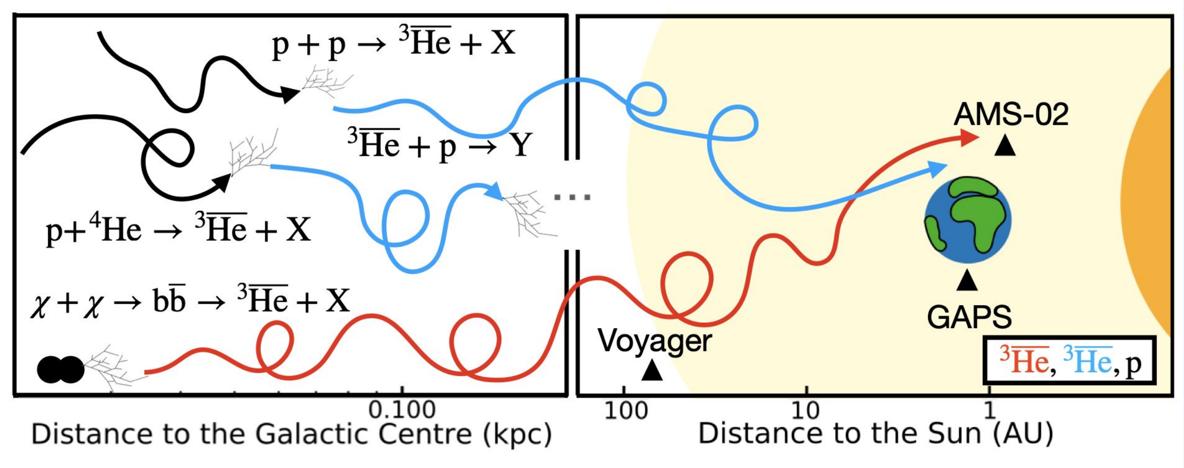
Advanced coalescence model based on femtoscopy measurements

based on Eur.Phys.J.C 83 (2023) 9, 804

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

[1] Technische Universität München
[2] INFN Torino
[3] INFN and University Bologna

Antinuclei in cosmic rays

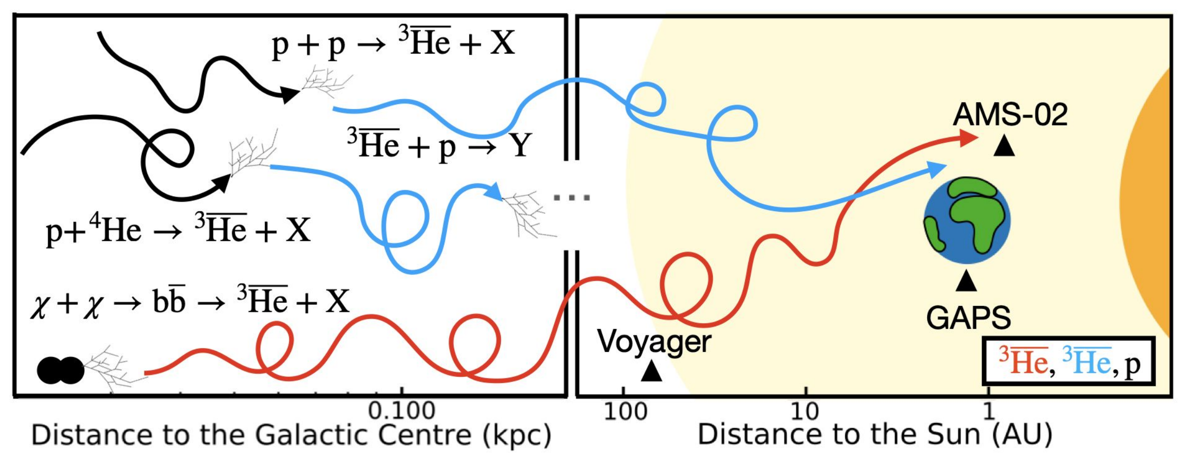


Antinuclei production:

- 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)

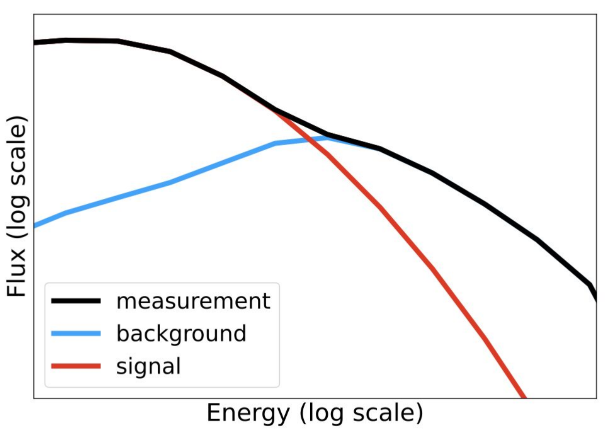
Antinuclei in cosmic rays



Antinuclei production:

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

antinuclei cosmic ray flux



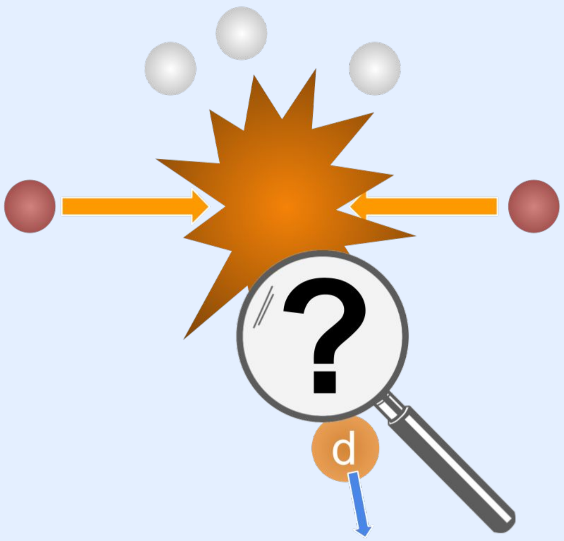
- High Signal/Noise ratio (~10^2-10^4) at low E_{kin} expected by models
- To correctly interpret any future measurement we need precise knowledge of
  - production of antinuclei
  - annihilation

ALICE Collab., Nature Phys. (2022)

Modelling (anti)nuclei production

Overview of production models

(Anti)nuclear production described by two models:



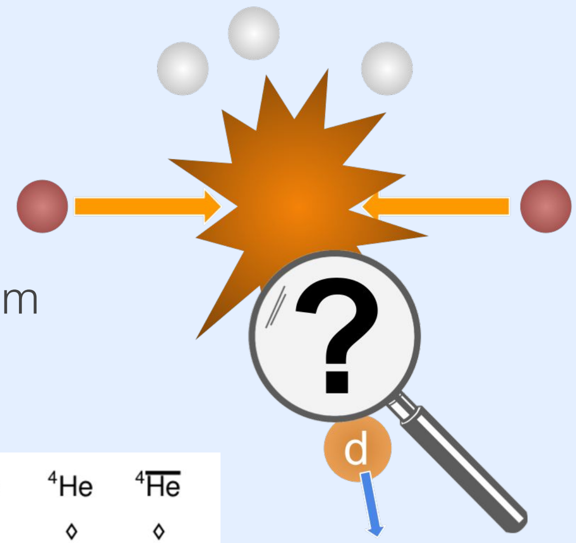
Modelling (anti)nuclei production

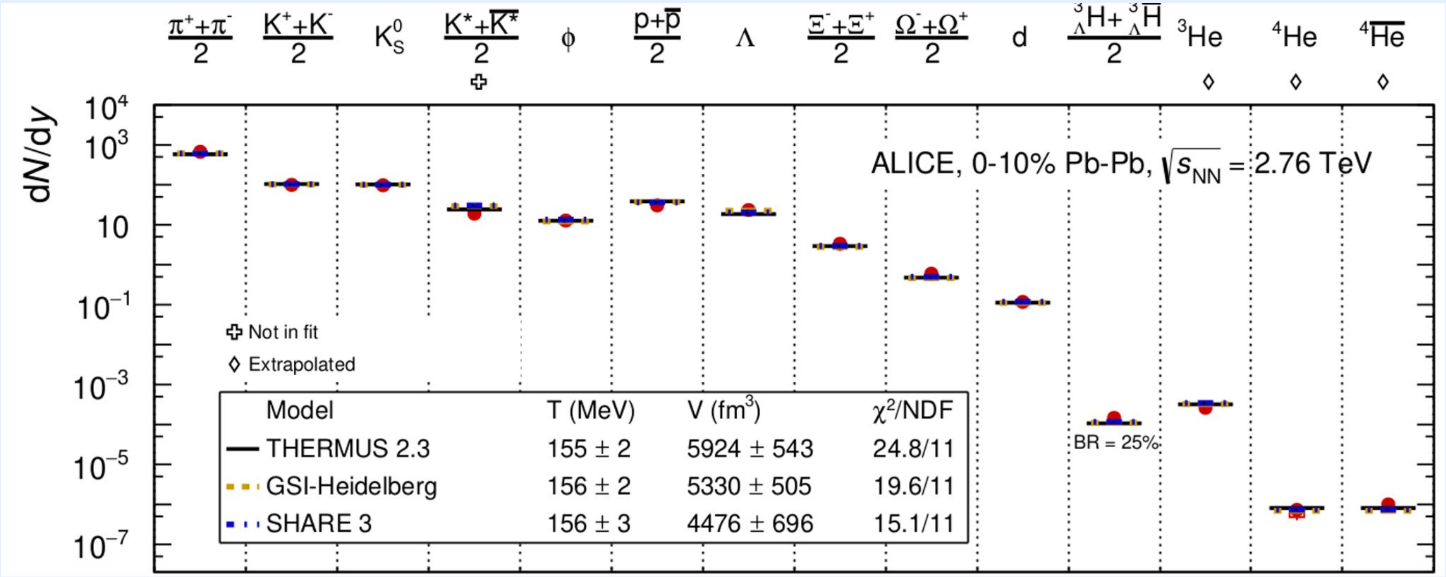
Overview of production models

(Anti)nuclear production described by two models:

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~155 MeV)
- ➤ No dynamical description of nuclei formation





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

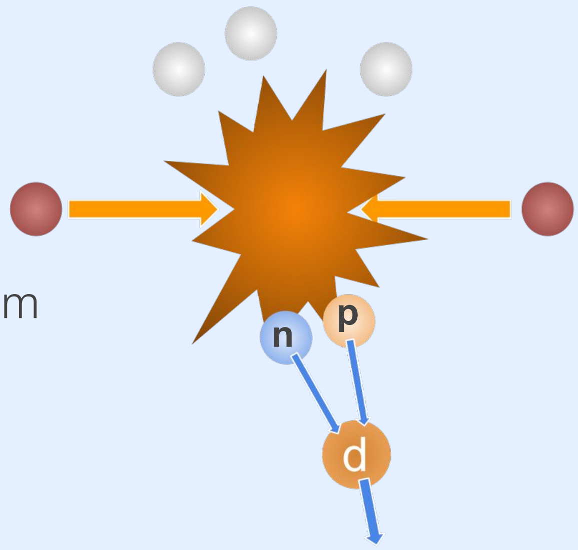
Modelling (anti)nuclei production

Overview of production models

(Anti)nuclear production described by two models:

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~155 MeV)
- ➢ No dynamical description of nuclei formation



Coalescence model

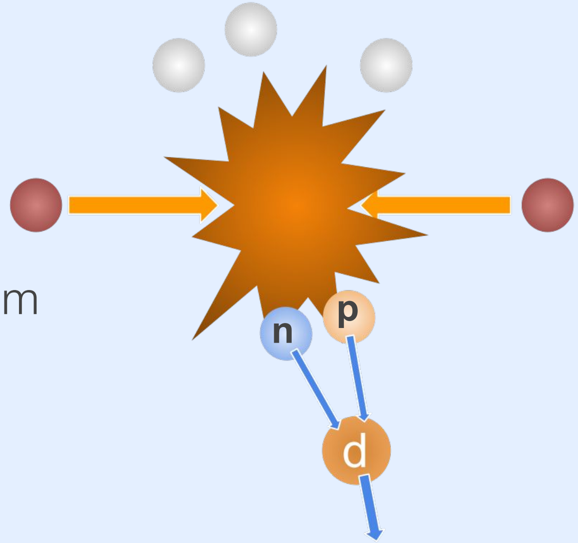
- ➢ Nucleons bind after chemical freeze-out if they are close in phase-space

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

Modelling (anti)nuclei production

Overview of production models

(Anti)nuclear production described by two models:

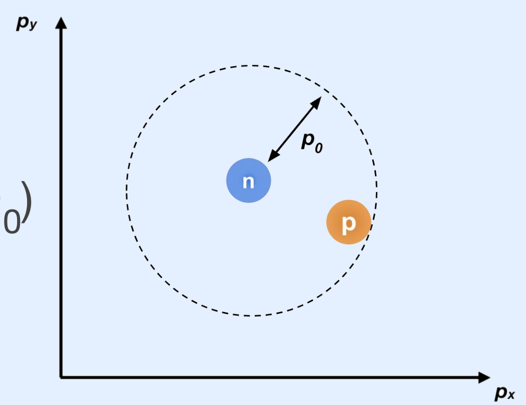


Statistical hadronization (SHM)

- 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~155 MeV)
- No dynamical description of nuclei formation

Coalescence model

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

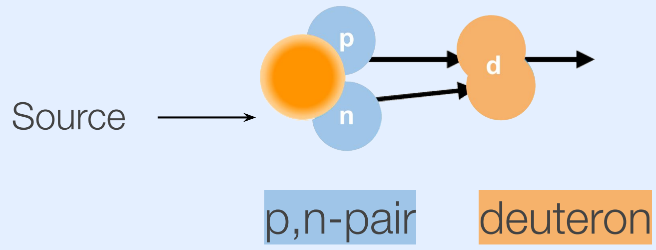


Butler et al., Phys. Rev. 129 (1963) 836

The coalescence model

Wigner function formalism

What do we need for coalescence?

