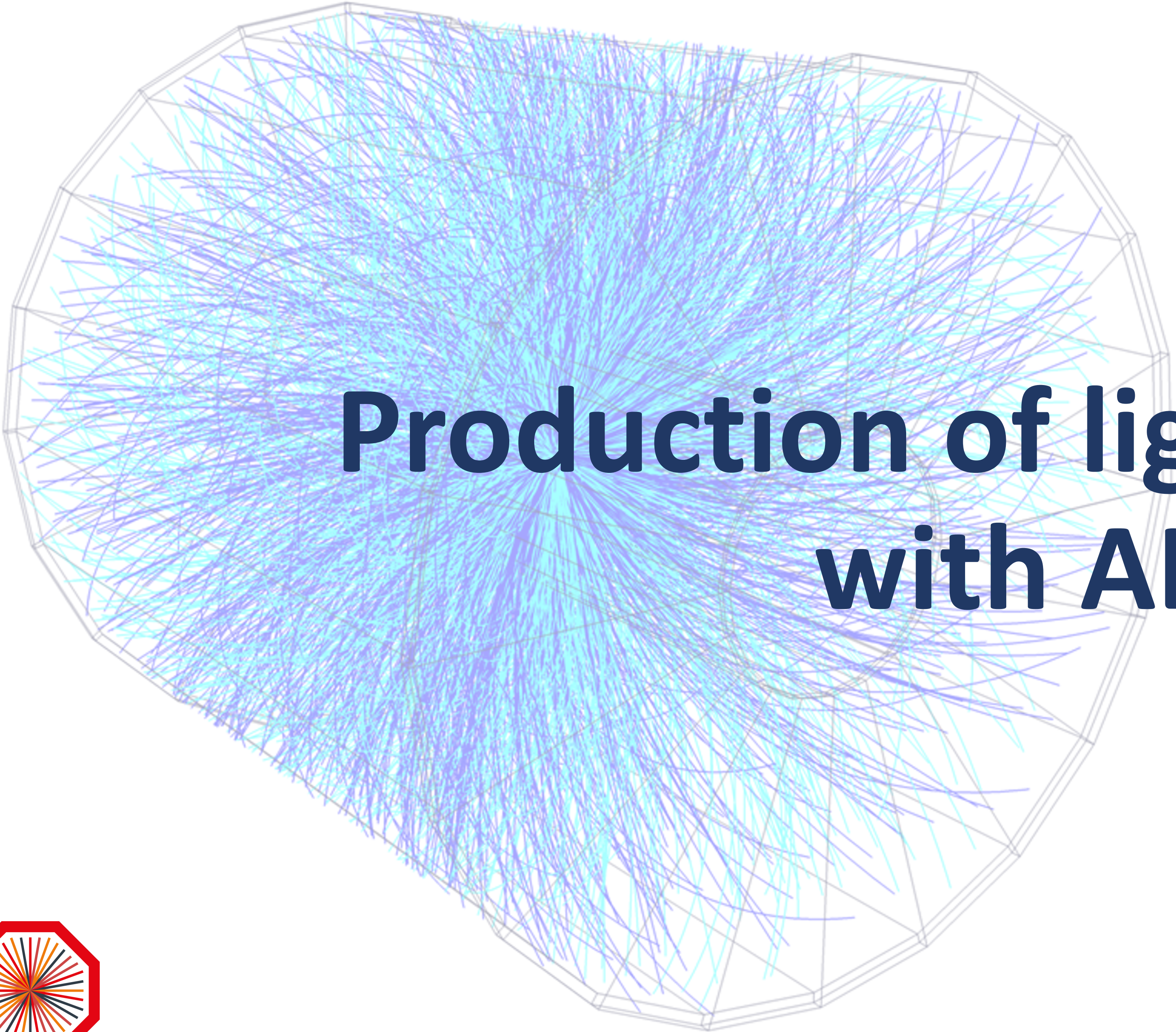
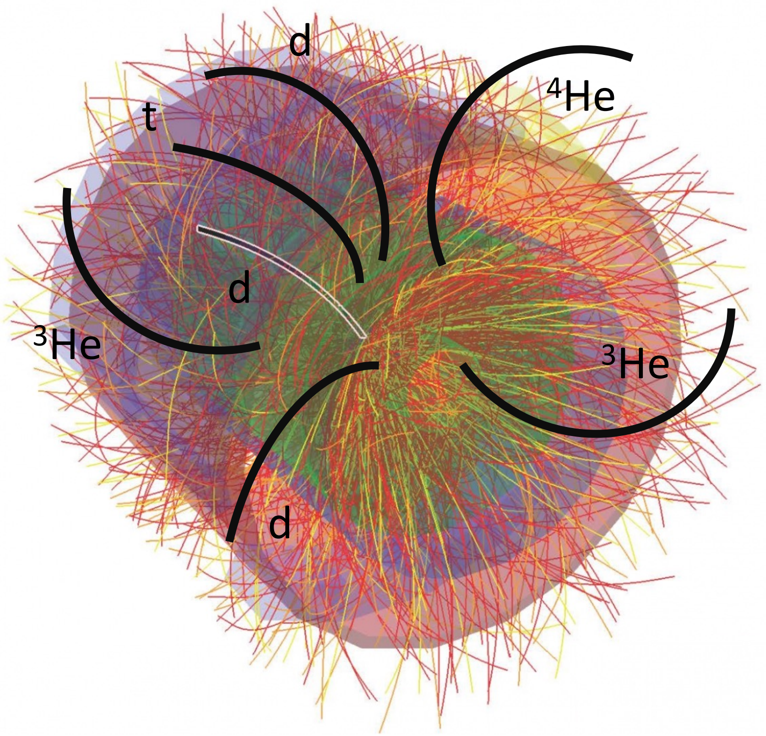


Production of light (anti)nuclei with ALICE at the LHC

Chiara Pinto
Technische Universität München

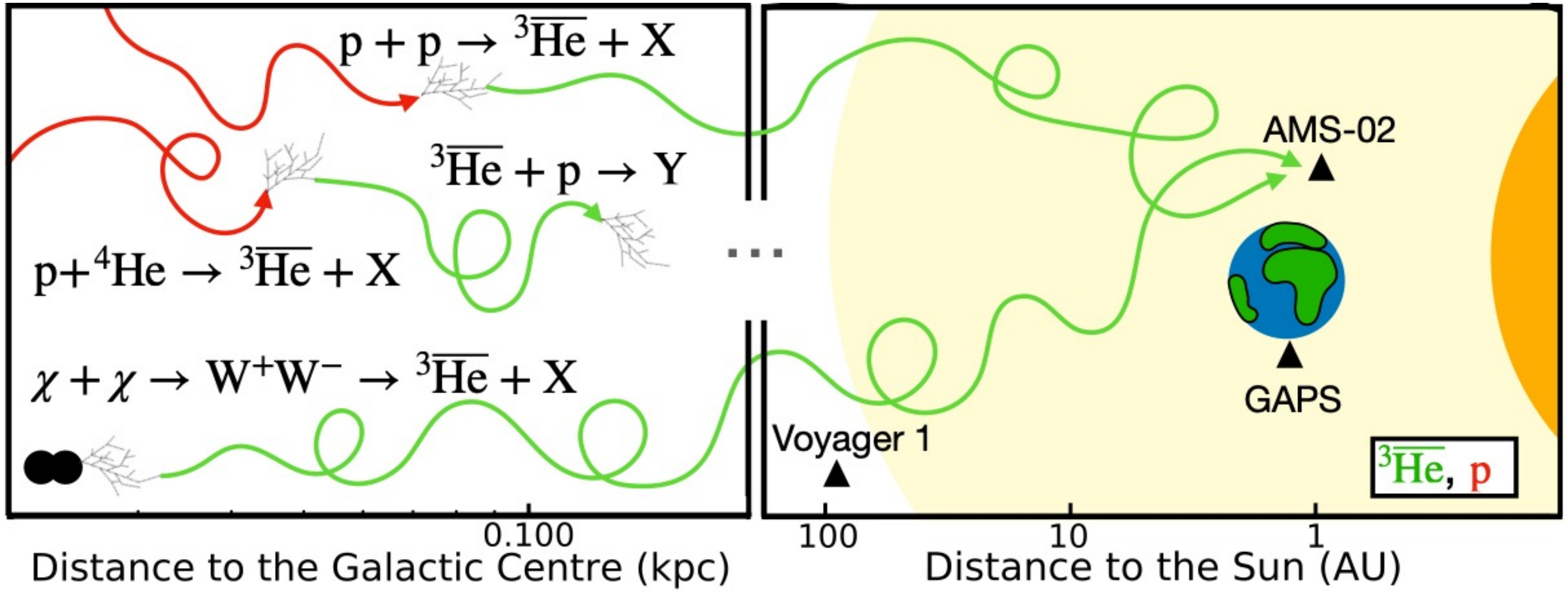
Zimányi School, Budapest – 9 Dec. 2021

Physics motivation



- Multi-baryon states are produced in high energy hadronic collisions at the LHC
- (Anti)nuclei measurement studies are crucial
  - microscopic production mechanism
  - *input in the indirect dark matter searches through antinuclei probe*

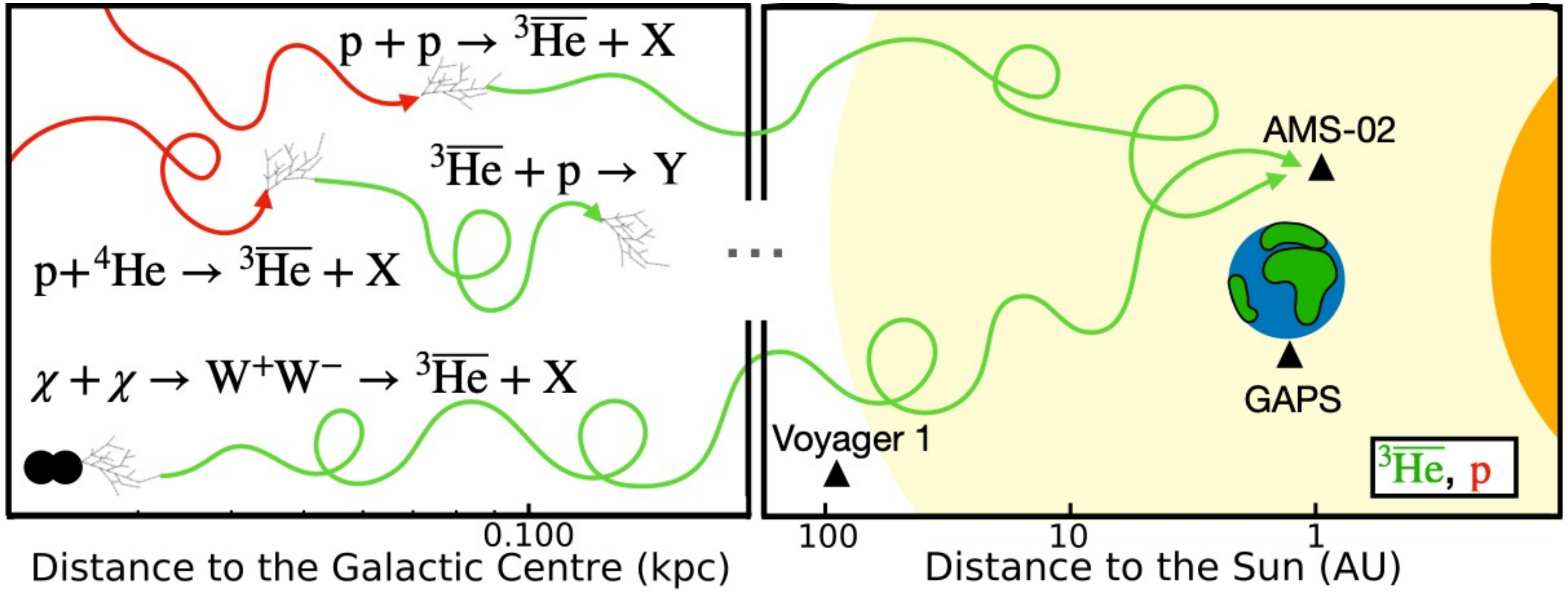
Antinuclei as dark matter probe

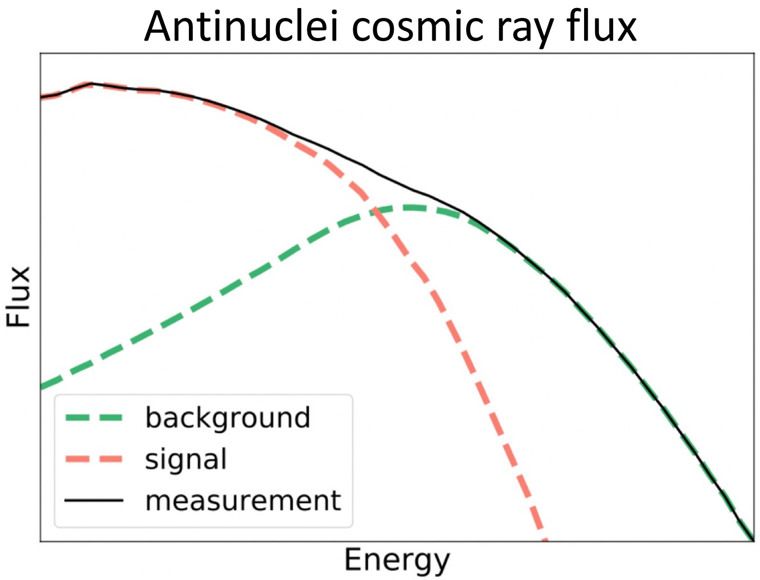


Antinuclei production:

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

Antinuclei as dark matter probe





To determine exact primary and secondary fluxes → precise knowledge of antinuclei production, propagation and annihilation is needed

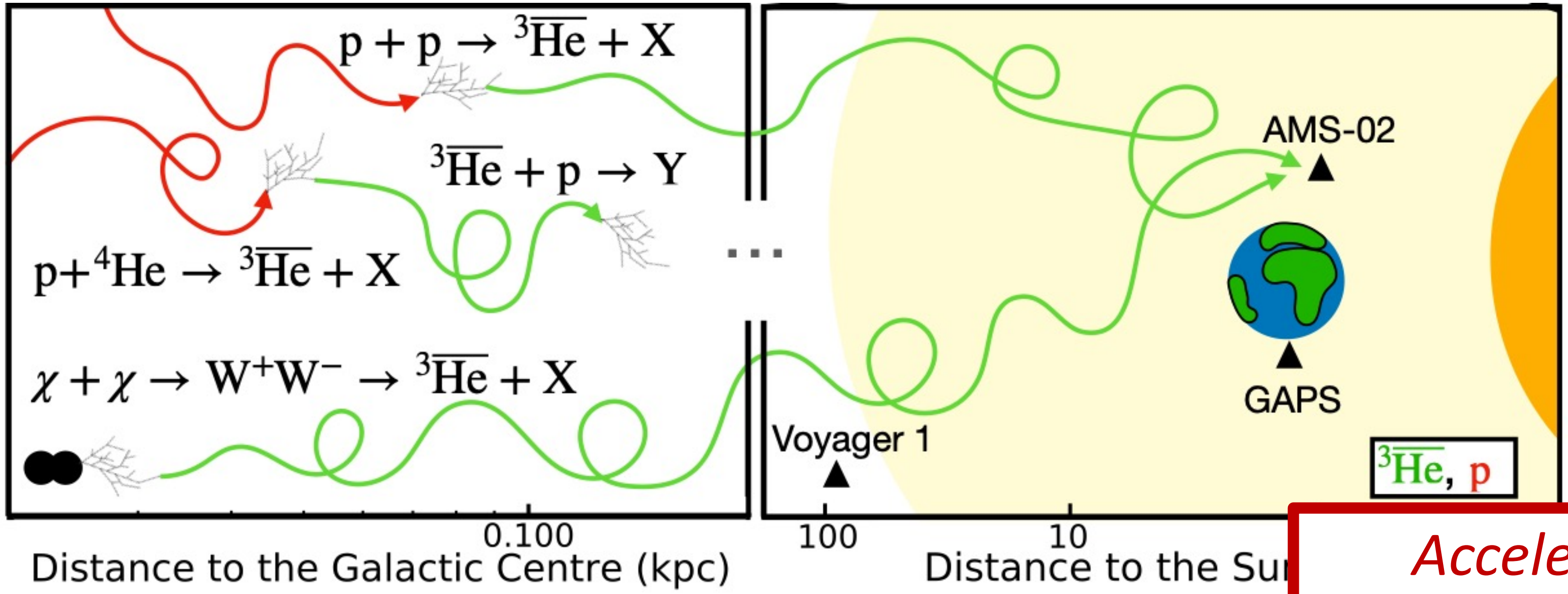
Transport equation: $$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \mathbf{div}(D_{xx}\mathbf{grad}\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi \frac{dp}{dt} - \frac{p}{3}(\mathbf{div} \cdot \mathbf{V})\psi\right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}$$

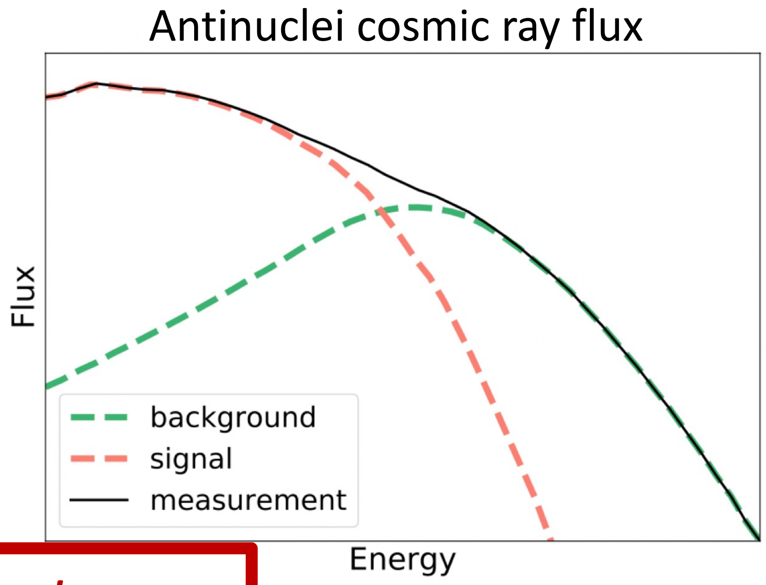
Source Function

Propagation: diffusion, convection…

Fragmentation, annihilation

Antinuclei as dark matter probe





Accelerator experiments

To determine exact primary and secondary fluxes → prec ... clei production, propagation and annihilation is needed

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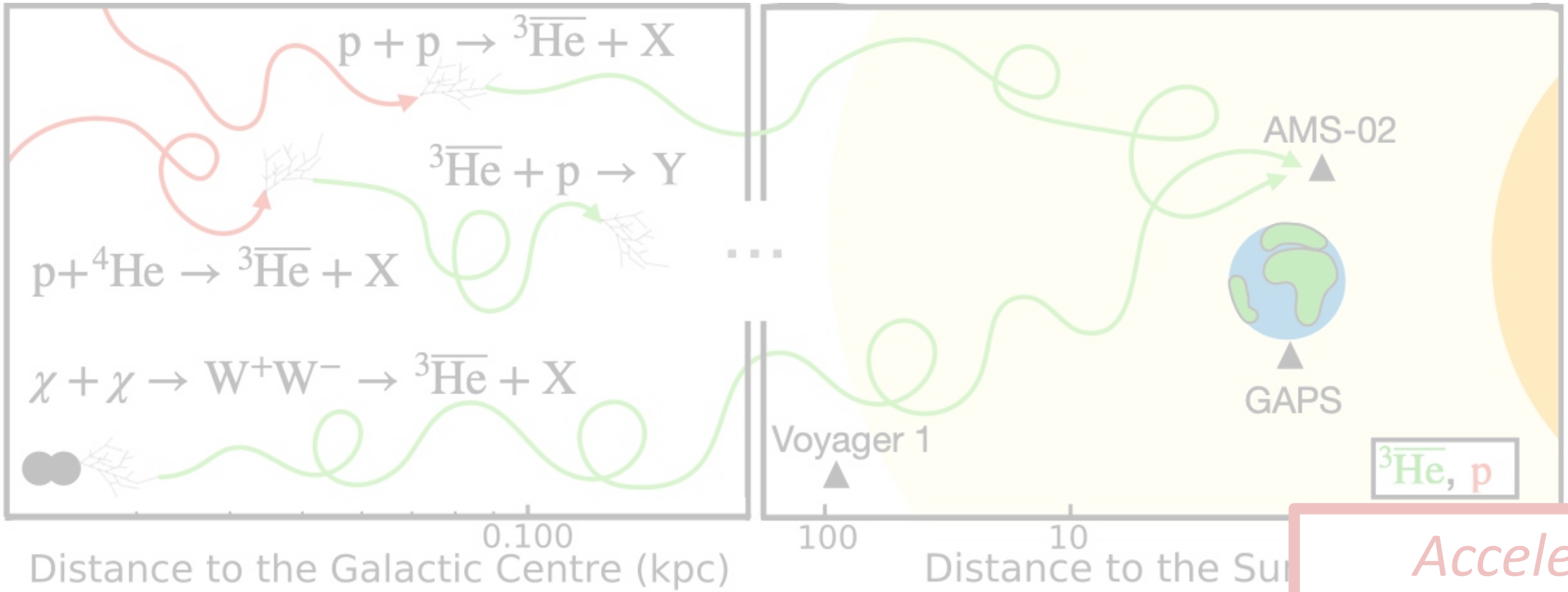
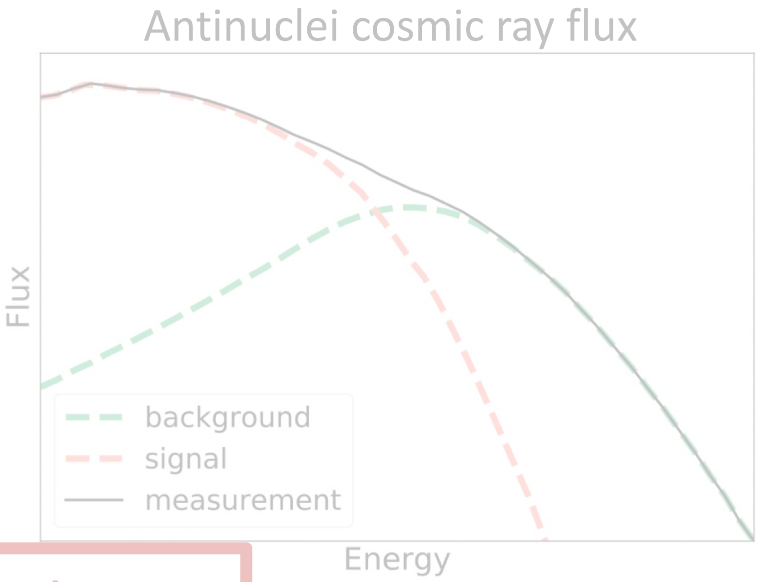
Source Function | **Propagation: diffusion, convection…** | **Fragmentation, annihilation**

Antinuclei as dark matter probe





Accelerator experiments

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Production

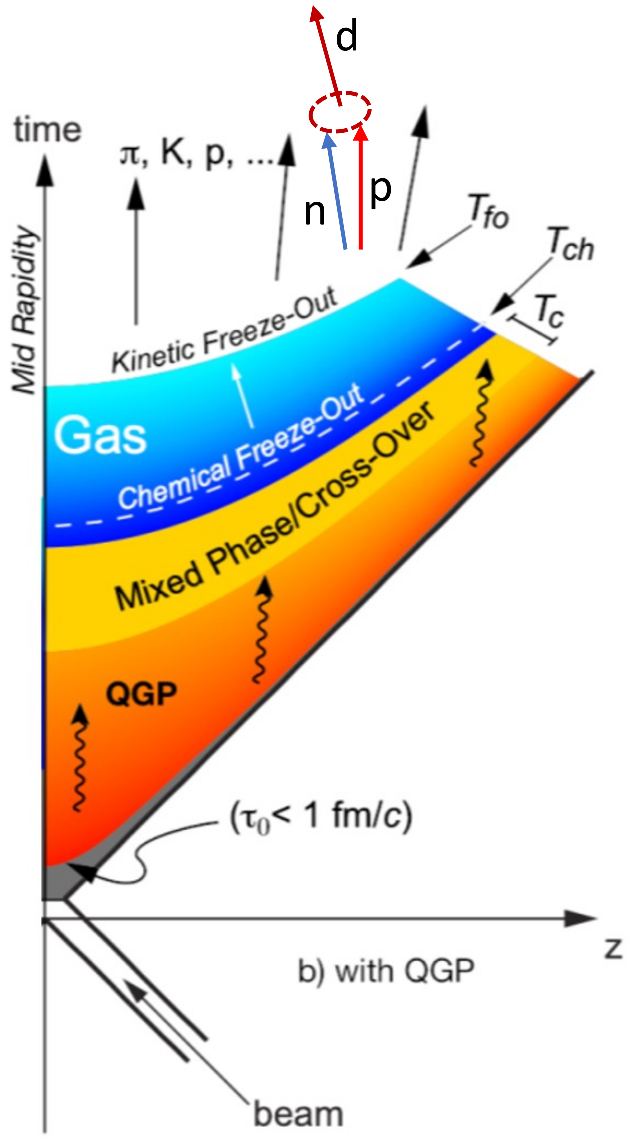
Transport equation: $$\frac{\partial \psi}{\partial t} = q(\mathbf{r},p) + \mathbf{div}(D_{xx}\mathbf{grad}\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi\frac{dp}{dt} - \frac{p}{3}(\mathbf{div}\cdot\mathbf{V})\psi\right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}$$

