Neutrino experiments as dark sector factories

from HNLs to ALPs

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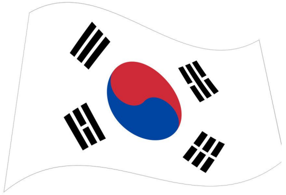
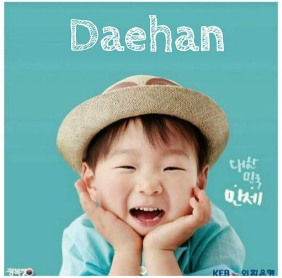
Light Dark World 2024

KAIST August 12, 2024

Instituto de Física Teórica UAM-CSIC

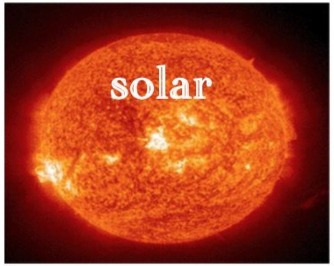
CSIC
Consejo Superior de Investigaciones Científicas



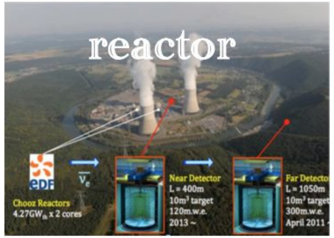


Credit: Zahra Tabrizi, CERN Cosmo Coffee, 02/28/24

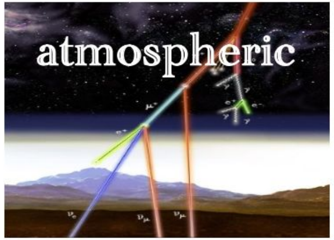
Status of Neutrino Physics in 2024



Super-Kamiokande, Borexino, SNO



MBL: Daya Bay, RENO, Double Chooz
LBL: KamLAND



IceCube, Super-Kamiokande

T2K, MINOS, NOvA

mixing angles:

$\sin^2\theta_{12}$ @ 4%

$\sin^2\theta_{13}$ @ 3%

$\sin^2\theta_{23}$ @ 3%

mass squared differences:

Δm^2_{21} @ 3%

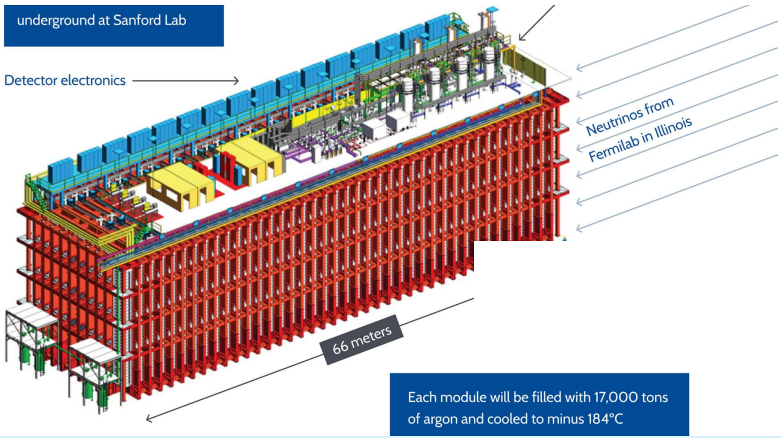
$|\Delta m^2_{31}|$ @ 1%

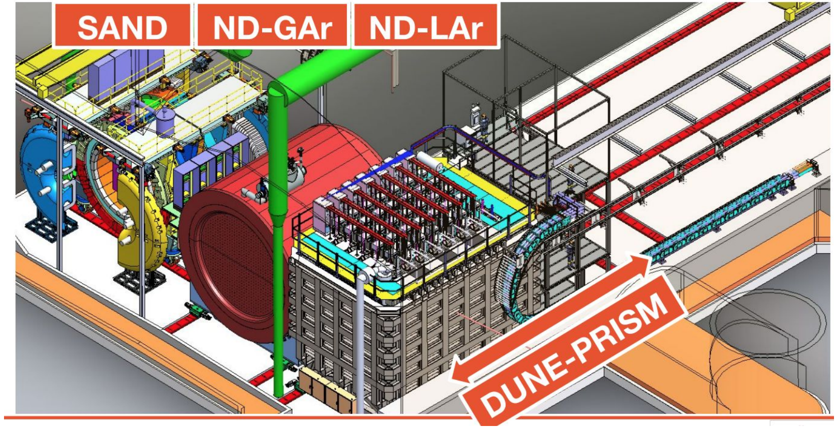
Future: DUNE, T2HK , JUNO

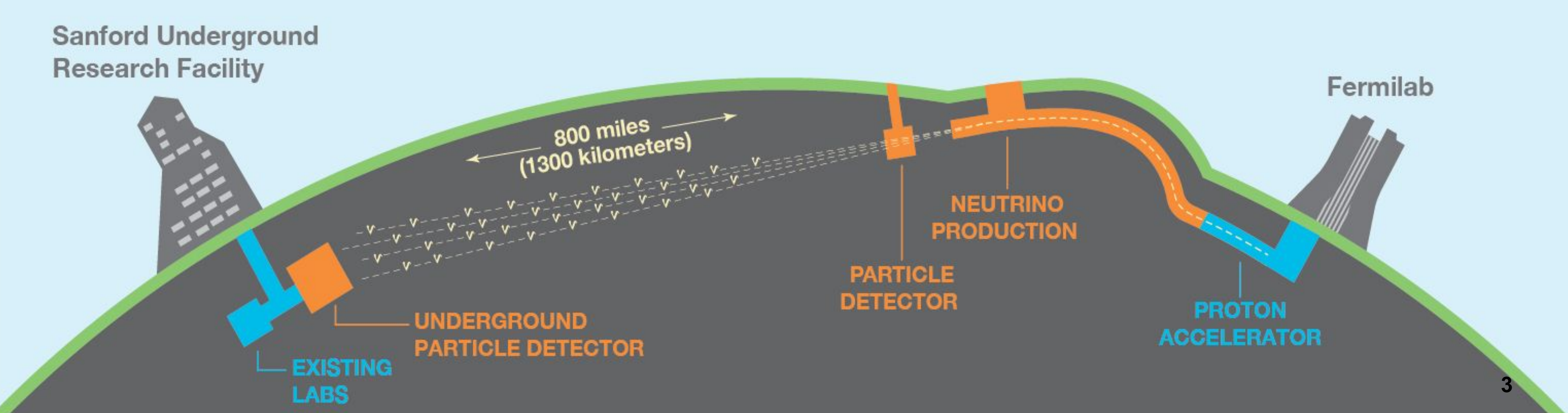
- Increase the precision
- CP-phase
- Mass hierarchy

Also:
Mass scale? Dirac or Majorana?
Sterile?

The *flagship* DUNE experiment

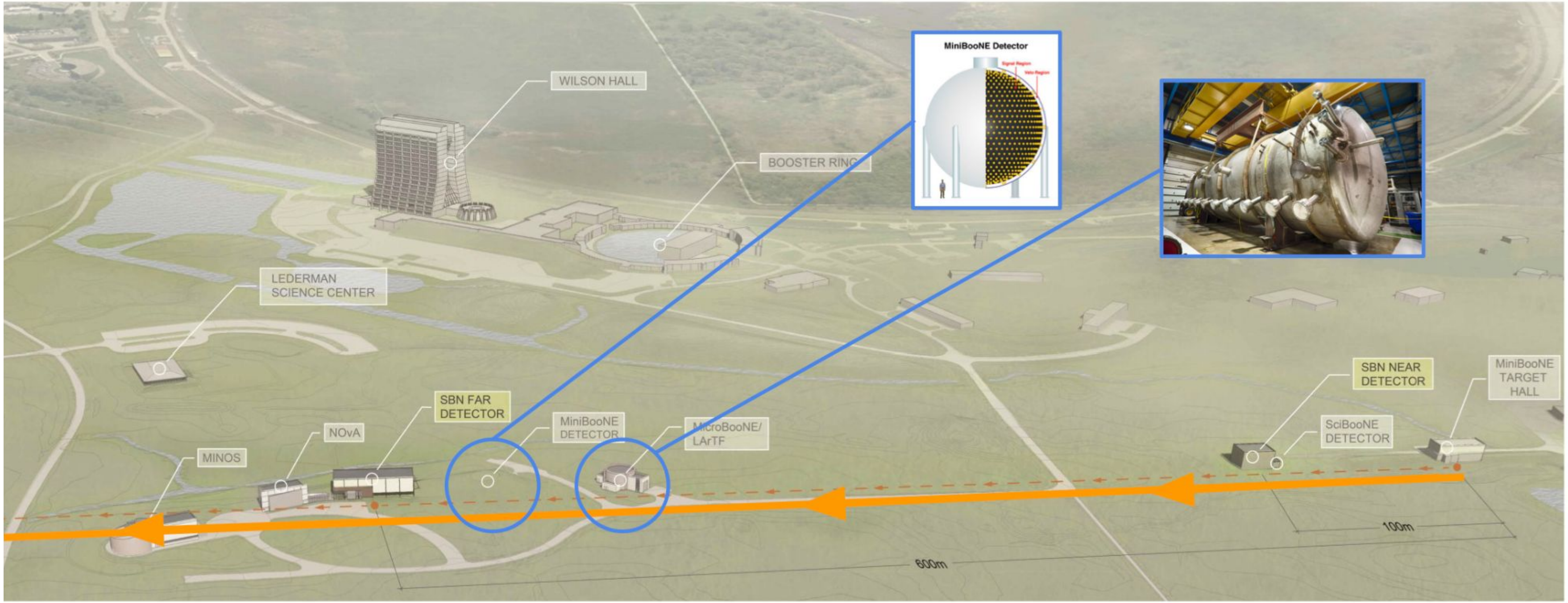






Fermilab Short Baseline Program

Fermilab Short Baseline Program (SBN) features three LArTPC detectors on the Booster Neutrino Beamline (BNB) → SBND (near detector), MicroBooNE, Icarus (far detector)

