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

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(CERN)

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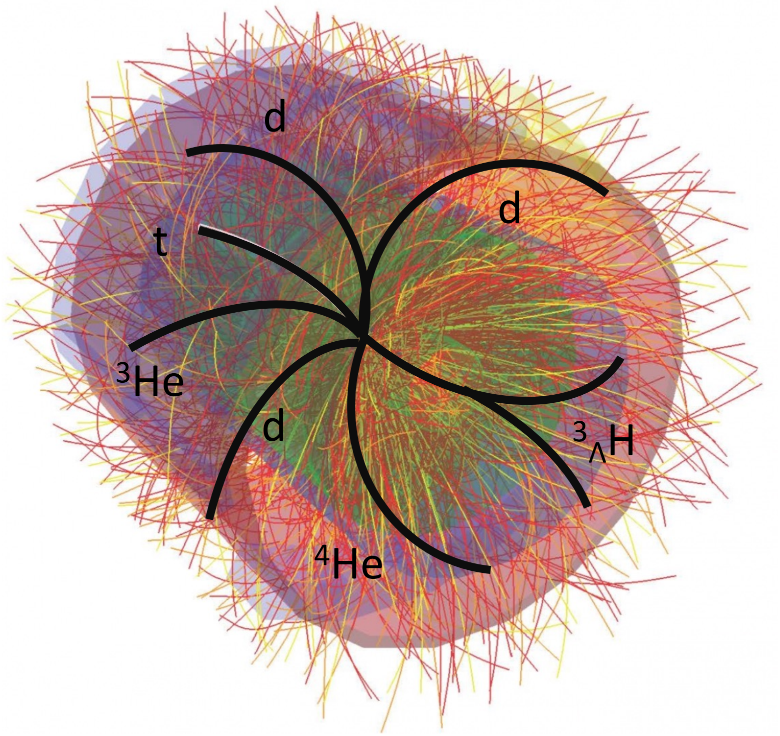
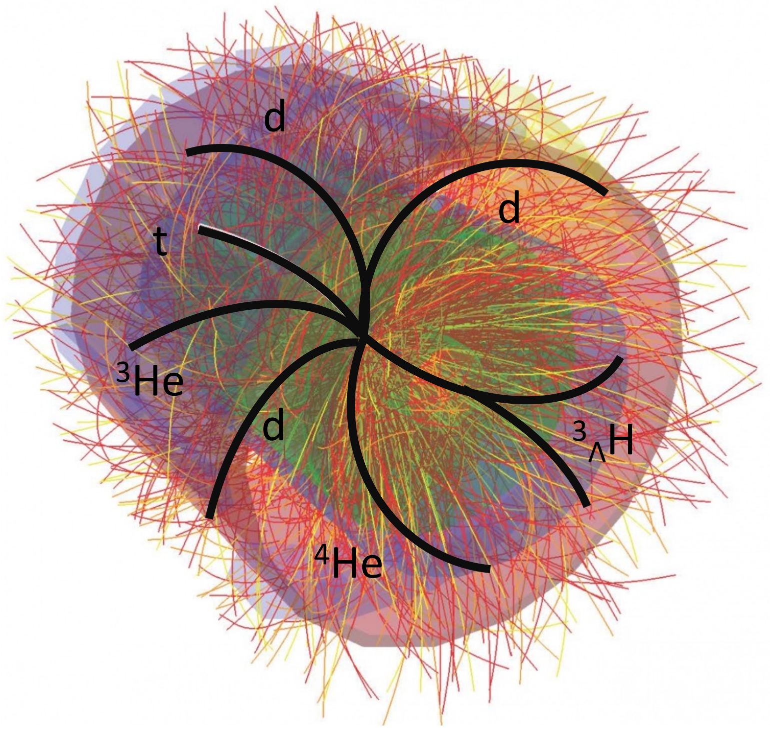
EMMI Workshop
5^{th} Workshop on Antimatter, Hypermatter and Exotica Production
Salerno

Production of (anti)(hyper)nuclei at the LHC



- In ultra-relativistic heavy-ion collisions at the LHC a hot and dense hadron gas phase is produced
- Temperature of the system is T ~ 155 MeV

Production of (anti)(hyper)nuclei at the LHC



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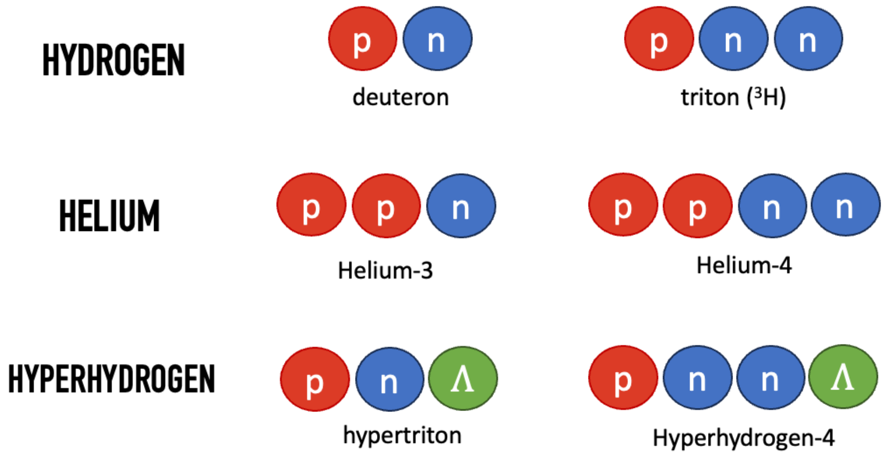
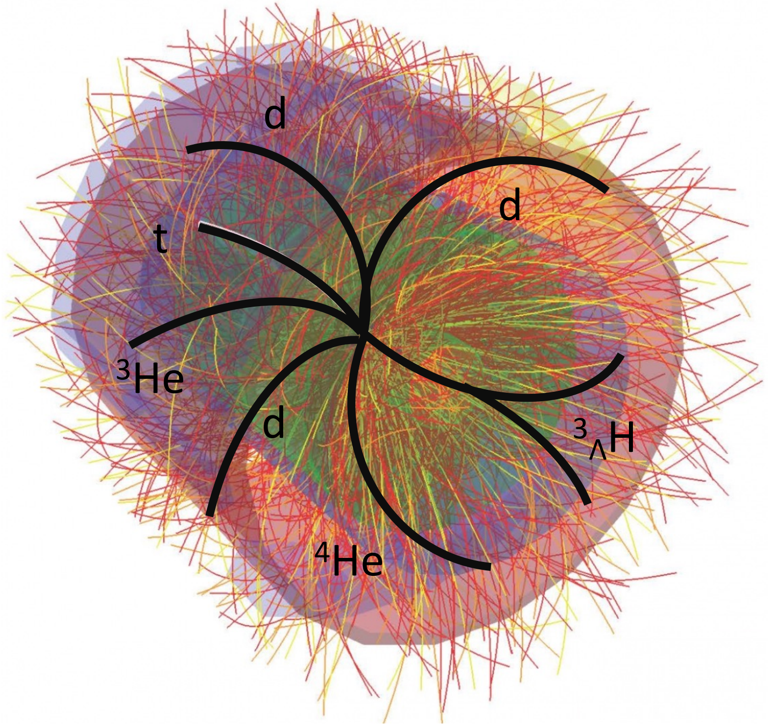


Production of (anti)(hyper)nuclei at the LHC



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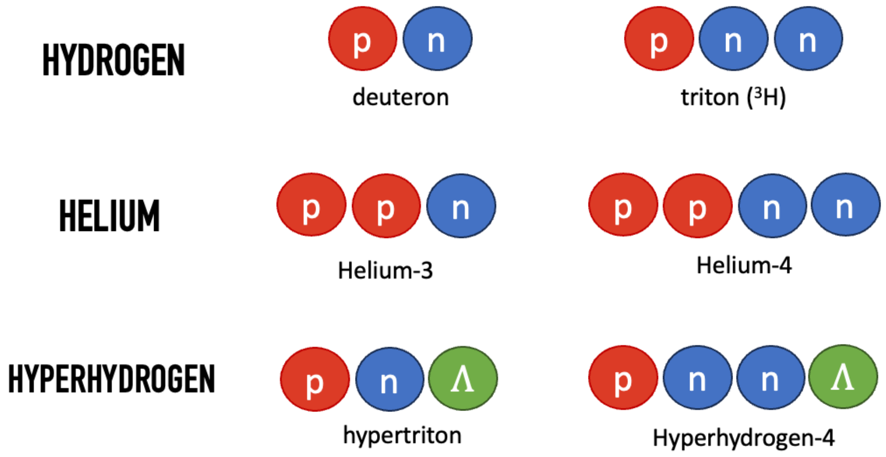
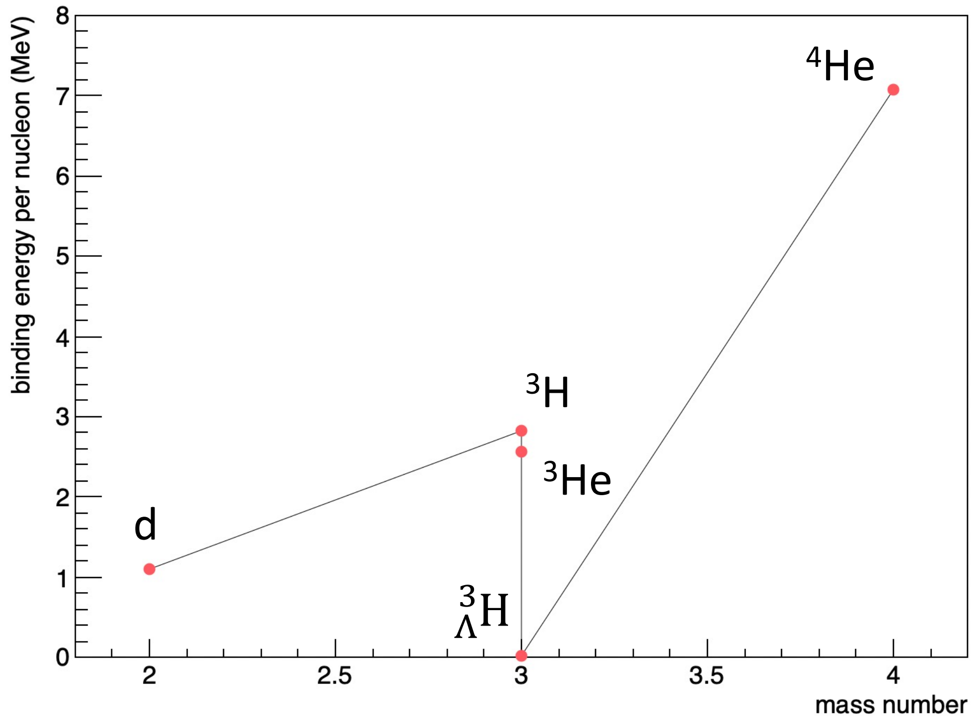
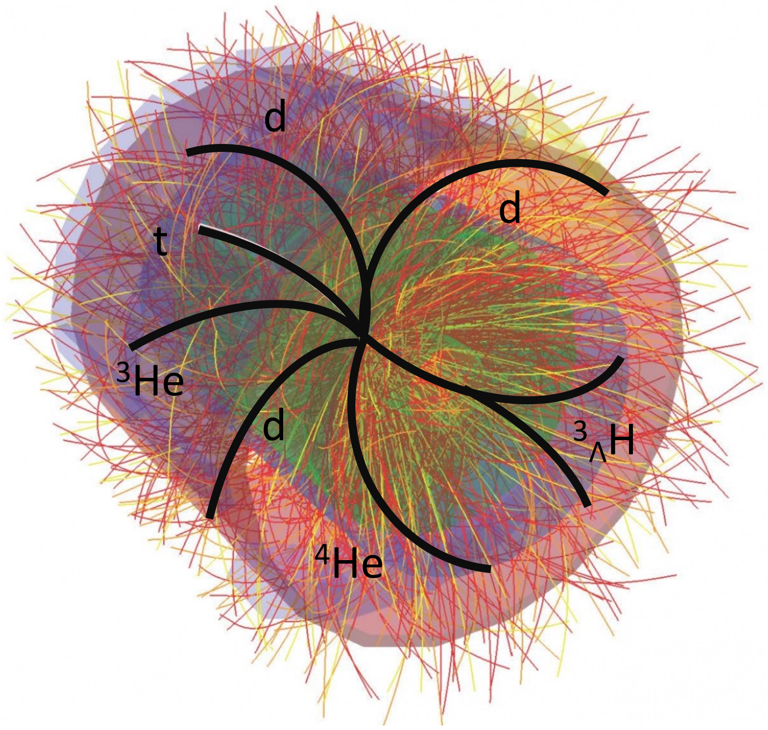
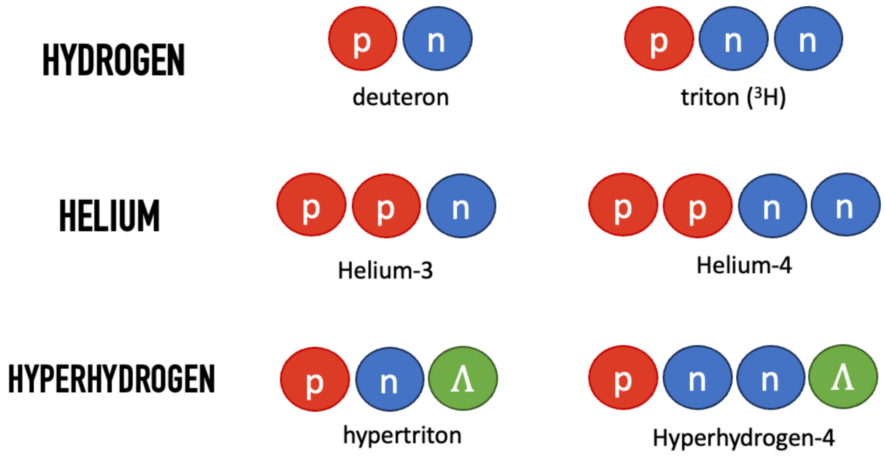




Production of (anti)(hyper)nuclei at the LHC





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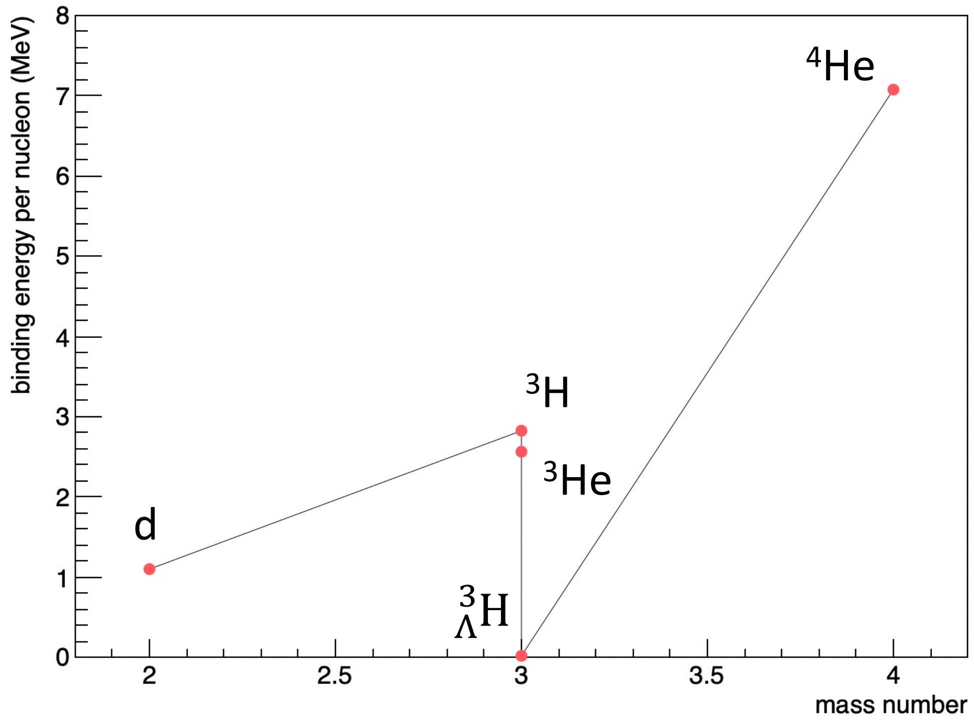
⇒ how can they survive the hadronic phase environment?



Production models

- Two classes of phenomenological models available:

  - **statistical hadronization** (SHM)

    → nuclei are produced at phase boundary at T=155 MeV

    ASSUMPTIONS

    - compact point-like particles
    - large mean-free path → do not interact and survive the evolution of the system

    → works very well for integrated yields

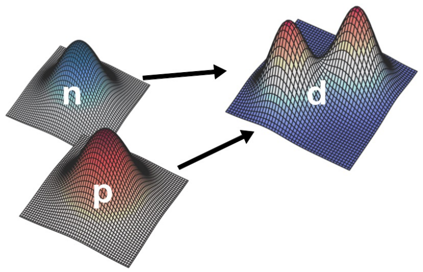
    → extended to small systems with local conservation of charges

  - **coalescence**

    → nuclei produced by coalescence of nucleons at the end of the evolution of the system, when the temperature is already diluted

    → formation probability is calculated by folding the phase-space distributions of nucleons with the Wigner density of the bound state

    → sensitive to the interplay between the nucleus wavefunction and the system size



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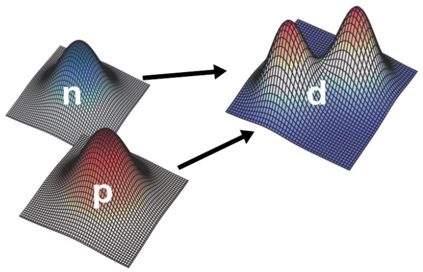
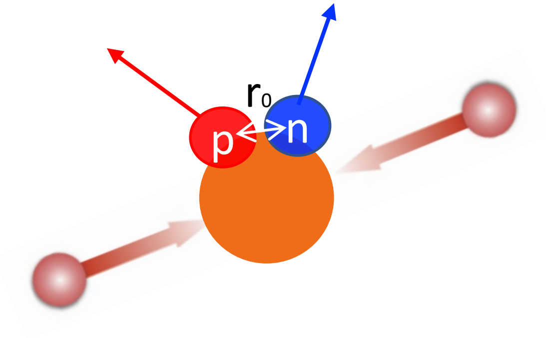
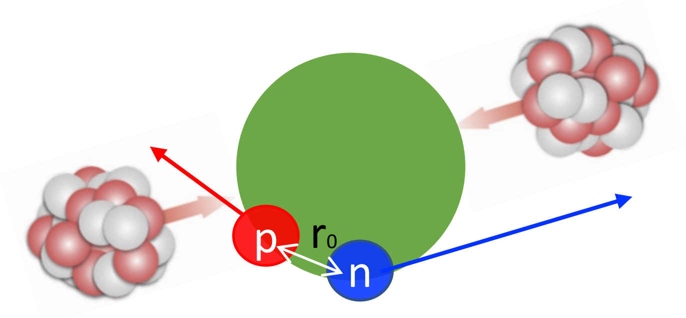


Main difference:
- for coalescence **size** matters,
- for SHM only **mass** matters

Size of nuclei vs. size of system





pp[1], p—Pb[2]: $r_0 = 1–1.5$ fm

Pb—Pb[3]: $r_0 = 3–6$ fm

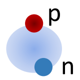
Small collision systems

Heavy-ions

charged-particle multiplicity

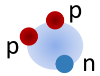
$\langle dN_{ch} / d\eta \rangle_{|\eta|<0.5}$

d



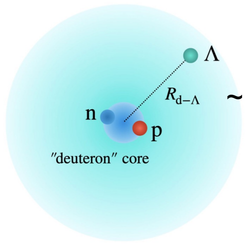
r ~ 1.96 fm

^{3}He



r ~ 1.8 fm

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

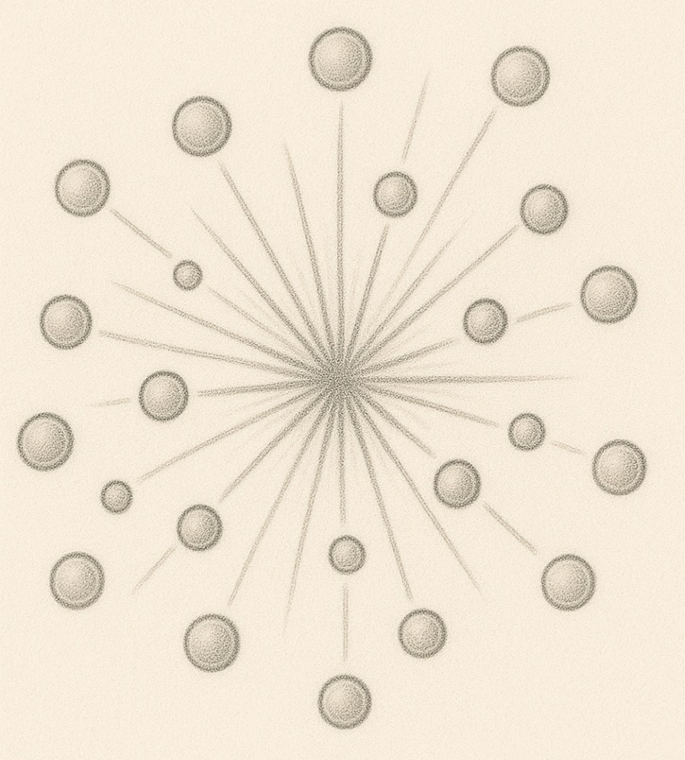


~ 10 fm

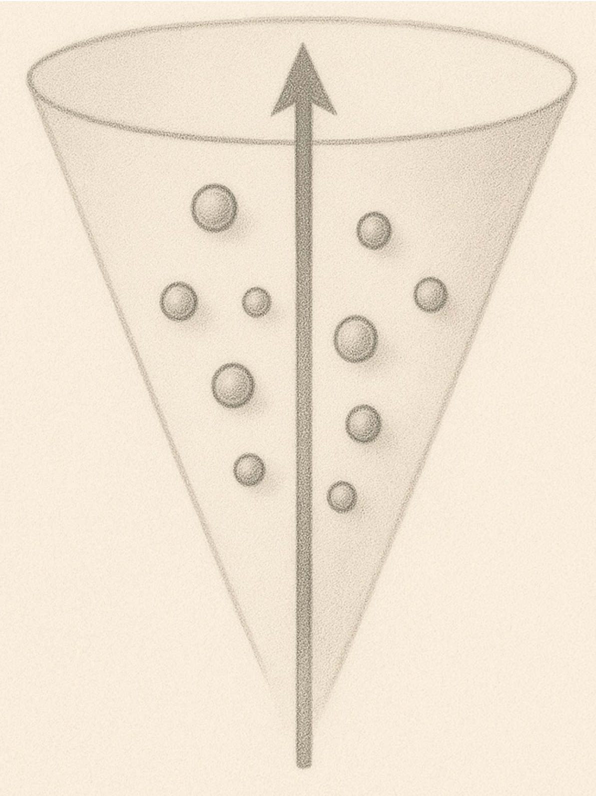
[1] PRC 99 (2019) 024001
[2] PRL 123 (2019) 112002
[3] PRC 96 (2017) 064613

Testing coalescence mechanism with jets

One way to investigate the coalescence mechanism is by focusing in a small phase-space region (jet cone) and comparing the production of nuclei by coalescence there wrt the minimum bias production (UE)



Underlying Event: particle production from MPIs



Jets: particle production from single parton shower

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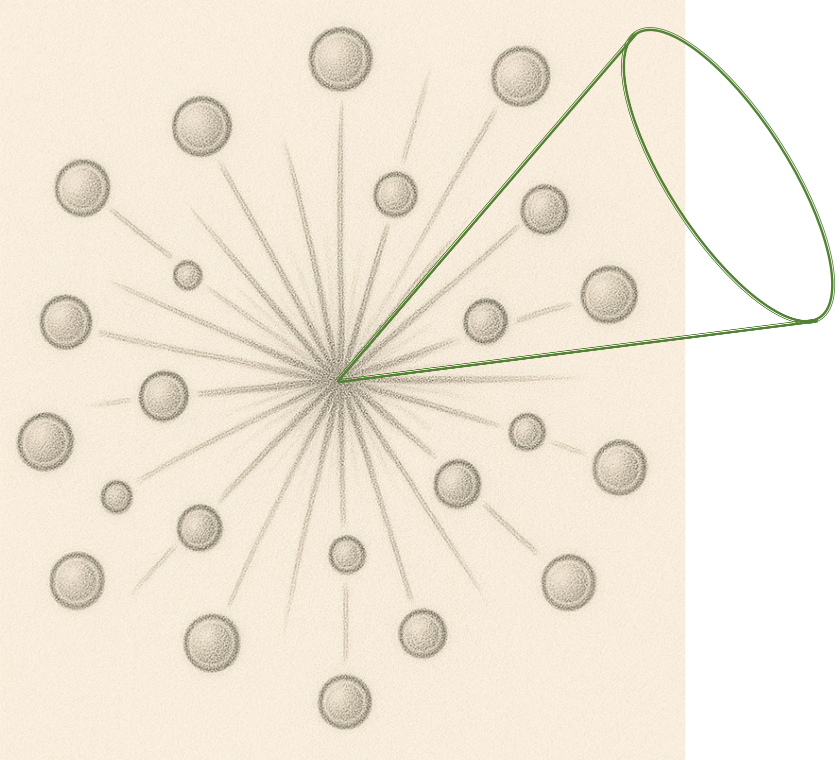

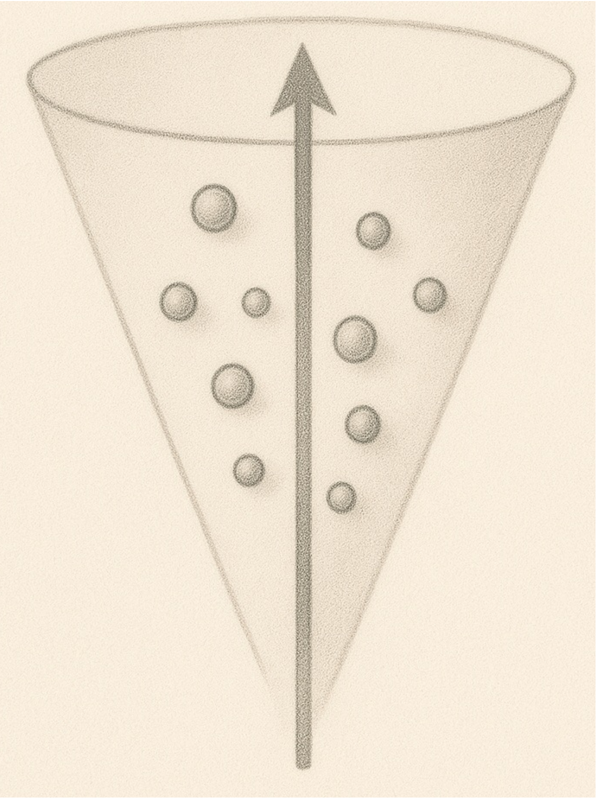

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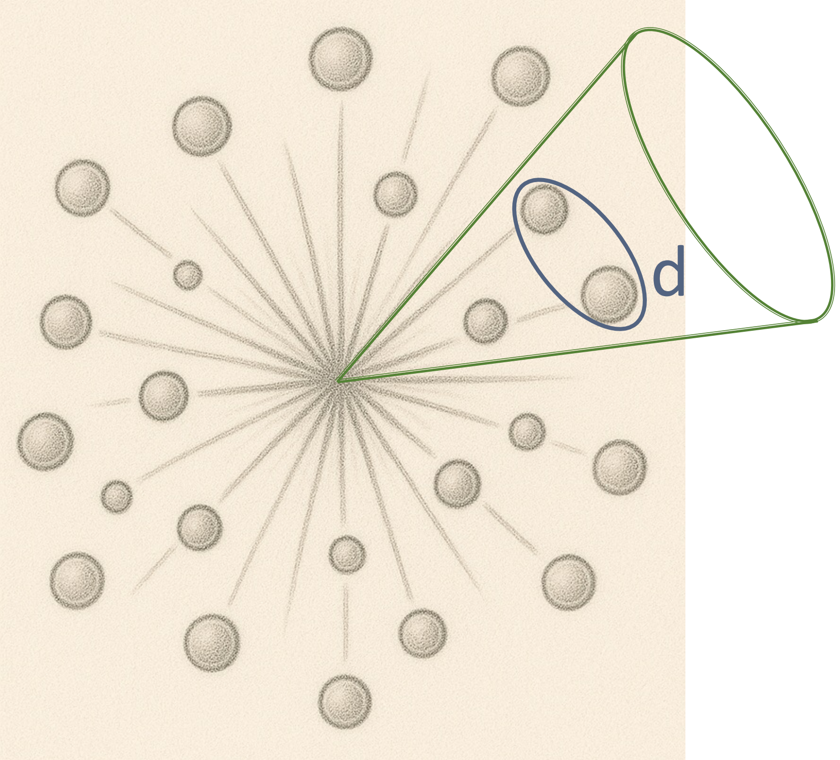
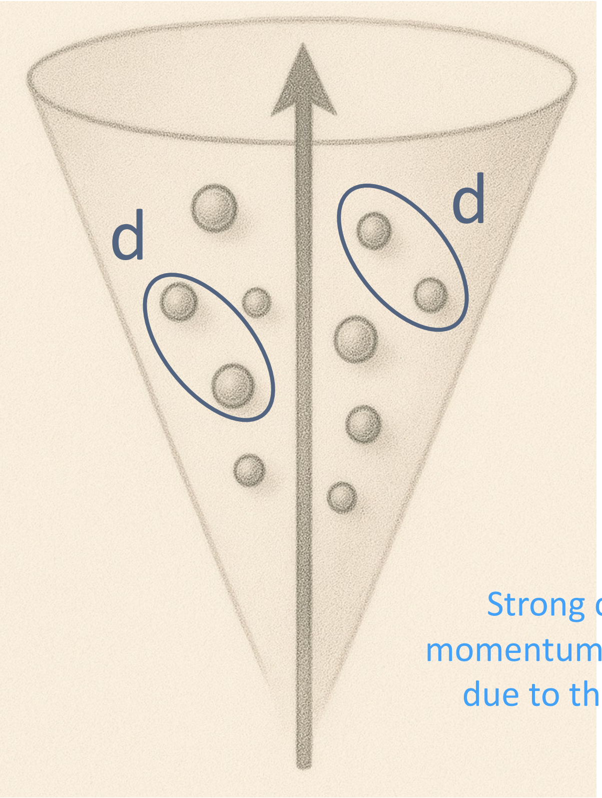




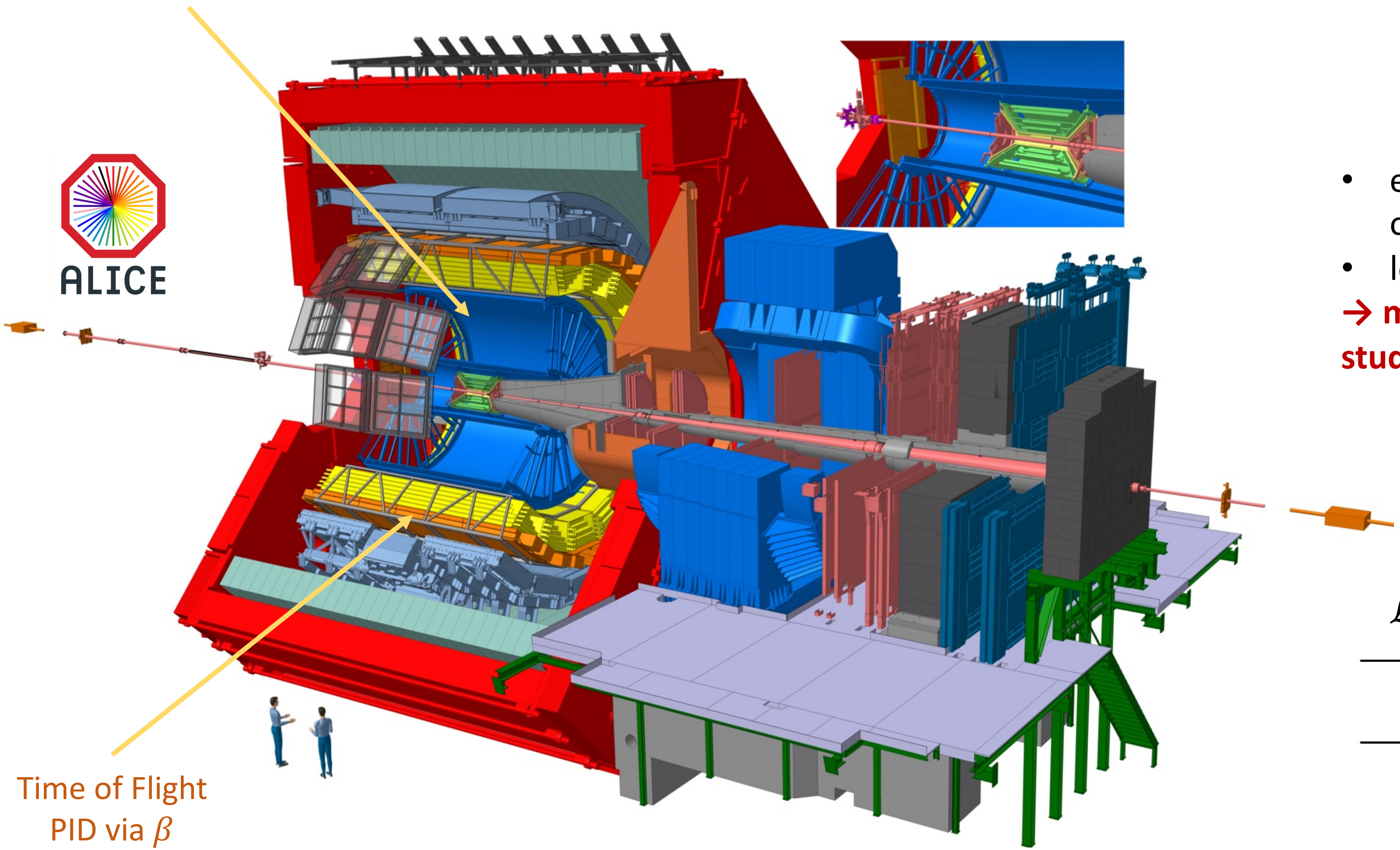
Strong constraints on space-momentum correlations of nucleons due to the same parton shower

Underlying Event: particle production from MPIs

Jets: particle production from single parton shower

ALICE at the LHC

Time Projection Chamber
PID via dE/dx



Time of Flight
PID via β

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

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

$\mathcal{L}_{\text{int}}$ (MB)	Run 2	Run 3
pp	30/nb	130/pb
Pb-Pb	1/nb	3/nb

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

Nucleus production in and out of jets

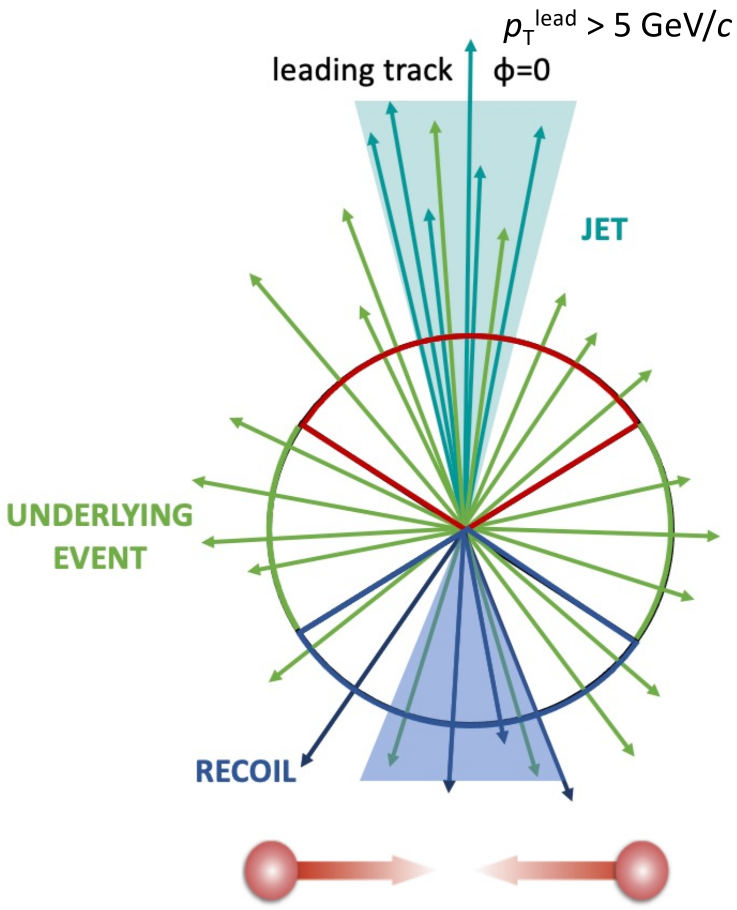
- Powerful tool to investigate coalescence mechanism is the study of nuclear production in and out of jets
- In jets nucleons are created close to each other in phase-space, as they come from the same parton shower

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

B_2 quantifies the amount of deuterons produced wrt its constituents
→ deuteron formation probability

$$B_2 = \frac{\frac{1}{\Delta y \Delta \phi\, p_T^{\mathrm{d}}} \frac{dN_{\mathrm{d}}}{dp_T}}{\left(\frac{1}{\Delta y \Delta \phi\, p_T^{\mathrm{p}}} \frac{dN_{\mathrm{p}}}{dp_T}\right)^2}$$

