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The dark side of ALICE: from antinuclei interactions to dark matter searches in space

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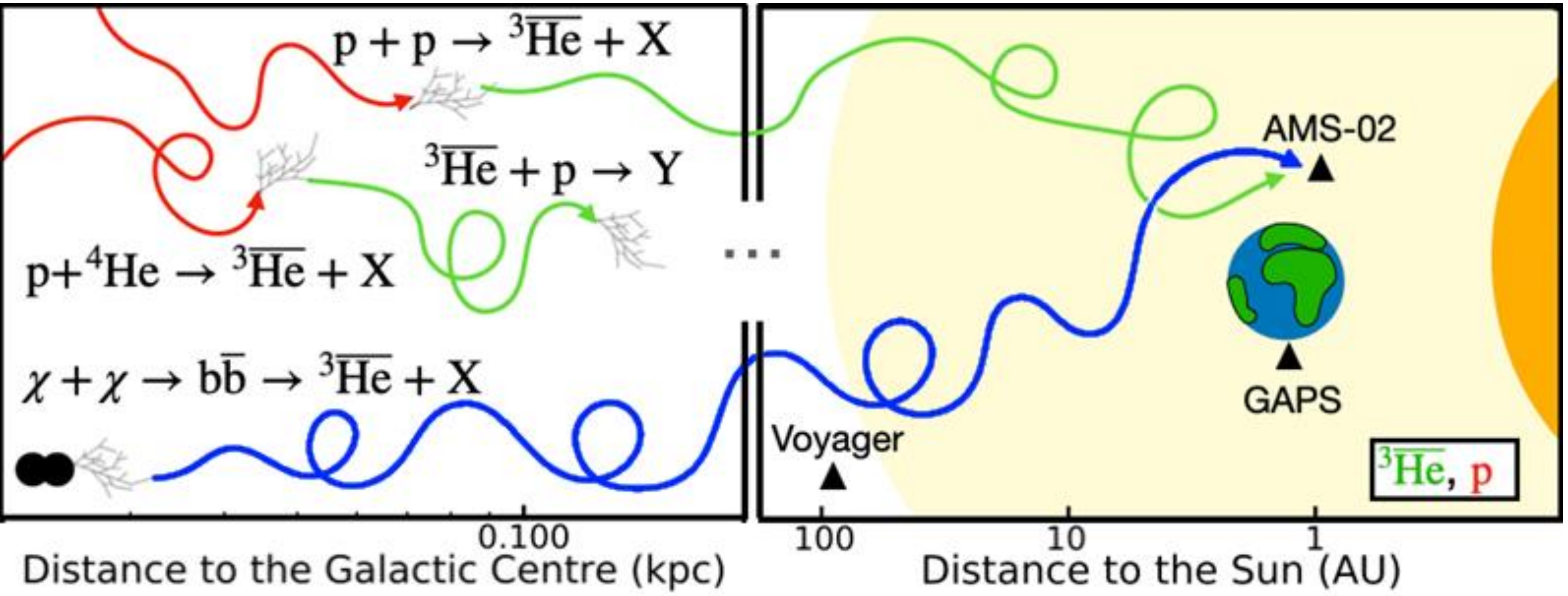
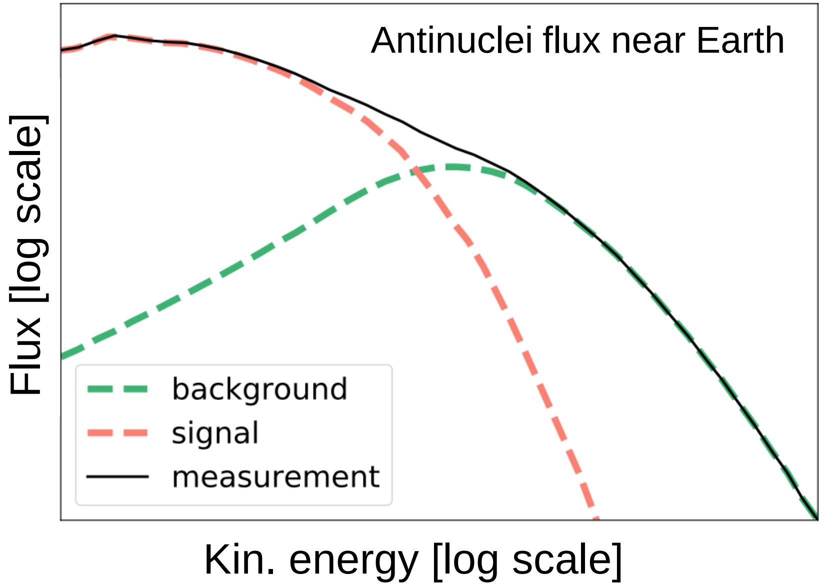
ALICE

Introduction

- Antinuclei in space (searched by AMS-02, GAPS) may result from:
  - **Dark matter annihilation (or decay) and/or segregated antimatter (signal)**
  - **Interaction of cosmic rays with the interstellar gas (background)**

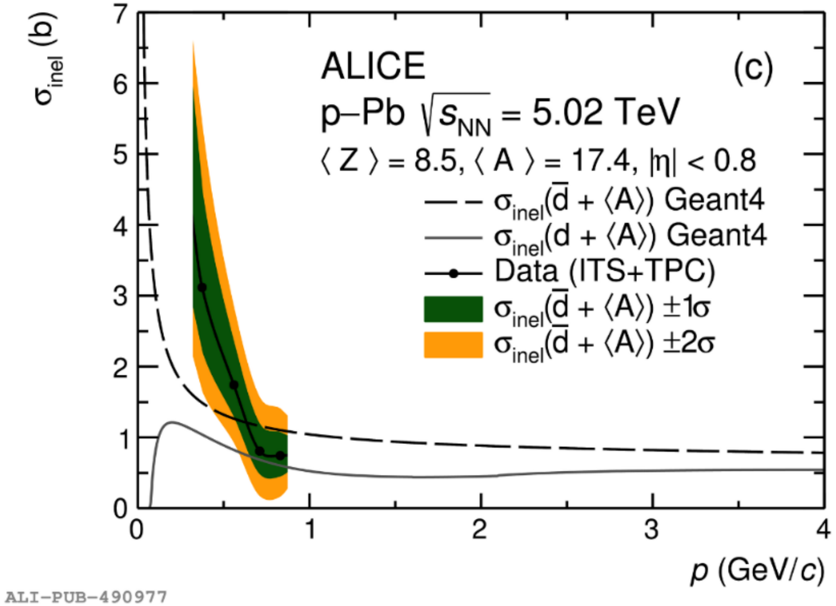
- Yields (for both channels) depend mainly on:
  - Antinuclei formation mechanisms
  - Particle transport in the galaxy (e.g. diffusion, convection)
  - **Attenuation due to inelastic scatterings with the interstellar gas**

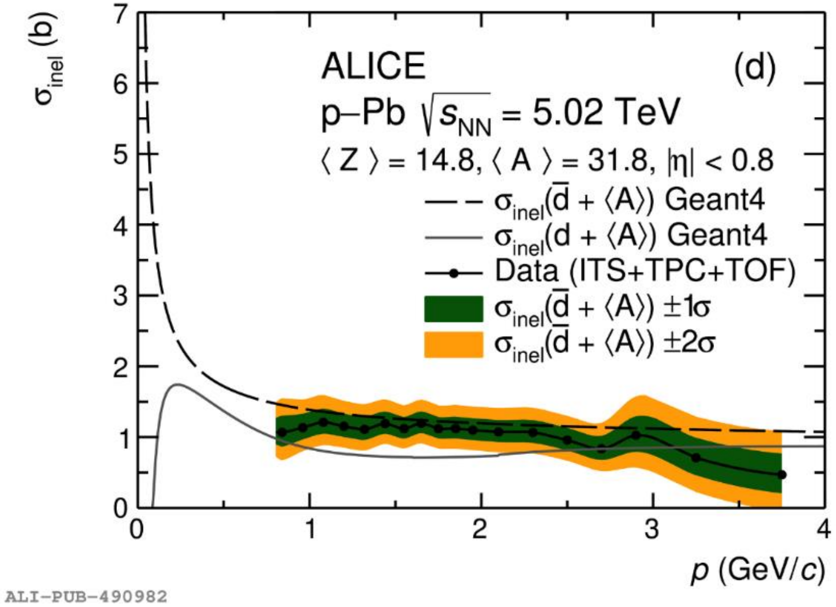




Antinuclei σ_{inel} measurements

- Antinuclei inel. cross section (σ_{inel}) with matter only poorly constrained since the 70s [1]
- Still today, σ_{inel} of antinuclei are mostly taken from some parametrizations based:
  - on a combination of $\sigma_{tot/el}(\bar{p}p)$ with Glauber model (GEANT 4) [2]
  - on a combination of antiproton and antineutron σ_{inel} [3]
- Recently ALICE started to contribute directly to this field by measuring σ_{inel} of $\bar{d}$, $^3\overline{He}$ and $^3\bar{H}$ [4-5]
- This talk focuses on A=3 results

