Coalescence in MC generators and implications for cosmic ray studies

Maximilian Horst[1], Chiara Pinto[1], Laura Fabbietti[1], Bhawani Singh[1], Luca Barioglio[2], Francesca Bellini[3], Sushanta Tripathy[3]

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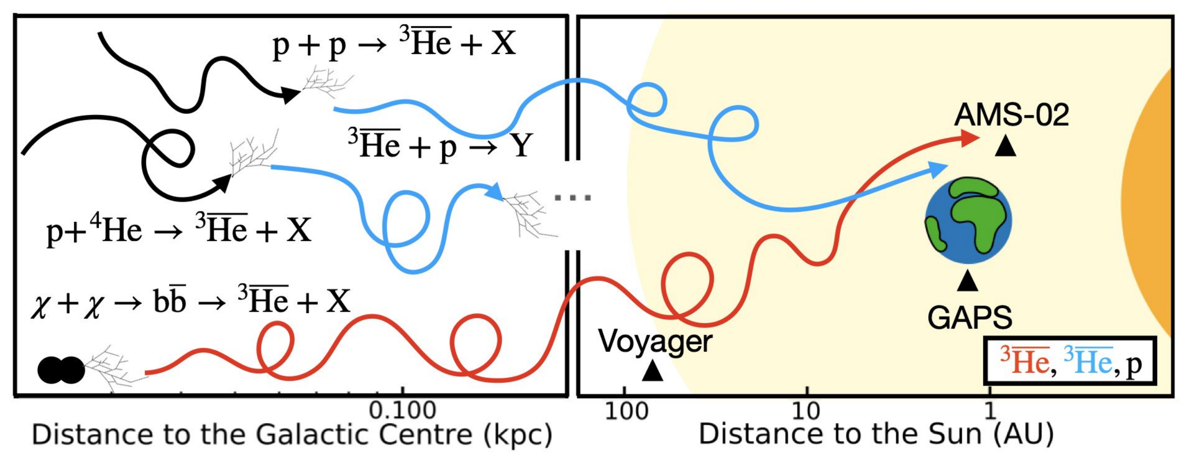
[3] INFN and University Bologna

Cosmic Rays
Antinuclei in cosmic rays



Antinuclei production:

- ➤ pp, p–A and (few) A–A reactions between primary **cosmic rays** and the interstellar medium
- ➤ **dark-matter** annihilation processes

ALICE Collab., Nature Phys. (2022)

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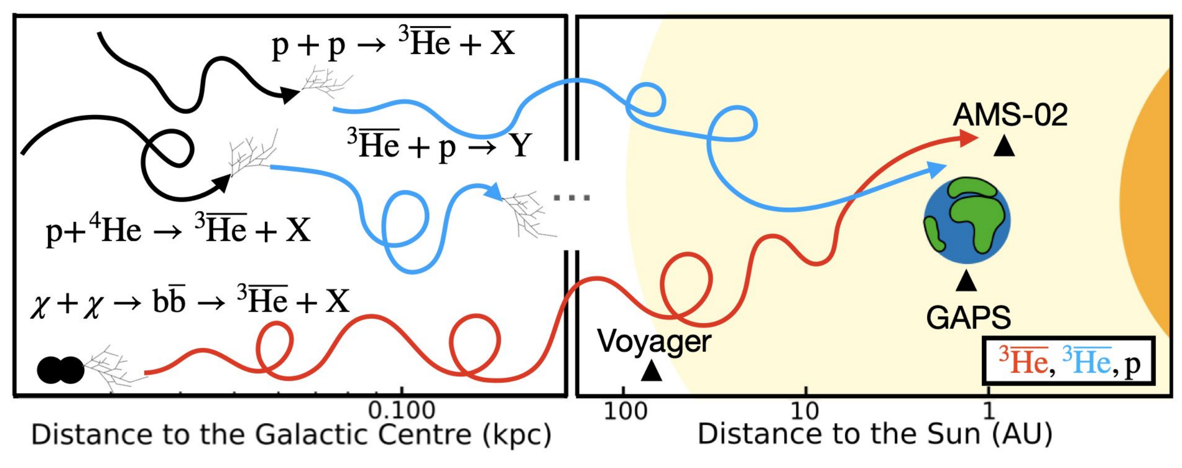

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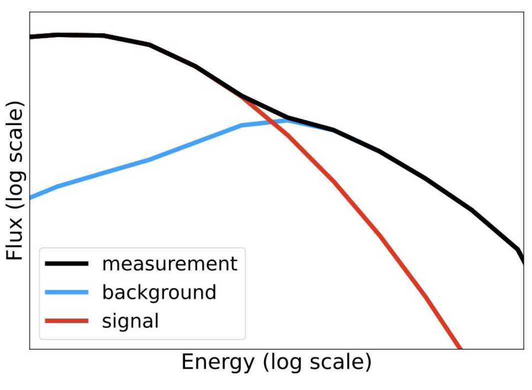
antinuclei cosmic ray flux



ALICE Collab., Nature Phys. (2022)

- ➤ To correctly interpret any future measurement of antinuclear fluxes (only antip measured so far)
- ➤ Need to determine exact primary and secondary fluxes → precise knowledge of antinuclei production, propagation and annihilation is needed
- ➤ High Signal/Noise ratio (~10^2-10^4) at low E_{kin} expected by models

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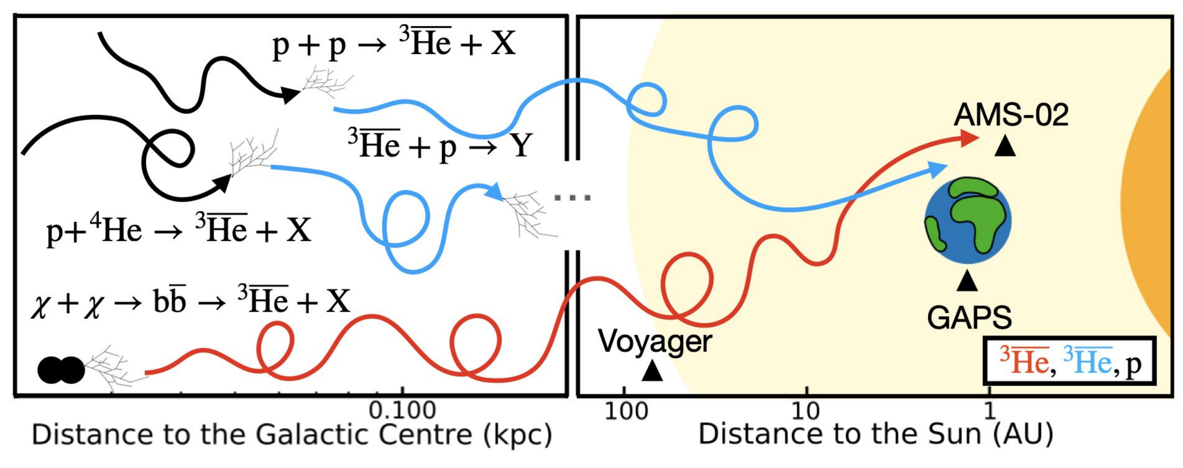

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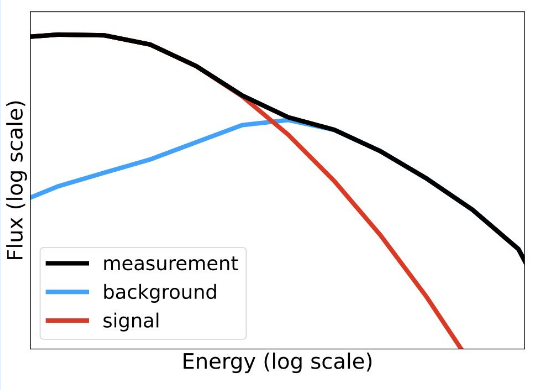

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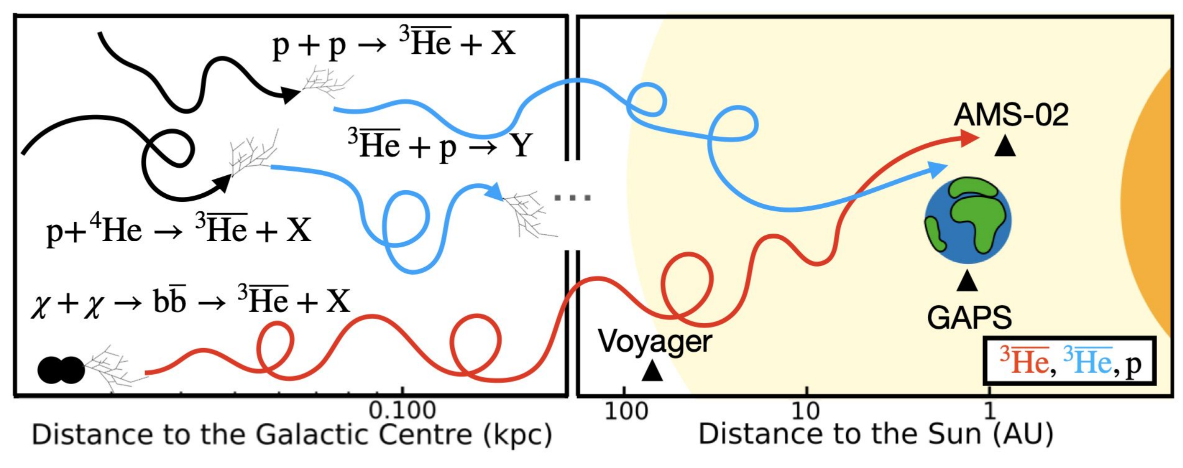

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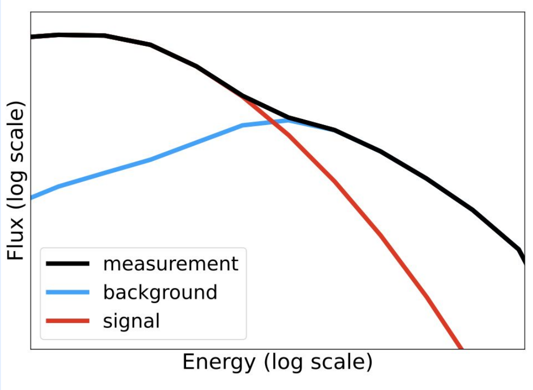

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See S. Königstorfer talk (Tue. 12 am)

