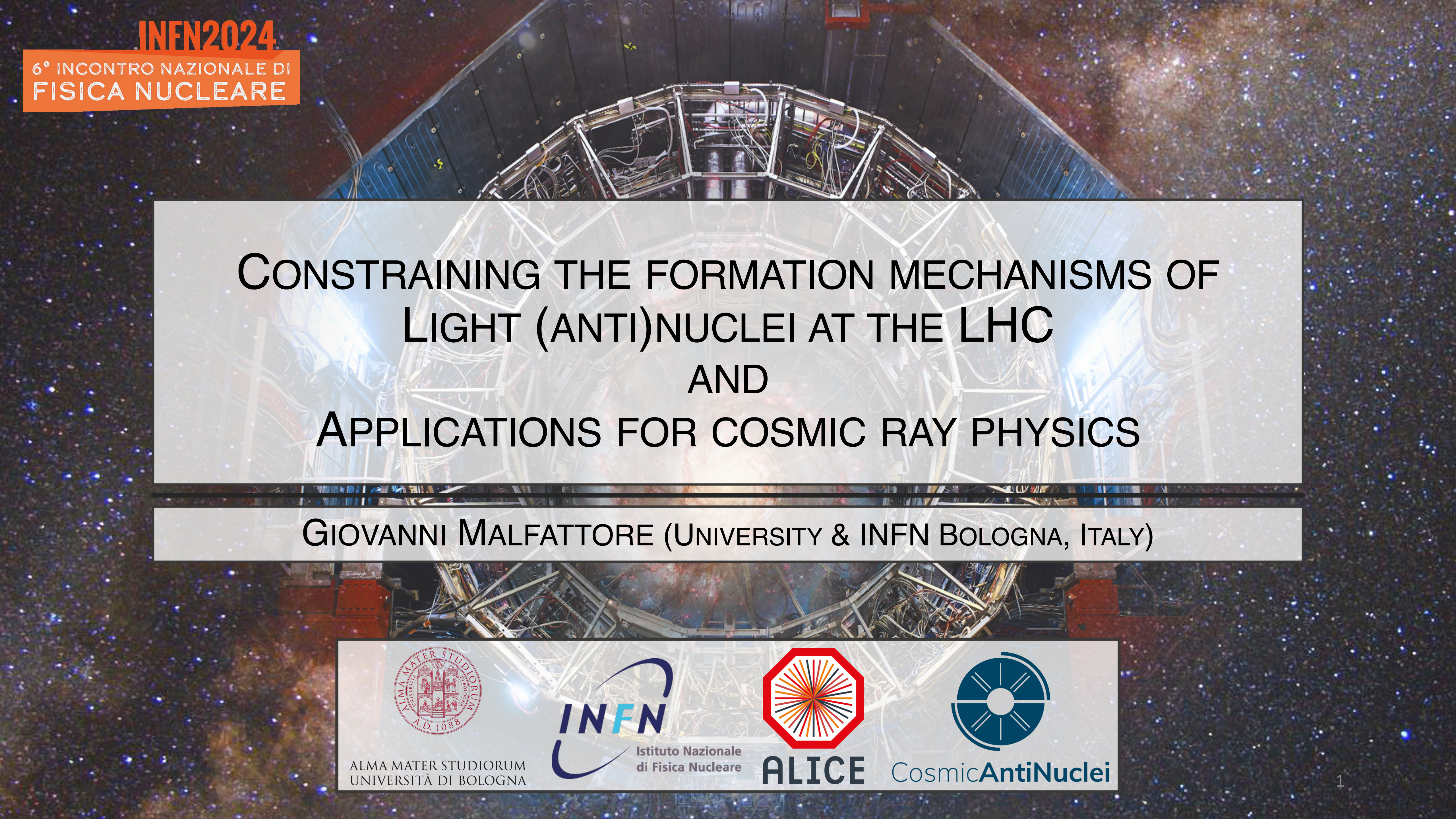

INFN2024
6° INCONTRO NAZIONALE DI
FISICA NUCLEARE

CONSTRAINING THE FORMATION MECHANISMS OF LIGHT (ANTI)NUCLEI AT THE LHC AND APPLICATIONS FOR COSMIC RAY PHYSICS

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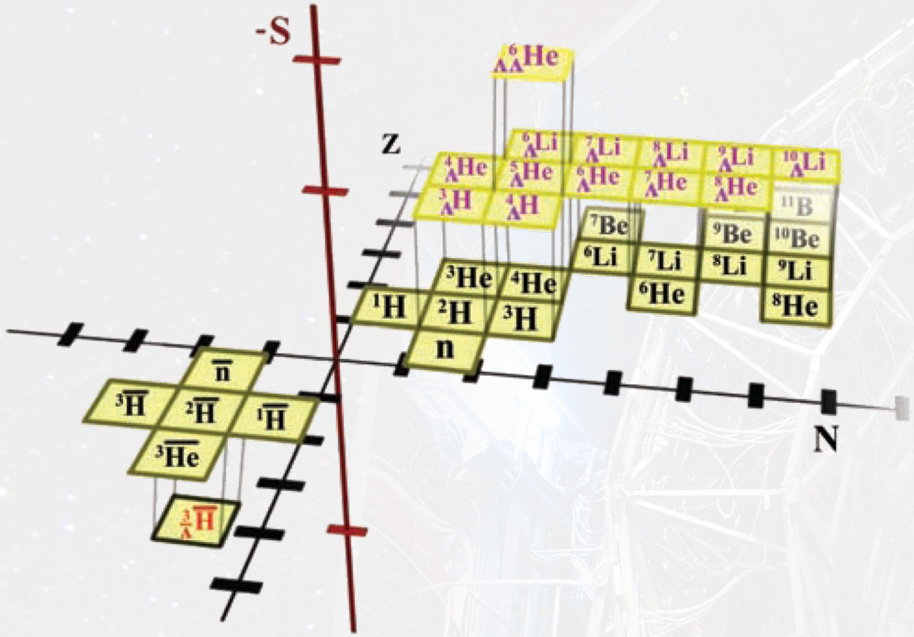
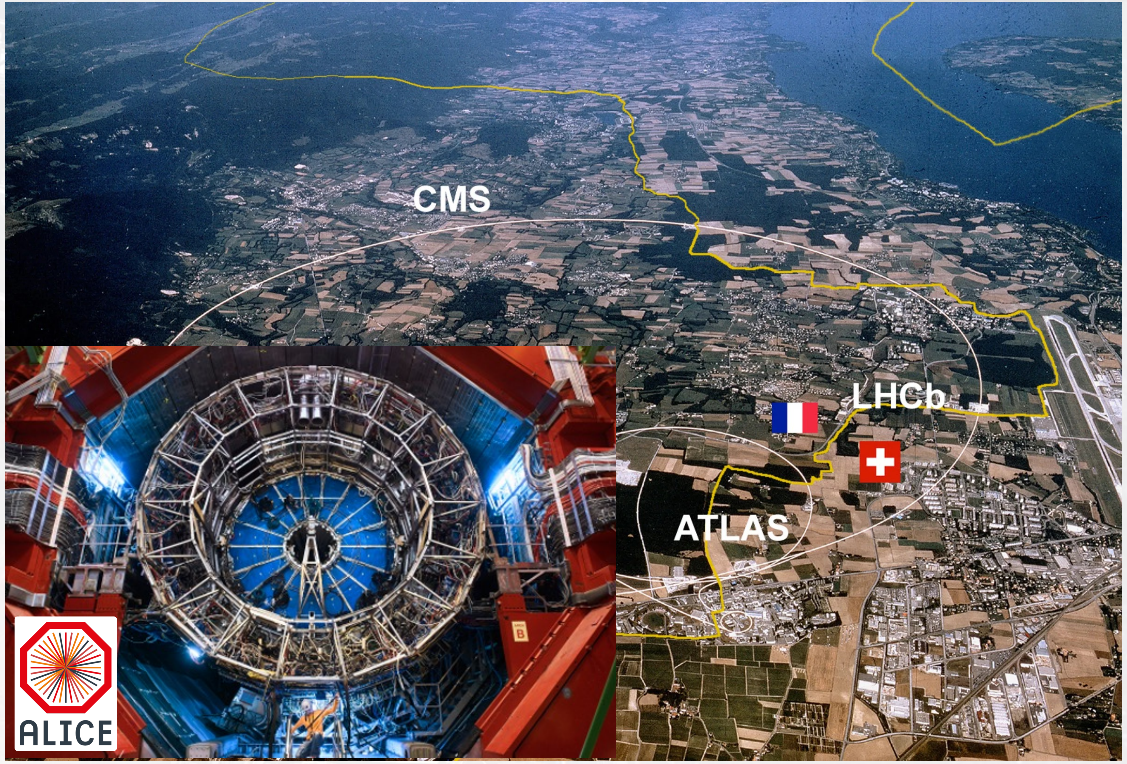
INFN
Istituto Nazionale
di Fisica Nucleare

ALICE

CosmicAntiNuclei

Light (anti)nuclei production in high-energy collisions





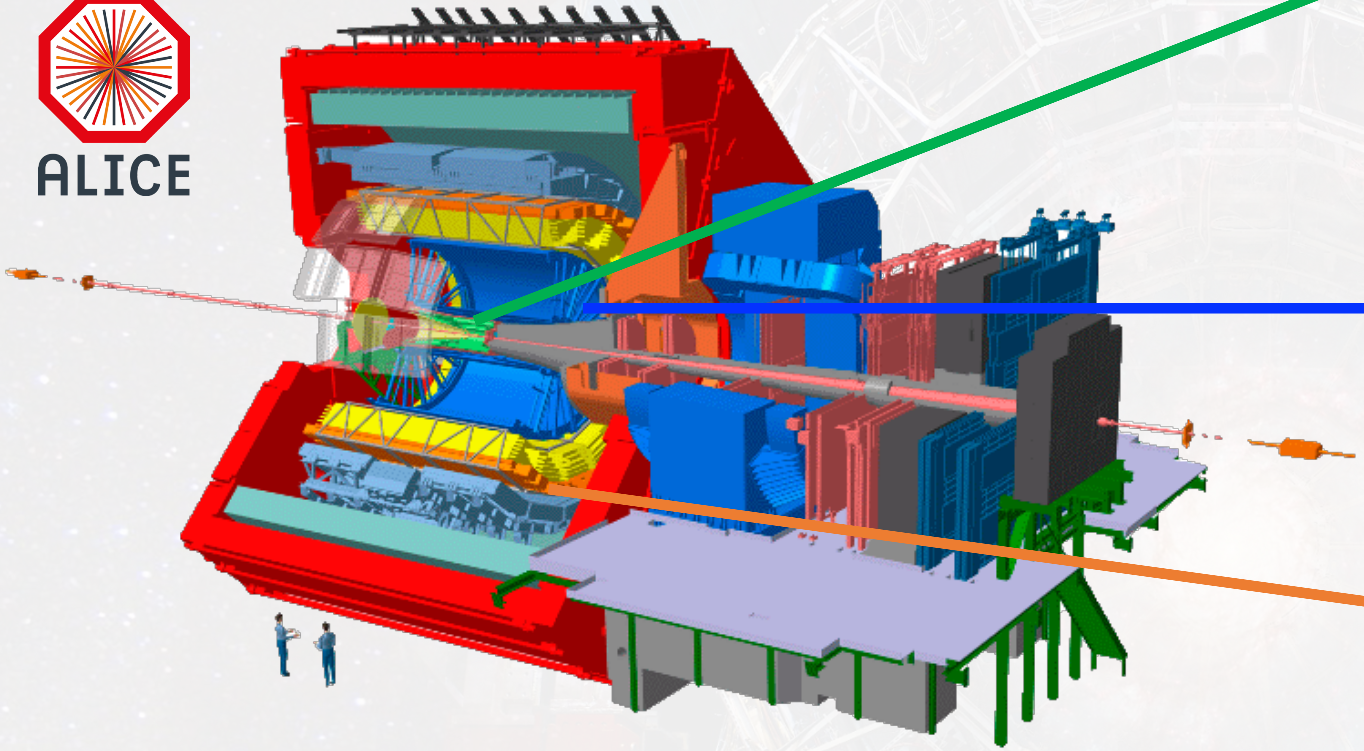
The production **mechanism** of light (anti)nuclei in high energy collisions is **not fully understood** and is still an open question that is being actively addressed both **theoretically** and **experimentally**

Low binding energy (B_E ~ 2 MeV) and **large mass** imply that their formation is strongly sensitive to the chemical freeze-out temperature (~ 100 B_E)

Light (anti)nuclei can be produced at the LHC and are being studied by **ALICE** in pp and heavy-ion collisions

ALICE: upgraded for LHC Run3

A Large **I**on **C**ollider **E**xperiment



Inner Tracking System (ITS)

- 7 layer pixel detector
- 10 m^2 (12.5 GP) silicon tracker based on MAPS
- With respect of Run 2: Less material budget, improved tracking performance at low p_T

Time Projection Chamber (TPC)

- GEM-based readout pads
- Operating in **continous readout**
- PID via **energy loss (dE/dx)** in the TPC gas

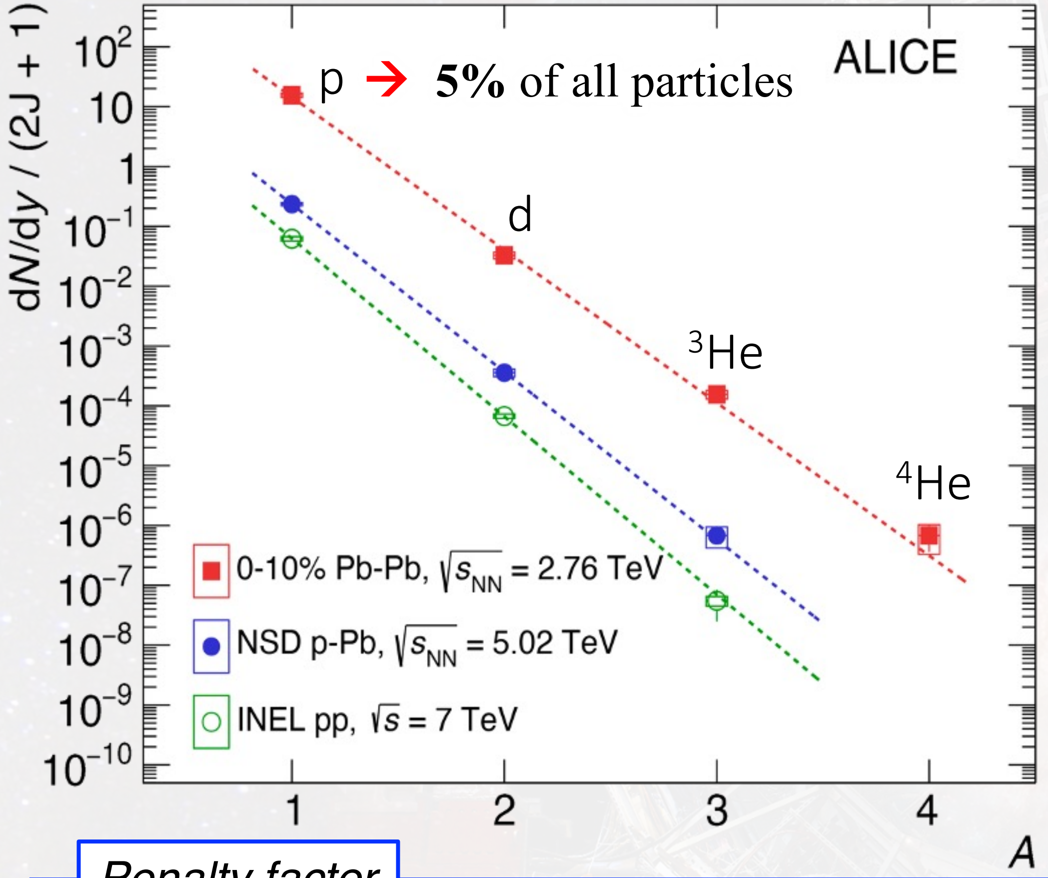
Time Of Flight detector (TOF)

- PID via **time-of-flight** measurements
- Operating in **continous readout**

In addition, the new **Integrated Online-Offline system (O2)** has been developed to perform Run 3 events reconstruction and analysis.

