Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

CosmicAntiNuclei

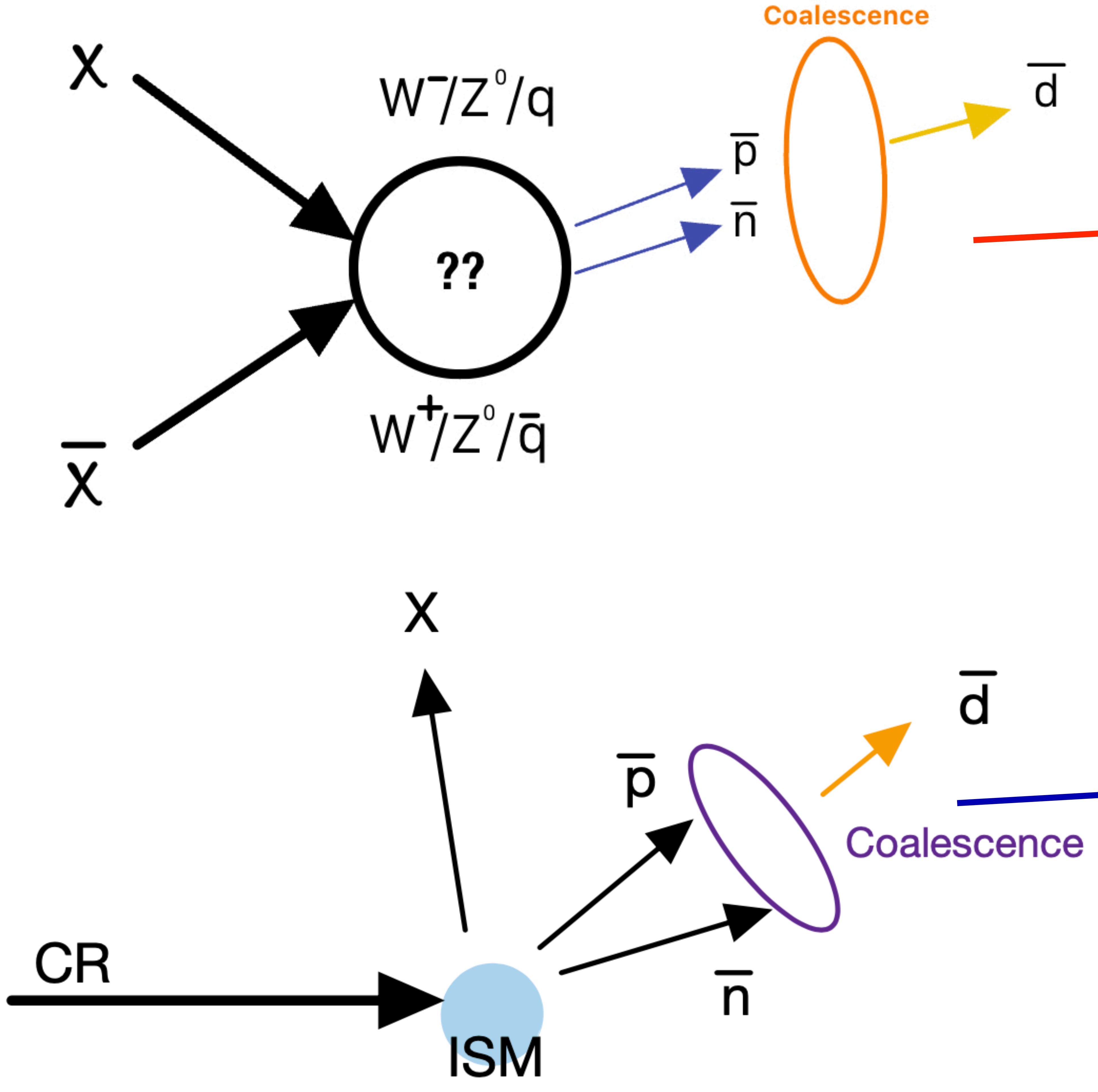
Antideuteuron production from beauty hadron decay

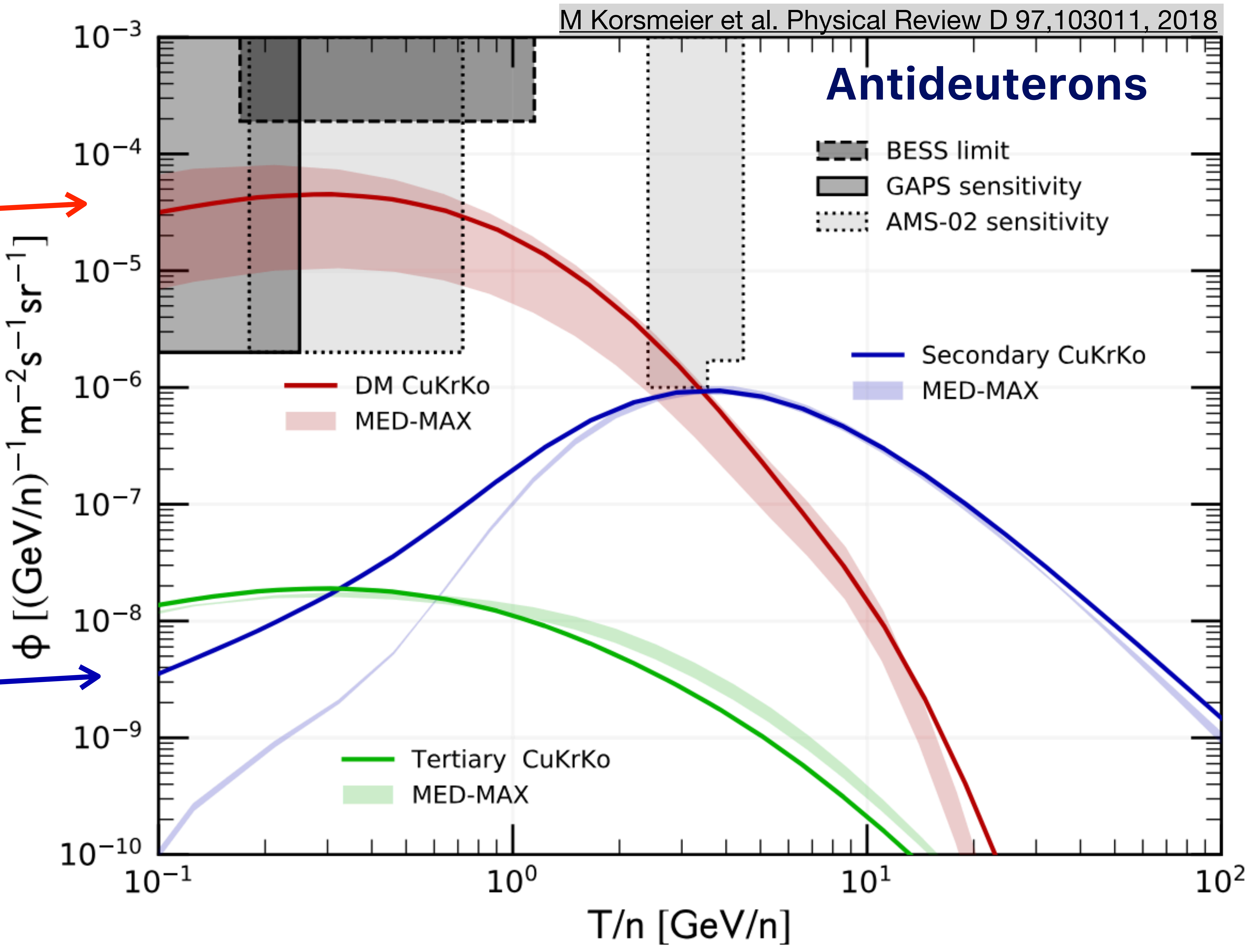
A path for collider searches

Marta Razza, University of Bologna, INFN

18/06/2025

Light antinuclei in cosmic rays





- $\bar{d}$, $^{3}\overline{He}$, $^{4}\overline{He}$ are currently in reach at accelerators. In cosmic rays they have never been observed, searches are ongoing.

