Light Dark Matter at the DUNE Near Detector

Kevin J. Kelly
FNAL Theory Group
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Outline

- Dark Photon + Light Fermion/Scalar DM
  - Thermal Relic DM
  - DUNE-PRISM
  - On- and off-axis searches for DM

- Mono-neutrino Events and Neutrinophilic DM
  - Extending the SM with (B-L) Symmetry
  - Large missing-momentum events at the DUNE Near Detector
  - Searching for thermal relic neutrinophilic DM at DUNE

Light Dark Photon + Dark Matter

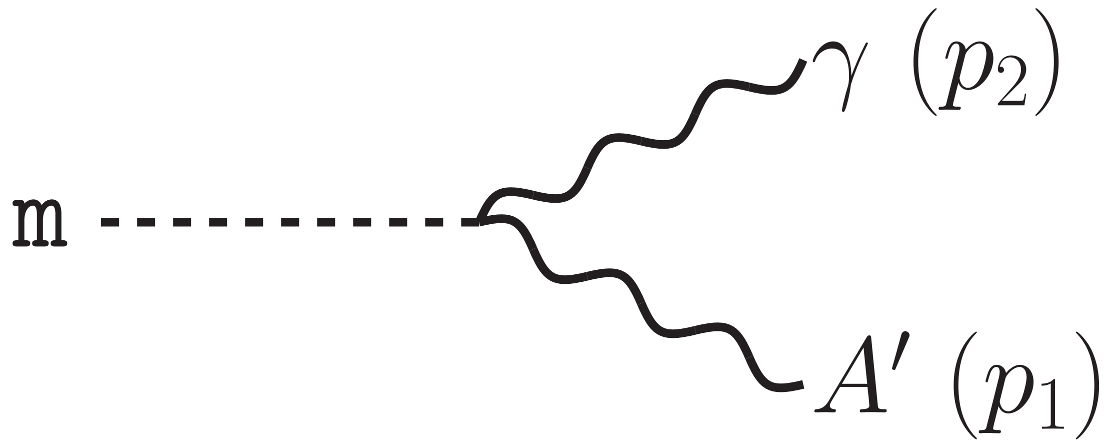
[1903.10505]

Dark Photon + Light DM Model of Interest

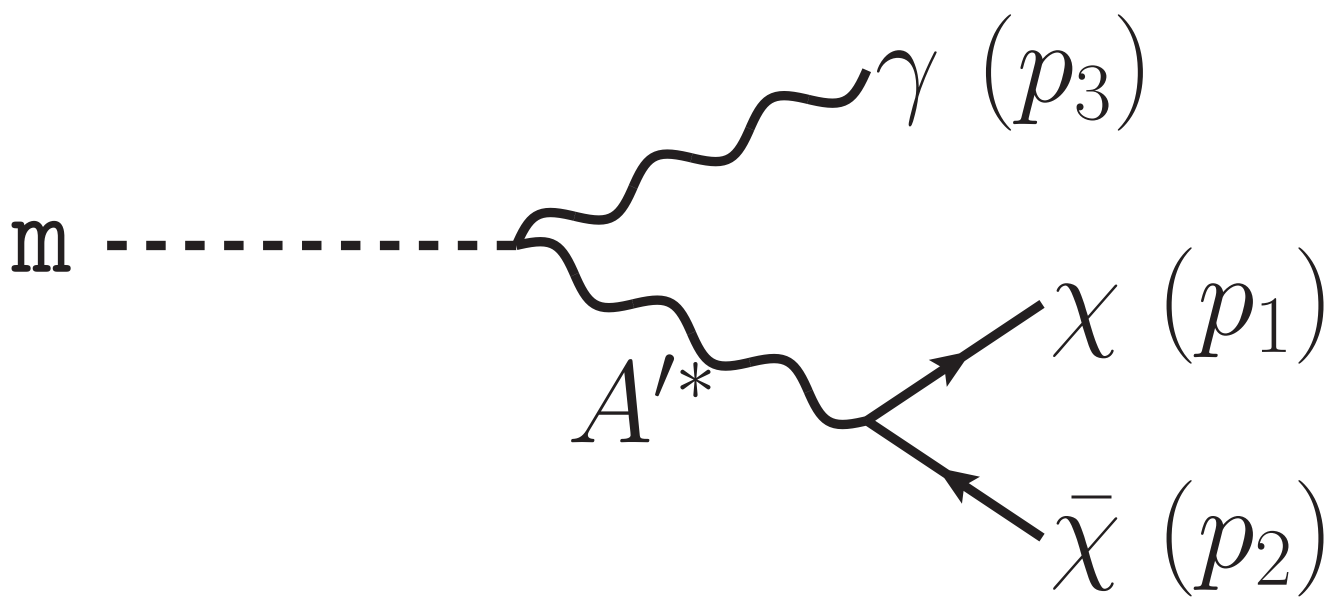
$$\mathscr{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{M_{A'}^2}{2} A'_\mu A'^\mu + \bar{\chi} i \gamma^\mu \left(\partial_\mu - i g_D A'_\mu \right) \chi - M_\chi \bar{\chi} \chi \,.$$

(or similar with scalar DM)

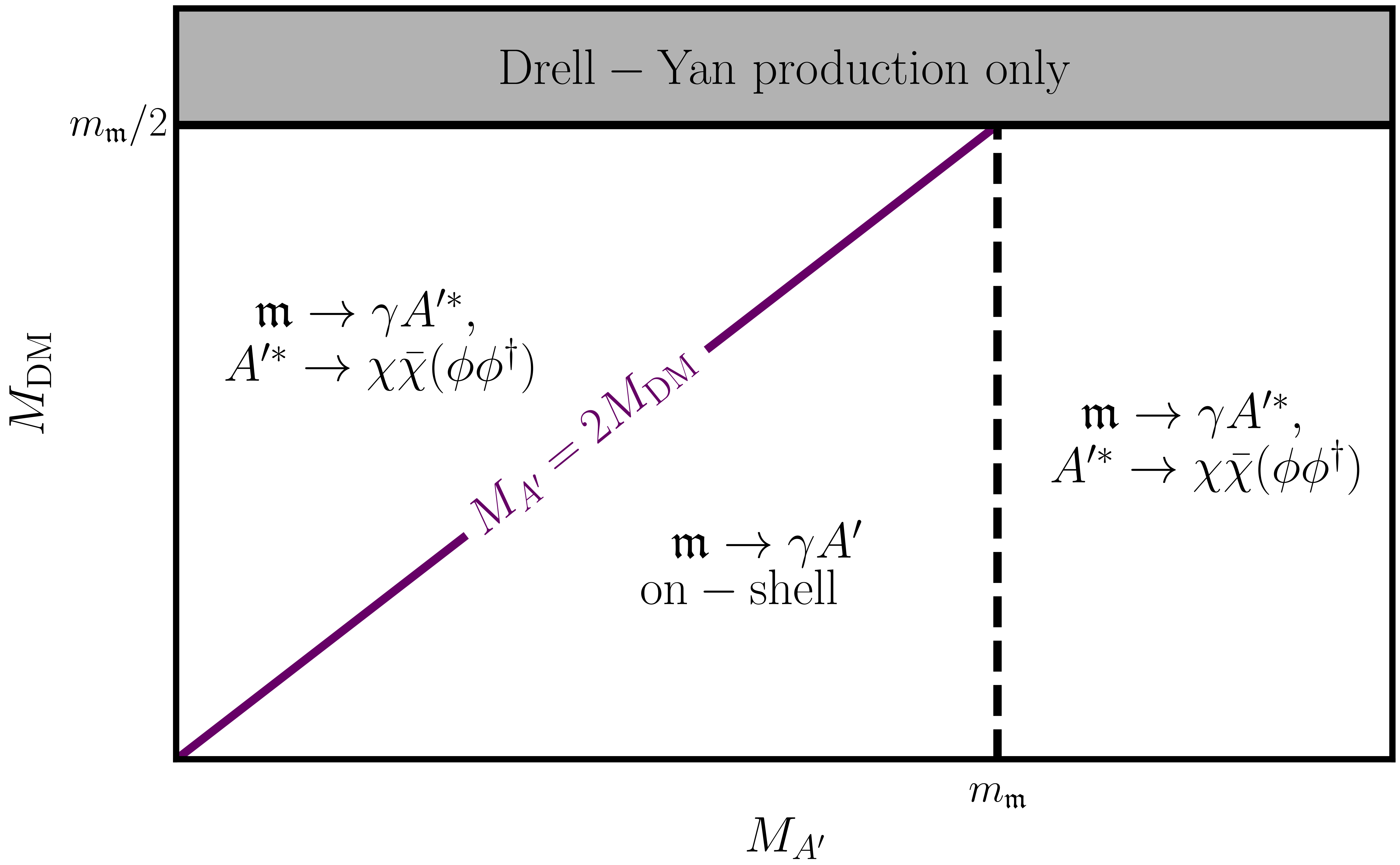
In a fixed-target environment, many neutral mesons that can decay $\mathfrak{m} \to \gamma\gamma$ are produced. With suitable masses, they can decay instead by



Or



Where in parameter space are we looking?



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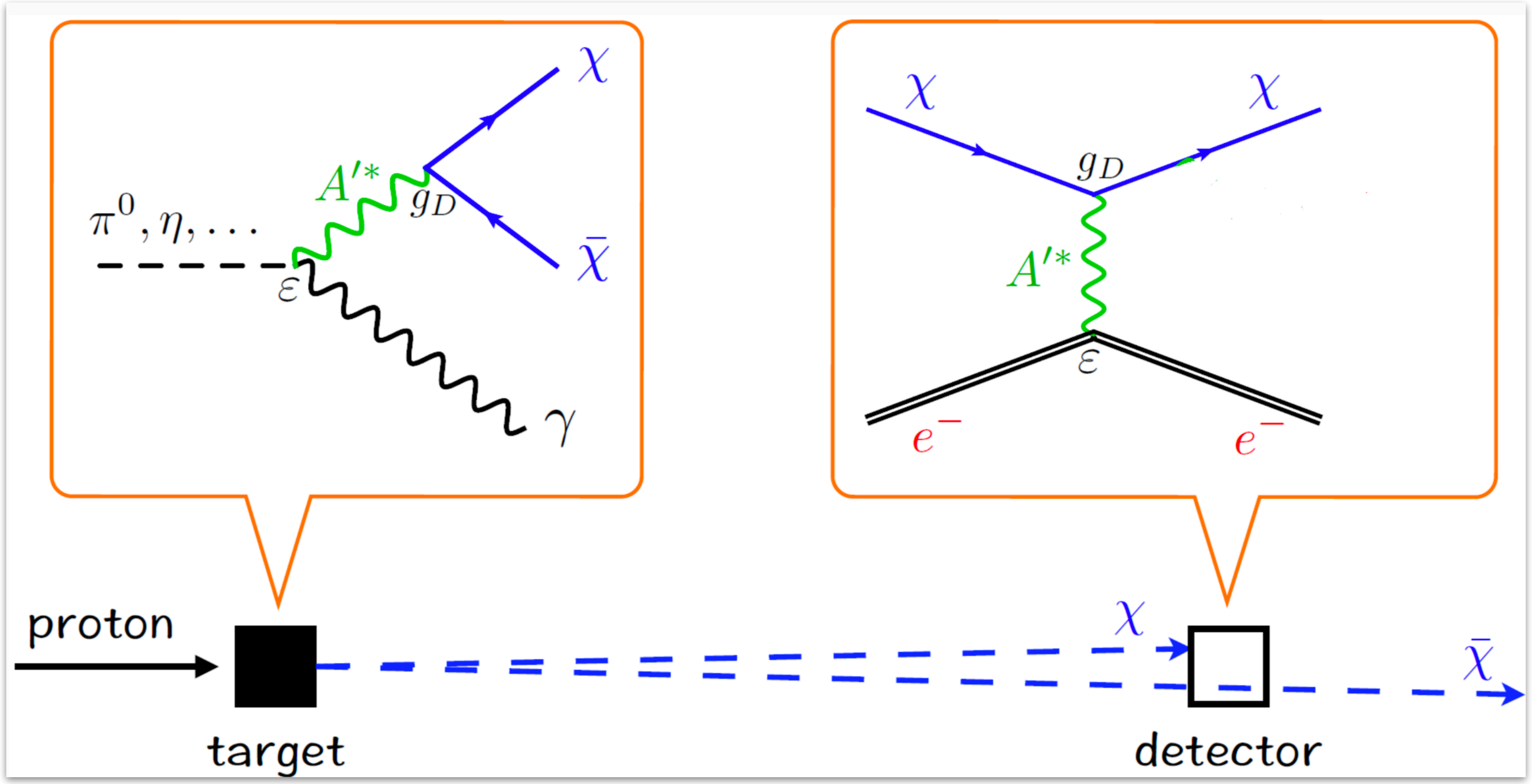
Detection Signature

- Some fraction of the produced DM will travel in the direction of the DUNE Near Detector.

