HADRON 2023

Constraining the formation mechanisms of Light (anti)nuclei at the LHC and Applications for cosmic ray physics

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ALICE
CosmicAntiNuclei

Light (anti)nuclei at the LHC - the antinucleus factory

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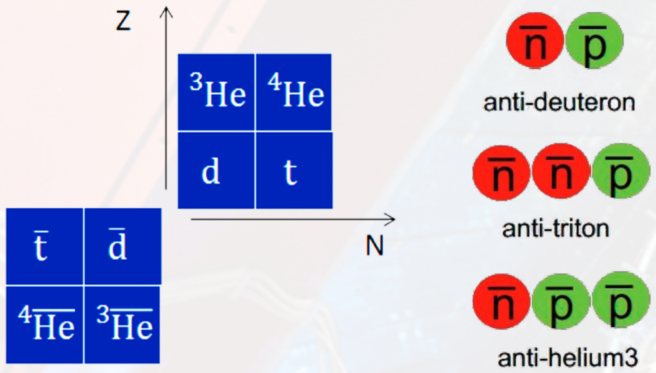
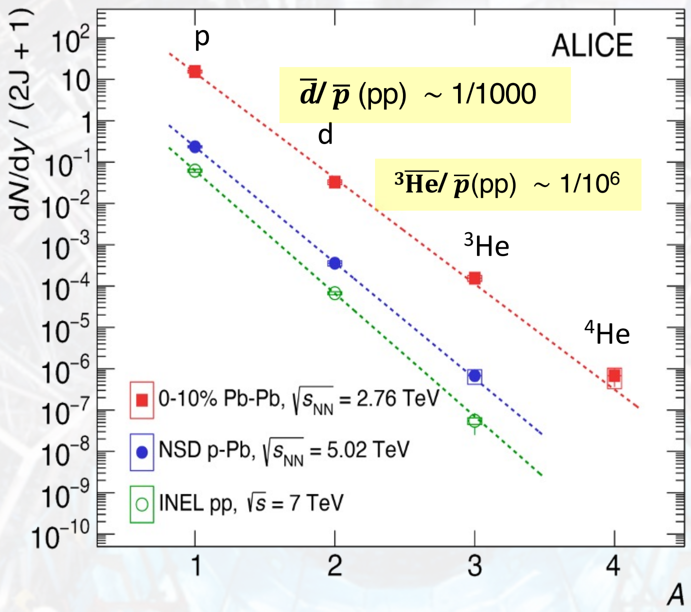


The production **mechanism** of light (anti)nuclei in high energy collisions is **not fully understood**

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

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

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



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

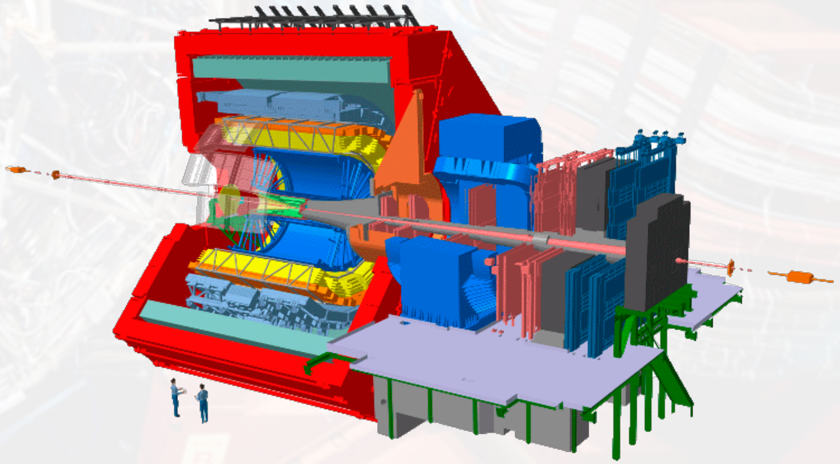
At LHC, same amount of matter and antimatter[1]
→ Ideal conditions for studying **antinuclei**

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

[1] Physical Review C97, 024615 (2018)

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

See **Marika**'s talk for an exhaustive overview of these (anti)nuclei measurements performed during LHC Run1 and Run2!



(Anti)nuclei production in statistical hadronisation (thermal) models

- Hadrons emitted from the interaction region in thermal equilibrium when the fireball reaches the freeze-out
- Abundances are fixed at chemical freeze-out (T_{chem})

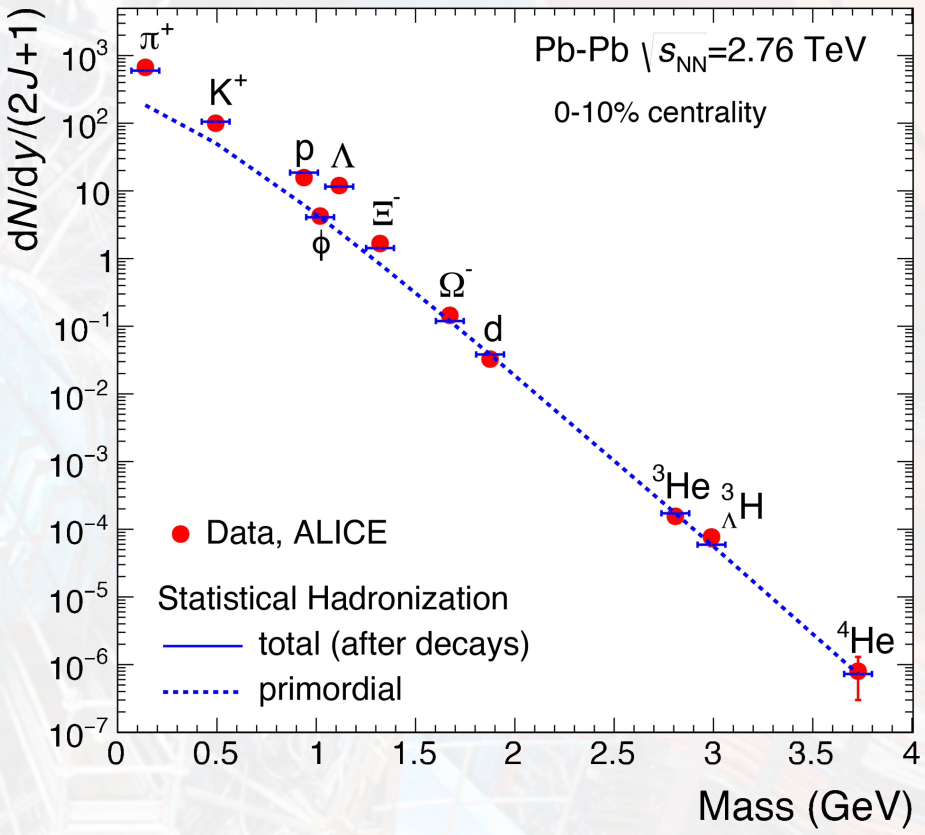
The abundance of nuclei strongly depends on the T_{chem} as

$$\mathrm{d}N/\mathrm{d}y \sim \exp(-m/T_{\mathrm{chem}})$$

- Nuclei have large mass m
- Little or no feed-down from higher mass states

Notes:

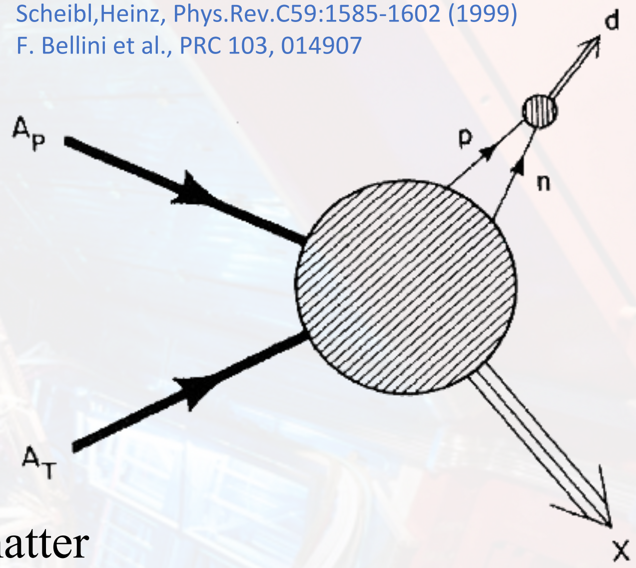
- SHM predict **particle abundances**
- Nuclei might **break and re-form** between chemical and kinetic freeze-out in heavy-ion collisions
- Extension to pp collisions → **canonical** ensemble and exact conservation of quantum numbers over a correlation volume



Andronic, A. et al., Nature 561, 321–330 (2018)

(Anti)nuclei production in coalescence models

J. I. Kapusta, Phys.Rev. C21, 1301 (1980)
Scheibl,Heinz, Phys.Rev.C59:1585-1602 (1999)
F. Bellini et al., PRC 103, 014907



Nucleons close in the phase space at the freeze-out can form a nucleus via **coalescence**
Formation probability is related to the **coalescence parameter B_A**

NUCLEUS — NUCLEONS — PROTONS — NEUTRONS

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

- **Simple coalescence approach: $|\boldsymbol{p}_\mathbf{p} - \boldsymbol{p}_\mathbf{n}| < p_0$ → only nucleon momentum** (and spin) matter

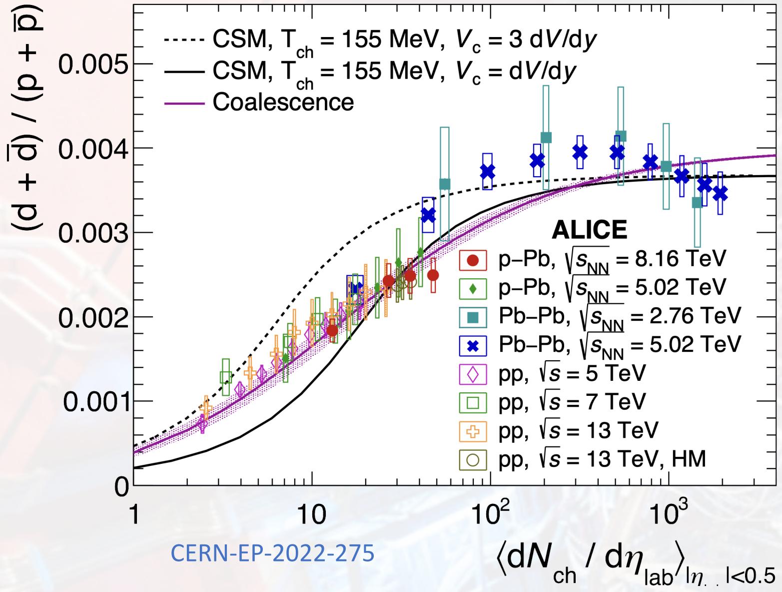
- **Wigner-function approach → nucleon momentum** and **position, nucleus wavefunction** matter

The expansion of highly-excited state (after collisions) leads to kinetic freeze-out with nucleons
→ Described by a QM density matrix → Projection onto particle states at the detector gives particle spectra
→ Final state interaction admits bound-state solutions → **nuclei**

i.e., for d: $\mathbf{r} = \boldsymbol{r}_\mathbf{p} - \boldsymbol{r}_\mathbf{n}$, $q = (\boldsymbol{p}_\mathbf{p} - \boldsymbol{p}_\mathbf{n})^2$, $\phi_d(\mathbf{r_d}, \mathbf{p_d}) \propto \varphi_d e^{i\mathbf{p}_d \cdot \mathbf{r}_d}$,
where φ_d is the deuteron internal wavefunction,
$S_2(r)$ the source of nucleons

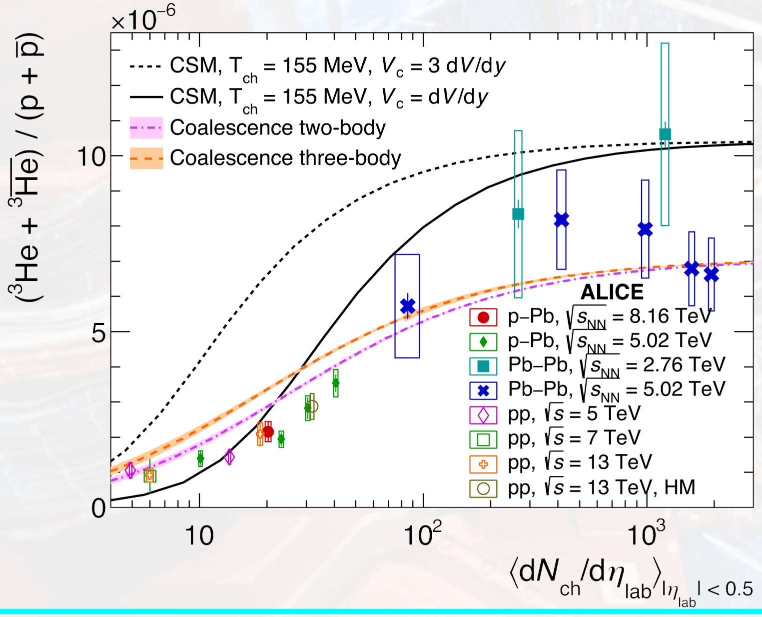
$$B_2(p) \approx \frac{2(2s_d+1)}{m(2s_N+1)^2}(2\pi)^3 \int d^3\vec{r}\, |\varphi_d(\vec{r})|^2 S_2(\vec{r})$$

