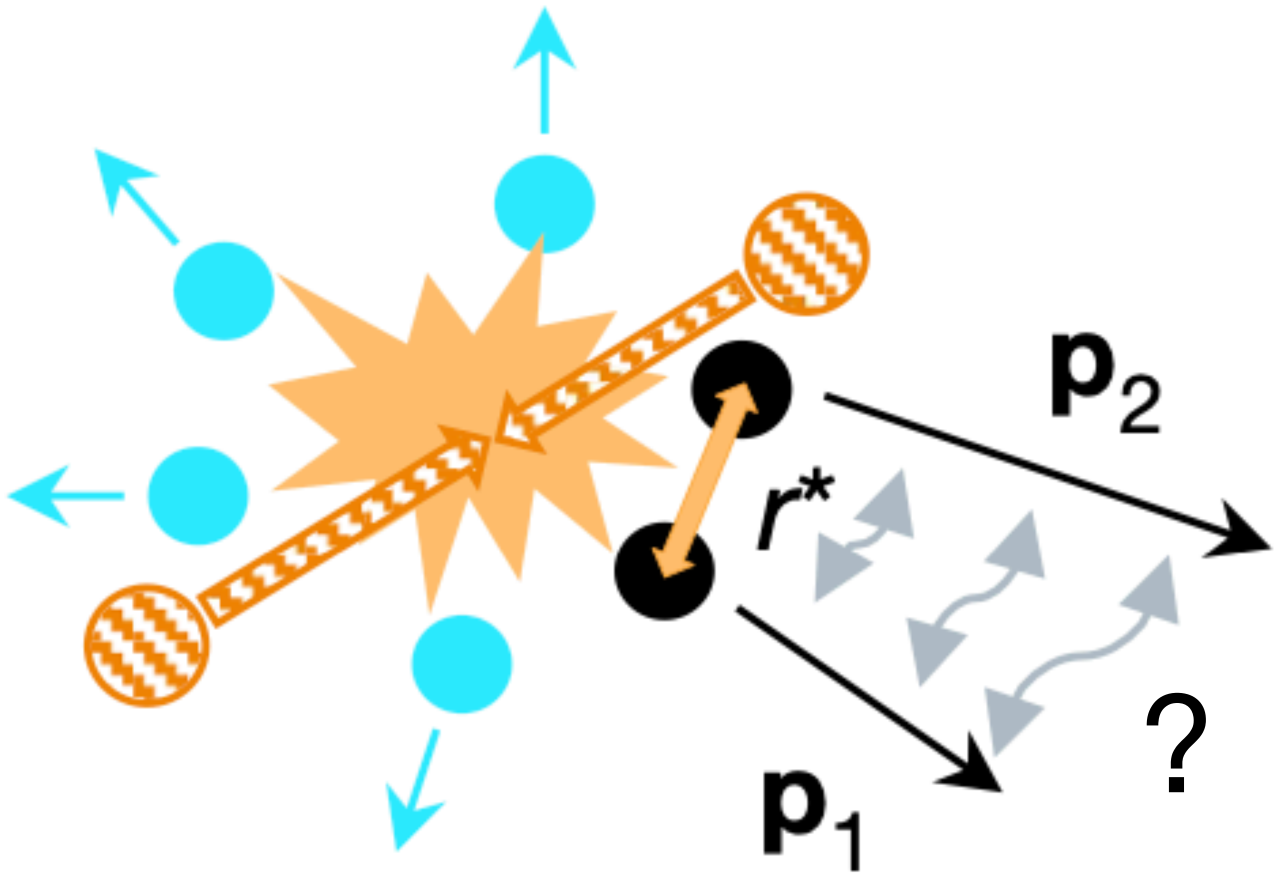

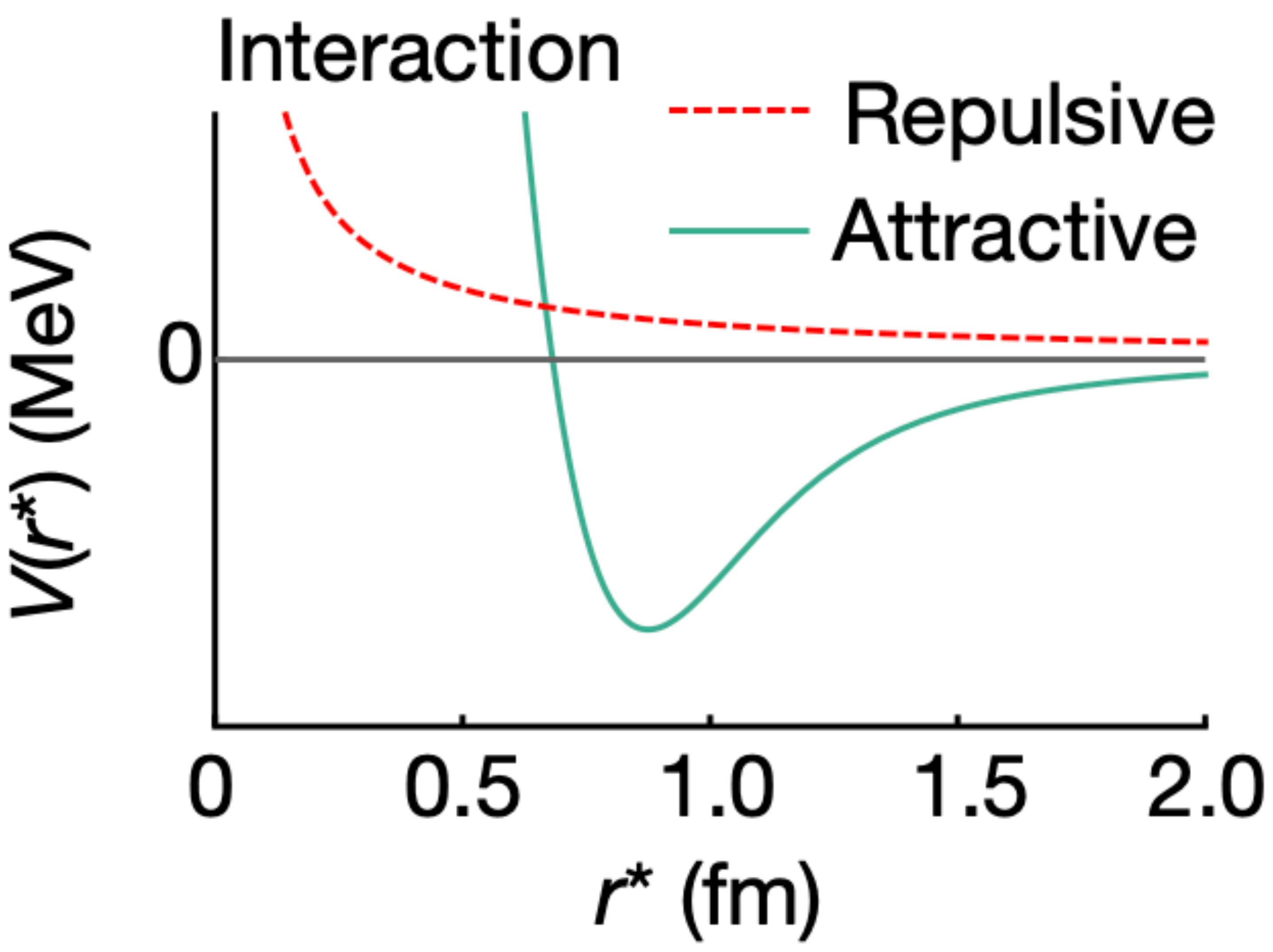

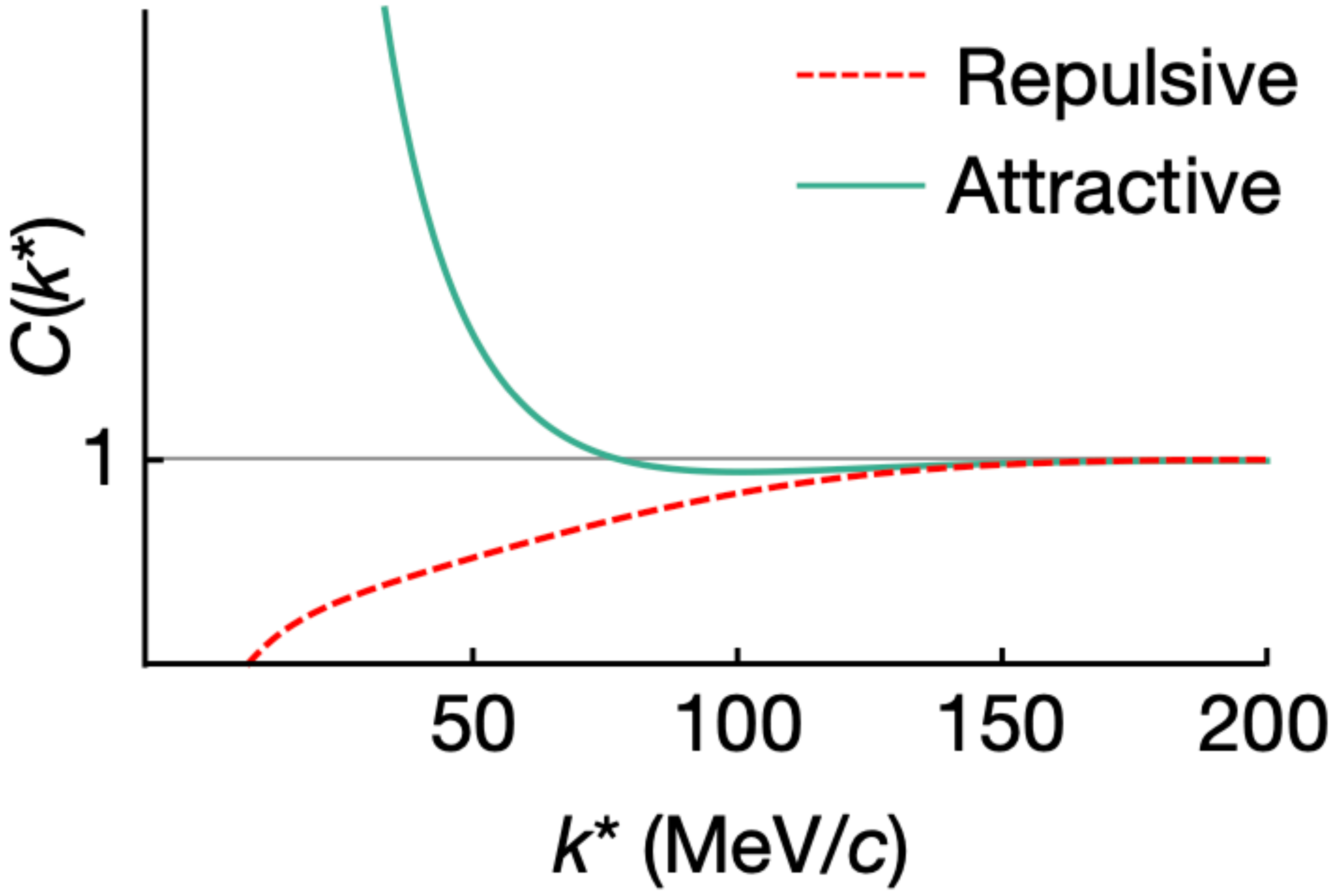

Emission source $S(r^*)$

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

Correlation function $C(k^*)$

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

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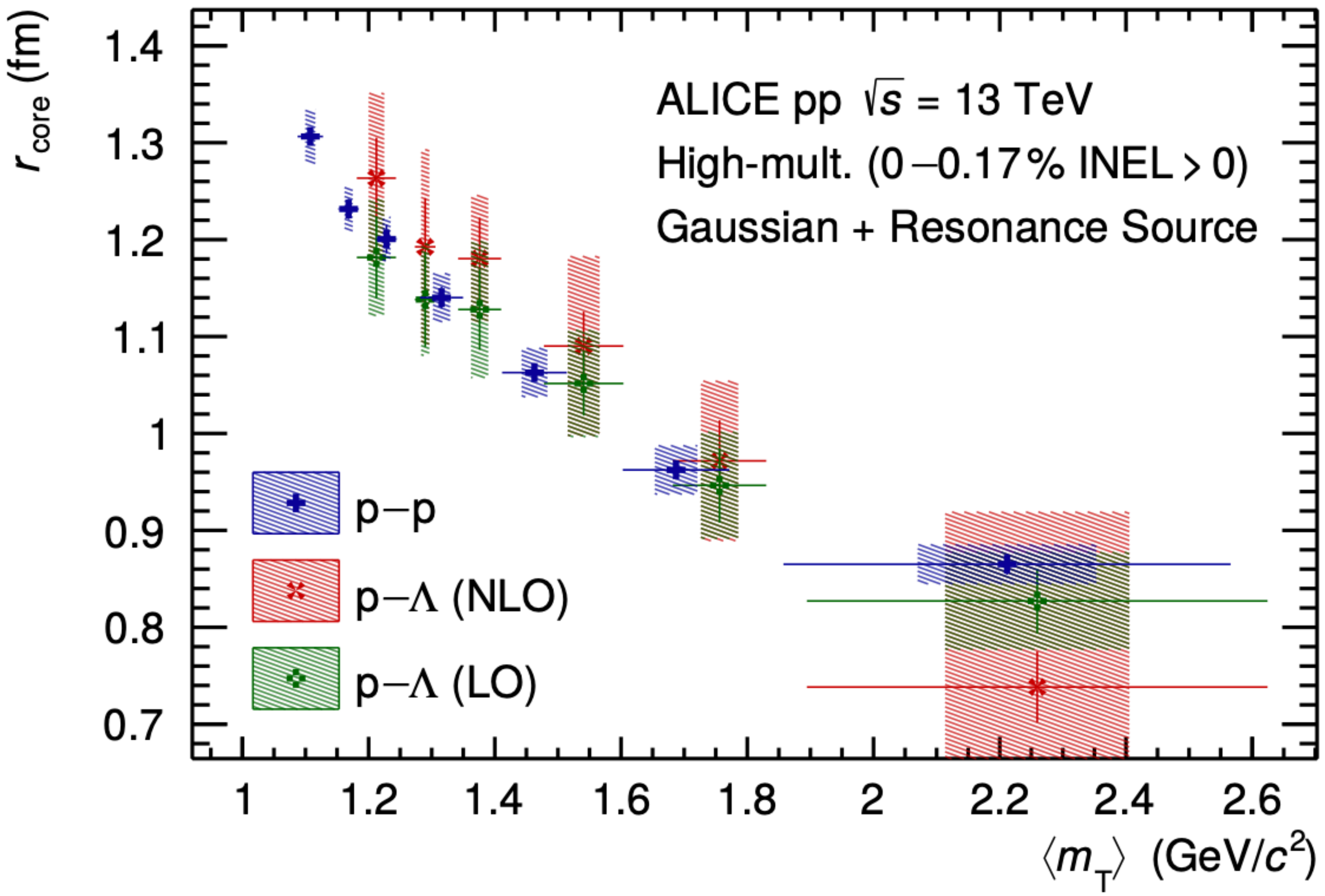
Emission source

- Emission source constrained using data-driven method.
- Common source observed for different hadron pairs if accounted for m_T scaling.
- p-p pairs used to constrain the core radius of the emissions source.

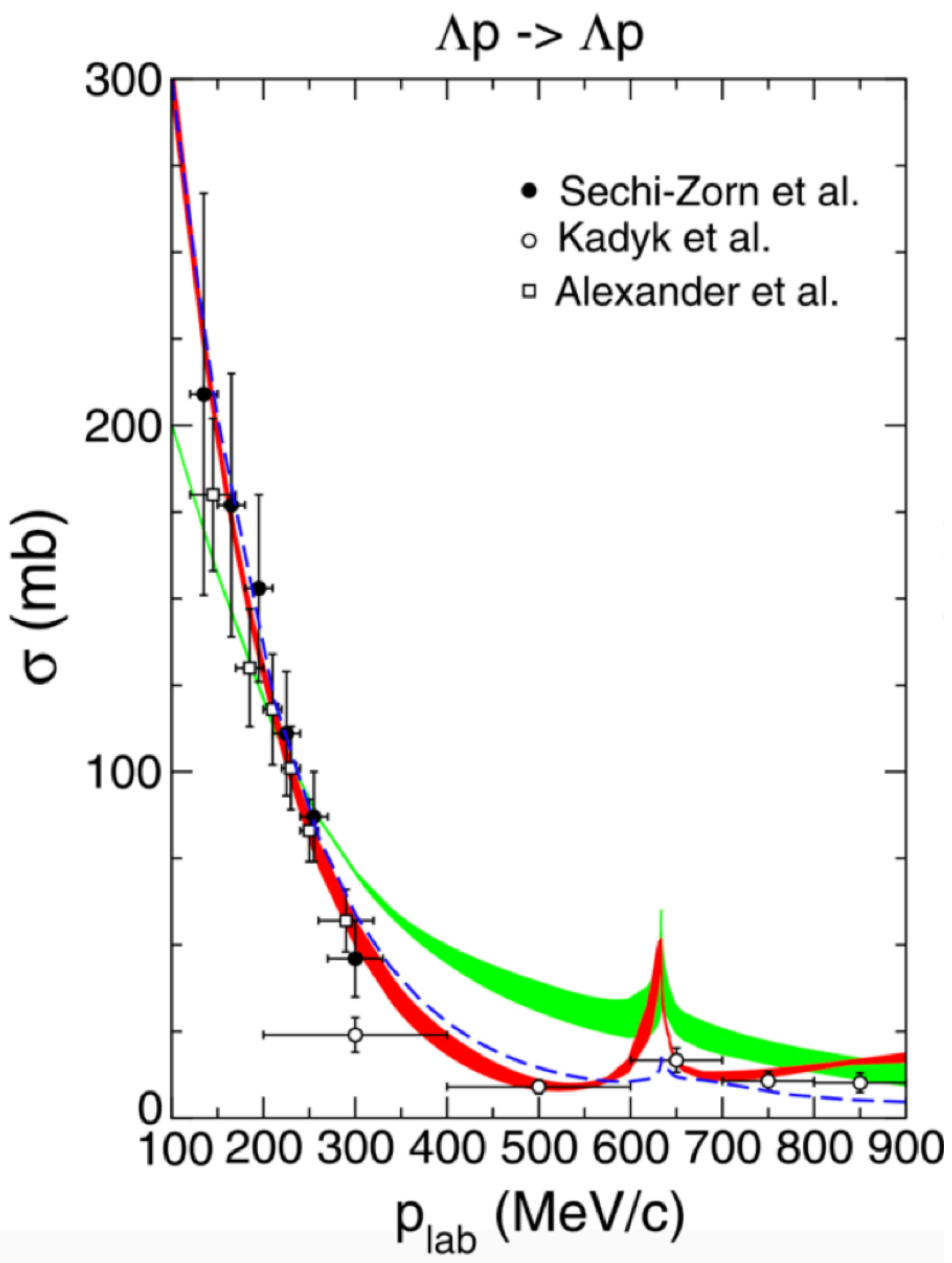
ALICE Coll., PLB 811, 135849 (2020)



Small interparticle distances (~1–2 fm) -> sensitivity to short-range interactions as the strong force.

|S|=1 sector: p-Λ interaction

- Available scattering data -> large uncertainties, no data for low momenta.

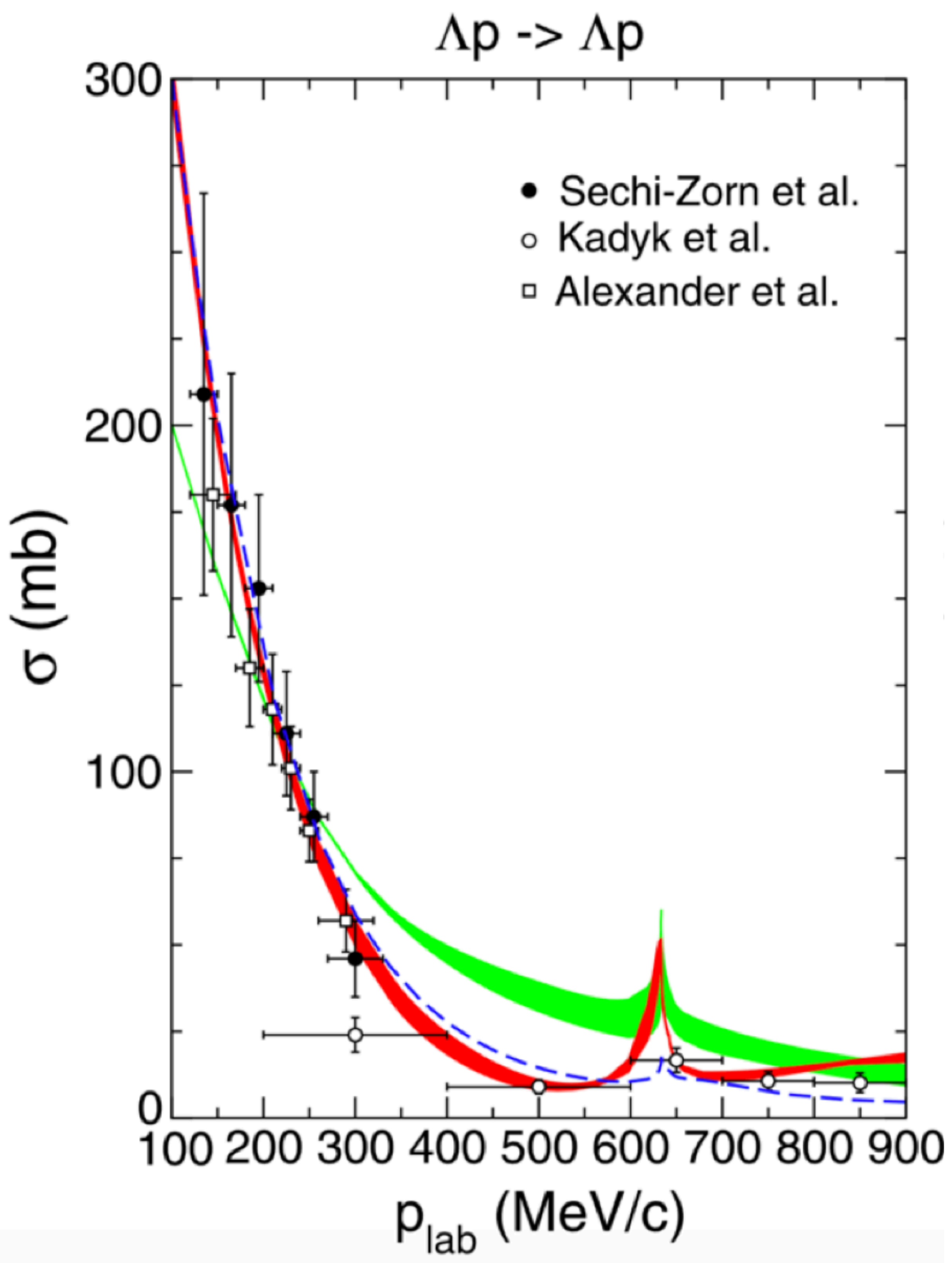


LO from H. Polinder, J. Haidenbauer, U. Meiβner, NPA 779, 224 (2006) and NLO from J. Haidenbauer, N. Kaiser et al., NPA 915, 24 (2013).

ALICE Coll., arXiv:2104.04427

|S|=1 sector: p-Λ interaction

- Available scattering data -> large uncertainties, no data for low momenta.
- Next-to-leading-order calculations are preferred by femtoscopic measurement.



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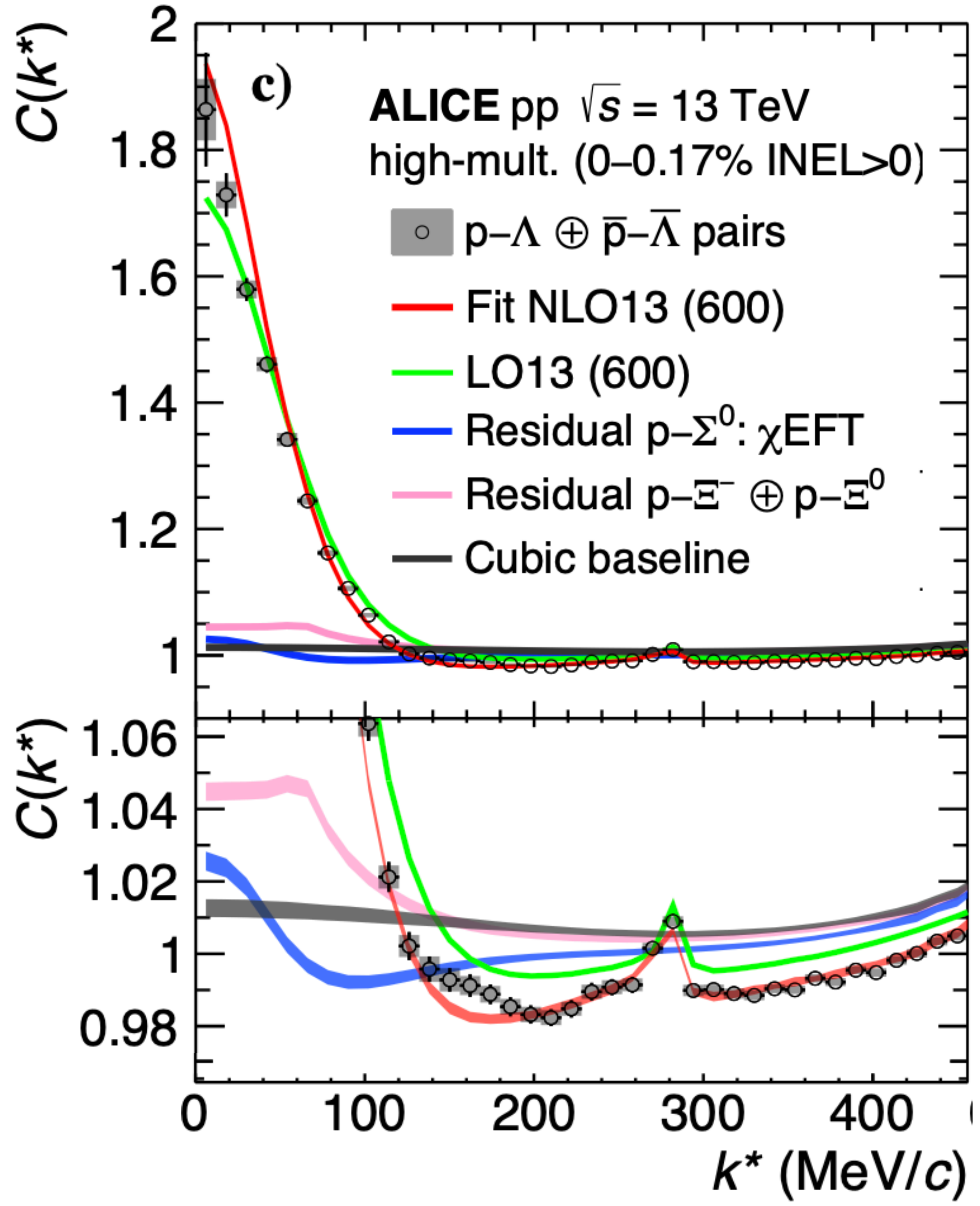
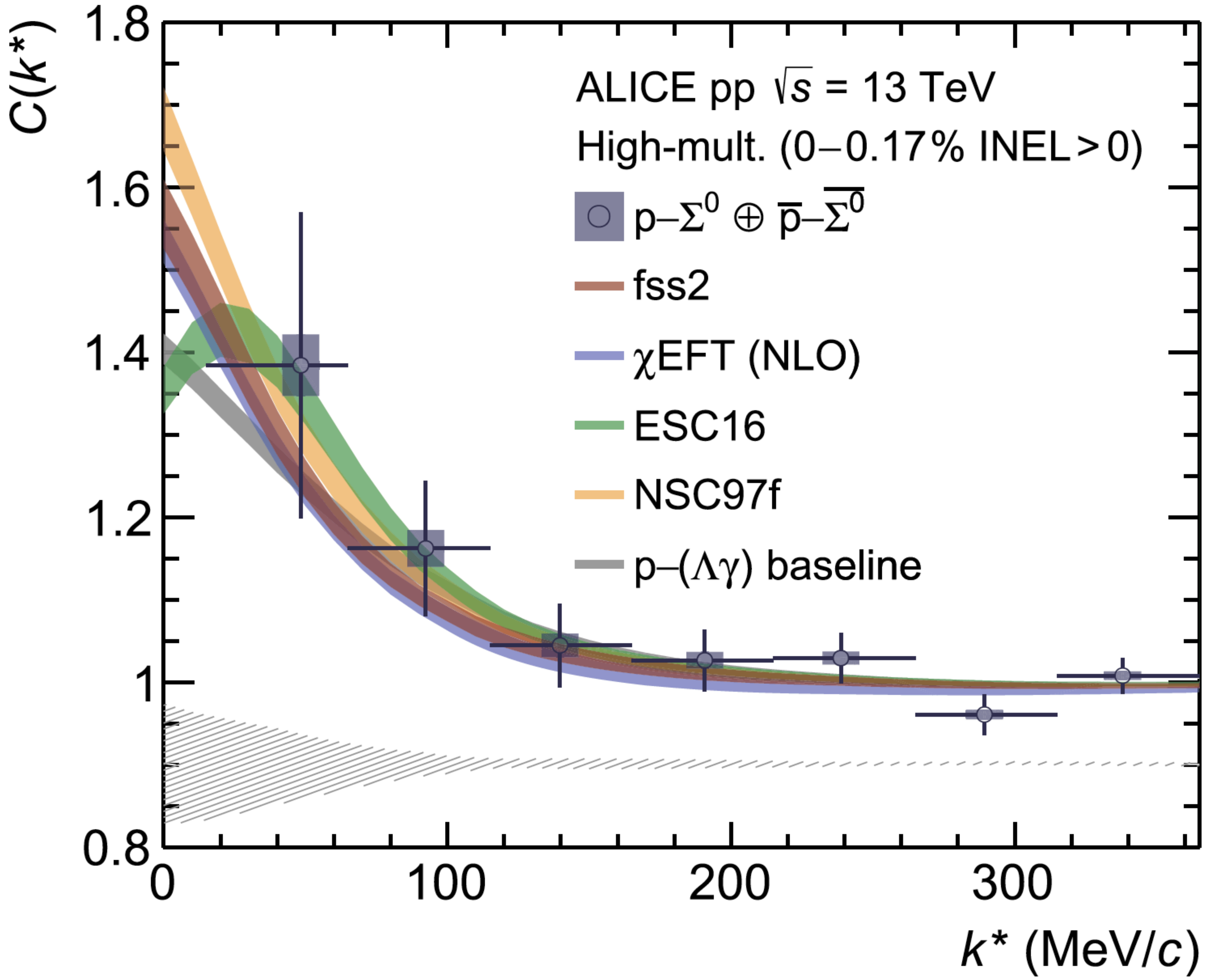


ALICE Coll., arXiv:2104.04427

|S|=1 sector: p-Σ interaction

- Measured shallow p-Σ^0 strong interaction-> won't have large influence for EoS.