- Via kinetic mixing with the standard model photon, the DM can scatter off nucleons or electrons in the detector.



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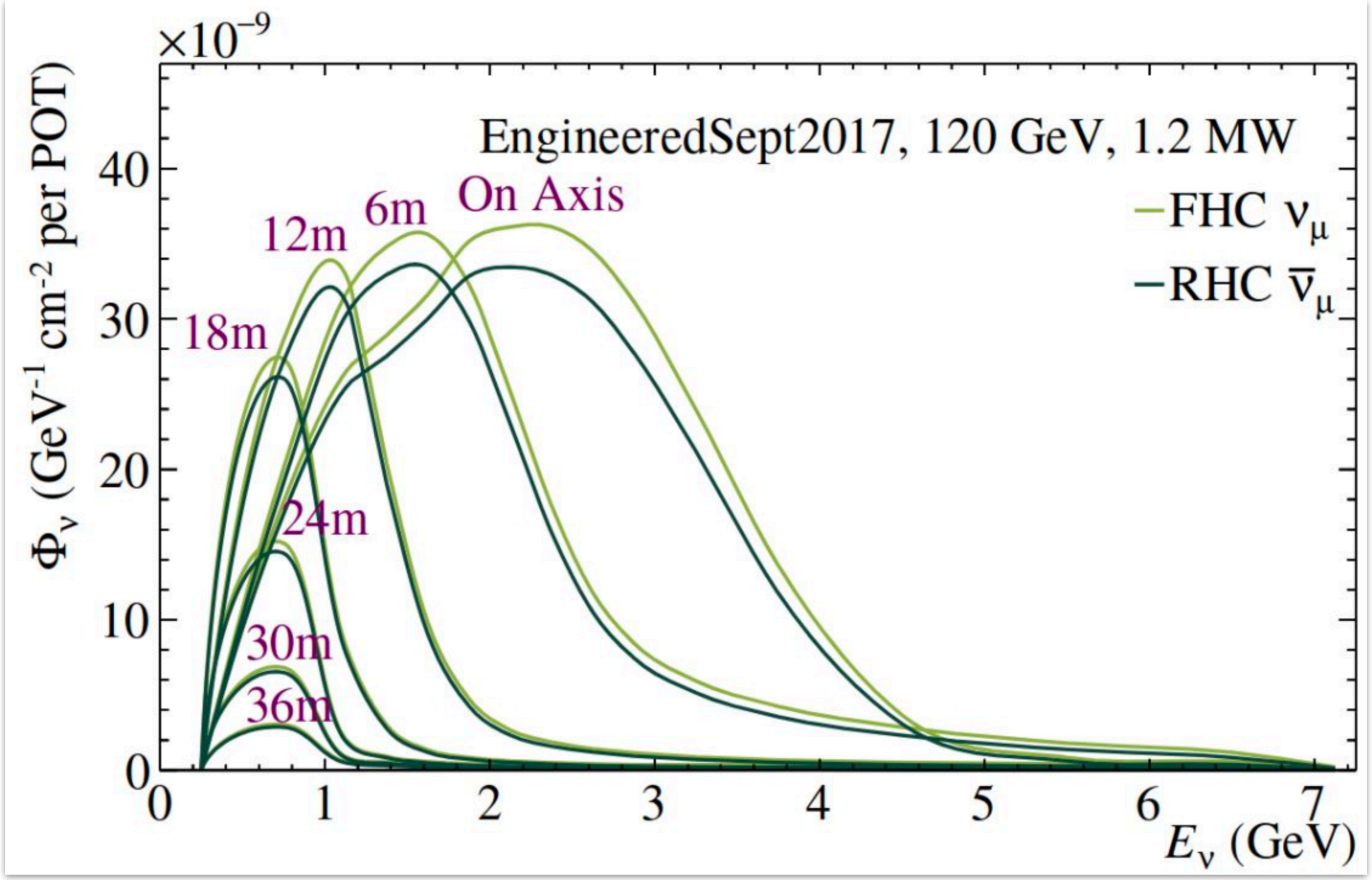
Let's talk about Backgrounds

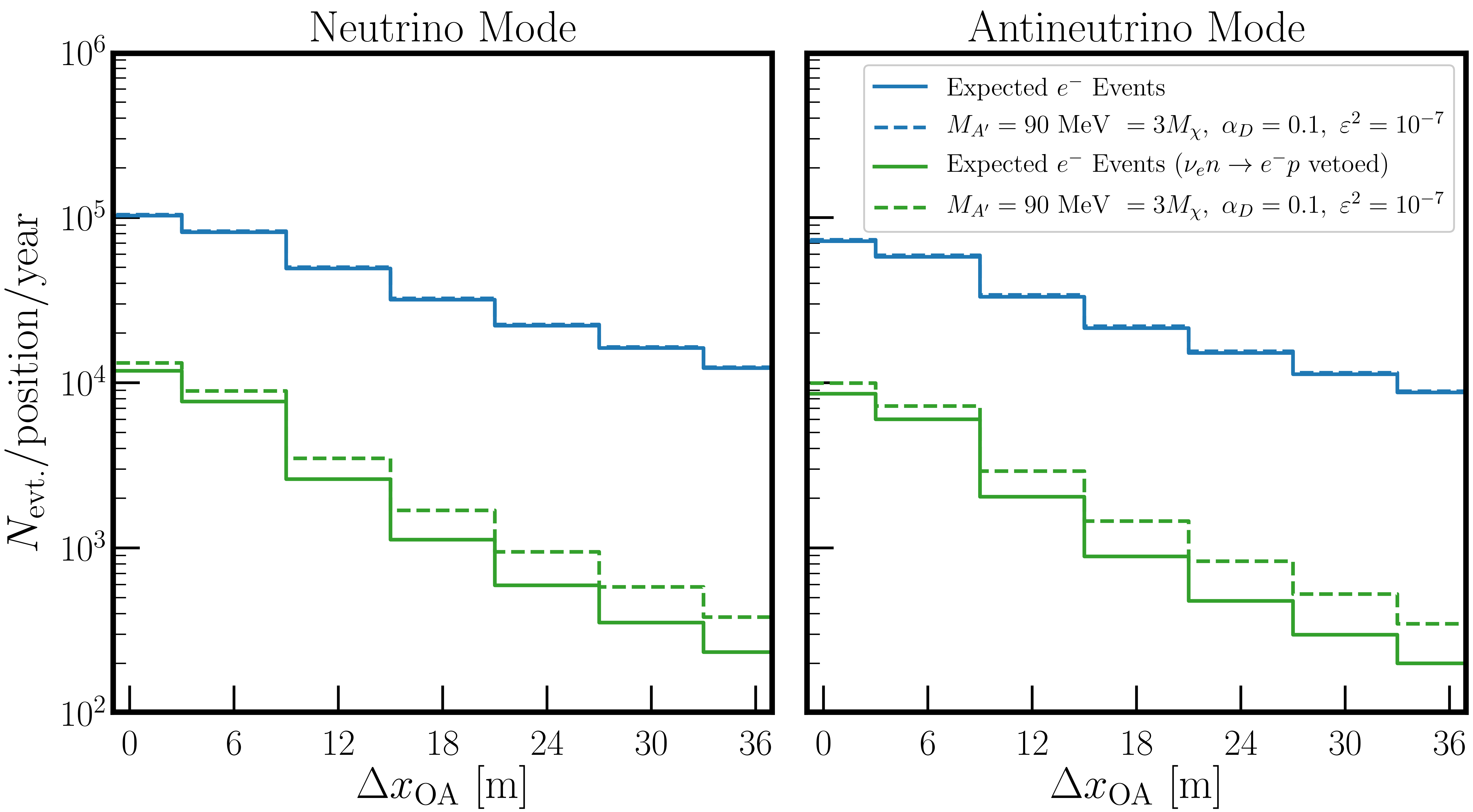
- Signal looks identical to neutrino-nucleus neutral-current scattering or $\nu_\mu e^- \to \nu_\mu e^-$
- If just performing a counting experiment, this strategy will be background dominated.
- Going beyond a counting experiment is difficult — shape of the neutrino flux (in energy space) is constrained using $\nu_\mu e^- \to \nu_\mu e^-$ measurements!
- Our proposed solution: utilize the DUNE-PRISM proposal.

DUNE-PRISM



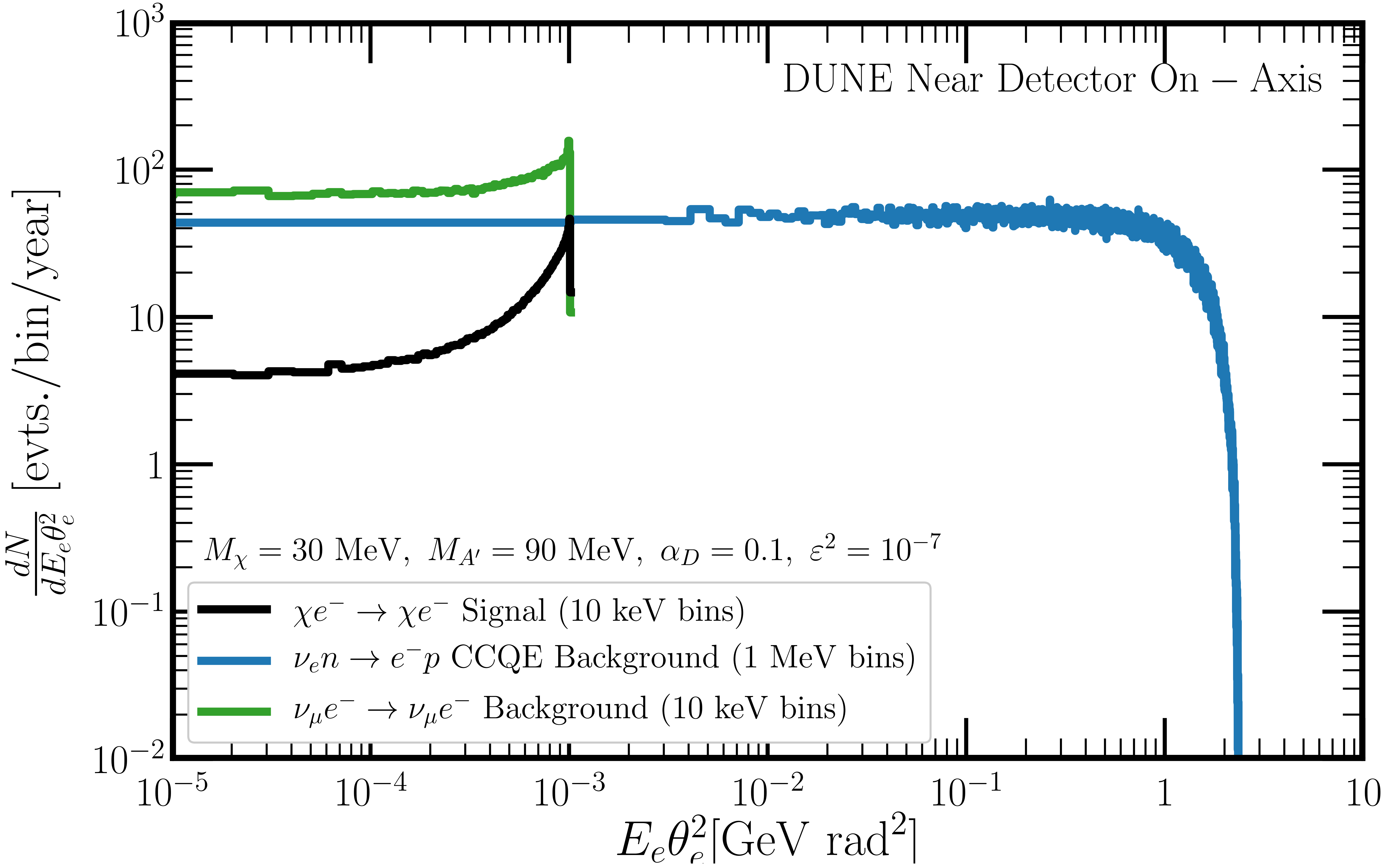
Proposal: move the near detector transverse to the beam direction. Relative flux at different off-axis positions is predictable from meson decay kinematics. Neutrino beam is focused (coming from charged mesons), but DM flux is unfocused!