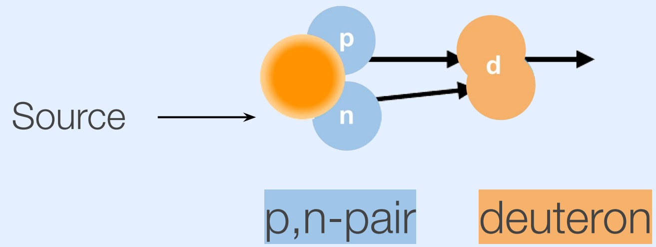


Kachelriess et al. EPJA 57 (5) 167, 2021

The coalescence model

Wigner function formalism

What do we need for coalescence?



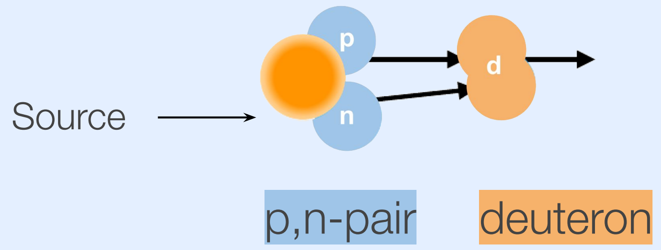
1. Use event generators (PYTHIA 8.3 & EPOS 3)
2. Emulate experimental multiplicity trigger
3. Calibrate (anti)nucleon momentum distribution
4. Take resonance cocktail from SHM
5. Tune emission source
6. Employ realistic wavefunction

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

The coalescence model

Wigner function formalism

What do we need for coalescence?



1. Use event generators (PYTHIA 8.3 & EPOS 3)
2. Emulate experimental multiplicity trigger
3. Calibrate (anti)nucleon momentum distribution
4. Take resonance cocktail from SHM
5. Tune emission source
6. Employ realistic wavefunction

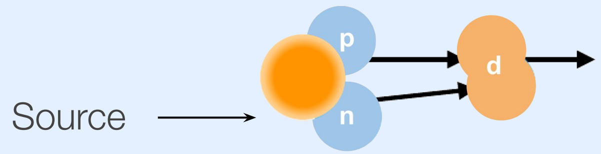
→ **model predicts deuteron p_T spectrum**

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

The coalescence model

Wigner function formalism

What do we need for coalescence?



p,n-pair   deuteron

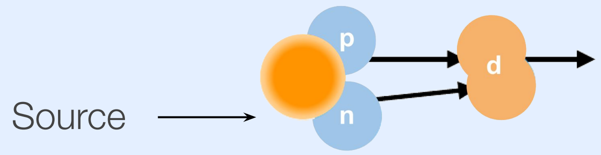
Quantum mechanics: $d^3N/dP^3 = \mathrm{Tr}(\rho_d \rho_{Nucl})$

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

The coalescence model

Wigner function formalism

What do we need for coalescence?



p,n-pair deuteron

$q = (p_p - p_n)/2$
$r = r_p - r_n$

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

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

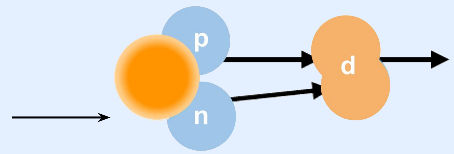
Kachelriess et al. EPJA 57 (5) 167, 2021

The coalescence model

Wigner function formalism

What do we need for coalescence?

Source



p,n-pair deuteron

$q = (p_p - p_n)/2$

$r = r_p - r_n$

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

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

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

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

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
- H_{np} is the spatial distribution of nucleons. Assuming a **Gaussian source**

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

Kachelriess et al. EPJA 57 (5) 167, 2021
Kachelriess et al. EPJA 56 (1) 4, 2020

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
- H_{np} is the spatial distribution of nucleons. Assuming a **Gaussian source**

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

some simple calculations 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

deuteron size (3.2 fm)

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

Two-particle emitting source size

Kachelriess et al. EPJA 57 (5) 167, 2021
Kachelriess et al. EPJA 56 (1) 4, 2020

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
- H_{np} is the spatial distribution of nucleons. Assuming a **Gaussian source**

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

some simple calculations later:

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

deuteron size (3.2 fm)

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

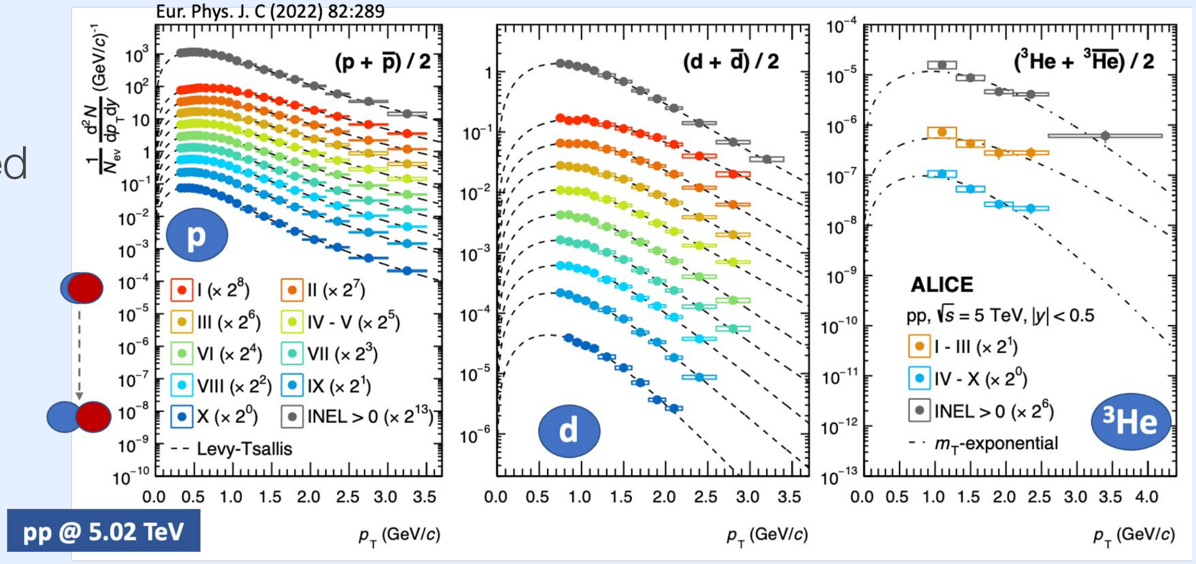
Constrained from data!

Kachelriess et al. EPJA 57 (5) 167, 2021
Kachelriess et al. EPJA 56 (1) 4, 2020

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

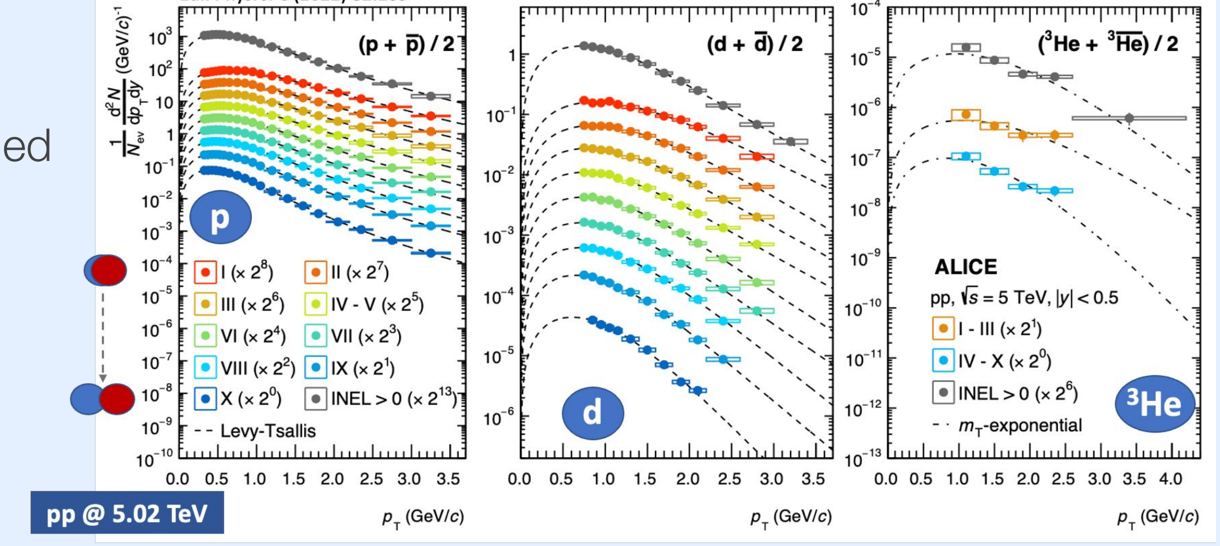


Light (anti)nuclei measured in ALICE

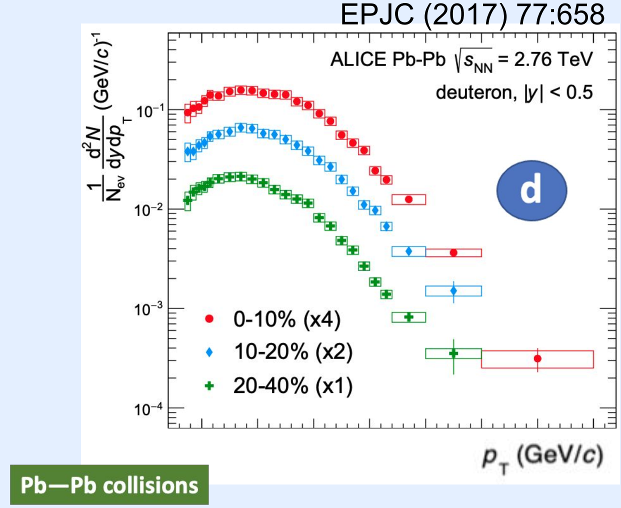
Transverse momentum spectra

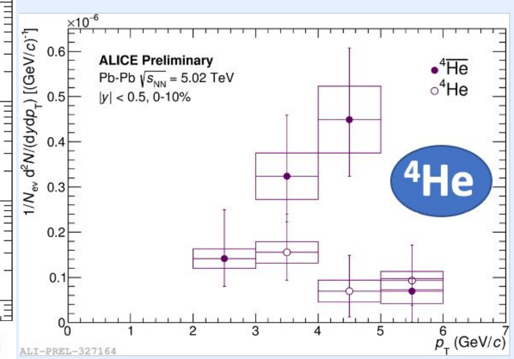
- Comprehensive measurements of light (anti)nuclei have been carried out in ALICE, from pp to Pb–Pb
- From (anti)deuterons to (anti)^{3}He and (anti)^{4}He

Eur. Phys. J. C (2022) 82:289



EPJC (2017) 77:658



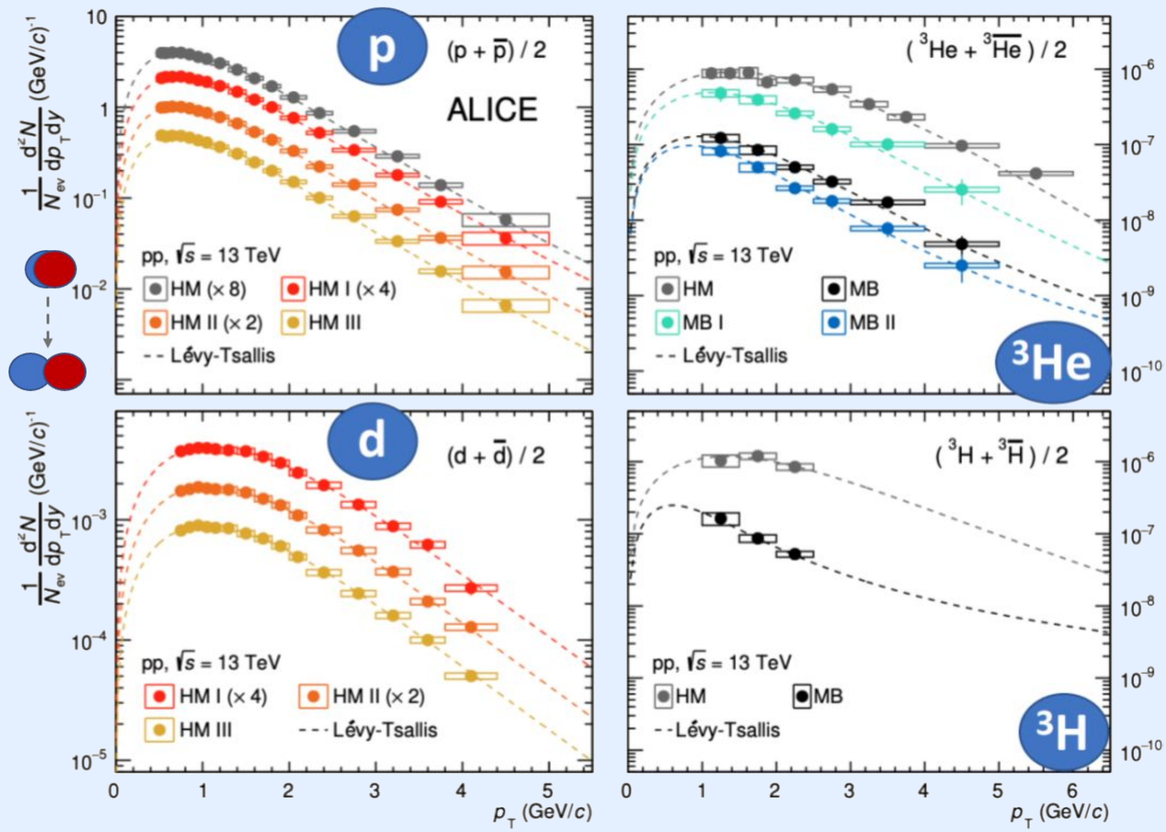


Light (anti)nuclei measured in ALICE

Transverse momentum spectra

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

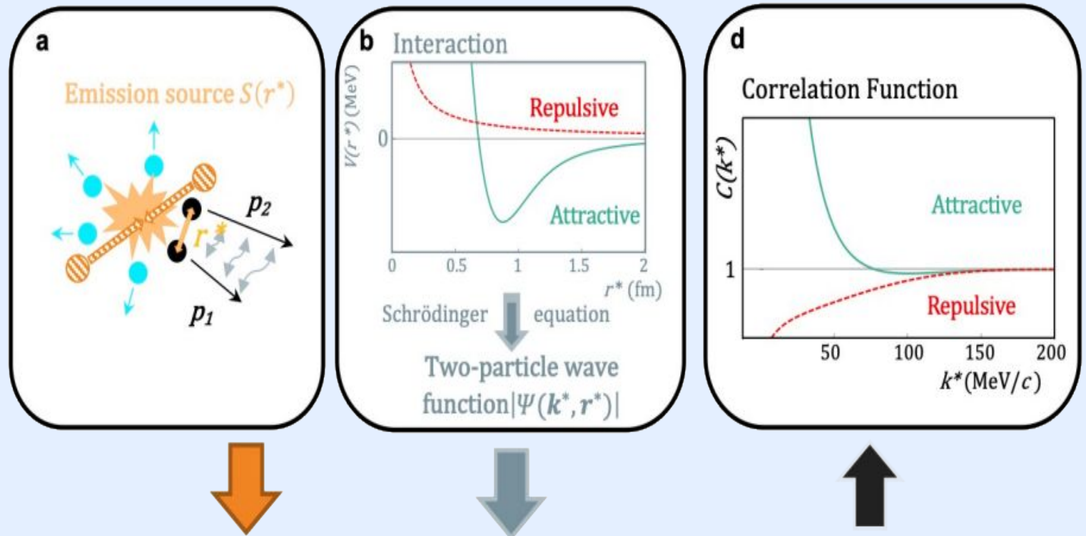


ALICE Coll., JHEP 01 (2022) 106

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)



c

$$C(k^*) = \int S(r^*) \; |\Psi(k^*, r^*)|^2 \, d^3r^* = \xi(k^*) \cdot \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

