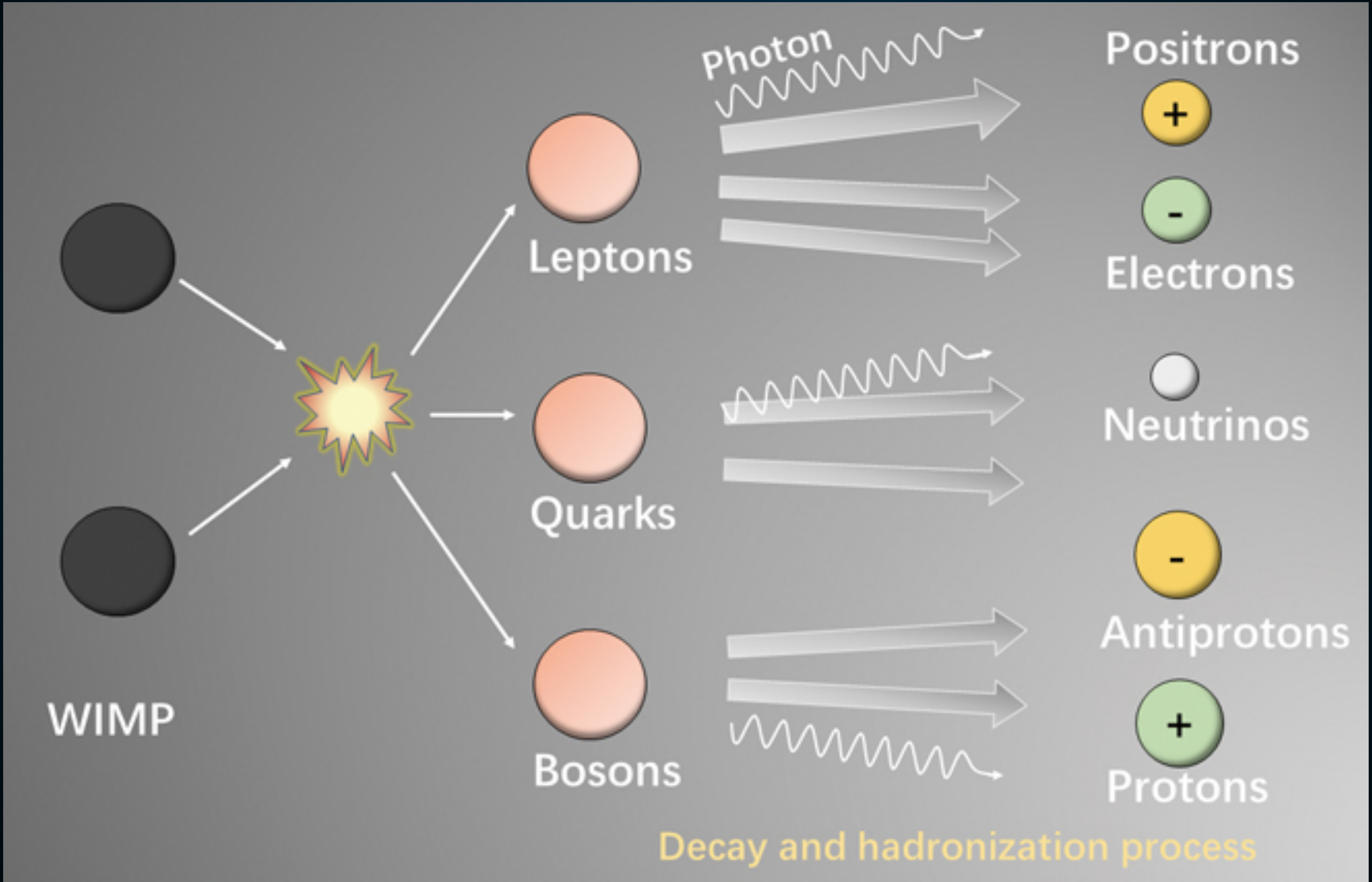
Tim Linden

Dark Matter Searches with Cosmic-Ray Antinuclei

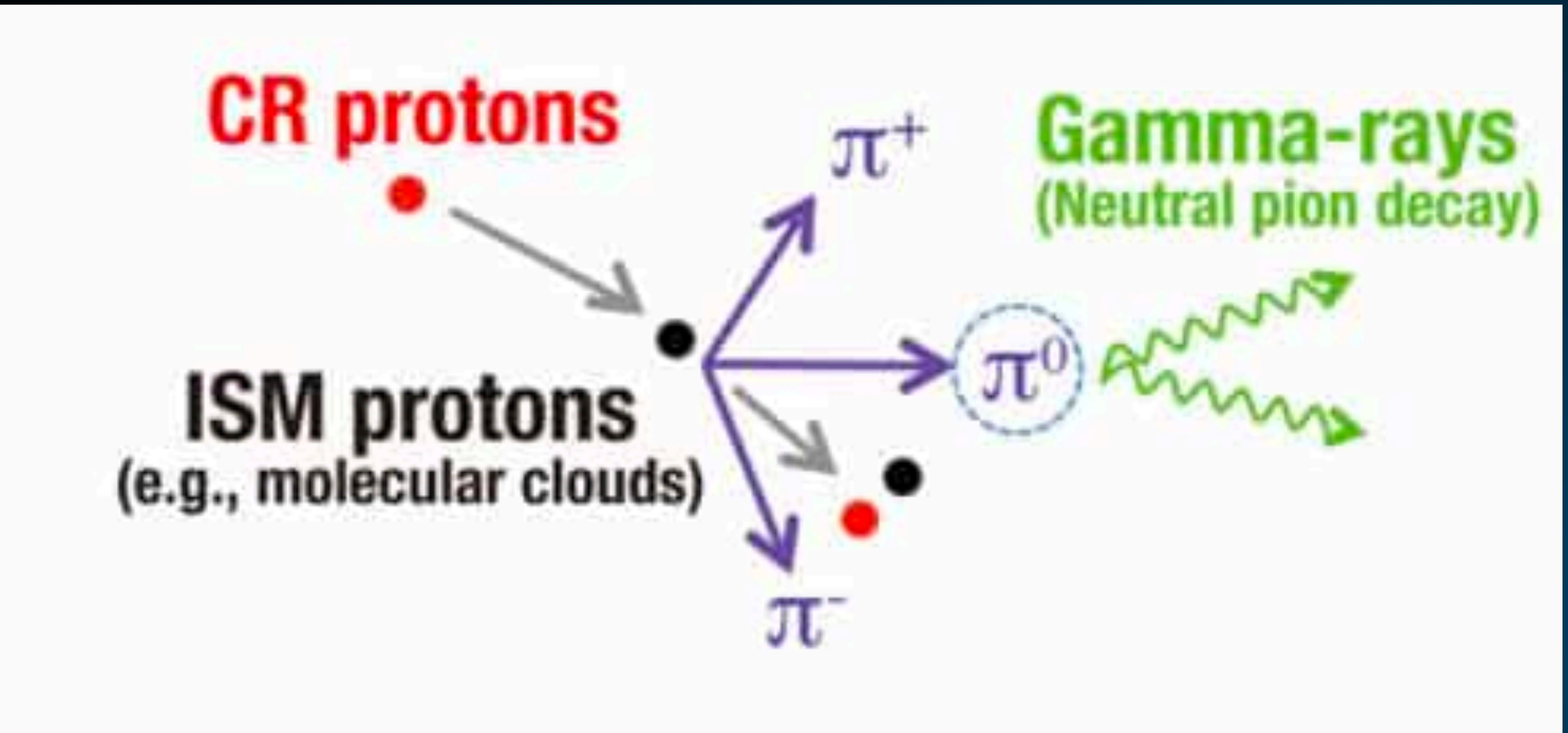
Stockholms universitet

Dark Matter Annihilation and Indirect Detection



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