Signal-to-Background as off-axis angle increases



This shape should be well-predicted (meson decay kinematics), even if the energy spectrum of the neutrinos cannot be constrained as well.

Vetoing the ν_e CCQE Background with Kinematics



Even if final-state proton is lost in CCQE event, kinematics of the electron may allow us to effectively veto all of these events.

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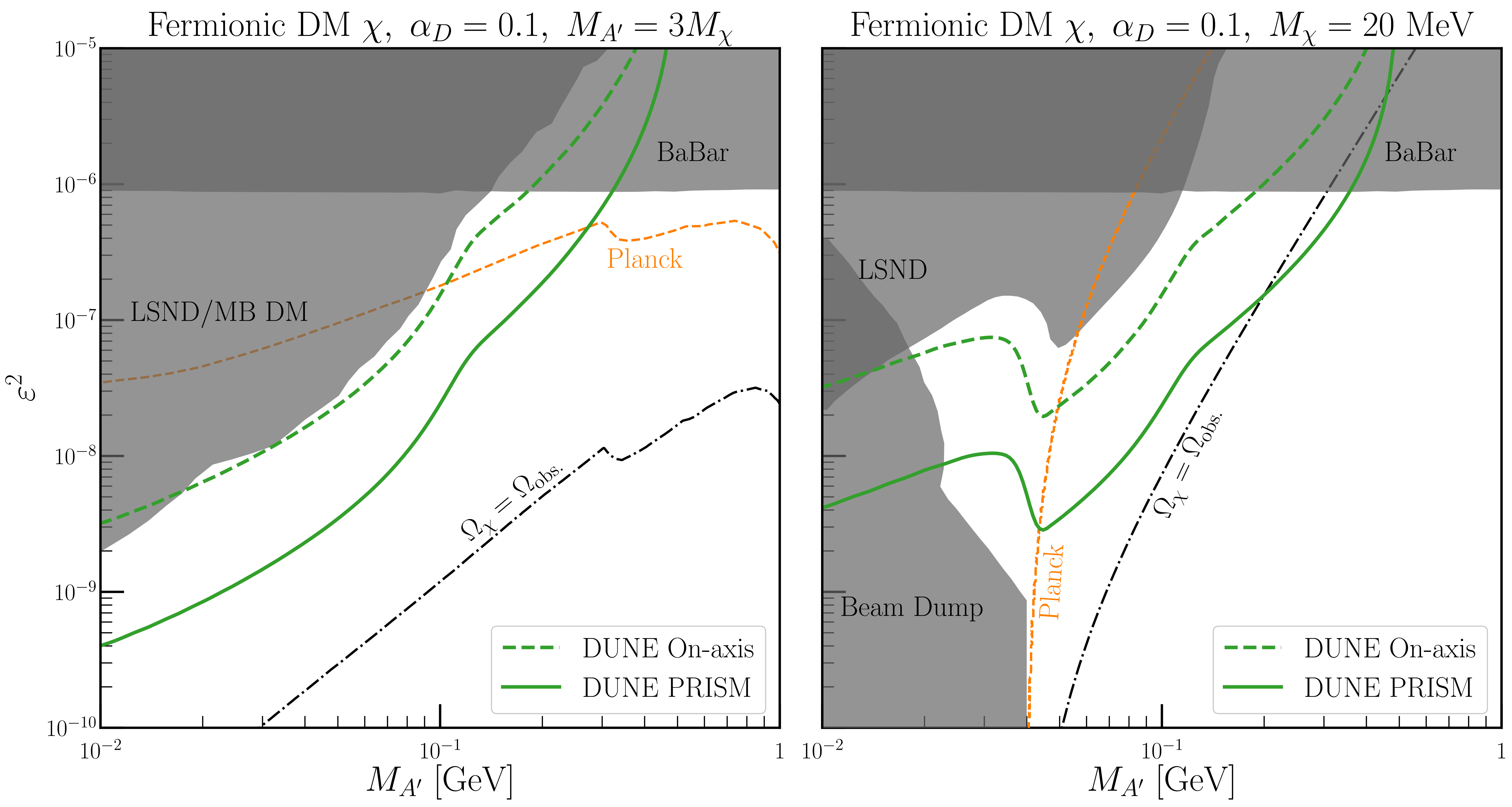
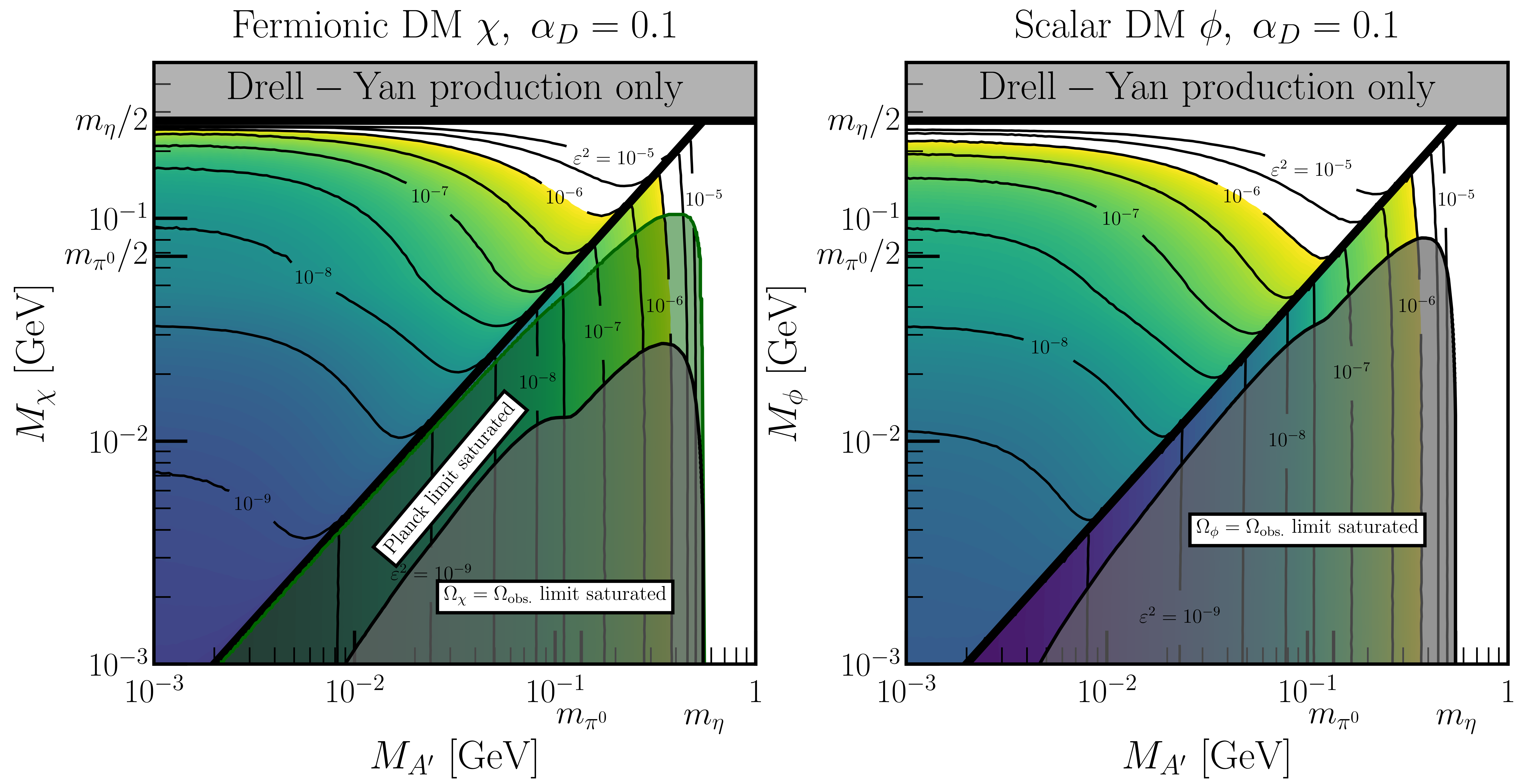
Results — Counting Experiments on- and off-axis, Fermionic DM



Results with Scalar DM are similar, although relic density targets are closer to being achievable. Nucleon scattering significantly weaker (see [1903.10505]).

Broader, two parameter search



Neutrinophilic Dark Matter

[1802.00009], [1901.01259]

First Assumption: (B-L) Conservation

If (B-L) is a good symmetry of nature, what are the consequences?

- Neutrinos are Dirac Particles
- Extensions beyond the standard model are non-trivial. Let's focus on adding a scalar ϕ

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Only renormalizable operator allowed:

$$\mathscr{L} \supset \frac{\lambda_c^{ij}}{2} \nu_i^c \nu_j^c \phi^\dagger$$

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Extending to higher operator dimension:

$$\mathscr{L} \supset \frac{\lambda_c^{ij}}{2}\nu_i^c \nu_j^c \phi^\dagger + \frac{1}{\Lambda_{\alpha\beta}^2}\left(L_\alpha H\right)\left(L_\beta H\right)\phi + \mathrm{h.c.}.$$

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After EWSB:

$$\mathscr{L} \longrightarrow \frac{\lambda_c^{ij}}{2}\nu_i^c \nu_j^c \phi^\dagger + \frac{\lambda_{\alpha\beta}}{2}\nu_\alpha \nu_\beta \phi + \frac{\lambda_{\alpha\beta}}{v}\nu_\alpha \nu_\beta \phi h + \mathcal{O}(h^2),$$

$$\lambda_{\alpha\beta} \equiv \frac{v^2}{\Lambda_{\alpha\beta}^2}$$

What constraints exist on the parameters of interest?

Most constraints: rare decays when ϕ is kinematically accessible: Higgs, charged mesons, and double-beta-like decays.

