CosmicAntiNuclei

INFN BOLOGNA
Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

Antinuclei from beauty-hadrons

Results and plans

Marta Razza, Università di Bologna, INFN

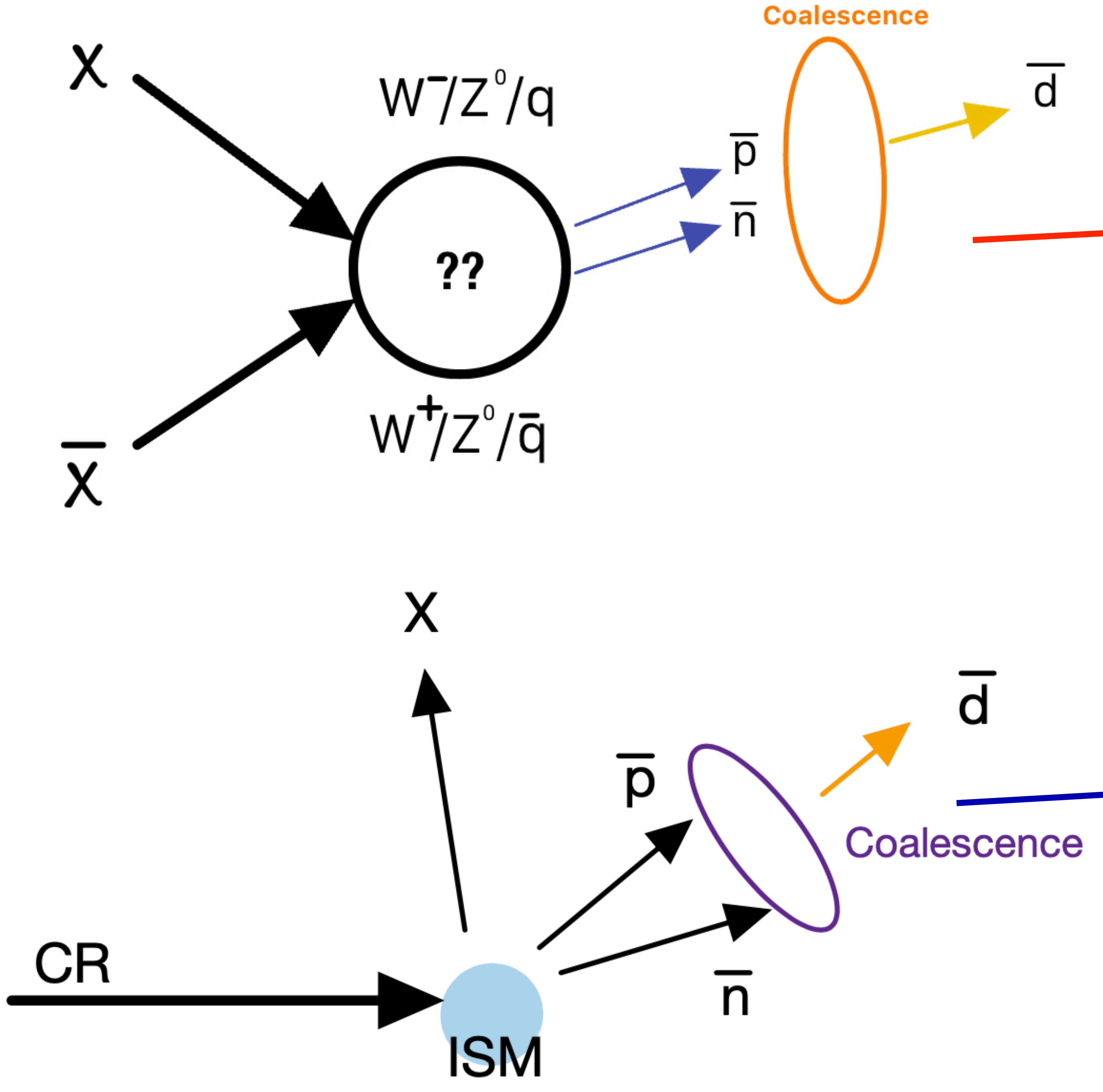
26/03/2025

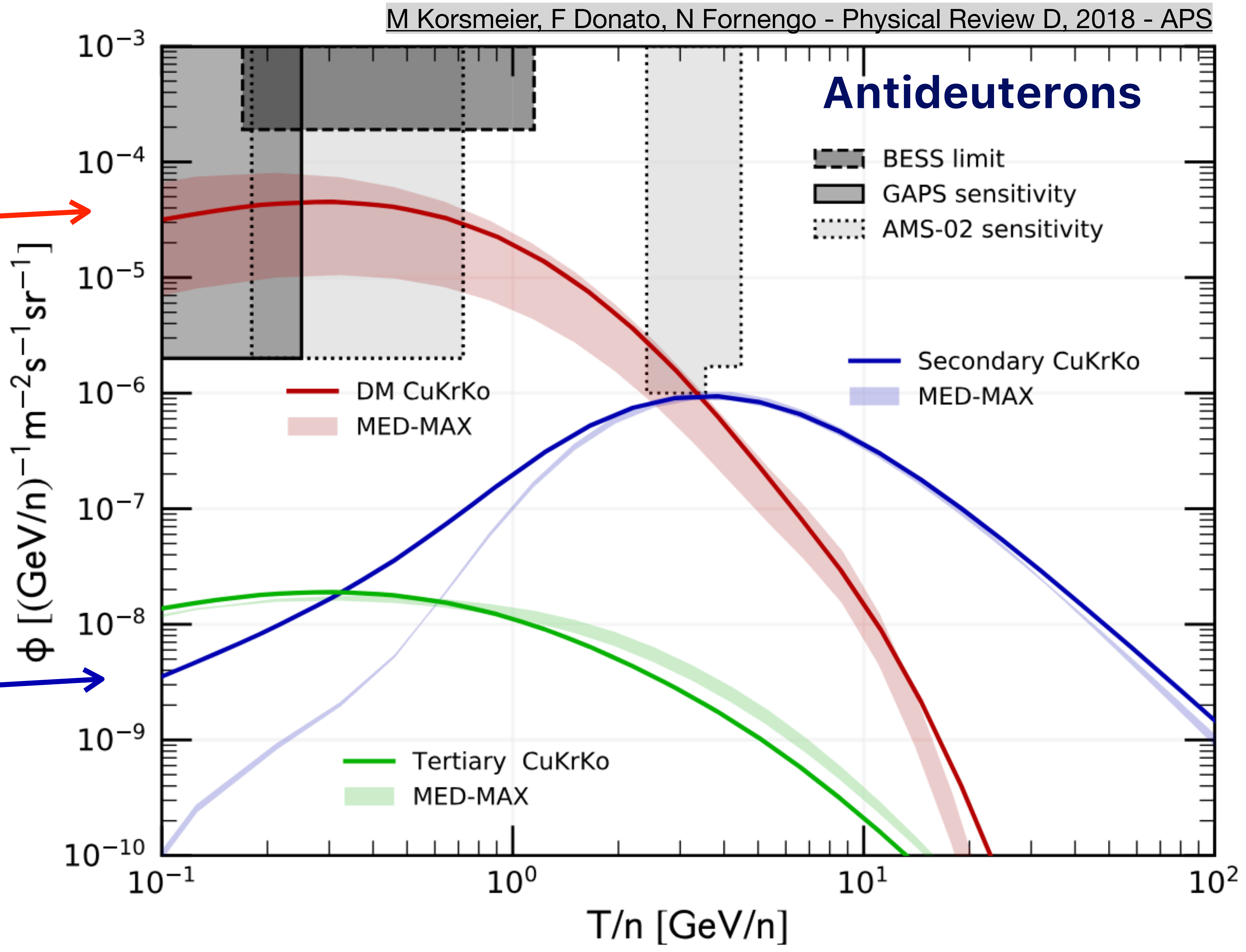
Few words about me

- I am Marta Razza, I studied at the University of Bologna.
- I got the master's degree in Physics at the University of Bologna in October 2024.
- I worked on a thesis titled "Study of antideuteron production from $\overline{\Lambda}_b$" under the supervision of Prof. Francesca Bellini and Dr. Nicolò Jacazio.
- From the beginning of March 2025 I work as a research fellow within the group CosmicAntiNuclei under the supervision of Prof. Francesca Bellini.

Introduction

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

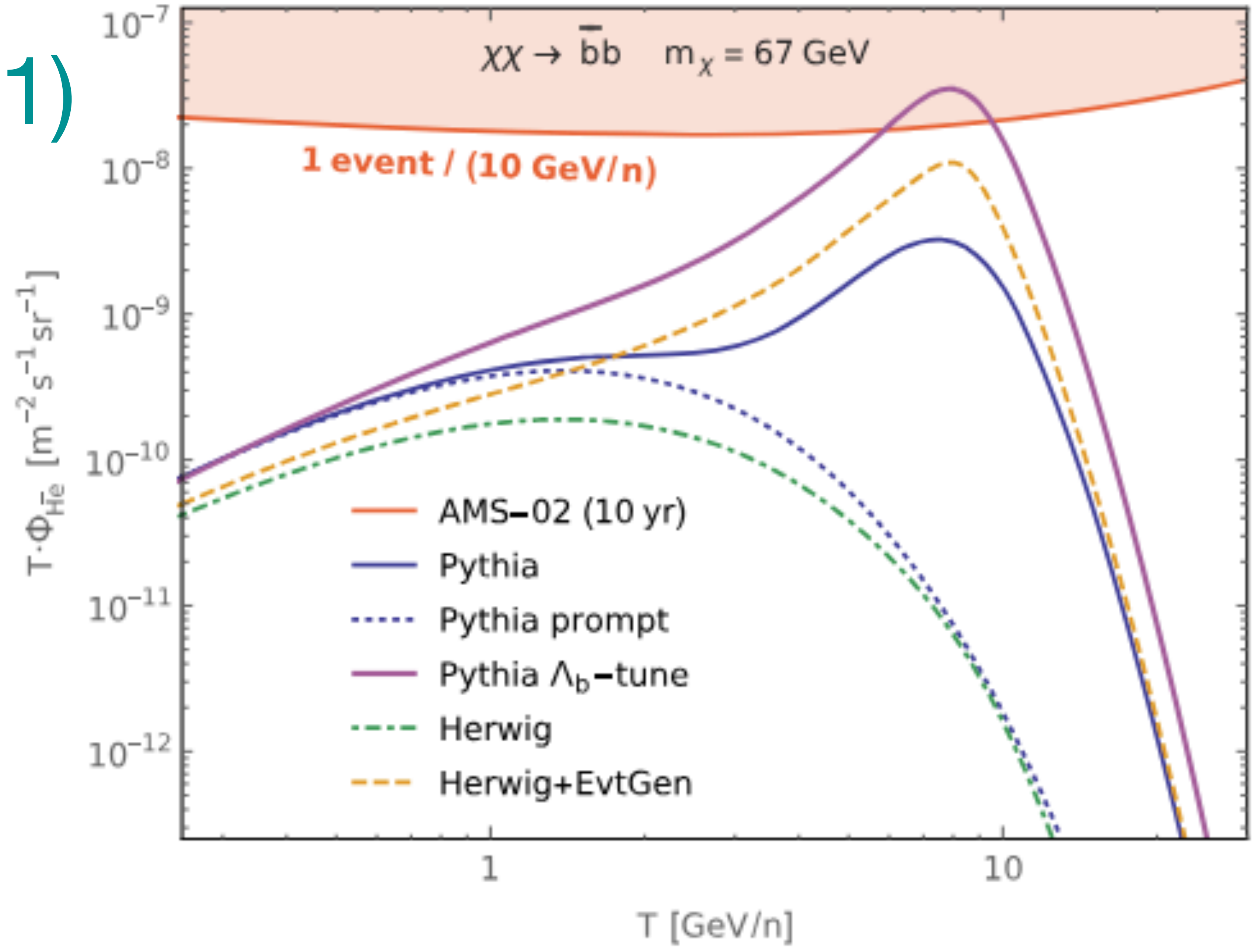
- A new channel, proposed:

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

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

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

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



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

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

Otherwise underestimated by a factor ~ 3

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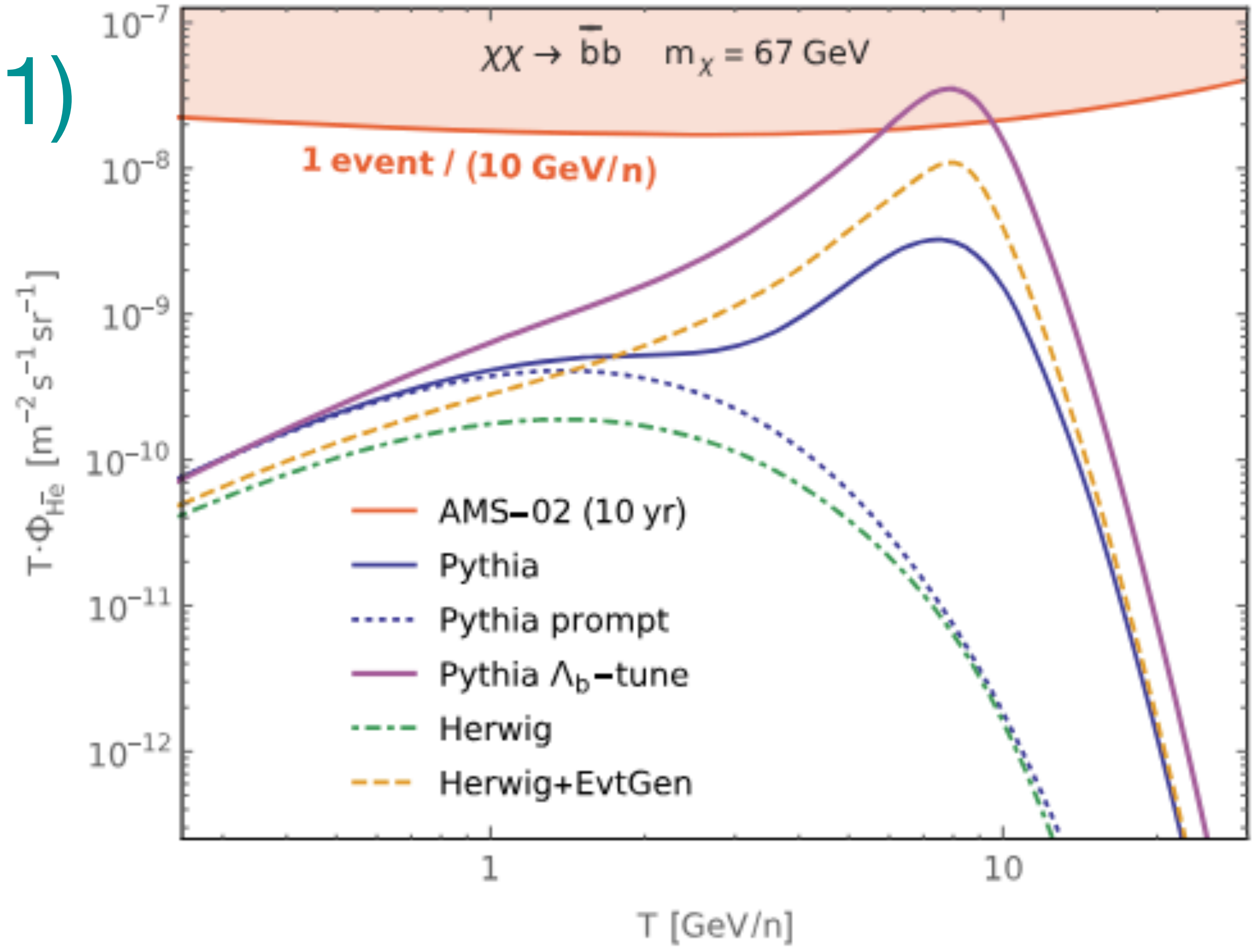

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Goal: To provide a first estimate of the branching ratio (BR) for the decay $\overline{\Lambda}_b \to \bar{\mathrm{d}} + X$.

This channel has 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.

