

Long-lived particle production through the DUNE-PRISM concept

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Accelerator-based neutrino experiments offer a competitive environment to search for long-lived particles with sub-GeV masses. Yet, many theoretical models involving such particles predict very similar phenomenology and nearly identical final-state signatures. In view of this, we study the capabilities of upcoming experiments—specifically the DUNE near detectors—to distinguish between different classes of long-lived particles and the mechanisms by which they are produced. We expound how the experiment’s excellent energy resolution, combined with the possibility to move the detector off-axis (the DUNE-PRISM concept), work in tandem to improve the discrimination power.

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I. INTRODUCTION

The search for phenomena beyond the Standard Model (SM) of particle physics is wide-ranging, comprising searches for the mechanism behind neutrino masses, considerations of interactions between dark matter and the SM, and endeavors for precision understanding of the Higgs mechanism, among others. Increasing the likelihood of such beyond-SM (BSM) discoveries requires casting a wide net, and fully leveraging existing and future experimental facilities to carry out as many distinct searches as possible. Terrestrial neutrino facilities—many sourced by high-intensity, high-energy proton beams—offer a plethora of possible new-physics searches. This is especially true of neutrino near-detector facilities, awash in a large flux of neutrinos and, potentially, BSM particles that can leave novel signatures in detectors.

Following the discussion of many recent studies (see, e.g., Refs. [1,2] for in-depth discussion), we are interested in the prospects of discovering one or more new-physics particles in neutrino facilities in the coming decade(s). Some of the most exciting prospects for discovery come from long-lived particles (LLPs), motivated in many specific BSM contexts, where such a particle is produced

associated with the high-intensity proton-target collisions¹ and travels to the neutrino detector, decaying inside. The advantage here is that the decay signatures of such long-lived particles are typically distinct enough from the expected neutrino-scattering type of backgrounds, allowing for low-background searches to be performed simultaneously with the neutrino-beam operation of these facilities.

Many scenarios predict such LLP production in these contexts, arising from a number of distinct production mechanisms. These include (but are not limited to)

- (i) Neutral/charged meson decays,
- (ii) Proton bremsstrahlung,
- (iii) Electromagnetic interactions (e.g., $e^\pm$ bremsstrahlung, e^+e^- annihilation...).

If working in a specific new-physics model, then some linear combination of these production mechanisms is predicted, typically as a function of the LLP mass. For instance, if working with a “secluded dark photon,”² the relative importance of these production mechanisms will depend on detector considerations as well as the dark photon’s mass. Typically at low masses, the decay $\pi^0 \rightarrow \gamma A'$ dominates, where other mechanisms become more relevant as the mass increases.

One way of detecting the existence of these LLPs is through their decays to SM particles in the neutrino detector(s) of interest. Neutrino detectors that are situated in proton-driven neutrino beams tend to be designed to

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¹Many specific production modes exist, and we will discuss several concrete ones in this work. Other, more exotic scenarios (e.g., production of a new, long-lived state due to neutrino upscattering in the nearby matter), may be applicable as well.

²Here we imagine a particle with a mass $m_{A'}$ that interacts with the SM purely through kinetic mixing with the SM $U(1)$ gauge group.

detect outgoing charged particles as well as photons. With particle identification (separation of muons and pions, or electrons and photons, for instance) as a benefit, searches for LLP decays allow for a rich set of signal topologies. As with the production mechanisms depending on the LLPs' mass(es), so do the potential decay channels. Especially when restricting to “viable” decay channels (i.e., ones that a modern neutrino detector can identify and meaningfully separate from background events), this becomes more evident. For instance, considering only states detectable in a neutrino detector, a LLP with a mass below ~ 100 MeV can only decay into photons and/or electrons. This mass range is of particular importance for the upcoming neutrino-facility dark sectors program, which has relative strength against other LLP searches in the sub-GeV regime due to the beam energies and detector designs present.

Often, the specific models of interest will yield common signatures, e.g., the LLP decaying into an electron/positron pair in the detector—such phenomenology is present when considering dark photons, Higgs-portal scalars, leptophilic gauge bosons, and more. If allowing for additional invisible particles (i.e., neutrinos) in the final state, then heavy neutral lepton models will also predict the same phenomena. With that in mind, and with hopeful discoveries of these anomalous signals on the horizon, it is wise to consider our capabilities for distinguishing between different models which predict the same experimental signatures.

A plethora of neutrino facilities are currently operating or soon will be; many of which are suitable for carrying out these searches. For specificity, we will focus our study on the upcoming Deep Underground Neutrino Experiment (DUNE) and its near detectors. This is because the DUNE program naturally aligns with many of the hallmarks of these searches—a relatively high-energy proton beam (120 GeV), detector distances on the order of several hundred meters, and relatively large detectors with highly capable particle identification and energy/momentum reconstruction. These traits will be further bolstered if the DUNE multipurpose detector is constructed as part of the experiment's phase II, where a magnetized gaseous-argon time-projection chamber will allow for many world-leading BSM searches. Lastly, we will also demonstrate how the planned DUNE-PRISM strategy (where the near detector moves to sample the transverse direction of the beam) will prove useful in our endeavor of distinguishing new-physics scenarios.

The remainder of this work is organized as follows. We begin with some discussion of the experimental setup and context of these searches in Sec. II, and then in Sec. III we discuss the models (both in terms of UV-complete theories and in terms of phenomenologically minded simplified frameworks) that we will consider in this work. We also present the details of the Monte Carlo simulation underpinning this study. Section IV presents our analysis and

potential for distinguishing among these scenarios, and Sec. V offers some concluding remarks.

II. EXPERIMENTAL SETUP AND OVERALL MOTIVATION

We will explore models leading to decay signatures from LLP at the DUNE near detector (ND). In addition to analyzing the signatures at the detector placed along the beam, we will also utilize the DUNE-PRISM design, which allows some of the near detectors to be moved away from the beam axis. In the past, these signatures have been well studied in the context of specific model building, where one starts from the Lagrangian and works out the signal events and backgrounds. Instead of this standard approach, we intend to instead highlight common signal aspects that cut across various models. This can be useful in identifying the particular production mechanism(s) giving rise to the LLP signature in the detector.

In order to remain concrete, we will restrict ourselves to considering renormalizable dark-sector models—dark scalars, dark photons, etc.—and assume that any other LLP model will be subdominant in the mass range of interest. Since we will be analyzing DUNE sensitivity, we will consider LLPs lighter than $m_X \lesssim 1$ GeV, and heavier than the MeV scale (so that visible decays can produce particles that the DUNE ND can detect).

DUNE, primarily designed for producing an intense, collimated neutrino beam, operates in a similar fashion to many proton fixed-target experiments. Its near-detector complex consists of a 120 GeV proton beam striking a graphite target; proton-proton collisions then lead to production of SM mesons. If LLPs exist, they may be produced in rare meson decays or directly from the proton beam (e.g., from proton bremsstrahlung). The resulting LLPs, depending on their trajectory and lifetime, may reach the DUNE ND and decay inside. We are interested in distinct signatures which are challenging for neutrino-scattering backgrounds to mimic. In this work, we are focused on distinguishing between different classes of new-physics production in such a facility—we refer the interested reader to Refs. [3–5] for more thorough analysis of separating signal from background in this context.

The DUNE ND also benefits from the DUNE-PRISM technique, where two primary detector components can move up to 30 m in the direction transverse of the beam. This is very useful in dark-sector identification (see, e.g., Ref. [6]), as different production mechanisms will lead to more-or-less geometrically focused LLP fluxes. This comes somewhat from model specifics (e.g., the collinear enhancements present in proton-proton bremsstrahlung), and somewhat from the parent SM particle leading to the LLP production—some SM particles, such as charged kaons, are focused in the neutrino beam whereas others are not. Even taking data purely on-axis, the $\mathcal{O}(\text{few})$ meters

radial span of the ND will allow for some differentiation due to this feature.

III. THEORETICAL FRAMEWORK

In this section, we detail the theoretical framework and background information regarding DUNE’s long-lived particle sensitivity. We first provide a brief summary of specific benchmark models, which we will use as inspiration for the remainder of the work. In doing so, we will explore the parameter space in which DUNE offers novel sensitivity, motivating the mass range and lifetimes of interest for such analyses. After doing so, we provide details of the more model-independent analysis framework that we will utilize for the remainder of this work.

A. Benchmark models

We focus on three benchmark models with qualitatively distinct LLP production mechanisms, but leading to very similar signatures in the detector.

Dark Higgs. This model introduces a light scalar field ϕ (the “dark scalar”) that mixes with the SM Higgs boson through a small mixing angle θ [7–12]. The phenomenology of the model is mostly characterized by a two-dimensional parameter space spanned by the scalar mass m_ϕ and the mixing angle θ . Due to its mixing with the Higgs boson, the dark scalar acquires couplings to SM fermions that are proportional to the corresponding SM Yukawa couplings, scaled by the mixing angle. If θ is sufficiently small, ϕ decays may be suppressed to extent that the scalar becomes long-lived.

The dominant production mechanisms of ϕ in a proton fixed-target setup such as a neutrino beam’s target station depend sensitively on the ϕ mass. For m_ϕ below the kaon-pion mass difference, $m_K - m_\pi \simeq 354$ MeV, production is primarily driven by two-body decays of charged mesons, in particular $K^\pm \rightarrow \pi^\pm \phi$. If $m_\phi > m_K - m_\pi$, production in meson decays becomes kinematically forbidden, and proton bremsstrahlung processes such as $pp \rightarrow pp\phi$ become the dominant production mode. References [13,14] provide further detail regarding the production rates of dark Higgs bosons from kaon decay and from proton bremsstrahlung, respectively.

In the dark Higgs model, the mixing angle θ and the dark Higgs mass govern its proper lifetime. Dark Higgs bosons can decay into SM particles— e^+e^- , $\mu^+\mu^-$, $\pi^+\pi^-$, depending on the mass. Isocontours of various rest frame lifetimes $c\tau$ are shown as dashed gray lines ranging from 1 cm to 10^4 m in the left panel of Fig. 1. We simulate the dark Higgs production assuming ten years of data collection at the DUNE near detector (1.47×10^{22} protons on target, in total). Accounting for the dark Higgs lifetime and the production kinematics, we determine the parameter space for which we expect to observe ten or more signal events

given this exposure.³ The resulting parameter space is shown in the left panel of Fig. 1 for production from kaon decay (blue) and from proton bremsstrahlung (red) to indicate the expected sensitivity of DUNE to this model. In this model, all decays of the dark Higgs are “fully visible,” and in principle the DUNE near detector can identify the final states. Previous studies have explored the possibility of signal-to-background separation of such final states, e.g., Refs. [3–5]—the true experimental sensitivity will necessarily be shaped by such considerations, but we choose to present iso-contours of expected signal rates for simplicity.