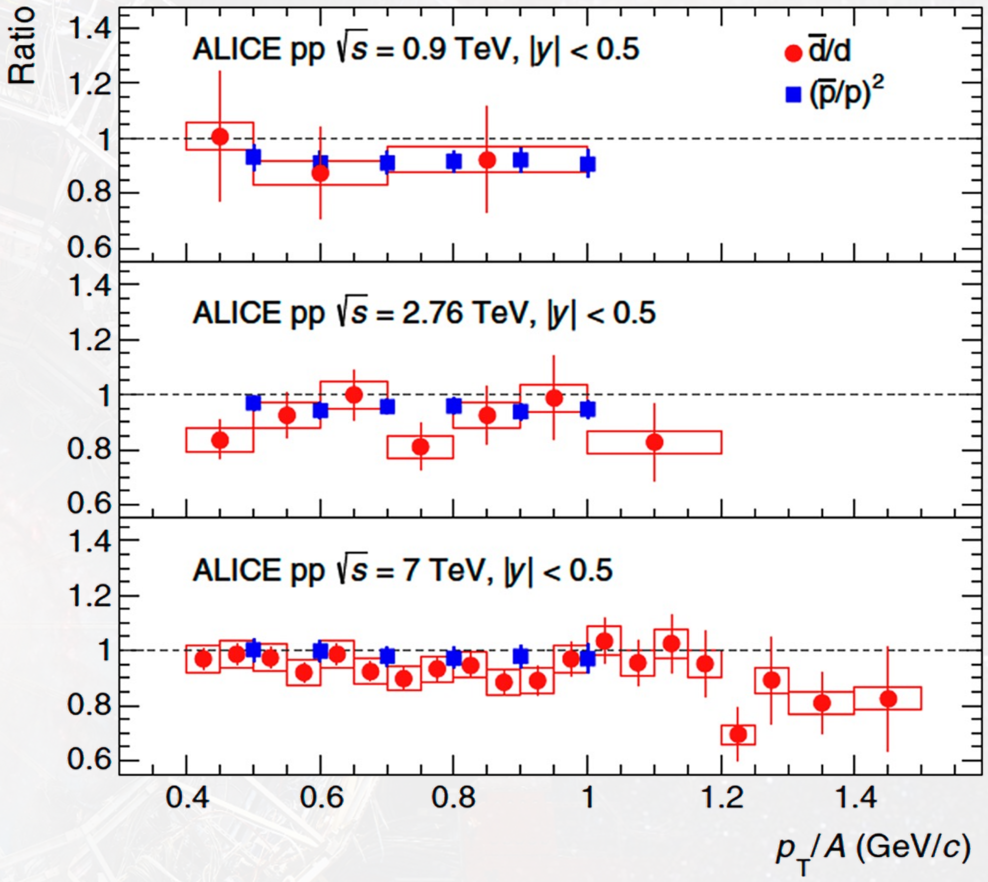
Light (anti)nuclei at the LHC, the antinucleus factory

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



p → **5%** of all particles

Physical Review C97, 024615 (2018)



Penalty factor

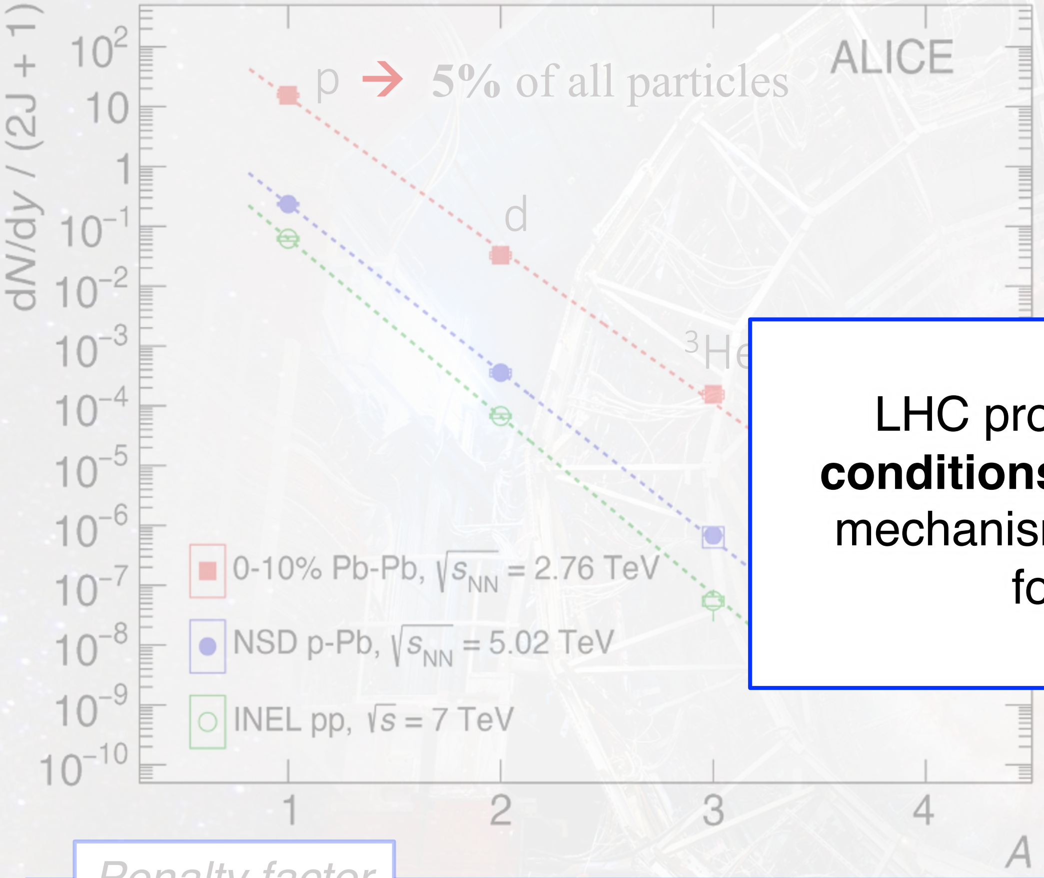
$\bar{d}/\bar{p}$ (Pb-Pb) ~ 1/300　　$^{3}\overline{He}/\bar{p}$ (Pb-Pb) ~ $1/10^5$

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

At the LHC, $\frac{\text{antimatter}}{\text{matter}} \sim \mathbf{1}$

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

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



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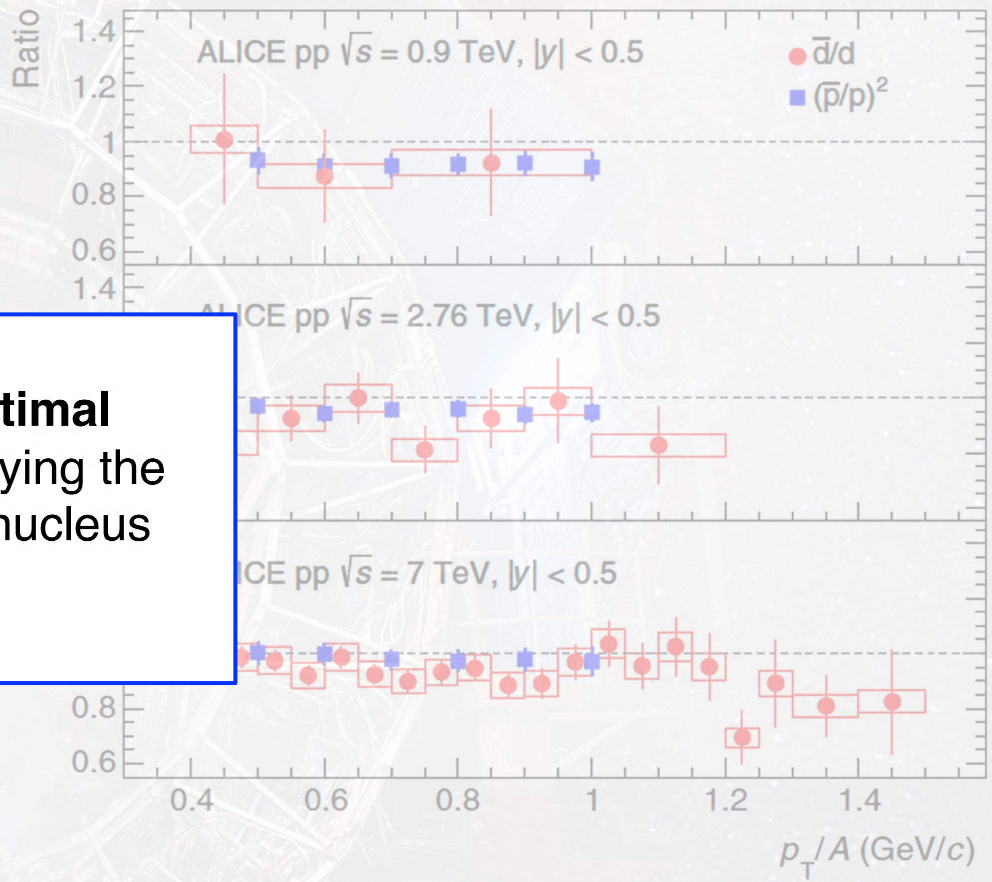


LHC provides **optimal conditions** for studying the mechanism of antinucleus formation

Penalty factor

$\bar{d}/\bar{p}$ (Pb-Pb) ~ 1/300

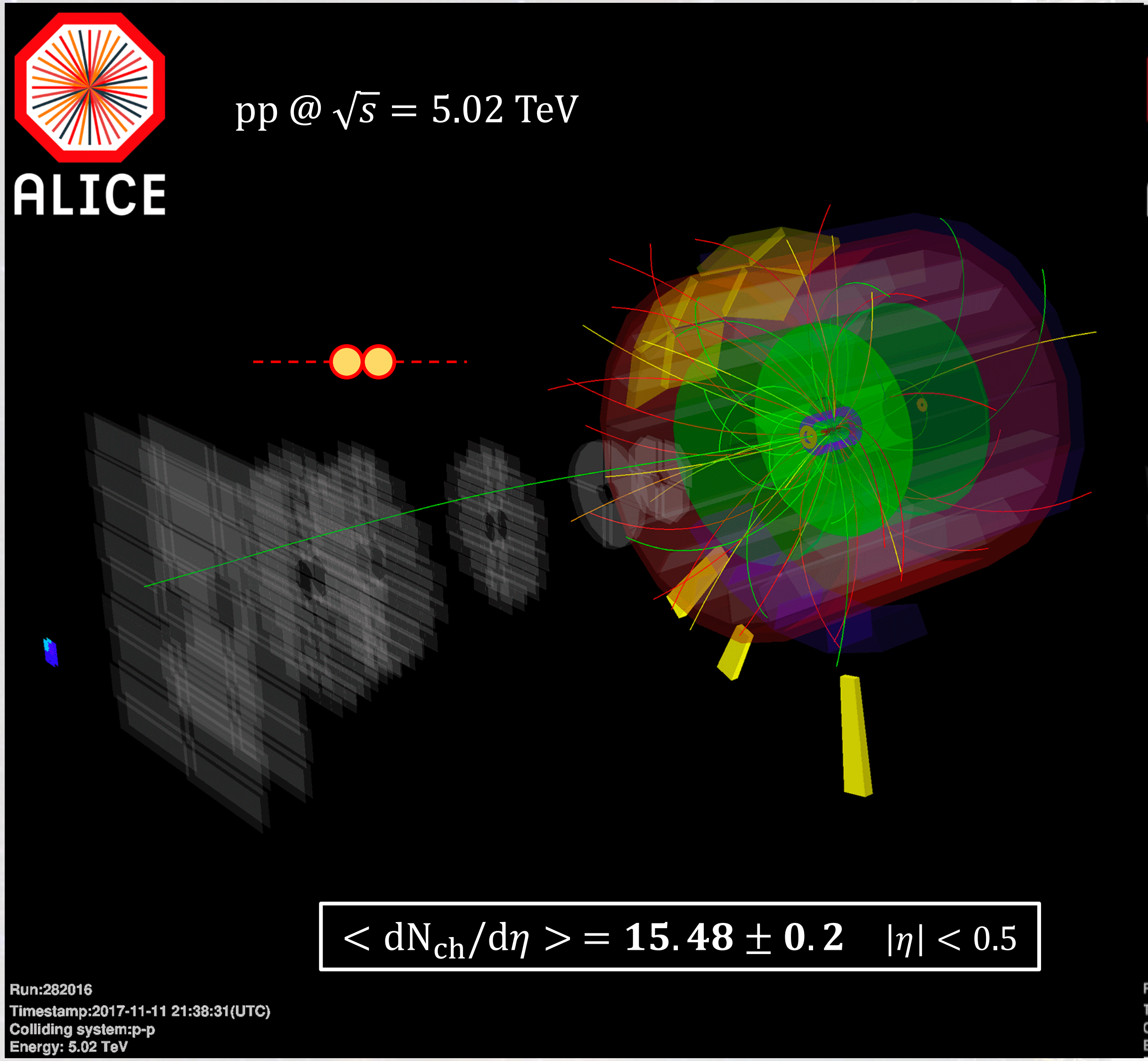
$^3\overline{He}/\bar{p}$ (Pb-Pb) ~ 1/10^5