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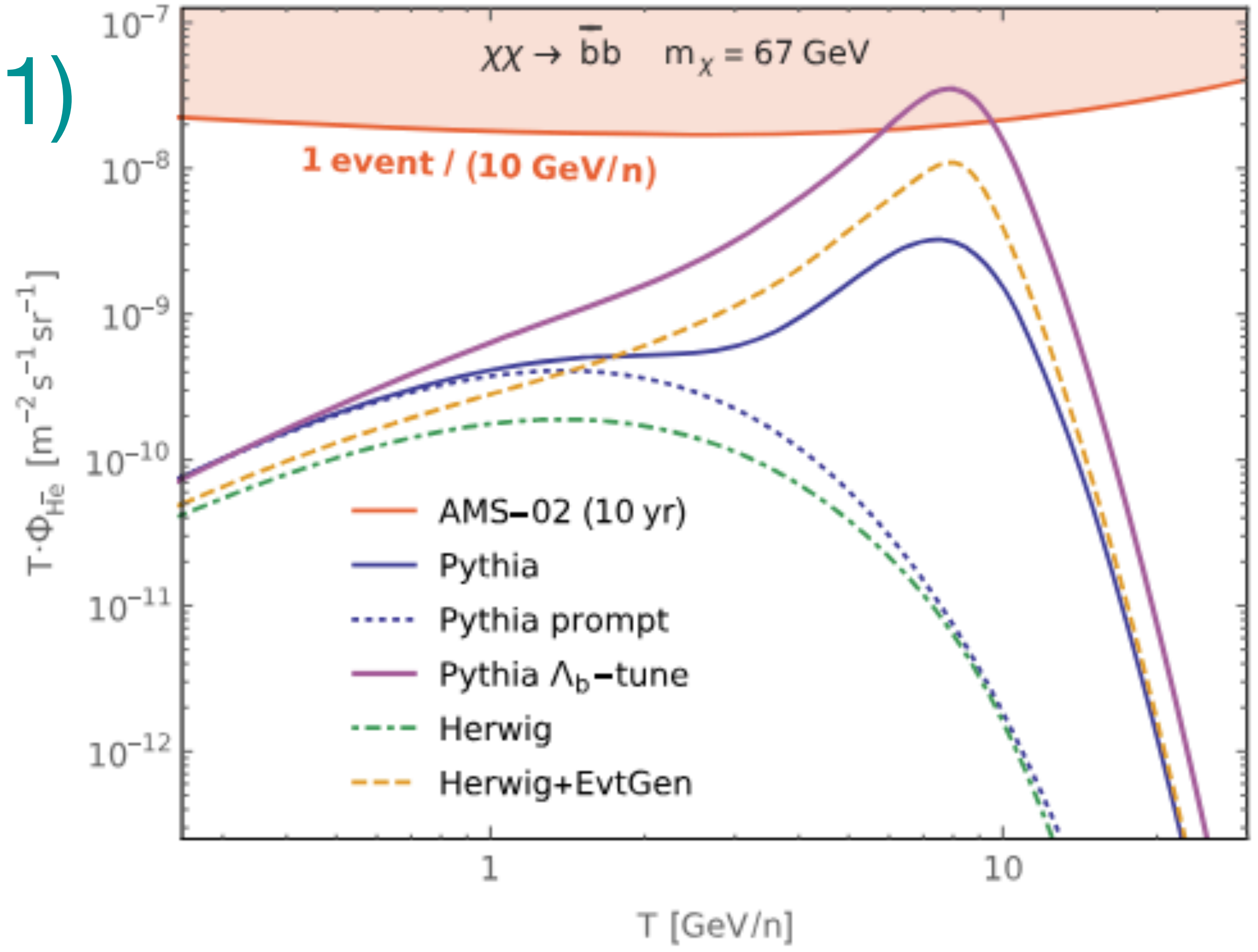

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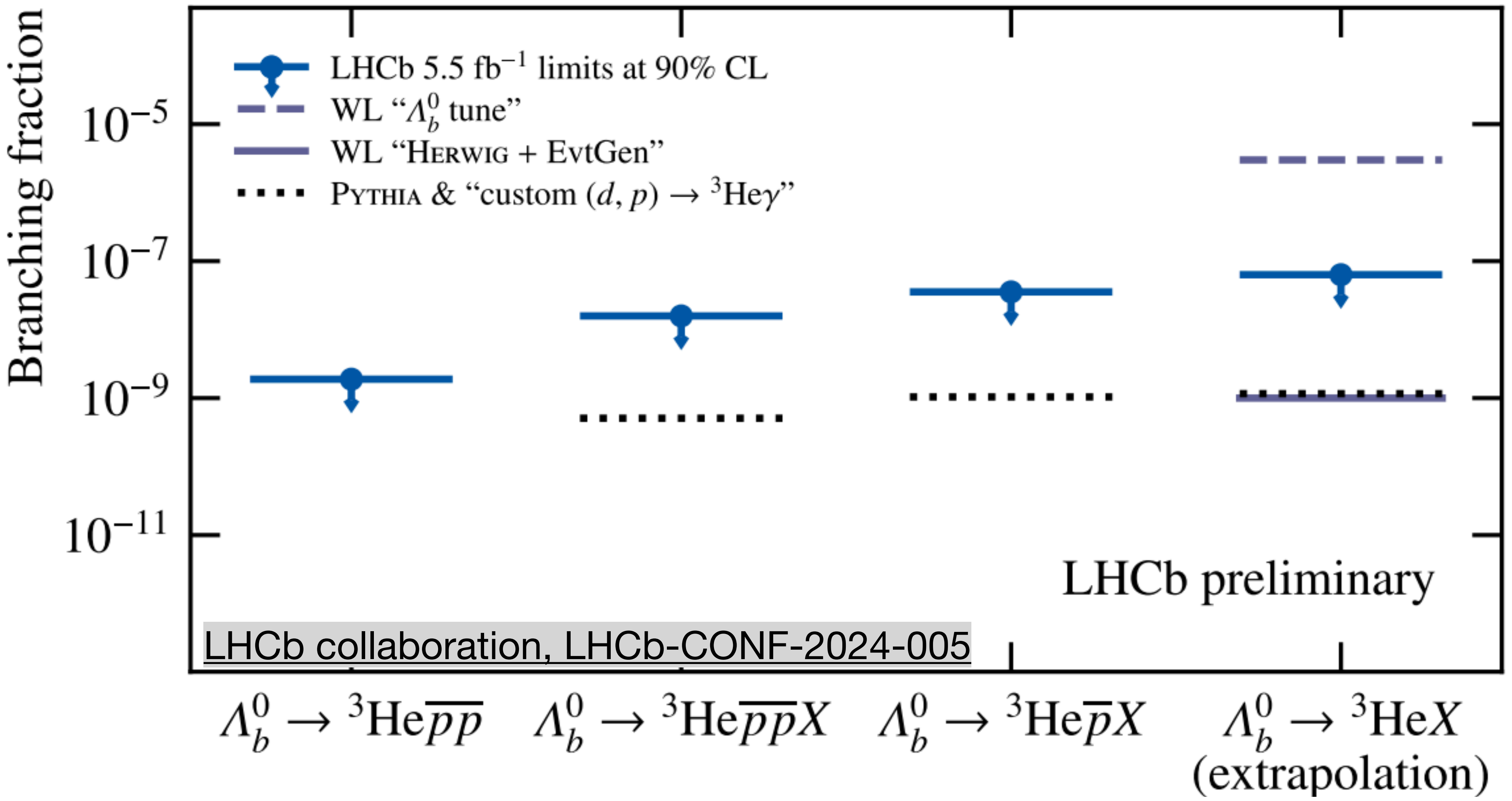
LHCb most recent result for $\Lambda_b \to {}^3\mathrm{He}$, 07/24



LHCb collaboration, LHCb-CONF-2024-005

General overview of my thesis

- PYTHIA MC generator to simulate proton-proton collision at $\sqrt{s}$ = 13.6 TeV, tuning the simulation as WL21.

- The parameter varied is **probQQtoQ** from 0.081 to 0.24. This 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 manual: https://arxiv.org/pdf/2203.11601

- Implementation of a classical coalescence model.

- $\overline{\Lambda_b}$ scenario implemented in a state-of-the-art quantum coalescence model

- **Estimation of the branching ratio** using the two models.

Antideuteron production from b-decays

How to form the antideuteron

pp collisions in PYTHIA at $\sqrt{s}$ = 13.6 TeV

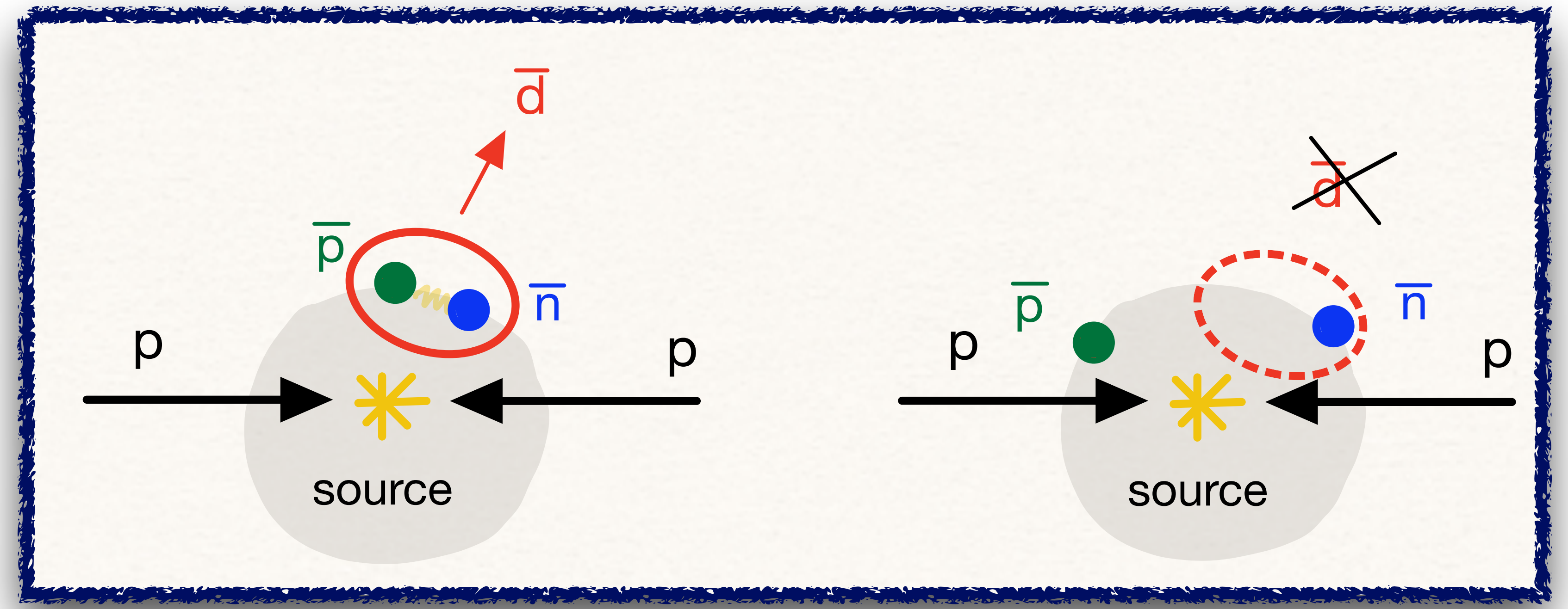
↓

$\bar{p}$ and $\bar{n}$ production from $\overline{\Lambda}_b$ decay

↓

Coalescence process

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 formation process of the (anti)nucleus.

M.Di Mauro et al. : arXiv:2411.04815

Coalescence models

- I implemented a **Classical Model**
- Antinucleons merge if :

$$|\vec{p_1} - \vec{p_2}| < p_c$$

where $p_c = 219 \text{ MeV/c}$ according to WL21,

and if:

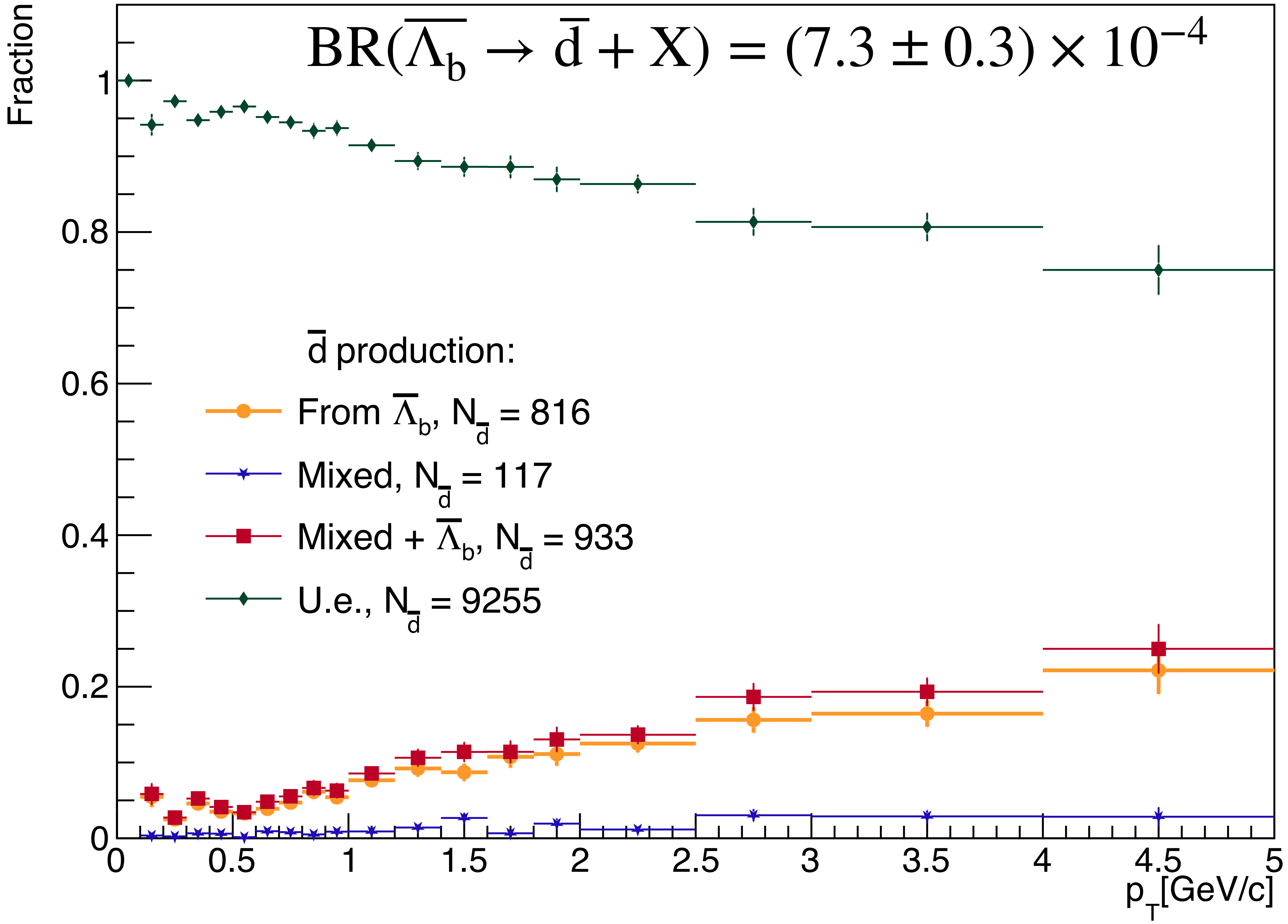
$$|\vec{r_1} - \vec{r_2}| < 1 \text{ fm}$$

- Causality is considered for antinucleons coming from two different sources.

