

# Exotic particles and nuclei

## Latest results in relativistic particle collisions

F. Bellini (Bologna University and INFN, Bologna - Italy)

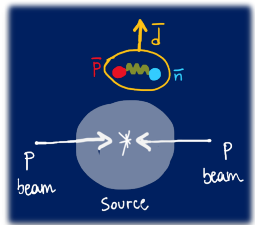
Quark Matter 2023 - Houston, 7<sup>th</sup> September 2023

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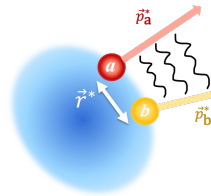
# Light nuclei and hypernuclei as a laboratory

## Composite states

- Bound by the nuclear interaction as a “residual” strong interaction → fundamental QCD
- Lifetime and binding energy of light hypernuclei reflect the strength of the Y-N interaction



Production mechanisms



Hadron-hadron interactions



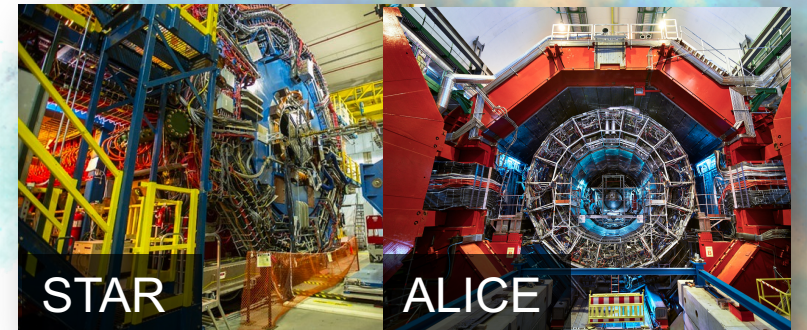
Input for astrophysics

## *In this talk:*

- Unprecedentedly large data samples enabling multi-differential studies
- New “tools”
- Precision tests of models at high and low energy, pp and AA
- More experiments joining the effort

Disclaimer: a personal selection of results – my apologies for omitting your favourite one!

# Production



# Production models for bound states

## Statistical hadronisation (SHM)

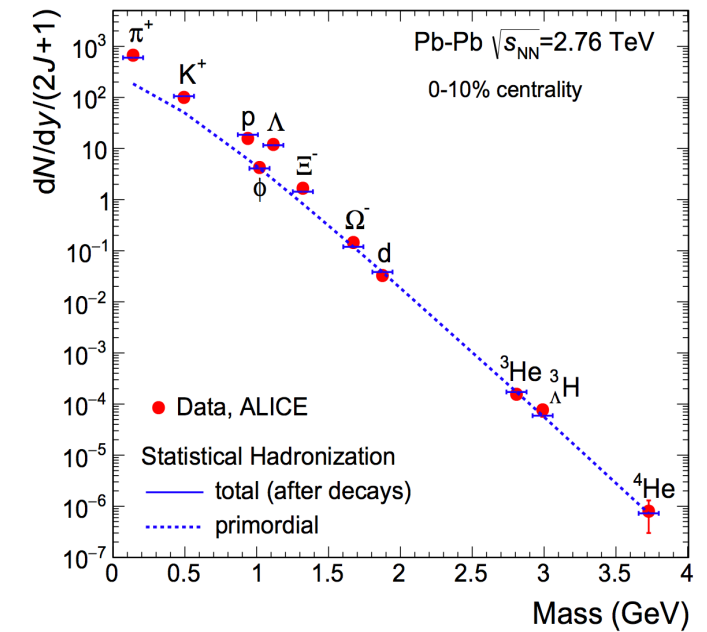
- Abundances:  $dN/dy \sim \exp(-m / T_{\text{ch}})$
- $B_E \ll T_{\text{ch}} \leftrightarrow$  survival in hadronic phase?
- Feeddown from excited states matters
- Extension to small systems via canonical approach (CSM)

## Coalescence

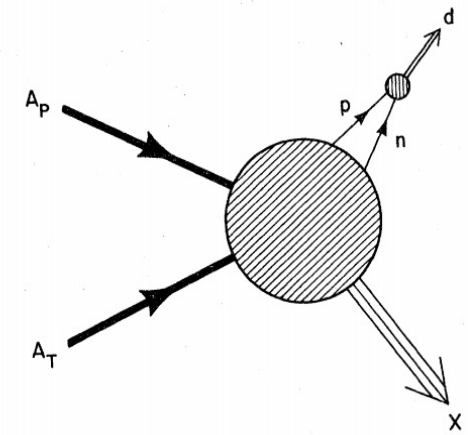
- If nucleons are nearby and have similar momenta
- Result of final state interactions among nucleons
- Explicit dependence on the size of the system and the nucleus size

## Transport/reaction-based

- Dynamical modeling of cluster formation
- UrQMD, SMASH, PHQMD, ...



A. Andronic et al., Nature 561, 321 (2018)



Butler and Pearson, PR 129, 836 (1963)  
Kapusta, PRC 21, 1301 (1980)

# Production from low to high energy

## Low to intermediate energy AA:

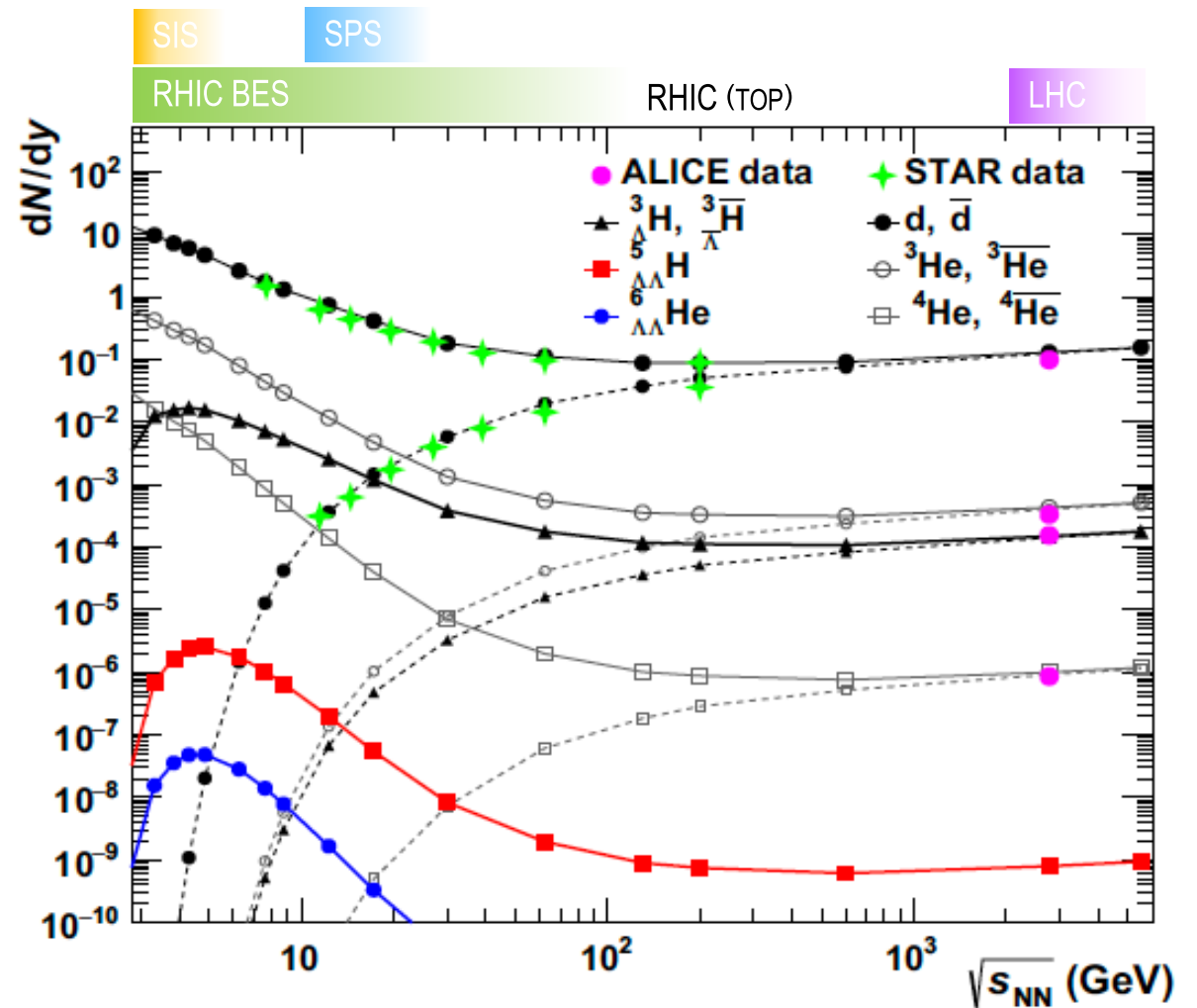
- Hadronic interactions
- Target fragmentation
- High  $\mu_B \leftrightarrow$  matter dominates

## High energy AA:

- Long lived fireball + hadronic phase
- Transport of baryon number
- Low to zero  $\mu_B \leftrightarrow$  antimatter

## High energy pp collisions:

- Small emitting source
- Jets  $\leftrightarrow$  closer to e+e- environment

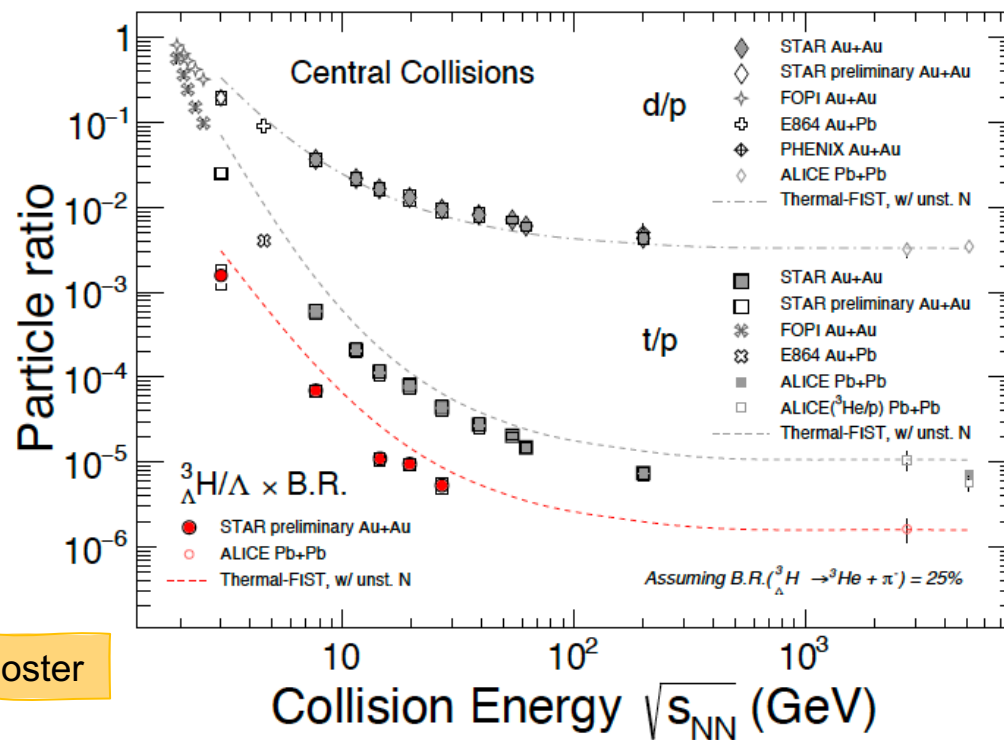


B. Doenigus, EPJ A 56 (2020) 258

SHM predictions from A.Andronic et al., PLB 697 (2011) 203–207

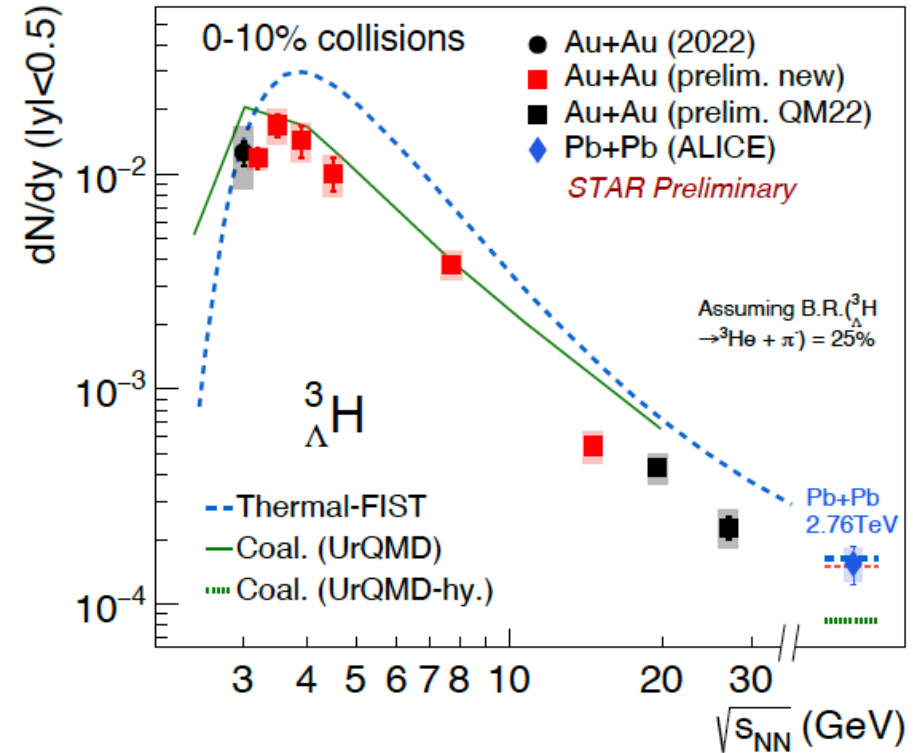
# Energy dependence qualitatively reproduced by models

- At low energy,  $t/p$  and  ${}^3\Lambda/\Lambda$  ratios are systematically overestimated by thermal model
- ${}^3\Lambda$  trend as a result of the interplay between increasing baryon density and stronger strangeness canonical suppression towards low energies.



