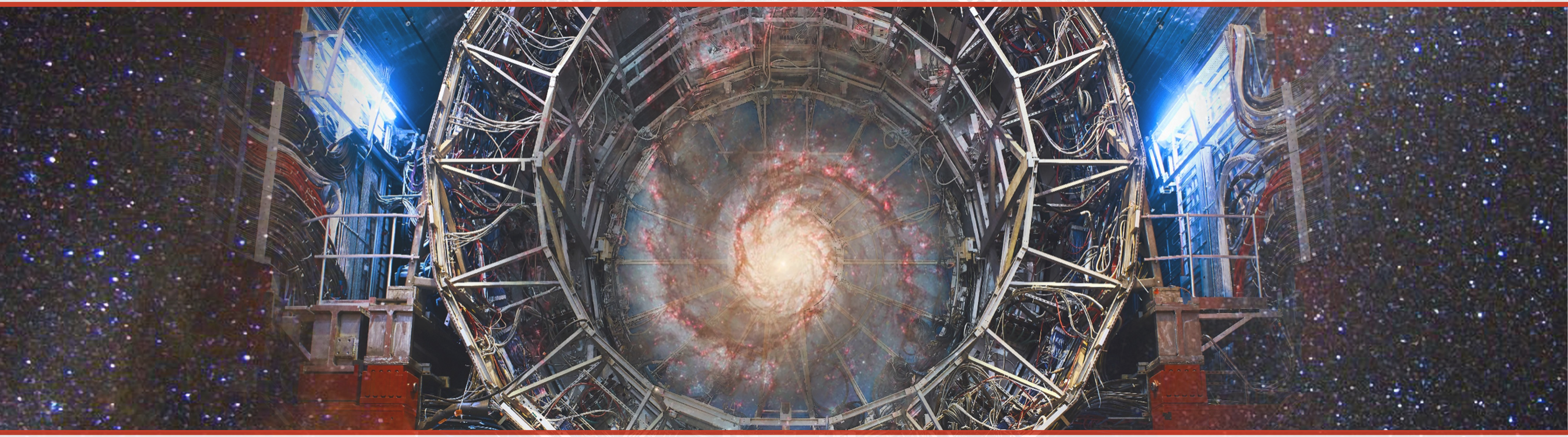
(Anti)nuclei production mechanisms and latest constraints from ALICE at the LHC



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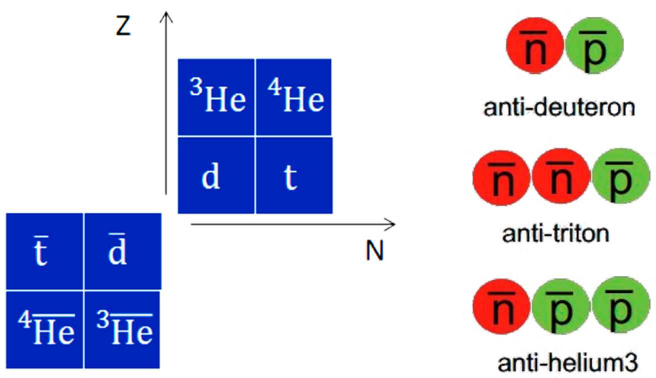
INFN Istituto Nazionale di Fisica Nucleare

CosmicAntiNuclei

ALICE

Introduction

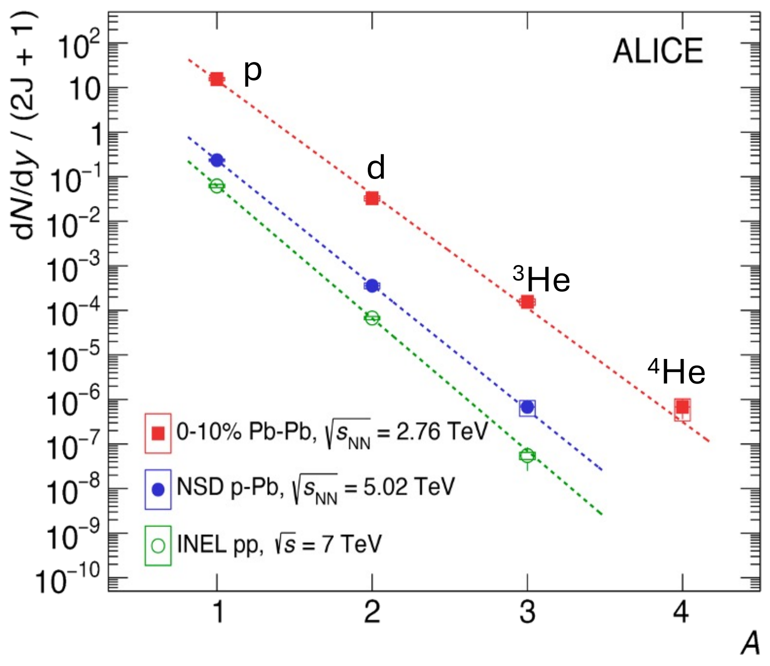


The production **mechanism** of light (anti)nuclei in high-energy collisions is **not fully understood**

Low binding energy and **large mass** implies that their formation is strongly sensitive to the temperature

Astrophysics applications: measurements in controlled conditions constrain searches for **antimatter** from dark matter in cosmic rays

ALICE, *Phys. Lett. B* ***800***, *135043 (2020)*



Rarely produced in high-energy collisions
→ Requires **large integrated luminosity**

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

At LHC, **same amount of matter and antimatter**[1]
→ Ideal conditions for studying **antinuclei**

Nuclei production described by **models**:
- Statistical hadronization model (**SHM**)
- **Coalescence**

[1] Physical Review C97, 024615 (2018)

ALICE

The ALICE collaboration has performed several (anti)nuclei measurements since the beginning of operations

The ALICE apparatus is particularly suited for **light (anti)nuclei identification**

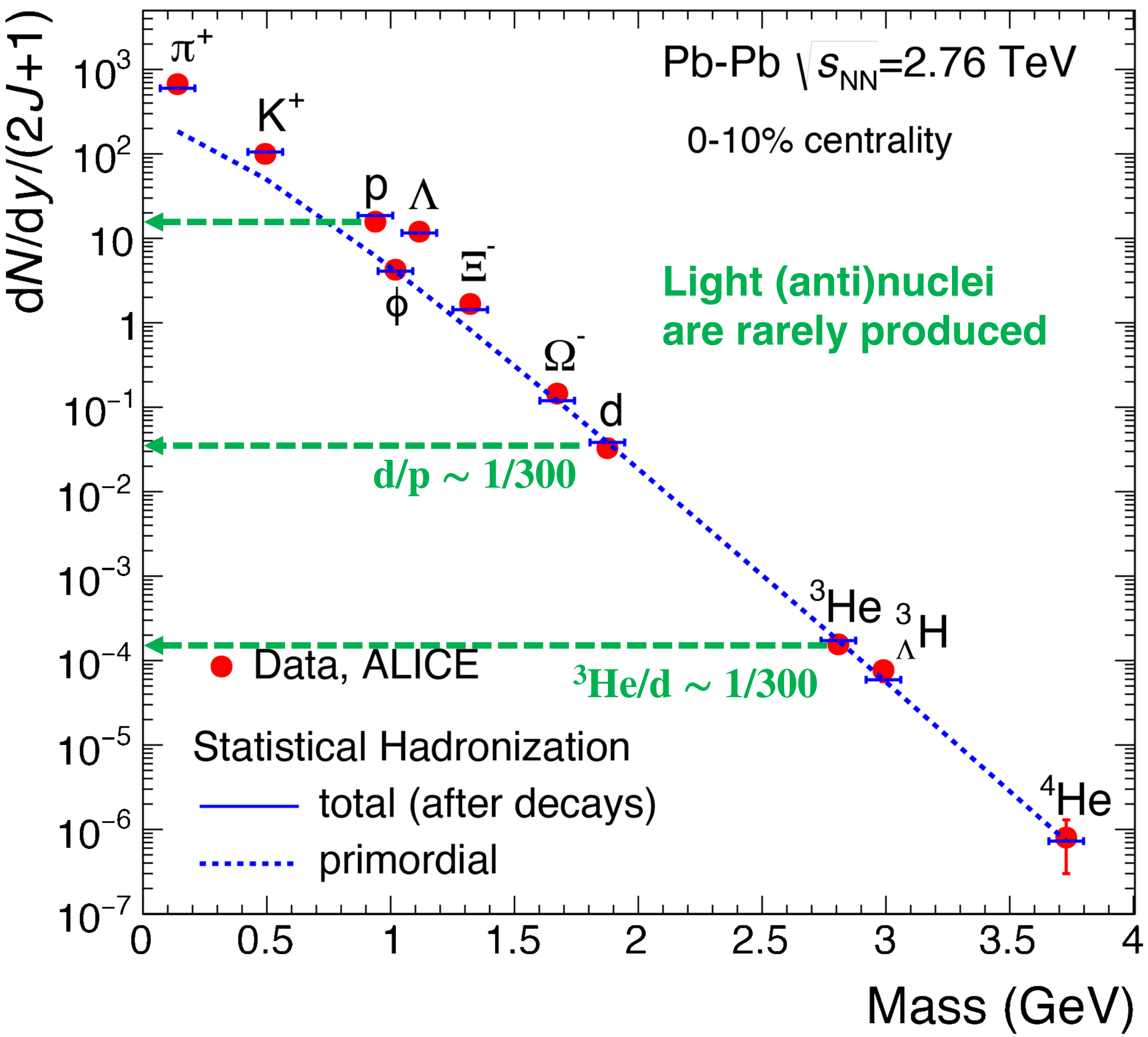
(Anti)nuclei in the Statistical Hadronization Model (SHM)