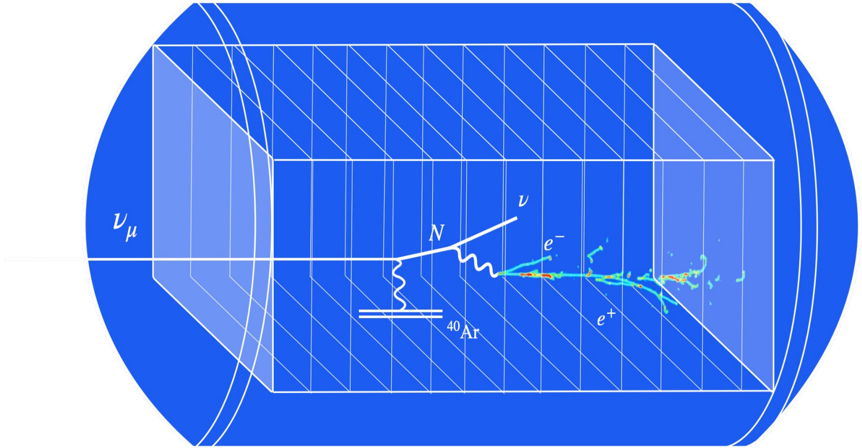


arXiv/1503.01520

LArTPC Detectors

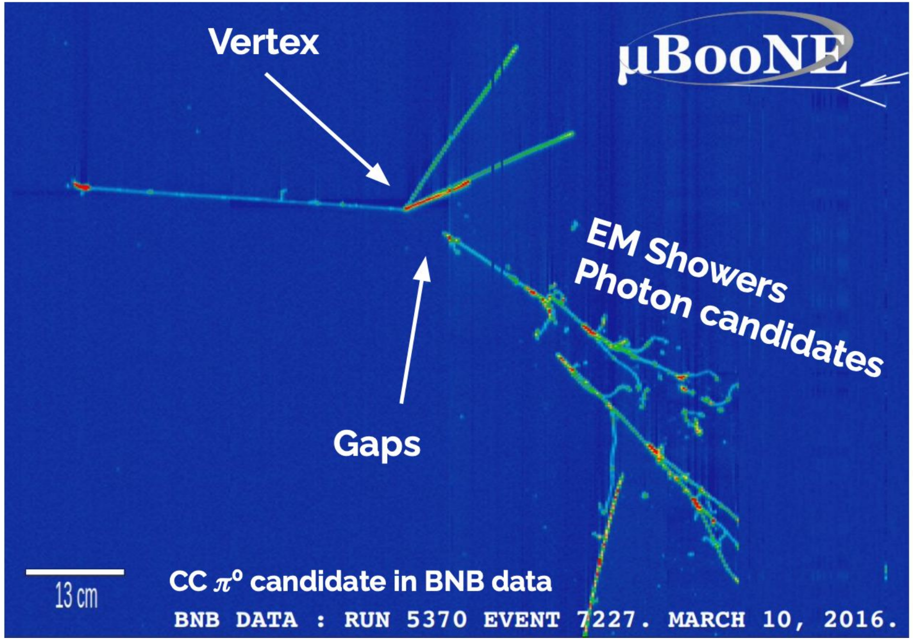
Newer neutrino detectors utilising LArTPC technology

Improved hadronic vertex ID | Better spatial resolution | Improved calorimetry



Schematic of MicroBooNE TPC and cryotank (HNL upscattering)

LArTPCs are like a digital bubble chamber allowing for 3D images of the neutrino interaction



Mark Ross-Lonergan, NeuTel 2021

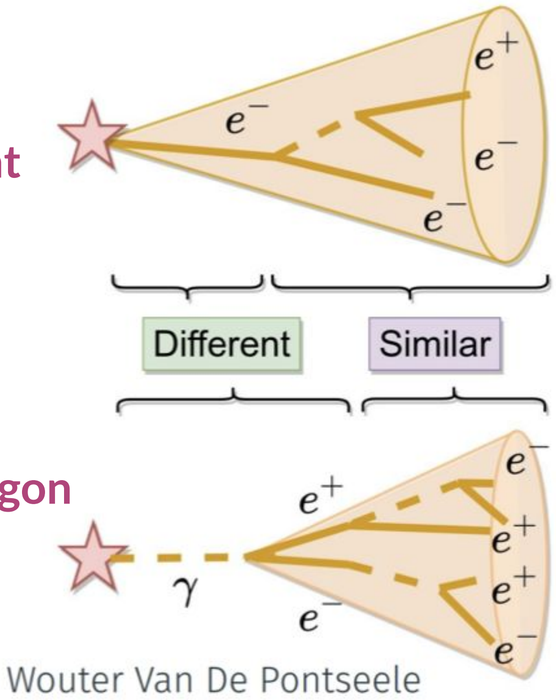
LArTPC Detectors

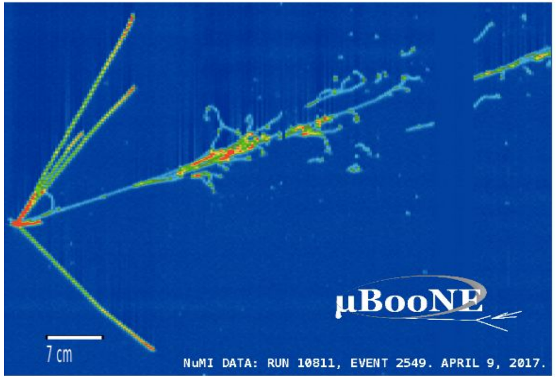
LArTPCs make $e^{\pm}$ and photon final states distinguishable

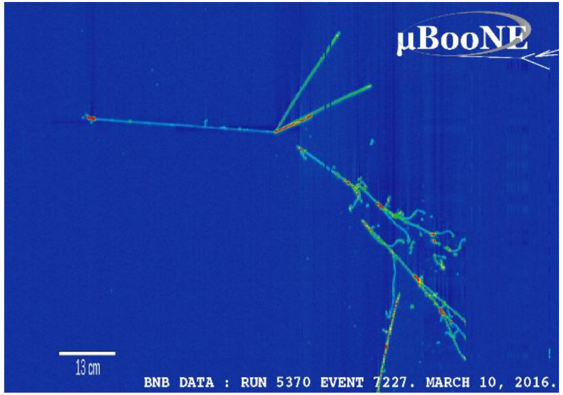
Spatial resolution

a. electrons begin to shower at vertex

b. photons travel ~15cm in Argon before pair converting





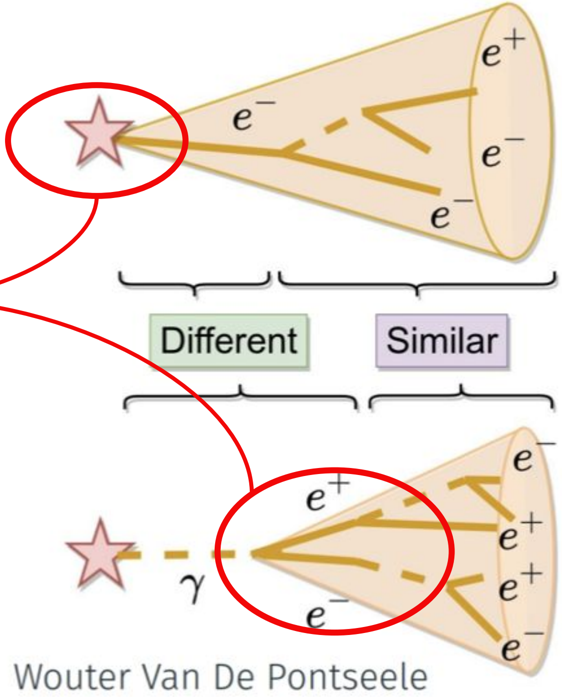


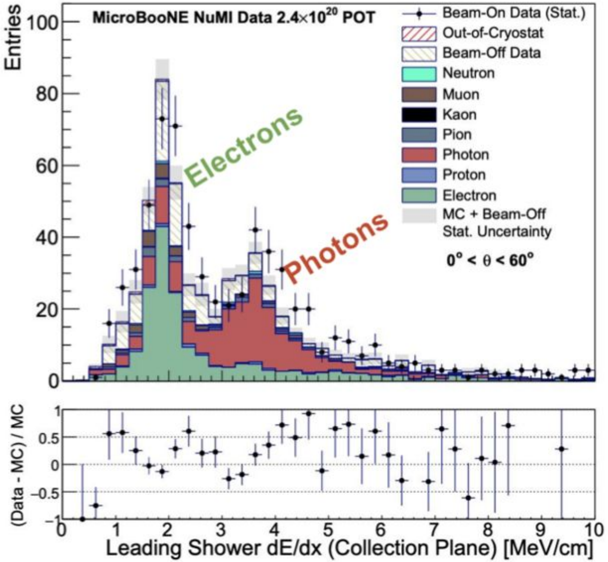
LArTPC Detectors

LArTPCs make e$^{\pm}$ and photon final states distinguishable

Calorimetry

a. Photons deposit twice the energy per unit length as single electron





arXiv:2101.04228

The case for neutrino experiments

- High POT (~1e21)
  - → *large flux of charged and neutral mesons*
  - → *Potentially sizeable flux of BSM particles*
- Large detector masses ~ O(1e2) tonnes
  - → *Potentially larger interaction cross-sections*

The case for neutrino experiments

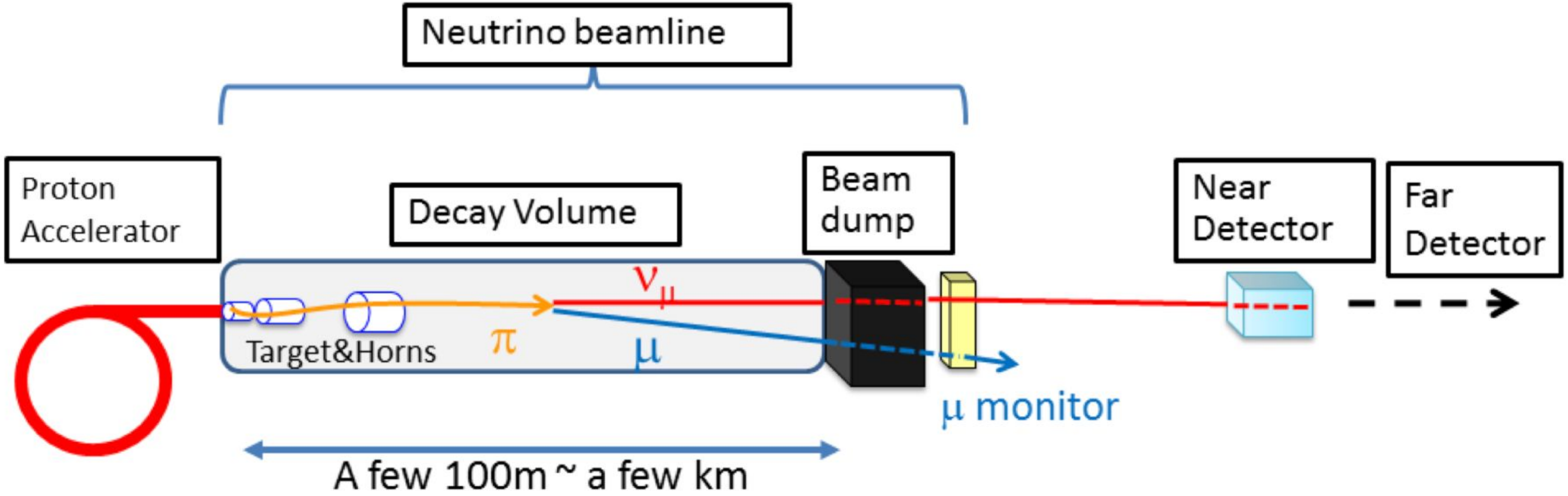
- ➔ Good PID (p, μ, e, γ reconstructed) and calorimetry
- ➔ Parasitic → *shared cost with neutrino projects*