$p_{\mathrm{T}}^{\mathrm{p}} = p_{\mathrm{T}}^{\mathrm{d}}/2$

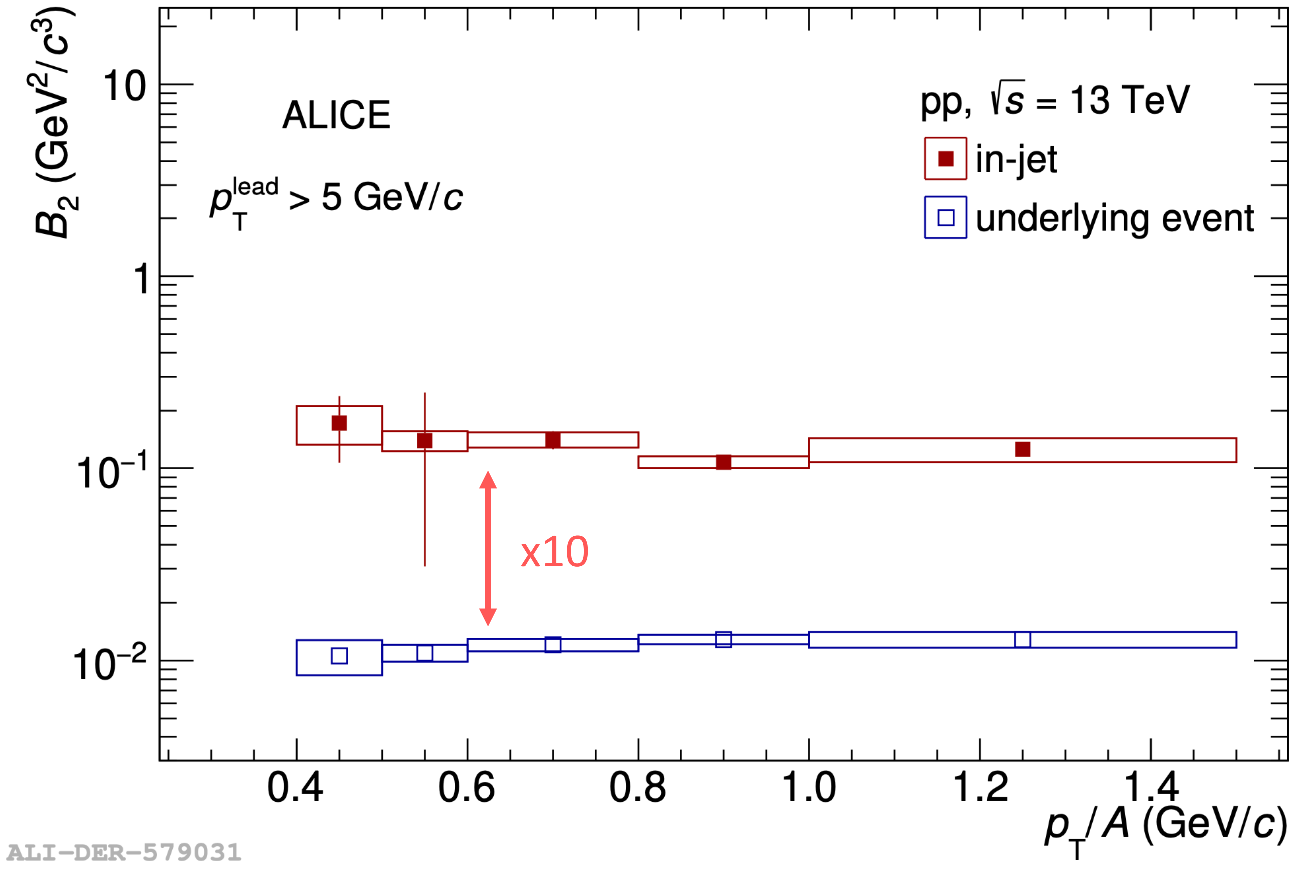


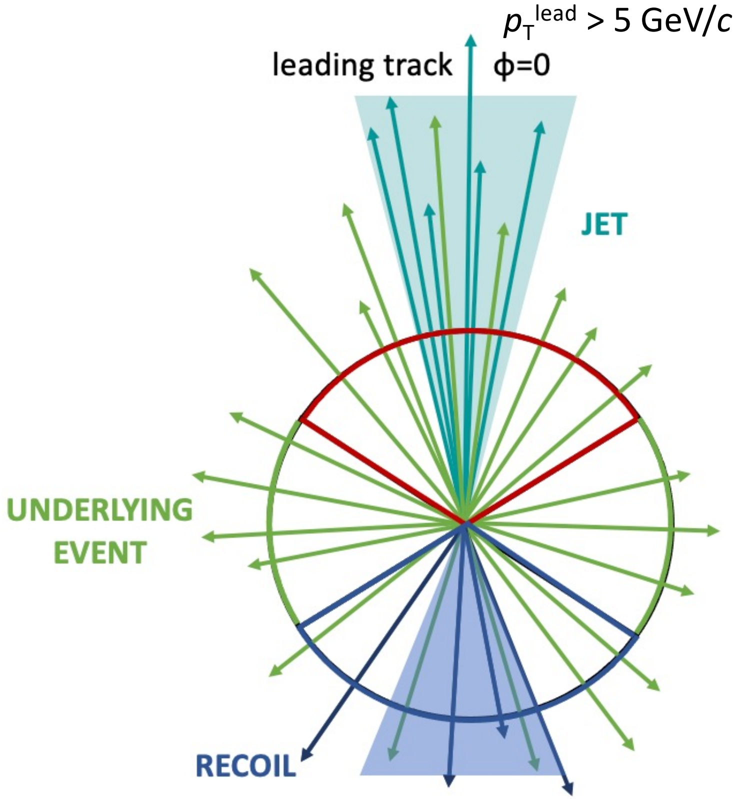
Toward: |Δϕ| < 60°
Transverse: 60° < |Δϕ| < 120°
Away: |Δϕ| > 120°

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

Coalescence parameters in and out of jets

pp

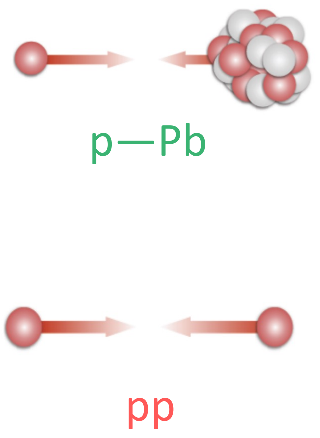


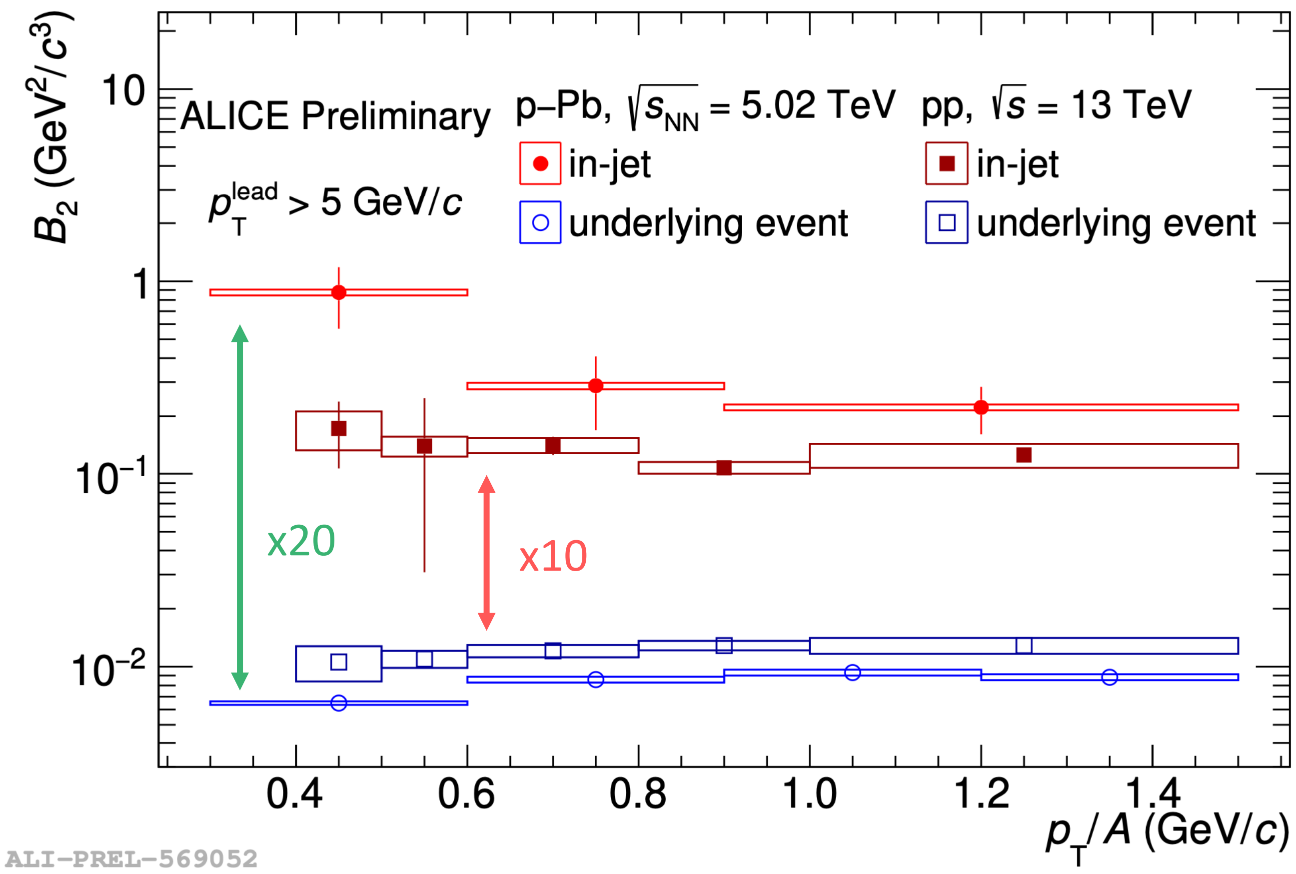


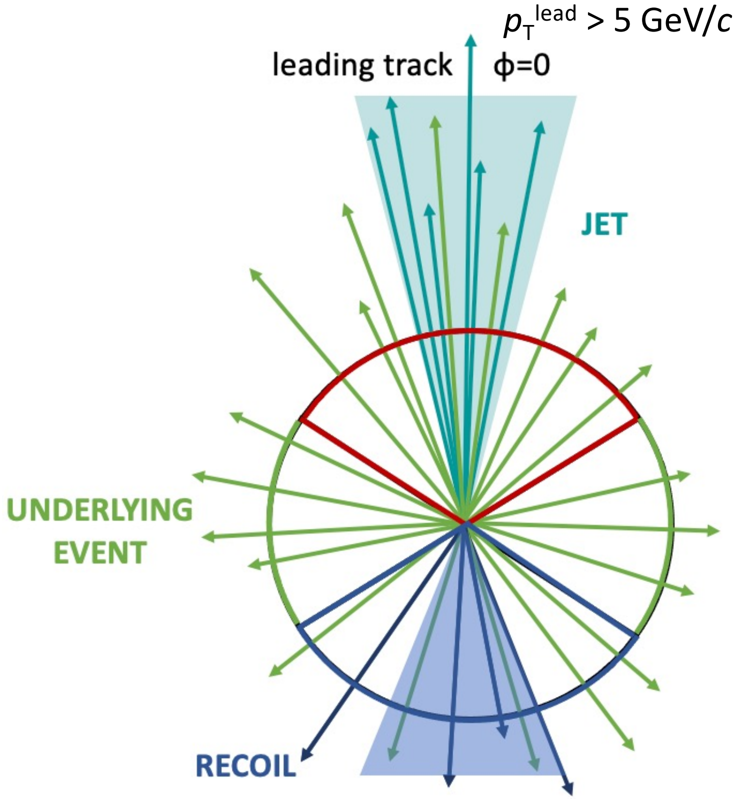
- *Enhanced deuteron coalescence probability in jets wrt UE is observed for the first time in pp collisions*
- Due to the reduced distance in phase space of hadrons in jets compared to those out of jets → favors coalescence picture

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

Coalescence parameters in and out of jets







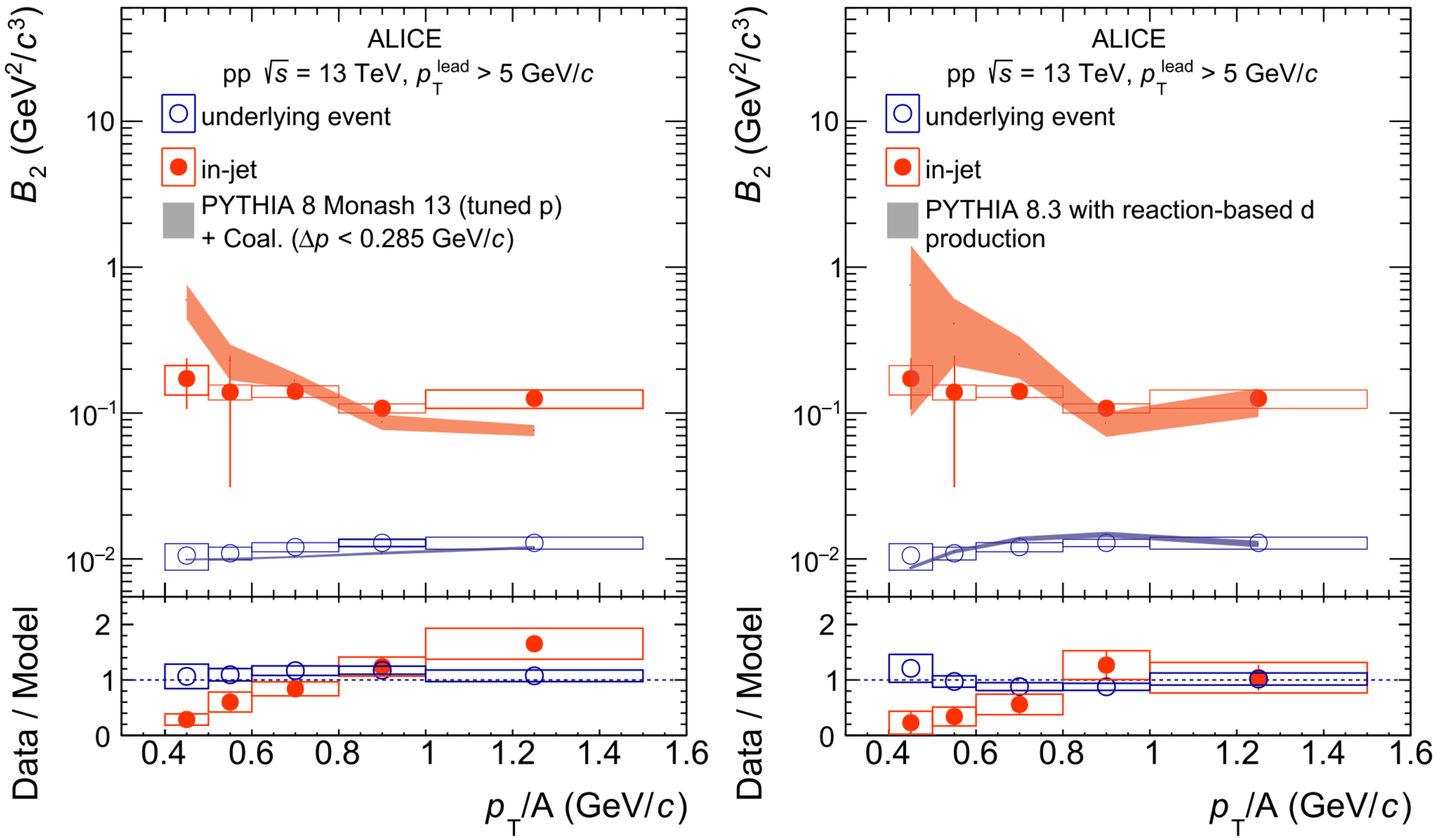
- B_2 in-jet in p—Pb is larger than B_2 in-jet in pp
  → *could be* related to the different particle composition of jets in pp and p—Pb
- B_2 in UE in p—Pb is smaller than B_2 in UE in pp due to the larger source size in p—Pb (pp[(1)]: r_0∼ 1 fm, p—Pb[(2)]: r_0∼ 1.5 fm)

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

Take-home messages

- Phase-space constraints on the nucleons affect the coalescence probability of the final state
- Coalescence probability consistently evolves with increasing emitting system (pp → p—Pb)
- Coalescence models – either simplistic ones, where nucleus is formed if $|\Delta p| < p_0$ or reaction-based ones (Pythia 8.3) – describe the gap UE-Jet

Comparison to coalescence models



- B_2 UE PYTHIA describes the trend of data
- B_2 in-jet PYTHIA reproduces difference between UE and jet but shows a decreasing trend not observed in data → p_T trend to be further investigated

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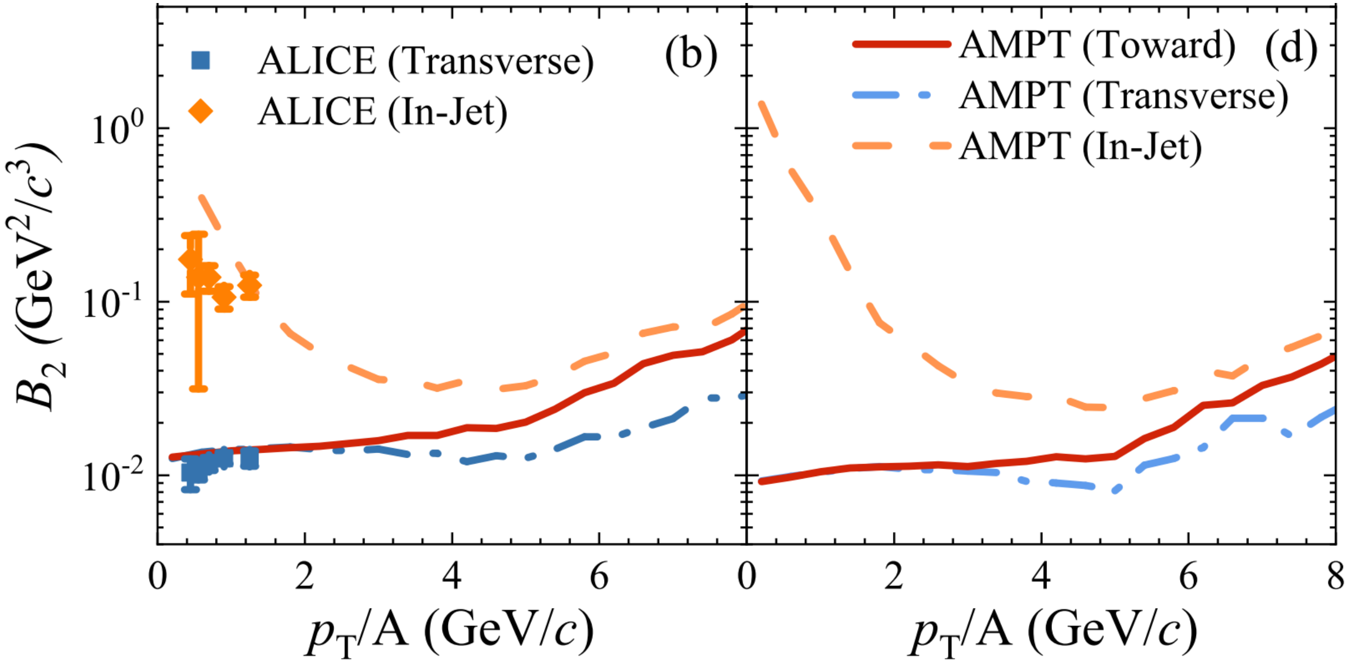
Is this all?

- These measurements inspired several phenomenological studies, that provide complementary interpretations of the results

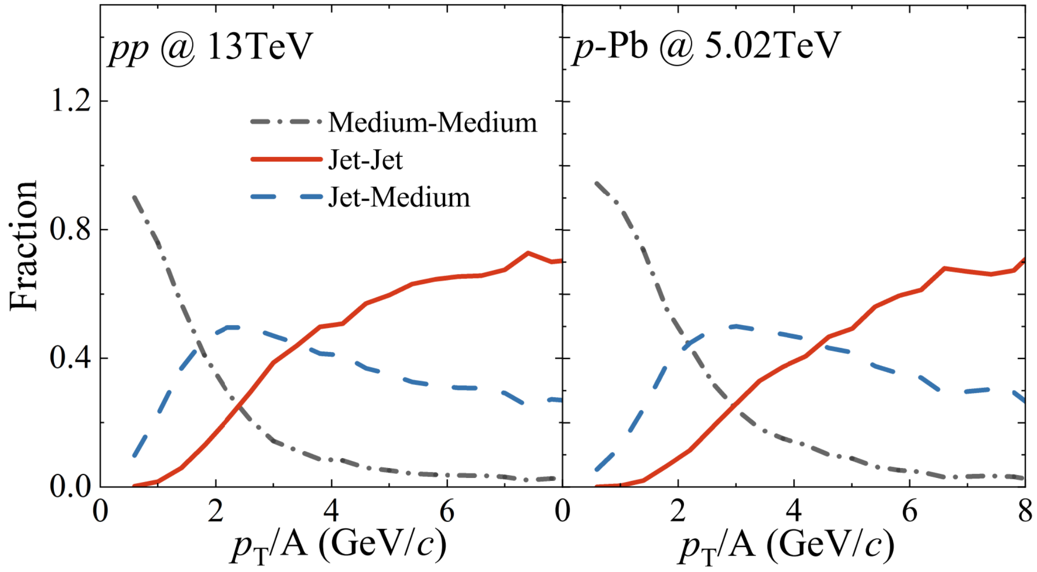
Other interpretations

Yi-Heng Feng et al., *Jet-Induced Enhancement of Deuteron Production in pp and p-Pb Collisions at the LHC*

https://doi.org/10.1016/j.physletb.2024.139102



Enhanced deuteron coalescence probability in jets wrt UE is expected at higher p_T and due to nucleons from UE binding with nucleons from jet at low-p_T



- Low-p_T enhancements come from coalescence of nucleons inside the **jet** with the **medium** nucleons
- Coalescence of nucleons inside the jet dominates deuteron production at higher p_T (> 4 GeV/c)

Other interpretations – II

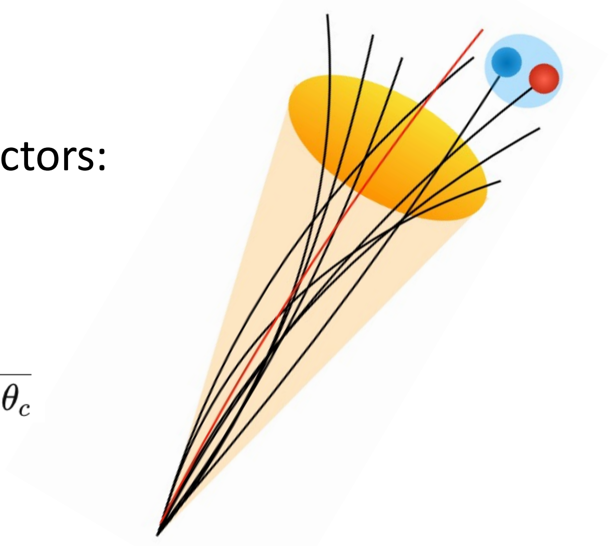
S. Mrowczynski, *Enhancement of deuteron production in jets*
https://doi.org/10.5506/APhysPolB.55.6-A2

The enhancement of the B_2 in jets relative to B_2 in UE is due to two independent factors:

1. Collimation of nucleons in jets

   nucleons in jets are closer in space than in the UE

$$N_D^{\text{jet}} \propto \frac{1}{1-\cos\theta_c}$$



   Going from an isotropic distribution (θ_c = 180°) to a highly collimated jet ($\theta_c \approx$ 20°) boosts the deuteron yield *even before* thinking about the details of deuteron formation

2. Baryon-emitting source is significantly smaller than a deuteron

   r_d ~ 2 fm vs r_{source} ~ 1 fm in UE and ~ 0.3 fm in the jet

Take-home messages

- Phase-space constraints on the nucleons affect the coalescence probability of the final state
- Coalescence probability consistently evolves with increasing emitting system (pp → p—Pb)
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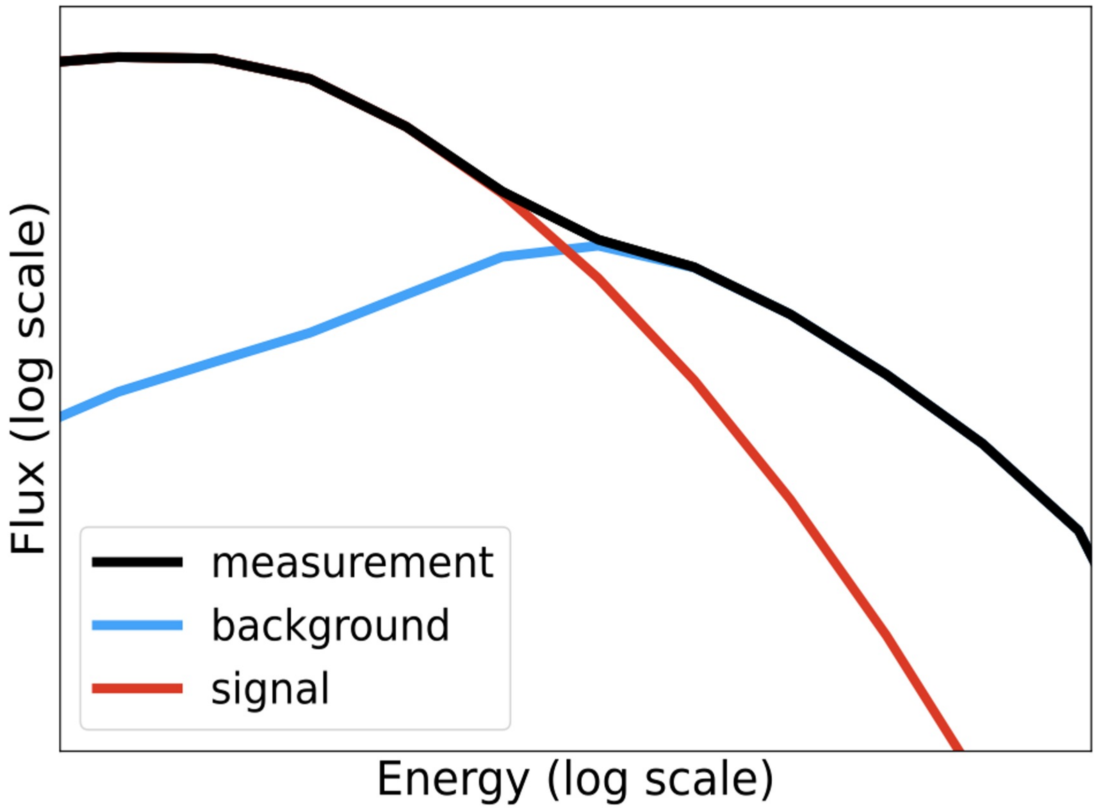
Is this all?

- These measurements inspired several phenomenological studies, that provide complementary interpretations of the results

- Does the energy available in the jet affect the production of nuclei?
  - ➢ Systematic study of the production of nuclei in jets vs p_T^{jet} and R^{jet} are needed

Astrophysics applications: Dark Matter searches

Flux of antinuclei from cosmic rays



High Signal/Noise ratio (~$10^2 - 10^4$) at low E_{kin} expected by models

BKG → constrained by measurements at accelerators

DM → magnitude depends on hypothesis of m_{DM}

Antinuclei production in our Galaxy:

- Interactions of primary cosmic rays and the interstellar medium

  CRs + ISM → pp collisions

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

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

- Dark-matter annihilation processes

  $\chi\chi \rightarrow b\bar{b} \rightarrow$ SM

  $\chi\chi \rightarrow W^+W^- \rightarrow q\bar{q} \rightarrow$ SM

production of antinuclei from parton showers!

energy in the parton shower depends on m_{DM} hypothesis

Astrophysics applications: Dark Matter searches

Dark-matter annihilation processes

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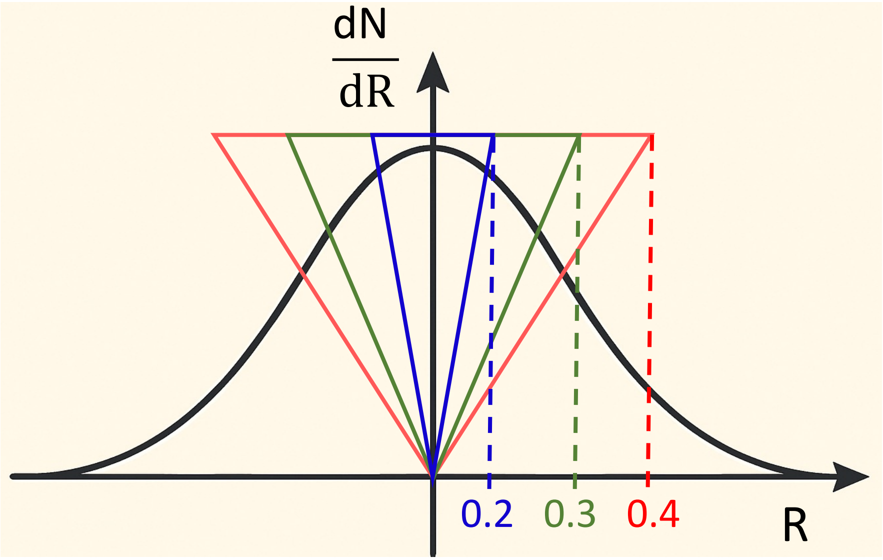
production of antinuclei from parton showers

how to select different-sized parton showers?



$R^{jet} \rightarrow$ jet parameter

Selecting different jet radii cuts out particles from the jet cone, without selecting different radii of the parton shower

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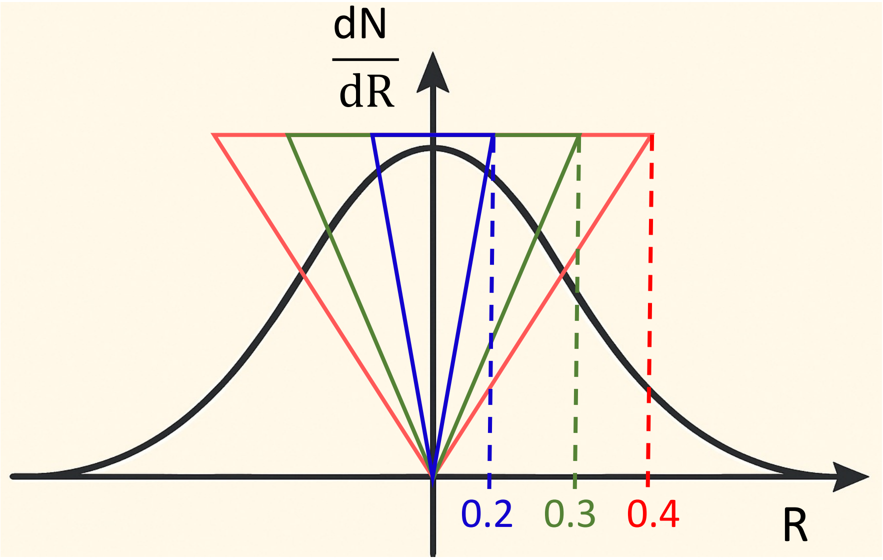
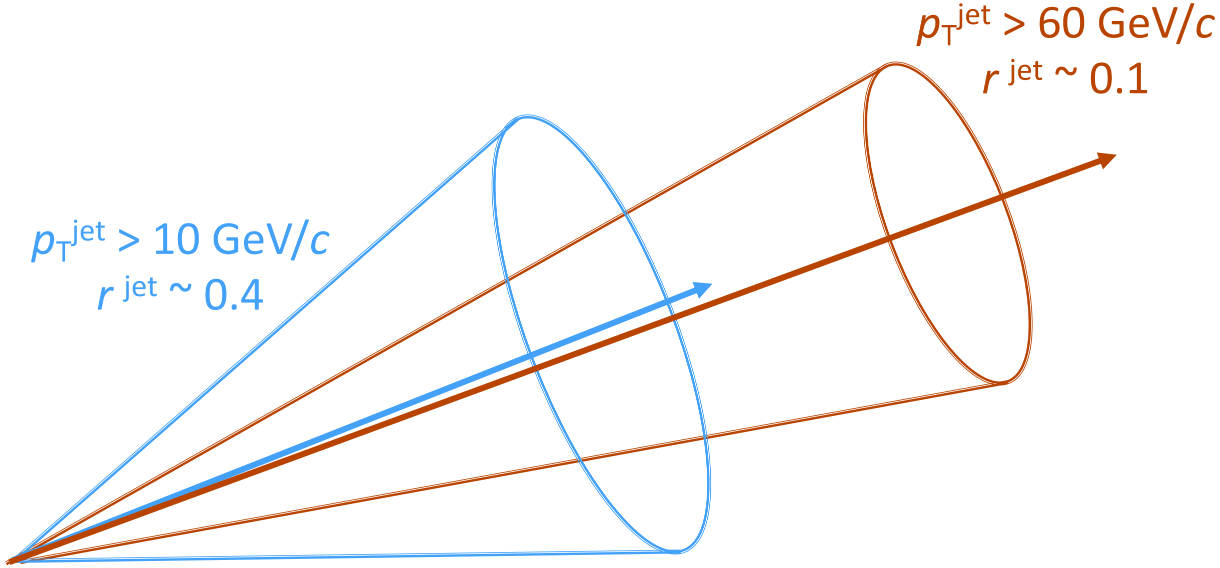




$R^{jet} \rightarrow$ jet parameter

Selecting different jet radii cuts out particles from the jet cone, without selecting different radii of the parton shower

Increasing $p_T^{jet} \rightarrow$ selects smaller jet radii (r^{jet})

The radius of the parton shower decreases with increasing jet p_T

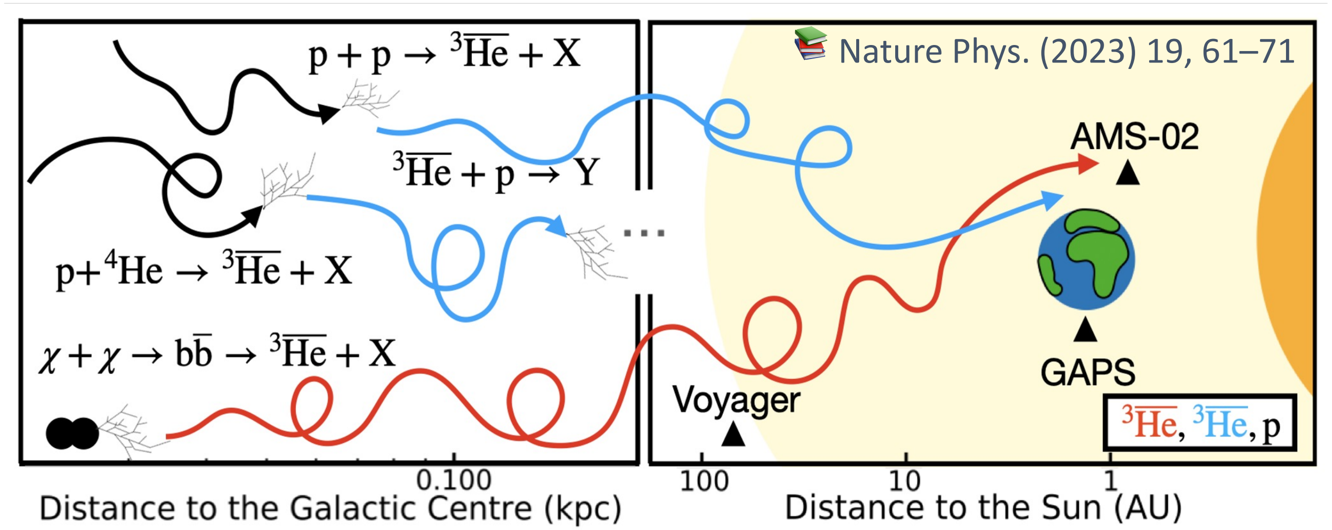
Summary

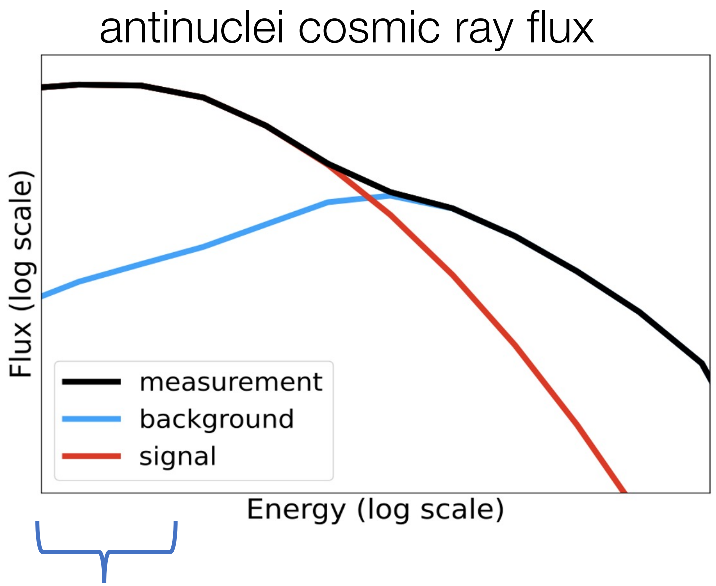
- Measurements of the production of (anti)(hyper)nuclei are key to investigate the **production mechanism**
- **Measurements in jets** are an interesting tool to investigate the coalescence mechanism, as they allow us to select different corners of the phase-space and see how it affects the coalescence probability
- **Experimental challenge** is to get **precision measurements** of nuclei (A = 2, 3, 4) in and out of jets, with a systematic scan as a function of the size of the parton shower
- Interesting applications of these measurements to dark matter indirect searches

Thank You...