- **Statistical physics-based** model
- The hadrons are emitted from the source in **thermal equilibrium** at chemical freeze-out $T = T_{chem}$ [1]
- The abundances depend on the hadron **mass m, T_{chem}** and **spin degeneracy** as

$$\mathrm{d}N/\mathrm{d}y \propto (2J+1)\, e^{-\frac{m}{T_{\mathrm{chem}}}}$$

- The SHM can be extended **from high- to low-multiplicity systems** via **canonical formulation (CSM)**: the baryon number B, the electric charge Q and the strangeness S values are conserved exactly across the **correlation volume V_C** [2]
- The SHM predicts **abundances** but not the **p_T-dependent** yield

[1] Andronic, A. et al., *Nature 561, 321–330 (2018)*
[2] Vovchenko, V. et al., *Phys. Letters B 785, 171-174 (2018)*



(Anti)nuclei in coalescence models

- **Microscopical** model

- Nuclei are formed from nucleons close in the **phase space** and matching the right spin-isospin configuration

- The formation probability is related to the **coalescence parameter B_A**

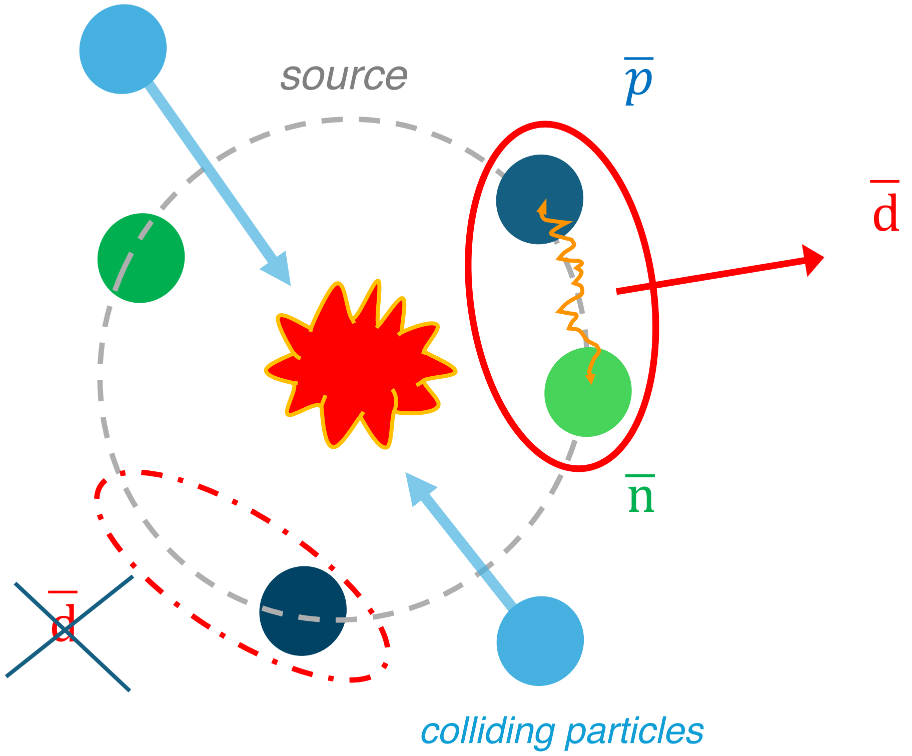
- B_A can be **experimentally** defined as

NUCLEUS — NUCLEONS

$$E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3} = B_A \left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^Z \Bigg|_{\vec{p}_\mathrm{p} = \frac{\vec{p}_A}{A}} \left(E_\mathrm{n} \frac{\mathrm{d}^3 N_\mathrm{n}}{\mathrm{d}p_\mathrm{n}^3} \right)^N \Bigg|_{\vec{p}_\mathrm{n} = \frac{\vec{p}_A}{A}}$$

PROTONS — NEUTRONS

- B_A can be estimated theoretically with quantum-mechanical treatment that rely on the nucleon **momenta**, **positions** and the **nucleus wavefunction**

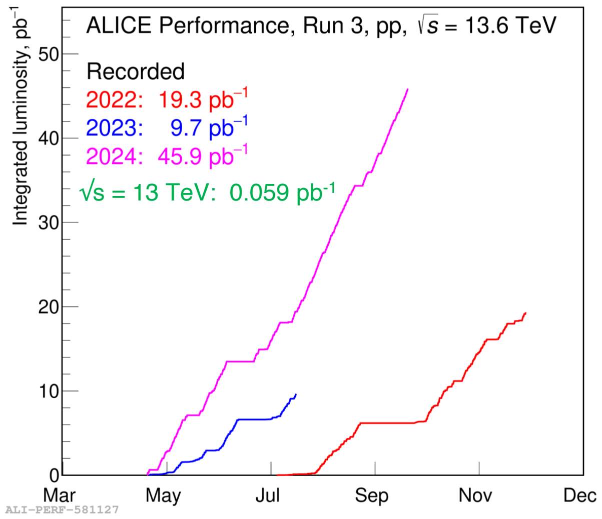


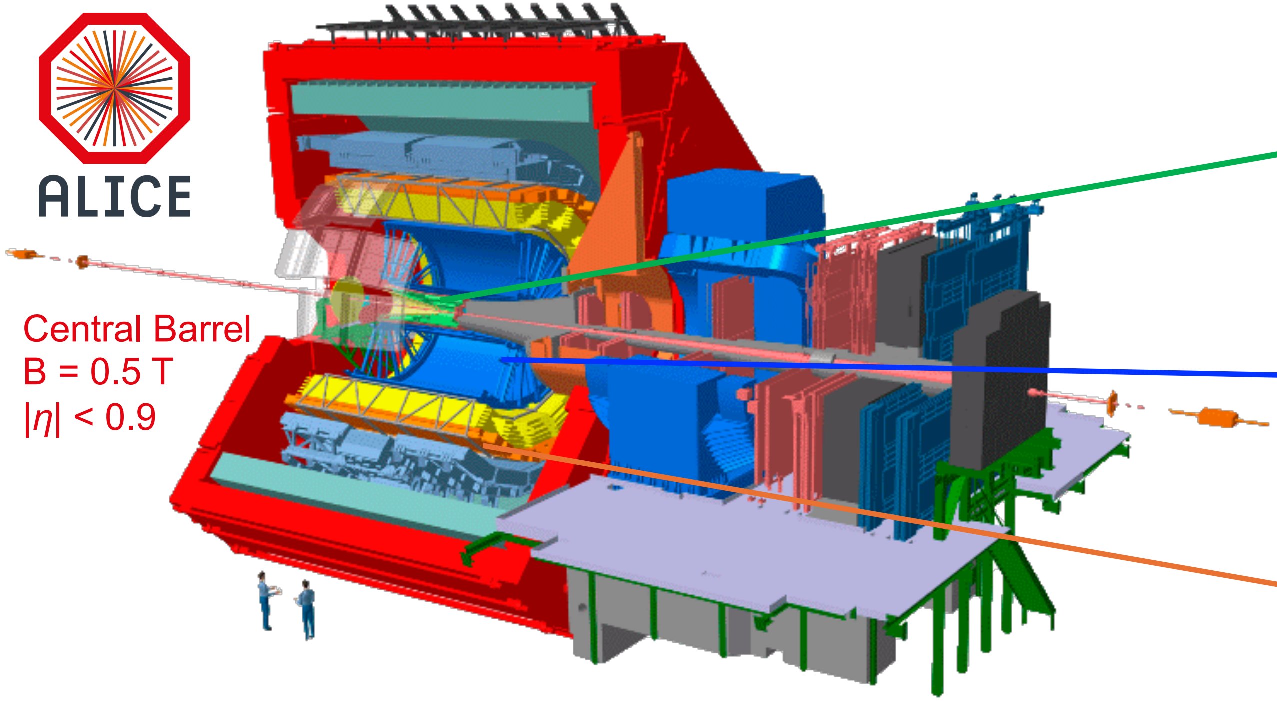
J. I. Kapusta, *Phys.Rev. C21, 1301 (1980)*
Scheibl, Heinz, *Phys.Rev.C59:1585-1602 (1999)*

The ALICE experiment at the Large Hadron Collider

Major upgrades during Long Shutdown 2 (2018-2021)
→ A **new powerful** detector for LHC Run 3

The new **Integrated Online-Offline system** developed to perform Run 3 event reconstruction and analysis
→ Up to **5 times** Run 2 interaction rate in ALICE in Pb-Pb
→ Unprecedentedly large data samples