We see that, for dark Higgs masses between 10 MeV and 10 GeV, the particle is long-lived by neutrino-experiment standards and has sizeable decay branching ratios into final states of interest, most notably e^+e^- and $\mu^+\mu^-$ for the mass range of interest. The existing constraints shown (gray shaded regions) arise from previous experimental results, Refs. [14–18].

Dark photon. As a second benchmark scenario, we consider the dark photon model which introduces a new $U(1)_D$ gauge symmetry and associated gauge boson A' that kinetically mixes with the SM photon, thereby acquiring couplings to charged SM particles [19–22]. The couplings strength is ϵq , where ϵ is the kinetic mixing parameter and q is the electric charge of the SM particle. If $\epsilon \ll 1$, as required by experimental constraints, these interactions are feeble, and in the absence of any other interactions A' tends to be long-lived. Its lifetime depends on both its mass and the kinetic mixing parameter, similar to the dark-Higgs scenario.

In a proton beam-dump environment, a number of production mechanisms are possible; which one dominates depends on the dark photon mass, $m_{A'}$. For $m_{A'}$ below a few-hundred MeV, production predominantly occurs via two-body neutral meson decays, e.g., $\pi^0 \rightarrow \gamma A'$. In contrast, above the η meson mass, production via proton-proton bremsstrahlung, $pp \rightarrow ppA'$, typically dominates. We direct the interested reader to Ref. [13] for thorough discussion of these production modes in the context of the DUNE near detector complex.

Dark photon decay channels (see, e.g., Ref. [23]) for the mass range of interest are into similar final states as the dark Higgs model and are generally of interest for the DUNE detectors; e^+e^- , $\mu^+\mu^-$, and so on. This leads to comparable, large lab-frame lifetimes for the dark photon model as the dark Higgs model for the region of parameter space which we target. Such lifetime isocontours are shown in the right panel of Fig. 1 as a function of the dark photon mass and the kinetic mixing with the SM.

We simulate dark photon production and decay, again for 1.47×10^{22} protons on target (ten years of data collection),

³Simulation code to reproduce this result, as well as the corresponding dark photon projections, is available upon request.

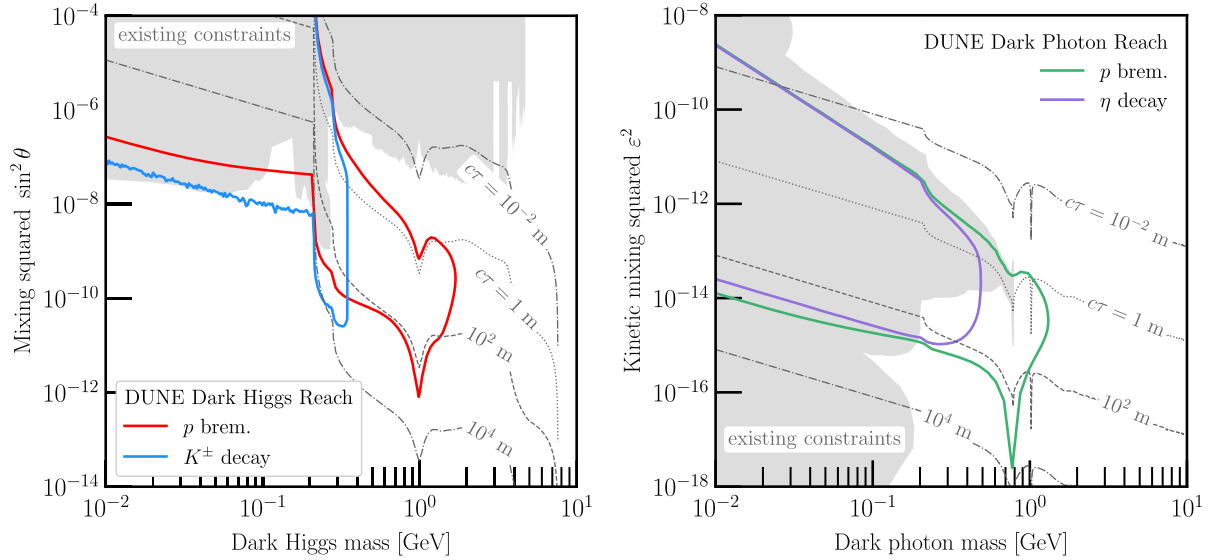


FIG. 1. Approximate reach of DUNE to discover model-specific long-lived particles for 10 signal events, dark Higgs (left) and dark photons (right), assuming ten years of data collection (1.47×10^{22} protons on target). Sensitivity from different production mechanisms corresponds to different color contours—the left panel shows charged kaon decay (blue) and proton bremsstrahlung of a scalar boson (red), where the right panel shows neutral η meson decay (purple) and proton bremsstrahlung of a vector boson (green). The colored contours are projections computed in this work and denote the region of parameter space where the expected number of reconstructed LLP decays in the DUNE ND fiducial volume satisfies $N_{\text{sig}} \geq 10$ (assuming negligible backgrounds). The LLP proper lifetime and branching ratios entering N_{sig} follow the standard benchmark prescriptions used in Refs. [1,2] (and references therein). We define “visible” LLP decays as fully reconstructible final states containing charged tracks in the near detector. Contours of lifetimes of the particles are shown by various gray lines, and gray shaded regions indicate parameter space excluded by existing searches [1,2].

calculating regions of parameter space for which ten or more signal events are expected. These are shown as purple and green regions for dark photons produced via η meson decay and proton bremsstrahlung, respectively.

We see that DUNE sensitivity will extend beyond the reach of existing searches, including those of Refs. [24–30], largely due to the intensity of the proton beam and the relative detector position. Even in the mass range where η decays dominate, proton bremsstrahlung provides a comparable sensitivity, since the difference in production rates between the two mechanisms is less than an order of magnitude, and the more forward-boosted dark photons from bremsstrahlung experience reduced geometric suppression in the detector [13]. Again, we find that for the range of masses between approximately 10 MeV and 1 GeV, these production mechanisms are relevant, and that a wide range of proper lifetimes of the long-lived particle can be tested in the DUNE facility.

In comparing the two panels of Fig. 1, we see that considerable parameter space exists in the $200 \text{ MeV} \lesssim m \lesssim 1 \text{ GeV}$ range for which DUNE can make a discovery in either of these models. If such a new-physics signal is detected, a natural question will be whether the new events arise from a dark Higgs (where $K^\pm \rightarrow \pi^\pm \phi$ production is expected to dominate) or from a dark photon (where $\eta \rightarrow \gamma A'$ dominates). Further explorations of where bremsstrahlung can dominate

for the production of a scalar or vector, at masses closer to a GeV, will warrant its own investigation as well.

Leptophilic gauge boson. Similar to the dark photon scenario, we will also consider models with gauge symmetries of the form $U(1)_{L_\alpha - L_\beta}$, where $\alpha, \beta \in \{e, \mu, \tau\}$ are lepton flavor indices [31–33]. Models of this type are anomaly-free SM extensions whose phenomenology in beam-dump environments and elsewhere is qualitatively different from the dark Higgs and dark photon models [29]. One phenomenological feature of gauged $L_\alpha - L_\beta$ models is the possibility of producing the new gauge boson, V , in three-body charged-meson decays such as $K^+ \rightarrow \mu^+ \nu_\mu V$, where V is radiated off the charged-muon or muon-neutrino line in the final state.⁴ We do not display leptophilic gauge boson sensitivity for simplicity; we refer the interested reader to, for example, Refs. [13,34] for further discussion of this model in the context of DUNE.

In all three models (as well as others not considered here), a number of common features are present. First, given the

⁴Such three-body decays are possible in dark photon models but very often lead to smaller LLP yields than neutral-meson (π^0 and η) decays. In leptophilic gauge boson models, those neutral-meson decays depend on loop-induced kinetic mixing, where direct couplings to charged leptons/neutrinos can allow for relatively larger production rates.

high energy of the protons striking the target, the $\sim \text{MeV}$ – GeV LLPs produced will be highly boosted, focusing the LLPs in the forward direction. This focusing is largely independent of the details of the production mechanism. Moreover, in all three models the LLPs can decay into pairs of charged leptons, $\ell^+\ell^-$, where $\ell = e, \mu$. A neutrino detector such as the DUNE ND is well suited for studying such final states; calorimetric energy measurements along with shower/track reconstruction allow for the determination of the decaying particle’s invariant mass. But discriminating between $\ell^+\ell^-$ from ϕ , A' , and V decay is disproportionately more difficult.

Note that other LLP scenarios are easier to tell apart. An example is a heavy neutral lepton (HNL) mixing with the SM neutrinos. HNLs cannot decay into just an electron/positron or muon/antimuon pairs; only decays involving an extra final-state neutrino, such as $(e^+e^-\nu$ and $\mu^+\mu^-\nu)$ are possible. The lack of an peak in the $\ell^+\ell^-$ invariant-mass distribution distinguishes HNL models from the scenarios considered here, as has been explored [35].

The absolute signal rates expected in our three benchmark models depend strongly on the underlying parameters, in particular the LLP mass and mixing parameter. However, given the unknown value of the mixing parameter, the total signal rate does not offer any model discrimination power, therefore we will focus mostly on the shape of kinematic distributions. We will moreover use the number of signal events and the LLP lifetime as phenomenological variables. In principle, using these two as well as the LLP mass introduces an extra degree of freedom relative to concrete models, where the only degrees of freedom are a mass and a coupling to the SM. In these concrete scenarios, for a given mass, the coupling simultaneously determines the LLP lifetime and the expected event rate. Allowing these two quantities to be separate allows for a more holistic, model-generic comparison (see, e.g., Refs. [35,36] for motivation of this approach).