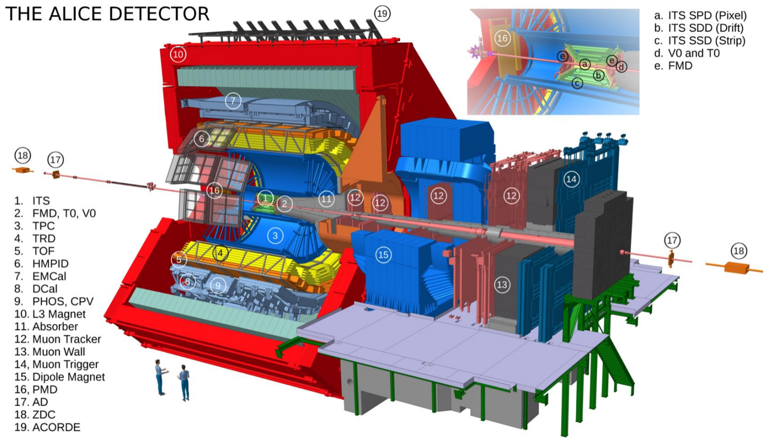


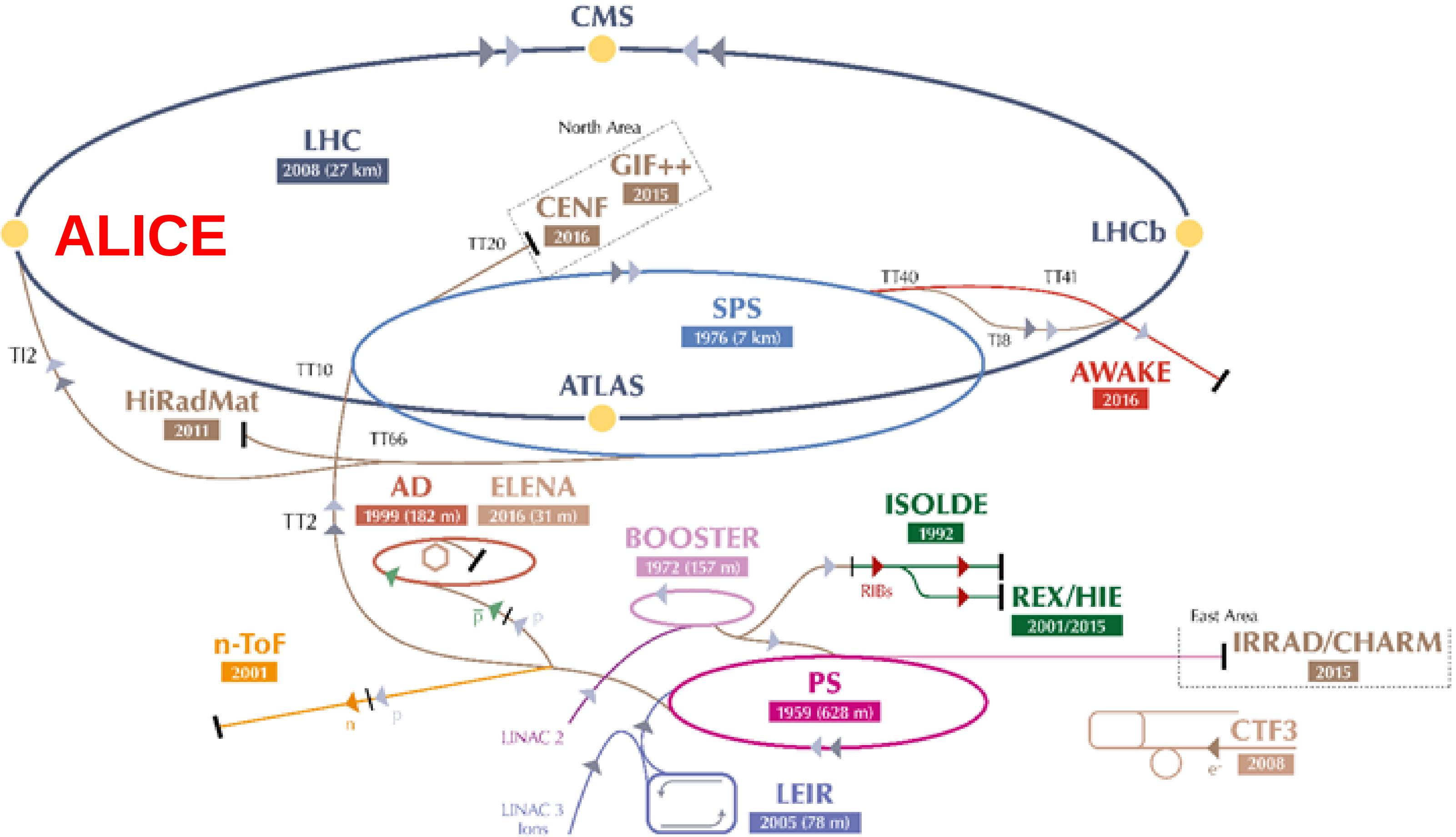


PRL 125 (2020) 162021

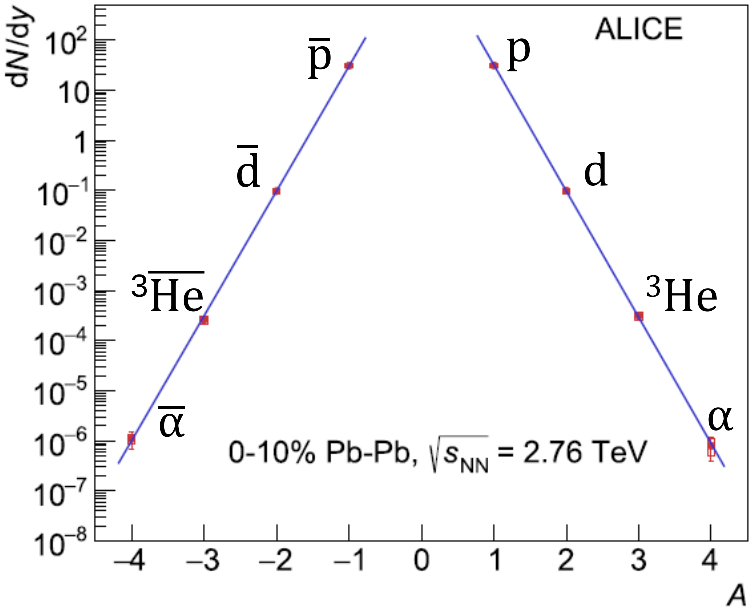
[1] S. P. Denisov et al., Nuclear Physics B 31 (1971) 253
[2] V. Uzhinsky et al., Physics Letters B 705 (2011) 235
[3] A. A. Moiseev, J. F. Ormes, Astroparticle Physics 6 (1997) 379
[4] PRL 125 (2020) 162021
[5] arxiv.org/2202,01549

