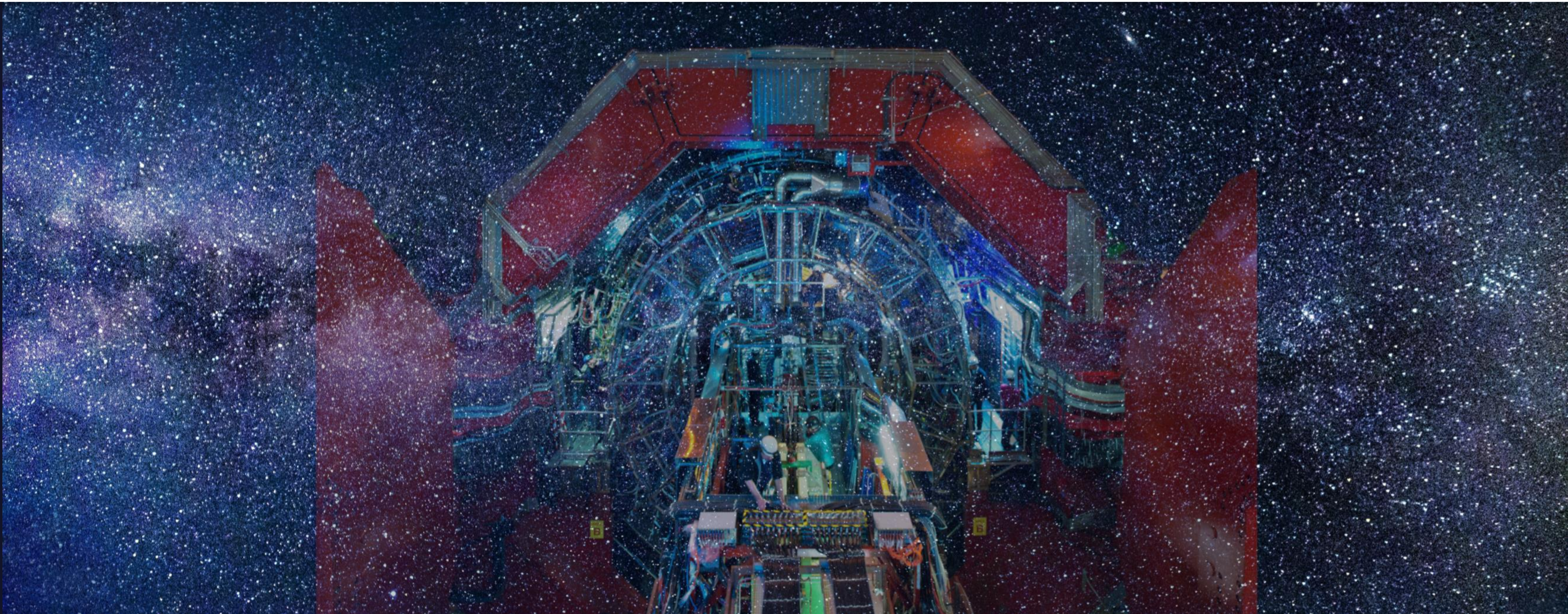
CosmicAntiNuclei

F. Bellini (Università di Bologna)
Aperitivi Scientifici - INFN Bologna
16 Aprile 2021

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA



CosmicAntiNuclei is an interdisciplinary project starting in July 2021 and hosted by the DIFA at the University of Bologna and the Technical University of Munich. It is funded with a H2020 ERC starting grant.

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

European Research Council
Established by the European Commission

The project aims at **constraining cosmic antinuclei fluxes for indirect dark matter searches with precision measurements of rare antimatter cluster formation.**

Outline for today:

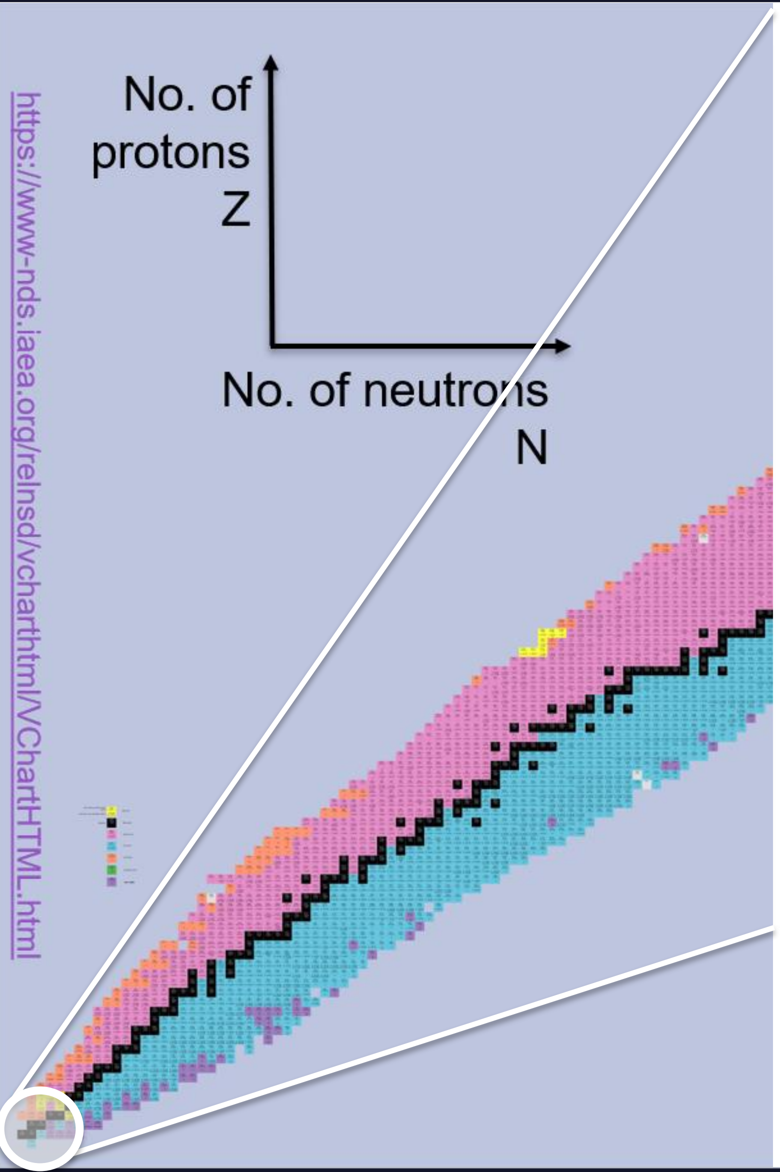
- Cosmic antinuclei as smoking guns for DM
- What is needed to determine antinuclei fluxes
- ALICE as antinucleus detector and LHC as an antimatter factory
- Investigating formation of antinuclei by coalescence
  - Production rates and coalescence probability
  - Two-particle momentum correlations
- CosmicAntiNuclei executive summary

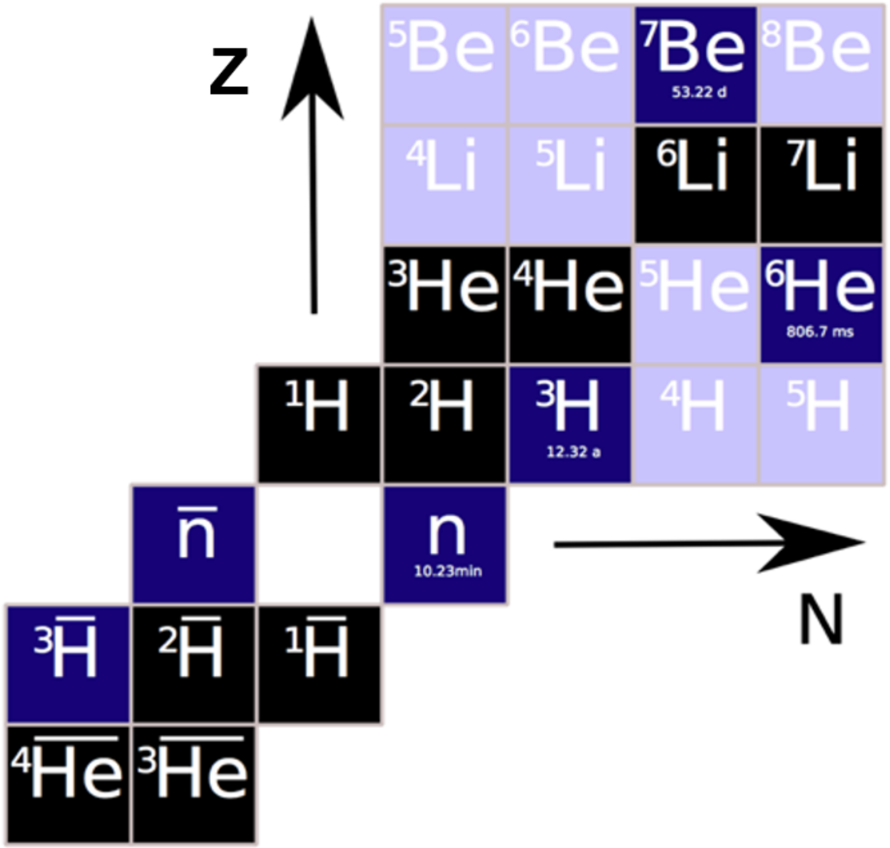
CosmicAntiNuclei - **Constraining cosmic antinuclei fluxes for indirect dark matter searches with precision measurements of rare antimatter cluster formation.**

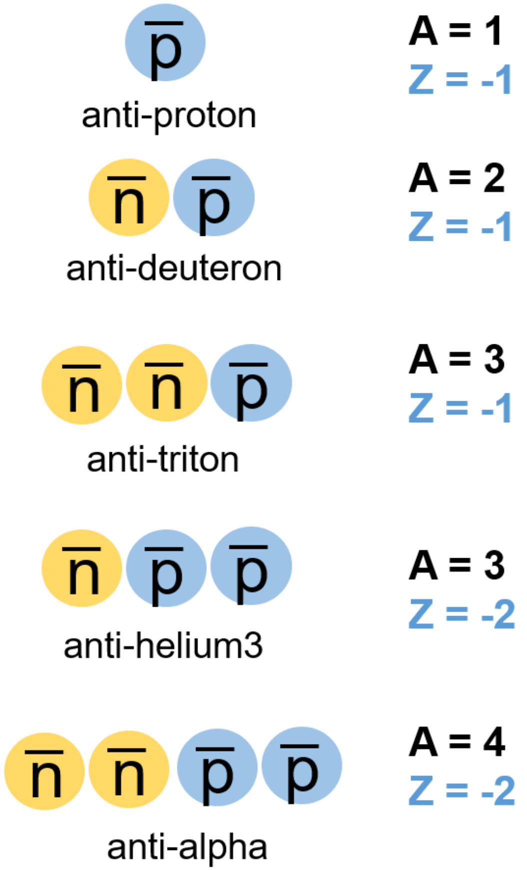
Outline for today:

- **Cosmic antinuclei as smoking guns for DM**
- What is needed to determine antinuclei fluxes
- ALICE as antinucleus detector and LHC as an antimatter factory
- Investigating formation of antinuclei by coalescence
  - Production rates and coalescence probability
  - Two-particle momentum correlations
- CosmicAntiNuclei executive summary

Light antinuclei







The **anti-^{4}He** is the heaviest antinucleus observed so far, first seen by the STAR experiment at RHIC in 2011, measured by **ALICE in Pb-Pb collisions at the LHC:** $[^4He/p]_{PbPb} \sim 10^{-8}$ *[Nucl. Phys. A 971 (2018) 1-20]*

Light antinuclei as "smoking gun" for dark matter

Evidence for the presence of Dark Matter (DM) comes from astrophysical / cosmological observations.

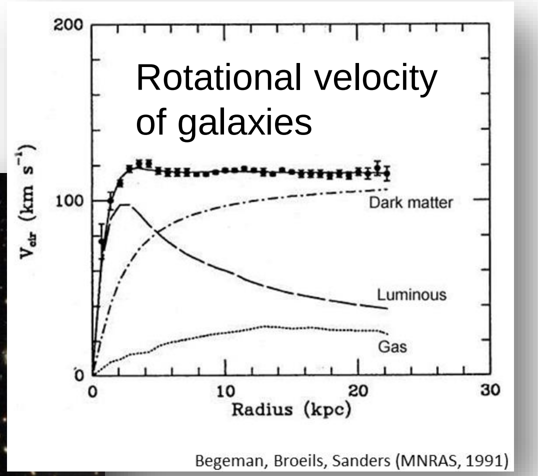
So far, dark matter has evaded (in)direct detection.

<u>One</u> hypothesis is that DM is constituted by **Weakly Interacting Massive Particles** (WIMP, χ) that are thermal relics of the early Universe (**m_χ ~ few GeV – few TeV**)

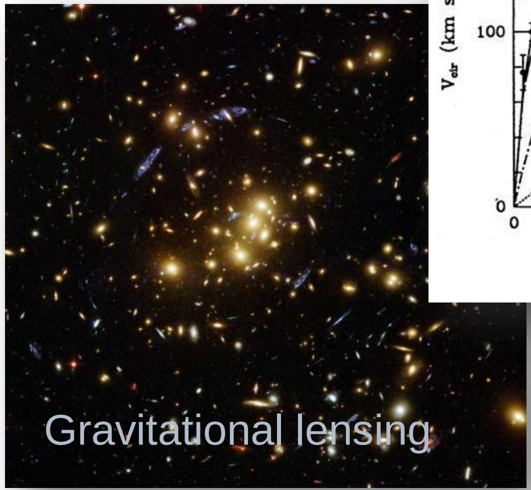
Indirect searches for DM look for signals from $\chi\bar{\chi}$ pair annihilation or χ decay into Standard Model particles in the Galactic halo ⟶ ballon and space-borne experiments

Antideuterons and **anti-helium** are promising smoking guns because of the **low background** of antimatter from high-energy interactions of **cosmic rays** (CR) in the Galaxy.

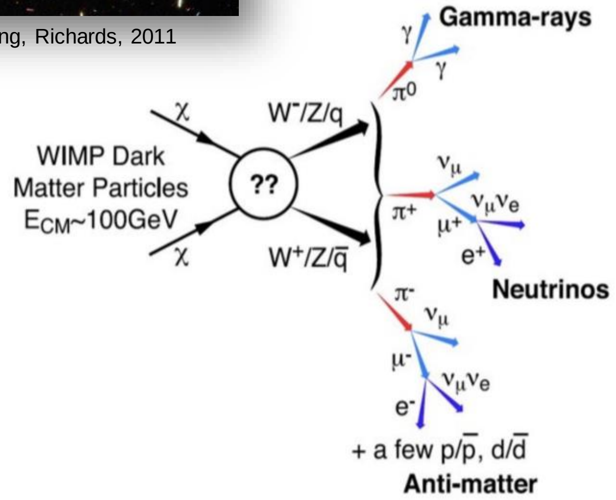
For a recent review, see P. von Doentichem, JCAP08(2020)035



Begeman, Broeils, Sanders (MNRAS, 1991)



Massey, Kitching, Richards, 2011



Searching for antinuclei in cosmic rays *[past]*

Balloon-borne Experiment with Superconducting Spectrometer, BESS-Polar I-II

[K. Abe et al., Adv. Space Res. 60 (2017) 806-814]

- 11 balloon flights from 1993 to 2008
- systematic measurements of low-energy CR antiprotons (<3.5 GeV)
- BESS-Polar II (2007): ~4.7 billion CR events recorded
- no antihelium candidate found

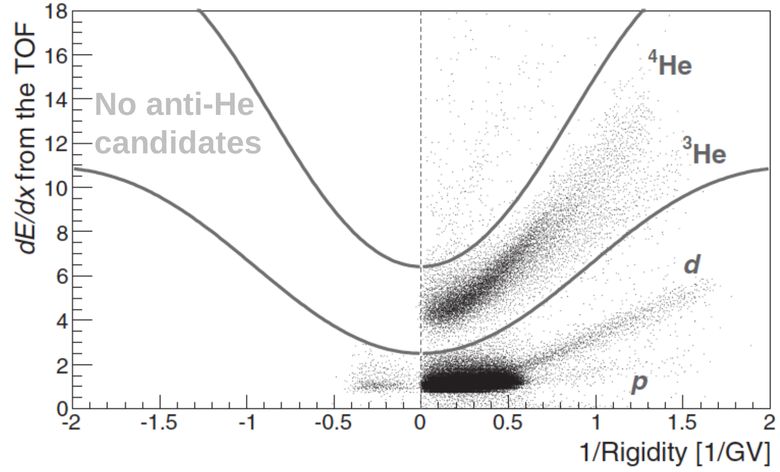
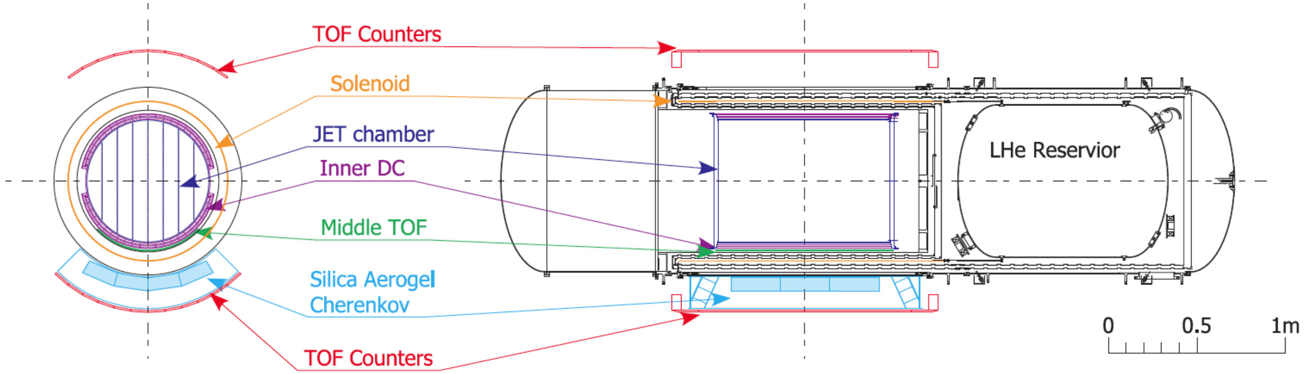


Fig. 6. Selection of He ($\overline{\text{He}}$) in BESS-Polar II. The plot shows dE/dx from the TOF versus R^{-1}. The $|Z| = 2$ particles are between the lines.