Cosmic Rays

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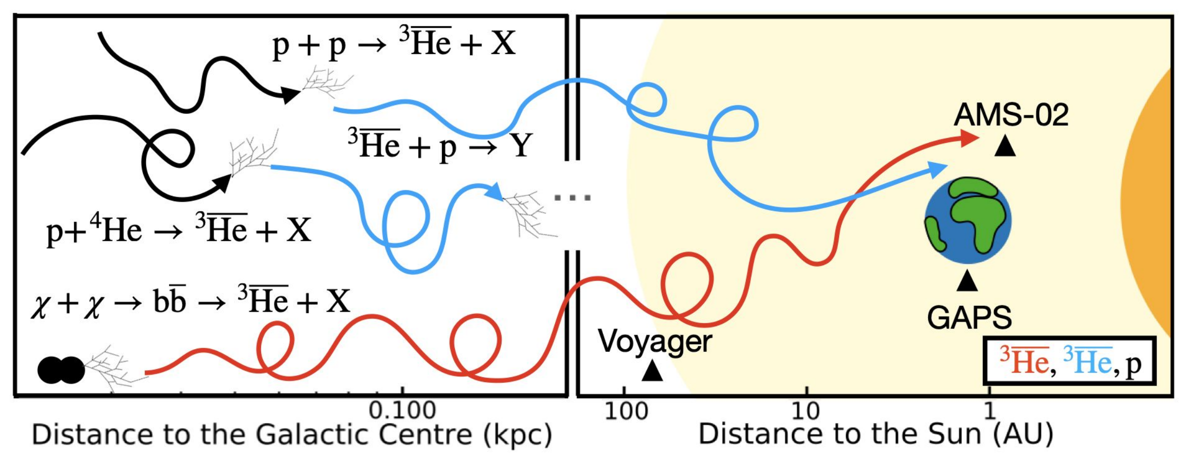

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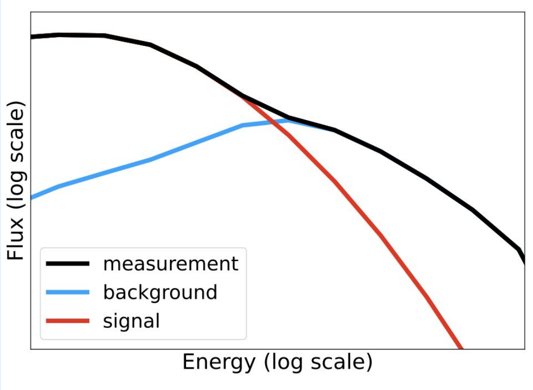

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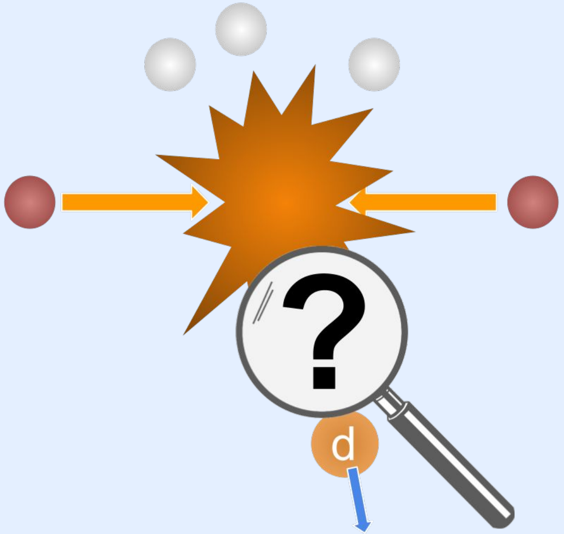
Modelling (anti)nuclei production

Overview of production models

(Anti)nuclear production described by two models:



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Statistical hadronization (SHM)

- ➤ Particle yields (including nuclei) described by filling the available phase-space after the collision
- ➤ Works very well with a common temperature of the medium (T=154 MeV)
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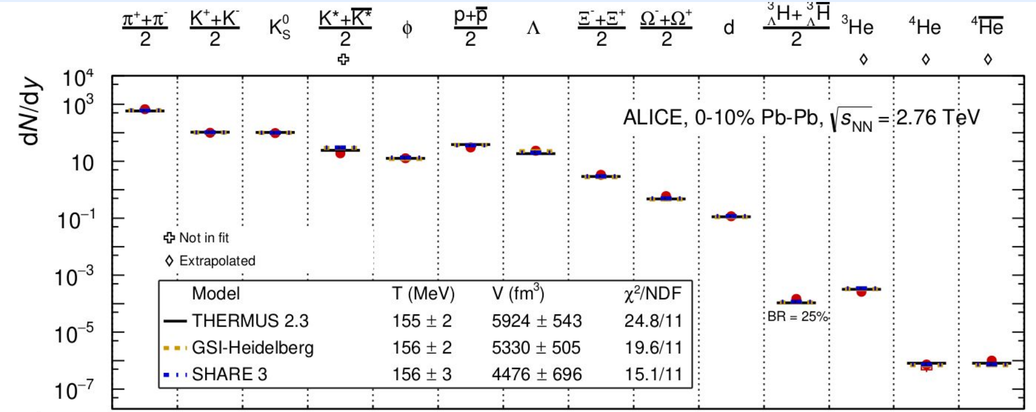

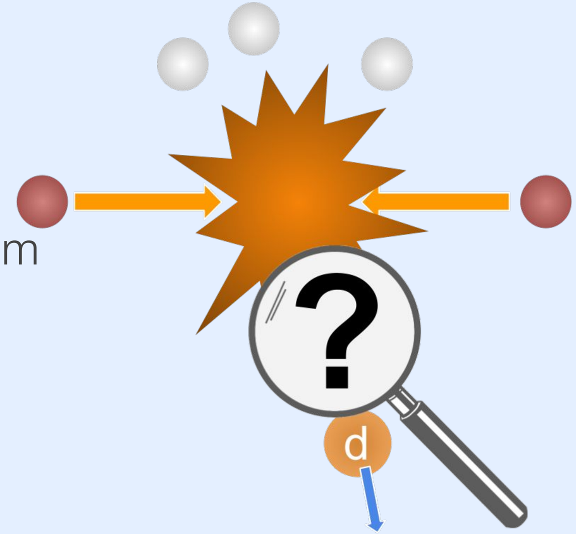

Andronic et al., Nature 561 (2018) 321–330

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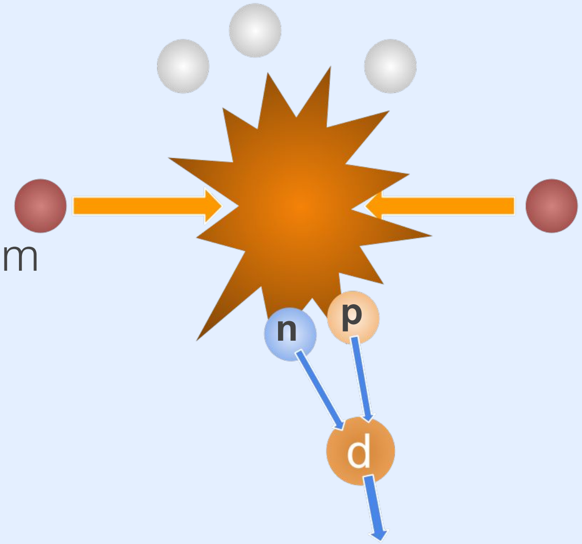
Coalescence model

- Nucleons bind after chemical freeze-out if they are close in phase-space



Butler et al., Phys. Rev. 129 (1963) 836

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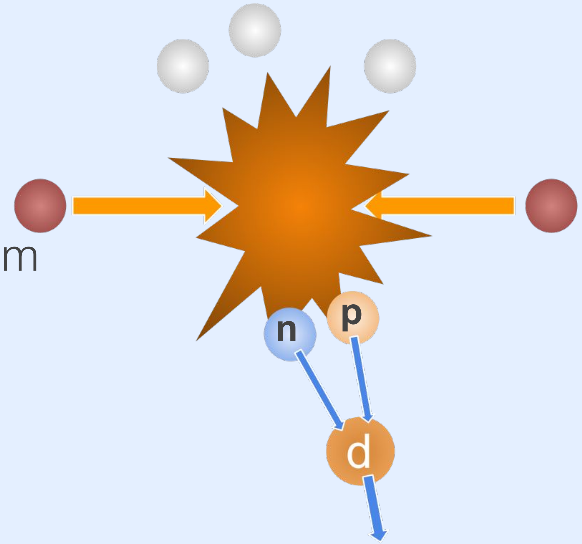
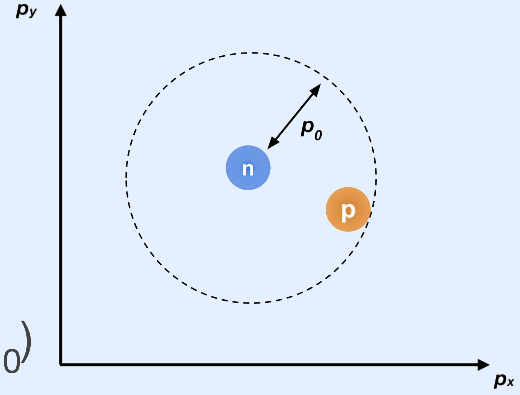


Coalescence model

- ➤ Nucleons bind after chemical freeze-out if they are close in phase-space
- ➤ Common implementation: Spherical Approximation ($\Delta p < p_0$)



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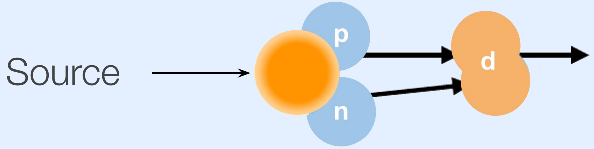
The coalescence model

Wigner function formalism

What do we need for coalescence?



p,n-pair deuteron

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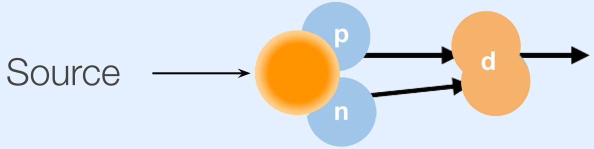

p,n-pair   deuteron

Quantum mechanics: $d^3N/dP^3 = \mathrm{Tr}(\rho_d \rho_{Nucl})$

Kachelriess et al. EPJA 57 (5) 167, 2021

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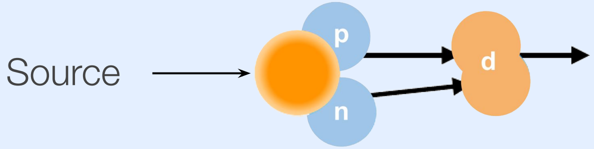

$q = (p_p - p_n)/2$

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$d^3N/dP^3 = \int d^3q \int d^3r_p \int d^3r_n$ *Deuteron Density* *Nucleon Density*

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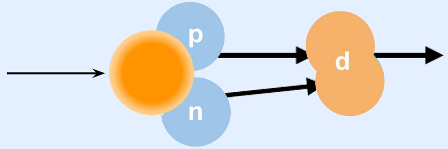

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$d^3N/dP^3 = S \int d^3q \int d^3r_p \int d^3r_n\, W(q,r)\ \ W_{pn}(p_p,p_n,r_p,r_n)/(2\pi)^6$

Spin-Isospin statistics factor (=⅜ for deuterons)

Wigner function of deuteron

Wigner function of p-n state

Kachelriess et al. EPJA 57 (5) 167, 2021

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Two-nucleon Wigner function

$$W_{np}(\vec{P}/2+\vec{q},\vec{P}/2-\vec{q},r_n,r_p) = H_{np}(\vec{r}_n,\vec{r}_p)G_{np}(\vec{P}/2+\vec{q},\vec{P}/2-\vec{q})$$

- G_{np} is the momentum distribution of nucleons
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Nucleon momentum phase-space

with

deuteron size (3.2 fm)

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Two-particle emitting source size

Kachelriess et al. EPJA 57 (5) 167, 2021

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previous similar approaches*
neglected ±q
→ we use event generators!

