MEASUREMENTS OF (ANTI)NUCLEI IN pp AT $\sqrt{s}$ = 13.6 TeV

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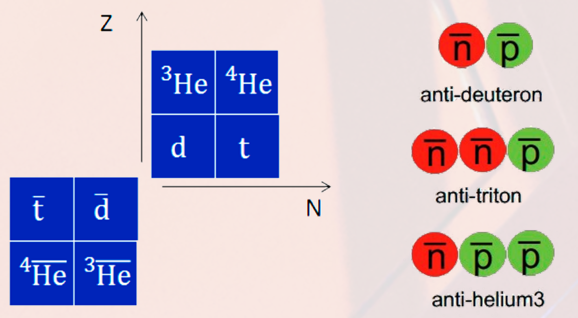
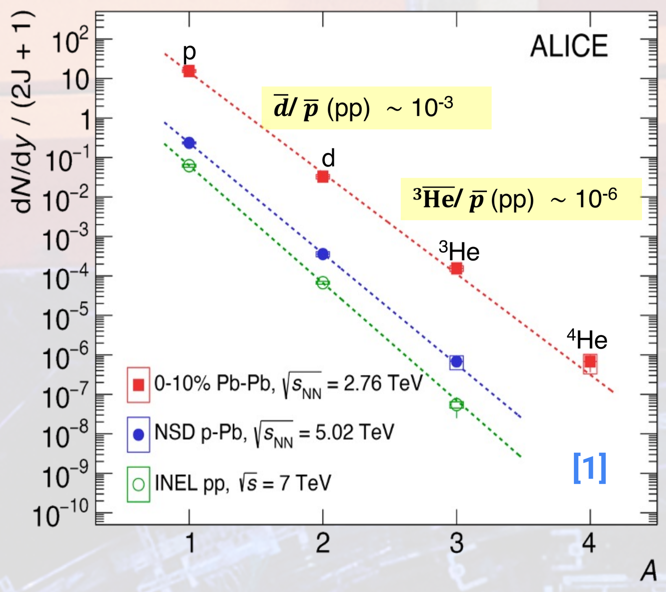
Physics Motivation





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

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

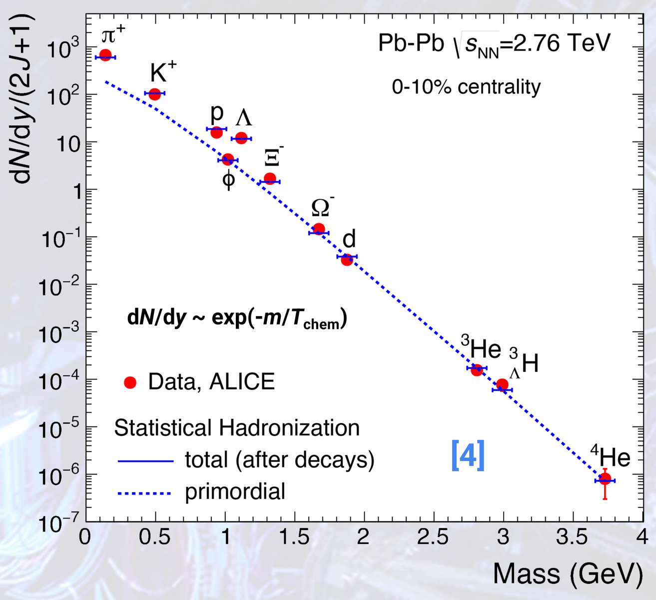
From the Cosmos to the laboratory!
Measurements of light (anti)nuclei production in controlled conditions are used to constrain the dominant background for dark matter searches in space: antimatter produced in cosmic ray interactions with interstellar medium

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

At LHC, same amount of matter and antimatter[2]
→ Ideal conditions for studying **antinuclei**.

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

The Statistical Hadronization model



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

dN/dy ~ exp(-*m*/T_{chem})

→Nuclei have large mass, so they have little or no feed-down from higher mass states

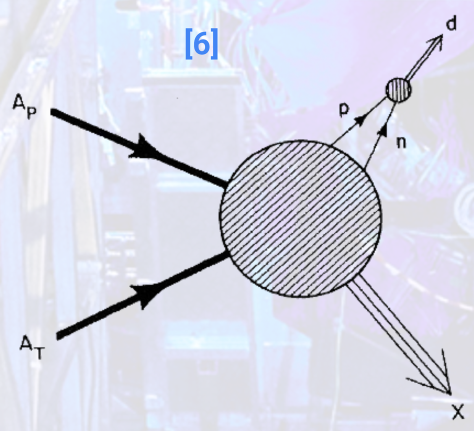
The SHM can be extended from high to low multiplicity systems via canonical formulation[5]