See talk by Richard Van de Water,
U.S. Cosmic Visions 2017

"Future possibilities at Proton fixed target experiments"

Neutrino Experiments

Typical setup



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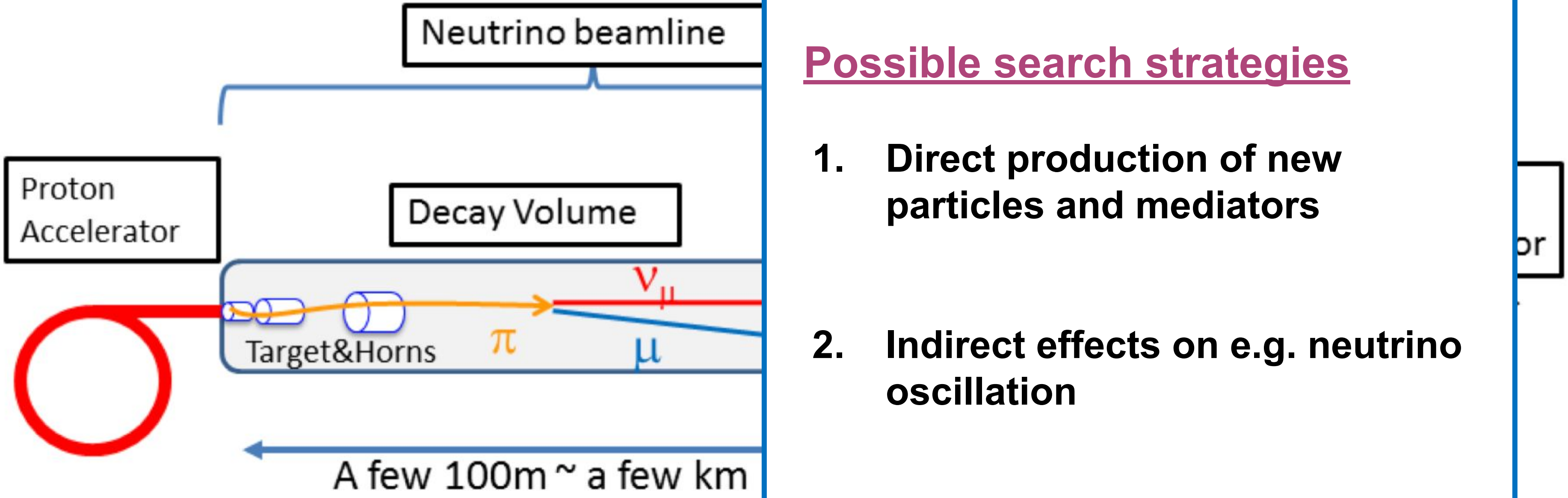


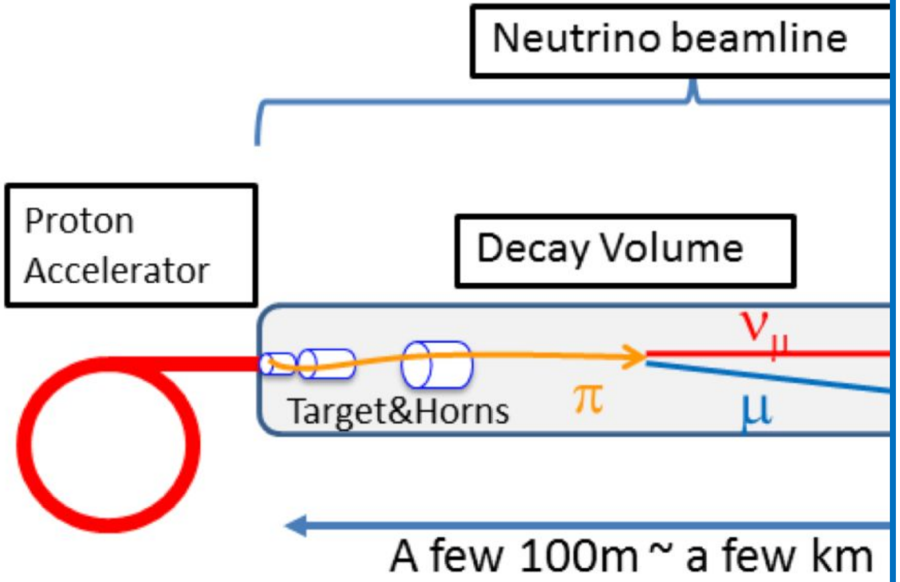
Possible search strategies

1. **Direct production of new particles and mediators**

2. **Indirect effects on e.g. neutrino oscillation**

Neutrino Experiments

Typical setup



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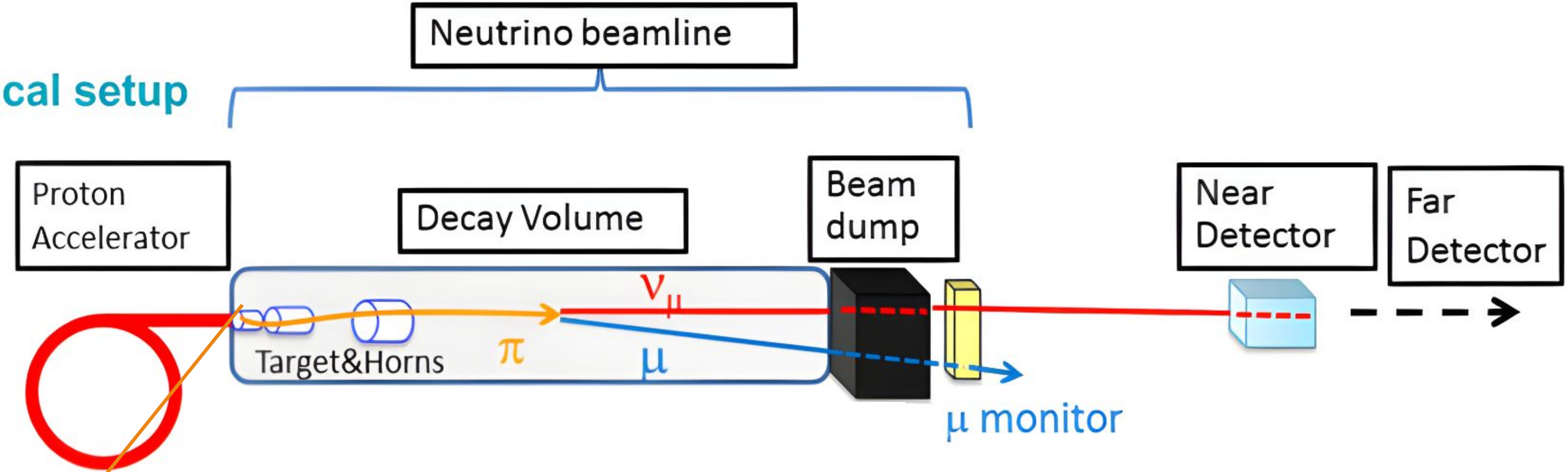

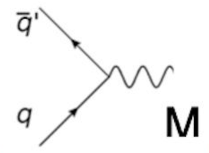

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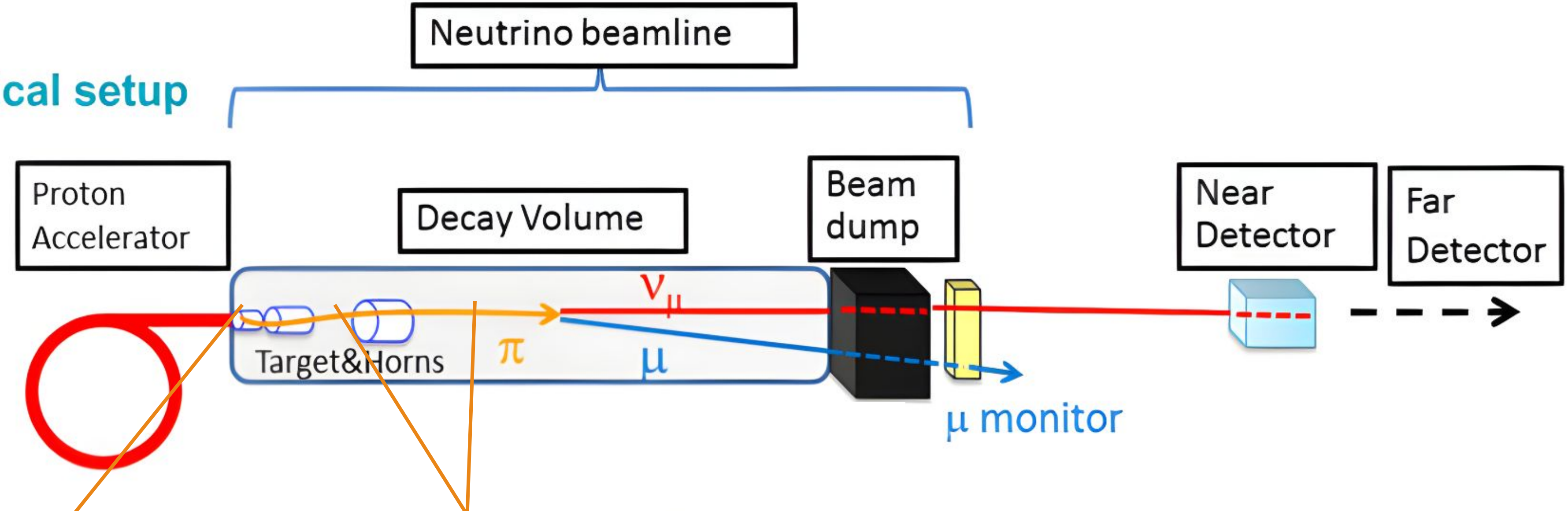
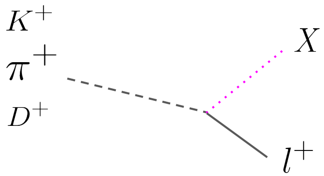