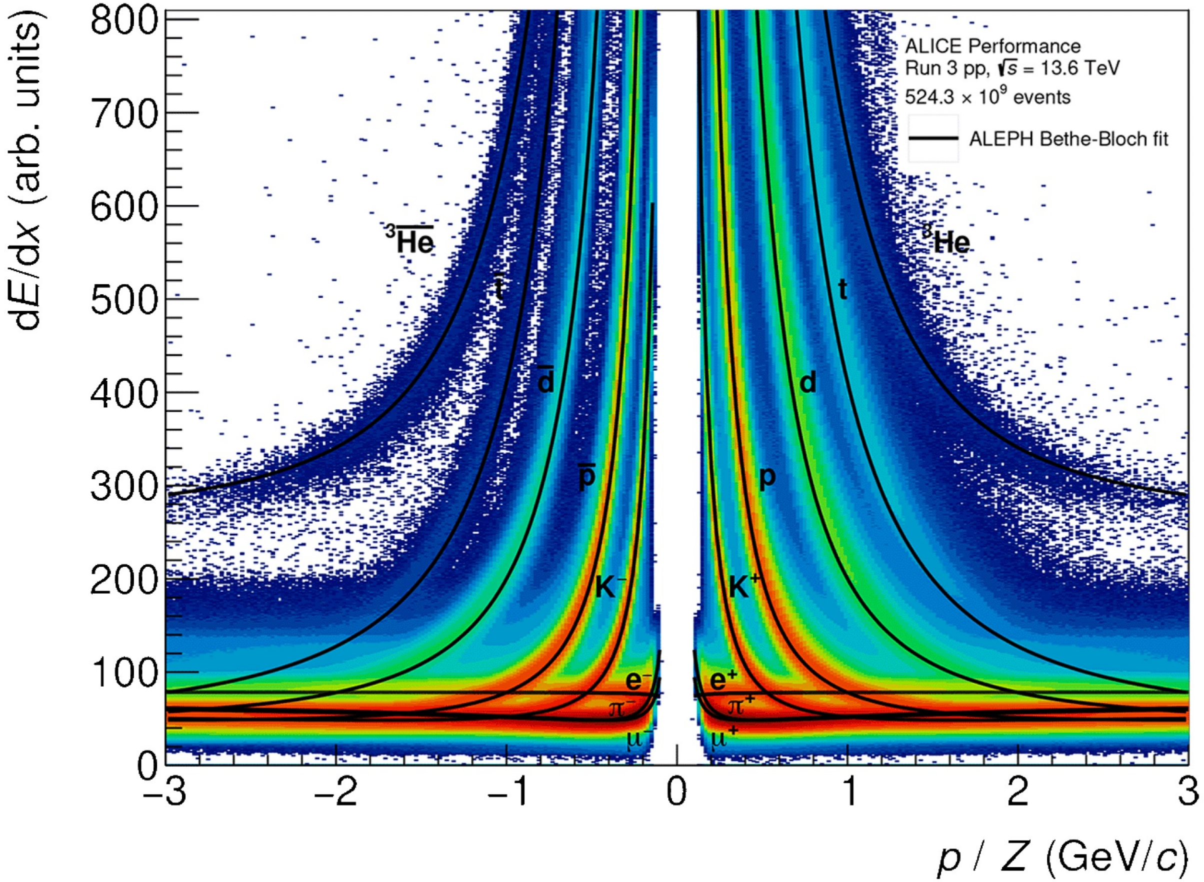
Inner Tracking System (ITS)
- 7 layers pixel detector
- 10 m^2 (12.5 GP) silicon tracker based on MAPS

Time Projection Chamber (TPC)
- GEM-based readout pads
- PID via **energy loss (d*E*/dx)** in the TPC gas

Time Of Flight detector (TOF)
- PID via **time-of-flight** measurements

Light (anti)nuclei identification in ALICE

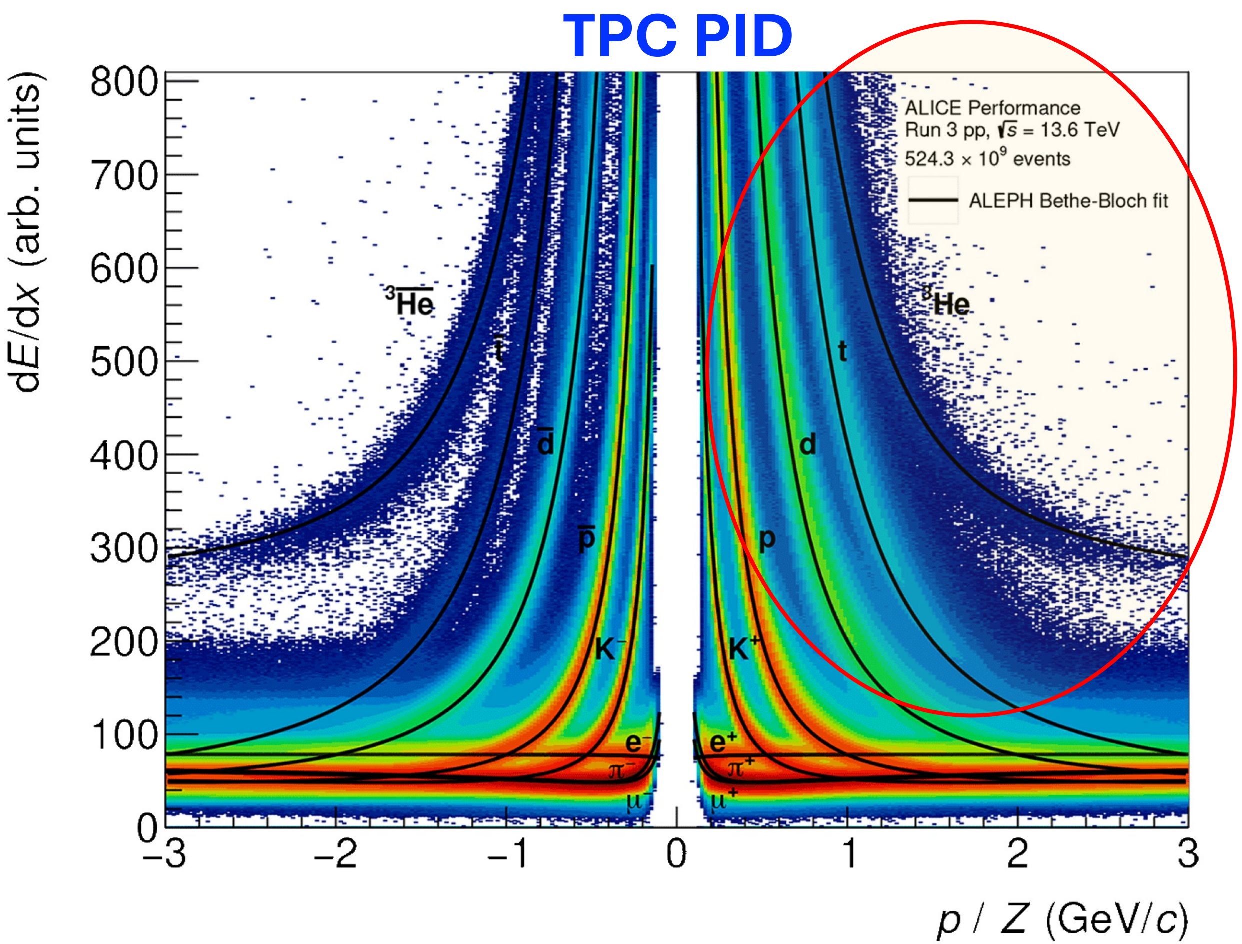
TPC PID



Low momentum (p_T < 1–3 GeV/c) PID via energy loss in the gas

dE/dx resolution ~ 5% in pp

Light (anti)nuclei identification in ALICE

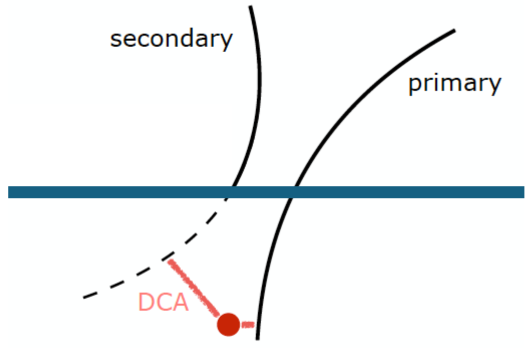


Low momentum ($p_T < 1$–3 GeV/c) PID via energy loss in the gas

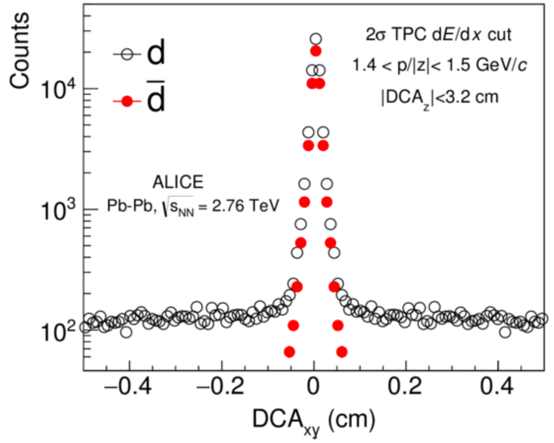
dE/dx resolution ~ 5% in pp

Secondary contamination due to knock out from detector material (for **nuclei**, not antinuclei)