Source Function

Propagation: diffusion, convection…

Fragmentation, annihilation

(Anti)nuclei production



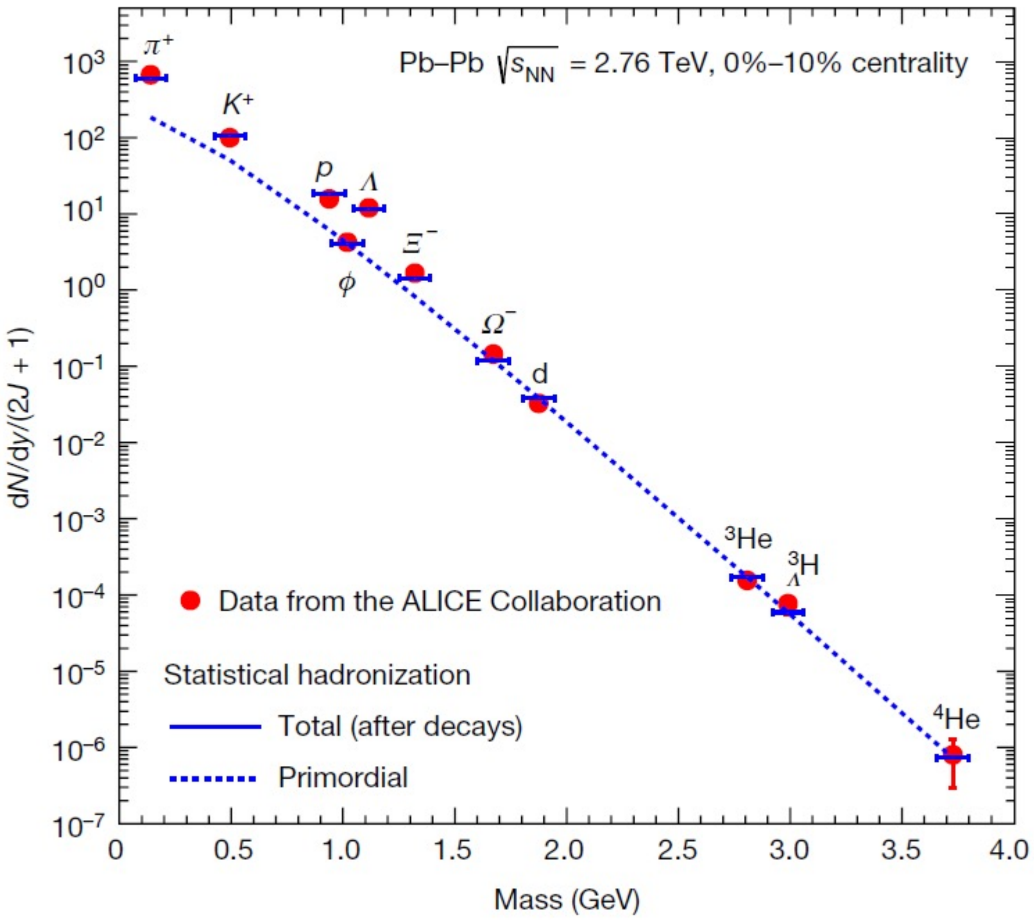
- At LHC energies ($\sqrt{s}$ =1–13 TeV) same amount of matter and anti-matter is expected ($\mu_B \sim 0$)
- Production mechanism still under debate
- Two classes of phenomenological models:
  - **statistical hadronization** → works very well for integrated yields (even for nuclei!)
  - **coalescence**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

Statistical models

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

  ⇒ 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 ~ 2 MeV for d*)

  ⇒ how can they survive the hadronic phase environment (T_{chem} ~ 156 MeV)?

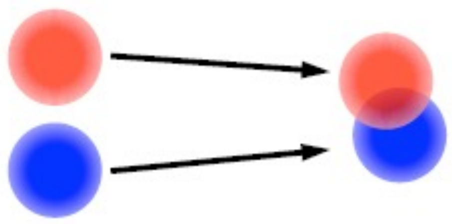


→ In Pb-Pb collisions, particle yields of light flavor hadrons are described over 9 orders of magnitude with a **common** chemical freeze-out temperature of T_{chem} ≈ **156 MeV**.

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

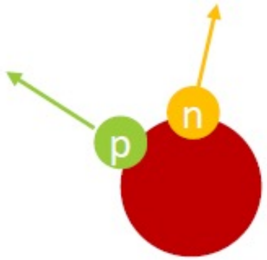
Coalescence models

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



- 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
- Coalescence parameter B_A is the key parameter

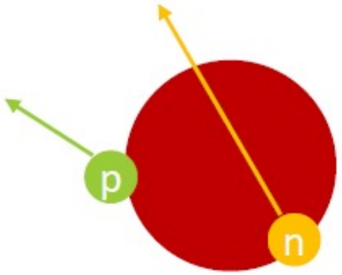
$$B_A(p_T^p) = E_A \frac{d^3 N_A}{d p_A^3} \Big/ \left(E_p \frac{d^3 N_p}{d p_p^3} \right)^A \Bigg|_{p_T^p = p_T^A / A}$$



- Experimental parameter tightly connected to the coalescence probability

Larger B_A ⟺ Larger coalescence probability

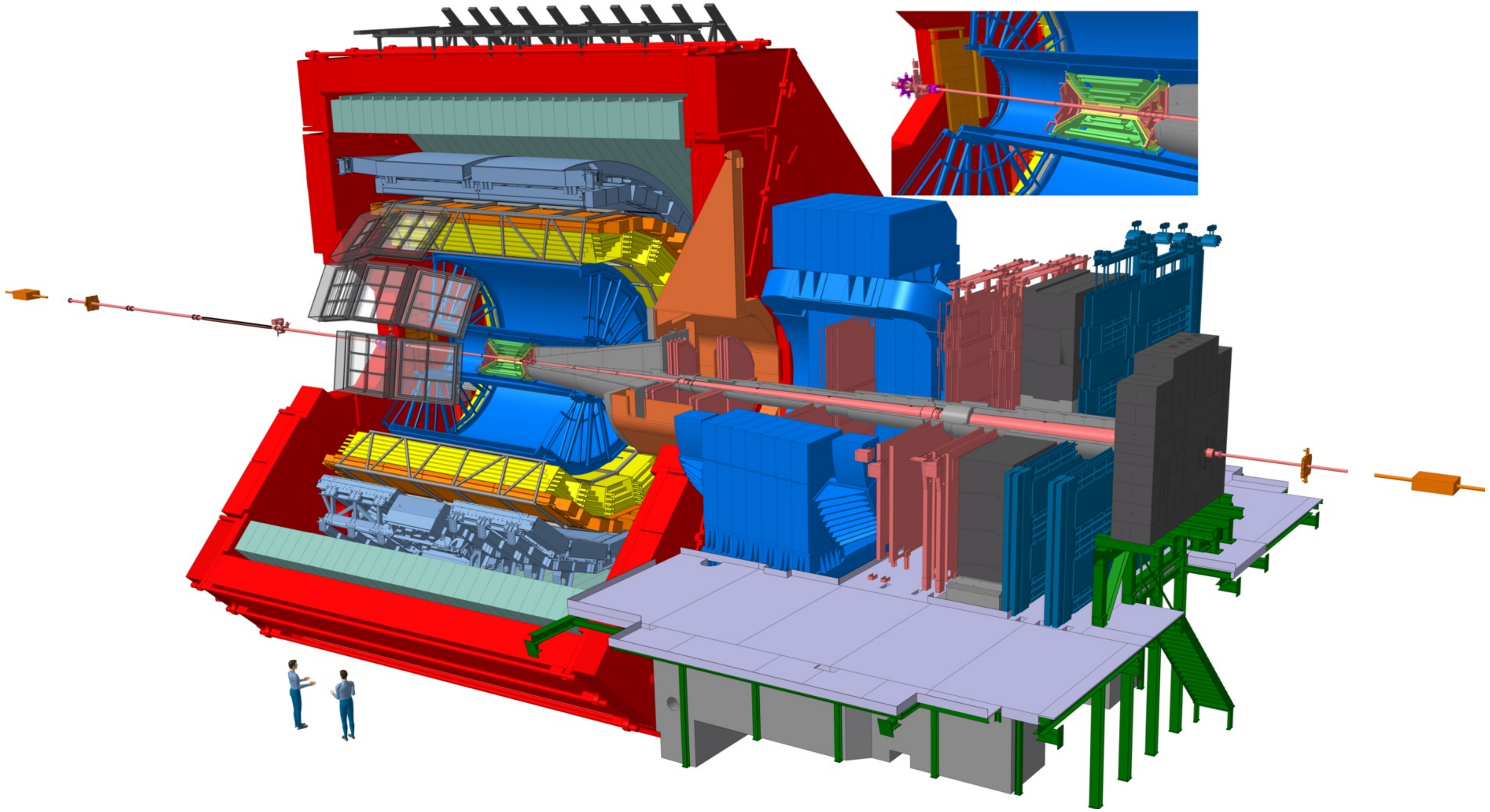
- Coalescence probability depends on the system size



Small distance in space
(Only momentum correlations matter)
⟺ large B_A

Large distance in space
(Both momentum and space correlations matter)
⟺ small B_A

The ALICE detector



- 19 sub-detectors
- pp, p—Pb, Pb—Pb collisions at $\sqrt{s}$ up to 13 TeV
- Excellent tracking and PID capabilities over a broad momentum range
- Low material budget

→ Most suited detector at the LHC for the study of (anti)nuclei produced in high energy collisions

The ALICE detector

Time Of Flight

$\sigma_{PID} \sim 70$ ps for pp

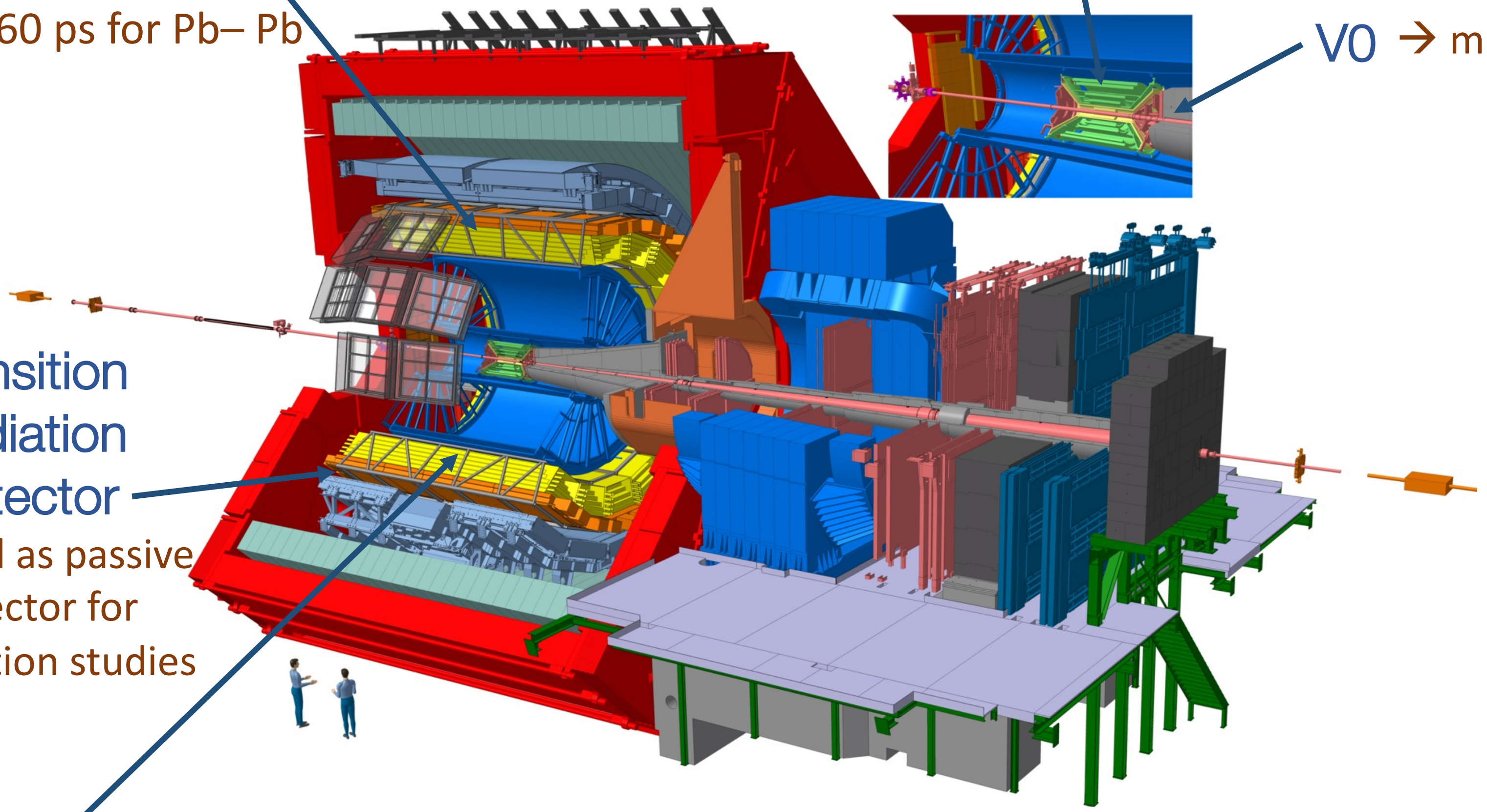
$\sigma_{PID} \sim 60$ ps for Pb– Pb

Inner Tracking System → $\sigma_{DCAxy} < 100\ \mu m$ for $p_T > 0.5$ GeV/c in Pb—Pb

V0 → multiplicity estimators used as trigger:

Minimum Bias → 0 – 100%

High Multiplicity → 0 – 0.1%



Transition Radiation Detector

→ used as passive detector for absorption studies

Time Projection Chamber → $\sigma_{dE/dx} \sim 5.5\%$ for pp

$\sigma_{dE/dx} \sim 7\%$ for Pb—Pb

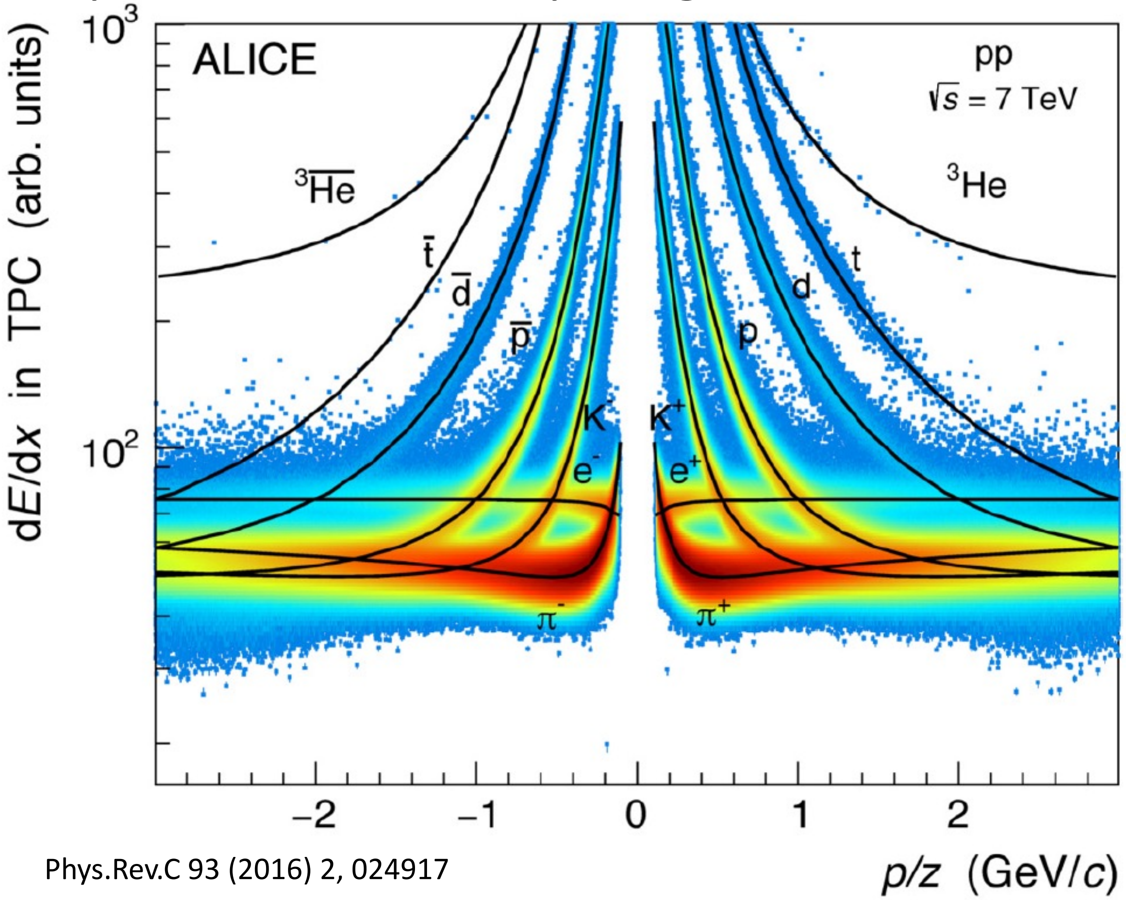
- 19 sub-detectors
- pp, p—Pb, Pb—Pb collisions at $\sqrt{s}$ up to 13 TeV
- Excellent tracking and PID capabilities over a broad momentum range
- Low material budget

→ Most suited detector at the LHC for the study of (anti)nuclei produced in high energy collisions

Nuclei identification

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

- (anti)^{3}He well separated from the other particle species over the full *p* range



Phys.Rev.C 93 (2016) 2, 024917

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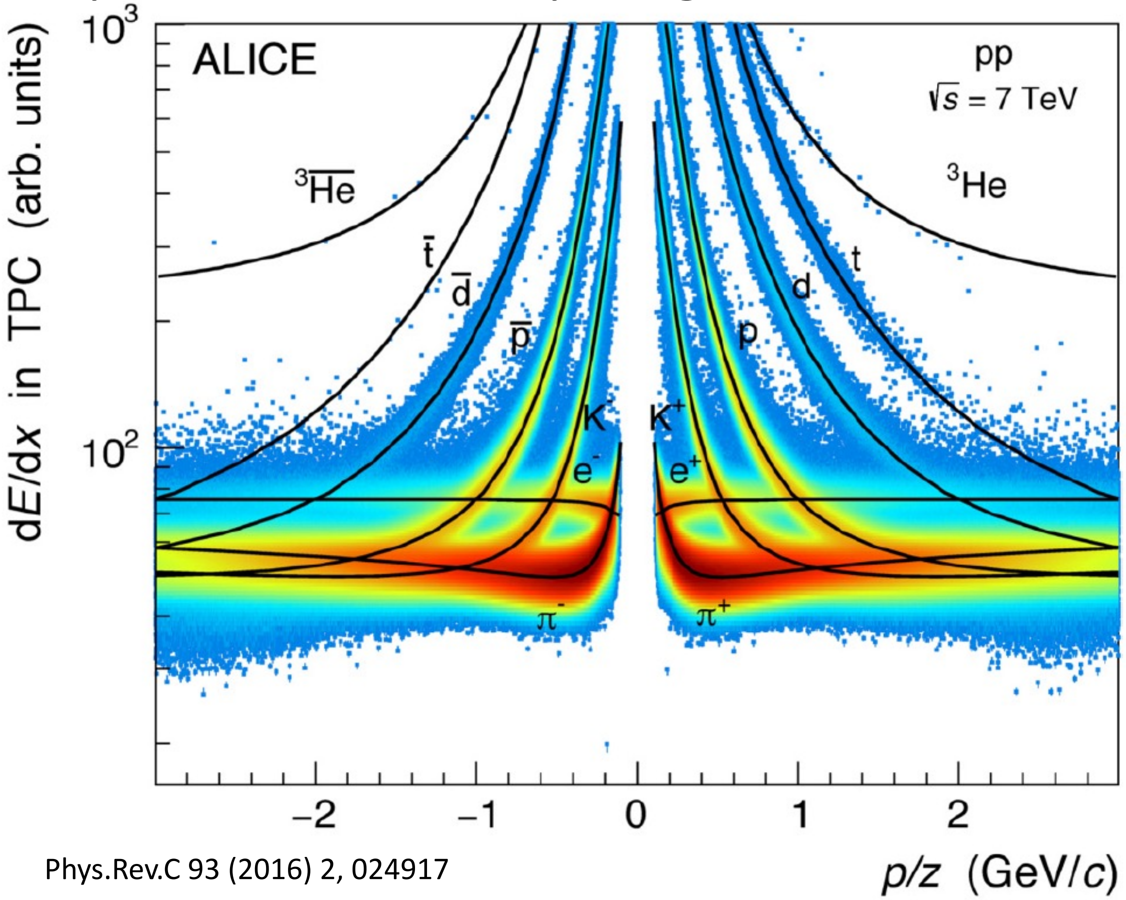