@ target

Meson decay in flight



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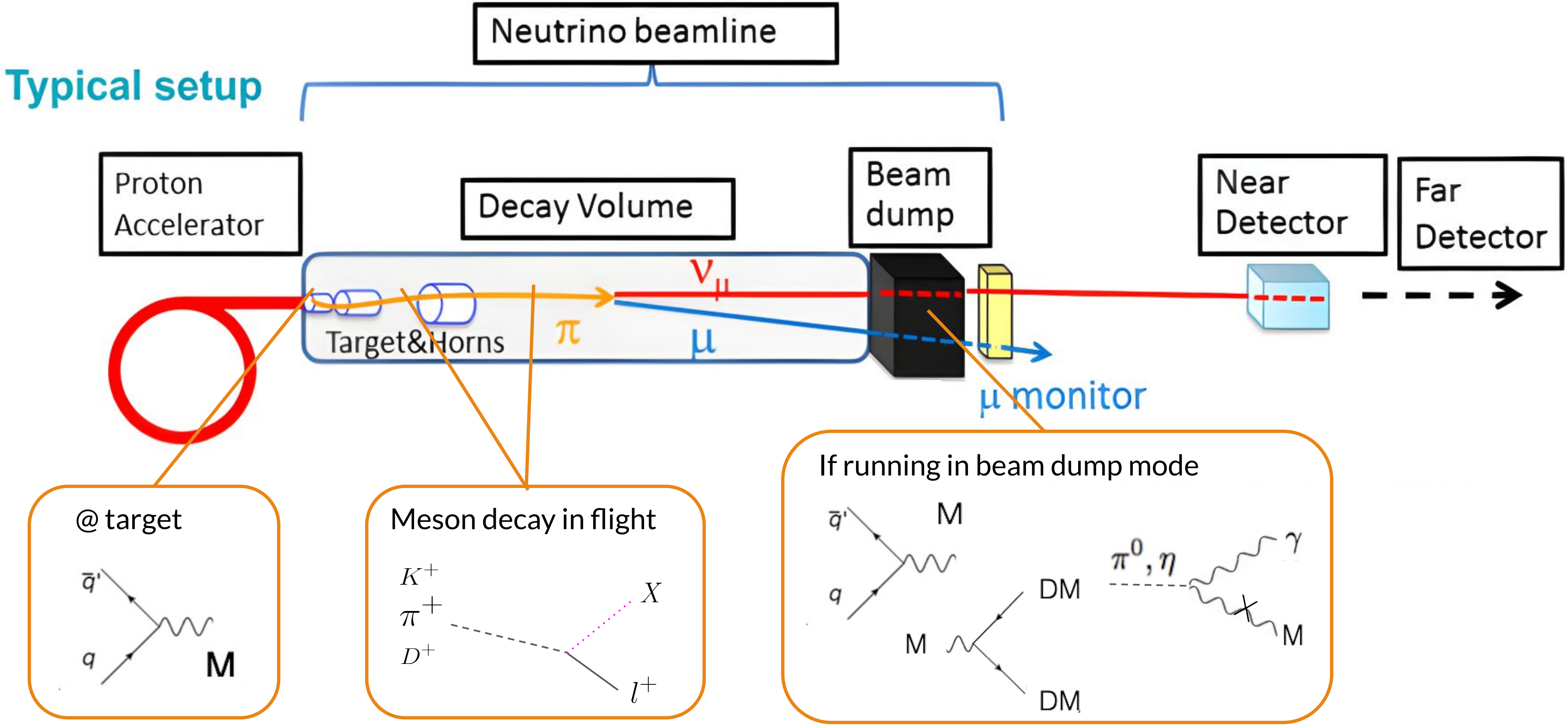

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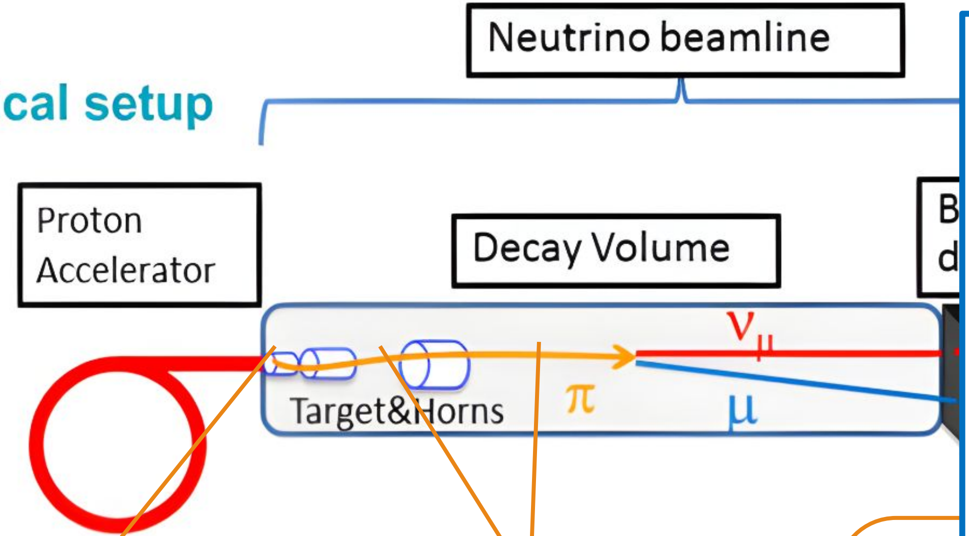

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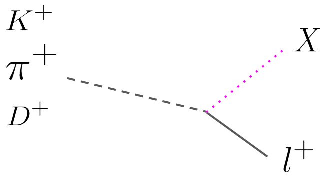
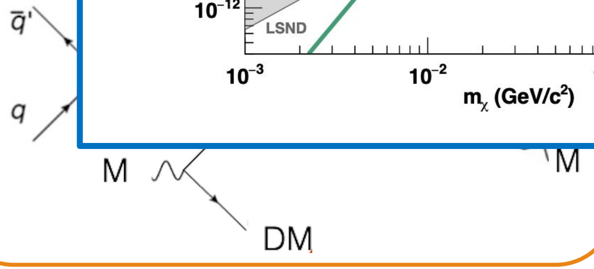
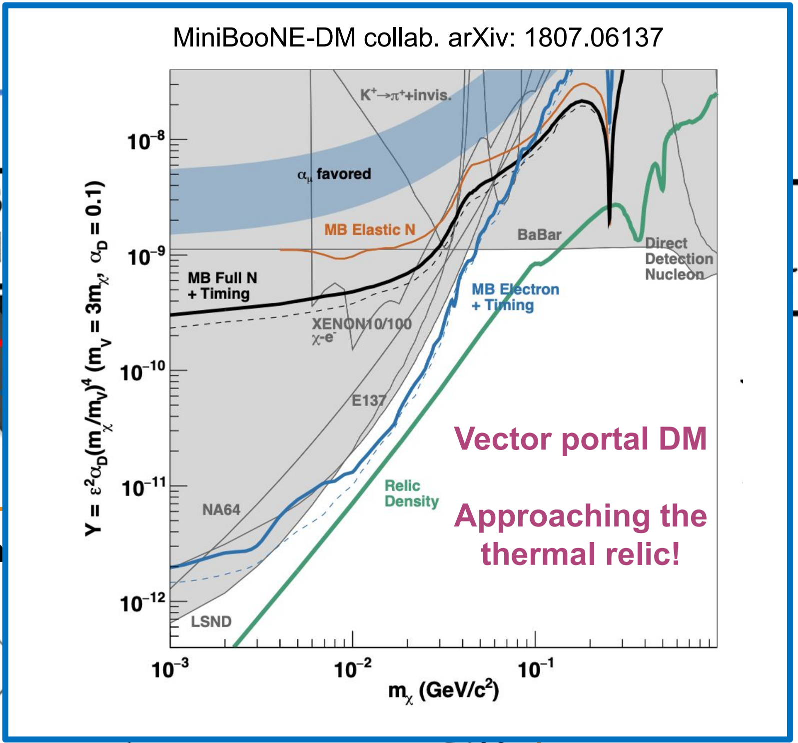


