Simplified Frameworks for BSM at Short Baselines

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Outline

- Motivation for Simplified Frameworks
- Basics of long-lived particle (LLPs) searches at neutrino experiments
- Simplified Frameworks for LLPs
    - Example: new light scalar or fermion LLP produced in Kaon decays, which subsequently decays to an e^+e^- pair
- Example matching to UV models
- Interpretation in the case of null result / limit
    - Existing limits and future sensitivity at DUNE
- Interpretation in the advent of a signal excess
    - Parameter estimation
    - Model discrimination

Motivation

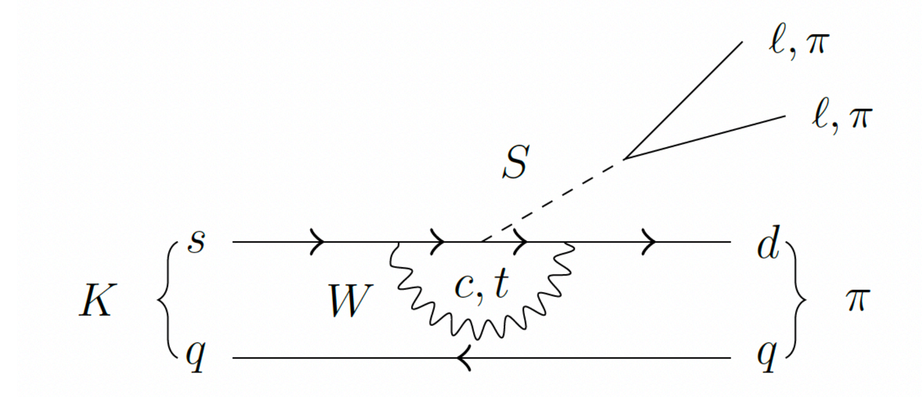
- Accelerator-based neutrino beam experiments provide a powerful tool to search for new light weakly coupled particles
  - Intense proton beams, large collision luminosities, forward fixed target kinematics, sensitive modern neutrino detectors…
- Leading bounds come from past neutrino beam experiments, while promising prospects exist for current and planned future experiments
- Modern neutrino beam experiments are now pursuing dedicated BSM searches
- Exciting outlook! But significant challenges remain to realizing an impactful BSM program (purpose of this workshop is to move forward in addressing some of these challenges)
- How can we maximize the physics impact of an experimental analysis?

The top-down approach to BSM searches

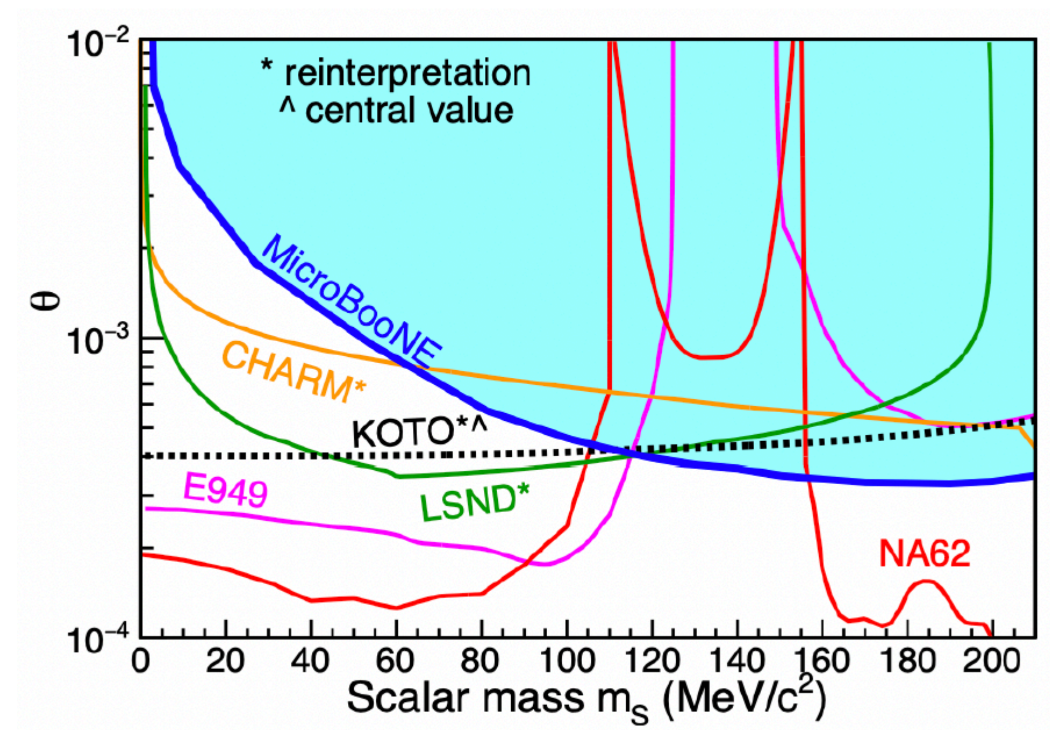
- Theorists propose a model to solve some problem, e.g., the Higgs portal scalar:

$$-\mathcal{L} \supset (AS + \lambda S^2)H^\dagger H \quad \Rightarrow \quad \mathcal{L} \supset \sin\theta\, S \left(\frac{2m_W^2}{v} W_\mu^+ W^{\mu +} + \frac{m_Z^2}{v} Z_\mu Z^\mu - \sum_f \frac{m_f}{v} \bar{f} f \right)$$

- The phenomenology of the model is explored and the experimental sensitivity to its signatures is estimated
  - The model predicts characteristic kinematic features, as well as correlations between production and detection mechanisms/rates



- Experimentalists perform search and interpret results with the context of a specific model
  - Same signature/final state may arise in a variety of other models



[Abratenko et.al, 2106.00568]

Motivation for *Simplified Frameworks* for BSM searches

- The "top-down" approach is warranted and should continue, but there is also value for developing a more model-independent approach to BSM searches at neutrino experiments

- Similar signatures involving the same detectable final-state particles arise in a variety of distinct BSM models, thus a more flexible theoretical framework allows higher efficiency and broader impact of experimental analyses

- The presentation of experimental results in a simplified framework would more readily allow for reinterpretations by theorists in a variety of models, including those that have not yet been envisioned

- Signal event rates and kinematics can often be boiled down to a handful of primary quantities