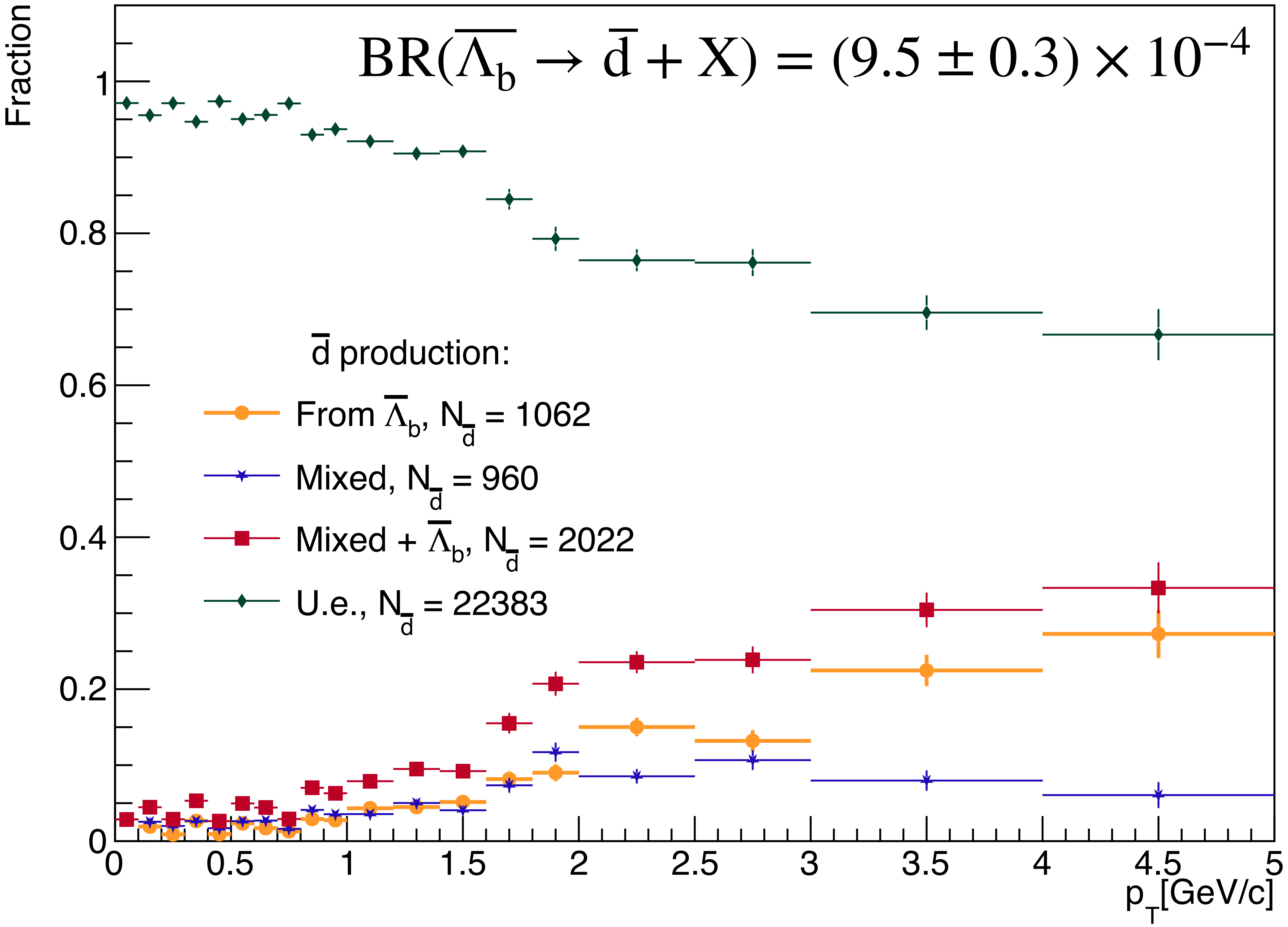
- A state-of-the-art **Quantum mechanical model**
M.Mahlein, L.Barioglio, F.Bellini,L.Fabbietti,C.Pinto, B.Singh, S.Tripathy, Eur. Phys. J. C (2023) 83 :804
- The probability to coalesce is given by the projection of the (anti)proton and (anti)neutron wave functions over the antideuteron one.
arXiv:2302.12696 and K.Blum et al., PRC 103, 014907 (2021) for derivation
- Dimension of the source is considered ($r = 1 \text{ fm}$)
- Antideuteron description via wave function (several possible models, here simple gaussian probability)
- I implemented the $\overline{\Lambda_b}$ decay scenario to perform a comparison

First results

Classical model



Quantum mechanical model



- Antideuterons are considered formed via: antinucleons from $\overline{\Lambda_b}$ decay only, from u.e. only or one from $\overline{\Lambda_b}$ and one from u.e. (mixed case).

This branching ratio has never been reported in literature

Next step: more general picture

Antideuteron production from b-decays

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

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

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

- Aim: Extract the branching ratios of the two following decays using a different description for the wave-function

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

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

Antideuteron production from b-decays

How to form the antideuteron

Injection in PYTHIA of $N_{\overline{\Lambda}_b/B^-} = 10^8$

↓

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

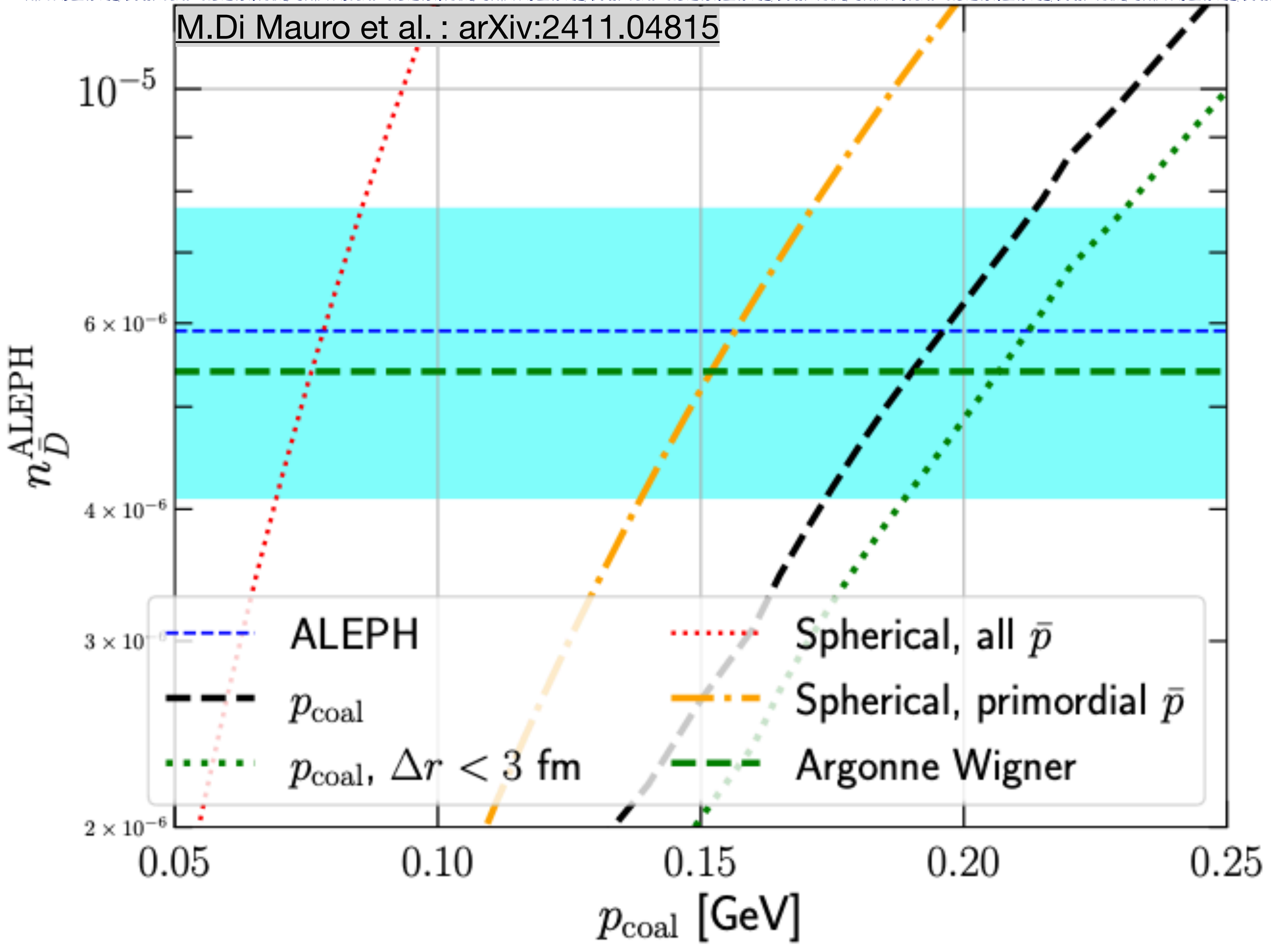
↓

Coalescence process

Coalescence via afterburner with Argonne ν_{18}

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

M.Di Mauro et al. : arXiv:2411.04815



- Argonne ν_{18} wave function, that is tuned on p-p and n-p scattering data, is used for this analysis. Wiringa et al., Phys. Rev. C 51, 38 (1995)
- 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 successfully to predict antideuterons from Dark Matter M.Di Mauro et al. : arXiv:2411.04815

Scenarios studied

For both injection of B^- and $\overline{\Lambda}_b$ I considered the following scenarios:

- Flat spectrum with probQQtoQ = 0.081, $\eta \in [-1,1]$ and $p \in [0,10]$ GeV/c
- Flat spectrum with probQQtoQ = 0.24, $\eta \in [-1,1]$ and $p \in [0,10]$ GeV/c

- Realistic spectrum in p_T with probQQtoQ = 0.081, $\eta \in [-1,1]$
- Realistic spectrum in p_T with probQQtoQ = 0.24, $\eta \in [-1,1]$

Reasons behind the selection of scenarios

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

```
particle: id="5122" name="Lambda_b0" antiName="Lambda_bbar0" spinType="2" chargeType="0" colType="0" m0="5.61940" tau0="4.40000e-01"
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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"
channel: onMode="1" bRatio="0.0546000" meMode="22" products="-14 13 4122"
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channel: onMode="1" bRatio="0.0172000" meMode="22" products="-16 15 4122"
channel: onMode="1" bRatio="0.0032000" meMode="22" products="-16 15 4124"
channel: onMode="1" bRatio="0.0043000" meMode="22" products="-16 15 14122"
channel: onMode="1" bRatio="0.0008000" products="2112 421"
channel: onMode="1" bRatio="0.0000048" products="2212 -211"
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channel: onMode="1" bRatio="0.0000200" products="3122 333"
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channel: onMode="1" bRatio="0.0220000" products="4122 211 -211 -211"
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channel: onMode="1" bRatio="0.0120000" meMode="22" products="-2 1 2 2101"
channel: onMode="1" bRatio="0.4411147" meMode="23" products="-2 1 4 2101"
channel: onMode="1" bRatio="0.0910000" meMode="43" products="-2 4 1 2101"
channel: onMode="1" bRatio="0.0120000" meMode="22" products="-4 3 2 2101"
channel: onMode="1" bRatio="0.0800000" meMode="43" products="-4 3 4 2101"
```

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

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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.

Realistic spectra

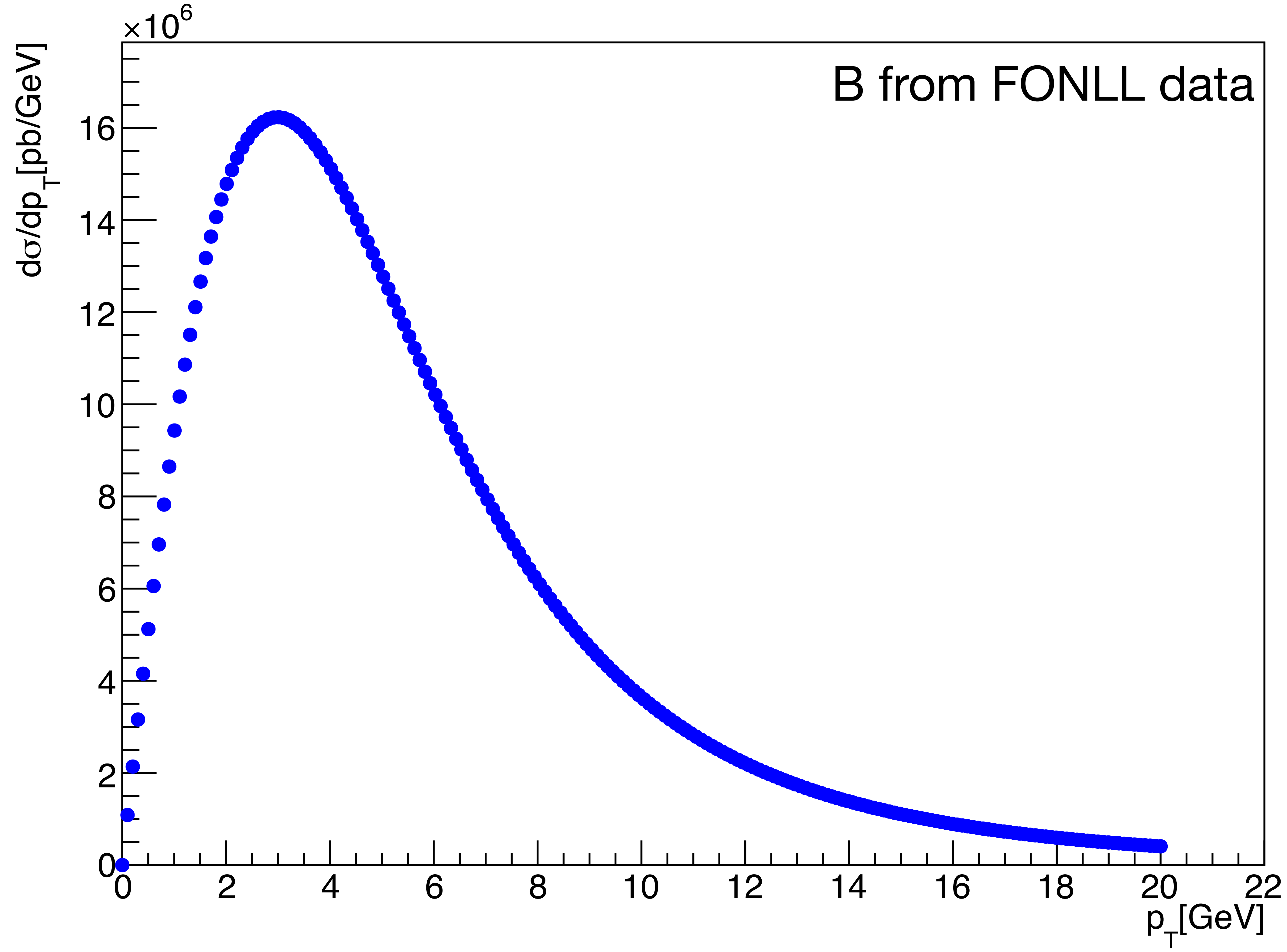
Then $d\sigma/dp_T$ for B hadrons was computed via FONLL and the one for the $\overline{\Lambda_b}$ extracted thanks to this formula:

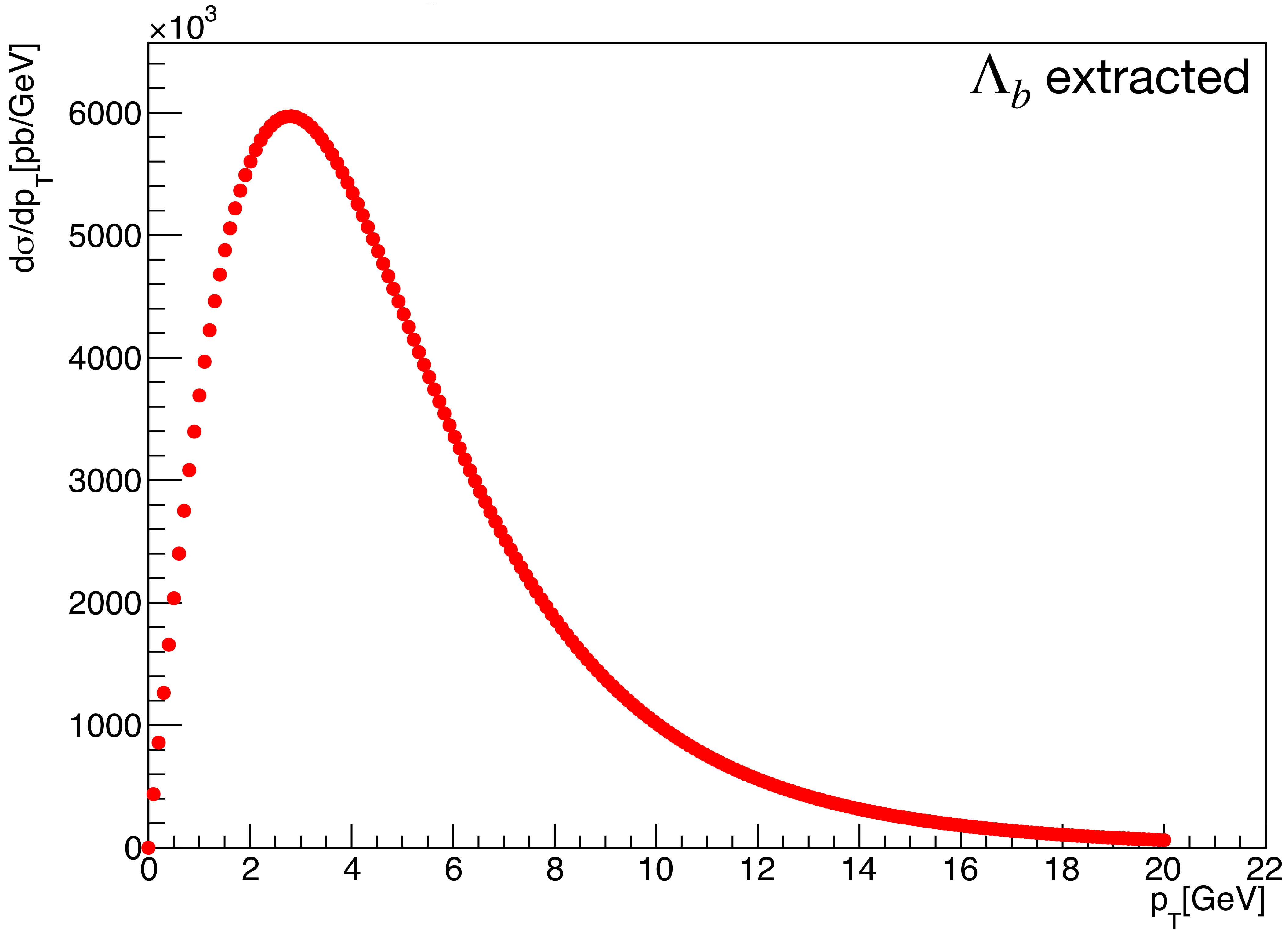
$$\frac{f_{\Lambda_b}}{f_u + f_d} = (0.404 \pm 0.017 \pm 0.027 \pm 0.105) \times [1 - (0.031 \pm 0.004 \pm 0.003) \times p_{\mathrm{T}}(\mathrm{GeV})]$$

https://arxiv.org/abs/1111.2357

Experimentally determined by the LHCb collaboration.

The realistic spectra are:

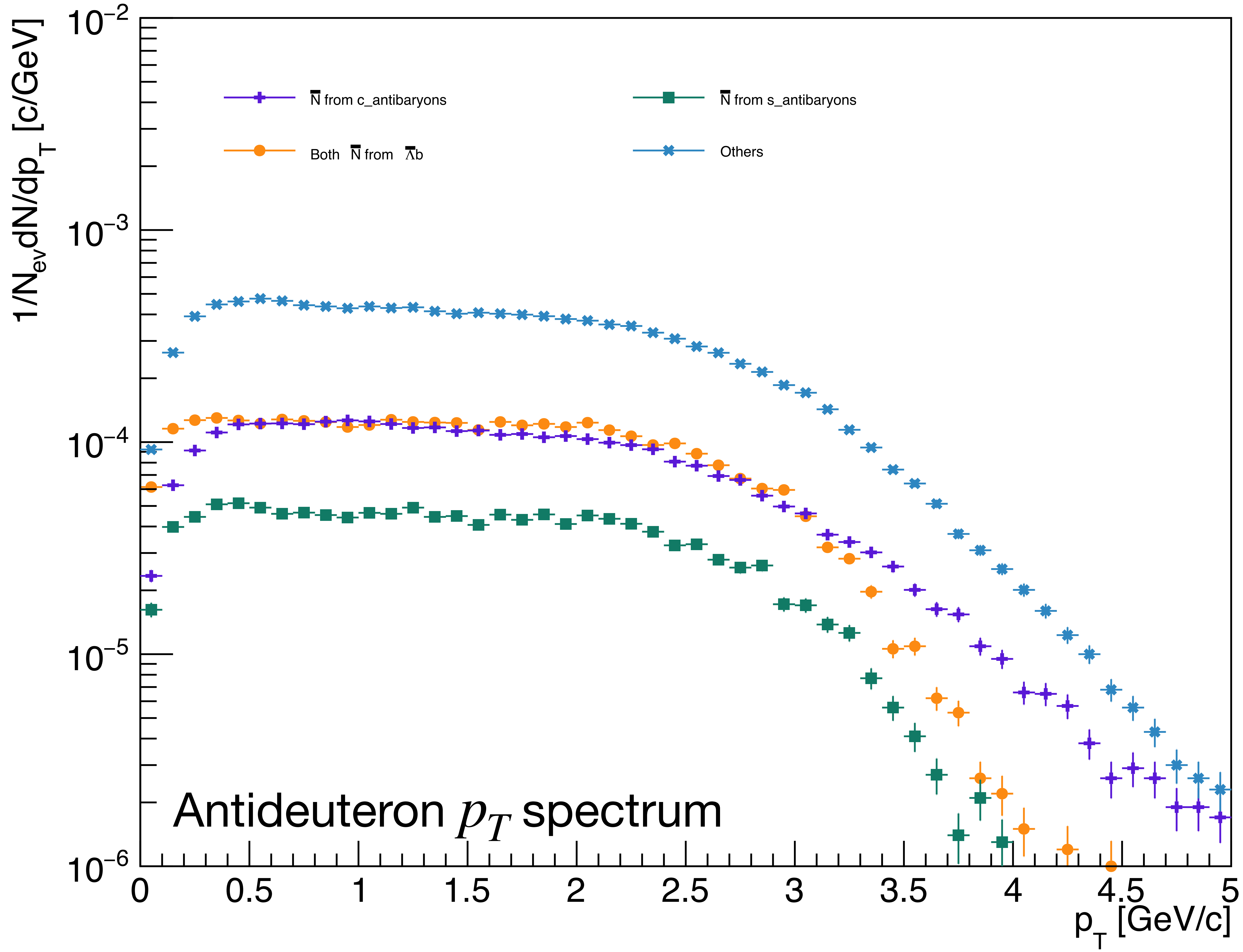




Results: $\overline{\Lambda_b} \rightarrow \bar{\mathrm{d}} + X$

$\mathrm{BR}(\overline{\Lambda_b} \rightarrow \bar{\mathrm{d}} + \mathrm{X}) = (1.977 \pm 0.005) \times 10^{-3}$

- **Flat $\overline{\Lambda_b}$ spectrum** with **probQQtoQ = 0.081**, $\eta \in [-1,1]$ and $p \in [0,10]$ GeV/c, $N_{\overline{\Lambda_b}} = 10^8$



In the plot four cases are shown:

1. **Orange**: both antinucleons directly produced from $\overline{\Lambda_b}$ decay
2. **Purple**: one of the antinucleons comes from a charmed (anti)baryon produced from $\overline{\Lambda_b}$ decay
3. **Green**: one of the antinucleons comes from a strange (anti)baryon produced from $\overline{\Lambda_b}$ decay
4. **Blue**: other cases

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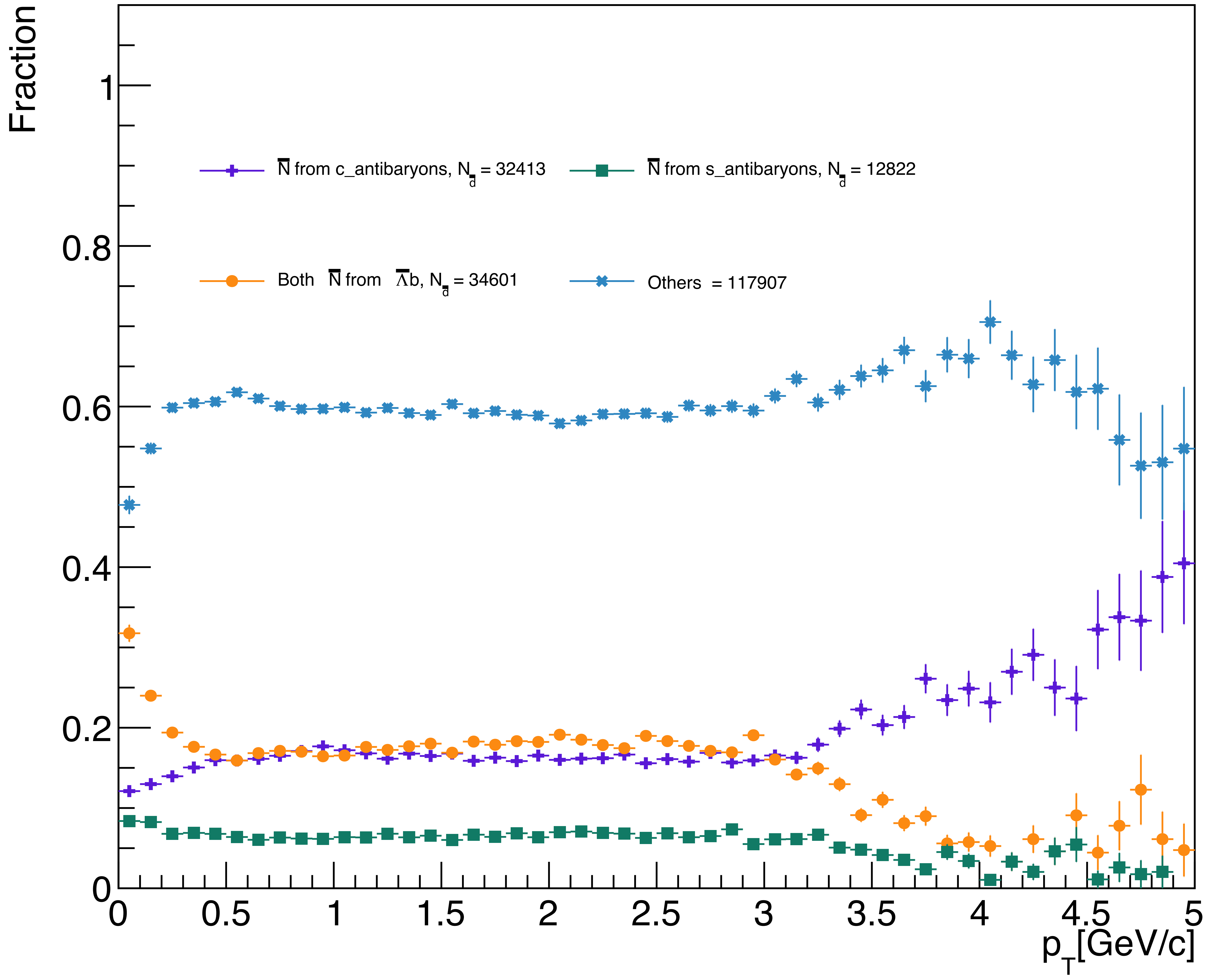
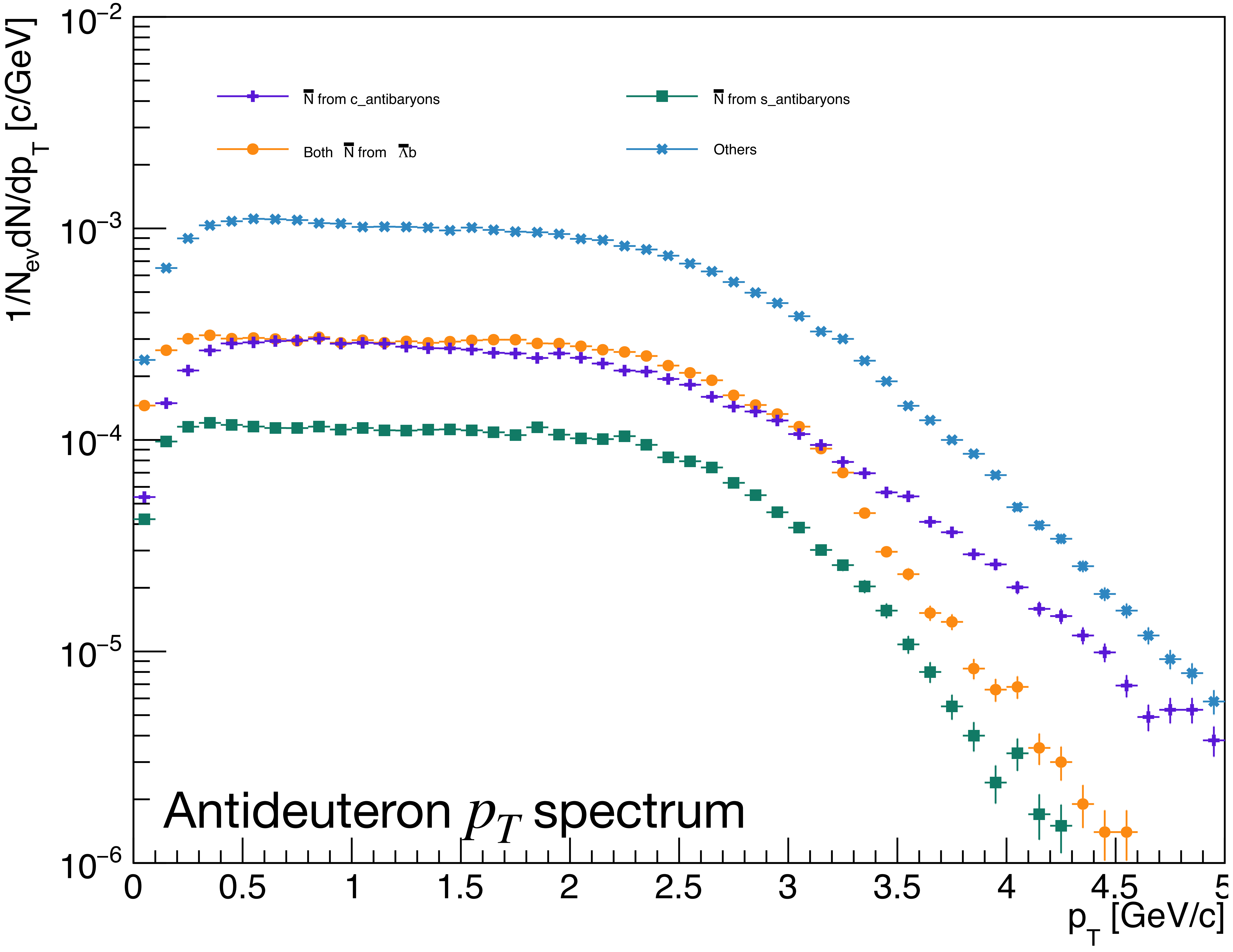
The fraction of antideuterons produced in each case over the total number is shown

