(ANTI)NUCLEI AT THE LHC

OVERVIEW OF PRODUCTION MEASUREMENTS WITH RUN1+2 DATA

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ALICE

CosmicAntiNuclei

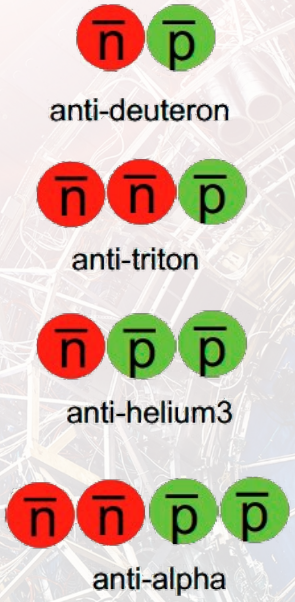
Light (anti)nuclei in high-energy collisions

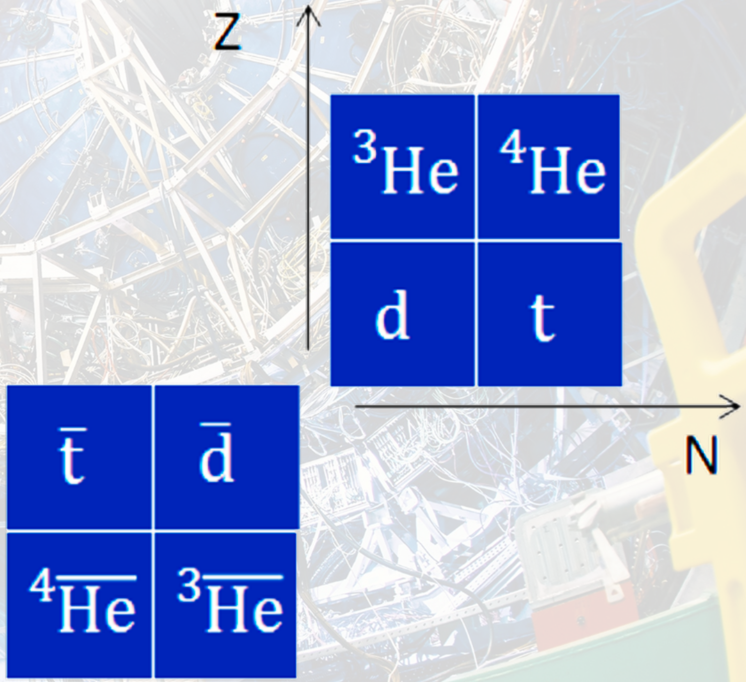
We consider **light** nuclei if $Z \leq 2$

$p \rightarrow \bar{p}\,,\; n \rightarrow \bar{n}$ → ***antinuclei***

The study of light (anti)nucleus **formation** in **high-energy collisions** is fundamental for several reasons:

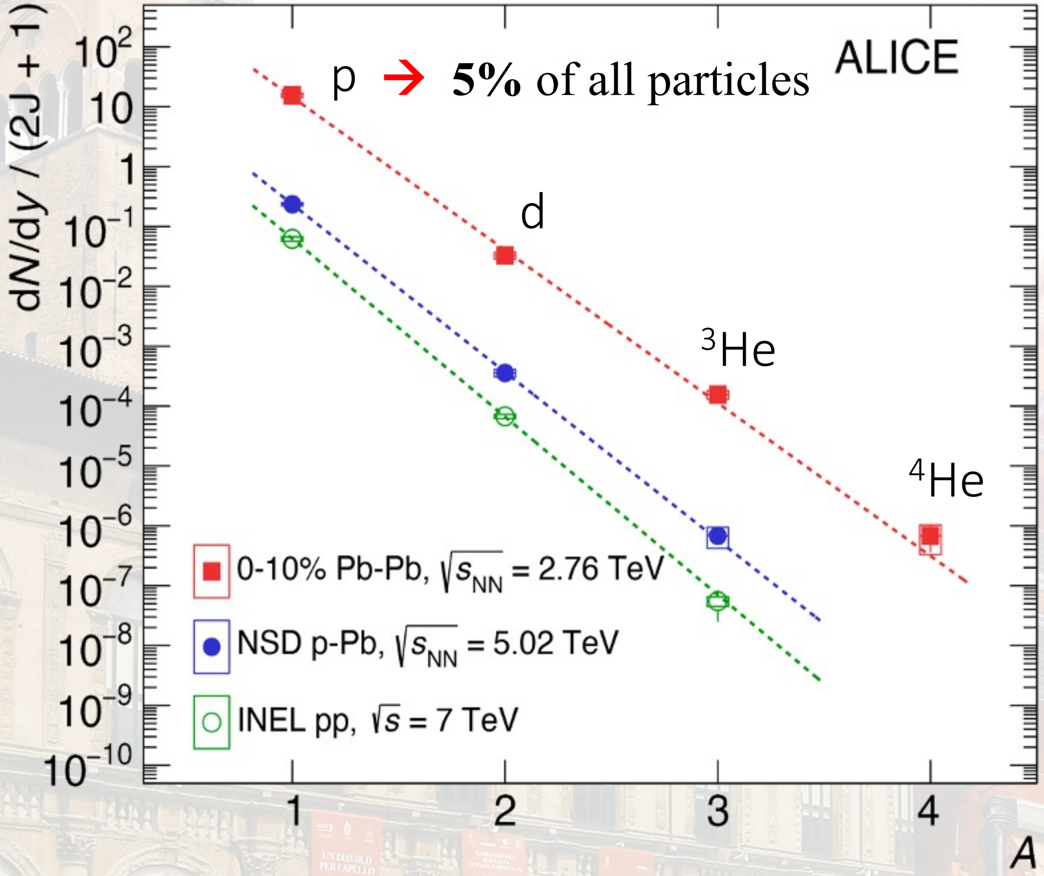
- Their production **mechanism** is still **not fully understood**
- **Low binding energy** $(1 - 10\ \mathrm{MeV})$ implies that light (anti)nucleus formation is strongly dependent on the chemical freeze-out conditions and the dynamics of the emitting source
- **Astrophysics applications**: measurements in controlled conditions costrain searches for **antimatter** from dark matter in cosmic rays



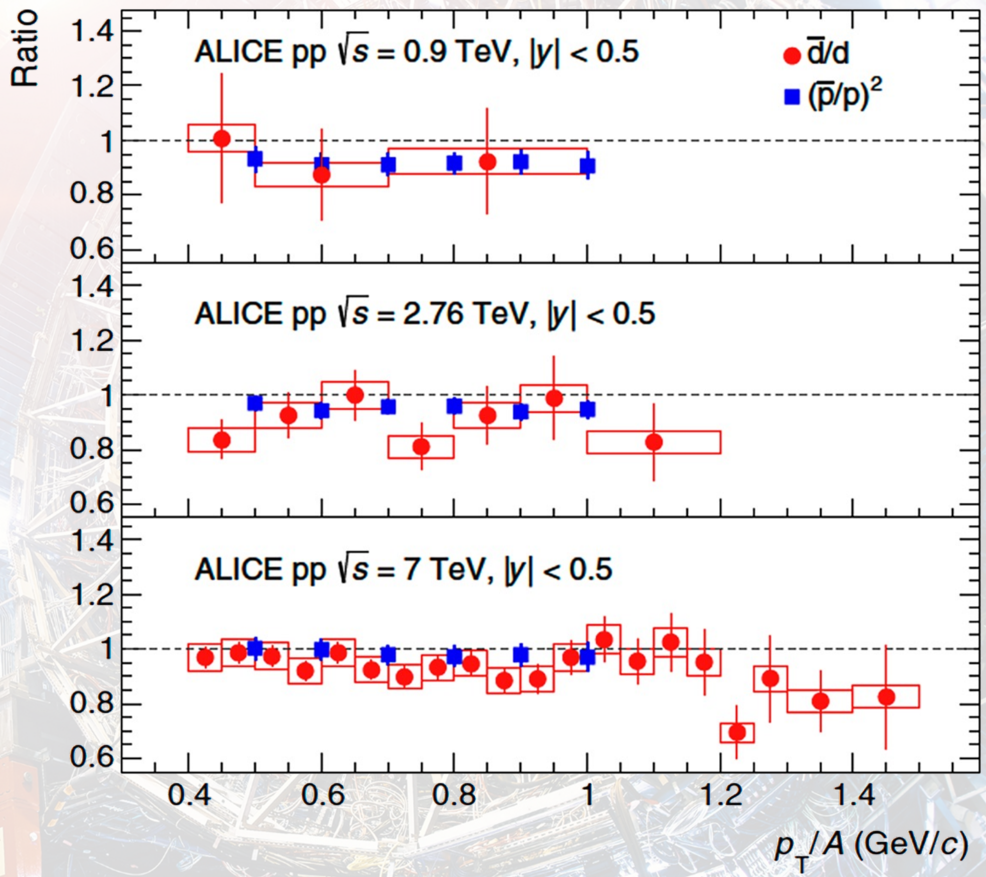


LHC is an antinucleus factory

S. Acharya *et al.* [ALICE], Phys. Lett. B **800**, 135043 (2020)



Physical Review C97, 024615 (2018)