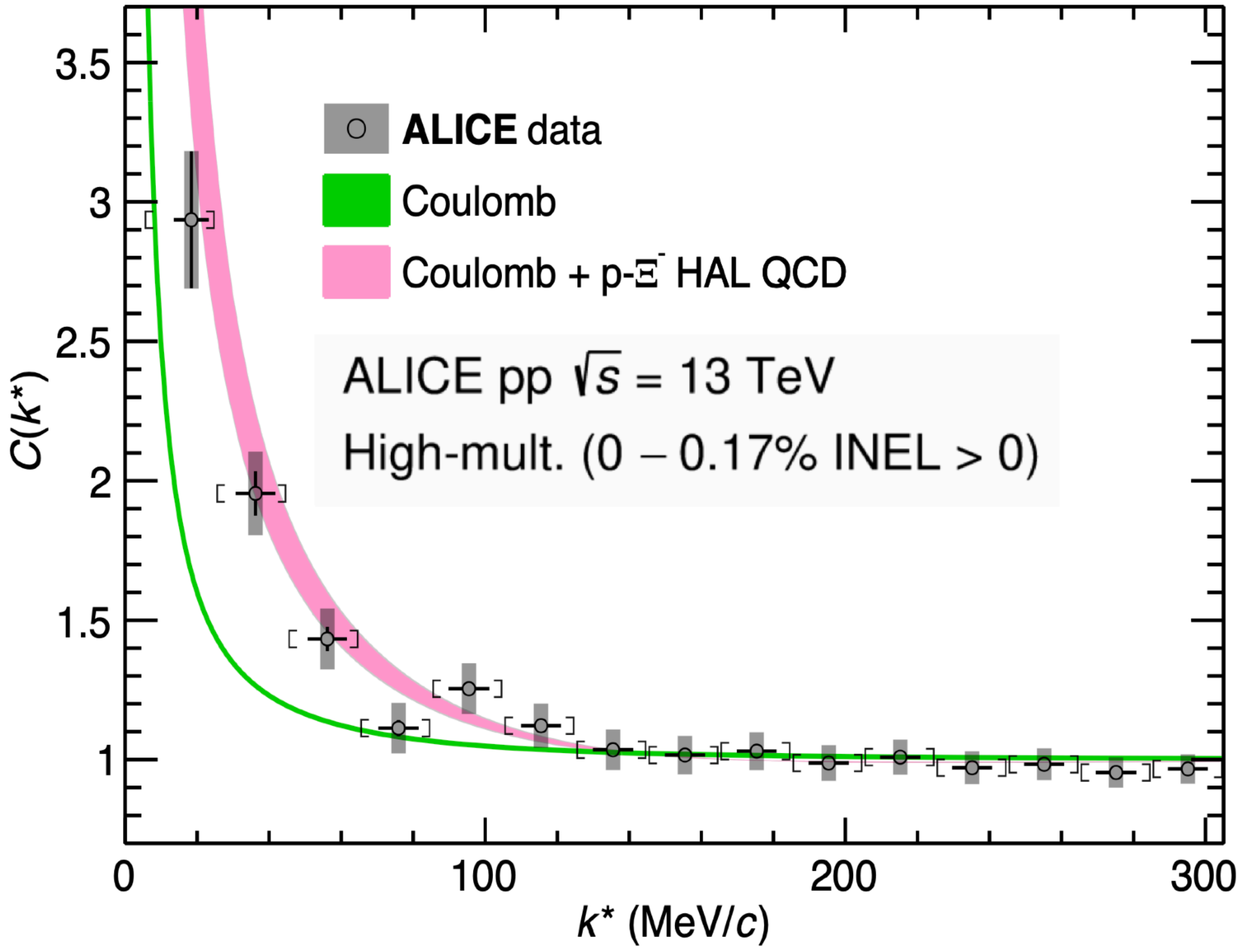
ALICE Coll., PLB 805, 135419 (2020)

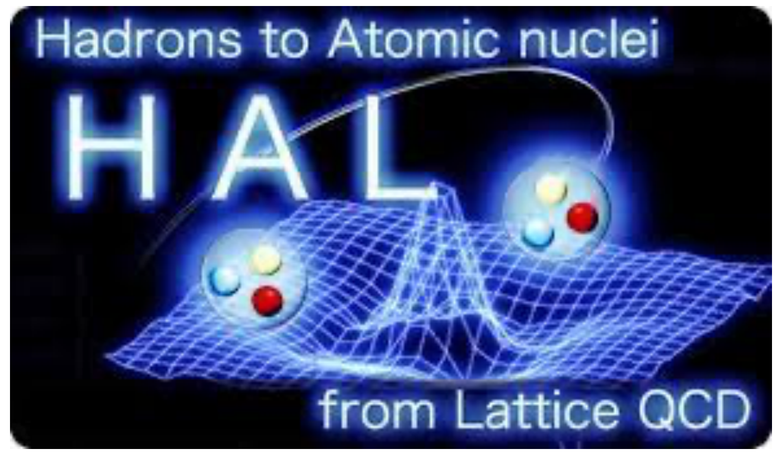


|S|=2 sector: p-Ξ⁻ interaction

ALICE Coll., Nature 588, 232–238 (2020)

- The next candidate to appear in neutron star core is Ξ^- hyperon. Strongly dependent on the interaction sign and strength!
- Data shows behaviour beyond Coulomb interaction only.
- Inclusion of the HAL QCD potentials near physical masses [1] is in agreement with the data.
- Stiffening of the EoS is expected as HAL QCD predicts slightly repulsive interaction in pure neutron matter at finite densities!



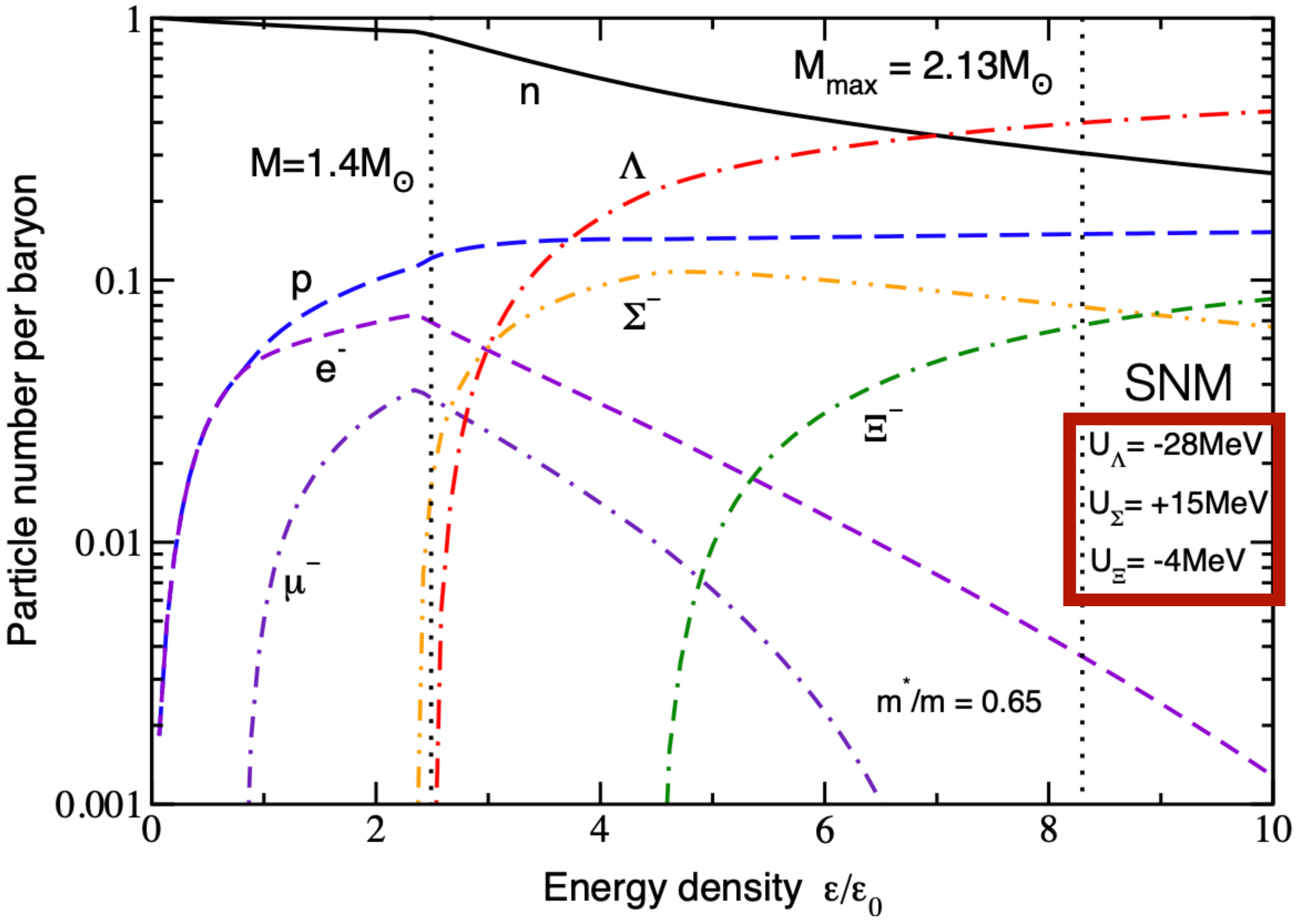


[1] T. Hatsuda, Front. Phys. 13(6), 132105 (2018)

Updated estimates for neutron stars

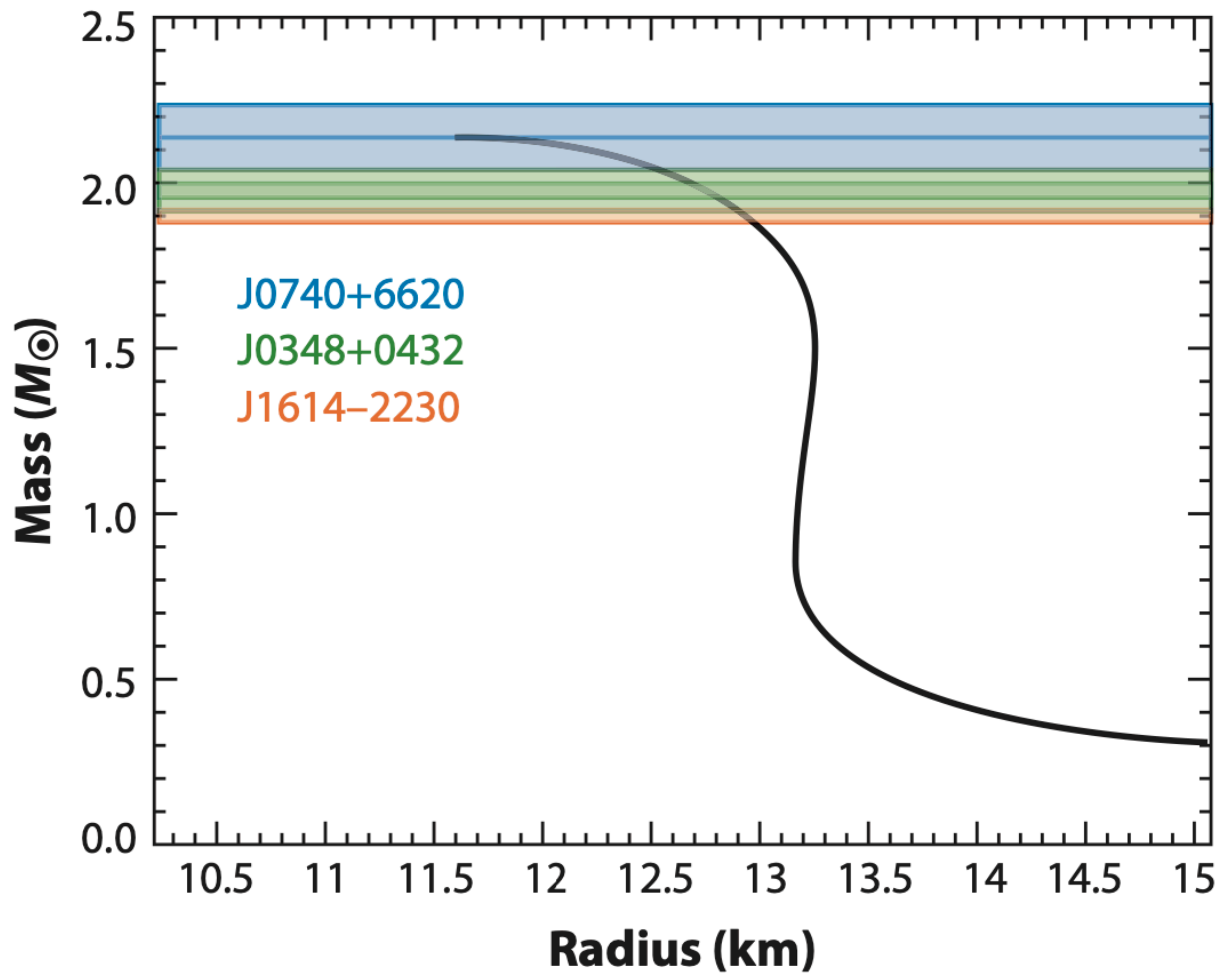
- Usage of HAL QCD potentials results in Ξ production onset at high densities and stiffening of the EoS.

Courtesy J. Schaffner-Bielich 2020



Based on: Weissenborn S., Chatterjee D., Schaffner-Bielich J., Nucl. Phys. A881:62 (2012)
Schaffner-Bielich J., Mishustin, IN. Phys. Rev. C 53:1416 (1996)
Hornick N, et al., Phys. Rev. C 98:065804 (2018)

Courtesy J. Schaffner-Bielich and B. Dönigus 2020



Fabbietti et al., Annu. Rev. Nucl. Part. Sci 71, 377-402 (2021)

Such EoS could explain the heavy ~2M0 neutrons stars.

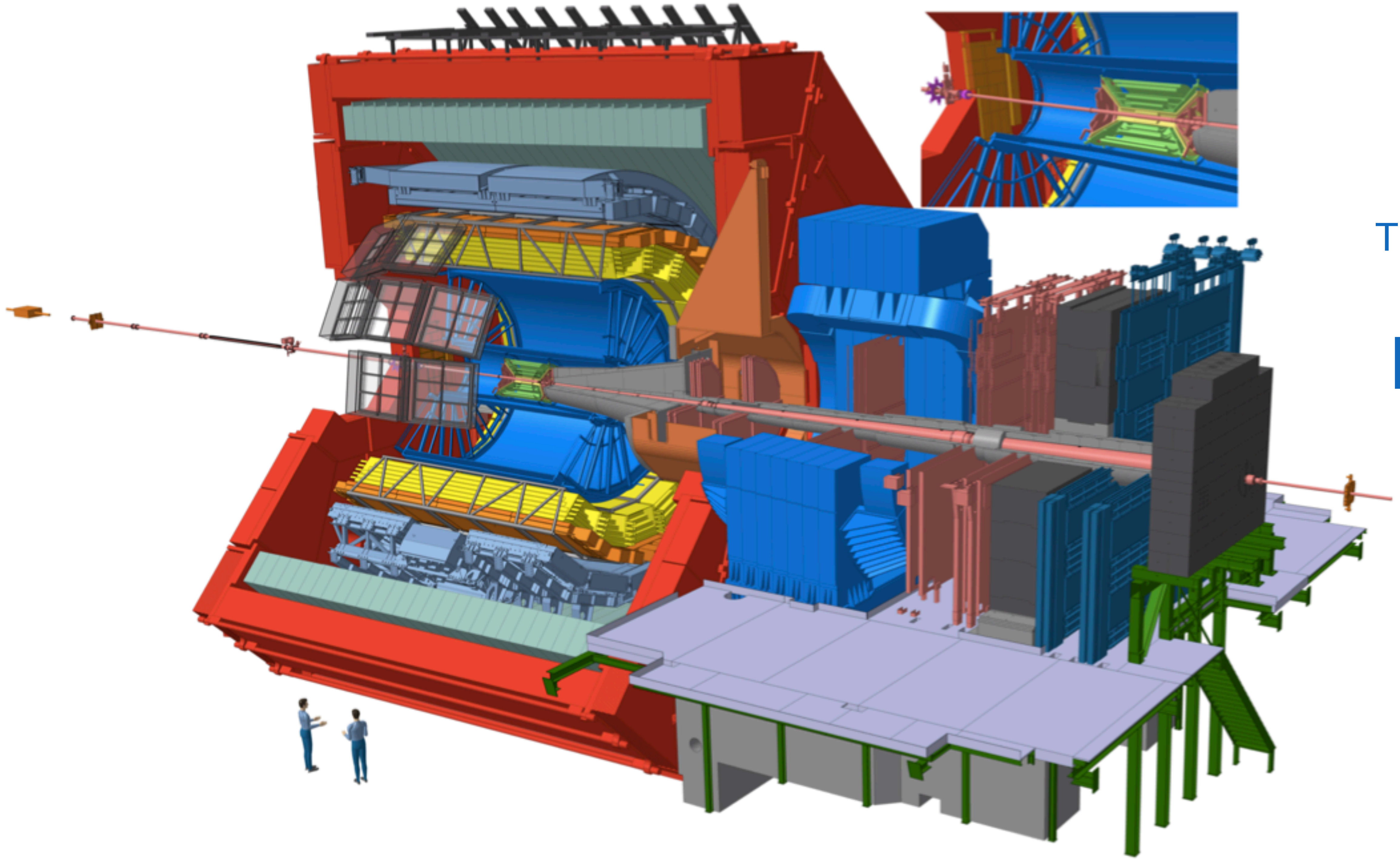
Is this the end of hyperon puzzle? No!*

*ALICE Coll., Phys. Rev. Lett. 127, 172301(2021)

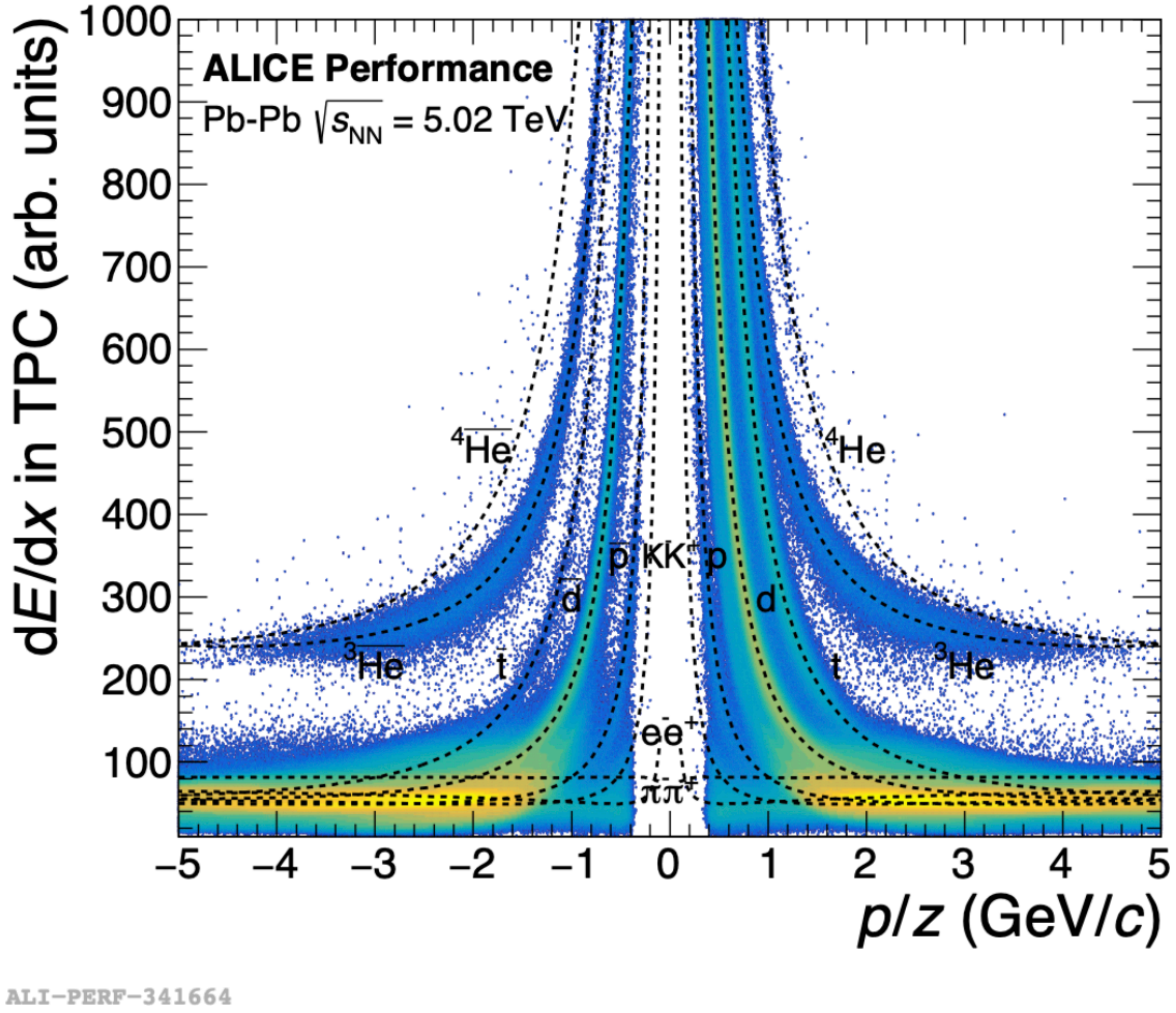
Light antinuclei in the galaxy and at the LHC

(Anti)nuclei at the LHC

- Excellent tracking and particle identification (PID) capabilities of ALICE.
- LHC - the antimatter factory including antinuclei production! [1]



