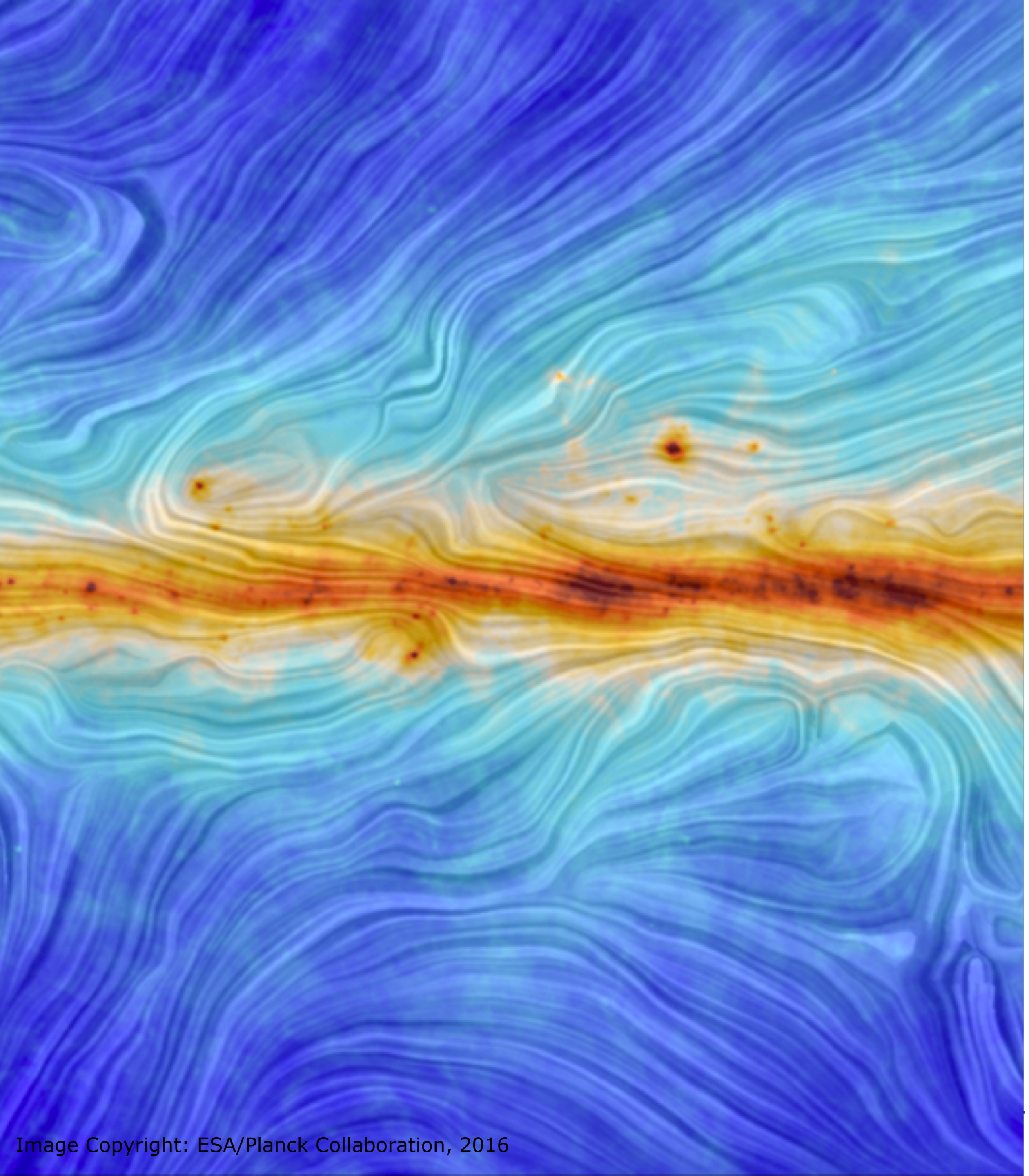


ANTIMATTER MEASUREMENTS AT THE LHC AND IMPLICATIONS FOR INDIRECT DARK MATTER SEARCHES

F. Bellini *(CERN, Switzerland)*

57th International Winter Meeting on Nuclear Physics

Bormio, 22nd January 2019

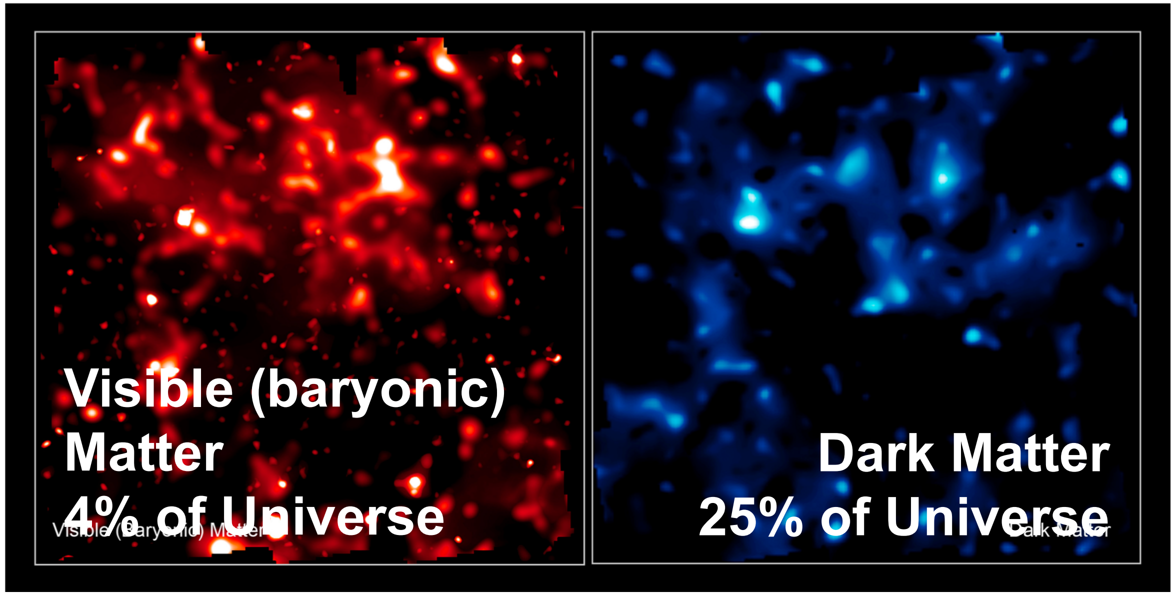
Outline

- Anti-matter from dark matter annihilation
- Background from secondary cosmic ray
- LHC as anti-matter factory
- Results from the LHC with impact for indirect searches
    1. **anti-proton cross section from p-He collisions in LHCb fixed target**
    2. **anti-deuteron and anti-^{3}He in pp collisions with ALICE**
- Outlook

Disclaimer: not possible to have a comprehensive list of models and calculations, but a personal selection.

Searching for dark matter WIMPs

One hypothesis is that DM is constituted by **WIMPs (χ) = weakly interacting massive particles** that are thermal relics of the early Universe.



Copyright: Hubble/COSMOS

Direct searches look for elastic scattering of a WIMP on nuclei in the detector, production at colliders *[→ G. Landsberg, 21/01]*

Indirect searches look for signals from **$\chi\chi$ pair annihilation** or **χ decay into standard model particles** in the Galaxy (e.g. in the Galactic halo).

Focus on: indirect searches for anti-matter in cosmic rays (CR)
→ Look for anti-deuterium and anti-^{3}He because of low secondary CR background

Signal = anti-nuclei from Dark Matter source (1)

1. Anti-p and anti-n are produced by **WIMP annihilation into SM channels**
2. Anti-deuterons and anti-^{3}He produced via **coalescence** of anti-nucleons

Modeling of the DM source depends on the details of the particle physics model and the DM density in a given point of the Galaxy

$$q_{\mathrm{DM}}(E_{\bar{D}}, \vec{x}) = \frac{1}{2}\left(\frac{\rho(\vec{x})}{m_{\mathrm{DM}}}\right)^2 \langle\sigma v\rangle_{b\bar{b}} \frac{dN_{\bar{D}}^{b\bar{b}}}{dE_{\bar{D}}}$$

[M. Korsmeier, F. Donato, N. Fornengo, PRD 97 (2018) 103011]

- thermally-averaged annihilation **cross section** into SM channel, e.g. $\langle\sigma v\rangle_{\chi\chi\rightarrow \mathrm{bbar}} \sim 3 \times 10^{-26}$ cm^3/s
- **DM mass**, e.g. $30 < m_{\mathrm{DM}} < 100$ GeV
- energy spectrum of the products

[M. Tanabashi et al. (PDG), PRD 98 (2018) 030001]

- DM density in the vicinity of the solar system, $\rho^{\mathrm{local}}_{\mathrm{DM}} \sim 0.4$ GeV/cm^3

Signal = anti-nuclei from Dark Matter source (2)

1. Anti-p and anti-n are produced by **WIMP annihilation into SM channels**
2. Anti-deuterons and anti-^{3}He produced via **coalescence** of anti-nucleons

Anti-nucleons coalesce into anti-nuclei if they are close in phase-space, a condition which is encoded in the coalescence probability B_A

$$E_A \frac{dN_A}{d^3P_A} = B_A \left(E_p \frac{dN_p}{d^3P_p} \right)^Z \left(E_n \frac{dN_n}{d^3P_n} \right) \Bigg|^N_{P_p = P_n = P_A/A}$$

related to

[M. Korsmeier, F. Donato, N. Fornengo, PRD 97 (2018) 103011; P. Chardonnet, J. Orloff, P. Salati, PLB 409 (1997) 313; and others…]

- coalescence momentum p_C → tuned to e+e- data *[ALEPH, PLB 639 (2006) 129]*
- **Mass** of the nucleus

[K. Blum et al., PRD 96 (2017) 103021; R. Scheibl, U. Heinz, (1999) PRC 59 (1999) 1585-1602; FB, A. Kalweit, arXiv:1807.05894v2]

- **Size of the nucleus** relative to the **size of the source** (Hanbury-Brown-Twiss interferometry)
- Nucleus **wave-function** (quantum-mechanical approach)

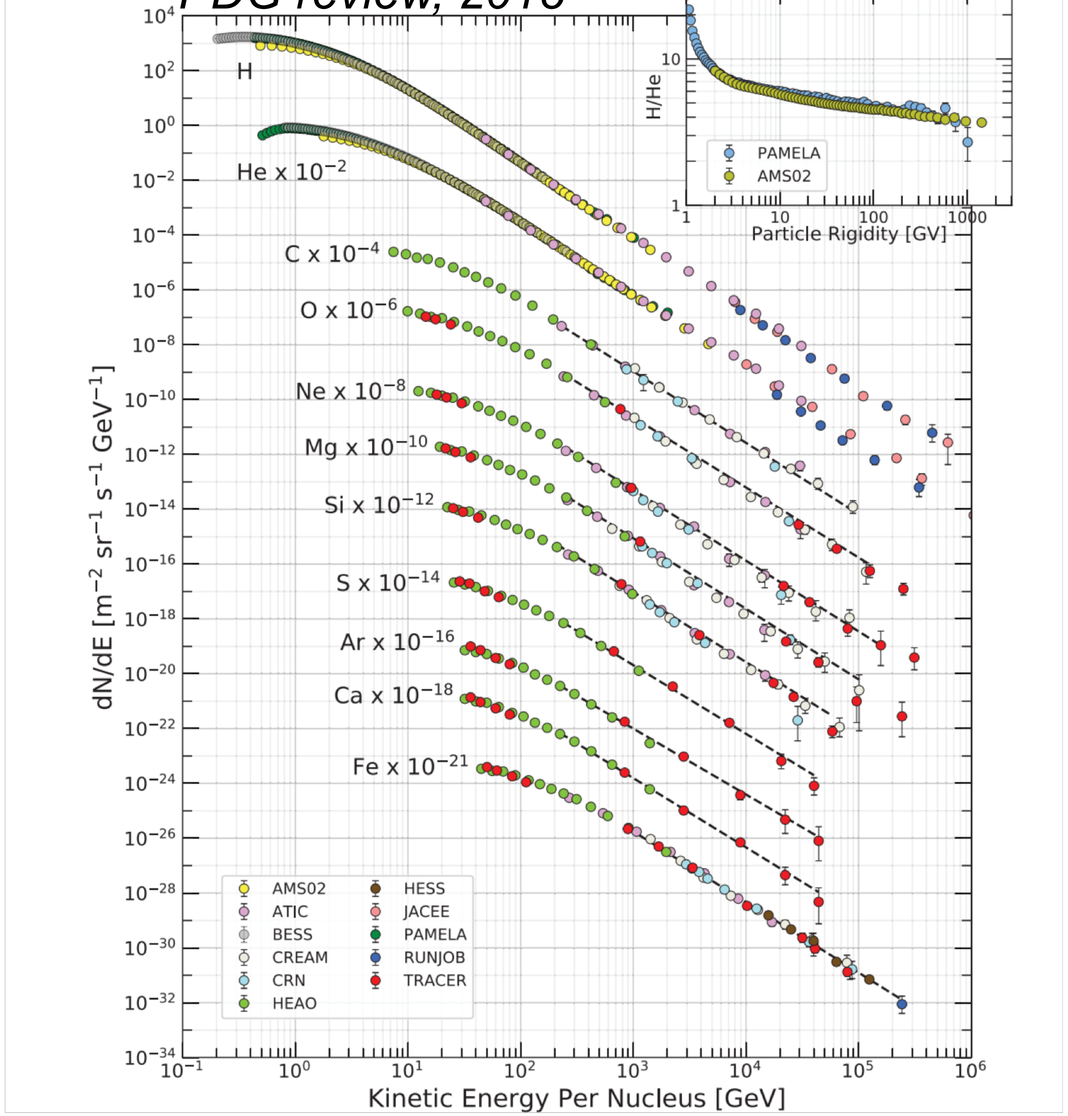
Background = secondary Cosmic Ray source (1)

Largest fractions of primary CR are protons and helium.
There are no anti-nuclei as primary CR.

Secondary anti-p, anti-d, anti-^{3}He produced by interaction of **primary CR with the InterStellar Matter** (pp, p-He, …) constitute a background for the DM signal.

→ the Galaxy as "fixed target experiment"

PDG review, 2018



Background = secondary Cosmic Ray source (2)

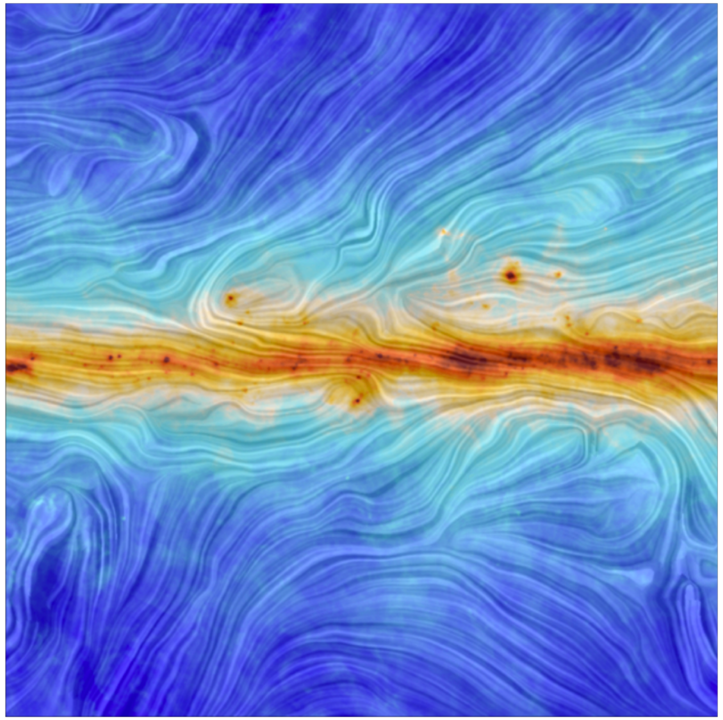
Production of secondary anti-nuclei by **spallation** reactions of primary CR with ISM

- Need **cross-sections** for anti-p production in pp, p-He, p-A
- **Threshold** for anti-nuclei production
  - to produce anti-d by pp in c.m. $\sqrt{s} \geq 6\ m_p$ ⟶ lab frame / Galaxy: $E \geq 17 m_p$
- By **coalescence** mechanism
  - same as the DM signal, but different anti-nucleon distributions
  - coalescence momentum unknown

Flux calculations sensitive to the astrophysical details

→ Introduce model dependency

- Acceleration by Super Novae remnants
- Diffusion in the galactic magnetic field (~μGauss)
- Energy loss / gain (for loosely bound nuclei, break-up dominates)
- Solar modulations (matter mostly at low *E*, where DM signal prominent)



Background = secondary Cosmic Ray source (2)

Production of secondary anti-nuclei by **spallation** reactions of primary CR with ISM

- Need **cross-sections** for anti-p pr… p-He, p-A

MEASURE AT LHC

- **Threshold** for anti-nuclei production
  - to produce anti-d by pp in c.m. $\sqrt{s} \geq 6\, m_p \longrightarrow$ lab frame / Galaxy: $E \geq 17 m_p$
- By **coalescence** mechanism
  - same as the DM signal, but differen… distributions
  - coalescence momentum unknown

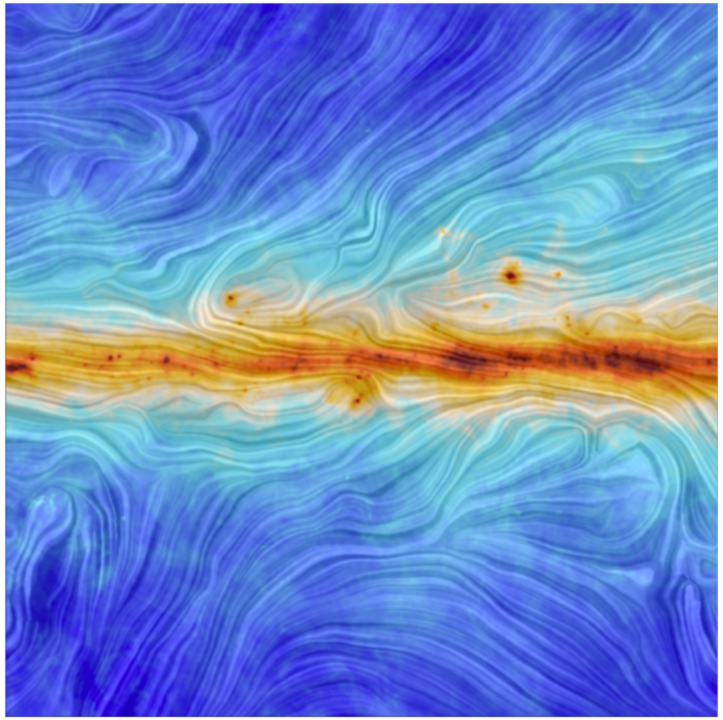
TUNE ON LHC DATA

Flux calculations sensitive to the astrophysical details

→ Introduce model dependency

- Acceleration by Super Novae remnants
- Diffusion in the galactic magneti… (~μGauss)
- Energy loss / gain (for loosely bound nuclei, …)
- Solar modulations (matter mostly at low E, where DM signal pro…inent)