$\bar{d}/\bar{p}$ (Pb-Pb) ~ 1/300 $^3\overline{He}/\bar{p}$ (Pb-Pb) ~ 1/10^5

$\bar{d}/\bar{p}$ (pp) ~ 1/1000 $^3\overline{He}/\bar{p}$(pp) ~ 1/10^6

RECAP $\frac{\text{antimatter}}{\text{matter}} \sim \mathbf{1}$

Pb-Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV, only 0.005% are $\bar{d}$

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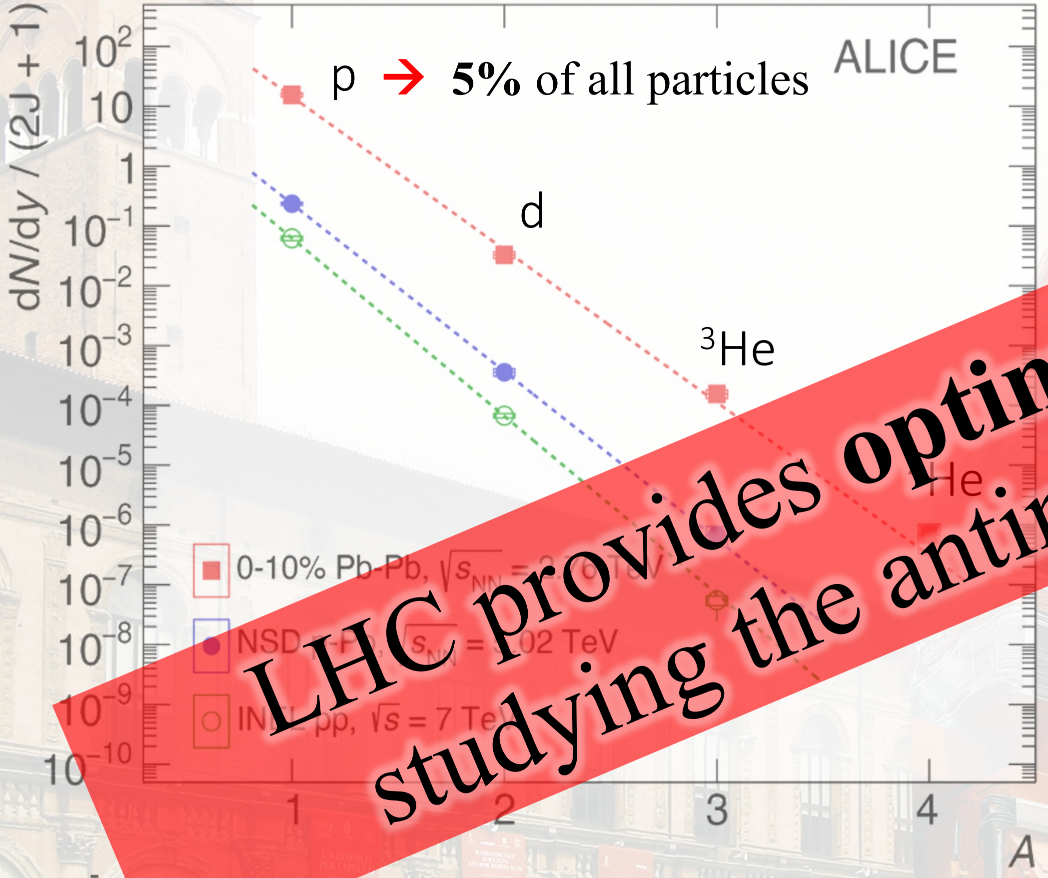

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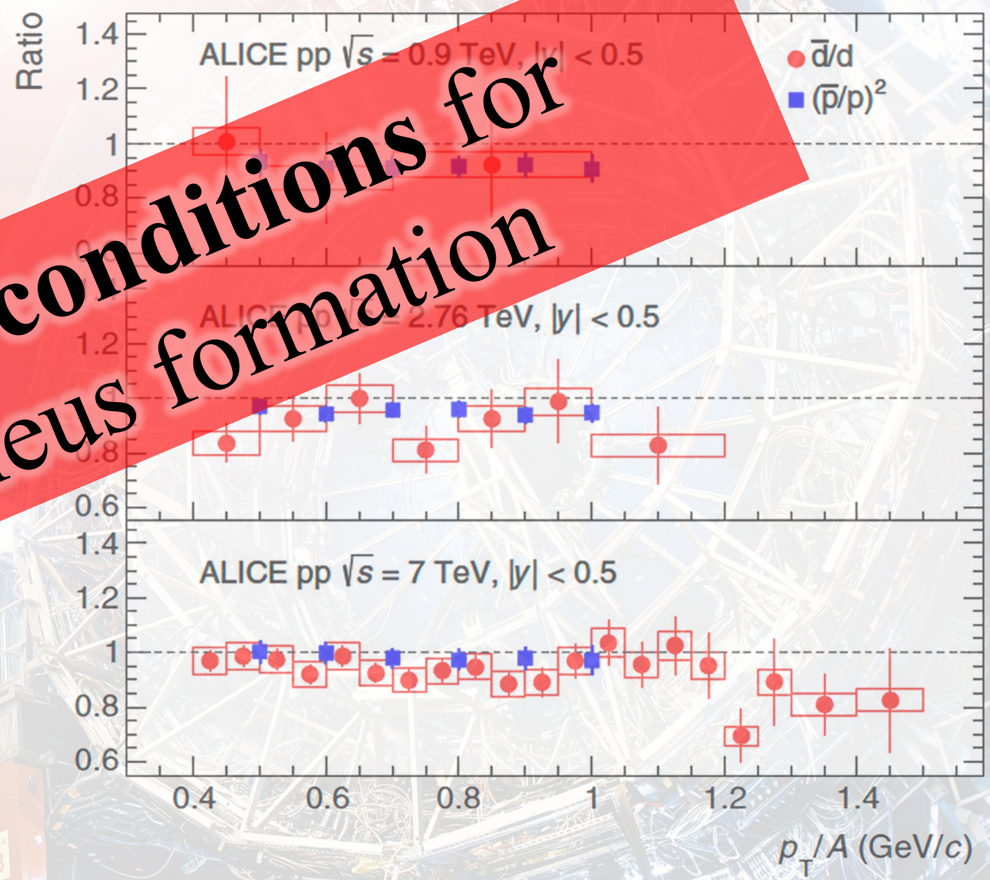


LHC provides optimal conditions for studying the antinucleus formation

$\bar{d}/\bar{p}$ (Pb-Pb) ~ 1/300 $\quad {}^3\overline{He}/\bar{p}$ (Pb-Pb) ~ $1/10^5$

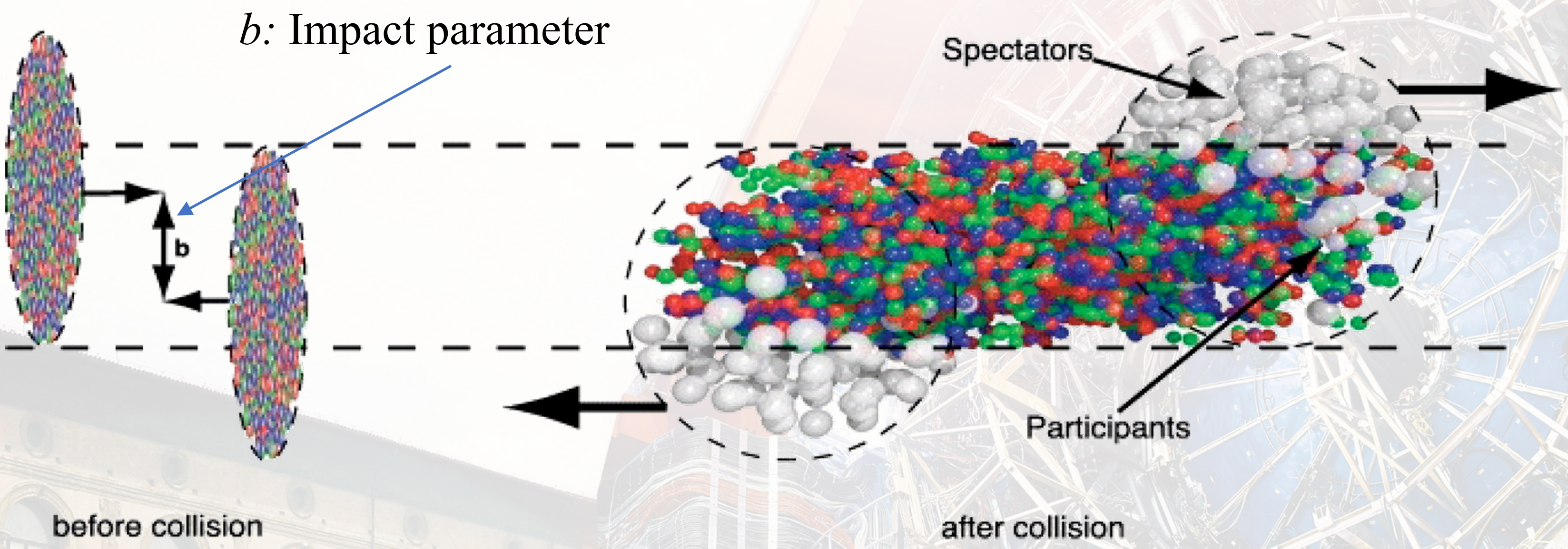
$\bar{d}/\bar{p}$ (pp) ~ 1/1000 $\quad {}^3\overline{He}/\bar{p}$ (pp) ~ $1/10^6$