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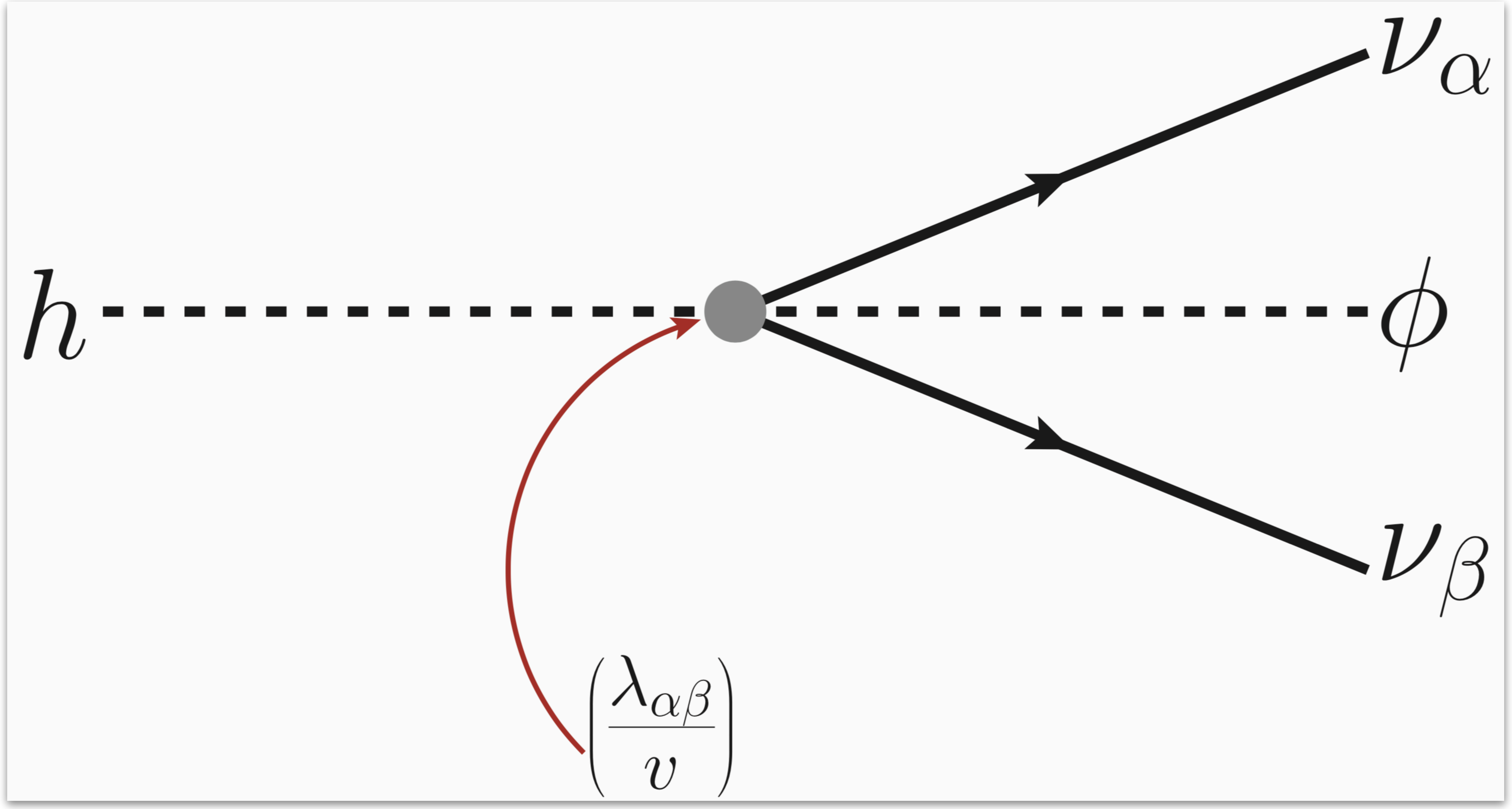
- Higgs Decays ($\frac{\lambda_{\alpha\beta}}{v}\nu_\alpha\nu_\beta\phi h$ generates $h \to \nu_\alpha\nu_\beta\phi$)



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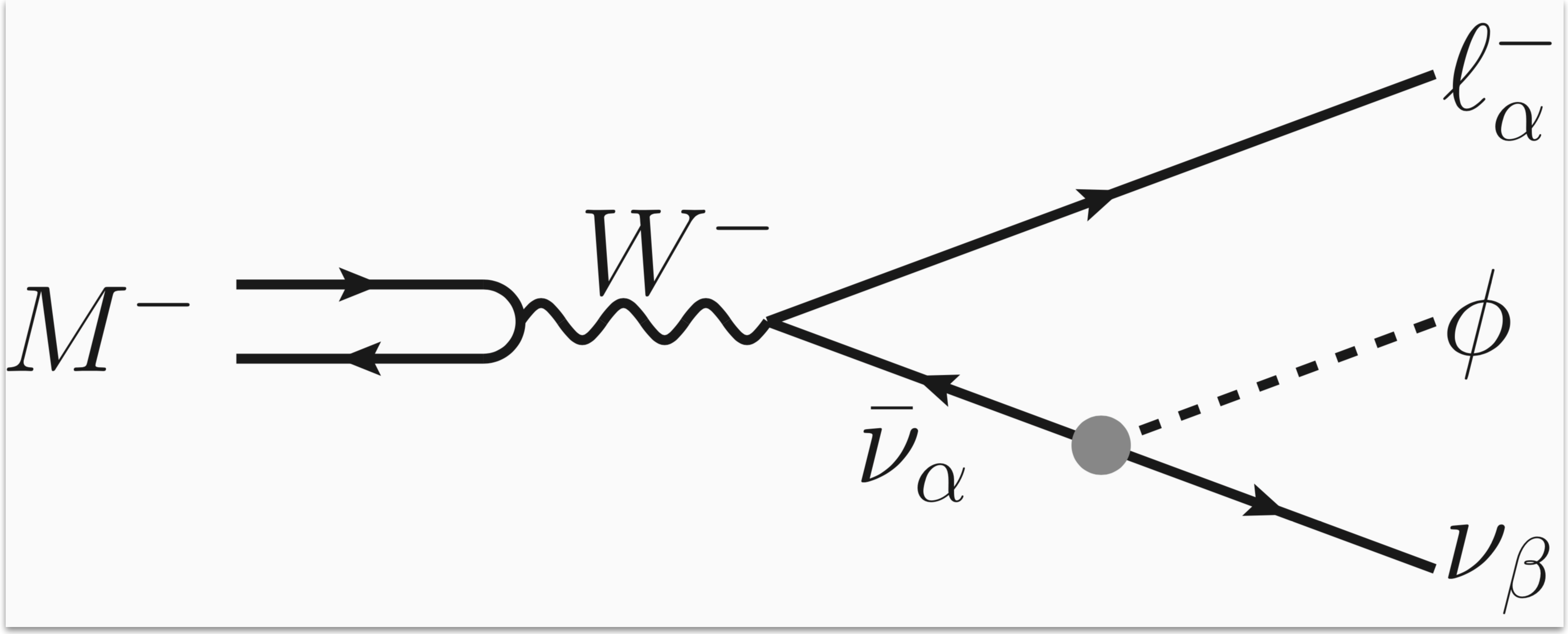
- Rare meson decays, e.g. $K^+ \to \mu^+ \overline{\nu}_\mu \phi$ as a contribution to the search for $K^+ \to \mu^+ \nu_\mu \nu \overline{\nu}$



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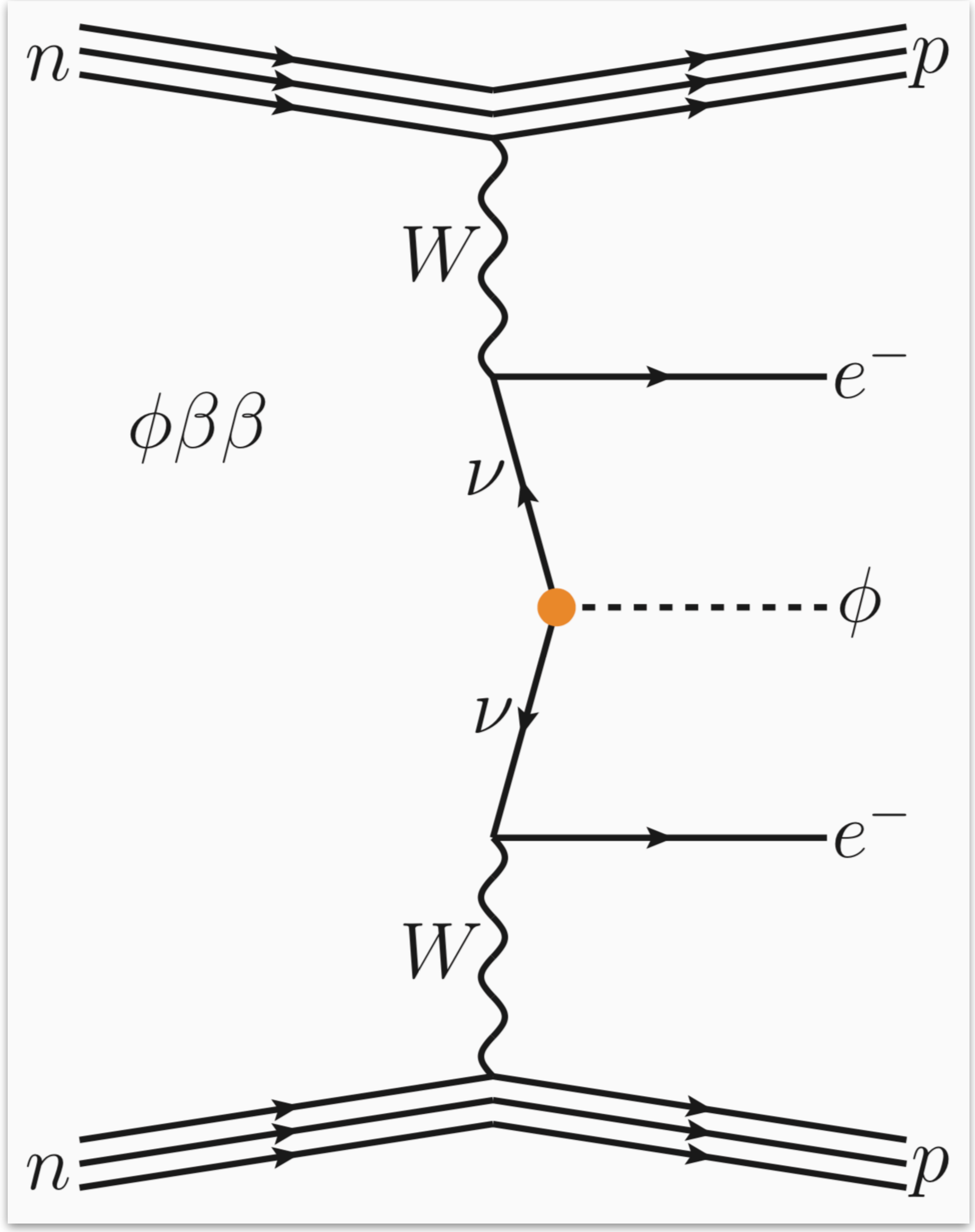
- "ϕ-full double-beta decay" as a contribution to neutrino-full $2\nu\beta\beta$



