The future of antinuclei production studies

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Technical University Munich
NA61++/SHINE Workshop CERN
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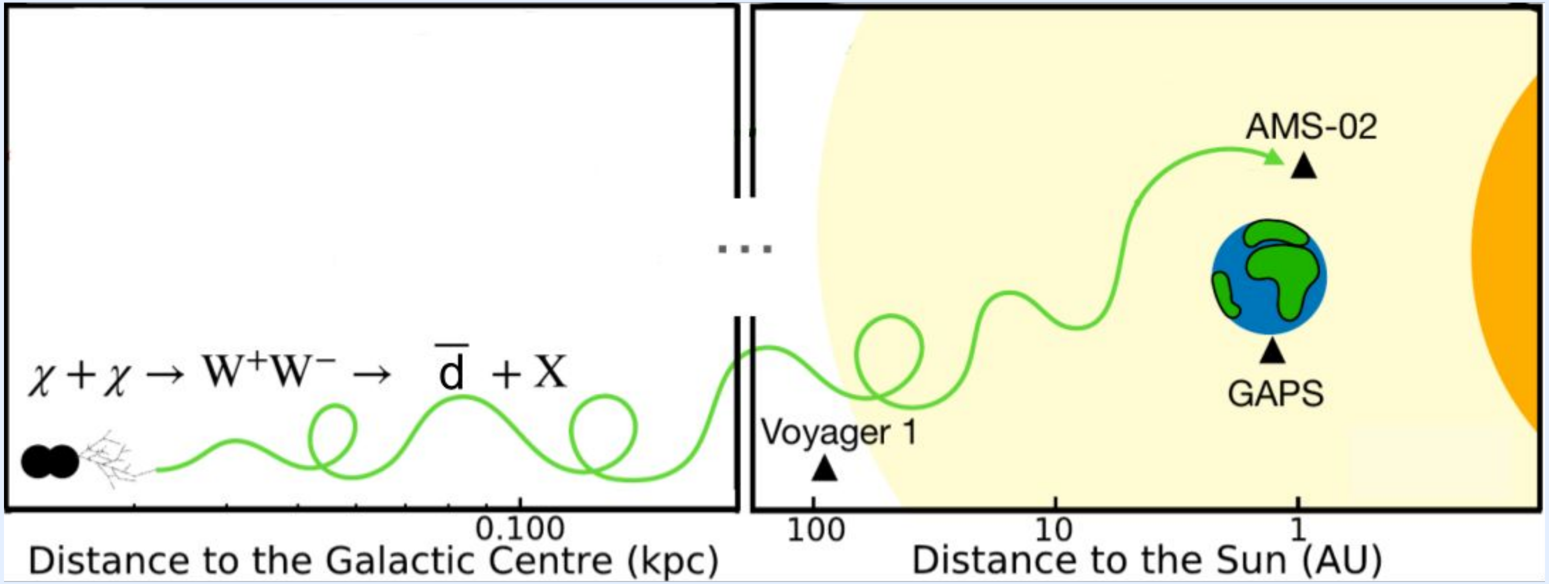
Cosmic Rays

Antinuclei in cosmic rays



ALICE Collab. arXiv:2202.01549v1

➤ Antinuclei could be a probe for indirect Dark Matter searches

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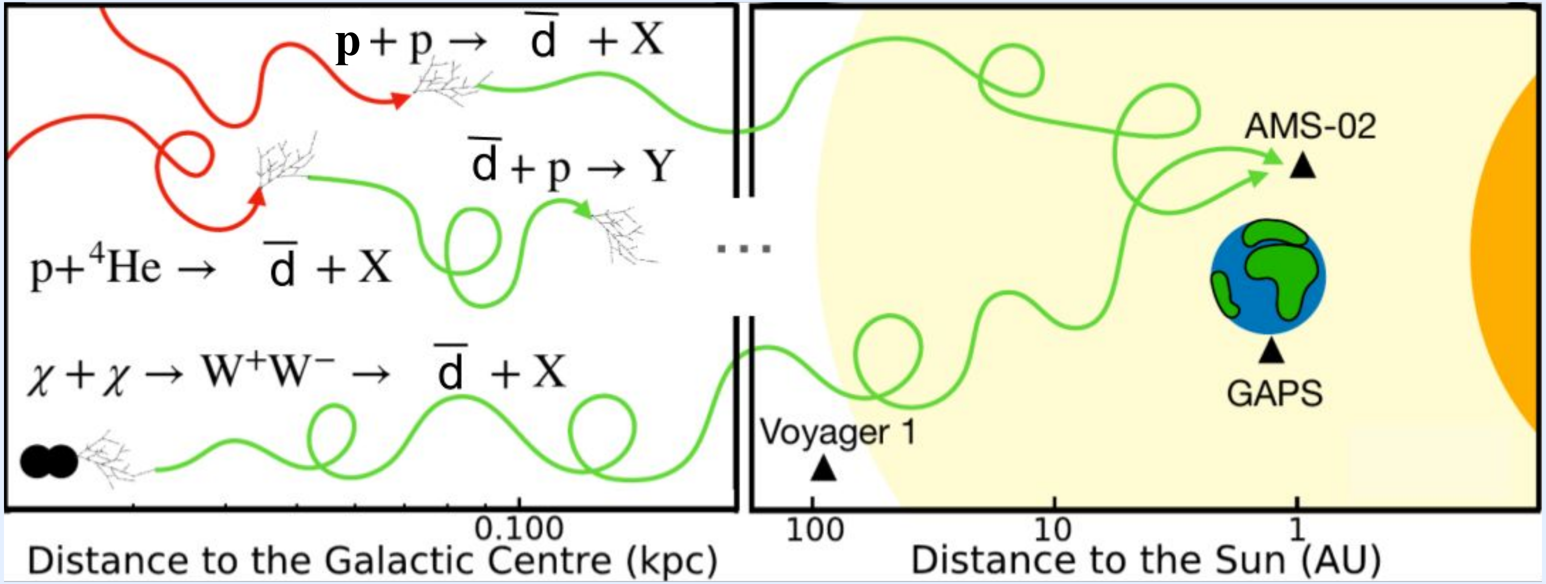

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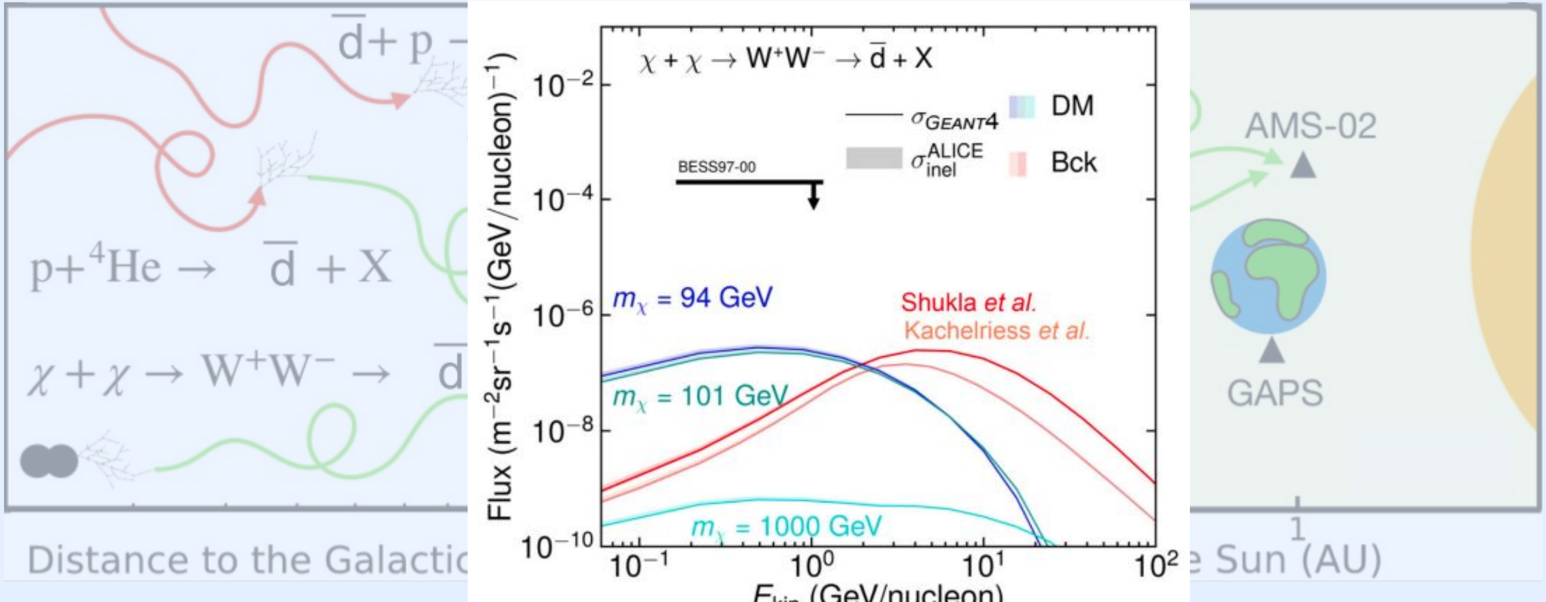

