Simplified Frameworks for Long-Lived Particles at Neutrino Facilities

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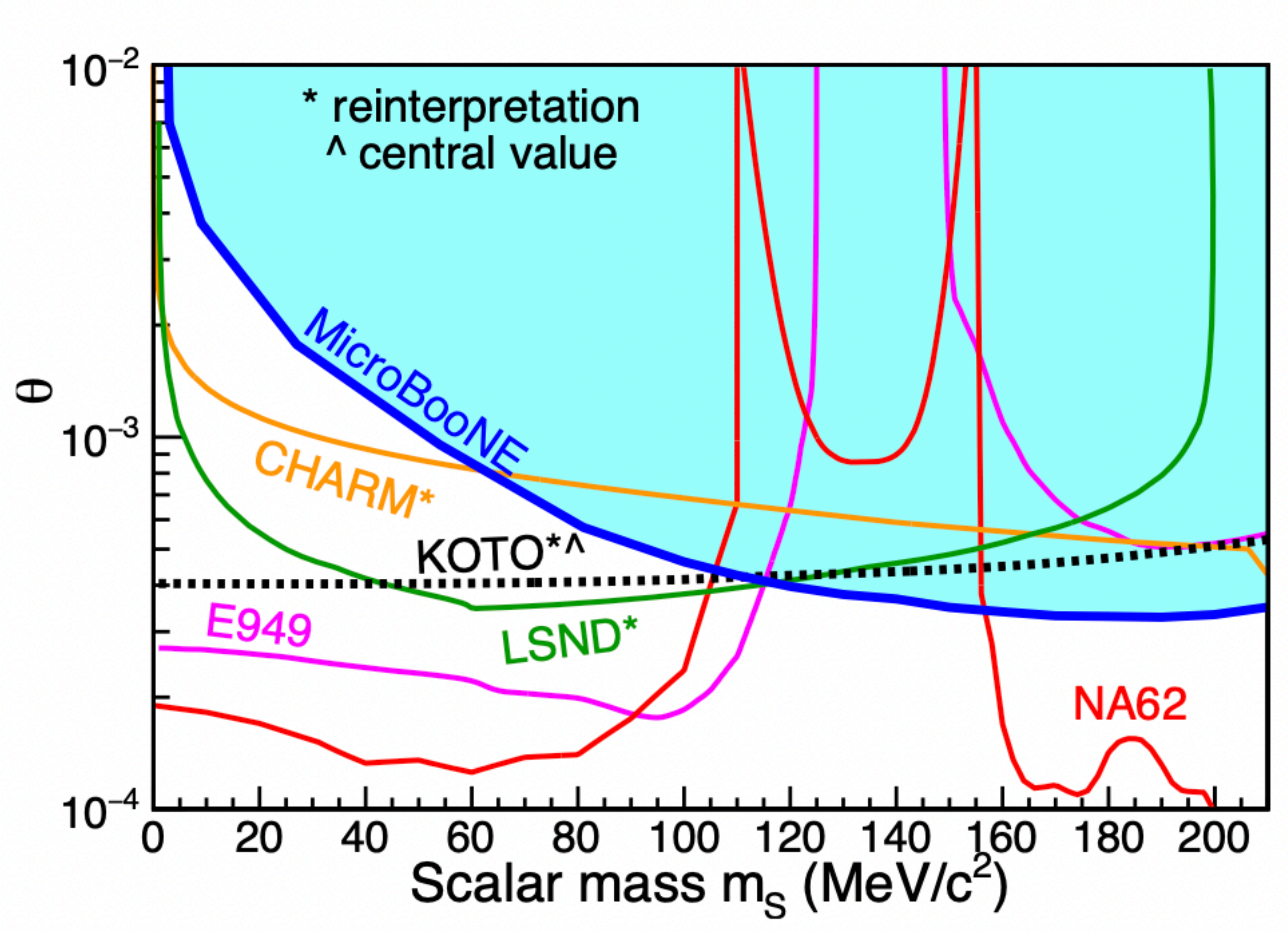
Motivation for A More Flexible Framework

- Neutrino experiments, such as MicroBooNE, T2K, and DUNE, have large luminosity and can offer a powerful approach in the search for new light weakly coupled physics.
- The "top-down" approach is warranted and should continue, 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, a more flexible theoretical framework allows higher efficiency of the experiments.
- The presentation of experimental results in a simplified framework would more readily allow for reinterpretations in a variety of models, including those that have not yet been envisioned.
- 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.



Example of experimental results presented in a model-specific parameter space for Higgs-Portal Scalar (HPS)

[P. Abratenko et.al, 2021, arXiv: 2106.00568]

Simplified Framework! (What it is?)

- characterized by quantities that most directly determine the event rates and final state kinematics of the signal under consideration and can be applied to a class of models
- The relevant quantities include masses and lifetime of the particles in interest, decay branching ratio, production and scattering cross sections, production energy and position distributions, etc.
- These primary quantities that are directly constrained or measured in particular experimental analysis can be mapped to more complicated and complete descriptions (simplified model Lagrangian, Effective Field Theories, UV completion models).
- Models with different detectable signatures are categorized into different frameworks! In principle, a simplified framework approach can be developed for each signature of light BSM states that have been explored in recent years.

Relevant Quantities for Signal Rate Determination

- Determine the flux of particles X entering the detector in certain time range: $\Phi_X = \frac{N_{\text{POT}} c_{\mathfrak{m}}}{A_{\text{Det.}}} \varepsilon\left(\mathfrak{m}; m_X, \ldots\right) \text{Br}\left(\mathfrak{m} \to X\right)$

  (Note that $\varepsilon\left(\mathfrak{m}; m_X, \ldots\right)$ can be estimated using Monte Carlo simulation and can depend also on other particles that emerge from the decay.)