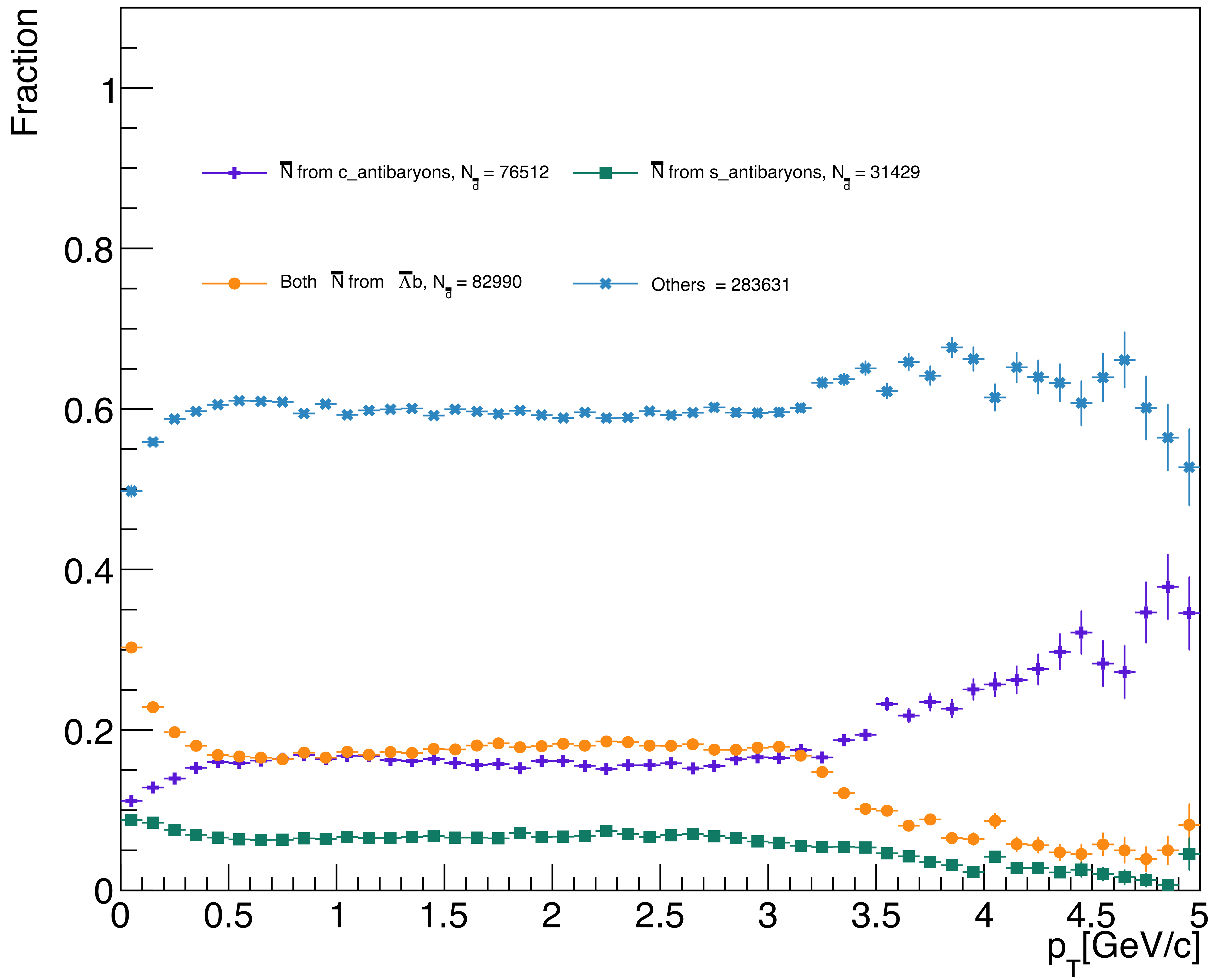


$\overline{\Lambda_b} \rightarrow \bar{d} + X$

$\mathrm{BR}(\overline{\Lambda_b} \rightarrow \bar{d} + X) = (4.746 \pm 0.007) \times 10^{-3}$

- **Flat $\overline{\Lambda_b}$ spectrum** with **probQQtoQ = 0.24**, $\eta \in [-1,1]$ and $p \in [0,10]$ GeV/c





$N_{\overline{\Lambda_b}} = 10^{\cdot}$

$\overline{\Lambda_b} \to \bar{d} + X$

$\mathrm{BR}(\overline{\Lambda_b} \to \bar{d} + X) = (1.985 \pm 0.005) \times 10^{-3}$

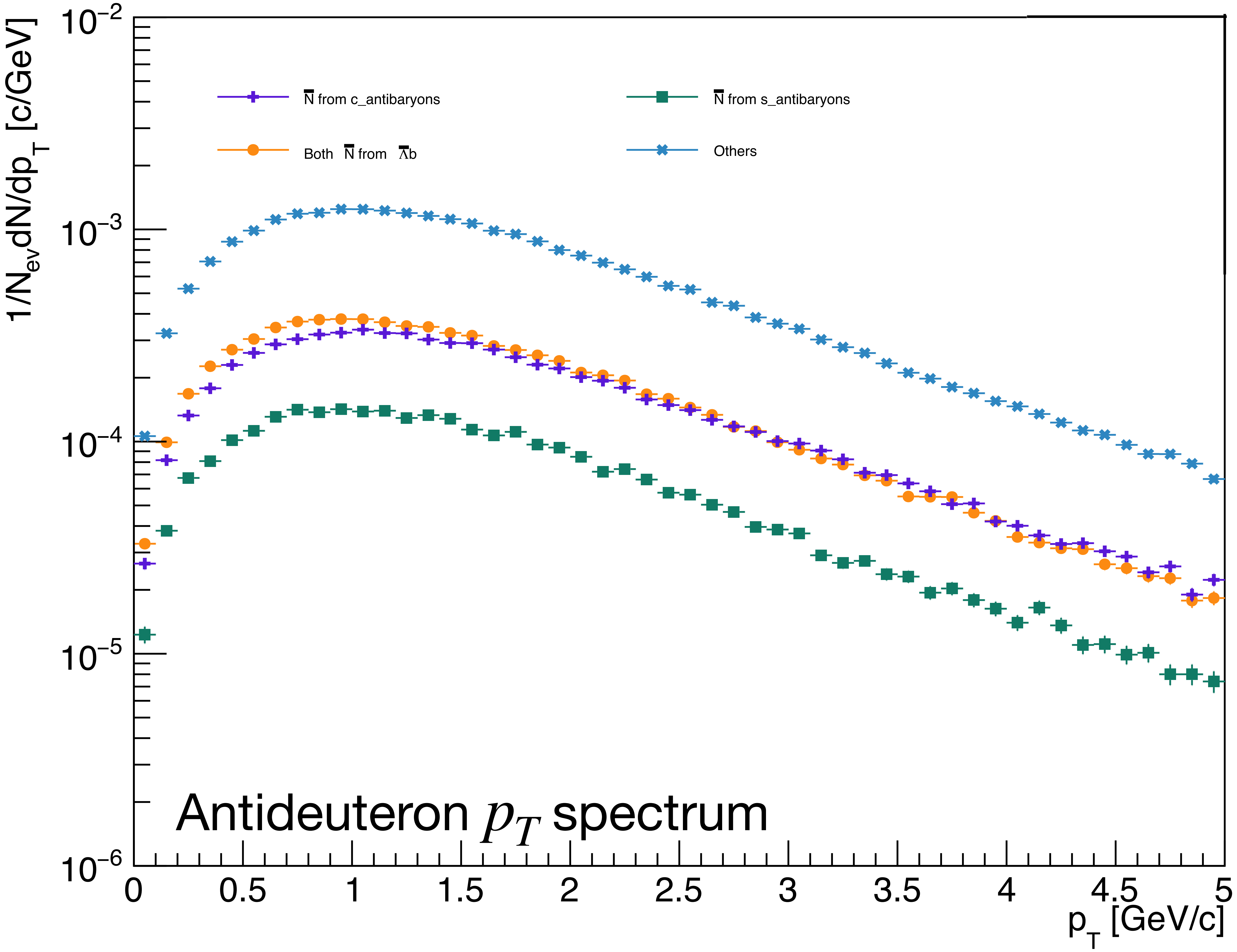
- **Realistic $\overline{\Lambda_b}$ spectrum** in p_T with **probQQtoQ = 0.081**, $\eta \in [-1,1]$

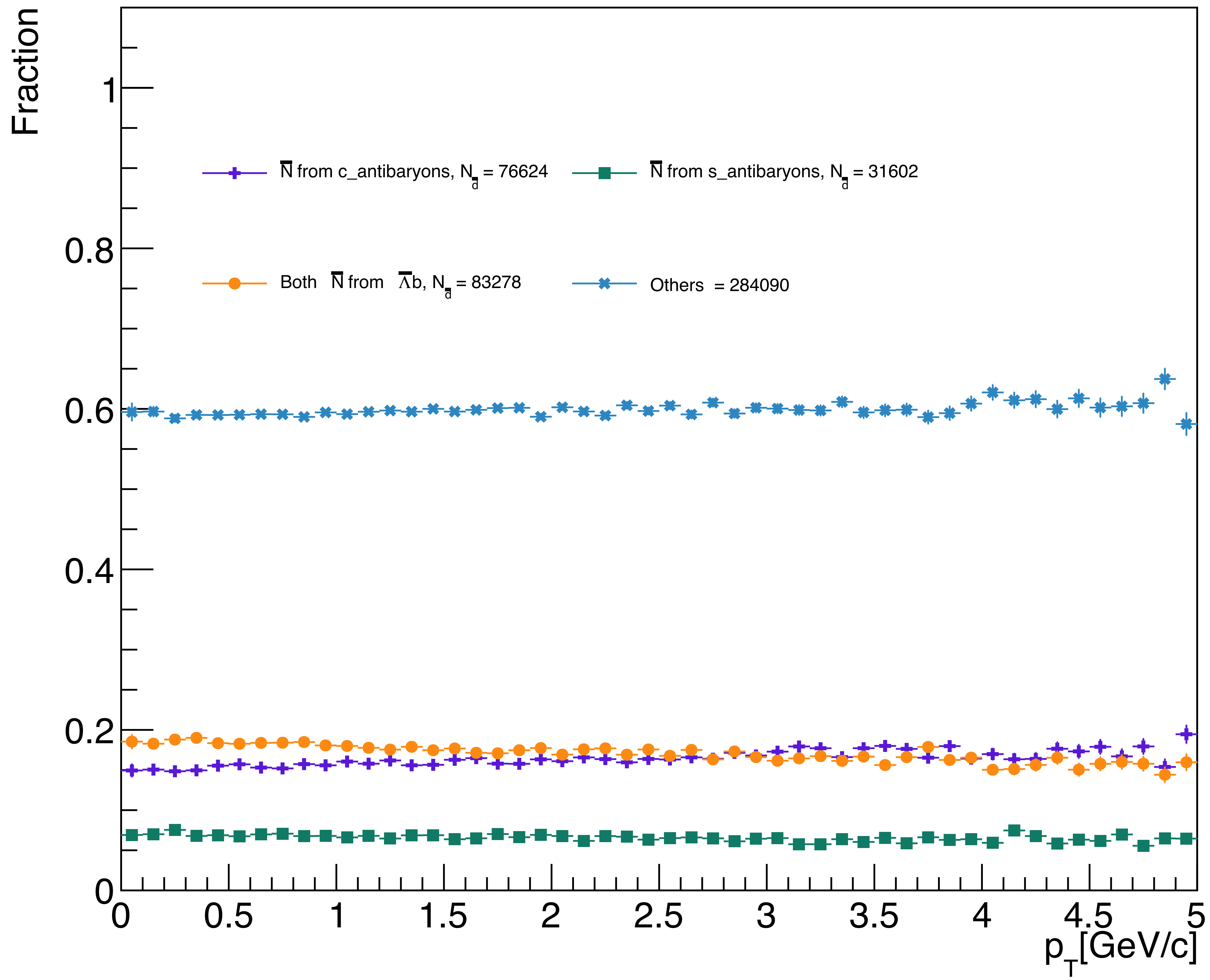
$N_{\overline{\Lambda_b}} = 10^8$

$\overline{\Lambda_b} \to \bar{d} + X$

$\mathrm{BR}(\overline{\Lambda_b} \to \bar{d} + X) = (4.756 \pm 0.007) \times 10^{-3}$

- **Realistic $\overline{\Lambda_b}$ spectrum** in p_T with **probQQtoQ = 0.24**, $\eta \in [-1,1]$