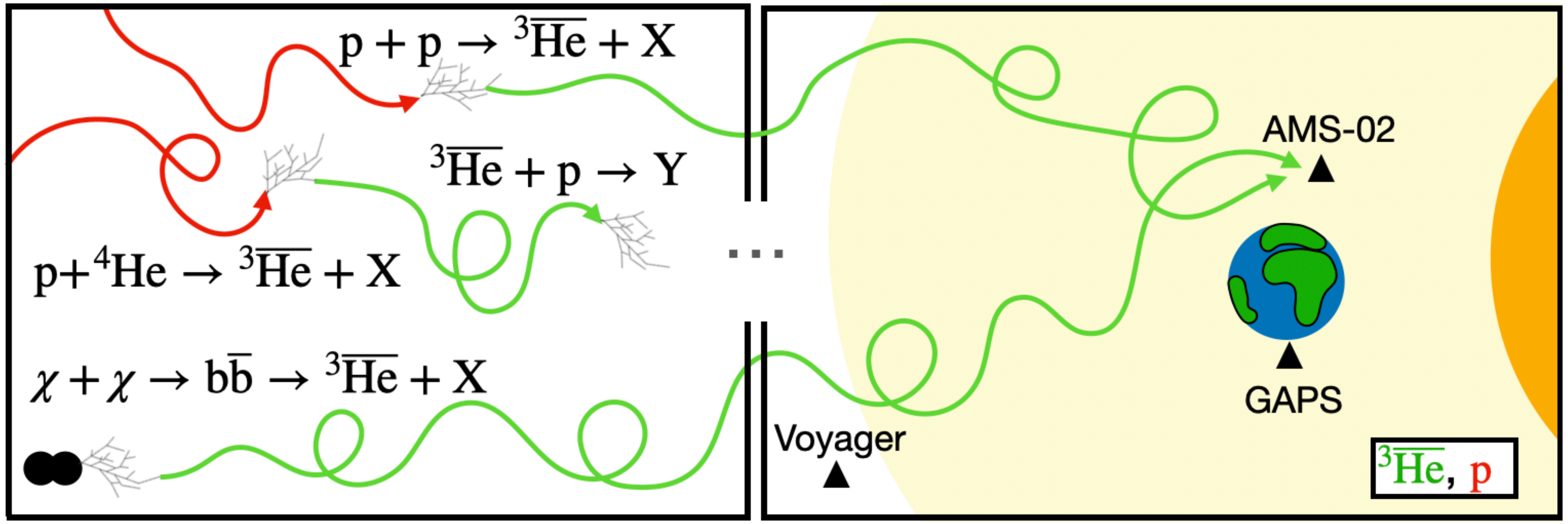
TPC measurement

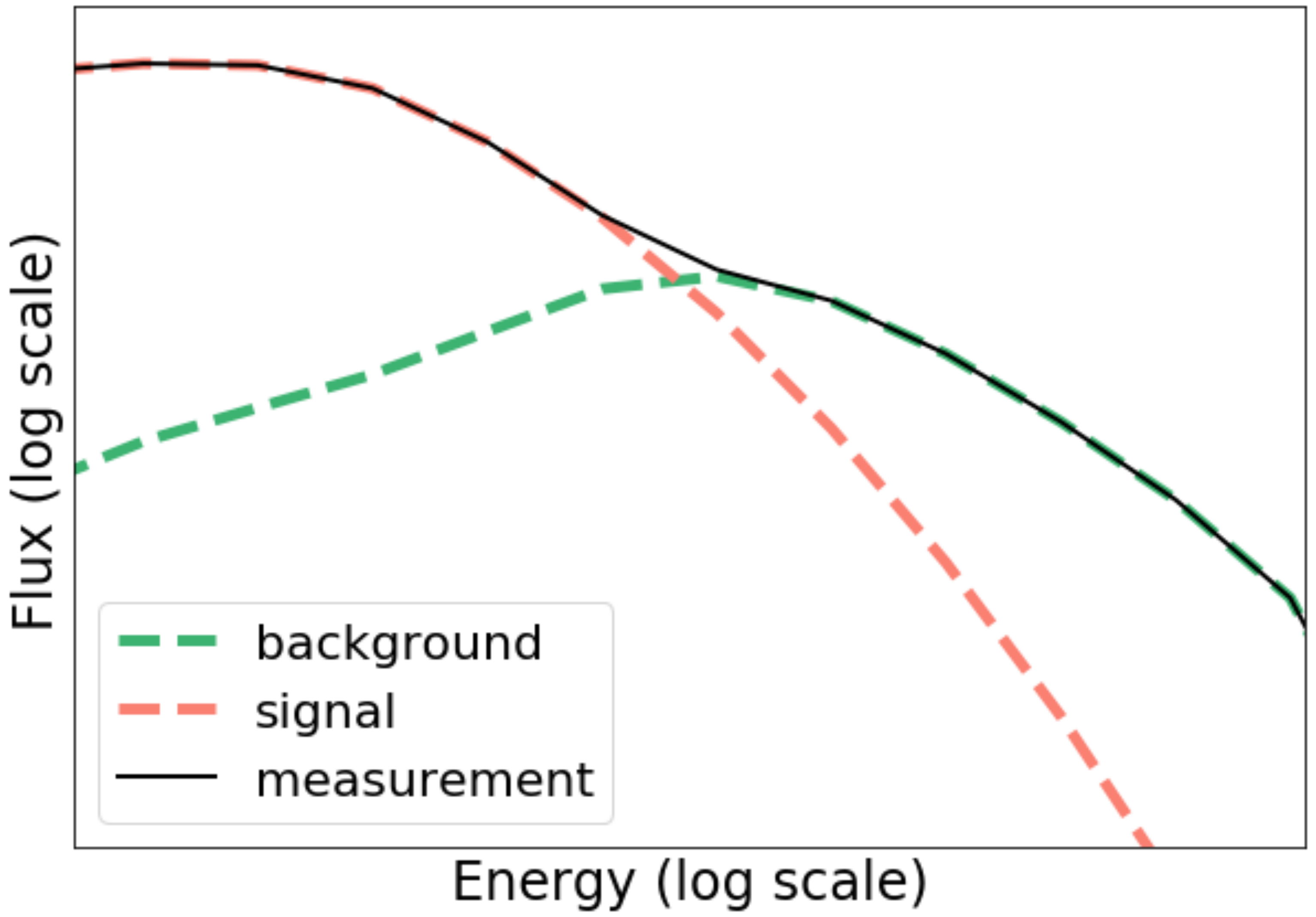


[1] ALICE Coll., PRC 97, 024615 (2018)

Motivation: search for dark matter

- Antinuclei cosmic rays: possible “smoking gun” signature of dark matter.
- Essentially free of astrophysical background.
- Calculations require:
    - antinuclei production,
    - antinuclei annihilation.





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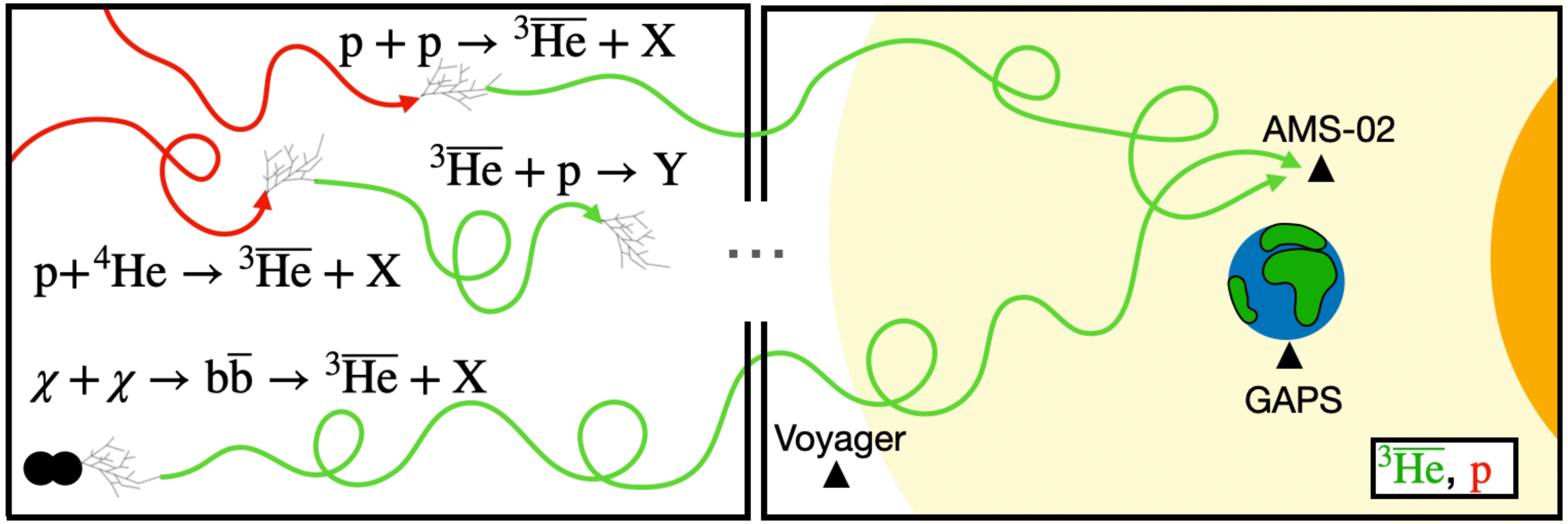
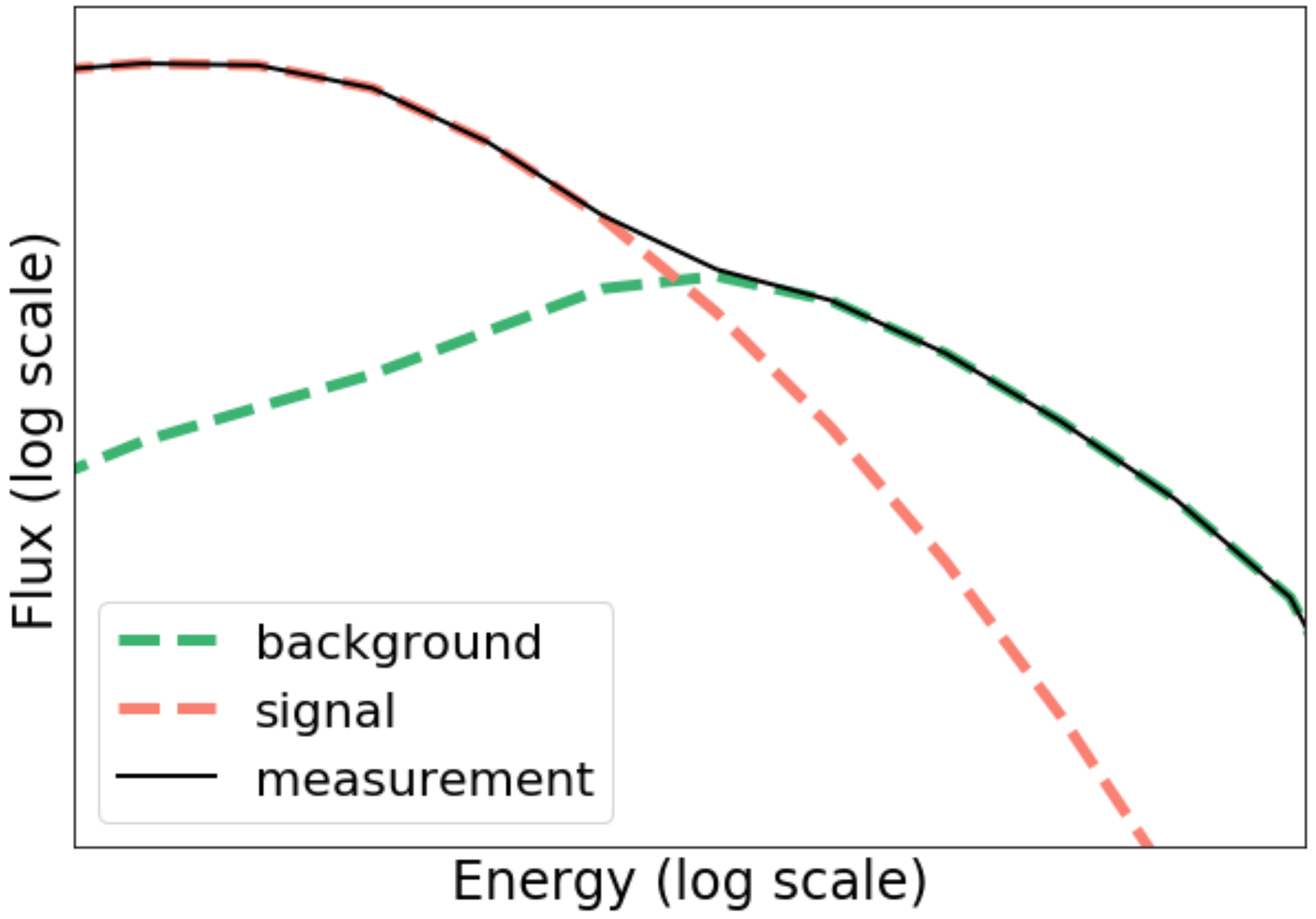
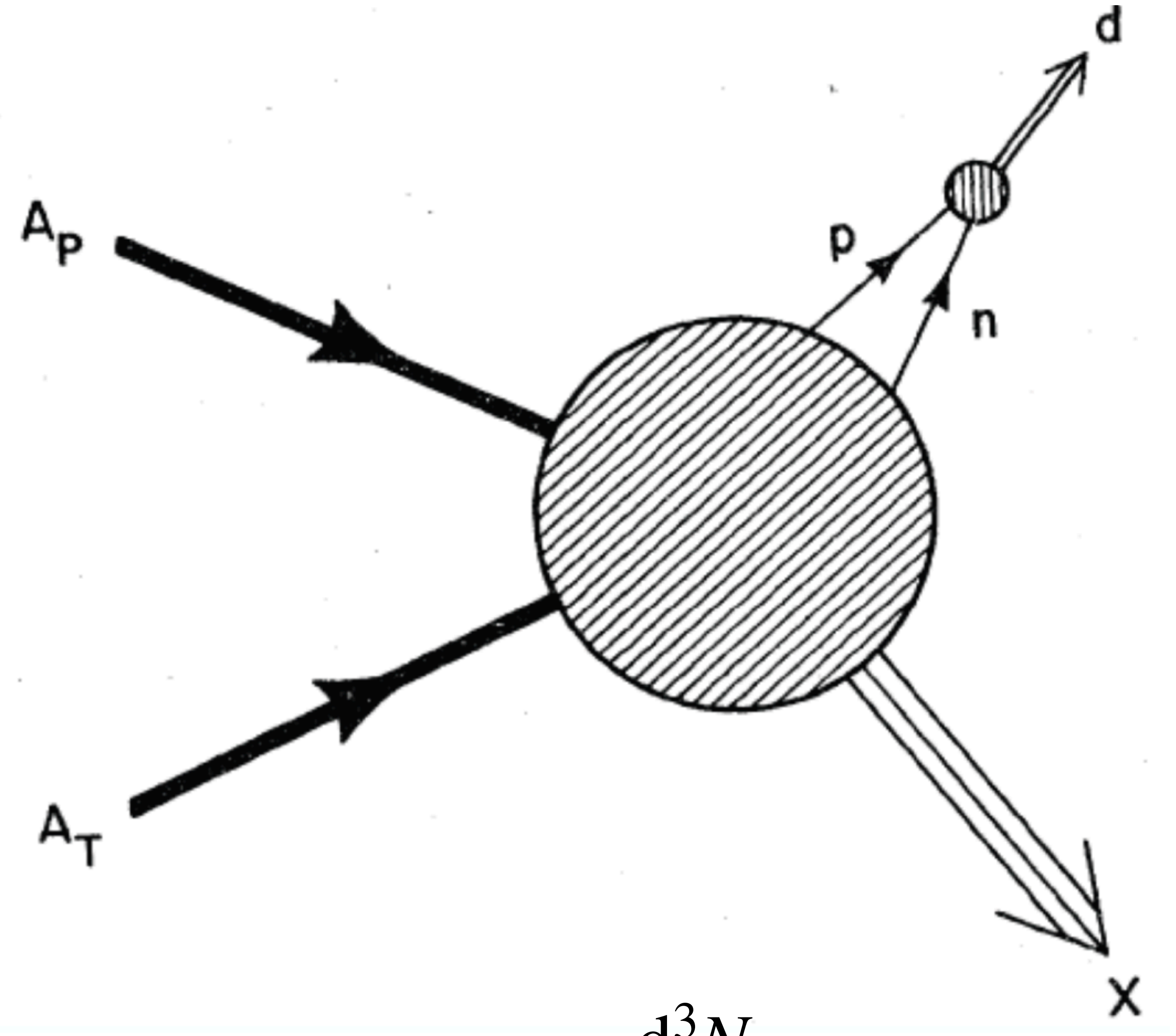




Light antinuclei production

J. I. Kapusta, Phys. Rev. C21, 1301 (1980)

- Coalescence model
  - Nucleons close in phase space -> possibility to coalescence.
  - Coalescence parameter B_A -> probability for the nucleons to coalesce.



$$B_A = \frac{E_A \frac{d^3 N_A}{d^3 p_A}}{\left(E_p \frac{d^3 N_p}{d^3 p_p} \right)^A}$$

Statistical hadronization model:
Andronic et al. Nucl. Phys. A 772, 167-199 (2006)

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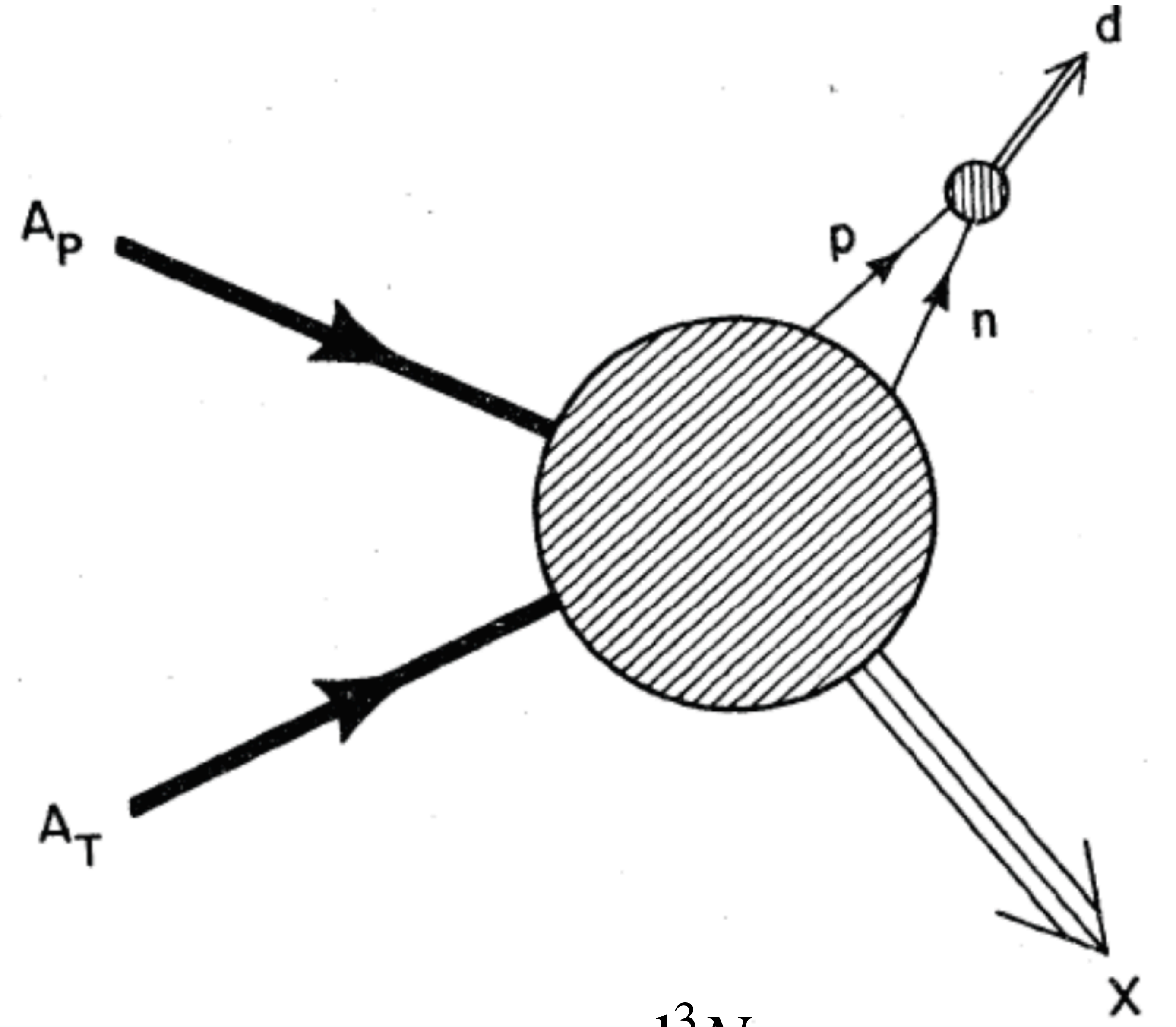

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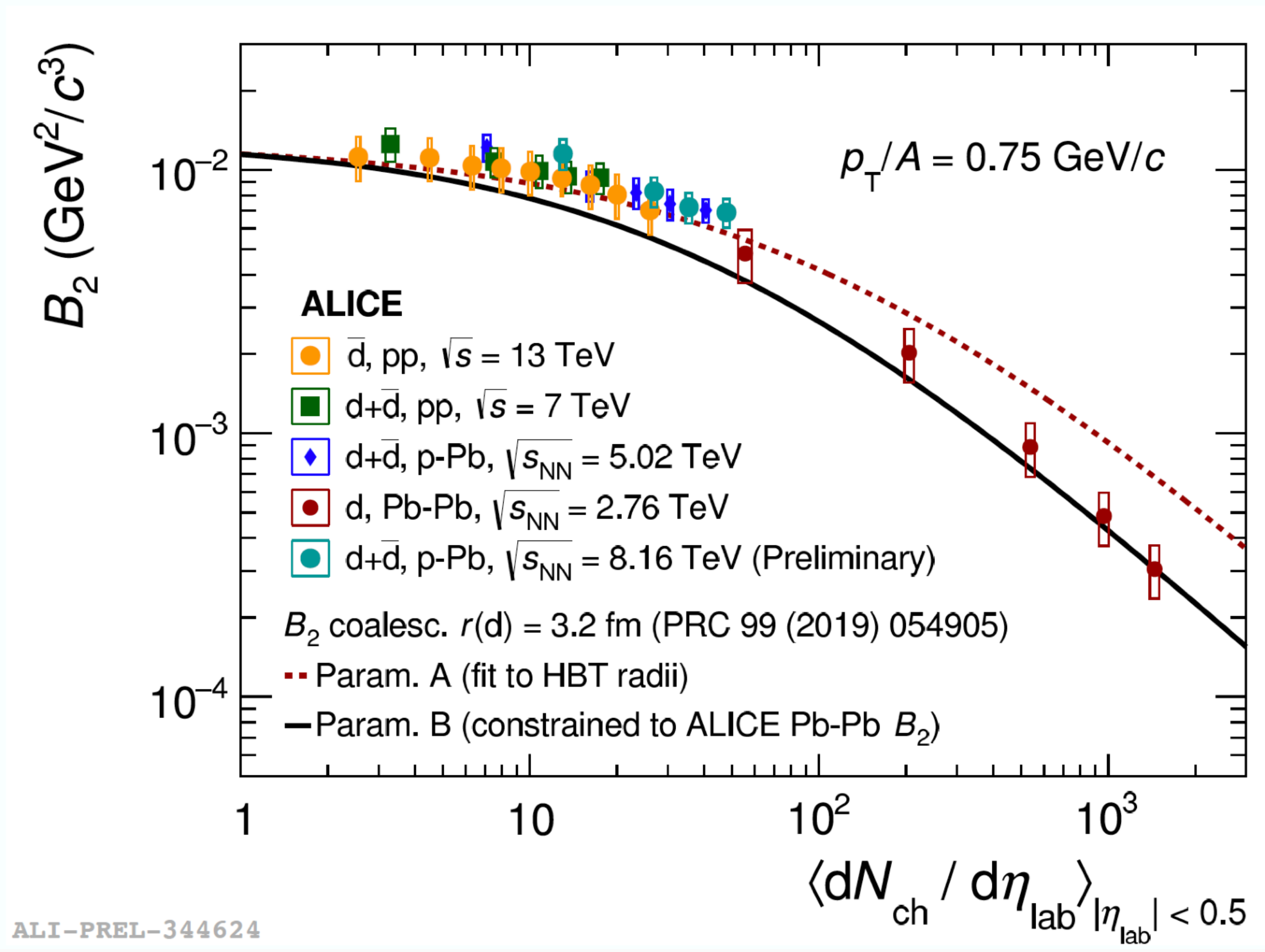
  - Event-by-event coalescence
    - ❖ Assume that nucleons coalesce if their relative momenta is below coalescence momentum p_0.
    - ❖ p_0 can be related to B_A

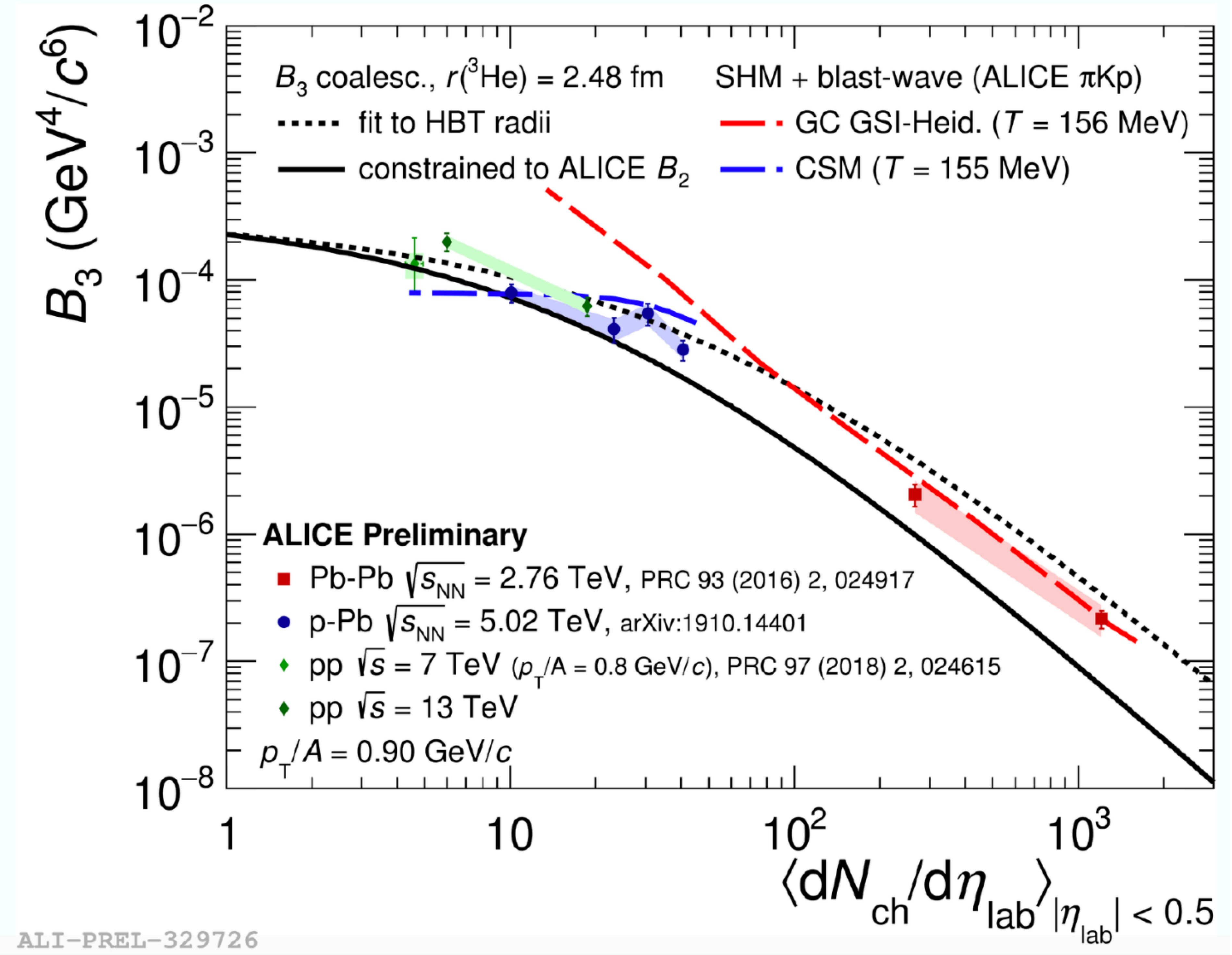
$$B_A = A \left(\frac{4\pi}{3} \frac{p_0^3}{m_N} \right)^{A-1}$$

Statistical hadronization model:
Andronic et al. Nucl. Phys. A 772, 167-199 (2006)

Coalescence parameter measurements

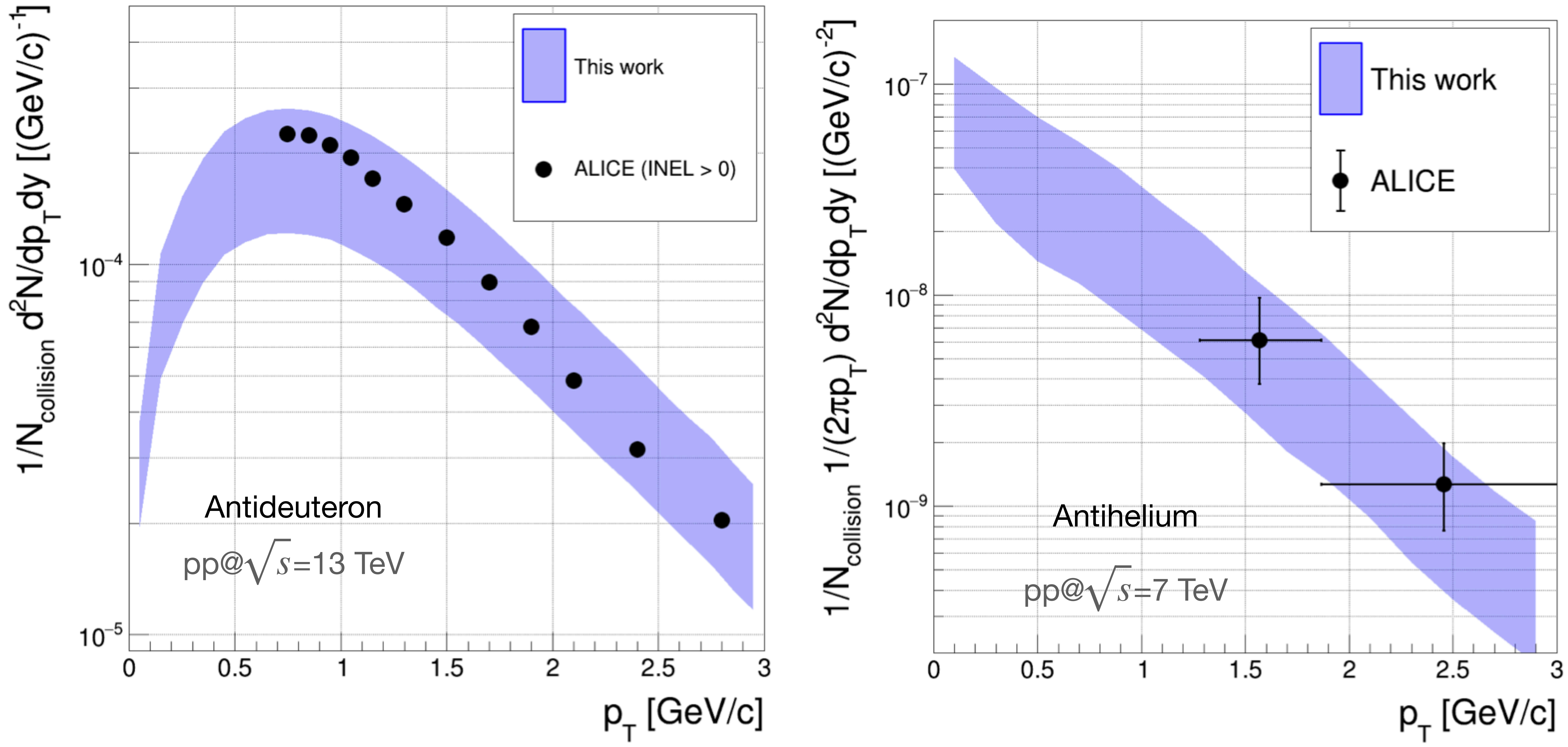
- The coalescence probability depends on the system size as it evolves smoothly with multiplicity.





