HADRON 2021

19TH INTERNATIONAL CONFERENCE ON HADRON SPECTROSCOPY AND STRUCTURE

Inelastic interaction of antinuclei with matter: first experimental constraints with ALICE

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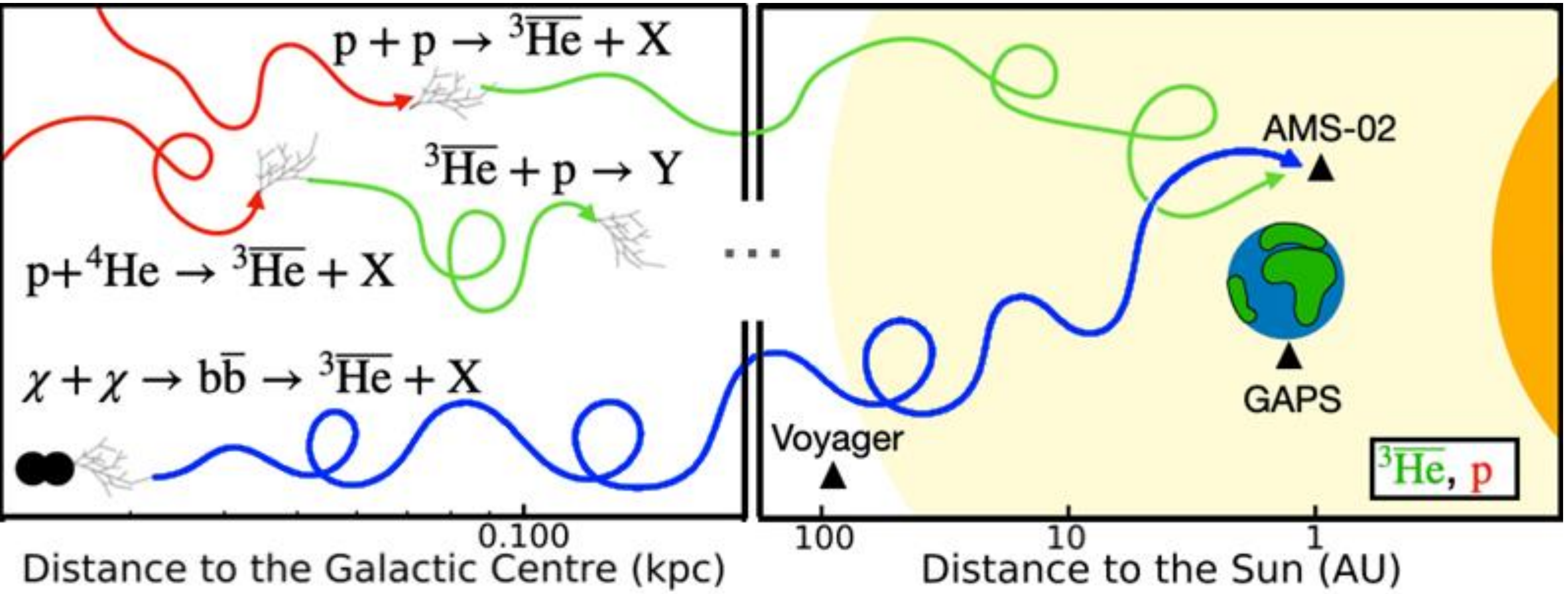
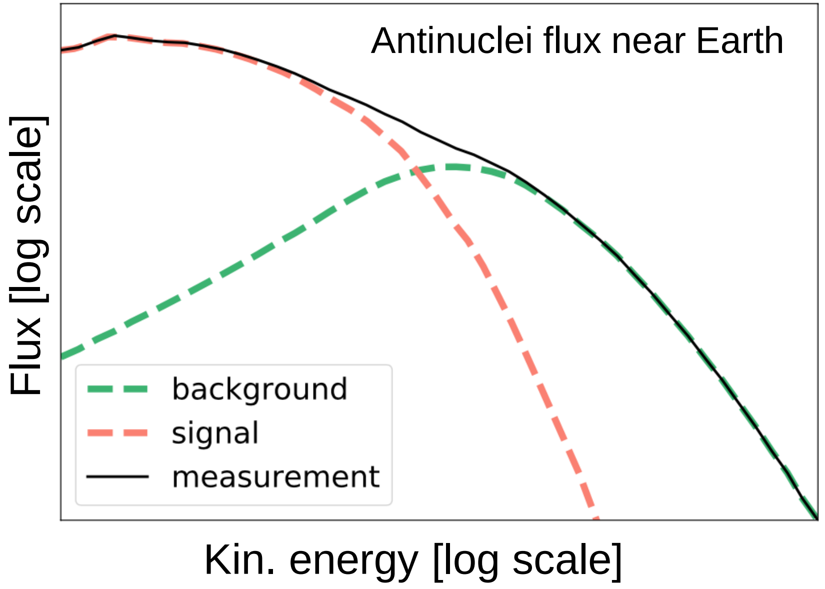
[1]CERN

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**





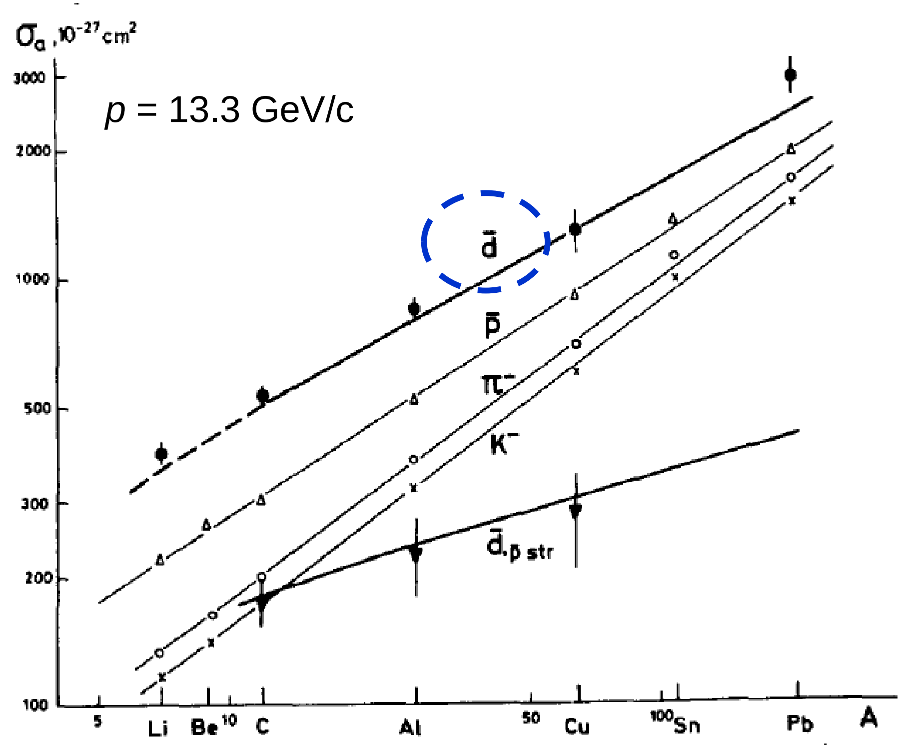
Antinuclei σ_{inel} measurements

Relevant inel. cross sections (σ_{inel}) only poorly constrained for antinuclei heavier than $\bar{p}$:

- **Antideuterons ($\bar{d}$) measured at U70 (Serpukhov) only at *p* = (13.3, 25) GeV/c [1]**
- **No measurements for $^{3}\overline{He}$ performed so far**

Still today, σ_{inel} of antinuclei are mostly taken from some parametrizations based e.g.

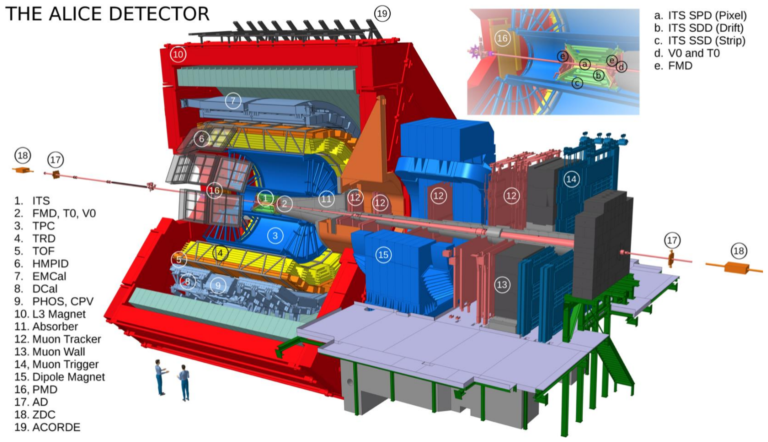
- on a combination of $\sigma_{tot/el}(\bar{p}p)$ with Glauber model (Geant4) [2]
- on a combination of antiproton and antineutron σ_{inel} [3]