TUNE ON ASTRO DATA



Copyright: ESA/Planck Collaboration, 2016

Antiproton production in p-He with LHCb

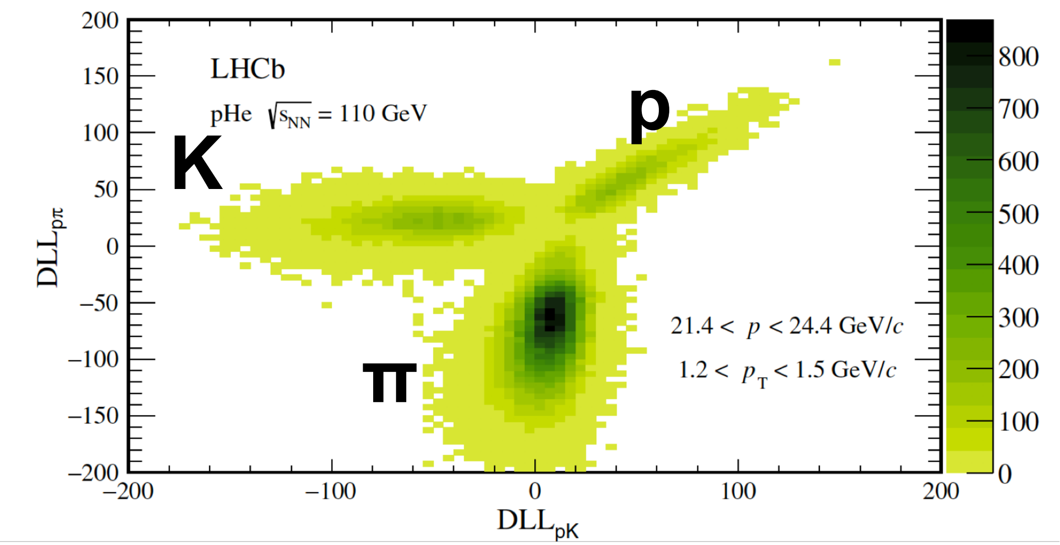
p-He collisions in **fixed target mode with SMOG**

[JINST 9 (2014) P12005, → G. Manca, 24/01]

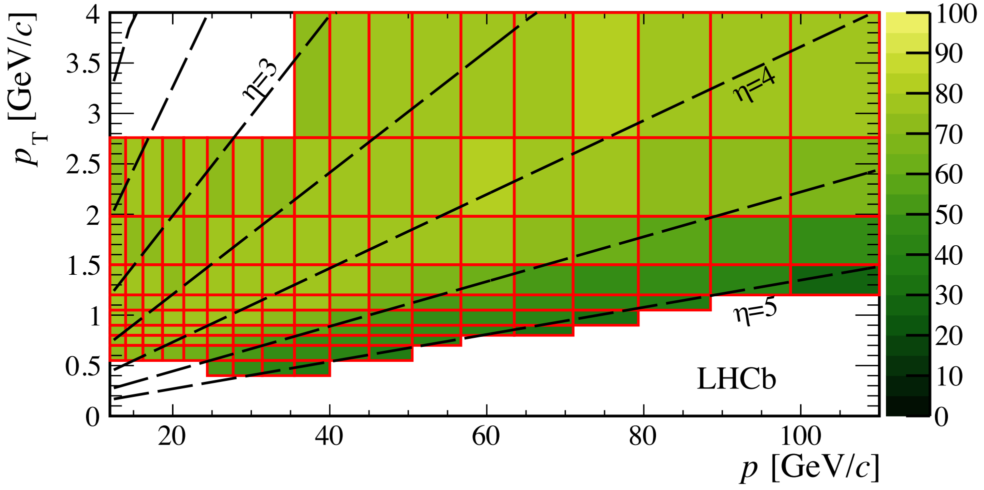
E_{beam} = 6.5 TeV, $\sqrt{s_{NN}}$ **= 110 GeV**

Analysis details:

- 33M reconstructed p-He collisions
- in p-N frame, $-2.8 < y^* < 0.2$
- PID with RICH I ($12 < p < 60$ GeV/c) and RICH II ($30 < p < 110$ GeV/c)
- Momentum resolution better than 1% for $p < 110$ GeV/c
- Dominated by systematic uncertainty, < 10%



LHCb, PRL 121, 222001 (2018)



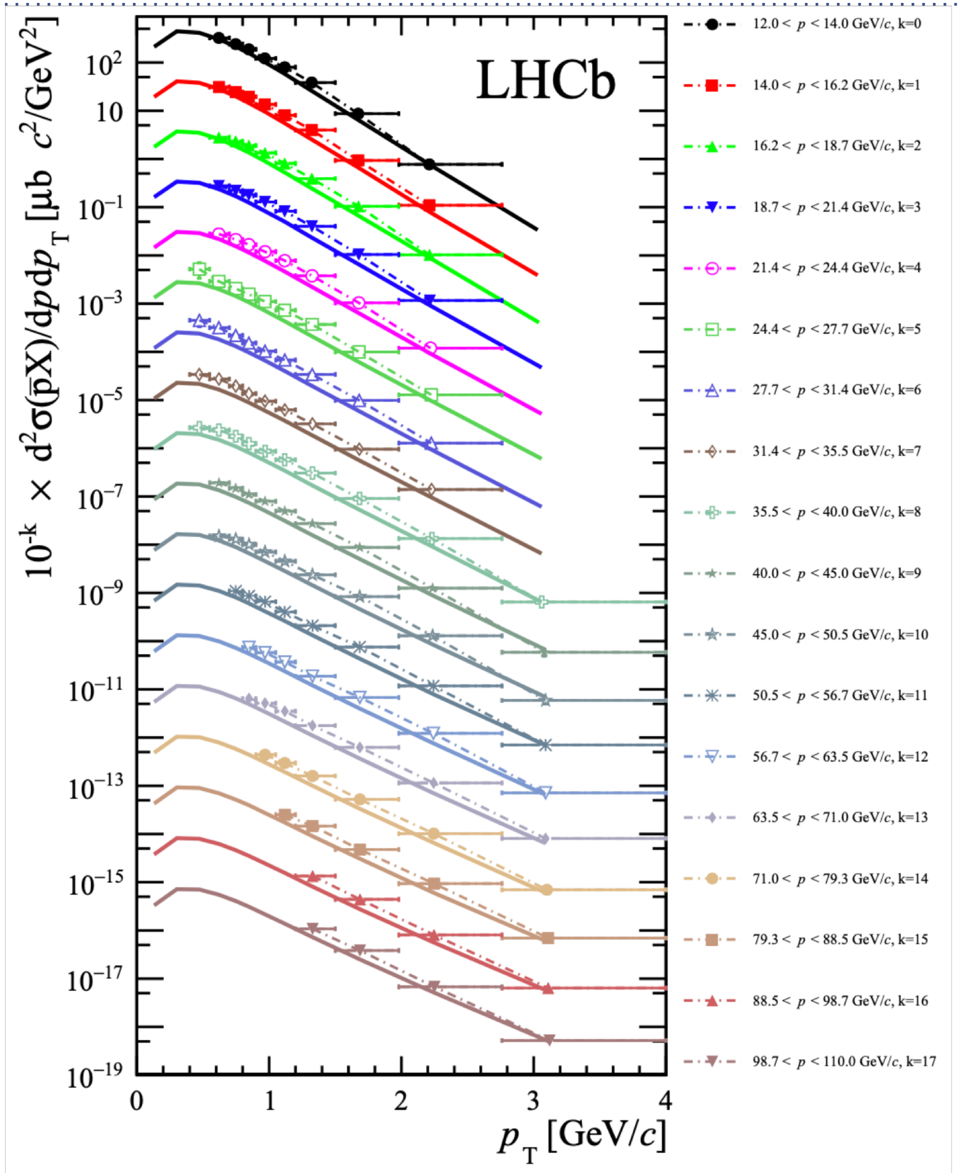
Antiproton production in p-He with LHCb

p-He collisions in **fixed target mode with SMOG**
[JINST 9 (2014) P12005, → G. Manca, 24/01]
E_{beam} = 6.5 TeV, $\sqrt{s_{NN}}$ **= 110 GeV**

Analysis details:

- 33M reconstructed p-He collisions
- in p-N frame, $-2.8 < y^* < 0.2$
- PID with RICH I ($12 < p < 60$ GeV/c) and RICH II ($30 < p < 110$ GeV/c)
- Momentum resolution better than 1% for $p < 110$ GeV/c
- Dominated by systematic uncertainty, < 10%

Precise multi-differential measurement of the antiproton cross-section

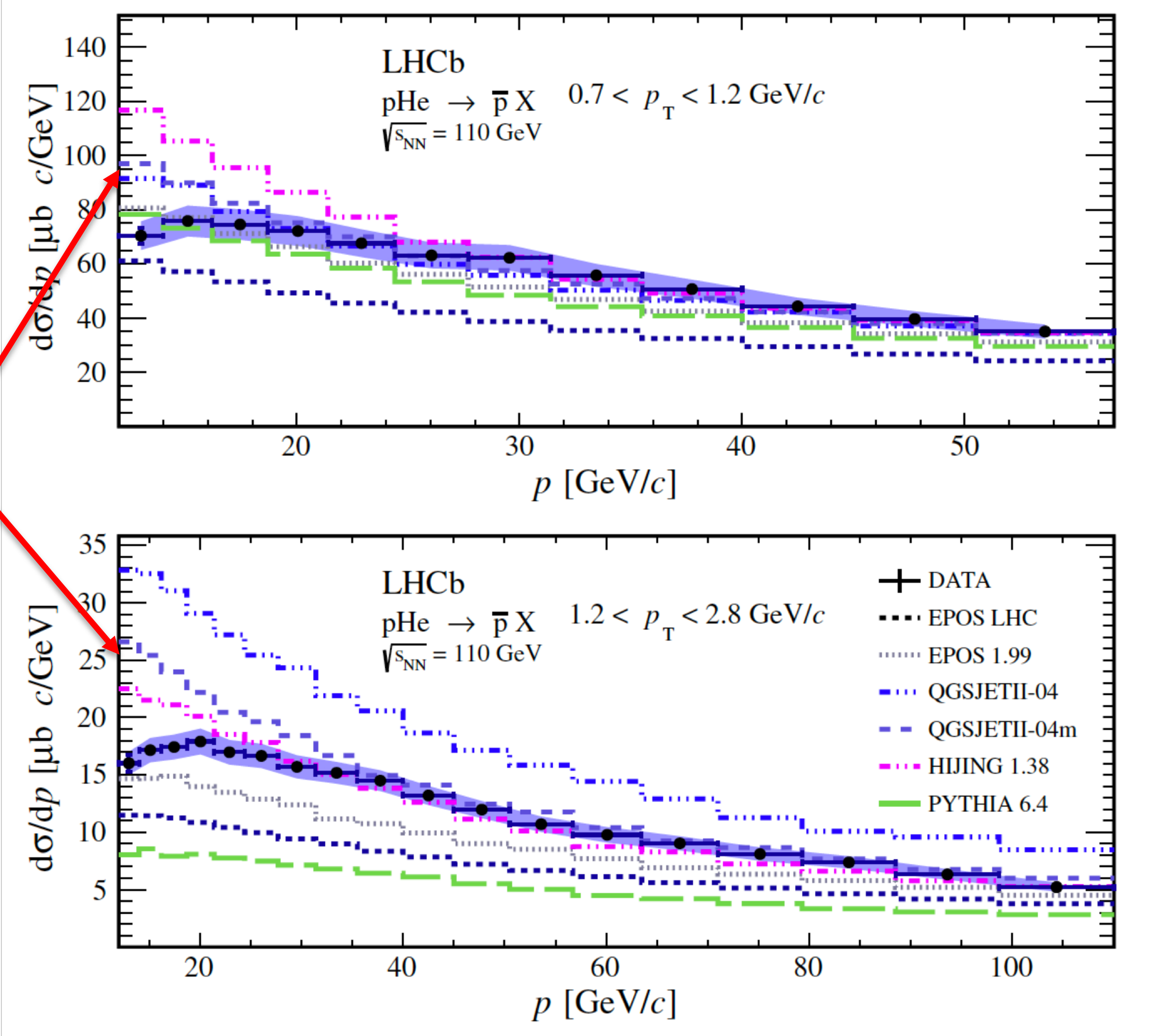


Antiproton production in p-He with LHCb

p-He collisions in **fixed target mode with SMOG**
[JINST 9 (2014) P12005, → G. Manca, 24/01]
E_{beam} = 6.5 TeV, $\sqrt{s_{NN}}$ = **110 GeV**

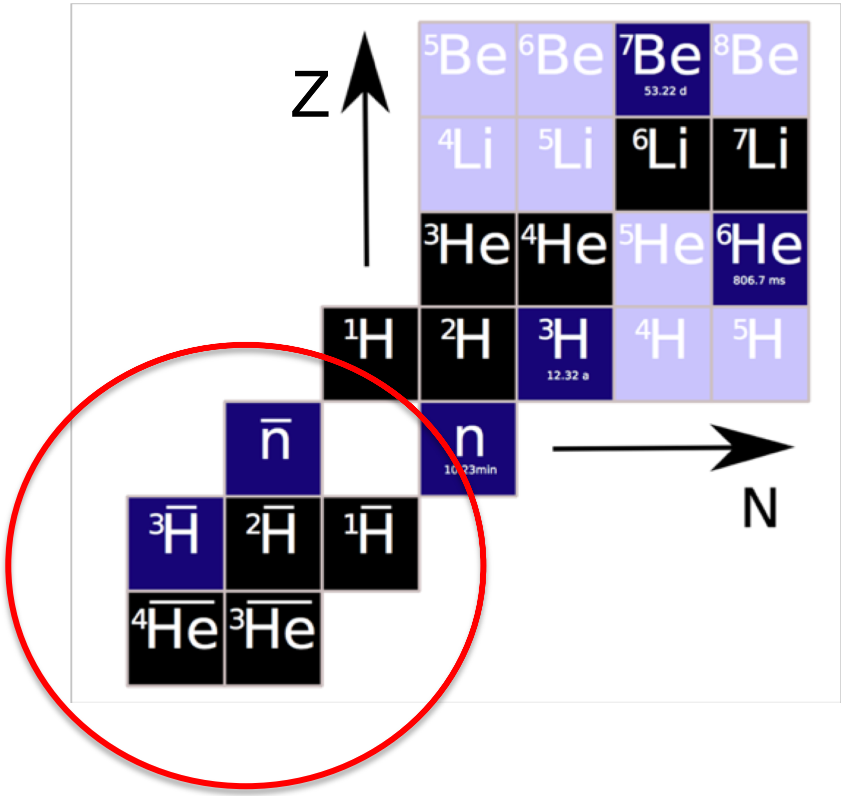
Data compared to hadronization models, including low-energy extension of QGSJETII-04 (**m**) motivated by CR anti-protons

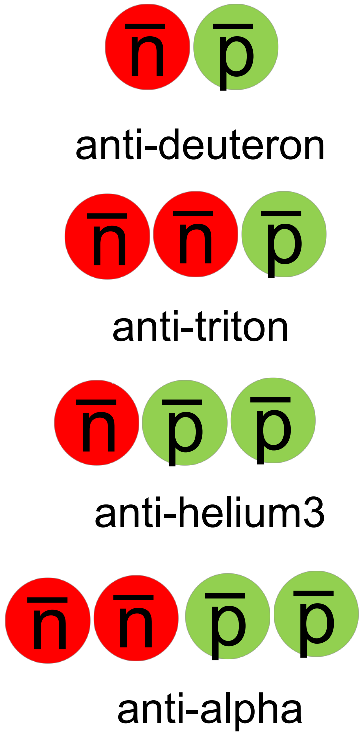
- Unsatisfactory descriptions at low *p*
- Yield differences up to 2x

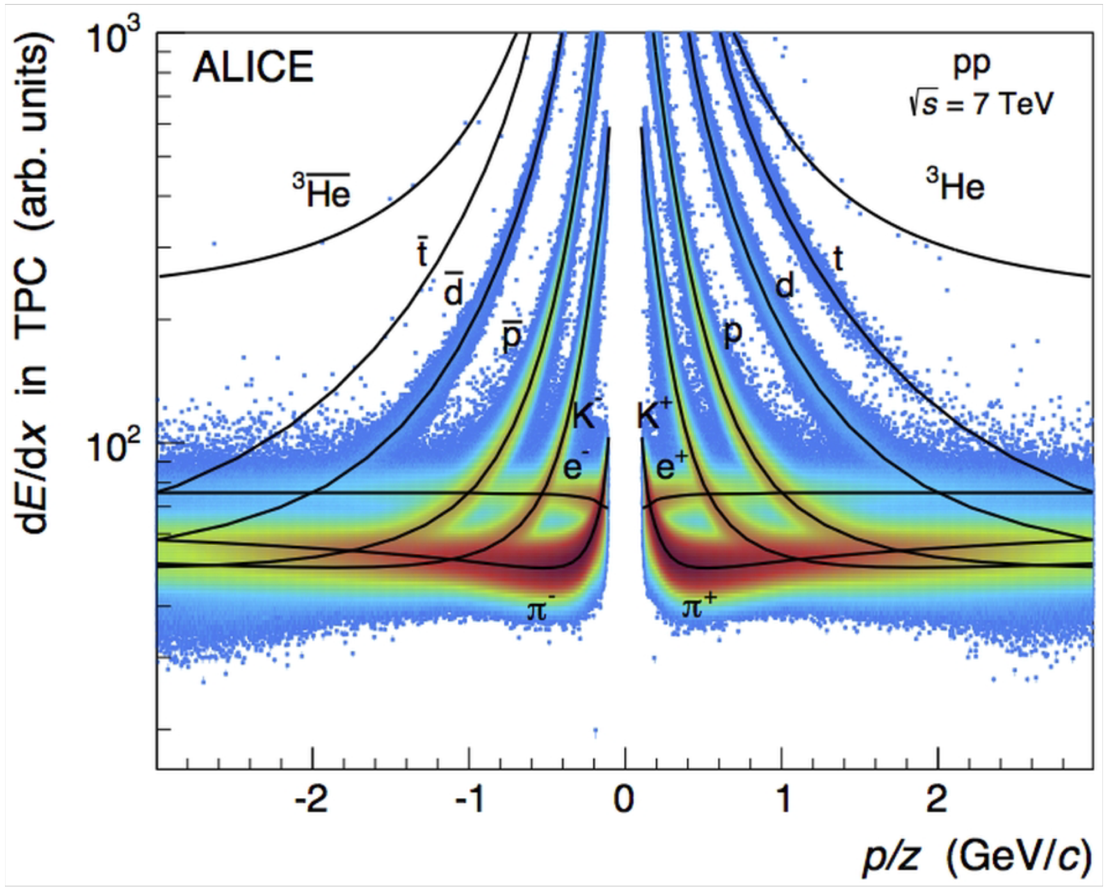


LHCb, PRL 121, 222001 (2018)