In this model, nuclei are produced at the same temperature with other light hadrons

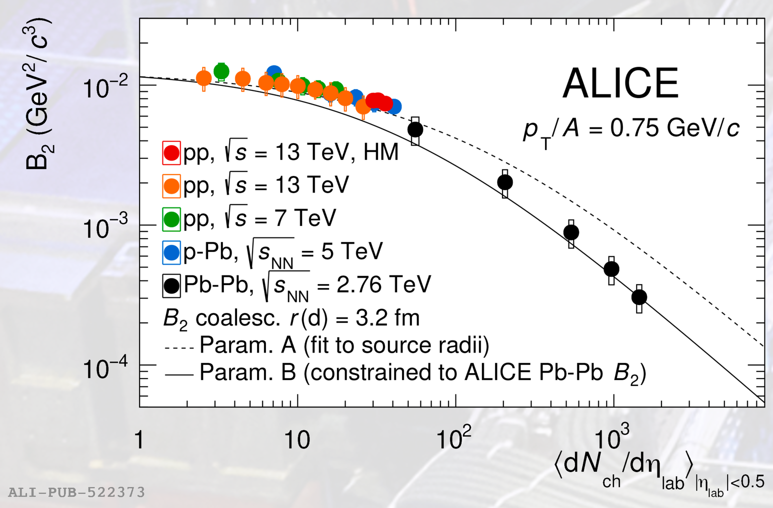
The Coalescence model

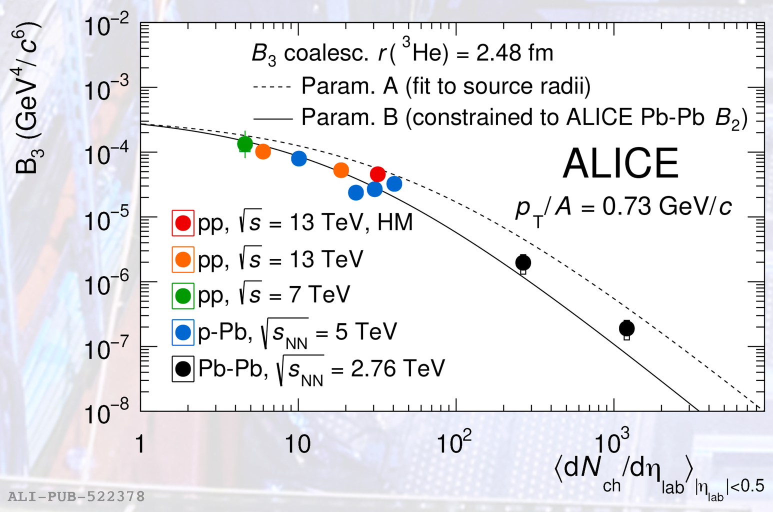
Nucleons close in the phase space at kinetic freeze-out can form a nucleus via **coalescence**
Formation probability is related to the **coalescence parameter B_A**

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



→Wigner-function approach:
nucleons' **relative** momentum and position, nucleus wavefunction matters





The dependence of **coalescence probability** on the charged-particle multiplicity is related to the nucleons **source size**
e.g., High multiplicity (Pb-Pb)
→ significant drop, effect of space separation in a large source (~2-5 fm radius)

The ALICE DETECTOR at the LHC RUN 3

The main physics goal of the **ALICE** experiment is the study of the dense and hot matter created in ultra-relativistic heavy-ion collisions: the **Quark-Gluon-Plasma**.

The excellent **Particle IDentification** (PID) capabilities of ALICE apparatus allow to identify particles down to very low transverse momentum (~100 MeV/c) exploiting different complementary techniques

New Inner Tracking System (ITS2)
7 layers of silicon pixel sensors
Reduced material budget (wrt Run1+2)
Used for vertexing and tracking

Upgraded Time Projection Chamber (TPC)
GEM-based
Used for tracking and PID via dE/dx