$\bar{d}/\bar{p}$ (pp) ~ 1/1000

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

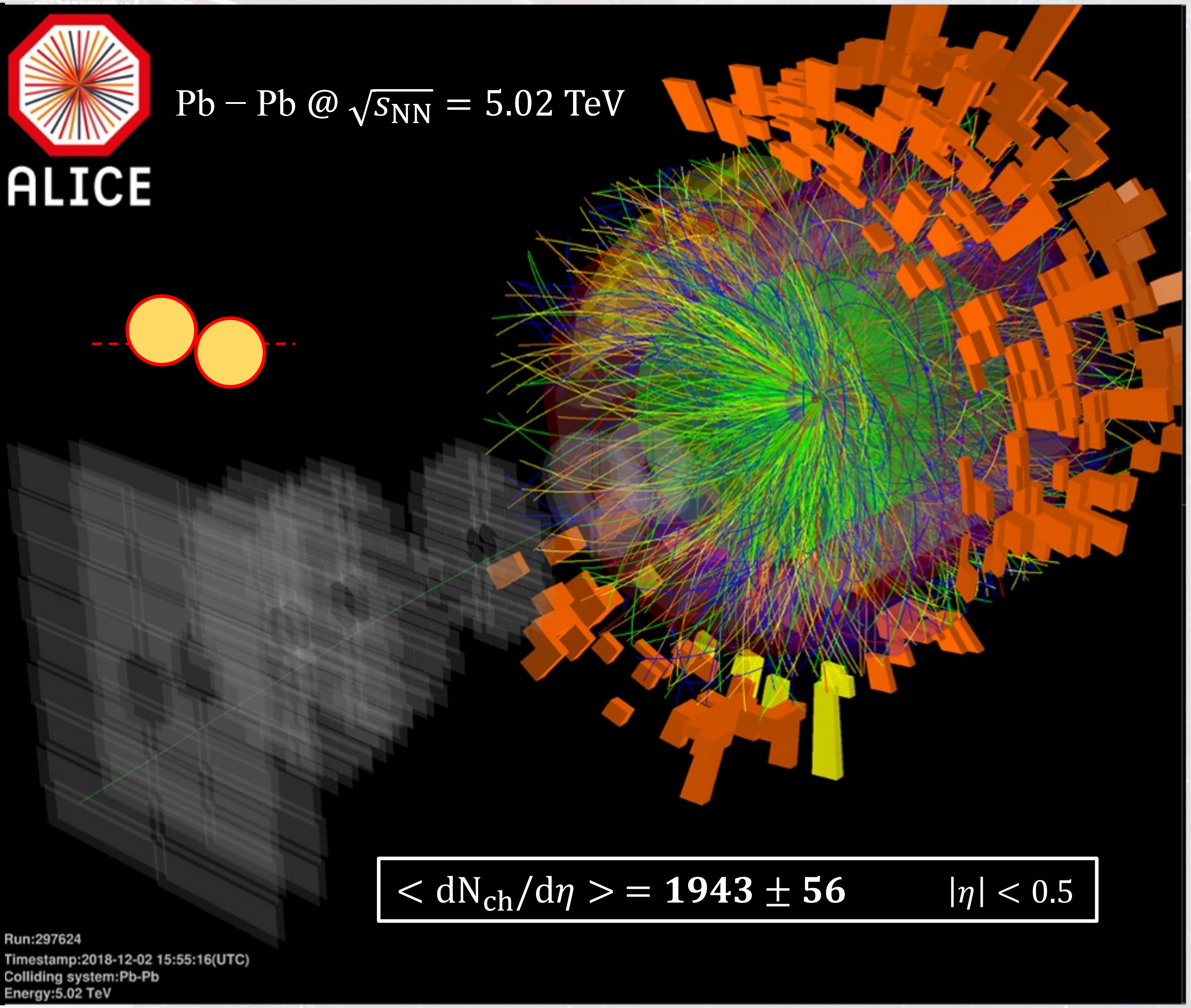
At the LHC, $\frac{\text{antimatter}}{\text{matter}} \sim 1$

Multiplicity: “small” systems vs “large” systems



pp @ $\sqrt{s} = 5.02$ TeV

$< \mathrm{dN_{ch}}/\mathrm{d}\eta > = \mathbf{15.48 \pm 0.2} \quad |\eta| < 0.5$

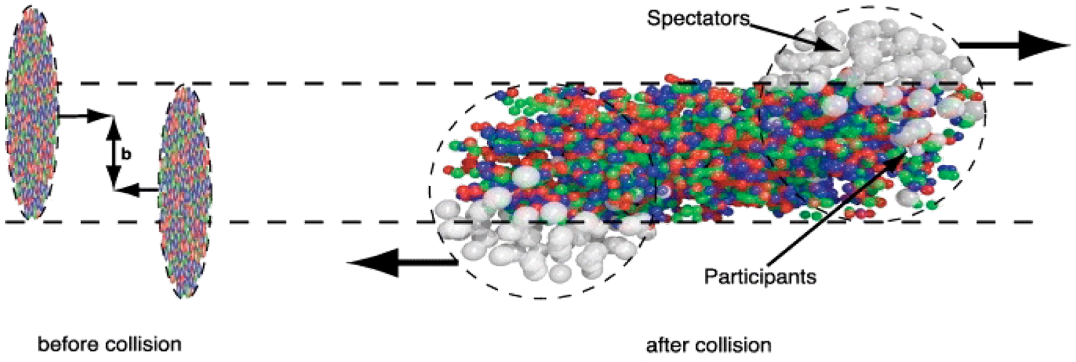


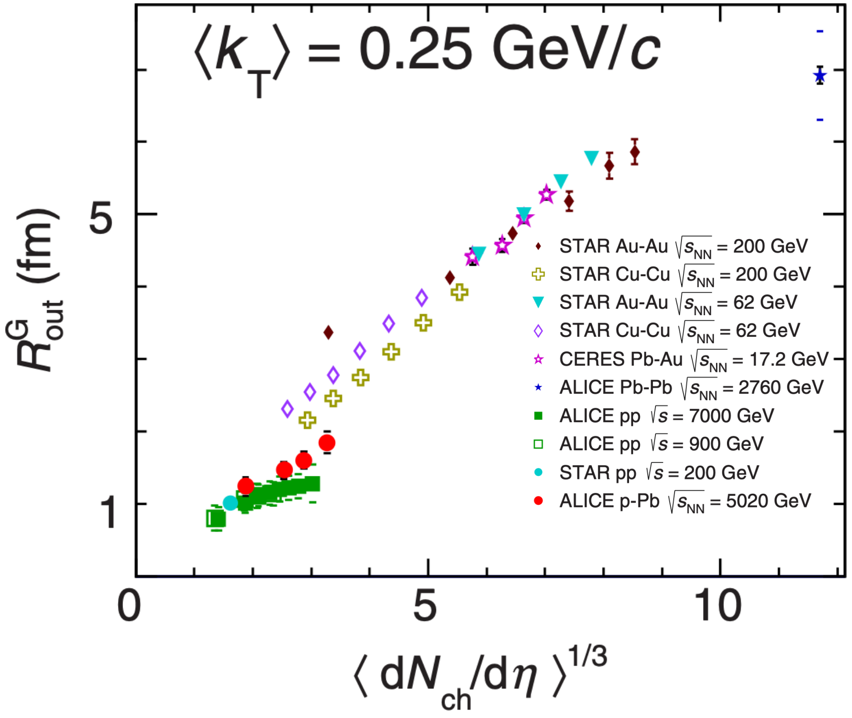
Pb – Pb @ $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

$< \mathrm{dN_{ch}}/\mathrm{d}\eta > = \mathbf{1943 \pm 56} \quad |\eta| < 0.5$

Multiplicity: “small” systems vs “large” systems

Pb-Pb collisions **geometry** strongly characterises the particle multiplicity → **centrality**





Central collisions
→High number of participants
→High multiplicity

Peripheral collisions
→Low number of participants
→Low multiplicity

Comparison of 2-pions femtoscopic radii as a function of the measured charged-particle density multiplicity for various collision systems and energies

Run:282016
Timestamp:2017-11-11 21:38
Colliding system:p-p
Energy: 5.02 TeV

Colliding system:Pb-Pb
Energy:5.02 TeV

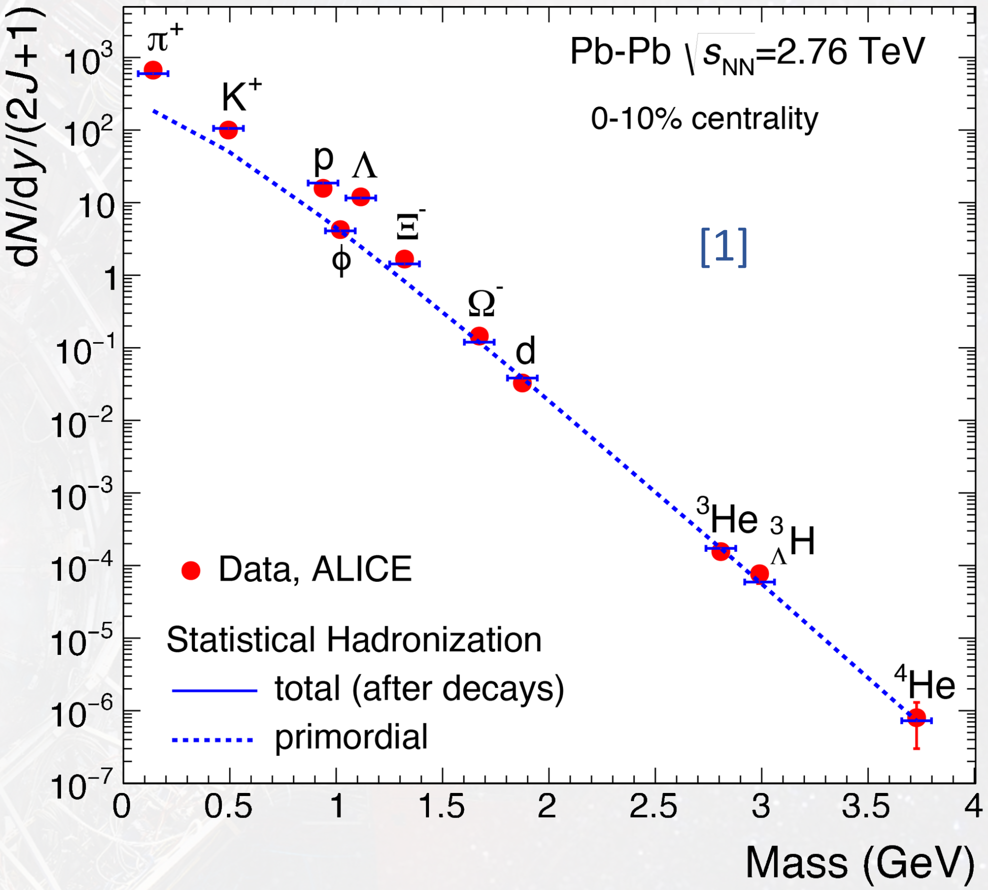
(Anti)nuclei in the Statistical Hadronization Model

- The hadrons are emitted from the interaction region in **thermal equilibrium** and abundances are fixed at the chemical freeze-out (T_{chem})[1]
- The abundances depend on the hadron **mass m, T_{chem}** and **spin degeneracy** as

$$dN/dy \sim (2J+1)\exp(-m/T_{chem})$$

- Light **(anti)nuclei are not** strongly **affected** by **feed-down**
- Due to their low binding energy, nuclei might **break and re-form** between chemical and kinetic freeze-out in **heavy-ion collisions**
- The SHM can be extended **from high- to low-multiplicity systems** via **canonical formulation**: the barion number B, the electric charge Q and the strangeness S values are conserved exactly across the **correlation volume V_C**[2]

[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

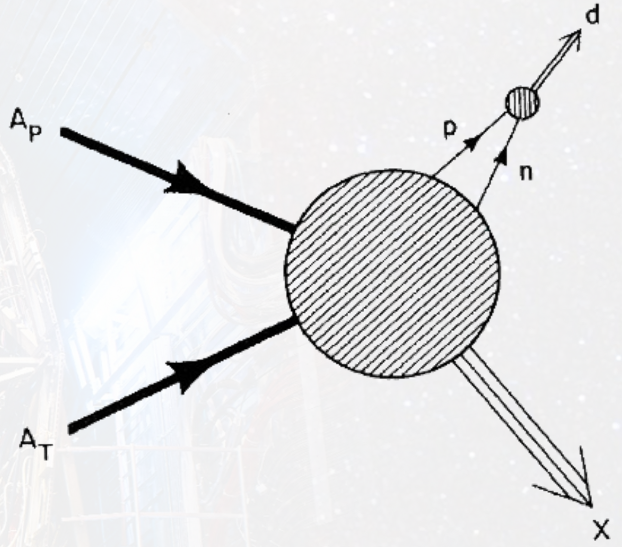
J. I. Kapusta, Phys.Rev. C21, 1301 (1980)
Scheibl,Heinz, Phys.Rev.C59:1585-1602 (1999)
F. Bellini et al., PRC 103, 014907

Nucleons form a nucleus via coalescence if they are close in the **phase space** and match the right spin-isospin configuration
The formation probability is related to the **coalescence parameter B_A**

NUCLEUS — NUCLEONS

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

PROTONS — *NEUTRONS*



- **Simple coalescence approach**

$| p_\mathrm{p} - p_\mathrm{n} | < p_0$ **Only nucleon momentum** (and spin) matter

(Anti)nuclei in Coalescence models

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Scheibl,Heinz, Phys.Rev.C59:1585-1602 (1999)
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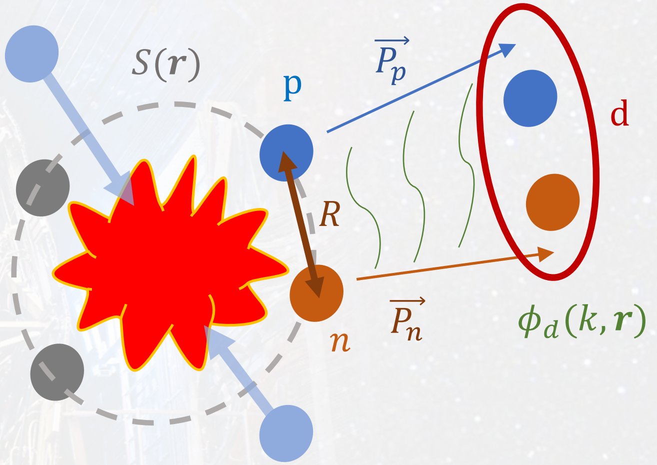
NUCLEUS — NUCLEONS