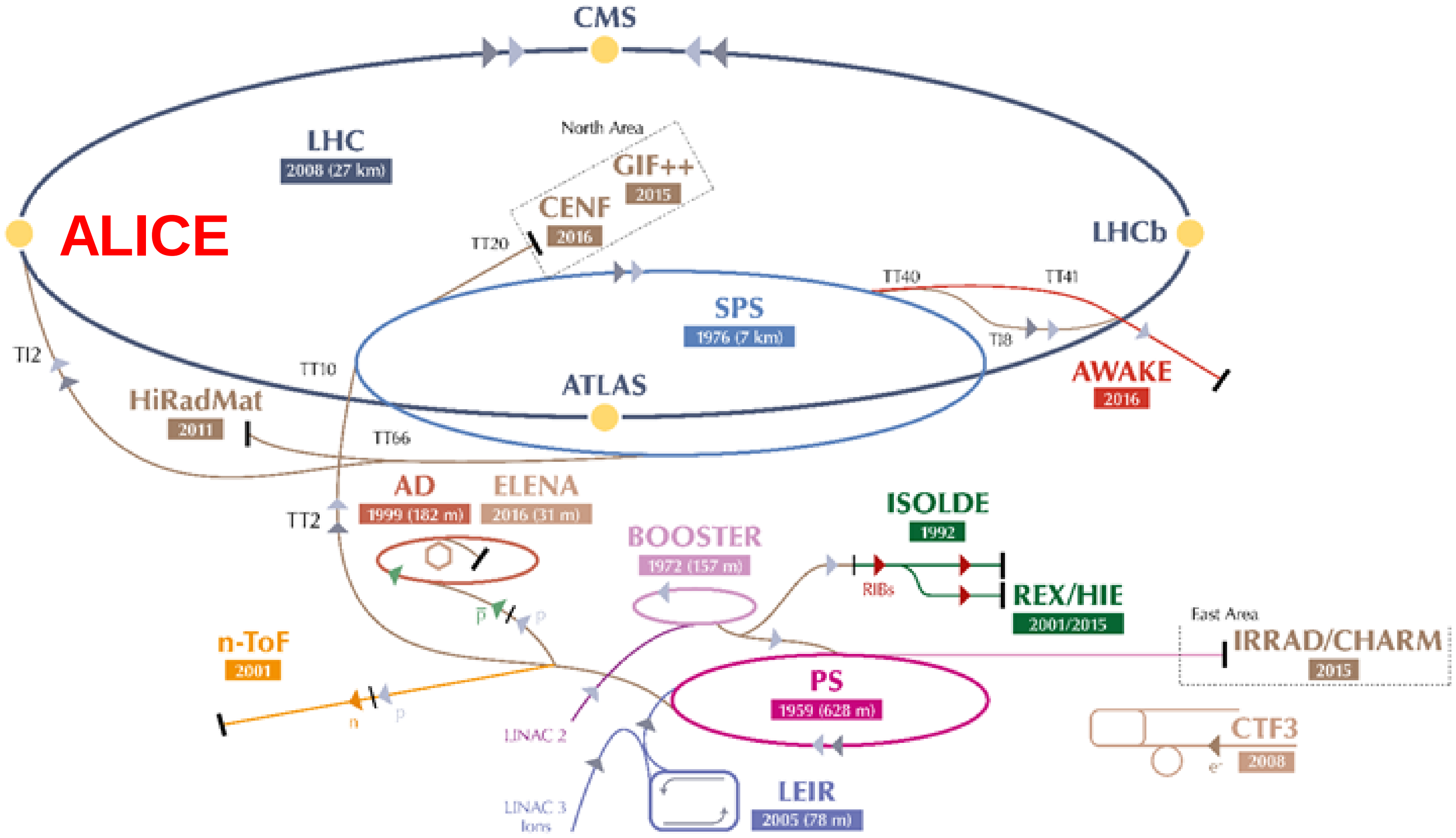


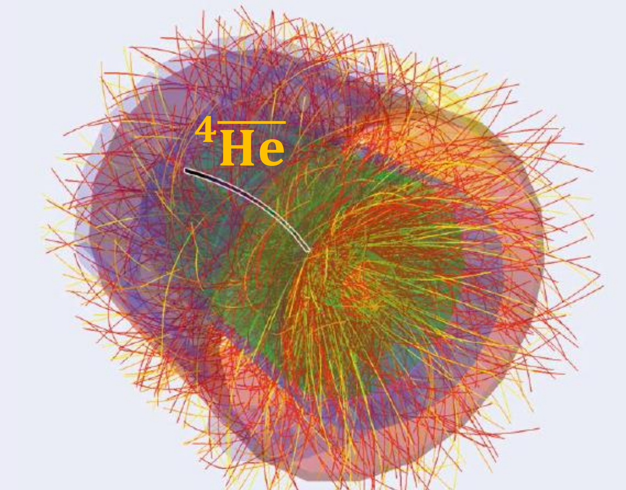
[1] Denisov et al., Nuclear Physics B 31 (1971) 253

[1] Denisov et al., Nuclear Physics B 31 (1971) 253
[2] Uzhinsky et al., Physics Letters B 705 (2011) 235
[3] Moiseev, Ormes, Astroparticle Physics 6 (1997) 379

The ALICE experiment



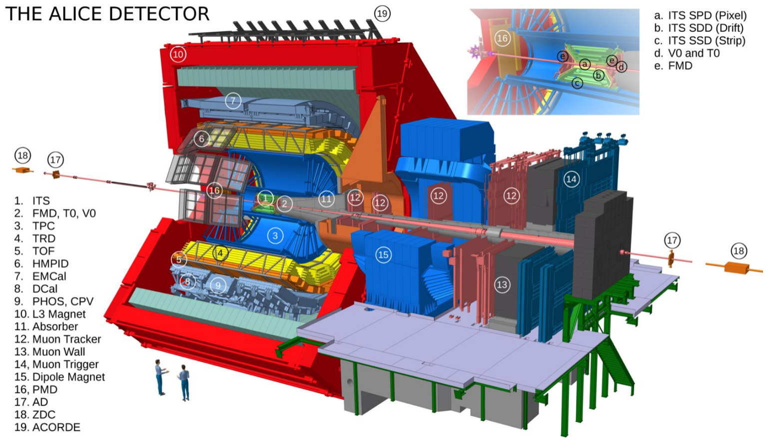


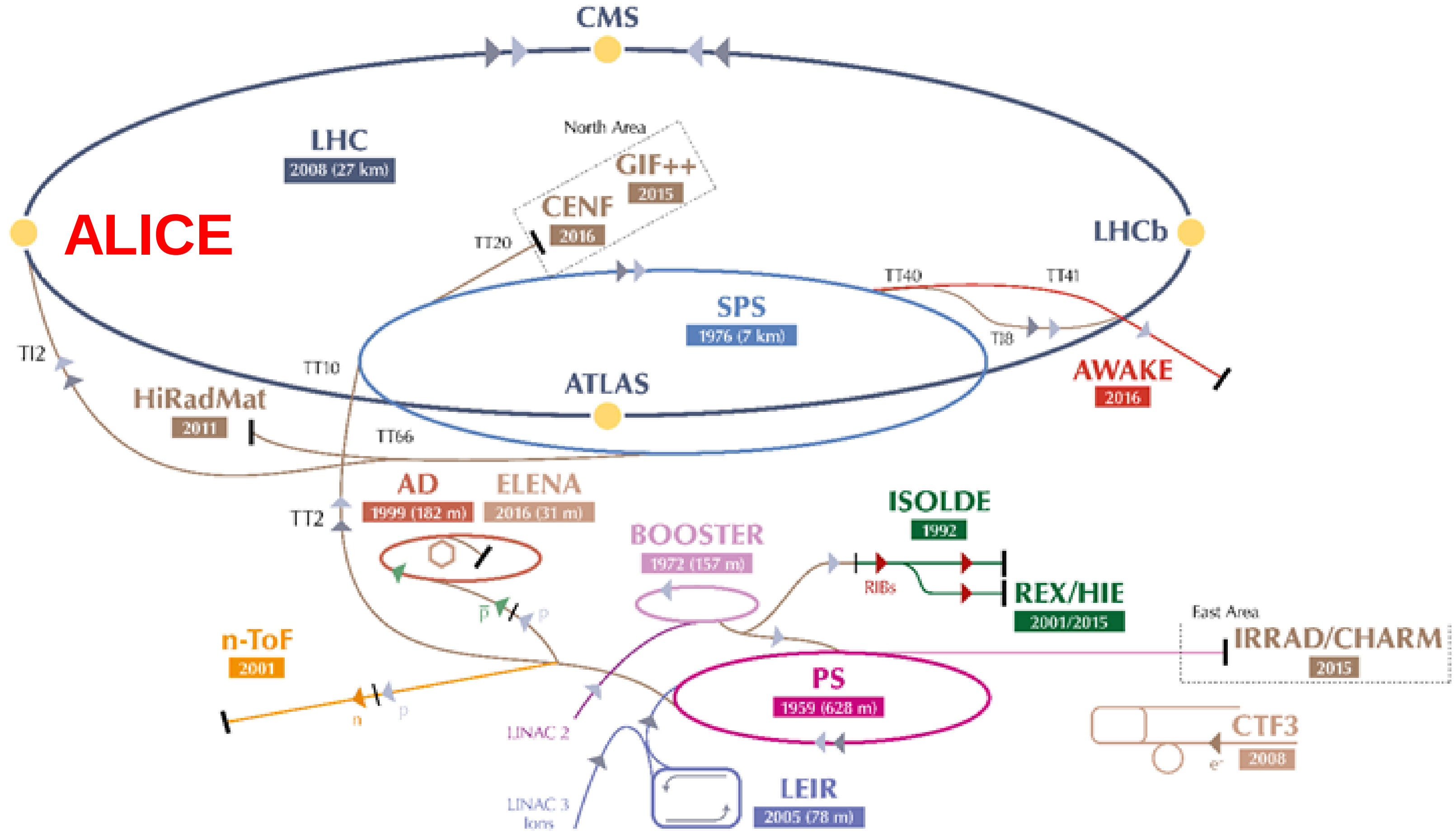


[*CERN Courier*, Sept. 2015]

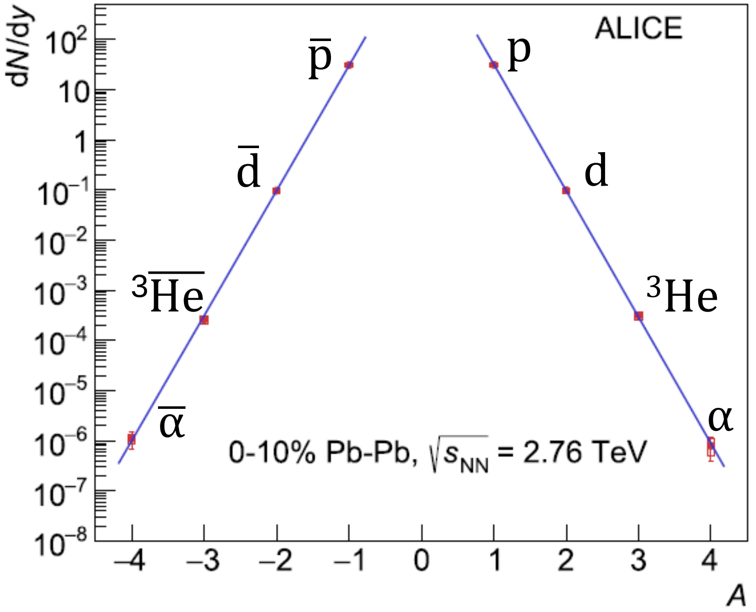
The unique tracking and PID capabilities of ALICE allow for the detection of light nuclei and antinuclei produced at the LHC