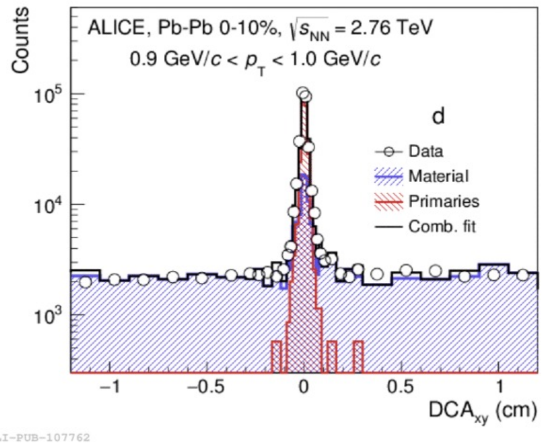
→ Corrected during data analysis via Distance of Closest Approach (**DCA**)



DCA to the PV of deuteron and anti-deuteron candidates

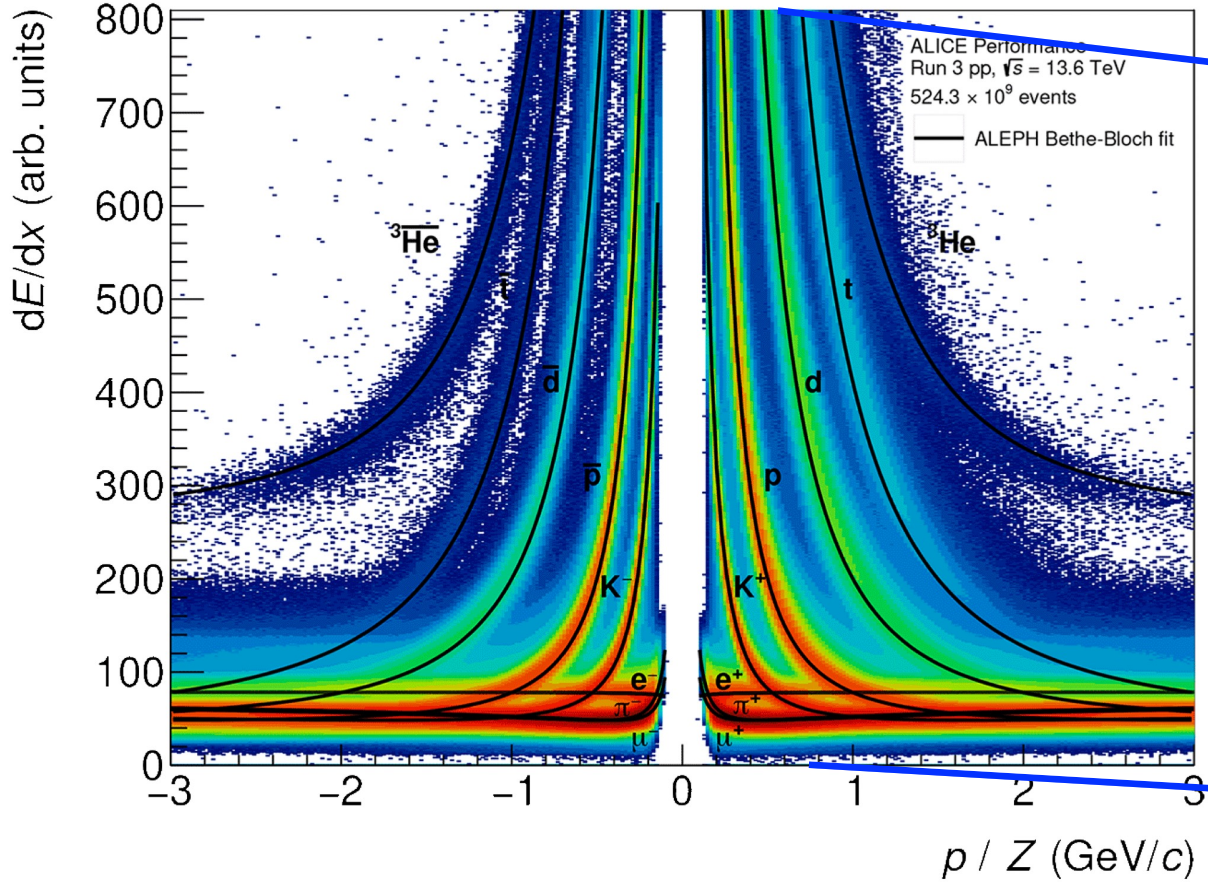


Template fit to the DCA to the PV of deuteron candidates

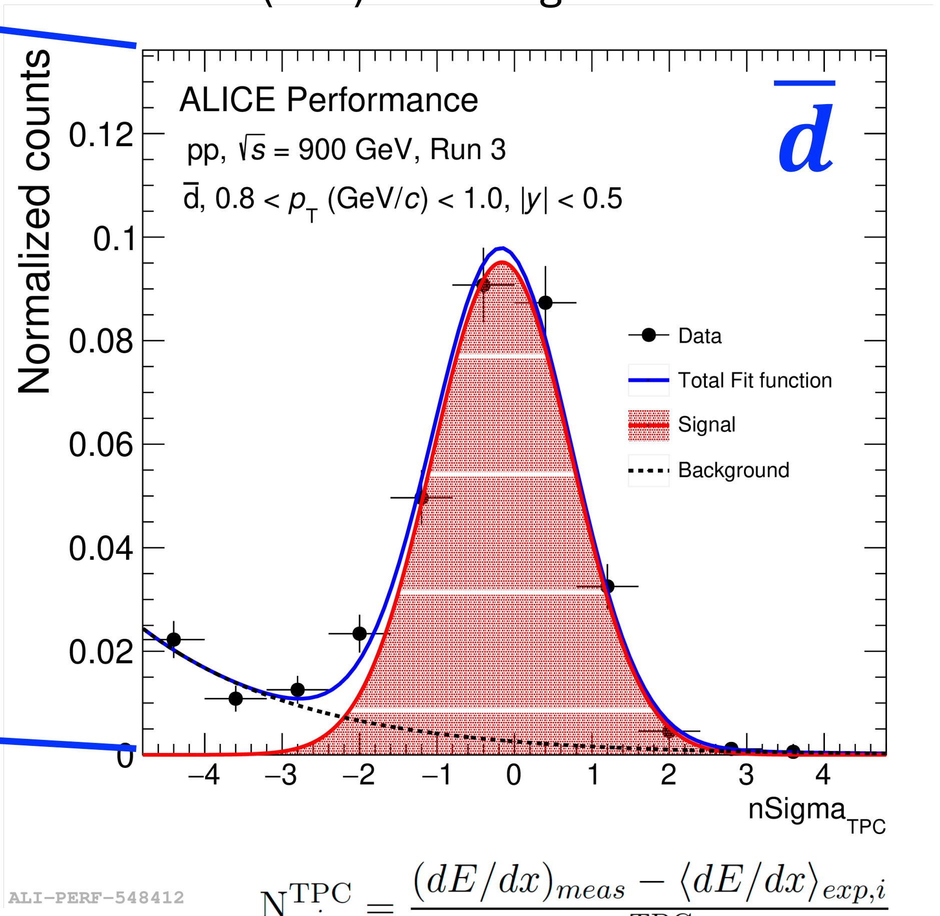


Light (anti)nuclei identification in ALICE

TPC PID



(anti)nuclei signal in TPC



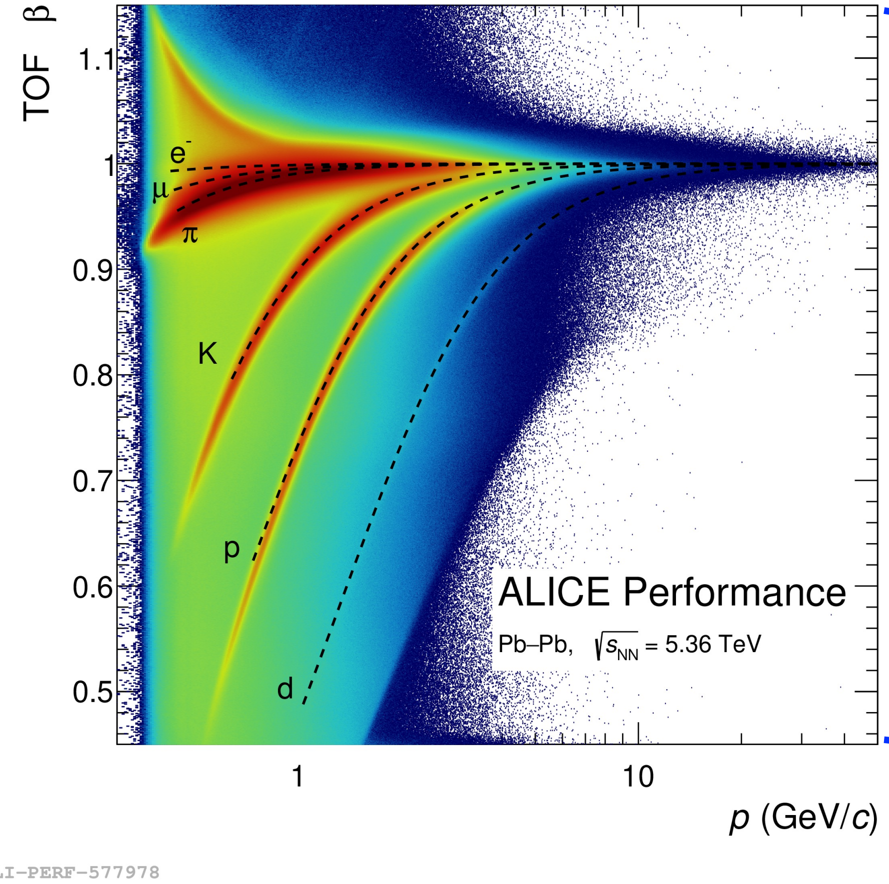
$$N_{\sigma,i}^{\mathrm{TPC}} = \frac{(dE/dx)_{meas} - \langle dE/dx\rangle_{exp,i}}{\sigma_i^{\mathrm{TPC}}}$$