BESS-Polar I+II
2004, 2007



Searching for antinuclei in cosmic rays *[future]*

General AntiParticle Spectrometer

[T. Aramamki et al., Astro. Phys. 74 (2016) 6-13]

- an Antarctic balloon mission, first flight planned in late 2021
- will search for low-energy (E<0.25 GeV/n) cosmic-ray antinuclei
- designed to precisely measure the flux of anti-p, anti-d and anti-He
- based on an exotic atom technique (nuclear capture of low-energy antiparticles and decay producing X-rays) + ToF + dE/dx

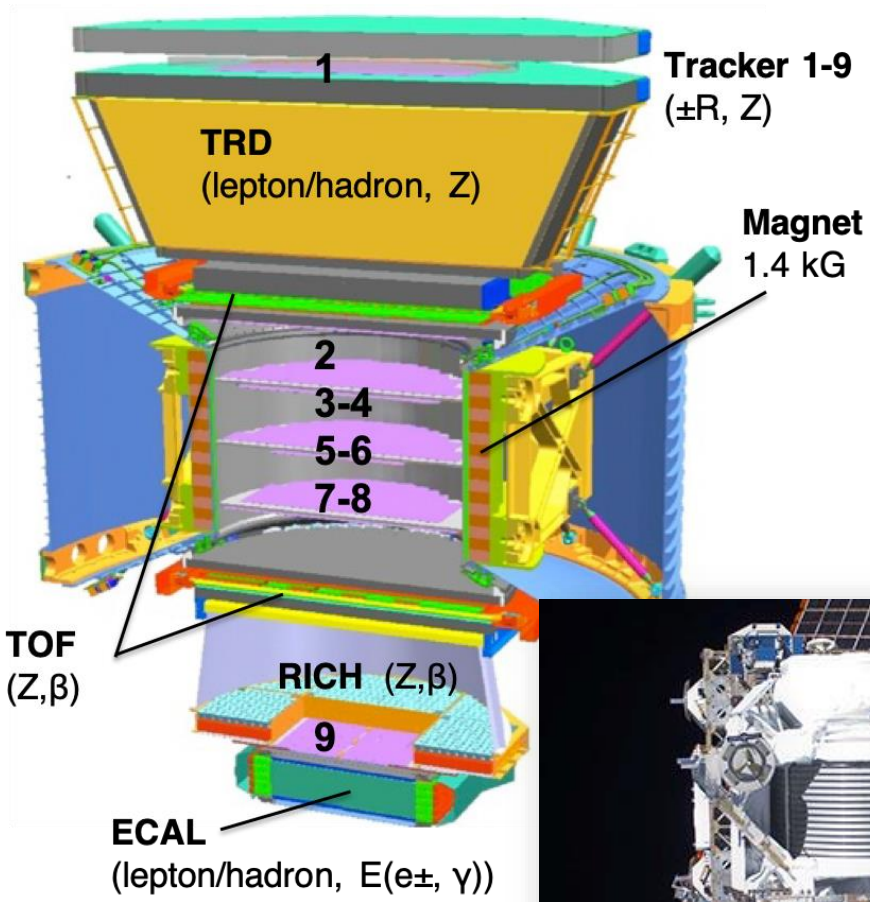
GAPS detector assembly

Searching for antinuclei in cosmic rays *[present]*

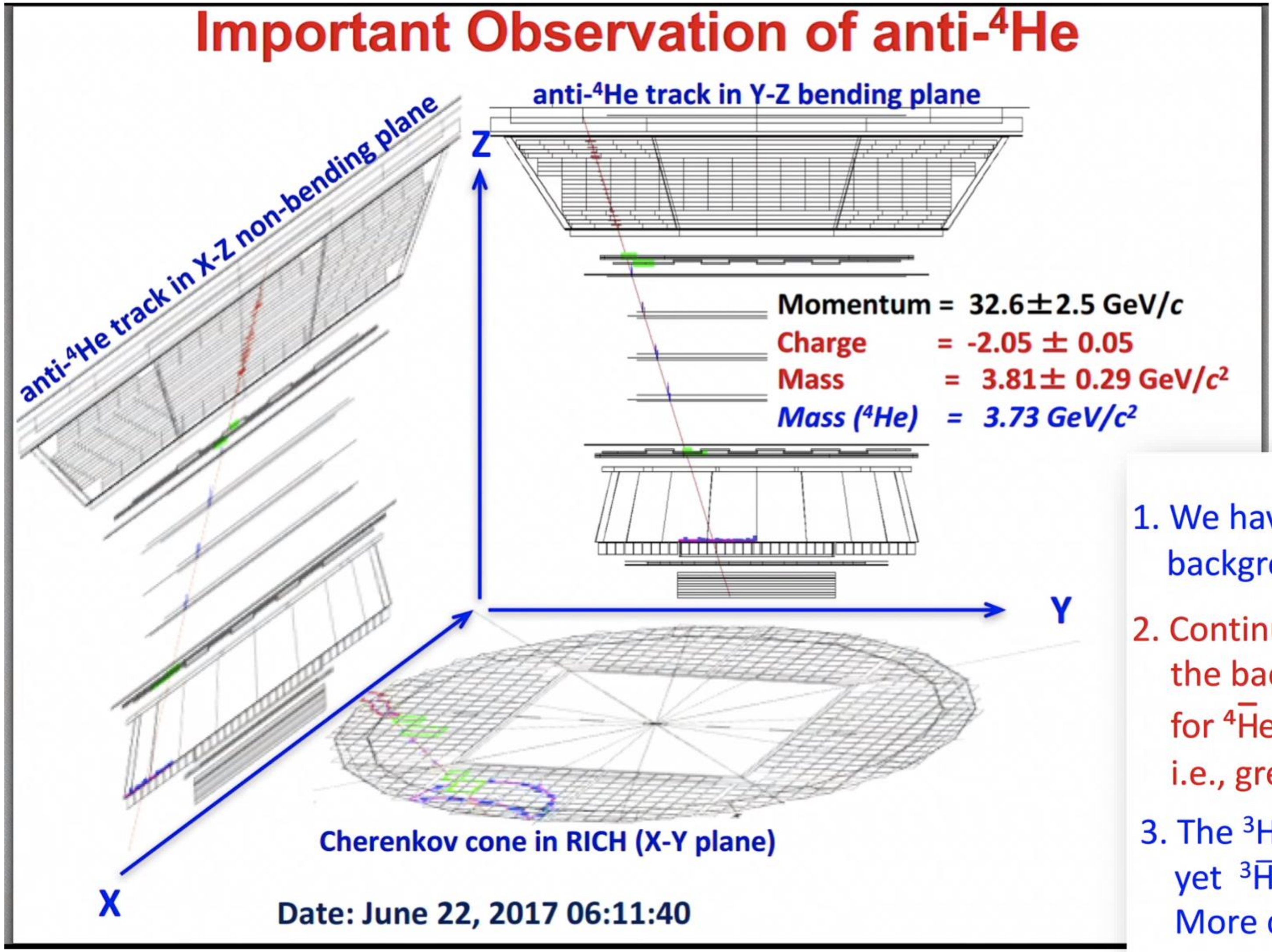
Alpha **M**agnetic **S**pectrometer

[G.M. Viertel et al., NIM A419 (1998) 295-299; AMS Collab., Phys. Rep. 894, 1 (2021)]

- Operating continuously on the ISS since 2011
- Expected to take data till the ISS lifetime/2028
- Allows for multiple and independent measurement of charge (Z), energy (β, p, E) and charge sign (±)
- Separates CRs chemical and isotopic composition in GeV to TeV range
- >175 billion cosmic rays collected up to now
  → *any antinuclei?*



$^{3}\overline{He}$ and $^{4}\overline{He}$ candidates in AMS-02



6 anti-^{3}He + 2 anti-^{4}He candidates reported by S. Ting at the May 2018 CERN Colloquium

not yet confirmed (indico)

Observations on $^{4}\overline{He}$

1. We have two $^{4}\overline{He}$ events with a background probability of 3×10^{-3}.
2. Continuing to take data through 2024 the background probability for $^{4}\overline{He}$ would be 2×10^{-7}, i.e., greater than 5-sigma significance.
3. The ^{3}He/^{4}He ratio is 10-20% yet $^{3}\overline{He}/^{4}\overline{He}$ ratio is 300%. More data will resolve this mystery.

CosmicAntiNuclei - **Constraining cosmic antinuclei fluxes for indirect dark matter searches with precision measurements of rare antimatter cluster formation.**

Outline for today:

- Cosmic antinuclei as smoking guns for DM
- **What is needed to determine antinuclei fluxes**
- ALICE as antinucleus detector and LHC as an antimatter factory
- Investigating formation of antinuclei by coalescence
  - Production rates and coalescence probability
  - Two-particle momentum correlations
- CosmicAntiNuclei executive summary

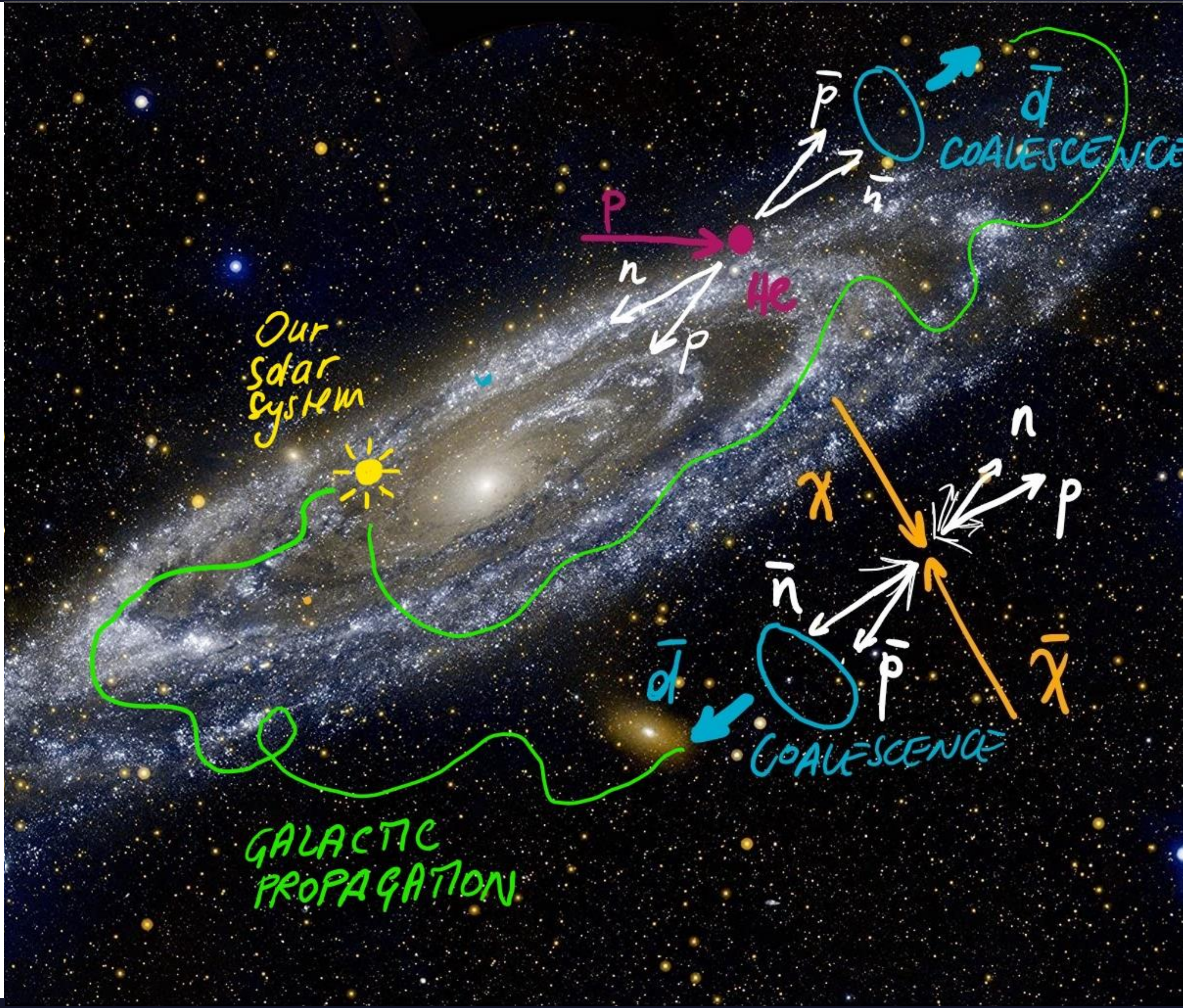
Interpreting results from experiments in space/balloons

Signal = **antinuclei** from **dark matter source**

Background = secondary cosmic rays from **hadronic interactions** of primary CR with the InterStellar Matter (**pp, p-He**…) in the Galaxy

Ingredients needed to predict rates:

- antimatter cluster **formation mechanisms**
- model of **cosmic ray propagation** in the Galaxy and the heliosphere
- **annihilation** cross section of antinuclei in the ISM and the detector materials