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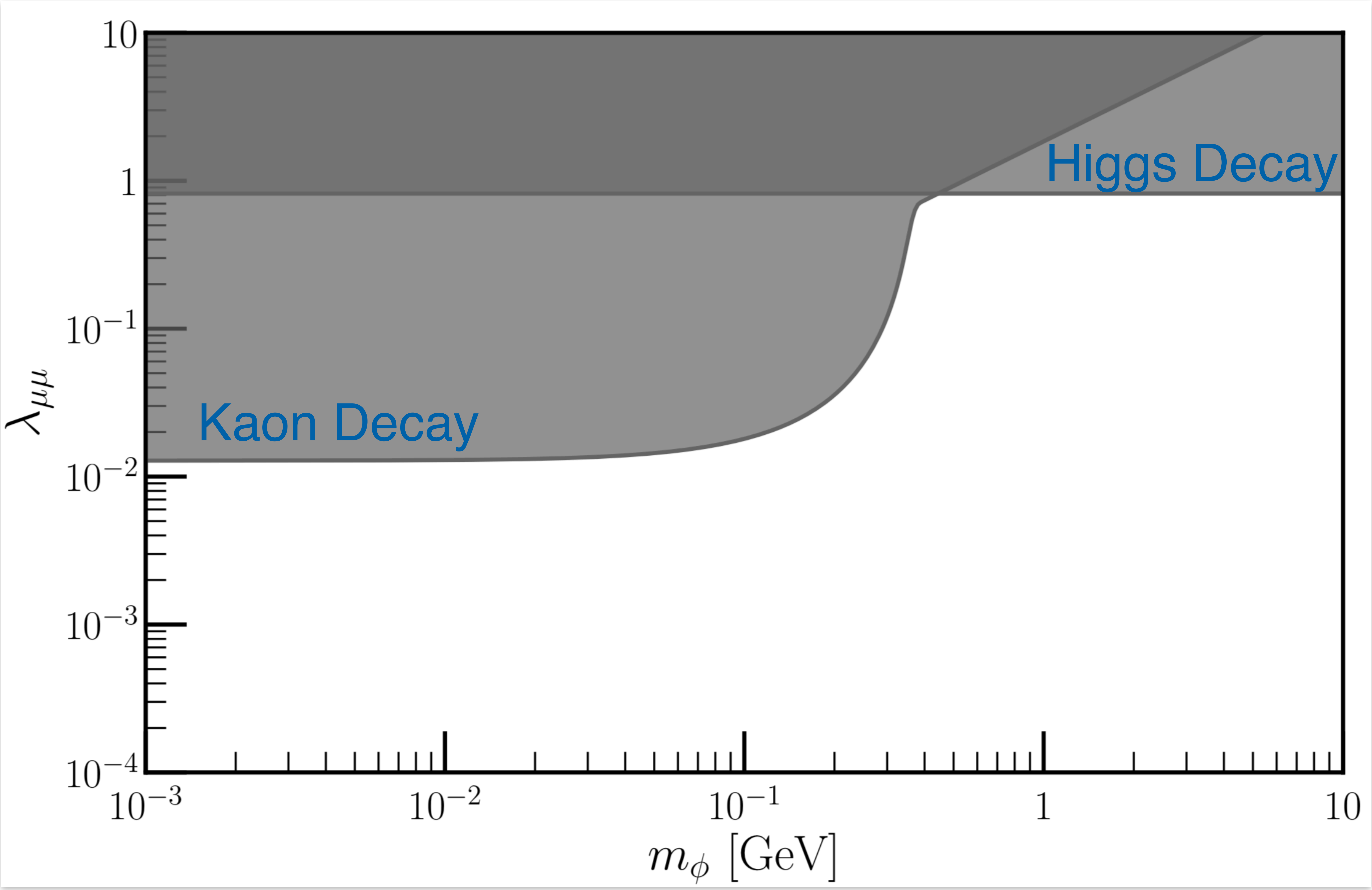
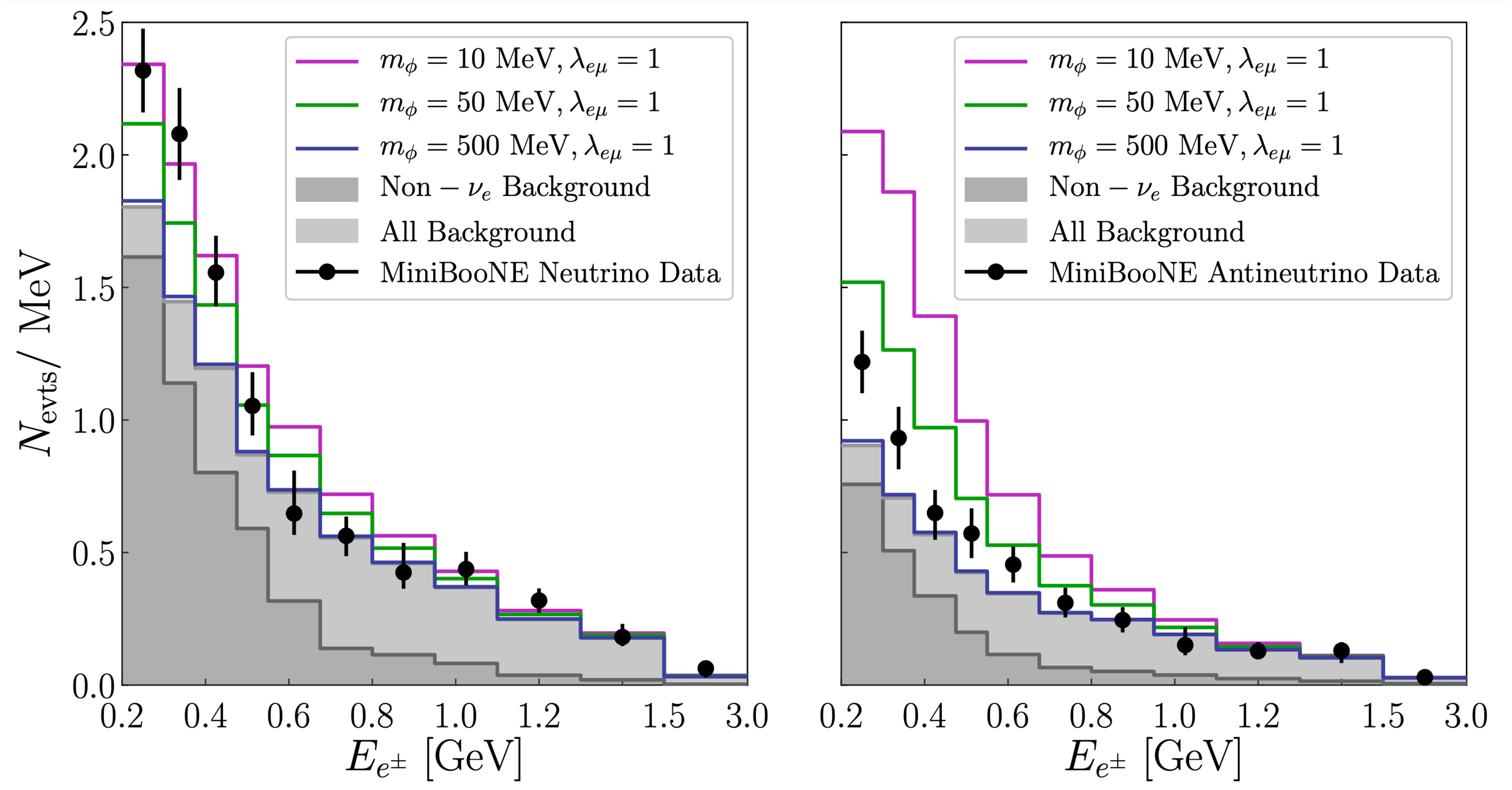
Constraints in muon-coupled Channel



An Aside, MiniBooNE/LSND



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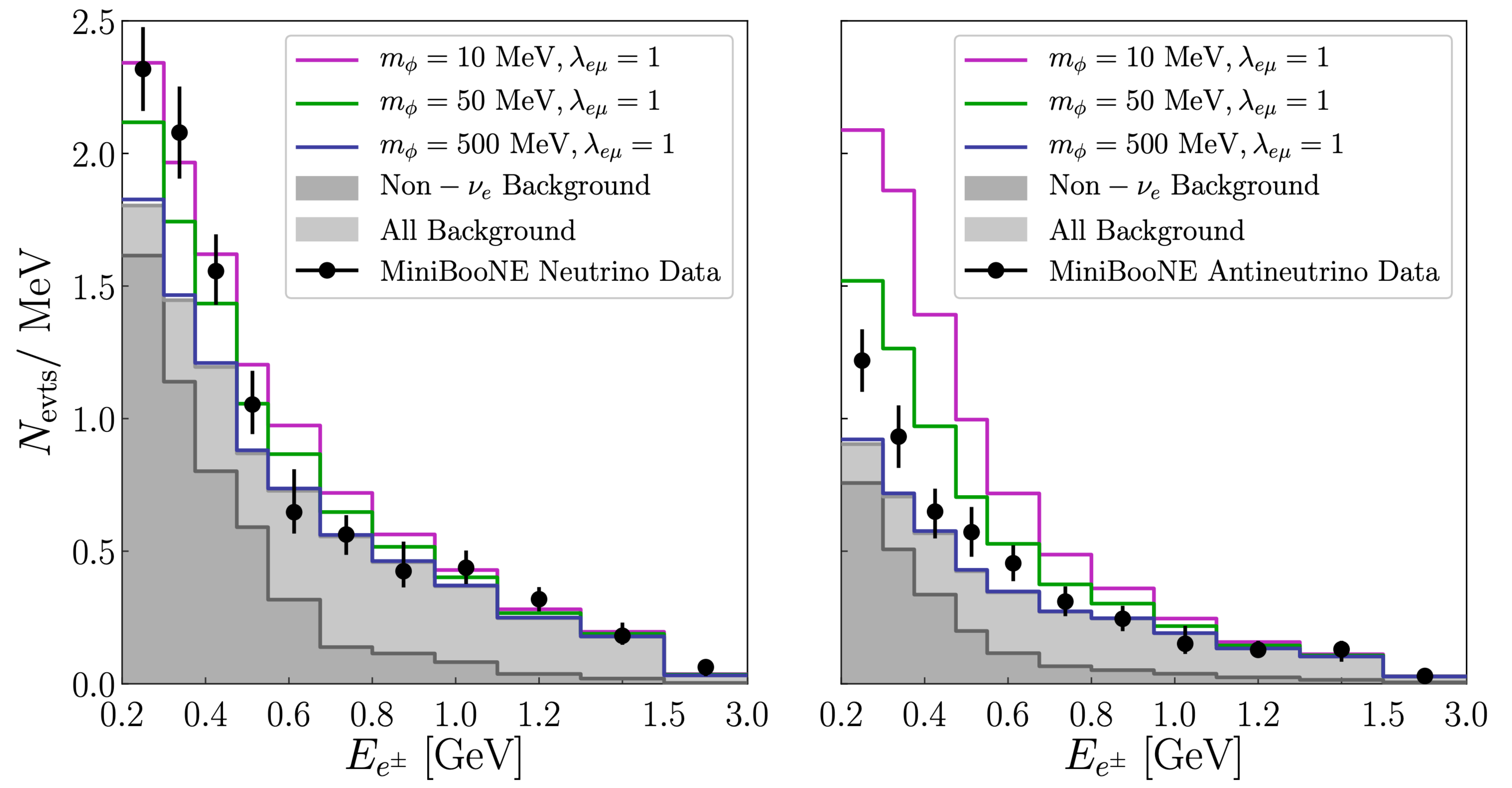

$m_\phi \sim 50$ MeV, with flavor-violating vertex, could explain MiniBooNE!

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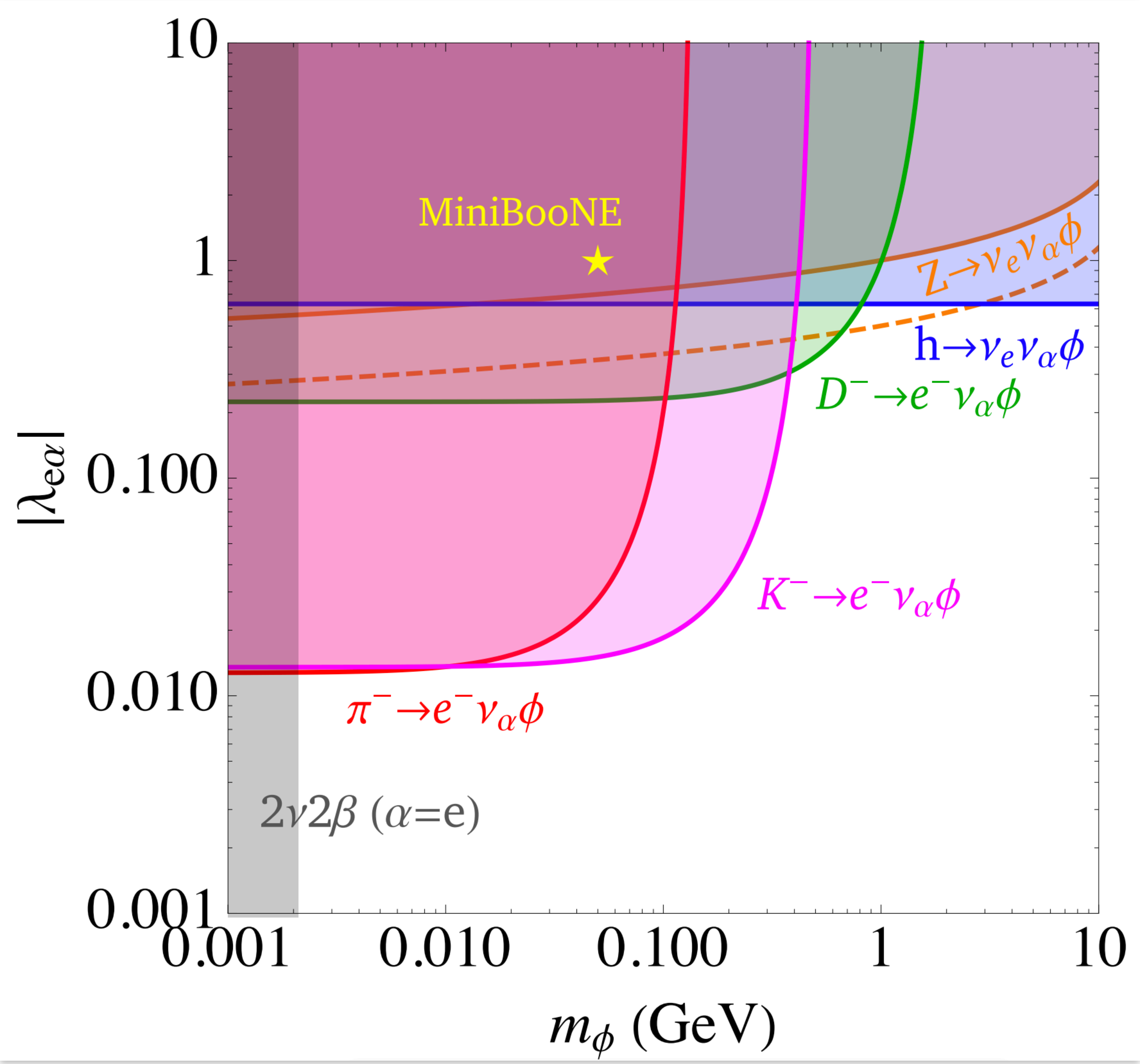