The ALICE experiment





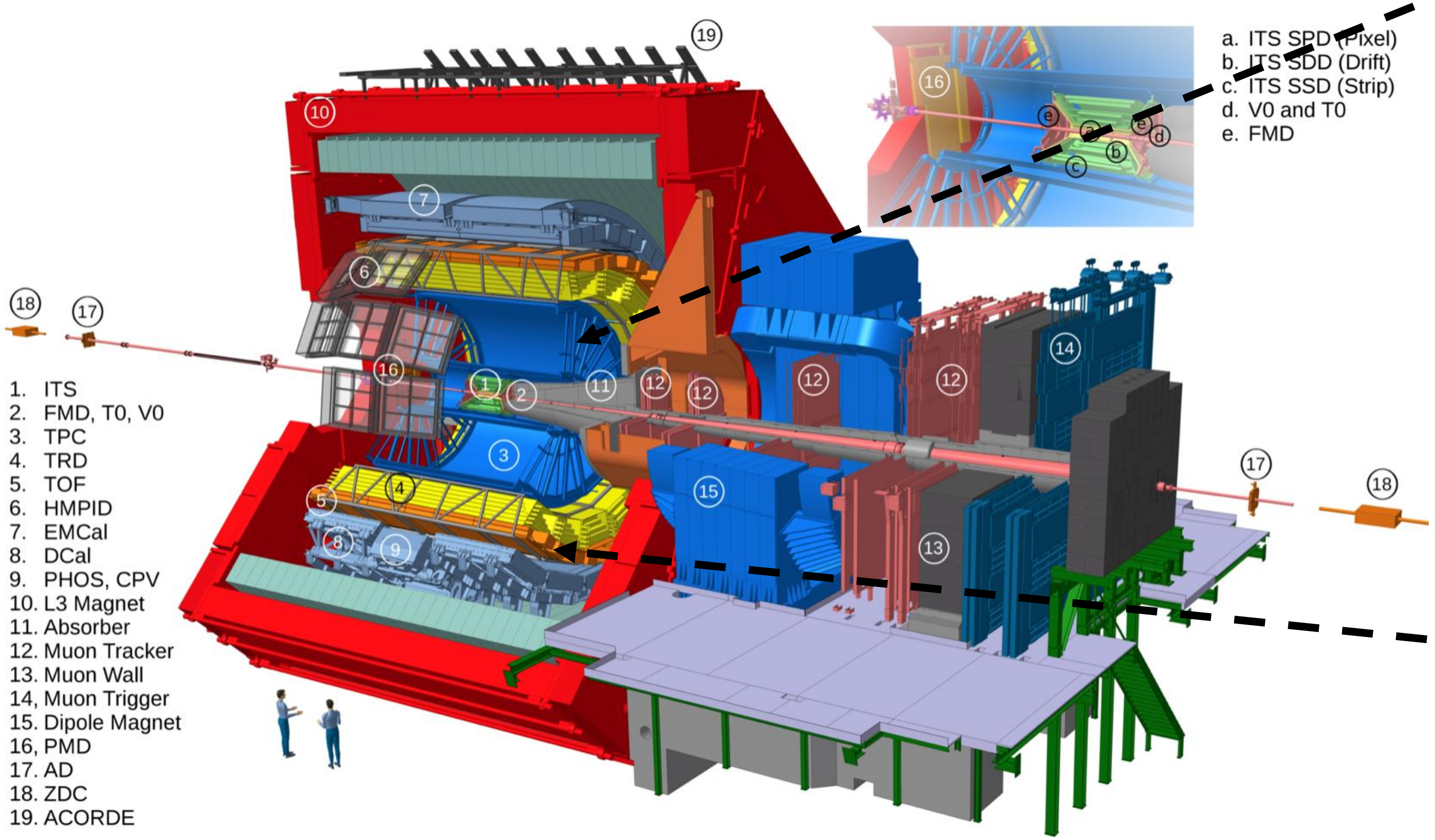
ALICE, PRC 97 (2018) 024615



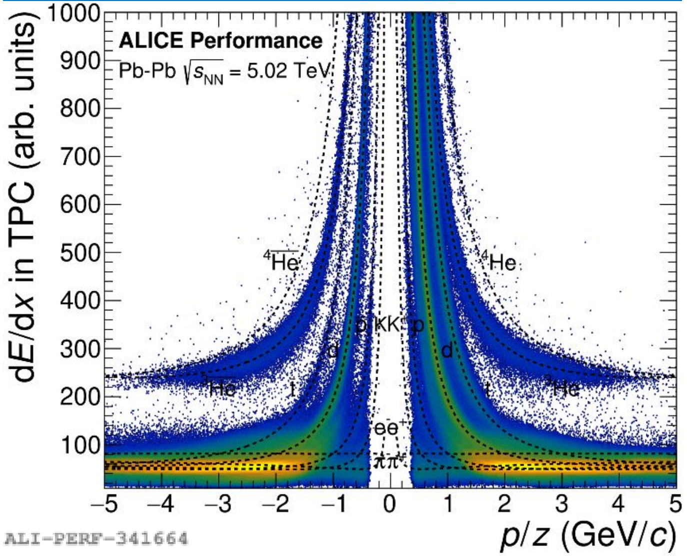
→ **Matter and antimatter nuclei are produced *almost* at the same rate at LHC**

$N_A/N_p \sim 3\cdot10^{-3(A-1)}\ N_p$ (in Pb-Pb collisions at mid-rapidity)

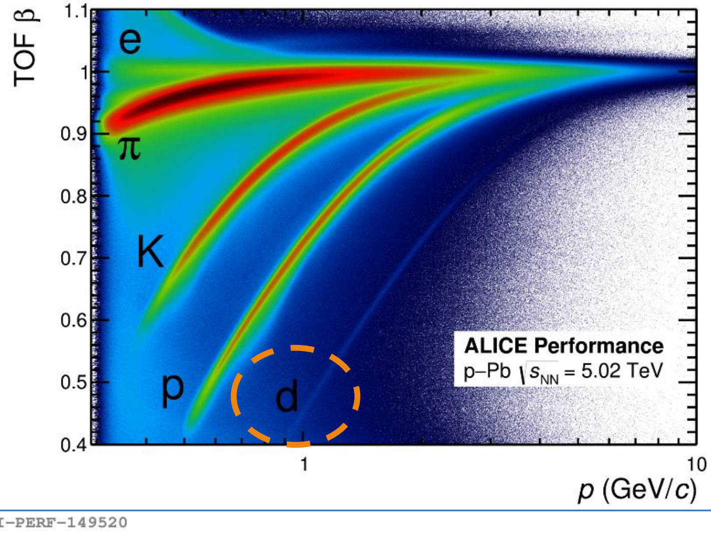
Particle Identification



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



TOF (|η|<0.9), Multigap RPC, PID (time-of-flight)



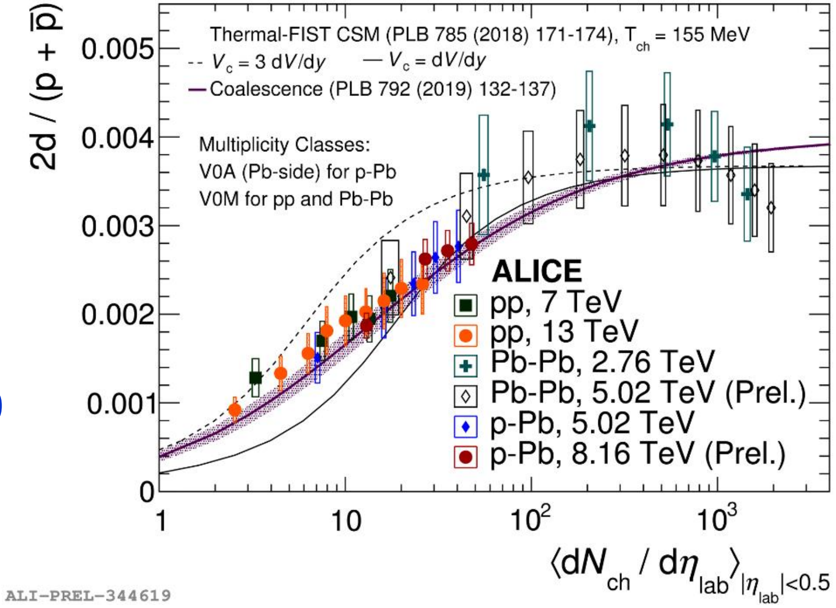
Run 1 (2009-2013)	Run 2 (2015-2018)
pp 0.9, 2.76, 7, 8 TeV	pp 5.02, 13 TeV
p-Pb 5.02	p-Pb 5.02, 8.16 TeV
Pb-Pb 2.76 TeV	Pb-Pb 5.02 TeV Xe-Xe 5.44 TeV

(Anti)nuclei measurements in ALICE *(among many others)*

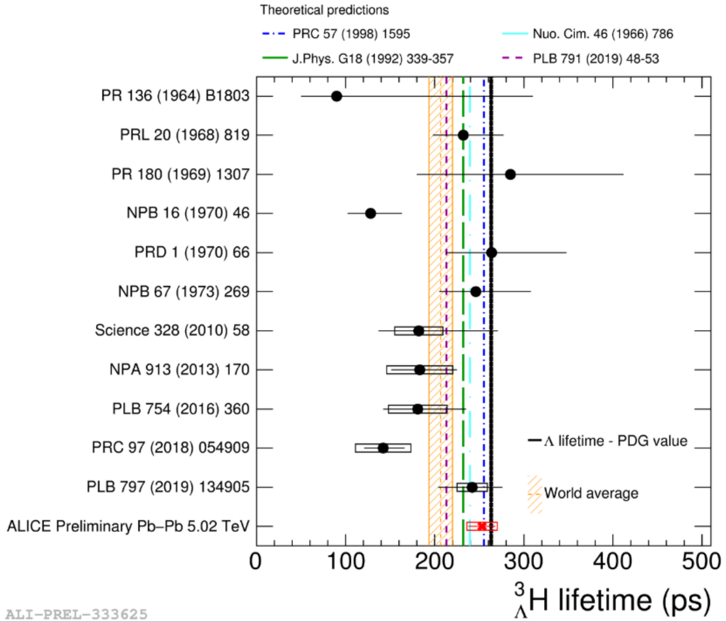
- Production yields of d, t, ^{3}He, ^{4}He, $^3_\Lambda$H and of the corresponding antiparticles measured in all collision systems/energies at LHC
  → to better understand (anti)nucleisynthesis mechanisms in hadron-hadron collisions: Hadron coalescence vs SHM

- *Highest precision* **determination of $^3_\Lambda$H lifetime and of $^3_\Lambda$H separation energy** (B_Λ) → See F. Mazzaschi talk, Fri. 30/09

- *Unprecedented* experimental constrains on the **mass difference between matter-antimatter nuclei**

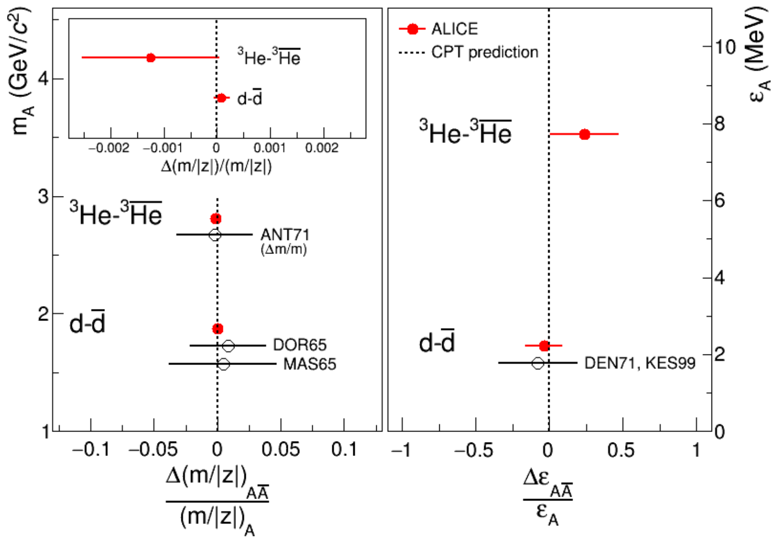


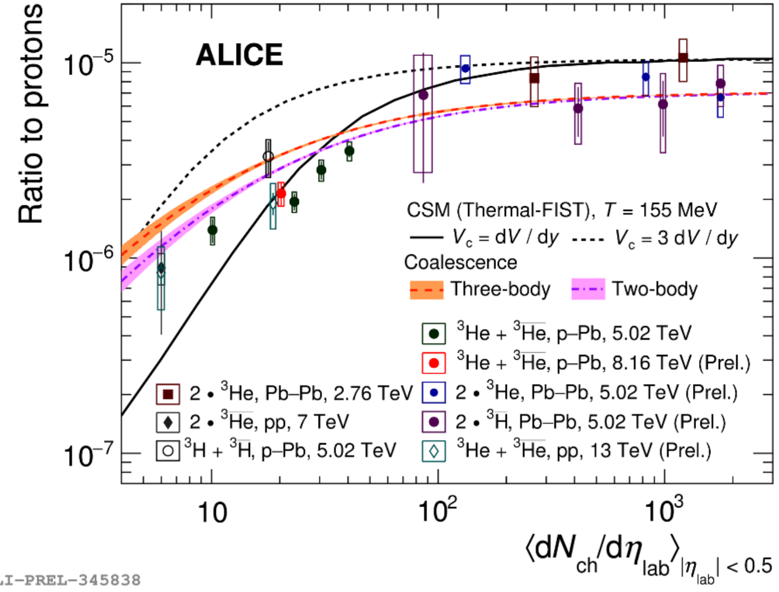
ALI-PREL-344619



ALI-PREL-333625

ALICE, Nat Phys 11 (2015) 811





ALI-PREL-345838

Method(s) to measure σ_{inel}

TOF/TPC matching efficiency in Pb-Pb coll.