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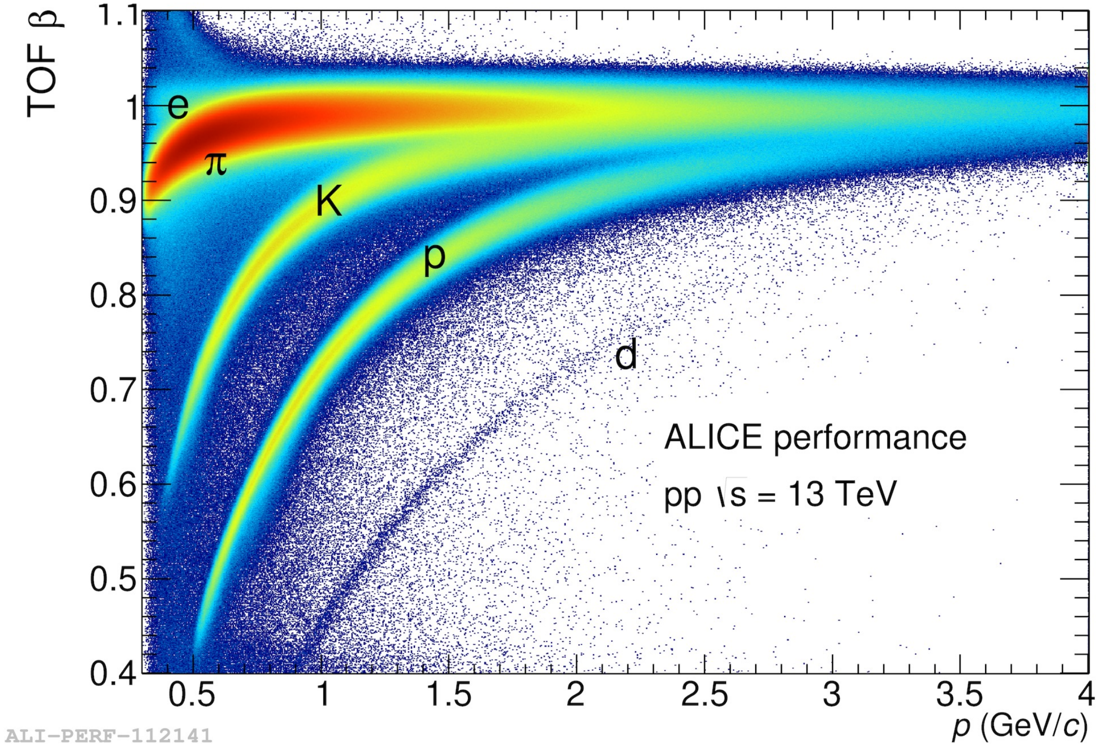
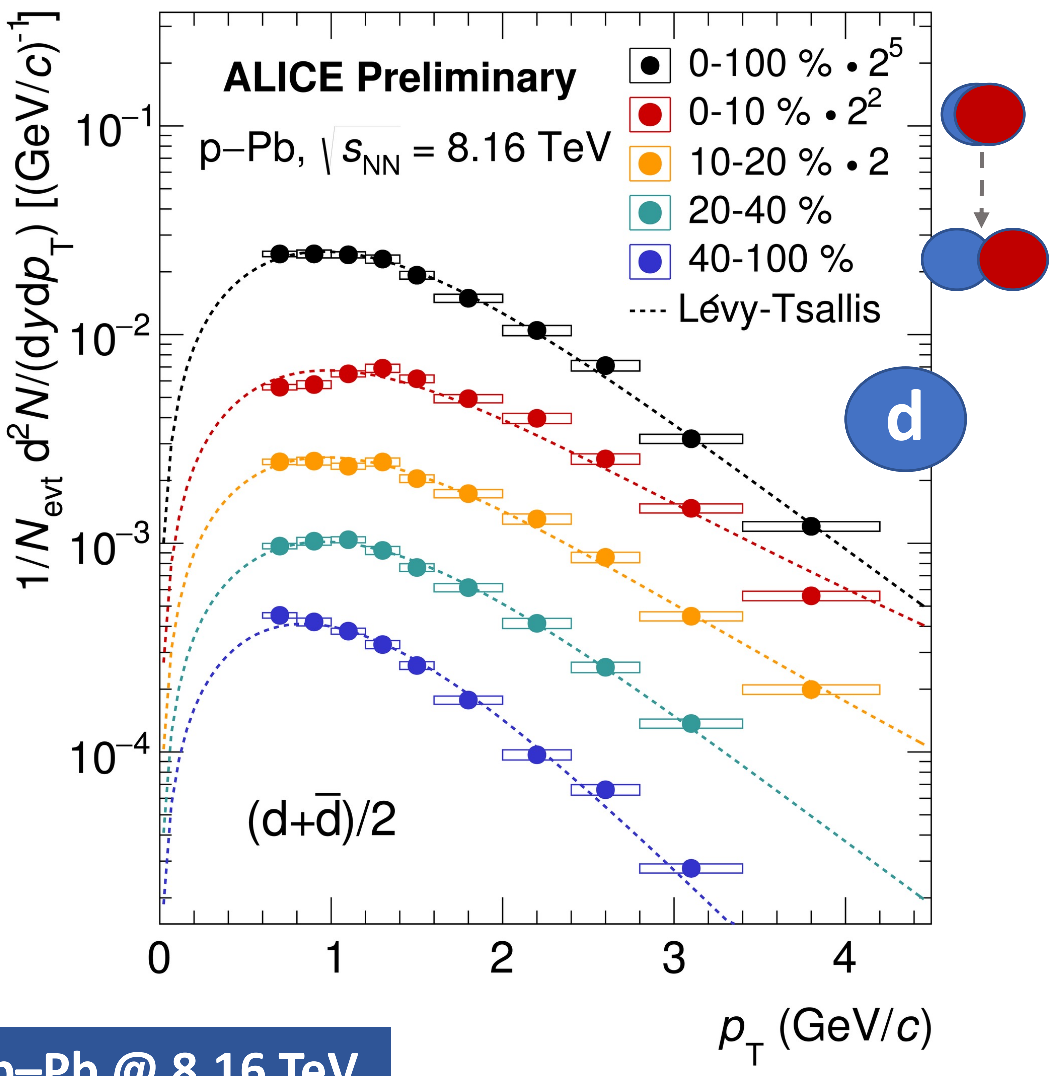
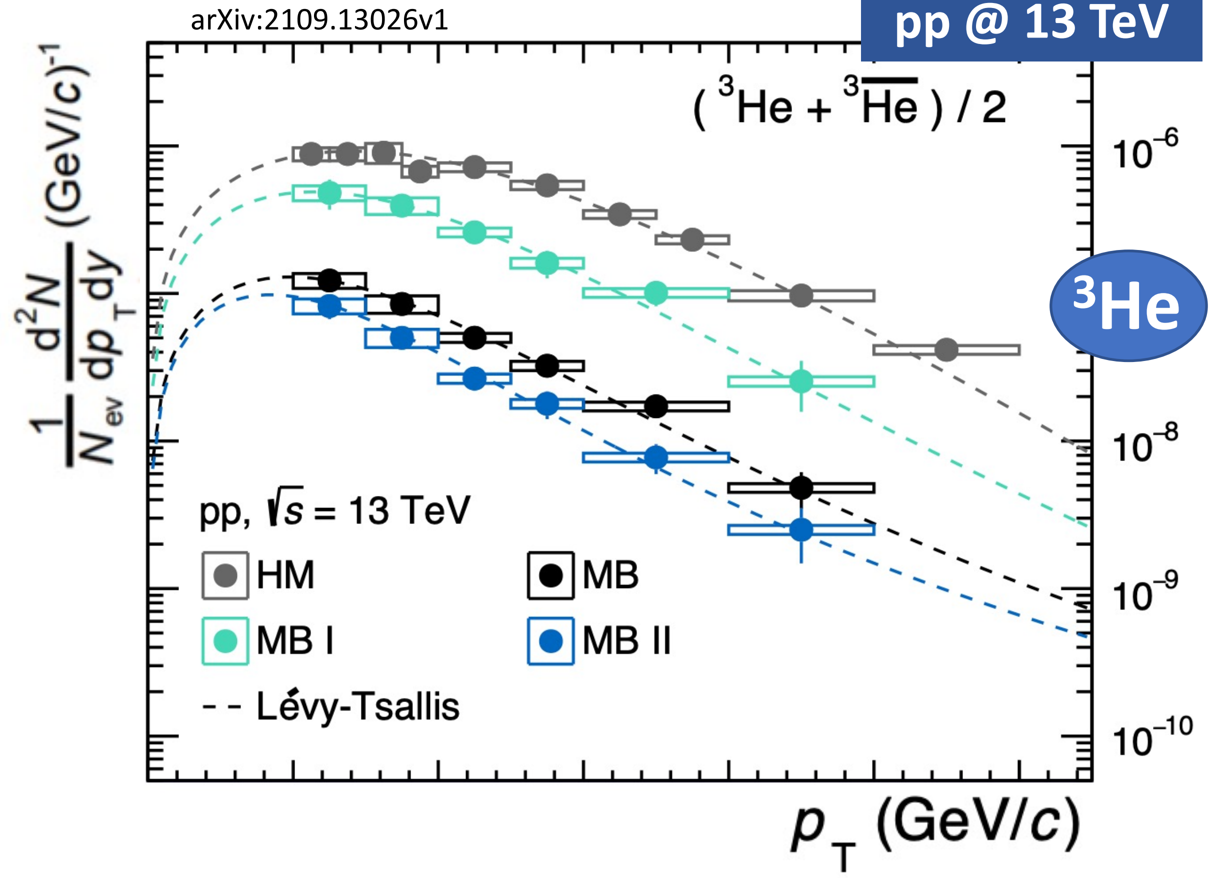


Higher p region (above 1 GeV/c) → PID via velocity β measurements in TOF

Light (anti)nuclei in small systems



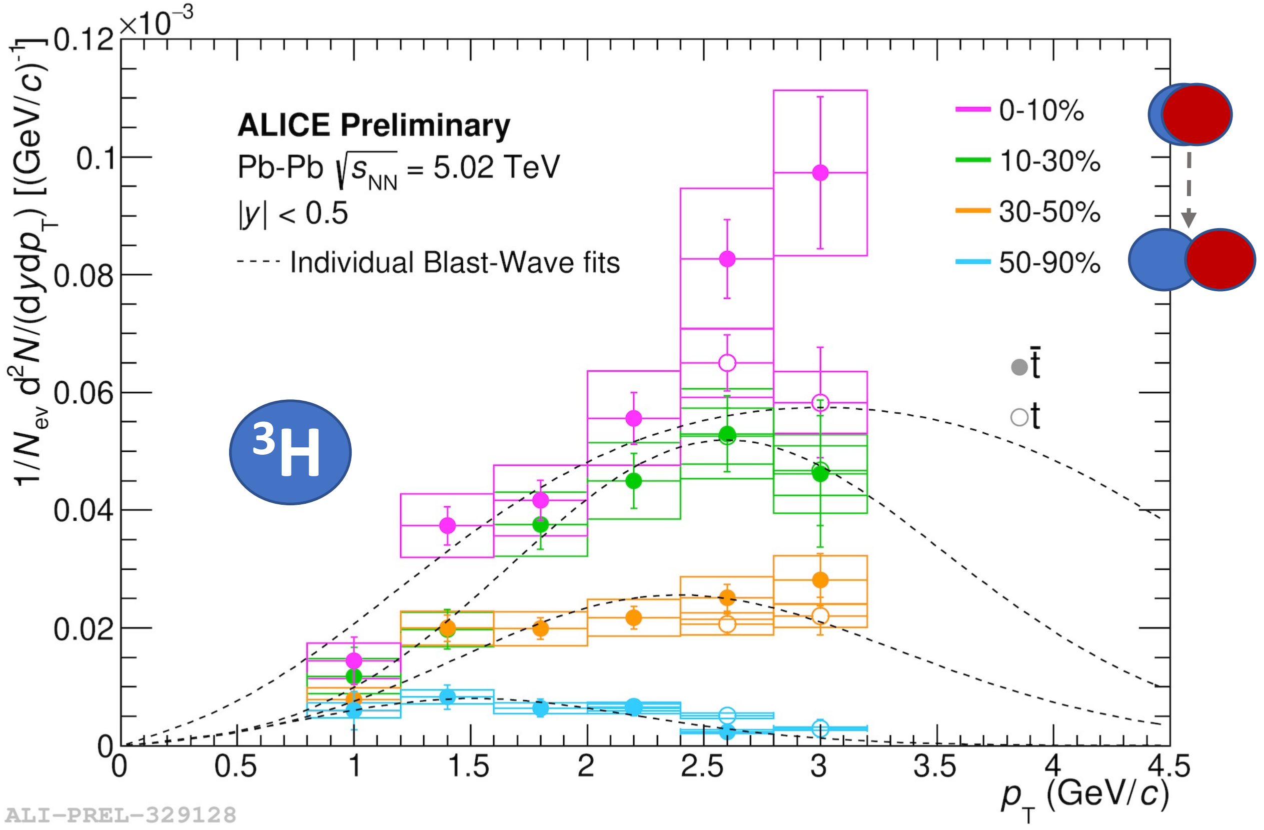
p–Pb @ 8.16 TeV

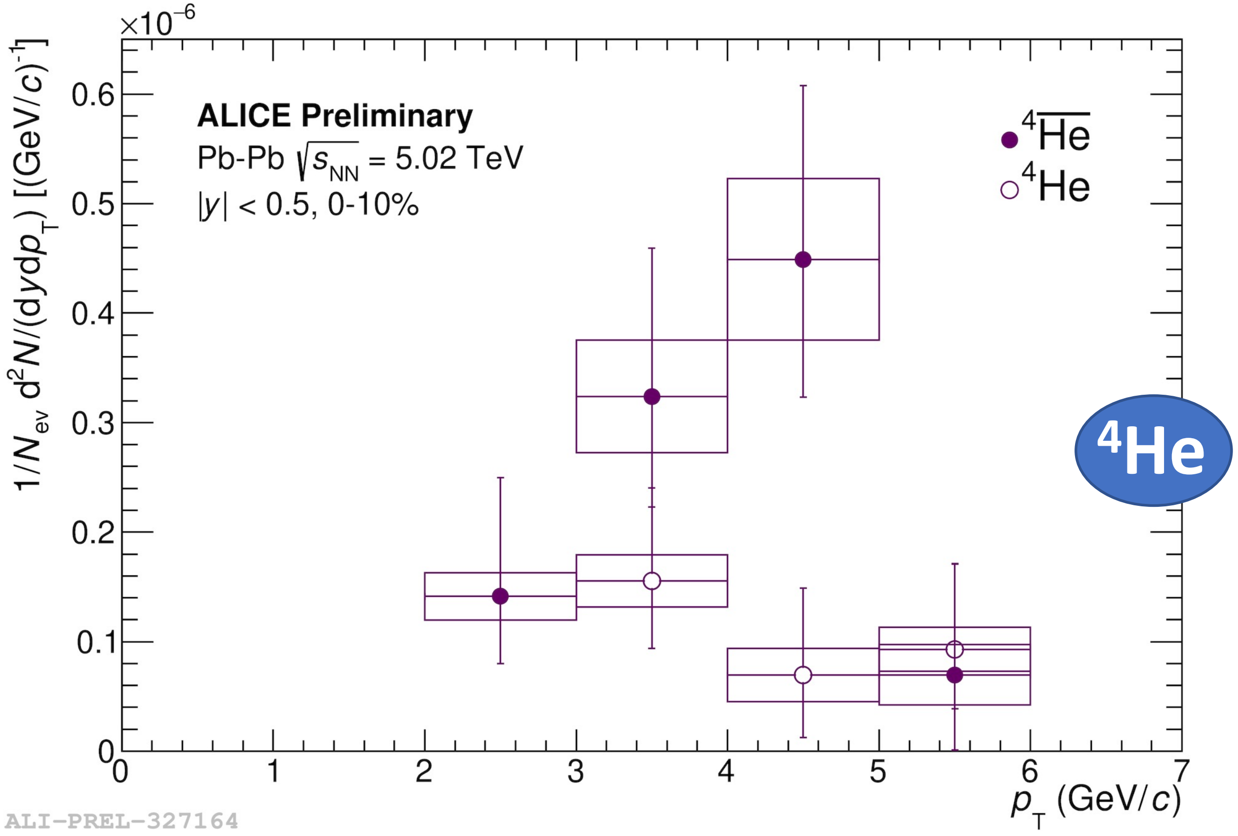


pp @ 13 TeV

- p_T spectra fitted with Lévy-Tsallis function
  ⇒ Extrapolation to unmeasured regions

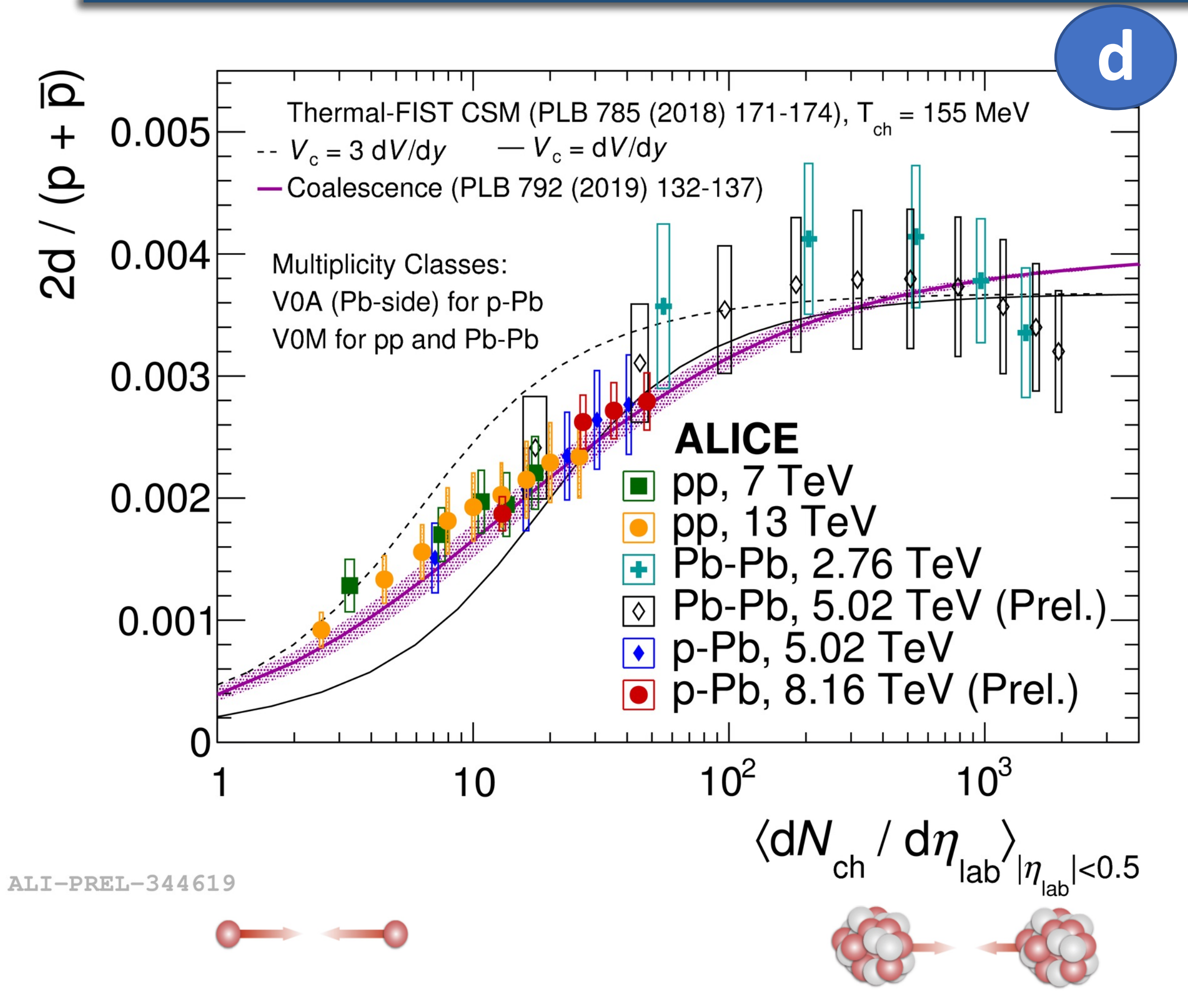
- Light (anti)nuclei up to ^{4}He have been measured in Pb—Pb collisions, thanks to a larger amount of data available

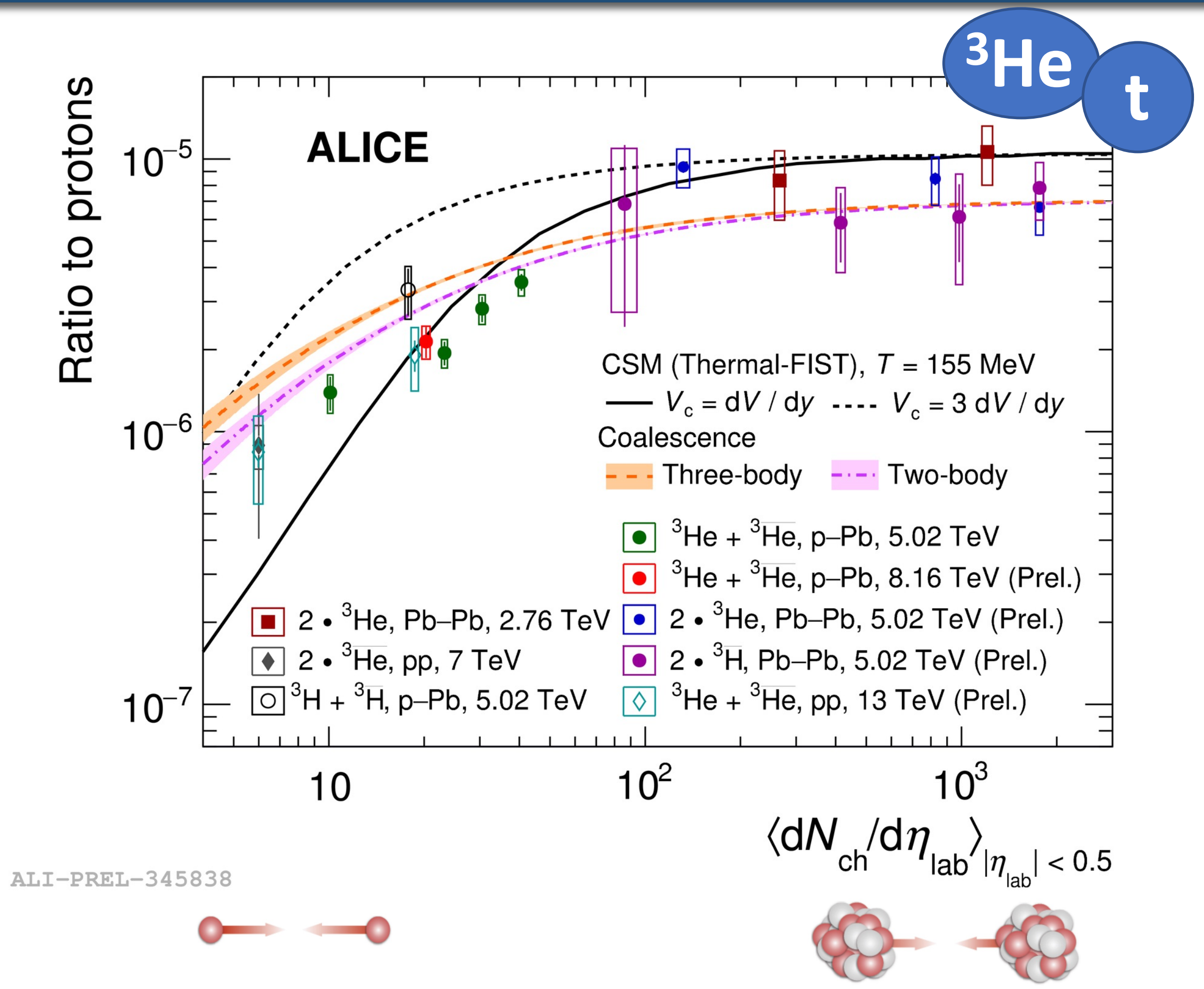




- ^{3}H nuclei have been measured in several mult. classes in Pb—Pb collisions

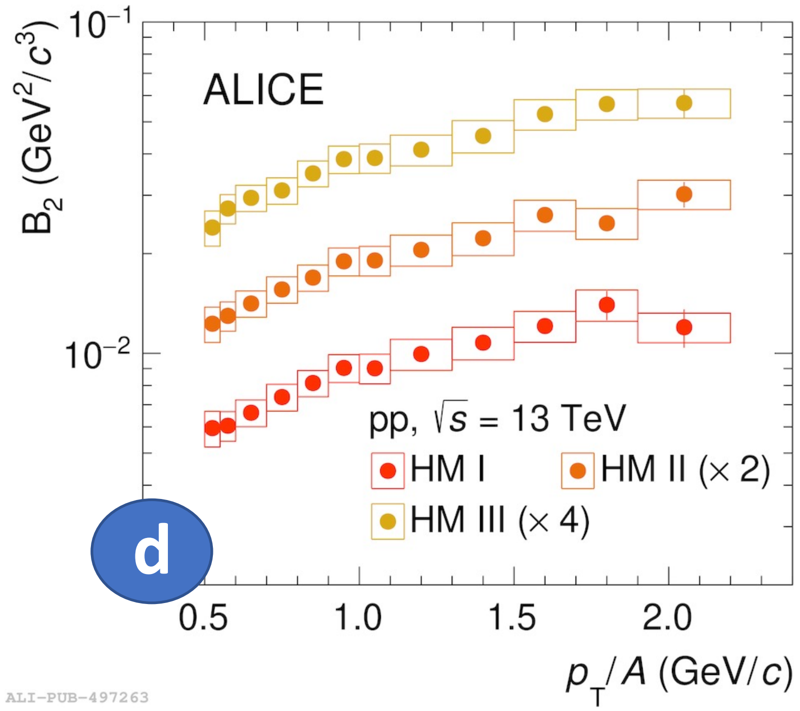
Ratio to protons – models comparison

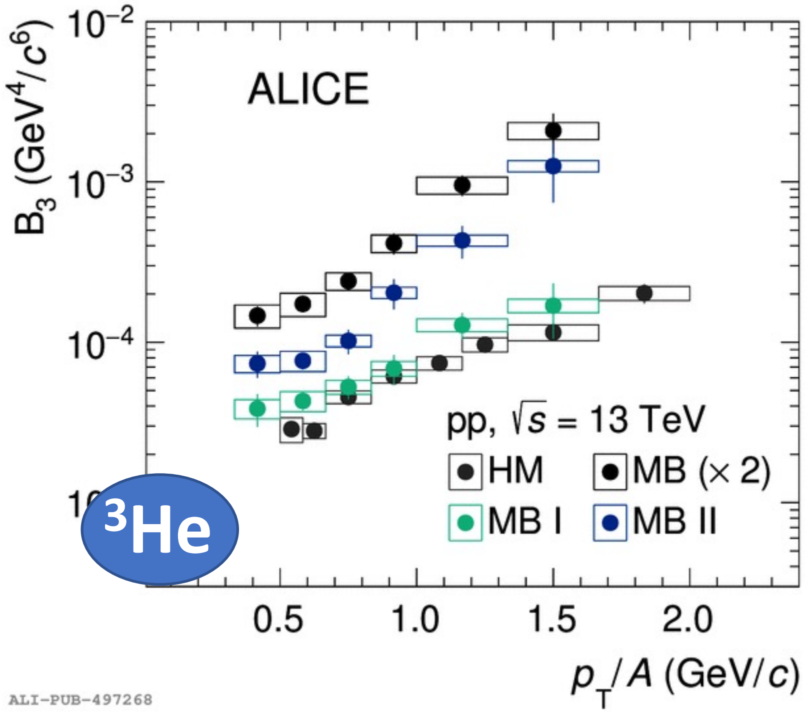




- Smooth transition across different collision systems and energies
- Light nuclei production seems to depend only on multiplicity
- Results challenge the models for A=3 nuclei