- Determine the energy (E_X) and spatial distribution (along the beam axis, z) of the X particles from the decay using simulation, which gives the differential flux $d^2\Phi_X / dE_X dz$

- Finally, determine the number of event for the final state signal of interest:

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

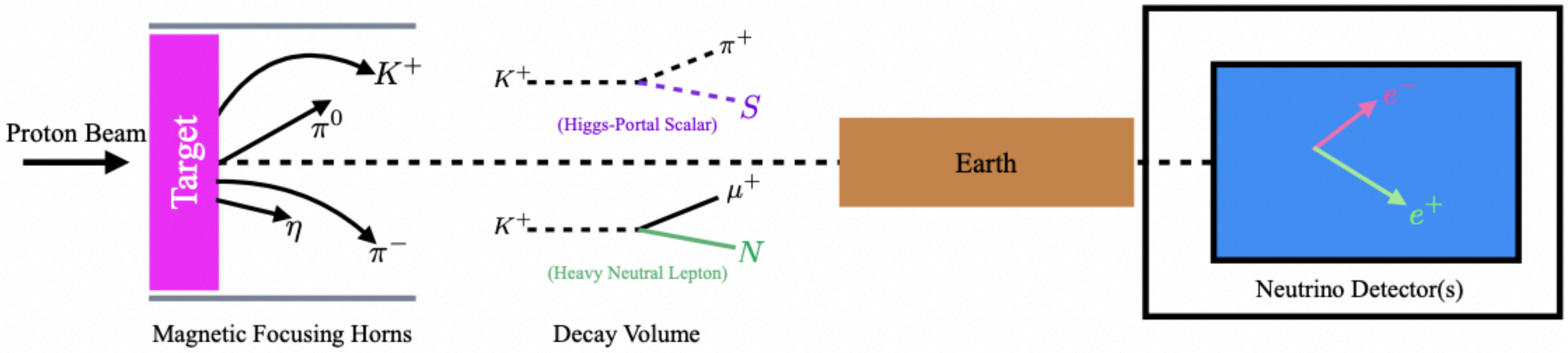
with $P_{\text{Decay}}\left(E_X, \zeta\right) = \frac{1}{\gamma_X \beta_X c\tau_X} e^{-\frac{\zeta}{\gamma_X \beta_X c\tau_X}}; \quad \gamma_X = E_X / m_X$

$\Longrightarrow$ Once a specific parent meson $\mathfrak{m}$ and signal channel F are chosen, beyond experiment-specific information, $N^F_{\text{sig.}}$ depends only on 3 parameters: $\{m_X, c\tau_X, \text{Br}\left(\mathfrak{m} \to X\right) \times \text{Br}\left(X \to F\right)\}$

Simplified Framework Example: LLPs at neutrino experiments

- Consider a simplified framework for long-lived particles (LLPs) at neutrino experiments, specifically meson decaying into a new particle X and X decaying into some final states in the neutrino detector.

- Our work focuses on $K^{\pm} \to \pi^{\pm} + X$ and $X \to e^{+}e^{-}(+\nu)$, and we consider two distinct cases:
  - Scalar case with long-lived neutral scalar S: $\{m_S,\ \ c\tau_S,\ \ \mathrm{Br}(K \to \pi S) \times \mathrm{Br}(S \to e^{+}e^{-})\}$
  - Fermion case long-lived neutral fermion N: $\{m_N,\ \ c\tau_N,\ \ \mathrm{Br}(K \to \mu N) \times \mathrm{Br}(N \to e^{+}e^{-}\nu)\}$



Example Mapping to Theoretical Description

- Simplified-model Lagrangian: $\mathscr{L} \supset -\frac{1}{2}m_S^2 S^2 - g_{K\pi} S\pi^- K^+ + \mathrm{h.c.} - g_e S\bar{e}e - g_\chi S\bar{\chi}\chi$ (scalar case)

  In the case of the minimal Higgs portal with a "dark Higgs" boson,

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

  The coupling $g_{K\pi}$ arises from the quark-level effective Lagrangian: $\mathscr{L} \supset -[g_{ds} S\, \bar{d}_L s_R + \mathrm{h.c.}]$ with

$$g_{K\pi} = g_{ds}\langle \pi | \bar{d}_L s_R | K \rangle, \quad |\langle \pi | \bar{d}_L s_R | K \rangle| = \frac{1}{2}\frac{m_K^2 - m_\pi^2}{m_s - m_d}$$

- EFT that respect the SM gauge symmetries: $\mathscr{L} \supset -\frac{(C_d)^j_i}{\Lambda} S\, \overline{Q}^i_L H\, d_{Rj} - \frac{(C_e)^j_i}{\Lambda} S\, \overline{L}^i_L H\, e_{Rj} + \mathrm{h.c.}$

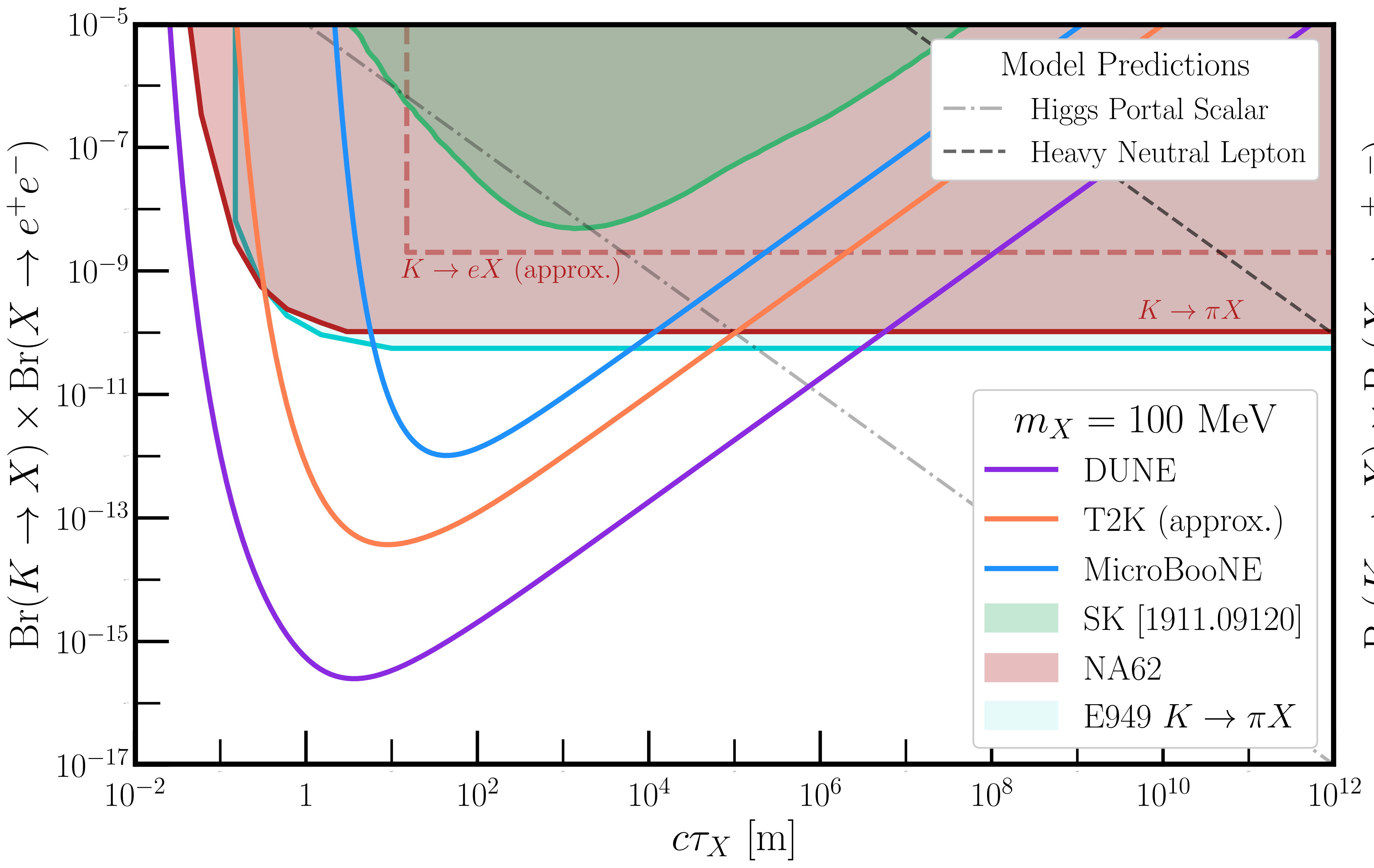
- UV completion example: $\mathscr{L} \supset |D_\mu \Phi|^2 - M_\Phi^2 |\Phi|^2 + \cdots - [(y'_d)^j_i\, \overline{Q}^i_L\, \Phi\, d_{Rj} + (y'_e)^j_i\, \overline{L}^i_L\, \Phi\, e_{Rj} - A S H^\dagger \Phi + \mathrm{h.c.}]$