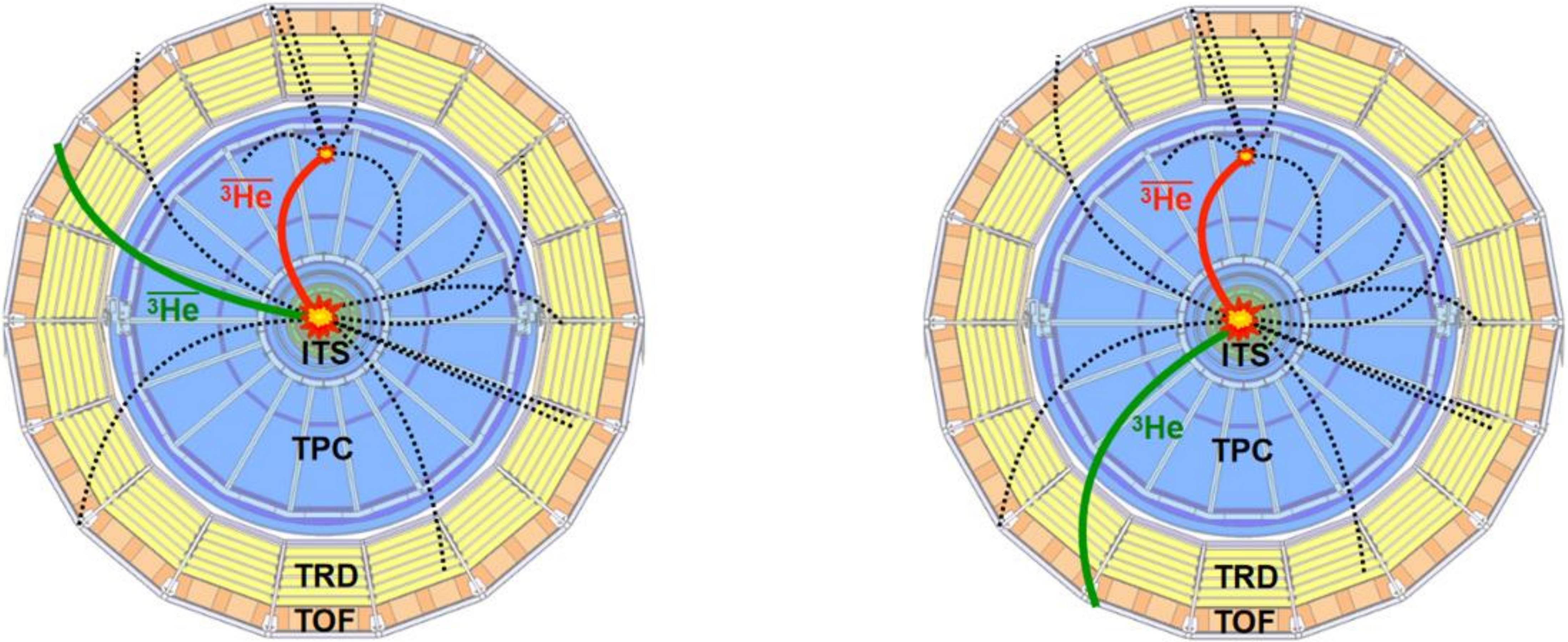
High statistics

No access to very-low momenta

Antiparticle/particle raw ratio in pp, p-Pb coll.

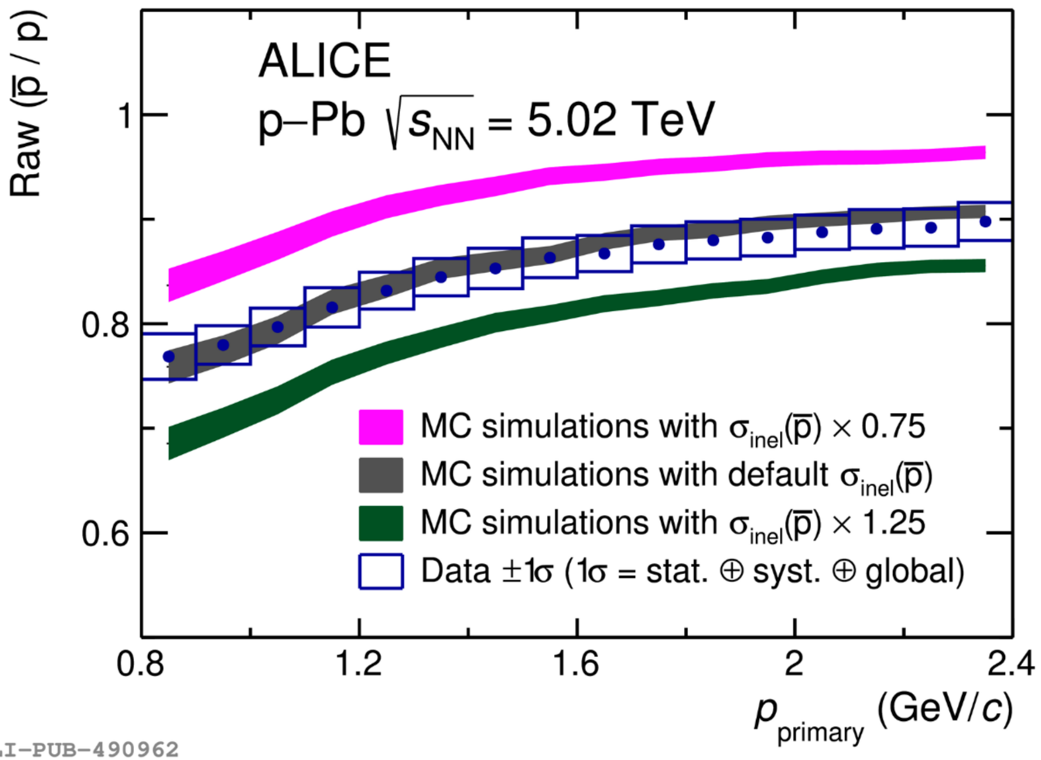
Access to low momenta

Background from secondary particles



Antiparticle-to-particle ratio

ALICE, PRL 125 (2020) 162001

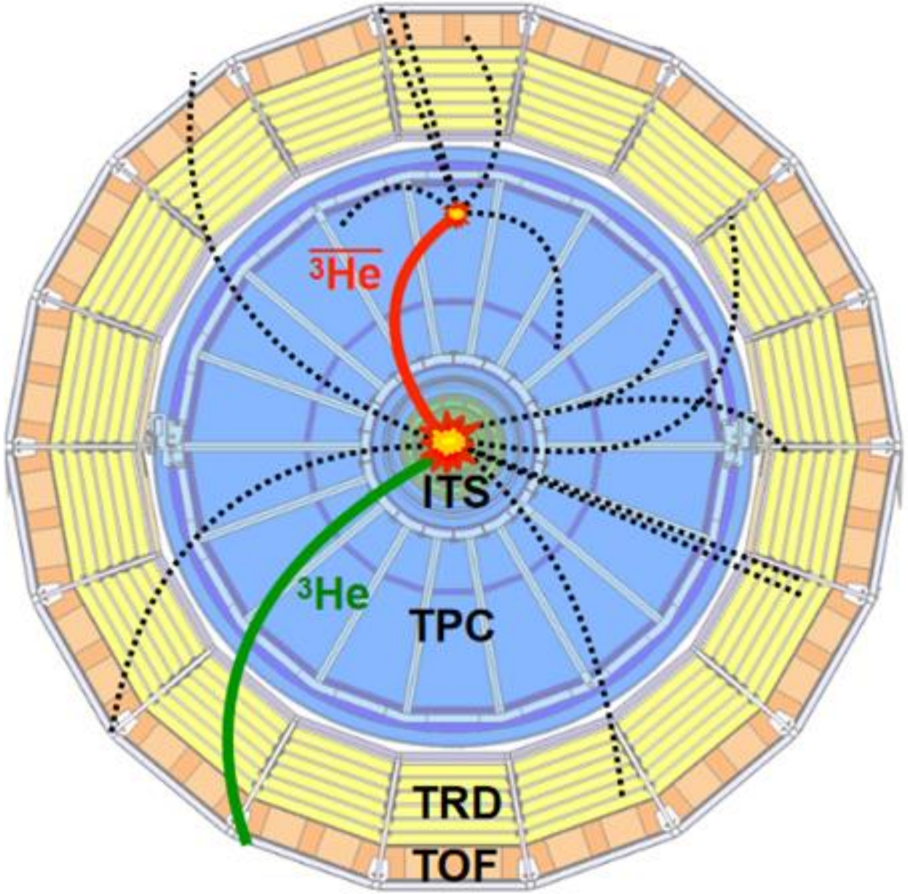


ALI−PUB−490962

Antiparticle/particle raw ratio in pp, p-Pb coll.

Access to low momenta

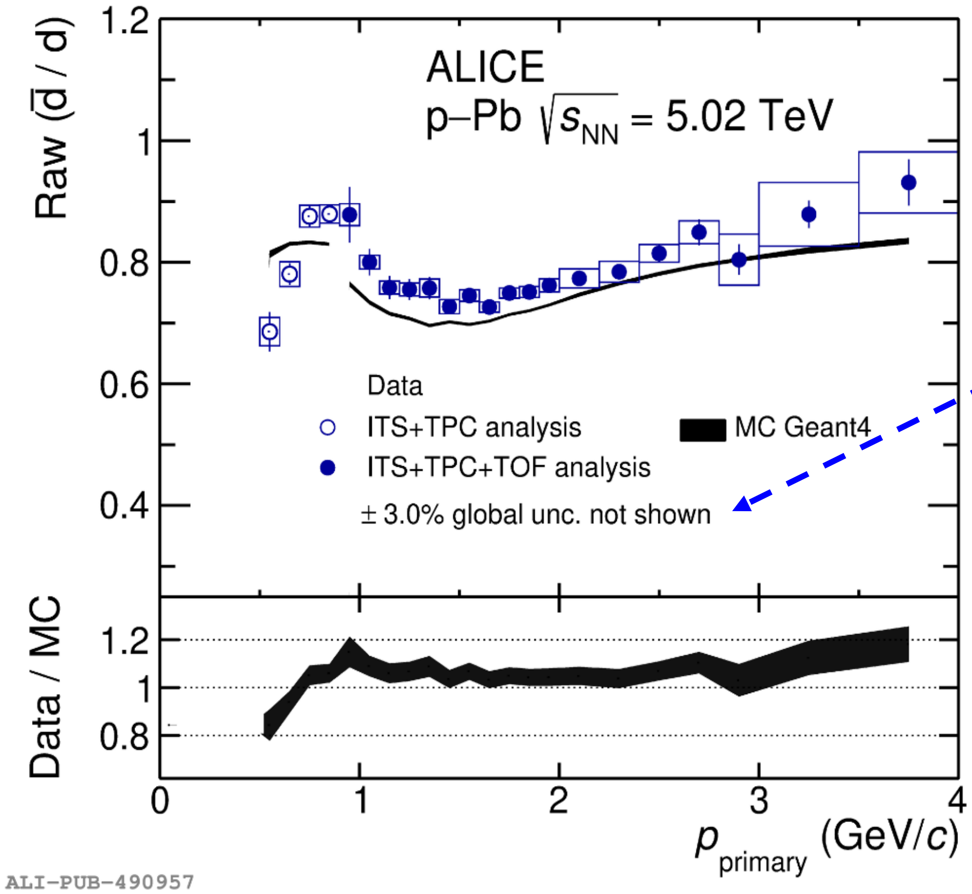
Background from secondary particles



Antiparticle-to-particle ratios are mainly sensitive to the variation of the inelastic cross section

→ they can be used to measure $\sigma_{inel}(\bar{d}\text{-A})$, $\sigma_{inel}(^{3}\overline{He}\text{-A})$

