NUCLEI MEASUREMENTS IN RUN 3 WITH ALICE

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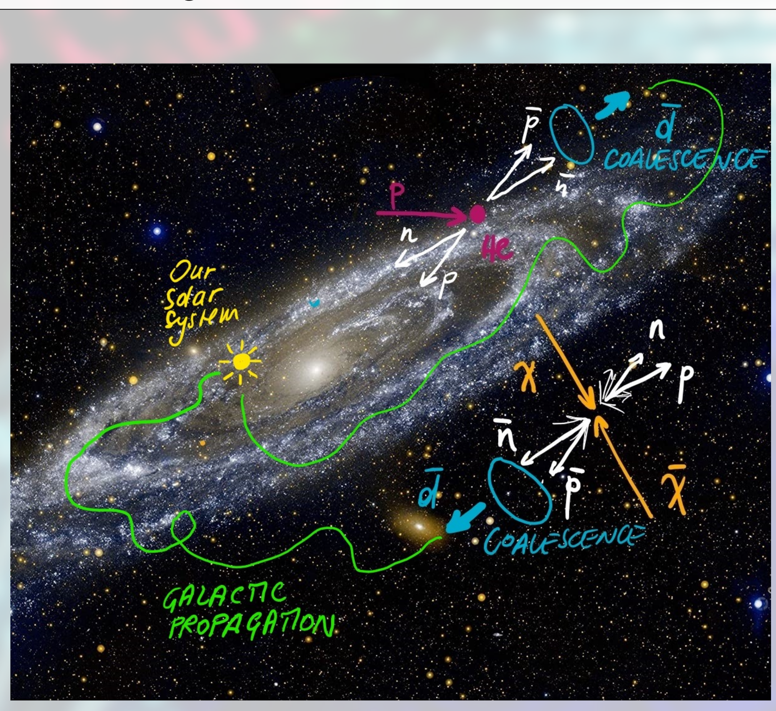
(Anti)nuclei: from the laboratory to the Cosmos

The production mechanism of light (anti)nuclei in high-energy collisions is **not fully understood**[1].

Their low binding energy ($B_E \sim 2$ MeV) and large mass implies that their formation is extremely sensitive to the chemical freeze-out temperature ($T_f \sim 100\ B_E$).

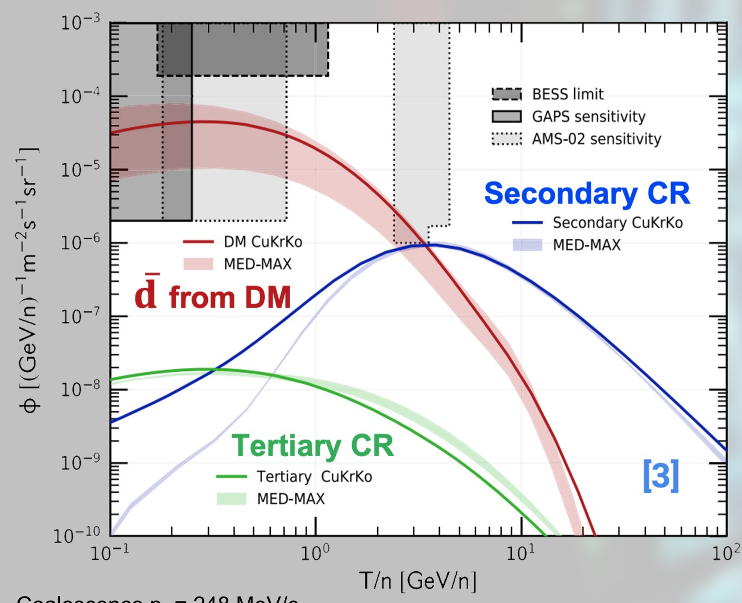
Measuring light (anti)nuclei production in controlled conditions can be used to constrain the dominant background for **dark matter searches** in space: antimatter produced in cosmic ray interactions with interstellar medium.



The detection of cosmic antideuterons and antihelium nuclei is a promising "smoking gun" signature [3].

These predictions require modeling of the production mechanisms of (anti)nuclei.