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

PROTONS — *NEUTRONS*



- **Wigner-function approach (state-of-the-art model)**

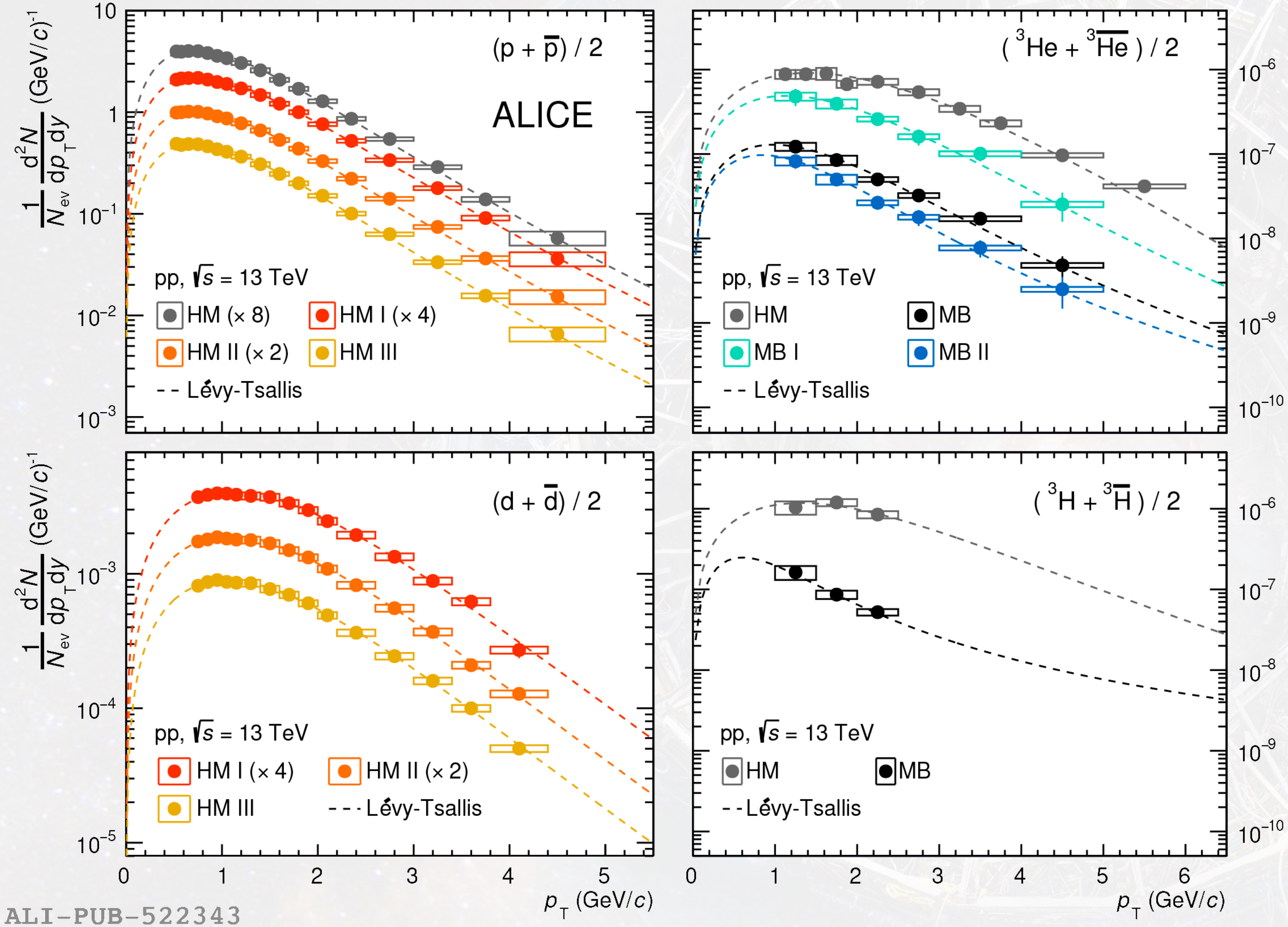
Nucleon momentum and **position, nucleus wavefunction** matter

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*: $\mathbf{r} = \boldsymbol{r}_p - \boldsymbol{r}_n$, $q = (\boldsymbol{p}_p - \boldsymbol{p}_n)^2$, $\phi_d(\mathbf{r}_d, \mathbf{p}_d) \propto \varphi_d e^{i\boldsymbol{p}_d \cdot \boldsymbol{r}_d}$,
where φ_d is the deuteron internal wavefunction,
$S_2(r)$ the source of nucleons

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

The particle yield: our main observable

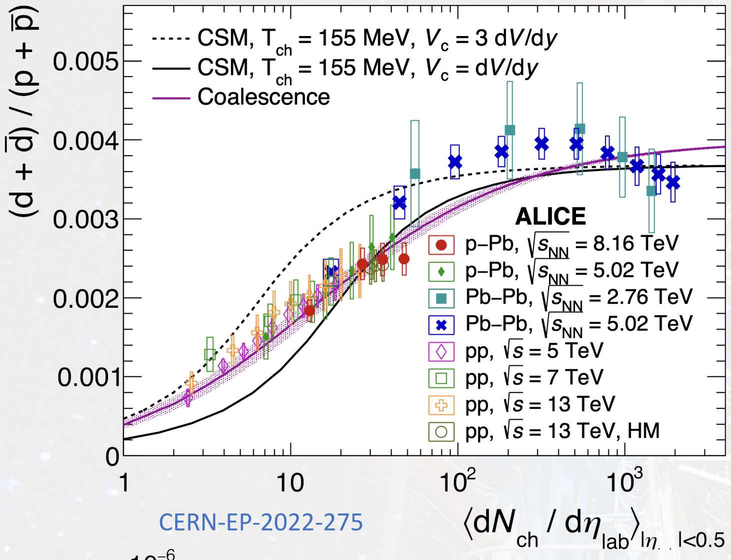


ALI-PUB-522343

- The yield is measured in **inelastic pp collisions** and as a function of the particle **multiplicity**
- An **hardening** of the production spectra is observed with increasing multiplicity (also observed in **proton spectra**)
- Comprehensive set of data for **deuteron**, measured in all collision systems as a function of multiplicity.
  Less data for **helium** and **triton → Run 3**
- The **integrated yield** is estimated summing the **measured yield** to the yield extrapolated in the unmeasured p_T region with a Levy-Tsallis function

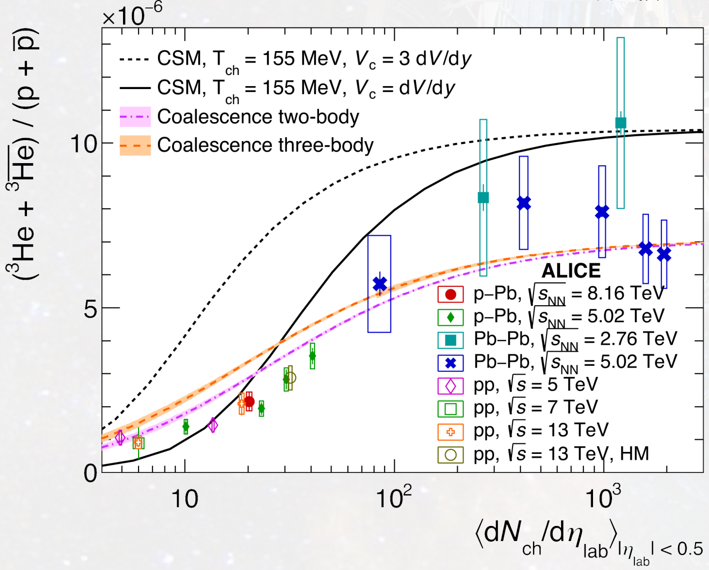
SHM or Coalescence? Nuclei over p ratio

Small objects (d, ^{3}He…)



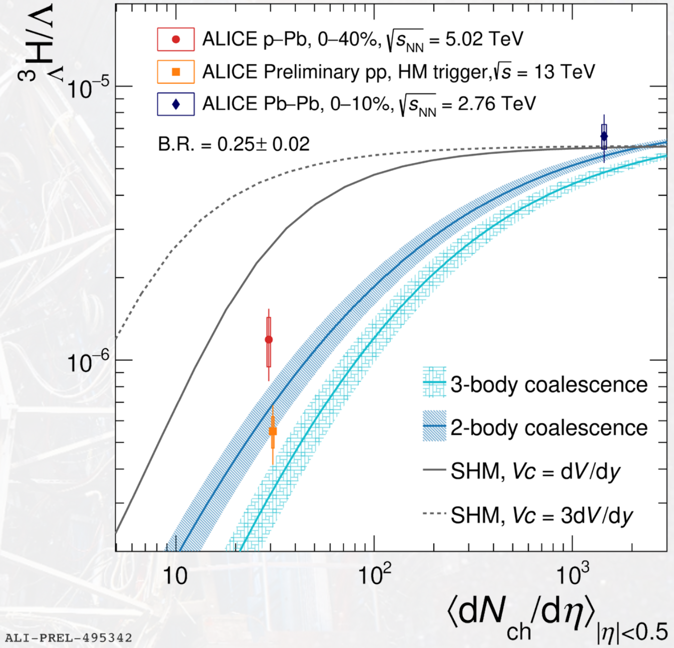
CERN-EP-2022-275

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



Theoretical models provide a better description of **deuteron** production than of $^3\overline{\mathrm{He}}$

Large objects ($^3_\Lambda$H …)

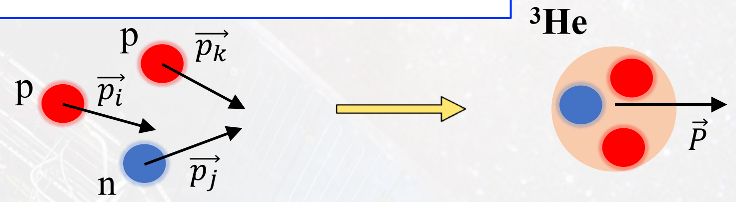


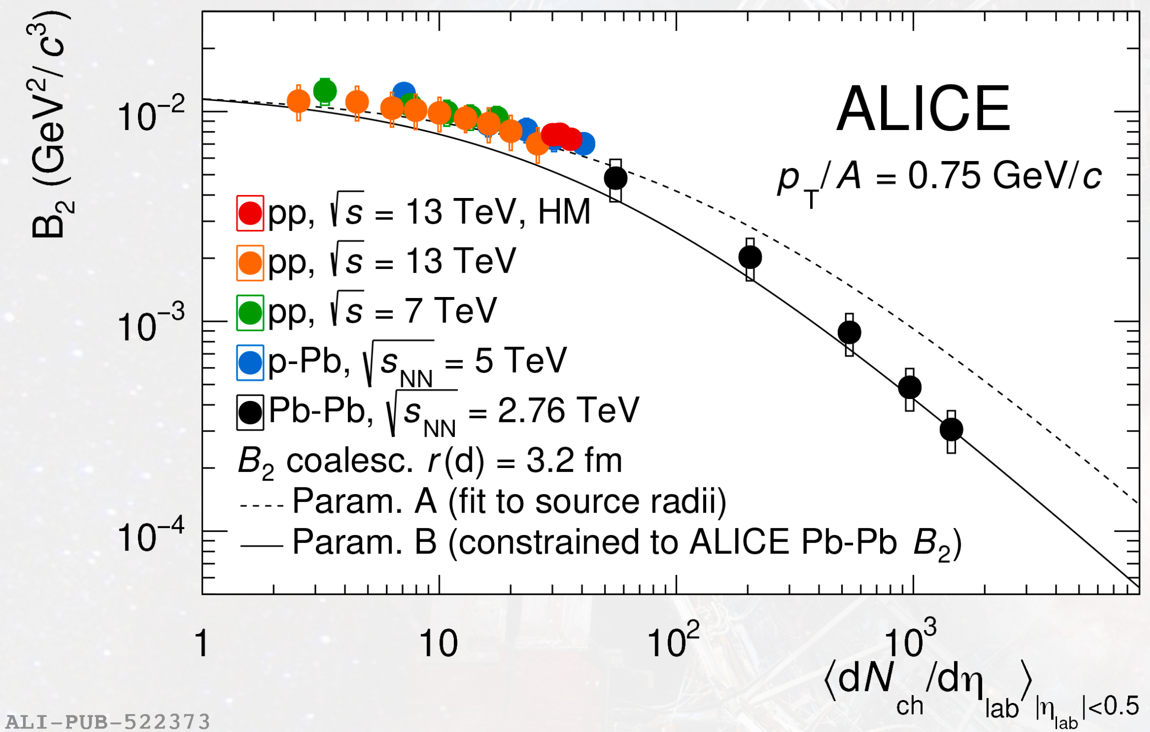
$^3_\Lambda$H is strongly sensitive to coalescence space constraint