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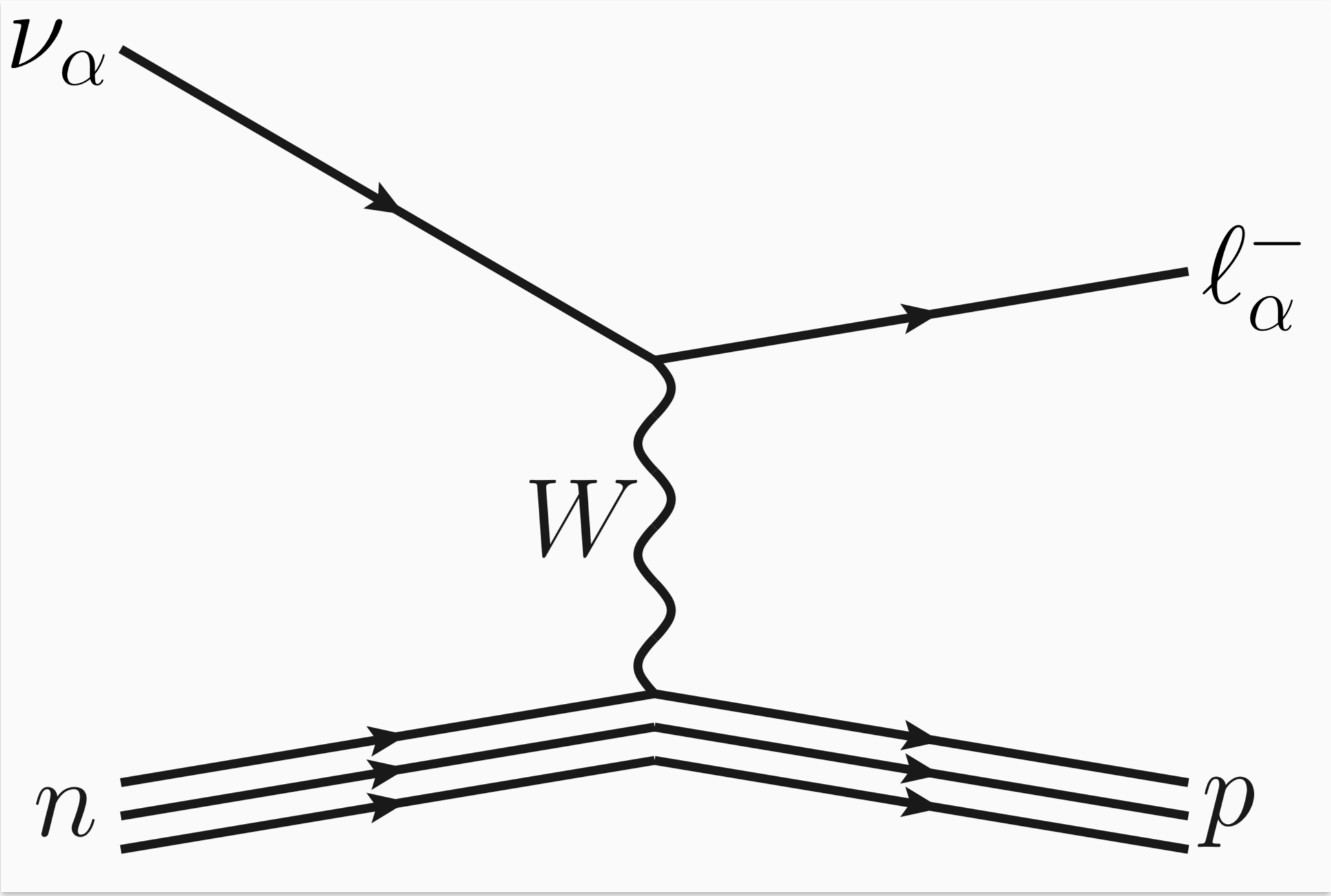
Neutrino Beamsstrahlung — Monoν Events

Previous constraints relied on the mediator being kinematically accessible in a decay. Let's explore what happens when it's kinematically accessible in scattering.

SM CC Interaction



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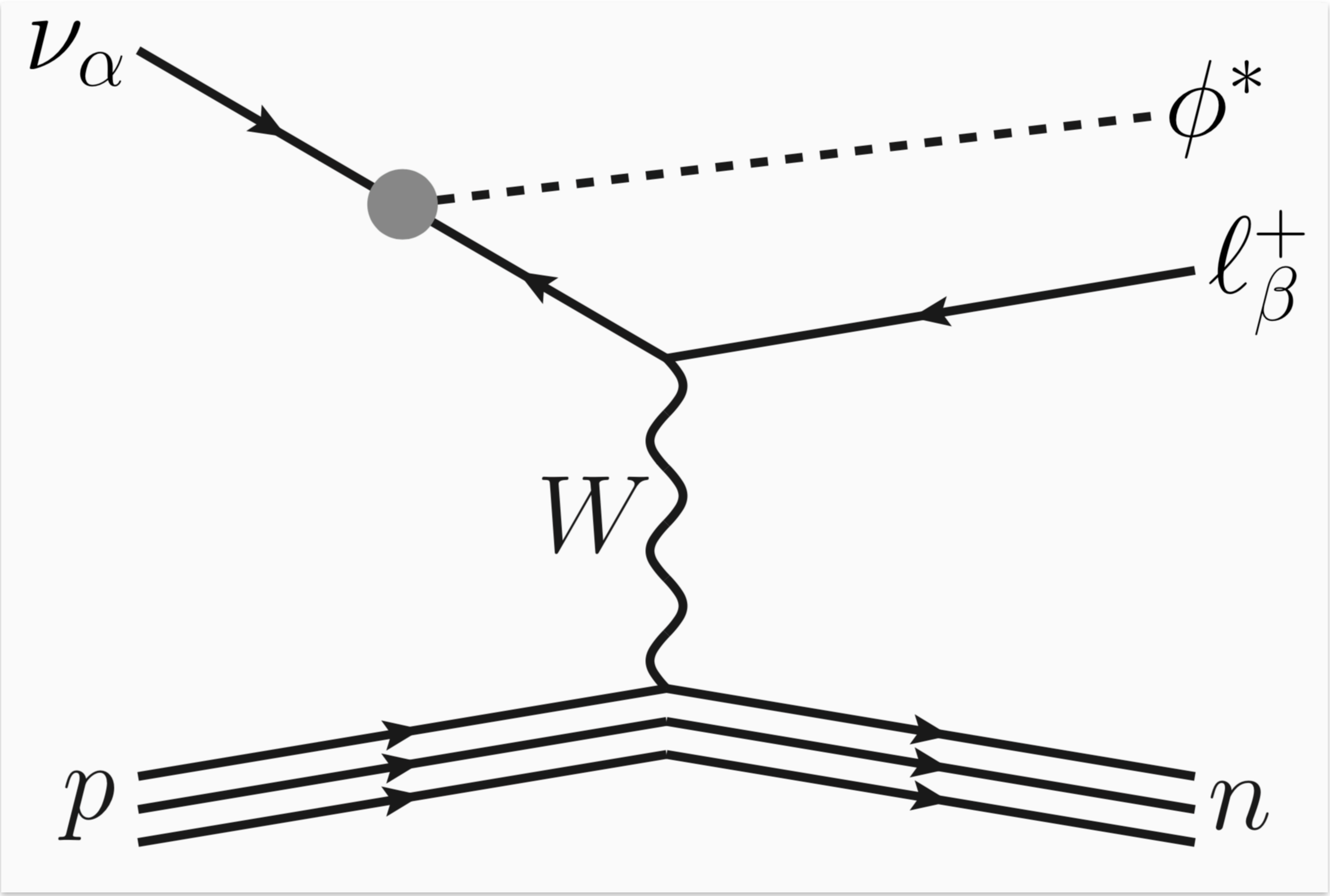
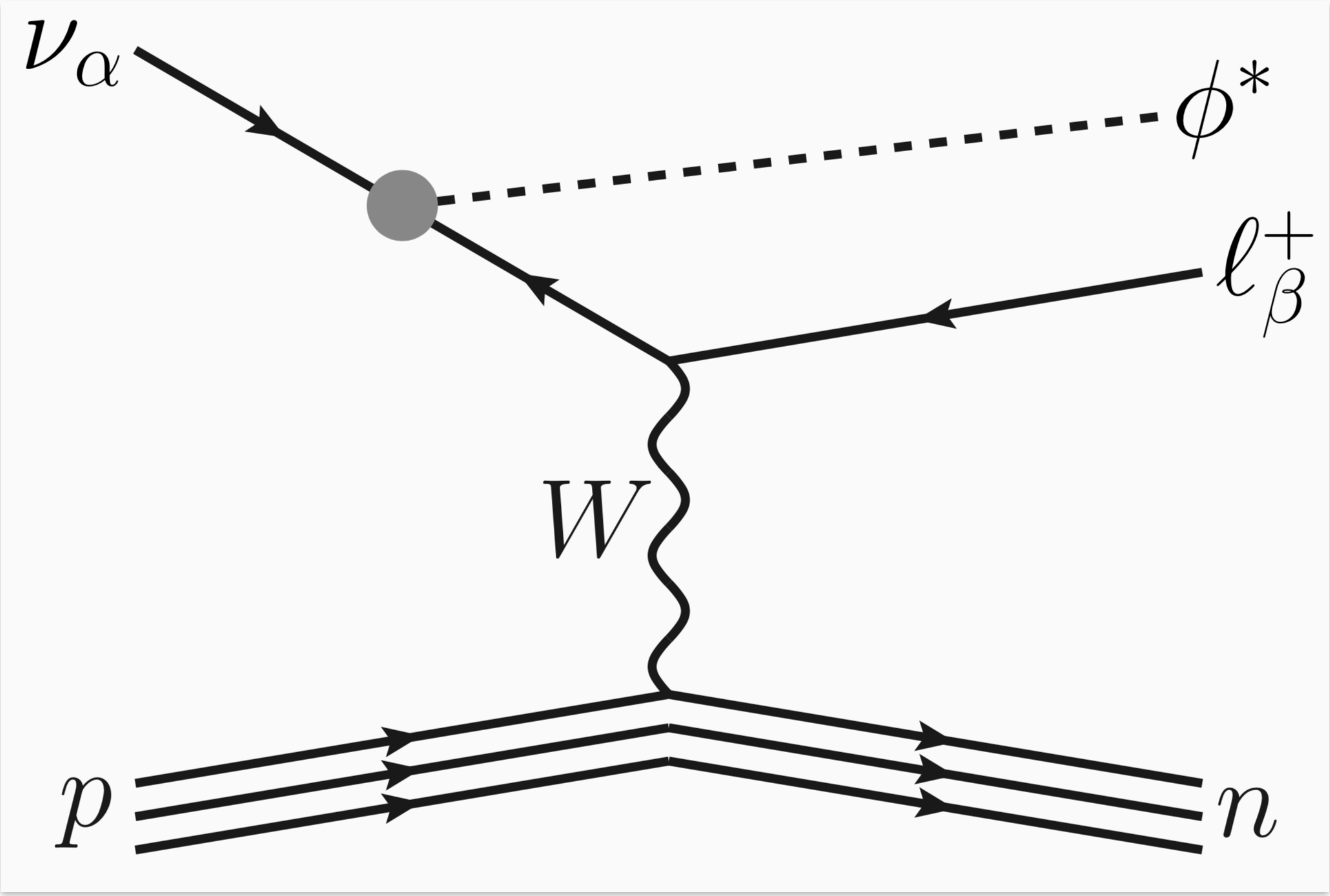
Beamsstrahlung



$$m_\phi < E_\nu$$

Key Characteristics of Monoν



- Wrong-sign lepton generated: neutrino beam produces positively-charged lepton.
- ϕ carries away significant energy — reconstructing the event as a 2 to 2 scattering provides a small neutrino energy.
- ϕ carries away significant transverse momentum — reconstructed visible energy has large missing momentum.