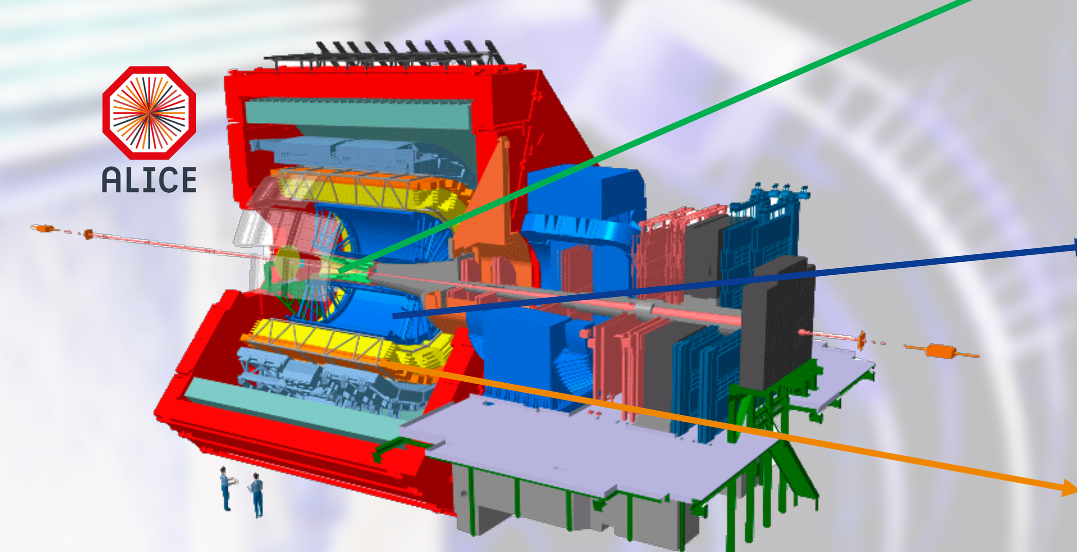
The ALICE apparatus fulfils the perfect conditions for measuring **(anti)nuclei** and comparing their production yields in relation to two phenomenological models:
- Statistical hadronization **(SHM or CSM)**
- **Coalescence**



Coalescence p_0 = 248 MeV/c
Uncertainty bands: propagation model

ALICE upgraded for Run 3

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



Inner Tracking System (ITS)
- 7 layer pixel detector
- 10 m2 (12.5 GP) silicon tracker based on MAPS
- Less material budget, improved tracking performance at low p_T

Time Projection Chamber (TPC)
- GEM-based readout pads
- Continous readout allowed
- PID via energy loss (dE/dx) in the TPC gas

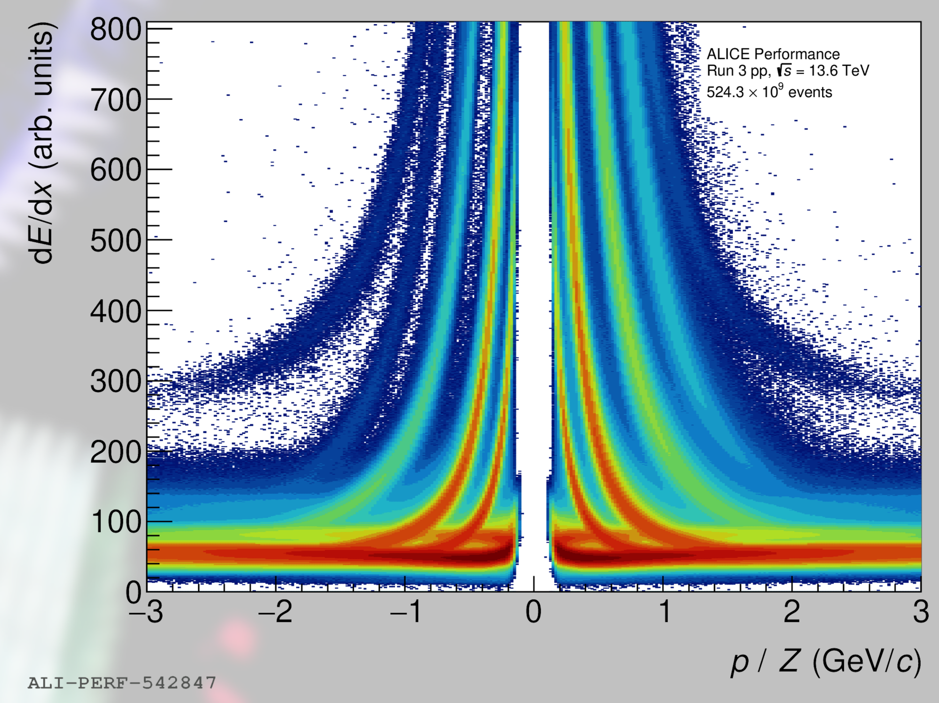
Time Of Flight detector (TOF)
- PID via time-of-flight measurements

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

LHC Run 3 target **integrated luminosity**[8]:

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.



