ExtreMe Matter Institute EMMI

EMMI Rapid Reaction Task Force

Understanding light (anti-)nuclei production at RHIC and LHC

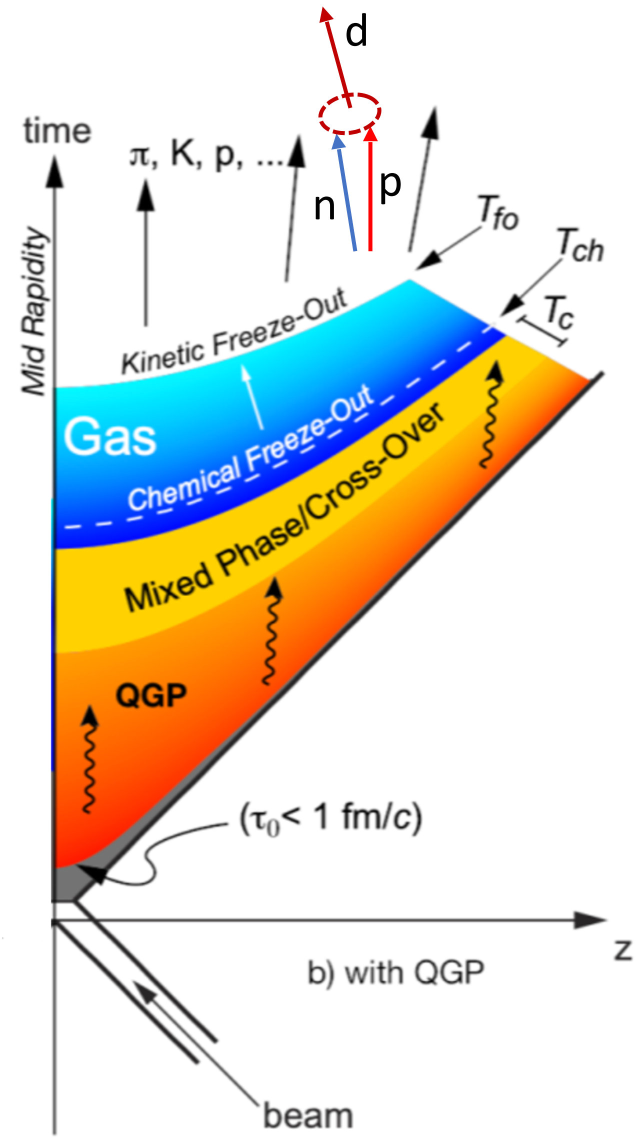
April 8 - 12, 2024

SB1 Lecture Hall, GSI, Darmstadt , Germany

# Experimental overview on light (anti) (hyper)nuclei production at the LHC

Chiara Pinto
(CERN)

# Production of (anti)nuclei at the LHC



- At LHC energies ($\sqrt{s}$ ~ 1–13 TeV) same amount of matter and anti-matter is measured ($\mu_B$ ~ 0)
- Production mechanism still under debate
- Two classes of phenomenological models available:
  - **statistical hadronization →** works very well for integrated yields (even for nuclei!)
  - **coalescence →** describes fairly well the ratio to protons of integrated yields

chiara.pinto@cern.ch

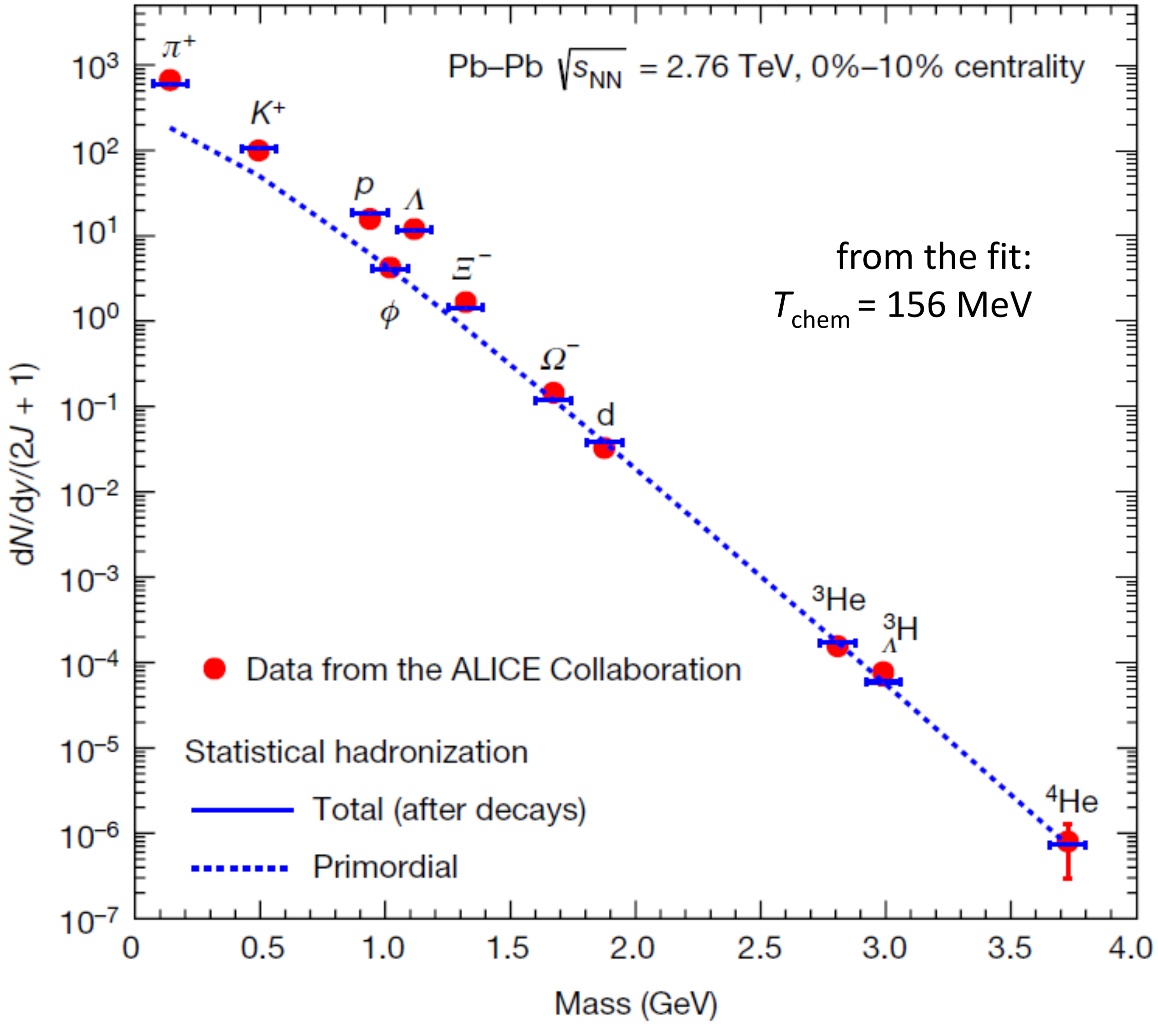
# Modelling the production of (anti)nuclei

## Statistical models (SHMs)

- Hadrons emitted from a system in statistical and chemical equilibrium
- dN/dy $\propto$ exp(-m/$T_{chem}$ )

  $\Rightarrow$ Nuclei (large m): large sensitivity to $T_{chem}$
- Light nuclei are produced during phase transition (as other hadrons)
- Typical binding energy of nuclei ~ few MeV (*$E_B \sim$ 2 MeV for d*)

***$\Rightarrow$ how can they survive the hadronic phase environment ($T_{chem} \sim$ 156 MeV )?***

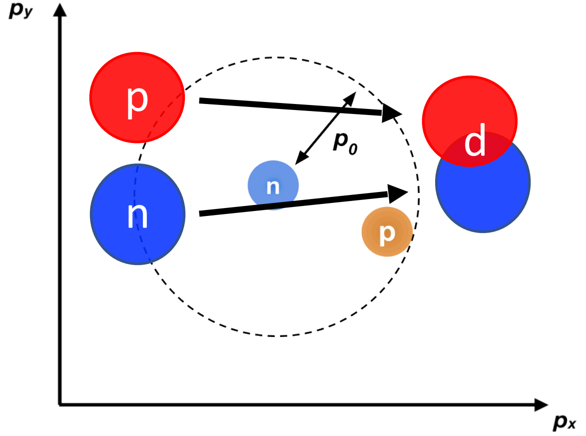


Andronic et al., Nature 561, 321–330 (2018)

# Modelling the production of (anti)nuclei

## Coalescence models

- Simplest implementation: *spherical approximation* → if (anti)nucleons are close in phase space ($\Delta \boldsymbol{p} < \boldsymbol{p}_0$) and match the spin state, they can form a (anti)nucleus

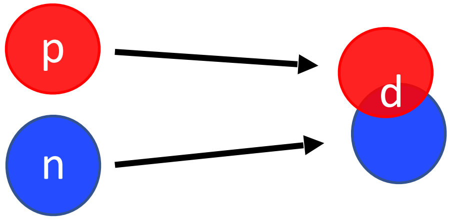


Butler et al., Phys. Rev. 129 (1963) 836

chiara.pinto@cern.ch

# Modelling the production of (anti)nuclei

## Coalescence models



- Simplest implementation: *spherical approximation* → if (anti)nucleons are close in phase space ($\Delta \boldsymbol{p} < \boldsymbol{p}_0$) and match the spin state, they can form a (anti)nucleus

- State-of-the-art models use the *Wigner function formalism* → (anti)nuclei arise from the overlap of the (anti)nucleons phase-space distributions with the Wigner density of the bound state

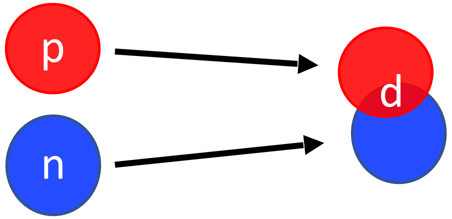
📚 Butler et al., Phys. Rev. 129 (1963) 836

📚 Mahlein et al., EPJC 83 (2023) 9, 804

chiara.pinto@cern.ch

# Modelling the production of (anti)nuclei

## Coalescence models



- Simplest implementation: *spherical approximation* → if (anti)nucleons are close in phase space ($\Delta \boldsymbol{p} < \boldsymbol{p}_0$) and match the spin state, they can form a (anti)nucleus

- State-of-the-art models use the *Wigner function formalism* → (anti)nuclei arise from the overlap of the (anti)nucleons phase-space distributions with the Wigner density of the bound state

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

📚 Mahlein et al., EPJC 83 (2023) 9, 804

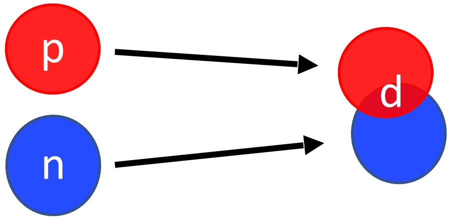
- Microscopic description

- Key observable is the coalescence parameter $B_A$ → experimental observable tightly connected to the coalescence probability: Larger $B_A \Longleftrightarrow$ Larger coalescence probability

$$B_A(p_T^p) = E_A \frac{d^3 N_A}{d\, p_A^3} \Big/ \left( E_p \frac{d^3 N_p}{d\, p_p^3} \right)^A \Bigg|_{p_T^p = p_T^A / A}$$

# Modelling the production of (anti)nuclei

## Coalescence models



- Simplest implementation: *spherical approximation* → if (anti)nucleons are close in phase space ($\Delta \boldsymbol{p} < \boldsymbol{p}_0$) and match the spin state, they can form a (anti)nucleus
- State-of-the-art models use the *Wigner function formalism* → (anti)nuclei arise from the overlap of the (anti)nucleons phase-space distributions with the Wigner density of the bound state
- Microscopic description

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

Mahlein et al., EPJC 83 (2023) 9, 804

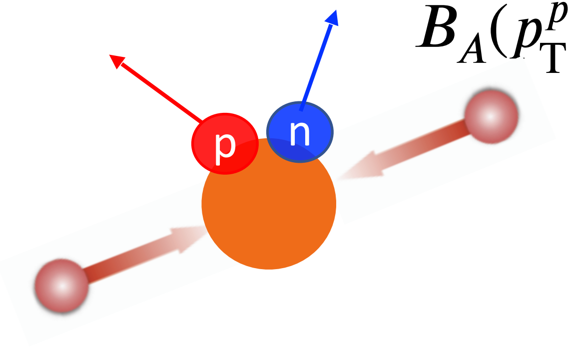
- Key observable is the coalescence parameter $B_A$ → experimental observable tightly connected to the coalescence probability: Larger $B_A$ ⟺ Larger coalescence probability

[1] PRC 99 (2019) 024001

[2] PRL 123 (2019) 112002

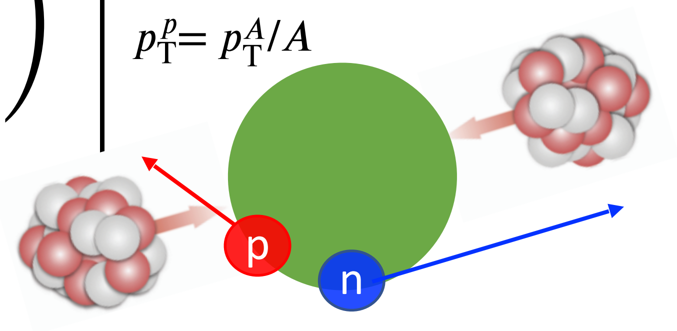
[3] PRC 96 (2017) 064613

$$B_A(p_T^p) = E_A \frac{d^3 N_A}{d p_A^3} \Big/ \left( E_p \frac{d^3 N_p}{d p_p^3} \right)^A \Bigg|_{p_T^p = p_T^A / A}$$



Small distance in space

(Only momentum correlations matter)



Large distance in space

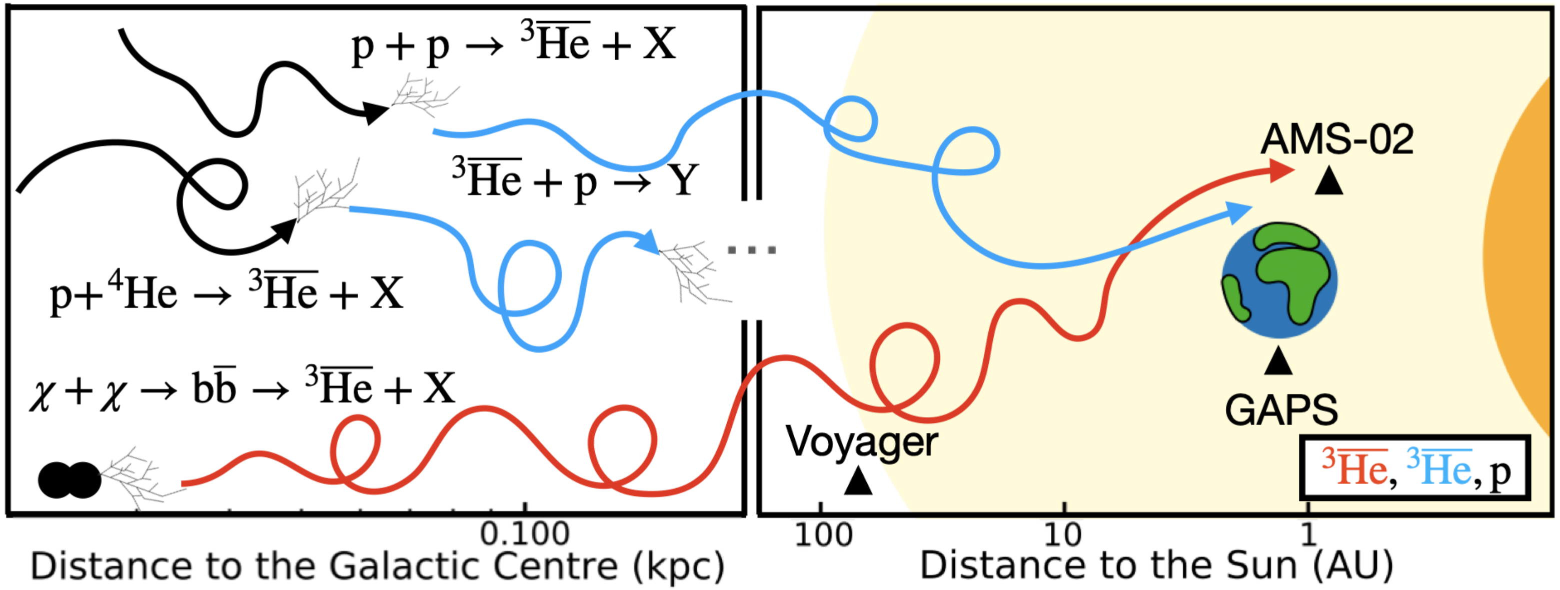
(Both momentum and space correlations matter)

pp[1], p—Pb[2]: $r_0$ = 1–1.5 fm ⟺ large $B_A$

Pb—Pb[3]: $r_0$ = 3–6 fm ⟺ small $B_A$

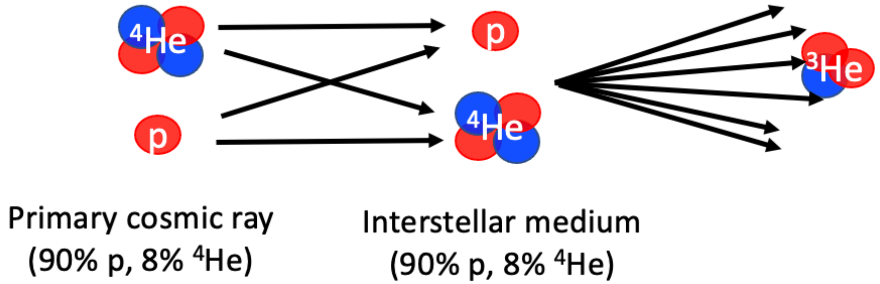
chiara.pinto@cern.ch

# Astrophysics applications



**Antinuclei production:**

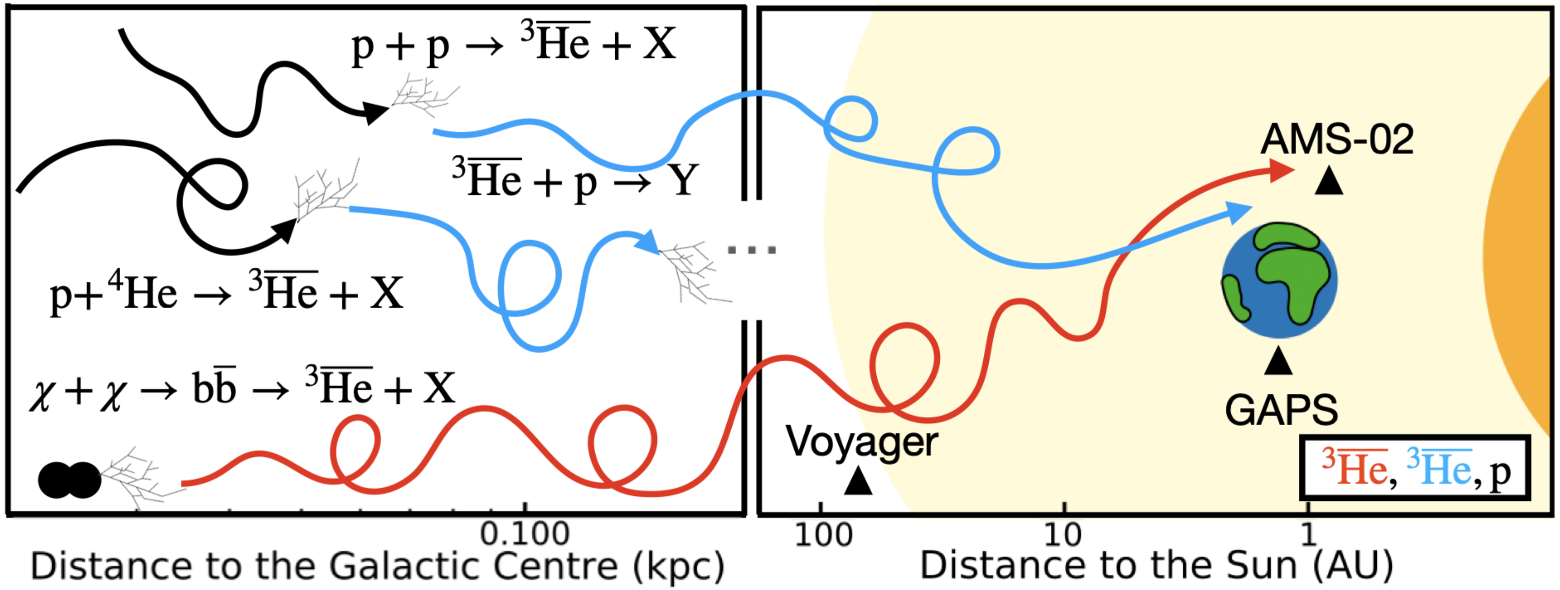
- pp, pA and (few) AA reactions between primary cosmic rays and the interstellar medium
- dark-matter annihilation processes



Nature Phys. (2023) 19, 61–71

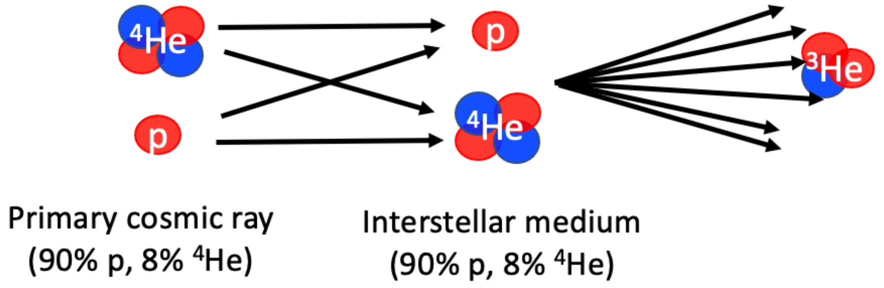
chiara.pinto@cern.ch

# Astrophysics applications

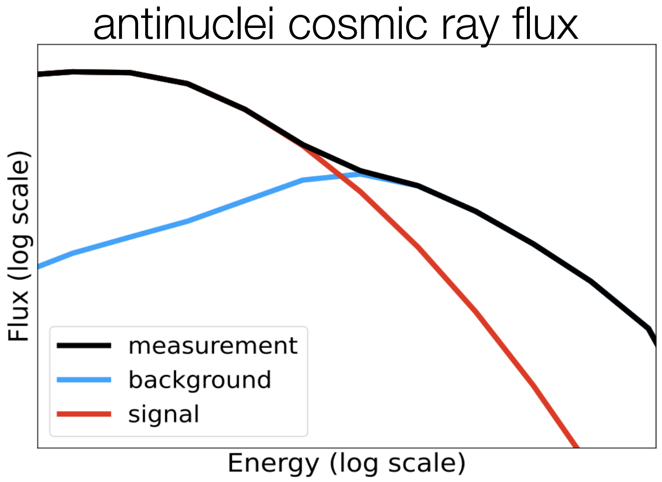


**Antinuclei production:**

- pp, pA and (few) AA reactions between primary cosmic rays and the interstellar medium
- dark-matter annihilation processes



- 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
  1. production of antinuclei
  2. annihilation

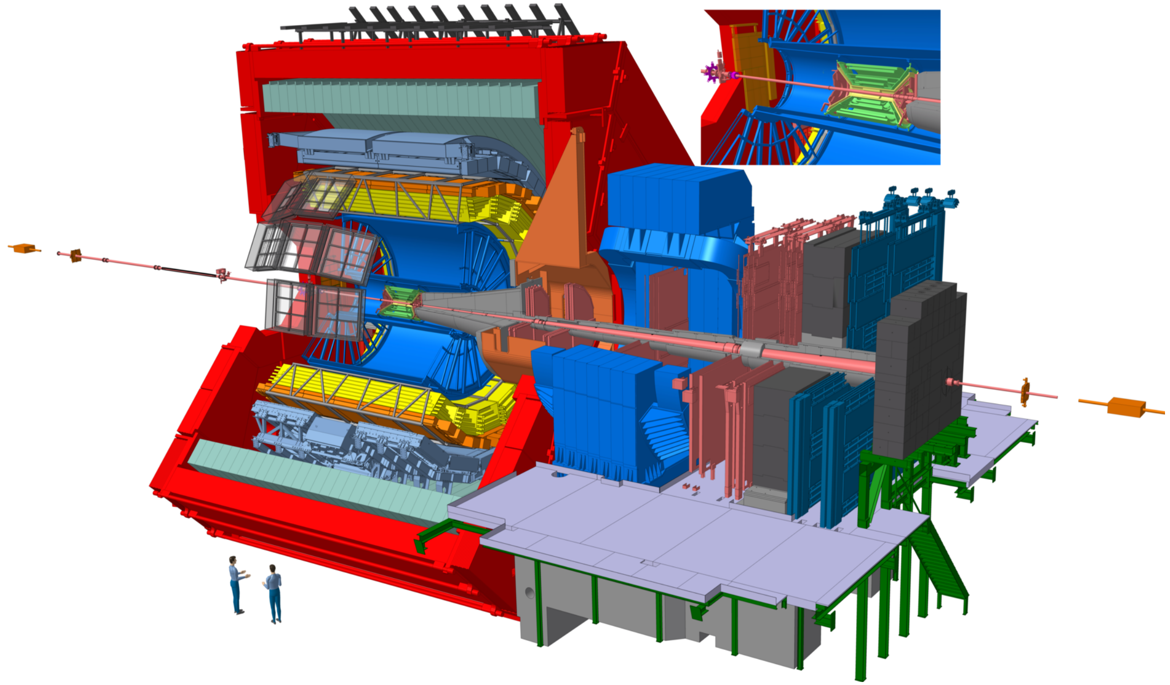


Nature Phys. (2023) 19, 61–71

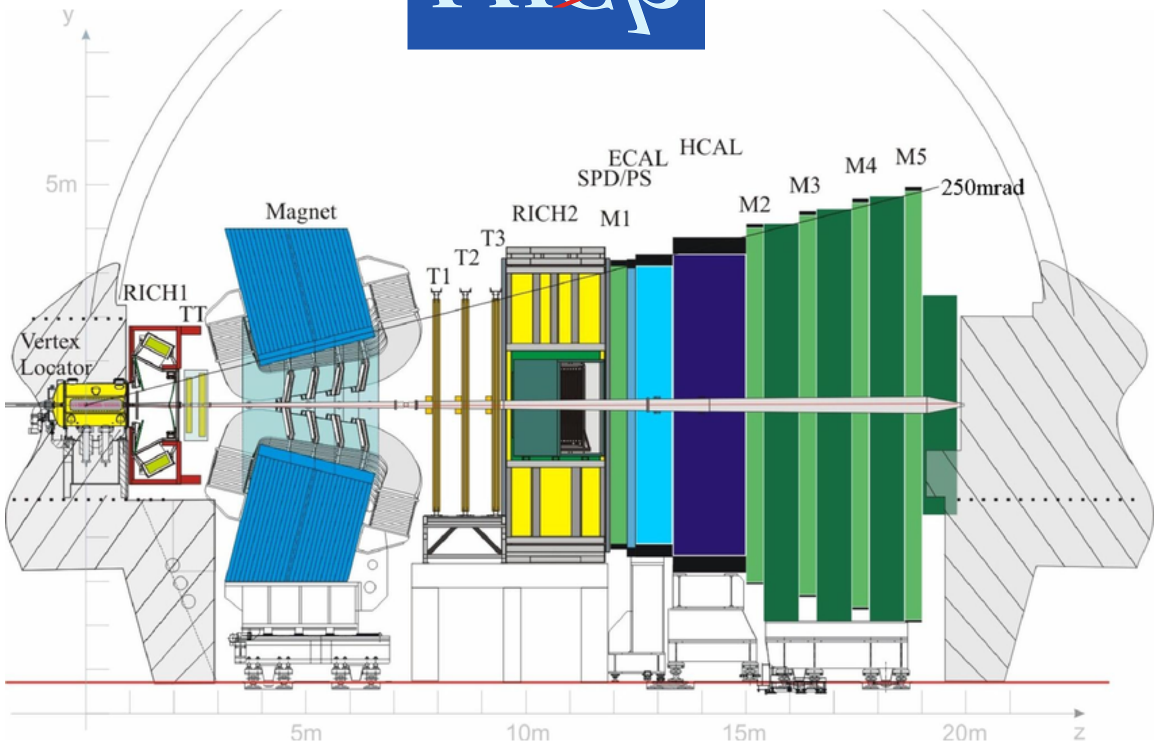
chiara.pinto@cern.ch

# Experimental efforts at the LHC

ALICE



LHCb



📚 ALICE Collaboration, 2008 *JINST* **3** S08002

- excellent tracking & PID capabilities over broad *p* range
- low material budget

**→ most suited detector at the LHC for the study of nuclei**

📚 LHCb Collaboration, 2008 *JINST* **3** S08005

- excellent vertexing ($\sigma_{\mathrm{IP}}$ = 15+29/$p_{\mathrm{T}}$ [GeV] μm, $\sigma_p$= 0.5% – 1.0%)
- excellent PID separation for K, $\pi$ and p with O(10) GeV/*c*

**→ recently joined the nuclei-business!**

chiara.pinto@cern.ch

# Identification of nuclei with LHCb

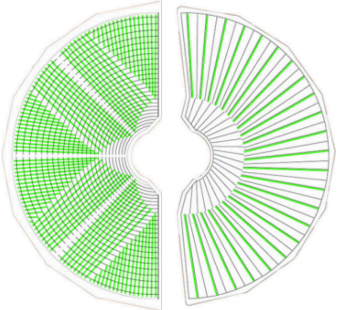
LHCb detector not designed to identify light (anti)nuclei

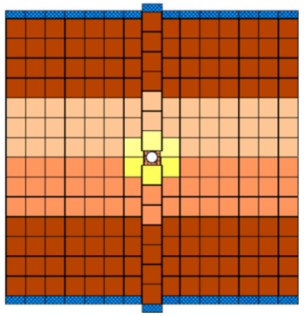
↓

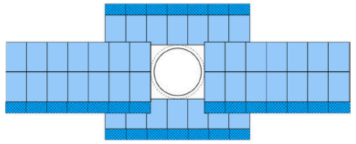
Use information from the tracking system

1 **Ionisation losses** in silicon sensors: **$Z^2$ dependence** in Bethe-Bloch

→ dE/dx in VELO, TT, IT to **identify He**


VELO: 2 x 21 layers

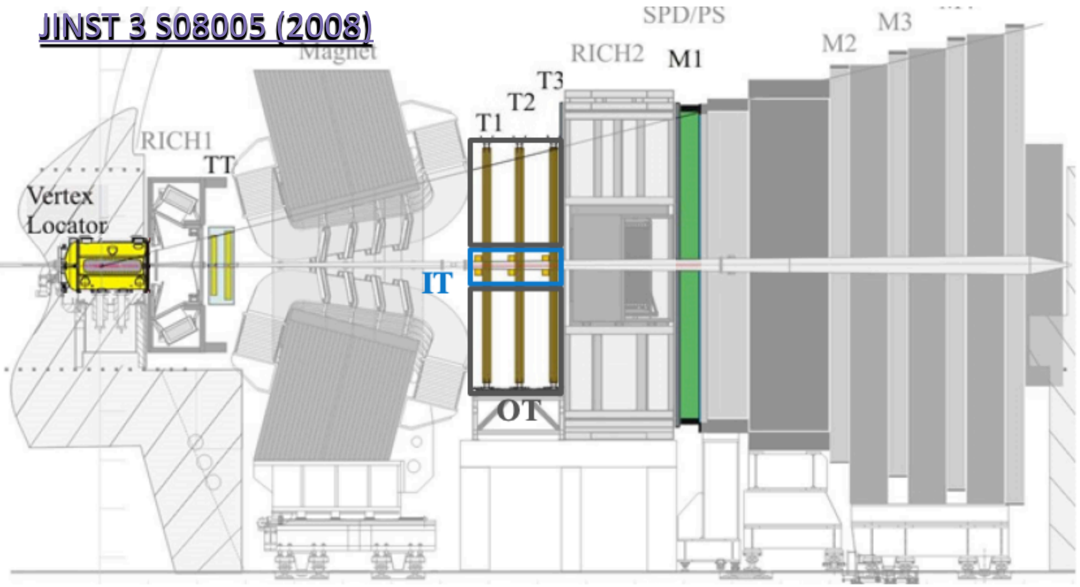

TT: 4 layers


IT: 12 layers

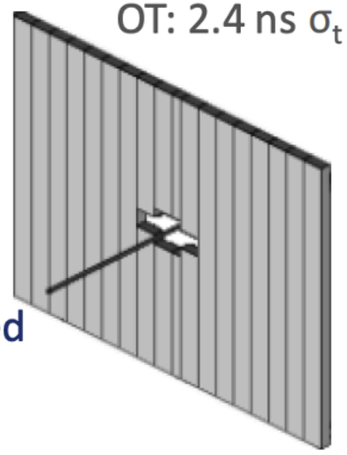
2 Light nuclei slower than c: **M dependence** of particle speed