Antideuteron-to-deuteron raw ratio



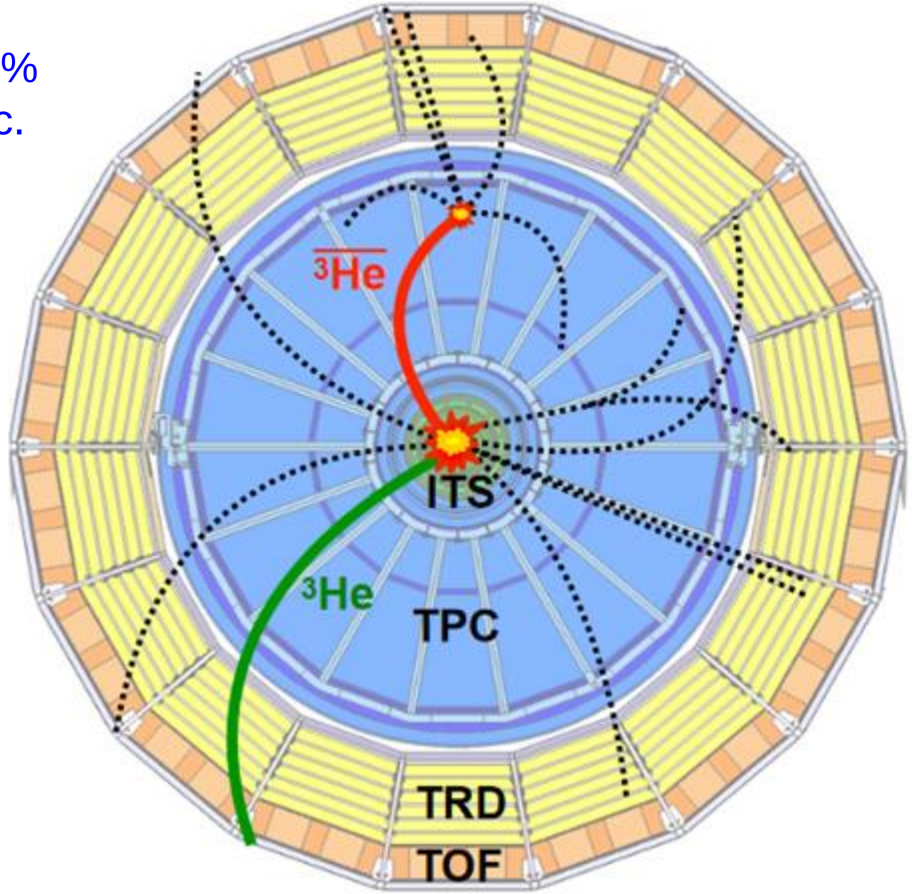
ALICE, PRL 125 (2020) 162001

Global contribution ±3% from primordial $\bar{d}$/d unc.

Antiparticle/particle raw ratio in pp, p-Pb coll.

Access to low momenta

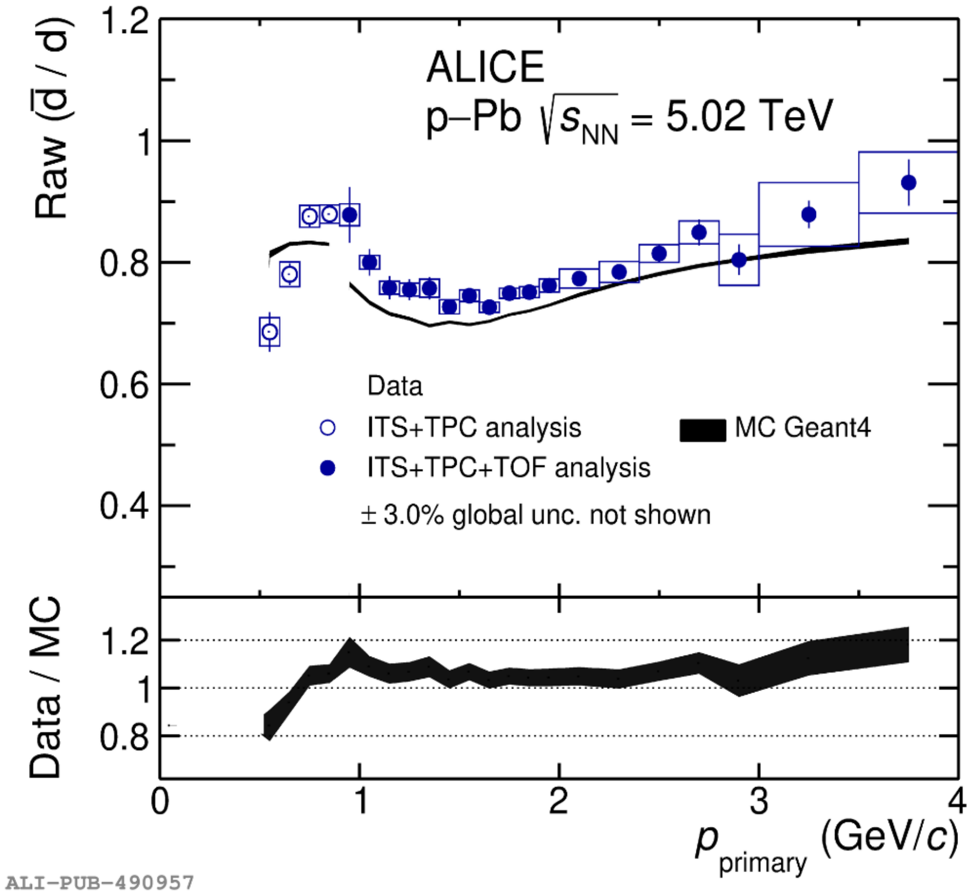
Background from secondary particles



$\sigma_{inel}(\bar{d})$ can be experimentally constrained by varying $\sigma_{inel}(\bar{d})$ in simulations

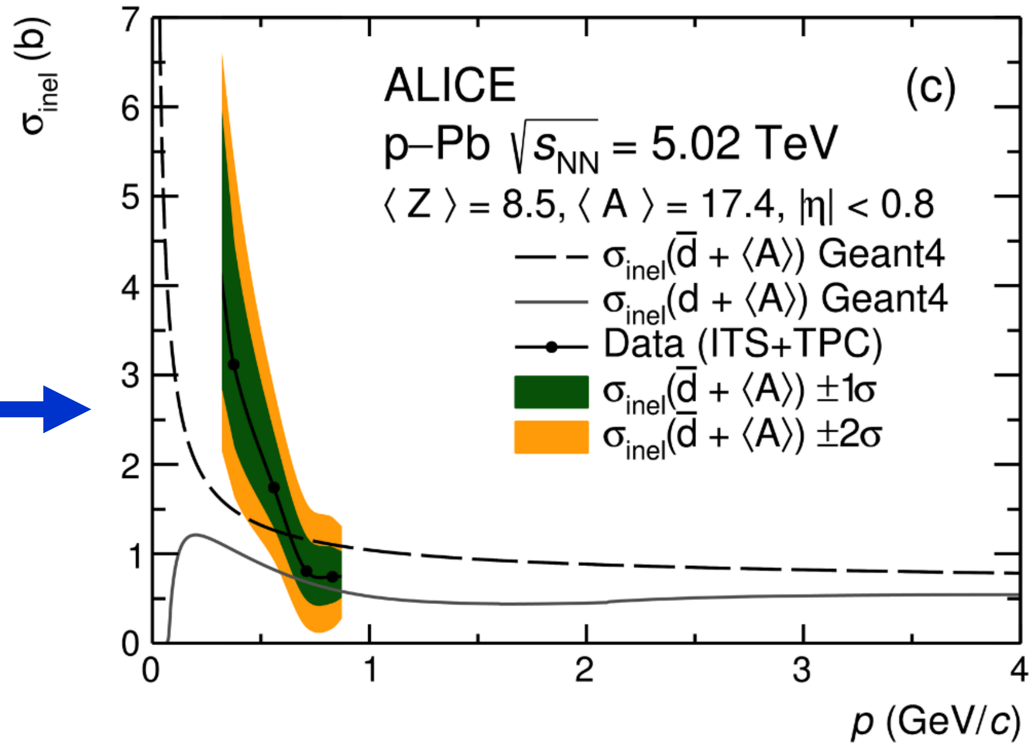
σ_{inel}(d) is fixed to the Geant4 parameterisations