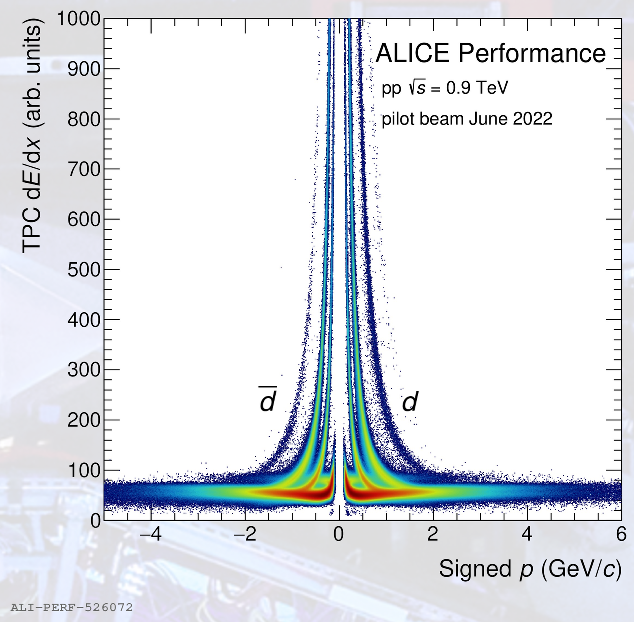
Time-Of-Flight detector (TOF)
Upgraded electronics to allow for continuous readout
PID via time-of-flight measurements

Anti-deuteron in pp at $\sqrt{s}$ = 900 GeV

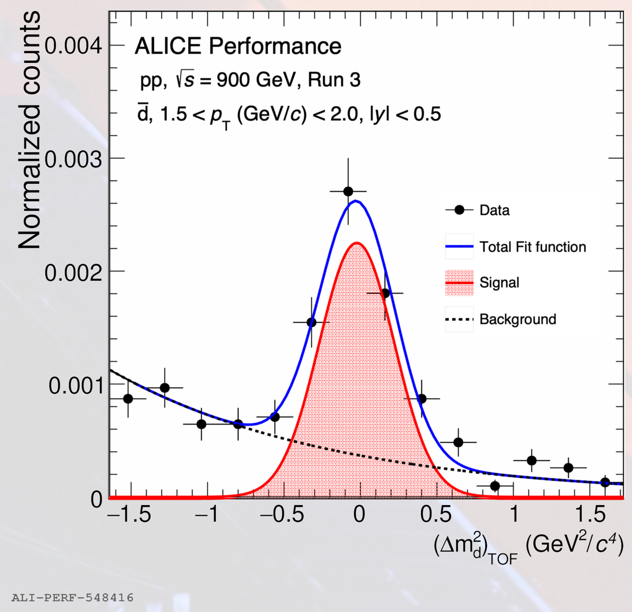
The very first collisions of the LHC Run 3 were collected at $\sqrt{s}$ = 900 GeV in Oct. 2021 and Jun. 2022.

This sample allows for comparison with Run 1 light (anti)nuclei production measurements, but with the **improved capabilities of the new ALICE apparatus**.

The antideuteron measurement employs both TPC and TOF identification capabilities:



In TPC, PID is performed measuring the energy loss (dE/dx) of particles in the gas as a function of the rigidity. Antideuteron candidates are preselected requiring a dE/dx compatible within 5σ with the expected signal for $\bar{d}$.



The antideuteron yield is extracted by fitting the distribution of the difference between the squares of the mass reconstructed using the TOF information and the nominal mass.

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

where:
p is the particle momentum
t is the measured time
L is the particle length

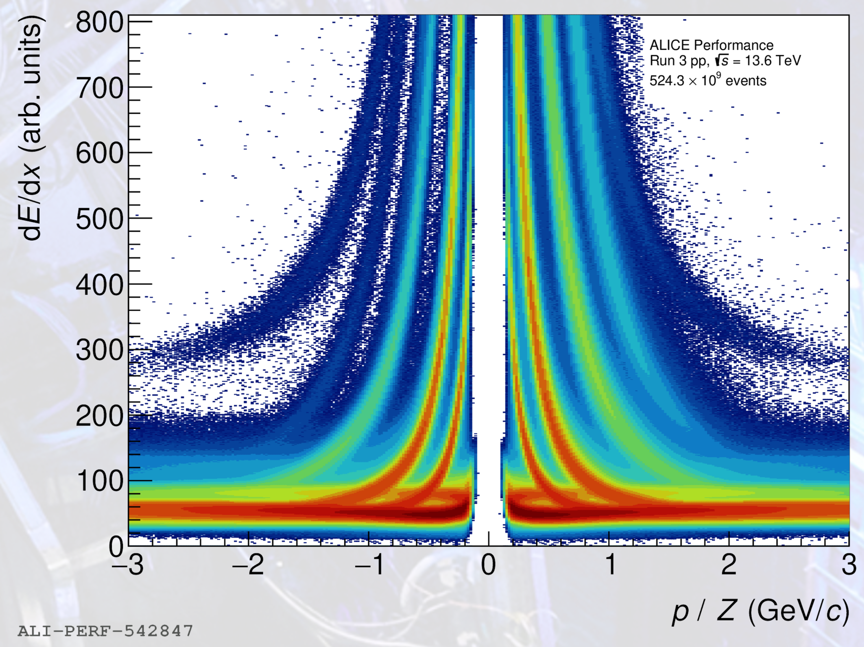
Anti-helium-3 in pp at $\sqrt{s}$ = 13.6 TeV