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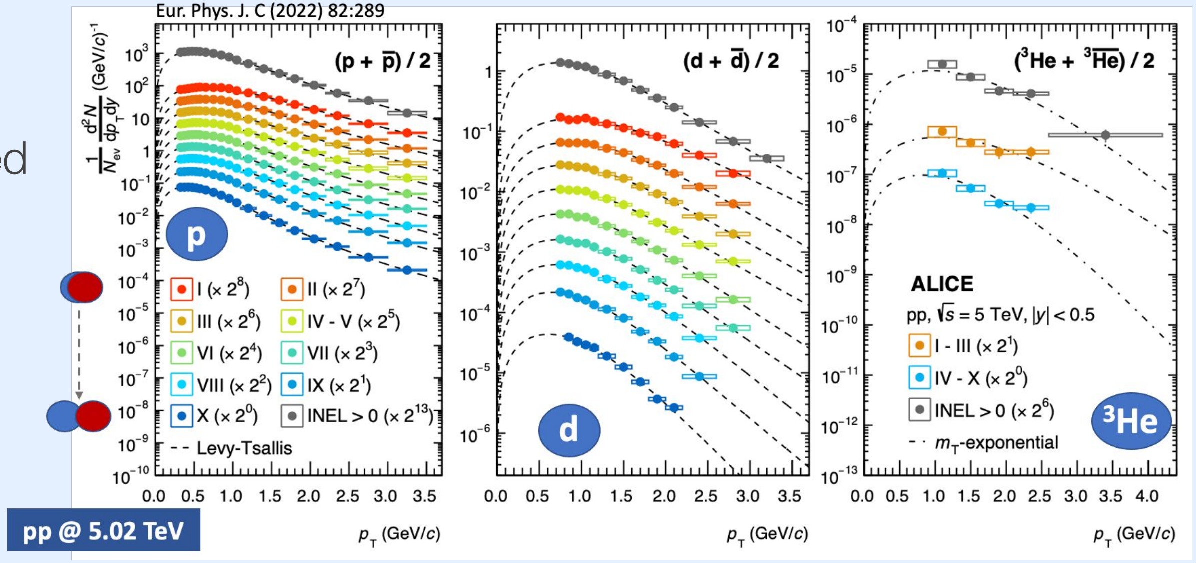
Light (anti)nuclei measured in ALICE

Transverse momentum spectra

- Comprehensive measurements of light (anti)nuclei have been carried out in ALICE, from pp…

- From (anti)deuterons to (anti)^{3}He



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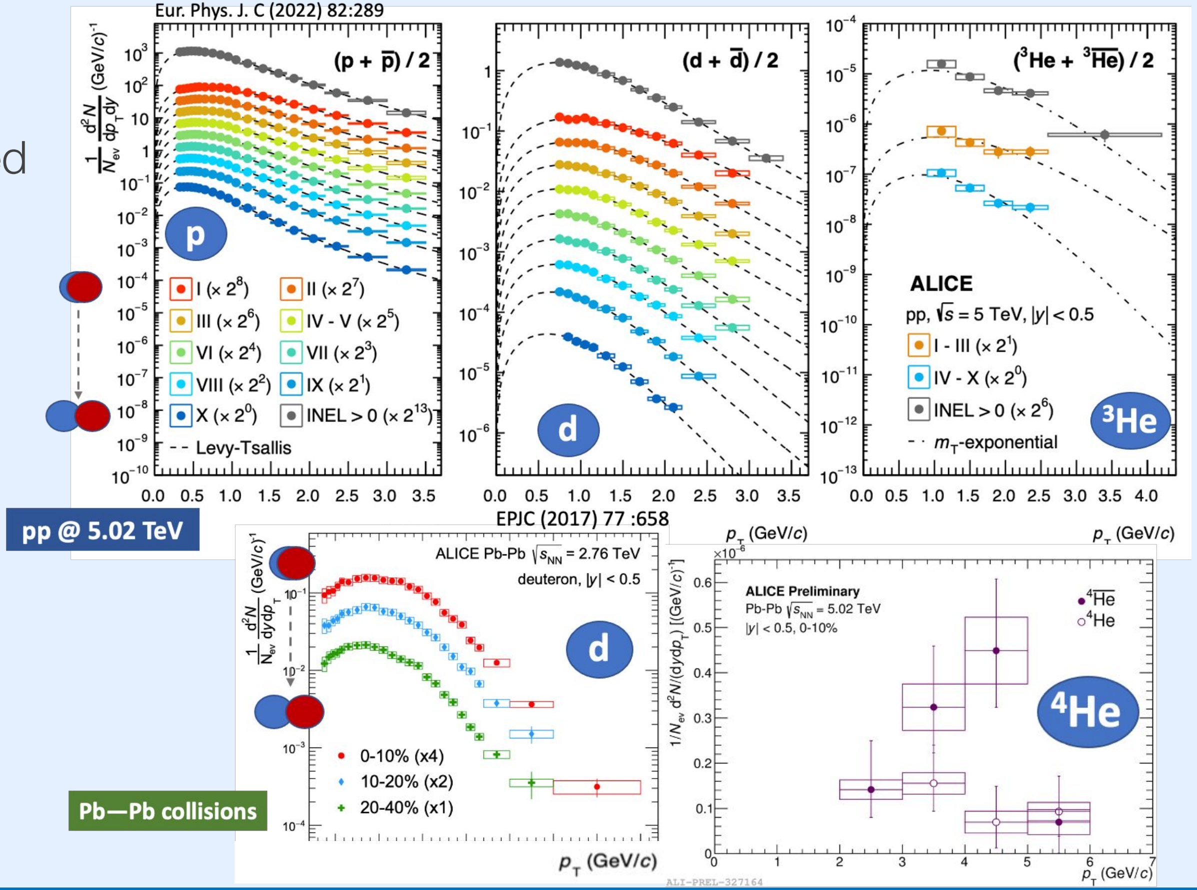

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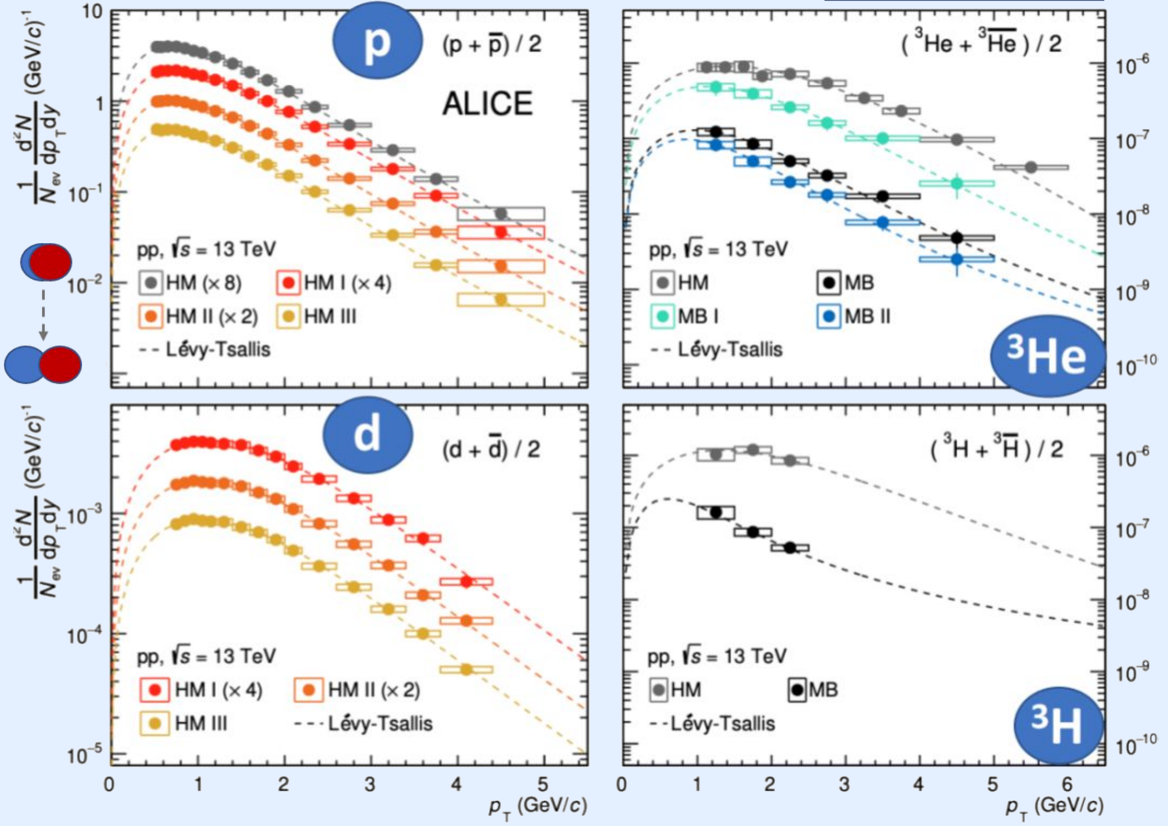
HM pp @ 13 TeV

- Comprehensive measurements of light (anti)nuclei have been carried out in ALICE, from pp to Pb–Pb
- From (anti)deuterons to (anti)^{3}He and (anti)^{4}He
- **High multiplicity** (HM) class in **pp collisions at 13 TeV** (→ 0-0.17% centrality class)
- In HM class both production spectra and emitting source size measurements available

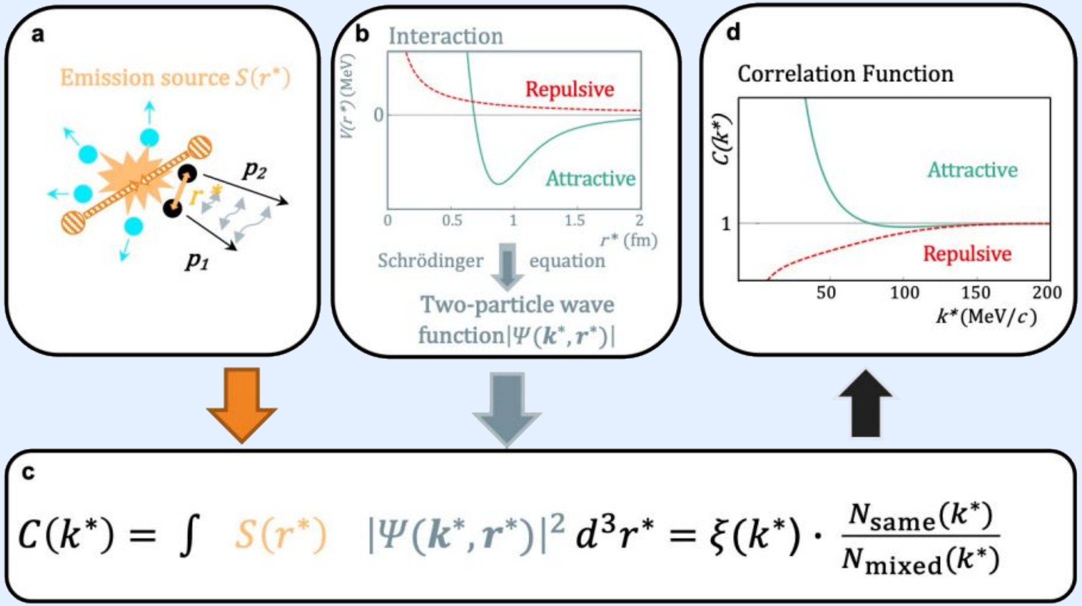


ALICE Coll., JHEP 01 (2022) 106

Emission source size measured in ALICE

Femtoscopy

- ALICE is pioneering the study of the strong interaction using femtoscopic correlations
- Momentum correlations can be employed to explore two-particle dynamics
- The **correlation function** depends on two ingredients:
  - Emission source function
  - Two-particle wave function (quantum statistics + Coulomb + strong interaction)