Light (anti-)nuclei production with ALICE

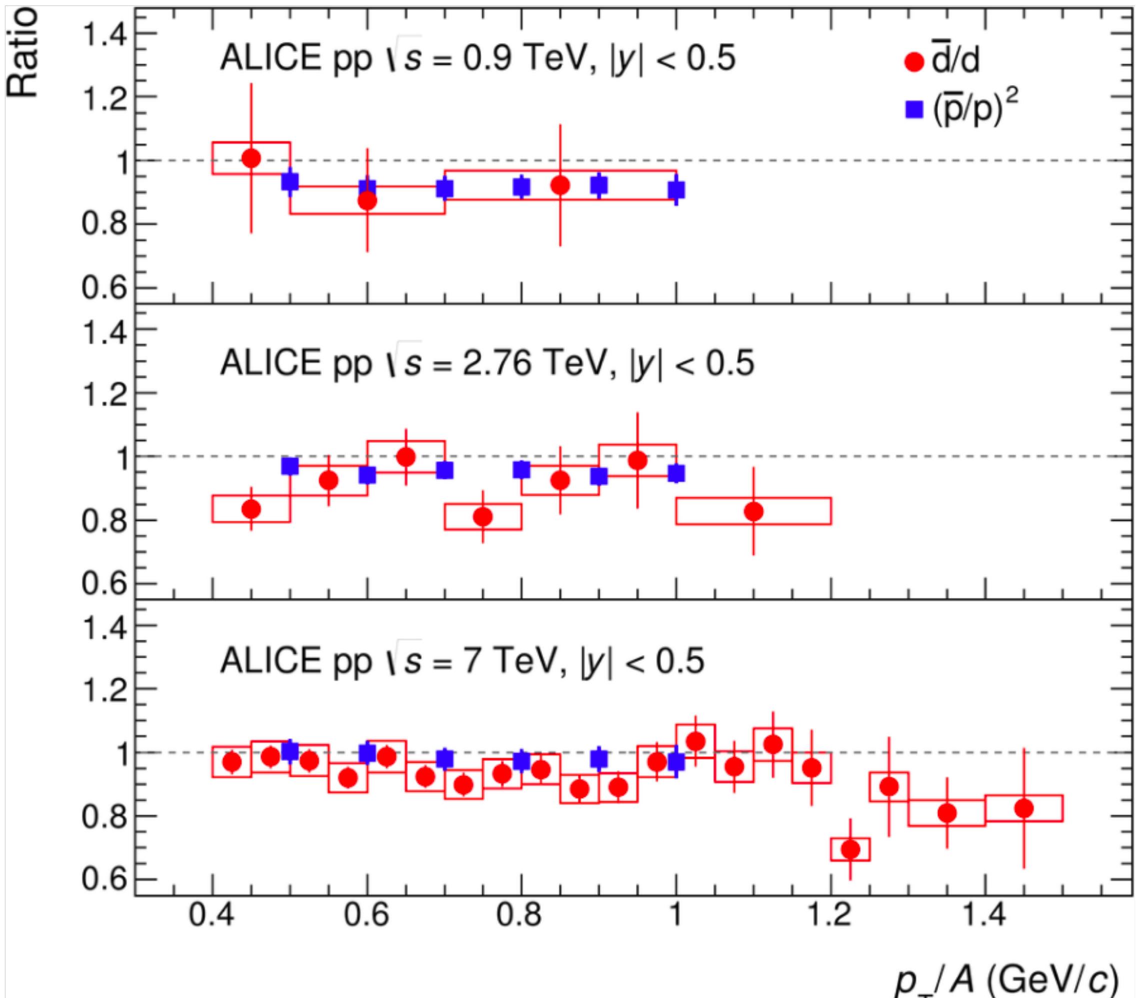






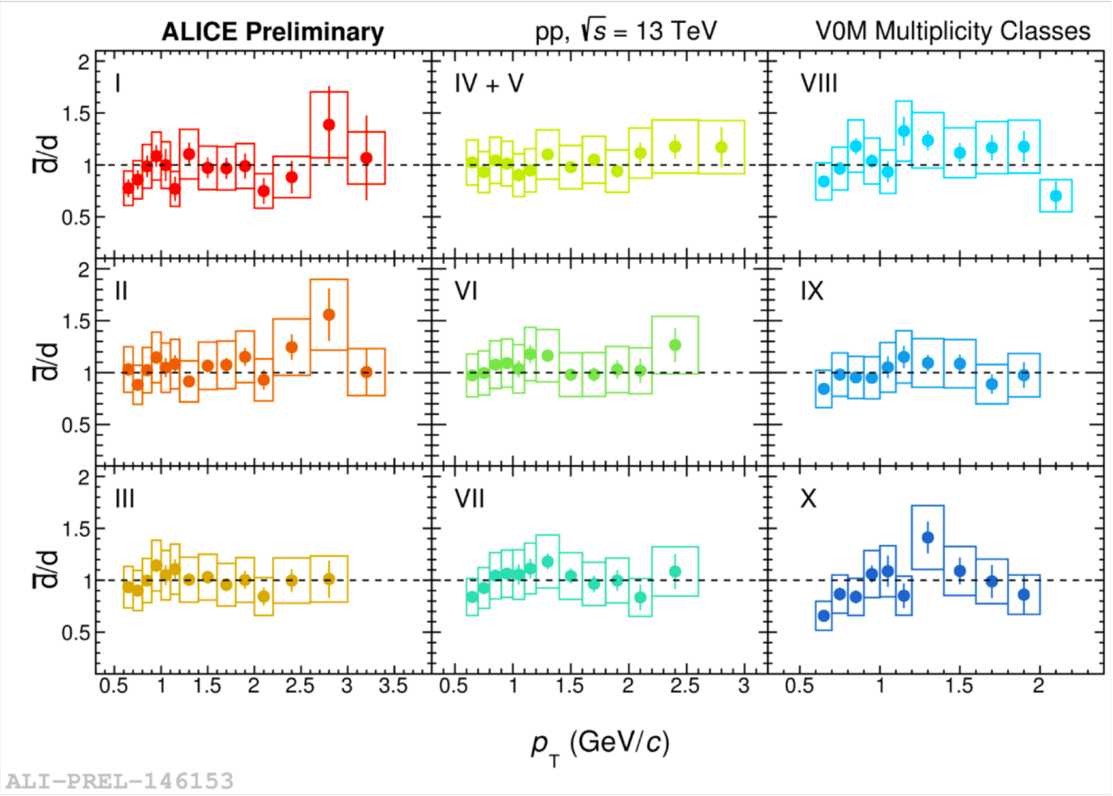
Anti-nuclei up to A = 4 are currently in reach at accelerators.
The anti-alpha is the heaviest observed so far and was first seen by the STAR experiment in 2011, and recently measured by ALICE at the LHC in Pb-Pb collisions (2018).

LHC as "anti-matter factory"



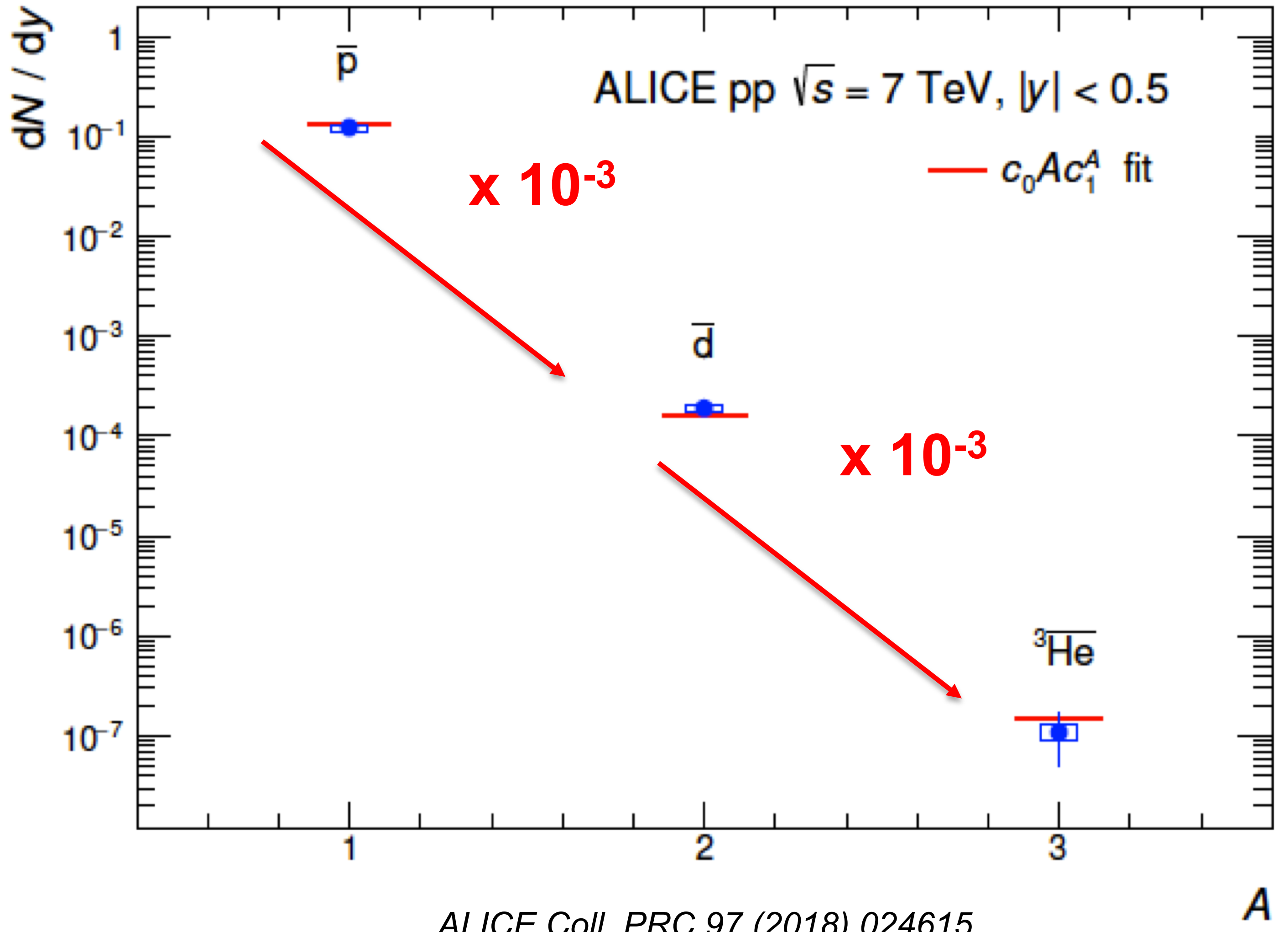
ALICE, PRC 97 (2018) 024615

Anti-matter / matter ~ 1 at the LHC
Independently of p_T and multiplicity



ALICE, paper in preparation – talk of M. Colocci, QM 2018

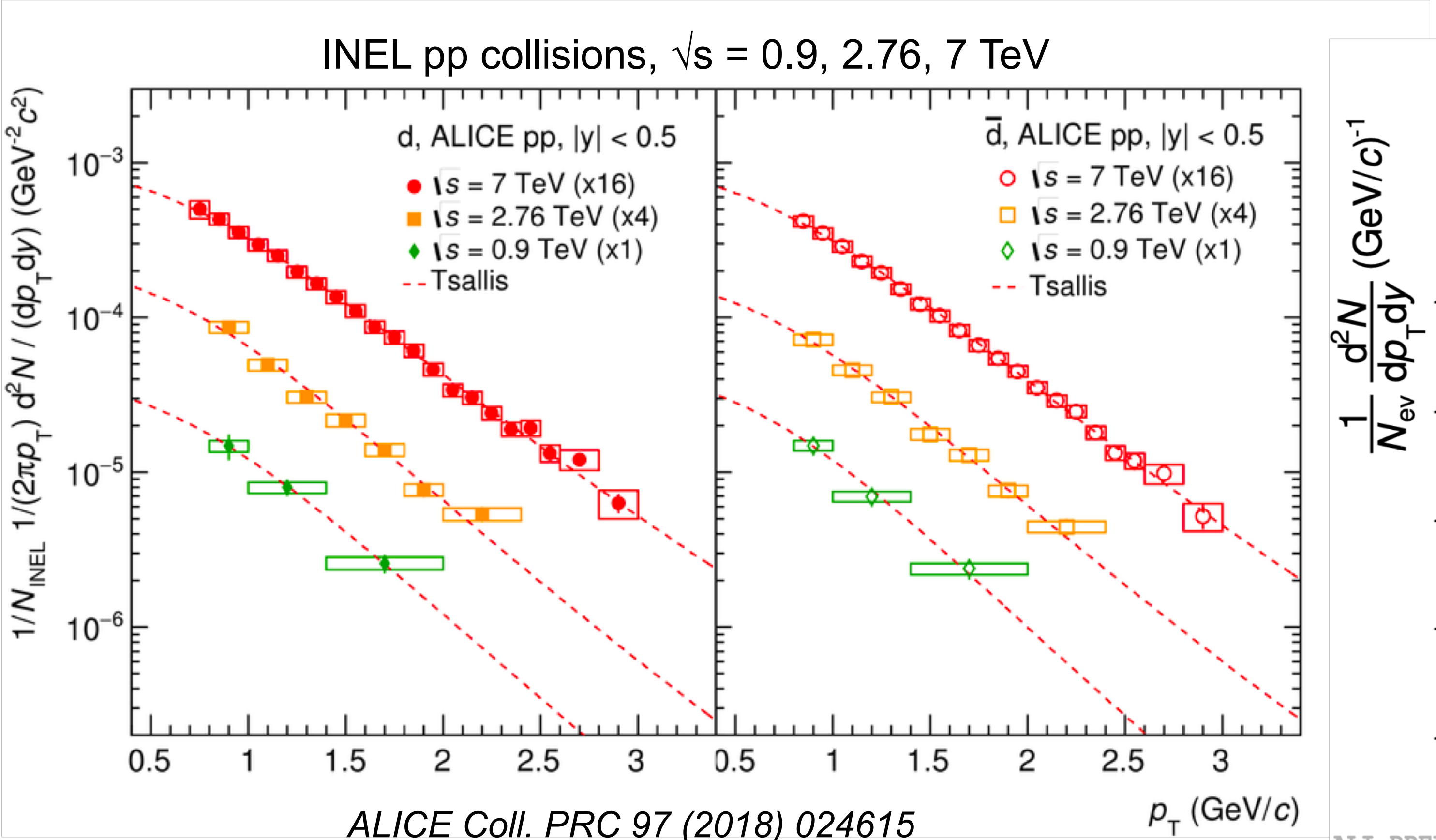
Anti-nuclei production in pp at the LHC

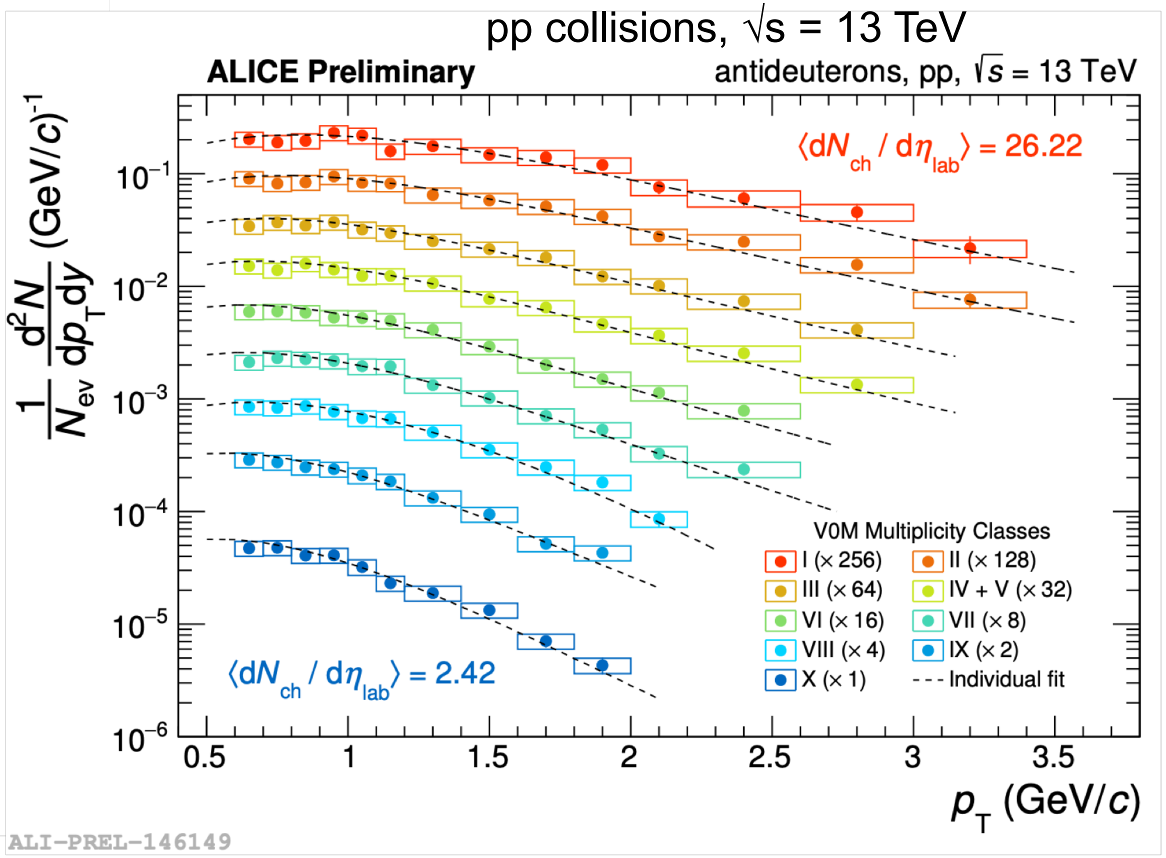


ALICE Coll. PRC 97 (2018) 024615

In pp collisions the "**penalty factor**" for increasing the mass number by adding one nucleon is **~10^3**.

