Tim Linden

Excesses in Cosmic-Ray Antinuclei

Stockholms universitet

Thermal Cross-Section
1 Observed Photon Within 10° of Galactic Center
$<\sigma v>$ ($cm^3 s^{-1}$)
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

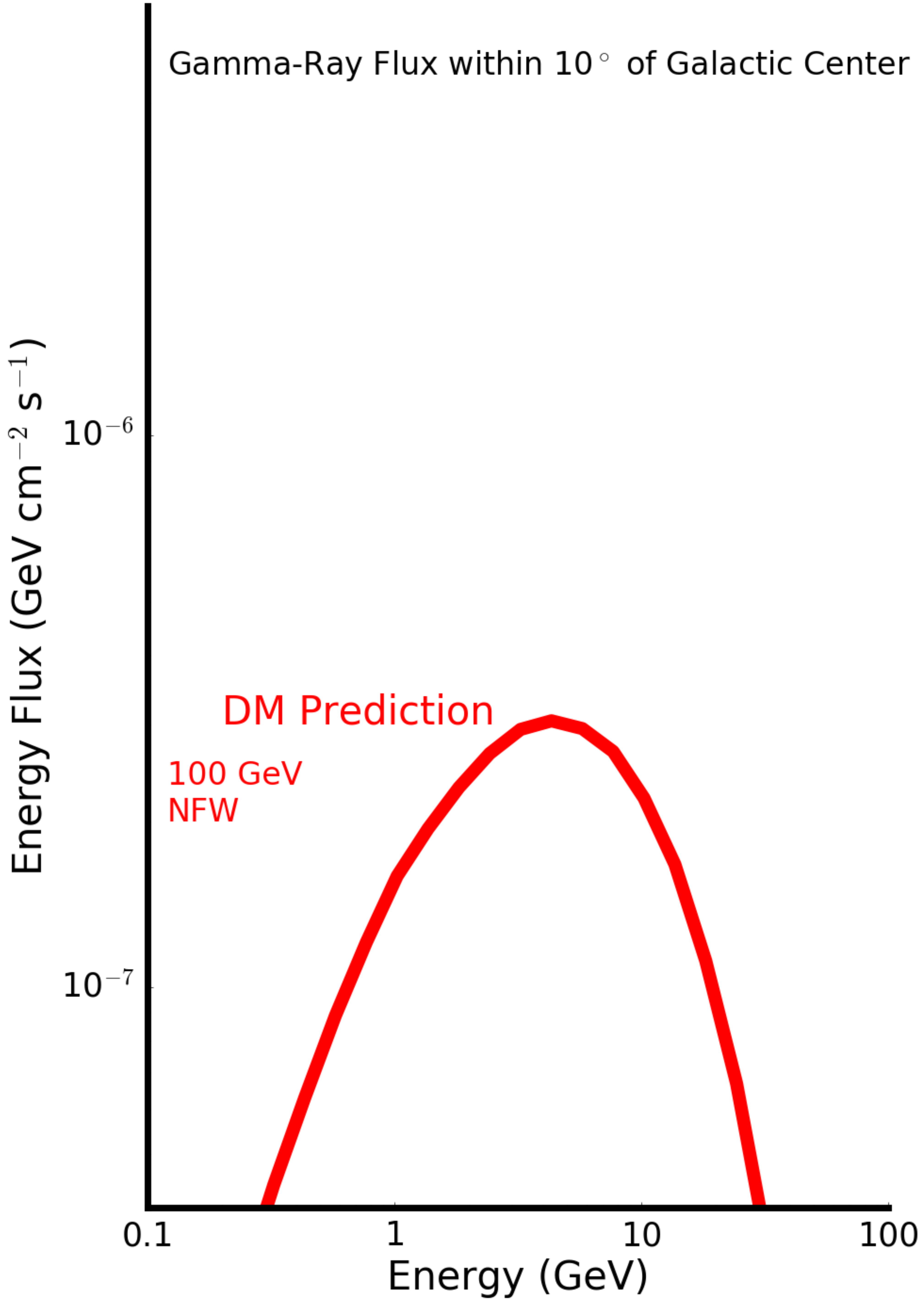
Thermal WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

Annihilation Final State (?)



Thermal WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

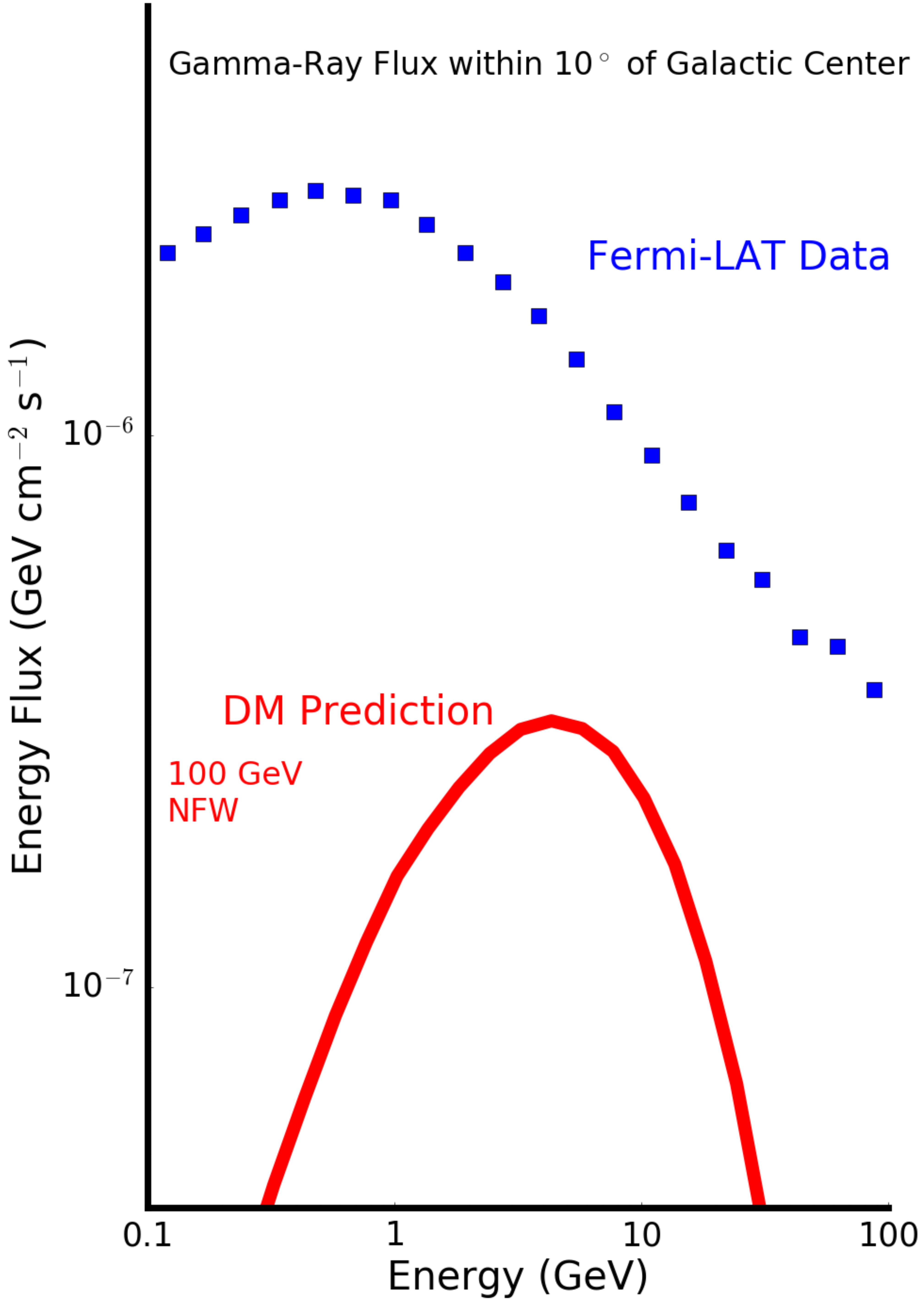
Dark Matter Mass (?)

Annihilation Final State (?)

Milky Way Star-Formation Rate (Galactic Dynamics)

Diffusion Constant in Galactic Center (Hydrodyanmics)

Activity of Supermassive Blackhole (?)



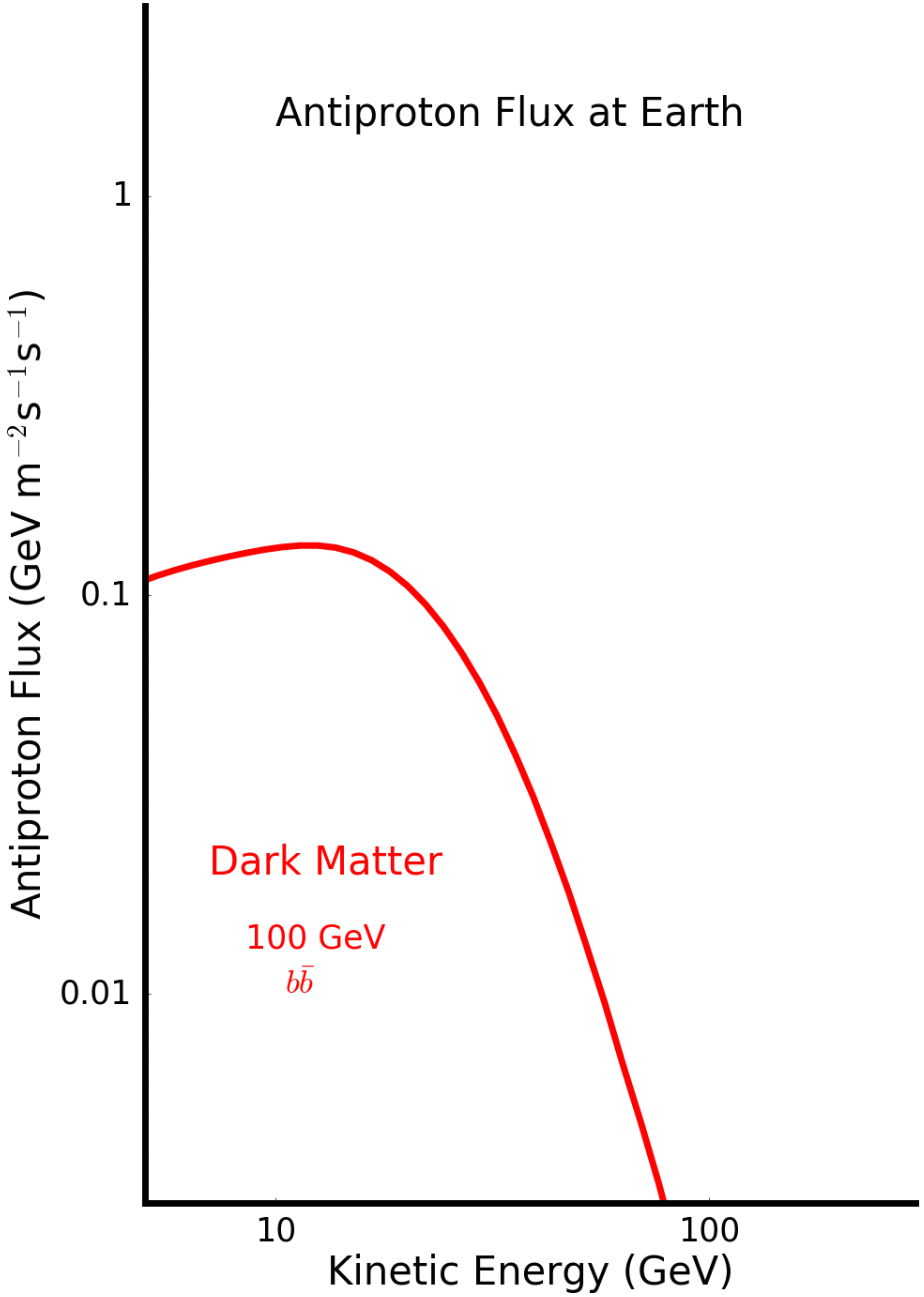
Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

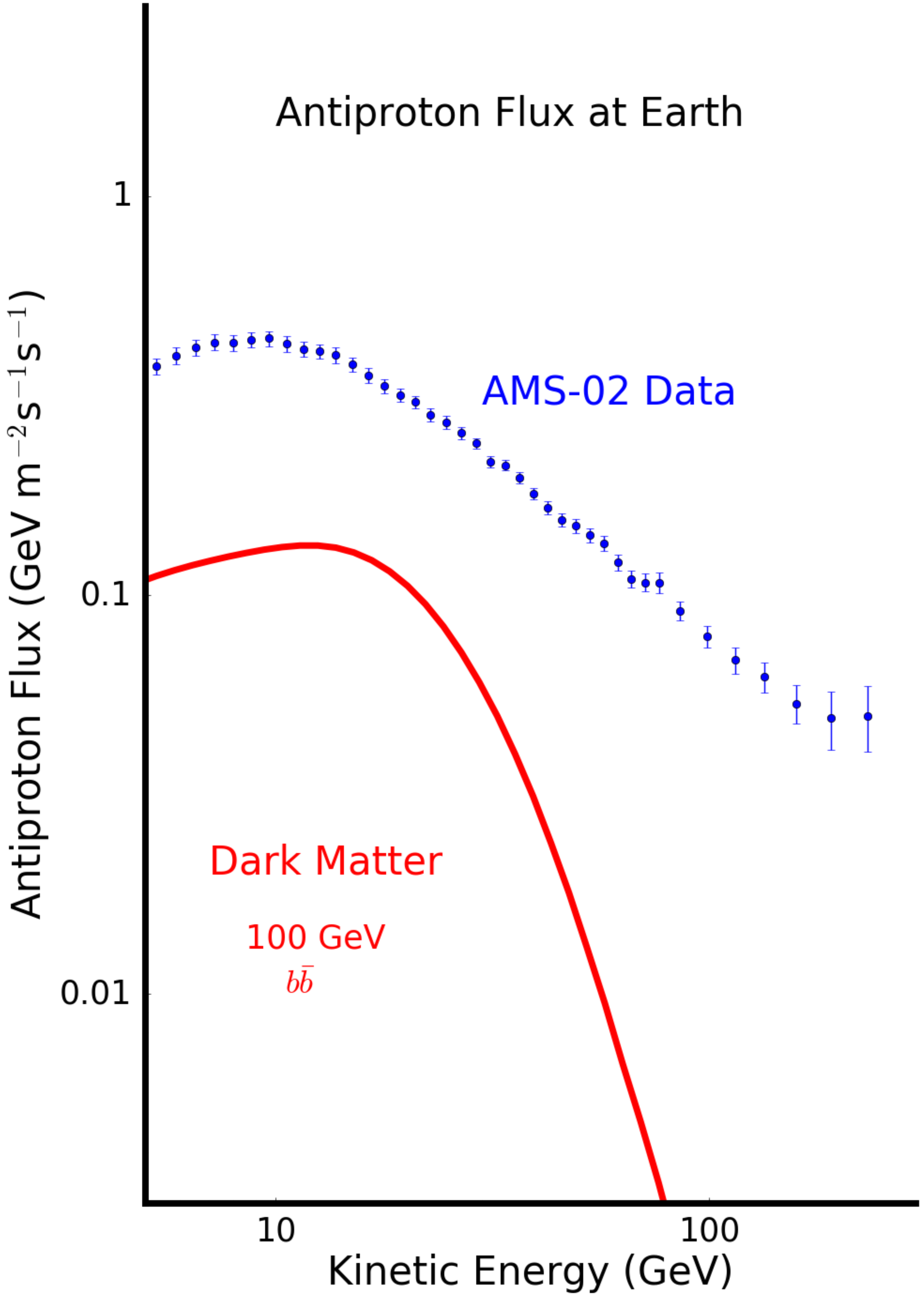
Convection of Annihilation Products from GC (Winds?)



Thermal WIMPs and the Story of Tantalus

- Local Dark Matter Density
- Thermal Cross-Section (Early Universe)
- Hadronic Component of Dark Matter Final State
- Convection of Annihilation Products from GC (Winds?)

- Local Gas Density
- Local Supernova Rate



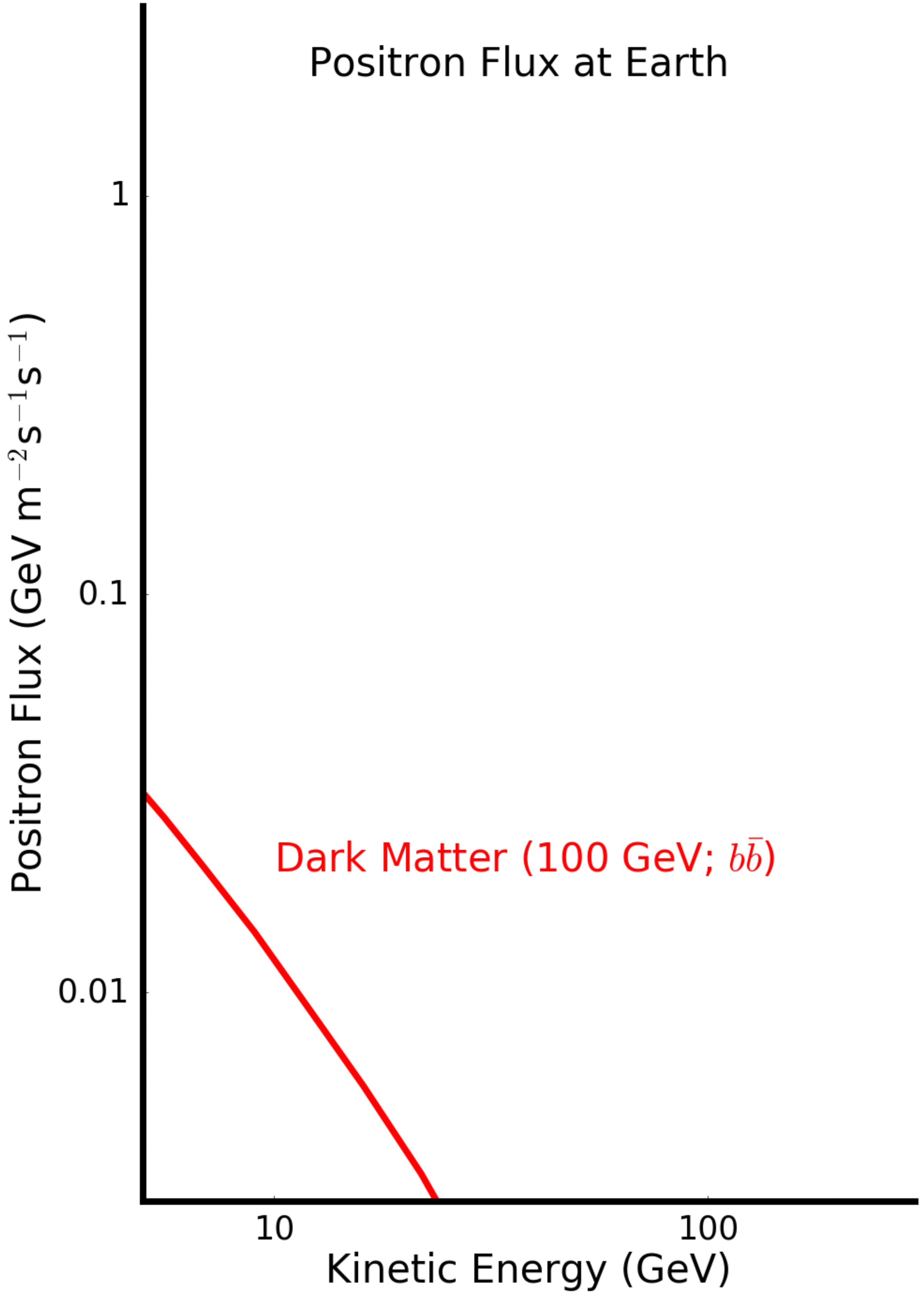
Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)



Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

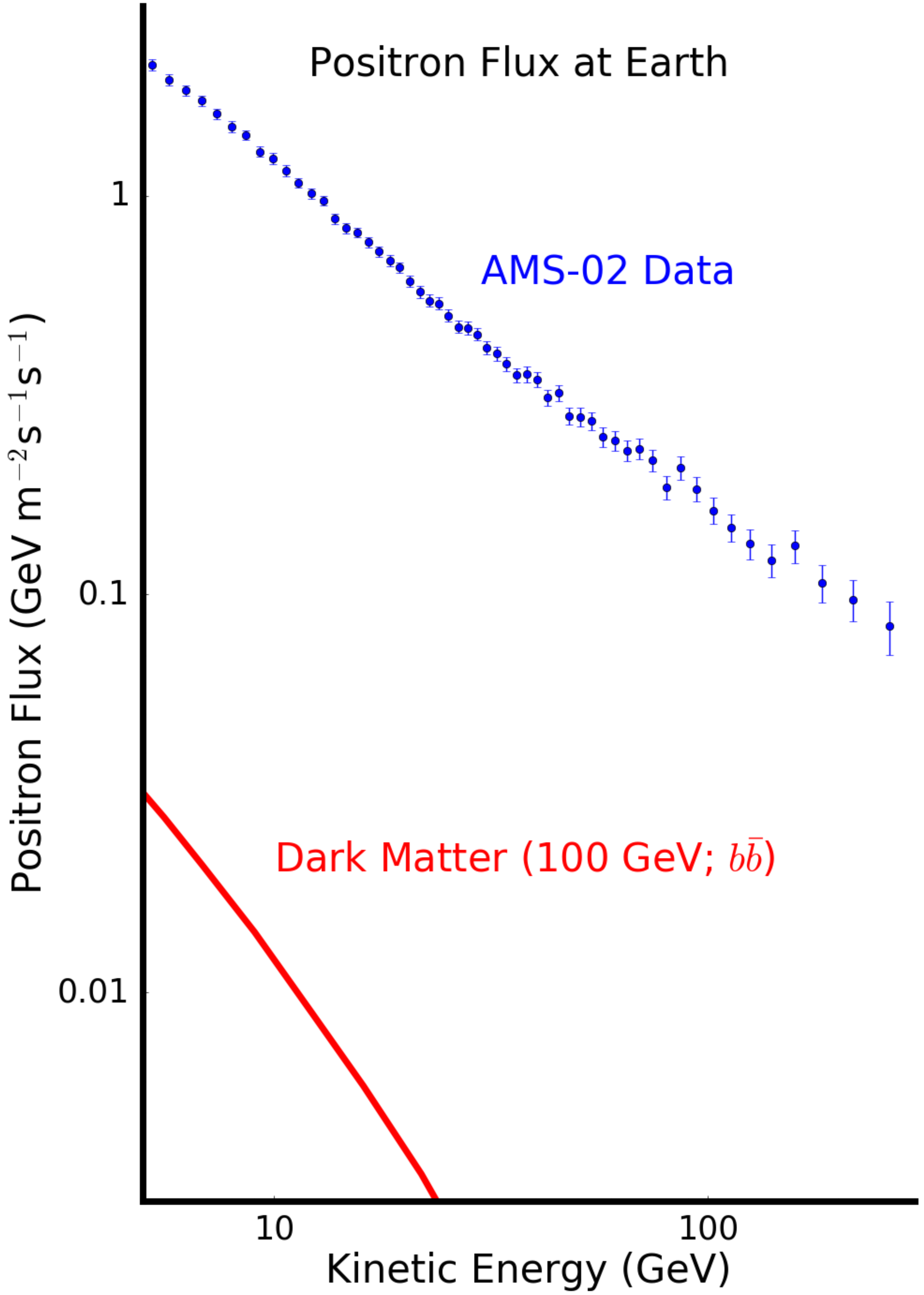
Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Pulsar Birth Rate

e^+e^- Acceleration Efficiency in Pulsar Magnetospheres



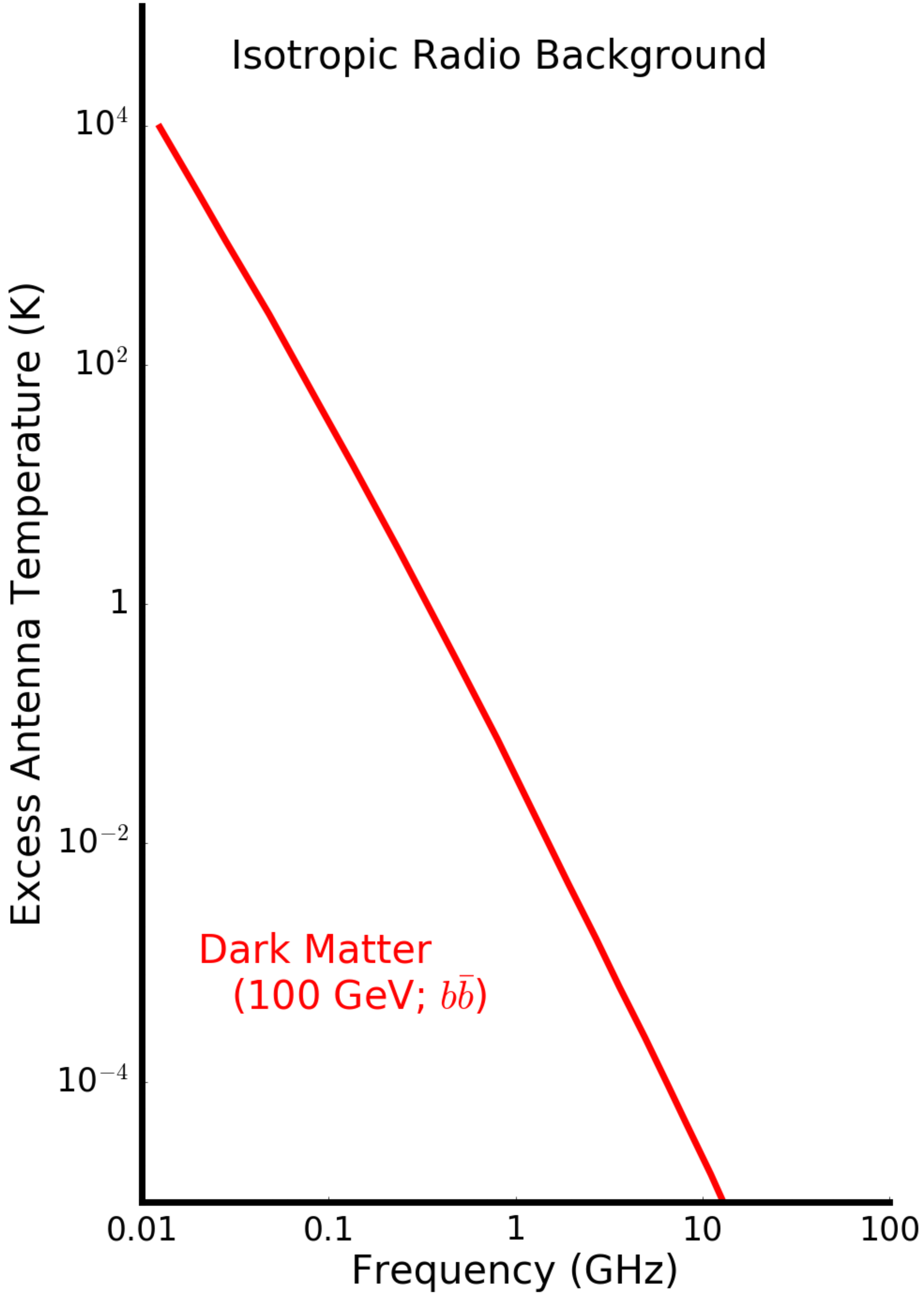
Thermal WIMPs and the Story of Tantalus

Extragalactic Dark Matter Density

Thermal Cross-Section (Early Universe)

e+e- Energy Fraction in Dark Matter Annihilation

Intergalactic Magnetic Fields



Thermal WIMPs and the Story of Tantalus

Extragalactic Dark Matter Density

Thermal Cross-Section (Early Universe)