Spares

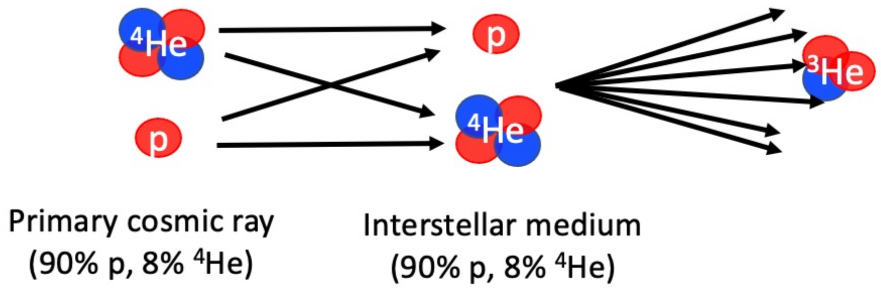
Astrophysics applications: Dark Matter





Antinuclei production in our Galaxy:

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

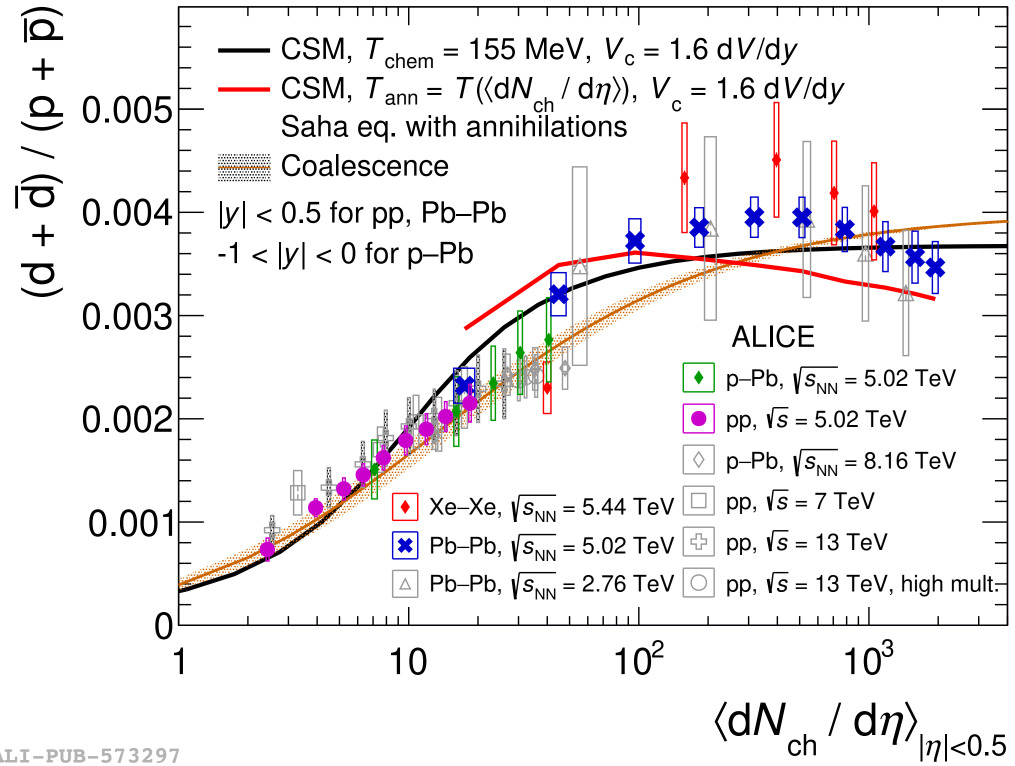


- dark-matter annihilation processes

- 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

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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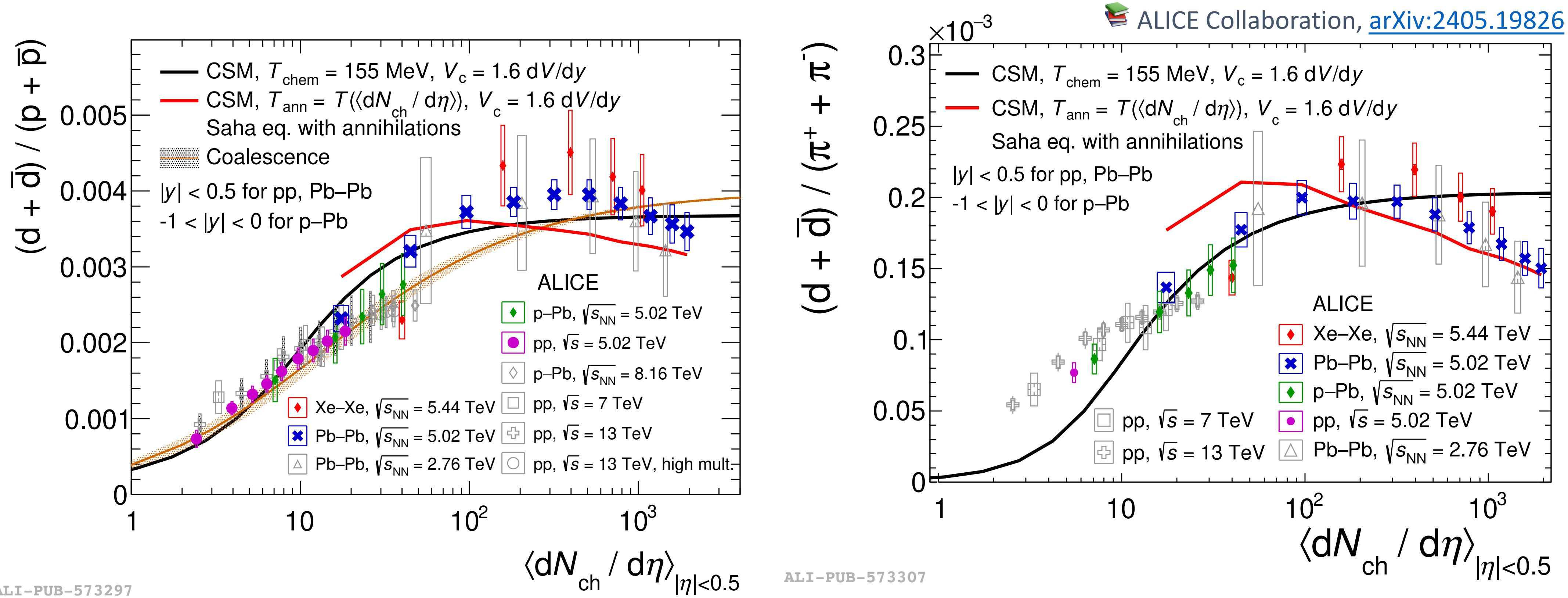

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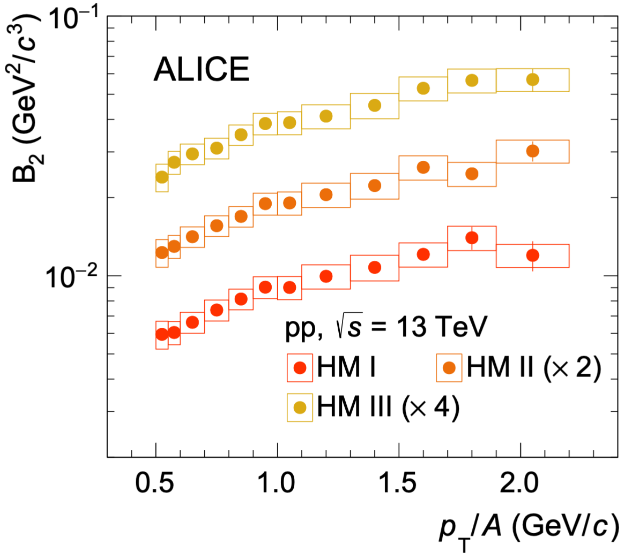
- Both CSM and **coalescence**[3] predictions qualitatively reproduce the trend and overall yields, but neither of the models catch all data points
- CSM-I at low multiplicity does not reproduce d/π ratio, but CSM-II at high multiplicity catches the decreasing trend

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

Testing coalescence model using B_2

- Important observable in accelerator measurements: coalescence parameter B_A

$$B_A\left(p_{\mathrm{T}}^{\mathrm{p}}\right) = \frac{1}{2\pi p_{\mathrm{T}}^{\mathrm{A}}} \frac{\mathrm{d}^2 N_{\mathrm{A}}}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}^{\mathrm{A}}} \bigg/ \left(\frac{1}{2\pi p_{\mathrm{T}}^{\mathrm{p}}} \frac{\mathrm{d}^2 N_{\mathrm{p}}}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}^{\mathrm{p}}}\right)^A$$



ALICE Collaboration, JHEP 01 (2022) 106

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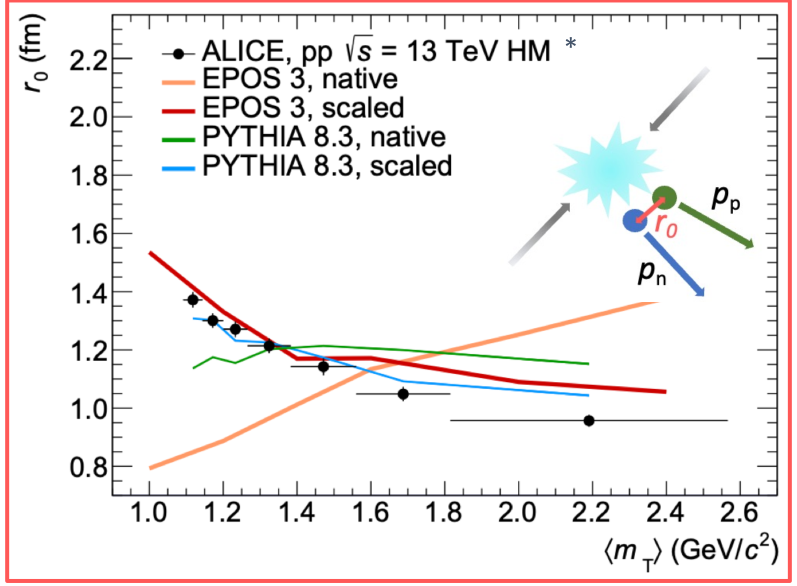
- Comparison to state-of-the-art coalescence models based on Wigner formalism showed that there are 2 key ingredients:
  - *emission source size*



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

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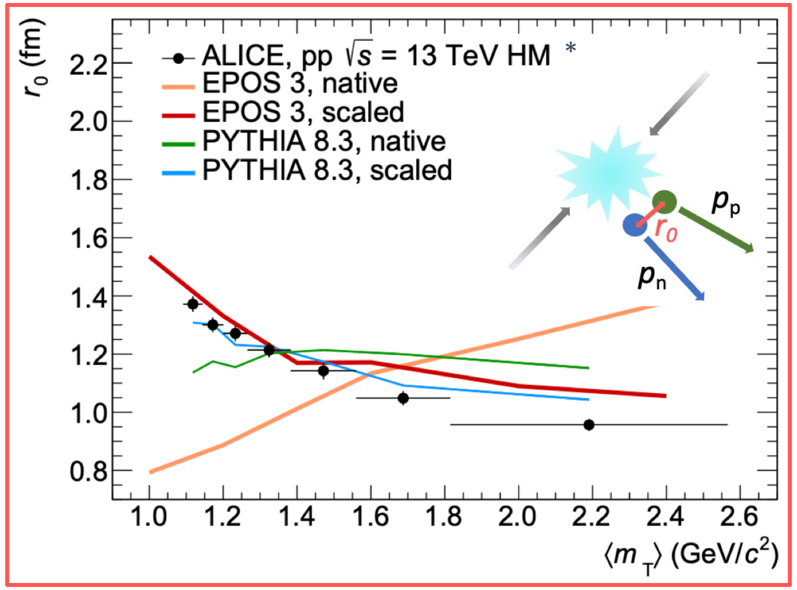

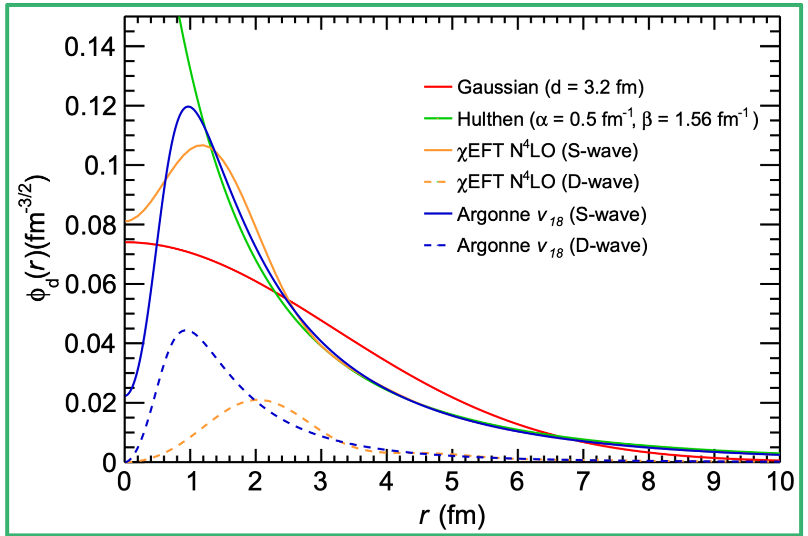

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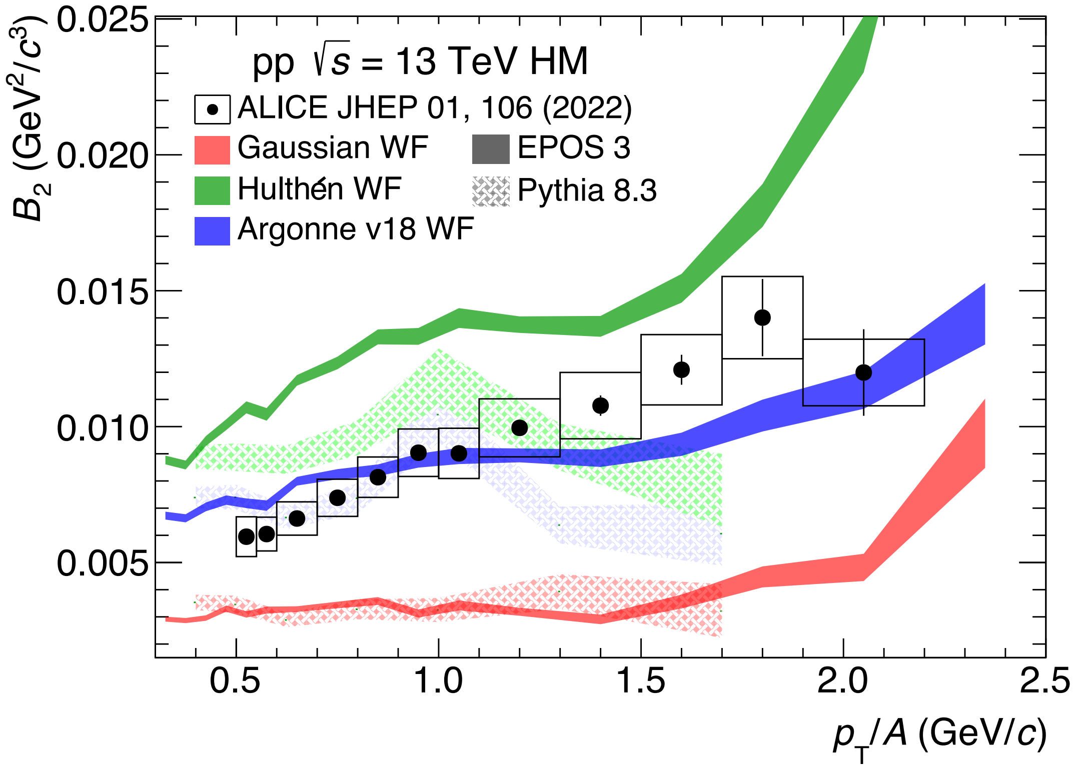

State-of-the-art coalescence model describes deuteron momentum distributions and coalescence parameter, using realistic WF and measured r_0!

$\longleftrightarrow$

Production measurements can be used to constrain the nuclear wavefunction!

* ALICE Collaboration, PLB 811 (2020) 135849
ALICE Collaboration, JHEP 01 (2022) 106
Kachelrieß et al., EPJA 56 1 (2020) 4
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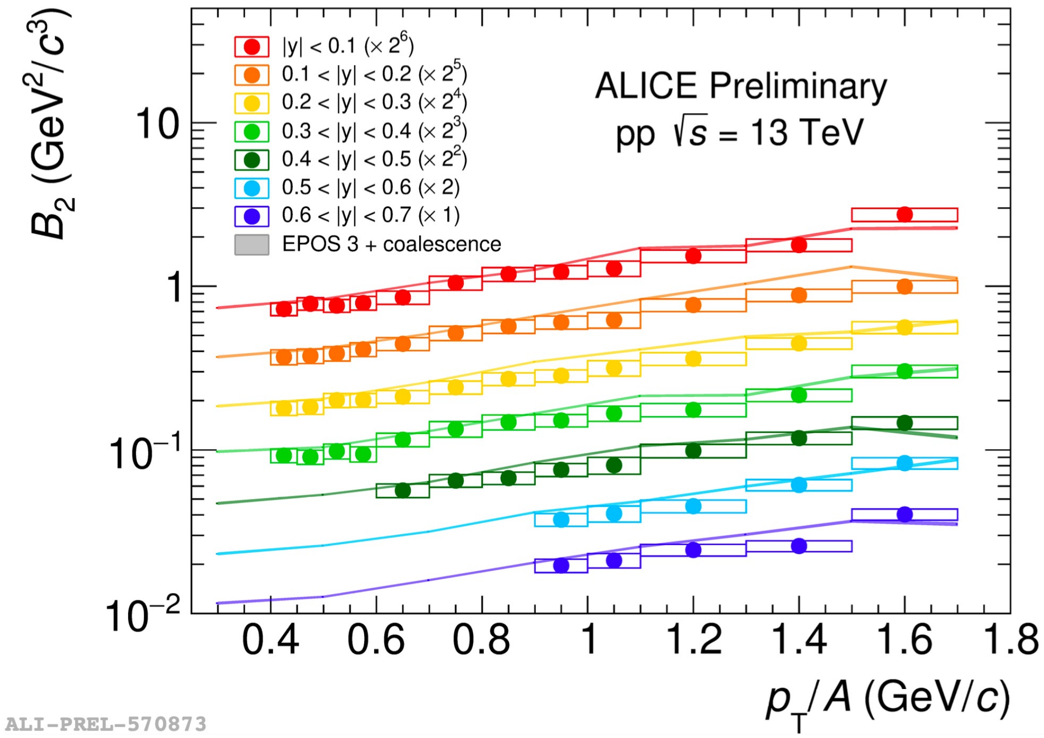
B_2 vs rapidity with ALICE



- 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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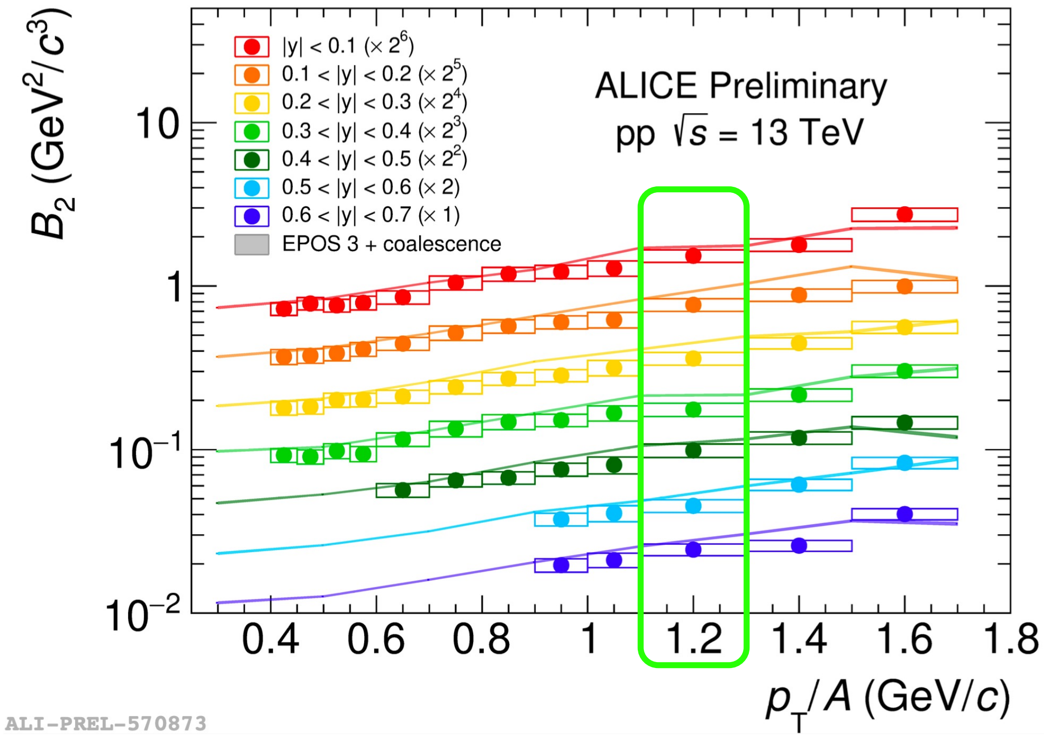

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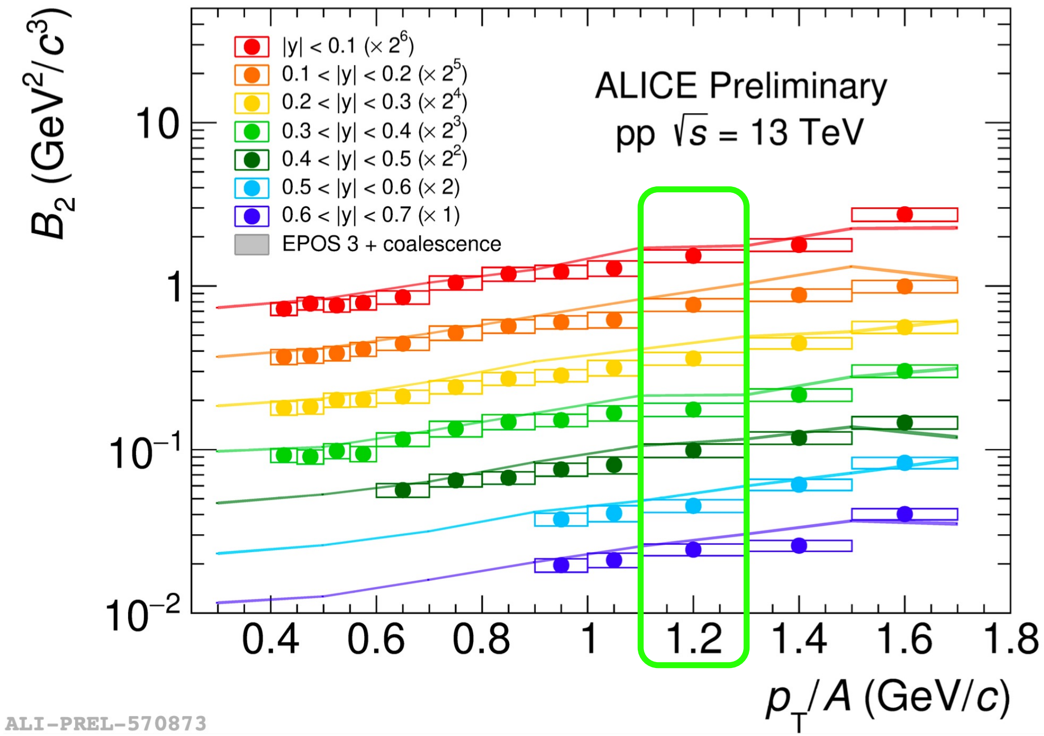

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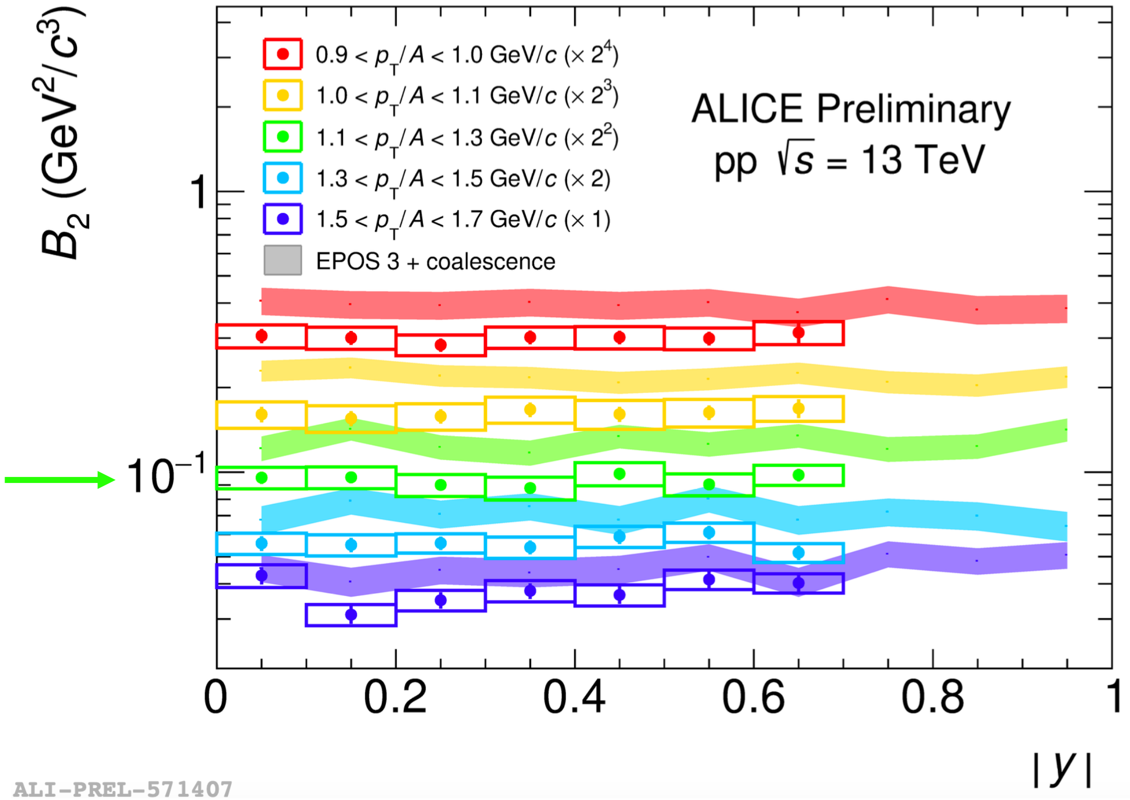
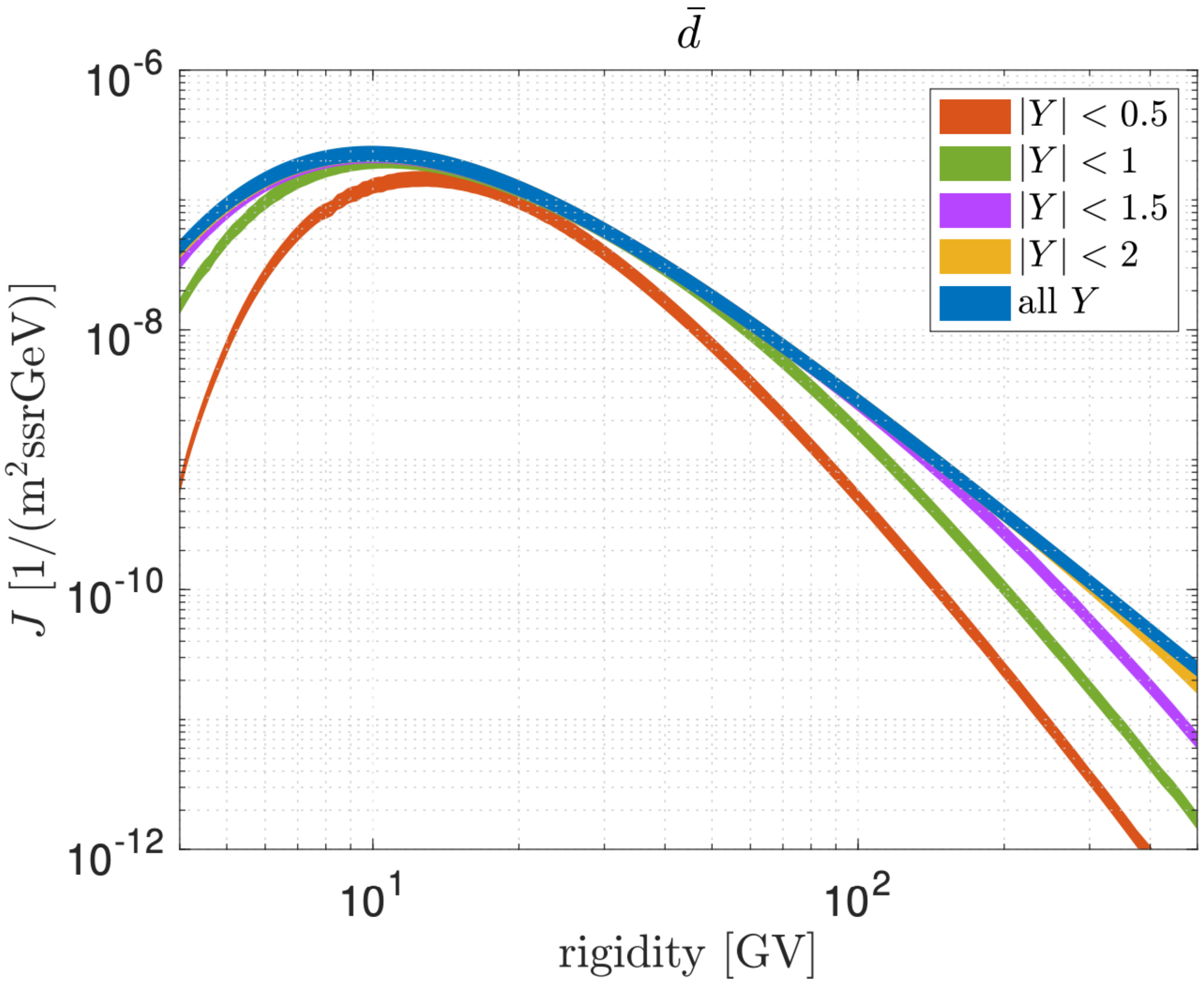


- Rapidity and p_T dependence of B_2 is extrapolated to forward rapidity using coalescence model + Pythia 8.3 and EPOS as event generators

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

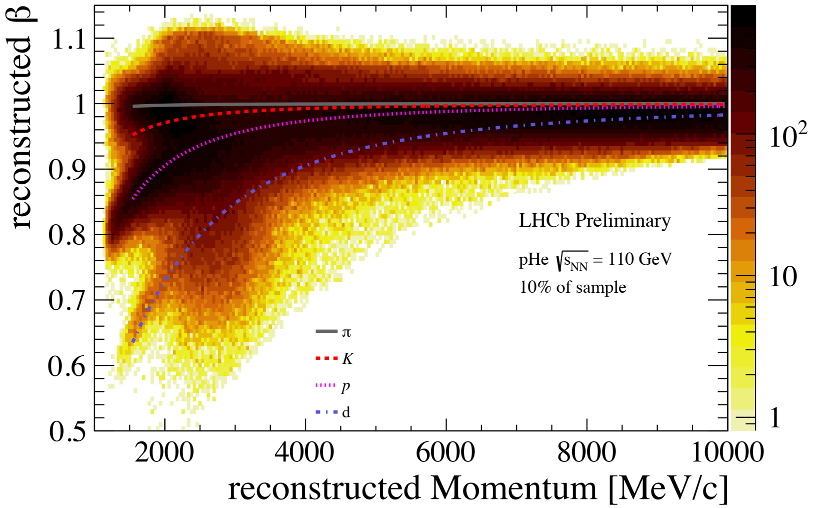
* K. Blum, Phys. Rev. D 96, 103021 (2017)

[1] ALICE Collaboration, arXiv:2211.02491

K. Blum, arXiv:2306.13165

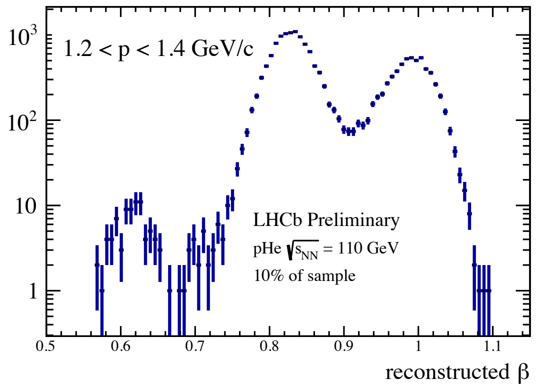
(anti)deuterons at forward rapidity

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



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

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



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

LHCb Collaboration, [JINST 3 S08005 (2008)]

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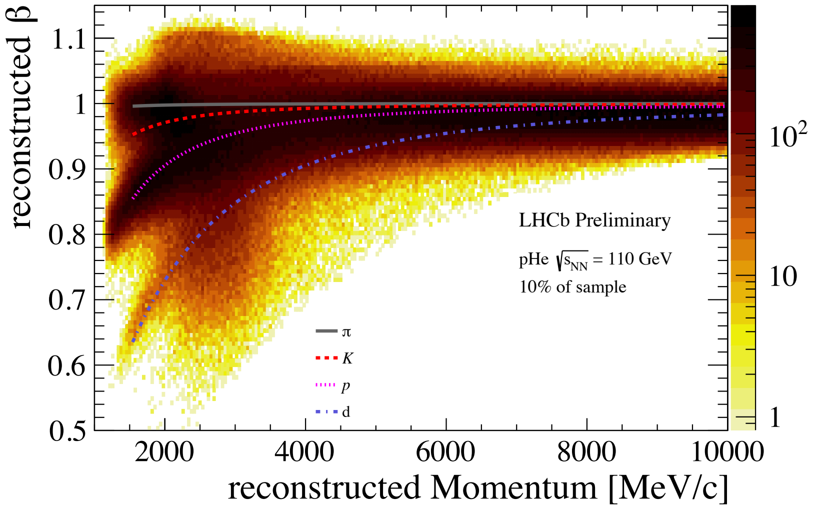
CMS program in LHC Run4 ($|y| \lesssim 2$)



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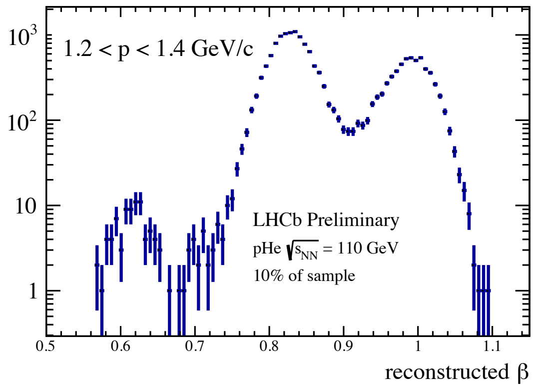

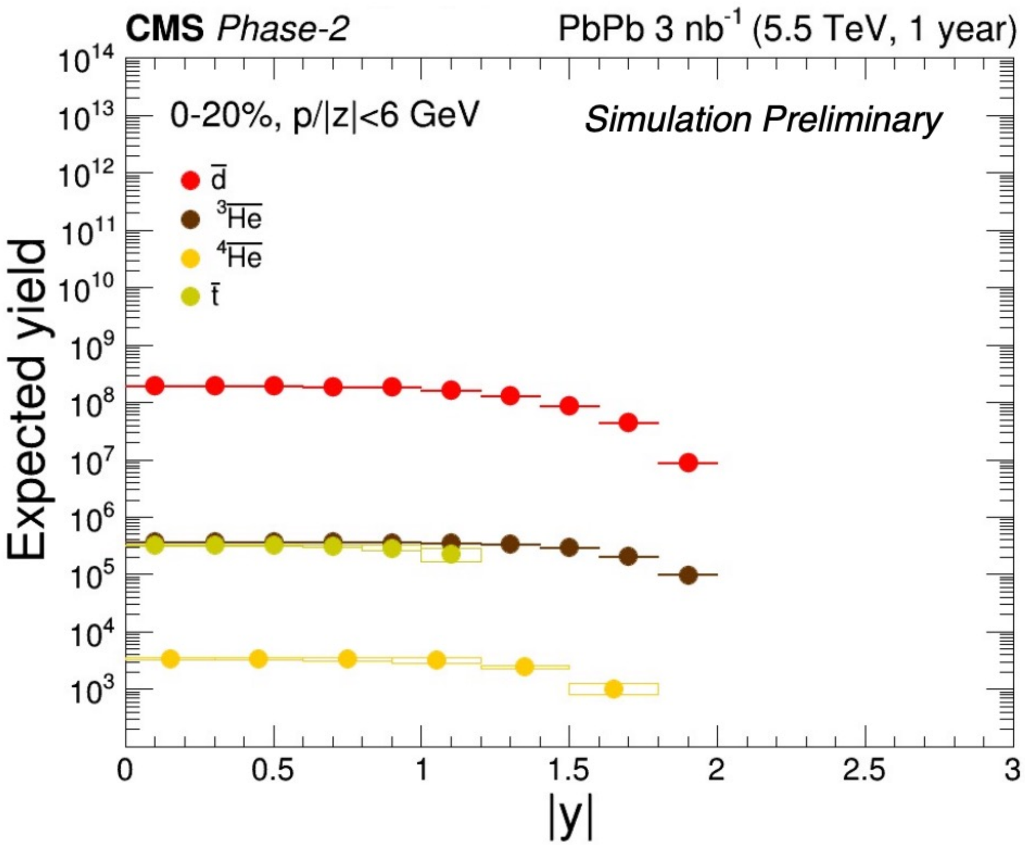

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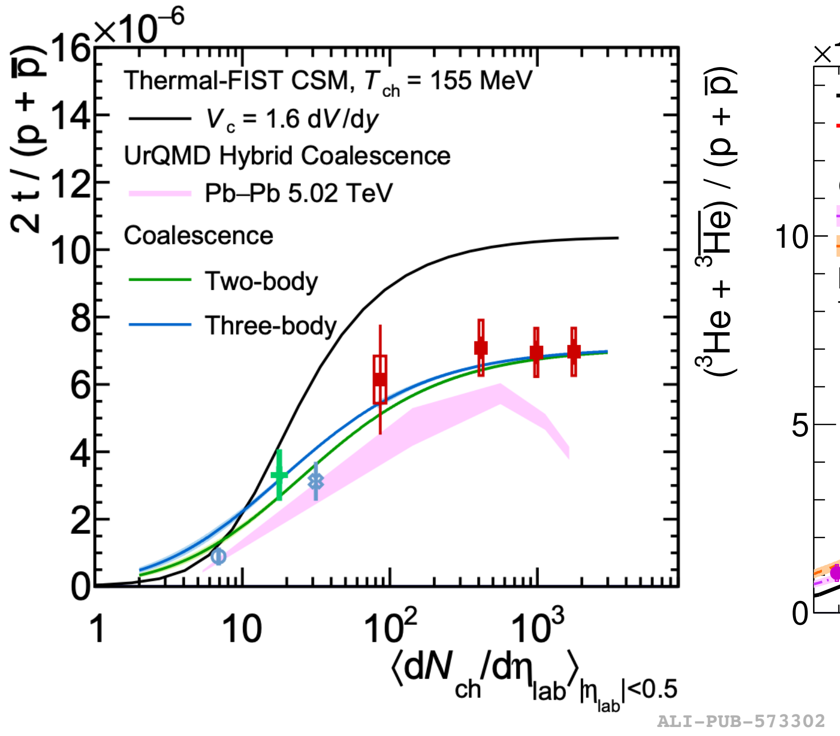
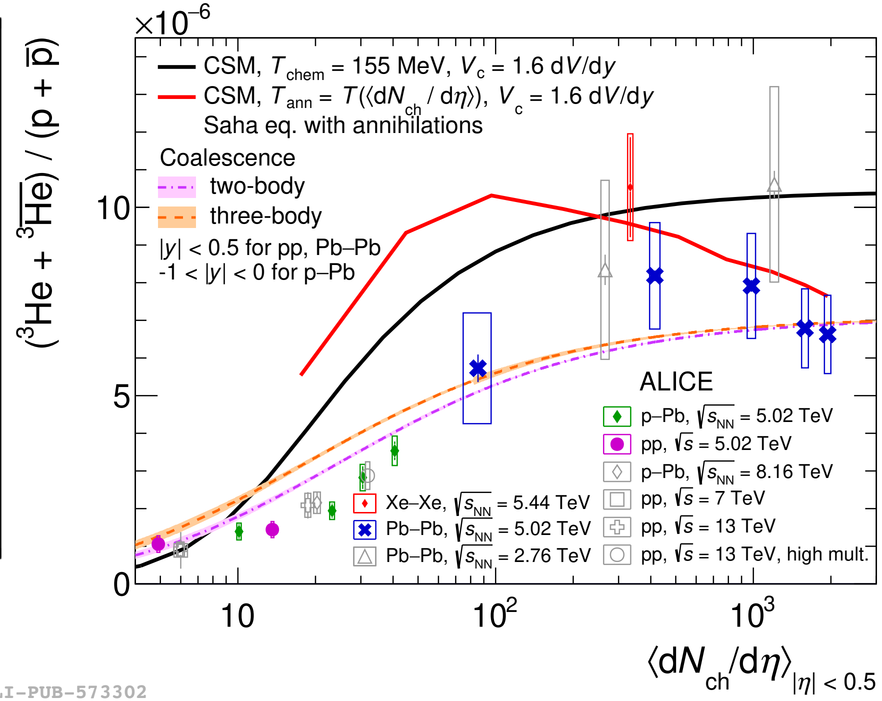
LHCb Collaboration, JINST 3 S08005 (2008)

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

Testing production models with A=3





- Measurements of yields of nuclei with A=3 challenge the models
- 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
Vovchenko, Koch, PLB 835, 137577 (2022)
ALICE Collaboration, PRC 107 (2023) 064904
Sun, Ko, Doenigus, PLB 792 (2019) 132-137
ALICE Collaboration, arXiv:2405.19826

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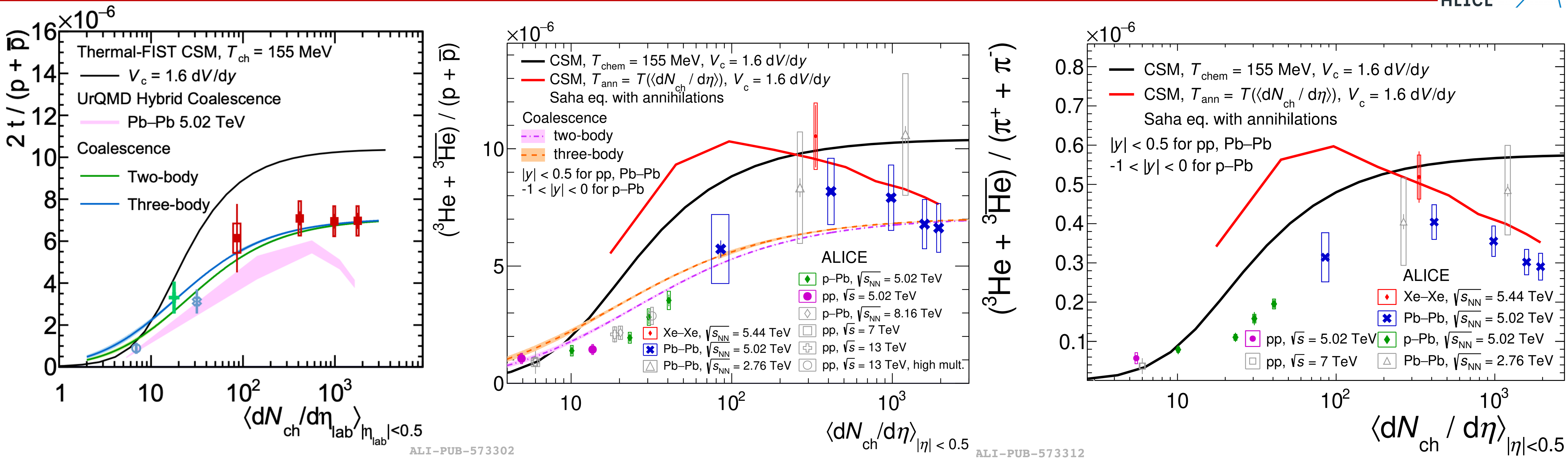

- Measurements of yields of nuclei with A=3 challenge the models
- Neither of the CSM models or **coalescence** predictions reproduce the trend of the ratios, but qualitatively reproduce the overall yields
- As for d/π and d/p ratios, CSM-II at high multiplicity catches the decreasing trend