S. Leung, poster

Thermal-FIST: V. Vovchenko et al. PLB (2020) 135746



J. Yuanjing, poster

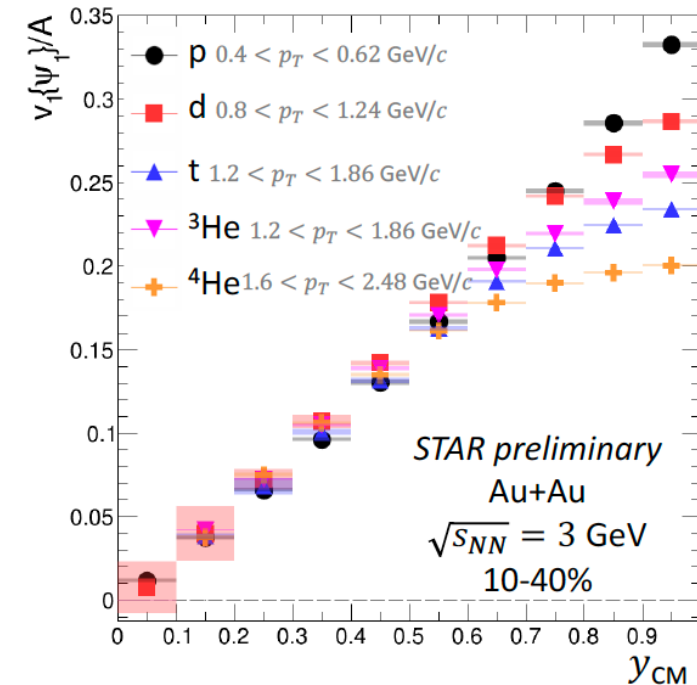
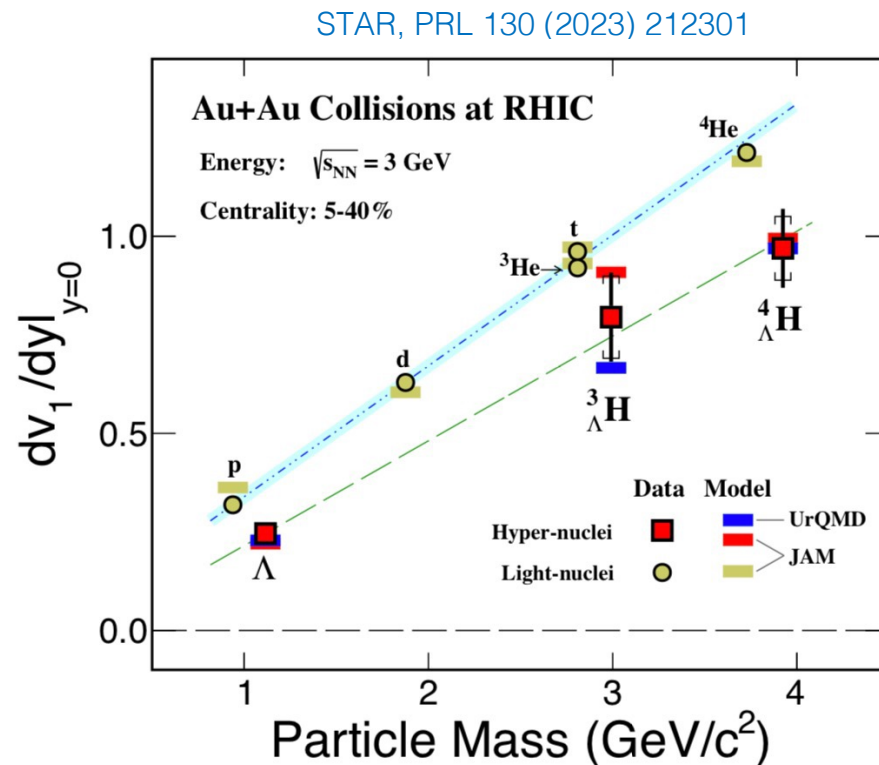
Coalescence: T. Reichert, et al. PRC 107 (2023) 014912

# Directed flow of nuclei at low $\sqrt{s_{NN}}$

*Coalescence + nuclear fragmentation*

A-scaling of directed flow  $v_1$  of light (hyper)nuclei and hypernuclei at low energy is reproduced by coalescence models qualitatively

... breaks towards target rapidity due to nuclear fragment contribution to  $v_1$



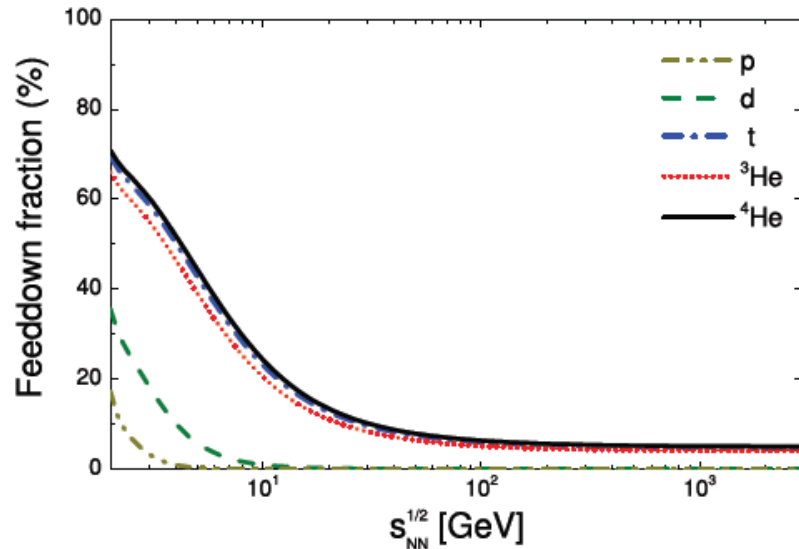
C. Han, wed 6/9

R. Reed, mon 6/9

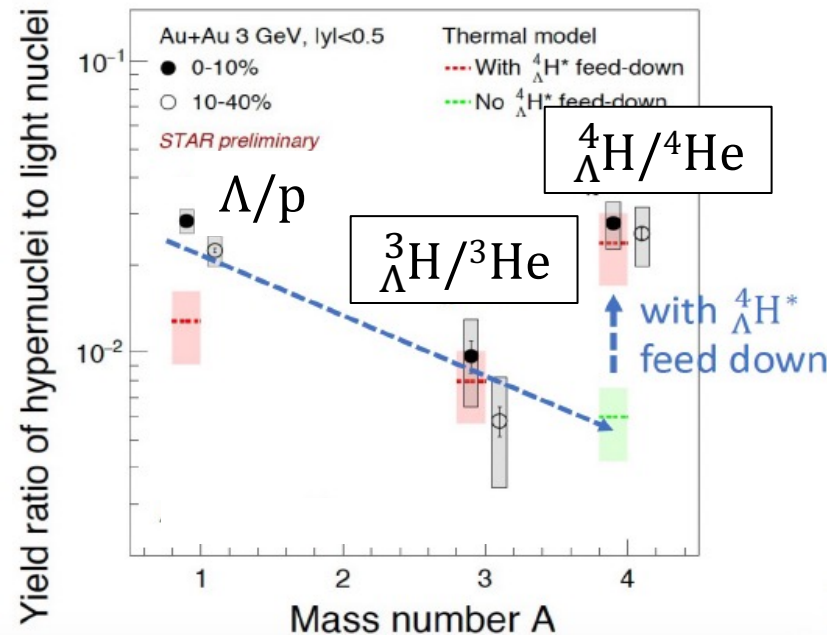
# Feeddown from excited states

Corrections for decays of excited nuclei to the final yields are relevant:

- For all light nuclei: strong effect for  $\sqrt{s_{NN}} < 10$  GeV but small at the LHC
- For  $A=4$  hypernuclei at low energy



V. Vovchenko, et al. PLB 809 (2020) 135746



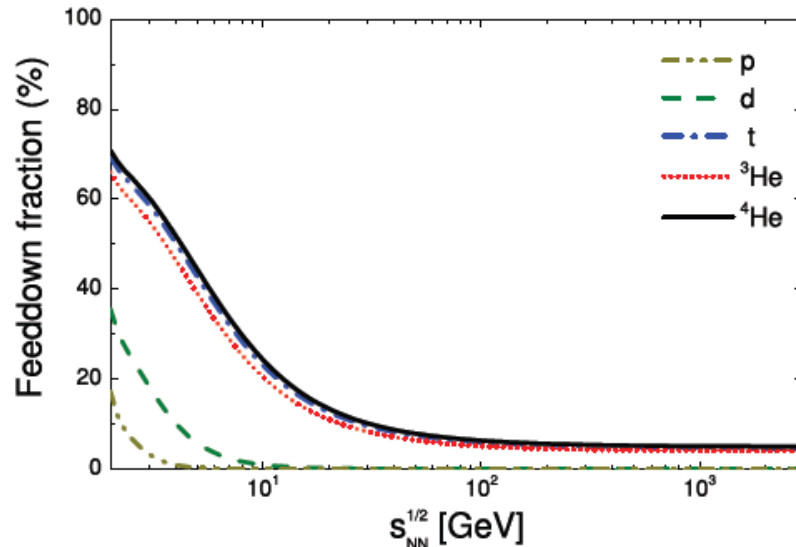
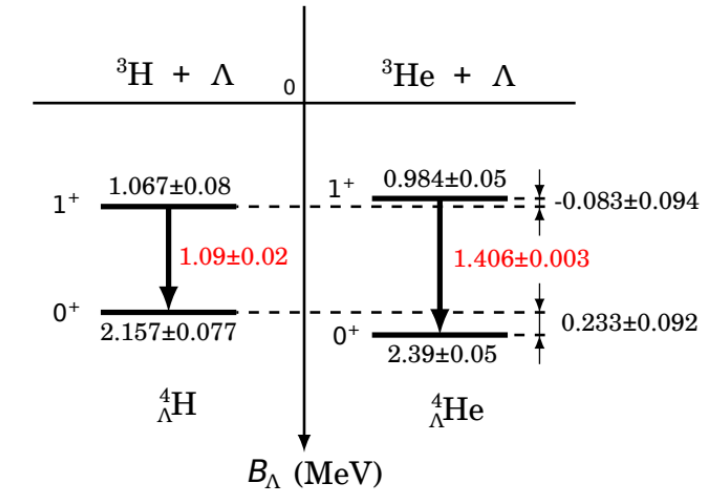
# Feeddown from excited states

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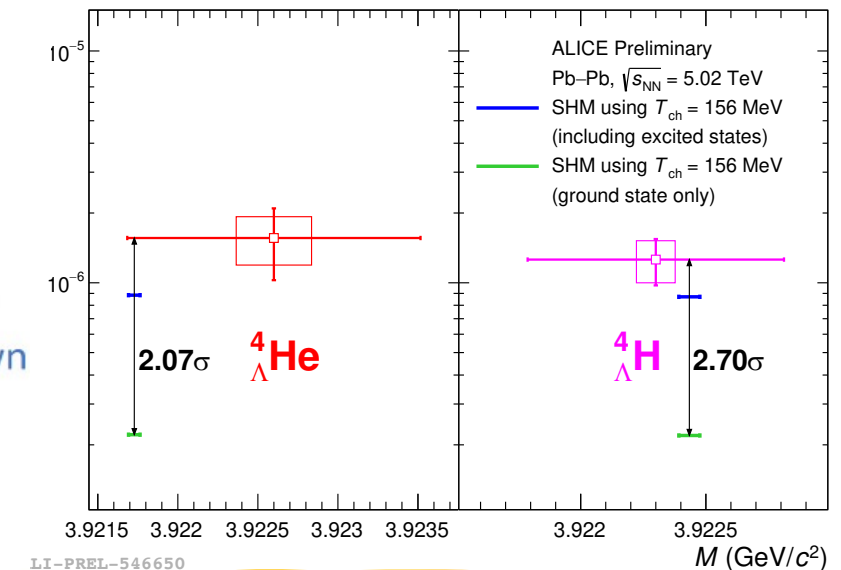
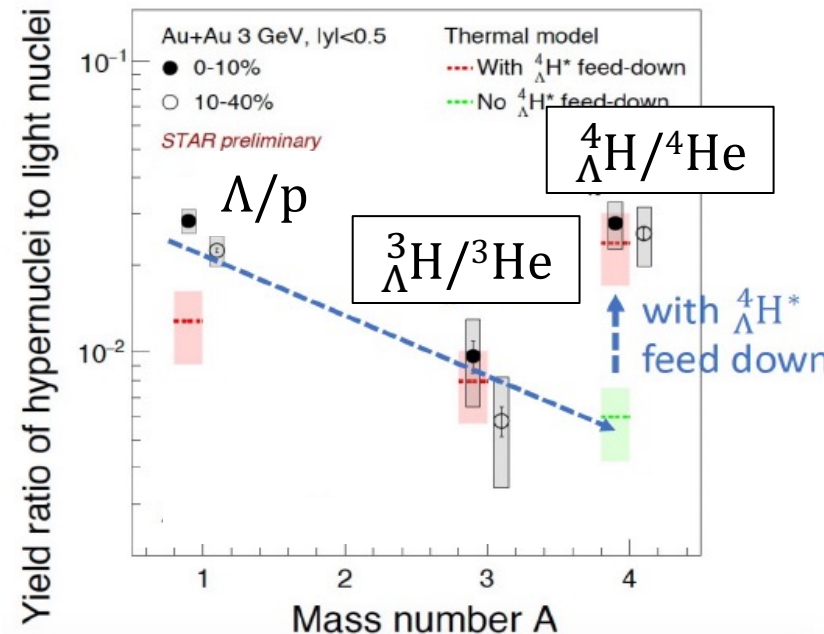
- For all light nuclei: strong effect for  $\sqrt{s_{NN}} < 10$  GeV but small at the LHC
- For  $A=4$  hypernuclei at low energy **and at the LHC**

→ to be accounted for in all model approaches

→ possibility to infer the number of excited states



V. Vovchenko, et al. PLB 809 (2020) 135746

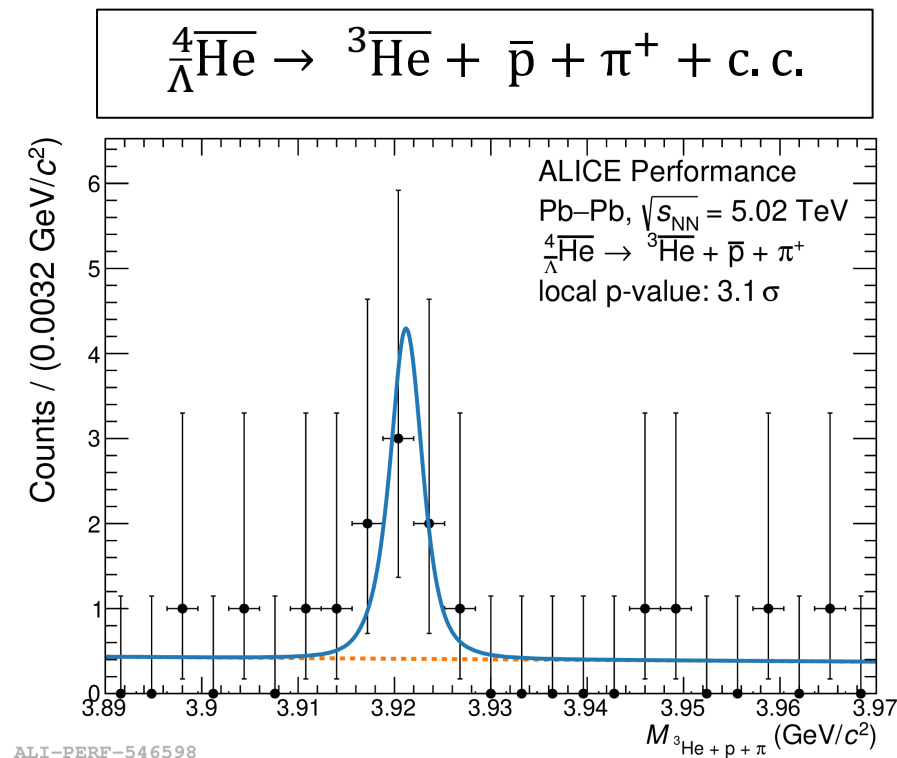
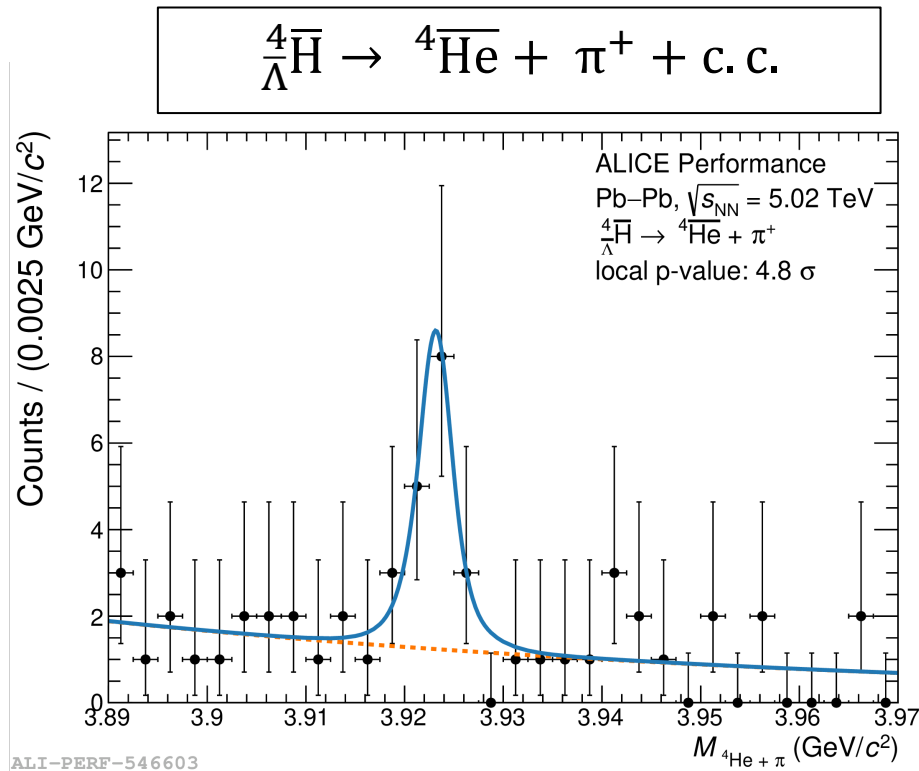


