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

M. Kachelrieß, S. Ostapchenko, and J. Tjemands

1Institutt for fysikk, NTNU, Trondheim, Norway and
2D.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. $b\bar{b}$ 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 $\Lambda_b$ 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 $\Lambda_b$ decays.

A condition that the scenario of WL21 leads to a detectable antihelium flux is that the branching ratio $BR(b \rightarrow \Lambda_b)$ is sufficiently large. In order to achieve such a large branching ratio, WL21 increased the diquark formation parameter $\text{probQQtoQ}$ of Pythia in their so-called “$\Lambda_b$ tune”. WL21 noted that this change also significantly boosts prompt antinucleon production. They compensated the resulting over-production of antideuterons by reducing at the same time the coalescence momentum, which is a free parameter in their approach, by a factor 0.6.

The conceptual error of WL21 is that the change of $\text{probQQtoQ}$ cannot simply be compensated by a reduction 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, $e^+e^- \rightarrow \bar{p}pX$. For a change of $\text{probQQtoQ}$ from the default value 0.09 to 0.24—which is the value reproducing the value of the branching ratio $b \rightarrow \Lambda_b = 0.1$ chosen in WL21—the resulting proton multiplicity is compared in Table 1 to measurements. For instance at $\sqrt{s} = 91$ GeV, the predicted proton multiplicity in the “$\Lambda_b$ tune” is $33\sigma$ away from the one measured [3]. For comparison, the standard settings in Pythia predict a $\Lambda_b$ multiplicity in electron-positron annihilations at the $Z$-resonance of 0.016, which is less than $1\sigma$ away from the value $0.031 \pm 0.016$ 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, $dN/dy \mid |y|<0.5$, of protons, kaons and pions measured by ALICE at LHC at $\sqrt{s} = 7$ TeV [4]. Note also that the increased diquark formation reduces the production rate of all mesons, aggravating the variance of the “$\Lambda_b$ tune” with observations. Finally, the condition not to overproduce the antiproton flux measurements [5] from AMS-02 requires to reduce the annihilation rate of dark matter in the “$\Lambda_b$ tune” relative to the value allowed using the default version of Pythia.

Another caveat in the approach of WL21 is the use of Pythia to “predict” the branching ratio $BR(\Lambda_b \rightarrow \bar{u}u(\bar{u}d)) = 0.012$ which controls the formation rate of antihelium-3. Such ratios are external input parameters into Pythia, which represent in the case of yet unobserved decays simply educated guesses. In this specific case, the ratio is $\approx |V_{ub}|^2/|V_{cb}|^2$, while one expects an additional suppression if diquarks are formed. Comparing branching ratios of such $\Lambda_b$ decays to observations, we find indeed that Pythia overestimates their rate by a factor 4-5, which is further enhanced in the $\Lambda_b$ tune. In particular, Pythia using the standard settings overestimates the measured branching ratio $BR(\Lambda_b \rightarrow \Lambda^-_b \bar{p}p\pi^+) = (2.65 \pm 0.29) \times 10^{-4}$ [3] by a factor 5.6 and in the $\Lambda_b$-tune by a factor 17. This corresponds to a $42\sigma$ and $144\sigma$ deviation from measurements, respectively. Reducing $BR(\Lambda_b \rightarrow \bar{u}u(\bar{u}d))$ correspondingly would make the antihelium-3 flux undetectable for AMS-02 even if the “$\Lambda_b$ tune” would be viable.

In conclusion, the “$\Lambda_b$ tune” of Pythia which WL21 argue to lead to an antihelium-3 flux detectable by AMS-02 is excluded by a wealth of measurements of (anti-) baryon

| $\sqrt{s}$ | $10$ GeV | $29-35$ GeV | $91$ GeV | $130-200$ GeV |
|-----------|----------|-------------|----------|--------------|
| Obs.      | $0.266 \pm 0.008$ | $0.640 \pm 0.050$ | $1.050 \pm 0.032$ | $1.41 \pm 0.18$ |
| WL21      | $0.640$        | $1.161$        | $2.102$        | $2.33$         |

**TABLE I**: Multiplicity of (anti-) protons in electron-positron annihilations

| Particle | $dN/dy$, LHC | $dN/dy$, $\Lambda_b$ tune |
|----------|--------------|--------------------------|
| proton   | $0.124 \pm 0.009$ | $0.328$ |
| kaon     | $0.286 \pm 0.016$ | $0.231$ |
| pion     | $2.26 \pm 0.10$   | $1.90$  |

**TABLE II**: Measurements of $dN/dy$ at mid-rapidity ($|y|<0.5$) in proton-proton collisions at $\sqrt{s} = 7$ TeV for $p$, $K^+$ and $\pi^+$.
and (anti-) meson production at accelerators. Even so, the future observation of (anti-) helium-3 production in baryon decays can potentially have a profound impact on the study of hadronisation, as noted already by WL21. This rate varies by orders of magnitude between event generators based on different hadronisation models and may thus be used to discriminate these models.

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