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

The coalescence parameter B_A

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





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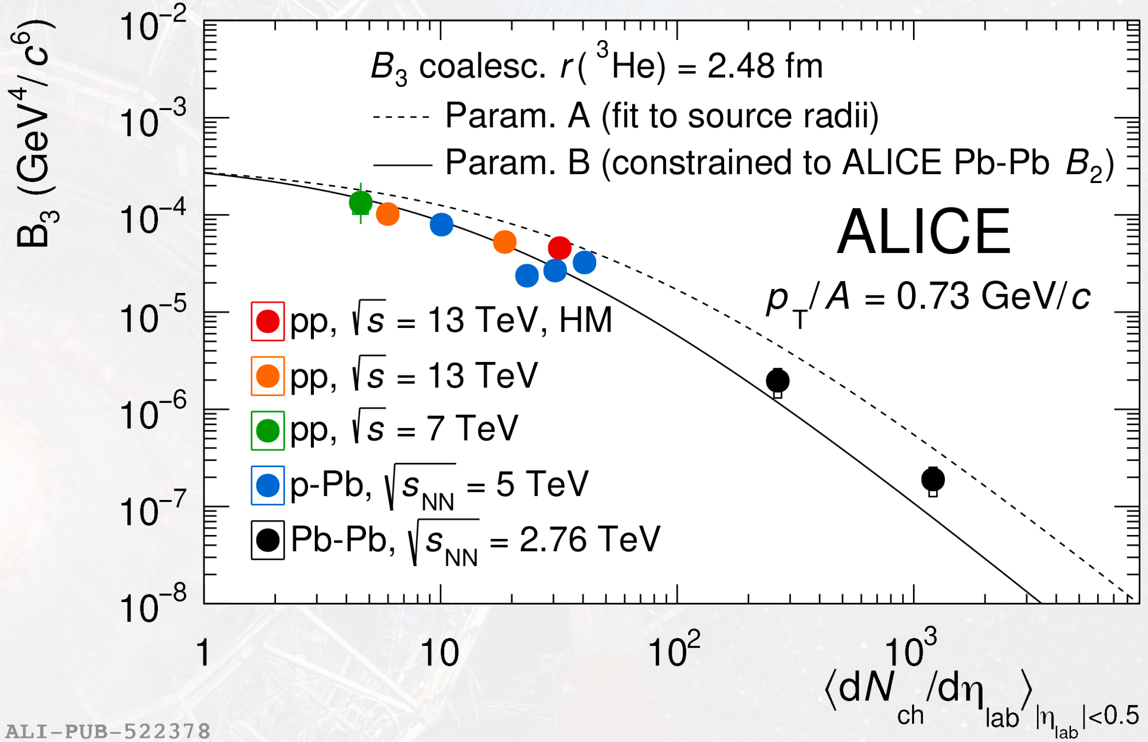
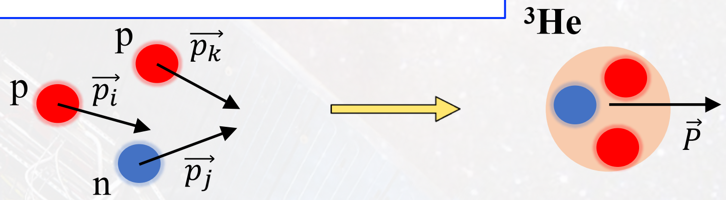


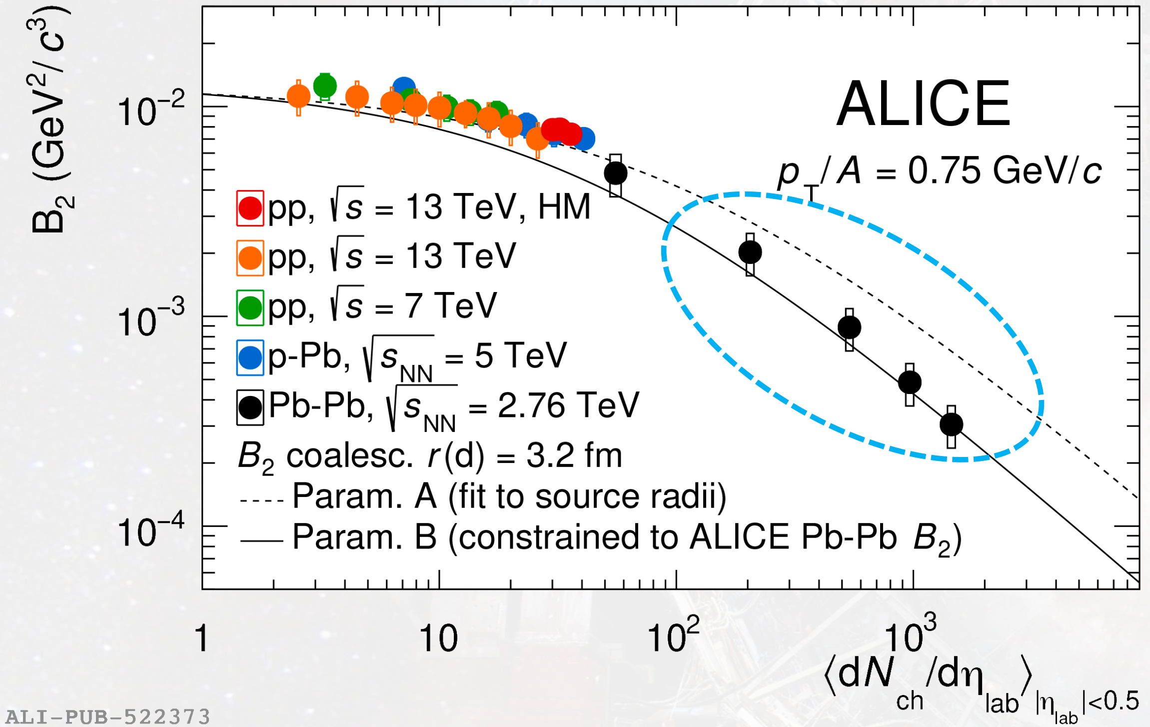
ALI-PUB-522378

Dependence of **coalescence probability** on the charged particle multiplicity (→ dependence on the particle-emitting **source size**)

The coalescence parameter B_A

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





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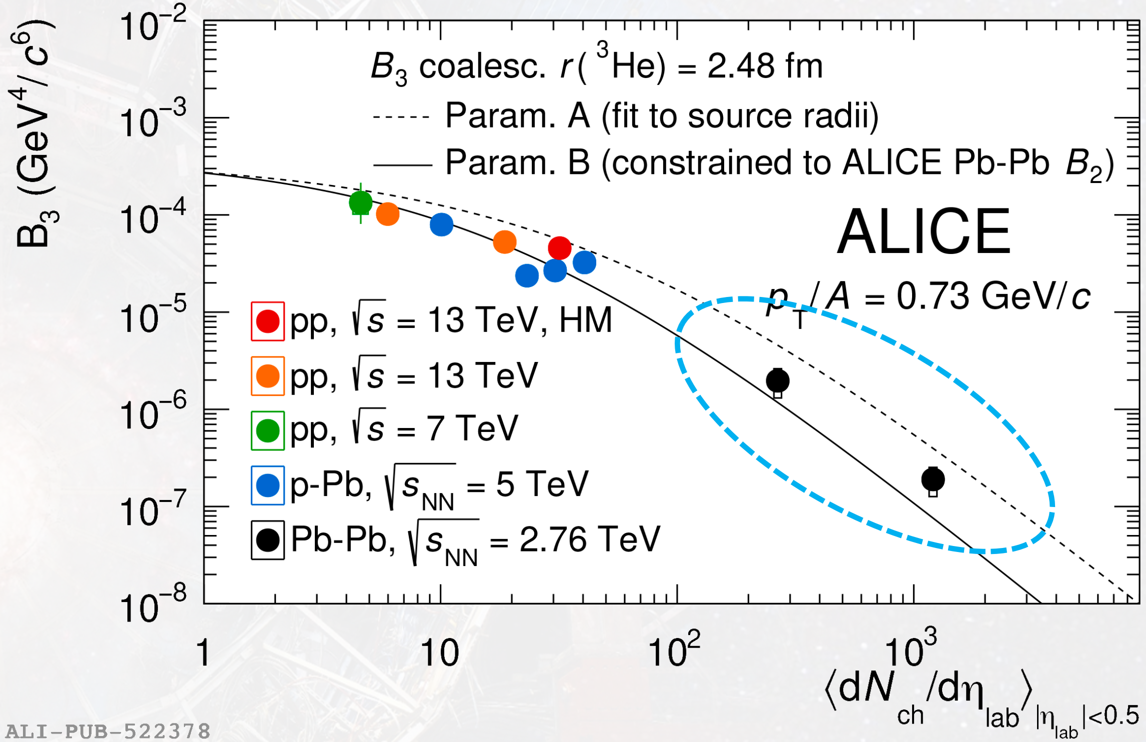


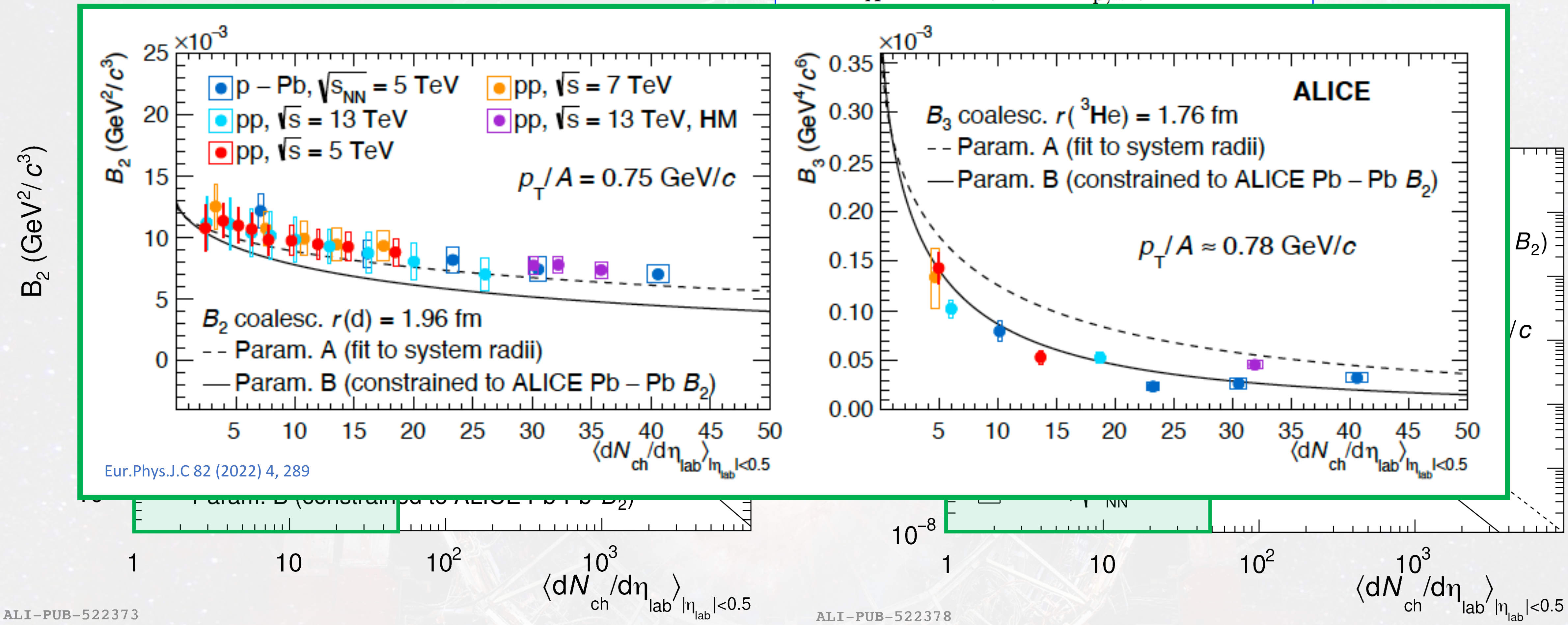
ALI-PUB-522378

Dependence of **coalescence probability** on the charged particle multiplicity (→ dependence on the particle-emitting **source size**)

In **high multiplicity (Pb-Pb)**, significant drop observed, effect of space separation in a large source (~2-5 fm radius)

The coalescence parameter B_A

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



Eur.Phys.J.C 82 (2022) 4, 289

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ALI-PUB-522378

Dependence of **coalescence probability** on the charged particle multiplicity (→ dependence on the particle-emitting **source size**)

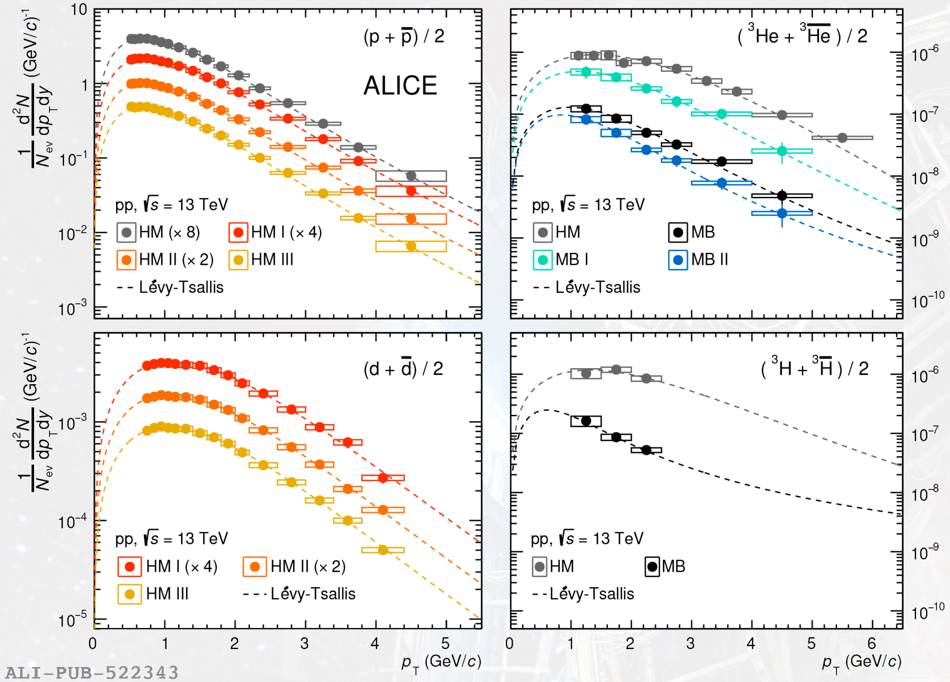
In **high multiplicity (Pb-Pb)**, significant drop observed, effect of space separation in a large source (~2-5 fm radius)

In **low multiplicity (pp, p-Pb)** a **weak dependence** on multiplicity in small sources (~ 1 fm radius) is observed

Exploring the particle yield vs nucleon source connection

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

- **Investigate the wavefunction** of the d,$\bar{d}$
- **Constrain** coalescence models



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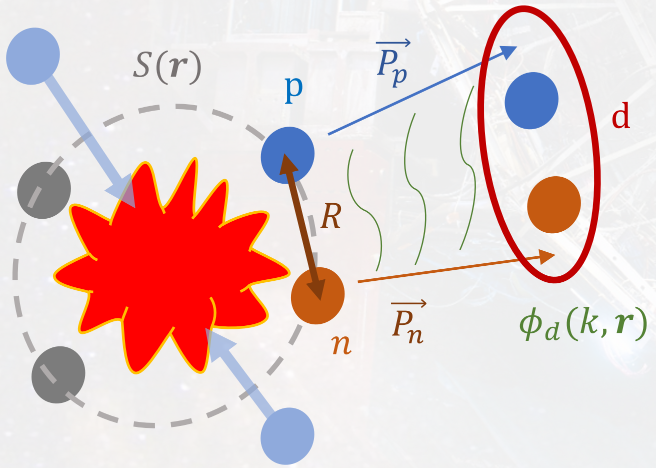