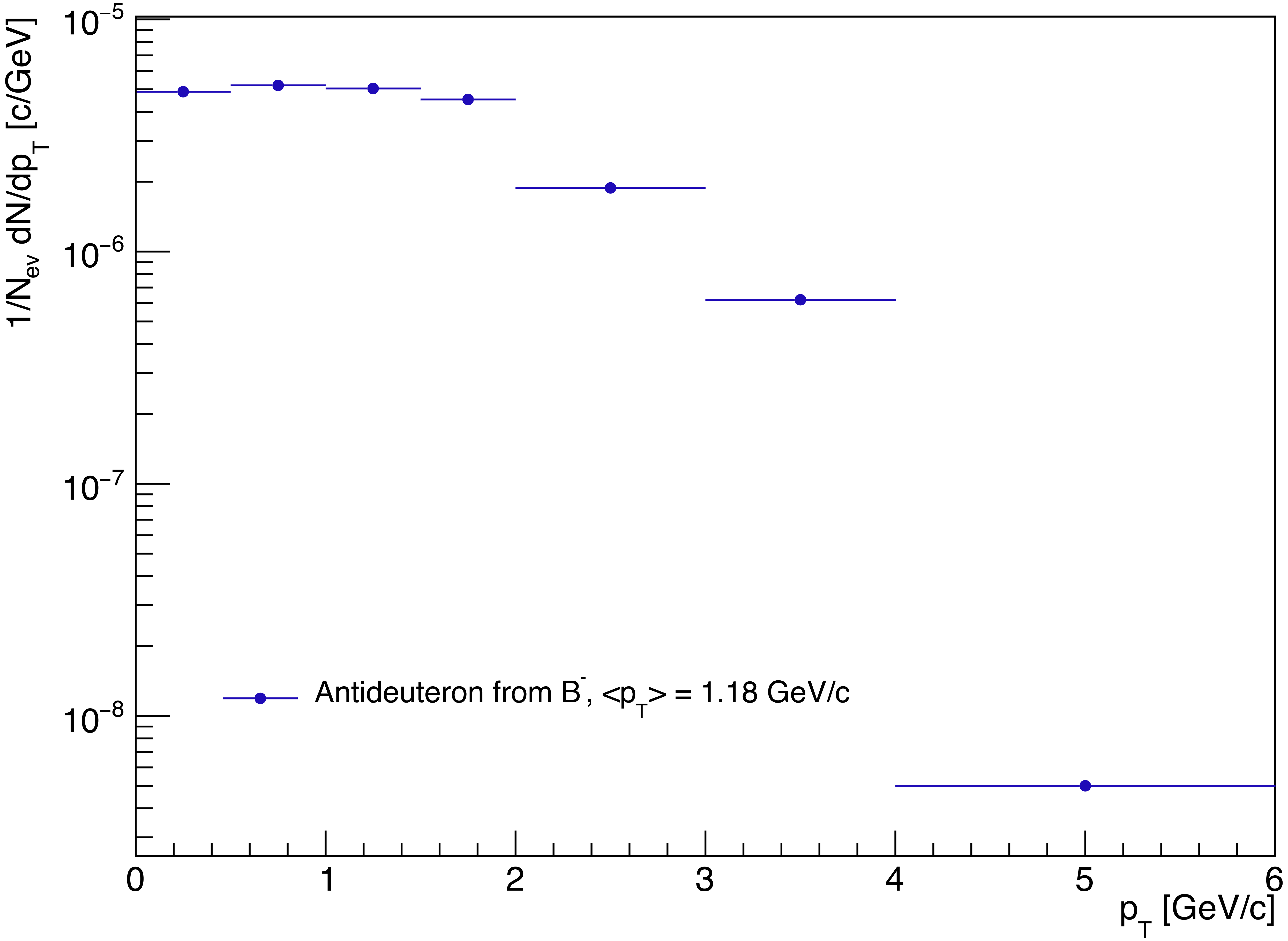


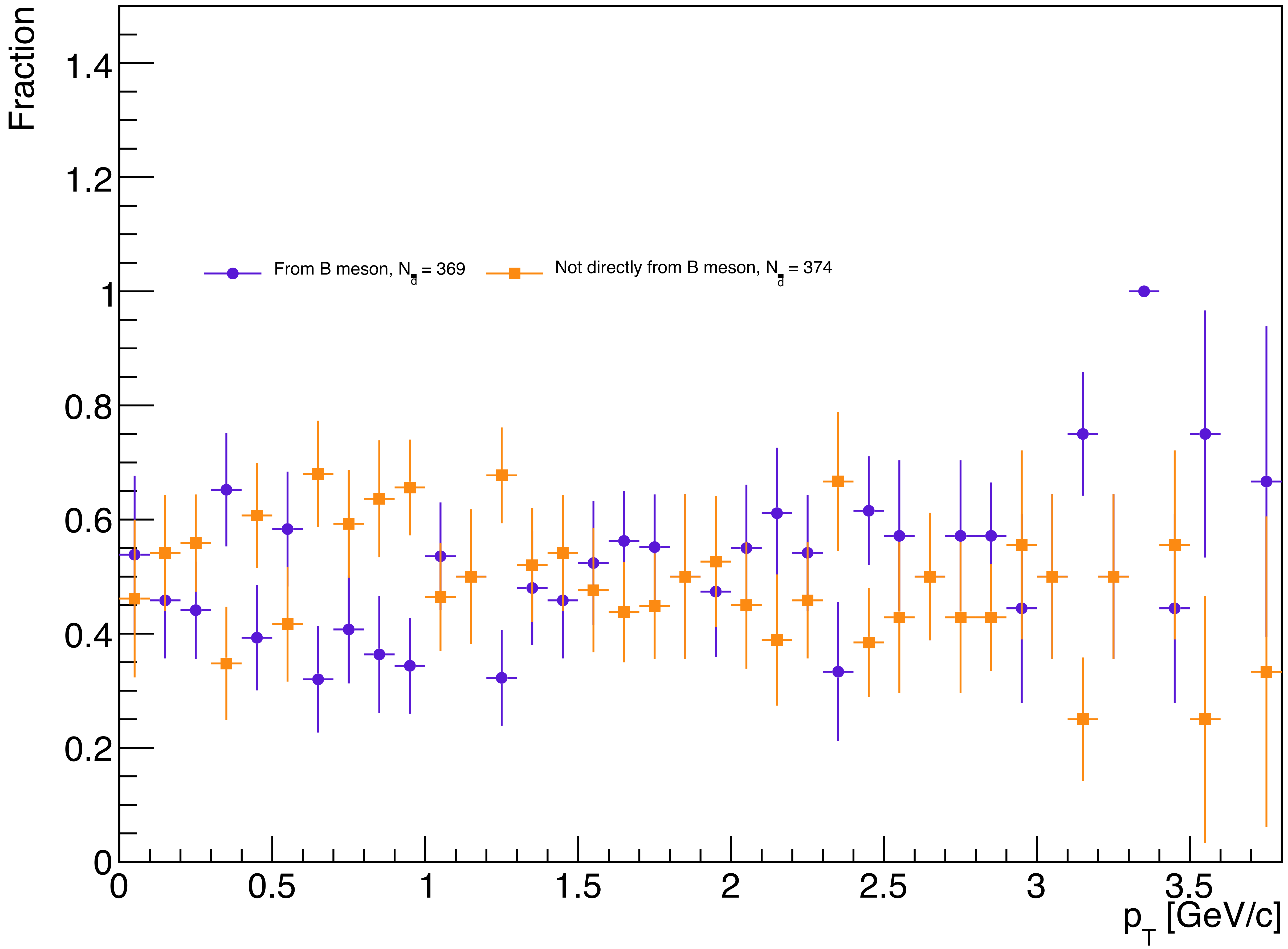
$N_{\overline{\Lambda_b}} = 10^8$

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

$\mathrm{BR}(\mathrm{B}^- \rightarrow \bar{\mathrm{d}} + \mathrm{X}) = (7.43 \pm 0.27) \times 10^{-6}$

- **Flat B^- spectrum** with **probQQtoQ = 0.081**, $\eta \in [-1,1]$ and $p \in [0,10]$ GeV/c



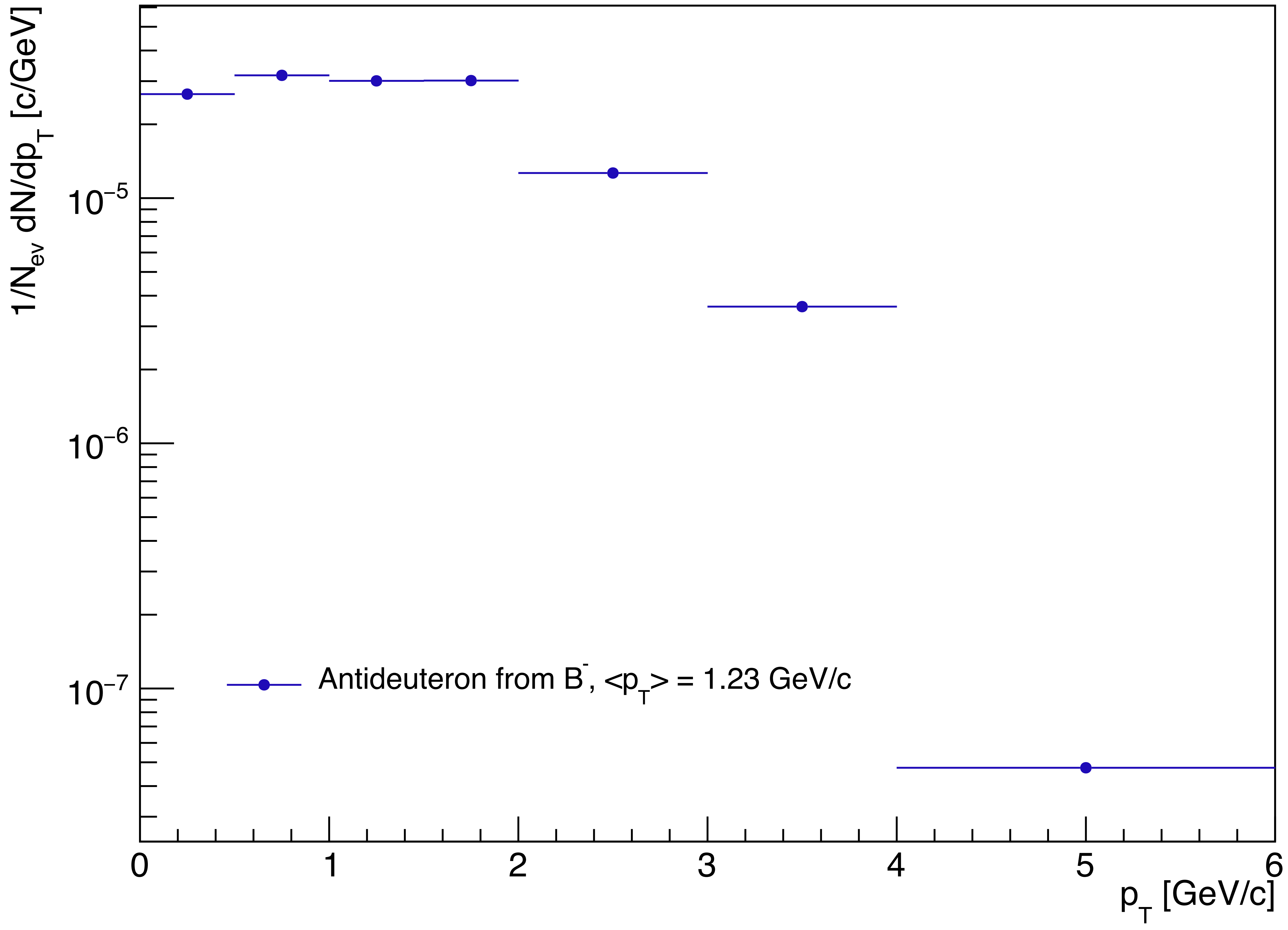


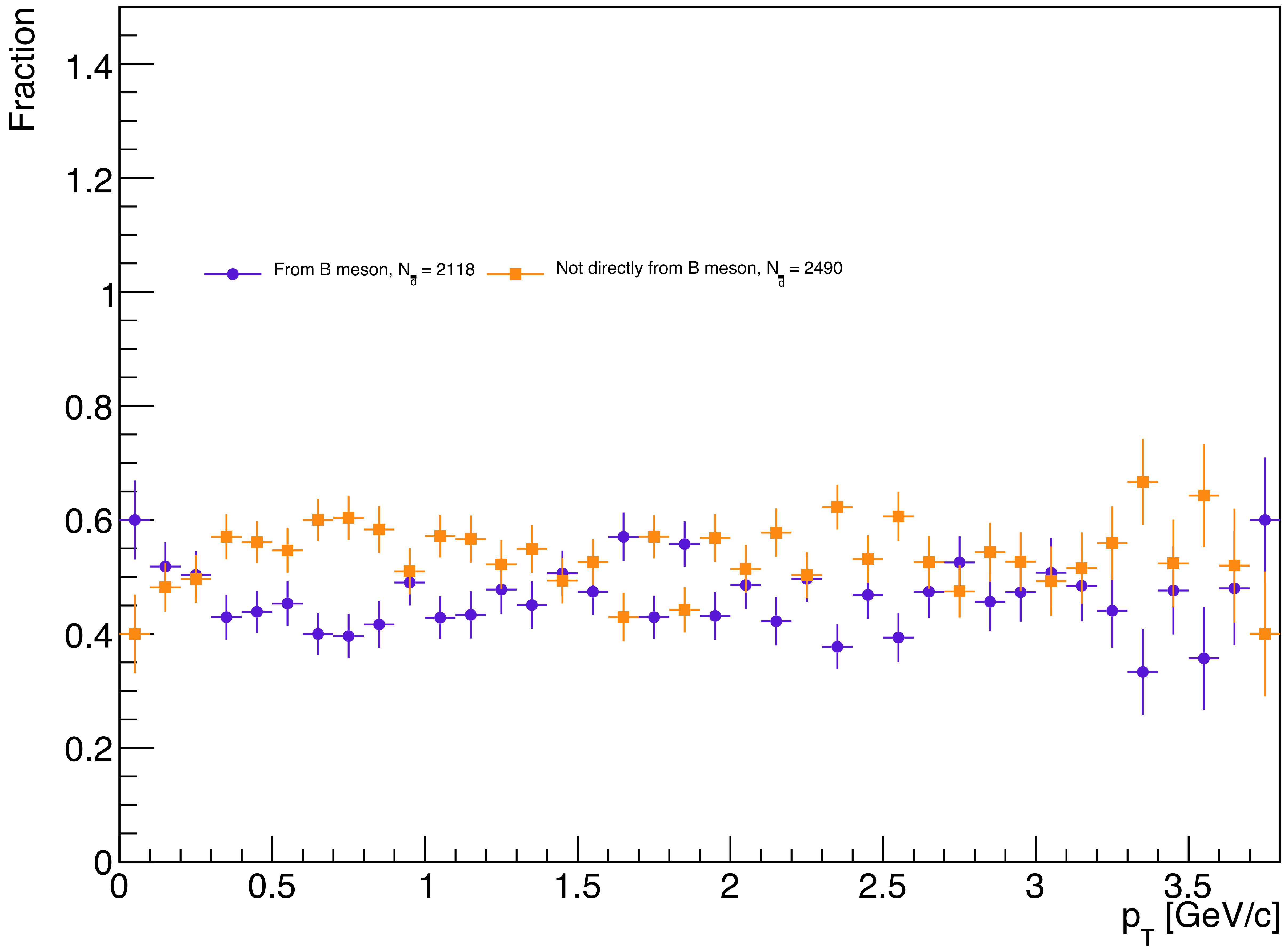
$N_{B^-} = 10^8$

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

$\mathrm{BR}(\mathrm{B}^- \rightarrow \bar{\mathrm{d}} + \mathrm{X}) = (4.608 \pm 0.068) \times 10^{-5}$

- **Flat B^- spectrum** with **probQQtoQ = 0.24**, $\eta \in [-1,1]$ and $p \in [0,10]$ GeV/c