The ALICE experiment





ALICE, PRC 97 (2018) 024615

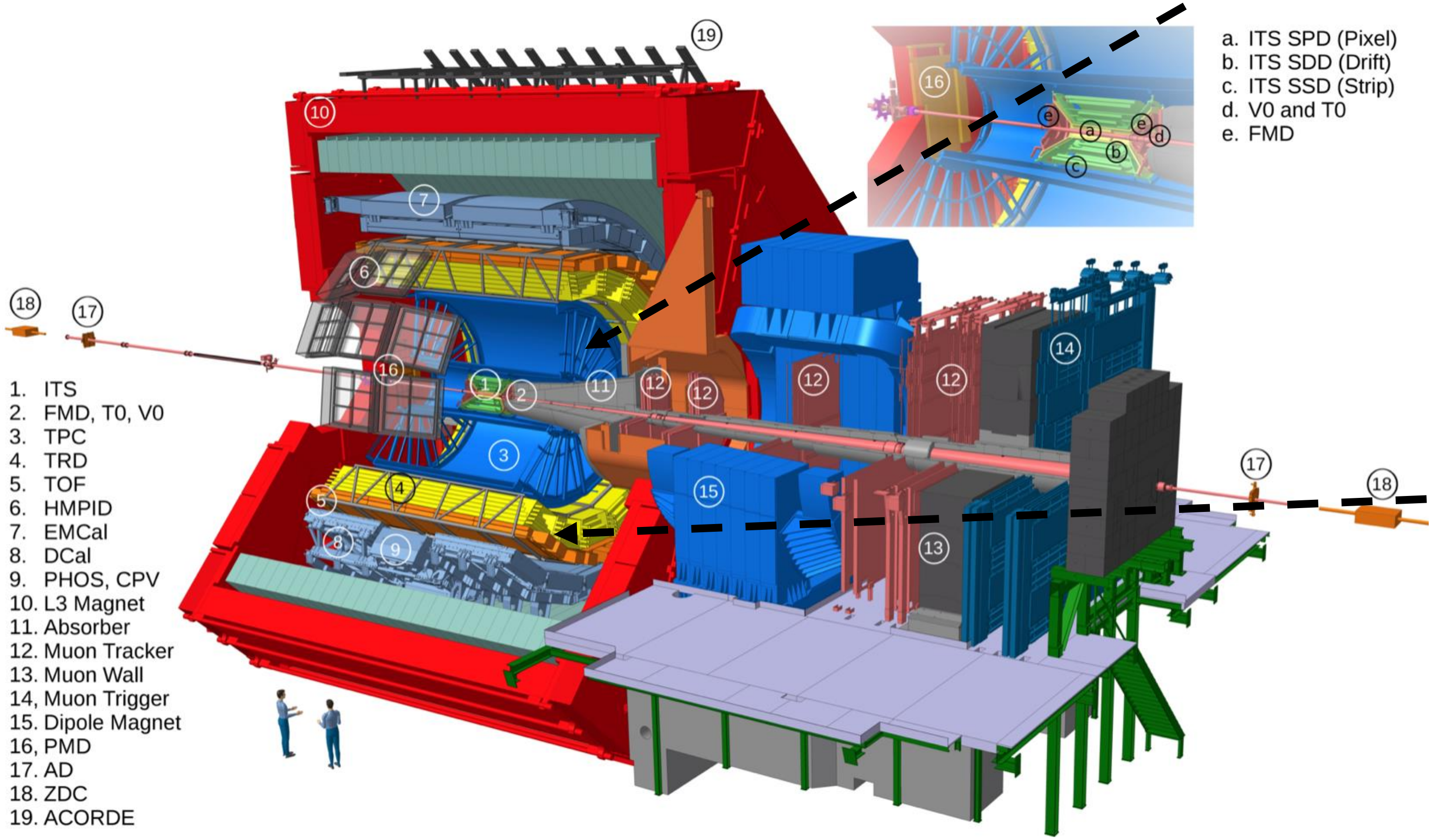


→ **Matter and antimatter nuclei are produced *almost* at the same rate at LHC**

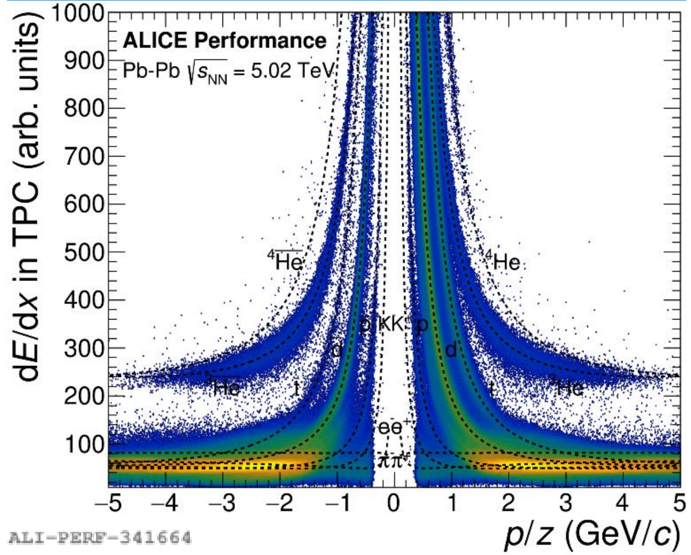
$N_A/N_p \sim 3 \cdot 10^{-3(A-1)}\ N_p$ (in Pb-Pb collisions at midrapidity)

See **L. Barioglio talk** [Heavy-Ions Session]: “Study of the dynamics of the production of light nuclei in small systems with ALICE”

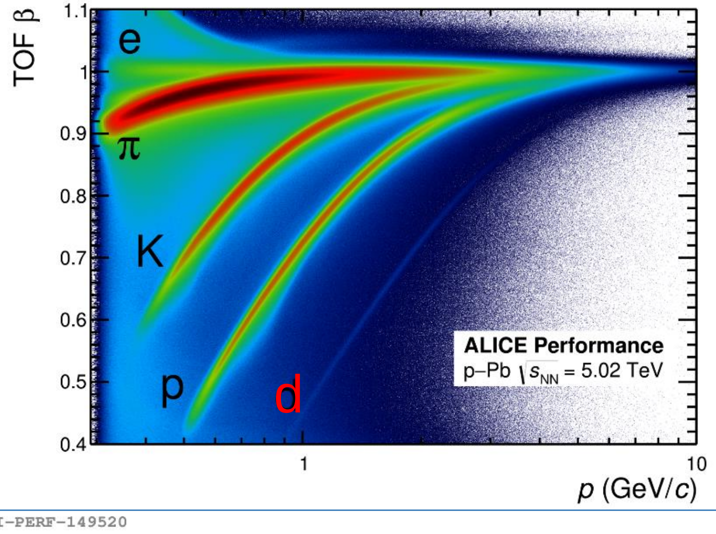
Particle Identification



TPC ($|\eta|<0.9$)
Gas-filled cylindrical barrel, MWPC readout
Tracking, PID (dE/dx)

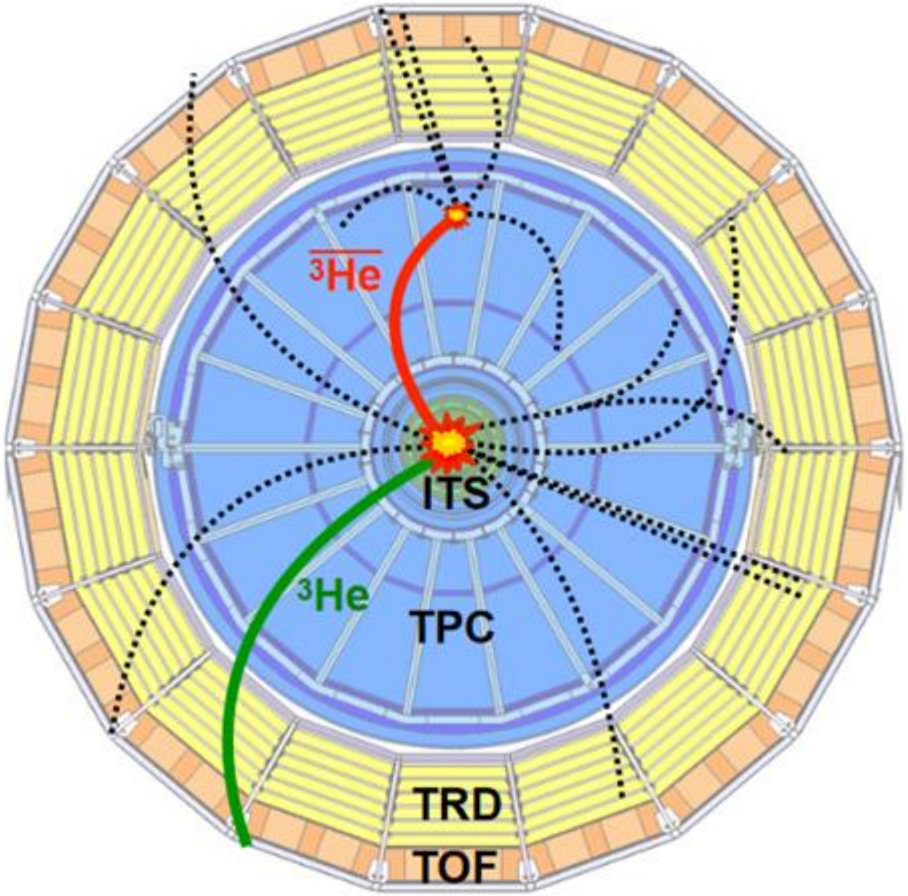


TOF ($|\eta|<0.9$), Multigap RPC, PID (time-of-flight)

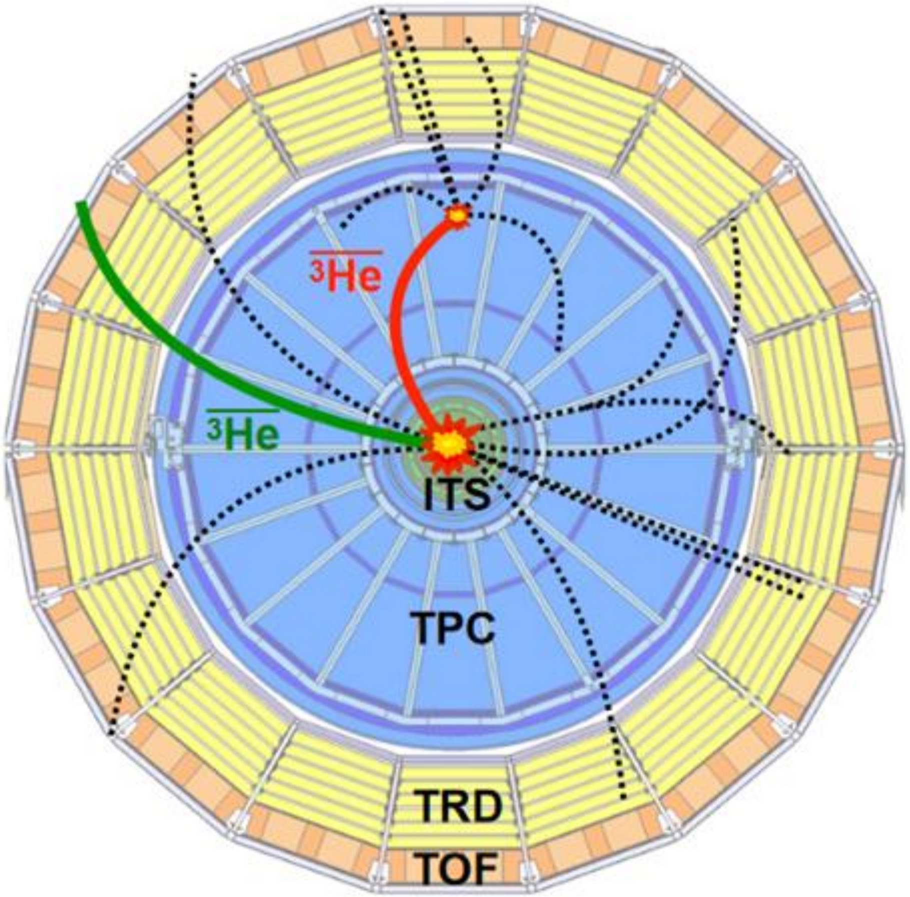


The two observables

(I) Antiparticle-to-particle ratio (raw)