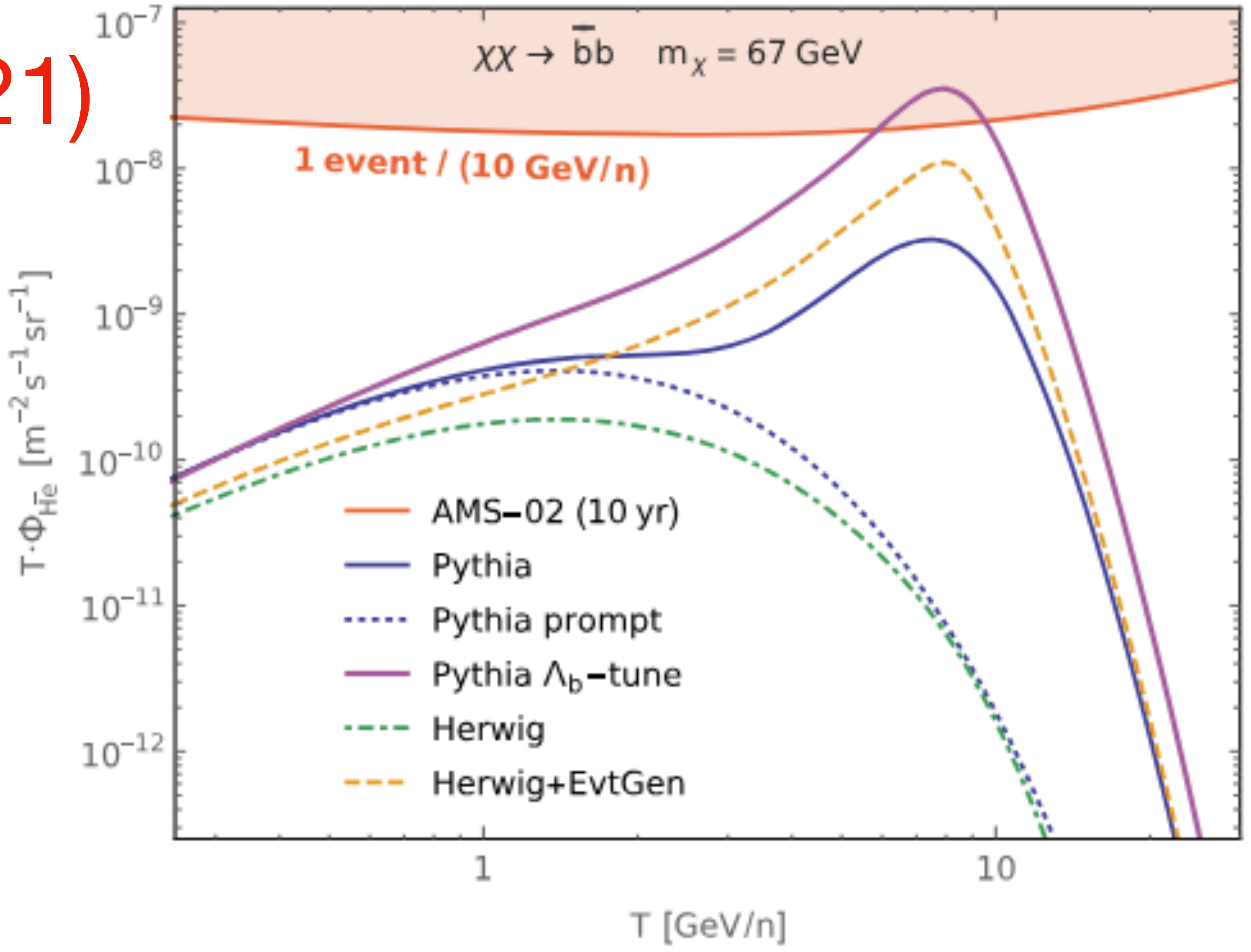
CR: Cosmic Ray

ISM: InterStellar Matter

Antinuclei production from $\overline{\Lambda}_b$

(WL21)

M.W. Winkler, T.Linden - Physical Review Letter 126,101101,2021 - APS



$$m(\overline{\Lambda}_b) = 5.62\,\mathrm{GeV/c^2}$$

- A new channel, proposed:

$$\chi\bar{\chi} \to b\bar{b} \to \overline{\Lambda}_b + X$$

$$\overline{\Lambda}_b \longrightarrow {}^3\overline{\mathrm{He}} + \mathrm{p} + \mathrm{p}$$

$^3\overline{\mathrm{He}}$ flux is expected to be detected by 10-years sensitivity of AMS-02.

- Flux obtained tuning PYTHIA to match LEP data for the transition rate:

$$\mathrm{f(b \to \Lambda_b)} = 0.1^{+0.04}_{-0.03}$$

Otherwise underestimated by a factor ~ 3

Antinuclei production from $\overline{\Lambda}_b$

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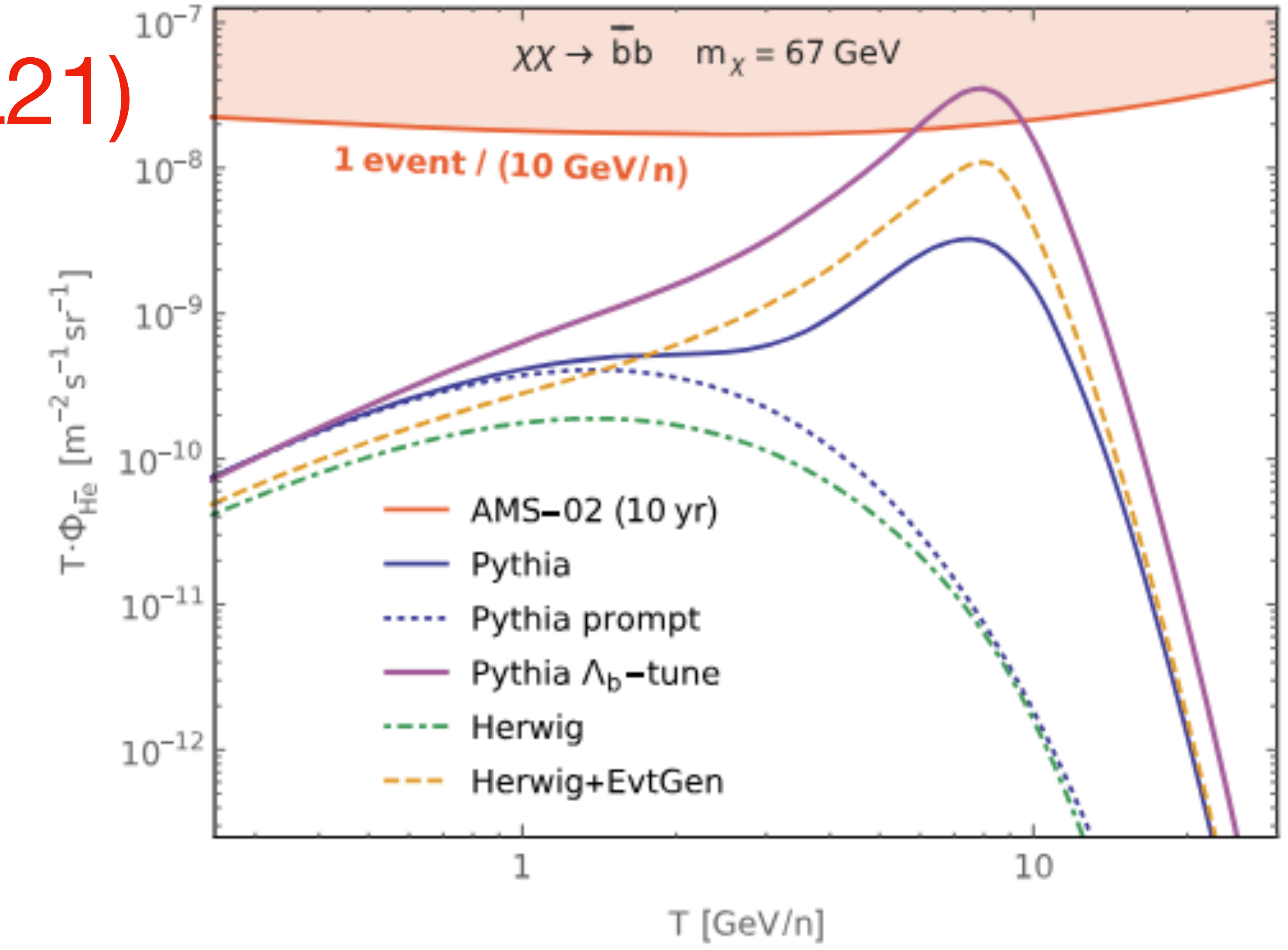

