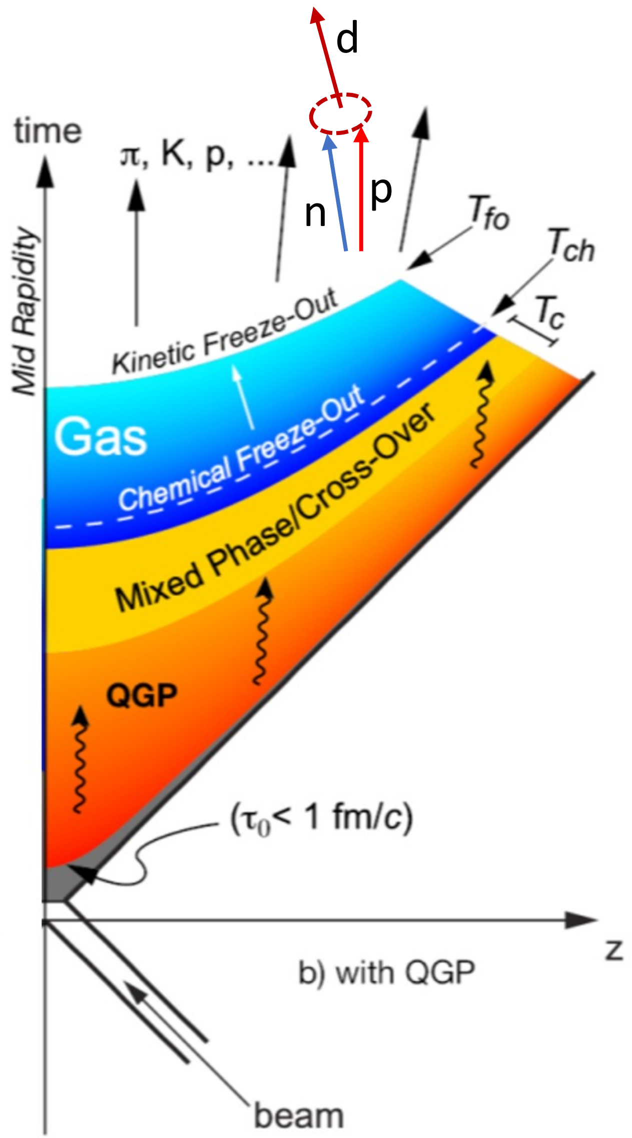
Experimental overview on light (anti)(hyper)nuclei production at the LHC

Chiara Pinto
(CERN)

6 June 2024

Production of (anti)nuclei at the LHC



- At LHC energies ($\sqrt{s} \sim$ 1–13 TeV) same amount of matter and anti-matter is measured[1] ($\mu_B \sim 0$)
- Production measurements useful to investigate the **hadronization mechanism**
- Three 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
  - relativistic **hydrodynamics** + coalescence afterburner → survival of bound states in hadron gas phase with intense rescattering
- Interesting also for astrophysics applications
  - **Cosmic ray** fluxes of antinuclei → dark matter searches
  - **Particle interactions** → neutron stars and equation of state

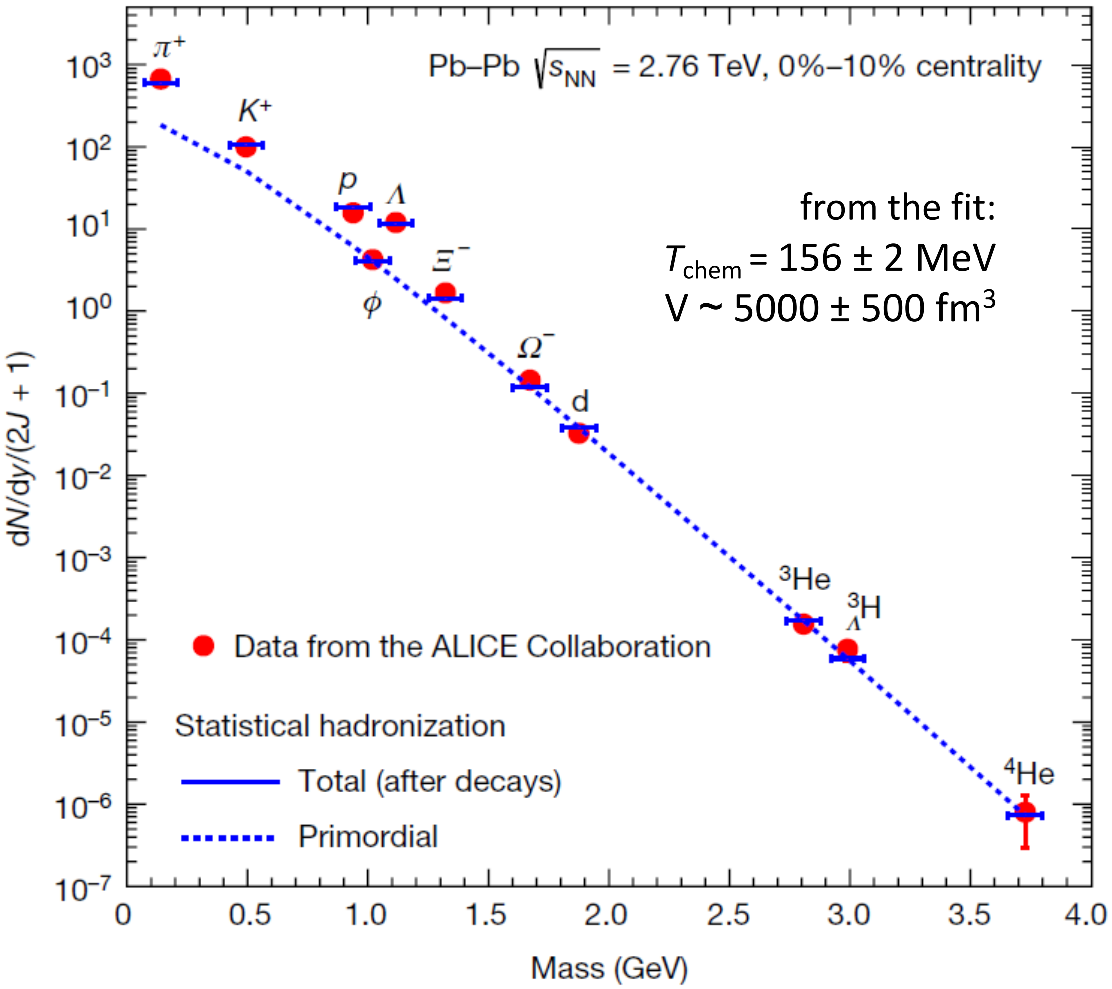
[1] ALICE Collaboration, arXiv:2311.13332

Modelling the production of (anti)nuclei

Statistical models (SHMs)

- Hadrons emitted from a system in statistical and chemical equilibrium
- 3 free parameters: V, T_{chem}, μ_B
  – Particle ratios → volume V cancels
  – Baryochemical potential μ_B fixed by $\bar{p}$/p ratio
  → one remaining parameter T_{chem}
- dN/dy ∝ exp(-m/T_{chem})

  ⇒ Nuclei (large m): large sensitivity to T_{chem}
- Typically used in Pb—Pb, for small systems the canonical ensemble is needed (CSM) → exact conservation of B, Q and S is required only in the correlation volume (V_c)



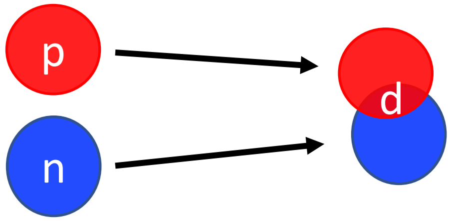
B:baryon number, Q:charge, S: strangeness content

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

Modelling the production of (anti)nuclei

Coalescence models

- 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

Modelling the production of (anti)nuclei

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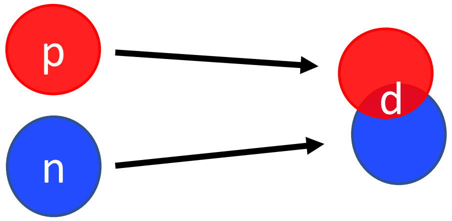

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- Microscopic description

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

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

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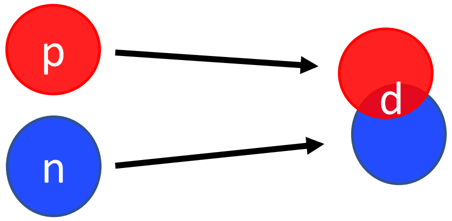
Modelling the production of (anti)nuclei

Coalescence models



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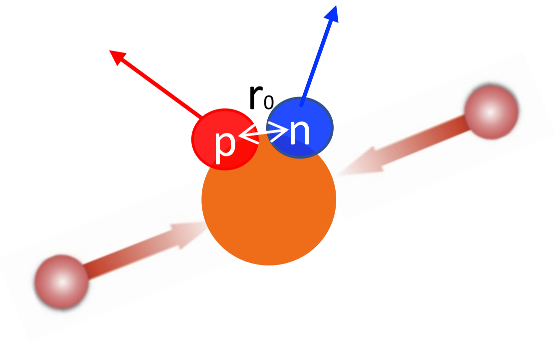
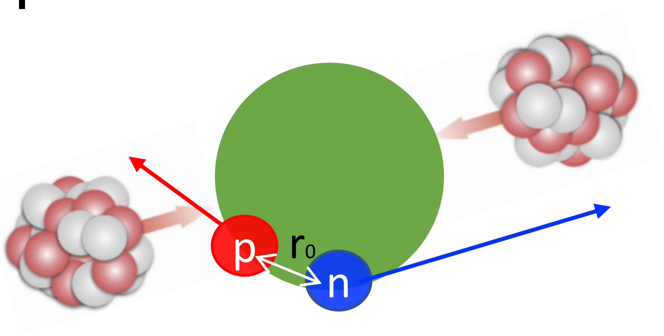
[1] PRC 99 (2019) 024001
[2] PRL 123 (2019) 112002
[3] PRC 96 (2017) 064613



pp[1], p—Pb[2]: r_0 = 1–1.5 fm

Small distance in space
(Only momentum correlations matter)

⟺ large B_A

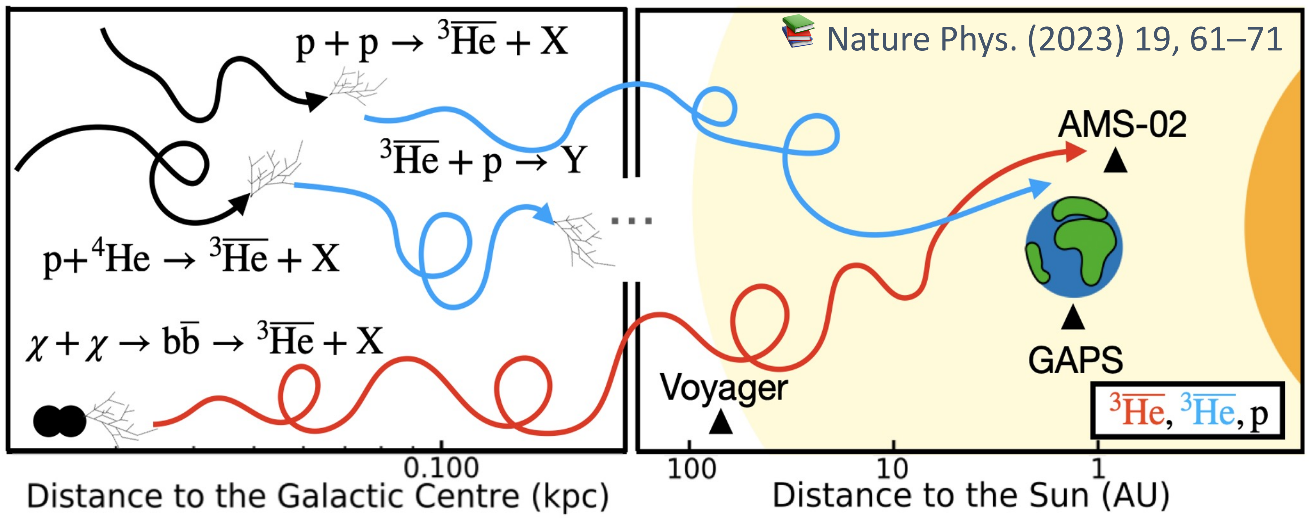


Pb—Pb[3]: r_0 = 3–6 fm

Large distance in space
(Both momentum and space correlations matter)

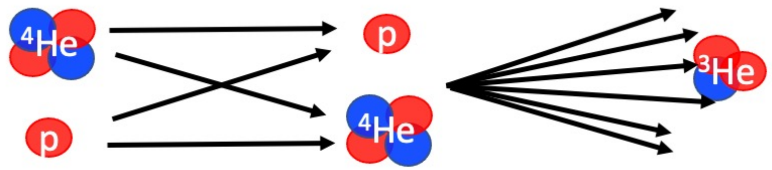
⟺ small B_A

Astrophysics applications: Dark Matter



Antinuclei production in our Galaxy:

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

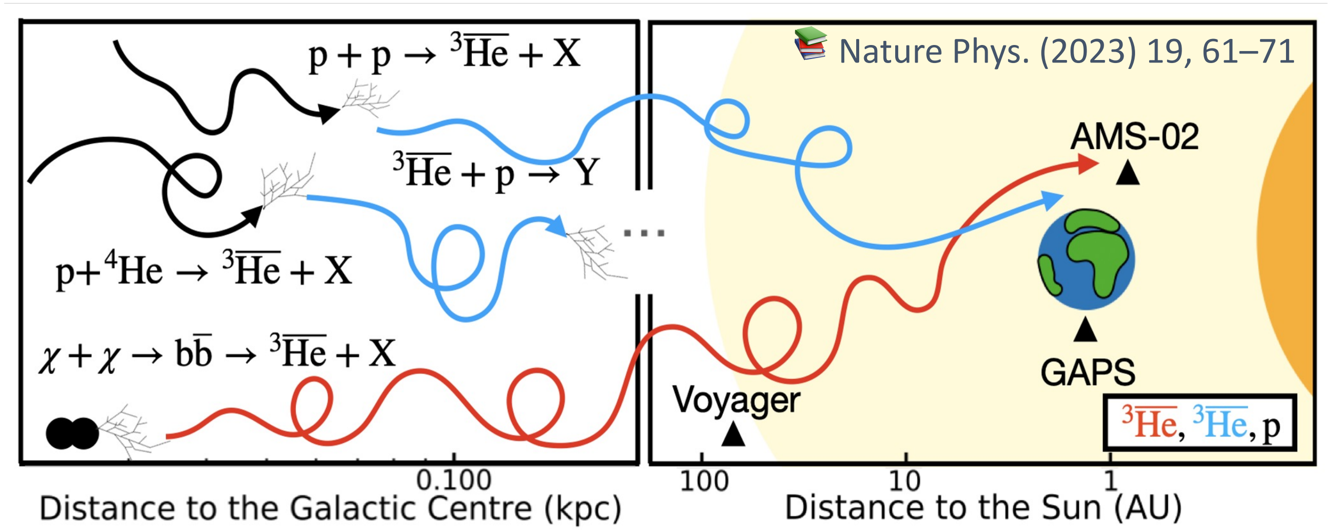


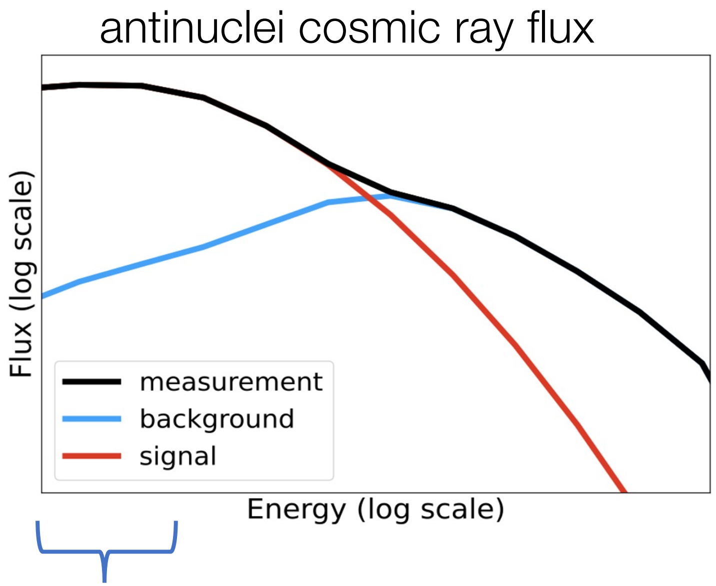
Primary cosmic ray (90% p, 8% ${}^4He$)

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

- dark-matter annihilation processes

Astrophysics applications: Dark Matter





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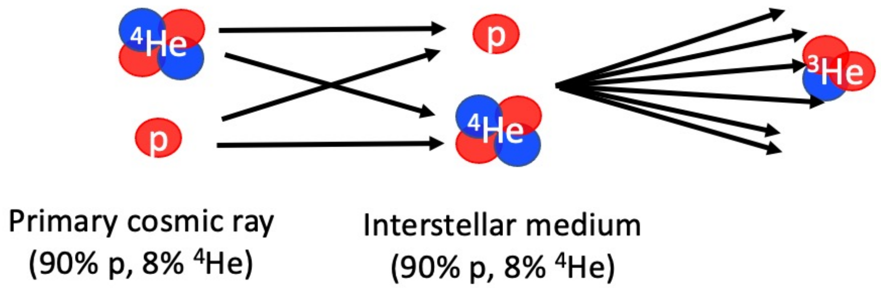
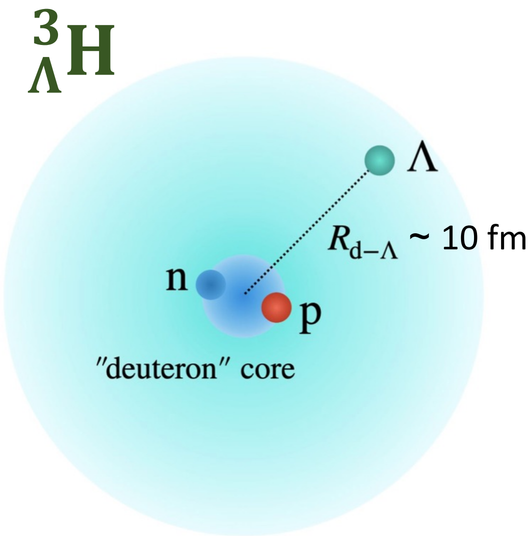


- dark-matter annihilation processes

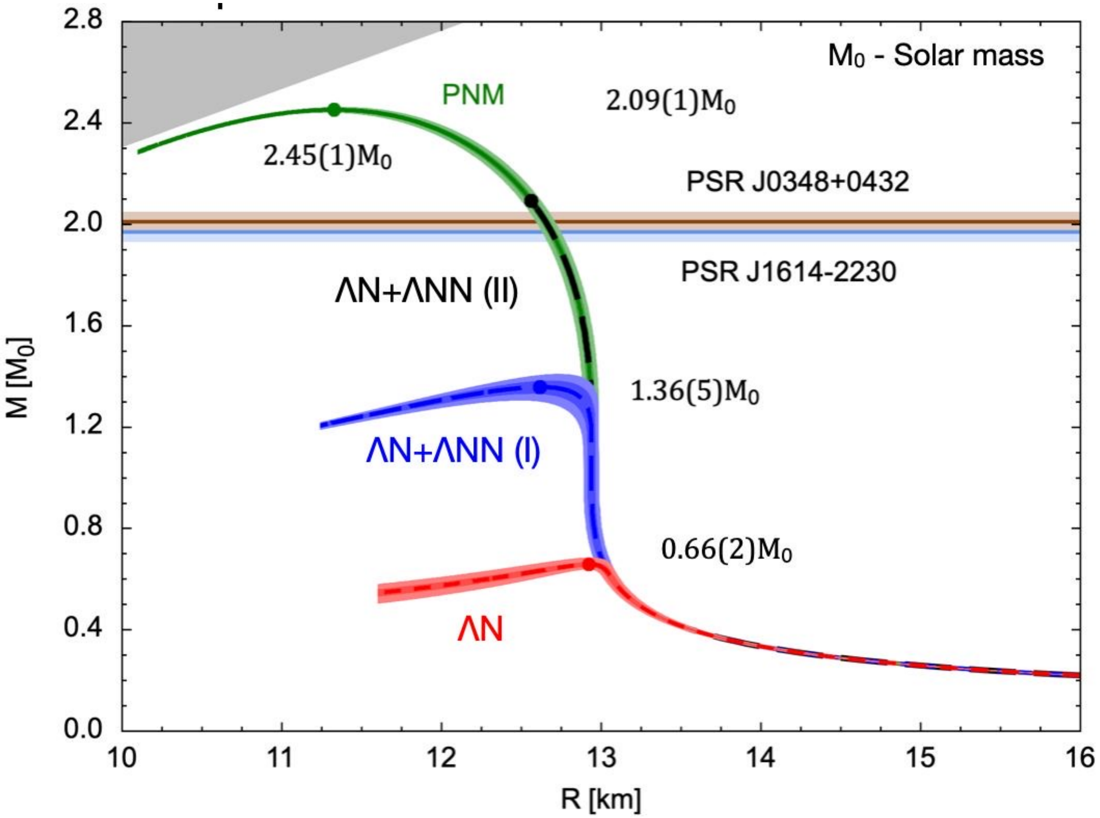
- High Signal/Noise ratio (~$10^2 - 10^4$) at low E_{kin} expected by models
- To correctly interpret any future measurement, we need precise knowledge of
  1. production of antinuclei
  2. annihilation

Astrophysics applications: neutron stars



- At the LHC, $^{3}_{\Lambda}\mathrm{H}$ has been measured in pp, p-Pb, and Pb–Pb collisions
- $^{3}_{\Lambda}\mathrm{H}$ powerful probe for investigating the nucleon–Λ interaction
- Crucial for the calculation of the equation of state (EoS) and the neutron star mass-radius relation

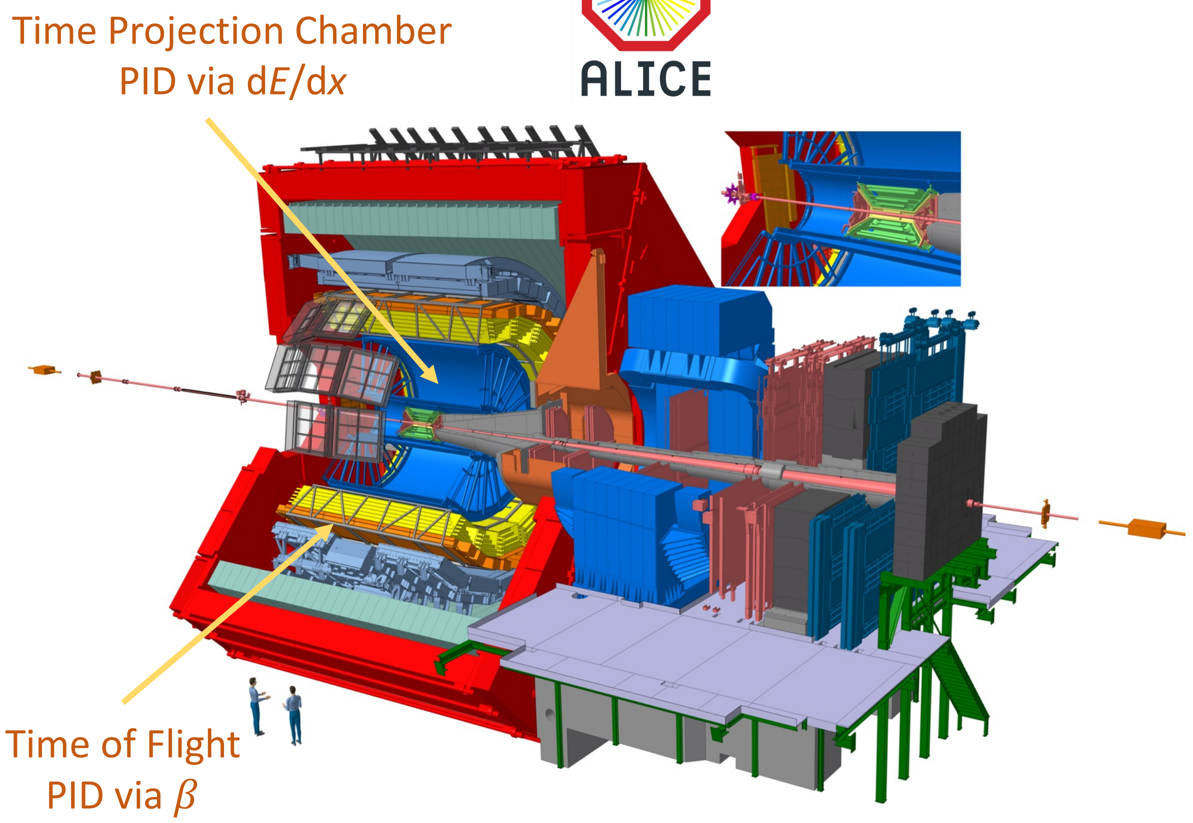
D. Lonardoni et al., PRL 114, 092301 (2015)



- 3-body hyperon-nucleon interaction is key in the softening of the EoS and the consequent reduction of the predicted maximum mass
- different results on the maximum mass not necessarily incompatible with the observed neutron stars

Experimental efforts at the LHC

Experimental efforts at the LHC



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

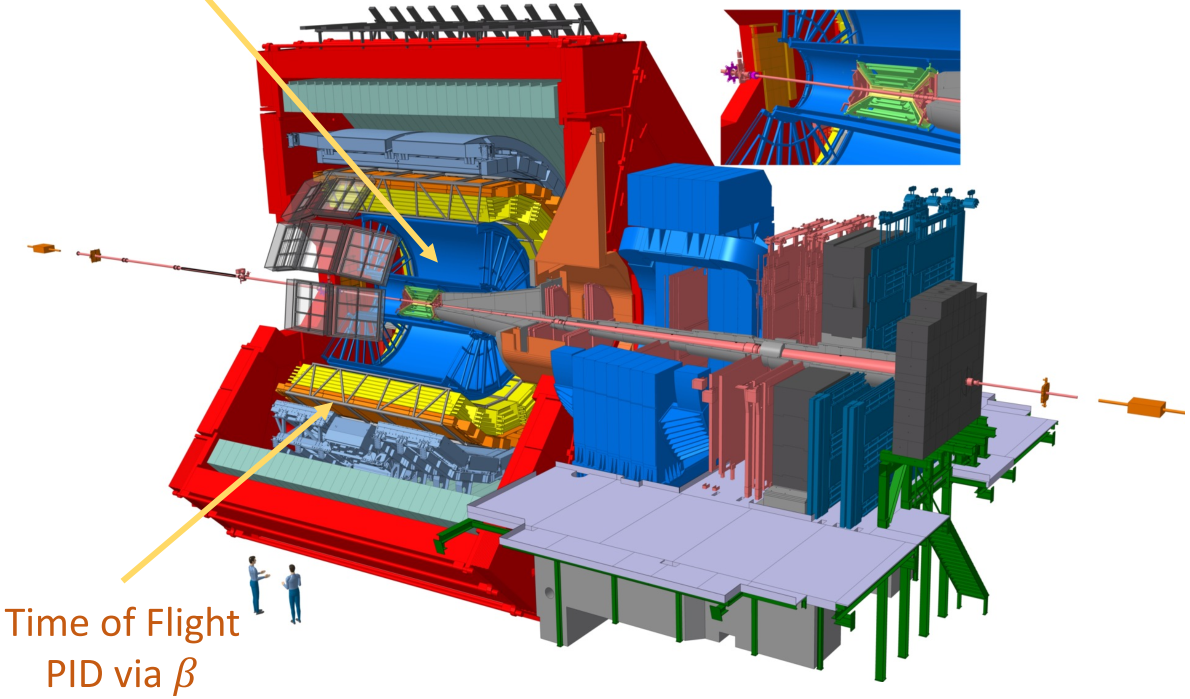
- excellent tracking & PID capabilities over broad p range
- low material budget

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

Experimental efforts at the LHC

ALICE

Time Projection Chamber
PID via dE/dx



Time of Flight
PID via β

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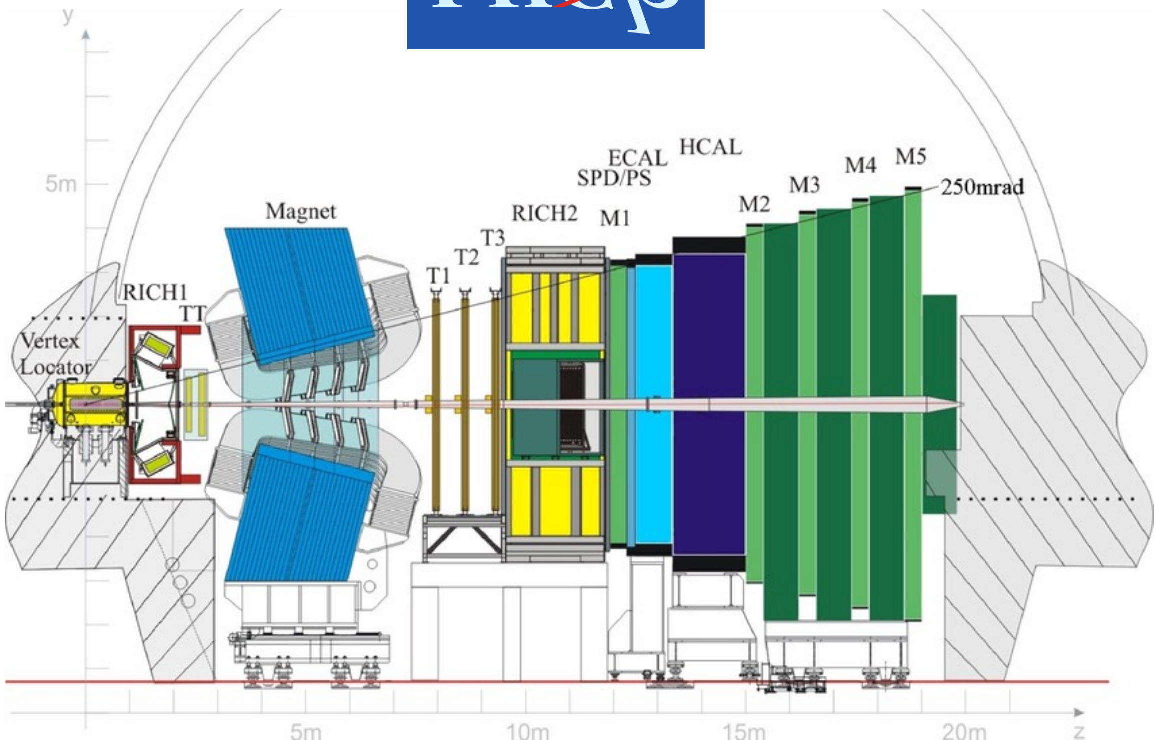
LHCb



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

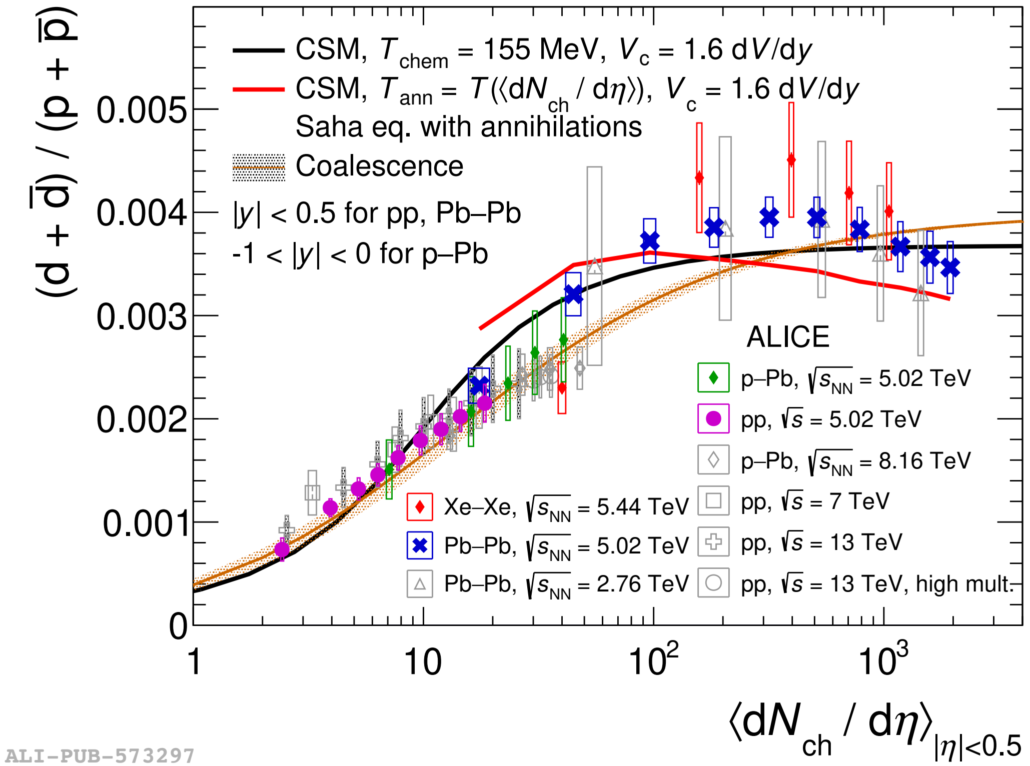
- excellent vertexing and PID separation for K, π and p with O(10) GeV/c
- covering forward rapidity and with SMOG → several energies & systems

→ recently joined the nuclei business!