Coalescence parameters VS p_T/A

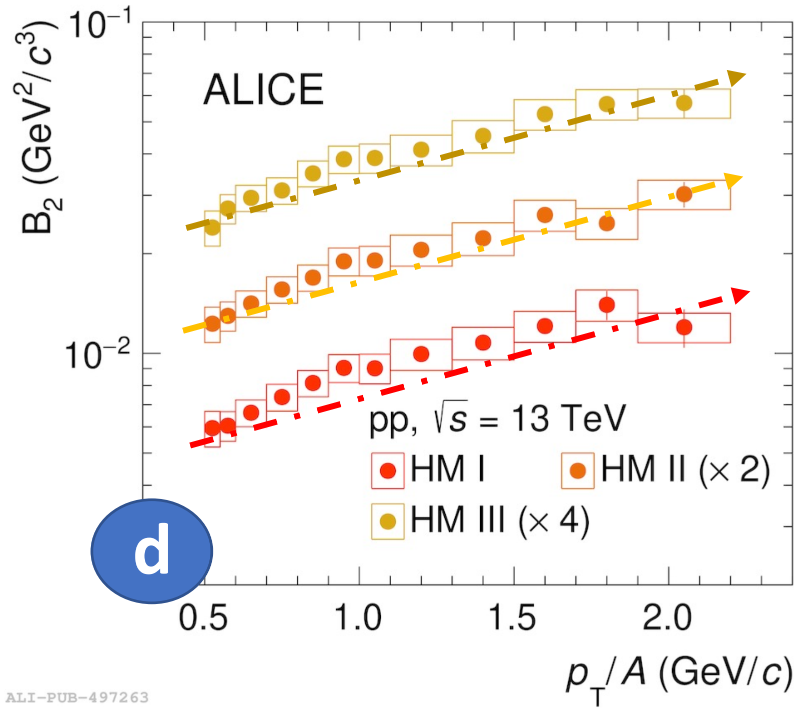


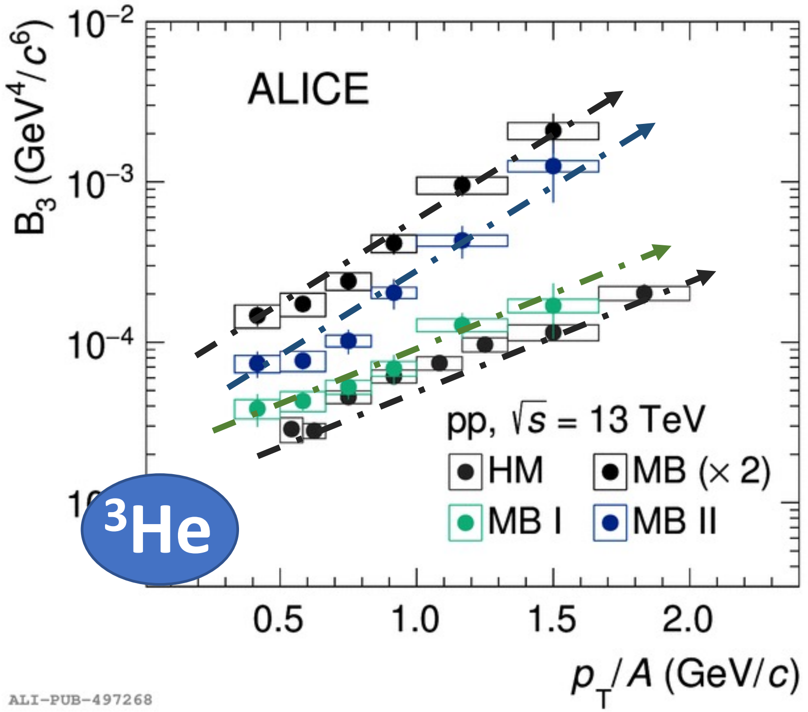


HM pp @ 13 TeV

Focus on HM data sample → narrow multiplicity interval covered

Coalescence parameters VS p_T/A





HM pp @ 13 TeV

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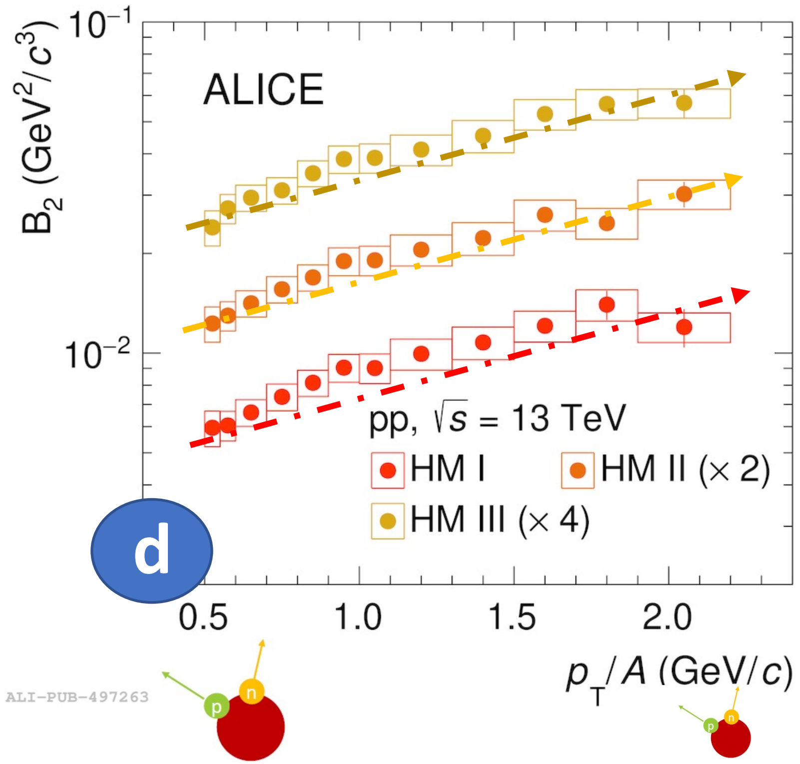
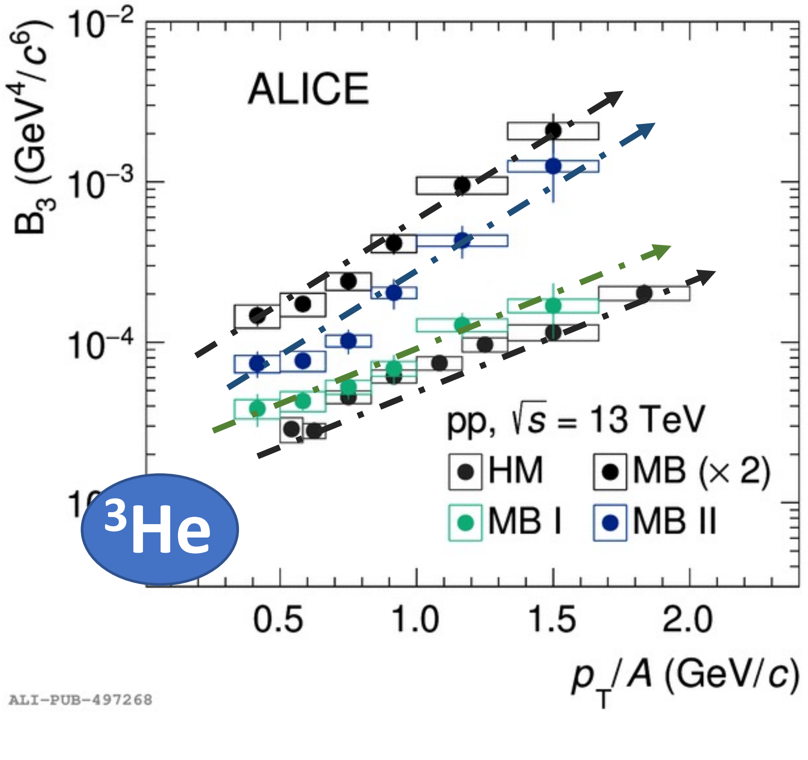
- B_2 and B_3 increase as a function of p_T/A

Coalescence parameters VS p_T/A





HM pp @ 13 TeV

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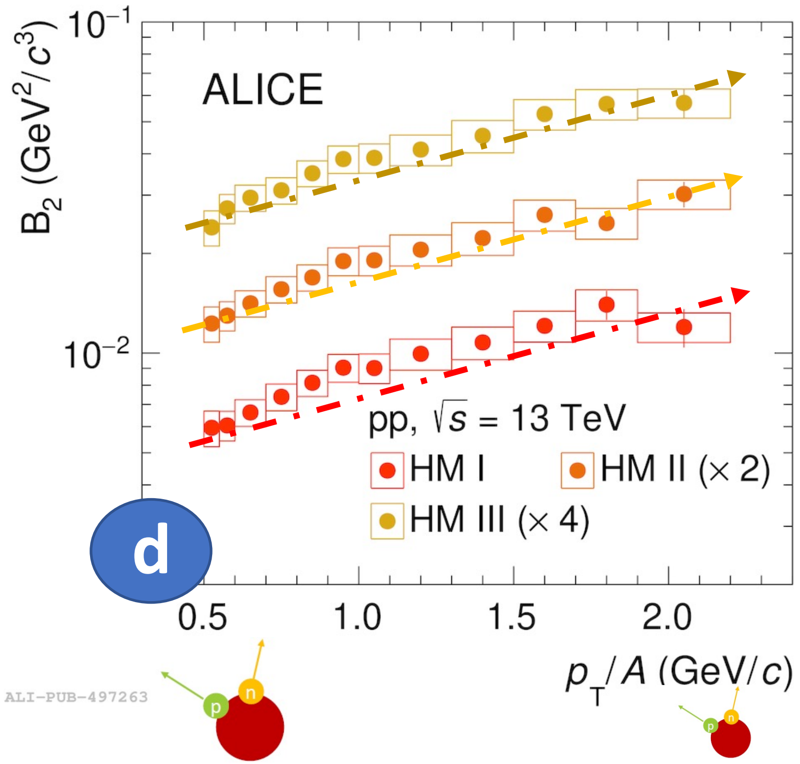
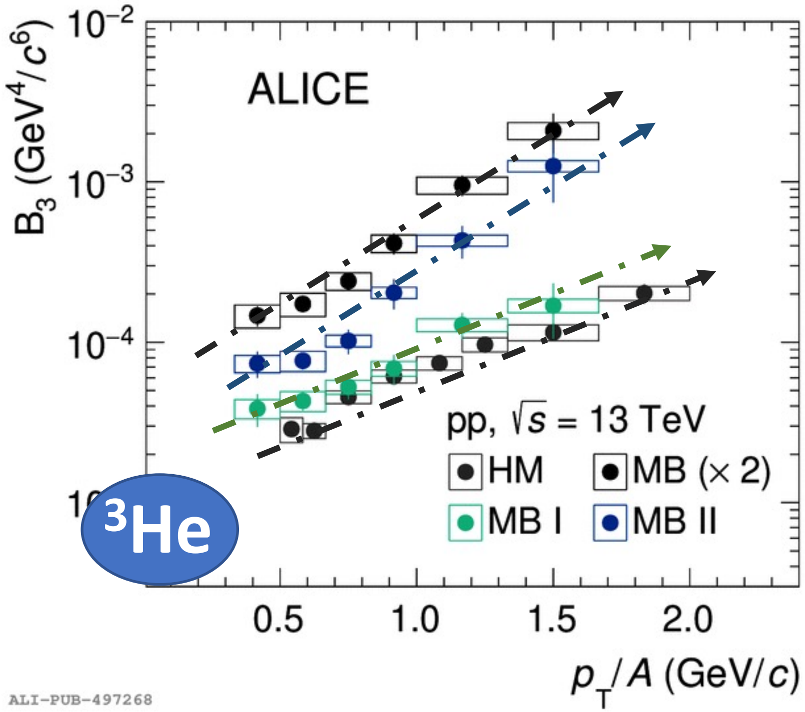
- B_2 and B_3 increase as a function of p_T/A
  - effect of the decrease of the system size (R) with transverse momentum
  - $B_A \propto R^{3(1-A)}$

Coalescence parameters VS p_T/A





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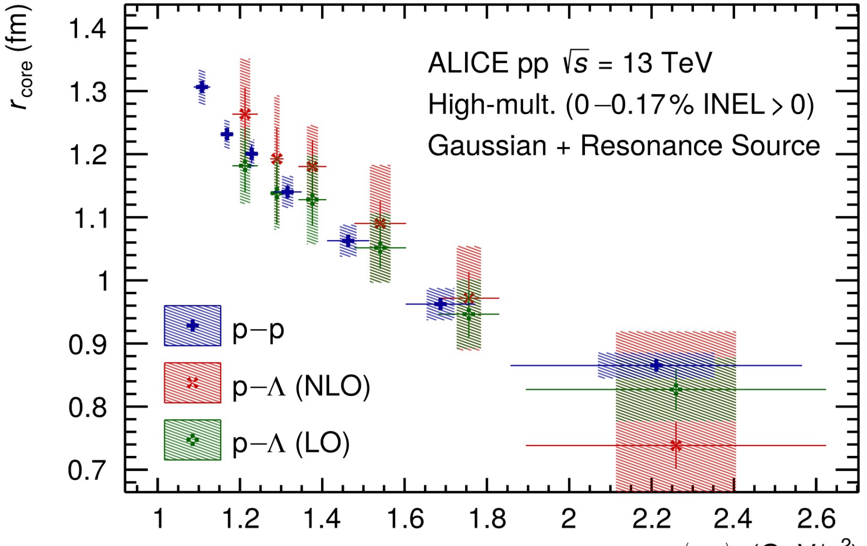


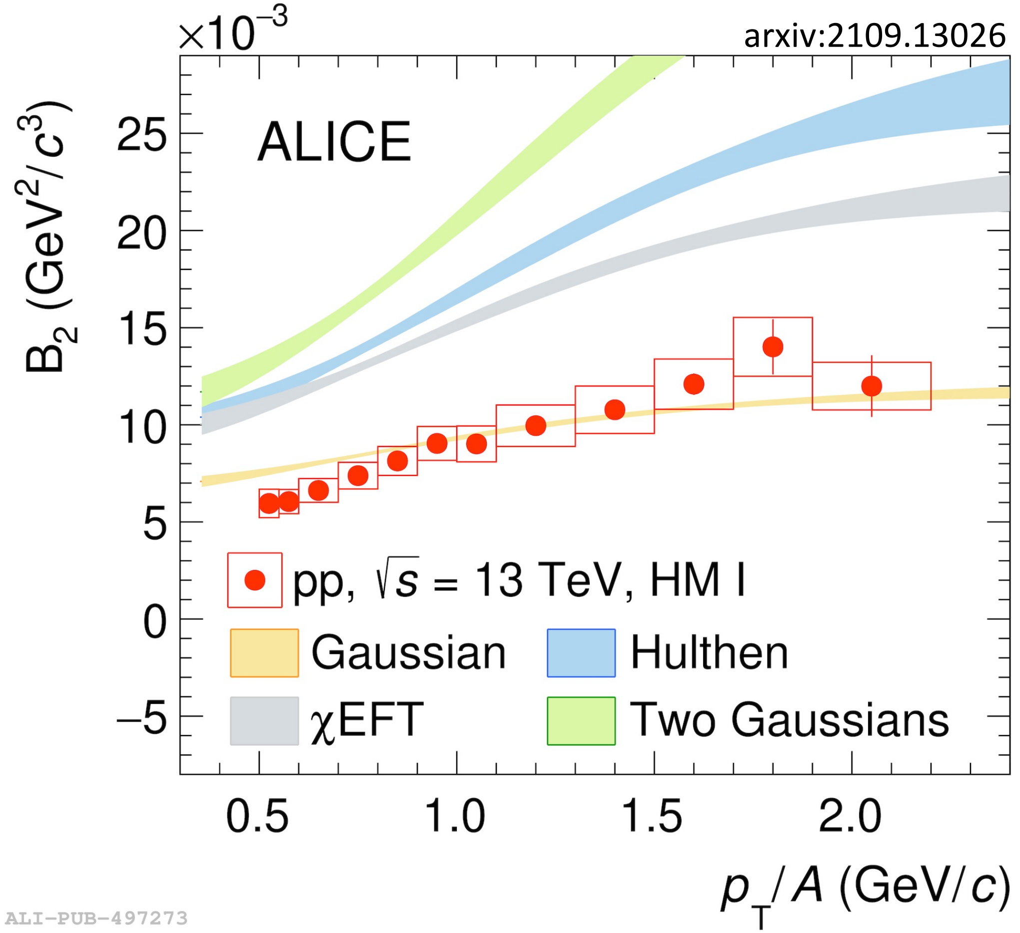
PLB 811 (2020) 135849

$\propto p_T$

- B_2 and B_3 increase as a function of p_T/A
  - effect of the decrease of the system size (R) with transverse momentum
  - $B_A \propto R^{3(1-A)}$
  - measurement of R is crucial → femtoscopic techniques

Coalescence parameters VS p_T/A

- B_A measurements useful to constrain nuclei wave function
  - HM data sample also used for the precise measurement of the source radii (*PLB 811 (2020) 135849*)



source size

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

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

PRC 99 (2019) 044913

deuteron wave function

r_d = 3.2 fm

HM pp @ 13 TeV

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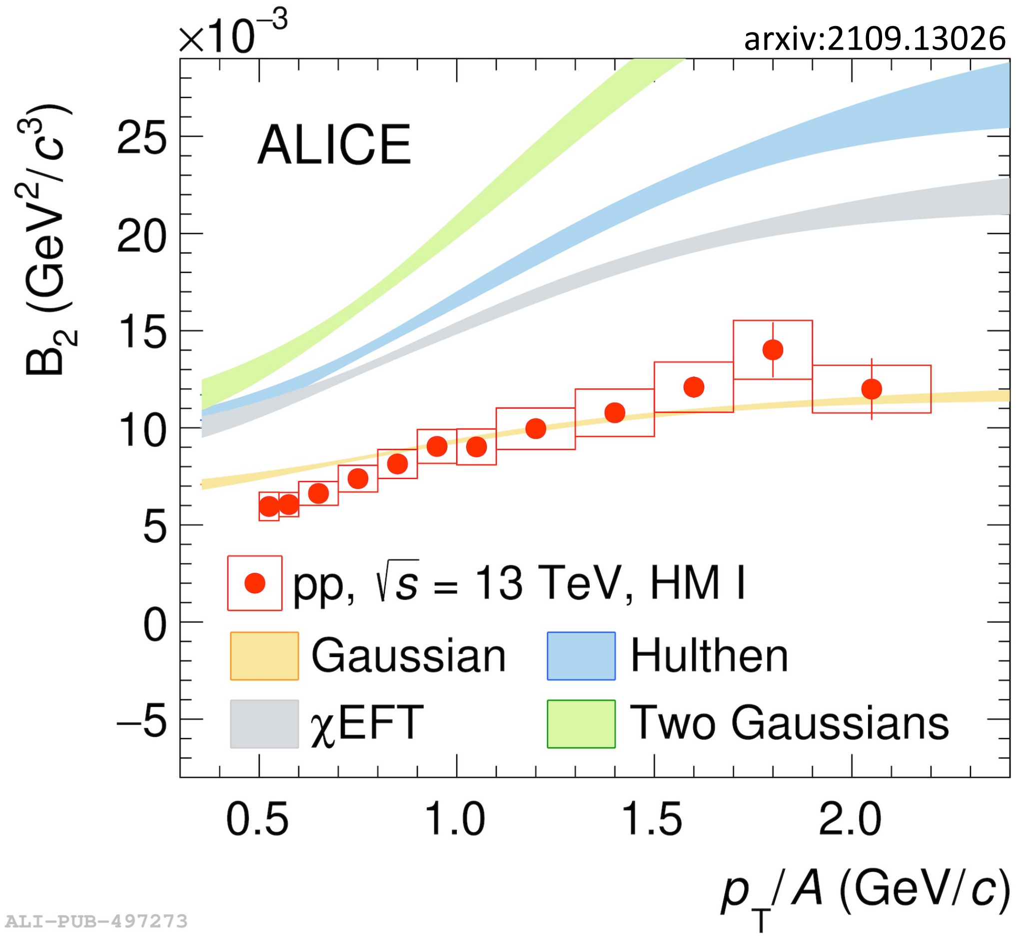

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PRC 99 (2019) 044913

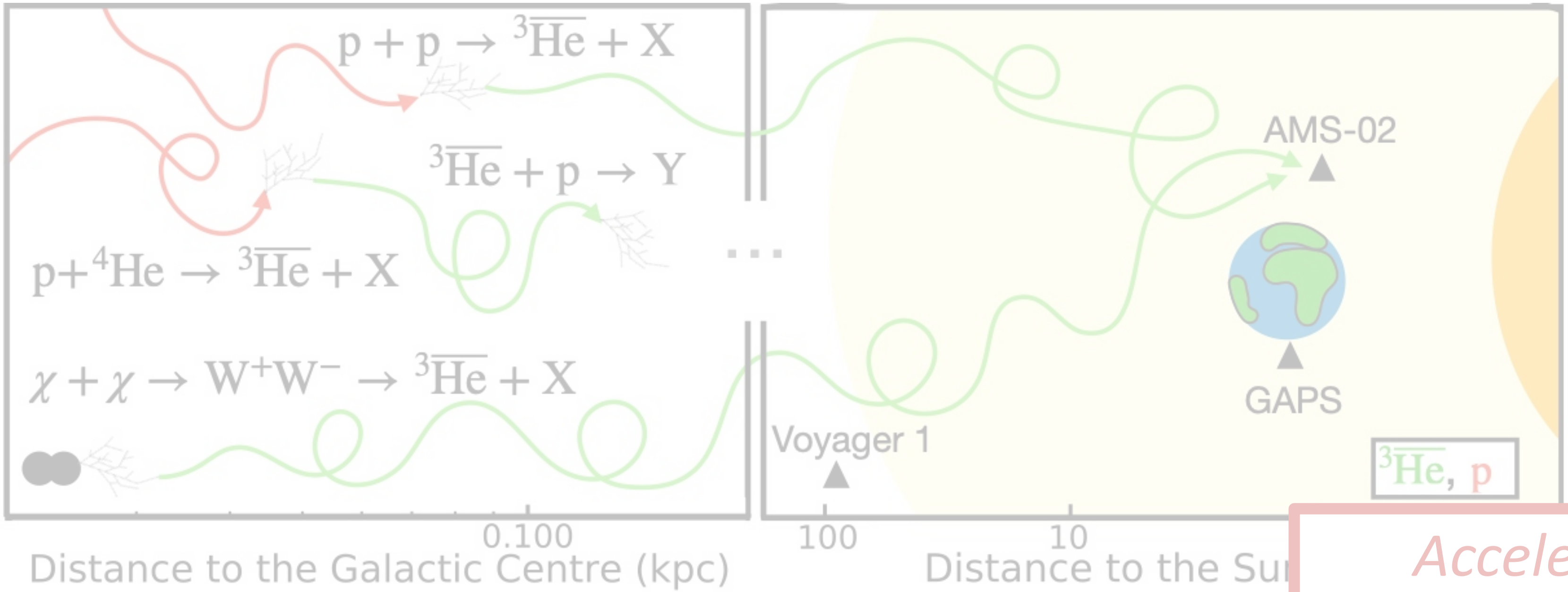
deuteron wave function

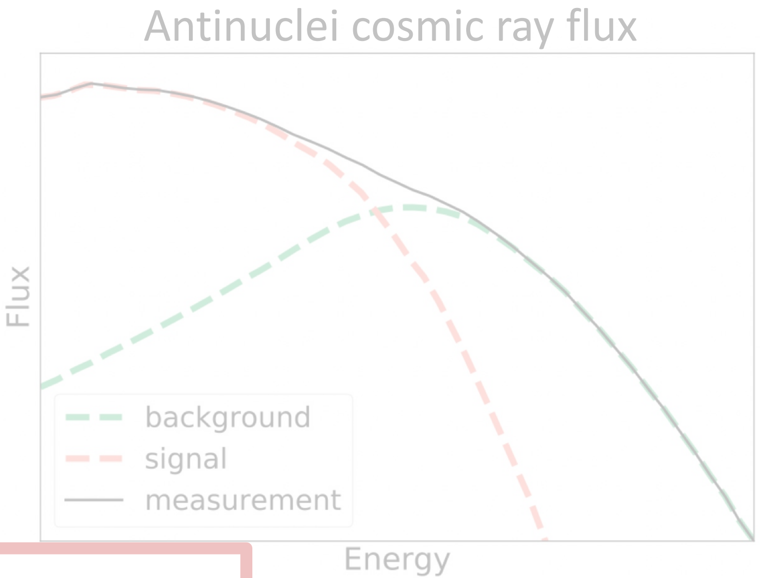
r_d = *3.2* fm

- Data favour Gaussian wave function
- From low-energy scattering experiments Hulten should be favoured

HM pp @ 13 TeV

Antinuclei as dark matter probe





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Source Function

Propagation: diffusion, convection…

Absorption

Fragmentation, annihilation

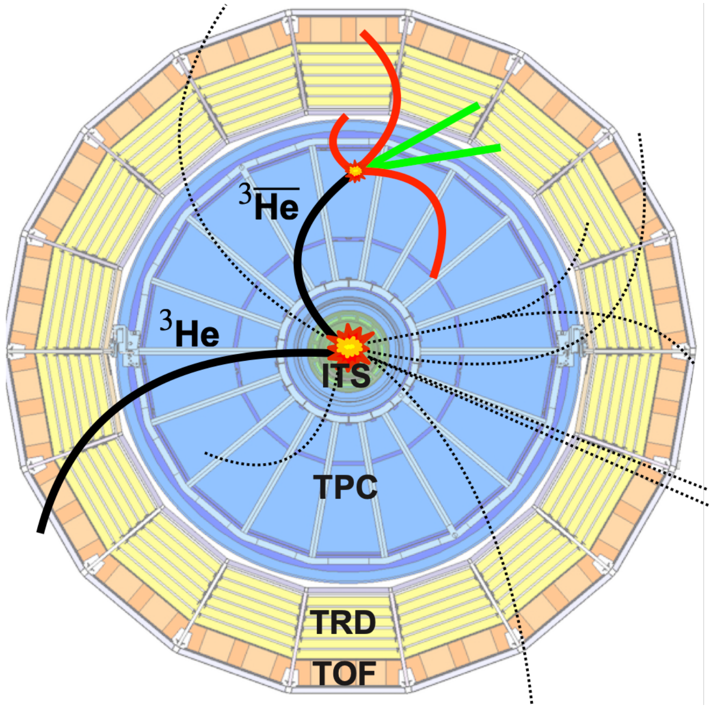
Antinuclei absorption

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 (pp 13 TeV)