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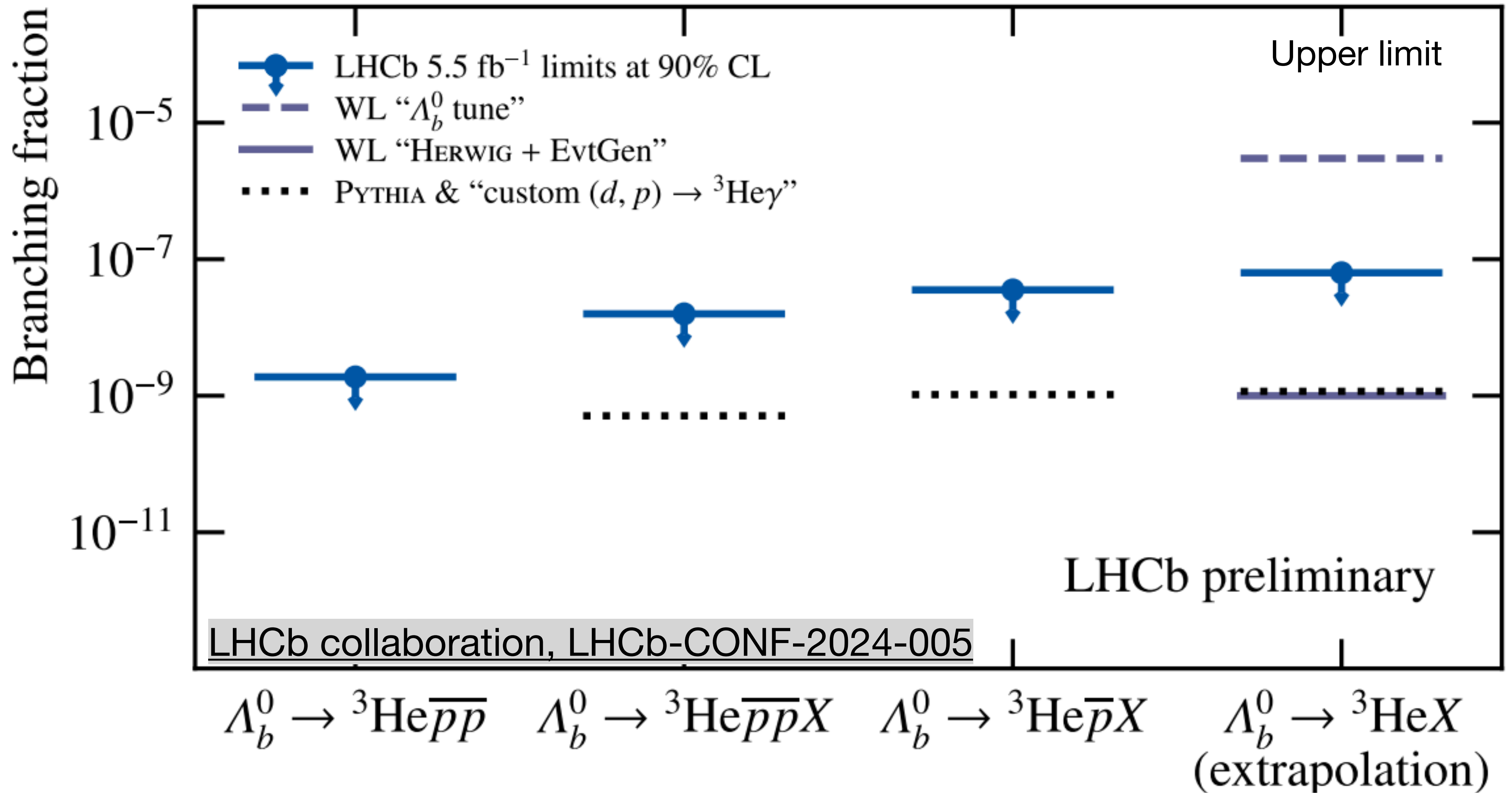
LHCb most recent result for $\Lambda_b \to {}^3\mathrm{He}$, 07/24



Antinuclei production beauty hadron decays

- The dark matter annihilation process can lead to the production of $b\bar{b}$ and then b-hadrons can be produced via hadronization.

$m(\bar{\mathrm{d}}) \sim 1.9\ \mathrm{GeV}/\mathrm{c}^2$

- Considering the: $m(\overline{\Lambda_b}) = 5.62\,\mathrm{GeV}/\mathrm{c}^2$ and $m(B^-) = 5.28\,\mathrm{GeV}/\mathrm{c}^2$, we cannot exclude the production of antideuterons from B mesons as well.

Goal: Extract the branching ratios of the two following decays:

$$\overline{\Lambda_b} \rightarrow \bar{\mathrm{d}} + X$$

$$B^- \rightarrow \bar{\mathrm{d}} + X$$

These channels have never been observed at the accelerators and the formation of $\bar{\mathrm{d}}$ is simpler to study since it involves the coalescence of only two antinucleons.

How to form antideuteron

Injection in PYTHIA of $\mathrm{N}_{\overline{\Lambda}_\mathrm{b}}, \mathrm{N}_{\mathrm{B}^-} = 10^8$ with $\eta \in [-1,1]$

↓

$\overline{\mathrm{p}}$ and $\overline{\mathrm{n}}$ production from $\overline{\Lambda}_b, B^-$ decays

↓

Coalescence process

Production in PYTHIA

- To simulate the production in PYTHIA of the hadrons of interest $\overline{\Lambda}_b, B^-$, a realistic spectrum was used.

FONLL Heavy quark production website, Cacciari et al. JHEP05(1998)007

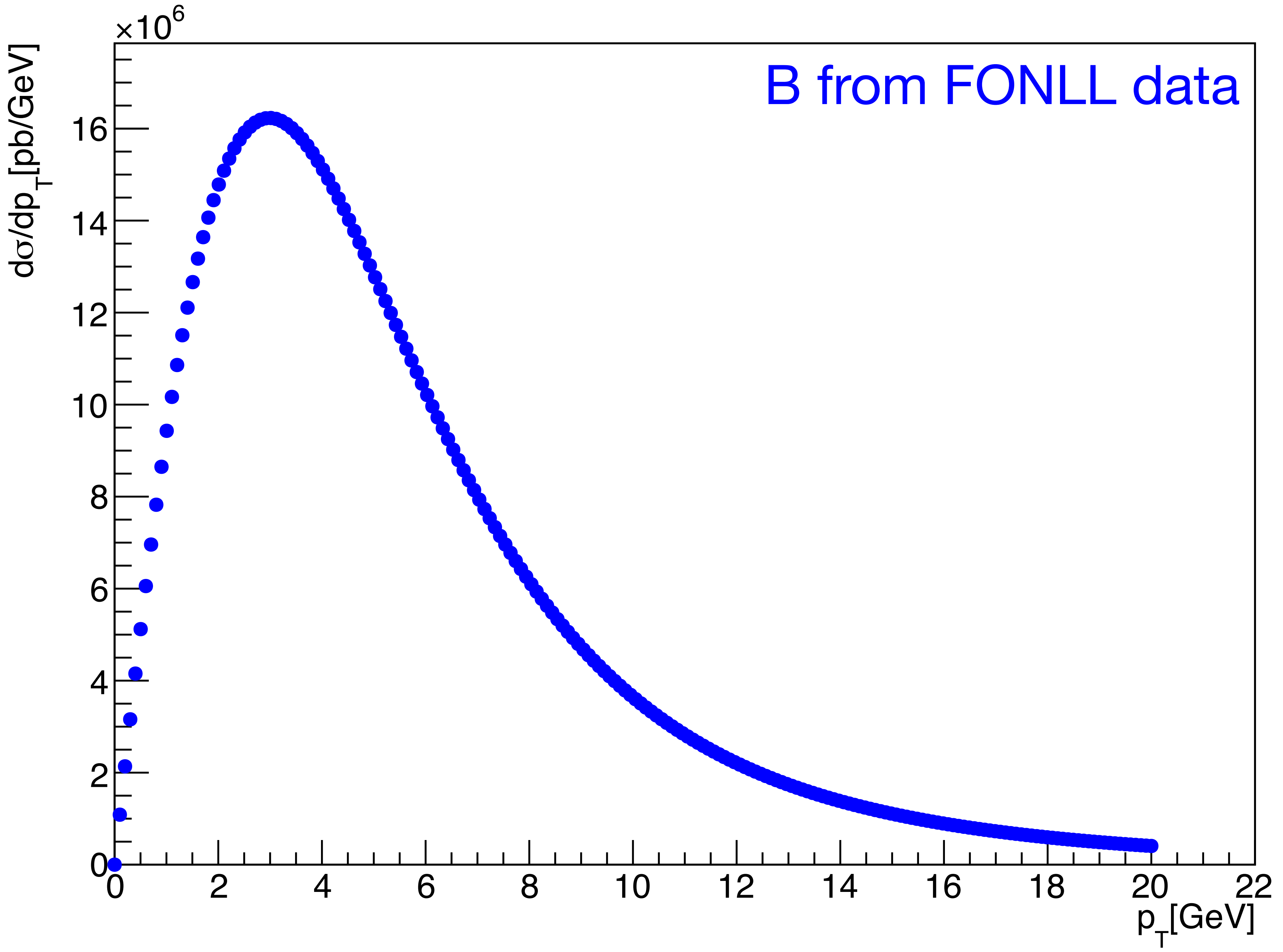
- $d\sigma/dp_T$ for B hadrons was computed via FONLL and the one for the $\overline{\Lambda_b}$ extracted thanks to this formula:

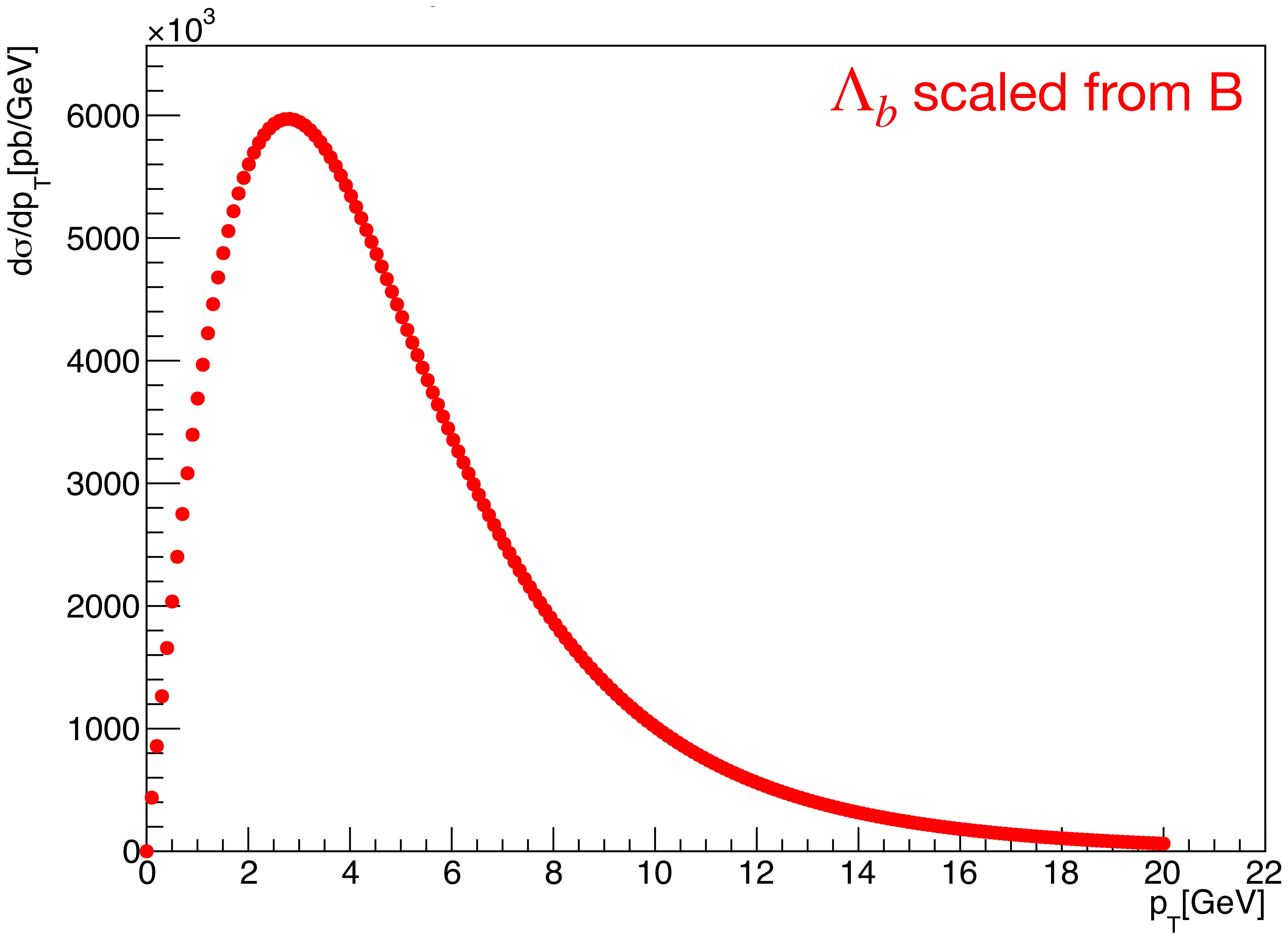
$$\frac{f_{\Lambda_b}}{f_u + f_d} = (0.404 \pm 0.017 \pm 0.027 \pm 0.105) \times [1 - (0.031 \pm 0.004 \pm 0.003) \times p_{\mathrm{T}}(\mathrm{GeV})]$$

The LHCb collaboration, PHYSICAL REVIEW D 85, 032008

Experimentally determined by the LHCb collaboration.

- The realistic spectra are:





Production in PYTHIA

- The parameter **probQQtoQ** directly affects the relative production rates of baryons compared to mesons.

```
parm  StringFlav:probQQtoQ  (default = 0.081; minimum = 0.0; maximum = 1.0)
```
the suppression of diquark production relative to quark production, i.e. of baryon relative to meson production.

Pythia 8 manual: https://arxiv.org/pdf/2203.11601

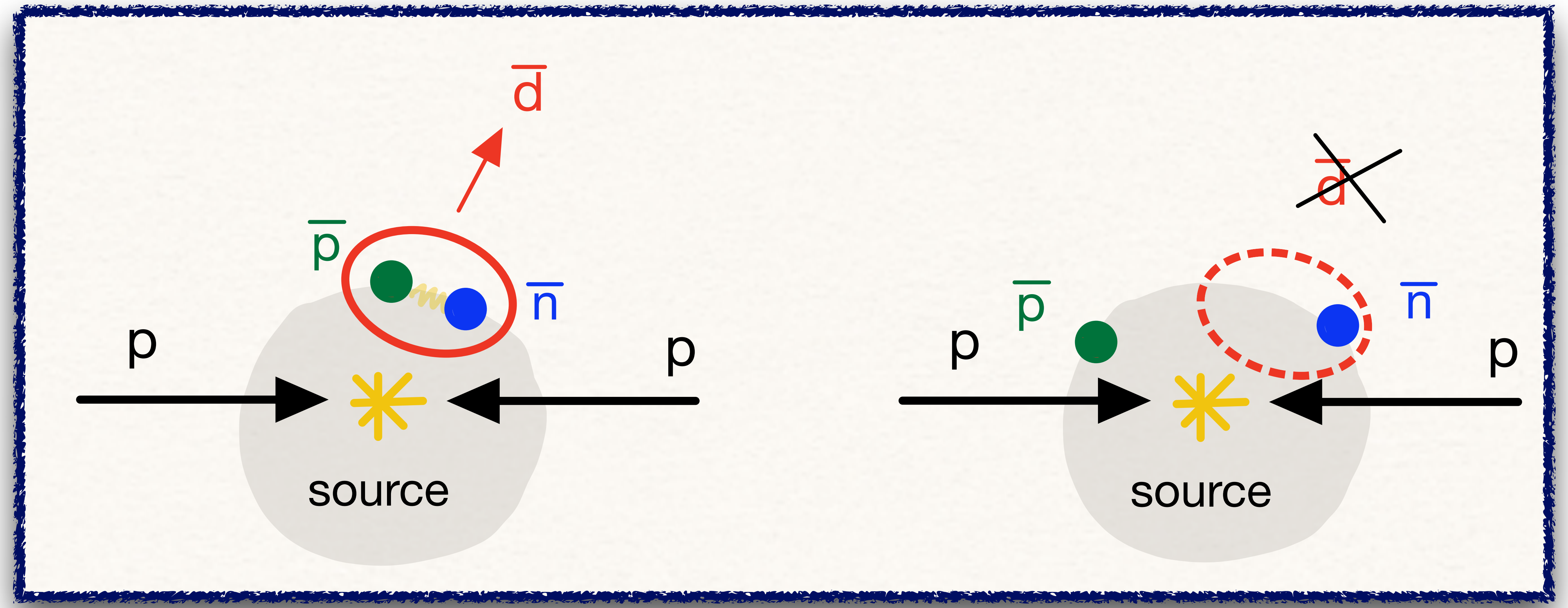
- The variation of this parameter influences the value of the transition rates: $f(b \to \Lambda_b, B)$.

Di Mauro,et al. *preprint arXiv:2504.07172* (2025).

- The value of **probQQtoQ** is set to **0.17** to best match the data. From: private communication with the author.

Coalescence mechanism

Coalescence is the mechanism by which two or more (anti)nucleons, sufficiently close in phase space, can bind together to form a (anti)nucleus due to the attractive (nuclear) strong interaction.



- Using a simple description of the coalescence process, antinucleons can merge if the following condition is satisfied:

$$|\vec{p_1} - \vec{p_2}| < p_{coal}$$

(Approach used by WL21)

- p_{coal} cannot be determined from first principles and it may be dependent on the process (e.g. collision system!)