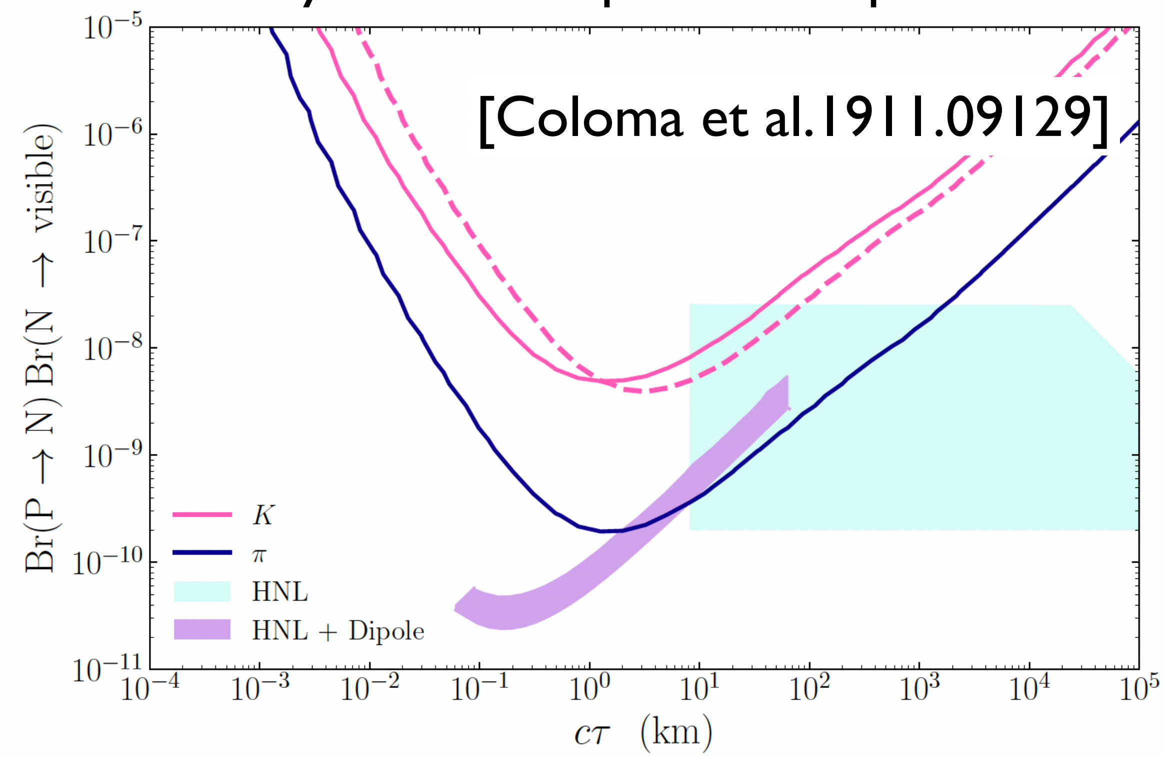
- Searches designed to maximize coverage with simplified framework may actually translate to a broader coverage of models due to the wider range of allowed final state kinematics.

What is a simplified framework?

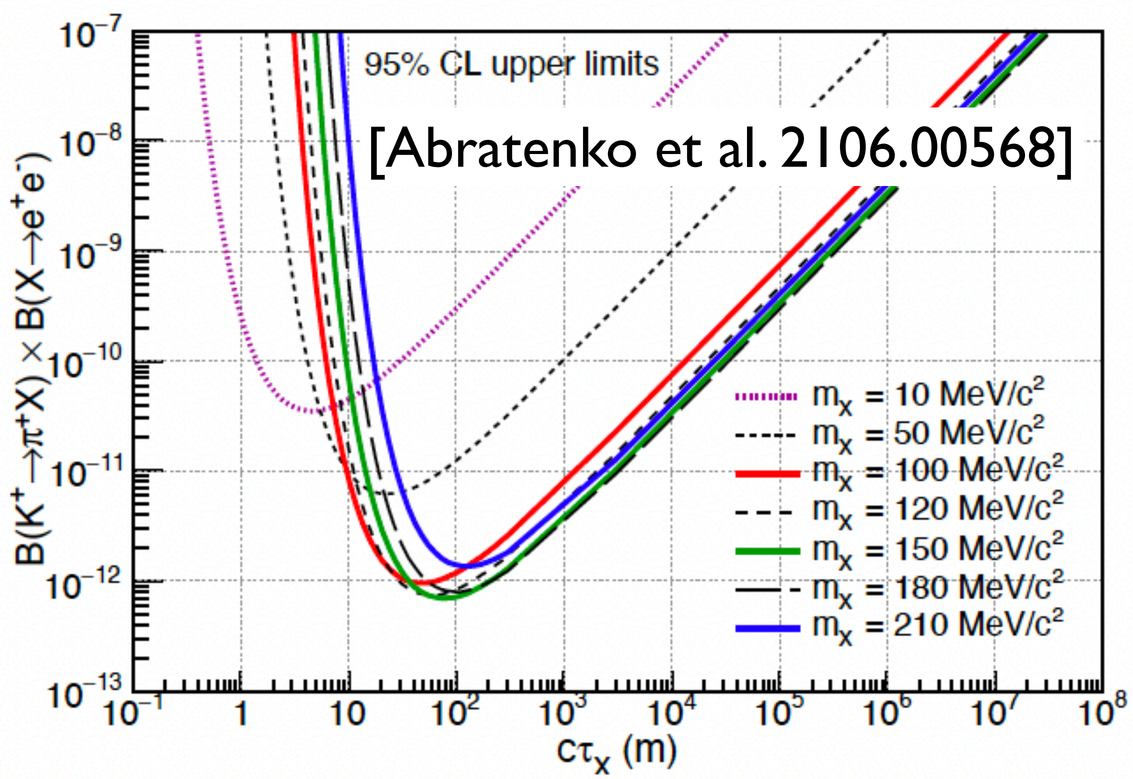
- A framework for interpreting experimental searches characterized by a few primary quantities that most directly determine the signal event rates and final state kinematics
- The relevant primary quantities include masses and lifetimes of the particles of interest, decay branching ratios, production and scattering cross sections, production energy and position distributions, …
- These primary quantities may be directly constrained or measured in experimental analyses
- These limits or measurements on primary quantities can be mapped to more complex theoretical descriptions (simplified model Lagrangian, Effective Field Theories, UV complete models) — an exercise for theorists
- In principle, a simplified framework approach can be developed for each signature / final state of interest to experiments