Antideuteron inel. cross section

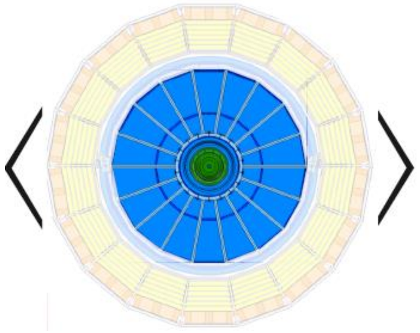


ALI-PUB-490957

ALICE, PRL 125 (2020) 162001



ALI-PUB-490977

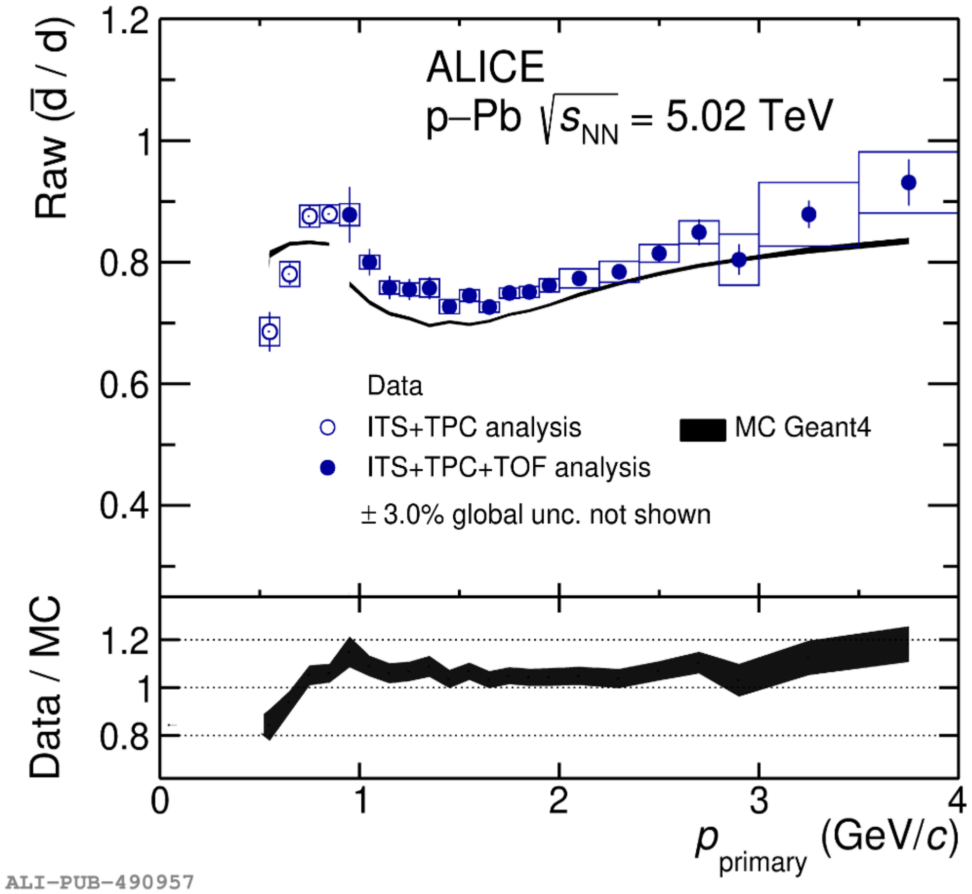


Hint for a significant deviation from the Geant4 parametrization at low momentum

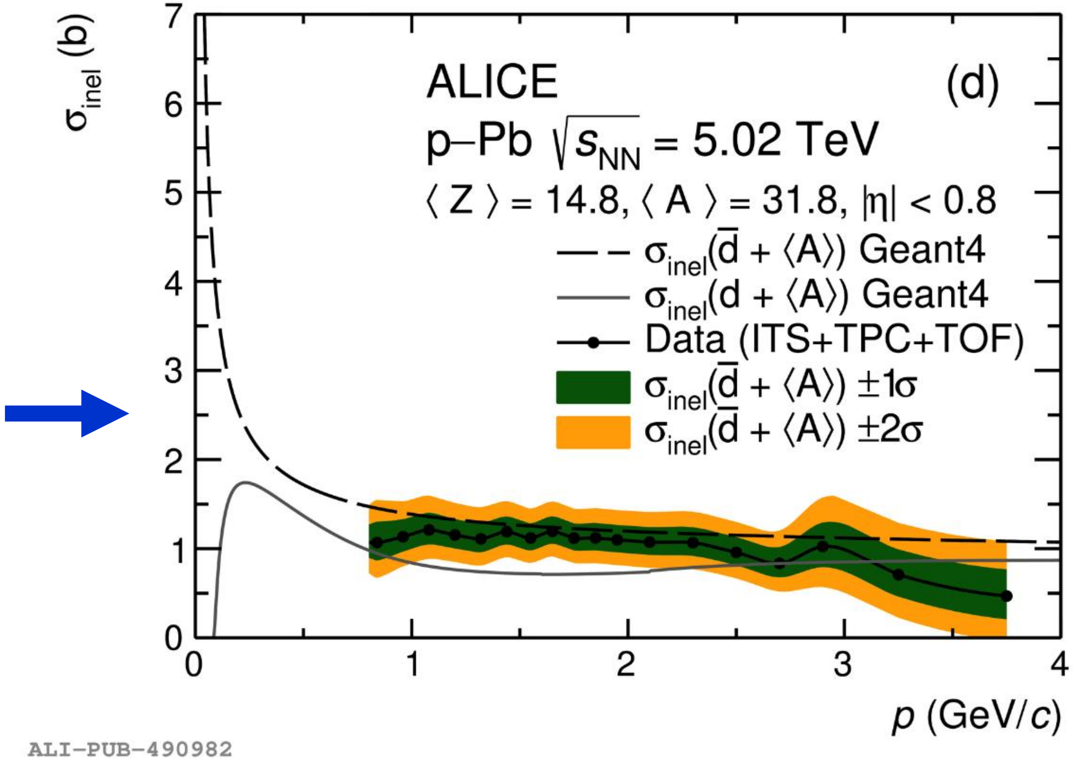
$\sigma_{inel}(\bar{d})$ can be experimentally constrained by varying $\sigma_{inel}(\bar{d})$ in simulations

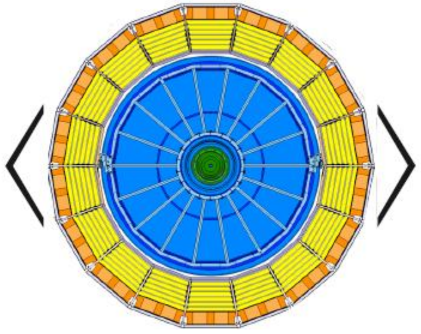
$\sigma_{inel}(d)$ is fixed to the Geant4 parameterisations

Antideuteron inel. cross section



ALICE, PRL 125 (2020) 162001

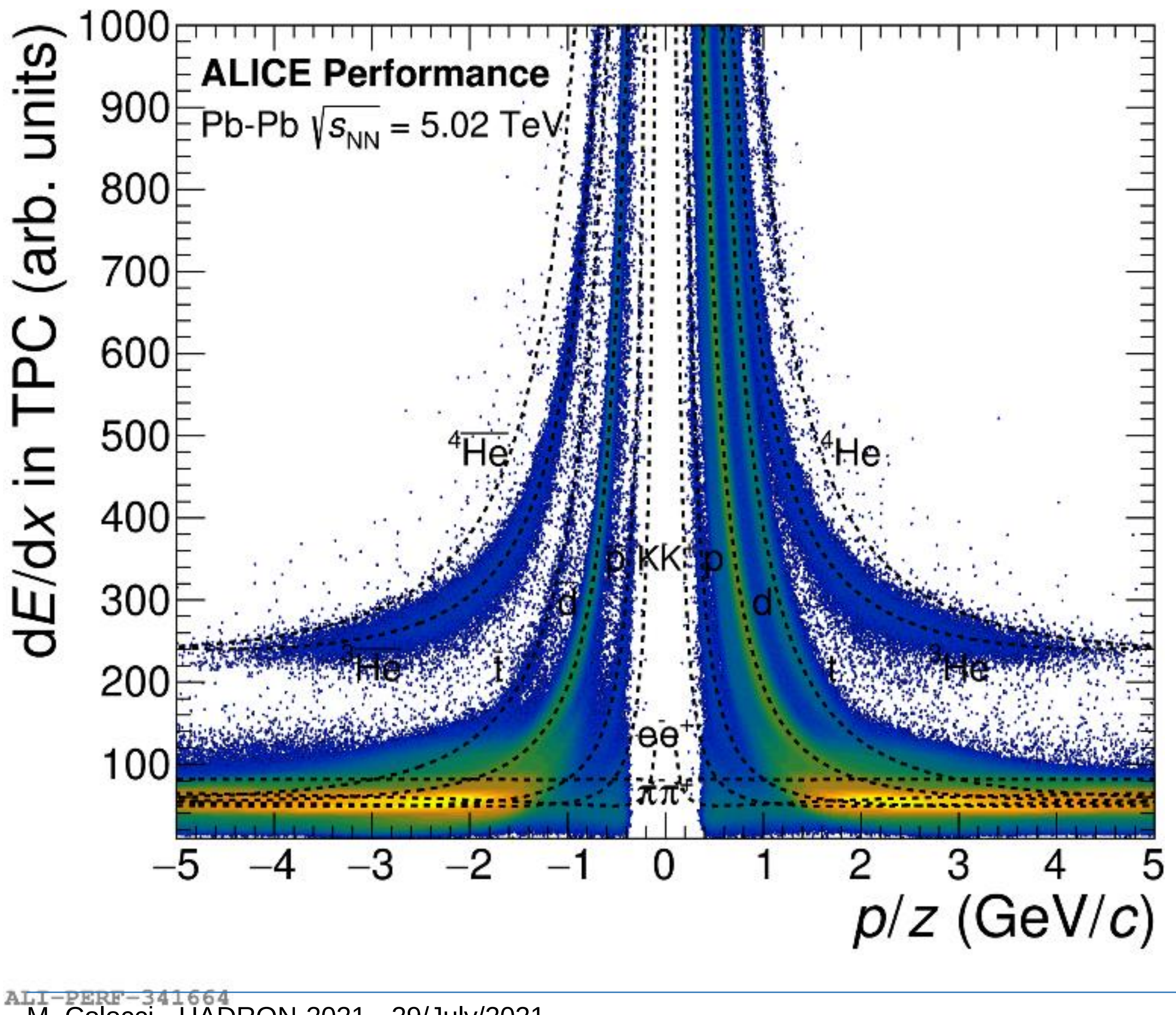




$\sigma_{inel}(\bar{d})$ can be experimentally constrained by varying $\sigma_{inel}(\bar{d})$ in simulations

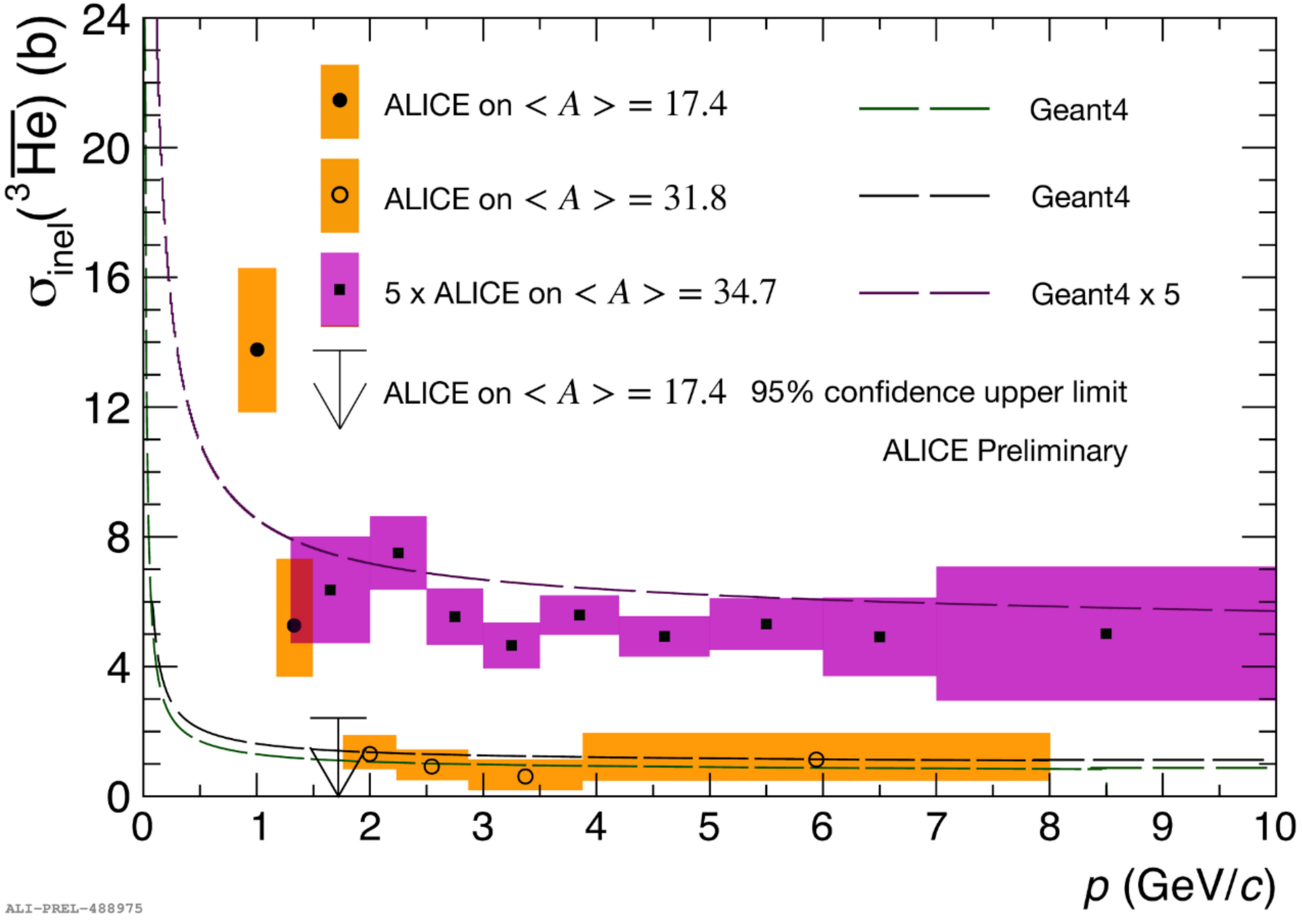
σ_{inel}(d) is fixed to the Geant4 parameterisations

$^{3}\overline{\mathrm{He}}$ signal (Pb-Pb collisions)