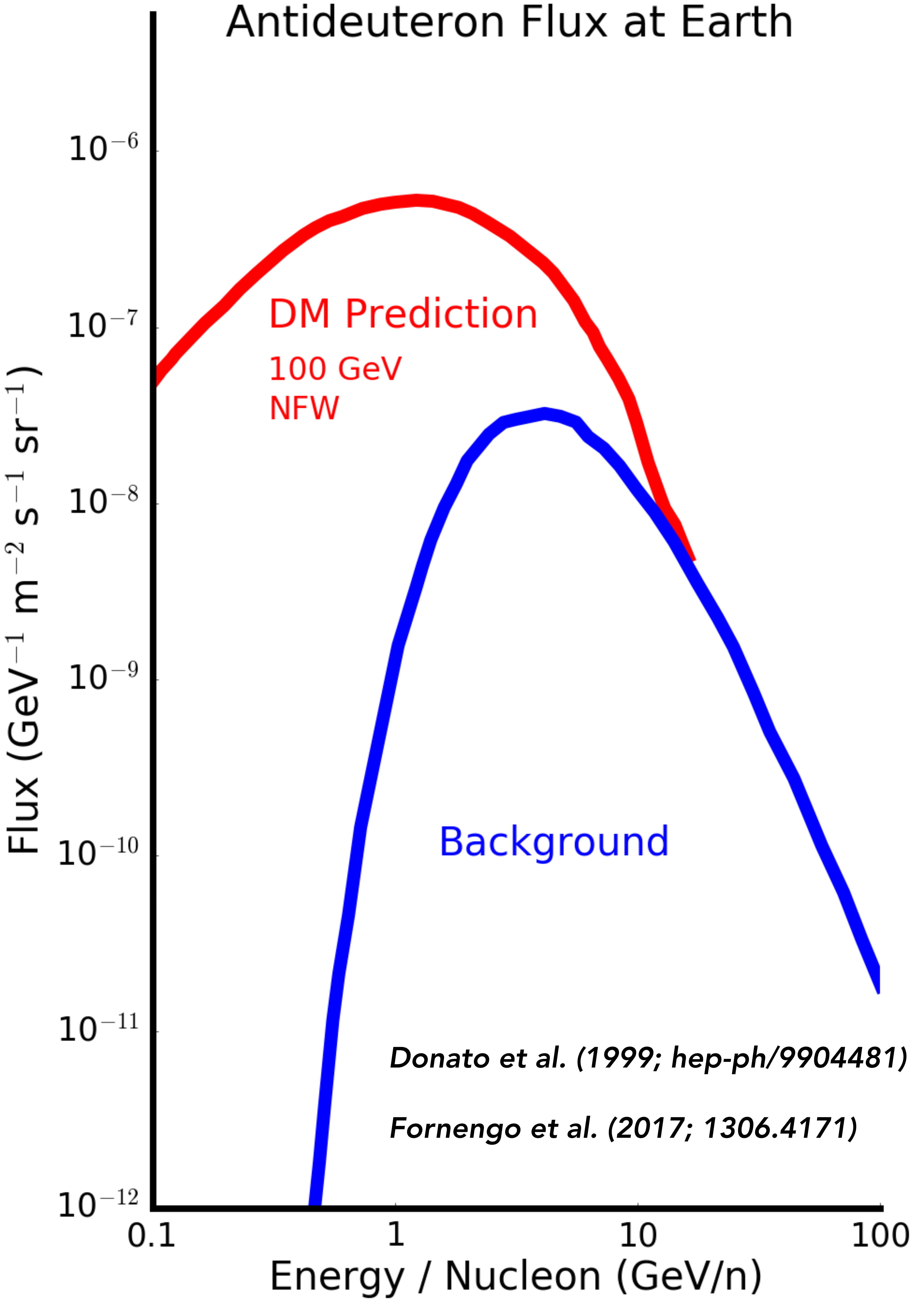
AntiNuclei: A Clean Search Strategy



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

Astrophysical Antinuclei - Most be moving relativistically!

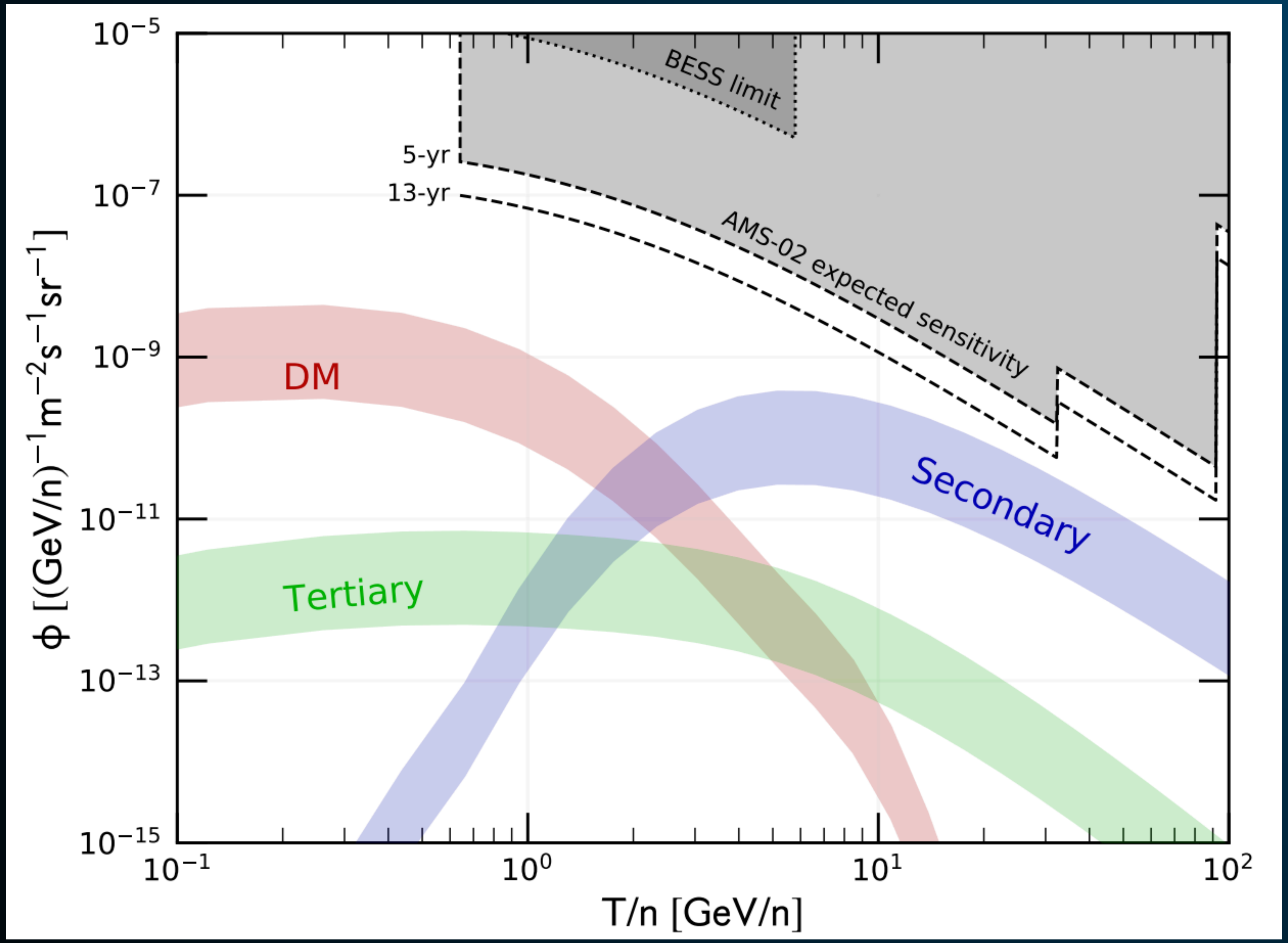
Dark Matter Antinuclei - Can be slow!