Testing production models with A=2

Testing production models with A=2

ALICE Collaboration, arXiv:2405.19826



- 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 (CSM-I) or with **annihilation** temperature depending on multiplicity[2] (CSM-II)
- 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

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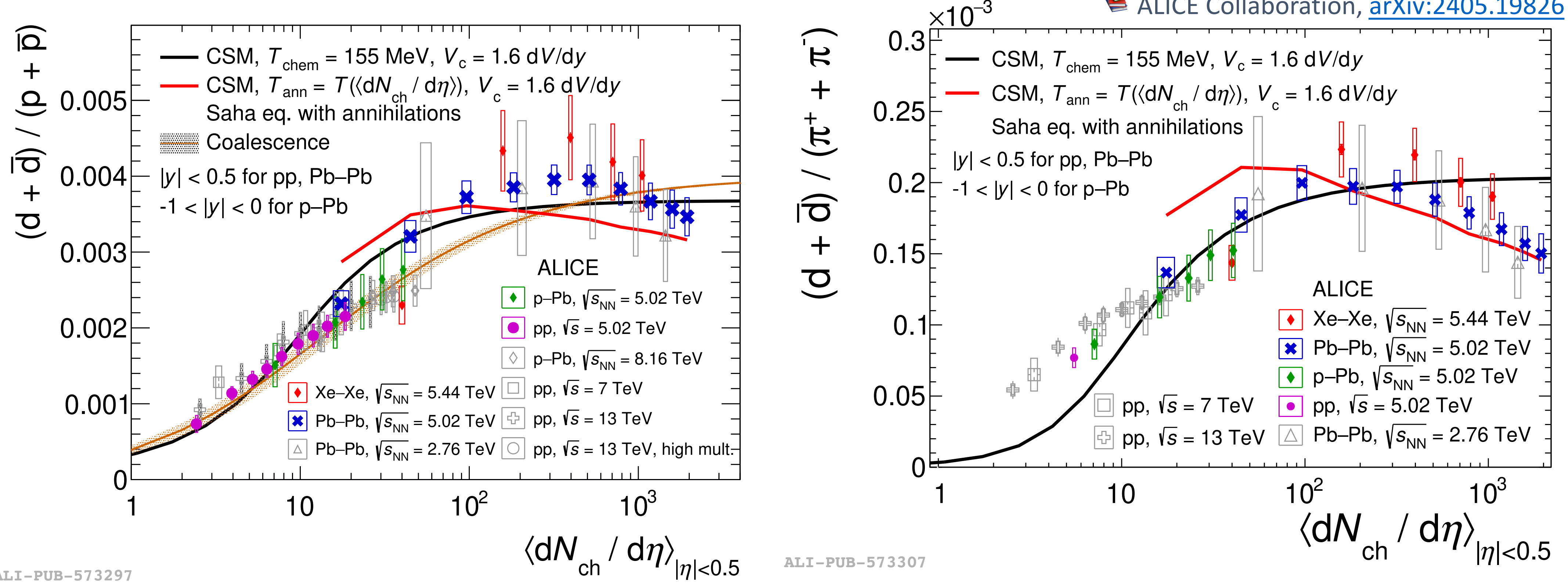

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- CSM-I at low multiplicity does not reproduce d/π ratio, but CSM-II at high multiplicity catches the decreasing trend

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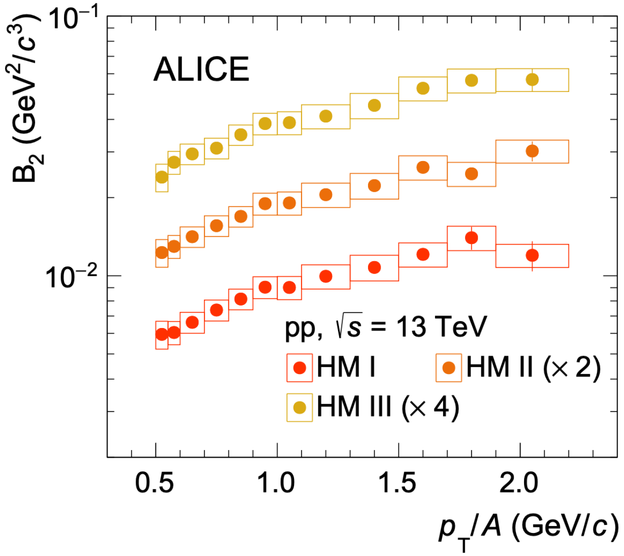
Testing coalescence model using B_2

- Important observable in accelerator measurements: coalescence parameter B_A

$$B_A\left(p_T^p\right) = \frac{1}{2\pi p_T^A}\frac{d^2N_A}{dy dp_T^A} \bigg/ \left(\frac{1}{2\pi p_T^p}\frac{d^2N_p}{dy dp_T^p}\right)^A$$



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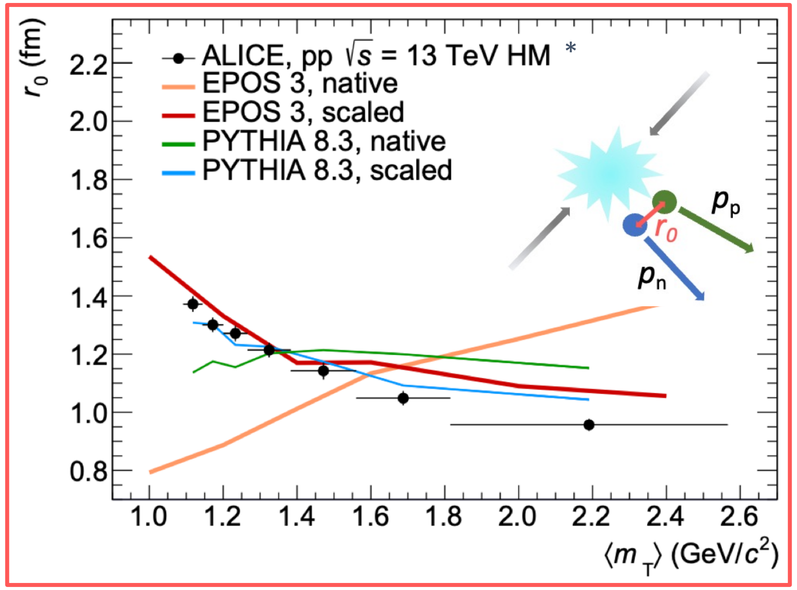
- Comparison to state-of-the-art coalescence models based on Wigner formalism showed that there are 2 key ingredients:
  - *emission source size*



*ALICE Collaboration, PLB 811 (2020) 135849
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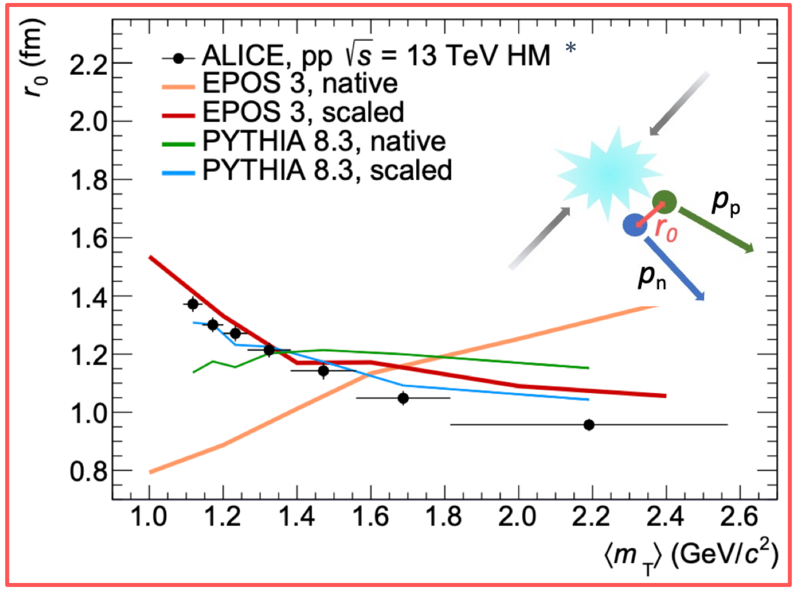
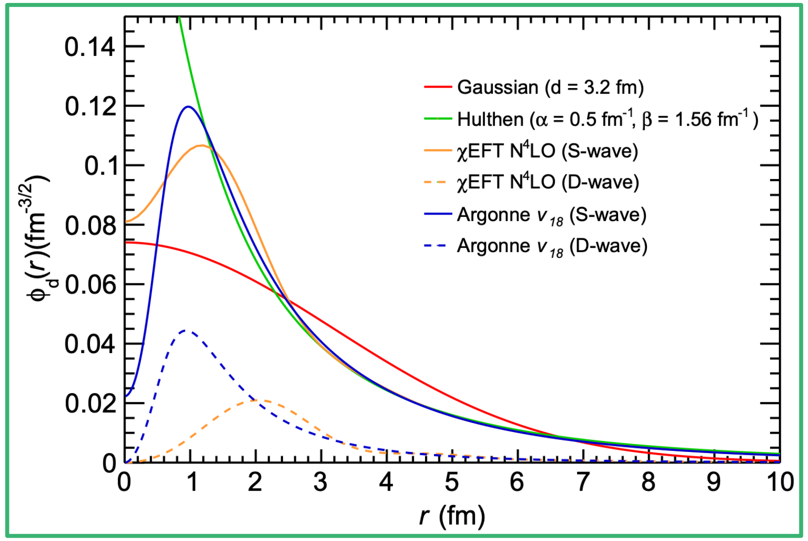
  - *emission source size*
  - *deuteron wave function*





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- Comparison to state-of-the-art coalescence models based on Wigner showed that there are 2 key ingredients:
  - *emission source size*
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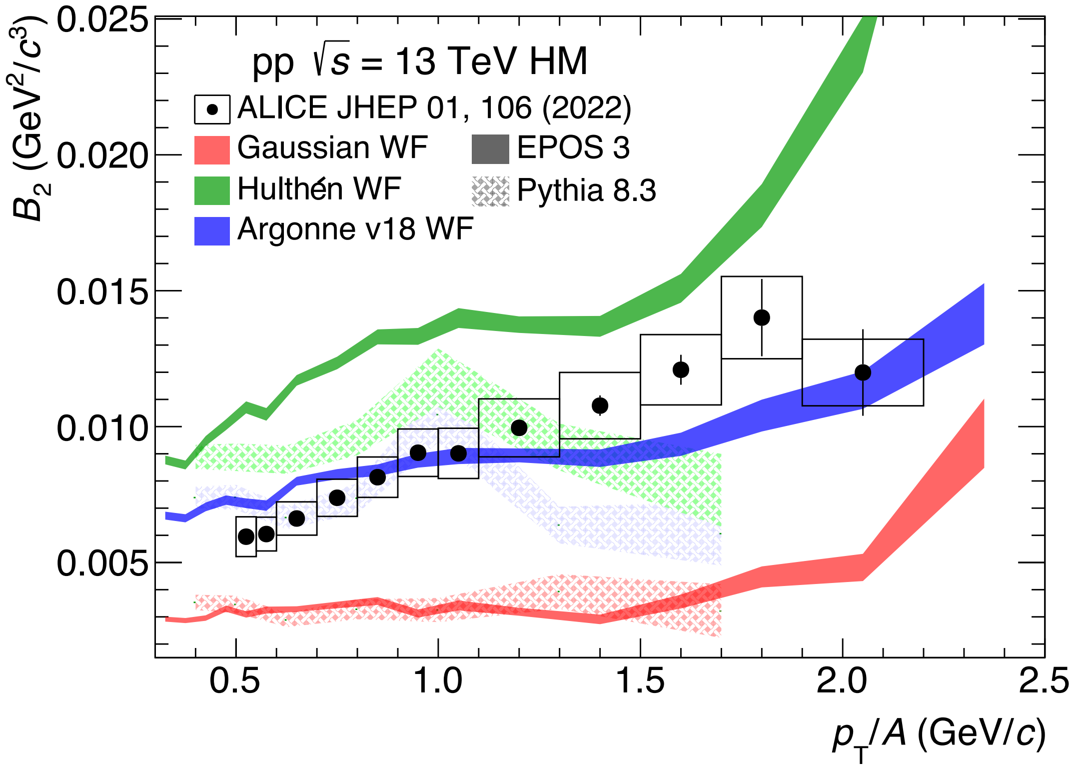

State-of-the-art coalescence model describes deuteron momentum distributions and coalescence parameter, using realistic WF and measured r_0!

$\leftrightarrow$

Production measurements can be used to constrain the nuclear wavefunction!

* ALICE Collaboration, PLB 811 (2020) 135849
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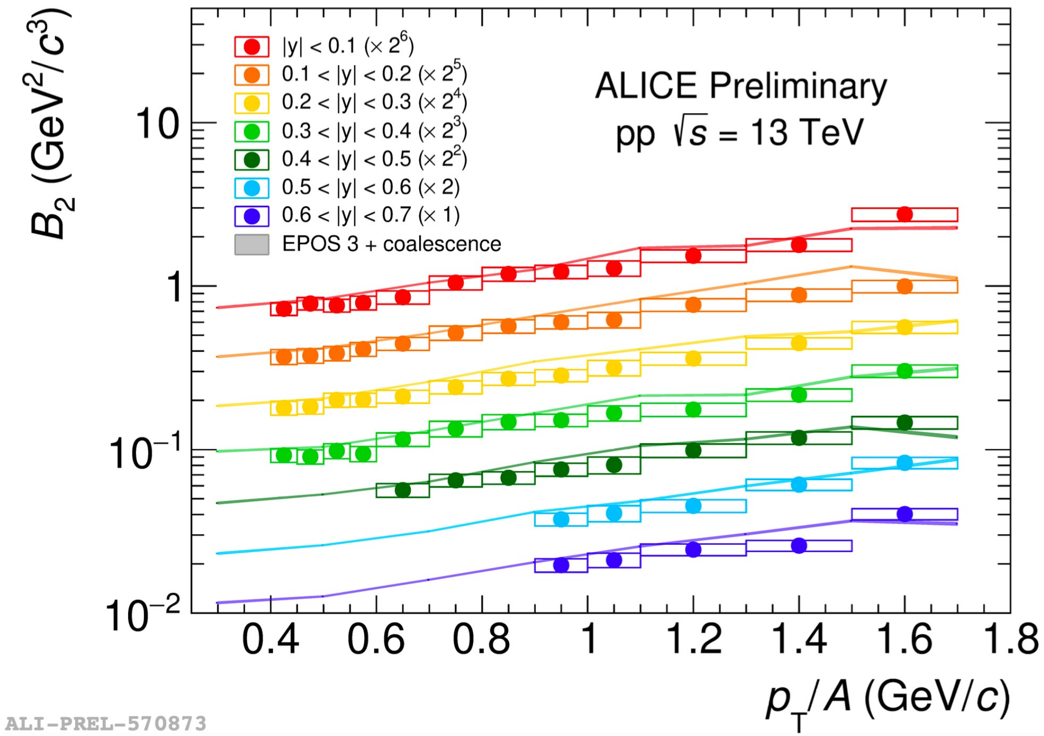
B_2 vs rapidity with ALICE



- ALICE measurements cover the midrapidity region (|y|<0.5), while astrophysical models extrapolate to forward region
- Current acceptance of ALICE detector allows one to extend the measurement of antinuclei up to |y| = 0.7

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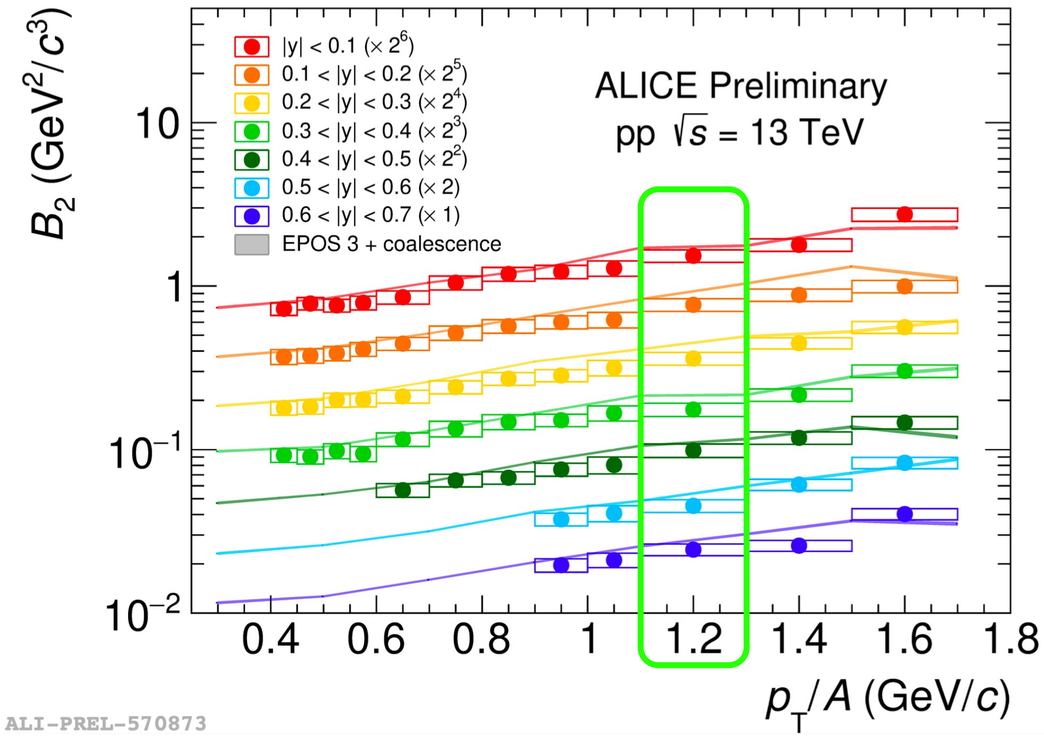

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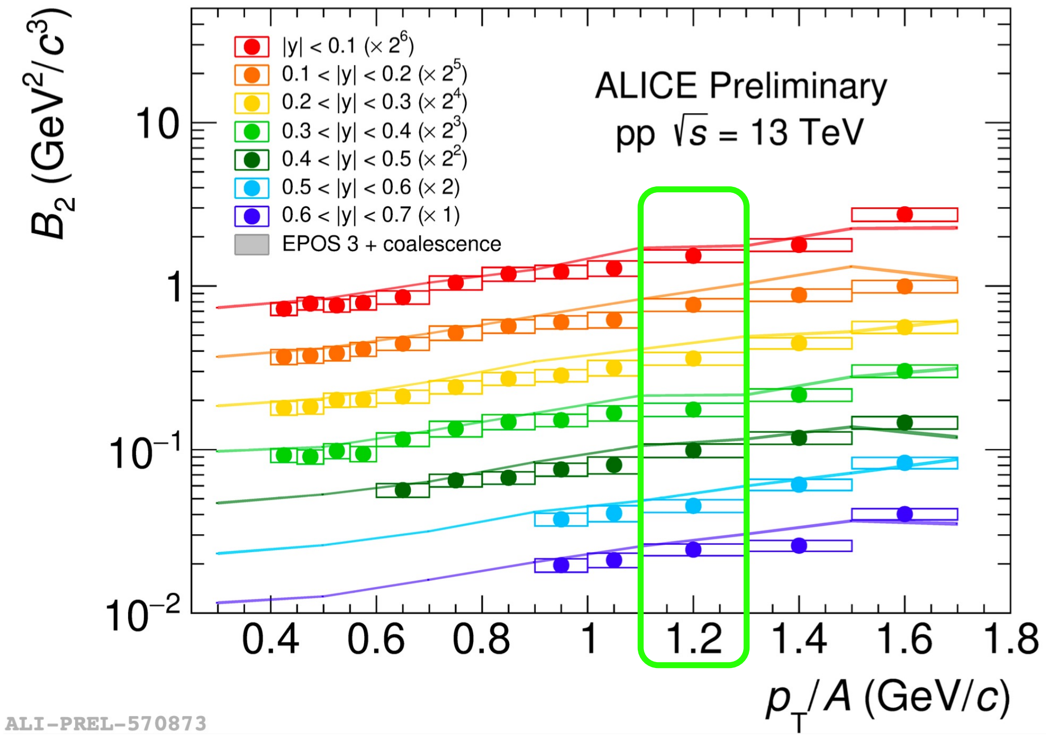

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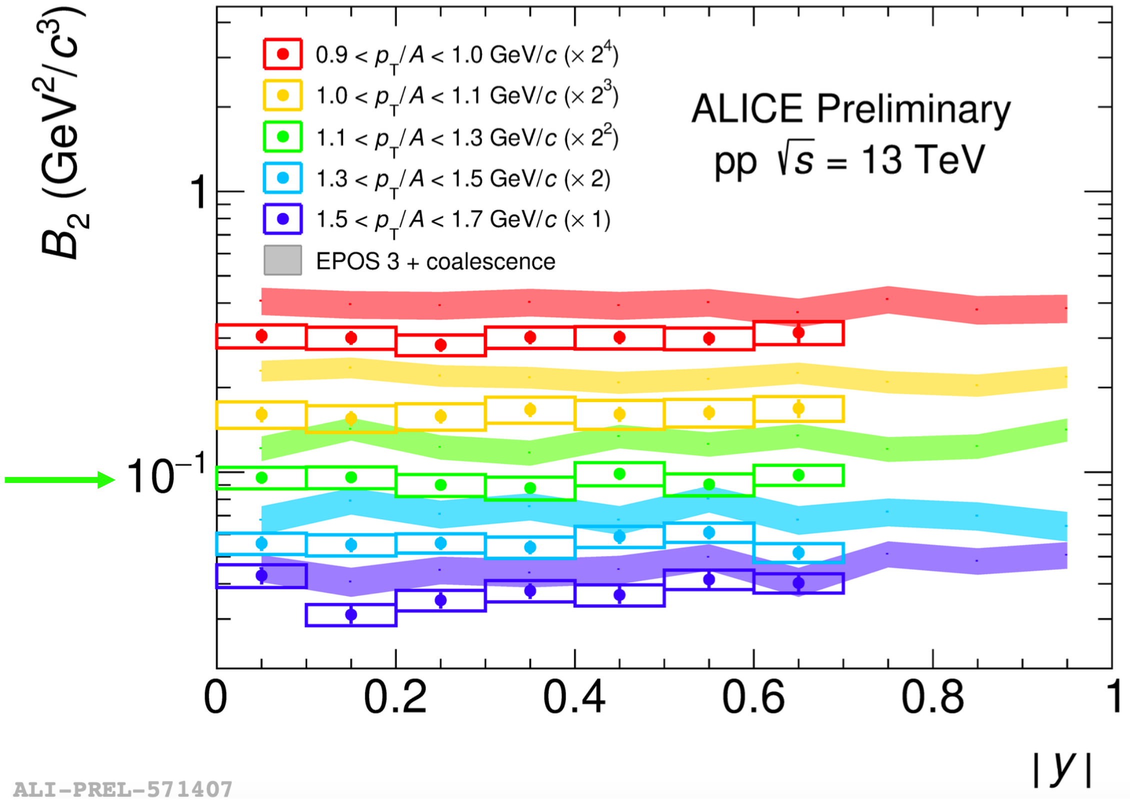
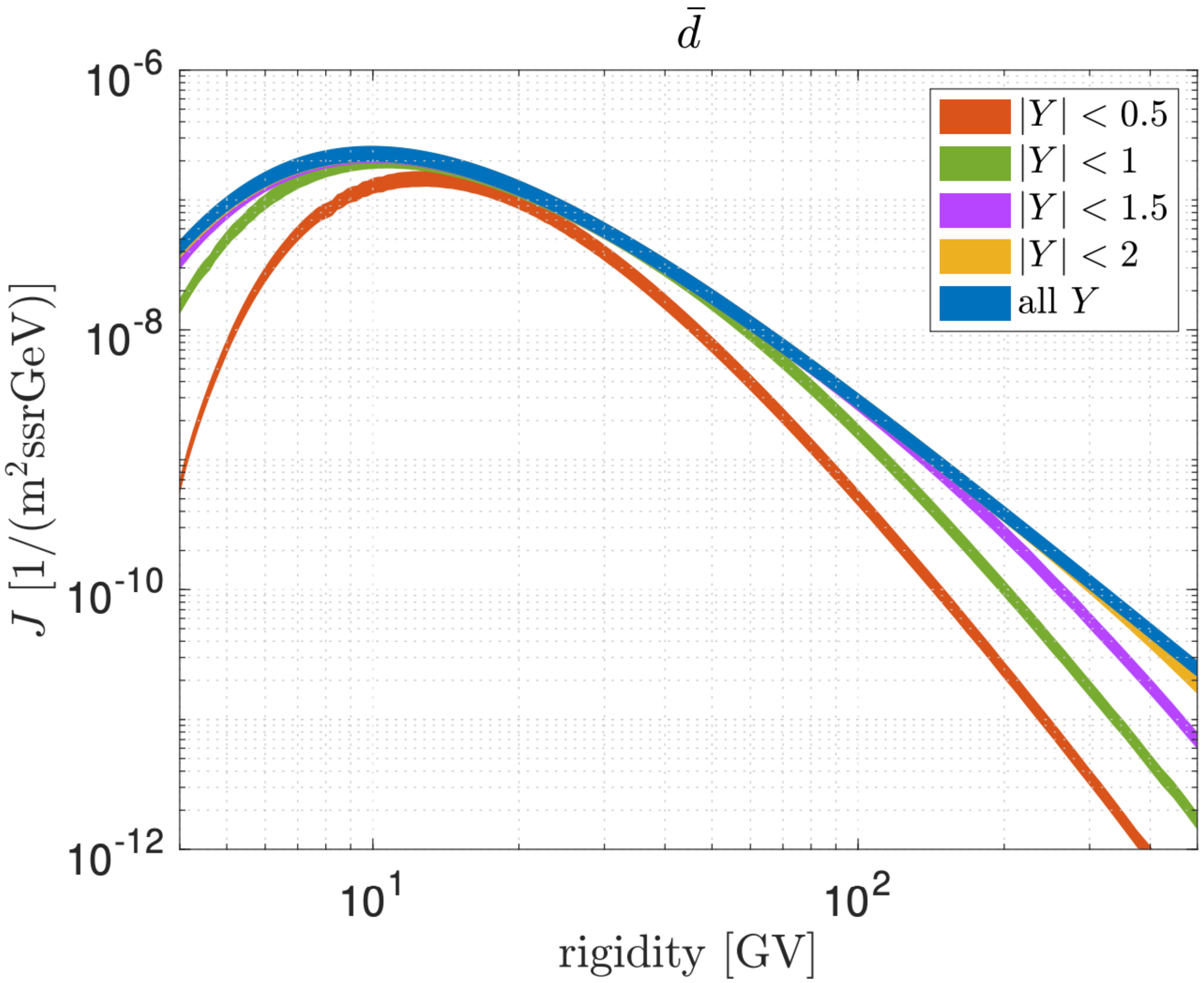


- Rapidity and p_T dependence of B_2 is extrapolated to forward rapidity using coalescence model + Pythia 8.3 and EPOS as event generators

Flux of antinuclei in CRs



- 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,** in reach with:
  - → future ALICE3[1] detector acceptance ($|y| \lesssim 4$)
  - → LHCb experiment with fixed target
  - → CMS in Run4
- Extrapolation to **lower energies** (~GeV) is needed for astrophysical models

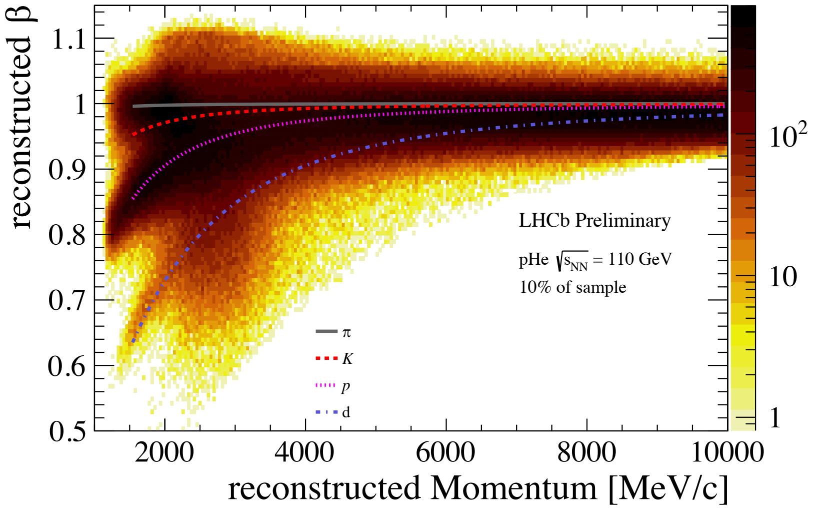
* K. Blum, Phys. Rev. D 96, 103021 (2017)

1 ALICE Collaboration, arXiv:2211.02491

K. Blum, arXiv:2306.13165

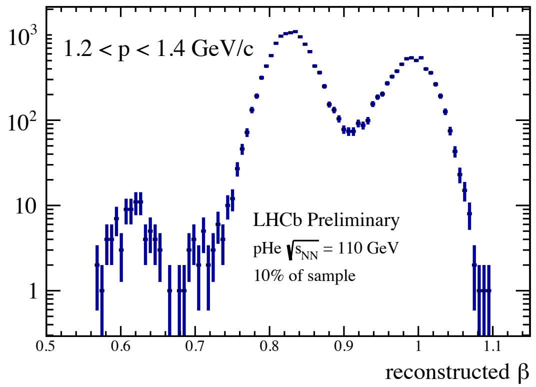
(anti)deuterons at forward rapidity

- LHCb can be used as a fixed-target experiment (**SMOG**)
- Collect physics samples with different **targets** and different **centre of mass energies** ($\sqrt{s_{NN}} \in$ [30,115] GeV)



Time-of-Flight
→ identification of **d**,
separation of ^{3}**He**, ^{4}**He**

pHe, $\sqrt{s_{NN}} = 110$ GeV



$2 \lesssim |\eta| \lesssim 5$

LHCb Collaboration, JINST 3 S08005 (2008)

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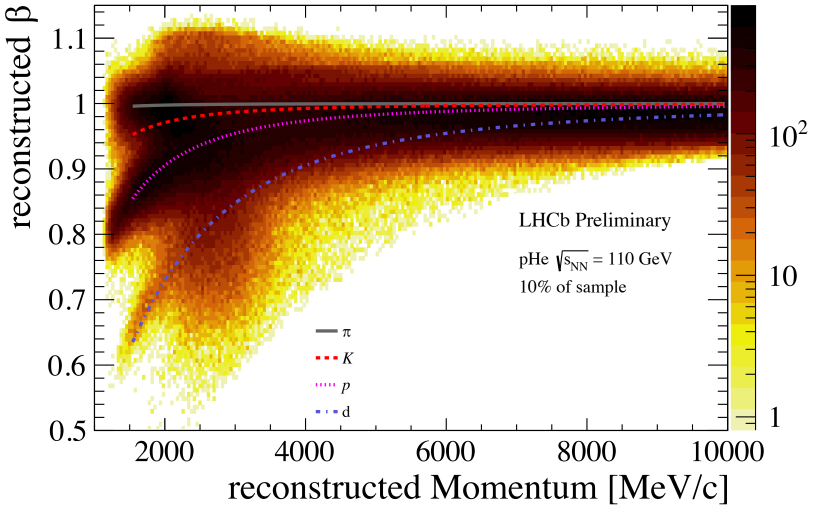
CMS program in LHC Run4 ($|y| \lesssim 2$)



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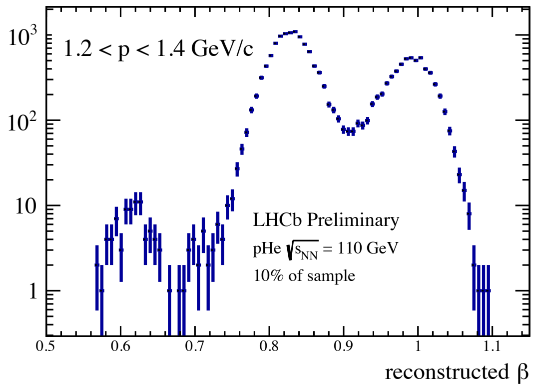

