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Proceeding Paper

Charged-Meson-Induced New Physics in Beam-Focused Neutrino Experiments †

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Abstract: We discuss the phenomenology of dark-sector signals coming not only from the conventionally-used neutral meson decays but also from recently-realized charged-meson decays. We argue that charged mesons can be overlooked even though there are efficient sources of dark-sector particles. Two applications are presented: a dark-sector interpretation of the MiniBooNE excess and an anomalous appearance of ν_τ in the near detector of beam-focused neutrino experiments.

Keywords: charged meson decays; MiniBooNE excess; anomalous ν_τ appearance

1. Introduction

The existence of dark matter in the universe is supported by many pieces of evidence in a wide range of scales, from galactic and inter-galactic scales to cosmological scales [1]. All these observations are rooted in its gravitational interaction, and its particle nature can be understood through its hypothetical non-gravitational interactions. Therefore, for the last few decades, a tremendous amount of theoretical/experimental effort has been made to detect dark matter signals through its non-gravitational interactions [2]. However, no conclusive observations have been made so far, excluding more parameter space in the relevant dark matter models, while most of these experiments are designed to be sensitive to one of the most popular dark matter candidates, the weakly interacting massive particles.

In light of this situation, alternative dark matter candidates are being investigated more carefully. Among them, light dark matter (MeV to sub-GeV mass) has been receiving particular attention as it can still be a thermal dark matter candidate and is less constrained by existing searches. To be consistent with the observed dark matter relic abundance, this dark matter should be feebly interacting with Standard Model (SM) particles, often involving similar mass range mediators. Thus, the dark matter search program has now been extended to a more generic dark-sector search program. Due to the expected mass scale, energy-frontier facilities are not essential. Instead, intensity-frontier experiments using relatively low-energy beams can play a crucial role.

In terms of mediators, there are various scenarios often quoted as Higgs portals, axion or axion-like particle portals, neutrino portals, and vector portals (see, e.g., ref. [3]). The idea is that dark-sector particles including dark matter can be connected to the SM sector particles via these portals. Therefore, light dark matter and light mediator searches are naturally interconnected, giving rise to richer phenomenological aspects. In addition to the portal scenarios, there are various phenomenological motivations of dark-sector physics. For example, models of light dark matter and light mediators have been proposed to explain various unresolved experimental anomalies (e.g., MiniBooNE excess [4–6]).

Considering all these aspects, neutrino experiments will be sitting among the theoretical and experimental issues mentioned above, and they have great potential to address those issues. In particular, near future beam-focused neutrino experiments, such as the

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Deep Underground Neutrino Experiment (DUNE) [7], feature a high intensity beam, high-precision near detectors, and good background rejection and, therefore, we expect that they provide unique opportunities, especially for dark-sector physics.

2. "Meson-Scopic" New Physics Probes

In many of the existing studies, neutral mesons have been routinely utilized as sources of dark-sector particles (see, e.g., refs. [3,8,9]). For example, in the vector-portal dark-matter scenario, a dark photon comes from the decay of π^0 or η through a kinetic mixing, and then the dark photon decays to a dark-matter pair. For the axion-like particle interacting with photons, an axion-like particle can be produced by the Primakoff process of photons, and the neutral mesons are major sources of photons. Basically, neutral mesons have played a crucial role in the production of new physics particles.

What about charged mesons? One can imagine the case in which a bosonic mediator comes from a three-body decay of charged mesons. In the beam-focused neutrino experiments, charged mesons are focused by the magnetic horn system. However, a naive consideration of phase-space suppression in the three-body decay process would result in a subdominant or negligible decay width as compared to the above-mentioned two-body decay process of neutral mesons.

Let us first consider the two-body decay of charged mesons, e.g., $\pi^+ \to \ell^+\nu_\ell$. As is well-known, its corresponding decay width is helicity-suppressed to satisfy the angular momentum conservation in the decay process. By contrast, once another particle, say mediator ϕ, is added in the final state, i.e., $\pi^+ \to \ell^+\nu_\ell\phi$, this helicity suppression can be evaded since the additional particle allows for kinematic configurations to satisfy the angular momentum conservation and the decay phase space can be fully exploited. As a consequence, a large enhancement in decay width is expected (see, e.g., refs. [10,11]). Moreover, in their decay to a massive vector mediator, it is even more enhanced due to the existence of the longitudinal polarization [10,11].