Nuclei over p ratio

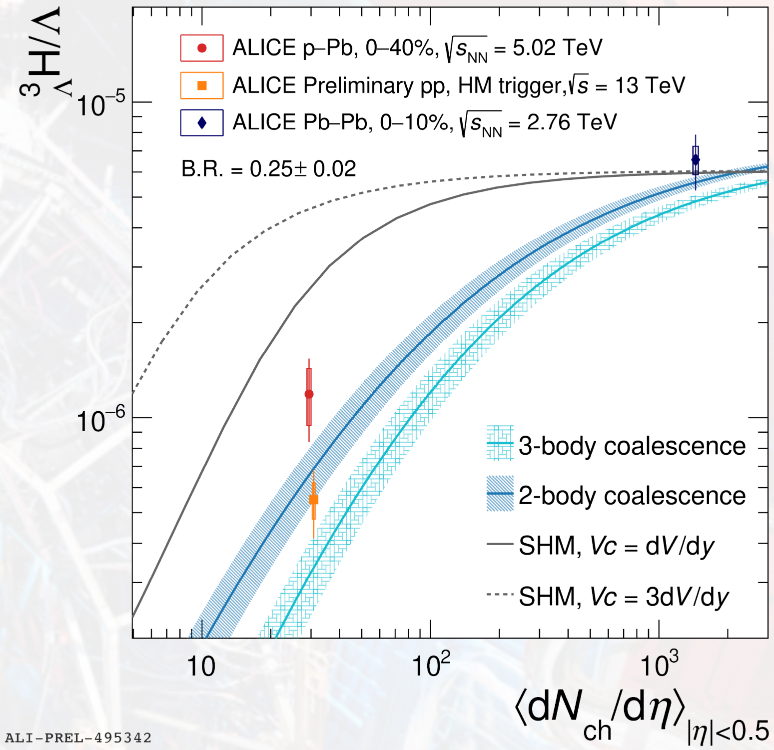


CERN-EP-2022-275

d/p **rises** with charged particle multiplicity or particle density
→ Coalescence model agrees with the data



Theoretical models provide a better description of the **deuteron** (wrt **$^3\overline{He}$**) production



$^3_\Lambda$**H** is strongly sensitive to coalescence space-constraint

Recent $^3_\Lambda$**H/Λ** measurements exclude with high significance the canonical version of the SHM with $V_c > 3\ dV/dy$, while support **coalescence**

Our main observable: the particle yield

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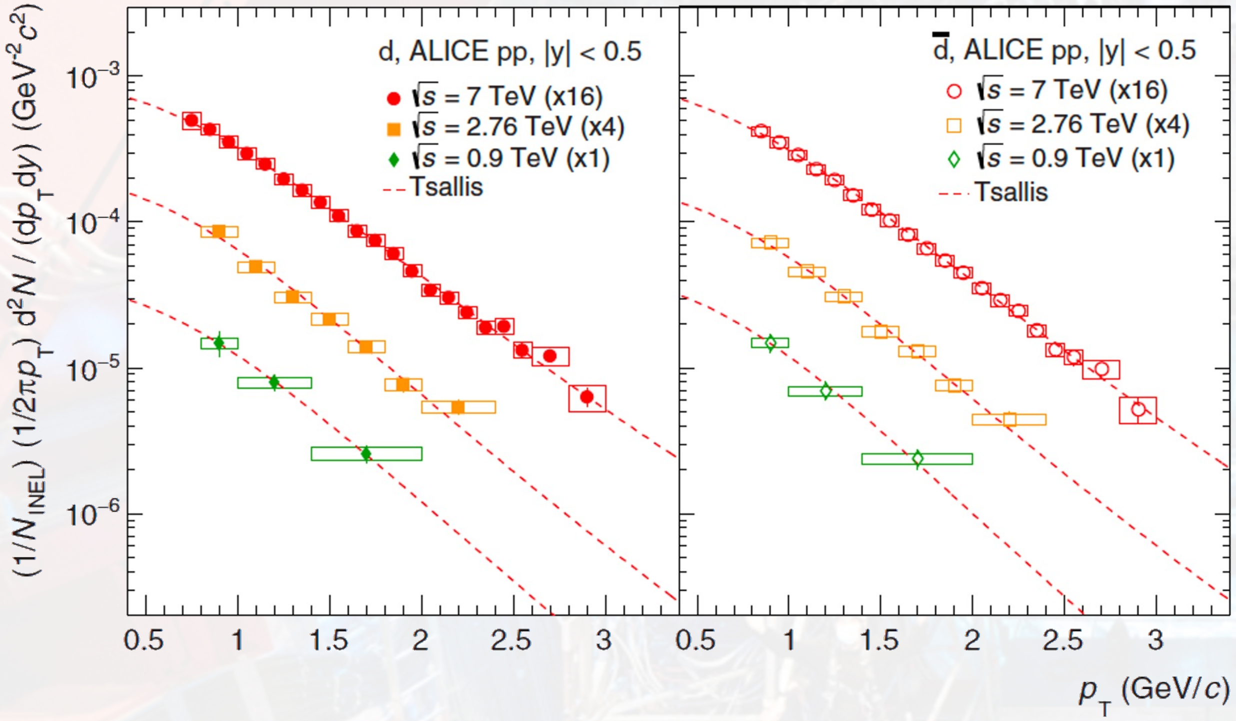
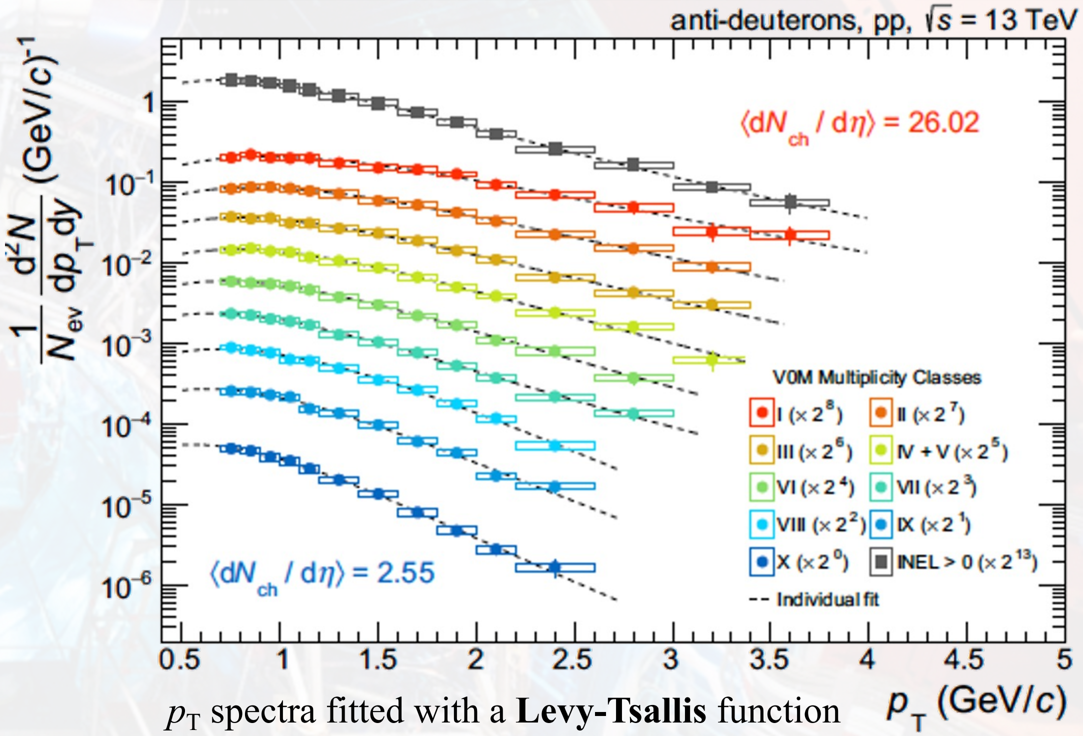




p_T spectra fitted with a **Levy-Tsallis** function

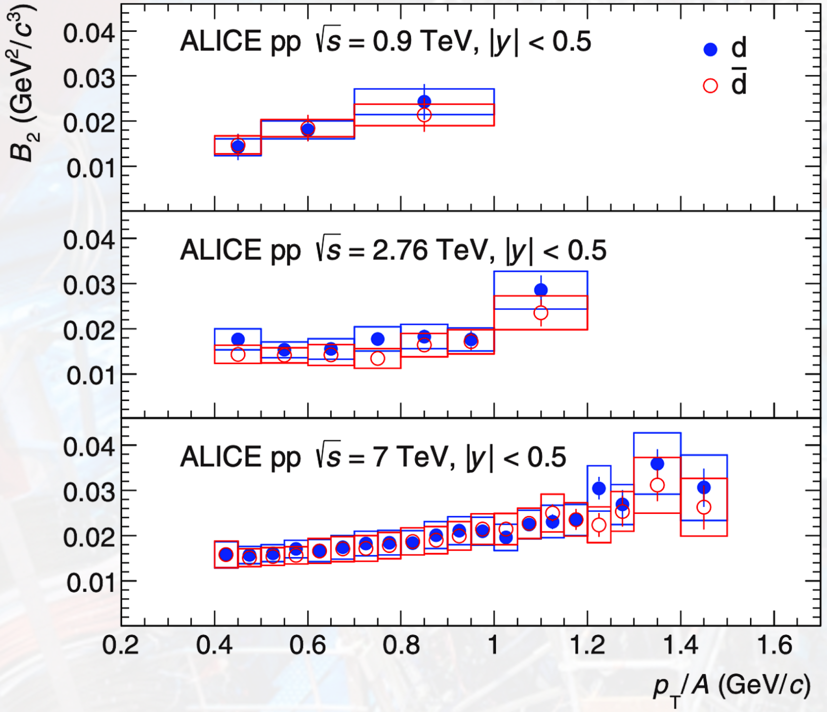
Measured in **inelastic pp collisions** and as a function of the **multiplicity**

Production spectra get **harder** with increasing multiplicity → Hardening also observed in **proton spectra**

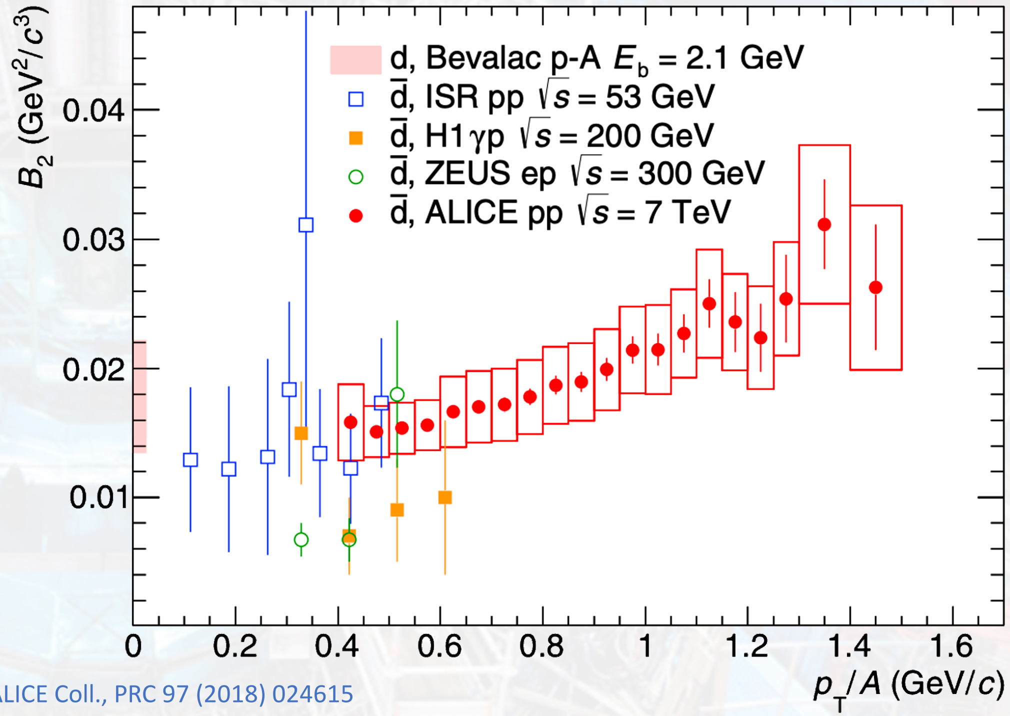
New Run 3 ALICE measurements will allow the extension **of** the **p_T coverage** in pp collision at **√s = 900 GeV** (lowest LHC energy) and **new measurements at the highest energy so far, √s = 13.6 TeV**

Derived observable: coalescence probability

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



First ALICE measurement (Run1)



ALICE Coll., PRC 97 (2018) 024615

High precision of ALICE data → also multidifferential (p_T & multiplicity)

Derived observable: coalescence probability

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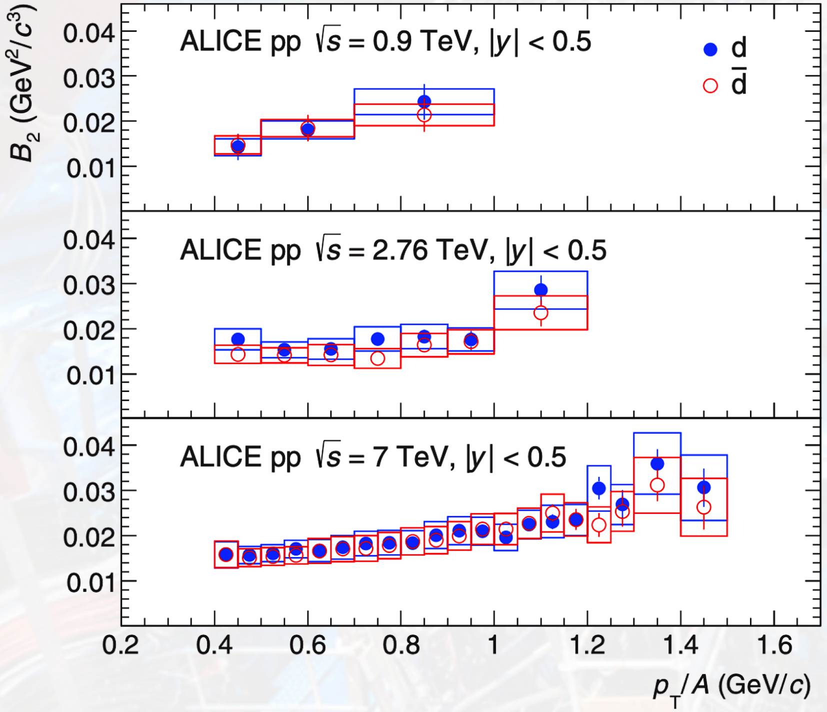