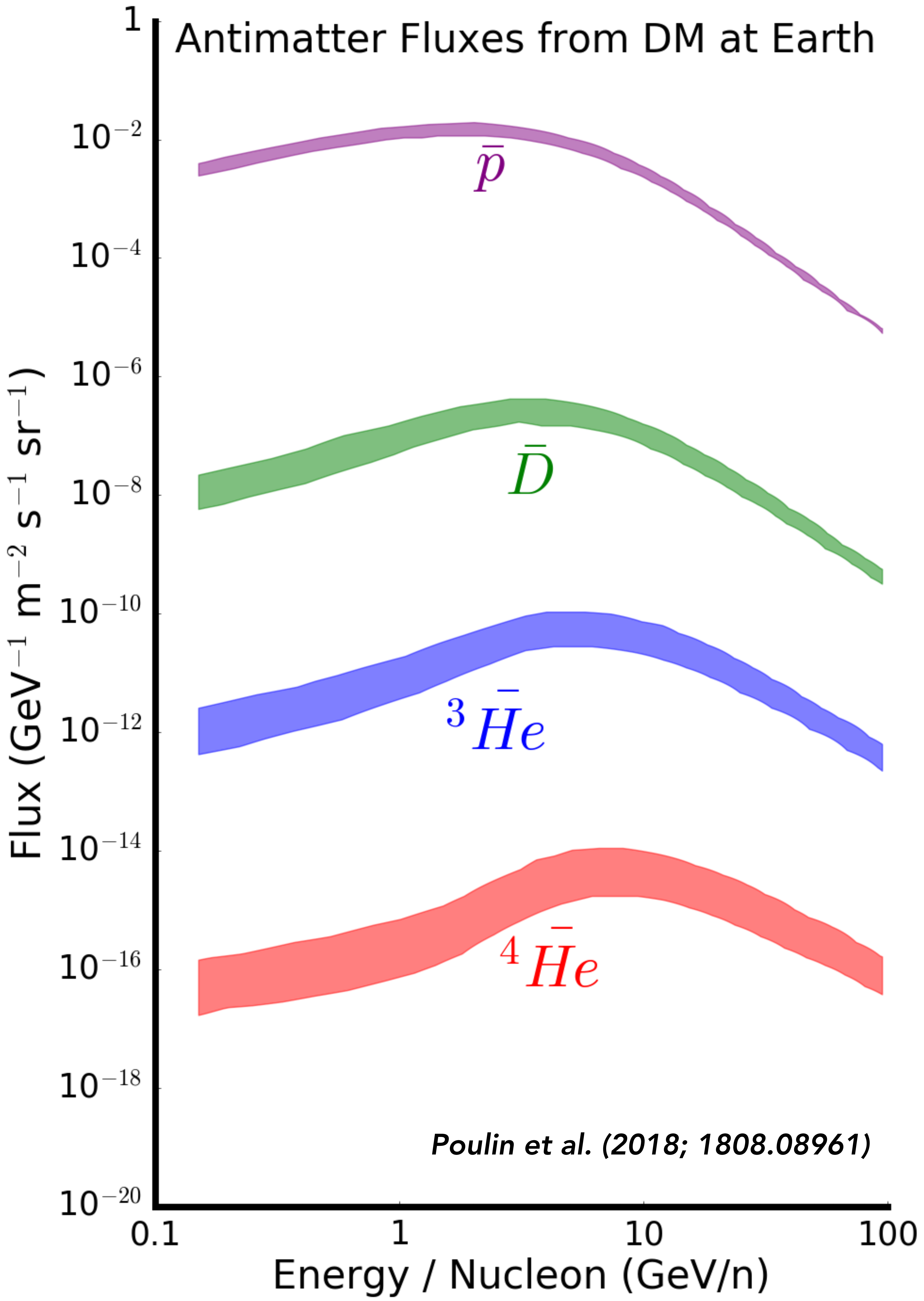
AntiNuclei: A Clean Search Strategy

Antihelium background even cleaner than antideuterons

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



Korsmeier (2017; 1711.08465)