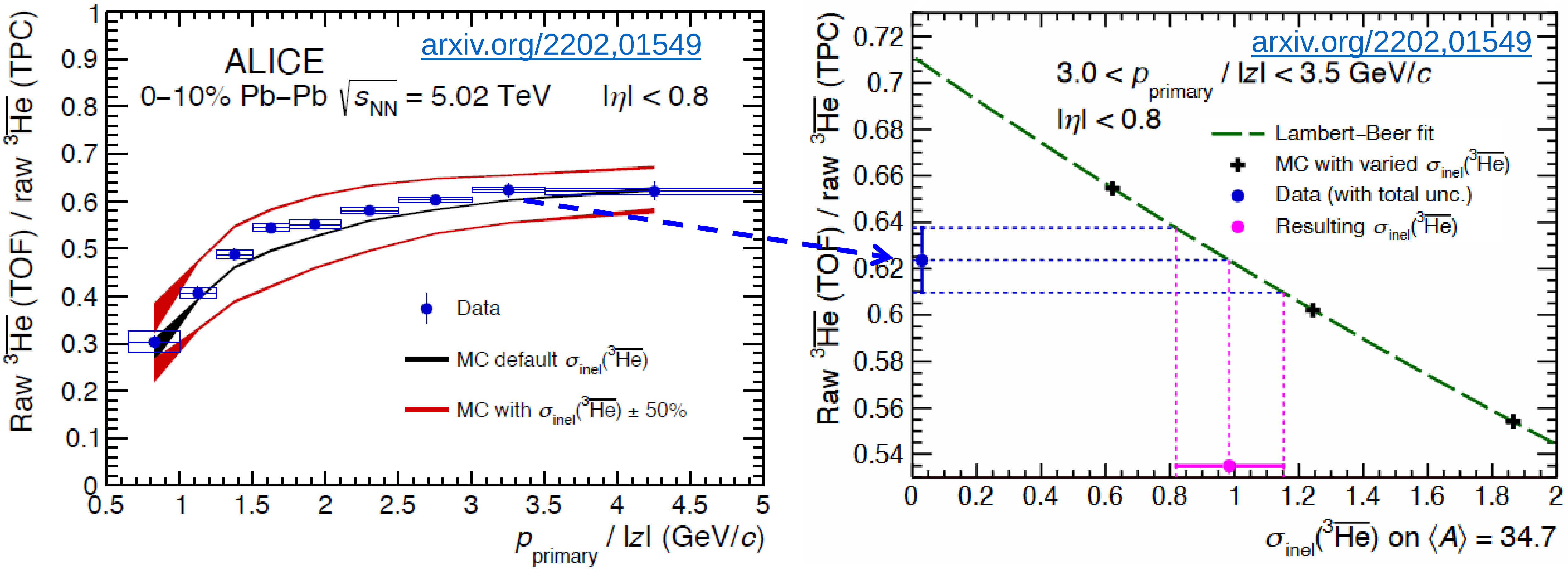


(II) TOF-to-TPC counts (raw)



Both provide consistent results

TOF-to-TPC counts ($^3\overline{\mathrm{He}}$)

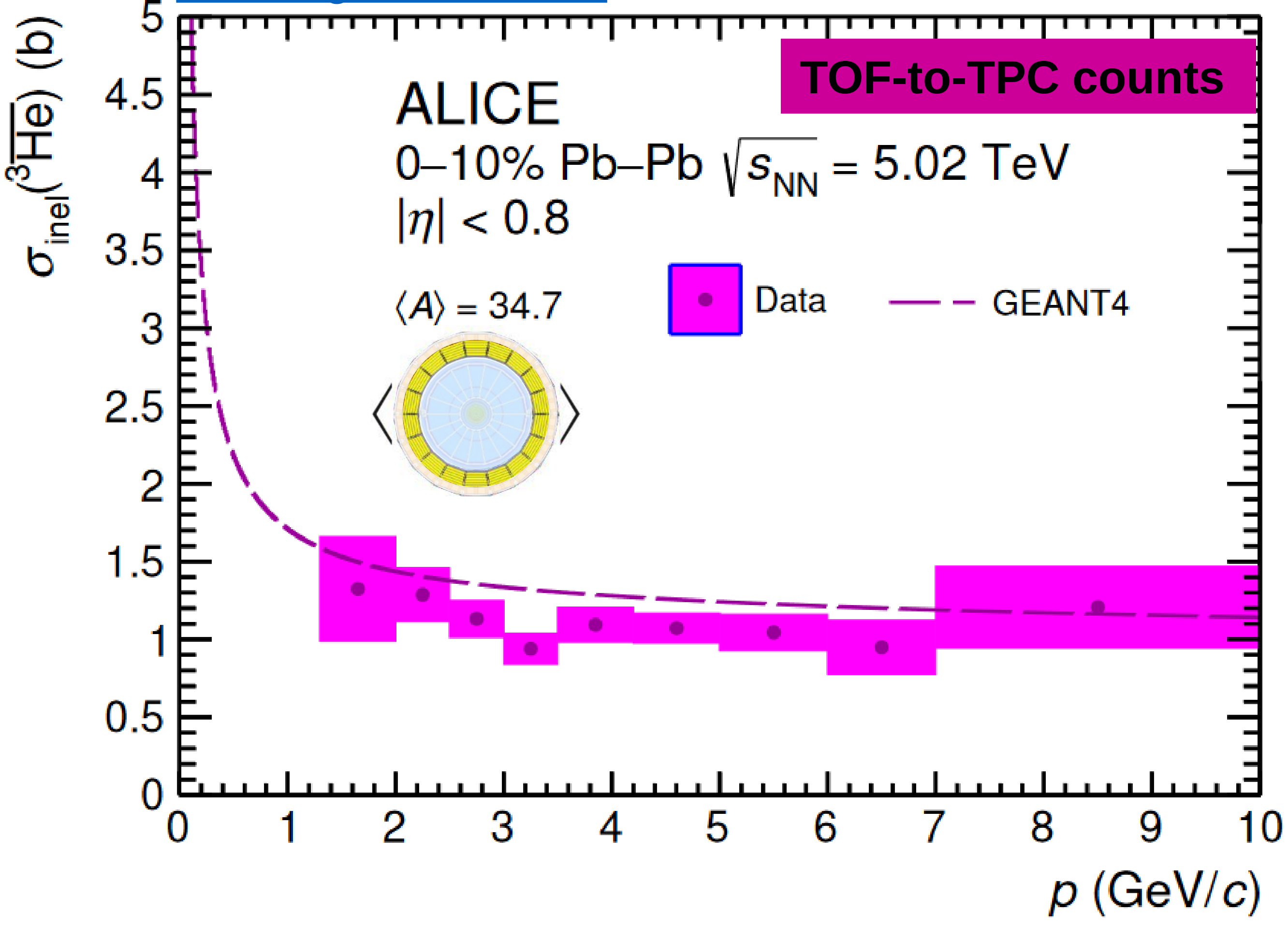


TOF-to-TPC counts are mainly sensitive to the variation of the inelastic cross section

MC default ≡ σ_{inel} fixed to the GEANT 4 parameterisation

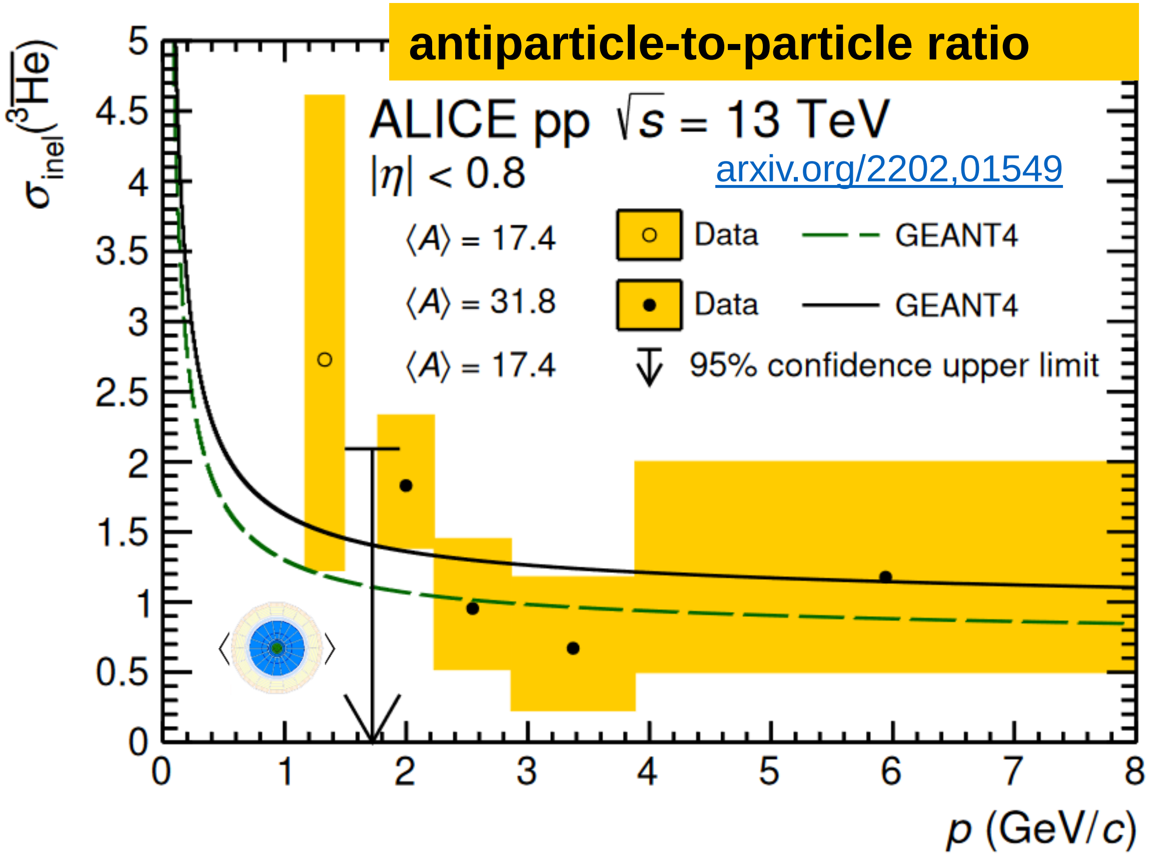
$\sigma_{inel}(^3\overline{He}\text{-A})$