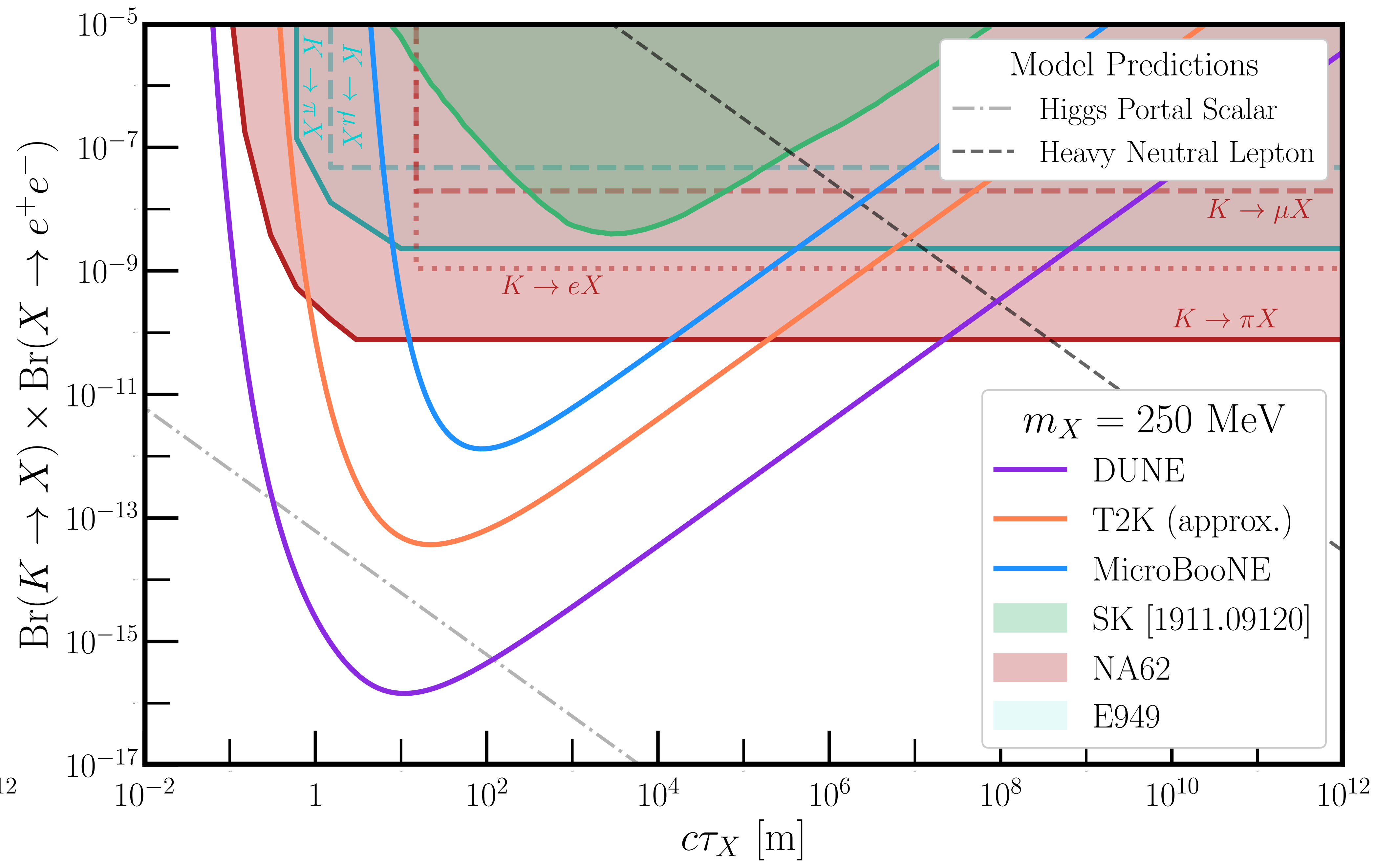
  Integrating over the scalar doublet Φ gives $(C_d)^j_i = \frac{(y'_d)^j_i A}{M_\Phi^2}$, $\quad (C_e)^j_i = \frac{(y'_e)^j_i A}{M_\Phi^2}$