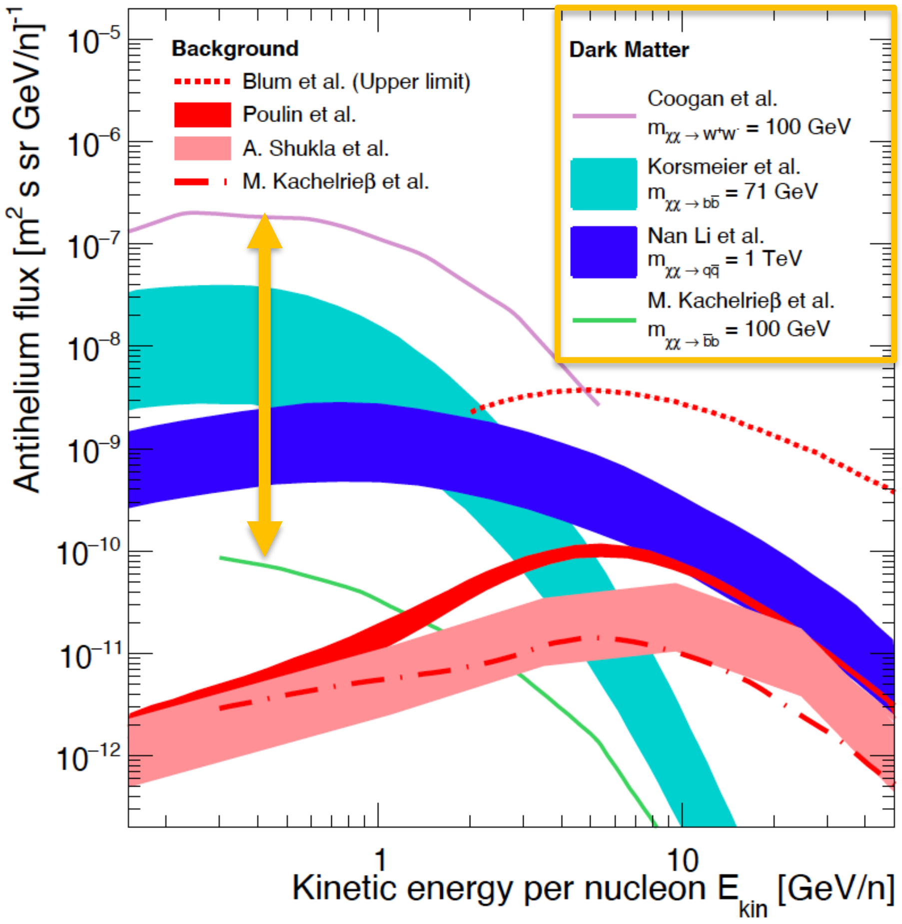
Modeling the dark matter source

Depends on the **details of the particle physics model** and the **DM density** in a given point of the Galaxy

$$q_{\rm DM}(E_{\bar{D}},\vec{x}) = \frac{1}{2}\left(\frac{\rho(\vec{x})}{m_{\rm DM}}\right)^2 \langle\sigma v\rangle_{b\bar{b}} \frac{dN^{b\bar{b}}_{\bar{D}}}{dE_{\bar{D}}}$$

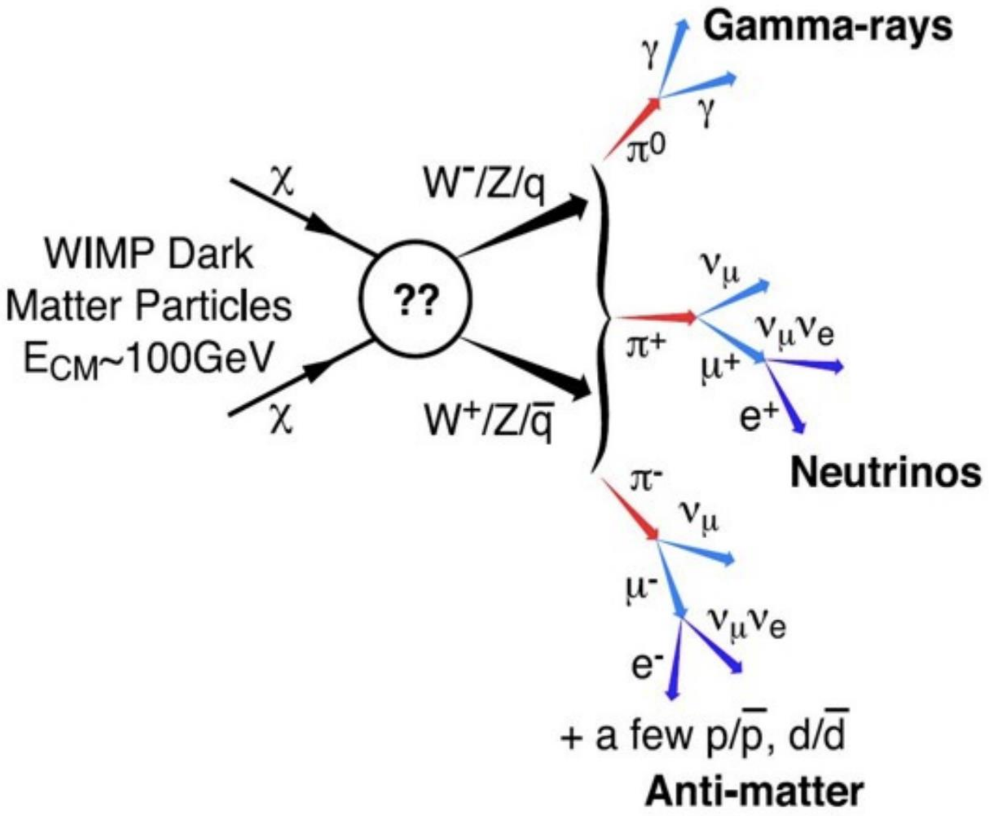
- thermally-averaged annihilation cross section into SM channel e.g. $\langle\sigma v\rangle_{\chi\chi\to \rm bbar}$ ~ 3 x 10^{-26} cm^3/s *[M. Korsmeier at al. PRD 97 (2018) 103011*
- DM mass, e.g. 70 < m_{DM} < 100 GeV
- energy spectrum of the products
- DM density in the vicinity of the solar system, ρ^{local}_{DM} **~ 0.4 GeV/cm³** *[M. Tanabashi et al. (PDG), PRD 98 (2018) 030001]*

P. von Doentichem et al., JCAP08(2020)035



Signal = antinuclei from dark matter source

1. Anti-p and anti-n are produced by **WIMP annihilation into SM channels**
2. Anti-deuterons and anti-^{3}He are produced via **coalescence** of anti-nucleons



Antinucleus formation by coalescence

Nuclei form at kinetic freeze-out by coalescence of nucleons close enough in phase space.
[S.T. Butler and C. A. Pearson, Phys.Rev. 129, 836 (1963); J. I. Kapusta, PRC 21, 1301 (1980); H. Sato and K. Yazaki, PLB 98, 153 (1981); J. L. Nagle et al., PRC 53, 367 (1996)]

Production depends on the **coalescence probability *B*$_A$**,

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

Nucleus distributions

Nucleon distributions

In cases in which the **nucleus is large w.r.t. the source**, the phase space is reduced to the momentum space ("simple" coalescence models).

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

Nucleus mass

Nucleon mass

Coalescence momentum

Modelling the signal

$$\chi + \bar{\chi} \rightarrow \bar{\mathrm{d}} + X$$

1. Anti-p and anti-n are produced by **WIMP annihilation into SM channels**
2. Anti-deuterons and anti-^{3}He produced via **coalescence** of anti-nucleons

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

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

The production of anti-nuclei from DM annihilation is typically modeled according to
[e.g. M. Korsmeier at al., PRD 97 (2018) 103011; P. Chardonnet et al., PLB 409 (1997) 313; and others…]

- the coalescence momentum p_0
  - → unknown, it is tuned on data and assumed to be momentum-independent
- the **mass** of the nucleus
- simple **A**-scaling assumed
  - → ignores the internal structure of the nucleus

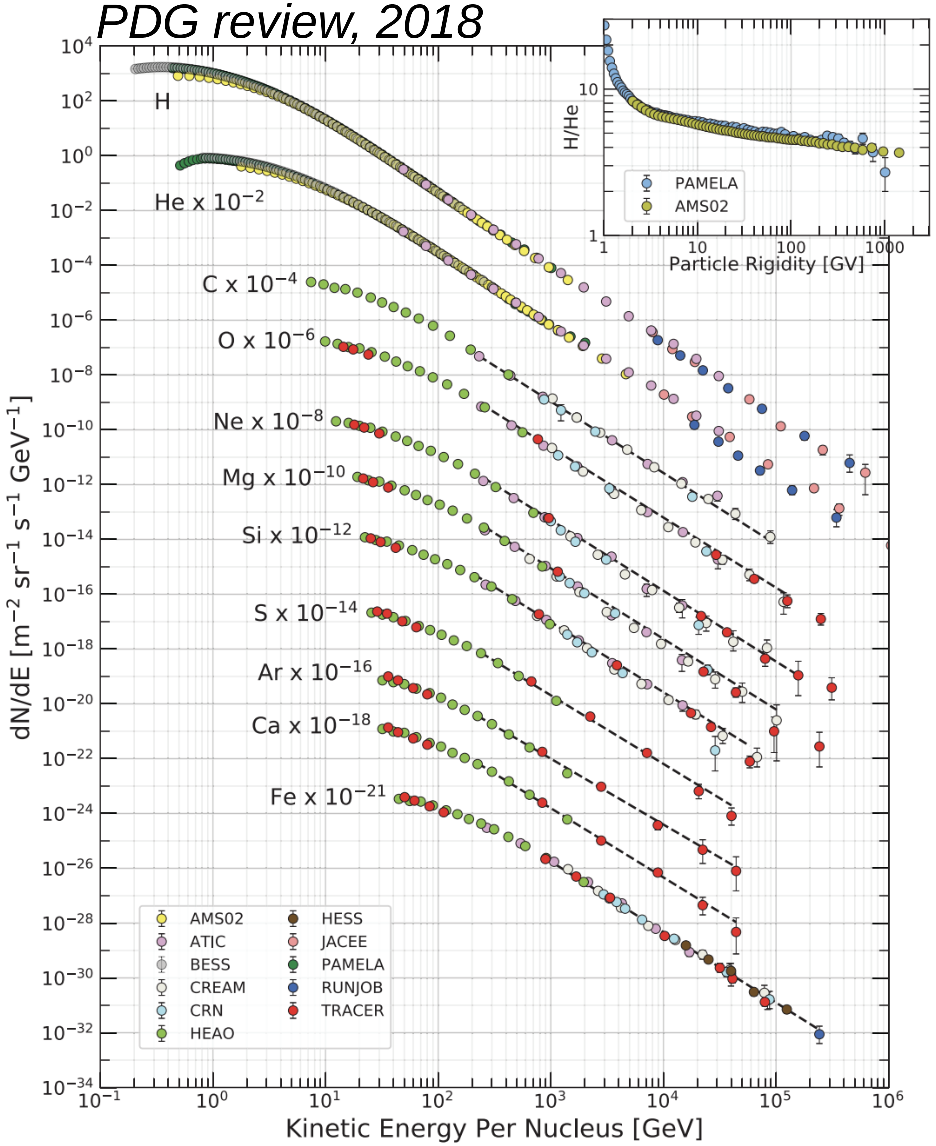
Background = secondary cosmic ray source

The largest fractions of primary CR are protons and helium.
There are no antinuclei as primary CR.

Secondary anti-p, anti-d, anti-^{3}He produced by interaction of **primary CR with the InterStellar Matter** (pp, p-He, …) constitute a background for the DM signal.

→ the Galaxy as “fixed target experiment”

PDG review, 2018



Modeling the background

Modeling the production of secondary anti-nuclei by spallation reactions of primary CR with ISM, e.g.

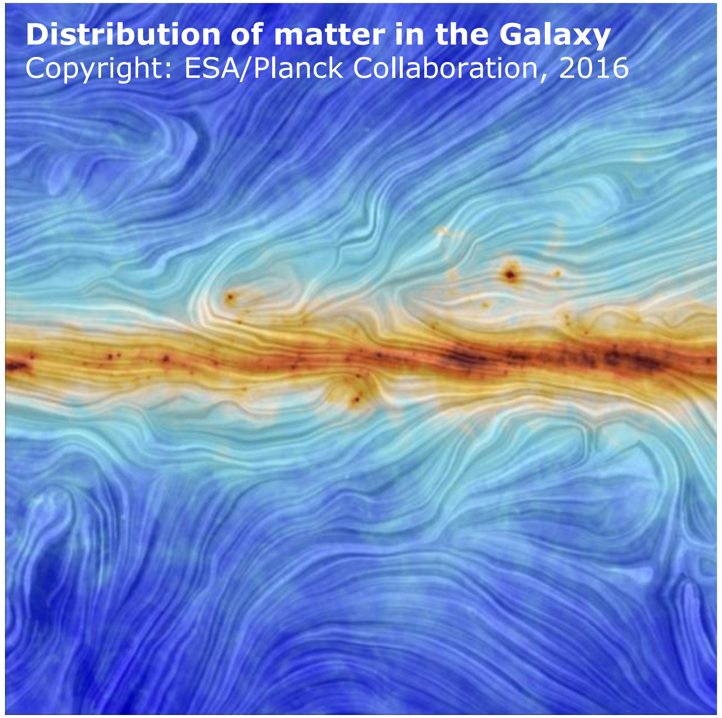
$$\mathrm{p} + \mathrm{p} \to \bar{\mathrm{d}} + X \qquad \mathrm{p} + {}^3\mathrm{He} \to \bar{\mathrm{d}} + X$$

$$\bar{\mathrm{p}} + \mathrm{p} \to \bar{\mathrm{d}} + X \qquad \bar{\mathrm{p}} + {}^3\mathrm{He} \to \bar{\mathrm{d}} + X$$

...

- Depends on the **cross-sections** for $\bar{\mathrm{p}}$ production in pp, p-He, p-A
- Considers the **threshold** for anti-nuclei production
  - to produce anti-d by pp in c.m. $\sqrt{s} \geq 6\ m_p$ ⟶ lab frame / Galaxy: $E \geq 17 m_p$
- Is performed via the **coalescence** mechanism
  - same as the DM signal, but different anti-nucleon distributions
  - coalescence momentum unknown
- In addition, a tertiary CR component: $\bar{\mathrm{d}} + \mathrm{p} \to \bar{\mathrm{d}} + X$

  $\bar{\mathrm{d}} + {}^3\mathrm{He} \to \bar{\mathrm{d}} + X$



Towards estimating the antinuclei flux

Predictions for the anti-matter flux for signal from DM and background from secondary/tertiary CR require as input

CONSTRAIN WITH LHC DATA

- **C** ... n
- **Coalesce**... n
- **Cross-sections** for anti-p productio...

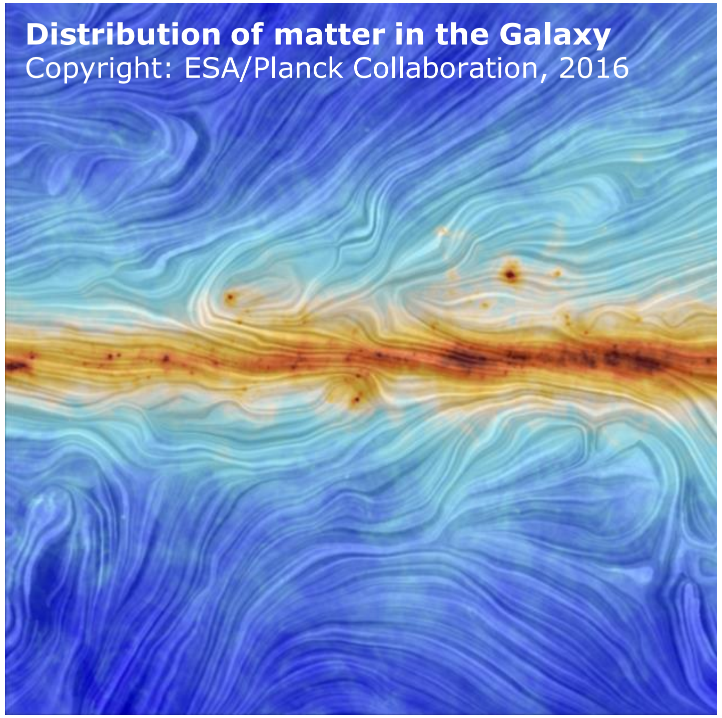
MEASURE AT LHC

Flux calculations are **sensitive** to the astrophysical details, i.e. how particles **propagate in the Galaxy**

→ Introduce model dependency

- Acceleration by Super Novae remnants
- Diffusion in the ga... tic field (~μGauss)
- Energy loss / gain (for loosely bou... ...ak-up dominates)
- Solar modulations (matter mostly at low *E*, where DM signal prominent)