arxiv.org/2202,01549

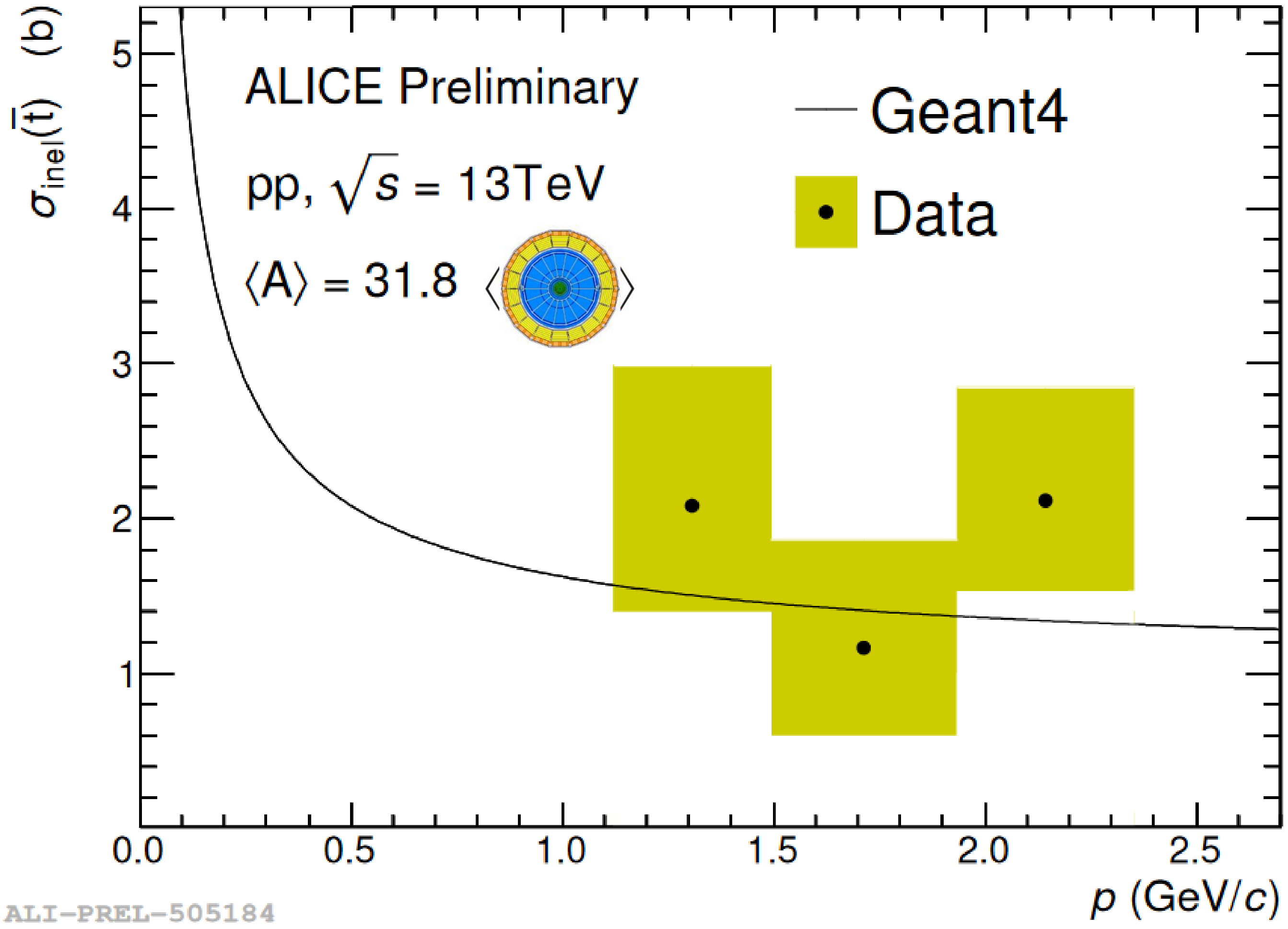


1st ever measurement of $^3\overline{He}$ absorption cross section in matter

Both observables provide comparable results:

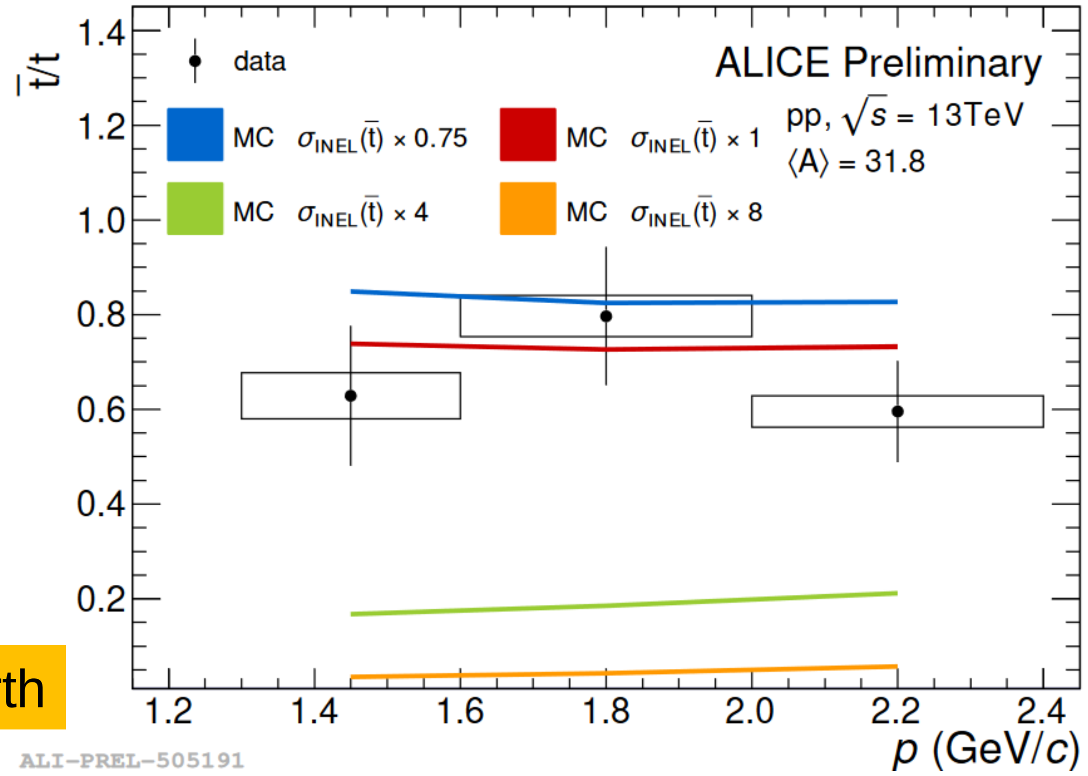


Antitriton inelastic cross section



1st ever measurement of $\bar{t}$ absorption cross section in matter

$\sigma_{inel}(\bar{t}\text{-A})$ in good agreement with GEANT 4, but with large uncertainties:



Next slides: impact of the measurement on $^{3}\overline{\text{He}}$ flux near Earth

$^{3}\overline{\mathrm{He}}$ source: Dark Matter (I)

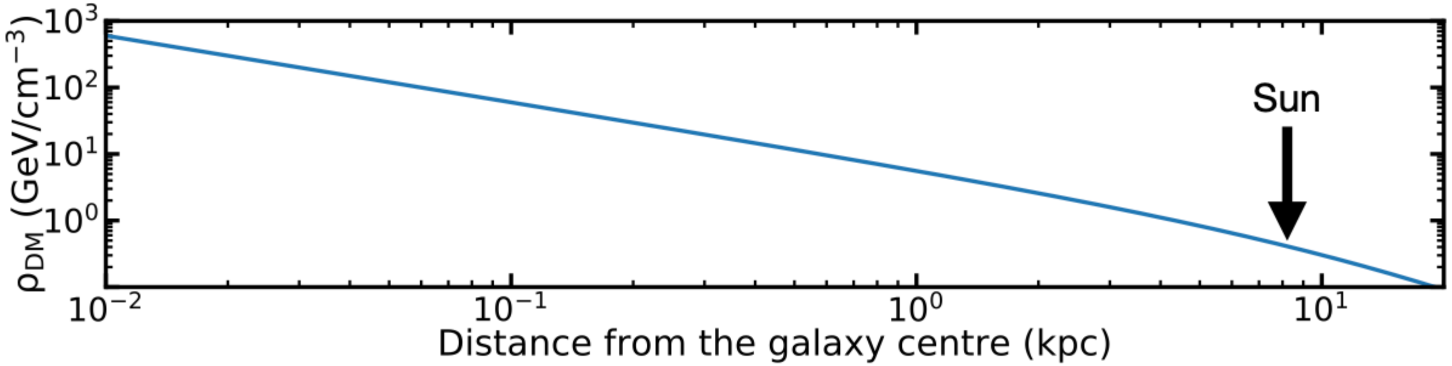
SOURCE(S) → PROPAGATION → ANNIHILATION

DM density distrib.