RECAP $\quad \frac{\text{antimatter}}{\text{matter}} \sim 1$

Pb-Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV, only 0.005% are $\bar{d}$

Centrality of the collisions

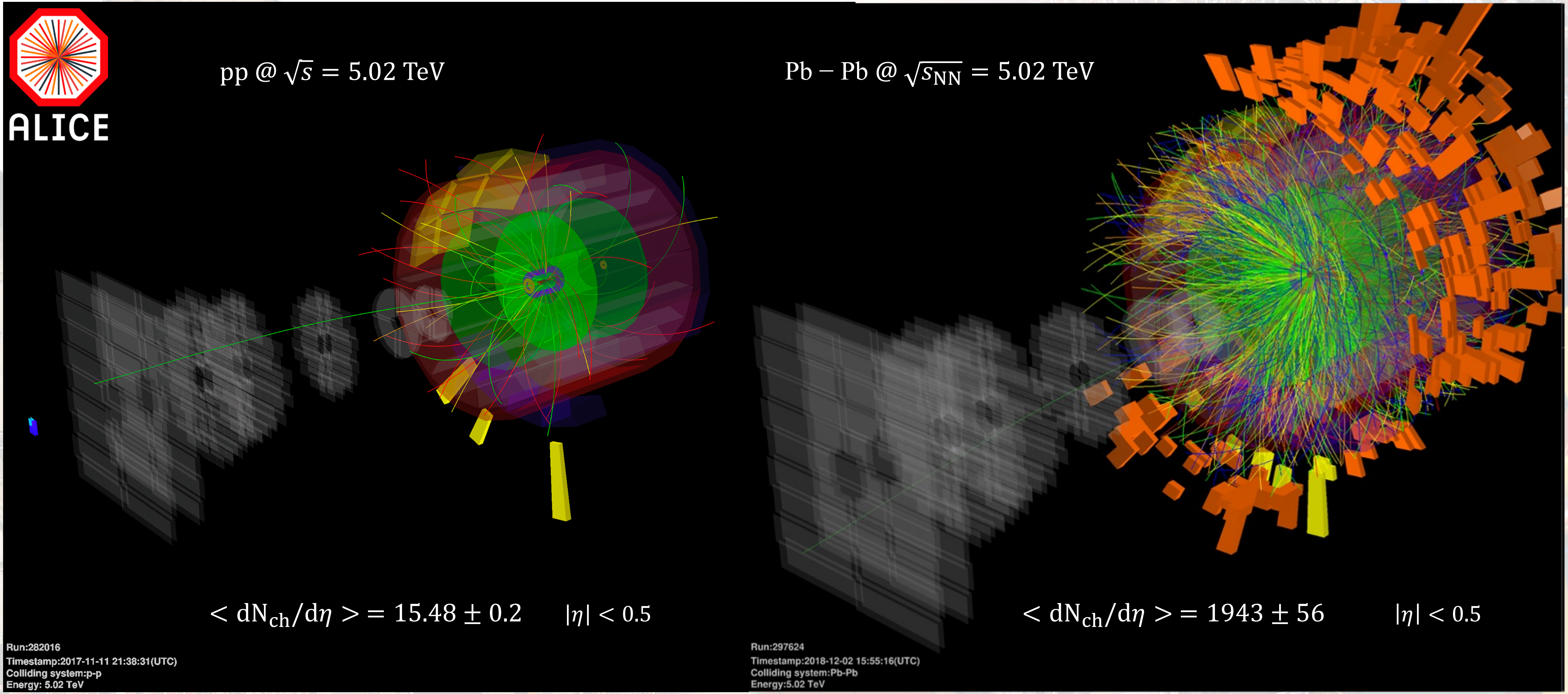
- **Centrality:** degree of overlap of two colliding nuclei



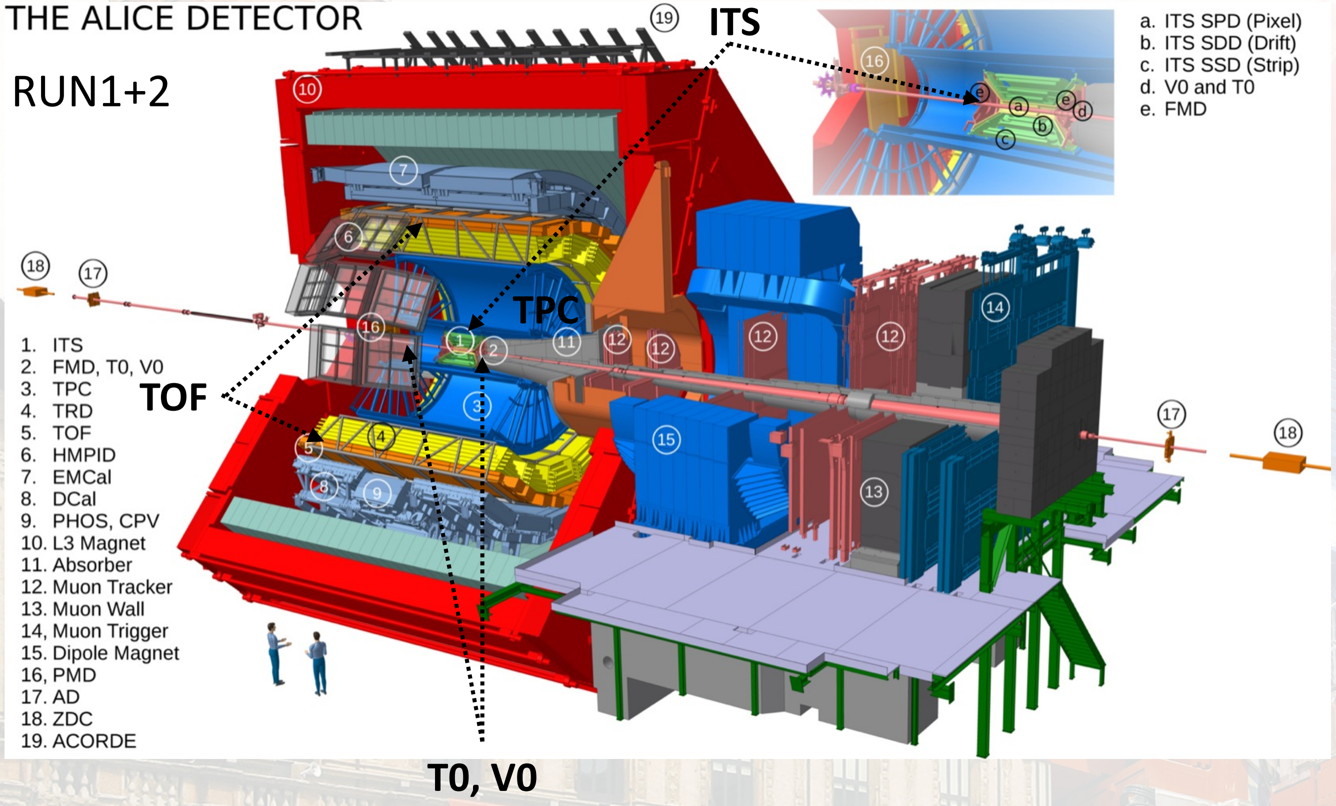
- **Central collisions:**
  Small impact parameter *b*
  High number of participant nucleons
  High multiplicity

- **Peripheral collisions:**
  Large impact parameter *b*
  Low number of participant nucleons
  Low multiplicity

Multiplicity: pp vs Pb – Pb collisions



Particle identification (PID) of (anti)nuclei



ITS (|η|<0.9)

6 layers silicon detectors

Pixel, Drift and Strip detectors

Trigger, vertex, tracking, PID (dE/dx)

TPC (|η|<0.9)

Gas-filled cylindrical barrel, MWPC readout, 90 m^3

Tracking and vertexing, PID (dE/dx)