B. Simulation details

We now describe how we simulate LLP production, propagation, and decay. In DUNE, mesons are produced in collisions of 120 GeV protons with a fixed target. Our starting point are Monte Carlo event samples produced by the full DUNE beamline simulation [37,38], which contain in particular detailed kinematic information about charged mesons produced in the target. The simulation accounts for the effect of the magnetic focusing horns, the production of secondary particles, and the propagation of mesons prior to their decay. The DUNE simulation does not include neutral mesons (as they do not contribute to the neutrino flux); to understand LLP production from neutral-meson decay, we simulate their production using Pythia-8. Specifically, we generate sample meson fluxes by colliding 120 GeV protons on at-rest target protons (using the flag `SoftQCD:all`),

collecting the outgoing neutral mesons. In doing so, we do not account for secondary processes, as this would require a more sophisticated simulation using (for instance) Geant-4 [39–41]. Including secondary production would lead to a slight increase in meson and LLP fluxes, so our approach is conservative. We simulate the two- and three-body decays of mesons into LLPs directly⁵; proton-proton bremsstrahlung production of the scalar and vector LLPs is simulated using the formalism presented in Refs. [14,42,43]. Once the LLP is produced, we track its propagation in the laboratory frame.

Given that the main goal of this paper is to explore differences between LLP models, we begin in Fig. 2 by showing the distribution of LLP energies, E_X , and production angles, p_T/p_z . Here, X stands for ϕ , A' , or V ; p_T and p_z are the transverse and longitudinal components of the LLP momentum, respectively. In all cases, we have assumed an LLP mass of $m_X = 200 \text{ MeV}$. The DUNE ND covers approximately the range $p_T/p_z \lesssim 4 \times 10^{-3}$ when positioned on-axis. The different panels in Fig. 2 correspond to different production mechanisms; the top panel shows two-body decays of kaons (left) and η mesons (right), whereas the bottom panels show production via proton-proton bremsstrahlung of a scalar (left) or vector (right) LLP.

After accepting only those LLPs with small enough p_T/p_z to intersect the DUNE ND in the on-axis position, we may inspect the LLP energy distribution. This is presented in Fig. 3(top), again for four production mechanisms all with $m_X = 200 \text{ MeV}$. We note here that the fluxes shown in Fig. 3 are all area-normalized. We see that proton-proton bremsstrahlung yields higher-energy LLPs than meson decay due to the collinear divergence of bremsstrahlung production. Comparing different meson decays, we note that LLPs from η decay are higher in energy than those from kaon decay. This is because electrically neutral η s are not focused, so only LLPs from the decays of the highest-energy η s are sufficiently boosted in the forward direction to intersect the detector. LLPs from $K^\pm$, on the other hand, are forward-focused also at lower energies thanks to the magnetic horns.

While the fluxes shown in Figs. 2 and 3 are instructive, they cannot be directly translated into event rates in the detector. This is because the probability of the LLP decaying inside the detector is a nontrivial function of the LLP energy. In the limit that the LLP lifetime is much longer than the distance to the detector, this probability becomes proportional to m_X/E_X , favoring decays of less boosted particles. For shorter rest-frame lifetimes, more

⁵Two-body decays are simulated trivially in the meson’s rest frame (isotropically) then boosted back to the laboratory frame. For three-body decays, we calculate the allowed Dalitz phase space for the decay and sample it uniformly, effectively ignoring the matrix element of these decays. Because the mesons are highly boosted, the impact of the matrix element should be negligible on observables related to the LLP flux downstream.

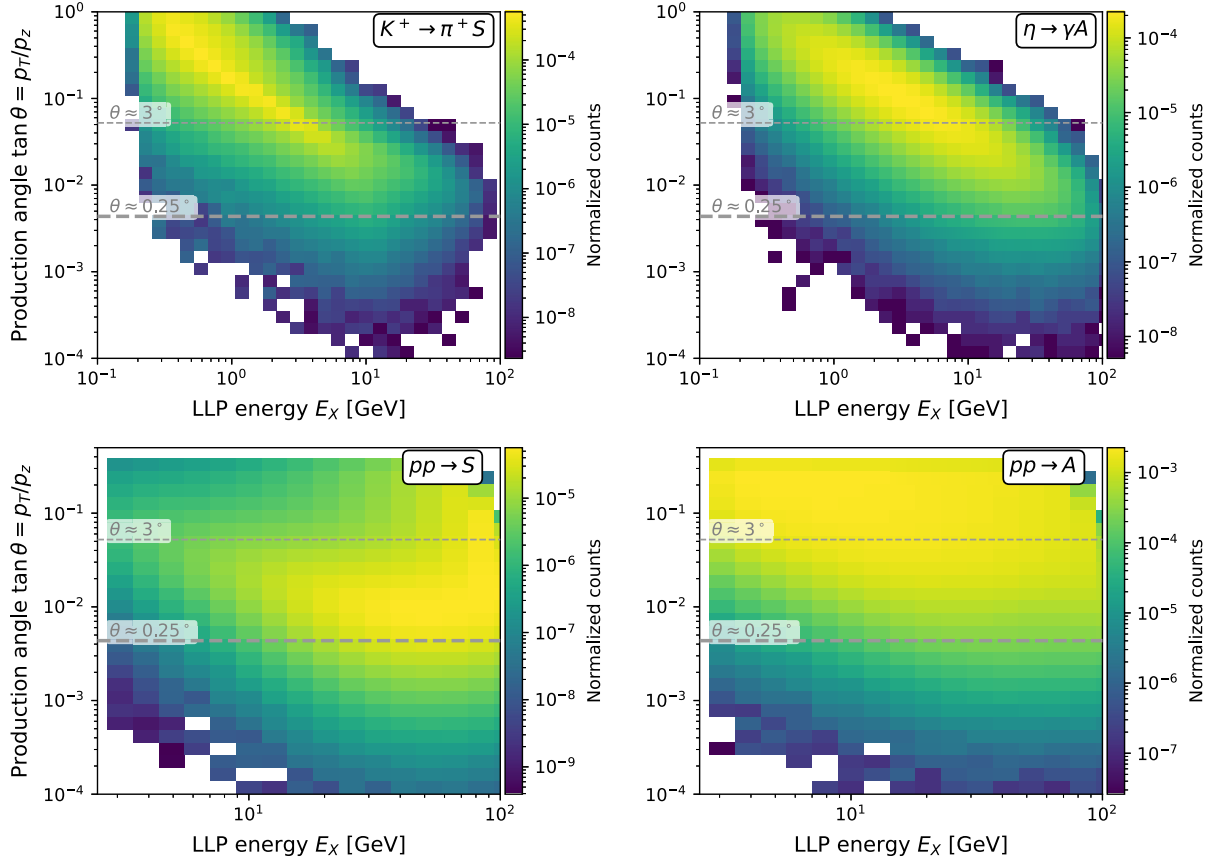


FIG. 2. Kinematics of LLPs produced in the DUNE/LBNF beamline in the energy-vs-transverse momentum fraction plane.

boosted particles will instead have a higher likelihood of decaying inside the instrumented detector volume. In Fig. 4, we depict how this effect is incorporated for the fluxes shown in Fig. 3, now including the probability of the decay happening in the detector when the LLP lifetime is $c\tau = 10^5$ m. An alternative, shorter-lifetime (10 m) event-rate distribution is presented in the appendix in Fig. 12.

We are interested in going beyond purely energy-based observables to motivate better discrimination between these different LLP production modes. To that end, we also incorporate spatial information, specifically the (transverse) distance between the beam axis and the decay vertex inside the detector— $r_T = \sqrt{x^2 + y^2}$ (assuming the beam axis is in the $+z$ -direction). Considering this radial information, we allow our analysis to extend to a larger radial geometry, allowing for a combined analysis of event distributions with respect to *simultaneously* the deposited energy and the vertex of the event. This approach allows us to emulate the scenario where the detector is positioned off-axis, akin to the proposed DUNE-PRISM setup. We see the radial distribution of events (in a hypothetically large detector volume) up to tens-of-meters of transverse radius in Fig. 3 (bottom)—many of the qualitative takeaways we understood from flux distributions are present here for the different production modes. We will demonstrate how this

additional information adds to our statistical separation between production mechanisms in the following—the differentiation arises strongly from the differences between the parent production distributions, e.g., the difference in focusing between charged kaons and neutral etas.

Statistical approach. Thus far, we have relied on visual inspection of one-dimensional histograms to distinguish among production modes. To provide a more statistically rigorous comparison, we perform a binned likelihood analysis and present results in terms of the standard likelihood-ratio test statistic, $\Delta\chi^2 \equiv -2\Delta \ln \mathcal{L}$. We choose a particular truth hypothesis (e.g., a LLP with mass 200 MeV, produced via charged kaon decay, with a lifetime of 100 m) and simulate an expected event distribution according to this scenario. In general, we fix the total expected event rate to be $N_{\text{tot}} = 10$ or 100 signal events in a given hypothesis—in typical scenarios, this will be suitable to establish discovery in DUNE without having already been detected by other facilities [3–6, 13, 44–46]. We then compare this hypothesis against a range of test hypotheses, allowing the test lifetime to vary between 10^{-2} – 10^7 m. In general, we study discrimination between two concrete production hypotheses, denoted X (truth) and Y (test). To interpolate continuously between these two end point hypotheses at fixed total normalization, we construct