The LHC Run 3 allowed to reach the **highest energy** ever in pp collisions with the record of $\sqrt{s}$ = 13.6 TeV.

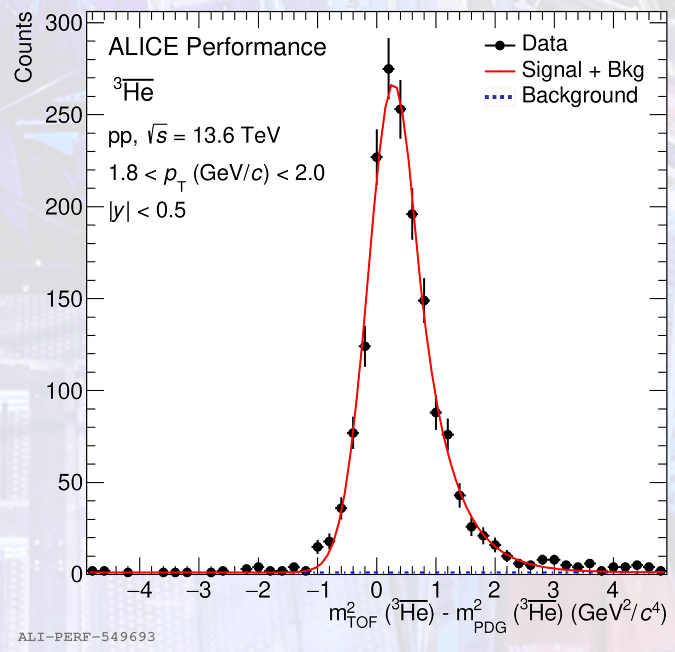
This gives opportunities to study the production of A = 3 light (anti)nuclei, like (anti)helium, in this newly available energies
→ fundamental input to investigate coalescence by computing **B_3**.

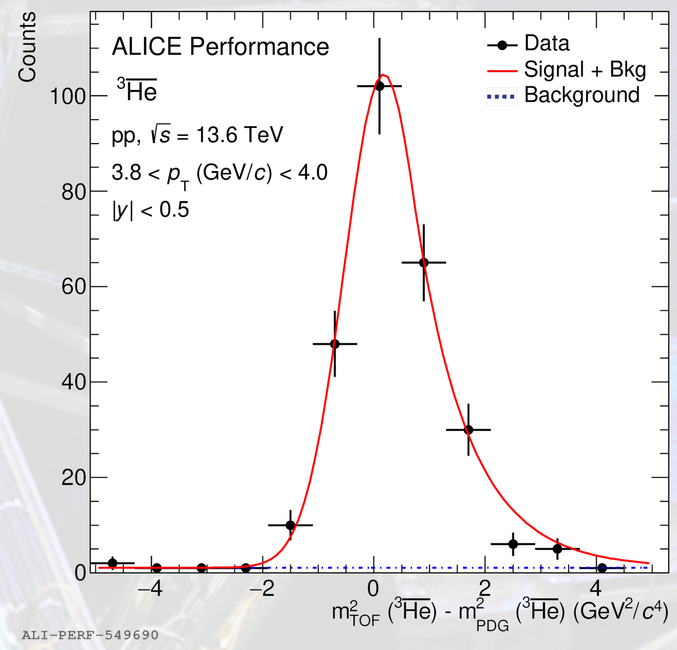
The $^3\overline{He}$ signal extraction is performed by preselecting the candidates with TPC (within a 5σ ideal response) and then computing their mass using the information from TOF.

The signal is extract from the difference between the squared TOF masses, like for the (anti)deuteron case.



TPC response for pp $\sqrt{s}$ = 13.6 TeV collisions. The $^3\overline{He}$ signal is fitted with ALEPH Bethe-Bloch functions (in black).