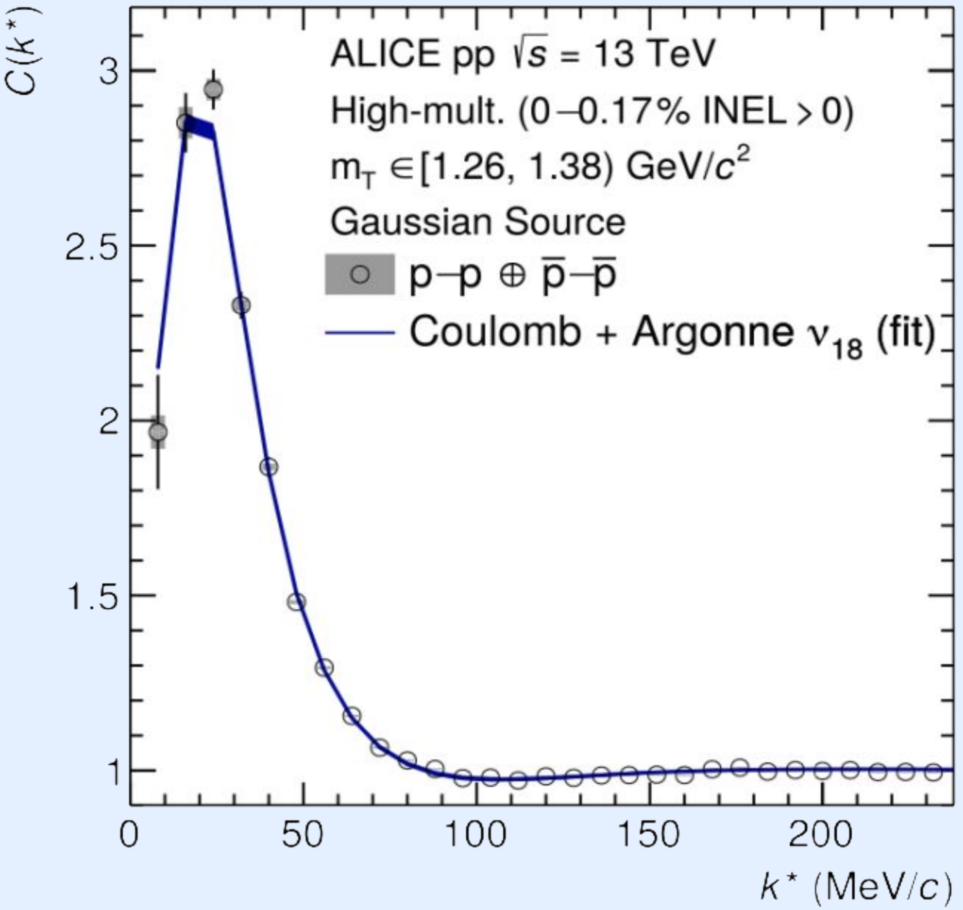
If we measure C(k*) and use a known interaction (e.g. nucleon-nucleon) we can study the emission source

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

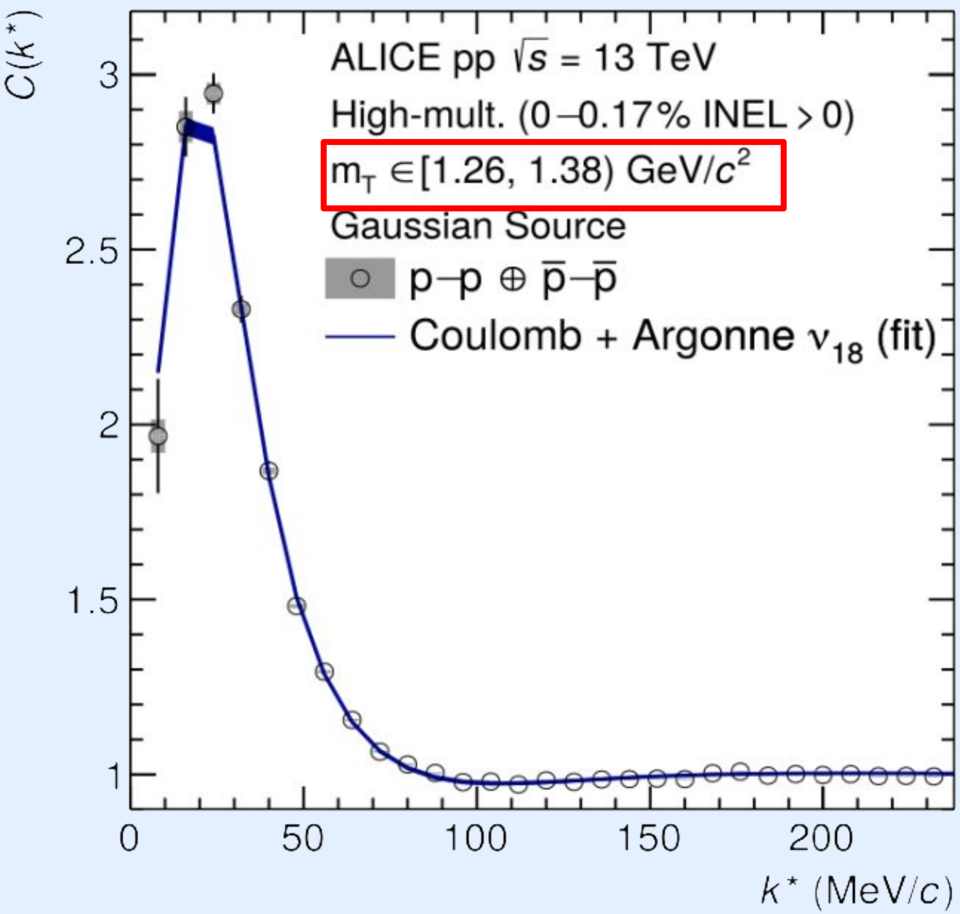


ALICE Coll., PLB 811 (2020) 135849

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
- When done as a function of m_T

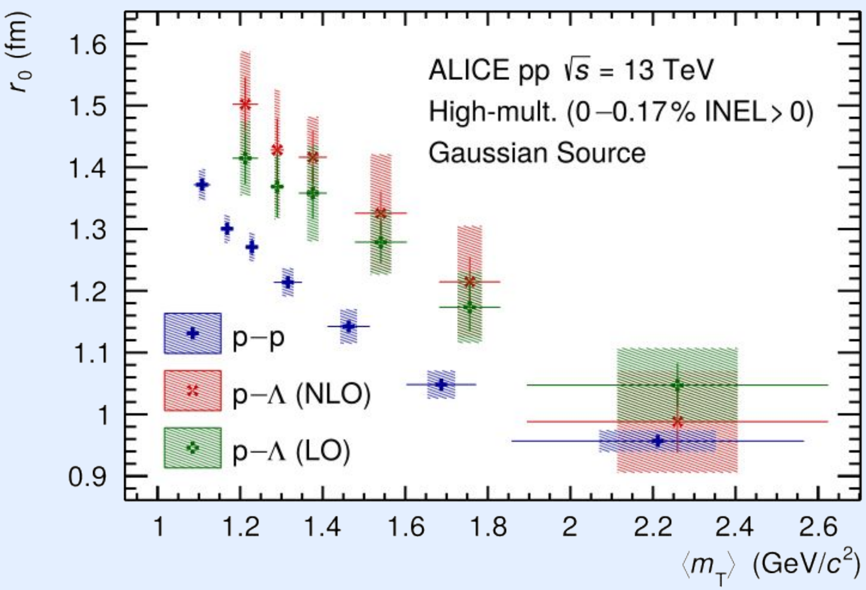


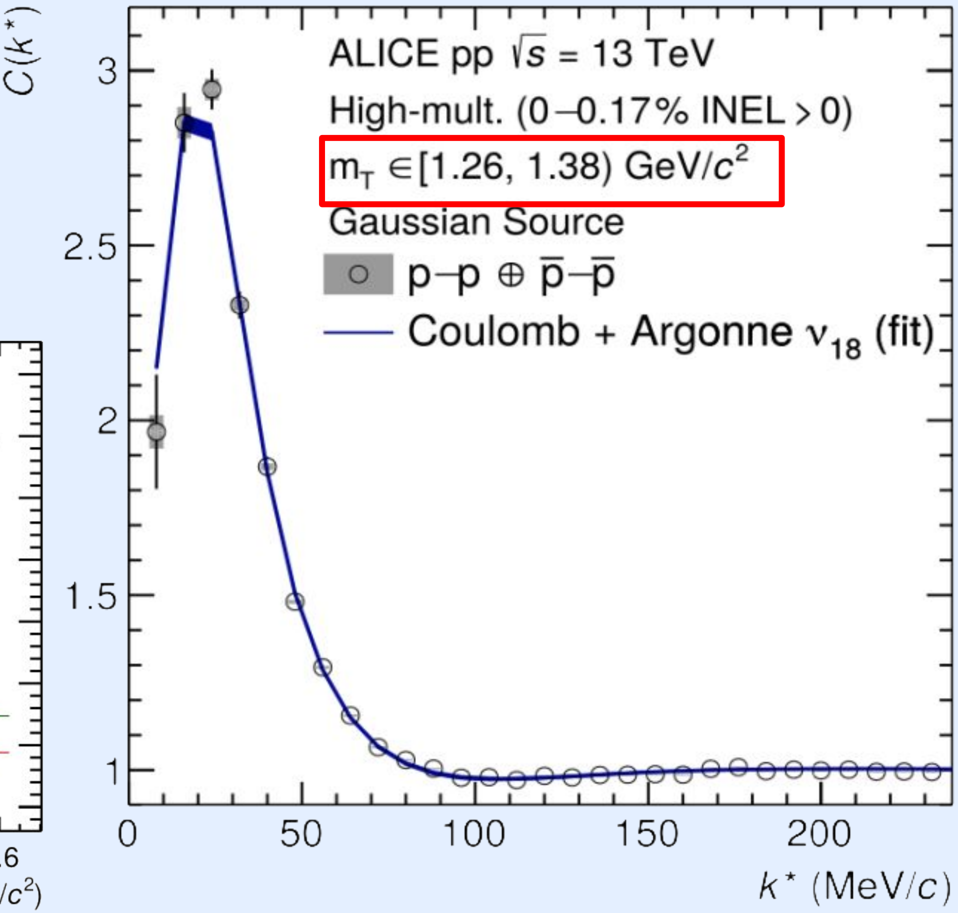
ALICE Coll., PLB 811 (2020) 135849

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
- ➤ When done as a function of m_T



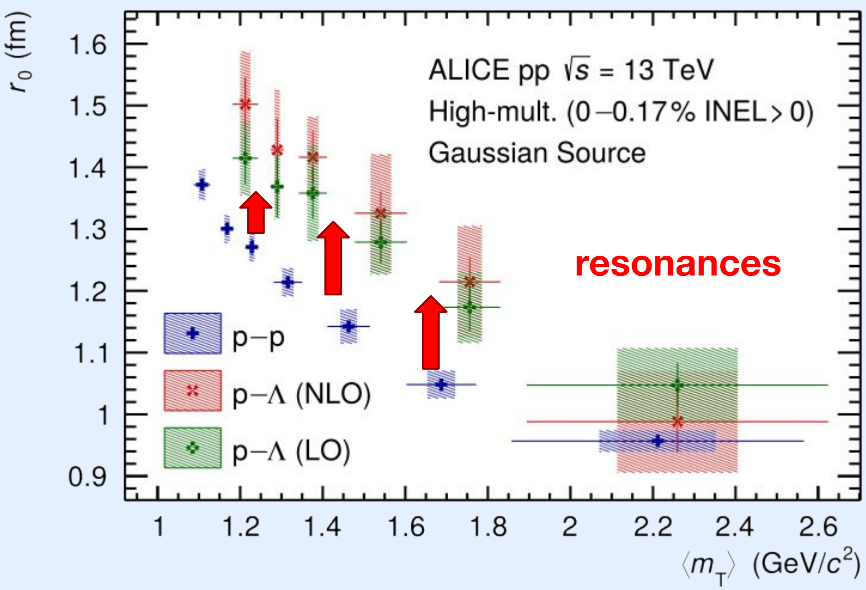


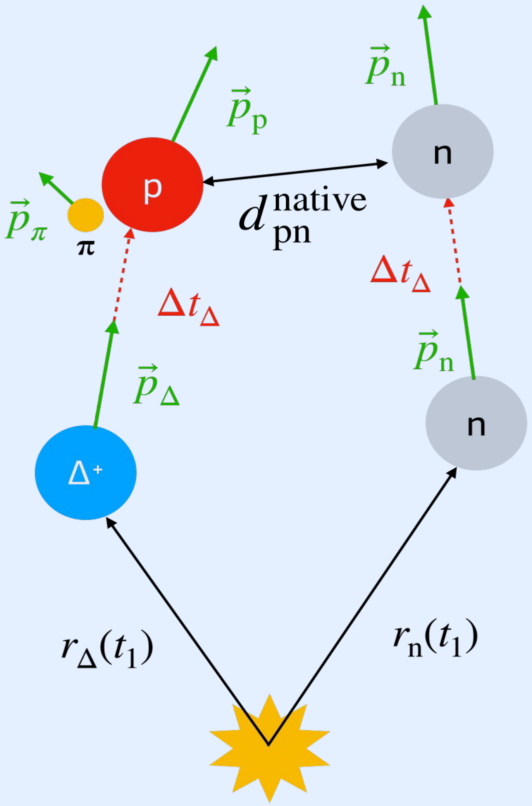
ALICE Coll., PLB 811 (2020) 135849

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
- When done as a function of m_T





also protons from resonance decays are used for coalescence!