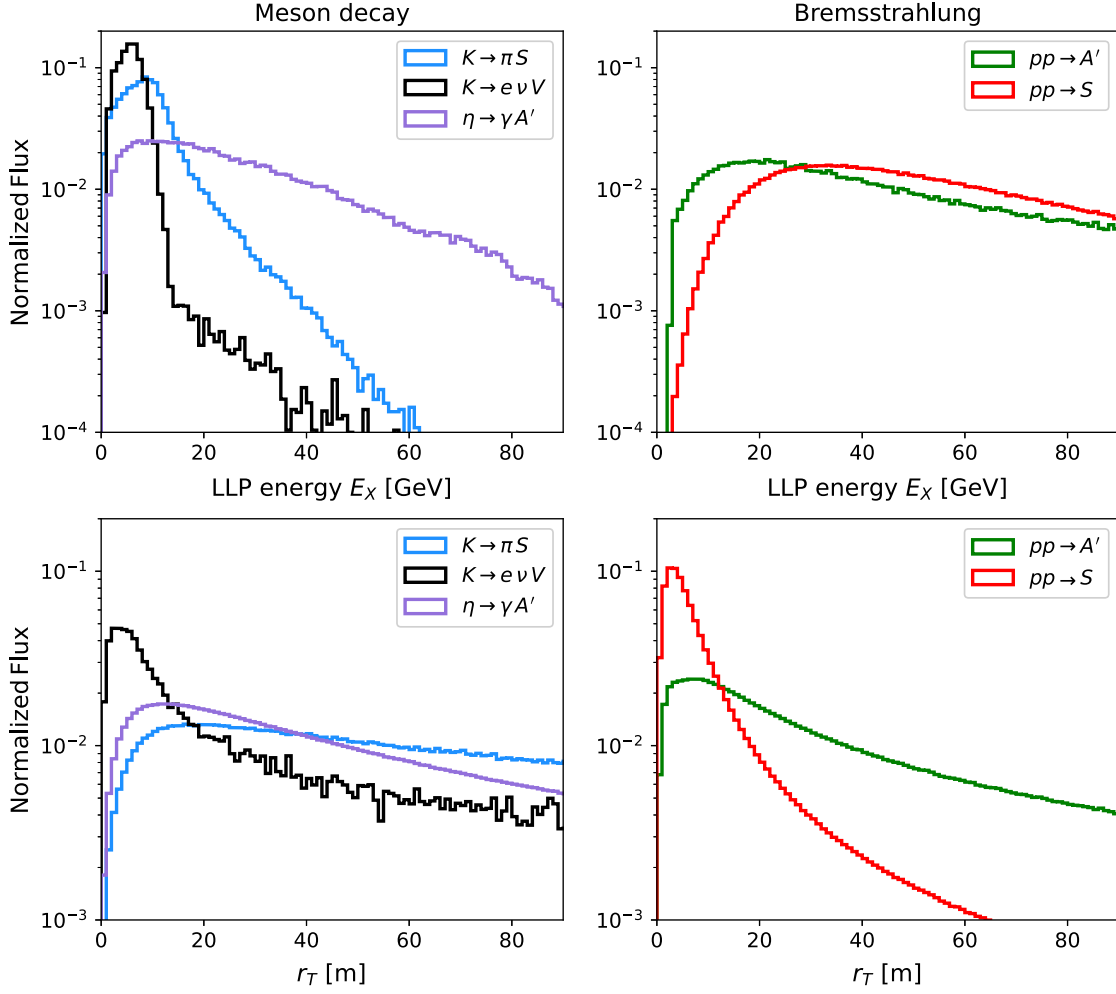


FIG. 3. Top panel: area-normalized LLP fluxes at the DUNE near detector as a function of LLP energy. We show results for the dark Higgs (S), dark photon (A'), and leptophilic gauge boson (V), and for several different production channels (left panel: kaon decays, right panel: bremsstrahlung). In all cases, we have assumed an LLP mass of $m_X = 200$ MeV. Bottom panel: area-normalized fluxes with respect to transverse radius for five long-lived particle production methods, all of which having $m_X = 200$ MeV.

test-predicted event-rate distributions as a function of a template-mixture parameter f_X (with $0 \leq f_X \leq 1$ and $f_Y \equiv 1 - f_X$). Concretely, for a set of observables binned into bins i [either E alone or (E, r_T)], we form normalized templates $p_i^A(c\tau)$ for $A \in \{X, Y\}$ satisfying $\sum_i p_i^A(c\tau) = 1$, and the expected number of events in bin i is

$$\mu_i(f_X, c\tau) = N_{\text{tot}}[f_X p_i^X(c\tau) + (1 - f_X) p_i^Y(c\tau)]. \quad (1)$$

Here f_X is an interpolation parameter used to connect the two discrete production hypotheses ($f_X = 1$ for pure X and $f_X = 0$ for pure Y), and we do not interpret f_X as a physical branching fraction. The discrimination between the two endpoint hypotheses is then quantified by the profiled likelihood-ratio separation,

$$\Delta\chi^2 = \min_{c\tau}[-2\ln\mathcal{L}(f_X=0, c\tau)] - \min_{c\tau}[-2\ln\mathcal{L}(f_X=1, c\tau)], \quad (2)$$

i.e., profiling over the test lifetime in each hypothesis. This provides us with a heuristic for separating the two hypotheses in the presence of a BSM signal.

Concretely, we evaluate this discrimination in two configurations: (i) using only the binned LLP energy distribution, and (ii) using a two-dimensional binned distribution in (E, r_T) , where r_T denotes the transverse displacement of the LLP decay vertex from the beam axis within the on-axis DUNE ND acceptance. In both cases we assume a high signal-to-background ratio and that the LLP invariant mass can be reconstructed with sufficient resolution from fully visible final states. We therefore fix the LLP mass when comparing production hypotheses and profile only over the test lifetime, as in Eq. (2). In a more rigorous analysis including backgrounds, we expect that we can utilize this same process. If signals dominate over backgrounds (or even with a signal-to-background ratio of order one), then the differences between signal candidate templates p_i^X will allow our statistical procedure

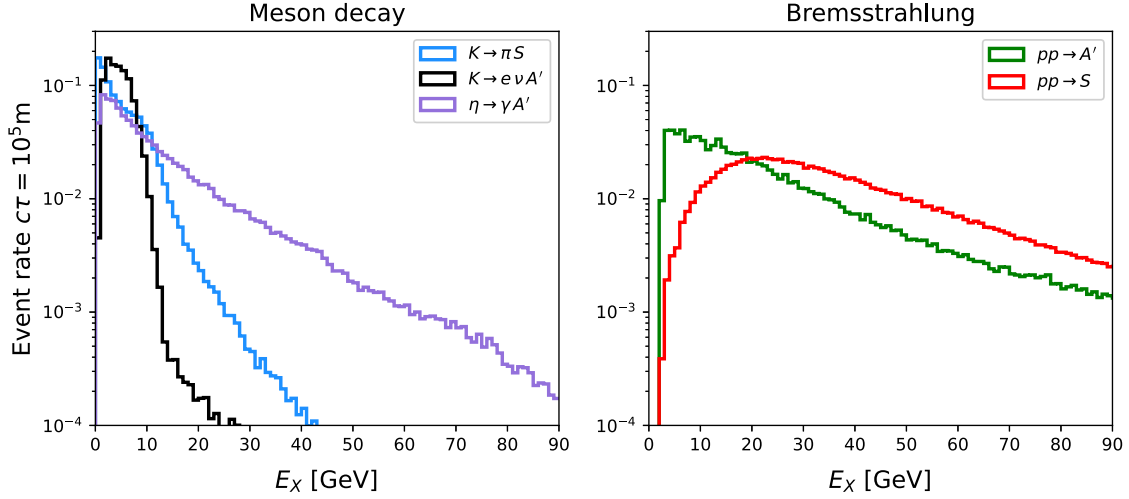


FIG. 4. Normalized event rates with respect to particle energy for five long-lived particle production methods, all of which having $m_X = 200$ MeV, where we fix the lifetime to be $c\tau = 10^5$ m. The left panel shows meson-decay production: two-body decay of a charged kaon (blue), two-body decay of an η meson (purple), and three-body radiative decay of a charged kaon (black). The right panel contrasts two proton-bremsstrahlung production modes: that of a vector (green) vs that of a scalar (red). For comparison, a smaller-lifetime (10 m) version of the expected event-rate distribution is shown in Fig. 12.

to discriminate between different signal models. On the other hand, if more substantial backgrounds exist, we envision alternative techniques, e.g., improved background rejection with multiple signals in mind from machine learning, to be necessary.

The event expectation is calculated in terms of the expected energy spectrum, as well as the off-axis position (measured by r_T) in cases where we consider the spatial information simultaneously in terms of 2D distributions. The distributions are binned with respect to energy between 0 and 100 GeV in 5 GeV bins, and with respect to off-axis position between 0 and 2.5 m in 25 cm bins. These bin sizes are relatively conservative compared with what the DUNE liquid argon near detector should be able to accomplish, however we do not expect that finer binning will improve the model-by-model discrimination substantially.

Finally, we will analyze the simulated data assuming that background contributions can be ignored. A great deal of phenomenological effort has explored the possibility of reducing SM backgrounds (e.g., from neutrino scattering) to various LLP signatures, especially final states with electrons and positrons in Refs. [4,5]. These strategies often take advantage of differences in the kinematic properties of LLP-decay signatures vs neutrino-scattering backgrounds, e.g., targeting specific invariant masses of final-states or the delay of a (relatively massive) LLP arriving in the detector after the (nearly massless) neutrinos, e.g., Refs. [47–50]. We refer the interested reader to these works for more detail.

IV. ANALYSIS AND RESULTS

In this section, we present a number of pairwise comparisons between different truth- and test-scenario

hypotheses, determining the ability to utilize energy and position information to differentiate between the two. First (in Sec. IVA), we compare among two-body production mechanisms, specifically two-body meson decays as well as proton/proton bremsstrahlung of LLPs. Then, motivated by leptophilic gauge bosons, we additionally compare against three-body meson decays as a production mode in Sec. IV B.

A. Comparisons between two production mechanisms

In these analyses, we will compare two different hypothetical production mechanisms, taking one as the assumed-true scenario and the other as a test hypothesis. For these comparisons, we will assume the total number of expected events is 10, and expect that the sensitivity will scale roughly linearly with this (so a factor of ten larger χ^2 discrimination if the number of signal events is 100, for instance). We will allow the fraction attributed to each of the two production mechanisms to vary (between 0 and 1), fixing the total expected events summed over the two mechanisms to 10.

Two-body decay—kaon vs eta production. As a first comparison, we choose the two, two-body meson decay channels discussed above: decays of $K^\pm \rightarrow \pi^\pm X$ and $\eta \rightarrow \gamma X$. We choose three representative assumed-true LLP lifetimes, 1, 10, and 100 m,⁶ and simulate event-rate distributions assuming production via either the $K^\pm$ or η

⁶Since the distance between production and the detector is approximately 500 m and accounting for the effect of the particles' boosts, lifetimes larger than ~ 100 m look roughly identical to the 100 m case.