Past studies employing simplified frameworks

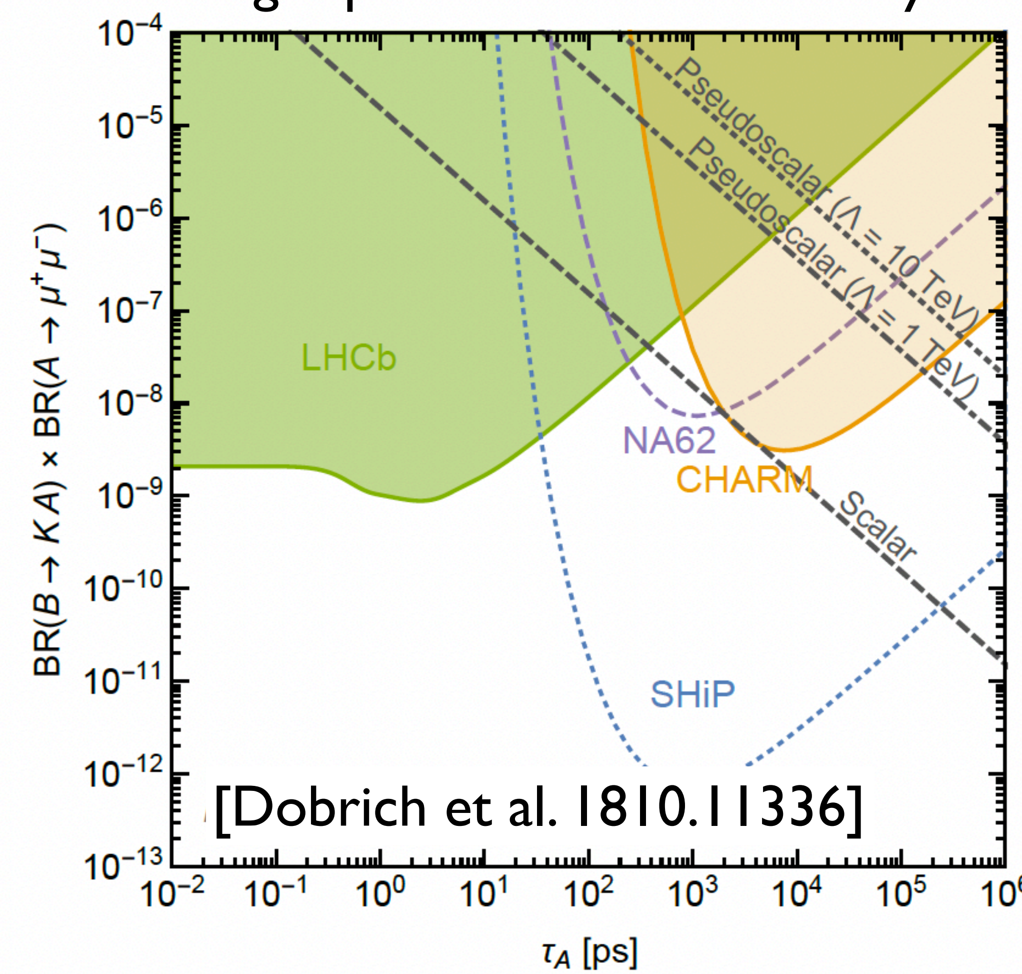
Heavy Neutral Leptons at Super-K



MicroBooNE Higgs portal search

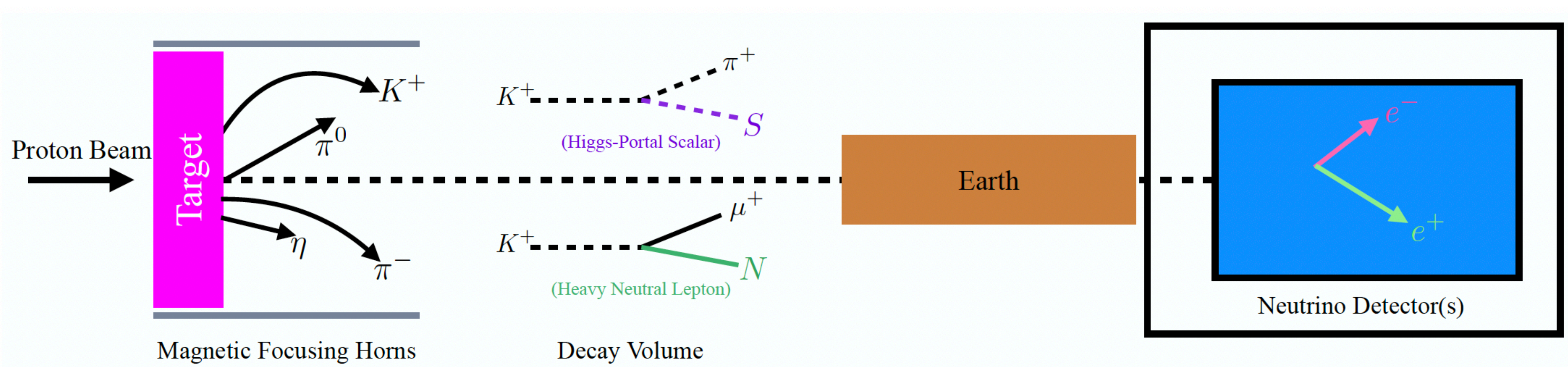


Light pseudoscalars in B decays



LLPs at neutrino experiments

- Consider a generic LLP, which we denote by X
- It may be produced in the proton-target collisions through several mechanisms. Here we will focus on rare meson decays, $m \to X$
- Once produced the LLP X may travel to the near detector and decay to a detectable visible final state F, i.e., $X \to F$



LLP event rates

- LLP flux

$$\Phi_X = \frac{c_{\mathfrak{m}} N_{\rm POT}}{A_{\rm Det.}} \varepsilon\left(\mathfrak{m}; m_X, \ldots\right) {\rm Br}\left(\mathfrak{m} \to X\right),$$

- LLP signal rate

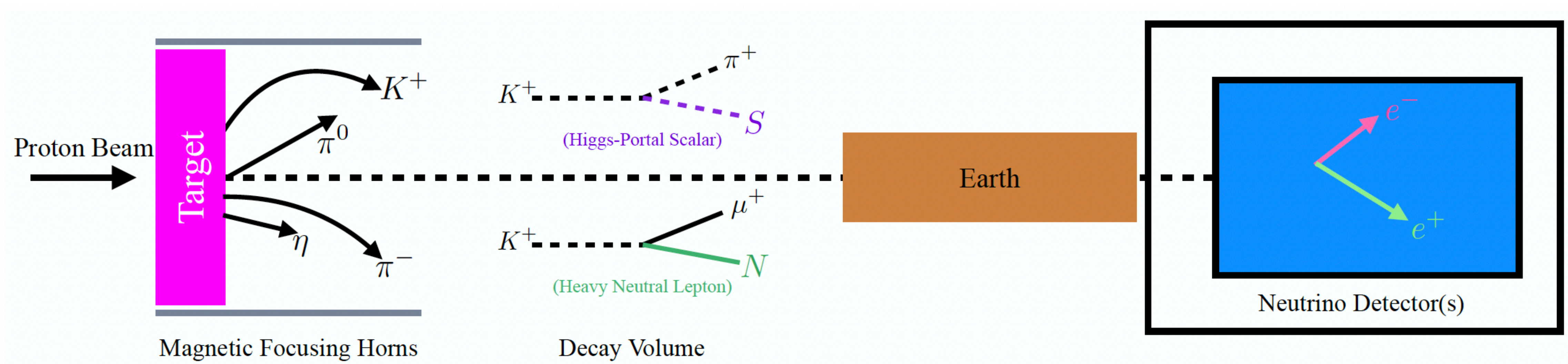
$$N^F_{\rm sig.} = \int dE_X \int_{A_{\rm Det.}} dA \int_0^{z_{\rm max}} dz \int_0^{L_{\rm Det.}} \left(\frac{d^2\Phi_X}{dE_x dz} P_{\rm Decay}\left(E_X, z' + D_{\rm Det.} - z\right) {\rm Br}\left(X \to F\right)\right) dz',$$

$$P_{\rm Decay}\left(E_X, \zeta\right) = \frac{1}{\gamma_X \beta_X c\tau_X} e^{-\frac{\zeta}{\gamma_X \beta_X c\tau_X}}; \quad \gamma_X = E_X/m_X$$

- Notice the event rate depends on three primary particle physics quantities:
  - Product of branching ratios — ${\rm Br}(m \to X){\rm Br}(X \to F)$
  - LLP mass — m_X
  - LLP lifetime — $c\tau_X$

Simplified framework example

- For the rest of the talk, we will consider an example simplified framework for LLPs at neutrino experiments
- Specifically, we consider Kaons decaying into a new LLP denoted X, and X decaying to final state of $e^+e^-(\nu)$ in the near detector
- We consider two cases:
  - Scalar case: $m_S, \quad c\tau_S, \quad \mathrm{Br}(K \to \pi S) \times \mathrm{Br}(S \to e^+e^-)$
  - Fermion case: $m_N, \quad c\tau_N, \quad \mathrm{Br}(K \to \mu N) \times \mathrm{Br}(N \to e^+e^-\nu)$



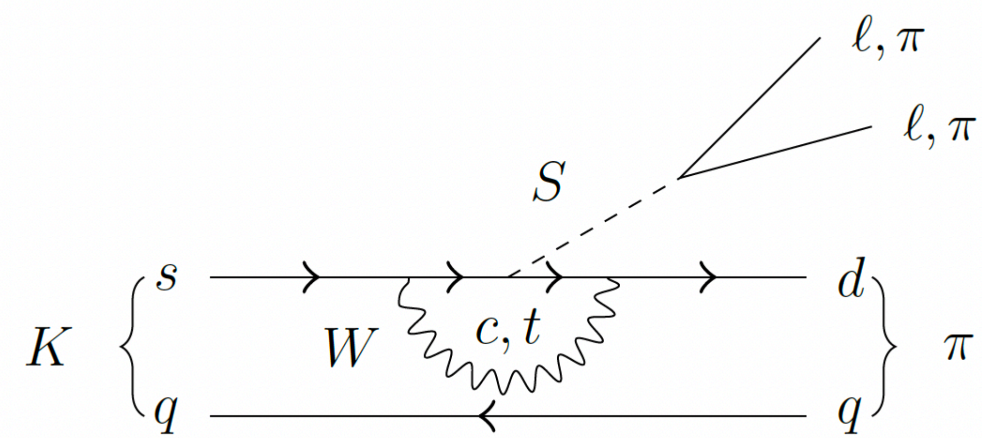
Mapping scalar to more UV complete descriptions