Low momentum (p_T < 1–3 GeV/c) PID via energy loss in the gas

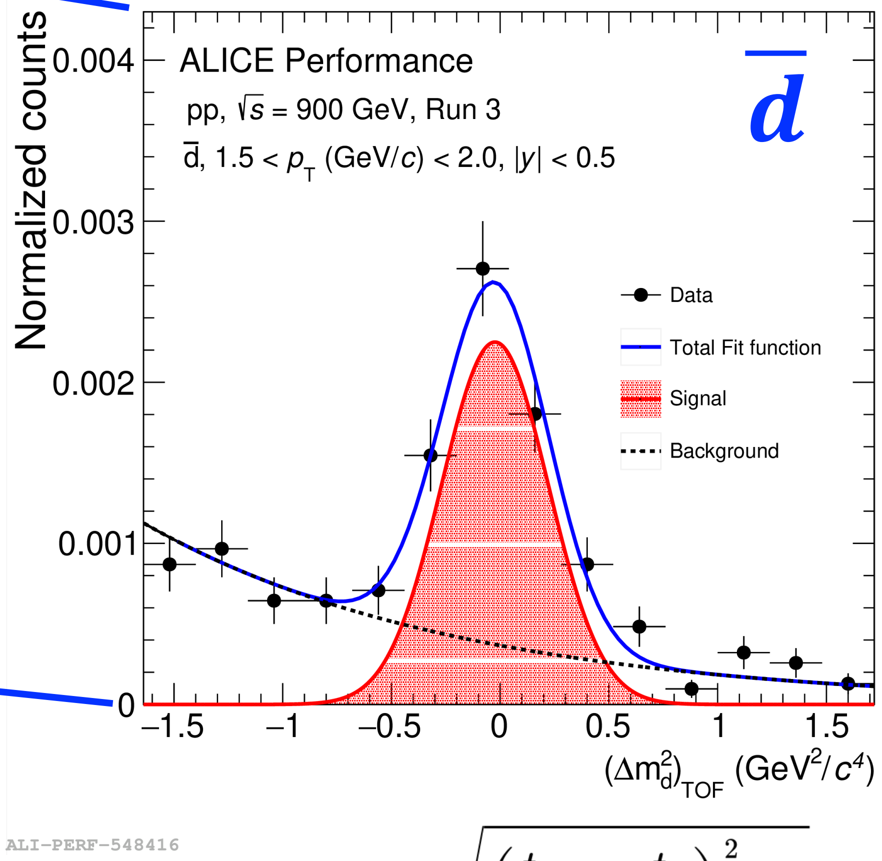
dE/dx resolution ~ 5% in pp

Light (anti)nuclei identification in ALICE

TOF PID



(anti)nuclei signal in TOF
(w/ TPC preselection)



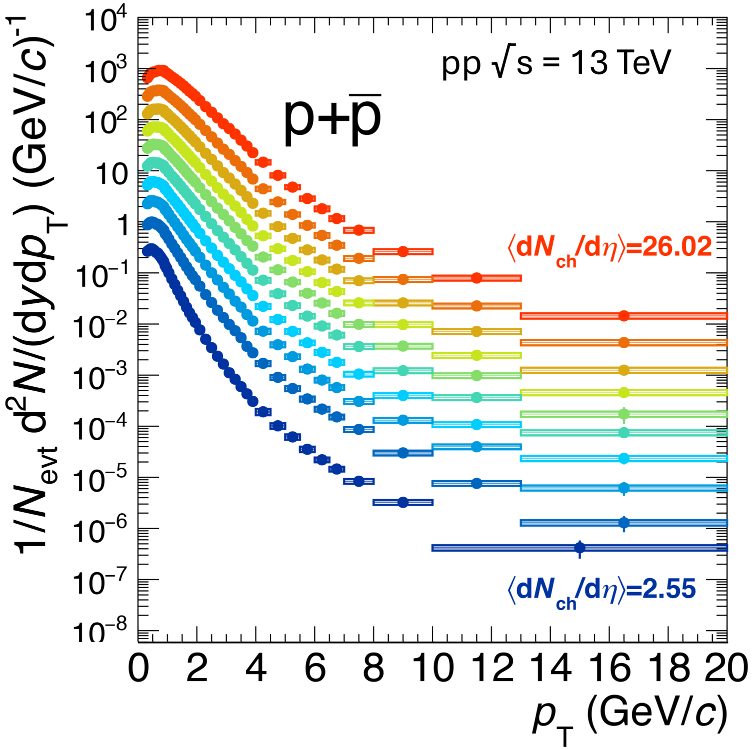
$$m_{TOF} = p\sqrt{\left(\frac{t_{TOF} - t_0}{L}\right)^2 - 1}$$

Intermediate momentum ($p_T < 5$ GeV/c) PID via time-of-flight

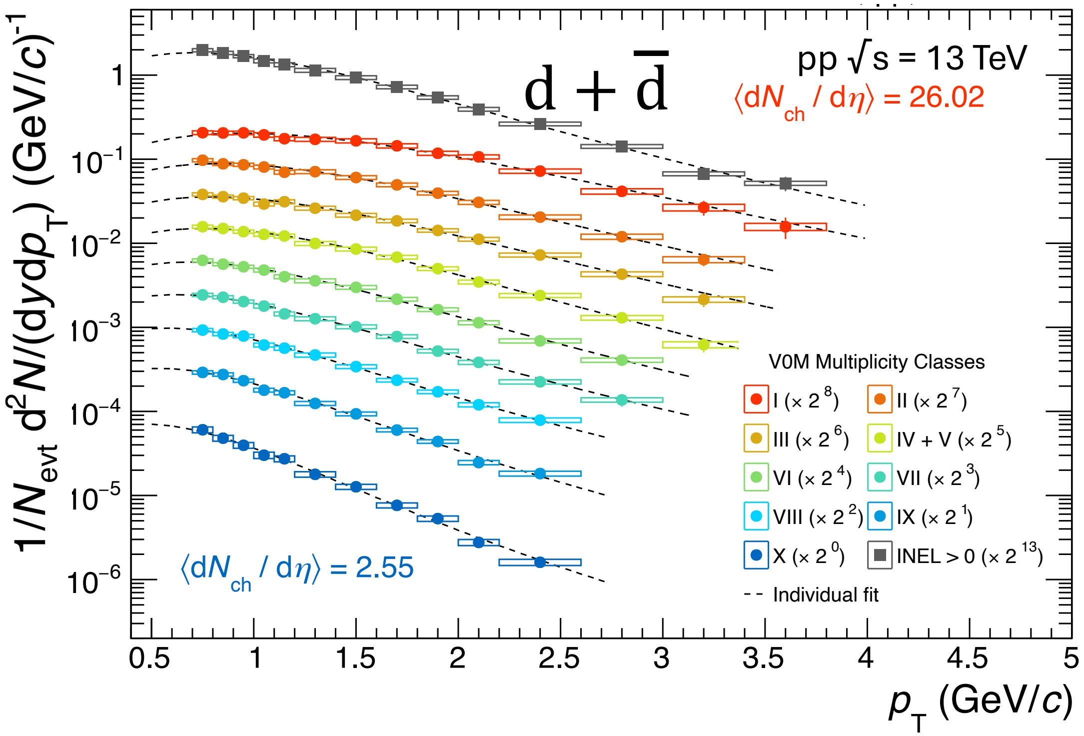
Resolution up to 50 ps in Pb-Pb collisions

Light (anti)nuclei measurements

ALICE, *Eur.Phys.J.C* 80 (2020) 8, 693



ALICE, *Eur.Phys.J.C 80 (2020) 9, 889*



Nuclei spectra:
→ p_T-dependent **yield** as a function of the multiplicity
→ our main observable