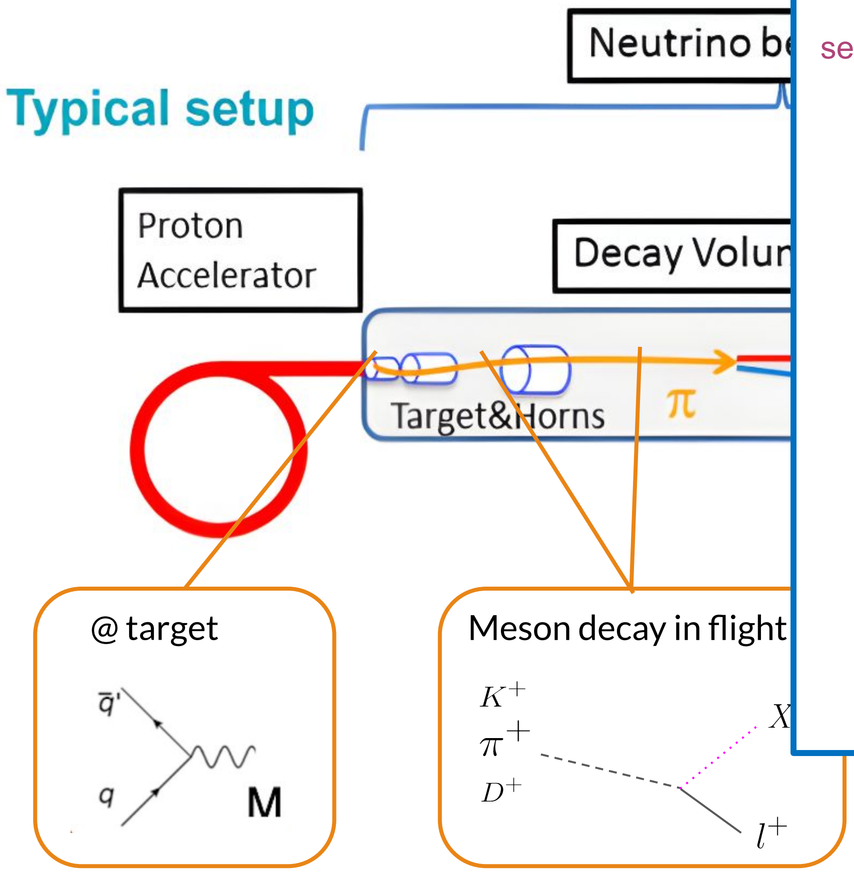
If run



MiniBooNE-DM collab. arXiv: 1807.06137

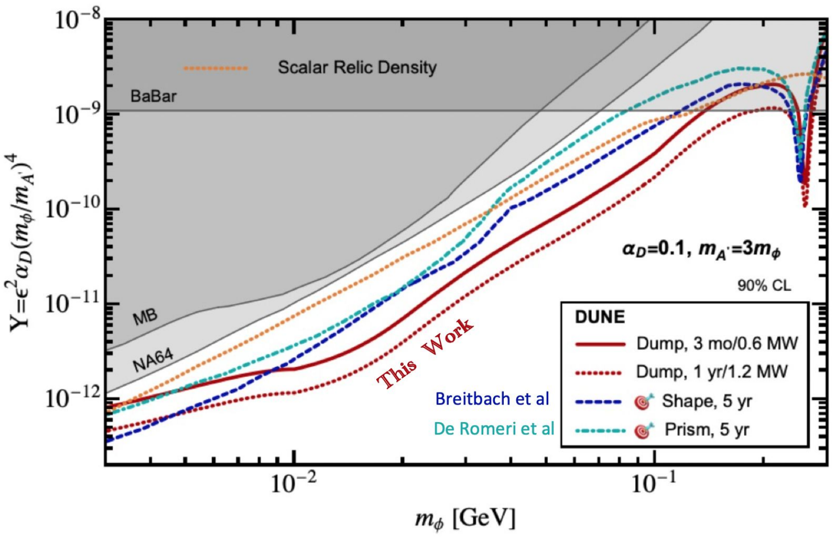


Neutrino Experiments



see Brdar et al, arXiv: 2206.06380: *BSM Targets at a "Target-less DUNE"*

Claim to probe parameter space for thermal scalar relic in only 3 months



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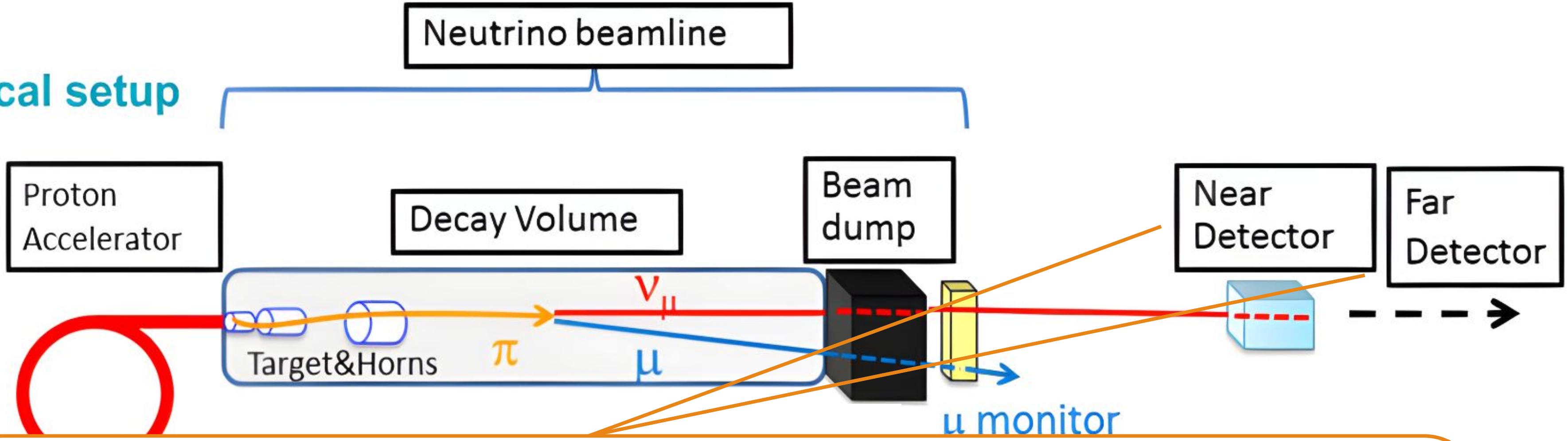
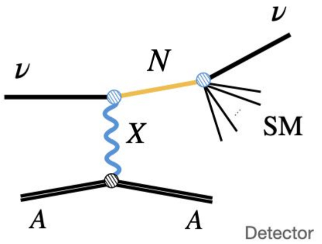
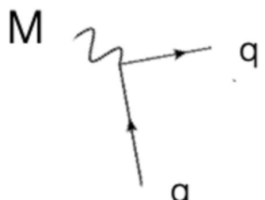


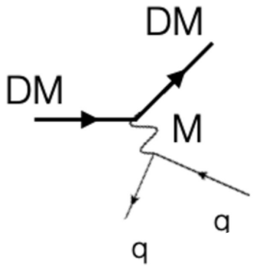
In detector neutrino scattering



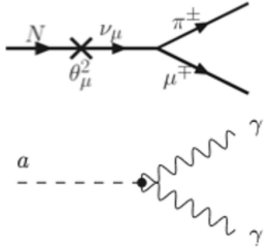
Long-lived mediator decay



DM scattering



Displaced decays



Plethora of NP

Among the NP options are:

- Light Z'
- HNLs
- Light Dark Matter
- ALPs
- .....

"Heavy Neutral Leptons via Axion-Like Particles at Neutrino Facilities"
AA, A. de Gouvea, B. Dutta, I. Shoemaker and Z. Tabrizi
ArXiv: 2311.07713 [hep-ph]

"A panorama of new-physics explanations to the MiniBooNE excess"
AA, J. Hoefken-Zink, M. Hostert, D. Massaro, S. Pascoli
ArXiv: 2308.02543 [hep-ph]

"Constraining light thermal inelastic dark matter with NA64'
AA, B. Banto Oberhauser, P. Crivelli, M. Hostert, D. Massaro, L. Molina Bueno, M. Mongillo, S. Pascoli
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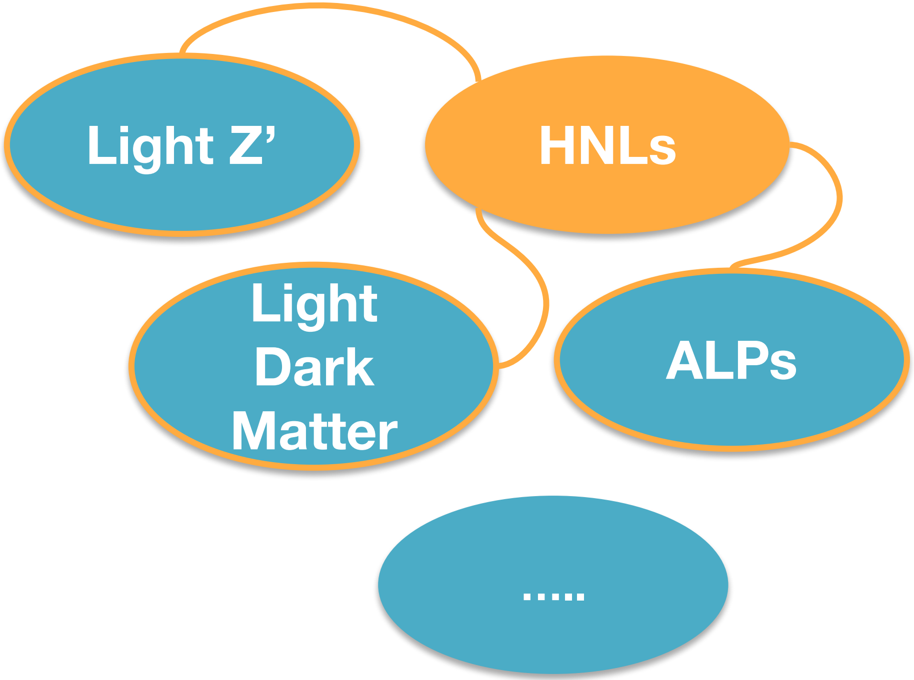

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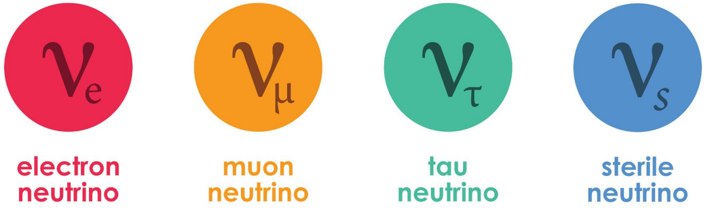
HNLs: The minimal scenario

Heavy neutral leptons are the typical BSM extension studied at neutrino experiments



- Singlet N couples to SM leptons through Higgs

$$\mathcal{L} \supset -y\bar{L}\left(i\sigma^2 H^*\right)N - \frac{M_N}{2}\overline{N^c}N$$

→ The only renormalizable coupling to a singlet fermion

HNLs: The minimal scenario

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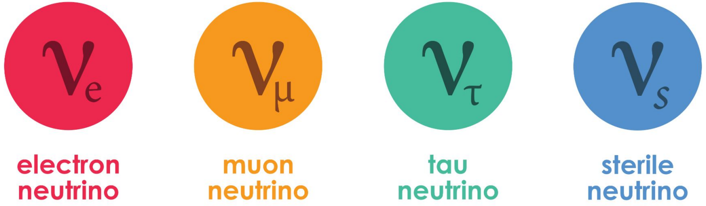
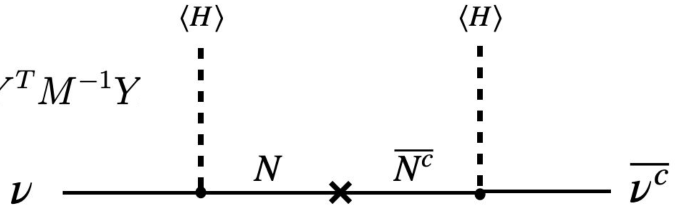


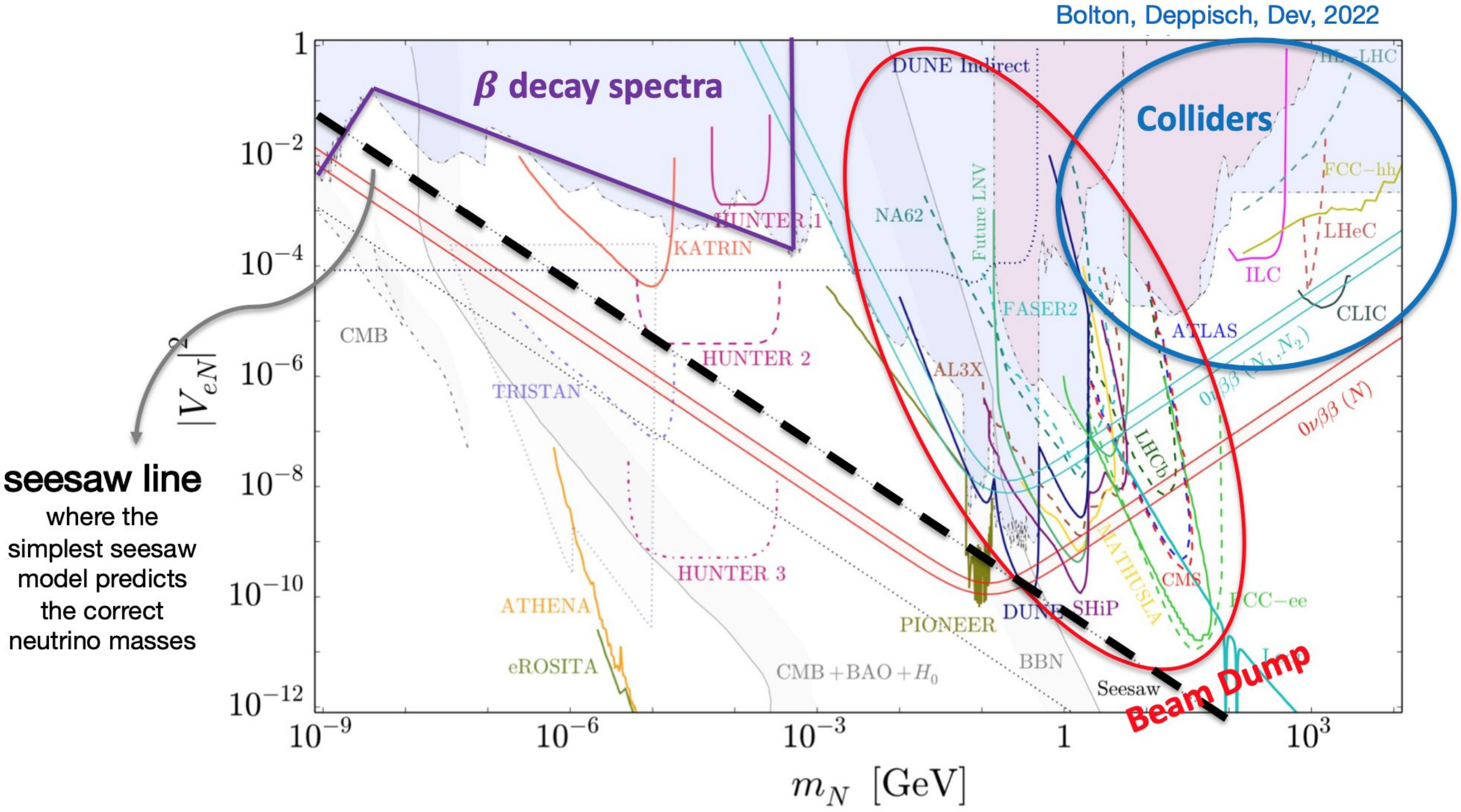
- Mass mixing with SM neutrinos and active–sterile neutrino oscillations
- Could explain neutrino mass $\longrightarrow$ **Type 1 seesaw**