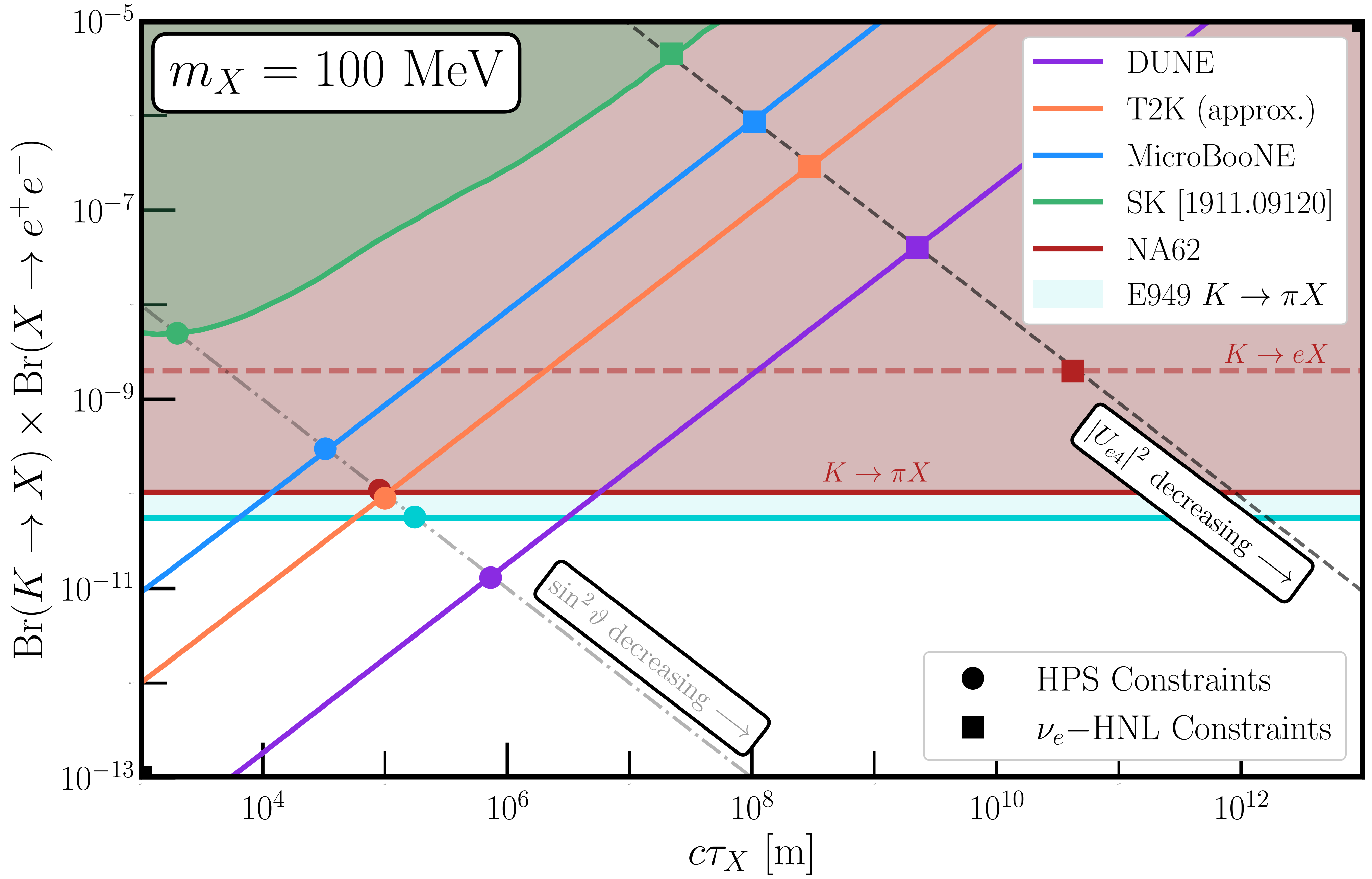
Similar construction of the effective Lagrangian and UV completion can be made for the neutrino portal and the vector portal, etc.

Experimental Simulation

- MicroBooNE KDAR (Kaon Decay At Rest) in NuMI [P. Abratenko et.al, 2021, arXiv: 2106.00568]
  - Reproduce the results using the given mass-dependent reconstruction efficiency and extended the mass range from below 210 MeV to just below the kaon mass
- T2K ND280 [K. Abe et.al, 2019, arXiv: 1902.07598]
  - utilize the heavy neutrino flux distributions to obtain the spectrum of $d\Phi_X/dE_X$;
  - take the spectrum provided for massless X which is properly rescaled to mitigate model assumptions and to match the official T2K results in our simulations
- DUNE [Barryman et.al, 2019, arXiv: 1912.07622]
  - make use of charged kaon distributions from the DUNE Beam Interface Working Group;
  - Incorporate the X flux distribution by the $K \to X$ decays simulation using Monte Carlo