- Simplified model Lagrangian

$$\mathcal{L} \supset -\frac{1}{2}m_S^2 S^2 - g_{K\pi} S\pi^- K^+ + \text{h.c.}$$
$$- g_e S\bar{e}e - g_\chi S\bar{\chi}\chi,$$

- Specific case of Higgs portal scalar

$$g_{K\pi} = \frac{3m_t^2 V_{td}^* V_{ts}}{32\pi^2 v^3}(m_K^2 - m_\pi^2)\sin\vartheta\,,$$
$$g_e = \frac{m_e}{v}\sin\vartheta\ .$$



Mapping scalar to more UV complete descriptions

- Quark level Lagrangian

$$\mathcal{L} \supset -[g_{ds}\, S\, \overline{d}_L s_R + \text{h.c.}],$$

$$g_{K\pi} = g_{ds}\langle \pi | \overline{d}_L s_R | K \rangle,$$

$$|\langle \pi | \overline{d}_L s_R | K \rangle| = \frac{1}{2}\frac{m_K^2 - m_\pi^2}{m_s - m_d}.$$

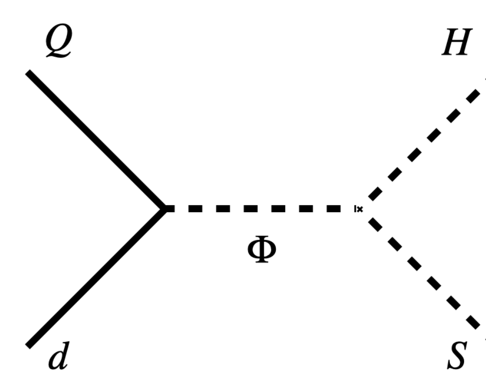
- Gauge invariant effective field theory

$$\mathcal{L} \supset -\frac{(C_d)_i^j}{\Lambda} S\, \overline{Q}_L^i\, H\, d_{Rj} - \frac{(C_e)_i^j}{\Lambda} S\, \overline{L}_L^i\, H\, e_{Rj} + \text{h.c.}\,,$$

$$[(C_d)_2^1 \neq 0,\ (C_e)_1^1 \neq 0\,]$$

- Example UV completion with 2HDM $[\Phi \sim (\mathbf{1}, \mathbf{2}, \frac{1}{2})]$

$$\begin{aligned}\mathcal{L} \supset\ & |D_\mu \Phi|^2 - M_\Phi^2 |\Phi|^2 + \cdots \\ & - [(y_d')_i^j\, \overline{Q}_L^i\, \Phi\, d_{Rj} + (y_e')_i^j\, \overline{L}_L^i\, \Phi\, e_{Rj} - A S\, H^\dagger\, \Phi + \text{h.c.}],\end{aligned}$$



Neutrino experiments and simulations

- MicroBooNE search for Higgs portal scalars [Abratenko et.al, 2106.00568]
  - Kaon decay-at-rest to scalars inside NuMI absorber, ~2 x 10^{20} POT
  - Reproduce MicroBooNE results using their mass-dependent reconstruction efficiency and extrapolate the mass range to just below the kaon mass

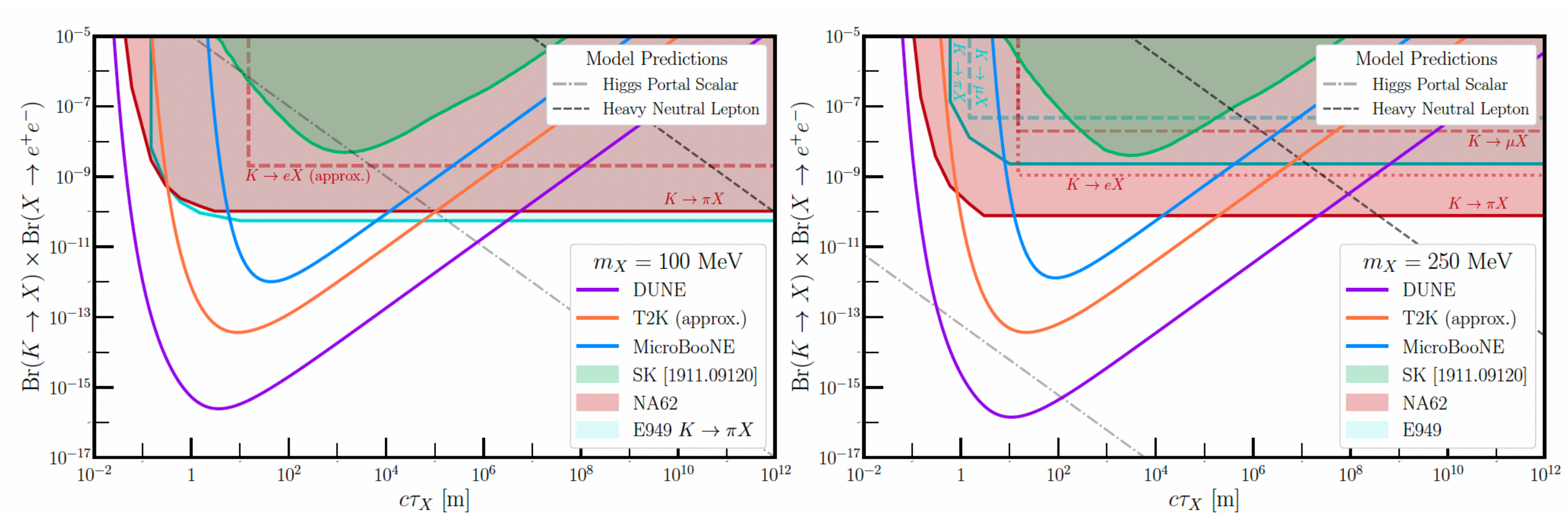
- T2K ND280 search for Heavy Neutral Leptons [Abe et.al, 1902.07598]
  - HNLs produced in Kaon decays in a variety of final states, ~1.2 x 10^{21} POT
  - Given efficiency for $N \to e^+e^-\nu$ is ~10% and largely independent of HNL mass
  - Use given heavy neutrino flux distributions to obtain HNL energy spectrum

- DUNE ND-GAr [Berryman et.al,1912.07622]
  - Proposed DUNE gaseous argon time projection chamber ND-GAr, five years running, ~1.5 x 10^{21} POT
  - Use Kaon events from the DUNE Beam Interface Working Group
  - Account for X flux distribution in energy and position in our simulation, which extends the sensitivity for short lived X
  - For interpretation of signal excess, we assume 3° angular resolution and a 5% energy resolution for reconstructed electrons