I. Vorobyev, Wed. 6/9

# First observation of A=4 antimatter at the LHC

## Appetizers:

- First A=4 (anti)hypernuclei observed at the LHC (Pb-Pb)
- First ever observation of  ${}^4_{\Lambda}\overline{\text{He}}$



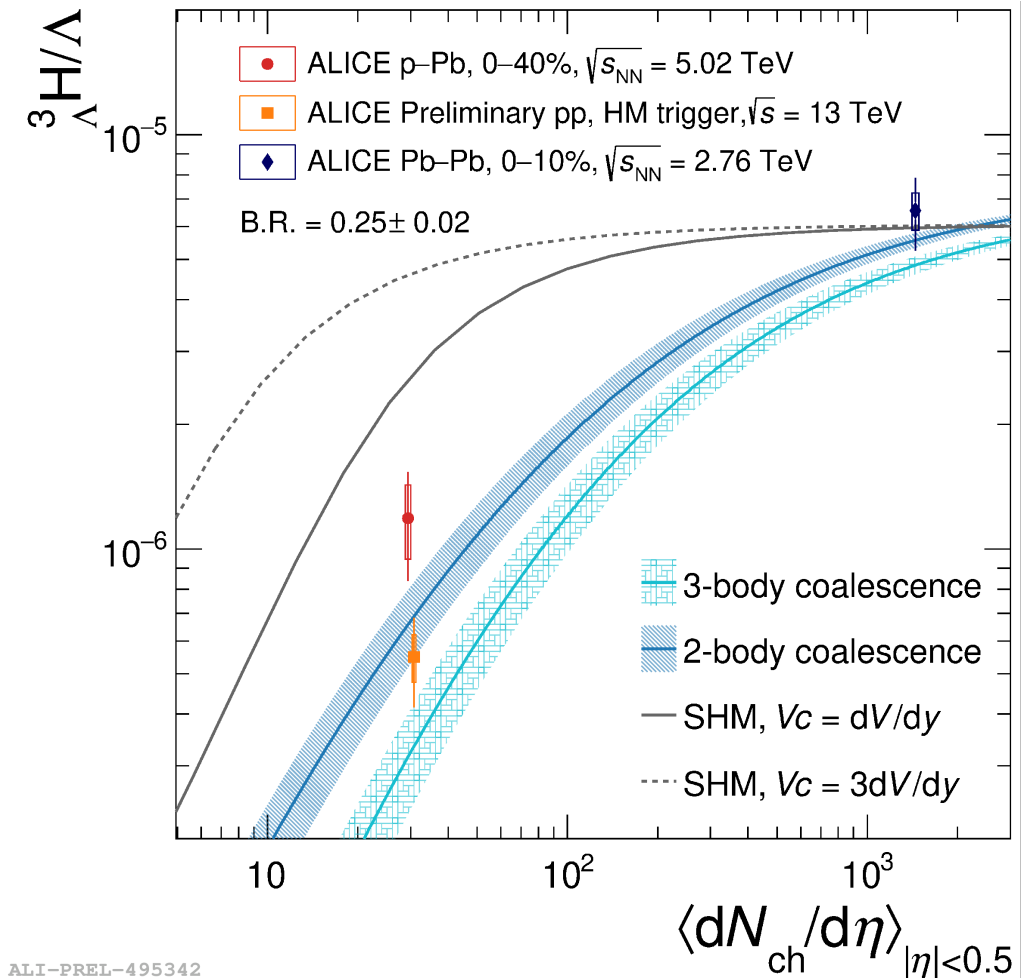
J. Ditzel, poster

# Hypertriton production at high energy

Due to the **large size** of the nucleus / **low  $B_A$** , large difference between theoretical predictions based on coalescence and SHM.

**First measurements in small systems** in p-Pb collisions and high-multiplicity pp collisions.

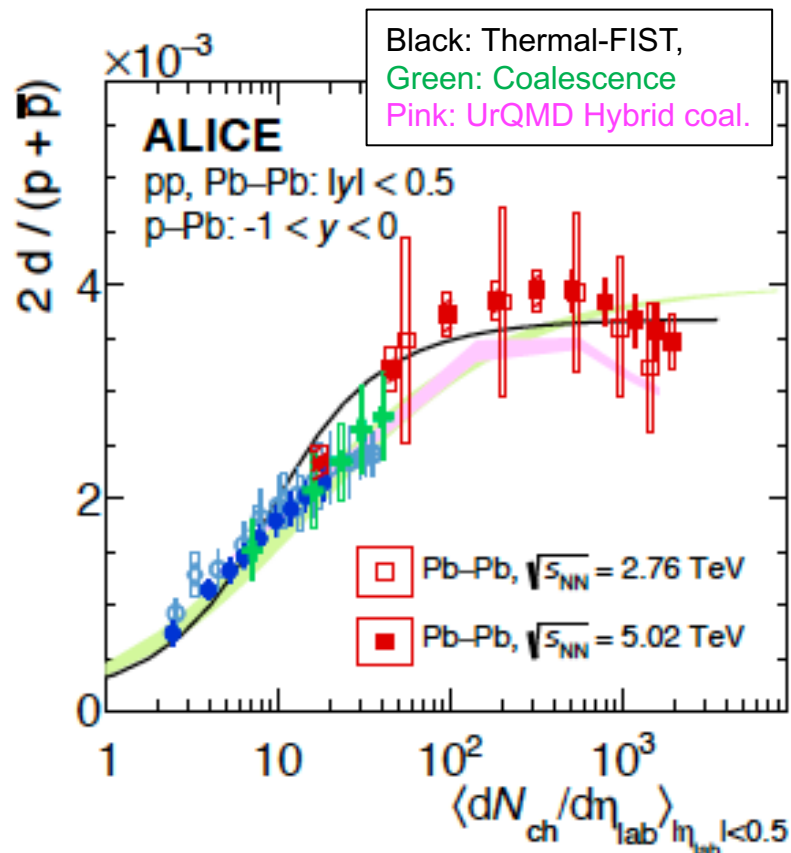
→ To be measured vs multiplicity to effectively constrain production models or limit their parameter space



p-Pb: ALICE, PRL 128 (2022) 25, 252003

# System size dependence of deuteron production

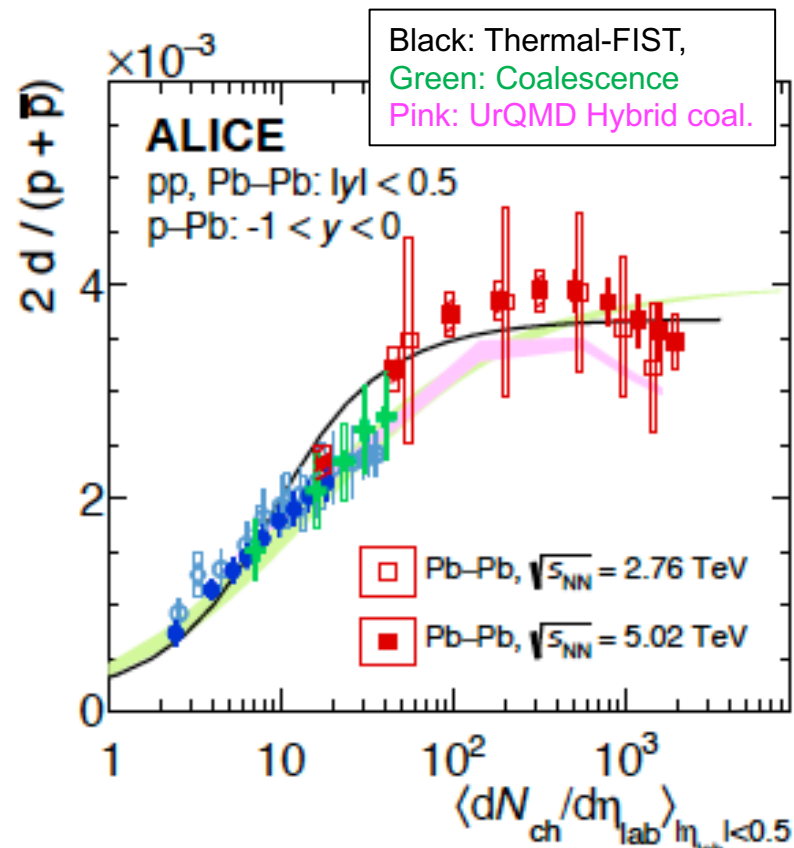
Multiplicity dependence of deuteron production at the LHC is **reproduced by models**  
... using a canonical-correlation volume that reproduces  $\bar{p} - \bar{d}$  negative correlations (EbyE)



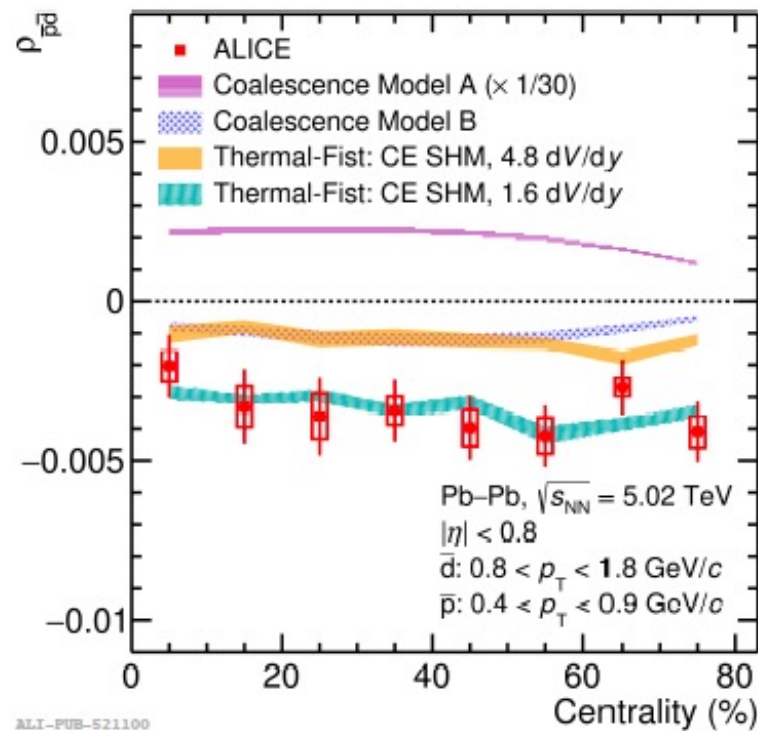
ALICE, PRC 107, 064904 (2023)

# System size dependence of deuteron production

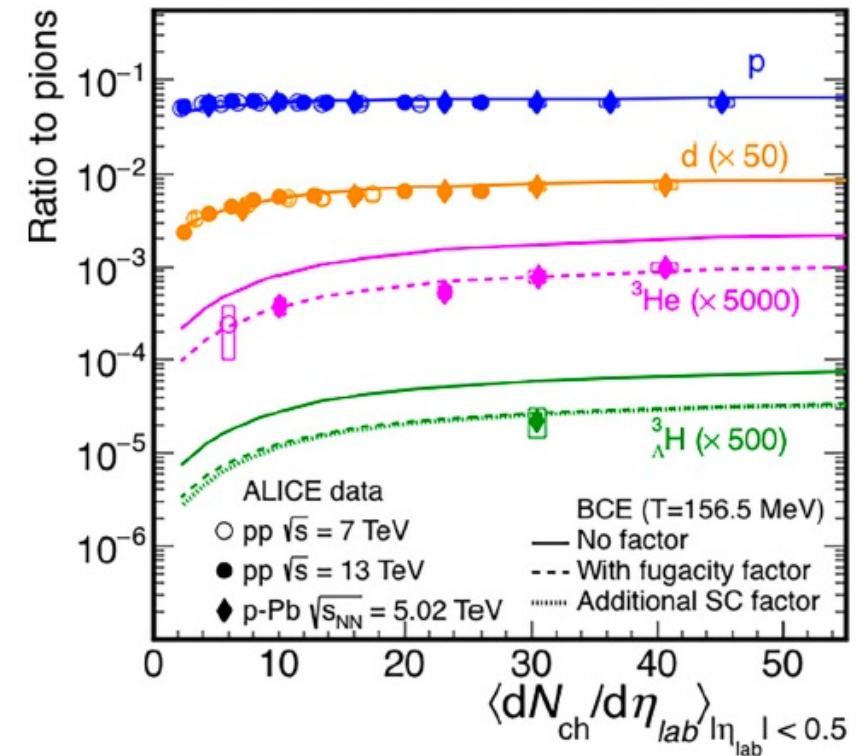
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ALICE, PRC 107, 064904 (2023)