→ **Time-of-flight** in OT and M1 to **identify d, distinguish $^3$He and $^4$He**

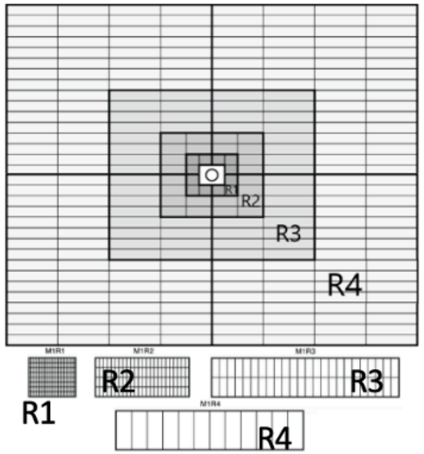
JINST 3 S08005 (2008)



OT: 2.4 ns $\sigma_t$



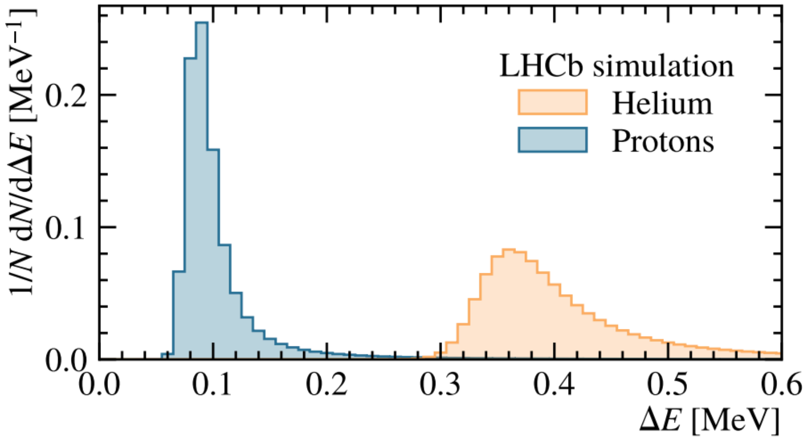
M1: 3-4 ns $\sigma_t$



https://cds.cern.ch/record/2881940/files/MPI23_v1.pdf

chiara.pinto@cern.ch

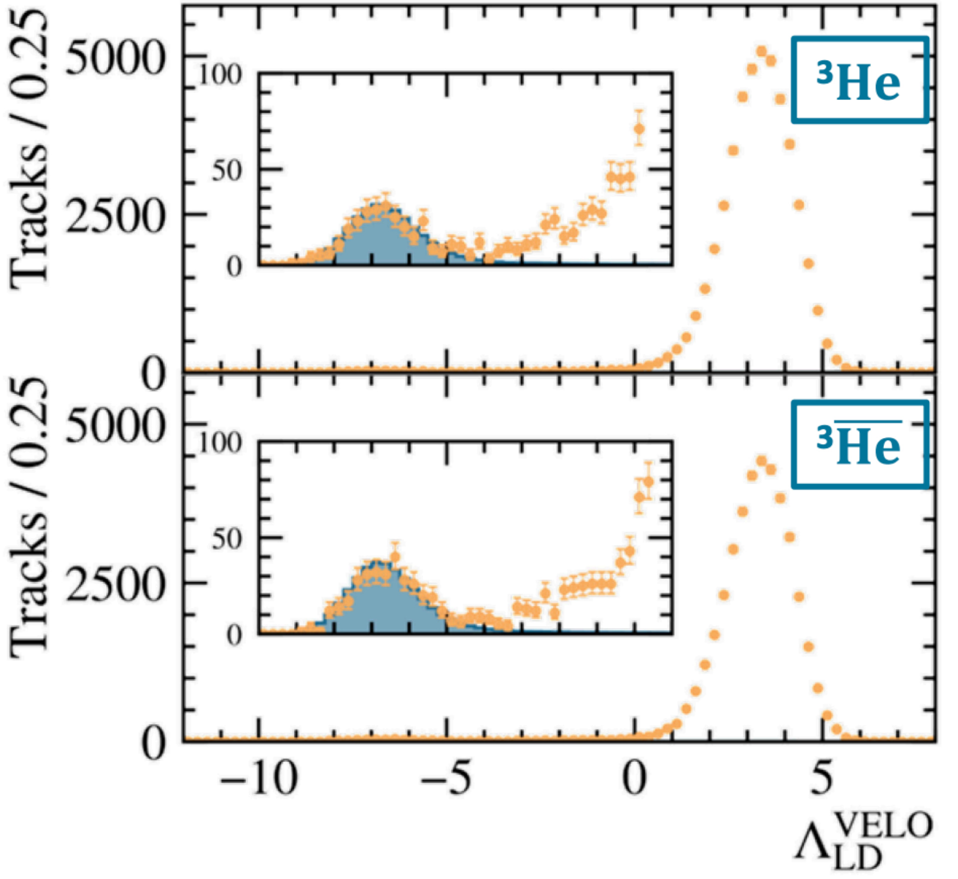
# Identification of Helium-3 with LHCb



Bethe-Bloch: Z=2 particles deposits ~4 times the energy of Z=1 particles

→ He: higher ADC counts and wider cluster size

**First (anti-)Helium candidates observed in *pp* in LHCb data!**



**Define Likelihood discriminators based on cluster size and ADC counts:**

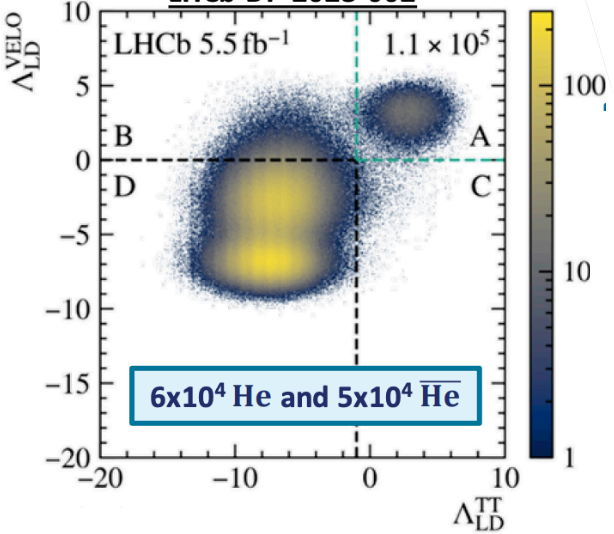
$$\mathcal{L}^X = \left(\prod_{i=1}^{n} \mathrm{PDD}_i^X\right)^{1/n} \quad , X = \{\mathrm{He}, \mathrm{Bkg}\}$$

$$\boxed{\Lambda_{\mathrm{LD}} = \log\mathcal{L}^{\mathrm{He}} - \log\mathcal{L}^{\mathrm{Bkg}}}$$

One discriminator for each subdetector:

- $\Lambda_{\mathrm{LD}}^{\mathrm{VELO}}$
- $\Lambda_{\mathrm{LD}}^{\mathrm{TT}}$
- $\Lambda_{\mathrm{LD}}^{\mathrm{IT}}$

**LHCb-DP-2023-002**



**6x10⁴ He and 5x10⁴ $\overline{\mathrm{He}}$**

**Performance:**

- **MisID** probability: $\mathcal{O}(10^{-12})$
- **Signal efficiency**: ~ 50%

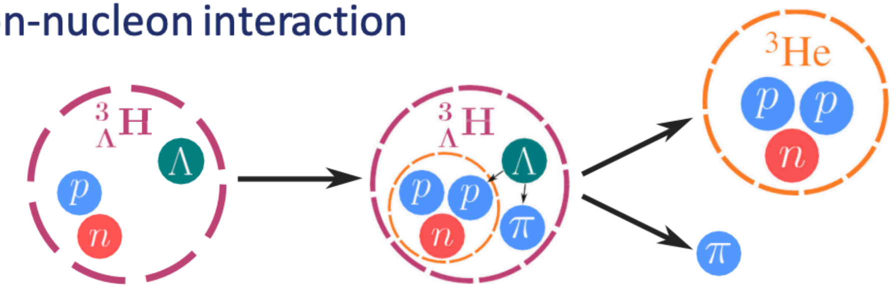
LHCb Collaboration, JINST 19 (2024) P02010

chiara.pinto@cern.ch

# Identification of hypertriton at LHCb

- Hypertriton life-time and binding energy gives access to hyperon-nucleon interaction

  → **Constrains on maximum mass of neutron stars**



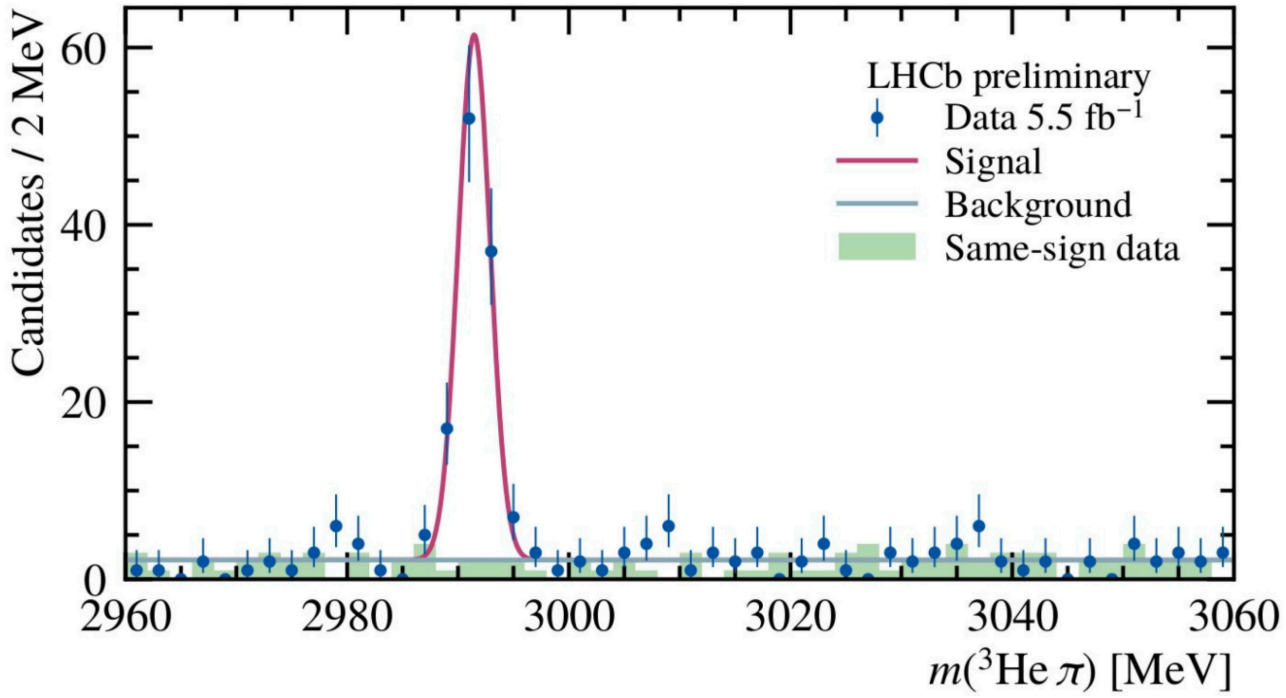
**Search for 2-body decay into He:**

$${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He}\,\pi^{-} + cc$$

**Results:**

(Run2 *pp* collisions at $\sqrt{s} = 13$ TeV)

- **Yields**:
  - 61 ± 8 Hypertriton
  - 46 ± 7 anti-Hypertriton
- Statistical **mass precision**: 0.16 MeV



This measurement shows the applicability of ³He reconstruction and paves the way for future measurements of astrophysical interest

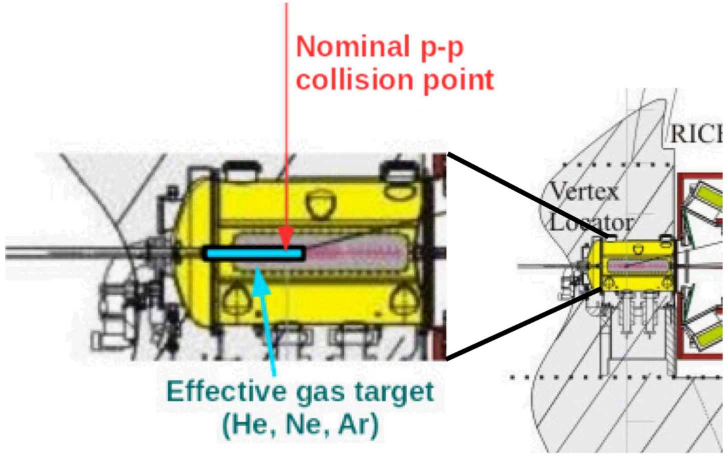
https://cds.cern.ch/record/2881940/files/MPI23_v1.pdf

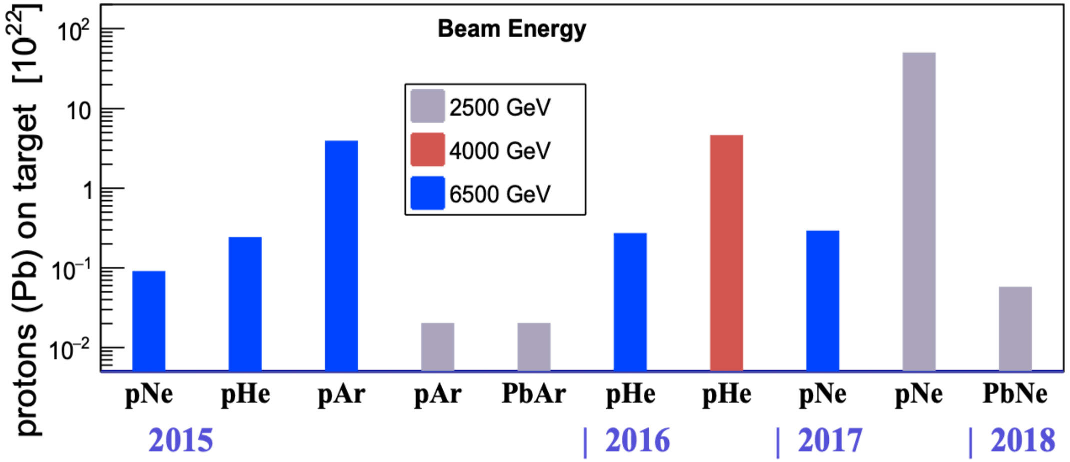
LHCb Collaboration, LHCb-CONF-2023-002 (EPS-HEP)

chiara.pinto@cern.ch

# Fixed-target programme at LHCb

- The *System for Measuring Overlap with Gas* (**SMOG**) can inject gas in LHC beam pipe around ±20 m from the LHCb IP
- SMOG exploited for LHCb **fixed-target physics programme** → Collected physics samples with different **targets** and different **centre of mass energies**





Unique opportunities at the LHC:

- Collisions with targets of mass number A intermediate between p and Pb → Reproduce CR interactions (pp, pHe)
- Energy range $\sqrt{s\mathrm{NN}} \in$ [30,115] GeV for beam energy in [0.45, 7] TeV → Unexplored gap between SPS and LHC/RHIC

**LHCb contribution is relevant for astrophysics applications!**

LHCb Collaboration, LHCb-PUB-2018-015

chiara.pinto@cern.ch

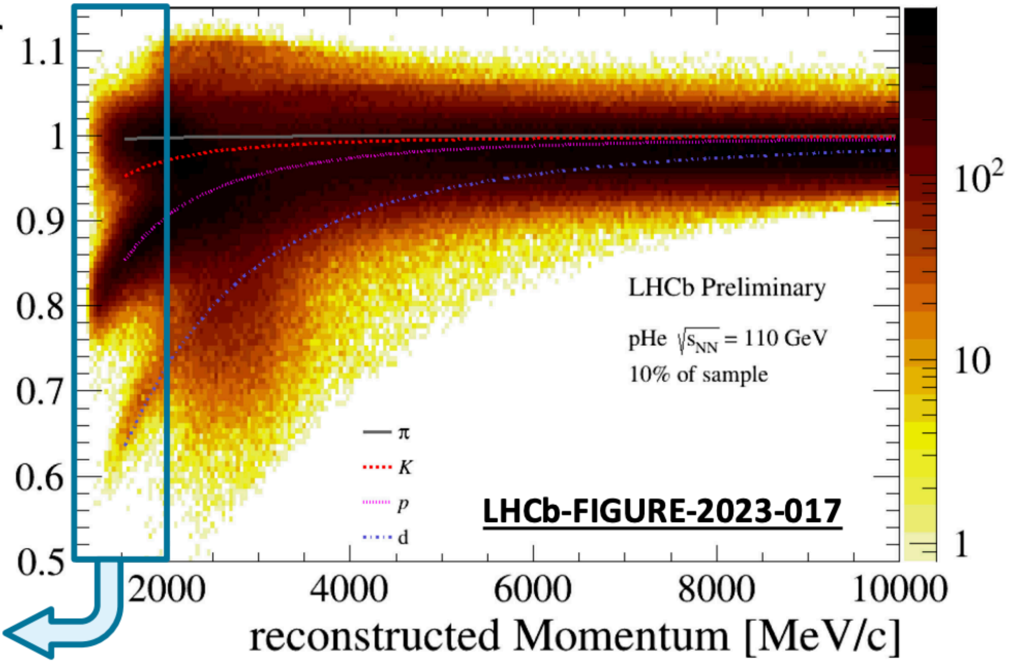
# (anti)deuteron identification with LHCb

**LHCb is now also capable of measuring (anti)deuterons**

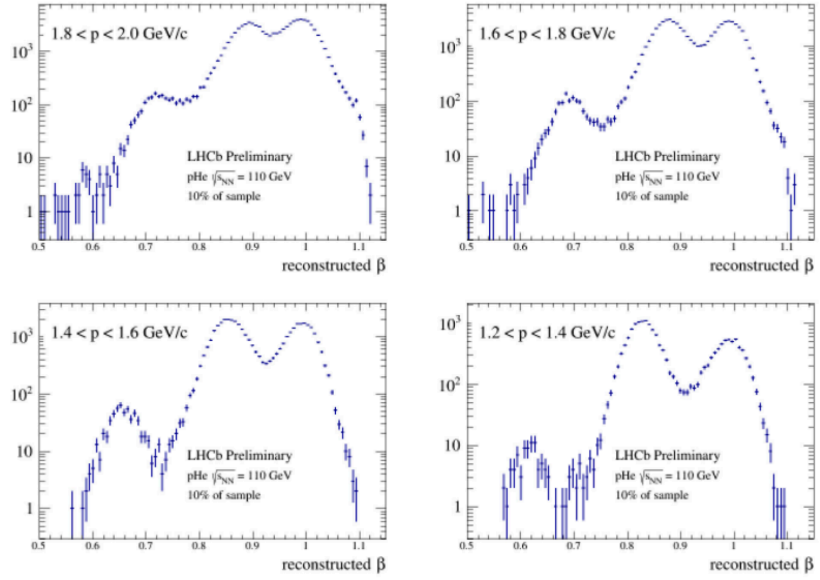
- *Time-of-flight based technique*
- Reconstructed tracks refitted to determine $\beta$
  → iterative procedure rerunning Kalman fit with different $\beta$ hypotheses

- **~10% of SMOG *p*He** ($\sqrt{s_{NN}} = 110$ GeV) dataset
- **Background suppression:** σ(β) < 0.02 , $\chi^2_{\text{OThits}}$/ndf <2

**First deuteron candidates observed in *p*He data!**



**LHCb-FIGURE-2023-017**

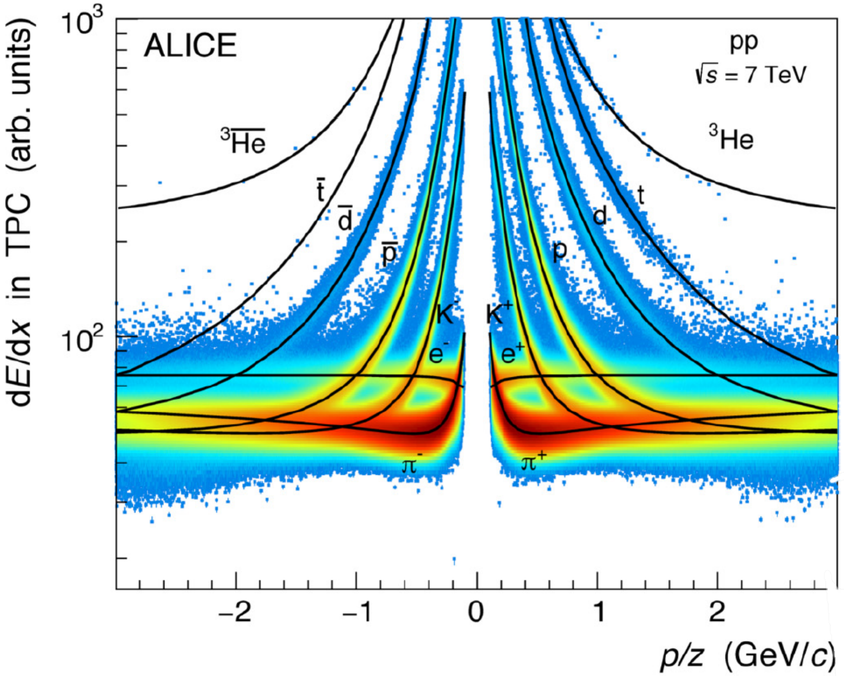


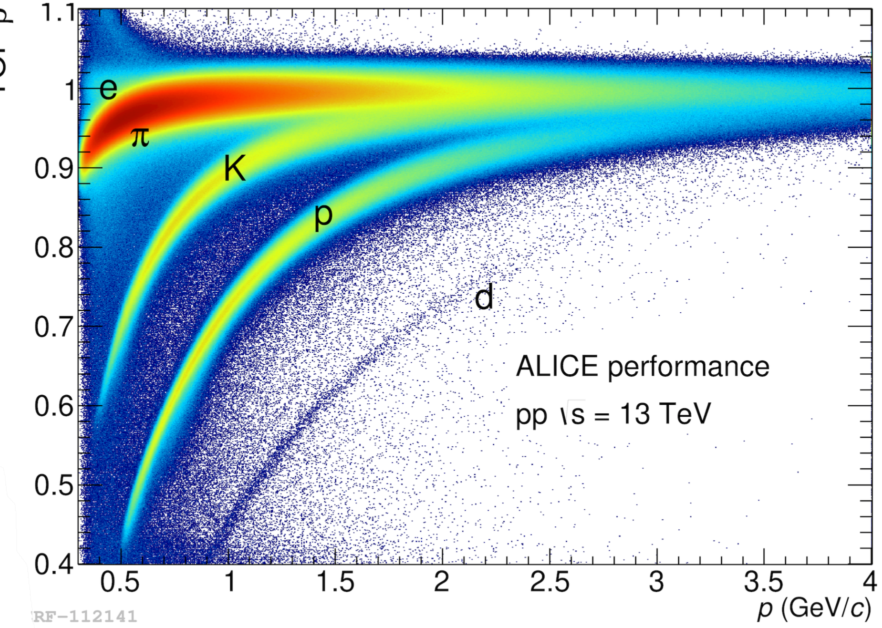
**LHCb-FIGURE-2023-017**

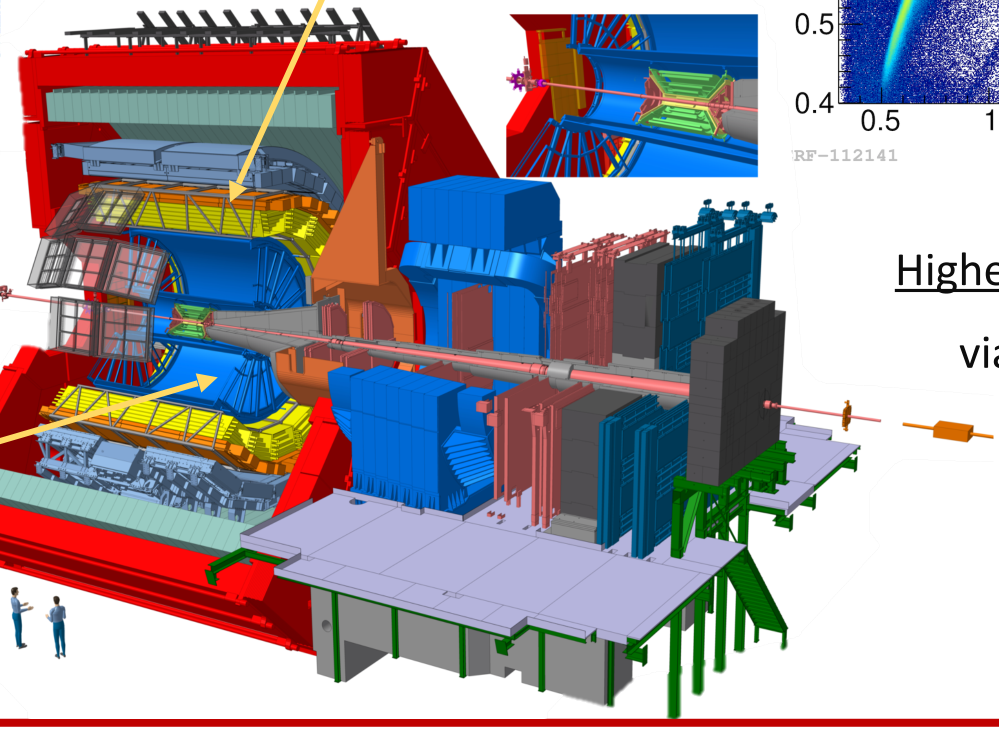
https://cds.cern.ch/record/2881940/files/MPI23_v1.pdf

# Identification of nuclei with ALICE

Low $p$ region (below 1 GeV/$c$) → PID via d$E$/dx measurements in TPC







Time Of Flight

PID via $\beta$

$\sigma_{PID}$ ~ 70 ps

Time Projection Chamber

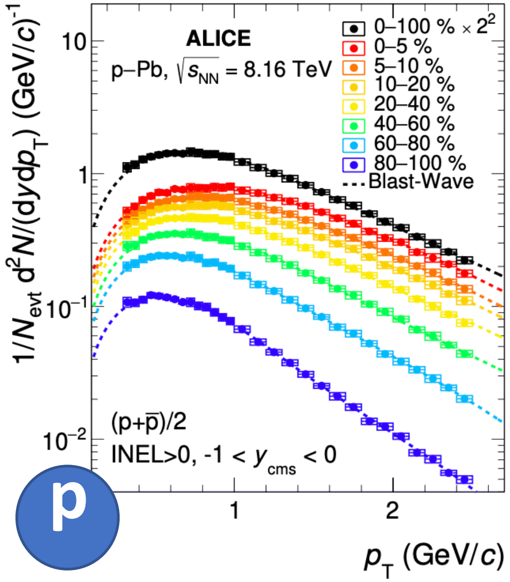
tracking, PID via d$E$/dx

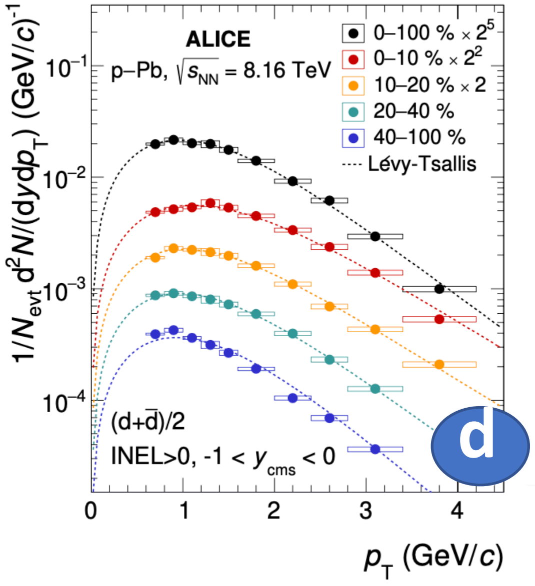
$\sigma_{dE/dx}$ ~ 6%

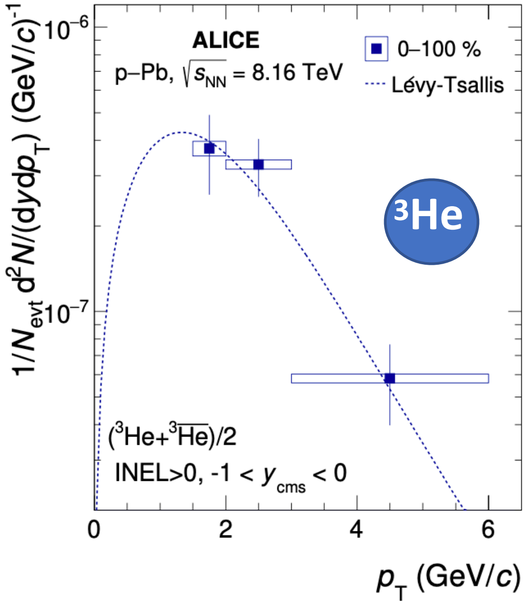
Higher $p$ region (above 1 GeV/$c$) → PID via velocity β measurements in TOF

# Measurement of light (anti)nuclei with ALICE

- In small systems such as pp and p—Pb collisions, all nuclei species have been measured, from p to ³He
- Momentum distributions fitted to extrapolate the yield in the unmeasured regions

