part 2

Connections to BSM

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Scenario 1: Little/No SM Background

Scenario 2:
Theoretically Clean SM Background

(picking up with S2p2)

Scenario 3: Experimentally Measurable Bkg.

Back to our Simple "Dark Photon" $U(1)$

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

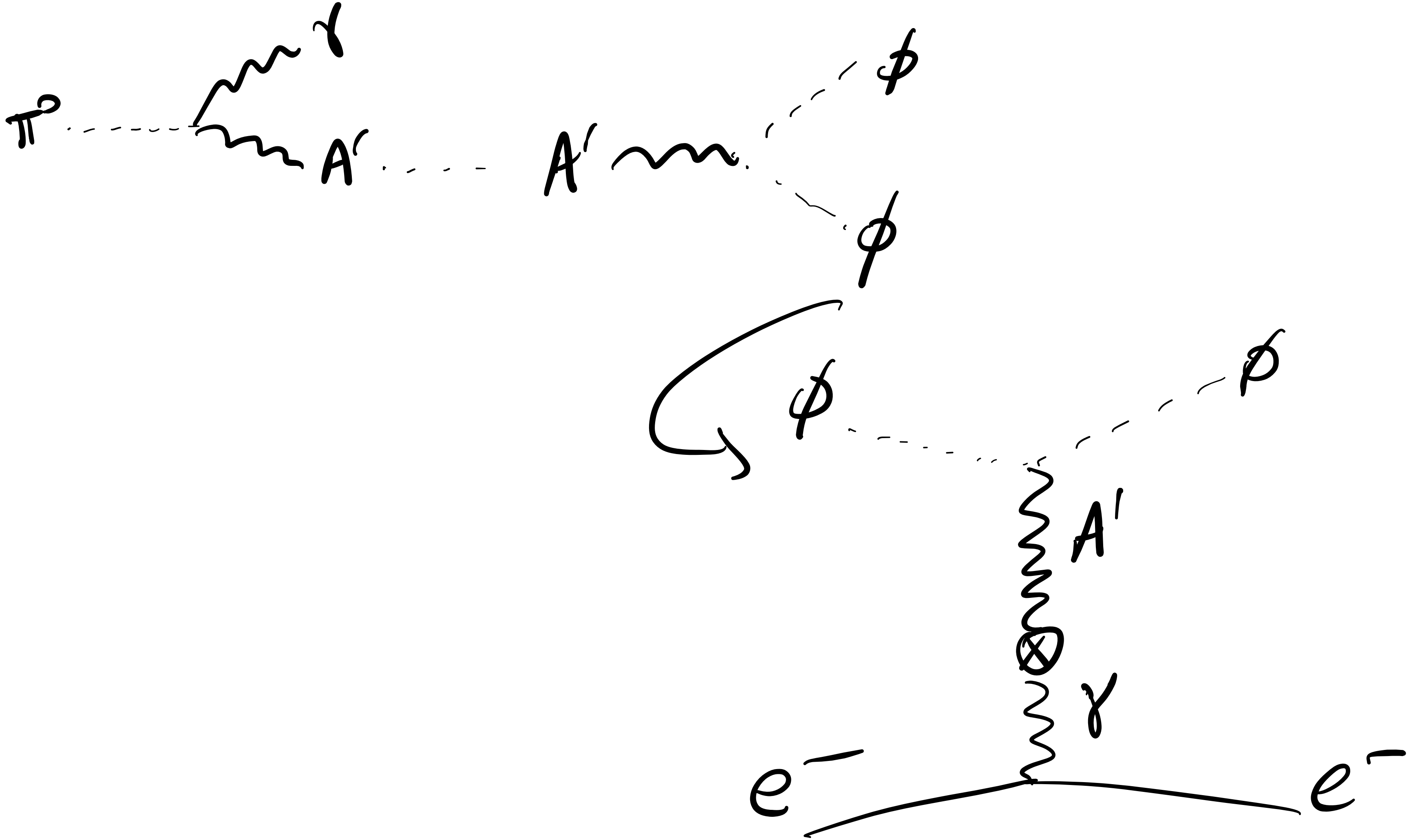
…plus one more ingredient

$$\mathcal{L} \mathrel{+}= |D_\mu \phi|^2 - m_\phi^2 |\phi|^2$$

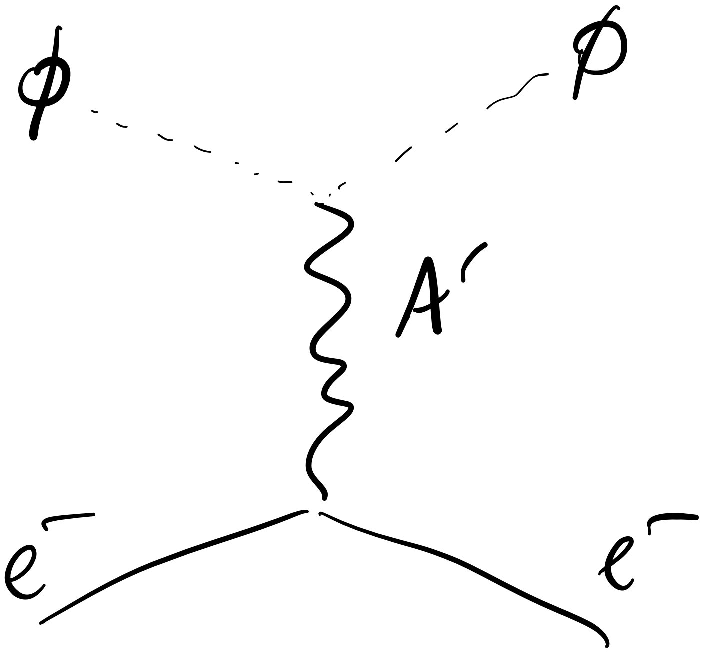
↳ Scalar Particle with Mass m_ϕ

$\phi - A'$ with Gauge Coupling $g_D \Rightarrow \alpha_D = g_D^2/4\pi$

Impact in Neutrino Facilities?



Advantages of Light DM in Neutrino Beam



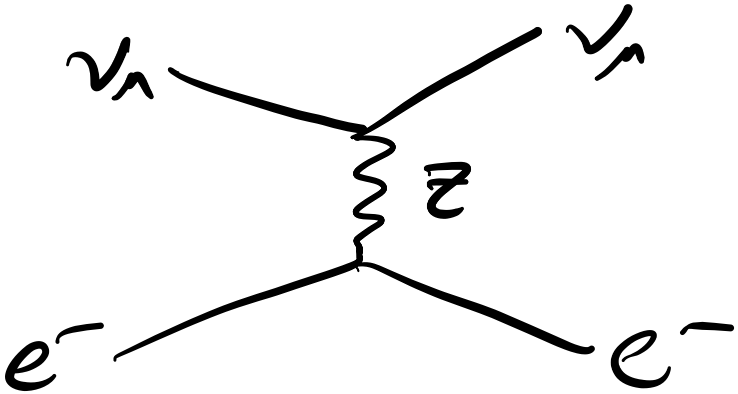
* ϕ Boosted: ~ GeV energies for $\mathcal{O}$(MeV) masses.

* $\mathcal{M} \sim \frac{1}{t - m_{A'}^2}$

  ↳ $t = -2 m_e E_e^{rec.}$

* Many Target e^-

Problems of Light DM in Neutrino Beam!



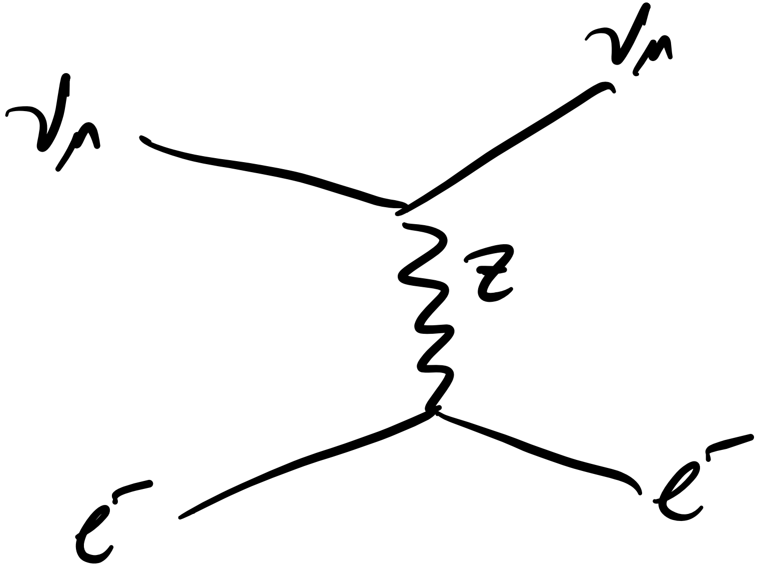
Why is this an existential problem?

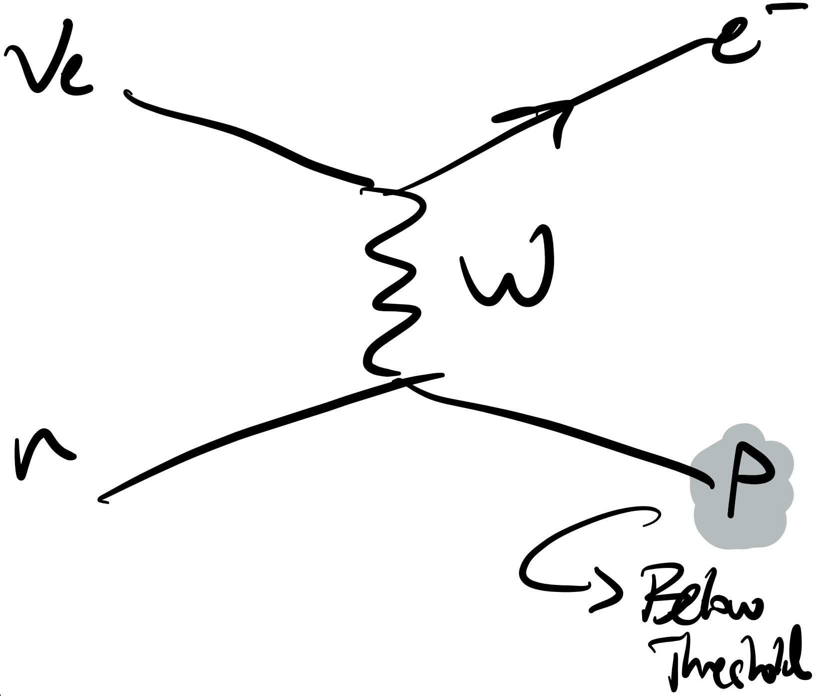
× $\sigma(\nu_\mu e^- \to \nu_\mu e^-)$ very well understood

$\Rightarrow \Phi(E_\nu)$ constrained by this process

Aside: νeES vs. ν_e CCQE

Consider the following two processes:

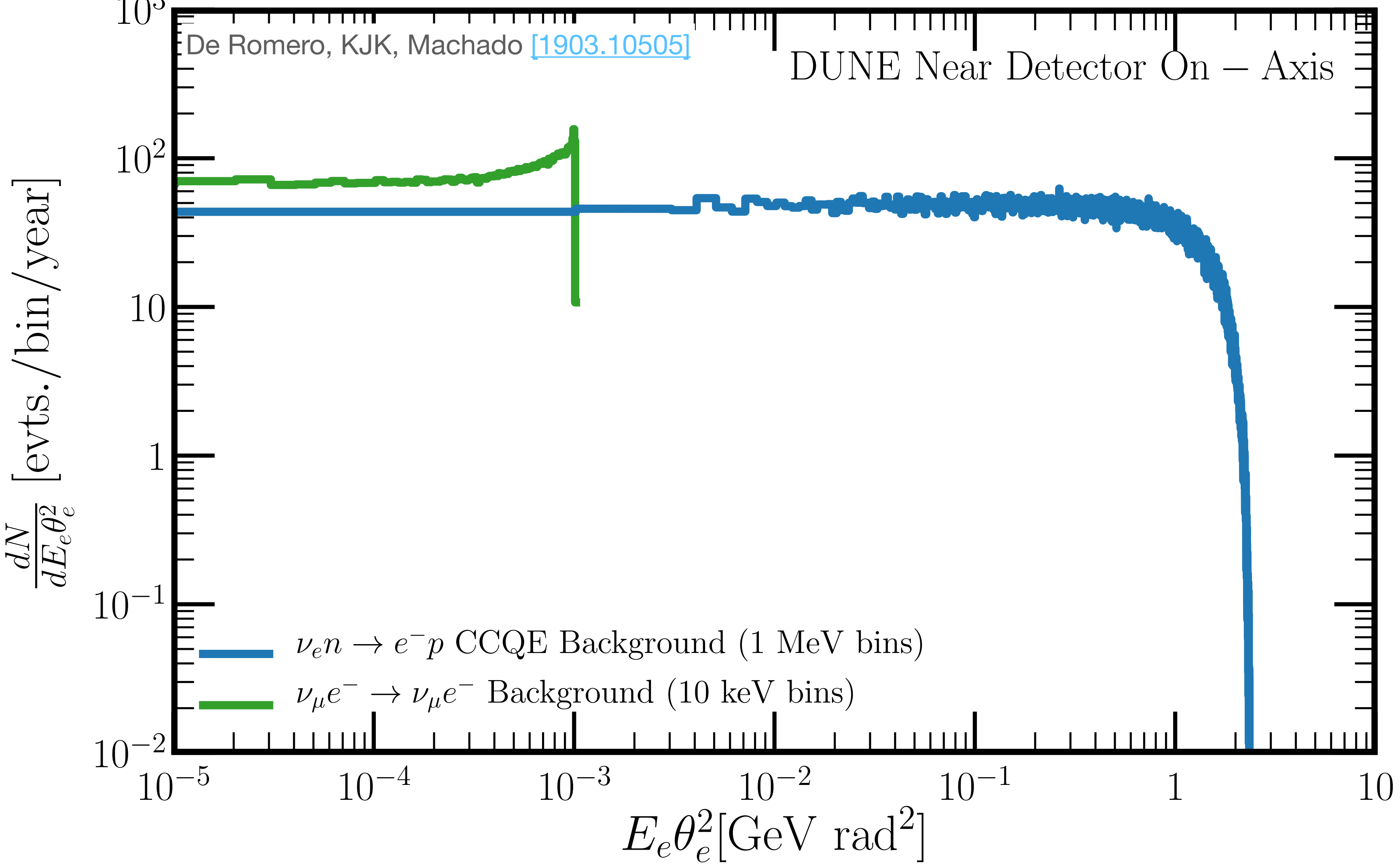




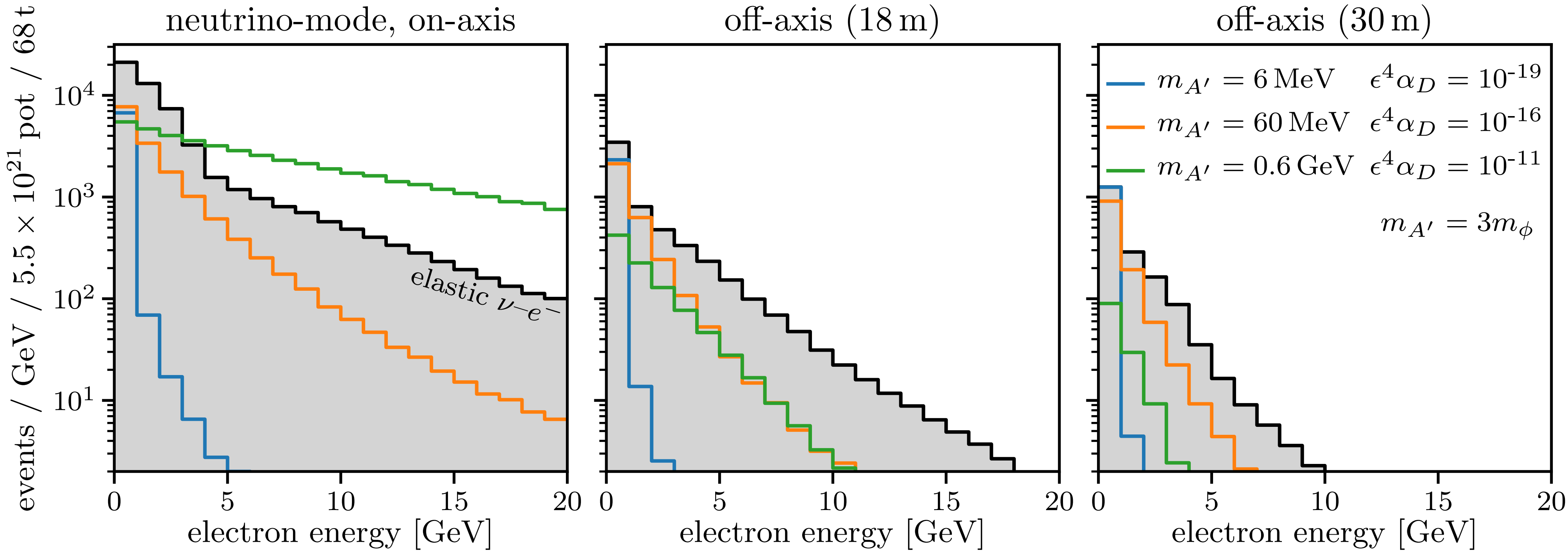
⇒ Kinematics (S.R.)

νe ES: $E_e \times \theta_e^2 < 2 m_e$

Real-life Event Distributions (DUNE ND)

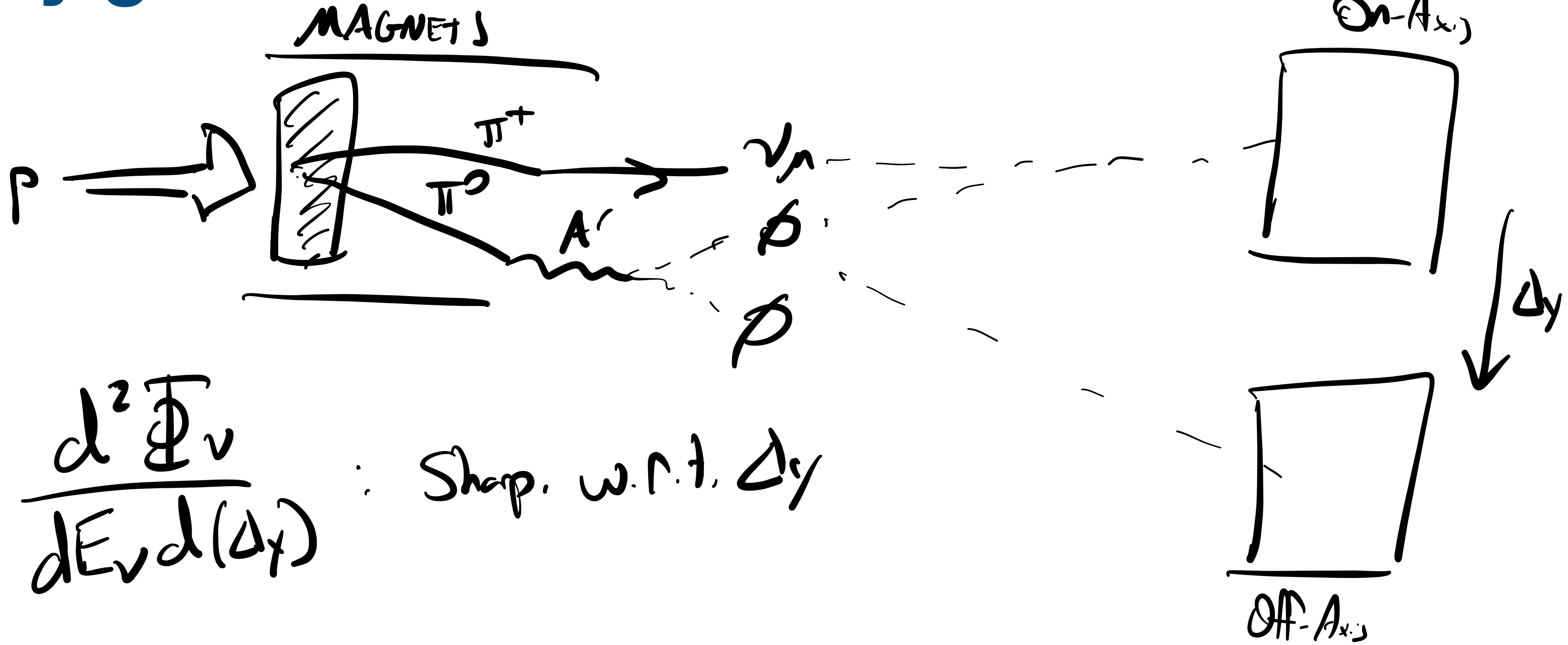


DM Signal vs. Neutrino Background



Breitbach et al [2102.03383]

Why go off-axis?