TOF (|η|<0.9)

Multi-gap Resistive Plate Chambers

Time resolution σ_{TOF} ~ 80 ps

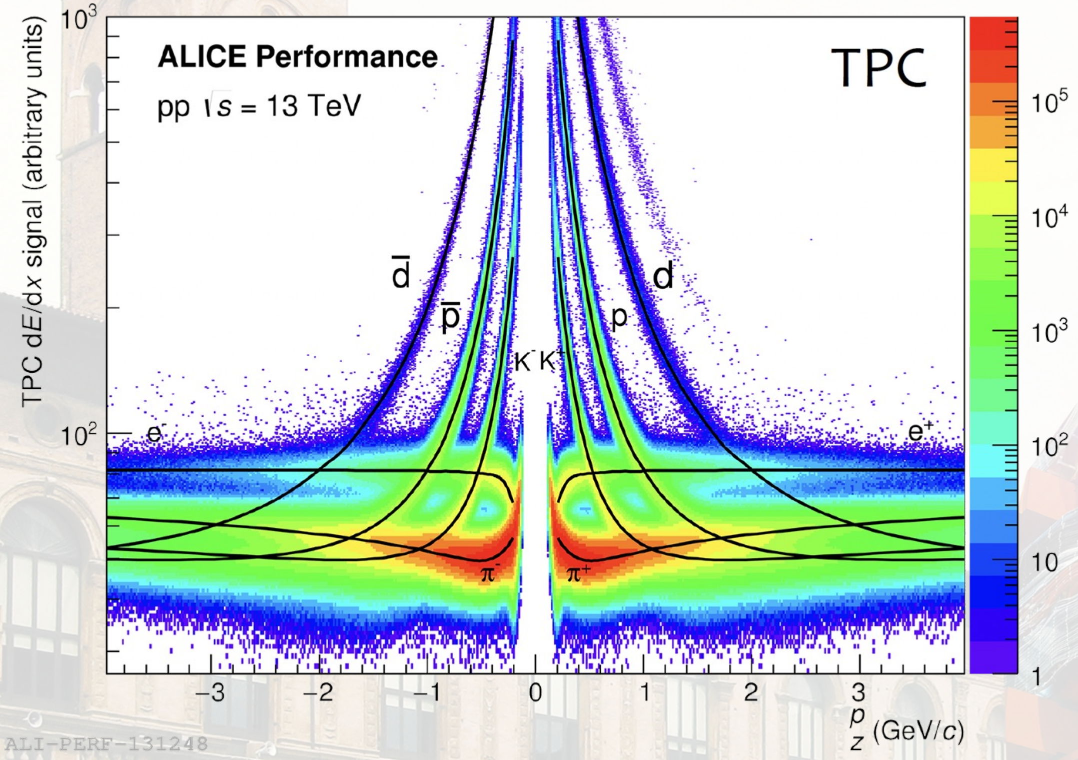
PID (time-of-flight)

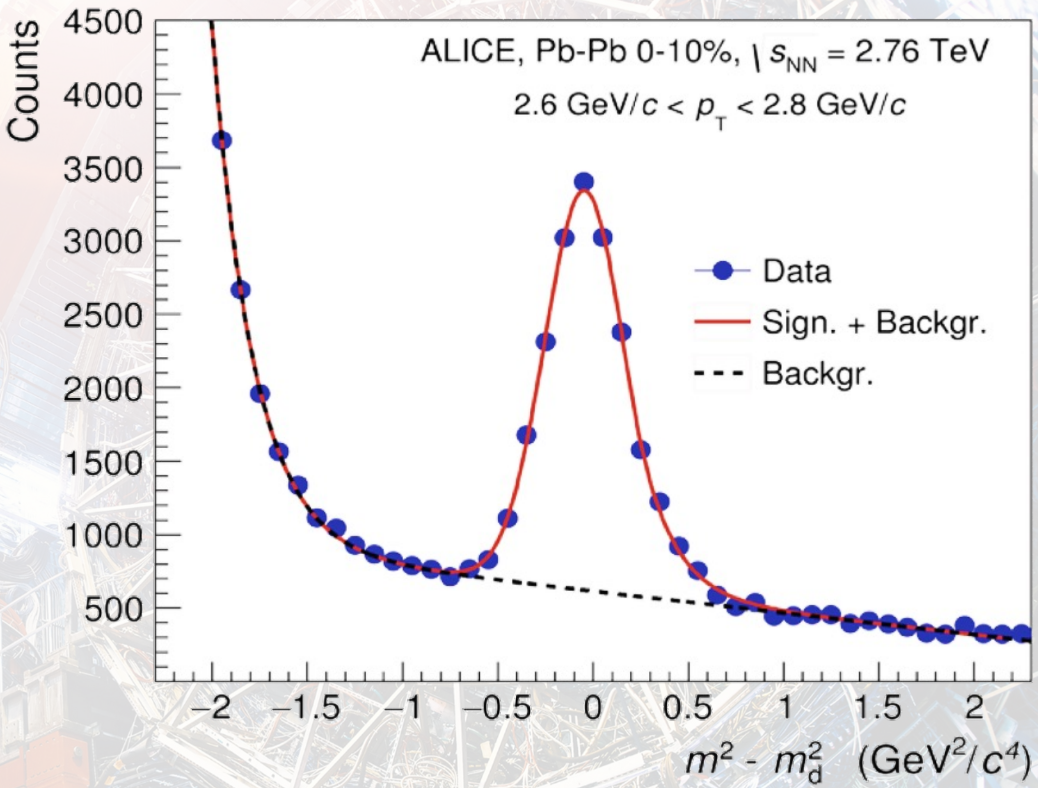
Run 1 (2009-2013)	Run 2 (2015-2018)
pp 0.9, 2.76, 7, 8 TeV	pp 5.02, 13 TeV
p-Pb 5.02	p-Pb 5.02, 8.16 TeV
Pb-Pb 2.76 TeV	Pb-Pb 5.02 TeV Xe-Xe 5.44 TeV

ALICE is uniquely equipped for particle identification (PID)

Most of known techniques are used: specific energy loss, time-of-flight, Cherenkov radiation, transition radiation, electromagnetic calorimetry and topological reconstruction of weak decays

Particle identification (PID) of (anti)nuclei





Low momenta

PID via specific ionization energy loss in TPC

$$\langle -\frac{dE}{dx} \rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln 2 \frac{m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Higher momenta

PID via time-of-flight measurements in TOF

$$m^2 = \frac{p^2}{c^2} \cdot \left(\frac{c^2 t^2}{L^2} - 1 \right)$$

Particle identification (PID) of (anti)nuclei

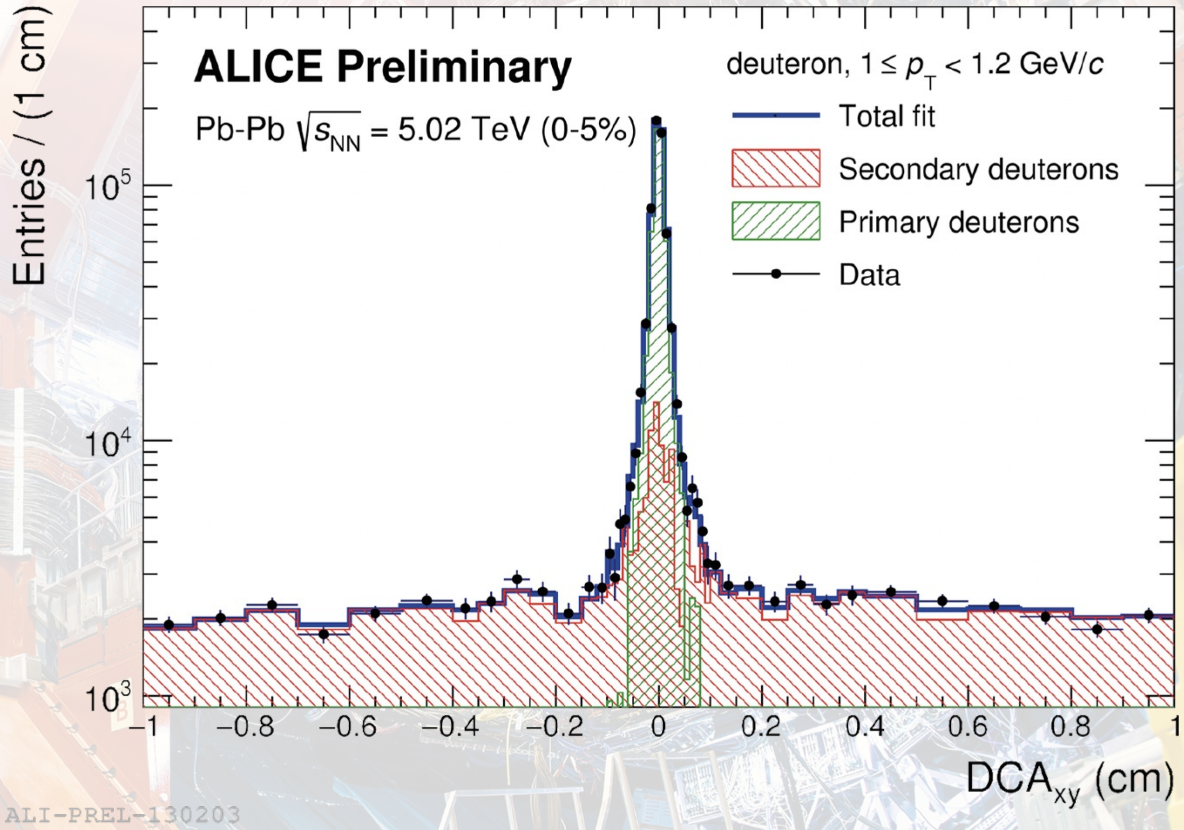
[PHYSICAL REVIEW C **97**, 024615 (2018)]

