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Antideuterons from dark matter and hadronization model dependence

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The antideuteron channel is currently one of the most promising channels for indirect detection of dark matter (DM). The coalescence model of antideuteron production is strongly dependent on two-particle correlations in each DM annihilation or decay event, and the hadronization scheme used when generating Monte Carlo events can therefore have a profound effect on the predicted antideuteron spectra. We investigate the antideuteron yield in dark matter annihilations on an event-by-event basis using the HERWIG++ Monte Carlo generator, comparing to earlier results based on PYTHIA, thereby estimating the uncertainties involved.

Poster based on Ref. [1].

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1. Introduction

One strategy towards detecting dark matter (DM) is searching for its self-annihilation (or decay) products. Annihilation of symmetric DM leads to equal production rates of matter and antimatter, while the cosmic ray flux from astrophysical sources is matter-dominated. Cosmic ray antiparticle fluxes are therefore especially well suited for DM searches. The production of antinuclei requires multiple antinucleons that are close in both space and momentum, and are particularly rare in astrophysical processes. The antideuteron is the simplest antinucleus (consisting of a $\bar{p}\bar{n}$-pair), and constitutes a very promising channel for DM detection.

Antideuteron production depends strongly on correlations between antinucleons, and is sensitive to momentum differences that are small or comparable to $\Lambda_{\rm QCD} \sim 200\,$MeV. One may therefore expect theoretical results to have a rather strong dependence on the hadronization models employed in Monte Carlo simulations. We here compare the results from the Monte Carlo event generators HERWIG++ [2] and PYTHIA [3], which employ the cluster fragmentation and string fragmentation hadronization models, respectively. The specifics of these models will not be discussed here, and we refer to the article [1] on which this contribution is based for further details.

The fusion of (anti)protons and (anti)neutrons into (anti)deuterons is usually described with the so-called coalescence model. This model is based on the assumption that nucleons with a momentum difference $\Delta p < p_0$ in the COM frame for some given p_0 will coalesce and form a nucleus. The momentum threshold p_0 has been found by comparing Monte Carlo generated events with antideuteron data from e^+e^--collisions at the ALEPH experiment [4] at LEP-I. This calibration yields best fit values of $p_0 \approx 110\,$MeV for HERWIG++ and $p_0 \approx 160\,$MeV for PYTHIA.

2. Production Spectra

We calculate the antideuteron spectra in the $XX \to W^+W^-$ and $XX \to b\bar{b}$ channels using HERWIG++ (v2.4.2) with $p_0 = 110\,$MeV, applying the coalescence criterion on a per-event basis. In our calculations, the DM particle X is the lightest MSSM neutralino, but the results are valid for any model of annihilating DM where there is no strong dependence on spin correlations. Our results were generated using 10^8 events for each annihilation channel and dark matter mass $M_{\rm DM}$, and are presented in terms of the scaled kinetic energy $x \equiv T/M_{\rm DM}$. We compare our results with the corresponding spectra calculated in PYTHIA (v8.135) with $p_0 = 160\,$MeV by Ref. [5], and use the difference as an estimate of uncertainty related to the hadronization procedure.

In the left plot of Fig. 1, we show the ratio $R \equiv \frac{dN/dx|_{\rm HERWIG++}}{dN/dx|_{\rm PYTHIA}}$ of the spectra from the two Monte Carlo generators. For the $b\bar{b}$ channel, we find that the spectra differ by a factor ~ 3 from $x \sim 10^{-1}$ down to $T \sim 10^{-2}\,$GeV. For the gauge bosons, the spectra differ by a factor ~ 2 for $10^{-3} \lesssim x \lesssim 0.5$. Outside these ranges the uncertainties increase dramatically.

While not obvious from this figure alone, we find that the point at low energies at which the ratio R crosses 1 appears at a constant value of x in the W^+W^- channel, while at a roughly constant value of T in the $b\bar{b}$ case. Since T, rather than x, is the relevant quantity for the observable intensity of antideuterons, this implies that for DM masses in the TeV range and above, observationally relevant energies could for W^+W^- lie in the high uncertainty region $x \lesssim 10^{-3}$.

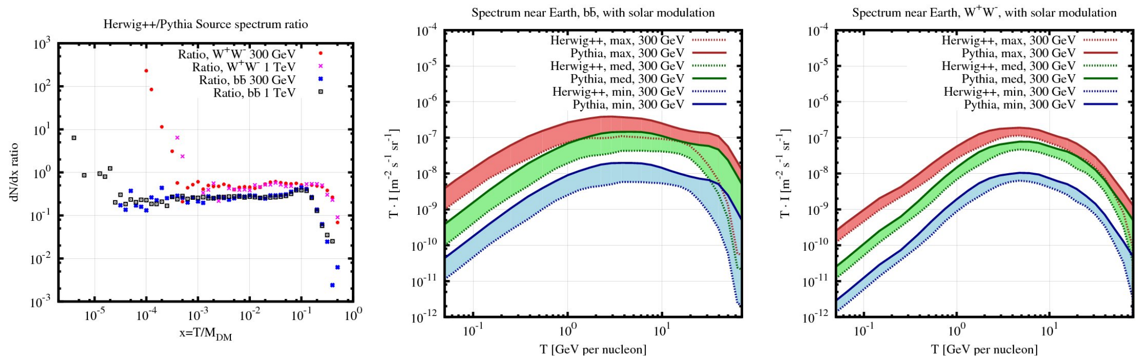

Figure 1: Left: Ratio of HERWIG++ to PYTHIA antideuteron spectra at production with DM masses of 300 GeV and 1 TeV. Middle and right: Antideuteron spectra from the $b\bar{b}$ and W^+W^- channels after propagation for $M_{\rm DM} = 300$ GeV.

3. Antideuteron spectrum near Earth

We calculate the antideuteron flux near Earth using a two-zone diffusion model for the Galaxy and the Navarro-Frenk-White (NFW) DM density profile, also taking solar modulation into account. The middle and right plots of Fig. 1 show the resulting antideuteron fluxes for 3 sets of propagation parameters, 'min', 'med' and 'max', presented in Ref. [6] to yield maximal, median and minimal antiproton fluxes from DM annihilations, while being compatible with the observed boron/carbon ratio.

The colored bands show estimated uncertainty from hadronization as the difference between the PYTHIA and HERWIG++ results. The high uncertainties previously seen at low energies do not appear at the this DM mass, but are expected in the W^+W^- case for higher masses.

4. Conclusions

We have calculated antideuteron yields in dark matter annihilation with quark and gauge boson final states, and investigated the contribution to the uncertainty from the hadronization procedure. In most of the observationally relevant energy range, we see an uncertainty in the predicted flux of a factor ~ 3 in the $b\bar{b}$ channel and a factor ~ 2 in the W^+W^- channel. At high energies, the uncertainties increase significantly in both channels, and for DM masses in the TeV range, we further expect high uncertainties at low energies in the W^+W^- channel.

References

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