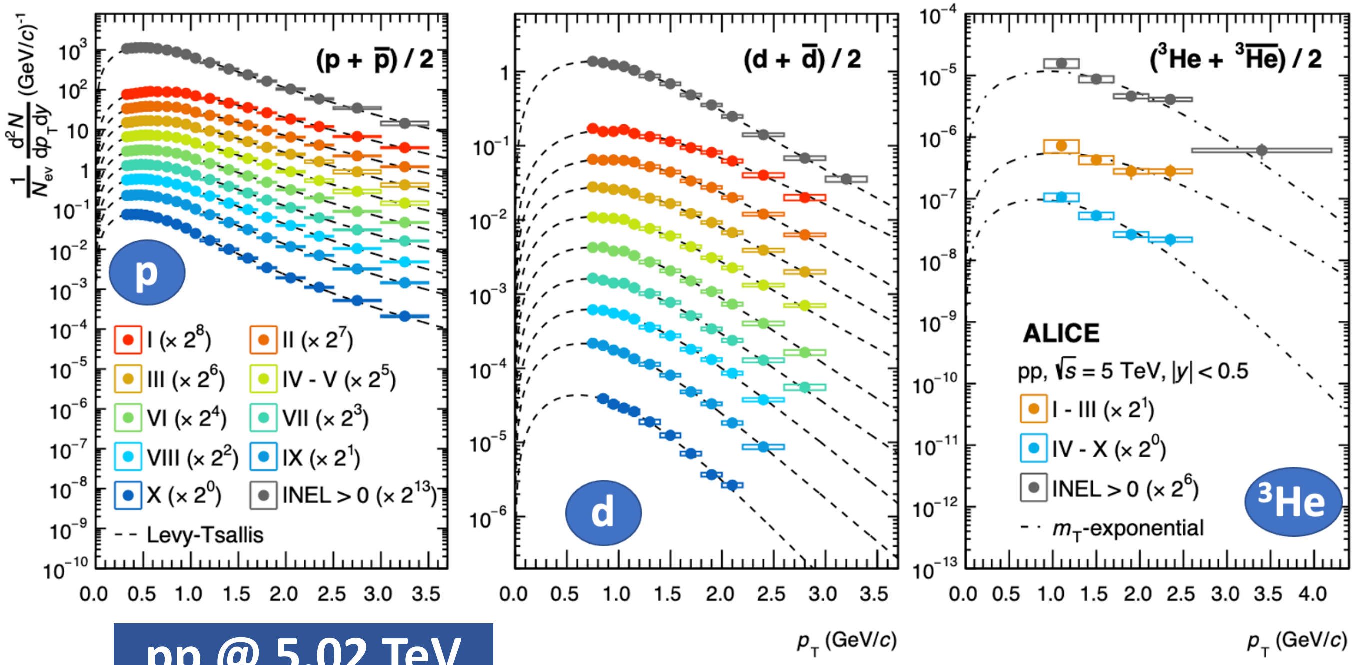






**p-Pb @ 8.16 TeV**

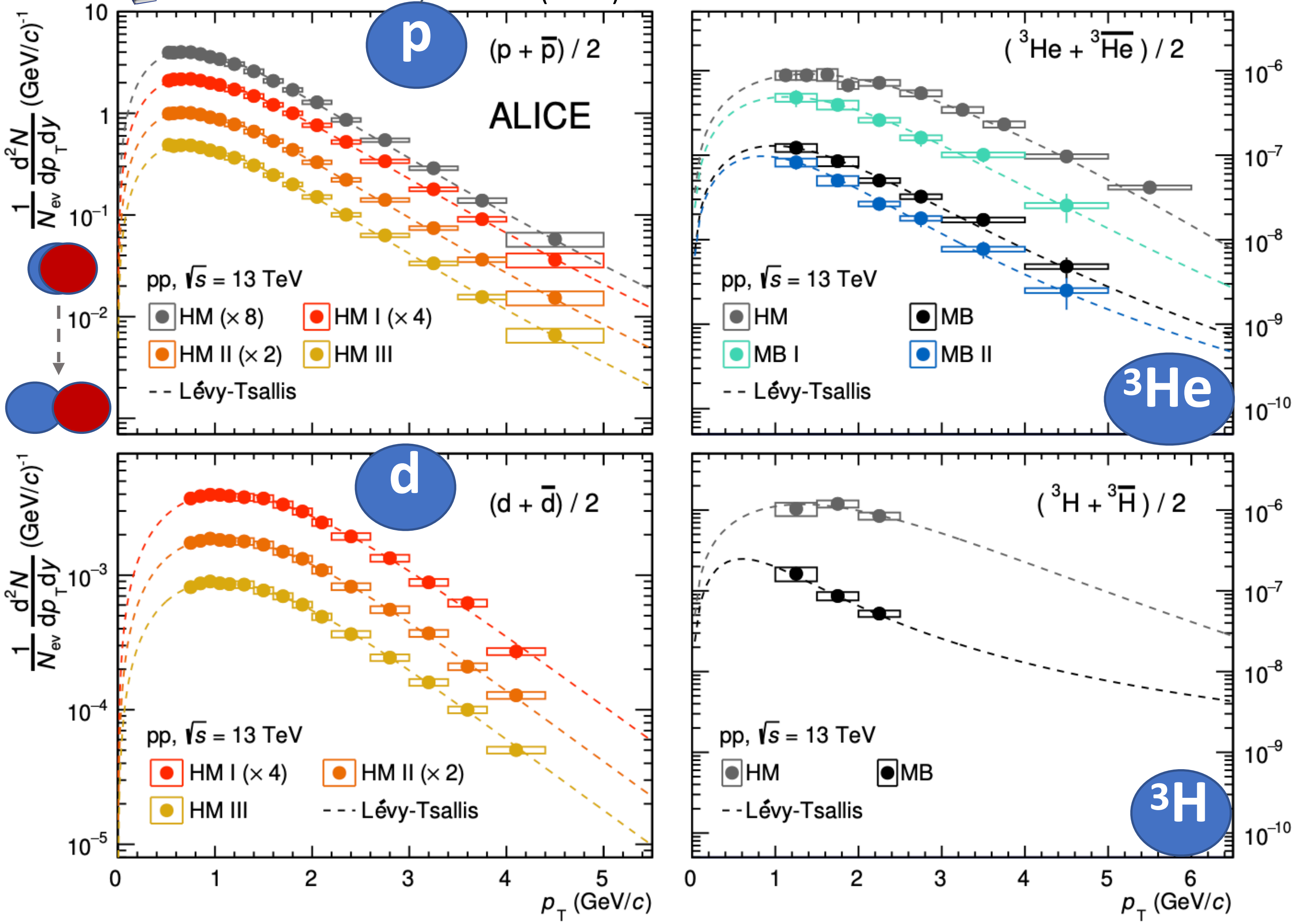
ALICE Collaboration, PLB 811 (2020) 135849



**pp @ 5.02 TeV**

ALICE Collaboration, EPJC (2022) 82:289

# Measurement of light (anti)nuclei with ALICE

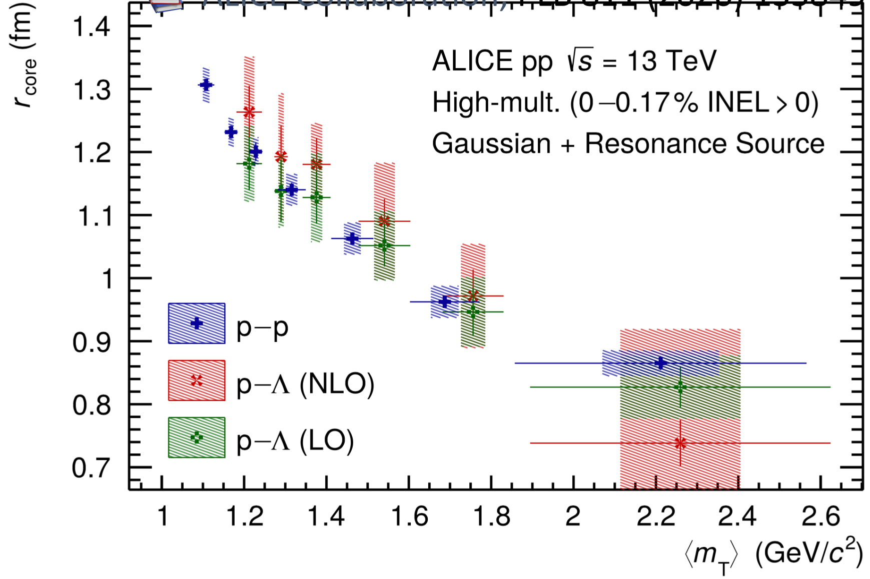


ALICE Collaboration, JHEP 01 (2022) 106

**HM pp @ 13 TeV**

- Focus on the HM data sample → narrow multiplicity interval covered (0-0.1%)
- Precise measurement of the emission source size $r_{\mathrm{core}}$ using femtoscopy is available

→ **crucial to test the coalescence model**



ALICE Collaboration, PLB 811 (2020) 135849

$\propto p_{\mathrm{T}}$

chiara.pinto@cern.ch

# Coalescence parameter

- Important observable in accelerator measurements: coalescence parameter $B_A$

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

- Theoretical prediction [1]

*emission source size*

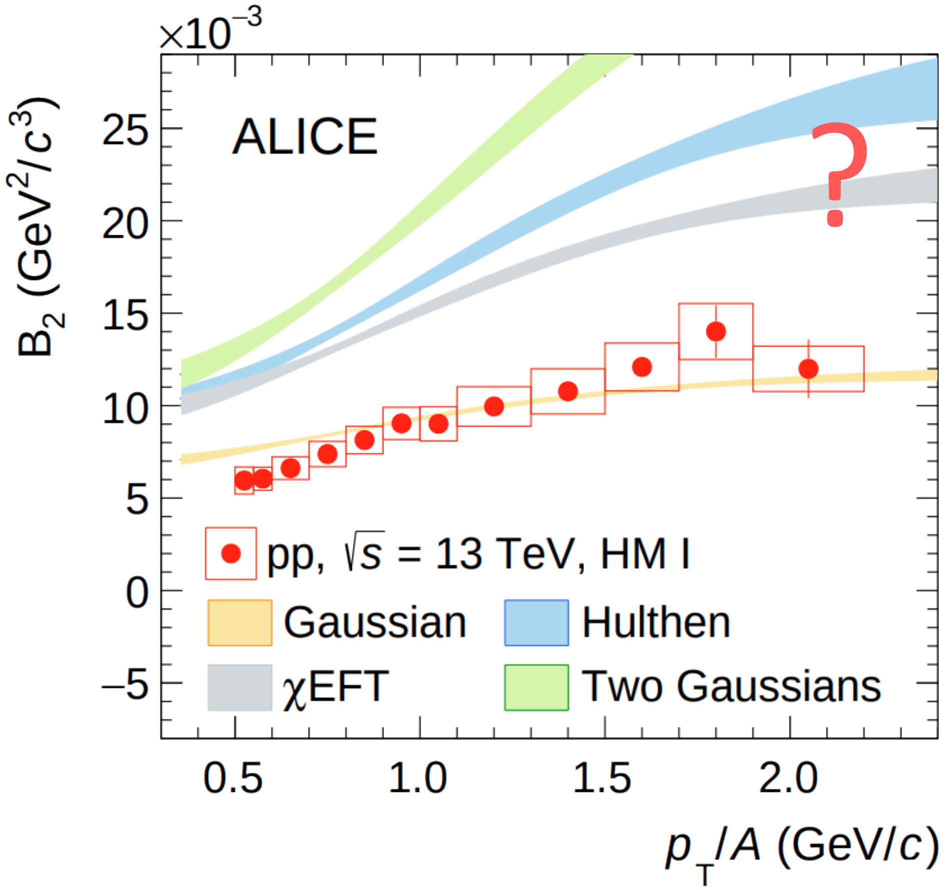
$$B_2(\vec{p}) \approx \frac{3}{2m}\int d^3q D(\vec{q}) e^{-R^2(p_T)\; q^2}$$

*deuteron wave function (size d = 3.2* fm)

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

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
- **$\chi$EFT:** Favoured by modern nuclear interaction experiments (e.g. Femtoscopy)
- **Argonne v18** (missing here)



ALICE Collaboration, JHEP 01 (2022) 106

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

Kachelrieß et al., EPJA 1 (2020) 4

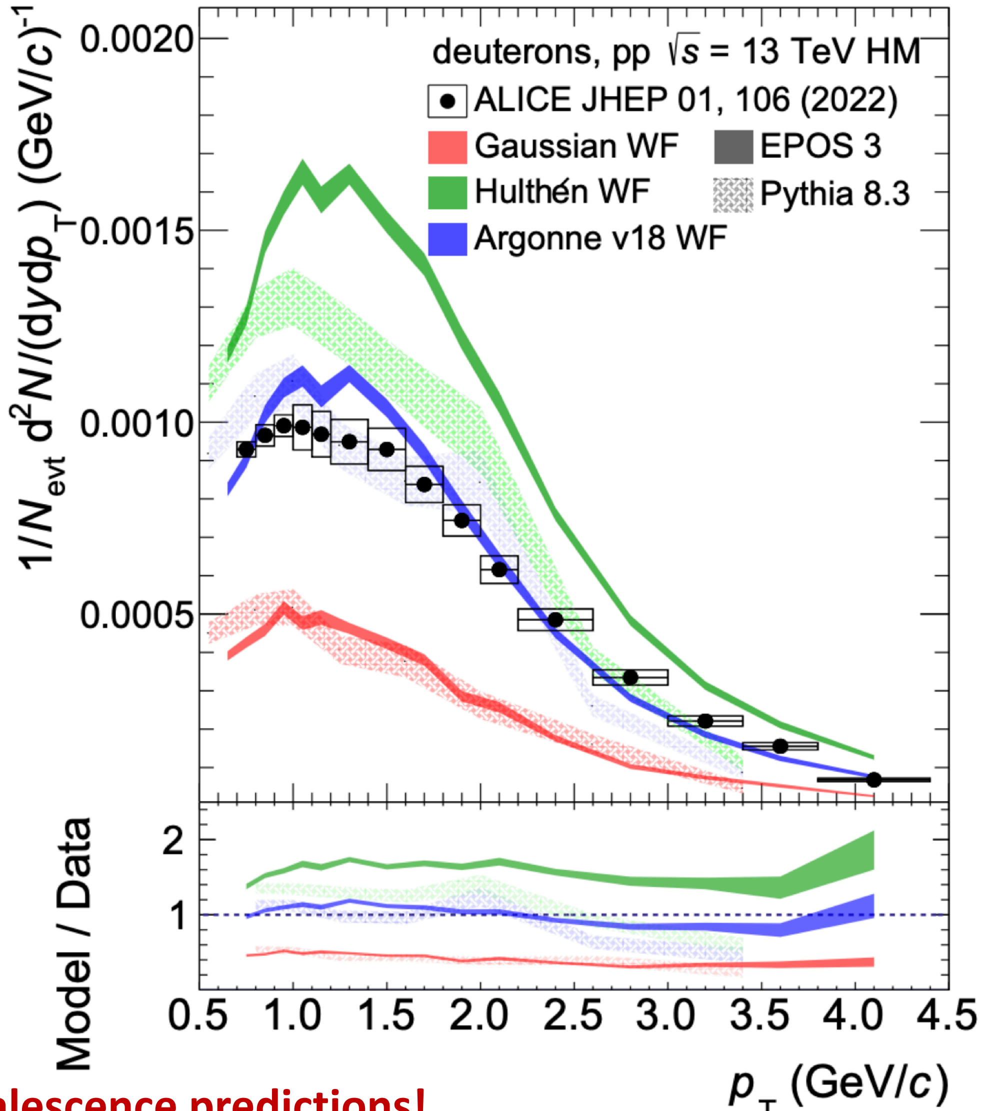
chiara.pinto@cern.ch

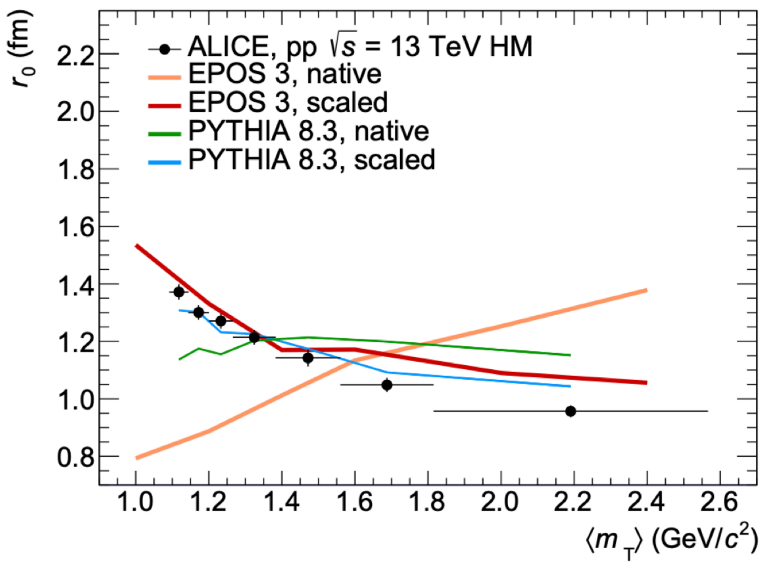
# State-of-the-art coalescence model

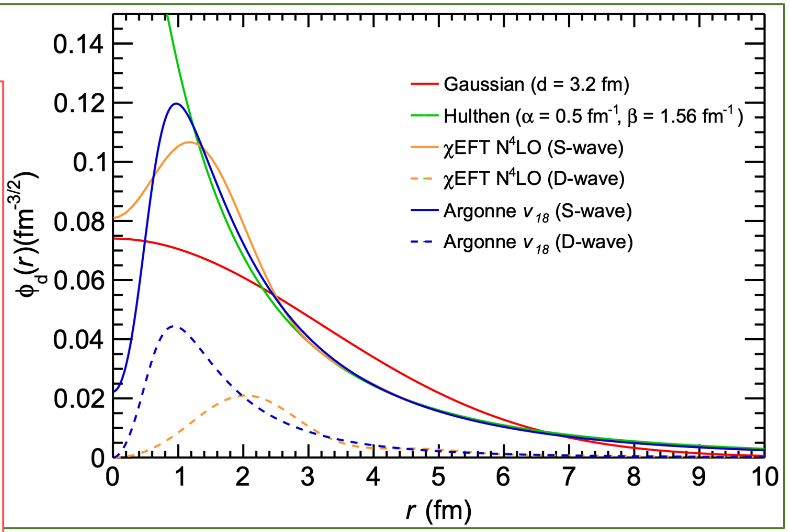
Coalescence afterburner based on Wigner function formalism

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

→ **model predicts deuteron $p_T$ spectrum**





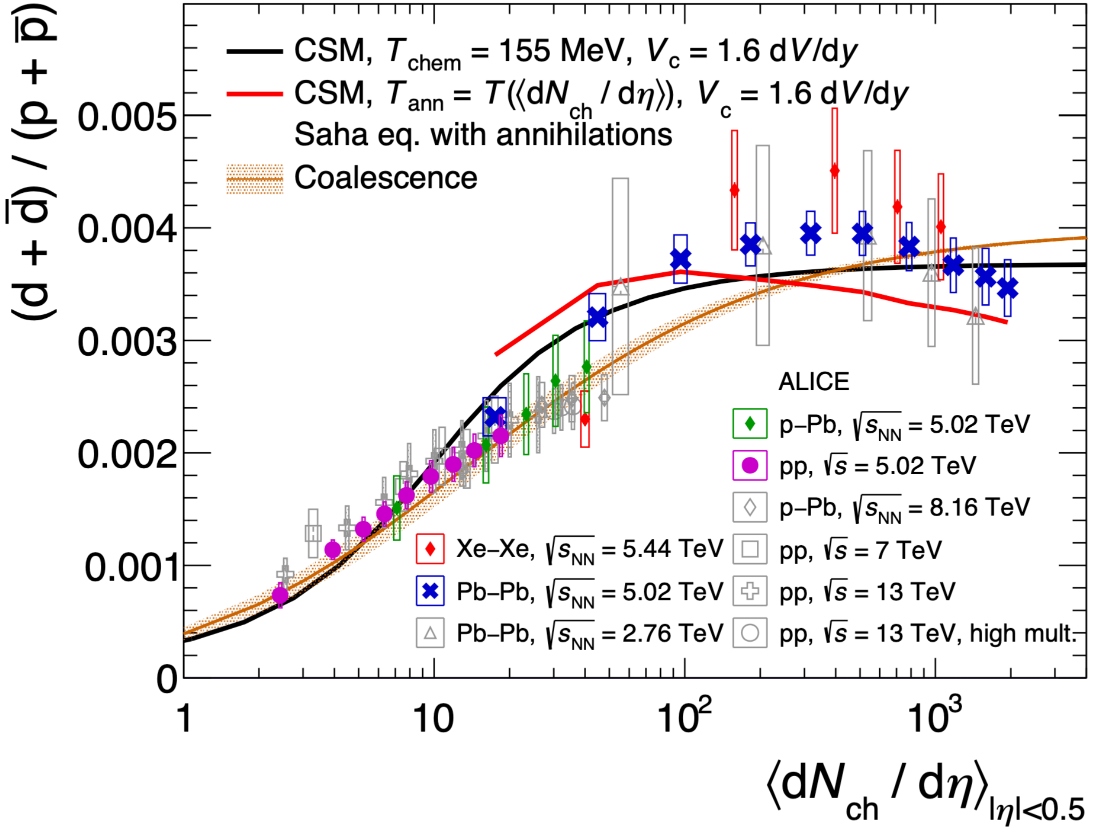


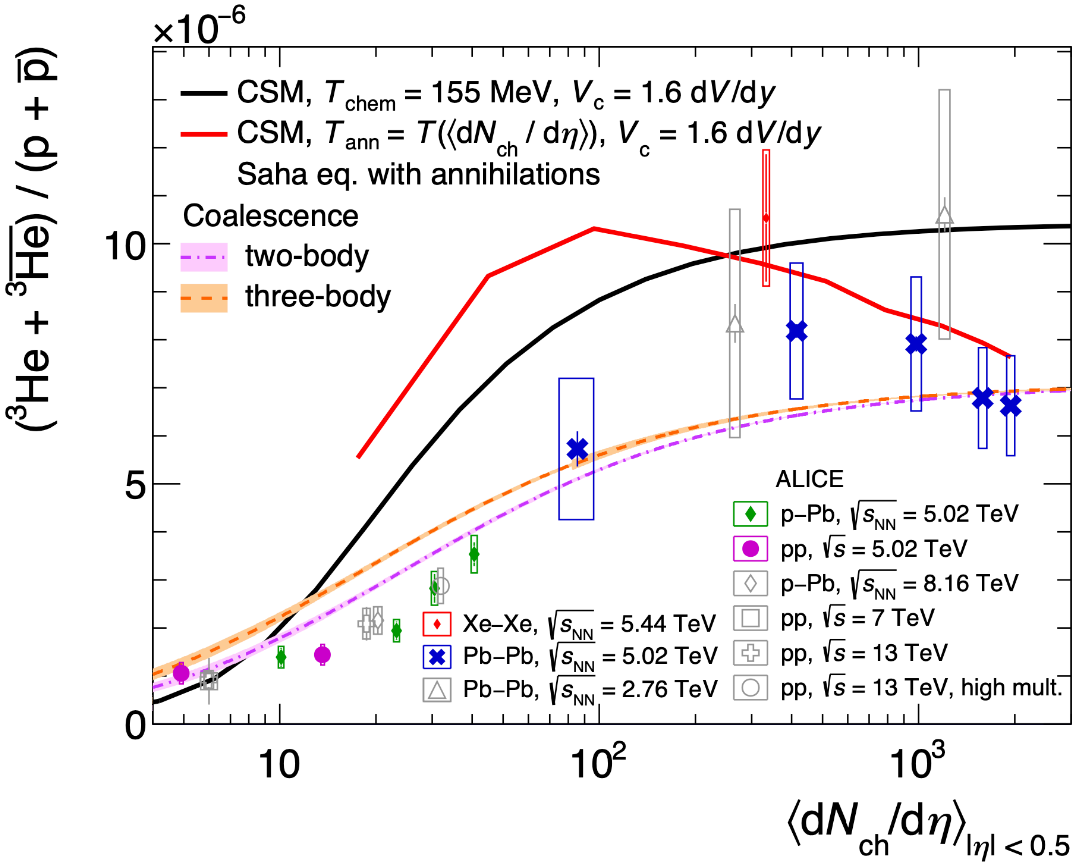
**Realistic wavefunction is key for coalescence predictions!**

Mahlein et al., EPJC 83 (2023) 9, 804

chiara.pinto@cern.ch

# Testing production models



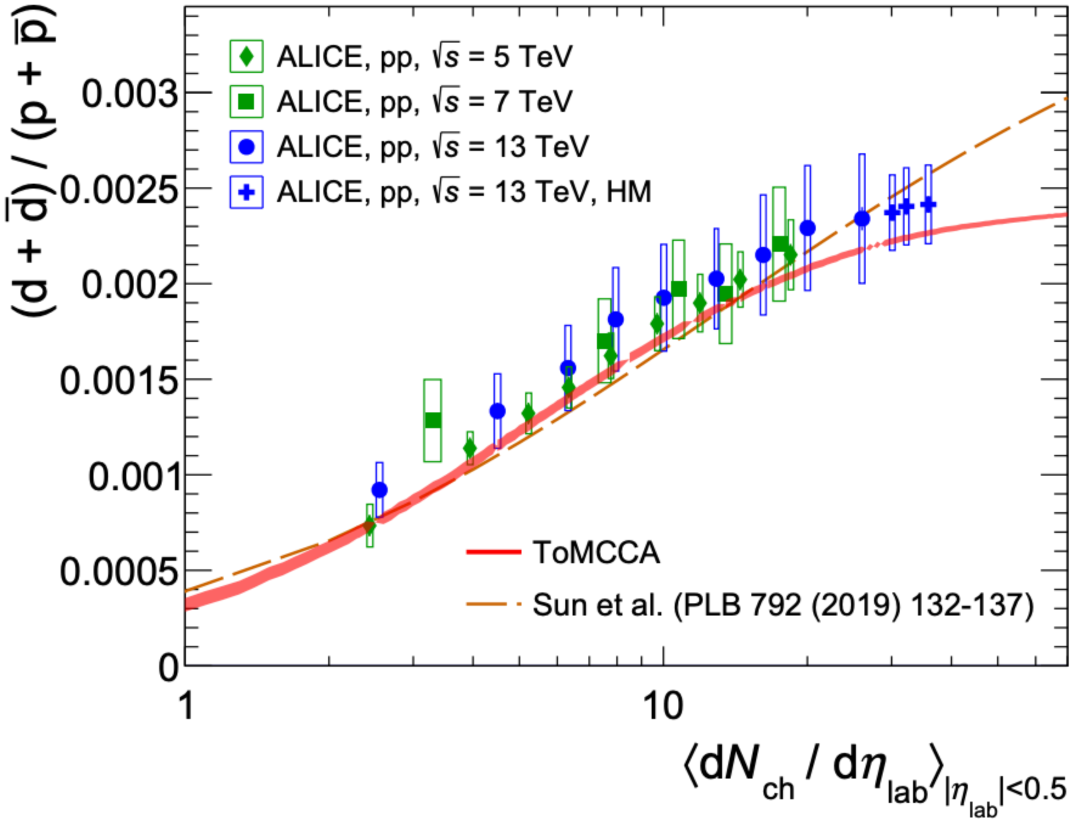


- **$V_c$=1.6 d$V$/dy** is the correlation volume needed to describe the net-deuteron number fluctuations in Pb–Pb collisions[1]
- **CSM →** either with fixed chemical temperature (black) or with **annihilation** temperature depending on multiplicity[2] (red)
- Both CSM and **coalescence[3]** predictions qualitatively reproduce the trend and overall yields, but neither of the models catch all data points

[1] ALICE Collaboration, PRL 131 (2023) 041901 [2] Vovchenko, Koch, PLB 835, 137577 (2022) [3] Sun, Ko, Doenigus, PLB 792 (2019) 132-137

chiara.pinto@cern.ch

# Testing production models



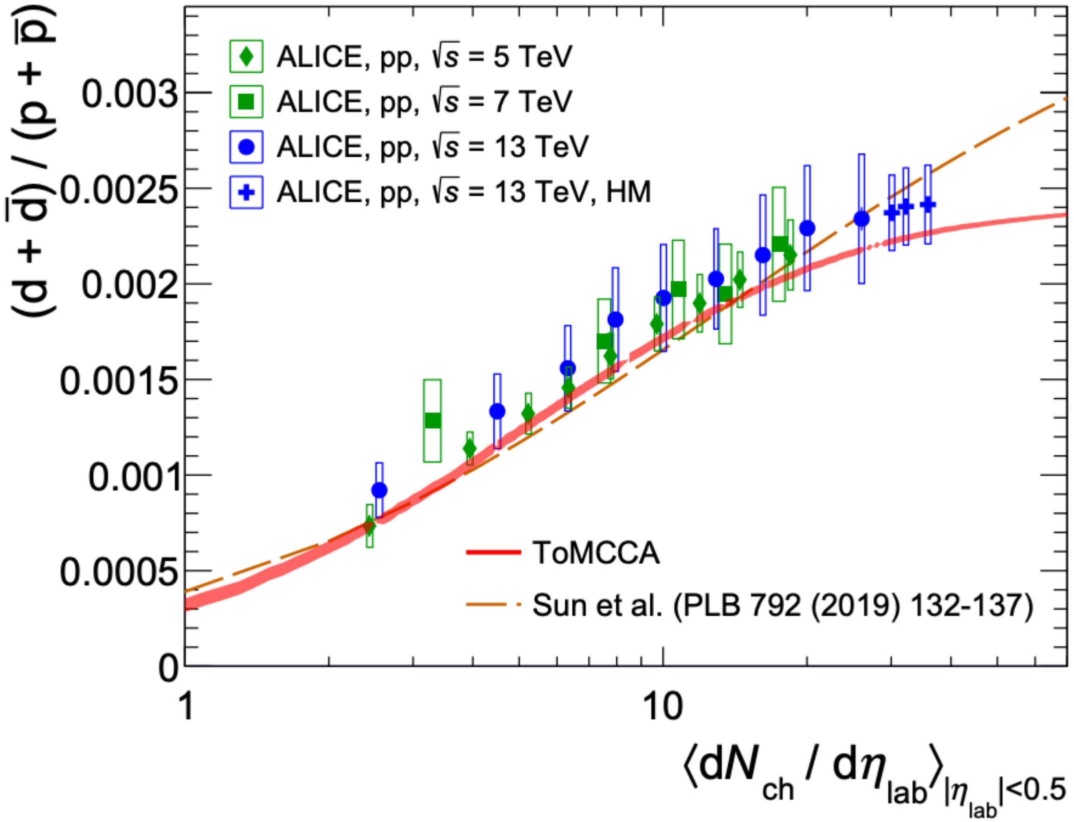
Predictions available only for the pp multiplicity range (1-70)

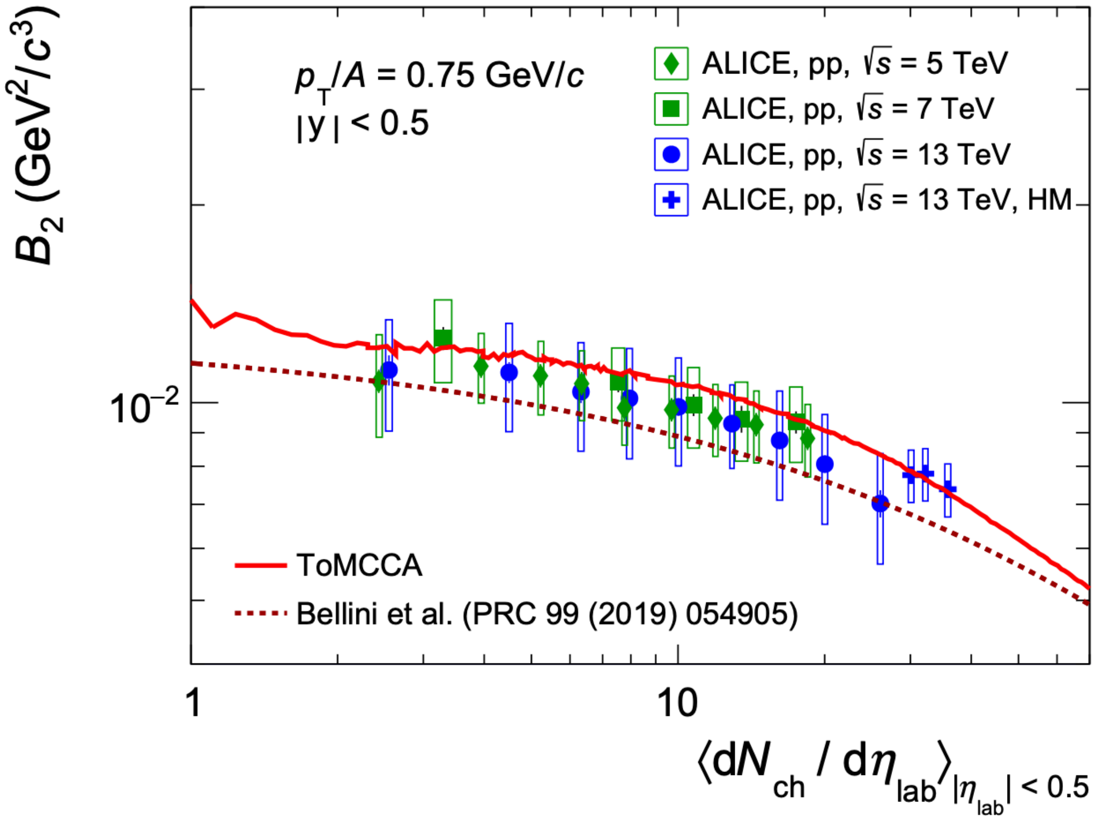
- **Coalescence** predictions of ToMCCA using Wigner function formalism & multiplicity-dependent input (momentum distributions of nucleons, source size and multiplicity distributions) reproduce all data points within 1sigma
- No $^3$He coalescence predictions yet

Mahlein, Pinto, Fabbietti, arXiv:2404.03352

chiara.pinto@cern.ch

# Testing production models





- **Coalescence** predictions of ToMCCA using Wigner function formalism & multiplicity-dependent input (momentum distributions of nucleons, source size and multiplicity distributions) reproduce all data points within 1sigma
- No $^3$He coalescence predictions yet
- Also coalescence parameter $B_2$ vs multiplicity is well reproduced by ToMCCA

More about ToMCCA during Maxi's talk!