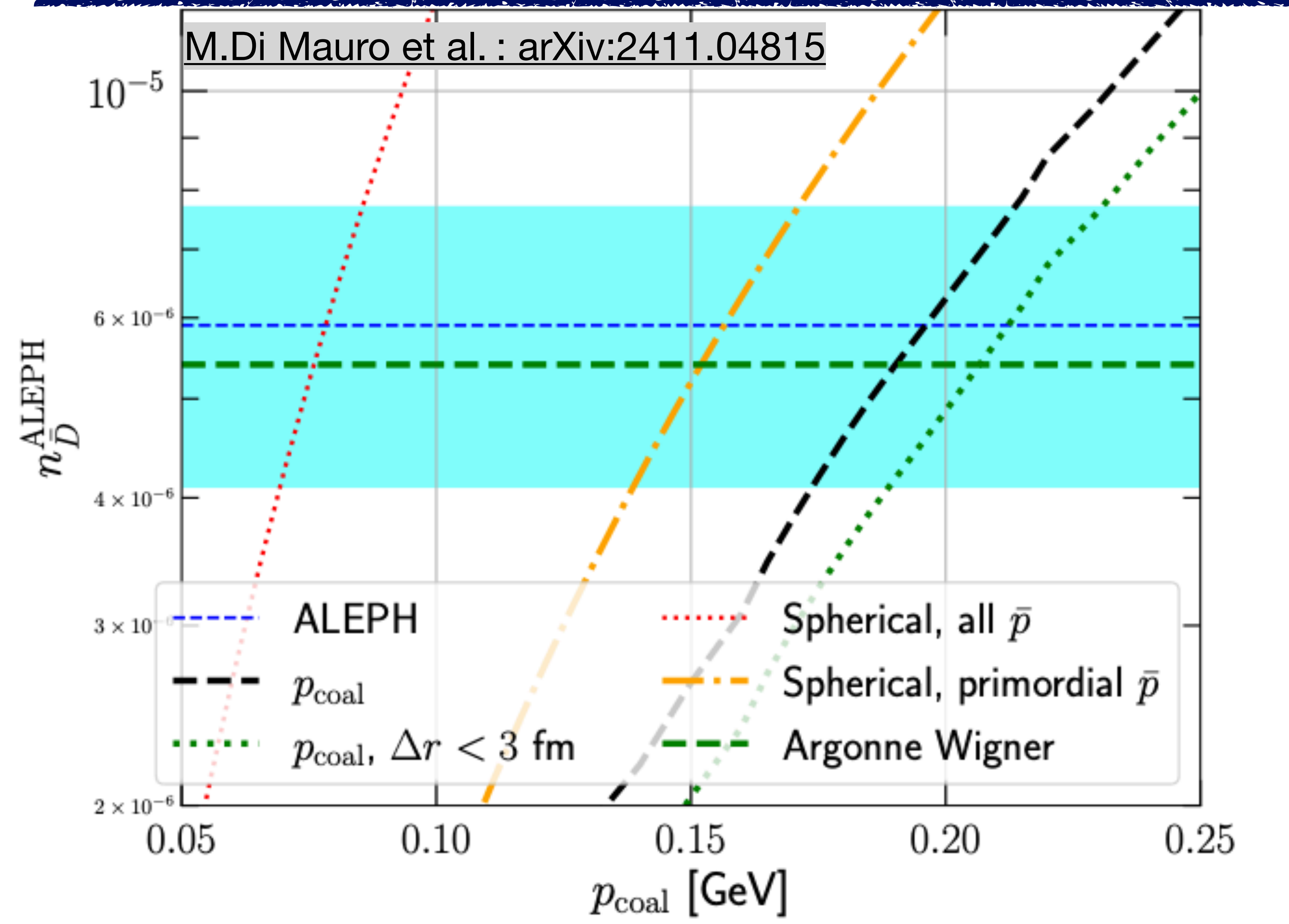
- In more detailed/sophisticated models, the formation probability depends on the nucleus wave-function, the momentum and the size of the particle emitting source (evidence from LHC data).

M.Di Mauro et al. : arXiv:2411.04815

Coalescence model

- A state-of-the-art quantum mechanical model is used in this work in which the probability to coalesce is given by the projection of the (anti)proton and (anti)neutron wave functions over the antideuteron one.
  arXiv:2302.12696 and K.Blum et al., PRC 103, 014907 (2021) for derivation
- The model was implemented within the CosmicAntiNuclei group. M.Mahlein et al. Eur. Phys. J. C (2023) 83 :804
- For the antideuteron wave-function, the Argonne ν_{18}, tuned on p-p and n-p scattering data, is used for this analysis. Wiringa et al., Phys. Rev. C 51, 38 (1995)

Argonne reproduces the ALEPH data for antideuteron while other approaches show yield dependence on the p_{coal} tuning.

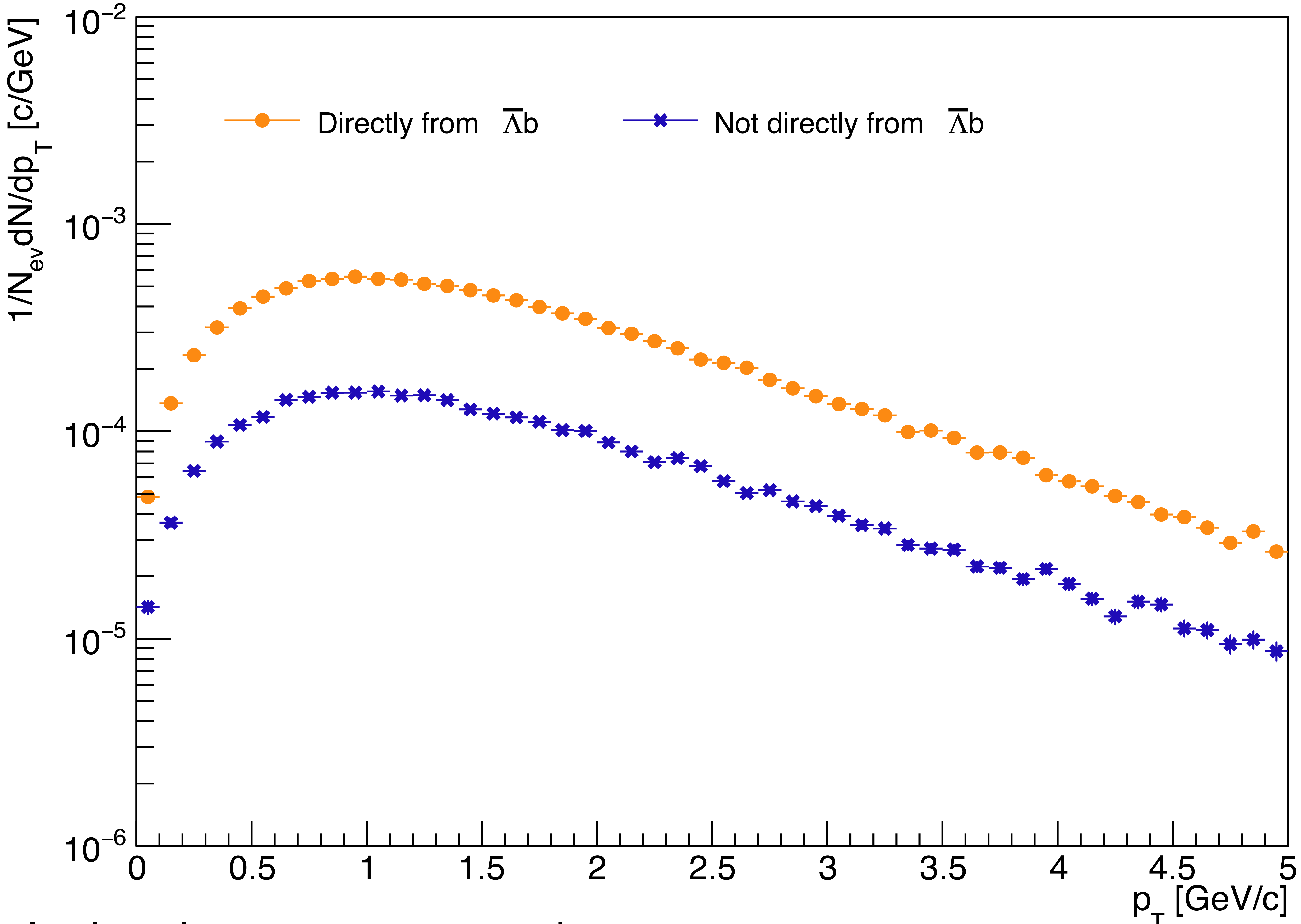


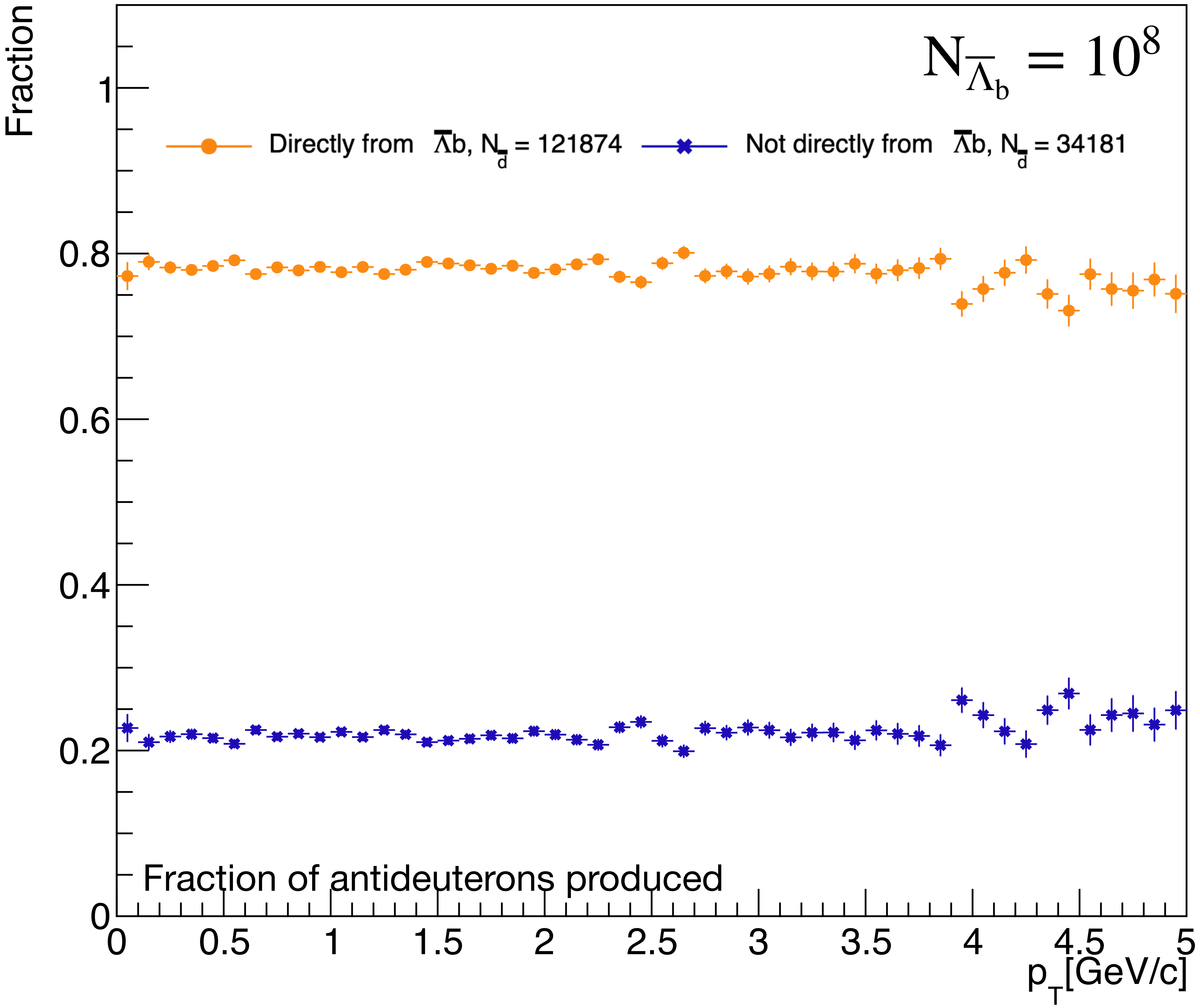
The strength of this approach lies in:

1. Realistic potential for deuteron and antideuteron,
2. Requires no further tuning of coalescence parameters
3. Proven to be the best at reproducing ALICE HM data M.Mahlein et al. Eur. Phys. J. C (2023) 83 :804
4. Used to predict antideuterons from Dark Matter M.Di Mauro et al. : arXiv:2411.04815

Results for $\overline{\Lambda_b} \to \bar{\mathrm{d}} + X$

$$\mathrm{BR}(\overline{\Lambda_b} \to \bar{\mathrm{d}} + \mathrm{X}) = (1.561 \pm 0.003) \times 10^{-3}$$



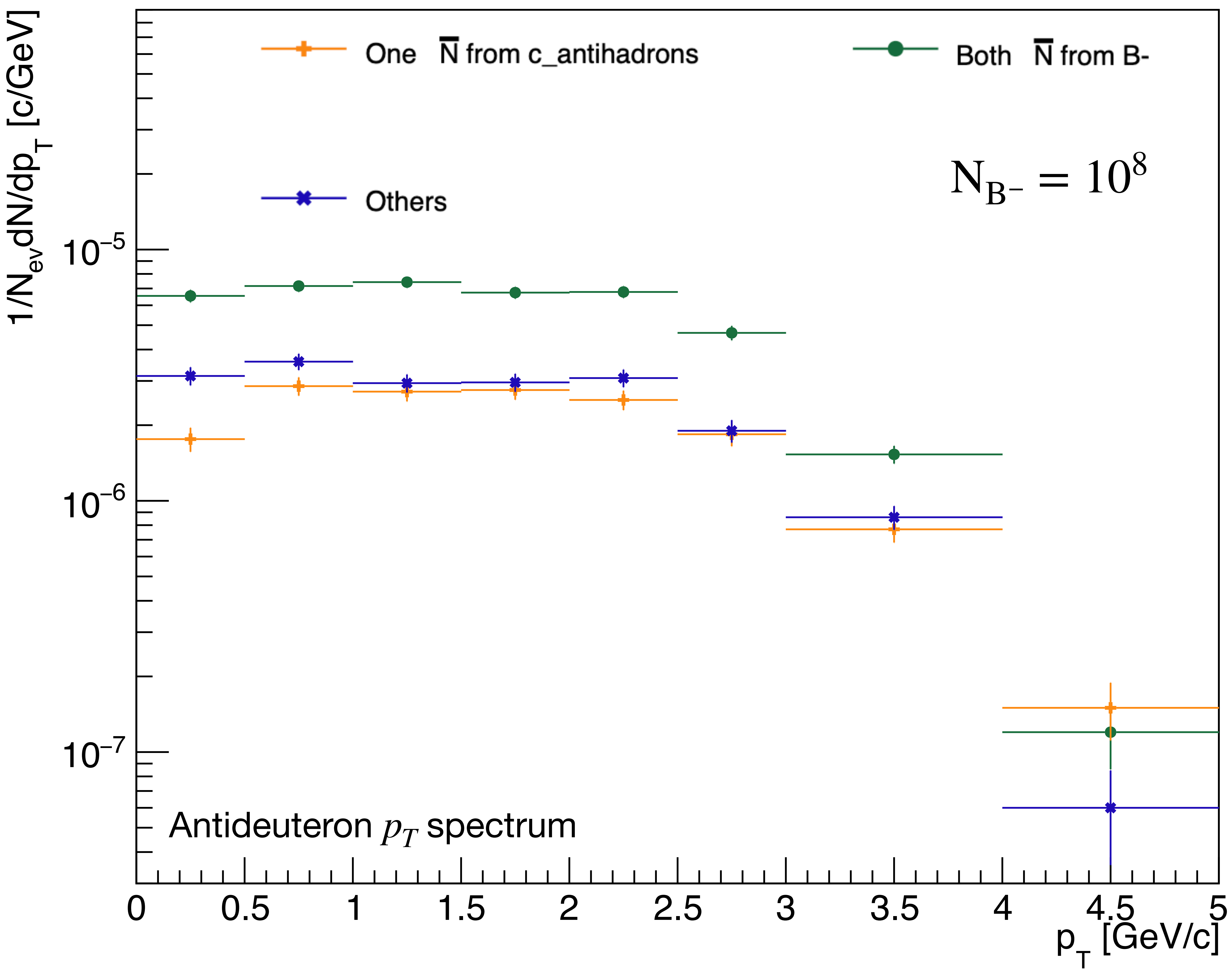


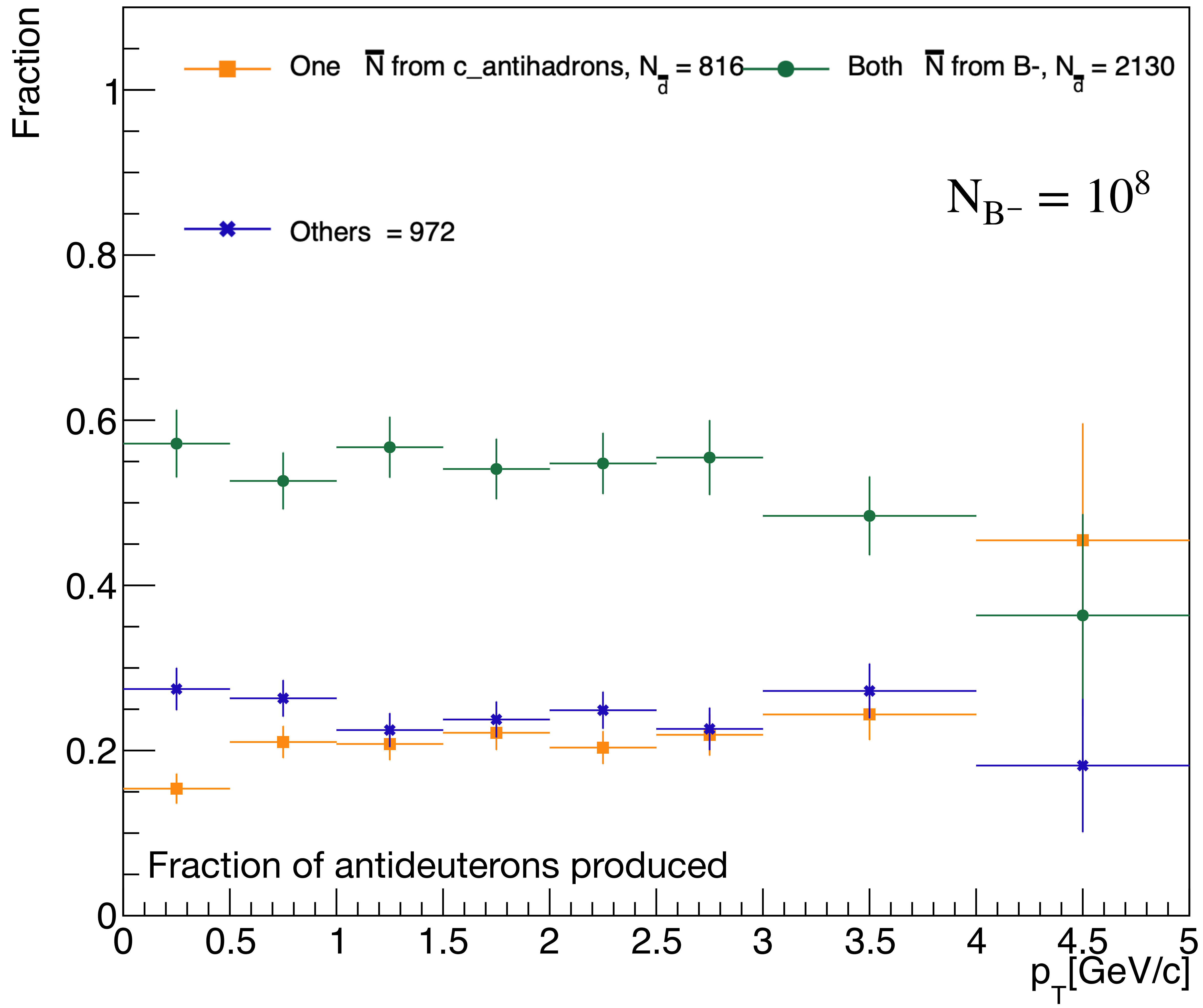
In the plot two cases are shown:

1. **Orange**: both antinucleons directly produced from $\overline{\Lambda_b}$ decay, $N_{\bar{d}} = 121874$
2. **Blue**: antinucleons are not directly produced from $\overline{\Lambda_b}$ decay $N_{\bar{d}} = 34181$

Results for $B^- \to \bar{d} + X$

$$BR(B^- \to \bar{d} + X) = (3.92 \pm 0.06) \times 10^{-5}$$





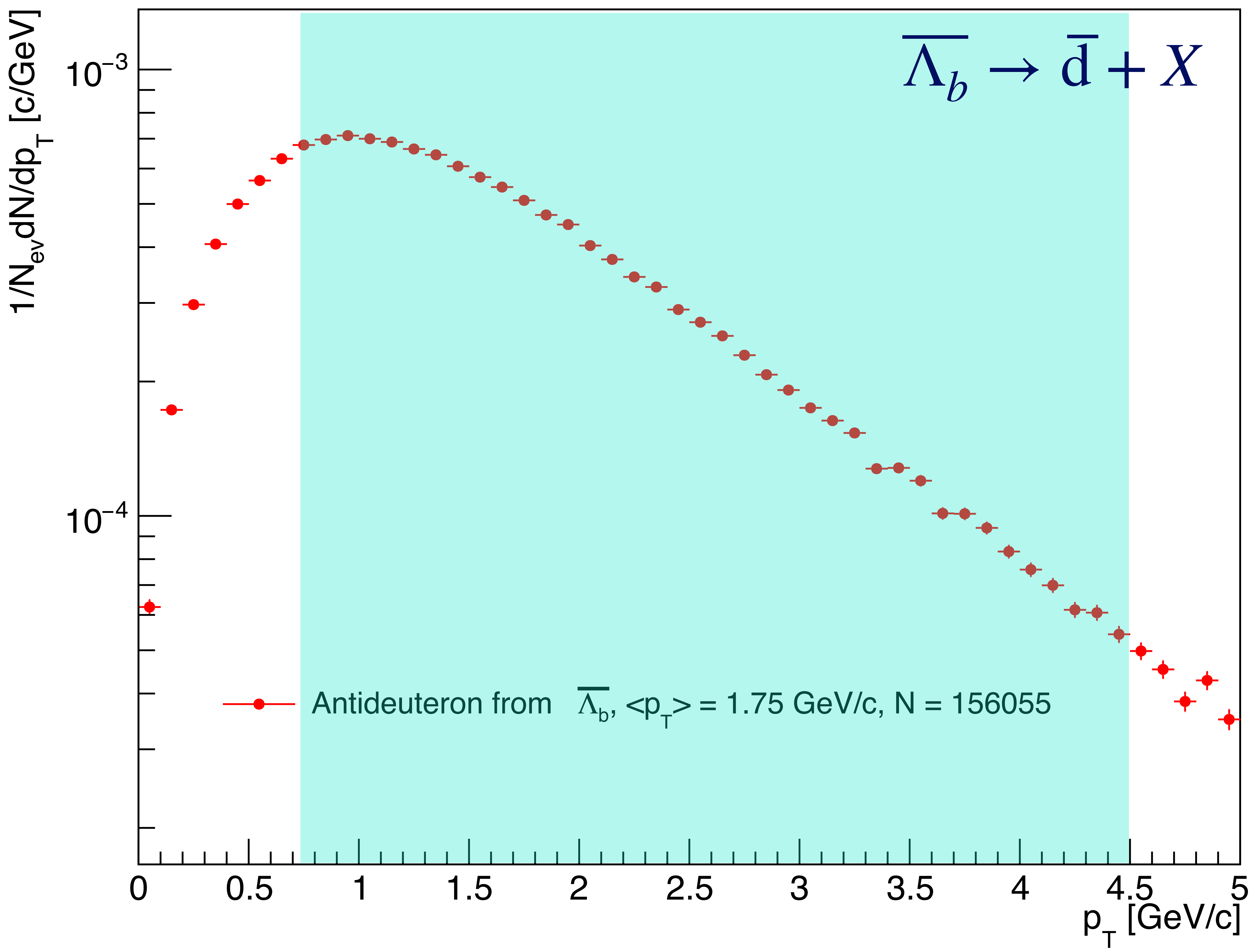
1. **Orange**: one antinucleon from B^- and the other one from a hadron containing a c quark, $N_{\bar{d}} = 816$
2. **Green**: both antinucleons directly produced from B^-, $N_{\bar{d}} = 2130$
3. **Blue**: other cases, $N_{\bar{d}} = 972$

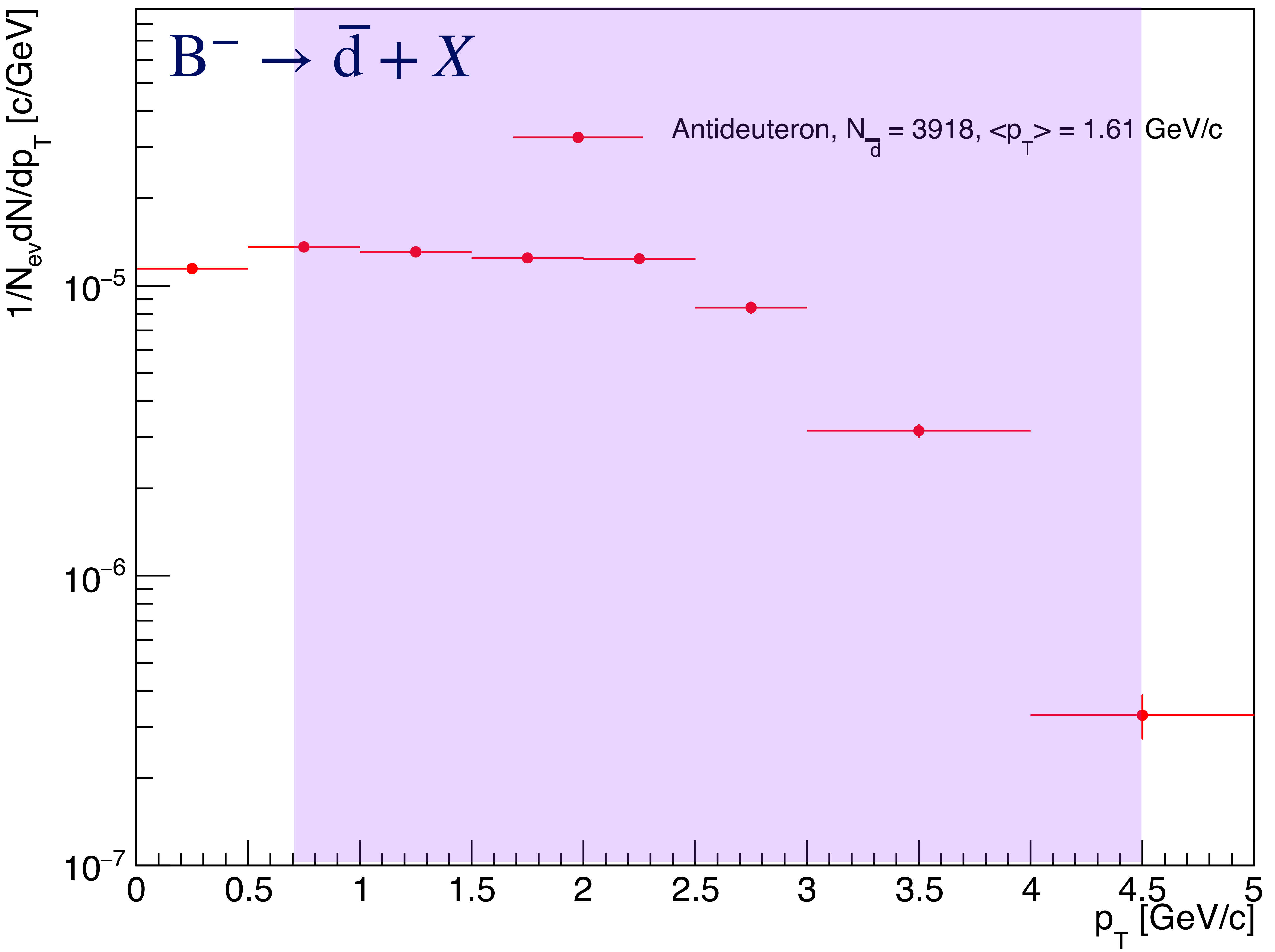
How many antideuterons from $\overline{\Lambda}_b$, B^- in ALICE?