ALICE Collaboration, PRL 131 (2023) 041901
Vovchenko, Koch, PLB 835, 137577 (2022)
ALICE Collaboration, PRC 107 (2023) 064904
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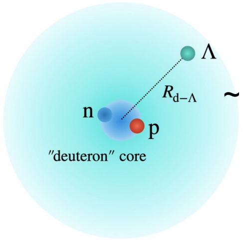
ALICE Collaboration, arXiv:2405.19826

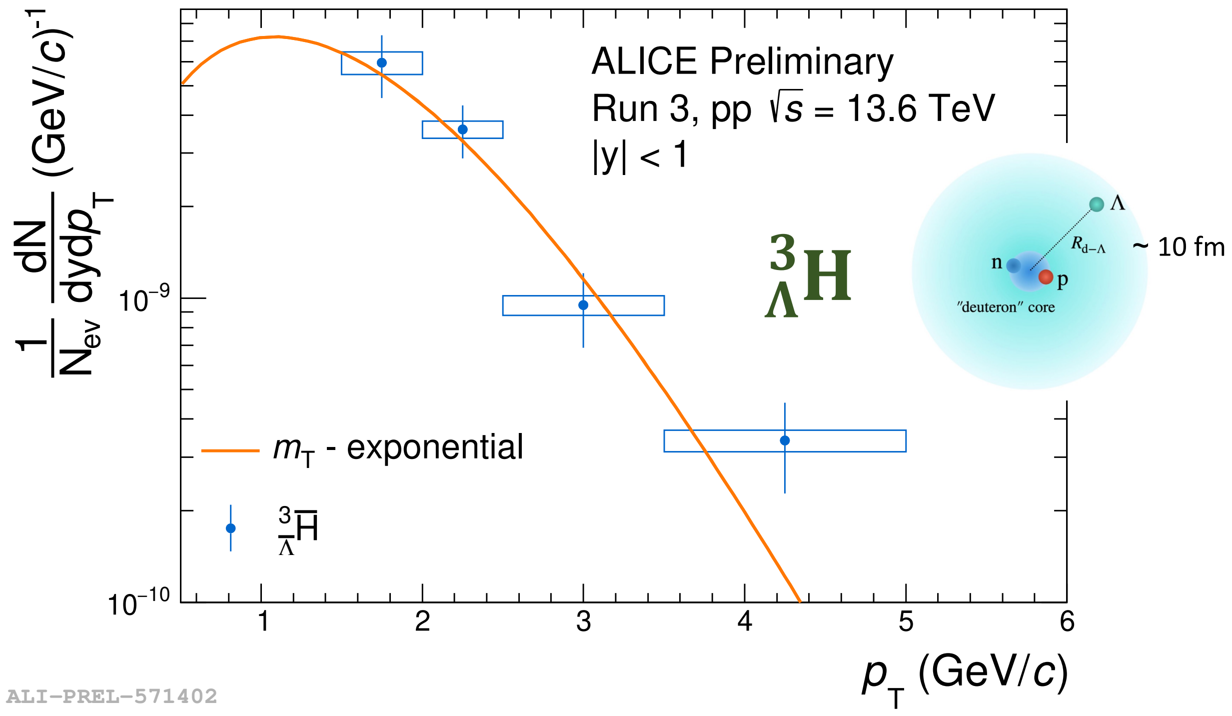
Testing production models with hypertriton

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



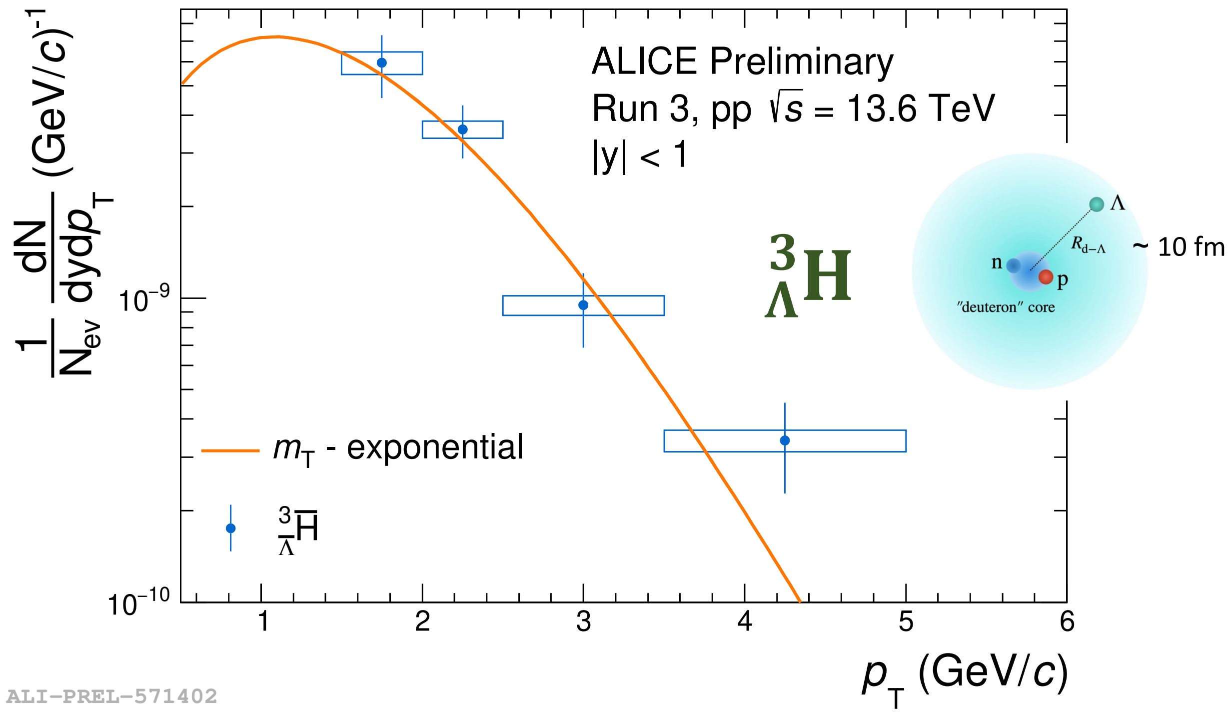
~ 10 fm

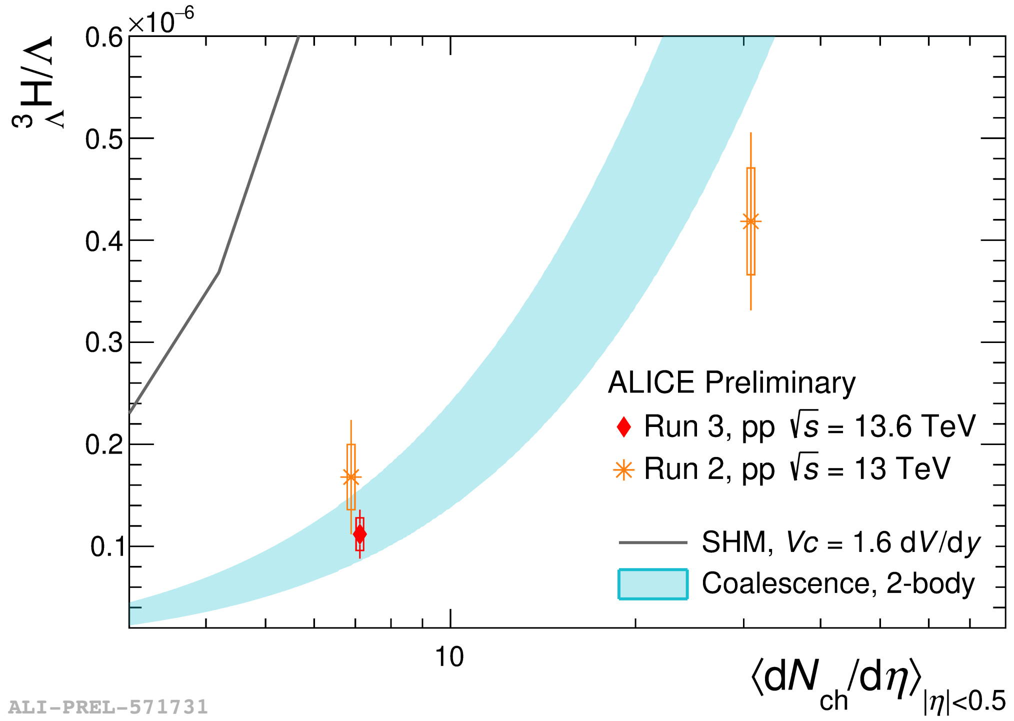
Testing production models with hypertriton



- 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





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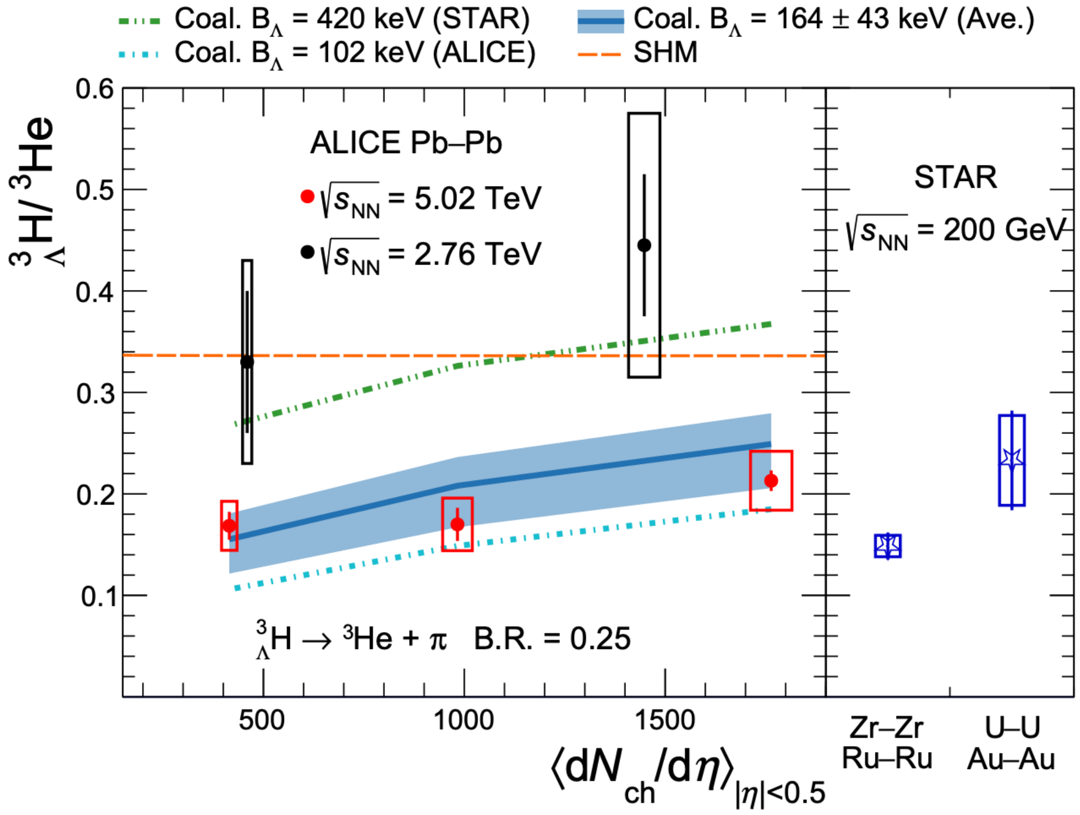
- Coalescence is sensitive to the **interplay** between the **size of the collision system** and the spatial extension of the **nucleus wave function**
- $^{3}_{\Lambda}$H/Λ ratio provides a powerful tool to investigate nuclear production mechanism → For small systems model **predictions are quite different**

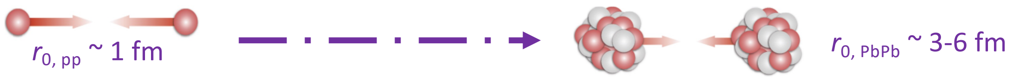
Hypertriton in Pb—Pb: test of production models

- ${}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}$ 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 ($m_{{}^{3}_{\Lambda}\mathrm{H}}$=2.991 and $m_{^3\mathrm{He}}$=2.809 GeV/c^2), but insensitive to their size [$r_{^3\mathrm{He}}$: 1.76 fm, $r_{{}^{3}_{\Lambda}\mathrm{H}\,(np\Lambda)}$: 4.9 fm ($B_\Lambda$= 2.35 MeV), $r_{{}^{3}_{\Lambda}\mathrm{H}\,(d\Lambda)}$: 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



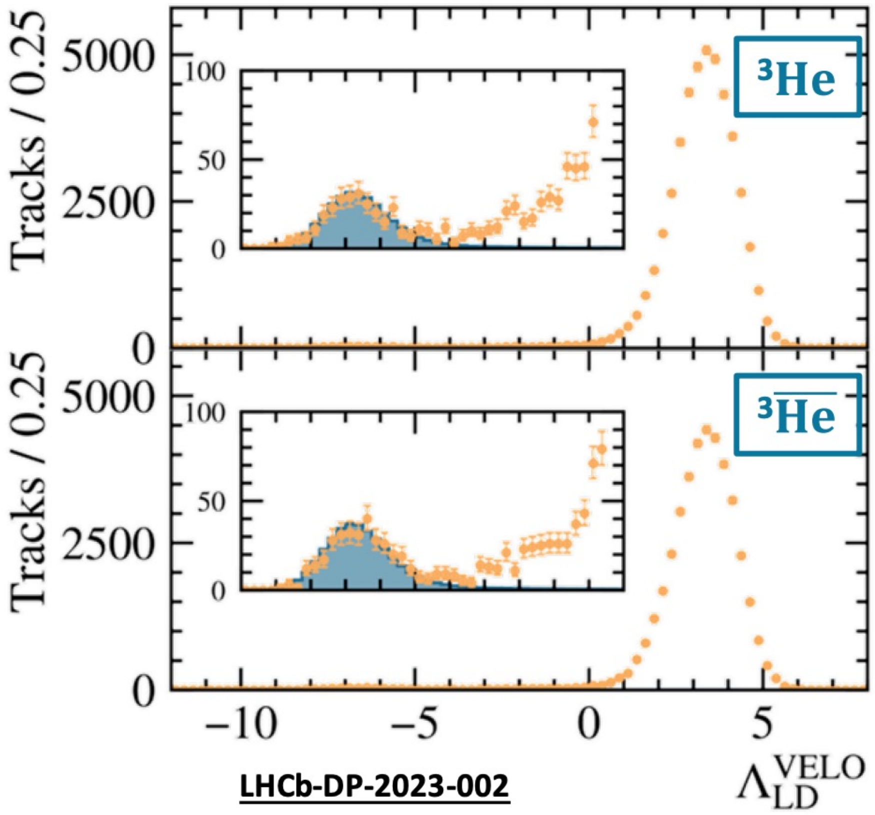


ALICE Collaboration, arXiv:2405.19839

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)

chiara.pinto@cern.ch

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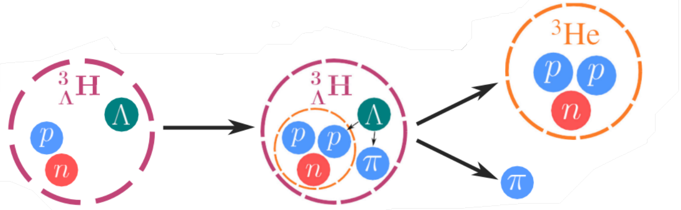
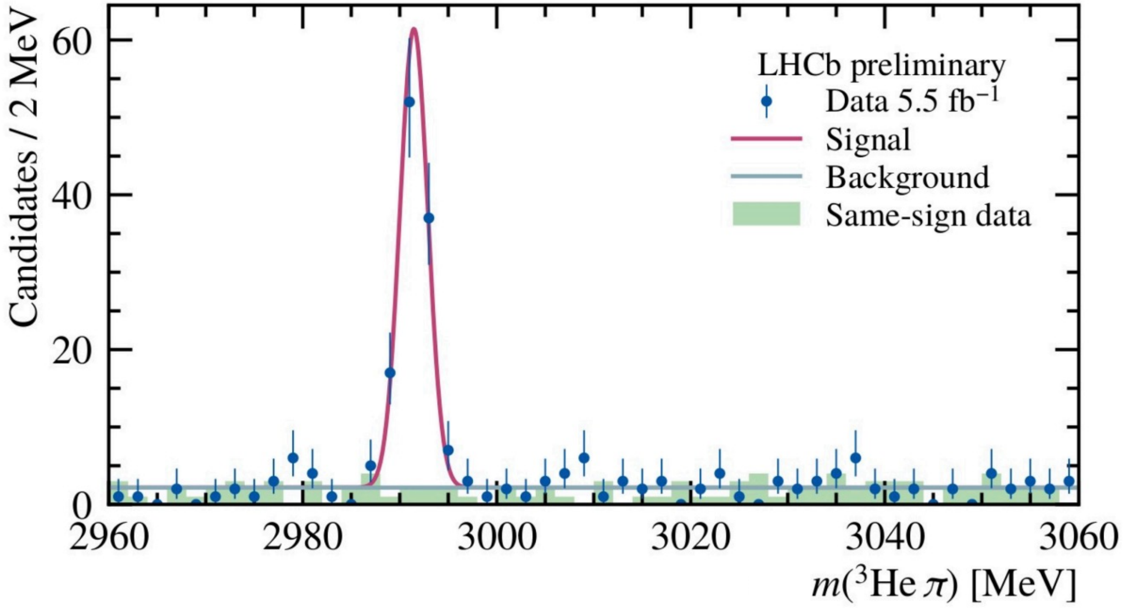
  → **He**: higher ADC counts and wider cluster size

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

$^3_\Lambda$H → ^{3}He + π^- and c.c.



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



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

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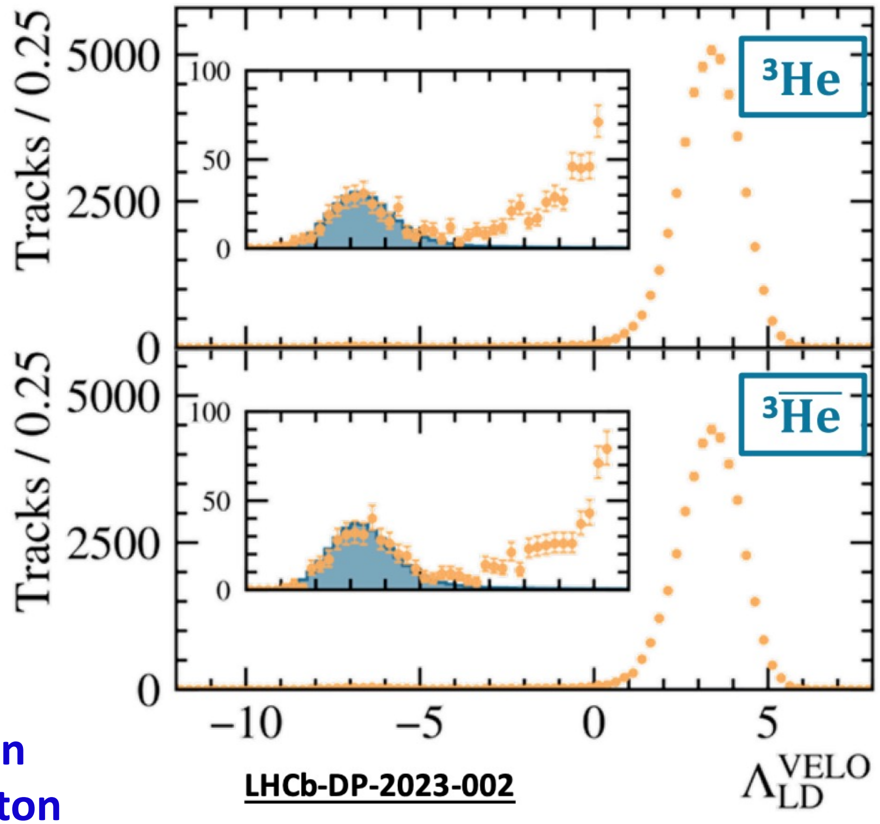
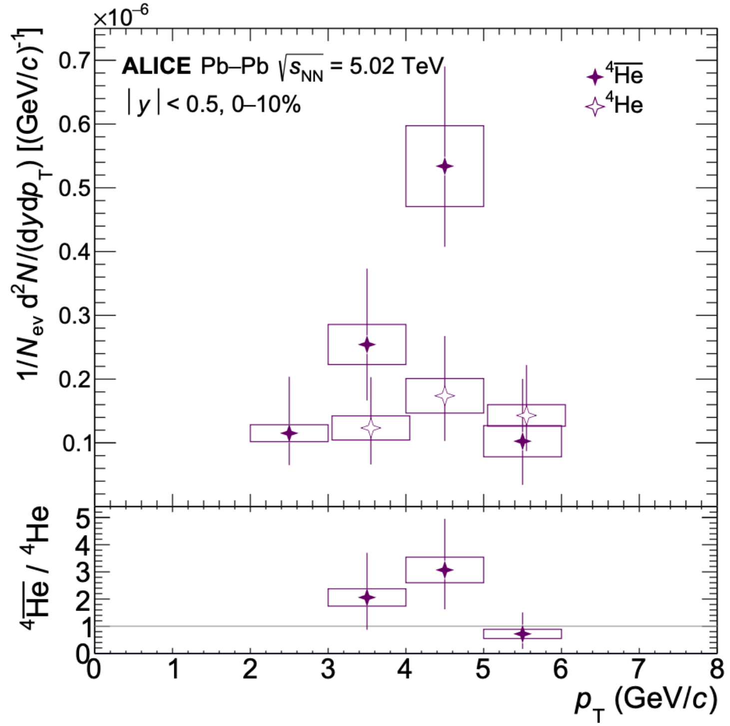


LHCb-DP-2023-002

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

chiara.pinto@cern.ch

Measurement of A=4 nuclei in Pb—Pb



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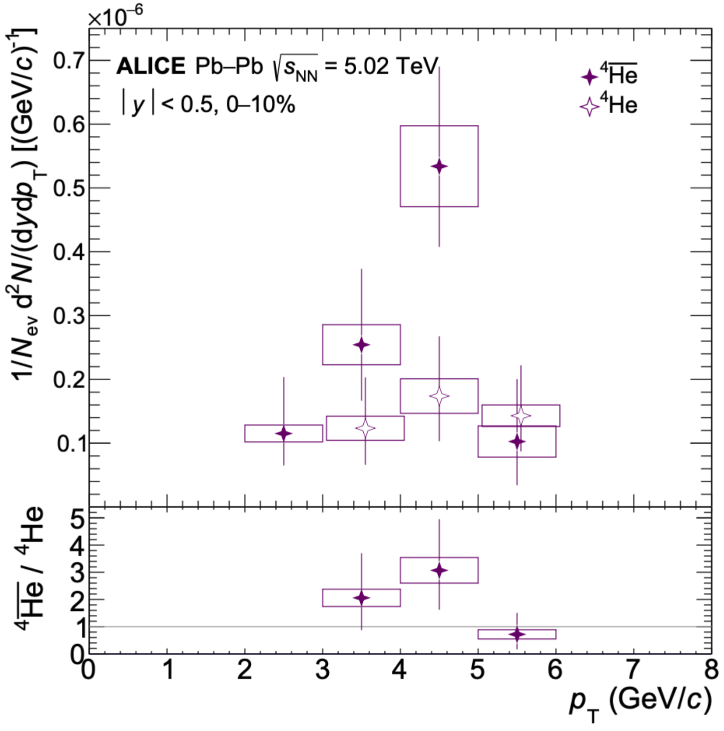
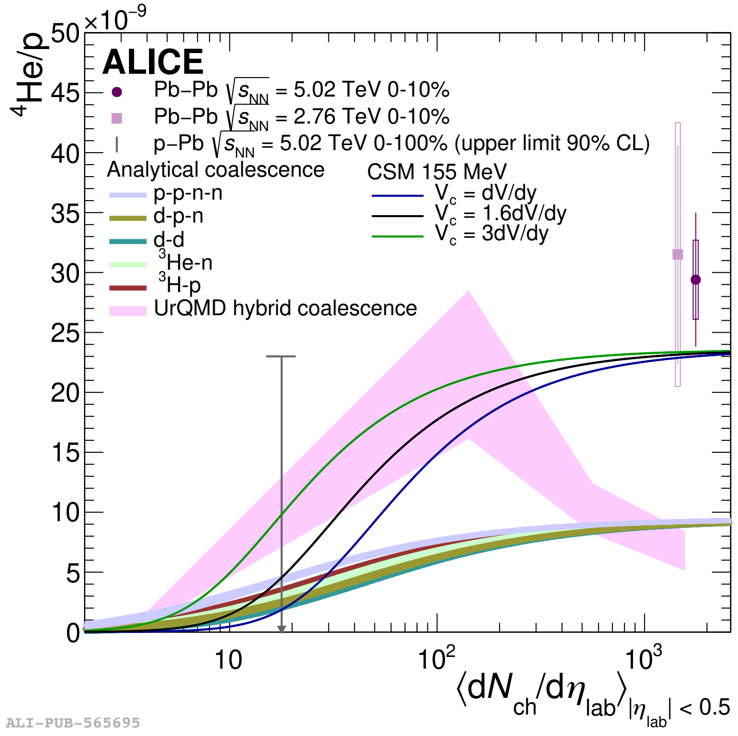
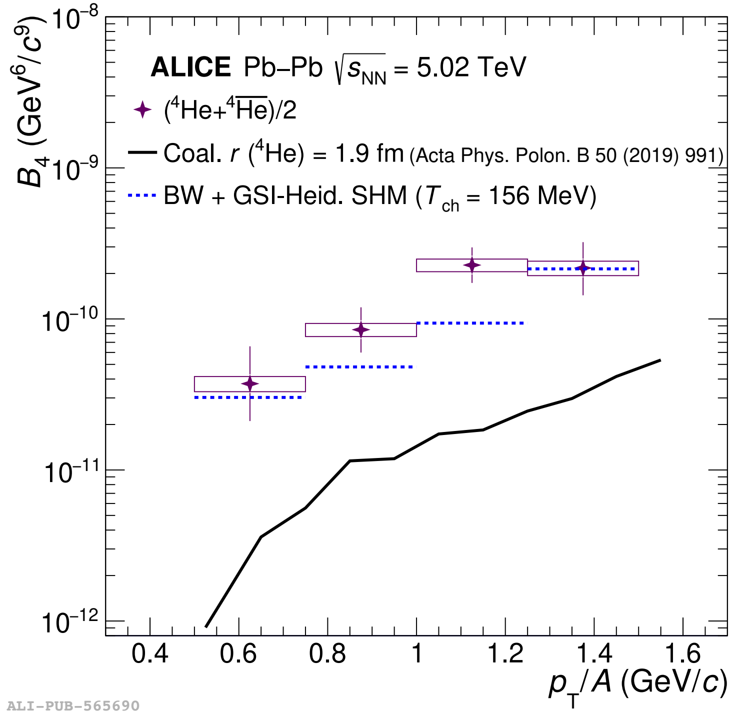
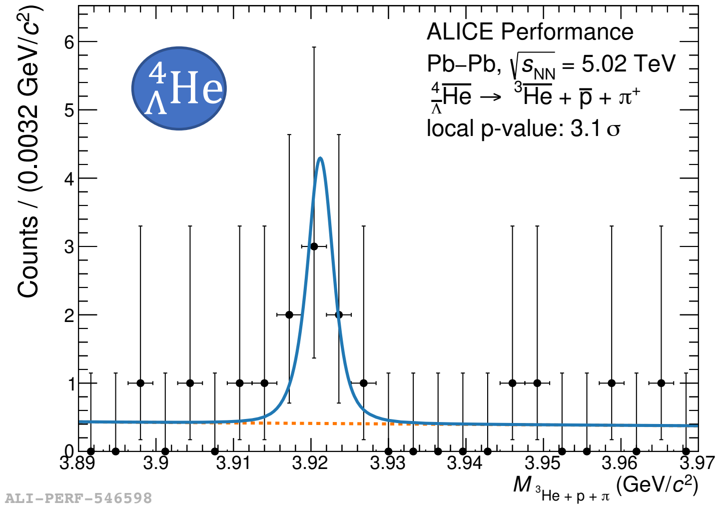


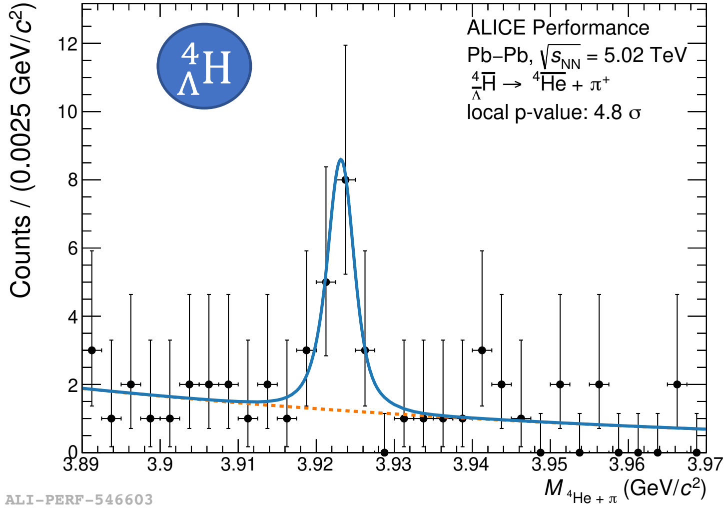


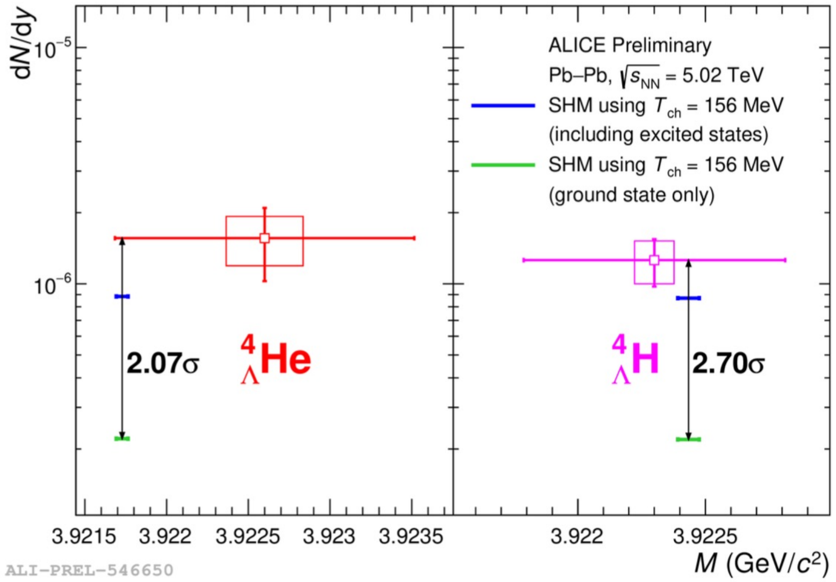


- ^{4}He is very compact and more bound than lighter nuclei: E_B~ 28 MeV, r ~ 1.7 fm
- ^{4}He/p ratio & B_4 in agreement with SHM, but the only available measurements are from Pb—Pb collisions → data needed at intermediate multiplicity where models differ
- Blast Wave using common parameters with the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

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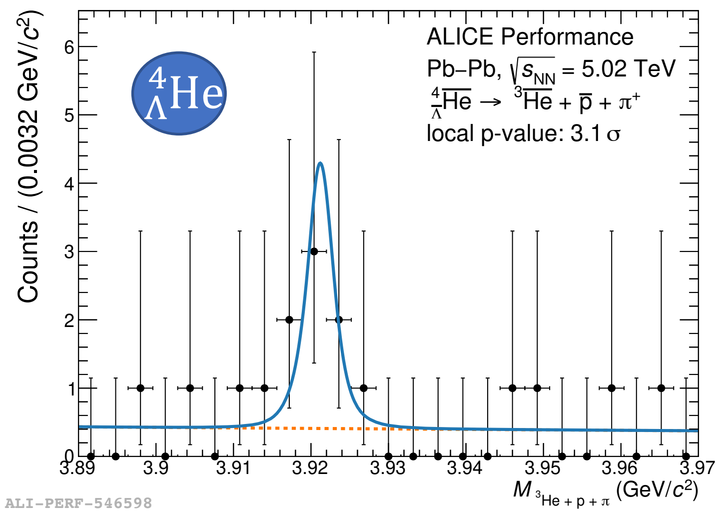
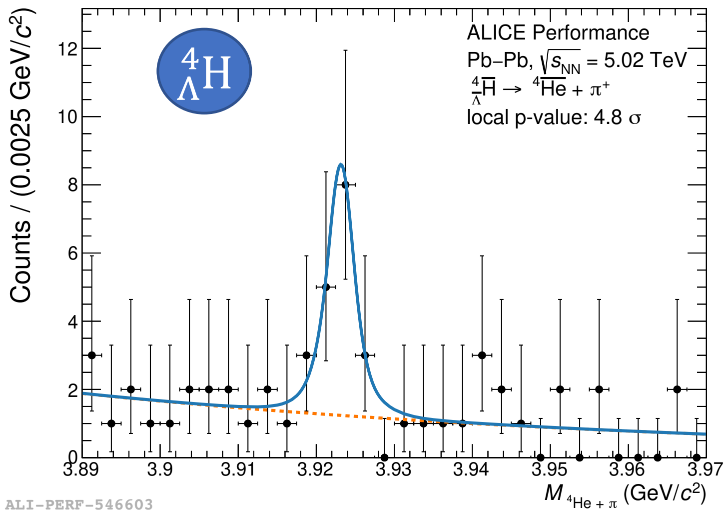
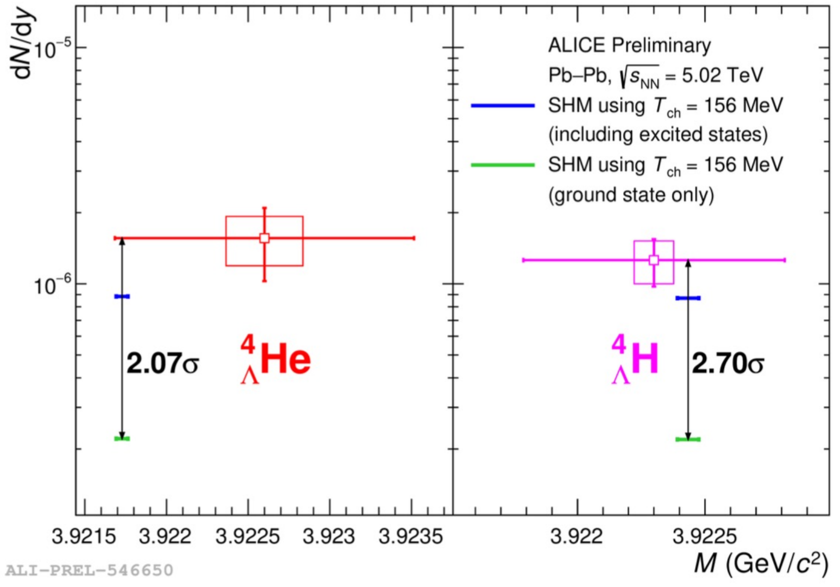
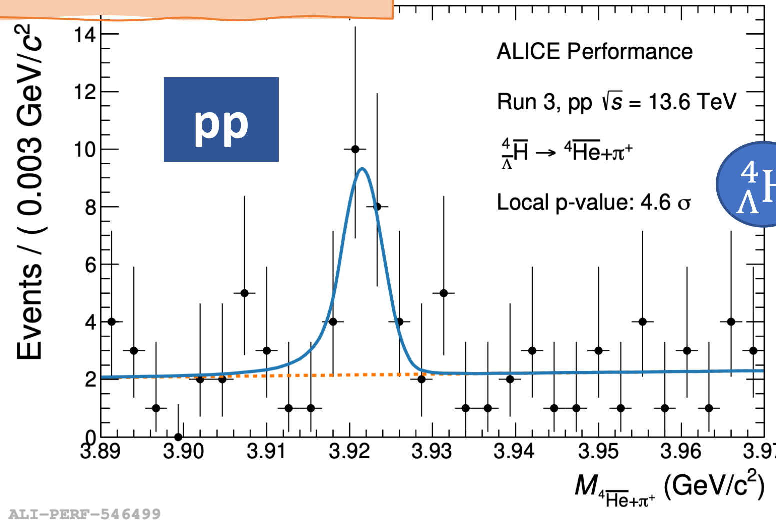






Pb—Pb

More to come with LHC Run3 data!