Measured antinuclei spectra

- Event-by-event simulations using EPOS-LHC event generator and coalescence afterburner.



Shukla et al., Phys. Rev. D 102, 063004 (2020)

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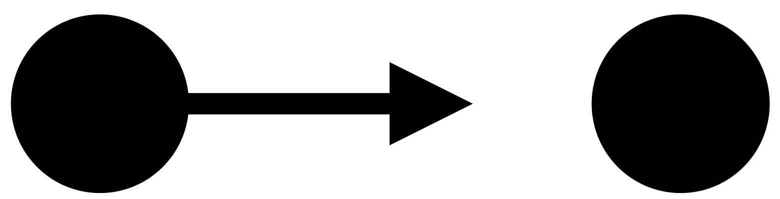
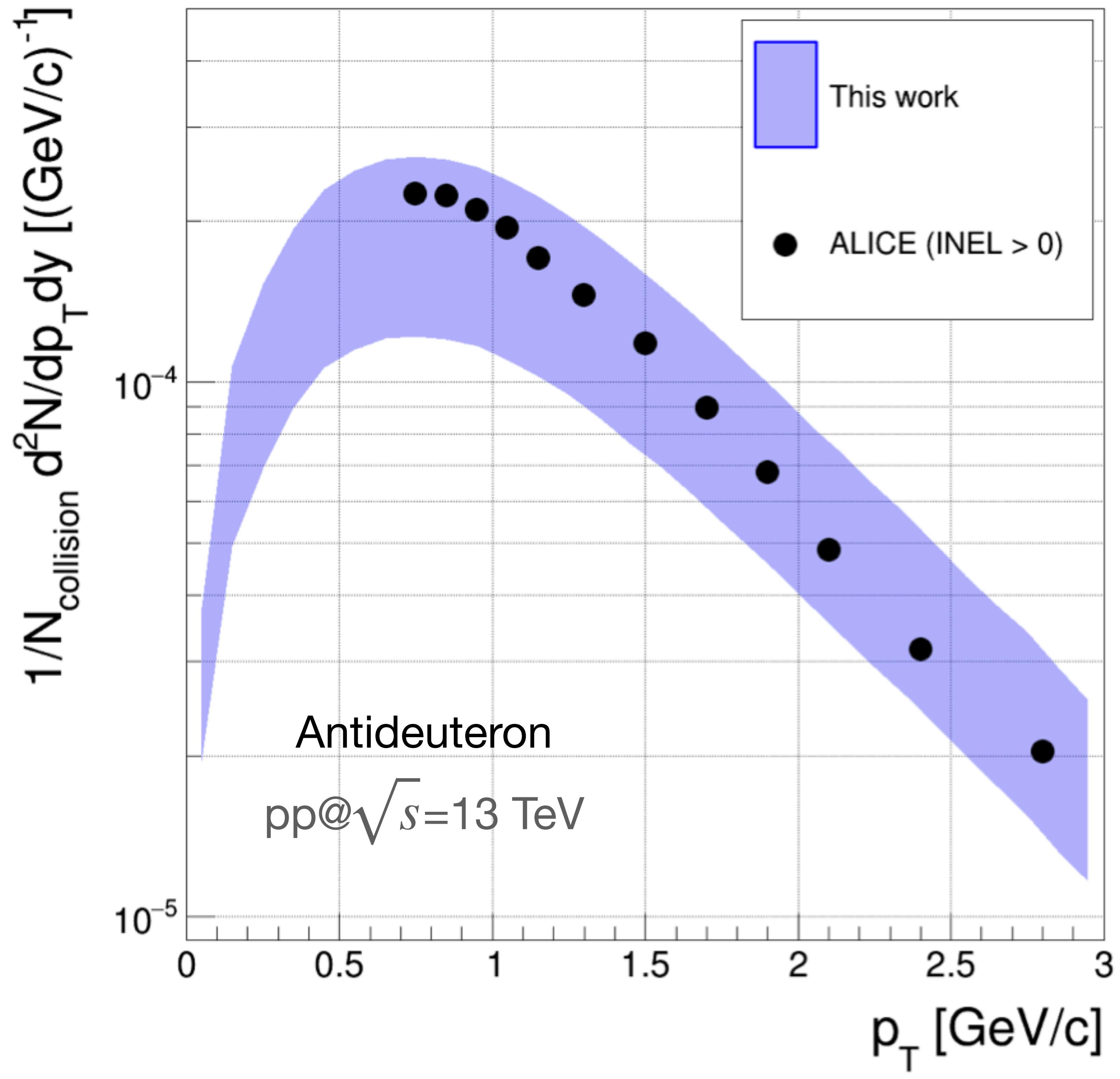
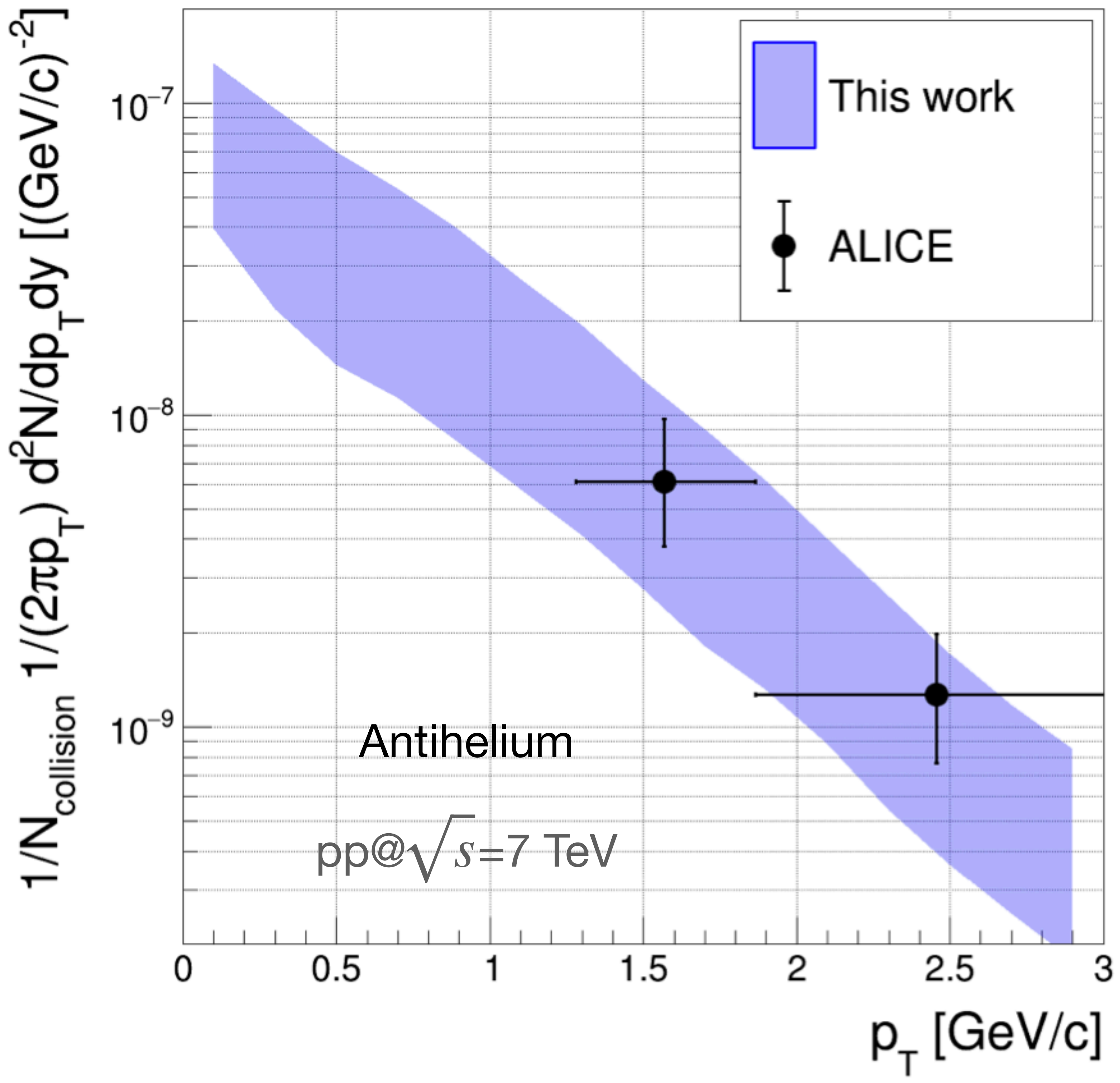
- What are collision energies of interest for antinuclei cosmic ray studies?







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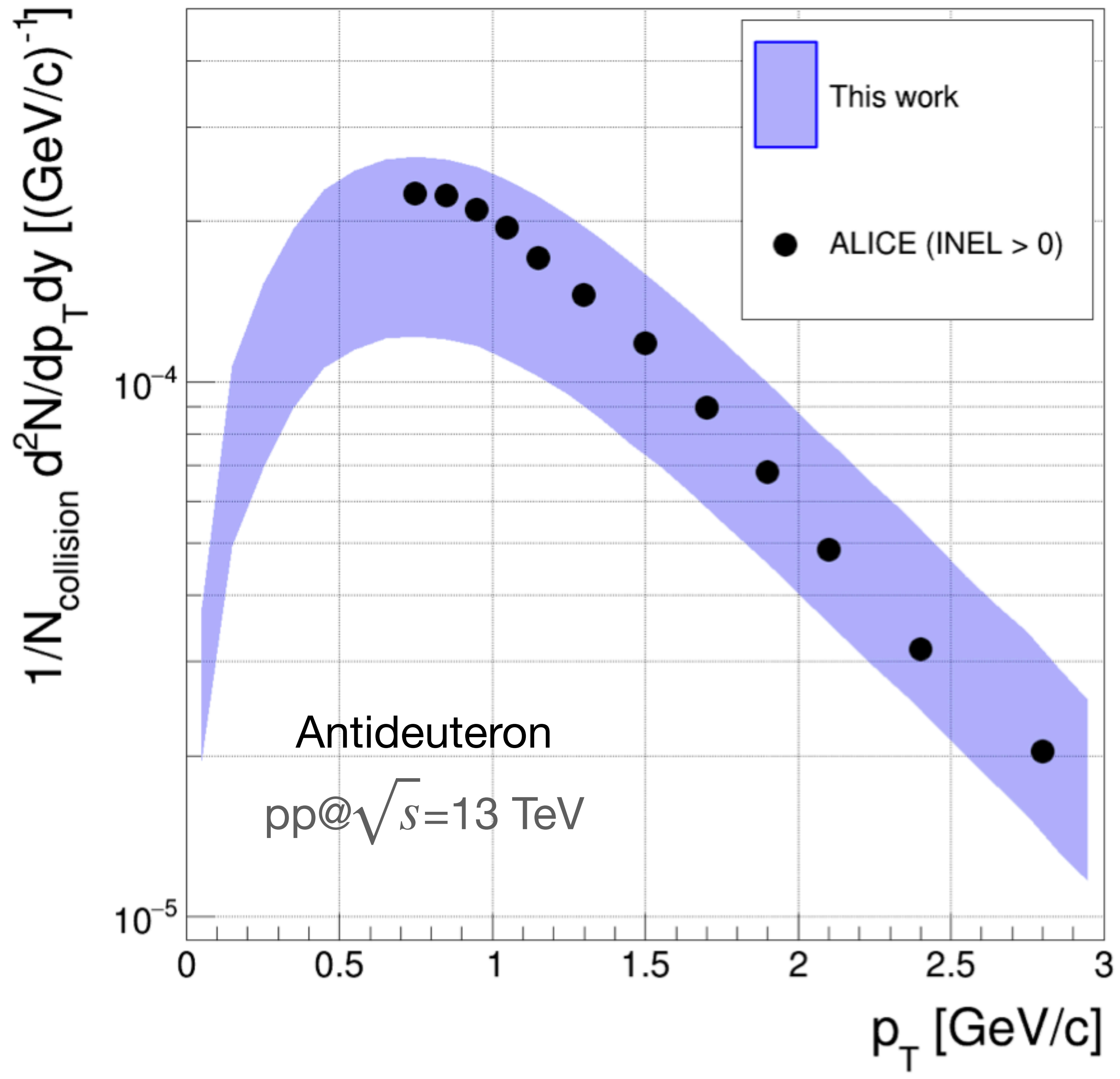
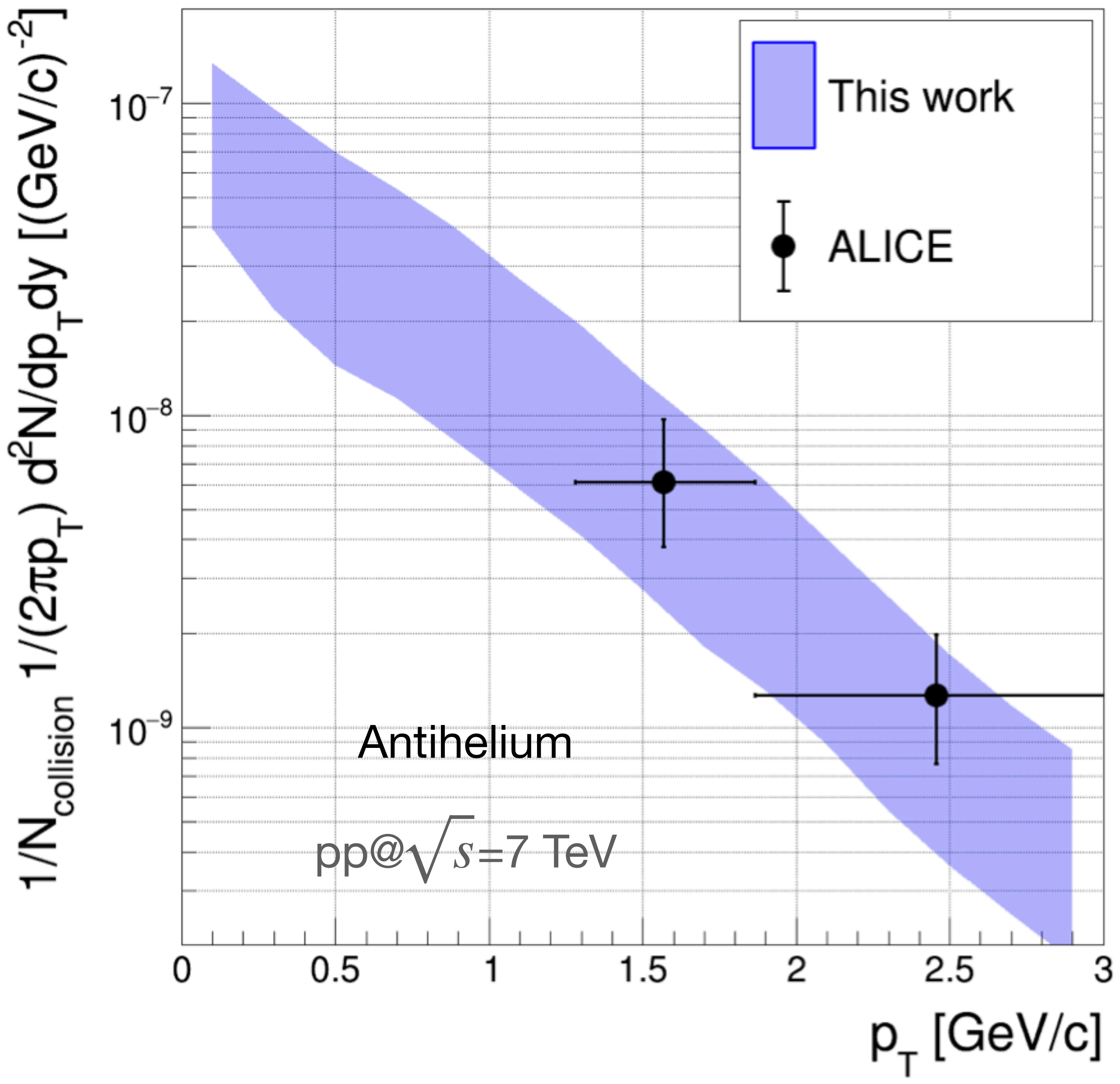
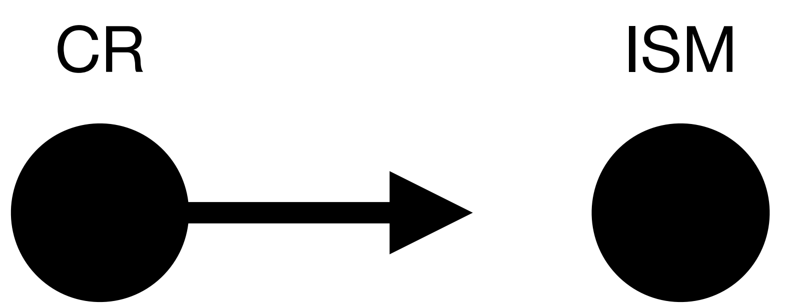
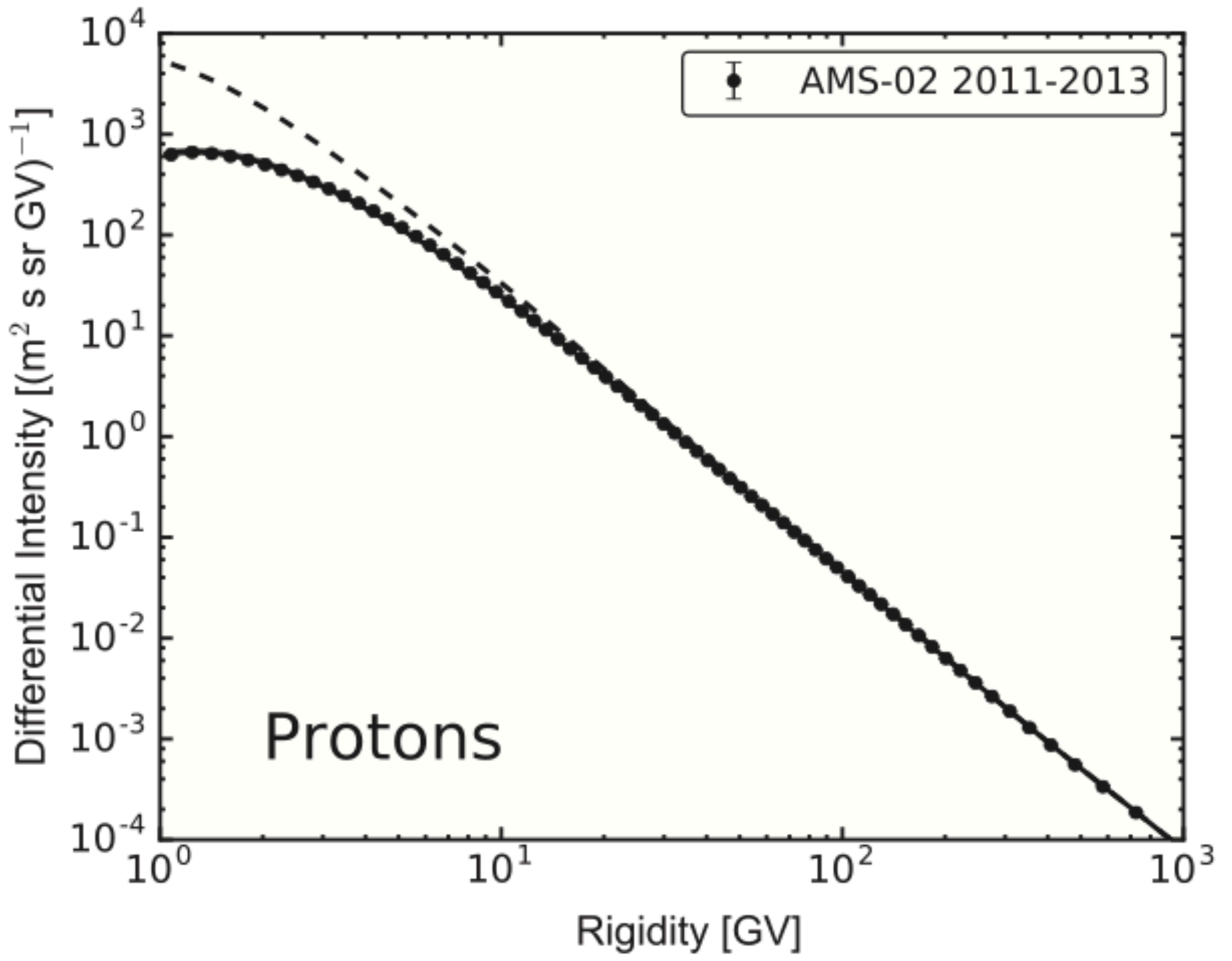






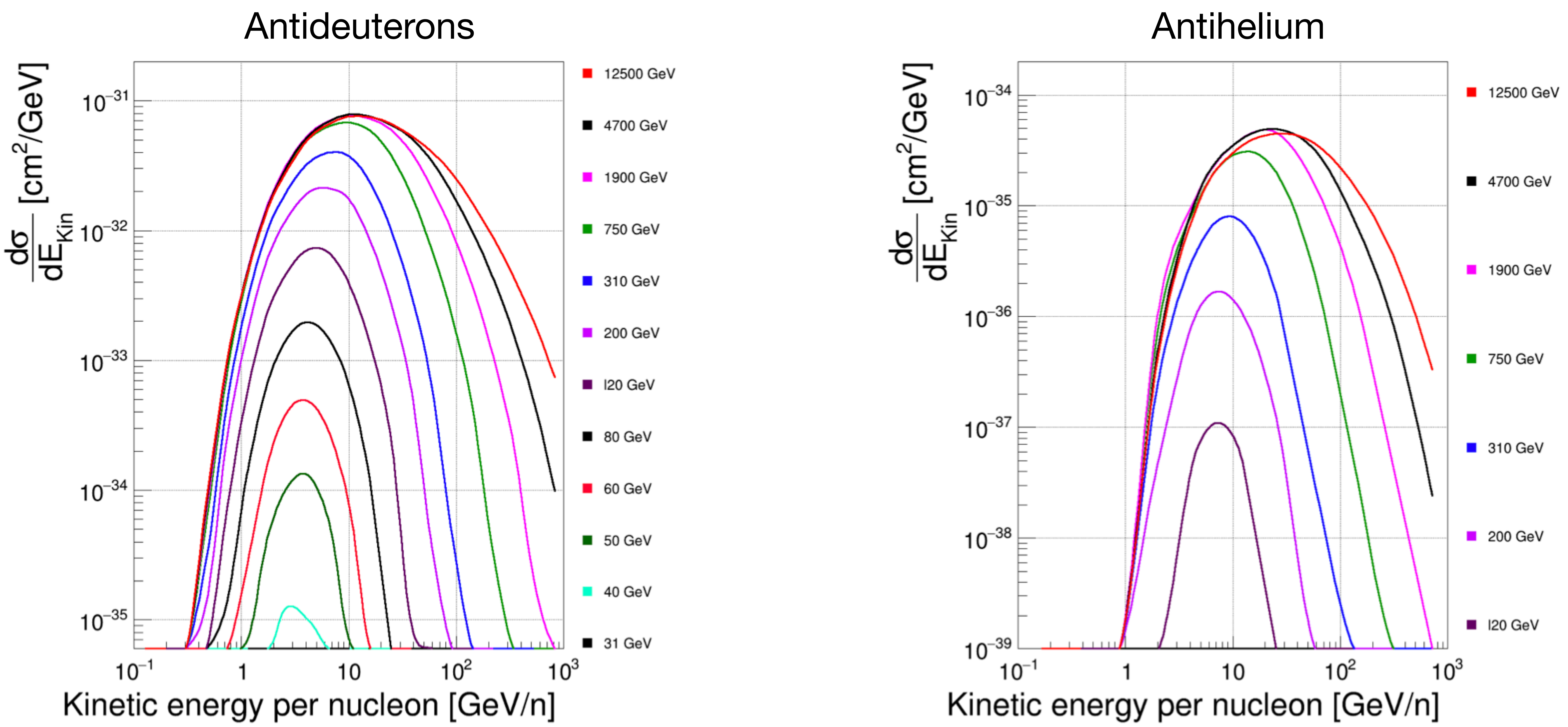


Shukla et al., Phys. Rev. D 102, 063004 (2020)

Boschini et al., ApJ 840, 115 (2017)

Predicted antinuclei spectra

- Input to cosmic ray studies -> antinuclei production spectra for different collision energies.