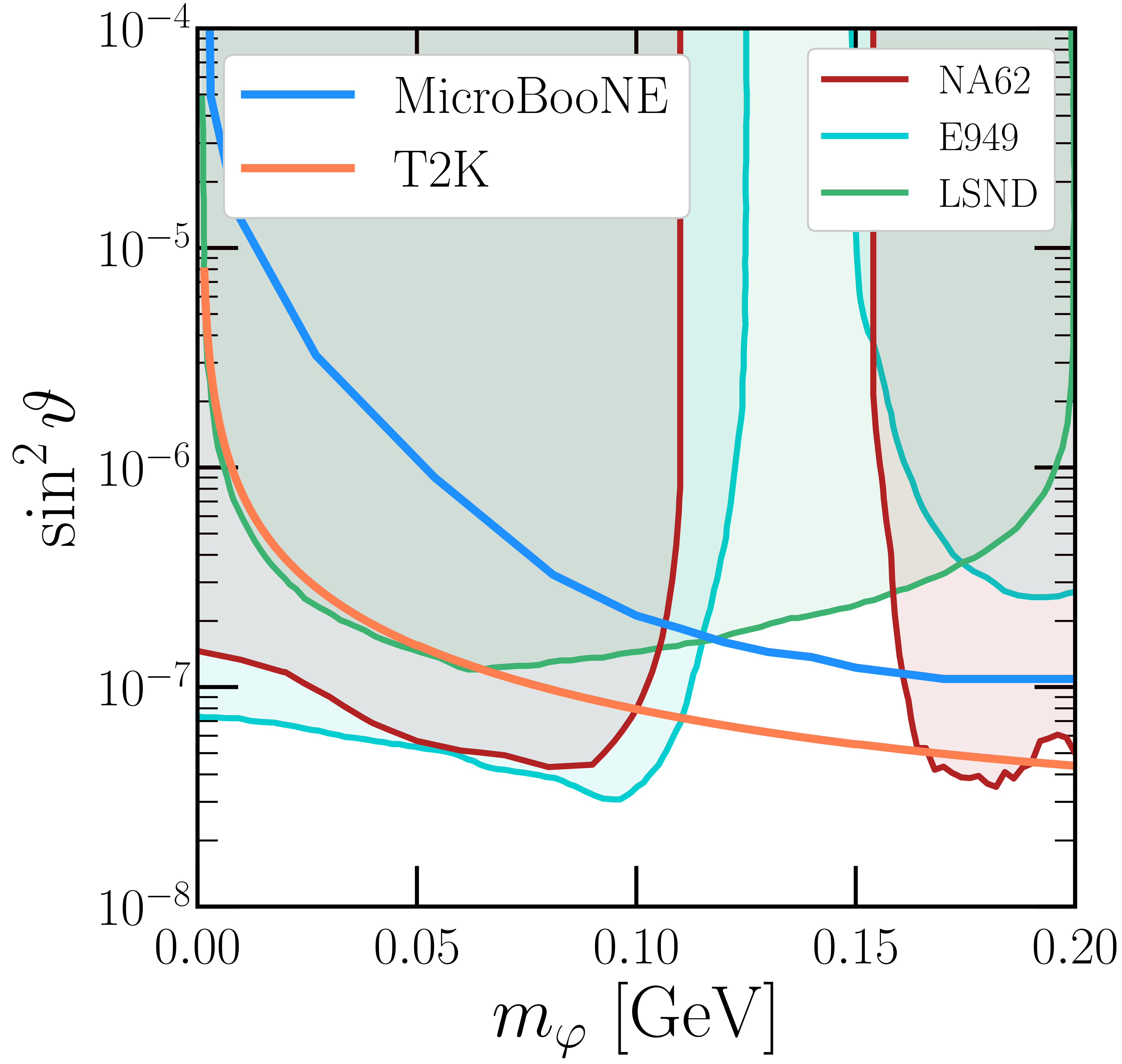






←Model-specific interpretation using simplified framework parameter space

Updated Constraints on Dark Higgs Parameter Space



Measurement in the Presence of Signal

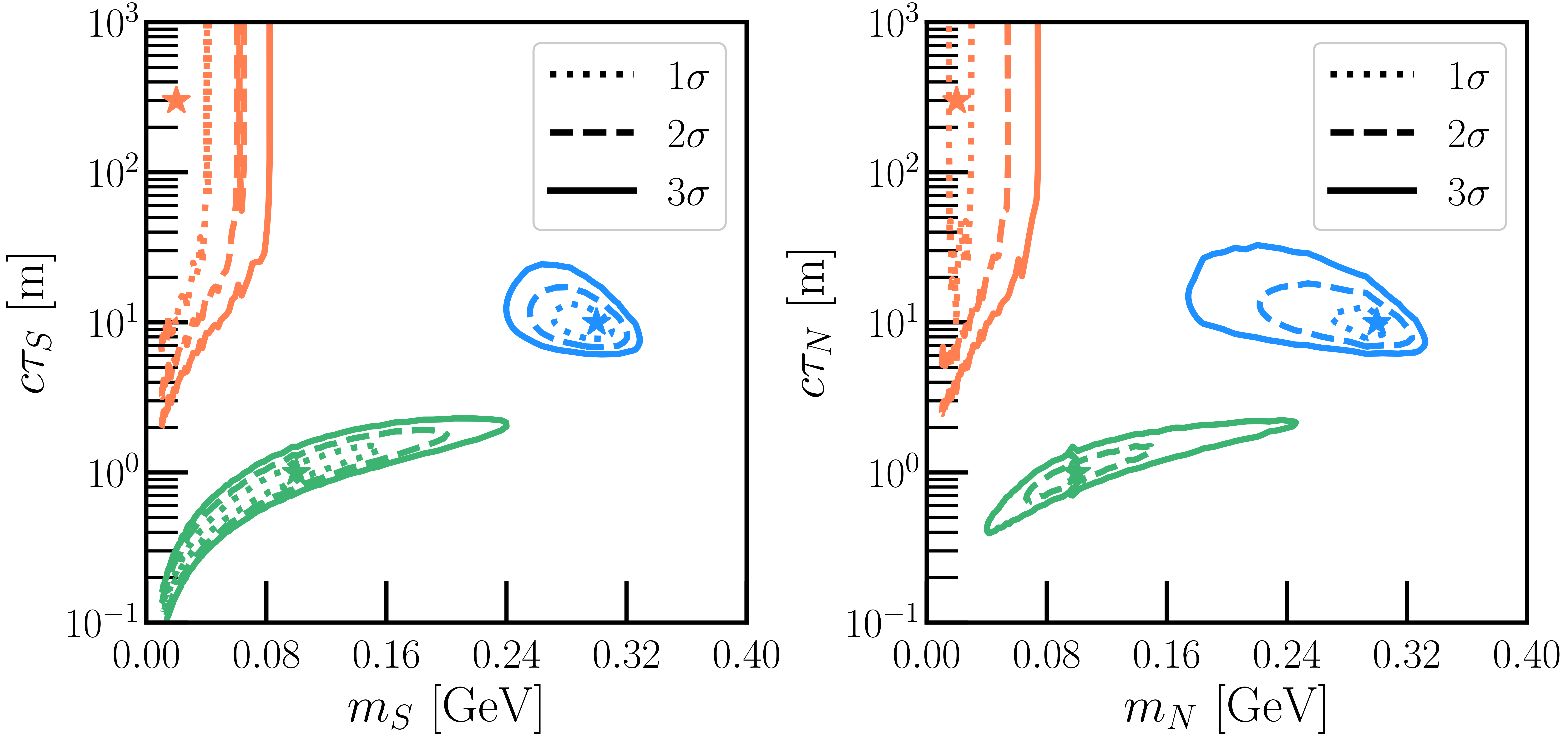
Consider a possible future scenario in which a 100-event signal excess in a LLP search is observed at DUNE ND-GAr, we attempt to answer two questions:

- Q1: How well the properties of a LLP can be measured?
- Q2: How well the discrimination can be made between fully-visible final states and partially visible final states?