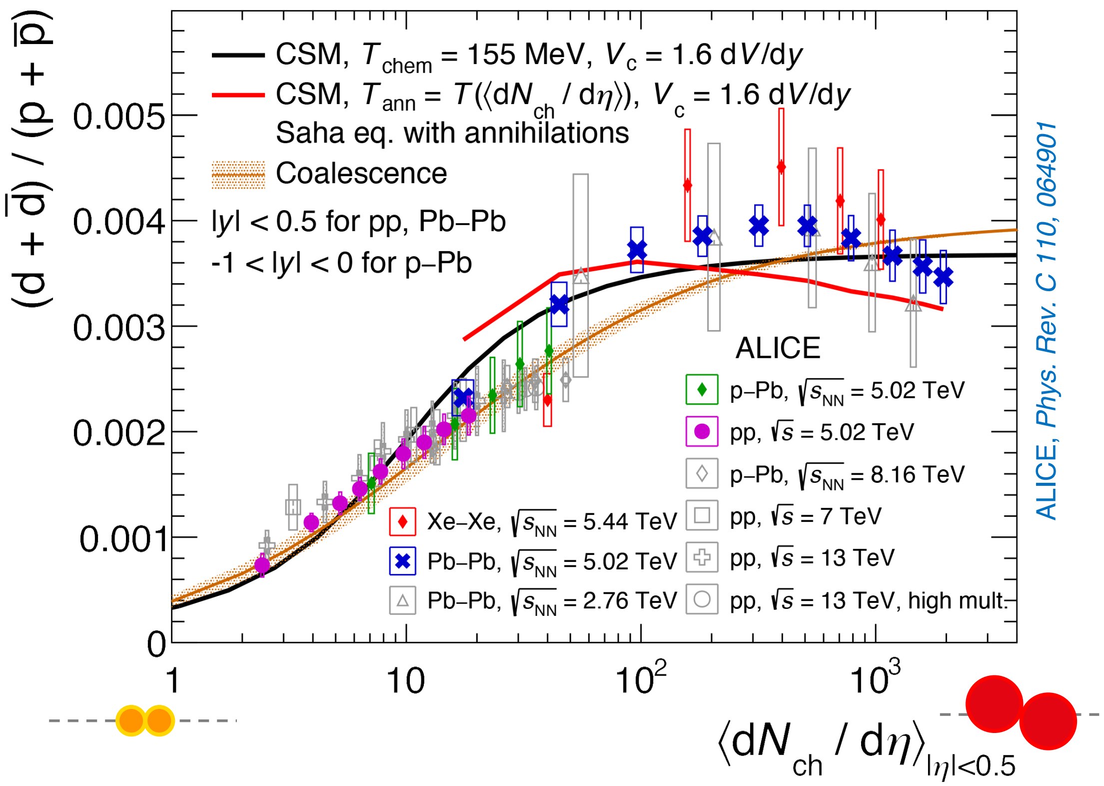
- Fundamental input to test **coalescence** via B_A estimation
- Spectra fit with **Lévy-Tsallis** distribution to extrapolate yield outside the measurements

- Measured in different **multiplicities**
→ spectra hardening observed with increasing multiplicity

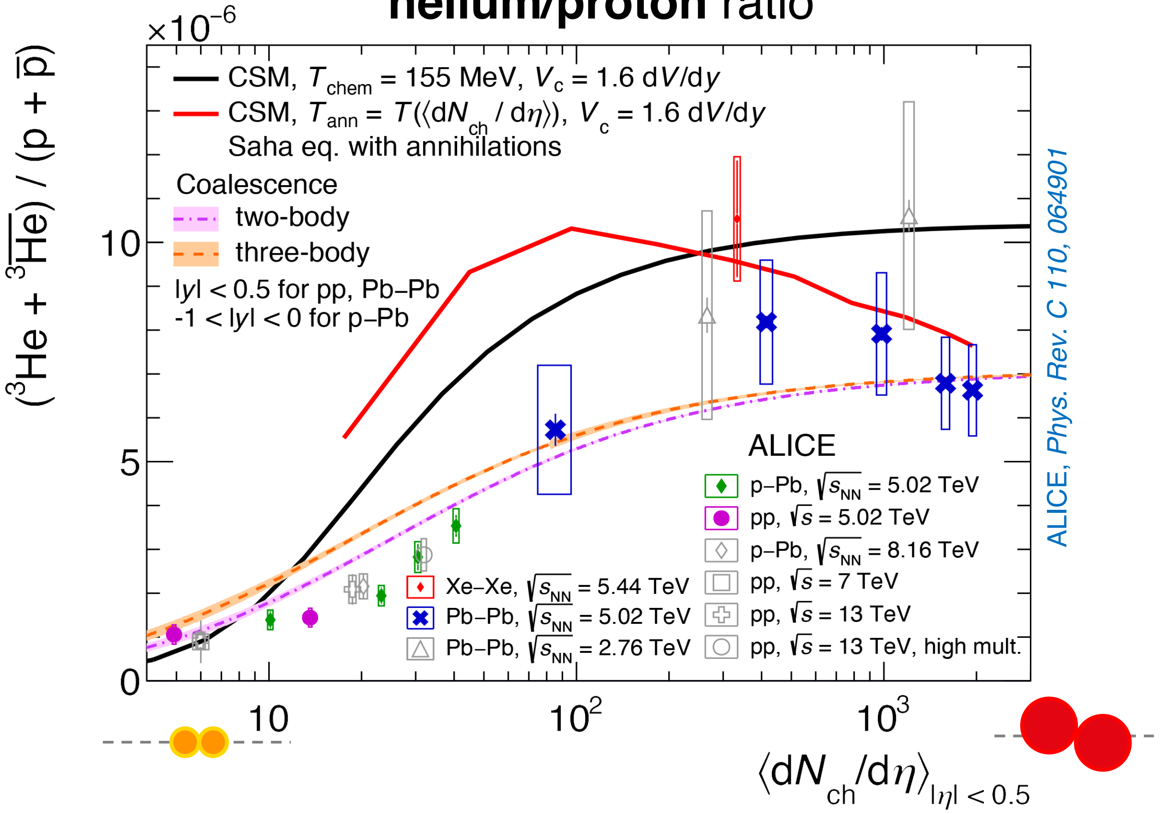
Model comparison - (anti)nuclei-over-protons ratio

Measured in various colliding systems (pp, p-Pb, Xe-Xe, ...)

deuteron/proton ratio



helium/proton ratio

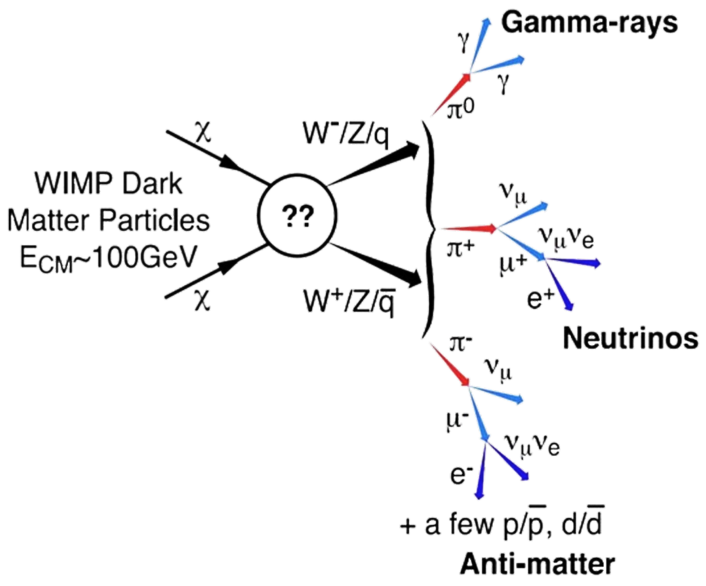


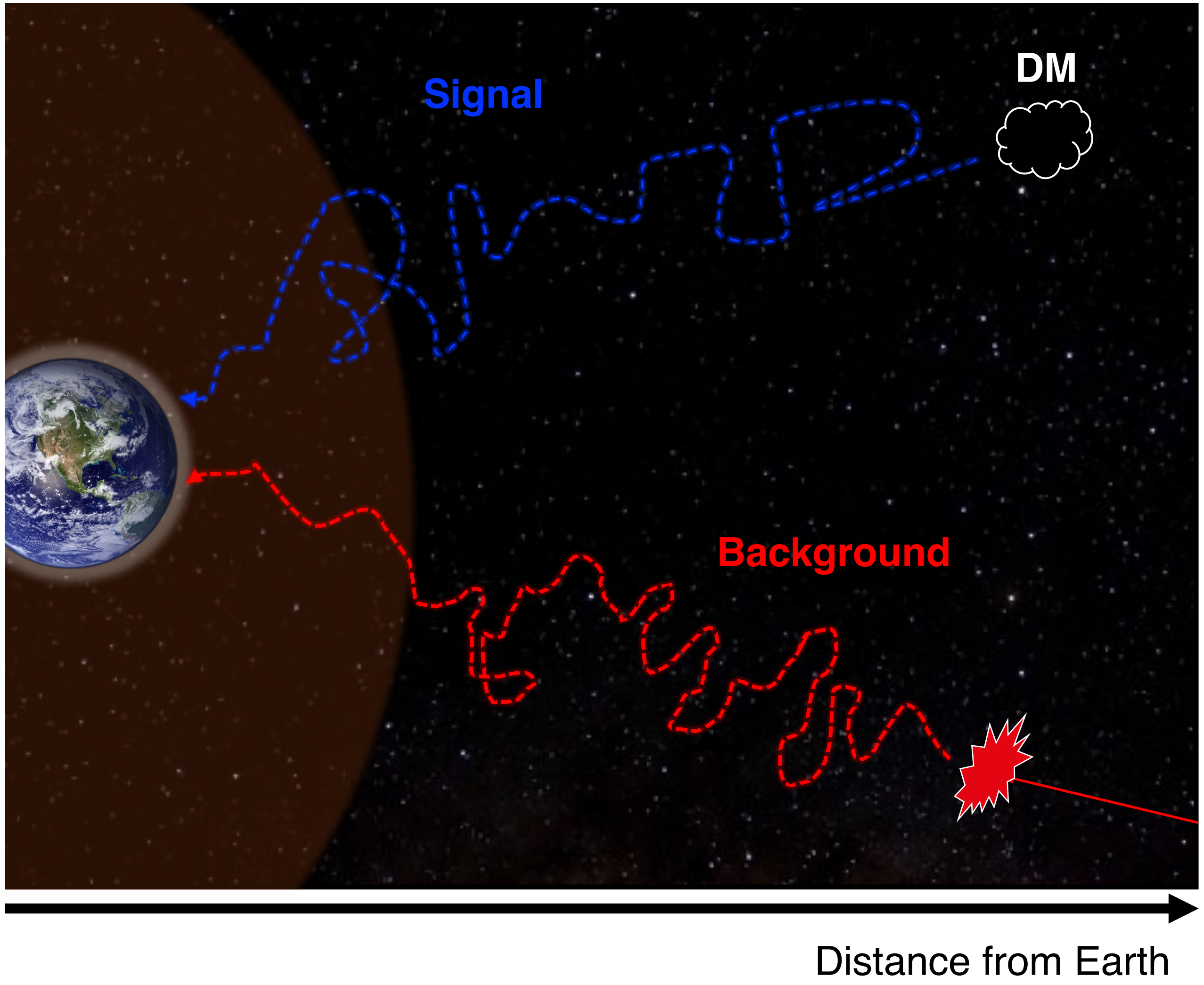
- d/p covered by wide set of measurements
- d/p **rises** with charged particle multiplicity
- Both **coalescence** and **CSM** agree with data