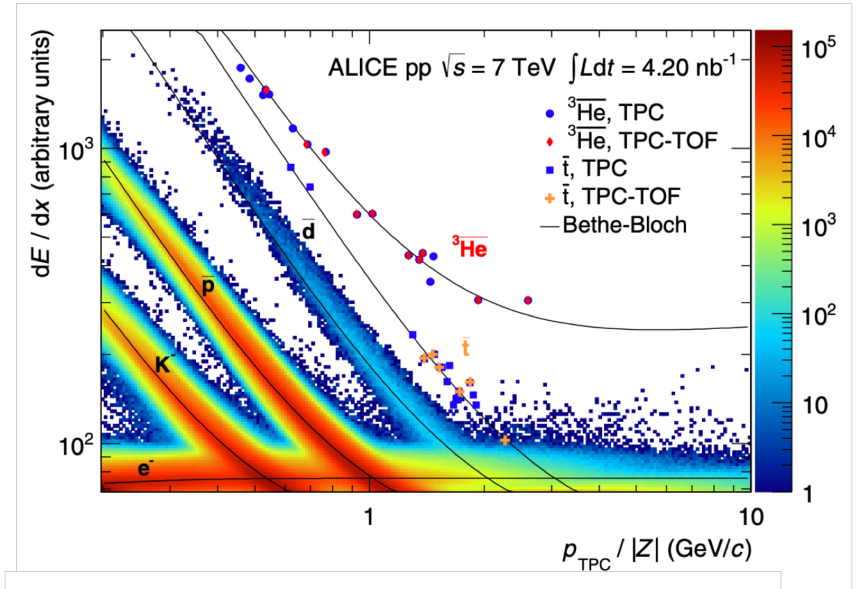
Anti-deuteron

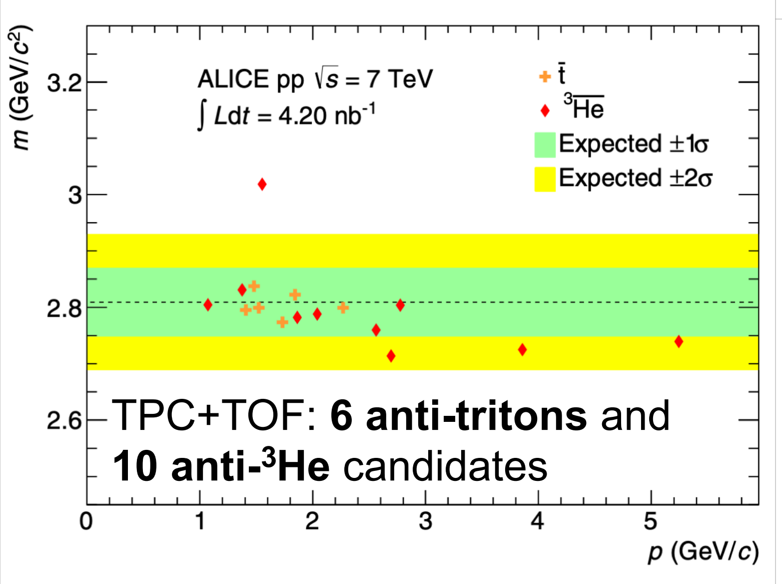




RUN II (2015 sample), pp $\sqrt{s_{NN}}$ = 13 TeV
Multiplicity dependence at 7 TeV → paper in preparation

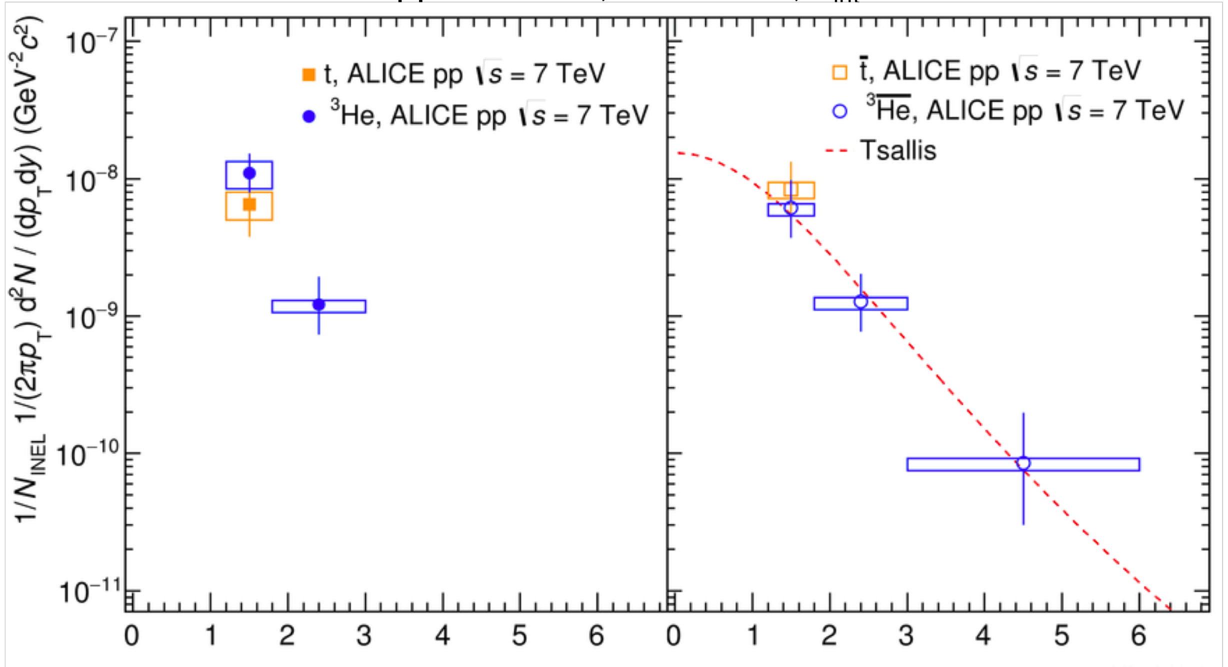
First observation of anti-^{3}He in pp collisions





TPC+TOF: **6 anti-tritons** and **10 anti-^{3}He** candidates

INEL pp collisions, $\sqrt{s}$ = 7 TeV, L_{int} = 4.2 /nb



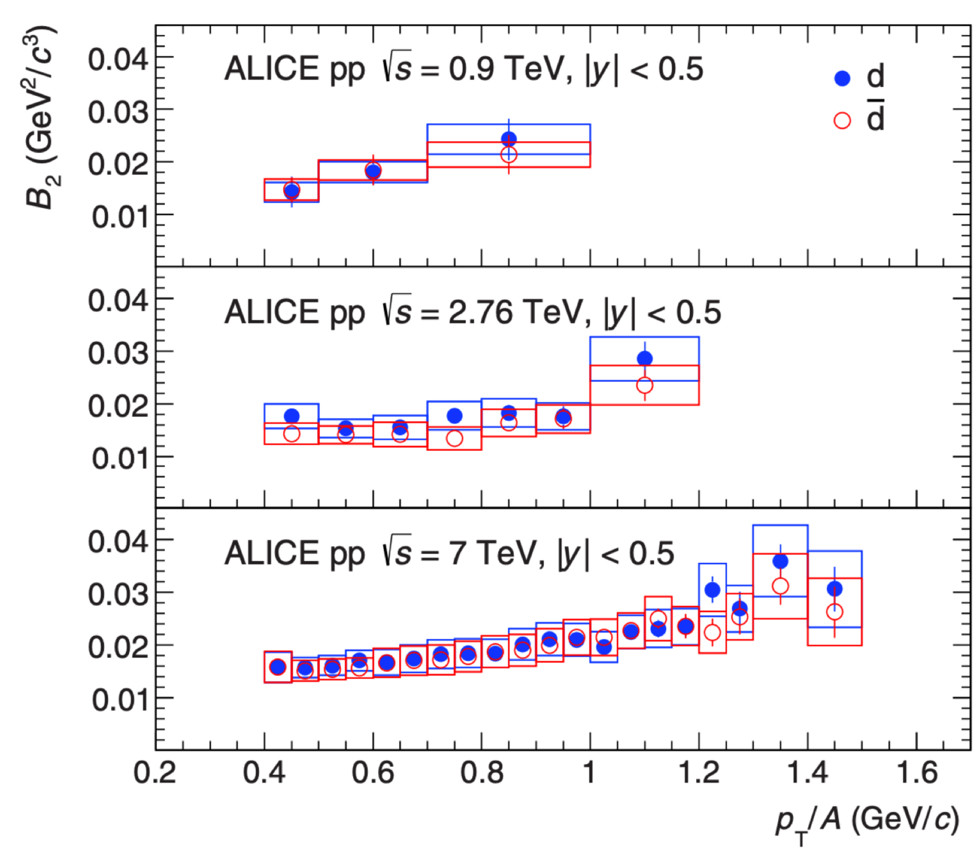
ALICE Coll. PRC 97 (2018) 024615

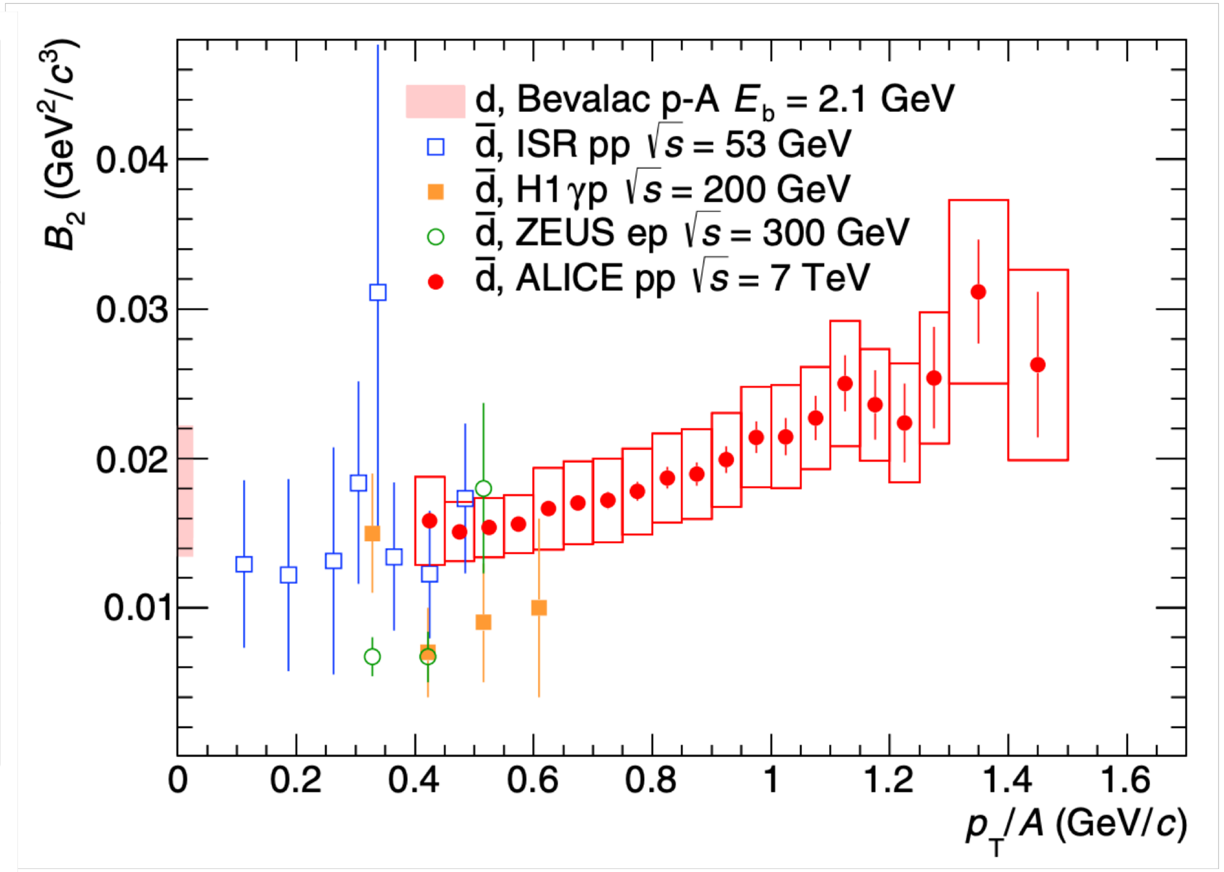
Precision dominated by statistical uncertainty
⟶ analysis being extended to Run II data

Dominating systematic uncertainties: **hadronic interaction cross section in the material** and **feed-down from hypertriton**

Measured coalescence parameter for anti-deuteron

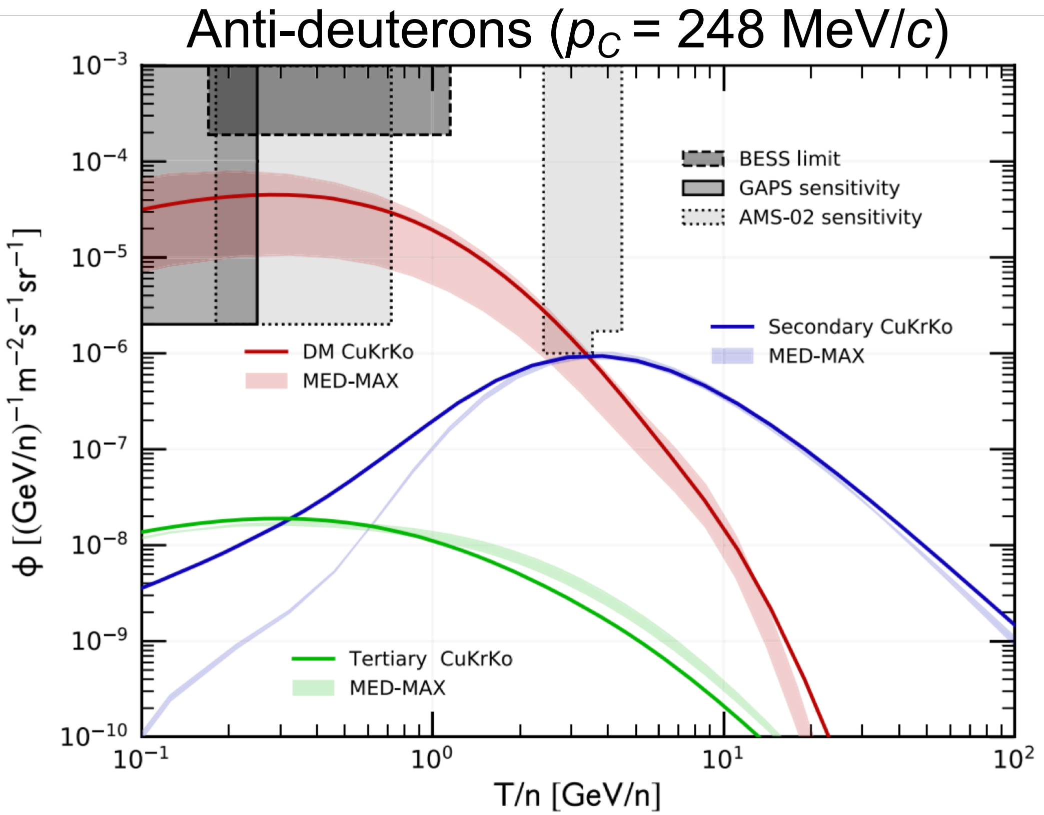
$$E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3} = B_A \left(E_{\mathrm{p,n}} \frac{\mathrm{d}^3 N_{\mathrm{p,n}}}{\mathrm{d}p_{\mathrm{p,n}}^3} \right)^A \Bigg|_{\vec{p}_\mathrm{p}=\vec{p}_\mathrm{n}=\frac{\vec{p}_A}{A}}$$





ALICE Coll. PRC 97 (2018) 024615

Low background for low-energy DM anti-d and anti-^{3}He



M. Korsmeier et al., PRD 97 (2018) 103011

Coalescence momentum p_0 constrained by ALICE measurement of B_2 in pp collisions at 7 TeV

$$0.01 < B_2 < 0.02 \text{ GeV}^2/c^3$$

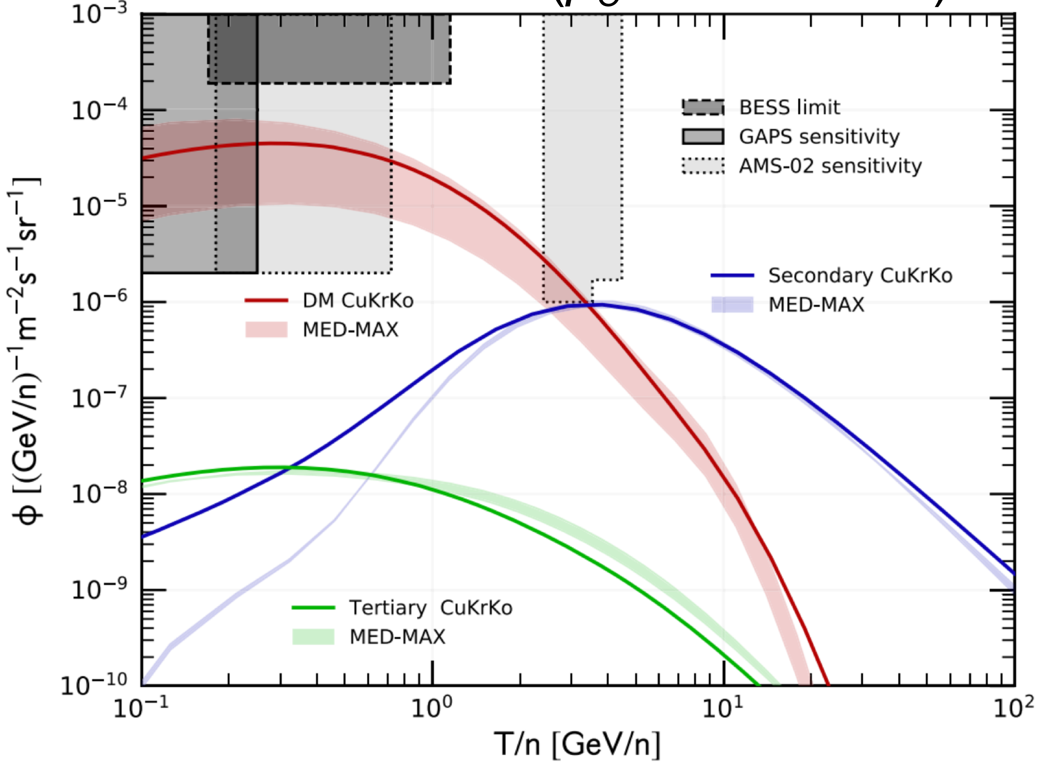
$$B_2 = \frac{m_D}{m_p m_n} \frac{\pi p_C^3}{6}$$

$$208 < p_C < 262 \text{ MeV}/c$$

- Uncertainties due to the modeling of the CR propagation

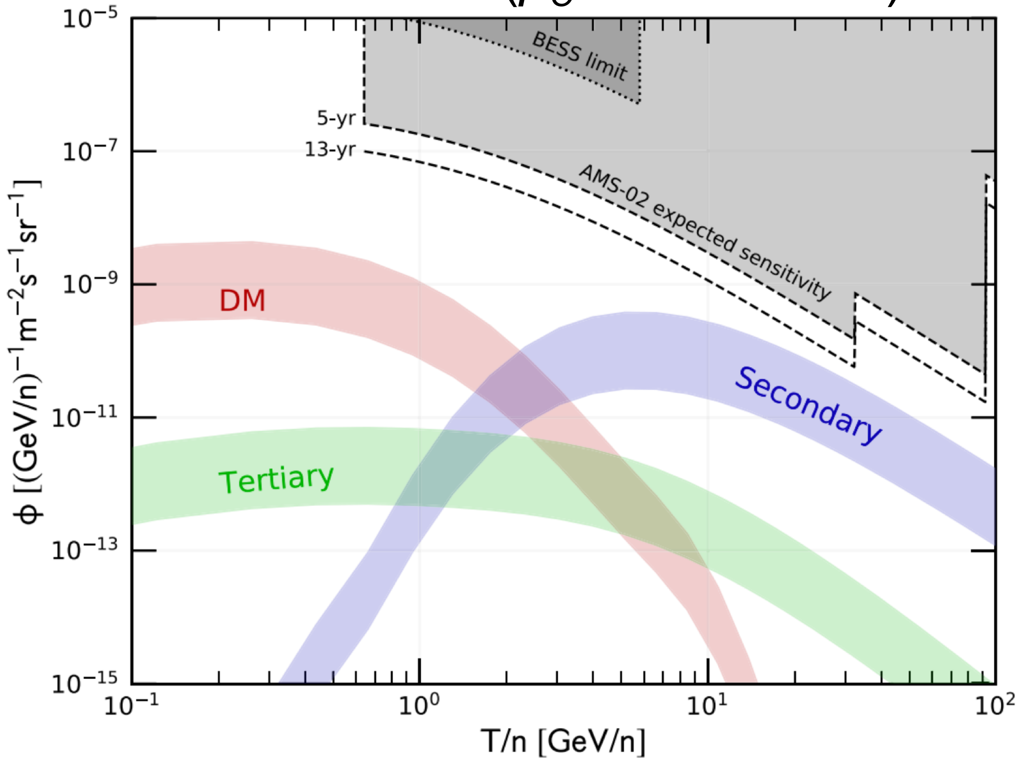
Low background for low-energy DM anti-d and anti-^{3}He

Anti-deuterons (p_C = 248 MeV/c)