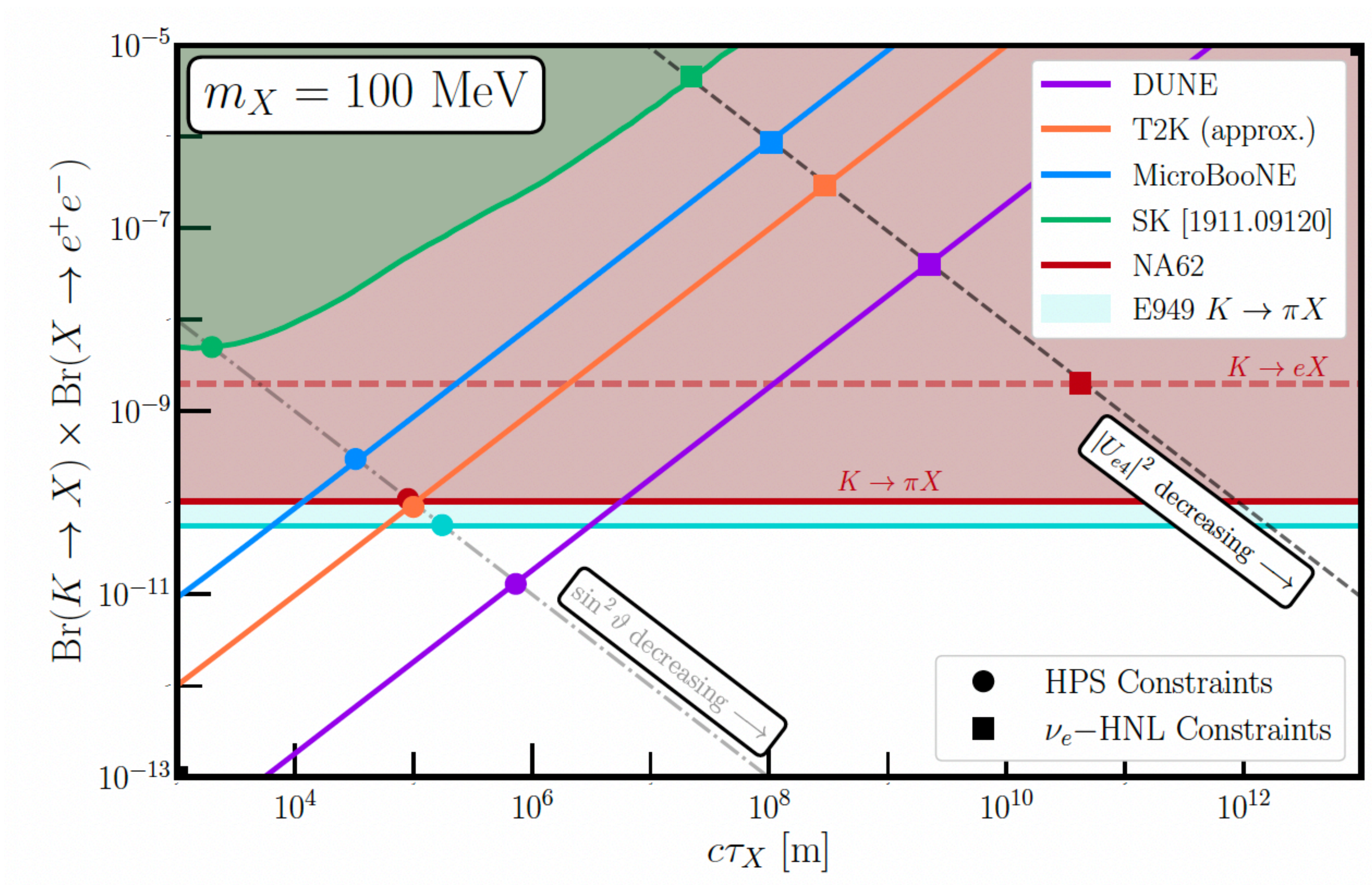
Interpretation in the case of null results / limits

Simplified framework constraints and sensitivity

- Constraints/sensitivities shown on branching ratio product as a function of LLP lifetime for fixed LLP mass
- Model specific predictions are shown for Heavy Neutral Lepton (black dashed) and Higgs portal scalar (gray dot dashed)
- Neutrino experiments have strongest sensitivity when lab frame decay length comparable to near detector baseline
- DUNE ND-GAr will be able to probe new parameter space over a broad range of lifetimes