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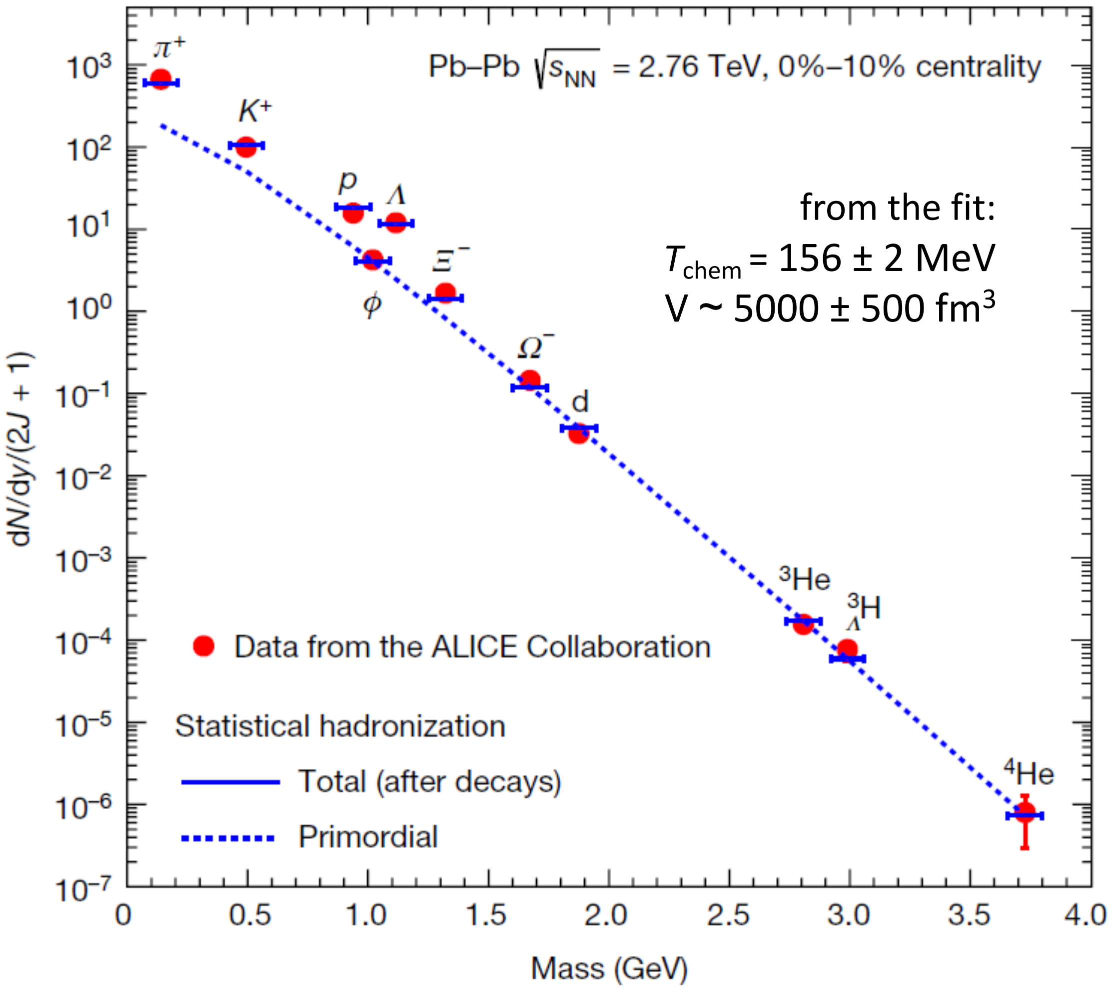
Modelling the production of (anti)nuclei

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})

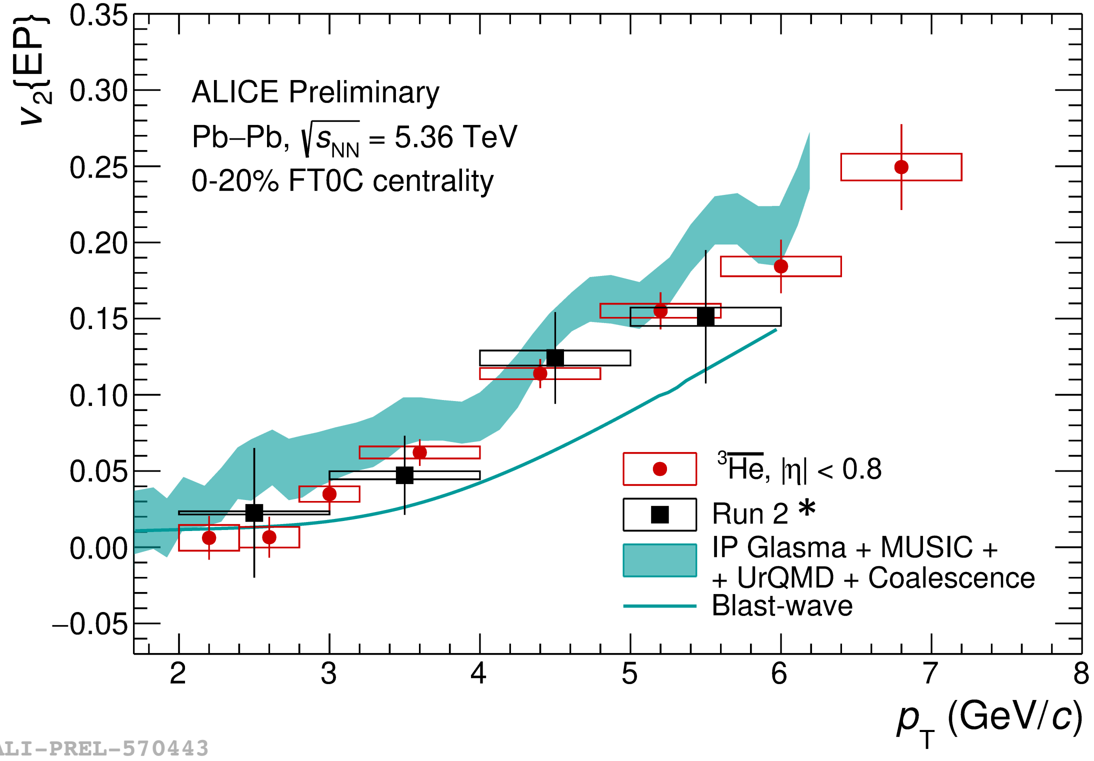
  ⇒ Nuclei (large m): large sensitivity to T_{chem}
- Typically used in Pb—Pb, for small systems the canonical ensemble is needed (CSM) → exact conservation of B, Q and S is required only in the correlation volume (V_c)

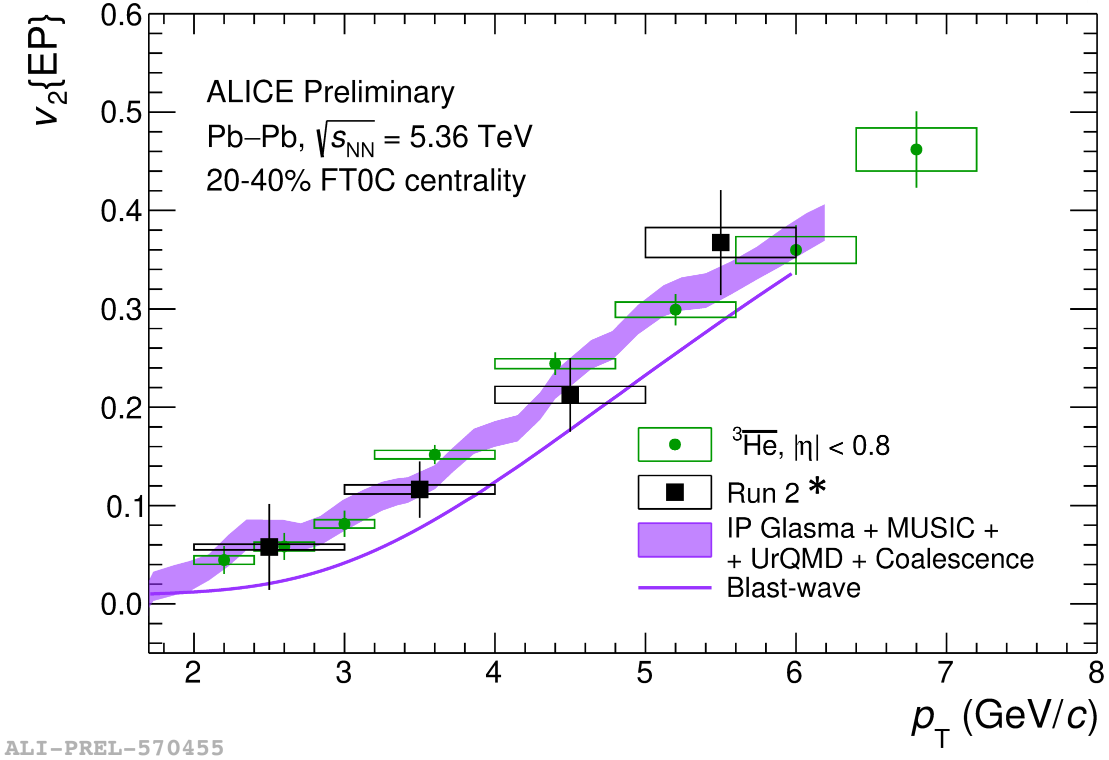


B:baryon number, Q:charge, S: strangeness content

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

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



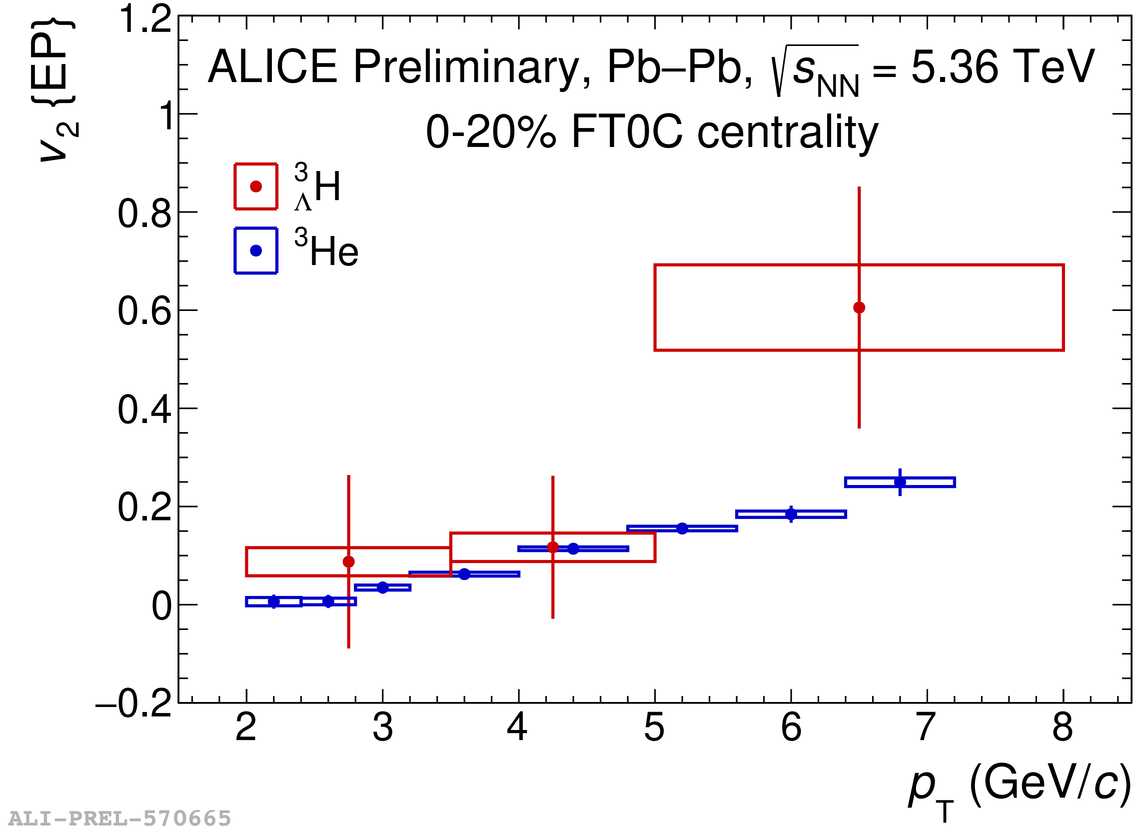


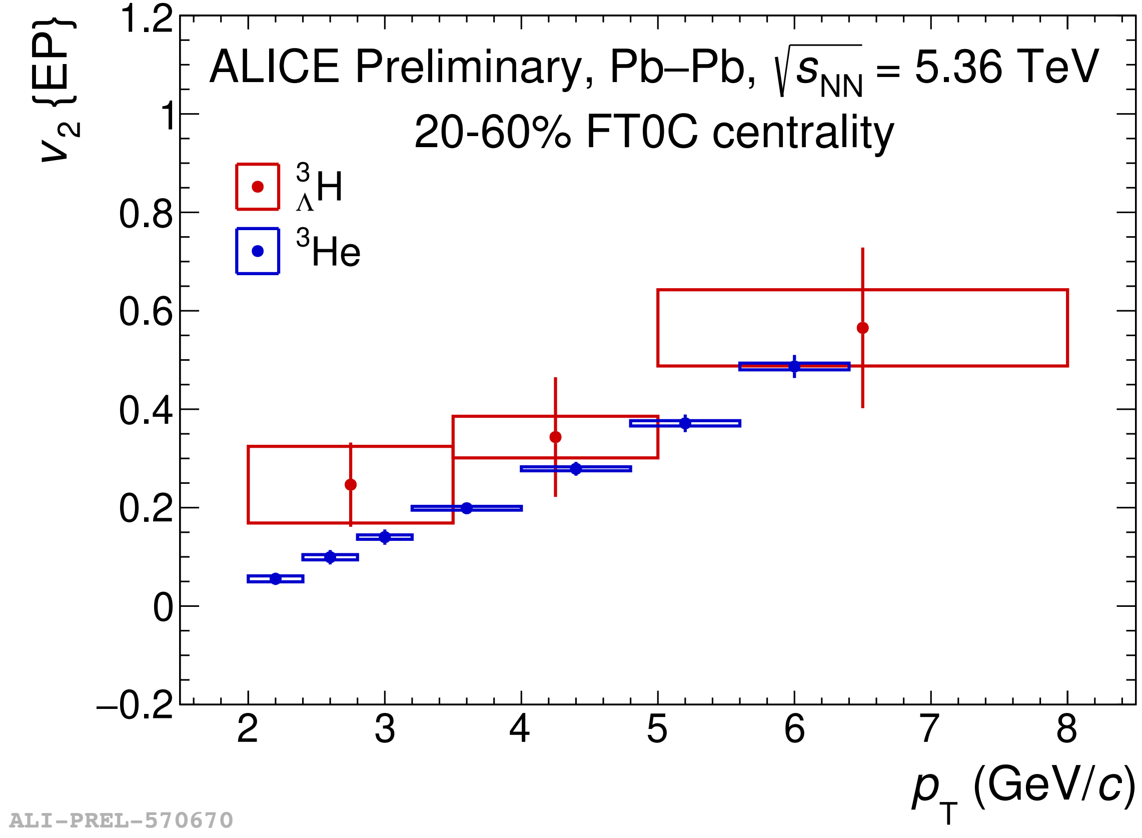
- ALICE Run3 statistics seems sensitive to the different production models using the elliptic flow v_2
- **Coalescence** is sensitive to a different production in-plane and out-of-plane
- Data are compared with the predictions of
  - Blast Wave model that uses the fit parameters of pi, K, p
  - coalescence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

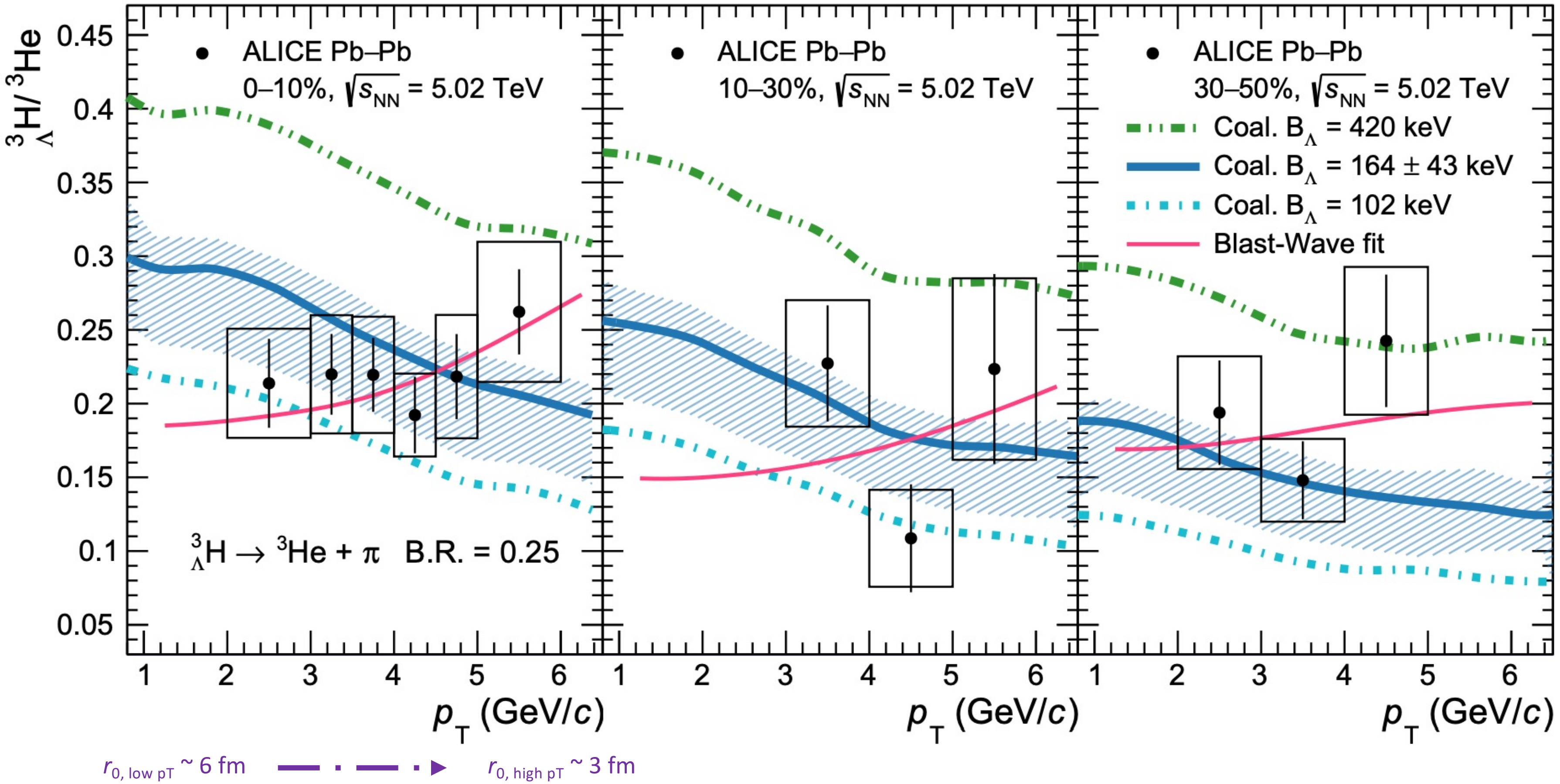




Hypertriton in Pb—Pb: test of production models

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

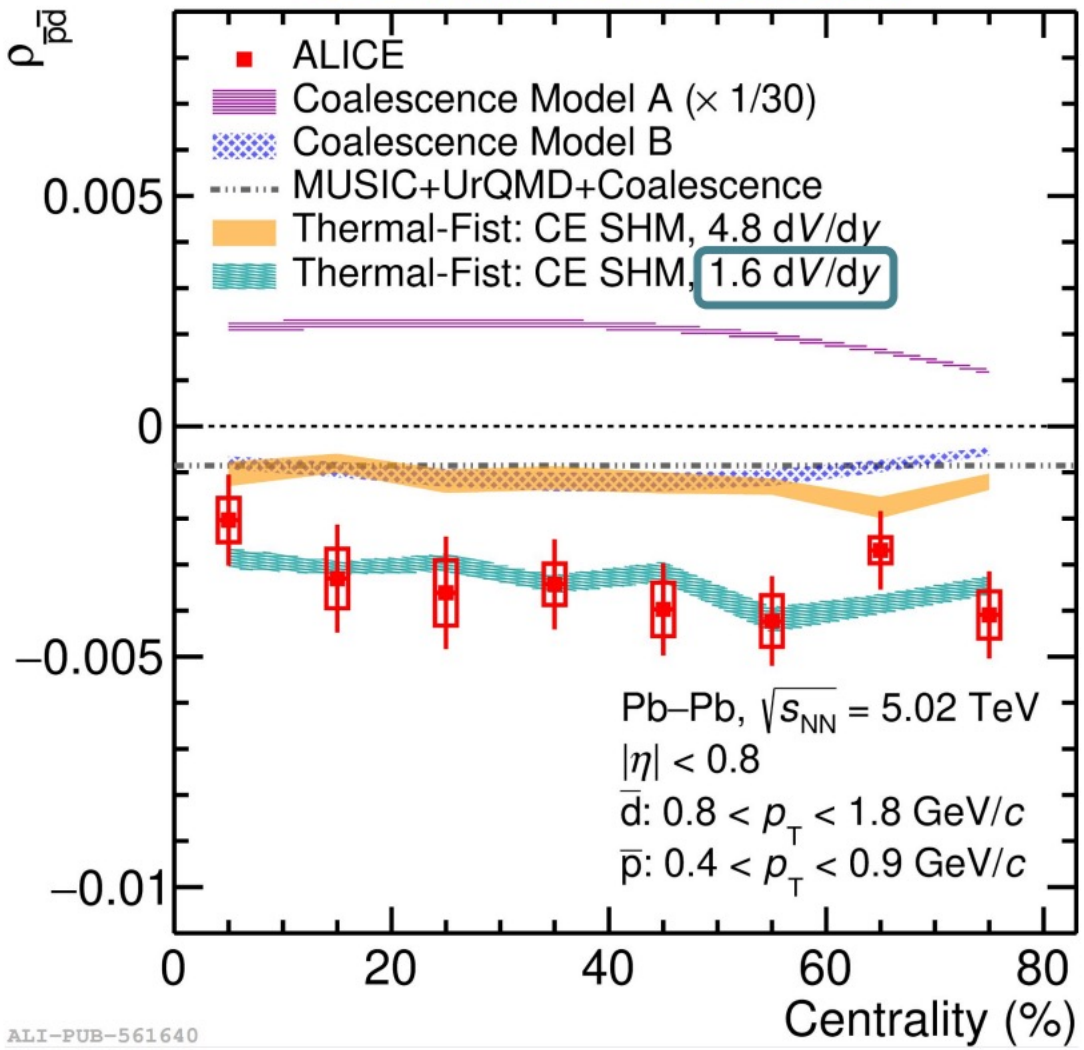
vs. p_{T}
  - Radial flow picture (Blast-Wave): higher mass states have a harder momentum spectrum
  - Coalescence: at large momentum smaller source radius, hence the state with the larger wave-function will get suppressed

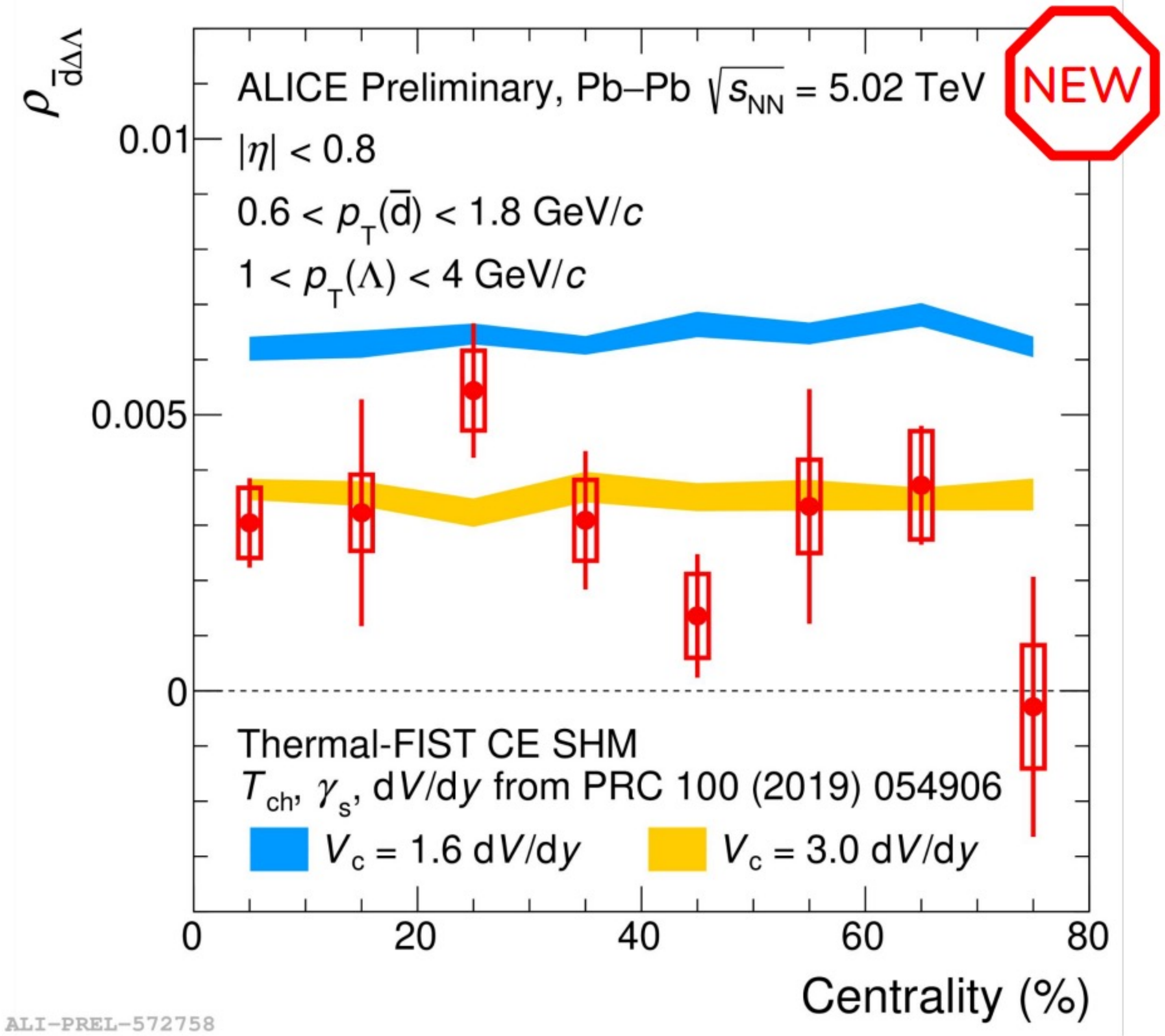


ALICE Collaboration, arXiv:2405.19839

Event-by-event fluctuations at the LHC

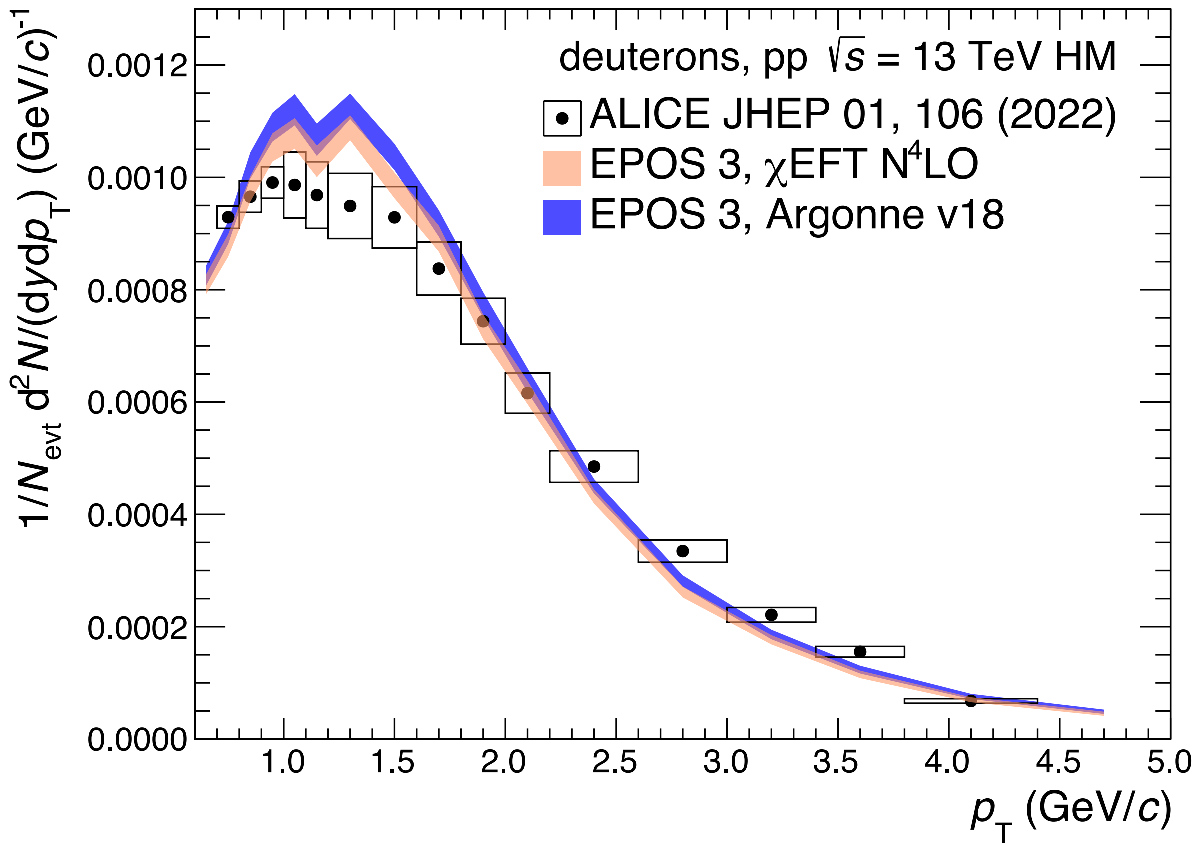
ALICE Coll., Phys. Rev. Lett. 131, 041901 (2023)

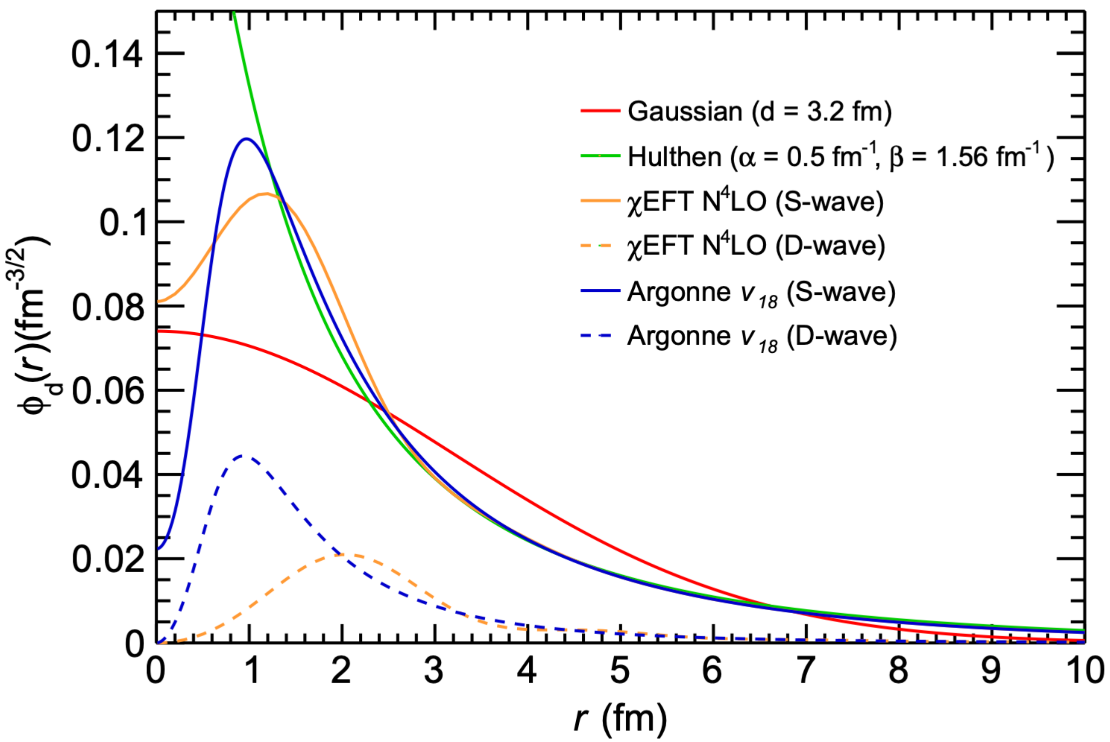




Testing coalescence model using B_2

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



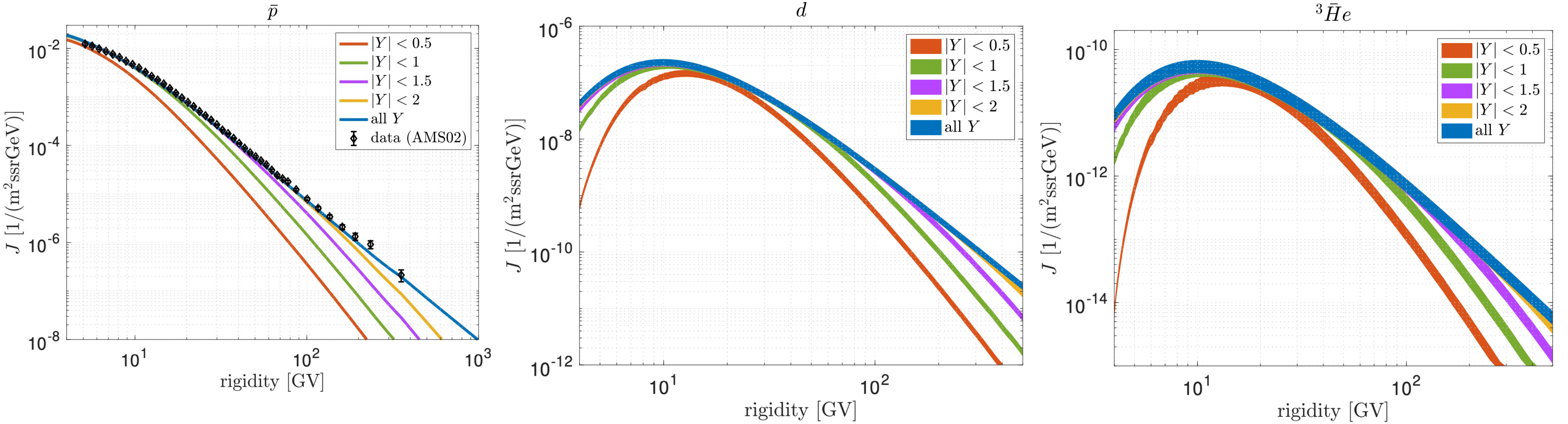


- **Hulthén*:** Favoured by low energy scattering experiments
- **Argonne v_{18}**:** phenomenological potential constrained to p-n scattering
- **χEFT:** Favoured by modern nuclear interaction experiments (e.g. Femtoscopy)

* 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

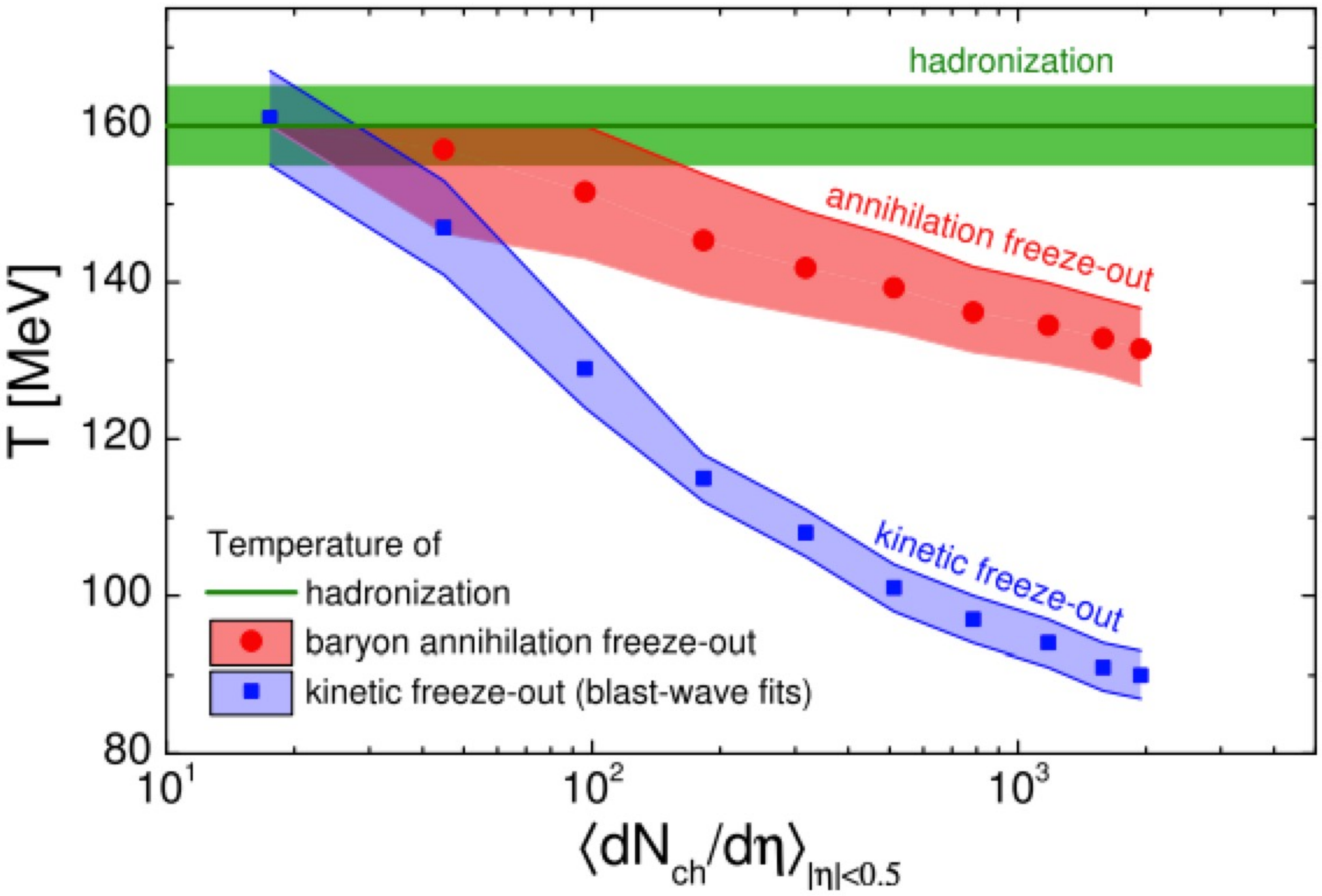
Mahlein et al., EPJC 83 (2023) 9, 804

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



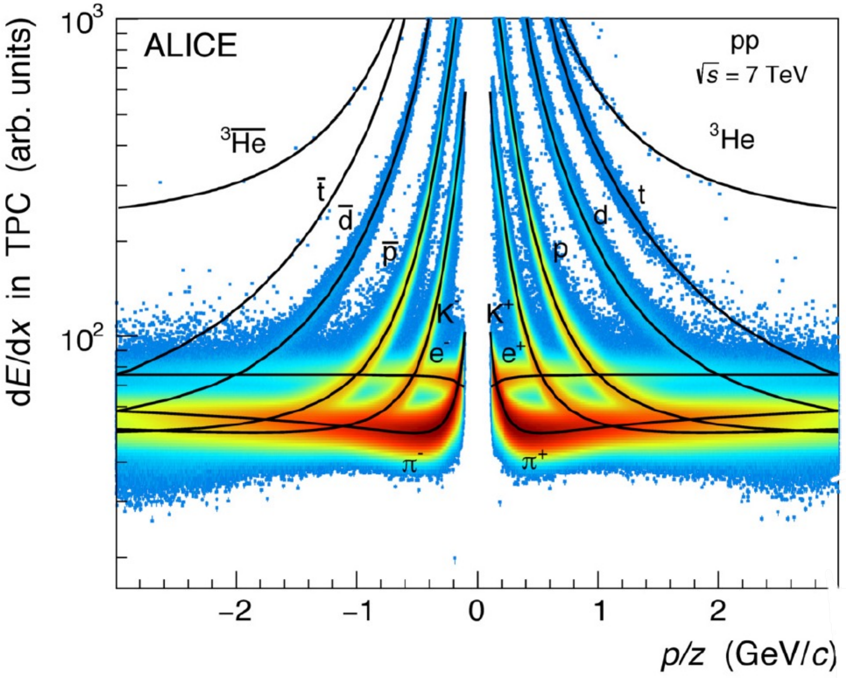
- Correlation volume fixed to 1.6 dV/dy
- Needed to describe the net-deuteron number fluctuations in PbPb collisions.
- Smaller than that of net-proton number fluctuations (3-5)dV/dy
- Temperature of annihilation depends on multiplicity

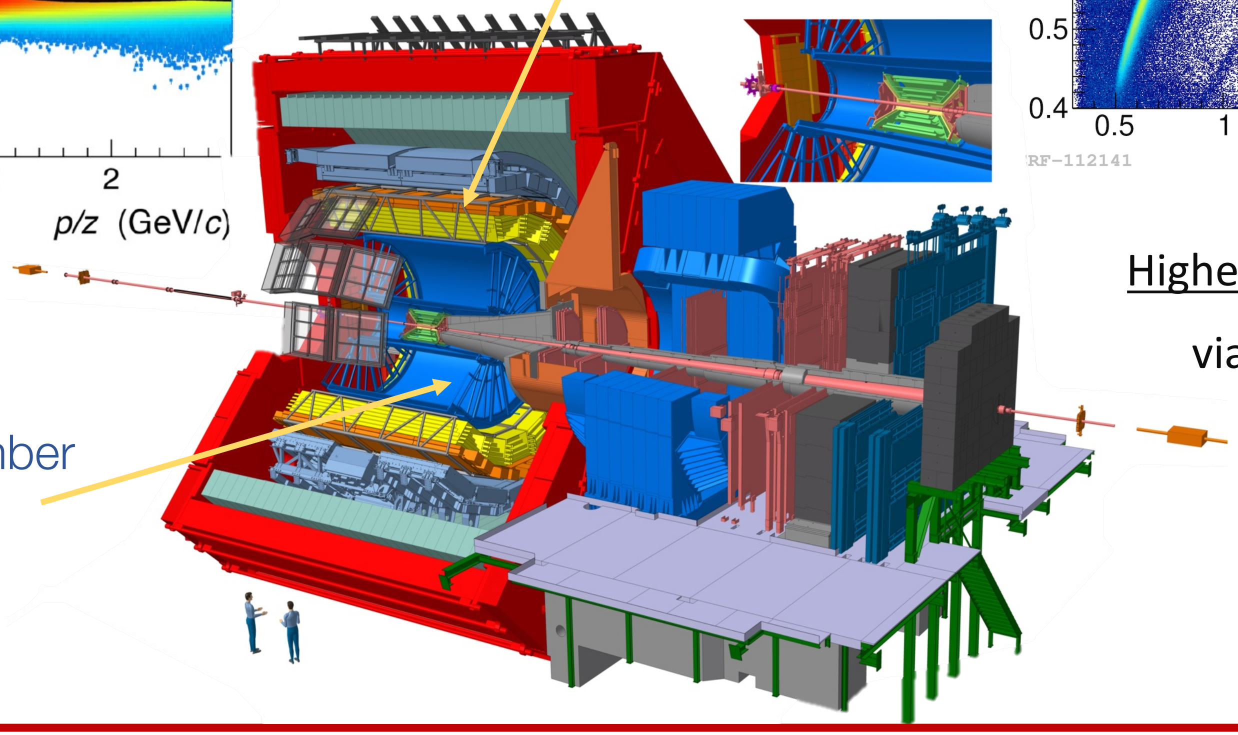
PLB 835, 137577 (2022)