M. Korsmeier et al., PRD 97 (2018) 103011

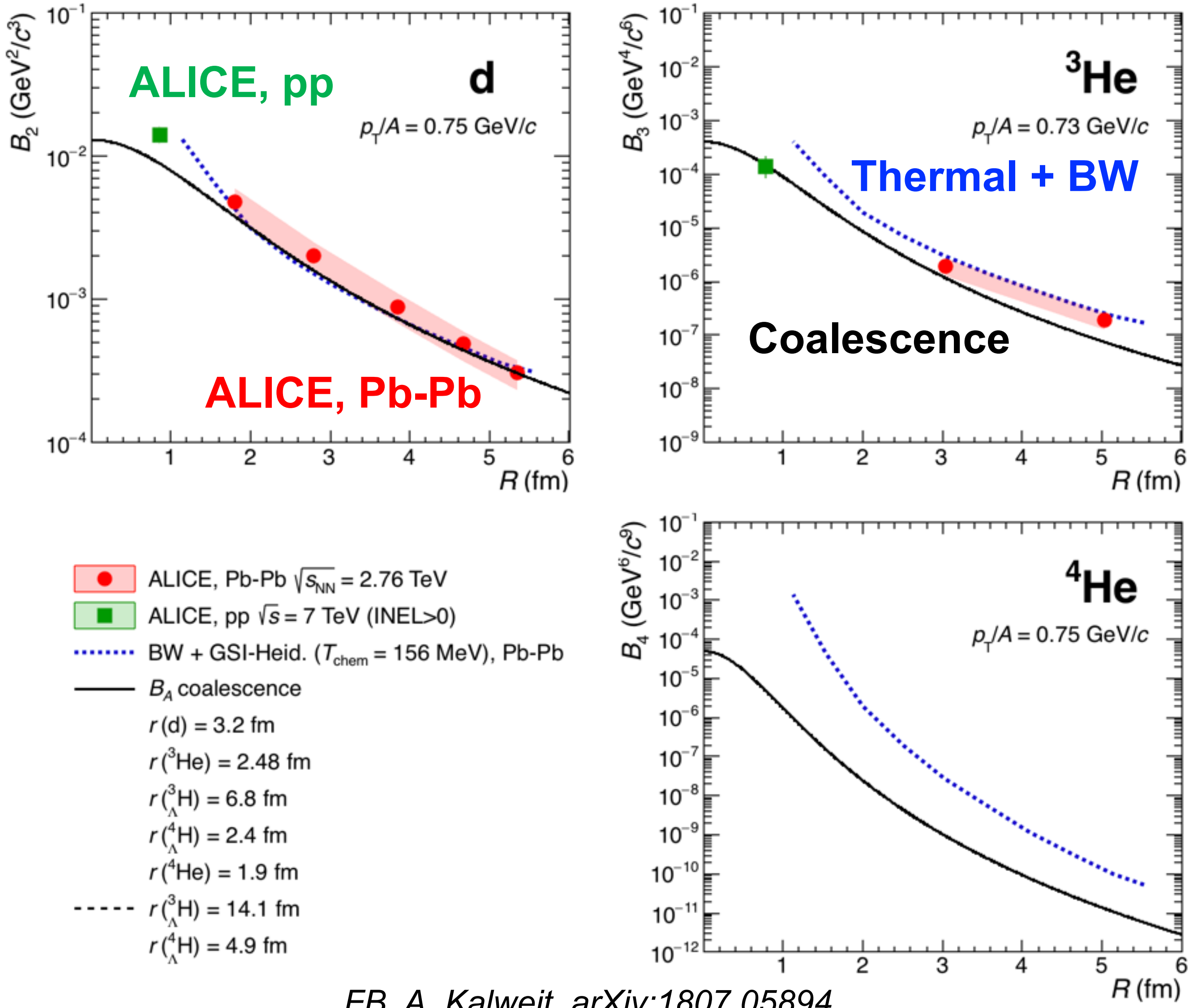
Anti-^{3}He (p_C = 248 MeV/c)



GAPS, AMS-02 sensitive to anti-deuteron signal but anti-^{3}He seems out of reach

✻ Caveat: scaling of coalescence with nuclear properties *[K. Blum et al., PRD 96, 103021 (2017)]*

Testing coalescence models



FB, A. Kalweit, arXiv:1807.05894

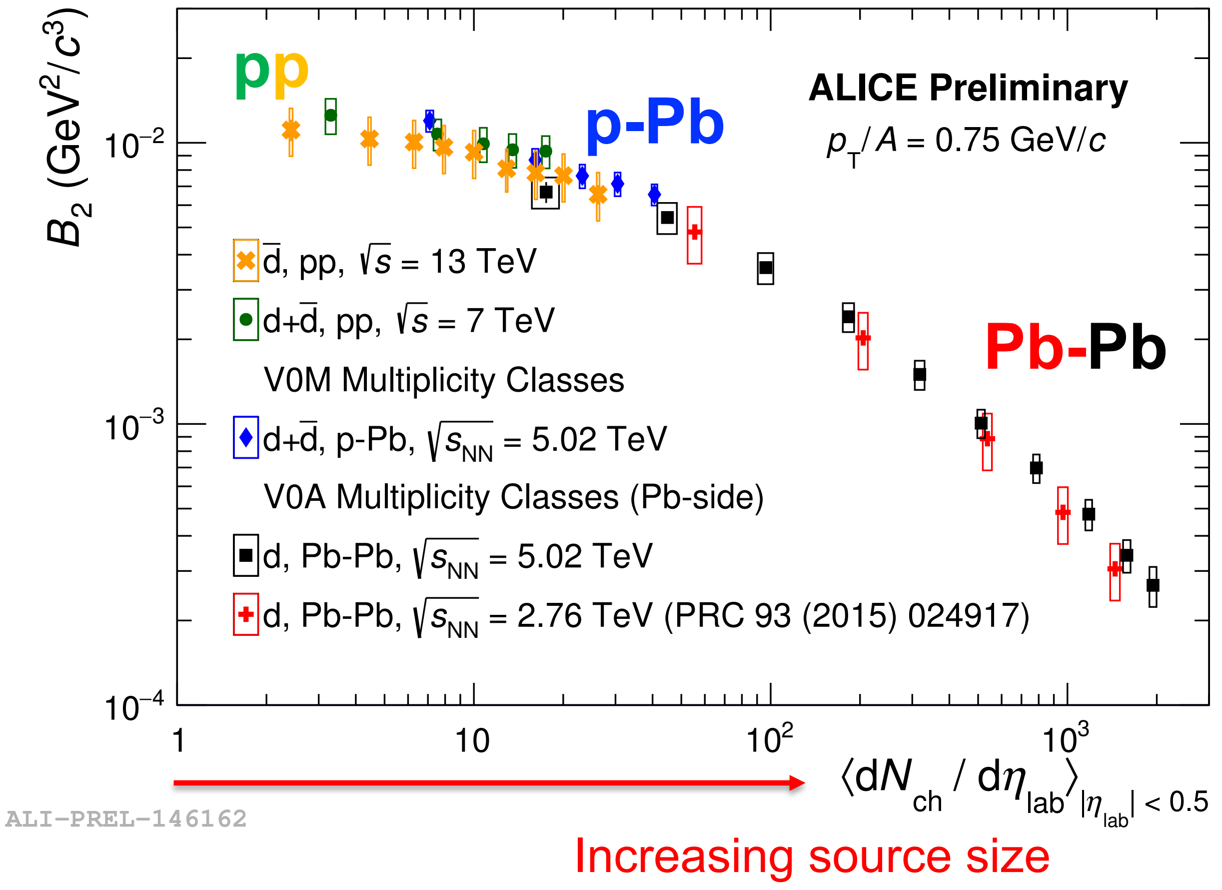
Reminder: production probability encoded in coalescence parameter B_A

$$B_A = \frac{2J_A+1}{2^A}\frac{1}{\sqrt{A}}\frac{1}{m_T^{A-1}}\left(\frac{2\pi}{R^2+(\frac{r_A}{2})^2}\right)^{3/2(A-1)}$$

The trend with multiplicity can be explained as an increase in the **source size** (radius R from HBT) in coalescence models
[Scheibl, Heinz, PRC 59 (1999) 1585; K. Blum et al., PRD 96, 103021 (2017)]

Scaling properties of coalescence can be tested by measuring systematically different (hyper-)nucleus species in different systems

Testing coalescence models



FB, A. Kalweit, arXiv:1807.05894

Reminder: production probability encoded in coalescence parameter B_A

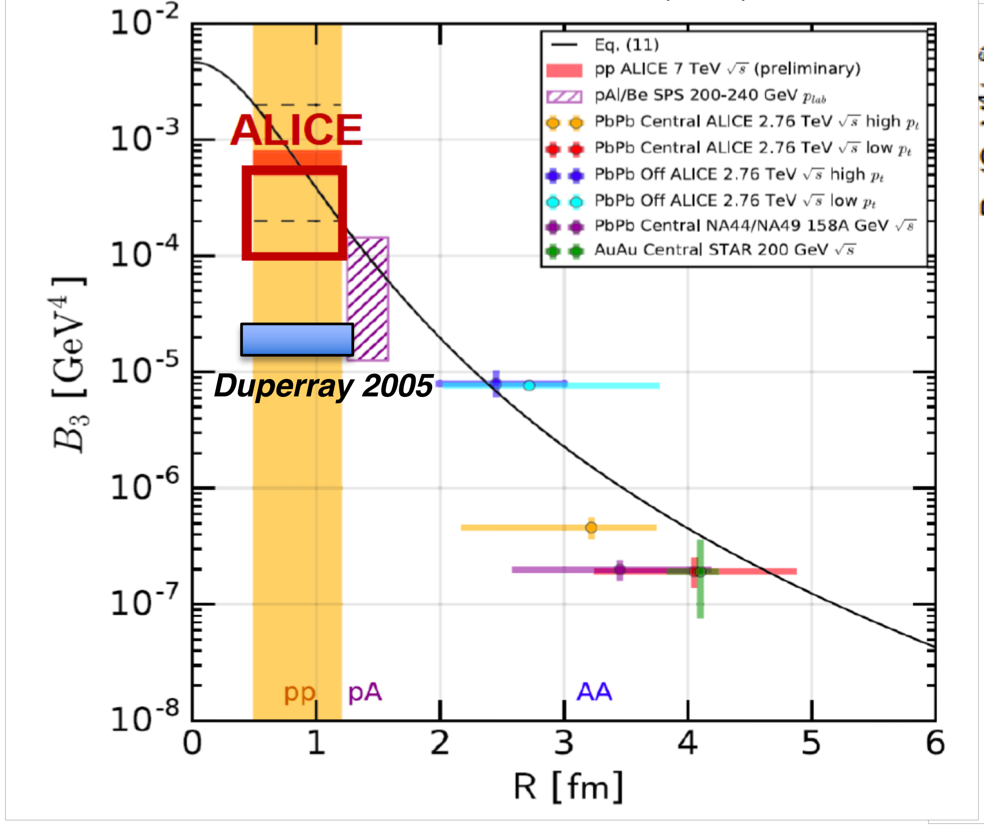
$$B_A = \frac{2J_A+1}{2^A}\frac{1}{\sqrt{A}}\frac{1}{m_T^{A-1}}\left(\frac{2\pi}{R^2+(\frac{r_A}{2})^2}\right)^{3/2(A-1)}$$

The trend with multiplicity can be explained as an increase in the **source size** (radius R from HBT) in coalescence models
[Scheibl, Heinz, PRC 59 (1999) 1585; K. Blum et al., PRD 96, 103021 (2017)]

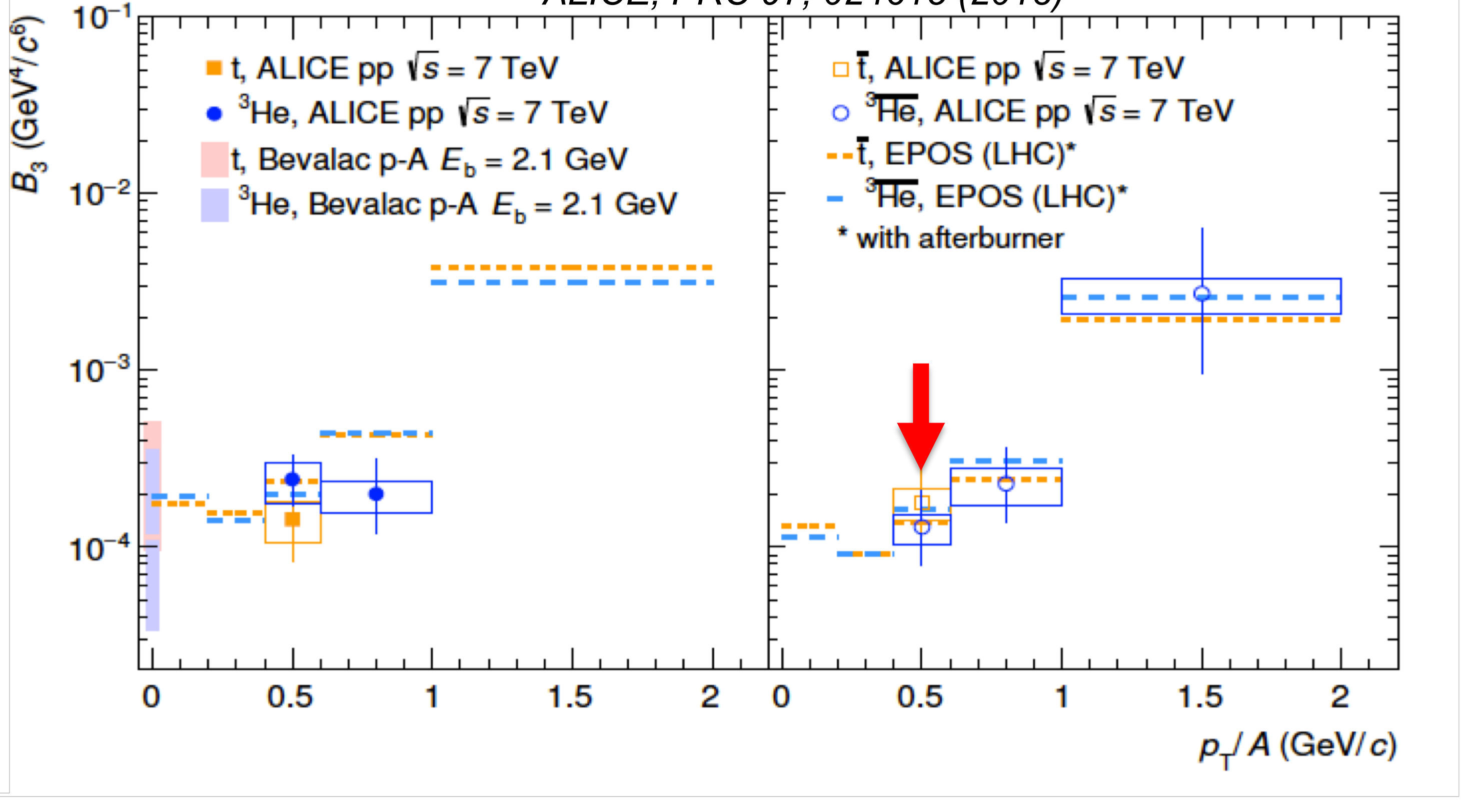
Scaling properties of coalescence can be tested by measuring systematically different (hyper-)nucleus species in different systems

Measurements at LHC with impact on astrophysics

K. Blum et al., PRD 96, 103021 (2017)



ALICE, PRC 97, 024615 (2018)



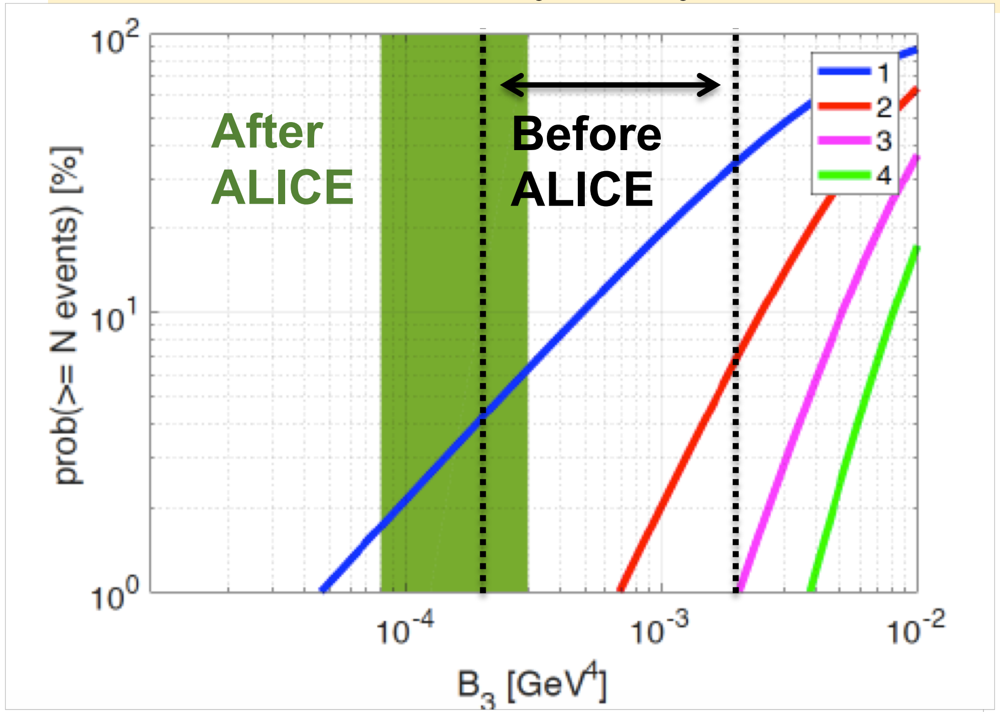
Previous estimates of the coalescence probability **underestimated by >10x**

[Duperray et al, PRD71 083013 (2005)]

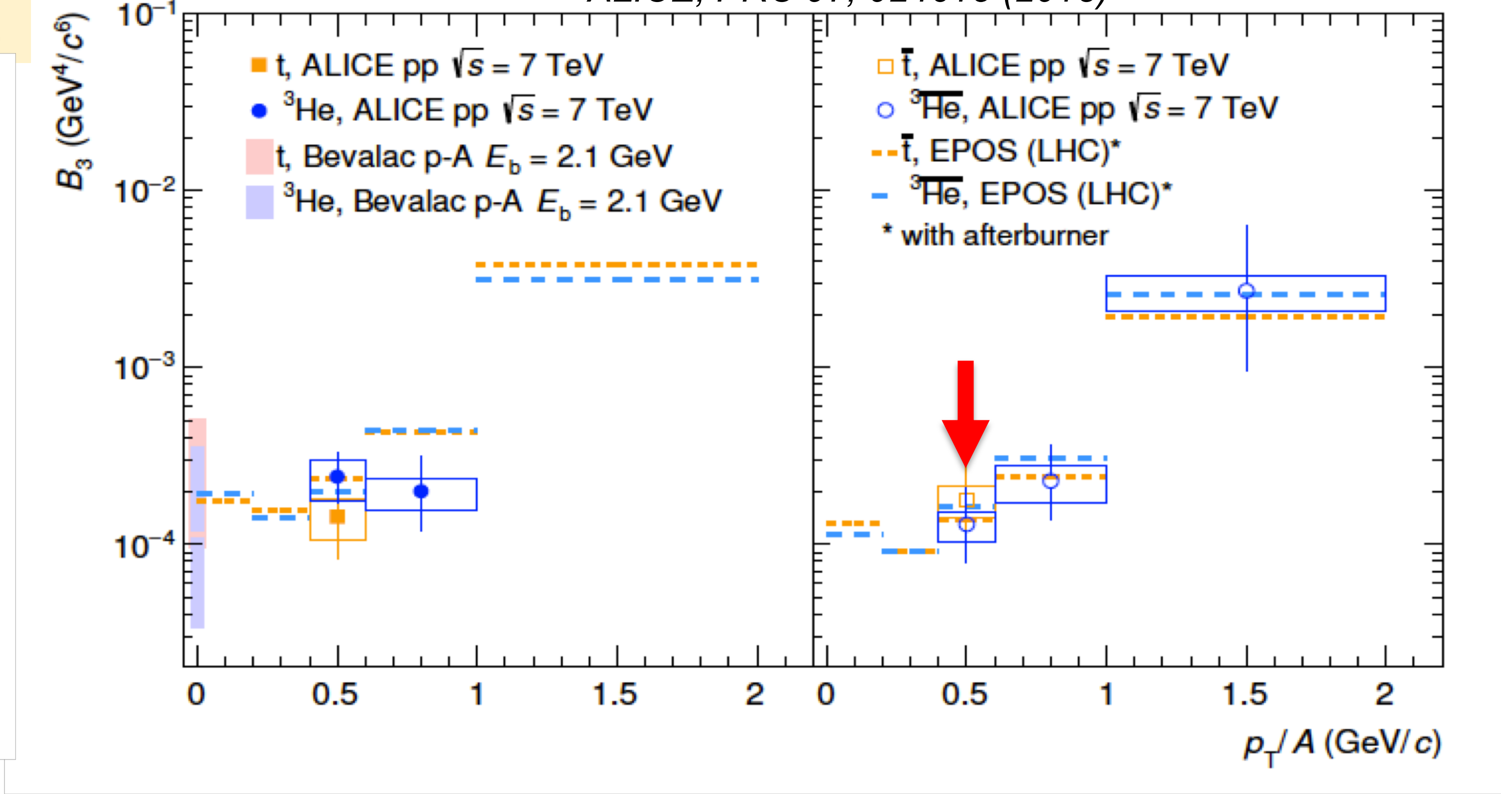
⟶ Translates into an **updated background estimate for DM searches** in space-based experiments (e.g. AMS-02)