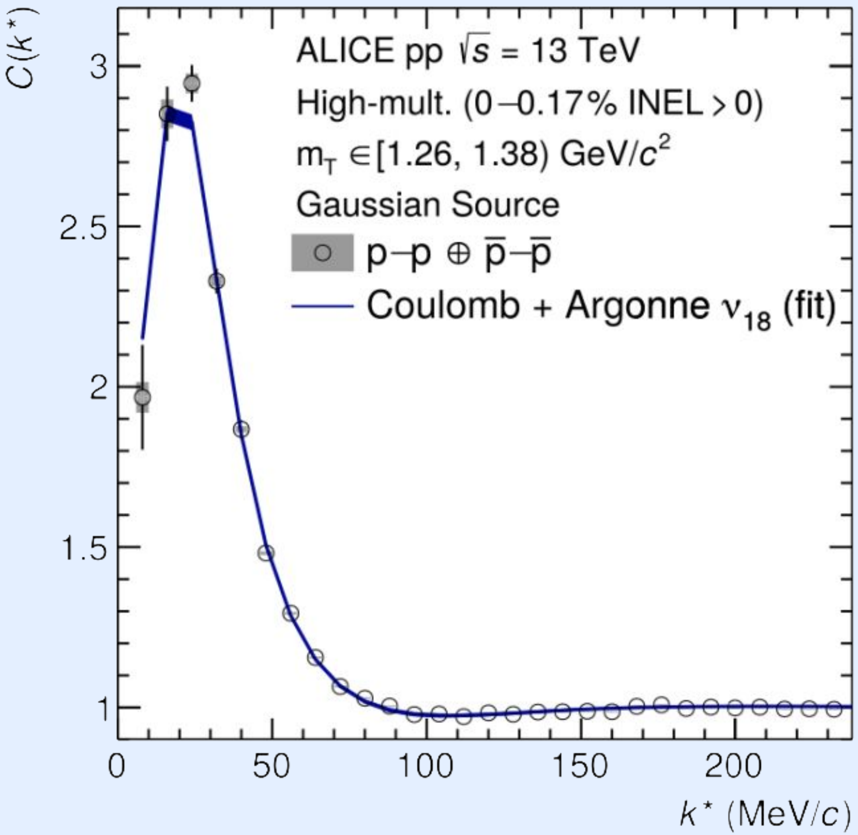
If we measure C(k*) and use a known interaction (e.g. nucleon-nucleon) we can study the emission source

ALICE Coll., Nature 588 (2020) 232-238

Emission source size measured in ALICE

Femtoscopy

- ➤ Good description of the interaction with Fermi-Dirac statistics, Coulomb and strong interaction (using v18)
- ➤ Only free parameter: the source size



ALICE Coll., PLB 811 (2020) 135849

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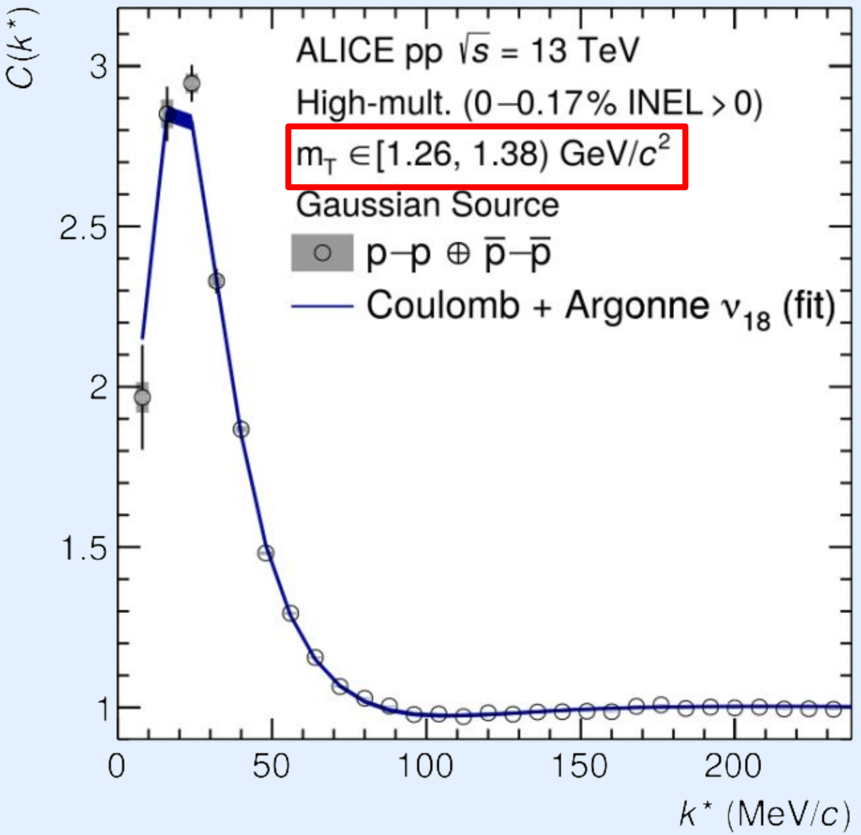

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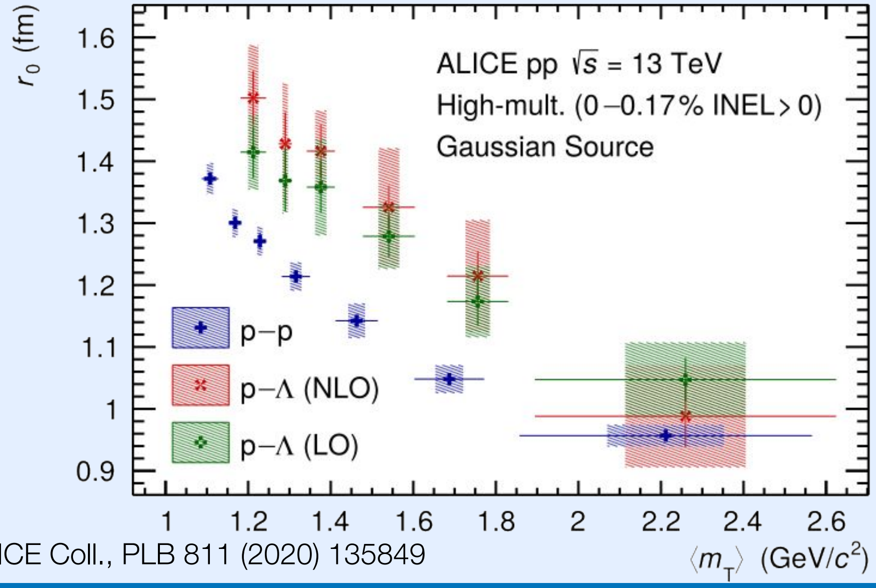

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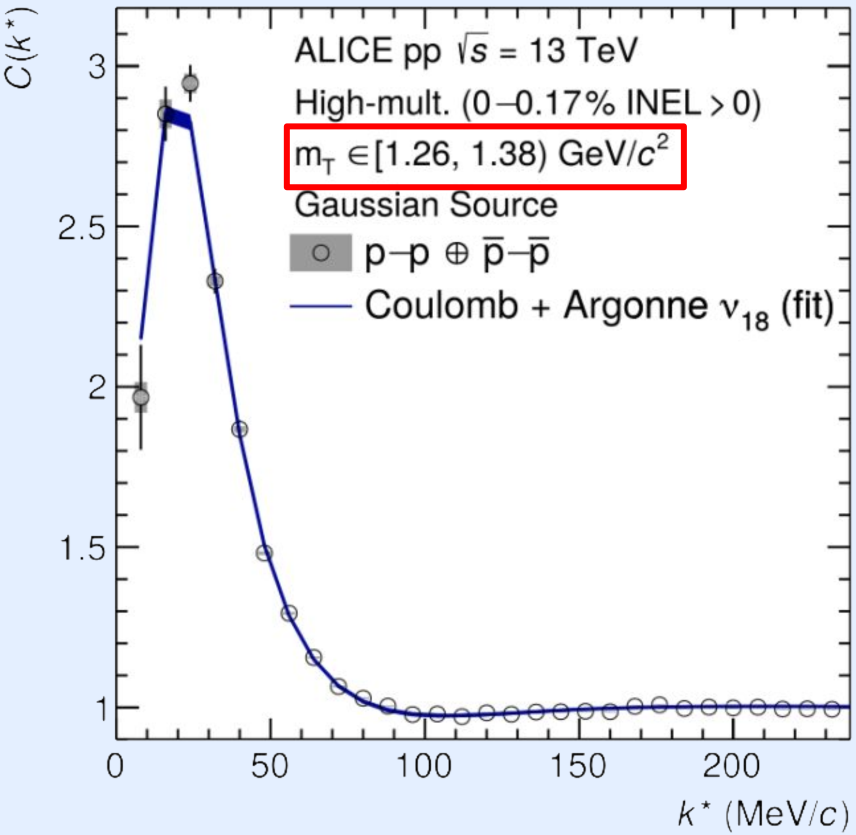

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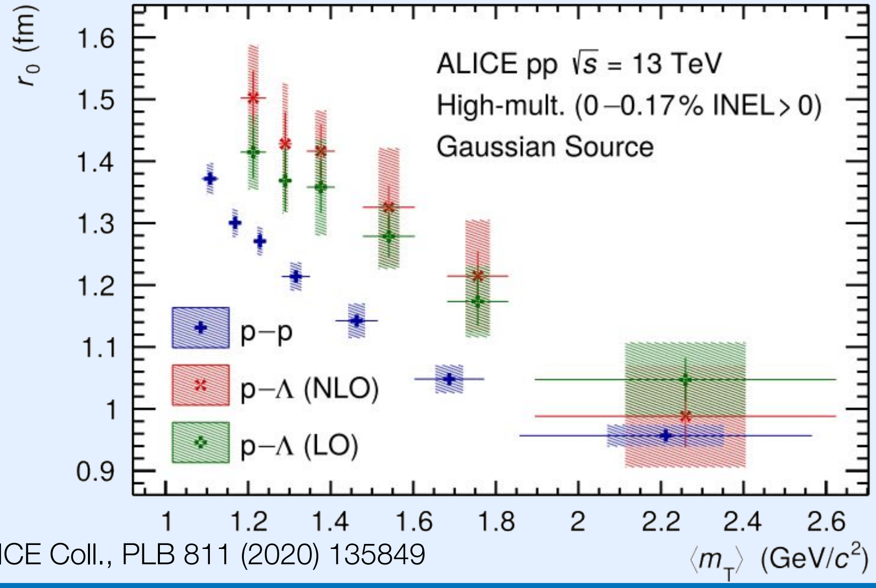