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

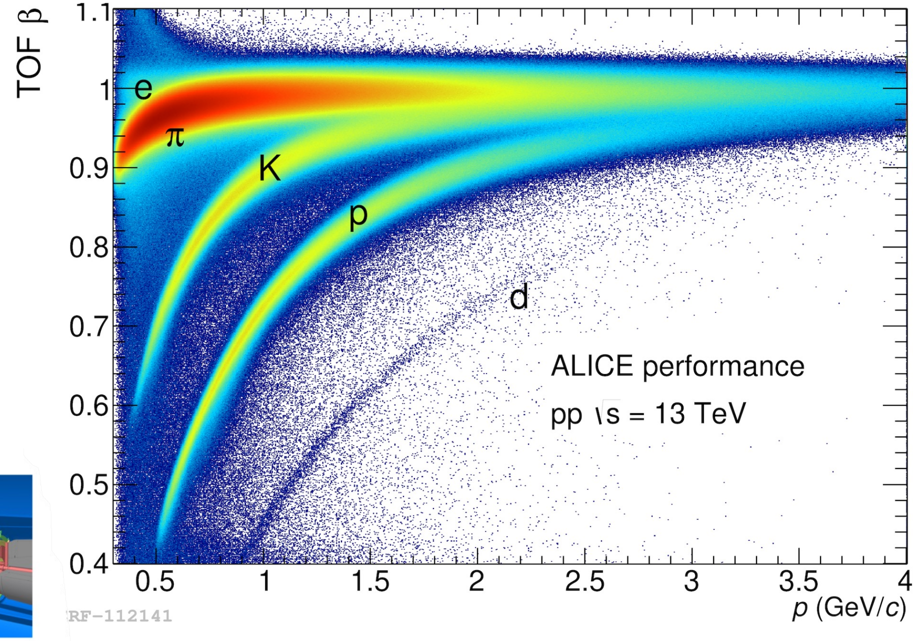
PID via β

σ_{PID} ~ 70 ps

Time Projection Chamber

tracking, PID via dE/dx

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

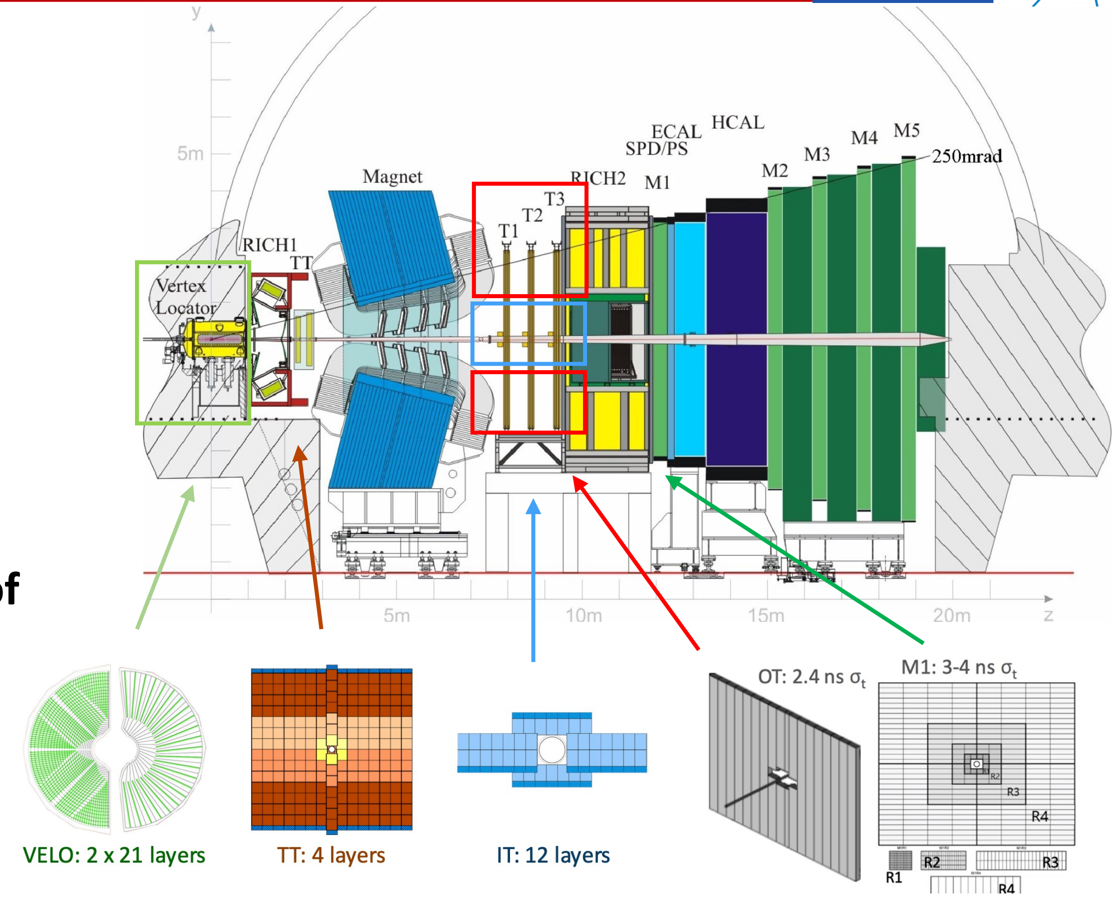


Higher p region (above 1 GeV/c) → PID via velocity β measurements in TOF

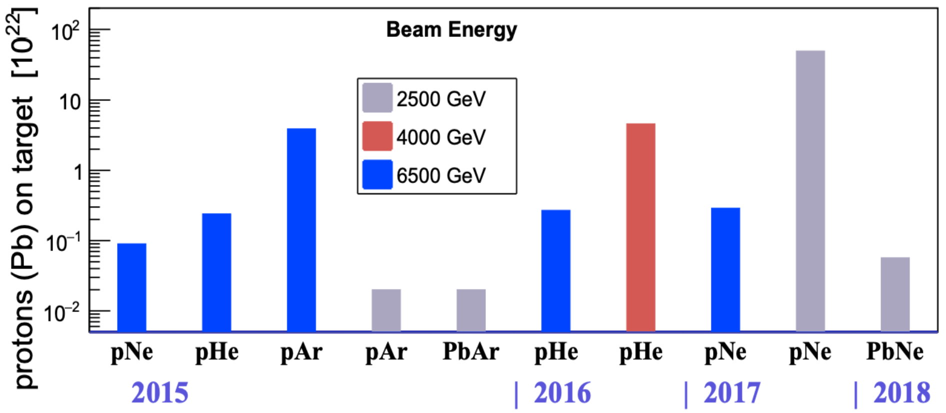
Identification of nuclei with LHCb

- 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) → $\beta = \Delta t / L$
  - 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**

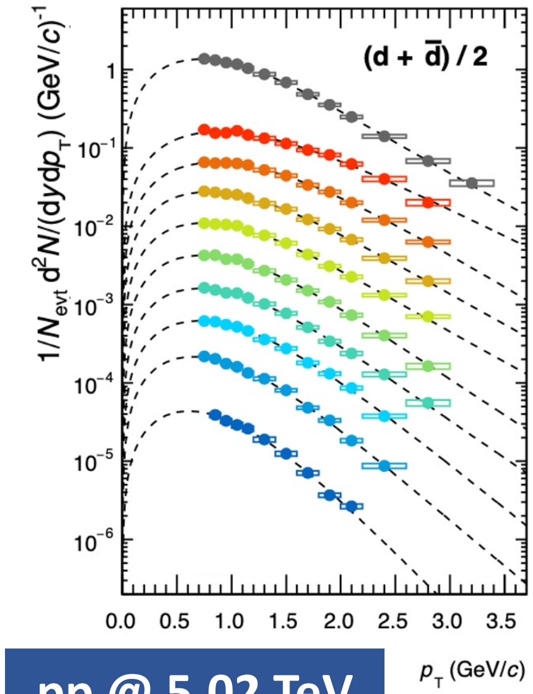


LHCb Collaboration, JINST 3 S08005 (2008)

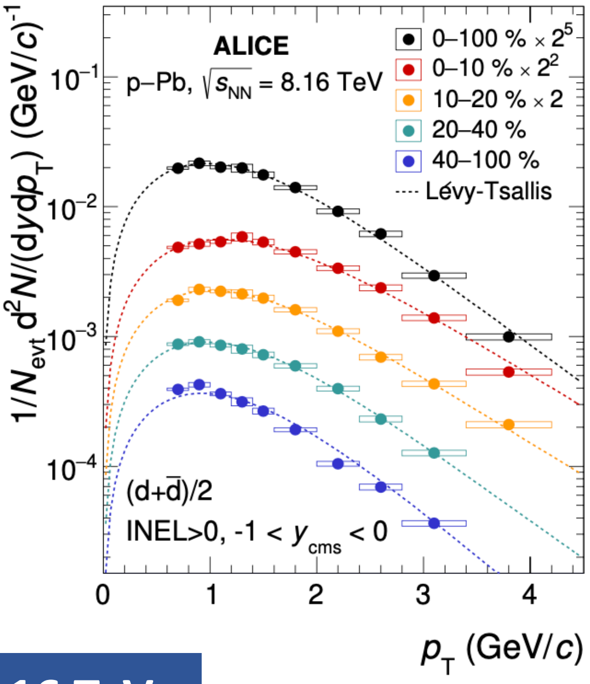


- Energy range $\sqrt{s_{NN}} \in$ [30,115] GeV for beam energy in [0.45, 7] TeV → Unexplored gap between SPS and LHC/RHIC

Measurement of (anti)nuclei with A=2

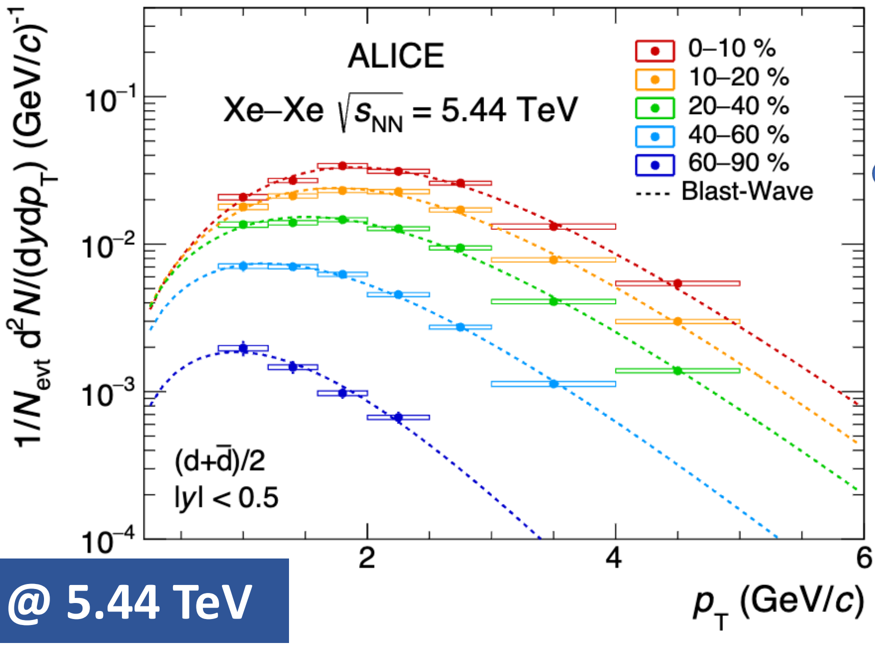


pp @ 5.02 TeV



p-Pb @ 8.16 TeV

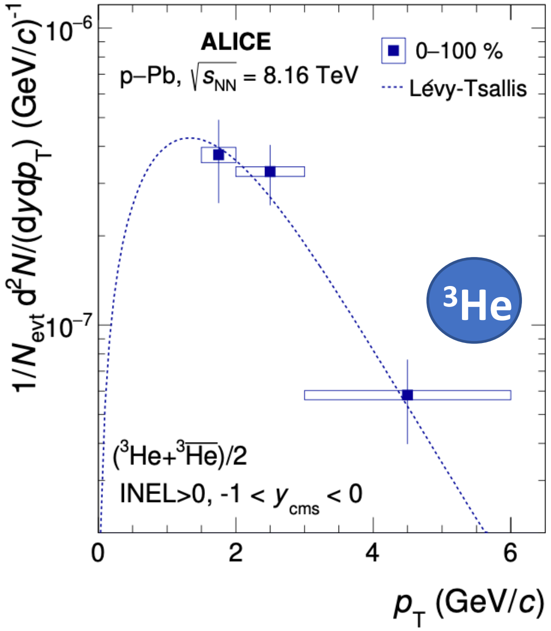
- Deuterons have been measured in narrow multiplicity classes in all systems, from pp to heavy-ions
- Momentum distributions fitted to extrapolate the yield in the unmeasured regions



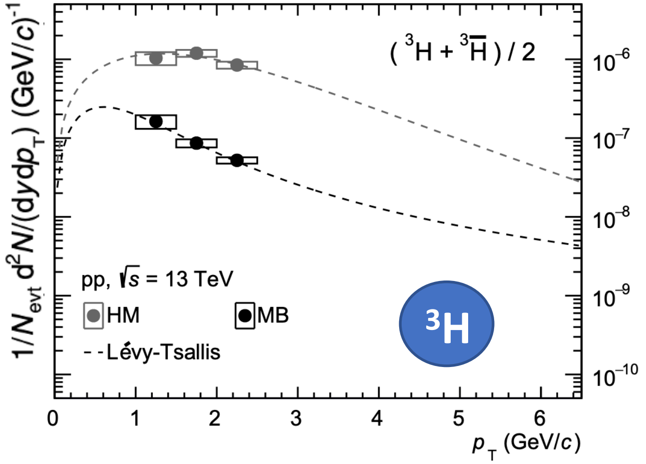
Xe–Xe @ 5.44 TeV

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

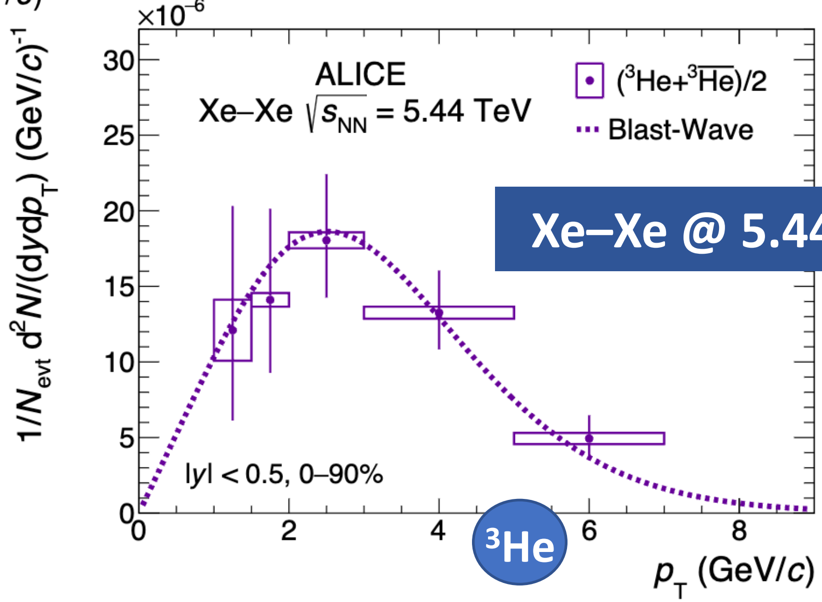


p-Pb @ 8.16 TeV

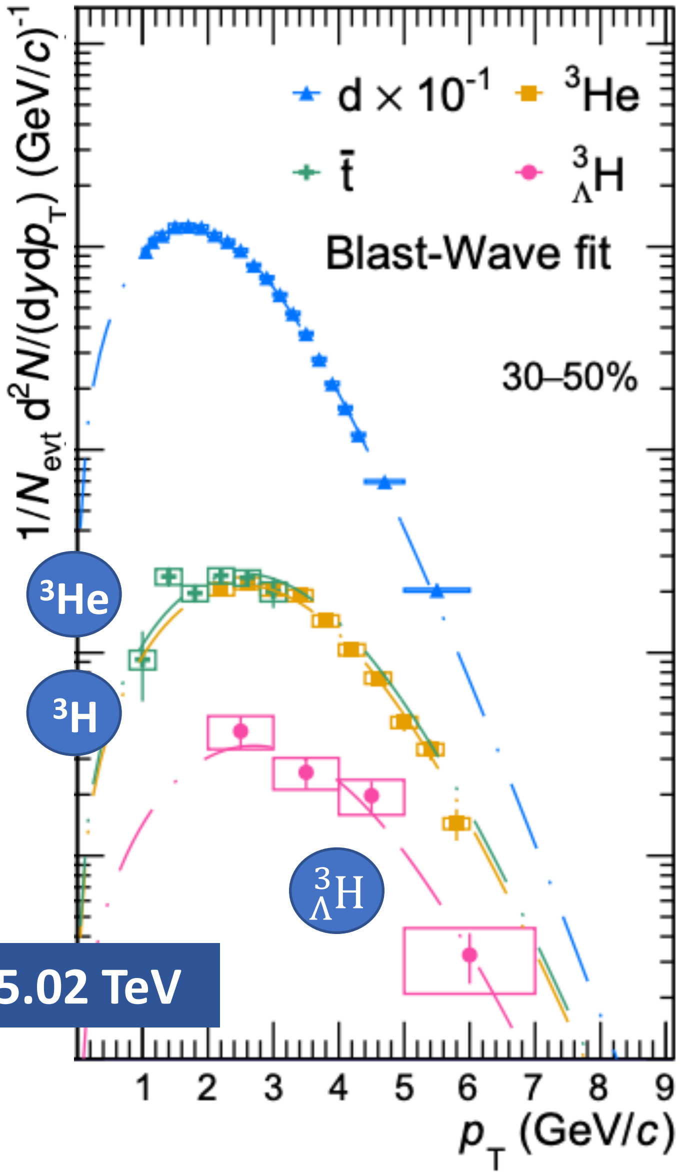


pp @ 13 TeV

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



Xe–Xe @ 5.44 TeV



Pb—Pb @ 5.02 TeV

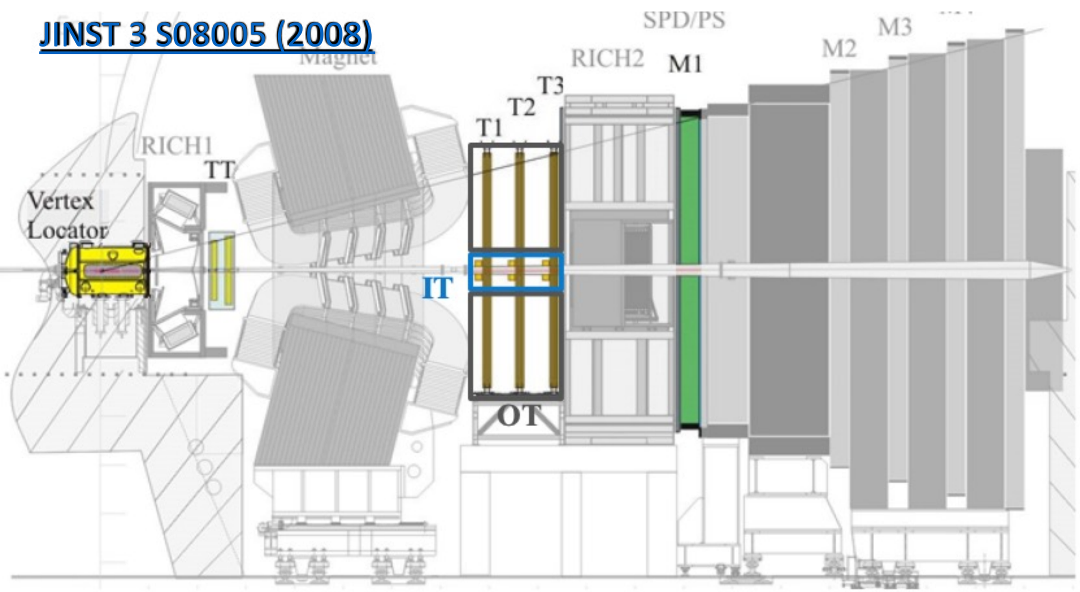
pp: ALICE Collaboration, JHEP 01 (2022) 106
p-Pb: ALICE Collaboration, PLB 846 (2023) 137795
Xe-Xe: ALICE Collaboration, arXiv:2405.19826
Pb-Pb: ALICE Collaboration, arXiv:2405.19839

Identification of nuclei with A=3 with LHCb

LHCb detector not designed to identify light (anti)nuclei

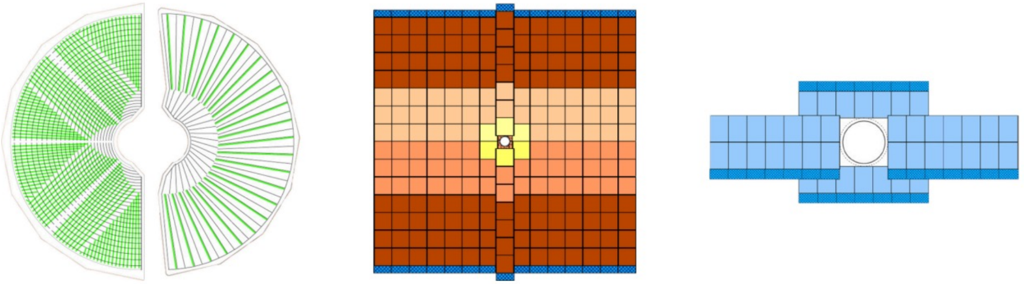
↓

Use information from the tracking system



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

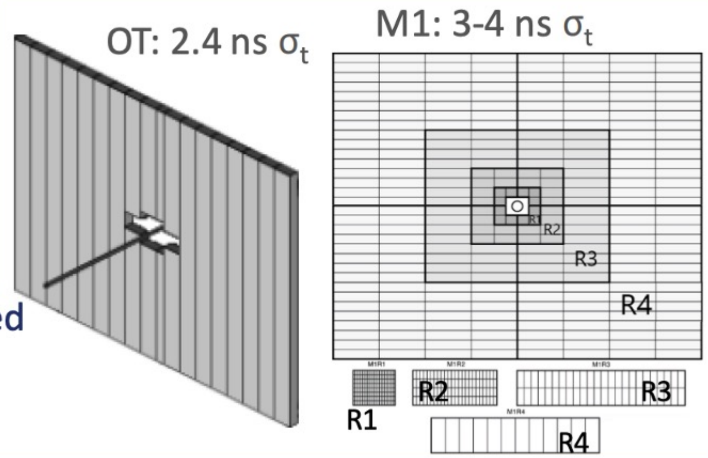
→ dE/dx in VELO, TT, IT to **identify He**



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

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

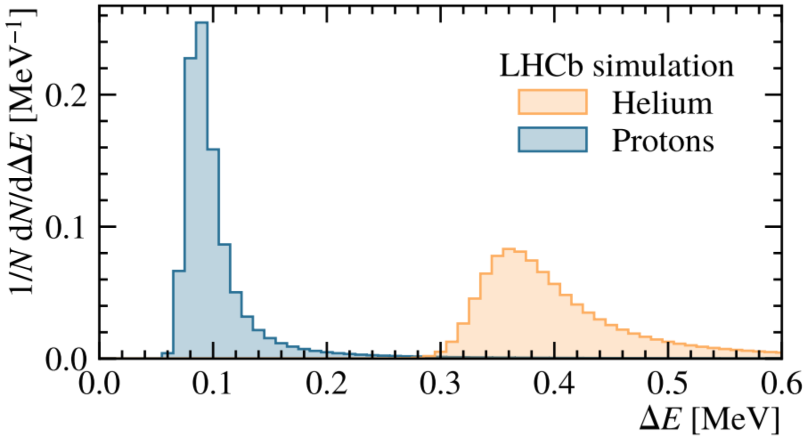
→ **Time-of-flight** in OT and M1 to **identify d, distinguish ^{3}He and ^{4}He**



- 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

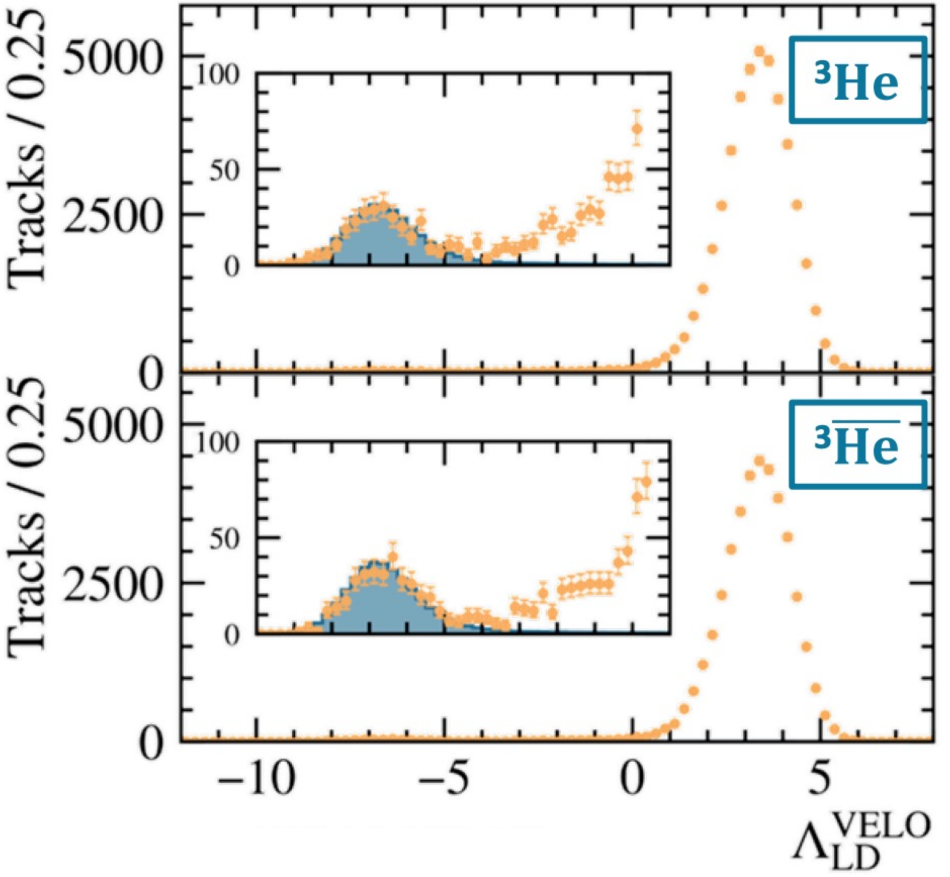
https://cds.cern.ch/record/2881940/files/MPI23_v1.pdf

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!



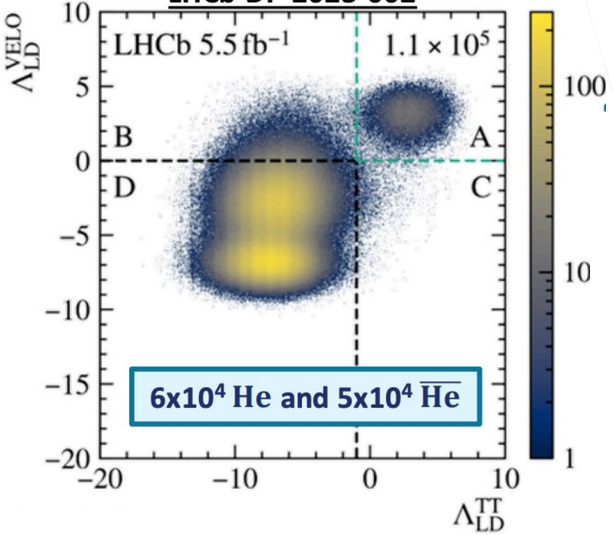
Define Likelihood discriminators based on cluster size and ADC counts:

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

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

One discriminator for each subdetector:
- Λ_{LD}^{VELO}
- Λ_{LD}^{TT}
- Λ_{LD}^{IT}

LHCb-DP-2023-002



6x10^4 He and 5x10^4 $\overline{\text{He}}$

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

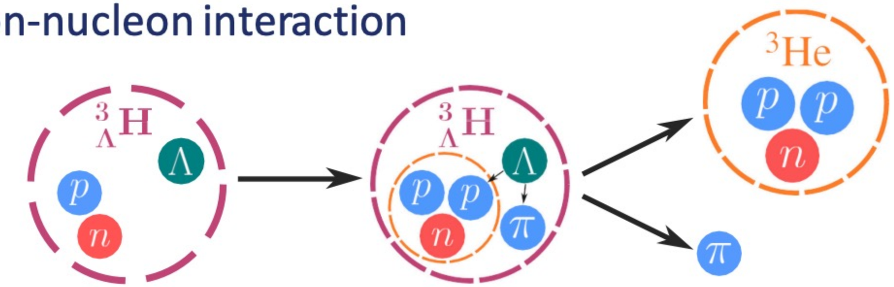
LHCb Collaboration, JINST 19 (2024) P02010

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:

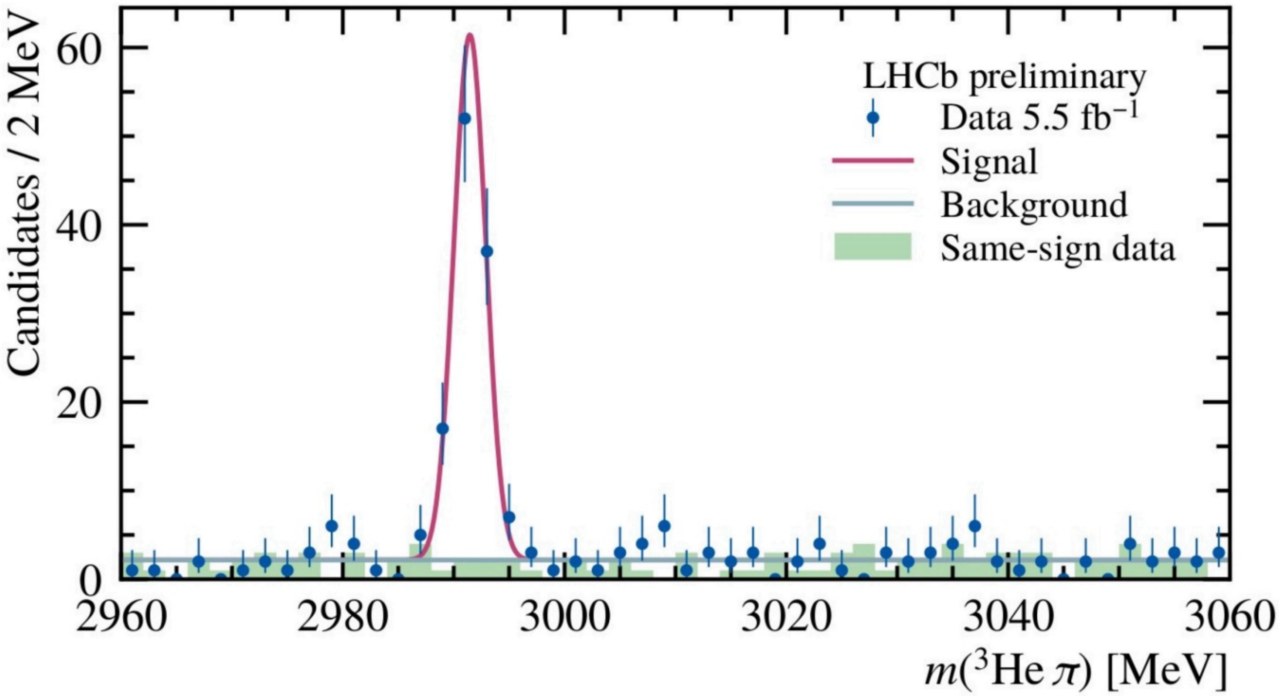
$$ {}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He}\,\pi^{-} + cc $$



Results:

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

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



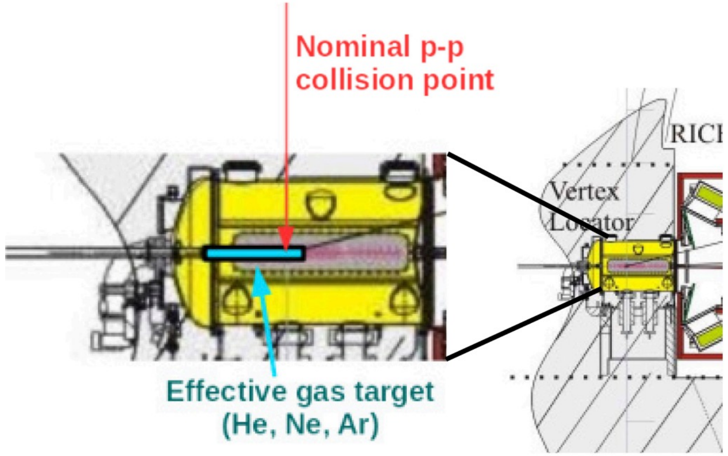
This measurement shows the applicability of ^{3}He reconstruction and paves the way for future measurements of astrophysical interest

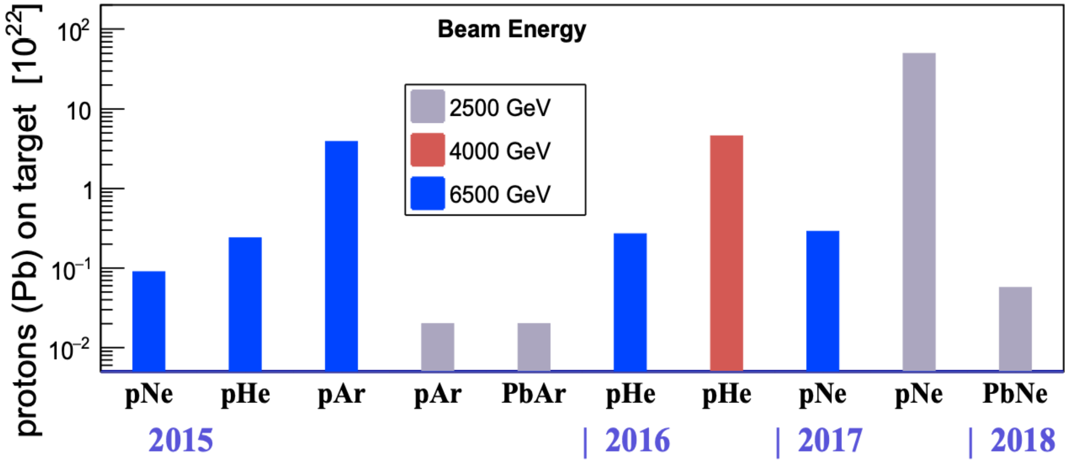
https://cds.cern.ch/record/2881940/files/MPI23_v1.pdf

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**





LHCb contribution is relevant for astrophysics applications!

Unique opportunities at the LHC:

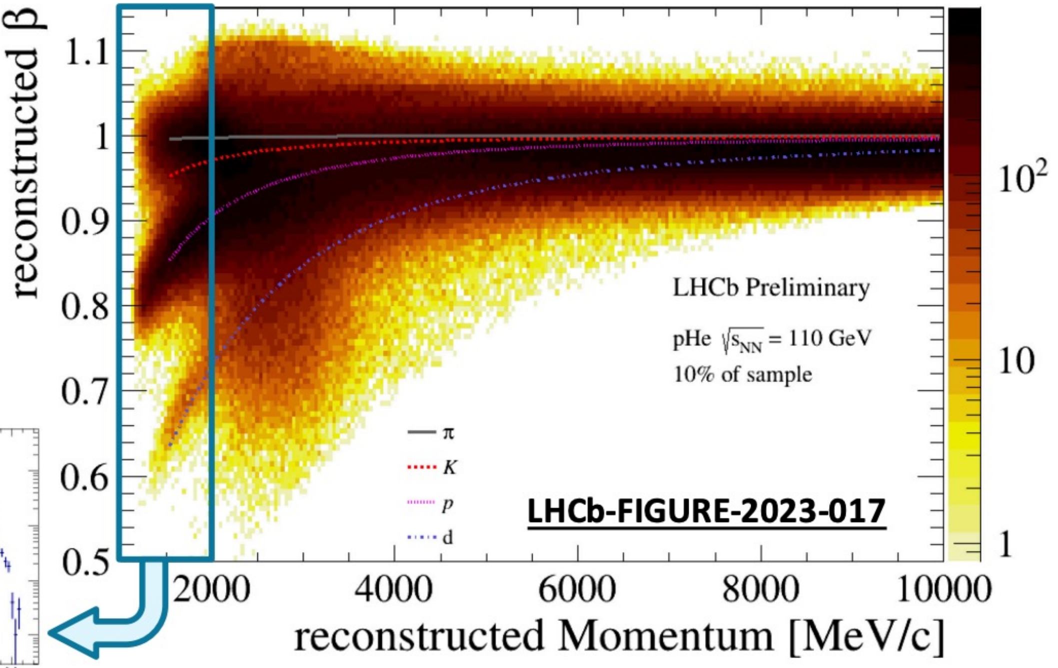
- Collisions with targets of mass number A intermediate between p and Pb → Reproduce CR interactions (pp, pHe)
- Energy range $\sqrt{s_{\mathrm{NN}}} \in [30,115]$ GeV for beam energy in [0.45, 7] TeV → Unexplored gap between SPS and LHC/RHIC

LHCb Collaboration, LHCb-PUB-2018-015

(anti)deuteron identification with LHCb

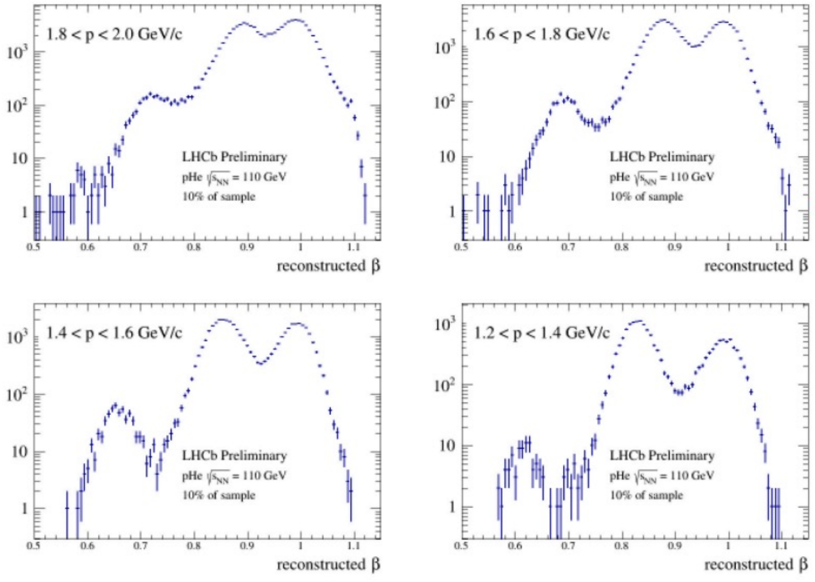
LHCb is now also capable of measuring (anti)deuterons

- *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:** $\sigma(\beta) < 0.02$, $\chi^2_{\mathrm{OThits}}/\mathrm{ndf} < 2$

First deuteron candidates observed in *p*He data!