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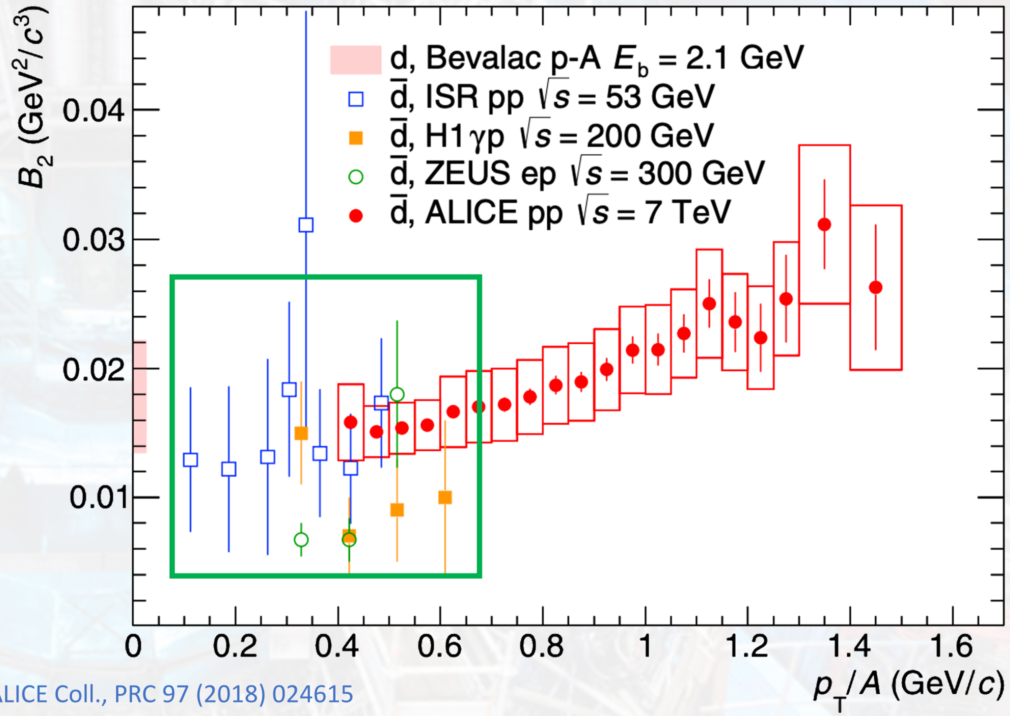

ALICE Coll., PRC 97 (2018) 024615

High precision of ALICE data → also multidifferential (p_T & multiplicity)

Low energy → No significant energy dependence

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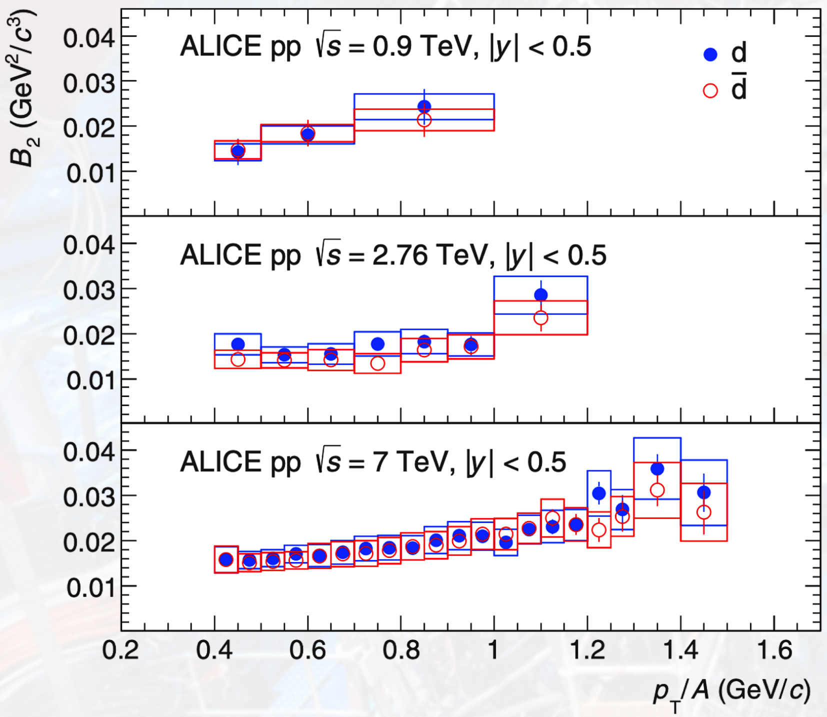

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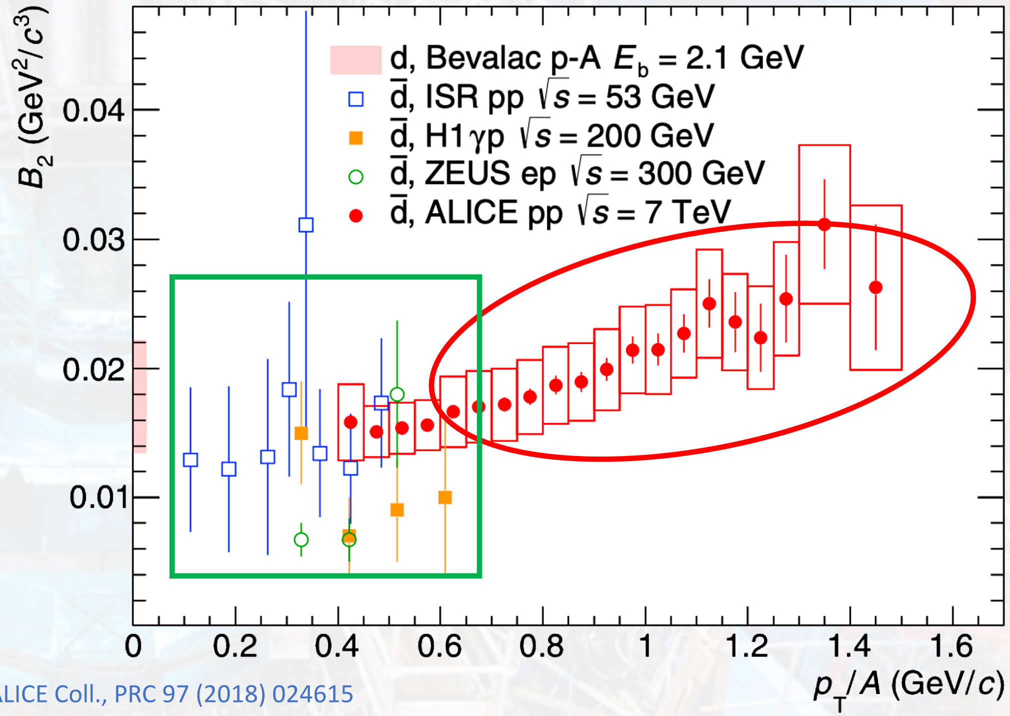


ALICE Coll., PRC 97 (2018) 024615

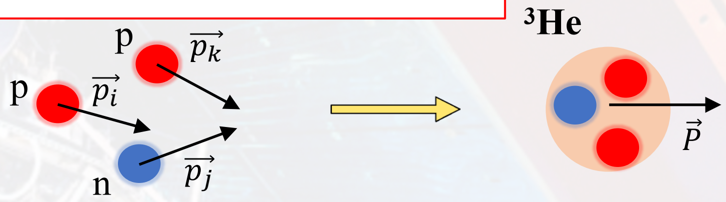
High precision of ALICE data → also multidifferential (p_T & multiplicity)

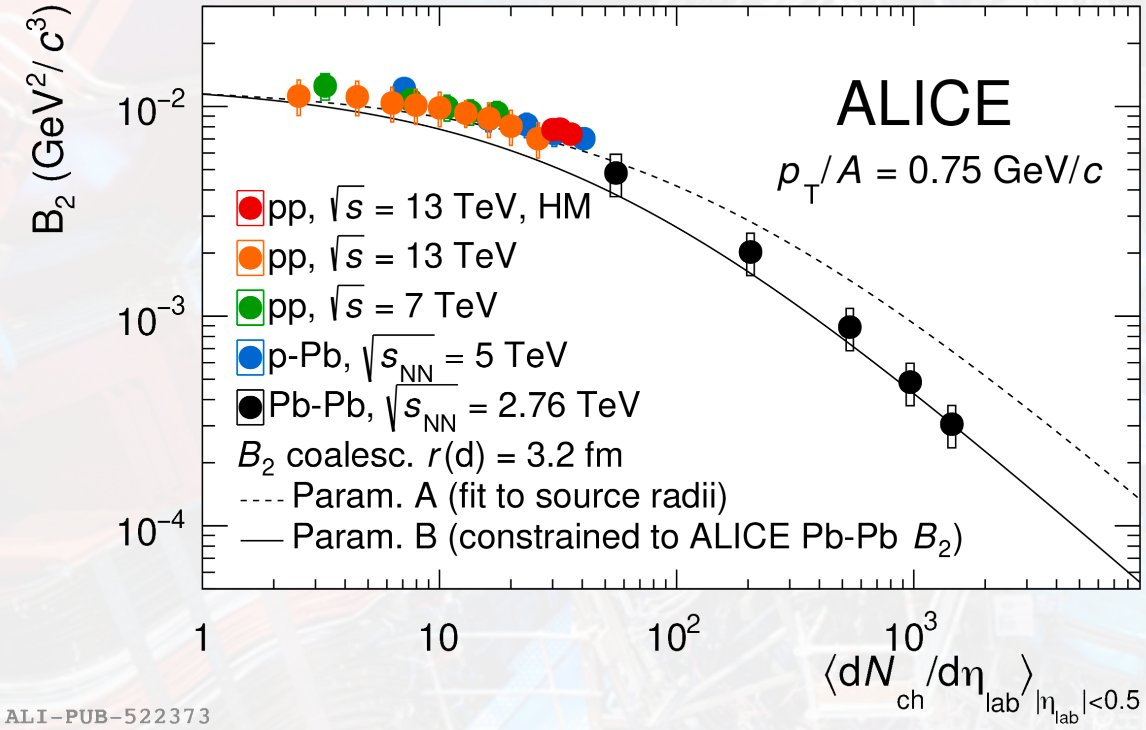
Low energy → No significant energy dependence

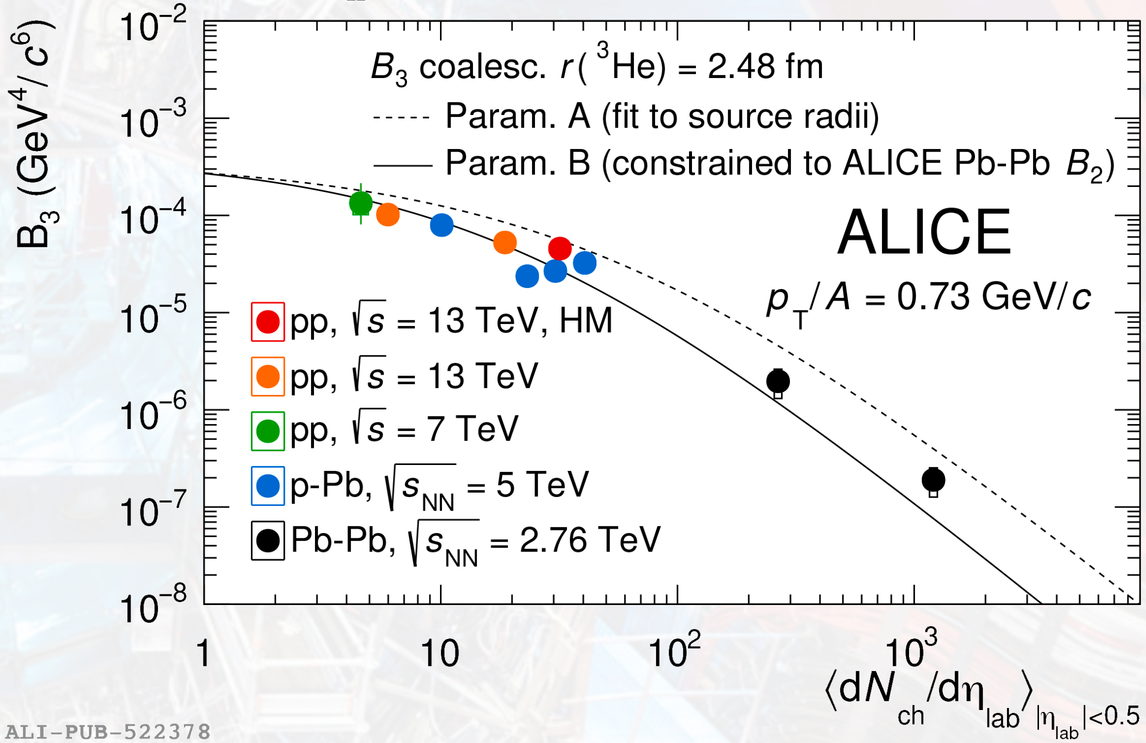
Trend with p_T → effect of **p_T shape** of proton

The coalescence parameter B_A

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







Dependence of **coalescence probability** on the charged particle multiplicity (→ **source size**):