We can understand advantages of this three-body decay channel of charged mesons, especially in the beam-focused experiments. For an example of vector-portal dark matter, the number of meson-induced dark-sector signal events is given by the number of produced mesons times branching fraction times fractions of signal flux entering the detector. The charged pion production rate is comparable to the neutral pion production rate, as far as the beam energy is large enough. Secondly, as discussed above, the charged meson decays can provide large branching fraction enhancement. Now, neutral particles are obviously unfocused, while charged particles are focused in the horn system. As a result, the dark-matter flux from the neutral meson decays spread widely in an angle, whereas the dark-matter flux from the charged meson decays are more forward-directed. Therefore, much more dark-matter flux from the charged meson decays can reach the detector, often appearing as the dominant source of dark-sector particles [12].

3. Application to the MiniBooNE Excess

Needless to say, the MiniBooNE excess of electron-like events at 4.8σ from a data sample corresponding to 18.75×10^{20} protons-on-target in neutrino mode and 11.27×10^{20} protons-on-target in antineutrino mode [4–6] is one of the observational motivations for new physics. A lot of explanations have been suggested, all involving neutrino-sector physics. Very roughly, they can be divided into three categories. First, in the target-horn complex, mesons might decay to a heavier neutrino through non-standard neutrino mixing; second, produced neutrinos might go through non-standard oscillations while they propagate to the detector; or third, new particles might be produced in the neutrino scattering and decay to visible particles mimicking the electron-like signature. Of course, some of the proposals are now in tension with other experiments but, in general, neutrino-sector-involving solutions are popular over non-neutrino-sector solutions including dark-sector solutions.

Typical dark-sector explanations assume the production of signals from the neutral mesons. For example, in the vector-portal dark-matter scenario, dark photons come from the decay of neutral mesons and decay to dark matter particles. If that were the main source of the MiniBooNE excess, the MiniBooNE off-target measurement [13] would have observed events originating from the same source modulo of the beam intensity, because neutral mesons promptly decay in both target and off-target modes, irrespective of the existence of the horn system. However, the off-target mode measurements show a null signal and, thus, the dark-sector explanations are less favored. Despite this major challenge, we found that dark-sector scenarios can get around this tension and be good solutions to the excess, using the charged meson decay channel that we have discussed so far [12].

In the vector-portal dark-matter scenario, a charged pion or kaon decays to a dark photon, which decays to dark matter (say χ). Here, we assume that a dark photon decays to the dark matter pair by 50%, and the other 50% is for the decay into an electron-positron pair, which is used for the detection part. Once a dark-matter particle reaches the detector, it scatters off a nucleon or a nucleus inelastically into a heavier dark-sector state (say, χ'). The χ' promptly decays back to dark matter and a dark photon which subsequently decays by 50% to a collimated pair of electrons, which develop an overlaid Cherenkov ring. Depending on the underlying model details, the mediator in the scattering could be different from the mediator responsible for dark matter production. In this case, since the mediator in the scattering has nothing to do with production of dark matter in this double-mediator scenario, it could be massless; for example, the scattering could be governed by a dipole operator.

Figure 1 shows an example of a fit result; the four plots are for the double-mediator scenario and they are of the visible energy spectrum in neutrino mode, the visible energy spectrum in antineutrino mode, the angular spectrum in neutrino mode, and the angular spectrum in antineutrino mode, from left to right. The dark yellow histograms are the combination of all known backgrounds while the dark blue histograms show the signal events predicted by our vector portal model. The latest MiniBooNE data are shown by the black dots together with their associated statistical errors. We also considered systematics reported in [6] and performed the usual weighted χ^2 fit. The resulting best-fit values are summarized in Table I of ref. [12]. We have found equally reasonable fits in the single-mediator scenario [12]. We have also checked whether or not the best-fit parameters are okay with the existing limits.