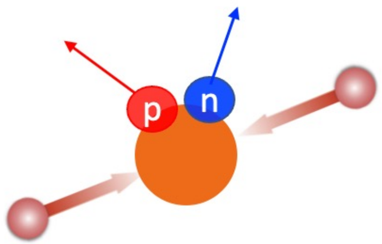


LHCb-FIGURE-2023-017

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**



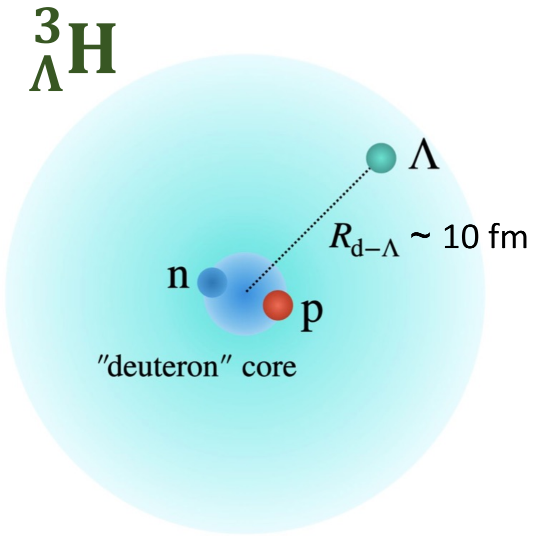
System size (pp, p—Pb): 1–1.5 fm

r_d : 1.96 fm

r_{3He}: 1.76 fm

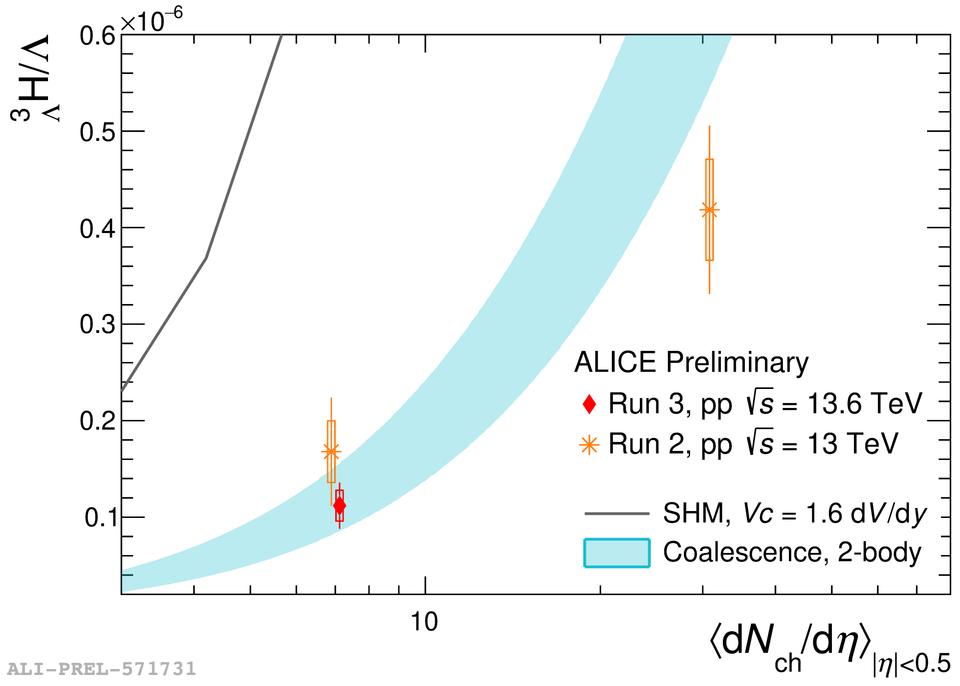
$r_{{}^{3}_{\Lambda}H\ (np\Lambda)}$: 4.9 fm ($B_\Lambda$= 2.35 MeV)

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

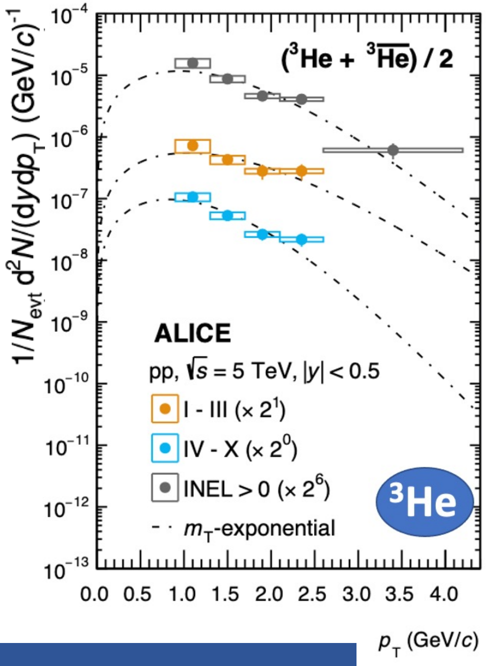


powerful probe for investigating the nucleon – Λ interaction

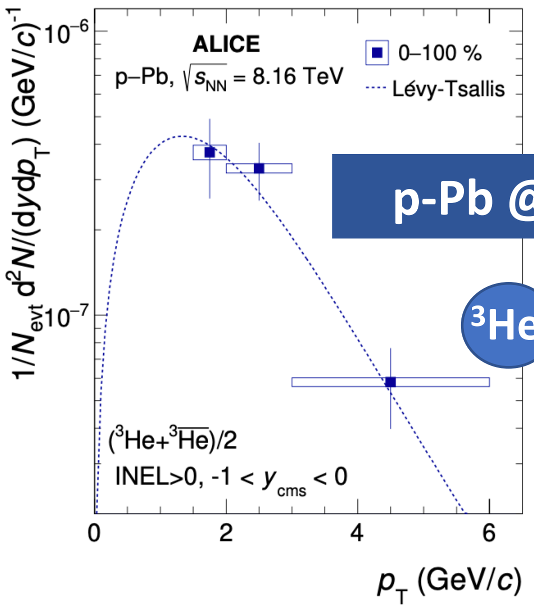
${}^{3}_{\Lambda}H/\Lambda$ ratio provides a powerful tool to investigate nuclear production mechanism



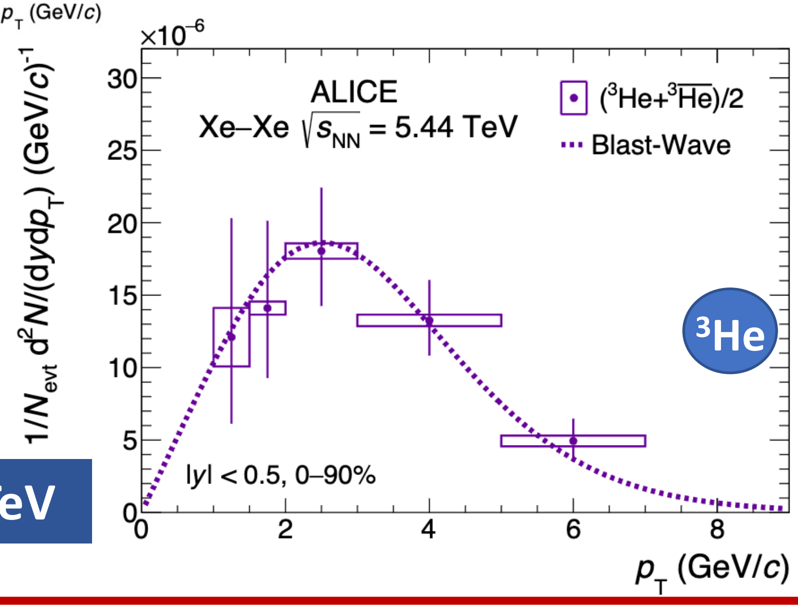
Measurement of (anti)nuclei with A=3



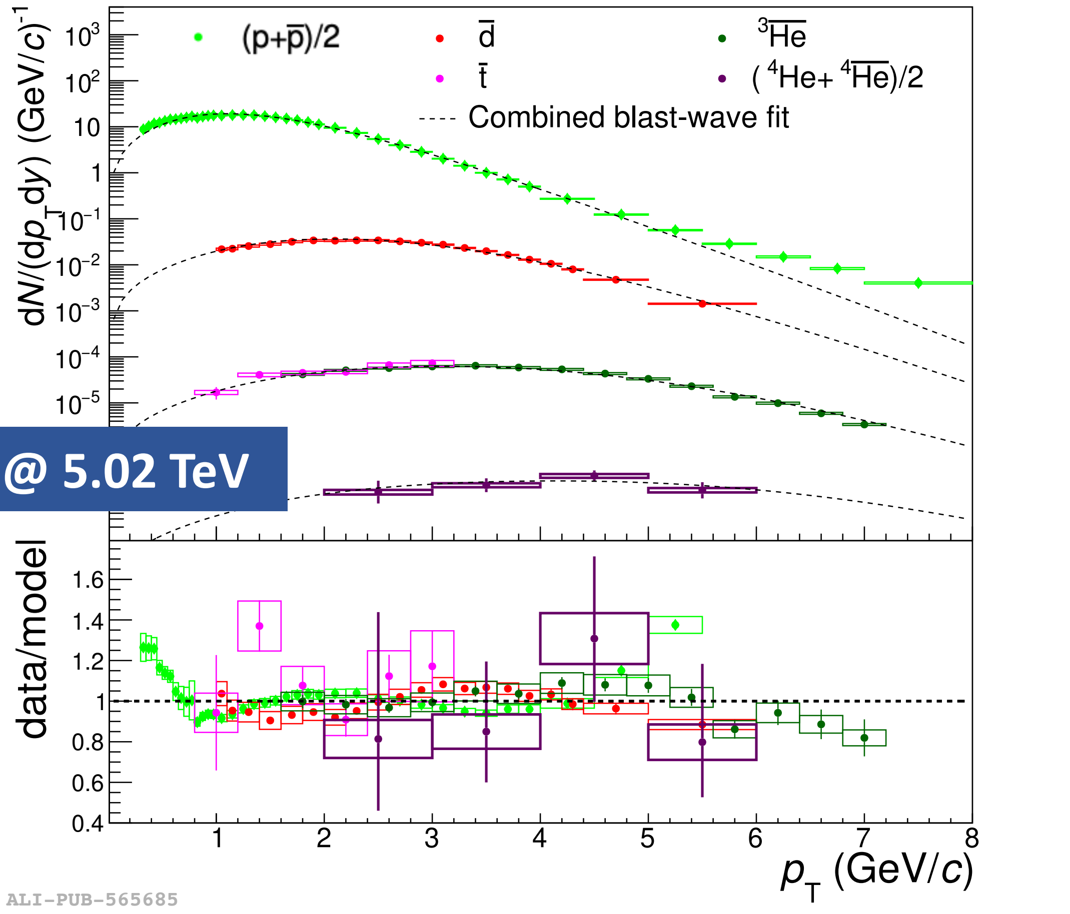
pp @ 5.02 TeV



p-Pb @ 8.16 TeV



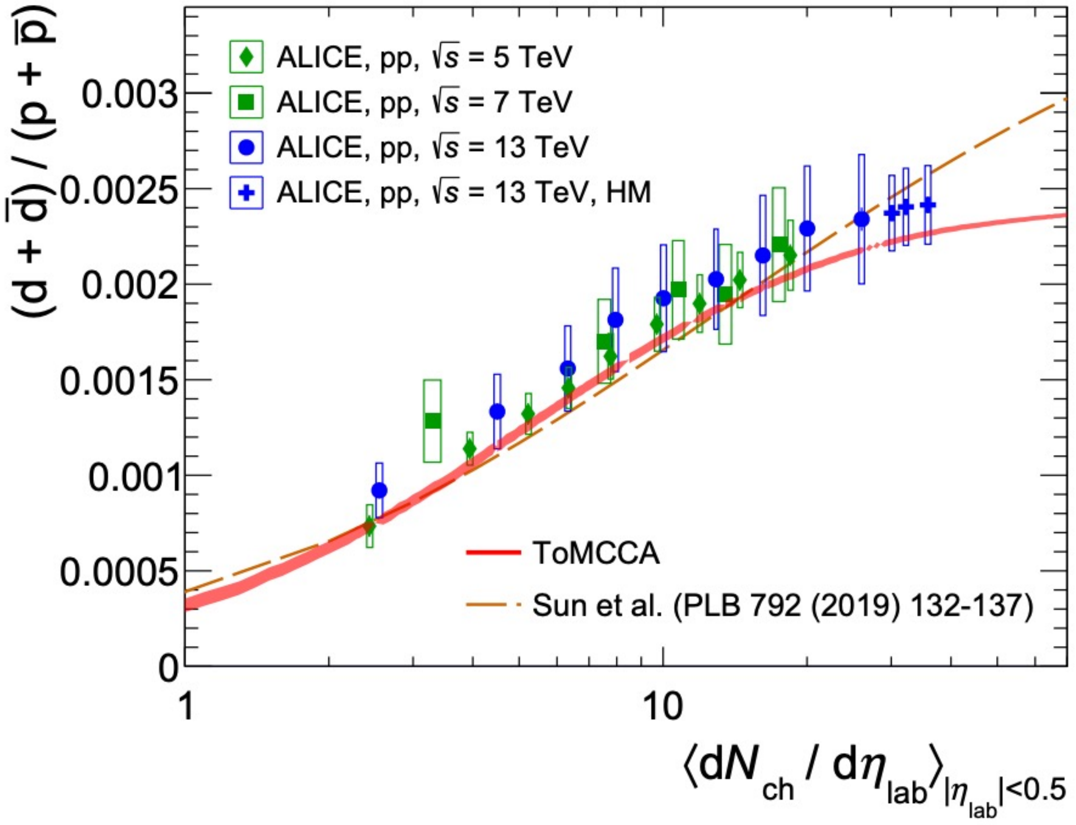
Xe–Xe @ 5.44 TeV



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

Testing production models (focus at low multiplicity)

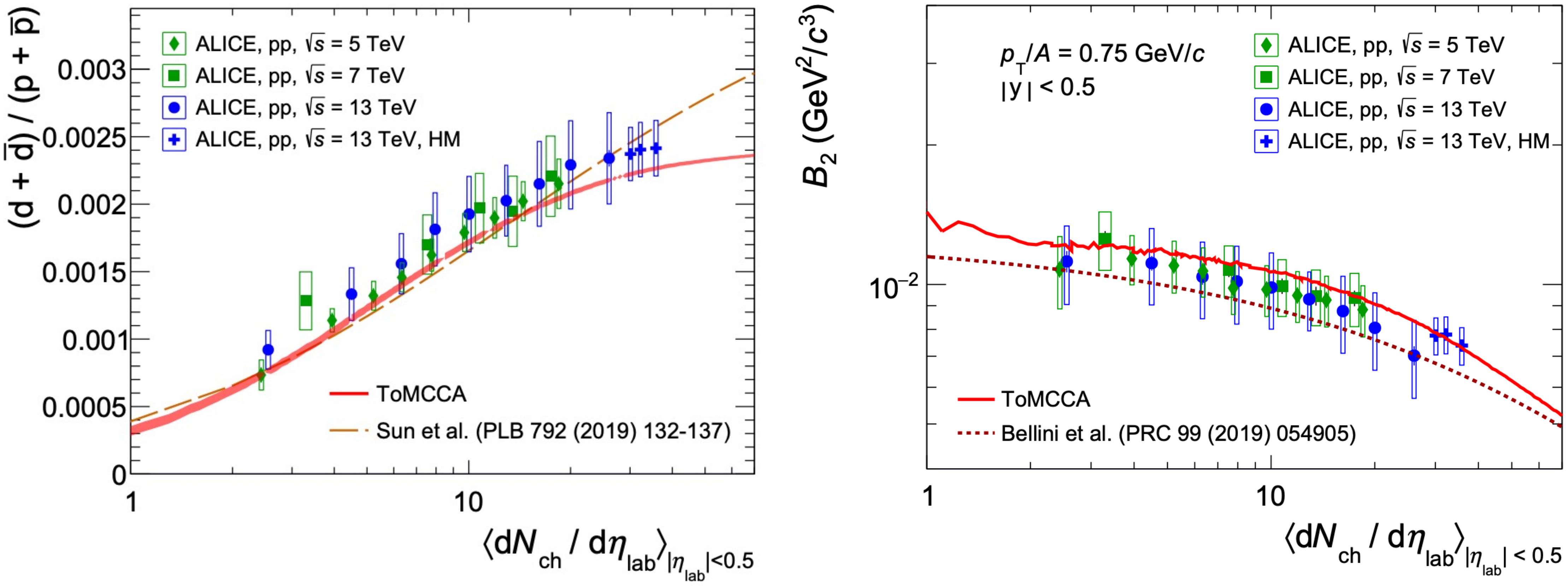


Predictions available only for the pp multiplicity range (1-70)

- **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)

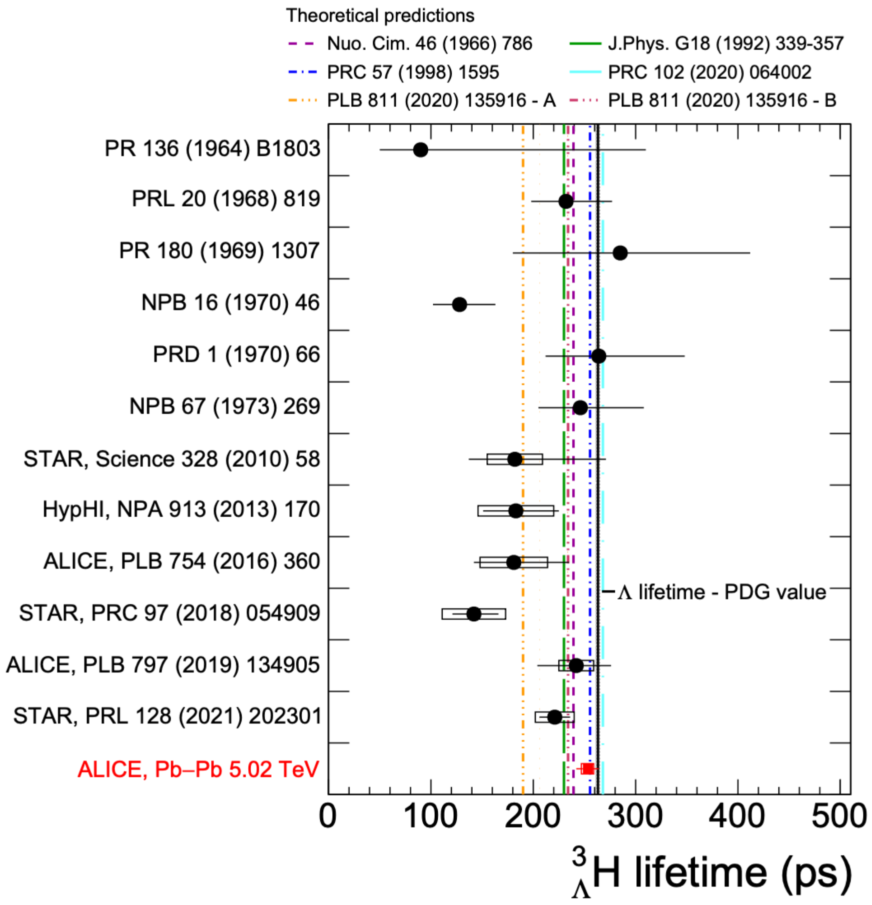


- **Coalescence** predictions of ToMCCA using Wigner function formalism & multiplicity-dependent input (momentum distributions of nucleons, source size and multiplicity distributions) reproduce all data points within 1sigma
- No ^{3}He coalescence predictions yet
- Also coalescence parameter B_2 vs multiplicity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

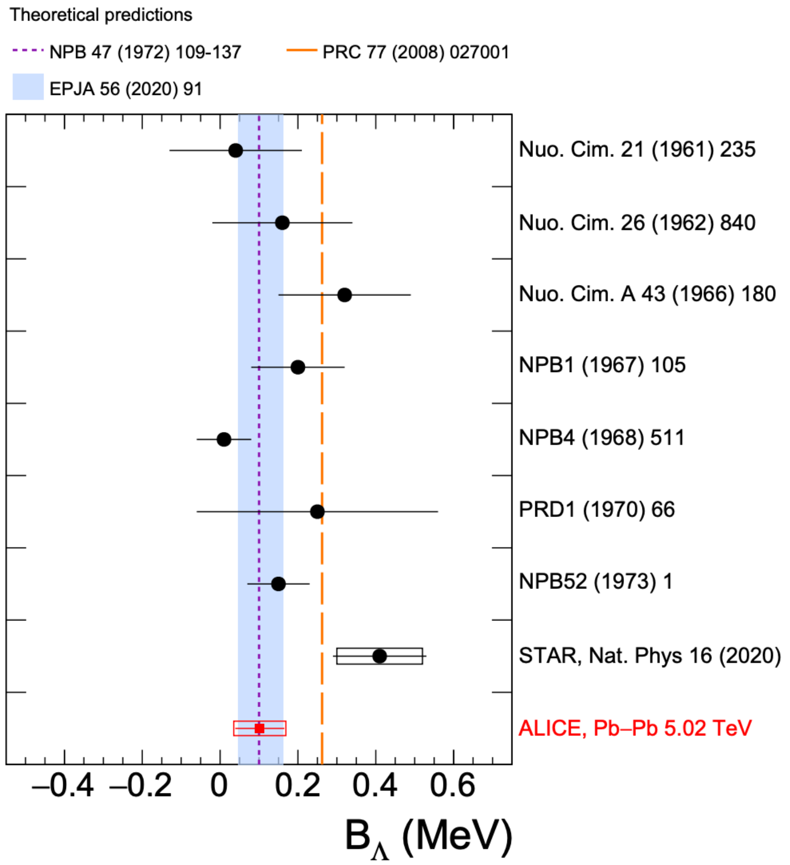
Mahlein, Pinto, Fabbietti, arXiv:2404.03352

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

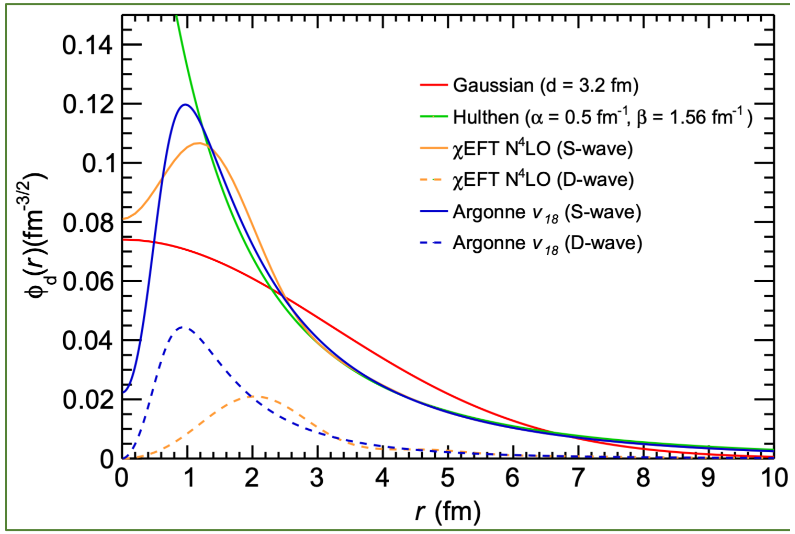
Phys. Rev. Lett. 131 (2023) 102302

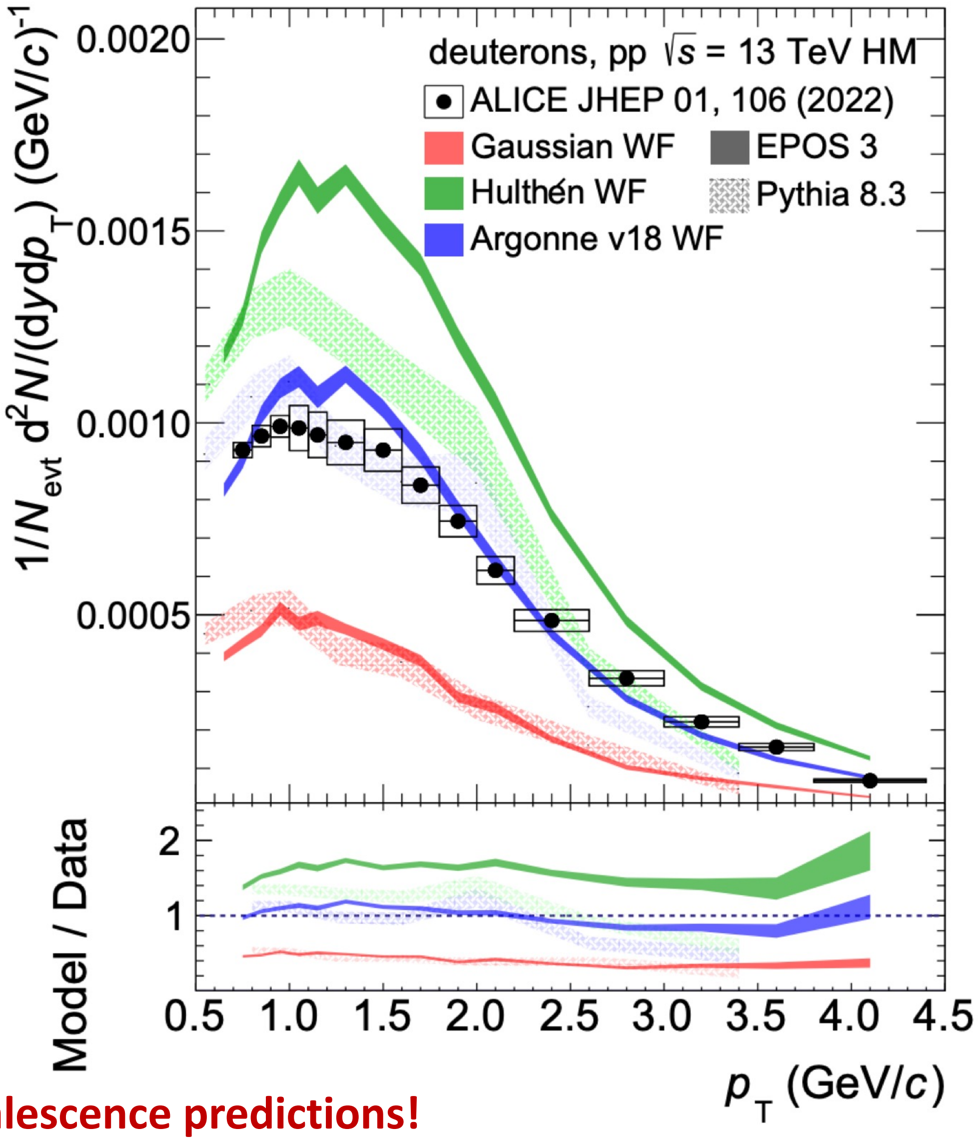
State-of-the-art coalescence model

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



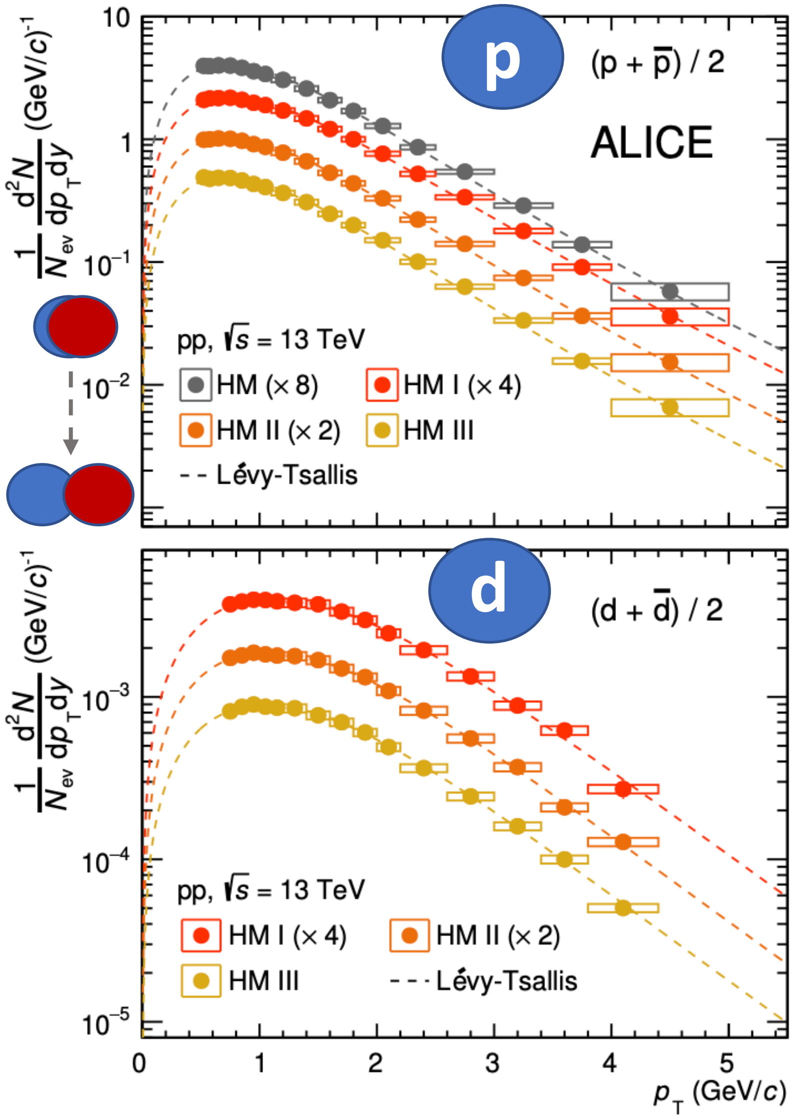


Mahlein et al., EPJC 83 (2023) 9, 804

Realistic wavefunction is key for coalescence predictions!

Measurement of light (anti)nuclei with ALICE

ALICE Collaboration, JHEP 01 (2022) 106

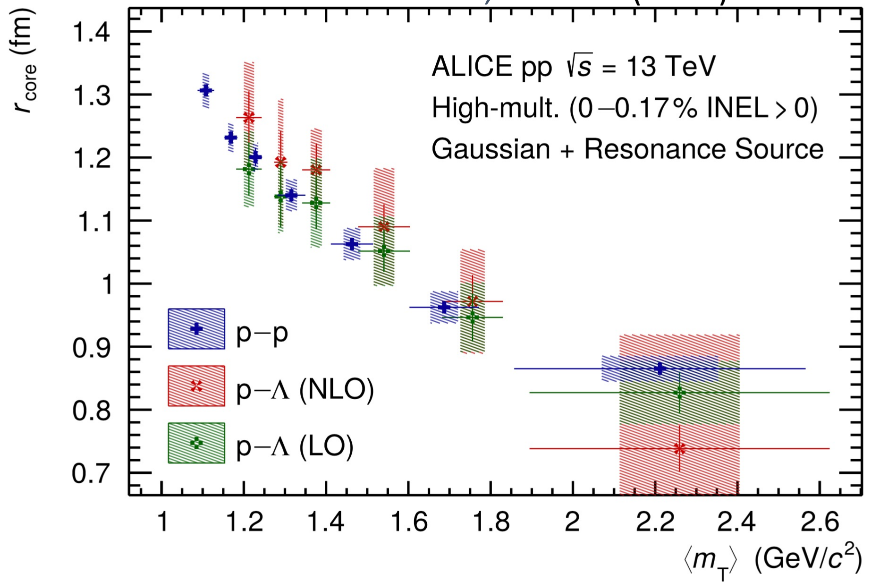


HM pp @ 13 TeV

- 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



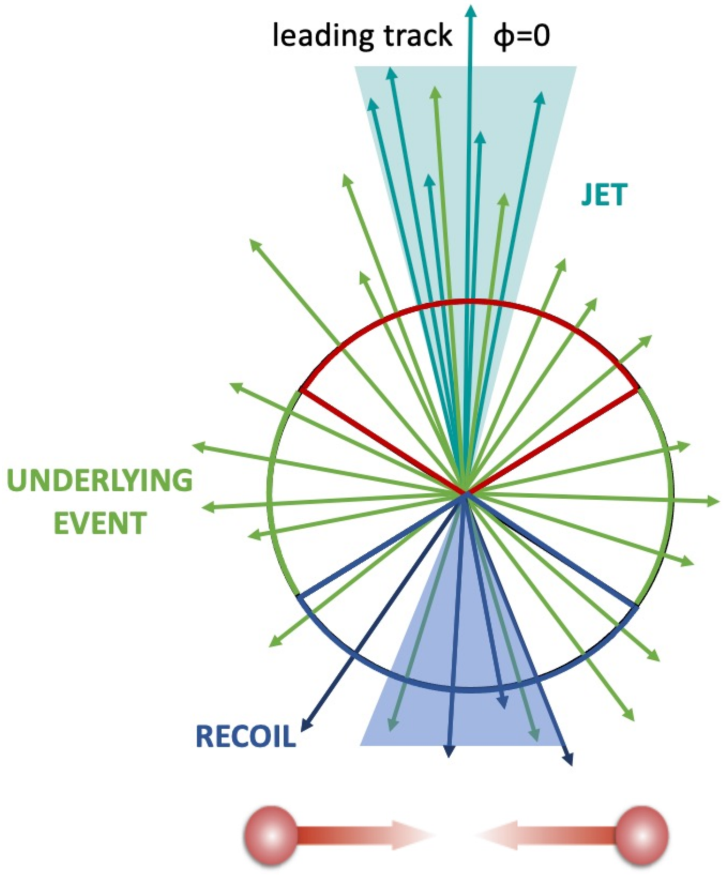
$\propto p_T$

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)

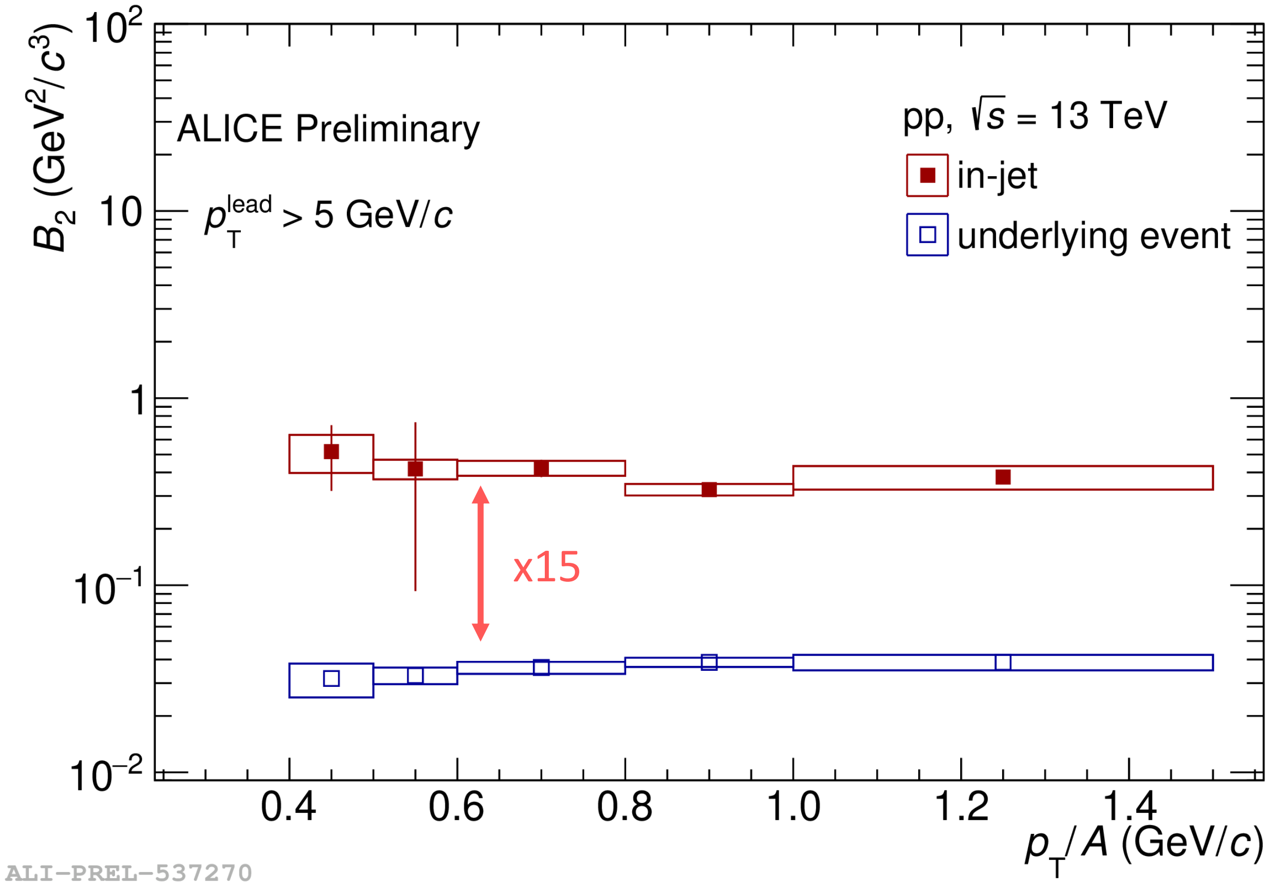
- Studying the antideuteron production in jets in small systems (pp, pA) is important to understand and model nuclear production
- Implications for cosmic ray physics
- Antideuteron in the Galaxy is produced in interactions of cosmic rays (p, ^{4}He) with kinetic energies of ~300 GeV

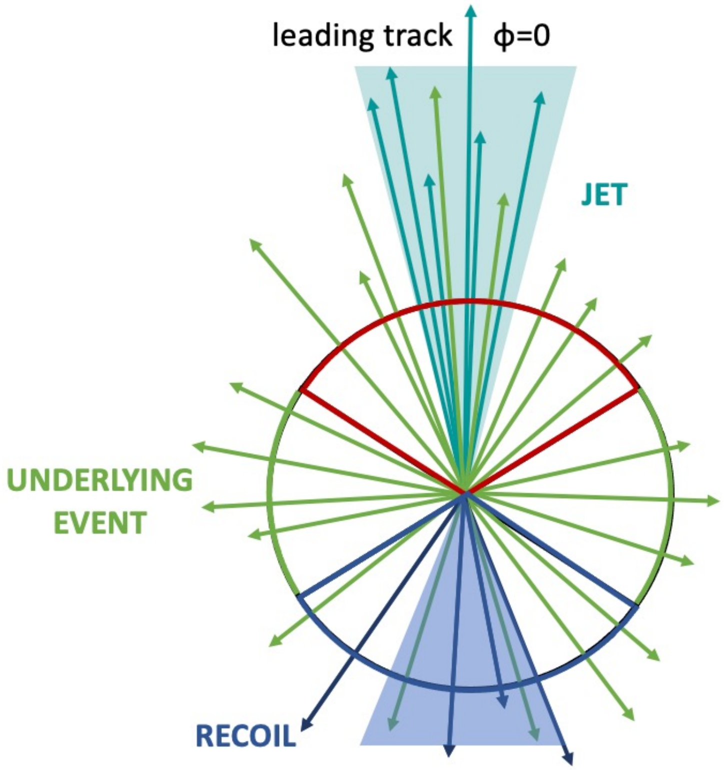


Toward: $|\Delta\phi| < 60°$
Transverse: $60° < |\Delta\phi| < 120°$
Away: $|\Delta\phi| > 120°$

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

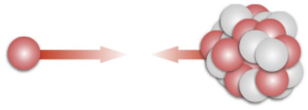




- *Enhanced deuteron coalescence probability in jets wrt UE is observed for the first time in pp collisions*
- Due to the reduced distance in phase space of hadrons in jets compared to those out of jets → favors coalescence picture