ALICE, PRL 131, (2023) 041901



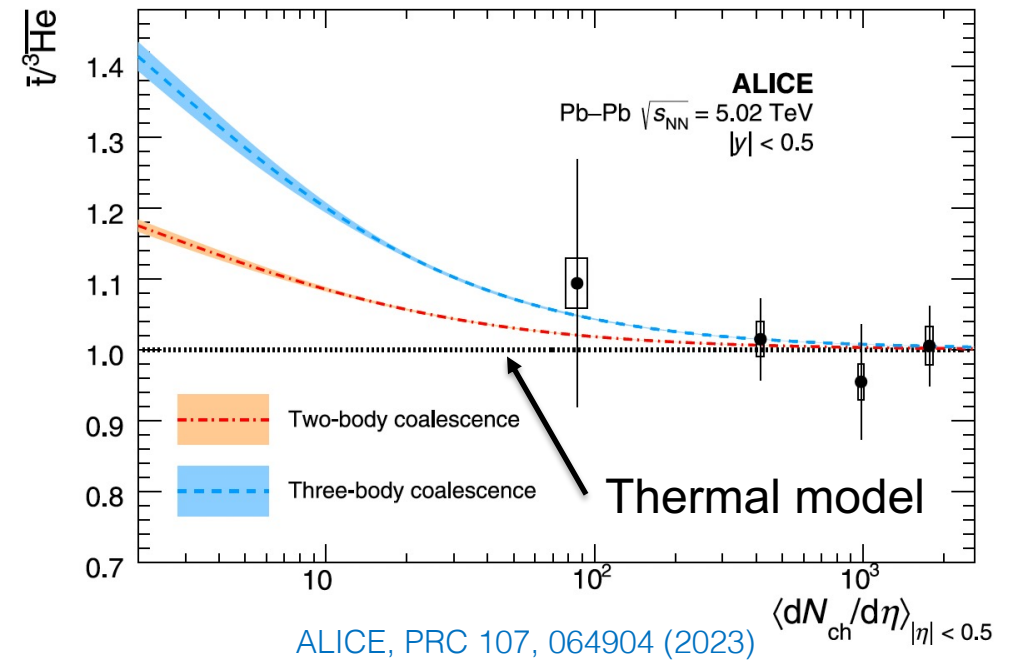
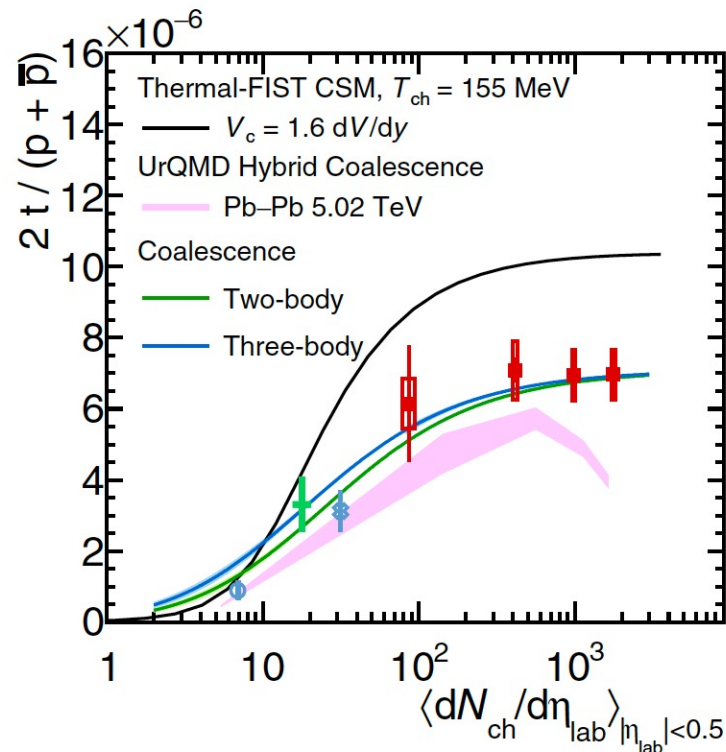
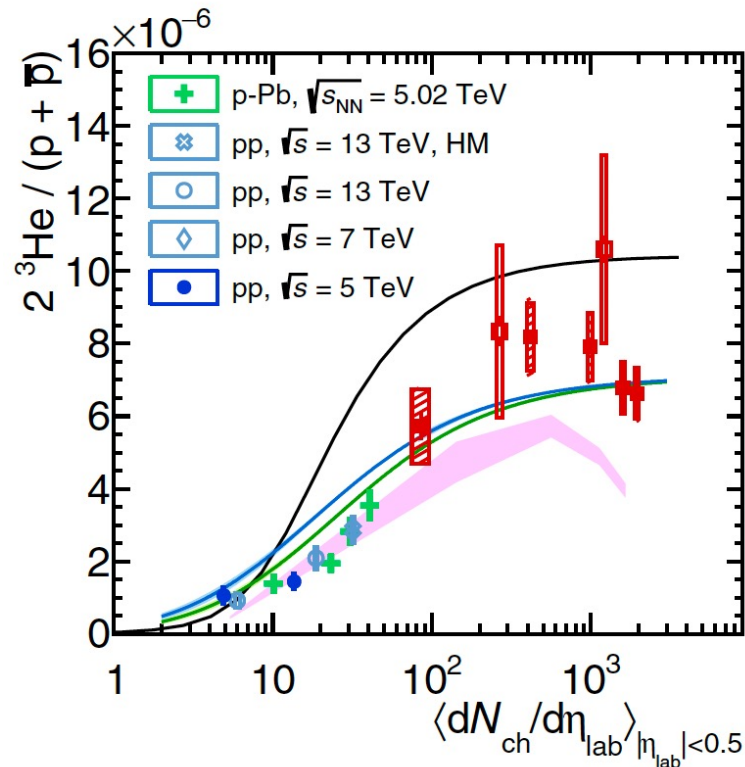
N. Sharma, K. Redlich et al., PRC107, 054903 (2023)

# Next in line: $^3\text{He}$ and triton

→ Clear need for more data on  $A=3$  nuclei

→ Potentially stringent test of coalescence model by measuring  $t/{}^3\text{He}$  in small systems

**Next:** with the unprecedentedly large samples from the LHC Run3



# Enhanced deuteron production in jets

## Test of coalescence

Enhanced d coalescence probability in jets wrt UE observed for the first time in pp collisions  
→ due to reduced distance in phase space of nucleons within jets

Larger enhancement in p-Pb wrt pp  
→ *particle composition in jets and broader source in UE?*

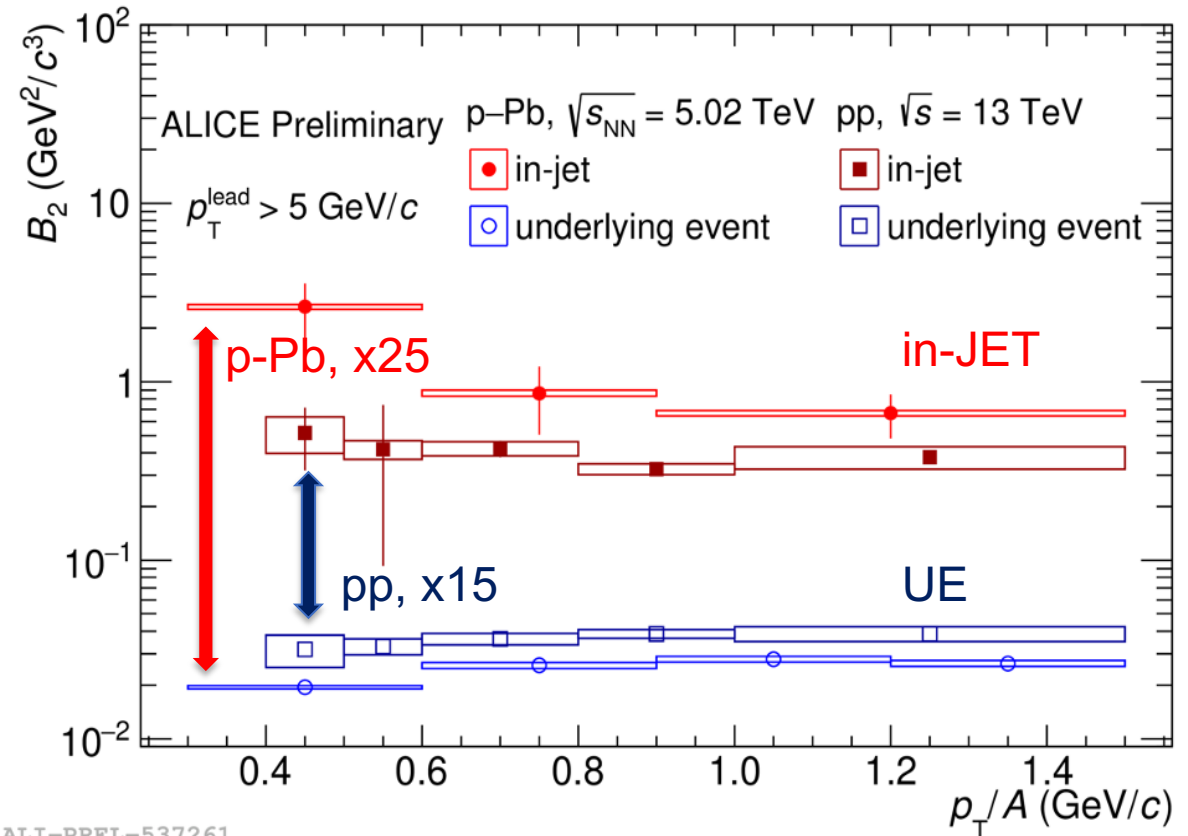
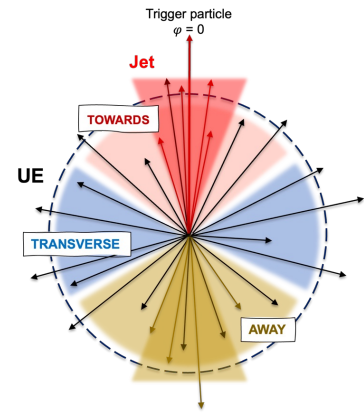
### Wishlist:

- Higher precision with run3 data
- Measurements with full jet reconstruction

M. Rasà, Poster

C. Pinto, Wed 6/9

In-jet vs UE  
classification  
based on  $\Delta\phi$



ALI-PREL-537261

pp: ALICE, PRL 131 (2023) 4, 042301

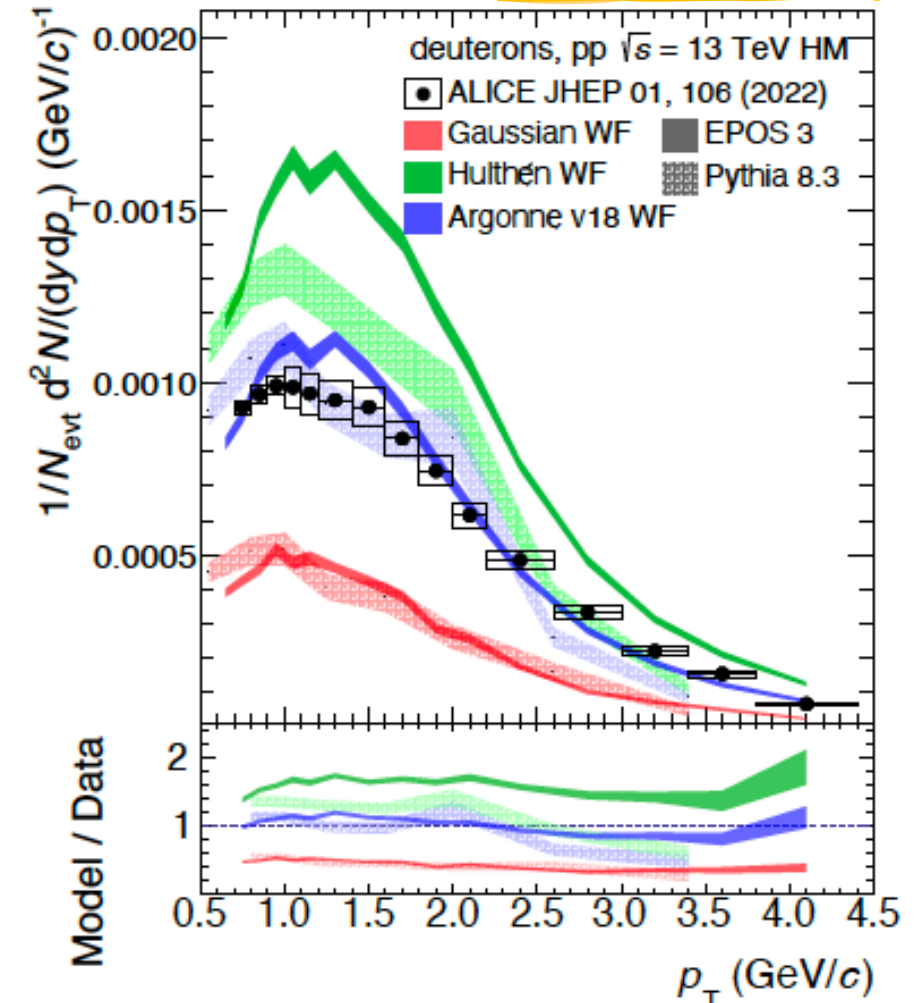
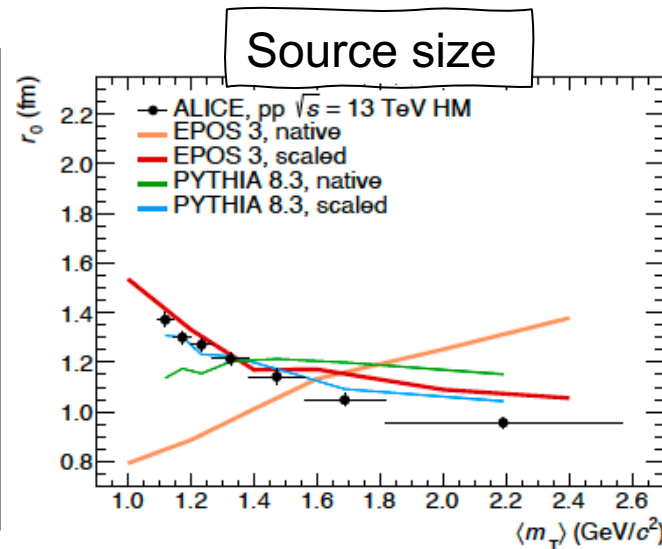
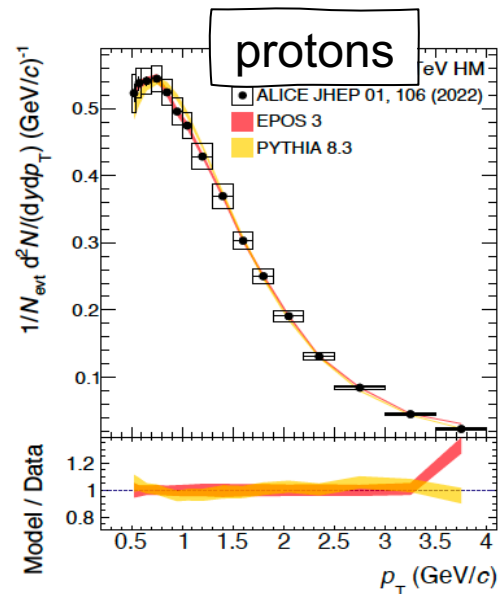
# Deuteron by coalescence from a realistic source

## *Improved modelling, event-by-event*

Application of Wigner-based coalescence for an afterburner to MC generators

→ deuteron spectrum **reproduced without any free parameters** by using ALICE data to implement a realistic source

C. Pinto et al, poster



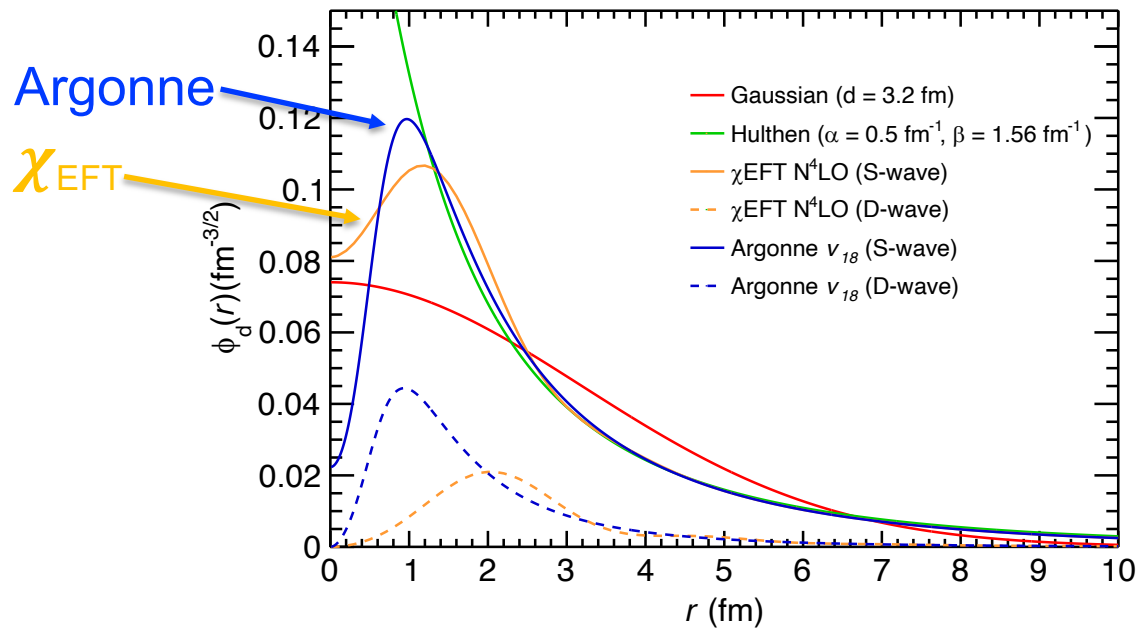
M. Mahlein et al, [arXiv:2302.12696](https://arxiv.org/abs/2302.12696)