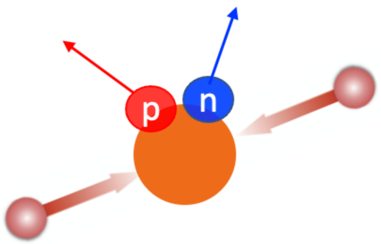
📚 Mahlein, Pinto, Fabbietti, arXiv:2404.03352

chiara.pinto@cern.ch

# Testing production models with hypertriton

- In small collision systems (as pp) size of system created in the collision is smaller or equal to that of the nucleus under study
- For small systems model **predictions are quite different**
- Coalescence is sensitive to the **interplay** between the **size of the collision system** and the spatial extension of the **nucleus wave function**

/Λ ratio provides a powerful tool to investigate nuclear production mechanism



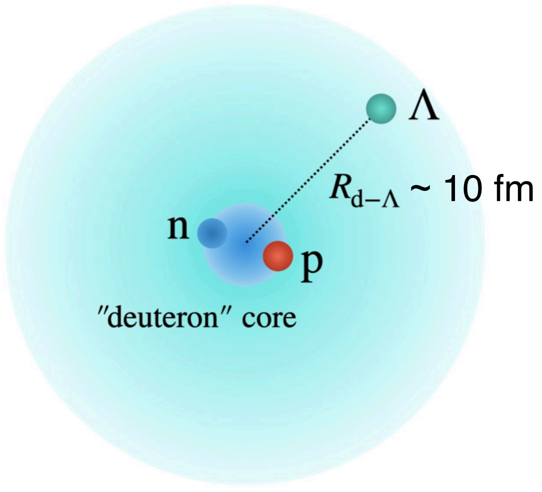
System size (pp, p—Pb): 1–1.5 fm

$r_d$ : 1.96 fm

$r_{3He}$: 1.76 fm

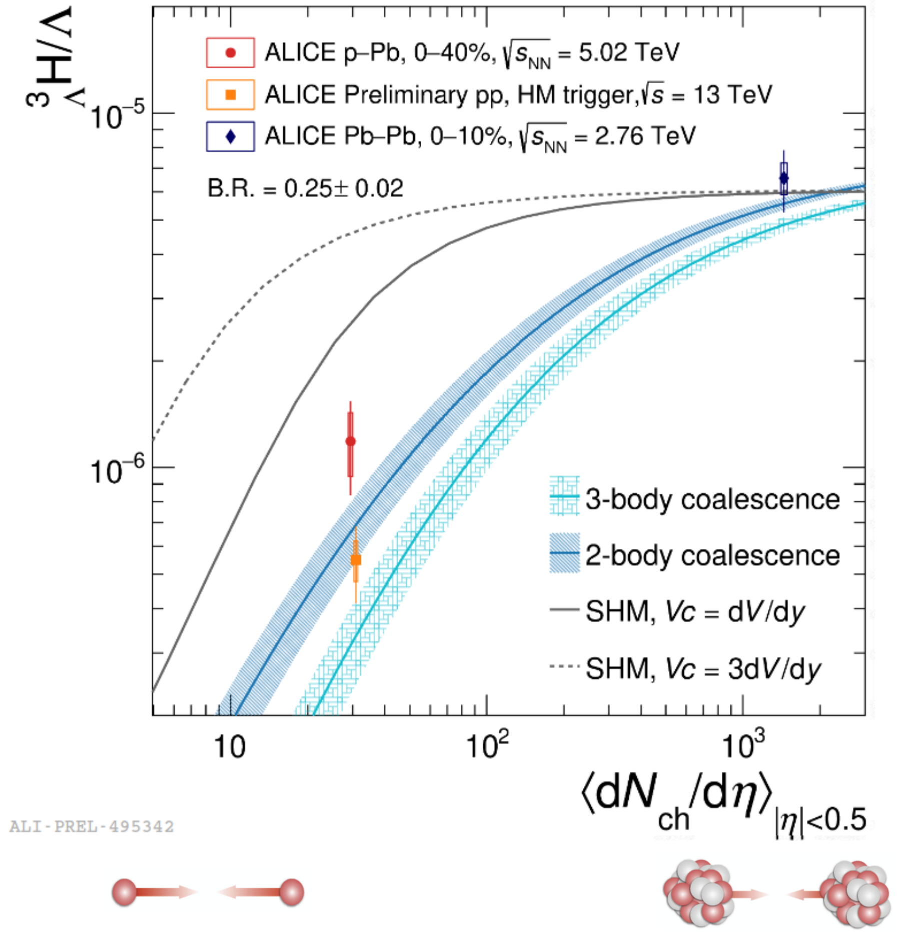
$r_{(np\Lambda)}$: 4.9 fm ($B_\Lambda$= 2.35 MeV)

$r_{(d\Lambda)}$: 10 fm ($B_\Lambda \sim$ 0.13 MeV)



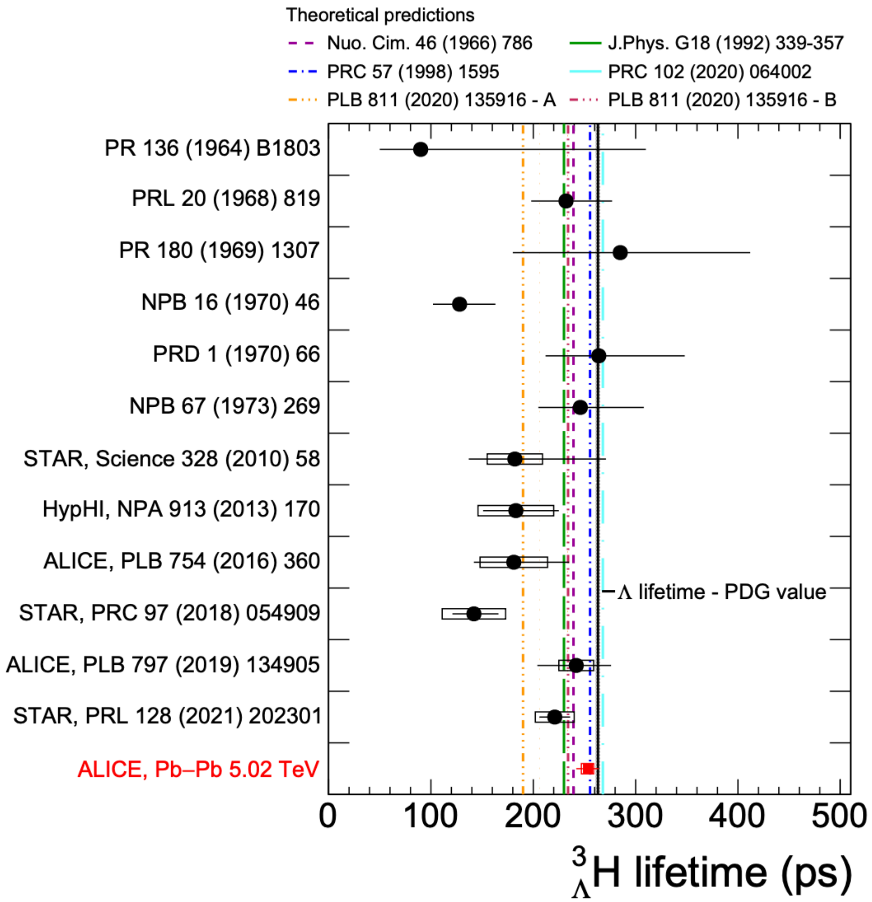
powerful probe for investigating the nucleon – Λ interaction

PLB 754 (2016) 360–372

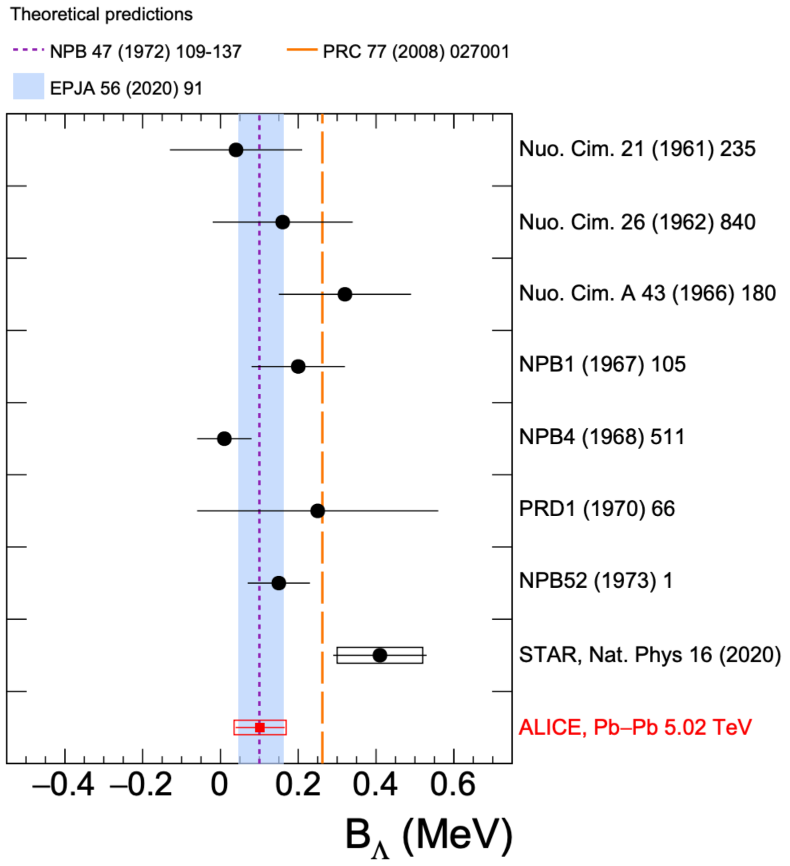


# Hypertriton lifetime & binding energy (Pb–Pb collisions)

$$\tau = [253 \pm 11\ (\mathrm{stat.}) \pm 6\ (\mathrm{syst.})]\ \mathrm{ps}$$



$$B_{\Lambda} = [102 \pm 63\ (\mathrm{stat.}) \pm 67\ (\mathrm{syst.})]\ \mathrm{keV}$$



- Models predicting a lifetime close to the free Λ one are favoured
- Strong hint that hypertriton is weakly bound

- $B_{\Lambda}$ compatible with zero → Weakly bound nature of $^{3}_{\Lambda}$H is confirmed

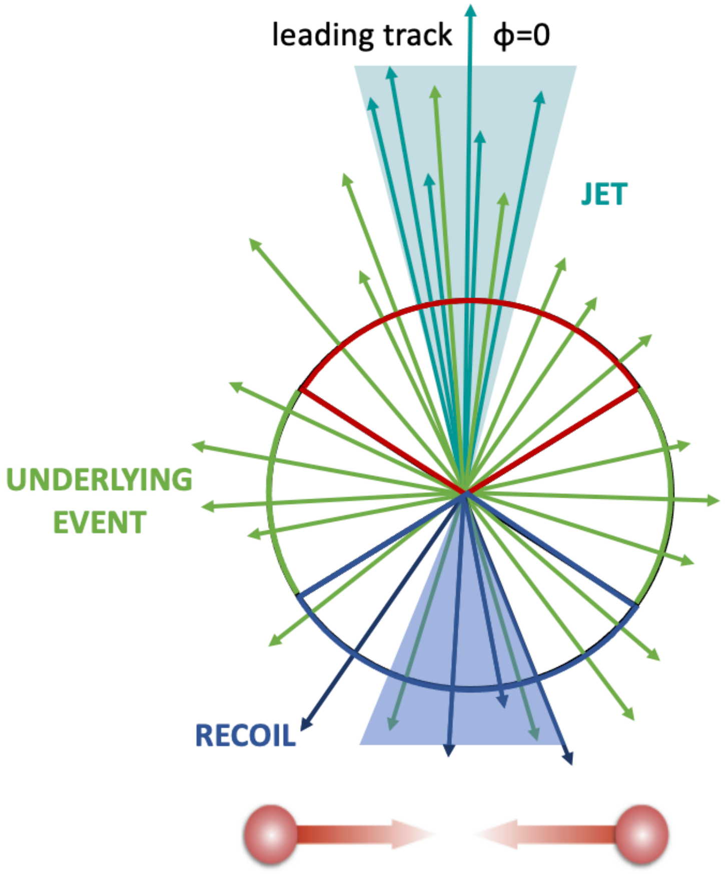
📚 Phys. Rev. Lett. 131 (2023) 102302

chiara.pinto@cern.ch

# Nuclear production in and out of jets

- Powerful tool to investigate coalescence mechanism is the study of nuclear production in and out of jets
- In jets nucleons have strong phase-space constraint

→ **Study $B_2$ in and out of jets**: jets obtained simply by subtracting the UE from the Toward region (Jet + UE)



Toward: $|\Delta\phi| < 60°$
Transverse: $60° < |\Delta\phi| < 120°$
Away: $|\Delta\phi| > 120°$

T. Martin et al., Eur. Phys. J. C (2016) 76: 299

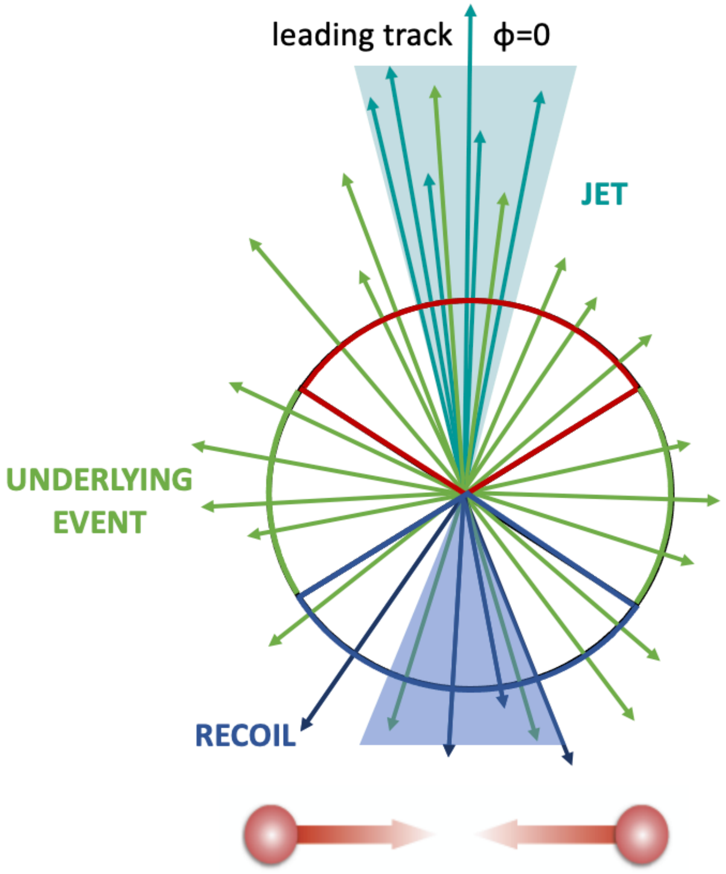
chiara.pinto@cern.ch

# Nuclear production in and out of jets

- Powerful tool to investigate coalescence mechanism is the study of nuclear production in and out of jets
- In jets nucleons have strong phase-space constraint

→ **Study $B_2$ in and out of jets**: jets obtained simply by subtracting the UE from the Toward region (Jet + UE)

- Studying the antideuteron production in jets in small systems (pp, pA) is important to understand and model nuclear production
- Implications for cosmic ray physics
- Antideuteron in the Galaxy is produced in interactions of cosmic rays (p, $^4$He) with kinetic energies of ~300 GeV



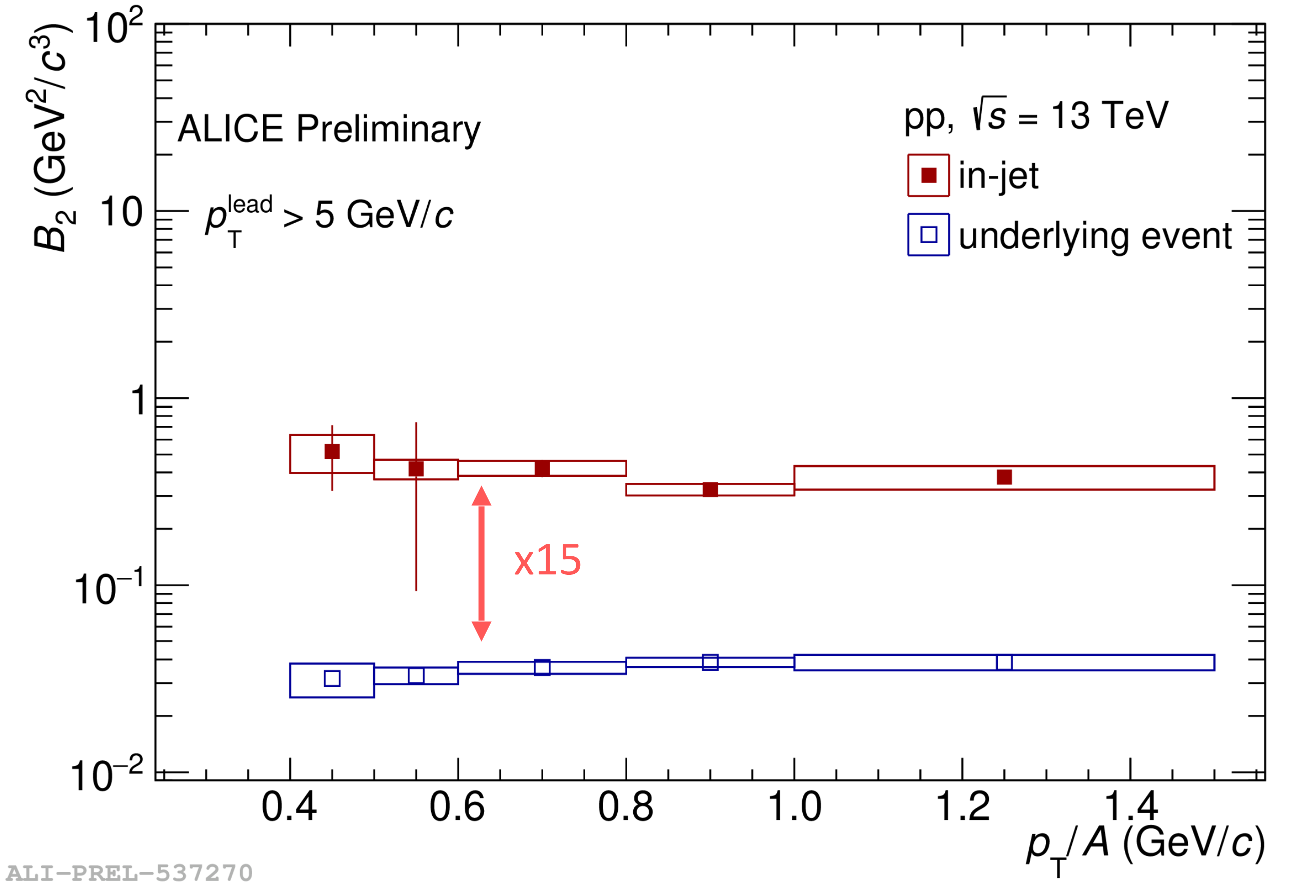
Toward: |Δϕ| < 60°
Transverse: 60° < |Δϕ| < 120°
Away: |Δϕ| > 120°

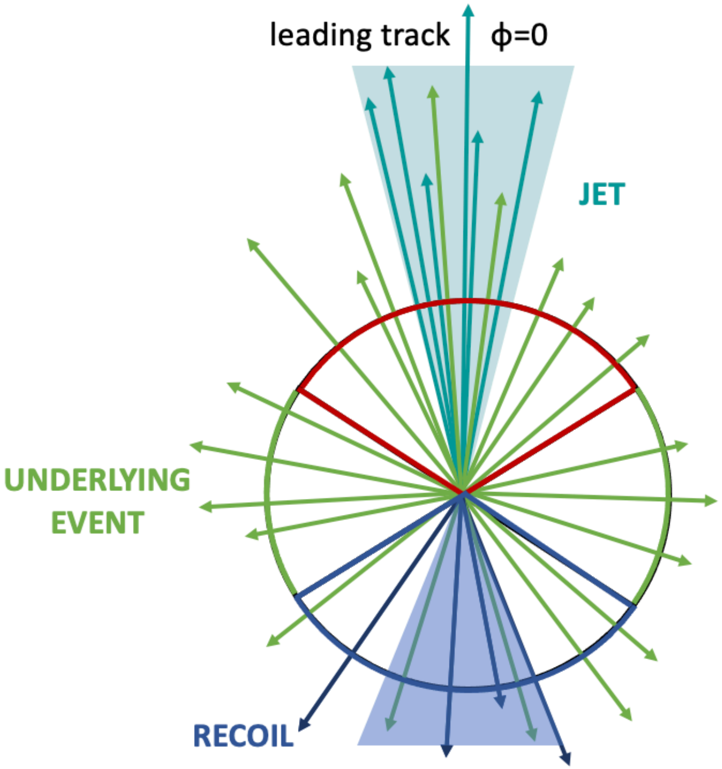
T. Martin et al., Eur. Phys. J. C (2016) 76: 299

Serksnyte et al., Phys. Rev. D 105 (2022) 8, 083021

chiara.pinto@cern.ch

# Coalescence parameters in and out of jets

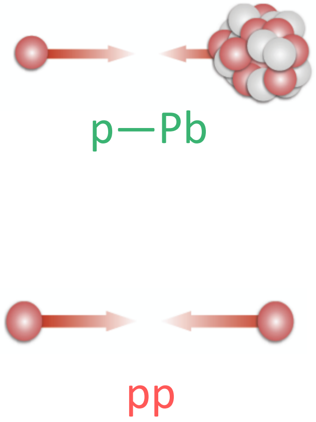


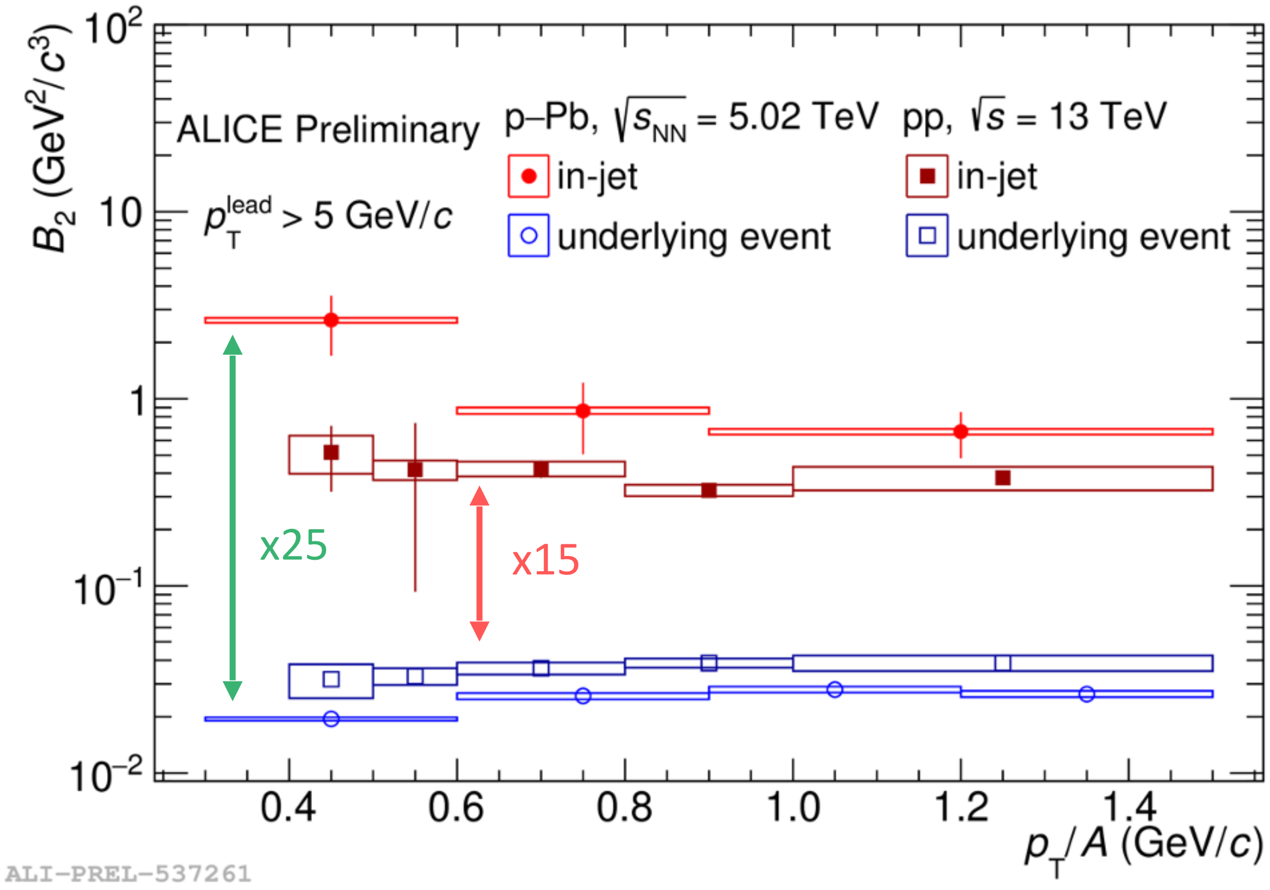


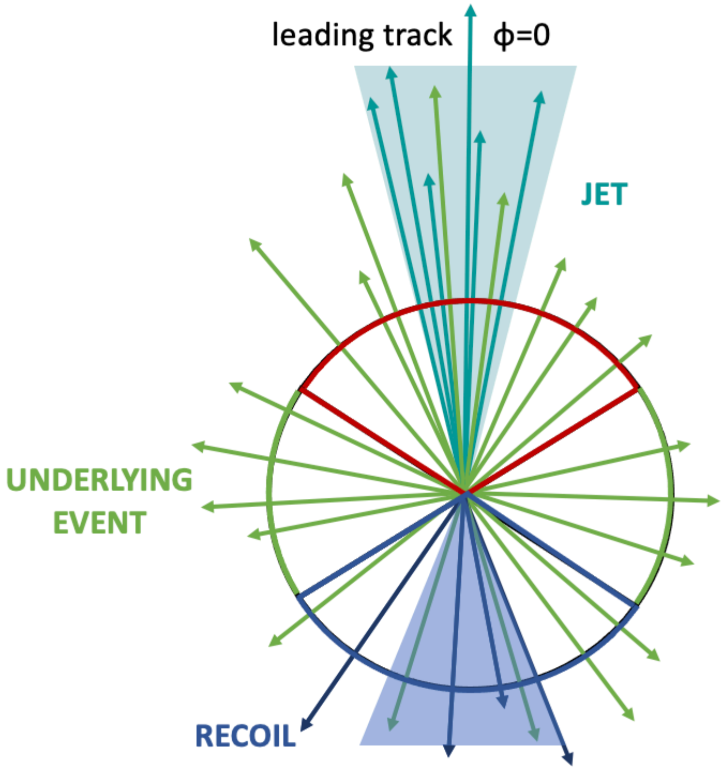
- *Enhanced deuteron coalescence probability in jets wrt UE is observed for the first time in pp collisions*
- Due to the reduced distance in phase space of hadrons in jets compared to those out of jets → favors coalescence picture

Phys.Rev.Lett. 131 (2023) 4, 042301

# Coalescence parameters in and out of jets







- $B_2$ in-jet in p—Pb is larger than $B_2$ in-jet in pp

  → *could be* related to the different particle composition of jets in pp and p—Pb → *to be further investigated*

- $B_2$ in UE in p—Pb is smaller than $B_2$ in UE in pp due to the larger source size in p—Pb (pp[1]: $r_0 \sim 1$ fm, p—Pb[2]: $r_0 \sim 1.5$ fm)

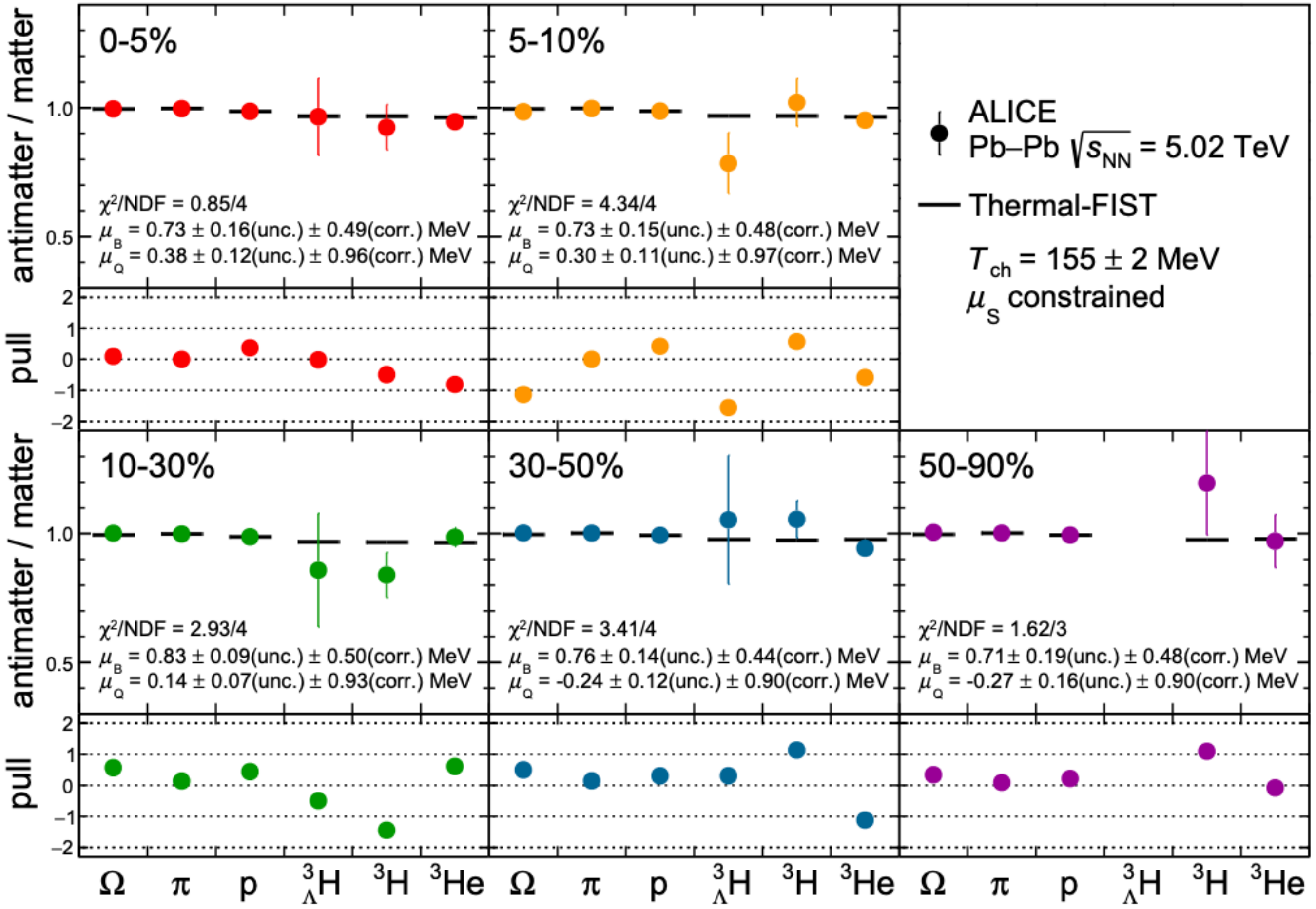
[1] Phys.Rev.C 99 (2019) 024001

[2] Phys.Rev.Lett. 123 (2019) 112002

Phys.Rev.Lett. 131 (2023) 4, 042301

chiara.pinto@cern.ch

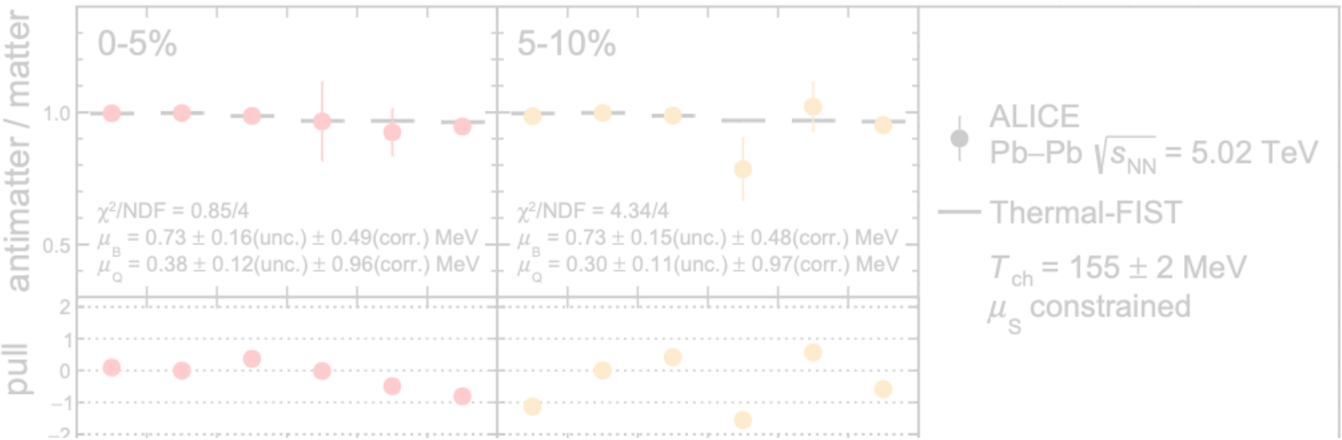
# Chemical potential at the LHC

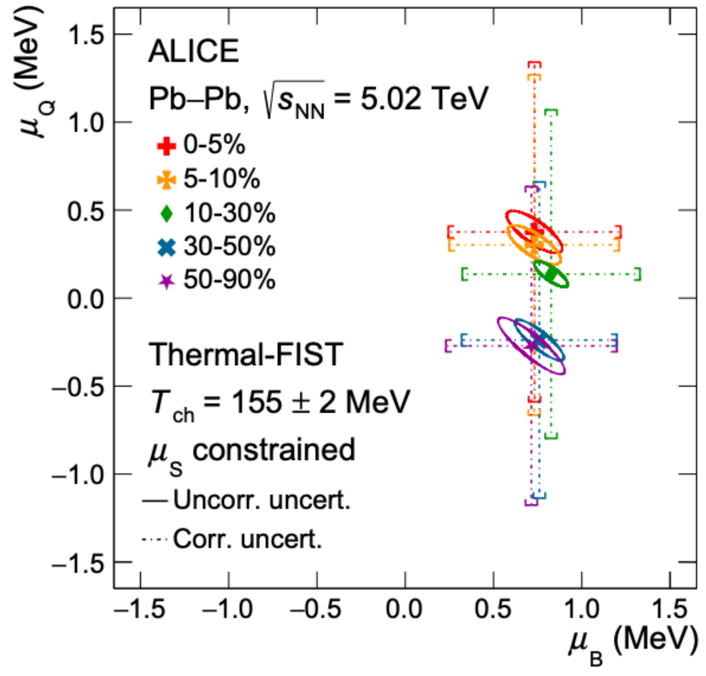


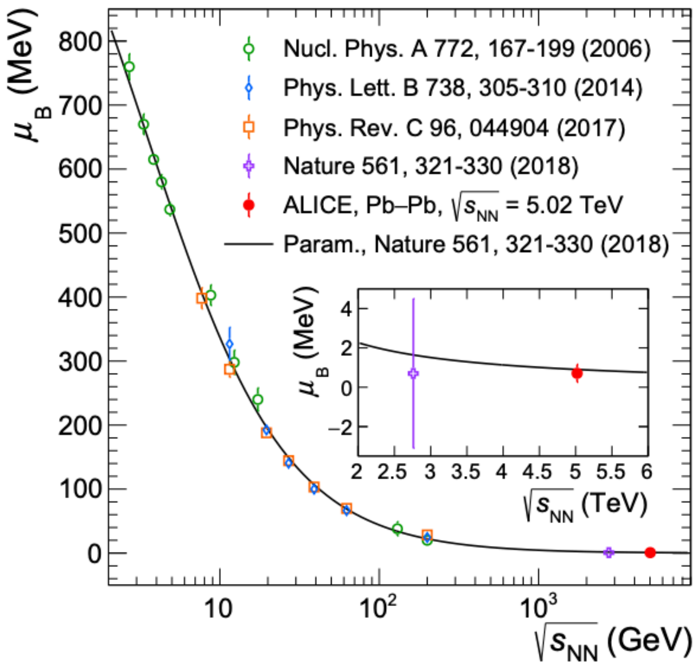
- $\mu_B$ and $\mu_Q$ are extracted fitting the antiparticle-to-particle yield ratios with the predictions of the grand-canonical SHM using the Thermal-FIST code