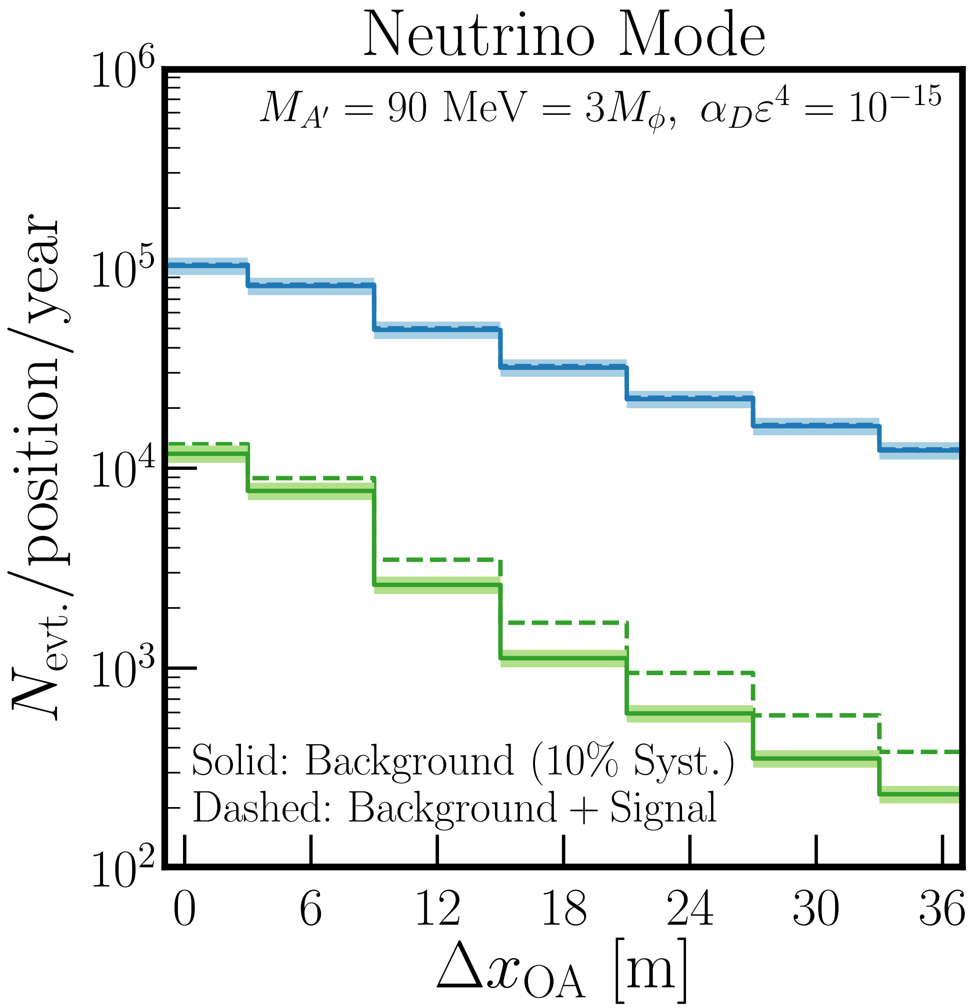


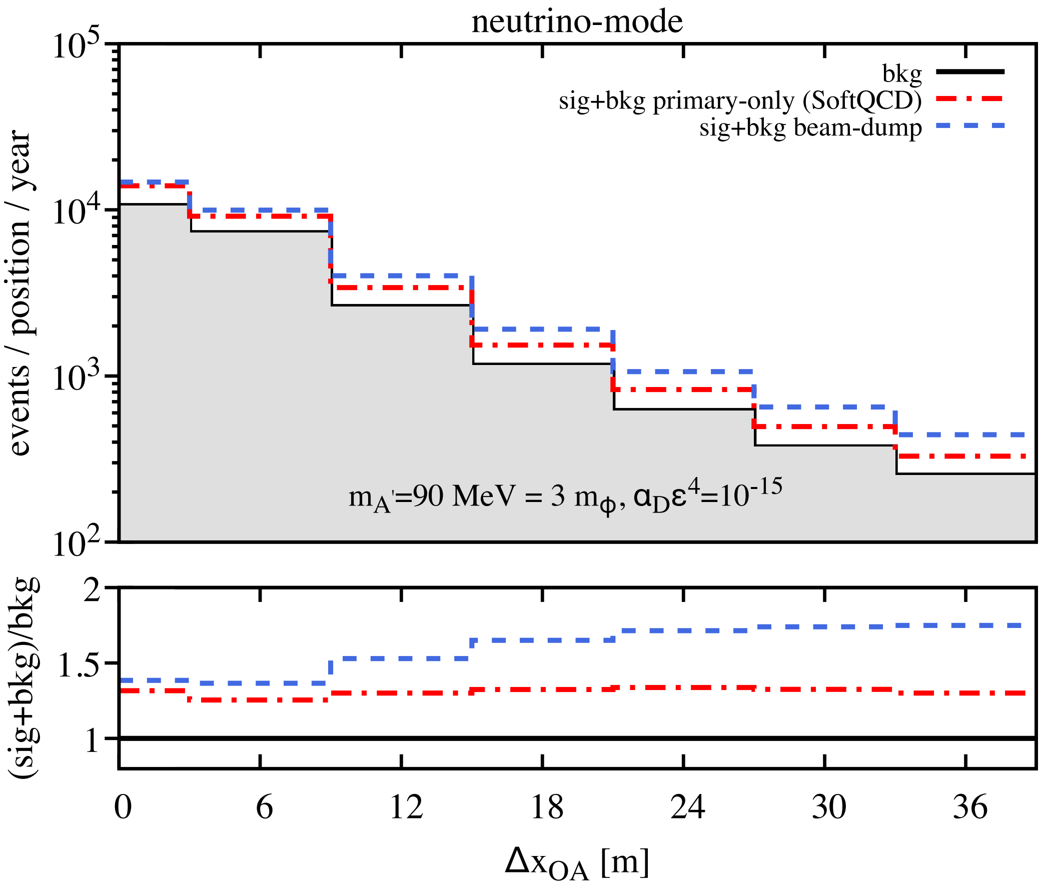
$$\frac{d^2\Phi_\nu}{dE_\nu\, d(\Delta_y)}$$: Sharp. w.r.t. Δ_y

$$\frac{d^2\Phi_\phi}{dE_\phi\, d(\Delta_y)}$$: Smooth w.r.t. Δ_y

On- vs. off-axis

Breitbach et al [2102.03383]

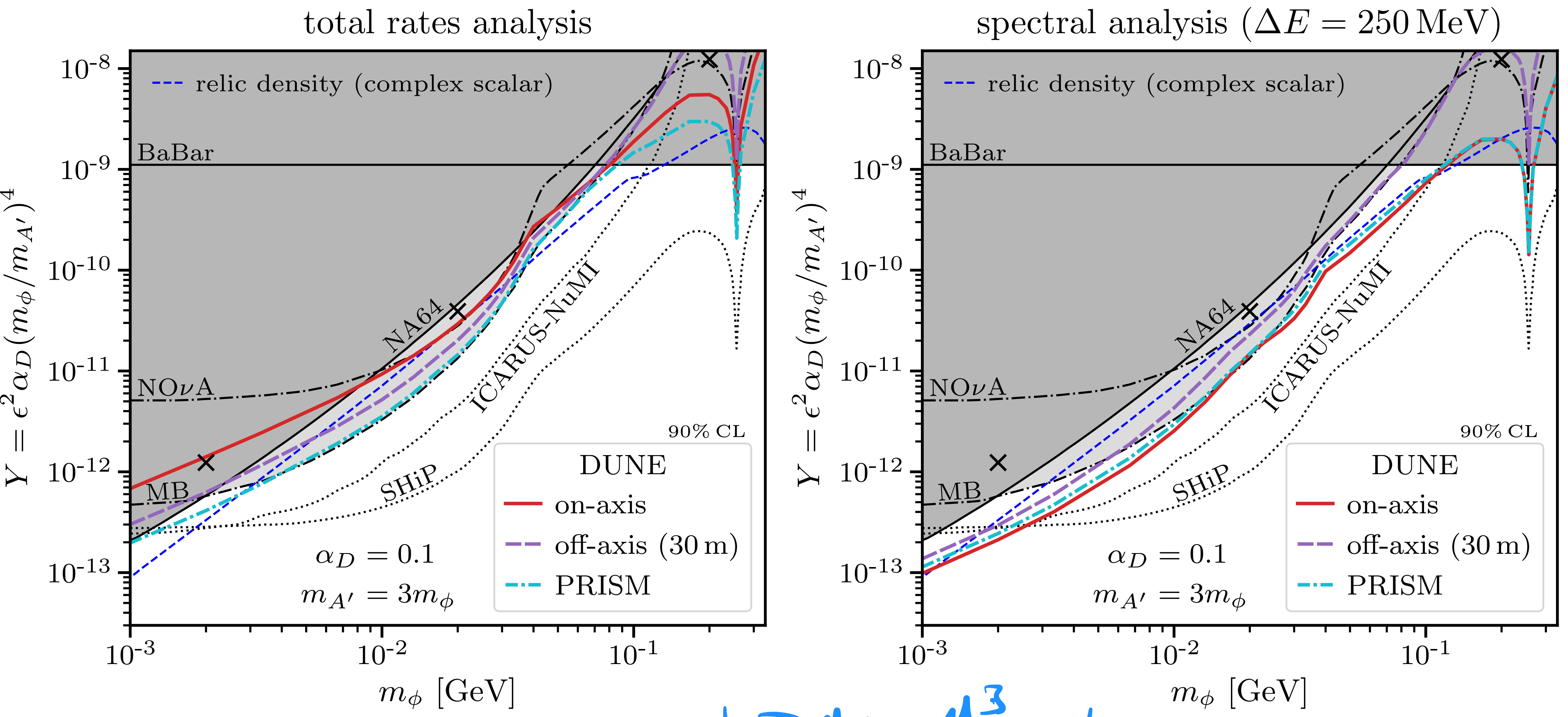




De Romero, KJK, Machado [1903.10505]

Sensitivity

Breitbach et al [2102.03383]
(can compare against De Romero, KJK, Machado [1903.10505])



LDMX, M^3, etc...

Scenario 3:

Challenging (but experimentally measurable) SM Background(s)

(following Coyle et al [2210.03753] for inspiration)

Sometimes, the desired physics "looks like" SM Neutrino Physics

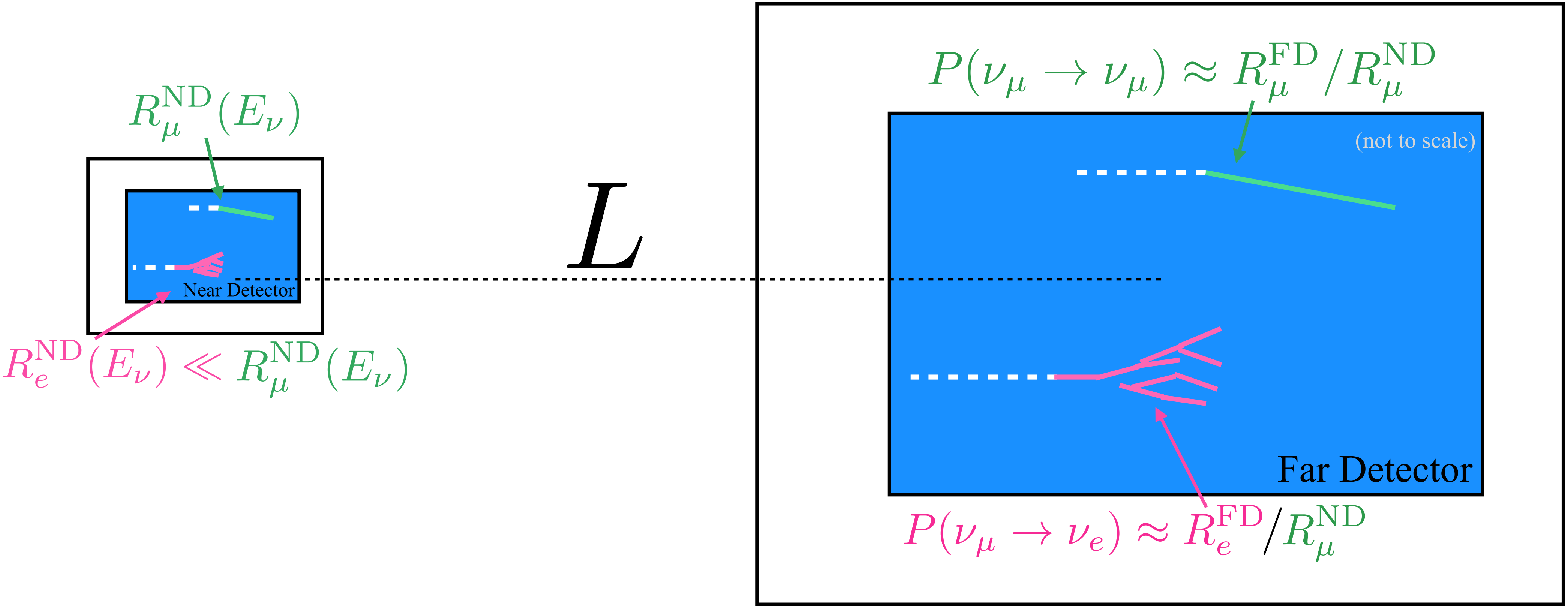
(sterile neutrinos 101)

$\Rightarrow$ Fourth neutrino with mass $\sim m_4 \sim 1\,\text{eV}$

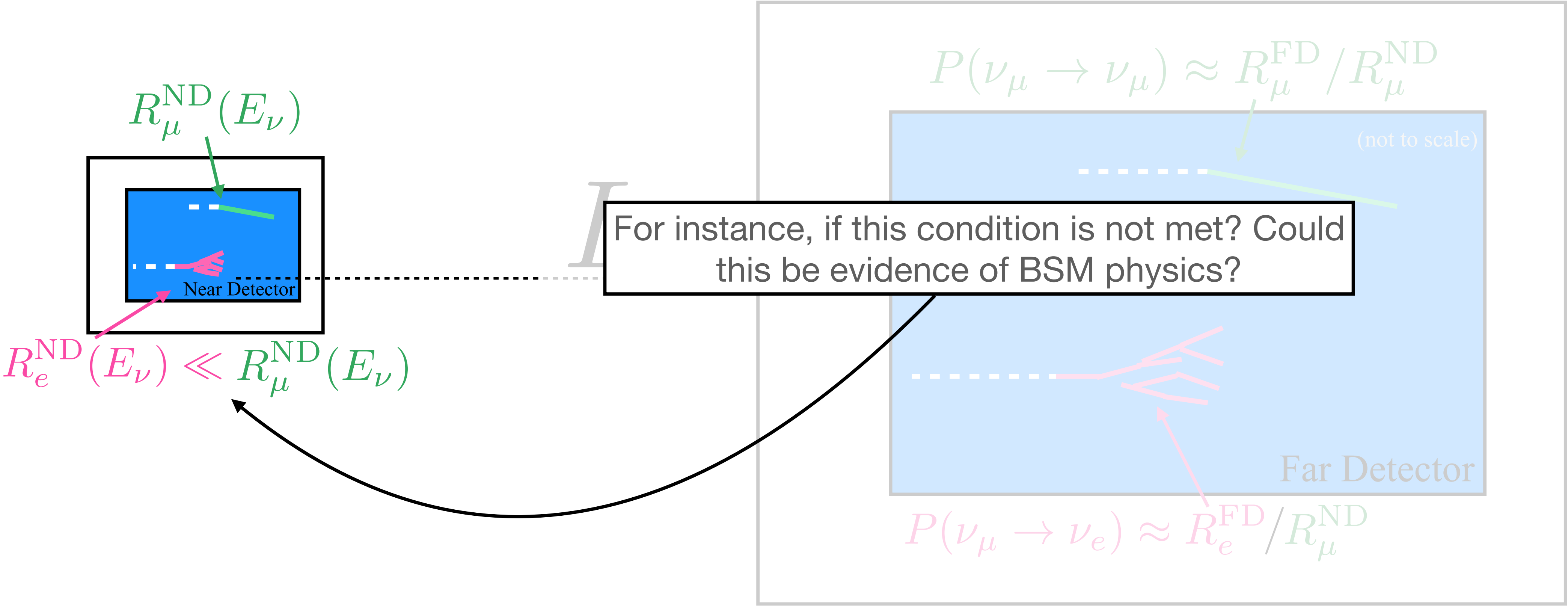
$$P_{\alpha\beta} \sim \sin^2(2\theta_{\alpha\beta}) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$\Rightarrow$ Energy dependence for our signal vs. SM expectation

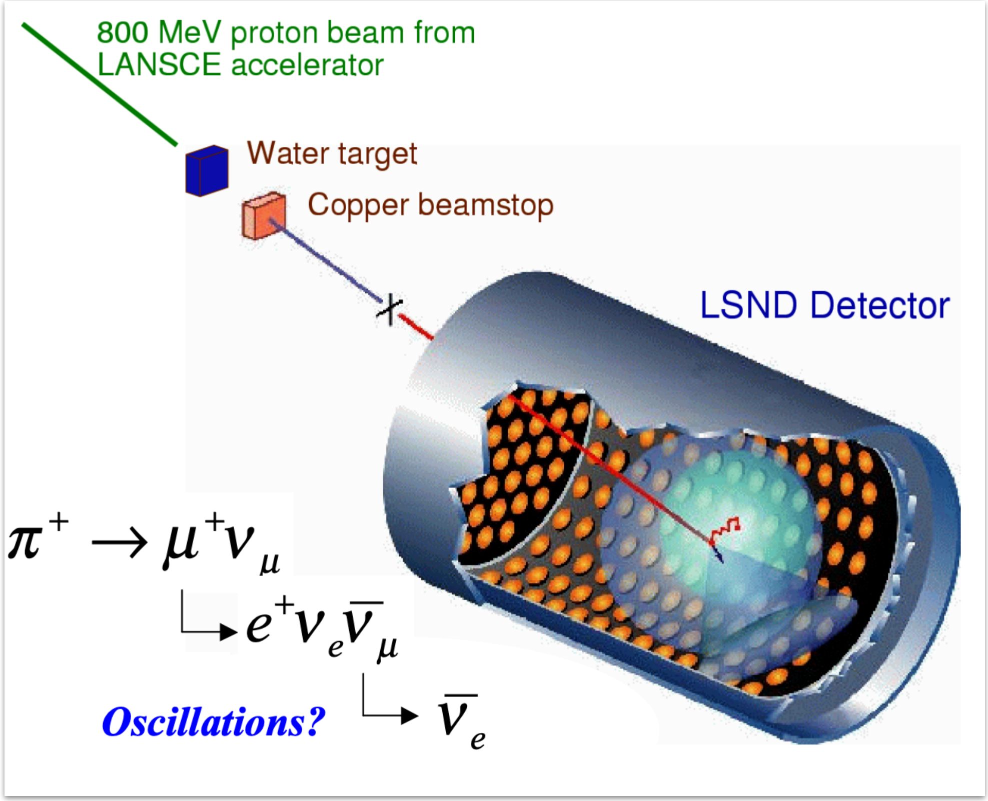
Deviations at Near Detector?



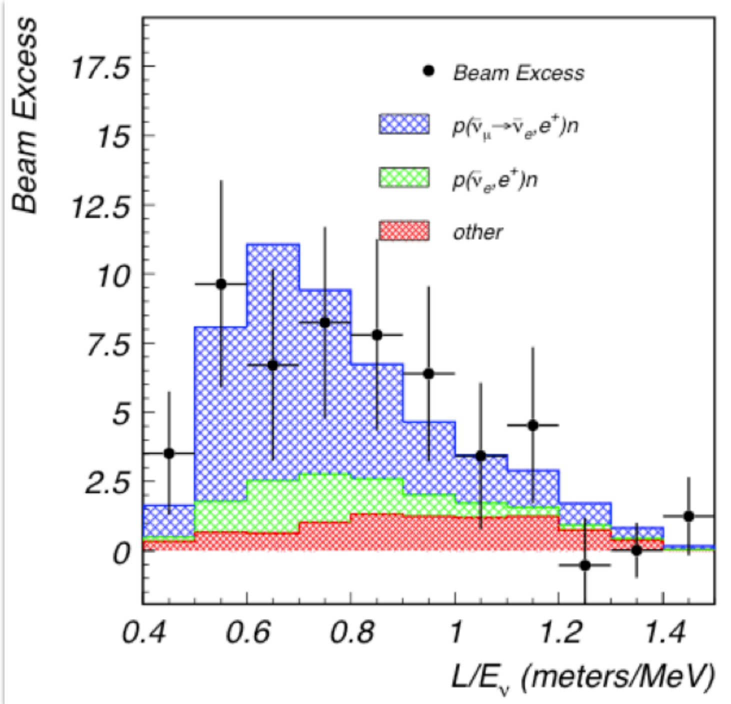
Deviations at Near Detector?



Liquid Scintillator Neutrino Detector (LSND)



$\overline{\nu}_\mu \to \overline{\nu}_e?$

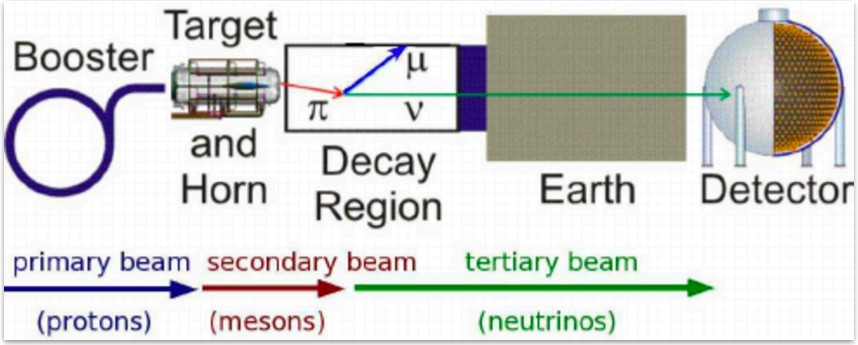


Neutrinos (mostly) from pion/muon decay-at-rest — O(30) MeV, roughly 50 meter baseline length.

Observed excess — $87.9 \pm 22.4 \pm 6.0 \longrightarrow P\left(\overline{\nu}_\mu \to \overline{\nu}_e\right) \approx 2.6 \times 10^{-3}$

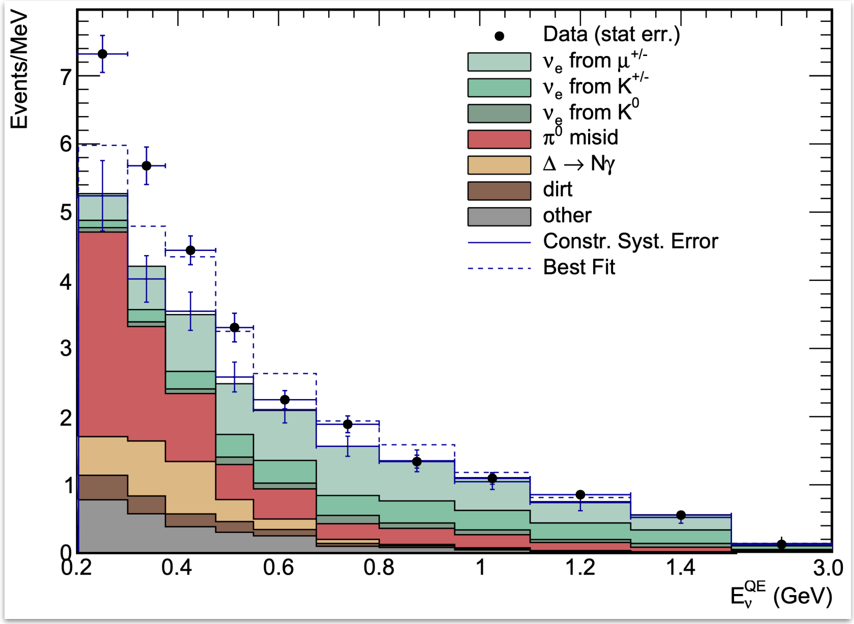
MiniBooNE

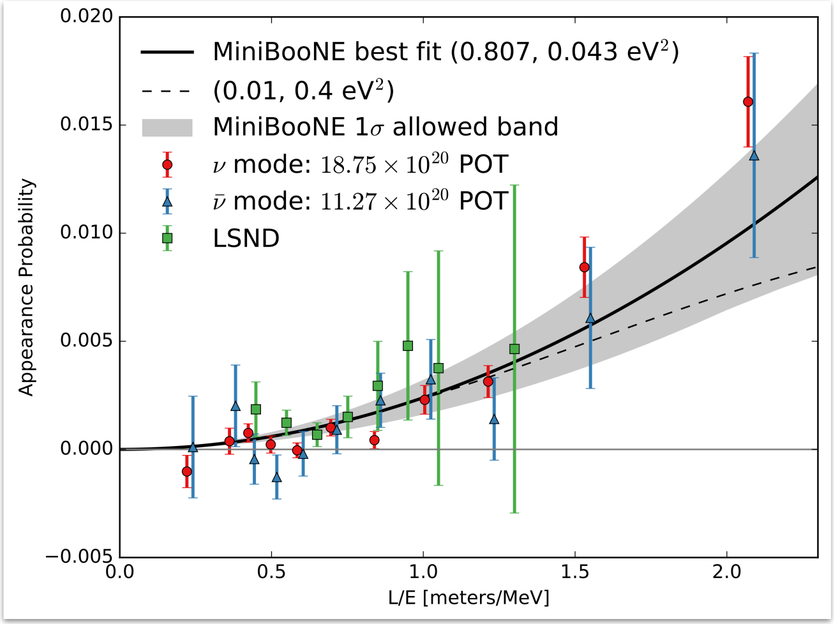
Designed to test the LSND anomaly — very different L, E, but similar L/E



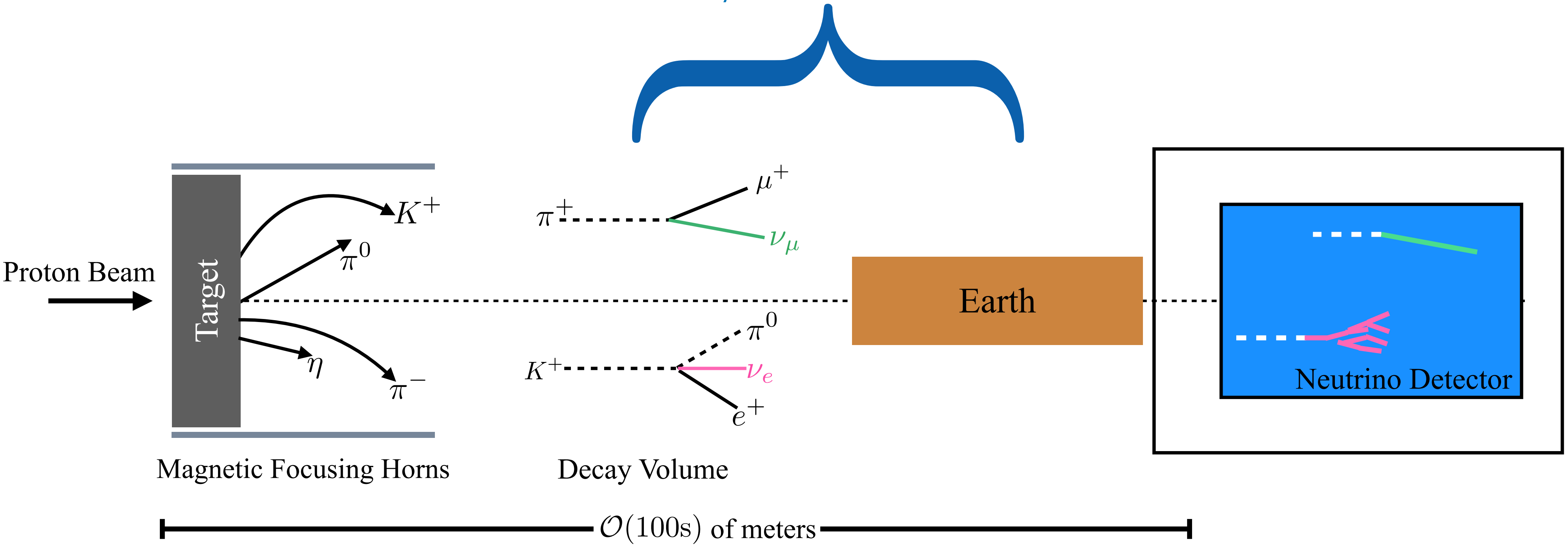
$$\nu_\mu \to \nu_e \text{ AND } \overline{\nu}_\mu \to \overline{\nu}_e?$$