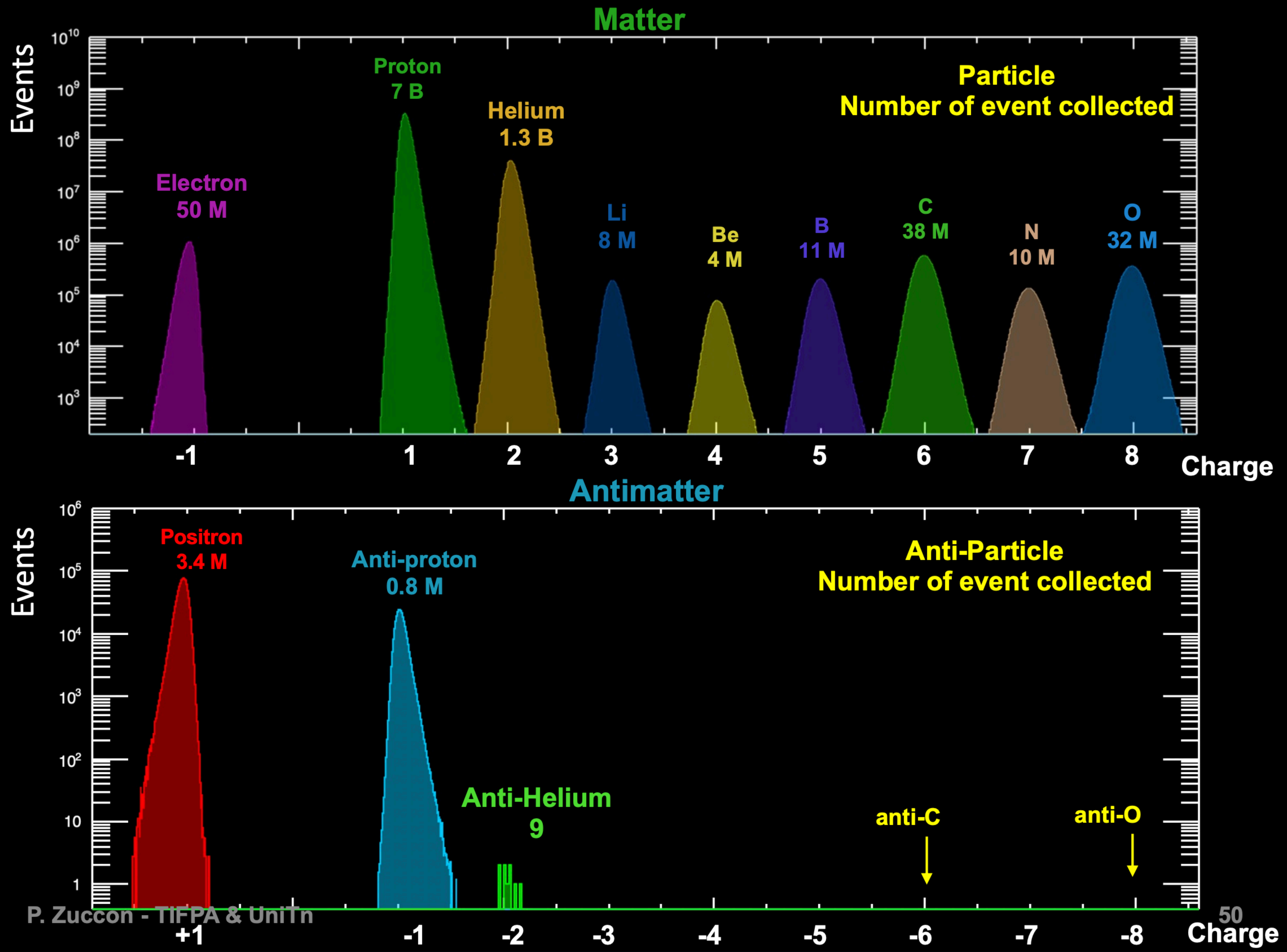
Tentative Evidence for Antinuclei

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

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

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

Key Insight - Coalescence Momentum for Antihelium Should Be Larger

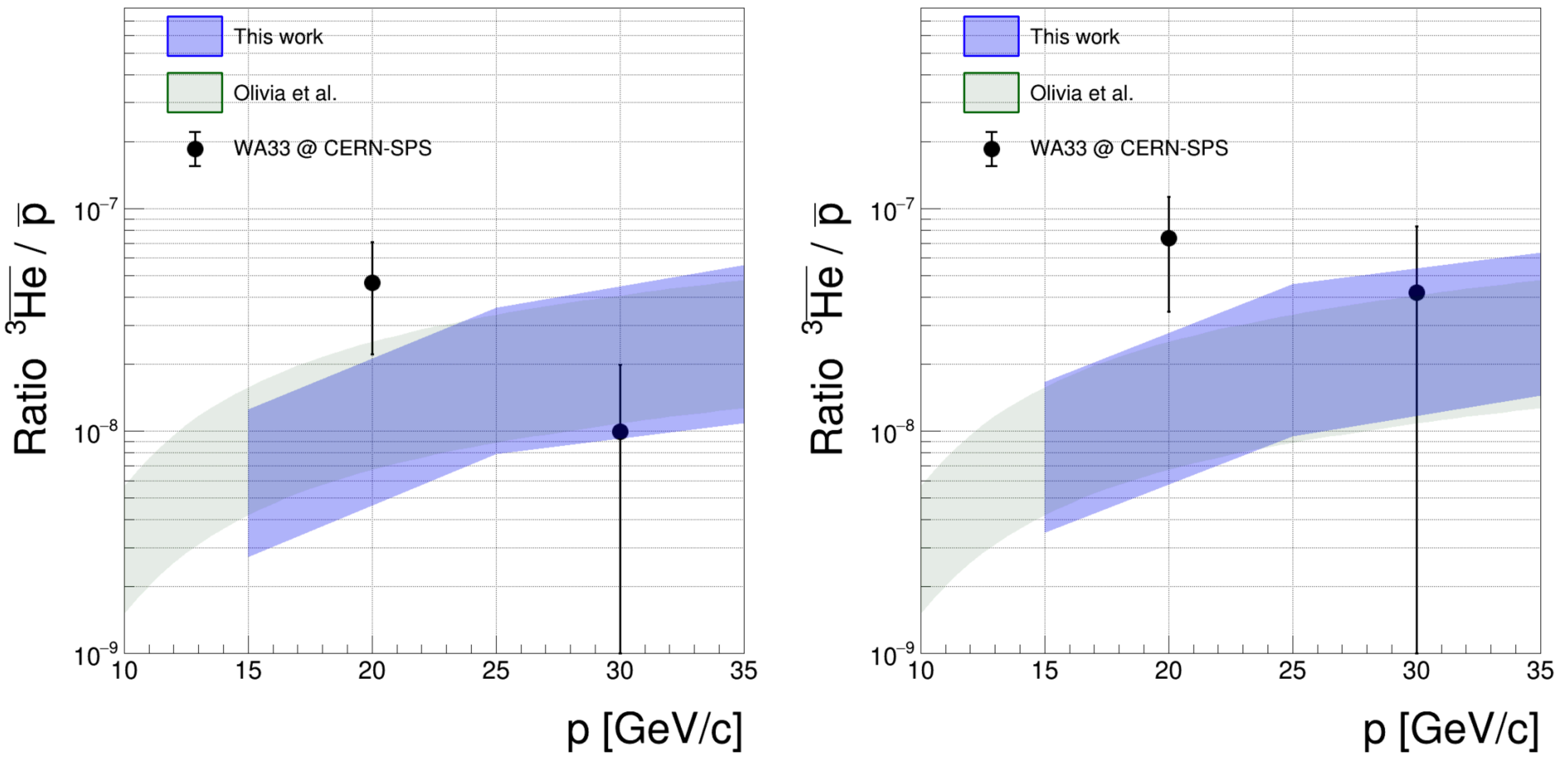


FIG. 4. The invariant production cross section ratio $^3\overline{\mathrm{He}}/\overline{p}$ as function of momentum p [GeV/c] in the laboratory frame for (left) p-Be at $p_{\mathrm{lab}} = 200\,\mathrm{GeV}/c$ and (right) p–Al at $p_{\mathrm{lab}} = 200\,\mathrm{GeV}/c$. The uncertainty bands for this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

Shukla et al. (2006.12707)

A New Method for Producing Antihelium

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

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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]

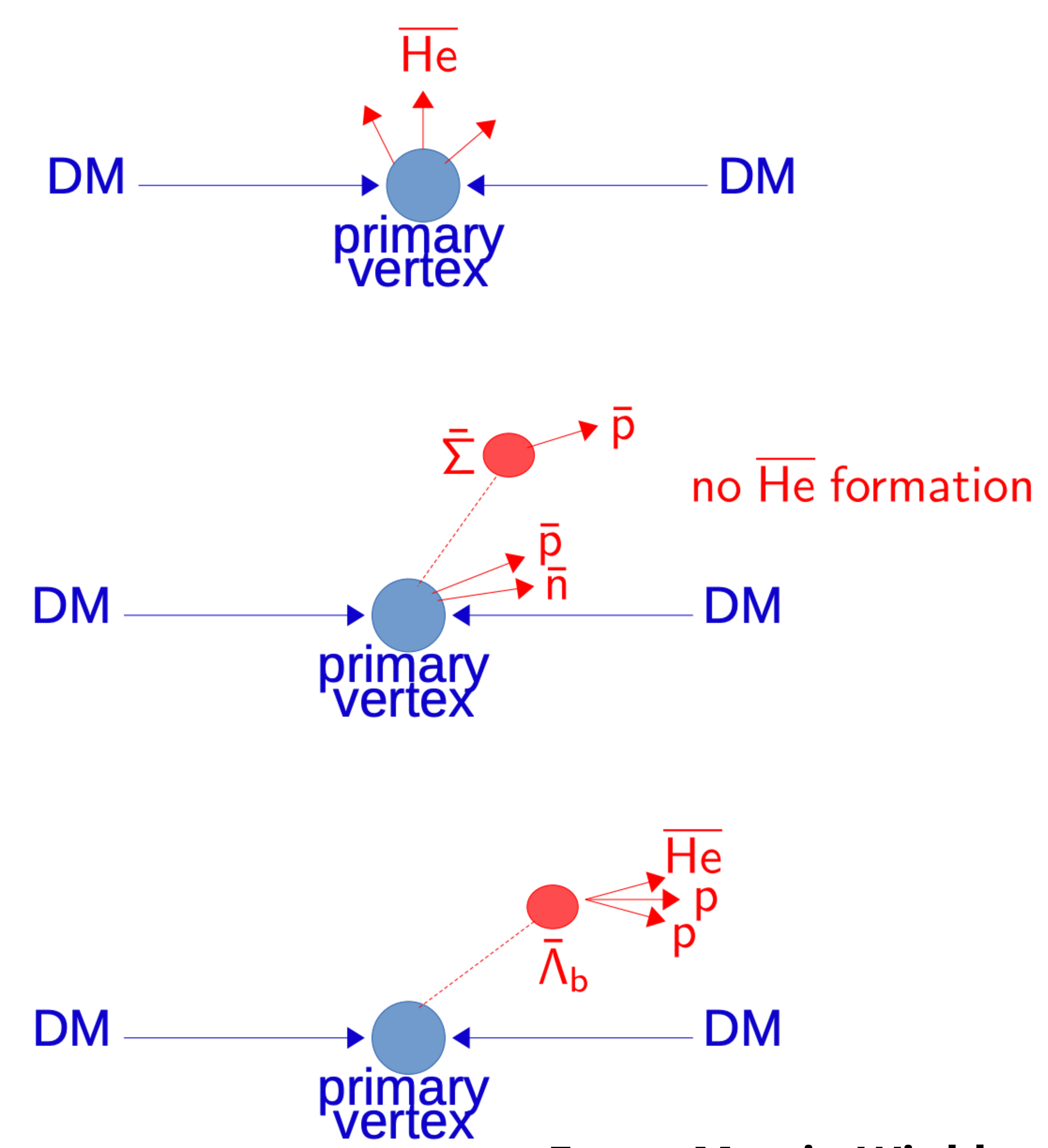
In this *letter*, we challenge the current understanding that standard dark matter annihilation models cannot produce a measurable antihelium flux. Our analysis examines a known, and potentially dominant, antinuclei production mode which has been neglected by previous literature – the production of antihelium 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.