Measurements at LHC with impact on astrophysics

Poisson prob. for detecting N≥1, 2, 3, 4
^{3}He-bar events in a 5-yr analysis of AMS02

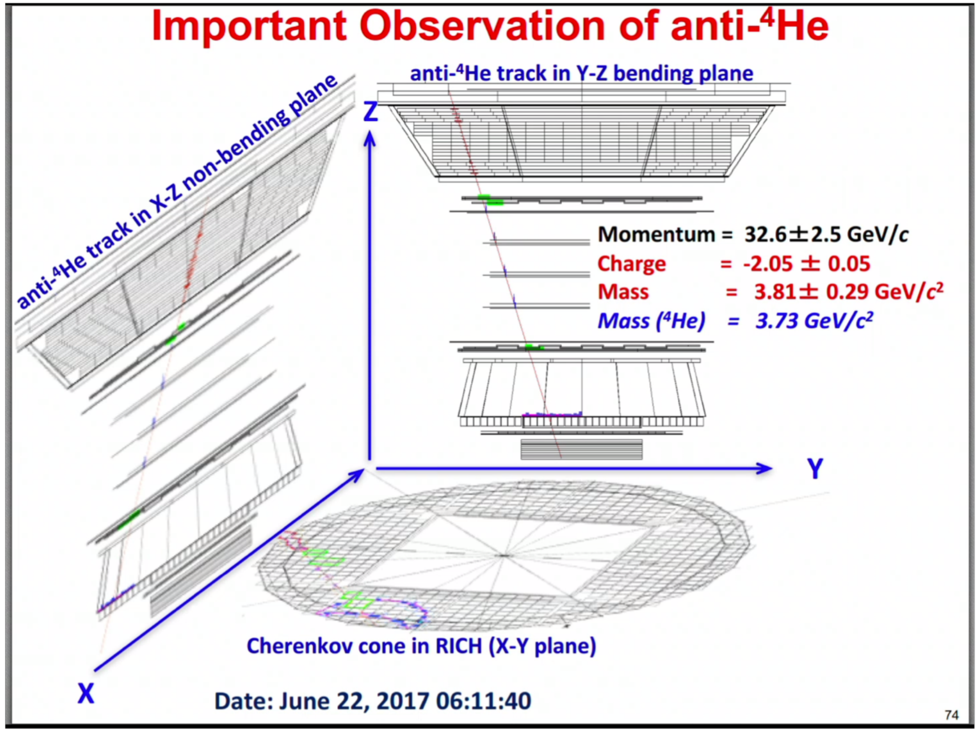


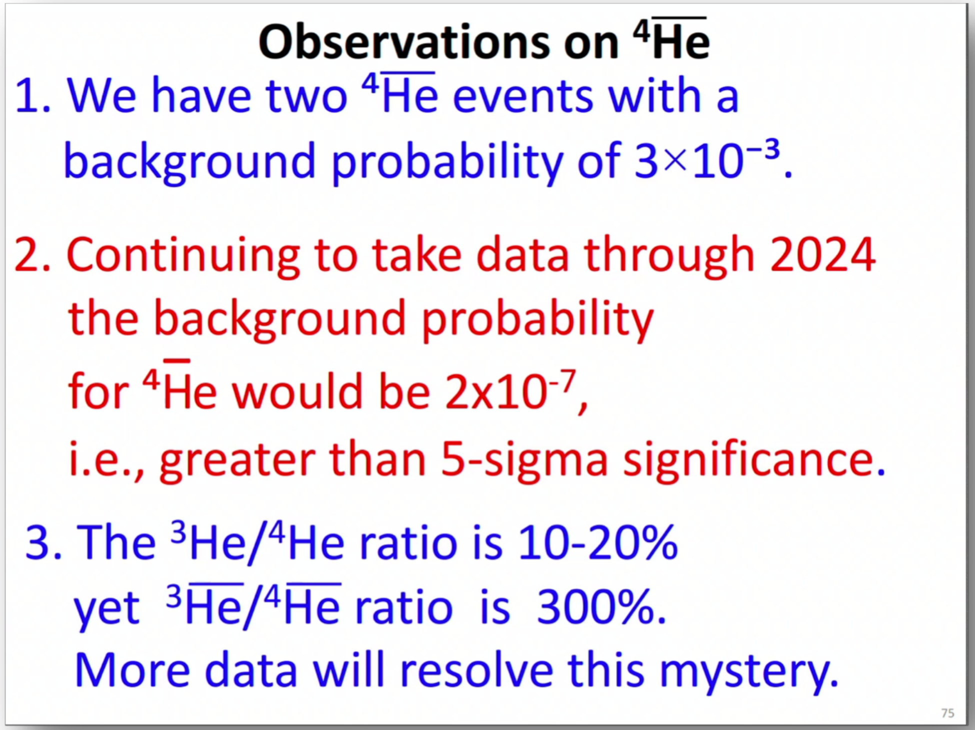
ALICE, PRC 97, 024615 (2018)



Previous estimates of the coalescence probability **underestimated by >10x**
[Duperray et al, PRD71 083013 (2005)]
⟶ Translates into an **updated background estimate for DM searches** in space-based experiments (e.g. AMS-02) *[K. Blum et al., PRD 96, 103021 (2017)]*

Anti-^{4}He in the Cosmos





Observations on $^{4}\overline{\text{He}}$

1. We have two $^{4}\overline{\text{He}}$ events with a background probability of 3×10^{-3}.
2. Continuing to take data through 2024 the background probability for $^{4}\overline{\text{He}}$ would be $2\text{x}10^{-7}$, i.e., greater than 5-sigma significance.
3. The ^{3}He/^{4}He ratio is 10-20% yet $^{3}\overline{\text{He}}/^{4}\overline{\text{He}}$ ratio is 300%. More data will resolve this mystery.

75

S. Ting (AMS), CERN Colloquium 24/05/2018

What is the source of the anti-^{4}He seen by AMS-02?

Anti-^{4}He measurement in pp collisions in reach with ALICE with the High-Luminosity LHC phase (Run3-4, 2021-2028) → measurement of production probability for *A = 4*

Secondary-to-secondary flux ratios

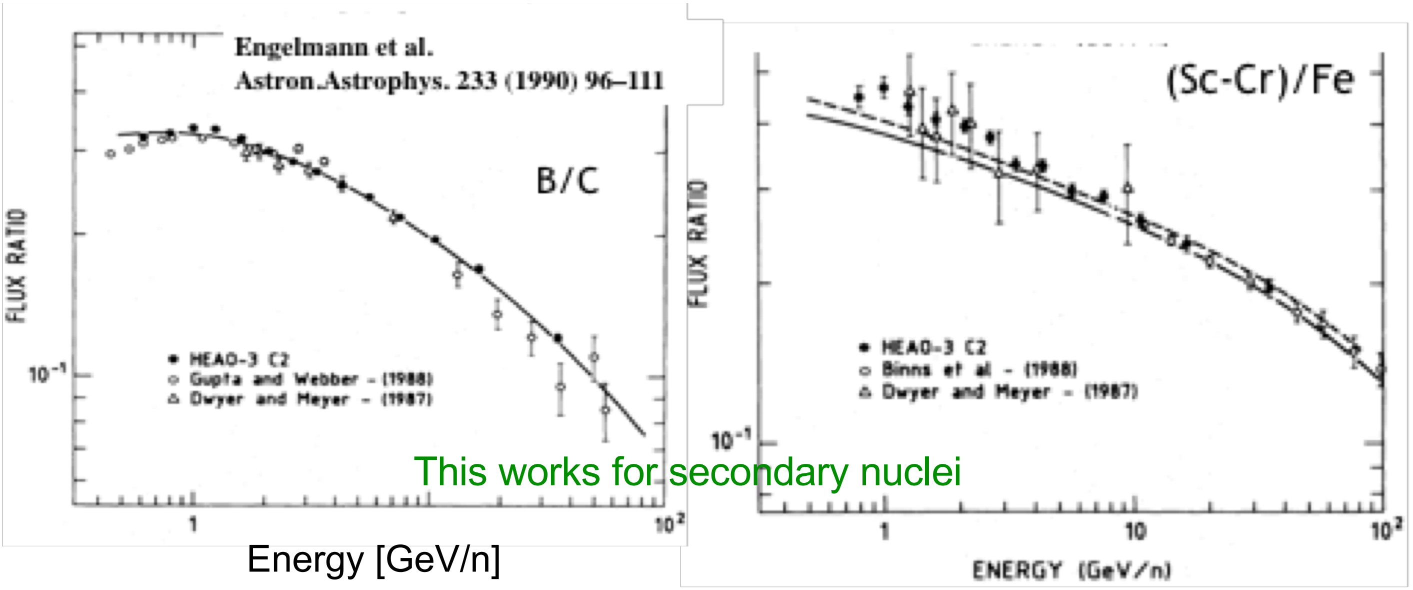
The flux of secondary anti-nuclei can be calculated with only minor sensitivity to the details of CR astrophysics if **secondary-to-secondary flux ratios** (at given rigidity) are used

⟶ astrophysical uncertainties largely cancel *[Katz et al. , Mon.Not.Roy.Astron.Soc. 405 (2010) 1458]*

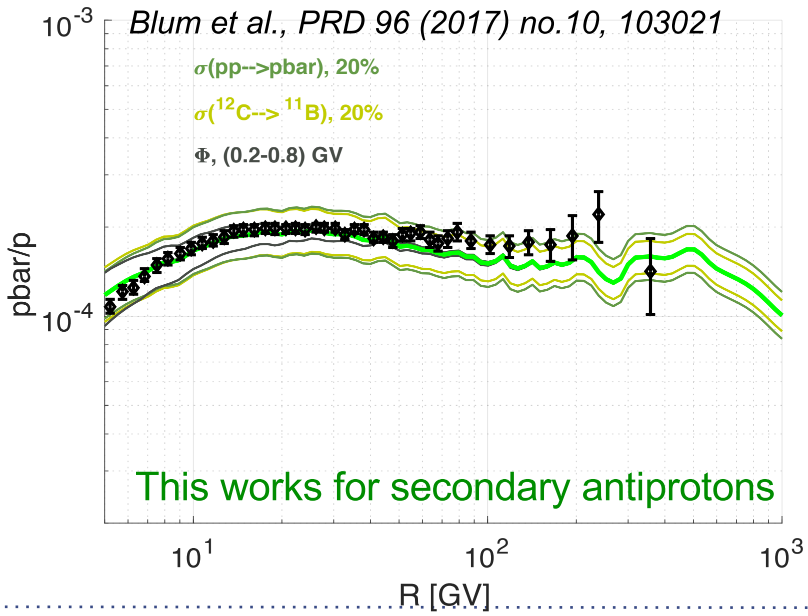
$$\frac{J_{\bar{\mathrm{d}}}(\mathcal{R})}{J_{\bar{\mathrm{p}}}(\mathcal{R})} = \frac{\int_{\epsilon_{\bar{\mathrm{d}}}}^{\infty} d\epsilon\, J_p(\epsilon)\, \frac{d\sigma_{pp\to\bar{\mathrm{d}}}(\epsilon,\epsilon_{\bar{\mathrm{d}}})}{d\epsilon_{\bar{\mathrm{d}}}}}{\int_{\epsilon_{\bar{\mathrm{p}}}}^{\infty} d\epsilon\, J_p(\epsilon)\, \frac{d\sigma_{pp\to\bar{\mathrm{p}}}(\epsilon,\epsilon_{\bar{\mathrm{p}}})}{d\epsilon_{\bar{\mathrm{p}}}} + \left(\sigma_{\bar{\mathrm{d}}}(\epsilon_{\bar{\mathrm{d}}}) - \sigma_{\bar{\mathrm{p}}}(\epsilon_{\bar{\mathrm{p}}})\right) J_{\bar{\mathrm{p}}}(\mathcal{R})}$$

$$\boxed{\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})}}$$

$Q_{a,b}(R)$ = net production of species a per unit ISM column density
$n_{a,b}(R)$ = particle density



This works for secondary nuclei



This works for secondary antiprotons

Perspectives at the LHC Runs 3 and 4

CR anti-nuclei flux ratio used to estimate amount of secondary anti-nuclei produced in cosmic ray interactions as **background for DM searches**
→ **Require** precision on B_A of the order of **O(10%) or better**

$$\frac{J_{\bar{\mathrm{d}}}(\mathcal{R})}{J_{\bar{\mathrm{p}}}(\mathcal{R})}\Big|_{\mathcal{R}=100\mathrm{GV}} \approx 4\times 10^{-4}\left(\frac{B_2}{1.5\times 10^{-2}\ \mathrm{GeV}^2}\right)$$

$$\frac{J_{^3\overline{\mathrm{He}}}(\mathcal{R})}{J_{\bar{\mathrm{p}}}(\mathcal{R})}\Big|_{\mathcal{R}=100\mathrm{GV}} \approx 2\times 10^{-7}\left(\frac{B_3}{1.5\times 10^{-4}\ \mathrm{GeV}^4}\right)$$

Report from the HL-LHC Workshop, arXiv:1812.06772

B_A	pp $\sqrt{s}$	L_{int}	Stat. unc.	Sys. Unc.
A = 2, 3	5.5	6 /pb	< 0.1%	O(10%)
	14	200 /pb	< 0.1%	
A = 4 **FIRST time!**	14	200 /pb	~ 10%	To be estimated

- Low p_T (≲ 0.5 GeV/*c*) most relevant ⟶ ALICE is in a good spot!
- Possibility to reduce systematics by measuring the hadronic cross-section of anti-nuclei in material
- Beyond ALICE capabilities: rapidity dependence (y = O(1)) and $\sqrt{s}$ = O(10 GeV)

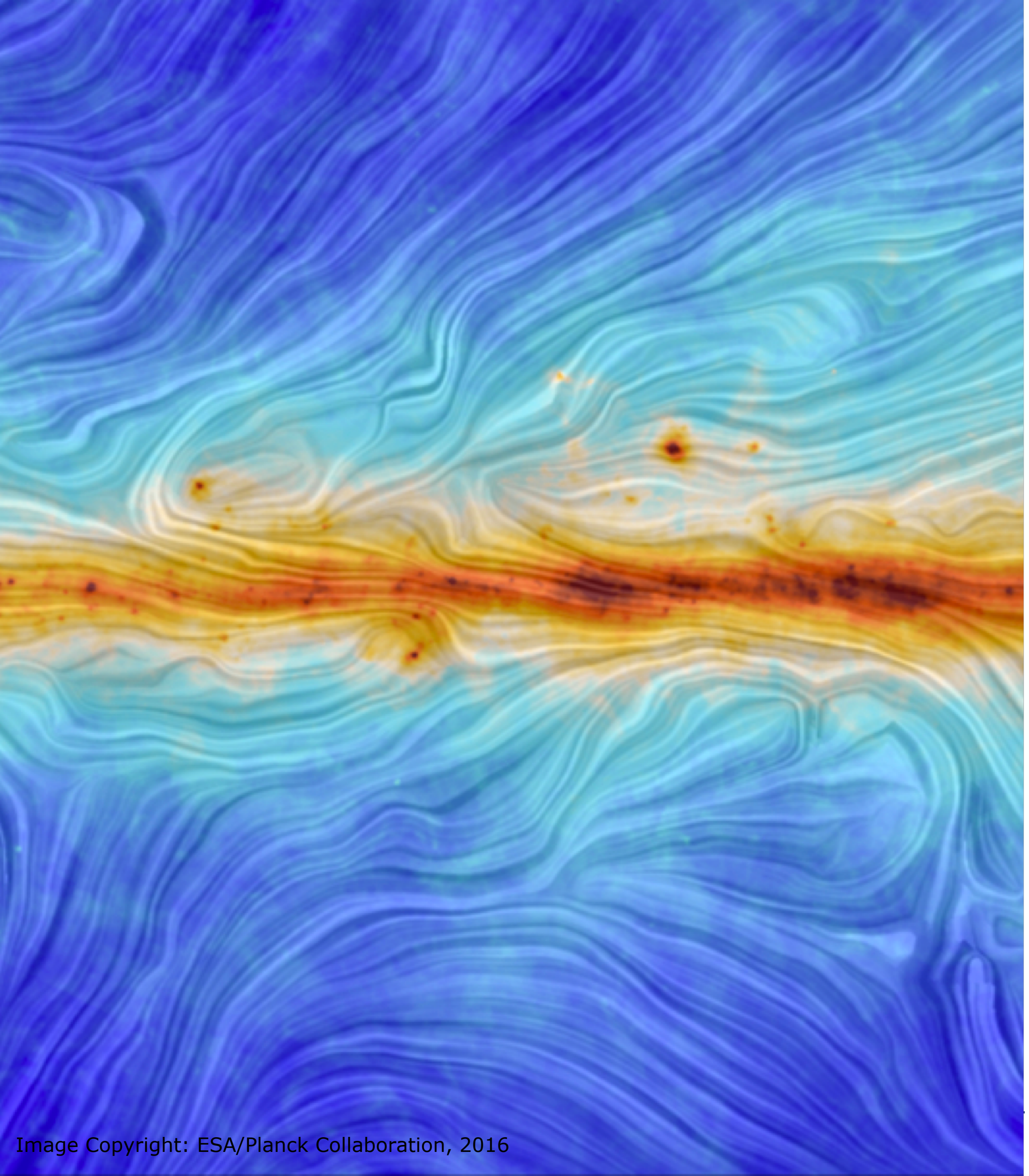
Summary

* **Anti-deuteron and anti-^{3}He** detection in CR look promising for indirect searches of DM, due to the **low background from secondary CR**

* LHC can be used as **anti-matter factory** to study the production of anti-p and light anti-nuclei

* Recent results from the LHC with impact for indirect searches
  1. **anti-proton cross-section from p-He collisions in LHCb fixed target**
  2. **anti-deuteron and anti-^{3}He in pp collisions with ALICE**

* The increased integrated luminosity foreseen for **Runs 3+4** will allow us to reach the 10% precision on the measured coalescence probability needed to constrain secondary CR anti-nuclei flux ratios.