ALICE Coll., PLB 811 (2020) 135849

The coalescence model

Wigner function formalism, tuned to ALICE measurements

Let's remember:

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

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

Constrained from data!

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

⇨ Test different hypotheses for the deuteron wave function

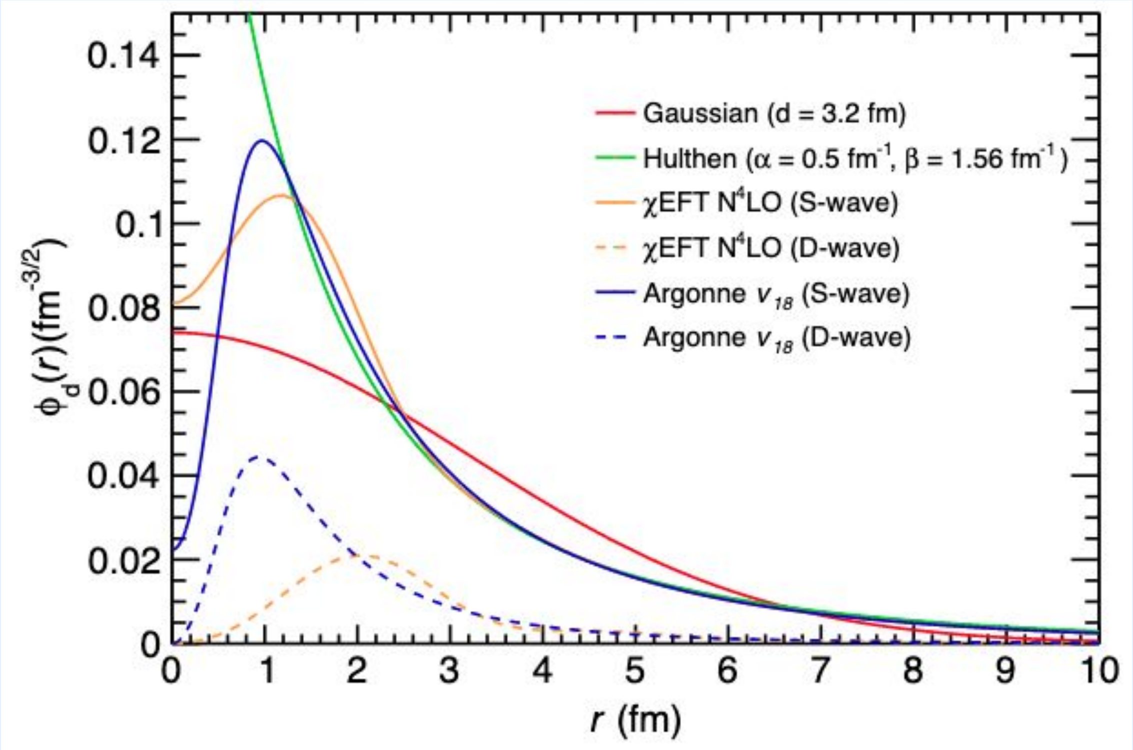
$$W(\vec{q},\vec{r}) = \int d^3\zeta\; \Psi(\vec{r}+\vec{\zeta}/2)\Psi^*(\vec{r}-\vec{\zeta}/2)e^{i\vec{q}\vec{\zeta}}$$

State of the art coalescence predictions

Wigner function formalism → wave functions

There are multiple models for the deuteron wave function

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



M. Mahlein et al., Eur.Phys.J.C 83 (2023) 9, 804

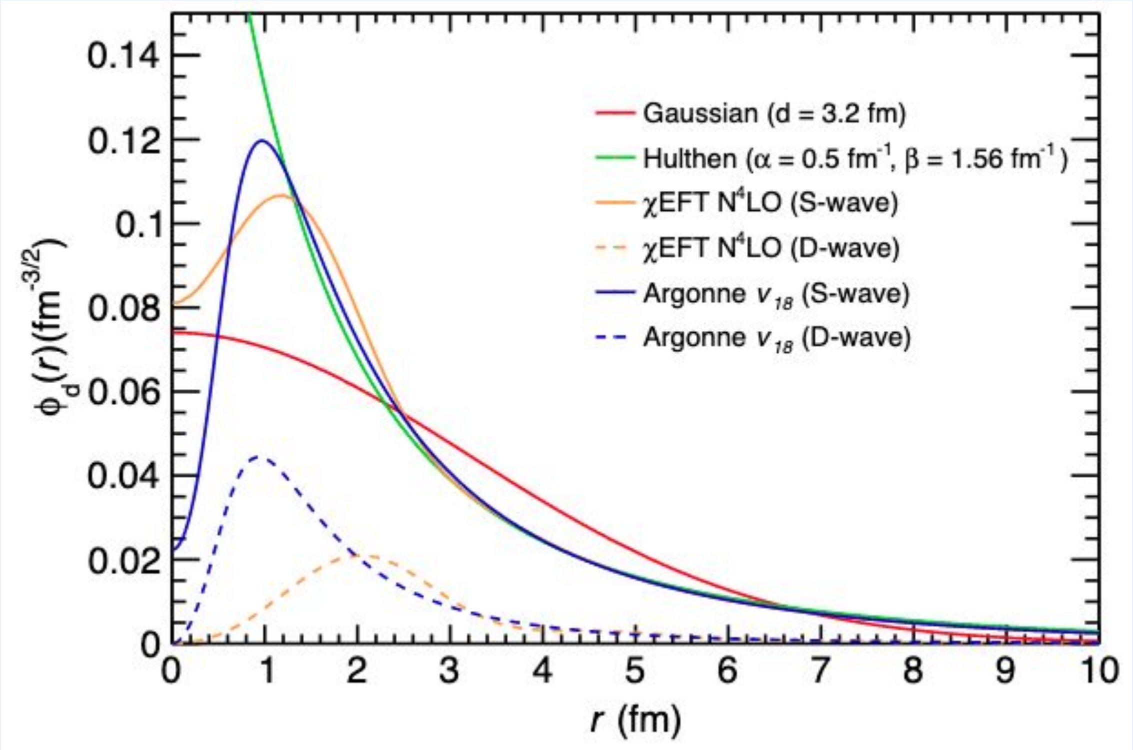
*Scheibl et al., PRC 59 (1999) 1585-1602
**Wiringa et al., PRC 51 (1995) 38-51

State of the art coalescence predictions

Wigner function formalism → wave functions

There are multiple models for the deuteron wave function

- Single Gaussian
- From *pion field theory* (Yukawa-like potential) ('50s)*:
  Hulthén **First time!**
- From pn scattering measurements**:
  Argonne v_{18} **First time!**



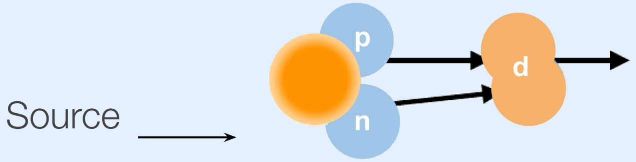
M. Mahlein et al., Eur.Phys.J.C 83 (2023) 9, 804

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

Parameter-free predictions

Wigner function formalism tuned to ALICE measurements

- Event-by-event coalescence afterburner with Wigner function formalism
- EPOS 3/Pythia 8.3 as event generator



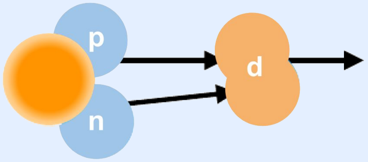
M. Mahlein et al., Eur.Phys.J.C 83 (2023) 9, 804

Parameter-free predictions

Wigner function formalism tuned to ALICE measurements

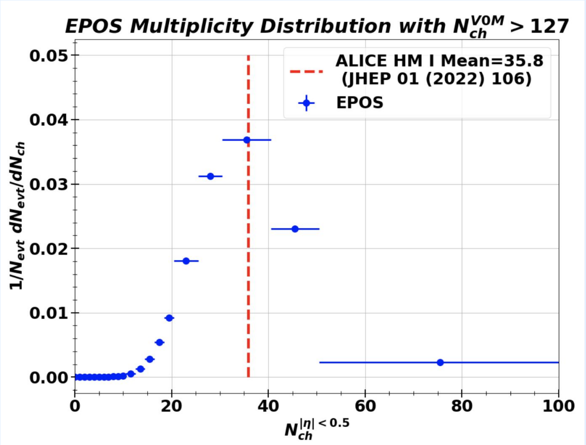
- Event-by-event coalescence afterburner with Wigner function formalism
- EPOS 3/Pythia 8.3 as event generator

Source



Ingredients

- Charged-particle multiplicity (35.8±0.5)

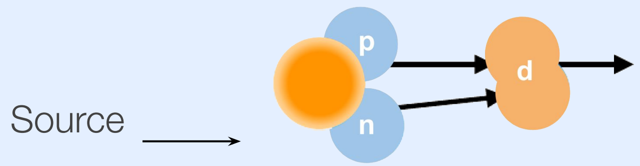


M. Mahlein et al., Eur.Phys.J.C 83 (2023) 9, 804

Parameter-free predictions

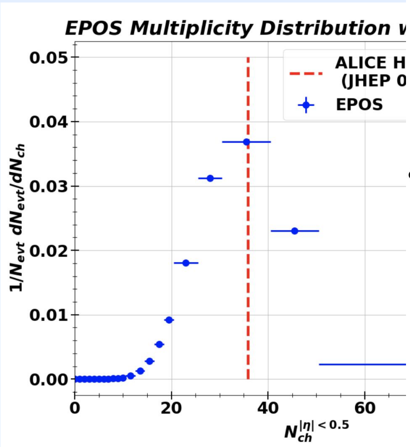
Wigner function formalism tuned to ALICE measurements

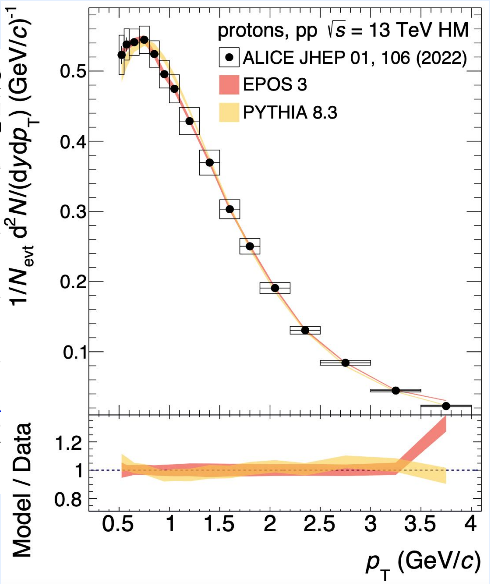
- ➤ Event-by-event coalescence afterburner with Wigner function formalism
- ➤ EPOS 3/Pythia 8.3 as event generator



Ingredients

- ➤ Charged-particle multiplicity (35.8±0.5)
- ➤ Protons (and neutrons) are tuned to p measurements from ALICE



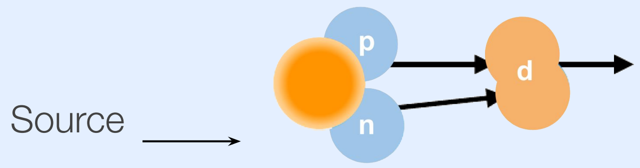


M. Mahlein et al., Eur.Phys.J.C 83 (2023) 9, 804

Parameter-free predictions

Wigner function formalism tuned to ALICE measurements

- Event-by-event coalescence afterburner with Wigner function formalism
- EPOS 3/Pythia 8.3 as event generator



Ingredients

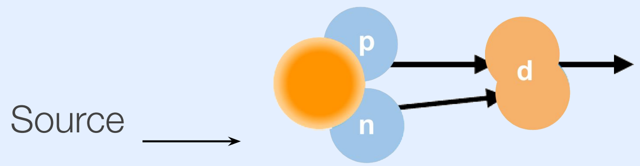
- Charged-particle multiplicity (35.8±0.5)
- Protons (and neutrons) are tuned to p measurements from ALICE
- Improved source model
  - resonance abundancies tuned to SHM

M. Mahlein et al., Eur.Phys.J.C 83 (2023) 9, 804

Parameter-free predictions

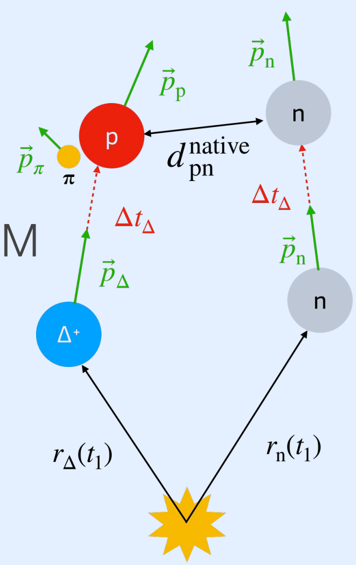
Wigner function formalism tuned to ALICE measurements