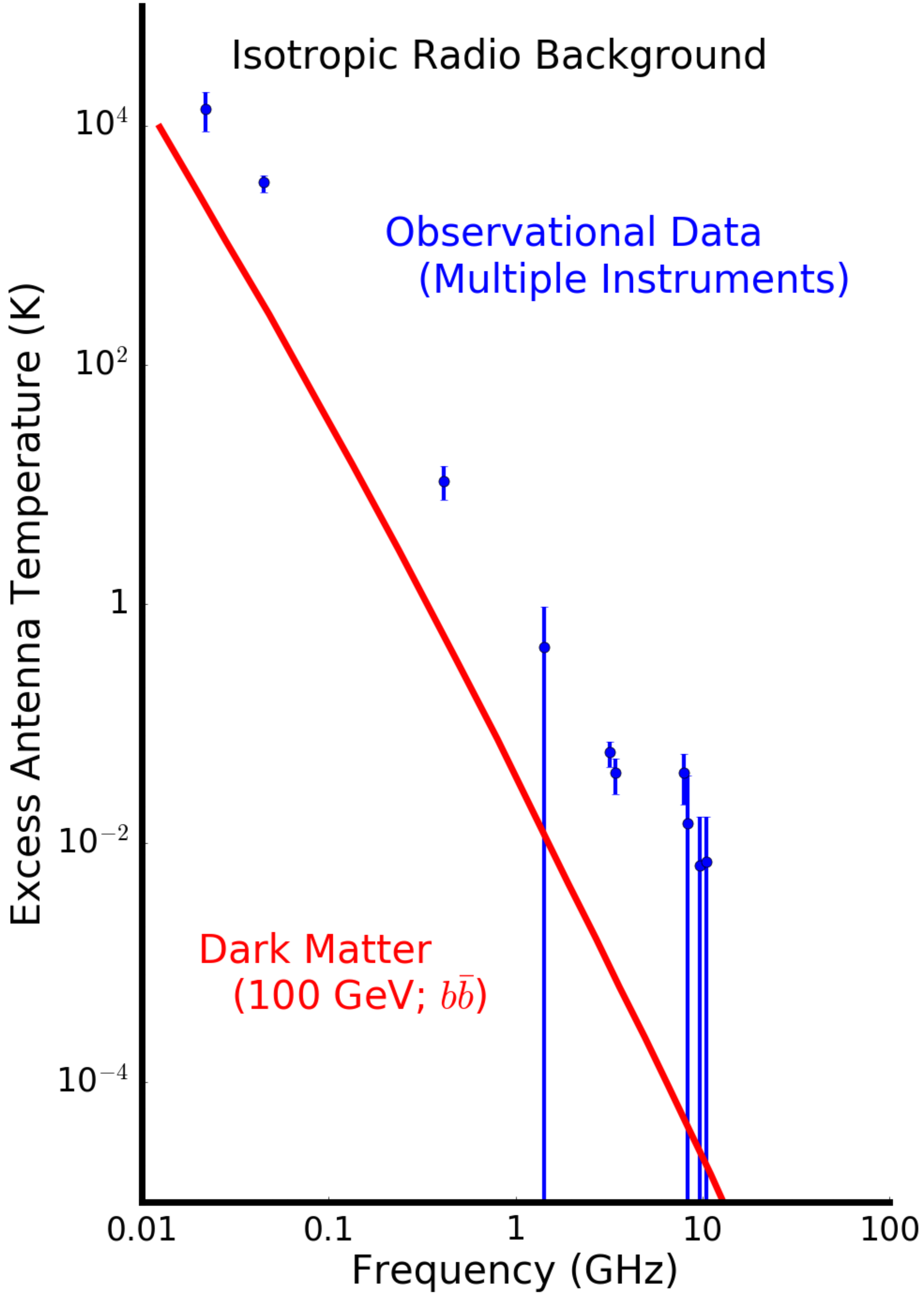
e+e- Energy Fraction in Dark Matter Annihilation

Intergalactic Magnetic Fields

Radio Luminosity in Starbursts and AGN

e+e- Reacceleration in Cluster Mergers

Redshift Dependence of Signal vs. CMB




Small Dark Matter Signal
Small Astrophysical Background
Large Dark Matter Signal
Small Astrophysical Background
Small Dark Matter Signal
Large Astrophysical Background
Large Dark Matter Signal
Large Astrophysical Background
Specificity (DM Flux / Astrophysics Flux)
Fraction of Dark Matter Flux


Small Dark Matter Signal
Small Astrophysical Background
Large Dark Matter Signal
Small Astrophysical Background
Easy
Small Dark Matter Signal
Large Astrophysical Background
Large Dark Matter Signal
Large Astrophysical Background
Specificity (DM Flux / Astrophysics Flux)
Fraction of Dark Matter Flux

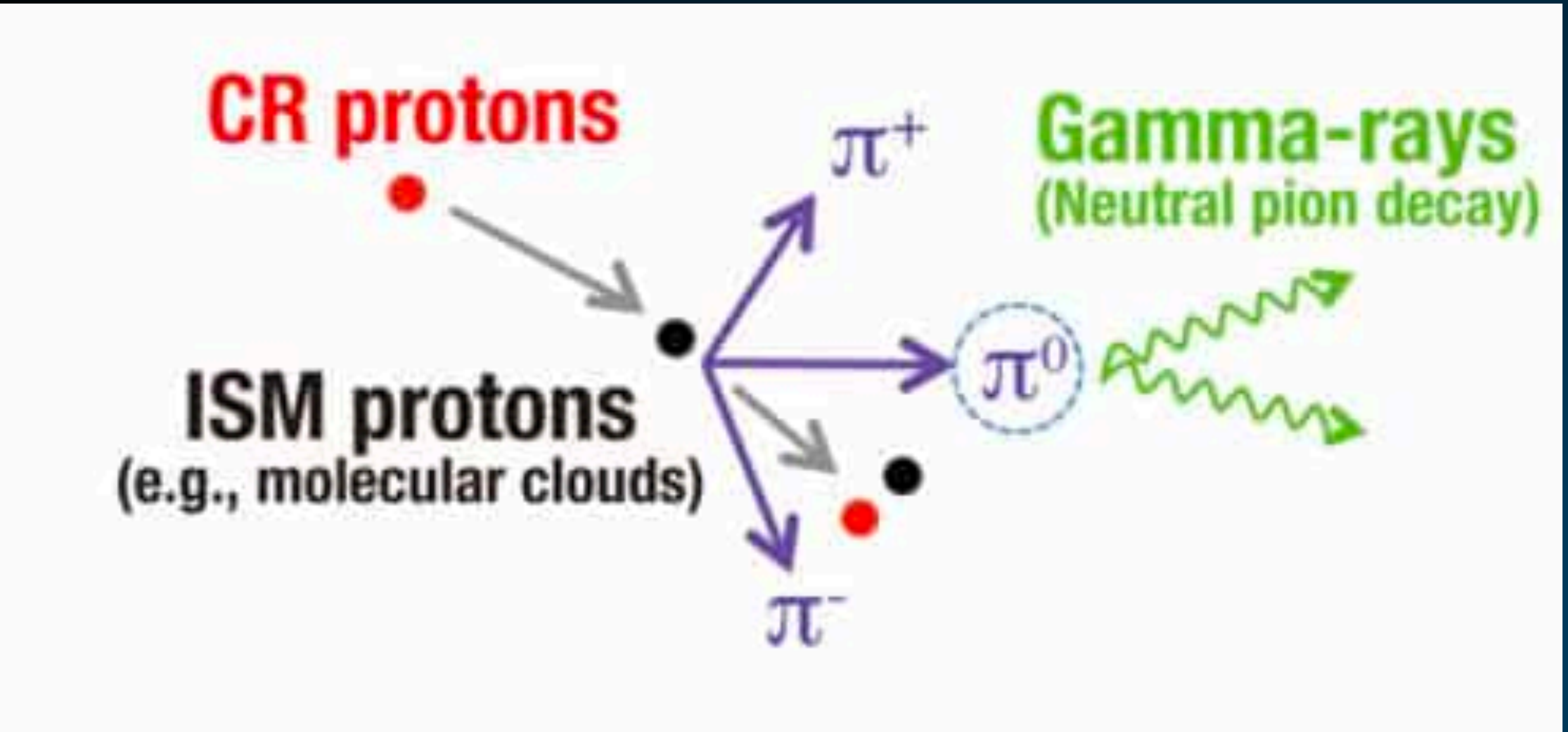

Small Dark Matter Signal
Small Astrophysical Background
Large Dark Matter Signal
Small Astrophysical Background
Easy
Easy
Small Dark Matter Signal
Large Astrophysical Background
Large Dark Matter Signal
Large Astrophysical Background
Specificity (DM Flux / Astrophysics Flux)
Fraction of Dark Matter Flux


Small Dark Matter Signal
Small Astrophysical Background
Large Dark Matter Signal
Small Astrophysical Background
Easy
Easy
Hard
Small Dark Matter Signal
Large Astrophysical Background
Large Dark Matter Signal
Large Astrophysical Background
Specificity (DM Flux / Astrophysics Flux)
Fraction of Dark Matter Flux


Small Dark Matter Signal
Small Astrophysical Background
Acceptable
Large Dark Matter Signal
Small Astrophysical Background
Easy
Easy
Small Dark Matter Signal
Large Astrophysical Background
Hard
Large Dark Matter Signal
Large Astrophysical Background
Specificity (DM Flux / Astrophysics Flux)
Fraction of Dark Matter Flux


Specificity (DM Flux / Astrophysics Flux)
Anti-Nuclei
Antiprotons
Gamma-Rays / Positrons
Fraction of Dark Matter Flux

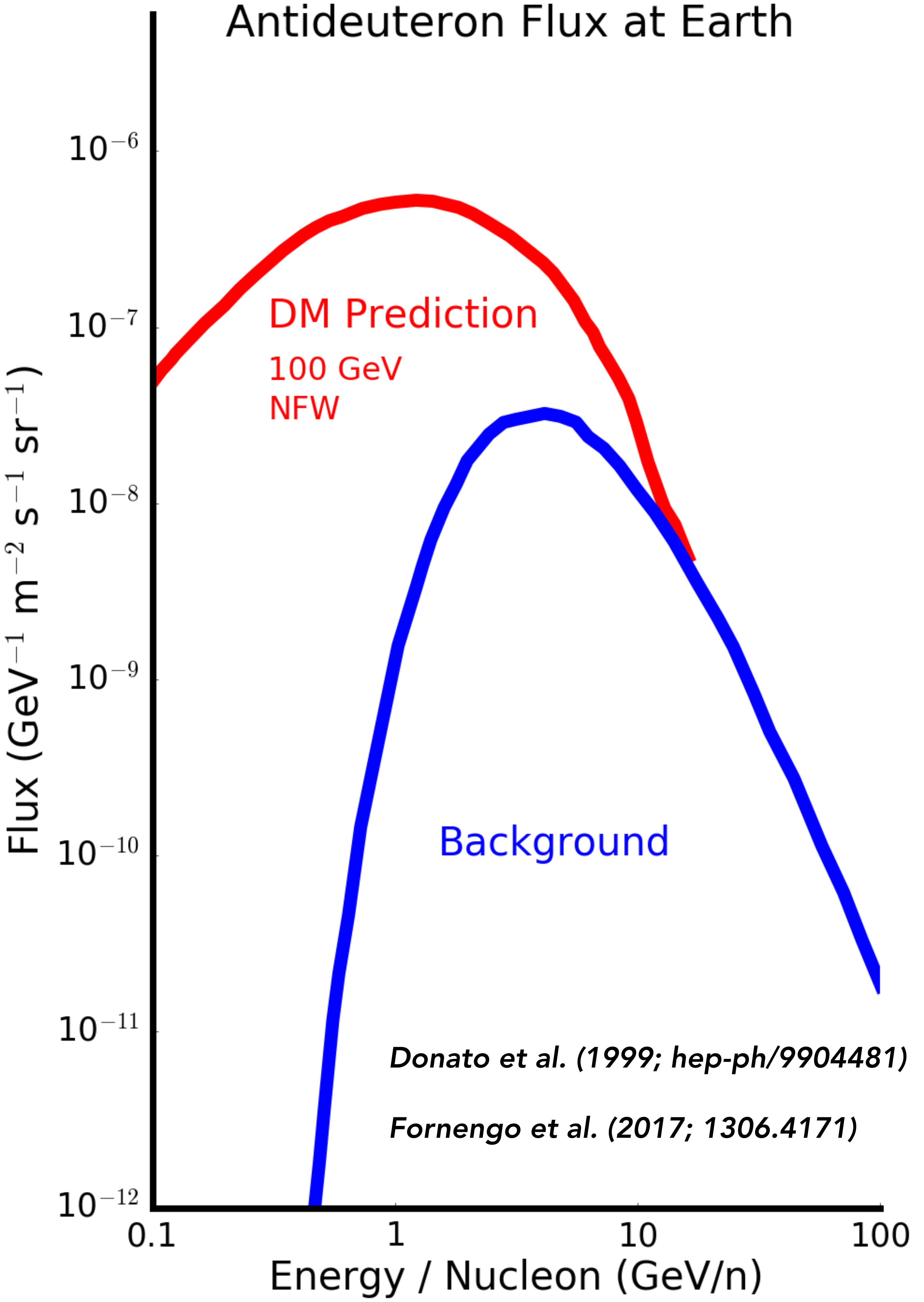
AntiNuclei: A Clean Search Strategy



Antinuclei carry away a significant fraction of the total momentum in a particle collision.

Astrophysical Antinuclei - Most be moving relativistically!

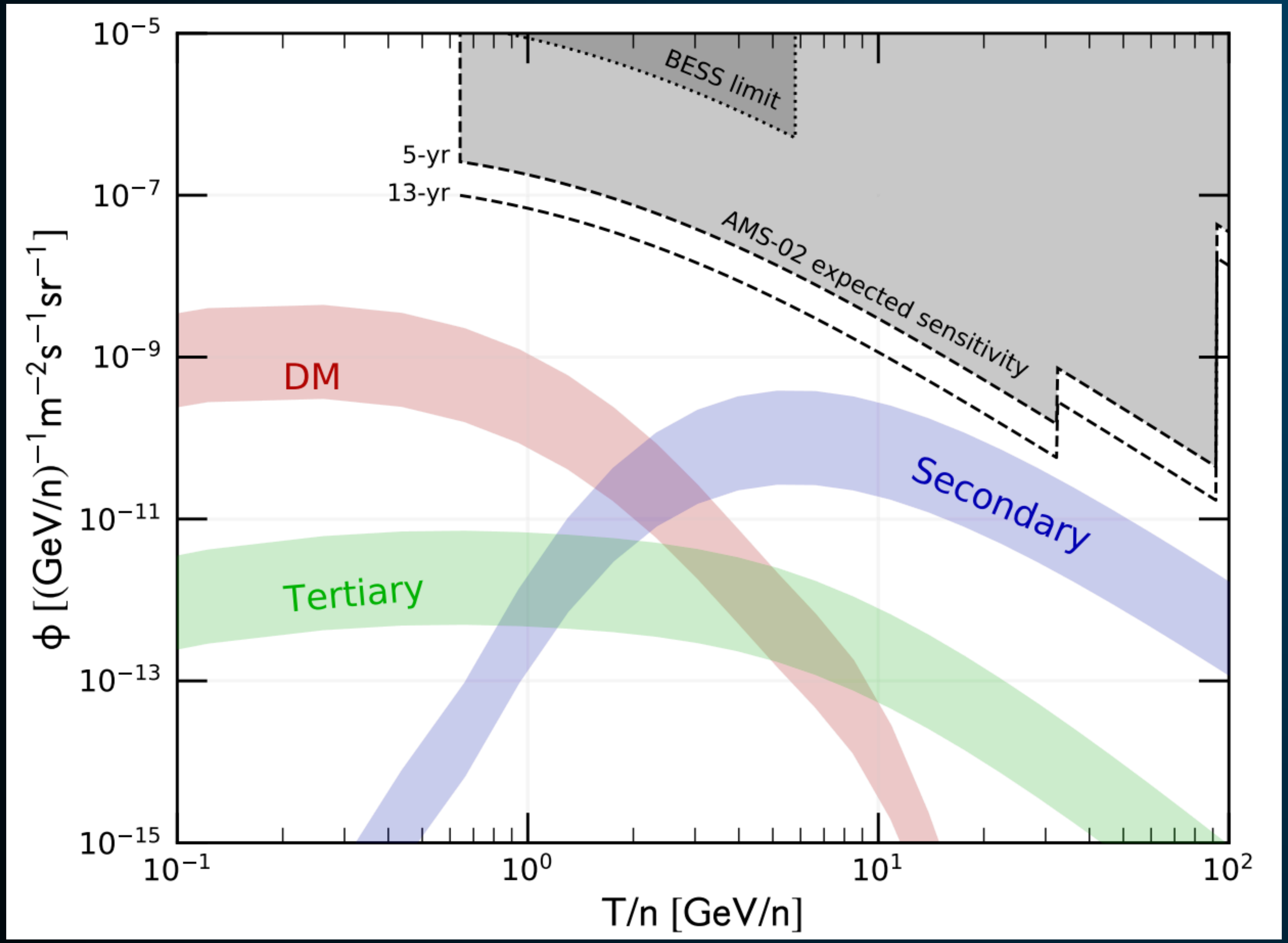
Dark Matter Antinuclei - Can be slow!



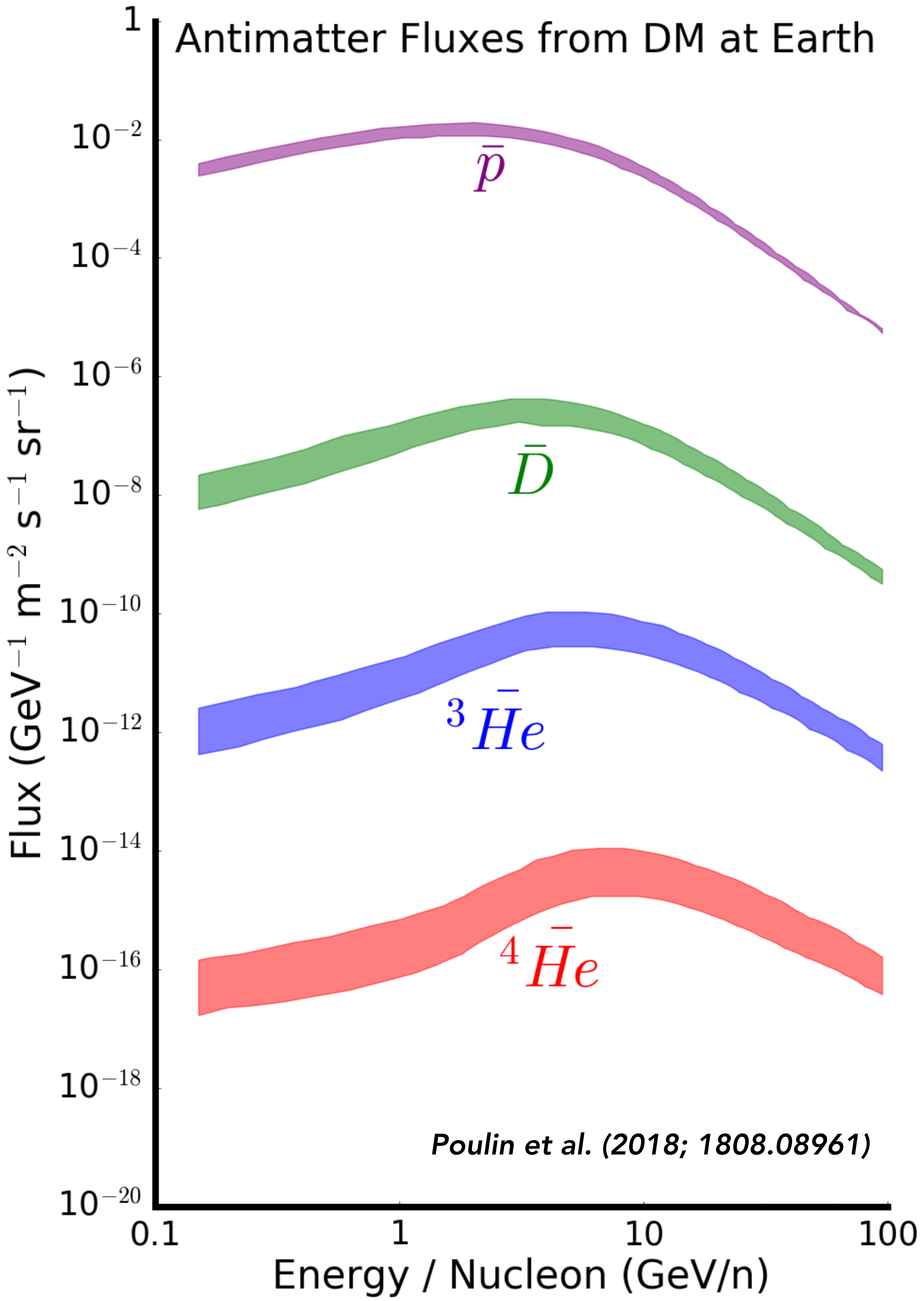
AntiNuclei: A Clean Search Strategy

Antihelium background even cleaner than antideuterons

But the flux is supposed to be <u>much</u> smaller.



Korsmeier (2017; 1711.08465)



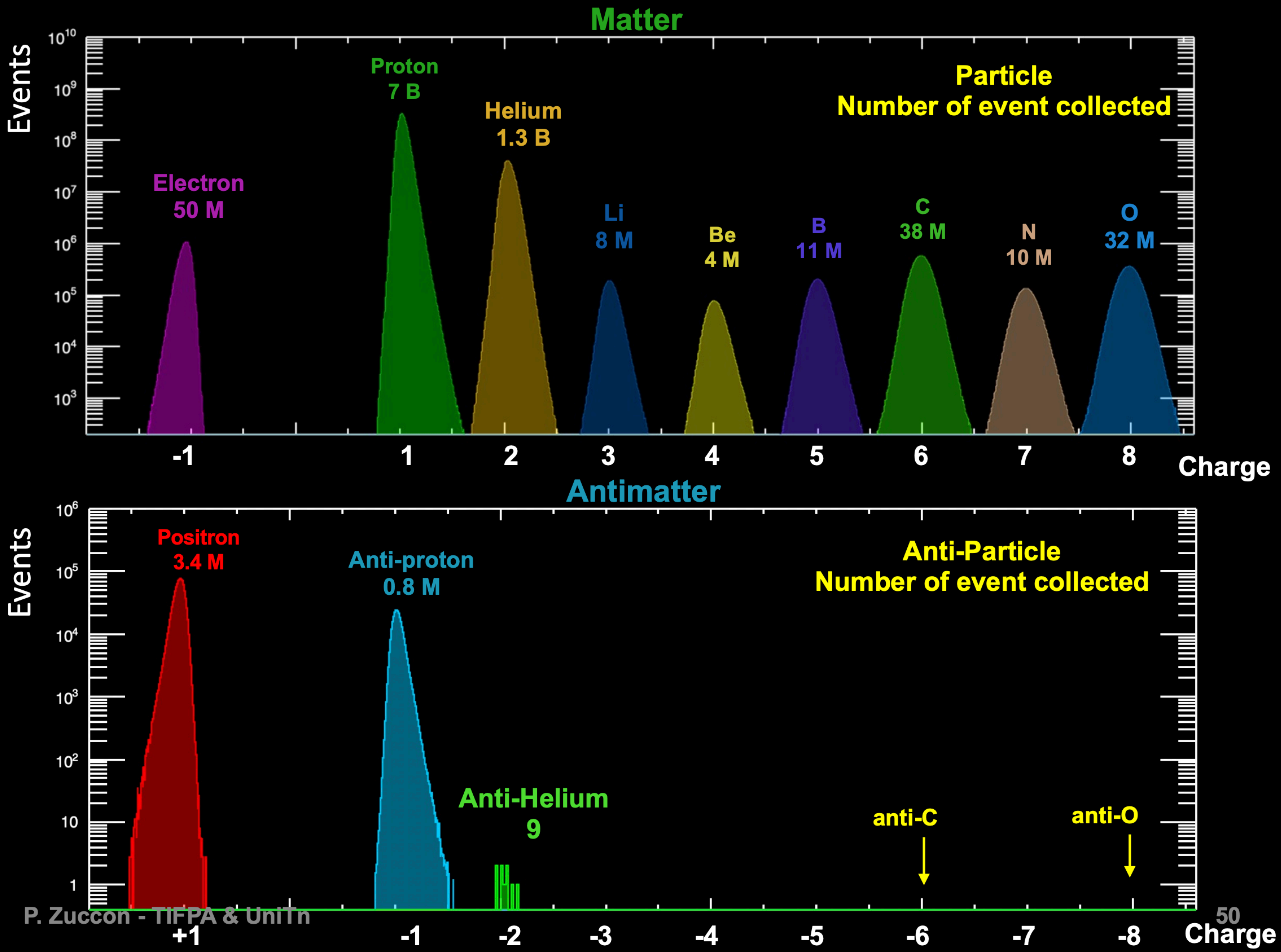
Tentative Evidence for Antinuclei

To date, we have observed eight events in the mass region from 0 to 10 GeV with Z= –2. All eight events are in the helium mass region.

Currently (having used 50 million core hours to generate 7 times more simulated events than measured events and having found no background events from the simulation), our best evaluation of the probability of the background origin for the eight $\overline{He}$ events is less than 3×10^{-8}. For the two $^4\overline{He}$ events our best evaluation of the probability (upon completion of the current 100 million core hours of simulation) will be less than 3×10^{-3}.

Note that for $^4\overline{He}$, projecting based on the statistics we have today, by using an additional 400 million core hours for simulation the background probability would be 10^{-4}. Simultaneously, continuing to run until 2023, which doubles the data sample, the background probability for $^4\overline{He}$ would be 2×10^{-7}, i.e., greater than 5-sigma significance.

slide from Sam Ting (La Palma Conference, April 9 2018)


Matter
Events
Particle
Number of event collected
Electron
50 M
Proton
7 B
Helium
1.3 B
Li
8 M
Be
4 M
B
11 M
C
38 M
N
10 M
O
32 M
Charge
Antimatter
Events
Anti-Particle
Number of event collected
Positron
3.4 M
Anti-proton
0.8 M
Anti-Helium
9
anti-C
anti-O
Charge

Method 1: Analytic Coalescence

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{\bar{\mathrm{p}}} \frac{d^3 N_{\bar{\mathrm{p}}}}{dp_{\bar{\mathrm{p}}}^3} \right)^Z \left(E_{\bar{\mathrm{n}}} \frac{d^3 N_{\bar{\mathrm{n}}}}{dp_{\bar{\mathrm{n}}}^3} \right)^{A-Z}$$

Method 1: Analytic Coalescence

$$R \propto p_0^{3(A-1)}$$

This is a general result for many enhancements - we need to either get more particles into the same momentum space - or make the momentum space for coalescence larger.

Method 2: Event-by-event Coalescence

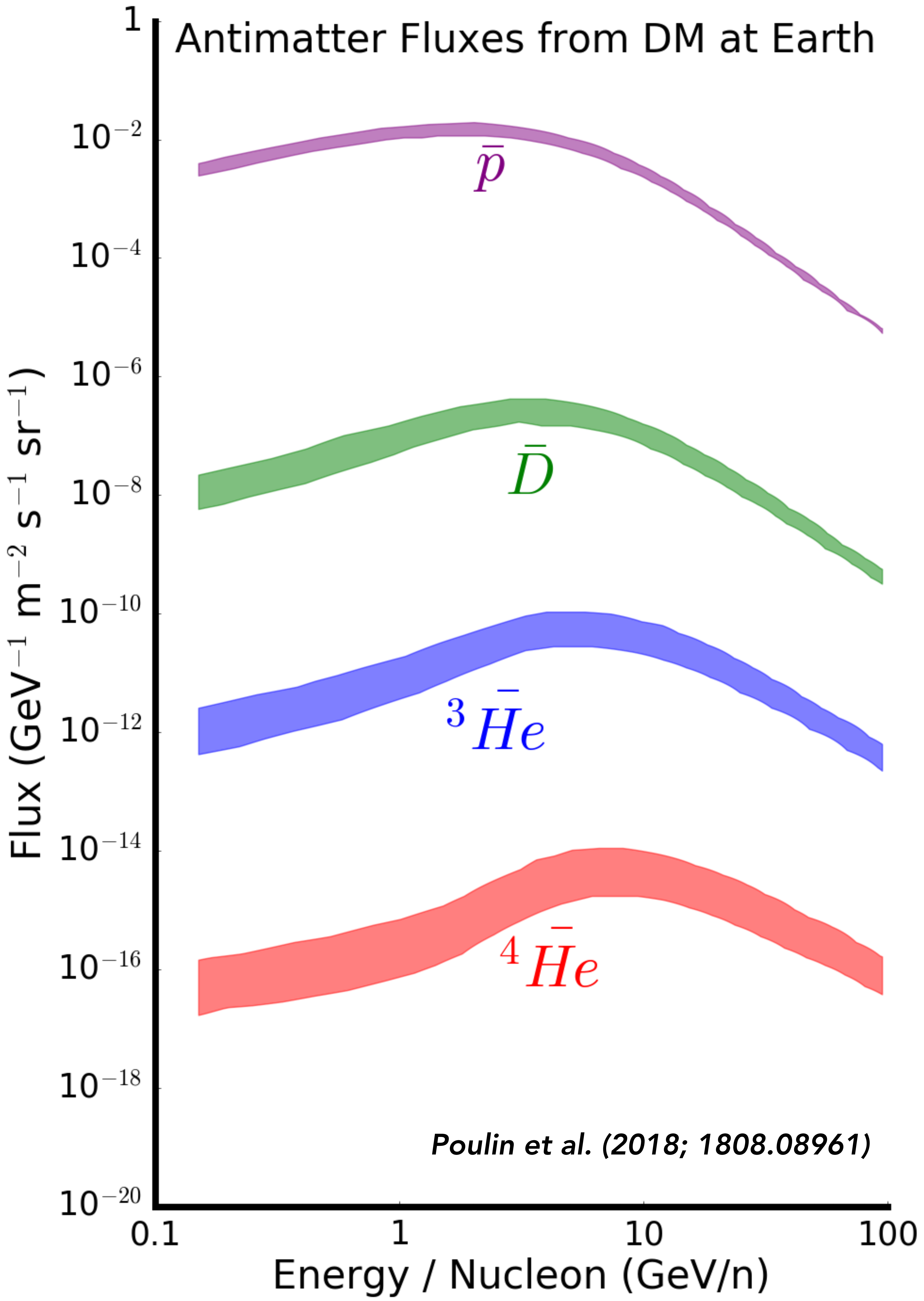
Boosting this Signal to Meet the Challenge?