- Measurement of reconstructed **anti^{3}He/^{3}He** ratio and compare to MC simulation expectations

  PRL 125, 162001 (2020)



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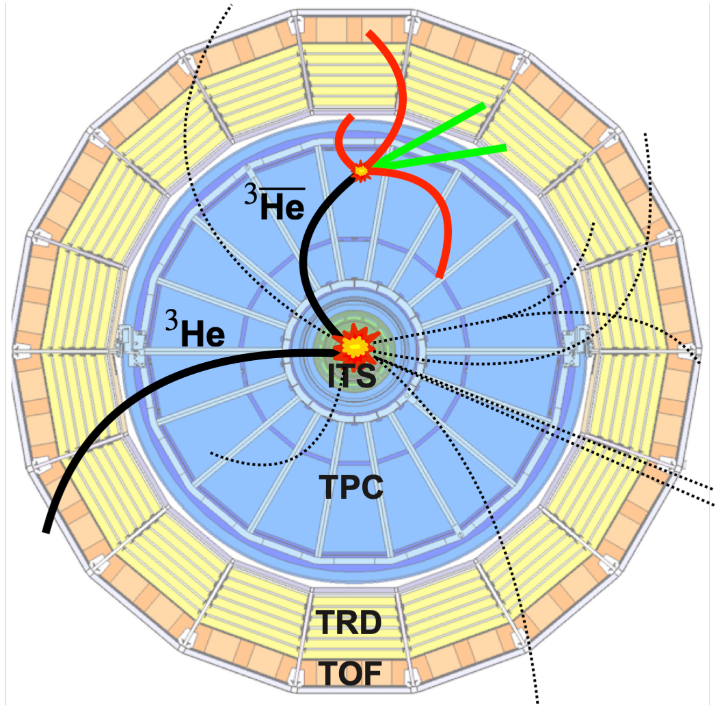
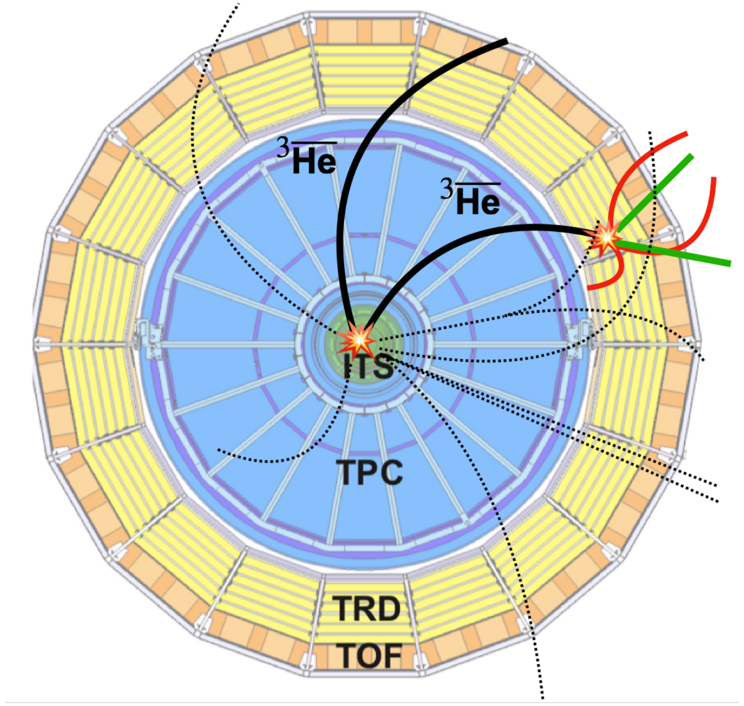


TOF/TPC-matching ratio (Pb-Pb 5.02 TeV)

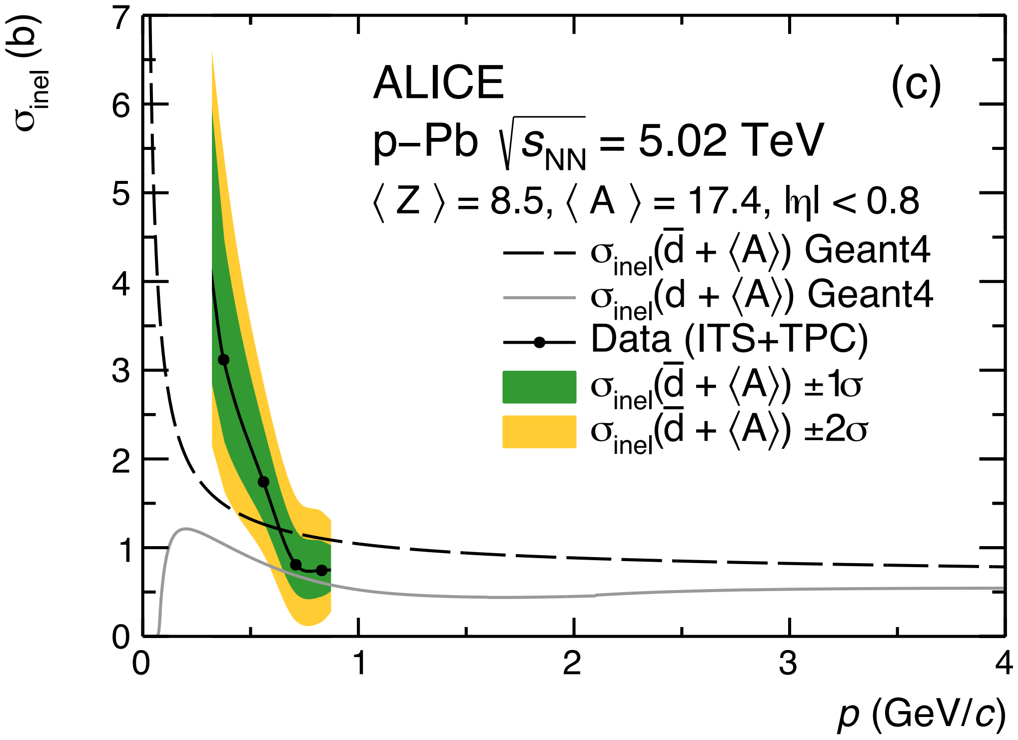
- Measurement of reconstructed **anti^{3}He$_{TOF}$/anti^{3}He$_{TPC}$** ratio and compare to MC simulation expectations

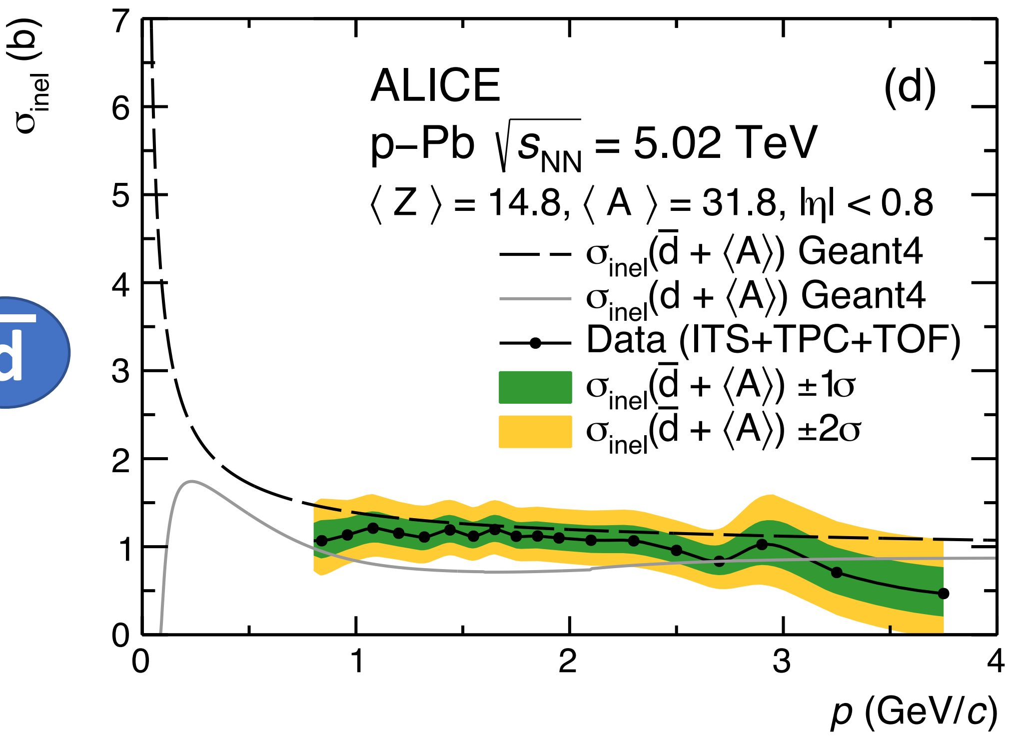


Inelastic cross section measurements: $\bar{d}$

Inelastic cross sections measured for different species

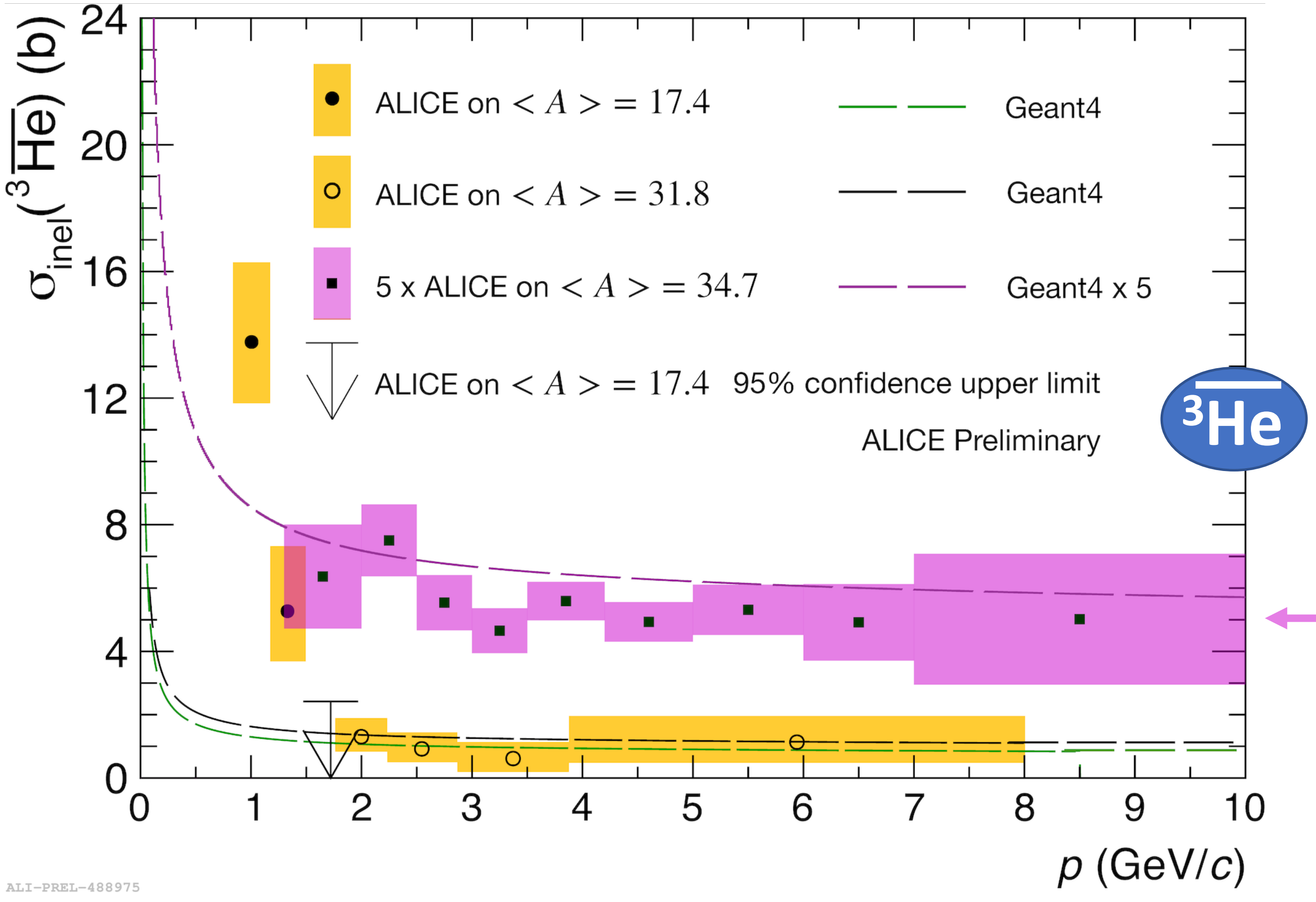
- **Antideuterons:**
  - good agreement with GEANT4 at high *p*
  - steeper rise than GEANT4 at low *p*





Inelastic cross section measurements: $^3\overline{He}$

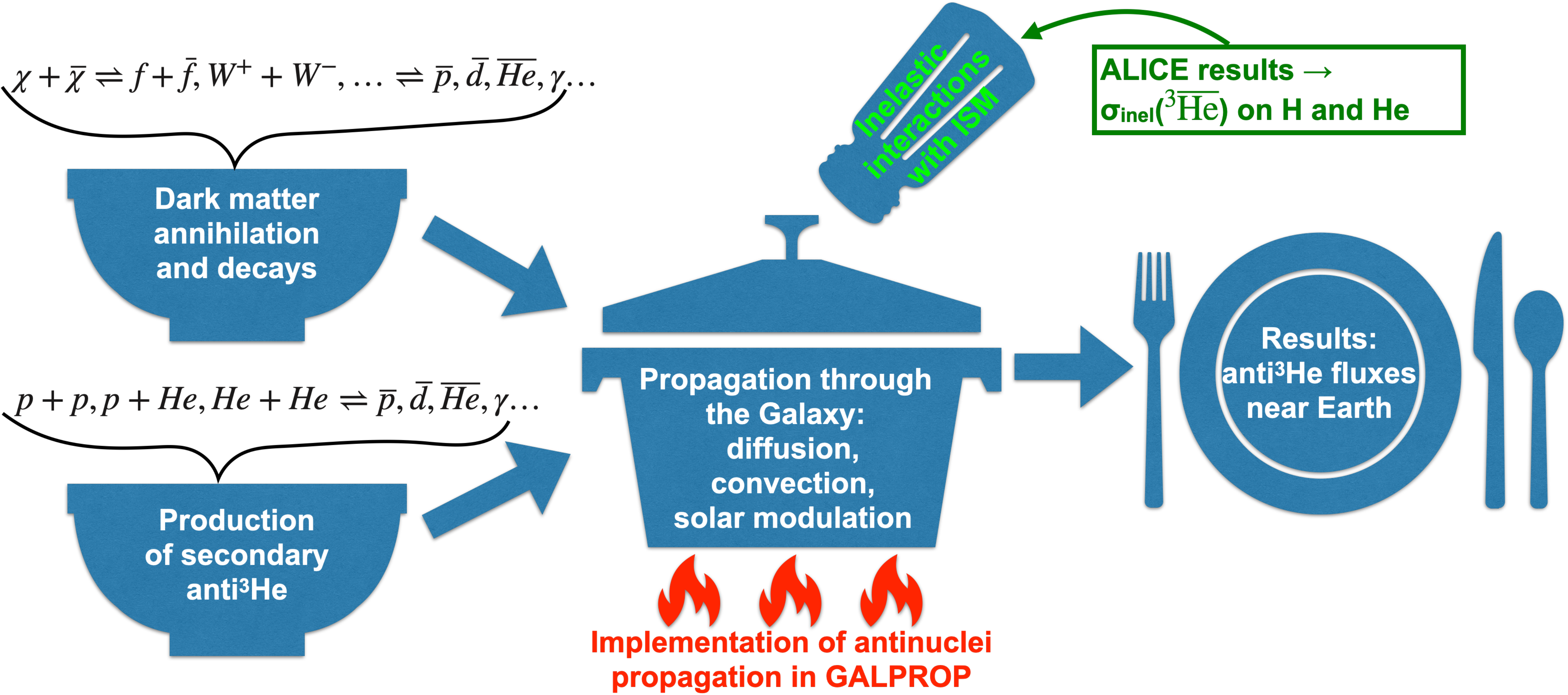
Inelastic cross sections measured for different species



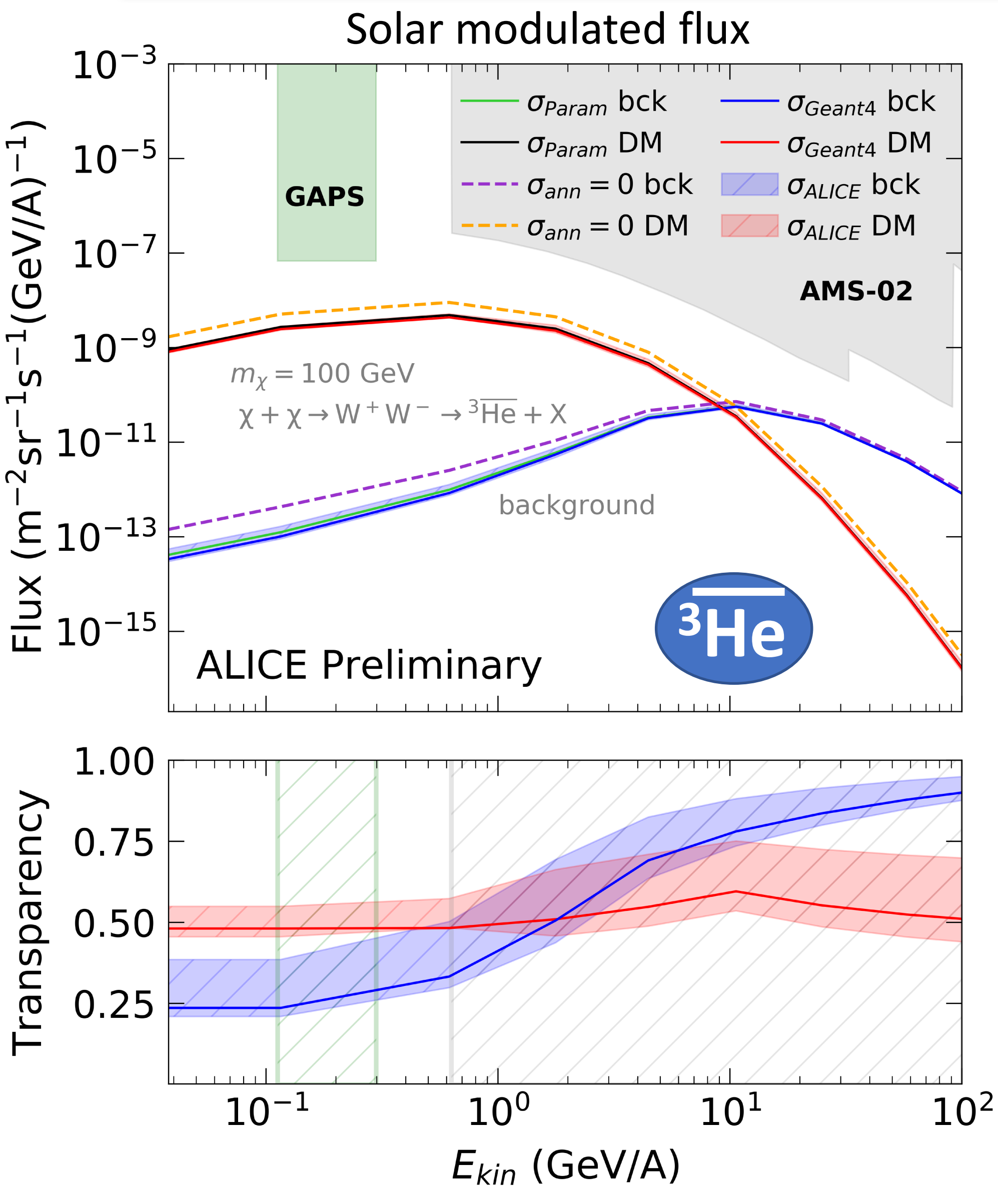
- **Anti^{3}He:**
  - much steeper rise than GEANT4 at low p
  - compatible with GEANT4 at high p

TOF/TPC-matching ratio method
scaled by factor 5 for better visibility

Recipe to cook antinuclei fluxes



Results on transparency of our Galaxy



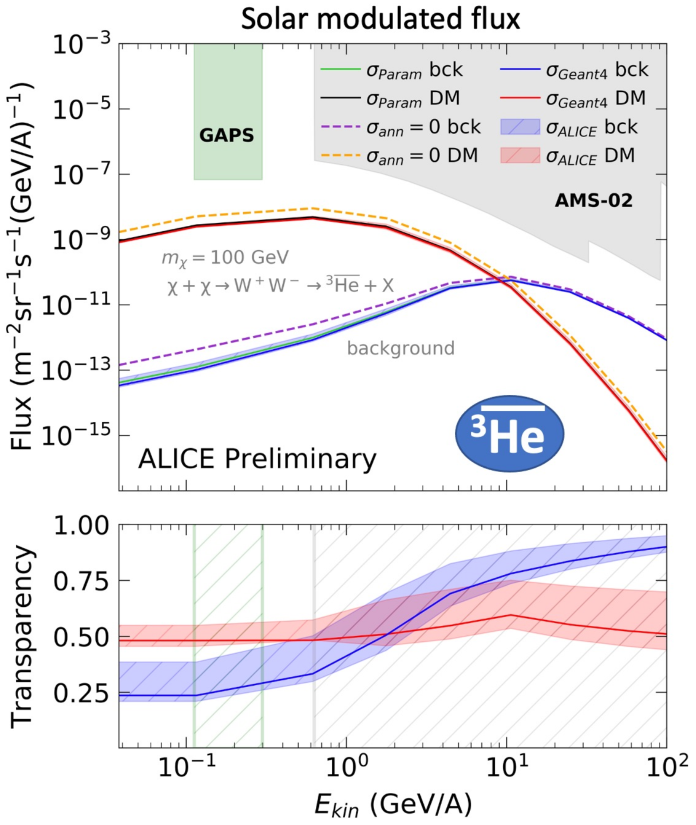
Transparency = $\frac{\text{flux with annihilation}}{\text{flux without annihilation}}$ = ( ) for bkg (DM)

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%)

Summary

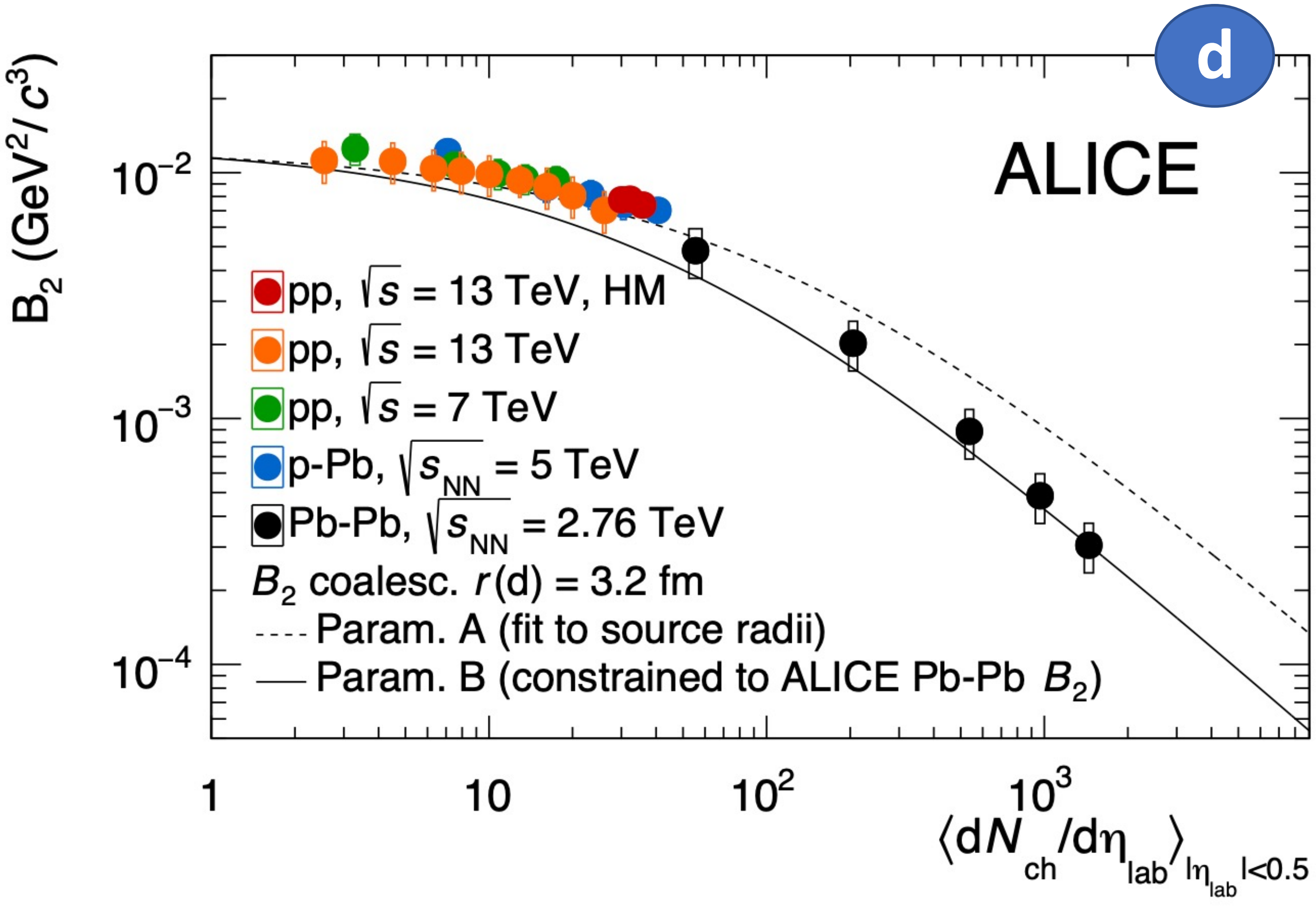
- Production of light (anti)nuclei has been studied in deep details with ALICE at the LHC in several collision systems and energies
  - *Run2* data fully analysed → looking forward to Run3 data!
- Experimental results challenge the models
- Light (anti)nuclei *production* and *absorption* studies at accelerators can provide crucial inputs for indirect dark matter searches
- First measurement of the *transparency* of our Galaxy to anti^{3}He



Thank you for your attention!