As secondary nuclei are copiously produced via spallation in the detector material by the impact of the primary particles, the study of distance of closest approach (DCA) can be studied to reduce the number of secondary nuclei

- **Nuclei**: abundance of secondary candidates, flat distribution around DCA_{xy} peak
- **Antinuclei**: no secondary candidates, only peak

Corrections must be performed, using simulated **Monte Carlo data** for estimate the secondary over fraction and correct the nuclei raw yield

Monte Carlo data is also fundamental for estimate the **efficiency x acceptance** for yield correction

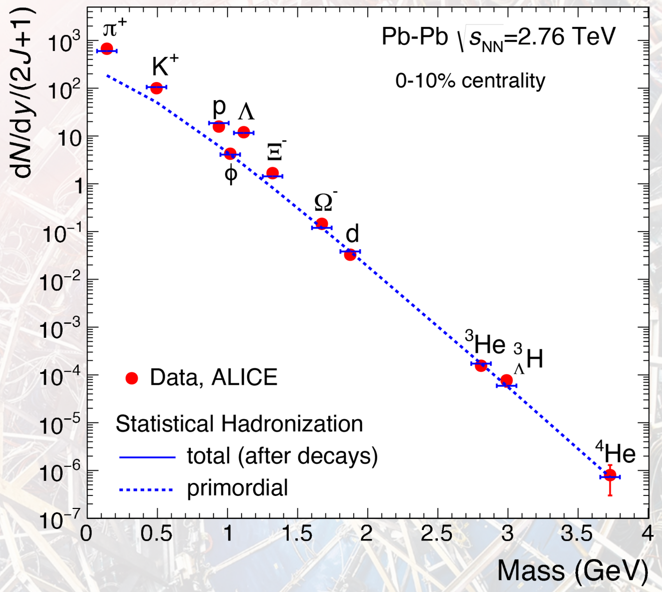


(Anti)nuclei production - Models

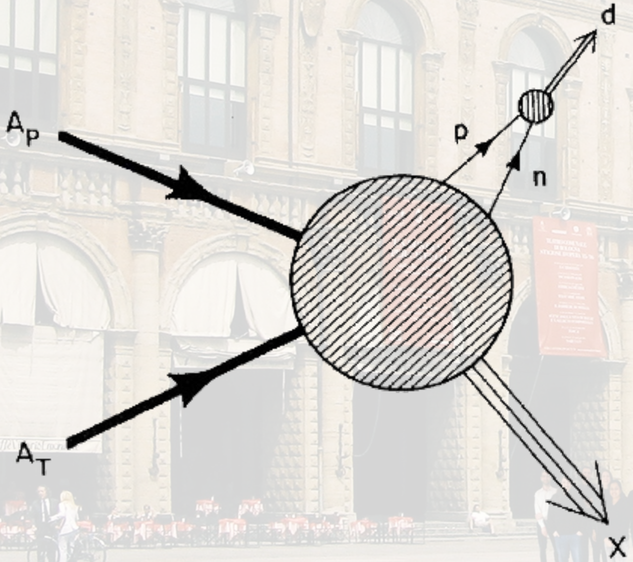
Thermal Model

- Hadrons emitted from the interaction region at statistical equilibrium when fireball reaches limiting temperature
- Abundances fixed at chemical freeze-out

Nuclei abundance strongly depends on the choice of T_{chem}:
- Large mass m
- Exponential dependence of the **yield** ~ exp(-m/ T_{chem})



Andronic, A., Braun-Munzinger, P., Redlich, K. et al. Decoding the phase structure of QCD via particle production at high energy. Nature 561, 321–330 (2018)



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

Coalescence model

- If (anti)baryons at freeze-out are close enough in phase space and (anti)nucleus can be formed
- Nuclei are formed by protons and neutrons which have similar velocities

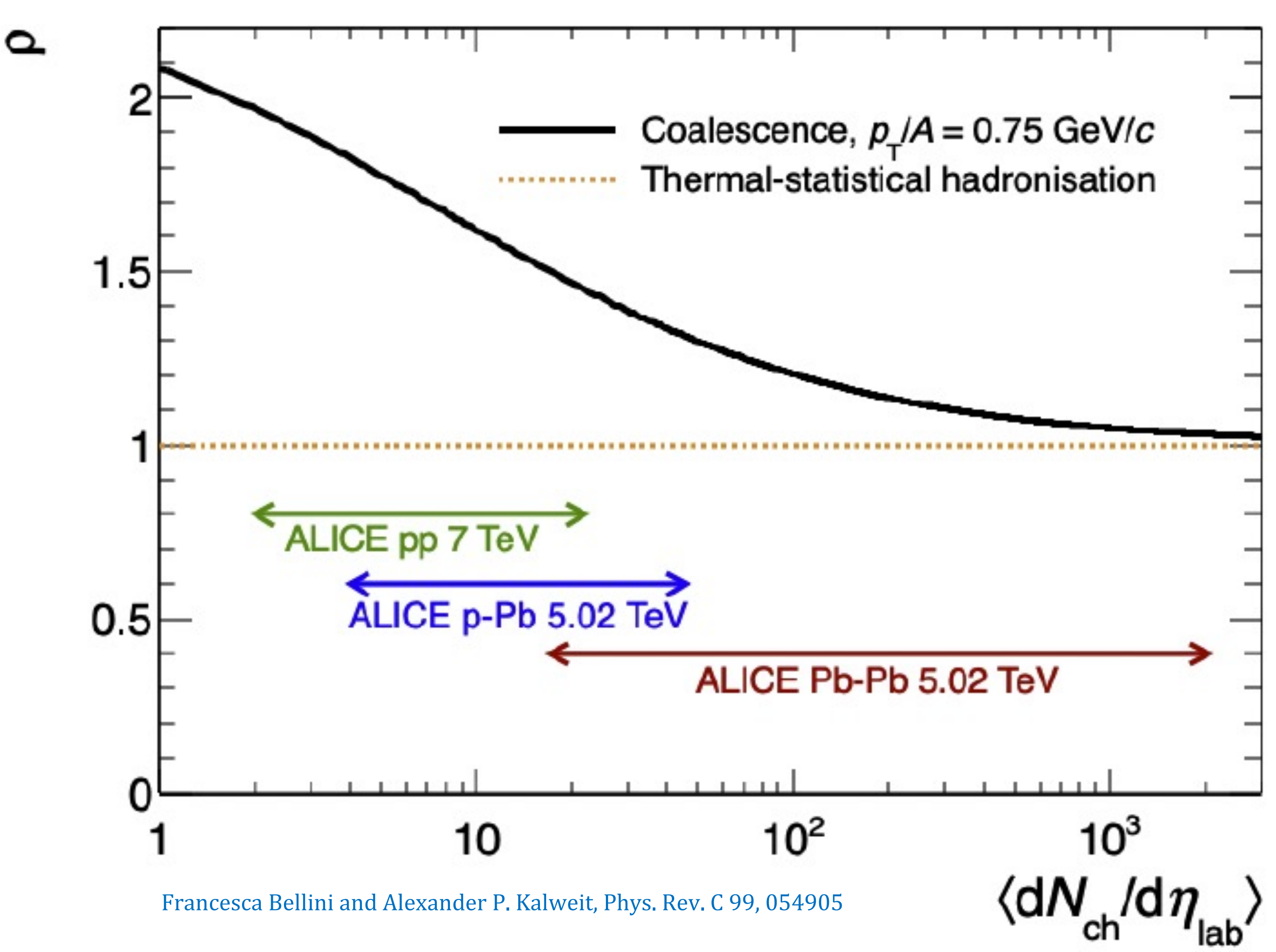
Nuclei might break and re-form during the time between the chemical freeze-out and the kinetic freeze-out