# Deuteron by coalescence from a realistic source

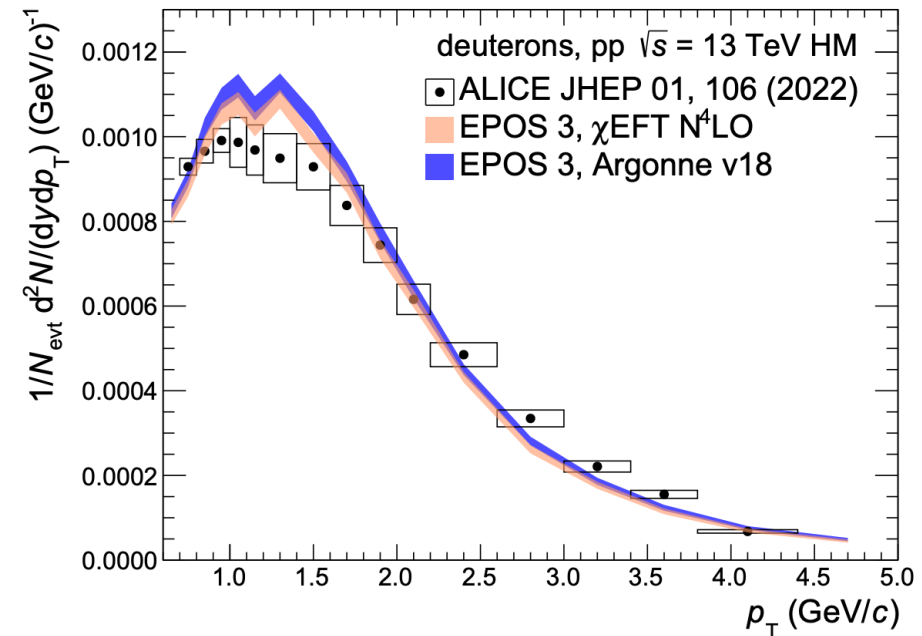
## Nucleus wavefunction

Hulthén, **Argonne v<sub>18</sub>** and  $\chi_{EFT}$  wavefunctions differ in the description of the core (low  $r$ )

$\chi_{EFT}$  shows less repulsion than Argonne v<sub>18</sub> but similar results for coalescence  
→ Not significantly affected by very-short range component of the interaction

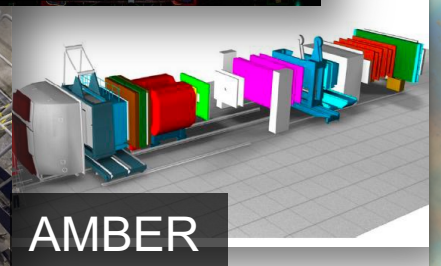
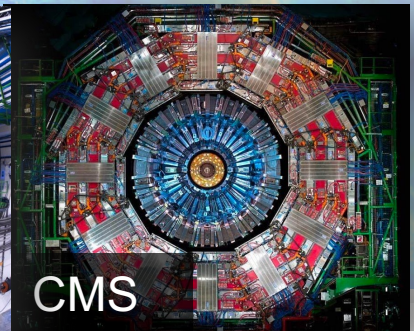


Hulthén: Heinz and Jacak, Ann. Rev. NPS. 49, 529 (1999)  
Argonne: Wiringa et al., PRC 51, 38 (1995)  
 $\chi_{EFT}$  N<sup>4</sup>LO: Entem et al, PRC 96, 024004 (2017)



M. Mahlein et al, [arXiv:2302.12696](https://arxiv.org/abs/2302.12696)

# Input to astrophysics



# From accelerators to the Cosmos

*Helping searches for cosmic antinuclei as dark matter smoking guns*

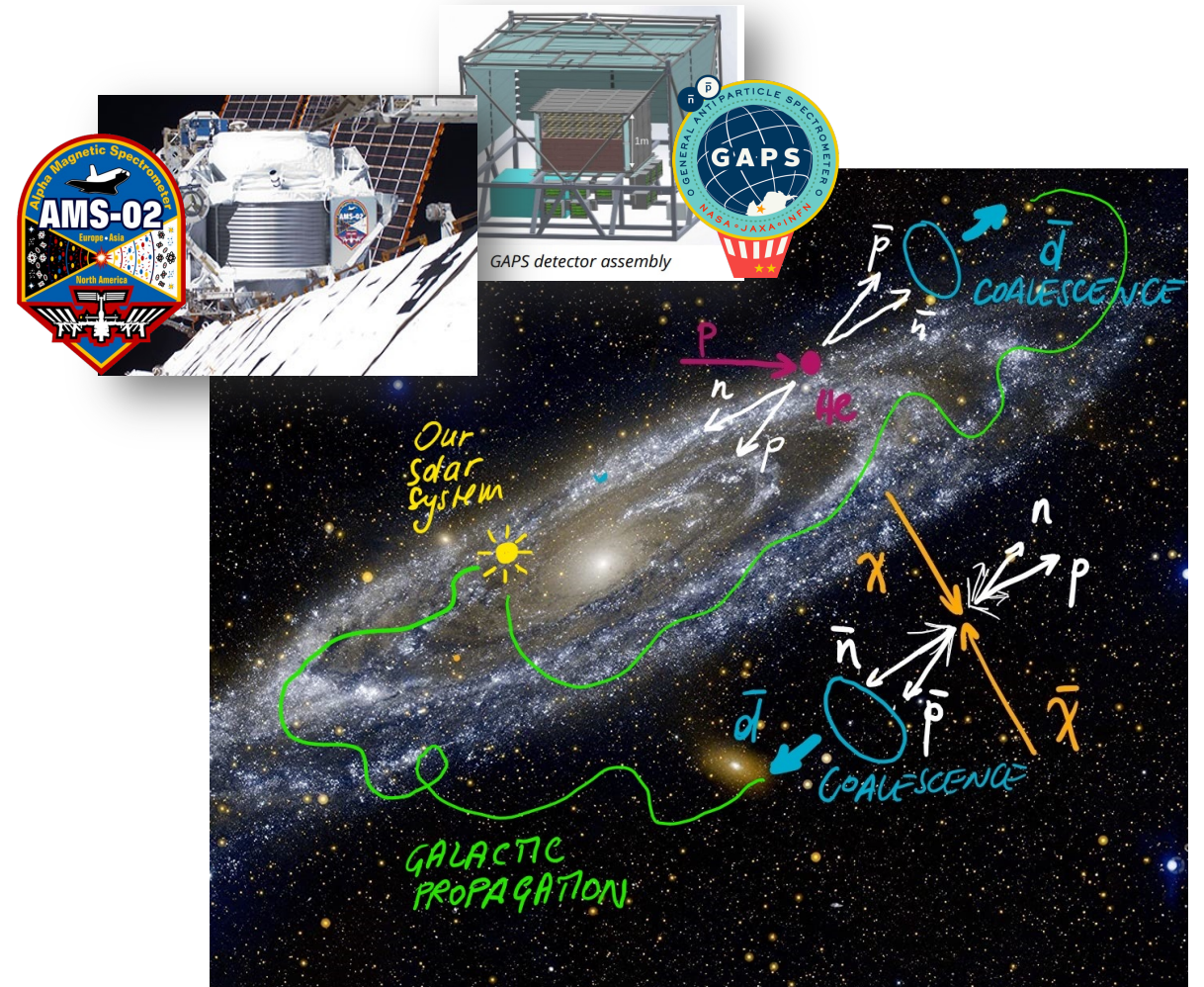
Accelerator experiments are in a unique position to provide the ingredients to estimate the flux of cosmic light antinuclei in space-based experiments

- cosmic ray physics
- indirect dark matter searches

Wishlist:

- **Antiproton** cross sections
- Validation/constraints for **production** models
- **Low  $\sqrt{s}$**  ( $\sim 10\text{--}20$  GeV), **forward** rapidity
- **Absorption** cross sections of antinuclei in matter

ALICE Nature Physics vol. 19, 61–71 (2023)

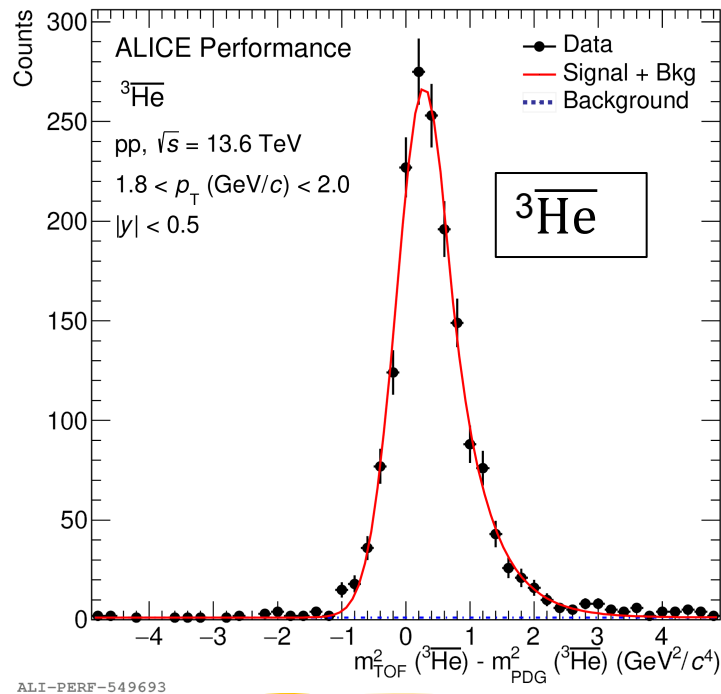


C. Pinto, Wed. 6/9

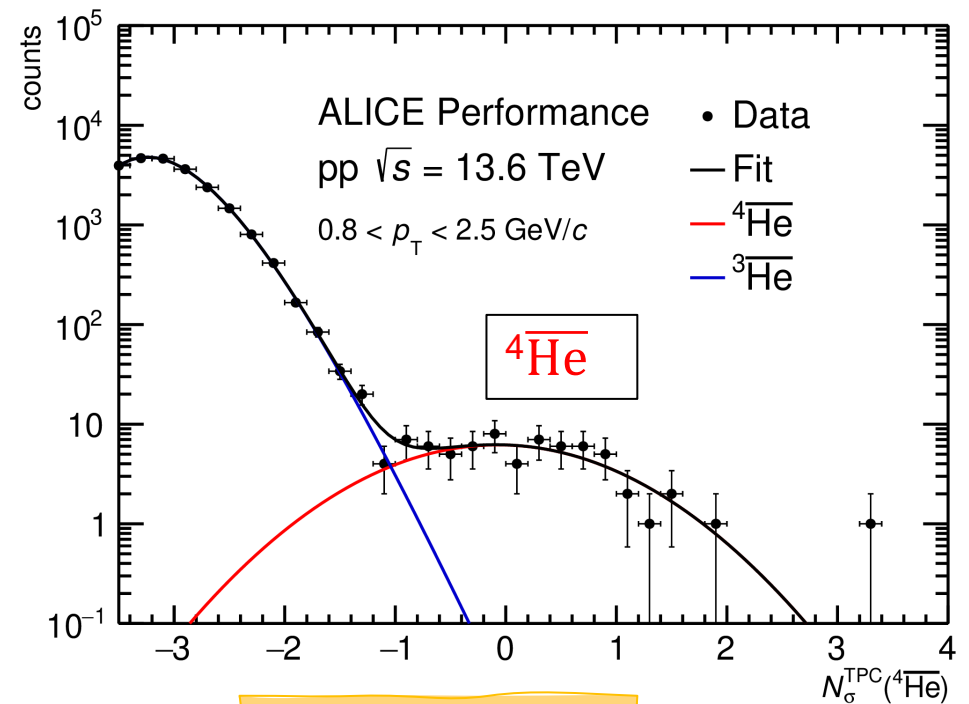
# Towards precision measurements of antihelium

**Appetizers:** from Run 3 pp collisions at 13.6 TeV

- Largest  ${}^3\overline{\text{He}}$  sample so far
- First signal of  ${}^4\overline{\text{He}}$  in pp collisions



G. Malfattore, poster



I. Vorobyev, Wed. 6/9

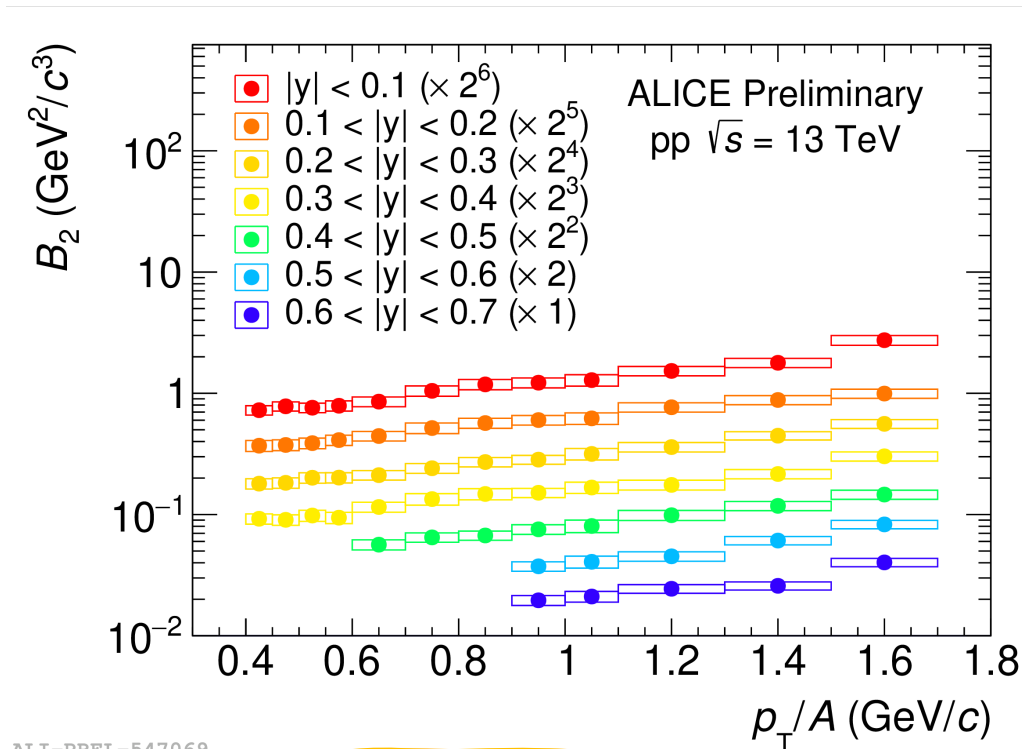
# Rapidity dependence of d production

*Input to model production in cosmic rays*

ALICE measurements used as input to extract expected flux of cosmic antideuteron

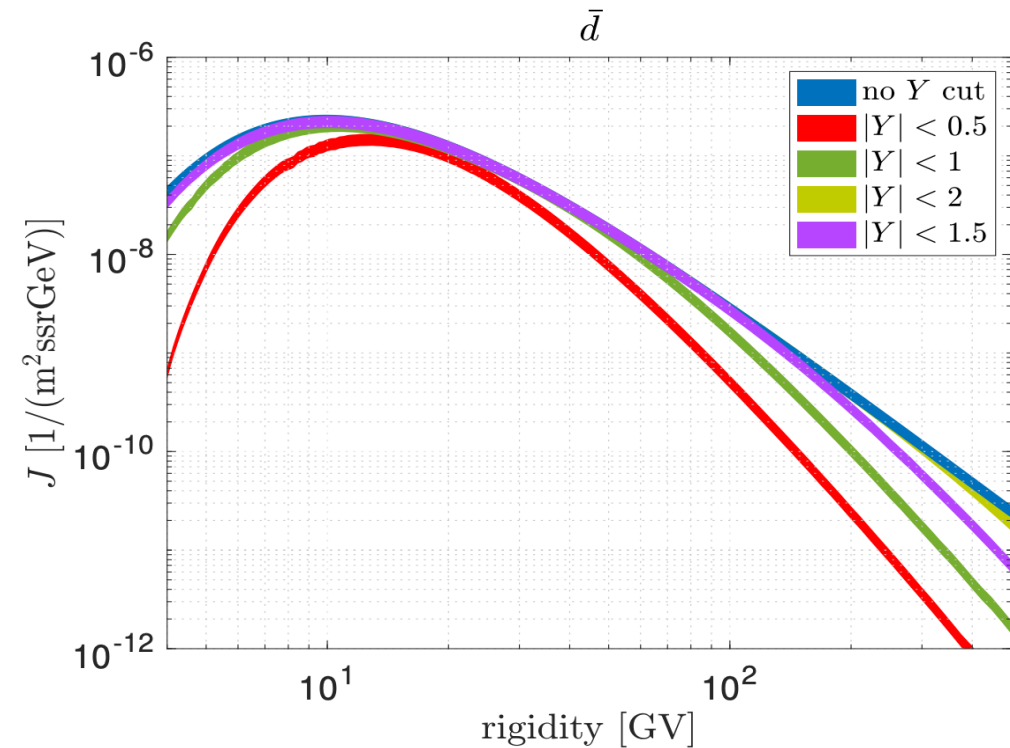
→ Most of the flux is for  $|y| < 2$

At ALICE, rapidity reach is limited by current detector acceptance → ALICE 3 after Run 4