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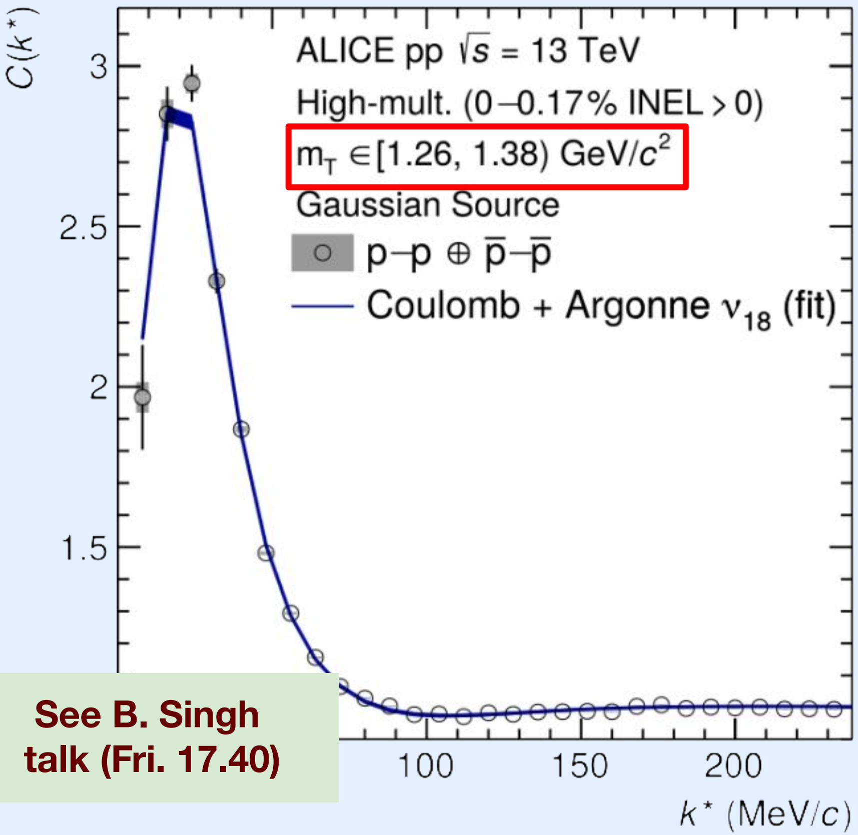

See B. Singh talk (Fri. 17.40)

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Wigner function formalism

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Constrained from data!

Kachelriess et al. EPJA 57 (5) 167, 2021
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The coalescence model

Wigner function formalism, tuned to ALICE measurements

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- More in general:

$$p(\sigma, q) = \int d^3r_p d^3r_n h(r_n)h(r_p)W(q,r)$$

- This allows us to calculate the coalescence probability for arbitrary Wigner functions

⇨ Probe different hypotheses for the deuteron wave function

$$W(\vec{q},\vec{r}) = \int d^3\zeta\ \Psi(\vec{r}+\vec{\zeta}/2)\Psi^*(\vec{r}-\vec{\zeta}/2)e^{i\vec{q}\vec{\zeta}}$$

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to take into account pn space-momentum correlations → we use event generators!

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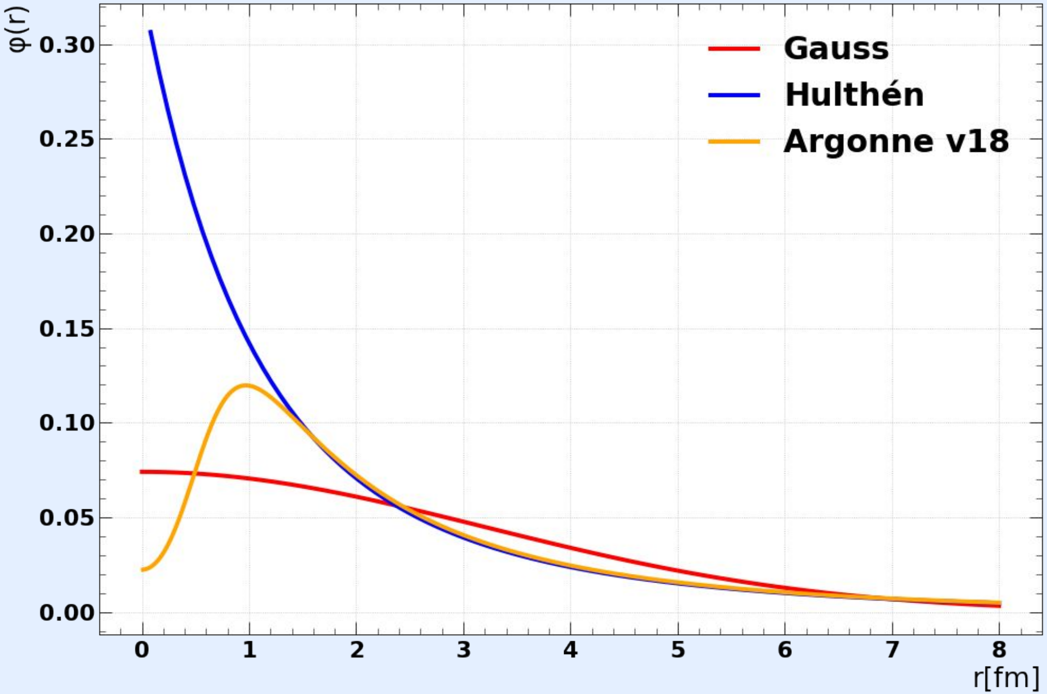
State of the art coalescence predictions

Wigner function formalism → wave functions

There are multiple models for the deuteron wave function

- ➤ Simplistic:
  Single Gaussian
- ➤ From *pion field theory* (Yukawa-like potential) (‘50s)*:
  Hulthén
- ➤ From pn scattering measurements**:
  Argonne ν_{18}

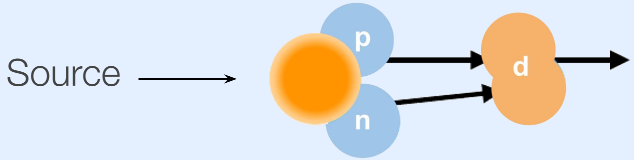


*Scheibl et al., PRC 59 (1999) 1585-1602
**Wiringa et al., PRC 51 (1995) 38-51

State of the art coalescence predictions

Wigner function formalism tuned to ALICE measurements

- Event-by-event coalescence afterburner with Wigner function formalism
- EPOS 3 as event generator



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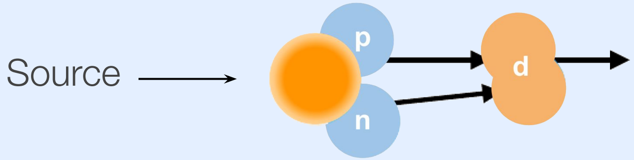
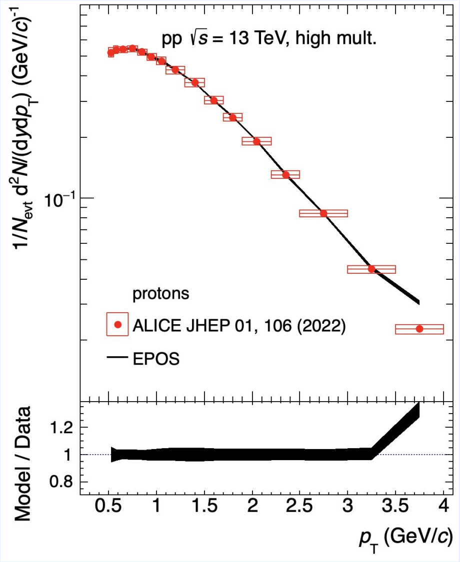


Ingredients 🧑‍🍳

- ➤ Protons (and neutrons) are tuned to p measurements from ALICE



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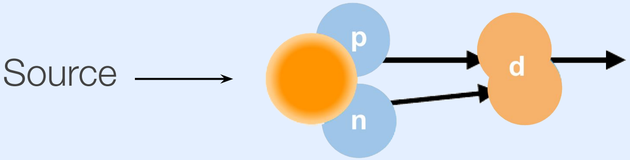
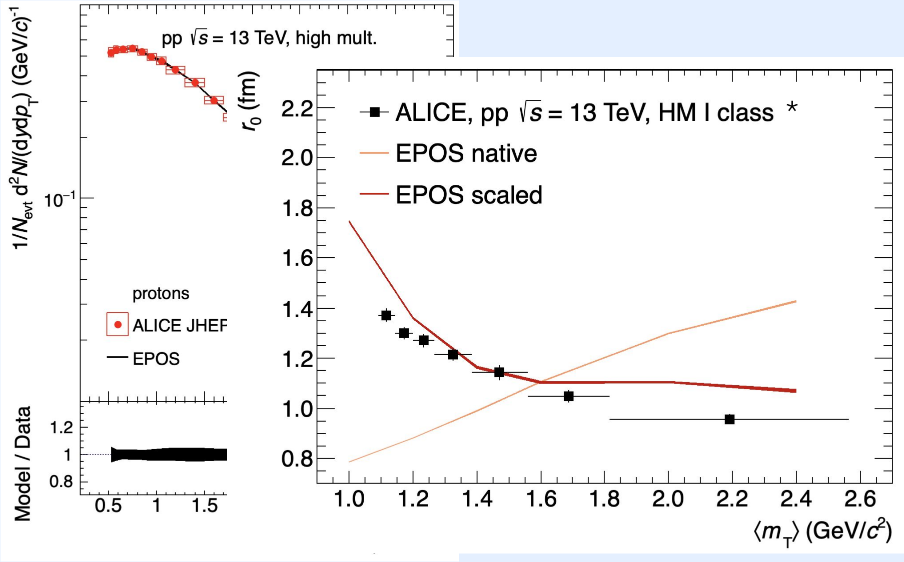


Ingredients 🧑‍🍳

- Protons (and neutrons) are tuned to p measurements from ALICE
- Event generator is tuned to measurements
  - source size
  - resonance cocktail
  - charged-particle multiplicity (35.8±0.5)