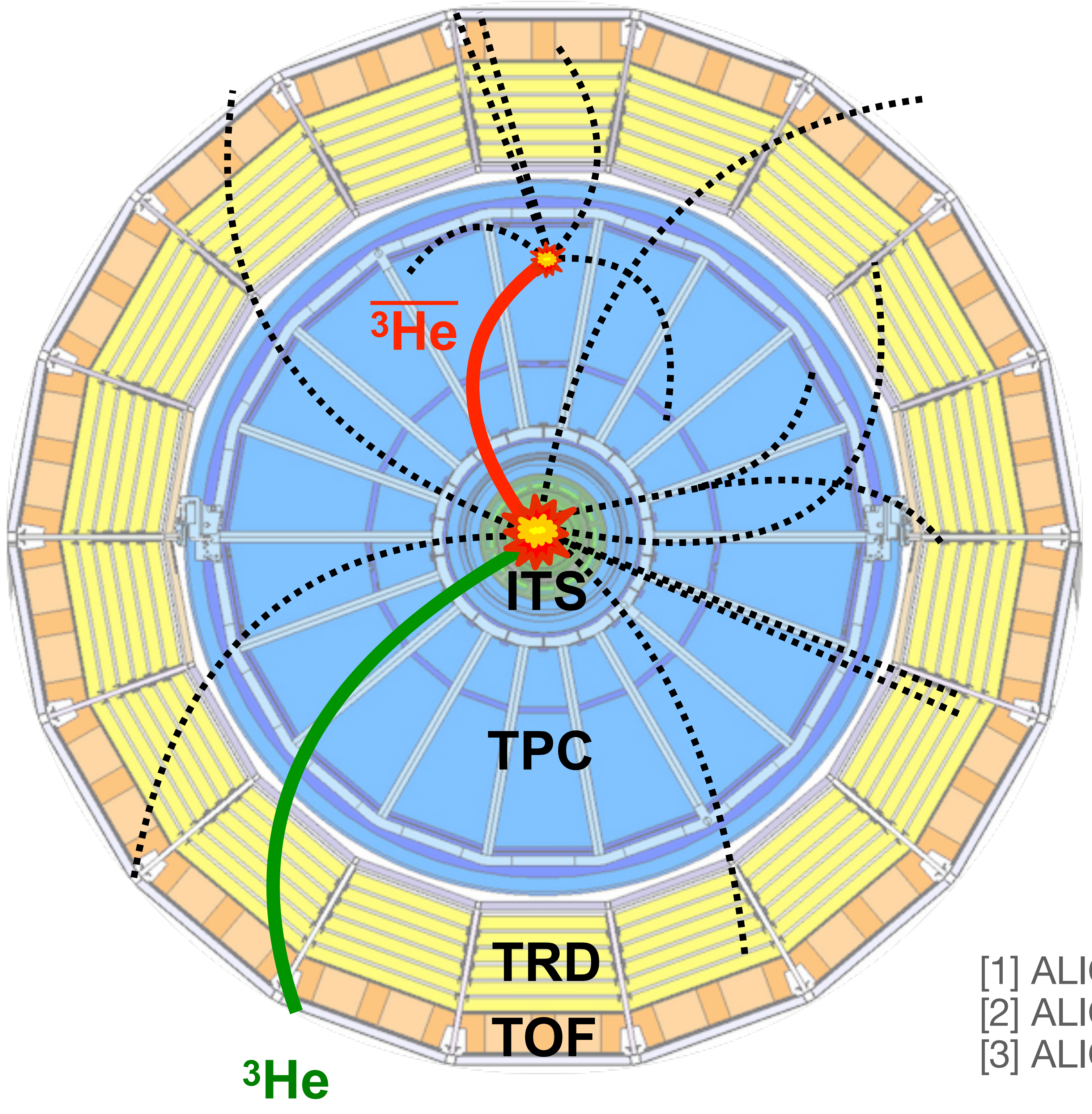


Shukla et al., Phys. Rev. D 102, 063004 (2020)

Measuring antinuclei inelastic cross section

Antimatter-to-matter ratio [2] (pp 13 TeV)

- Almost identical amount of particles and antiparticles produced [3].
- Measure reconstructed "anti-^{3}He/^{3}He" and compare results with MC simulations.



[1] ALICE Coll., JINST 3, S08002 (2008)
[2] ALICE Coll., PRL 125, 162001 (2020)
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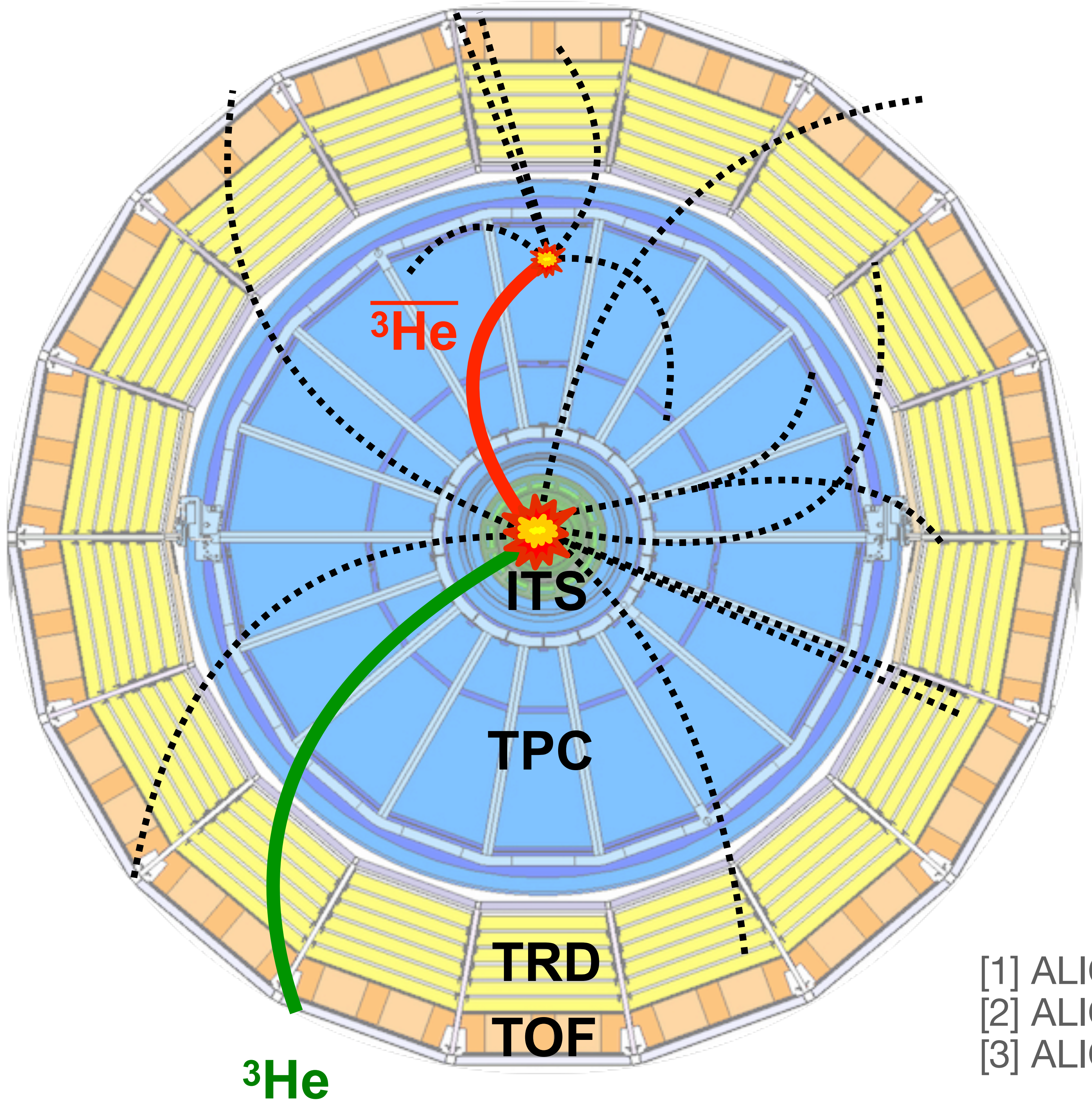
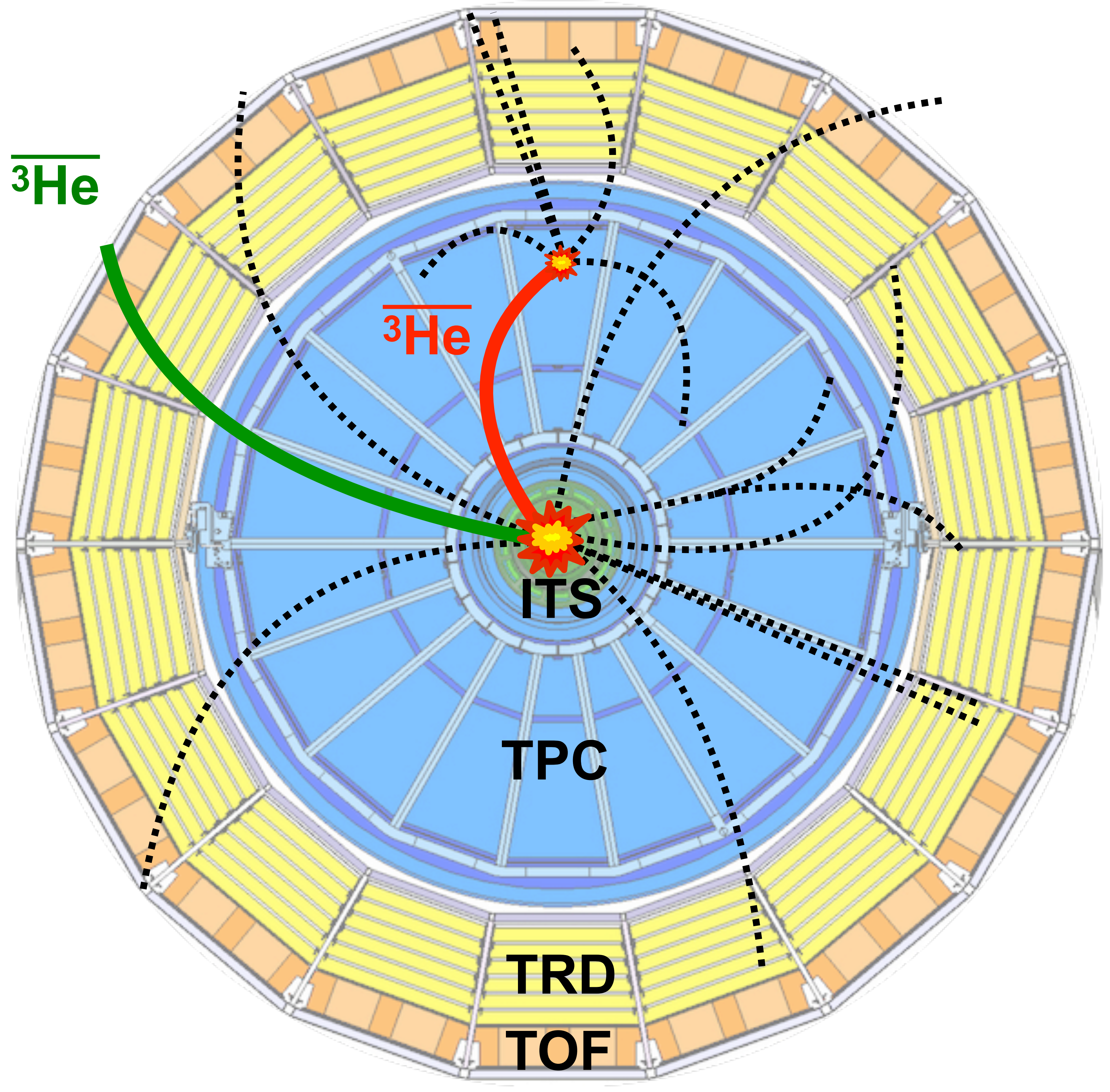


TPC-to-TOF matching (Pb–Pb 5.02 TeV)

- Measure “anti-^{3}He in TOF/anti-^{3}He in TPC” and compare results with MC simulations to extract the inelastic cross section.



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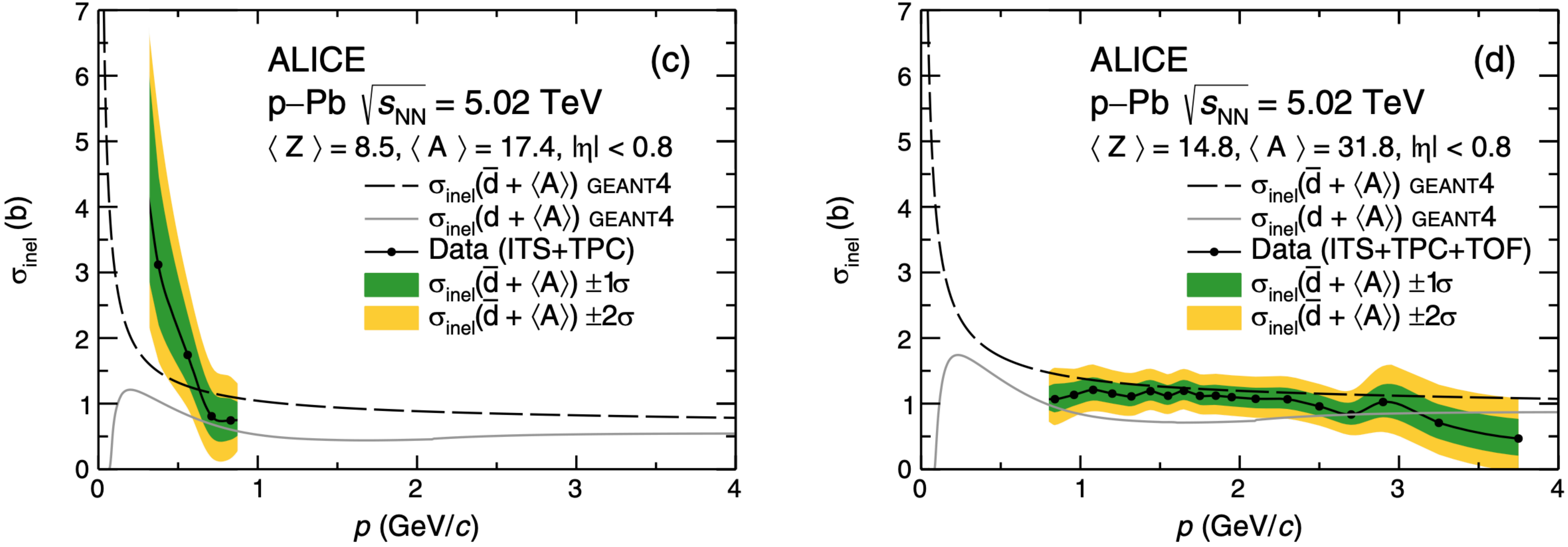
Antideuteron inelastic cross section

- Obtained using antimatter-to-matter ratio.
- High p region (TOF analysis): good agreement with Geant4 parameterisations.
- Low p region (ITS-TPC analysis): hint for steeper rise of σ_{inel} than in Geant4!



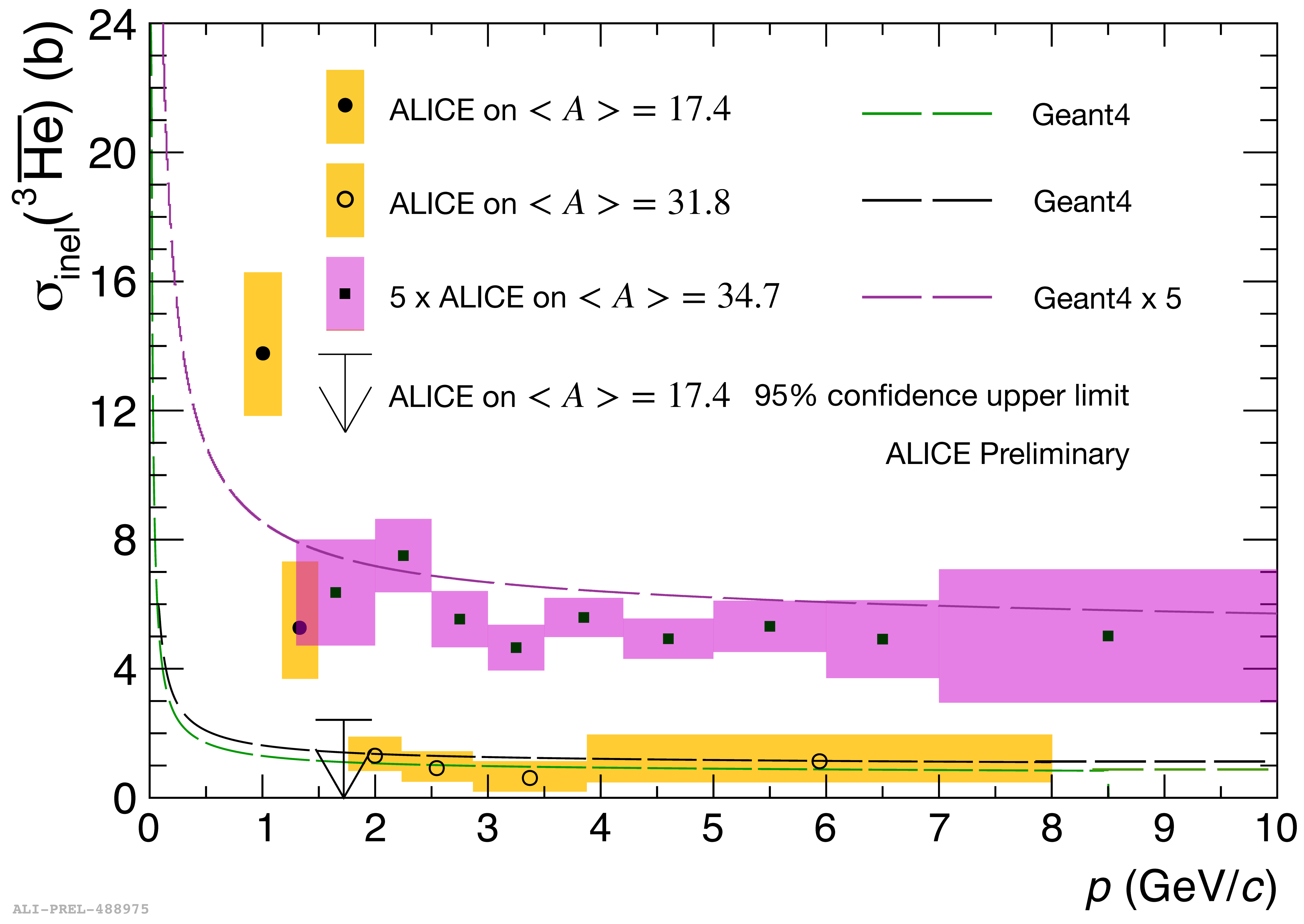
ALICE Coll., Phys. Rev. Lett. 125, 162001 (2020)

Antihelium inelastic cross section

- Low-momentum region accessible only with the antimatter-to-matter ratio.
- High-momentum region measured with better precision using TPC-to-TOF matching method.

The low-momentum region shows steeper rise than expected from modelling.

For p > 2.5 GeV/*c* the data are ~20% below Geant4.



Cosmic ray calculations

Transport equation

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

Source Function

Propagation: diffusion, convection…

Fragmentation, annihilation

Can be numerically solved using GALPROP code! Publicly available at: https://galprop.stanford.edu. Propagation parameters can be constrained by available cosmic ray measurements[1].

Implementation of antinuclei in GALPROP requires:

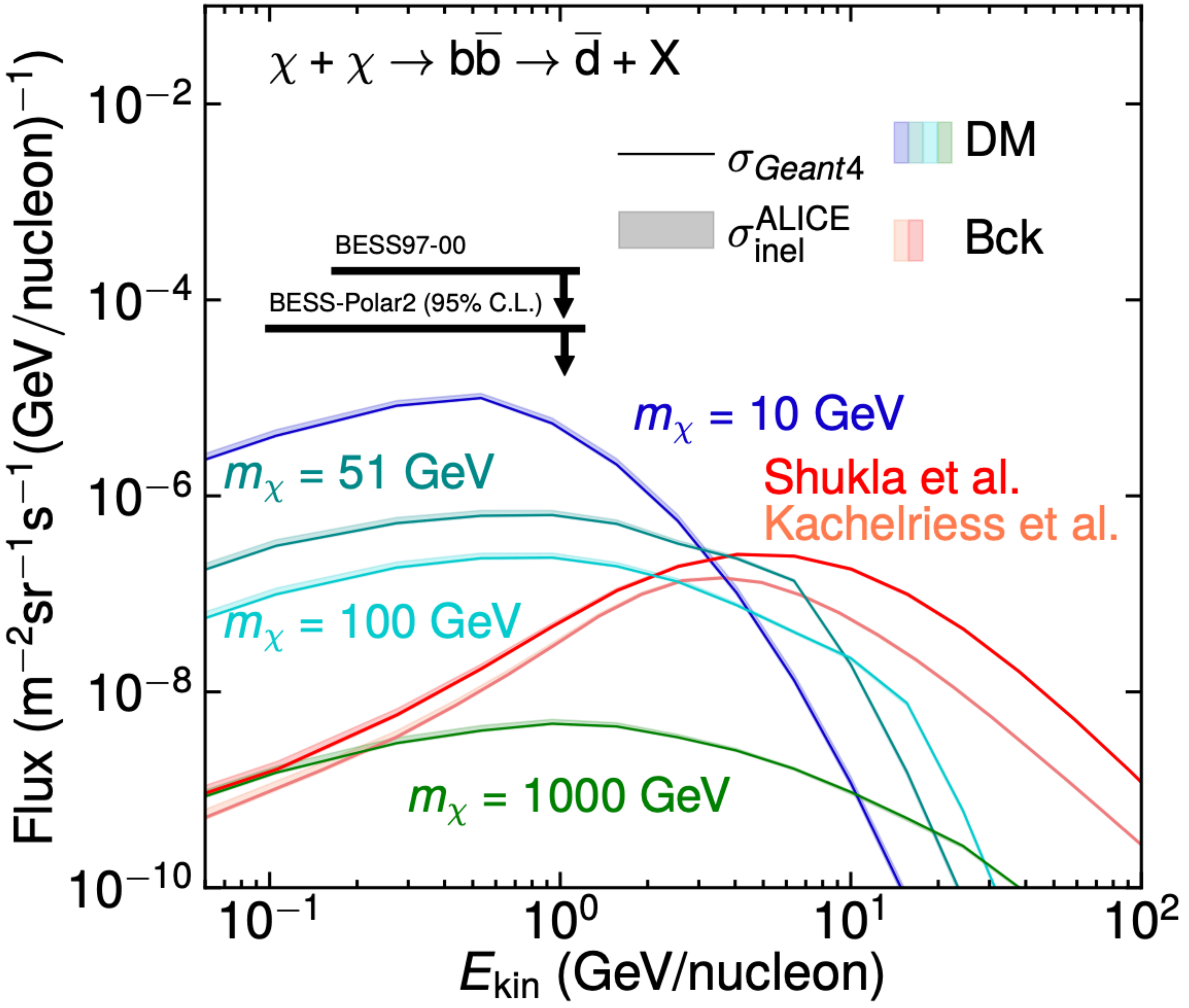
- source function: differential production cross section [2, 3],
- annihilation cross section.

[1] Boschini et al, ApJS 250, 27 (2020)
[2] Shukla et al, Phys. Rev. D. 102, 063004 (2020)
[3] Carlson et al, Phys. Rev. D. 89, 076005 (2014)

Antideuteron cosmic ray flux

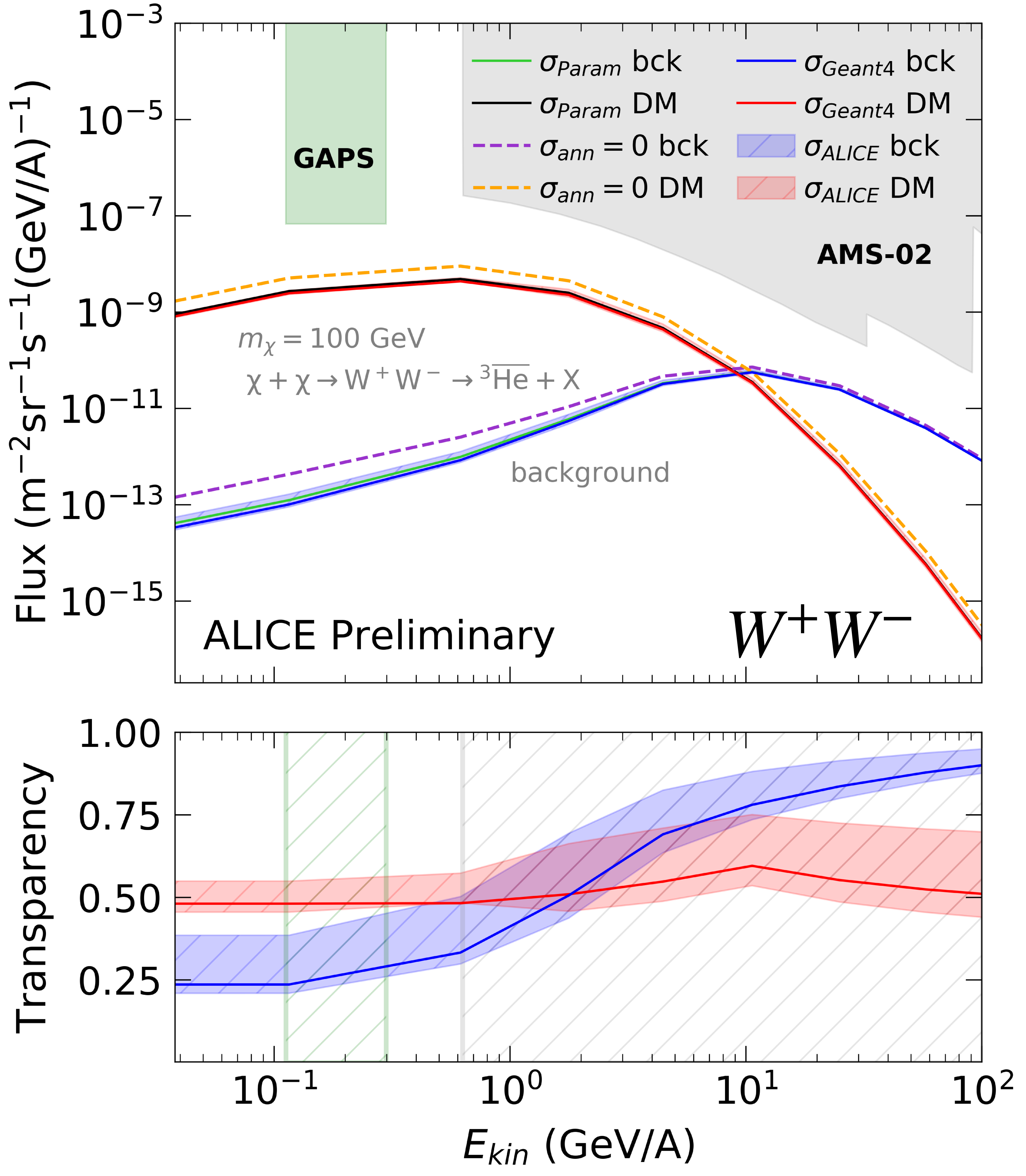
- Only uncertainties from inelastic cross section measurement are shown -> well constrained by ALICE.
- The production model used for background are validated by ALICE.
- At low kinetic energies, the signal-to-background ratio is very high!
- Observing low-energy cosmic ray antideuterons would be a smoking gun signal for exotic antinuclei production sources!