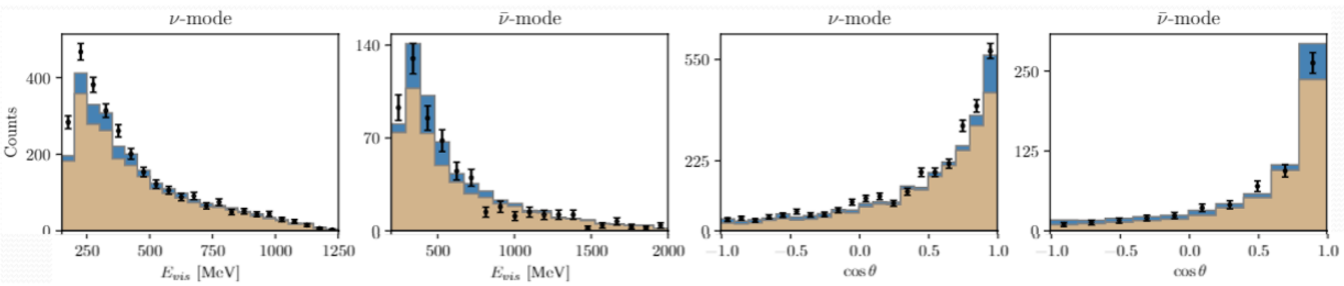

Figure 1. An example fit to the MiniBooNE excess. The dark yellow (dark blue) histograms describe the combination of all known backgrounds (the signal events from our vector-portal dark-matter scenario). The black dots are the latest MiniBooNE measurement data along with their statistical uncertainty. See the text for more details.

4. Anomalous ν_τ Appearance

Since the distance between the neutrino source and near detector is usually not large, it is very challenging for muon neutrinos to oscillate to tau neutrinos under the three-flavor framework. Of course, one could extend the neutrino sector and increase the chance of finding tau neutrinos, but we point out that light-mediator scenarios resulting in an anomalous appearance of ν_τ are actually available with charged meson decays, and there are many varieties. One simple scenario is that a charged meson decays to a neutrino-philic vector mediator, which exclusively decays to tau neutrinos. Surely, the appearance of ν_τ at a near detector can be a smoking-gun signal of new physics.

A practical challenge is how to detect ν_τ. We here briefly introduce an ongoing effort in the DUNE Collaboration. Basically, the τ from the ν_τ charged-current scattering does not travel long enough to identify its track separately, hence requiring a dedicated study. Three major channels are identified, the e-channel, μ-channel, and ρ-channel [14]. As τ's leave no identifiable tracks, some neutrino-induced processes are major backgrounds, e.g., ν_e/ν_μ charged-current events and ν_ℓ neutral-current events with false ρ identification. We here simply used the detection efficiency and background rejection efficiency reported by DUNE.

For an initial estimate, we performed some simulations in the following way. We basically began with the production of charged mesons, performed by GEANT4 [15]. Then, we checked whether their angular distance from the beam axis is below about 10 degrees. If so, we assumed that they were focused and their momentum was aligned with the beam axis. Otherwise, we discarded those charged mesons. We next checked whether they decayed before reaching the dump area according to the usual decay law. Once they decayed, we used a MadGraph simulation and sample events from the MadGraph output to describe their three-body decay process on an event-by-event basis. The produced vector mediator decayed to a tau neutrino pair, and we checked whether they entered the detector fiducial volume. Finally, we convolved the ν_τ charged-current scattering cross section [16] with an energy threshold. Our study shows that ν_τ events would, surprisingly, appear in the DUNE experiment [17].

5. Conclusions

We emphasized that neutrino facilities are new physics machines as well as neutrino factories. While neutral mesons have been conventionally used as sources of new physics particles, charged mesons are overlooked but efficient sources of new physics particles (e.g., mediators, dark matter) in the beam-focused neutrino experiments, as a focused flux of new particles and a large branching ratio enhancement of three-body charged meson decays is expected. Two example physics cases were discussed: an explanation for the MiniBooNE excess and the anomalous appearance of ν_τ in the near detector of beam-focused neutrino experiments. Finally, we emphasized that a number of applications of charged-meson three-body decays remain uninvestigated.

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Abbreviations

The following abbreviations are used in this manuscript:

SM	Standard Model
DUNE	Deep Underground Neutrino Experiment

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