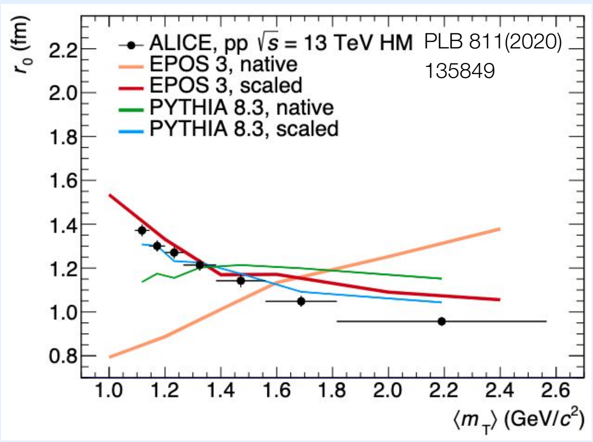
- Event-by-event coalescence afterburner with Wigner function formalism
- EPOS 3/Pythia 8.3 as event generator



Ingredients

- Charged-particle multiplicity (35.8±0.5)
- Protons (and neutrons) are tuned to p measurements from ALICE
- Improved source model
  - resonance abundancies tuned to SHM
  - source size
    - evt-by-evt propagation to obtain d_{pn}^{native}
    - m_T-dependent scaling tuned to data





M. Mahlein et al., Eur.Phys.J.C 83 (2023) 9, 804

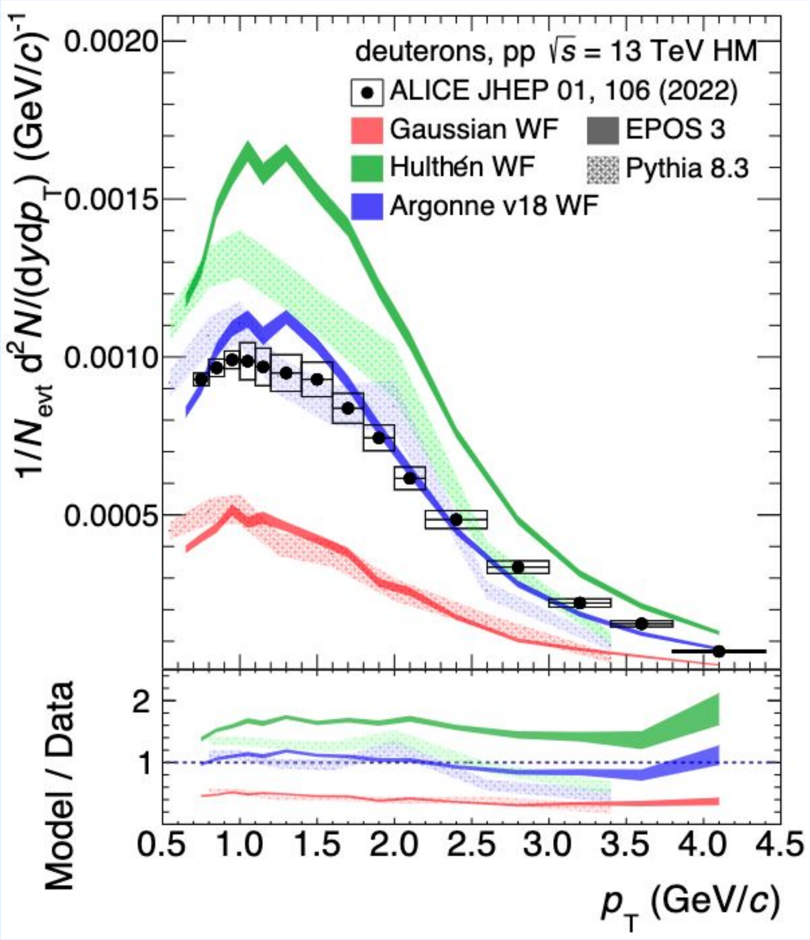
Parameter-free predictions

Wigner function formalism tuned to ALICE measurements

- ➤ Event-by-event coalescence afterburner with Wigner function formalism
- ➤ EPOS 3/Pythia 8.3 as event generator

Ingredients

- ➤ Charged-particle multiplicity (35.8±0.5)
- ➤ Protons (and neutrons) are tuned to p measurements from ALICE
- ➤ Improved source model
  - ➢ resonance abundancies tuned to SHM
  - ➢ source size
    - evt-by-evt propagation to obtain d_{pn}^{native}
    - m_T-dependent scaling tuned to data
- ➤ Realistic wavefunction: Argonne v_{18} best agreement



M. Mahlein et al., Eur.Phys.J.C 83 (2023) 9, 804

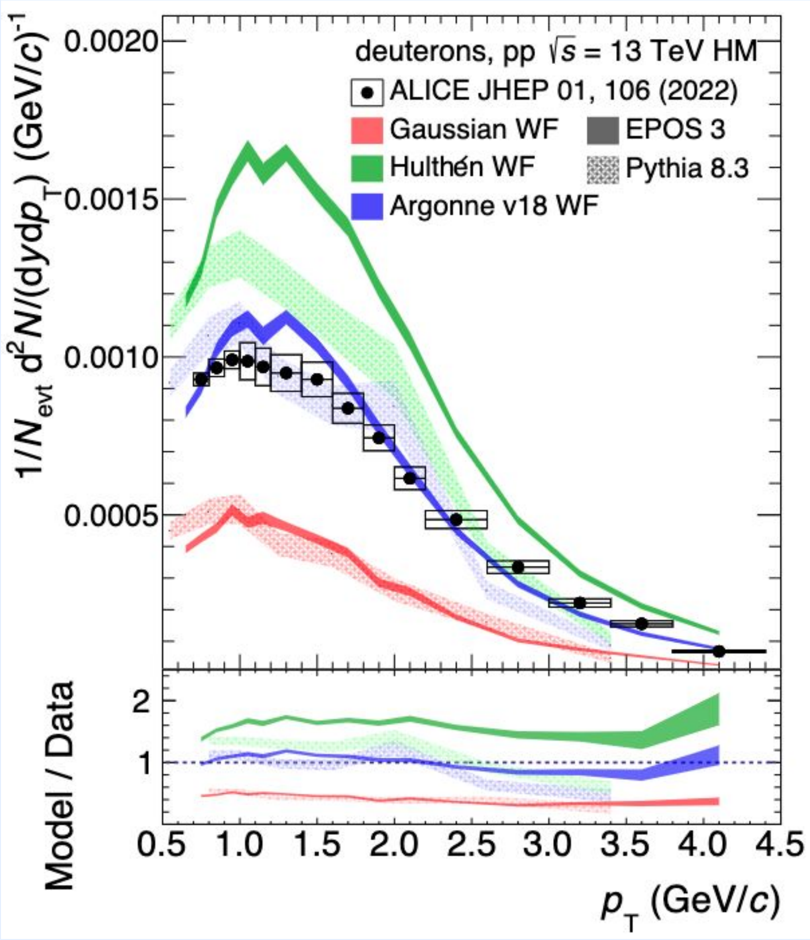
Parameter-free predictions

Wigner function formalism tuned to ALICE measurements

- ➤ Event-by-event coalescence afterburner with Wigner function formalism
- ➤ EPOS 3/Pythia 8.3 as event generator

Ingredients

- ➤ Charged-particle multiplicity (35.8±0.5)
- ➤ Protons (and neutrons) are tuned to p measurements from ALICE
- ➤ Improved source model
  - ➢ resonance abundancies tuned to SHM
  - ➢ source size
    - evt-by-evt propagation to obtain d_{pn}^{native}
    - m_T-dependent scaling tuned to data
- ➤ Realistic wavefunction: Argonne v_{18} best agreement

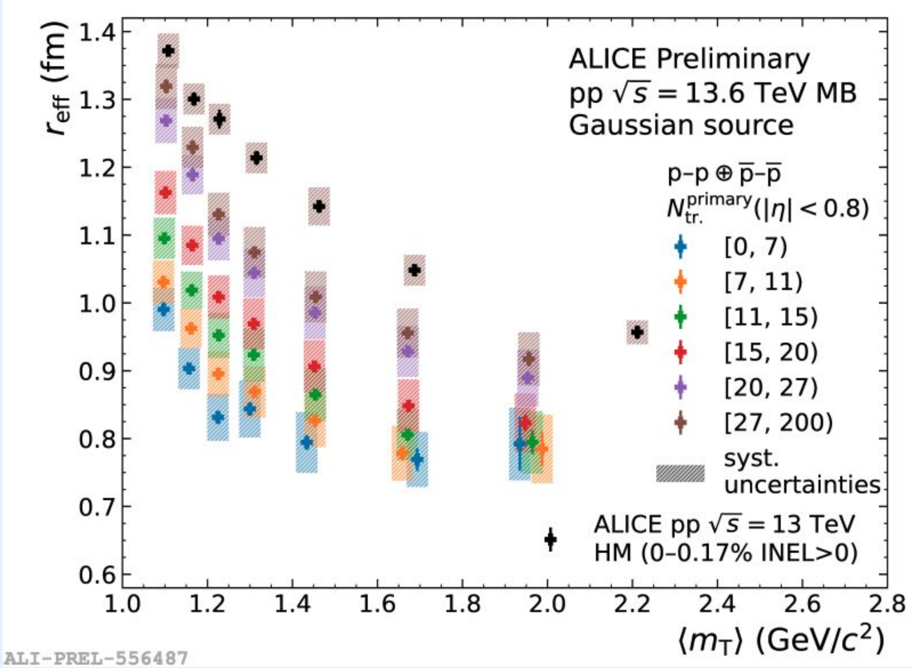


Model successfully reproduces data with no free-parameters!

M. Mahlein et al., Eur.Phys.J.C 83 (2023) 9, 804

Extending the model to different energies

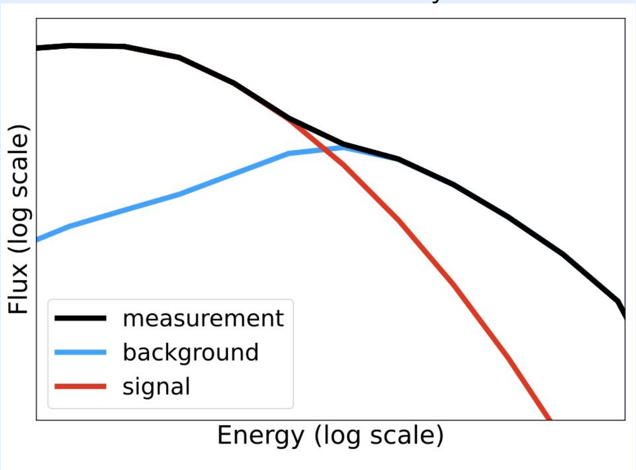
- The model is validated in HM pp $\sqrt{s}$ = 13 TeV, it can be extended to MB pp $\sqrt{s}$ = 13.6 TeV using LHC Run 3 statistics
- m_T-dependent r_0 have been measured by ALICE with Run 3 data as a function of multiplicity (primary charged tracks used as a proxy)



- On reverse mode, it can be used to predict the m_T-dependence of the emitting source size when deuteron spectra are available

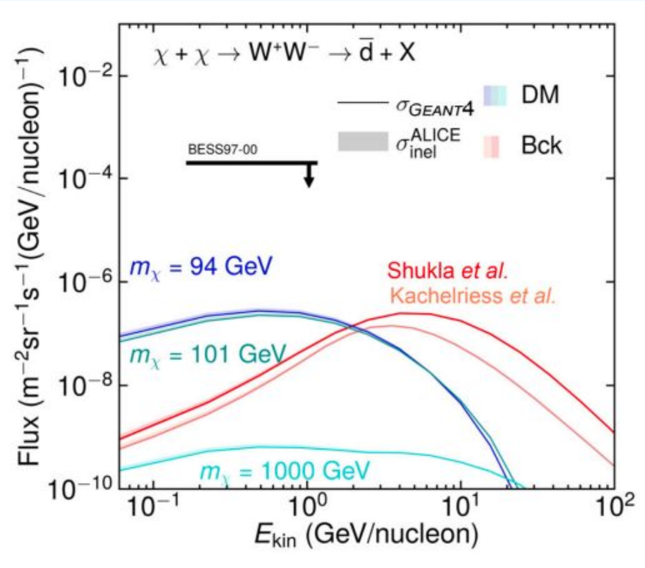
What's next?

antinuclei cosmic ray flux



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

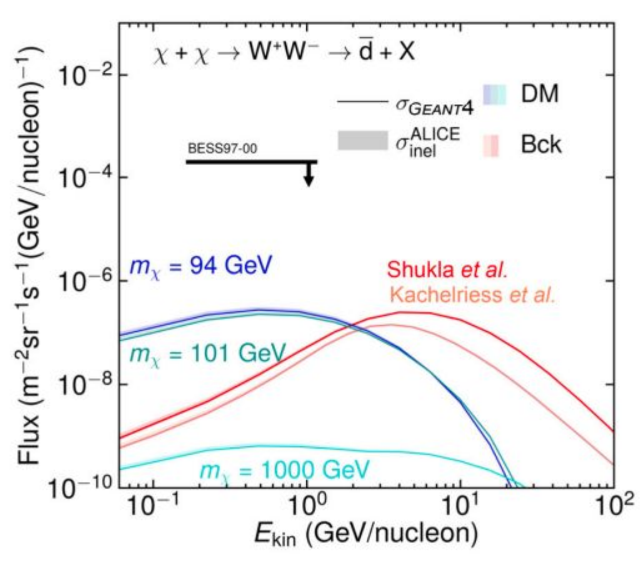
What's next?