ALICE Collaboration, arXiv:2311.13332

# Chemical potential at the LHC







- $\mu_B$ and $\mu_Q$ are extracted fitting the antiparticle-to-particle yield ratios with the predictions of the grand-canonical SHM using the Thermal-FIST code
- $\mu_Q = -0.18 \pm 0.90$ MeV
- $\mu_B = 0.71 \pm 0.45$ MeV (~8 times more precise than previous measurement)

- **Nuclear transparency regime** is reached (→ baryon transport from the colliding ions to the interaction region is negligible)
- **No centrality dependence**→ nuclear transparency also in central Pb–Pb (despite $\mu_B$>0 could be expected from a more significant baryon number transport at midrapidity

**The system created in Pb–Pb collisions at the LHC is on average baryon–free and electrically neutral at midrapidity → approaching the early Universe more than any other experimental facility**

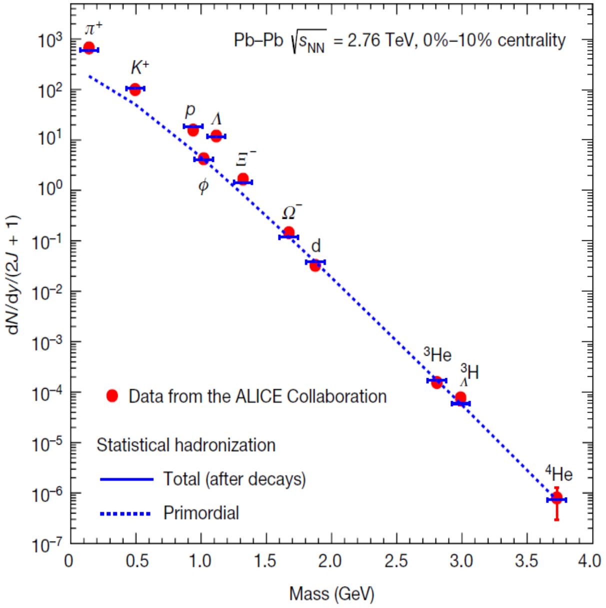
ALICE Collaboration, arXiv:2311.13332

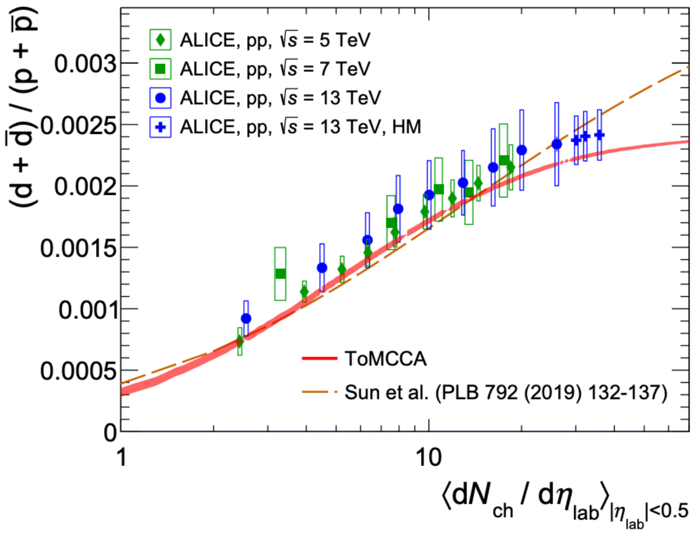
chiara.pinto@cern.ch

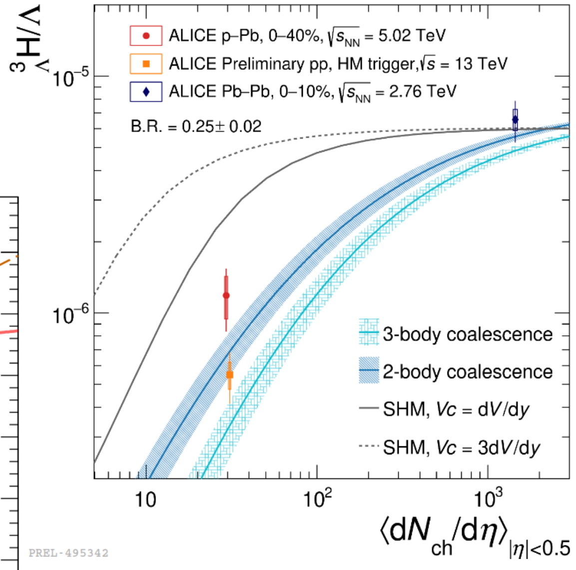
# Summary

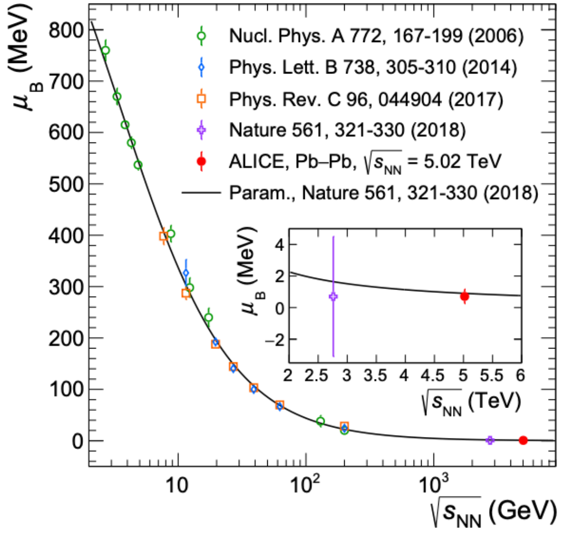
**Production mechanism still not understood**

- State-of-the-art coalescence model using Wigner function formalism describes d/p and $B_2$ vs multiplicity
- Hypertriton measurements in small systems favor coalescence
- SHM describes the integrated yields of all particles, from pions to hypernuclei
- Using SHM the chemical potential are calculated showing that nuclear transparency regime is reached at the LHC







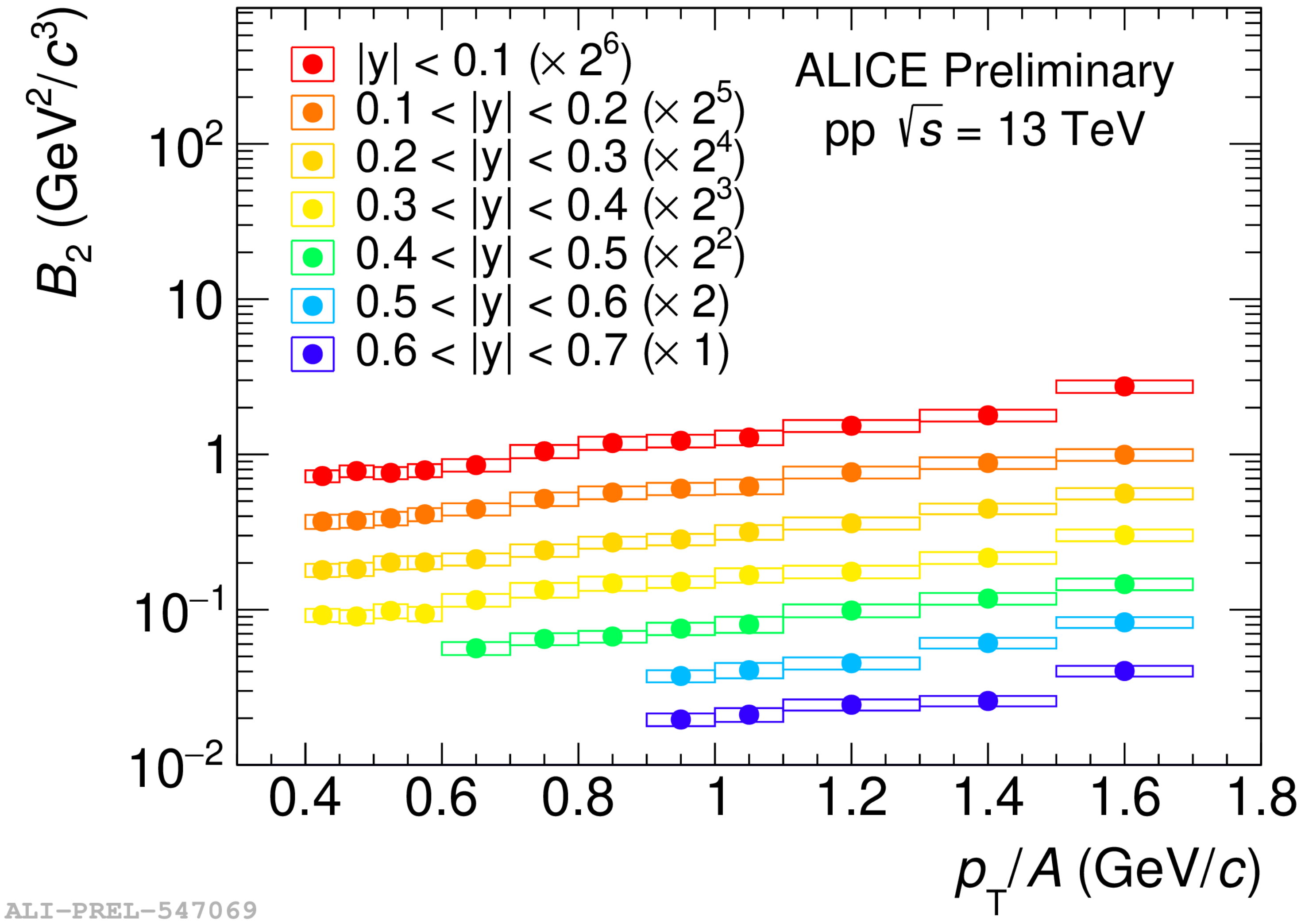


chiara.pinto@cern.ch

# Backup

chiara.pinto@cern.ch

# Coalescence parameter vs. rapidity



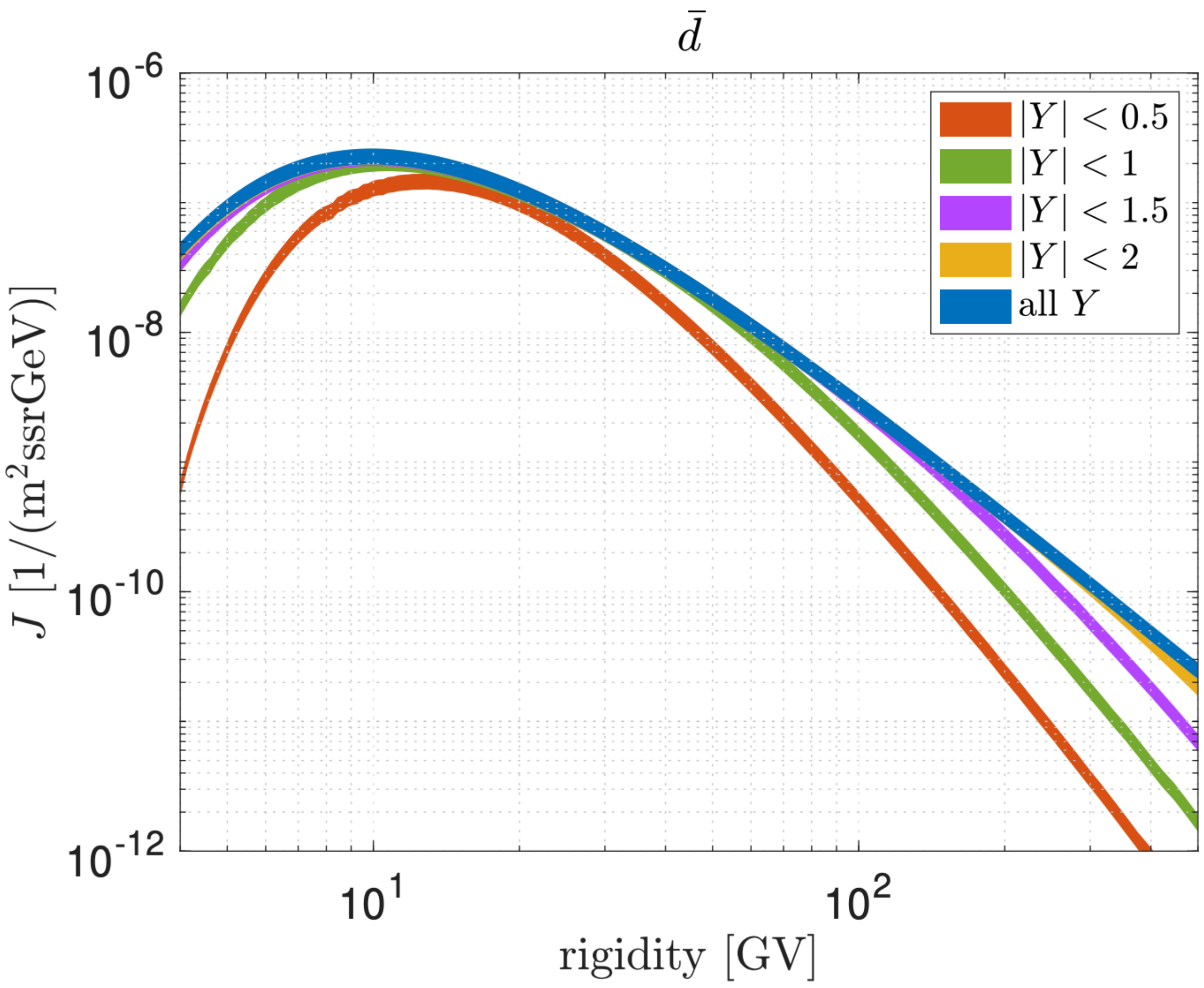
- ALICE measurements cover the midrapidity region (|$y$|<0.5), while astrophysical models extrapolate to forward region

- Current acceptance of ALICE detector allows us to extend the measurement of antinuclei up to $y$ = 0.7

- Rapidity and $p_T$ dependence of $B_2$ is extrapolated to forward rapidity using coalescence model + Pythia 8.3 and EPOS as event generators

chiara.pinto@cern.ch

# Antideuteron flux predictions vs. *y*



- Model predictions based on ALICE measurements are used as input to calculate antideuteron flux from cosmic rays* → dominant background in dark matter searches
- Most of the antideuteron yield from $|y| < 1.5$ → well in reach with future ALICE3(1) detector acceptance ($|y| \lesssim 4$) and current LHCb

Production models needed in astrophysics
→ Rapidity coverage is in reach of accelerator experiments
→ Extrapolation to lower energies (~GeV) is needed

K. Blum, arXiv:2306.13165

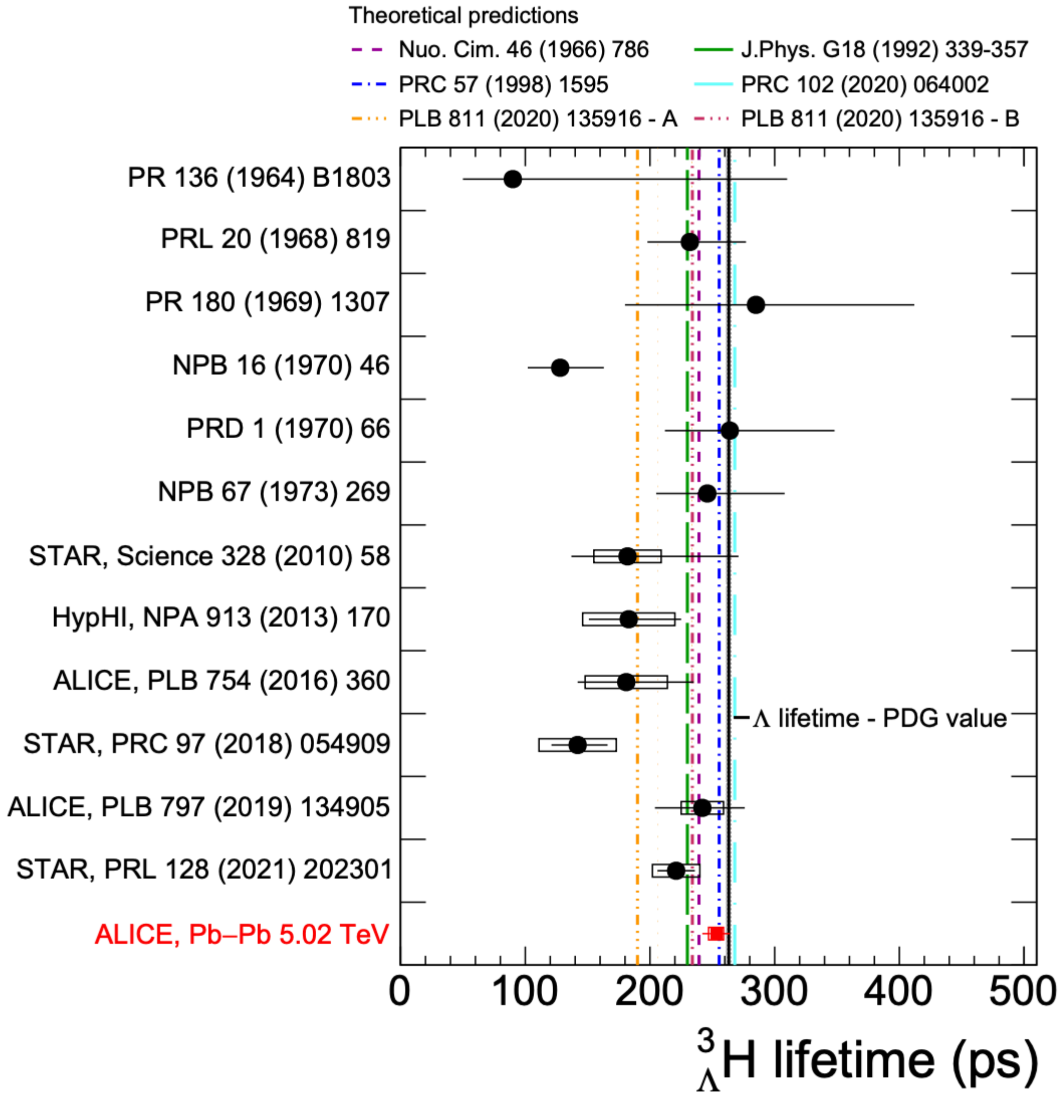
* K. Blum, Phys.Rev.D 96 (2017) 10, 103021

1 arXiv:2211.02491

# Hypertriton lifetime

$$\boxed{\tau = [253 \pm 11\ (\mathrm{stat.}) \pm 6\ (\mathrm{syst.})]\ \mathrm{ps}}$$

- Most precise measurement
- Compatible with latest ALICE and STAR measurements
- Models predicting a lifetime close to the free Λ one are favoured
- Strong hint that hypertriton is weakly bound, but $B_\Lambda$ is still needed to solve the puzzle



≥ 2020 models: assuming $B_\Lambda$ = 70 keV

< 2020 models: assuming $B_\Lambda$ = 130 keV

Phys. Rev. Lett. 131 (2023) 102302

chiara.pinto@cern.ch

# Hypertriton binding energy

$$B_{\Lambda} = [102 \pm 63\ (\mathrm{stat.}) \pm 67\ (\mathrm{syst.})]\ \mathrm{keV}.$$

- From the mass measurement to $B_{\Lambda}$

$$B_{\Lambda} = M_{\Lambda} + M_{d} - M_{^{3}_{\Lambda}\mathrm{H}}$$

- Weakly bound nature of $^{3}_{\Lambda}$H is confirmed by the latest ALICE measurement
  - $B_{\Lambda}$ compatible with zero
  - in agreement within 1σ with Dalitz and $\chi$EFT-based predictions
  - fully consistent with the lifetime measurement according to recent theoretical calculations [1, 2]

$r_{(np\Lambda)}$: 4.9 fm ($B_{\Lambda}$= 2.35 MeV)

$r_{(d\Lambda)}$: ~10 fm ($B_{\Lambda}$ ~ 0.13 MeV)

$$r_{^{3}_{\Lambda}\mathrm{H}\,(np\Lambda)}: 4.9\ \mathrm{fm}\ (B_{\Lambda} = 2.35\ \mathrm{MeV})$$

$$r_{^{3}_{\Lambda}\mathrm{H}\,(d\Lambda)}: \sim 10\ \mathrm{fm}\ (B_{\Lambda} \sim 0.13\ \mathrm{MeV})$$

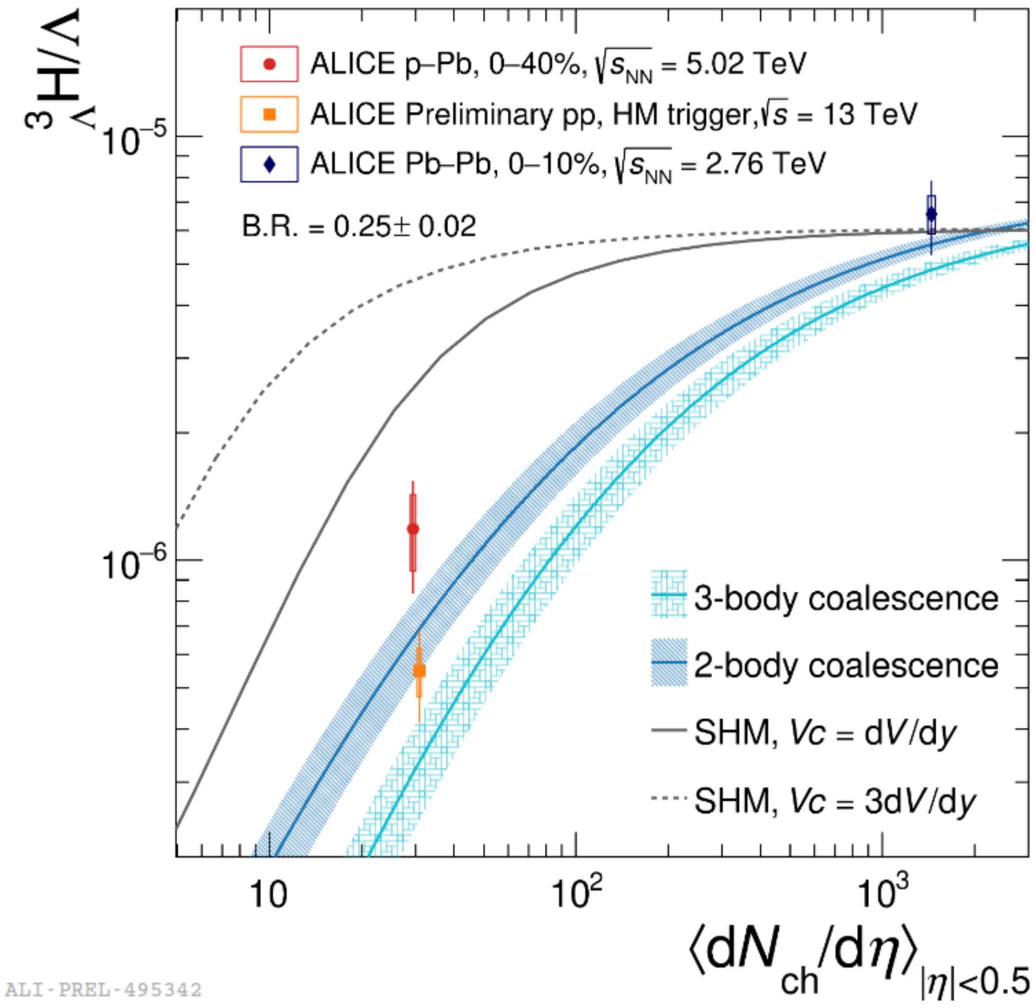
[1] Hildenbrand et al., PRC 102 (2020) 6

[2] Pérez-Obiol et al., PLB (2020) 811

Phys. Rev. Lett. 131 (2023) 102302

chiara.pinto@cern.ch

# Measurement of hypertriton in small collision systems



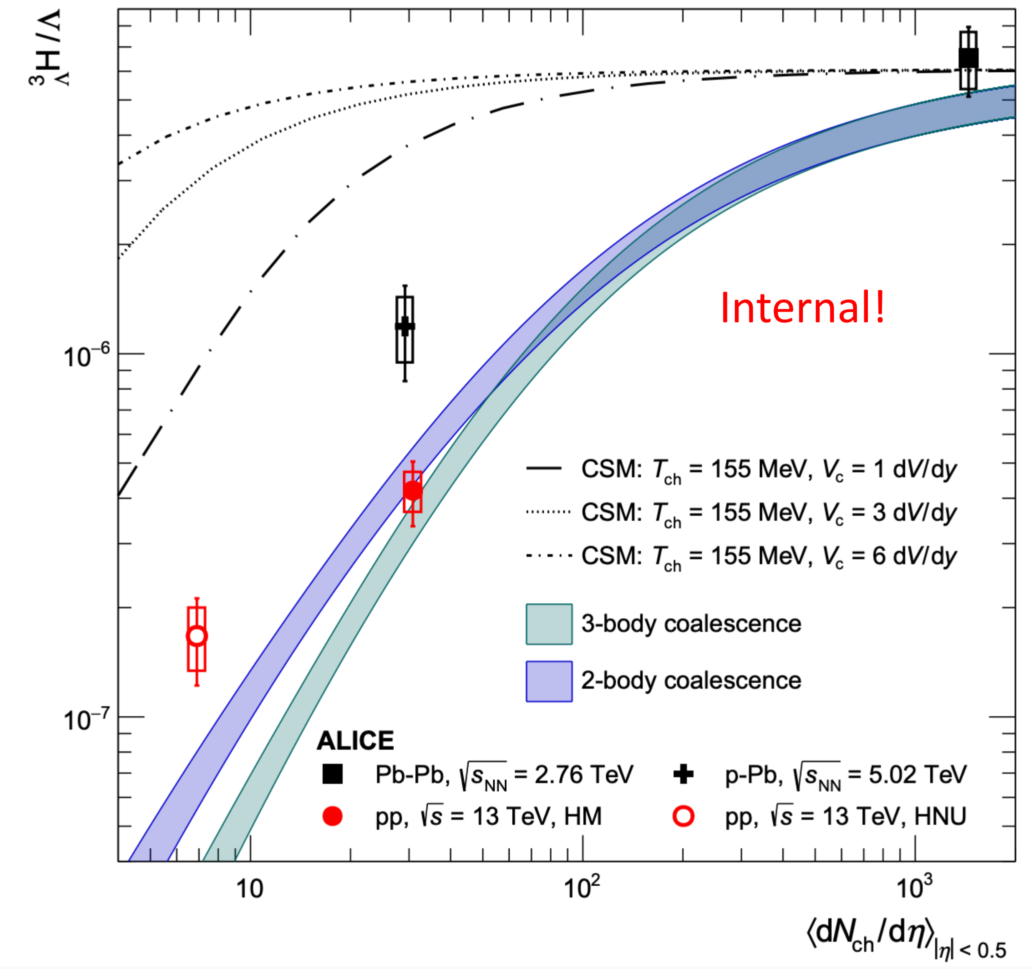
p—Pb: PRL 128 (2022) 25, 252003
Pb—Pb: PLB 754 (2016) 360-372

- **Pb—Pb collisions:**
  - small difference between the predictions from SHM and coalescence
- **pp and p—Pb collisions:**
  - large separation between production models
  - **measurements are in good agreement with 2-body coalescence**
  - tension with SHM at low charged-particle multiplicity density
  - configuration with $V_C$ = 3d$V$/dy is excluded by more than 6σ