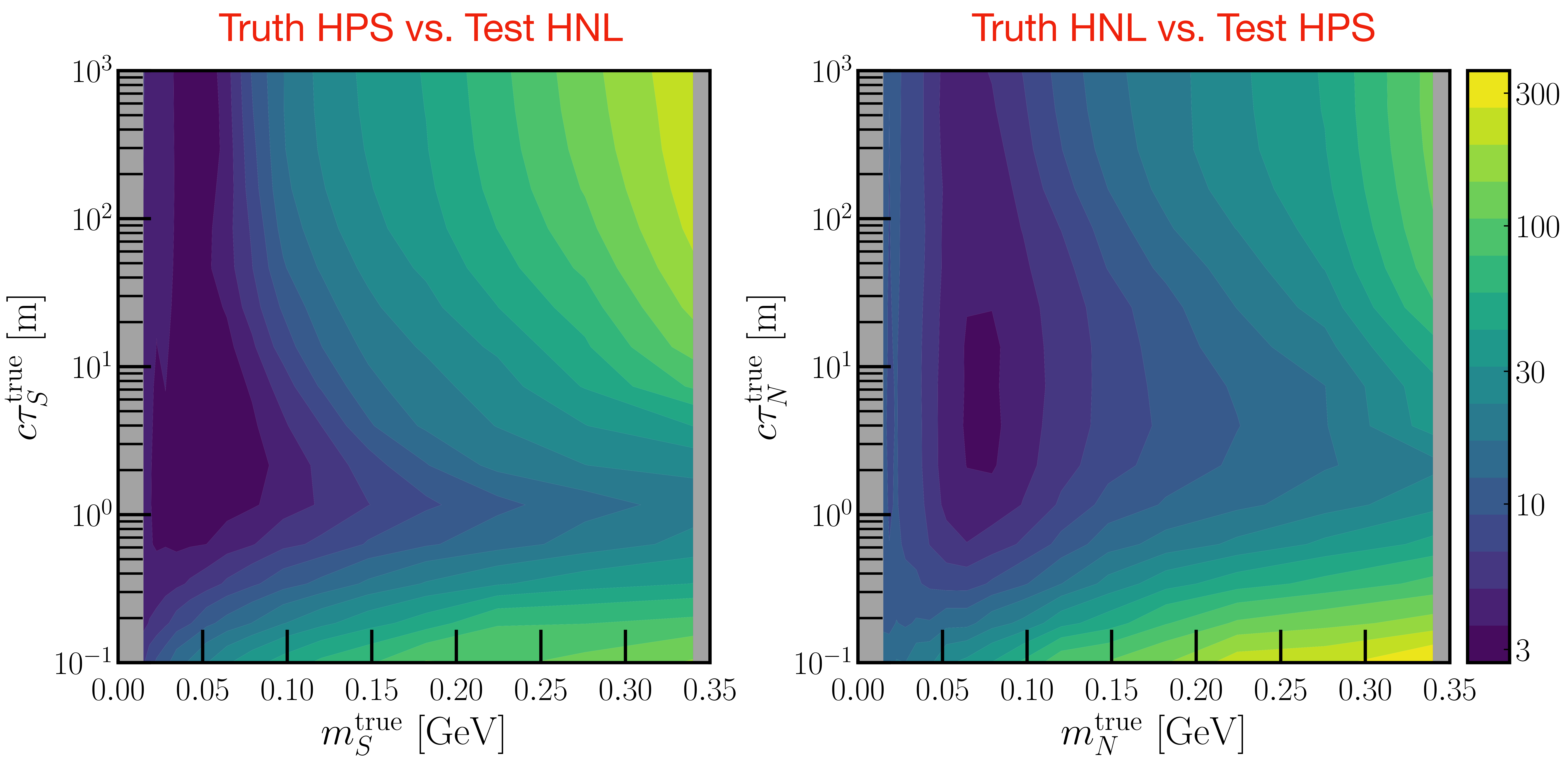
- The e^+e^- final states kinematics are sensitive to the LLP mass and lifetime, but not the branching ratio product. This allows us to represent the result in the $m_X - c\tau_X$ parameter space.
- Determine the kinematic variables of final-state e^+e^- pairs from the reconstructed 4-momenta:
  - Total energy $E_{e^+e^-}$, serving as a way of measuring the lifetime $c\tau_X$
  - Invariant mass $m_{e^+e^-}$, which is a good proxy for the parent mass m_X
  - Opening angle between e^+ and e^-, $\theta_{e^+e^-}$, which helps enhance the discrimination power between models

Mass-Lifetime Measurement Potential

($\{1\sigma,\ 2\sigma,\ 3\sigma\}$confidence-level regions, corresponding to $\Delta\chi^2 = \{2.3,\ 6.18,\ 11.83\}$)



Model Discrimination Potential: HPS vs HNL



Challenges & Outlook

- A variety of other proposed LLP scenarios involving different production mechanisms and decays:
  - prompt production mechanisms
  - different final states involving photons, hadrons, etc.
  - Production of dark matter and its subsequent scattering in the near detector

$\Longrightarrow$ It would be interesting to formulate and analyze simplified frameworks for other signatures of interest at neutrino beam experiments.

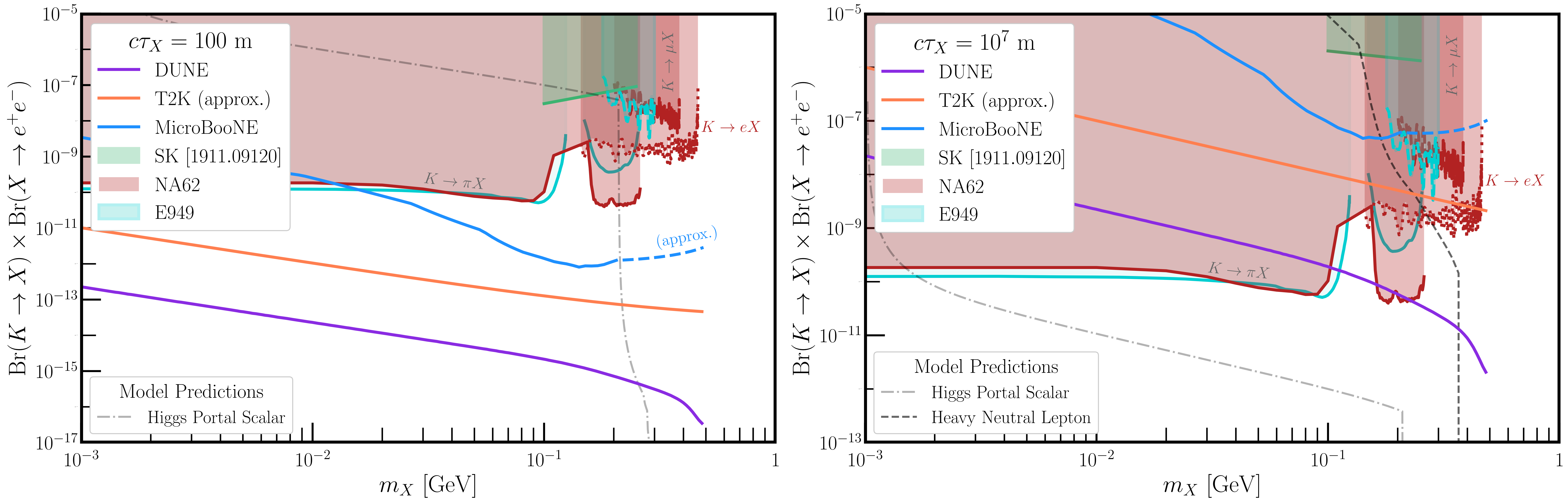
- one potential challenge is to devise a minimal parameterization of the cross section which adequately captures the kinematics of the scattered final state particle.