Lambda_b antibaryon has correct parameters to produce anti helium:

- **Antibaryon number of 1**
- **Mass: 5.6 GeV (pbar, nbar, pbar, p, p)**

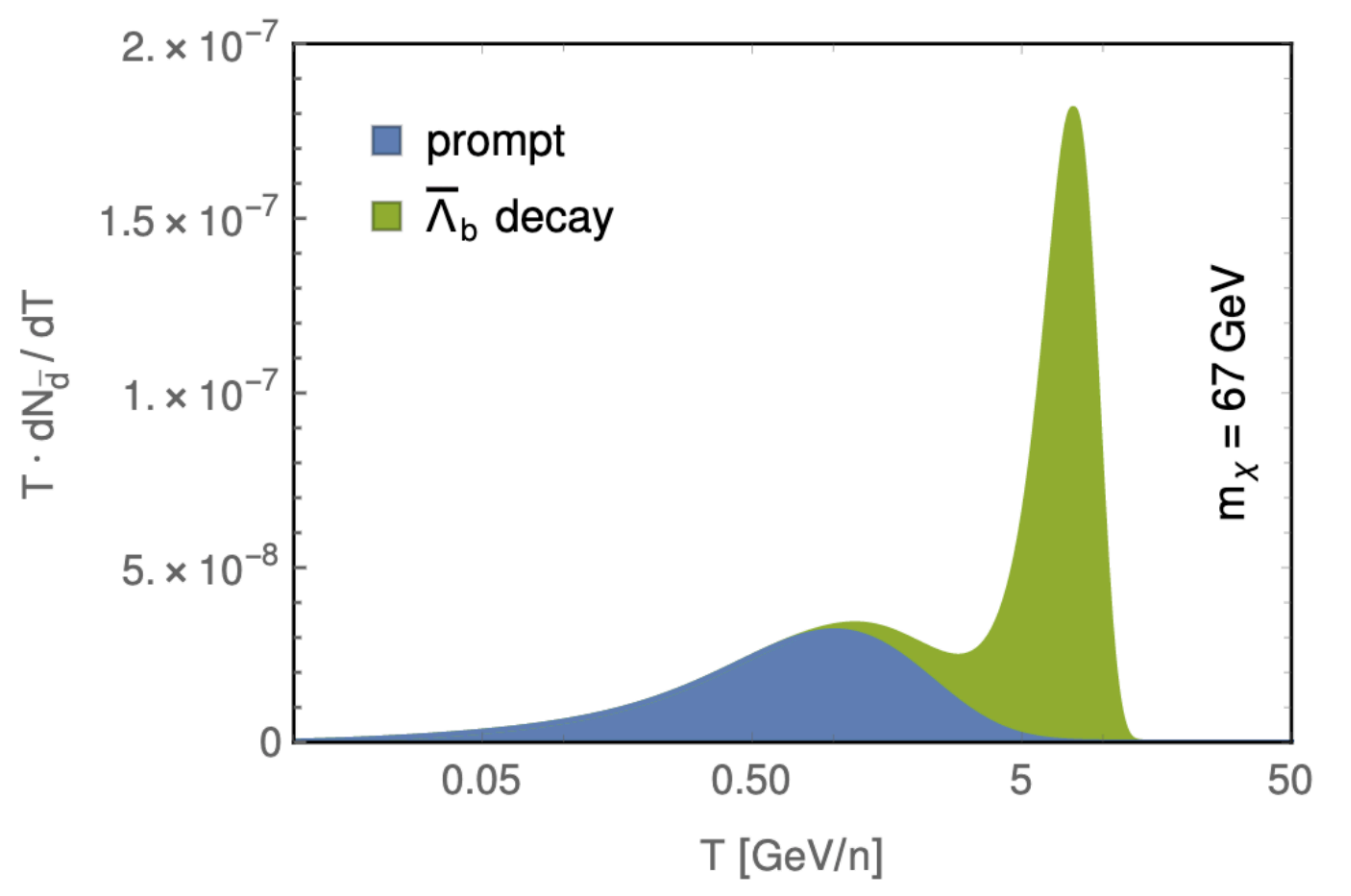


From: Martin Winkler

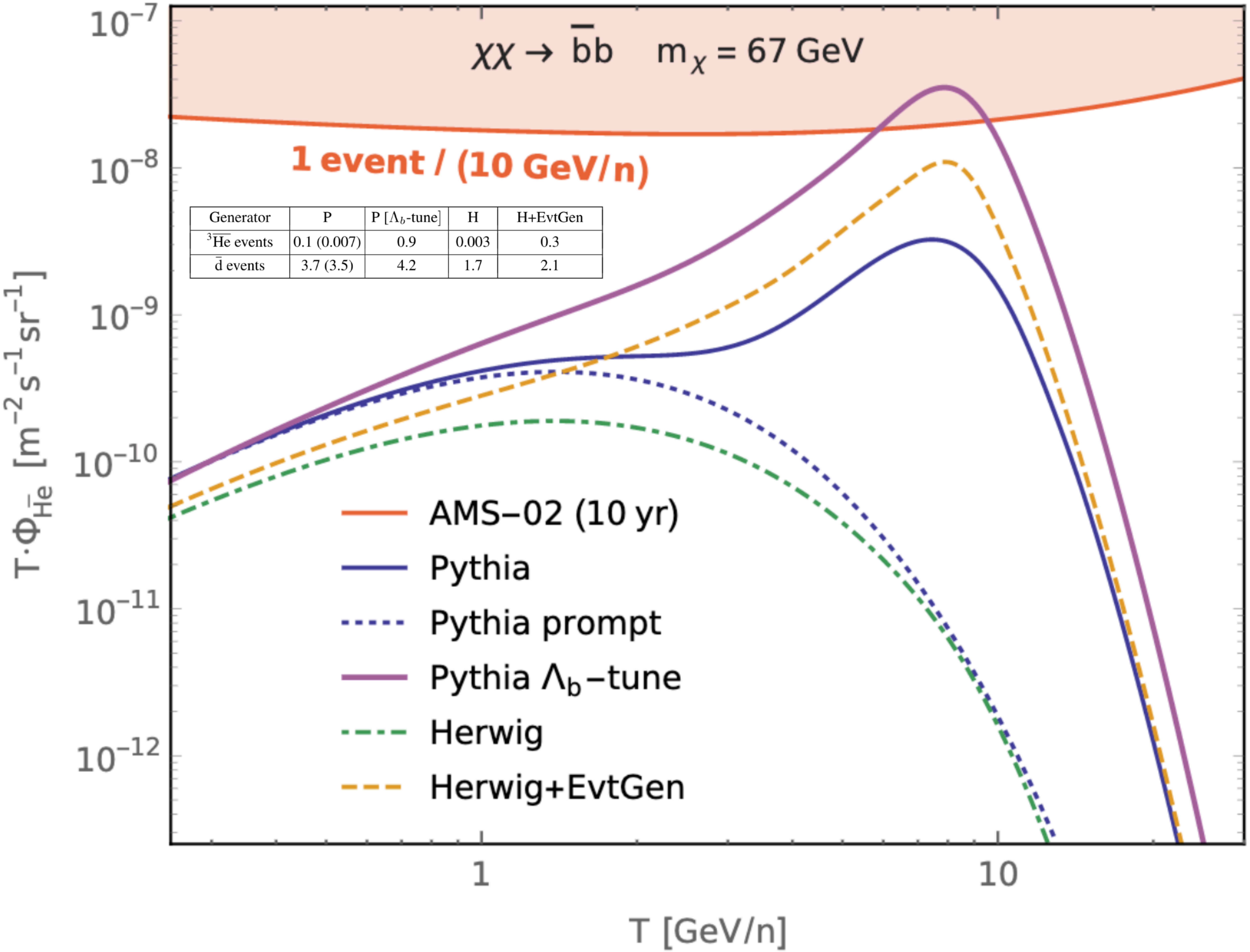
A New Method for Producing Antihelium

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

Moreover, the enhancement is at high-energies - producing an observable spectral feature.

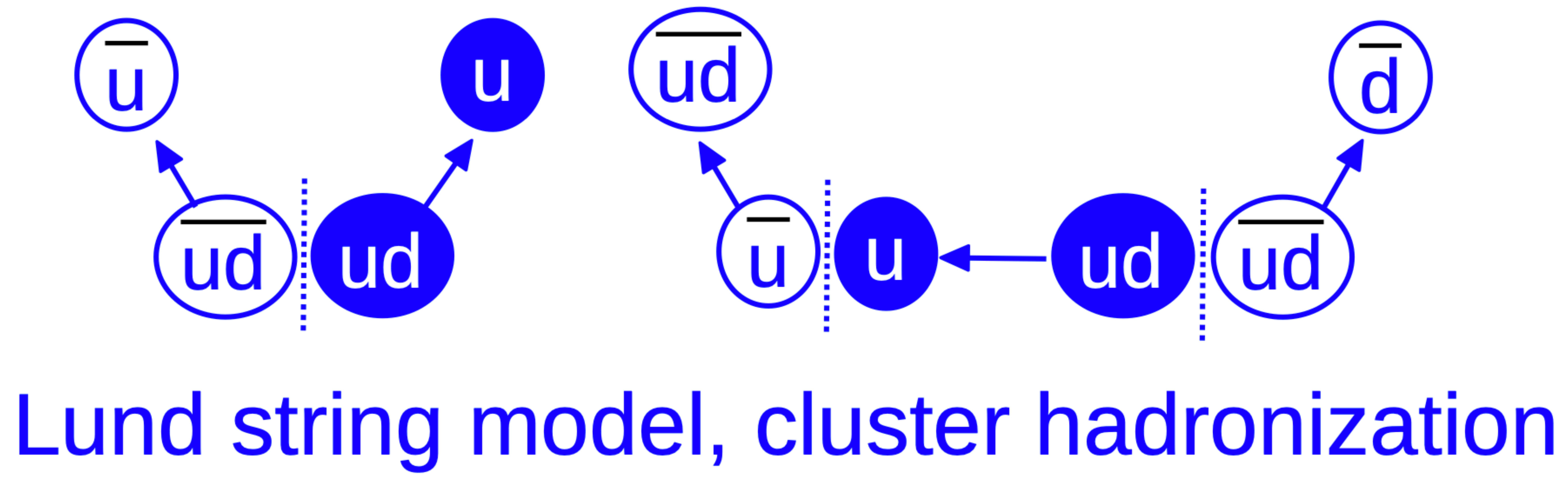


Winkler & Linden (2020; 2020.16251)