Expected antideuteron in ALICE

ALICE collaboration, The ALICE experiment: a journey through QCD

- In ALICE the identification of antideuterons is performed with Time Projection Chamber and Time Of Flight in the range $0.7 < p_T < 4.5$ GeV/c and $|\eta| < 0.8$:





The portion of the antideuteron spectra produced from $\overline{\Lambda}_b$ and B^- decays that falls in the acceptance and identification range is the one that is close to the maximum of the distribution!

Expected antideuteron in ALICE

- The luminosity target for the end of the Run 4 in ALICE is: $\mathrm{L} = 200\ \mathrm{pb}^{-1}$

- With $\sigma(\mathrm{pp} \to \mathrm{b}\bar{\mathrm{b}}) \simeq 3.5 \times 10^{8}\ \mathrm{pb}$ at the LHC ($\sqrt{s} = 14\ \mathrm{TeV}$)

  MCFM + Higgs European Strategy

  and $f(\mathrm{b} \to \Lambda_\mathrm{b}) = 0.089 \pm 0.012$, $f(\mathrm{b} \to \mathrm{B}^{+}) = 0.407 \pm 0.007$

  Amhis et al., The European Physical Journal C 81 (2021): 1-326.

- We estimate in $|\eta| < 1$:

$$\mathrm{N}_{\Lambda_\mathrm{b}} \sim 6 \times 10^{9} \qquad \mathrm{N}_{\mathrm{B}^{+}} \sim 3 \times 10^{10}$$

- The number of expected antideuterons on the basis of our BR estimations is:

$$\mathrm{BR}(\overline{\Lambda_\mathrm{b}} \to \bar{\mathrm{d}} + \mathrm{X}) = (1.561 \pm 0.003) \times 10^{-3}$$

$$\mathrm{BR}(\mathrm{B}^{-} \to \bar{\mathrm{d}} + \mathrm{X}) = (3.92 \pm 0.06) \times 10^{-5}$$

From $\overline{\Lambda}_b$

$$\mathrm{N}_{\bar{\mathrm{d}}} \simeq 9.7 \times 10^{6}$$

From B^{-}

$$\mathrm{N}_{\bar{\mathrm{d}}} \simeq 1.1 \times 10^{6}$$

- **Next step**: To perform the simulation of the ALICE detector, in order to account for its performance and guide the experimental search.

Thank you for the attention

Contacts:

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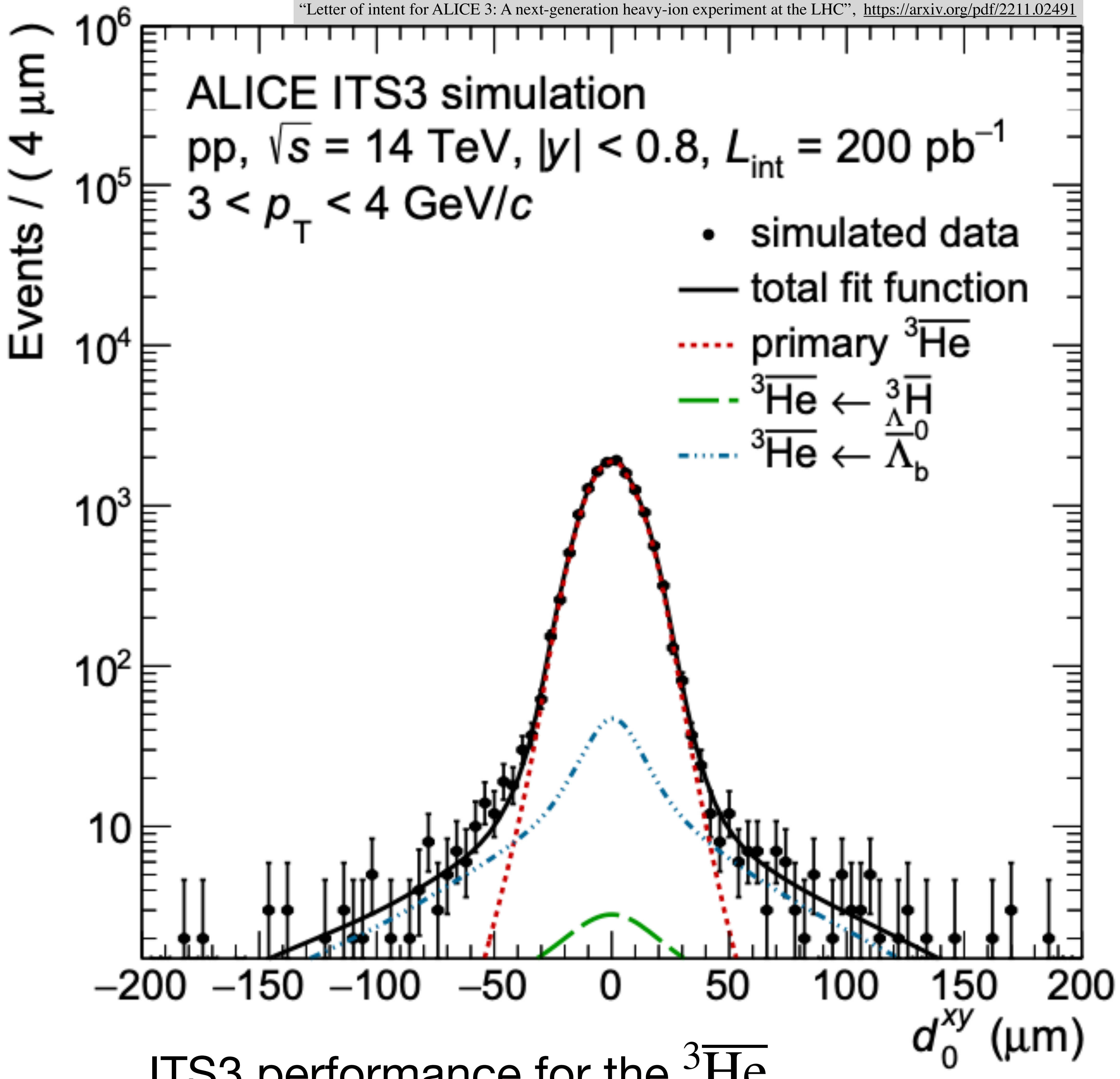
- marta.razza@cern.ch

How to distinguish primary from secondary candidates

"The ITS3 detector and physics reach of the LS3 ALICE Upgrade", https://arxiv.org/pdf/2409.01866

- During the Long Shutdown 3 a new Inner Tracking System (ITS3) will be installed.
- Extremely low material budget and proximity to the interaction point (19 mm) will lead to about a factor of two improvement in pointing resolutions for very low p_T (O(100MeV/c)), achieving 20 μm and 15 μm in the transverse and longitudinal directions.
- The enhanced resolution will be crucial for reconstructing particles like $\overline{\Lambda}_b$ (decay length $\approx$ 441μm), as it enables precise separation of the decay vertex from the primary vertex.

"Letter of intent for ALICE 3: A next-generation heavy-ion experiment at the LHC", https://arxiv.org/pdf/2211.02491



ITS3 performance for the $^3\overline{\mathrm{He}}$

Role of probQQtoQ in Pythia for $\overline{\Lambda}_b$ decay

To understand the importance of comparing the different values of probQQtoQ in PYTHIA:

```
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channel: onMode="1" bRatio="0.0096000" meMode="22" products="-12 11 4124"
channel: onMode="1" bRatio="0.0128000" meMode="22" products="-12 11 14122"
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channel: onMode="1" bRatio="0.0096000" meMode="22" products="-14 13 4124"
channel: onMode="1" bRatio="0.0128000" meMode="22" products="-14 13 14122"
channel: onMode="1" bRatio="0.0172000" meMode="22" products="-16 15 4122"
channel: onMode="1" bRatio="0.0032000" meMode="22" products="-16 15 4124"
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channel: onMode="1" bRatio="0.0008000" products="2112 421"
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channel: onMode="1" bRatio="0.0003800" products="100443 3122"
channel: onMode="1" bRatio="0.0220000" products="4122 211 -211 -211"
channel: onMode="1" bRatio="0.0200000" products="3122 311 211 211 -211 -211"
channel: onMode="1" bRatio="0.0120000" meMode="22" products="-2 1 2 2101"
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channel: onMode="1" bRatio="0.0120000" meMode="22" products="-4 3 2 2101"
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```

explicit decay modes

"Inclusive" modes

channel: onMode="1" bRatio="0.4411147" meMode="23" products="-2 1 4 2101"

- This mode decays to a ubar+d system and a c+(ud0) system, where the (ud0) is a "diquark"
- Varying the probQQtoQ parameter, we are modifying these decay modes as well.

parm **StringFlav:probQQtoQ** (default = **0.081**; minimum = **0.0**; maximum = **1.0**)
the suppression of diquark production relative to quark production, i.e. of baryon relative to meson production

Pythia manual: https://arxiv.org/pdf/2203.11601

- The fragmentation function represents the probability that a parton i produces a hadron h carrying a fraction z of the parton's momentum.

- For these "inclusive" modes this dependence plays an important role and it becomes crucial to have a comparison between a flat and a realistic spectrum of the particles injected.