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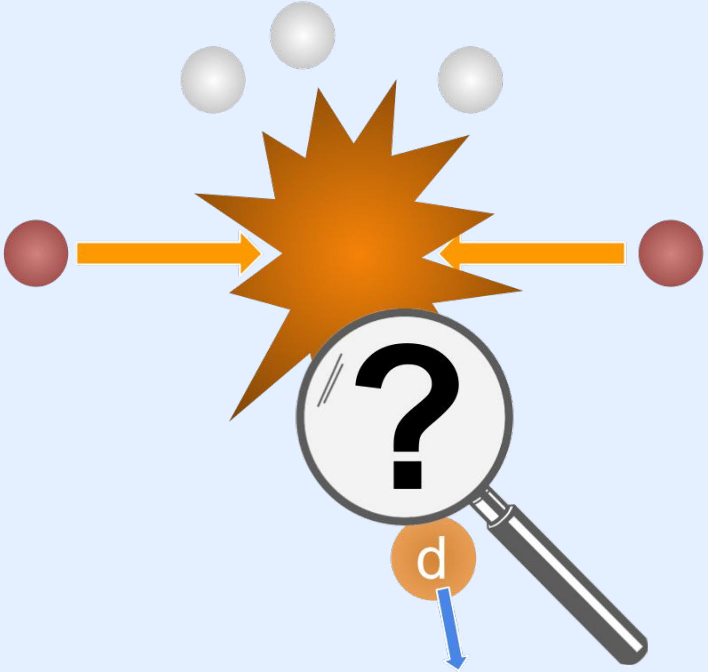
- ➤ Antinuclei could be a probe for indirect Dark Matter searches
- ➤ However: Astrophysical background from cosmic rays expected
- ➤ High Signal/Noise ratio (~10^2-10^4) at low E_{kin} expected by many models!

Modelling (anti)nuclei production

Overview of production models

(anti)nuclear production described by two models:



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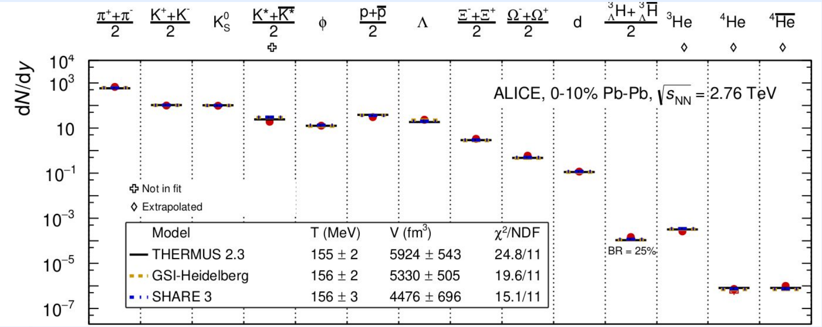
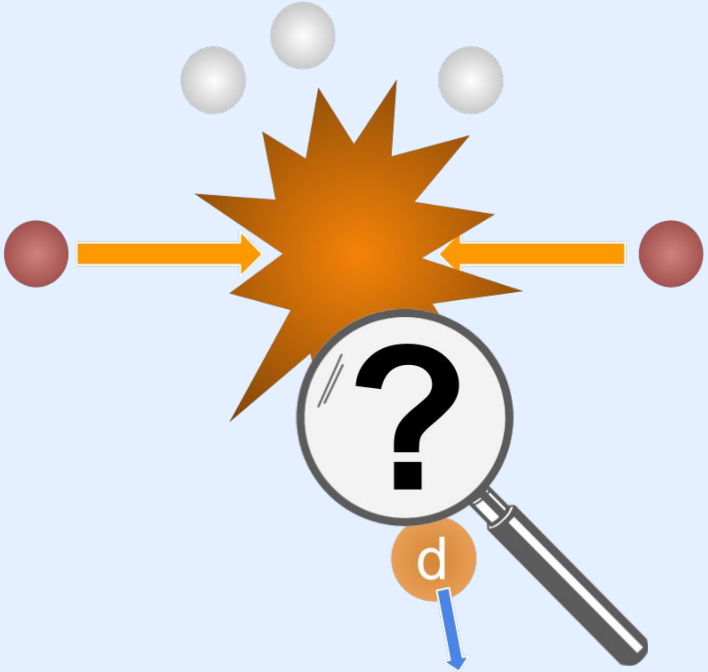
(anti)nuclear production described by two models:

Statistical hadronization

- ➤ 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)
- ➤ No microscopic description of nuclei formation





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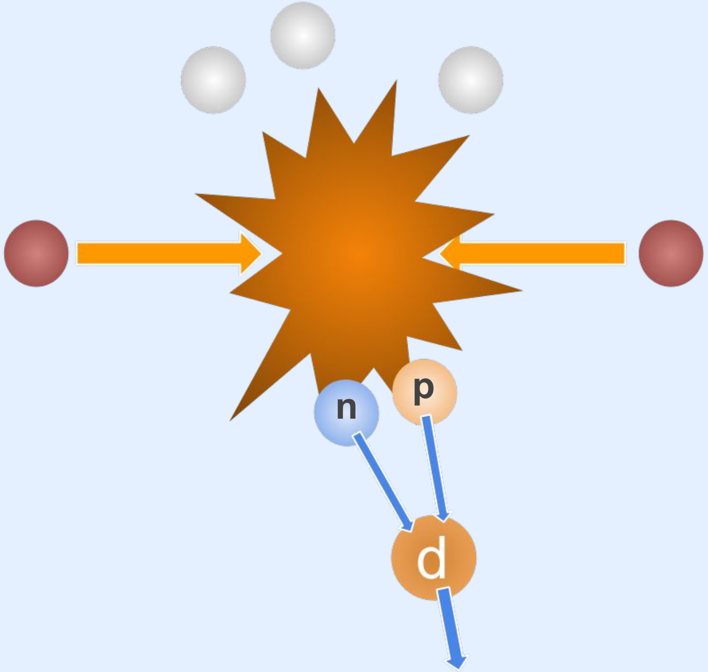
Coalescence model
- ➤ Nucleons bind after chemical freeze-out if they are close in phase-space



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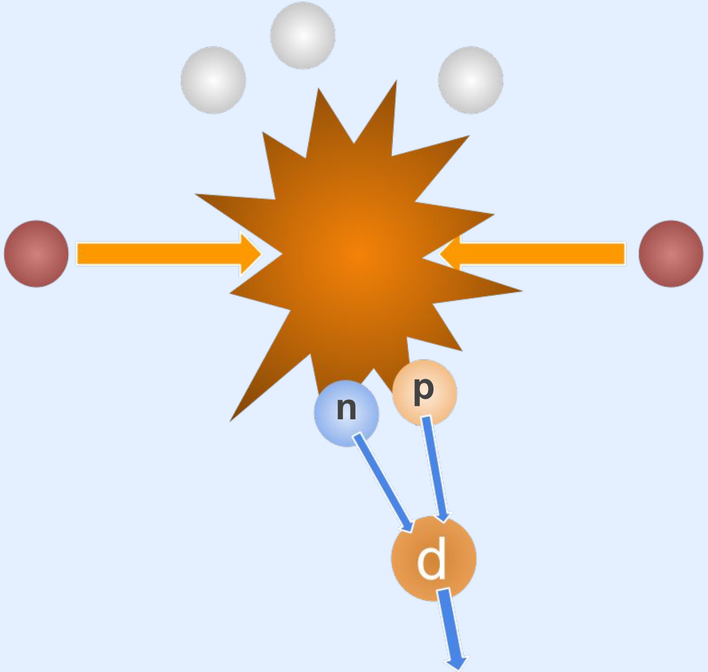
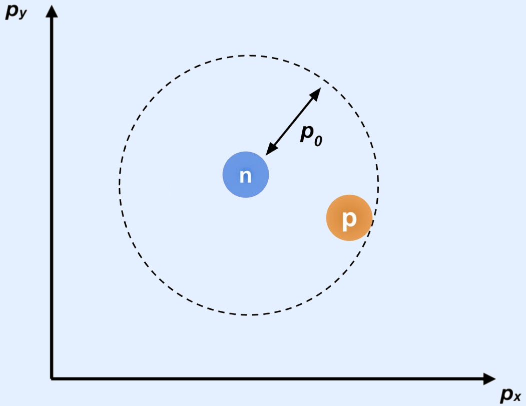