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

Serksnyte et al., PRD 105 (2022) 083021

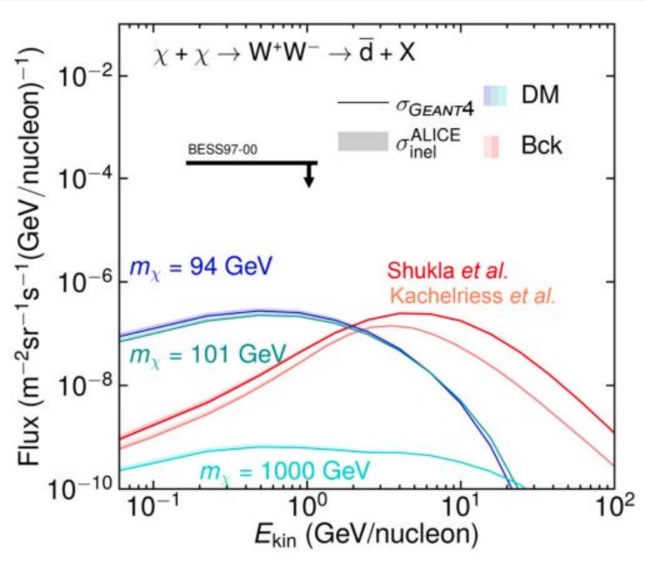
What’s next?



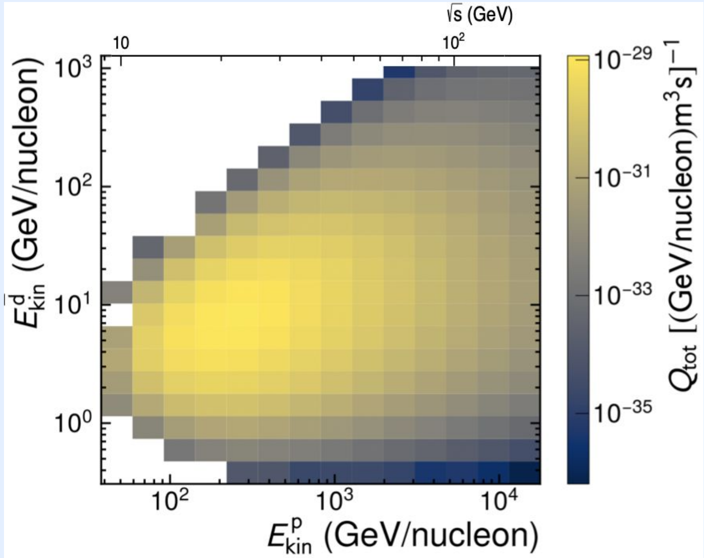
- Modelling antinuclei production is an essential backbone to interpret any future measurement of cosmic ray antinuclear fluxes
- Antideuteron production predominantly from collisions of protons of E_{kin}~200-500 GeV ($\sqrt{s}$ ~ 19-30 GeV for p-H)

Serksnyte et al., PRD 105 (2022) 083021

What's next?



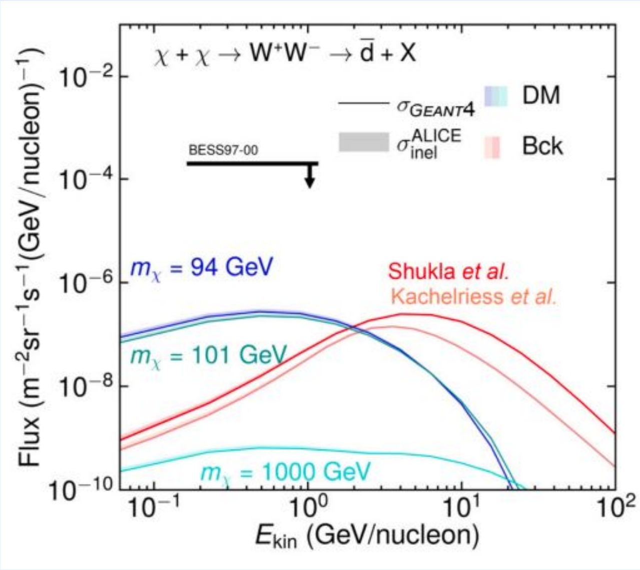
- Modelling antinuclei production is an essential backbone to interpret any future measurement of cosmic ray antinuclear fluxes
- Antideuteron production predominantly from collisions of protons of E_{kin}~200-500 GeV ($\sqrt{s}$ ~ 19-30 GeV for p-H)

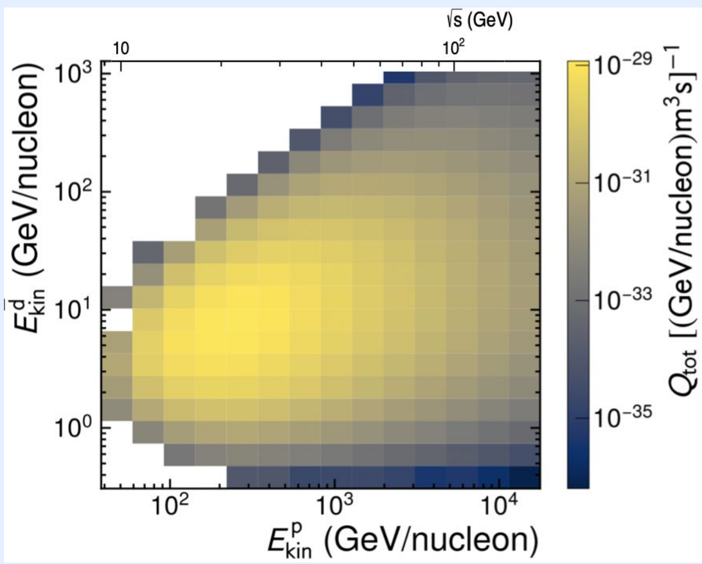


Antideuteron source function as a function of kinetic energy of the incoming proton and produced antideuteron

Serksnyte et al., PRD 105 (2022) 083021

What's next?



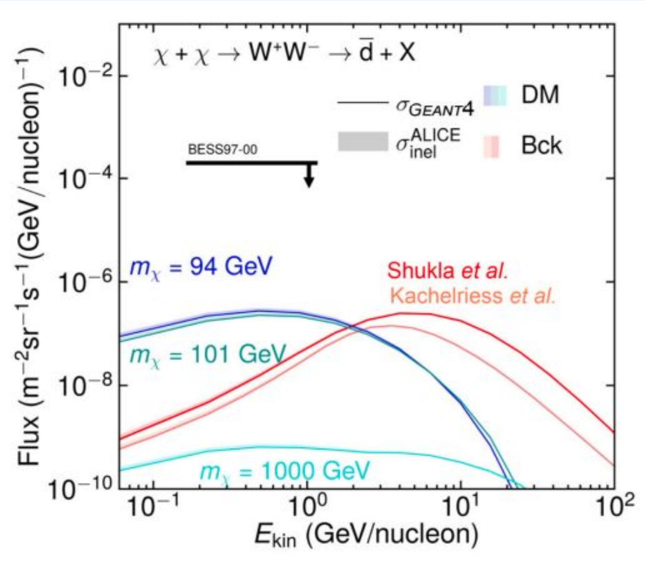


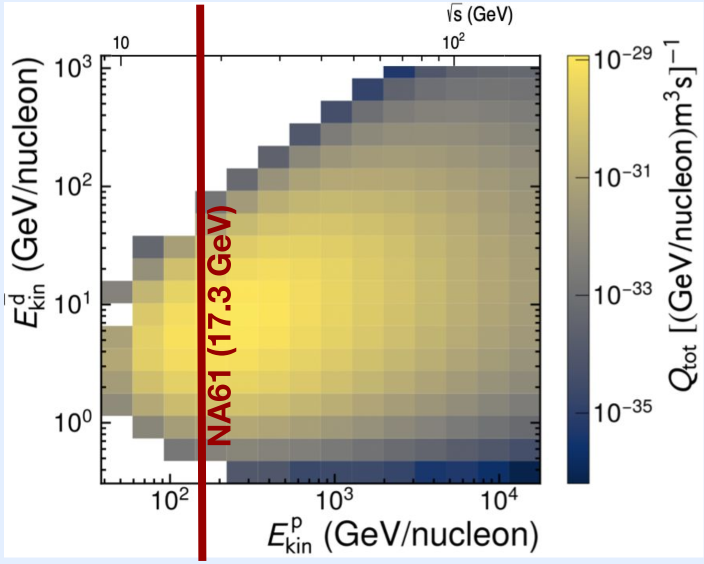
- Modelling antinuclei production is an essential backbone to interpret any future measurement of cosmic ray antinuclear fluxes
- Antideuteron production predominantly from collisions of protons of E_{kin}~200-500 GeV ($\sqrt{s}$ ~ 19-30 GeV for p-H)
- Modelling production of antideuterons for HM pp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

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

Serksnyte et al., PRD 105 (2022) 083021

What's next?





- 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
- Experimental measurements of production spectra & emitting source size at different energies needed → to extrapolate in the energy range of interest (ongoing efforts in NA61)

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

Serksnyte et al., PRD 105 (2022) 083021

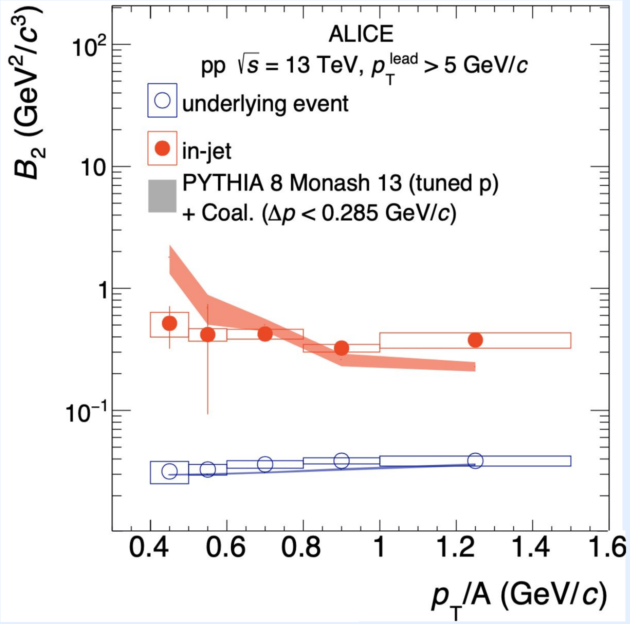
Backup slides

Applications in ALICE

- Once it is validated in HM pp $\sqrt{s}$ = 13 TeV, it can be used to predict the m_T-dependence of the emitting source size when deuteron spectra are available
  - MB pp $\sqrt{s}$ = 13 TeV & $\sqrt{s}$ = 900 GeV, m_T-integrated value measured (ongoing)
  - in-jet and UE pp $\sqrt{s}$ = 13 TeV

- B_2 in jets will be measured with anti-k_T jet finder algorithm using ALICE Run3 data (x10^4 increased statistics wrt Run2) as a function of
  - transverse momentum of the leading particle
  - jet multiplicity
  - jet resolution parameter

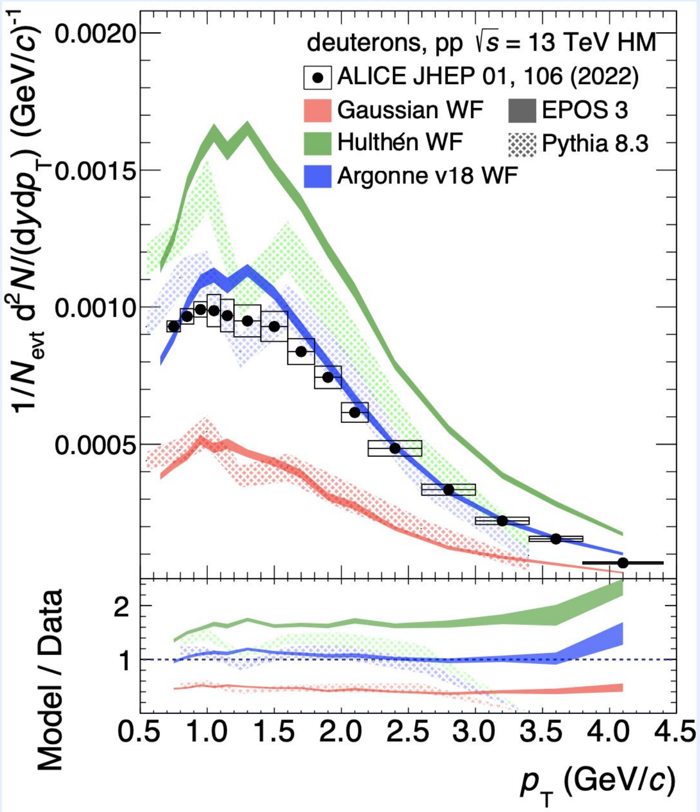
- Coalescence model calculations will need source size measurement → experimentally challenging



Summary of the model

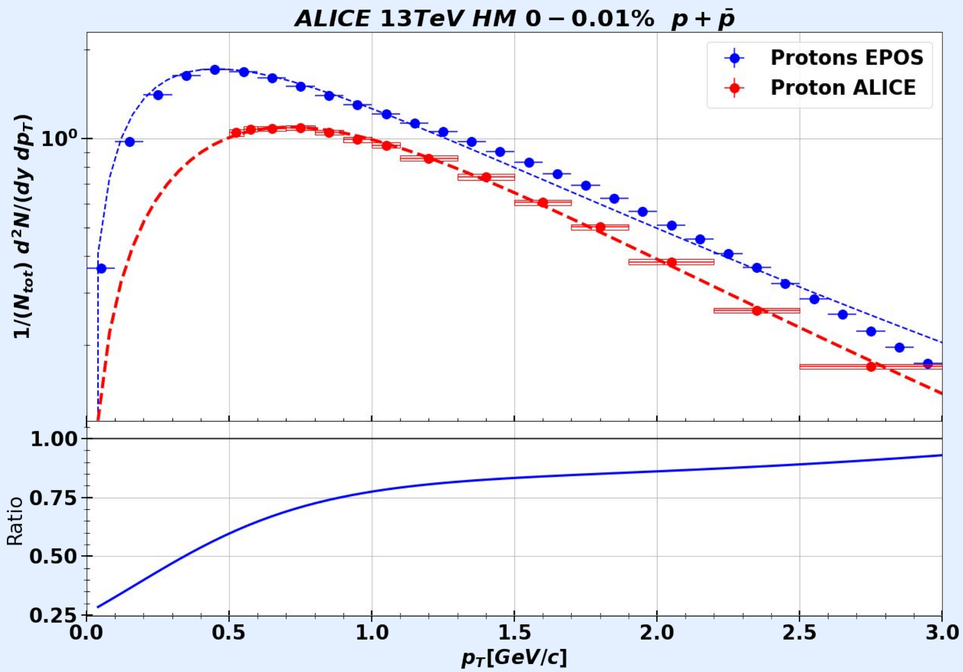
- Novel approach for coalescence based on Wigner function formalism is developed
- Deuteron production in high multiplicity pp collisions $\sqrt{s}$ = 13 TeV
- *If* we have control of the underlying physics
  - charged-particle multiplicity
  - (anti)nucleon momentum distributions
  - resonance cocktail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