TUNE ON ASTRO DATA

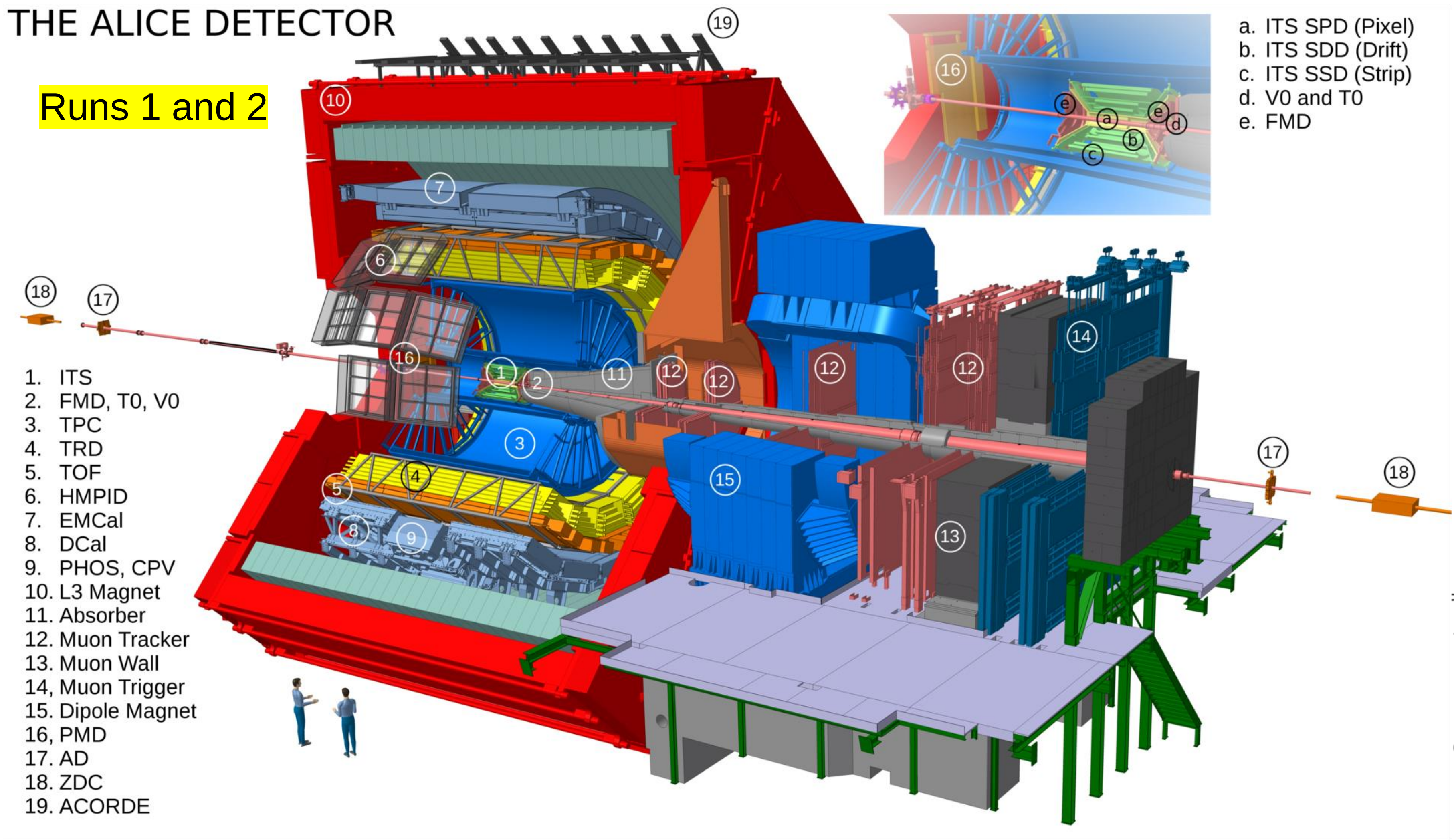


CosmicAntiNuclei - **Constraining cosmic antinuclei fluxes for indirect dark matter searches with precision measurements of rare antimatter cluster formation.**

Outline for today:

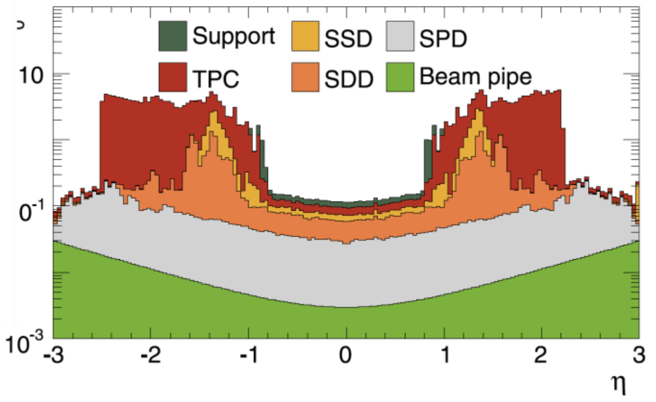
- Cosmic antinuclei as smoking guns for DM
- What is needed to determine antinuclei fluxes
- **ALICE as antinucleus detector and LHC as an antimatter factory**
- Investigating formation of antinuclei by coalescence
  - Production rates and coalescence probability
  - Two-particle momentum correlations
- CosmicAntiNuclei executive summary

A Large Ion Collider Experiment at the LHC



Int. J. Mod. Phys. A 29,1430044 (2014)

- Central barrel
  $|\eta| < 0.9$, B = 0.5 T
- Excellent tracking down to $p_T \sim 100$ MeV/c
- Complementarity of several PID techniques in $0.1 < p_T < 30$ GeV/c
- Lowest material budget at midrapidity at the LHC



(Anti-)nuclei identification in ALICE

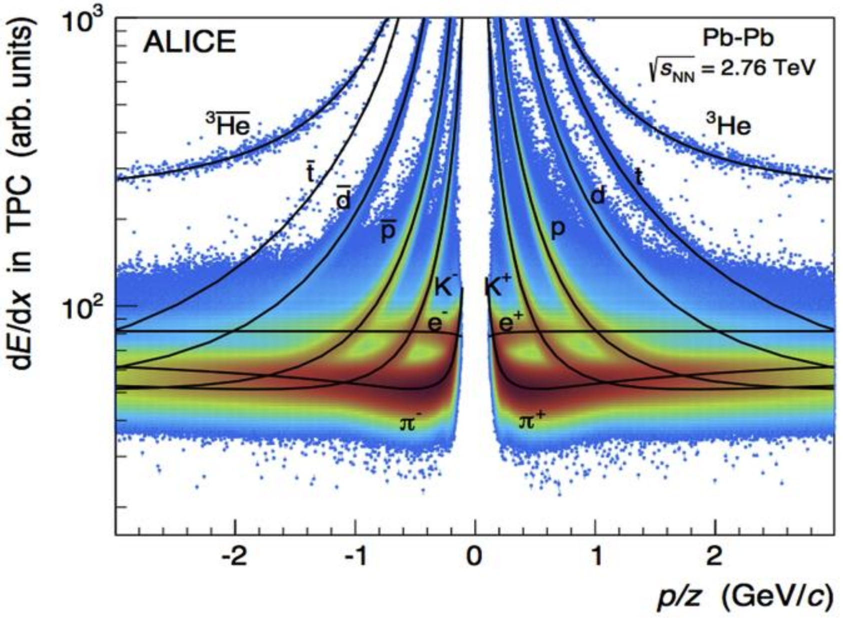
ALICE, Phys. Rev. C 93, 024917 (2015)
ALICE, Eur. Phys. J. C 77, 658 (2017)

Identification employs

- d*E*/dx in the ALICE **TPC** at low momenta
- Mass from time-of-flight measured in **TOF** at intermediate momenta
- Mass from Cherenkov angle in **HMPID** at high momenta

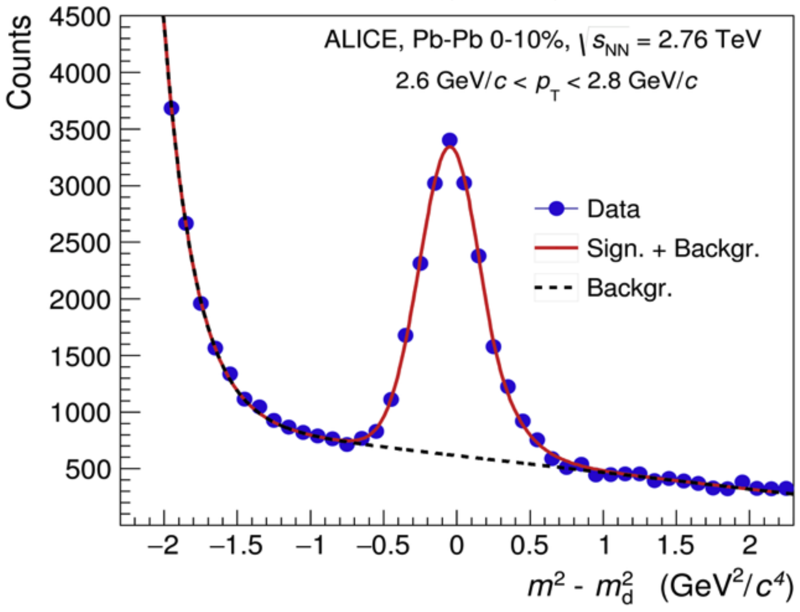
Specific ionization energy loss in TPC

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



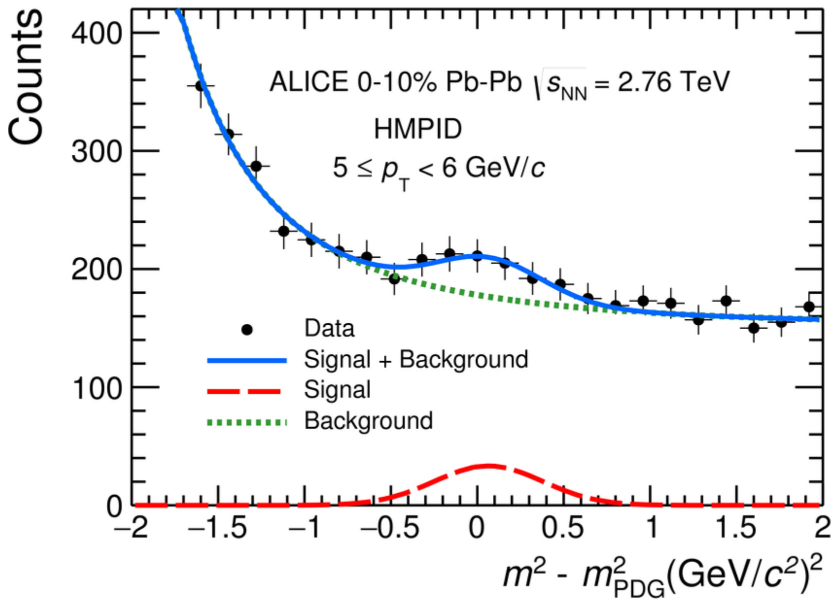
Deuteron signal extraction with TOF

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



Deuteron signal extraction with HMPID

$$m^2 = p^2\cdot(n^2\cos^2\theta_{Ckov}-1) \qquad n = 1.29$$



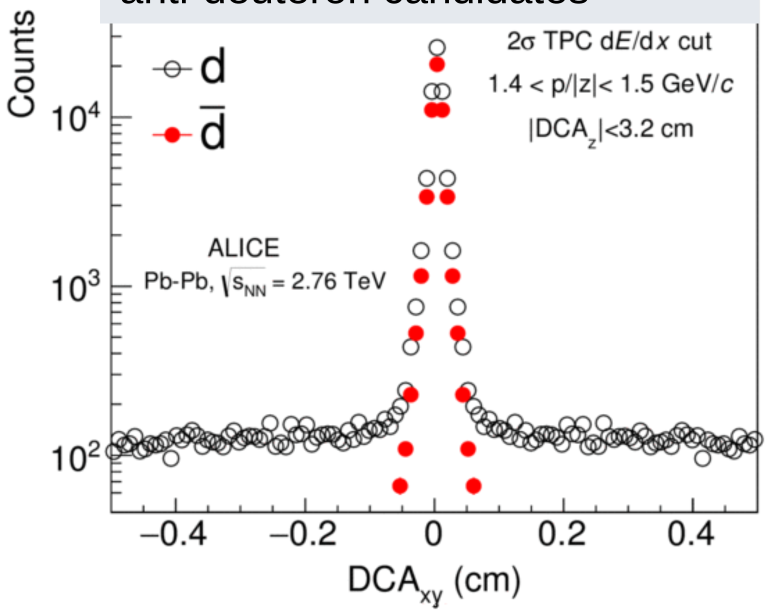
Dealing with detector material

Knock-out from detector material is a problem at low p_T

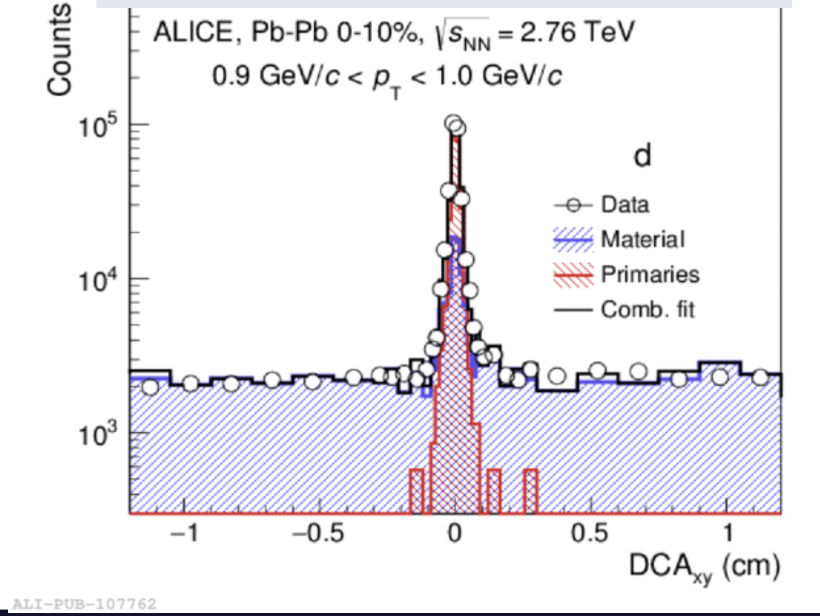
- Fits to the Distance of Closest Approach (DCA) to the primary vertex (PV) used to reject secondaries
- Source of background for **nuclei, not for anti-nuclei**

For anti-nuclei, large systematic uncertainty due to the poor knowledge of the **hadronic interaction cross section**

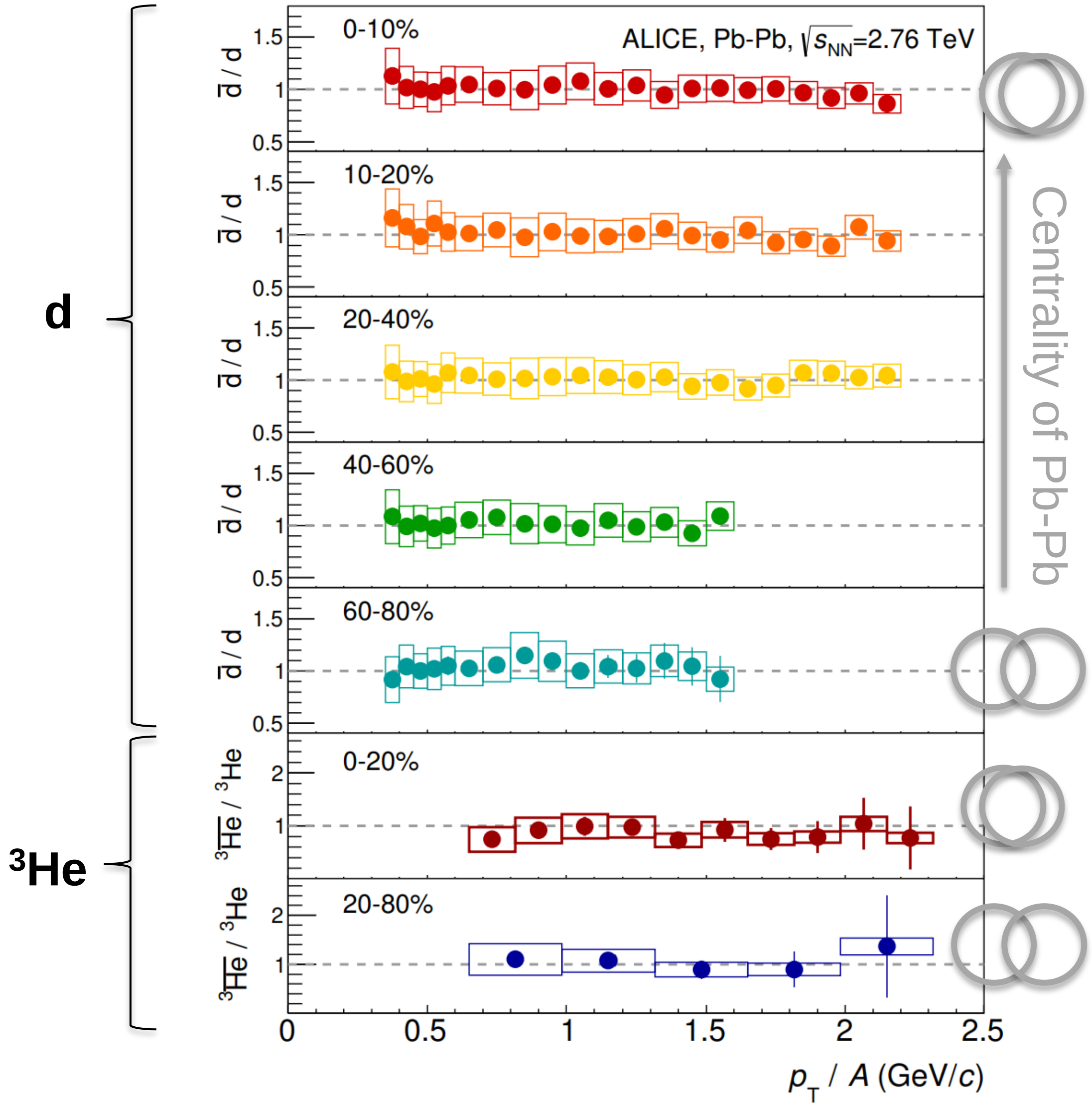
DCA to the PV of deuteron and anti-deuteron candidates