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

Lund String Model vs. HERWIG Cluster Model

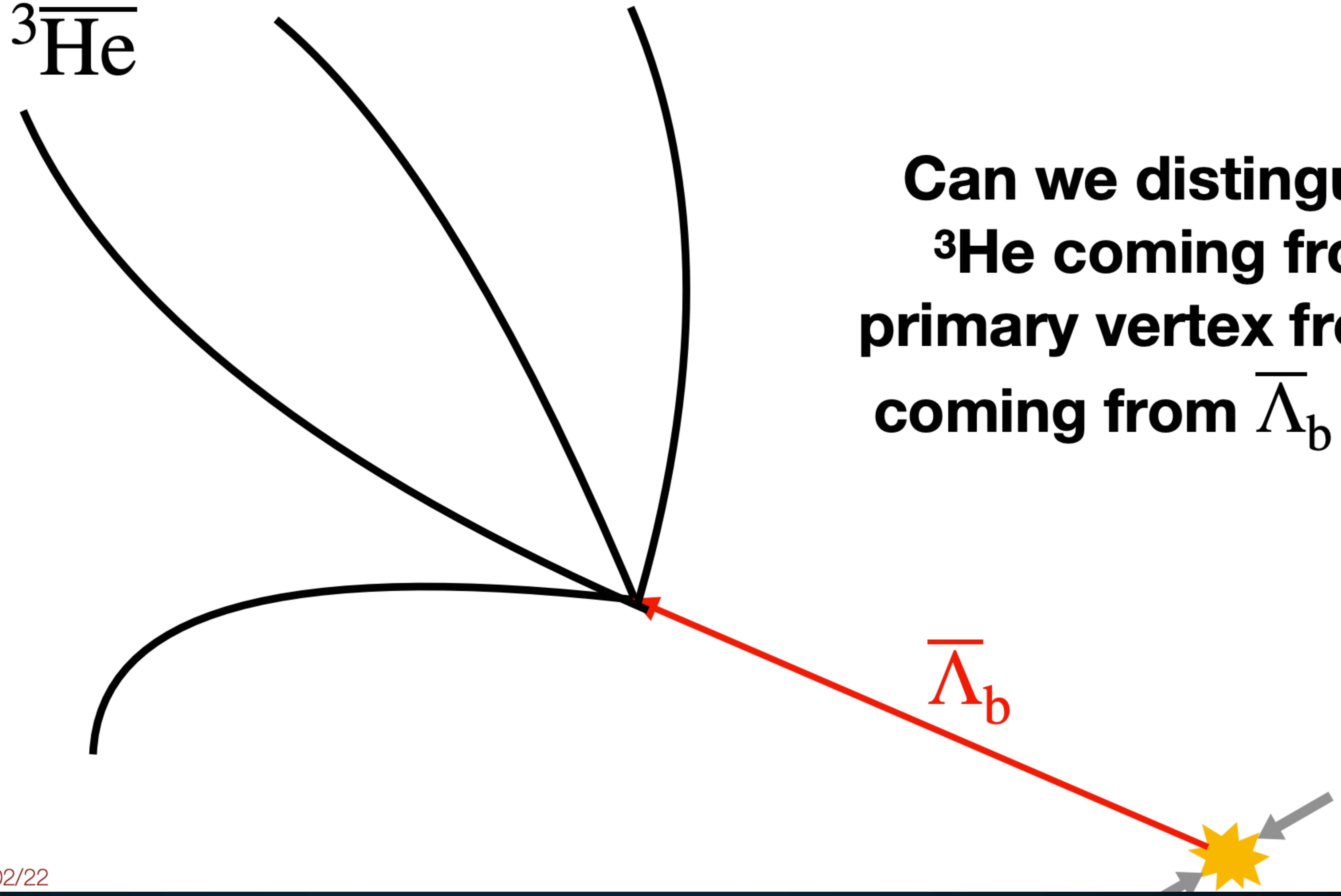


Two diquarks must be produced from vacuum to produce baryon number -3

- Lund String Model: Can be produced at every factorization step due to string breaking
- HERWIG Cluster Model: Only quark/anti-quark pairs are initially created.

-

Can We Find this At Particle Accelerators?

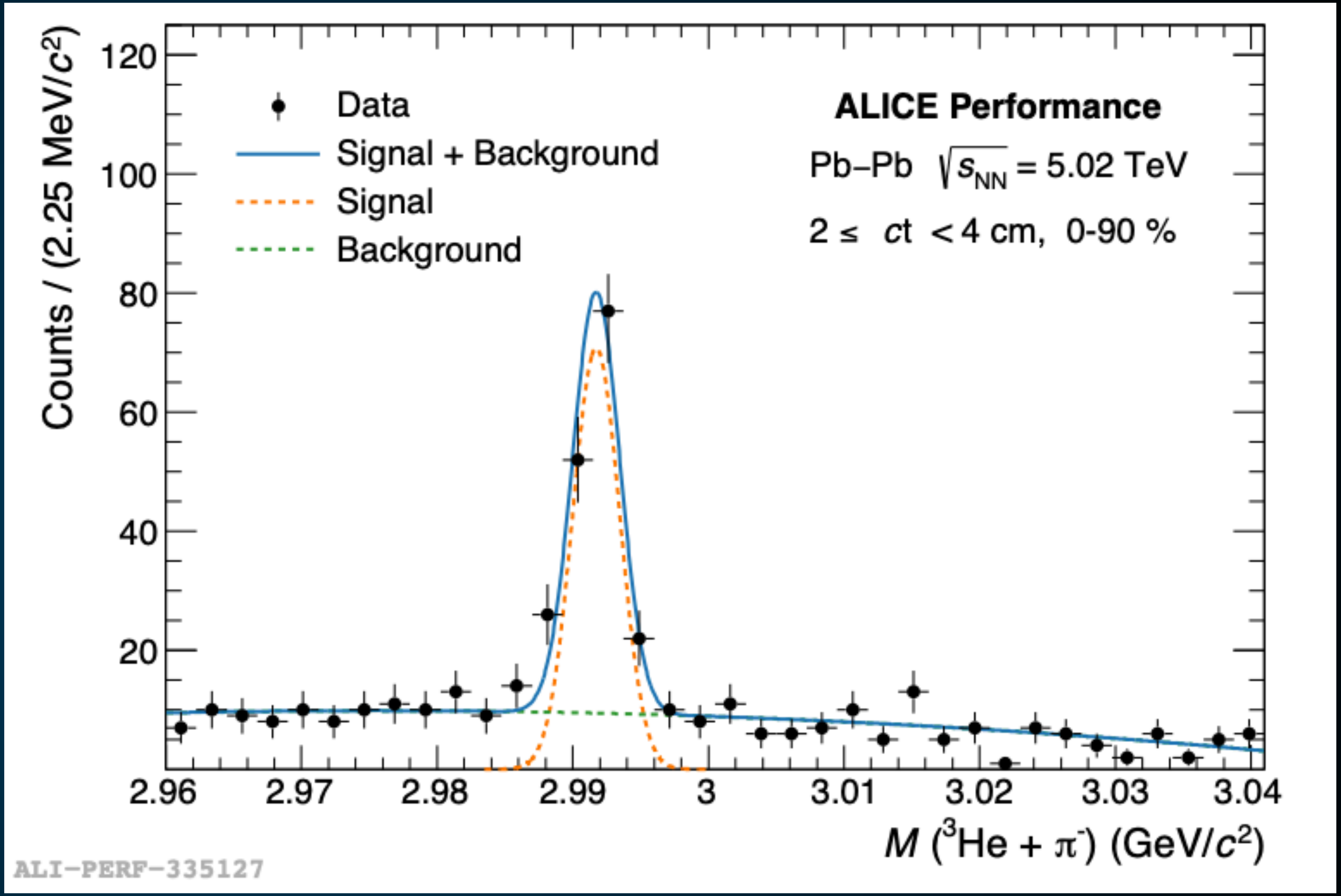


Can we distinguish the ^{3}He coming from the primary vertex from those coming from $\overline{\Lambda}_b$ decays?