Coalescence quantitatively describes the suppression in small systems
> the nuclear size matters at low charged-particle multiplicity

chiara.pinto@cern.ch

# Measurement of hypertriton in small collision systems



p—Pb: PRL 128 (2022) 25, 252003
Pb—Pb: PLB 754 (2016) 360-372

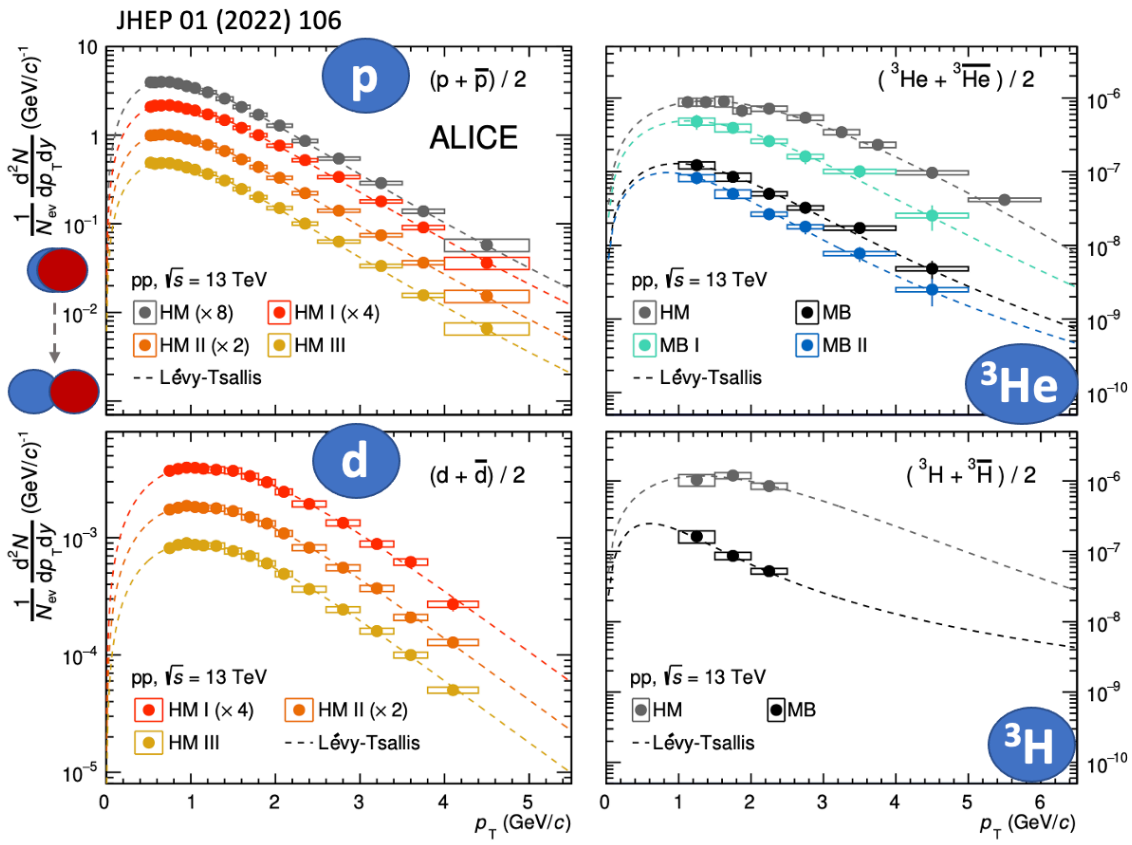
- **Pb—Pb collisions:**
  - small difference between the predictions from SHM and coalescence
- **pp and p—Pb collisions:**
  - large separation between production models
  - **measurements are in good agreement with 2-body coalescence**
  - tension with SHM at low charged-particle multiplicity density
  - configuration with $V_C$ = 3d$V$/dy is excluded by more than 6σ

Coalescence quantitatively describes the suppression in small systems
> the nuclear size matters at low charged-particle multiplicity

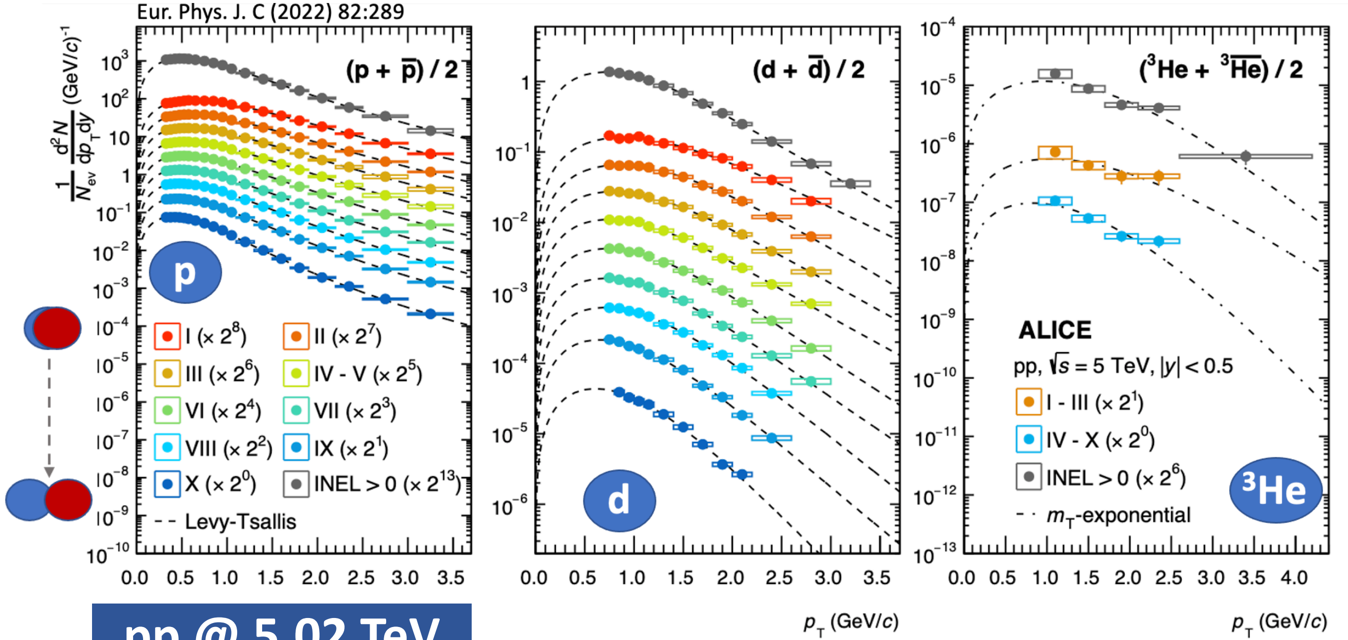
chiara.pinto@cern.ch

# Measurement of light (anti)nuclei with ALICE

- In small systems such as pp and p—Pb collisions, all nuclei species have been measured, from p to $^3$He
- Momentum distributions fitted with Lévy-Tsallis function to extrapolate the yield in the unmeasured regions



**pp @ 13 TeV**

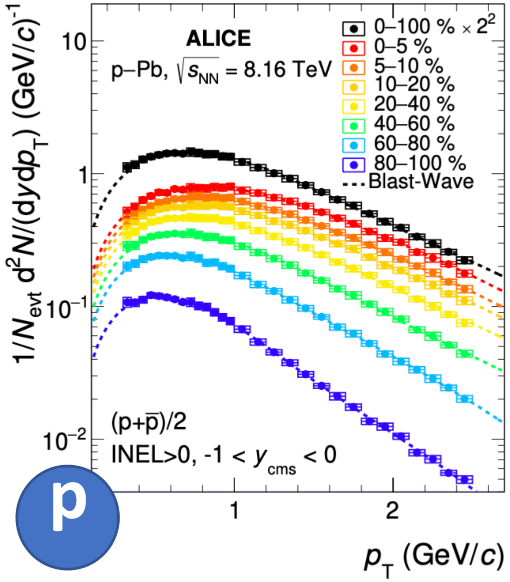


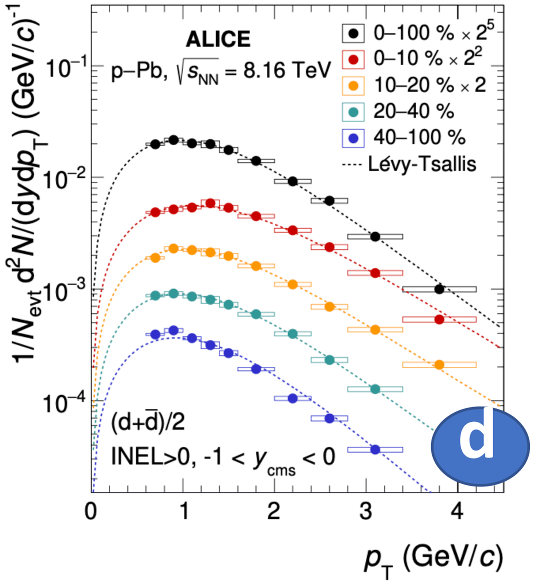
**pp @ 5.02 TeV**

chiara.pinto@cern.ch

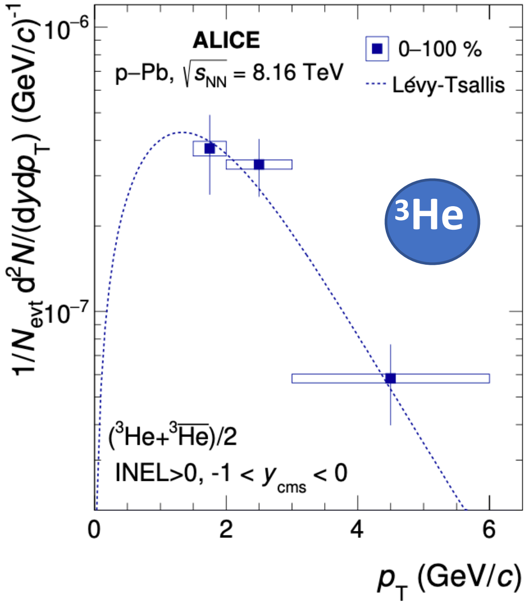
# Measurement of light (anti)nuclei with ALICE

- In small systems such as pp and p—Pb collisions, all nuclei species have been measured, from p to ³He
- Momentum distributions fitted with Lévy-Tsallis function to extrapolate the yield in the unmeasured regions

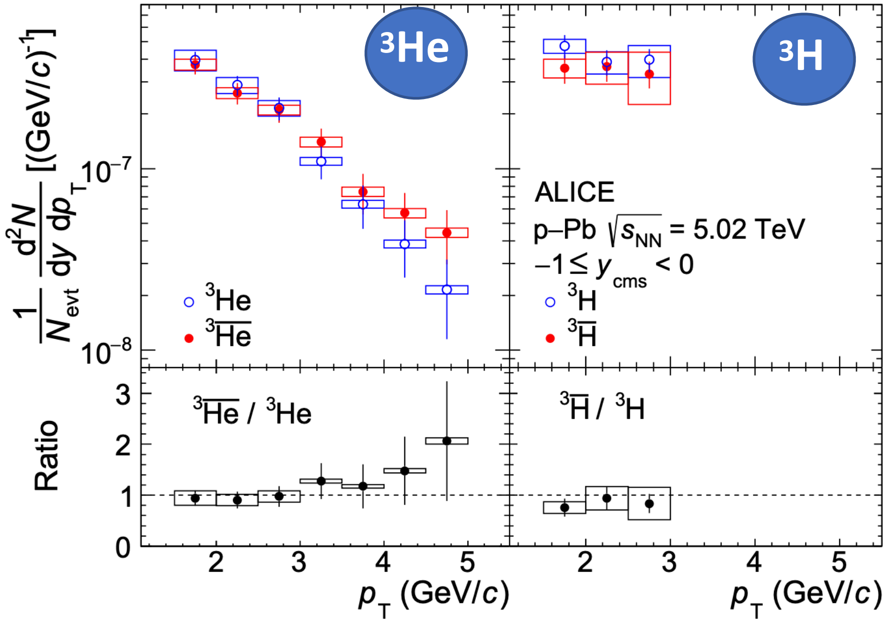


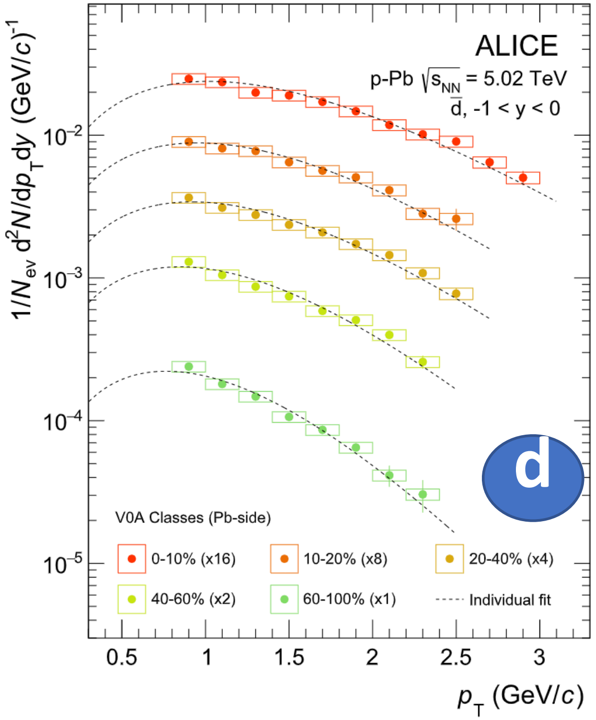


**p-Pb @ 8.16 TeV**



**p-Pb @ 5.02 TeV**





PLB 800 (2020) 135043

chiara.pinto@cern.ch

Phys.Rev.C 101 (2020) 4, 044906

# Inelastic cross section of antinuclei

ALICE measured the **inelastic cross section** for **antinuclei** using the LHC as antimatter factory and the ALICE detector as a target

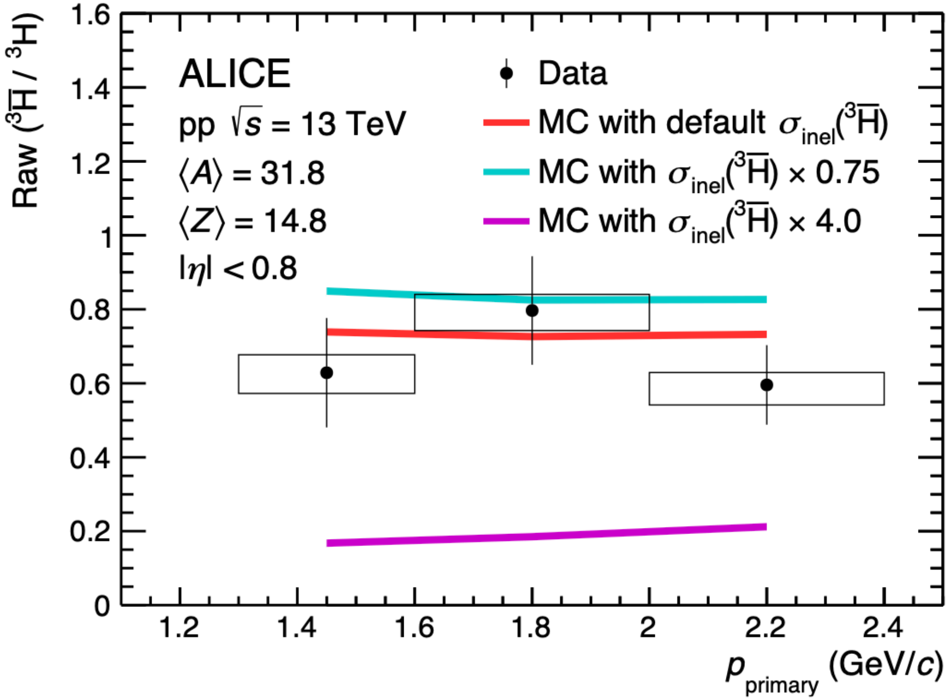
chiara.pinto@cern.ch

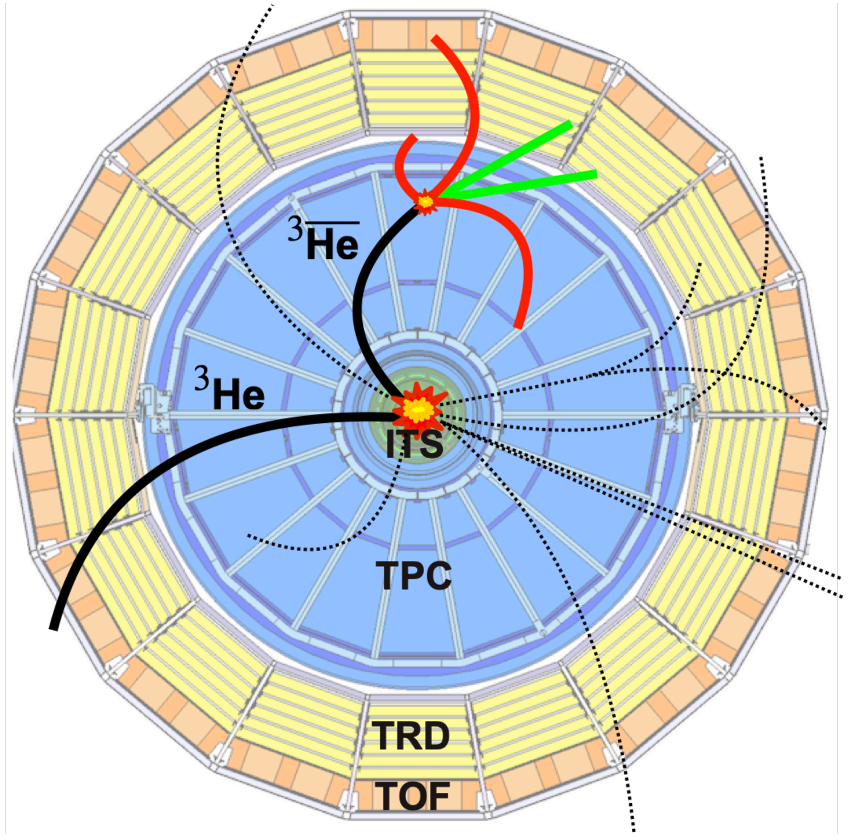
# Inelastic cross section of antinuclei

ALICE measured the **inelastic cross section** for **antinuclei** using the LHC as antimatter factory and the ALICE detector as a target

## Antimatter-to-matter ratio

- Measurement of reconstructed **anti³H/³H** ratio and compare to MC simulation expectations





**New!**

Phys.Rev.Lett. 125, 162001 (2020)

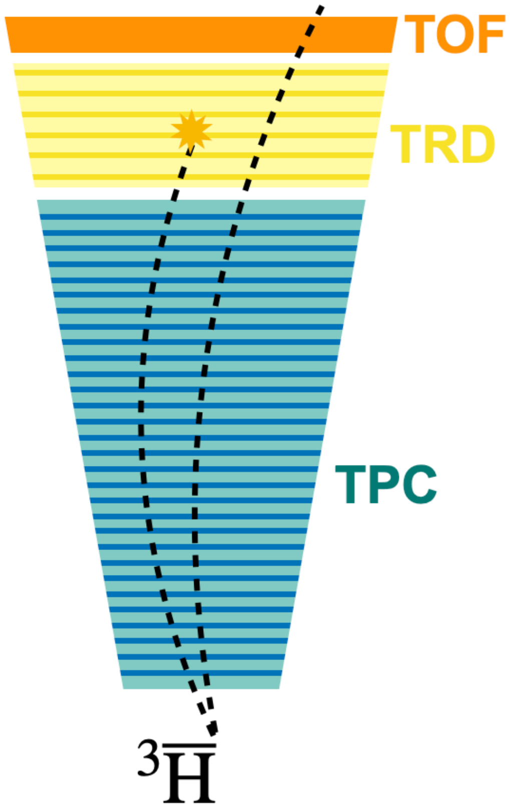
arXiv:2307.03603 [nucl-ex]

Sketch adapted from: Nature Phys. (2023) 19, 61–71

chiara.pinto@cern.ch

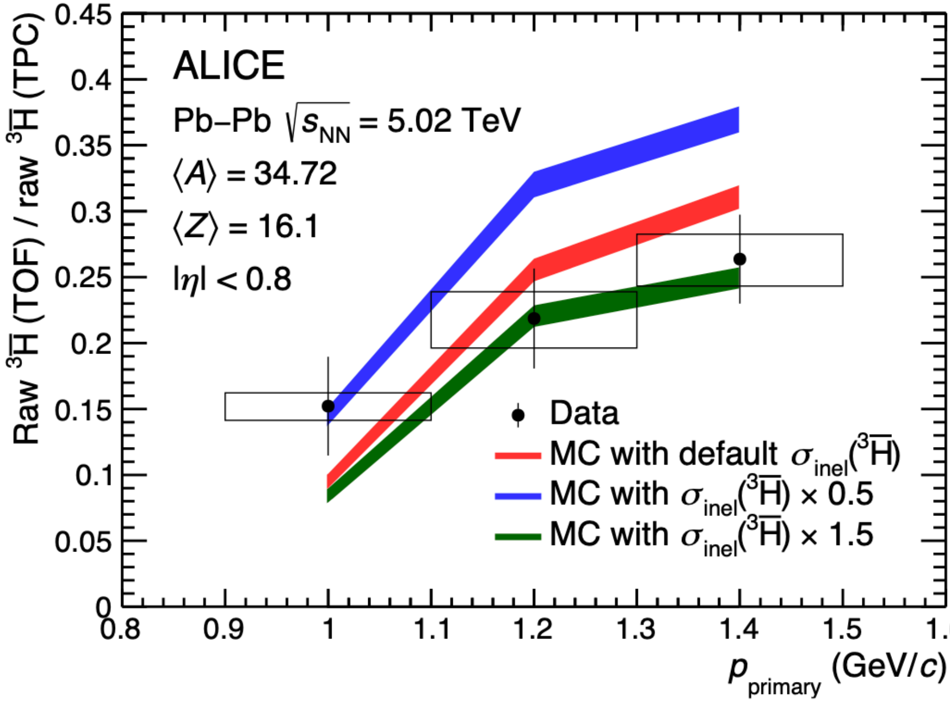
# Inelastic cross section of antinuclei

ALICE measured the **inelastic cross section** for **antinuclei** using the LHC as antimatter factory and the ALICE detector as a target



## TOF/TPC-matching ratio

- Measurement of reconstructed **anti$^{3}$H$_{TOF}$/ anti$^{3}$H$_{TPC}$** ratio and compare to MC simulation expectations



Phys.Rev.Lett. 125, 162001 (2020)

**New!**

arXiv:2307.03603 [nucl-ex]

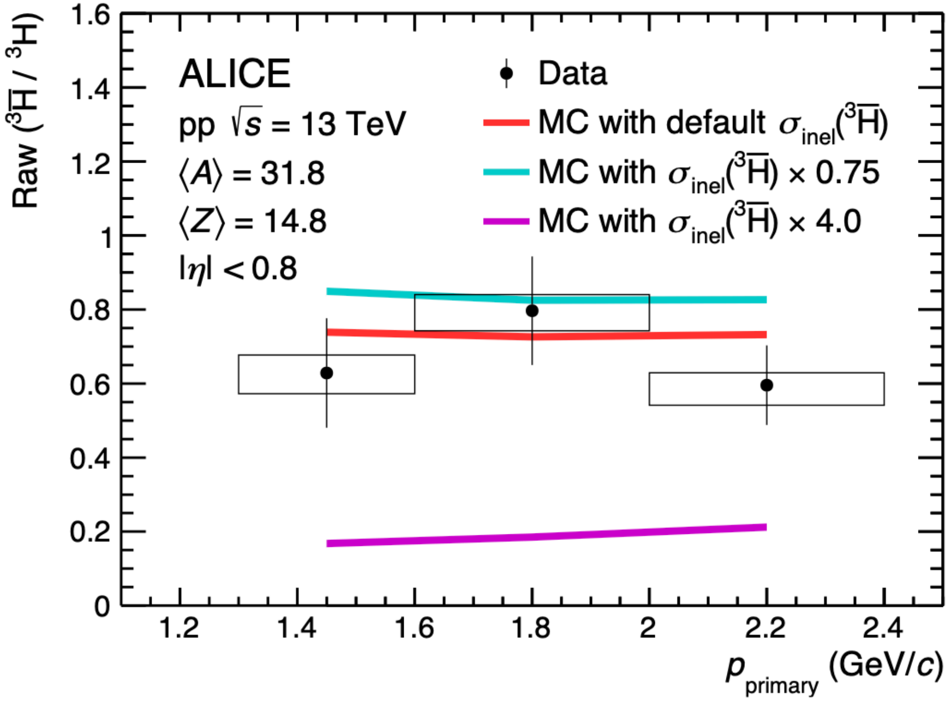
chiara.pinto@cern.ch

# Inelastic cross section of antinuclei

ALICE measured the **inelastic cross section** for **antinuclei** using the LHC as antimatter factory and the ALICE detector as a target

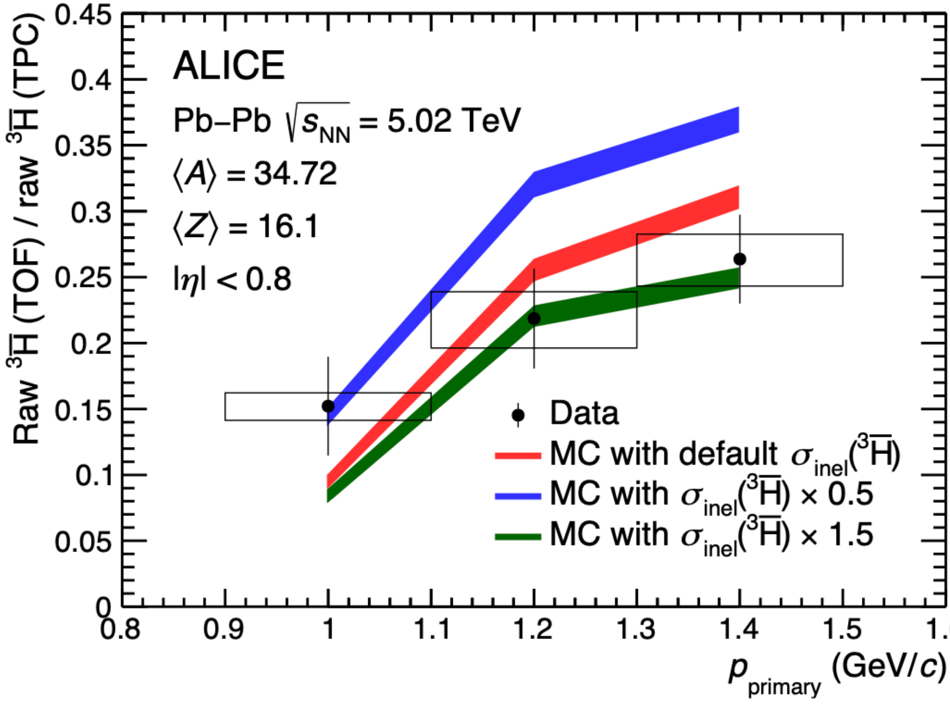
## Antimatter-to-matter ratio

- Measurement of reconstructed **anti$^3$H/$^3$H** ratio and compare to MC simulation expectations



## TOF/TPC-matching ratio

- Measurement of reconstructed **anti$^3$H$_{\mathrm{TOF}}$/ anti$^3$H$_{\mathrm{TPC}}$** ratio and compare to MC simulation expectations



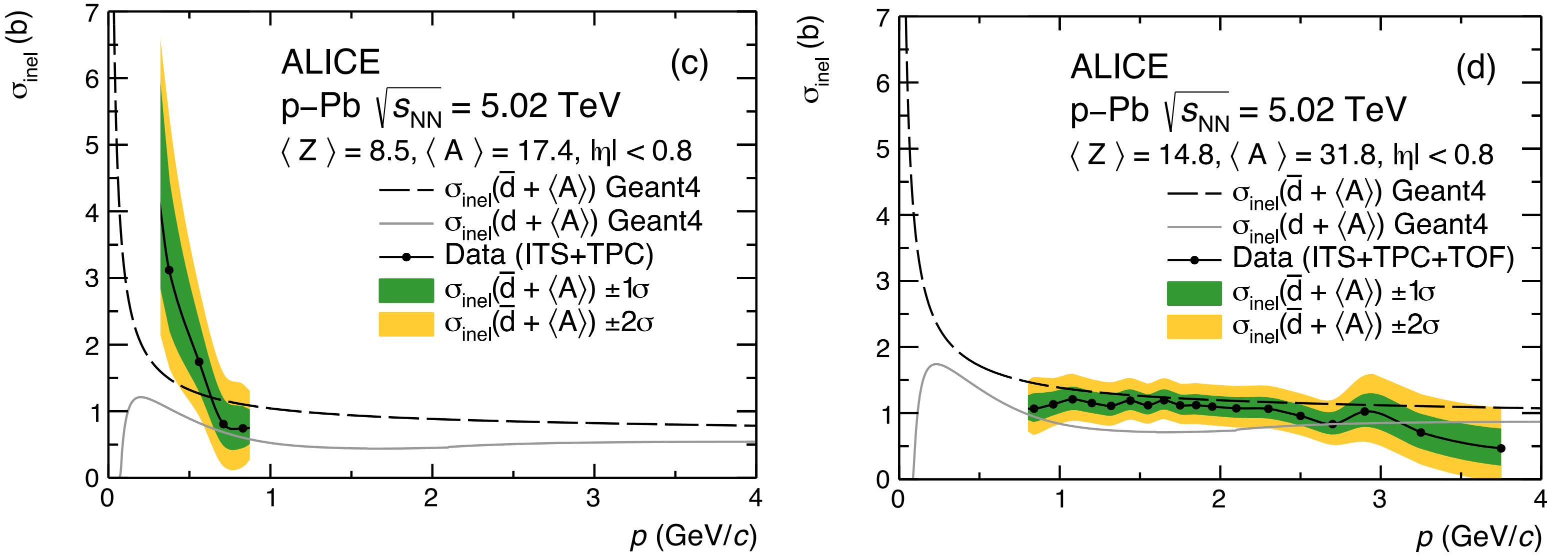
***New!***

Phys.Rev.Lett. 125, 162001 (2020)

arXiv:2307.03603 [nucl-ex]

# Inelastic cross section of antinuclei

ALICE measured the **inelastic cross section** for **antinuclei** using the LHC as antimatter factory and the ALICE detector as a target



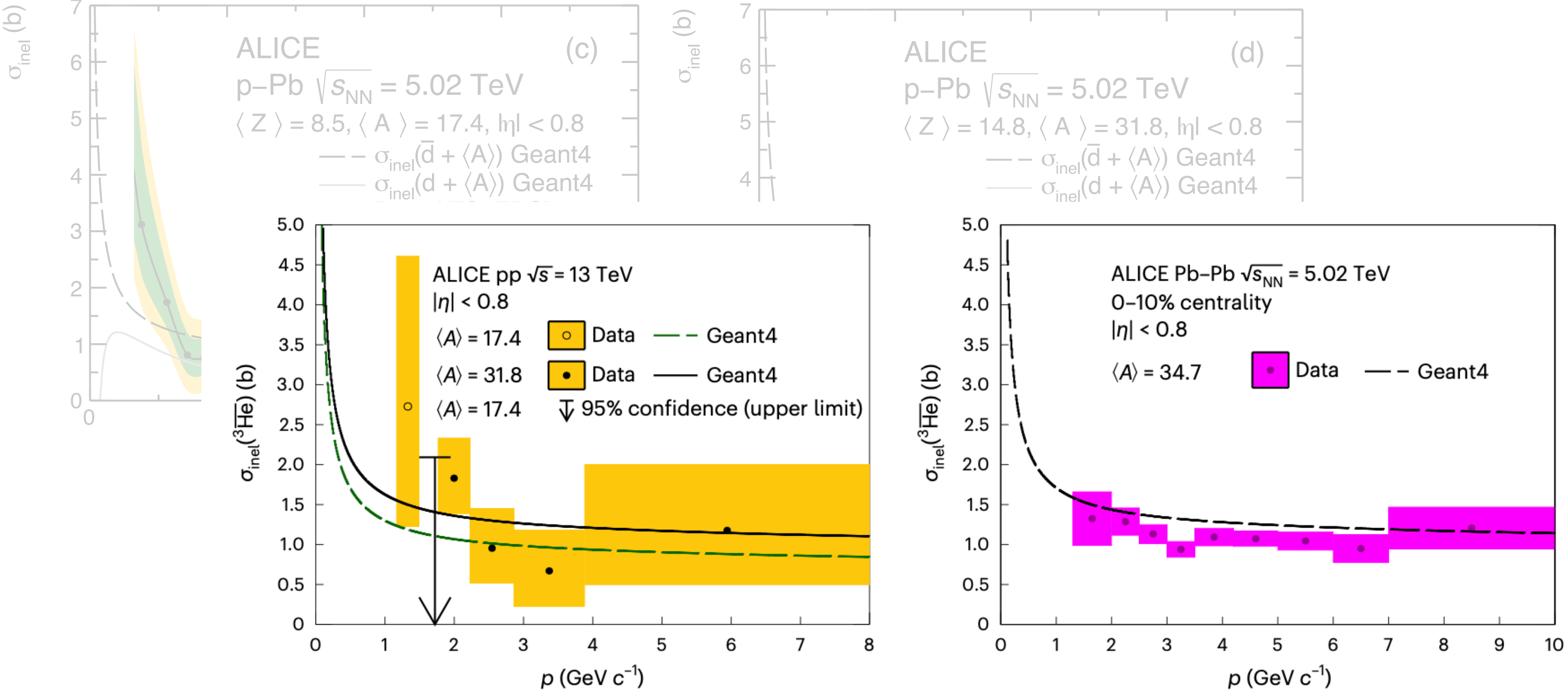
$\bar{d}$

antid: 📚 Phys.Rev.Lett. 125, 162001 (2020)

chiara.pinto@cern.ch

# Inelastic cross section of antinuclei

ALICE measured the **inelastic cross section** for **antinuclei** using the LHC as antimatter factory and the ALICE detector as a target