*ALICE Coll., PLB 811(2020) 135849

State of the art coalescence predictions

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- ➤ Event-by-event coalescence afterburner with Wigner function formalism
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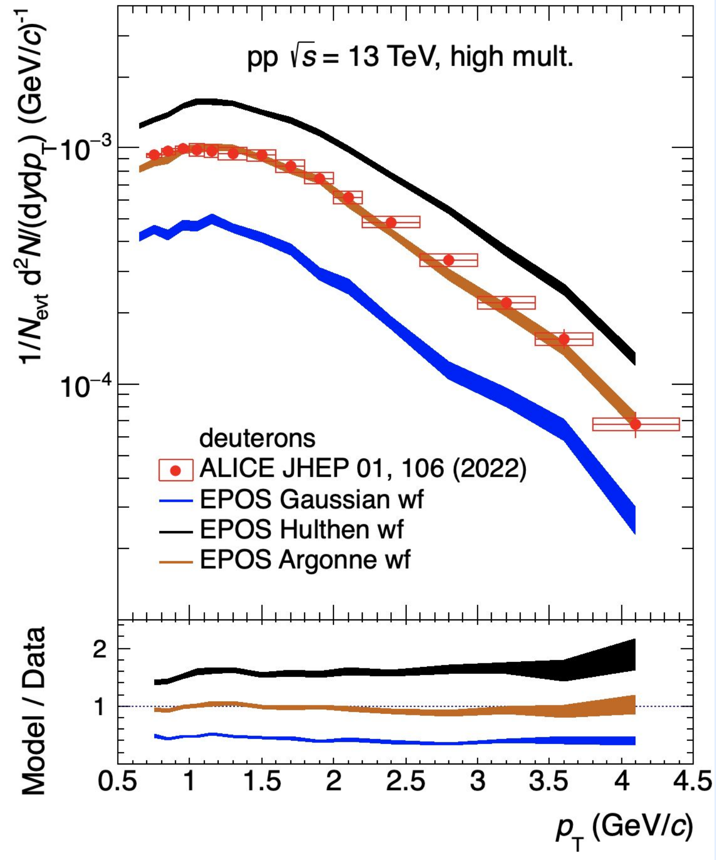
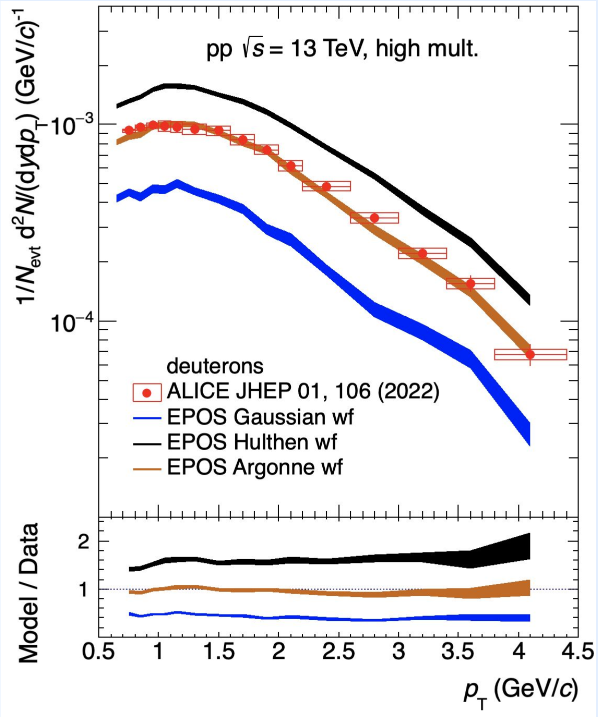
Ingredients 🧑‍🍳

- ➤ Protons (and neutrons) are tuned to p measurements from ALICE
- ➤ Event generator is tuned to measurements
  - ➢ source size
  - ➢ resonance cocktail
  - ➢ charged-particle multiplicity (35.8±0.5)
- ➤ Compare to measurements by ALICE
- ➤ Argonne WF shows the best agreement with measurements



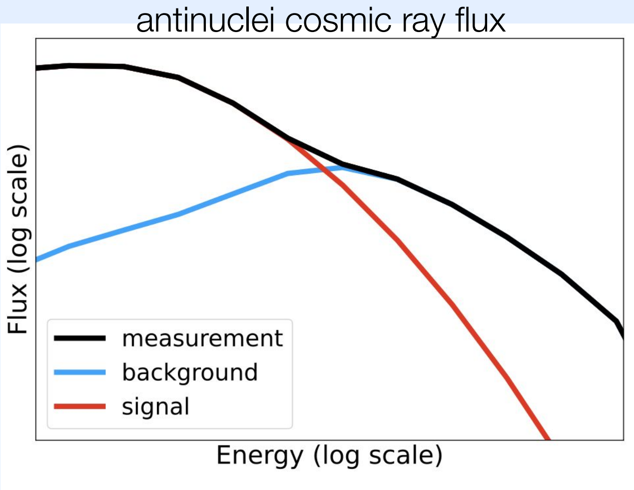
Summary

- Novel approach for coalescence based on Wigner function formalism is developed
- Deuteron production in high multiplicity pp collisions $\sqrt{s}$ = 13 TeV
- *If* we have control of the underlying physics
  - emission source size
  - (anti)nucleon momentum distributions
  - resonance cocktail
  - charged-particle multiplicity
  - realistic nucleus wavefunction



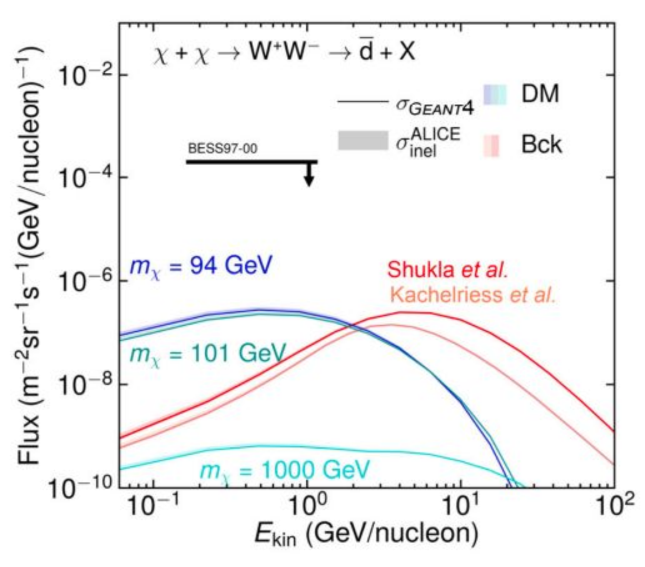
- Model successfully reproduces data with no free-parameters!

Conclusions



➤ Modelling antinuclei production is an essential backbone to interpret any future measurement of cosmic ray antinuclear fluxes

Conclusions



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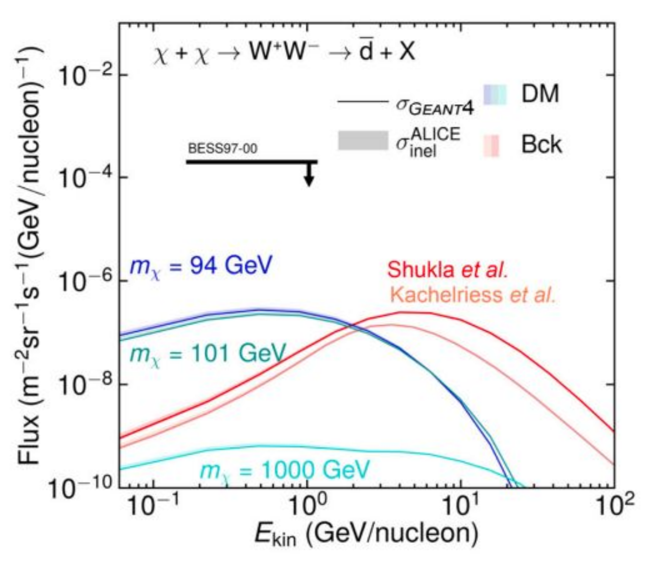
Conclusions



- ➤ Modelling antinuclei production is an essential backbone to interpret any future measurement of cosmic ray antinuclear fluxes
- ➤ Antideuteron production predominantly from collisions of protons of E_{kin}~200-500 GeV ($\sqrt{s}$ ~ 19-30 GeV for p-H)

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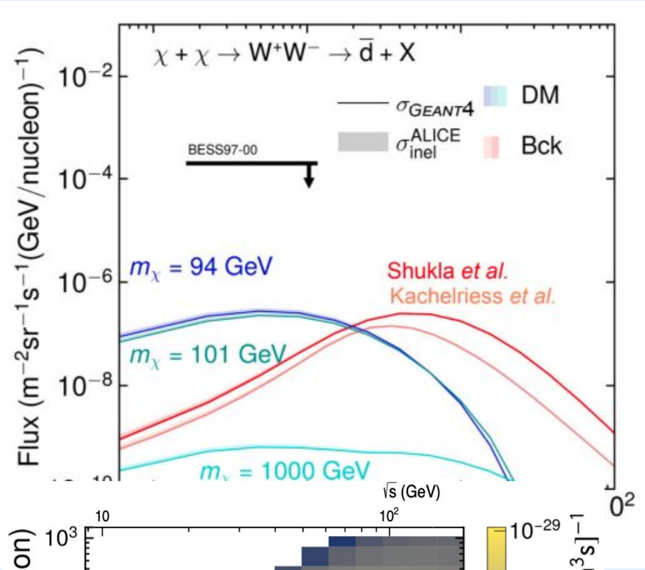

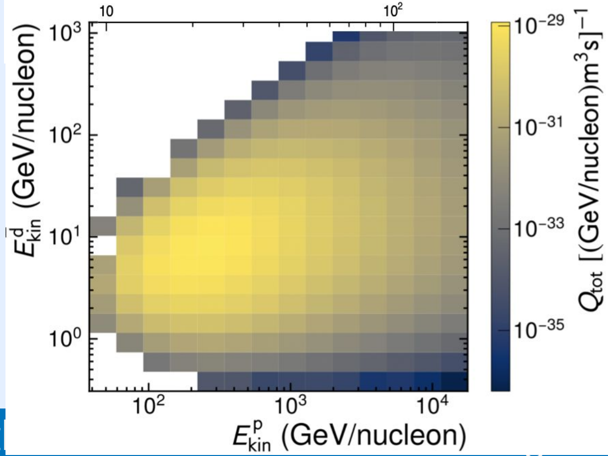

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Antideuteron source function as a function of kinetic energy of the incoming proton and produced antideuteron

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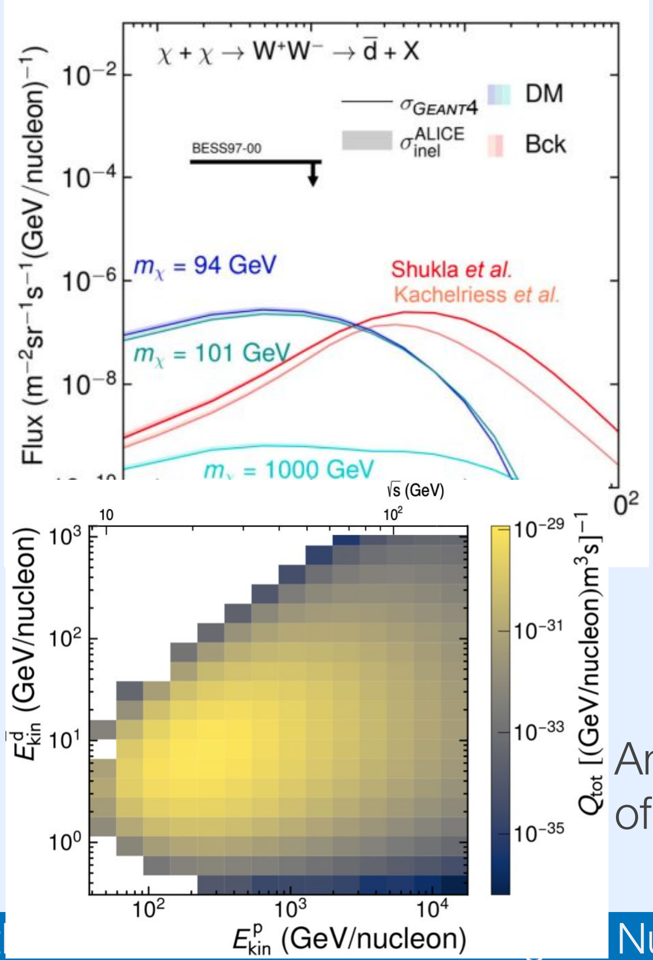
Conclusions



