Illuminating Excluded Dark Photon Parameter Space With SciBooNE

N. Everett[1,2,3,*] and P. Fox[1,†]

[1] *Theory Division, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[2] *Department of Physics, South Dakota Mines, Rapid City, SD 57701 USA*
[3] *Department of Mathematics, South Dakota Mines, Rapid City, SD 57701 USA*

(Dated: August 11, 2023)

Dark photons (A') are a theorized extension to the Standard Model (SM) which could help explain the mystery of dark matter. Dark photons acquire small couplings to SM fermions through kinetic mixing with the SM $U(1)$ hypercharge group. In this report, we investigate using the SciBooNE (Scintillator Booster Neutrino Experiment) experiment to search for dark photons. Due to the relatively low energy of the Booster Neutrino Beam, we limit our study to dark photons produced via $\pi^0 \to \gamma A'$ requiring $m_{A'} \le m_{\pi^0}/2$. This subsequently limits the dark photons decay modes to only $A' \to e^+e^-$. We present the expected sensitivity of SciBooNE to dark photons with these constraints and find that it does not probe any unexcluded parameter space. While SciBooNE may not be useful for probing this specific model for beyond the standard model (BSM) physics, we should strive to make full use of all experiments, both current and past, to further advance physics.

INTRODUCTION

One of the simplest extensions to the Standard Model (SM) is that of a new vector field with dark matter χ and a vector boson A' such that

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\varepsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu. \quad (1)$$

We will focus on the case where the dark photon A' with field strength $F'_{\mu\nu}$ is weekly coupled to the SM $U(1)$ hypercharge group with a field strength $F_{\mu\nu}$ and the strength of this kinetic mixing is characterized by ε. Additionally, we require $m_{A'} < 2m_\chi$ such that $A' \to \chi\bar{\chi}$ is energetically forbidden which ensures that A' must decay to SM particles.

This study focuses on searching for dark photons in the SciBooNE (Scintilator Booster Neutrino Experiment) detector on the Booster Neutrino Beam (BNB) at Fermi National Accelerator Laboratory (Fermilab). The SciBooNE experiment was of particular interest for a dark photon study because of its close proximity to the BNB target as seen in Table I. Close proximity to a beam target not only lessens the time of flight which is important for unstable particles, it also increase particle flux.

TABLE I: Table of neutrino experiments closest to beam targets with mean neutrino energy $\langle E_\nu \rangle$, and distance from target to detector $\overline{TD}$. [1–5]

Detector Name	Beam Name	$\langle E_\nu \rangle$ [GeV]	$\overline{TD}$ [m]
ANNIE	BNB	∼0.8	100
DUNE ND	LBNF	∼2.5	574
MiniBooNE	BNB	∼0.8	541
SBND	BNB	∼0.8	110
SciBooNE	BNB	∼0.8	100
T2K ND280	J-PARC	∼0.6	280

In our preliminary analysis, we only explored production from $\pi^0 \to \gamma A'$. A more detailed analysis could be conducted using additional modes of production such as $\eta \to \gamma A'$ or $pp \to ppA'$; however, due to the lower energies of the BNB's protons, we find these additional modes of production to be negligible when predicting SciBooNE's sensitivity.

DARK PHOTON PRODUCTION IN THE BOOSTER NEUTRINO BEAM

The BNB at Fermilab uses 8.89 GeV protons incident with a Beryllium target to produced both neutrinos and antineutrinos. The BNB has a pulse rate of 5 Hz which each pulse having $5E12$ protons on target (POT). Fixed target experiments, like experiments on the BNB, generally have a distinct statistics advantage over collider experiments. The BNB has $2E20$ POT/year (accounting for downtime) and primary produces ν_μ or $\bar{\nu}_\mu$ (depending on the configuration of the horn) producing only a tiny fraction of $\nu_e/\bar{\nu}_e$ as seen in Figure 1.