- **Neither of the models** describe data for (anti)helium in the full multiplicity range

Light antinuclei as smoking guns for Dark Matter

- Detection of light antinuclei in cosmic rays is proposed as **smoking gun** for annihilation of **Dark Matter particles** in the galactic halo
- A **background** is given by antinuclei produced by primary cosmic ray collisions with interstellar matter (pp, pA)





Light antinuclei as smoking guns for Dark Matter

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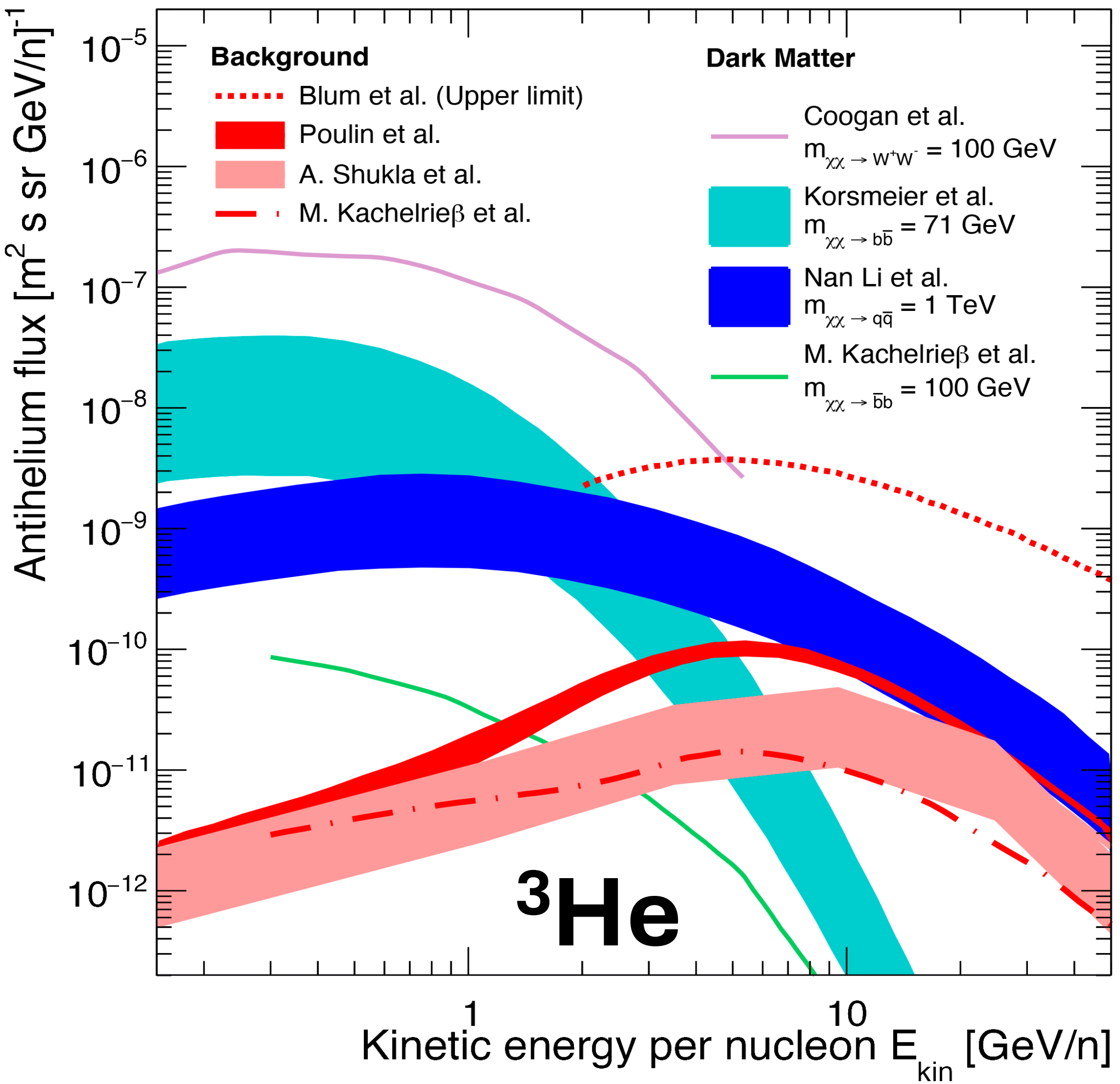
- A **background** is given by antinuclei produced by primary cosmic ray collisions with interstellar matter (pp, pA)
- Modelling of **signal** and **background** depends on the model of **formation** of antinuclei
- The background can be **constrained** with measurements in high-energy collisions at the LHC



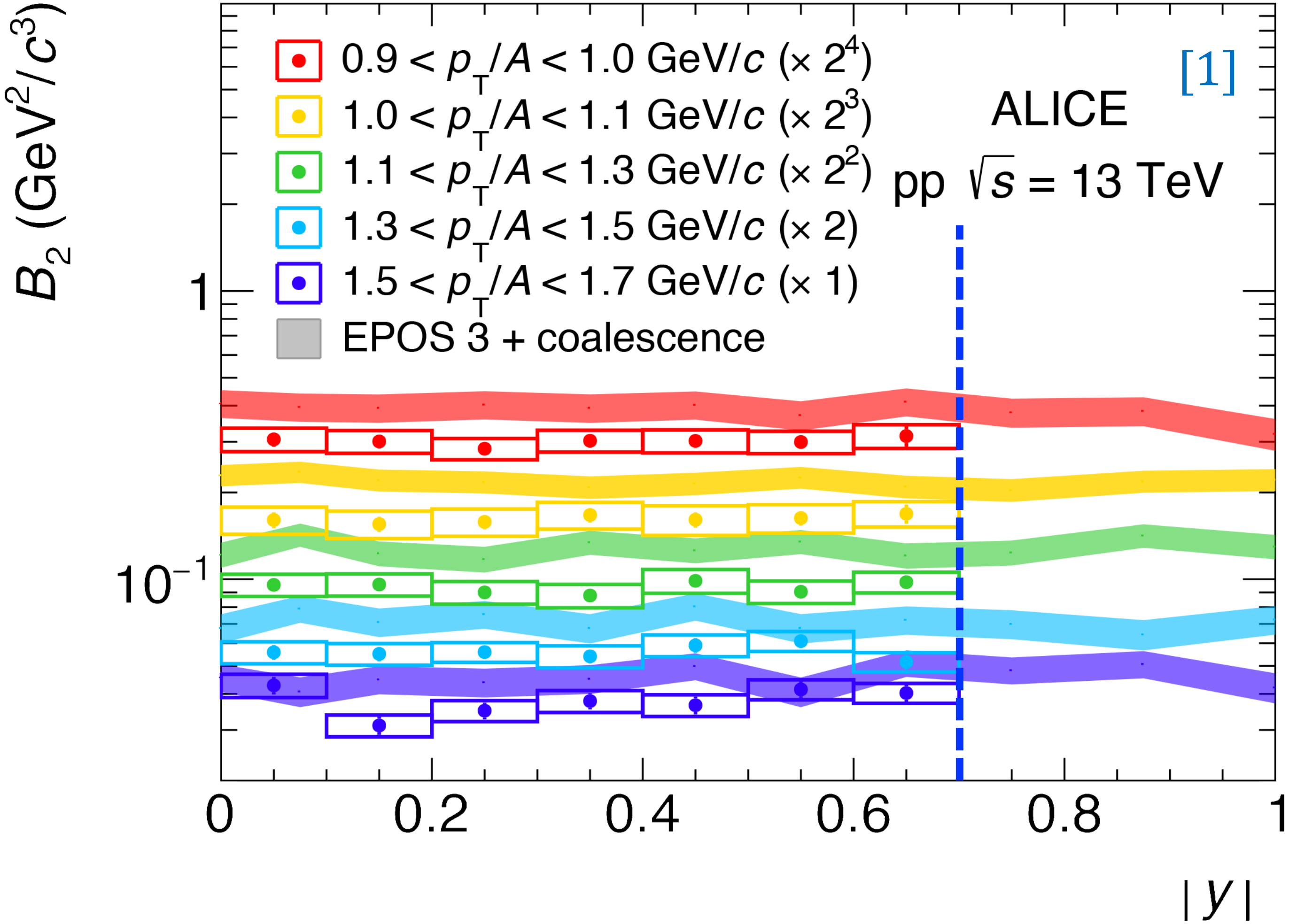
von Doetinchem, P. *et al.*, *JCAP* ***08***, *035 (2020)*