Coalescence model

- ➤ Nucleons bind after chemical freeze-out if they are close in phase-space
- ➤ Common implementation: Spherical Approximation

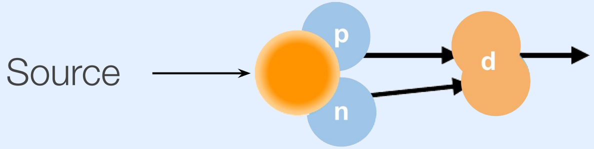
$$\Delta p < p_0$$



The coalescence model

Wigner function formalism

What do we need for coalescence?



p,n-pair deuteron

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Wigner function formalism

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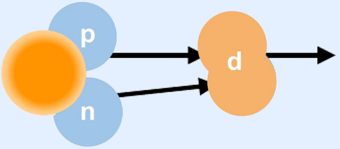

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Quantum mechanics: $d^3N/dP^3 = \mathrm{Tr}(\rho_d \rho_{Nucl})$

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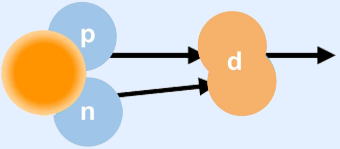

p,n-pair   deuteron

Quantum mechanics:

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

$$d^3N/dP^3 = \int d^3q \int d^3r_p \int d^3r_n \; \textit{Deuteron Density} \; \textit{Nucleon Density}$$

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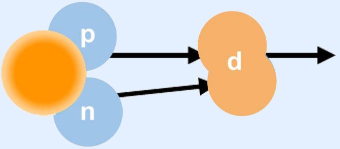

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$$d^3N/dP^3 = S \int d^3q \int d^3r_p \int d^3r_n \, W(q,r) \;\; W_{np}(p_n,p_p,r_n,r_p)/(2\pi)^6$$

Spin-Isospin statistics factor
(=⅜ for deuterons)

The coalescence model

Wigner function formalism

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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$$H_{np}(\vec{r}_n,\vec{r}_p) = h(\vec{r}_n)h(\vec{r}_p) = \frac{1}{(2\pi\sigma^2)^3}\exp\left(-\frac{\vec{r}_n^{\,2}+\vec{r}_p^{\,2}}{2\sigma^2}\right)$$

- Some simple calculation later

$$\frac{d^3N_d}{dP_d^3} = \frac{3\zeta}{(2\pi)^6}\int d^3q\ \mathrm{e}^{-q^2d^2}G_{np}(\vec{P}_d/2+\vec{q},\vec{P}_d/2-\vec{q})$$

Nucleon momentum phase-space

with

$$\zeta \equiv \left(\frac{d^2}{d^2+4\sigma^2}\right)^{3/2}$$

Emission source size

[2] Kachelries, Eur.Phys.J.A 56 (2020) 1, 4

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Constrained from data!

[2] Kachelries, Eur.Phys.J.A 56 (2020) 1, 4

What did ALICE do for (anti)nuclei studies?

(anti)nuclei measurements

- ➤ A variety of light (anti)nuclei has been measured in pp
- ➤ From (anti)Deuterons to (anti)Helium-3

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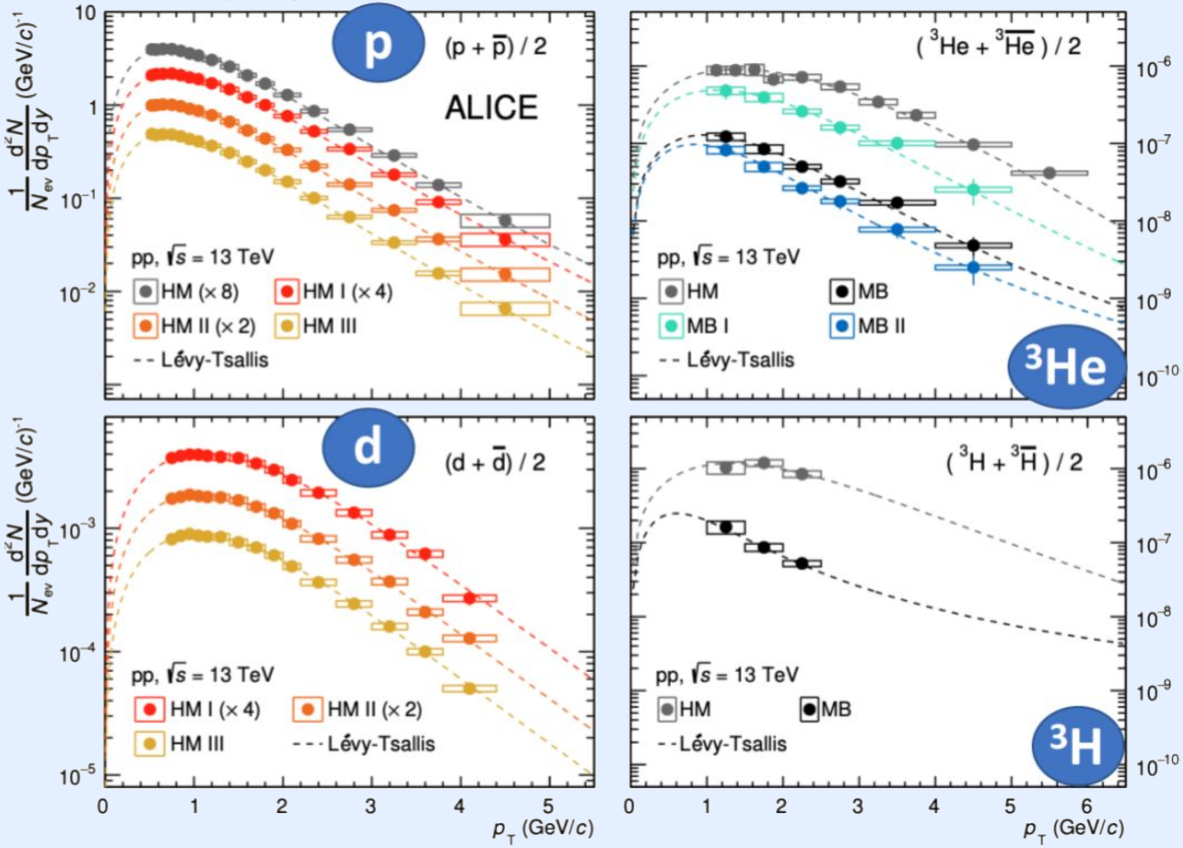

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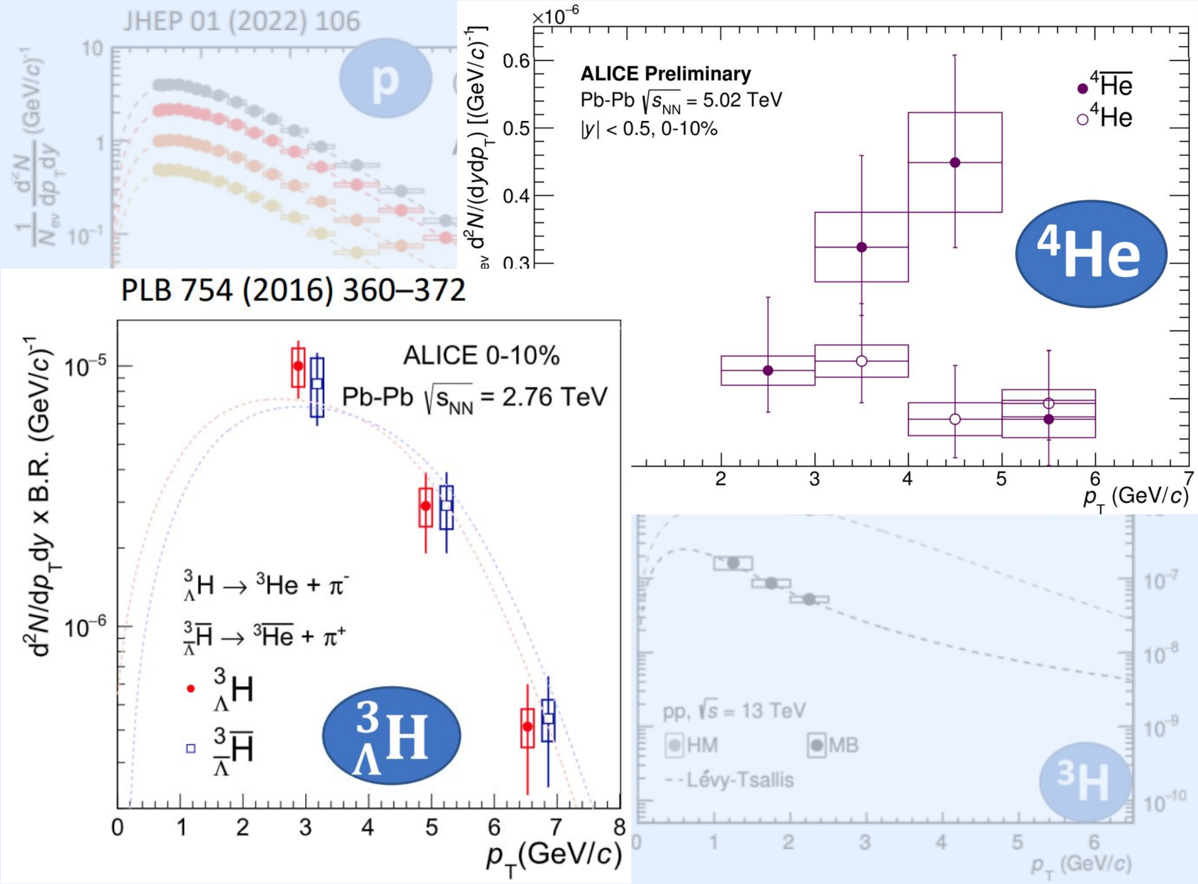
- In Pb–Pb: (anti)Helium-4 and (anti)Hypertriton