Dark photons are produced in the BNB primary through $\pi^0 \to \gamma A'$, though they can also be produced through $\eta \to \gamma A'$ or the bremsstrahlung process $pp \to ppA'$. The branching ration for a meson $\mathfrak{m} \in \{\pi^0, \eta\}$ with mass $m_\mathfrak{m}$ is given by

$$\text{Br}(\mathfrak{m} \to \gamma A') = \text{Br}(\mathfrak{m} \to \gamma\gamma) \times 2\varepsilon \left(1 - \frac{m_{A'}^2}{m_\mathfrak{m}^2}\right)^3 \quad (2)$$

as seen in Figure 2. A more complete description of modes of A' production is given in Ref. [6].

DETECTING DARK PHOTONS IN SCIBOONE

SciBooNE was formally a neutrino experiment in the BNB. It collected science data from June 2007 until Au-

* Noah.Everett@mines.sdsmt.edu
† PJFox@fnal.gov

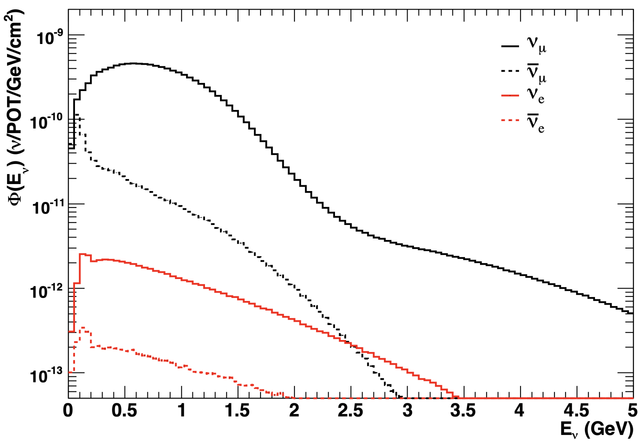

FIG. 1: Total neutrino flux predicted at the MiniBooNE detector which is situated ~ 540 m down stream of the BNB target. Figure taken from Ref. [3].

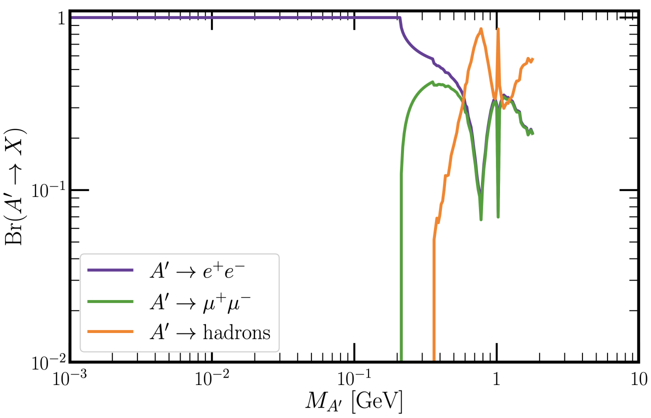

FIG. 2: Branching ratio of A' into likely (compared to other final states) and observable final states. Taken from [7] which was adapted from [6].

gust 2008 amassing $2.52E20$ POT $= (1.53\bar{\nu} + 0.99\nu)E20$ POT. The SciBooNE detector is made of three primary components each of which is comprised of segmented scintillators: SciBar [8], Electron Calorimeter (EC) [9], and the Muon Range Detector (MRD) [10]. For this analysis, we will focus on the SciBar as it is the only necessary part of the experiment needed to tag final state e^+e^-.

The SciBar is a $3 \times 3 \times 1.7$ m^3 segmented detector comprised of comprised of 14,336 plastic scintillator bars which are $1.3 \times 2.5 \times 300$ cm^3. The scintillator bars are read out by 224 multi-anode photo-multiplier tubes (MAPMTs), each of which has 64 channels. The scintillator bars are setup in alternating layers of vertical and horizontal bars giving SciBar excellent precision for a number of observables.

For a more complete analysis, both the EC and MRD would also be included. While the EC and MRD do not provide additional topological information, they provide the majority of information associated with the energy of the parent A'.