(Anti)nuclei pr

Thermal Model

- Hadrons emitted fr
  when fireball reach
- Abundances fixed

Nuclei abundance stro
- Large mass m
- Exponential depen



Francesca Bellini and Alexander P. Kalweit, Phys. Rev. C 99, 054905

$$\rho(p_T) \equiv \frac{B_A(^3\mathrm{H})}{B_A(^3\mathrm{He})}(p_T)$$

Andronic, A., Braun-Munzinger, P., Redlich, K. et al. Decoding the phase structure of QCD via particle production at high energy. Nature 561, 321–330 (2018)

space and
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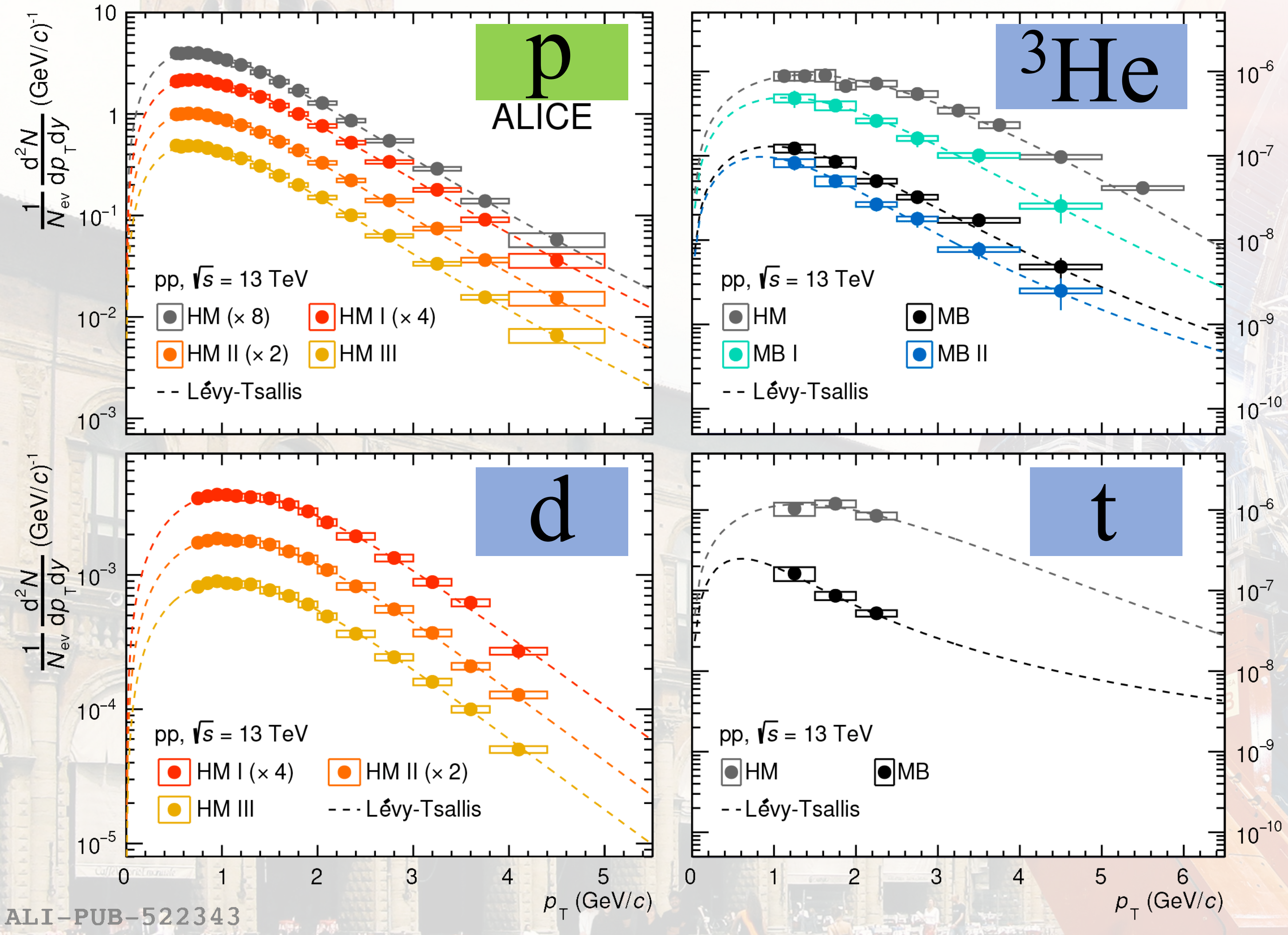
Our main observable: the particle yield

Coalescence model



Formation probability is related to the **coalescence parameter B_A**:

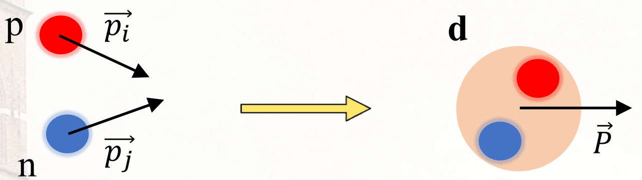
NUCLEUS — NUCLEONS

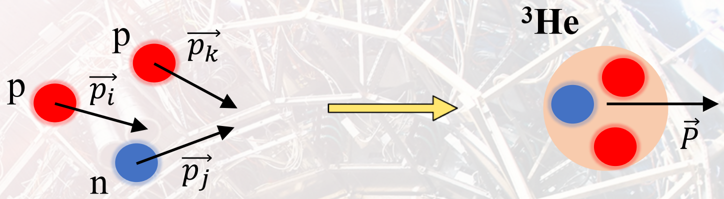
$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^Z \Bigg|_{\vec{p}_p = \frac{\vec{p}_A}{A}} \left(E_n \frac{d^3N_n}{dp_n^3} \right)^N \Bigg|_{\vec{p}_n = \frac{\vec{p}_A}{A}}$$