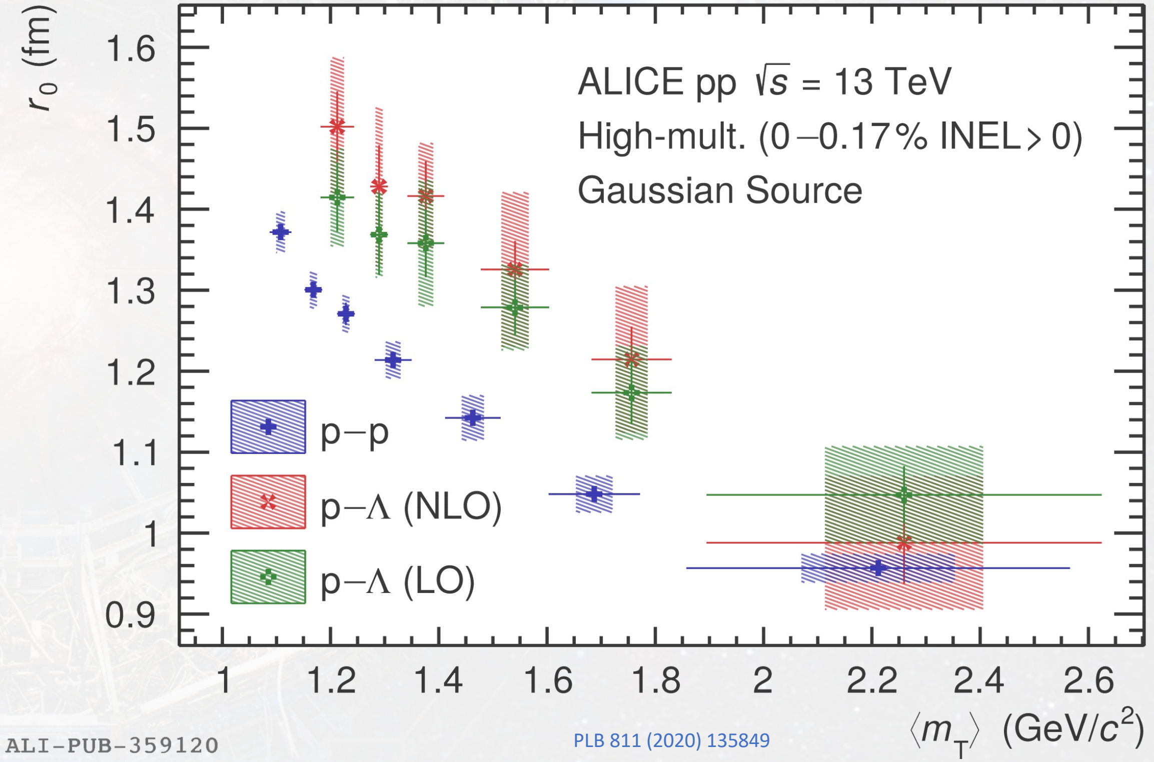

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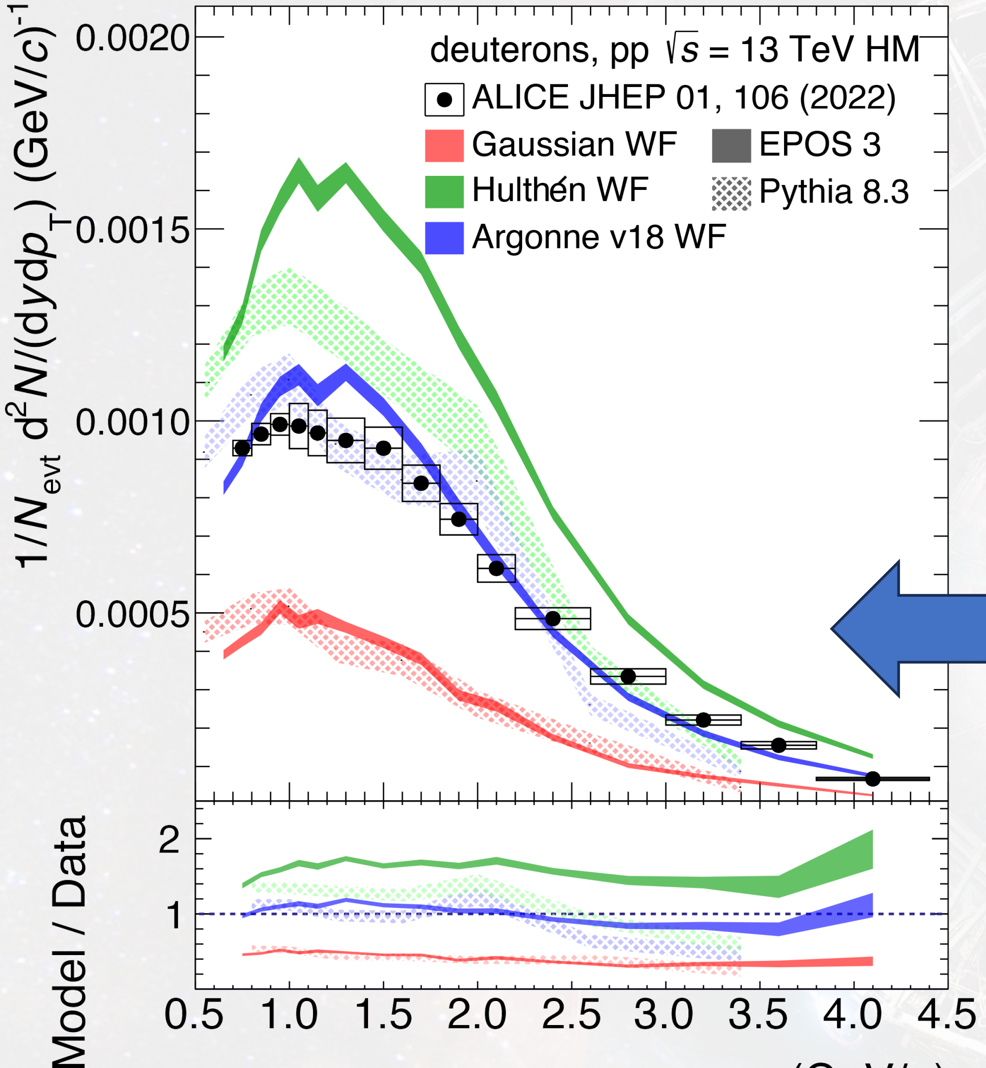
PLB 811 (2020) 135849

ALICE experimental input to coalescence modelling



Mahlein, M., Barioglio, L., Bellini, F. *et al.*
Eur. Phys. J. C **83**, 804 (2023).

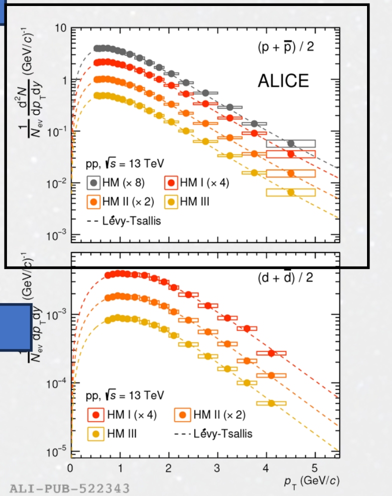
Recent study shows that the ALICE measurements of **production yield** and the **proton source radius** in the **same event class**, with the choice of a suitable wavefunction, allows for prediction of deuteron spectrum via coalescence with **no free parameters**.

→ Experimental input **crucial for coalescence modelling**

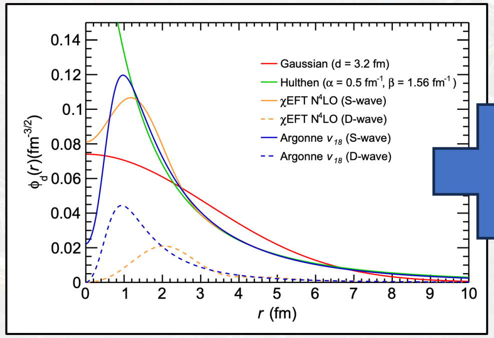
→ **Application to the study of cosmic ray fluxes**

Wigner-formalism based coalescence afterburner

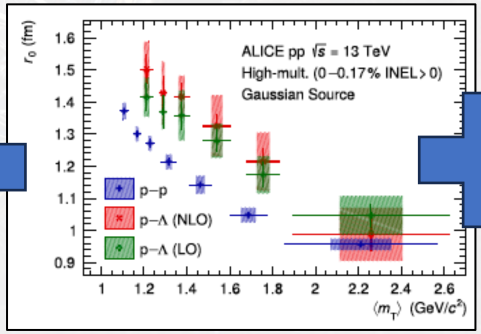
p_T spectra



Wavefunction for d

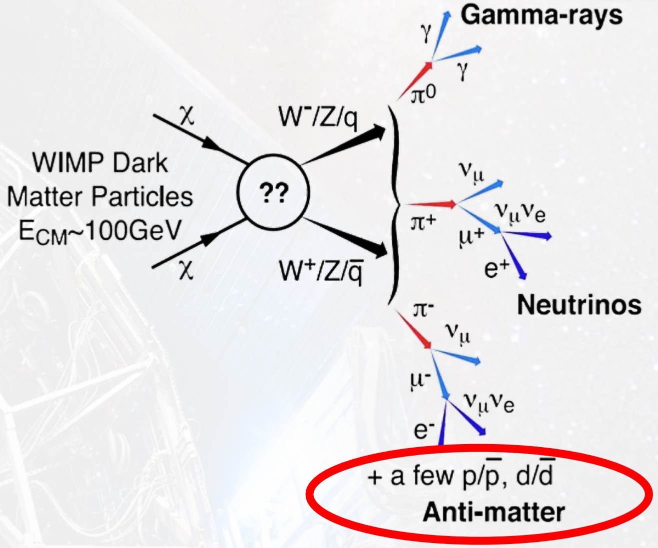


Nucleon source size



Light antinuclei as smoking guns for Dark Matter

[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 ($m_\chi \sim \text{few GeV} - \text{few TeV}$)p-p

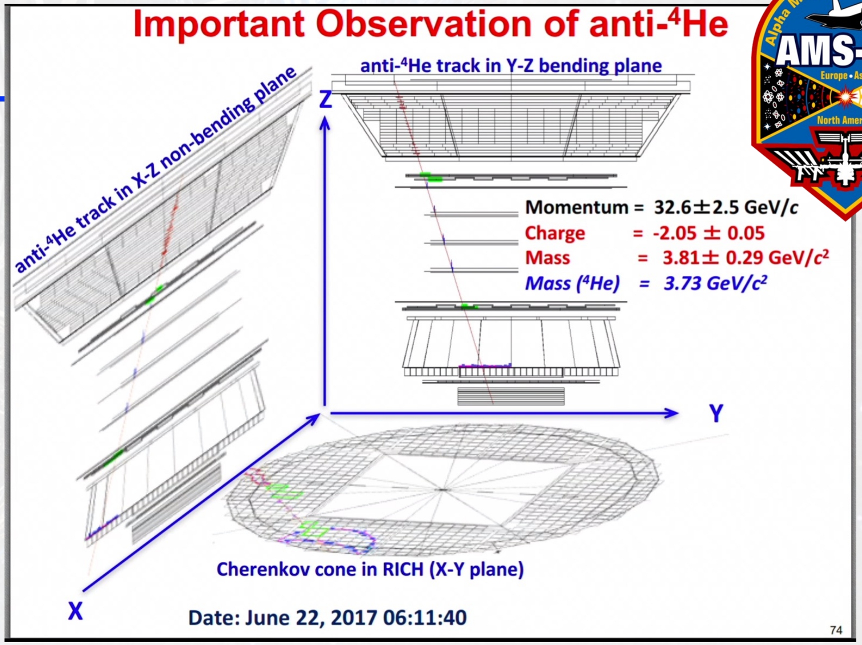
- Produced by $\chi\bar{\chi}$ **pair annihilation** or χ **decay** in the galactic halo
- **Low or no background from interactions of cosmic rays (CR)** with interstellar matter (ISM) → **to be estimated carefully!**
- Subject for indirect DM searches with space-based experiments as AMS-02 (ongoing) 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 $^3\overline{\text{He}}$ + 2 $^4\overline{\text{He}}$ candidates reported
*(As of today, **still not confirmed**)*



Important Observation of anti-^{4}He

anti-^{4}He track in Y-Z bending plane

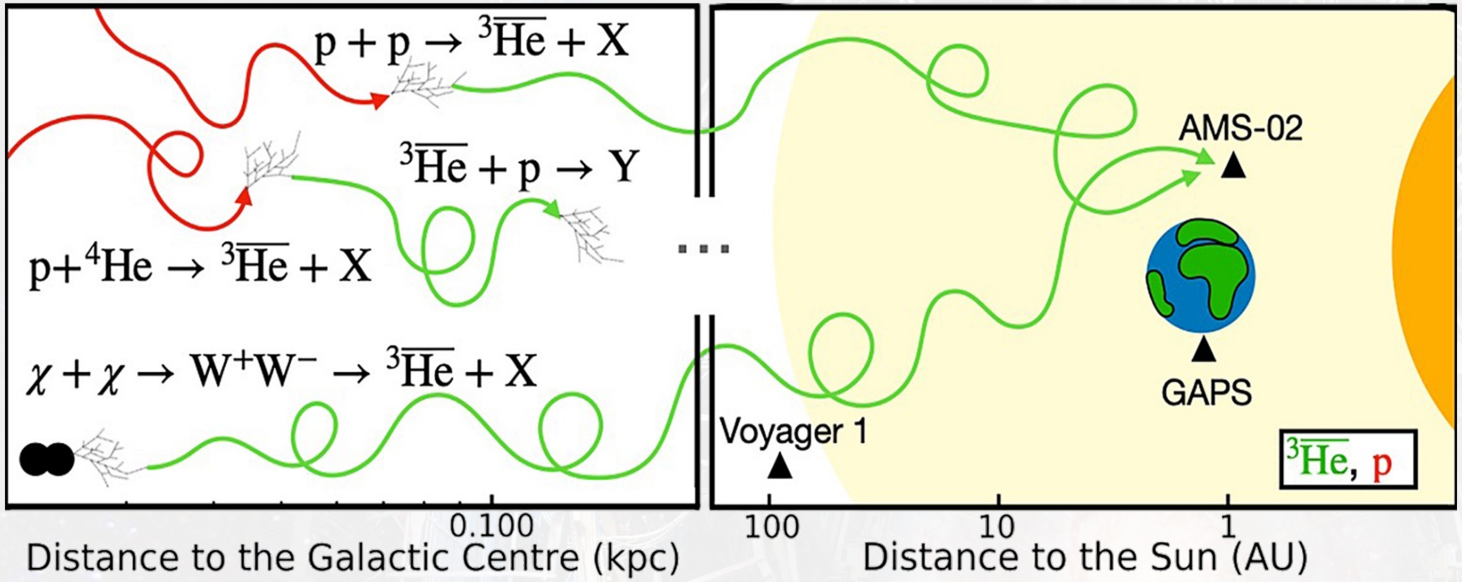
anti-^{4}He track in X-Z non-bending plane