1.) Coalescence Rates (1401.2461)

2.) Astrophysical Acceleration (2001.08749)

2.) Lambda_b Enhancement (2006.16251, 2106.00053)

3.) Strongly Coupled Dark Sectors (2211.00025)



Antihelium from Dark Matter

Eric Carlson,[1,2] Adam Coogan,[1,2,*] Tim Linden,[1,2,3,4,†] Stefano Profumo,[1,2,‡] Alejandro Ibarra,[5,§] and Sebastian Wild[5,¶]

[1]*Department of Physics, University of California, 1156 High St., Santa Cruz, CA 95064, USA*
[2]*Santa Cruz Institute for Particle Physics, Santa Cruz, CA 95064, USA***
[3]*Department of Physics, University of Chicago, Chicago, IL 60637*
[4]*Kavli Institute for Cosmological Physics, Chicago, IL 60637*
[5]*Physik-Department T30d, Technische Universität München, James-Franck-Straße, 85748 Garching, Germany*

(Dated: March 20, 2014)

Cosmic-ray anti-nuclei provide a promising discovery channel for the indirect detection of particle dark matter. Hadron showers produced by the pair-annihilation or decay of Galactic dark matter generate anti-nucleons which can in turn form light anti-nuclei. Previous studies have only focused on the spectrum and flux of low energy antideuterons which, although very rarely, are occasionally also produced by cosmic-ray spallation. Heavier elements ($A \geq 3$) have instead entirely negligible astrophysical background and a primary yield from dark matter which could be detectable by future experiments. Using a Monte Carlo event generator and an event-by-event phase space analysis, we compute, for the first time, the production spectrum of $^3\overline{\mathrm{He}}$ and $^3\overline{\mathrm{H}}$ for dark matter annihilating or decaying to $b\bar{b}$ and W^+W^- final states. We then employ a semi-analytic model of interstellar and heliospheric propagation to calculate the $^3\overline{\mathrm{He}}$ flux as well as to provide tools to relate the anti-helium spectrum corresponding to an arbitrary antideuteron spectrum. Finally, we discuss prospects for current and future experiments, including GAPS and AMS-02.

I. INTRODUCTION

Within the paradigm of Weakly Interacting Massive Particle (WIMP) dark matter, the pair-annihilation or decay of dark matter particles generically yields high-energy matter and antimatter cosmic rays. While the former are usually buried under large fluxes of cosmic rays of more ordinary astrophysical origin, antimatter is rare enough that a signal from dark matter might be distinguishable and detectable with the current generation of experiments. While astrophysical accelerators of high-energy positrons such as pulsars' magnetospheres are well-known, observations of cosmic anti-nuclei might provide a unique window into physics beyond the Stan-

cal backgrounds often prohibit the clean disentanglement of exotic sources, a recent analysis projects that the 1-year AMS-02 data will produce robust constraints on WIMP annihilation to heavy quarks below the thermal-relic cross-section for dark matter masses $30 \leq m_\chi \leq 200$ GeV [10].

In addition to antiprotons, Ref. [13] proposed new physics searches using heavier anti-nuclei such as antideuteron ($\overline{\mathrm{D}}$), antihelium-3 ($^3\overline{\mathrm{He}}$), or antitritium ($^3\overline{\mathrm{H}}$) forming from hadronic neutralino annihilation products. Although such production is of course highly correlated with the antiproton spectrum, the secondary astrophysical background decreases much more rapidly than the expected signal as the atomic number A is increased [14].

Key Insight - Coalescence Momentum for Antihelium Should Be Larger

While particle coalescence is hard to measure, the inverse process (fragmentation) is easier to measure. Helium's binding energy significantly exceeds deuteriums

$$p_0^{A=3} = \sqrt{B_{^3\overline{He}}/B_{\bar{D}}}\; p_0^{A=2} = 0.357 \pm 0.059 \text{ GeV/c.}$$

Can also use Heavy ion results (Berkeley Collider), which provide a lower-measurement of the coalescence momentum at a specific particle energy:

$$p_0^{A=3} = 1.28\; p_0^{A=2} = 0.246 \pm 0.038 \text{ GeV/c.}$$

Key Insight - Coalescence Momentum for Antihelium Should Be Larger

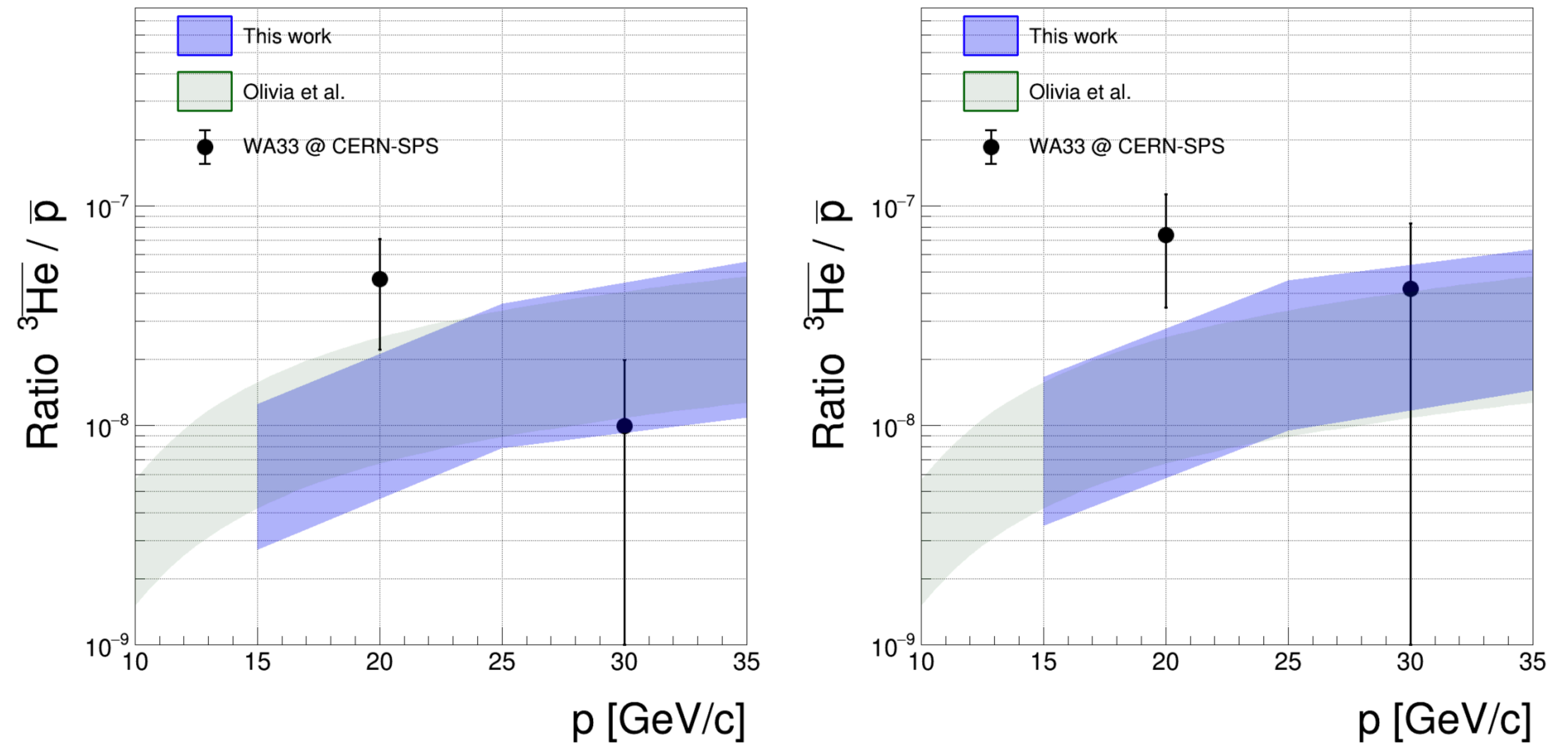
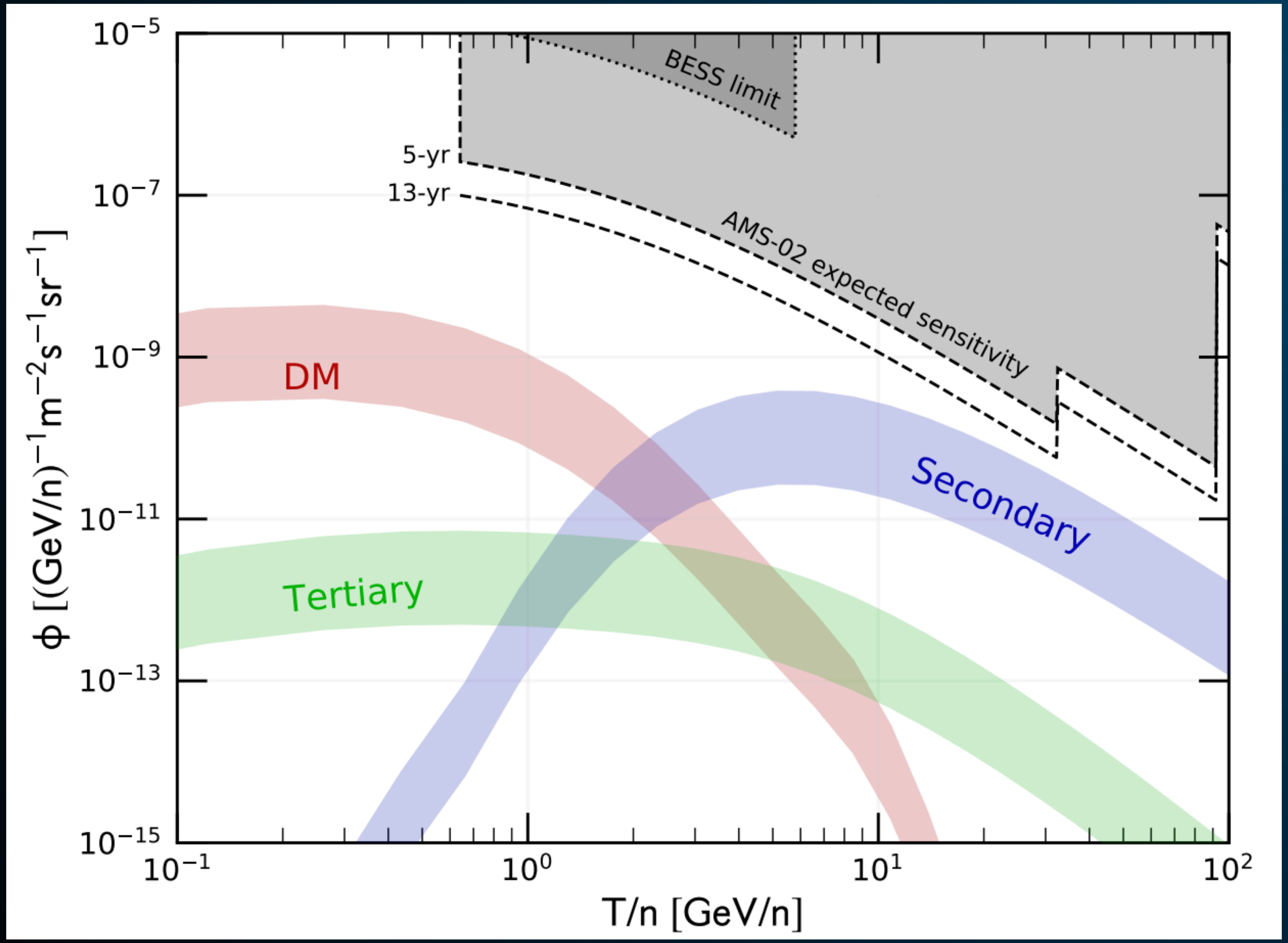


FIG. 4. The invariant production cross section ratio $^3\overline{\mathrm{He}}/\overline{p}$ as function of momentum p [GeV/c] in the laboratory frame for (left) p-Be at $p_{\mathrm{lab}} = 200\,\mathrm{GeV}/c$ and (right) p–Al at $p_{\mathrm{lab}} = 200\,\mathrm{GeV}/c$. The uncertainty bands for this work were estimated by varying the coalescence parameter from $p_{0,G}$ (59 MeV/c) to 130% of $p_{0,G}$ (77 MeV/c).

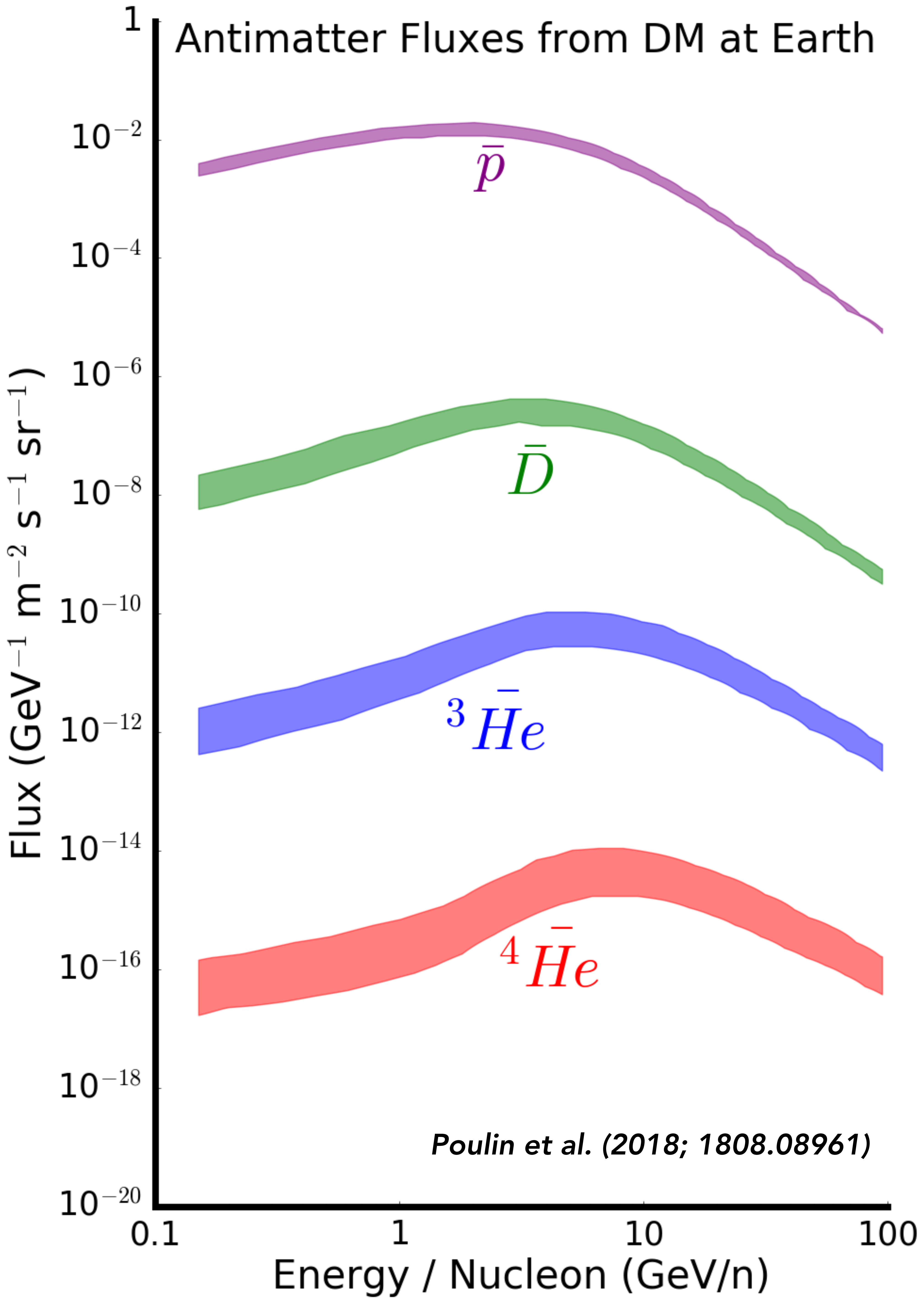
Shukla et al. (2006.12707)

Coalescence Models - Expected Helium Flux

Using more realistic estimates for the anti helium coalescence momentum produces a boosted anti helium flux, especially at low energies.



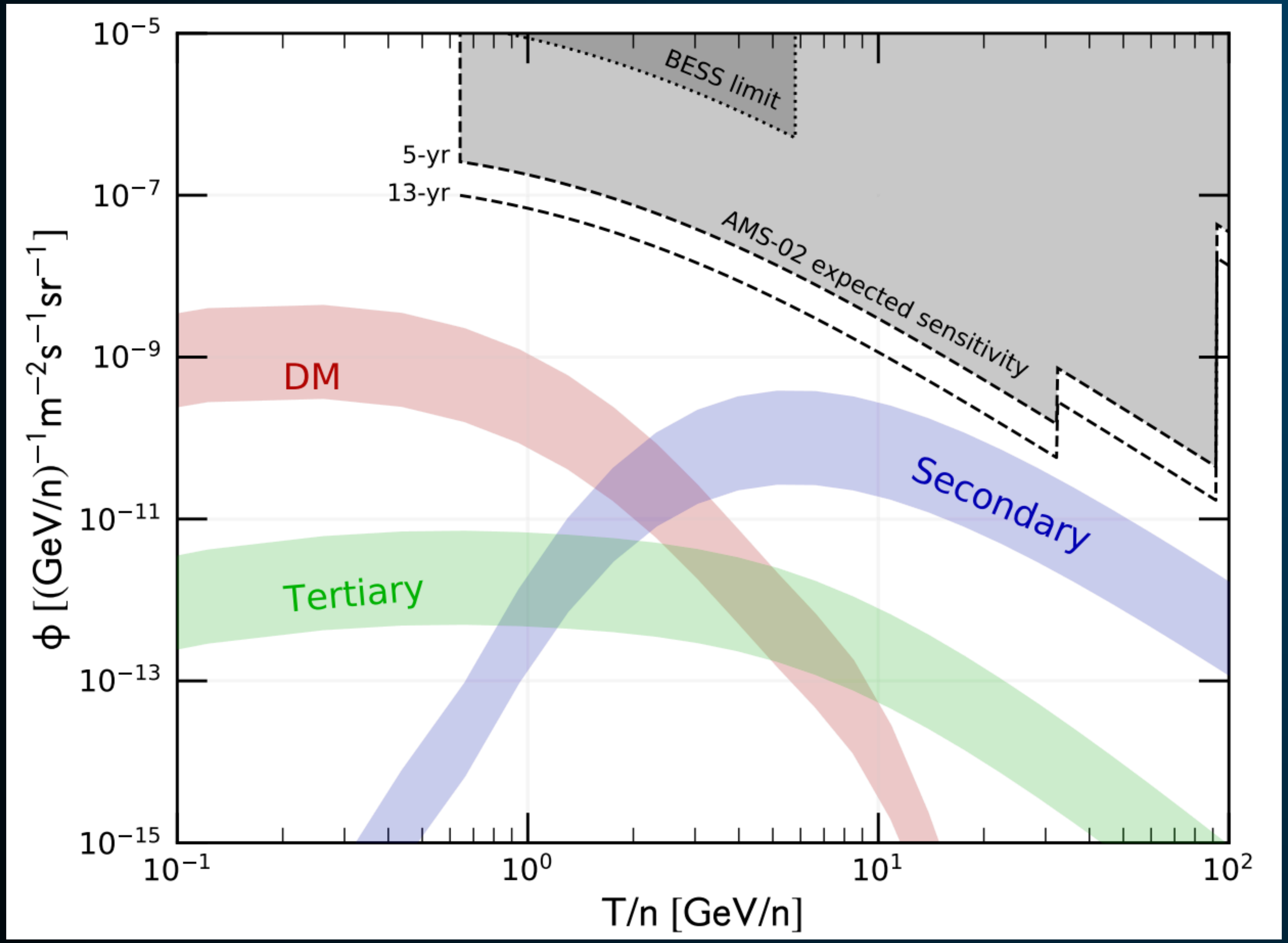
Korsmeier (2017; 1711.08465)



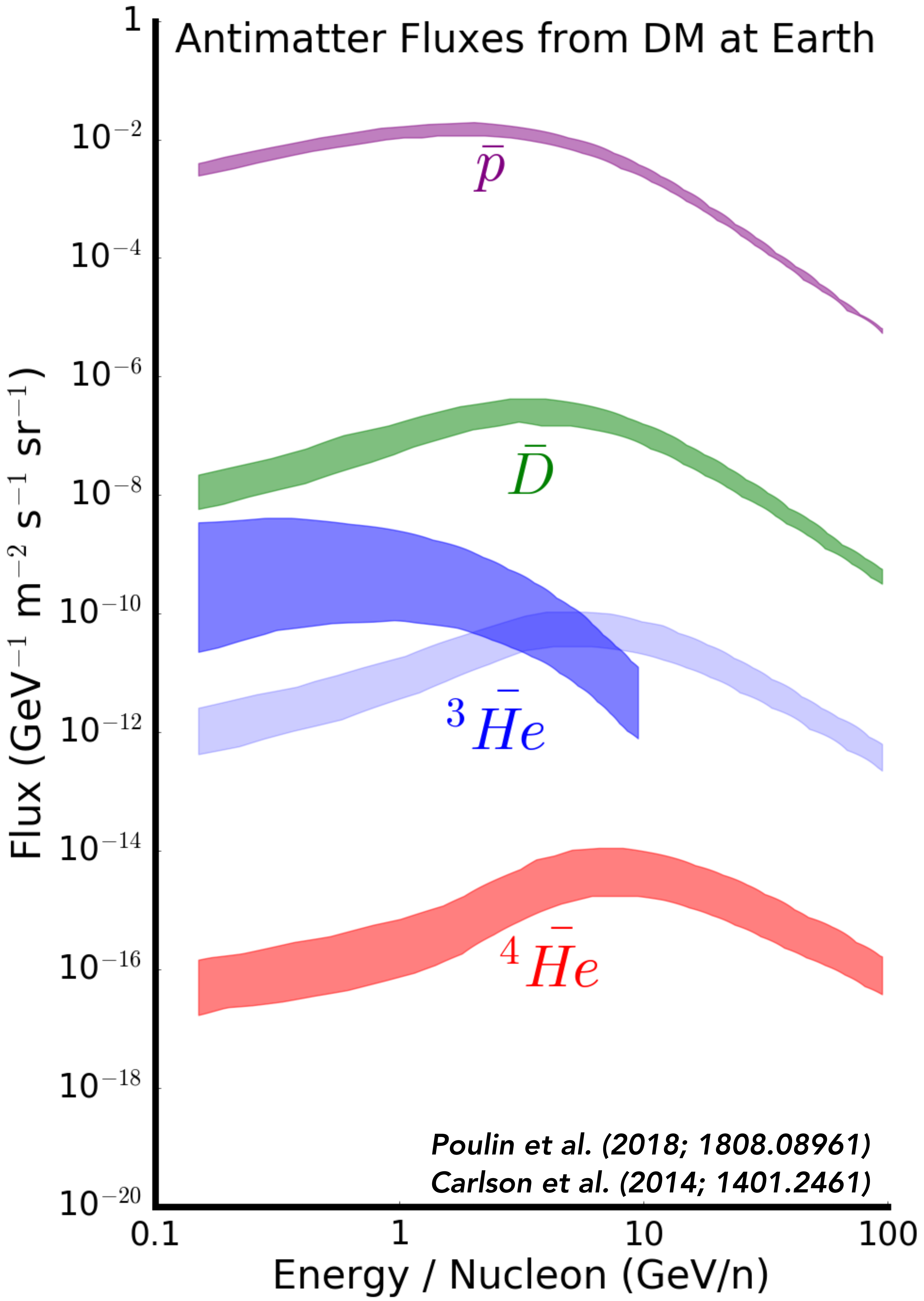
Poulin et al. (2018; 1808.08961)

Coalescence Models - Expected Helium Flux

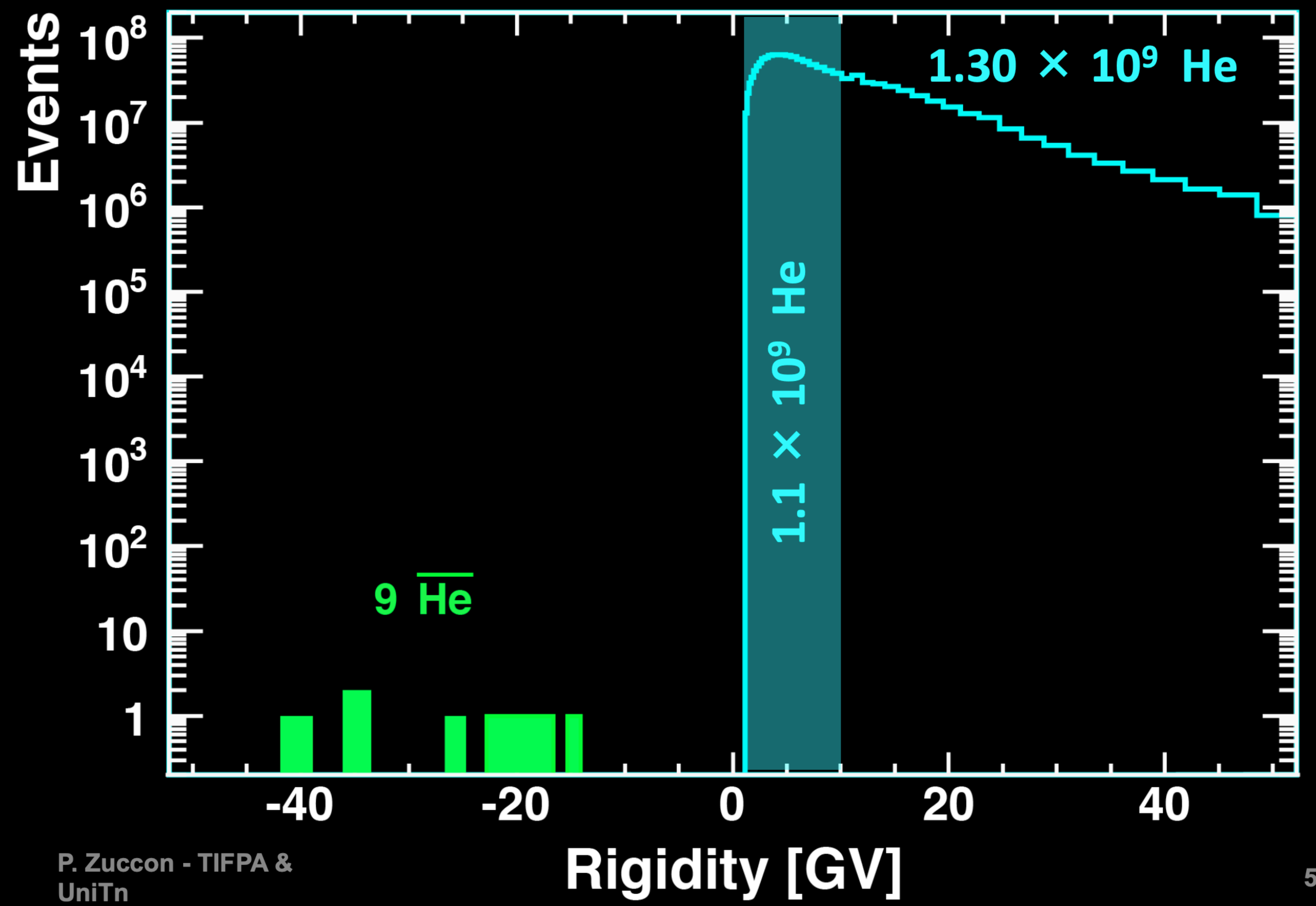
Using more realistic estimates for the anti helium coalescence momentum produces a boosted anti helium flux, especially at low energies.



Korsmeier (2017; 1711.08465)



However the Rigidity of these Antihelium Events is High



Idea 2: Move the Excess to High Energies

1.) Changing the coalescence model primarily affects the Helium yield when the total center of mass energy is small.

2.) Very good for predicted rates with GAPS, or low-energy AMS-02 observations.

3.) But AMS-02 antihelium are (generally reported) at energies of ~10 GeV/n.

Astrophysical Enhancements!