Serksnyte et al., arXiv:2201.00925



Transparency of the galaxy

- ALICE absorption measurement allows to estimate interstellar flux in kinetic energy range > 0.04 GeV/A.
- The background production model is based on ALICE light antinuclei production data.
- Uncertainties only from ALICE absorption measurement, small compared to other uncertainties.
- Rather constant transparency of 50% for typical DM scenario and 25–90% for background.



Summary

- Femtoscopic technique in ALICE at the LHC -> access to the strong interaction for different hadron pairs:
  - p-Λ - unprecedented precision,
  - p-Σ - first direct measurement,
  - p-Ξ - first ever measurement,
  - and others!
- Hyperon puzzle not solved yet as there are still some unknowns (3-body interactions, …)

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❖ Light antinuclei inelastic cross sections measured

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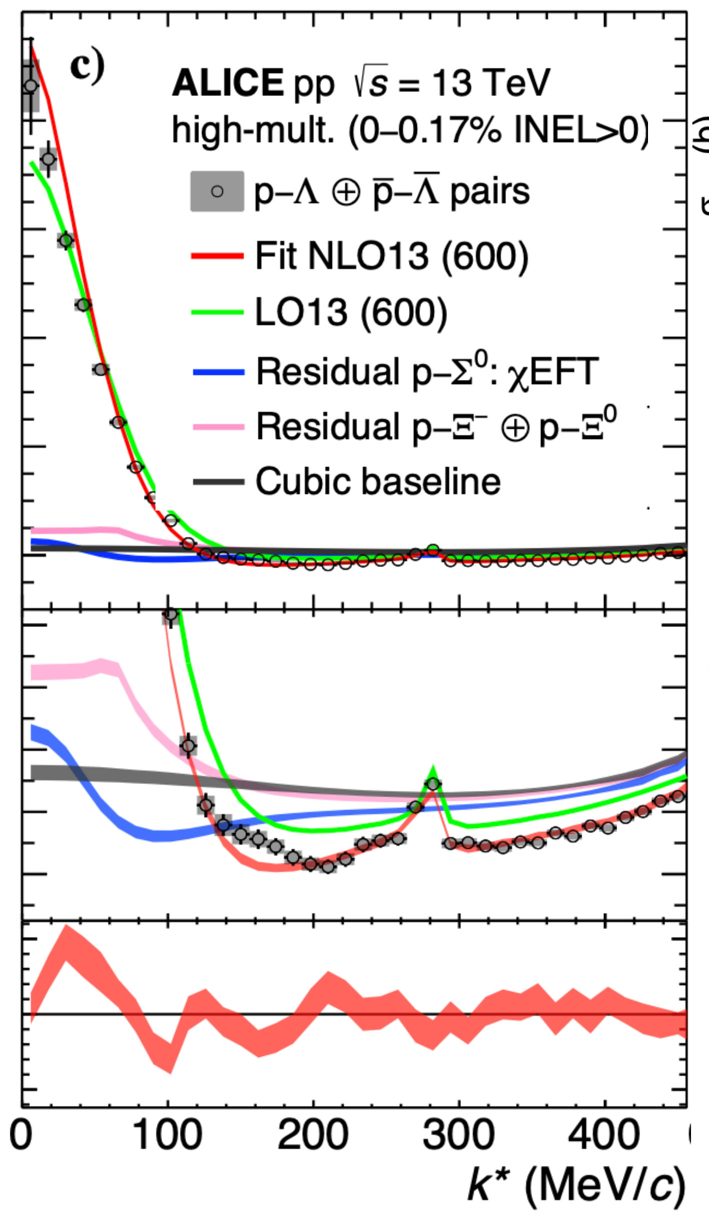

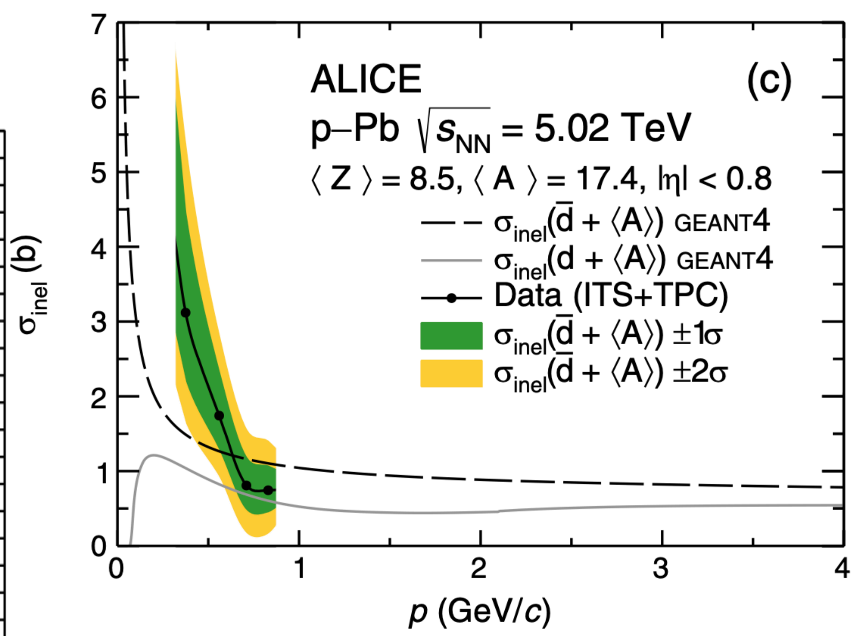

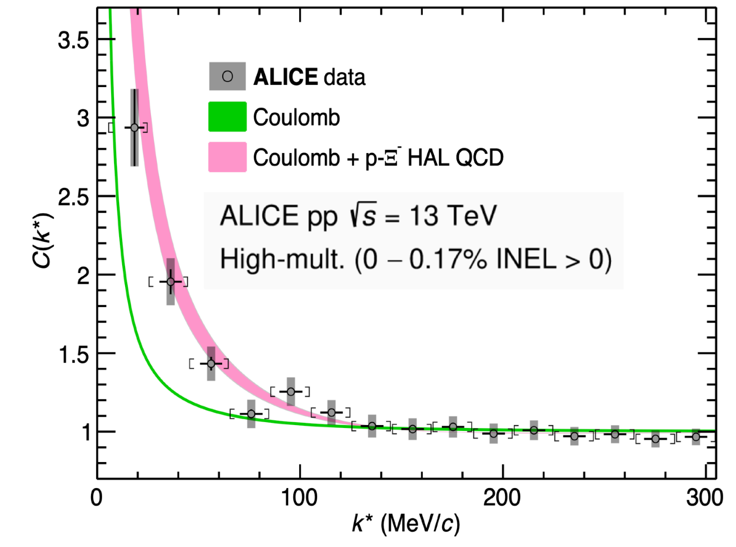

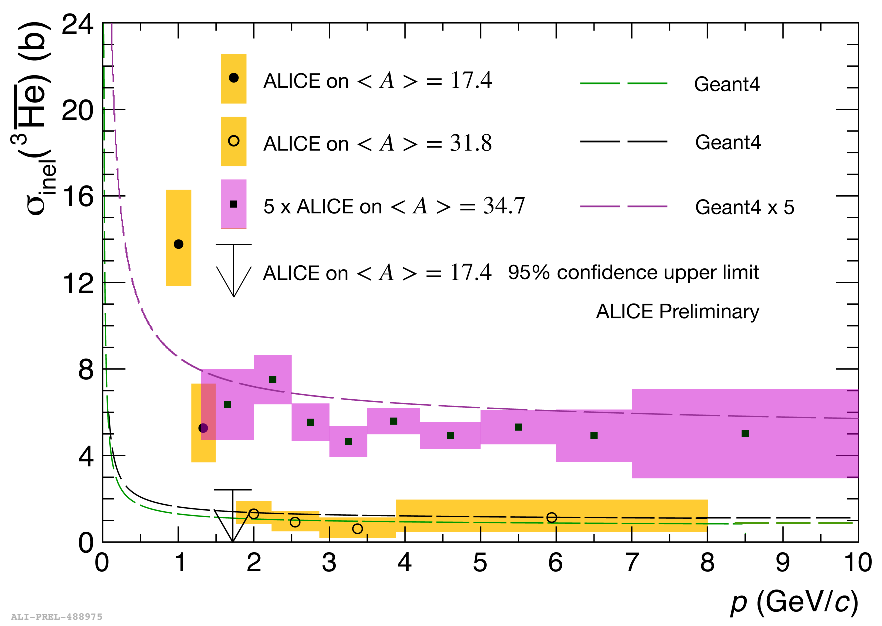

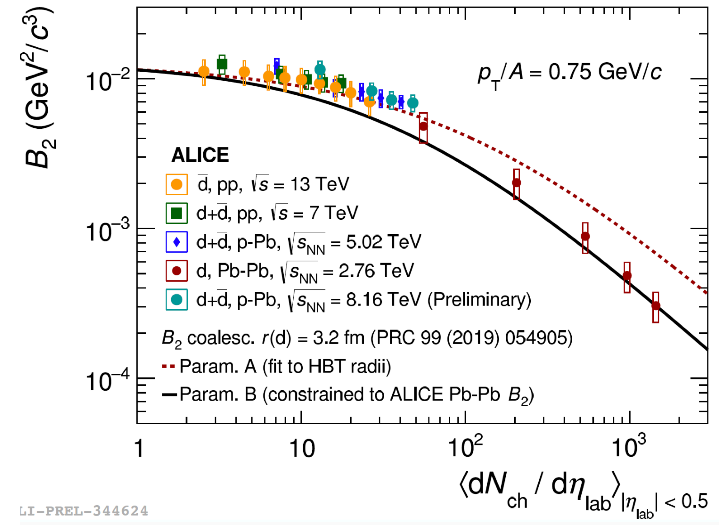

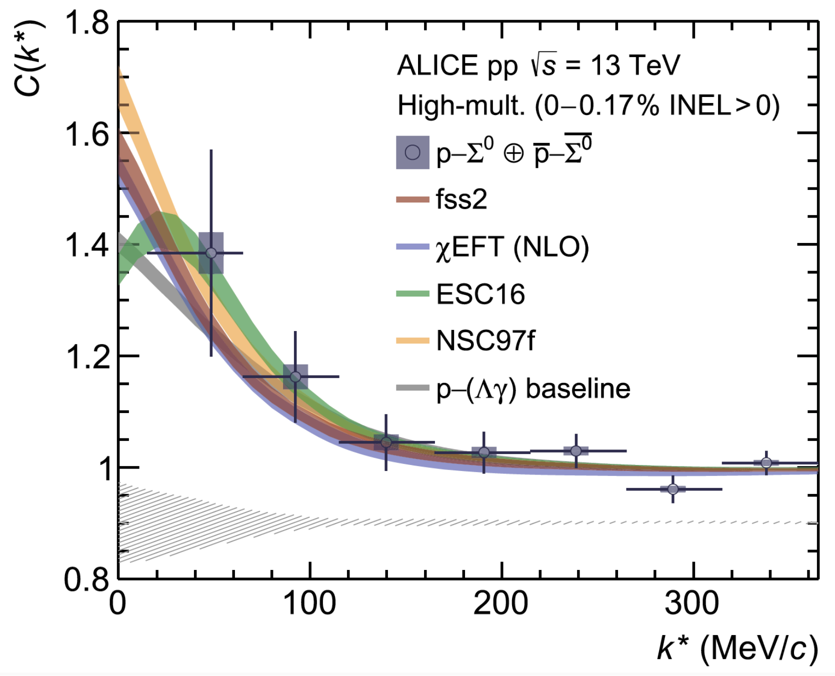

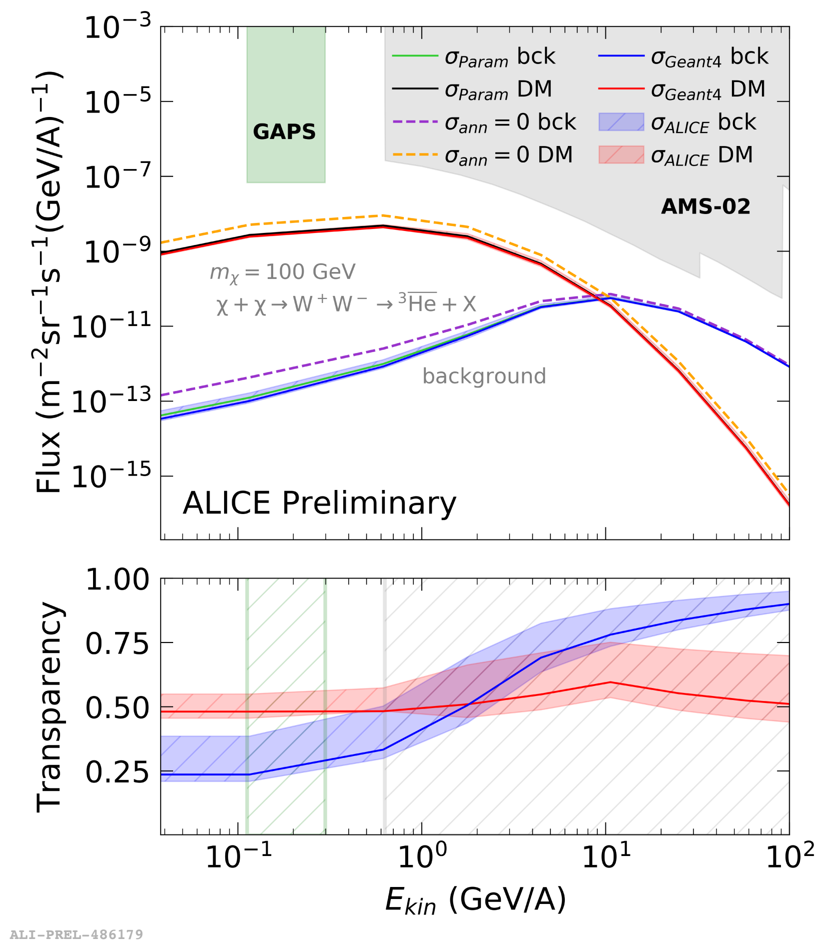

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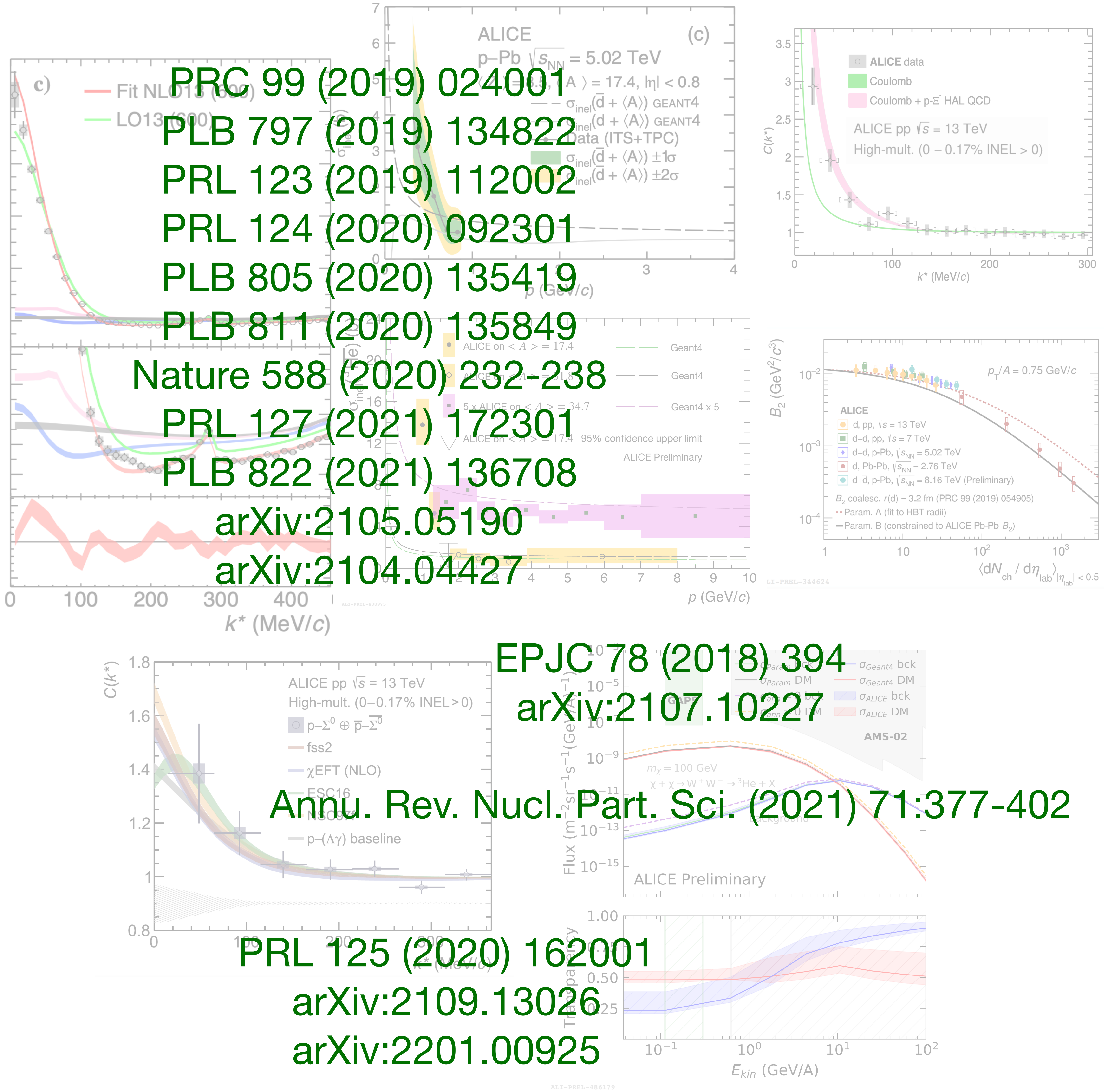


PRC 99 (2019) 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 092301
PLB 805 (2020) 135419
PLB 811 (2020) 135849
Nature 588 (2020) 232-238
PRL 127 (2021) 172301
PLB 822 (2021) 136708
arXiv:2105.05190
arXiv:2104.04427

EPJC 78 (2018) 394
arXiv:2107.10227

Annu. Rev. Nucl. Part. Sci. (2021) 71:377-402

PRL 125 (2020) 162001
arXiv:2109.13026
arXiv:2201.00925

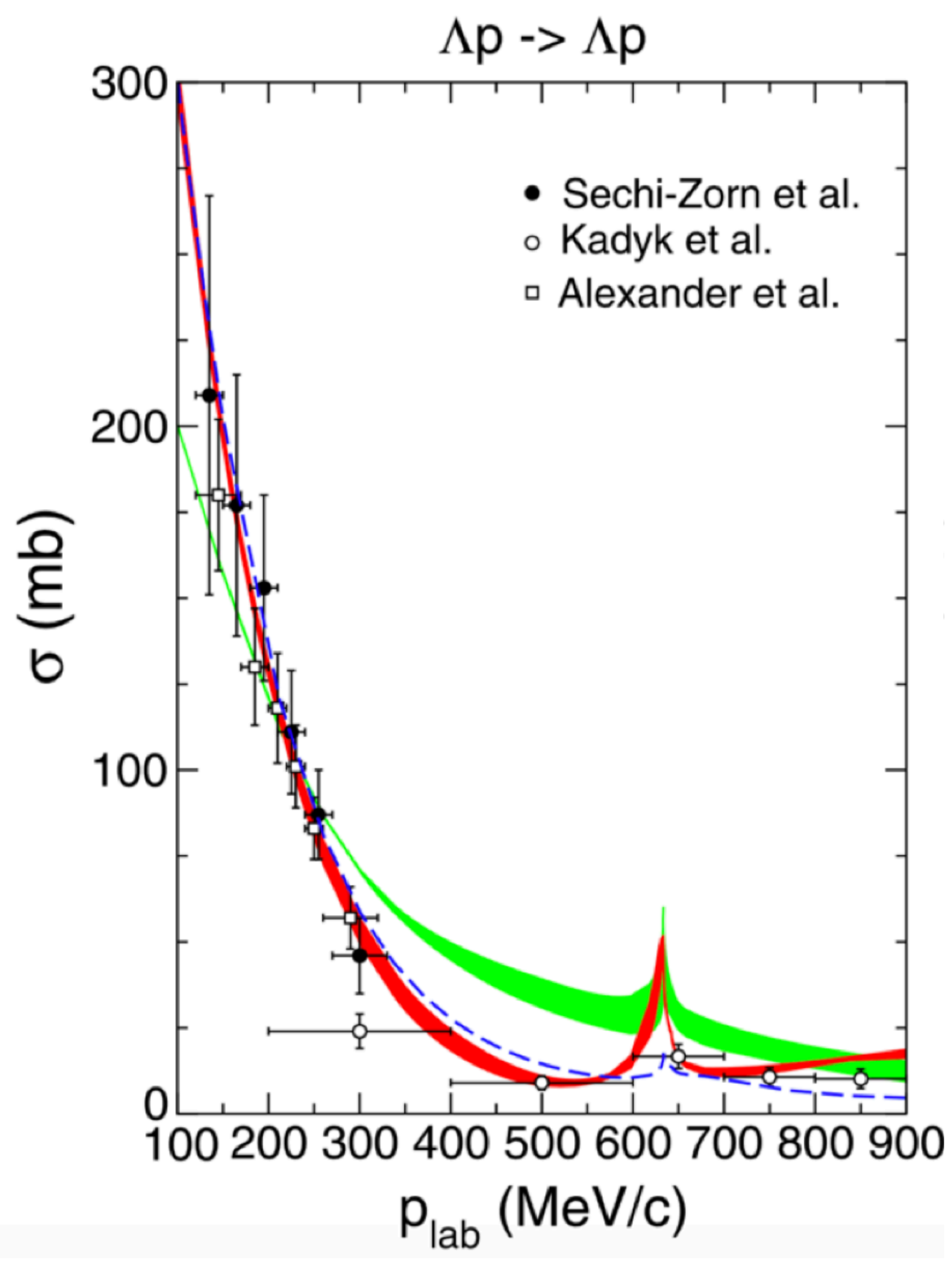
…

Thank your for your attention!

Back up

Measurements of strong interaction

- Two-particle interactions: scattering data:
  - not available at low momenta,
  - not accessible for all hyperons,
  - only data with large uncertainties available (~15–20%).



LO from H. Polinder, J. Haidenbauer, U. Meiβner, NPA 779, 224 (2006) and NLO from J. Haidenbauer, N. Kaiser et al., NPA 915, 24 (2013).

Measurements of strong interaction

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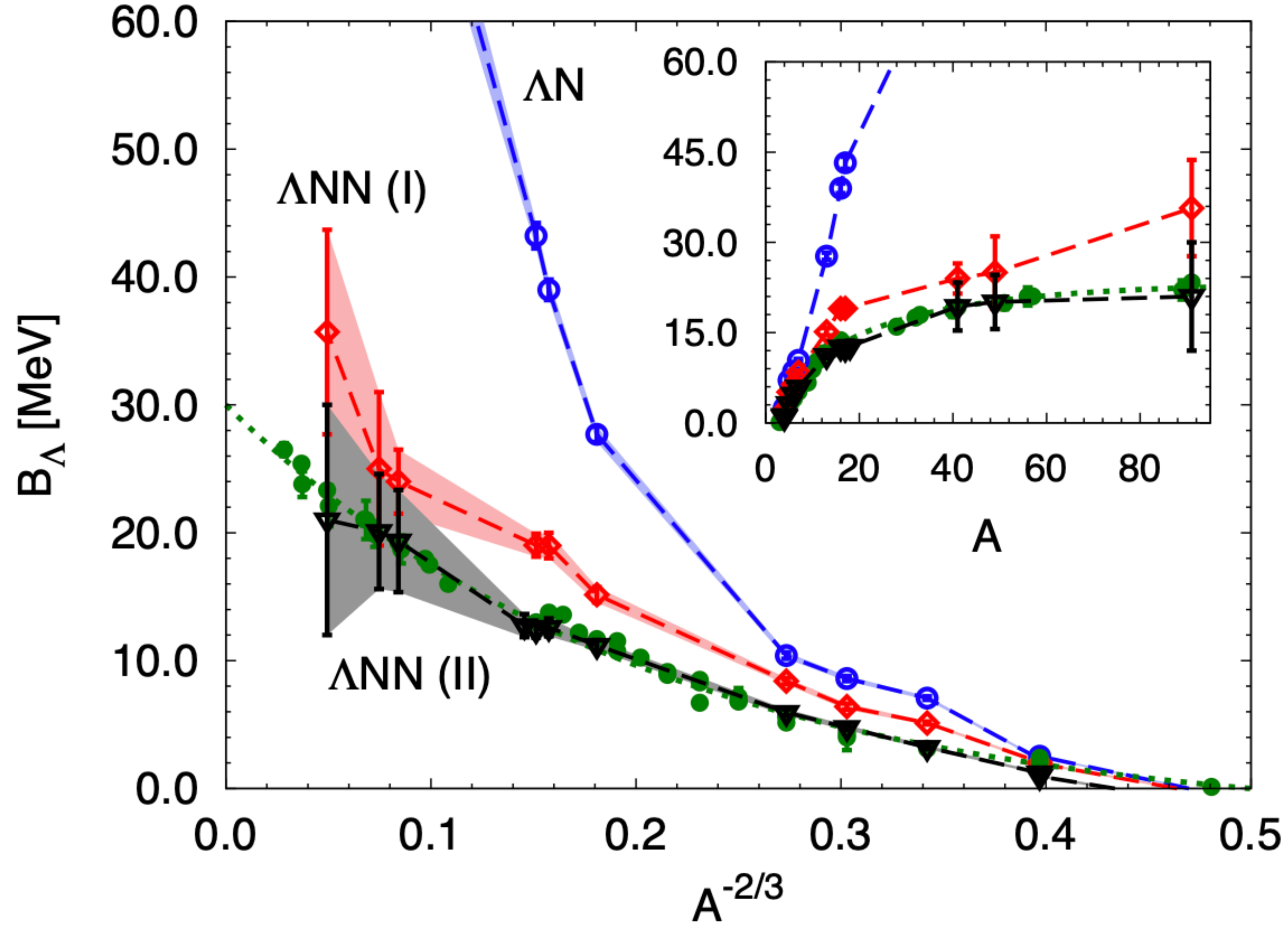

Lonardoni et al., Phys. Rev. C 89, 014314 (2014)