TPC response for pp √s = 13.6 TeV collisions (2022).

The Statistical Hadronization model

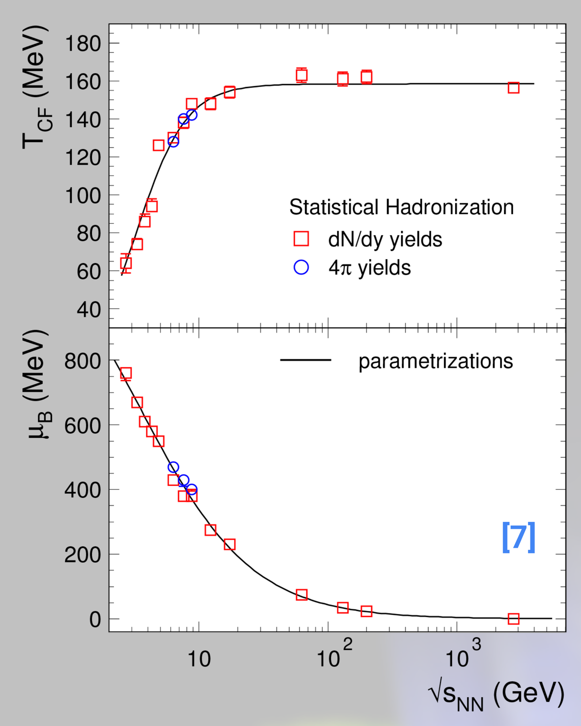
The hadrons are emitted from the interaction region in thermal equilibrium when the fireball reaches the chemical freeze-out: the **abundances** are **fixed** at **chemical freeze-out** (T_{chem})[3].

The abundance of the produced hadrons is **strongly dependent** on their **mass m** and T_{chem} as

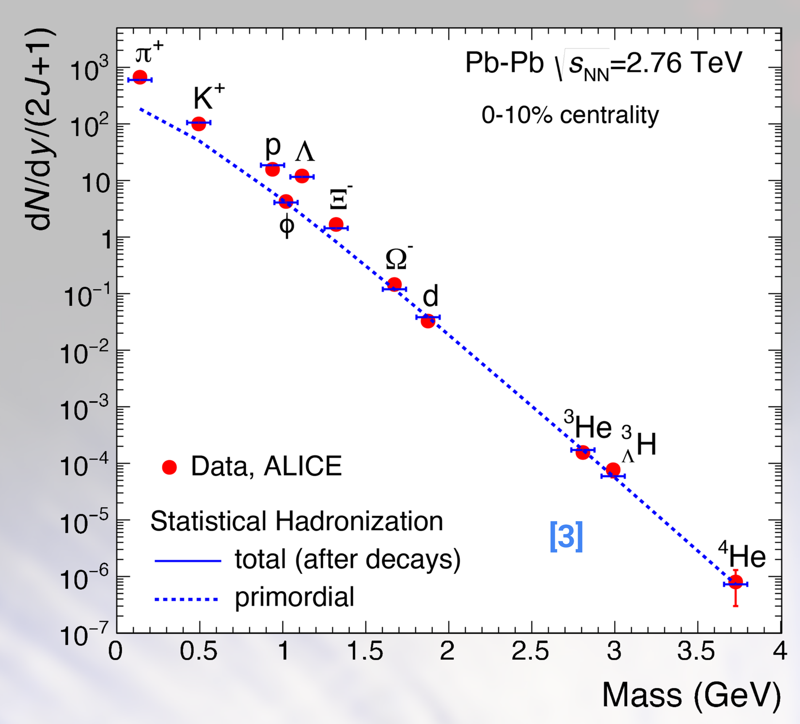
$$dN/dy \propto \exp(-m/T_{chem})$$

Light **(anti)nuclei abundance** is **not** strongly **affected** by resonance decays (**feed-down**). The SHM can be extended **from high-to-low multiplicity systems** via **canonical formulation**[4].

In this model, nuclei are produced at **the same temperature** with other light hadrons. Model parameters are **extracted from fit** to the experimental data.