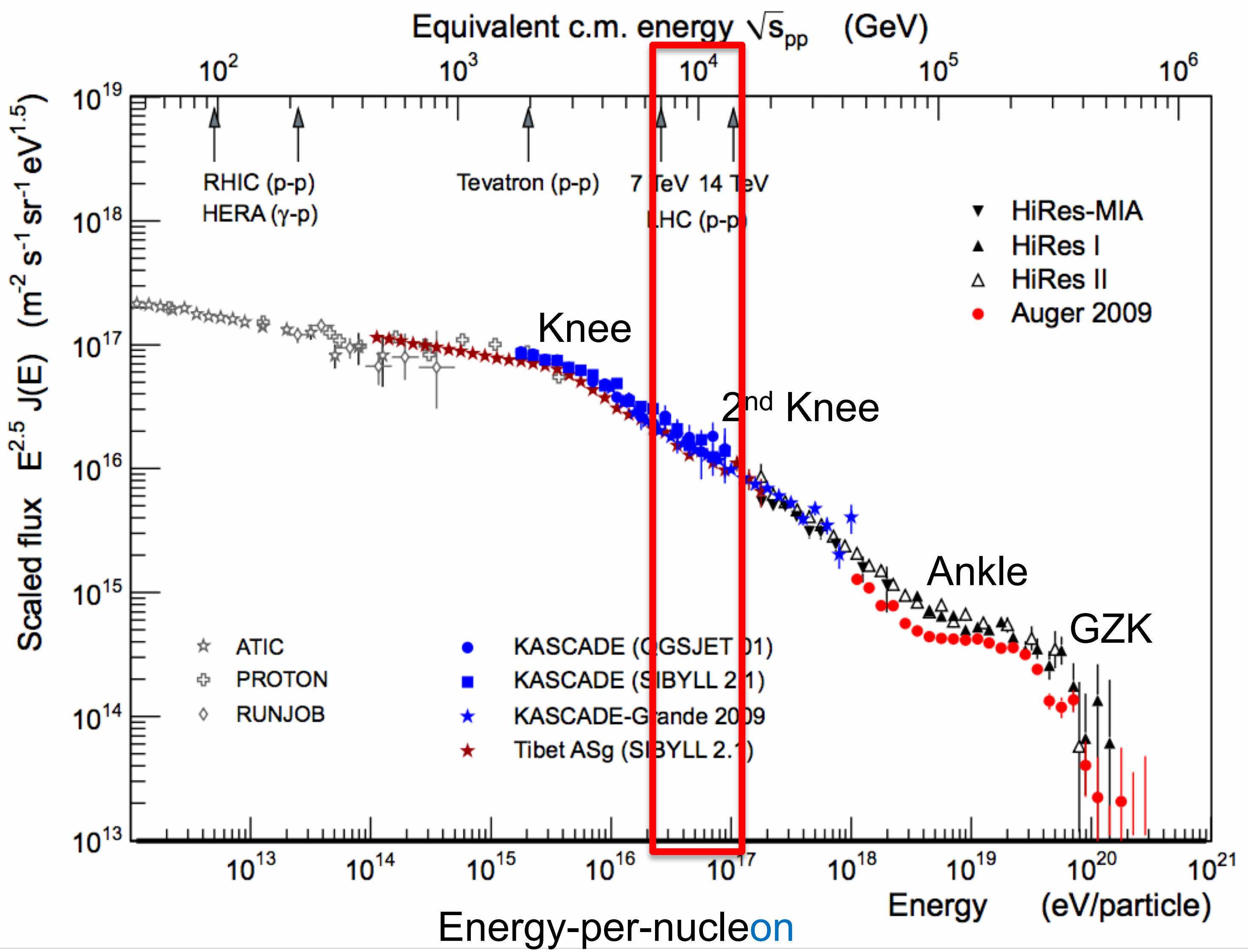


Thank you!

Contact: Francesca.bellini@cern.ch

Additional material

LHC meets cosmic rays

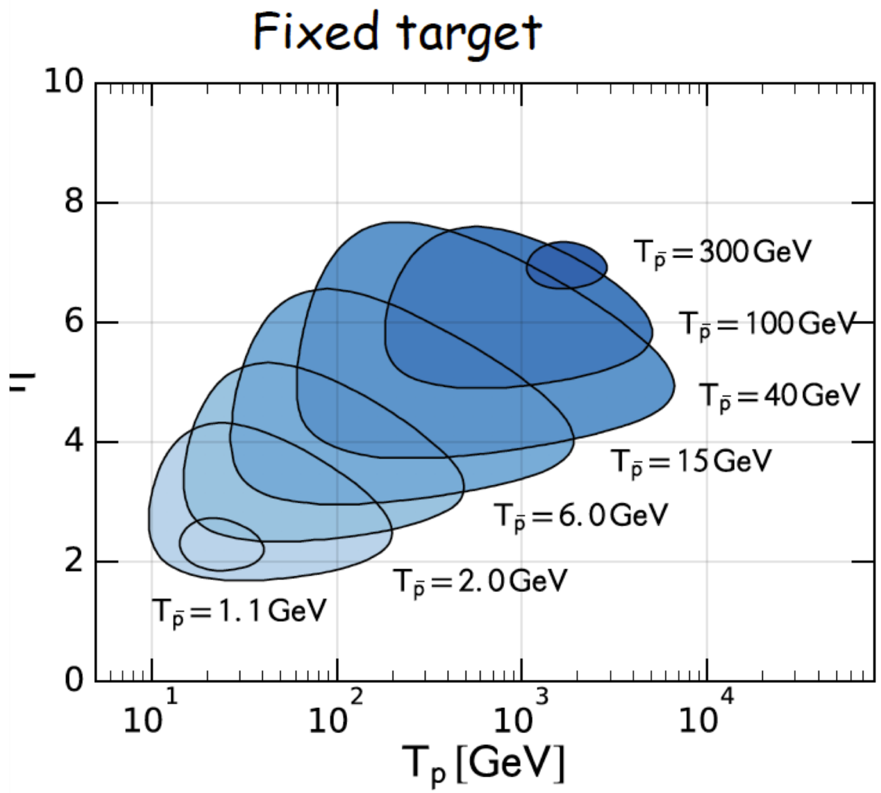


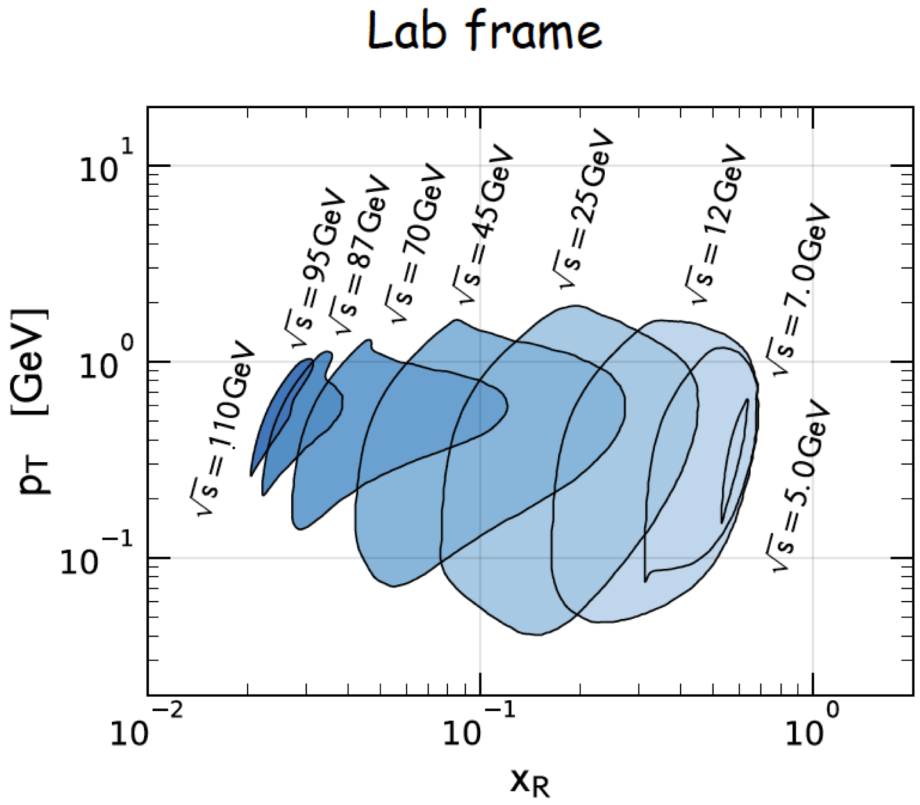
LHC pp collisions cover the energy-per-nucleon range between the 1st and the 2nd knee of the CR spectrum

LHC collision energy $\sqrt{s_{NN}}$ (TeV)		
System	Run I	Run II
pp	0.9, 2.76, 5.02, 7, 8	5, 13
p-Pb	5.02	5.02, 8.16
Pb-Pb	2.76	5.02
Xe-Xe	-	5.44

Parameter space to be covered

F. Donato, EMMI Workshop in Torino, Dec. 2017



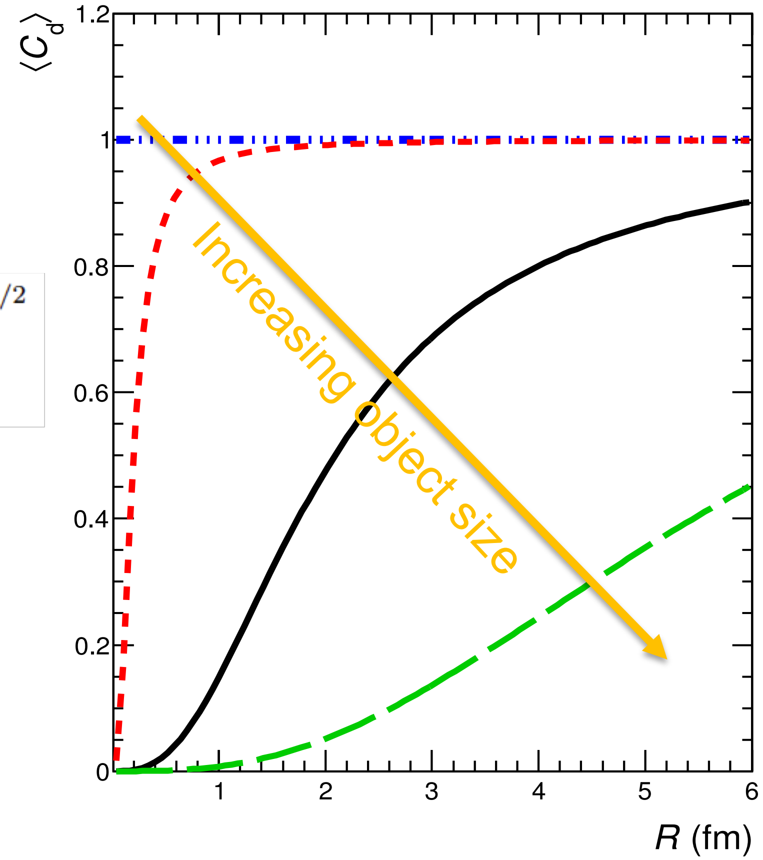


AMS02 accuracy is reached if pp→pbar cross section is measured with 3% accuracy inside the regions, 30% outside.

Coalescence probability for deuteron

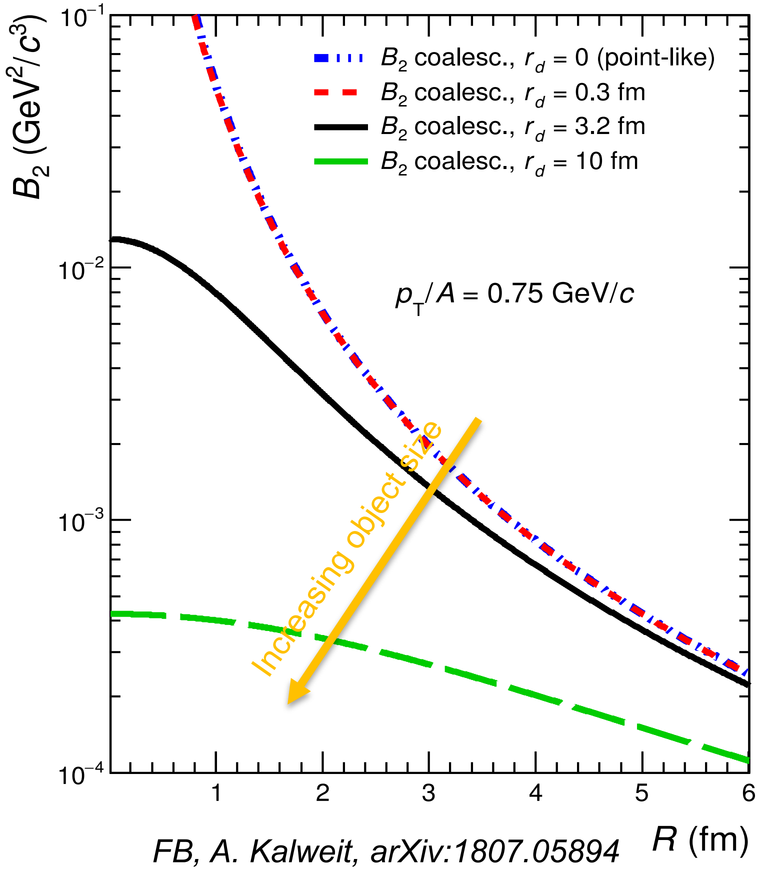
$$\langle C_d \rangle \approx \left[1 + \left(\frac{r_d}{2R(m_T)}\right)^2\right]^{-3/2}$$

Quantum-mechanical factor



Increasing source size

Coalescence parameter

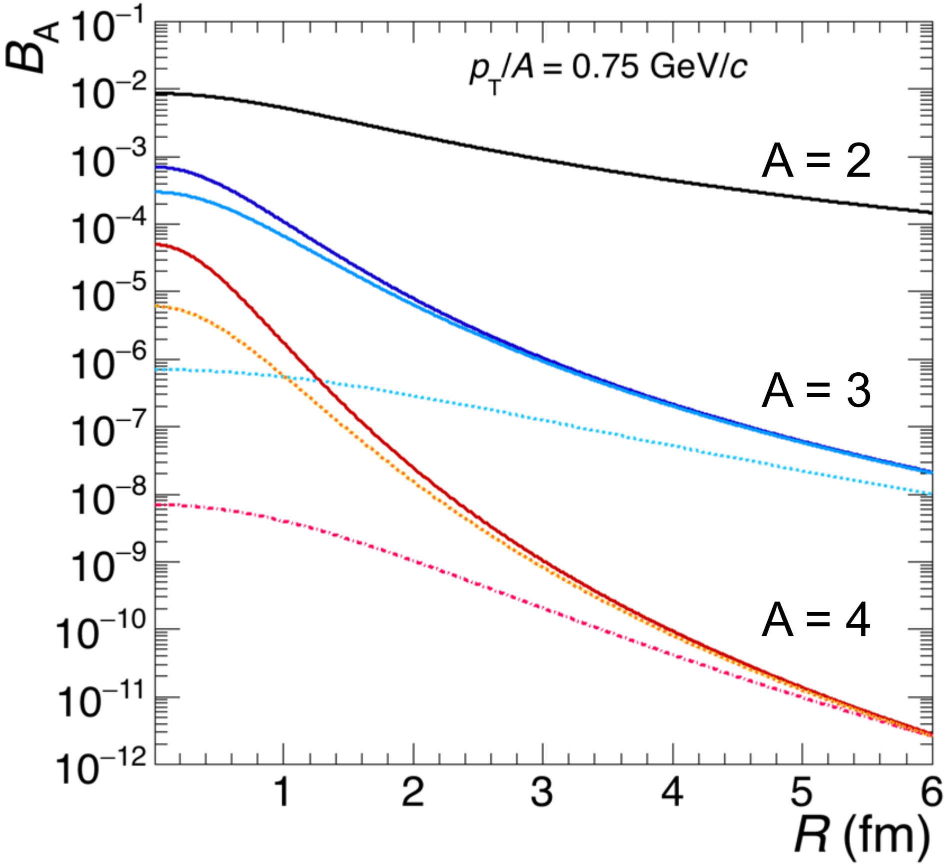


FB, A. Kalweit, arXiv:1807.05894

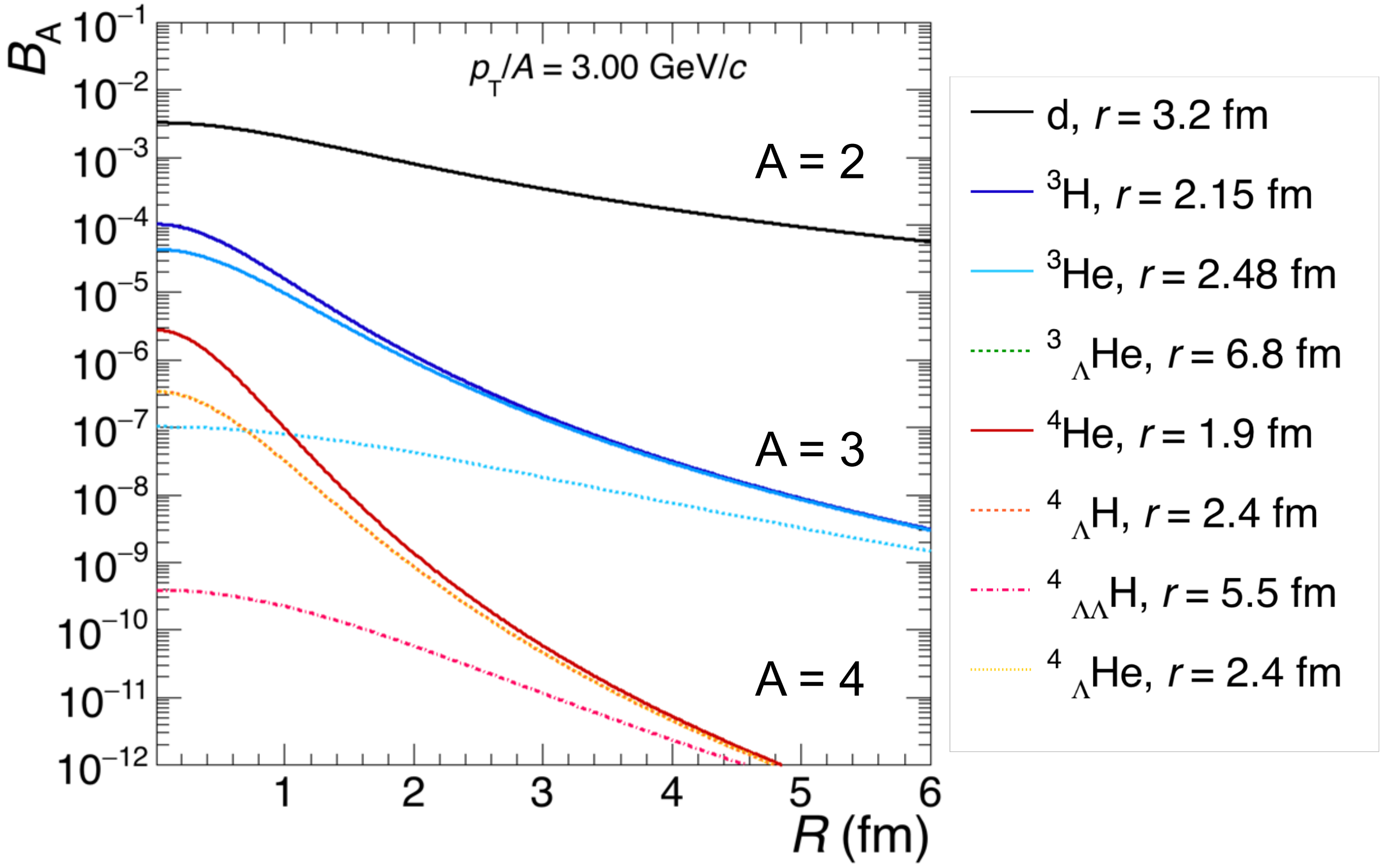
$$B_2 = \frac{3\pi^{3/2}\langle C_d \rangle}{2m_T R^3(m_T)}$$