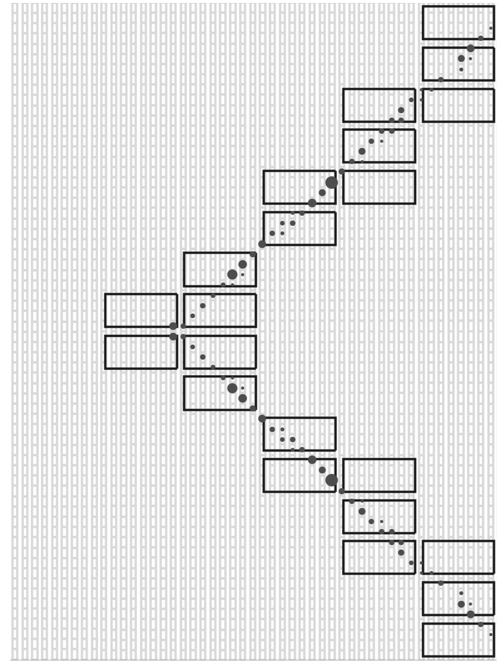

FIG. 3: Manufactured SciBooNE event display for $A' \to e^+e^-$ in the SciBar. The invisible A' enters from the left traveling with ~ 0 vertical momentum. It then decays into an electron-positron pair which are symmetric about the momentum of the A'.

BEAM SIMULATION

In this section, we detail the simulation process used to determine the expected sensitivity of SciBooNE. To constrain uncertainties associated with production of final state particles in the BNB, we employ existing beam simulations. These simulations exclusively contain final state particles which decay into neutrinos. Specifically, they contain $\pi^{\pm}$, $K^{\pm}$, and $\mu^{\pm}$. For this analysis we consider dark photons produced from $\pi^0 \to \gamma A'$. Using the assumption that $E_{\pi^\pm} \approx E_{\pi^0}$ and $N_{\pi^\pm} \approx N_{\pi^0}$ such that, for a final state $\pi^{\pm}$ in the beam simulation, a π^0 has the four-momentum

$$p_{\pi^0} = \left(E_{\pi^\pm}, \frac{|\vec{p}_{\pi^0}|}{|\vec{p}_{\pi^\pm}|} \vec{p}_{\pi^\pm} \right).$$

Then, a representative sample of dark photons is produced from $\pi^0 \to \gamma A'$. We assign the A', and subsequently γ, with a random direction in the π^0 rest frame, boost the A' into the laboratory frame, and check if its trajectory is incident with the SciBar. We notate the number of A' that are incident with the SciBar as $N_{\rm sci}$ as seen in Figure 4.

To calculate the total number of A' which would decay in the SciBar, we need to include lifetime, production rate, and decay branching ratio. Thus, the total amount of observable dark photons produced by $\pi^0 \to \gamma A'$ and

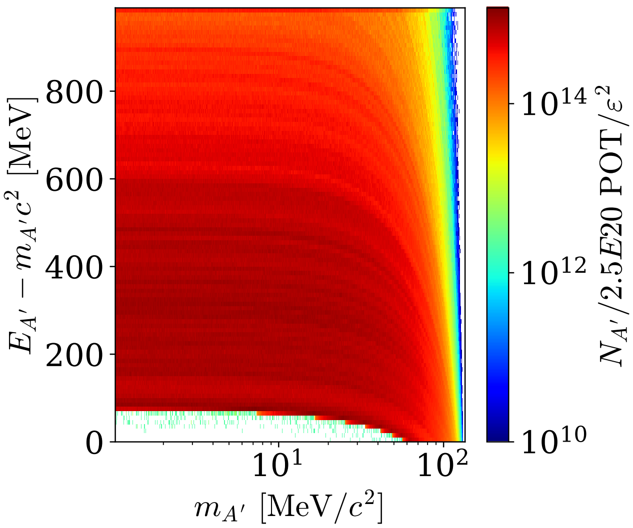

FIG. 4: Number of A' ($N_{A'}$) produced durring SciBooNE's entire $2.52E20$ POT exposure plotted against A' mass $m_{A'}$ and energy above rest mass $\Delta E \equiv E_{A'} - m_{A'}c^2$.