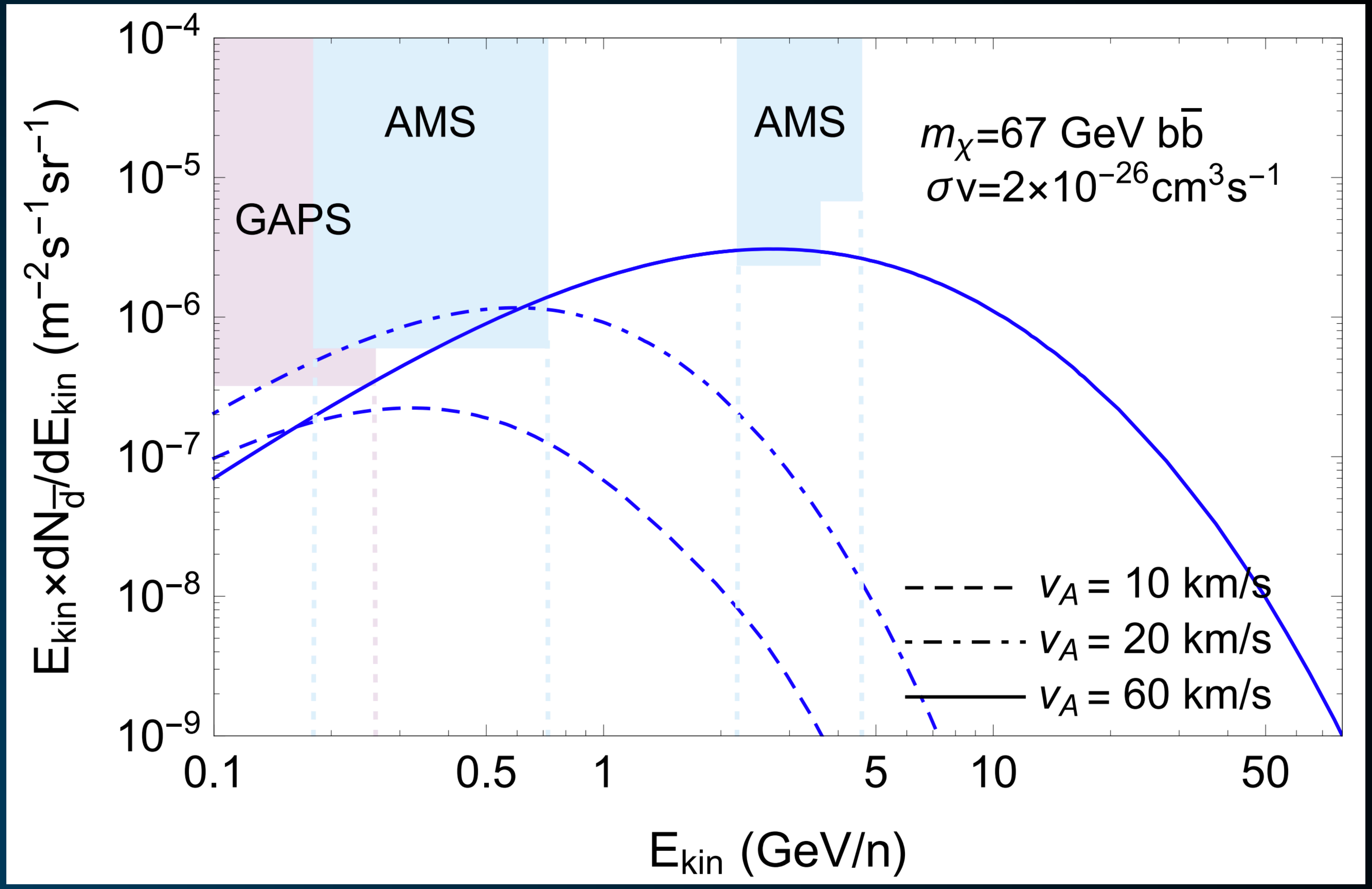
The current event rates depend on the detector sensitivity to anti-Helium.

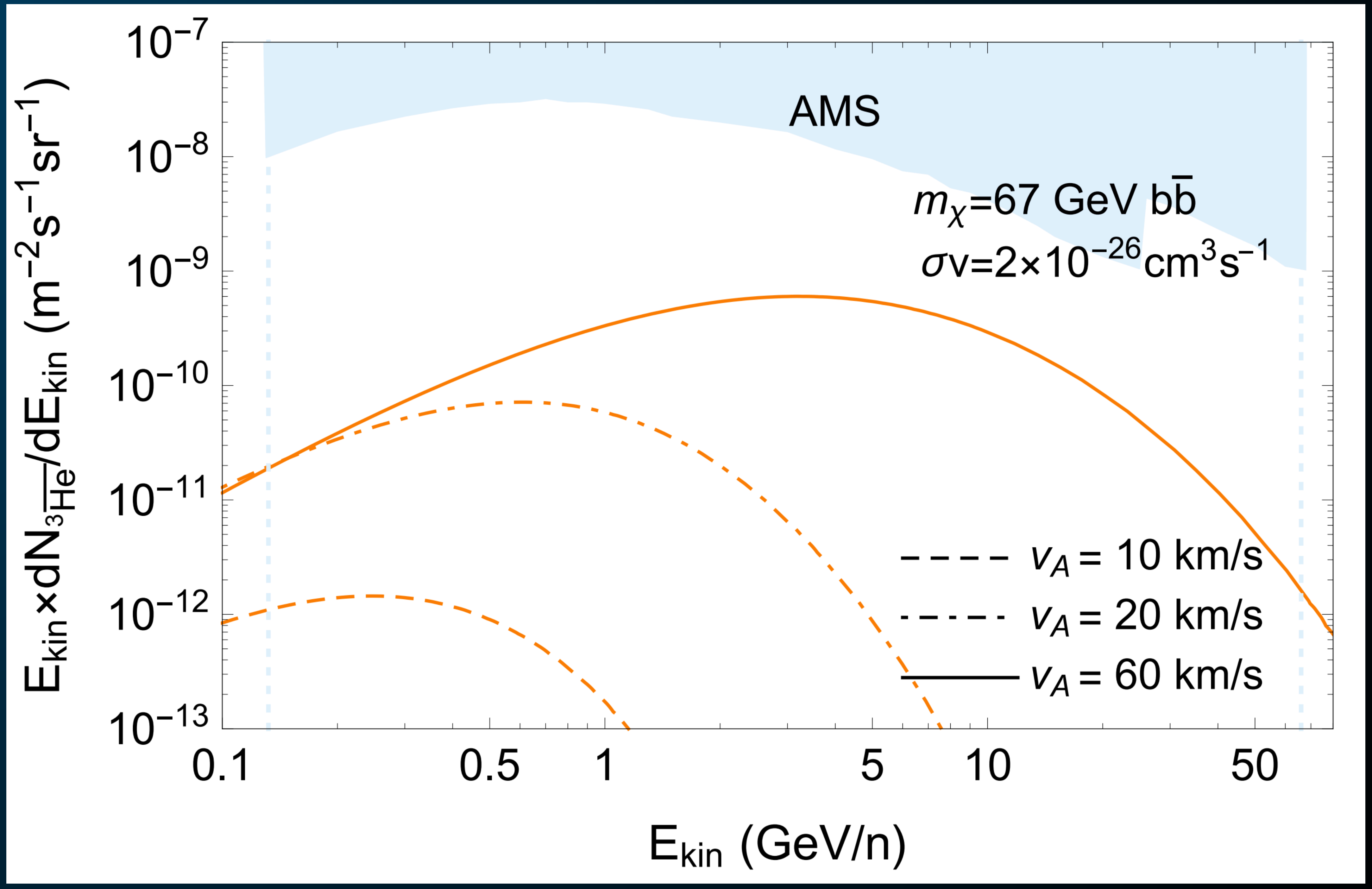
We lose many events because most anti-He are produced at energies that are too small to be detected.

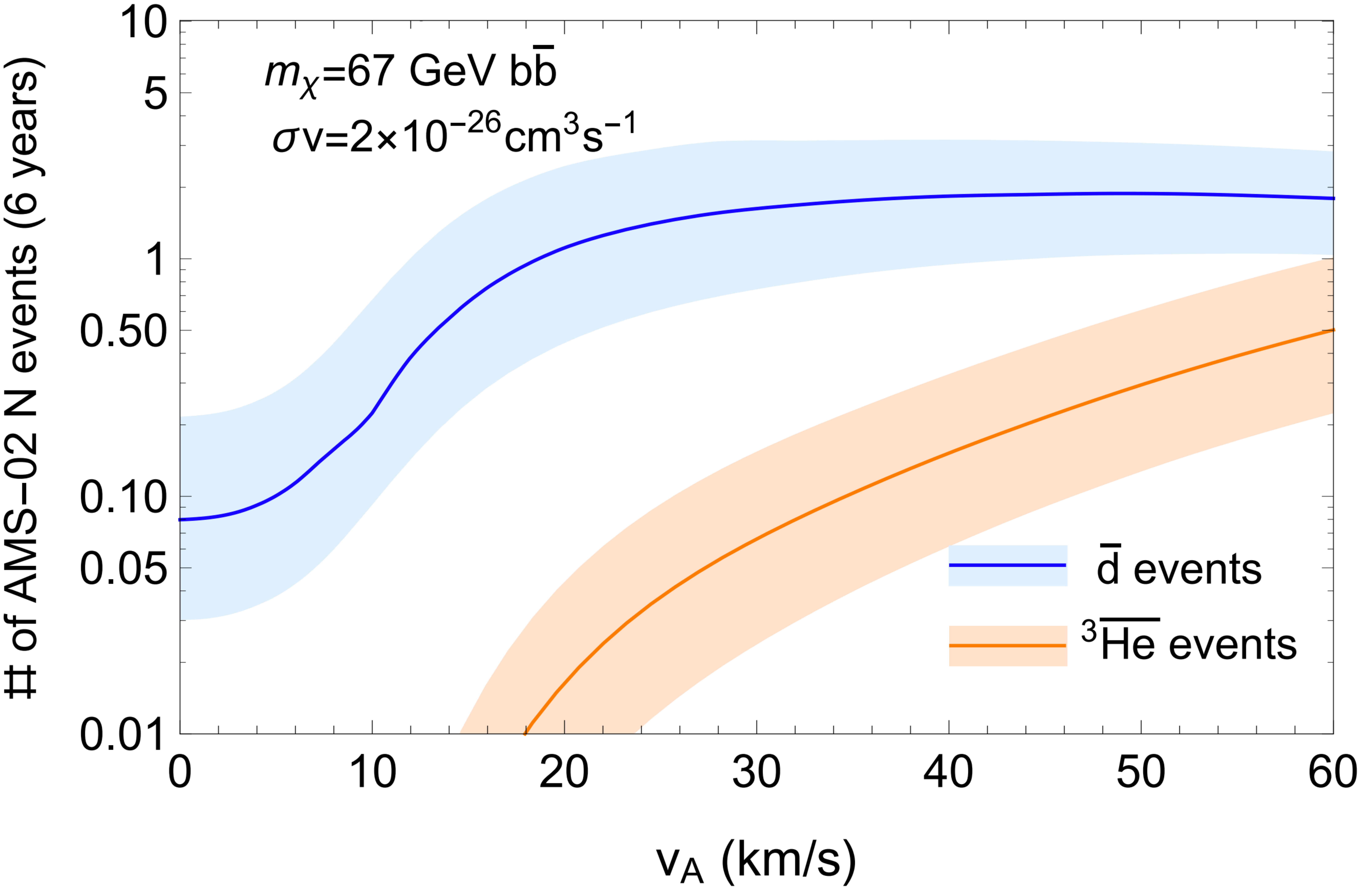
Use re-acceleration to boost the anti-He energies into the detectable range!

$$D_{pp}(R) = \frac{4}{3\delta(2-\delta)(4-\delta)(2+\delta)} \frac{R^2 v_A^2}{D_{xx}(R)}$$

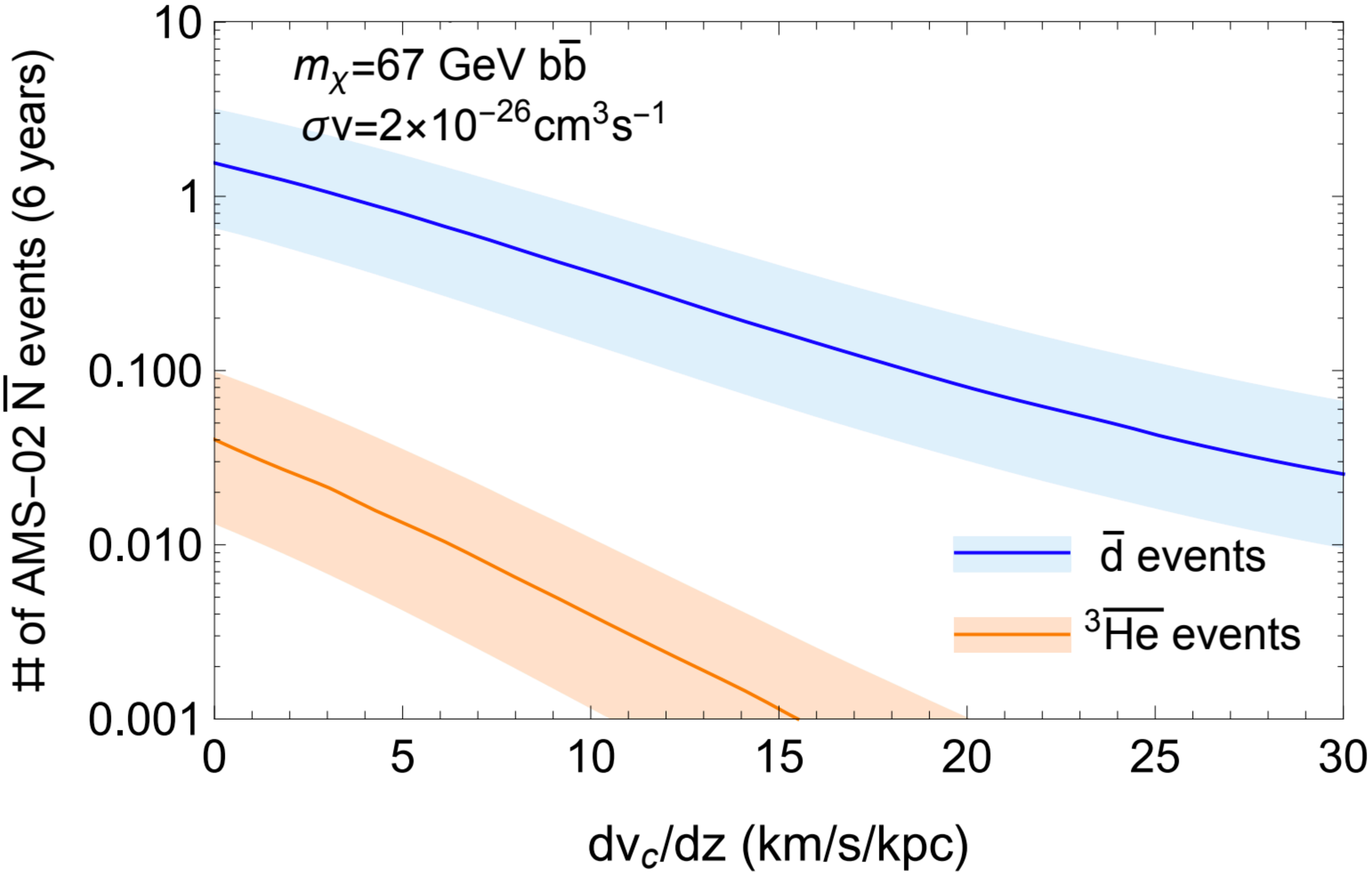
Cholis, Linden, Hooper (2020; 2001.08749)







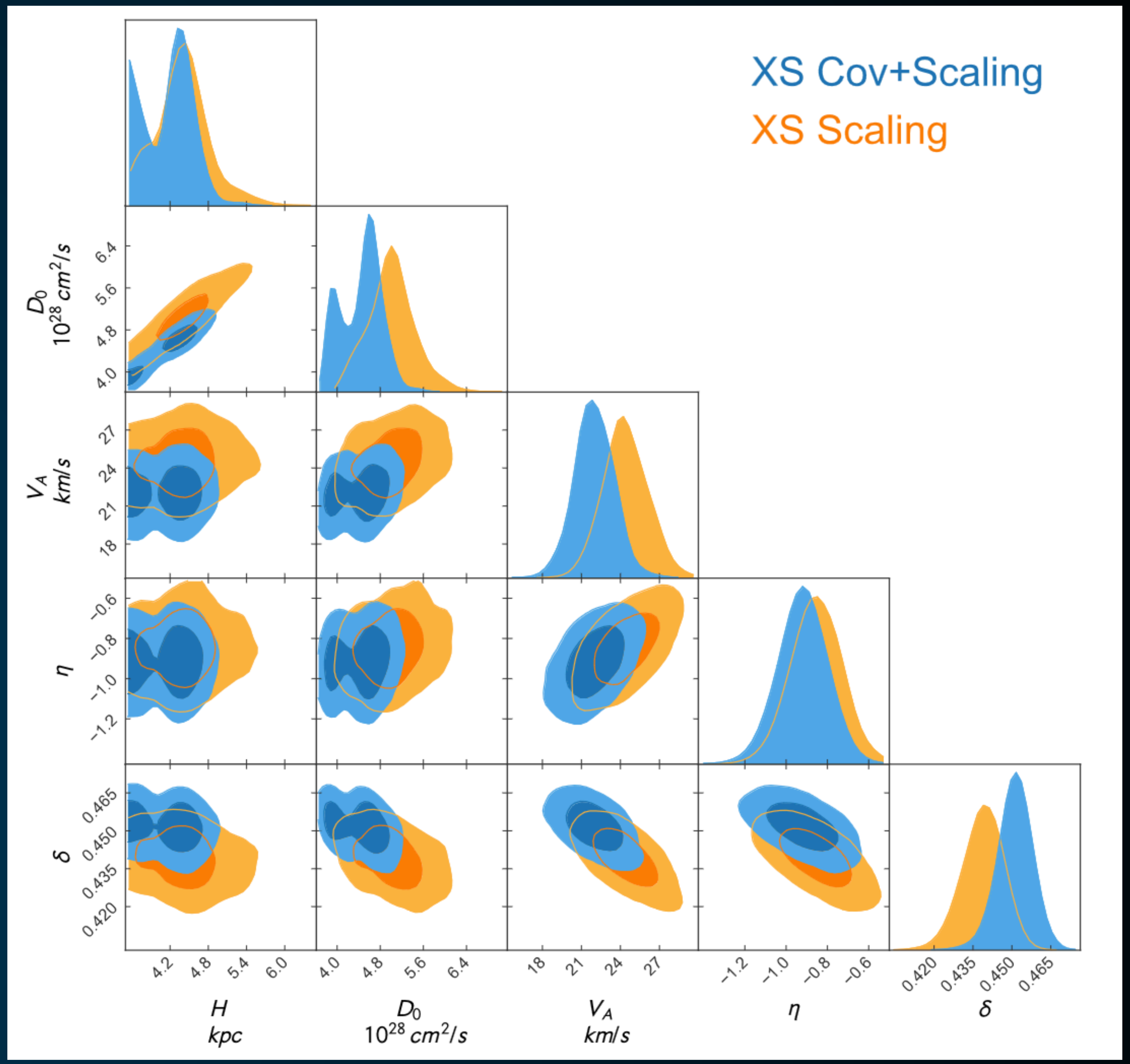
m_χ=67 GeV b$\bar{b}$
σv=2×10^{-26}cm^{3}s^{-1}
$\bar{d}$ events
$^3\overline{He}$ events
# of AMS−02 $\overline{N}$ events (6 years)
v$_A$ (km/s)
10
5
1
0.50
0.10
0.05
0.01
0
10
20
30
40
50
60



m_χ=67 GeV $b\bar{b}$
σv=2×10^{-26}cm^{3}s^{-1}
$\bar{d}$ events
$^3\overline{He}$ events
# of AMS–02 $\overline{N}$ events (6 years)
dv_c/dz (km/s/kpc)
10
1
0.100
0.010
0.001
0
5
10
15
20
25
30

Problem: Alfvén Velocity is Probably Not High

De la Torre Luque, TL, Winkler (2024; 2401.10329)



1.) Observations of cosmic-ray ratios strongly constrain fundamental diffusion parameters.

2.) Best-fit multi parameter models that fit e.g., B/C or heavy nuclei find v_a = 0 - 25 km/s.

- **Still possibly a contributor**

3.) Caveats:

- **Alfvén velocity is probably not homogeneous.**
- **Only need high Alfvén velocity in region where anti-He is produced (e.g., GC), not in rest of spatial volume.**

Korsmeier, Cuoco (2021; 2103.09824)

Idea 3: A New Method for Producing Antihelium

Dark Matter Annihilation Can Produce a Detectable Antihelium Flux through $\bar{\Lambda}_b$ Decays

Martin Wolfgang Winkler[1, *] and Tim Linden[1, †]

[1]*Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*

Recent observations by the Alpha Magnetic Spectrometer (AMS-02) have tentatively detected a handful of cosmic-ray antihelium events. Such events have long been considered as smoking-gun evidence for new physics, because astrophysical antihelium production is expected to be negligible. However, the dark-matter-induced antihelium flux is also expected to fall below current sensitivities, particularly in light of existing antiproton constraints. Here, we demonstrate that a previously neglected standard model process — the production of antihelium through the displaced-vertex decay of $\bar{\Lambda}_b$-baryons — can significantly boost the dark matter induced antihelium flux. This process can triple the standard prompt-production of antihelium, and more importantly, entirely dominate the production of the high-energy antihelium nuclei reported by AMS-02.

I. INTRODUCTION

The detection of massive cosmic-ray antinuclei has long been considered a holy grail in searches for WIMP dark matter [1, 2]. Primary cosmic-rays from astrophysical sources are matter-dominated, accelerated by nearby supernova, pulsars, and other extreme objects. The secondary cosmic-rays produced by the hadronic interactions of primary cosmic-rays can include an antinuclei component, but the flux is highly suppressed by baryon number conservation and kinematic constraints [3, 4]. Dark matter annihilation, on the other hand, occurs within the rest frame of the Milky Way and produces equal baryon and antibaryon fluxes [1, 5–7]

In this *letter*, we challenge the current understanding that standard dark matter annihilation models cannot produce a measurable antihelium flux. Our analysis examines a known, and potentially dominant, antinuclei production mode which has been neglected by previous literature – the production of antihelium through the off-vertex decays of the $\bar{\Lambda}_b$. Such bottom baryons are generically produced in dark matter annihilation channels involving b quarks. Their decays efficiently produce heavy antinuclei due to their antibaryon number and 5.6 GeV rest-mass, which effectively decays to multi-nucleon states with small relative momenta. Intriguingly, because any $^3\overline{\text{He}}$ produced by $\bar{\Lambda}_b$ inherits its boost factor, these nuclei can obtain the large center-of-mass momenta necessary to fit AMS-02 data [13].

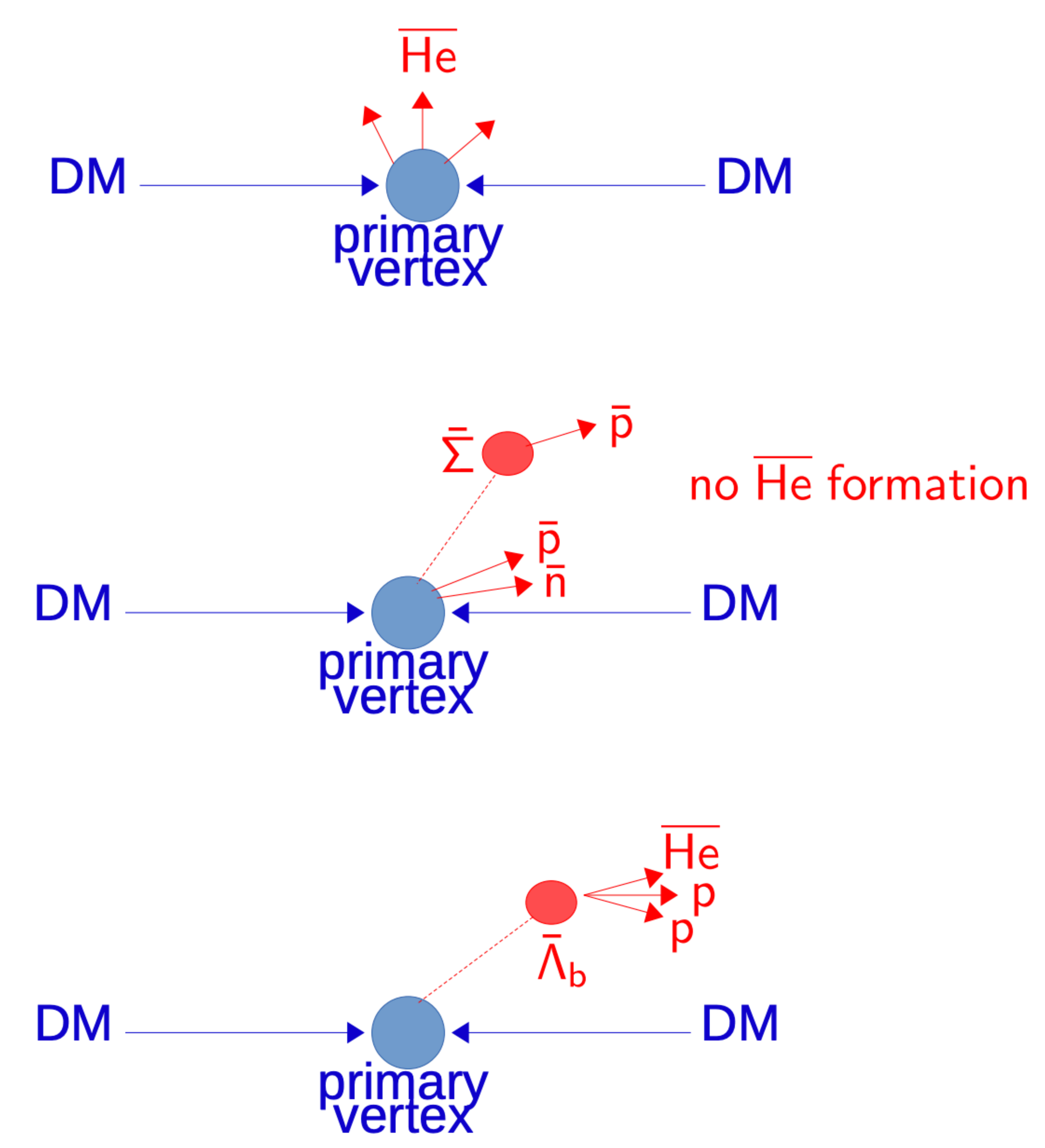
A Standard Model Resonance to Enhance Antihelium

Previous analyses have missed the (potentially) dominant contribution to anti-Helium production.

- **Requires Event-by-Event Coalescence**

$\overline{\Lambda}_b$ **has correct parameters to produce** $^3\overline{He}$**:**

- **Antibaryon number of 1**
  - **Mass: 5.6 GeV** $(\bar{p}, \bar{p}, \bar{n}, p, p)$
  - **Or:** $\bar{p}, \bar{n}, \bar{n}, p, p$ **because** $^3H \rightarrow {}^3He$



From: Martin Winkler

A Standard Model Resonance to Enhance Antihelium

$\overline{\Lambda_b}$ **has correct parameters to produce** $^3\overline{He}$**:**

- **Antibaryon number of 1**
  - **Mass: 5.6 GeV** ($\bar{p}, \bar{p}, \bar{n}, p, p$)
  - **Or:** $\bar{p}, \bar{n}, \bar{n}, p, p$ **because** $^3H \rightarrow {}^3He$

$$R \propto p_0^{3(A-1)}$$

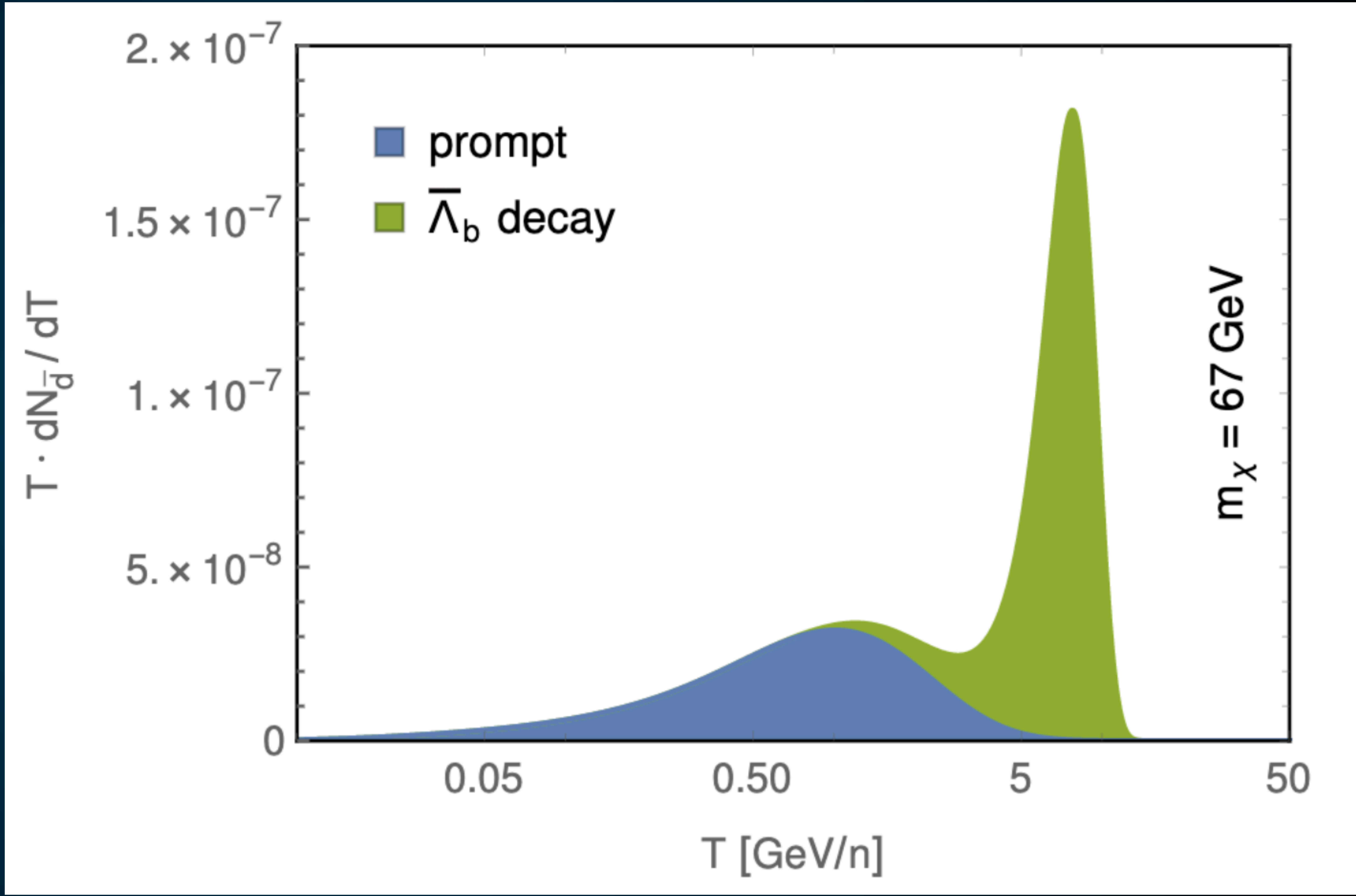
$$R \propto \exp[-(\mathrm{p_i} - \mathrm{p_f})]$$

Predicting the rate is far beyond our ability to solve hadronization.