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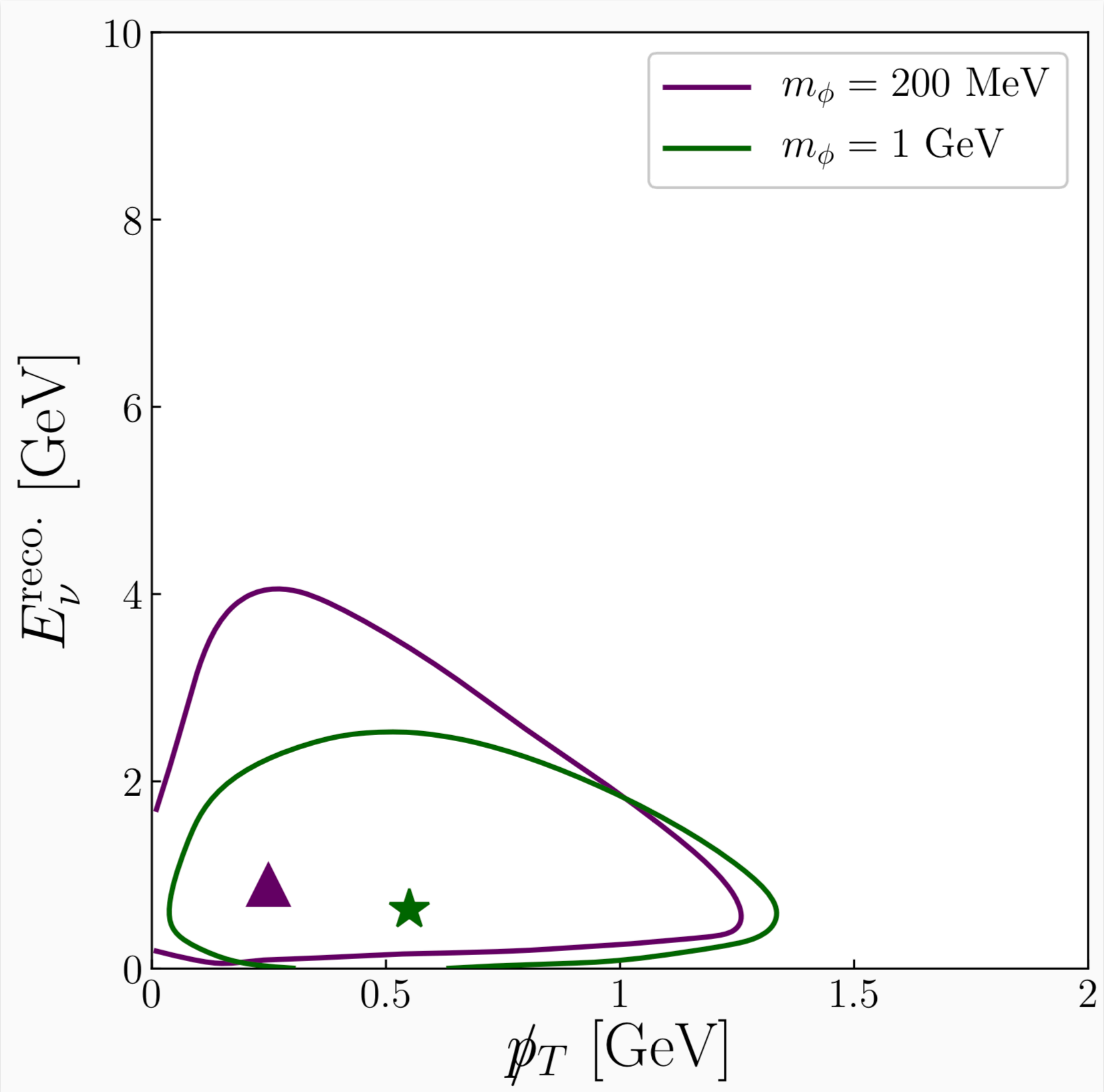
Signal Distributions



DUNE Near Detector, Flux-Integrated

Signal distribution depends on scalar mass. Lines encompass 90% of signal events.

Background distribution should live on y-axis.

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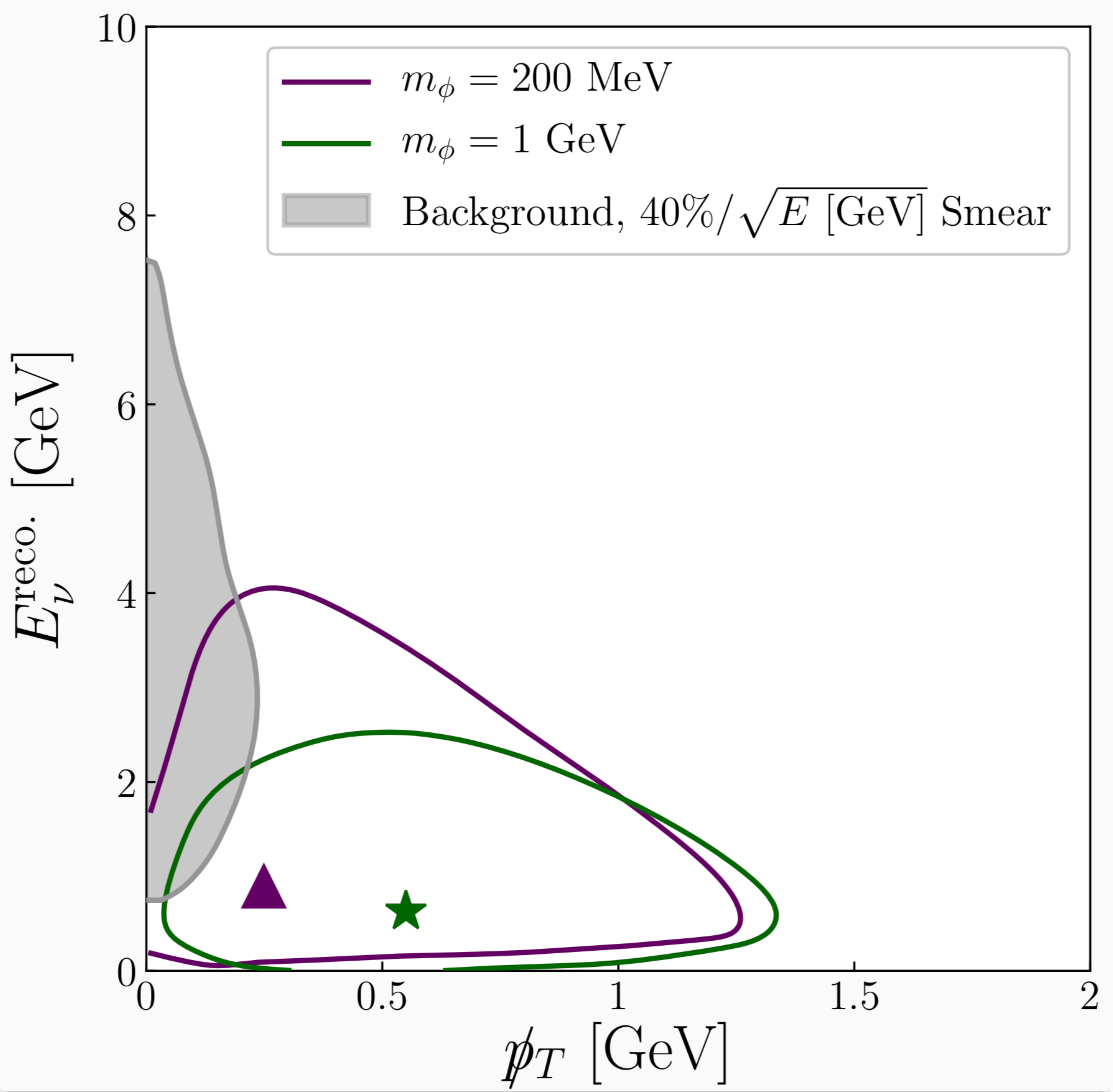

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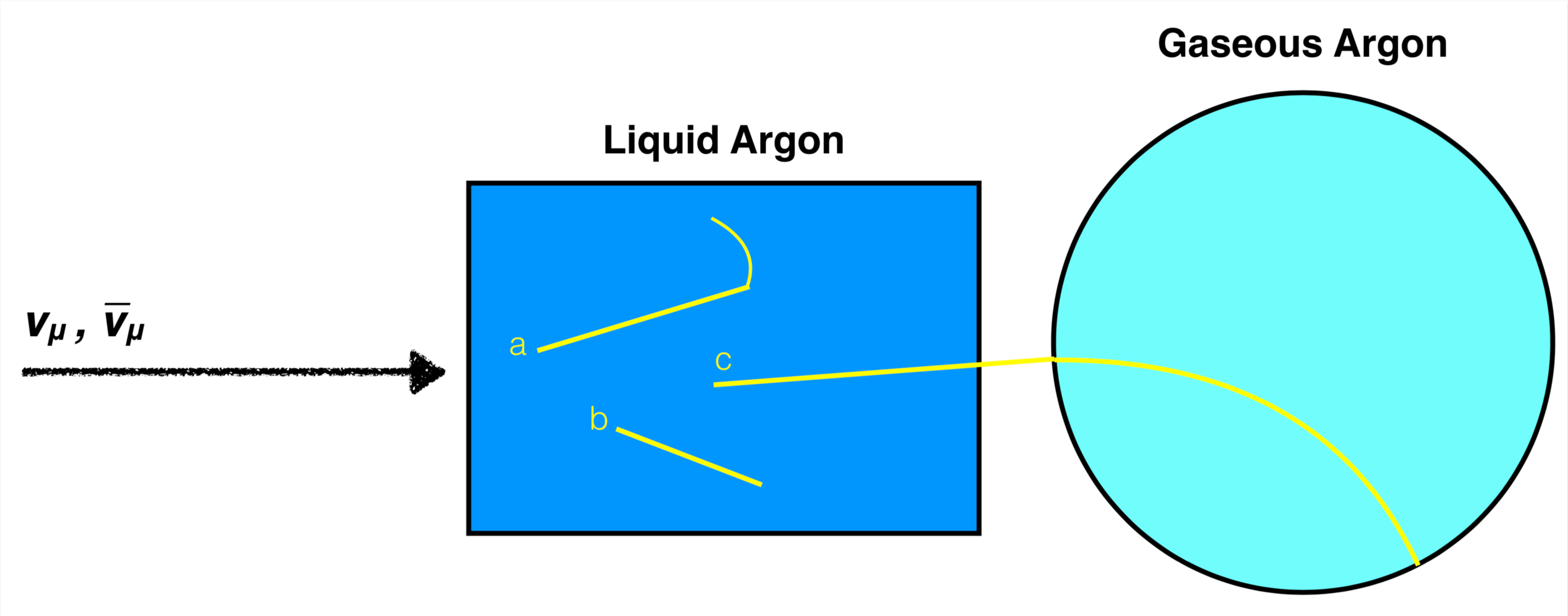
Exploiting Wrong-Sign Leptons