MiniBooNE Collab., [2006.16883]

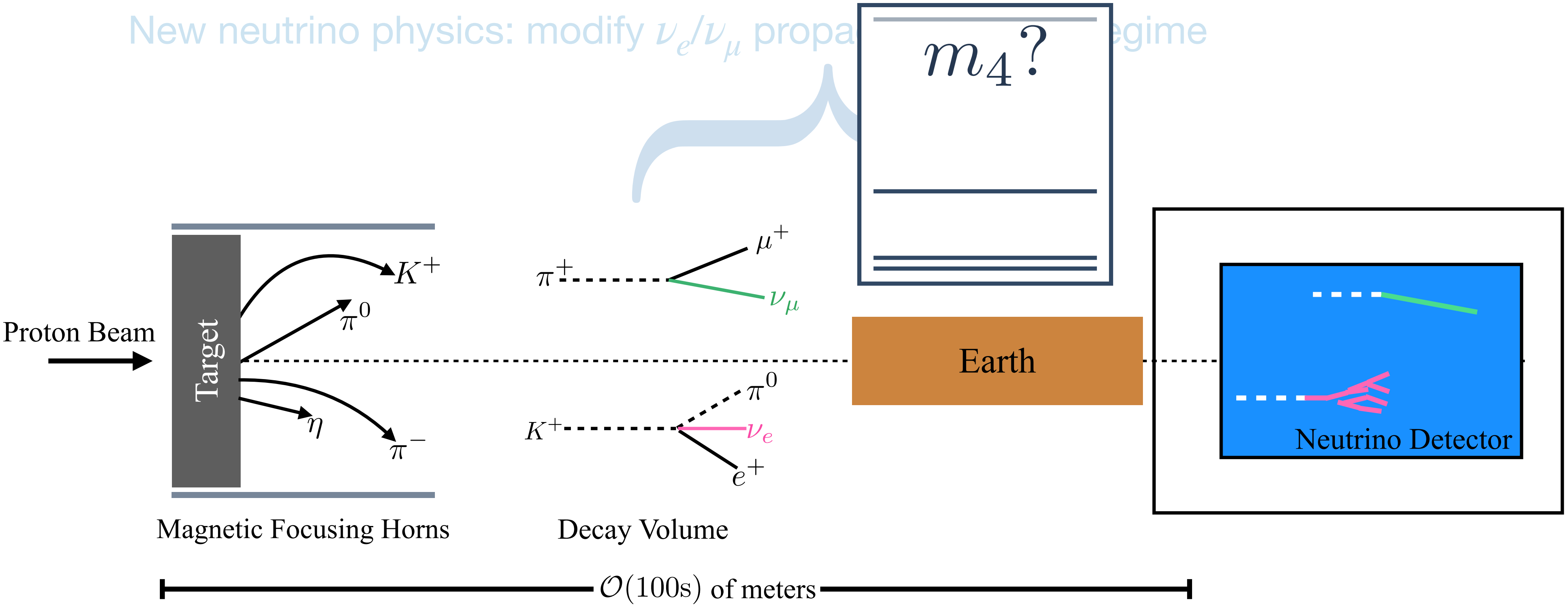




New neutrino physics: modify ν_e/ν_μ propagation in this regime



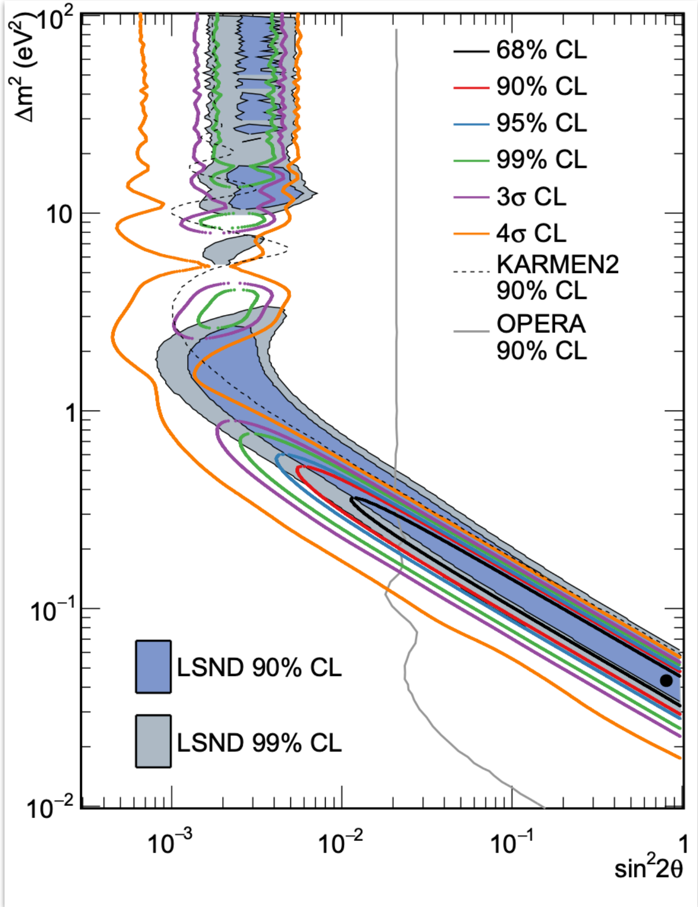
New neutrino physics: modify ν_e/ν_μ propa… …egime



$$P_{\alpha\beta} \approx \sin^2\left(2\theta_{\alpha\beta}\right)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

New mass scale $\Delta m^2 \gg \Delta m^2_{\mathrm{SM}}$

Fourth-neutrino interpretation



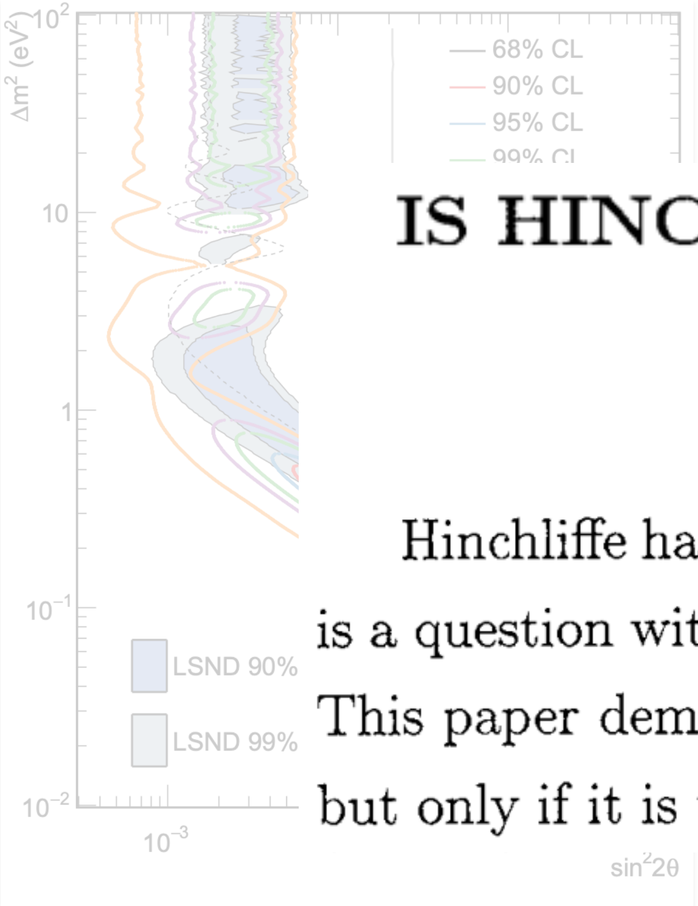
MiniBooNE Collab., [2006.16883]

If coming from oscillations, the results from LSND and MiniBooNE require a new mass eigenstate around the eV scale.

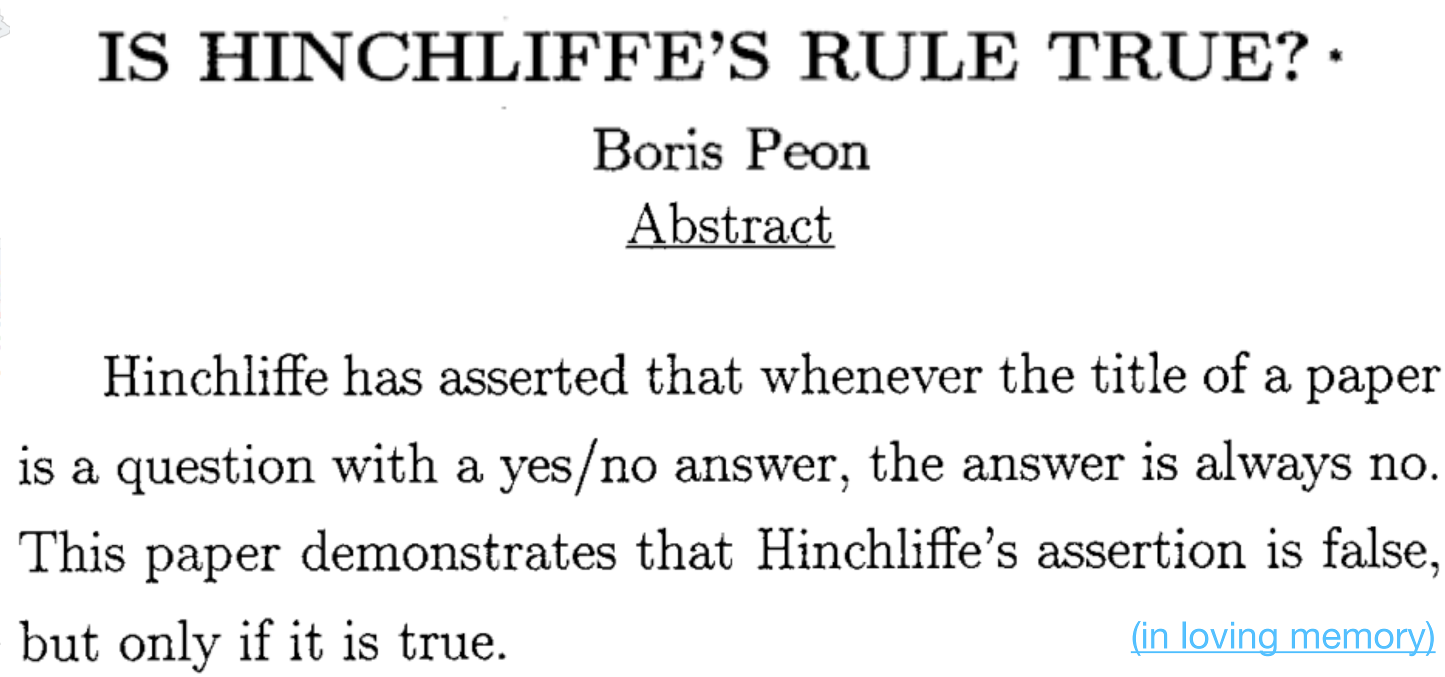
Combined with the observed invisible width of the Z-boson (LEP), any additional light neutrino(s) must be sterile — gauge singlets.

Is this 3+1 scenario compatible with global data?

Fourth-neutrino interpretation



MiniBooNE Collab., [2006.16883]


IS HINCHLIFFE'S RULE TRUE?

Boris Peon

Abstract

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that Hinchliffe's assertion is false, but only if it is true.

(in loving memory)

ND and
und the eV

the Z-boson
terile — gauge

oal data?

Consequences of Invoking a light (sterile) Neutrino

$$P_{\alpha\beta} \sim \sin^2(2\theta_{\alpha\beta}) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$\alpha = \mu$, $\beta = e$

$$\sin^2(2\theta_{\mu e}) = 4|U_{\mu 4}|^2 |U_{e4}|^2$$

$|U_{\mu 4}|^2 \to \sin^2(\theta_{24}) \times \cos^2(\theta_{14})$

$|U_{e4}|^2 \to \sin^2(\theta_{14})$

$$P_{\alpha\alpha} \sim 1 - \sin^2(2\theta_{\alpha\alpha}) \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$$\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

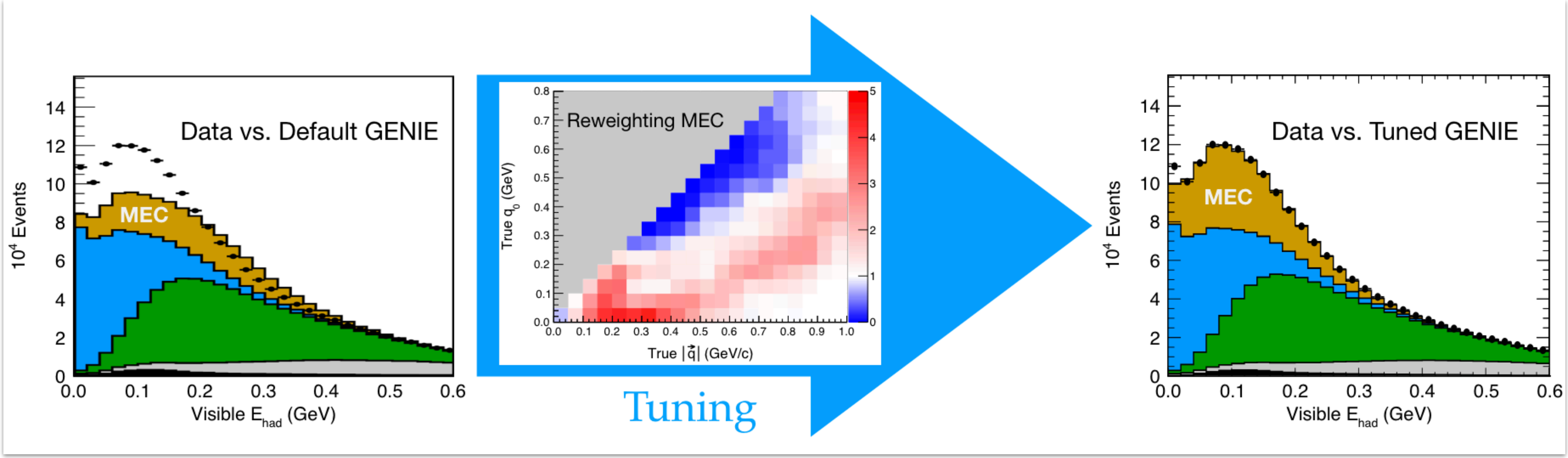
Impact at, e.g., NOvA ND

$$P_{\mu\mu} \approx 1 - \sin^2(2\theta_{\mu\mu})\,\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$$\frac{\Delta m^2 L}{4E_\nu} \simeq \text{[illegible]} \times \left(\frac{\Delta m^2}{eV^2}\right) \times \left(\frac{L}{m}\right) \times \left(\frac{GeV}{E_\nu}\right)$$

$\Rightarrow$ Nontrivial E_ν dependence on your ν_μ Event Rate

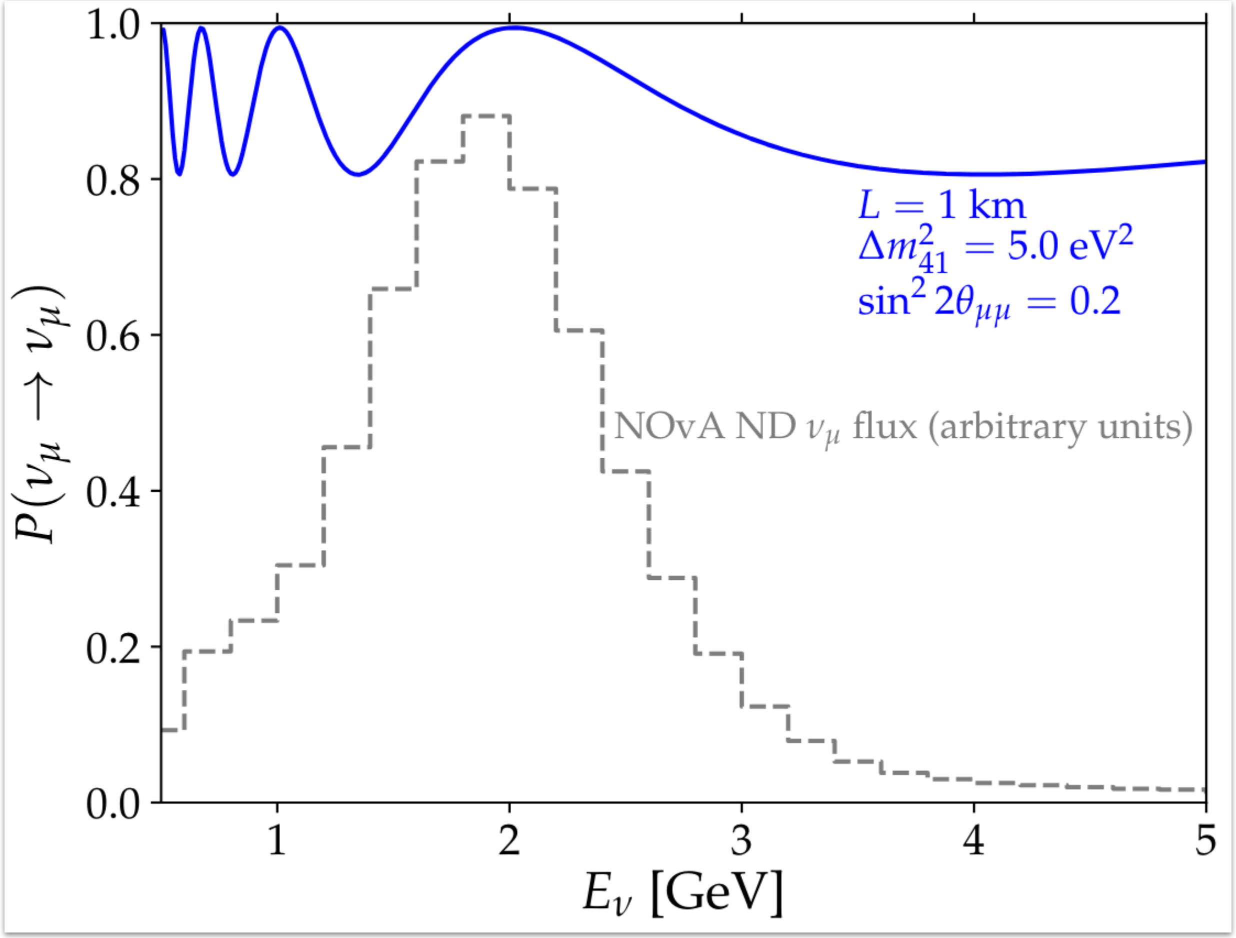
What do Experiments do with ND Data?



Coyle et al [2210.03753], adapted from NOvA [2006.08727]

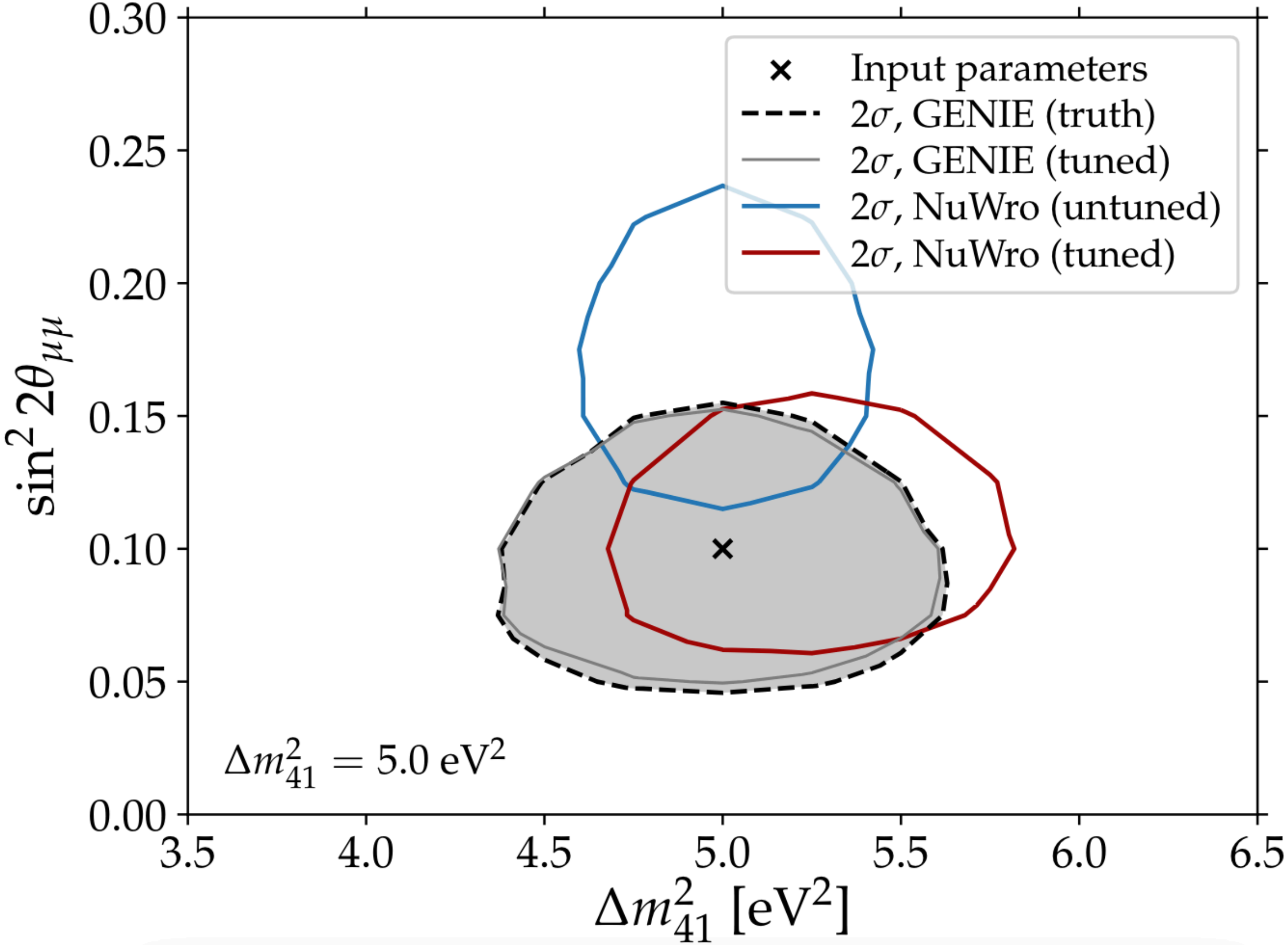
What if there is underlying new physics in this data?