$^{3}\overline{He}$

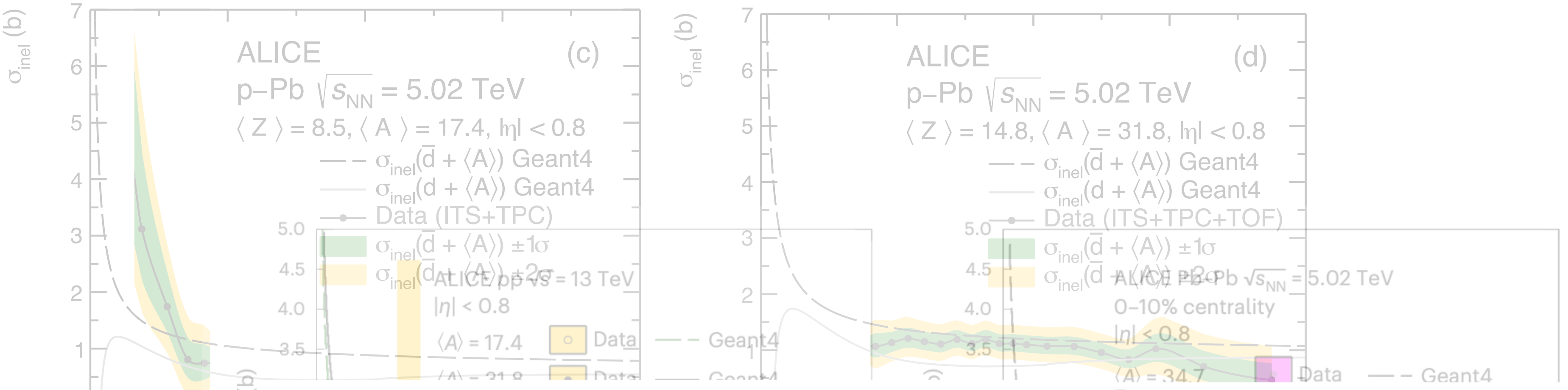
antid: Phys.Rev.Lett. 125, 162001 (2020)

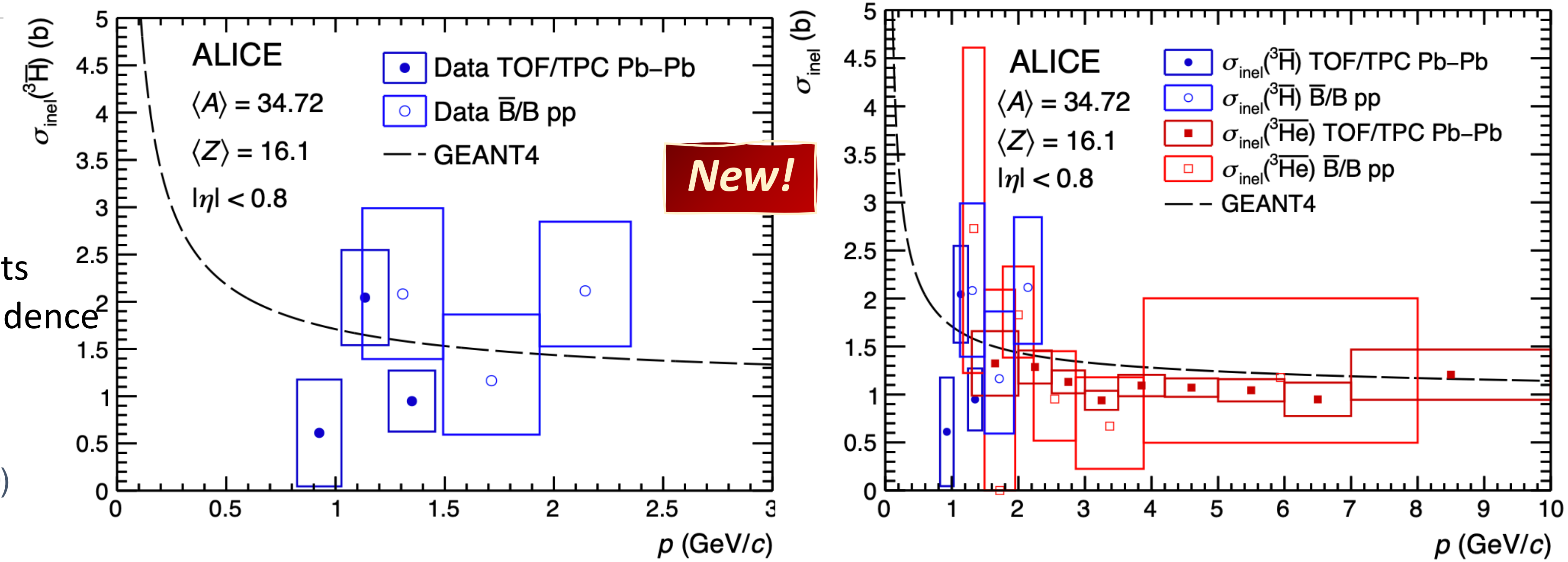
anti³He: Nature Phys. (2023) 19, 61–71

**chiara.pinto@cern.ch**

# Inelastic cross section of antinuclei

ALICE measured the **inelastic cross section** for **antinuclei** using the LHC as antimatter factory and the ALICE detector as a target





**New!**

**3H̄**

- → Complements previous measurements
- → Allows for the study of isospin dependence
- → Extends the $p$ range of ³H̄e

antid: Phys.Rev.Lett. 125, 162001 (2020)

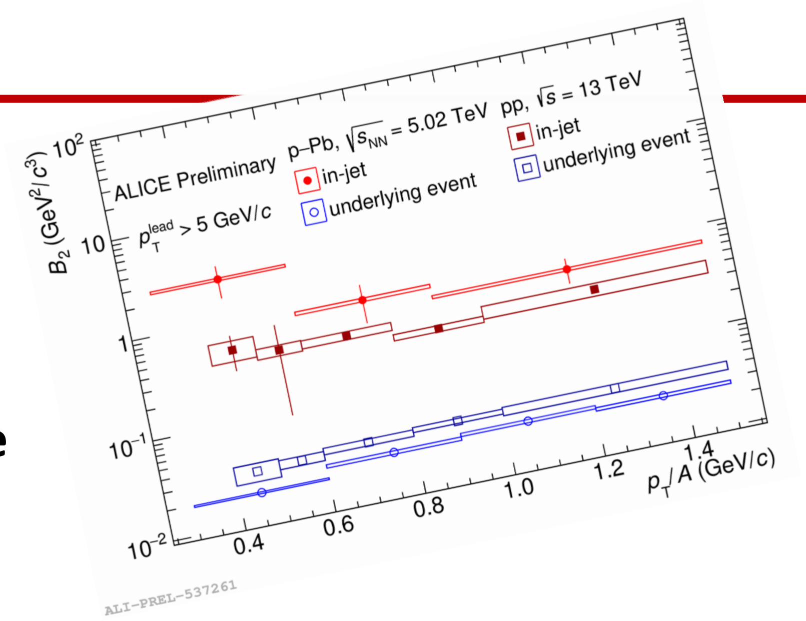
anti³He: Nature Phys. (2023) 19, 61–71

anti³H: arXiv:2307.03603 [nucl-ex]

# Summary

- Production of antinuclei measured at accelerators are crucial input in **astrophysical searches** for dark matter

- Antinuclear production **measurements in and out of jets** in pp and p—Pb collisions helps to further constrain the **coalescence** model



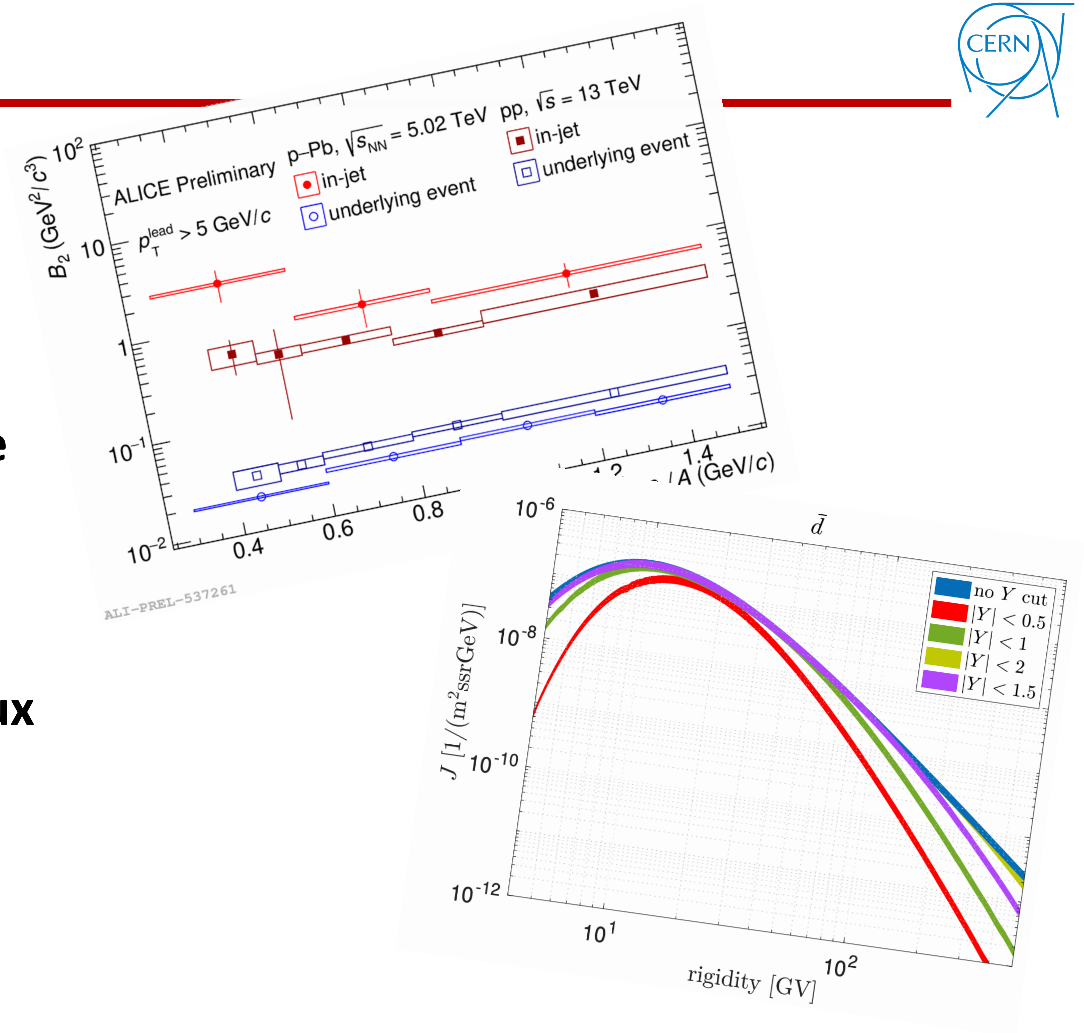
chiara.pinto@cern.ch

# Summary

- Production of antinuclei measured at accelerators are crucial input in **astrophysical searches** for dark matter

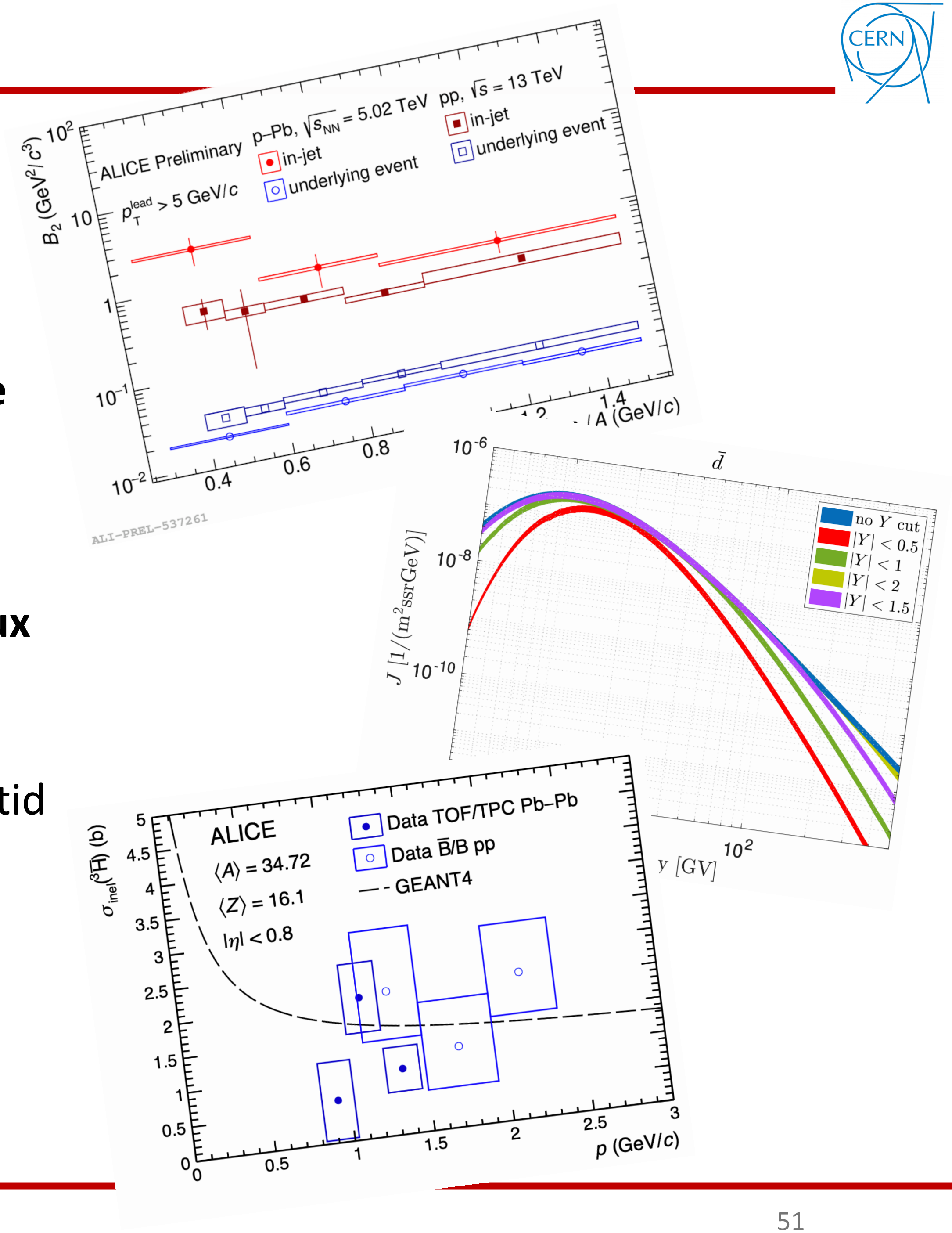
- Antinuclear production **measurements in and out of jets** in pp and p—Pb collisions helps to further constrain the **coalescence** model

- Measurements of **antinuclear production vs. rapidity** used to extrapolate $B_2$ at forward rapidity → predict antinuclear **flux from cosmic rays**



# Summary

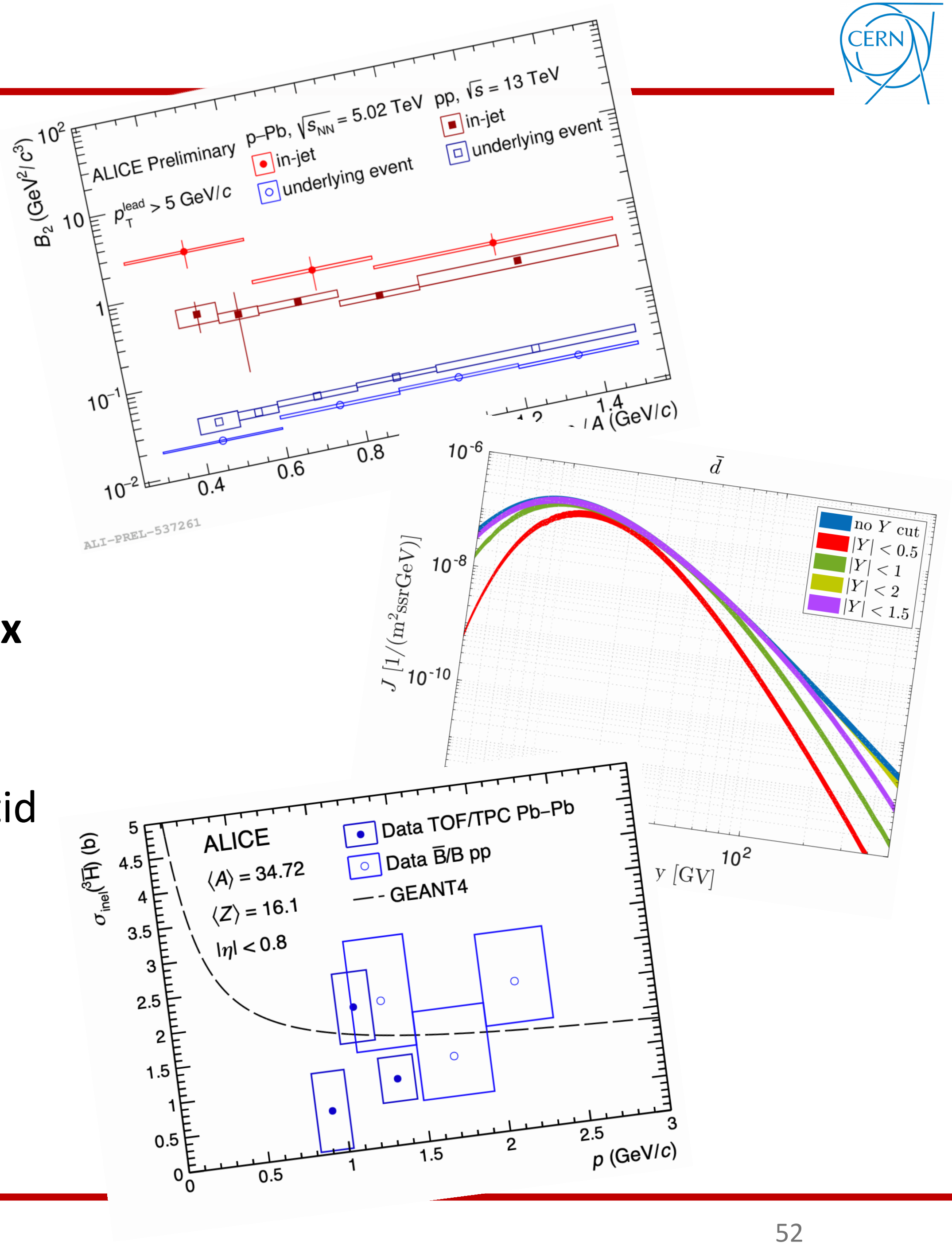
- Production of antinuclei measured at accelerators are crucial input in **astrophysical searches** for dark matter
- Antinuclear production **measurements in and out of jets** in pp and p—Pb collisions helps to further constrain the **coalescence** model
- Measurements of **antinuclear production vs. rapidity** used to extrapolate $B_2$ at forward rapidity → predict antinuclear **flux from cosmic rays**
- **Annihilation processes** have been studied with ALICE, from antid to $^3\overline{\text{He}}$ and $^3\overline{\text{H}}$



# Summary

- Production of antinuclei measured at accelerators are crucial input in **astrophysical searches** for dark matter
- Antinuclear production **measurements in and out of jets** in pp and p—Pb collisions helps to further constrain the **coalescence** model
- Measurements of **antinuclear production vs. rapidity** used to extrapolate $B_2$ at forward rapidity → predict antinuclear **flux from cosmic rays**
- **Annihilation processes** have been studied with ALICE, from antid to $^{3}\overline{\mathrm{He}}$ and $^{3}\overline{\mathrm{H}}$
- More to come with **LHC Run3** increased statistics!

I. Vorobyev's talk
Wed. 8:50

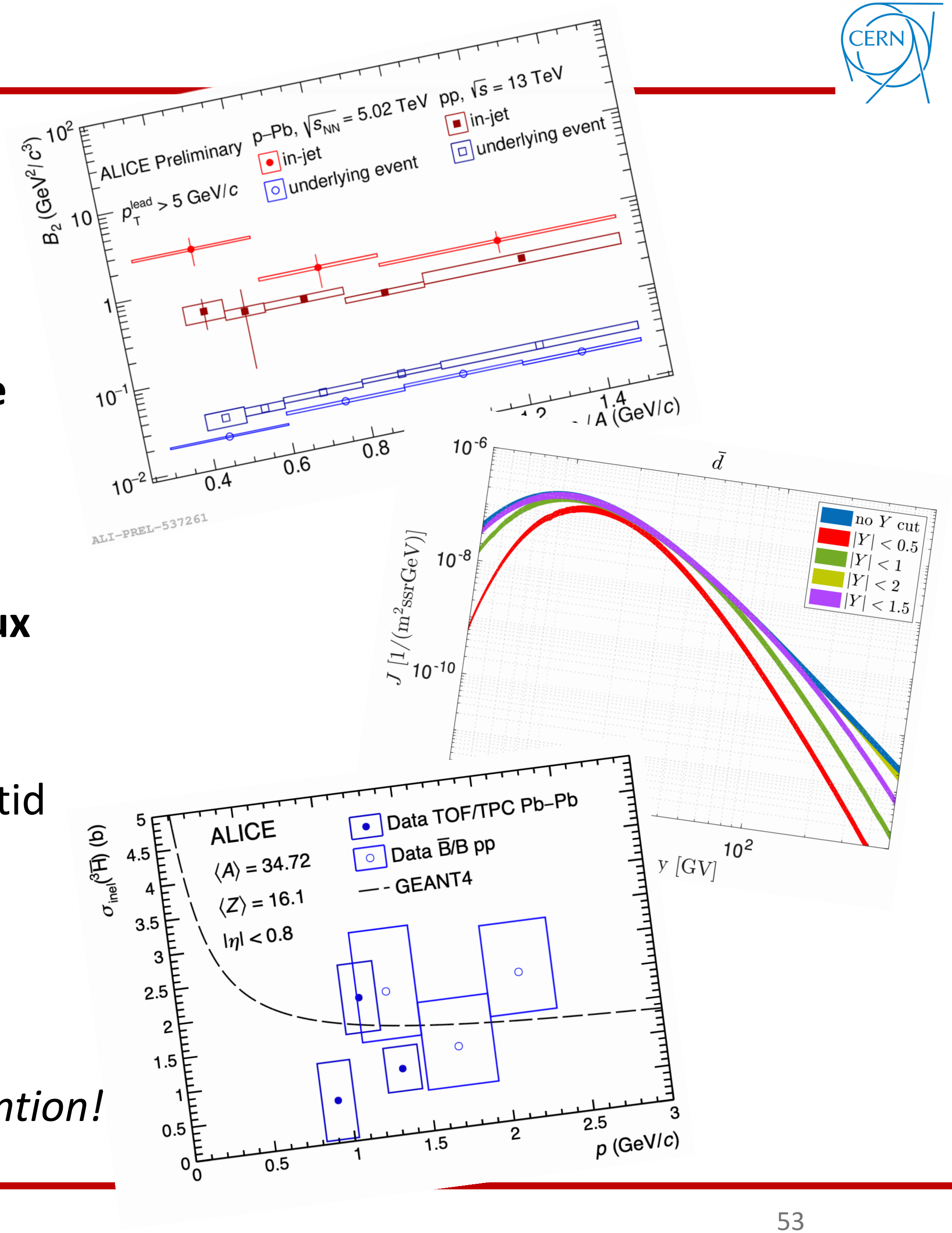


chiara.pinto@cern.ch

# Summary

- Production of antinuclei measured at accelerators are crucial input in **astrophysical searches** for dark matter
- Antinuclear production **measurements in and out of jets** in pp and p—Pb collisions helps to further constrain the **coalescence** model
- Measurements of **antinuclear production vs. rapidity** used to extrapolate $B_2$ at forward rapidity → predict antinuclear **flux from cosmic rays**
- **Annihilation processes** have been studied with ALICE, from antid to $^3\overline{\text{He}}$ and $^3\overline{\mathbf{H}}$
- More to come with **LHC Run3** increased statistics!