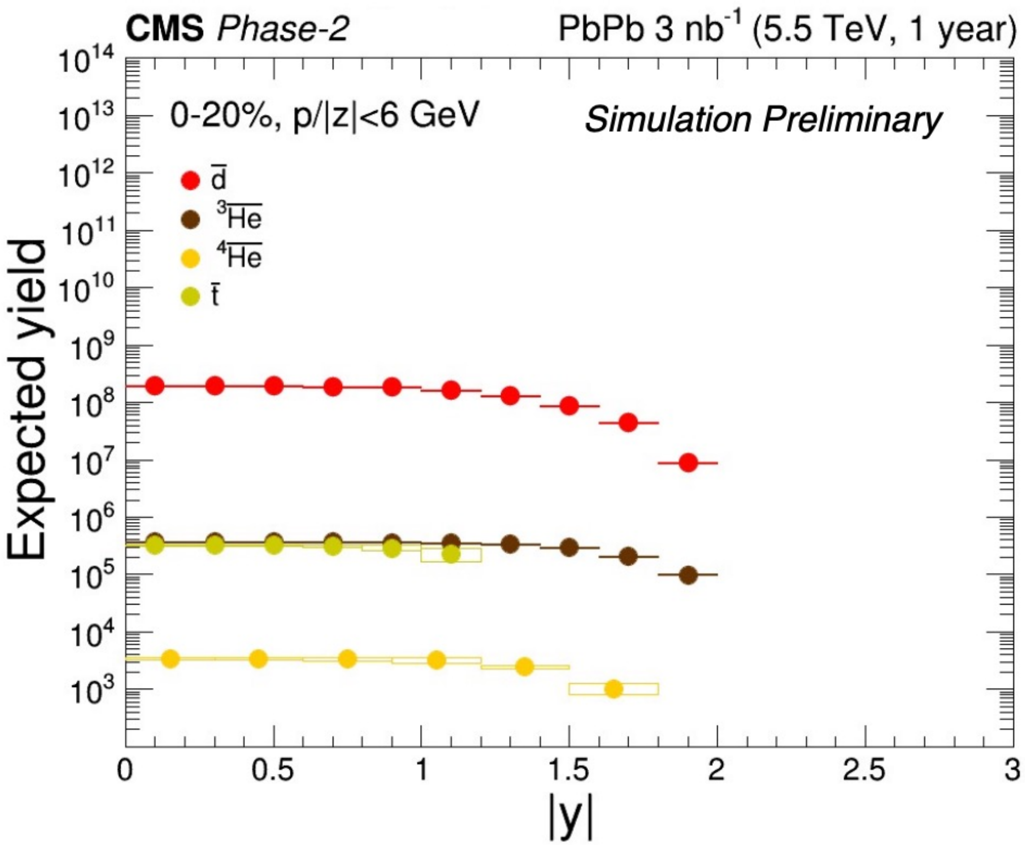

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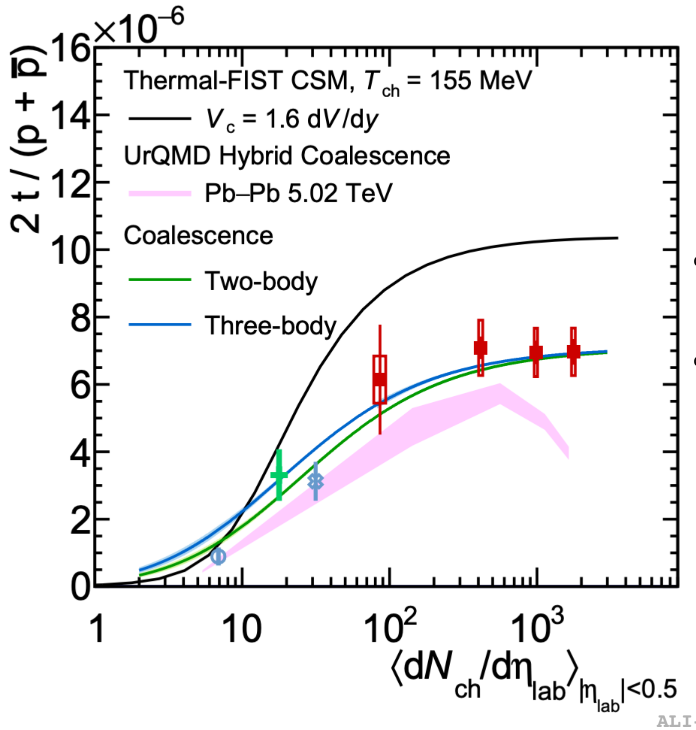
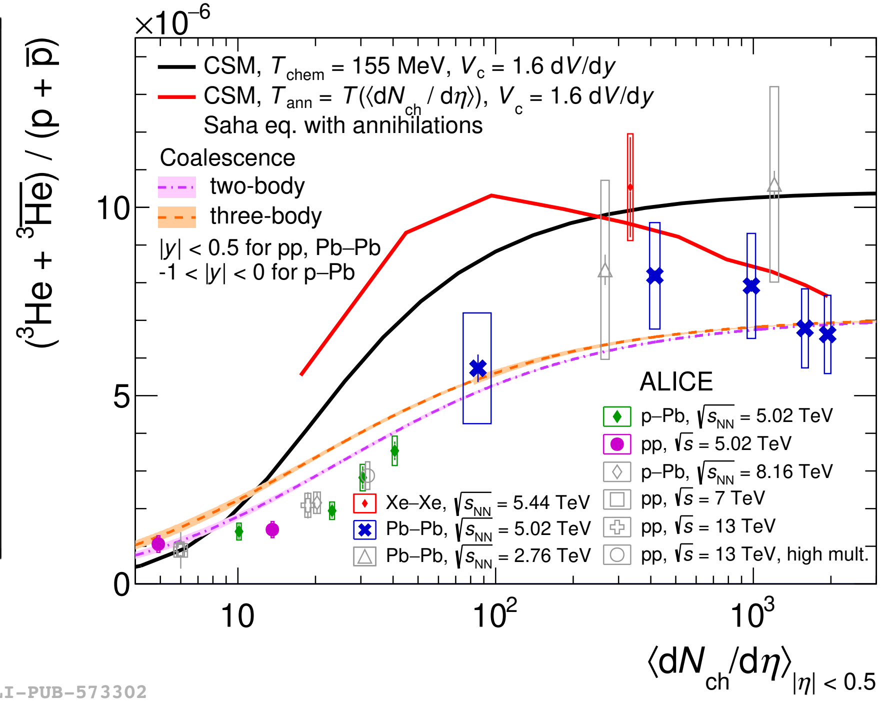
LHCb Collaboration, JINST 3 S08005 (2008)

CMS Collaboration, https://cds.cern.ch/record/2800541

Testing production models with A=3





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- Neither of the CSM models or **coalescence** predictions reproduce the trend of the ratios, but qualitatively reproduce the overall yields

ALICE Collaboration, PRL 131 (2023) 041901
ALICE Collaboration, PRC 107 (2023) 064904
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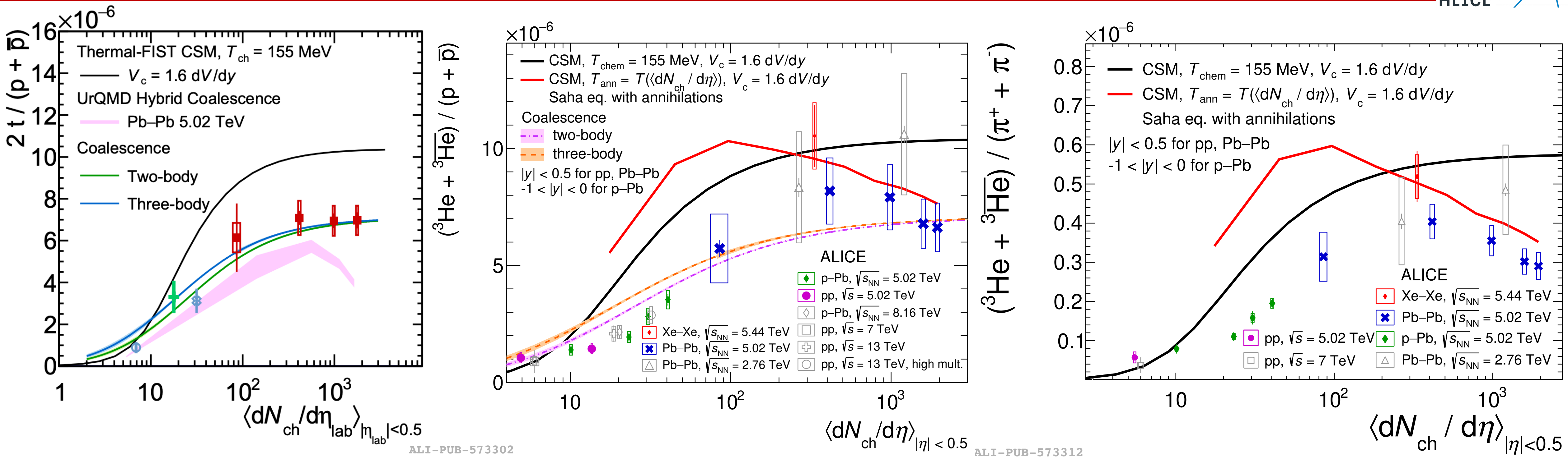

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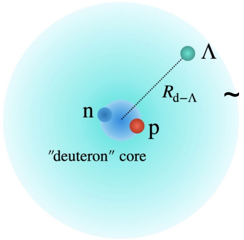
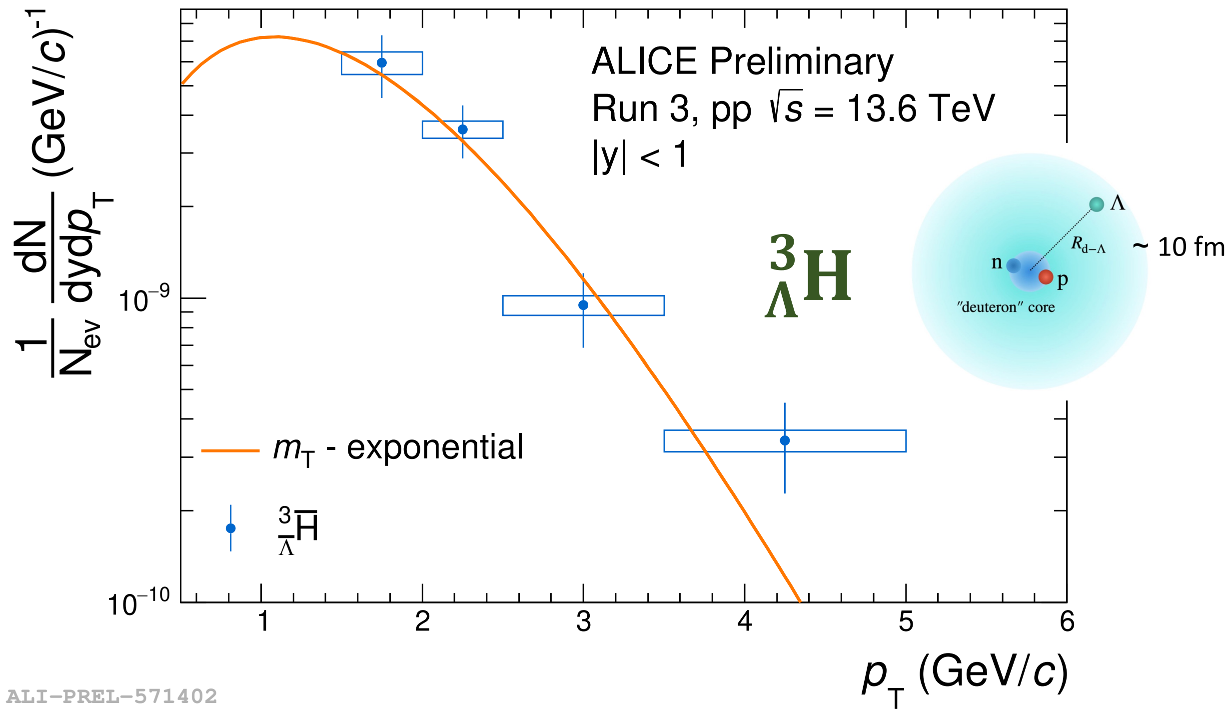
Testing production models with hypertriton

$^{3}_{\Lambda}\mathrm{H}$



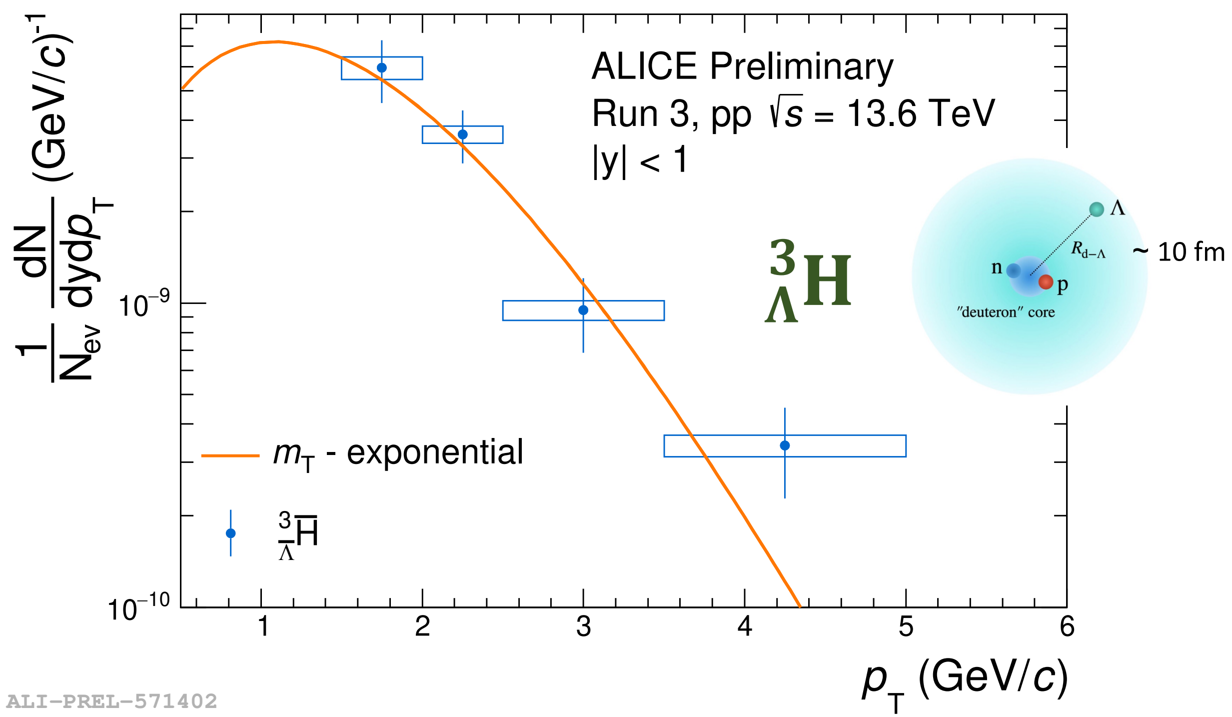
~ 10 fm

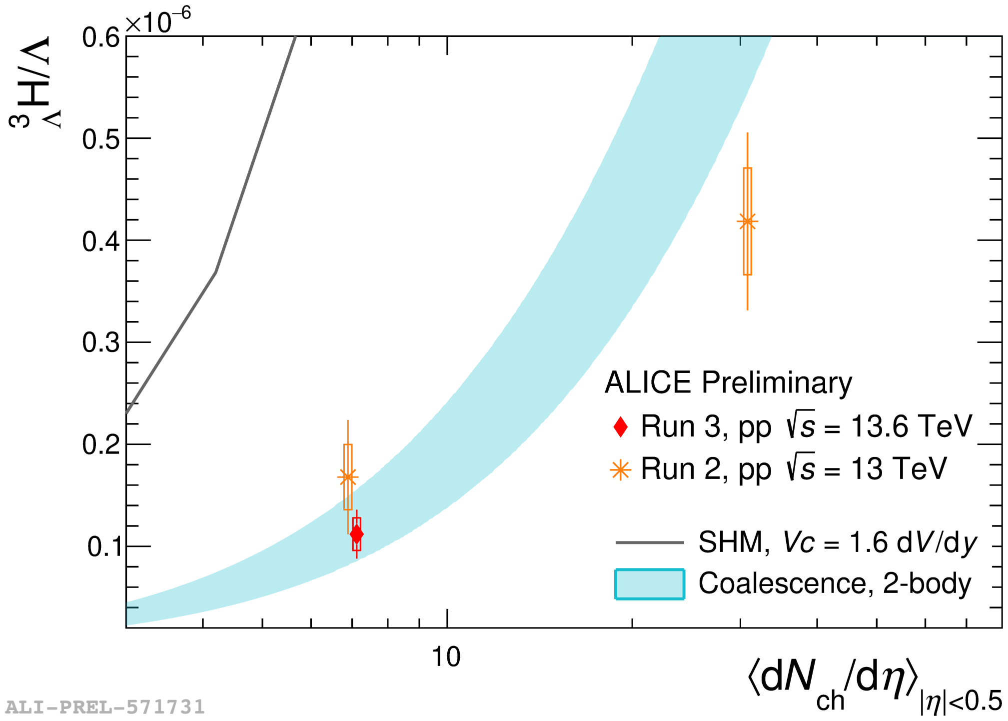
Testing production models with hypertriton



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

Testing production models with hypertriton





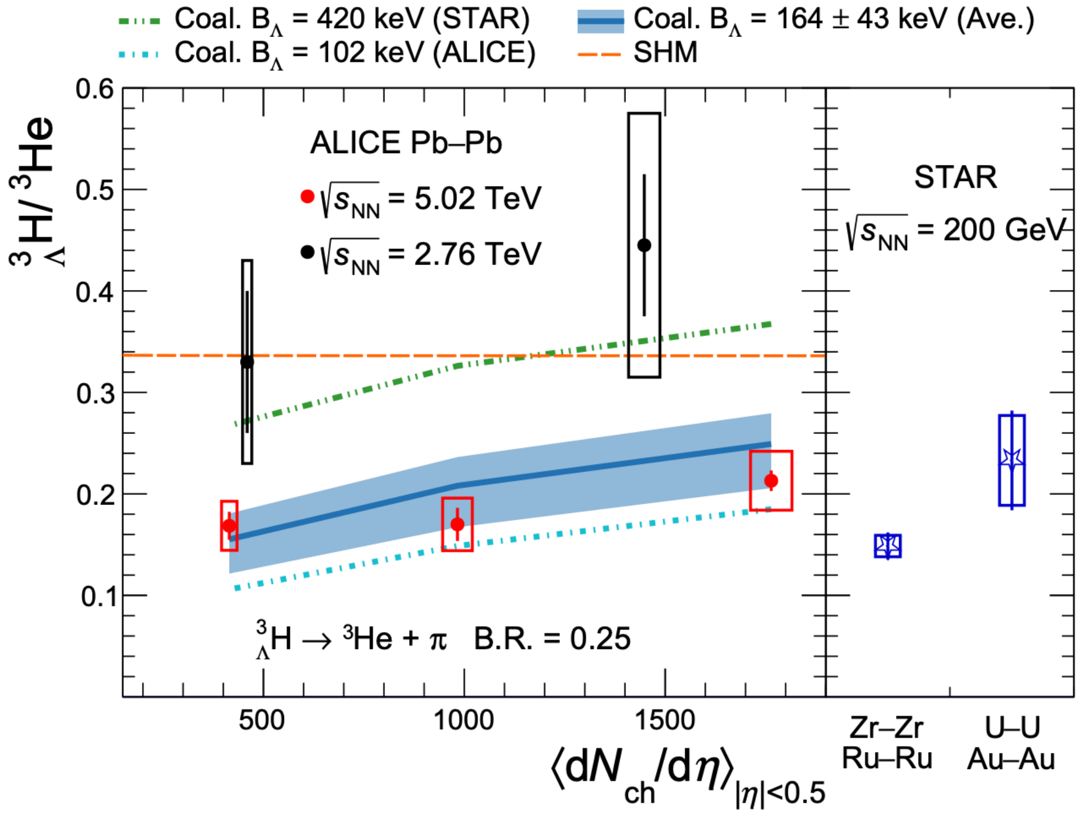
- In small collision systems (as pp) size of system created in the collision is smaller or equal to that of the nucleus under study
- Coalescence is sensitive to the **interplay** between the **size of the collision system** and the spatial extension of the **nucleus wave function**
- $^{3}_{\Lambda}$H/Λ ratio provides a powerful tool to investigate nuclear production mechanism → For small systems model **predictions are quite different**

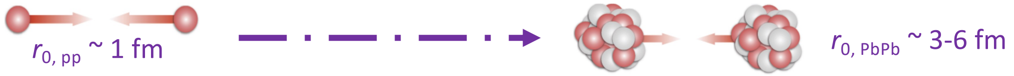
Hypertriton in Pb—Pb: test of production models

- ${}^{3}_{\Lambda}$H/^{3}He ratio allows for testing the production models

vs. $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$

  - **SHM** predicts a flat ratio: sensitive to their similar masses ($m_{{}^{3}_{\Lambda}H}$=2.991 and m_{3He}=2.809 GeV/c^2), but insensitive to their size [r_{3He}: 1.76 fm, $r_{{}^{3}_{\Lambda}H\ (np\Lambda)}$: 4.9 fm ($B_\Lambda$= 2.35 MeV), $r_{{}^{3}_{\Lambda}H\ (d\Lambda)}$: 10 fm ($B_\Lambda \sim$ 0.13 MeV)]
  - **coalescence** → interplay between the spatial extension of the nucleus wavefunction and the system size
  - better agreement with coalescence



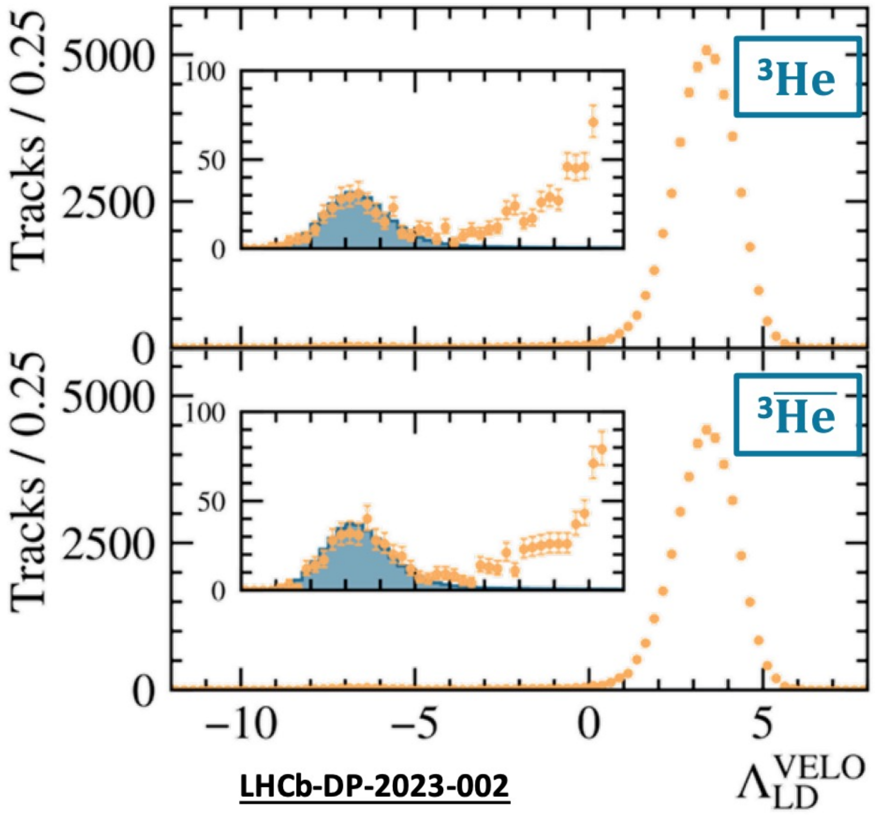


ALICE Collaboration, arXiv:2405.19839

Identification of ^{3}He and $^3_\Lambda$H at 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!



LHCb-DP-2023-002

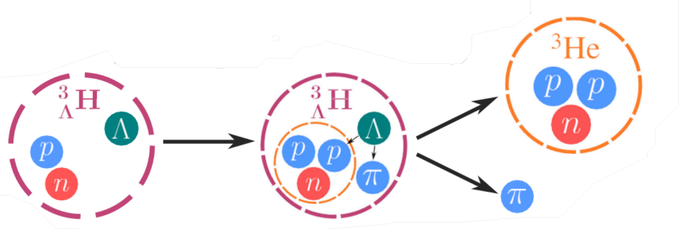
LHCb Collaboration, LHCb-CONF-2023-002 (EPS-HEP)

Identification of ^{3}He and $^3_\Lambda$H at LHCb

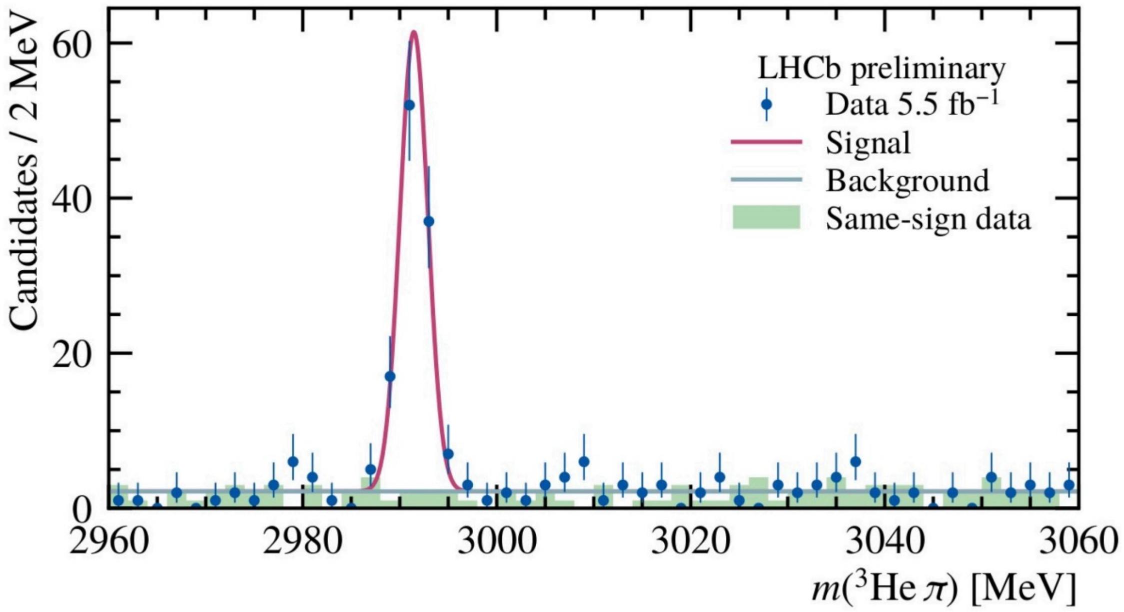
- Bethe-Bloch: Z=2 particles deposits ~4 times the energy of Z=1 particles
  → **He**: higher ADC counts and wider cluster size

- Application of ^{3}He identification:
- **Reconstruction of hypertriton** through the 2-body mesonic decay

$^3_\Lambda H \rightarrow {}^3He + \pi^-$ and c.c.



Run2 pp collisions, $\sqrt{s}$ = 13 TeV



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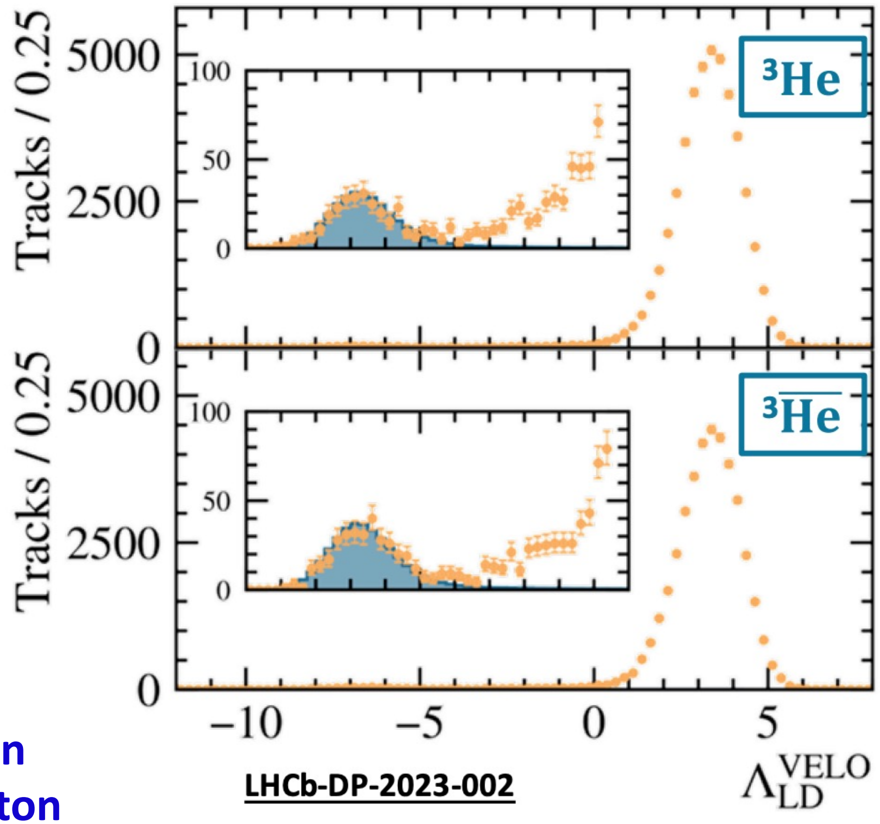
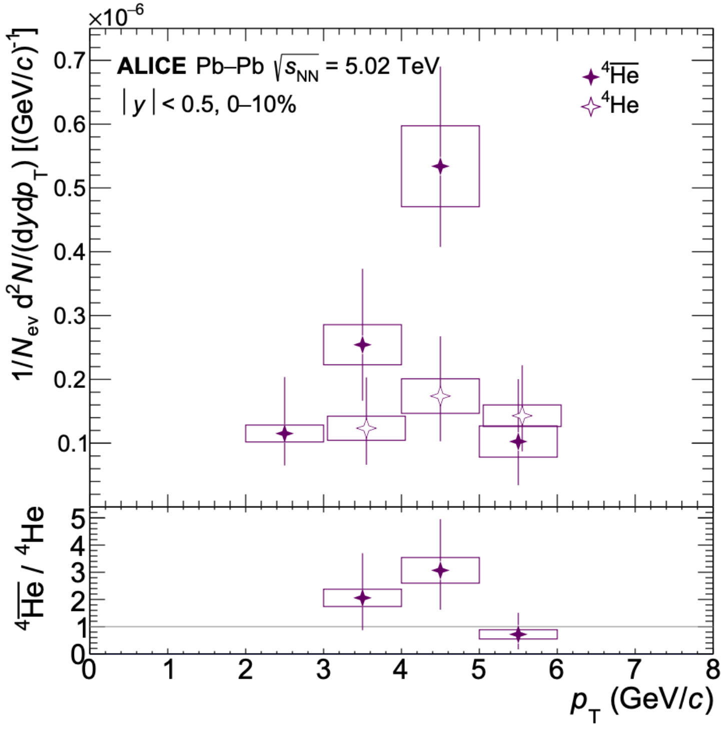


LHCb-DP-2023-002

Yields:
61 ± 8 Hypertriton
46 ± 7 antihypertriton
Statistical mass precision
0.16 MeV

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

Measurement of A=4 nuclei in Pb—Pb



- ^{4}He is very compact and more bound than lighter nuclei: E_B~ 28 MeV, r ~ 1.7 fm

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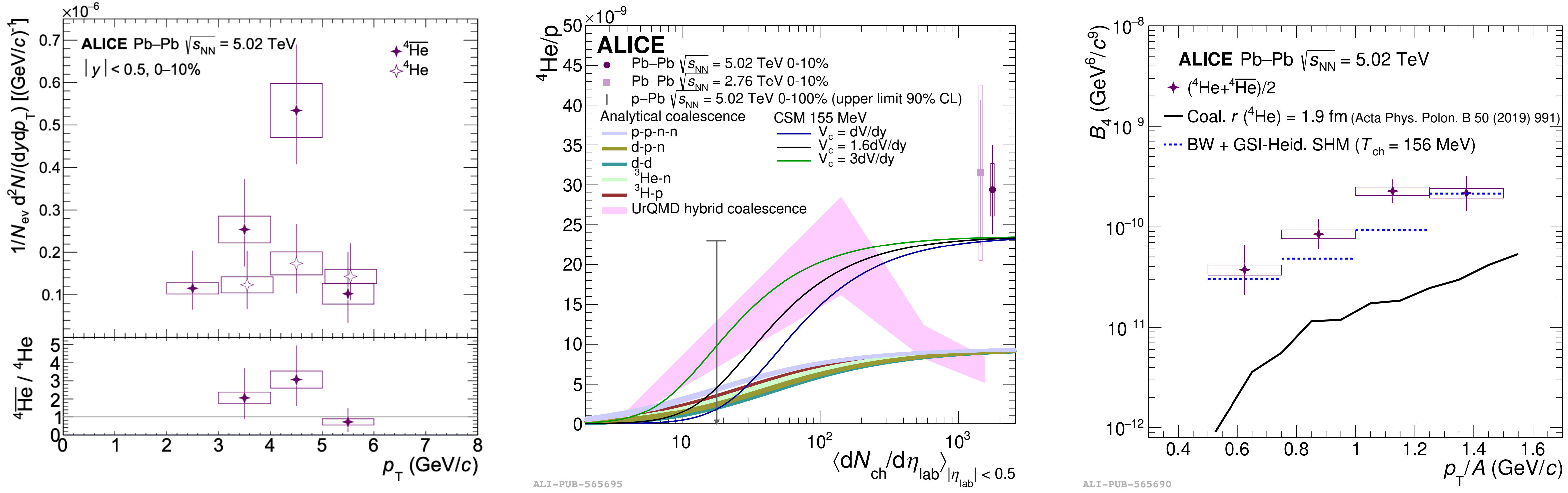
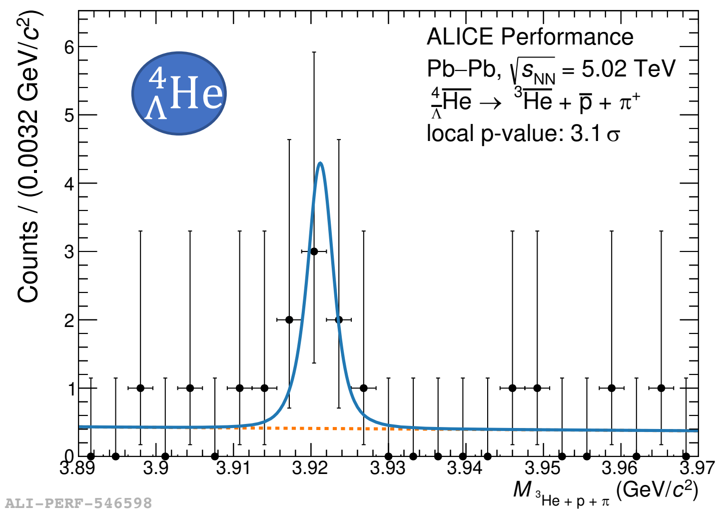
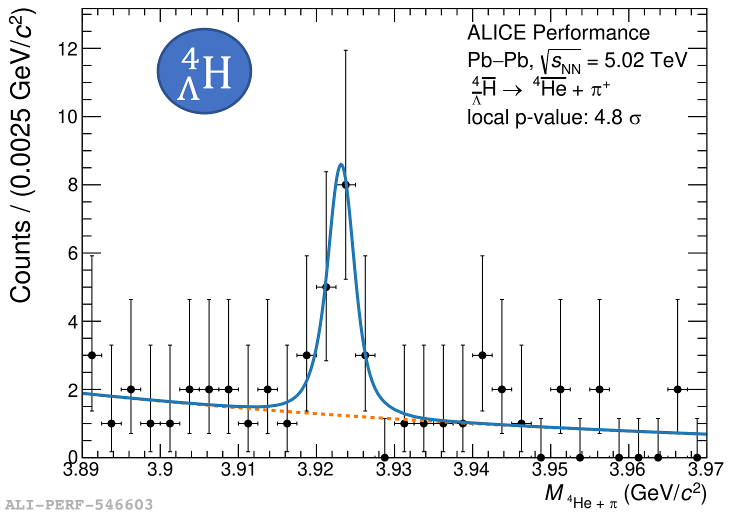
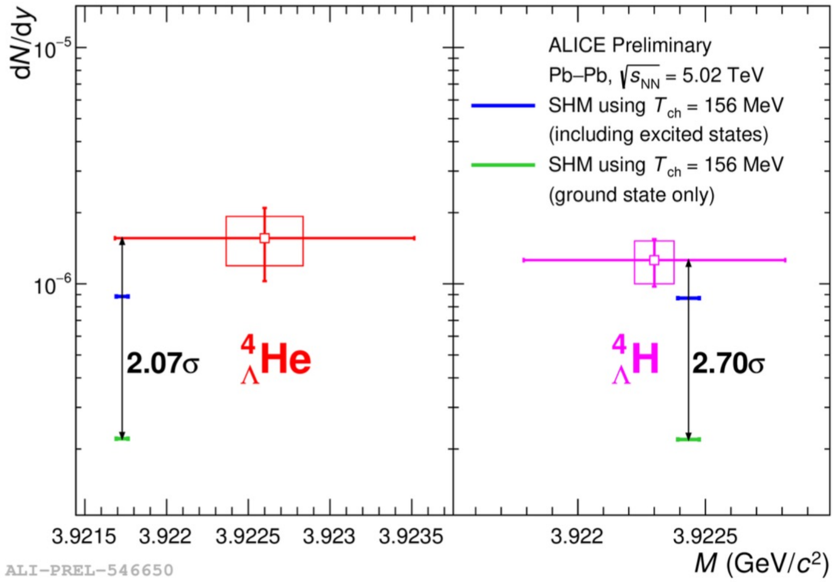