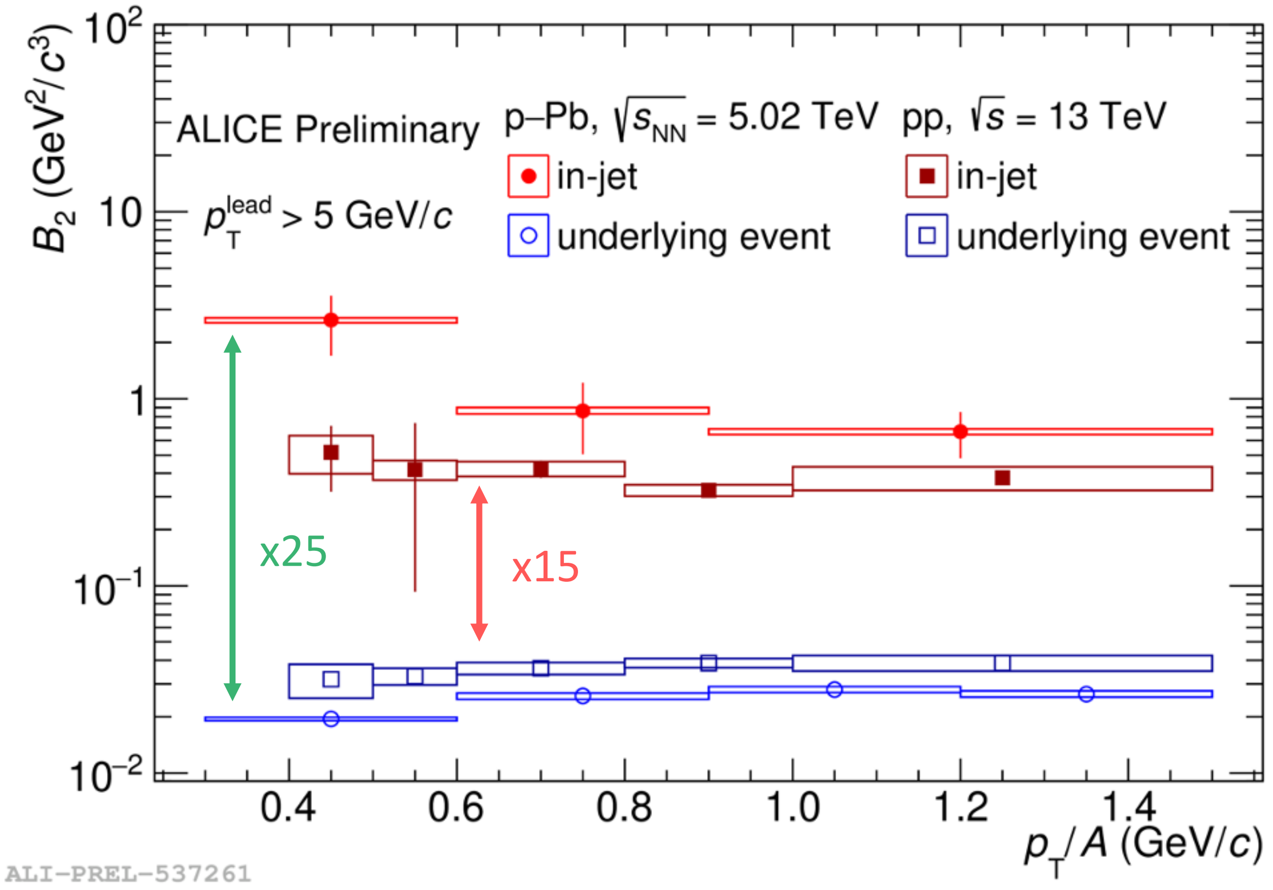
Phys.Rev.Lett. 131 (2023) 4, 042301

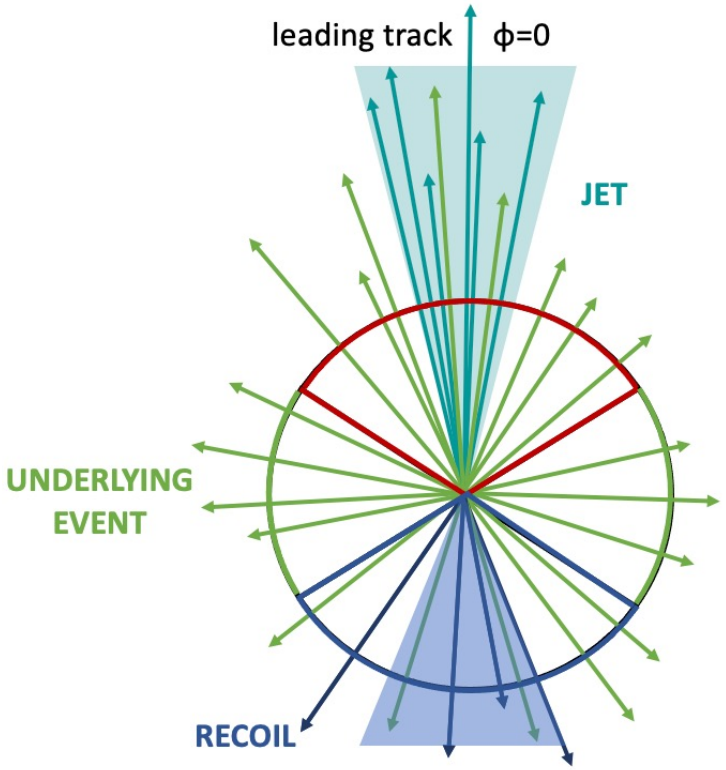
Coalescence parameters in and out of jets



p—Pb

pp

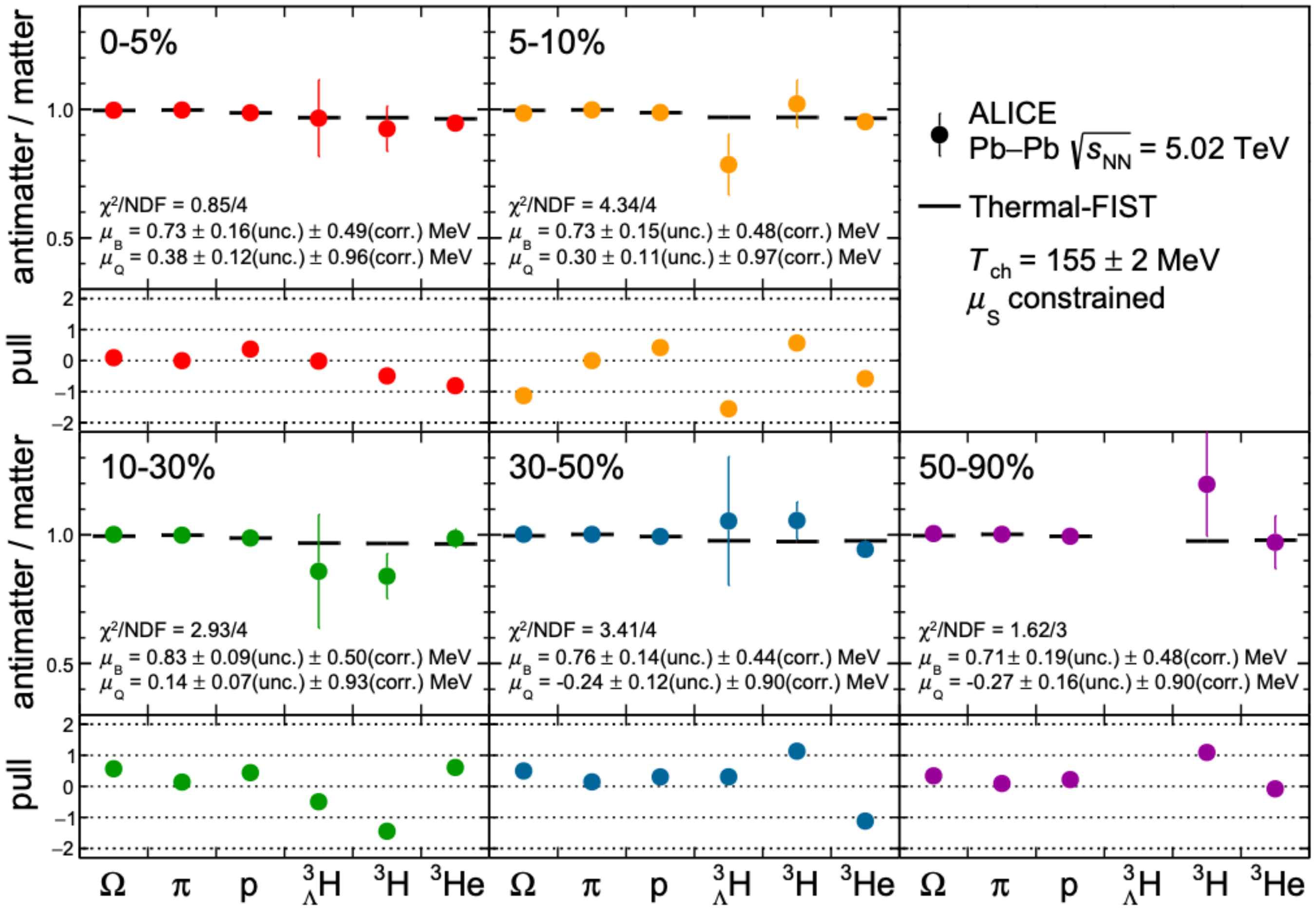




- B_2 in-jet in p—Pb is larger than B_2 in-jet in pp
  → *could be* related to the different particle composition of jets in pp and p—Pb → *to be further investigated*
- B_2 in UE in p—Pb is smaller than B_2 in UE in pp due to the larger source size in p—Pb (pp[1]: r_0~ 1 fm, p—Pb[2]: r_0~ 1.5 fm)

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

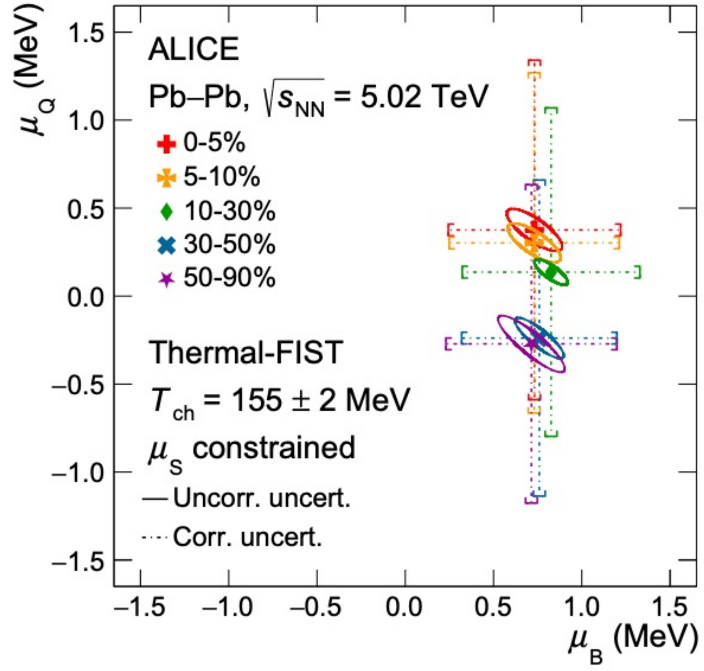
Chemical potential at the LHC

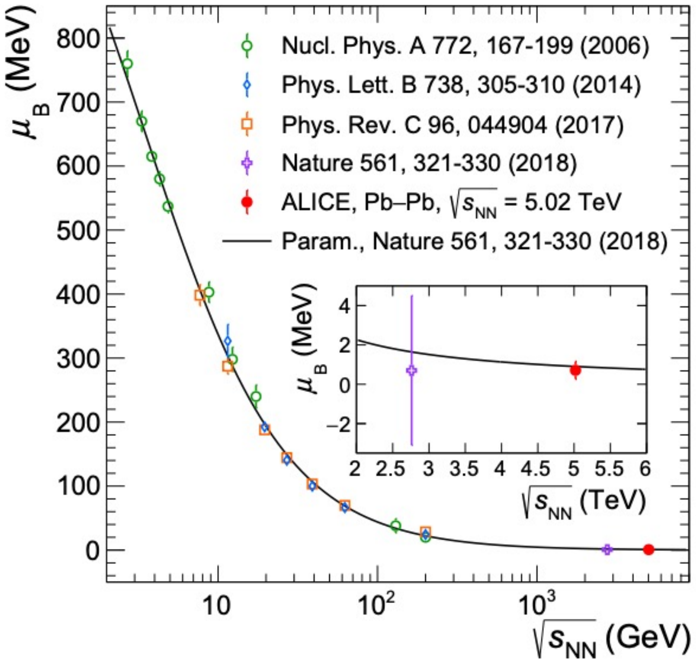


- μ_B and μ_Q are extracted fitting the antiparticle-to-particle yield ratios with the predictions of the grand-canonical SHM using the Thermal-FIST code

ALICE Collaboration, arXiv:2311.13332

Chemical potential at the LHC





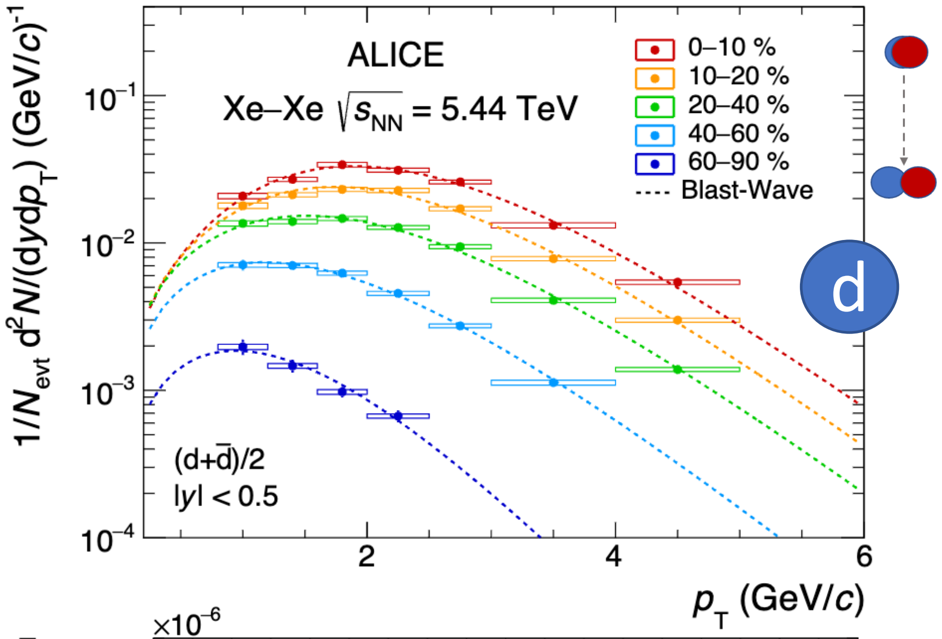
- μ_B and μ_Q are extracted fitting the antiparticle-to-particle yield ratios with the predictions of the grand-canonical SHM using the Thermal-FIST code
- $\mu_Q = -0.18 \pm 0.90$ MeV
- $\mu_B = 0.71 \pm 0.45$ MeV (~8 times more precise than previous measurement)

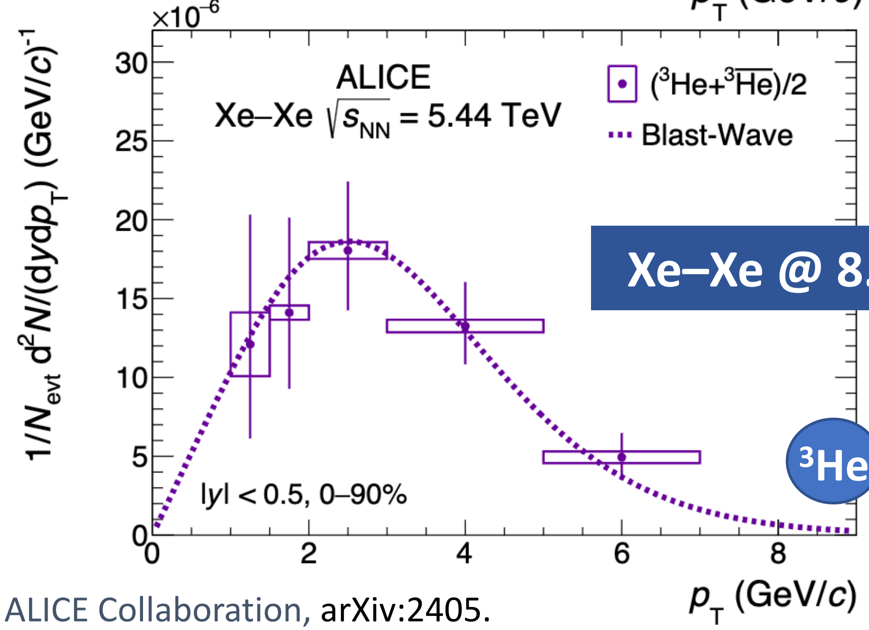
- **Nuclear transparency regime** is reached (→ baryon transport from the colliding ions to the interaction region is negligible)
- **No centrality dependence**→ nuclear transparency also in central Pb–Pb (despite μ_B>0 could be expected from a more significant baryon number transport at midrapidity

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

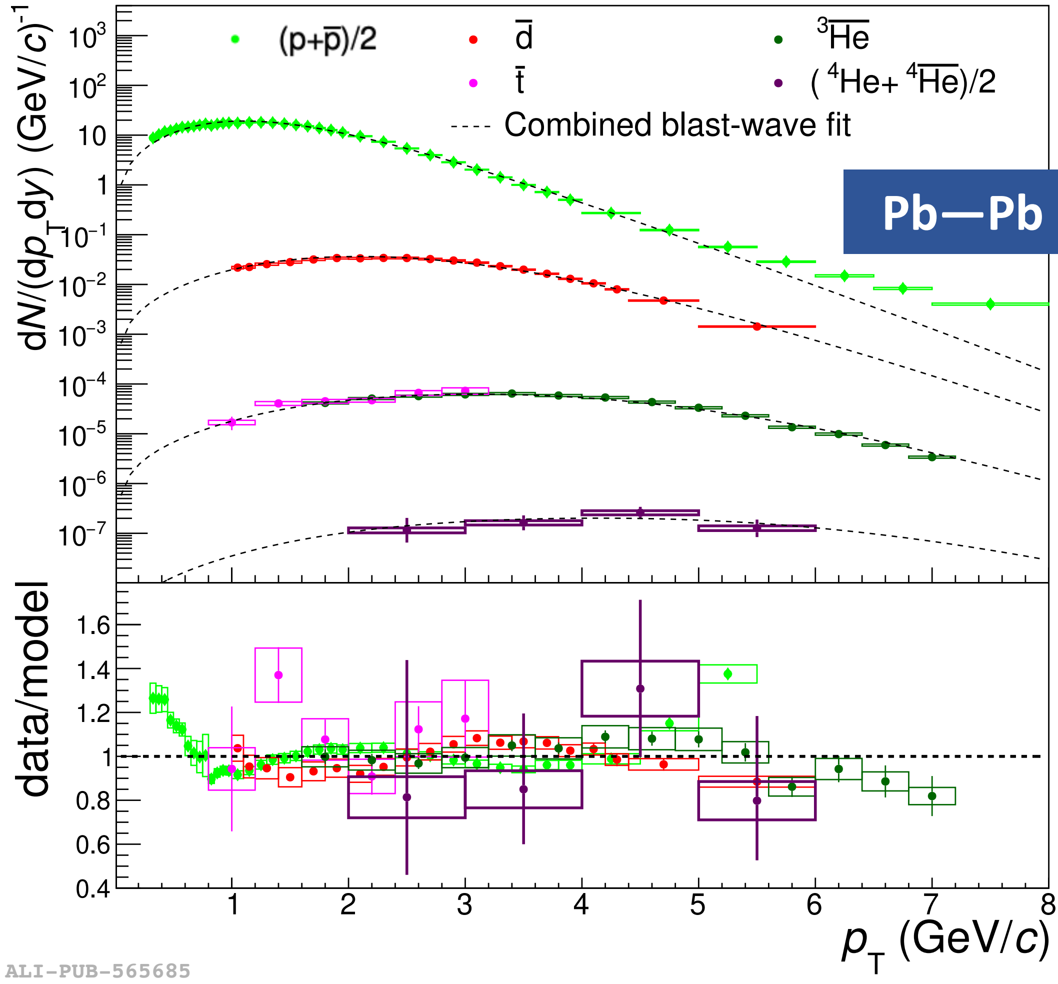
Light (anti)nuclei with ALICE: large systems





Xe–Xe @ 8.16 TeV

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

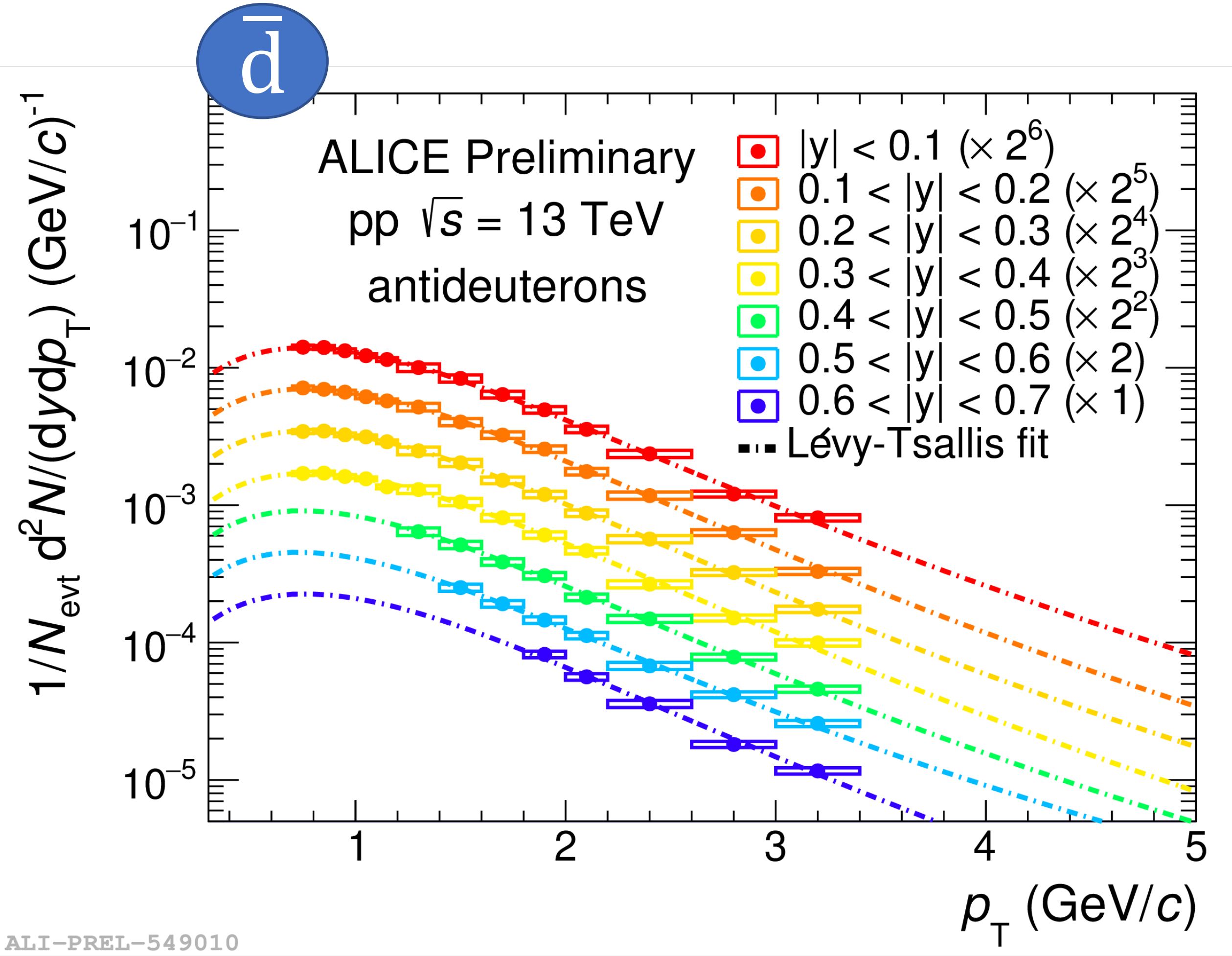


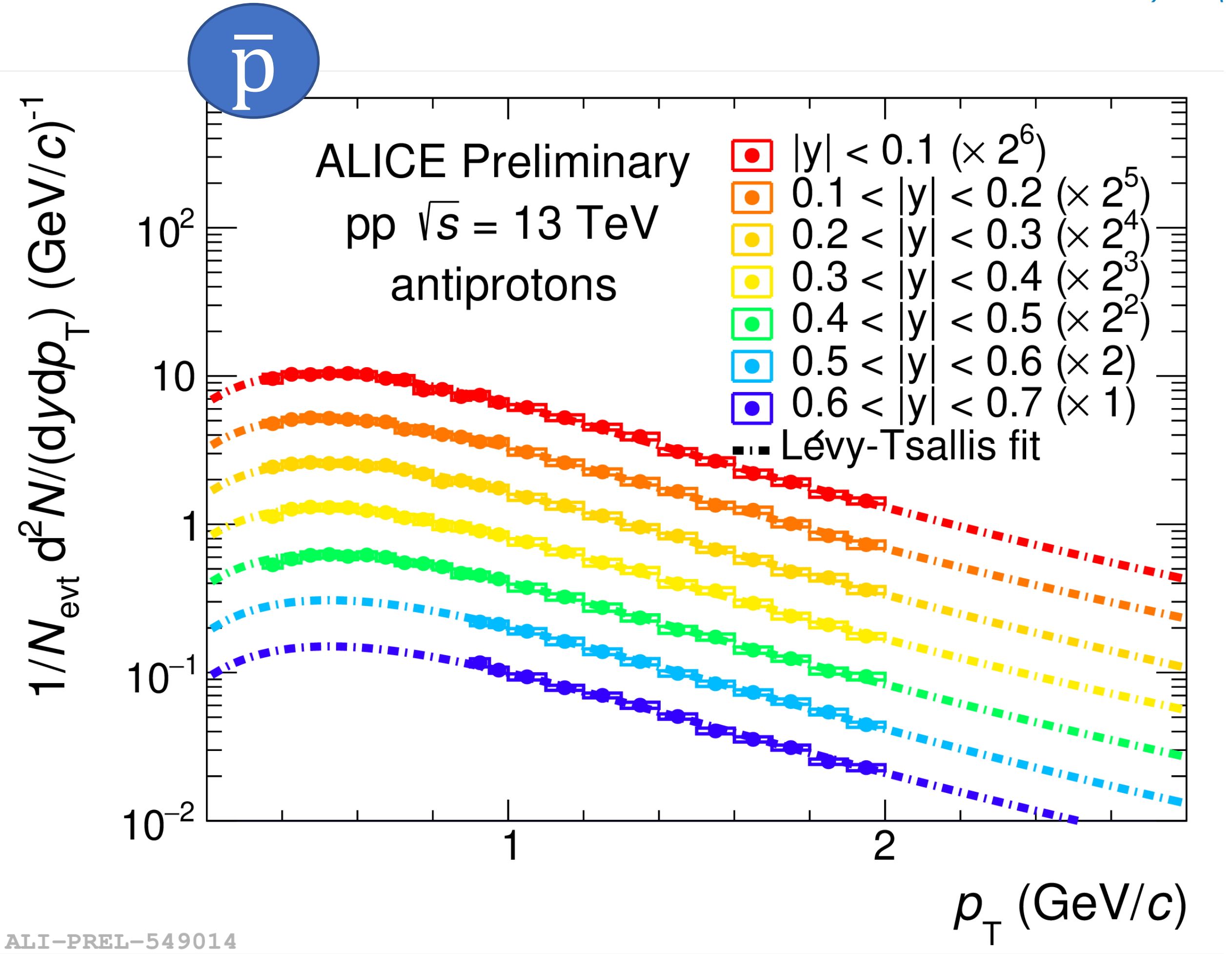
Pb—Pb @ 5.02 TeV

ALICE Collaboration, arXiv:2405.

ALICE Collaboration, arXiv:2311.11758

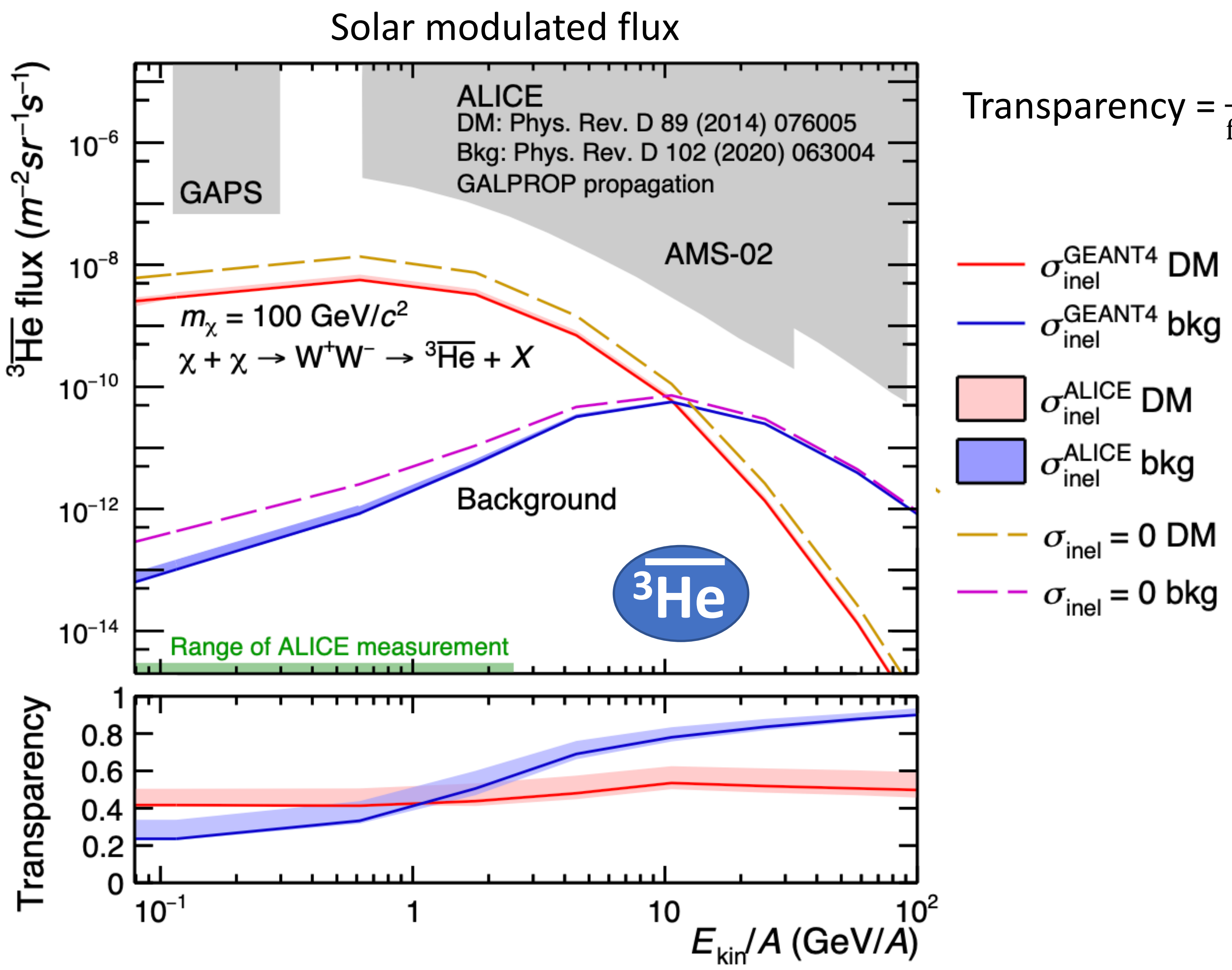
Spectra as a function of rapidity





- 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



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

Fluxes are model dependent

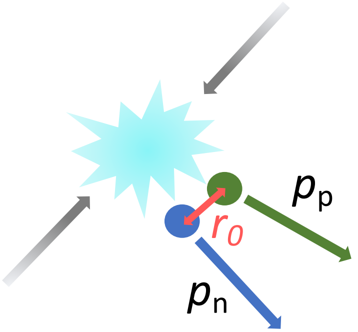
- **Our Galaxy is rather constantly transparent to ^{3}He passage**
- Data are in good agreement with Geant4 predictions
- Uncertainties on Transparency only due to absorption measurements (10-20%)

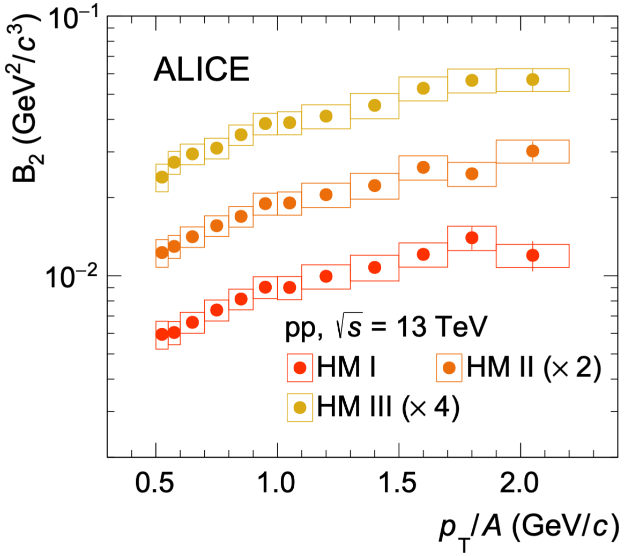
anti^{3}He: Nature Phys. (2023) 19, 61–71

Testing coalescence model using B_2

- Important observable in accelerator measurements: coalescence parameter B_A

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





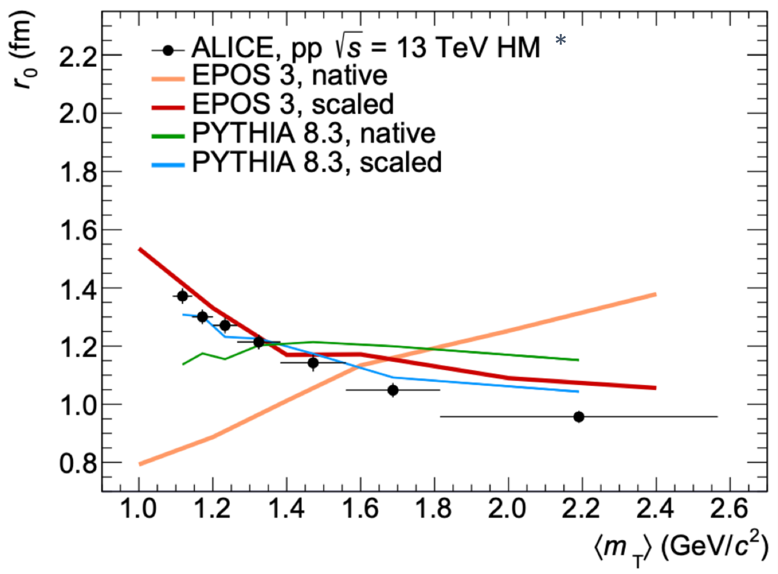
- Comparison to model predictions based on Wigner formalism
  - Using event generators (PYTHIA 8.3 & EPOS 3)
  - Calibrating (anti)nucleon momentum distribution & multiplicity distributions to measurements
  - Obtaining deuteron p distributions according to the probability:

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

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

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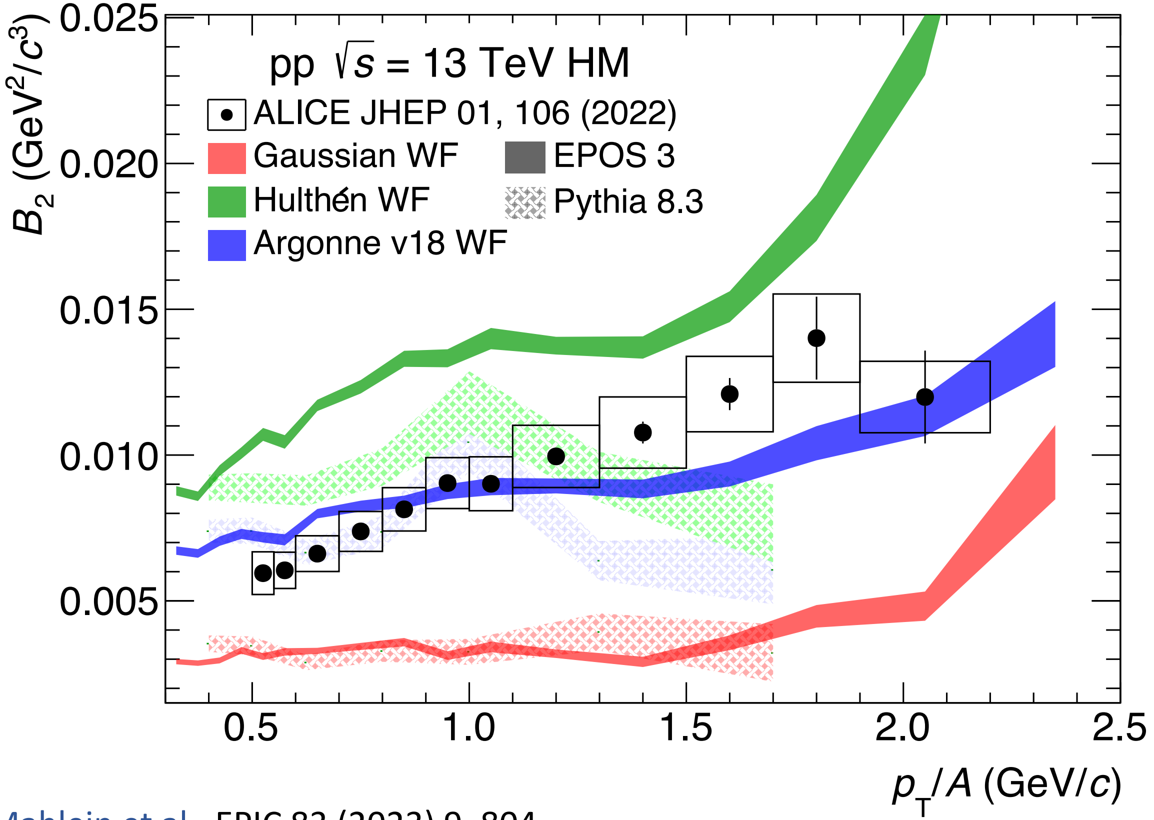
Testing coalescence model using B_2

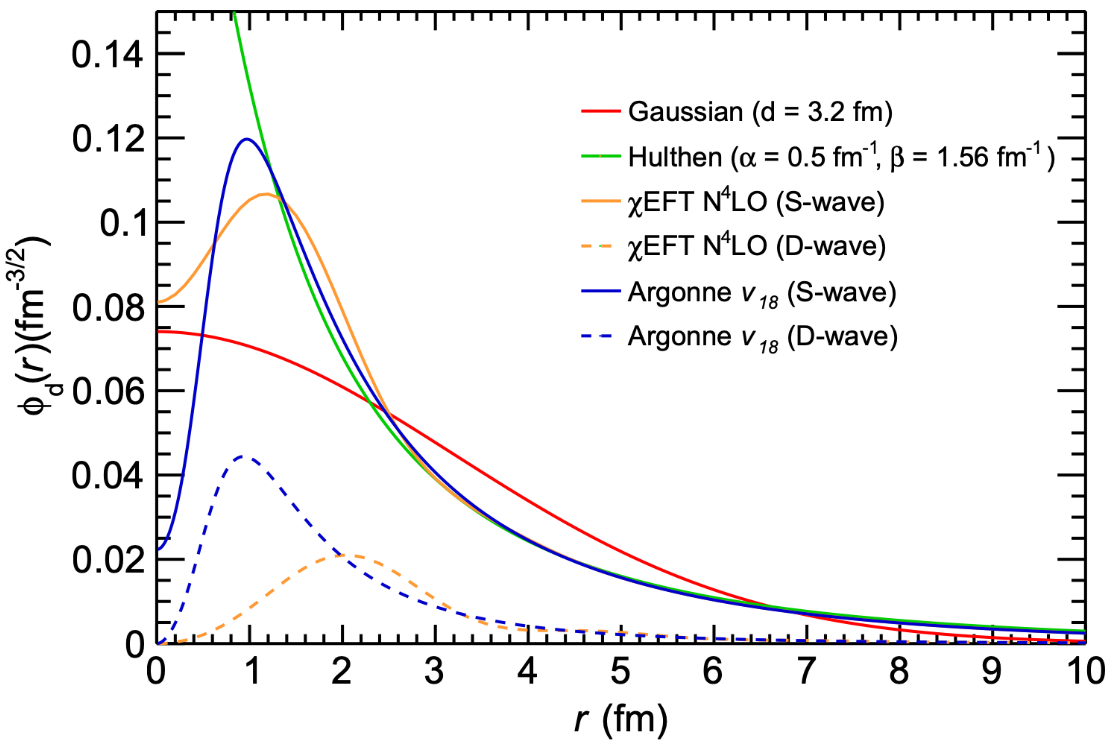
State-of the-art coalescence model describes deuteron momentum distributions and coalescence parameter!

↔

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