$c\tau$ ~ 450 µm

Can We Find this At Particle Accelerators?

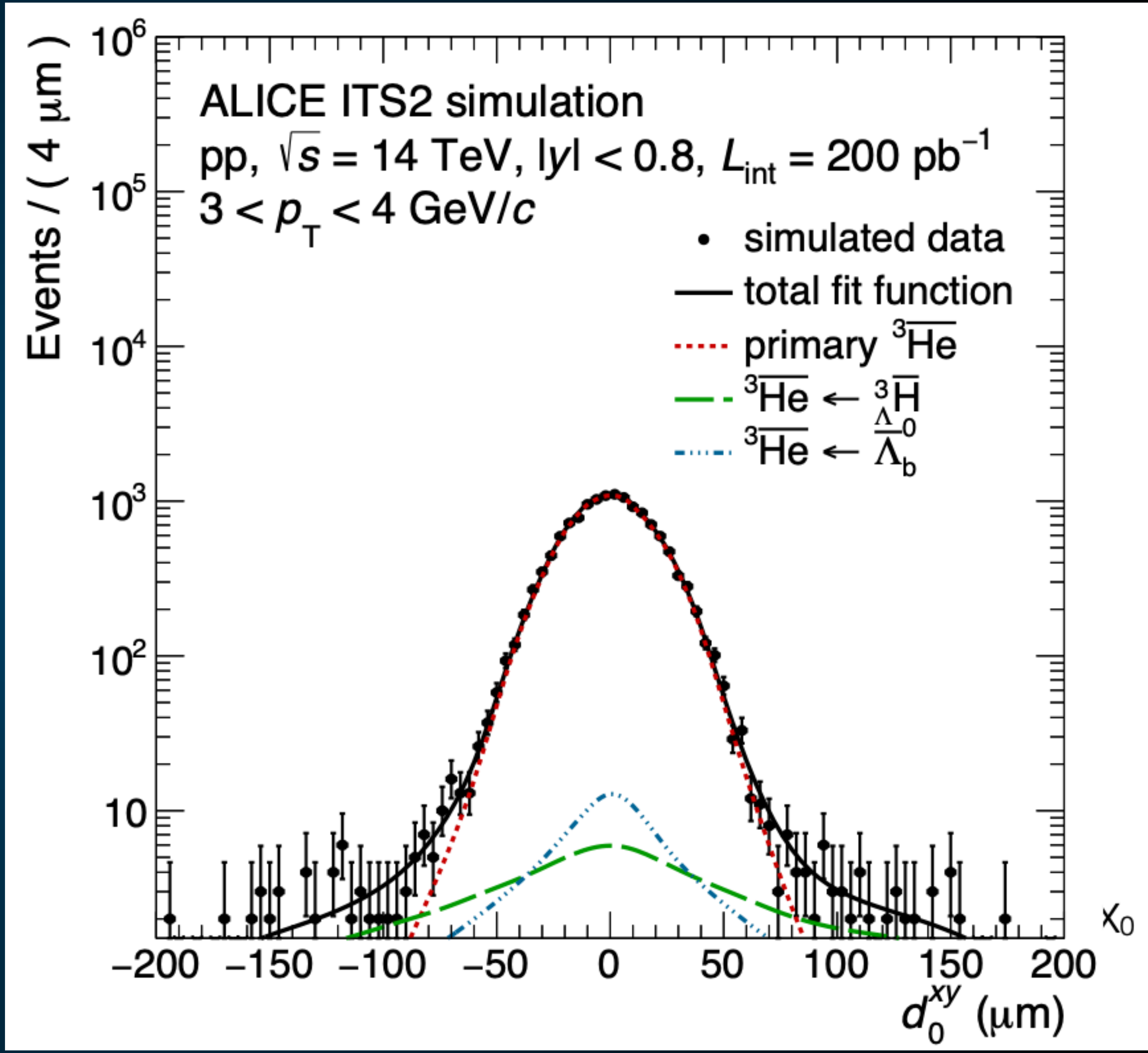
Current observations are not sensitive to this offset



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.

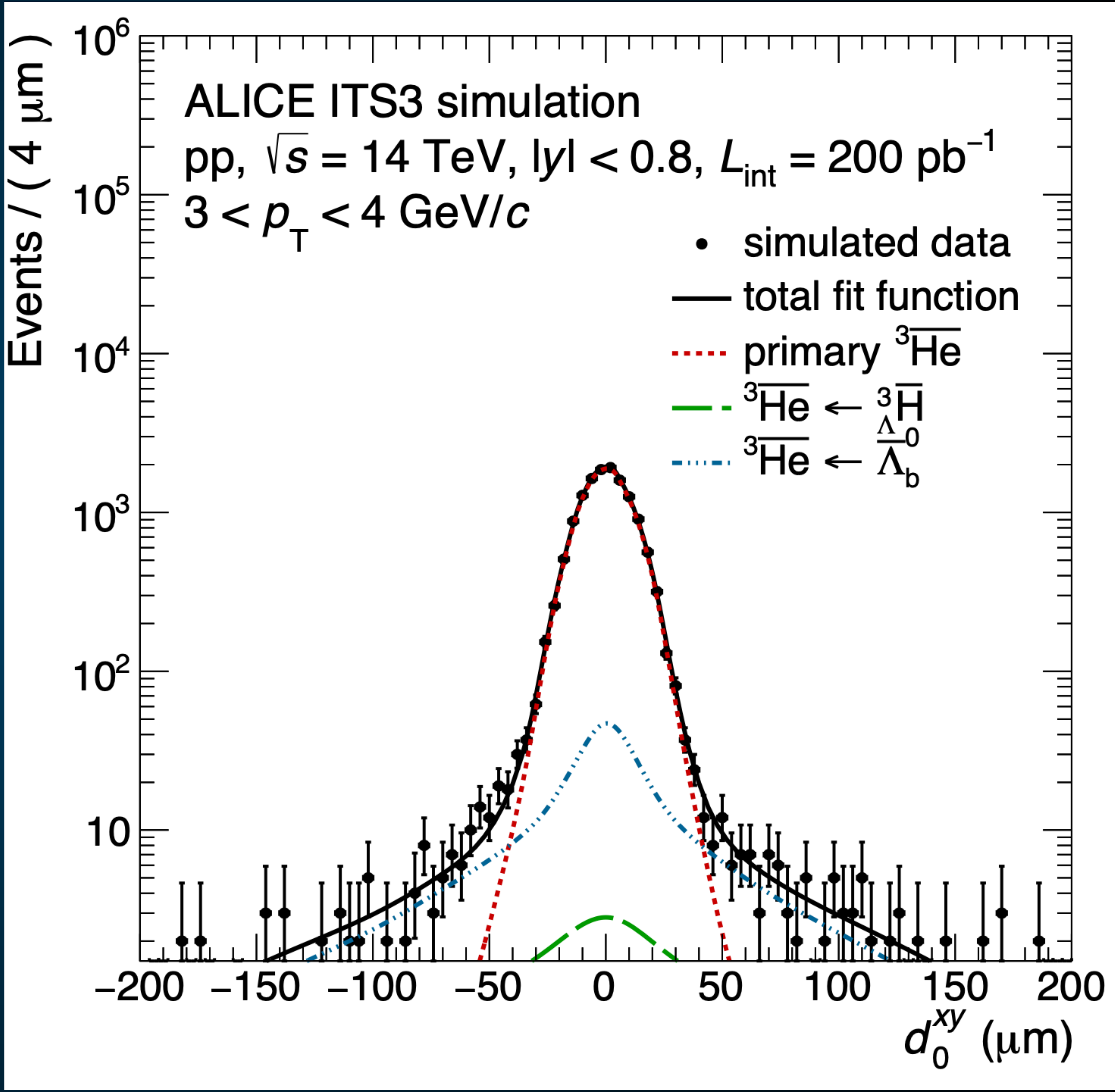


Can We Find this At Particle Accelerators?