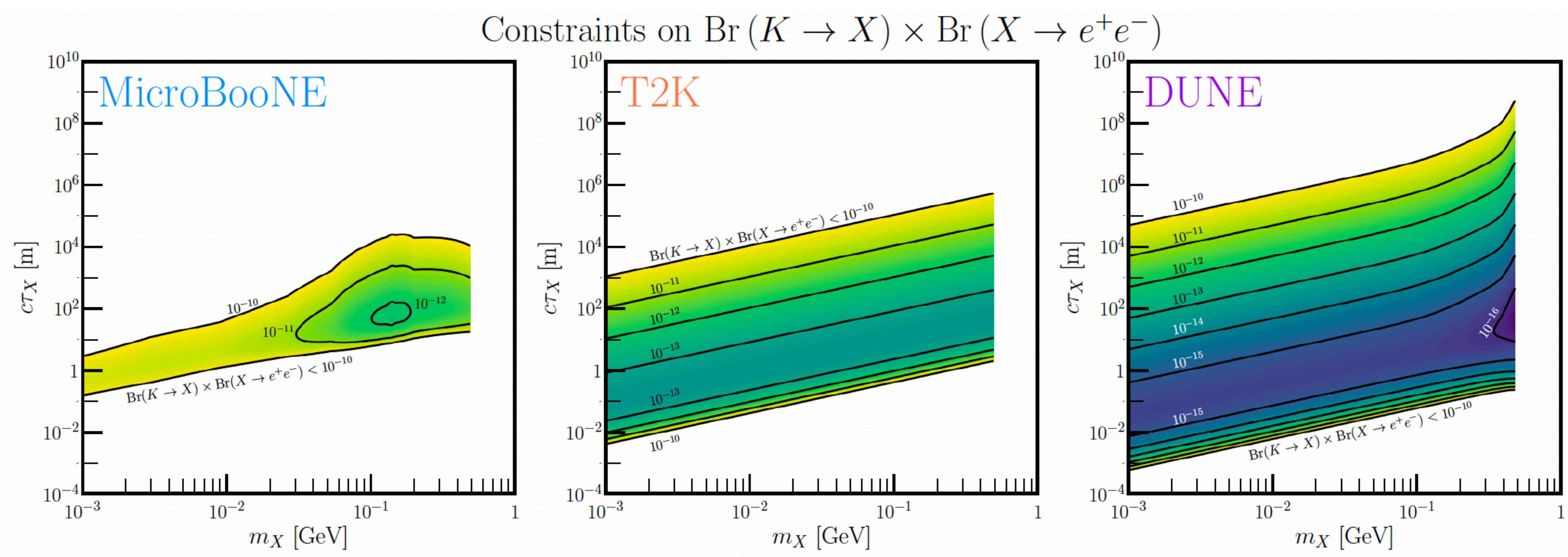


Visualizing model-specific constraints



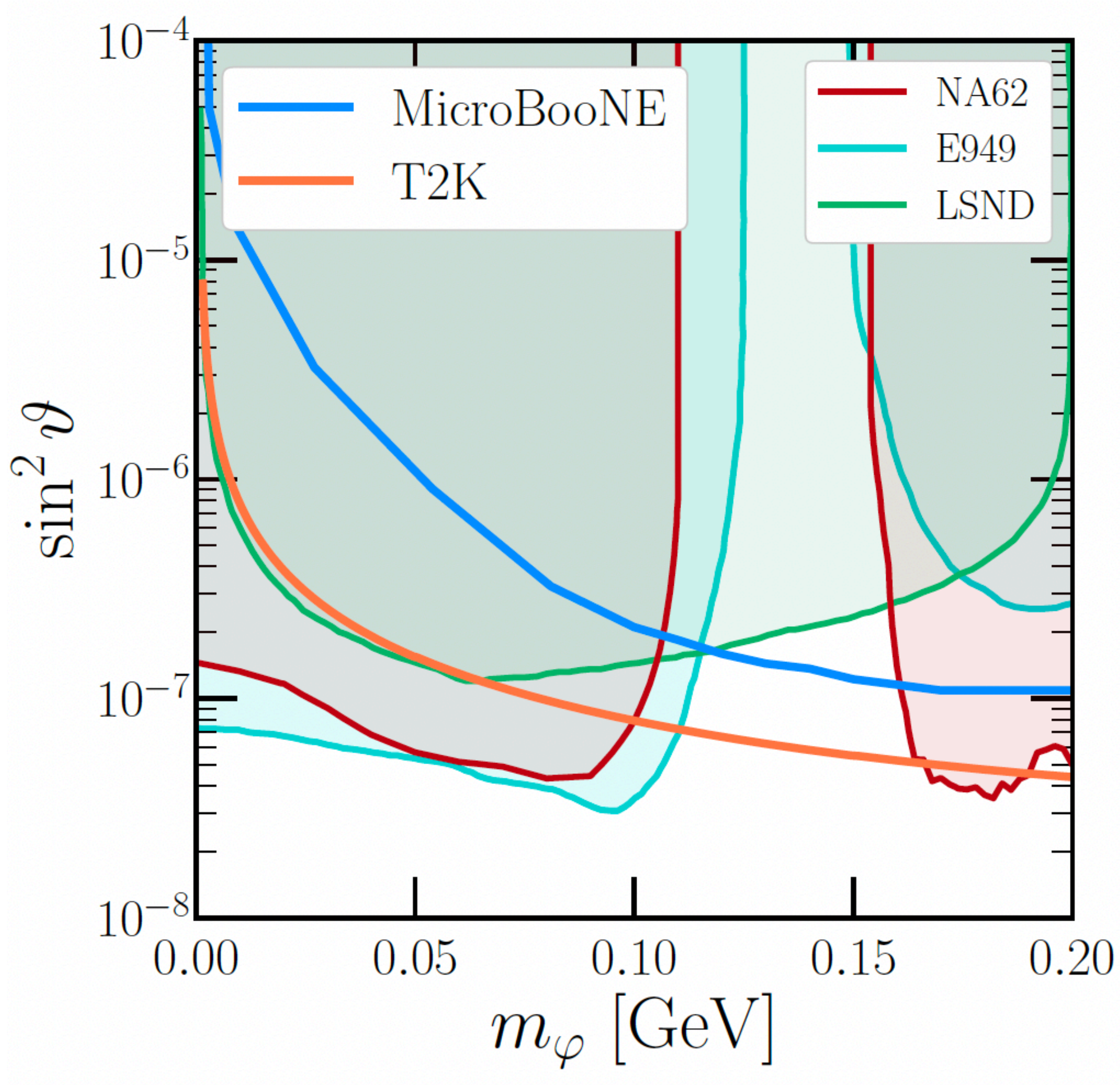
Simplified framework constraints and sensitivity

- Sensitivities shown to the branching ratio product as a function of the LLP mass and lifetime
- NA62 and E949 constrain branching ratio products below about 10^{-10}
- For a given LLP mass, there is some lifetime for which sensitivity is strongest, corresponding to when the lab frame decay length is approximately equal to the detector baseline (darker regions in the plots)



Reinterpretation within Higgs portal scalar

- The T2K ND280 HNL search in the $N \to e^+e^-\nu$ channel can be recast to the Higgs portal scalar model
- We map our T2K constraints on the simplified framework parameter space to the Higgs portal model parameter space, $m_\varphi - \sin^2\vartheta$, finding leading constraints in the ~ 100 MeV mass range



Interpretation in the advent of a signal excess

Measurement in the presence of a signal

- Next, consider a hypothetical future scenario in which DUNE ND-GAr observes 100 signals events. We attempt to address two questions:
  - How well can the properties of the LLP be measured?
  - How well can one distinguish between fully visible final states and those semi-visible final states with missing momentum?
- The final states kinematics are sensitive to the LLP mass and lifetime, as well as the underlying model. The event rate fixes branching ratio product.
- Determine the kinematic variables of final-state pairs from the reconstructed 4-momenta:
  - Total energy $E_{e^+e^-} = E_{e^+} + E_{e^-}$ — sensitive to the LLP lifetime
  - Invariant mass $m_{e^+e^-}$ — depends on parent LLP mass
  - Electron-positron opening angle $\theta_{e^+e^-}$ — sensitive to visible vs. semi-visible decays

Analysis for measurement & hypothesis testing

- Pseudo-data for DUNE ND-GAr is generated via Monte-Carlo simulation

- The simulated data are binned into 3d histograms (each of the 3 kinematic variables) with 20 bins in each dimension. The histogram is normalized to 100 total events.

- Compare the 3d histograms of the truth and a test point using the following test statistic,

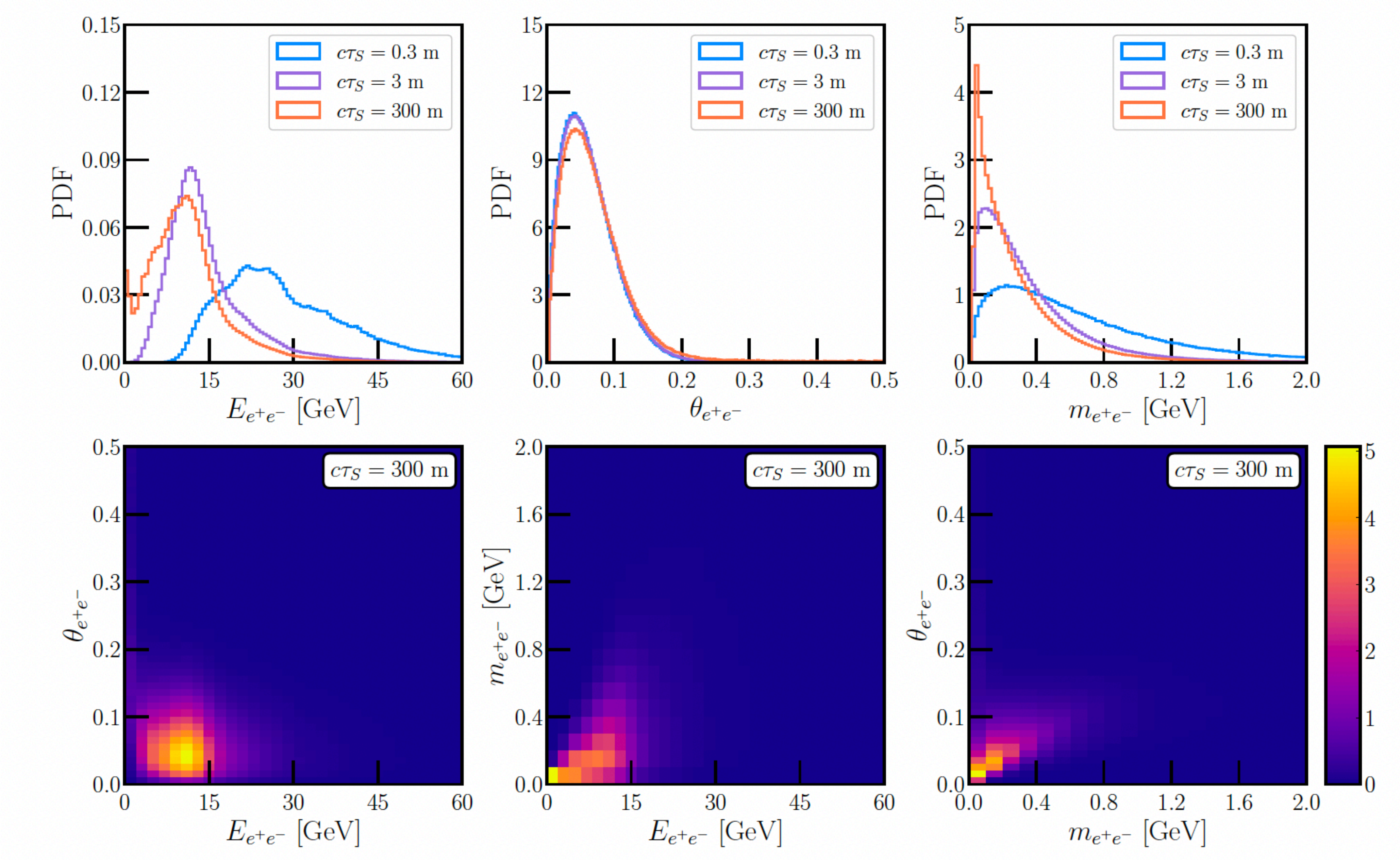
$$\chi^2 \equiv -2 \ln L(m_X, c\tau_X) = 2 \sum_{i=1}^{N} [\mu_i - n_i + n_i \ln \frac{n_i}{\mu_i}]$$

  with n_i = # of events expected in bin for the "truth" model, μ_i = # of events for the test hypothesis in the same bin