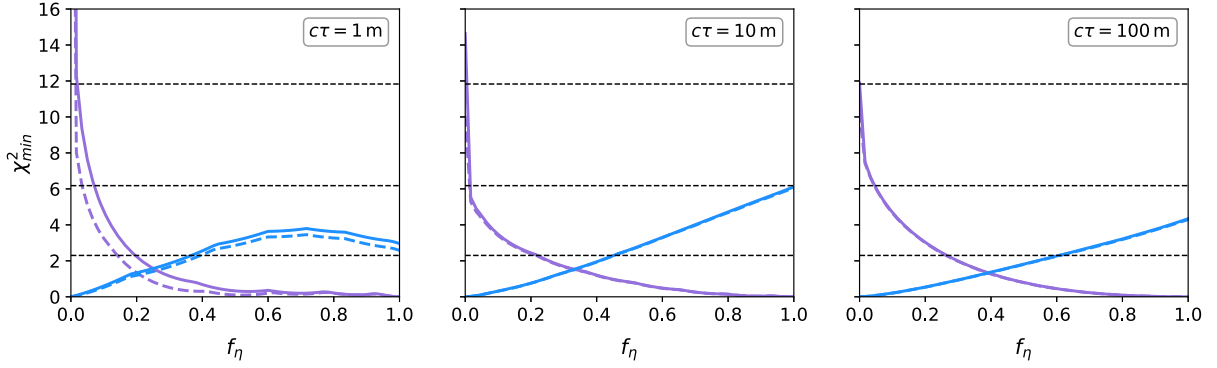


FIG. 5. Minimum likelihood comparison between the channels $K^\pm \rightarrow \pi^\pm S$ and $\eta \rightarrow \gamma A'$ for $m_S = m_{A'} = 200$ MeV. The horizontal axis shows the assumed production fraction from η decays, while the vertical axis gives the minimum χ^2 value obtained when testing a hypothesis against the true one. Curves in purple correspond to the case where the true hypothesis is η decay, and curves in blue correspond to kaon decay. Solid lines indicate a two-dimensional comparison that includes both energy and radial distributions, whereas dashed lines represent a one-dimensional comparison based only on the energy spectrum. The three dashed horizontal lines corresponds to values of 1σ , 2σ , and 3σ for reference. The 3 panels corresponds to different choices of LLP lifetimes, viz., 1, 10, and 100 m.

decay process. We then fit the data, assuming a test hypothesis of an admixture of the two production modes and a test lifetime, arriving at a chi-squared comparison. For a first analysis, we follow this process using the energy distributions of the LLPs only. These χ^2 values, as a function of the fitted η fraction $f_\eta = 1 - f_K$, are shown in Fig. 5 for the three assumed-true lifetimes. In each panel, the blue (purple) lines correspond to the case where the true production mechanism comes from η (K^+) decay. If we additionally include transverse-radius information of the event rates (within the on-axis detector), we arrive at the solid lines in each panel—the improvement attained by simultaneously including energy- and position-information is represented by the gap between the dashed and solid lines. As is evident, whether this improvement is significant depends on the truth hypothesis (including the assumed-true lifetime) at play.

In each case, a relevant figure of merit is the potential of ruling out the wrong production mode, i.e., ruling out $f_\eta = 1$ when the true production is from kaon decay and vice versa. Generically, we see that it is easier to rule out kaon production when the truth is eta production than the opposite case—this is related to the fact (see Fig. 3) that the LLPs from η decay, passing through DUNE ND, tend to be more energetic than those produced from K^+ decay. As a result, it is more challenging for a distribution of K -produced LLPs to mimic that of η -produced ones than vice versa, even when allowing the lifetime of the test hypothesis to vary.

Model-specific interpretation. If a dark photon exists and DUNE discovers it through η -decay production, we expect that we can confidently identify the new-physics particle as a dark photon instead of being a dark Higgs boson. The converse is not true: if a dark Higgs is discovered through $K^\pm$ decay, interpreting its nature will prove challenging.

Scalar production—Kaon-decay vs bremsstrahlung. For a second comparison, we consider two disparate production mechanisms of new scalar bosons: that from charged-kaon decay (blue) vs from proton bremsstrahlung (red). We use f_b to represent the production fraction according to bremsstrahlung and take $f_K = 1 - f_b$. The results of this χ^2 analysis are presented in Fig. 6. Especially for the small-lifetime case (1 m, left panel), we see that the inclusion of radial information has a significant impact. This is especially true when the truth hypothesis is bremsstrahlung production.

Model-specific interpretation: If a dark Higgs boson is discovered, it will be relatively straightforward (except in specific cases) to differentiate between whether it is dominantly produced via $K^\pm$ decay or proton bremsstrahlung. If the LLP's lifetime is small, the inclusion of r_T observations and the operation of DUNE-PRISM will aid substantially in this differentiation.

Vector production—Eta-decay vs bremsstrahlung. For production of vector-type LLPs, two common modes include neutral $\eta \rightarrow \gamma A'$ decays and proton-bremsstrahlung $pp \rightarrow A'$. We show the results of a differentiation-analysis between these two in Fig. 7, where the purple (green) lines correspond to the truth hypothesis being η decay (proton bremsstrahlung). The production fractions are defined as f_b for the bremsstrahlung production fraction and $f_\eta = 1 - f_b$ for the η decay.

We note that the vertical scale in Fig. 7 is suppressed relative to previous figures, demonstrating that differentiating between these two production modes with $\mathcal{O}(100)$ signal events (even with optimistic assumptions regarding background and reconstruction techniques) is extremely challenging. Even though adding in vertex position information (the increase from dashed to solid lines) modestly improves the $\Delta\chi^2$, these channels remain very challenging to disentangle.

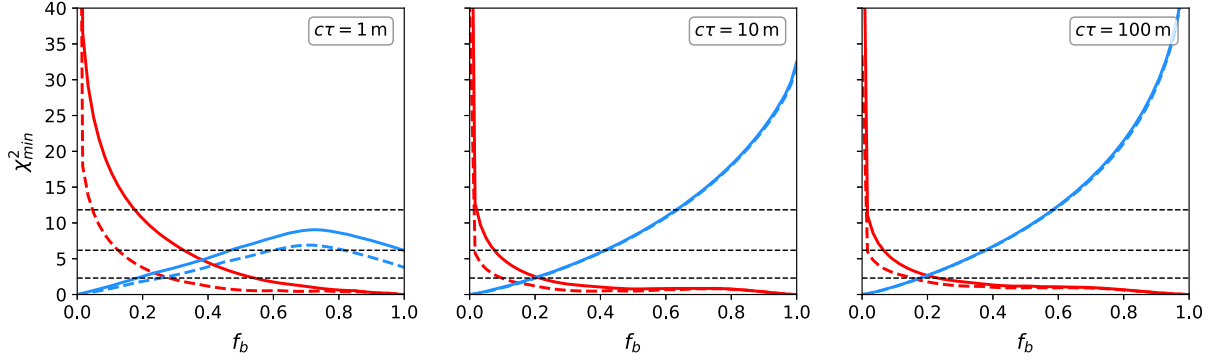


FIG. 6. Minimum likelihood comparison between the channels $pp \rightarrow S$ vs $K^\pm \rightarrow \pi^\pm S$ for $m_S = 200$ MeV. The horizontal axis shows the assumed production fraction from proton bremsstrahlung, while the vertical axis gives the minimum χ^2 value obtained when testing a hypothesis against the true one. Curves in red correspond to the case where the true hypothesis is proton bremsstrahlung, and curves in blue correspond to kaon decay.

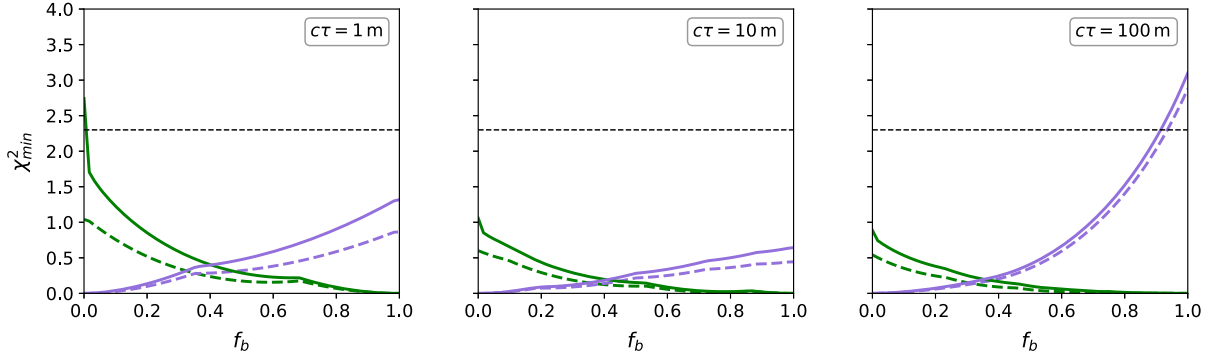


FIG. 7. Minimum likelihood comparison between the channels $pp \rightarrow A'$ vs $\eta \rightarrow \gamma A'$ for $m_{A'} = 200$ MeV. The horizontal axis shows the assumed production fraction from proton bremsstrahlung, while the vertical axis gives the minimum χ^2 value obtained when testing a hypothesis against the true one. Curves in green correspond to the case where the true hypothesis is proton bremsstrahlung, and curves in purple correspond to eta decay.

Model-specific interpretation: If we know that a new-physics signal is associated with a dark photon decay, it will prove very difficult to verify how the dark photons are produced.

Bremsstrahlung comparison—Scalar vs vector. As a final direct comparison between production hypotheses, we consider production purely via bremsstrahlung in an attempt to differentiate between the LLP being a scalar (red) vs a vector (green) particle. This is motivated in many LLP situations for mass ranges where such bremsstrahlung production is the dominant expectation but there is no *a priori* reason to expect a vector- vs scalar-LLP. We show the results of the comparison in Fig. 8. As with the η -decay vs bremsstrahlung case above, we see that the channels are extremely challenging to differentiate. The only likely hope in doing so would come from an analysis that can measure to significantly larger r_T , as exemplified in the difference between the red and green lines of Fig. 3(bottom). This should be possible with the DUNE-PRISM concept [51], however it may be challenging to collect sufficient statistics to differentiate between the two situations.

The LLP mass affects the boost distribution and thus the shapes in E and r_T , particularly near kinematic thresholds (notably $K \rightarrow \pi X$). We therefore repeat the discrimination analysis for $m_X = \{100, 200, 300\}$ MeV for all production-hypothesis pairs considered here. The resulting variation in discrimination power is modest and does not change our qualitative conclusions; accordingly we use $m_X = 200$ MeV as a representative benchmark in the main text and present the mass-scan results in Appendix B, focusing on proton bremsstrahlung for scalar vs kaon decay as an representative example in Fig. 11.