~17k $^{3}\overline{\mathrm{He}}$ reconstructed in Pb-Pb coll. (TPC)
~0.7k $^{3}\overline{\mathrm{He}}$ reconstructed in pp coll. (TPC)

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



- **TOF-to-TPC counts** and **$^3\overline{He}$-to-^3He raw ratio** employed

- Both methods provide compatible results (higher precision in Pb-Pb)

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

- Exp. data at very low momentum (p < 1.5 GeV/c) show large discrepancy w.r.t. Geant4 parametrization

- For p > 2.5 GeV/c Geant4 overestimates σ_{inel} by ~20%

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

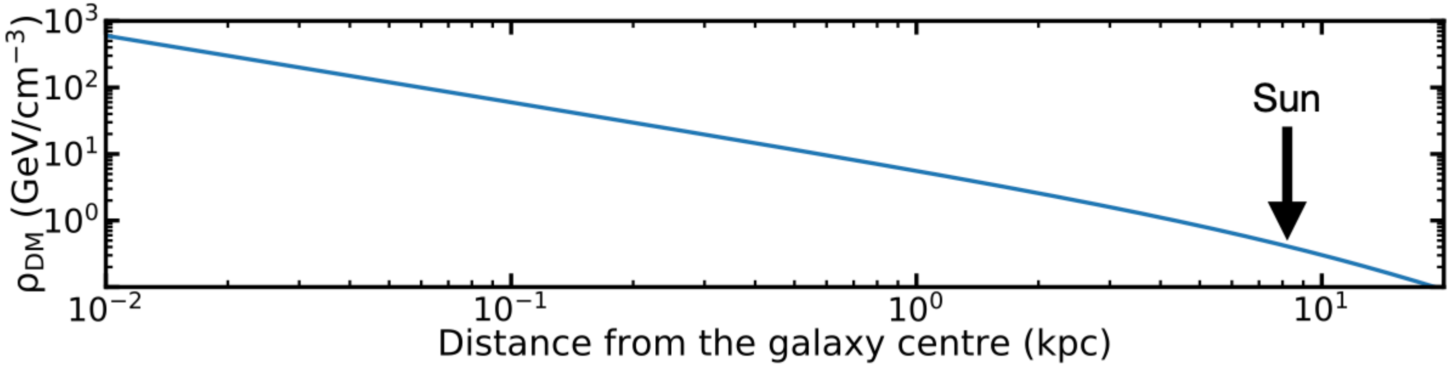
SOURCE(S) → PROPAGATION → ANNIHILATION

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

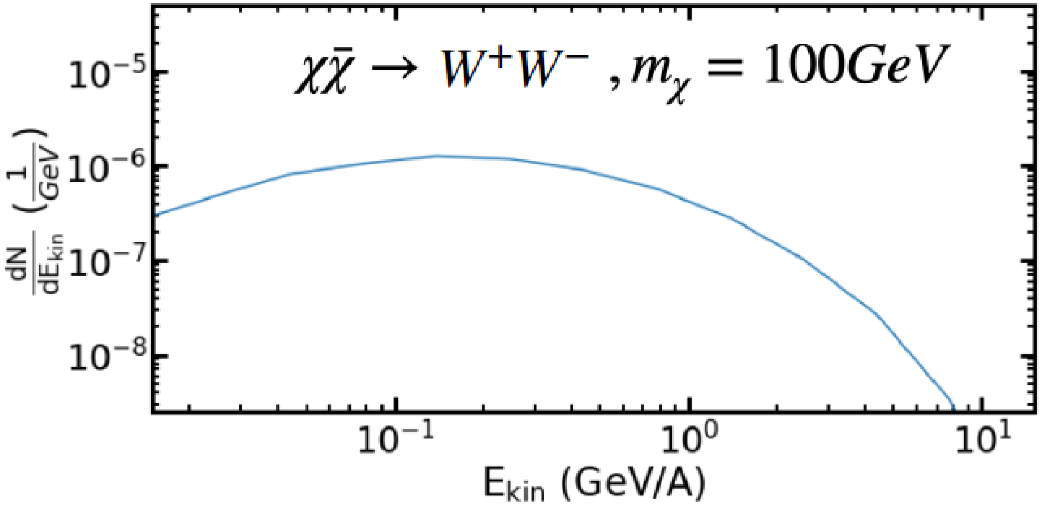
Source function

DM density distrib.

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



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

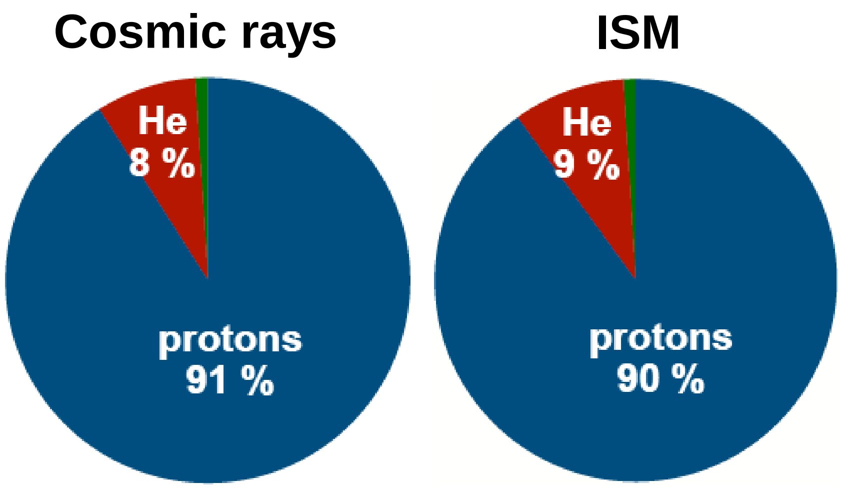


[1] Carlson et al., Phys Rev D 89 (2014) 076005
[2] Korsmeier et al., Phys Rev 97 (2018) 103011

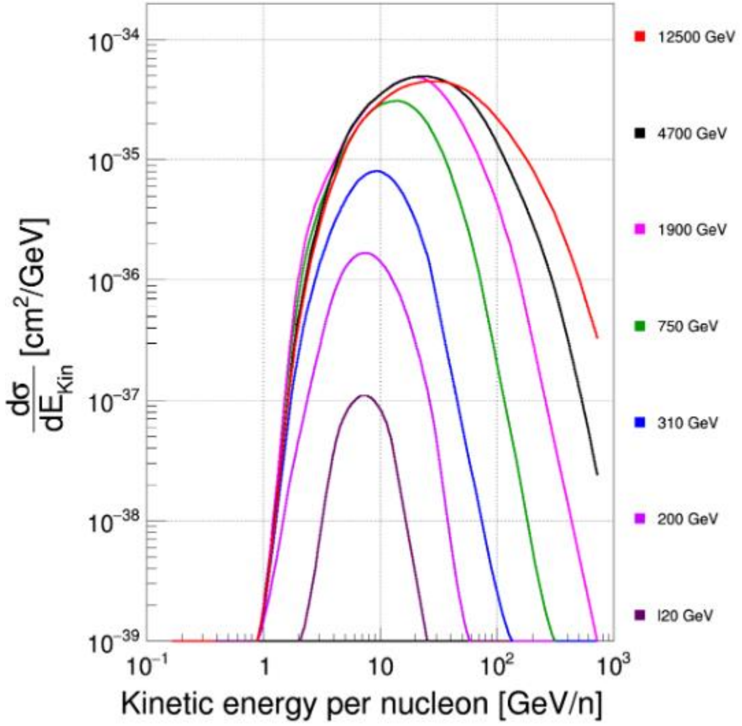
$^{3}\overline{\text{He}}$ source: cosmic rays (II)

SOURCE(S) → PROPAGATION → ANNIHILATION

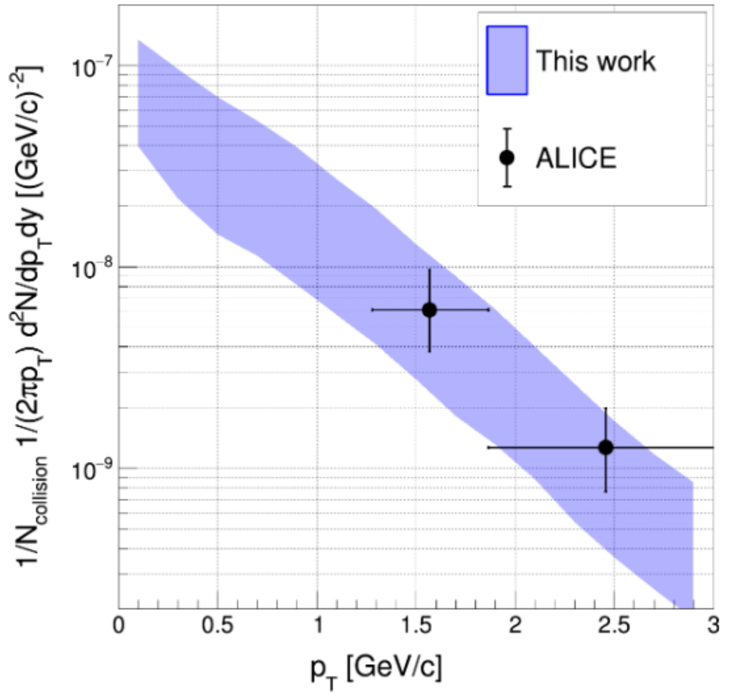
- 2^{nd} $^{3}\overline{\text{He}}$ source from interactions of cosmic rays with interstellar matter
- pp, p-^{3}He, ^{3}He-p, ^{3}He-^{3}He mostly relevant
- Production cross section in pp from [1]: EPOS LHC + coalescence afterburner
  Scaling factor $(A_{T}A_{P})^{11/15}$ for the other collision systems



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



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



[1] 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]

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

Source Function — Propagation: diffusion, convection… — Fragmentation, annihilation

- Propagation parameters (common for all particles)
  are constrained from available cosmic ray measurements [2]

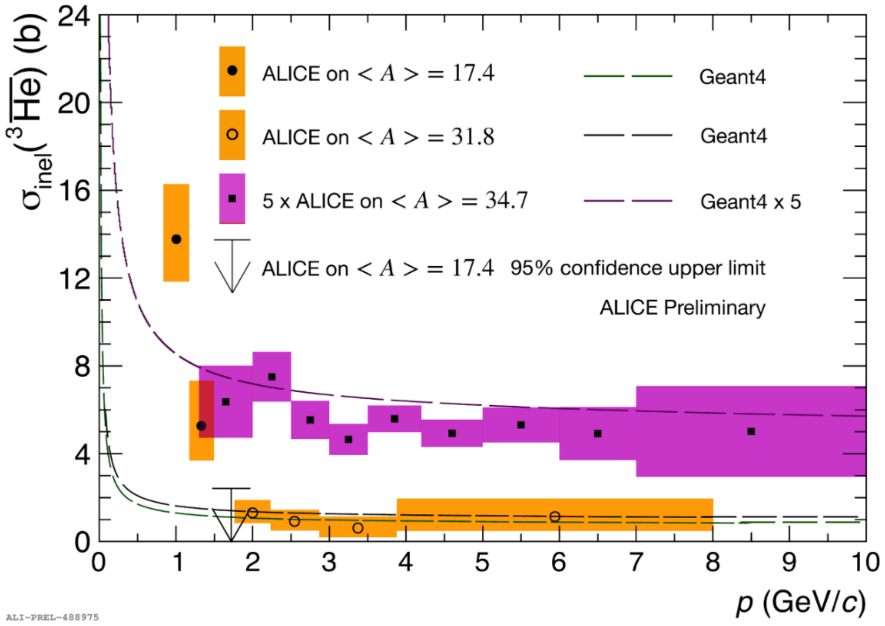
- Propagation from GALPROP down to the boundaries of Solar System
  → Helioshere (shielding cosmic rays) needs to be taken into account
  → Force Field approximation [3] accounts for solar modulation