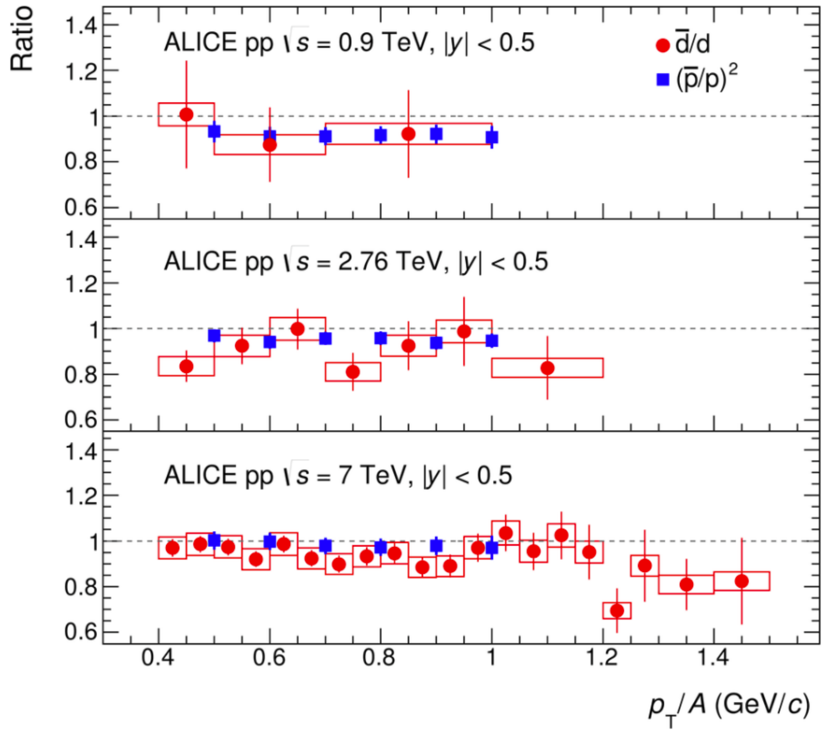
Template fit to the DCA to the PV of deuteron candidates



LHC is an anti-matter factory



Anti-matter / matter ~ 1 at the LHC
Independently of p_T and multiplicity/system



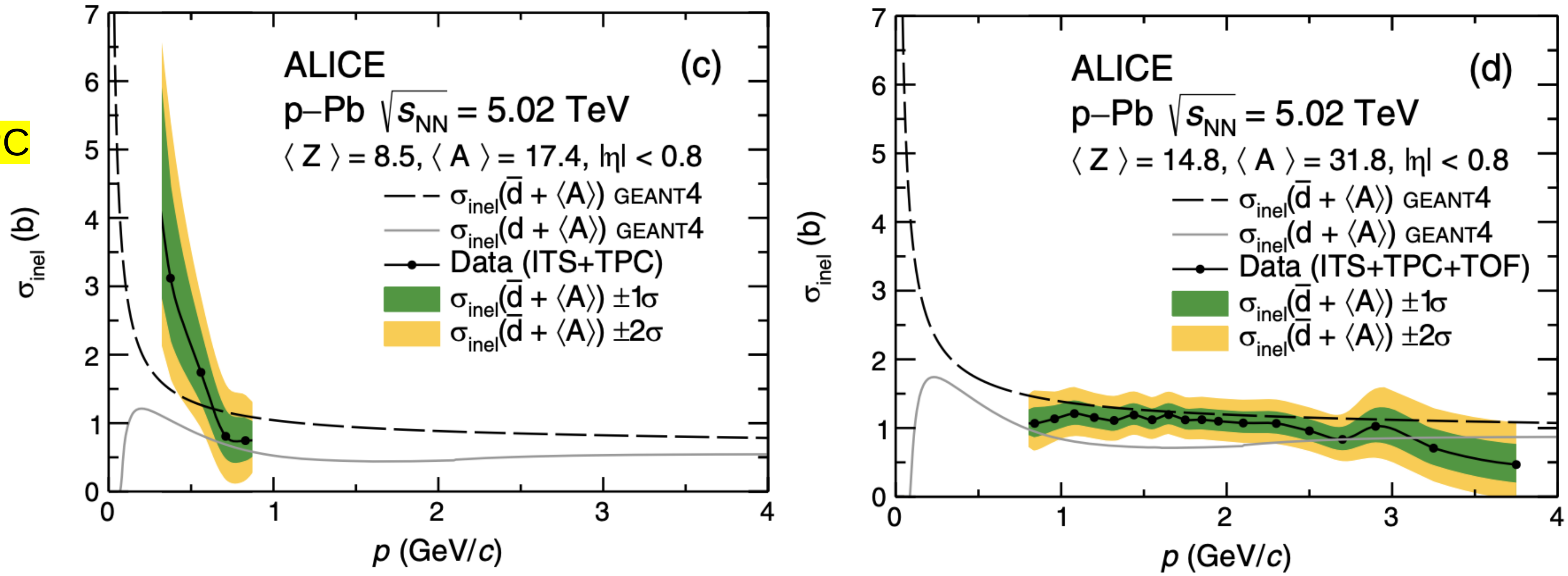
ALICE, PRC 93 (2015) 024917; PRC 97 (2018) 024615; PLB 794 (2019) 50-63; PLB 800 (2020) 135043; EPJC 80 (2020) 889

A new measurement of low-energy $\bar{d}$ inelastic cross section

First measurement of the antideuteron inelastic cross-section at low energy, 0.3 < *p* < 4 GeV/*c*, using the ALICE TPC and TOF detector material as a target.

Anti-^{3}He measurement in pp, Pb-Pb ongoing… stay tuned!
⟶ relevant for cosmic antinuclei

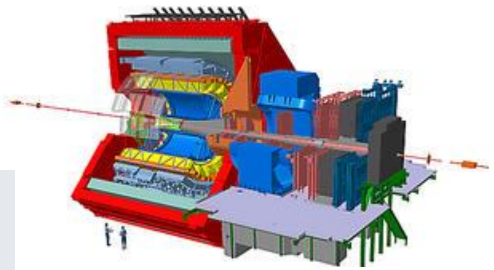
Using ITS+TPC



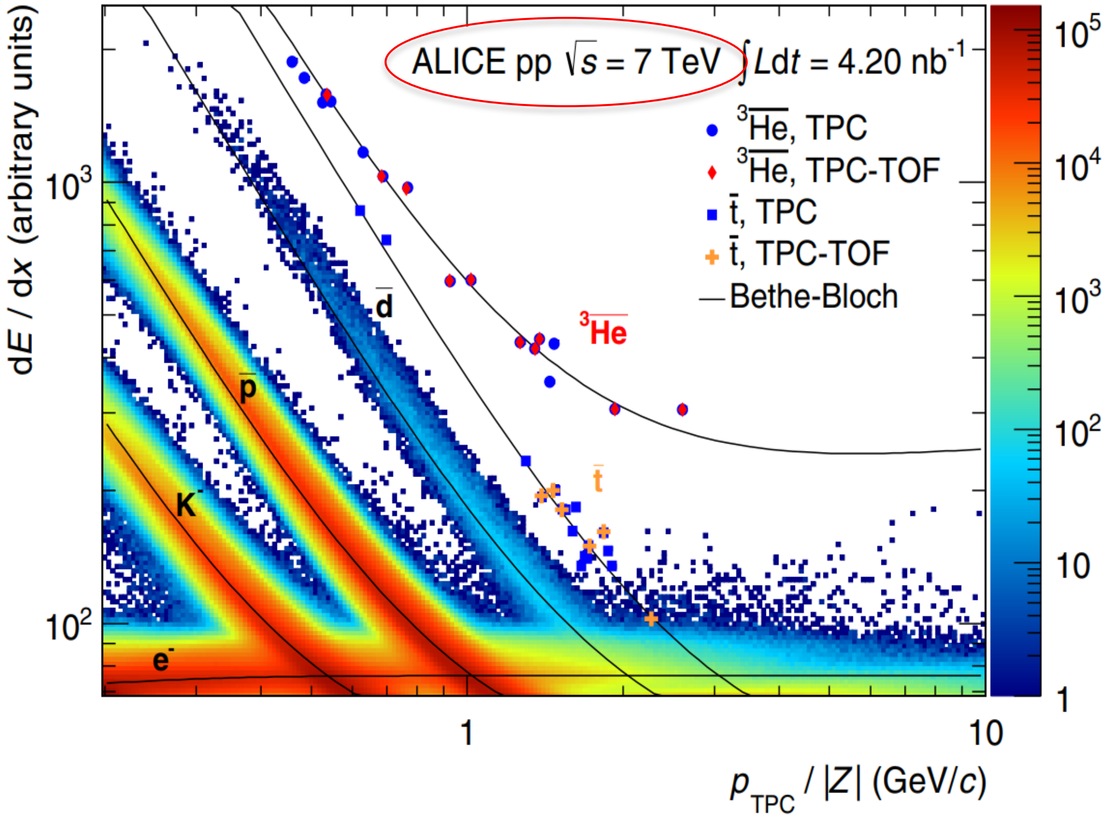
Using ITS+TPC +TOF

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

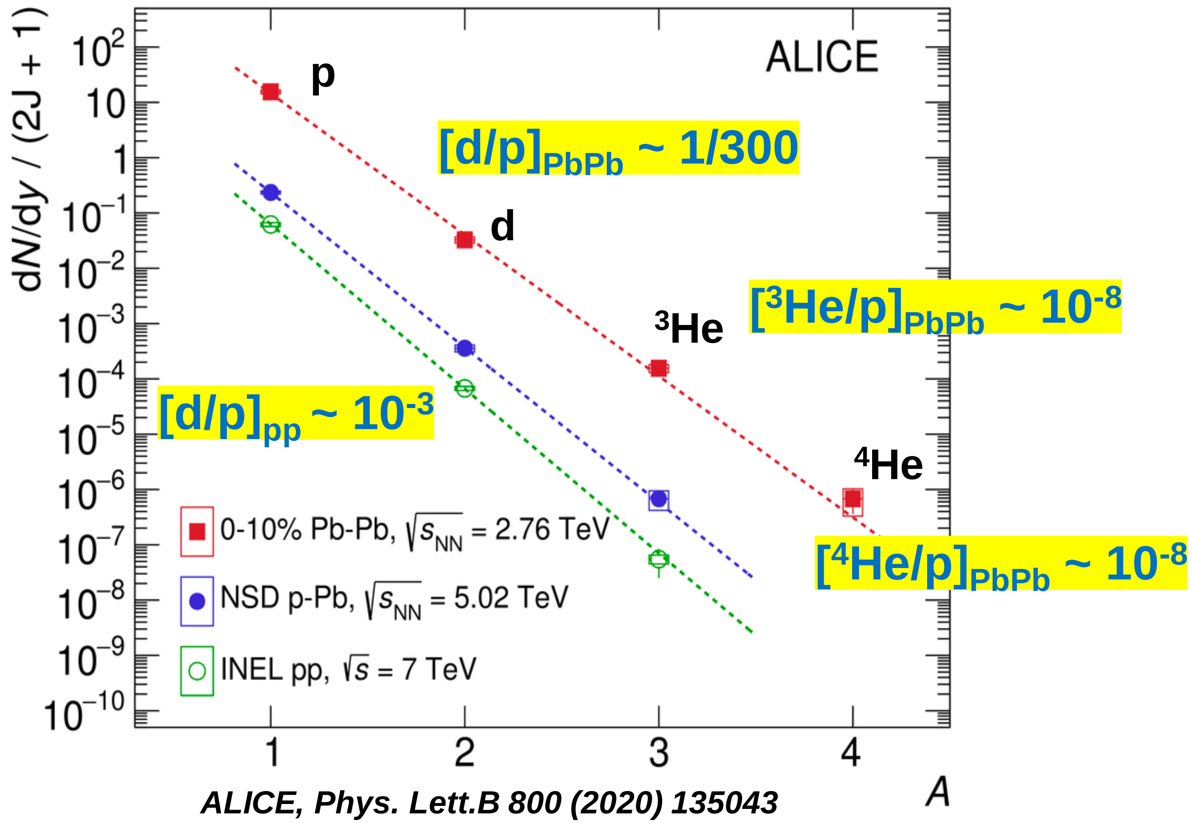
The antinucleus detector at the antinucleus factory



Example of antinuclei identification performance in pp collisions



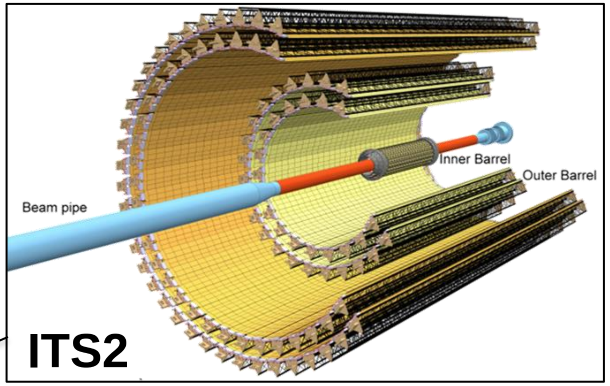
Measured "penalty factors" for light nuclei (and antinuclei)