Coyle et al [2210.03753]



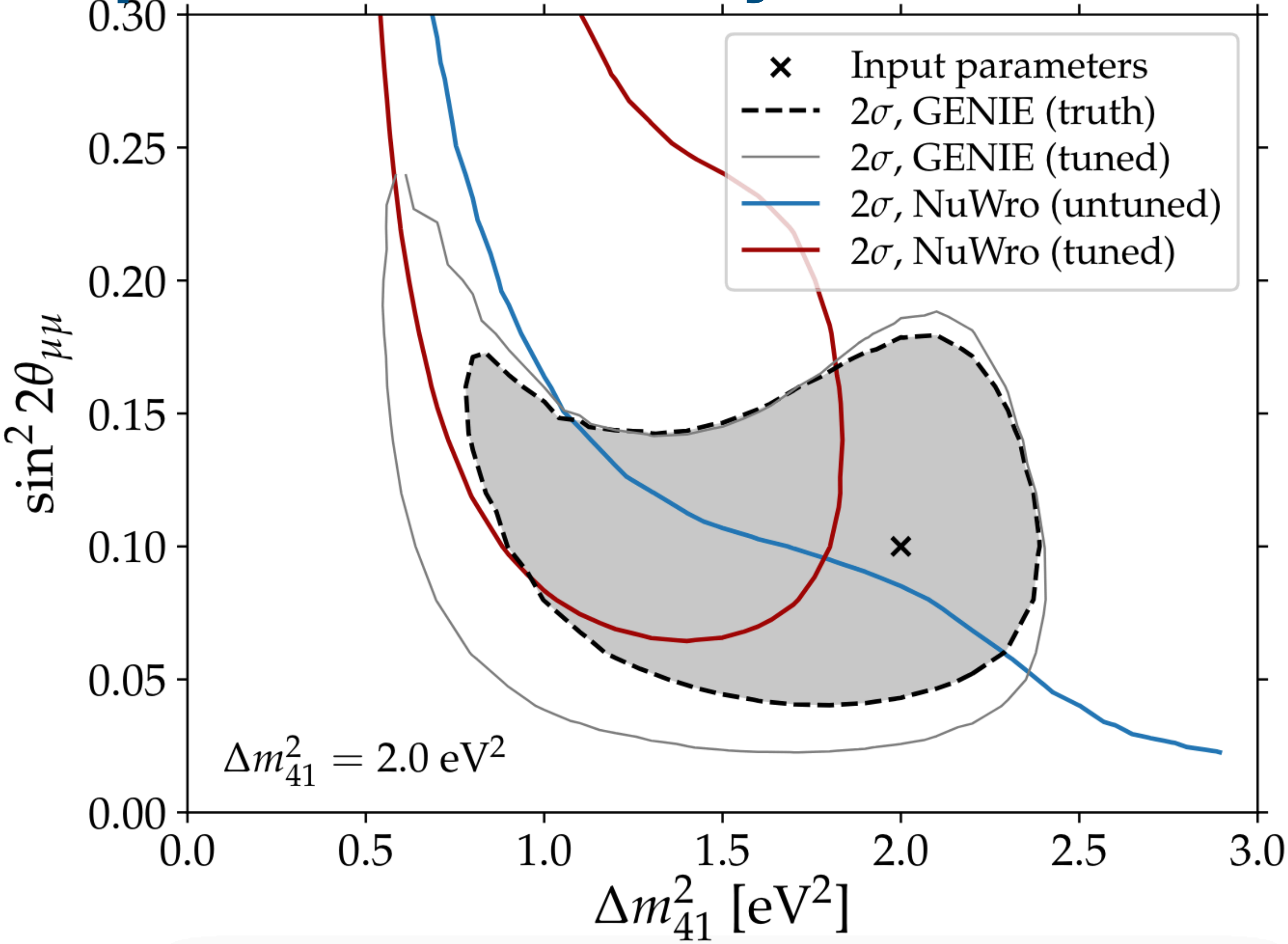
Coyle et al [2210.03753]

Impact on potential discovery? 🤔



Impact on potential discovery? v2… 😬

Coyle et al [2210.03753]



A second ND "background-swamped" model

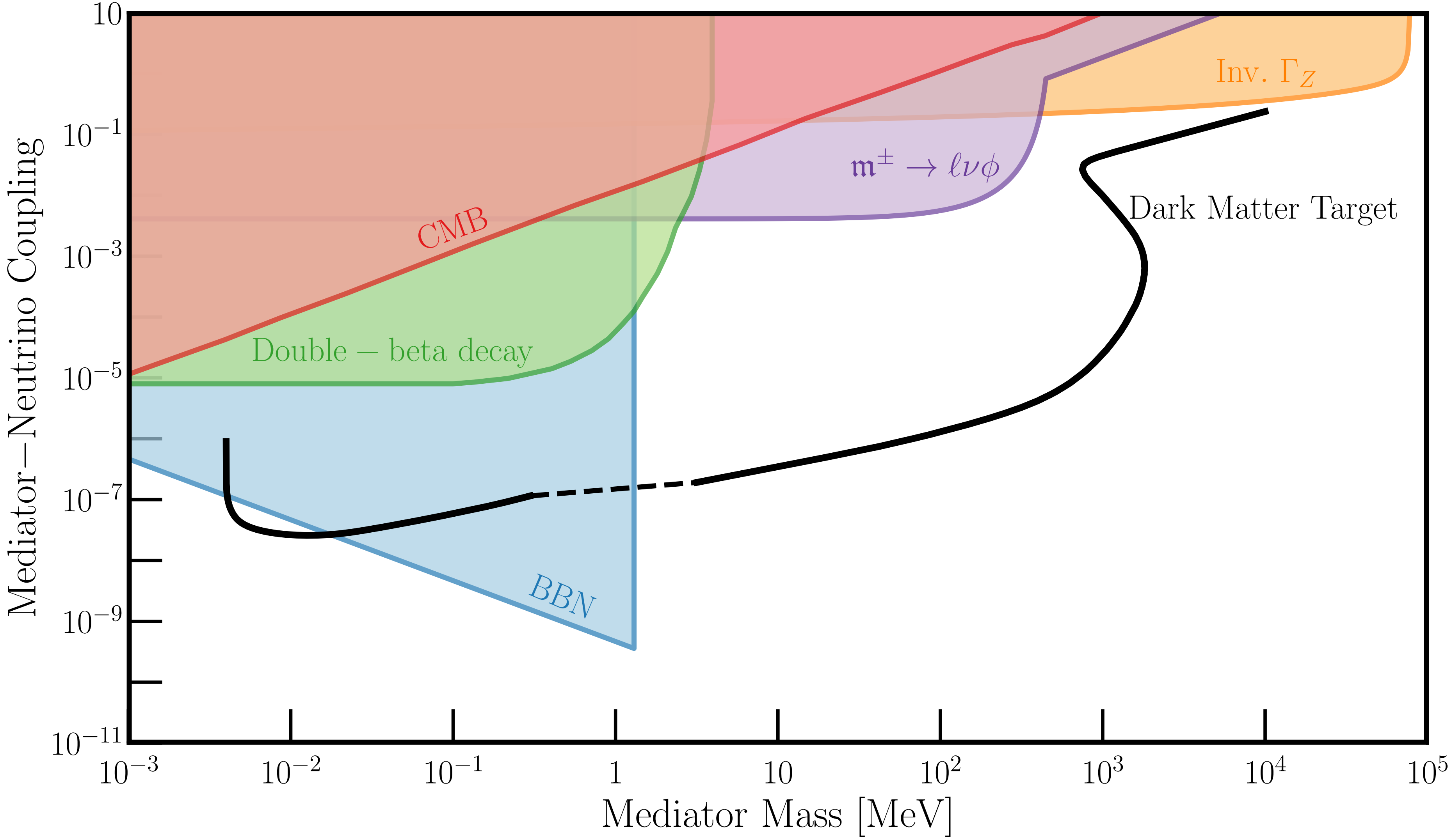
New particle ϕ scalar "neutrinophilic"

$$\mathcal{L} \propto \frac{(L_\alpha H)(L_\beta H)\phi}{\Lambda_{\alpha\beta}^2}$$

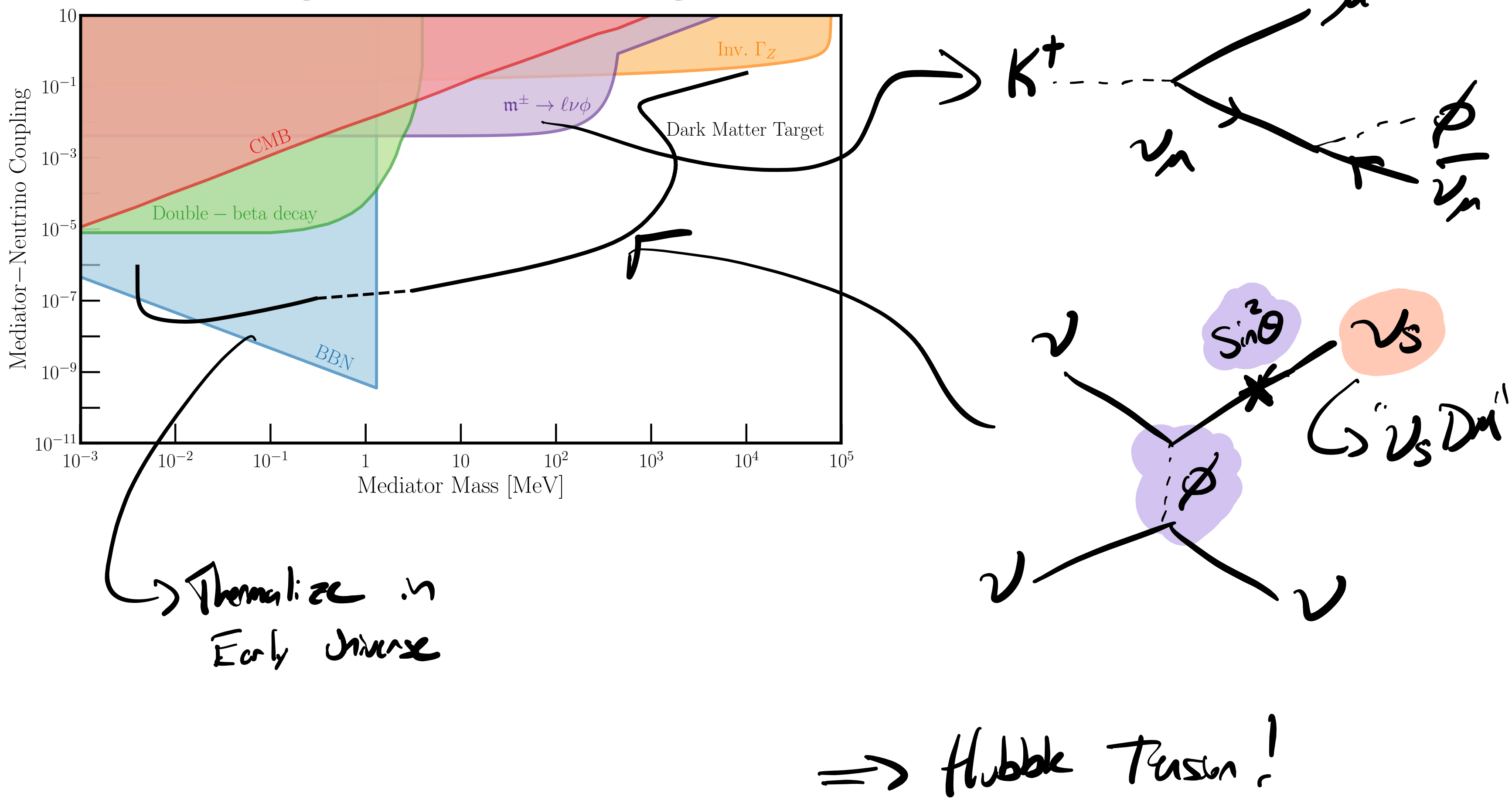
$$\Rightarrow \lambda_{\alpha\beta}\phi\nu_\alpha\nu_\beta$$

$\phi \sim$ MeV – GeV

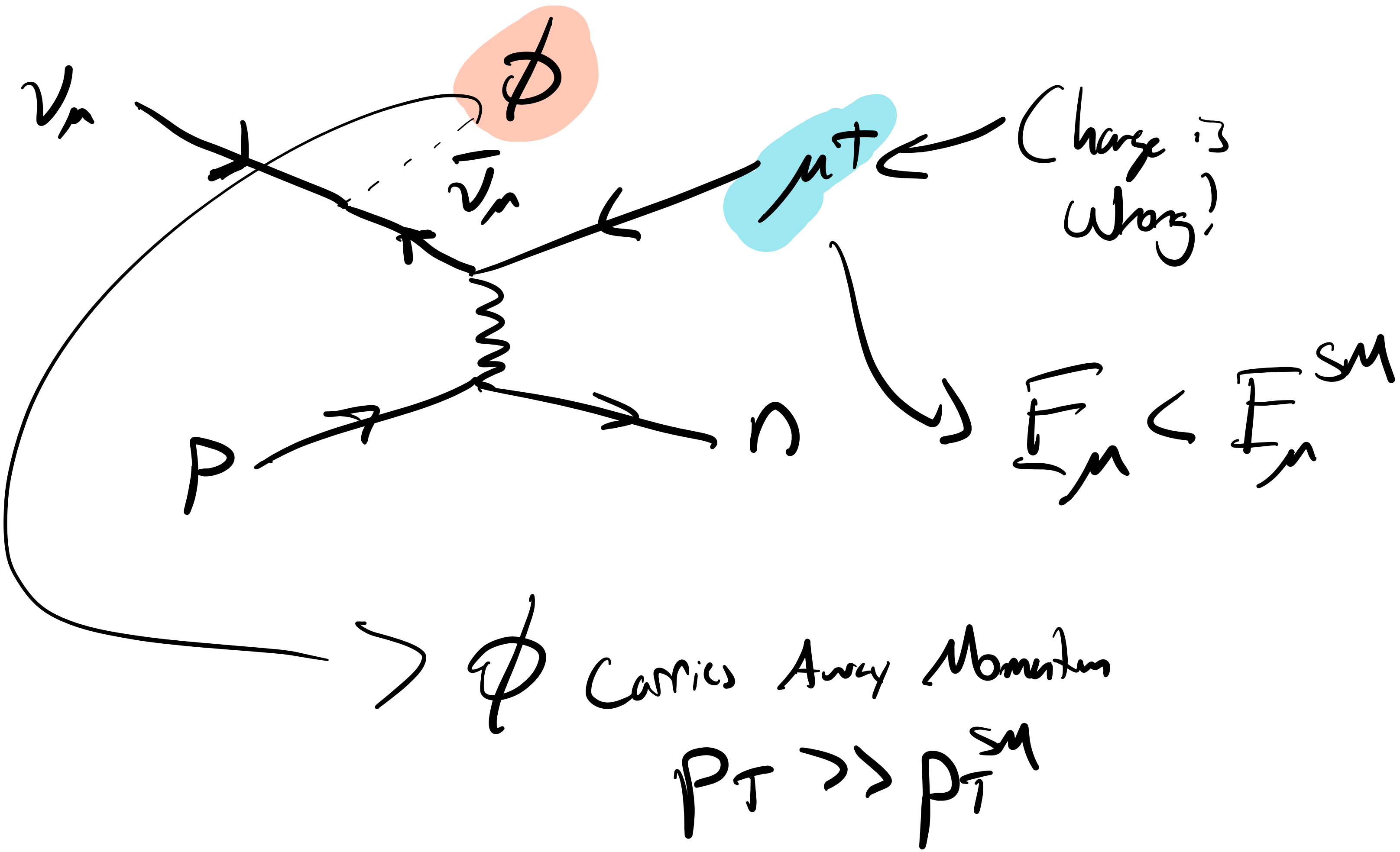
Broader motivation?



Breaking down regions…

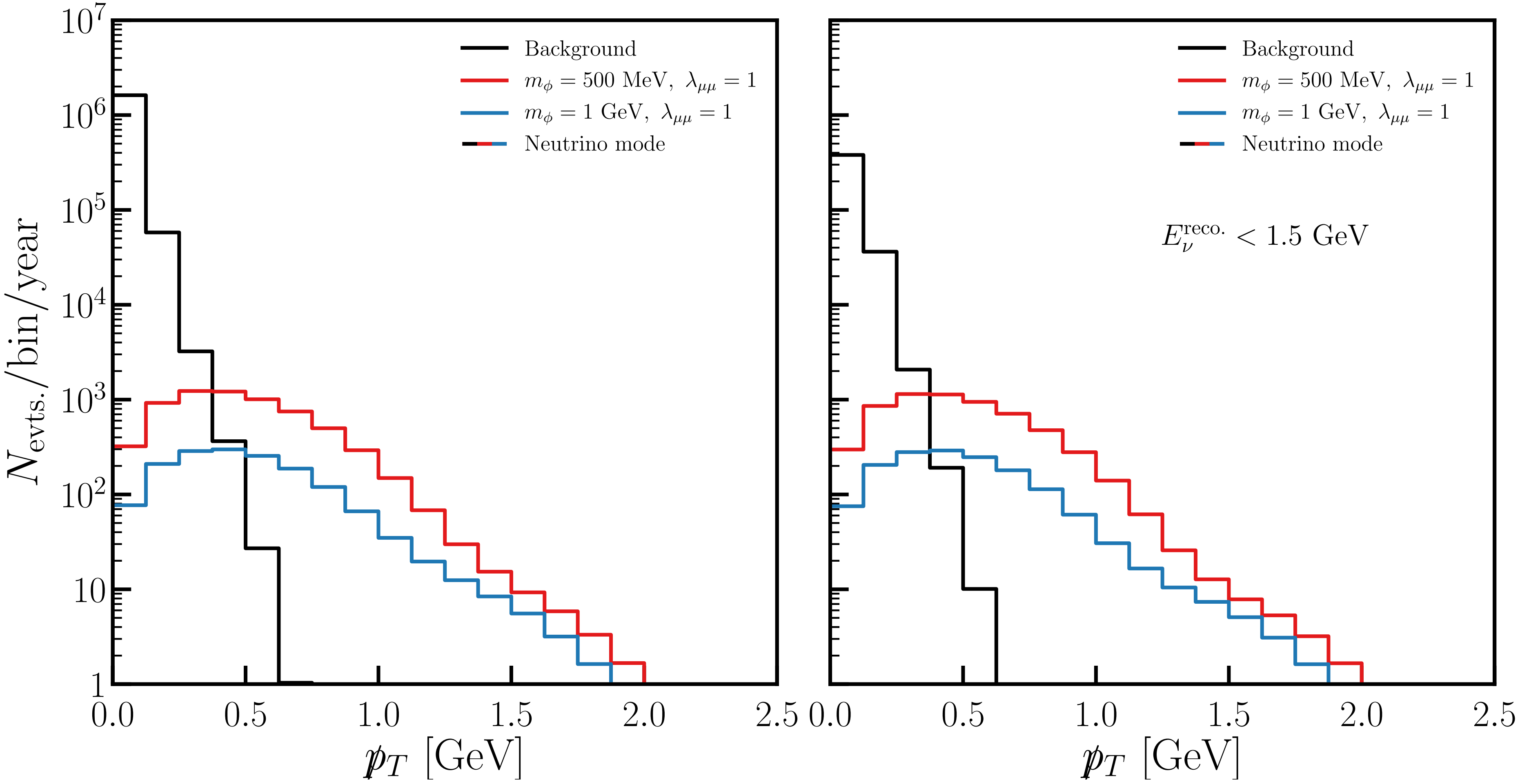


Neutrinophilic Scalars in Neutrino Facilities

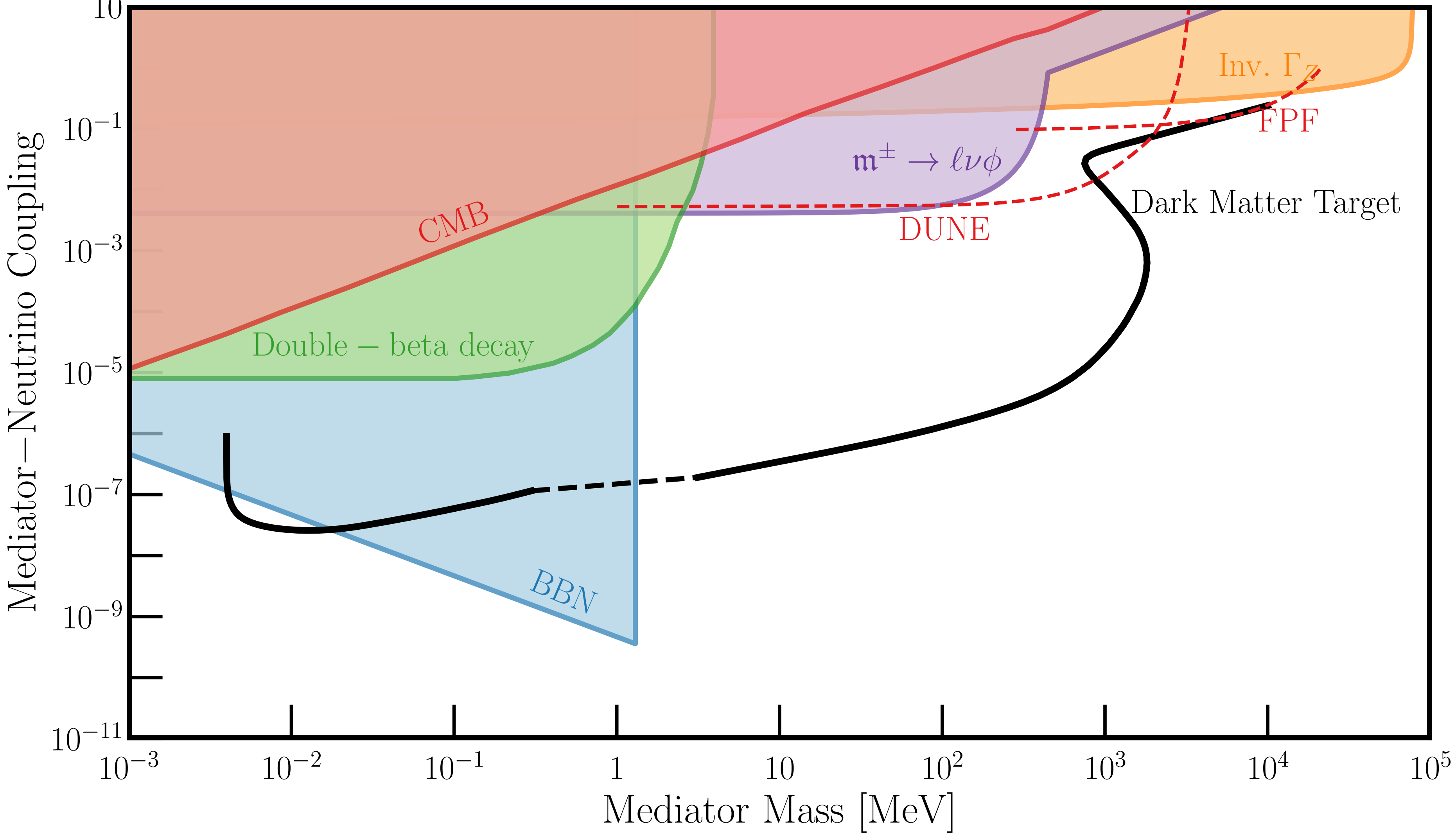


Signal vs. Background Kinematics

KJK & Zhang, [1901.01259]