- Though our work focuses on accelerator fixed-target neutrinos beam experiment, it is likely that a simplified framework approach may be generally useful for a variety of experiments/facilities searching for LLP signatures, such as ATLAS, CMS, LHCb, Belle-II, NA62, FASER, FASERnu, SND@LHC, the Forward Physics Facility, MATHUSLA, CODEXb, SHiP, etc.

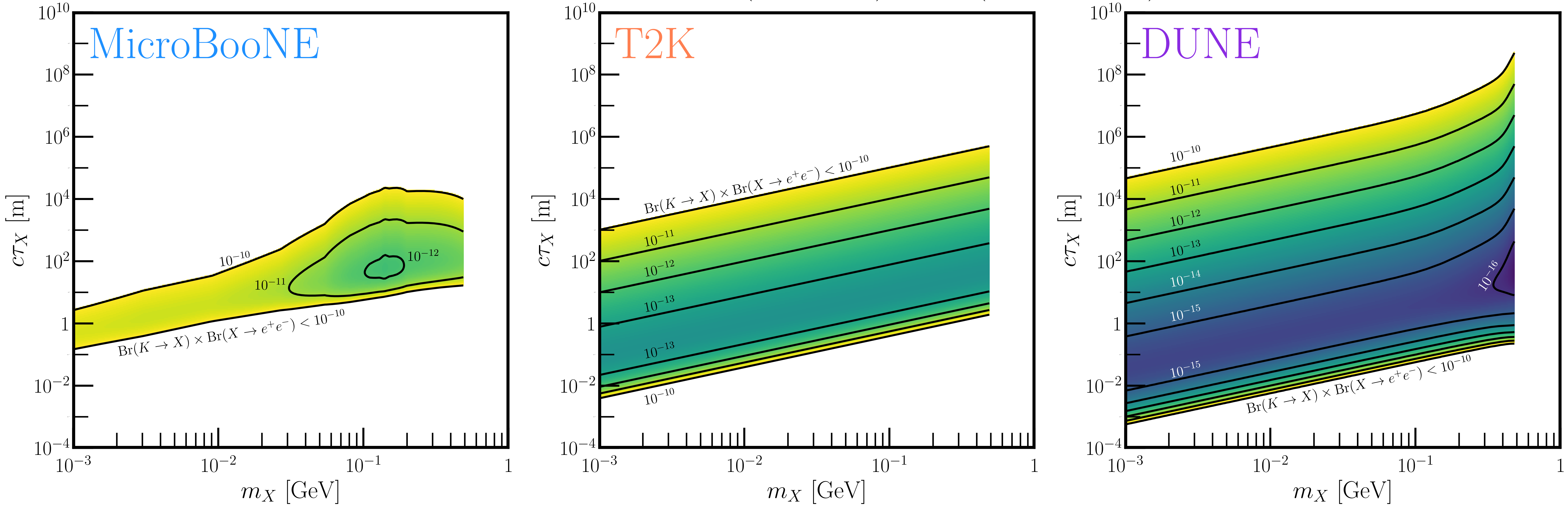
Summary & Conclusion

- Within the simplified framework approach, the results of experimental searches can be framed as constraints or measurements of the related primary quantities (such as mass, lifetime).
- Characterizing searches using this approach will allow for straightforward reinterpretations in a variety of more complete theoretical constructions (simplified models, EFTs, and UV completions).
- The simplified model approach not only allows us to reproduce and apply individual experimental analyses to a wide variety of model-specific scenarios but also allows for extension of the model scenarios in new and non-trivial ways.
  - Side benefit: We derived new leading constraints on the HPS model from a search for HNLs at T2K.
- We provided interpretations for a possible scenario in which a 100-event signal excess is observed at DUNE in the future.
  - In this case, one can extract measurements of the simplified framework parameters such as LLP mass and lifetime.
  - Model discrimination is favorable for some portions of detectable new-physics parameter space but more challenging for some other.

Backup Slides



Constraints on $\mathrm{Br}(K \to X) \times \mathrm{Br}(X \to e^+e^-)$



Simulation Method for Hypothesis Testing

- The pseudo-data for DUNE is simulated using Monte-Carlo method and our private code.

- The simulated data is binned into 3d histogram with respect to each of the 3 kinematic variables, with 20 bins in each dimension. The histogram is then normalized to 100 events.

- Compare the 3d histograms of the truth and a test point using Poissonian χ^2 test statistics (for possibly low bin counts) and scan over the $m_X - c\tau_X$ parameter space,