The coalescence parameter B_A

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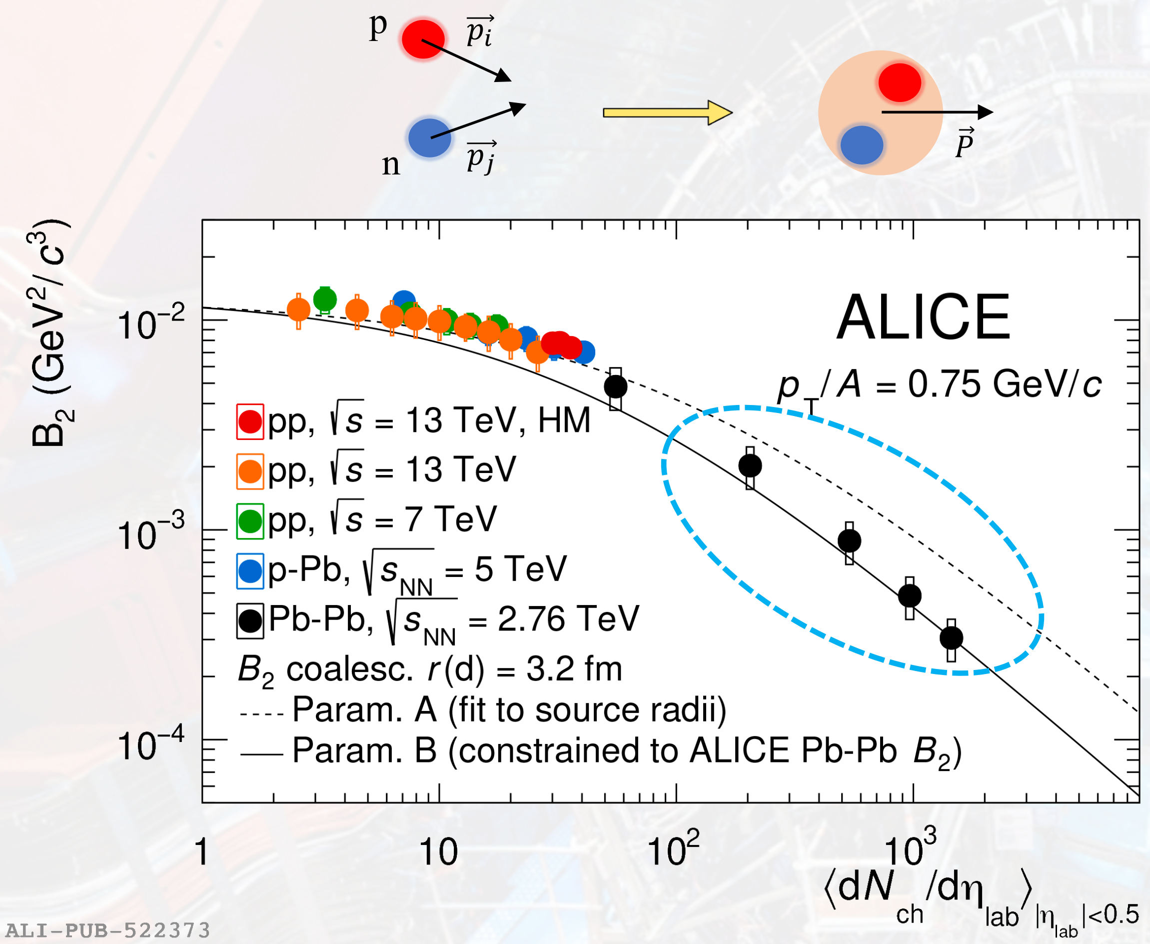
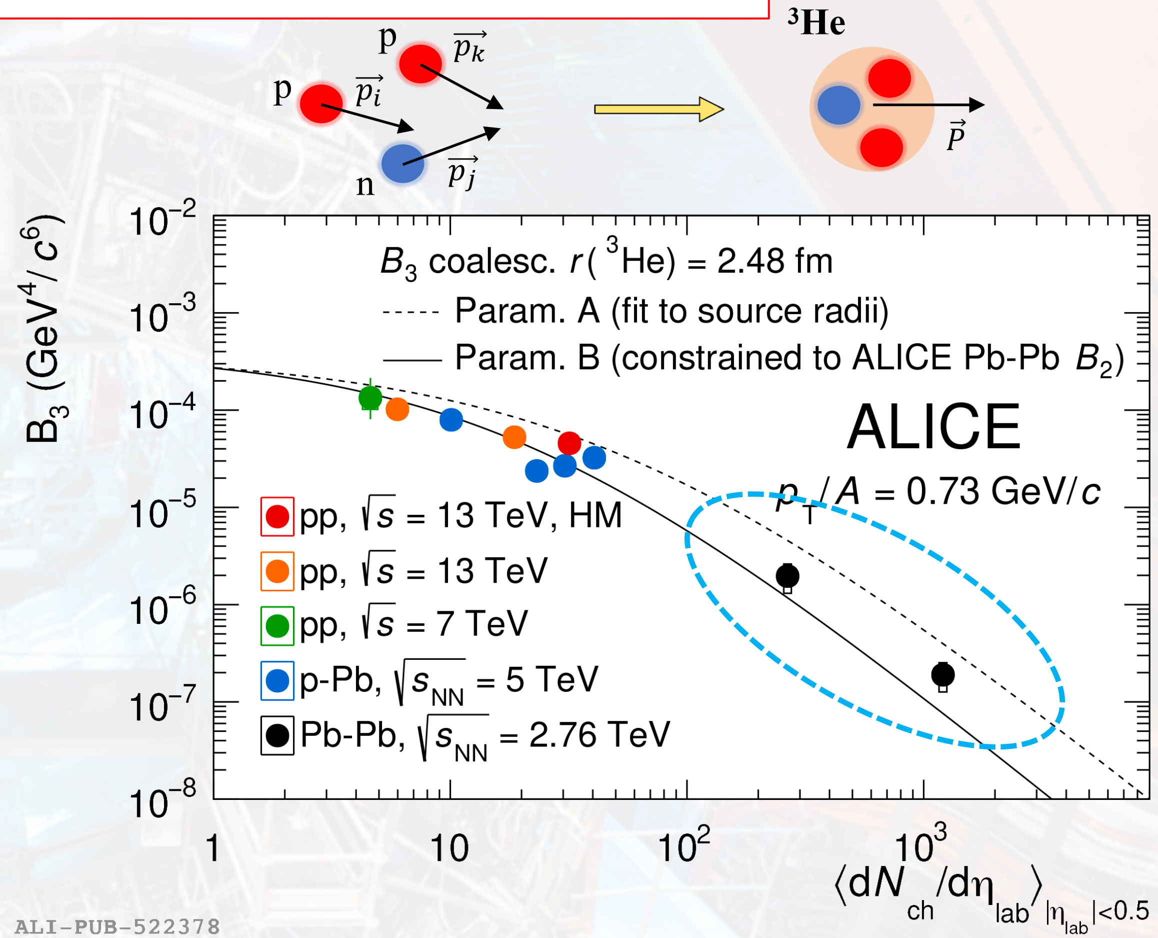
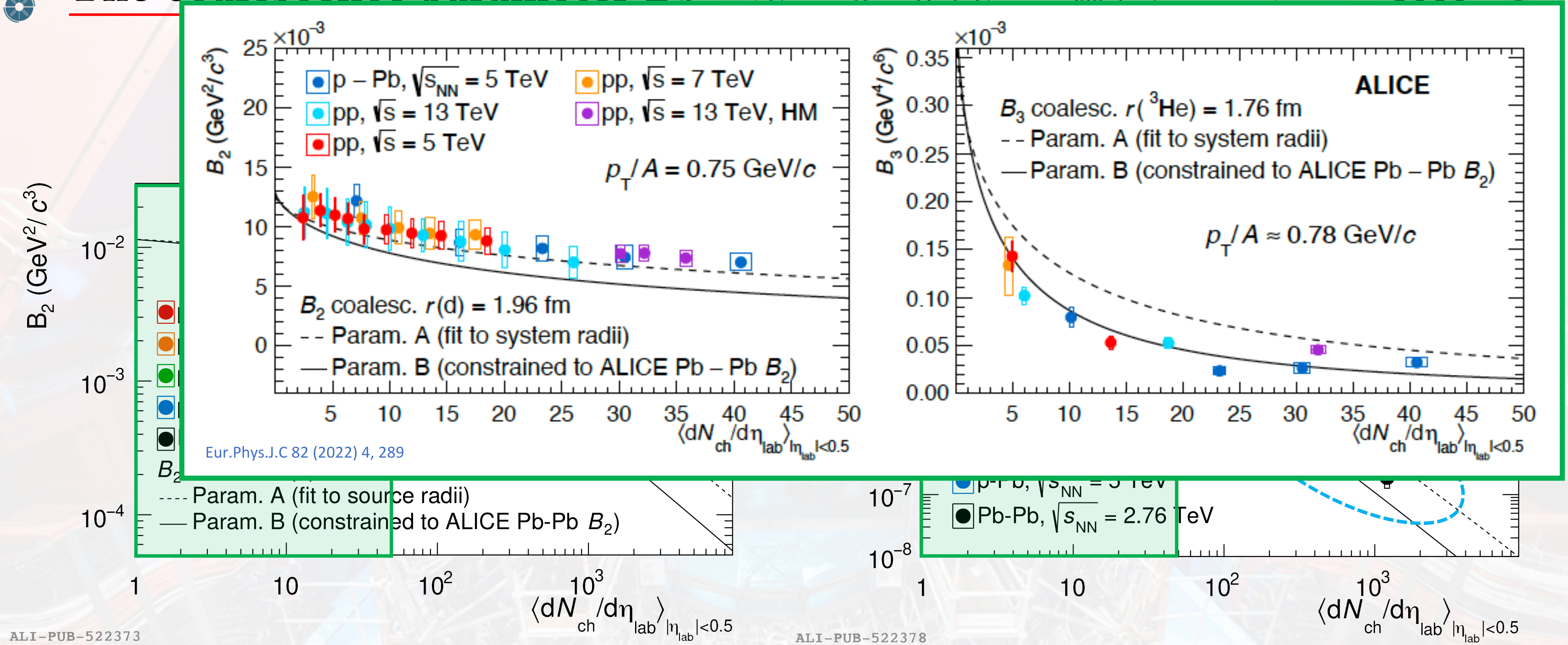




Dependence of **coalescence probability** on the charged particle multiplicity (→ **source size**):

High multiplicity (Pb-Pb) → significant drop → effect of space separation in a large source (~2-5 fm radius)

The coalescence parameter B_A

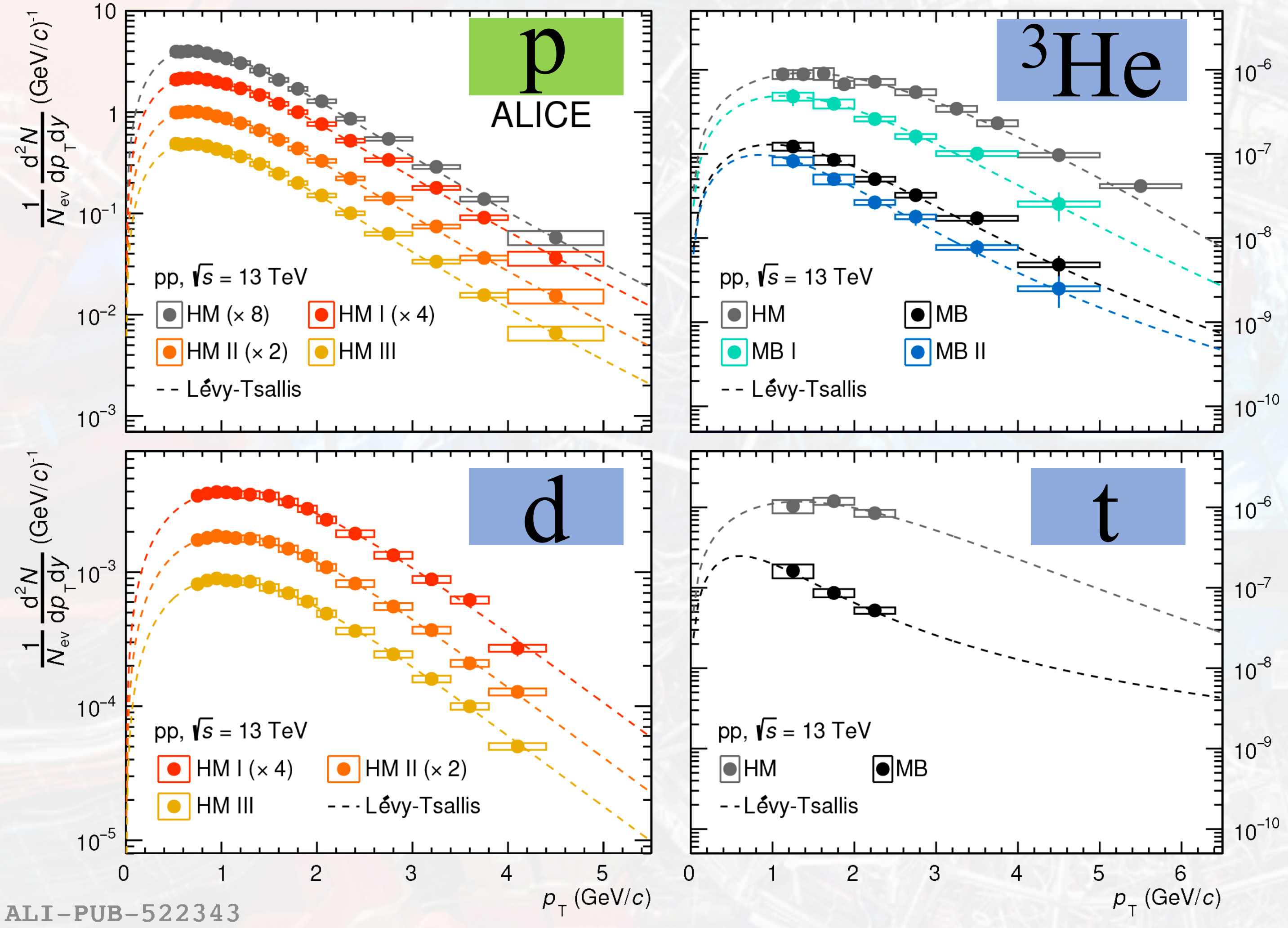


Dependence of **coalescence probability** on the charged particle multiplicity (→ source size):