Backup

Coalescence parameter B_2



Strong dependence of B_2 on collision system size

Continuous evolution of B_2 with multiplicity

- Smooth transition from small to large system size
- Single underlying production mechanism?

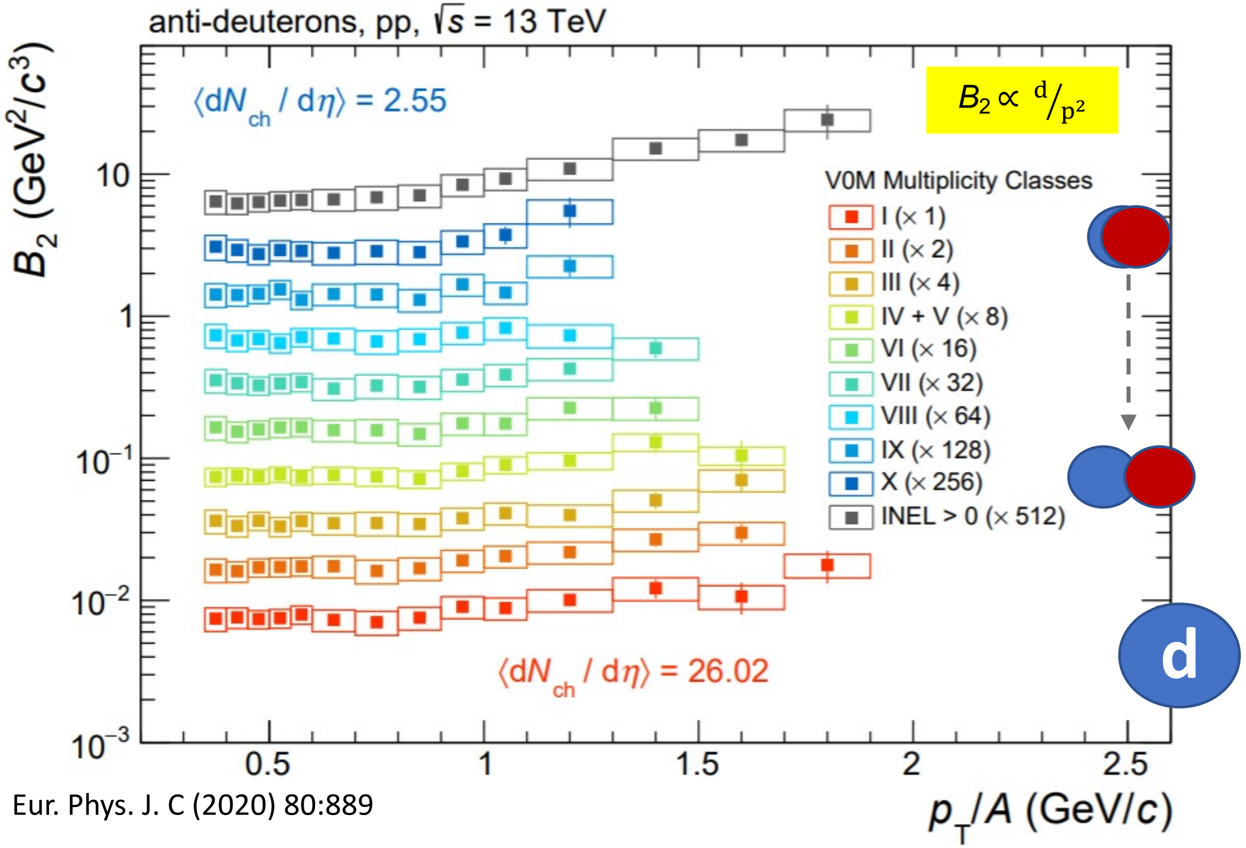
Similar conclusions apply also for B_3

Advanced coalescence models taking into account the size of the nucleus and of the emitting source predict similar trend

The evolution with multiplicity is explained as an increase in the source size R in coalescence models (e.g. *Scheibl, Heinz PRC 59 (1999) 1585*)

Coalescence parameters VS p_T/A

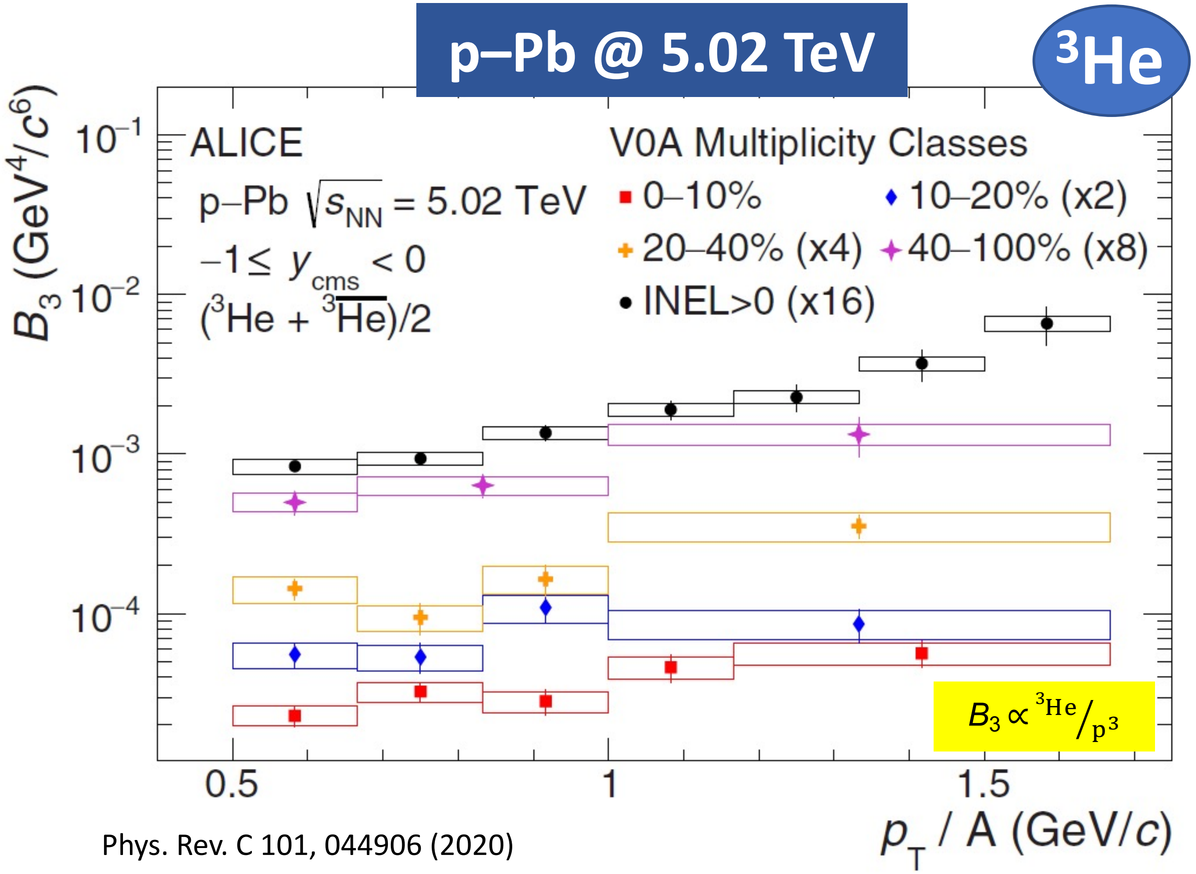
- B_A is rather flat in multiplicity classes
- B_A increases at high p_T/A in the MB class → related to hardening of proton spectra



Eur. Phys. J. C (2020) 80:889

MB pp @ 13 TeV

p–Pb @ 5.02 TeV



Phys. Rev. C 101, 044906 (2020)

→ *is the probability of forming a (anti)nucleus constant with p_T?*

Astrophysical implications

ANTINUCLEI PRODUCTION

BKG

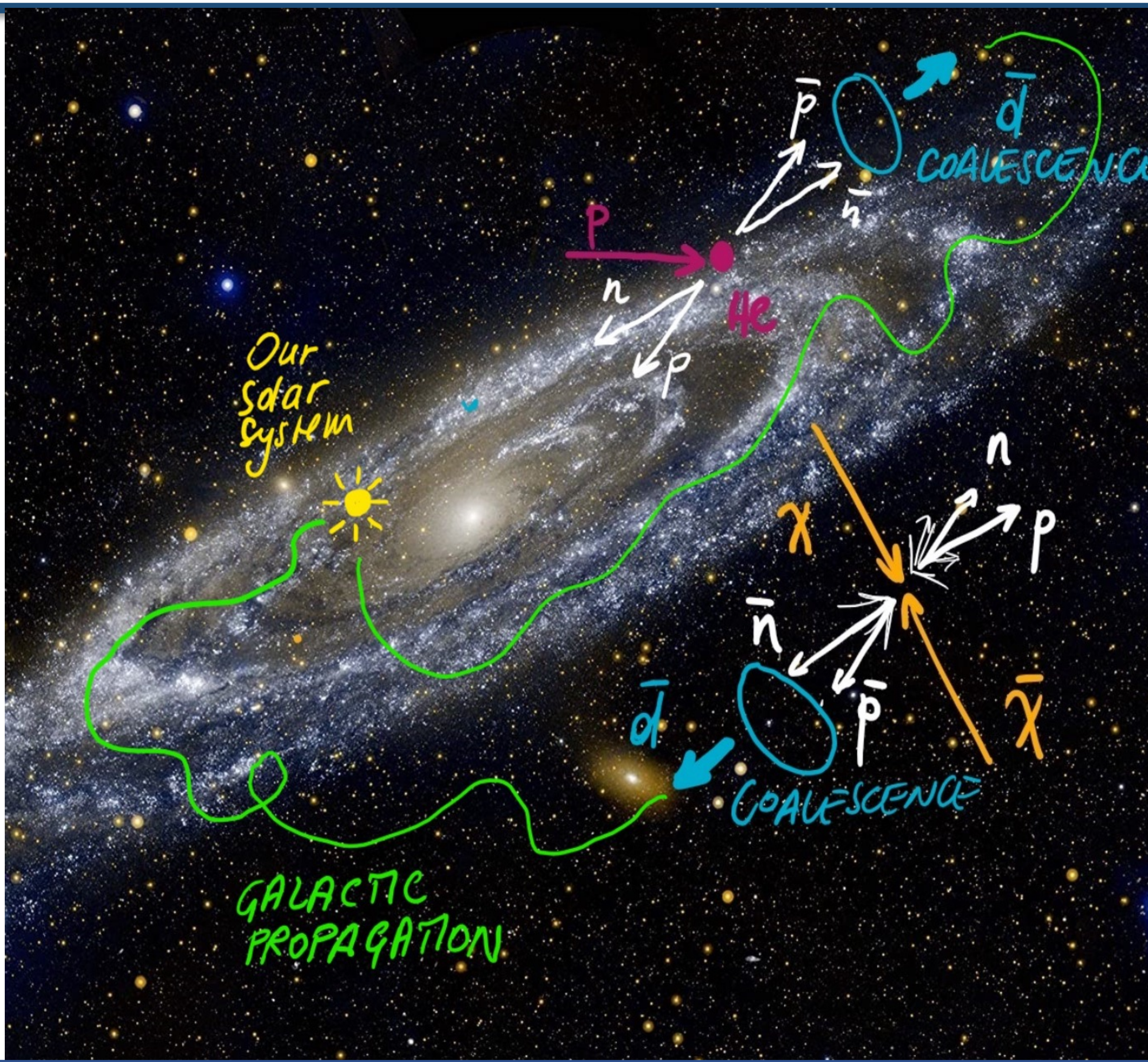
1. Secondary cosmic rays from hadronic interactions of primary CR with the InterStellar Matter (pp, p-He...) in the **Galaxy**

SIGNAL

2. Dark matter annihilation

- Search for Dark Matter through antinuclei probe is chased by several experiments (GAPS, AMS, BESS, ...)
- Need to determine exact primary and secondary fluxes, which require precise knowledge of antinuclei production, propagation and annihilation

Experiments at accelerators can provide crucial inputs for dark matter searches



Antinuclei fluxes near Earth

Ingredients needed to predict primary and secondary fluxes:

- antimatter cluster **formation mechanisms**
- model of **cosmic ray propagation** in the Galaxy and the heliosphere
- **annihilation** cross section of antinuclei in the ISM and the detector materials

Transport equation of antinuclei:

$$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \mathbf{div}(D_{xx}\mathbf{grad}\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi \frac{dp}{dt} - \frac{p}{3}(\mathbf{div} \cdot \mathbf{V})\psi\right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}$$

Source Function | Propagation: diffusion, convection... | Fragmentation, annihilation

Production
- **DM**
- **CRs**

Propagation
- **Galaxy**
- **Heliosphere**

Absorption
Studied with ALICE at the LHC
- **Antinucleus/nucleus ratio**
- **TOF/TPC ratio**

✅ Coalescence models developed at accelerators are also used to calculate the probability that DM annihilation would create an antinucleus

Transverse plane activity

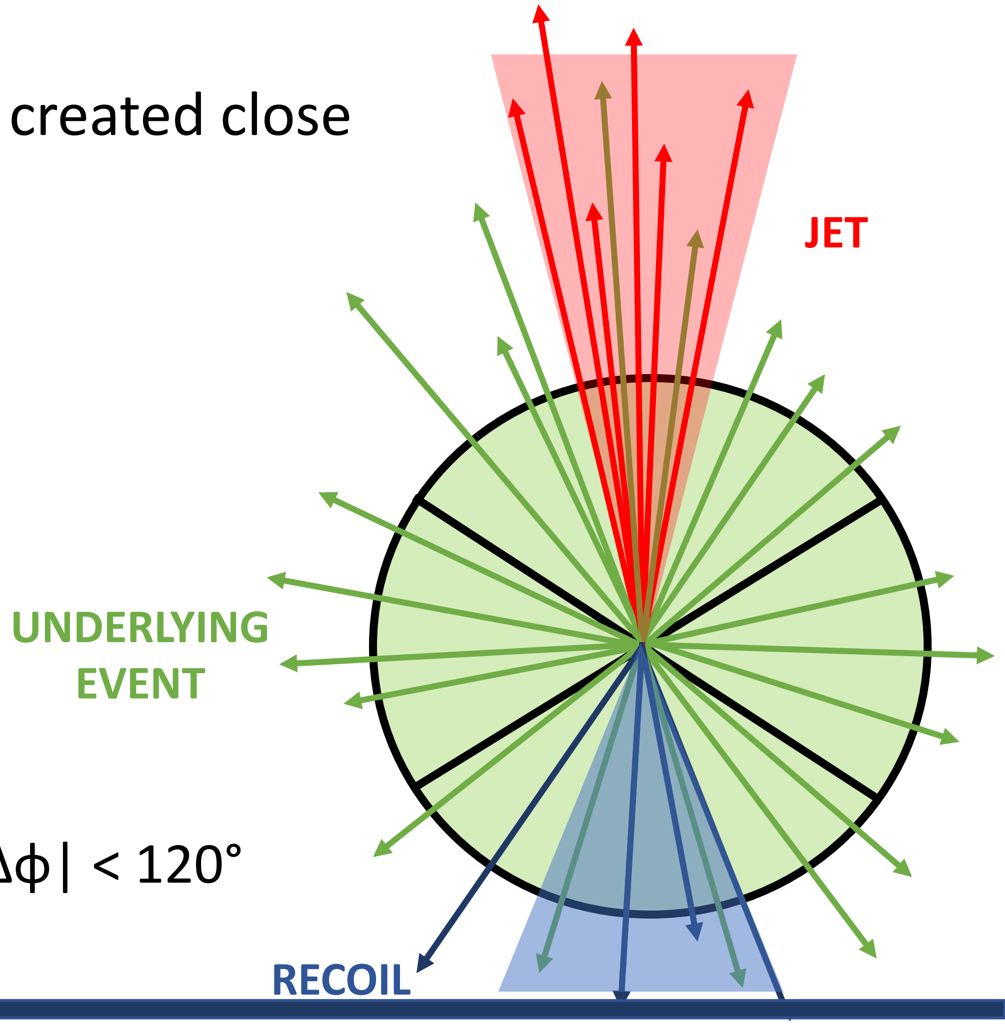
Small collision systems as pp are particularly interesting →

- system created in the collision has a size similar to that of the nucleus
- allows for the study of coalescence since nucleons are created close

UE activity quantified by the self-normalized charged-particle multiplicity:

$$R_T = \frac{N_{transverse}}{\langle N_{transverse} \rangle}$$

Low R_T ⇔ low UE
High R_T ⇔ high UE



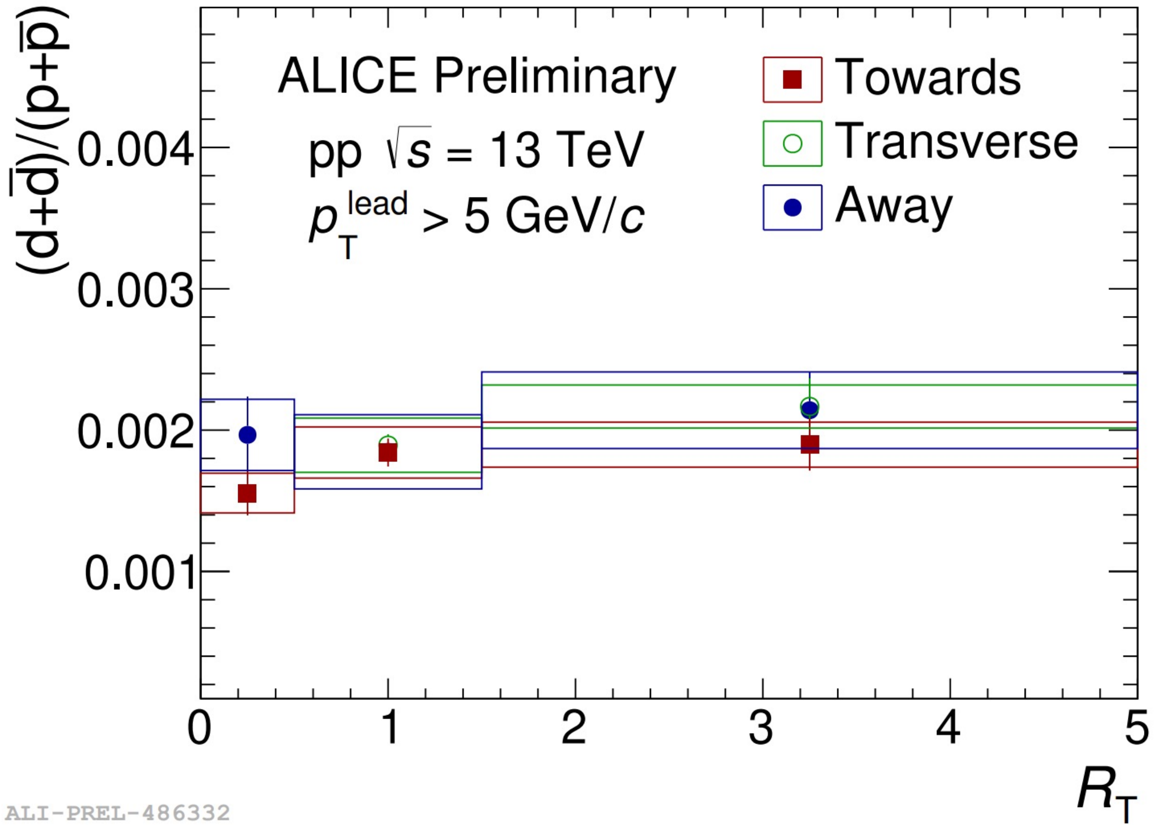
Toward: $|\Delta\phi| < 60°$
Transverse: $60° < |\Delta\phi| < 120°$
Away: $|\Delta\phi| > 120°$

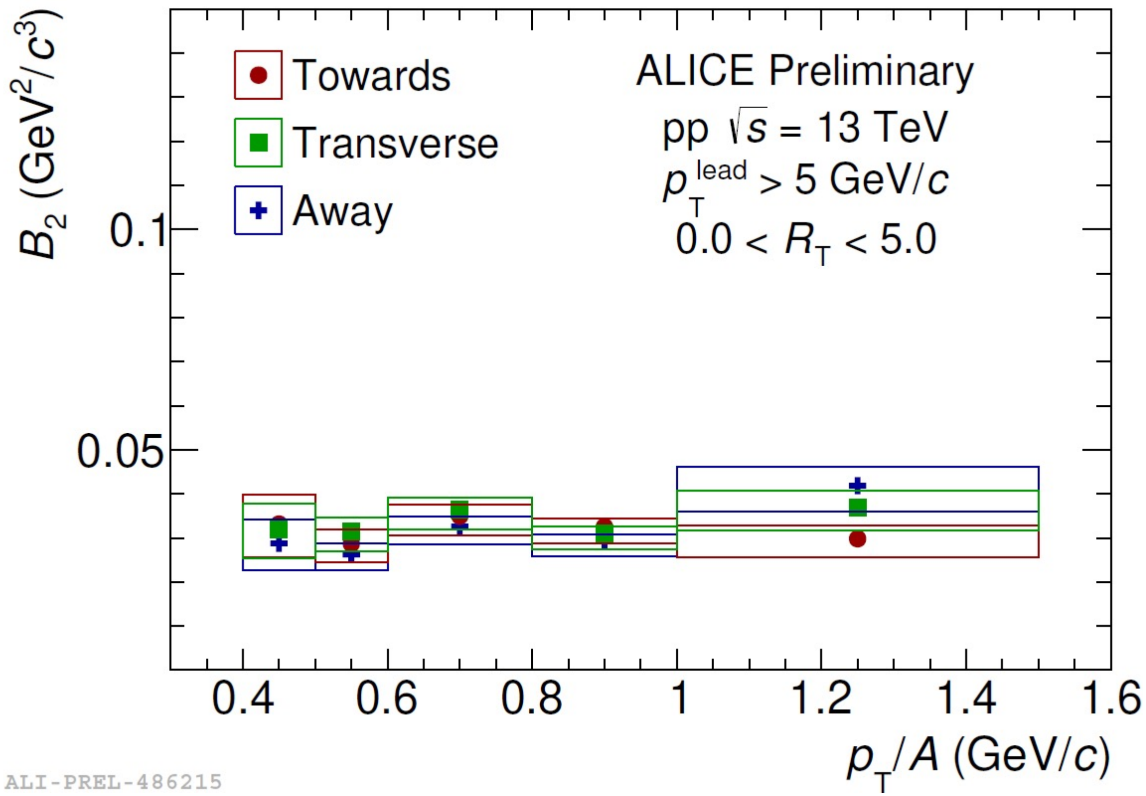
10.1140/epjc/s10052-016-4135-4

deuteron production vs R_T

pp @ 13 TeV

- First measurements of (anti)deuteron production in several R_T classes
- d-to-p integrated yields ratios weakly depend on R_T