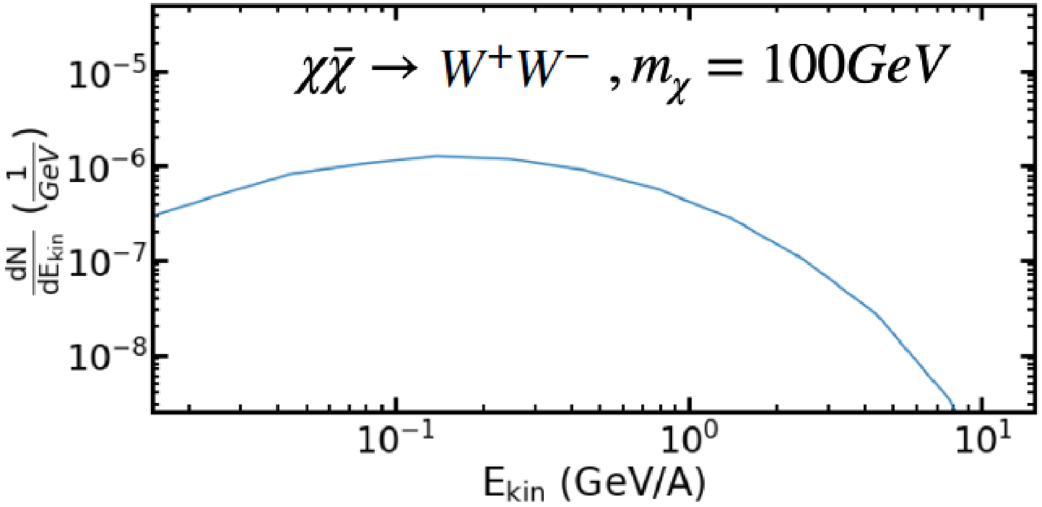
$$q(\mathbf{r}, E_{kin}) = \frac{1}{2}\frac{\rho^2_{\mathrm{DM}}(\mathbf{r})}{m^2_\chi}\langle\sigma v\rangle\frac{dN}{dE_{kin}}$$

Source function

$^{3}\overline{\mathrm{He}}$ spectrum



- Navarro-Frank-White profile for ρ_{DM} [1]
- WIMP candidates → W^+W^-
- $\langle\sigma v\rangle = 2.6 \cdot 10^{-26}\ cm^3\ s^{-1}$ [2]
- $^{3}\overline{\mathrm{He}}$ spectrum from [1]
  PYTHIA 8 + coalescence afterburner
  → peak at $E_{kin} \sim 0.1$ GeV/A

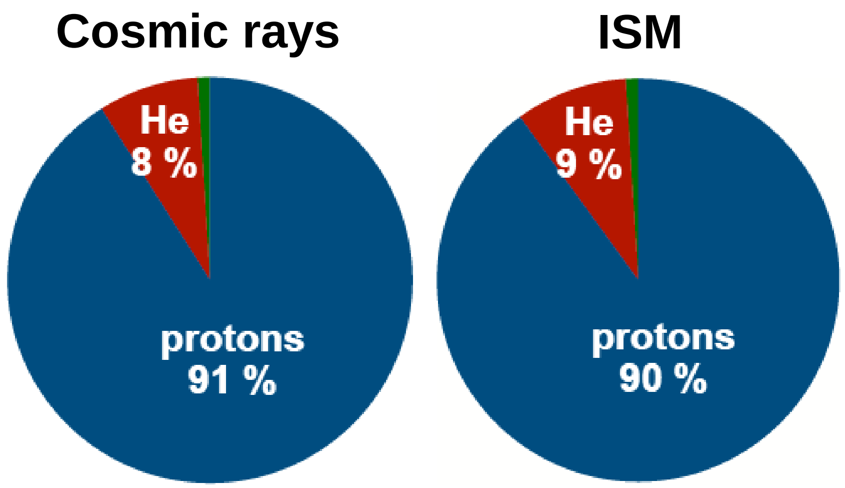


[1] E. Carlson et al., Phys Rev D 89 (2014) 076005
[2] M. Korsmeier, F. Donato, and N. Fornengo, Phys Rev 97 (2018) 103011

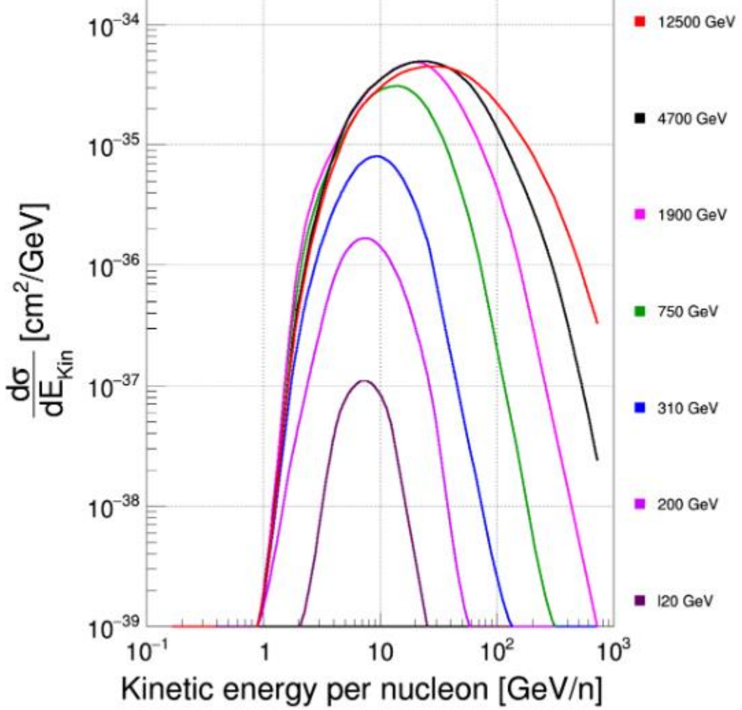
$^{3}\overline{\mathrm{He}}$ source: cosmic rays (II)

SOURCE(S) → PROPAGATION → ANNIHILATION

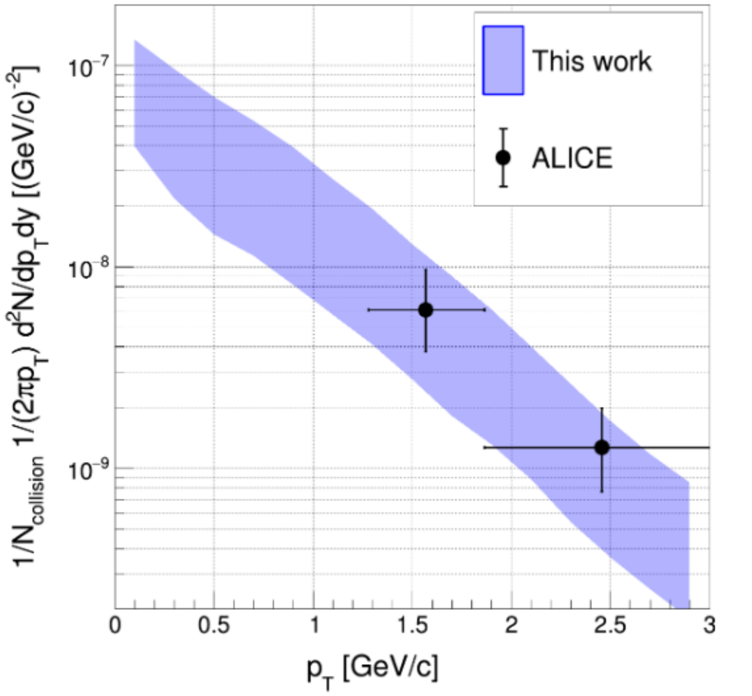
- 2nd $^{3}\overline{\mathrm{He}}$ source from interactions of cosmic rays with interstellar matter
- pp, p-^{4}He, ^{4}He-p, ^{4}He-^{4}He most relevant
- Production cross section in pp from [1]: EPOS LHC + coalescence afterburner
  Scaling factor $(A_T A_P)^{11/15}$ for the other collision systems



$^{3}\overline{\mathrm{He}}$ production XS in pp [1]



→ Validated with ALICE exp. data [1, 2]



[1] A. Shukla et al., Phys Rev D 102 (2020) 063004
[2] ALICE, Phys Rev C 97 (2018) 024615

Particle transport in the galaxy

SOURCE(S) → **PROPAGATION** → ANNIHILATION

Transport equation can be solved using GALPROP code [1]

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

Source Function | Propagation: diffusion, convection... | Fragmentation, annihilation