ALI-PREL-547069

C. Pinto, Wed 6/9



K. Blum, arxiv:2306.13165

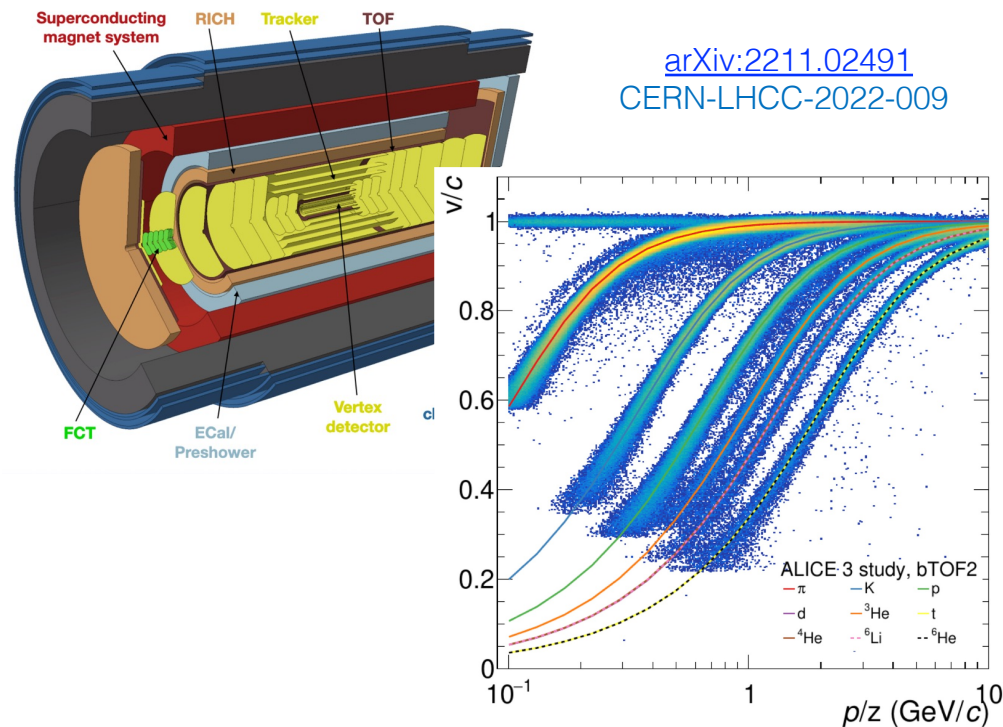
# More with next LHC upgrades

**CMS Phase-2 (Run 4):** identification win MTD within  $|y| < 2$

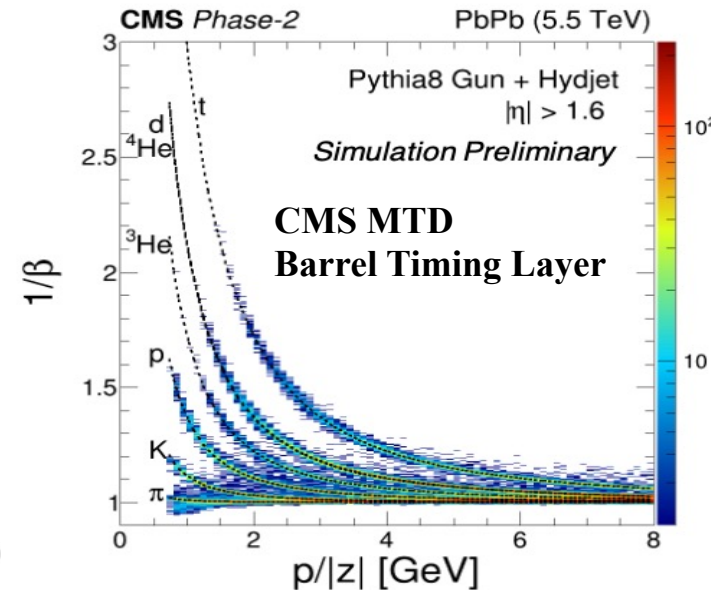
**ALICE 3 (Run 5):** acceptance  $|y| \lesssim 4$

→ search for new decay channels that could enhance antinuclei from DM, e.g.  $\bar{\Lambda}_b \rightarrow \bar{}^3\text{He} \text{ pp} + X$

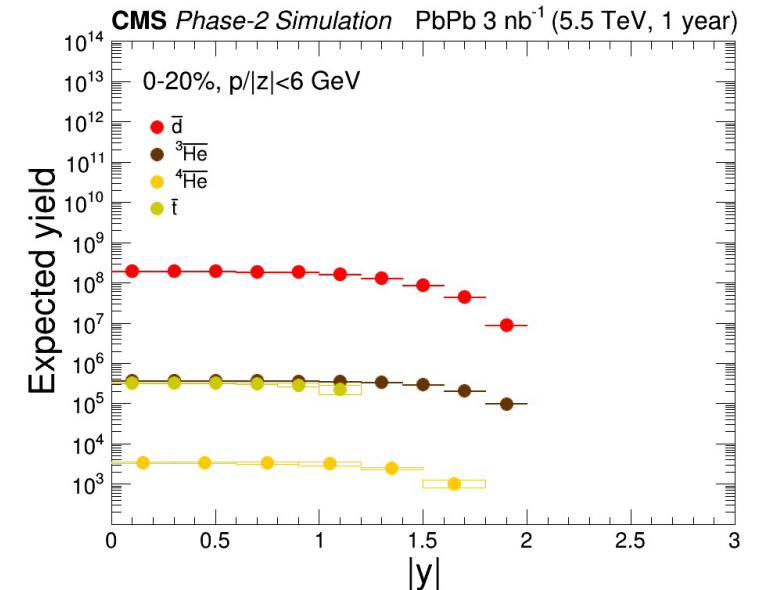
→ search for nuclei with charm (c-deuteron)...



CERN-CMS-DP-2021-037



Zhenyu Ye, Wed 6/9

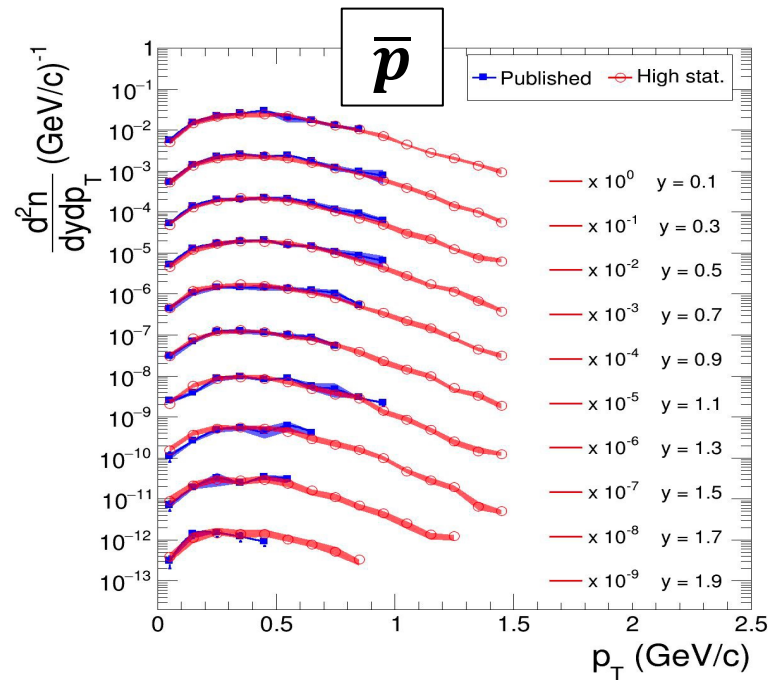


# Rapidity dependence of p, d production at low energy

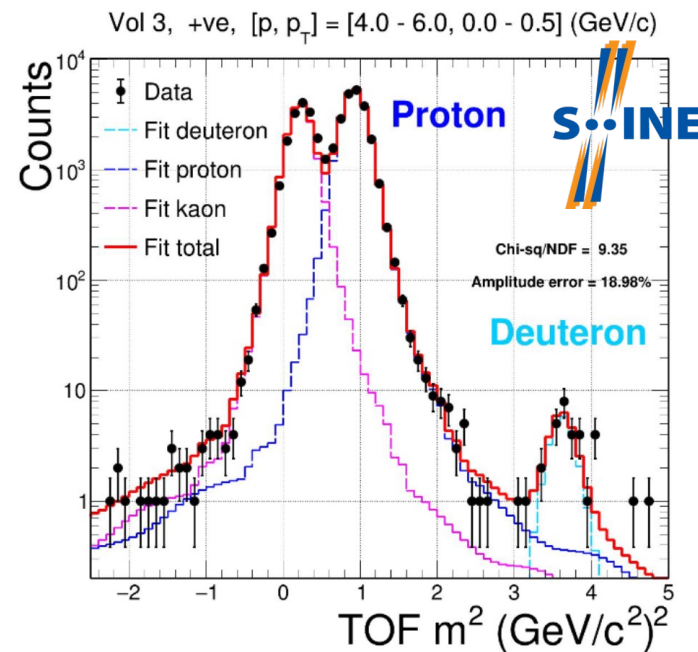
*Input to model production in cosmic rays*

## Appetizers:

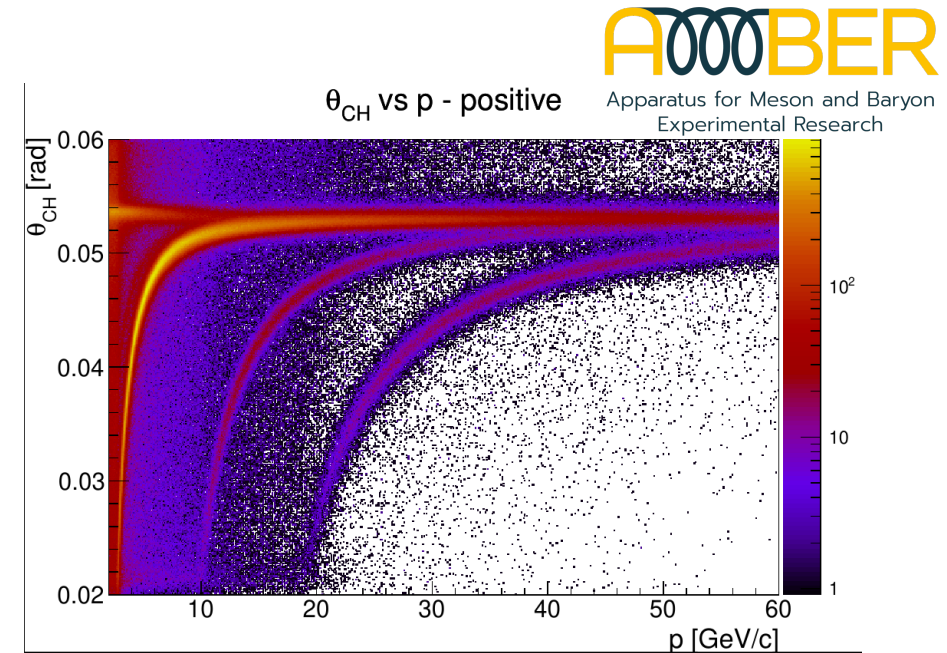
- **NA61/Shine**: high precision measurement of  $\bar{p}$  in  $|y| < 1.9$  and first  $\bar{d}$  signals in pp collisions
- **AMBER**: first data taking in may 2023, promising performance



A. Shukla, poster



D. Giordano, poster

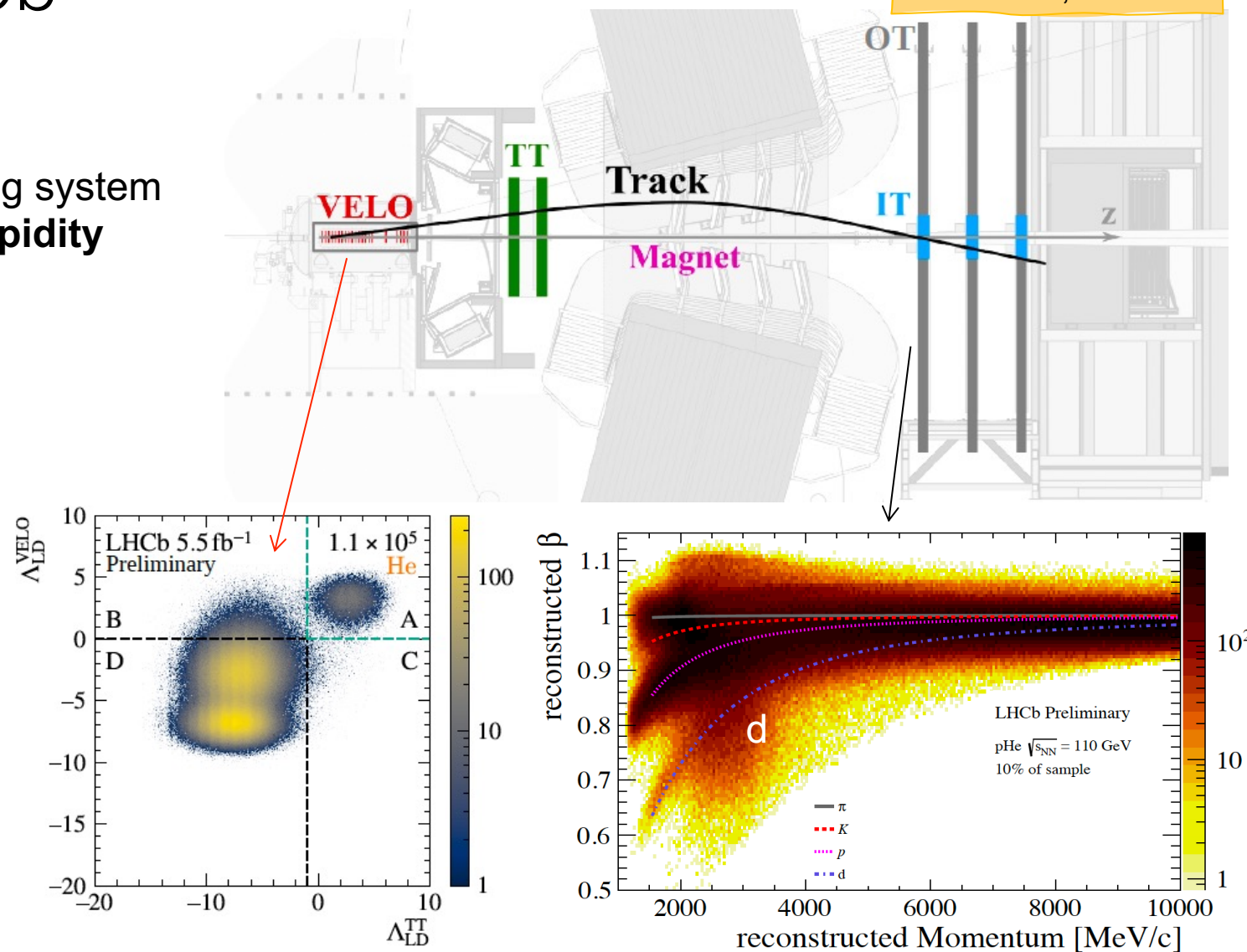


# First ${}^3\text{He}$ and ${}^3_{\Lambda}\text{H}$ in LHCb

*A new cowboy in town*

New strategy applied in LHCb using tracking system information to identify **nuclei at forward rapidity**