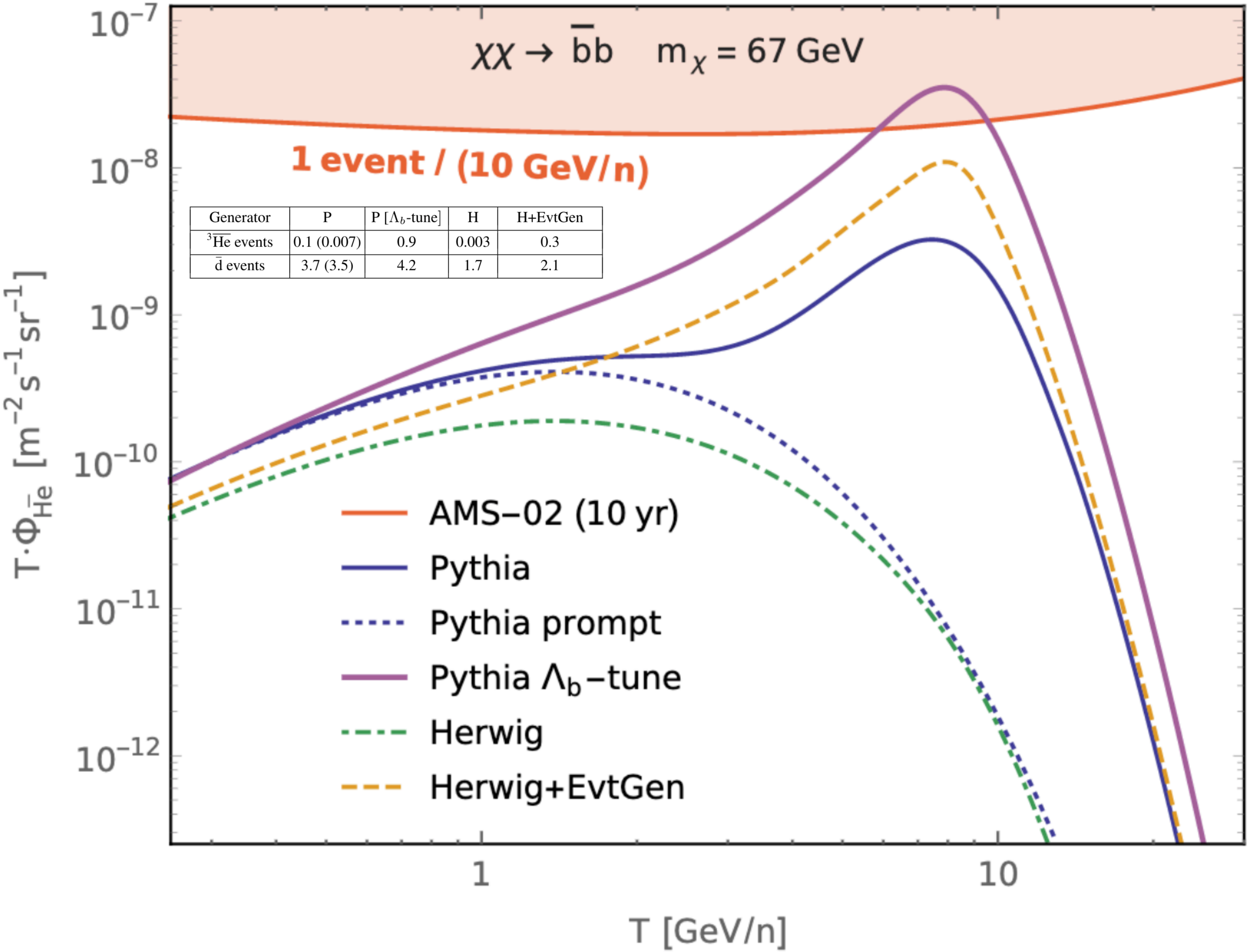
A High-Momentum Bump!

Can produce a significant enhancement of the total anti helium flux.

Moreover, the enhancement is at high-energies - matching the data.



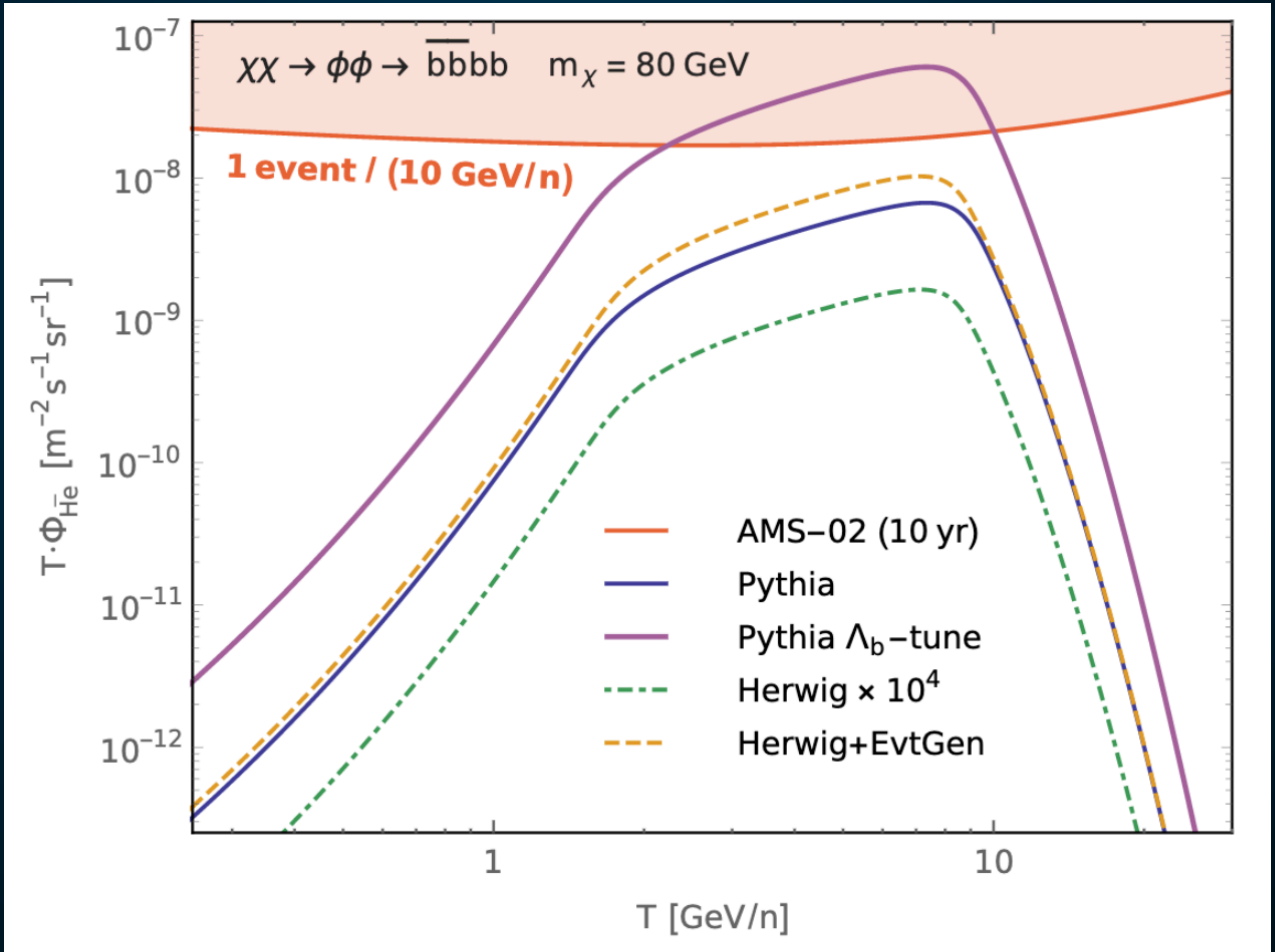
Winkler & Linden (2020; 2020.16251)



Generator	P	P [Λ_b-tune]	H	H+EvtGen
$^3\overline{He}$ events	0.1 (0.007)	0.9	0.003	0.3
$\bar{d}$ events	3.7 (3.5)	4.2	1.7	2.1

Building a Specific Dark Particle

Can further boost antihelium formation through the inclusion of a dark mediator that lies just above above the antihelium mass.



Winkler & Linden (2020; 2020.16251)

Ding, Li, & Zhou (2022; 2212.05239)

Uncertainties in the Rate

1.) $\overline{\Lambda_b}$ production rate

experiment	channel	measurement	Pythia (default)	Pythia (Λ_b-tune)
LEP [4, 5]	$f(b \to \Lambda_b)$	$0.101^{+0.039}_{-0.031}$	0.037	0.101
LEP [6]	$f(b \to \Lambda_b, \Xi_b, \Omega_b)$	0.117 ± 0.021	0.047	0.127
Tevatron CDF [7]	$\frac{f(b\to\Lambda_b)}{f(b\to B)}$	$0.281^{+0.141}_{-0.103}$	0.046	0.135
LHCb [8]	$\frac{f(b\to\Lambda_b)}{f(b\to B)}$	0.259 ± 0.018	0.048	0.134

Solution: Change the parameter: $\mathrm{probQQtoQ} \to 0.24$

Enhances diquark formation and $\overline{\Lambda_b}$ production.

Winkler & Linden (2020; 2020.16251)

Uncertainties in the Rate

1.) $\overline{\Lambda}_b$ production rate

Comment on "Dark Matter Annihilation Can Produce a Detectable Antihelium Flux through $\bar{\Lambda}_b$ Decays"

M. Kachelrieß[1], S. Ostapchenko[2], and J. Tjemsland[1]
[1] *Institutt for fysikk, NTNU, Trondheim, Norway and*
[2] *D.V. Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia*

In a recent Letter, Winkler and Linden [1] (hereafter WL21) suggested that a previously neglected standard model process, namely the production of antihelium-3 nuclei through decays of $\bar{\Lambda}_b$ baryons, can significantly boost the flux of antihelium-3, induced by annihilations or decays of dark matter. This suggestion uses the fact that dark matter particles will annihilate typically into the heaviest quark–anti-quark pair, i.e. $\bar{b}b$ pairs, if the particle is a Majorana fermion and its mass is below the mass of the standard model gauge bosons [2]. These (anti-) b quarks will in turn hadronise and form (anti-) b-mesons and (anti-) b-baryons which then decay weakly. As pointed out by WL21, the $\bar{\Lambda}_b$ baryon is especially suited for the production of antihelium-3 through a coalescence process, because its rest mass of 5.6 GeV is not much above the rest mass of 5 (anti)-nucleons. As a result of the small relative momenta of these nucleons, the production of antihelium-3 via coalescence is enhanced in $\bar{\Lambda}_b$ decays.

of the coalescence momentum, since this change affects all types of processes involving baryon and meson production. As an example, one can consider (anti-) proton production in electron-positron annihilations, $e^+e^- \to \bar{p}pX$. For a change of `probQQtoQ` from the default value 0.09 to 0.24—which is the value reproducing the value of the branching ratio $b \to \Lambda_b = 0.1$ chosen in WL21—the resulting proton multiplicity is compared in Table 1 to measurements. For instance at $\sqrt{s} = 91\,\mathrm{GeV}$, the predicted proton multiplicity in the "$\bar{\Lambda}_b$ tune" is 33σ away from the one measured [3]. For comparison, the standard settings in Pythia predict a Λ_b multiplicity in electron-positron annihilations at the Z-resonance of 0.016, which is less than 1σ away from the value 0.031 ± 0.016 given in Ref. [3]. As an example for the effects of a changed diquark formation parameter on pp collisions, we show in Table 2 the integrated yield at mid-rapidity, $\mathrm{d}N/\mathrm{d}y\,|_{|y|<0.5}$, of protons, kaons and pions measured by ALICE at LHC at $\sqrt{s} = 7\,\mathrm{TeV}$ [4]. Note also that the

Claims:

1.) Changing probQQtoQ is not needed because previous data was within uncertainties.

2.) Changing probQQtoQ breaks models of light baryon formation (at 33σ in certain LEP cross-sections)

Uncertainties in the Rate

1.) $\overline{\Lambda}_b$ production rate

Response to Comment on "Dark Matter Annihilation Can Produce a Detectable Antihelium Flux through $\bar{\Lambda}_b$ Decays"

Martin Wolfgang Winkler* and Tim Linden†
Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden

In a recent paper we showed that the decay of intermediate $\bar{\Lambda}_b$ baryons can dramatically enhance the antihelium flux from dark matter annihilation. Our antihelium predictions were derived using several implementations of the Pythia and Herwig event generators which were calibrated to existing data on antideuteron and antihelium formation. Kachelrieß et al. have argued for a smaller antihelium flux compared to our most optimistic Monte Carlo model. However, we show that the arguments by Kachelrieß et al. are either incorrect or irrelevant for antihelium formation. Thus, the results of our original paper remain unchanged.

Summary of Original Paper – The AMS-02 cosmic-ray experiment has tentatively detected a handful of cosmic-ray antihelium events [1]. This observation is puzzling, since neither astrophysical processes nor dark matter annihilation were thought to produce a detectable antihelium flux. In recent work [2], we demonstrated that a previously neglected standard-model process – the production of antihelium nuclei through the decay of intermediate $\bar{\Lambda}_b$ baryons – could dramatically enhance the antihelium production rate from dark matter annihilation. The key insight is that $\bar{\Lambda}_b$, due to its antibaryon number and 5.6 GeV rest-mass, efficiently decays to multi-antibaryons states with small relative momentum which coalesce into antihelium.

The antihelium flux from $\bar{\Lambda}_b$ decay depends on (1) the rate of $\bar{\Lambda}_b$ baryon production in dark matter annihilations to

As we will show below, these statements are either incorrect or inapplicable to our study. Moreover, we stress that even if the analysis of KOT21 were entirely correct, these criticisms amount to only a factor of ~3 adjustment in a novel factor of ~100 effect first pointed out in our original paper.

First, statement (1) is incorrect. The fraction $f(b \to \Lambda_b)$ has been determined by a variety of LEP [4–6], Tevatron [7] and LHC [8] measurements. Several of the most relevant results are listed in Table I, together with the predicted rate from both default Pythia models and our Λ_b-tune model. Standard Pythia implementations predict a Λ_b-production rate that falls below results from several independent experiments and channels at a combined significance exceeding 10σ. Our Λ_b-tune model, on the other hand, provides a good fit to LEP data. It still underpredicts the data from hadron colliders, signal-

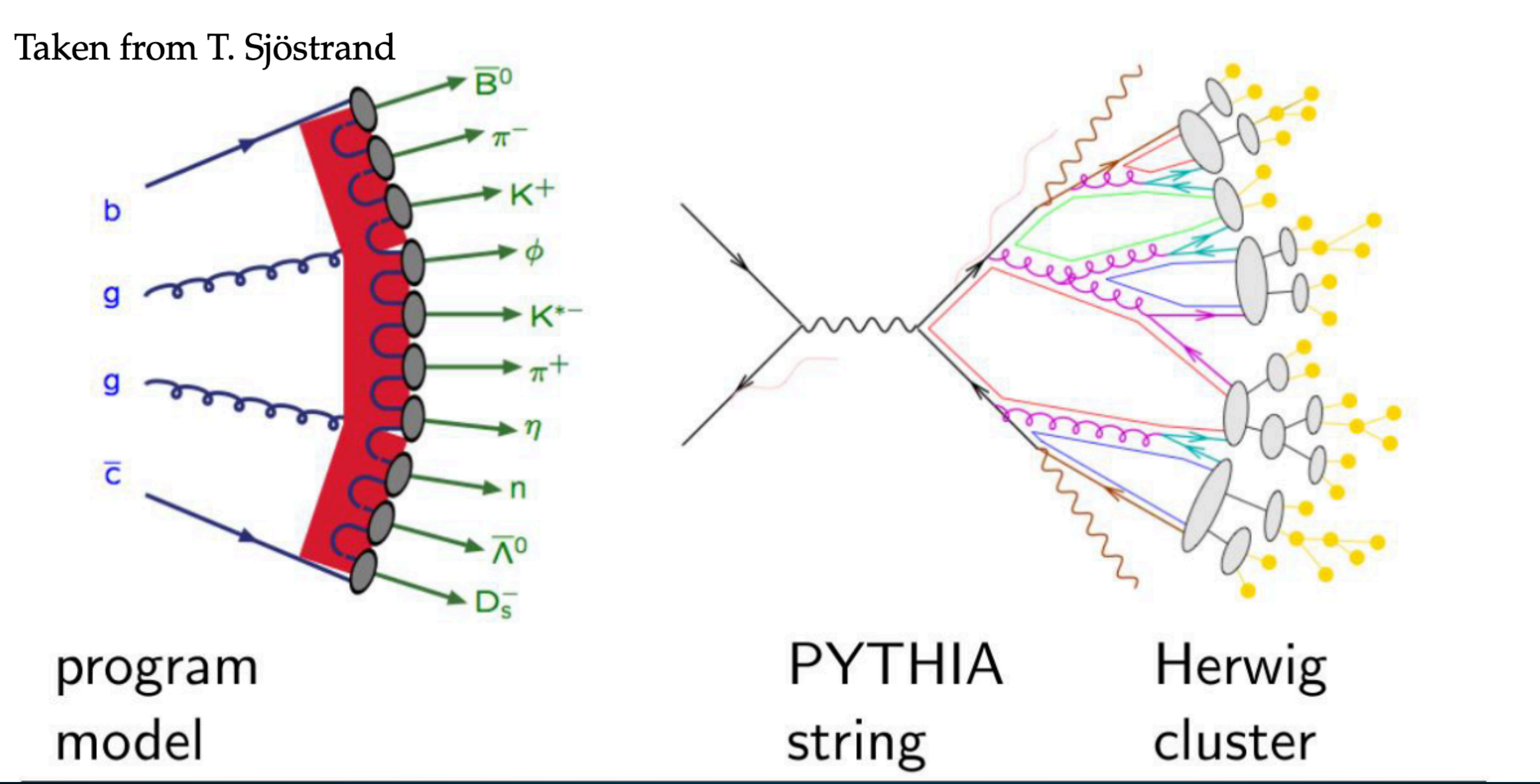
Claims:

1.) Untrue: Errors in Pythia Models were above 10σ.

2.) True - but irrelevant - if you want to get b-quark physics right, it is reasonable to tune the model to b-quark physics.

Uncertainties in the Rate

2.) $\overline{\Lambda_b} \to {}^3\mathrm{He}$ rate



Pythia:

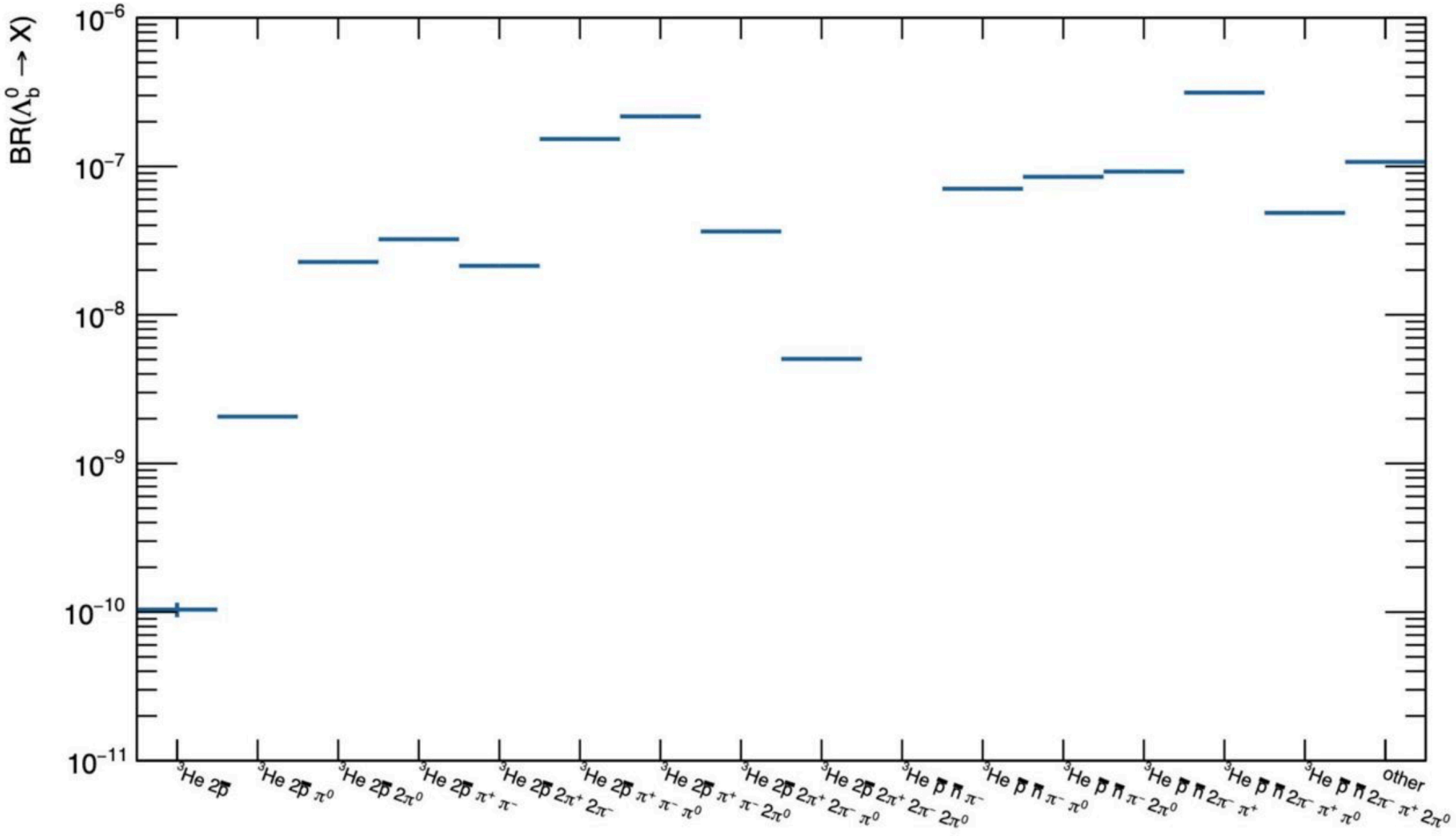
$$P(\overline{\Lambda_b} \to {}^3\overline{\mathrm{He}} + X) \sim 10^{-6}$$

Herwig:

$$P(\overline{\Lambda_b} \to {}^3\overline{\mathrm{He}} + X) \sim 10^{-9}$$

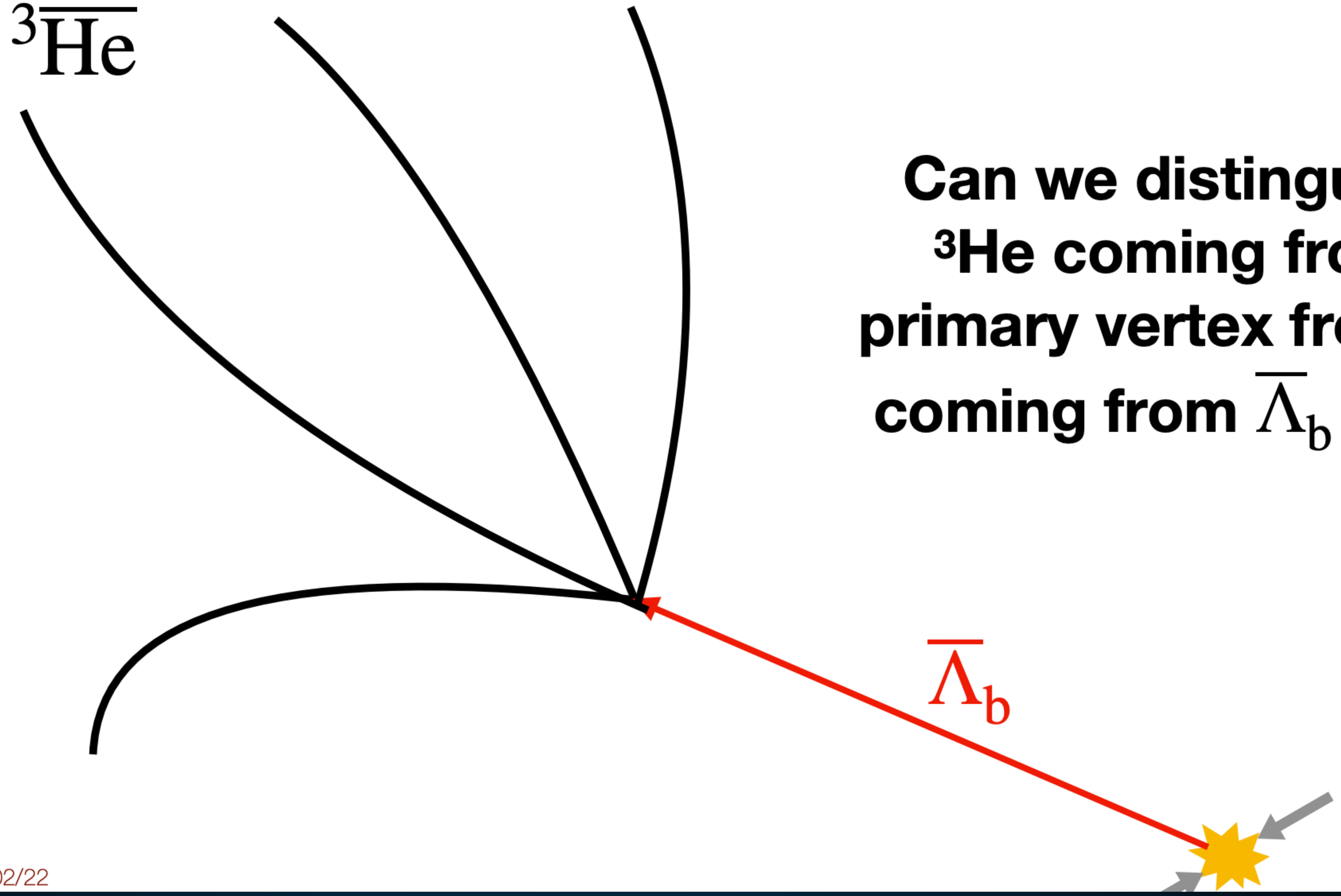
Problem: New Limits from LHCb (Preliminary)

Why an inclusive search?



Exclusive decays require the reconstruction of a large amount of particles (which reduces the efficiency x acceptance for the reconstruction) or imply very small BR

Can We Find this At Particle Accelerators?