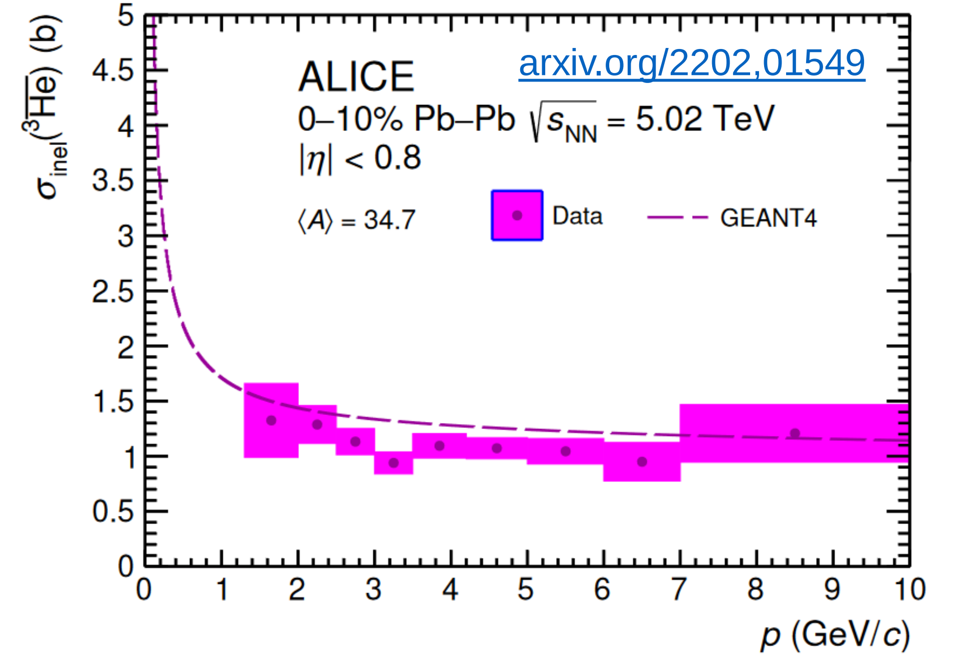
- Propagation parameters (common for all particles) are constrained from available cosmic ray measurements [2]
- Propagation from GALPROP down to the boundaries of Solar System
  → Heliosphere (shielding cosmic rays) needs to be taken into account
  → Force Field approximation [3] accounts for solar modulation

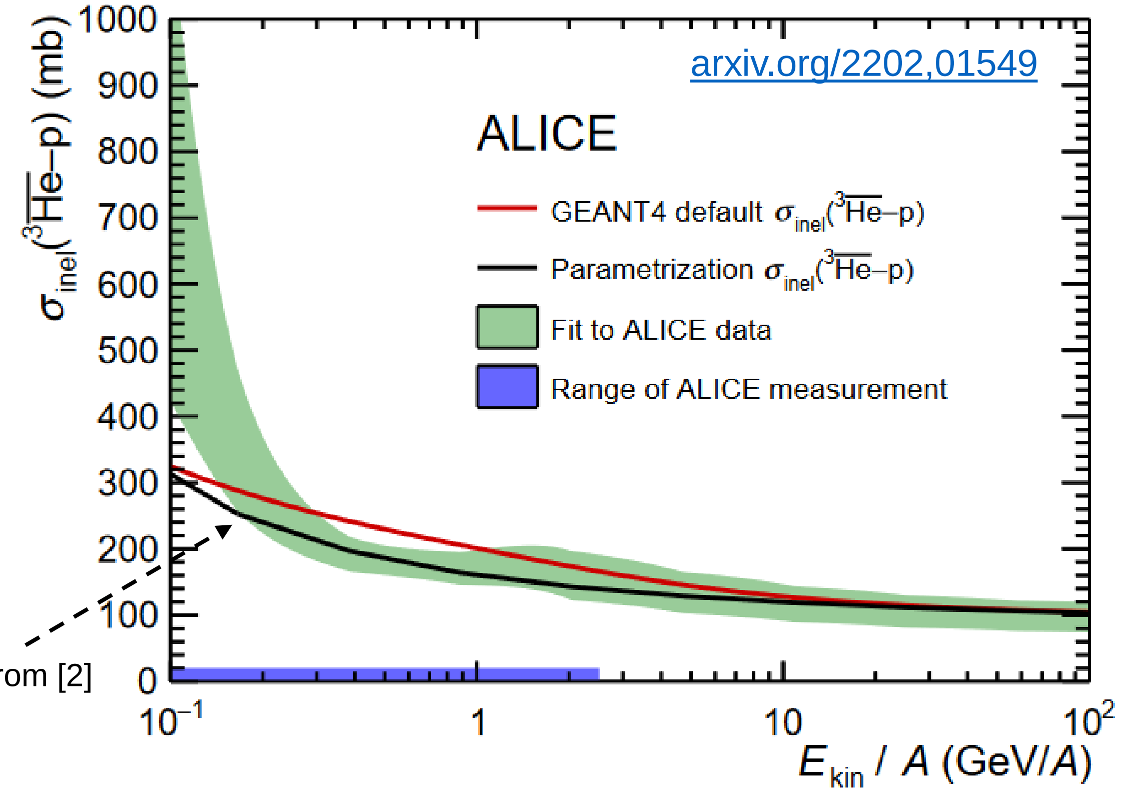
[1] https://galprop.stanford.edu/
[2] M. J. Boschini et al, Astrophys J Suppl 250 (2020) 27
[3] L. Gleeson, W. Axford, Astrophys J 154 (1968) 1011

$^{3}\overline{\mathrm{He}}$ annihilation

SOURCE(S) → PROPAGATION → ANNIHILATION

- $^{3}\overline{\mathrm{He}}$ nuclei may interact inelastically with ISM and get “absorbed”
- Proton and helium targets most relevant
- $\sigma_{inel}(^{3}\overline{\mathrm{He}}\text{-p})$ from GEANT 4 rescaled using ALICE experimental data
- 8% uncertainty from A scaling [1] is valid for all targets





Alternative param. from [2]

[1] V. Uzhinsky et al, Phys. Lett. B 705 (2011) 235
[2] M. Korsmeier, F. Donato, and N. Fornengo, Phys Rev 97 (2018) 103011

Results: $^3\overline{\mathrm{He}}$ flux near Earth

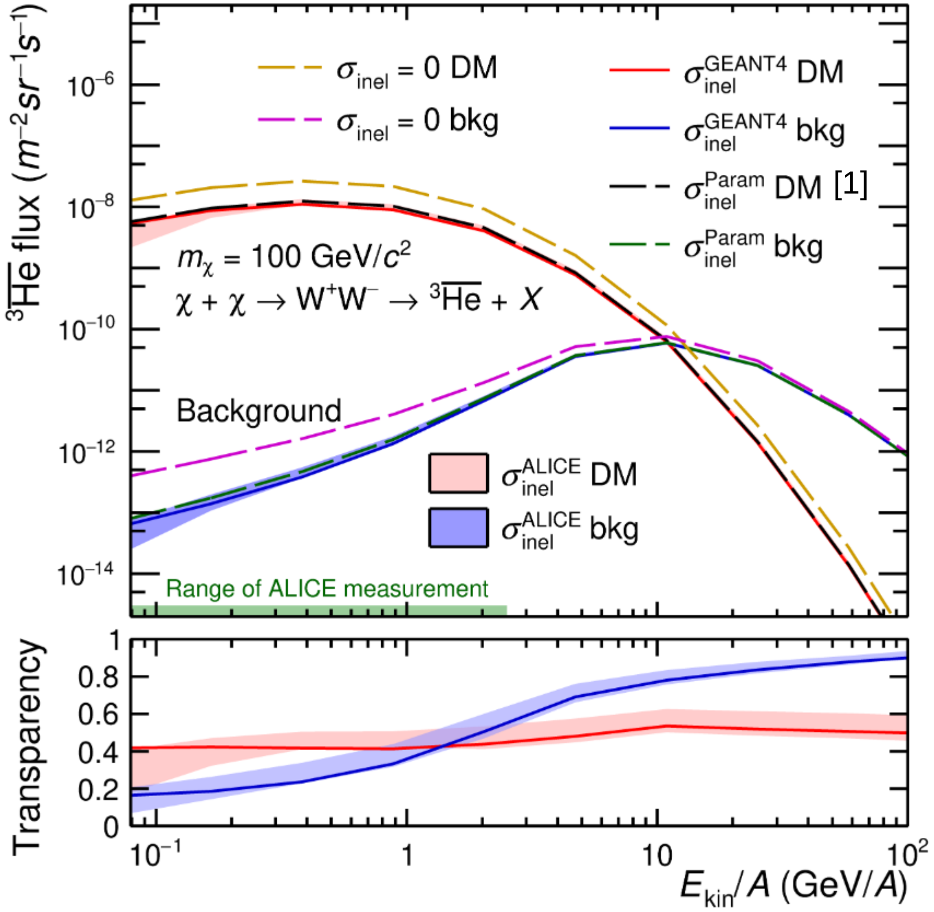
Alternative parametrizations of σ_{inel}(p) give similar results (*inside the heliosphere*)

Uncertainty only on σ_{inel} from ALICE exp. data*
***small compared to other unc. in the field**