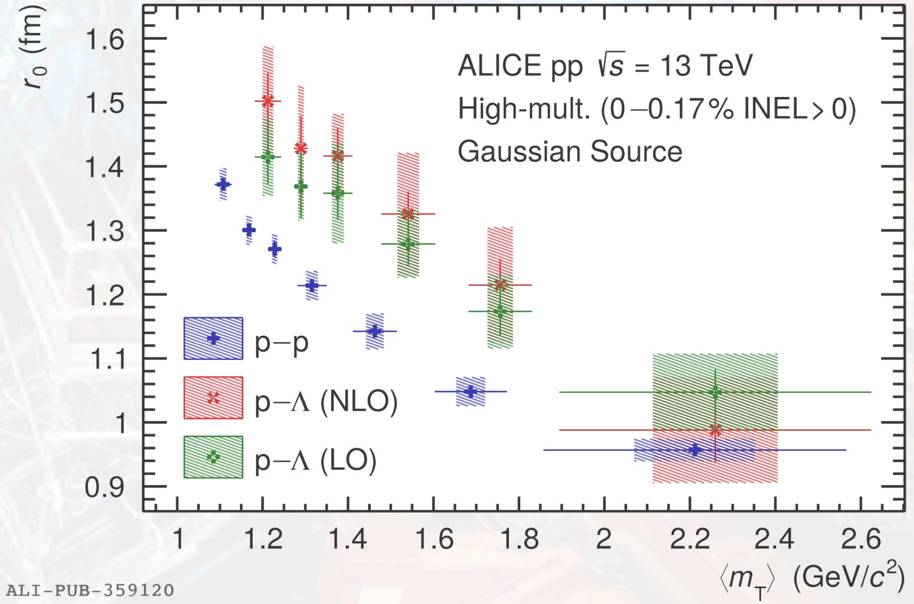
High multiplicity (Pb-Pb) → significant drop → effect of space separation in a large source (~2-5 fm radius)

Low multiplicity (pp, p-Pb) → weak dependence on multiplicity in small sources (~ 1fm radius)

Particle yield and nucleon source measurement



Measurement of **production yield** in High-multiplicity (HM) pp accompanied by a measurement of the **particle-emitting source radius** in the same event class



PLB 811 (2020) 135849

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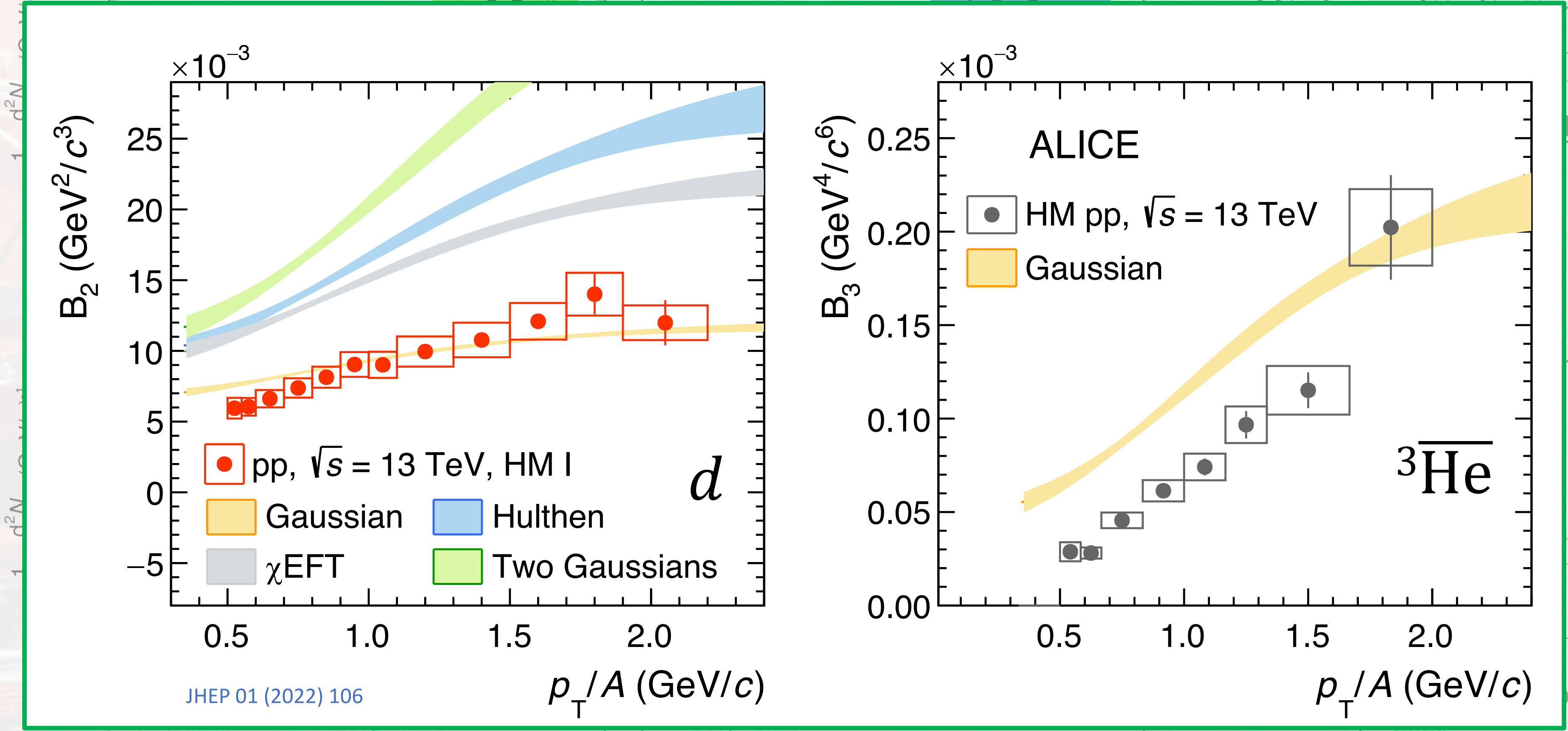
Particle yield and nucleon source measurement

Measurement of **production yield** in ... (HM) pp accompanied by a ... he **particle-emitting source** ... e event class



JHEP 01 (2022) 106

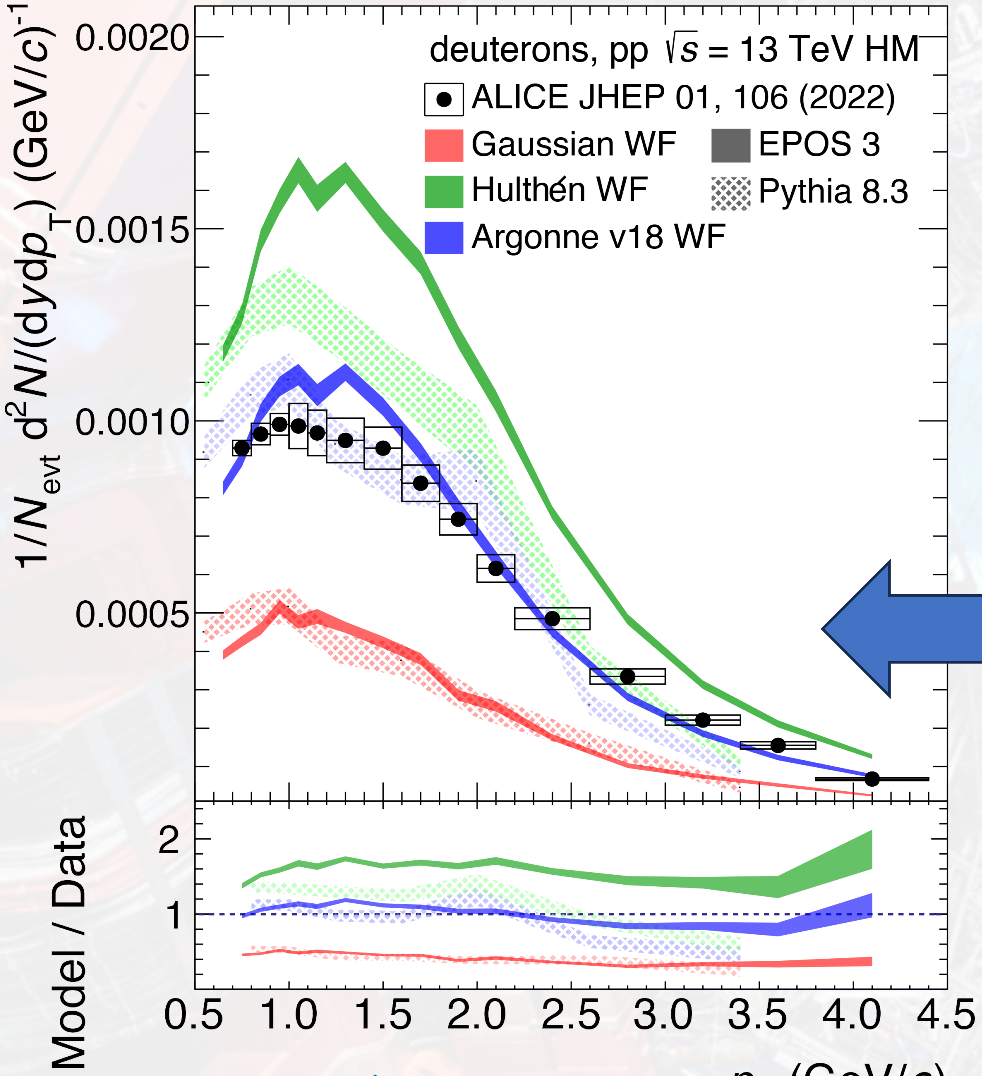
→ Allows us to use measurement of B_2 to **investigate also the wavefunction** of the $d,\bar{d}$

ALI-PUB-522343

ALI-PUB-359120

PLB 811 (2020) 135849

ALICE experimental input to coalescence modelling



M. Horst et al., [arXiv:2302.12696](https://arxiv.org/abs/2302.12696)

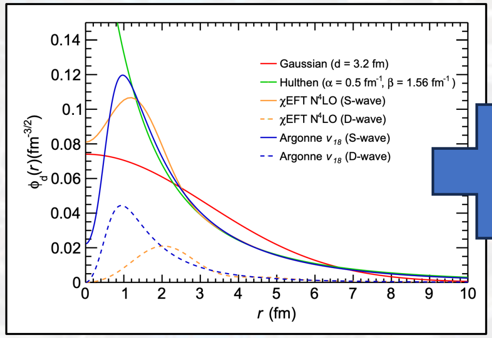
Recent study shows that the ALICE measurements of **production yield** and the **proton source radius** in the **same event class**, with the choice of a suitable wavefunction, allow for prediction of deuteron spectrum via coalescence with **<u>no free parameters</u>**.

→ Experimental input **crucial for coalescence modelling**

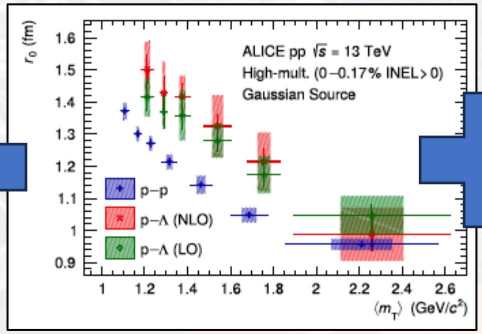
→ **Application to the study of cosmic ray fluxes**

Wigner-formalism based coalescence afterburner

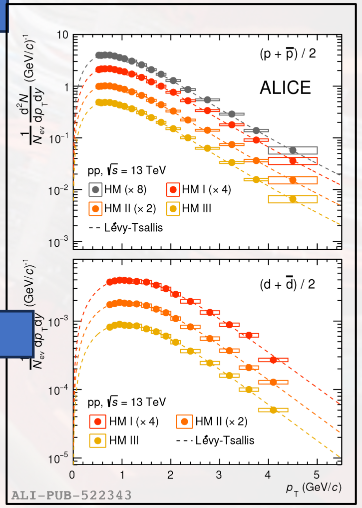
Wavefunction for d



Nucleon source size



p_T spectra



Light antinuclei as smoking guns for Dark Matter

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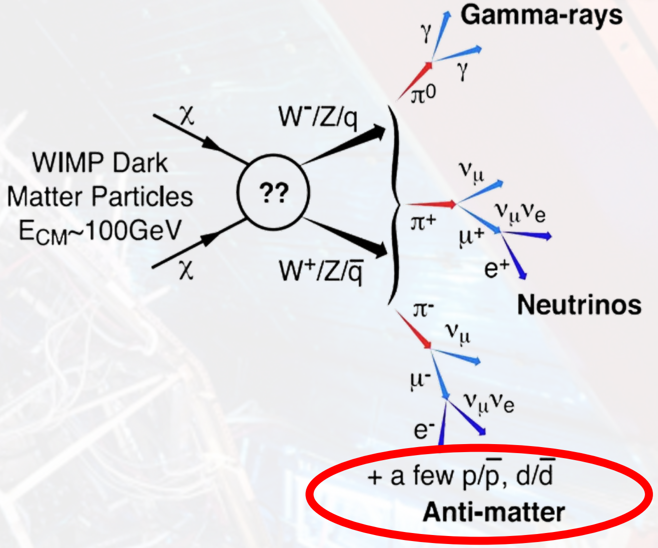
[M. Korsmeier, F. Donato, N. Fornengo, Phys. Rev. D 97, 103011 (2018)]

Cosmic ray antideuteron and antihelium nuclei have been suggested as possible **smoking guns** for dark matter **WIMPs**, χ ($m_\chi \sim$ few GeV – few TeV)p-p

- Produced by **$\chi\bar{\chi}$ pair annihilation** or **χ decay** in the galactic halo
- **Low or no background from interactions of cosmic rays (CR)** with interstellar matter (ISM) → **to be estimated carefully!**
- Subject for indirect DM searches with space-based experiments as AMS-02 (ongoing) or GAPS (planned end of 2023)
  → **Observable: cosmic antinuclei flux**