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Antideuteron source function as a function of kinetic energy of the incoming proton and produced antideuteron

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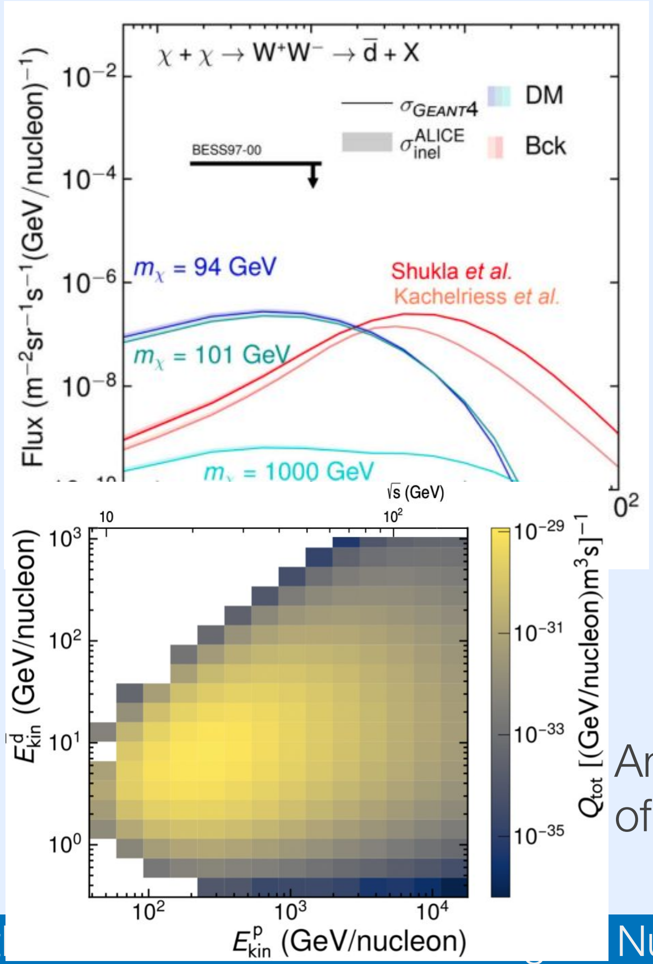
Conclusions

- Modelling antinuclei production is an essential backbone to interpret any future measurement of cosmic ray antinuclear fluxes
- Antideuteron production predominantly from collisions of protons of E_{kin}~200-500 GeV ($\sqrt{s}$ ~ 19-30 GeV for p-H)
- Modelling production of antideuterons for HM pp collisions at 13 TeV is only the first piece of a much more complicated puzzle
- Extrapolation in the energy range of interest
- More experimental data at lower energies needed!



Antideuteron source function as a function of kinetic energy of the incoming proton and produced antideuteron

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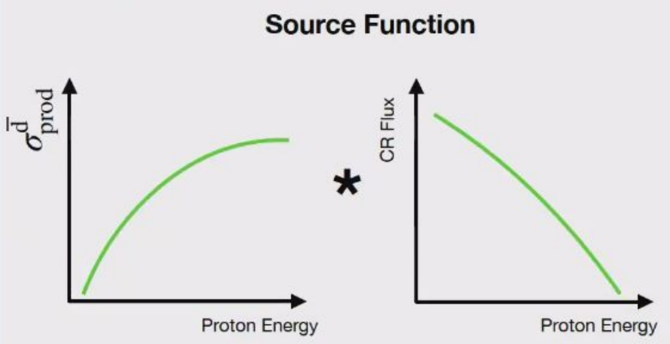
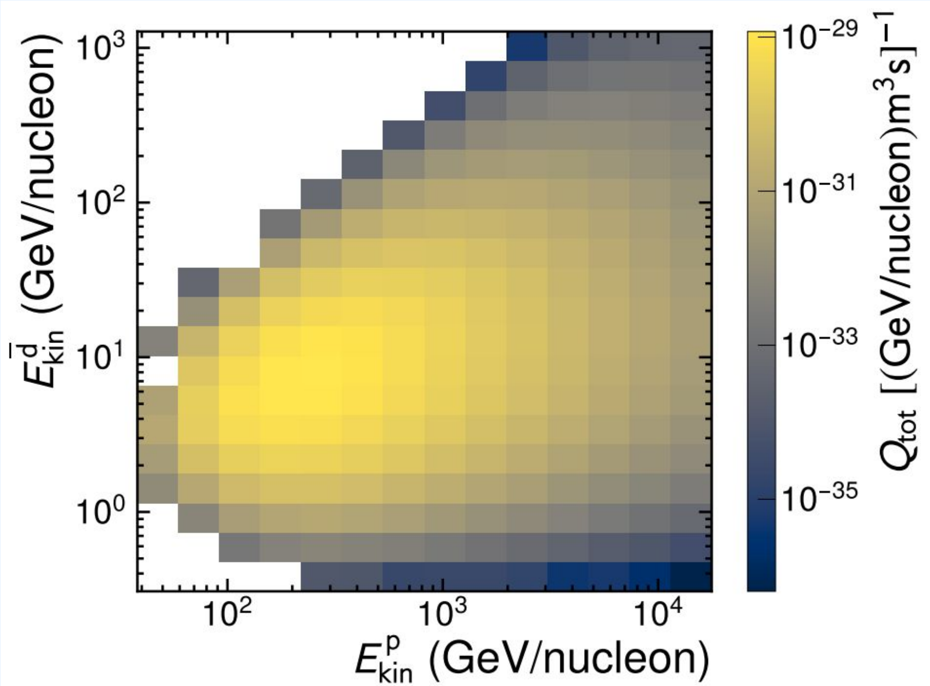
Backup slides

Cosmic Rays

Production energy of antinuclei

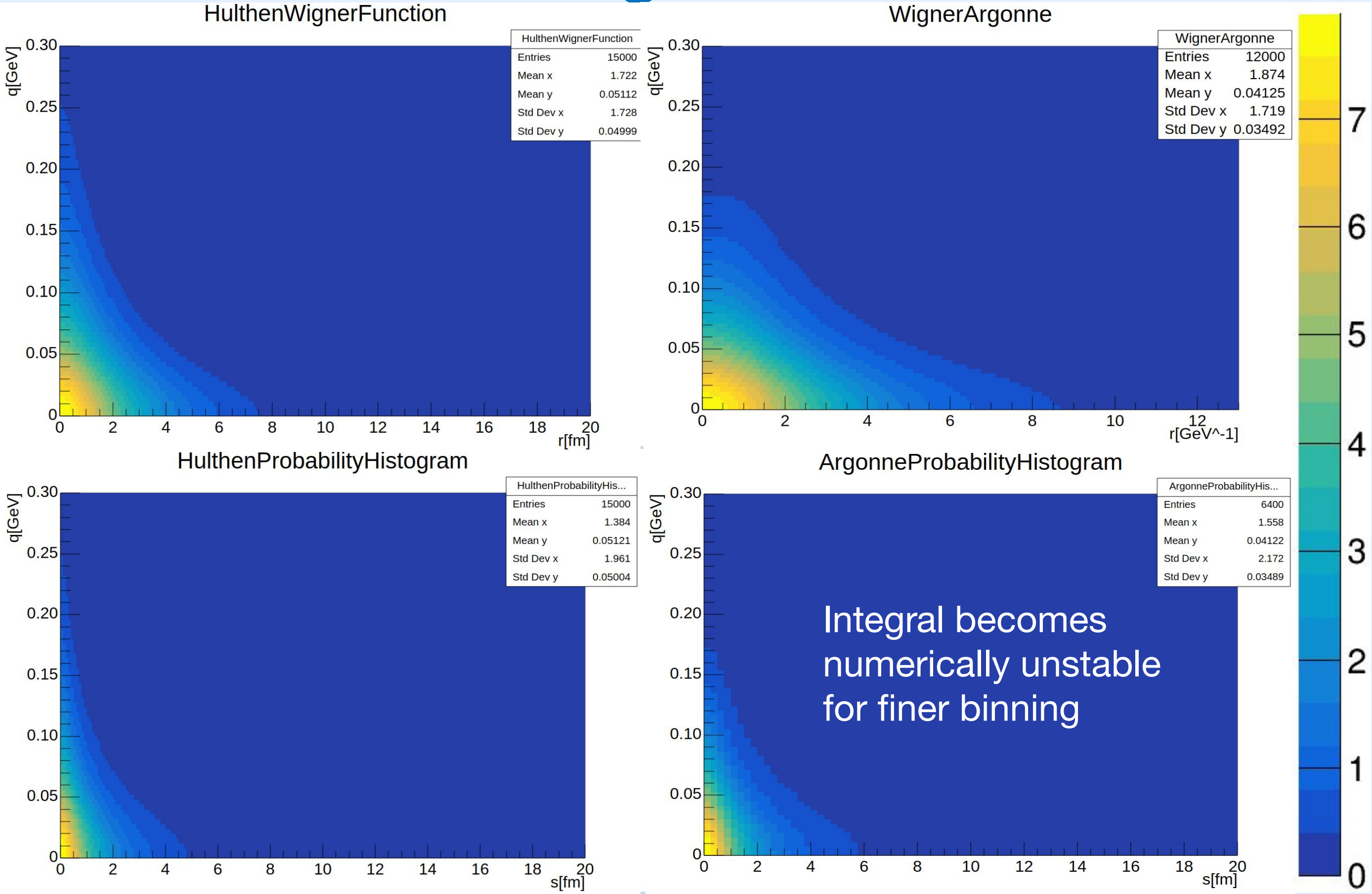
- Antideuteron source function as a function of kinetic energy of the incoming proton and produced antideuteron
- Antideuteron production predominantly for protons of E_{kin}~200-500 GeV ($\sqrt{s}$ ~ 19-30 GeV for p-H)