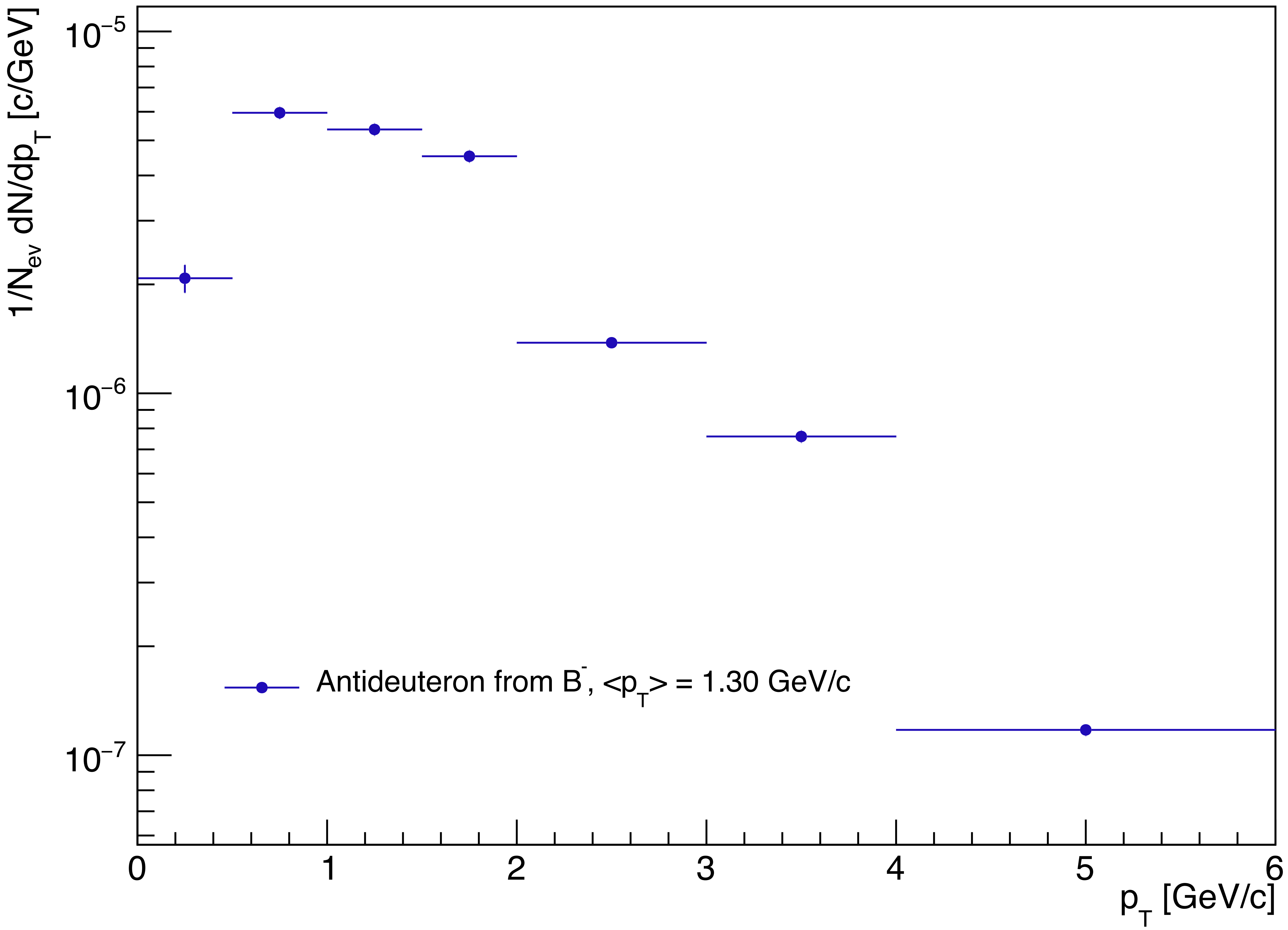


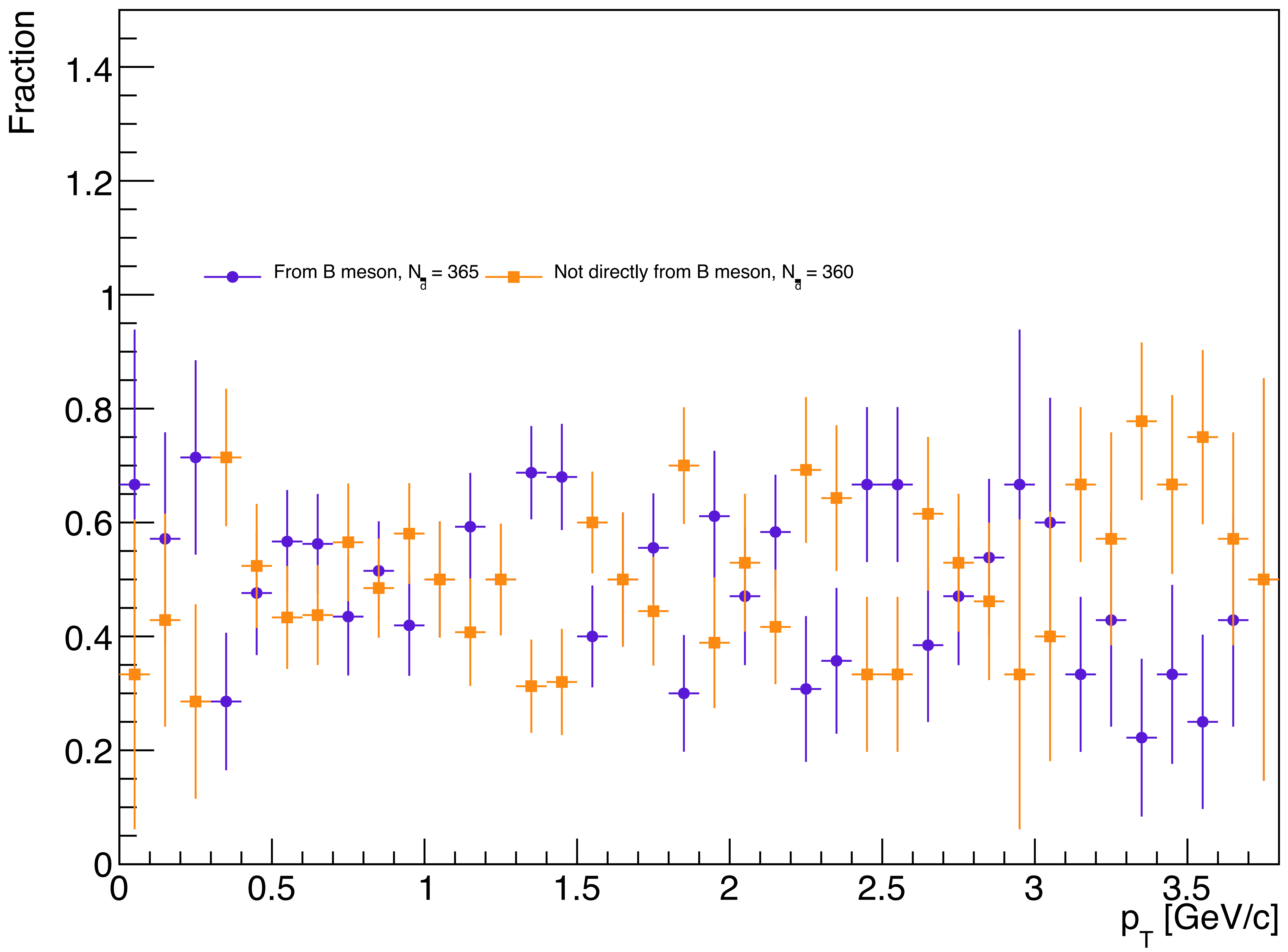
$\mathrm{N}_{\mathrm{B}^-} = 10^8$

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

$\mathrm{BR}(B^- \to \bar{d} + X) = (7.25 \pm 0.27) \times 10^{-6}$

- **Realistic B^- spectrum** in p_T with **probQQtoQ = 0.081**, $\eta \in [-1,1]$



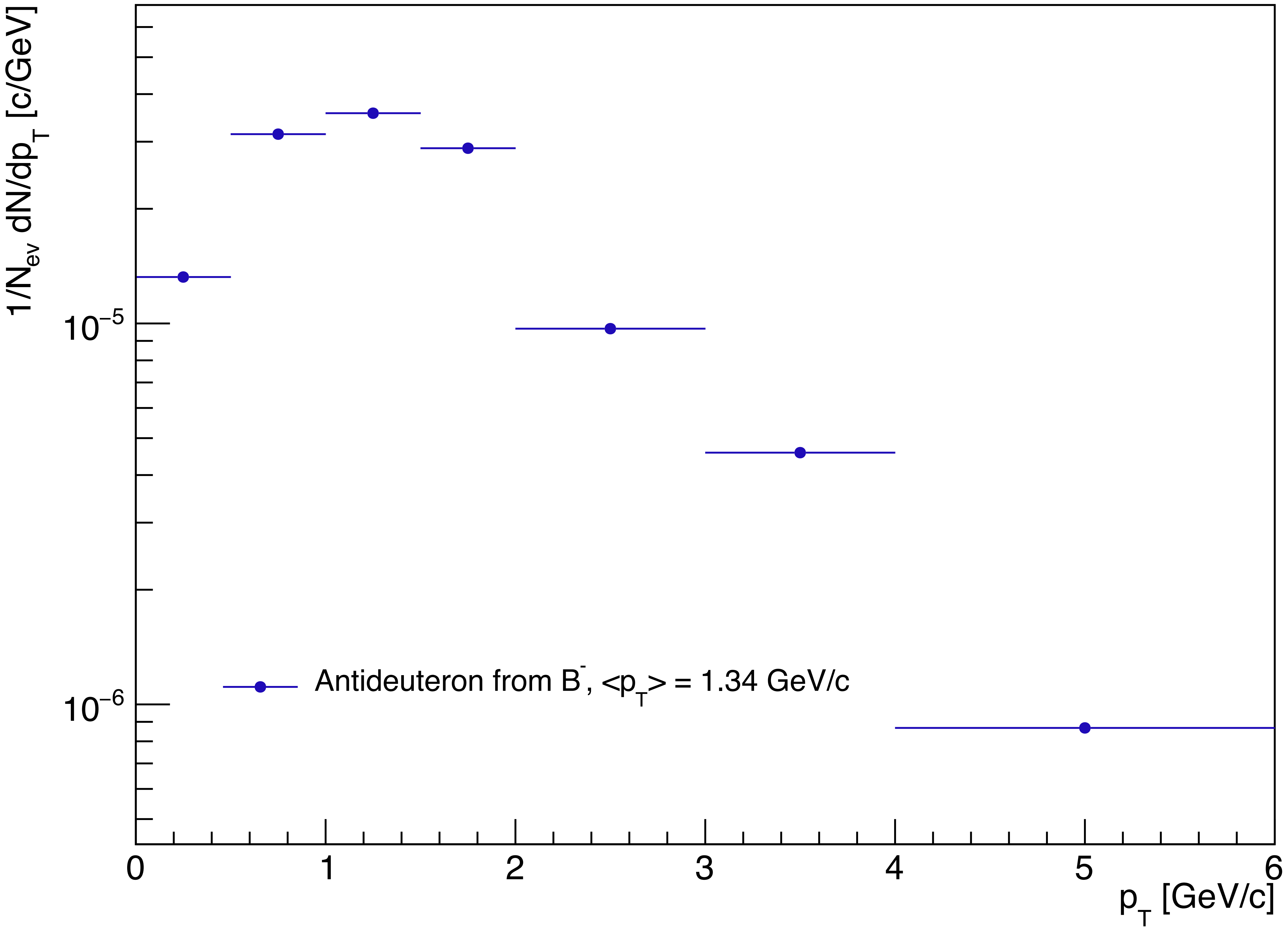


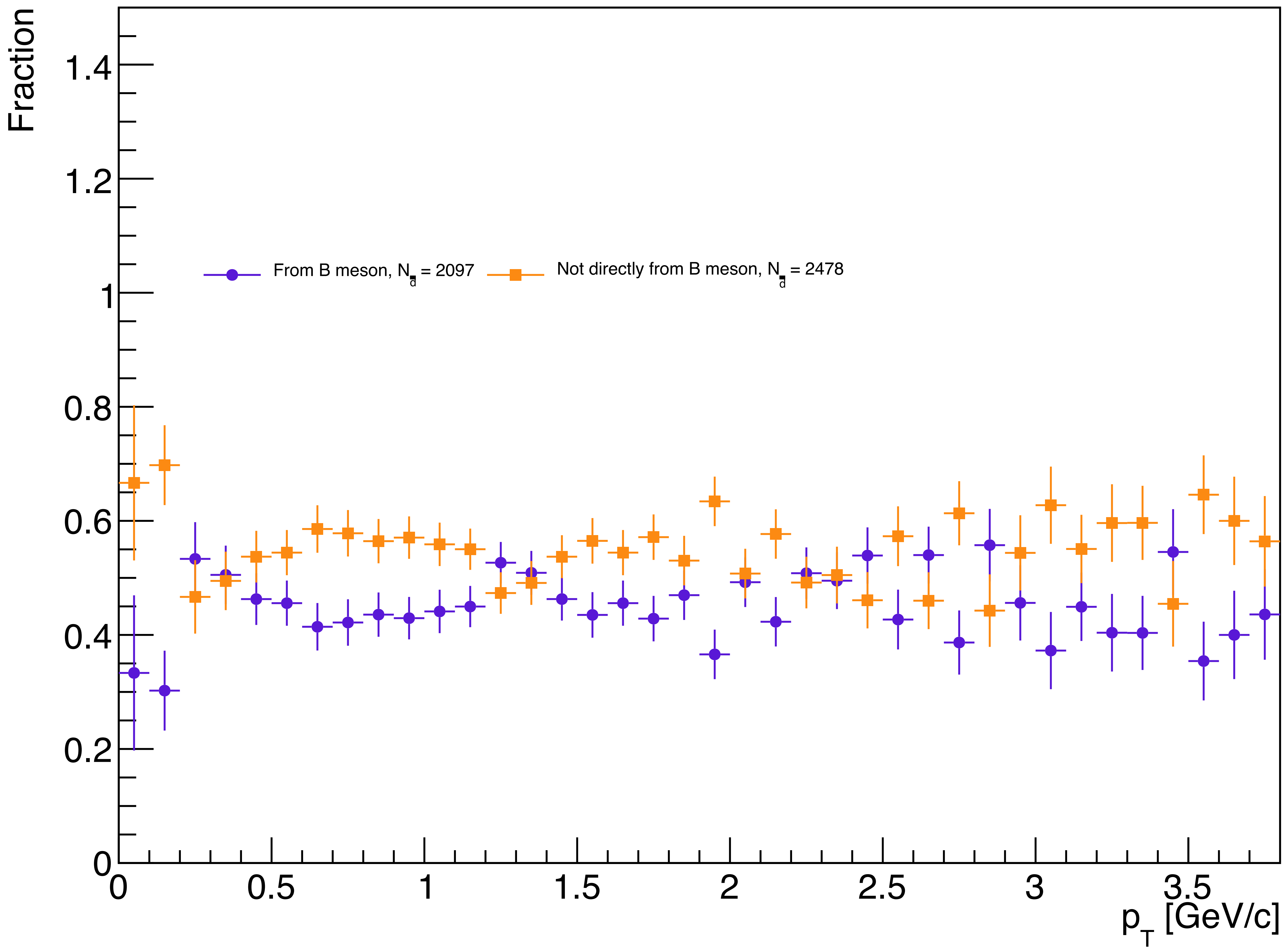
$N_{B^-} = 10^8$

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

$\mathrm{BR}(\mathrm{B}^- \to \bar{\mathrm{d}} + \mathrm{X}) = (4.58 \pm 0.68) \times 10^{-5}$

- **Realistic B^- spectrum** in p_T with **probQQtoQ = 0.24**, $\eta \in [-1,1]$





$\mathrm{N_{B^-}} = 10^8$

Summary of estimated branching ratios

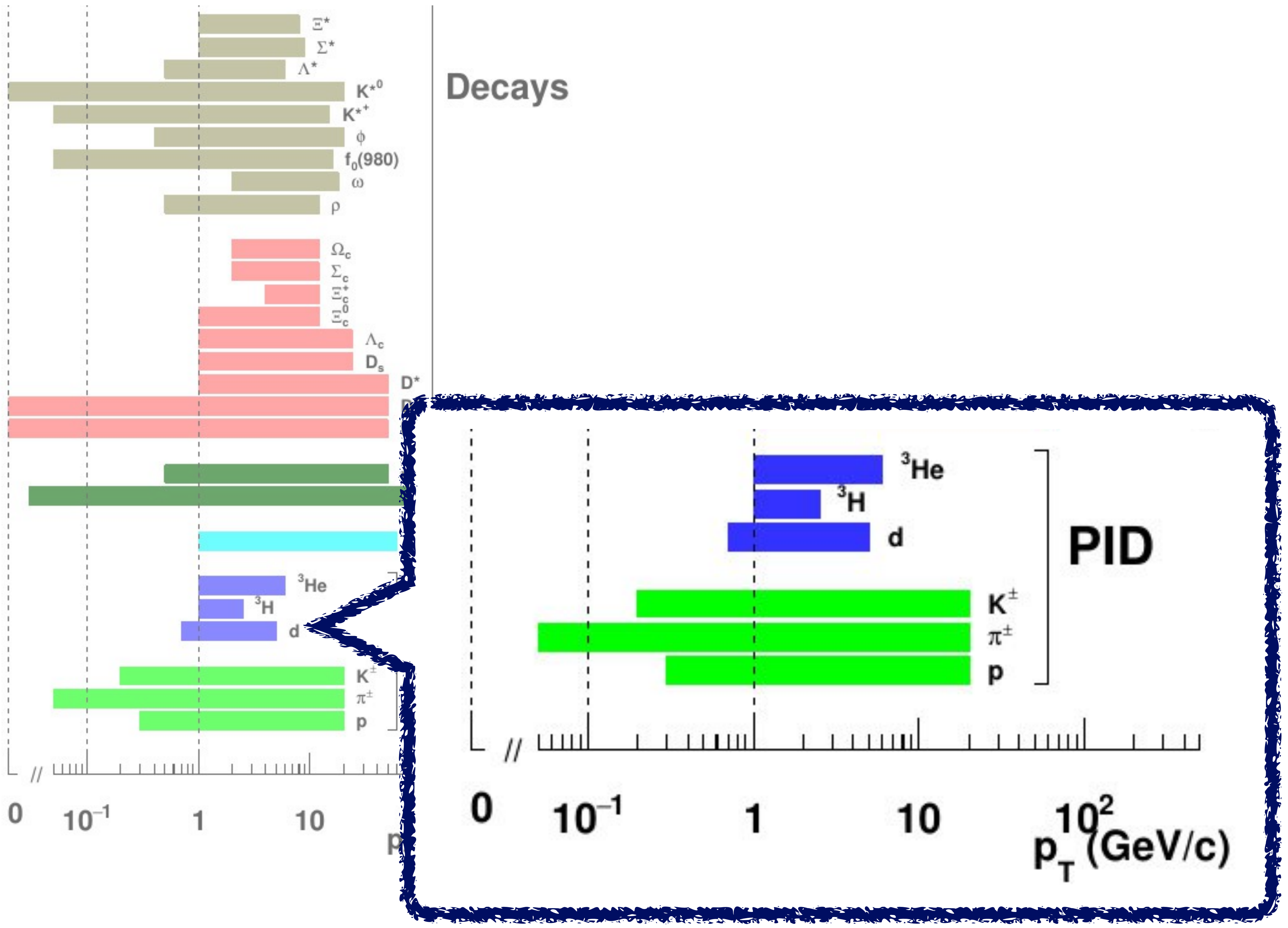
	$\mathrm{BR}(\overline{\Lambda_b} \to \bar{d} + X)$	$\mathrm{BR}(B^- \to \bar{d} + X)$
Flat spectrum probQQtoQ 0.081	$(1.977 \pm 0.005) \times 10^{-3}$	$(7.43 \pm 0.27) \times 10^{-6}$
Flat spectrum probQQtoQ 0.24	$(4.746 \pm 0.007) \times 10^{-3}$	$(4.608 \pm 0.068) \times 10^{-5}$
Realistic spectrum probQQtoQ 0.081	$(1.985 \pm 0.005) \times 10^{-3}$	$(7.25 \pm 0.27) \times 10^{-6}$
Realistic spectrum probQQtoQ 0.24	$(4.756 \pm 0.007) \times 10^{-3}$	$(4.58 \pm 0.68) \times 10^{-5}$

How many antideuterons from $\overline{\Lambda}_b$ in ALICE?