B. Model-inspired comparison of three production mechanisms

Here, in contrast to the above, we focus on a specific comparison between three production mechanisms, inspired by models of dark gauge bosons. We simultaneously consider production via proton bremsstrahlung, decays of η mesons, and the three-body decay from charged kaons, $K^+ \rightarrow \ell^+ \nu V$. Such production mechanisms could all play a comparable role for detection in an experiment

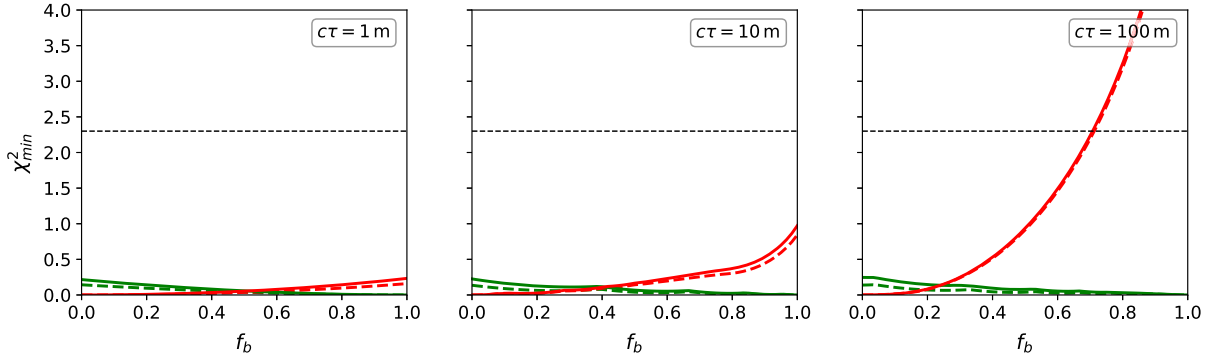


FIG. 8. Minimum likelihood comparison between the channels $pp \rightarrow S$ vs $pp \rightarrow A'$ for $m_S = m_{A'} = 200$ MeV. The horizontal axis shows the assumed production fraction from proton bremsstrahlung to dark photon, while the vertical axis gives the minimum χ^2 value obtained when testing a hypothesis against the true one. Curves in green correspond to the case where the true hypothesis is proton bremsstrahlung to dark photon, and curves in red correspond to proton bremsstrahlung to scalar.

such as DUNE in, for instance, models where $L_\mu - L_\tau$ lepton number is promoted to a gauge symmetry. For the following, we assume that the mass of the LLP is fixed to 200 MeV and that we can detect 100 signal events (in

contrast to the 10-signal-event expectation in the previous subsection). We consider potential truth lifetimes of 1 and 100 m, but allow the test lifetime to vary independently in our analyses.

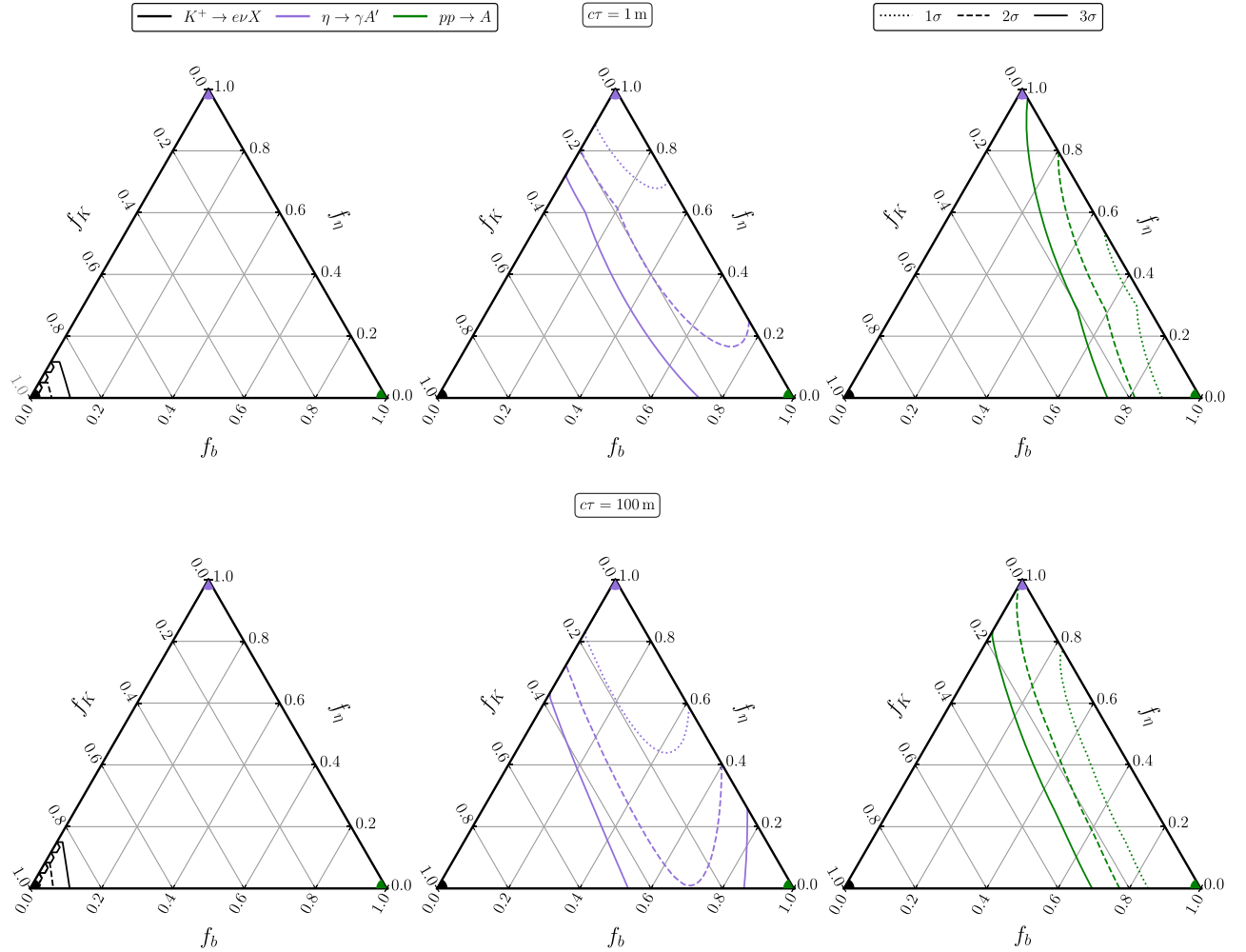


FIG. 9. Minimum likelihood comparison among production hypotheses: $\eta \rightarrow A'$, $pp \rightarrow A'$, and $K \rightarrow \nu_e e Z'$ for different values of the proper decay length $c\tau$.

To allow for three production modes to vary simultaneously we define scaling parameters f_b , f_η , and f_K (corresponding to the modes listed above), but fix $f_b + f_\eta + f_K = 1$. In our comparisons, we find that the inclusion of both energy- and spatial-information (E_X and r_T distributions, respectively) provides $\mathcal{O}(1)$ improvement over energy-based analyses alone, without significantly changing the main takeaways of such analyses. In Appendix B we compare the results of such one-dimensional and two-dimensional analyses; that aside, the remainder of this subsection focuses on two-dimensional analyses with both energy and spatial information included.

To visualize the interplay between the three signal hypotheses, we employ ternary plots, as shown in Fig. 9, for benchmark decay lengths of $c\tau = \{1, 100\}$ m (top and bottom rows, respectively). Each corner of the triangle represents a pure production mode: the left vertex corresponds to $f_K = 1$, the right vertex to $f_b = 1$, and the top vertex to $f_\eta = 1$, with the production fractions summing to unity at every point

$$f_\eta + f_K + f_b = 1.$$

Contours in each triangle indicate regions of constant χ^2 assuming one of the three channels as the true production mode. In both rows, the left-most triangle corresponds to kaon three-body decay, the central triangle to η decay, and the right-most triangle to proton bremsstrahlung. Dashed and solid lines indicate different confidence levels— 1σ and 2σ respectively—for each hypothesis being tested against mixtures of all three.

The sharp localization near the kaon vertex (left panels, in black) illustrates its strong discriminatory power: even small admixtures of other channels lead to a poor fit. In contrast, the broader and flatter contours for the bremsstrahlung hypothesis (right panels, in green) indicate that it can be more easily mimicked by other channels, consistent with our earlier observation that η and bremsstrahlung contributions are partially degenerate. Overall, the ternary representation provides a compact and intuitive visualization of the distinguishability among the three production mechanisms across the full range of possible mixtures, complementing the 1D and 2D χ^2 analyses discussed in Appendix B.

As the lifetime increases to $c\tau = 100$ m (bottom row), the corresponding boost factor becomes larger and making the discrimination for the kaon three-body decay hypothesis slightly less robust. On the other hand, when the true hypothesis is η decay (center panel, purple), it can still be imitated by proton bremsstrahlung, and vice versa: the bremsstrahlung hypothesis can also be mimicked by η decay, although the discriminatory power for η decay worsens whereas the impact on proton bremsstrahlung remains unchanged by the increase in lifetime.

V. CONCLUSIONS

In this work we have explored the prospects for distinguishing different production mechanisms of long-lived particles (LLPs) at the DUNE near detector. Whereas most existing studies emphasize sensitivity to specific LLP models, our focus is on the complementary question of how well distinct production modes can be disentangled, in a statistical sense, once a signal is observed. We consider representative benchmark models—a dark Higgs, a dark photon, and anomaly-free $L_\alpha - L_\beta$ scenarios—and study their dominant production channels: (i) two-body meson decays, (ii) bremsstrahlung off the primary proton beam, and (iii) three-body meson decays. For meaningful comparisons, we fix both the signal event yield and the LLP mass when contrasting different channels. Our analysis employs pairwise comparisons of production mechanisms, allowing for the possibility of mixed production fractions, and is further extended to simultaneous three-channel comparisons visualized using ternary plots. To quantify discrimination power, we construct truth and test hypotheses using binned χ^2 statistics based on both the visible energy and the transverse displacement of LLP decays within the DUNE detector.

Our results demonstrate that kinematic information is crucial for disentangling different LLP production mechanisms at DUNE. While the visible energy spectrum alone often leaves substantial degeneracies, the inclusion of transverse displacement can break these degeneracies and enable robust model separation even with modest signal statistics [$\mathcal{O}(10-100)$ events]. In particular, we find that separation between kaon and η channels, as well as between charged-meson decays and proton bremsstrahlung, improves significantly once spatial information is taken into account, underscoring the importance of exploiting the full DUNE-PRISM capabilities and accounting for the effect of magnetic horns on charged-meson momentum distributions. Moreover, distinguishing three-body meson decays—which are especially relevant for $U(1)$ gauge-boson mediator models—from either two-body meson decays or bremsstrahlung proves relatively straightforward. By contrast, discriminating LLPs produced via meson decays from those produced via proton bremsstrahlung remains challenging; in such cases, additional observables, such as timing information, may be necessary to achieve concrete separation. These studies have been performed under optimistic assumptions regarding signal/background separation; a more thorough analysis is necessary in the case of discovery. In these cases, we naturally expect that separating production mechanisms will provide even greater challenges.