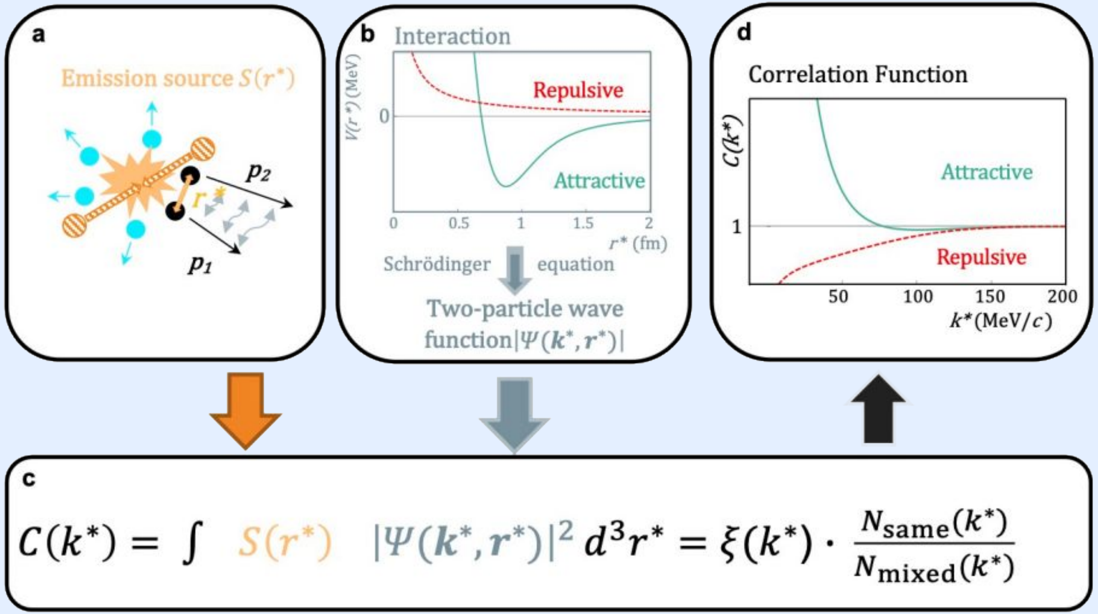


What did ALICE do for (anti)nuclei studies?

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:
  - Particle emission source
  - Two-particle wave function (quantum statistics + Coulomb + strong interaction)

Nature 588 (2020) 232-238



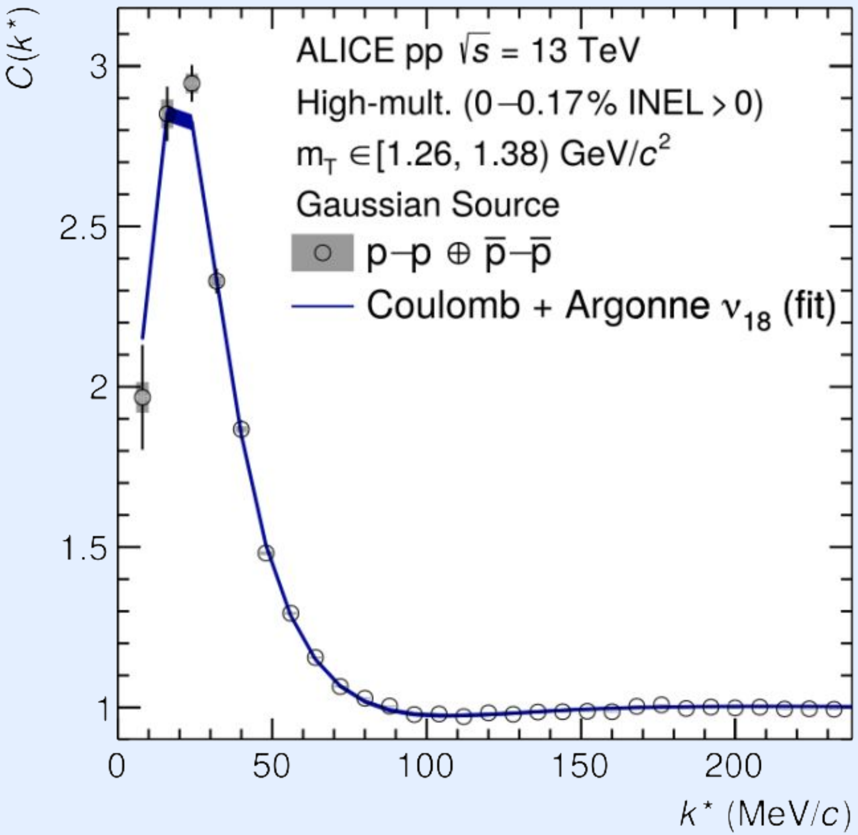
If we measure C(k*) and use a known interaction (e.g. nucleon-nucleon) we can study the emission source

What did ALICE do for (anti)nuclei studies?

Femtoscopy

PLB 811 (2020) 1358249

- Good description of the interaction with Fermi-Dirac statistics, Coulomb and strong interaction (using χ_{EFT})
- Only free parameter: the source size



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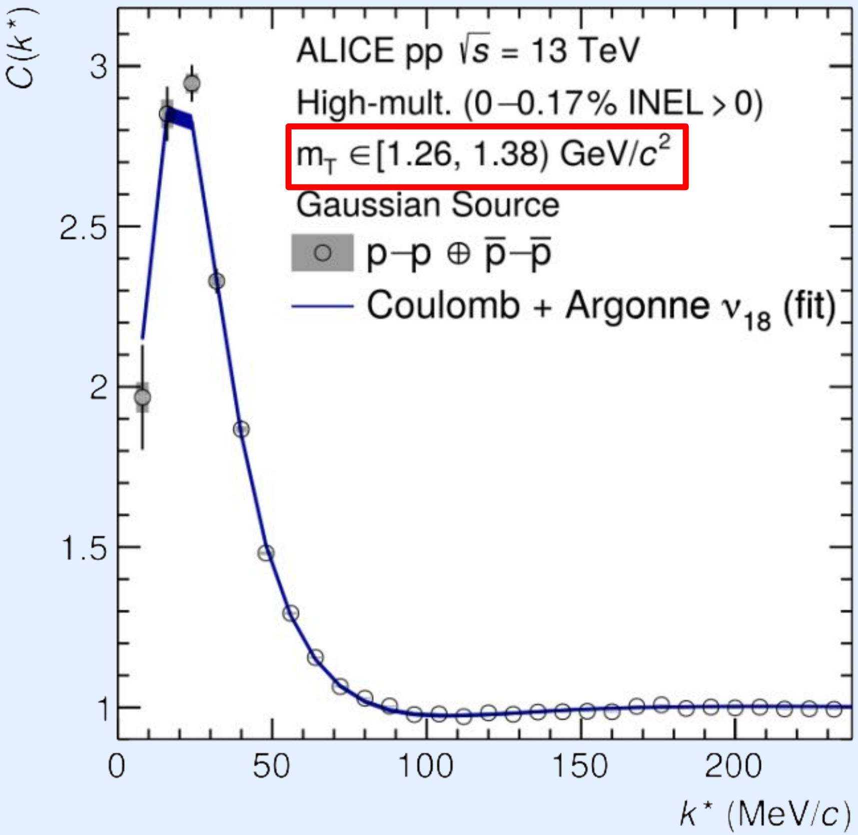