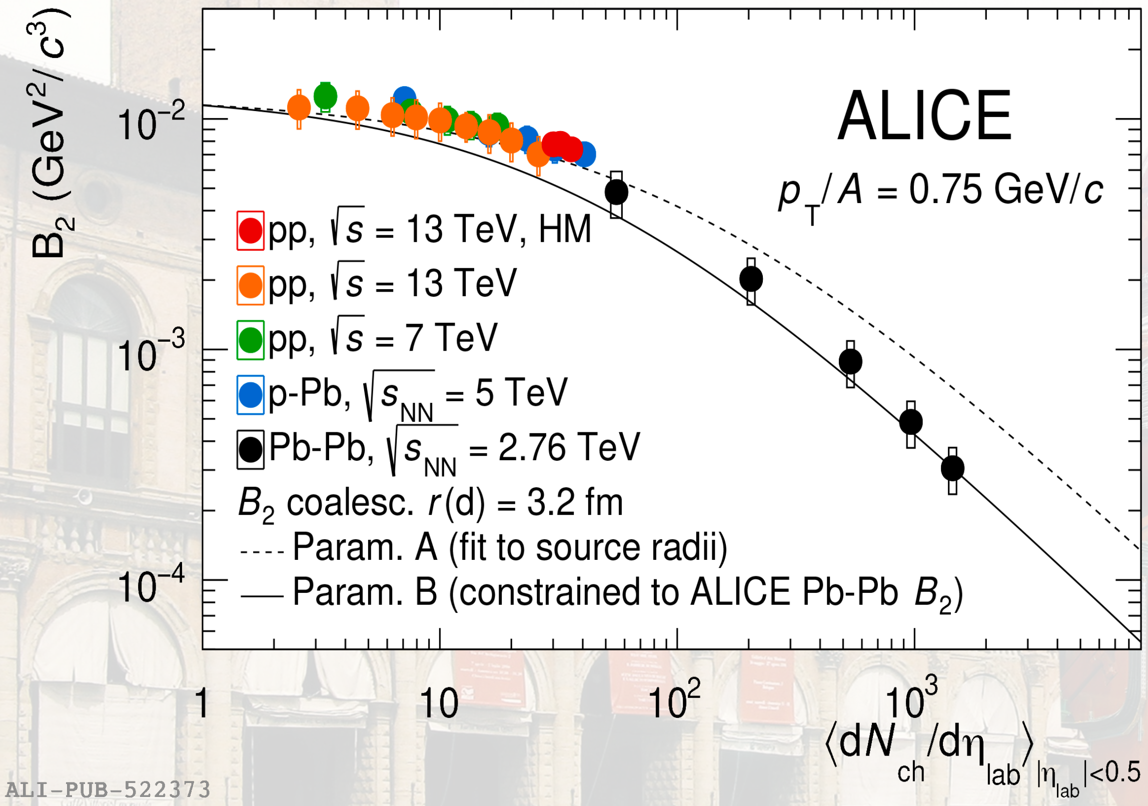
PROTONS — NEUTRONS

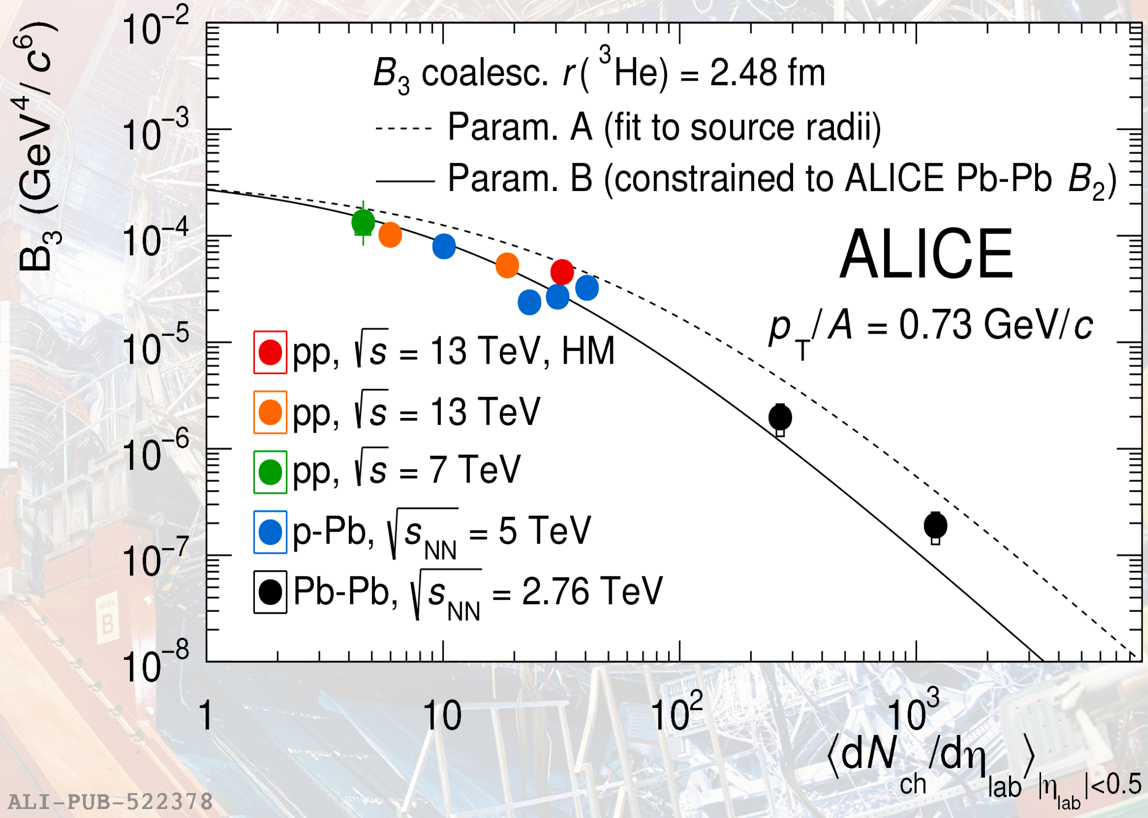
Experimentally defined based on the **particle yields**

The coalescence parameter B_A

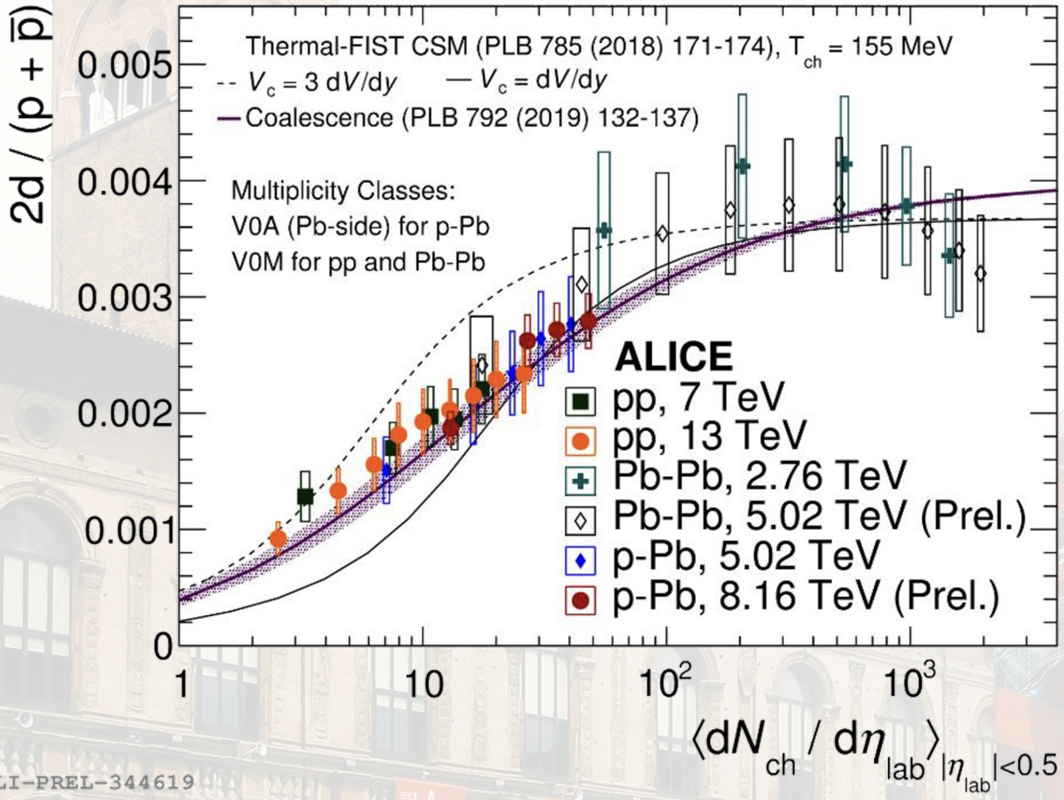


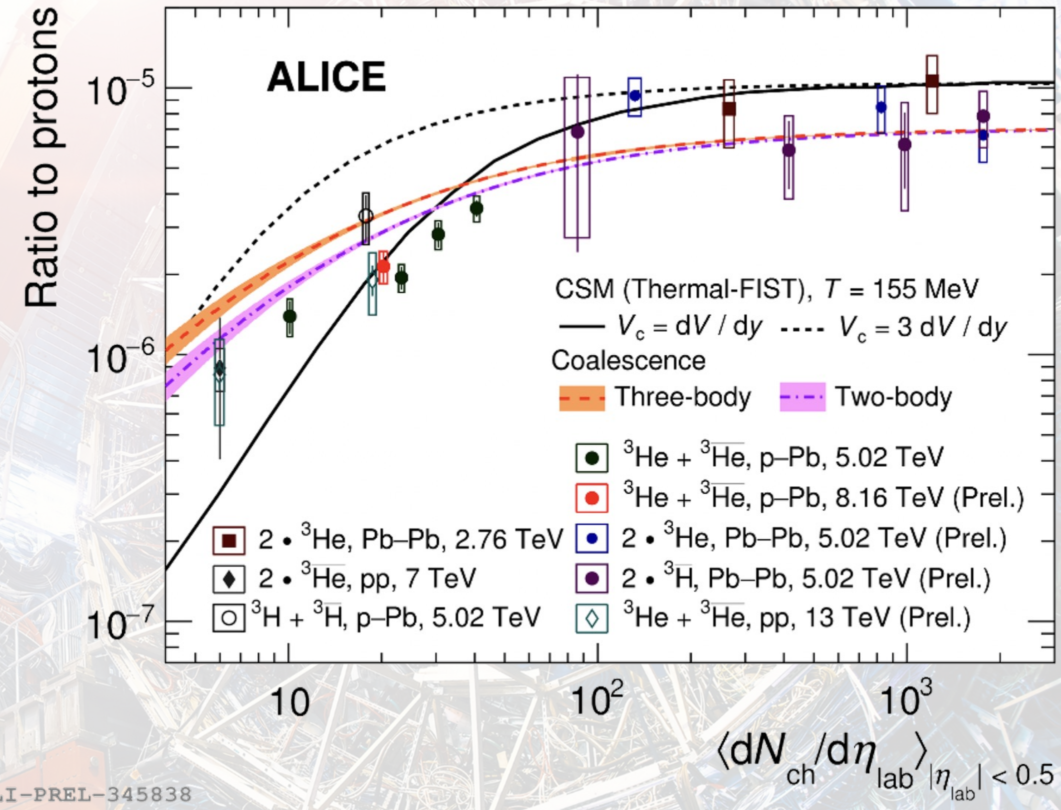






Nuclei over p ratio





d/p **rises** with charged particle multiplicity or particle density → consistent with coalesence