The approach developed here is broadly applicable to LLP searches at fixed-target experiment facilities. By moving beyond discovery sensitivity and quantifying

model discrimination, our work illustrates the critical role that detector geometry and kinematic observables will play in the interpretation of any future LLP signal. In future studies it will be valuable to incorporate more realistic background estimates, detector response, and extended model spaces, including scenarios with two or more accessible production channels. Taken together, our results strengthen the physics case for DUNE as a leading facility in exploring the nature of long-lived particles beyond the Standard Model, and underscore the discovery potential of near-detector facilities.

Note added. While this work has been reviewed and approved as a DUNE theory paper by the DUNE Collaboration, the results presented herein represent the views of the authors and not of the DUNE Collaboration as a whole.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: ADDITIONAL KINEMATIC DISTRIBUTIONS: EXTENDED RADIAL DISTRIBUTIONS, VARYING LLP MASS, ALTERNATIVE LLP LIFETIMES

In analyzing expected LLP fluxes at the DUNE near detector, we constructed Fig. 3(bottom), which displays the transverse-radius distribution of various LLP production mechanisms. This was key in connecting the LLP detection to the DUNE-PRISM concept, where observations at small and large radii can assist in disentangling different production mechanisms and therefore different models of LLPs. In doing so, we fixed our analysis to LLP masses of 200 MeV—here, we repeat this procedure but allowing the LLP mass to vary. The resulting fluxes, separated by production mechanism, are shown in Fig. 10: charged-kaon decay (blue, top-left panel), η decay (purple, top-right), bremsstrahlung of a vector (green, bottom-left), and bremsstrahlung of a scalar (red, bottom-right).

We see that the LLP fluxes from charged-kaon decay have substantial mass-dependence, becoming more

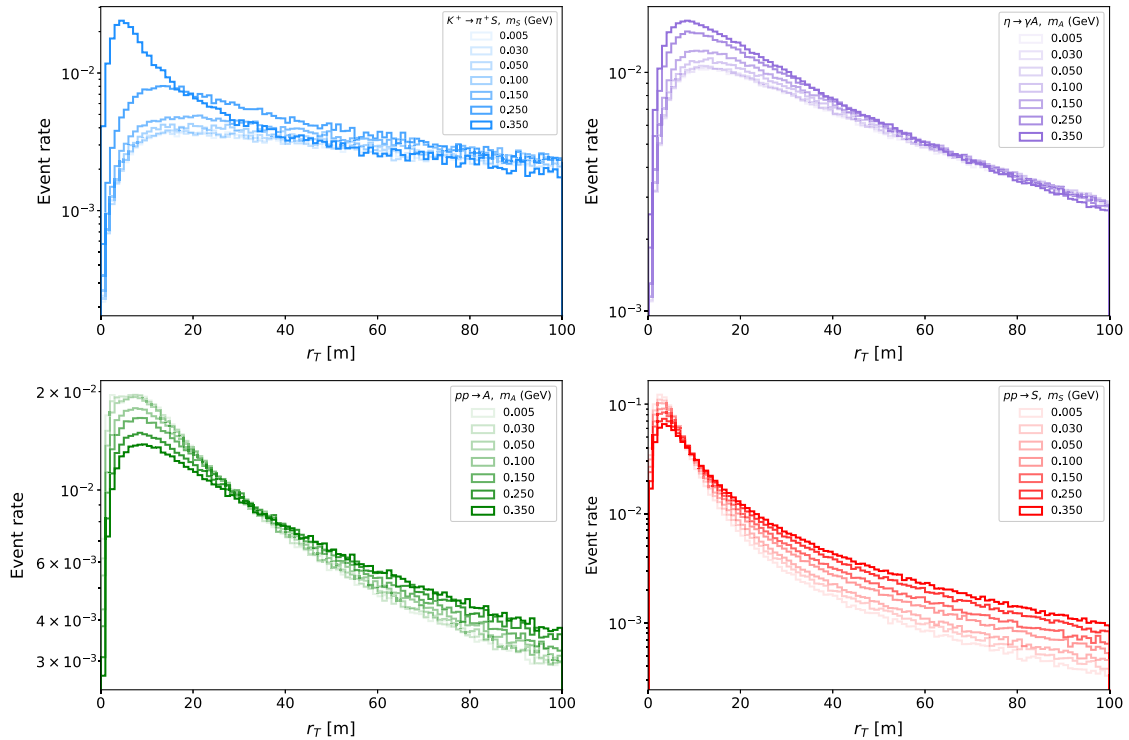


FIG. 10. Normalized event rates as a function of transverse radius with varying masses.

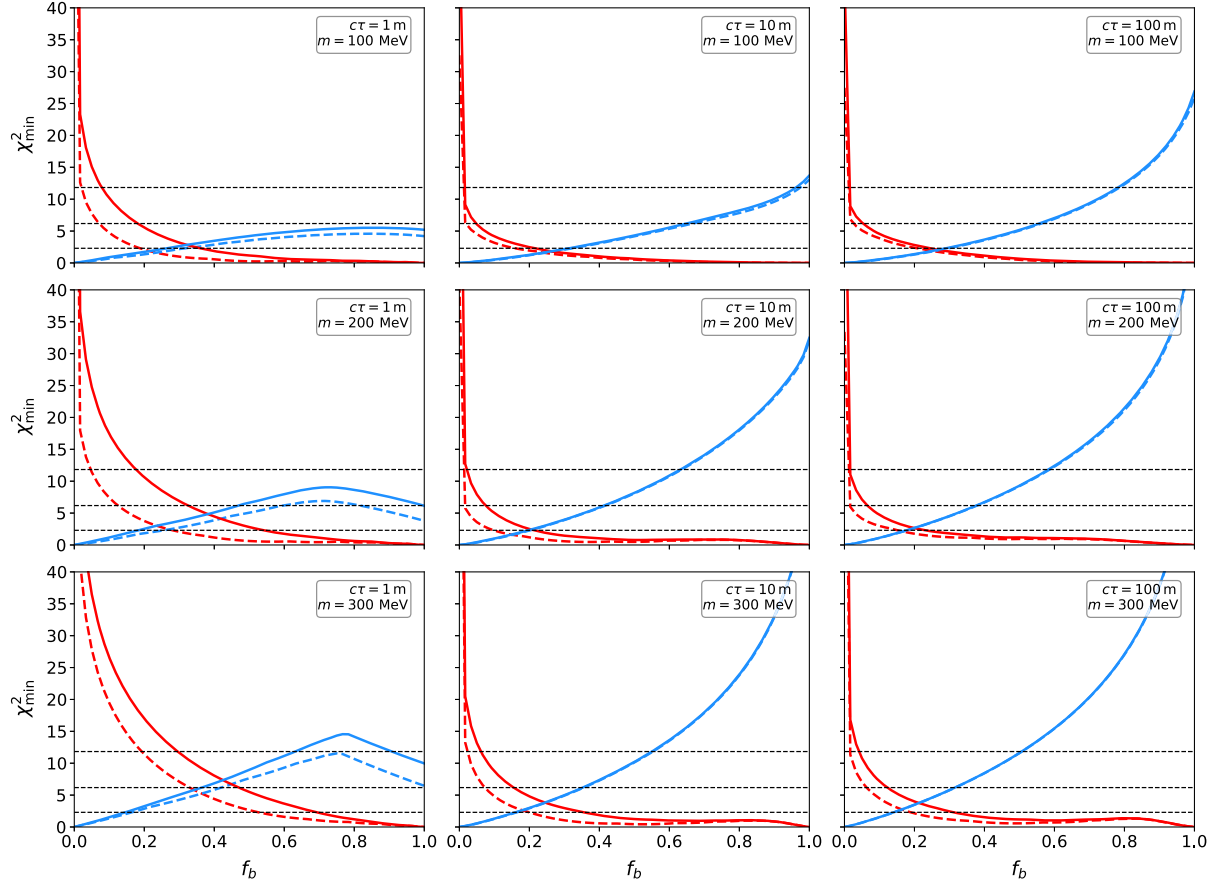


FIG. 11. Minimum likelihood comparison between the channels $pp \rightarrow S$ vs $K^\pm \rightarrow \pi^\pm S$ for three different mass choices for dark scalar, viz., $m_S \in \{100, 200, 300\}$ MeV. The horizontal axis shows the assumed production fraction from proton bremsstrahlung, while the vertical axis gives the minimum χ^2 value obtained when testing a hypothesis against the true one. Curves in red correspond to the case where the true hypothesis is proton bremsstrahlung, and curves in blue correspond to kaon decay.

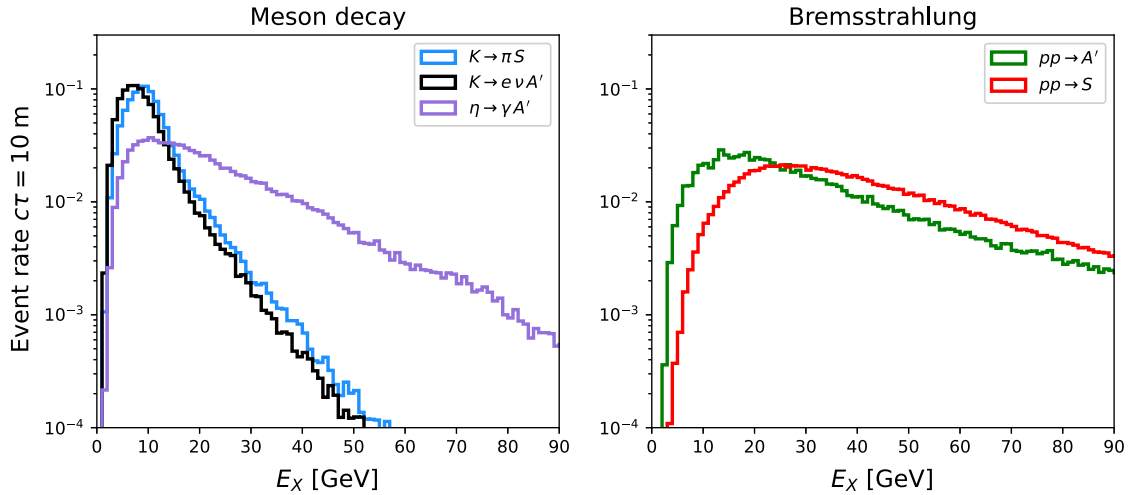


FIG. 12. Expected event-rate distributions for different production mechanisms (see Fig. 4 for a comparison), but with a shorter LLP lifetime of $c\tau = 10$ m.

forward-peaked as the mass increases. This is in contrast to the fluxes from η decay, which remain more radially spread. This difference arises due to the narrowing kinematical threshold as we approach the $m_K - m_\pi \sim \mathcal{O}(0.4 \text{ GeV})$ window, in addition to the magnetic focusing of the charged kaons but not the neutral η mesons. In the bottom panels, we see that the mass-dependence of LLP fluxes from proton bremsstrahlung has similar characteristics when considering vector or scalar bosons, however the variance is not very large.