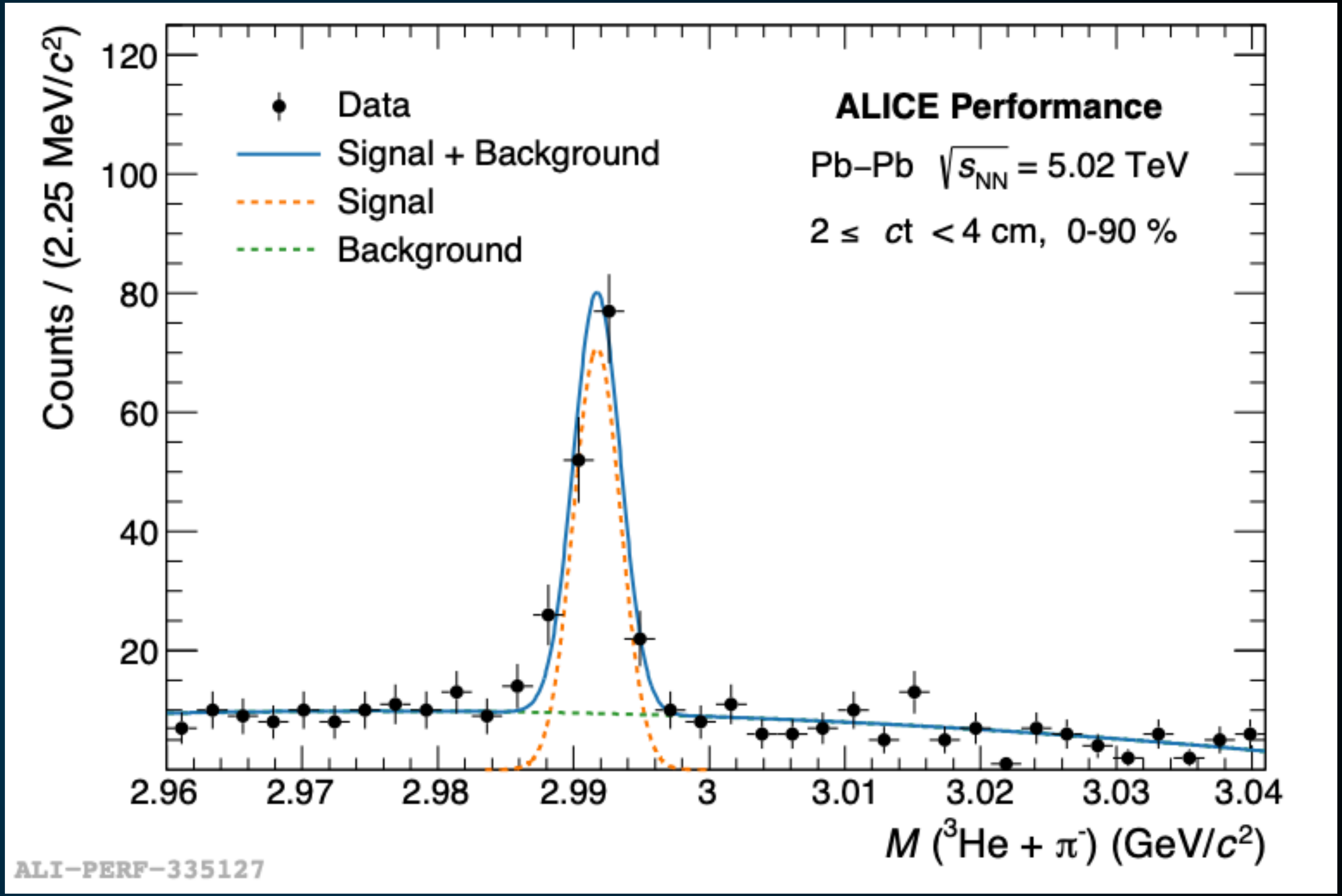


Can we distinguish the ^{3}He coming from the primary vertex from those coming from $\overline{\Lambda}_b$ decays?

$c\tau$ ~ 450 μm

Can We Find this At Particle Accelerators?

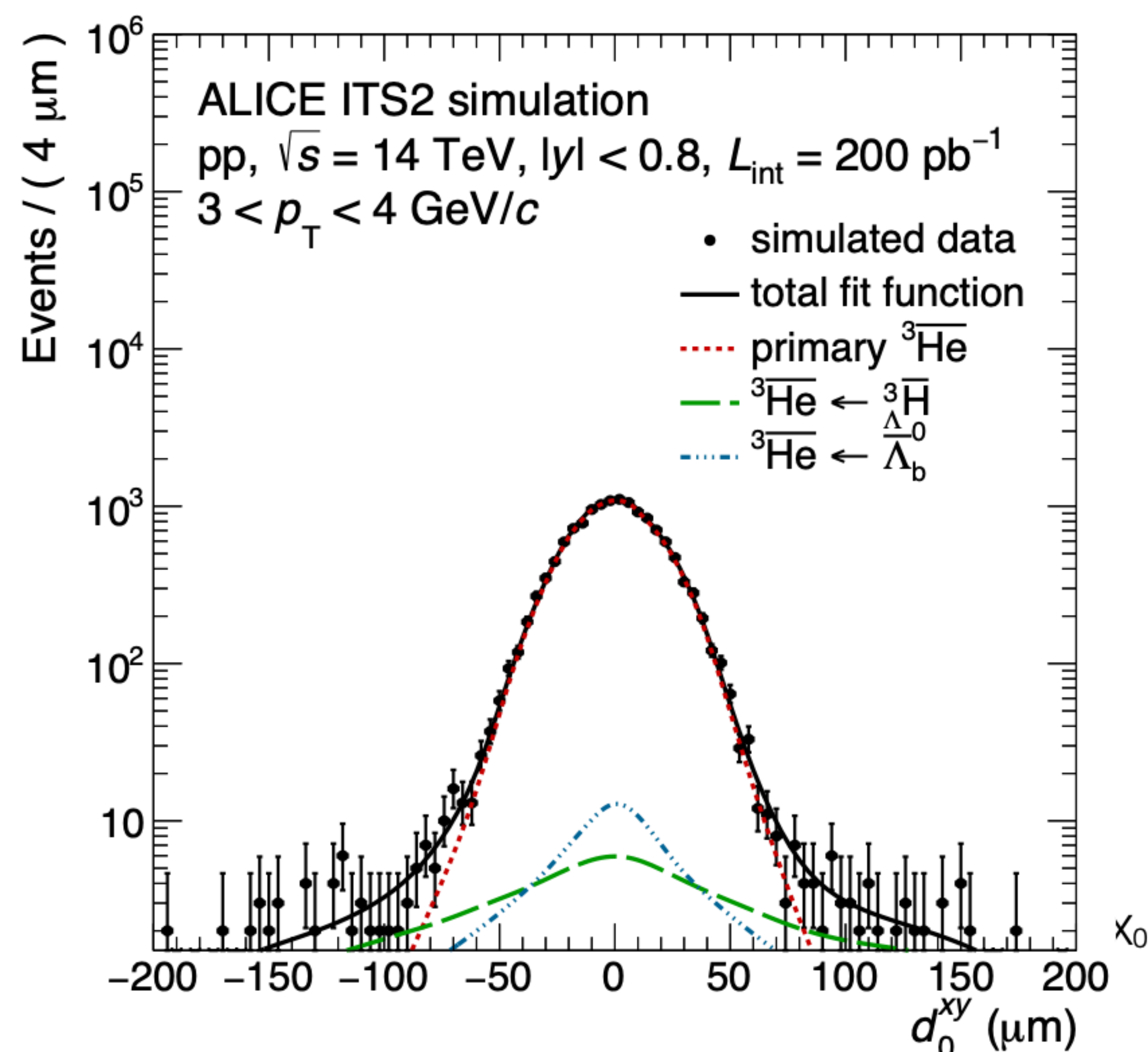
Current observations are not sensitive to this offset



Can We Find this At Particle Accelerators?

Current observations are not sensitive to this offset

The ITS2 run of ALICE is unlikely to be able to detect the signal, but may provide a hint if the antihelium production rate is near the upper limits of our predictions.

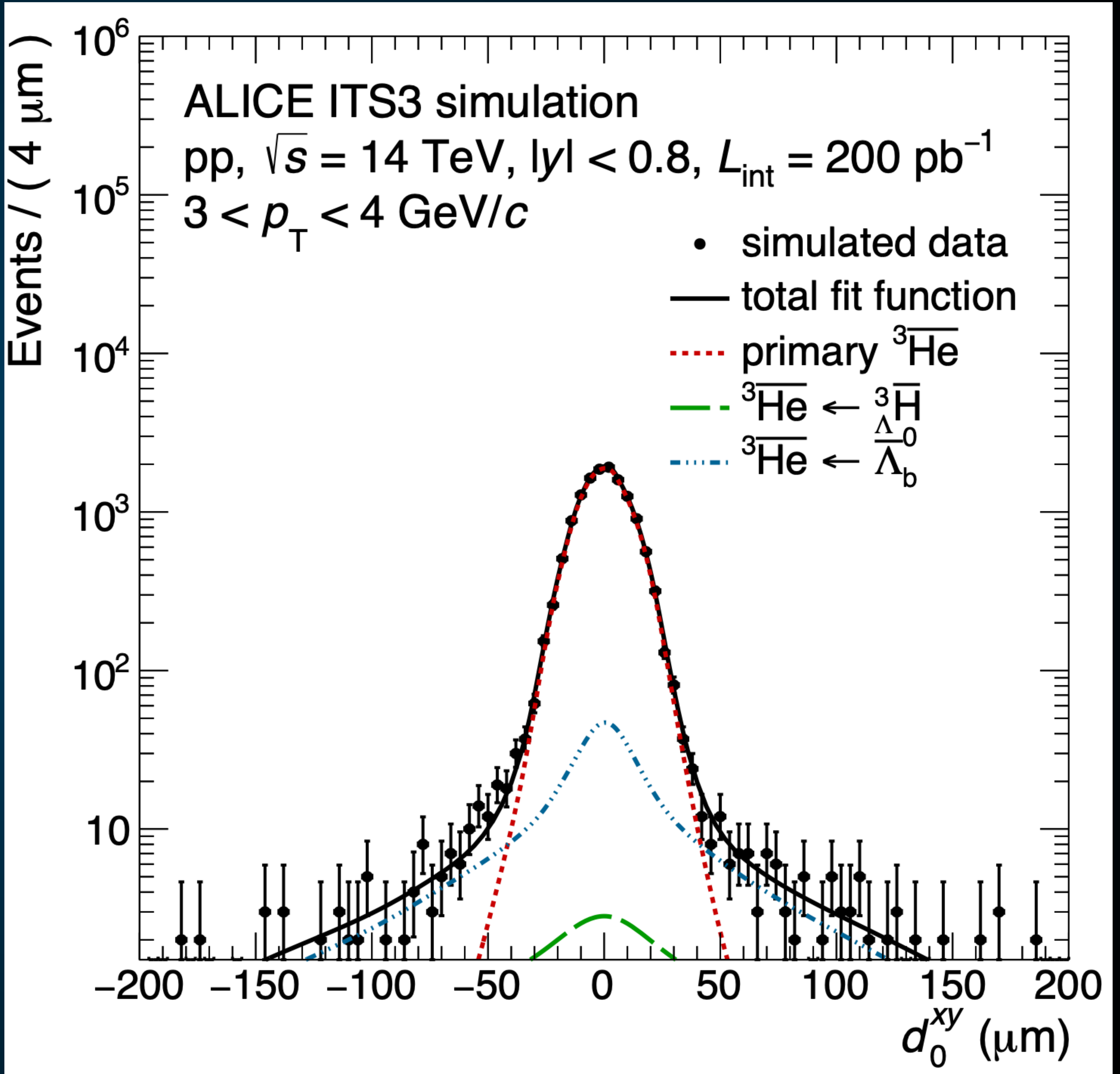


Can We Find this At Particle Accelerators?

Current observations are not sensitive to this offset

The ITS2 run of ALICE is unlikely to be able to detect the signal, but may provide a hint if the antihelium production rate is near the upper limits of our predictions.

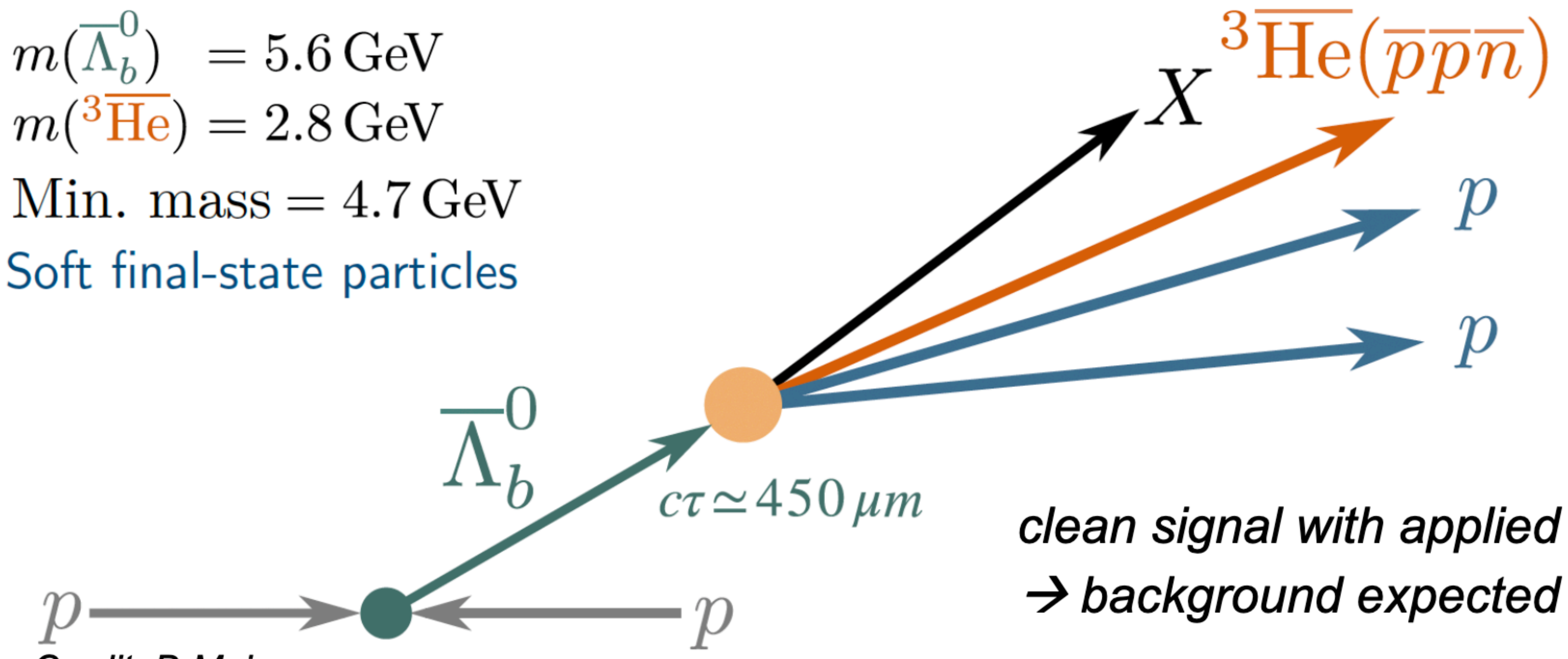
The upcoming ITS3 experiment from ALICE will be able to differentiate the Λ_b channel



Search for antihelium from $\overline{\Lambda}_b^0$ decays: Search strategy

Run 2 pp@13 TeV (5.5 fb^{-1})

LHCb-CONF-2024-005



Credit: D.Moise

clean signal with applied He and p PID
→ background expected only from combinatorics

Measure:

$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}} + \mathrm{p} + \mathrm{p}) \text{ (exclusive mode)}$$

$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}} + \mathrm{p} + \mathrm{p} + \mathrm{X}) \text{ (inclusive mode)}$$

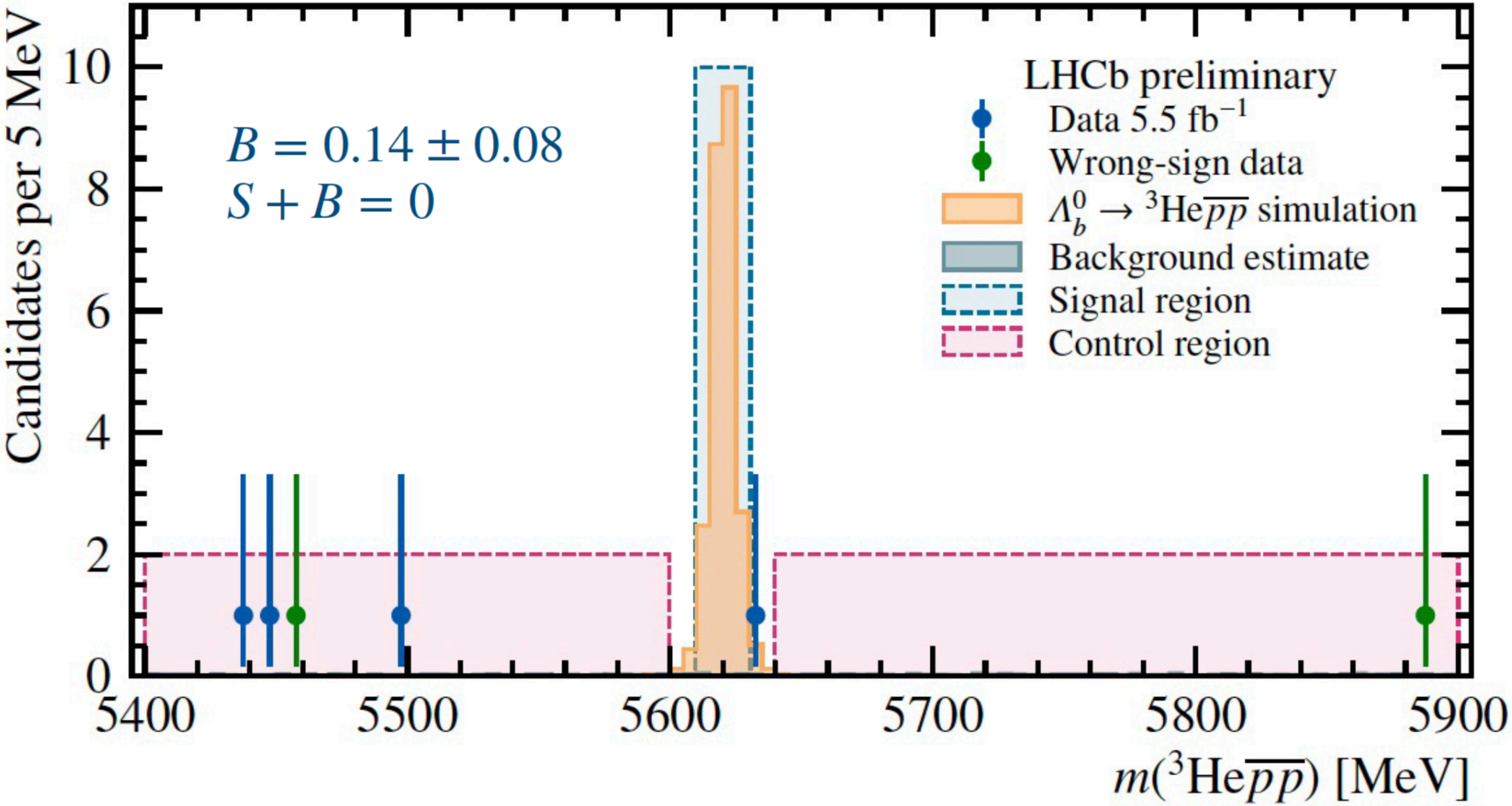
$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}} + p + \mathrm{X}) \text{ (inclusive mode)}$$

→ use decay models to extrapolate to $\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}} + \mathrm{X})$

Search for antihelium from $\overline{\Lambda}_b^0$ decays: Invariant-mass spectra

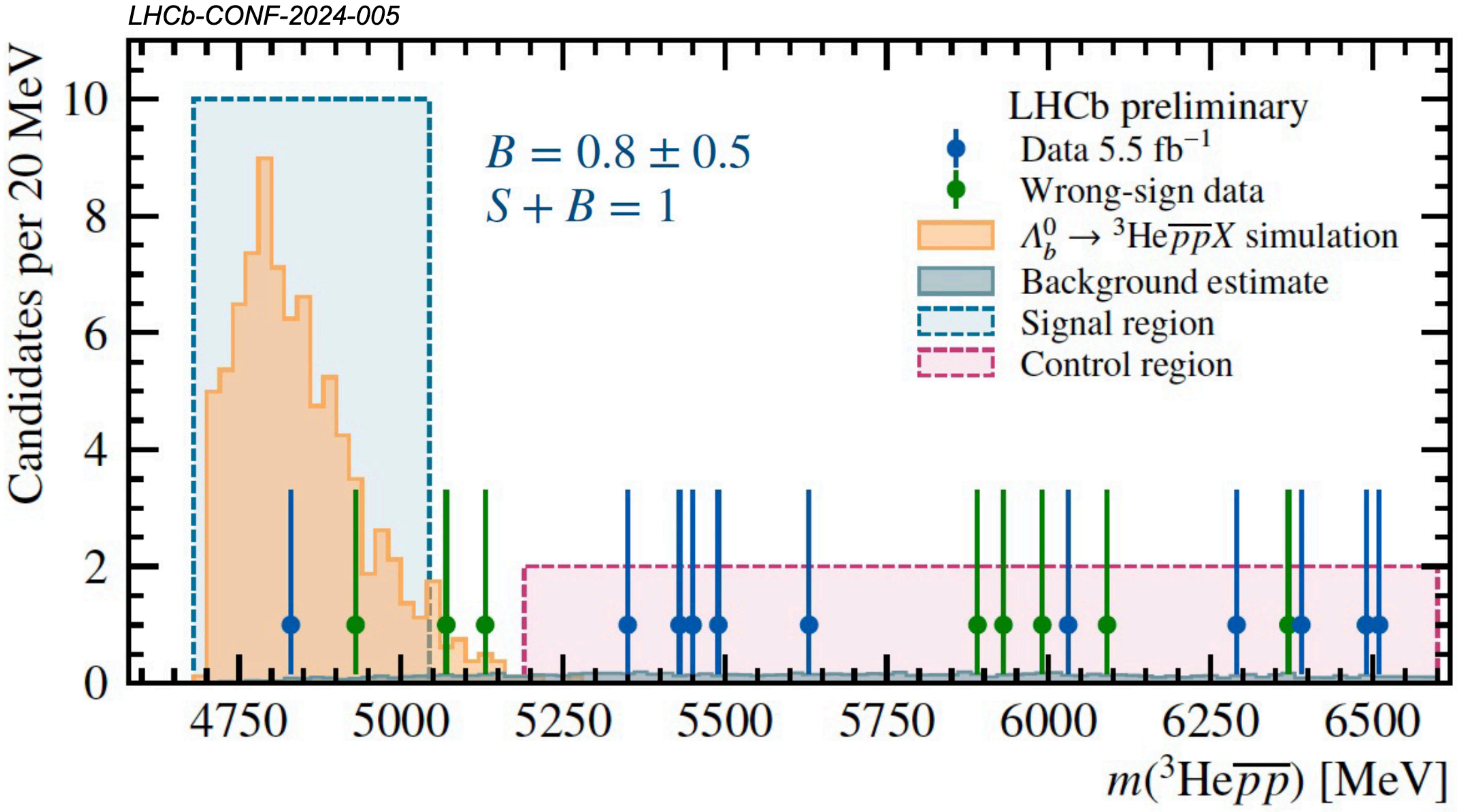
$\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}} + \mathrm{p} + \mathrm{p}$ (exclusive mode)

LHCb-CONF-2024-005



Search for antihelium from $\overline{\Lambda}_b^0$ decays: Invariant-mass spectra

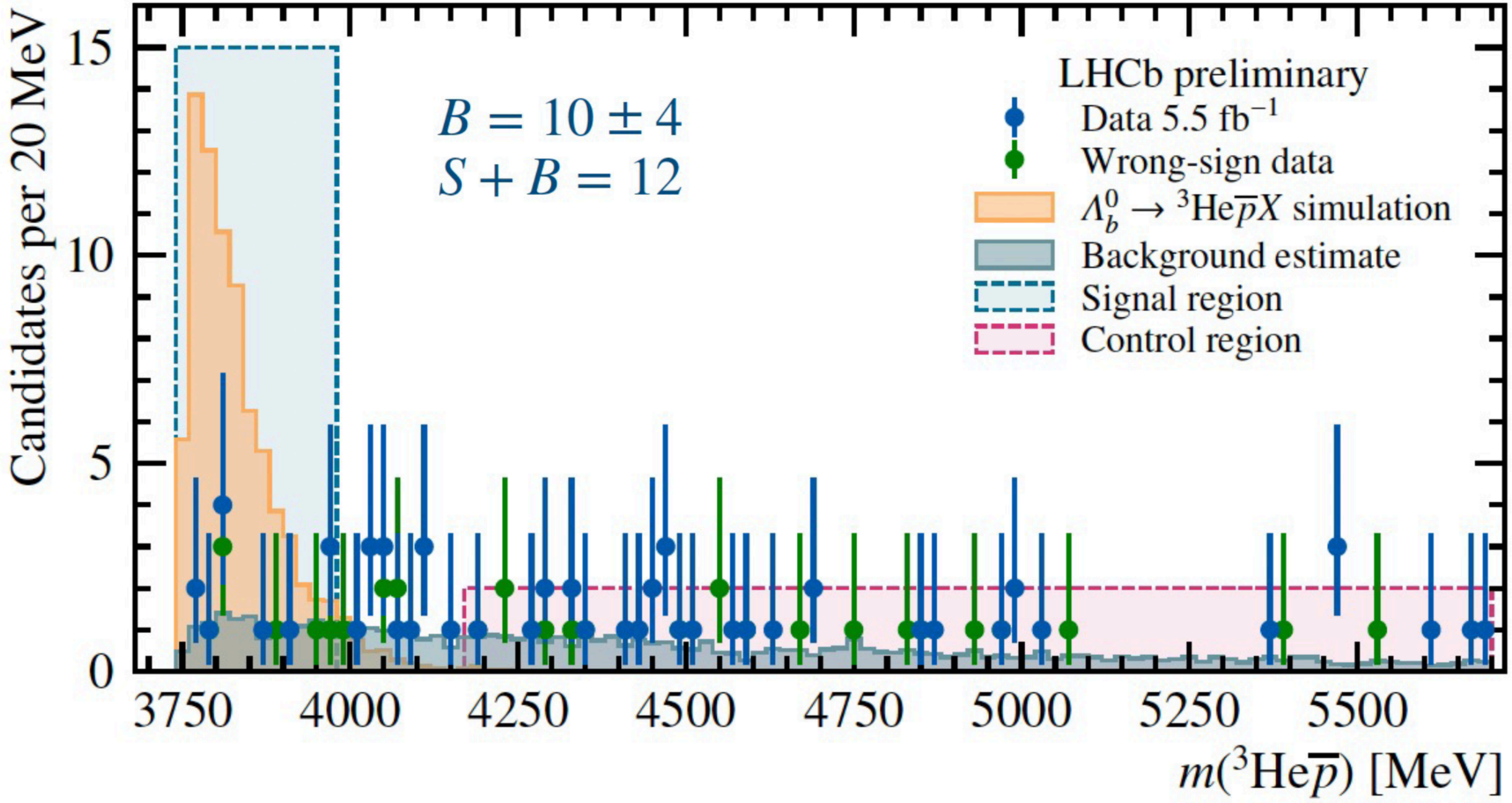
$\overline{\Lambda}_b^0 \rightarrow {}^3\overline{\mathrm{He}} + \mathrm{p} + \mathrm{p} + \mathrm{X}$ (inclusive mode)



Search for antihelium from $\overline{\Lambda}_b^0$ decays: Invariant-mass spectra

$\overline{\Lambda}_b^0 \to {}^3\overline{\text{He}} + \text{p} + \text{X}$ (inclusive mode)