Rapidity dependent coalescence and cosmic antinuclei

The ALICE (anti)nuclei measurements are performed at $|y| < 0.5$

→ ALICE acceptance limit for nuclei: **$|y| < 0.7$**

→ **Forward rapidity** dependence of B_2 is extrapolated via coalescence + MC (EPOS)



[1] ALICE, *Physics Letters B 860 (2025) 139191*

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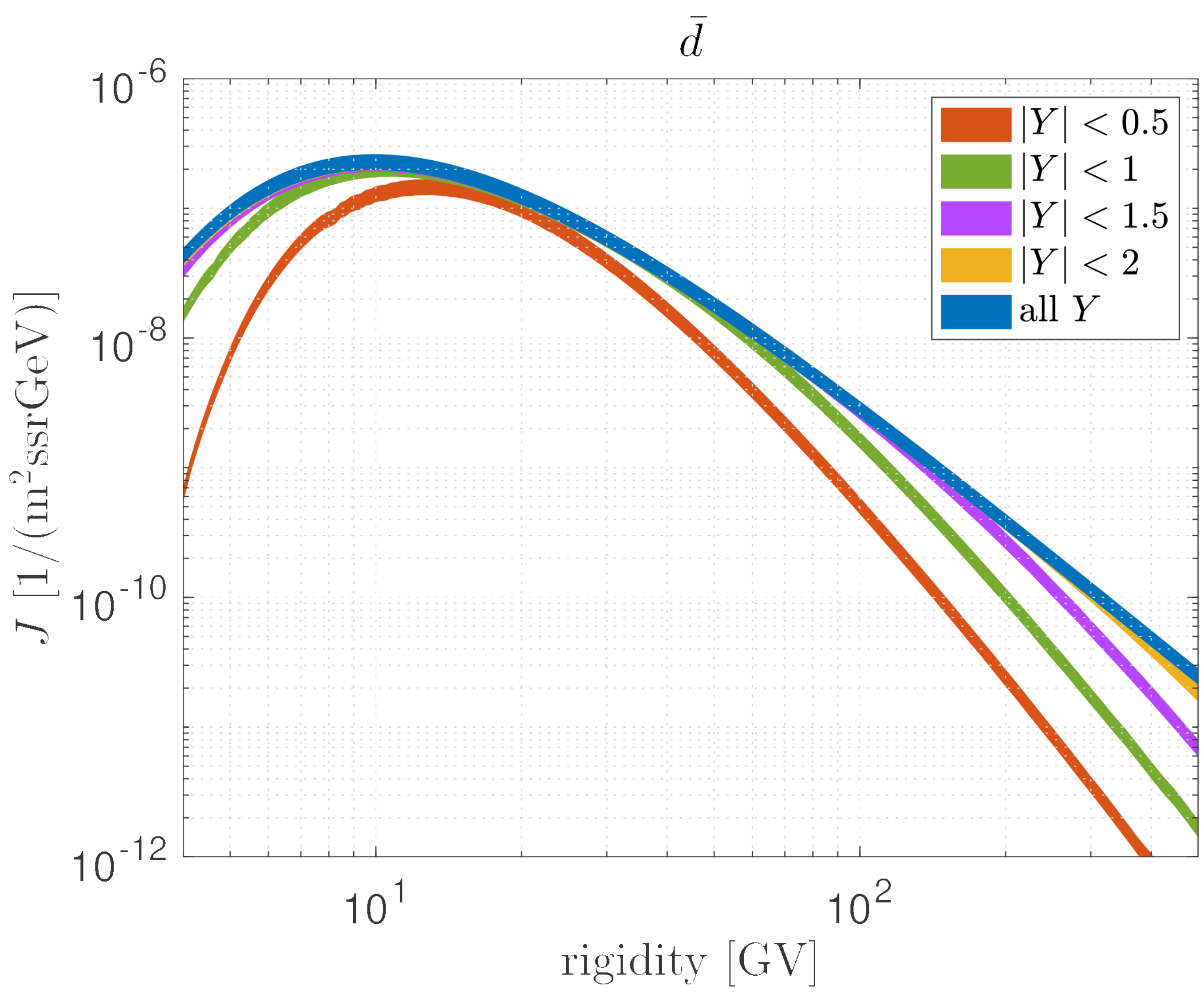
→ ALICE acceptance limit for nuclei:
$|y| < 0.7$
→ **Forward rapidity** dependence of B_2 is extrapolated via coalescence + MC (EPOS)

The ALICE data can be used to estimate the **antideuteron flux** from cosmic rays
→ **Dominant background** in DM searches
→ Flux of antideuterons from CRs is produced in the **rapidity interval** $|y| < 1.5$[2]



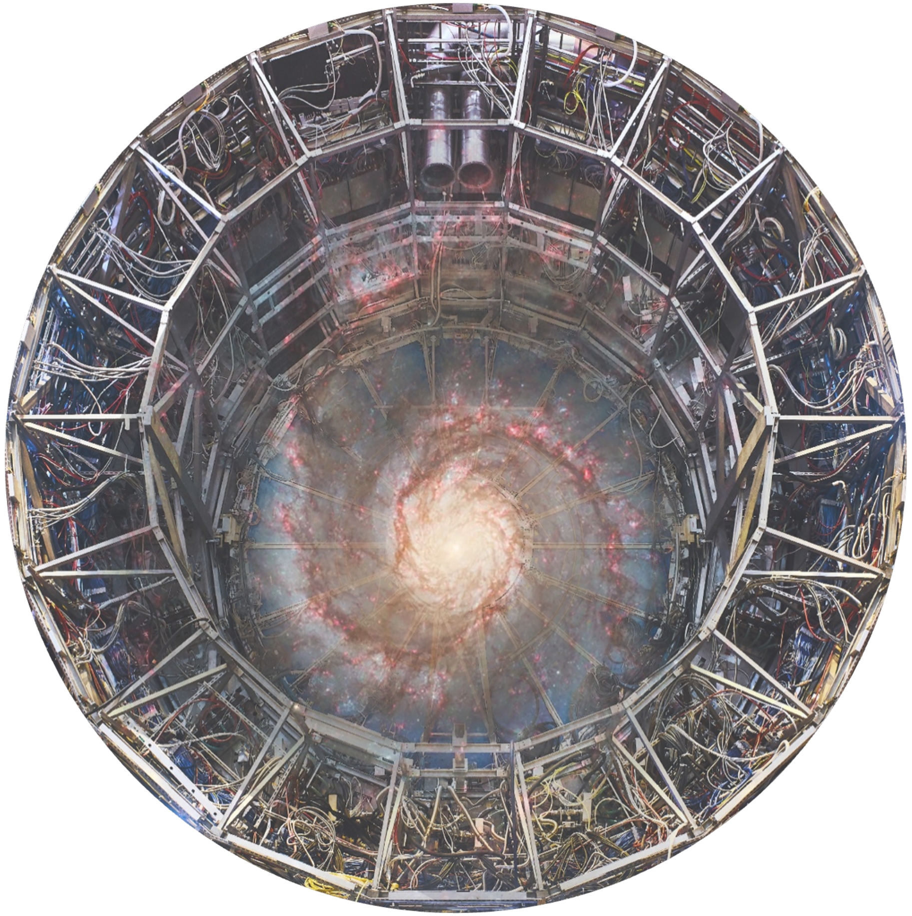
[1] ALICE, *Physics Letters B 860 (2025) 139191*
[2] Blum, K., *Phys.Rev.C 109 (2024) 3, L031904*

Conclusions

- LHC, as an **antimatter factory**, is used to study the production of light (anti)nuclei by the **ALICE experiment**

- The measurements performed by ALICE shed light on the **formation mechanisms** of light (anti)nuclei in different collision systems and energies
  → measured data compared to different theoretical models (SHM, coalescence), but **no definitive** answer yet
  → need for new state-of-the-art measurements with **LHC Run 3**!

- The measurements are fundamental inputs to models of the production of **cosmic antinuclei** for indirect dark matter searches



Thank you for the attention