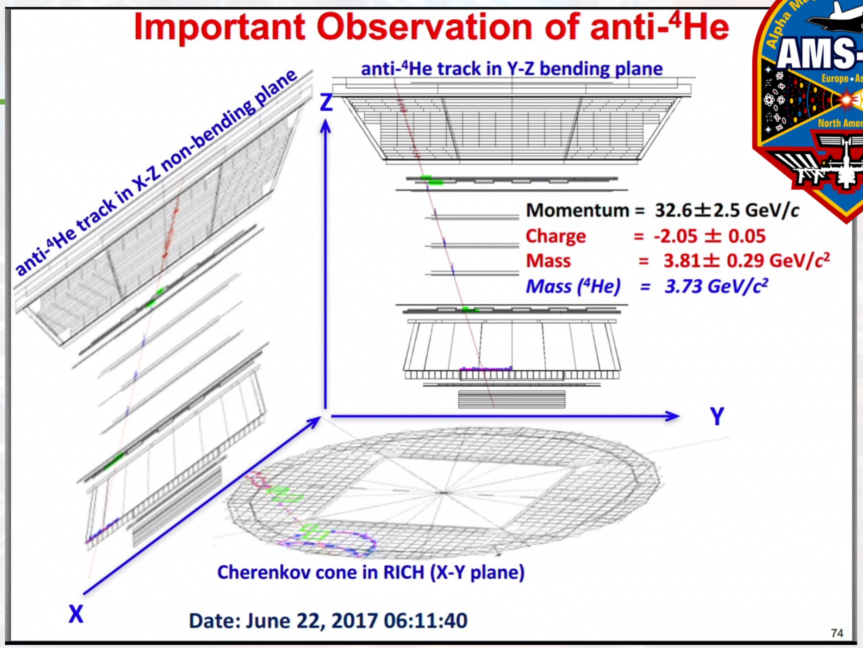


AMS-02

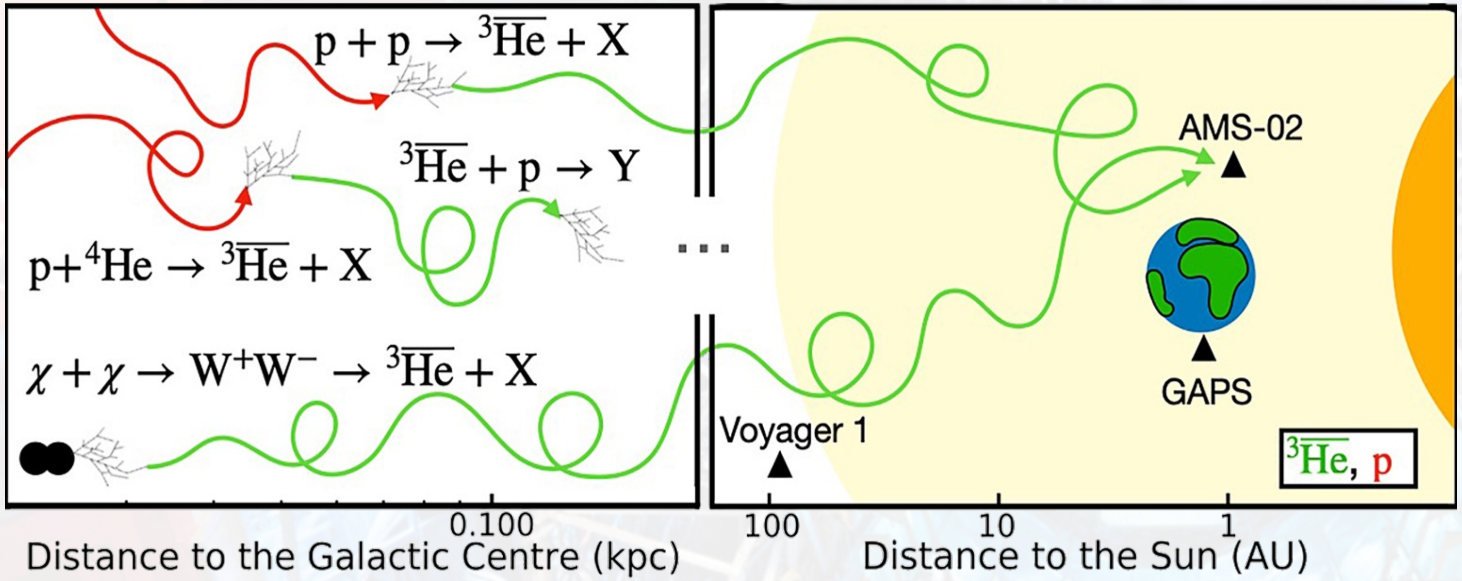
The Alpha Magnetic Spectrometer (**AMS**) detector allows for multiple and independent measurement of CR charge (with sign) and energy
→ Separate CR chemical and isotopic composition in GeV to TeV range

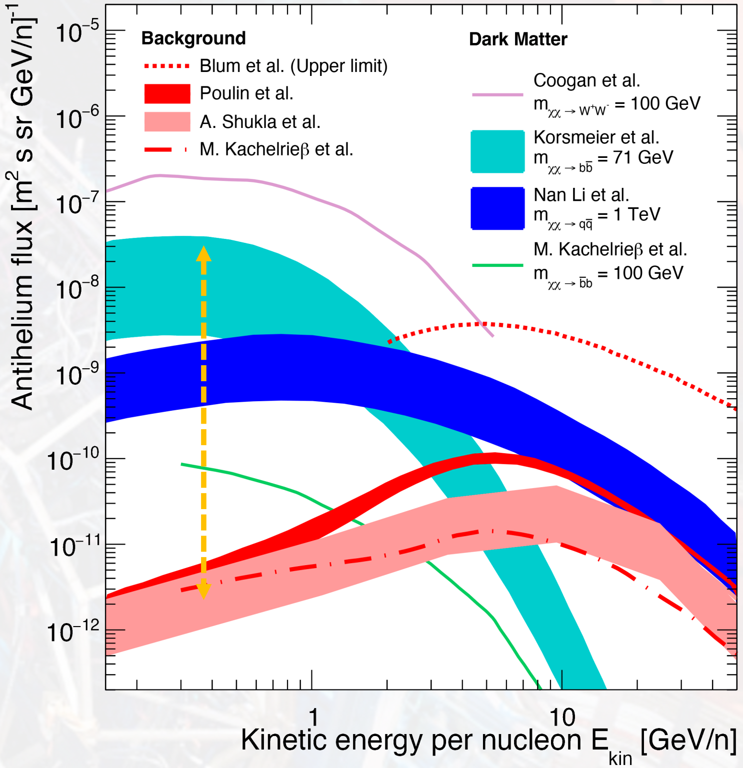
It collected > 220 billions CRs up to now, but any **antinucleus** signal?

→ 6 $^{3}\overline{\mathrm{He}}$ + 2 $^{4}\overline{\mathrm{He}}$ candidates reported
(to be confirmed)



Towards prediction of cosmic antinuclei flux





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

Ingredients:

- **DM signal**: dark matter source and processes
- **Background:** secondary CR from pp, p-A collisions in space (*e.g. tuned Monte Carlo generators*)
- **Antiproton production cross section** constrained with measurements (*e.g. LHCb, AMBER, …*)
- **Formation mechanism of antinuclei** → typically via **coalescence** → **constrain with data!**
- **Propagation** in the Galaxy and the heliosphere → parameters **constrained from CR measurements**
- Antinucleus **inelastic cross section** to account for **absorption** by ISM

Measurement of the inelastic $^3\overline{\text{He}}$ cross section

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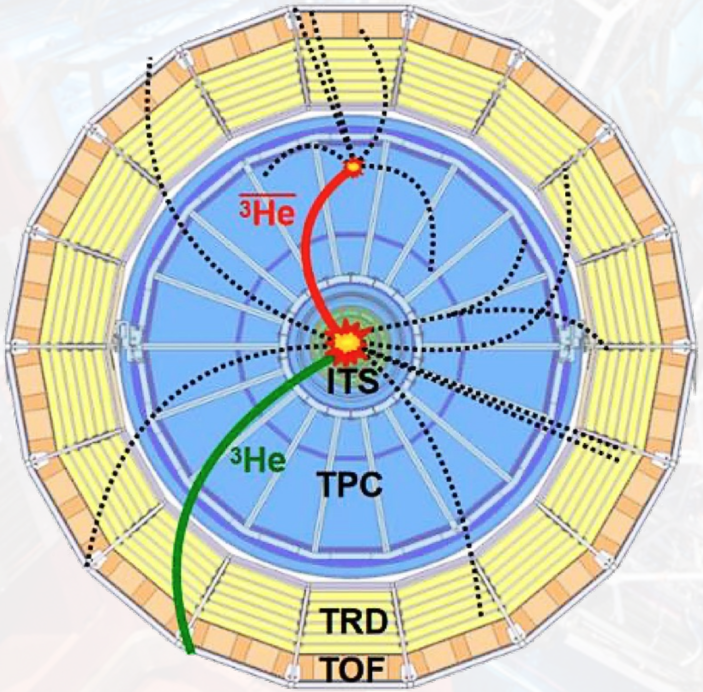
σ_{inel} ($^3\overline{\text{He}}$ – A) – how to estimate it with ALICE?

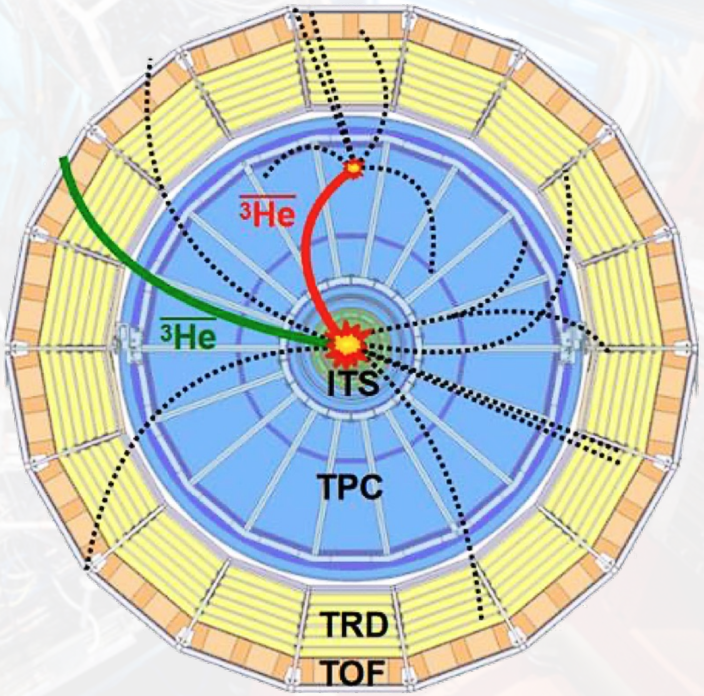
Antimatter-to-matter ratio method:
Measurement of reconstructed $^3\overline{\text{He}}$ / ^{3}He ratio and comparison with MC simulation

Pros: access to lower momentum
Cons: higher background from secondaries, relies on σ_{inel}



TOF-to-TPC ratio method:
Measurement of reconstructed $^3\overline{\text{He}}_{TOF}$ / $^3\overline{\text{He}}_{TPC}$ ratio and comparison with MC simulation

Pros: Higher stats, larger momentum range available
Cons: No access to low momenta

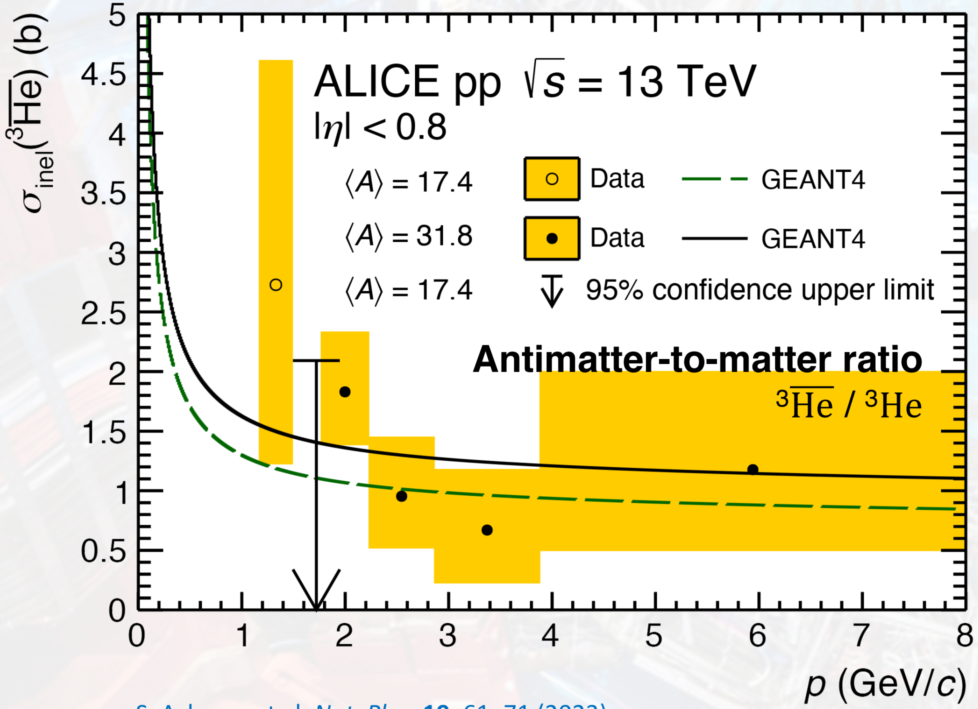


Measurement of the inelastic $^{3}\overline{\text{He}}$ cross section

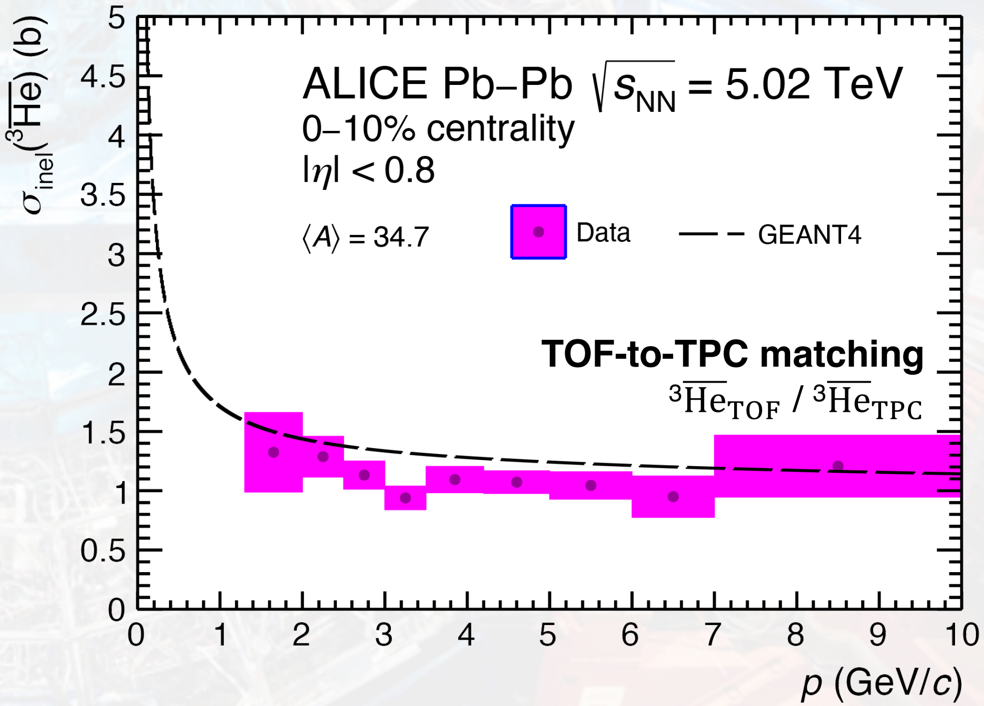
σ_{inel} ($^{3}\overline{\text{He}}$ – A) – the results