LHCb-CONF-2024-005

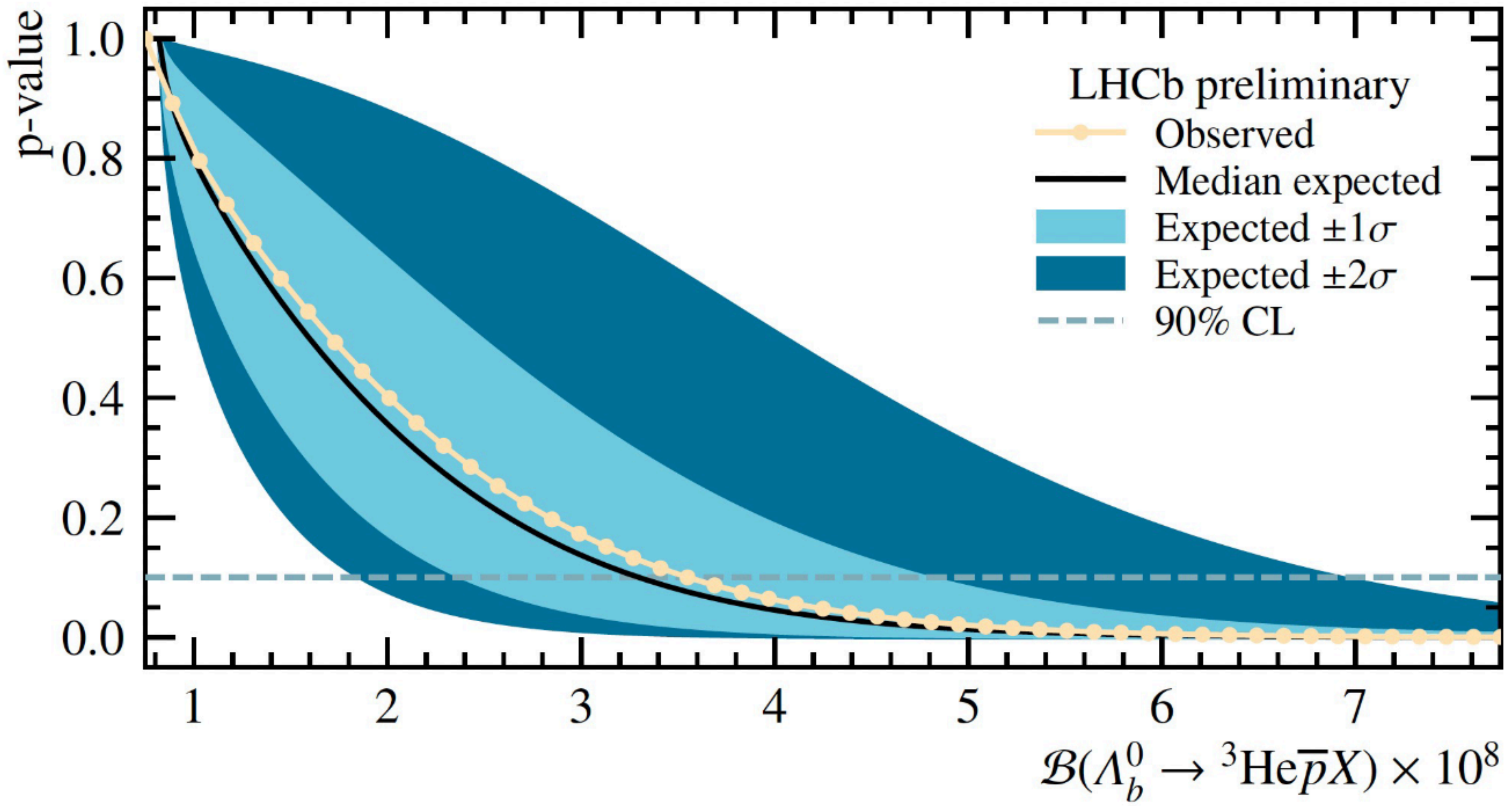


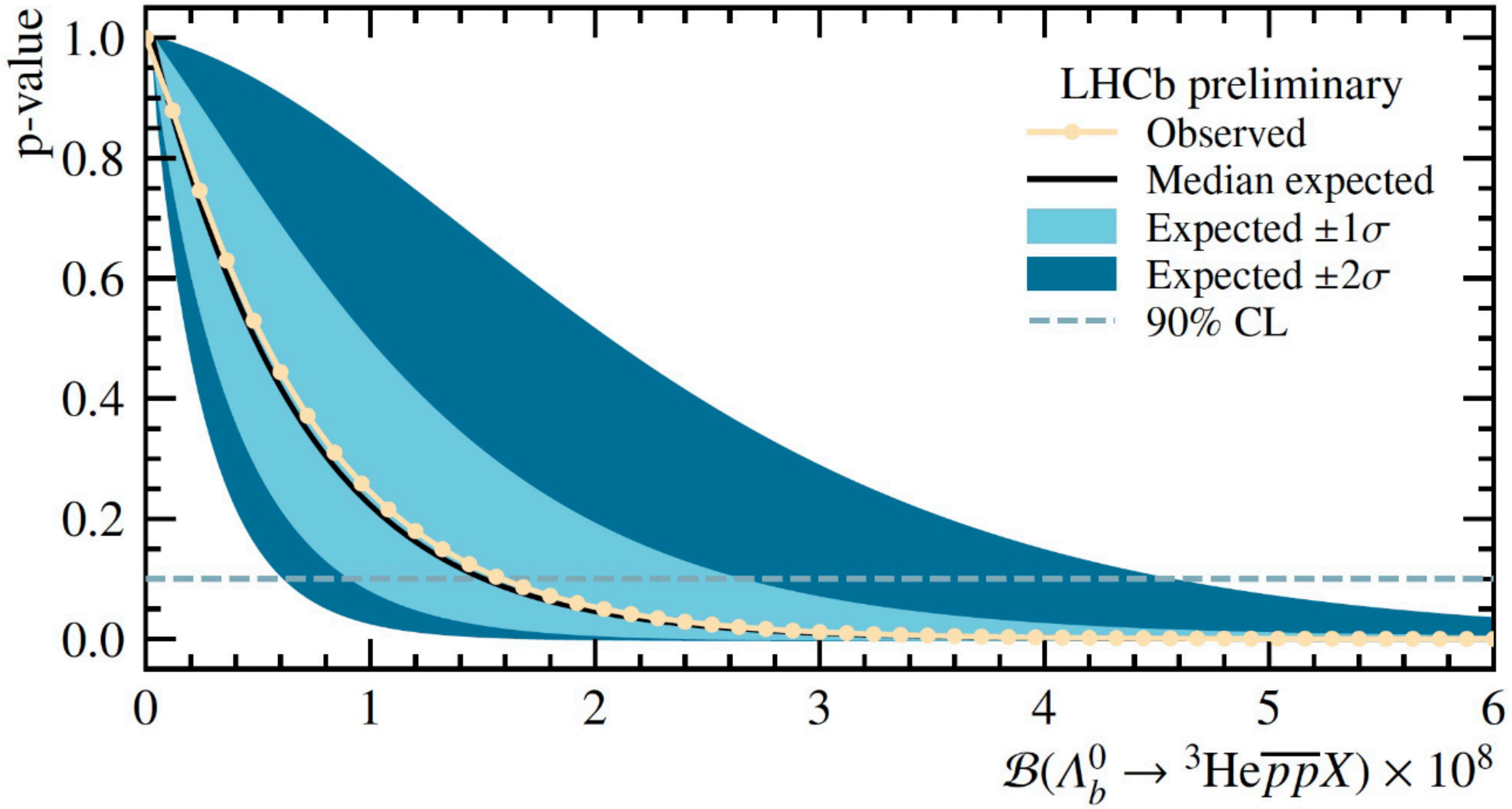
No significant signal found for any of the decay modes

Search for antihelium from $\overline{\Lambda}_b^0$ decays: Measured upper limits

- Upper limit for $\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}} + \mathrm{p} + \mathrm{p})$ with no signal candidate using profile-likelihood method *NIM A, Vol.458,3,745 (2001)*
- For inclusive modes, limits via $\mathrm{CL_s}$ method *J. Phys. G28, 2693 (2002)*
- *Including systematic uncertainties (dominating is the background estimate)*

LHCb-CONF-2024-005





$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}pp) < 1.9 \times 10^{-9} \text{ at } 90\% \text{ CL}$$

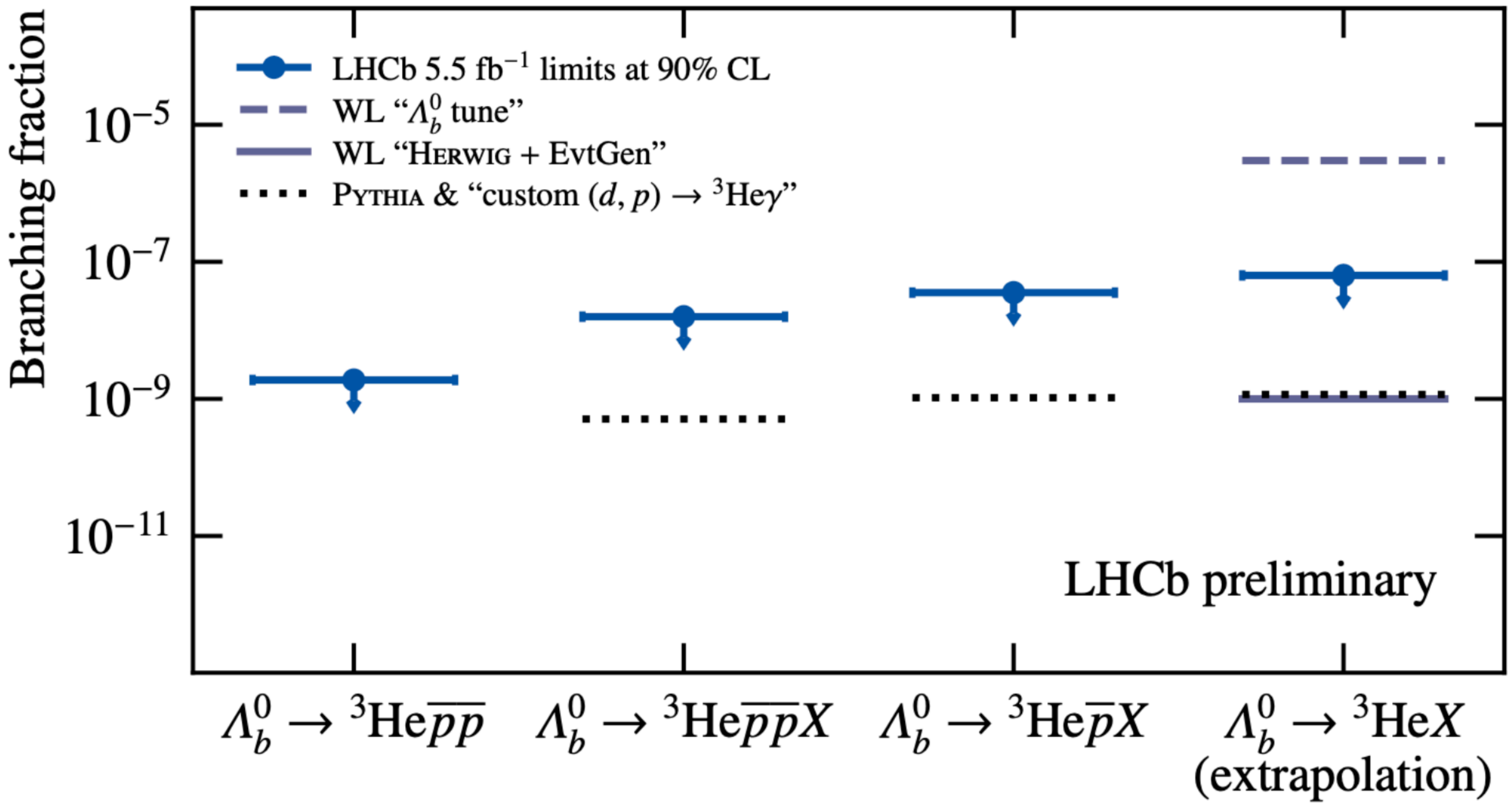
$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}ppX) < 1.6 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}pX) < 3.6 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

Search for antihelium from $\overline{\Lambda}_b^0$ decays: Extrapolation to $\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}X)$

Conservative extrapolation assuming isospin symmetric production of nucleons

LHCb-CONF-2024-005



$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}X) < 6.3 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

Some Caveats

1.) LHCb results are preliminary

2.) There is a factor of two offset, because tritium decays to $^3\mathrm{He}$ in space.

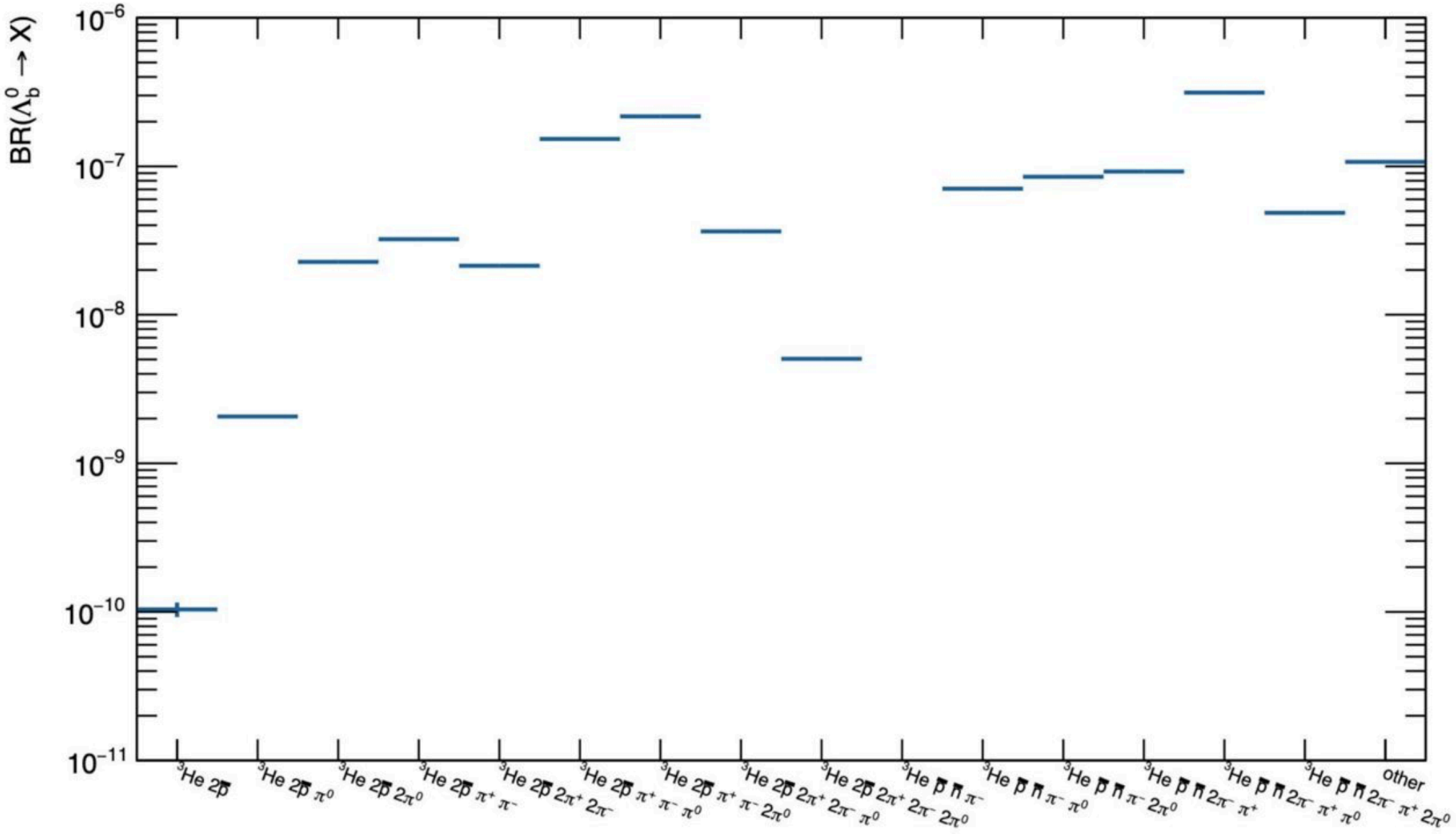
- This can potentially be larger, because $\overline{p} + \overline{n} + \overline{n} + p + n$ has smaller kinetic energy (117 anti-tritium detected by LHCb, but no spectrum)

3.) Unclear how inclusive cross-sections are calculated with additional pions (which may make the momentum of the $\overline{^3\mathrm{He}}$ and p harder to distinguish).

4.) No searches for $\overline{^3\mathrm{H}} + n + n + \pi^+$. This could dominate, for example, if the proton and $\overline{^3\mathrm{He}}$ quickly re-annihilate due to Coulomb attraction.

Problem: New Limits from LHCb (Preliminary)

Why an inclusive search?



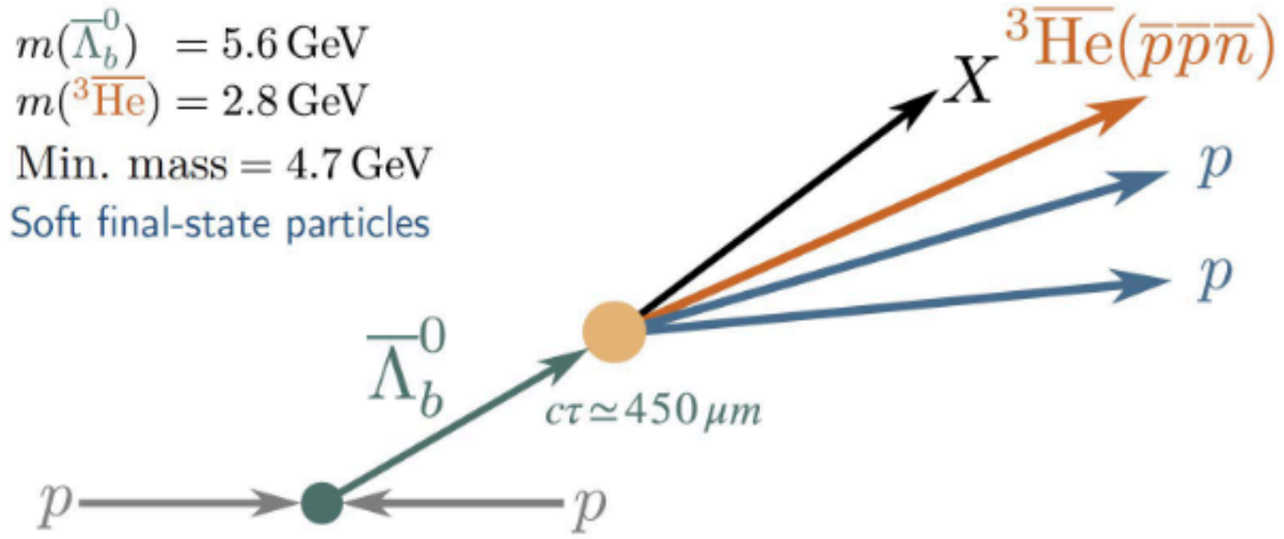
Exclusive decays require the reconstruction of a large amount of particles (which reduces the efficiency x acceptance for the reconstruction) or imply very small BR

LHCb (Anti)hypertriton and (Anti)helium

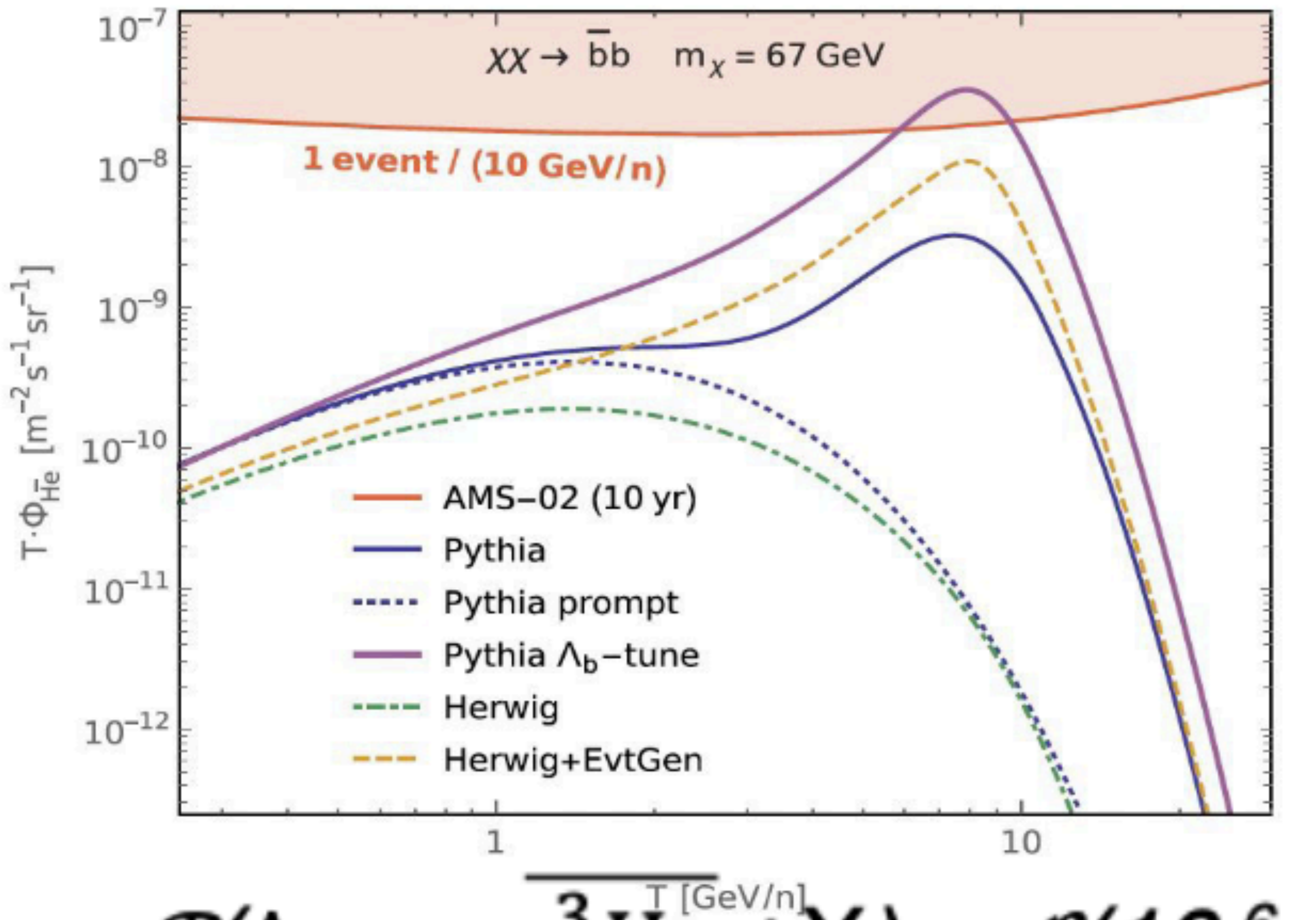
T.Pöschl

First ever measurement of (anti)hypertrion and (anti)Helium yields by LHCb (pp at 13 TeV, 5.5 fb-1)

- Hypetriton signal (~110 counts seems too small)
- $\overline{^3He}$ clear signal thanks to velo, but no cross section yet
- No signal for the $\Lambda_b \longrightarrow \overline{^3He}$ +X



PRL 126(2021)101101



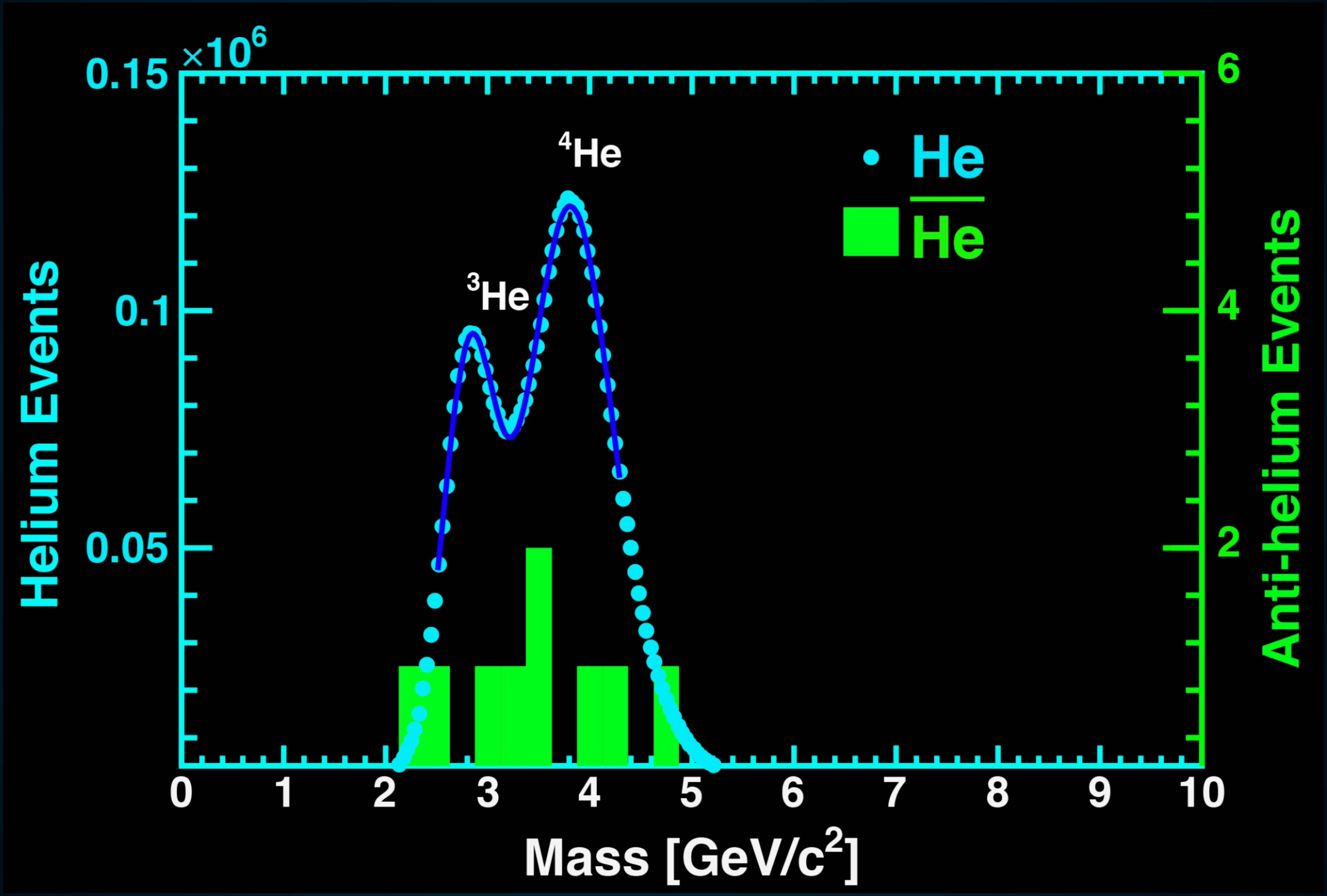
$\mathcal{B}(\Lambda_b \longrightarrow \overline{^3He}$ +X) ≈ $\mathcal{O}(10^{-6})$

$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\text{He}}pX) < 3.6 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

TIM

- $\overline{^3He}$ cross section measurements to be 'compared' to the ALICE data are necessary to verify the analysis
- Checks on Λ_b kinematics in LHCb
- Diplaced $\overline{^3He}$ measurements possible with ALICE
- $\bar{d}$ from Λ_b studies still open and very interesting

Problem: Are We Actually Observing Antihelium 4?

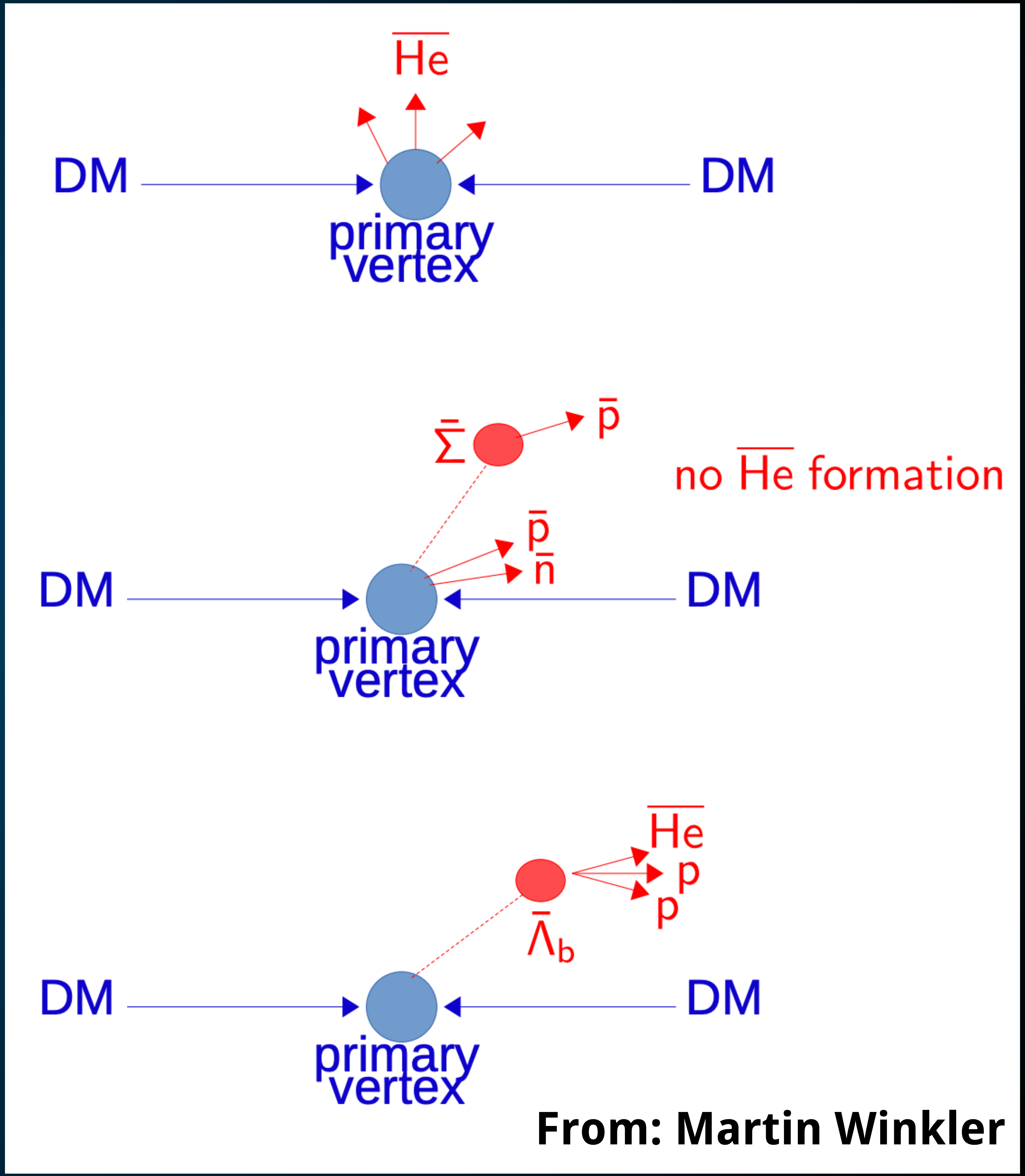


Cannot Enhance Antihelium-4 with Λ_b

$\overline{\Lambda}_b$ has correct parameters to produce $^3\overline{\mathrm{He}}$:

- Antibaryon number of 1
- Mass: 5.6 GeV

Too light to produce $^4\overline{\mathrm{He}}$!