- ^{4}He is very compact and more bound than lighter nuclei: E_B~ 28 MeV, r ~ 1.7 fm
- ^{4}He/p ratio & B_4 in agreement with SHM, but the only available measurements are from Pb—Pb collisions → data needed at intermediate multiplicity where models differ
- Blast Wave using common parameters with the other nuclei describes B_4

Hypernuclei in the A=4 sector





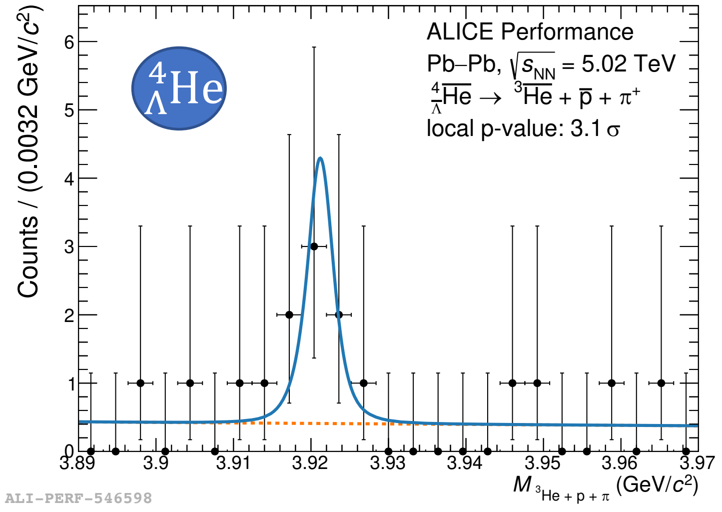


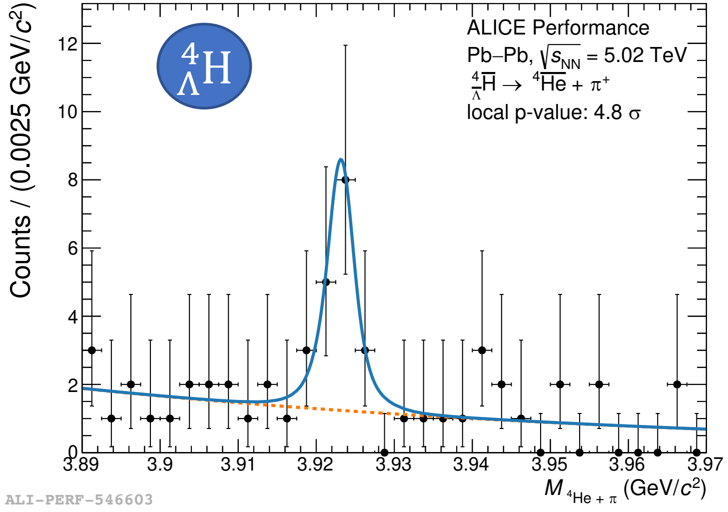
Pb—Pb

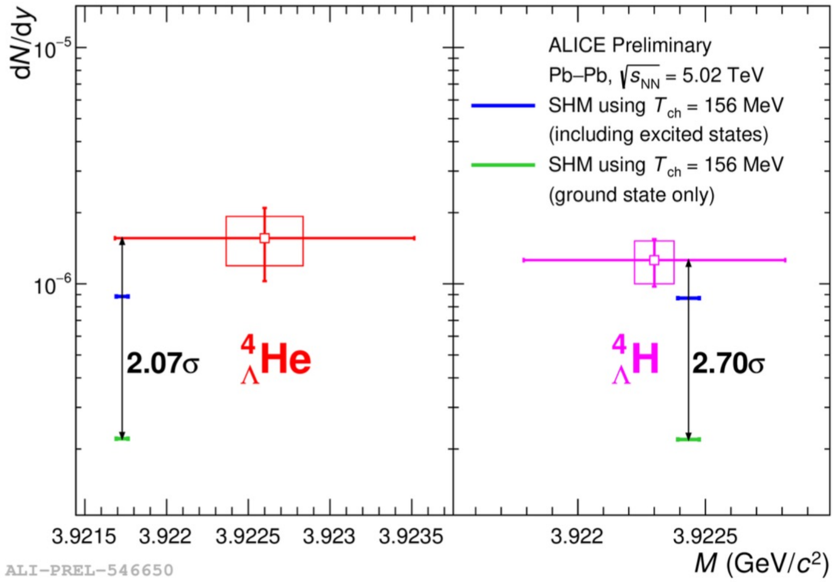
- First ever observation of anti$^4_\Lambda$He!
- **Hypernuclei** with **A=4** in Pb-Pb collisions are compared to predictions of SHM
  - penalty factor ~ 300 from $^4_\Lambda$He to $^4_\Lambda$H due to strangeness content
- But their yield may be enhanced due to larger binding energy wrt A=3 & existence of excited states (spin degeneracy)

→ Measured yields in **agreement** with the presence of **excited states**

Hypernuclei in the A=4 sector

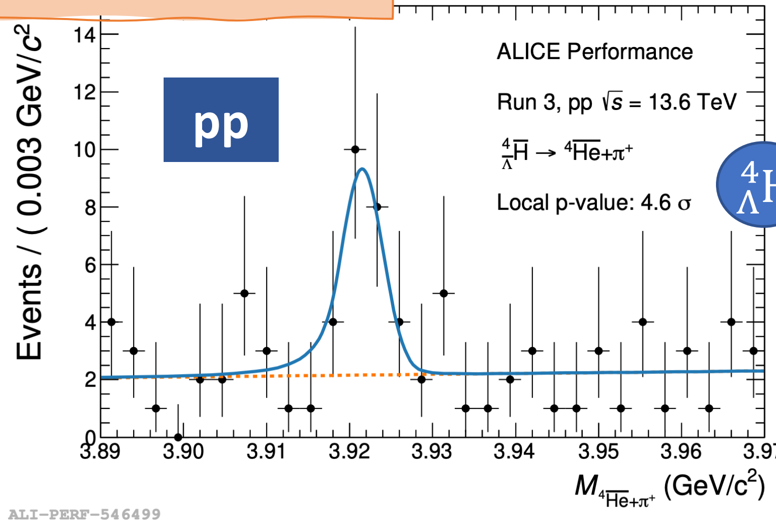






Pb—Pb

More to come with LHC Run3 data!



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Summary

- Measurements of the production of (anti)(hyper)nuclei is fundamental to investigate the **hadronization mechanism**
- The models on the market describe **different aspects** of the production but none of them can describe all observations, at all multiplicities and at all collision energies
- We have **many observables** that have significantly **different model predictions** → powerful probes to distinguish among the models
- Now the **experimental challenge** is to get **precision measurements** to finally close the debate

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- Other powerful tools to distinguish among the models, not covered in this talk, are the ^{3}He/^{3}H ratio vs p_{T}, ${}^{3}_{\Lambda}\mathrm{H}$/^{3}He ratio vs p_{T}, elliptic flow v_2 of nuclei and hypernuclei, nuclei in and out of jets, ^{3}H·p/d^{2} ratio vs dN_{ch}/dη etc…

Summary

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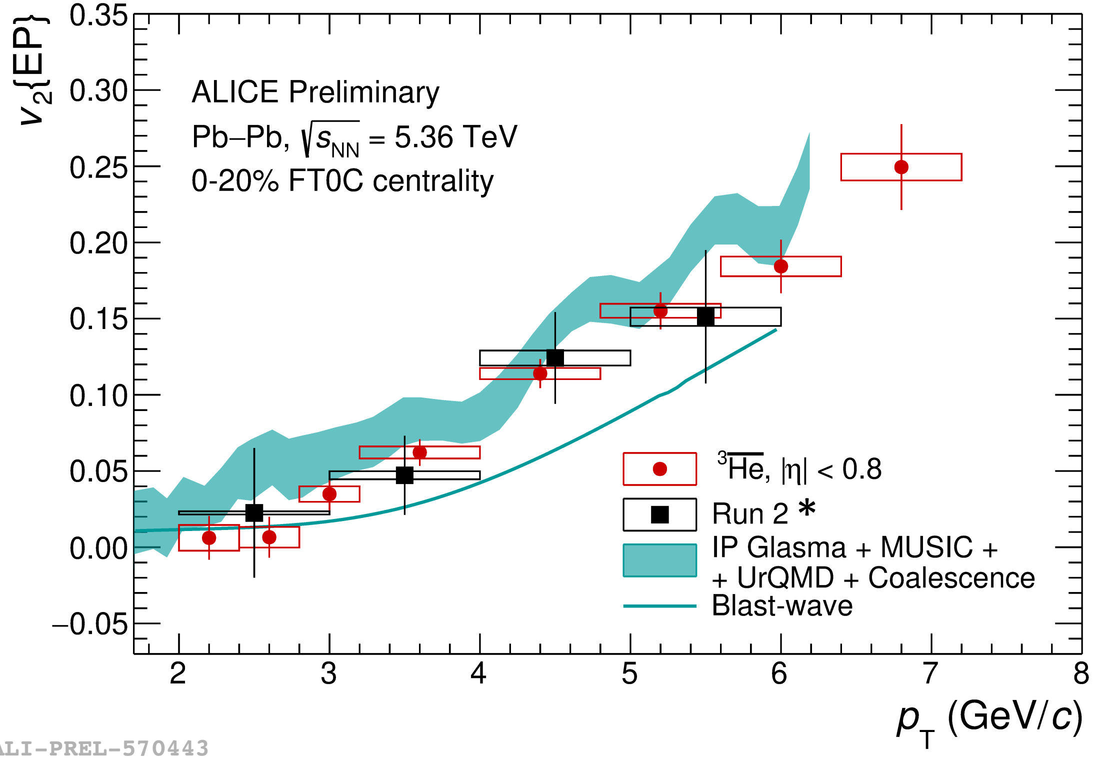
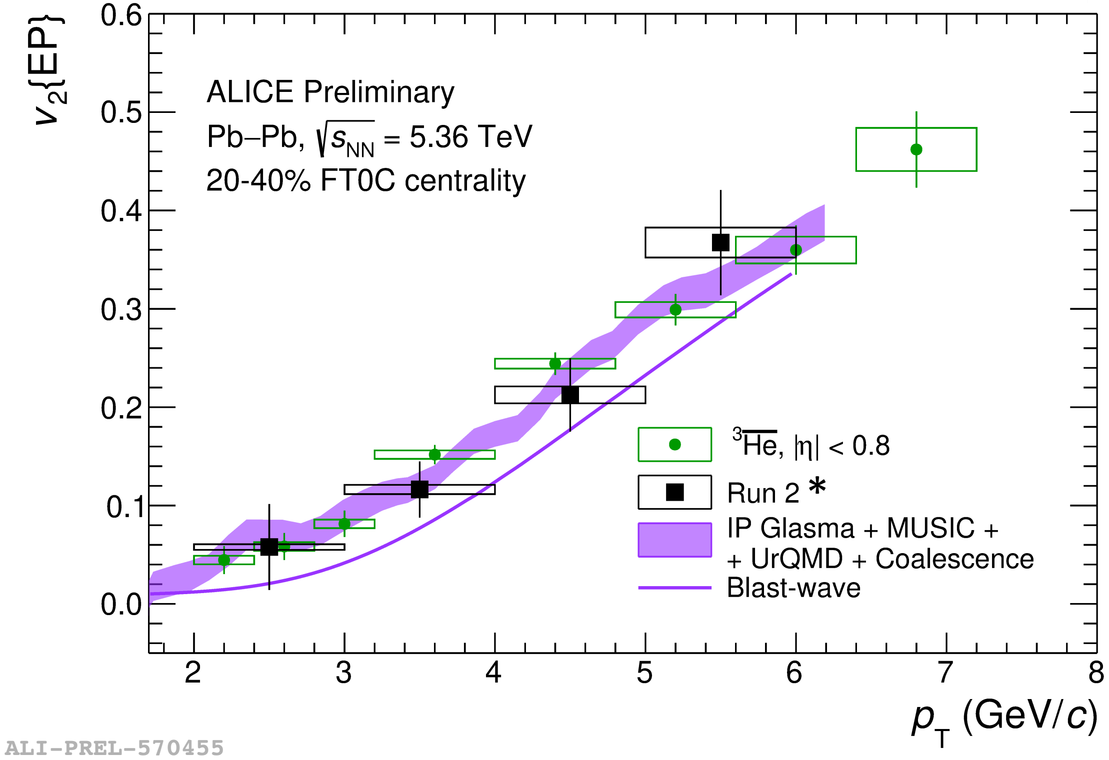
Spares

v_2 of ^{3}He: another test of production models



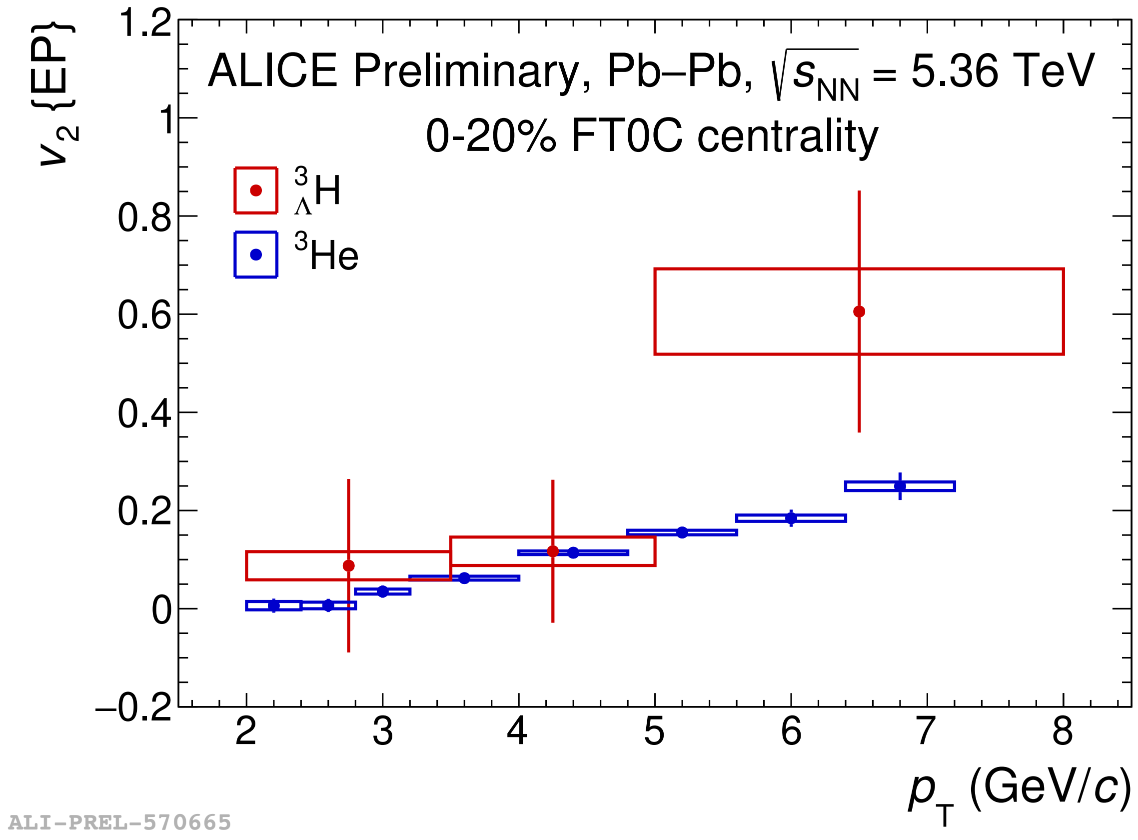


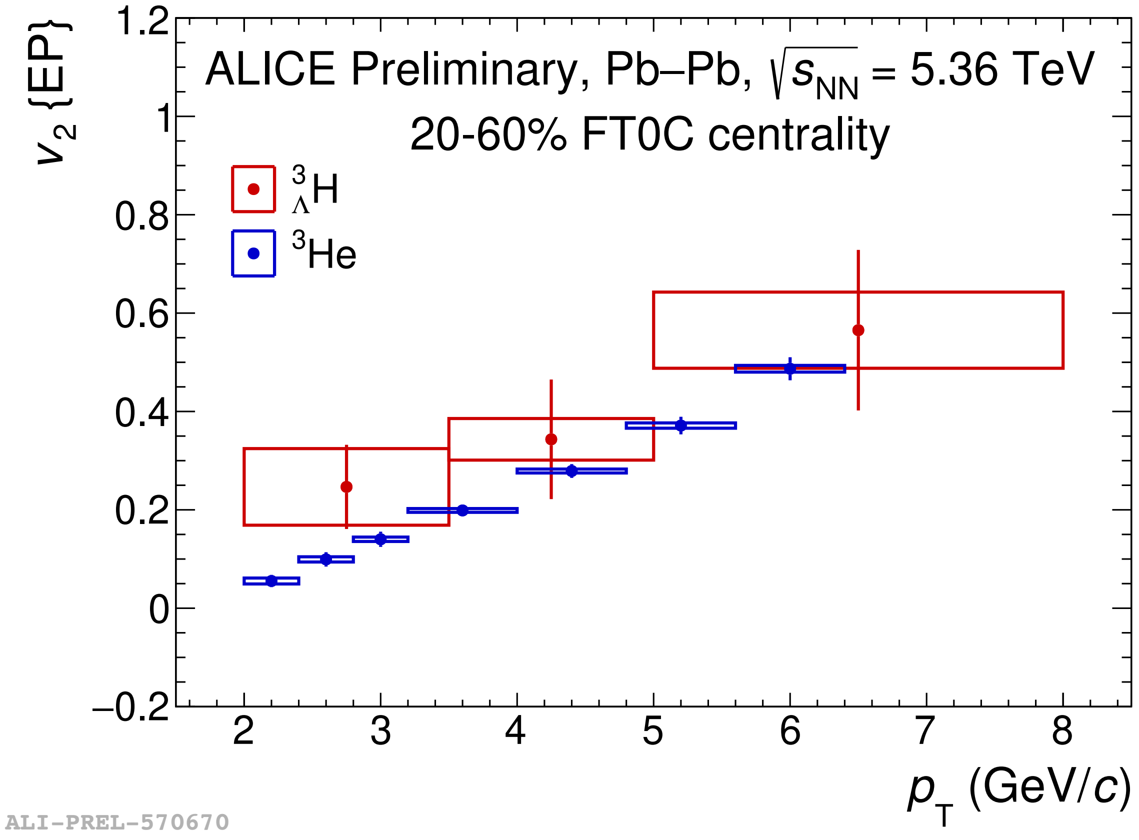
- ALICE Run3 statistics seems sensitive to the different production models using the elliptic flow v_2
- **Coalescence** is sensitive to a different production in-plane and out-of-plane
- Data are compared with the predictions of
  - Blast Wave model that uses the fit parameters of pi, K, p
  - coalescence model + hydrodynamics

* ALICE Collaboration, PLB 805 (2020) 135414

Elliptic flow of hypertriton measured by ALICE

- ALICE delivered the first experimental measurement of hypertriton elliptic flow!
- Compatible with ^{3}He v_2, due to their similar masses
- Large uncertainties

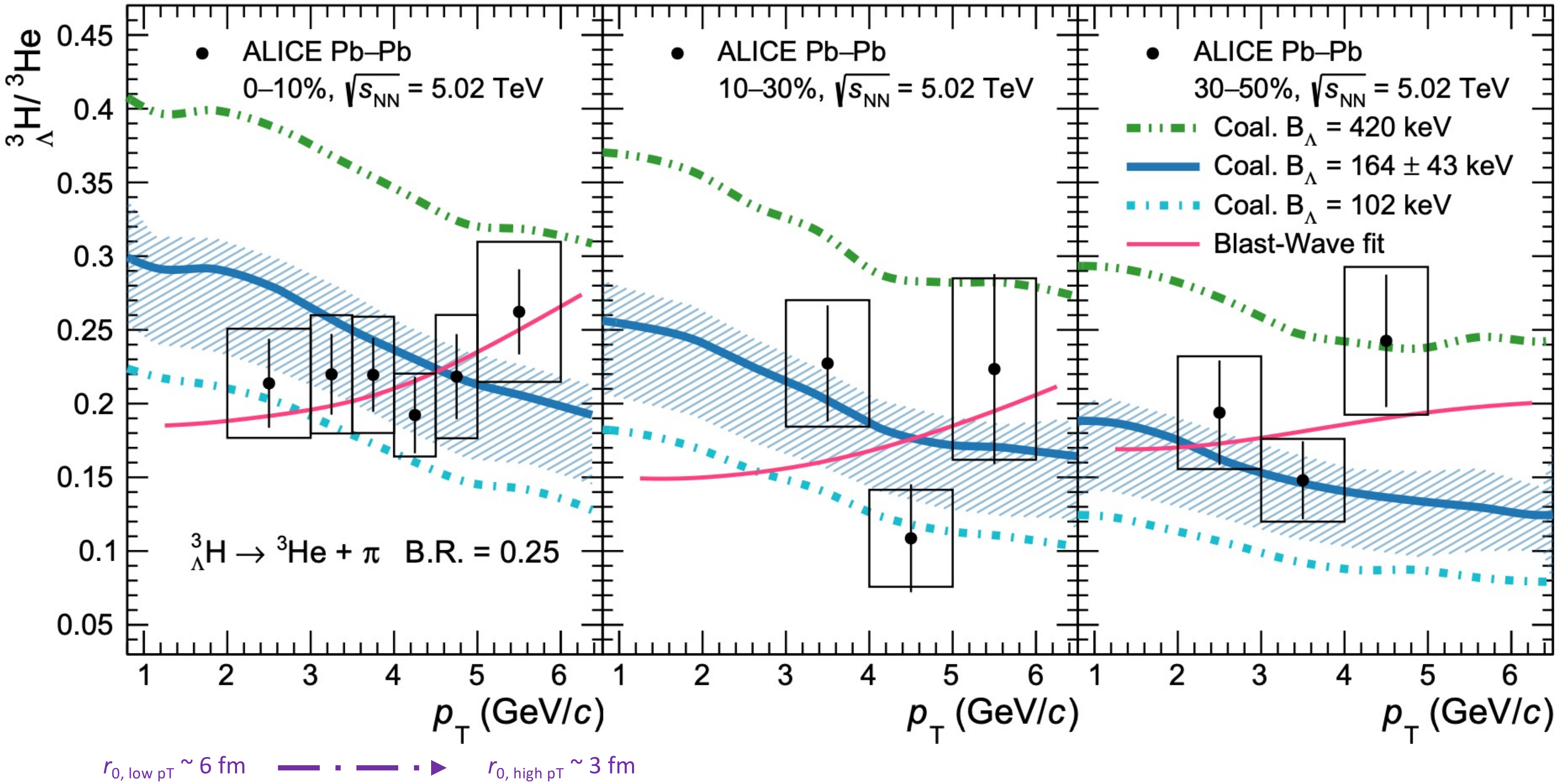




Hypertriton in Pb—Pb: test of production models

- ${}^{3}_{\Lambda}$H/^{3}He ratio allows for testing the production models

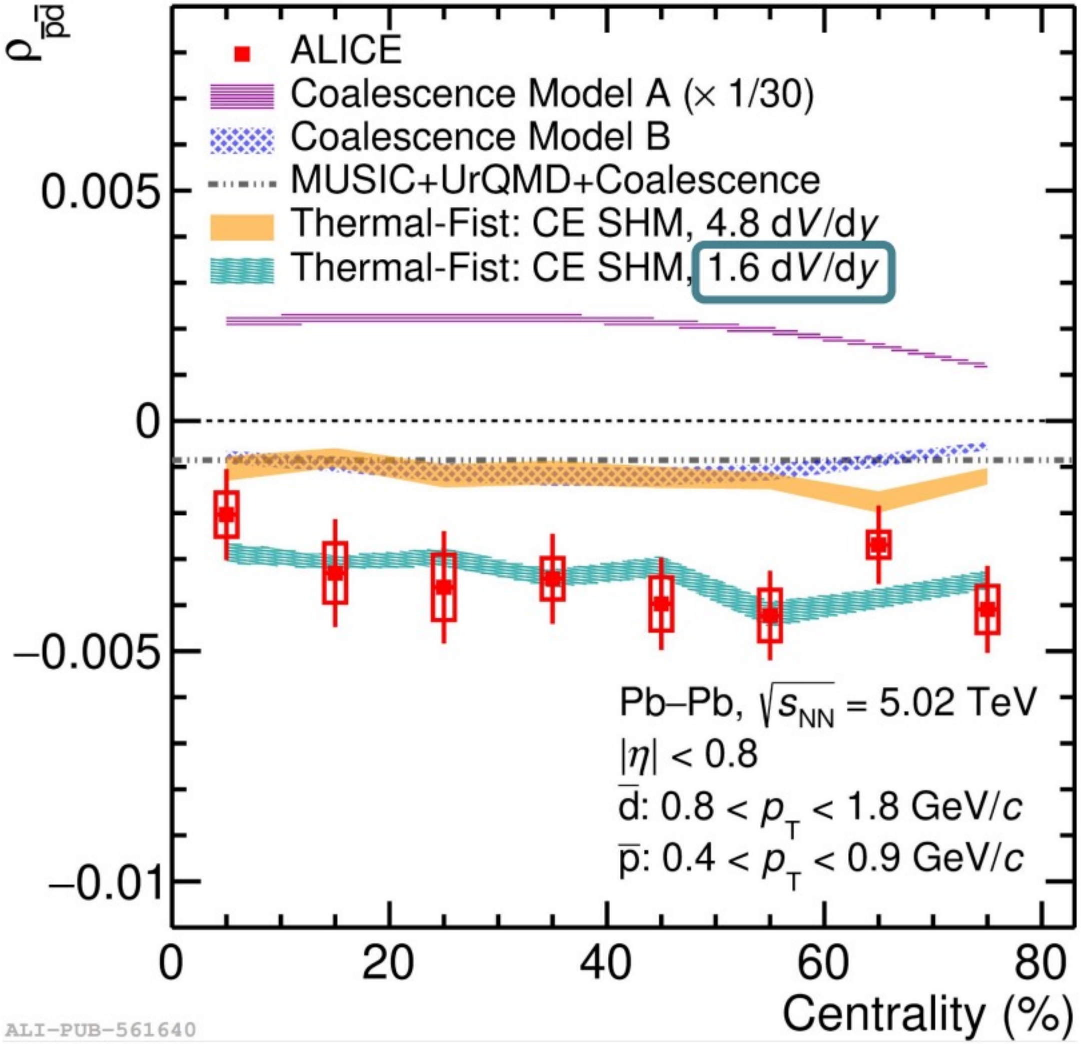
vs. p_T
  - Radial flow picture (Blast-Wave): higher mass states have a harder momentum spectrum
  - Coalescence: at large momentum smaller source radius, hence the state with the larger wave-function will get suppressed

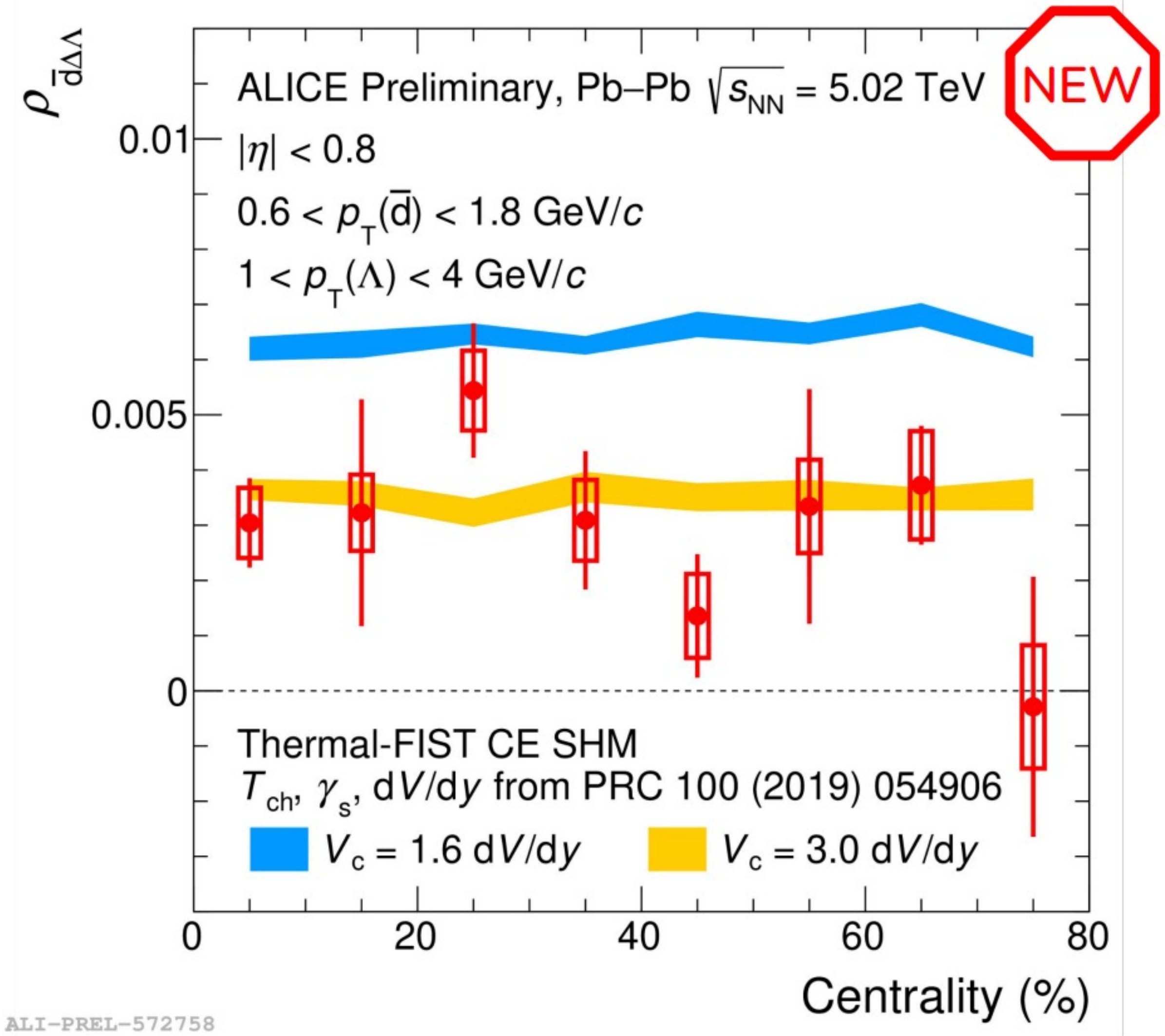


ALICE Collaboration, arXiv:2405.19839

Event-by-event fluctuations at the LHC

ALICE Coll., Phys. Rev. Lett. 131, 041901 (2023)





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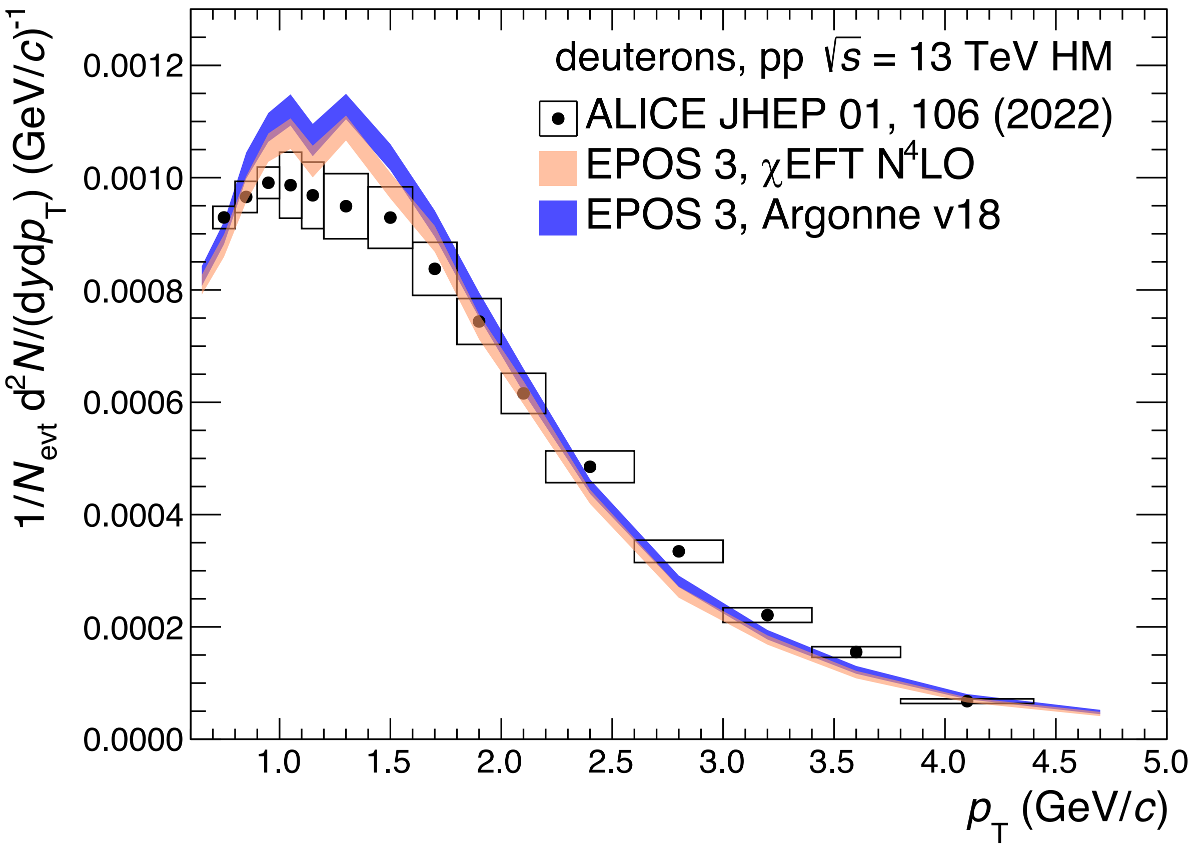
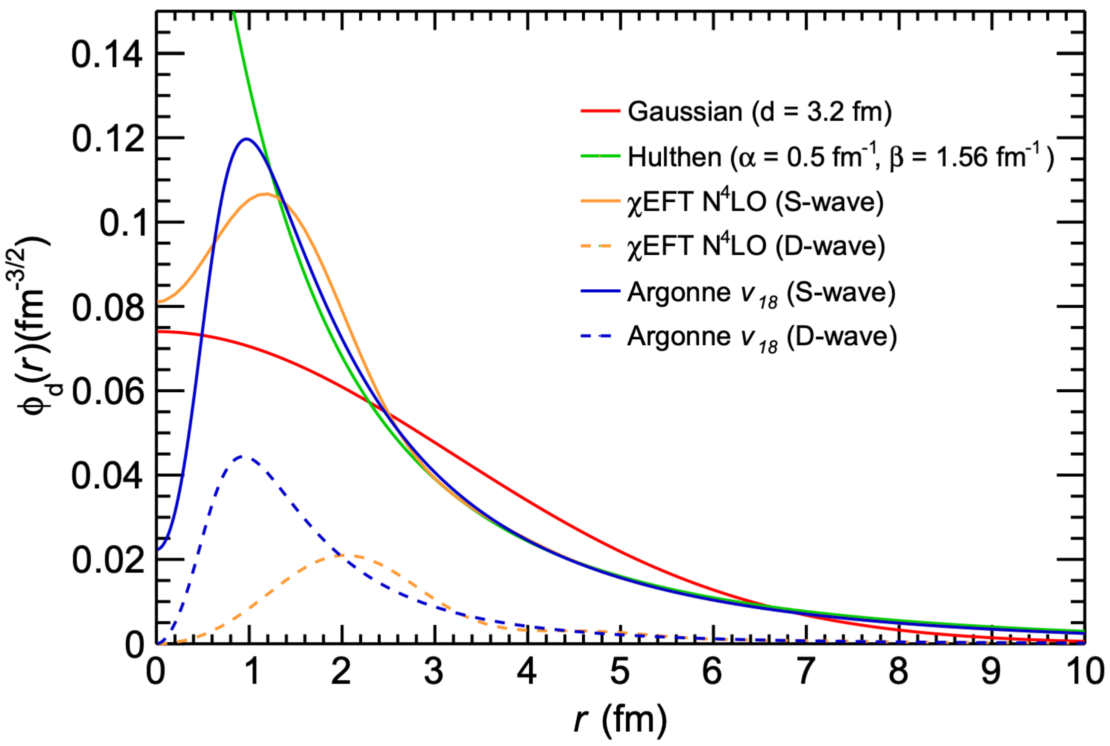
Testing coalescence model using B_2