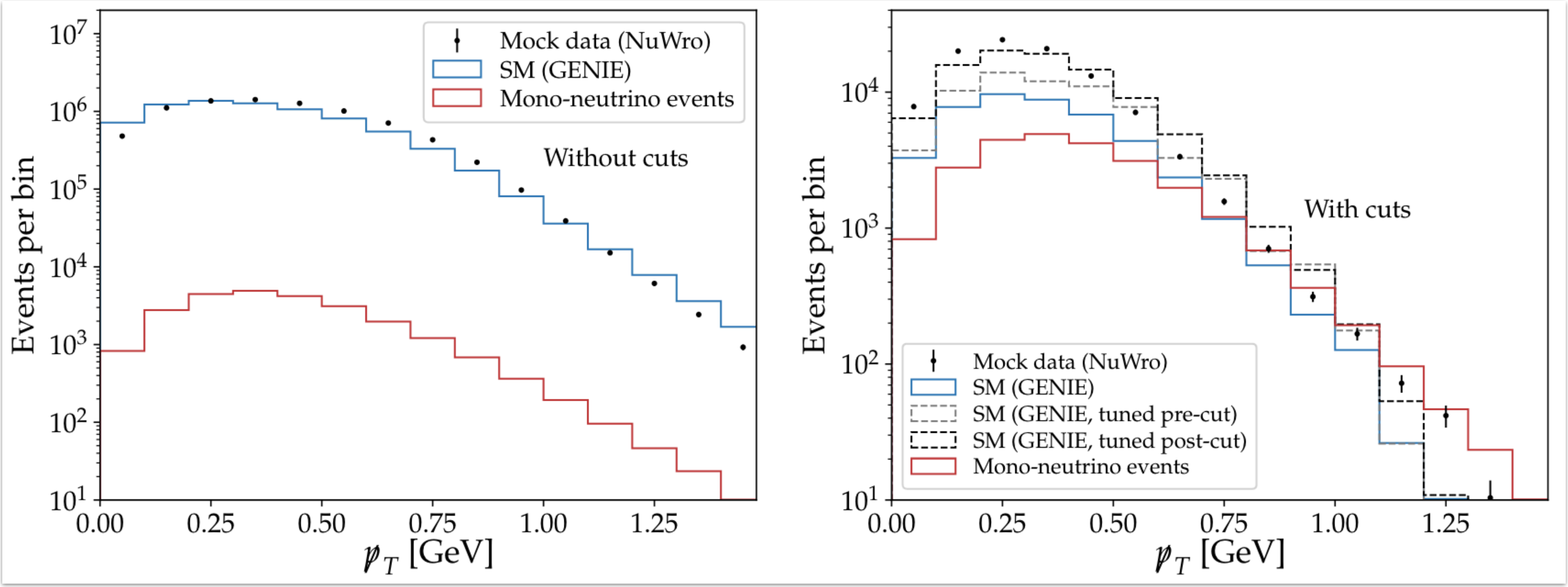


Sensitivity Estimates



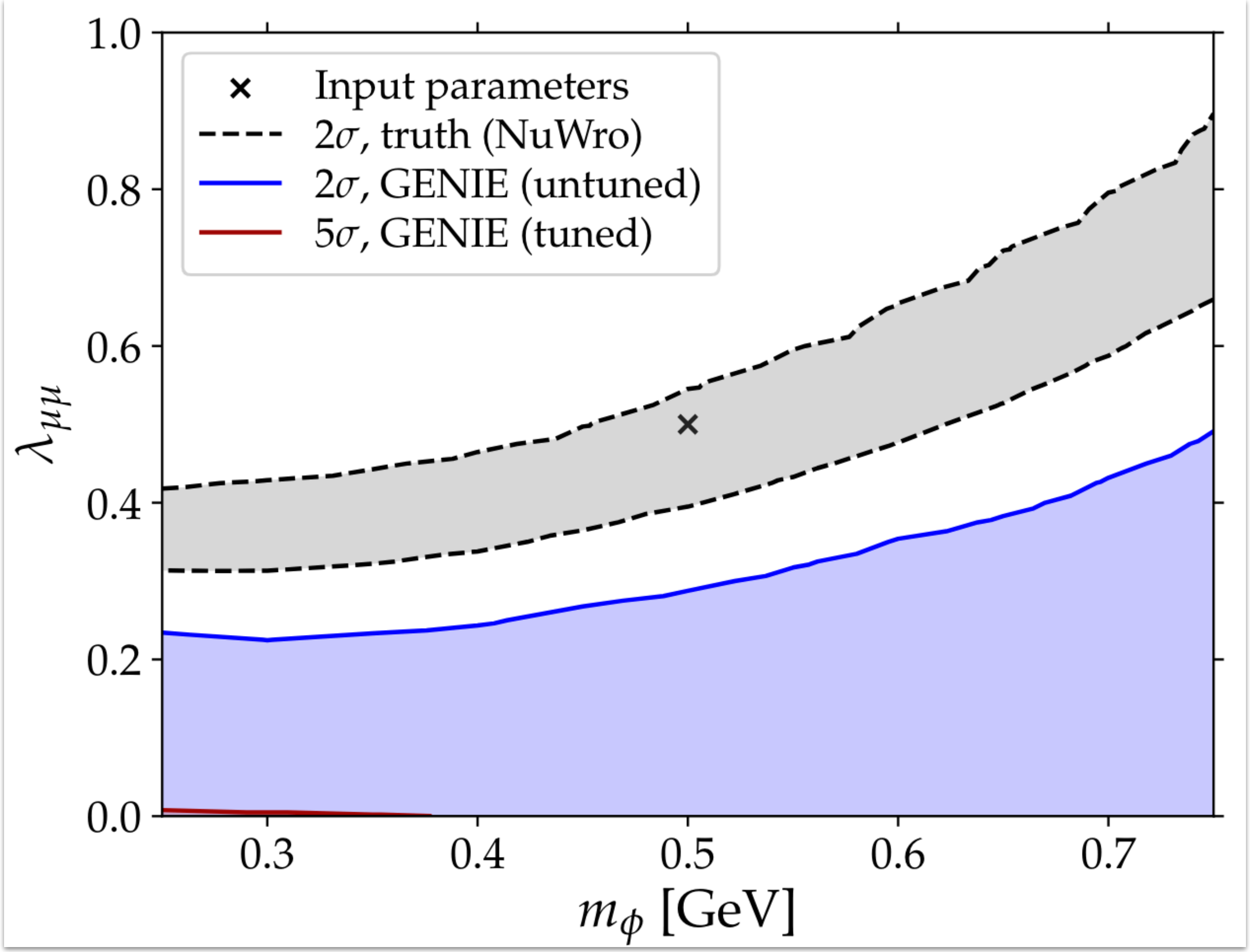
Re-enter Coyle/Li/Machado…

Coyle et al [2210.03753]



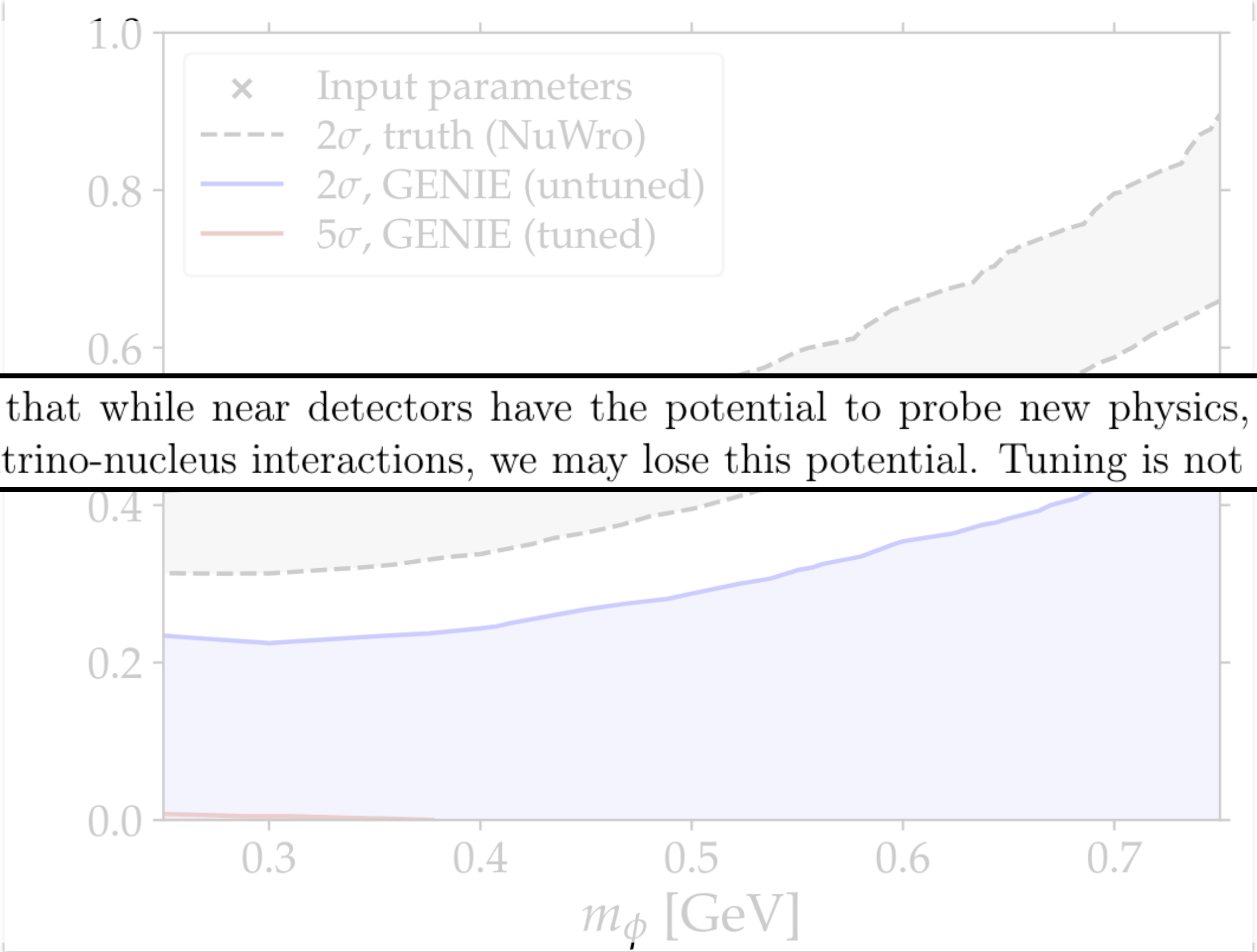
Impact of tuning on these searches

Coyle et al [2210.03753]



Impact of tuning on these searches

Coyle et al [2210.03753]



This shows that while near detectors have the potential to probe new physics, without proper modeling of neutrino-nucleus interactions, we may lose this potential. Tuning is not the solution.

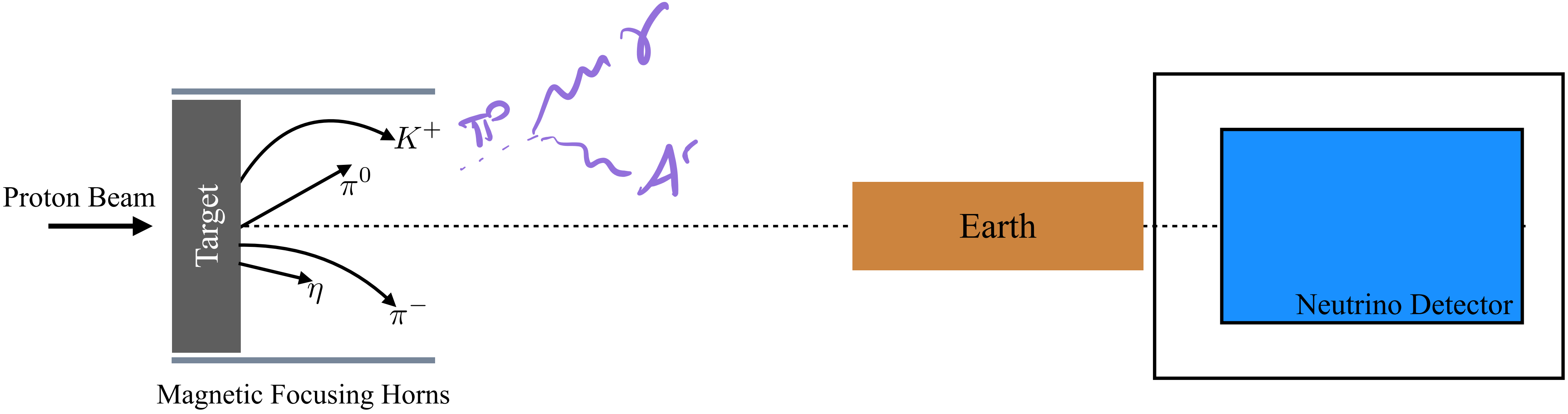
Backup

Novel BSM Production Mechanisms in Thick Targets — Electromagnetic Production

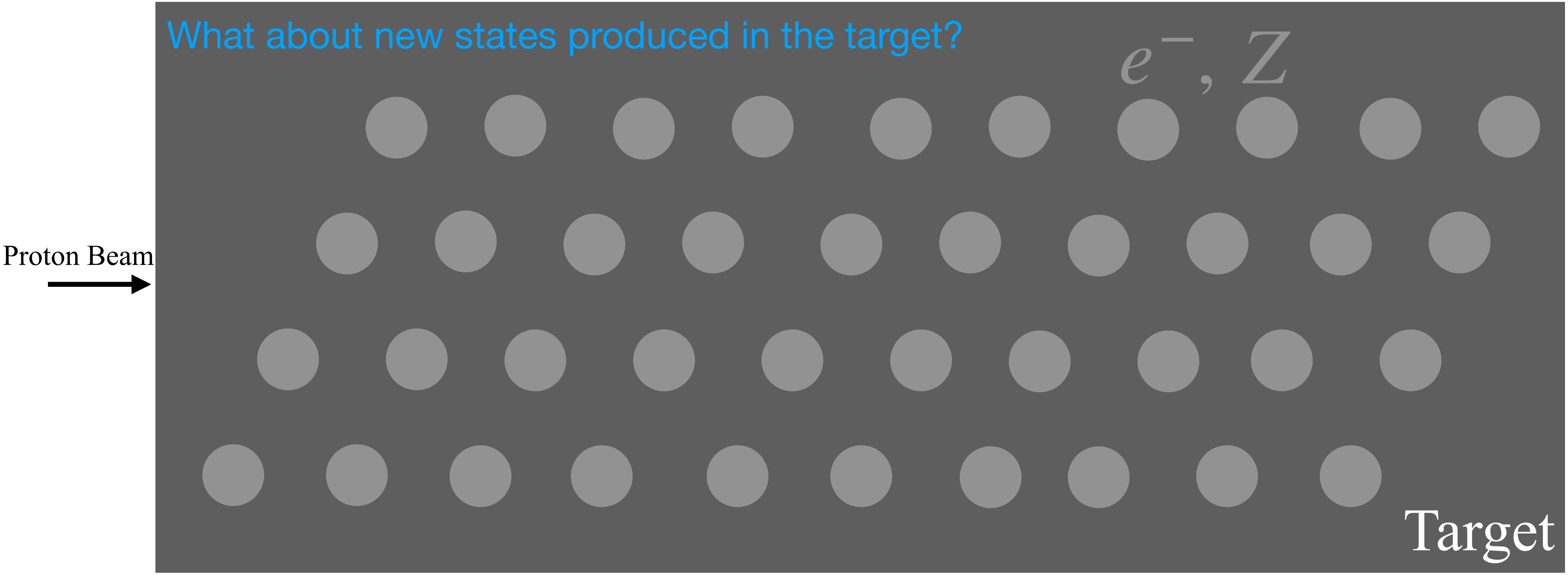
https://github.com/kjkellyphys/PETITE

“Nonstandard” BSM Production?

What about new states produced in the target?



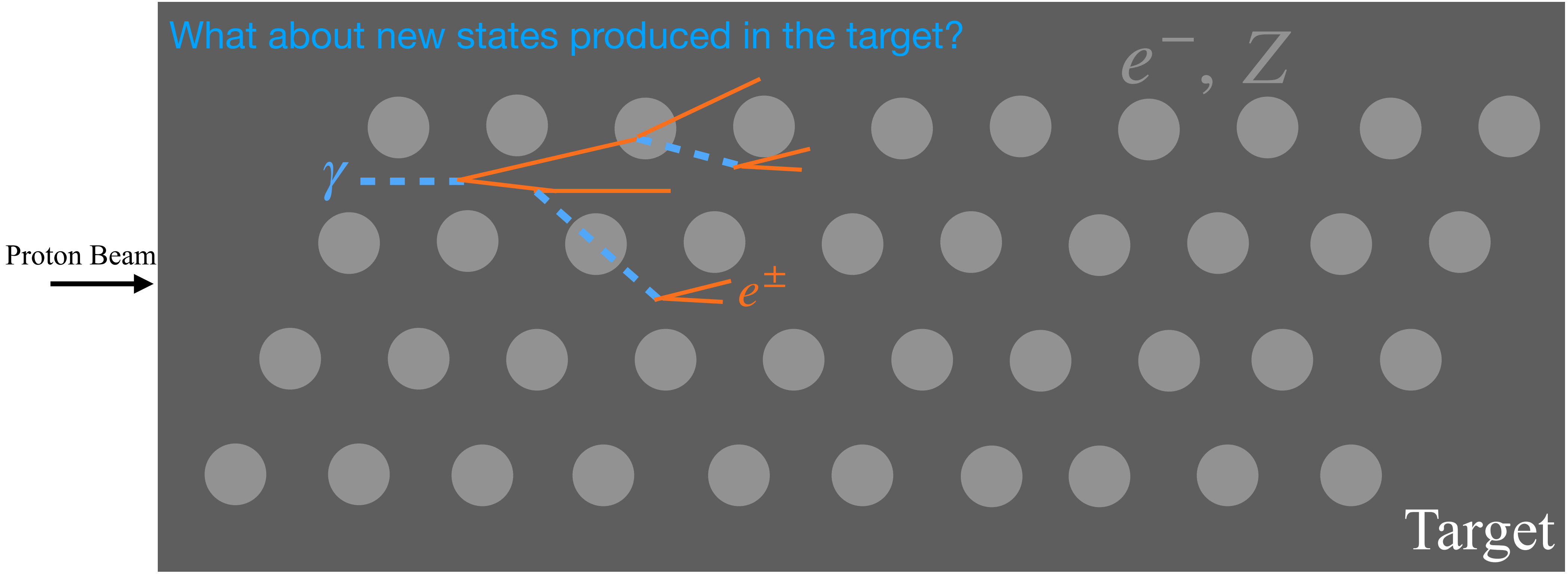
“Nonstandard” BSM Production?



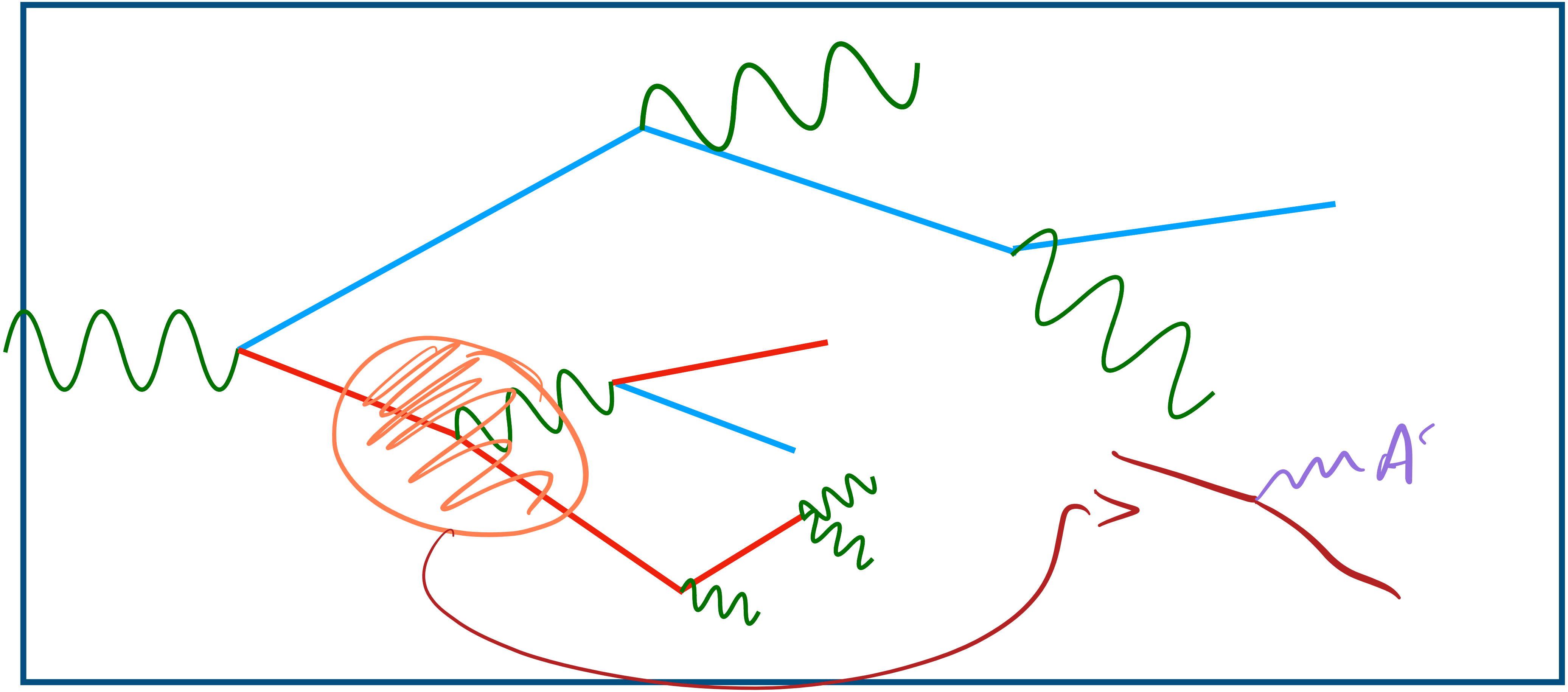
“Nonstandard” BSM Production?

Every Hadronic/Electromagnetic interaction in the target is a potential for BSM production!

many interactions = many opportunities for production



The big challenge: kinematics



The big challenge: kinematics

We are (often) interested in detectors in the ~forward region that have a small solid angle with respect to the incident beam.

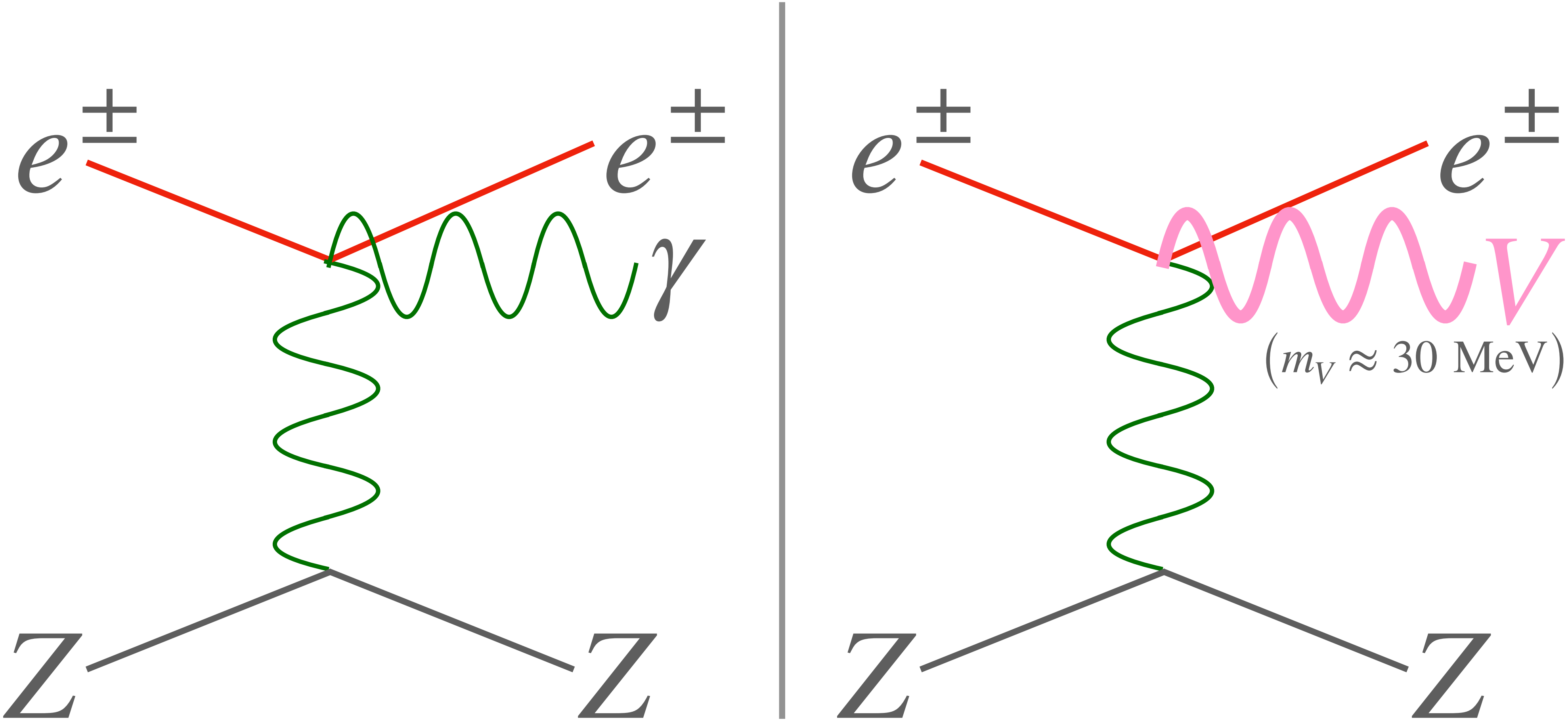
Any small effect in *directionality* of BSM production can have a profound effect.