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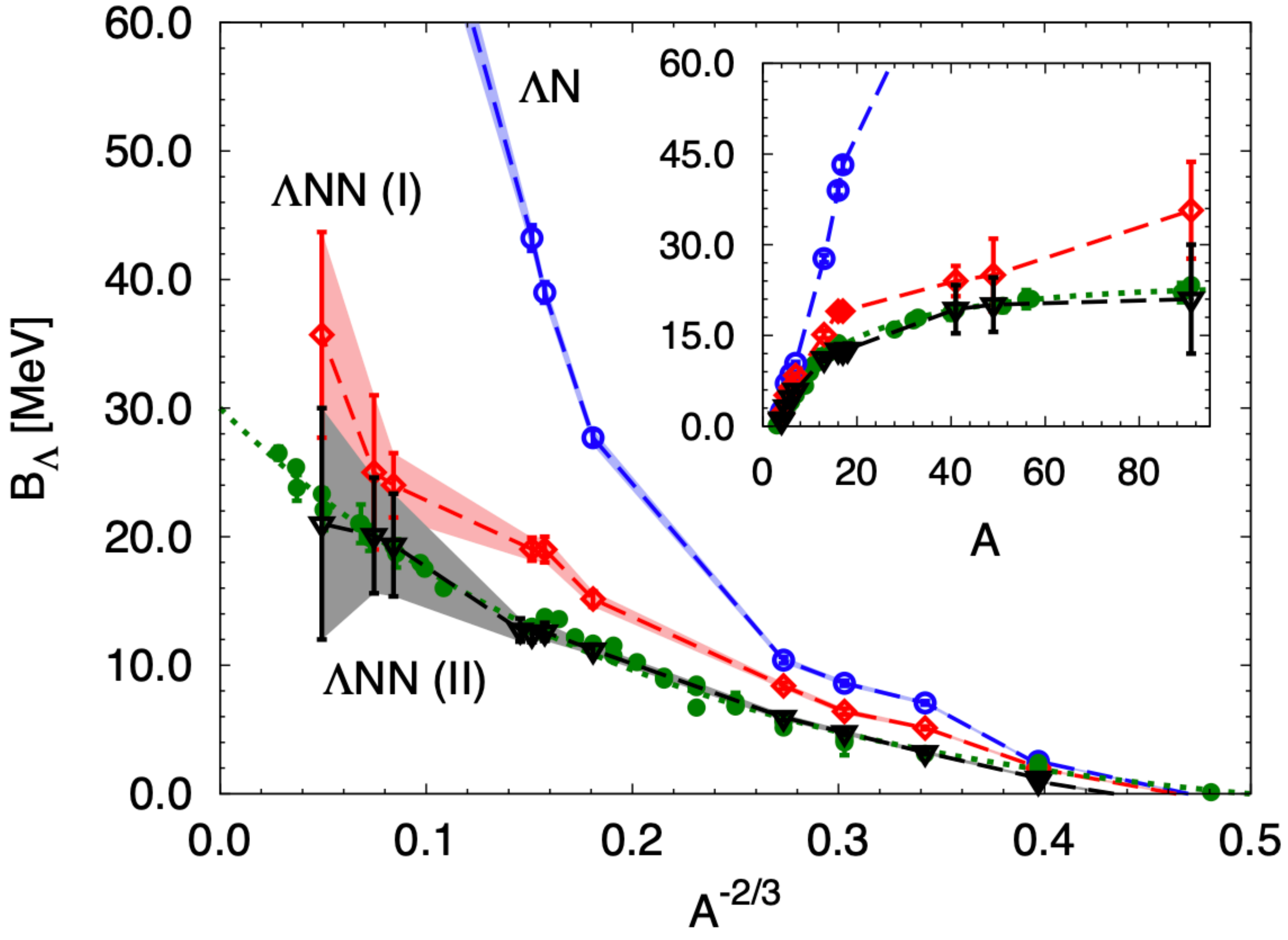


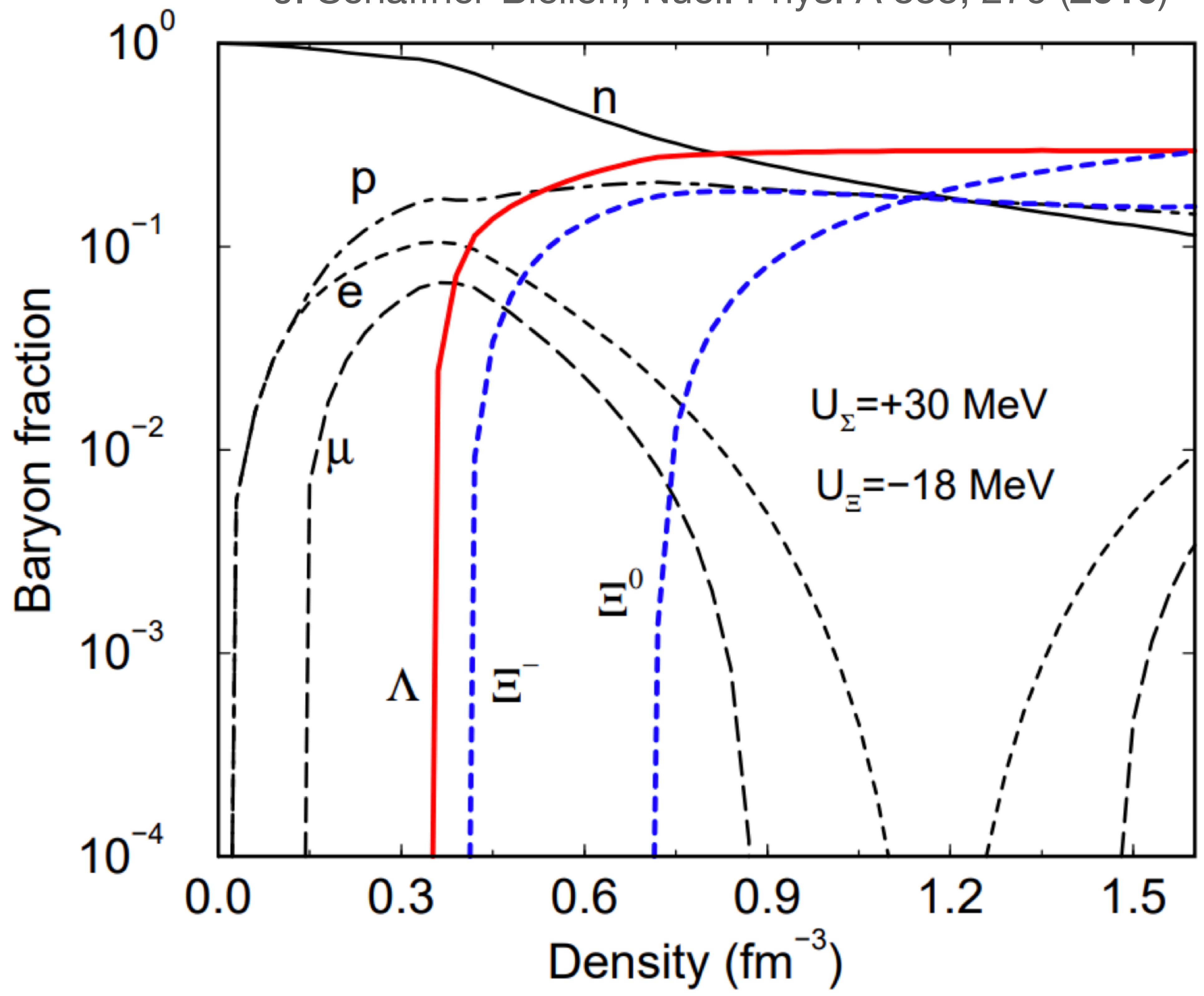
Lonardoni et al., Phys. Rev. C 89, 014314 (2014)

Alternative method: Femtoscopy technique!

p-Ξ⁻ interaction

- The next candidate to appear in neutron star core is Ξ^- hyperon. Strongly dependent on the interaction sign and strength!

J. Schaffner-Bielich, Nucl. Phys. A 835, 279 (**2010**)



Obtained using models adjusted to hypernuclear data and hadronic atom data!

p-ϕ interaction and neutron stars

- At large densities, Y-Y interactions can play a role in EoS.
- Y-Y interactions can be modelled as effective ϕ meson exchange.
- For neutron star studies, the N–ϕ coupling constant is of interest as the Y-Y interaction can be linked to $g_{\phi Y} \propto g_{\phi N}$ [1].

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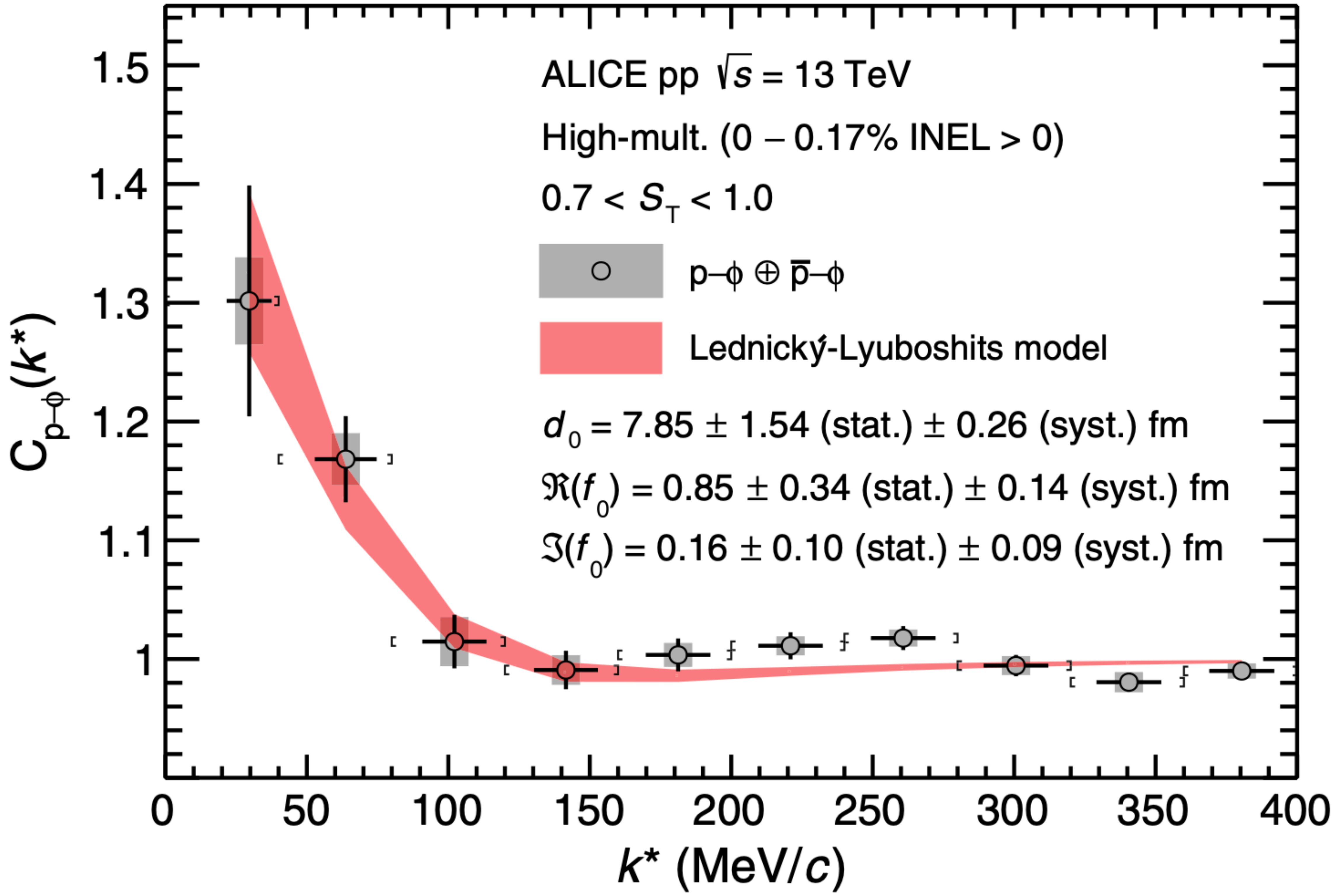
- Extracted scattering parameters [2] suggest that interaction is dominated by elastic contributions in vacuum.
- Fit to Yukawa-type potential yields the coupling constant $g_{\phi N} = 0.14 \pm 0.03$ (stat) $\pm$ 0.02 (syst).

ALICE Coll., Phys. Rev. Lett. 127, 172301(2021)



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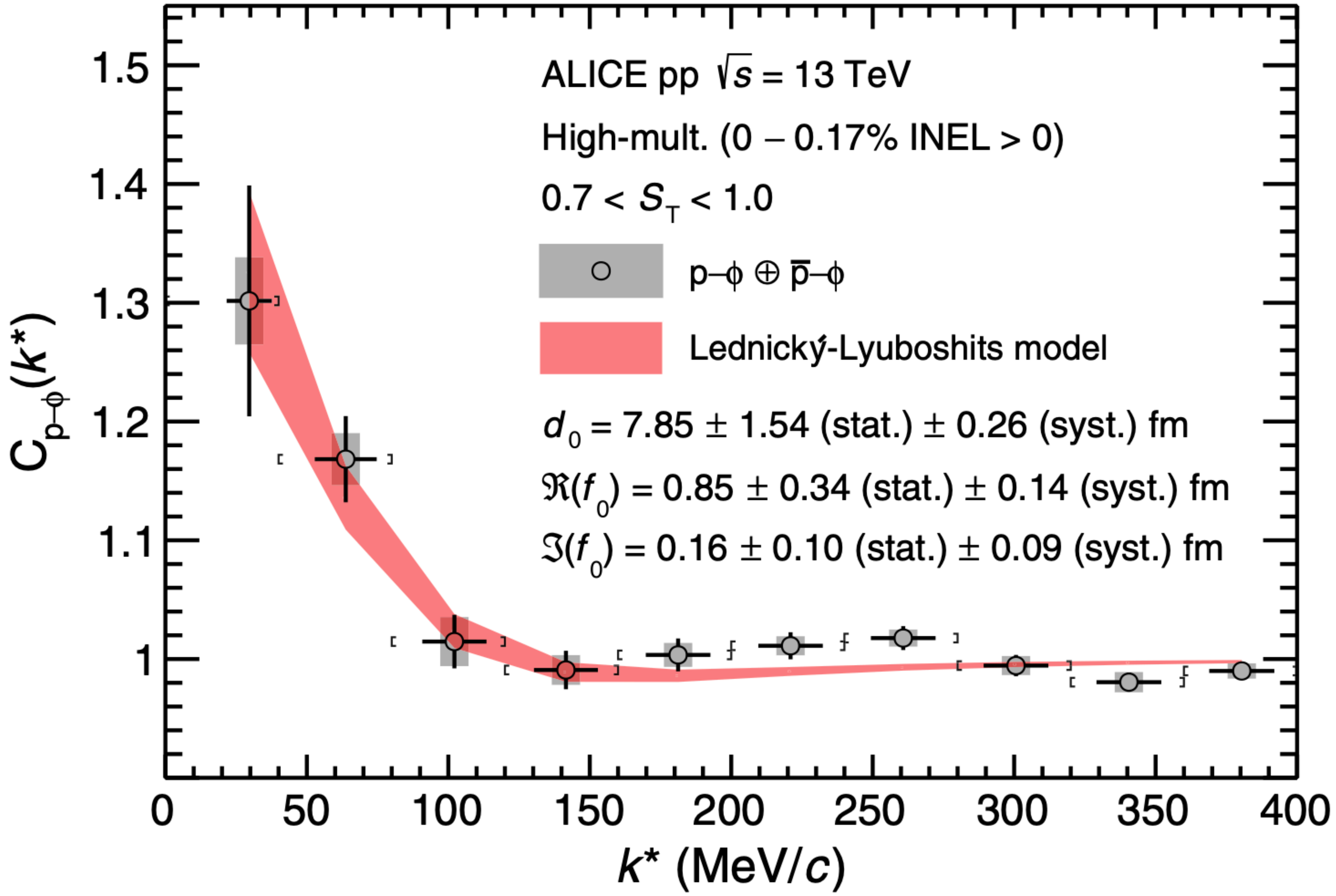

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Next step - three-body interactions.

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Emission source

- Data-driven analysis provided two source components:
  - general: Collective effects induce m_T scaling which can be well approximated by a Gaussian core;
  - specific: Decaying resonances require source correction.
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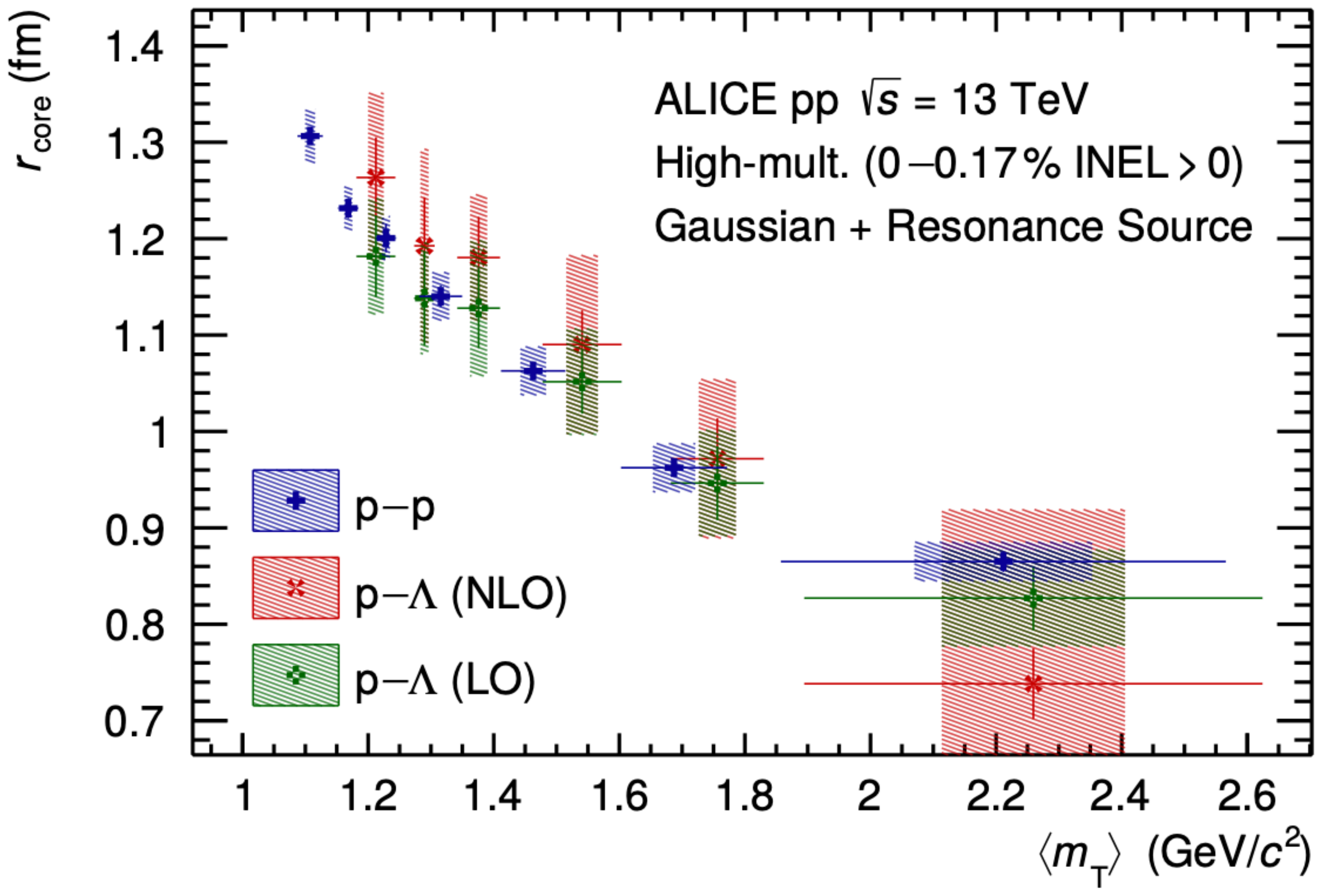
ALICE Coll., PLB 811, 135849 (2020)



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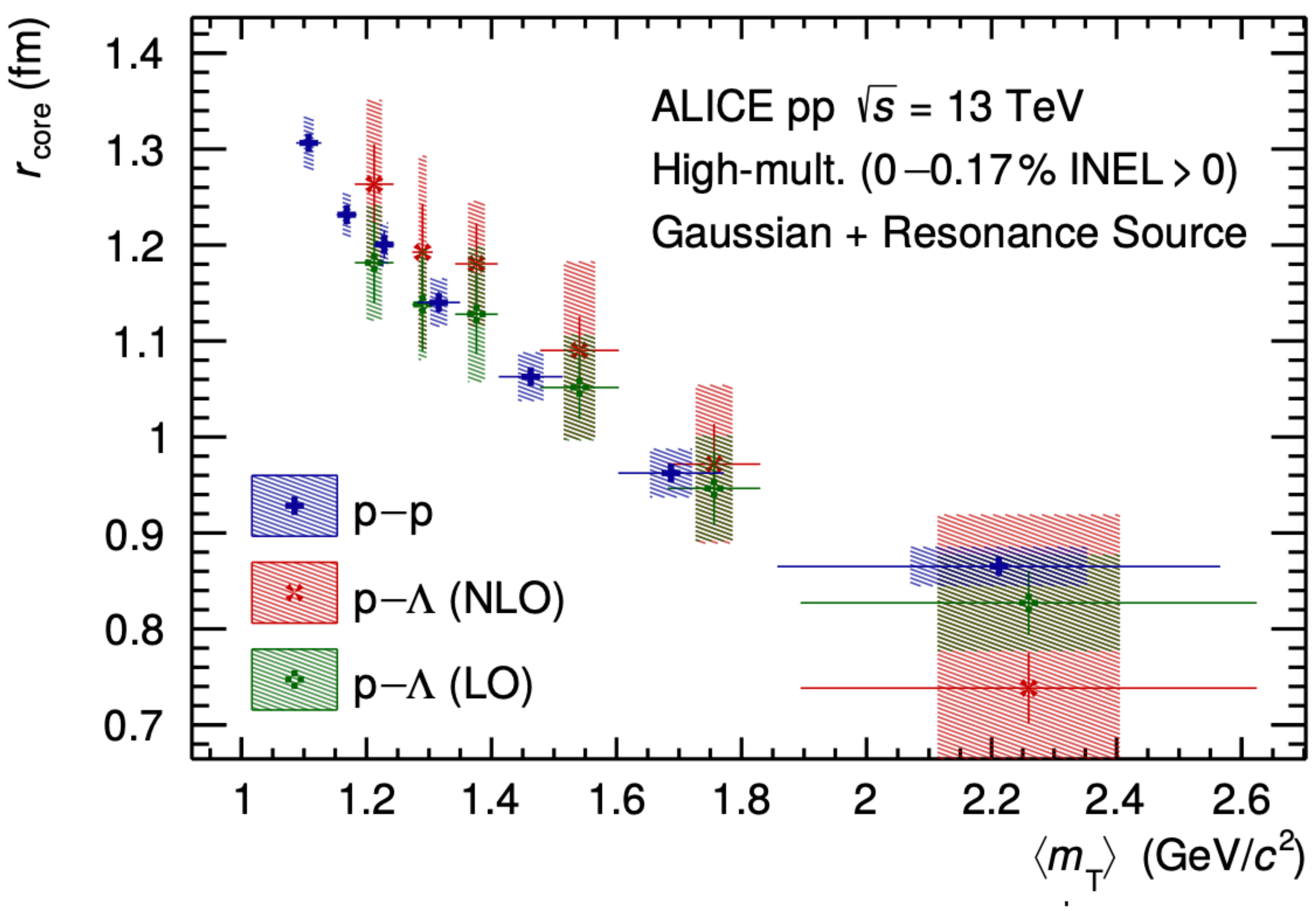
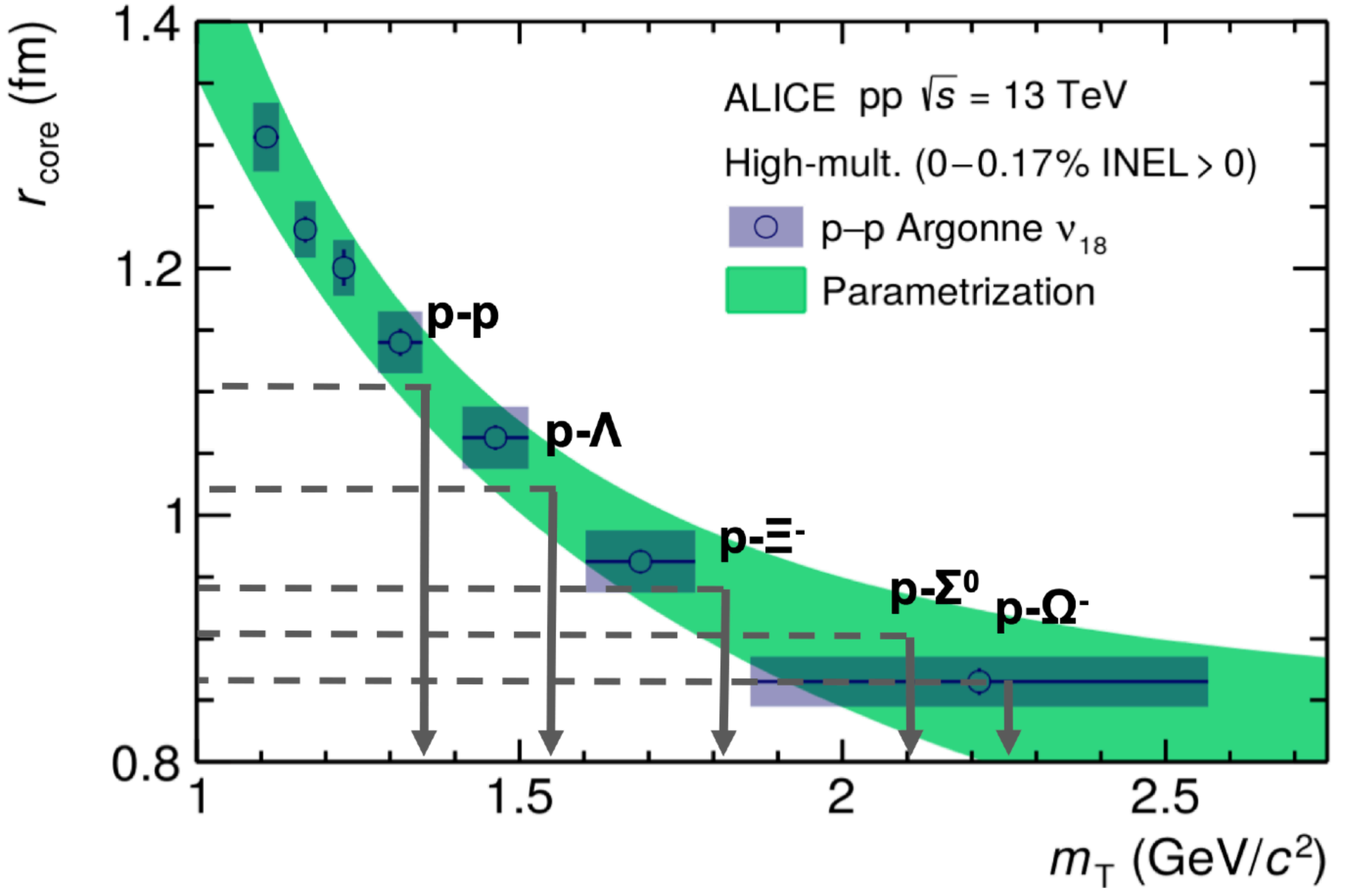
Small interparticle distances (~1–2 fm):
- provide sensitivity to short-range interactions as the strong force,
- mimic large baryonic densities.