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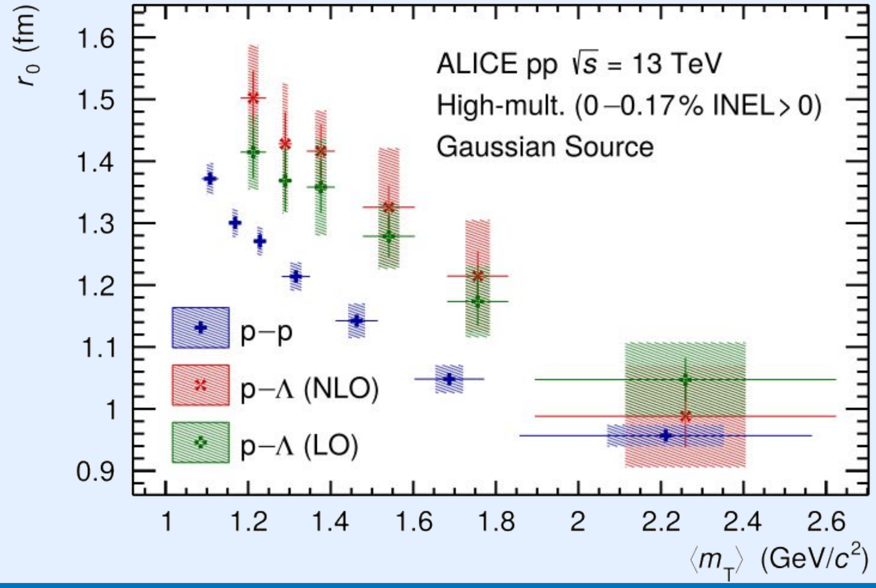

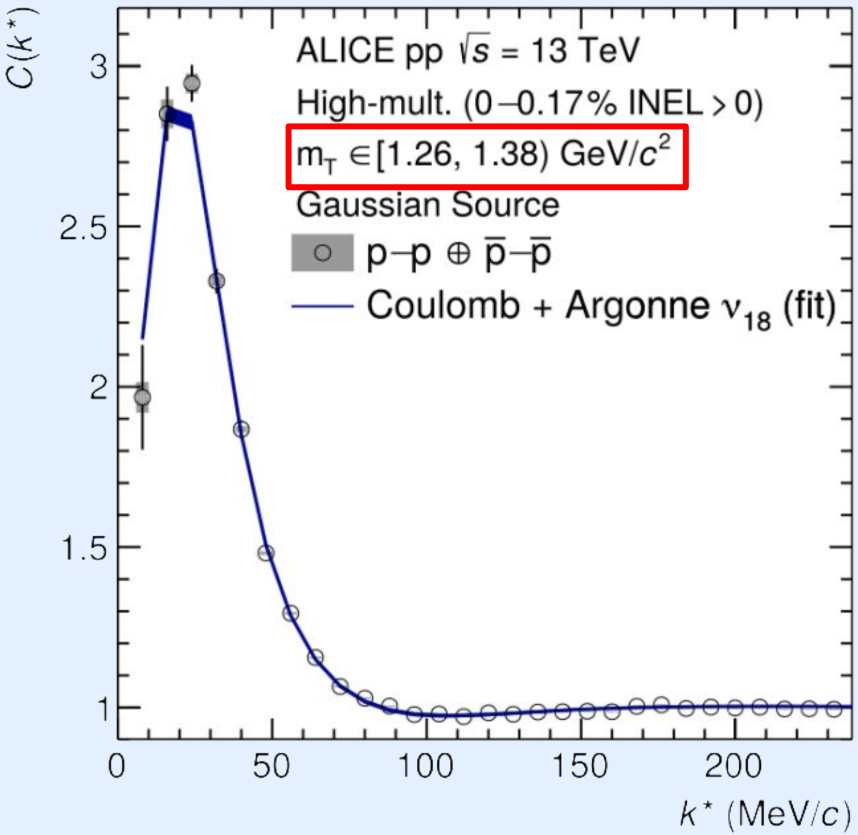

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Constrained from data!

[2] Kachelries, Eur.Phys.J.A 56 (2020) 1, 4

State of the art coalescence predictions

Wigner function formalism, tuned to ALICE measurements

- Let's remember:

$$\frac{d^3N_d}{dP_d^3} = \frac{3\zeta}{(2\pi)^6}\int d^3q\, \mathrm{e}^{-q^2d^2} G_{np}(\vec{P}_d/2+\vec{q}, \vec{P}_d/2-\vec{q})$$

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Constrained from data!

- The term $3\zeta\mathrm{e}^{-q^2d^2}$ can be interpreted as a coalescence probability depending on the relative momentum q and the source size σ
- More 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

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

State of the art coalescence predictions

Wigner function formalism, tuned to ALICE measurements

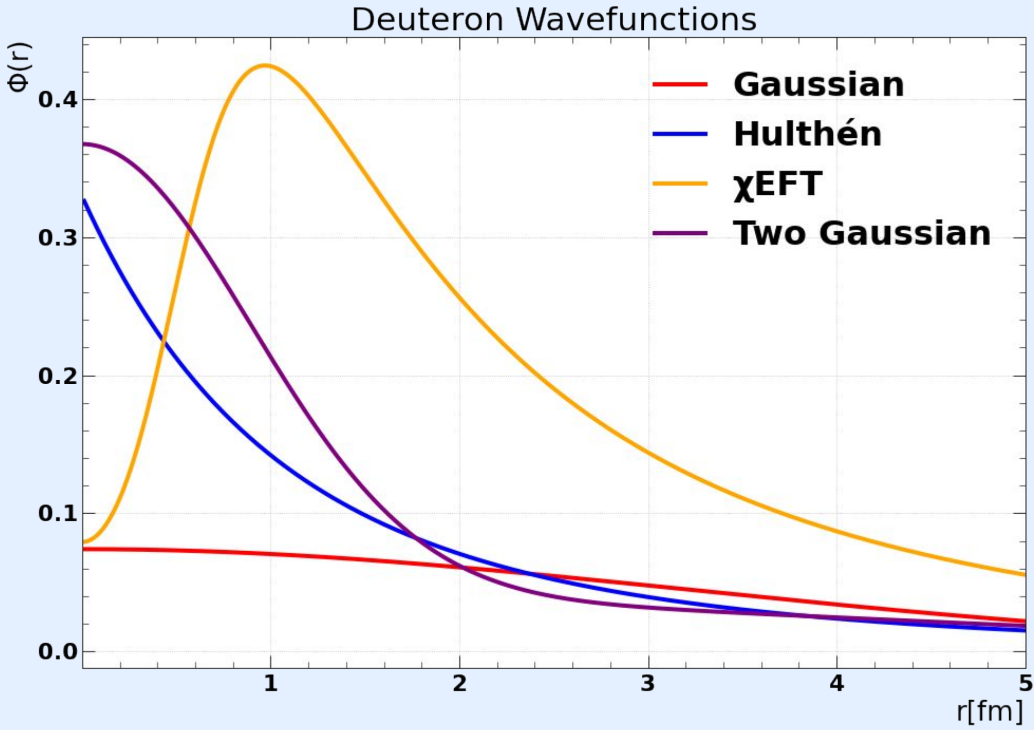
- There are multiple models for the deuteron wave function
- Simplistic:

  Single Gaussian
- From *pion field theory* (Yukawa-like potential) ('50s):

  Hulthén
- Simplification of Hulthén ('50s):

  Two Gaussian
- From modern χ_{EFT}:

  Argonne v_{18}



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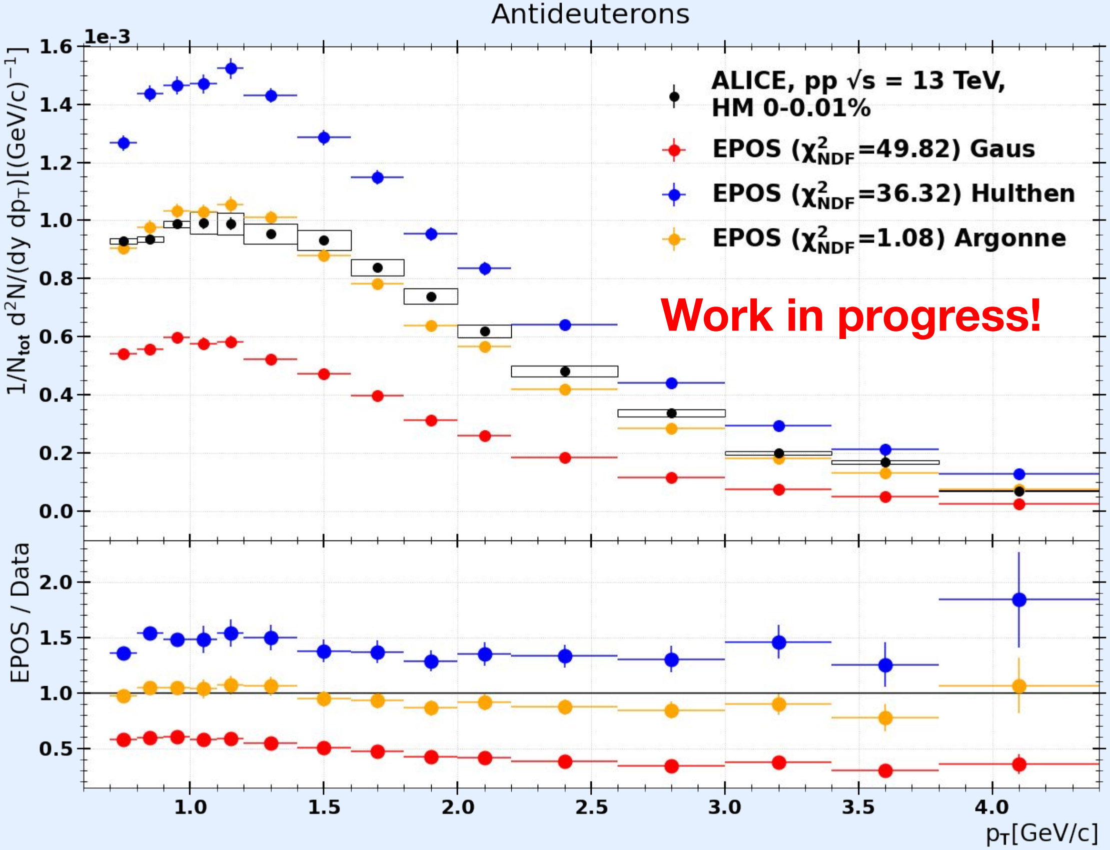
- Event-by-event coalescence afterburner with Wigner function formalism
- EPOS 3 as event generator
- Correct the event generator to measurements
  - source size,
  - momentum distributions,
  - charged particle multiplicity
- Compare to measurements by ALICE
- Argonne (χ_{EFT}) WF shows a good compatibility with measurements



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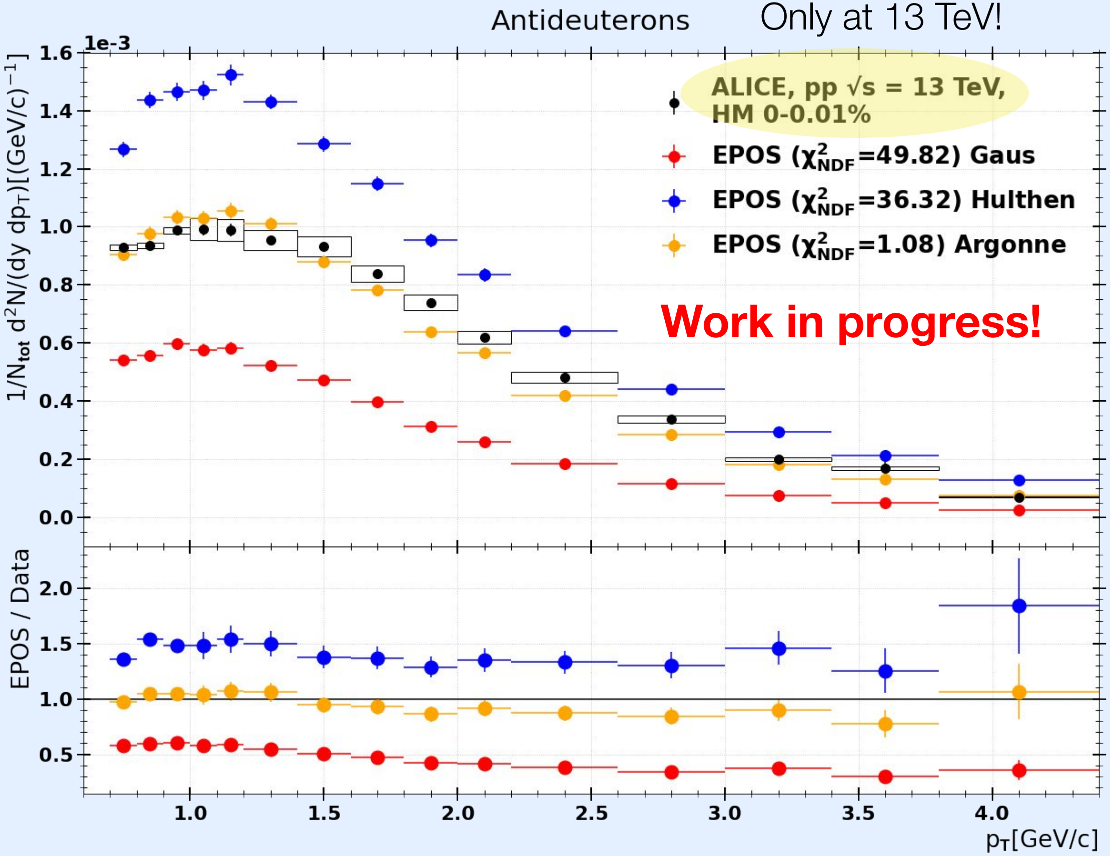
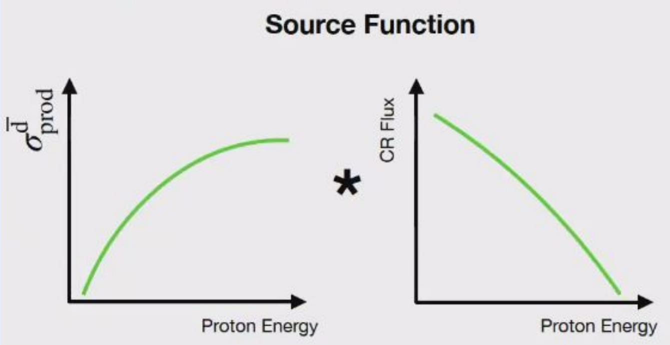
Only at 13 TeV!

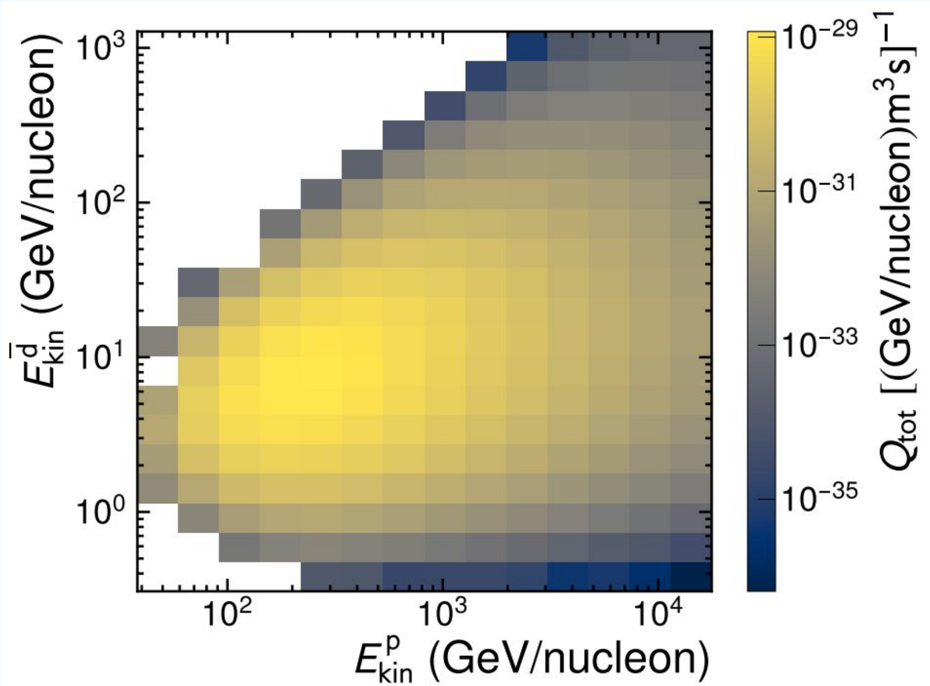


Cosmic Rays

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)