Cosmic Ray Antihelium from a Strongly Coupled Dark Sector

Martin Wolfgang Winkler,[1,2,*] Pedro De La Torre Luque,[2,†] and Tim Linden[2,‡]

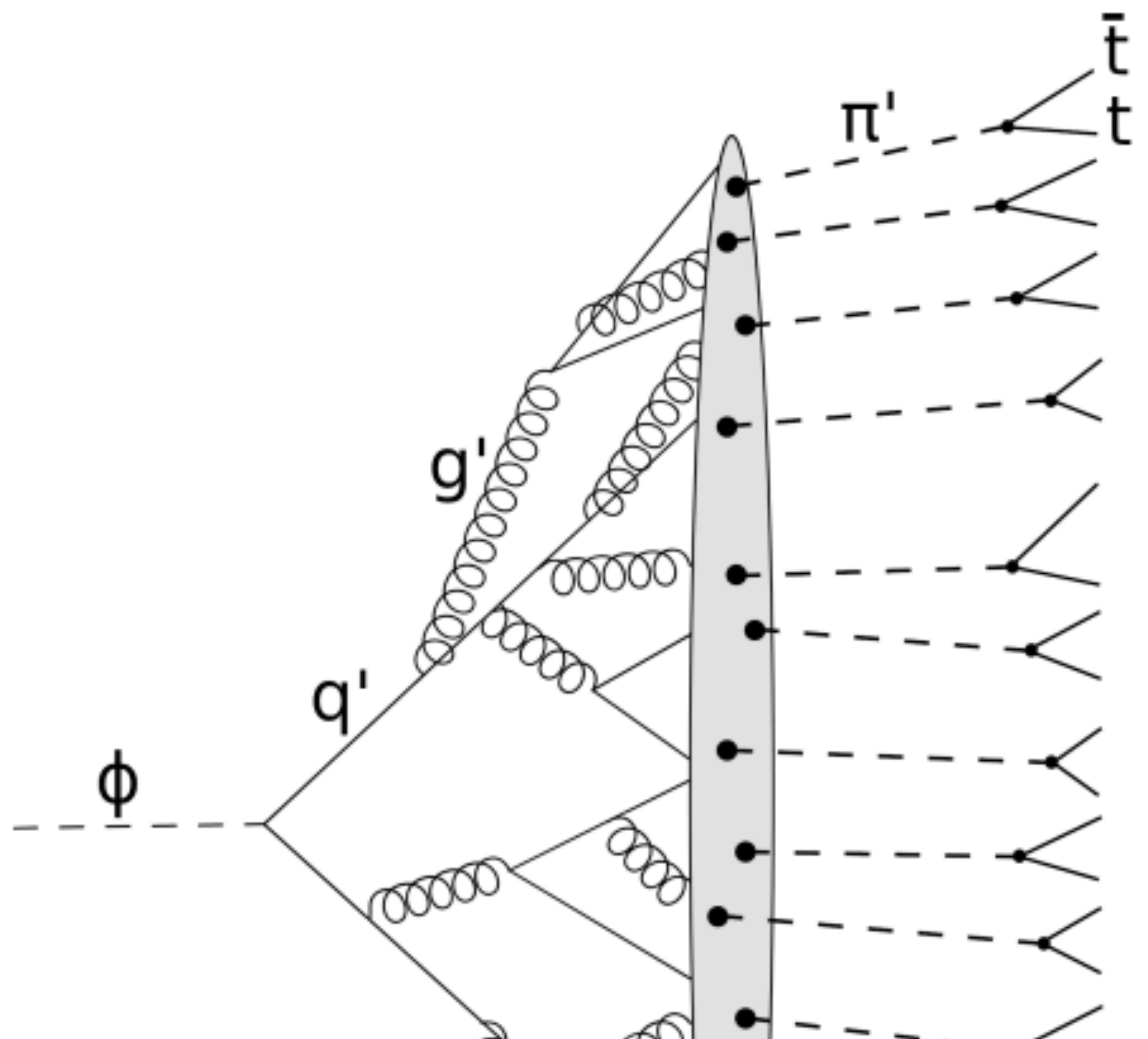
[1] *Department of Physics, The University of Texas at Austin, Austin, 78712 TX, USA*

[2] *The Oskar Klein Centre, Department of Physics, Stockholm University, AlbaNova, SE-10691 Stockholm, Sweden*

Standard Model extensions with a strongly coupled dark sector can induce high-multiplicity states of soft quarks. Such final states trigger extremely efficient antinucleus formation. We show that dark matter annihilation or decay into a strongly coupled sector can dramatically enhance the cosmic-ray antinuclei flux – by six orders of magnitude in the case of $^4\overline{\text{He}}$. In this work, we argue that the tentative $^3\overline{\text{He}}$ and $^4\overline{\text{He}}$ events reported by the AMS-02 collaboration could be the first sign of a strongly coupled dark sector observed in nature.

I. INTRODUCTION

Cosmic-ray (CR) antinuclei are among the most promising targets in the indirect search for particle dark matter (DM). While the formation of antinuclei by DM annihilation or decay is strongly suppressed compared to *e.g.* gamma rays, the astrophysical antinuclei backgrounds – which arise from interactions of cosmic ray protons and helium with the interstellar gas – are extremely low. Therefore, the unambiguous discovery of even a single cosmic-ray antinucleus could provide smoking-gun evidence for particle DM [1, 2].



Strongly Coupled Dark Sectors

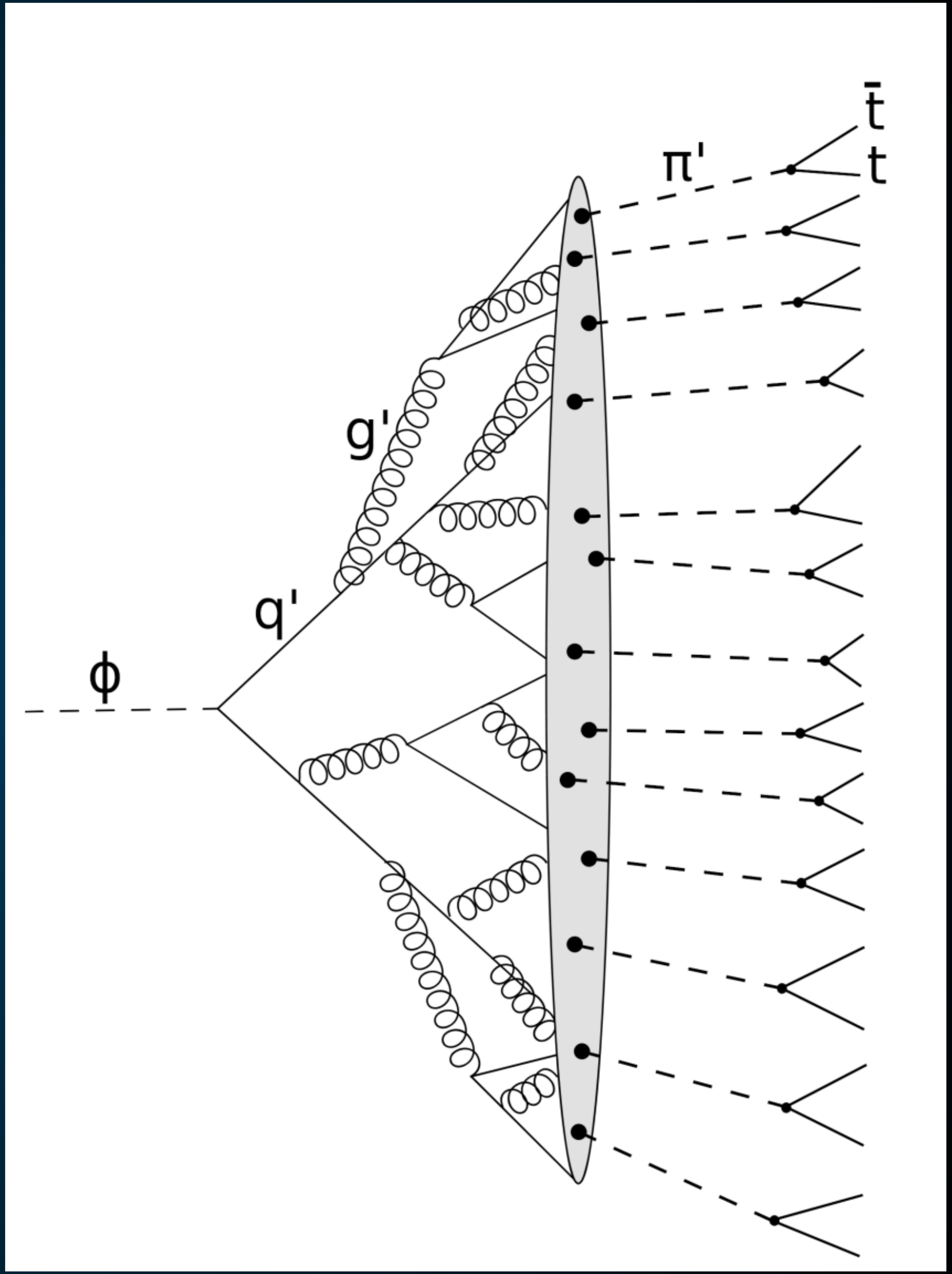
Just make a ton of quarks.

The production of heavy nuclei scales strongly with the number of quarks in the final state.

In QCD, a single 100 GeV annihilation produces O(100) pions

The dark matter model looks like a dark version of QCD.

$$\mathcal{L} \supset -\frac{1}{2}\,\mathrm{Tr}\,G'_{\mu\nu}G'^{\mu\nu} - \bar{q}'(i\not{D} - m_{q'})q'$$



Strongly Coupled Dark Sectors

The dark pions need to be very heavy — so the dark matter also has to be very heavy.

For annihilating dark matter — we are limited by unitarity.

For decaying dark matter, we are not.

DM type	Annihilating	Decaying
Input Parameters		
m_χ [TeV]	150	5000
m_ϕ [TeV]	50.4	375
$m_{\pi'}$ [GeV]	380	700
$N_{\pi'}$	256	1024
$\langle\sigma v\rangle$ [cm^{3}s^{-1}]	6.6×10^{-24}	–
Γ [s^{-1}]	–	9×10^{-30}
Antinuclei Events at AMS-02		
$^3\overline{\text{He}}$	15.6	20.3
$^4\overline{\text{He}}$	1.0	3.1
$\bar{\text{d}}$	19.3	1.2
Antinuclei Events at GAPS		
$\bar{\text{d}}$	0.7	0

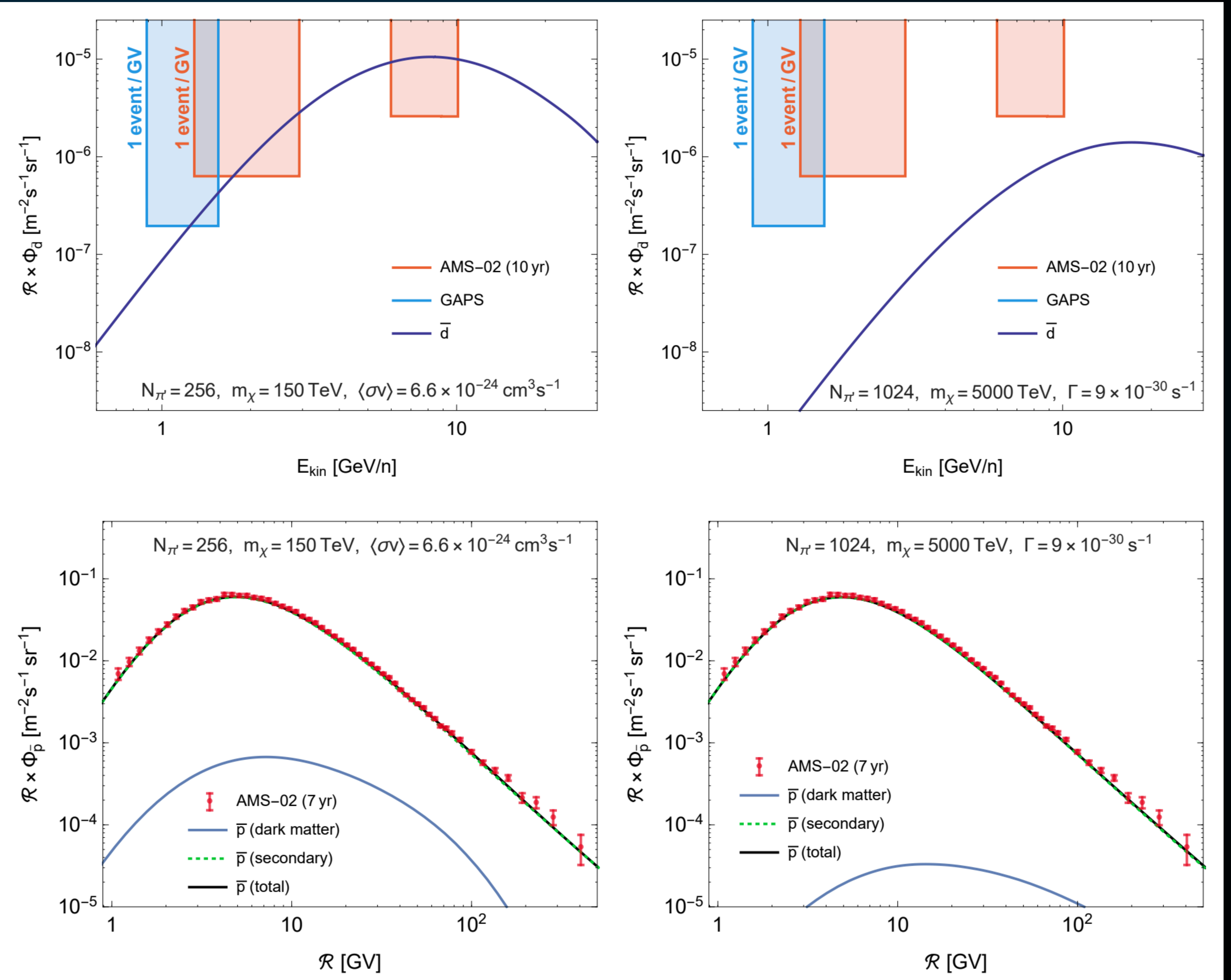
Strongly Coupled Dark Sectors

This significantly boosts the anti helium production rate — by a factor of n^9 for antihelium 3 and n^{12} for antihelium 4

Strongly Coupled Dark Sectors

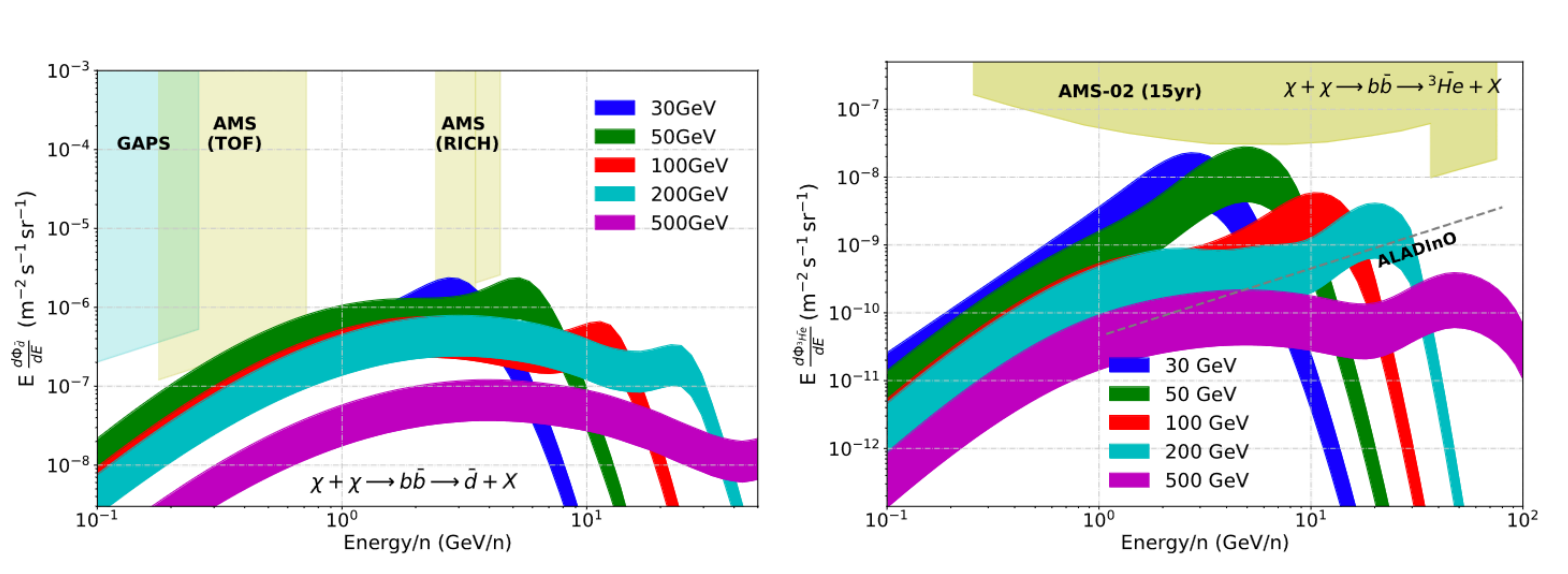
Can accomplish this without producing too many antideuterium or antiprotons.

May be compatible with a 2-sigma excess in collider experiments.



Strongly Coupled Dark Sectors

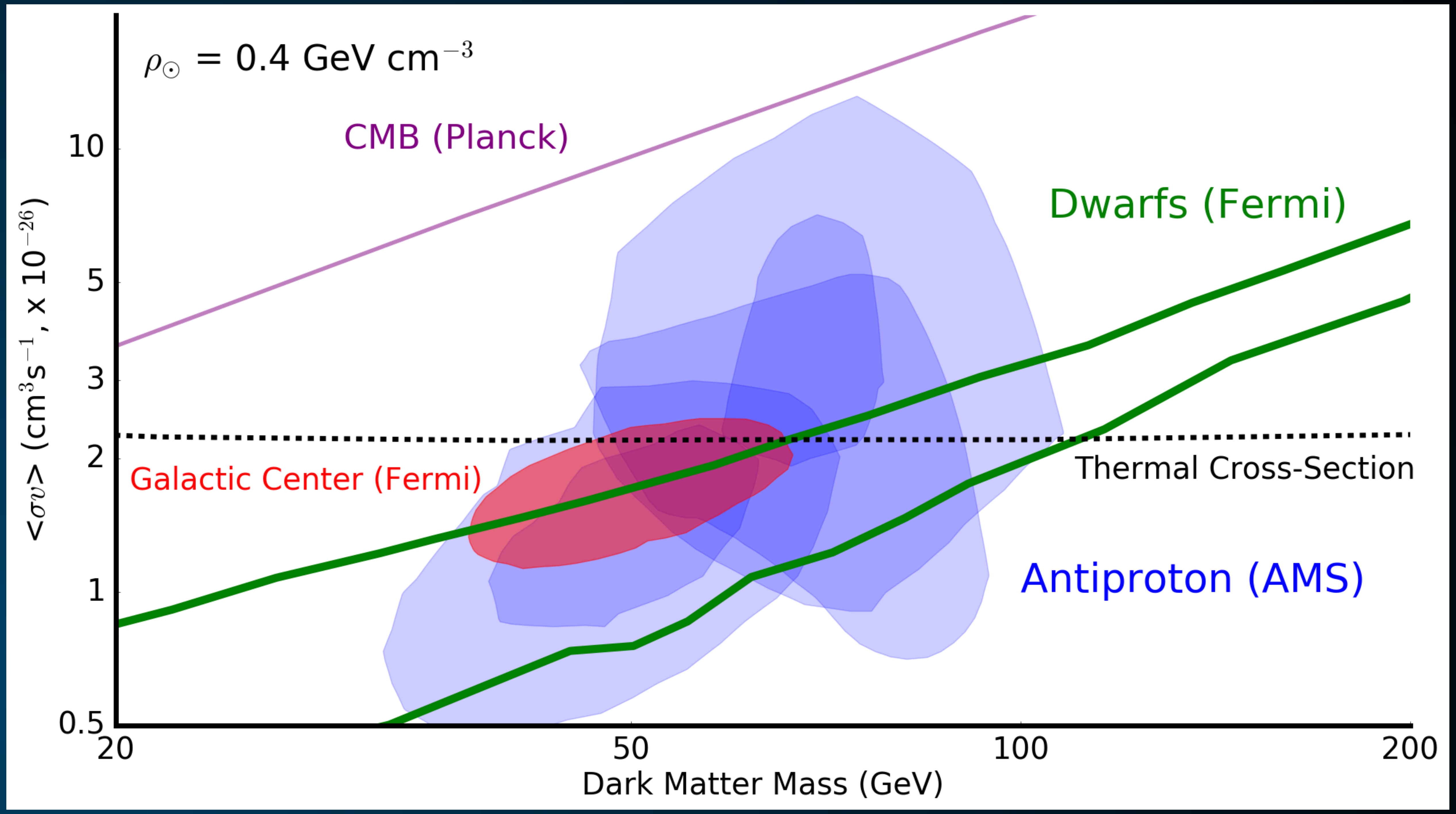
De la Torre Luque, Winkler, TL (2024; 2404.13114)



To Do Quantitative Predictions it is worth constraining models with antiprotons.

Standard models should not be seen yet, even with $\overline{\Lambda_b} \rightarrow {}^3\mathrm{He}$

Increasingly Unlikely Methods for Producing Antihelium



Coalescence - Essentially predicts the number of quarks that will fuse into anti helium

Reacceleration - Important when the particle is very low energy (from coalescence) and also has charge +2 (antihelium specific)

Λ_b - Antiproton decays were already accounted for by standard models, ability to produce antihelium was not known.

Dark Sectors - Antiproton production is small due to heavy DM mass. Antihelium is enhanced (compared to typical rates for heavy dark matter, ~O(10^6).

Where do the *AMS-02* anti-helium events come from?

Vivian Poulin,[1] Pierre Salati,[2] Ilias Cholis,[3,1] Marc Kamionkowski,[1] and Joseph Silk[1,4,5]

[1] *Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA*
[2] *LAPTh, Université Savoie Mont Blanc & CNRS, 74941 Annecy Cedex, France*
[3] *Department of Physics, Oakland University, Rochester, MI 48309, USA*
[4] *Sorbonne Universités, UPMC Univ. Paris 6 et CNRS, UMR 7095, Institut dAstrophysique de Paris, 98 bis bd Arago, 75014 Paris, France*
[5] *Beecroft Institute of Particle Astrophysics and Cosmology, Department of Physics, University of Oxford, Denys Wilkinson Building, 1 Keble Road, Oxford OX1 3RH, UK*

(Dated: March 26, 2019)

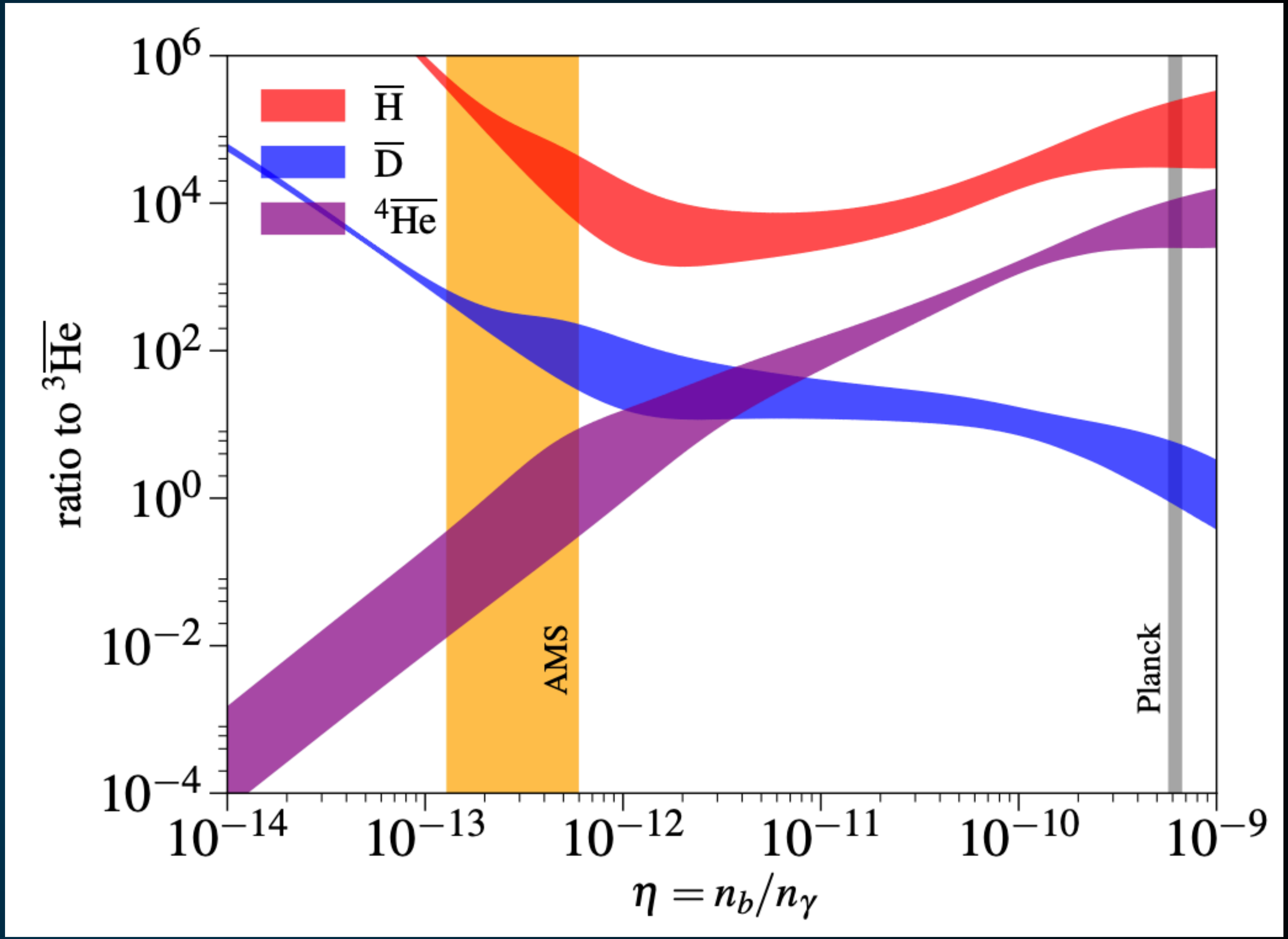
We discuss the origin of the anti-helium-3 and -4 events possibly detected by *AMS-02*. Using up-to-date semi-analytical tools, we show that spallation from primary hydrogen and helium nuclei onto the ISM predicts a $\overline{^{3}\mathrm{He}}$ flux typically one to two orders of magnitude below the sensitivity of *AMS-02* after 5 years, and a $\overline{^{4}\mathrm{He}}$ flux roughly 5 orders of magnitude below the *AMS-02* sensitivity. We argue that dark matter annihilations face similar difficulties in explaining this event. We then entertain the possibility that these events originate from anti-matter-dominated regions in the form of anti-clouds or anti-stars. In the case of anti-clouds, we show how the isotopic ratio of anti-helium nuclei might suggest that BBN has happened in an inhomogeneous manner, resulting in anti-regions with a anti-baryon-to-photon ratio $\bar{\eta} \simeq 10^{-3}\eta$. We discuss properties of these regions, as well as relevant constraints on the presence of anti-clouds in our Galaxy. We present constraints from the survival of anti-clouds in the Milky-Way and in the early Universe, as well as from CMB, gamma-ray and cosmic-ray observations. In particular, these require the anti-clouds to be almost free of normal matter. We also discuss an alternative where anti-domains are dominated by surviving anti-stars. We suggest that part of the unindentified sources in the 3FGL catalog can originate from anti-clouds or anti-stars. *AMS-02* and *GAPS* data could further probe this scenario.

Antihelium Production in Antidomains

If the big bang is asymmetric - different regions may have inverted antiparticle/ particle dominance.

Anticlouds (and potentially antistars will form), undergoing BBN and later stellar fusion.

Can produce a significant (low-energy anti helium abundance)



Poulin et al. (2018; 1808.08961)

Conclusions

These are non-standard approaches. Even if dark matter is a WIMP, it may not produce antihelium.

However, if antihelium is detected, these are among the most reasonable methods for producing such an exotic particle.

All of these avenues are experimentally testable with upcoming colliders.