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

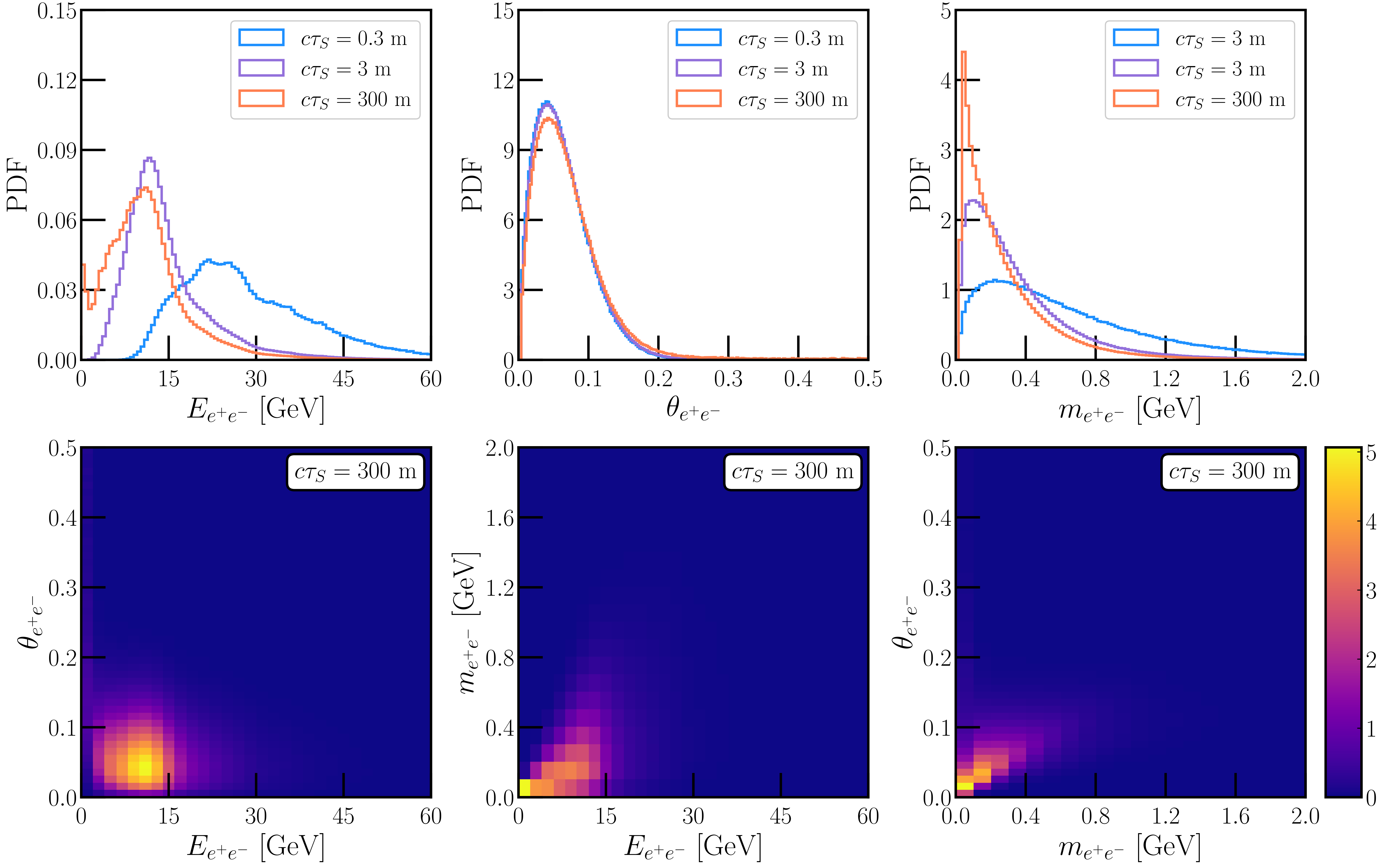
  with n_i = #events expected in bin i for the "truth" model, μ_i = # for the test hypothesis in the same bin.

- Given the predicted backgrounds of e^+e^- events in the DUNE ND-GAr are negligible, the backgrounds are neglected in the χ^2 test.

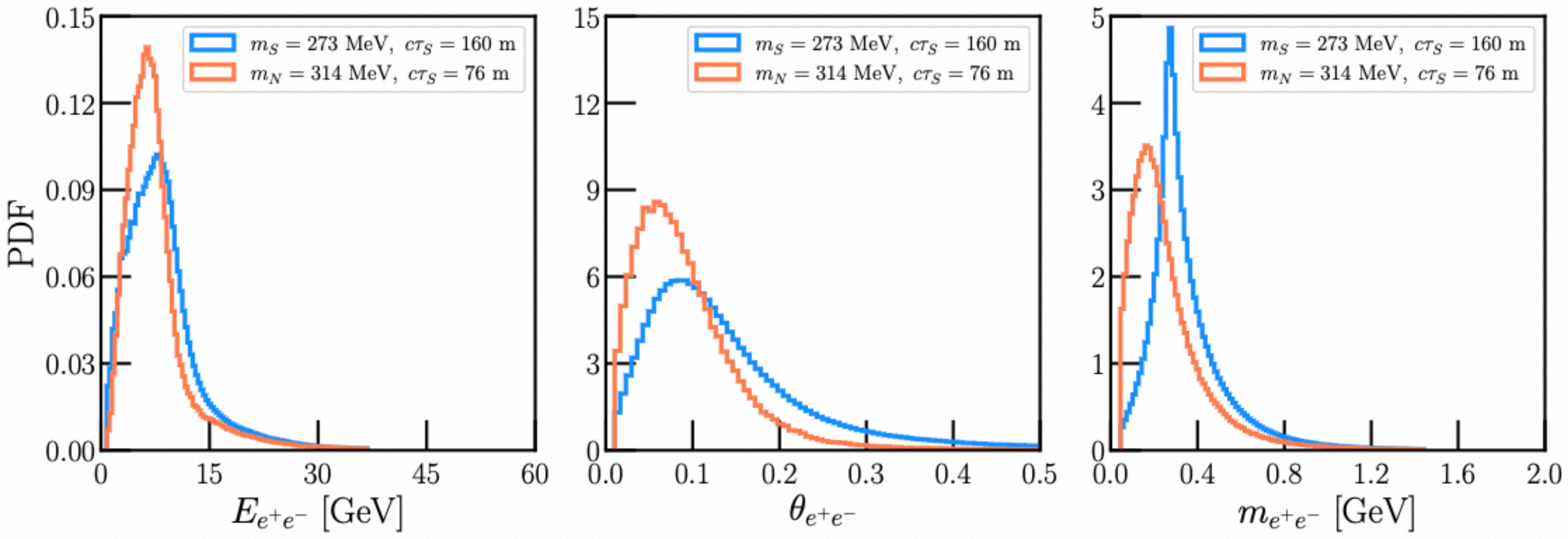
- To determine the parameter estimation capability, choose a truth $\{m_X, c\tau_X\}$ and scan over the $m_X - c\tau_X$ parameter space, then estimate the contours of $\Delta\chi^2$ with respect to the minimum corresponding to difference CLs.

- For discrimination between two models, assume one is true and choose a $\{m_X, c\tau_X\}$, then compare this truth point against all $\{m_X, c\tau_X\}$ of the other model and determine the minimal $\Delta\chi^2_{model}$ obtained in this process— the larger $\Delta\chi^2_{model}$ means clearer distinction between two model hypotheses.

Simulated-Event Kinematics for Hypothesis Testing



(Clear case)



A zoom-in comparison of the kinematic variable distributions for model discrimination

(Confusing case)