We want to

(a) Generate sample SM showers, and

(b) Resample those SM vertices to produce BSM states, tracking kinematics precisely.

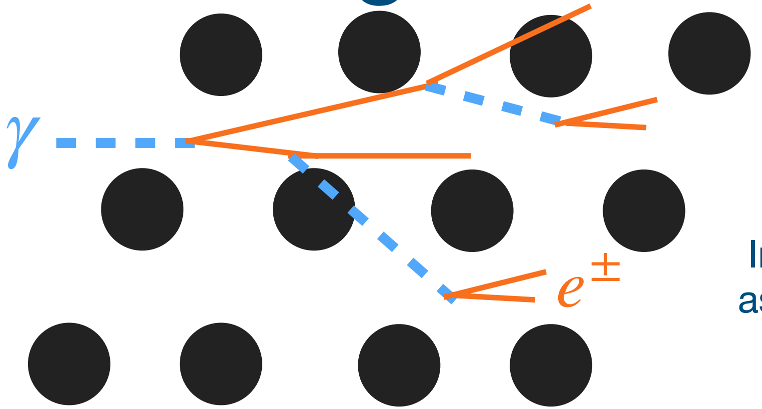
SM vs. BSM Bremsstrahlung



Comparing the two — big issue is kinematical distributions of outgoing particles

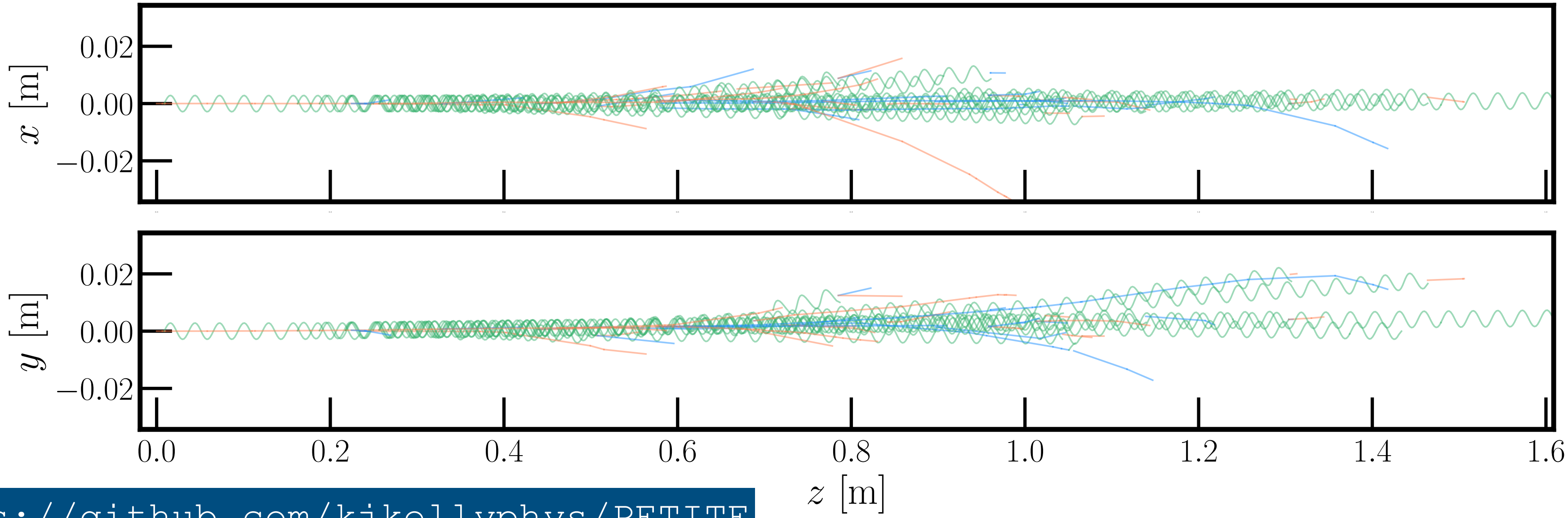
Blinov, Fox, KJK, Machado, Plestid [2401.06843]

Introducing PETITE



PETITE allows for rapid simulation of EM cascades in thick targets that can be processed for determination of BSM flux predictions

Includes SM effects for energy loss, multiple Coulomb scattering, as well as hard scattering processes. Compares extremely well against dedicated tools (e.g. GEANT-4) and analytic results (Tsai/Whitis '66)

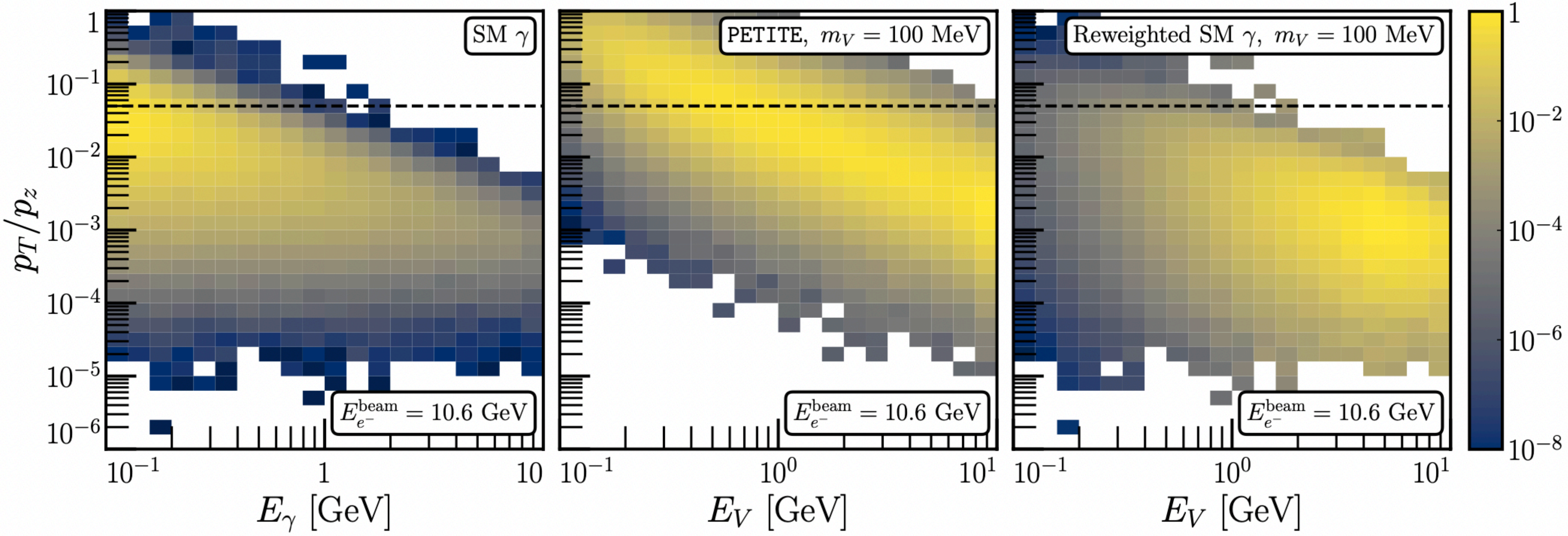


https://github.com/kjkellyphys/PETITE

Care with Kinematics

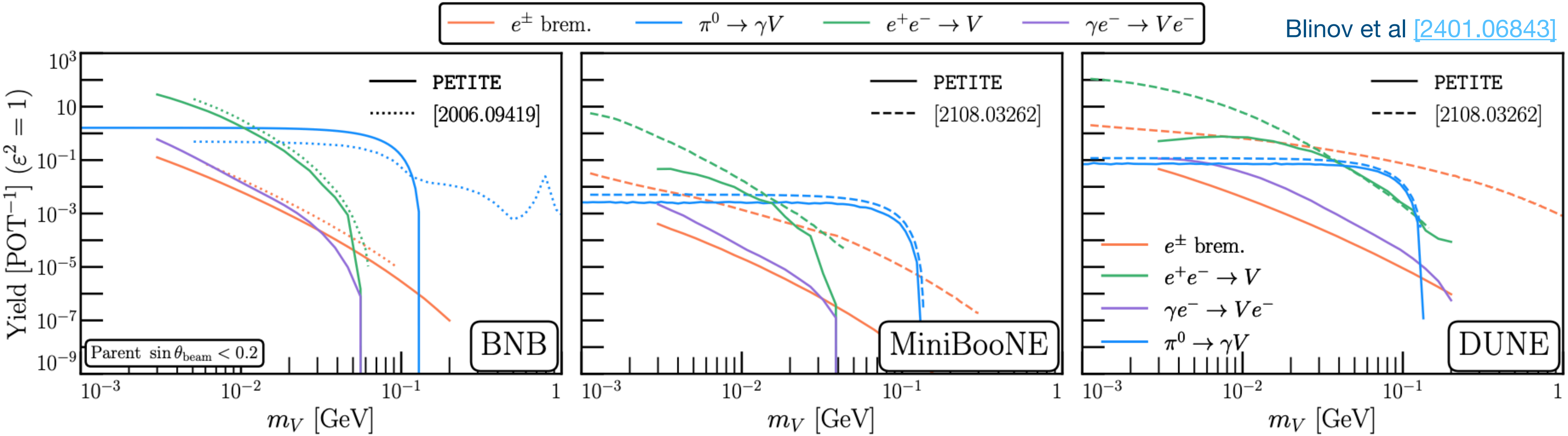
Trying to turn daughter photons into daughter dark photons is tricky because of different kinematics. This has a significant impact, especially for very forward detectors.

Blinov, Fox, KJK, Machado, Plestid [2401.06843]



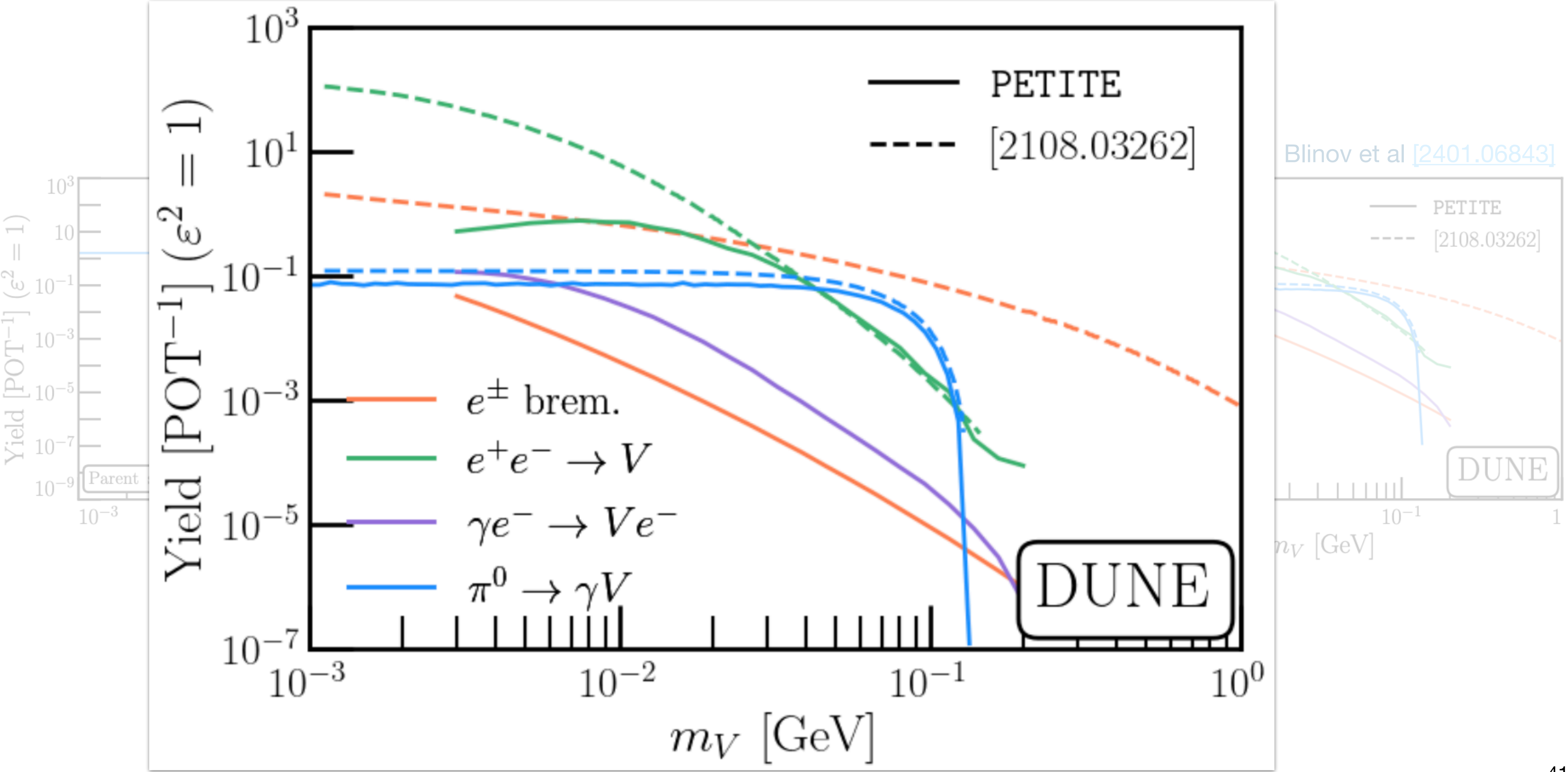
Yields from PETITE

Blinov et al [2401.06843]



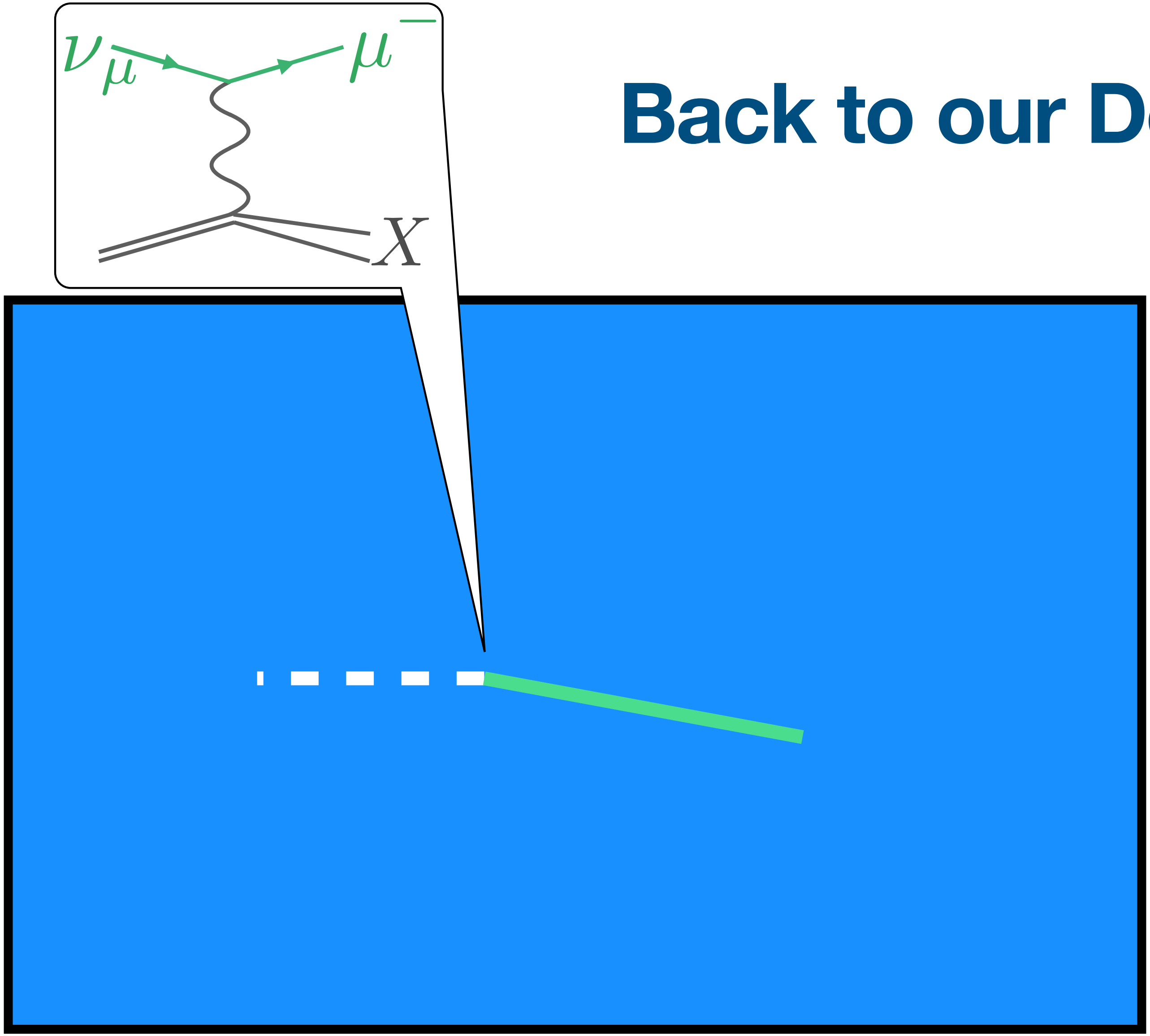
Yields from PETITE

Blinov et al [2401.06843]

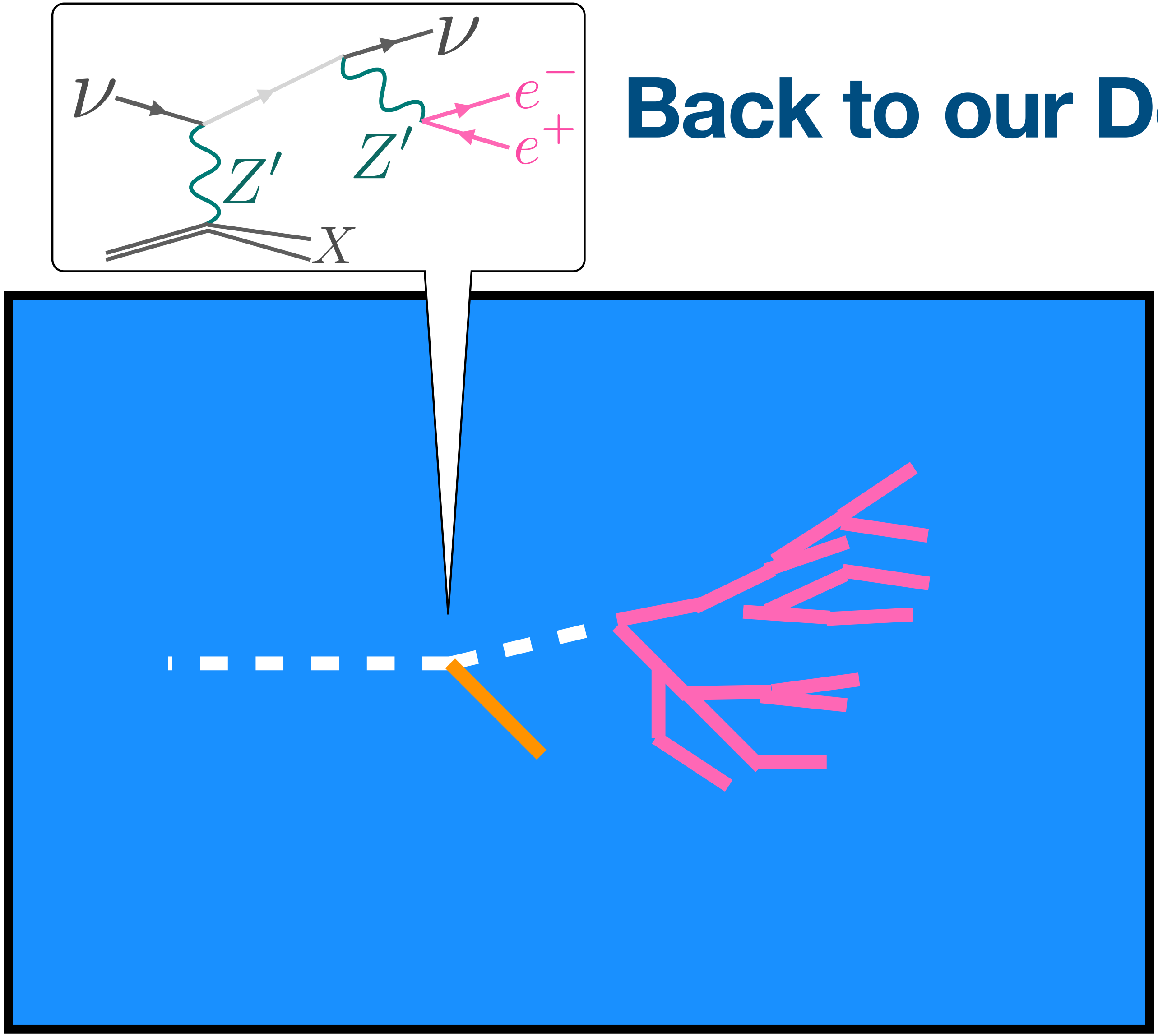


More intricate BSM Scenarios/ Signatures — “dark neutrinos”

Back to our Detector



Back to our Detector



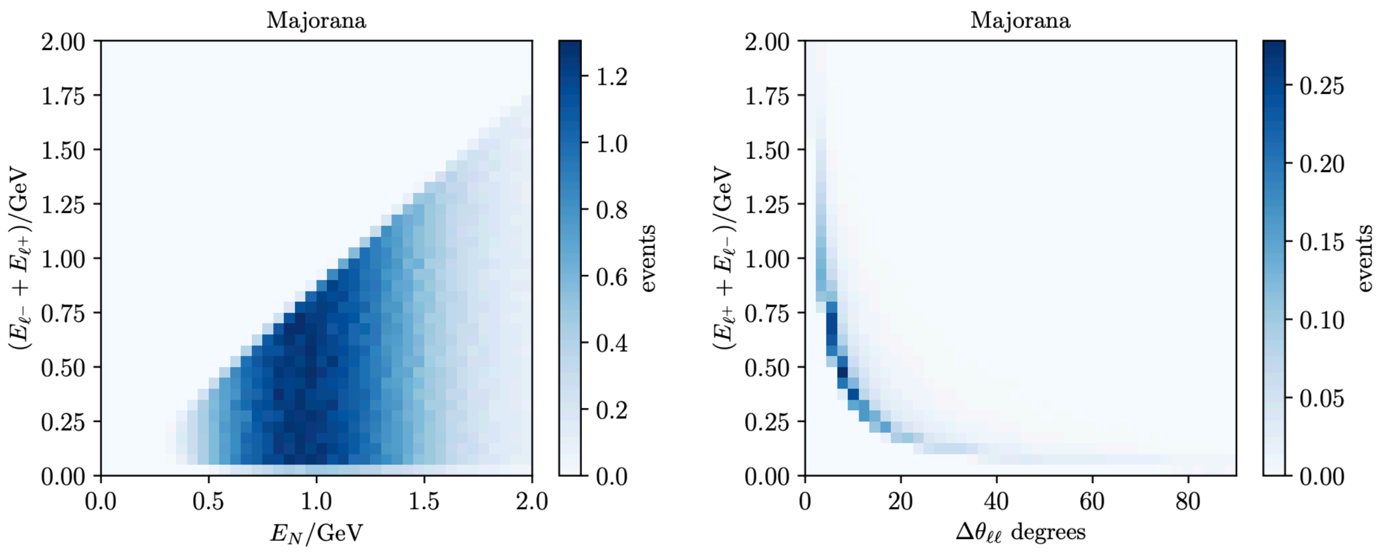
Unexpected neutrino-scattering can lead to novel signatures in the detector. Are we prepared to search for these?