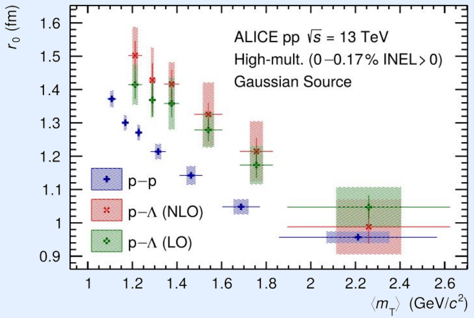
Šerkšnytė, et al. PHYSICAL REVIEW D 105, 083021 (2022)

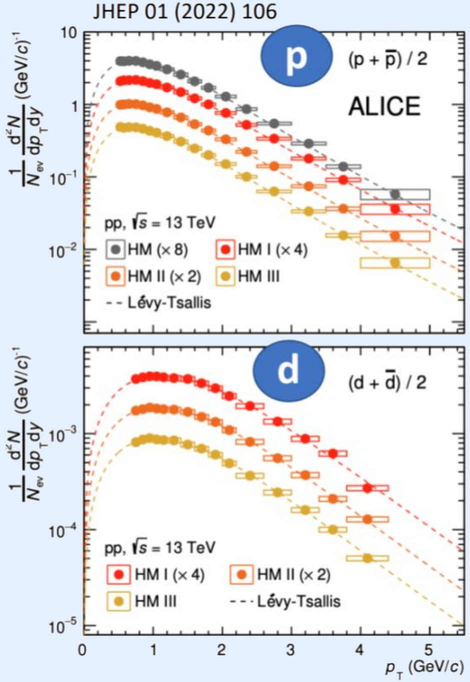
What do we need from NA61

- NA61 energy of √s~20 GeV is perfect to study antideuterons for cosmic rays
- Large acceptance for forward/backward rapidity give important insights for astrophysics (production at forward rapidity is poorly measured)

<u>What we need from NA61 to study nuclei formation:</u>

- Emission source size measurements via two-particle correlation
- (Anti)nucleon momentum distributions
- (Anti)nuclei production measurements





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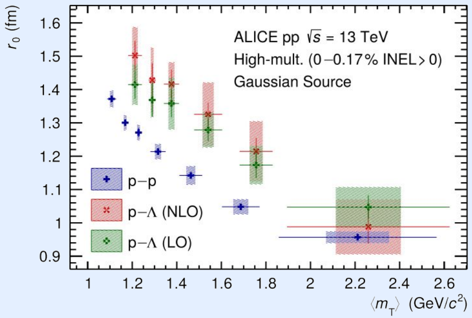
Thanks for the amazing Workshop!



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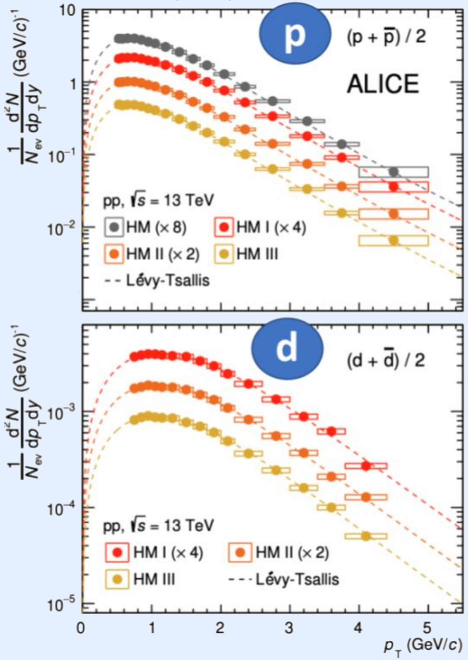
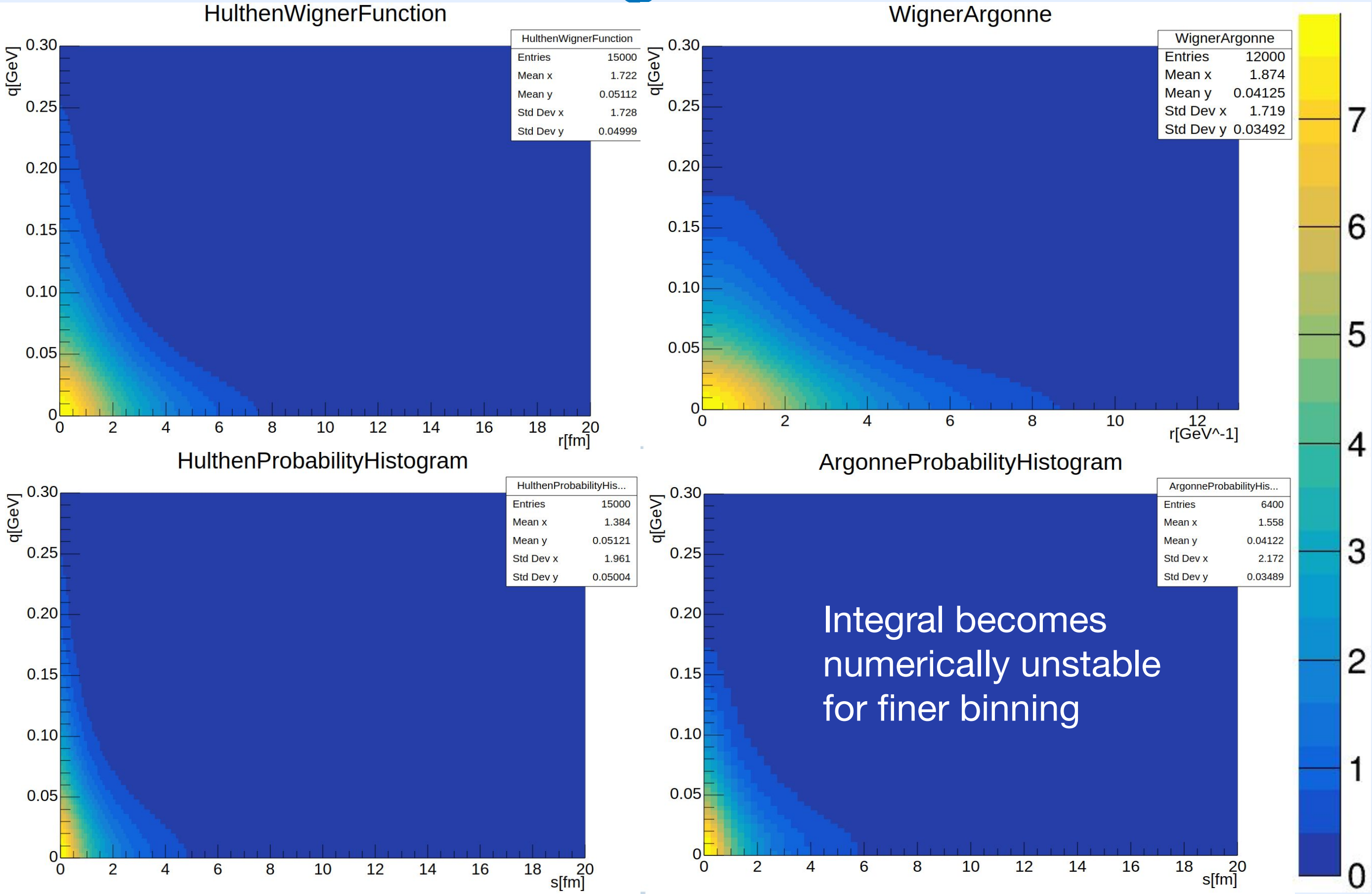