Significant impact on $^{3}\overline{\text{He}}$ propagation in space

- 1st measurement of $^{3}\overline{\text{He}}$ absorption cross section in matter
- Compatible results (higher precision in Pb-Pb)
- Experimental data show **2σ agreement** wrt GEANT4



S. Acharya et al. *Nat. Phys.* **19**, 61–71 (2023)

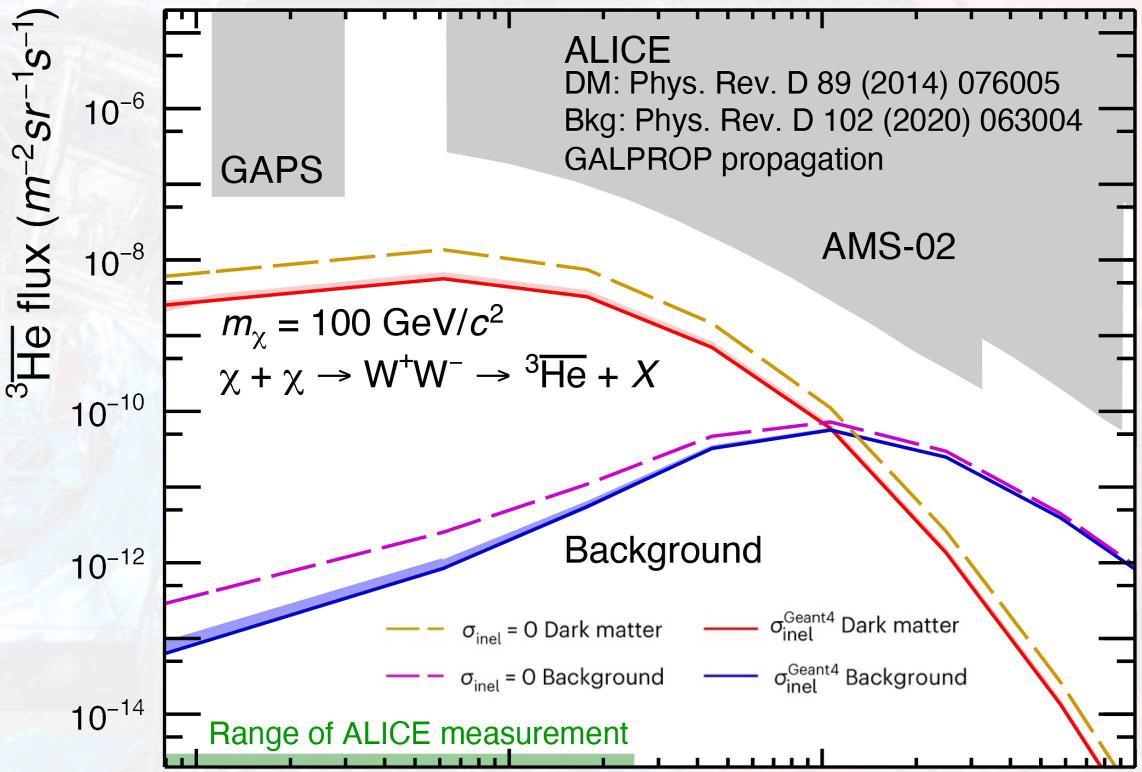


Transparency of the Galaxy to (anti)helium fluxes

- $^3\overline{\mathrm{He}}$ fluxes depend on the effect of different inelastic cross sections

- Small uncertainties on cosmic ray fluxes from $\sigma_{\mathrm{inel}}(^3\overline{\mathrm{He}})$ compared to other uncertainties in the field

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



Transparency of the Galaxy to (anti)helium fluxes

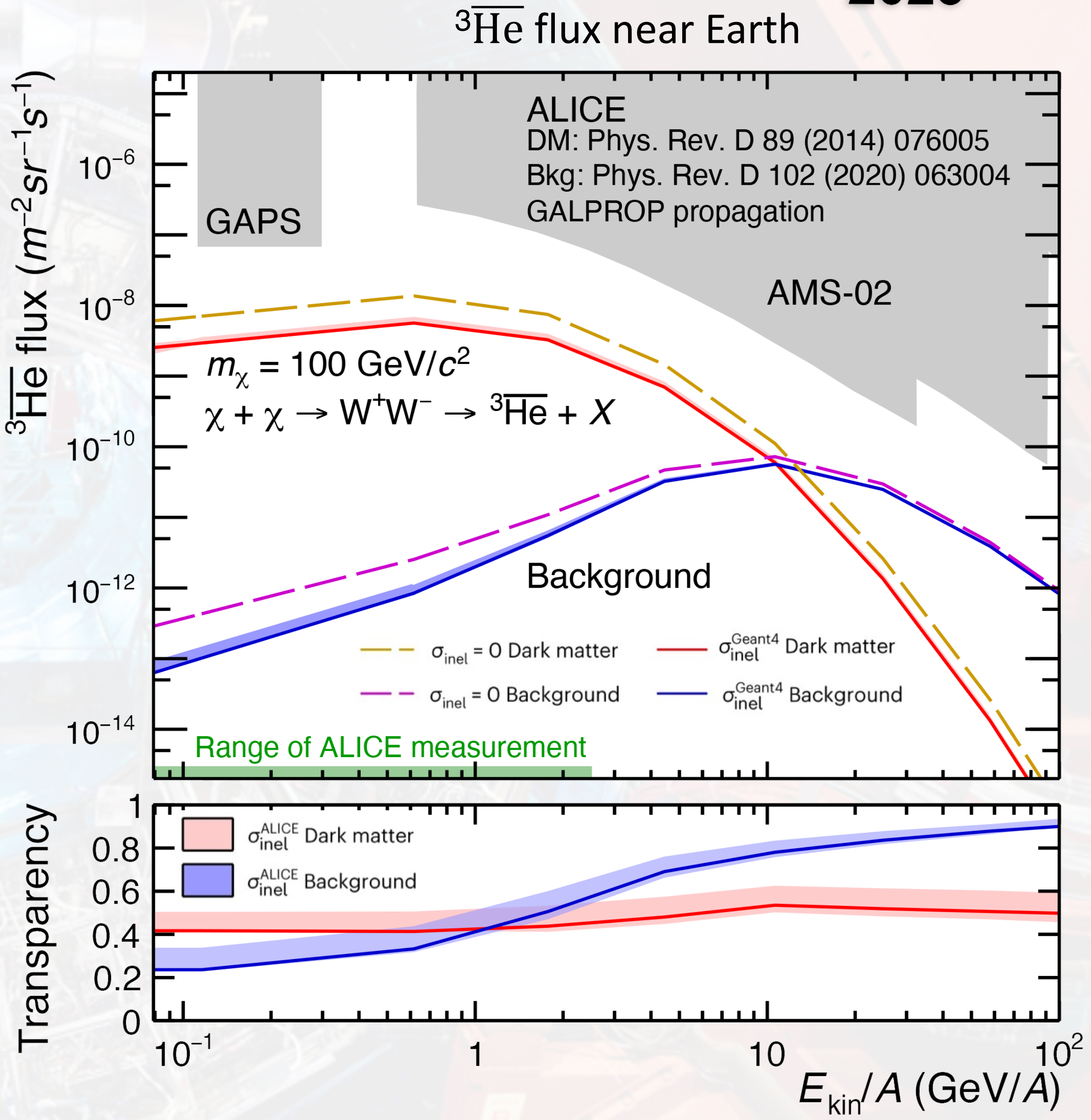
- $^{3}\overline{\mathrm{He}}$ fluxes depend on the effect of different inelastic cross sections

- Small uncertainties on cosmic ray fluxes from $\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$ compared to other uncertainties in the field

- $\text{Transparency} = \dfrac{\mathrm{Flux}(\sigma_{\mathrm{inel}})}{\mathrm{Flux}(\sigma_{\mathrm{inel}}=0)}$

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

The Galaxy is **highly transparent** to $^{3}\overline{\mathbf{He}}$ nuclei



The ALICE apparatus: upgraded for LHC Run3

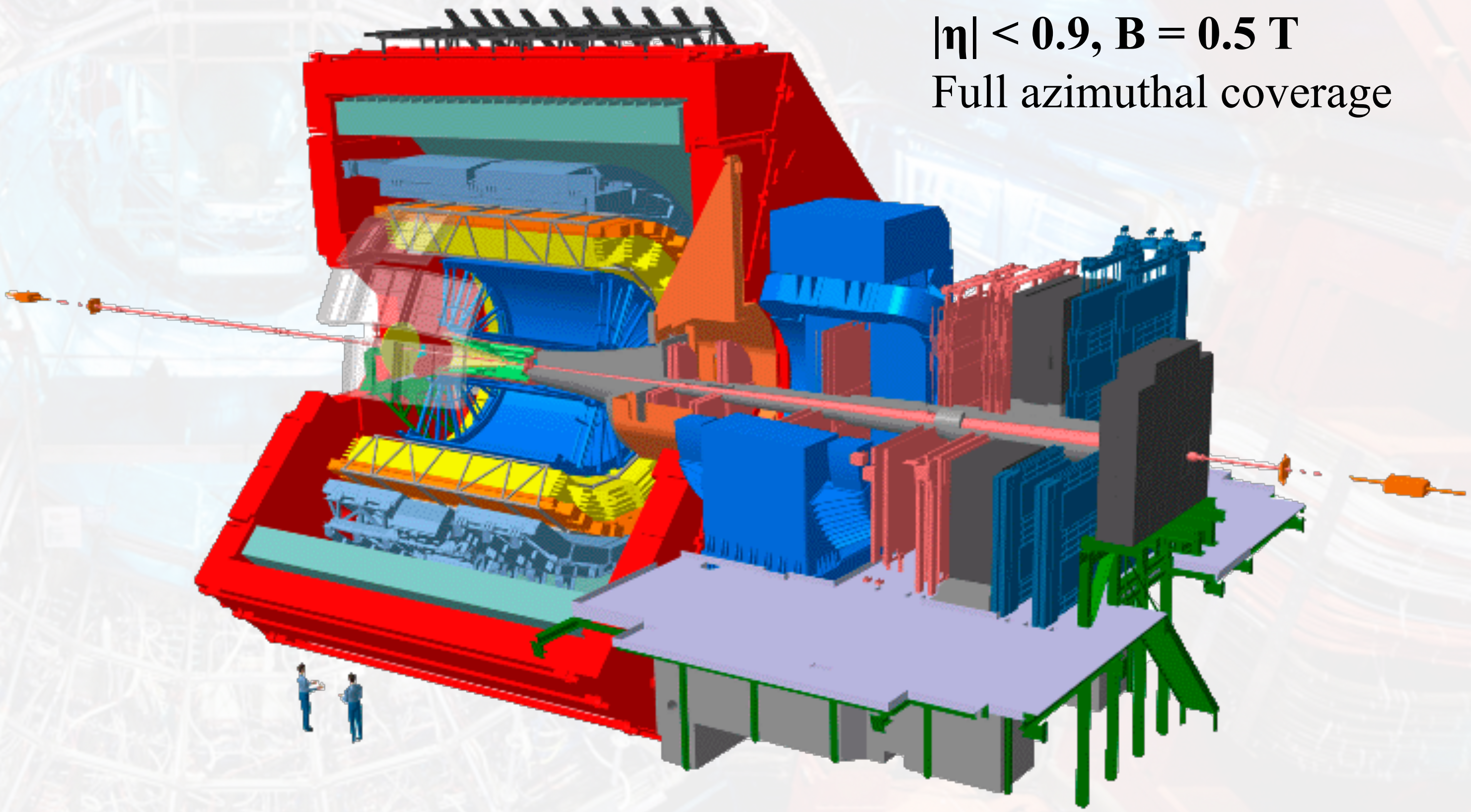
The unique tracking and particle identification (PID) capabilities of ALICE, allow the detection of light (anti)nuclei produced during LHC collisions

For antinuclei measurement we use:
- The Inner Tracking System (ITS2)
- The Time Projection Chamber **(TPC)**
- The Time-Of-Flight detector **(TOF)**

To measure **(anti)nuclei** we need:
- **Excellent tracking down to low p_T** (~100 MeV/c) → ITS2 + TPC
- Discrimination between **primary** and secondary (from material) nuclei → ITS2
- **Low material budget** → ITS2
- Excellent **PID** performance → TPC +TOF

Run 3 ALICE performance allow for antinuclei measurements!