“Dark neutrinos” are a possible solution to the MiniBooNE low-energy excess (since to MiniBooNE, overlapping electron pairs look like a single electron)
Bertuzzo et al [1807.09877]
Ballett et al [1808.02915]

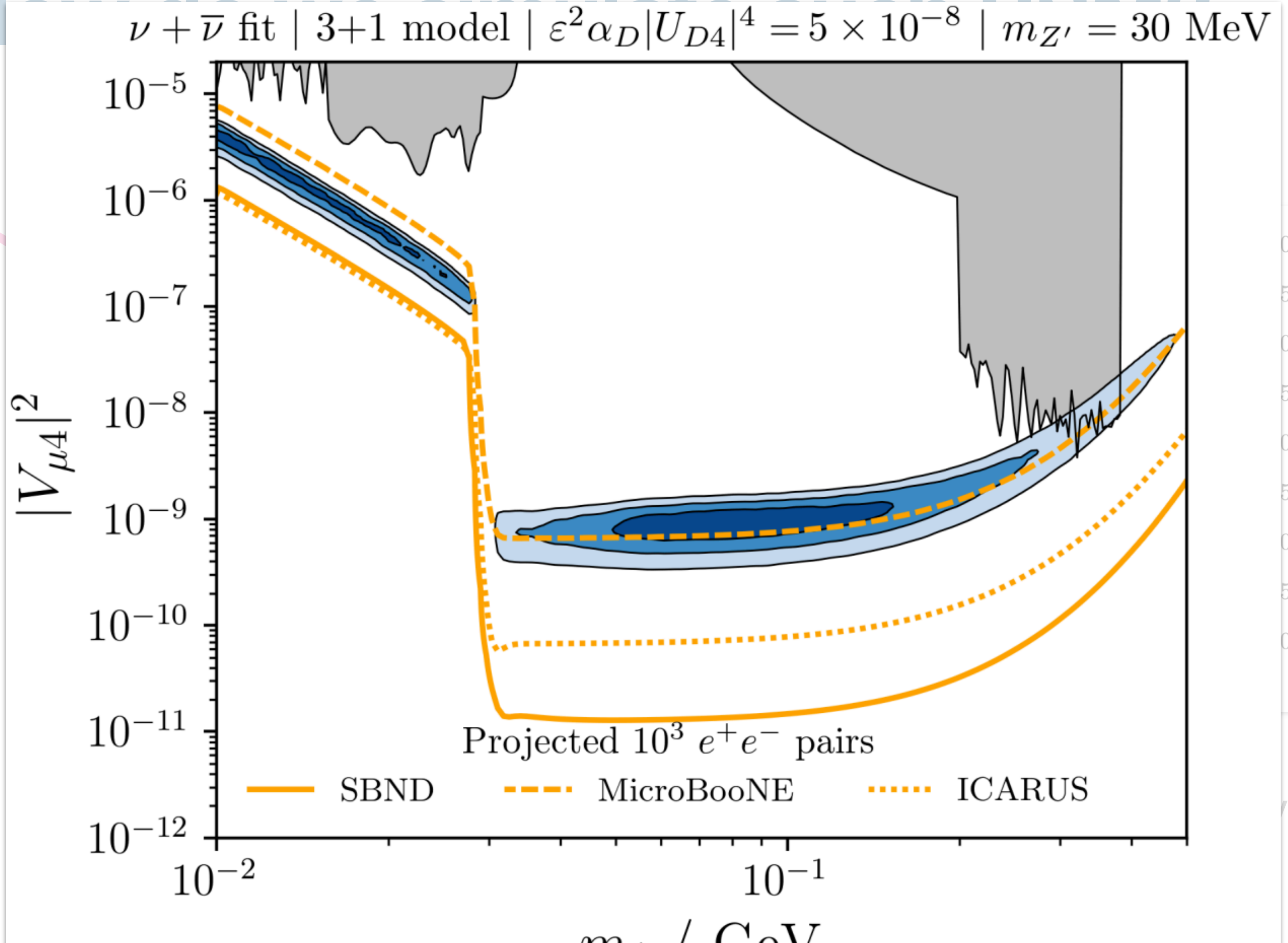
How do we simulate such BSM?

DarkNews Generator

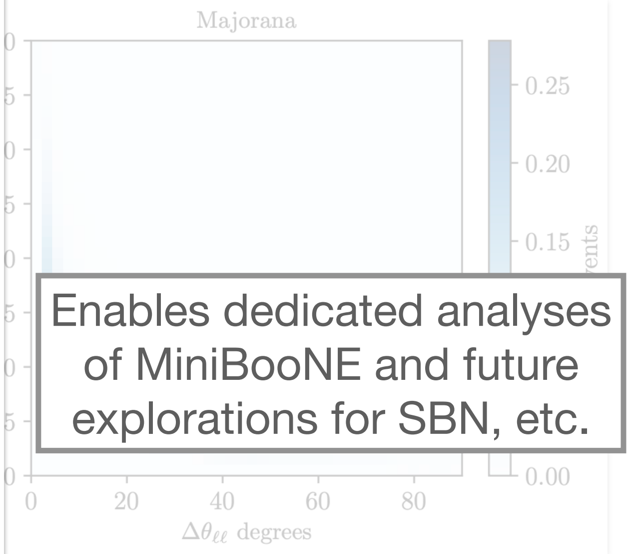
Abdullahi et al [2207.04137]



DarkNews — purpose-built tool for upscattering-type signatures.



Abdullahi et al [2308.02543]



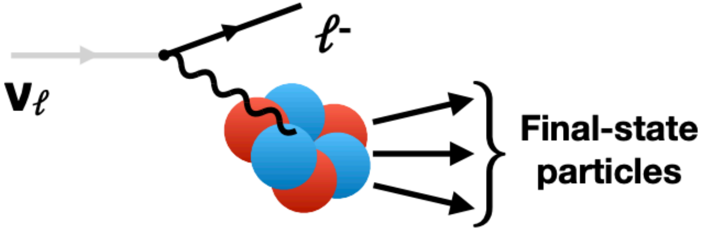
Enables dedicated analyses of MiniBooNE and future explorations for SBN, etc.

pe signatures.

Another approach? Isaacson et al [2205.06378]

Factorizability + Modularity!

(courtesy Will Jay)



$$|\mathcal{M}|^2 = L_{\mu\nu}\frac{1}{P^2}W^{\mu\nu} \rightarrow \langle\Psi_0|J^\dagger_\mu(q)|\Psi_f\rangle\langle\Psi_f|J_\nu(q)|\Psi_0\rangle$$

Leptonic tensor:
Calculable analytically in SM or BSM scenario.

Hadronic tensor:
Complicated multi-scale object, encoding all the hadronic/nuclear physics

$|\Psi_0\rangle$: Initial state (say, ^{40}Ar or H_2O)

$|\Psi_f\rangle$: Final state (nuclear remnant + outgoing pions, kaons, etc…)

Interfaces well with NuHepMC event record format, Gardiner et al [2310.13211]