$$M_\nu \simeq -\frac{v^2}{2} Y^T M^{-1} Y$$



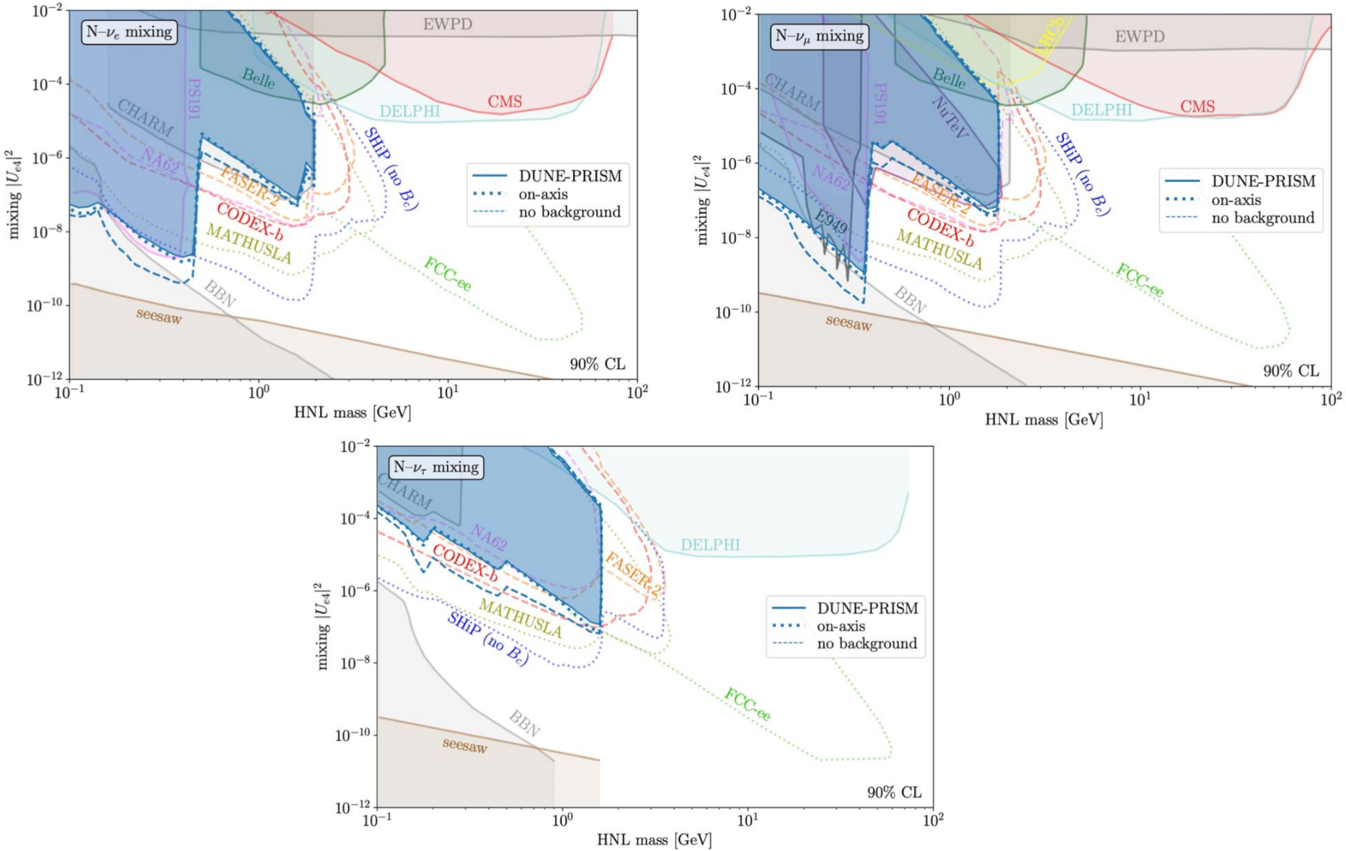
- **Very heavy N** $\longrightarrow$ $m_\nu \simeq -\frac{m_D^2}{M}$
- **Very small mixing** $\longrightarrow$ $|U_{\alpha h}|^2 \simeq 10^{-10} \frac{[\mathrm{GeV}]}{M}$

HNLs: The minimal scenario



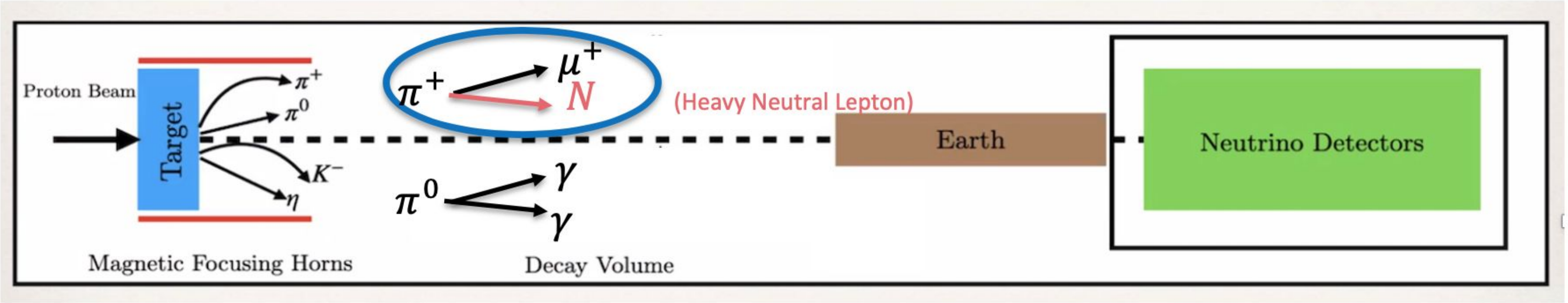
HNLs: The minimal scenario

Breitbach, Buonocore, Frugiuele, Kopp, Mittnacht, JHEP (2022)

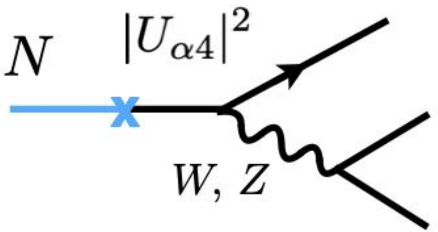


HNLs: The minimal scenario

ROADBLOCK: Production and detection through neutrino mixing



Event rate suppressed by $|U_{\alpha N}|^4$

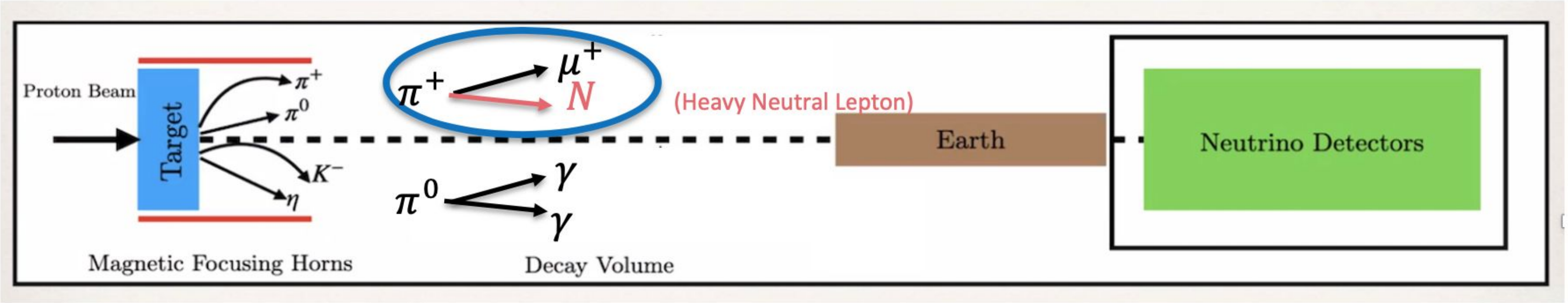


Typically **long-lived** and have **weaker-than-weak** interactions

→ Challenging to probe **seesaw region** and below

HNLs: The minimal scenario

ROADBLOCK: Production and detection through neutrino mixing



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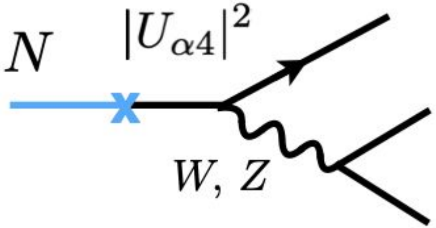


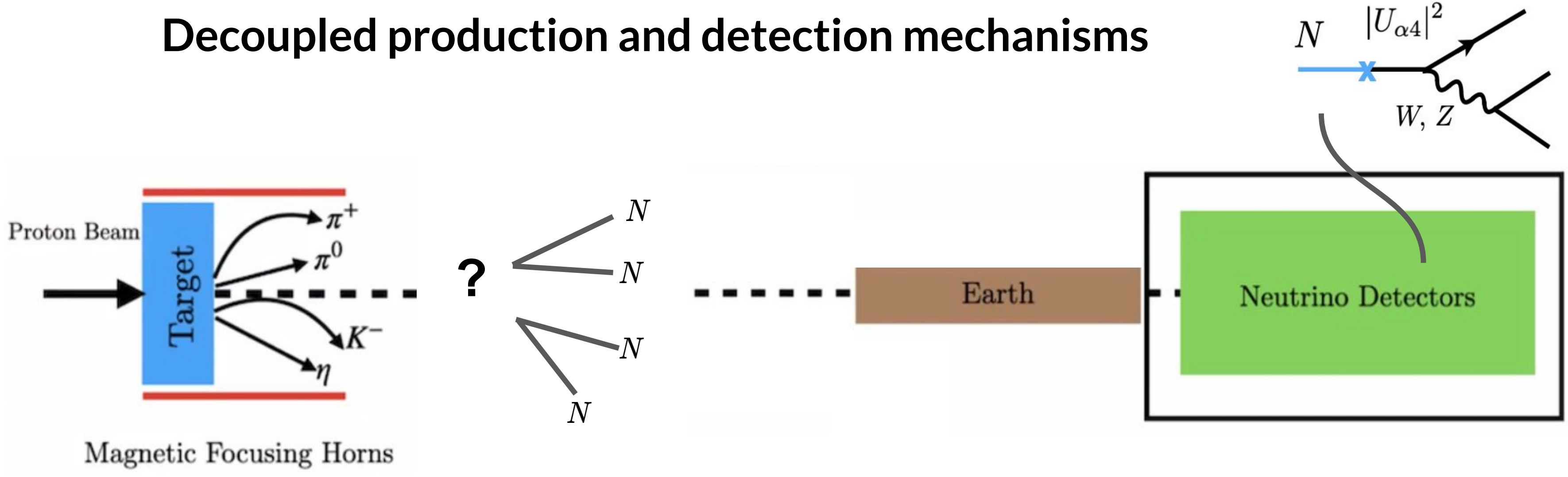
How to bypass the roadblock?