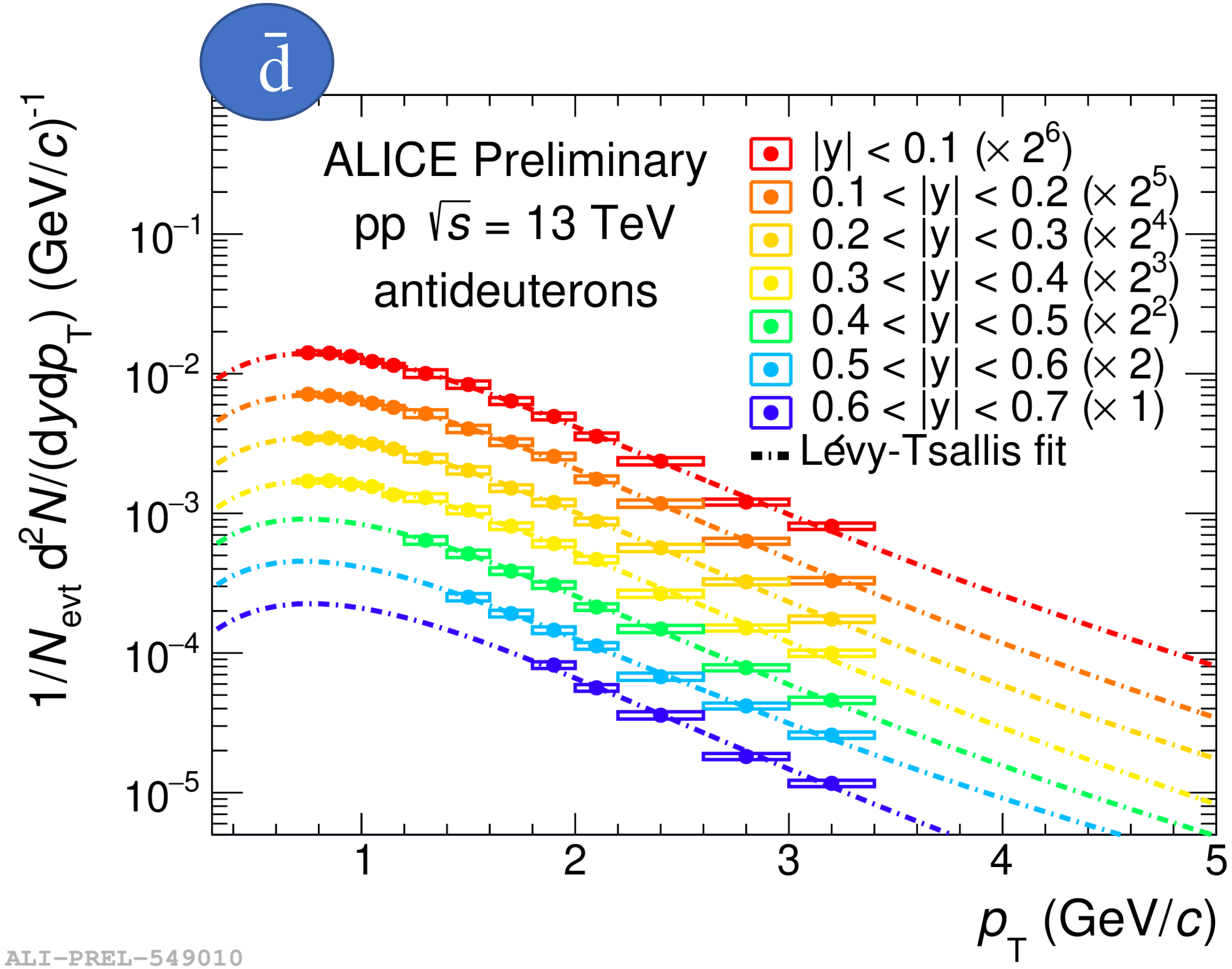
I. Vorobyev's talk
Wed. 8:50



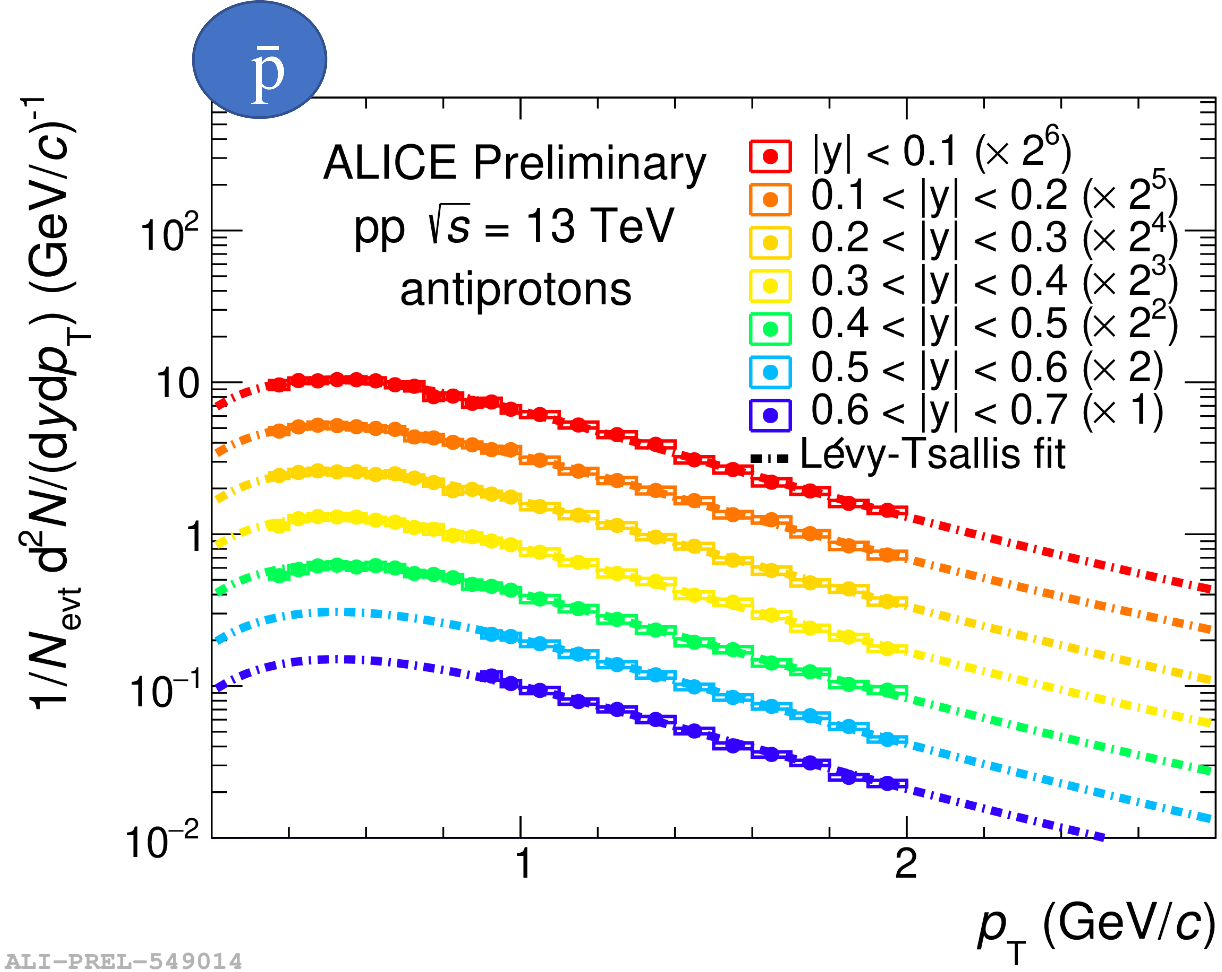
*Thank you for your attention!*

chiara.pinto@cern.ch

# Spectra as a function of rapidity



ALI-PREL-549010



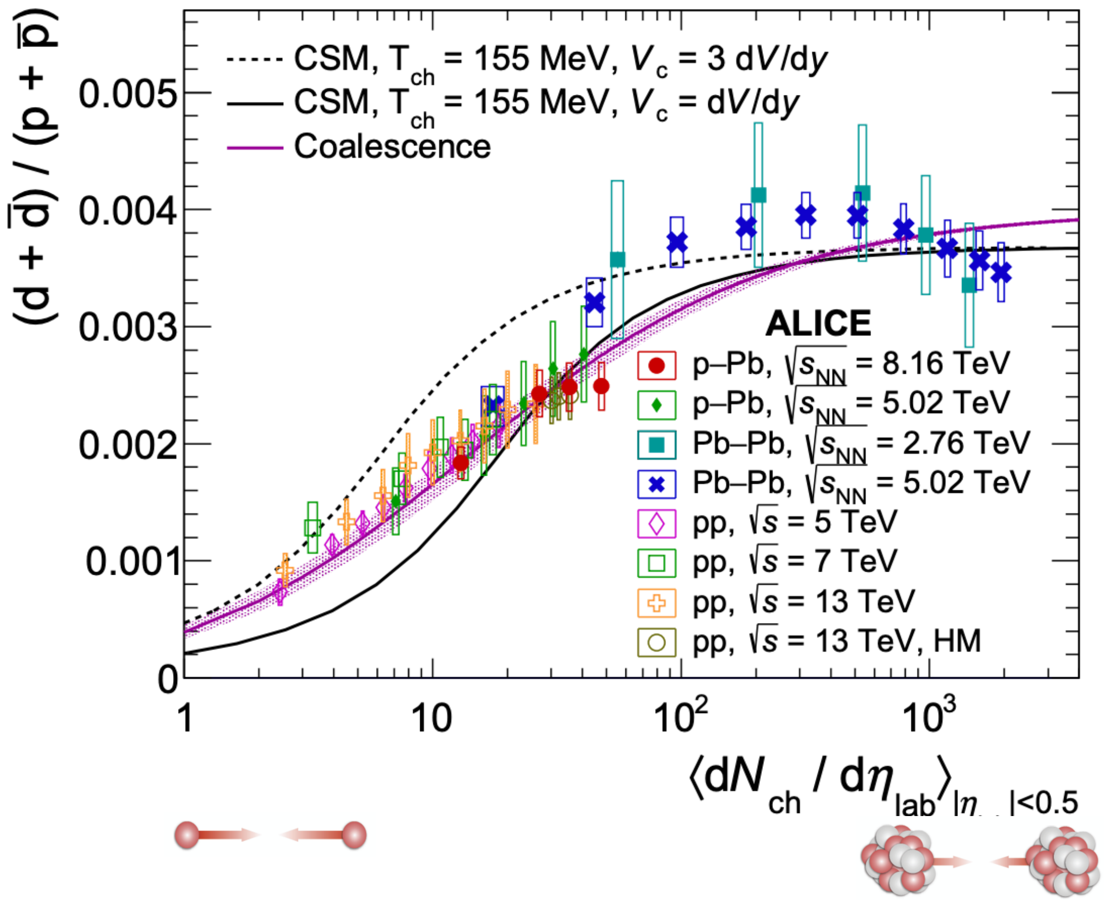
ALI-PREL-549014

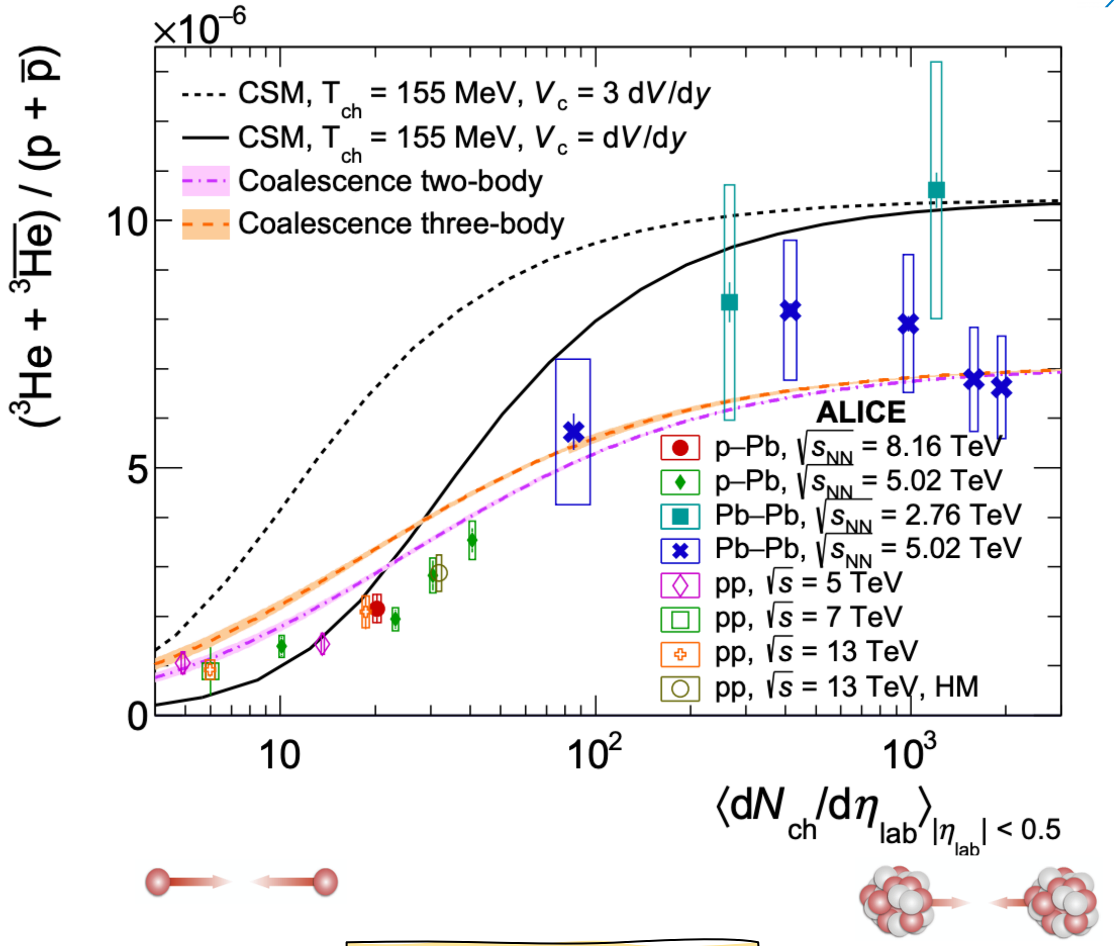
- Current acceptance of ALICE detector allows to extend the measurement of antinuclei up to $y = 0.7$
- All rapidity classes show a common trend with $y$, for both species (ratio to $|y| < 0.1$ is ~1)

**New!**

**chiara.pinto@cern.ch**

# Production of (anti)nuclei





- Production of (anti)nuclei has been extensively measured by ALICE
- Coalescence model describes well the data for A = 2, 3
- ALICE measurements cover the midrapidity region (|y|<0.5), while astrophysical models extrapolate to forward region

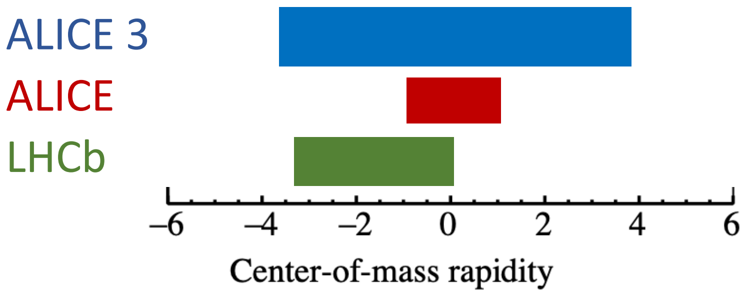
I. Vorobyev’s talk
Wed. 8:50

arxiv:2212.04777

# Strategy

**IDEA**

- Study of rapidity dependence of antiprotons and antideuterons
- Coalescence parameter $B_2$ as a function of rapidity
- Comparison with a simple coalescence model

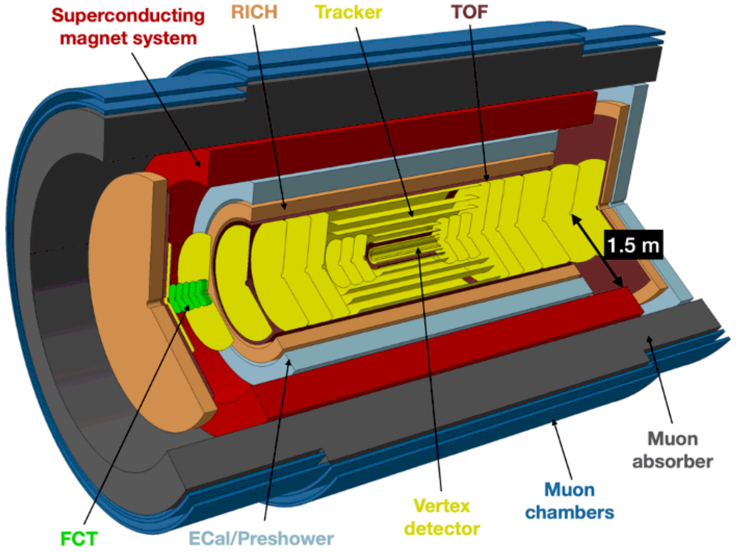


**DATASET**

- pp collisions @ 13 TeV, full 2016 + 2017 + 2018 ESD tracks
- ~ 1.6 · $10^9$ events (after selection cuts)

**MC** (JIRA)

- 2016 pp, 13 TeV - Pythia8 Monash2013 + injected (hyper)nuclei – based on G4



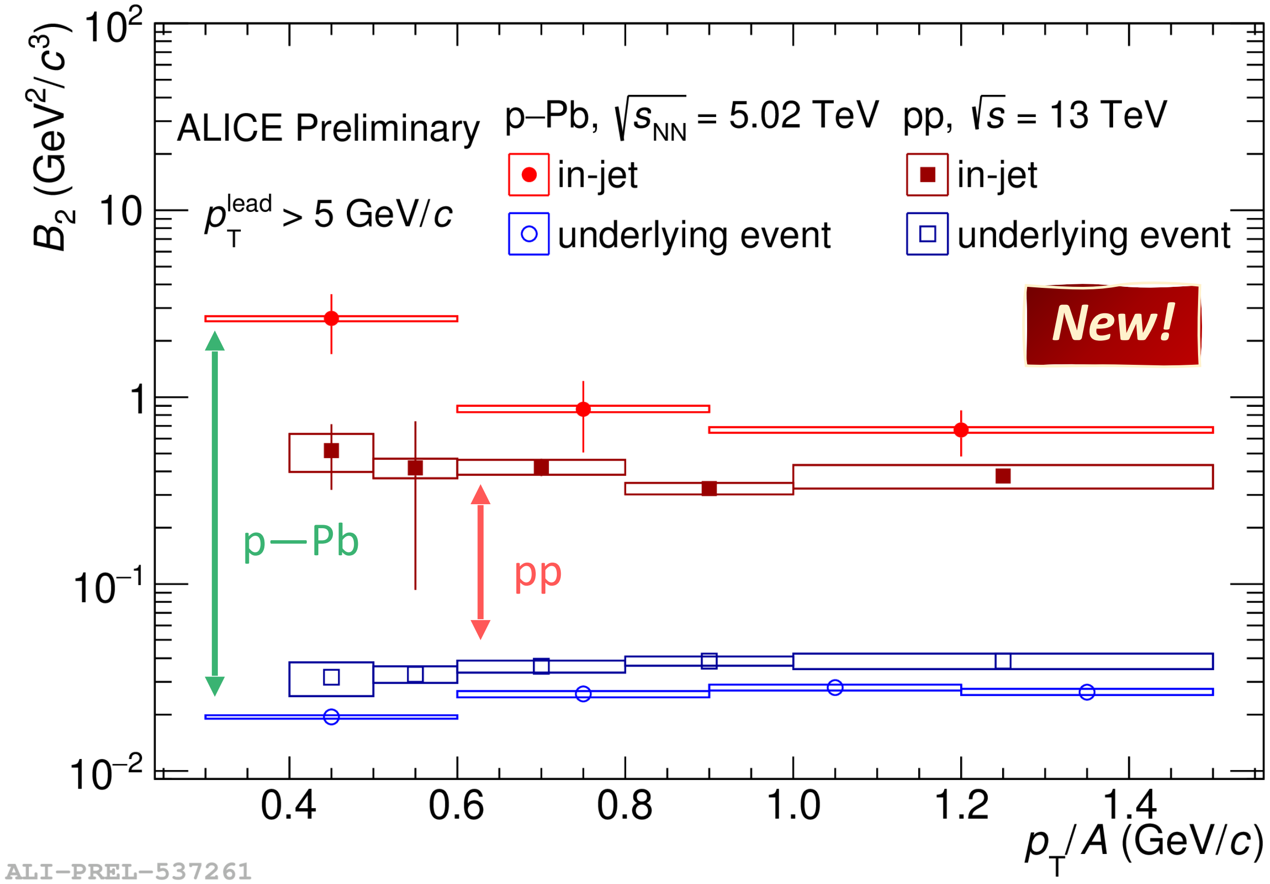
**RESULTS**

- Measurements up to y=0.7
- *y*-differential measurements will be possible with ALICE 3 (rapidity coverage → $|y| \lesssim 4$) (eprint:1902.01211 [physics.ins-det])

Analysis Note

chiara.pinto@cern.ch

# Coalescence parameters in and out of jets

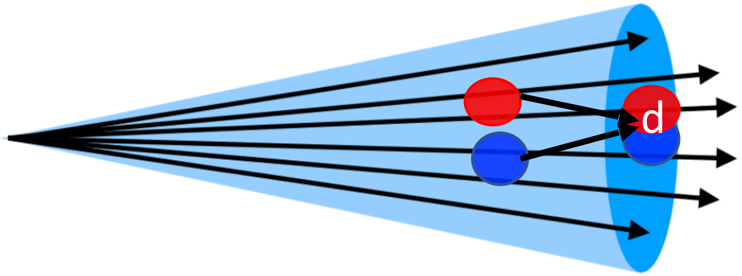


- $B_2$ in-jet even more enhanced than $B_2$ in UE in p—Pb collisions (factor ~25)

- $B_2$ in-jet in p—Pb is larger than $B_2$ in-jet in pp

  → *could be* related to the different particle composition of jets in pp and p—Pb

- $B_2$ in UE in p—Pb is smaller than $B_2$ in UE in pp due to the larger source size in p—Pb (pp[1]: $r_0$ ~ 1 fm, p—Pb[2]: $r_0$ ~ 1.5 fm)



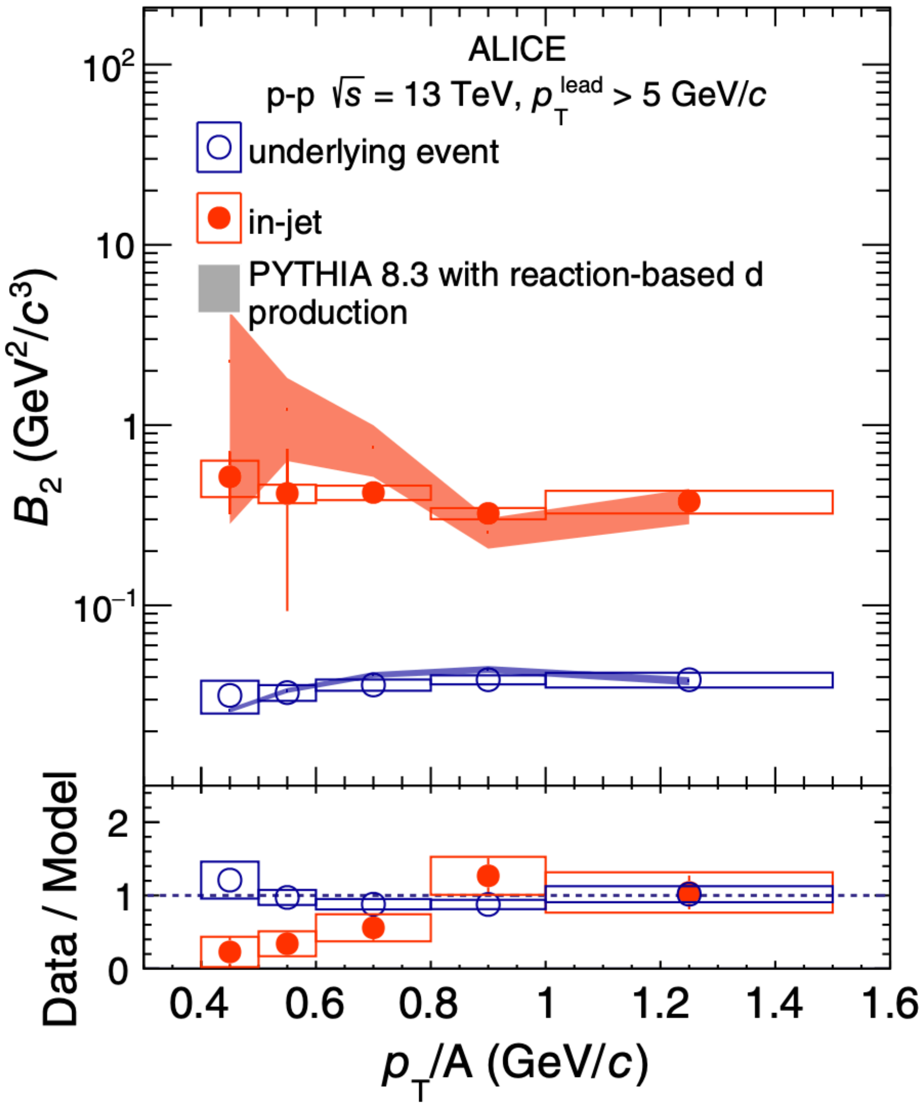
Phys.Rev.Lett. 131 (2023) 4, 042301

[1] Phys.Rev.C 99 (2019) 024001

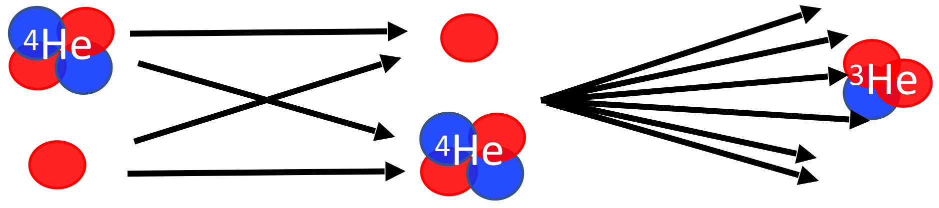
[2] Phys.Rev.Lett. 123 (2019) 112002

chiara.pinto@cern.ch

# Coalescence parameters in and out of jets



- $B_2$ in-jet ∼ 15 times larger than $B_2$ in UE
- *Enhanced deuteron coalescence probability in jets wrt UE is observed for the first time in pp collisions*
- Due to the reduced distance in phase space of hadrons in jets compared to those out of jets → favors coalescence picture



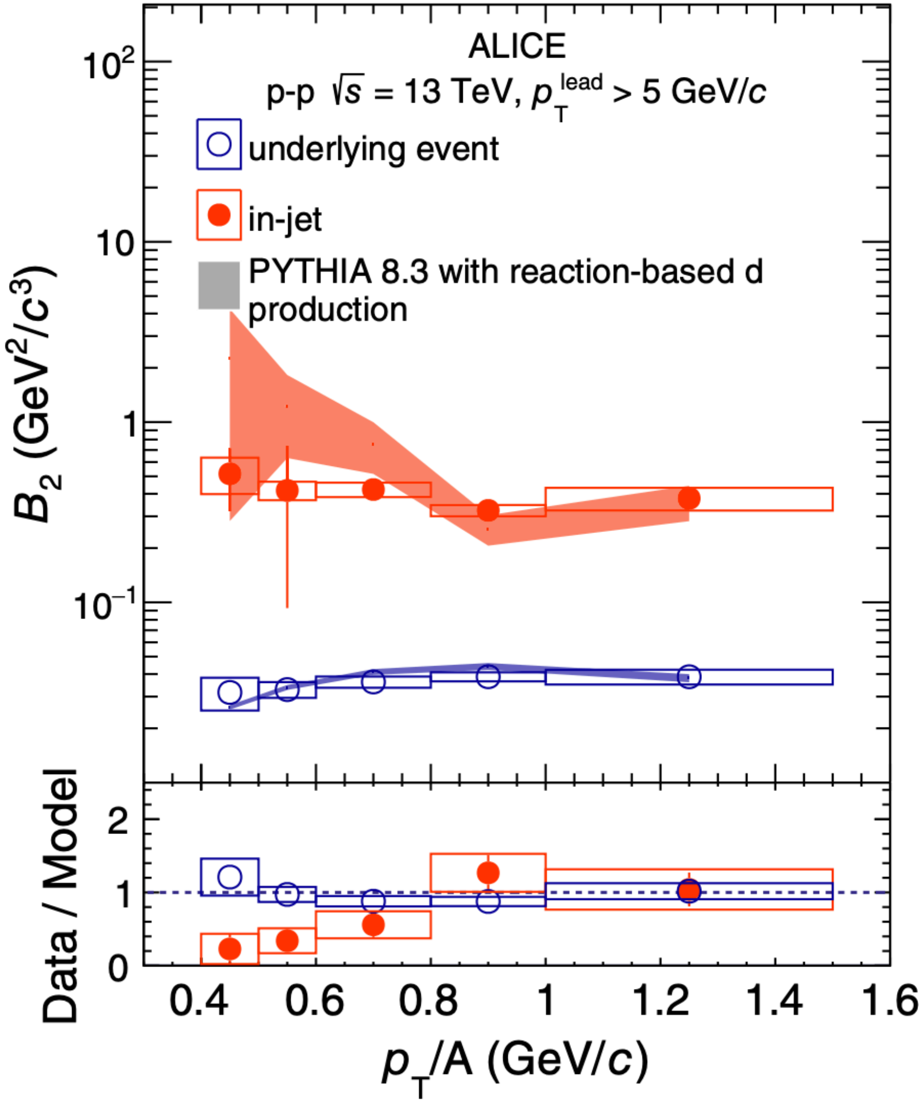
Primary cosmic ray
(90% p, 8% $^4$He)

Interstellar medium
(90% p, 8% $^4$He)

Phys.Rev.Lett. 131 (2023) 4, 042301

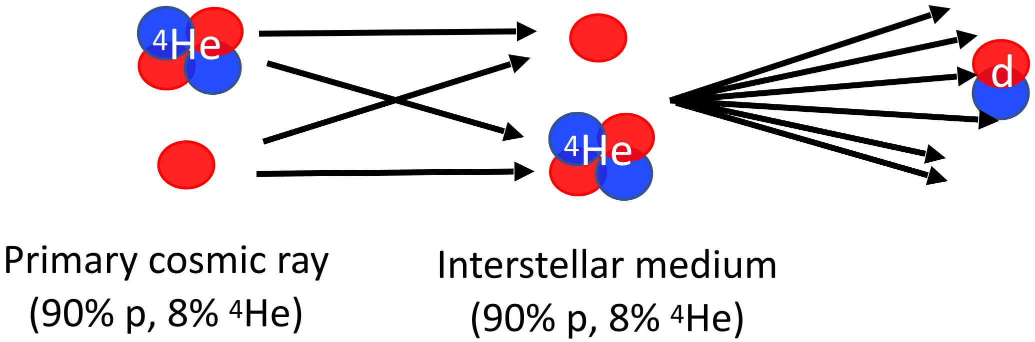
chiara.pinto@cern.ch

# Coalescence parameters in and out of jets



Phys.Rev.Lett. 131 (2023) 4, 042301

- $B_2$ in-jet ∼ 15 times larger than $B_2$ in UE
- *Enhanced deuteron coalescence probability in jets wrt UE is observed for the first time in pp collisions*
- Due to the reduced distance in phase space of hadrons in jets compared to those out of jets → favors coalescence picture

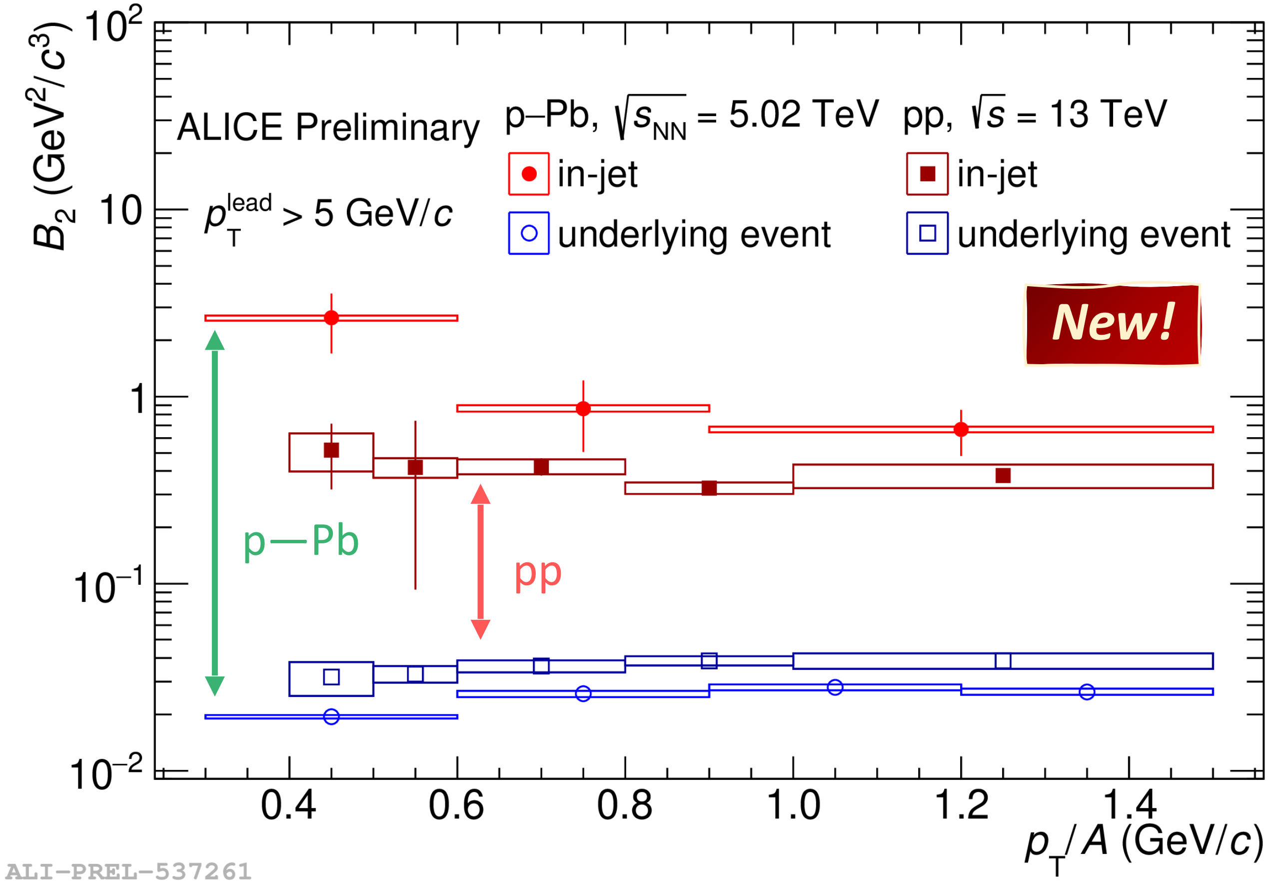


Primary cosmic ray
(90% p, 8% $^4$He)

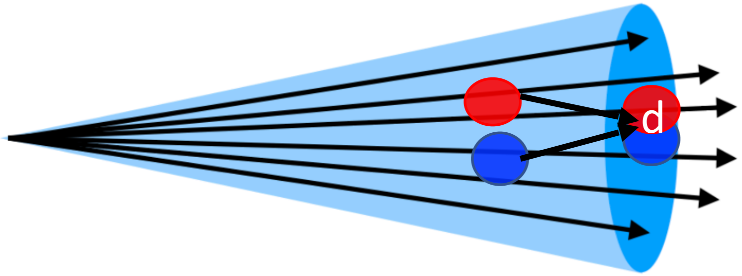
Interstellar medium
(90% p, 8% $^4$He)

chiara.pinto@cern.ch

# Coalescence parameters in and out of jets



- $B_2$ in-jet even more enhanced than $B_2$ in UE in p—Pb collisions (factor ~25)
- $B_2$ in-jet in p—Pb is larger than $B_2$ in-jet in pp → *could be* related to the different particle composition of jets in pp and p—Pb
- $B_2$ in UE in p—Pb is smaller than $B_2$ in UE in pp due to the larger source size in p—Pb (pp[1]: $r_0$~ 1 fm, p—Pb[2]: $r_0$~ 1.5 fm)



Phys.Rev.Lett. 131 (2023) 4, 042301

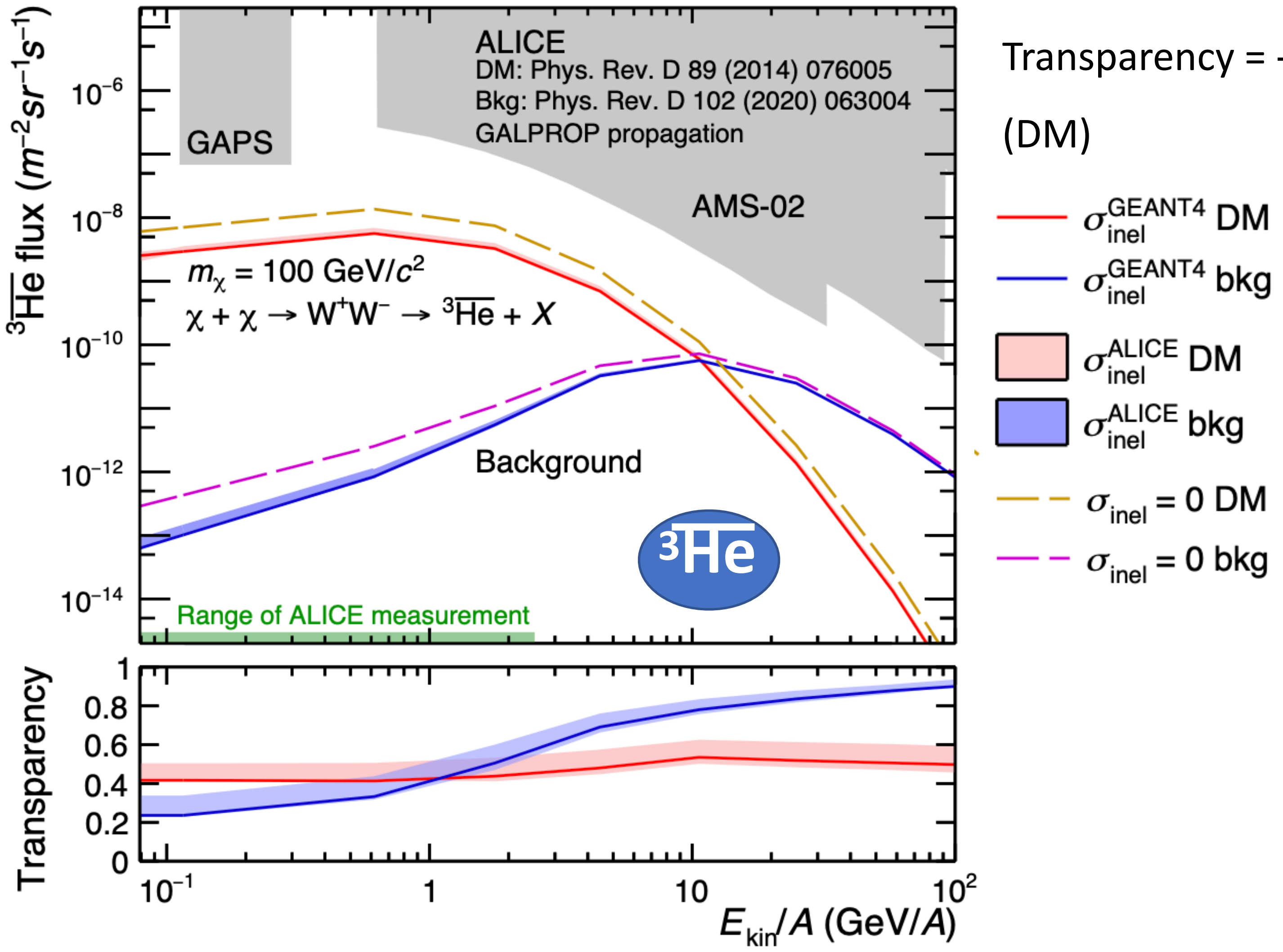
[1] Phys.Rev.C 99 (2019) 024001

[2] Phys.Rev.Lett. 123 (2019) 112002

chiara.pinto@cern.ch

# Transparency of Galaxy to anti$^3$He

Solar modulated flux



Transparency = $\frac{\text{flux with annihilation}}{\text{flux without annihilation}}$ = ▨ ▨ / – – – (——— / – – –) for bkg

(DM)

- Fluxes are model dependent
- **Our Galaxy is rather constantly transparent to $^3$He passage**
- Data are in good agreement with Geant4 predictions
- Uncertainties on Transparency only due to absorption measurements (10-20%)

anti$^3$He: Nature Phys. (2023) 19, 61–71

chiara.pinto@cern.ch