ALICE Coll., PLB 811, 135849 (2020)





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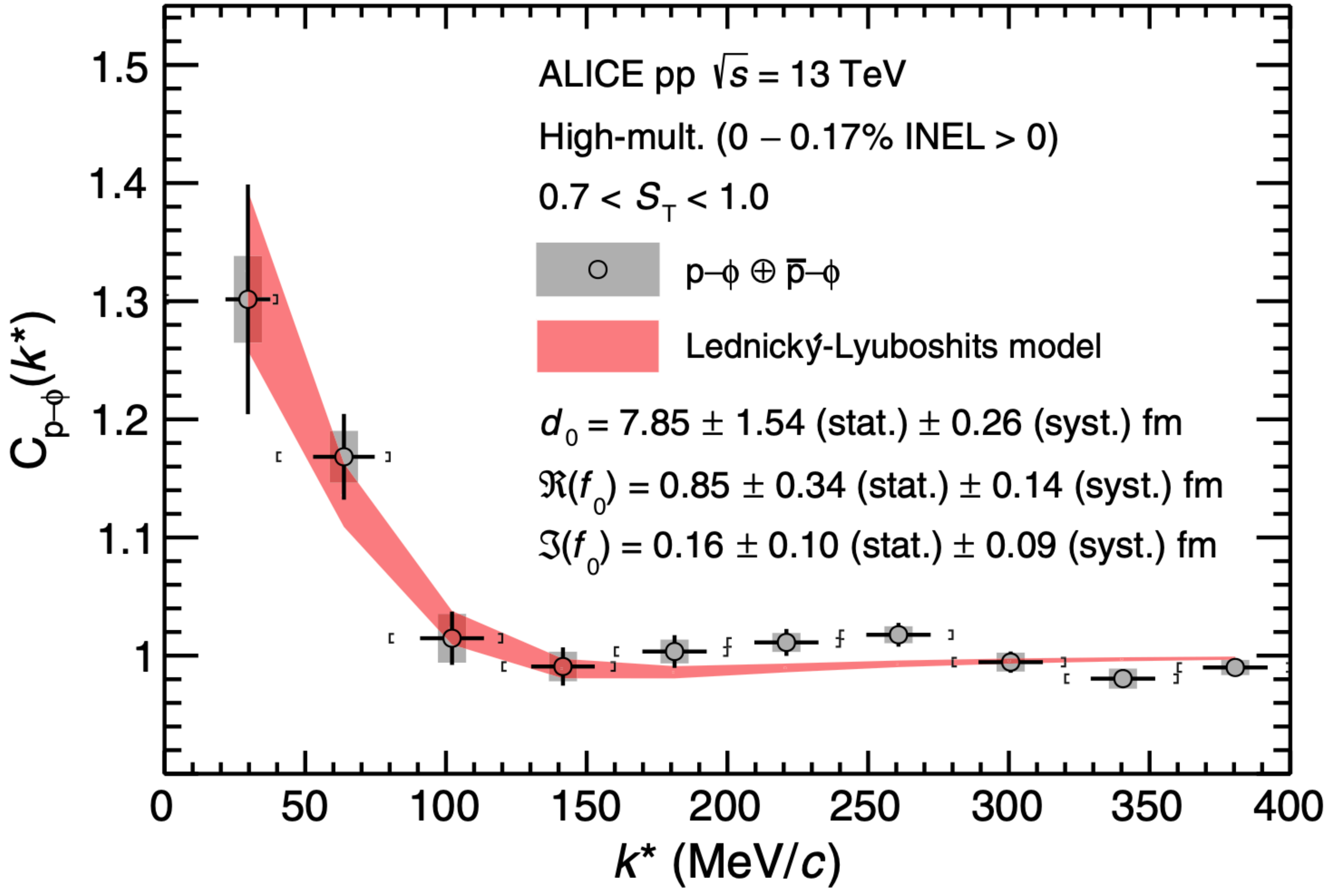

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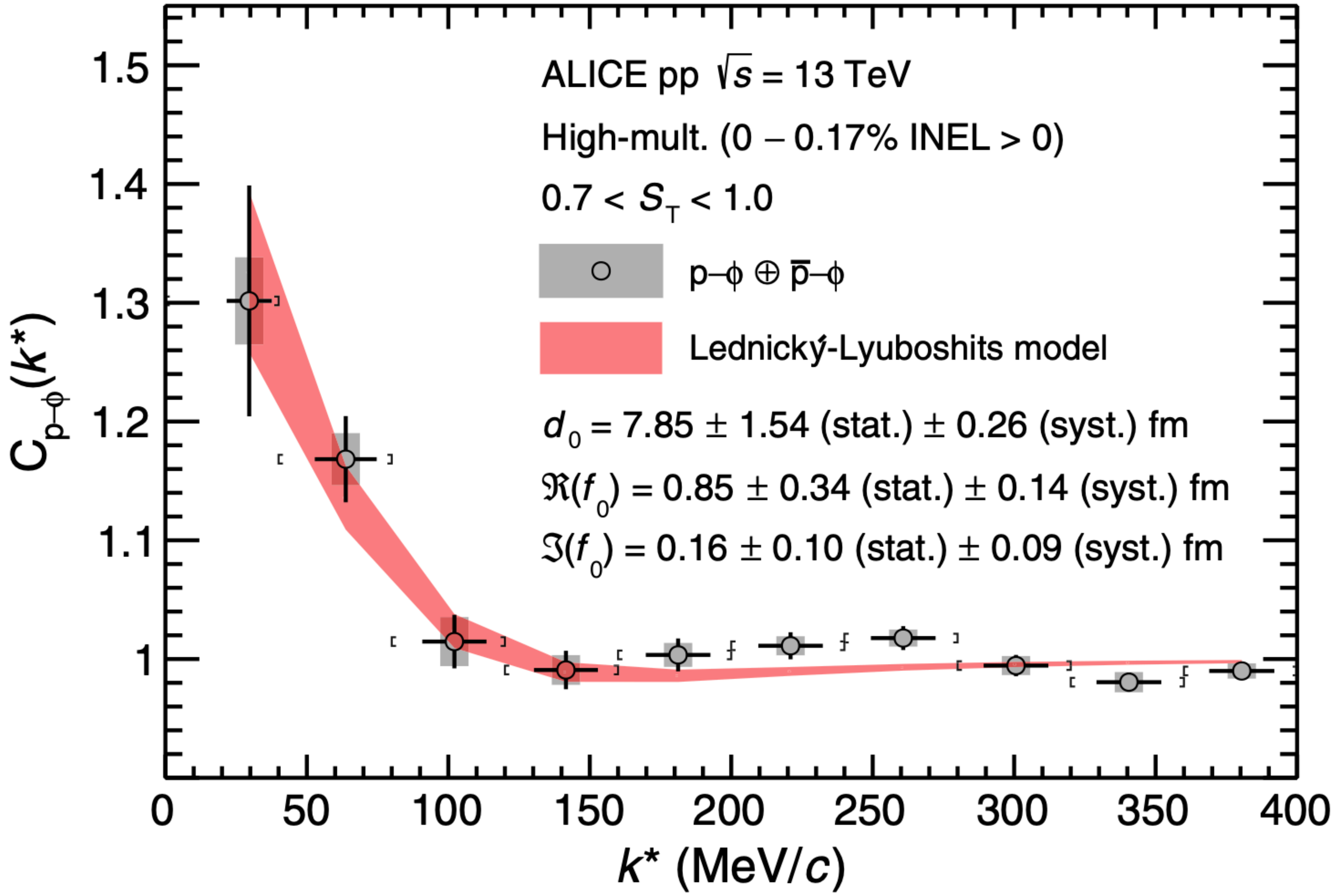

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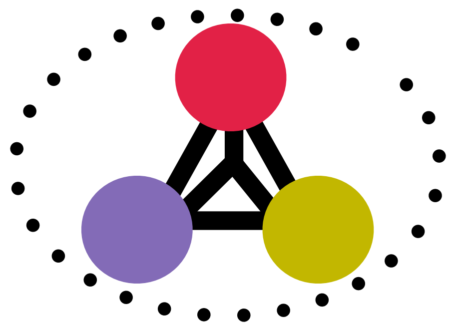
3-body interactions

- Measuring three-particle correlation functions



$$C(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \equiv \frac{N_3(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)}{N_1(\mathbf{p}_1) \cdot N_1(\mathbf{p}_2) \cdot N_1(\mathbf{p}_3)} \propto \frac{N_{same}(Q_3)}{N_{mixed}(Q_3)}$$

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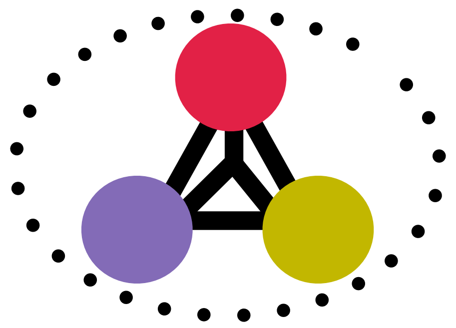

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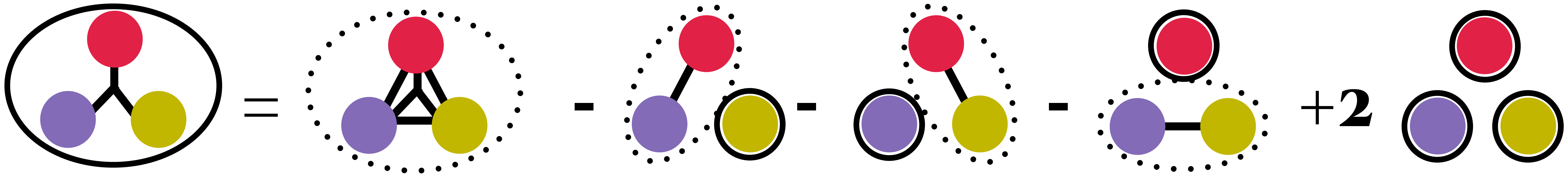

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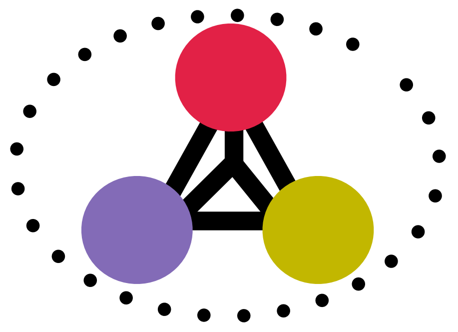

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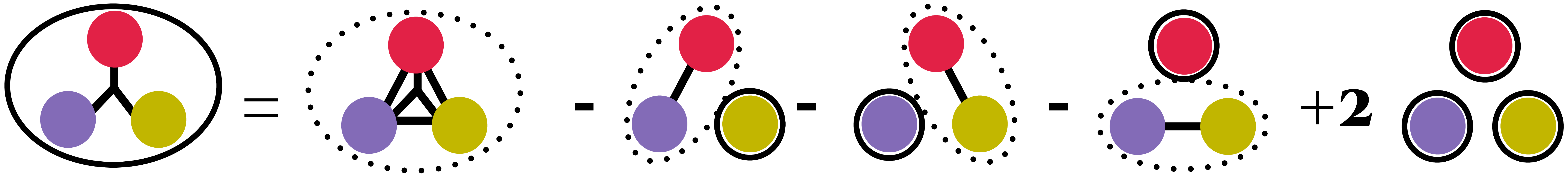

- Lower-order contributions accessible with data-driven method using mixed events or with projector method [2]

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p-p-p and p-p-Λ correlation functions

- p-p-p measurement suggests repulsive three-body effects bellow Q_3~0.23 GeV/*c* with nσ= 2.9σ (< 0.4 GeV/*c*).
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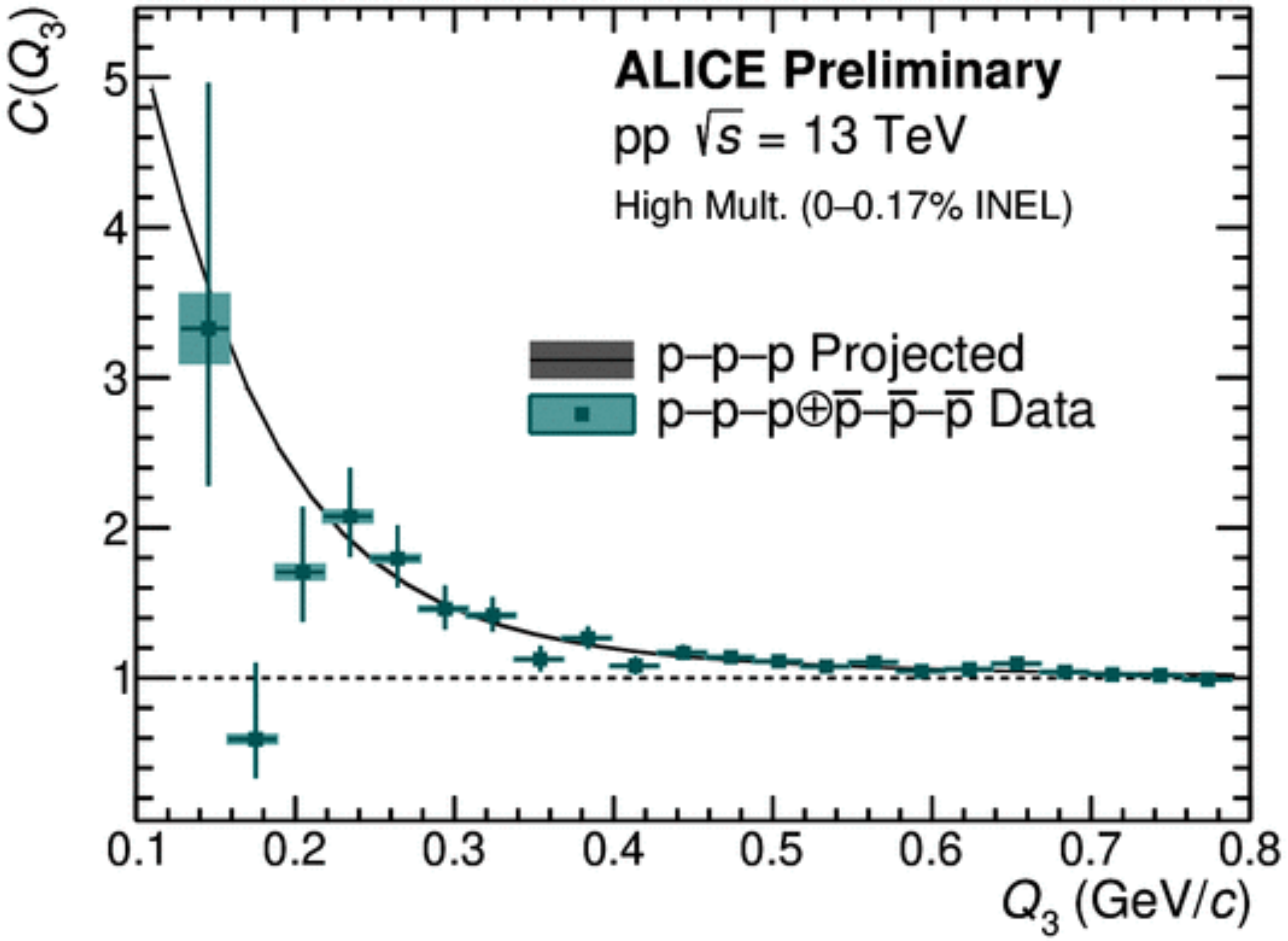

ALI-PREL-487054

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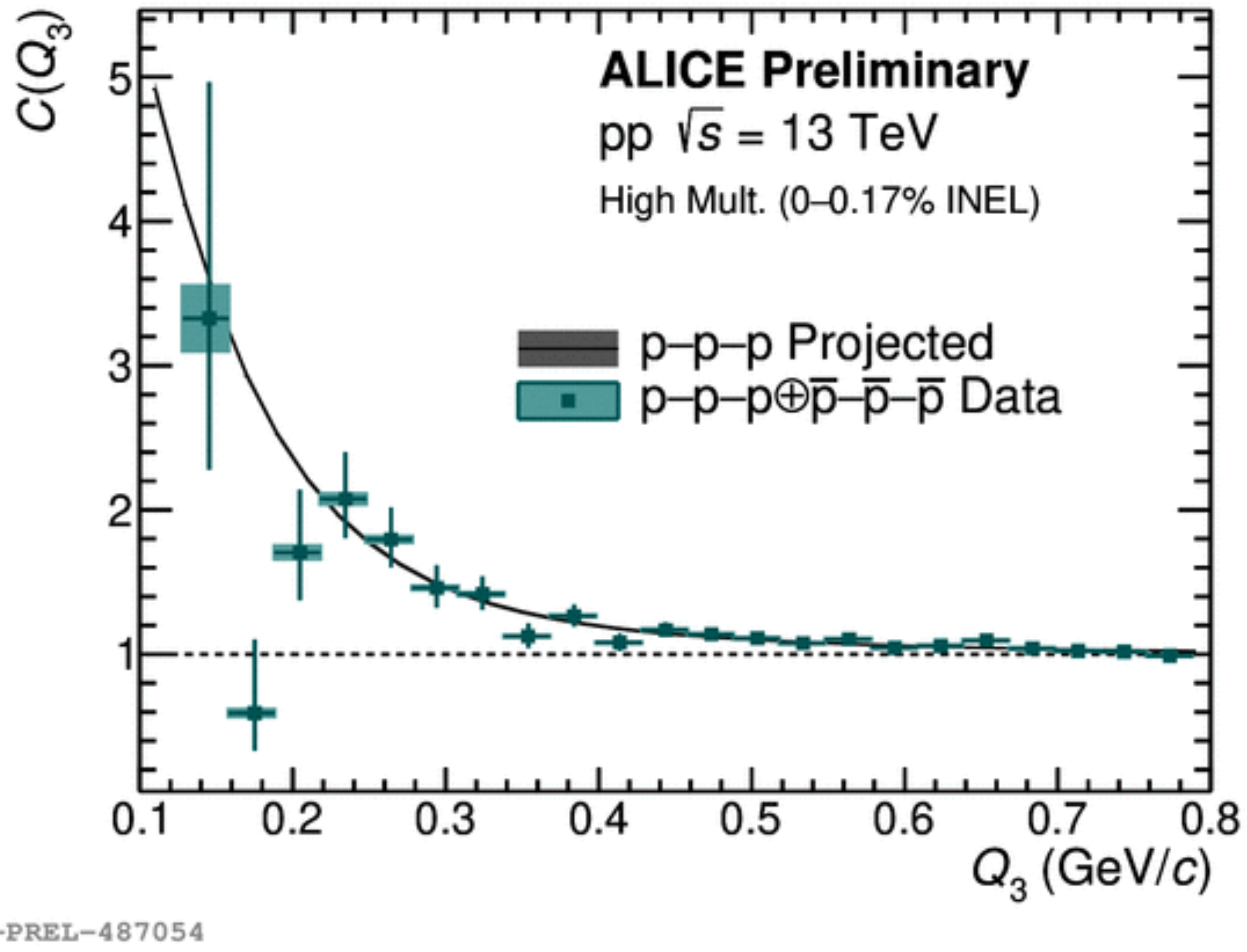
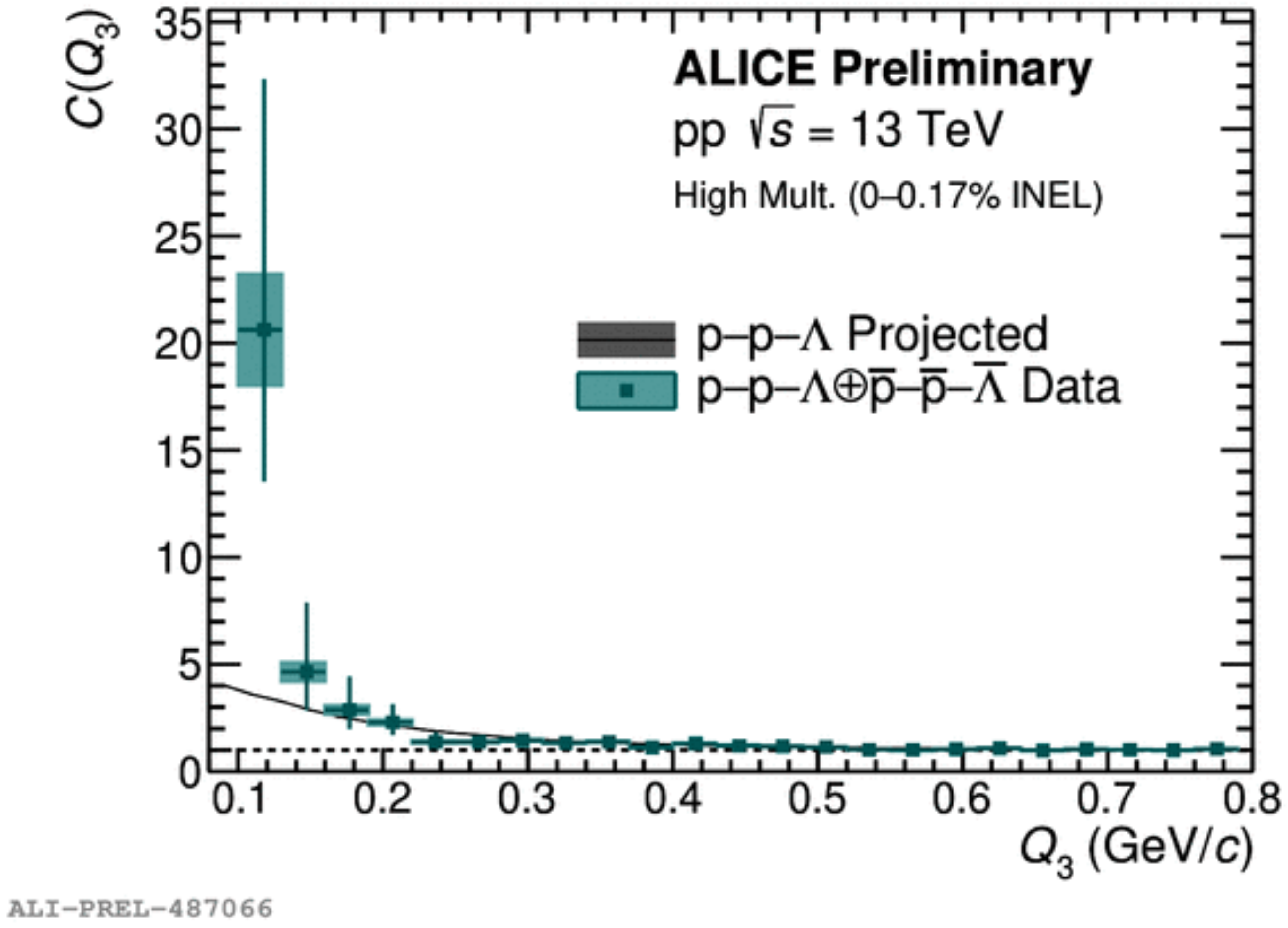
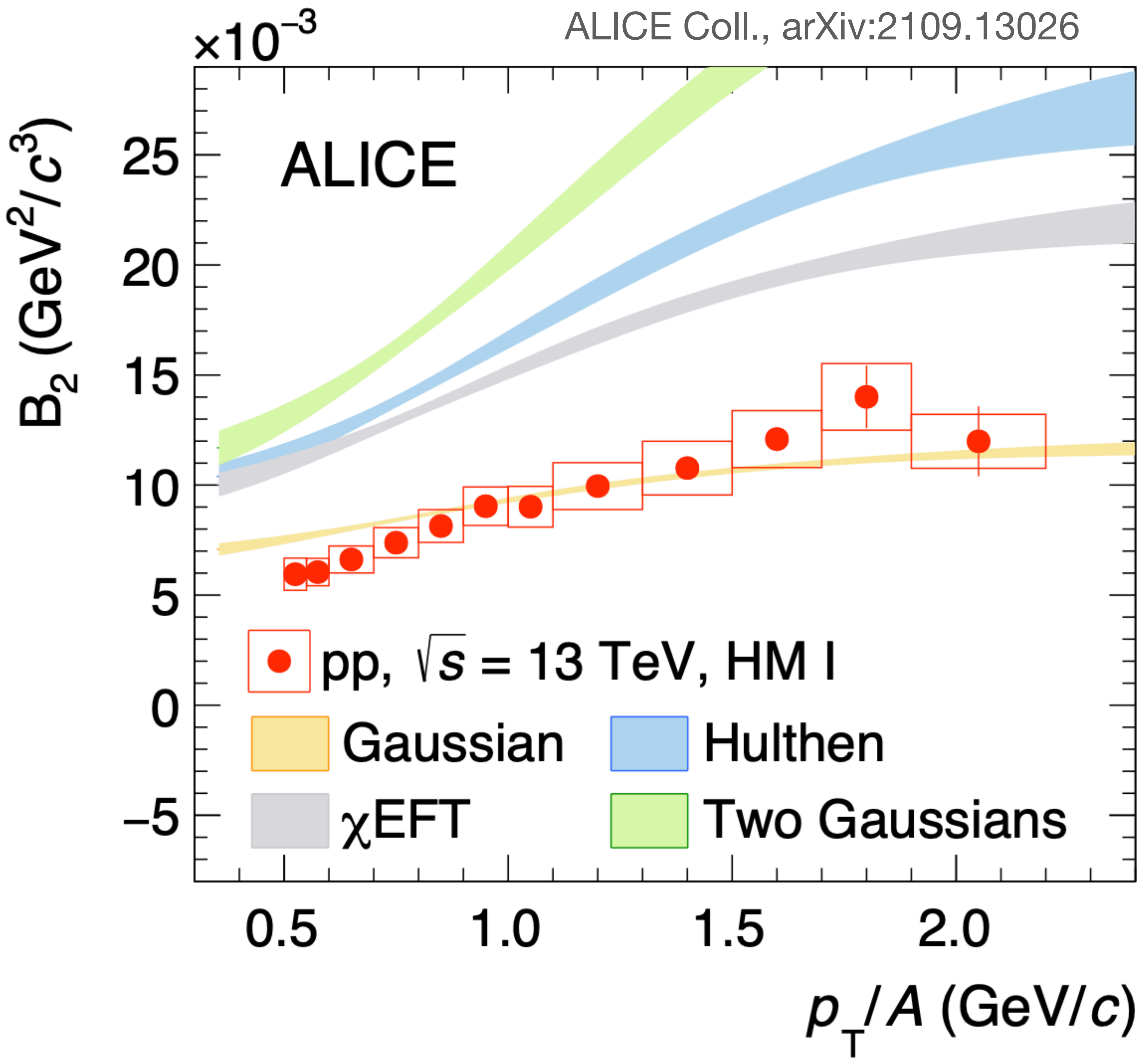




Coalescence parameter measurements

- The coalescence probability depends on the system size as it evolves smoothly with multiplicity.
- The dependence can be rather well described using theoretical B_A formula[1]:



$$B_A = \frac{2J_A+1}{2^A\sqrt{A}}\frac{1}{m^{A-1}}\left[\frac{2\pi}{R^2(m_T)+(r_A/2)^2}\right]^{\frac{3}{2}(A-1)}$$

- B_A here is given for a Gaussian wave function.
- But it can be written for other deuteron wave functions.

Gaussian wave function reproduces the data best!

[1] Blum et al. Phys. Rev. C 99 no. 4, 044913 (2019)