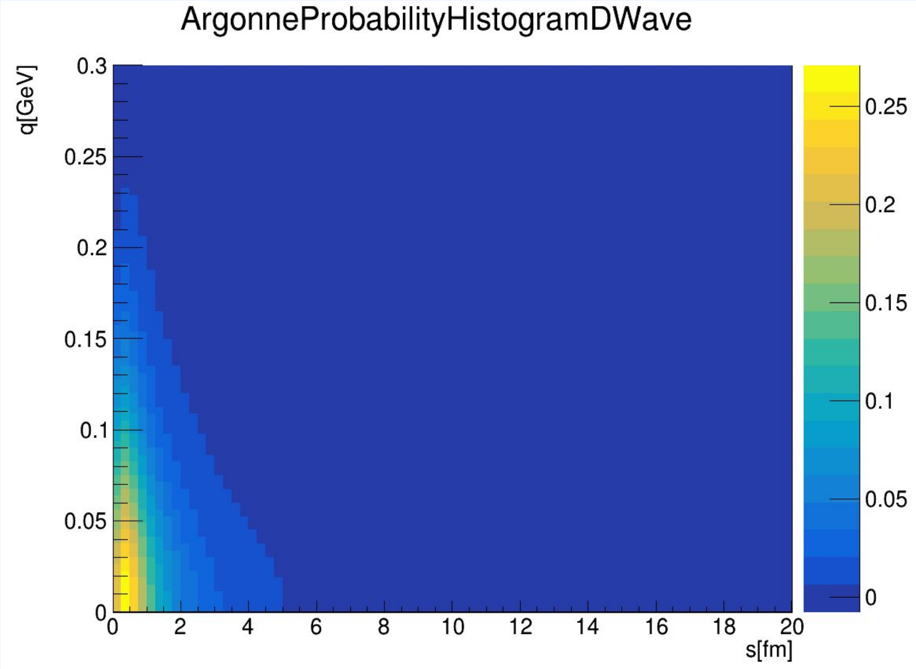
Backup slides

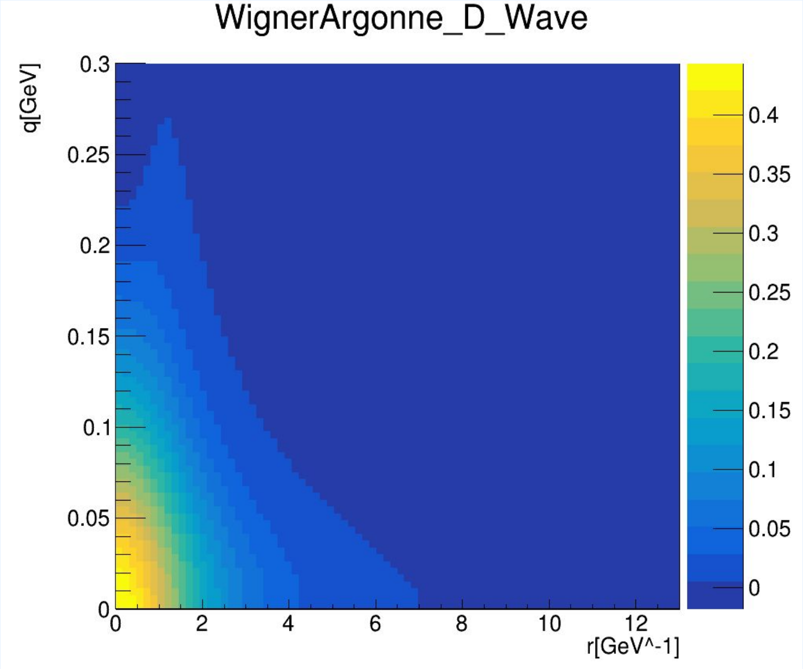
New Wiger functions/Probabilities



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

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]

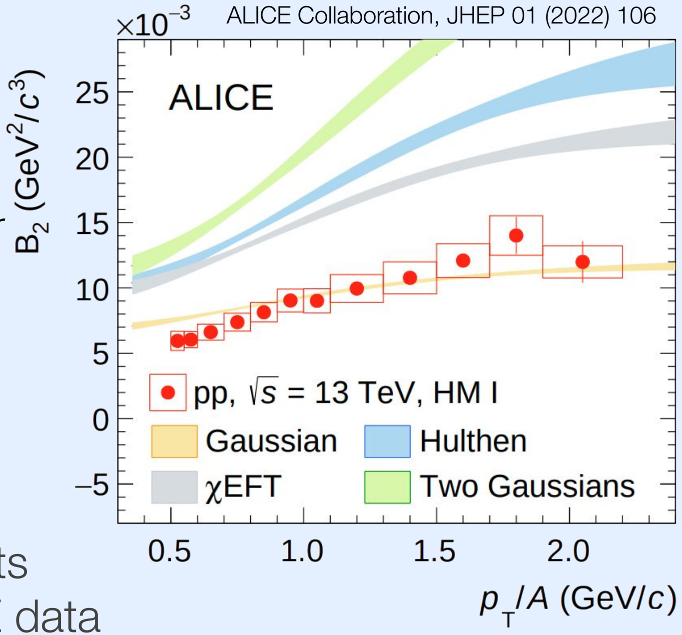
Emission source size

* keep it in mind for later!

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

Deuteron wave function

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



Testing different wave functions:

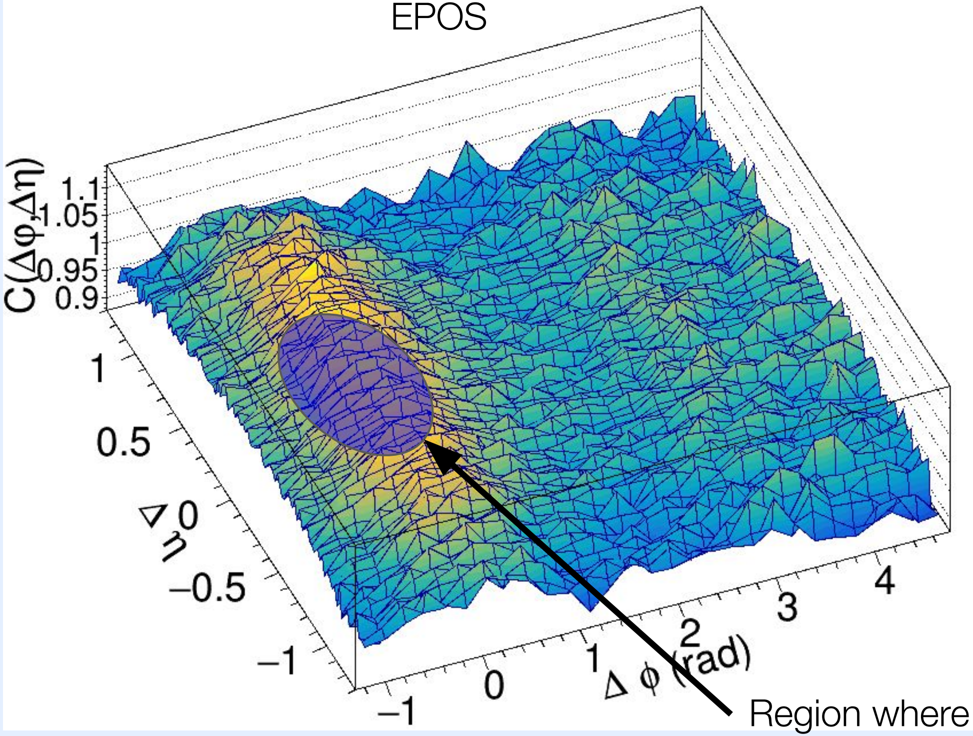
- **Hulthén:** Favoured by low energy scattering experiments
- **Gaussian:** Best description of currently available ALICE data
- **Two Gaussians:** Approximates Hulthén, easy to use in calculations
- ***χ*EFT:** Favoured by modern nuclear interaction experiments (e.g. Femtoscopy)

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

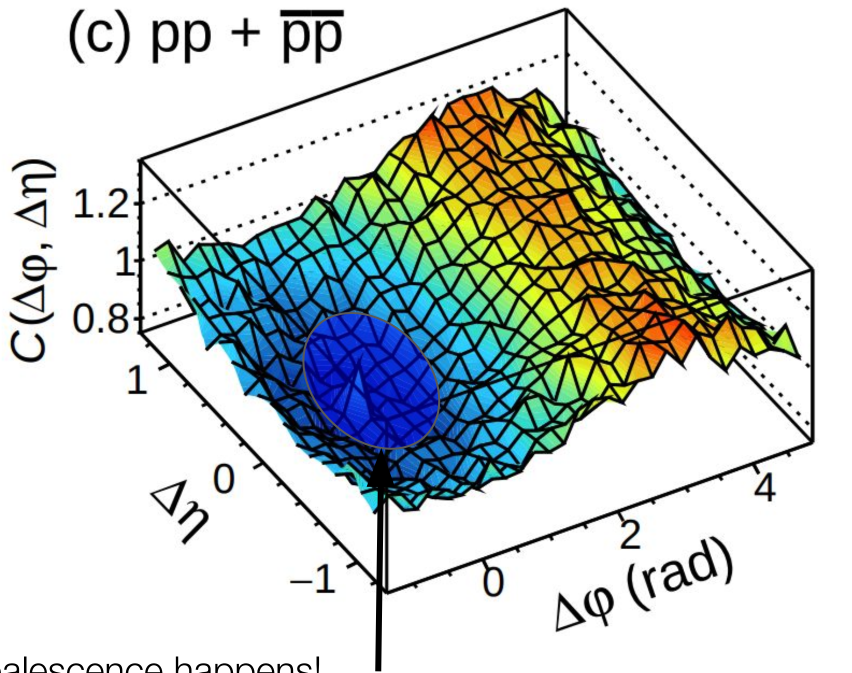
Correlations comparison

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