Energy dependence of chemical freeze-out parameters T_{CF} and μ_B.

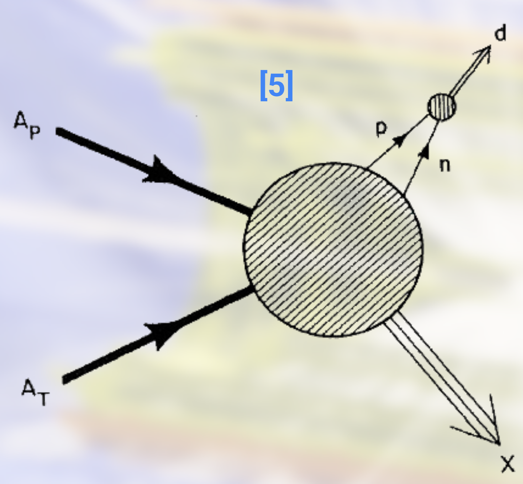


Mass dependence of hadron yields divided by the spin degeneracy factor (2J+1).

The Coalescence model

The nucleons produced close to each other in the phase space can bind and form an (anti)nucleus by means of final state interactions[5].

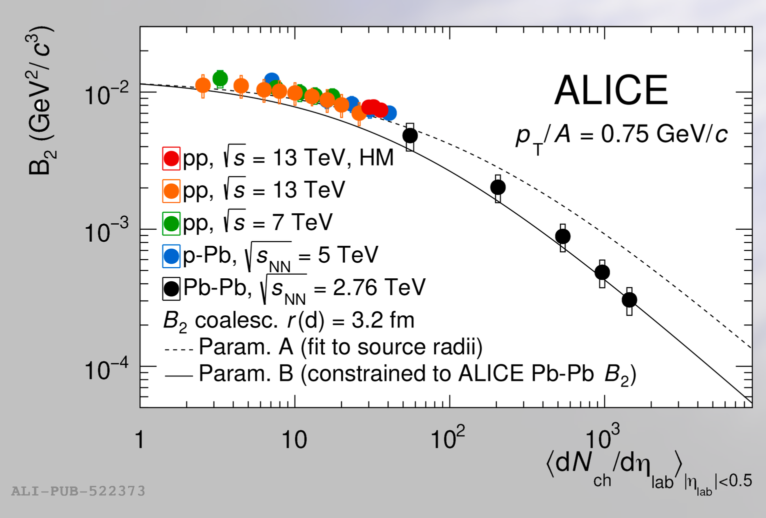
The formation probability is related to the **coalescence parameter B_A**, experimentally estimated as

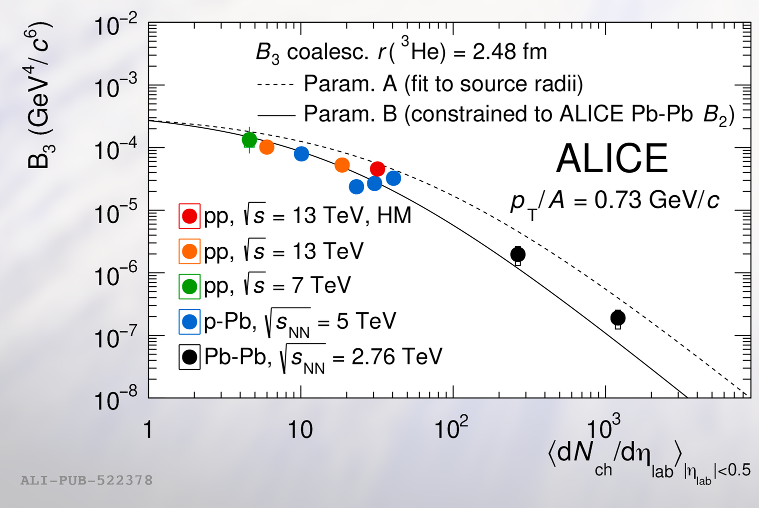


$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3}\right)^Z \Bigg|_{\vec{p}_p = \frac{\vec{p}_A}{A}} \left(E_n \frac{d^3N_n}{dp_n^3}\right)^N \Bigg|_{\vec{p}_n = \frac{\vec{p}_A}{A}}$$

NUCLEUS — NUCLEONS — PROTONS — NEUTRONS

The state-of-the-art coalescence model is based on the **Wigner-function approach:** the nucleons' **relative momentum and position** and the **nucleus wavefunction** are considered.