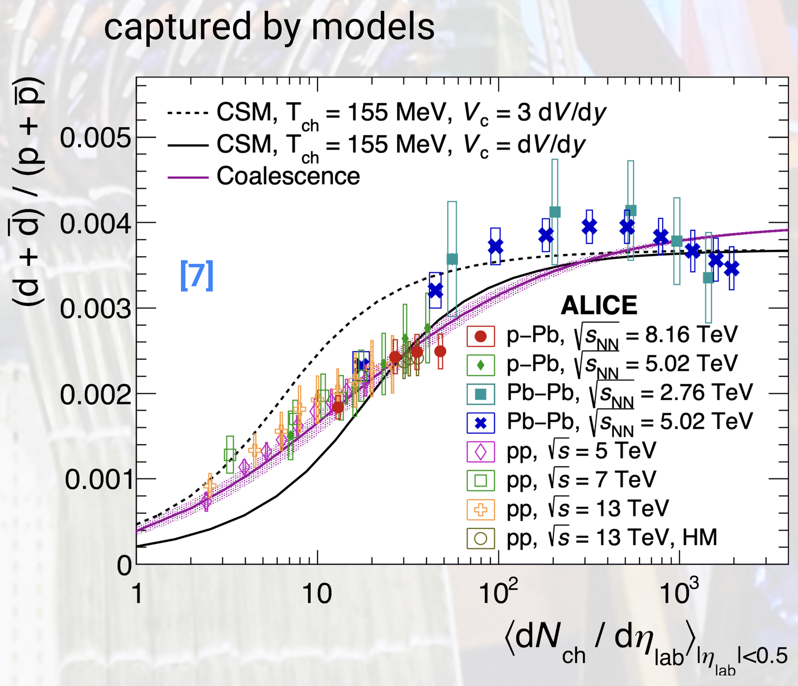


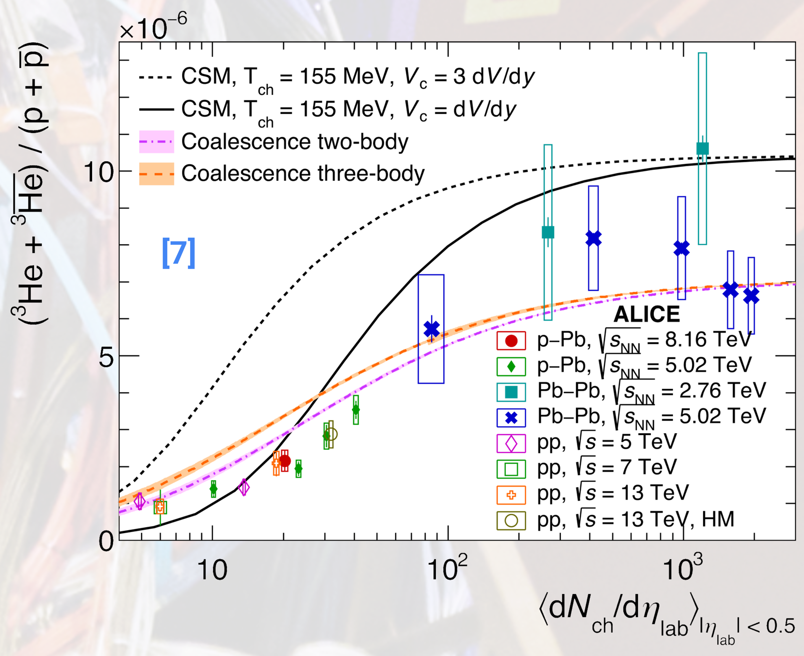


The (anti)helium signal is extracted for different ranges of p_T (from 1 GeV/c up to 6 GeV/c) in via the TOF detector. The difference between the squared masses is fitted with a function defined as the sum of an asymmetric gaussian function (in red) for the (anti)helium signal, and a constant function (in blue for the background).

(Anti)nuclei over (anti)protons ratio

The ratio of yields of **nuclei over protons**[7] is sensitive to the light nuclei production mechanism
→ Excellent probe for the **nucleon source** properties
→ Continuous trend as a function of <$dN_{ch}/d\eta_{lab}$> in different colliding systems qualitatively captured by models





The **(anti)deuteron/(anti)proton** ratio is
→ Well described by coalescence approach at low multiplicity
→ Better described by coalescence at low multiplicity wrt CSM calculations
→ Well described by CSM at high multiplicity

The **(anti)helium/(anti)proton** ratio is
→ Well described by coalescence approach at low multiplicity
→ Need for more precise (Run 3) measurements to investigate the tension between models (such as the $^3\overline{He}$ analysis shown in the previous panel!)

References

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[7] ALICE collaboration, CERN-EP-2022-275