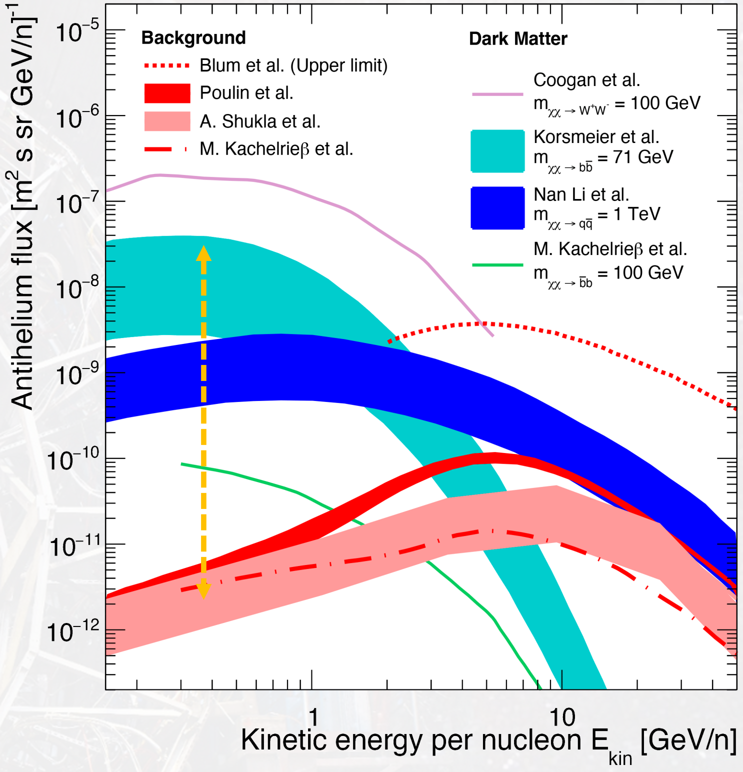
Momentum = 32.6±2.5 GeV/c
Charge = -2.05 ± 0.05
Mass = 3.81± 0.29 GeV/c^2
Mass (^{4}He) = 3.73 GeV/c^2

Cherenkov cone in RICH (X-Y plane)

Date: June 22, 2017 06:11:40

Towards prediction of cosmic antinuclei flux





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

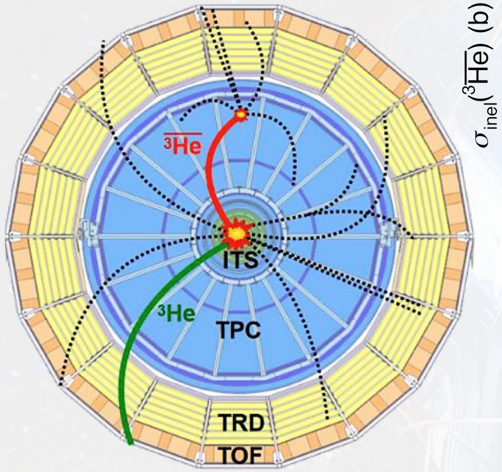
Ingredients:

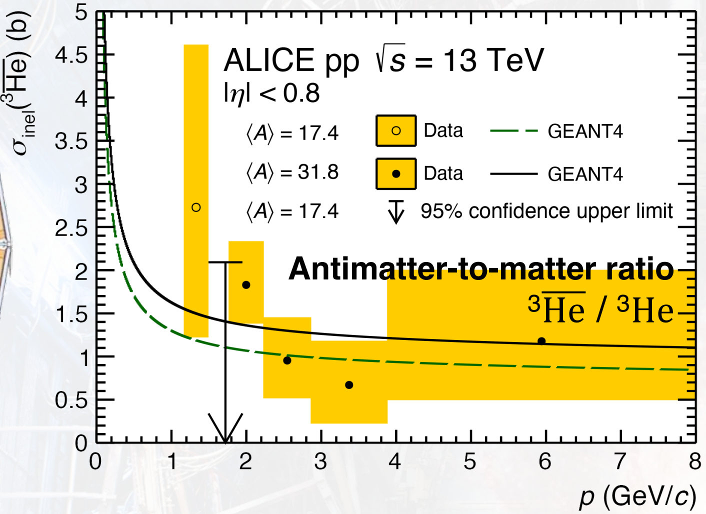
- **DM signal**: dark matter source and processes
- **Background:** secondary CR from pp, p-A collisions in space (*e.g. tuned Monte Carlo generators*)
- **Antiproton production cross section** constrained with measurements (*e.g. LHCb, AMBER, ...*)
- **Formation mechanism of antinuclei** → typically 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 $^{3}\overline{\mathrm{He}}$ cross section

Acharya, S. *et al.*
Nature Physics **19**, 61–71 (2023)

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

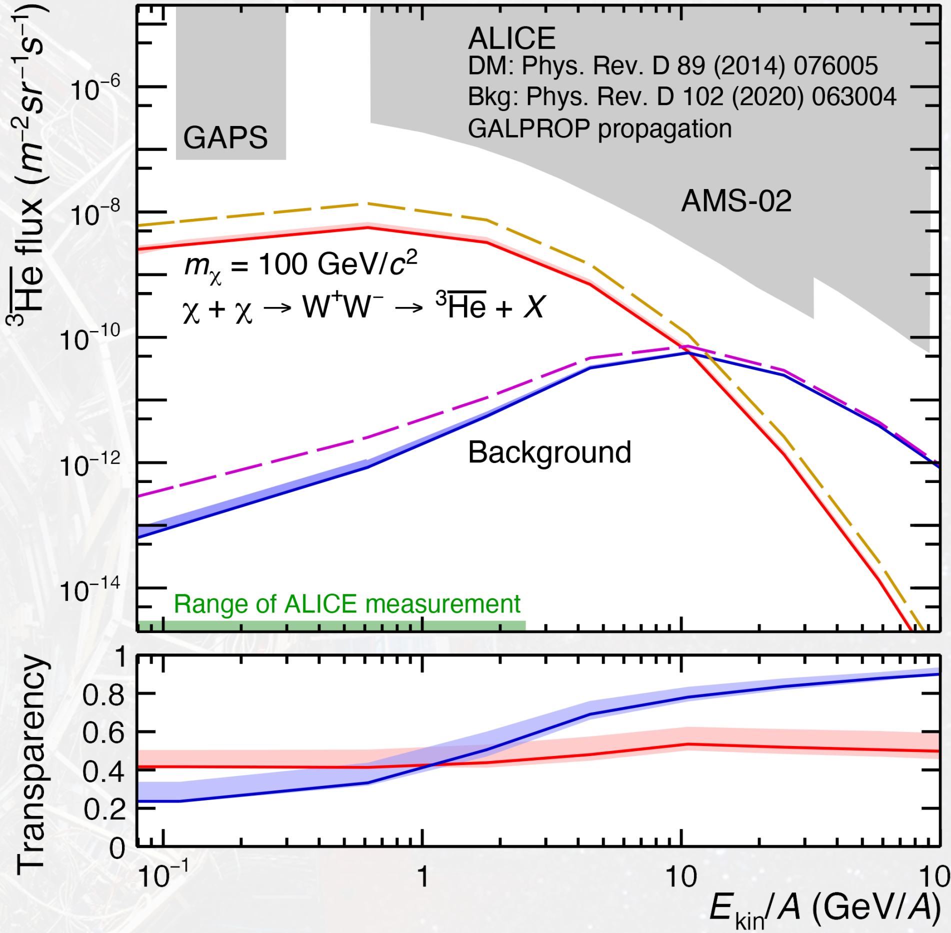




Antimatter-to-matter ratio
$^{3}\overline{\mathrm{He}}\ /\ ^{3}\mathrm{He}$

- 1st measurement of $^{3}\overline{\mathrm{He}}$ absorption cross section in matter
- Experimental data and GEANT4 parametrization show a **2σ agreement**
- Significant impact on $^{3}\overline{\mathrm{He}}$ propagation in space

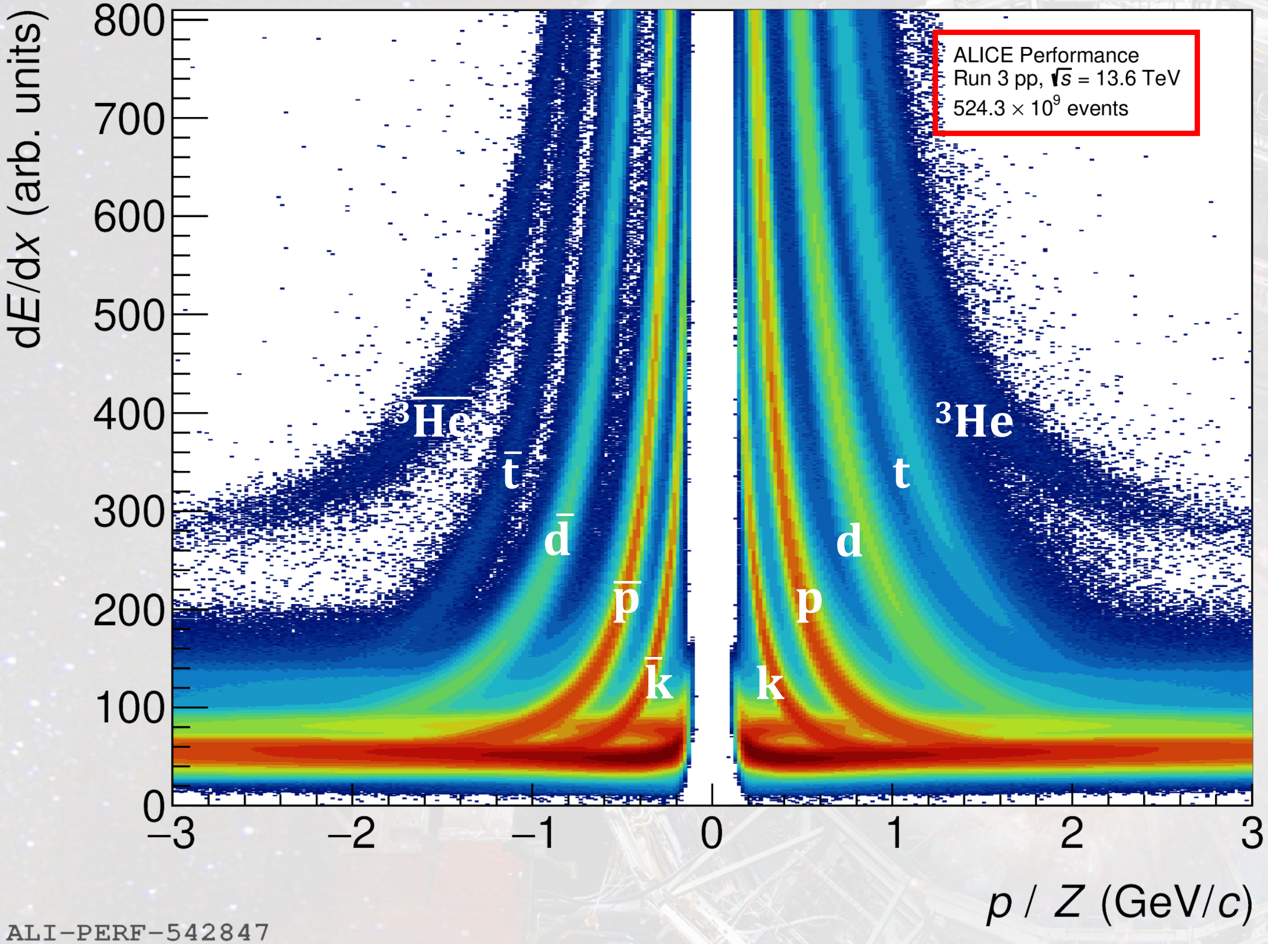
$^{3}\overline{\mathrm{He}}$ flux near Earth



$$\frac{\mathrm{Flux}(\sigma_{\mathrm{inel}})}{\mathrm{Flux}(\sigma_{\mathrm{inel}}=0)} =$$

$^{3}\overline{\mathrm{He}}$ transparency at low E_{kin}:
25% from CR interactions → The Galaxy is **highly**
50% from DM candidates **transparent** to $^{3}\overline{\mathbf{He}}$ nuclei