- Given that backgrounds in the DUNE ND-GAr are expected to be negligible, backgrounds are neglected in the test.

Signal kinematics (scalar case)

- Scalar simplified framework with mass fixed to $m_S = 50\,\mathrm{MeV}$
- Several notable features, e.g., short-lived scalars (30 cm decay length) prefer significantly larger $E_{e^+e^-}$, and due to imperfect energy resolution, those electrons/positrons display broader distributions in $E_{e^+e^-}$, $m_{e^+e^-}$

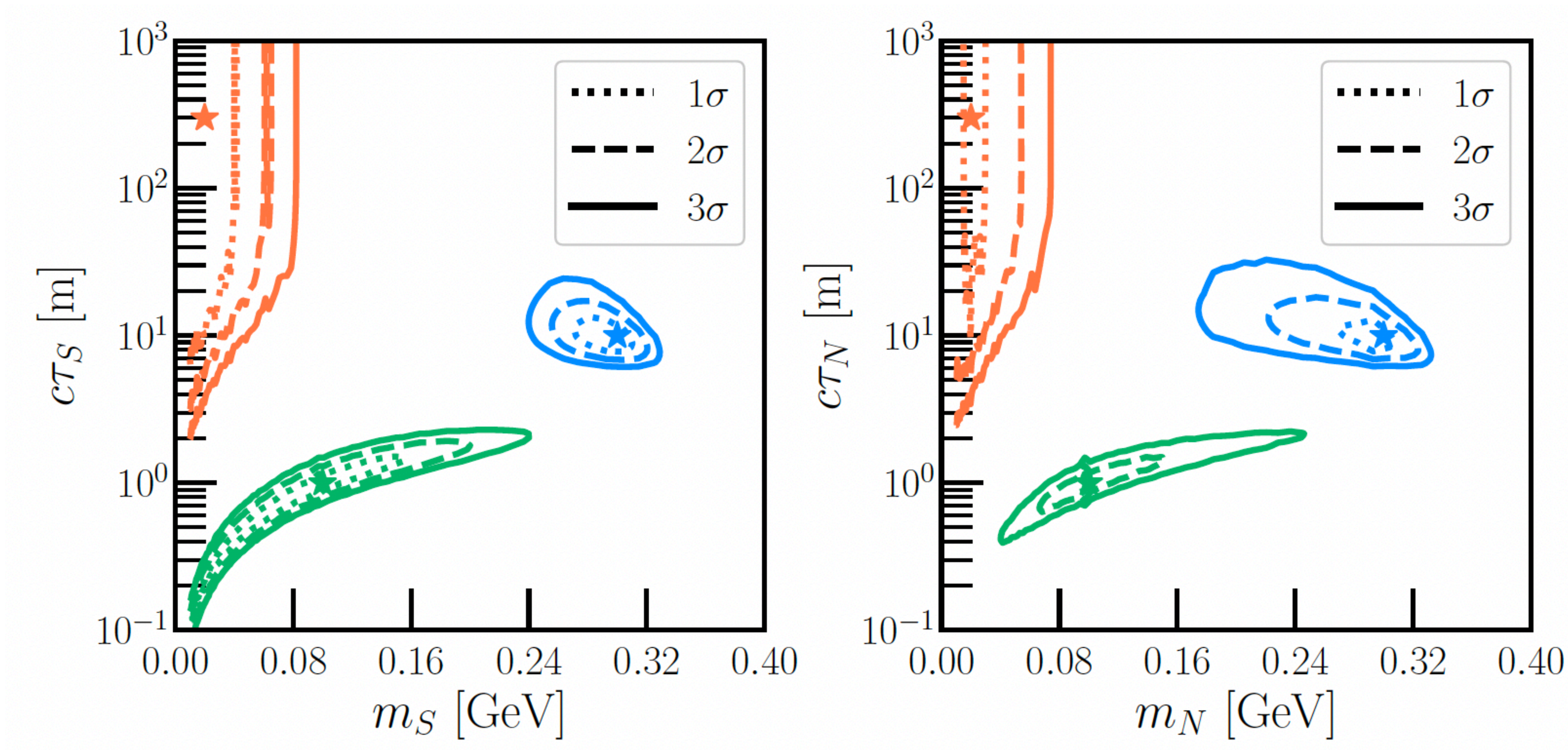


Mass and lifetime measurement potential

- Test measurement capability for three truth cases:

$$\{m_X, c\tau_X\} = \{20\,\text{MeV}, 300\,\text{m}\}, \{100\,\text{MeV}, 1\,\text{m}\}, \{300\,\text{MeV}, 10\,\text{m}\}$$

- Heavy, moderate-lifetime — LLP mass and lifetime may both be measured (blue)
- Long lifetime — only a lower limit on the lifetime may be obtained (orange)
- Short lifetime — challenging to measure the LLP mass (green)