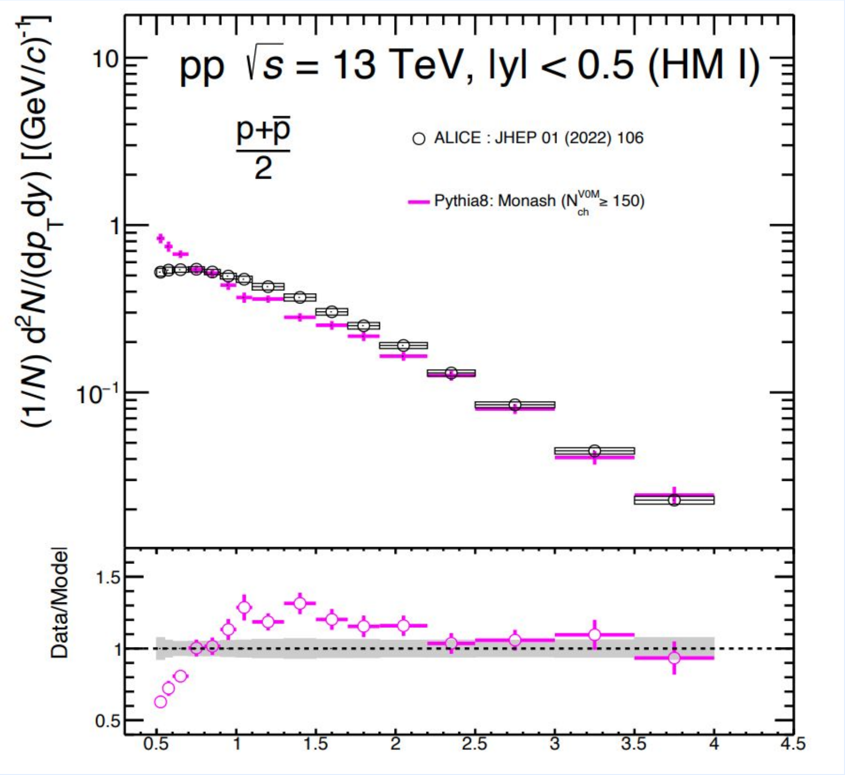
- Model successfully reproduces data with no free-parameters!



arXiv:2302.12696

Protons native from evt generators



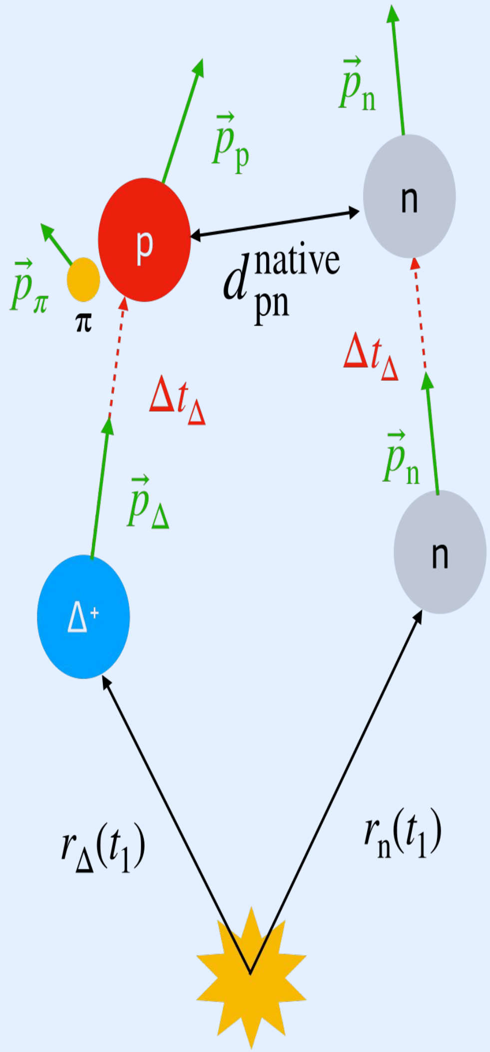


Applications

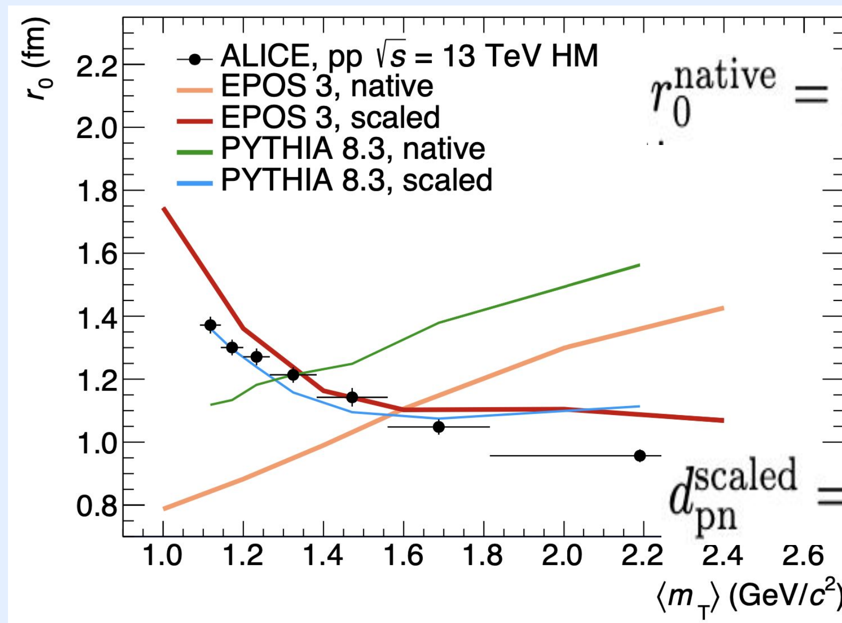
- Experimental measurements of production spectra & emitting source size at lower energies needed → to extrapolate the antinuclear production in the energy range of interest for astrophysics ($\sqrt{s}$ ~ 19-30 GeV)

- Once it is validated in HM pp $\sqrt{s}$ = 13 TeV, it can be used to predict the m_T dependence of the emitting source size when production spectra are available
  - MB pp $\sqrt{s}$ = 13 TeV, m_T-integrated value measured (ongoing)
  - in-jet and UE pp $\sqrt{s}$ = 13 TeV

Source modelling



Event-by-Event propagation to calculate native distance between nucleons
m_T - dependent scaling evt-by-evt



$$r_0^{native} = (\sqrt{\pi}/4)\, r_\mu^{native}$$

mean value of d_{pn}^{native}

$$d_{pn}^{scaled} = \mathcal{S}(m_T)\, d_{pn}^{native}$$

$$\mathcal{S}(m_T) = r_0^{ALICE} / r_0^{native}$$

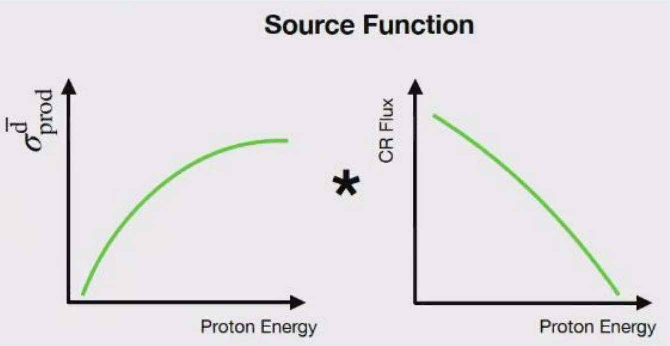
$r_0^{native} = (\sqrt{\pi}/4) <d_{pn}^{native}>$

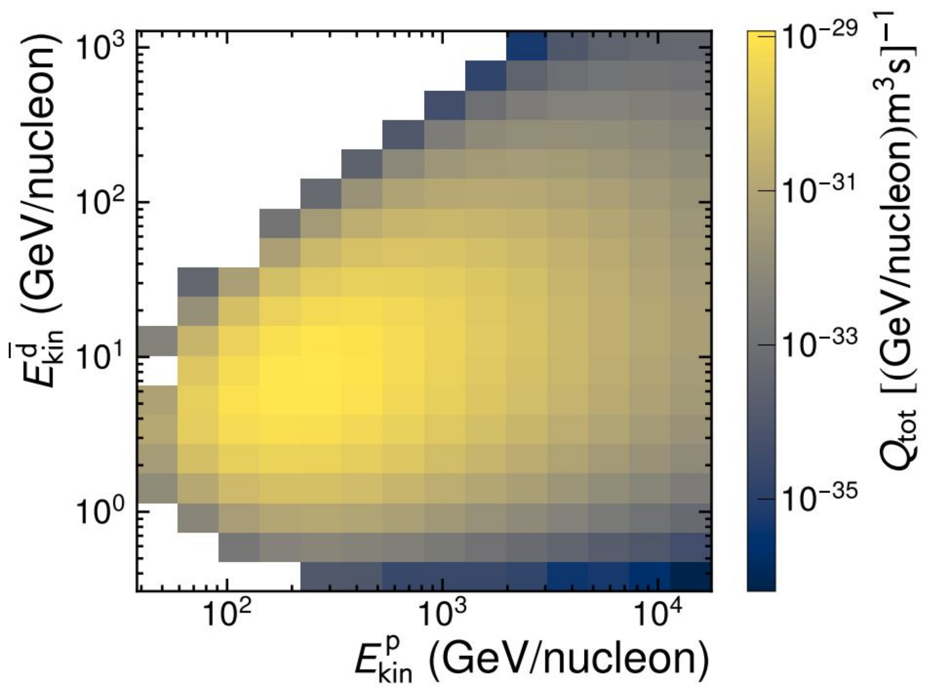
ALICE Coll., PLB 811(2020) 135849

Cosmic Rays

Production energy of antinuclei

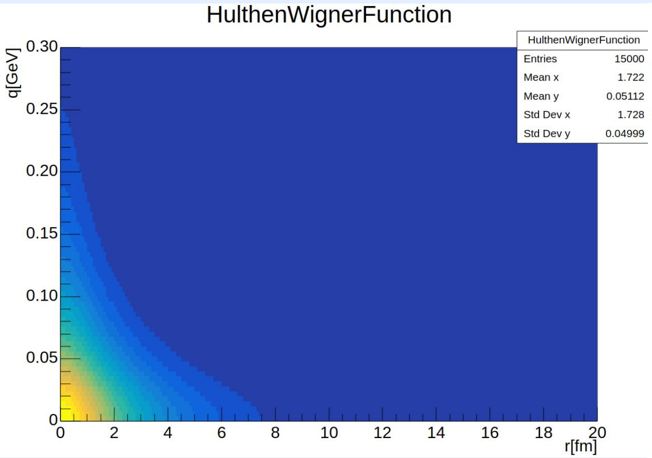
- Antideuteron source function as a function of kinetic energy of the incoming proton and produced antideuteron
- Antideuteron production predominantly for protons of E_{kin}~200-500 GeV ($\sqrt{s}$ ~ 19-30 GeV for p-H)

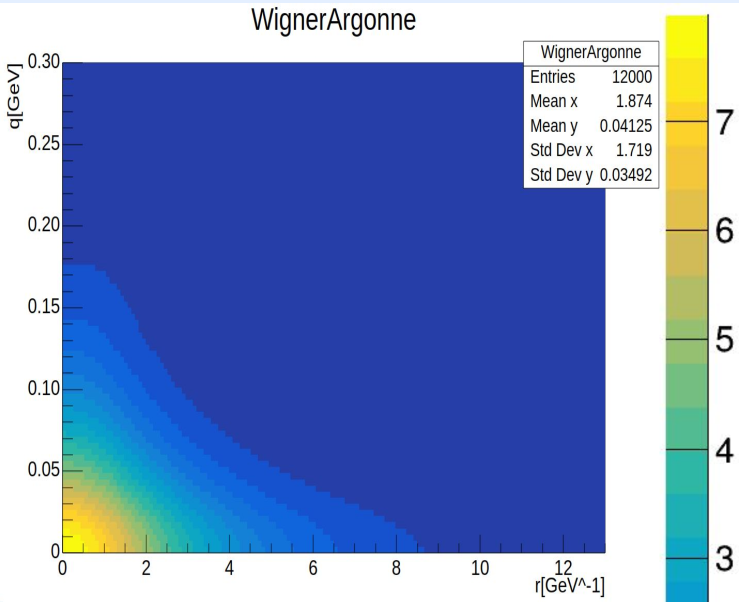


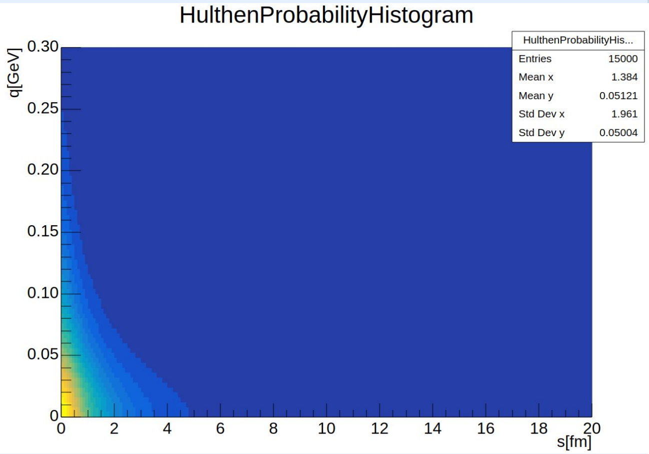


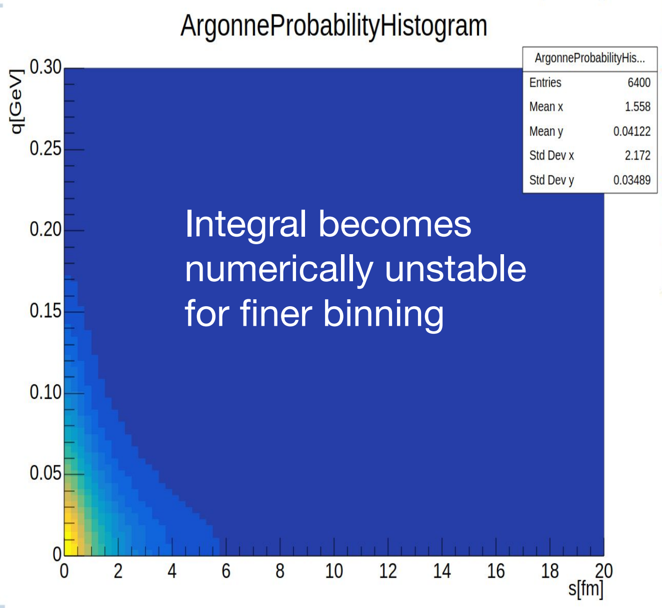
Šerkšnytė, et al. PHYSICAL REVIEW D 105, 083021 (2022)