A bigger dark sector

HNLs: A new option

Option:

Decoupled production and detection mechanisms



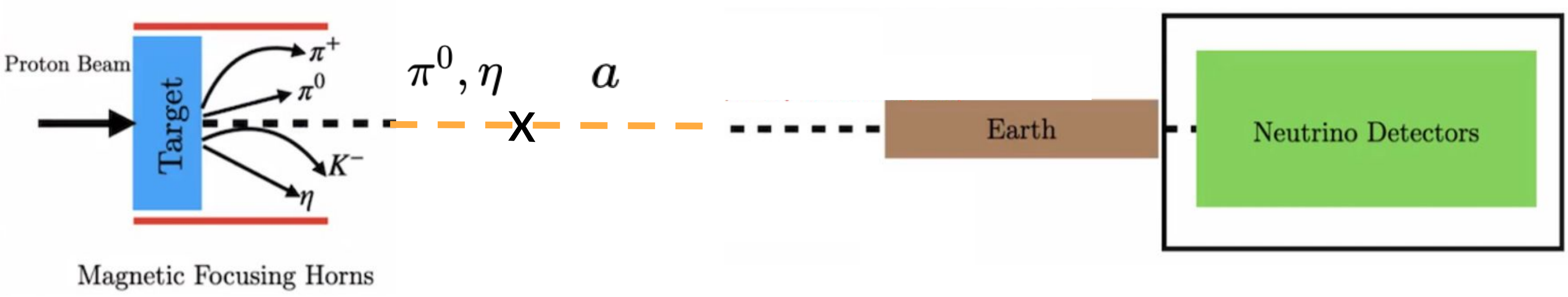
HNL production through ALPs

Option:

New *pseudoscalar*, a, that is mixed with the SM neutral pion and eta meson

$$\pi^0 \to \pi^0 + g_{\pi a} a$$
$$\eta \to \eta^0 + g_{\eta a} a$$

"Dark Matter and Neutrino Mass from the Smallest Non-Abelian Chiral Dark Sector"
J. M. Berryman, A. de Gouvea, K. J. Kelly, Y. Zhang
ArXiv: 1706.02722 [hep-ph]



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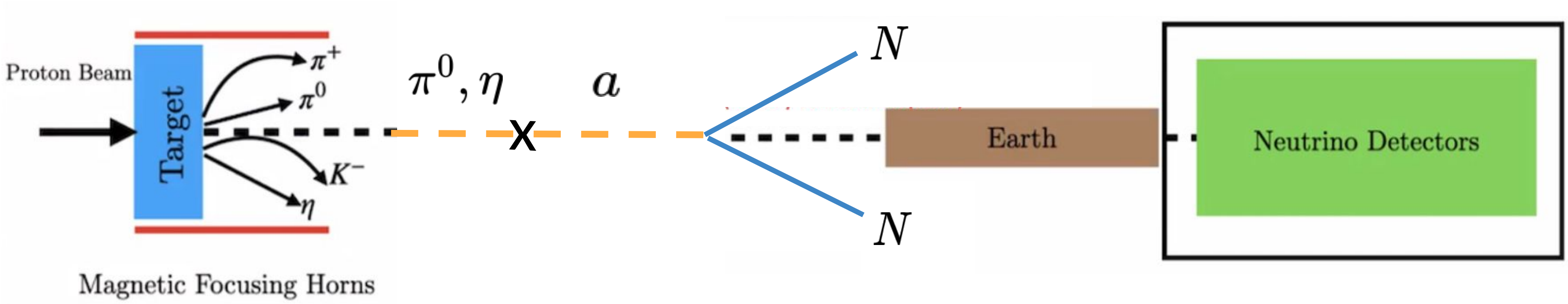
Analogous to $\pi^+ \rightarrow l^+ + \nu$ in SM



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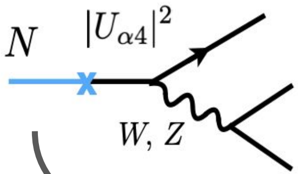
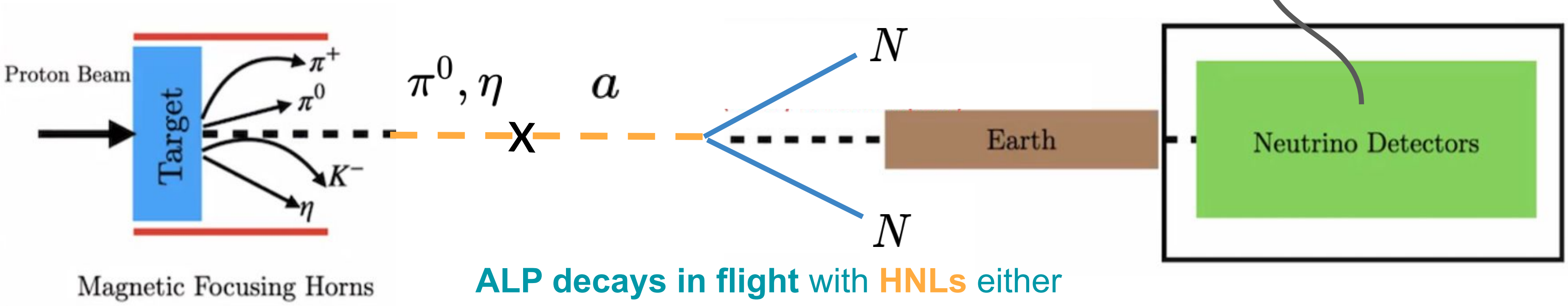
HNL production through ALPs

Option:

New *pseudoscalar*, a, couples to HNLs directly

Analogous to $\pi^+ \to l^+ + \nu$ in SM





ALP decays in flight with **HNLs** either **decaying** or **scattering** in the detector

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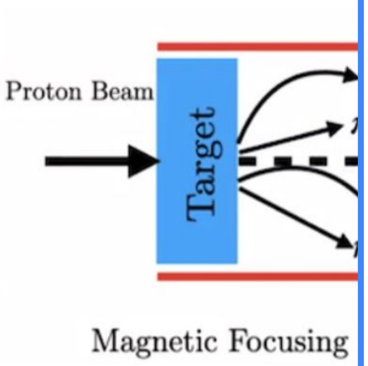
New *pseudoscalar*, a, couples to HNLs directly

Analogous to π

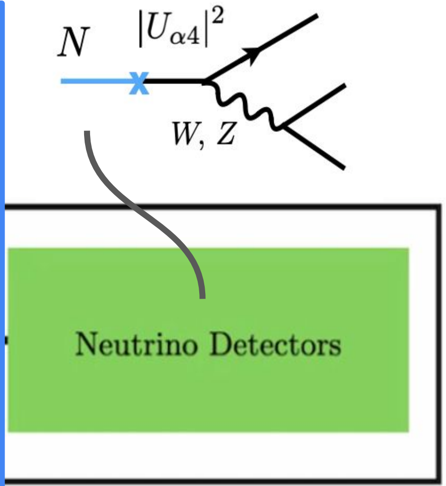


No neutrino mixing suppression at production

HNL event rate $\sim \theta_a{}^2 |U_\alpha|^2$

Enhanced wrt the usual HNL if $\theta_a{}^2 \gg |U_\alpha|^2$

Different angular distributions



“Heavy Neutral Leptons via Axion-Like Particles at Neutrino Facilities

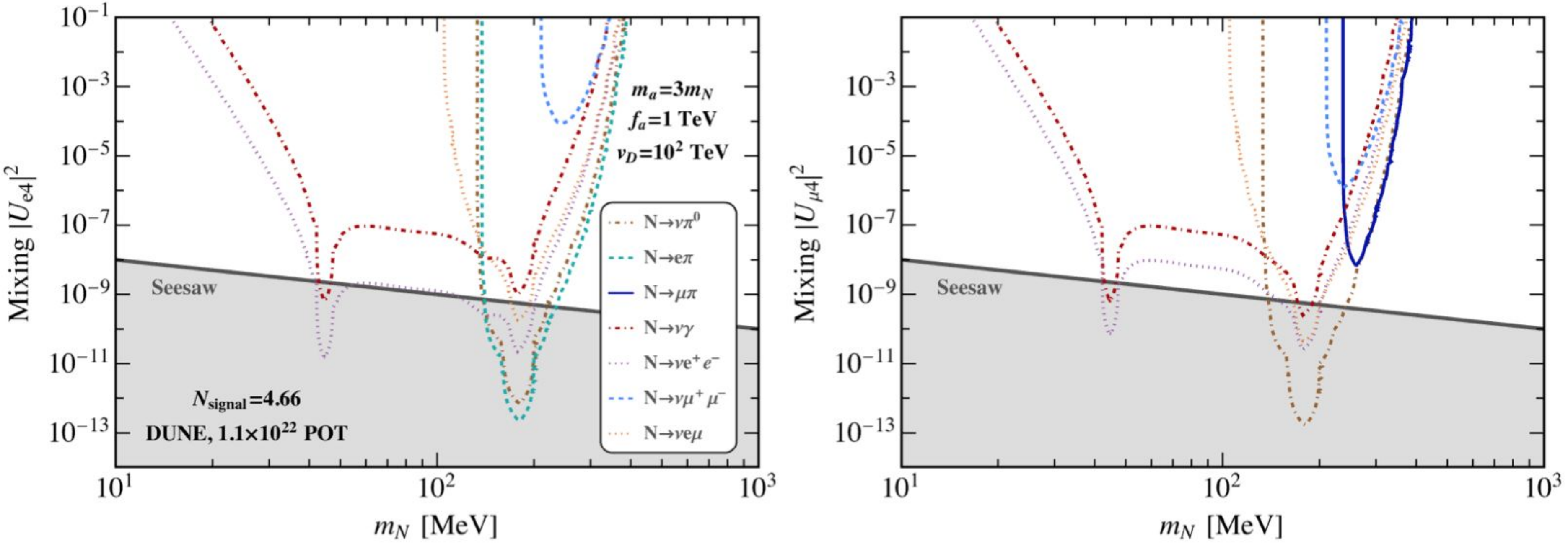
AA, A. de Gouvea, B. Dutta, I. Shoemaker and Z. Tabrizi