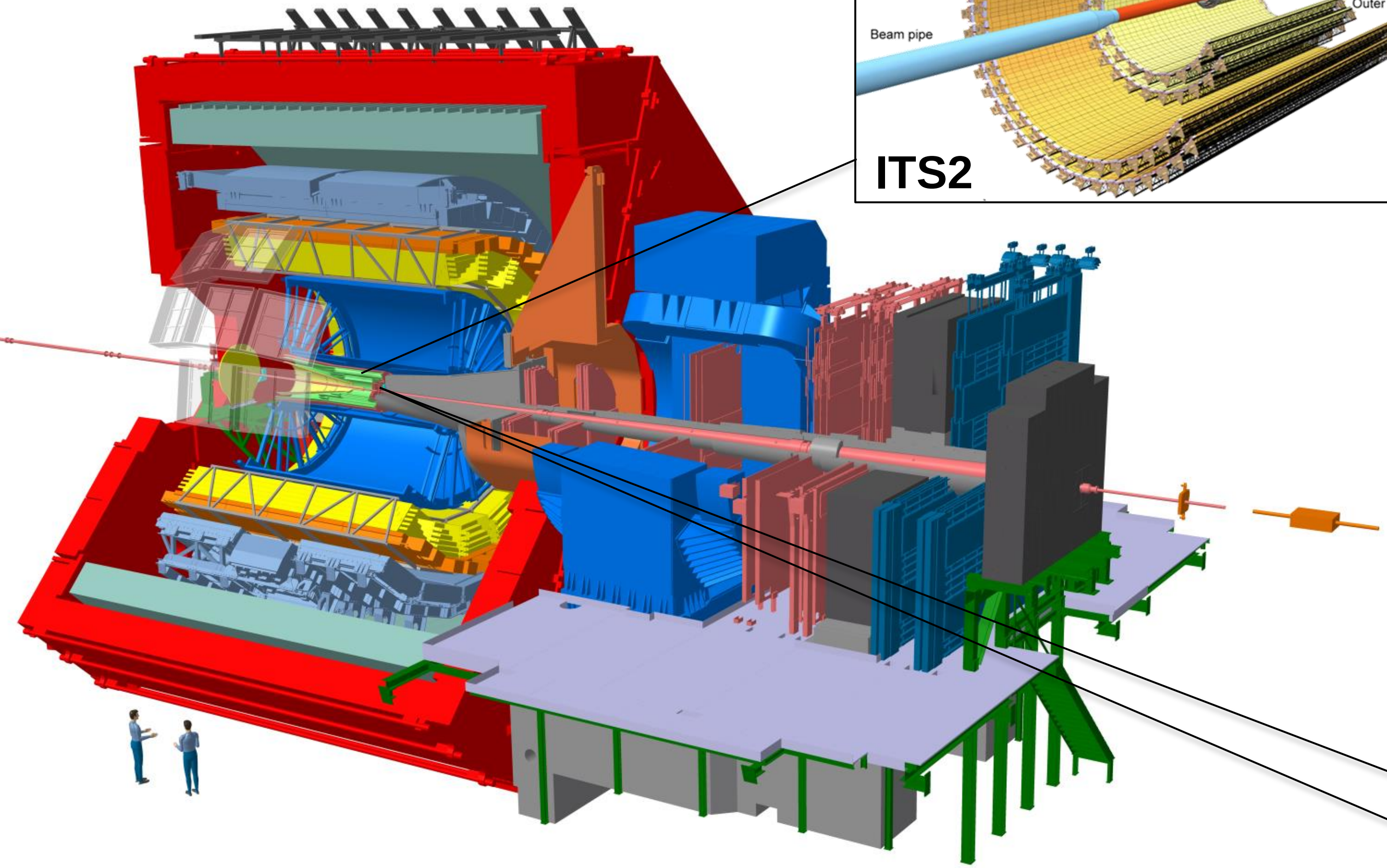


ALICE, Phys. Lett.B 800 (2020) 135043

ALICE upgraded for the LHC Run 3

ALICE-TDR-017 J.Phys.G 41 (2014) 087002





New Inner Tracking system (ITS2)

- 7 layers of Monolithic Active Pixel Sensors
- Innermost layer closer to the IP (r = 23 mm)
- Reduced material thickness (innermost layer $X/X_0 = 0.3\%$)

New TPC Readout Chambers

- Continuous readout on GEMs
- Read out at maximum Pb-Pb collision rate of 50 kHz

Update of readout

- The main PID detectors consolidated and speed-up (e.g., TOF readout update) to **preserve PID capabilities**

Integrated Online-Offline system (O^2)

New Muon Forward Tracker (**MFT**)
New Fast Interaction Trigger (**FIT**) Detector

CosmicAntiNuclei - **Constraining cosmic antinuclei fluxes for indirect dark matter searches with precision measurements of rare antimatter cluster formation.**

Outline for today:

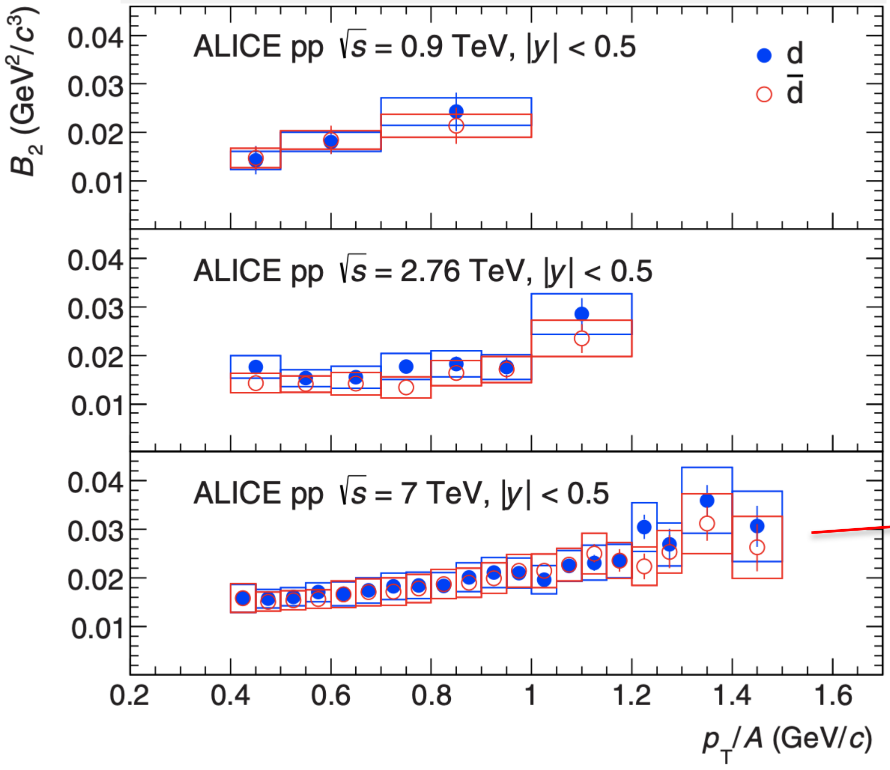
- Cosmic antinuclei as smoking guns for DM
- What is needed to determine antinuclei fluxes
- ALICE as antinucleus detector and LHC as an antimatter factory
- **Investigating formation of antinuclei by coalescence**
  - **Production rates and coalescence probability**
  - **Two-particle momentum correlations**
- CosmicAntiNuclei executive summary

Coalescence probability of (anti)deuteron

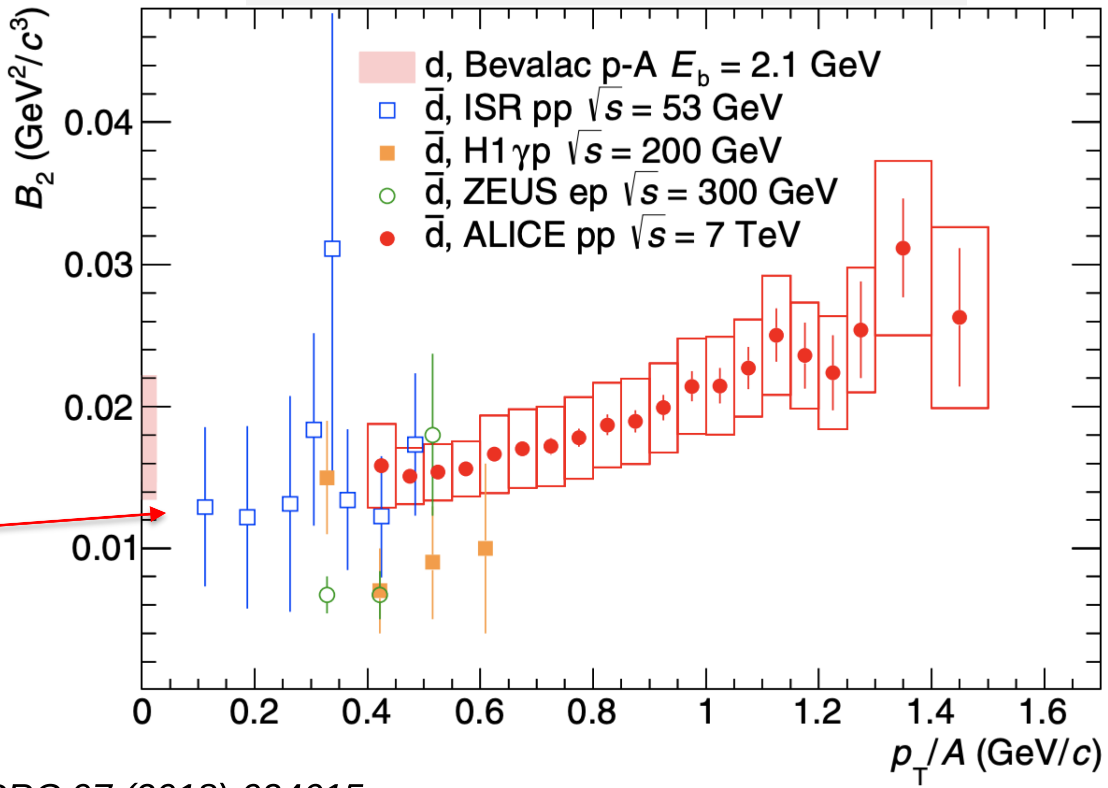
Experimental definition of coalescence probability: extracted from measured distributions of (anti)nuclei and (anti)protons

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{p,n} \frac{d^3 N_{p,n}}{dp_{p,n}^3} \right)^A \Bigg|_{\vec{p}_p = \vec{p}_n = \frac{\vec{p}_A}{A}}$$

Measurement in inelastic pp collisions

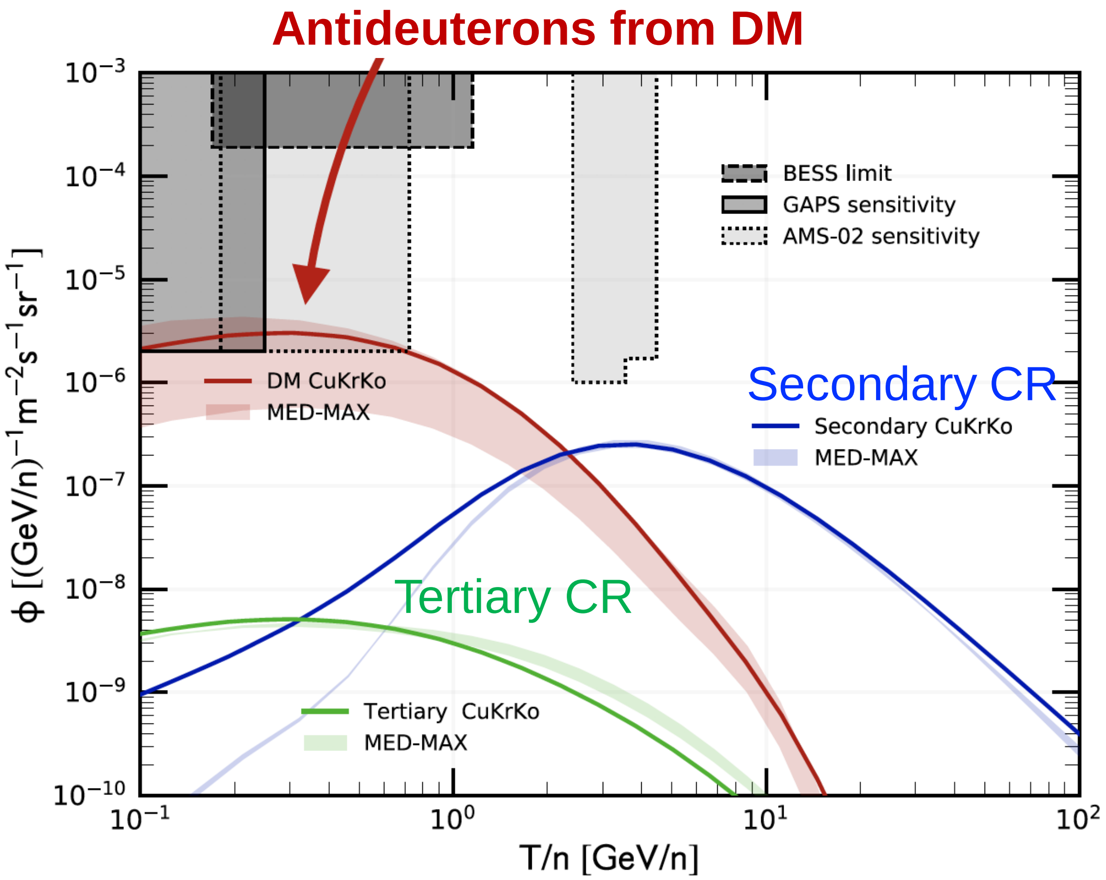


Compared lower energy collisions



ALICE Coll., PRC 97 (2018) 024615

Impact of ALICE B_2 measurement



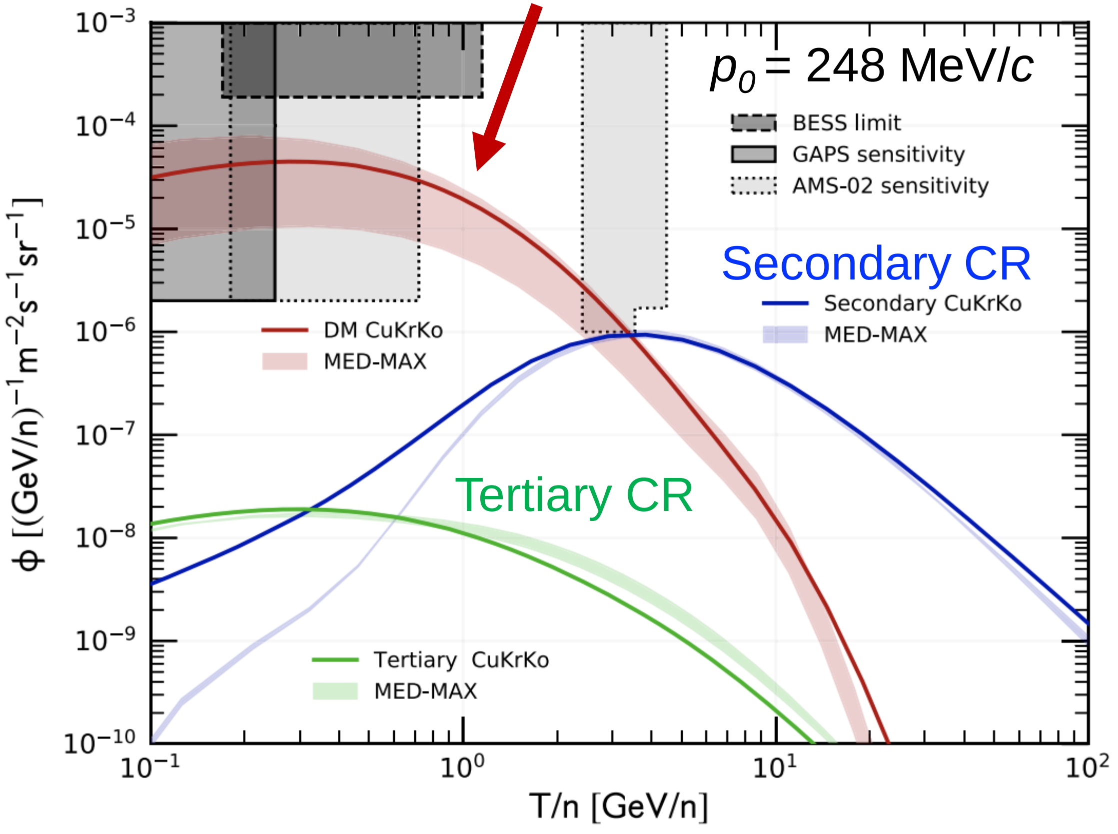
M. Korsmeier et al., PRD 97 (2018) 103011

Before ALICE:
Coalescence momentum p_0 constrained by ALEPH measurement of B_2 in e+e- collisions at LEP

Note that the spectrum of DM antideuterons is peaked at T/n < 1 GeV/c, where it is 1-2 orders of magnitude larger than the CR background

Impact of ALICE B_2 measurement

Antideuterons from DM



M. Korsmeier et al., PRD 97 (2018) 103011
Uncertainty bands: propagation model

Update with ALICE results in pp 7 TeV

Coalescence momentum p_0 constrained by measurement in min bias collisions:

$0.01 < B_2 < 0.02$ GeV^2/c^3

$$B_2 = \frac{m_d}{m_p m_n} \frac{\pi p_0^3}{6}$$

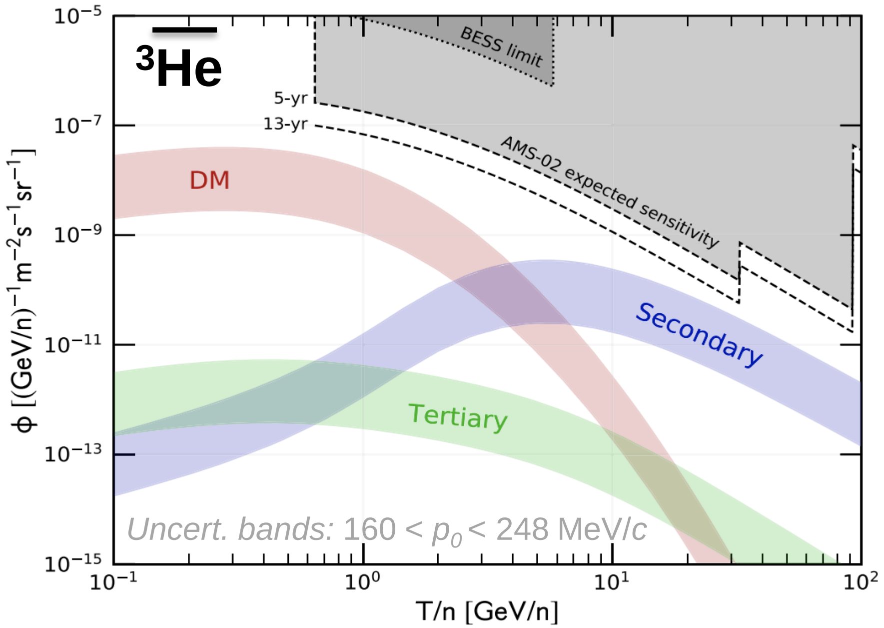
$208 < p_0 < 262$ MeV/c

Predictions for DM signal increased by >10x
Predictions for background flux increased by 2-3x

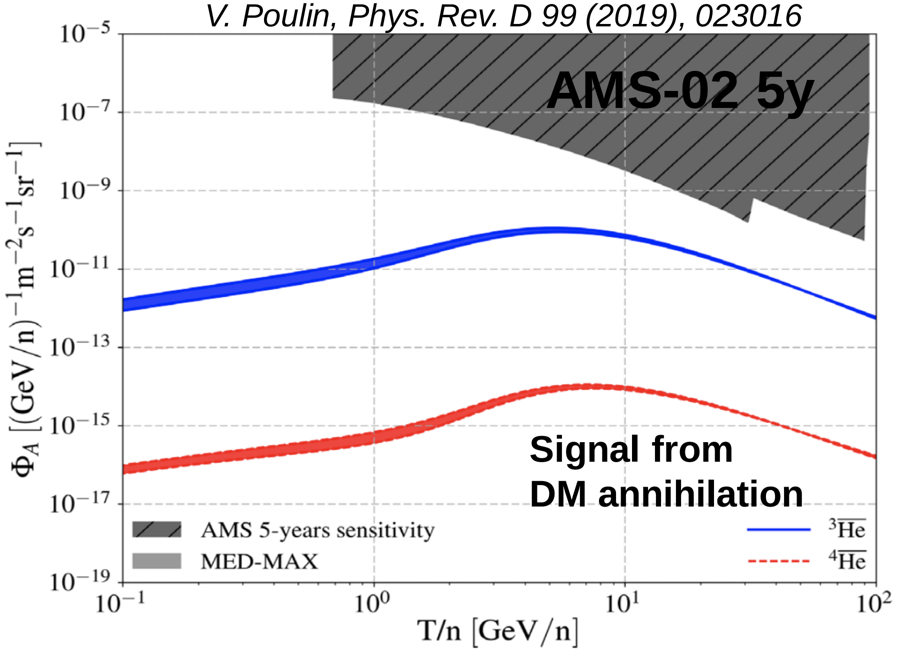
AMS-02, GAPS well sensitive to DM anti-d signal!

What about antihelium?

M. Korsmeier et al., PRD 97 (2018) 103011



V. Poulin, Phys. Rev. D 99 (2019), 023016



If ALICE 7 TeV B_2 measurements are used, with A,Z-scaling relation of B_A, the DM antihelium flux is below the sensitivity of AMS-02.

⟶ Is it really so? Then, where do the AMS-02 anti-He events come from?

$$B_A = \left(\frac{4\pi}{3}\frac{p^3_{coal}}{8}\right)^{A-1} \frac{m_A}{m_p^Z m_n^{A-Z}}$$

⟶ BUT going from anti-d to anti-He is not so trivial. Coalescence is a more complex process!

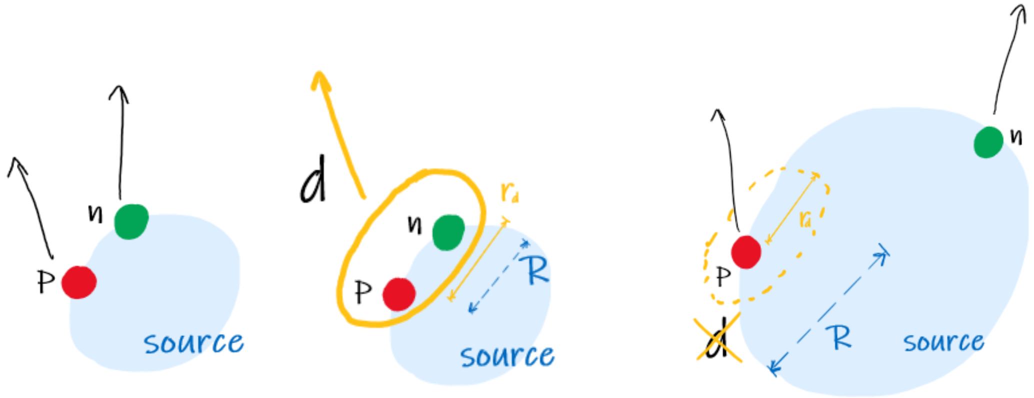
Test scaling properties of coalescence

In state-of-the-art coalescence models, based on a Wigner formalism, B_A depends on A, p_T and **the volume of the nucleus relative to that of the particle source.**

[R. Scheibl, U. Heinz, PRC 59. 1585-1602 (1999); K. Blum et al., PRD 96,103021 (2017); F.Bellini and A. Kalweit, PRC 99, 054905 (2019)]

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

Nucleon transverse mass (including momentum) — Source radius — Nucleus radius



The scaling properties of coalescence can be tested **by comparing different species** and by a **system-size scan** of the production of light (anti)nuclei.

→ The final-state charged-particle multiplicity per unit of rapidity is used as a proxy for the size of the source

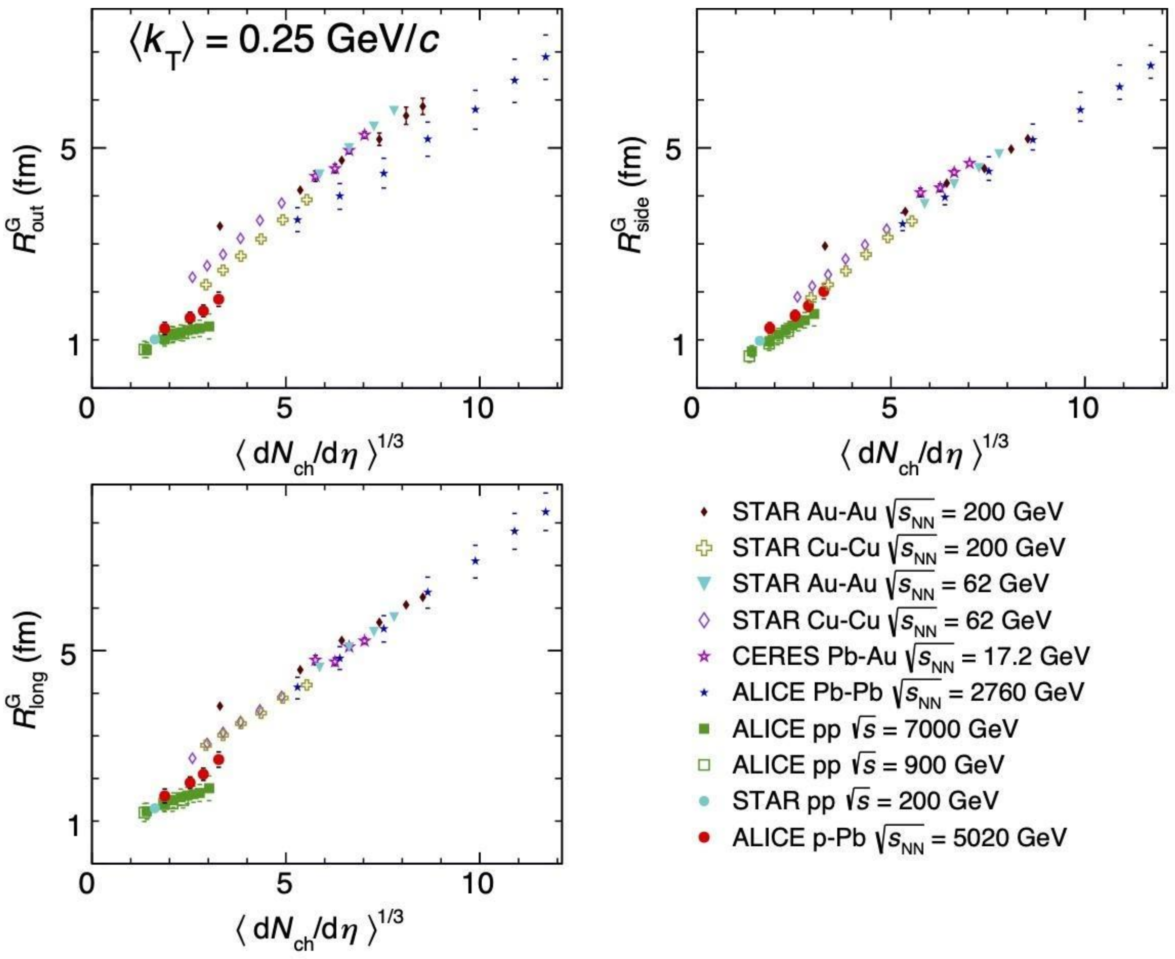
Determination of the size of the source

Idea originally borrowed from Hanbury-Brown-Twiss interferometric technique used to measure the distance of far astrophysical sources (e.g. Sirius) and applied to heavy-ion collisions.

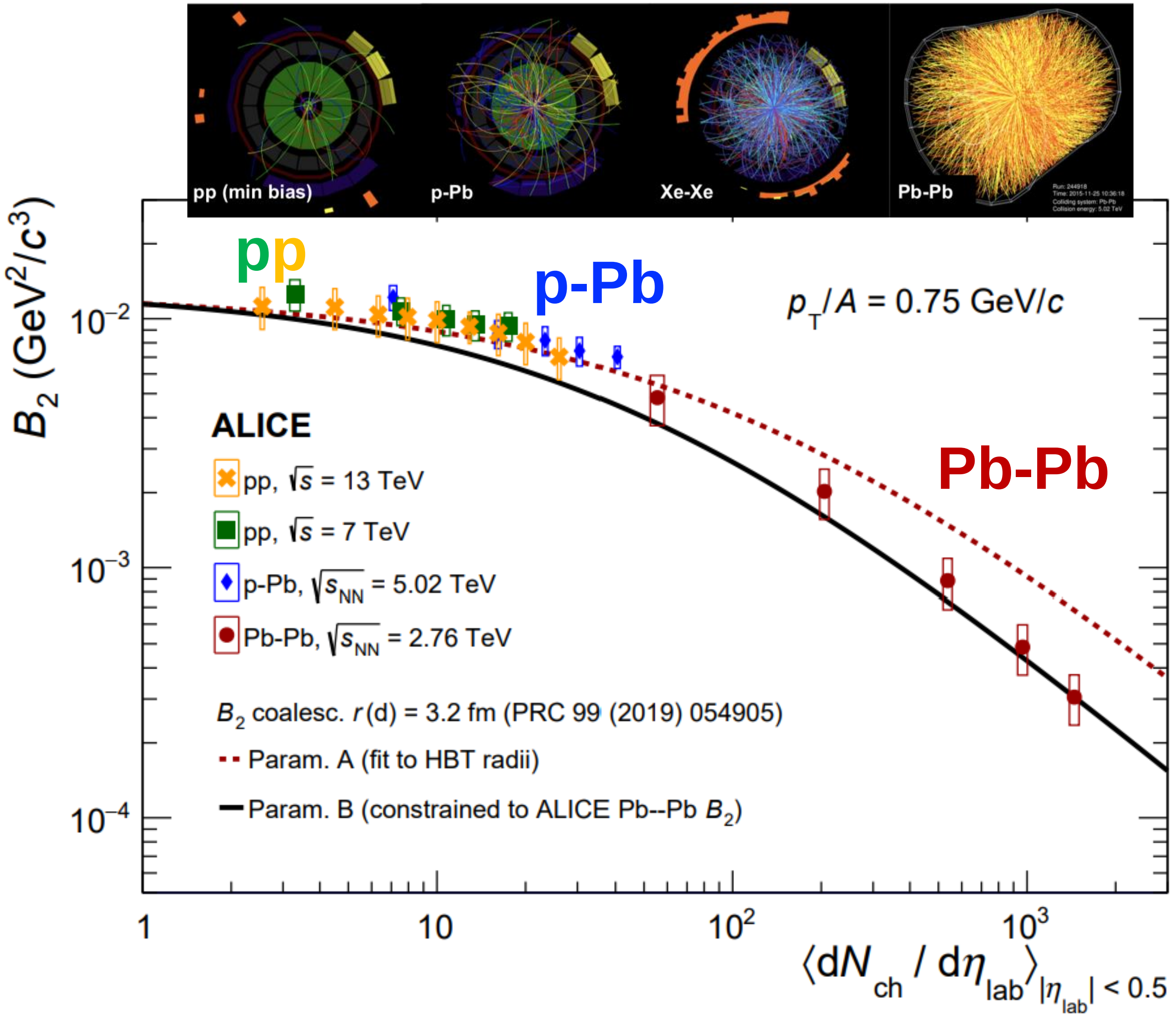
The measurement of two-particle momentum correlations gives access to the size of the region **(“source”) out of which particles are emitted with similar momenta**

- → For nucleons, this coincides with a necessary condition for coalescence
- → Depends on the average momentum of the pair, k_T

Measurements for pion and kaon pairs at the LHC show that the 3D radii of the “source” scale linearly with the cubic root of the charged-particle multiplicity density.