M. Durham, Mon 4/9



# First ${}^3\text{He}$ and ${}^3_{\Lambda}\text{H}$ in LHCb

*A new cowboy in town*

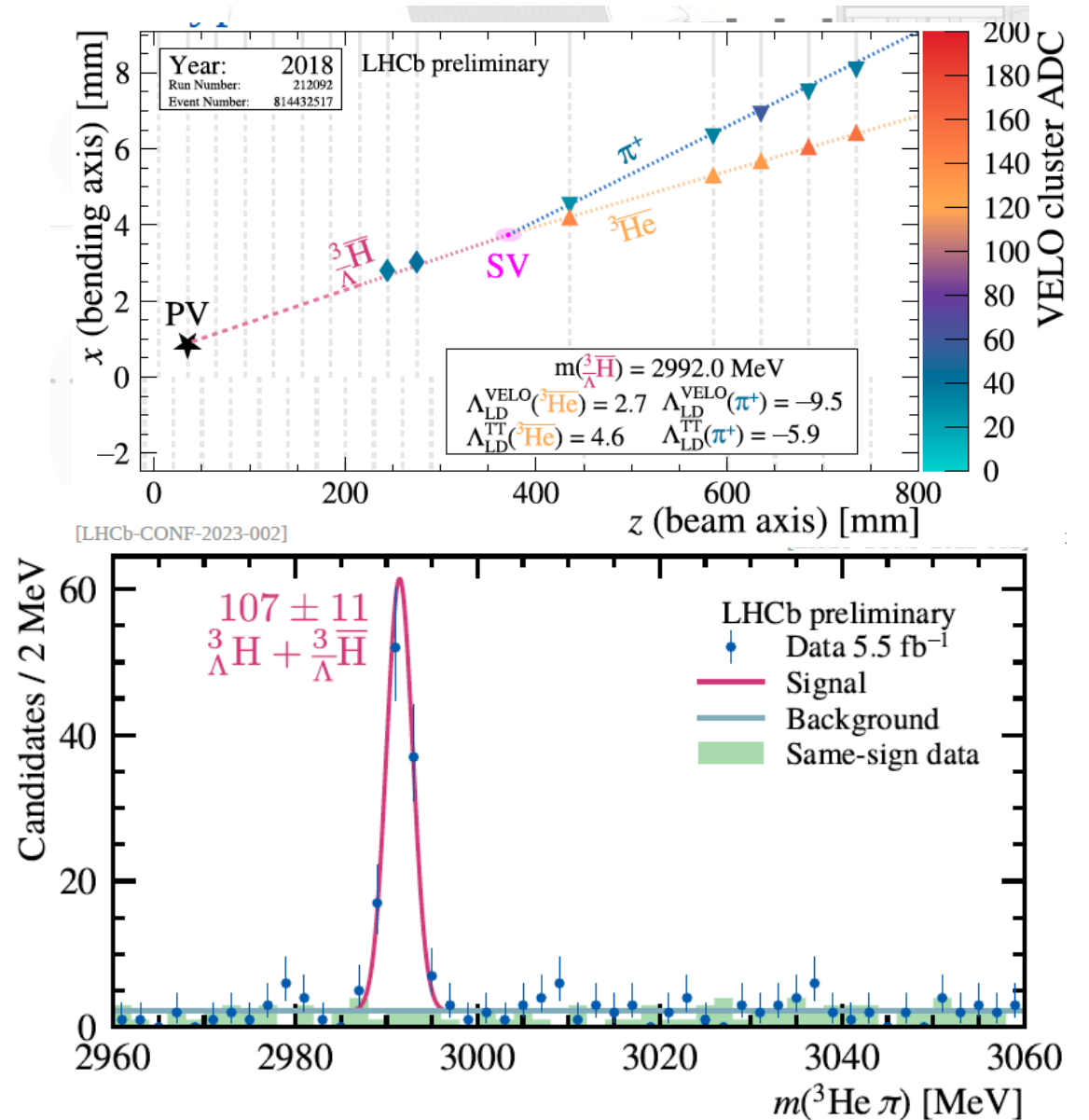
New strategy applied in LHCb using tracking system information to identify **nuclei at forward rapidity**

${}^3_{\Lambda}\text{H}$  two body decay exploited to obtain the **first signals of hypertriton in LHCb**

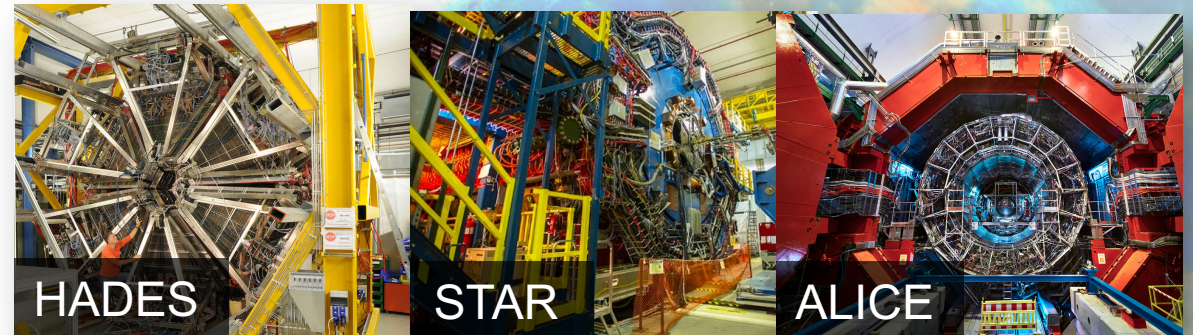
## Appetizers:

- antihelium at forward rapidity
- deuteron with SMOG in p-He at 110 GeV
- Searches for  $\bar{\Lambda}_b \rightarrow {}^3\bar{\text{He}} \text{ pp} + \text{X}$  decay
- hypertriton lifetime

C. Lucarelli, Poster



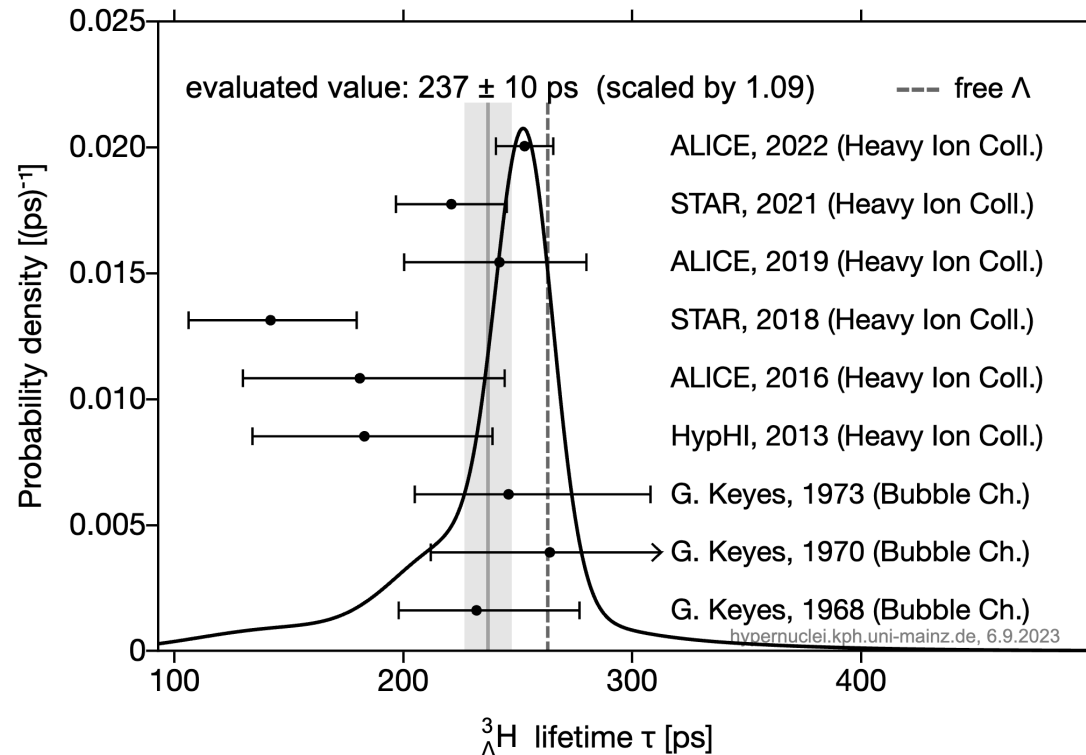
# Hypernuclei and h-h interactions



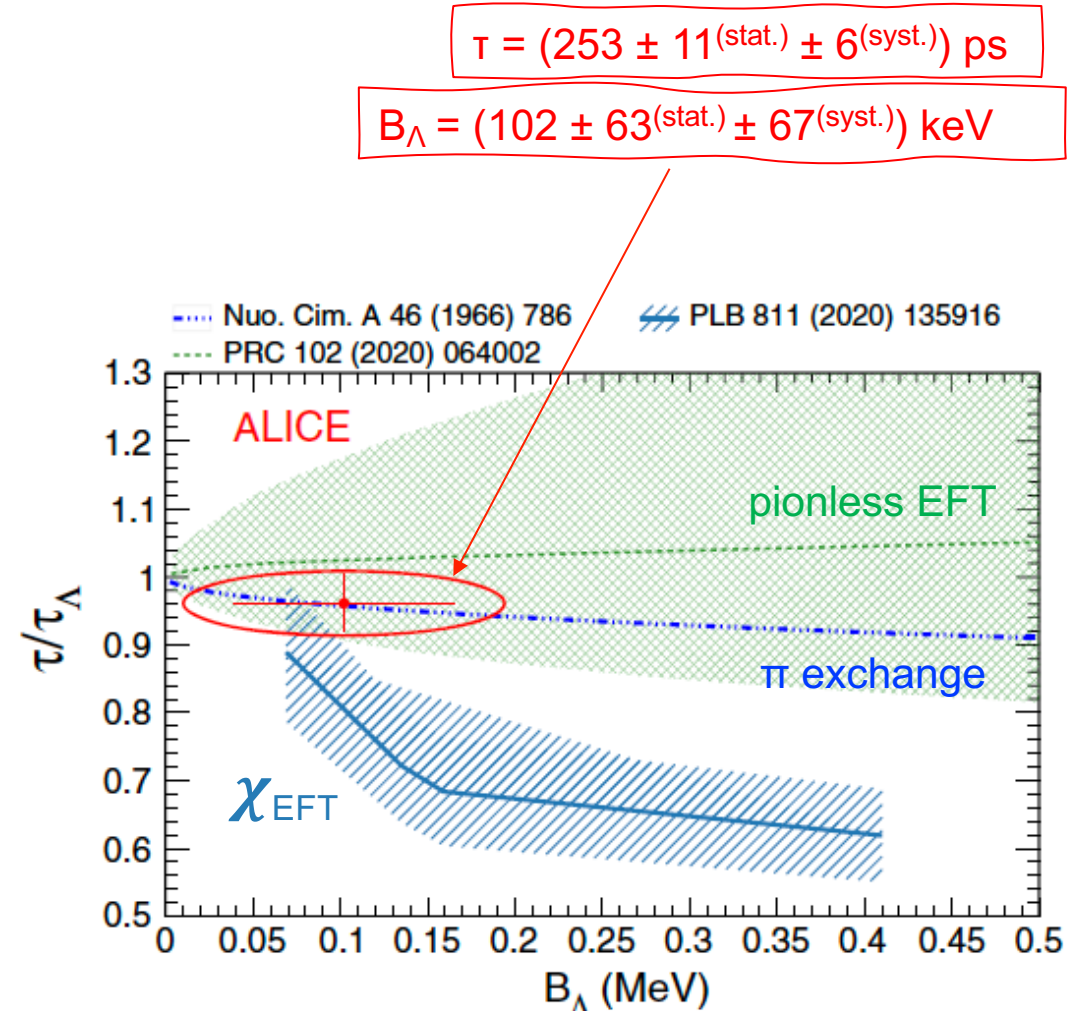
# Lifetime and $\Lambda$ separation energy of $^3_\Lambda\text{H}$

Most precise measurement to date by ALICE indicates that the  $^3_\Lambda\text{H}$  lifetime is compatible with the free  $\Lambda$  lifetime

- No longer an experimental “lifetime puzzle”
- The hypertriton is a weakly bound state



Source: [Mainz database](https://hypo.nuclei.kph.uni-mainz.de)

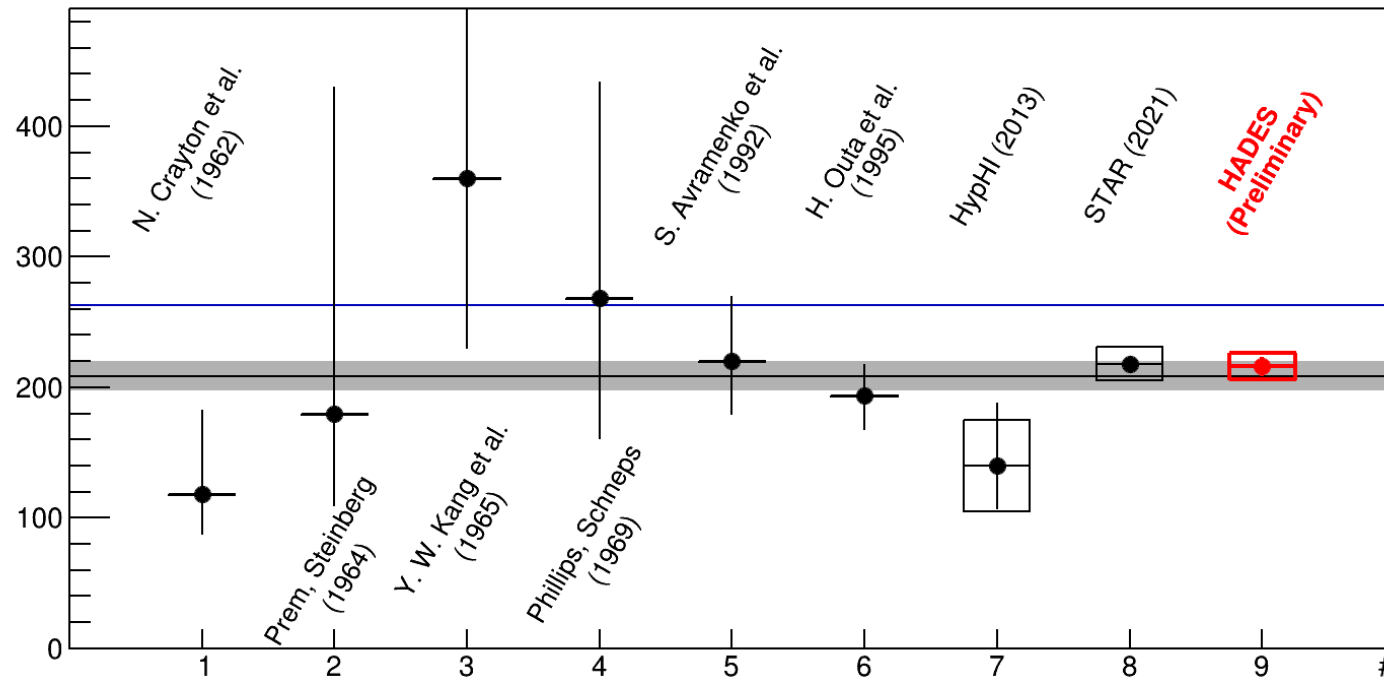


ALICE, PRL 131, 102302 (2023)

# Lifetime and $\Lambda$ separation energy of $^4_\Lambda\text{H}$

Latest precision measurement by HADES in Pb-Pb  $\rightarrow$   $A=4$  also entering precision era!