Another approach? Isaacson et al [2205.06378]

```
Version: 1.0.0
Authors: Joshua Isaacson, William Jay, Alessandro Lovato,
    Pedro A. Machado, Luke Pickering, Noemi Rocco,
    Noah Steinberg

Undergraduate Student Contributions:
    Diego Lopez Gutierrez, Sherry Wang, Russell Farnsworth
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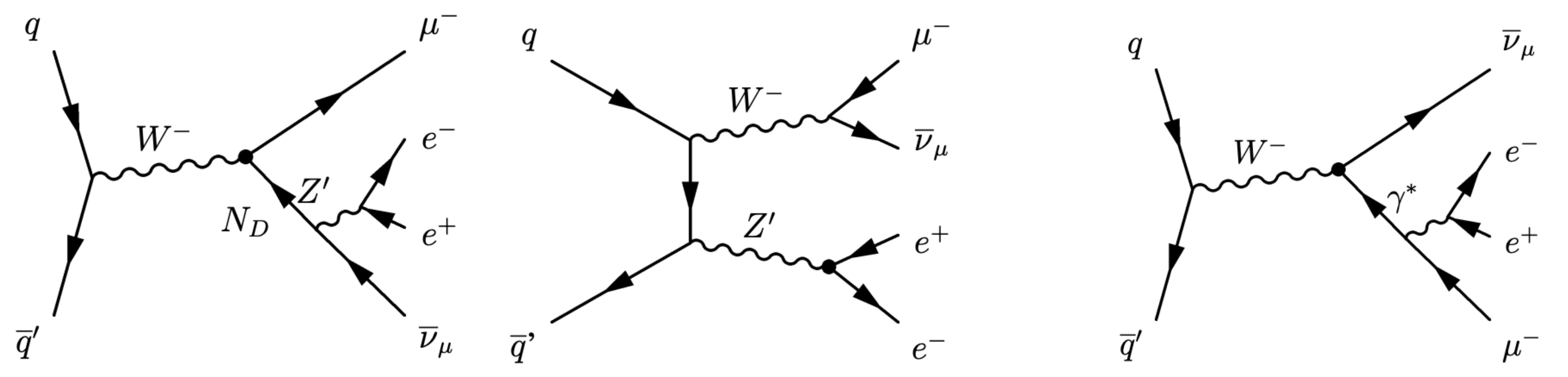
Factorizability + Modularity!

Complementary model searches with the LHC — Herwig et al [2310.13042]



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MicroBooNE Recast:

Higgs-Portal Scalar ⟶ Heavy Neutral Lepton

[2106.06548] KJK & P.A.N. Machado

MicroBooNE Search for Higgs-Portal Scalars

- Inspired by Batell et al [1909.11670], MicroBooNE sought a BSM signature in a particular dataset in 2021:

$$K^+ \to \pi^+ S, \quad S \to e^+ e^-$$

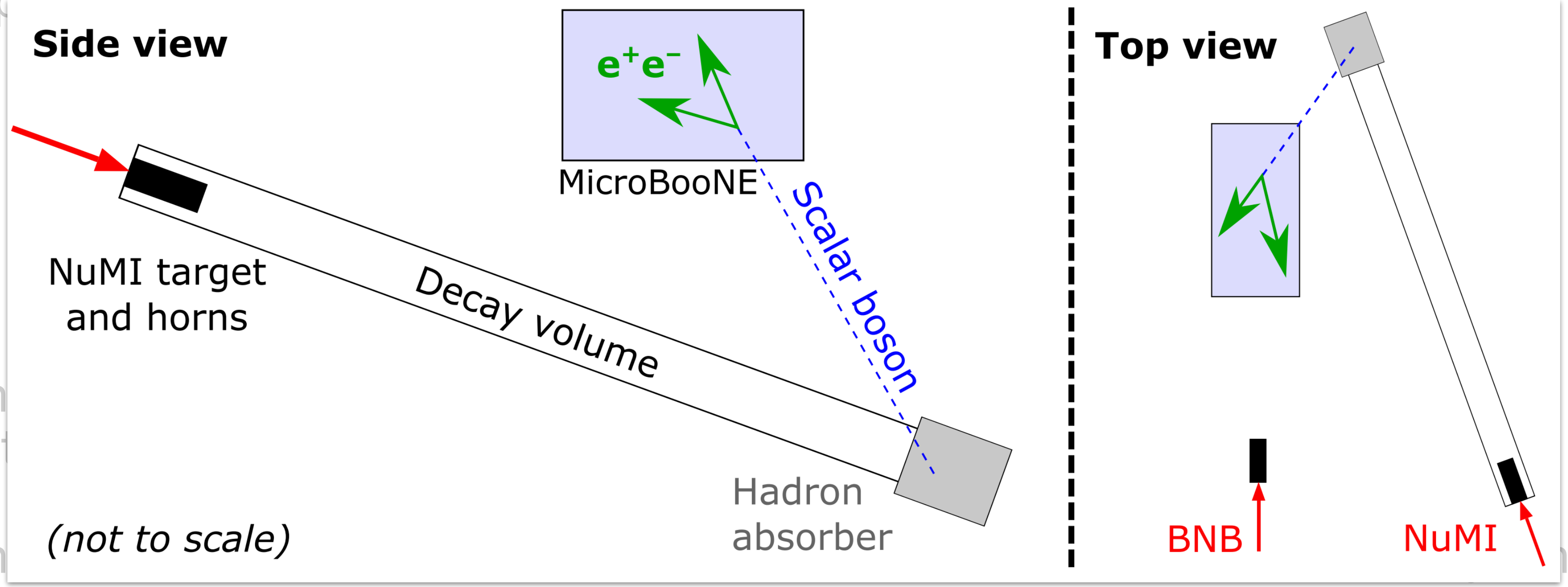
- These kaons are produced in the NuMI beam line or absorber, and decay within the absorber.

- The absorber is 100 m from MicroBooNE — the S must be moderately long-lived to reach MicroBooNE and decay inside.

MicroBooNE [2106.00568]

MicroBooNE Search for Higgs-Portal Scalars

- Inspired by Batell et al [1909.11670], MicroBooNE sought a BSM signature in a particular dataset in 2021:

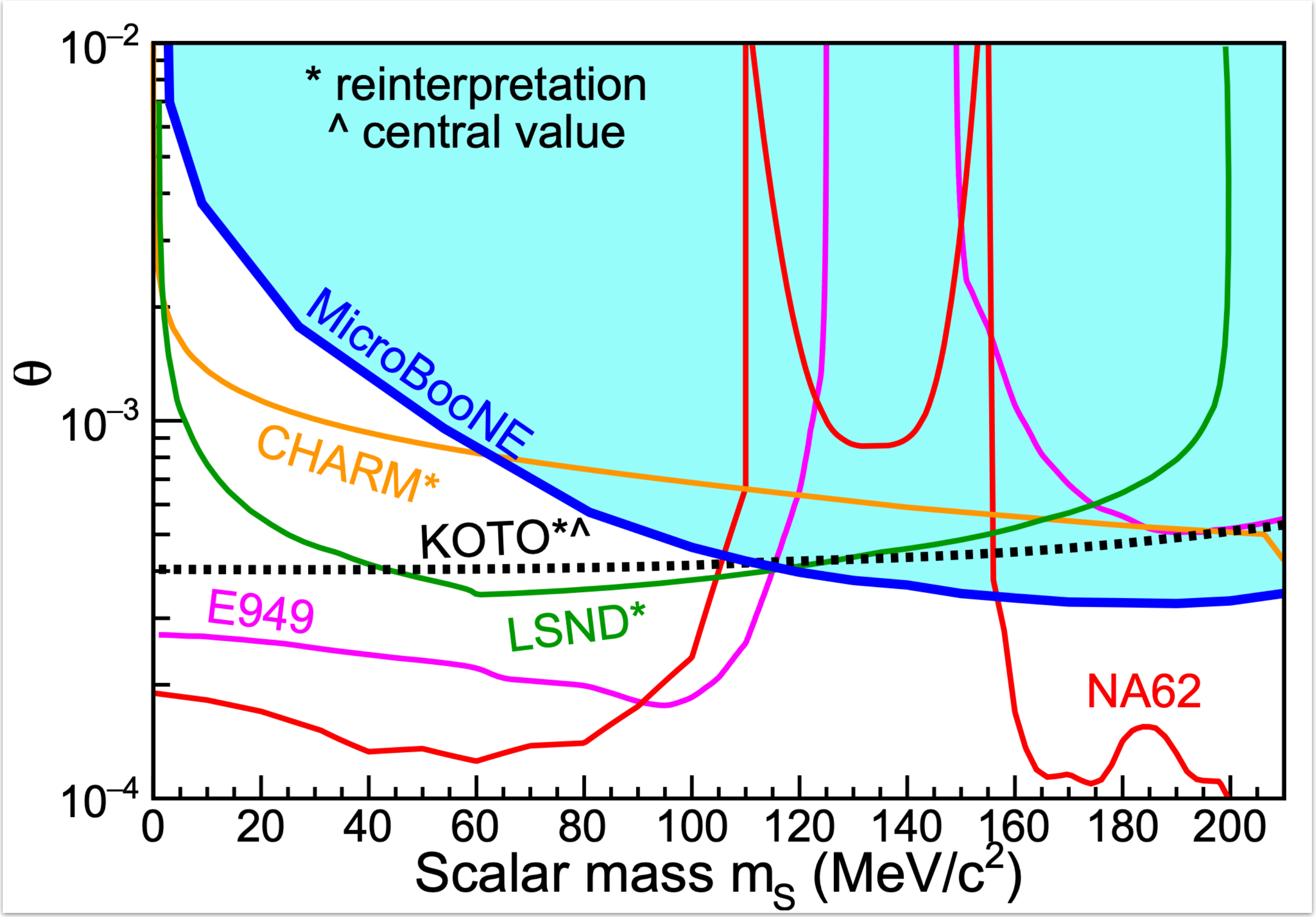


- Th… wi…
- Th… …ng-lived to reach MicroBooNE and decay inside.

MicroBooNE [2106.00568]

MicroBooNE Constraint

MicroBooNE [2106.00568]



Signal Rate from KDAR BSM

signal rate

flux of new particles

detector area

$$R_X = \Phi_X A_{\text{det.}} P\left(X \to e^+ e^-\right) \varepsilon(m_X)$$

probability of decay happening in detector

signal efficiency

$$\Phi_X = \frac{N_{\text{KDAR}} \text{Br}\left(K^+ \to X\right)}{4\pi D^2}$$

$$P \approx \frac{L_{\text{det.}}}{\gamma} \Gamma\left(X \to e^+ e^-\right)$$

Flux Example

$$\Phi_X = \frac{N_{\mathrm{KDAR}} \mathrm{Br}\left(K^+ \to X\right)}{4\pi D^2}$$

Scalar Model

$$\mathrm{Br}(K^\pm \to \pi^\pm \varphi) = 2 \times 10^{-3} \sin^2 \vartheta \, \rho_\varphi \left(\frac{M_\varphi^2}{m_{K^\pm}^2}, \frac{m_{\pi^\pm}^2}{m_{K^\pm}^2} \right)$$

HNL Model

$$\mathrm{Br}(K \to \mu N) \simeq \mathrm{Br}(K \to \mu \nu) |U_{\mu 4}|^2 \rho_N \left(\frac{m_\mu^2}{m_K^2}, \frac{m_N^2}{m_K^2} \right)$$

How to recast HPS to HNL?

- Without digging into the weeds, MicroBooNE recorded data and performed an analysis looking for $S \to e^+e^-$ signal events.
- This included a boosted decision tree (BDT) trained on signal and background Monte Carlo.
- After cutting on the BDT score, two* candidate events pass, on a background expectation of 1.9 ± 0.8 events.

TABLE II. Estimated signal selection efficiency (eff.) for a scalar boson decay inside the TPC, and event yield [unweighted (unwt.) and beam-on exposure-weighted (exp. wt.), with the expected signal for θ_{KCV}].

Category	Eff. (%)	Event count Unwt.	Event count Exp. Wt.
Beam-off dataset		10	1.1 ± 0.4
Neutrino simulation		16	0.8 ± 0.7
Signal (120 MeV/c^2)	14.0 ± 0.8	7268	4.9 ± 1.5
Signal (160 MeV/c^2)	14.9 ± 0.9	7654	12.2 ± 3.6

Goal: as a function of mass, determine the HNL model parameters that predict the *same* signal rate that MicroBooNE has excluded for the Higgs-portal scalar model.

Same Rate?

$$R_X = \Phi_X A_{\text{det.}} P\left(X \to e^+e^-\right)\varepsilon(m_X)$$

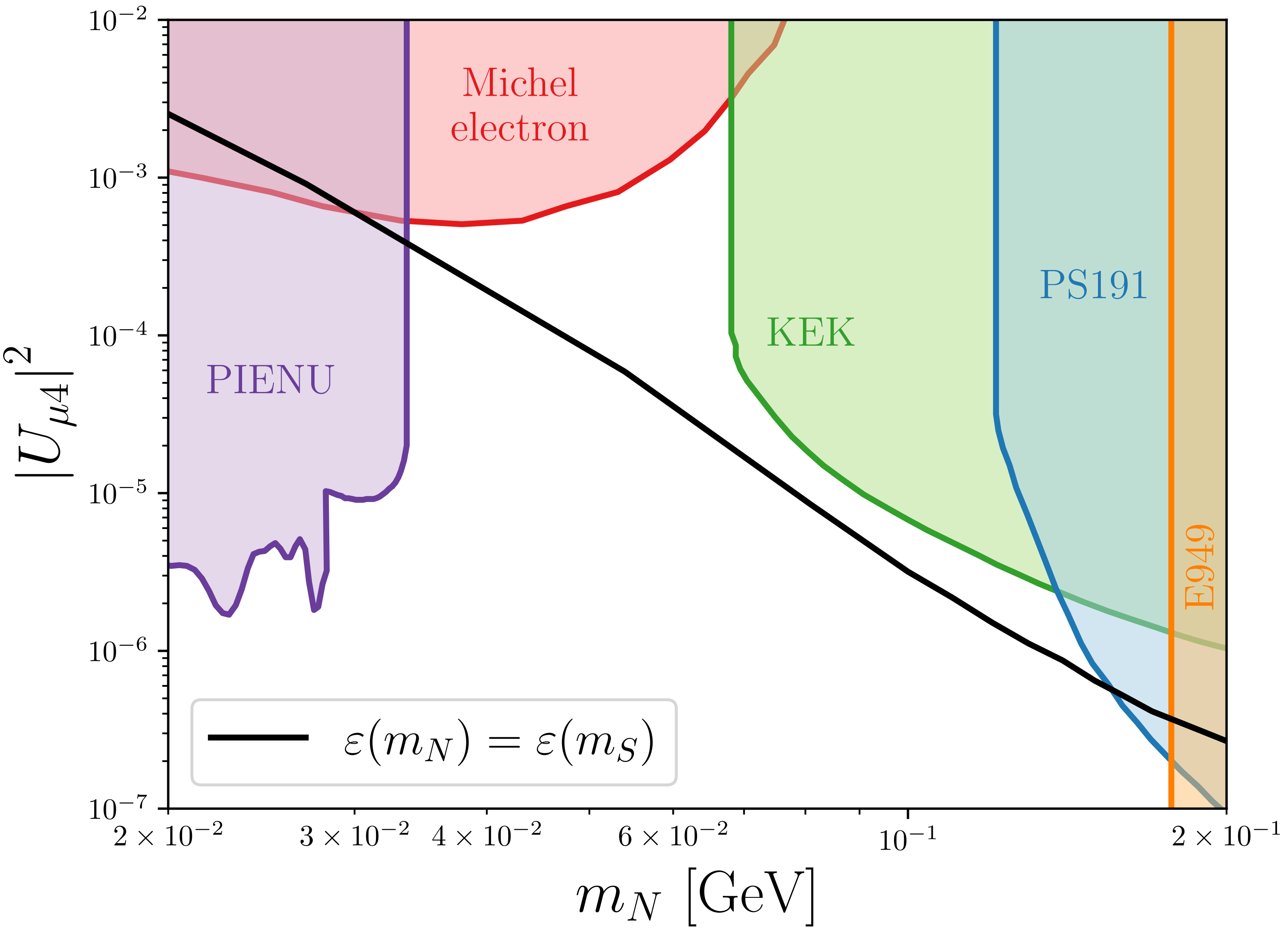
$$\frac{R_N}{R_S} \approx \frac{\text{Br}(K \to \mu N)}{\text{Br}(K \to \pi S)} \frac{m_N E_S \Gamma(N \to \nu e^+ e^-)}{m_S E_N \Gamma(S \to e^+ e^-)} \frac{\varepsilon(m_N)}{\varepsilon(m_S)}$$

Given or Calculable

Calculable given $|U_{\mu N}|^2$ (and proportional to that)

Pretend it's equal to $\varepsilon(m_S)$ for now

HPSRecast.ipynb



10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$|U_{\mu 4}|^2$
Michel
electron
PIENU
KEK
PS191
E949
$\varepsilon(m_N) = \varepsilon(m_S)$
2×10^{-2}
3×10^{-2}
4×10^{-2}
6×10^{-2}
10^{-1}
2×10^{-1}
m_N [GeV]

OK, what about efficiency?

$$R_X = \Phi_X A_{\text{det.}} P\left(X \to e^+e^-\right)\varepsilon(m_X)$$

$$\frac{R_N}{R_S} \approx \frac{\text{Br}(K \to \mu N)}{\text{Br}(K \to \pi S)}\,\frac{m_N E_S \Gamma(N \to \nu e^+e^-)}{m_S E_N \Gamma(S \to e^+e^-)}\,\frac{\varepsilon(m_N)}{\varepsilon(m_S)}$$

What goes into signal efficiency?

Training Information from MicroBooNE

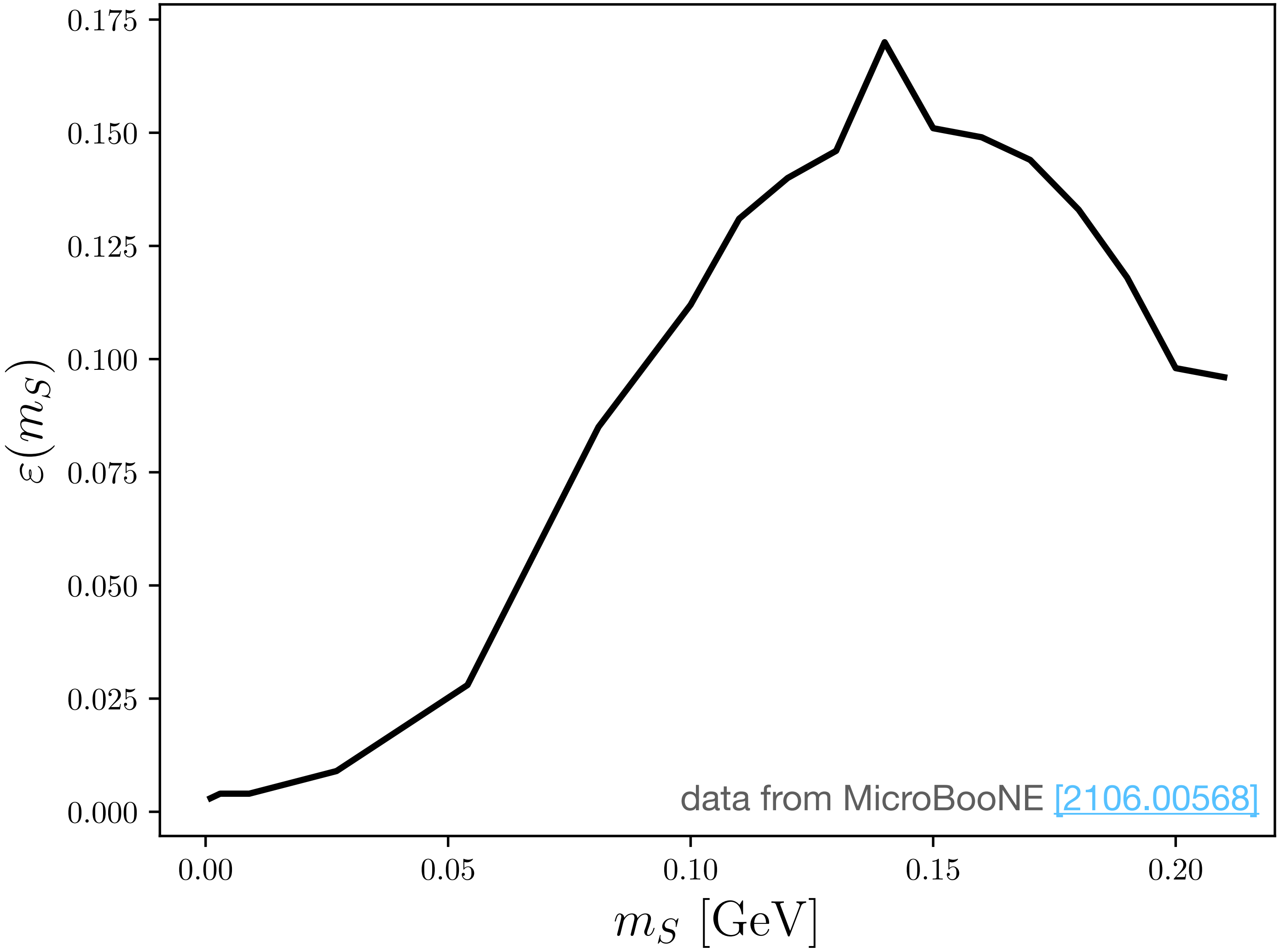
MicroBooNE [2106.00568]

We apply two different BDTs to the preselected candidates: one trained against cosmic backgrounds and one trained against neutrino interactions simulated inside the cryostat. Each BDT is trained separately over the run 1 events and run 3 events, i.e., there are four BDTs in total. We split the run periods because the use of the CRT in run 3 and the differences between forward and reverse horn current operations can change the topologies and properties of the background distributions that the BDTs are trained against. We use `xgboost` [27] to train and apply the BDTs. We train the BDTs on ten input variables each. Nine of the ten input variables are the same for the cosmic-focused and neutrino-focused BDTs. These are (1) the opening angle between the two reconstructed objects; (2) the opening angle in the plane transverse to the hadron absorber direction from the detector center; (3,4) the two angles between the two objects and the hadron absorber direction; (5) the Pandora track or shower score of the larger of the two objects (when ordered by number of hits); (6) the number of hits of the larger object; (7) the total number of hits contained in other objects in the slice, not including the two objects that form the decay candidate; (8) the maximum y coordinate, relative to the decay vertex position, of shower start positions or track start or end positions, for any other objects in the slice; and (9) the minimum z coordinate, relative to the decay vertex position, of shower start positions or track start or end positions, for any other objects in the slice. The last two variables are treated as "missing" within `xgboost` if the slice contains only two objects. The tenth input variable of the cosmic-focused BDT is the length of the larger object. The tenth input variable of the neutrino-focused BDT is the number of tracks in the slice. For all

Ansatz:

(1) dominates the signal efficiency as a function of BSM particle mass

HPS Efficiency



Generate e^+e^- events in the rest-frame of the decaying HPS/HNL

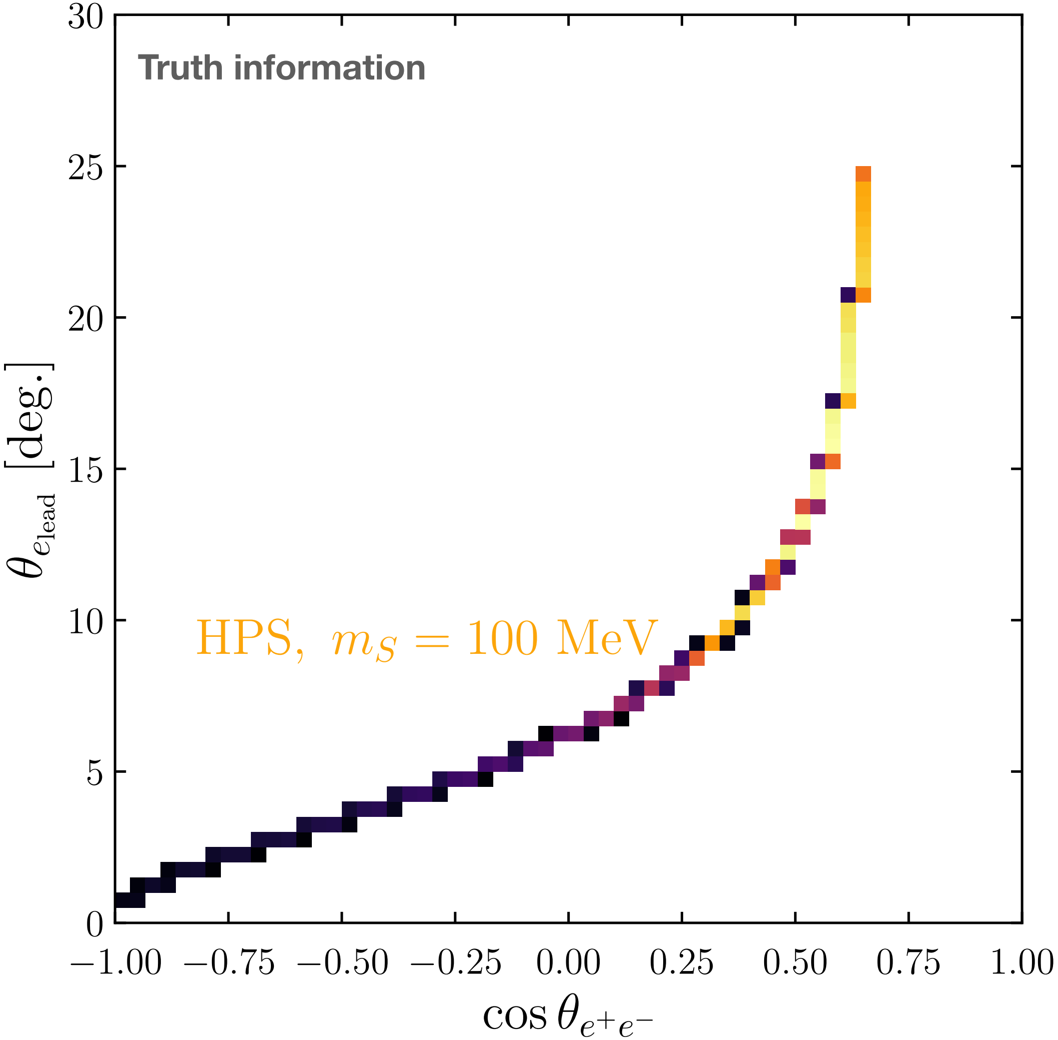
(depends on `RestFrame.py` for HNL three-body kinematics and `vegas` for phase-space sampling)

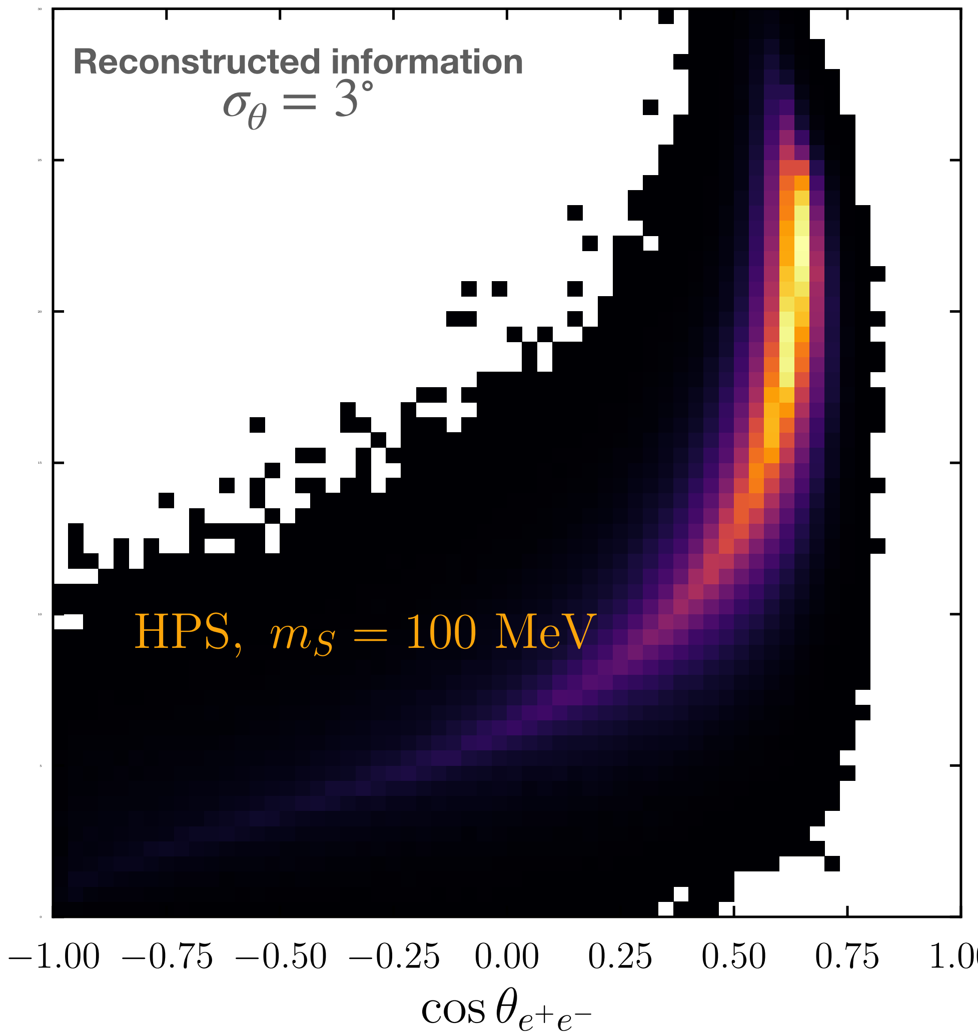
`RestFrame.py`

`LabFrame.py`

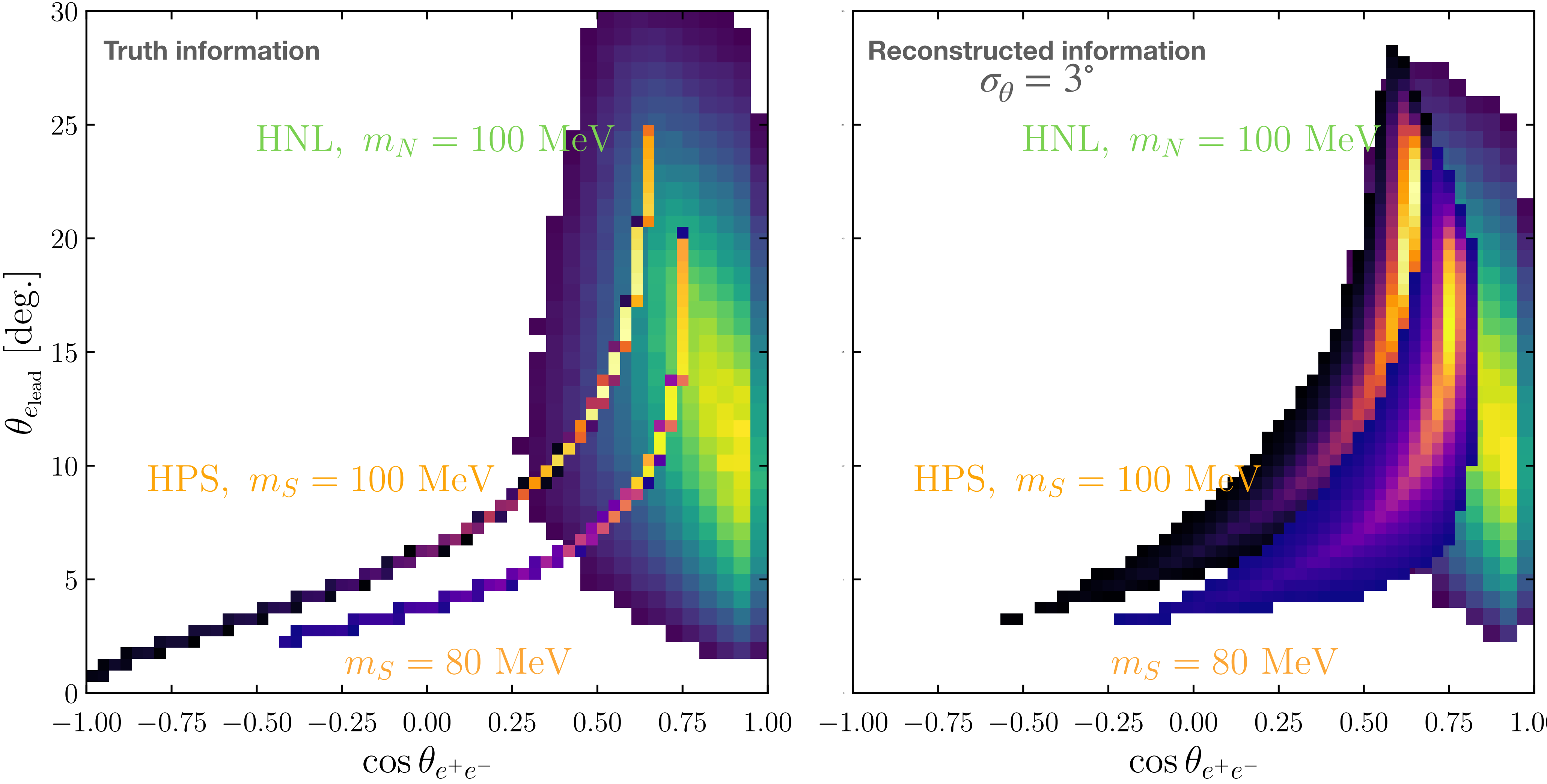
Transforms event to the laboratory frame, smears events, and performs different reconstruction/analyses on the events.

Event Distributions

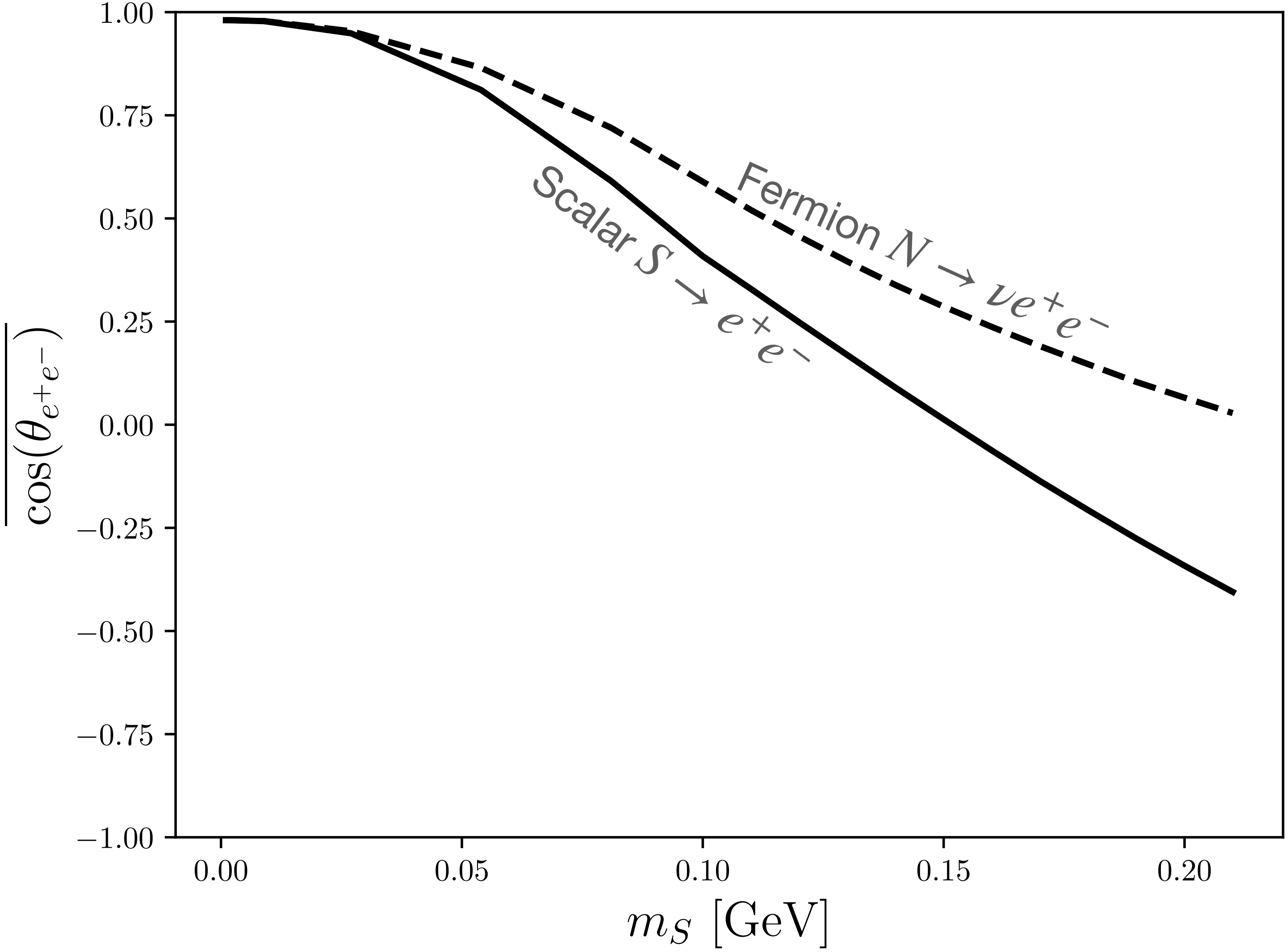




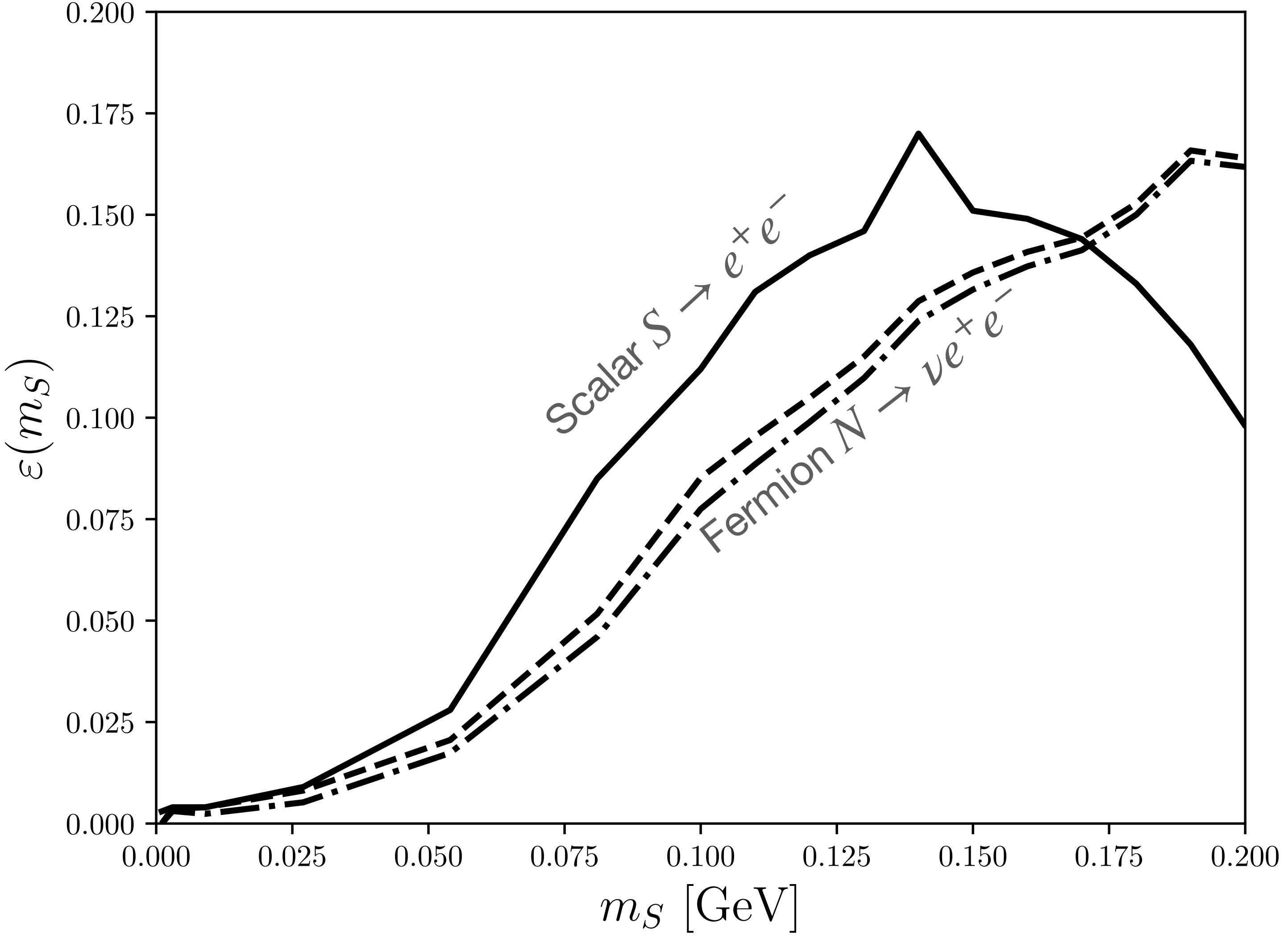
HNL vs HPS in this Kinematic Space



Average Opening Angles



Updated Efficiency for HNLs



New Constraint on HNLs