Difference between the 2 WFs is ~4%
→ Production of deuterons is not affected by the short-range interactions (<2 fm)



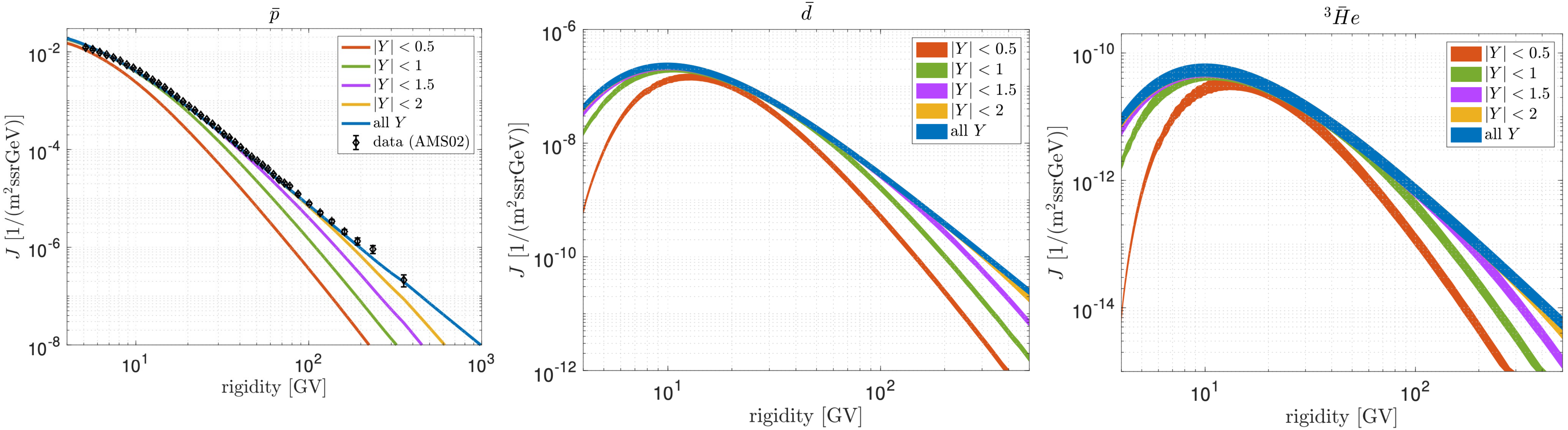


- **Hulthén*:** Favoured by low energy scattering experiments
- **Argonne v_{18}**:** phenomenological potential constrained to p-n scattering
- **χEFT:** Favoured by modern nuclear interaction experiments (e.g. Femtoscopy)

* Scheibl et al., PRC 59 (1999) 1585-1602
** Wiringa et al., PRC 51 (1995) 38-51
*** D. R. Entem et al., PRC 96 2 (2017) 024004

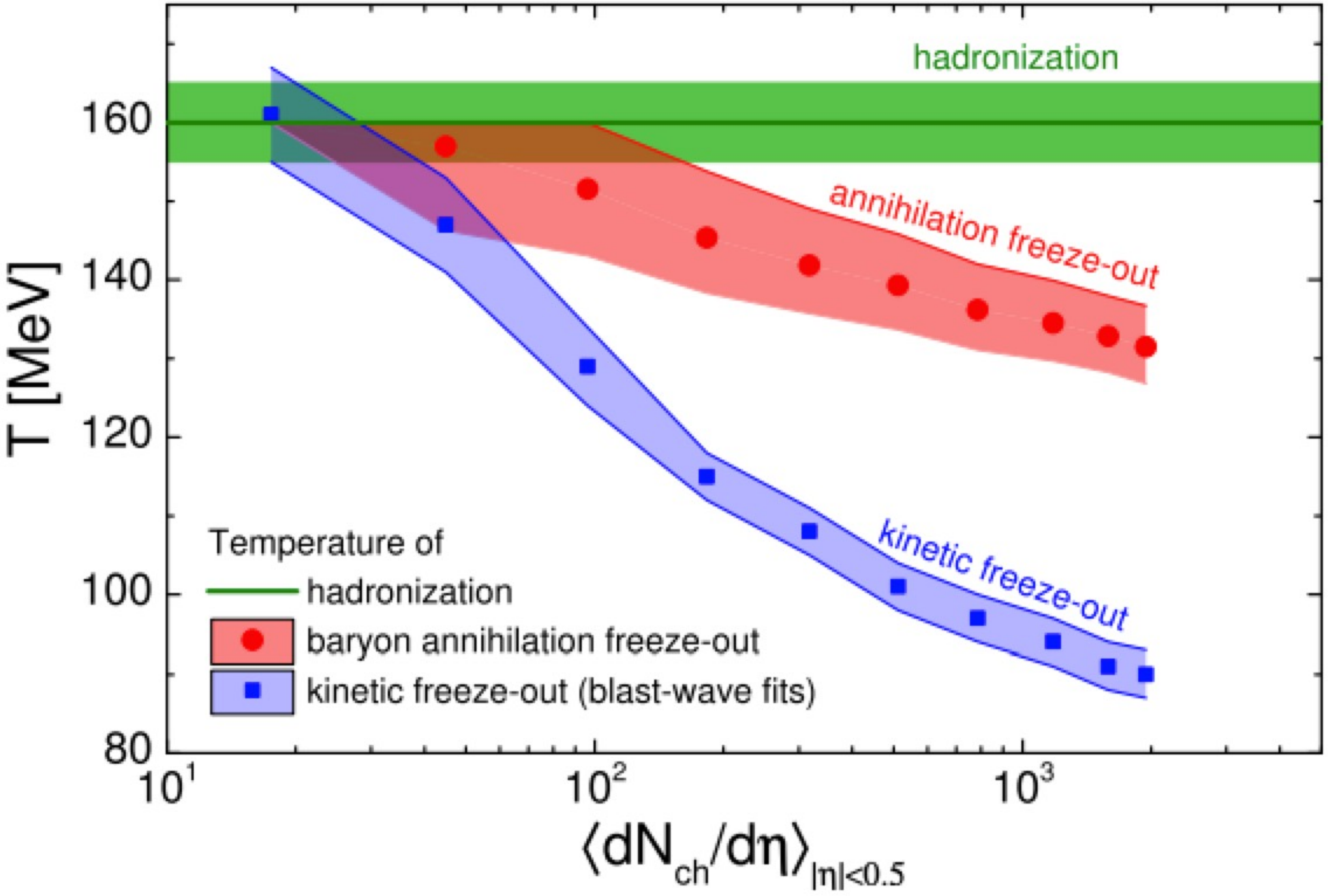
Mahlein et al., EPJC 83 (2023) 9, 804

Flux of antinuclei in CRs



K. Blum, [Phys. Rev. D 96, 103021 (2017)]
K. Blum, [arXiv:2306.13165]
M. Aguilar et al. (AMS02 Coll.), [PRL 117, 091103 (2016)]

CSM-II



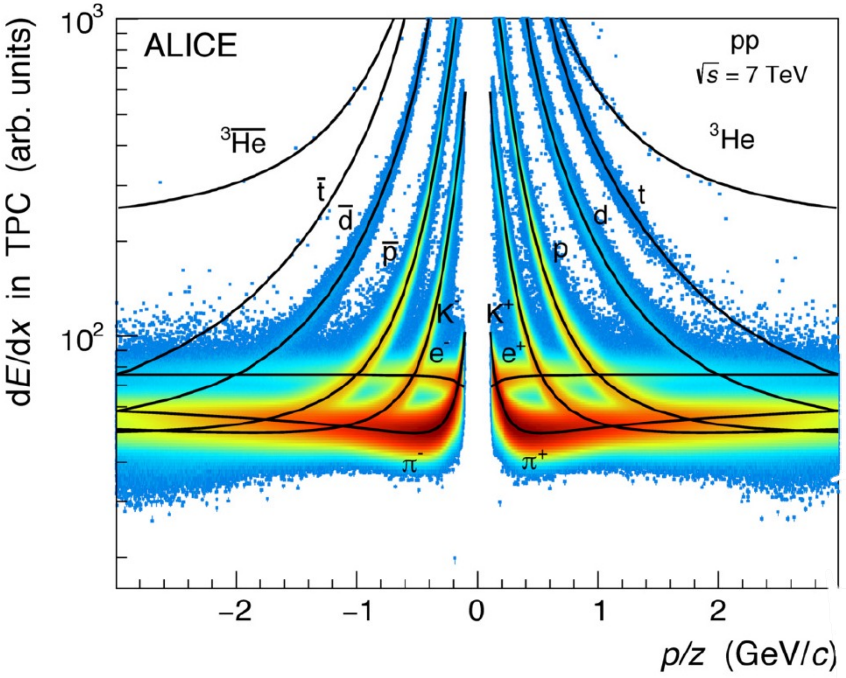
- Correlation volume fixed to 1.6 dV/dy
- Needed to describe the net-deuteron number fluctuations in PbPb collisions.
- Smaller than that of net-proton number fluctuations (3-5)dV/dy
- Temperature of annihilation depends on multiplicity

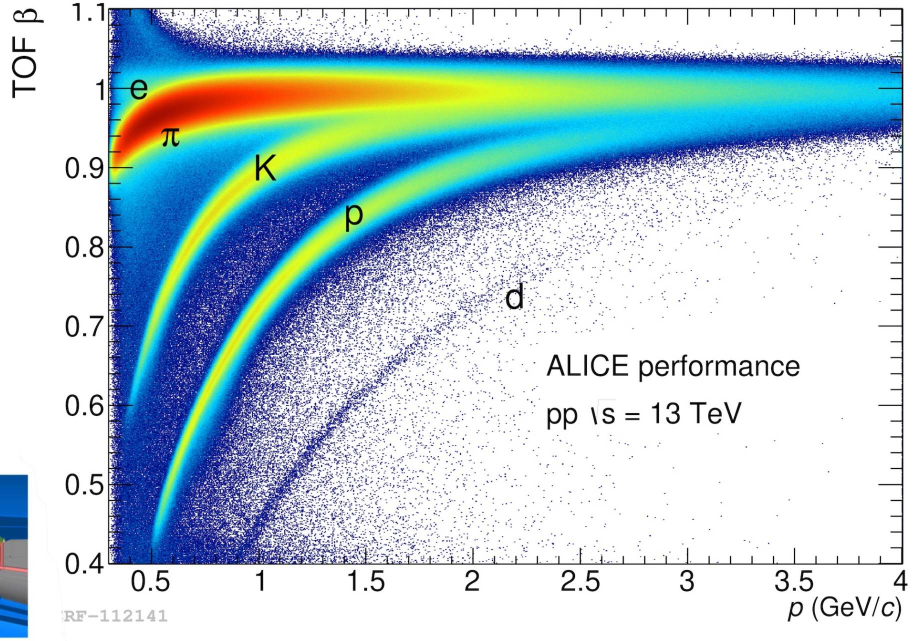
PLB 835, 137577 (2022)

For each multiplicity, the hadronic phase starts with hadronization at 160 MeV and expands in the state of partial chemical equilibrium which includes baryon annihilation reactions to reach chemical equilibrium at annihilation temperature

Identification of nuclei with ALICE

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

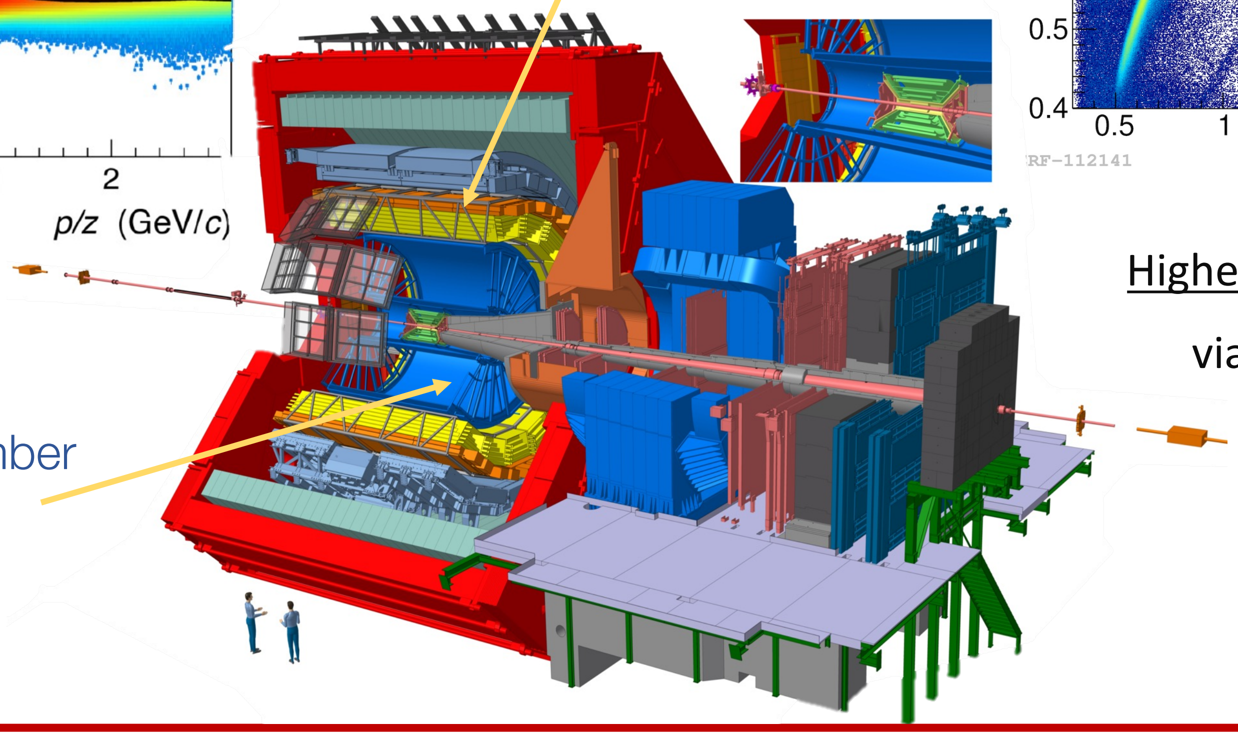




Time Of Flight

PID via β

σ_{PID} ~ 70 ps



Time Projection Chamber

tracking, PID via dE/dx

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

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

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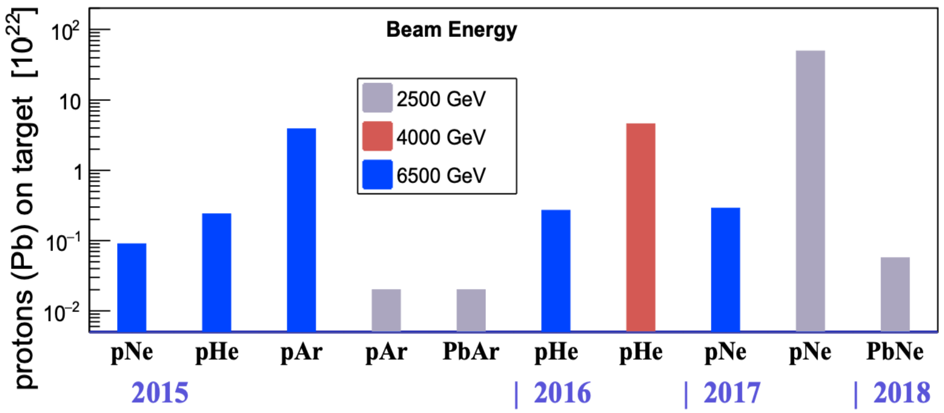
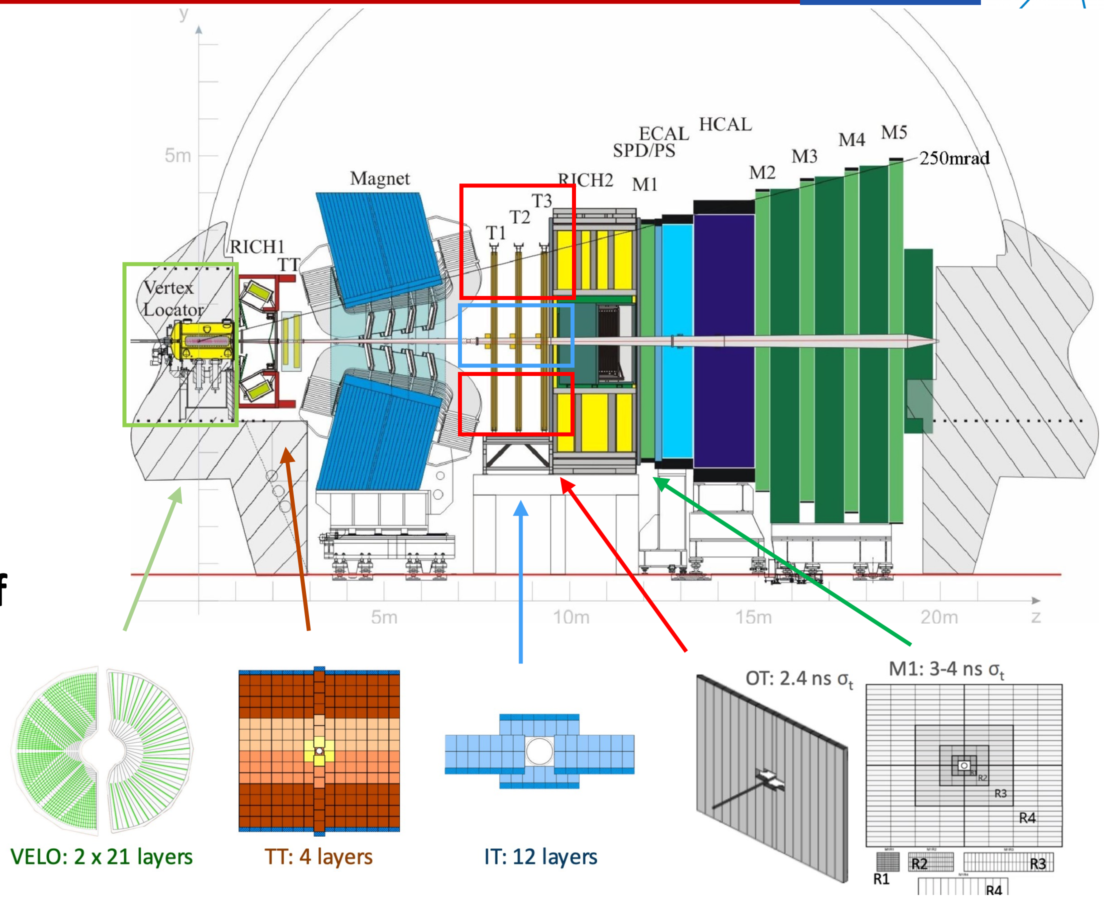
Identification of nuclei with LHCb

- LHCb detector not initially designed to identify light (anti)nuclei
- Use ***dE*/dx** $\propto$ **Z²** from the silicon detectors (VELO, TT, IT)
  - identification of **Helium**, good separation for Z≥2
- **Time-of-Flight** (OT, M1) → β = Δt / L
  - identification of **d**, separation of **³He, ⁴He**

- With **SMOG** can be used as a fixed-target experiment
- Collect physics samples with different **targets** and different **centre of mass energies**

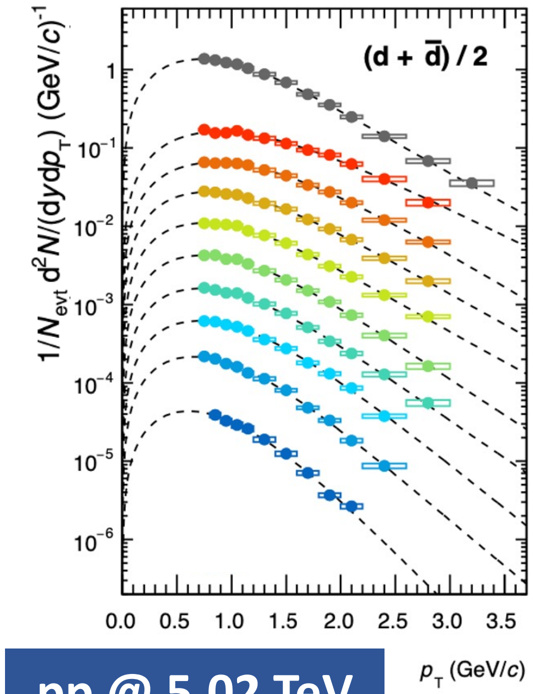




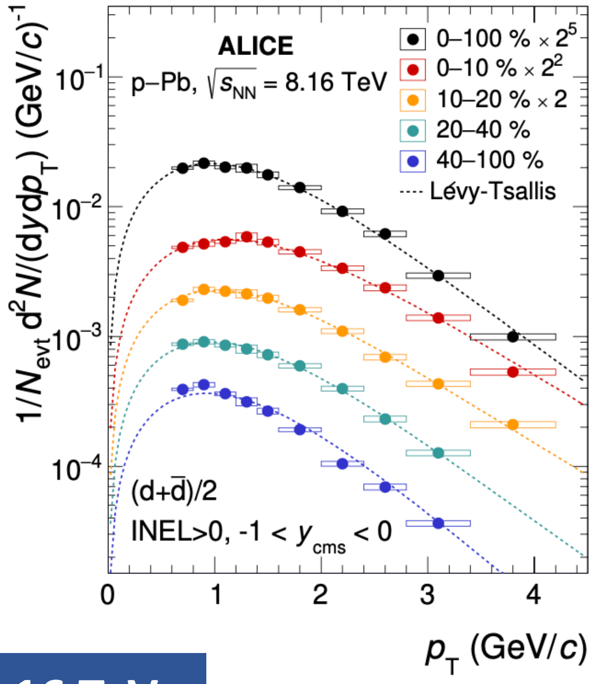
LHCb Collaboration, JINST 3 S08005 (2008)

- Energy range $\sqrt{s_{NN}} \in$ [30,115] GeV for beam energy in [0.45, 7] TeV → Unexplored gap between SPS and LHC/RHIC

Measurement of (anti)nuclei with A=2

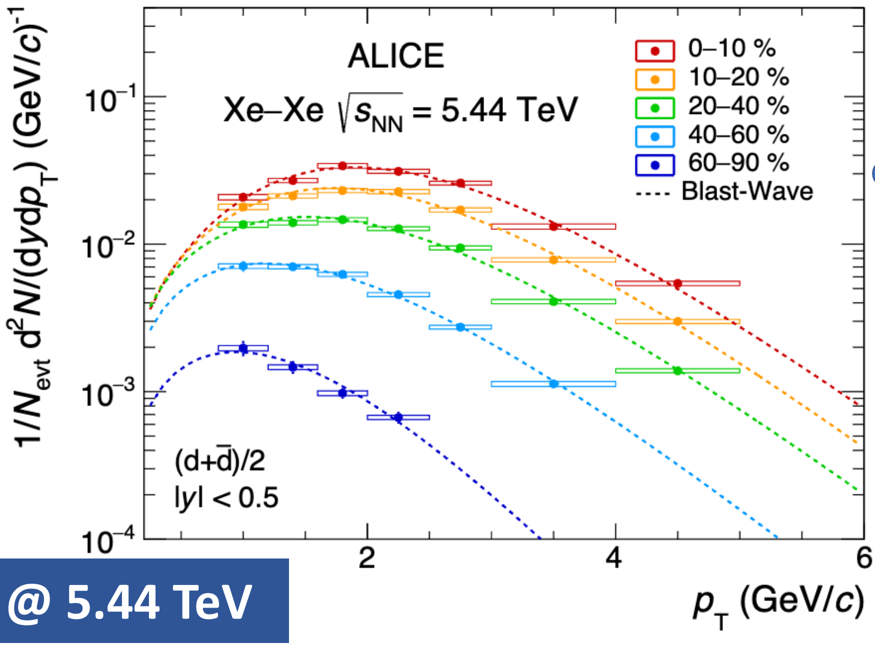


pp @ 5.02 TeV



p-Pb @ 8.16 TeV

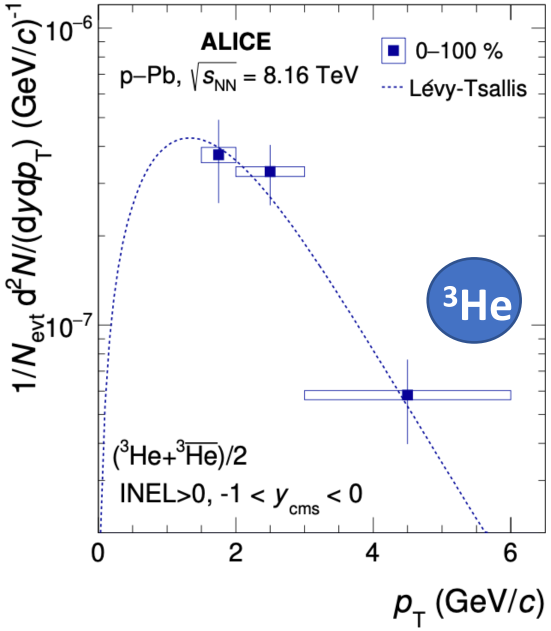
- Deuterons have been measured in narrow multiplicity classes in all systems, from pp to heavy-ions
- Momentum distributions fitted to extrapolate the yield in the unmeasured regions



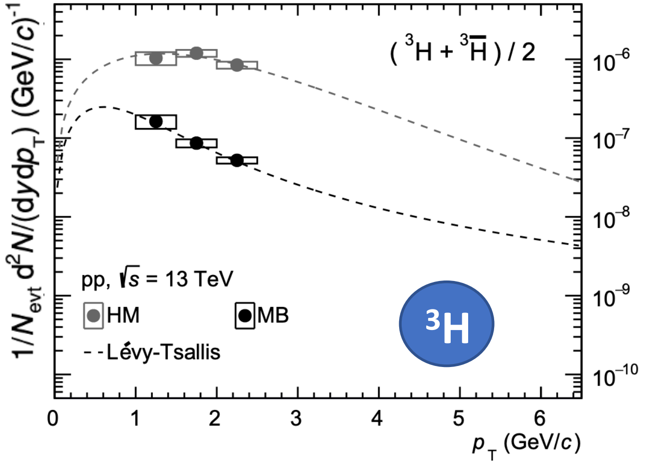
Xe–Xe @ 5.44 TeV

pp: ALICE Collaboration, EPJC (2022) 82:289
p-Pb: ALICE Collaboration, PLB 846 (2023) 137795
Xe-Xe: ALICE Collaboration, arXiv:2405.19826
Pb-Pb: ALICE Collaboration, arXiv:2311.11758

Measurement of (anti)nuclei with A=3

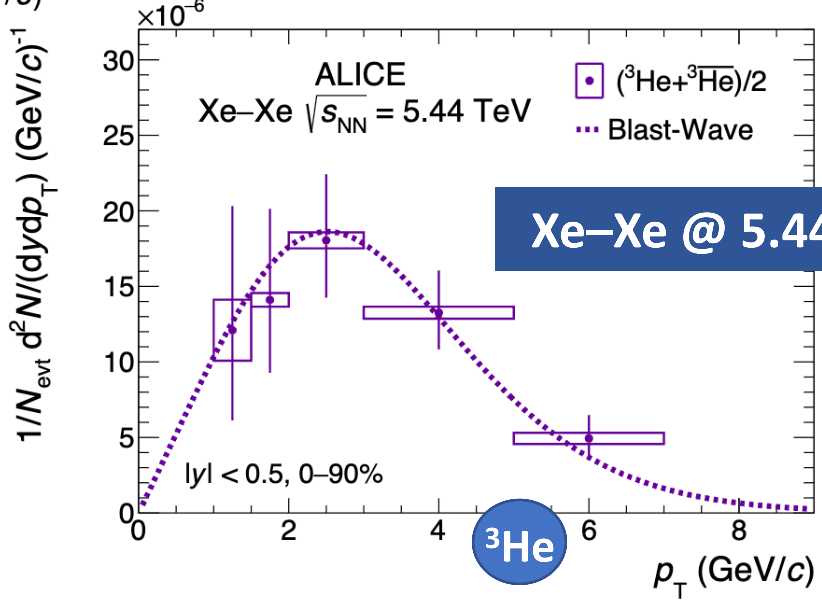


p-Pb @ 8.16 TeV



pp @ 13 TeV

(anti)^{3}He, (anti)^{3}H and (anti)$^{3}_{\Lambda}$H have been measured in all collision systems by ALICE



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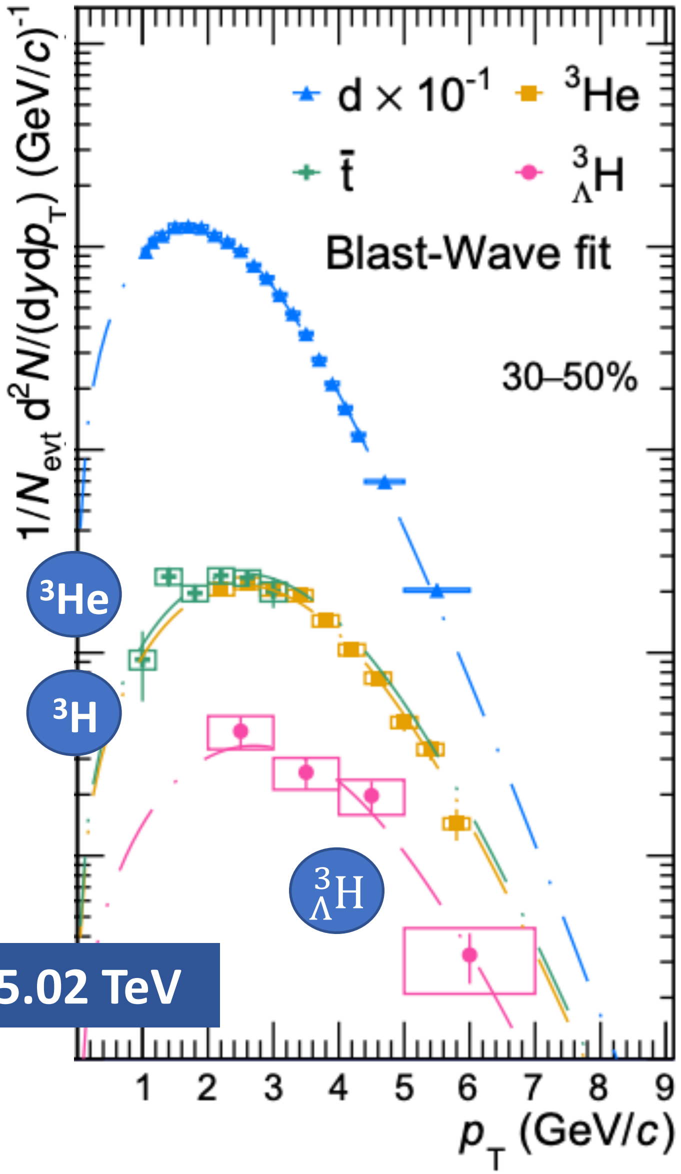
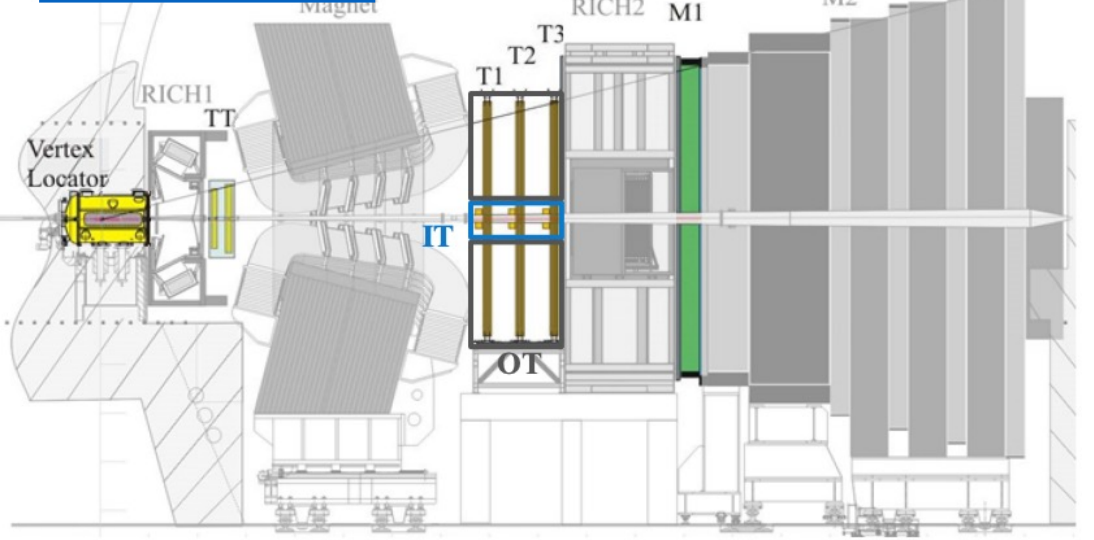