$$\tau = (216 \pm 7^{(\text{stat.})} \pm 10^{(\text{syst.})}) \text{ ps}$$



S. Spies, Mon. 4/9

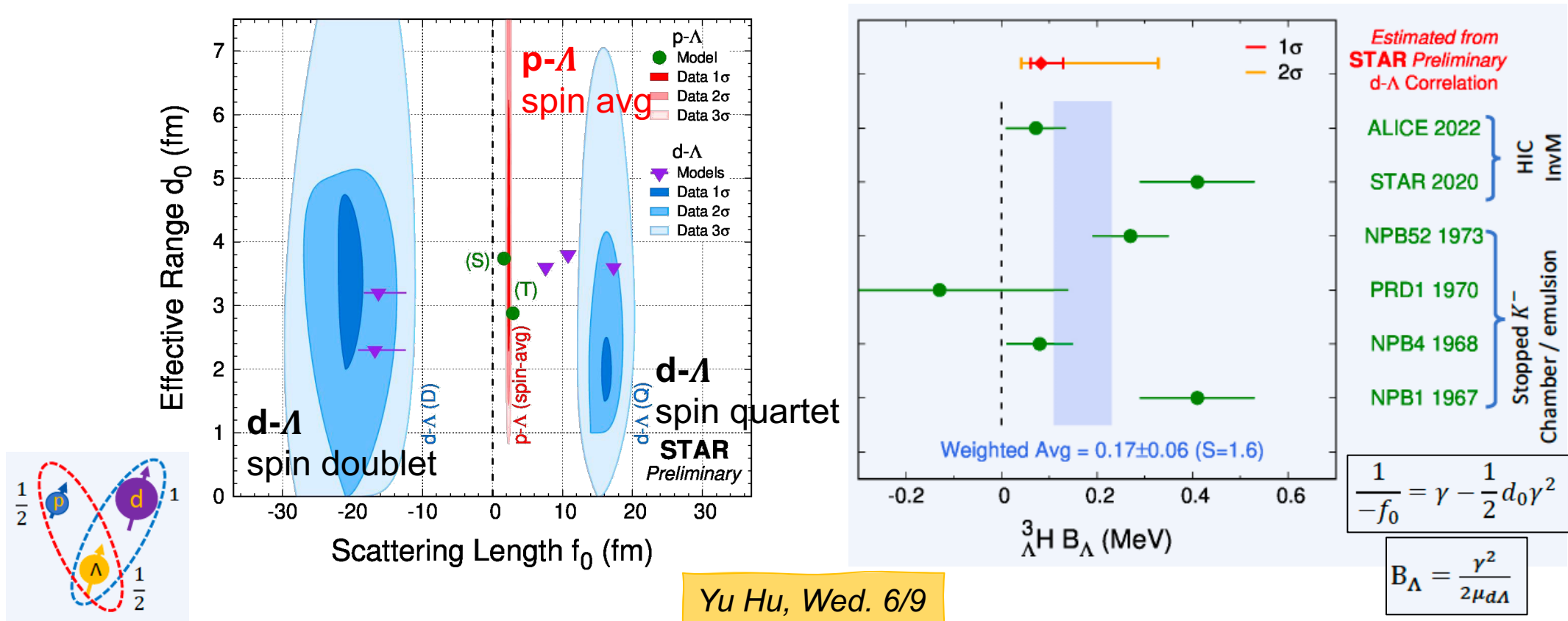
Blue line: free  $\Lambda$  lifetime

Black line: world average including HADES

# ${}^3_{\Lambda}\text{H}$ binding energy from d- $\Lambda$ femtoscopy

**First d- $\Lambda$  correlation measurements in heavy-ion collisions (low energy)**

→ Allowed for the extraction of  $\Lambda$  binding energy of hypertriton (consistent with world data)



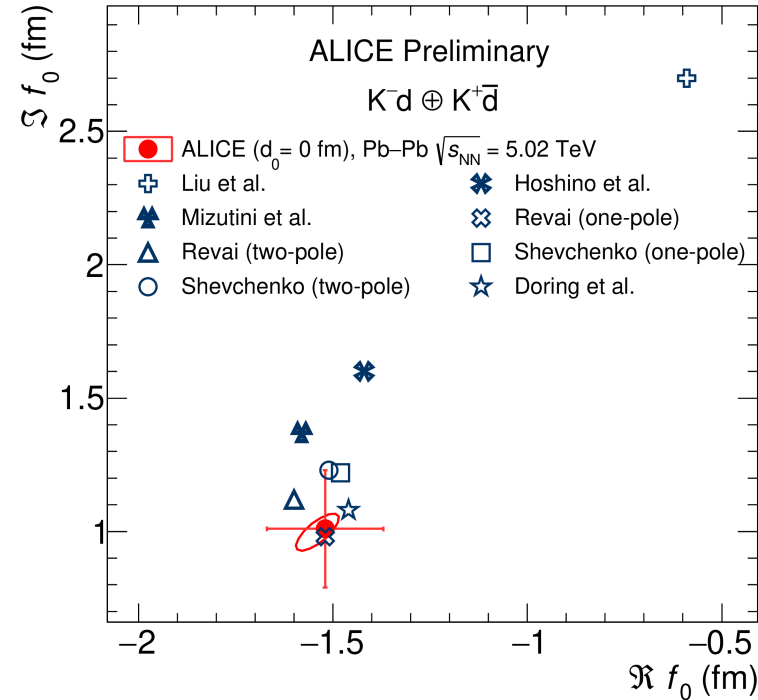
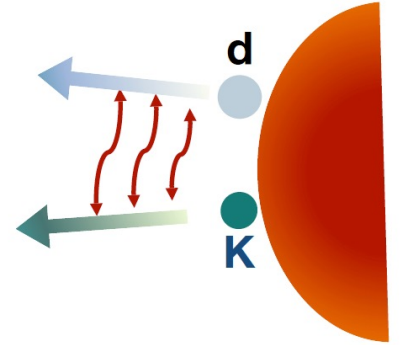
Yu Hu, Wed. 6/9

# Deuteron scattering and source from femtoscopy

**First** ever measurement of  $K^\pm$ -d scattering parameters

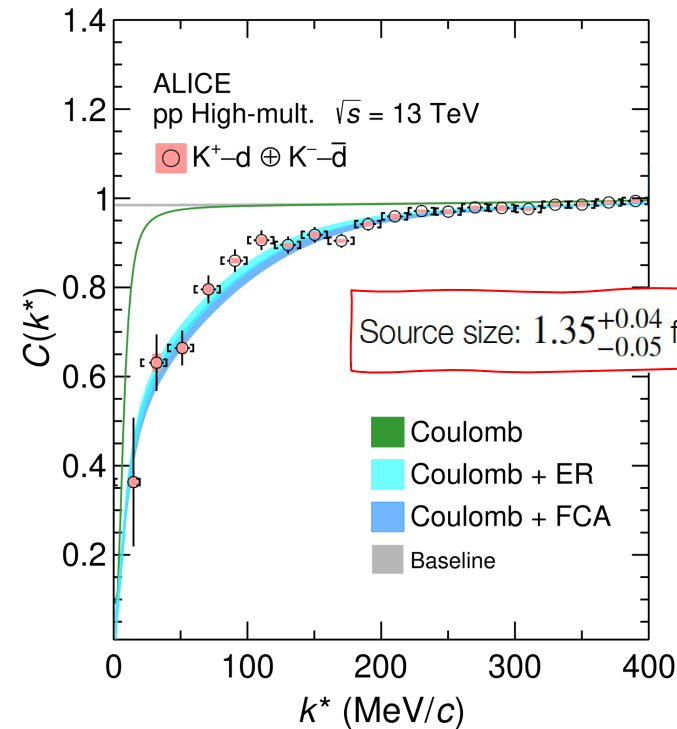
→ d are emitted at small distances within the source, as other hadrons

→ K-d interaction in pp is an effective 2-body interaction

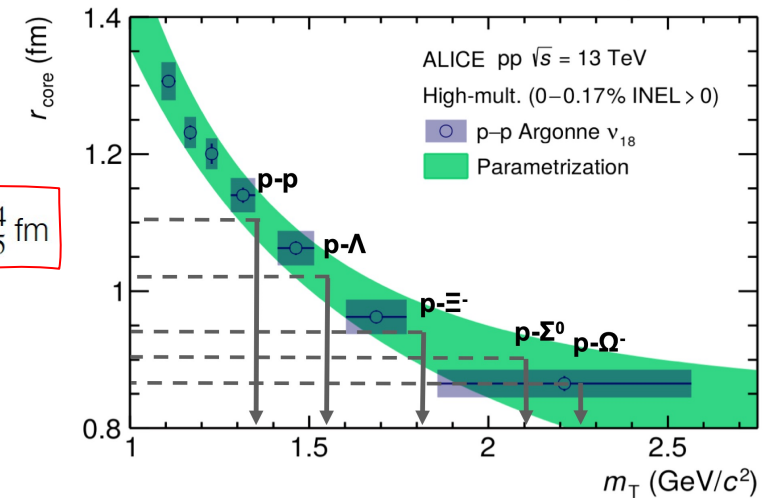


ALI-PREL-550469

W. Resa, poster



B. Singh, wed 6/9

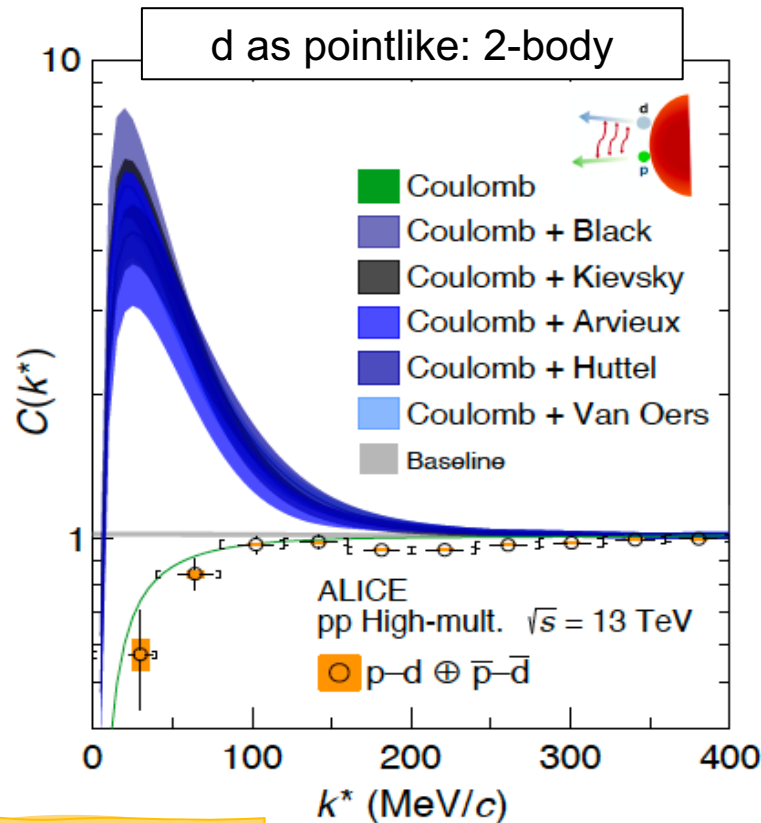
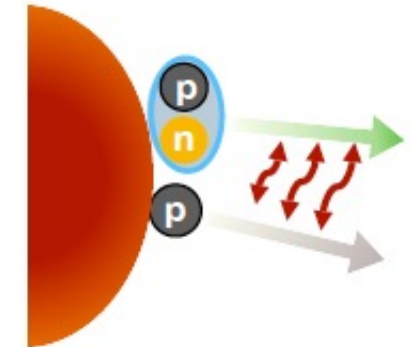


ALICE, PLB 811, 135849 (2020)

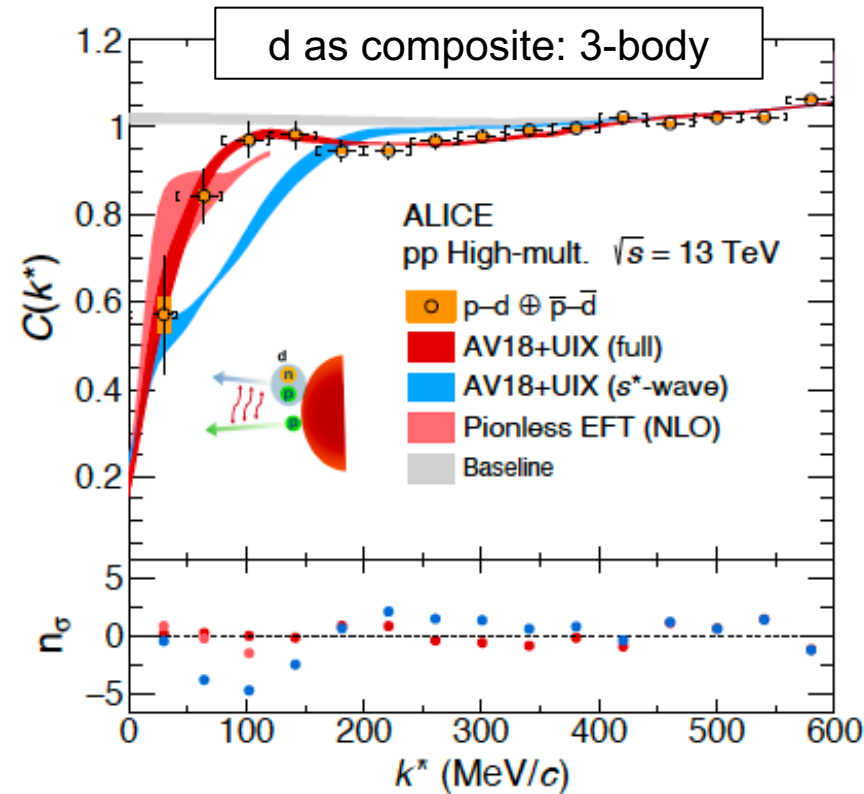
# p-d as a three-body system

The p-d correlations is reproduced by treating the deuteron as a composite particle

→ **access to the genuine three-body interaction**



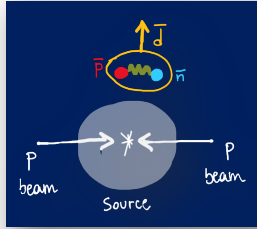
B. Singh, Wed. 6/9



O. V. Doce, poster

ALICE, arXiv:2308.16120v1, Theory: M. Viviani, et al., arXiv:2306.02478

# Closing remarks (a personal view)



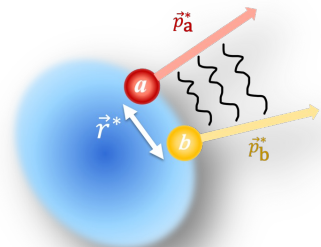
Production mechanisms: thermal/coalescence/transport

→ shift focus: they differ give similar results

New observables, more differential, more species, y-dependence

→ constraining power for models

→ wishlist: production in jet, forward-y, precision on  $A = 3$ ,  $A=4$



Hypertriton lifetime measured precisely

→  $\Lambda$  is weakly bound, closing the experimental puzzle

→ wishlist: precision on binding energy, branching ratio,  $A=4$

Femtoscscopy studies: a whole new chapter opened

→ formation from interaction potential

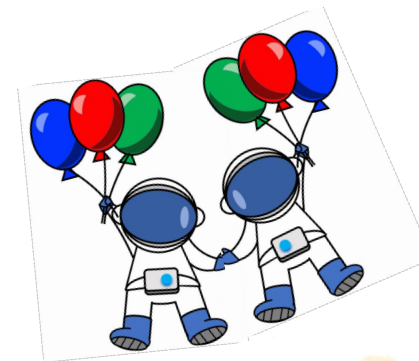
→ wishlist: 3-body femtoscopy, femtoscopy with light nuclei



Unique opportunity to contribute to neighbouring fields

→ nuclear astrophysics: neutron stars EoS

→ astroparticle: searches for cosmic antinuclei



# Thank you!

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CosmicAntiNuclei



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