Coalescence probability for (hyper-)nuclei with A≤4

B_A from coalescence at p_T/A = 0.75 GeV/c

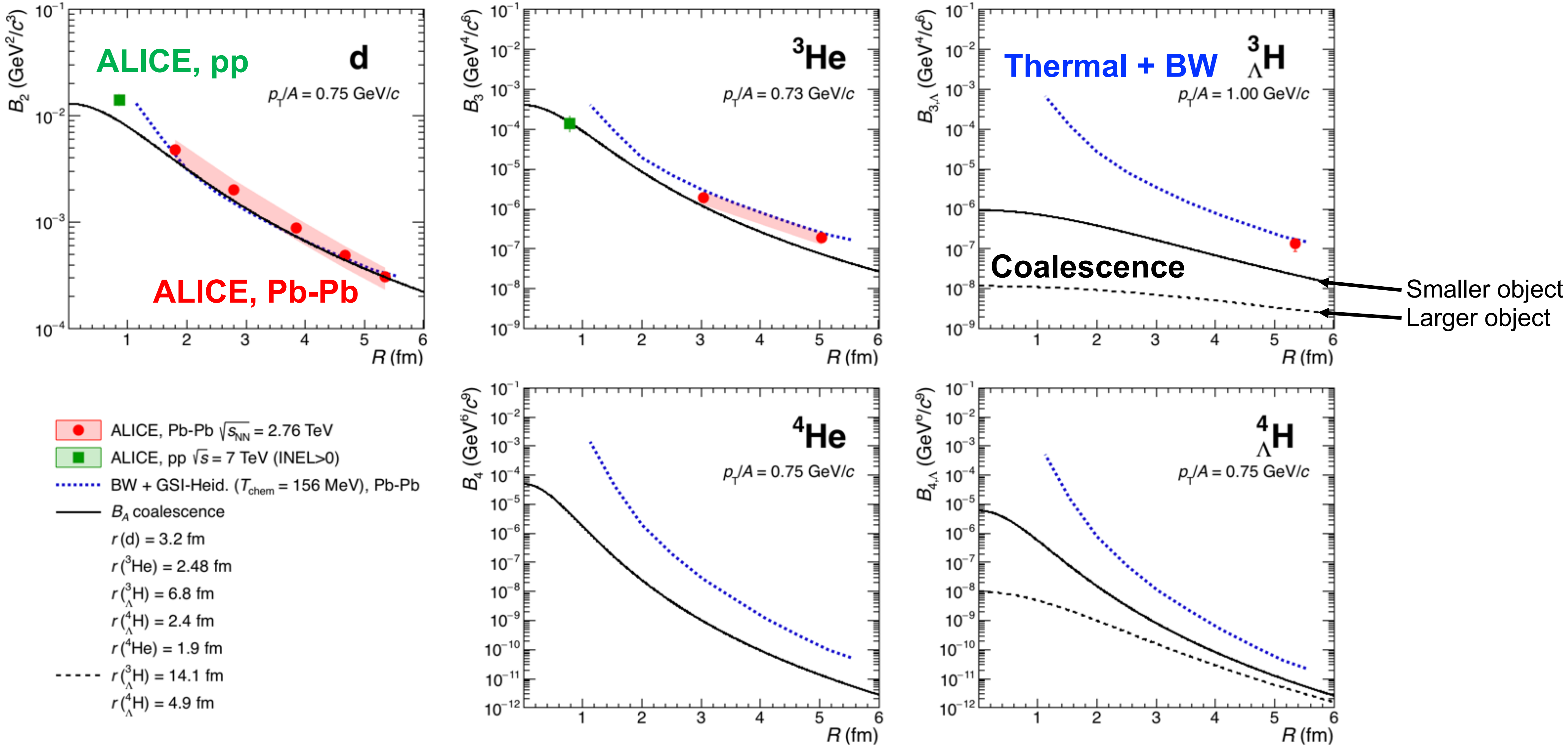


B_A from coalescence at p_T/A = 3 GeV/c

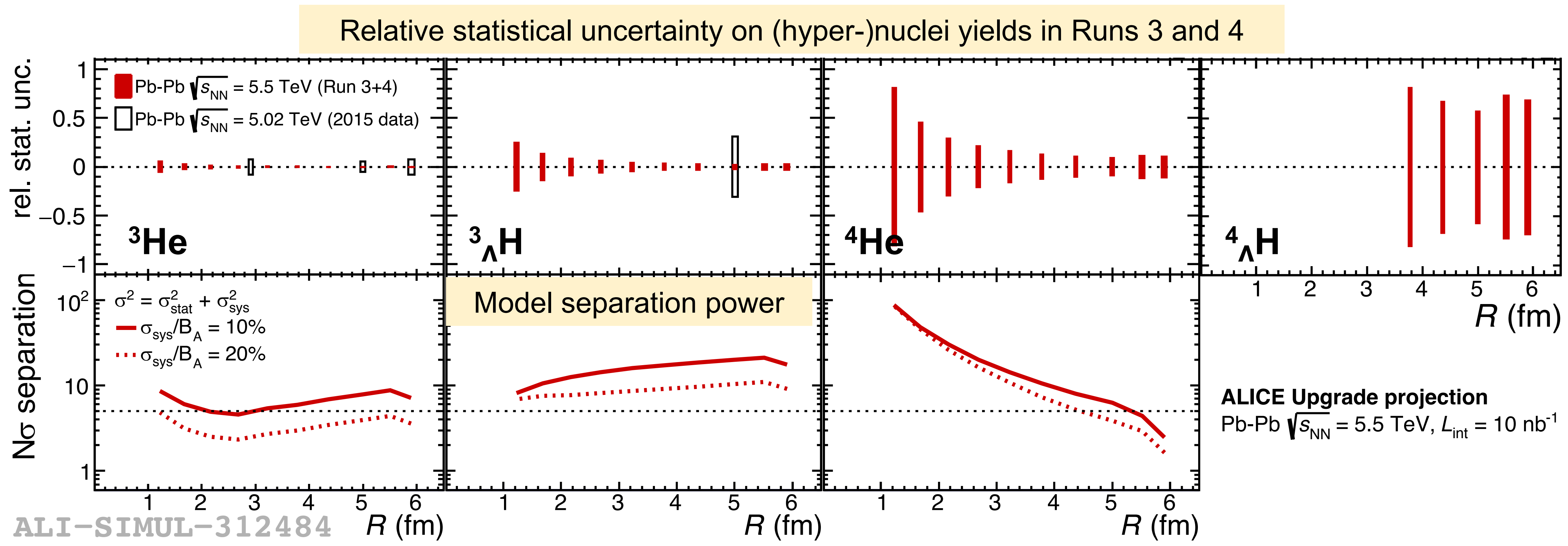


Coalescence probability decreases with transverse momentum for all A and R.

B_A vs R


ALICE, pp
d
ALICE, Pb-Pb
$p_T/A = 0.75$ GeV/c
B_2 (GeV^2/c^3)
^{3}He
$p_T/A = 0.73$ GeV/c
B_3 (GeV^4/c^6)
Thermal + BW
$^3_\Lambda$H
$p_T/A = 1.00$ GeV/c
$B_{3,\Lambda}$ (GeV^4/c^6)
Coalescence
Smaller object
Larger object
^{4}He
$p_T/A = 0.75$ GeV/c
B_4 (GeV^6/c^9)
$^4_\Lambda$H
$p_T/A = 0.75$ GeV/c
$B_{4,\Lambda}$ (GeV^6/c^9)
R (fm)
ALICE, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
ALICE, pp $\sqrt{s} = 7$ TeV (INEL>0)
BW + GSI-Heid. ($T_{chem} = 156$ MeV), Pb-Pb
B_A coalescence
r(d) = 3.2 fm
r(^{3}He) = 2.48 fm
r($^3_\Lambda$H) = 6.8 fm
r($^4_\Lambda$H) = 2.4 fm
r(^{4}He) = 1.9 fm
r($^3_\Lambda$H) = 14.1 fm
r($^4_\Lambda$H) = 4.9 fm

Test production models with L = 10 nb^{-1} at LHC Run 3+4

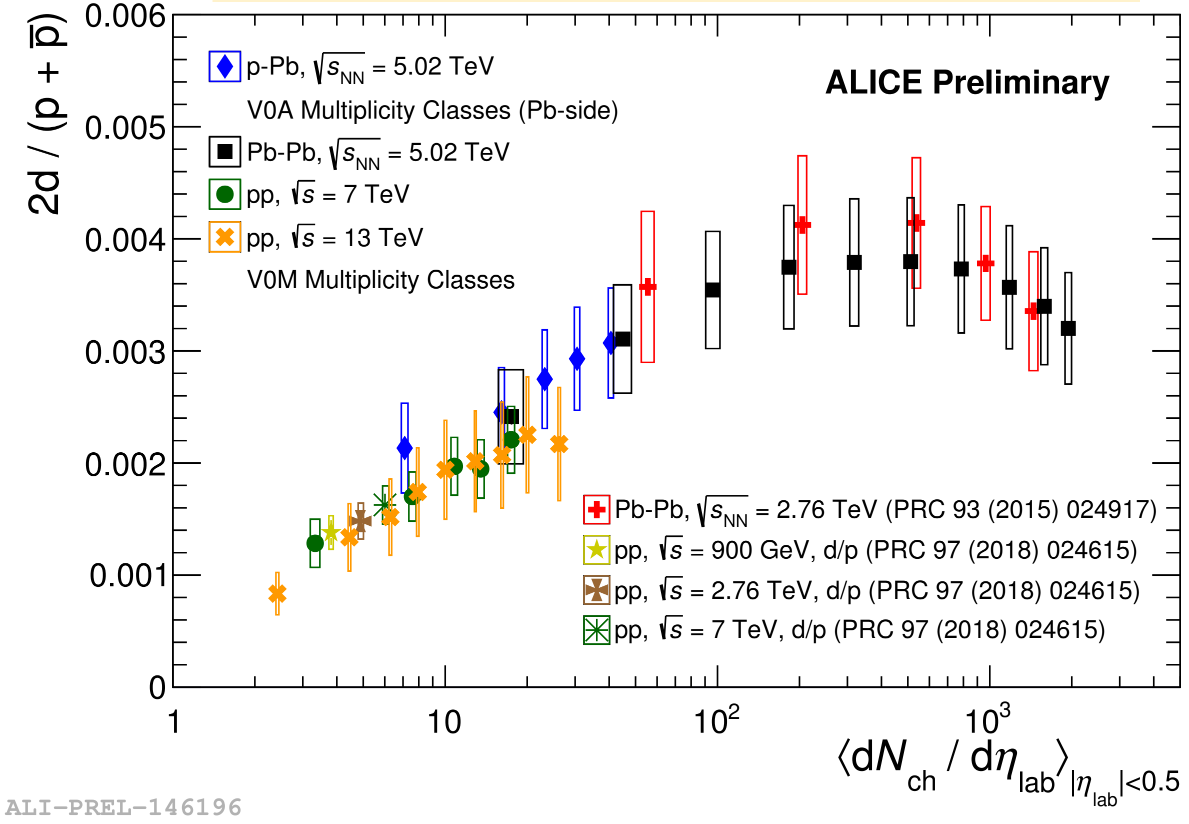


Report from the HL-LHC Workshop, arXiv:1812.06772

At the LHC Runs 3 and 4 (2021-2029), Pb-Pb integrated luminosity will be 100x larger than Runs 1 and 2
Nuclei with A = 3 and A = 4 will be measurable more differentially
⇢ **Hyper-triton** will allow for a ~10σ discrimination between models

Smooth relative production across collision systems

d/p ratio vs multiplicity across systems



Smooth evolution of d/p ratio with multiplicity across systems

No significant centrality dependence in Pb-Pb

- ✻ indication for decrease of d/p ratio in most central collisions

No significant $\sqrt{s_{NN}}$ dependence

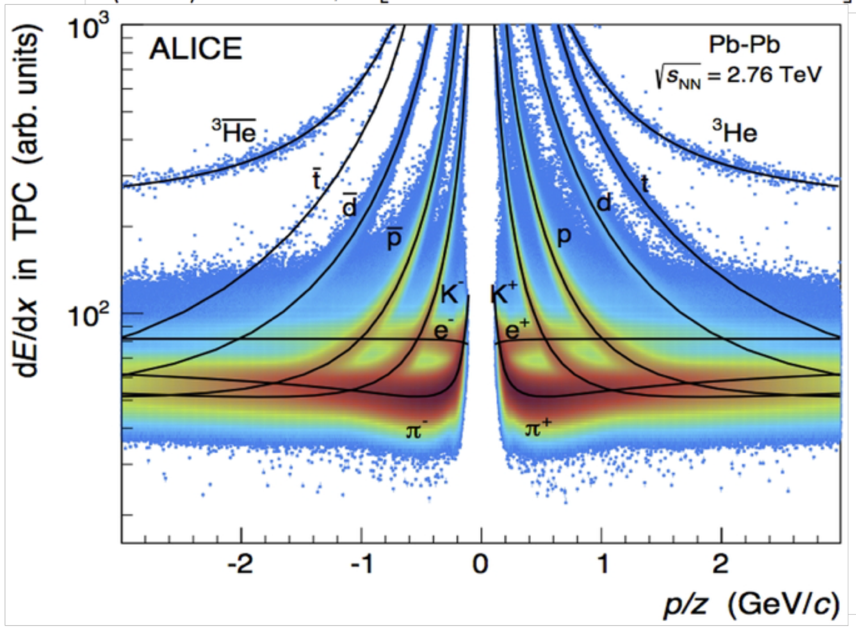
Nuclei and anti-nuclei identification in ALICE

- **Identification** at mid-rapidity
  - dE/dx in the ALICE **TPC** at low momenta
  - Mass from time-of-flight measured in **TOF** at intermediate momenta
  - Mass from Cherenkov angle in **HMPID** at high momenta

ALICE, Phys. Rev. C 93 (2015) 024917
ALICE, Eur. Phys. J. C 77 (2017) 658

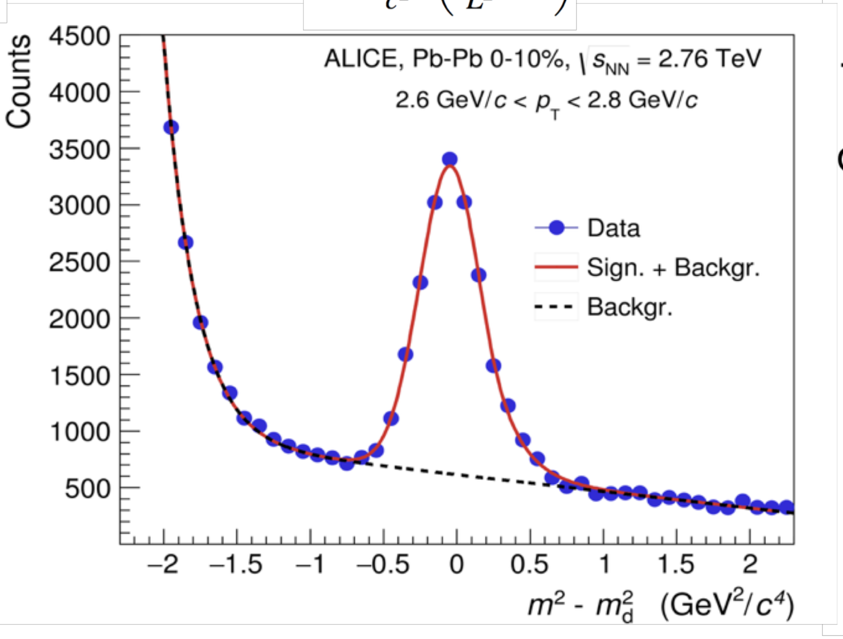
Specific ionization energy loss in TPC

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



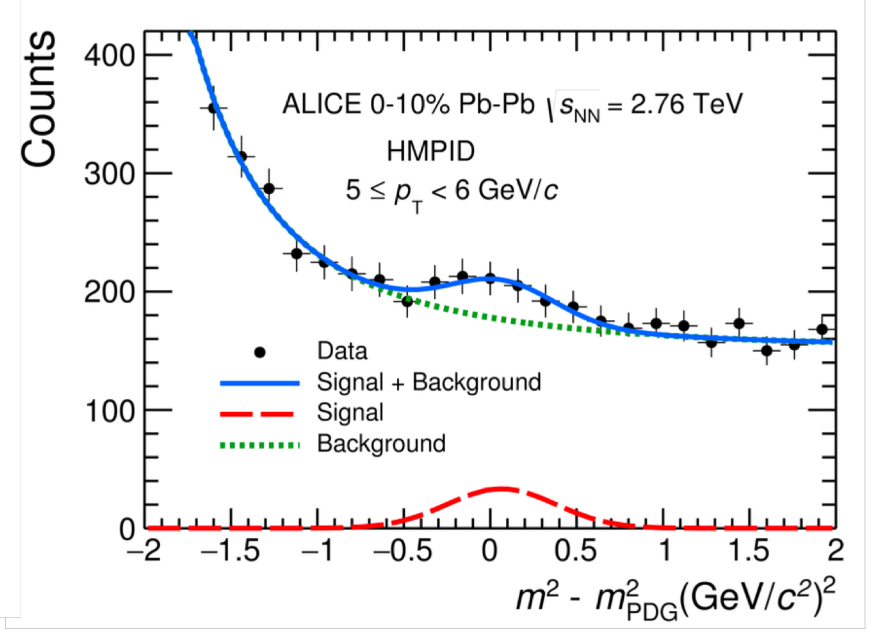
Deuteron signal extraction with TOF

$$m^2 = \frac{p^2}{c^2} \cdot \left(\frac{c^2 t^2}{L^2} - 1 \right)$$



Deuteron signal extraction with HMPID

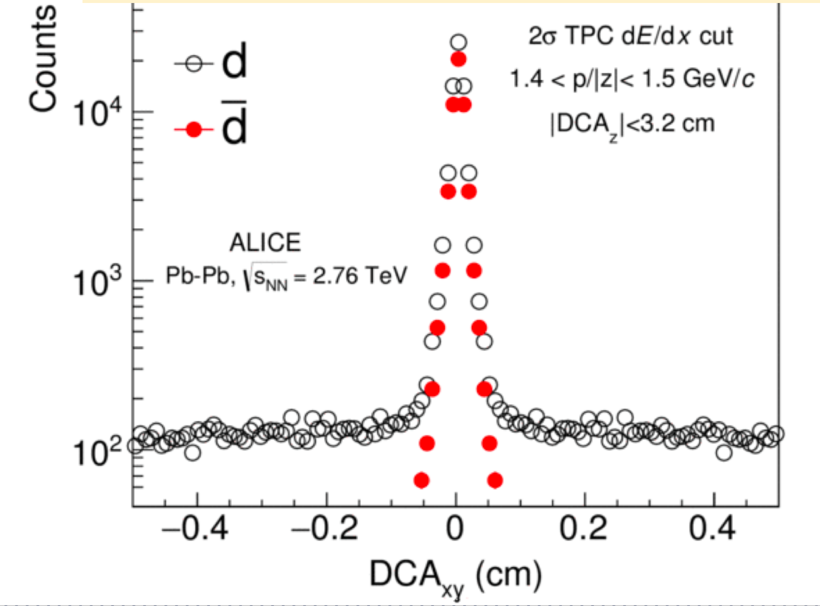
$$m^2 = p^2 \cdot (n^2 \cos^2 \theta_{\mathrm{Ckov}} - 1) \qquad n = 1.29$$



Dealing with detector material

- **Knock-out from detector material** is a background for **nuclei, not for anti-nuclei**
  - Fits to the Distance of Closest Approach (DCA) to the primary vertex (PV) used to reject secondaries
- Source of large systematic uncertainty for anti-nuclei, due to poor knowledge of the **hadronic interaction cross section**

DCA to the PV of deuteron and anti-deuteron candidates



Template fit to the DCA to the PV of deuteron candidates