Pb—Pb @ 5.02 TeV

pp: ALICE Collaboration, JHEP 01 (2022) 106
p-Pb: ALICE Collaboration, PLB 846 (2023) 137795
Xe-Xe: ALICE Collaboration, arXiv:2405.19826
Pb-Pb: ALICE Collaboration, arXiv:2405.19839

Identification of nuclei with A=3 with LHCb

[JINST 3 S08005 (2008)](https://doi.org/)



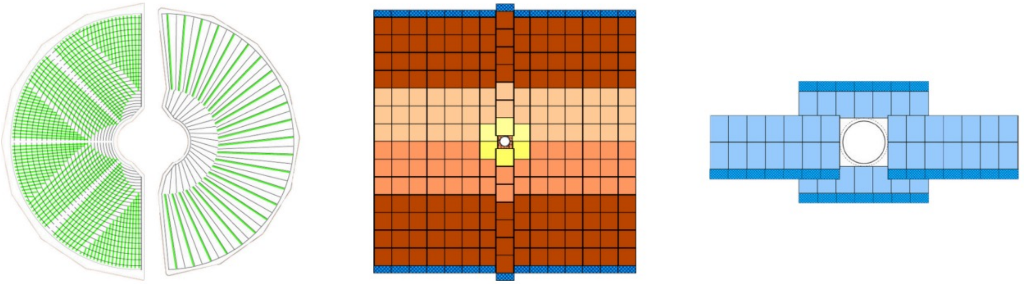
LHCb detector not designed to identify light (anti)nuclei

↓

Use information from the tracking system

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

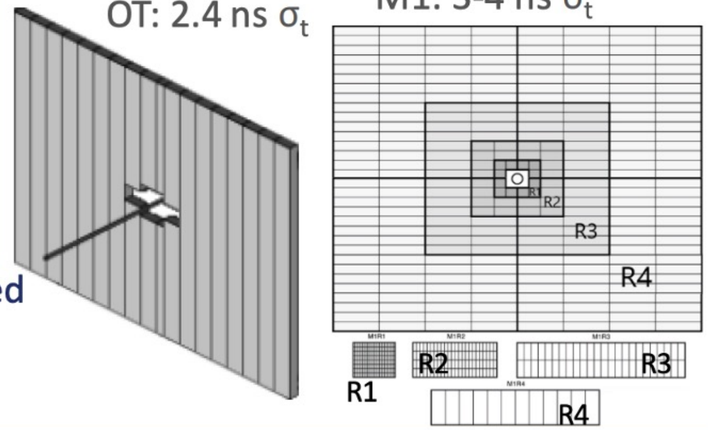
→ dE/dx in VELO, TT, IT to **identify He**



VELO: 2 x 21 layers — TT: 4 layers — IT: 12 layers

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

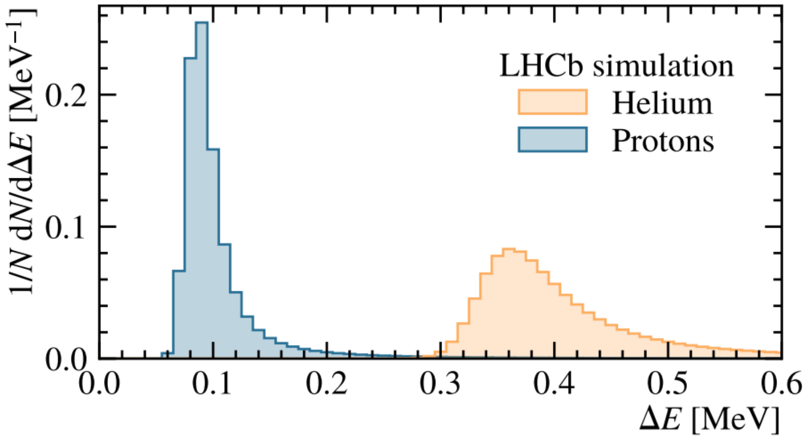
→ **Time-of-flight** in OT and M1 to **identify d, distinguish ^{3}He and ^{4}He**



- excellent vertexing (σ_{IP} = 15+29/p_T [GeV] μm, σ_p= 0.5% − 1.0%)
  - excellent PID separation for K, π and p with O(10) GeV/c

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

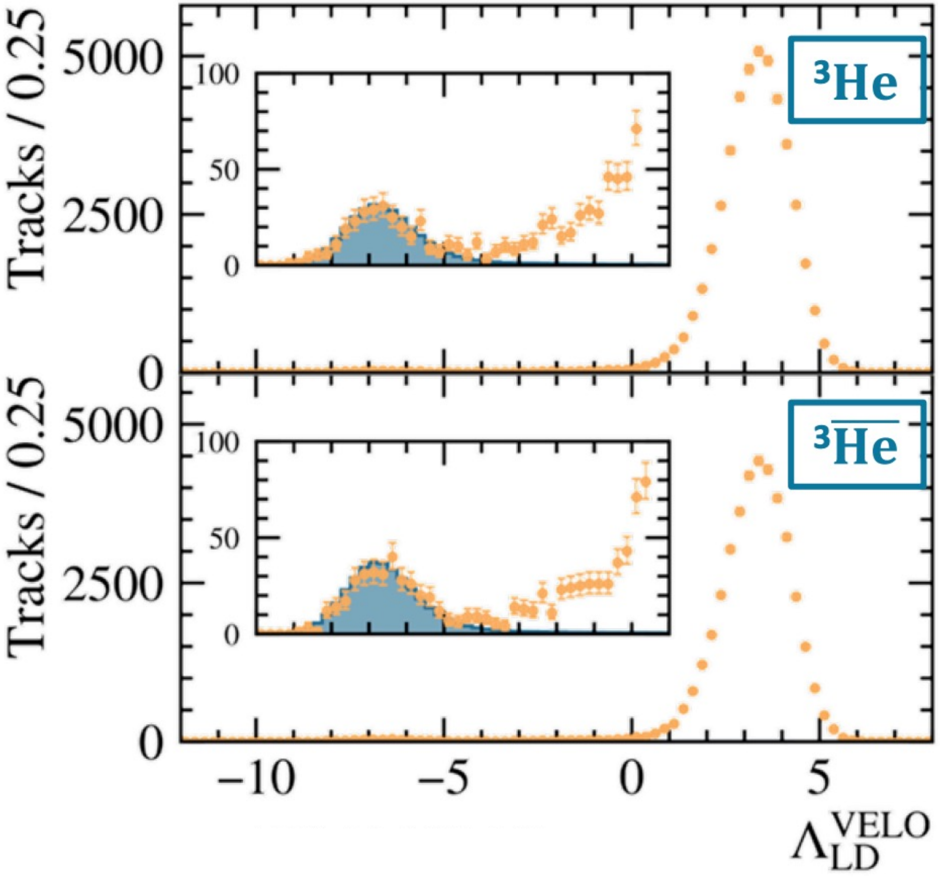
Identification of ^{3}He with LHCb



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!



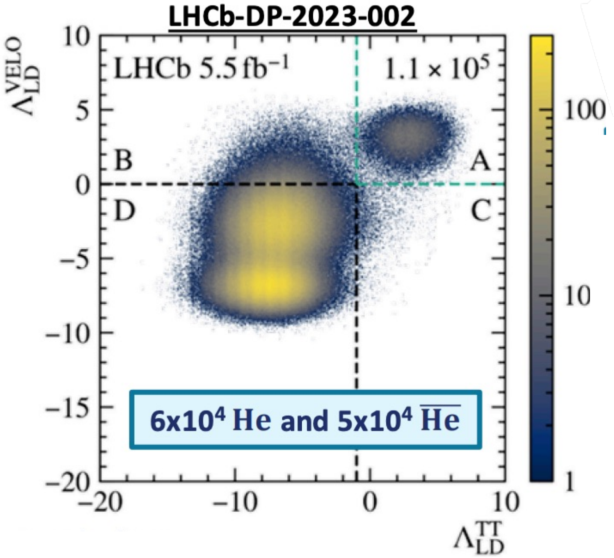
Define Likelihood discriminators based on cluster size and ADC counts:

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

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

One discriminator for each subdetector:

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



Performance:

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

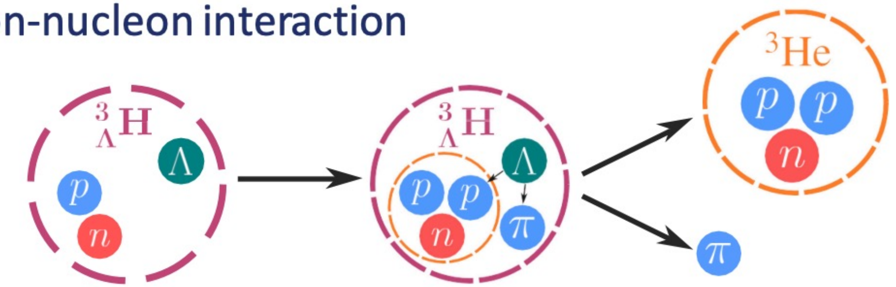
LHCb Collaboration, JINST 19 (2024) P02010

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:

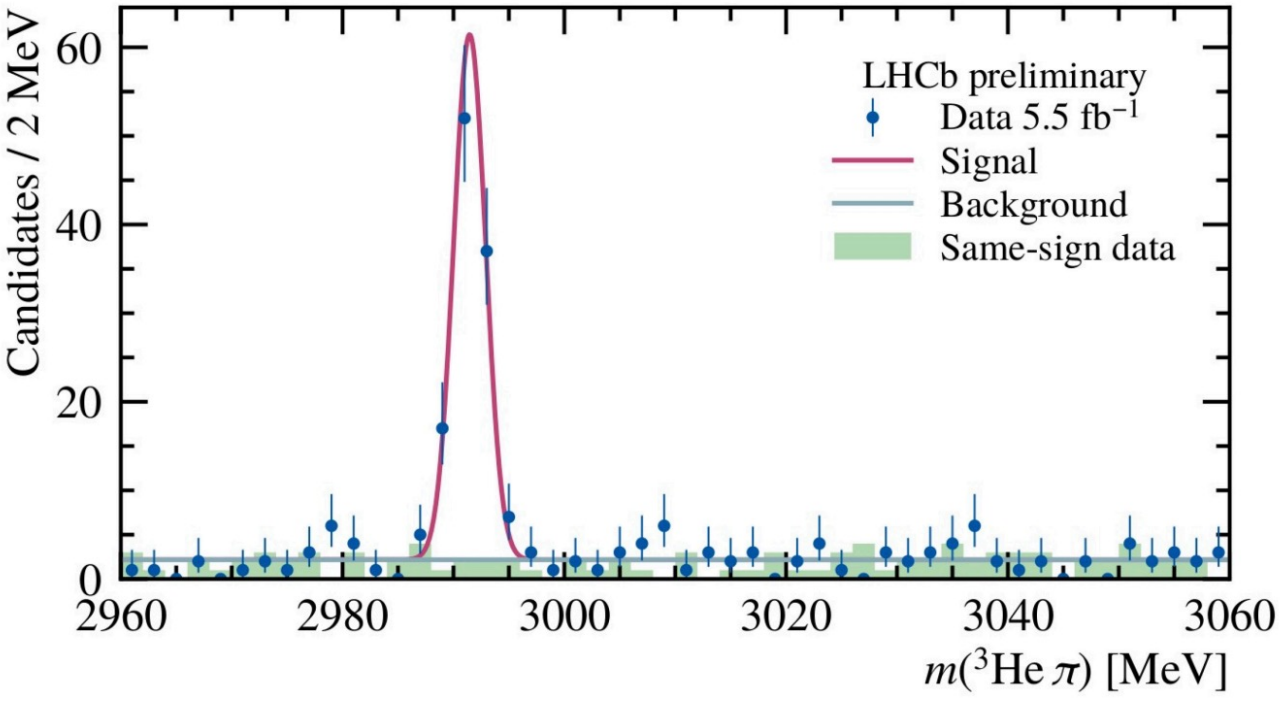
$$ {}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He}\,\pi^{-} + cc $$



Results:

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

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



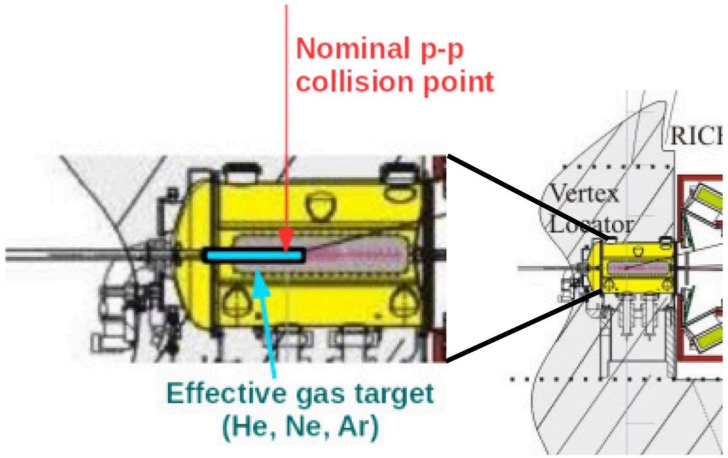
This measurement shows the applicability of ^{3}He reconstruction and paves the way for future measurements of astrophysical interest

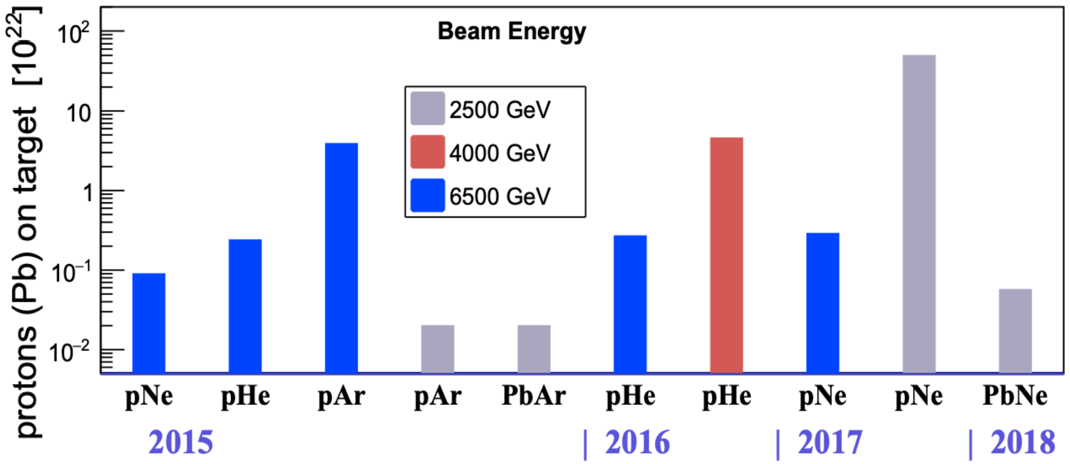
https://cds.cern.ch/record/2881940/files/MPI23_v1.pdf

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

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 $\sqrt{s_{NN}} \in [30,115]$ GeV for beam energy in [0.45, 7] TeV → Unexplored gap between SPS and LHC/RHIC

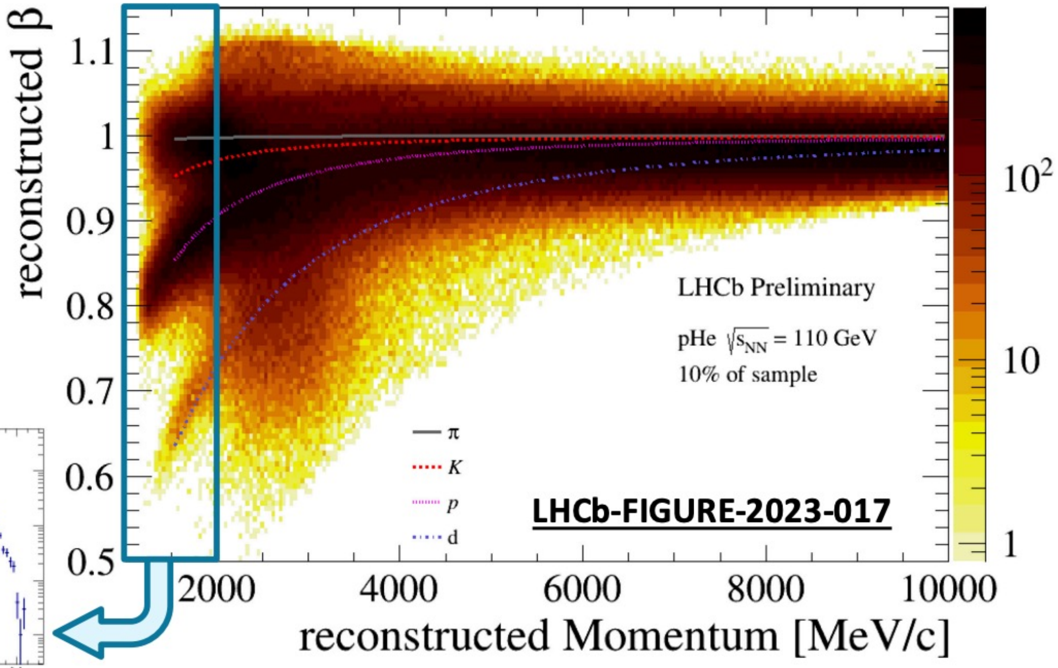
LHCb contribution is relevant for astrophysics applications!

LHCb Collaboration, LHCb-PUB-2018-015

(anti)deuteron identification with LHCb

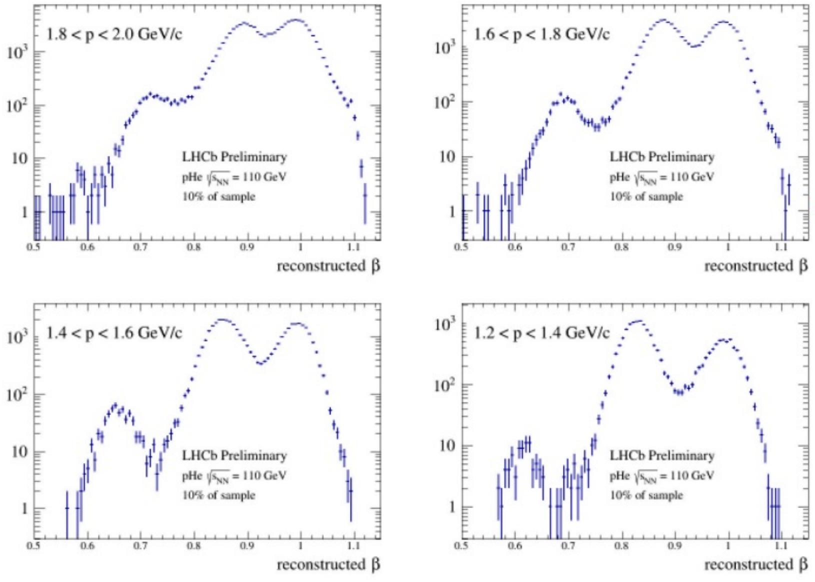
LHCb is now also capable of measuring (anti)deuterons

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



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

First deuteron candidates observed in *p*He data!



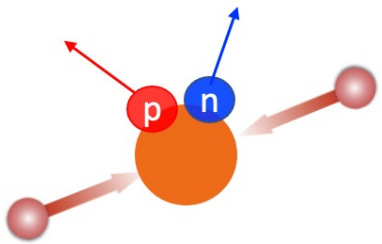
LHCb-FIGURE-2023-017

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

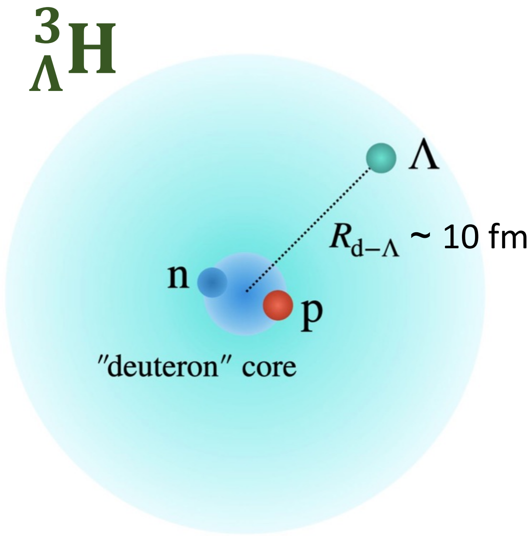
Testing production models with hypertriton

- 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**

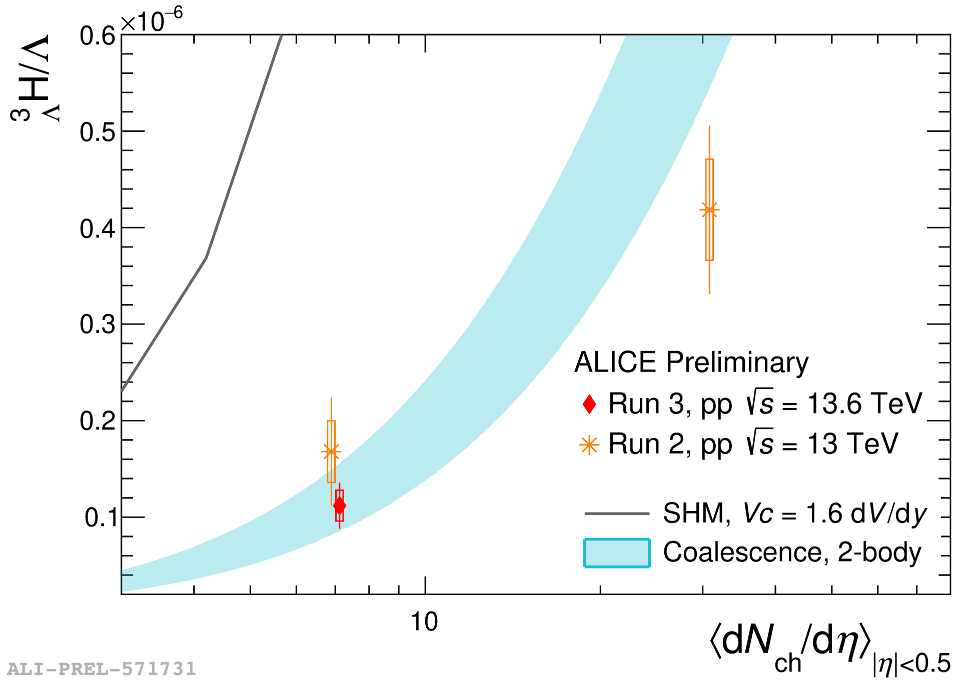
$^{3}_{\Lambda}H/\Lambda$ ratio provides a powerful tool to investigate nuclear production mechanism



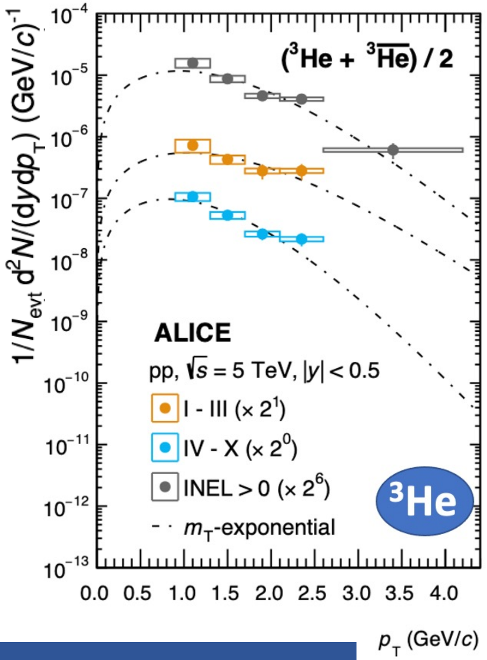
System size (pp, p—Pb): 1–1.5 fm
r_d : 1.96 fm
r_{3He}: 1.76 fm
$r_{^{3}_{\Lambda}H\,(np\Lambda)}$: 4.9 fm ($B_\Lambda$= 2.35 MeV)
$r_{^{3}_{\Lambda}H\,(d\Lambda)}$: 10 fm ($B_\Lambda \sim$ 0.13 MeV)



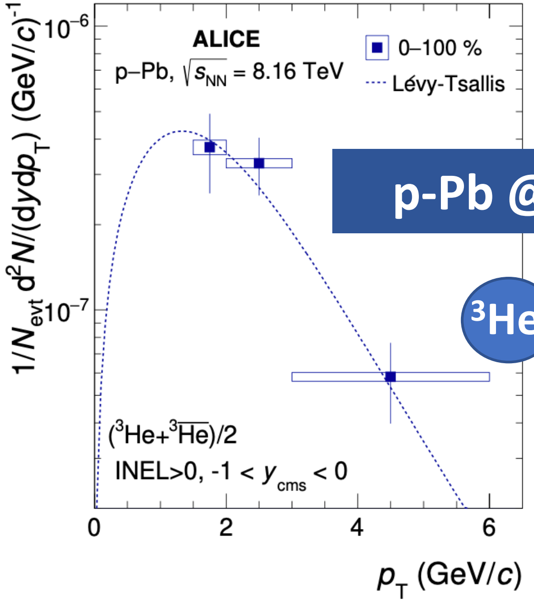
powerful probe for investigating the nucleon – Λ interaction



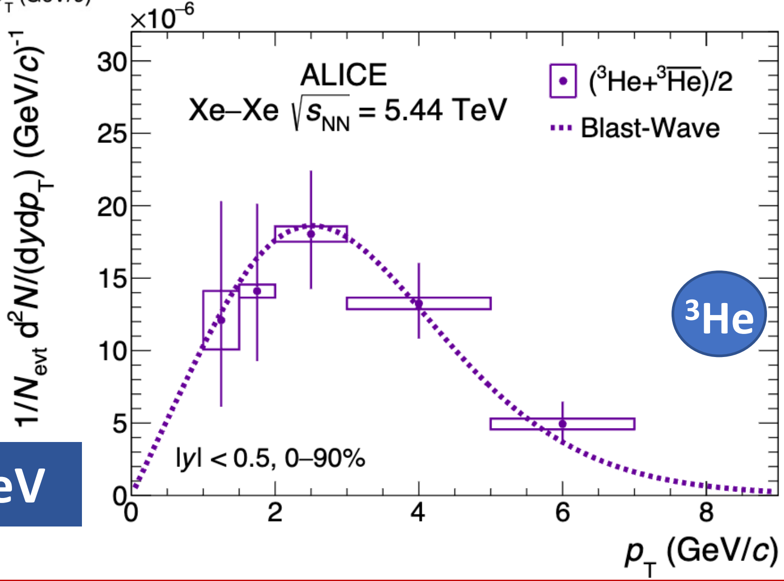
Measurement of (anti)nuclei with A=3



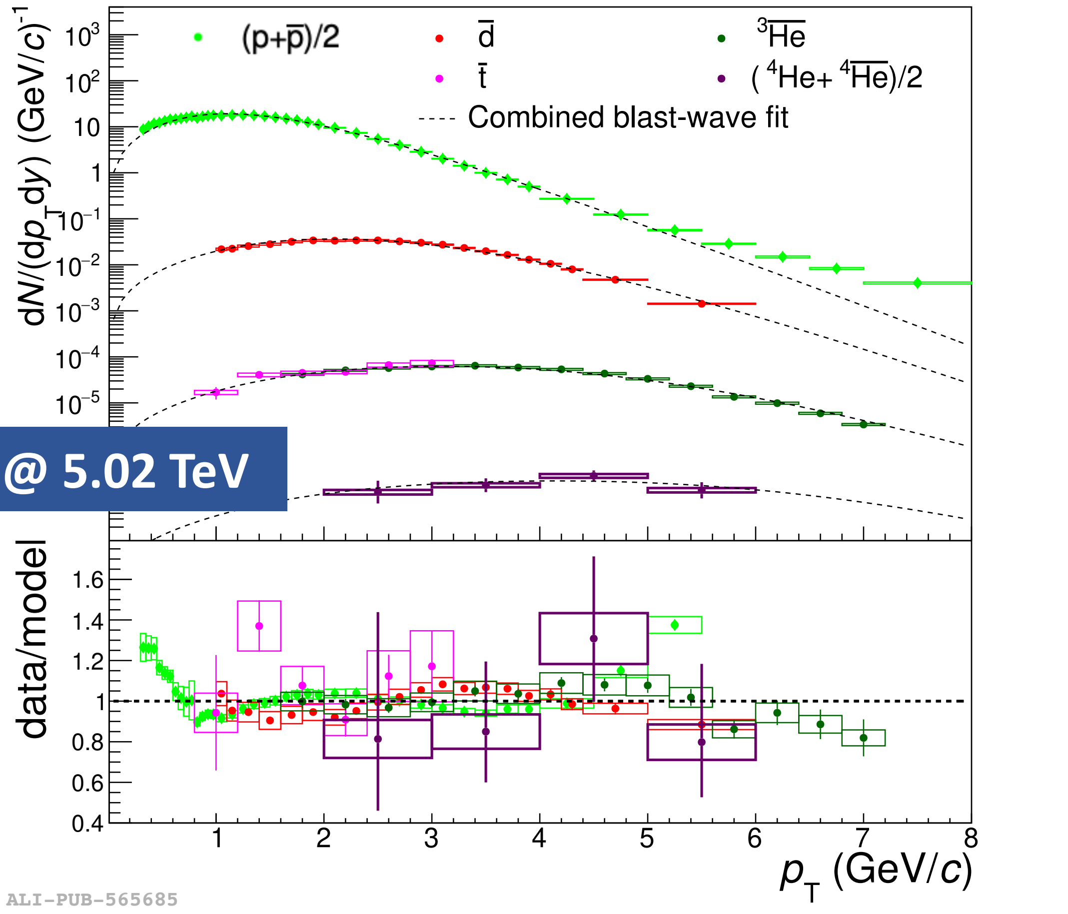
pp @ 5.02 TeV



p-Pb @ 8.16 TeV



Xe–Xe @ 5.44 TeV

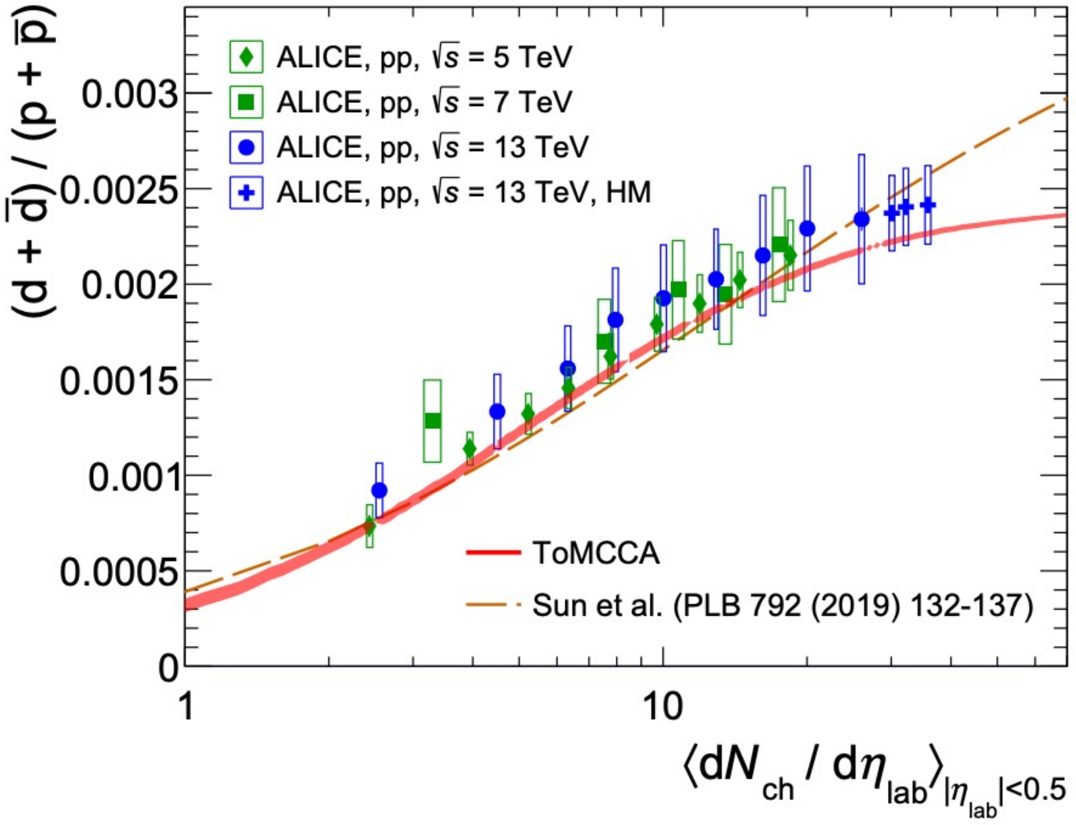


Pb—Pb @ 5.02 TeV

pp: ALICE Collaboration, EPJC (2022) 82:289
p-Pb: ALICE Collaboration, PLB 846 (2023) 137795
Xe-Xe: ALICE Collaboration, arXiv:2405.
Pb-Pb: ALICE Collaboration, arXiv:2311.11758

chiara.pinto@cern.ch

Testing production models (focus at low multiplicity)