Additionally in Sec. III, we inspected expected event rates from different LLP production modes, assuming a long lifetime of $c\tau = 10^5 \text{ m}$ (relative to the detector distance). We show a different, smaller choice of the lifetime for the same production mechanisms in Fig. 4. Due to the shorter lifetime, LLPs with larger energies are favored to reach the detector and decay within—we observe event-rate distributions shifted toward higher LLP energies as a result.

APPENDIX B: THREE-SIGNAL-HYPOTHESIS COMPARISON WITH ENERGY-/SPATIAL- INFORMATION

When considering three production mechanisms simultaneously in the analysis surrounding Fig. 9, we focused on the situation in which we analyzed expected event rates in terms of LLP energy and transverse position simultaneously. Here, we revisit these analyses, demonstrating the additional

information gleaned by including transverse-radius r_T information to the χ^2 fit.

We will demonstrate this improvement by comparing side-by-side analysis results assuming either (a) in left panels, the measurement potential using *only* LLP energy information, or (b) in the right panels, the measurement potential if r_T information is *additionally* incorporated. We do so for different assumed-true production mechanisms, showing the three possibilities simultaneously in a given figure: three-body kaon decay (black), η decay (purple), and proton bremsstrahlung (green), still restricting $f_K + f_\eta + f_b = 1$ in our analysis (f_b is not shown for simplicity here; the upper-right triangular half of each panel is forbidden by this restriction).

The first result is shown in Fig. 13 for a true lifetime of 1 m. We see that the kaon hypothesis (black) produces the most distinct, small measurement contours: it is relatively easy to differentiate this production from the other mechanisms. Additionally, the contours do not change significantly going from the left to right panels: for this case, the radius-dependence does not add much more information. In contrast, we see substantial improvement in the measurement contours for production via η decay (purple) and proton bremsstrahlung (green). For instance, this additional information provides additional means of separating the proton-bremsstrahlung and kaon-decay hypotheses, as evidenced by the green, solid line moving down from the left panel to the right one.

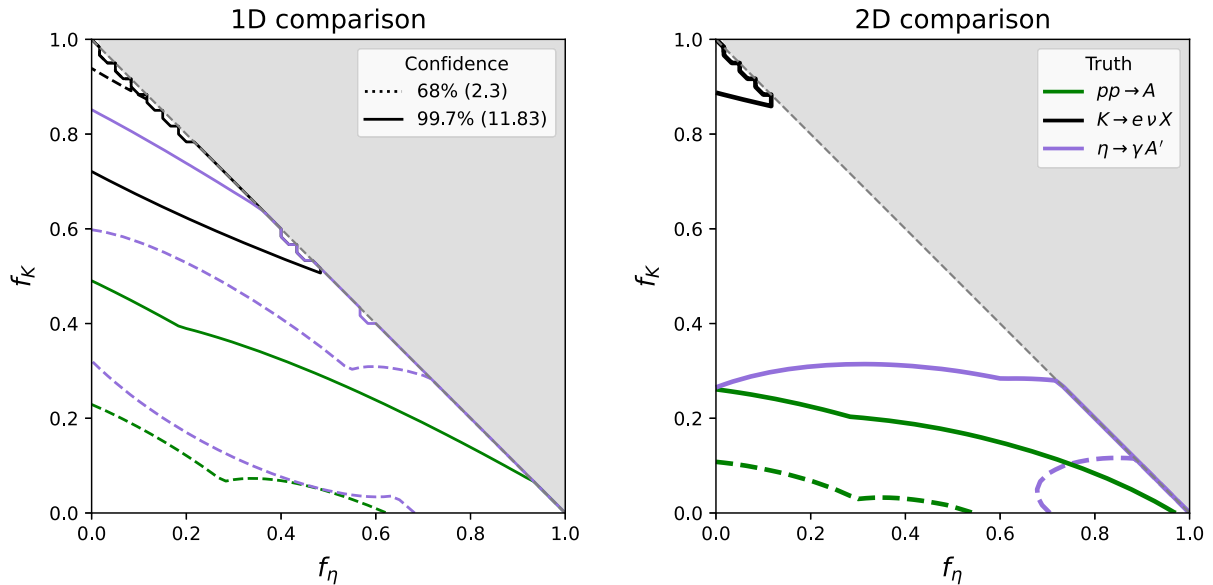
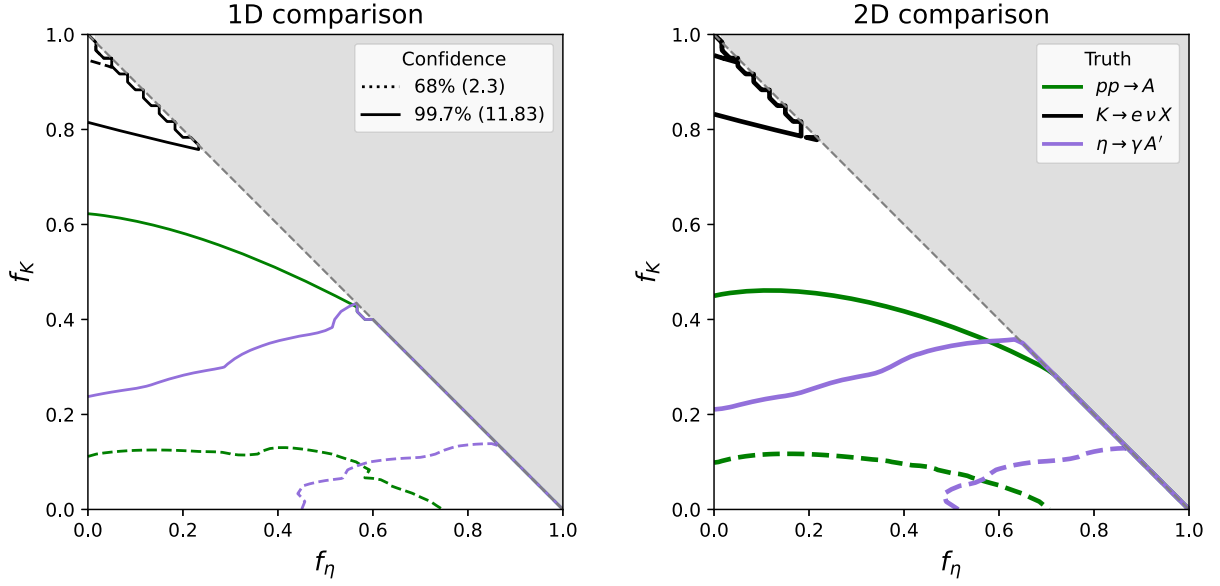
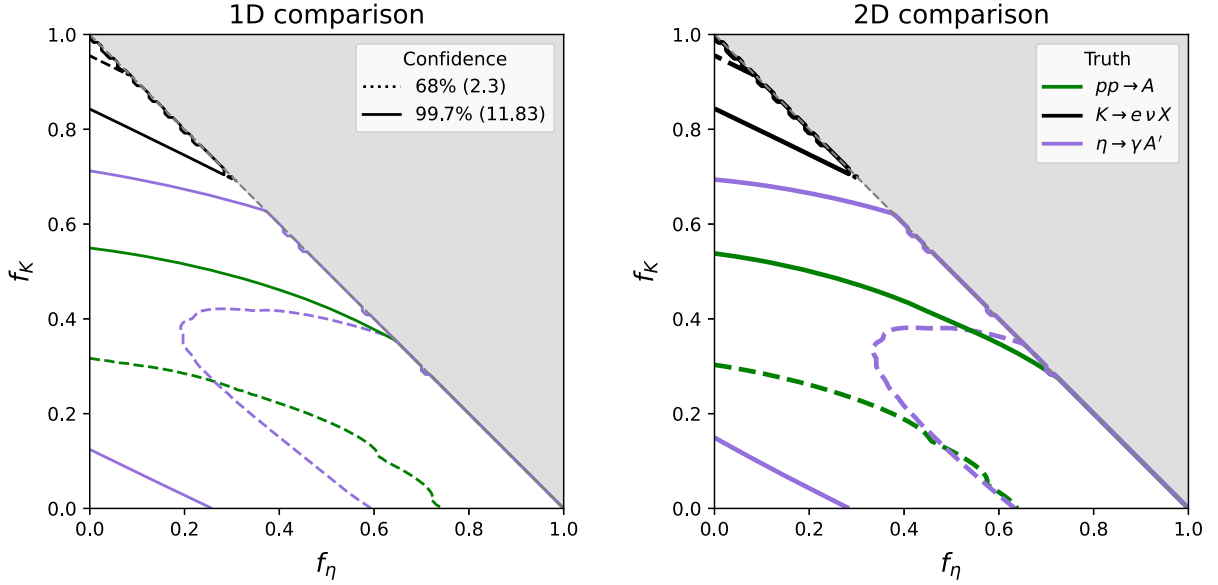


FIG. 13. Minimum likelihood comparison between the channels $\eta \rightarrow A'$, $pp \rightarrow A'$, and $K \rightarrow \nu_e, e, Z'$ for $c\tau = 100 \text{ m}$. The horizontal axis indicates the production fraction from η decays, while the vertical axis shows the production fraction from kaon decays. The left panel displays likelihood comparisons based solely on the energy distribution, whereas the right panel includes both energy and radial distributions. Solid lines denote the 3σ confidence contours, and dashed lines denote the 1σ contours. Black curves correspond to kaon three-body decays, purple to η decays, and green to proton bremsstrahlung. Here the lifetime of LLPs is set to $c\tau = 1 \text{ m}$.

FIG. 14. Minimum likelihood comparison $\eta \rightarrow A'$ vs $pp \rightarrow A'$ vs $K \rightarrow \nu_e e Z'$ for $c\tau = 10$ m.FIG. 15. Minimum likelihood comparison $\eta \rightarrow A'$ vs $pp \rightarrow A'$ vs $K \rightarrow \nu_e e Z'$ for $c\tau = 100$ m.

We show further comparisons, assuming true LLP lifetimes of 10 and 100 m in Figs. 14 and 15, respectively. Again, depending on the underlying truth, we find

modest improvement when spatial information is incorporated in the 2D comparisons vs in the energy-only 1D comparisons

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