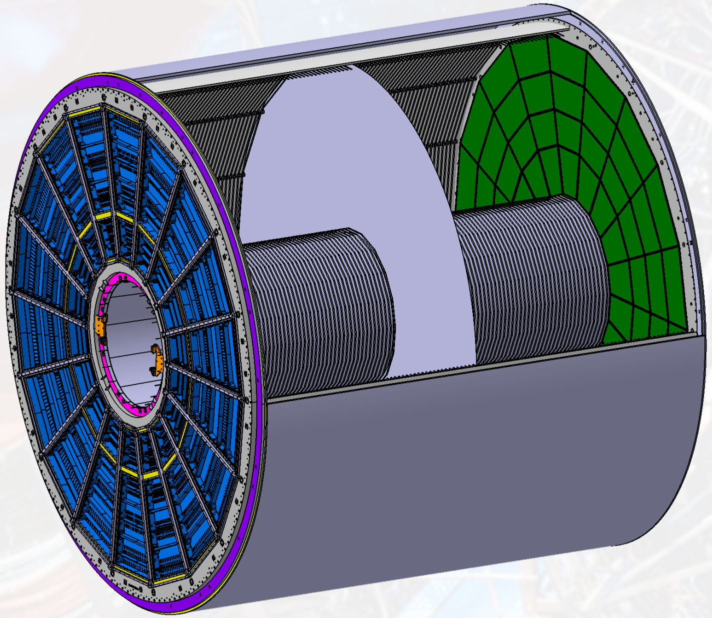
Central barrel:
$|\eta| < 0.9$, B = 0.5 T
Full azimuthal coverage

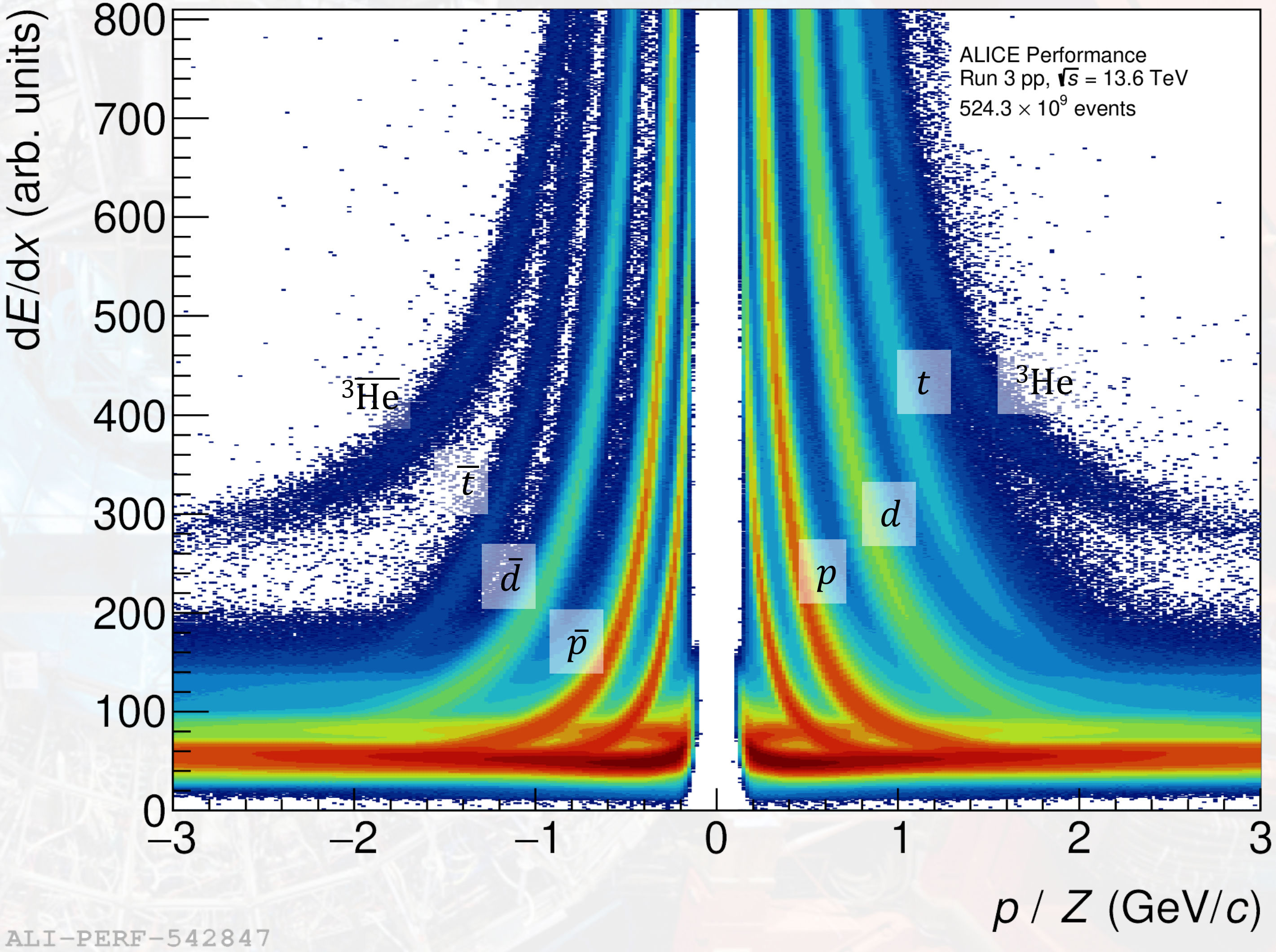


The ALICE apparatus: upgraded for LHC Run3

Time Projection Chamber (TPC)

- New GEM-based readout pads
- Rate restriction removal and ion backflow reduced to under 1%
- Allows for continuous readout





PID via dE/dx in the TPC gas

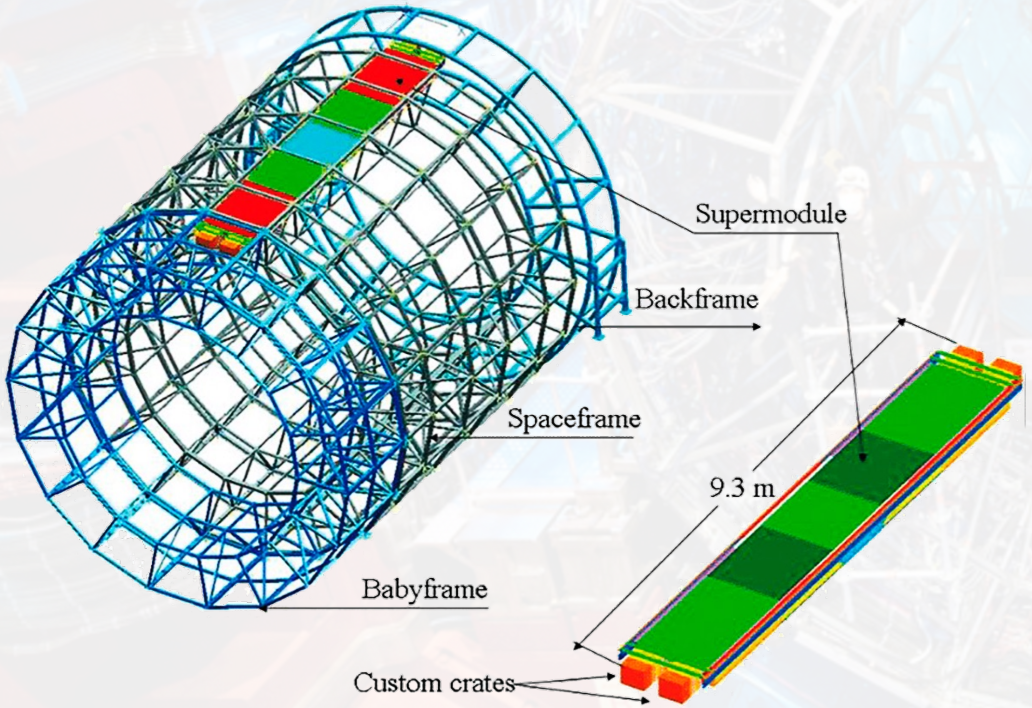
Excellent **separation** of different particle species at **low p_T**

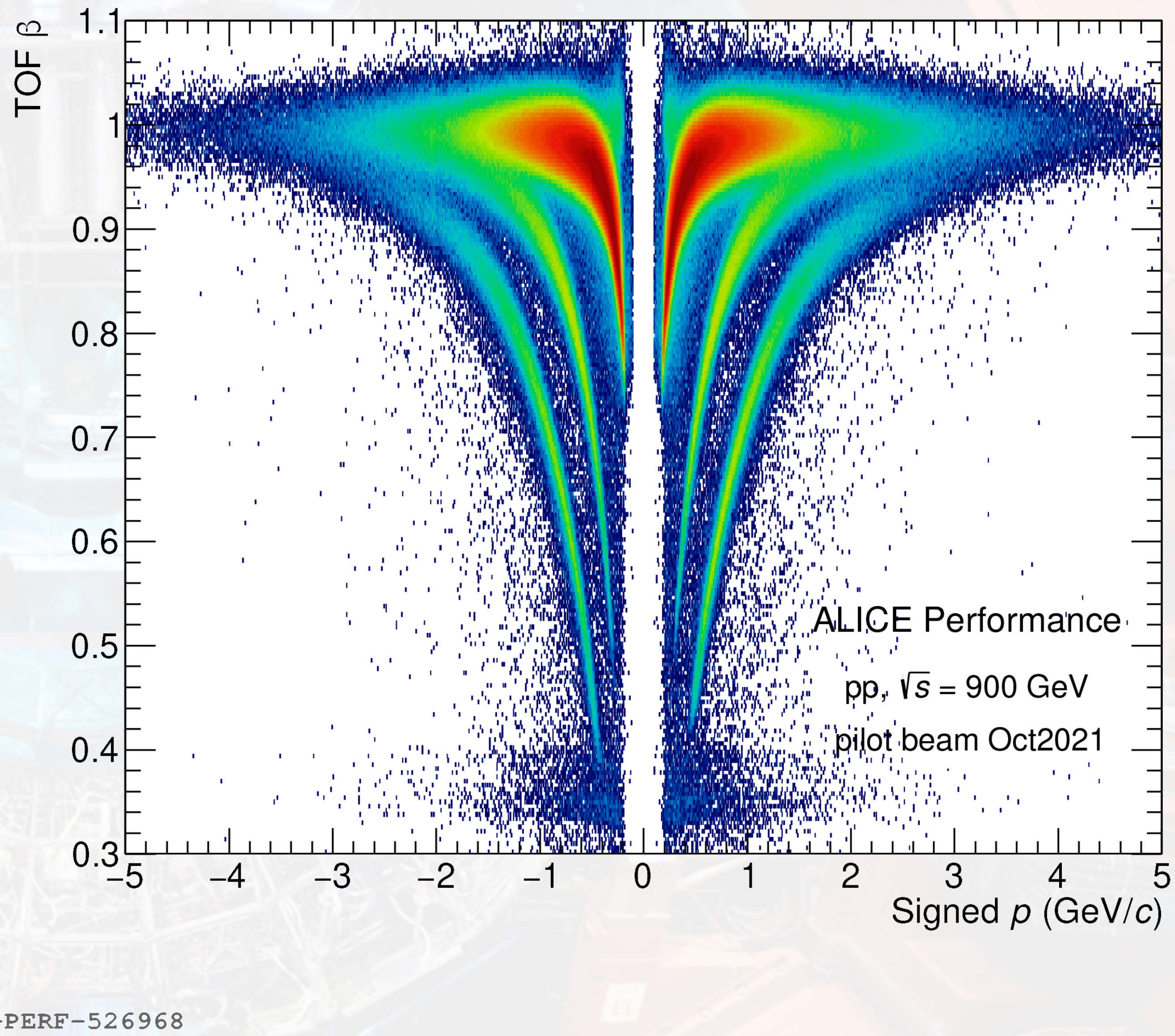
The ALICE apparatus: upgraded for LHC Run3

Time Of Flight detector (TOF)

- Upgrade of the readout system to allow for continuous readout
- Excellent **separation** of different particle species at **intermediate p_T**

PID via time-of-flight measurements





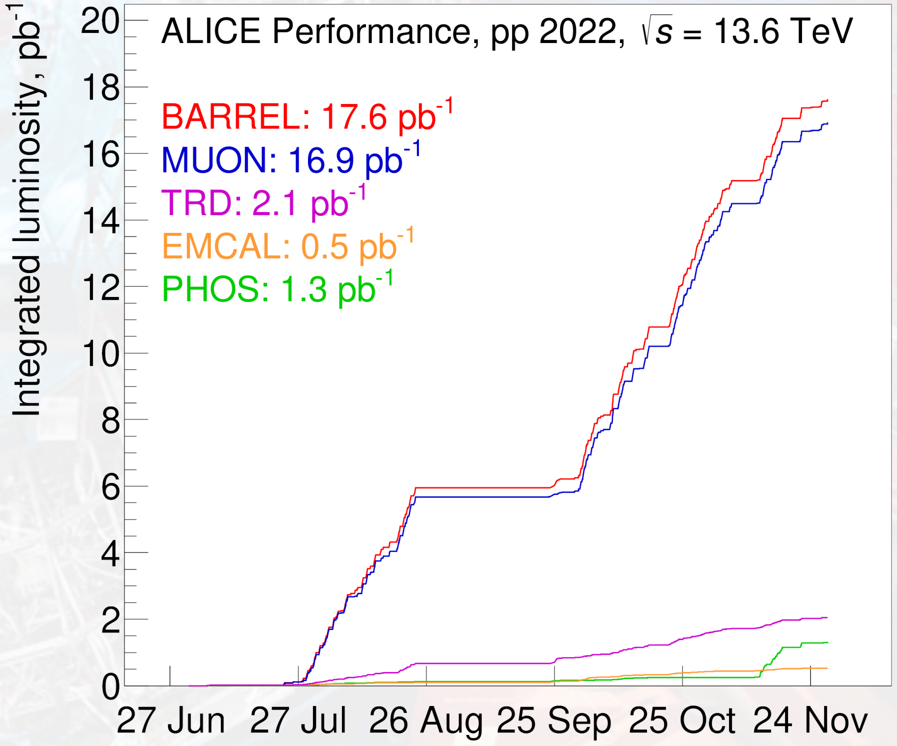
Outlook

- LHC can be used as **antimatter factory** to study the production of light (anti)nuclei
- The increased integrated luminosity foreseen for Runs 3 and 4 will allow us to study A=3 and A=4 (anti)nuclei with a similar statistical precision as reached for A=2 in Runs 1 and 2
- Data taking with pp collisions at $\sqrt{s}$ = 13.6 TeV and Pb-Pb at $\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV is **ongoing**
- First performance of the detector are promising for antinuclei identification in a broad momentum range

→ **Stay tuned for new results!**

arXiv:1812.06772

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



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Thank you for the attention