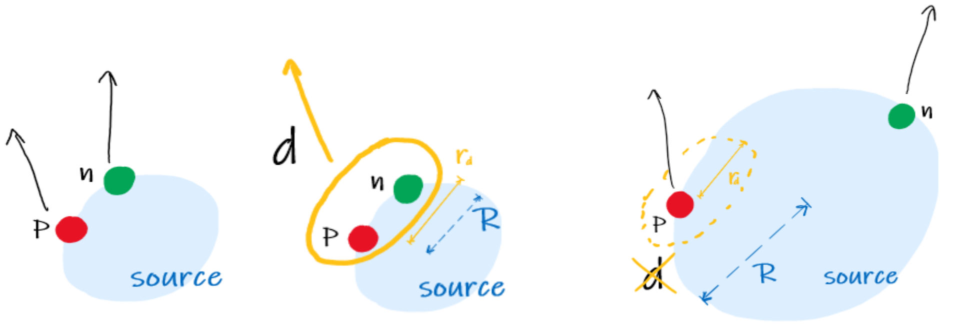
Test coalescence for (anti)deuteron



At the LHC, the most comprehensive and precise set of data is on **(anti)deuteron**

The trend with multiplicity across different collision systems can be explained within the coalescence model as due to the increase in the **size of the source.**

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



Recap: a lesson from the LHC

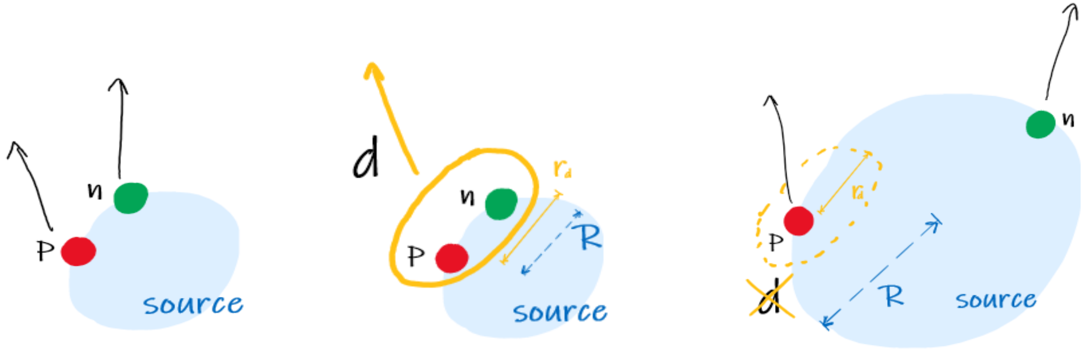
ALICE has measured (anti)d and (anti)^{3}He from pp to Pb-Pb collisions, as a function of the particle multiplicity in the final state (multiplicity = a proxy for the size of the source):

- Most comprehensive and precise set of data on **(anti)deuteron**
- **Data on ^{3}He still scarce**

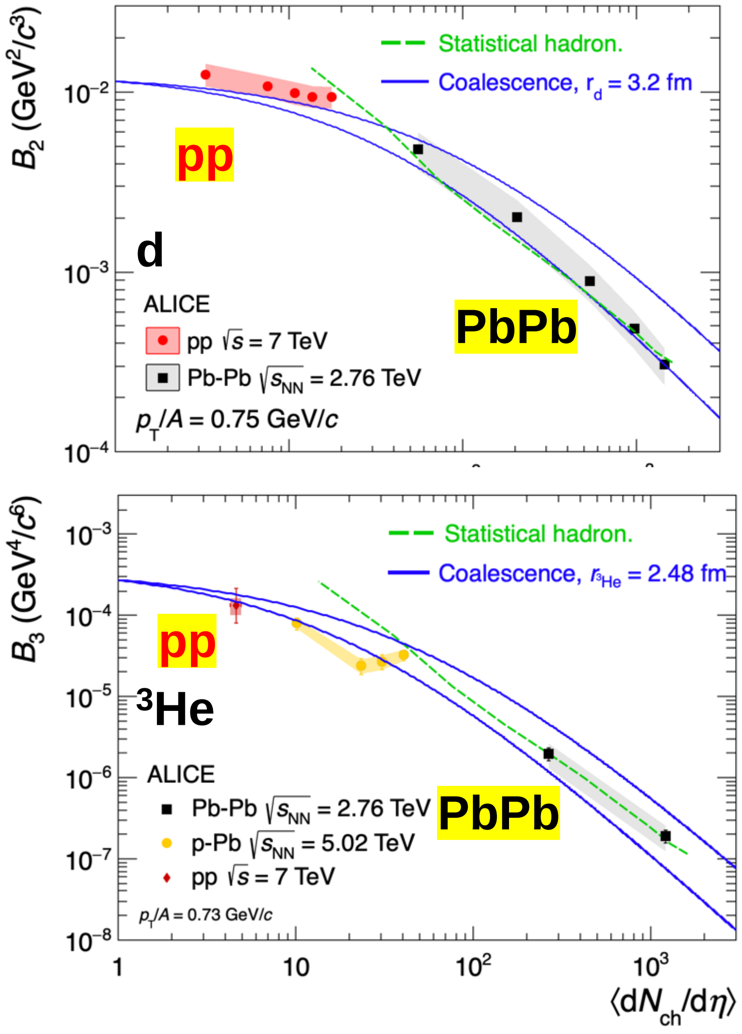
The coalescence probability depends also on

- the size of the nucleon-emitting **source**
- the size of the cluster (i.e. the **wave function**)

→ state-of-the-art coalescence based on Wigner formalism

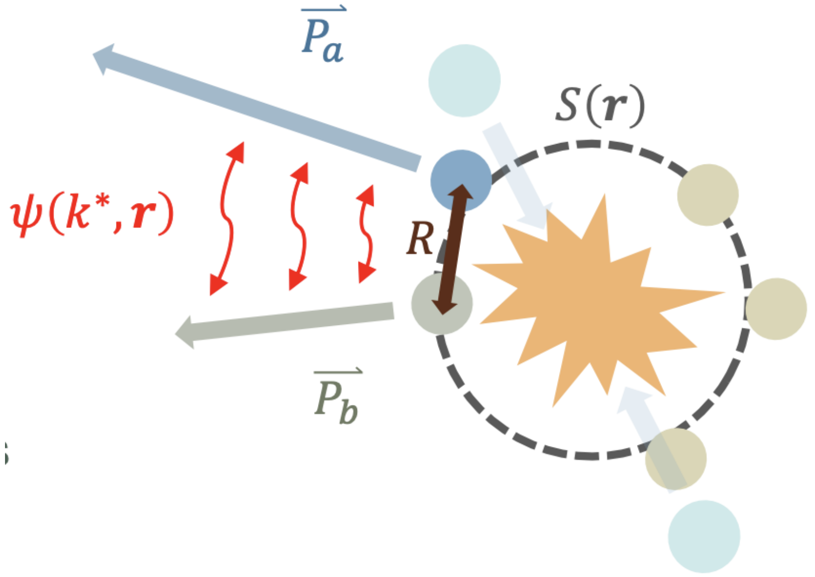


Simplified versions of *PLB 794 (2019) 50-63*, *PRC 101 (2020) 044906*



A new approach to coalescence via femtoscopic correlations

Two-particle momentum correlations provide information about the final-state interaction among particles
[e.g., ALICE, Nature 588, 232–238 (2020), PLB 811 (2020) 135849]



Credits: ALICE/TUM

Quantum-mechanical 2-body problem:

- Continuum solutions ⟶ information about the source
  - Two-particle momentum correlations used to measure size and lifetime of the system created in pp and heavy-ion collisions
- Discrete bound state solutions ⟶ coalescence
  [K.Blum, M. Takimoto, PRC 99, 044913 (2019); S. Bazak, S. Mrowczynski, EPJA 56, 193 (2020)]

$$\mathcal{B}_2(p) \approx \frac{2(2s_d+1)}{m(2s_N+1)^2}(2\pi)^3 \int d^3\mathbf{r}\, |\phi_d(\mathbf{r})|^2\, \mathcal{S}_2(\mathbf{r}) \Leftrightarrow \mathcal{B}_2(p) \approx \frac{2(2s_d+1)}{m(2s_N+1)^2} \int d^3\mathbf{k}\, \mathcal{F}_d(\mathbf{k})\, \mathcal{C}_2(p, \mathbf{k})$$

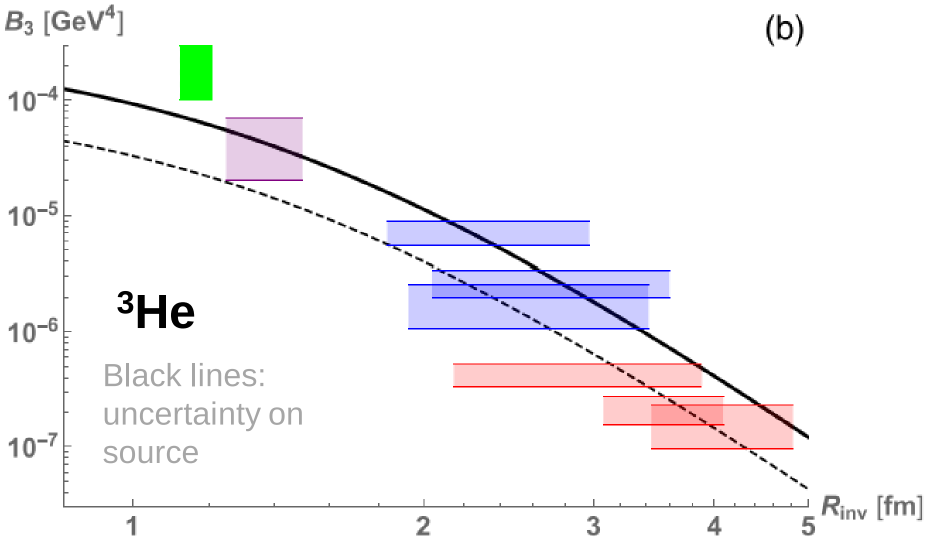
Coalescence probability (d example)

Nucleus wave function ⟺ Form factor

Source ⟺ Momentum correlation function

Novel approach of CosmicAntiNuclei

- **Constrain coalescence across collision systems by measuring the production rates and B_A for A=3 and A=4 (anti)nuclei**
  - exploiting the unprecedently large data samples of LHC Run 3
  - more abundant production in AA, at the price of having to describe a more complex source



K.Blum, FB, A. Kalweit, M.Puccio, PRC 103, 014907 (2021)

- Exploit the **fundamental relation between femtoscopic correlations and nuclear cluster formation**
  - Measure p-d, p-t femtoscopic correlations
  - Measure the size of the source

Note: a first work applying Wigner-formalism based coalescence to the context of CosmicAntiNuclei appeared only very recently *[Kachelriess et al., EPJA (2020) 56-4, arXiv:2002.10481]*

Antihelium in the LHC Run 3

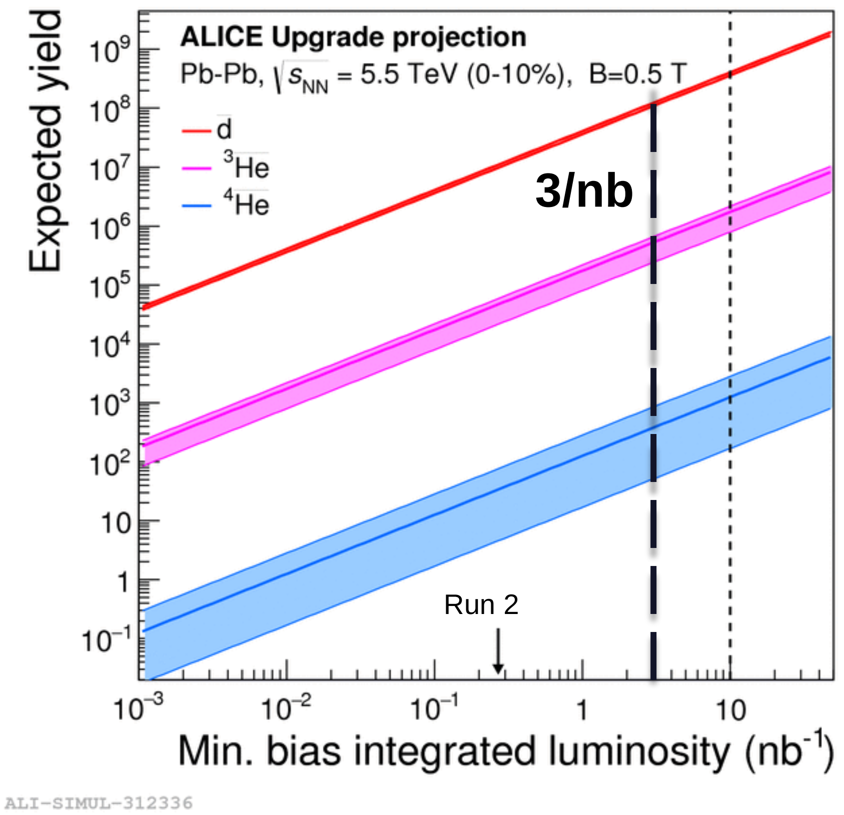
To meaningfully constrain flux calculations, a **precision** on B_A of the order of **O(10%) or better is required.**

- *ALICE operating in continuous readout after LS2 upgrade*

We expect **$2x10^6$ anti-3He in 200/pb pp 14 TeV** and **2000 anti-^{4}He** (+ as many nuclei) ⟶ *required precision in reach in Run 3 pp!*

B_A	pp $\sqrt{s}$	L_{int}	Stat. unc.	Sys. Unc.
A = 2, 3	5.5	6 /pb	**< 0.1%**	O(10%)
	14	200 /pb	**< 0.1%**	
A = 4	14	200 /pb	**~ 10%**	To be estimated

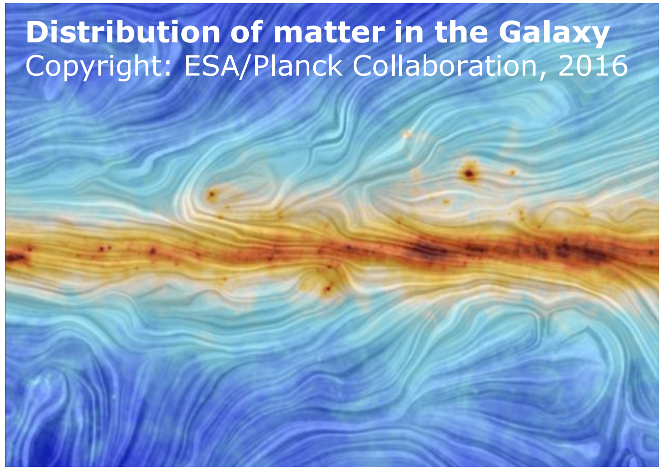
In addition, Pb-Pb will allow us to measure A=3 (4) with the same precision reached in Run1+2 for A=2 (3)



Modelling propagation in the Galaxy

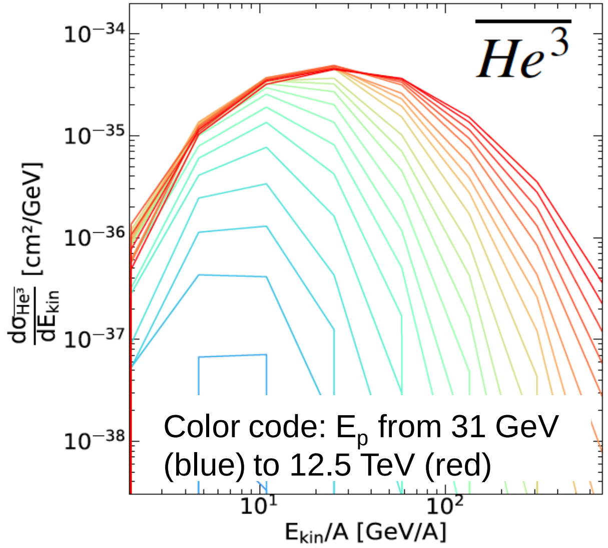
Flux calculations are sensitive to the details of particle propagation in the Galaxy → *model dependency*

- Acceleration by Super Novae remnants
- Diffusion in the galactic magnetic field *(~μGauss)*
- Energy loss / gain *(for loosely-bound nuclei, break-up dominates)*
- Solar modulations *(matters mostly at low E, where DM signal prominent)*
- Inelastic cross section of antinuclei *(measurement ongoing in ALICE)*



Employ state-of-the-art frameworks as GALPROP–HELMOD:

- Constrain propagation with measurements of CR p and heavier elements
  [using nuclei up to Z≤28, M. Boschini et al. arXiv:2006.01337]
- Implement antinuclei formation via coalescence as input
- Include (still ongoing) ALICE measurement of low-energy anti-^{3}He inelastic cross section



CosmicAntiNuclei - **Constraining cosmic antinuclei fluxes for indirect dark matter searches with precision measurements of rare antimatter cluster formation.**

Outline for today:

- Cosmic antinuclei as smoking guns for DM
- What is needed to determine antinuclei fluxes
- ALICE as antinucleus detector and LHC as an antimatter factory
- Investigating formation of antinuclei by coalescence
  - Production rates and coalescence probability
  - Two-particle momentum correlations
- **CosmicAntiNuclei executive summary**

CosmicAntiNuclei executive summary

1. **Measure** with **unprecedented precision antihelium production** and (anti)**nucleus-nucleon correlations** with ALICE at the LHC Run 3

   ⟶ The re-commissioning of the upgraded ALICE detector will be crucial for ensuring the expected performance, focus on TOF PID calibration here in Bologna

2. **Constrain** models of nuclear cluster formation via **coalescence**

   ⟶ Extract **coalescence probability** from measured yields

   ⟶ Employ a **novel approach** based on the measurement of nucleus-nucleon **correlations to characterize the source**

3. **Model** cosmic antinuclei **formation and propagation** in the Galaxy

   ⟶ Use validated coalescence model to calculate **energy distributions of cosmic antinuclei**
   ⟶ Employ state-of-the-art propagation models (e.g. GALPROP)

4. **Estimate the flux of secondary CR anti-^{3}He for existing and future experiments**

Conclusions

The **Cosmic Anti Nuclei** project, starting in July 2021, will

- provide an **experimental test of quantum-mechanical aspects of coalescence**
- clarify the formation of nuclear clusters in **high-energy interactions**, from pp to heavy-ions
- update predictions of **expected cosmic antinuclei fluxes**
- impact for **indirect dark matter searches** with AMS, GAPS
- foster collaboration between high-energy nuclear physics experiments and the astrophysical domain
- involve a wide range of expertise, due its interdisciplinary nature

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

European Research Council
Established by the European Commission

Thank you!

f.bellini@unibo.it