Expected antideuteron in ALICE

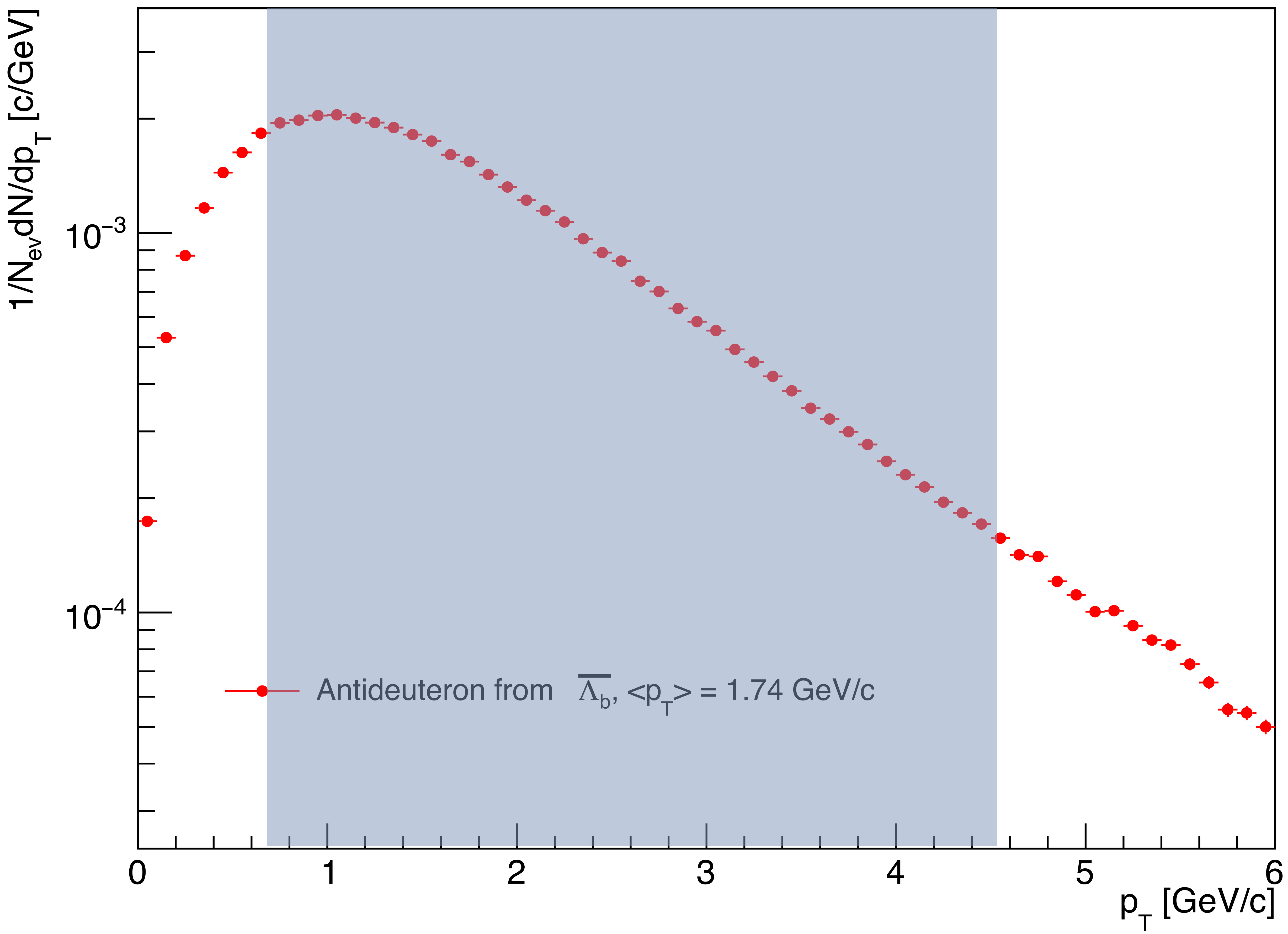
- In ALICE the identification of antideuterons is performed with TPC and TOF in the range:

$$0.7 < p_T < 4.5 \text{ GeV/c}$$



ALICE collaboration, The ALICE experiment: a journey through QCD

Using the **realistic $\overline{\Lambda}_b$ spectrum** **probQQtoQ 0.081**



Antideuterons produced from $\overline{\Lambda}_b$ decay are inside the range of acceptance in p_T of ALICE detector!

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 $f(\mathrm{b} \to \Lambda_\mathrm{b}) \simeq 0.1$ as measured at LEP.
  The OPAL Collaboration & G. Abbiendi et al.

We can extract: $\mathrm{N}_{\Lambda_\mathrm{b}} \sim O(10^{10})$

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

Realistic $\overline{\Lambda}_b$ spectrum probQQtoQ 0.081

$$\mathrm{N}_\mathrm{d} \simeq 1.4 \times 10^7$$

Realistic $\overline{\Lambda}_b$ spectrum probQQtoQ 0.24

$$\mathrm{N}_\mathrm{d} \simeq 3.3 \times 10^7$$

Outlook

- The main goal of my research assignment is to publish a paper containing all the information extracted and the scenarios examined.
- This represents a crucial step towards the measurement of these decay channels at the collider.
- This work has several implications for the coalescence process itself, but also for indirect dark matter searches.

Anti-deuteron production from $\overline{\Lambda_b}$ decay: a path for collider searches

Francesca Bellini* and Marta Razza†
Università di Bologna e INFN Bologna

Nicolò Jacazio‡
Università del Piemonte Orientale e INFN Torino

(Dated: March 24, 2025)

This paper explores the production of deuterons and antideuterons from Λ_b baryon decays in proton-proton collisions at a center-of-mass energy of 13.6 TeV, with a focus on the feasibility of measuring these particles in the ALICE experiment at the Large Hadron Collider (LHC). We present detailed predictions for the branching ratios of $\Lambda_b \to$ deuteron (d) and $\Lambda_b \to$ antideuteron ($\overline{d}$) decays, utilizing both coalescence models and simulations within the Pythia8 framework. The coalescence model is employed to describe the dynamics of light nuclei formation in the hadronization process, where quarks and gluons combine to form composite hadrons, including light nuclei like deuterons and antideuterons. Pythia8, a widely used event generator, provides a comprehensive simulation of particle production and decay processes in high-energy hadronic collisions, allowing us to estimate the production yields of these rare light nuclei from Λ_b decays.

These predictions are especially relevant for dark matter searches, as deuterons and antideuterons are expected to be important probes of dark matter annihilation and cosmic ray production. In particular, understanding the production mechanisms of such light nuclei in high-energy collisions could help refine models of dark matter interactions and provide new insights into cosmic ray origins. We assess the potential for detecting these particles in the ALICE detector, considering key experimental factors such as detector sensitivity, background contamination, and the expected event rates. We also discuss the feasibility of isolating deuteron and antideuteron signals from Λ_b decays in the presence of other particle production processes, such as those arising from heavy-ion collisions or proton-proton interactions.

Our findings suggest that the measurement of deuteron and antideuteron production from Λ_b decays is a promising and experimentally feasible task at the LHC. The results have significant implications for both our understanding of the hadronization process and for dark matter research, as the observation of these rare particles could provide new constraints on models of dark matter and particle astrophysics. The paper also outlines experimental strategies to optimize the detection and identification of these light nuclei, highlighting the challenges and proposing potential solutions to maximize the sensitivity of ALICE and similar experiments.

My Outlook

The work presented can be further extended and this is the reason why I would like to apply for the next PhD call at the University of Bologna.

Next steps would be:

- Run a full simulation of ALICE to include efficiency and assess feasibility in Run 3+4
- Start the analysis with already collected Run3 data to prepare for full sample
- Investigate the possibility for a dedicated trigger for Run 4

My Outlook

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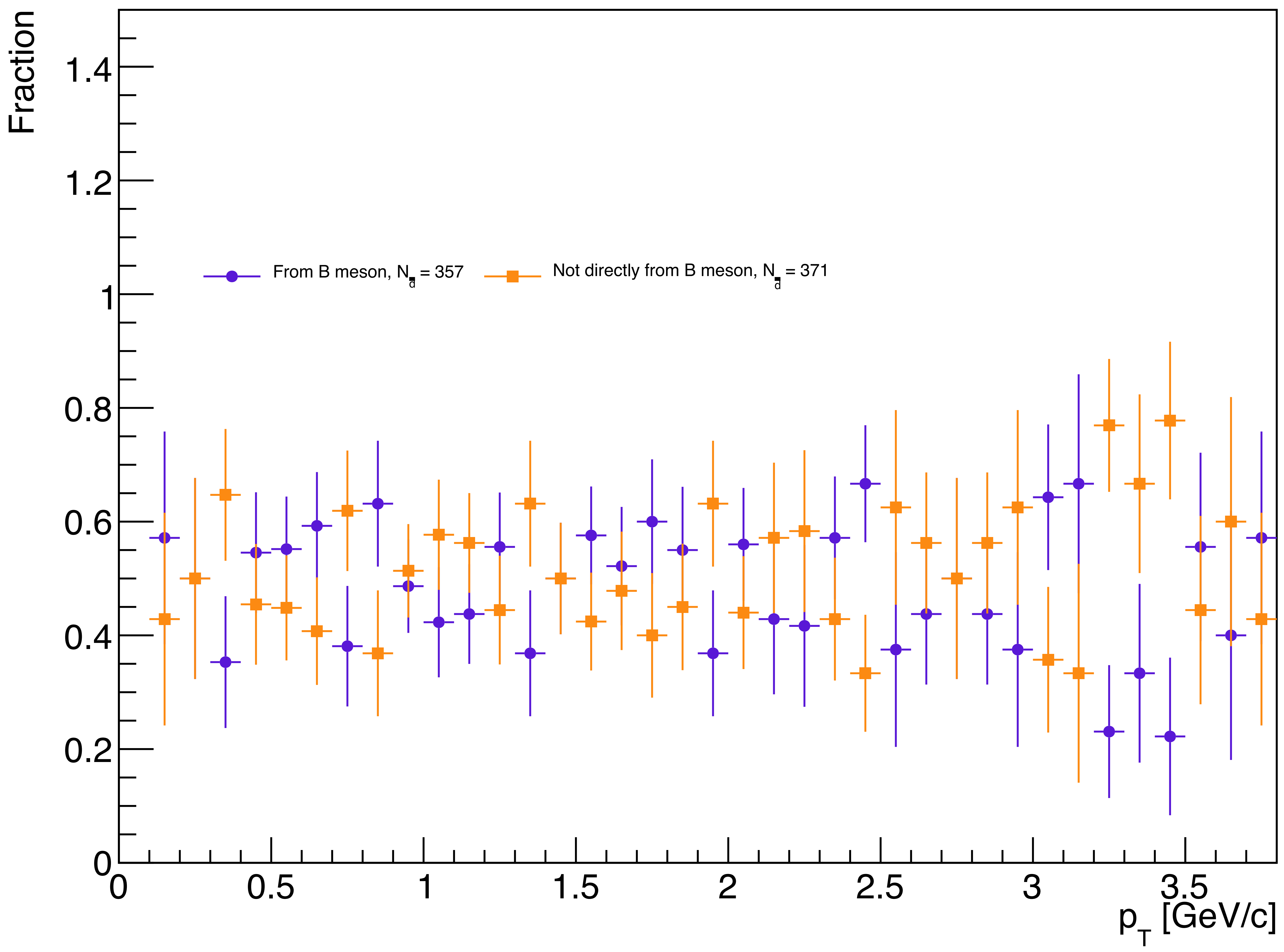
Thank you for the attention

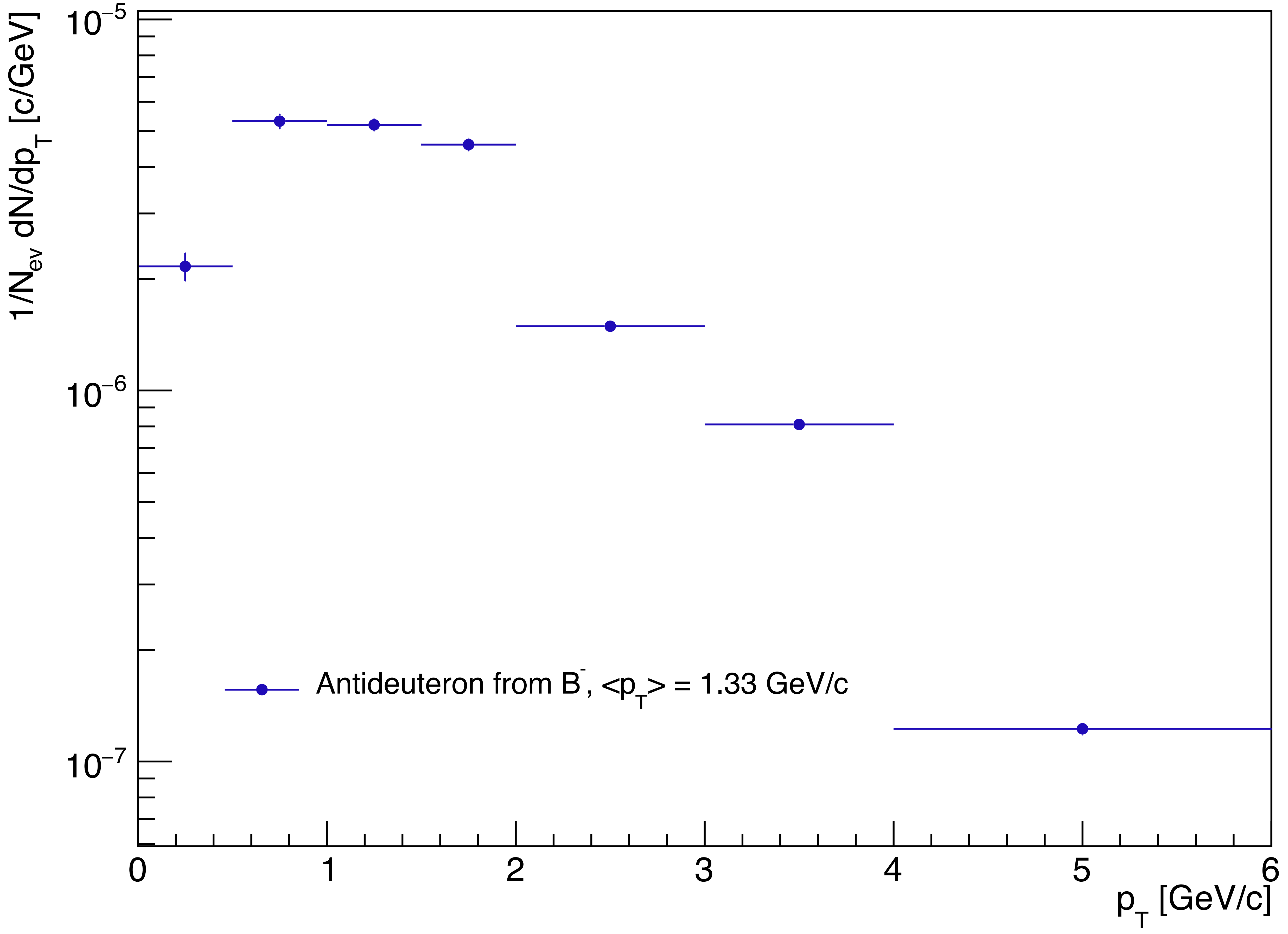
Back-up

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

$\mathrm{BR}(\mathrm{B}^- \to \bar{\mathrm{d}} + \mathrm{X}) = (7.28 \pm 0.27) \times 10^{-6}$

- **Realistic B^- spectrum** in p_T for B^- extracted from pp collisions at $\sqrt{s} = 13.6$ TeV simulated in PYTHIA (Monash Tune)





$\mathrm{N}_{\mathrm{B}^-} = 10^8$