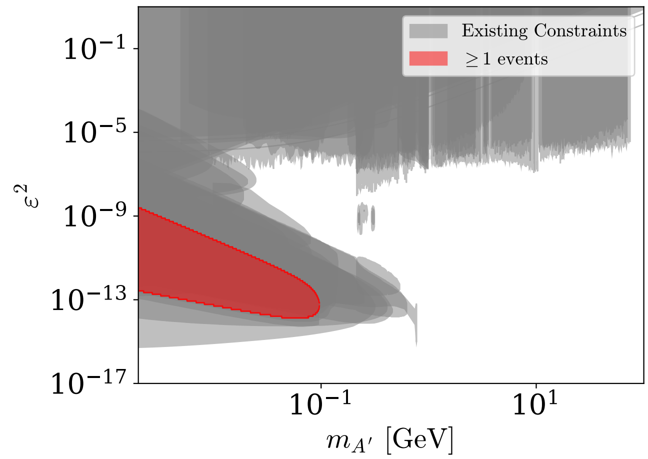

FIG. 5: Regions of parameter space of A' mass $m_{A'}$ vs. the kinetic mixing parameter squared ε^2 for which we expect ≥ 1 $A' \to \ell^+\ell^-$ events in SciBooNE's SciBar detector using its entire $2.52E20$ POT exposure. Currently excluded regions are in grey.

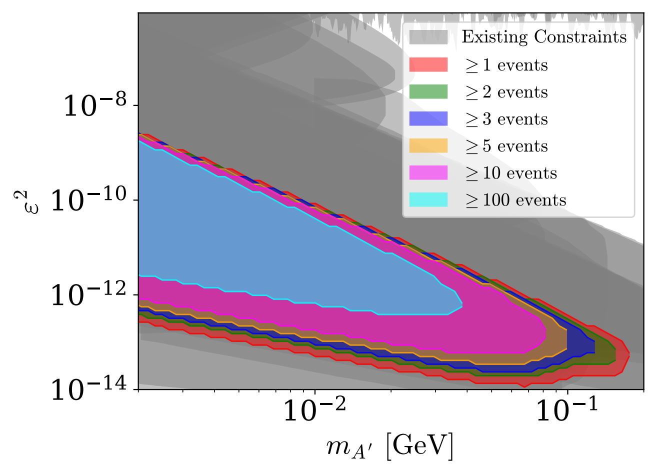

FIG. 6: Regions of parameter space of A' mass $m_{A'}$ vs. the kinetic mixing parameter squared ε^2 for which we expect a certain number of $A' \to \ell^+\ell^-$ events (as shown in the legend) in SciBooNE's SciBar detector using its entire $2.52E20$ POT exposure. Currently excluded regions are in grey.

which decay into e^+e^- is

$$N_{A'} = N_{\rm sci}\frac{2.52E20}{2.4E6} \times {\rm Br}(\pi^0 \to \gamma A') \times \left[\exp\left(\frac{-\Gamma d_f}{c\hbar\sqrt{\gamma^2-1}}\right) - \exp\left(\frac{-\Gamma d_i}{c\hbar\sqrt{\gamma^2-1}}\right)\right]. \quad (3)$$

The last term in (3) is the fraction of A' which decay inside the SciBar where γ is the Lorentz factor, Γ is the decay width

$$\Gamma(A' \to e^+e^-) = \frac{1}{3}\alpha\varepsilon^2\sqrt{1-\frac{3m_e^2}{m_{A'}^2}}\left(1+\frac{2m_e^2}{m_{A'}^2}\right), \quad (4)$$

and d_f and d_i are the final and initial distance of the SciBar which we take to be $d_f = 103$ m and $d_i = 100$ m.

RESULTS

In this section, we present and discuss the expected sensitivity of an A' search with SciBooNE. Figures 5 and 6 show the expected number of $A' \to e^+e^-$ decays expected within the SciBar detector over SciBooNE's entire $2.52E20$ POT. The color regions of these plots indicates the areas which SciBooNE is sensitive while grey indicates regions of parameter space already excluded by other experiments.

As we see in Figures 5 and 6, the region of parameter space SciBooNE is sensitive to is heavily excluded by multiple existing results. This is mostly due to the BNB's lower energies which do not allow for highly energetic process to produce A'. If an experiment like SciBooNE were situated on a higher energy beamline, it would be able to probe larger A' masses, thus expanding its parameter space sensitivity.

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