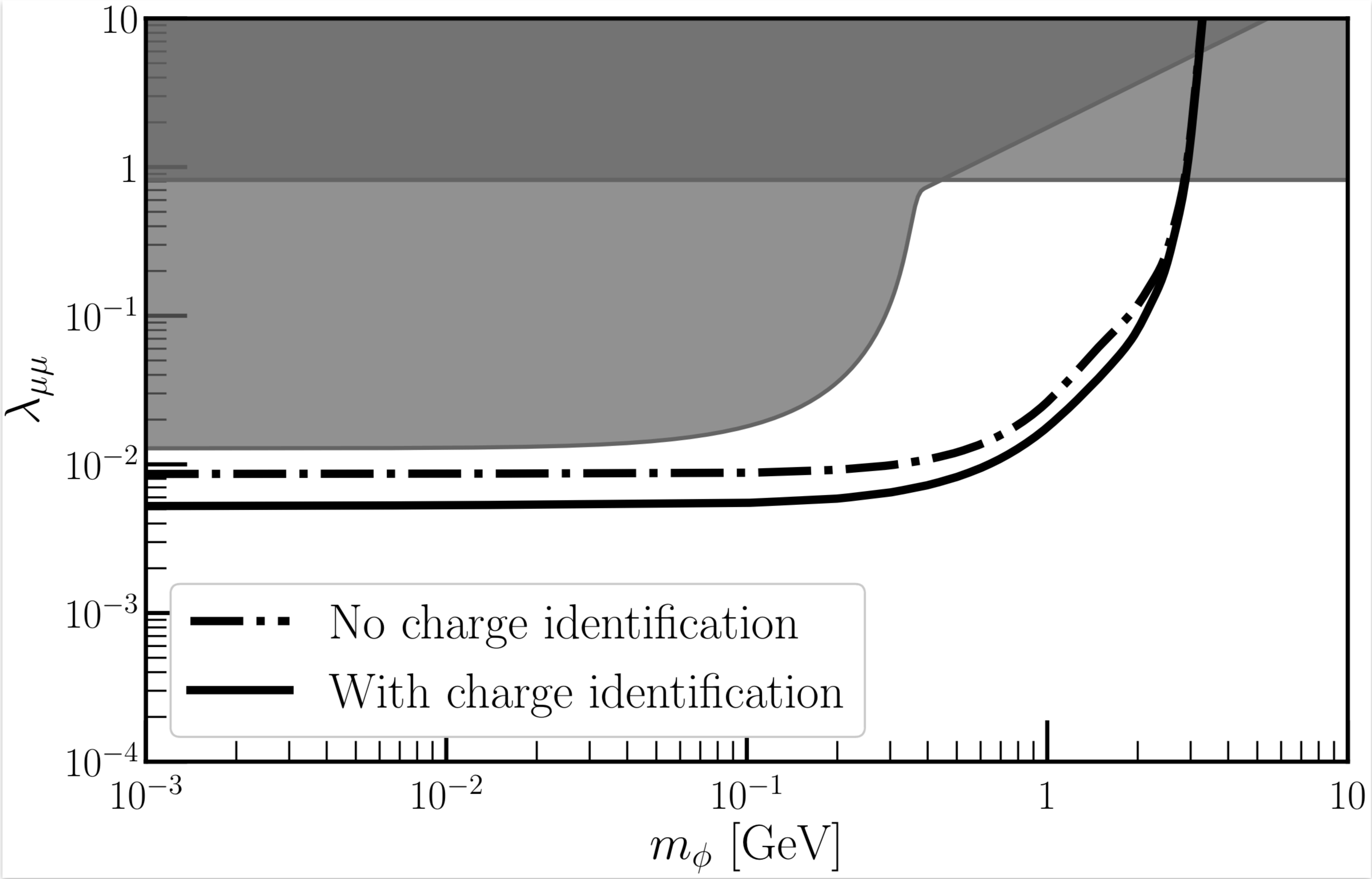
Two opportunities for determining muon charge in the DUNE Near Detector:

- Positively-charged muons always decay to a Michel electron (a). Only 25% of negatively-charged muons do (b). Our signal then can be events that produce a Michel electron (when operating in neutrino mode).
- With the proposed Gas Argon TPC, muons (energies above ~1 GeV) that reach the gas (c) may be charge-identified due to the magnetic field.



DUNE Sensitivity Reach (10 years Data Collection)

500 MeV bins in reconstructed energy, 125 MeV bins in transverse momentum. (95% CL)



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The Dark Matter Connection

We assumed that ϕ had (B-L) charge 2. What if it is a mediator to some dark matter particle(s)?

$\frac{1}{2} y_S \chi^2 \phi$	Scalar DM with (B-L) charge -1
$\frac{1}{2} y_F \overline{\chi}^c \chi \phi$	Fermion DM with (B-L) charge -1
$\frac{1}{6} y_3 \chi^3 \phi$	Scalar DM with (B-L) charge -2/3
$y_I \overline{\chi_1} \chi_2 \phi$	Inelastic Fermion DM with (B-L) charges q, q-2.

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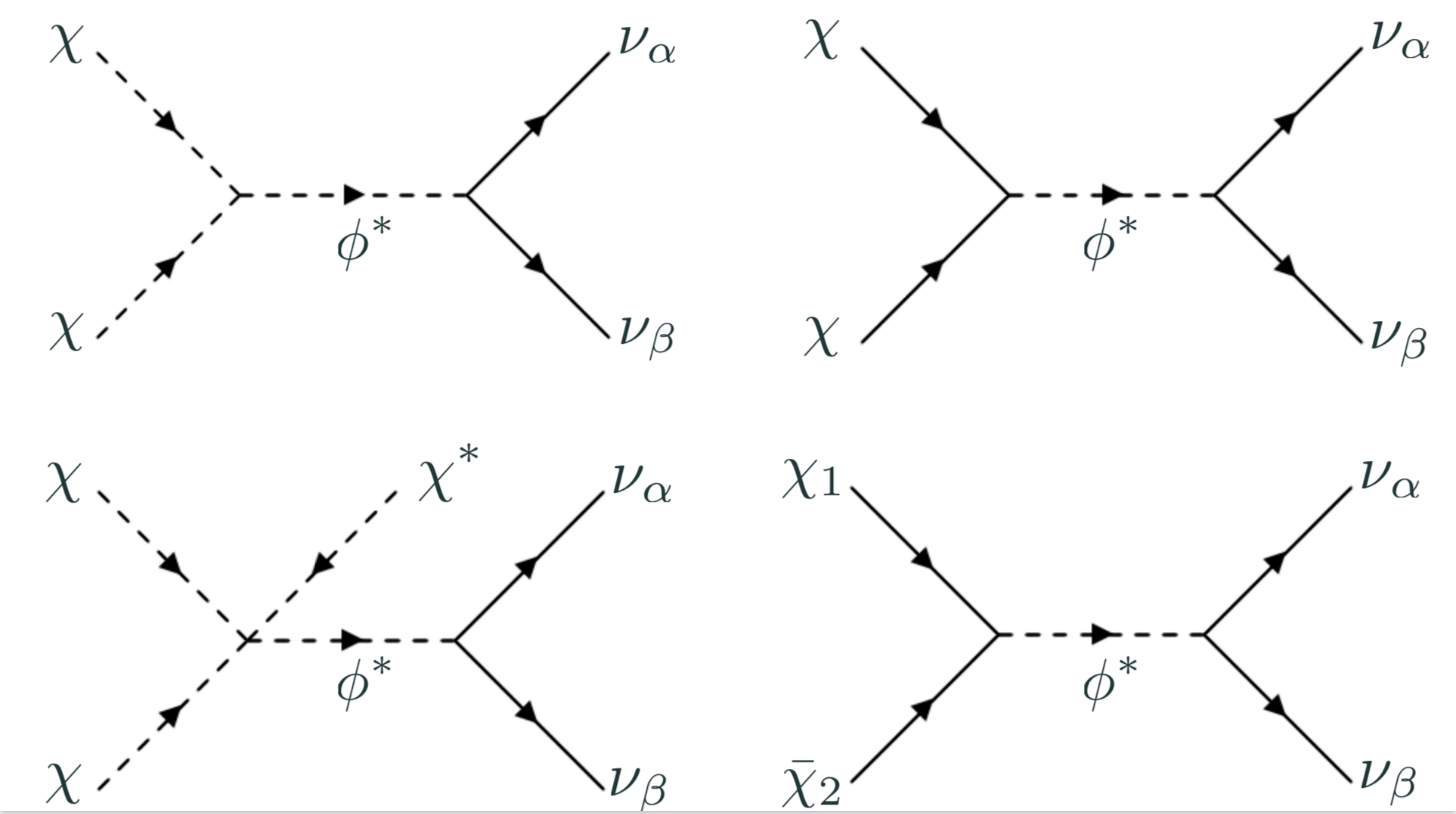
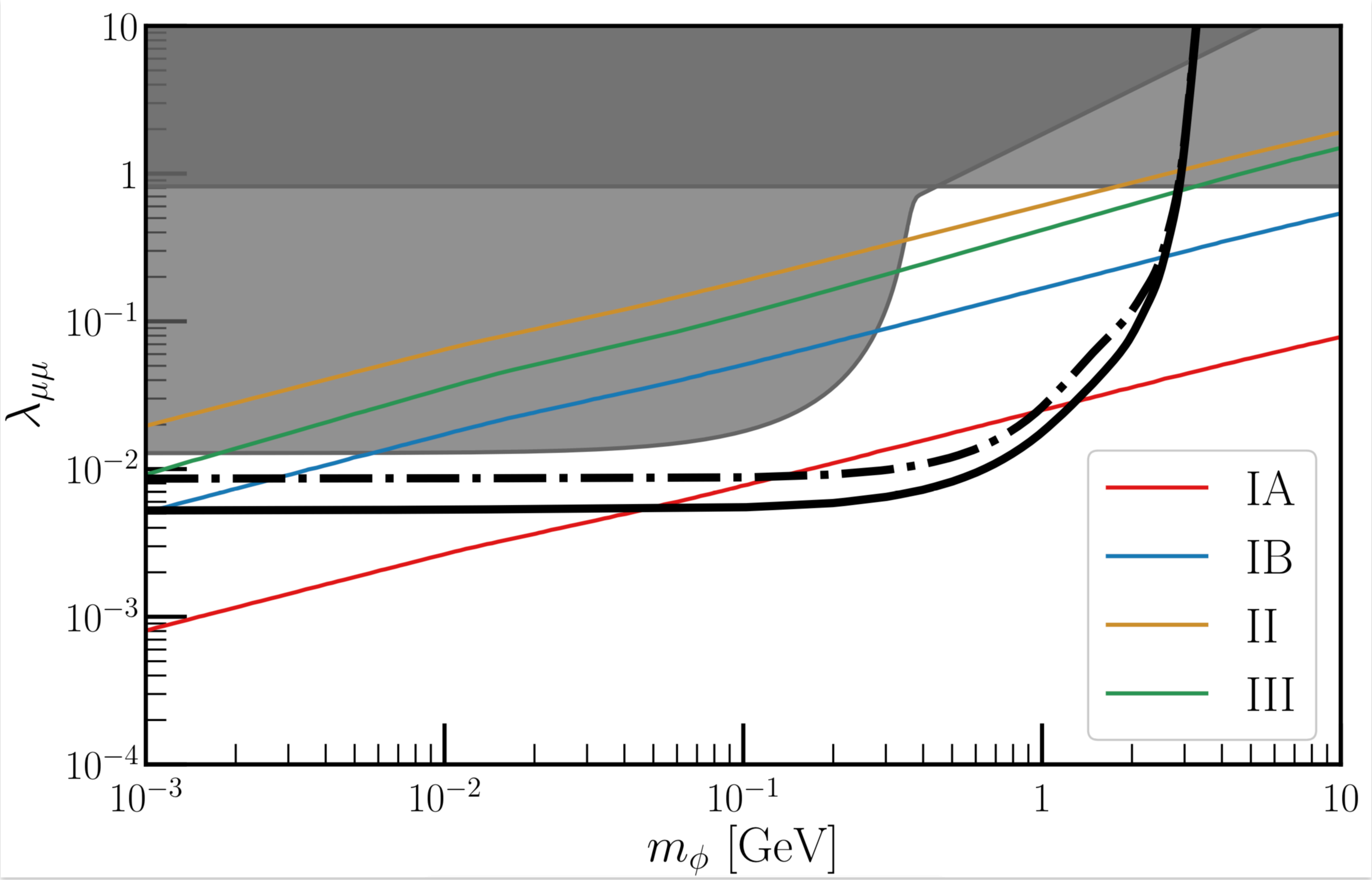


DUNE Reaching DM Targets

Assumptions: DM couples to ϕ as strongly as neutrinos, $m_\phi = 10 m_{\mathrm{DM}}$



Fermion

Scalar

Triple-Coupling

Inelastic

Conclusions

- DUNE will allow us to search for thermal DM in a variety of interesting ways.

  - DUNE-PRISM can do more than cross section measurements.
    - Focusing of neutrinos vs. DM provides interesting event spectra at on- and off-axis locations.
    - Sensitivity can reach theoretically motivated targets, especially when considering scalar DM

  - Inspired by collider mono-jet searches, mono-neutrino searches at the DUNE ND can allow for sensitivity to neutrinophilic scalars.
    - Scalar emission allows for events with large missing transverse momentum, low reconstructed neutrino energy, and (in this model) wrong-sign final-state muons.
    - Light dark matter may couple to the same mediator — DUNE can probe relic DM with this search strategy.