What's on its way in Run3: more (anti)helium

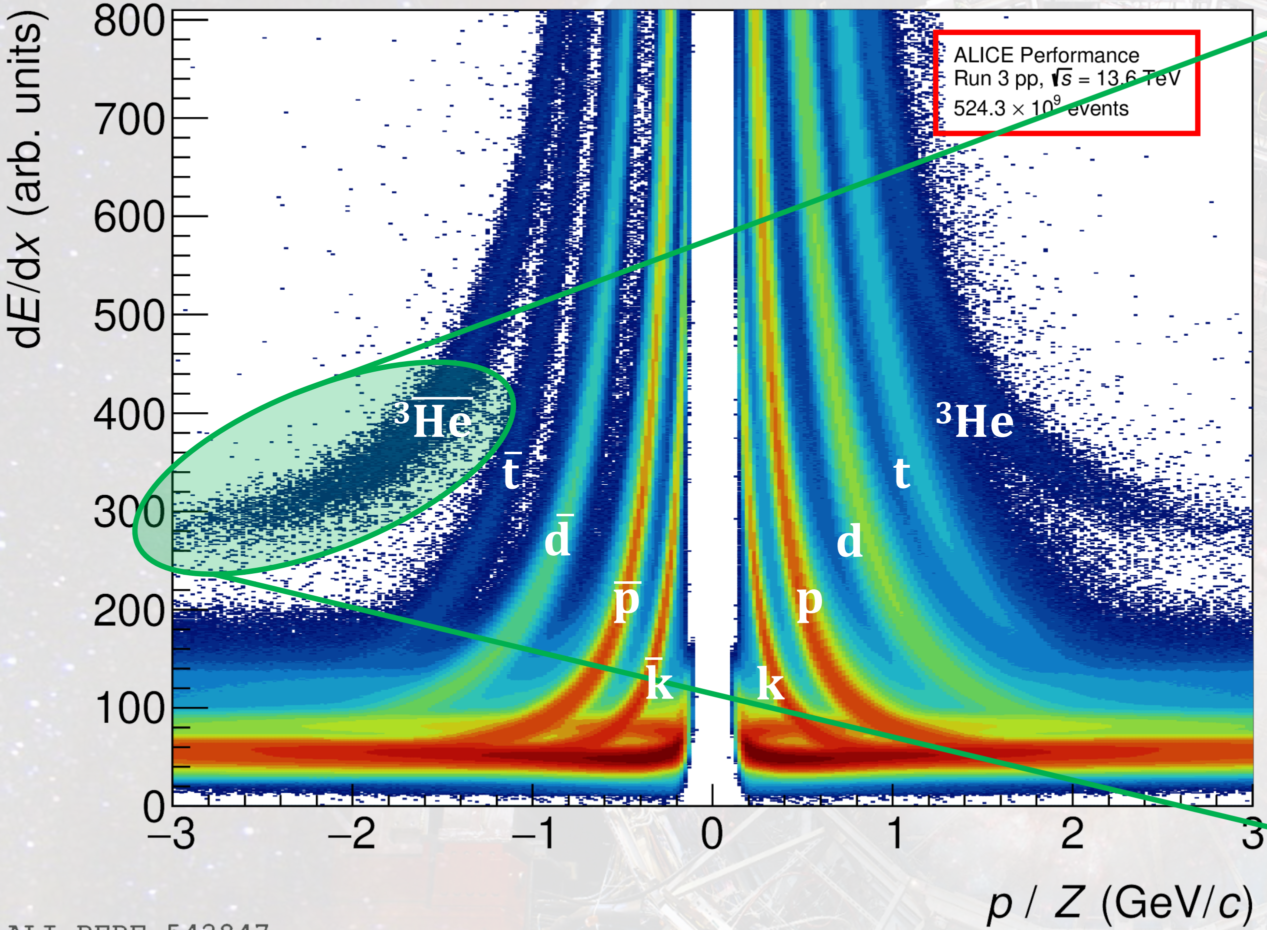


ALI-PERF-542847

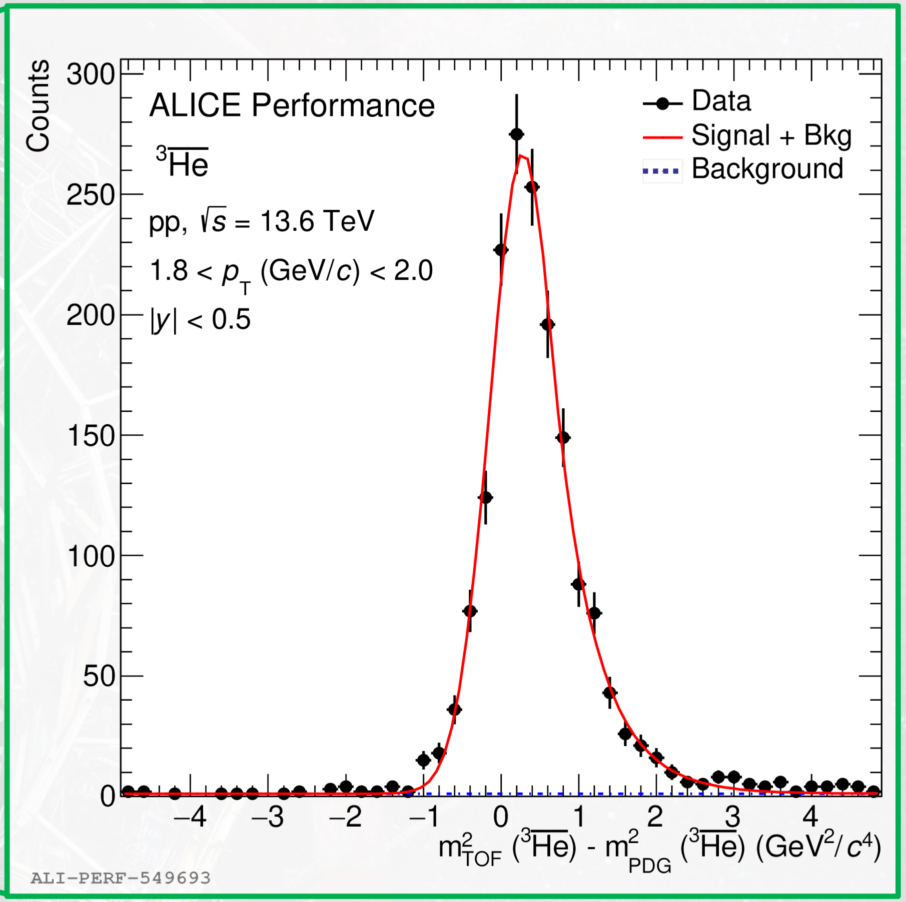
LHC Run 3 target **integrated luminosity:**
13 nb^{-1} (Pb-Pb) with interaction rates ~ **50 kHz**
200 nb^{-1} (pp) with interaction rates ~ **1 MHz**

In the LHC Run 3, the **highest energy** ever was reached in pp collisions with the record of $\sqrt{s}$ = 13.6 TeV.

What’s on its way in Run3: more (anti)helium



ALI-PERF-542847



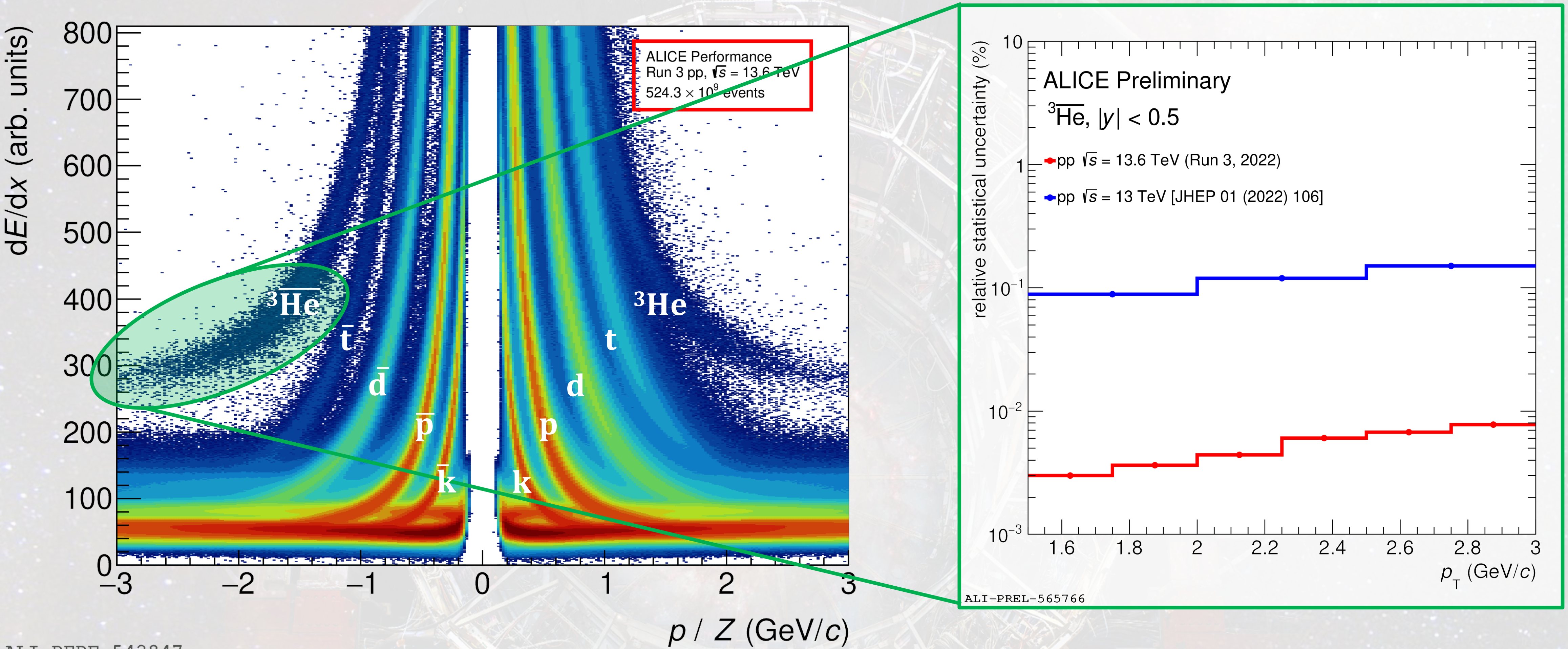
ALI-PERF-549693

LHC Run 3 target **integrated luminosity:**
13 nb^{-1} (Pb-Pb) with interaction rates ~ **50 kHz**
200 nb^{-1} (pp) with interaction rates ~ **1 MHz**

This record energy allows to study the production of A = 3 light anti-nuclei, like **anti-helium**:

- More differential and precise data on **B_3**
- Input to model **cosmic ^{3}He** formation

What's on its way in Run3: more (anti)helium



ALI-PERF-542847

ALI-PREL-565766

LHC Run 3 target **integrated luminosity:**
13 nb^{-1} (Pb-Pb) with interaction rates ~ **50 kHz**
200 nb^{-1} (pp) with interaction rates ~ **1 MHz**

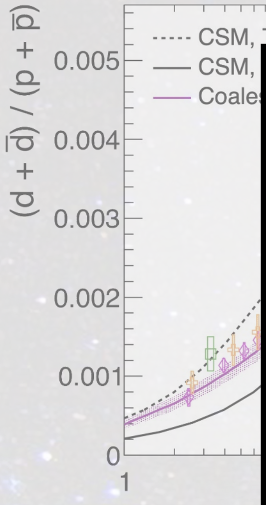
The **integrated luminosity foreseen** for both Run 3 and Run 4 will allow to study (anti)helium with a similar **statistical precision** as reached for (anti)deuteron in Run 1 and Run 2

THANK YOU FOR THE ATTENTION

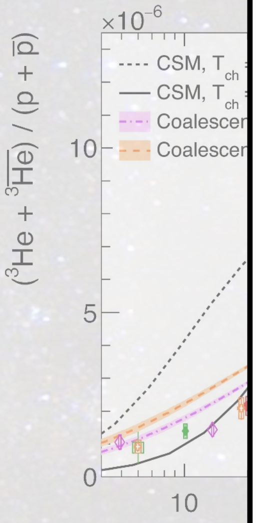
Backup

SHM or Coalescence? Nuclei over p ratio

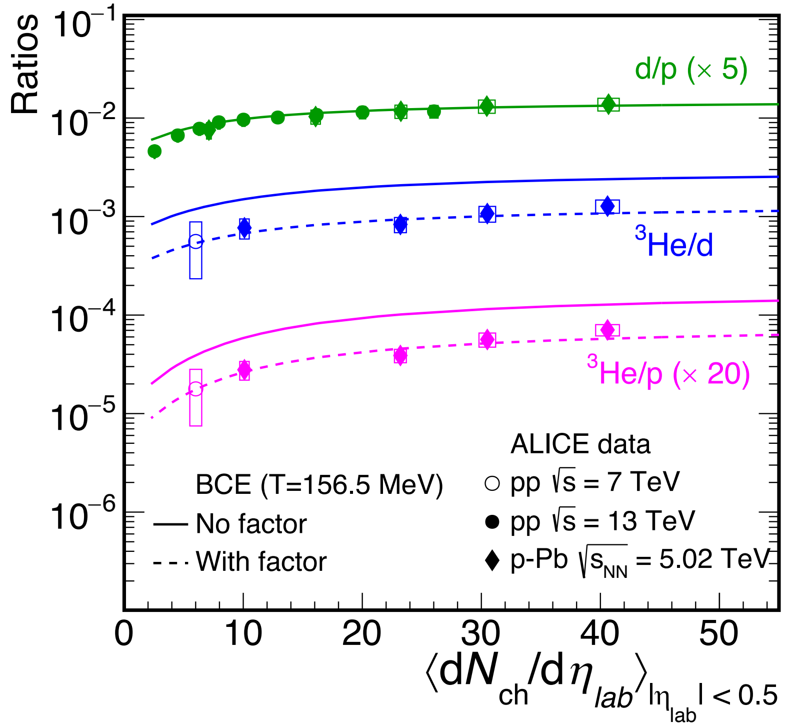
SMALL OBJECTS (d, ^{3}He...)



CERN-EP-

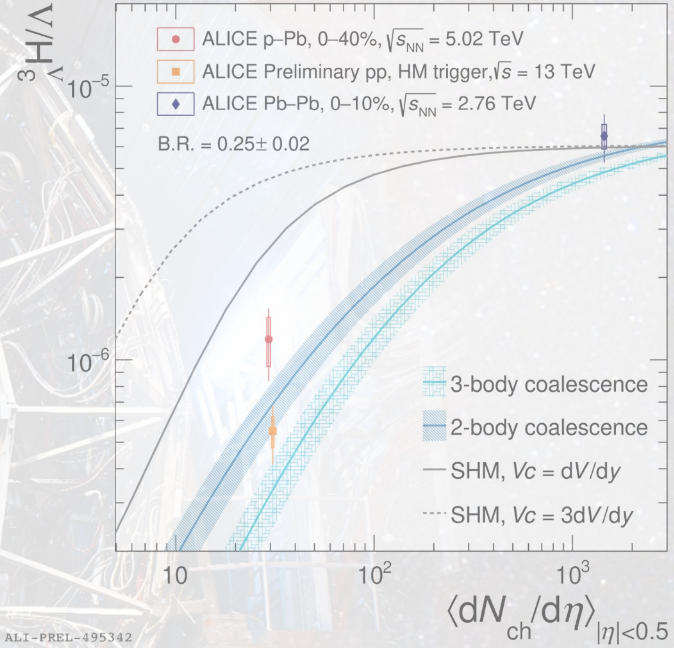


[3] N. Sharma, K. Redlich et al., PRC107, 054903 (2023)



Ratios d/p, $^3\text{He}/d$, and $^3\text{He}/p$ as a function of charged particle multiplicity and their comparison with the Baryonic Canonical Ensemble (BCE) approach[3]

LARGE OBJECTS ($^3_\Lambda$H ...)



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

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