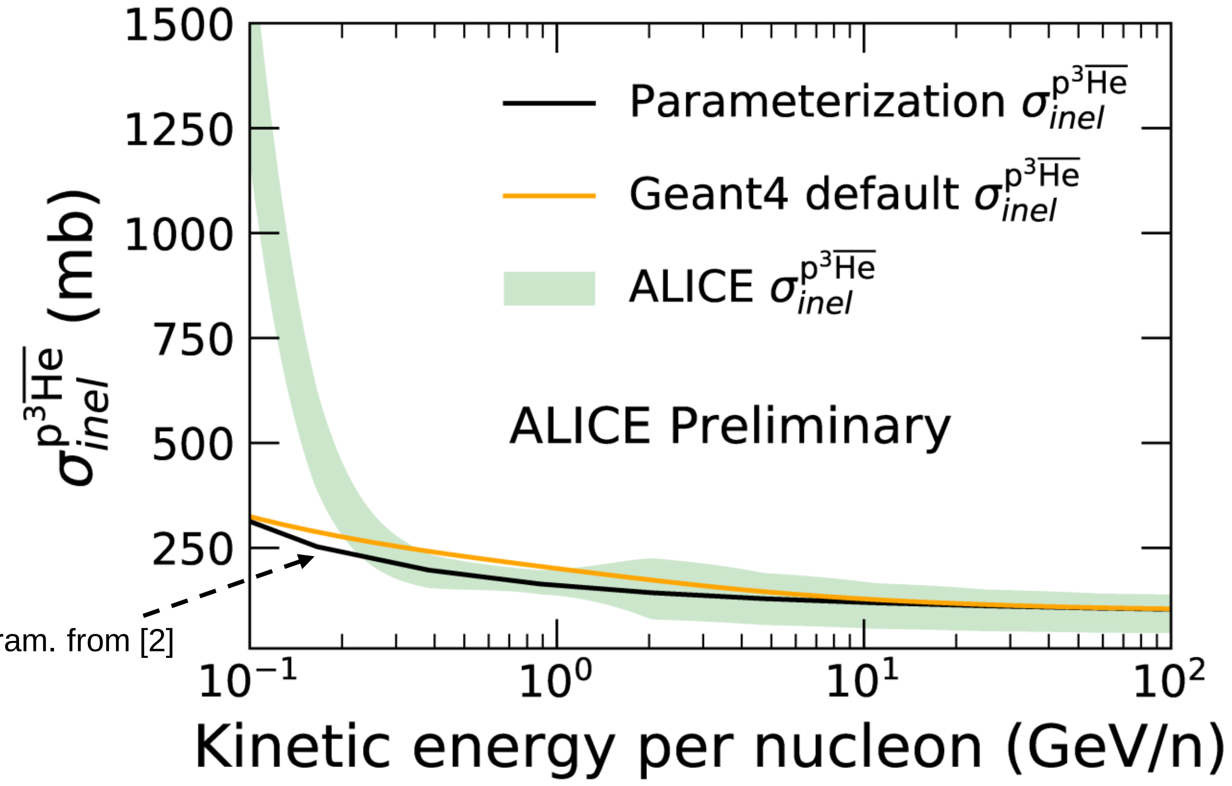
[1] https://galprop.stanford.edu/
[2] Boschini et al, Astrophys J Suppl 250 (2020) 27
[3] Gleeson, Axford, Astrophys J 154 (1968) 1011

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

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

- $^3\overline{\mathrm{He}}$ nuclei may interact inelastically with ISM and get “absorbed”
- Proton and Helium targets mostly relevant
- $\sigma_{inel}(^3\overline{\mathrm{He}}\text{-p})$ from Geant4 rescaled using ALICE experimental data
- 8% uncertainty from A scaling [1] is valid for all targets





Alternative param. from [2]

[1] Uzhinsky et al. Phys. Lett. B 705 (2011) 235
[2] Kormeier, Donato, Forengo, Phys Rev D97 no 10 (2018) 103011

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

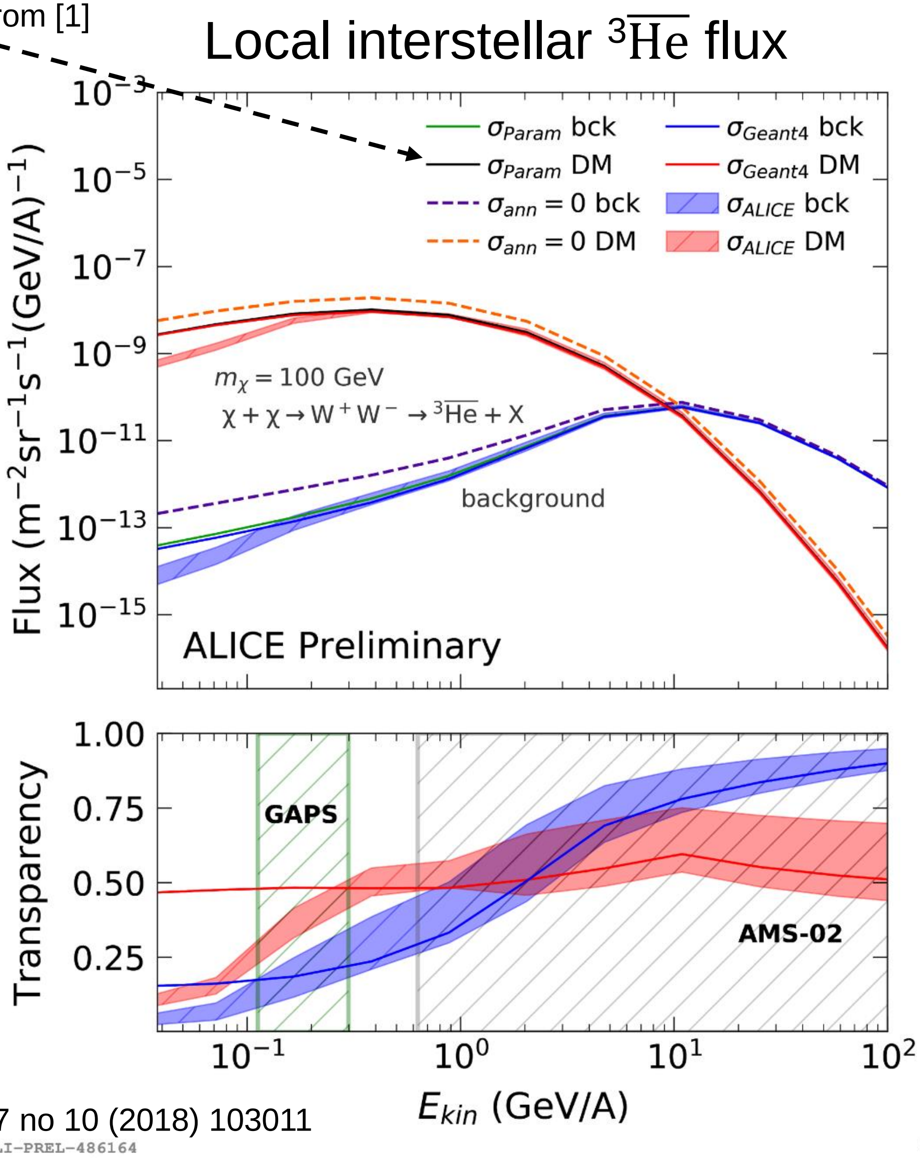
Alternative param. from [1]

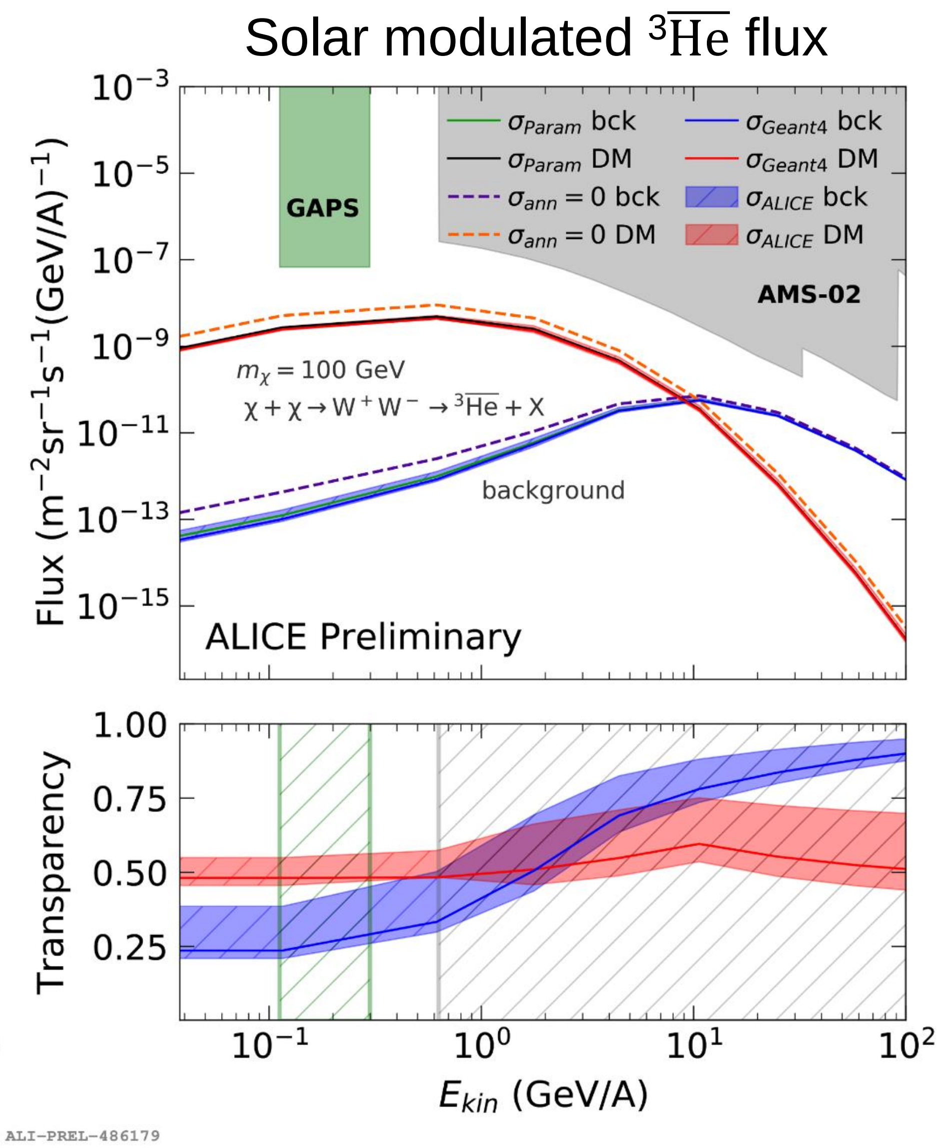
Alternative parametrizations give similar results (*inside the heliosphere*)

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_k):
25% from CR interactions
50% from typical DM candidates

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





[1] Kormeier, Donato, Forengo, Phys Rev D97 no 10 (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 **$^{3}\overline{\text{He}}$ 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 $\sigma_{inel}(^{3}\overline{\text{He}}\text{-A})$
→ High transparency of the galaxy to $^{3}\overline{\text{He}}$ flux

Thanks for your attention