The dependence of **coalescence probability** on the final-state charged-particle multiplicity is related to the nucleons **source size** (pp < Pb-Pb).

e.g., High multiplicity (Pb-Pb) → significant drop is observed, effect of space separation in a large source (~2-5 fm radius)

Anti-helium-3 in pp at √s = 13.6 TeV

In the LHC Run 3, the **highest energy** ever was reached in pp collisions with the record of √s = 13.6 TeV.

This record energy gives the opportunities to study the production of A = 3 light anti-nuclei, **like anti-helium,** with an unprecedented statistical precision: a **fundamental input** to investigate coalescence models by extracting **B_3**, also providing important ingredient for the modelling of **cosmic anti-helium** formation.

The $^3\overline{\text{He}}$ analysis is performed using both the **ALICE TPC** and **TOF** subdetector.

The signal extraction is performed by preselecting the candidates based on the dE/dx measured in the TPC as a function of rigidity. Candidates are **preselected within 5σ** of the expected signal.

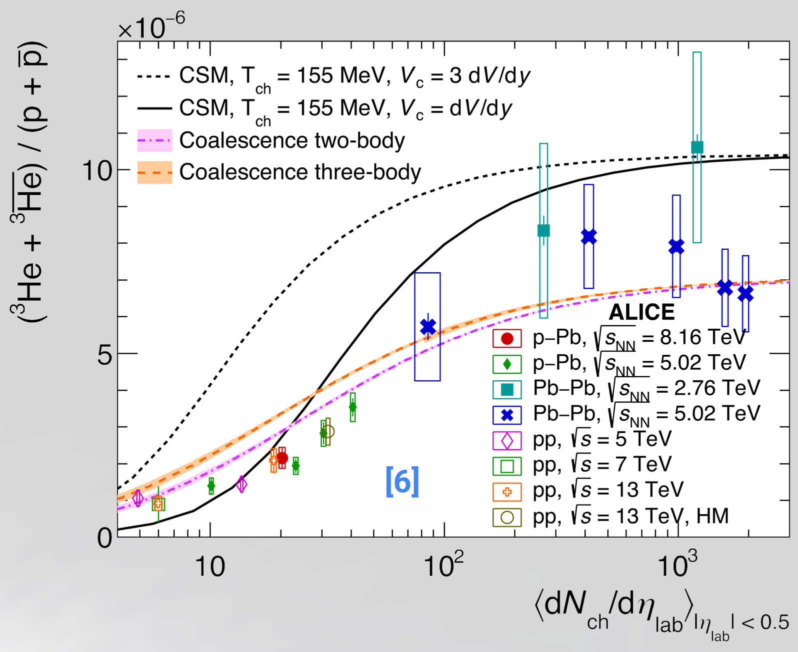
The signal extraction is then finalized **estimating the mass** of the candidates using the TOF detector to estimate the mass, as

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

Where ***p*** is the particle momentum, ***t*** is the measured time of flight and **L** is the track length.