New Wiger functions/Probabilities



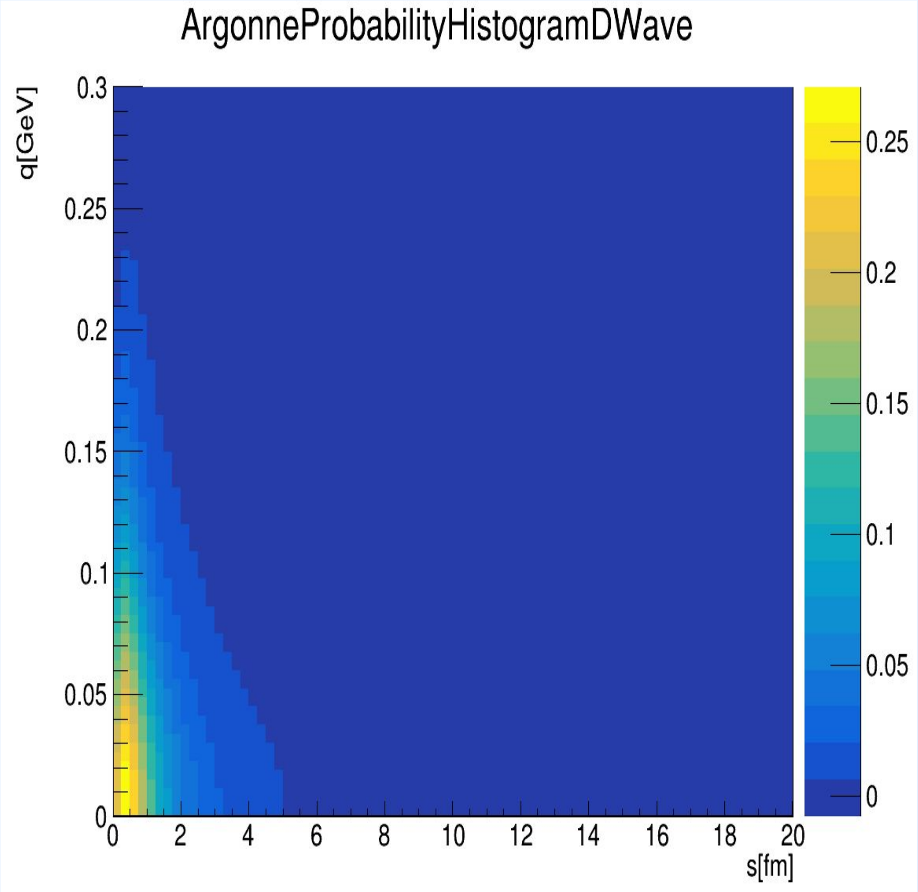


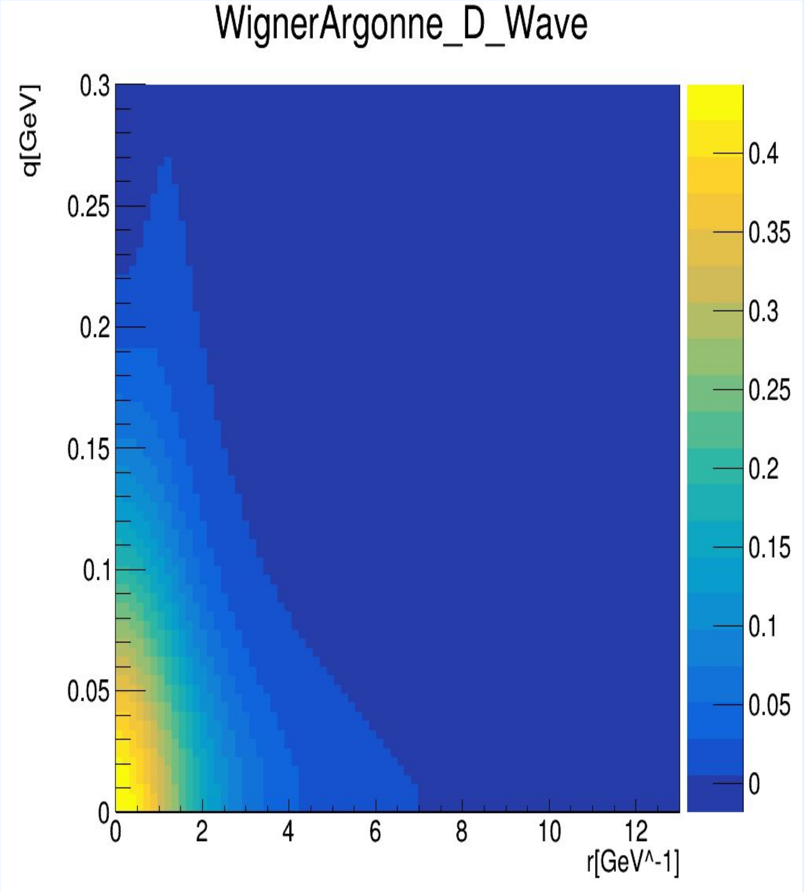




Integral becomes numerically unstable for finer binning

Argonne D-State probability





D-State probability is 6%

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

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	70	11.5
	p + Be		
CERN-SPS	p + Be	200	19.4
	p + Al		
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!

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

Modelling (anti)nuclei production

B_A predictions

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

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

- Theoretical prediction [1]

Emission source size

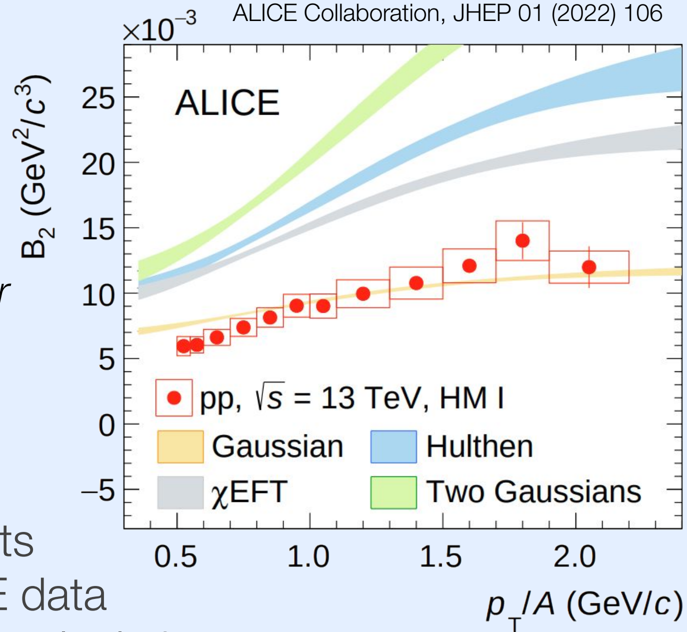
* *keep it in mind for later!*

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

Deuteron wave function

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

ALICE Collaboration, JHEP 01 (2022) 106



Testing different wave functions:

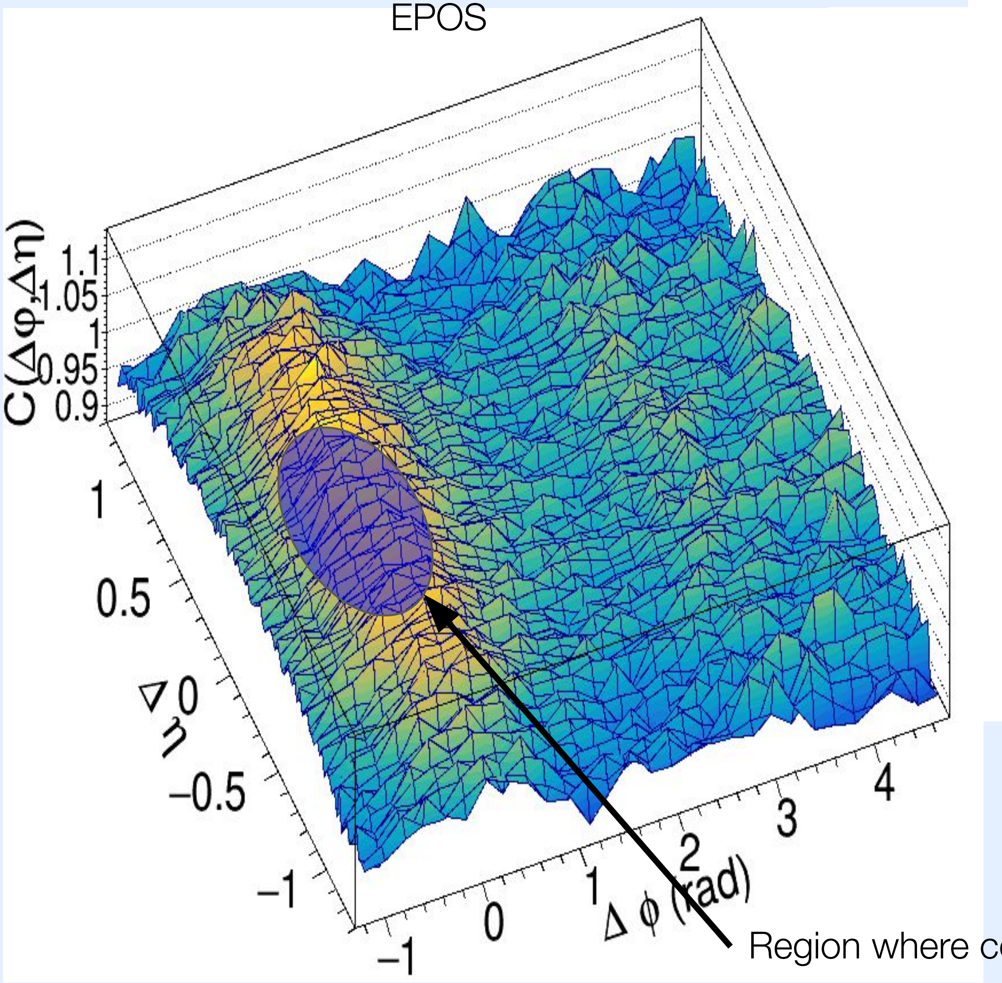
- **Hulthén:** Favoured by low energy scattering experiments
- **Gaussian:** Best description of currently available ALICE data
- **Two Gaussians:** Approximates Hulthén, easy to use in calculations
- **χEFT:** Favoured by modern nuclear interaction experiments (e.g. Femtoscopy)

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

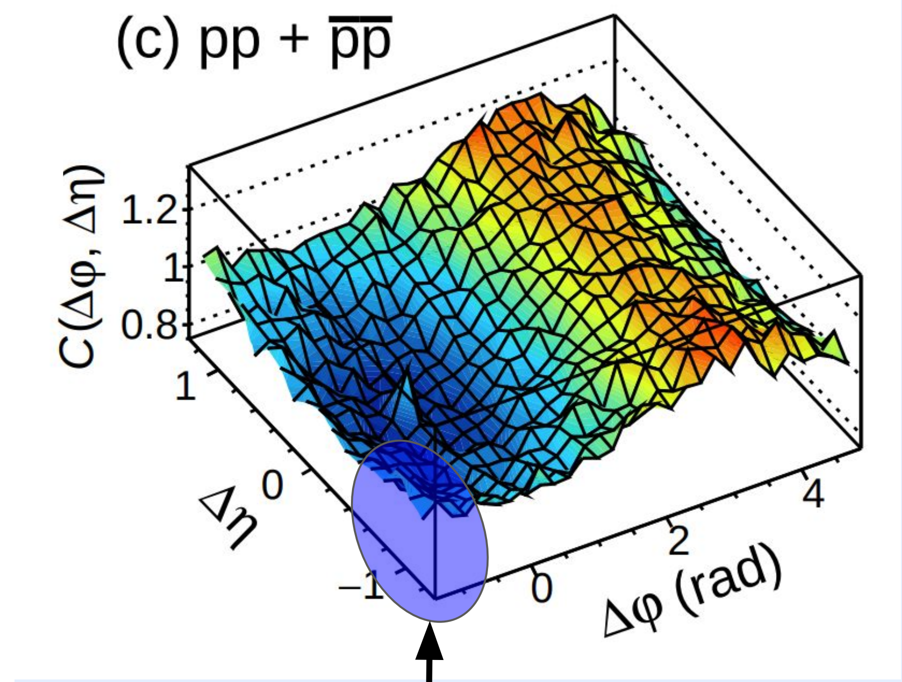
Correlations comparison

Δη-Δφ Correlation function

EPOS



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



Region where coalescence happens!