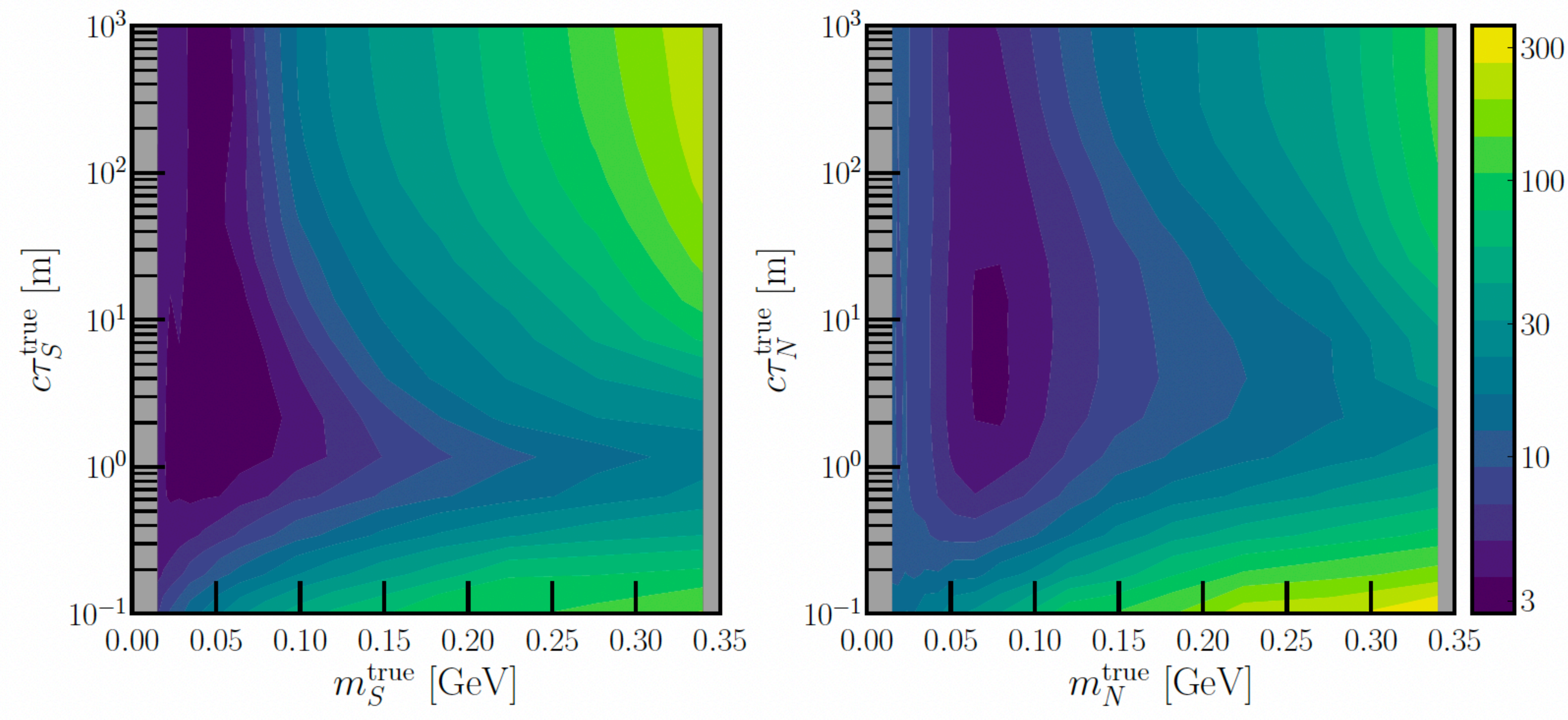


Scalar vs. Fermion discrimination (visible vs. semi-visible)

- We simulate "truth" data corresponding to one framework (scalar or fermion) and a corresponding mass/lifetime point $\{m_X^{\rm true}, c\tau_X^{\rm true}\}$, then fit the simulated data according to the other framework (fermion or scalar) with all mass lifetime pairs.
- We determine the mass/lifetime yielding the smallest test statistic

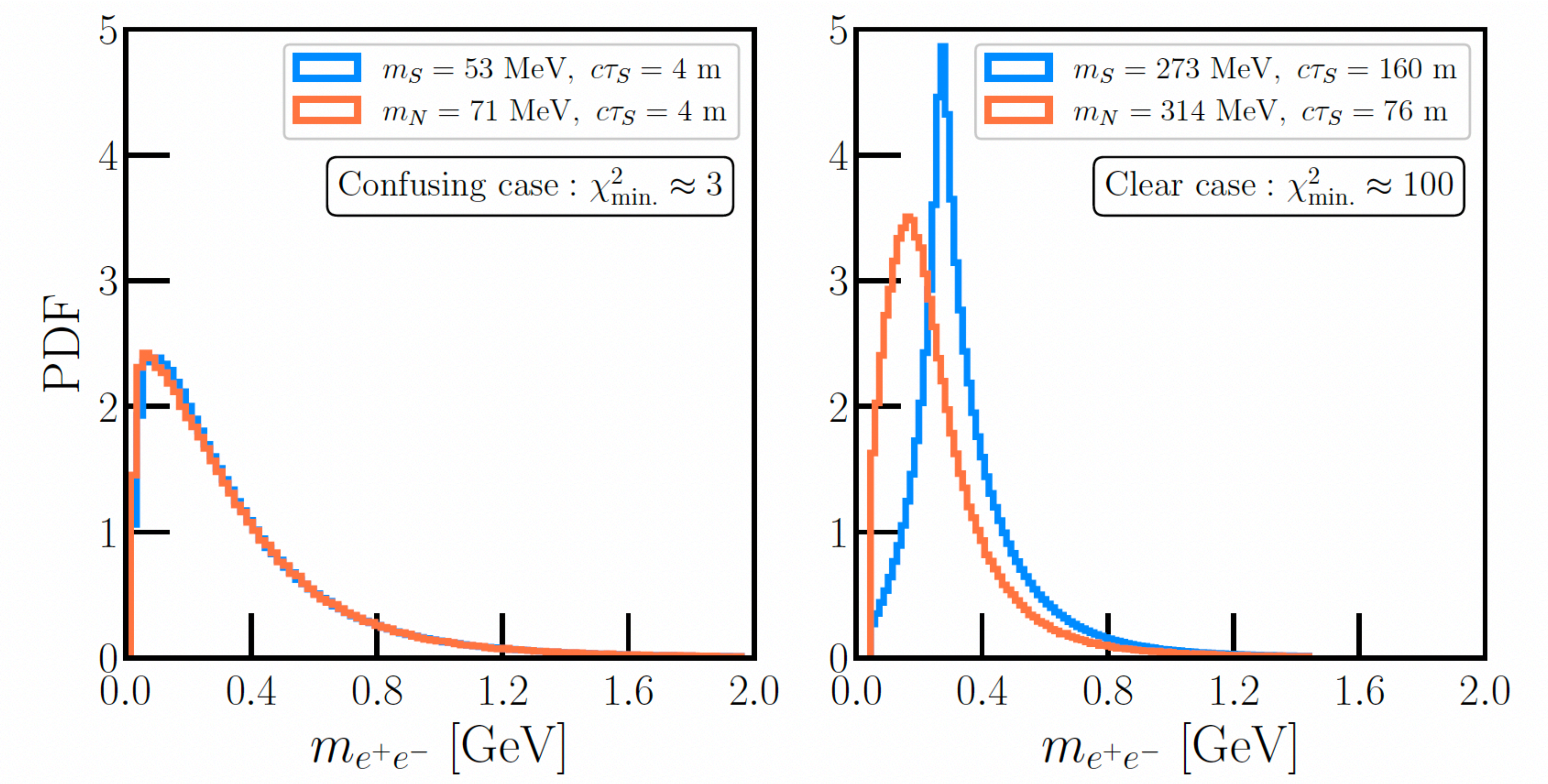
Minimum test statistic

Scalar truth fit to fermion | Fermion truth fit to scalar



Scalar vs. Fermion kinematics

- Kinematics of the scalar truth and best fit fermion share shown for a "confusing case" (small minimum χ^2) and a "clear case" (high minimum χ^2)



Simplified frameworks for other signatures of interest

- Other LLP signatures, with distinct production mechanisms and decays
  - Prompt production, such as in dark vector production through prompt neutral pion decays or proton bremsstrahlung
  - Different final states involving photons, muons, or hadrons
- Other scenarios of interest: dark matter (DM) production and re-scattering in near detector; inelastic DM; neutrino induced BSM signatures (e.g., dark neutrinos)
  - Potential challenge — how to to devise a minimal parameterization of scattering cross sections (elastic, up-, down-scattering) which adequately captures the kinematics of the scattered visible particles.
  - See Coloma et al. 2304.06765 for interesting recent work along this direction.

Summary and Outlook

- Simplified frameworks provide a flexible, model-independent framework in which to interpret the results BSM searches. It is complementary to the model-specific approach, which is also important and should continue.

- Simplified frameworks are specified by a small number of primary quantities (masses, lifetimes, branching ratios, cross sections, etc.), which directly determine the event rates and final state kinematics for the signature of interest.

- We have illustrated the simplified framework approach for the case of new LLPs produced in Kaon decays and decaying to e^+e^-.

- It would be interesting to formulate and study simplified frameworks for a variety of other BSM signatures of interest for neutrino experiments.

- Experiments should use simplified frameworks to interpret searches!