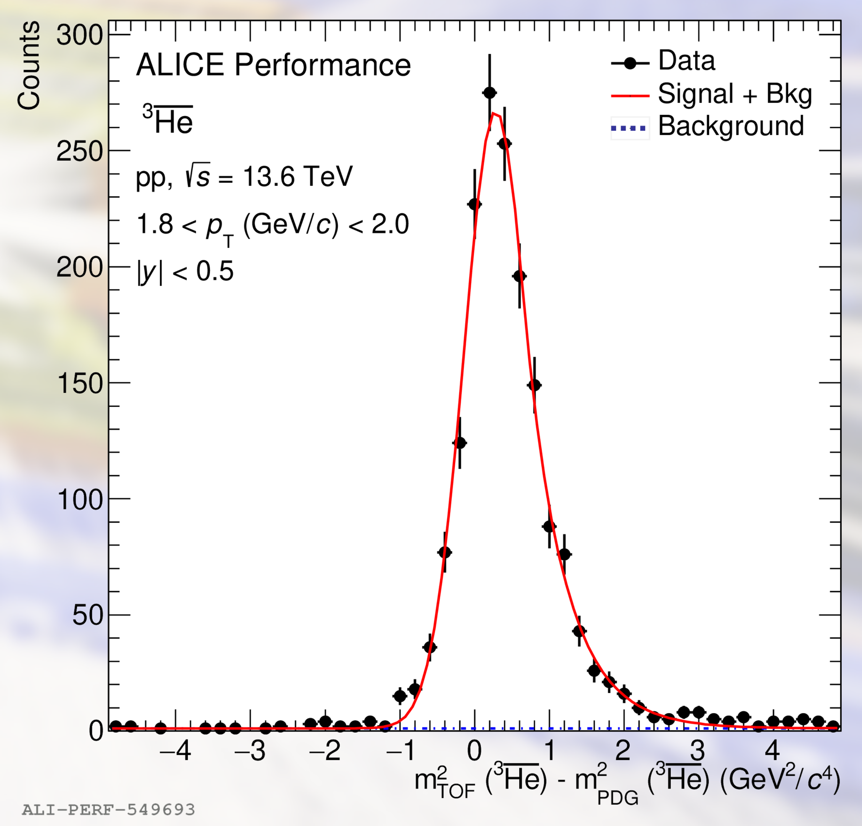
Nuclei over protons ratio

The yield ratio of **anti-helium over protons[6]** as a function of $\langle dN_{ch}/d\eta_{lab}\rangle$ in different colliding systems is sensitive to the production mechanism of light nuclei. For this reason, it is an excellent probe for the **nucleon source** properties.

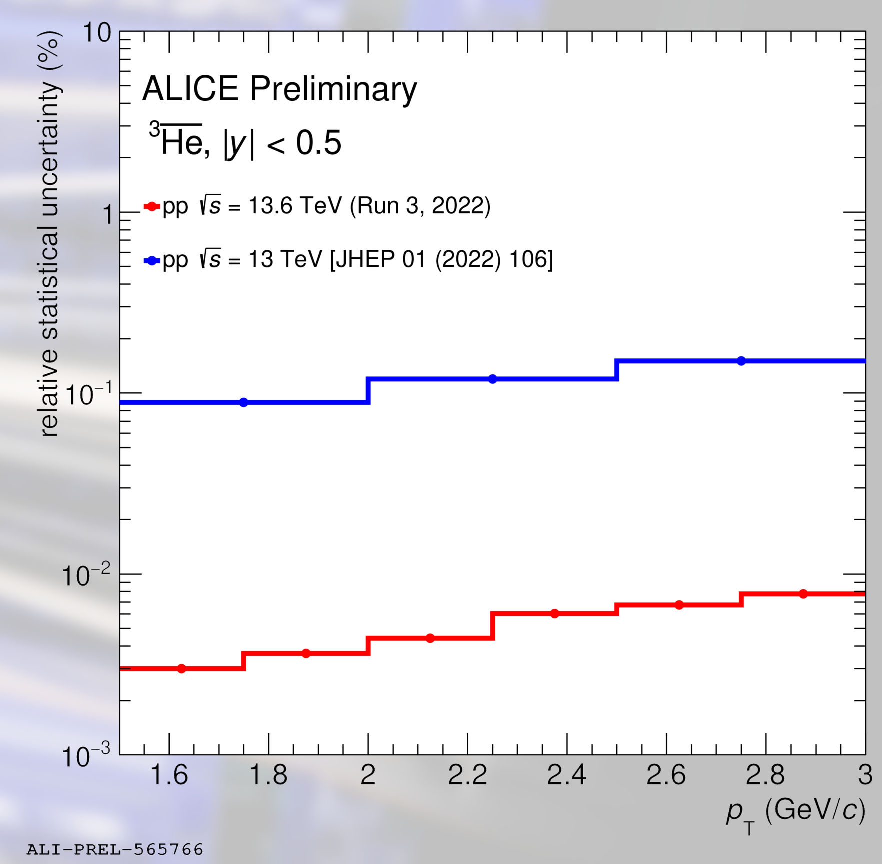


The ratio is **qualitatively described by coalescence** at low multiplicity.

Furthermore, **more precise measurements** are needed to investigate the tension between models **(Run 3)**.



The anti-helium signal is extracted for different ranges of p_T using the TOF. The difference between the squared masses is fitted with a function defined as the sum of an asymmetric gaussian function (in red) for the signal and a constant function (in blue) for the background.



Relative statistical error in anti-helium-3 produced in pp collisions in Run 2 vs Run 3 (2022 sample). In Run 3 statistical error is 10-50 times smaller.

References

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CosmicAntiNuclei