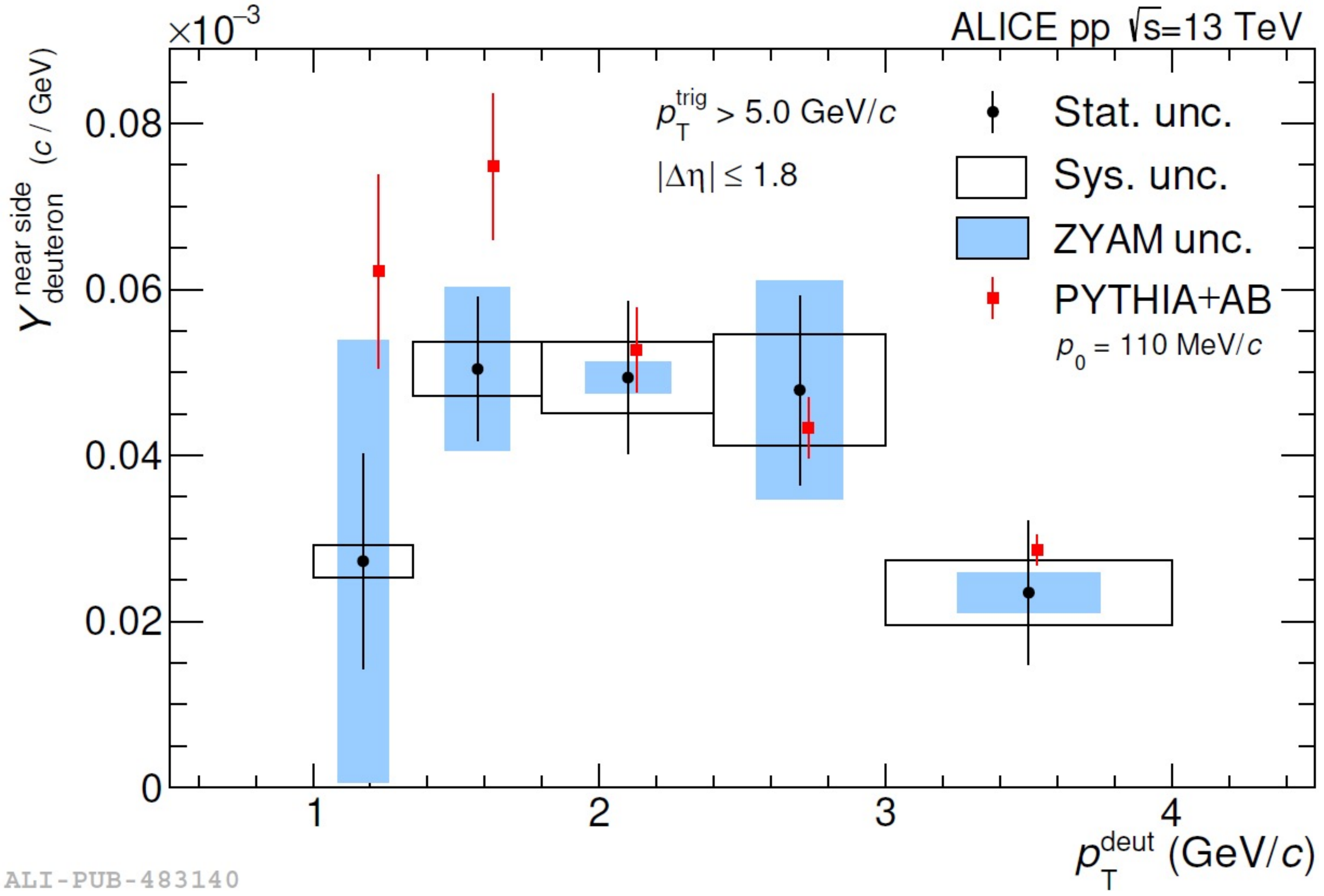




- B_2 is similar in all azimuthal regions, confirming that deuteron production is dominated by UE (Phys. Lett. B 819 (2021) 136440)

d production in jets

- Insight on (anti)d production in smaller phase space available in jet fragmentation
- High-p_T (p_T^{lead} > 5 GeV/c) trigger particle used as jet proxy
- Fraction of deuterons produced in the jet is ~ 8–15%, increasing with increasing p_T
- The majority of the deuterons are produced in the underlying event



Phys. Lett. B 819 (2021) 136440

pp @ 13 TeV

Simple coalescence models (I)

- B_A is related to the **probability** to form a nucleus via coalescence
- **Different implementations** of coalescence model

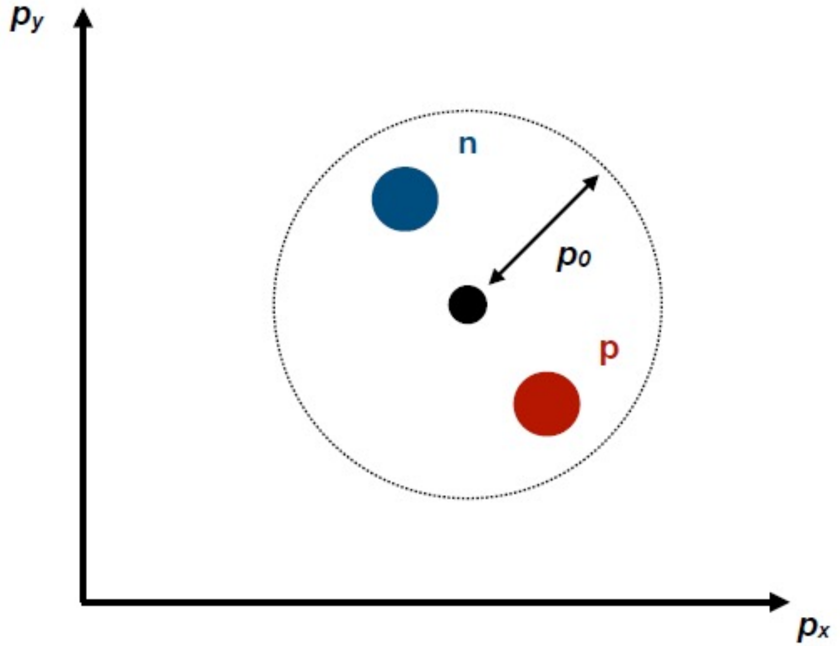
SIMPLEST COALESCENCE

Considers an emitting source of nucleons randomly distributed like a gas of nucleons in thermal and chemical equilibrium

Hypotheses:

- Neutron spectrum = proton spectrum (**isospin invariance**)
- **No space-time** distribution of the nucleons considered
- Nucleons with similar momentum ($\Delta \boldsymbol{p} < \boldsymbol{p_0}$ [=coalescence momentum]) can form a nucleus

$$B_A = \left(\frac{4\pi}{3}p_0^3\right)^{A-1} \frac{m_A}{m_p^A}$$

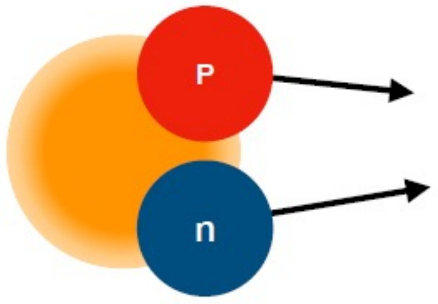


Consequences:

- B_A vs p_T is **flat**

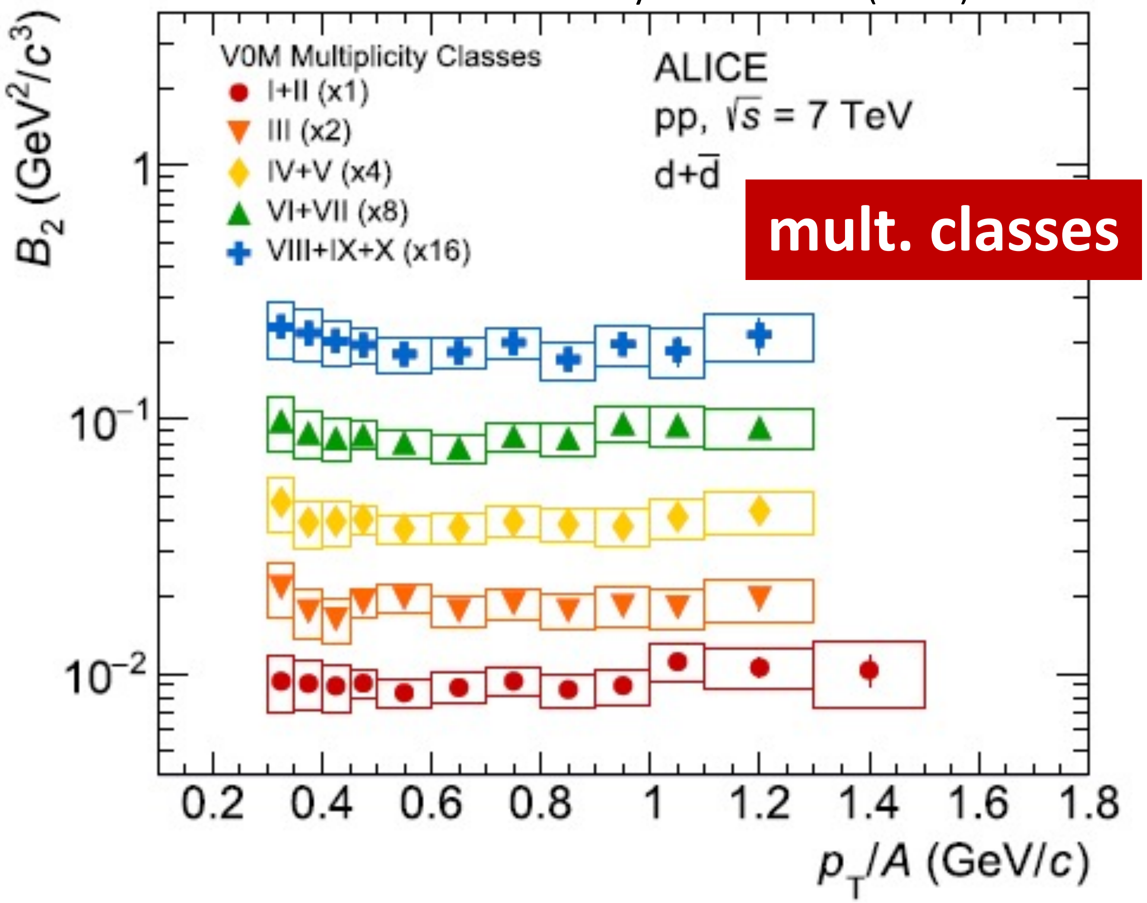
Applications:

- **pp collisions**: small volume (comparable with nucleus size) → nucleons are always close to each other

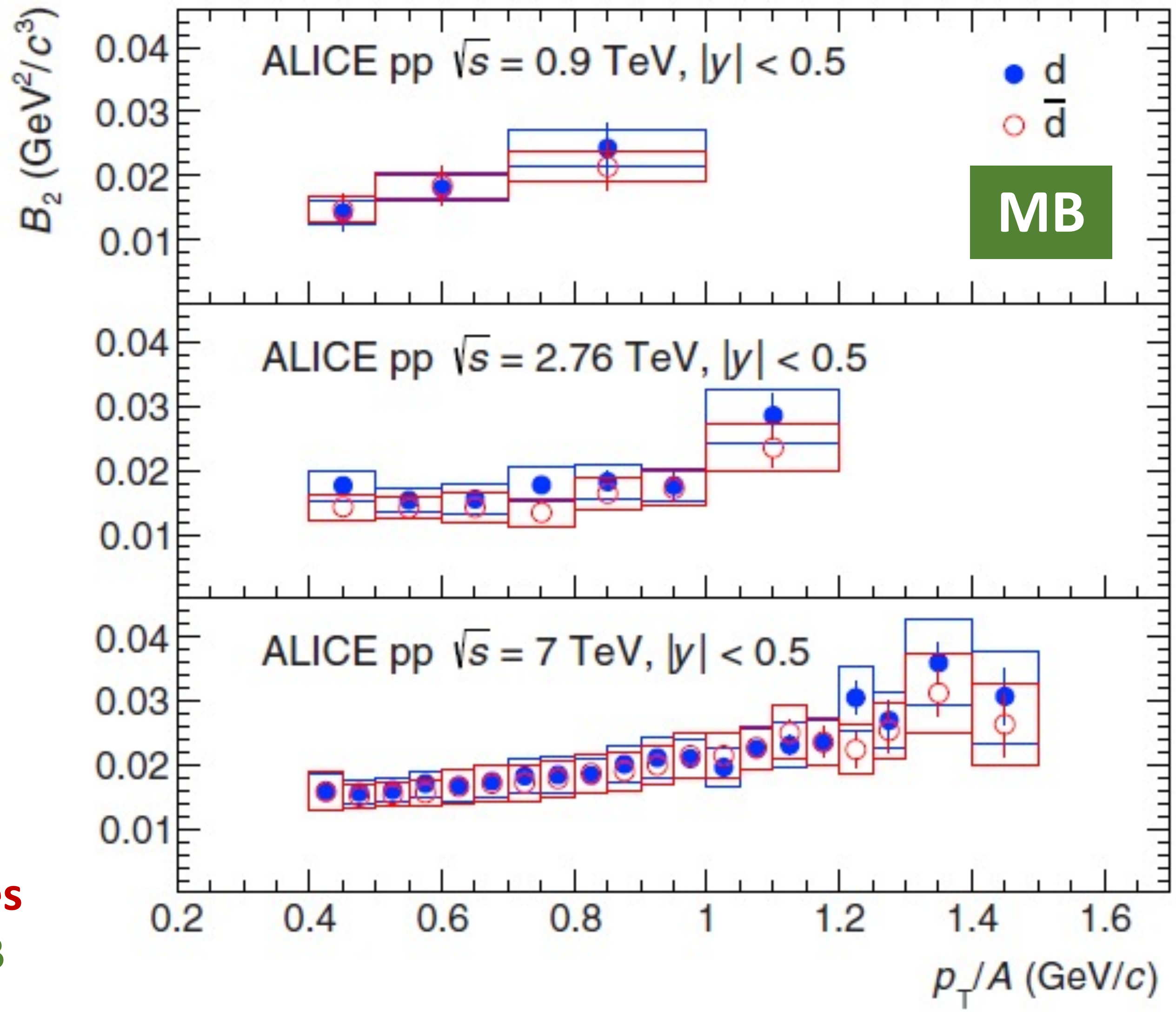


Simple coalescence models (II)

Phys. Lett. B 794 (2019) 50–63



Phys. Rev. C 97, 024615 (2018)



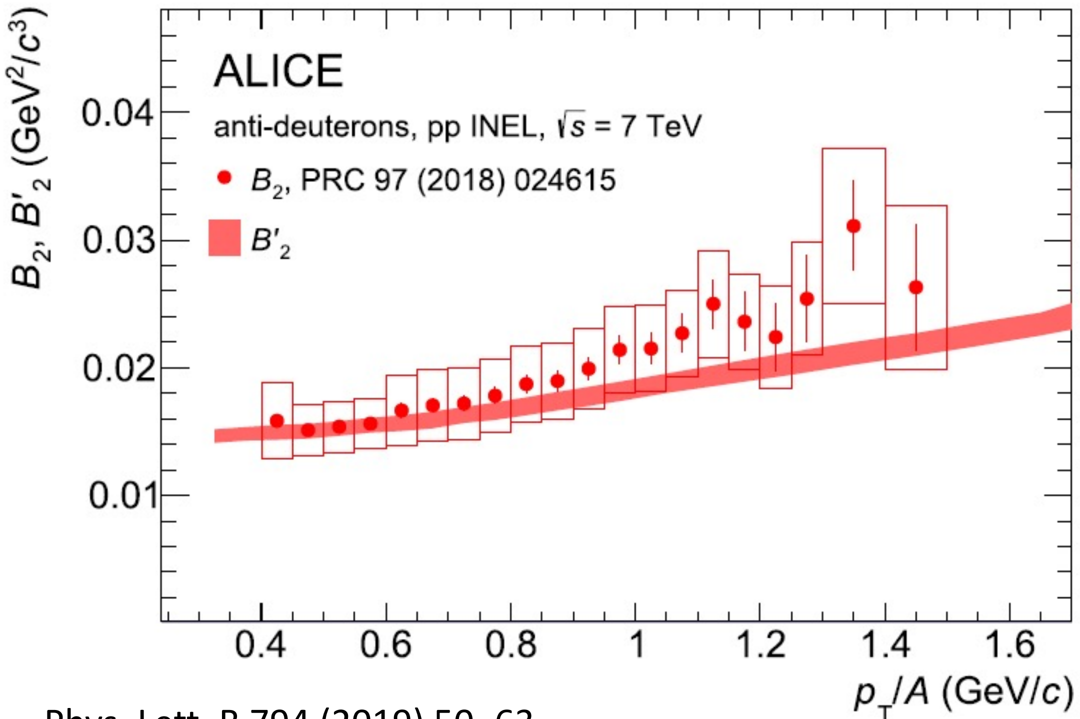
- B_A vs p_T is **flat** in small systems as pp → **in mult. classes**
- B_A vs p_T is **increasing** with increasing pT in pp → **in MB**

Simple coalescence models (III)

An **increasing B'_2** for the integrated-multiplicity class can be obtained from a **flat B_2** in each **multiplicity** class with

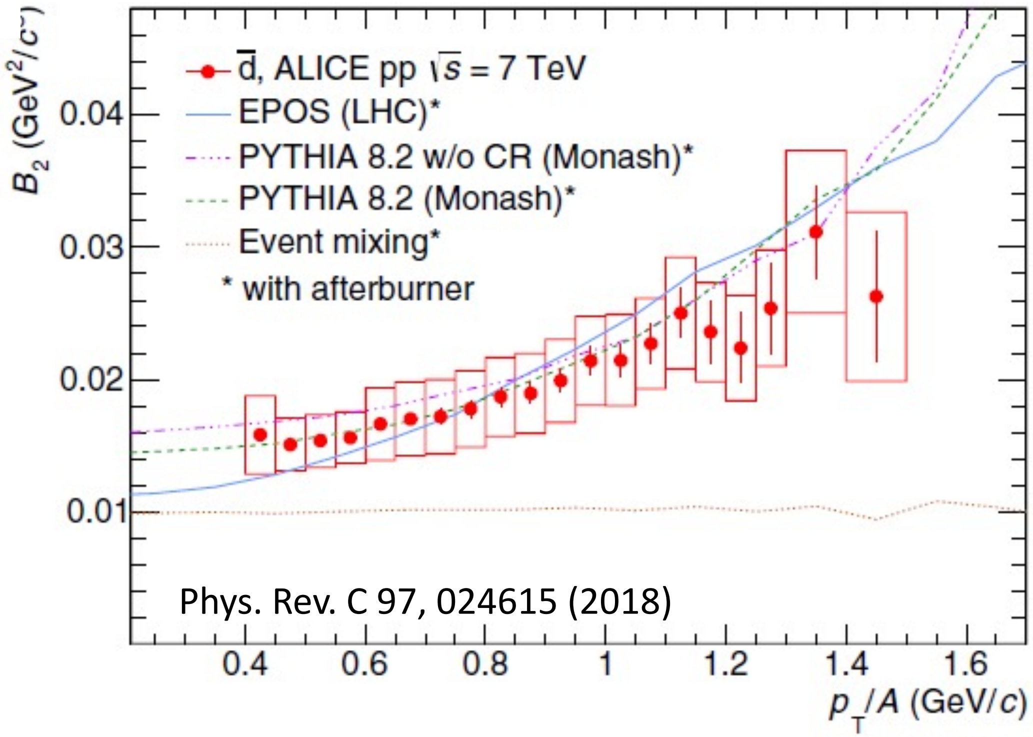
$$B'_2 = B_2 \frac{\sum_{i=0}^{n} (N_i/N)\, S_{p,i}^2}{\left[\sum_{i=0}^{n} (N_i/N)\, S_{p,i}\right]^2} \quad \text{with } S_{d,i} = B_2 S_{p,i}^2$$

Rise of B_2 : consequence of the **hardening** of the **proton spectra** with increasing multiplicity + hard scattering effect (high p_T)



Phys. Lett. B 794 (2019) 50–63

Rising trend with p_T reproduced by QCD-inspired models coupled to coalescence-based afterburner > only momentum correlations between nucleons are considered ($\Delta p < p_0$)



Phys. Rev. C 97, 024615 (2018)

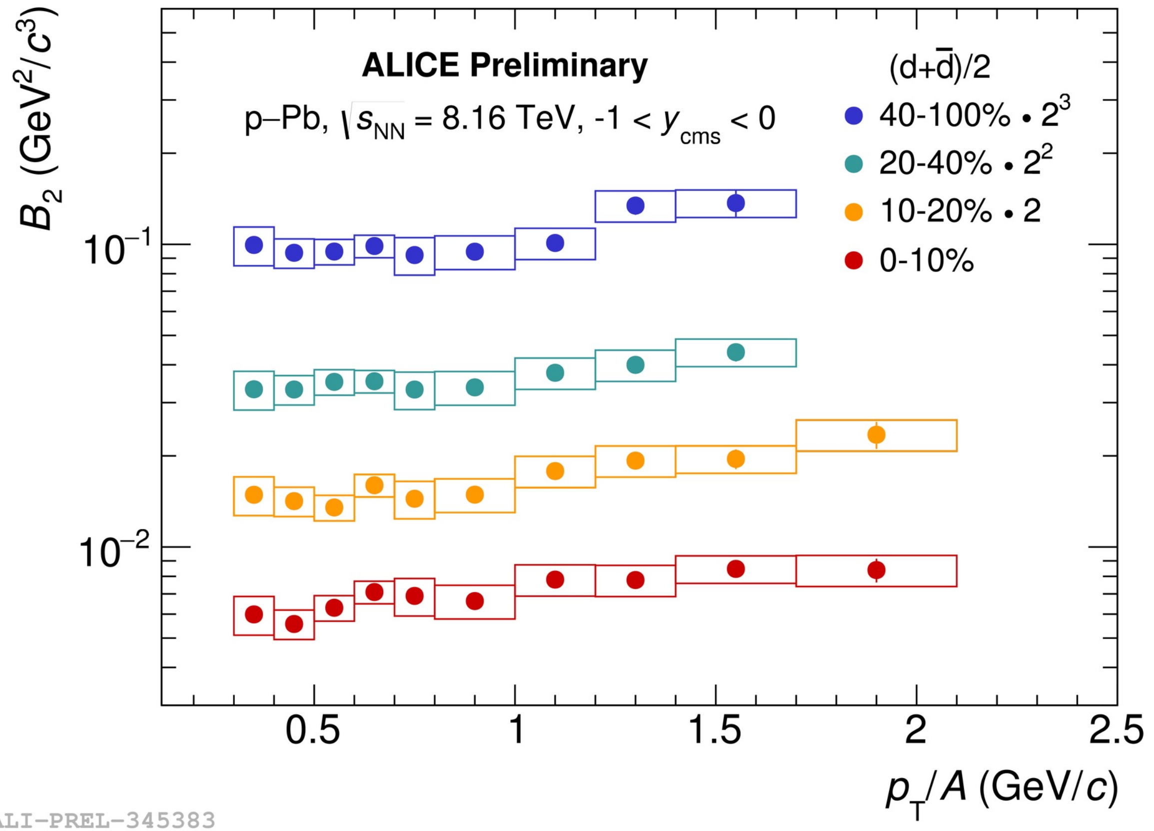
- B_2 is flat only in event mixing: uncorrelated pairs of nucleons
- Rising trend with p_T : hard scattering effect vs AA collisions where related to collective flow

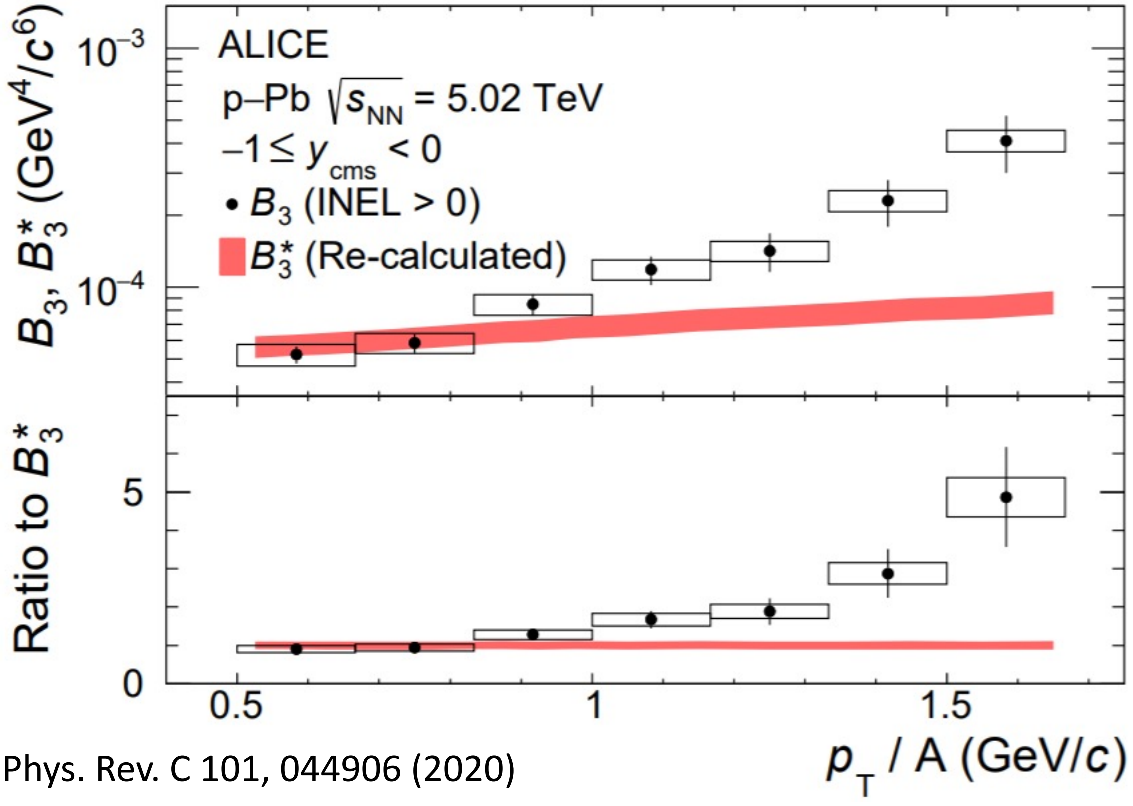
SIMPLE COALESCENCE IS A GOOD APPROXIMATION FOR d IN pp