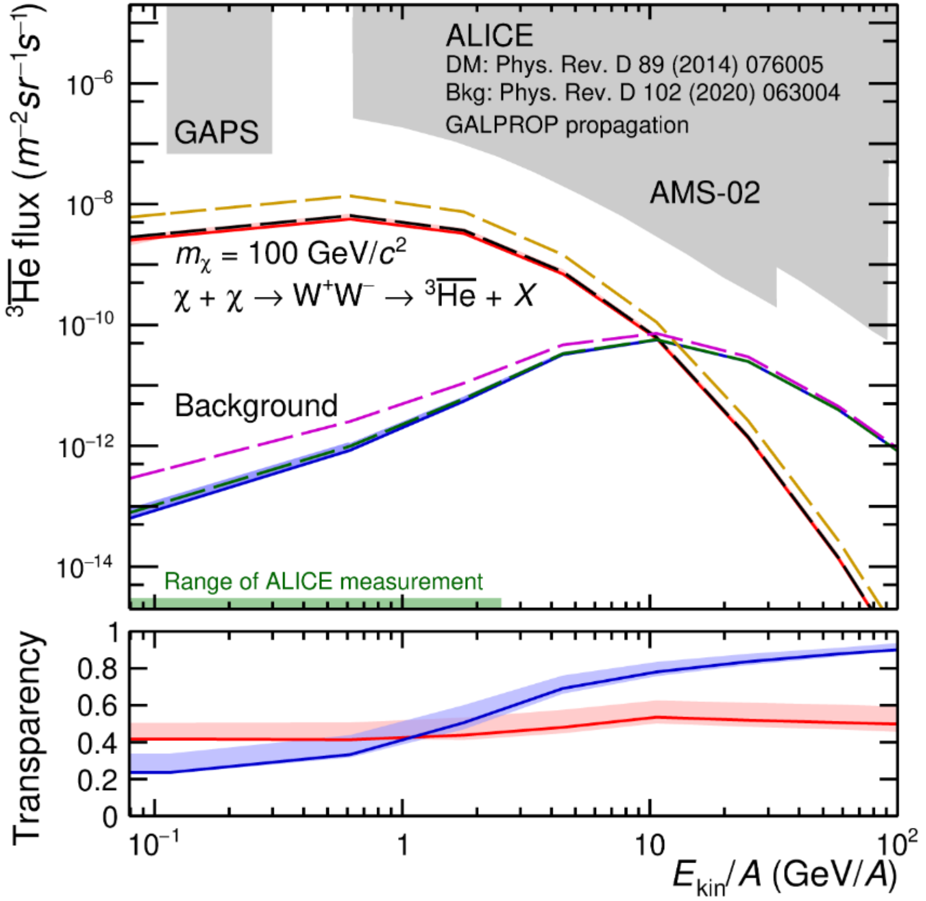
$^3\overline{\mathrm{He}}$ transparency (at low E_{kin}):
25% from CR interactions
50% from typical DM candidates

High transparency of the galaxy to $^3\overline{\mathrm{He}}$ flux

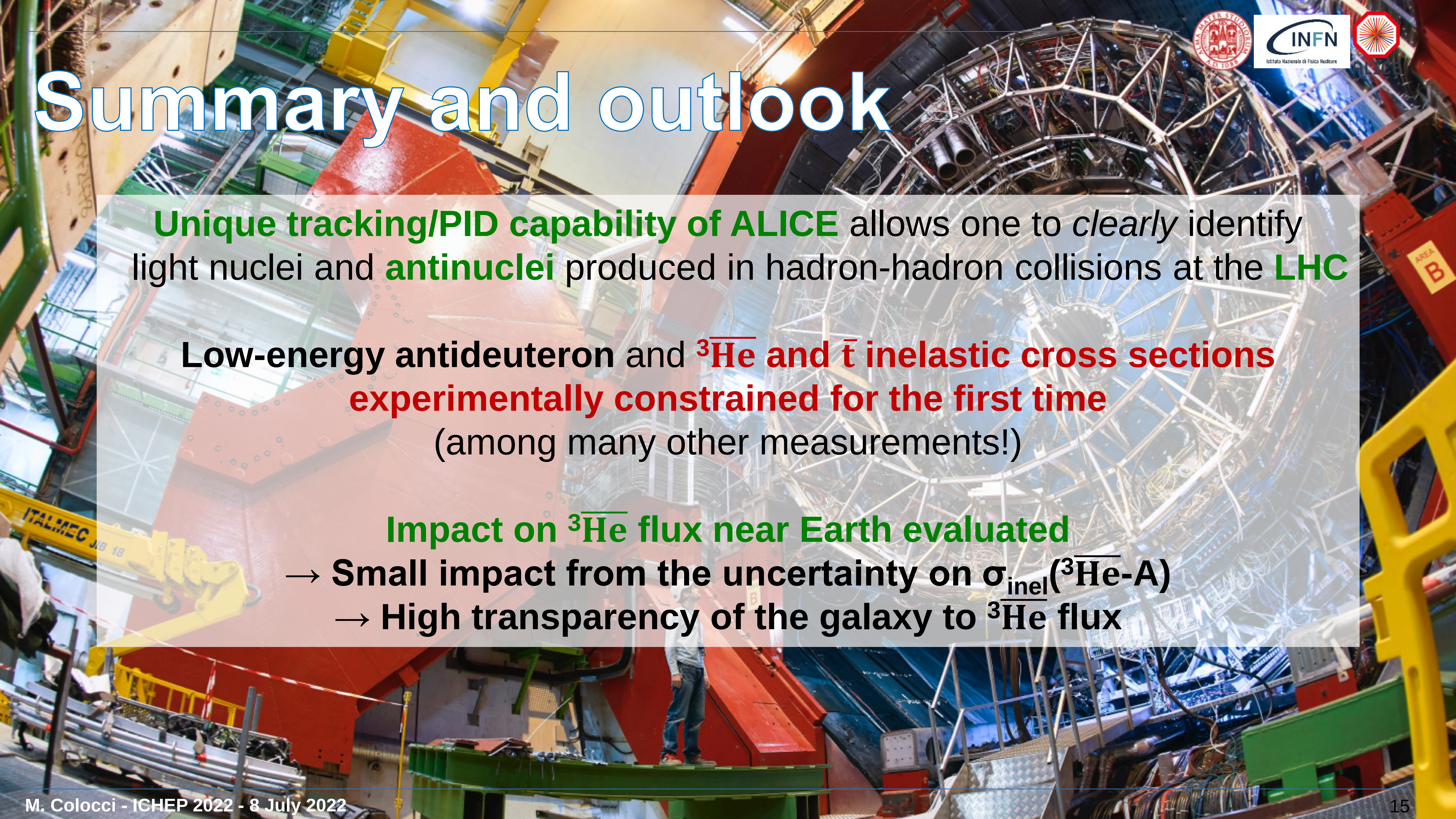
Local interstellar $^3\overline{\mathrm{He}}$ flux



Solar modulated $^3\overline{\mathrm{He}}$ flux



[1] M. Korsmeier, F. Donato, and N. Fornengo, Phys Rev 97 (2018) 103011



Summary and outlook

Unique tracking/PID capability of ALICE allows one to *clearly* identify light nuclei and **antinuclei** produced in hadron-hadron collisions at the **LHC**

Low-energy antideuteron and **$^{3}\overline{\text{He}}$ and $\bar{\text{t}}$ inelastic cross sections experimentally constrained for the first time**

(among many other measurements!)

Impact on $^{3}\overline{\text{He}}$ flux near Earth evaluated

→ Small impact from the uncertainty on σ_{inel}($^{3}\overline{\text{He}}$-A)

→ High transparency of the galaxy to $^{3}\overline{\text{He}}$ flux

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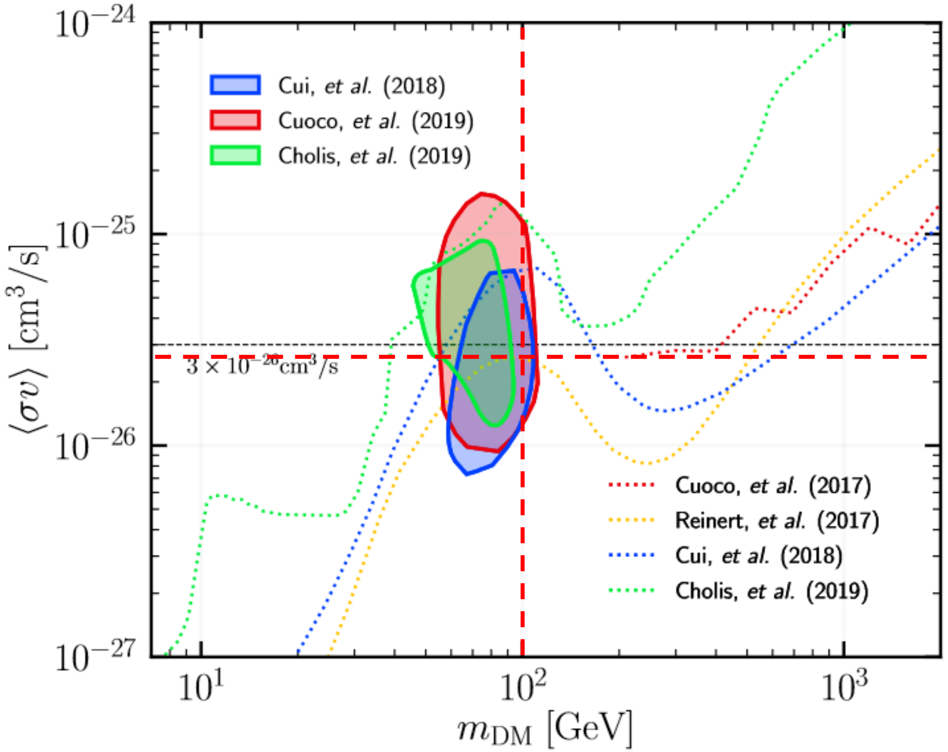
Thanks for your attention!

Back-up material

P. von Doetinchem, JCAP08 (2020) 035



L. Serksnyte et al, Phys. Rev. D 105 (2022) 083021