Saturation in HI collisions within the errors

Excellent consistence with coalescence for Z=1 nuclei → Z=2 not as good

Saturation in HI collisions within the errors

Light antinuclei as smoking guns for Dark Matter

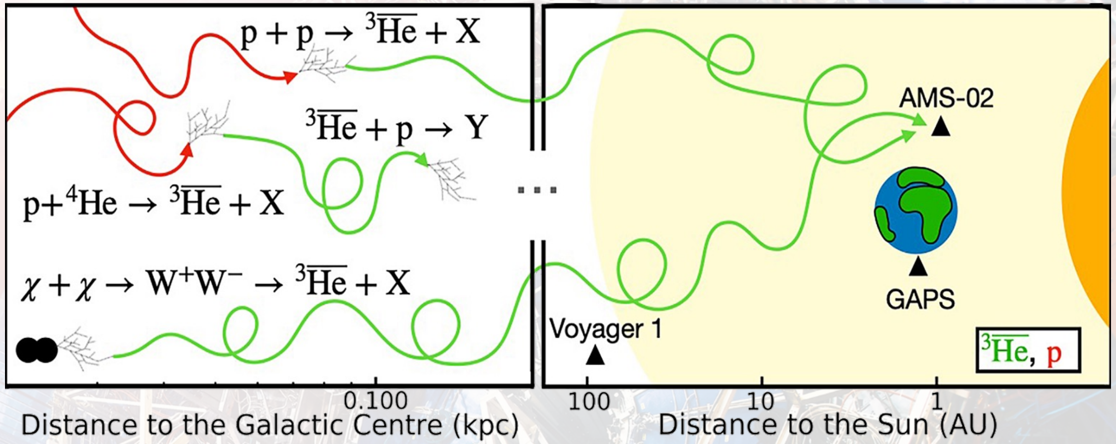
[M. Korsmeier, F. Donato, N. Fornengo, Phys. Rev. D 97, 103011 (2018)]

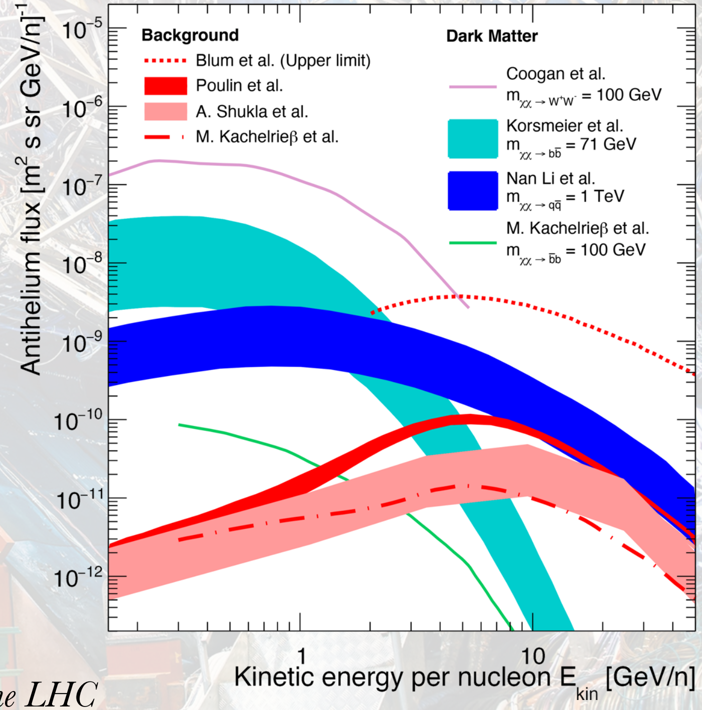
A significant number of **cosmological and astrophysical evidences** suggests the existence of **dark matter** (DM).

One possible strategy: search for products of DM **annihilation** in cosmic rays with space-based experiments (AMS, GAPS).

Light **antinuclei** ($\bar{d}$, $^{3}\overline{He}$) are considered promising detection channels for dark matter due to the expected low background from ordinary cosmic ray interactions with interstellar medium (mainly pp and p − A interactions).

To distinguish **primary and secondary** fraction in cosmic ray antideuteron and antihelium is essential to have knowledge of mechanisms of **antinuclei production**, their propagation in the galactic medium and annihilation.





P. von Doetinchem *et al.*, JCAP **08**, 035 (2020)

Light antinuclei as smoking guns for Dark Matter

[M. Korsmeier, F.

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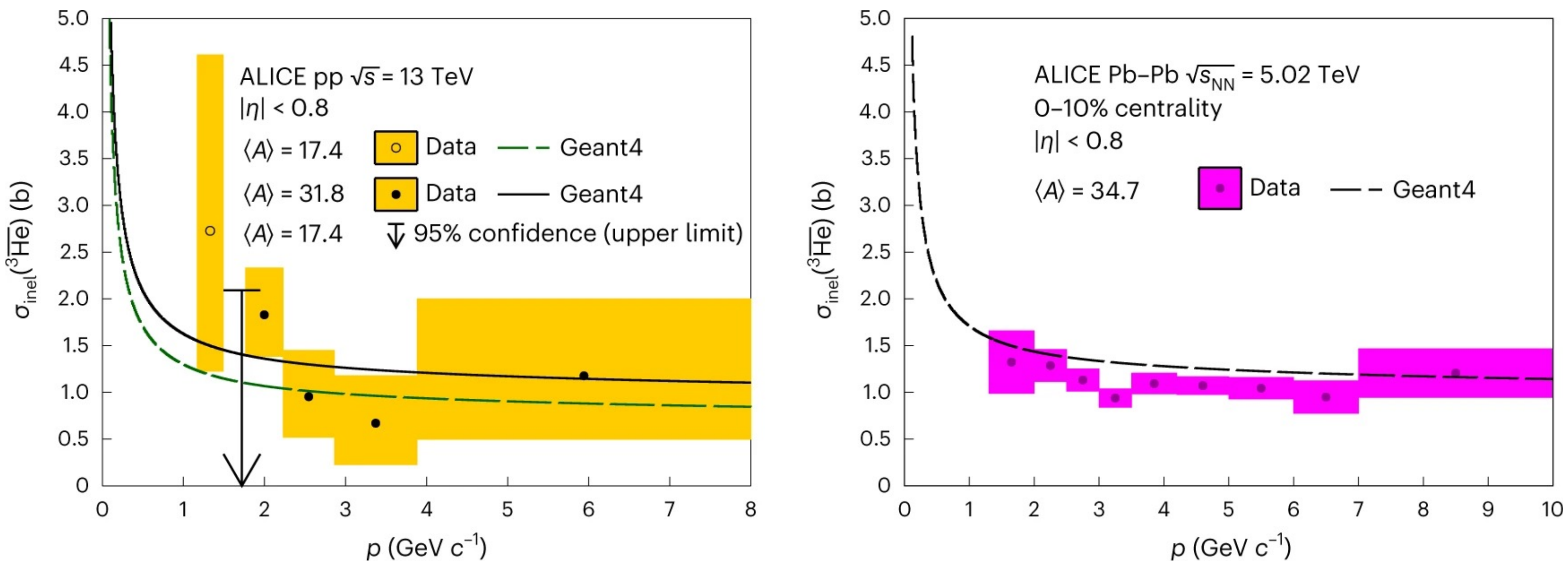
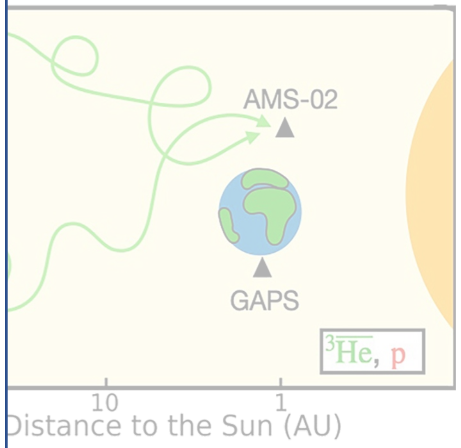
Measurement of anti-^{3}He nuclei absorption in matter and impact on their propagation in the Galaxy

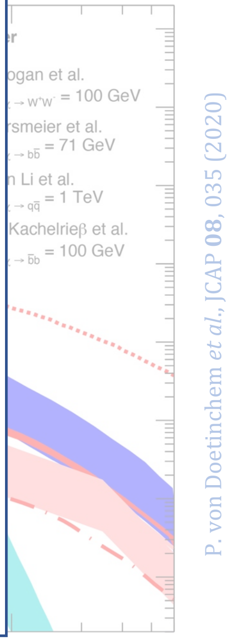
The ALICE Collaboration

Nature Physics **19**, 61–71 (2023) | Cite this article



Results obtained from pp collisions at $\sqrt{s}$ = 13 TeV (left); results from the 10% most central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (right). The curves represent the Geant4 cross sections corresponding to the effective material probed by the different analyses. The arrow on the left plot shows the 95% confidence limit on $\sigma_{inel}(^3\overline{He})$ for ⟨A⟩ = 17.4. The different values of ⟨A⟩ correspond to the three different effective targets (see the main text for details). All the indicated uncertainties represent standard deviations.





Thanks for your attention