Simple coalescence models (IV)

p–Pb collisions

B_2 weakly rising with p_T/A also in p–Pb collisions in mult. classes
> trend of B_2 in MB most probably explained by kinematic effect





Phys. Rev. C 101, 044906 (2020)

Rising trend of B_3 with p_T/A cannot be explained by simple coalescence hypothesis

MORE SOPHISTICATED COALESCENCE IS NEEDED FOR A=3 NUCLEI, CONSIDERING VOLUME DEPENDENCE

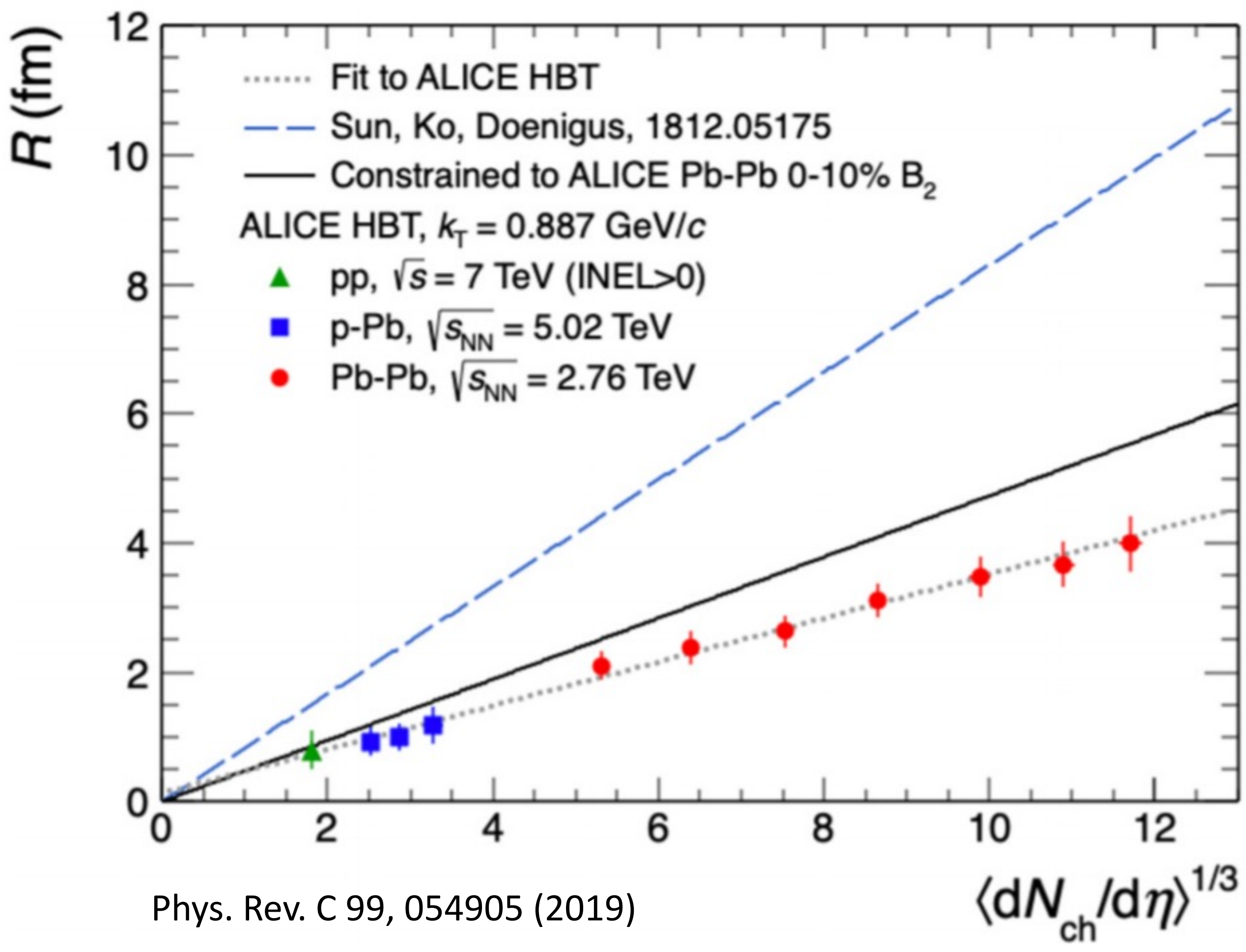
Advanced coalescence models

- **Space-time** distribution considered
- Coalescence probability given by **overlap** between **nucleus wave-function** (Wigner formalism) and **nucleon phase-space distribution**

  [Sun et al., Phys Lett B 792 (2019) 132-137]

- System size: **HBT radius R**
- R vs multiplicity: $R = a \langle dN/d\eta \rangle^{1/3} + b$

- When looking at B_A vs mult. the parameterization of R plays a crucial role in the predictions

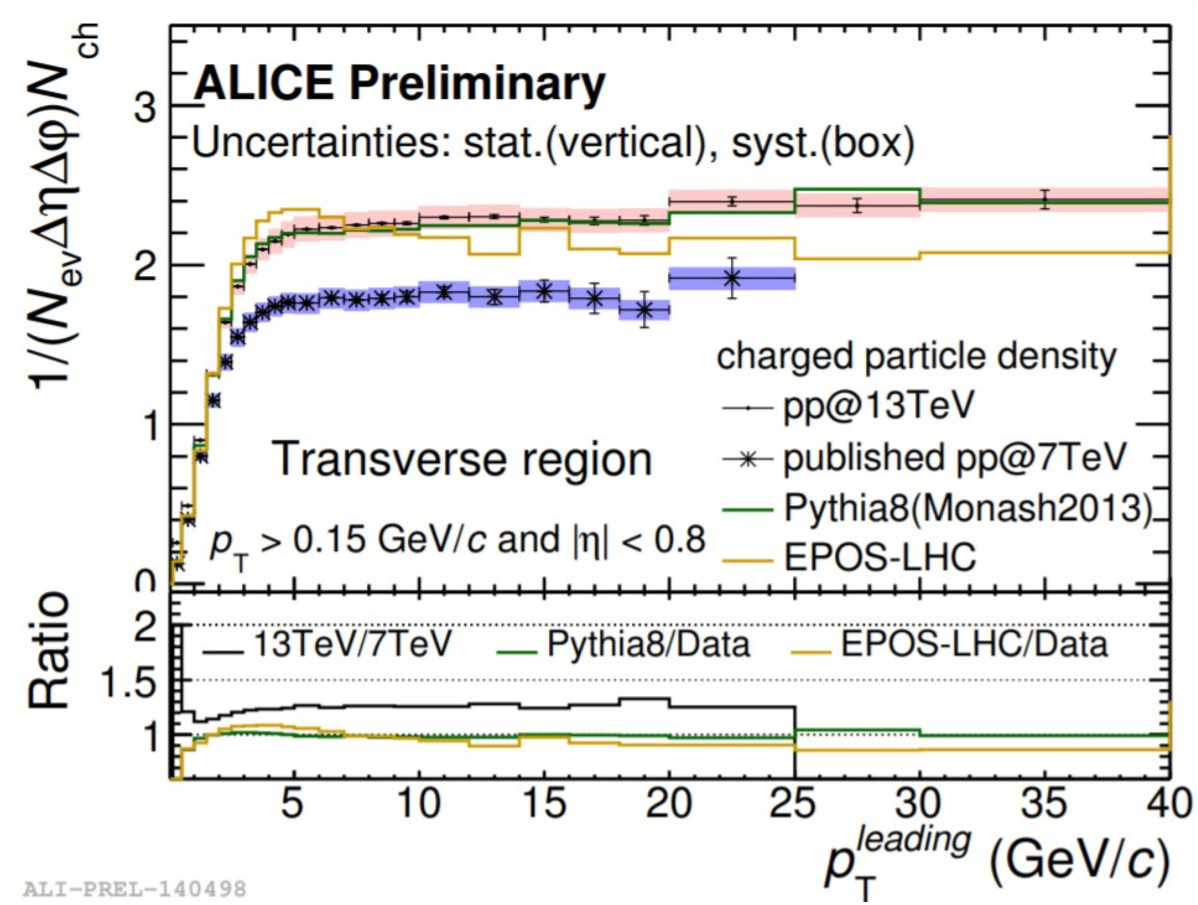


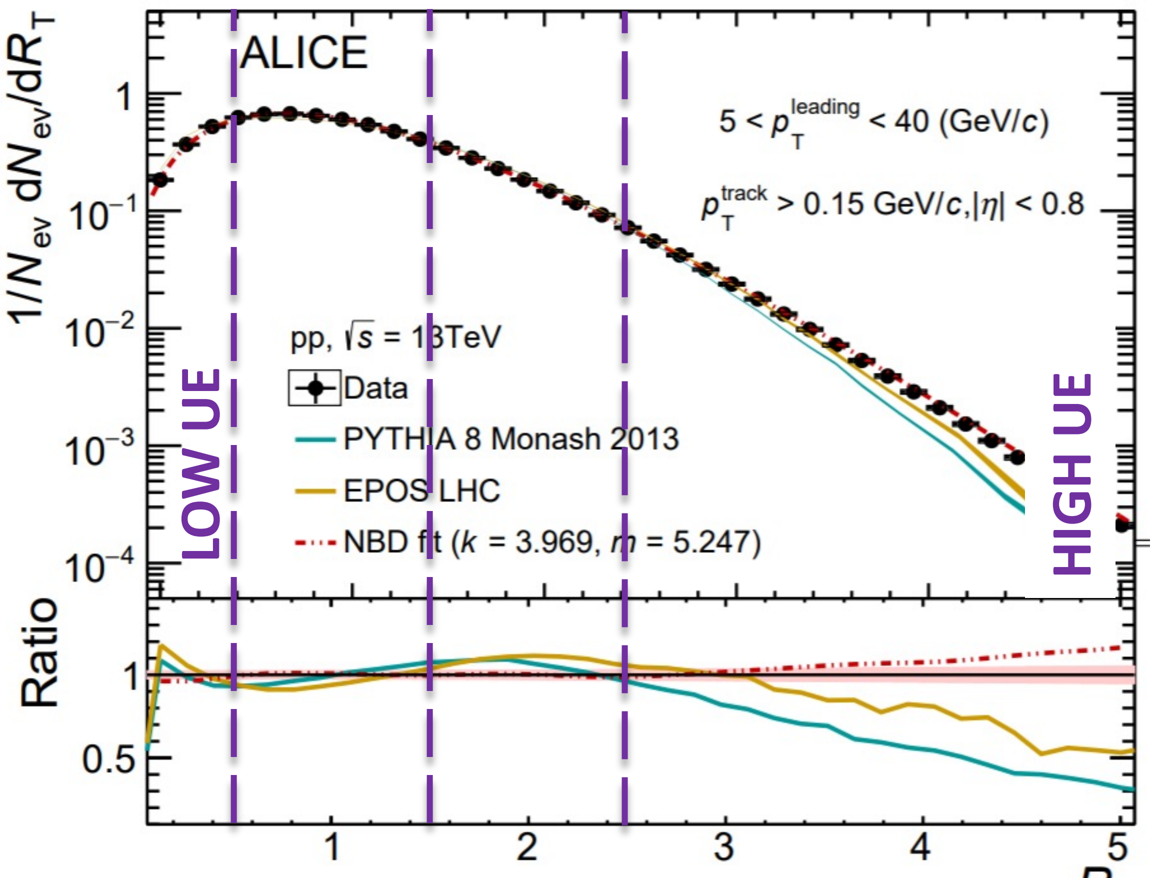
Phys. Rev. C 99, 054905 (2019)

Characterize the UE

- Plateau region (jet pedestal): $5 < p_T^{leading} < 40$ GeV/c

- Several intervals of R_T are selected in order to distinguish between low and high UE activity

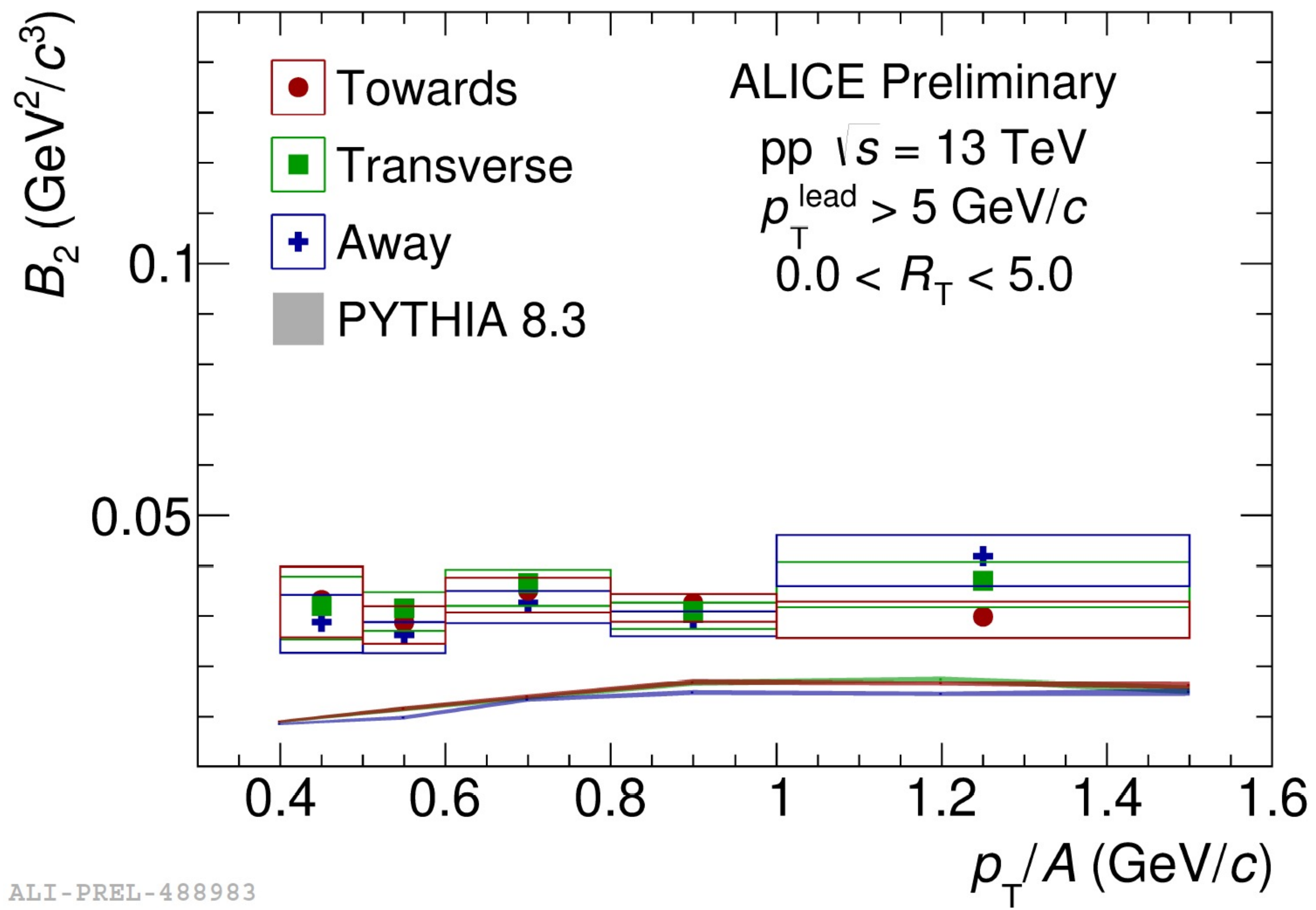




10.1007/JHEP04(2020)192

B_2 in the R_T–integrated case

New!



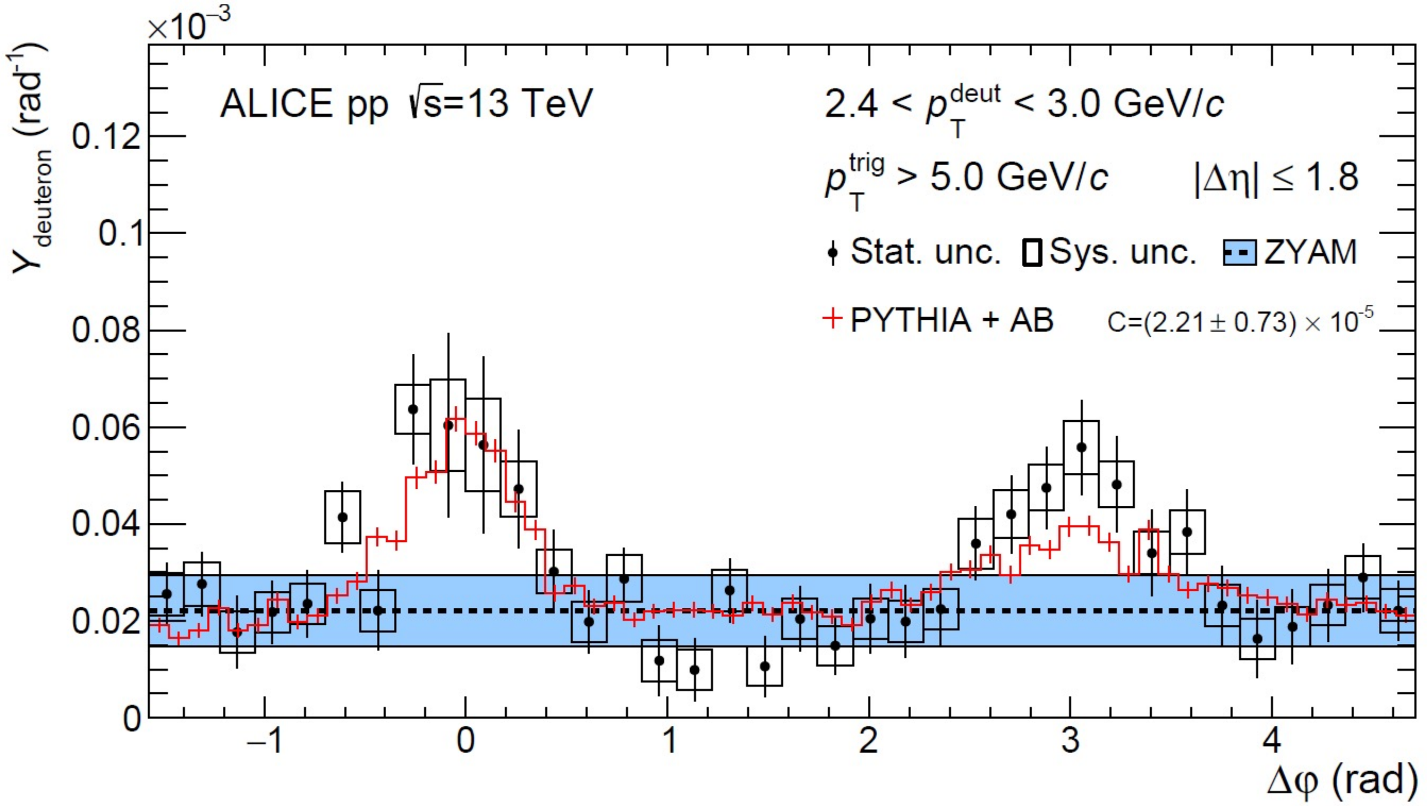
- B_2 parameter flat vs p_T/A → in agreement with simple coalescence
- Similar values of B_2 for Towards & Transverse regions → against naive expectations
- Comparison with Pythia 8.3 (including d production via coalescence and reactions)

- p_T-dependence & ordering are reproduced by simulations, but not the magnitude

pp @ 13 TeV

d production in jets (II)

- Insight on (anti)d production in smaller phase space available in jet fragmentation
- High-p_T (> 5 GeV/c) trigger particle used as jet proxy
- Measurement of (anti)d yields within $|\Delta\phi| < 0.7$ rad
  - Uncorrelated contribution subtracted with ZYAM (zero yield at minimum)
- (Anti)d yields is found to be 2.4–4.8 standard deviations above uncorrelated background ($p_T^d > 1.35$ GeV/c)
- Good agreement with PYTHIA calculation + coalescence afterburner



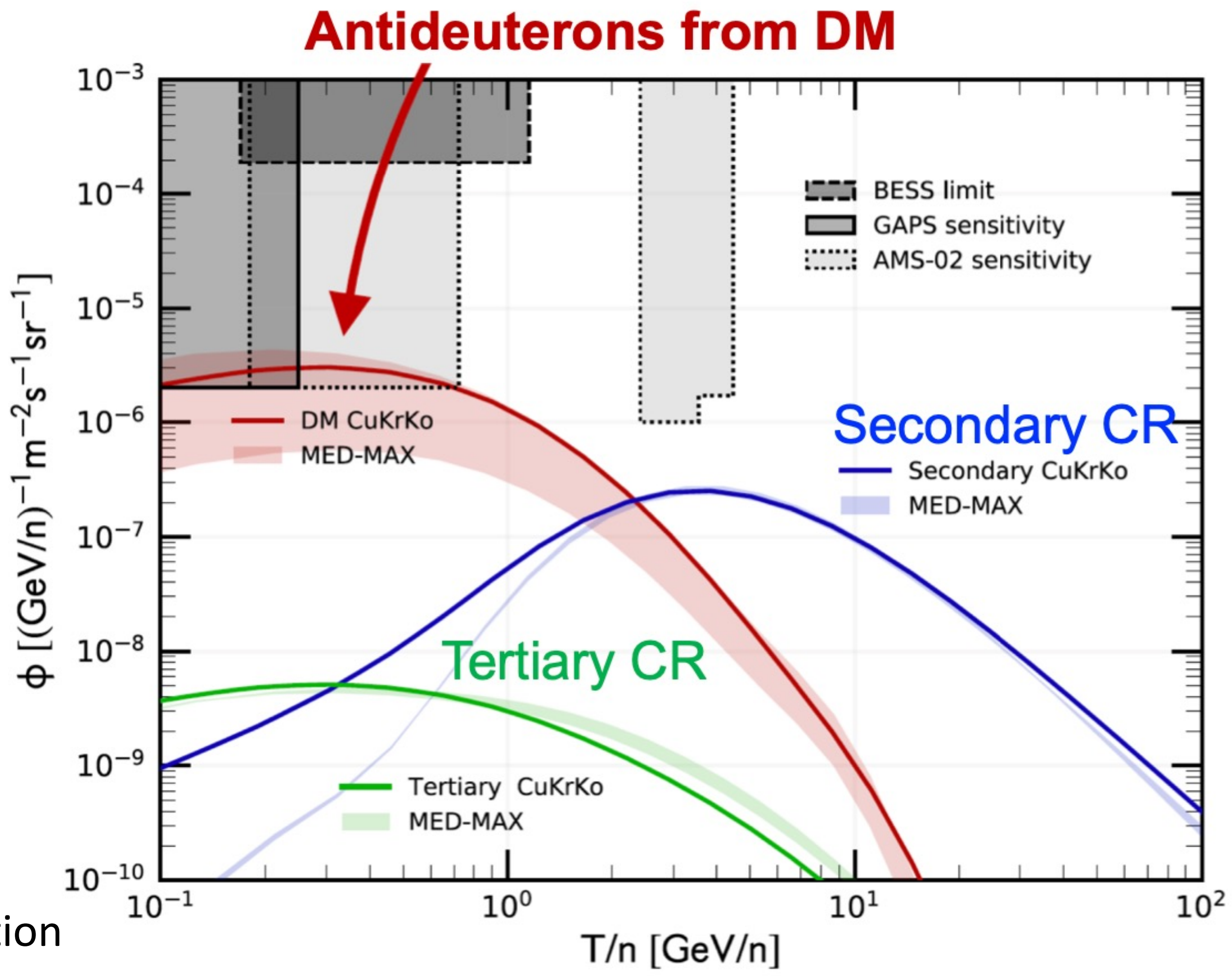
pp @ 13 TeV

arXiv:2011.05898 [nucl-ex]

CR antinuclei flux

- Search for Dark Matter through antinuclei probe is chased by several experiments (GAPS, AMS, BESS, ...)
- At low energy signal is enhanced wrt background
- Background estimate of CR antinuclei can be provided by accelerator experiments

✅ constrain the coalescence models with light (anti)nuclei measurements allows us to reduce the error on source function



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