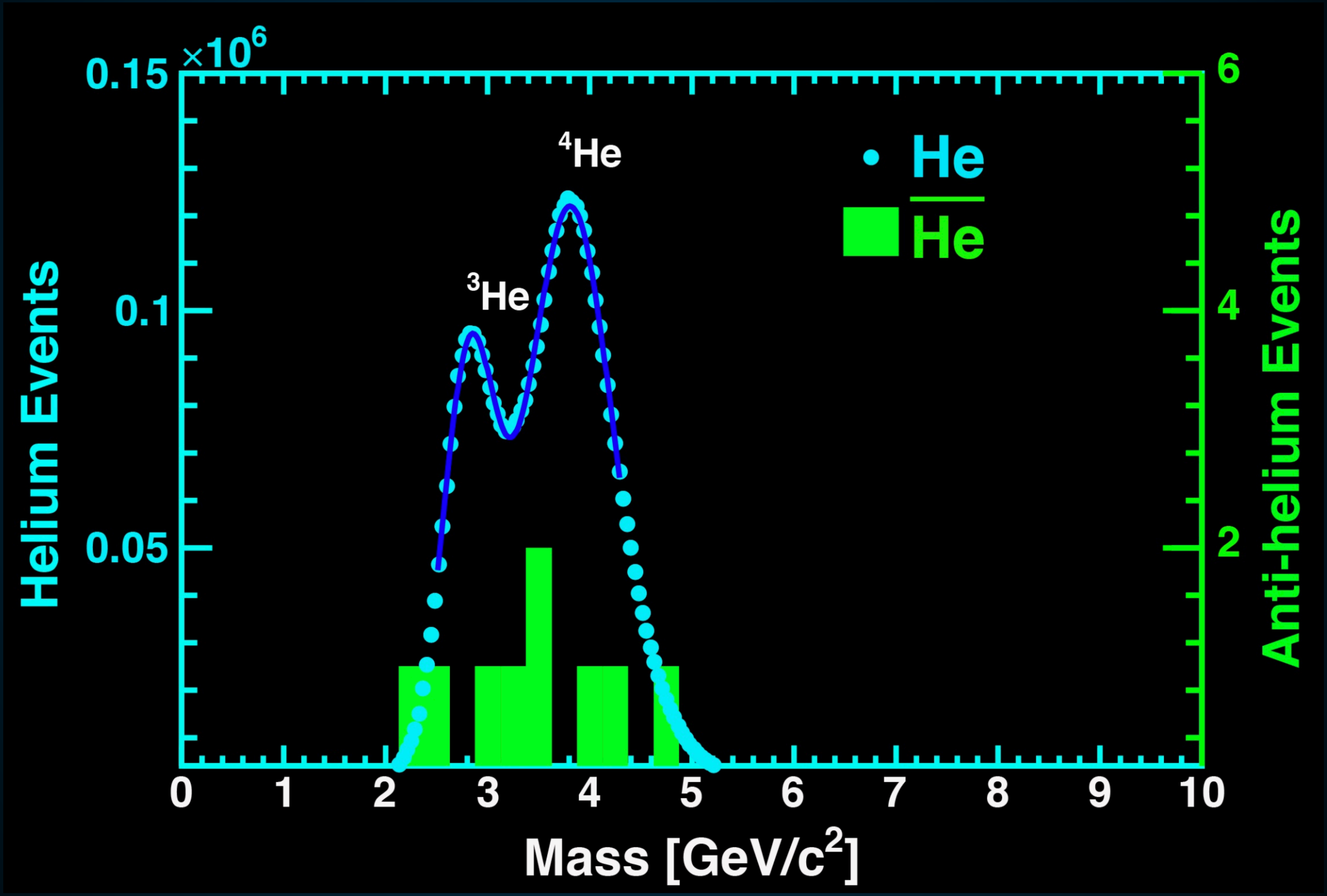
Current observations are not sensitive to this offset

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 Lambda_b channel for anti helium creation.



Problem: Are We Actually Observing Antihelium 4?

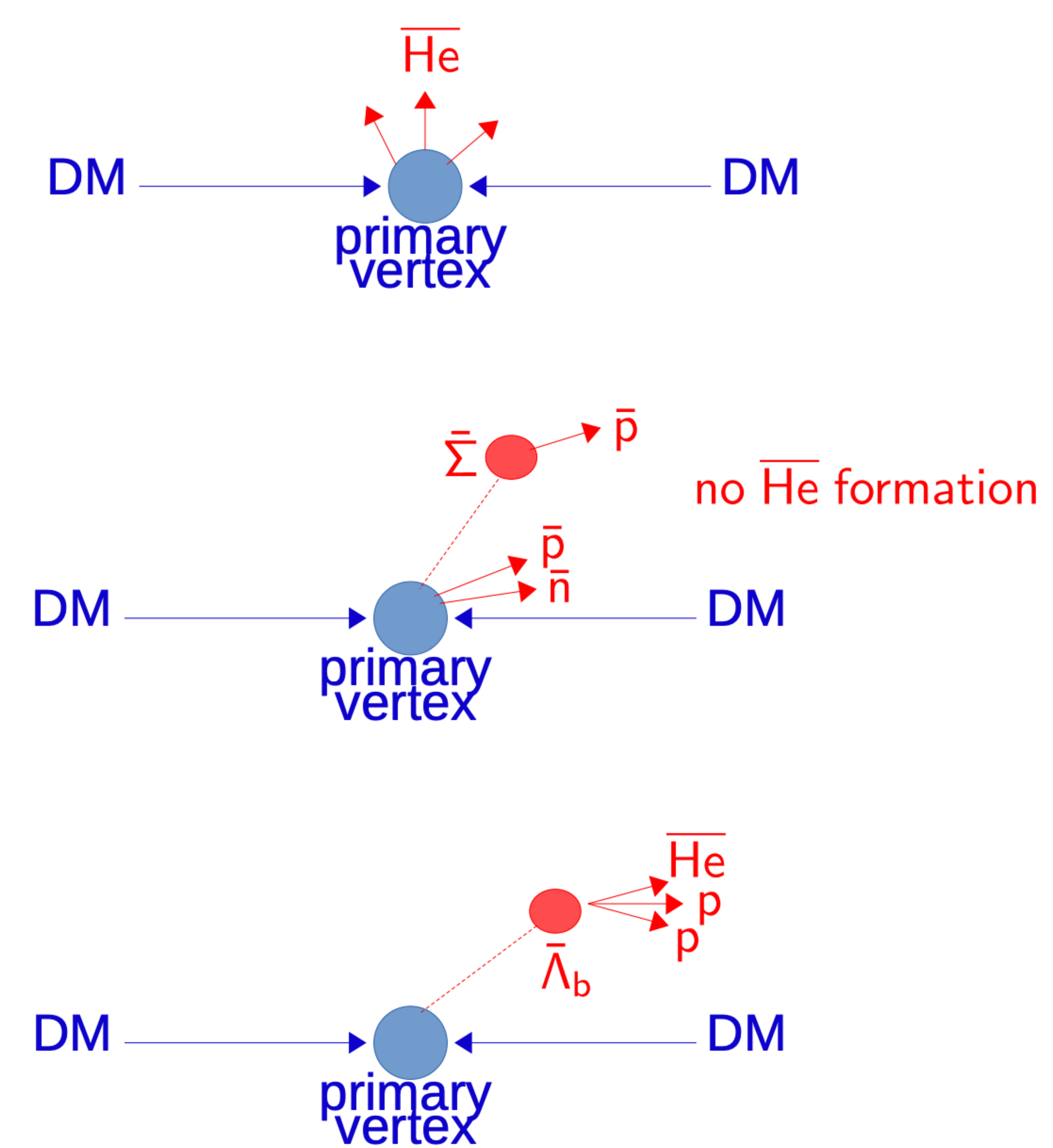


Cannot Enhance Antihelium-4 with Λ_b

Λ_b antibaryon has correct parameters to produce anti helium:

- Antibaryon number of 1
- Mass: 5.6 GeV (pbar, nbar, pbar, p, p)

Too light to produce antihelium-4!



From: Martin Winkler

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.