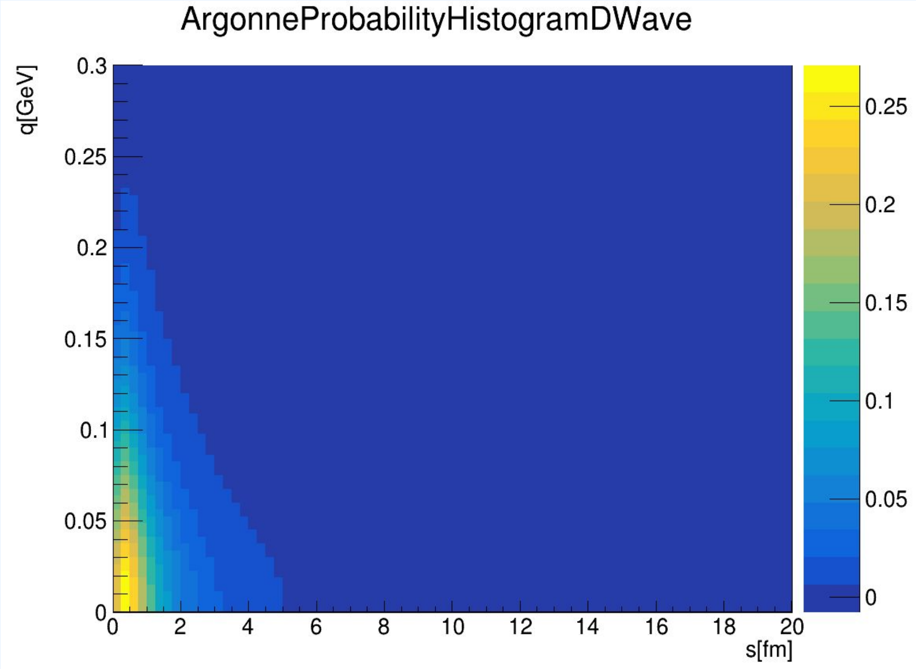
Šerkšnytė, et al. PHYSICAL REVIEW D 105, 083021 (2022)

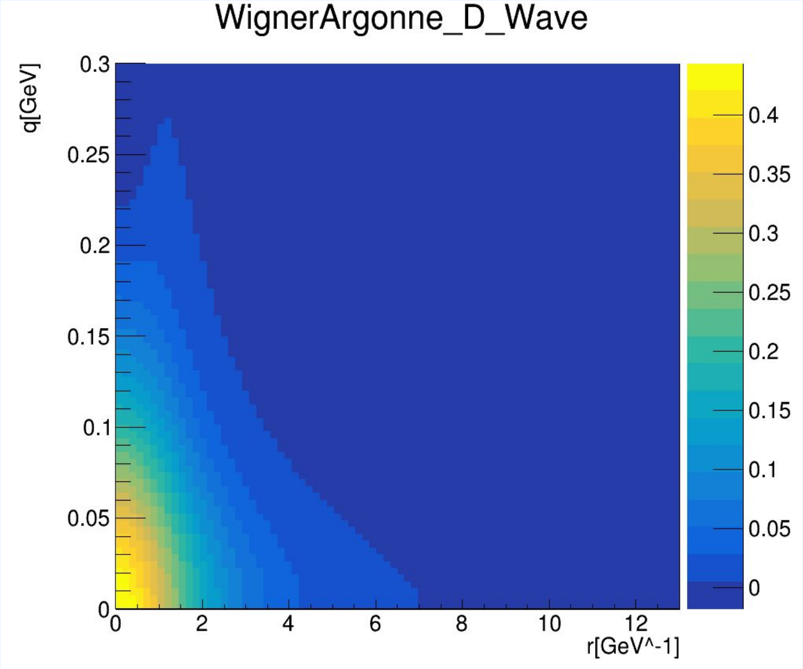
New Wiger functions/Probabilities



Integral becomes numerically unstable for finer binning

Argonne D-State probability





D-State probability is 6% → Maximum ~11% effect

Overview of (anti)nuclei data

(anti)nuclei measurements

- No measurement of antideuterons in the energy region (~19-30 GeV) relevant for astrophysics
- Most measurements are very old (~60s and 70s)
- NA61's energy (17.3 GeV) would be a perfect candidate to study antinuclei for astrophysics

We need precise measurements at the energies of interest to constrain (anti)nuclei production!

Experiment or Laboratory	Collision	p_{lab} (GeV/c)	$\sqrt{s}$ (GeV)
CERN	p + p	19	6.15
CERN	p + p	24	6.8
Serpukhov	p + p p + Be	70	11.5
CERN-SPS	p + Be p + Al	200	19.4
Fermilab	p + Be	300	23.8
CERN-ISR	p + p	1497.8	53
CERN-ALICE	p + p	4.3×10^5	900
CERN-ALICE	p + p	2.6×10^7	7000

(Highlighted: CERN 19 and 24 GeV rows) No antideuteron data!

Modelling (anti)nuclei production

B_A predictions

- Important observable in accelerator measurements: $\mathbf{B_A}$

$$B_A(p_T^p) = E_A \frac{d^3N_A}{dp_A^3} \Big/ \left(E_p \frac{d^3N_p}{dp_p^3} \right)^A$$

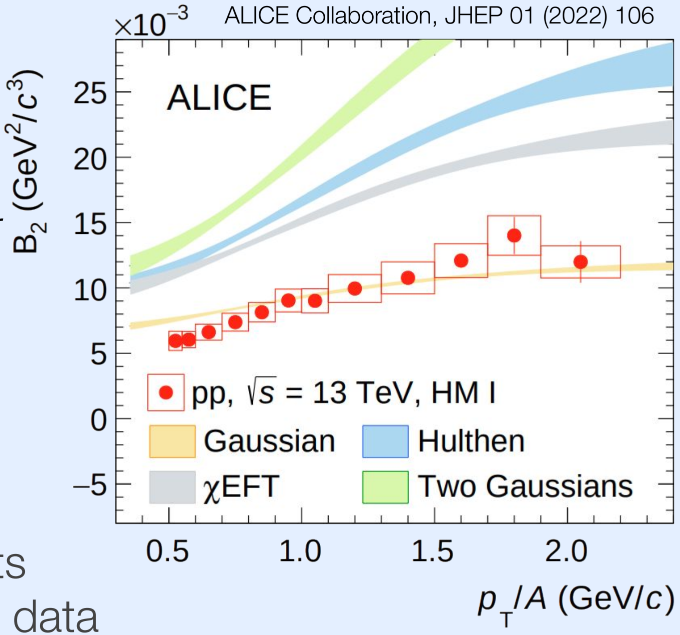
- Theoretical prediction [1]

$$B_2(\vec{p}) \approx \frac{3}{2m} \int d^3q D(\vec{q}) e^{-R^2(p_T)\; q^2}$$

$$D(\vec{q}) = \int d^3r |\phi_d(\vec{r})|^2 e^{-i\vec{q}\cdot\vec{r}}$$

Emission source size (* *keep it in mind for later!*)

Deuteron wave function



Testing different wave functions:

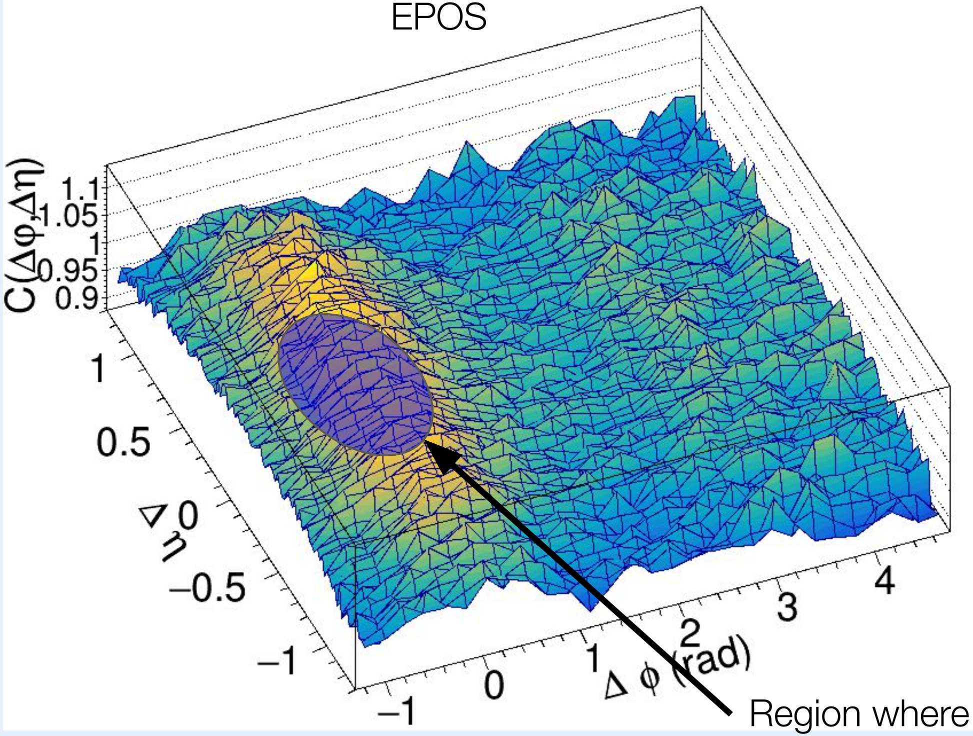
- **Hulthén:** Favoured by low energy scattering experiments
- **Gaussian:** Best description of currently available ALICE data
- **Two Gaussians:** Approximates Hulthén, easy to use in calculations
- **χEFT:** Favoured by modern nuclear interaction experiments (e.g. Femtoscopy)

[1] Blum, Takimoto, PRC 99 (2019) 044913

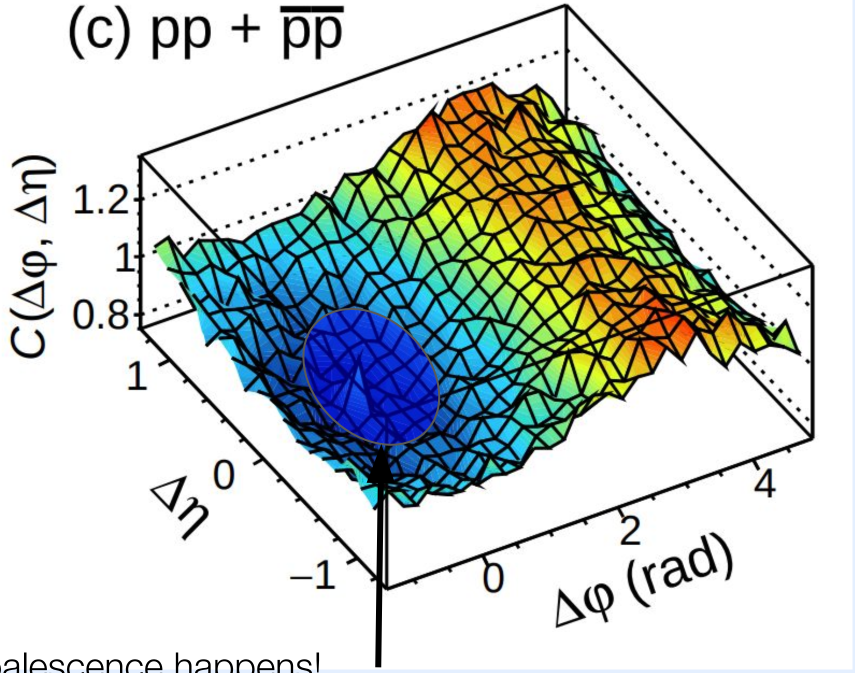
Correlations comparison

Δη-Δφ Correlation function

EPOS



ALICE (*Eur.Phys.J.C* 77 (2017) 8, 569)



Region where coalescence happens!

The advanced source model in EPOS

Scheme

Propagation scheme:

- We obtain a scaling factor as a function of m_T from the source size measurement
- We move the primordials out radially until we reach the scaled distance
- This distance ($\tilde{x}$) is the same for both primordials of the pair