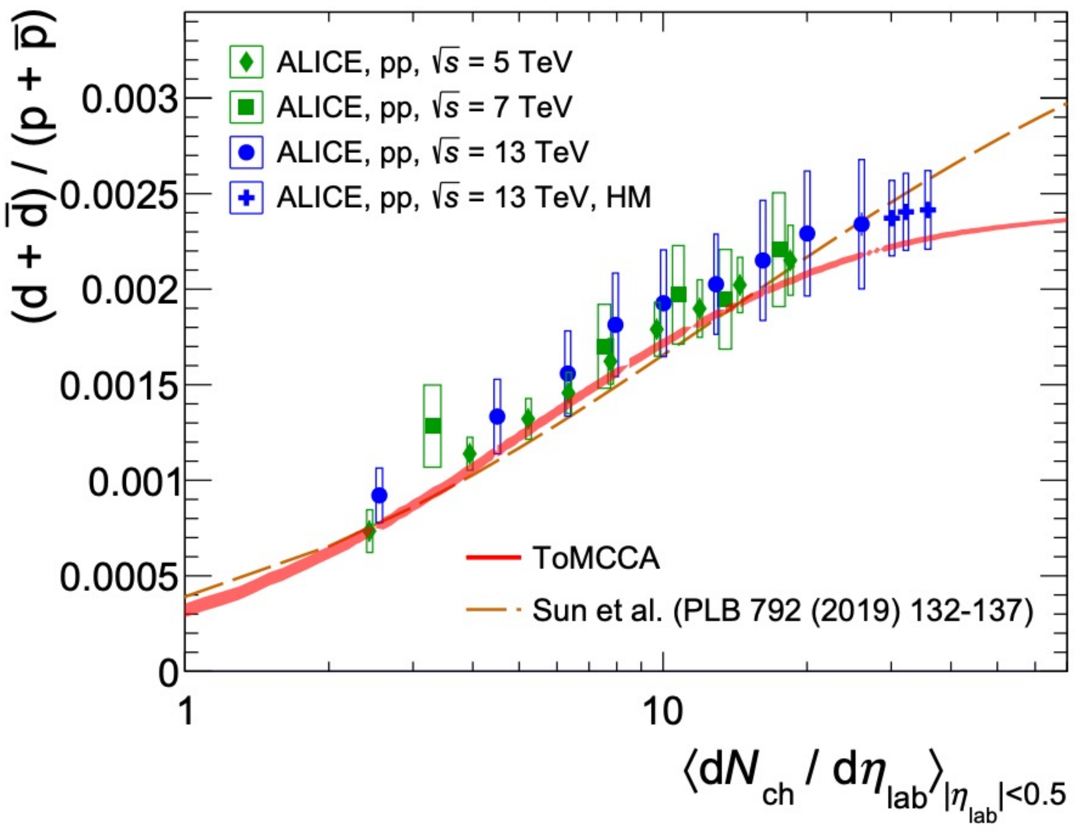


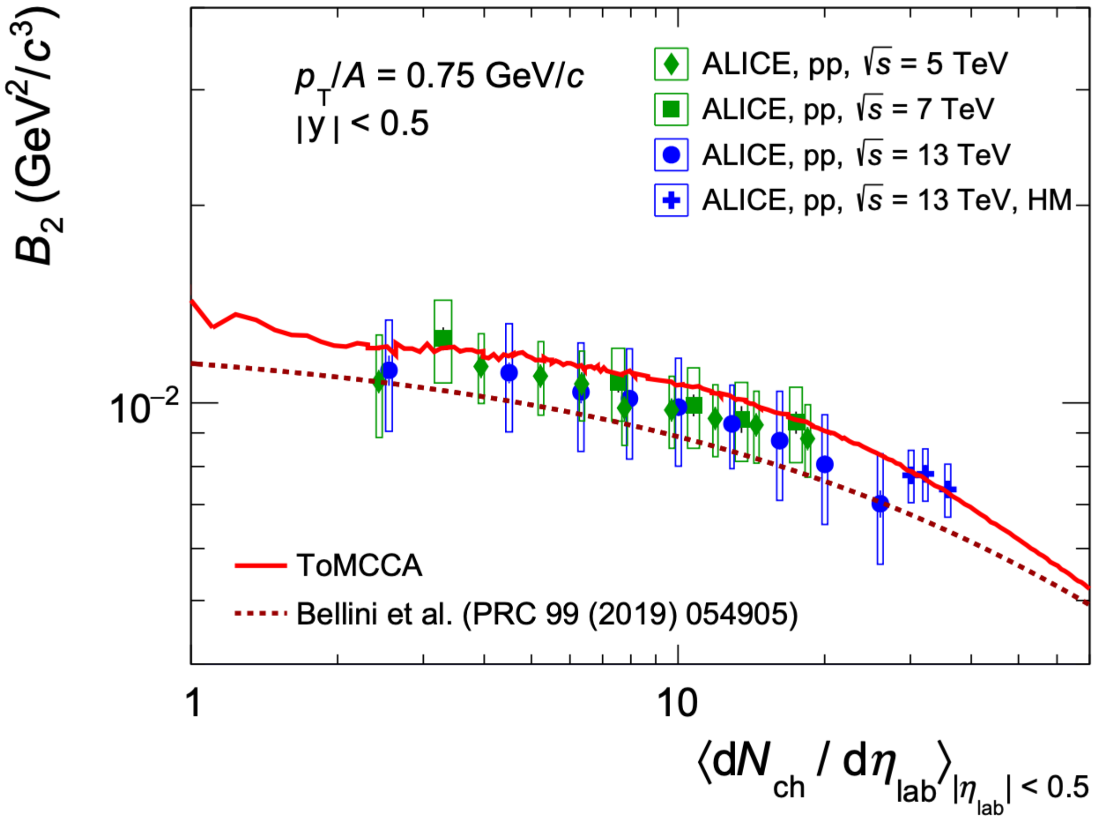
Predictions available only for the pp multiplicity range (1-70)

- **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

Testing production models (focus at low multiplicity)



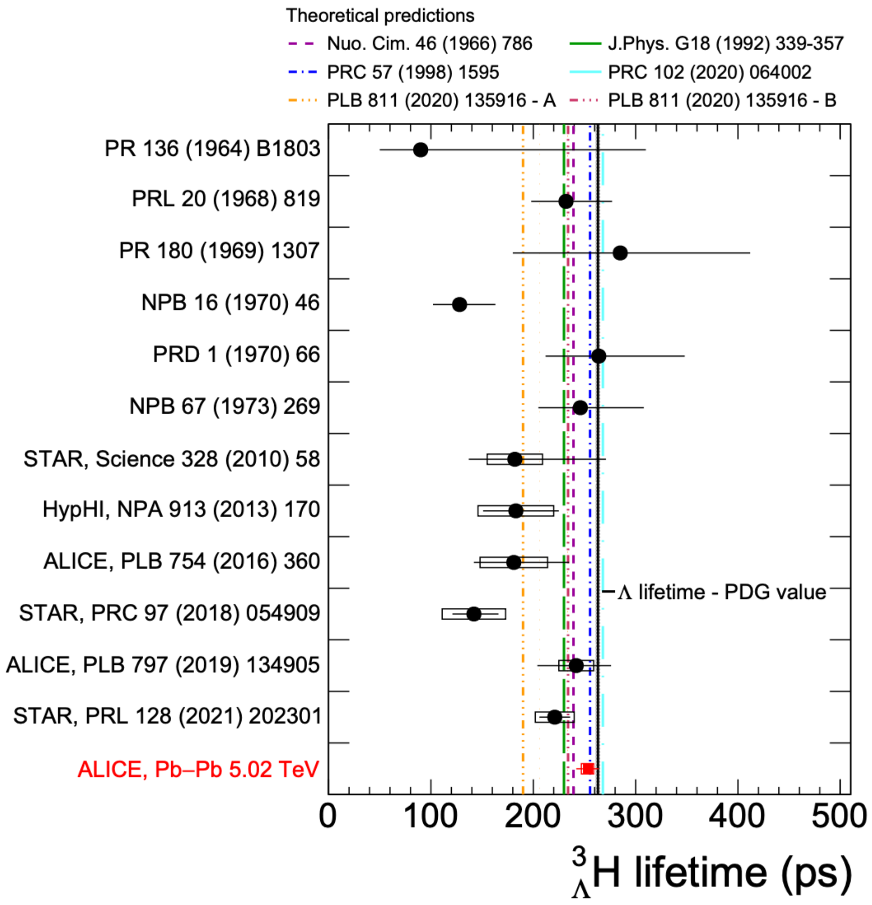


- **Coalescence** predictions of ToMCCA using Wigner function formalism & multiplicity-dependent input (momentum distributions of nucleons, source size and multiplicity distributions) reproduce all data points within 1sigma
- No ^{3}He coalescence predictions yet
- Also coalescence parameter B_2 vs multiplicity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

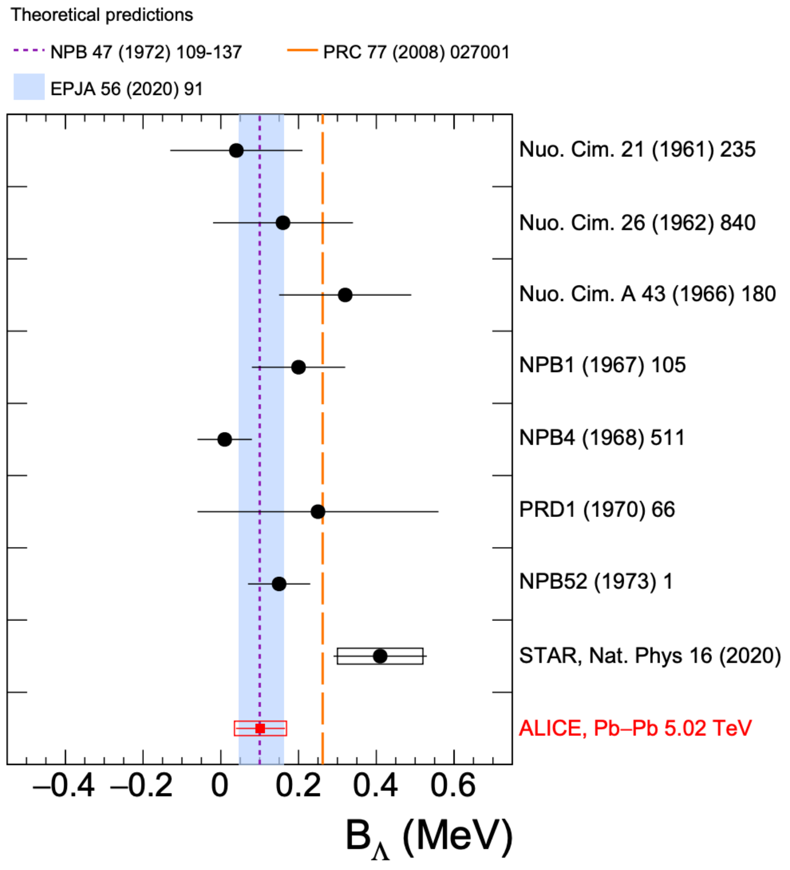
Mahlein, Pinto, Fabbietti, arXiv:2404.03352

Hypertriton lifetime & binding energy (Pb–Pb collisions)

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



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



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

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

Phys. Rev. Lett. 131 (2023) 102302

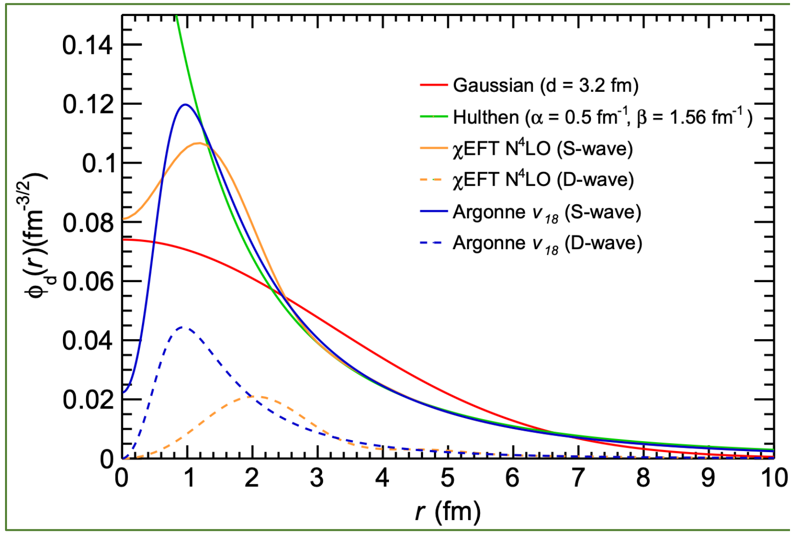
State-of-the-art coalescence model

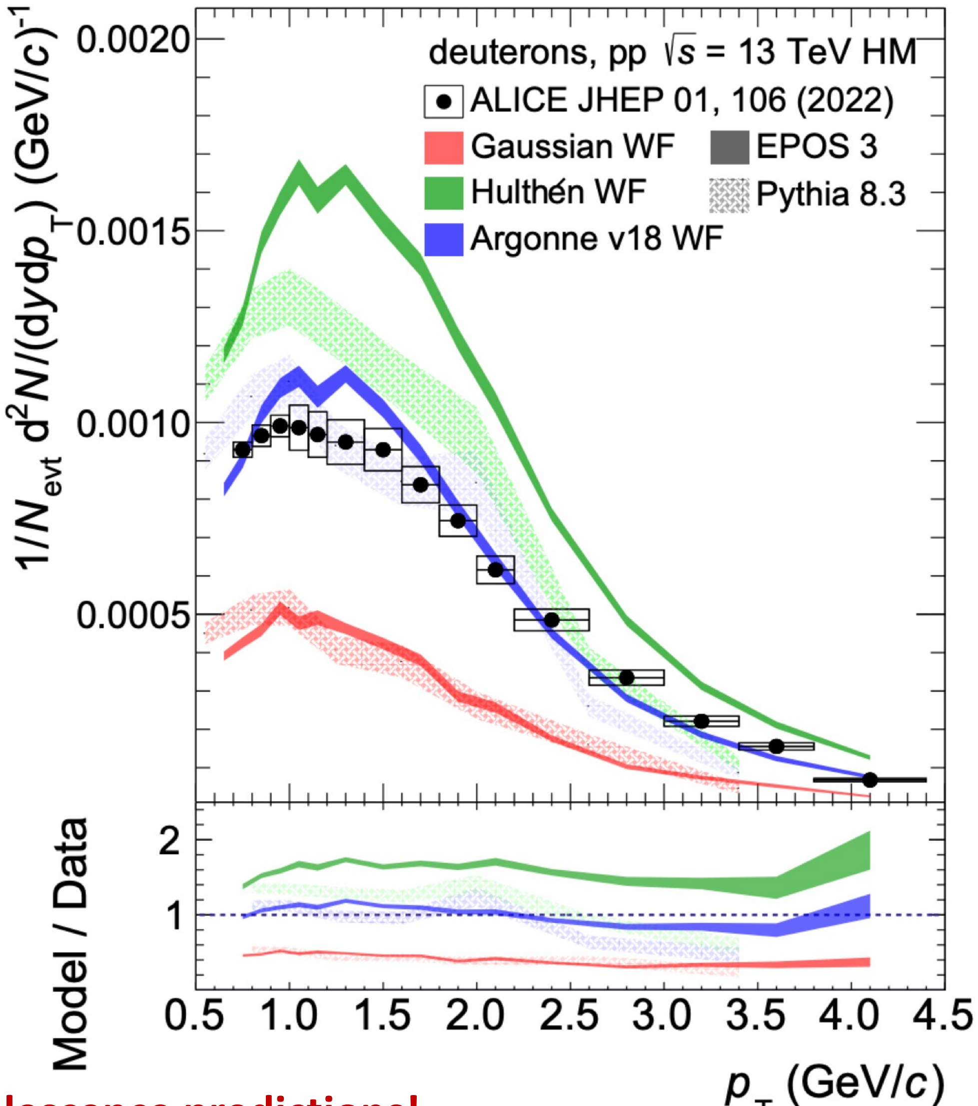
Coalescence afterburner based on Wigner function formalism

- 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

↓

- **Hulthén:** Favoured by low energy scattering experiments
- **Gaussian:** easiest WF calculation
- **Two Gaussians:** Approximates Hulthén, easy to use in calculations
- **χEFT:** Favoured by modern nuclear interaction experiments (e.g. Femtoscopy)
- **Argonne v18** phenomenological potential constrained to p-n scattering



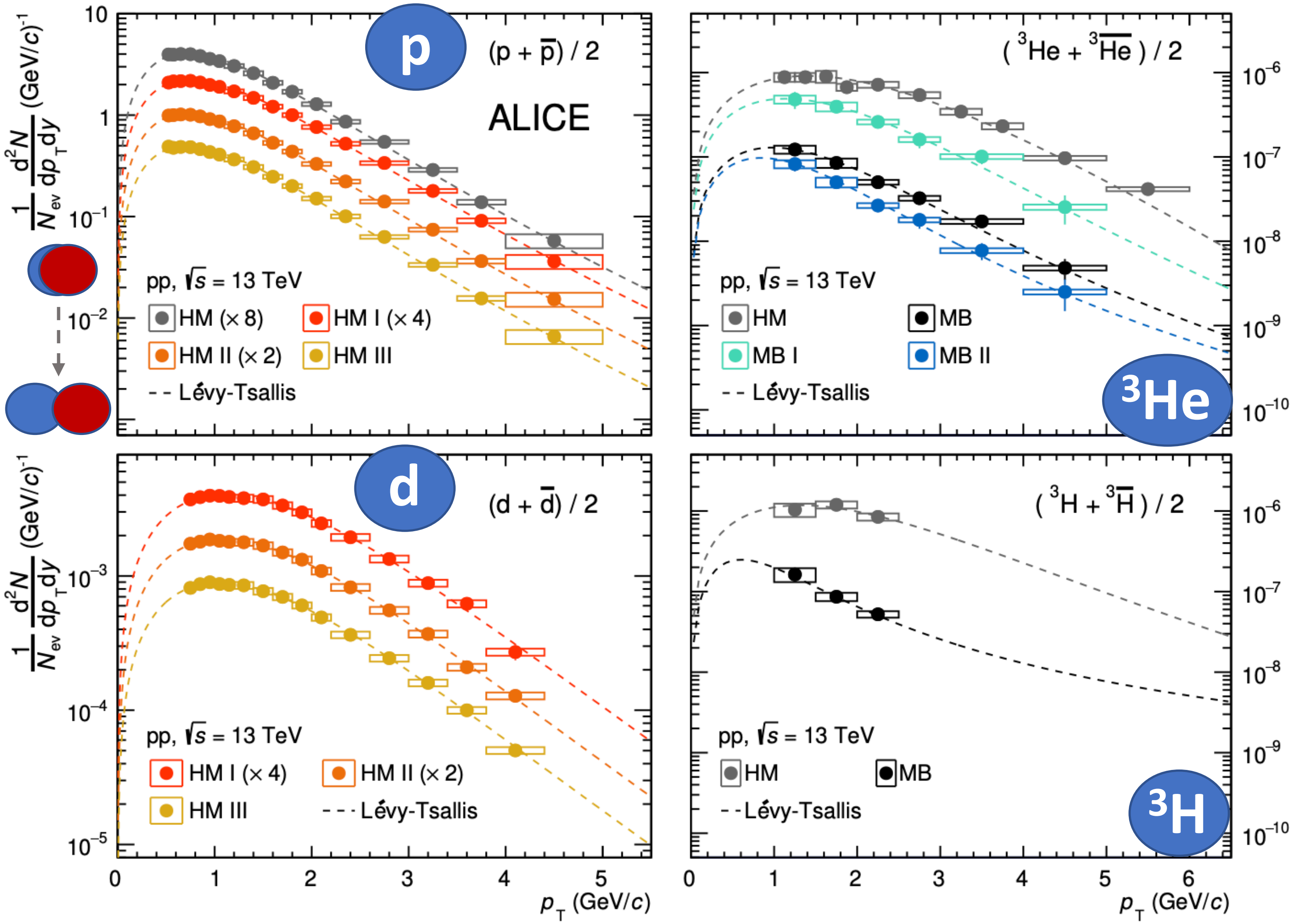


Mahlein et al., EPJC 83 (2023) 9, 804

Realistic wavefunction is key for coalescence predictions!

Measurement of light (anti)nuclei with ALICE

ALICE Collaboration, JHEP 01 (2022) 106

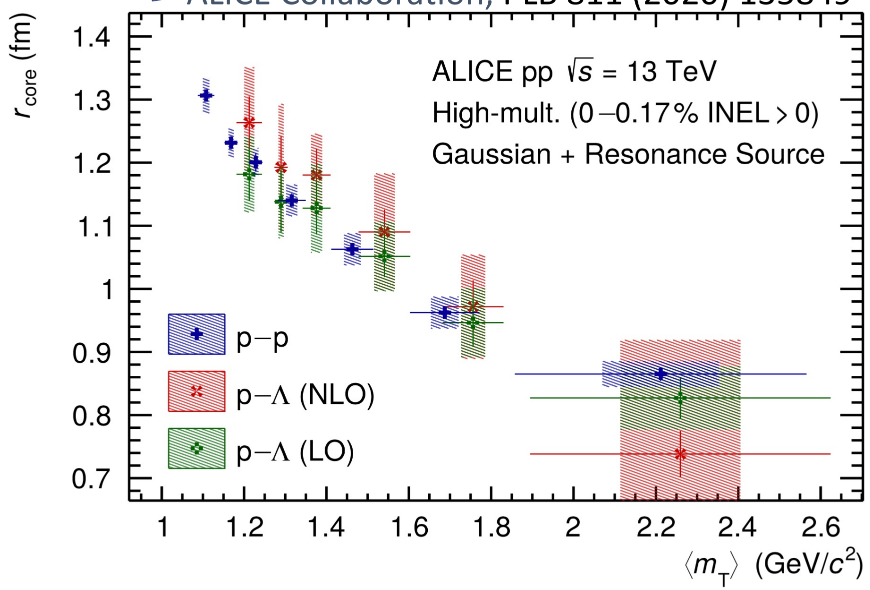


HM pp @ 13 TeV

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

→ **crucial to test the coalescence model**

ALICE Collaboration, PLB 811 (2020) 135849



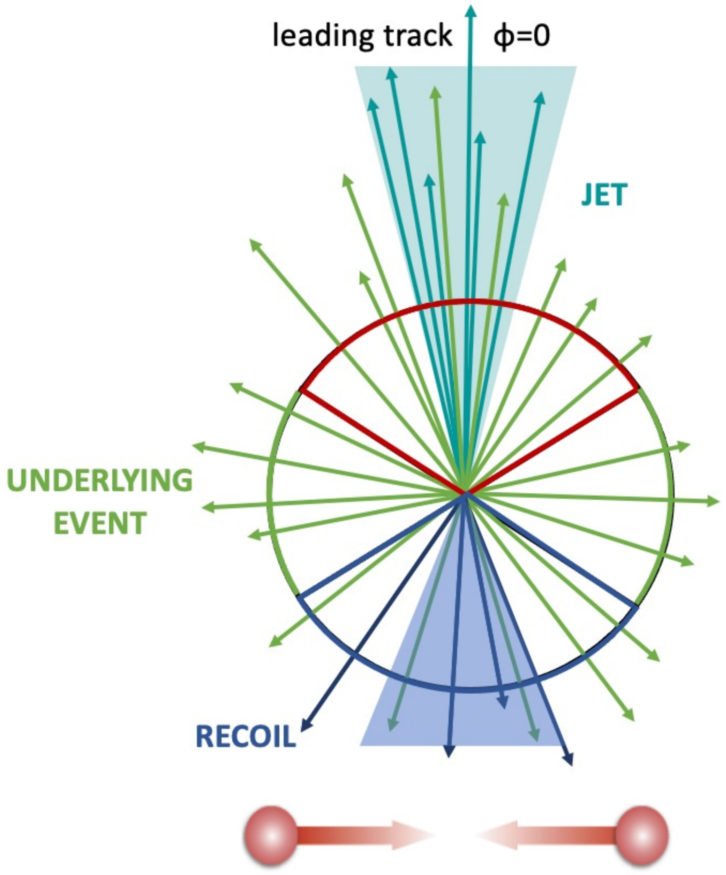
$\propto p_T$

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)

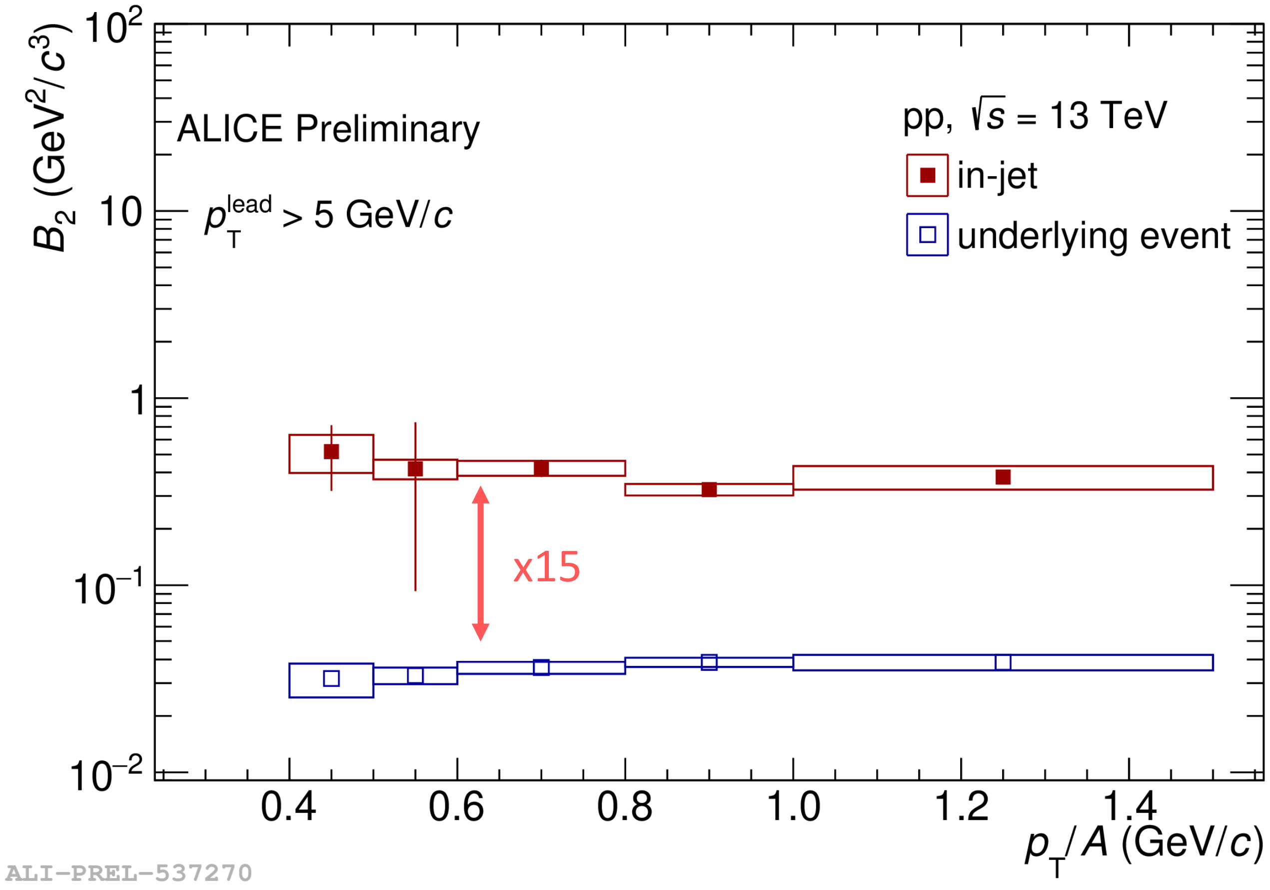
- Studying the antideuteron production in jets in small systems (pp, pA) is important to understand and model nuclear production
- Implications for cosmic ray physics
- Antideuteron in the Galaxy is produced in interactions of cosmic rays (p, ^{4}He) with kinetic energies of ~300 GeV

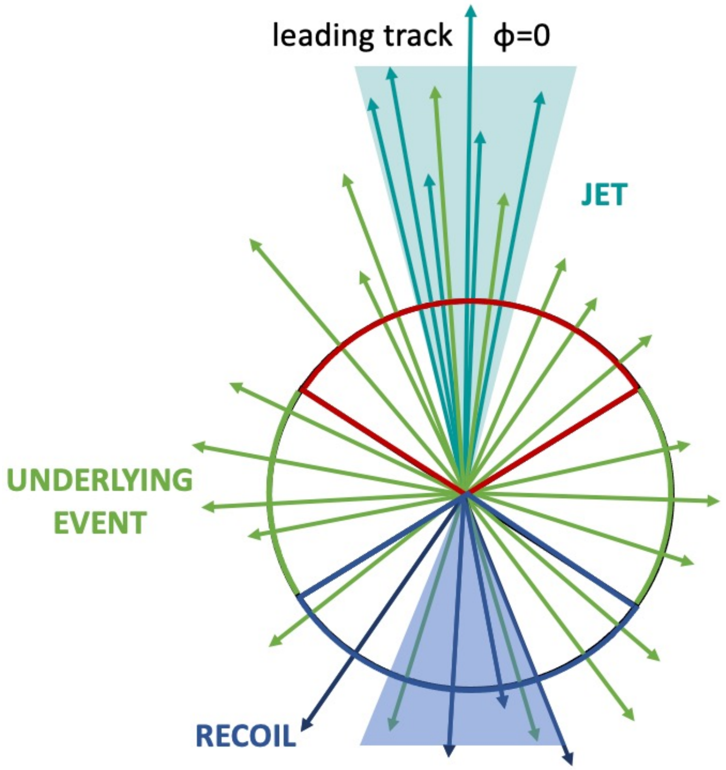


Toward: |Δϕ| < 60°
Transverse: 60° < |Δϕ| < 120°
Away: |Δϕ| > 120°

T. Martin et al., Eur. Phys. J. C (2016) 76: 299
Serksnyte et al., Phys. Rev. D 105 (2022) 8, 083021

Coalescence parameters in and out of jets

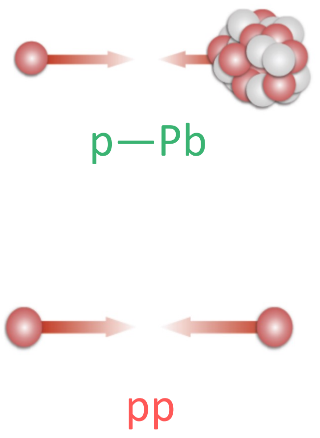


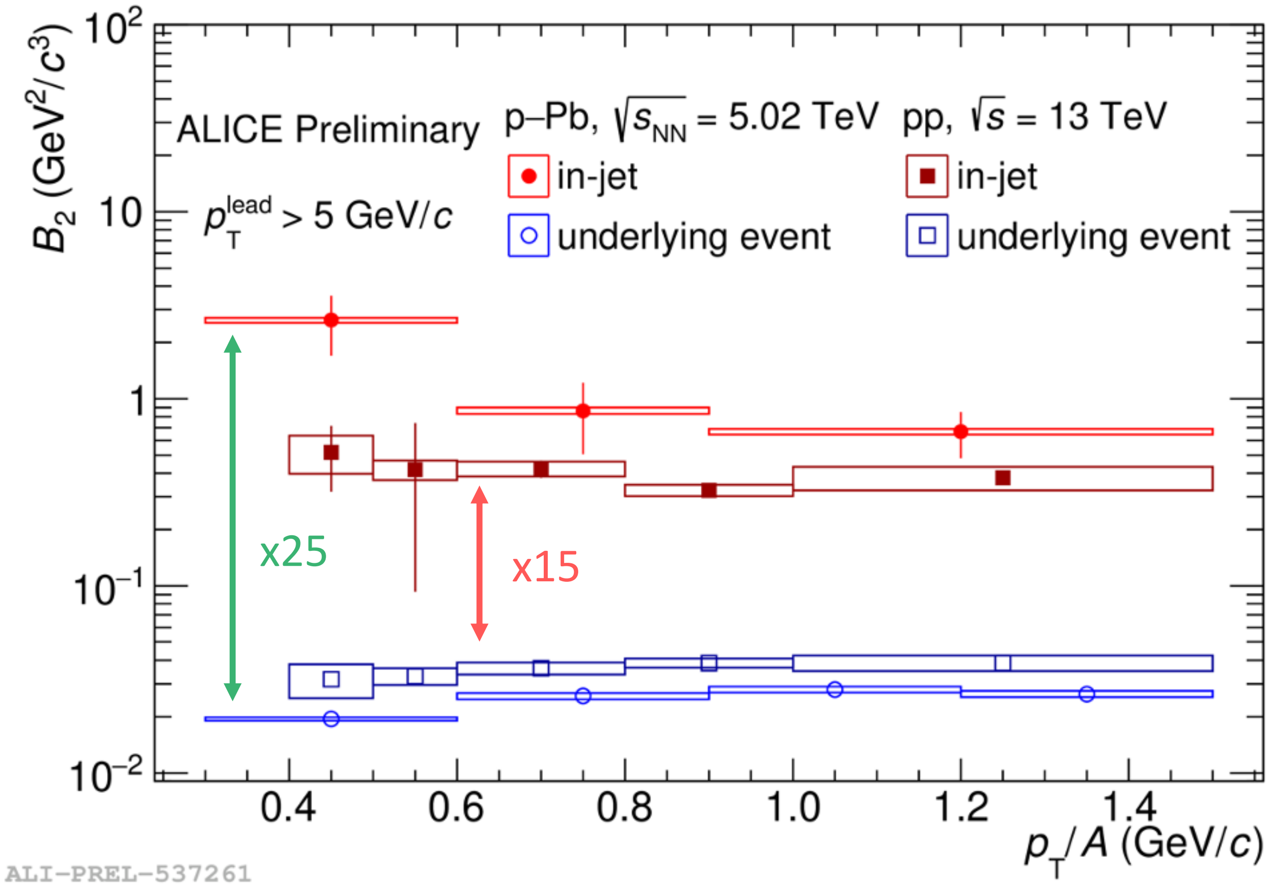


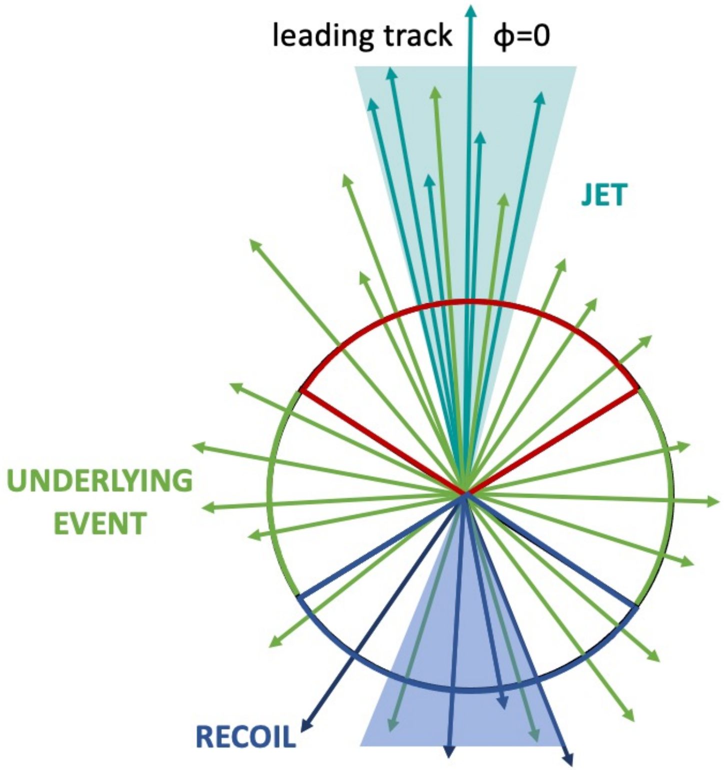
- *Enhanced deuteron coalescence probability in jets wrt UE is observed for the first time in pp collisions*
- Due to the reduced distance in phase space of hadrons in jets compared to those out of jets → favors coalescence picture

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

Coalescence parameters in and out of jets



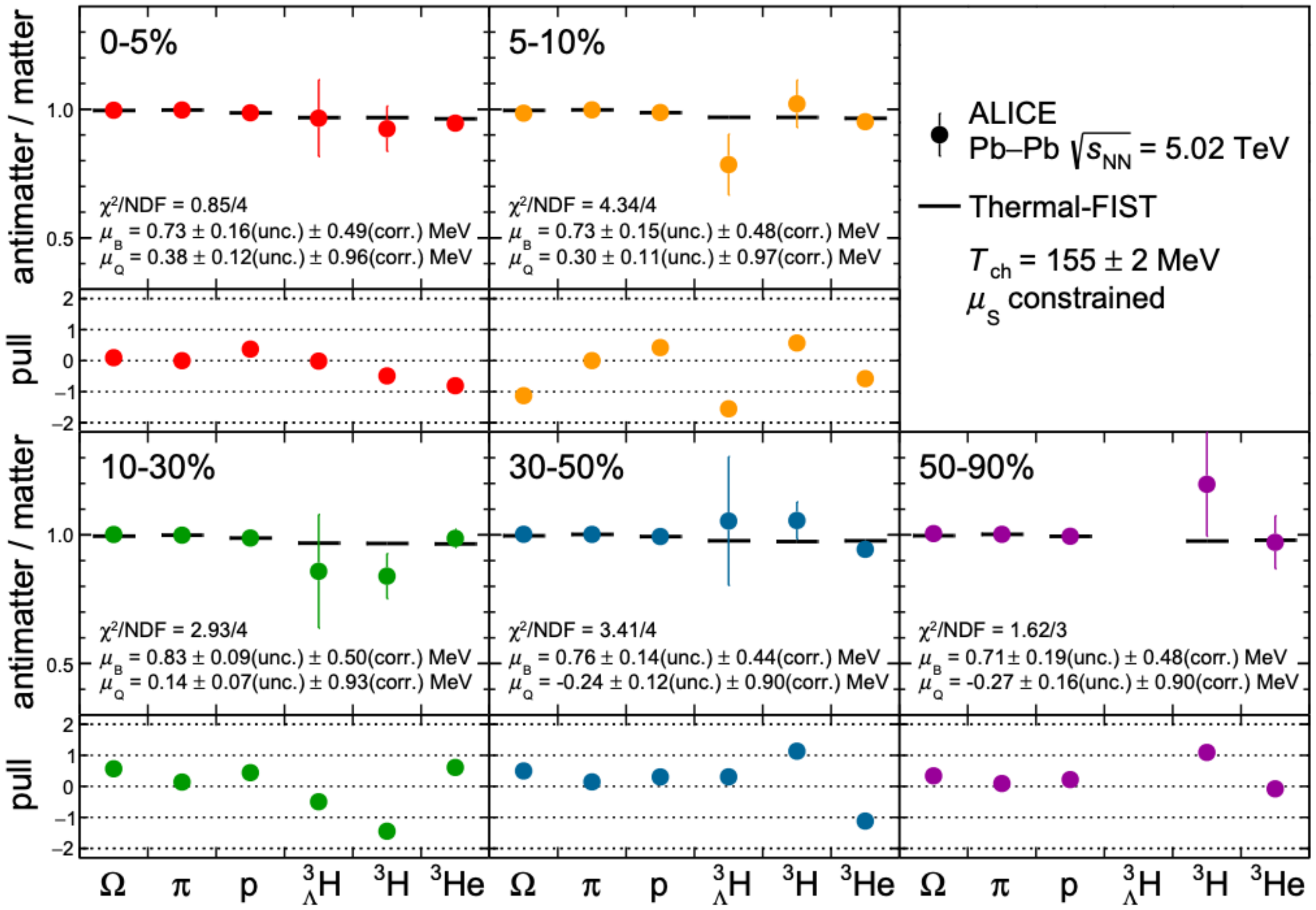




- B_2 in-jet in p—Pb is larger than B_2 in-jet in pp
  → *could be* related to the different particle composition of jets in pp and p—Pb → *to be further investigated*
- B_2 in UE in p—Pb is smaller than B_2 in UE in pp due to the larger source size in p—Pb (pp[1]: r_0~ 1 fm, p—Pb[2]: r_0~ 1.5 fm)

[1] Phys.Rev.C 99 (2019) 024001
[2] Phys.Rev.Lett. 123 (2019) 112002
Phys.Rev.Lett. 131 (2023) 4, 042301

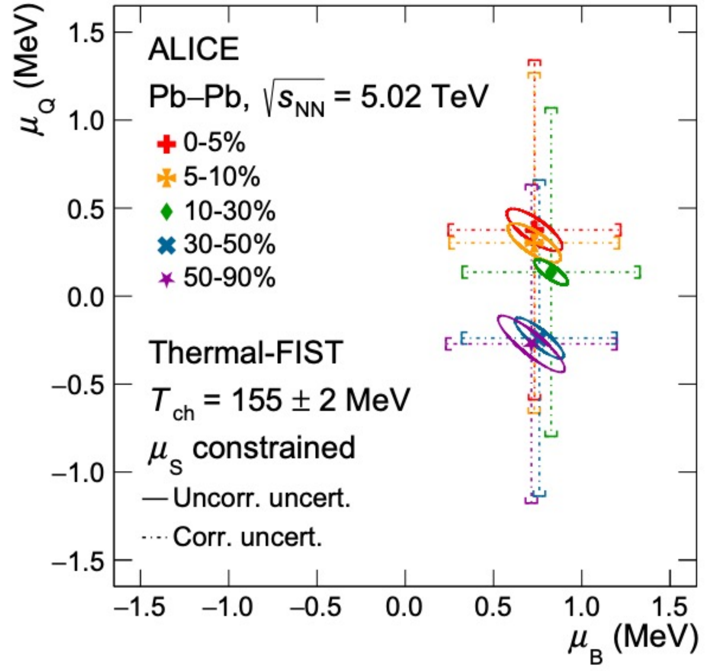
Chemical potential at the LHC

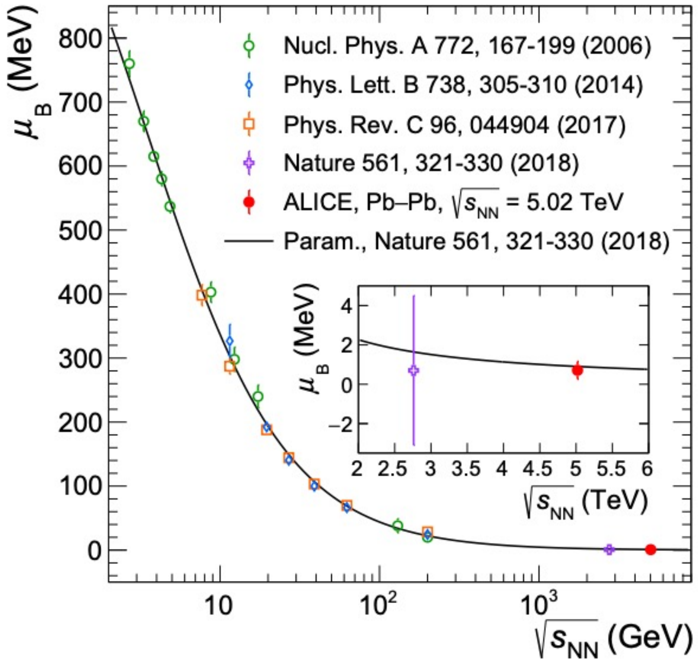


- μ_B and μ_Q are extracted fitting the antiparticle-to-particle yield ratios with the predictions of the grand-canonical SHM using the Thermal-FIST code

ALICE Collaboration, arXiv:2311.13332

Chemical potential at the LHC





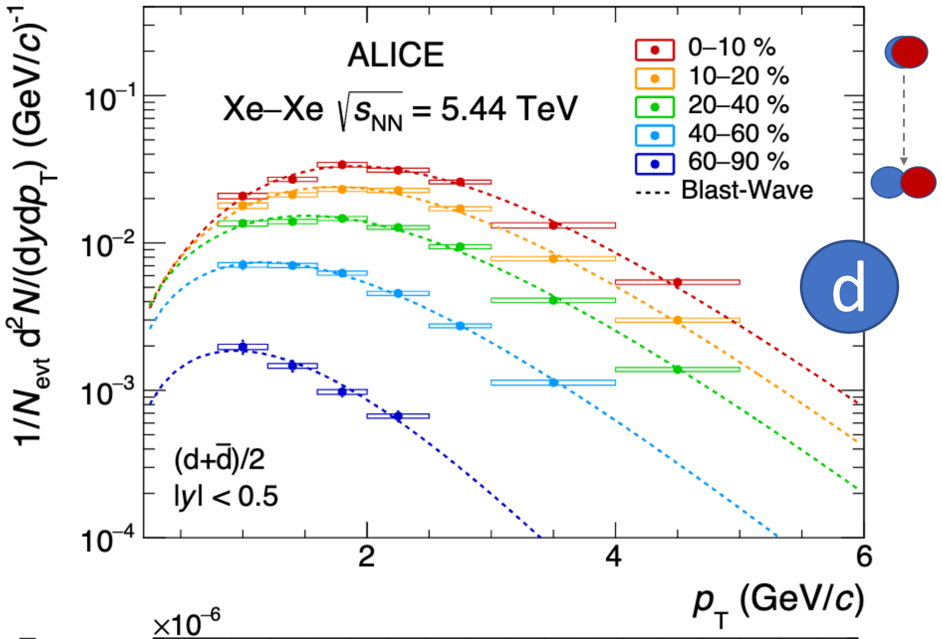
- μ_B and μ_Q are extracted fitting the antiparticle-to-particle yield ratios with the predictions of the grand-canonical SHM using the Thermal-FIST code
- $\mu_Q = -0.18 \pm 0.90$ MeV
- $\mu_B = 0.71 \pm 0.45$ MeV (~8 times more precise than previous measurement)

- **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

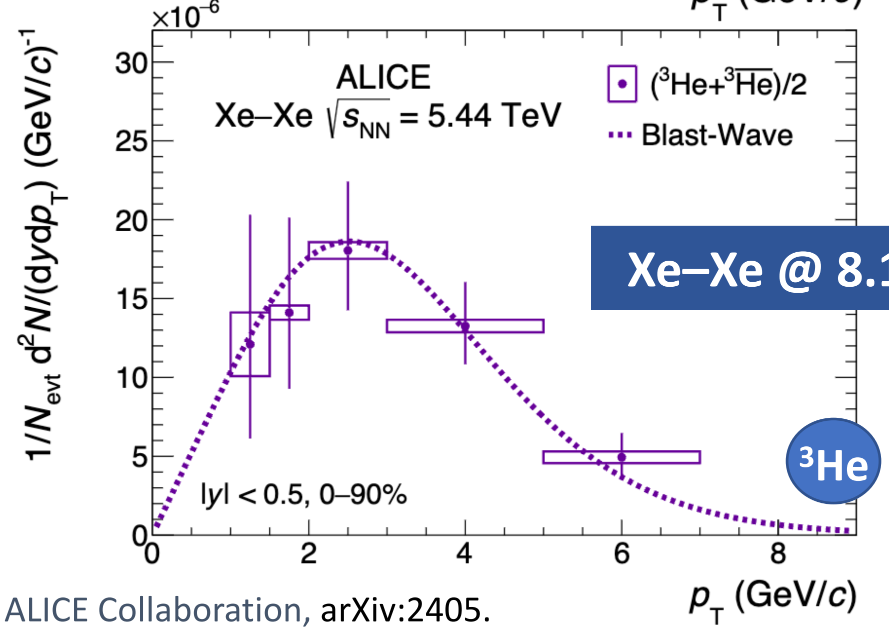
The system created in Pb–Pb collisions at the LHC is on average baryon–free and electrically neutral at midrapidity → approaching the early Universe more than any other experimental facility

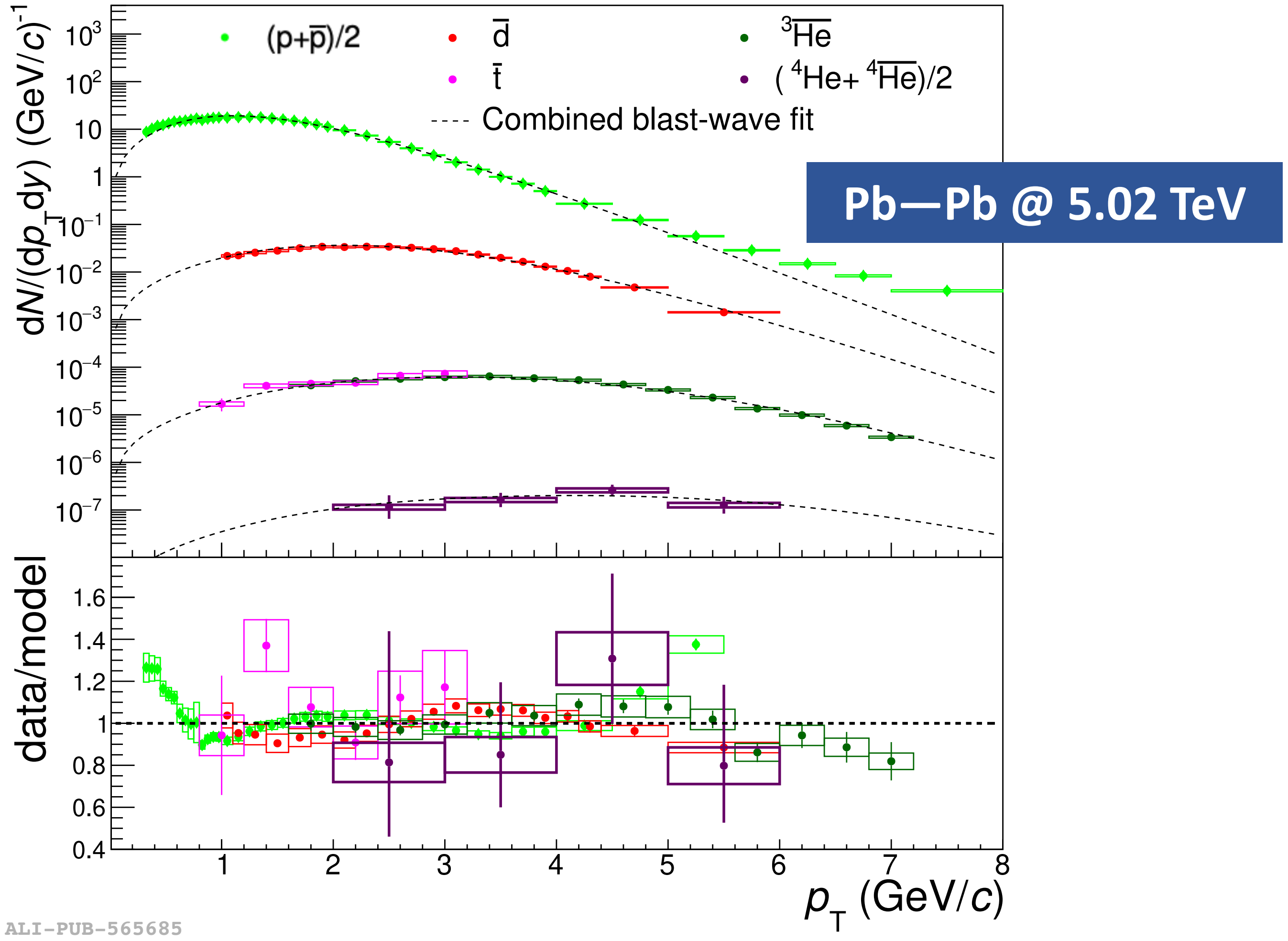
ALICE Collaboration, arXiv:2311.13332

Light (anti)nuclei with ALICE: large systems



- Recently measured d and ^{3}He in Xe—Xe collisions
- In Pb—Pb collisions (anti)nuclei up to ^{4}He are measured

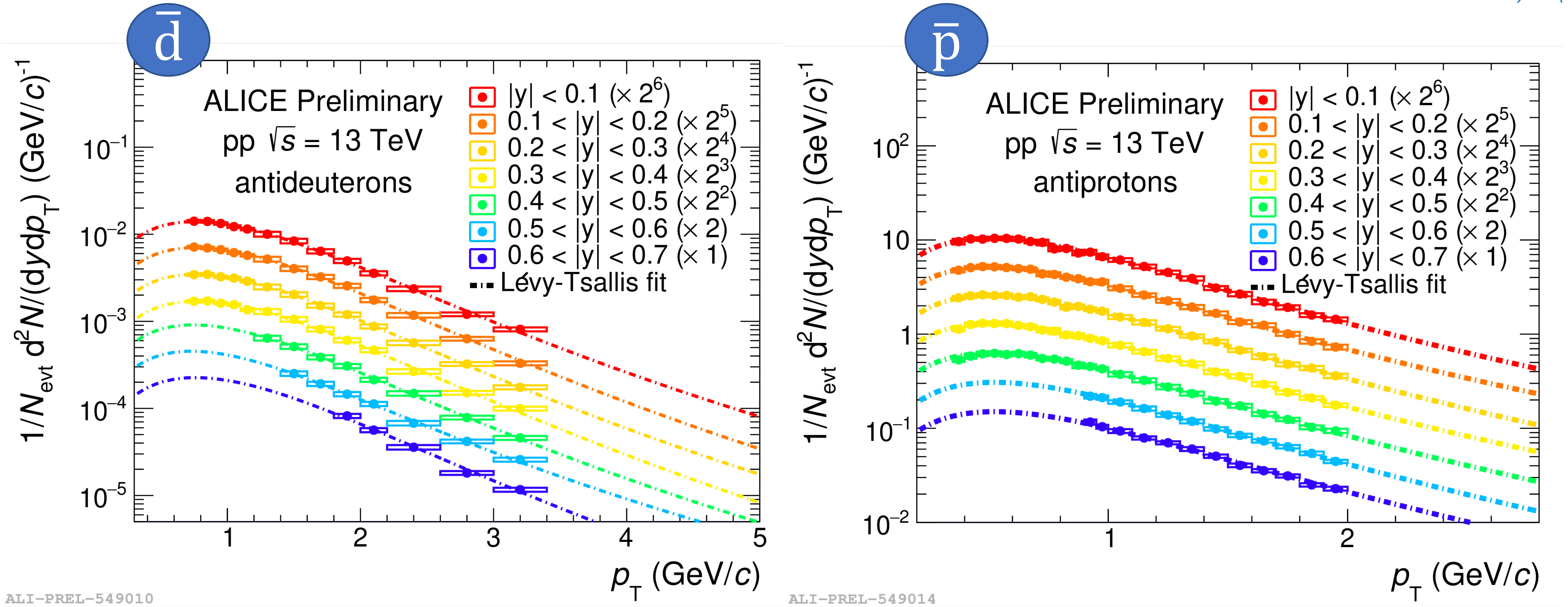




ALICE Collaboration, arXiv:2405.

ALICE Collaboration, arXiv:2311.11758

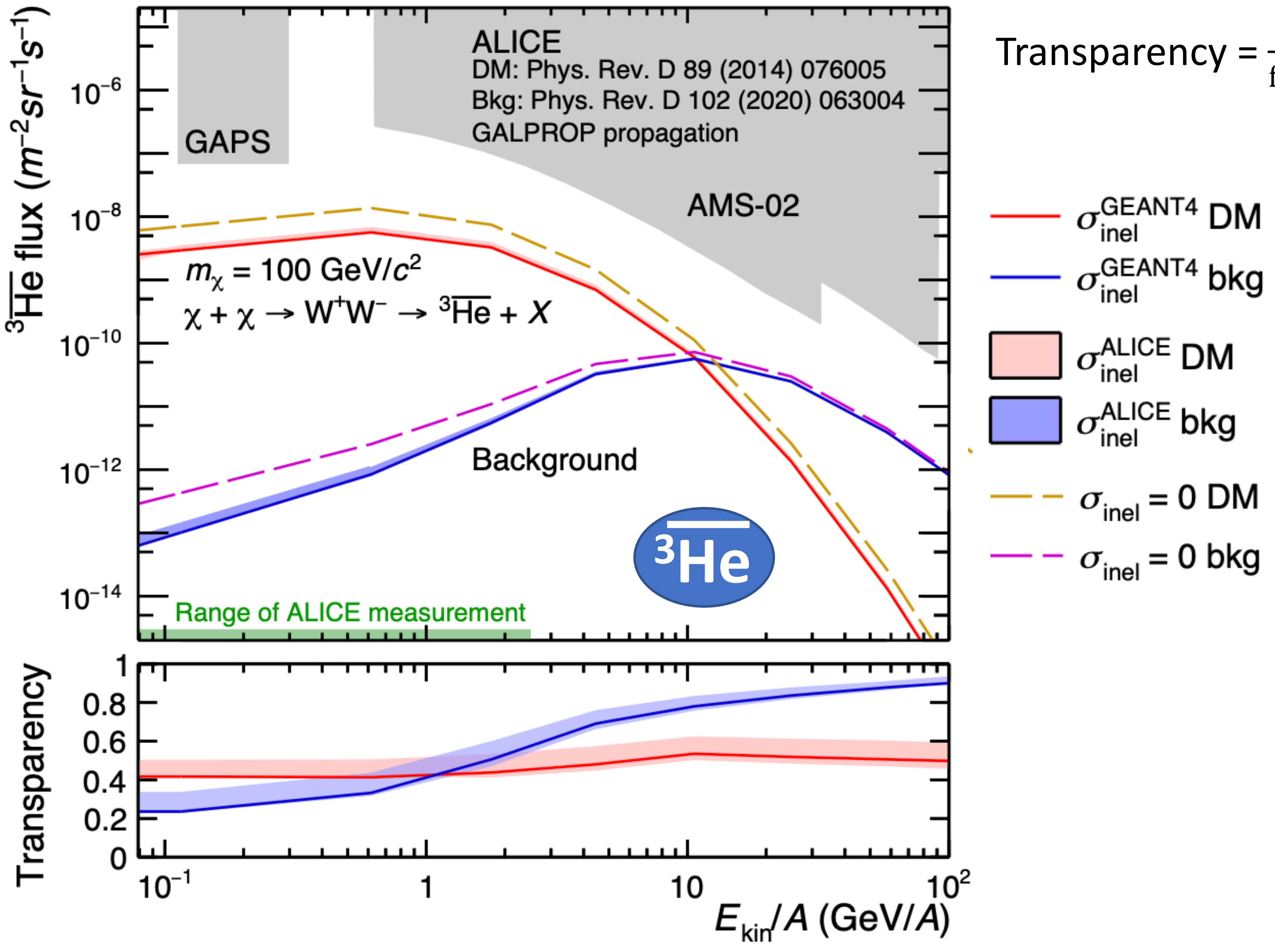
Spectra as a function of rapidity



- 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)

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

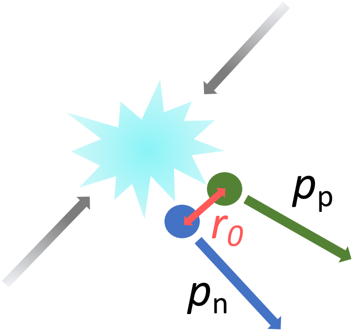
- **Our Galaxy is rather constantly transparent to ^{3}He passage**
- Data are in good agreement with Geant4 predictions
- Uncertainties on Transparency only due to absorption measurements (10-20%)

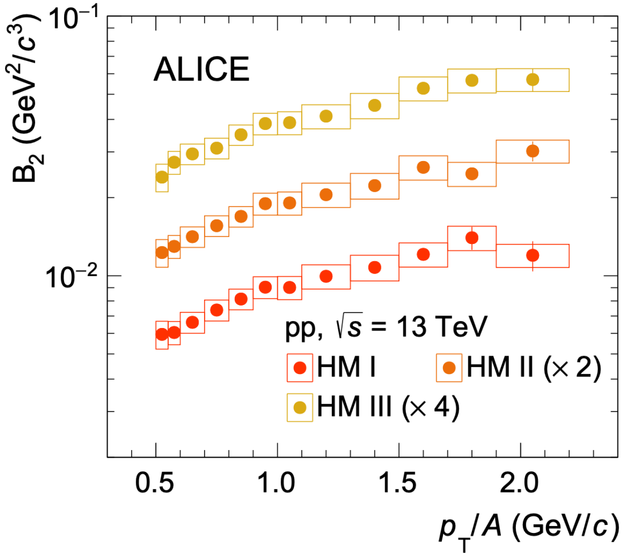
anti^{3}He: Nature Phys. (2023) 19, 61–71

Testing coalescence model using B_2

- Important observable in accelerator measurements: coalescence parameter B_A

$$B_A\left(p_T^p\right) = \frac{1}{2\pi p_T^A}\frac{d^2N_A}{dy dp_T^A} \Big/ \left(\frac{1}{2\pi p_T^p}\frac{d^2N_p}{dy dp_T^p}\right)^A$$





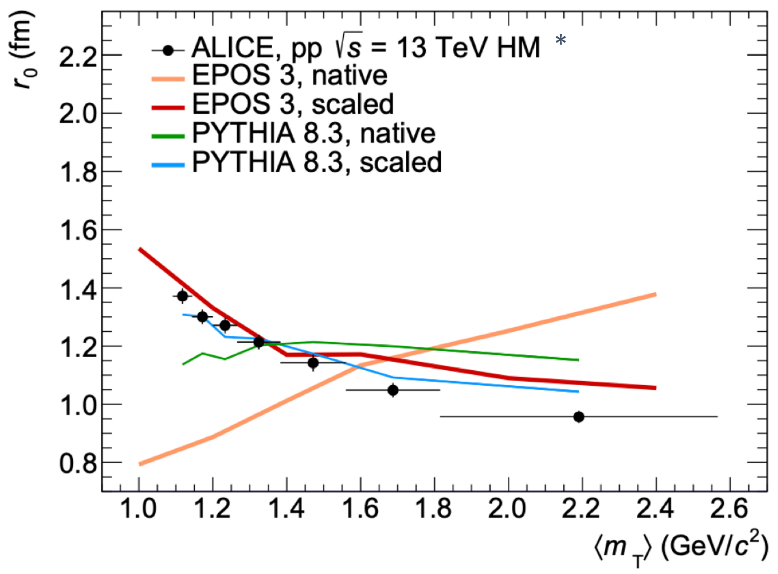
- Comparison to model predictions based on Wigner formalism
  - Using event generators (PYTHIA 8.3 & EPOS 3)
  - Calibrating (anti)nucleon momentum distribution & multiplicity distributions to measurements
  - Obtaining deuteron p distributions according to the probability:

$$\mathcal{P}(r_0, q) = \int d^3r_d \int d^3r\, H_{pn}(\vec{r}, \vec{r}_d; r_0)\, \mathcal{D}(\vec{q}, \vec{r})$$

emission source size → tuned to data

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

deuteron wave function → testing different ones



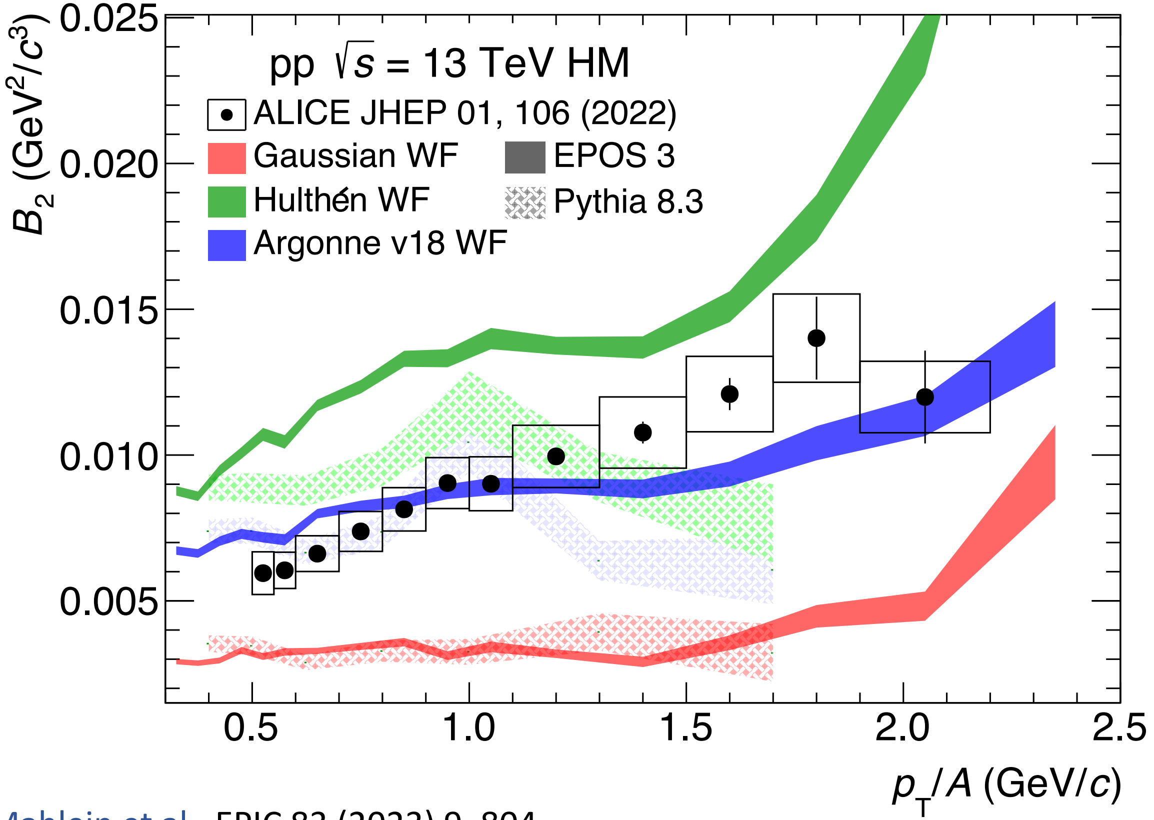
* ALICE Collaboration, PLB 811 (2020) 135849
ALICE Collaboration, JHEP 01 (2022) 106
Kachelrieß et al., EPJA 56 1 (2020) 4
Kachelrieß et al., EPJA 57 5 (2021) 167
Mahlein et al., EPJC 83 (2023) 9, 804

Testing coalescence model using B_2

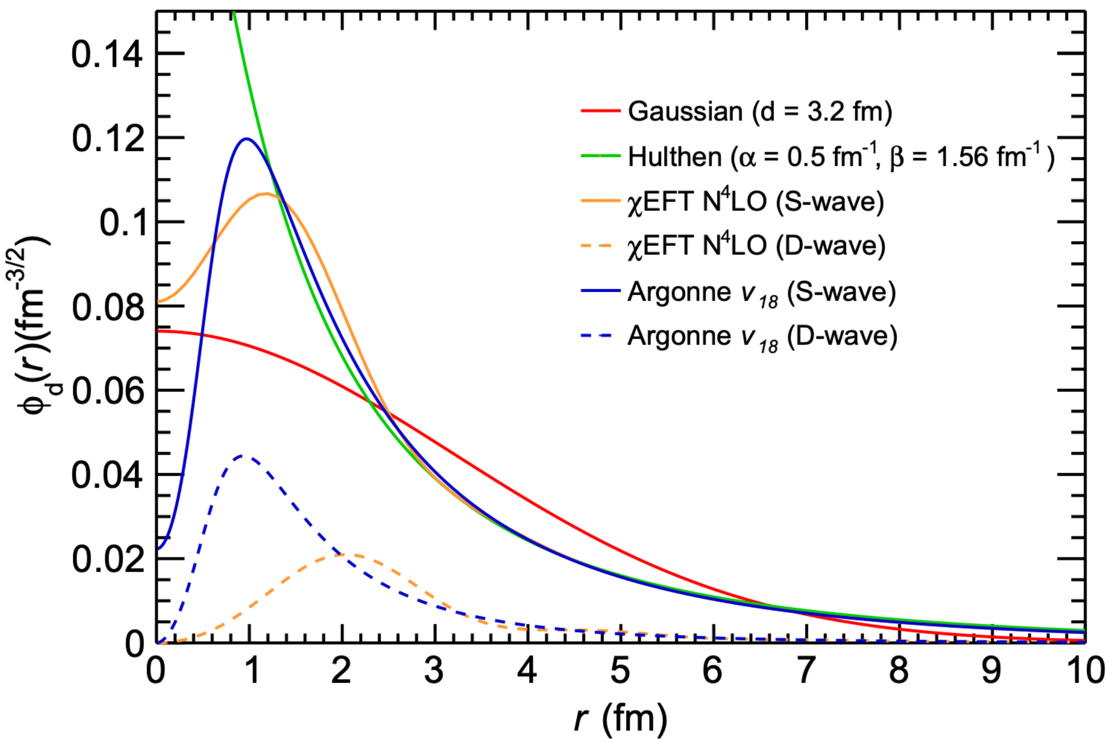
State-of the-art coalescence model describes deuteron momentum distributions and coalescence parameter!

↔

Production measurements can be used to constrain the nuclear wavefunction!



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



- **Hulthén*:** Favoured by low energy scattering experiments
- **Argonne v_{18}**:** phenomenological potential constrained to p-n scattering
- **χEFT:** Favoured by modern nuclear interaction experiments (e.g. Femtoscopy)

* Scheibl et al., PRC 59 (1999) 1585-1602

** Wiringa et al., PRC 51 (1995) 38-51

*** D. R. Entem et al., PRC 96 2 (2017) 024004