ArXiv: 2311.07713 [hep-ph]

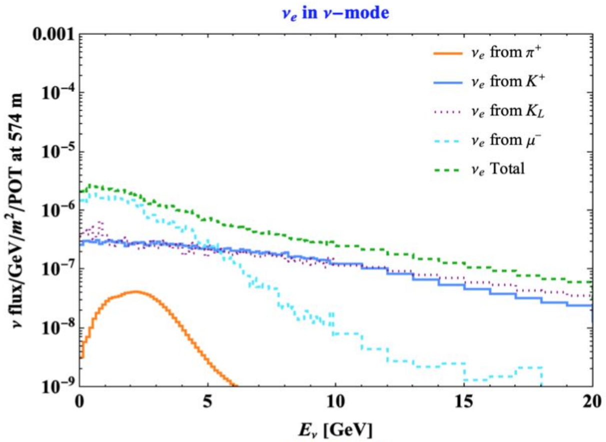
Sensitivity at DUNE

Potential to probe seesaw region

Sensitivity doesn't vary significantly between flavours

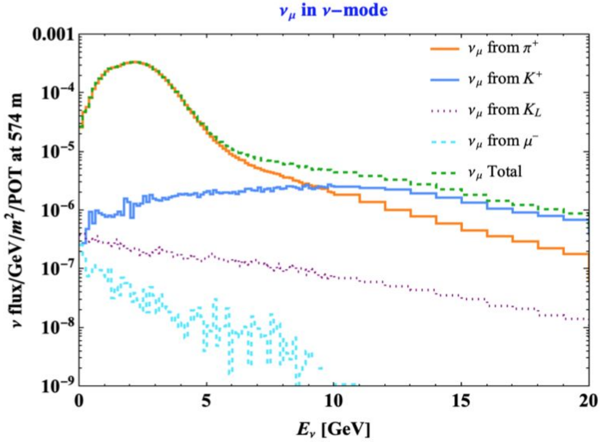


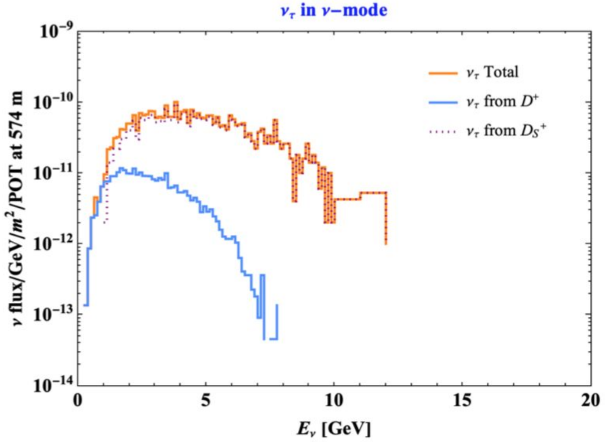
SM Neutrino fluxes



$$\phi_{\nu_e} \sim 2\times10^{-2}\ \phi_{\nu_\mu} \sim 10^4 \phi_{\nu_\tau}$$

Neutrino fluxes dependent on kaon, pion and charmed meson fluxes which vary significantly

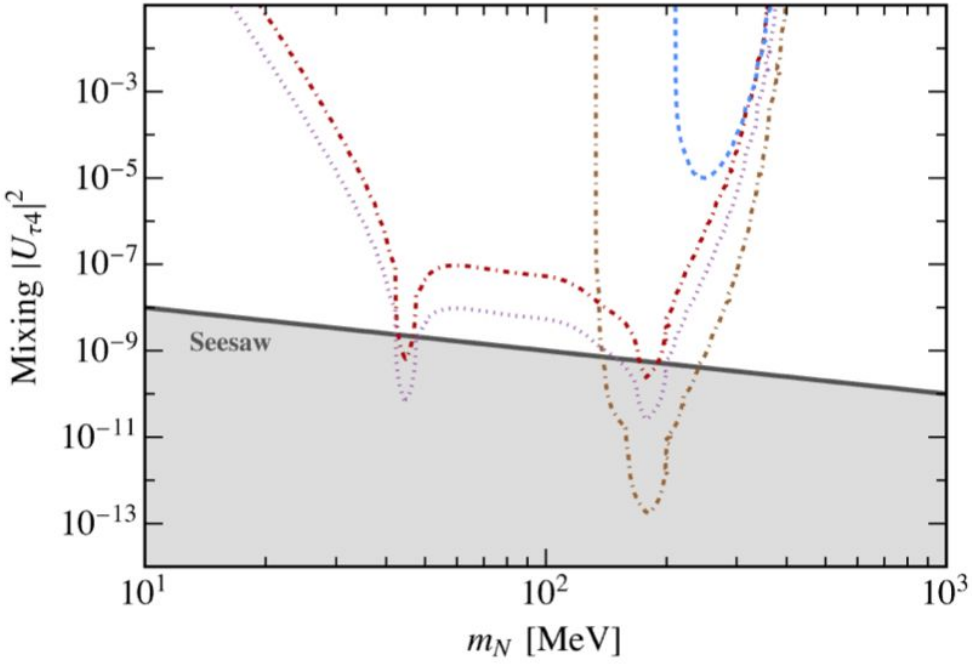


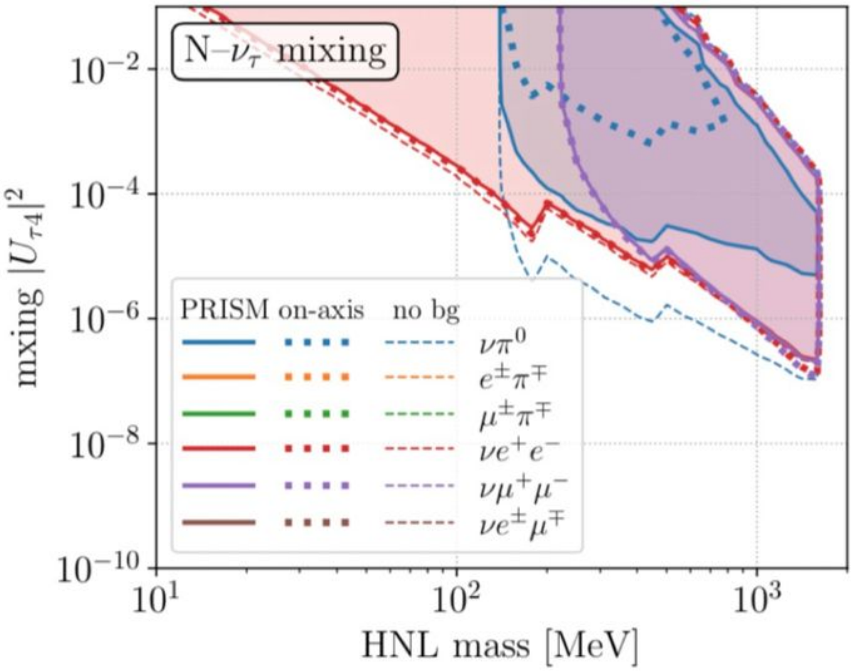


Sensitivity at DUNE

Weak dependence on flavour **significant** for tau mixing

$|\mathbf{U}_{\tau 4}|^2 \sim 10^3 |\mathbf{U}_{\mu 4}|^2$

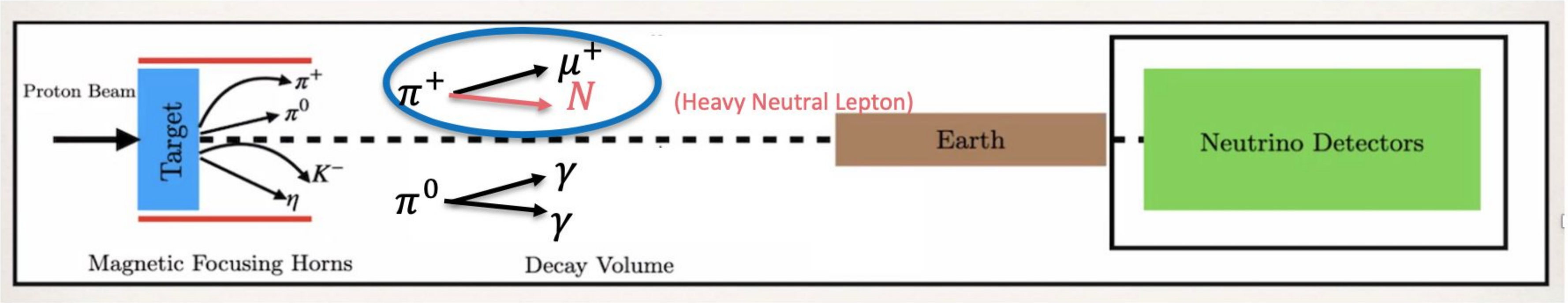


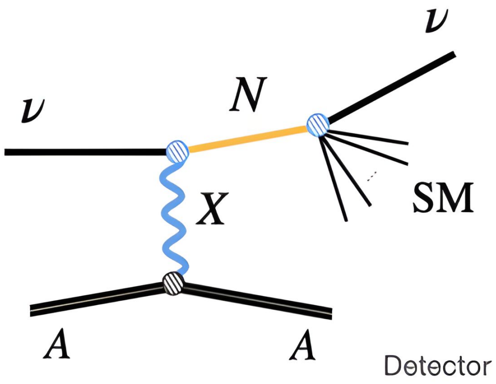


Potential signatures of the tau lepton!

HNLs: Light mediator

Option: Scattering in detector through a *light new mediator*, e.g. dark photon



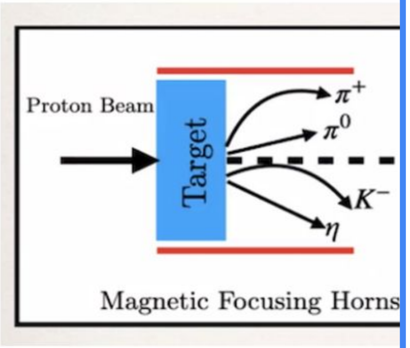


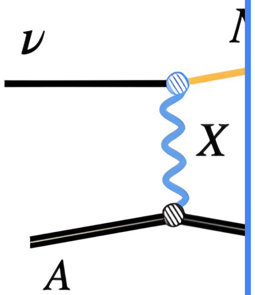
Enhanced scattering cross-section
compensates $|U_{\alpha N}|^4$ suppression

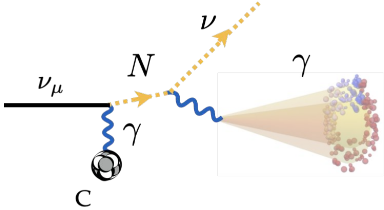
"A panorama of new-physics explanations to the MiniBooNE excess"
AA, J. Hoefken-Zink, M. Hostert, D. Massaro, S. Pascoli
ArXiv: 2308.02543 [hep-ph]

HNLs: Light mediator

Option: Scattering

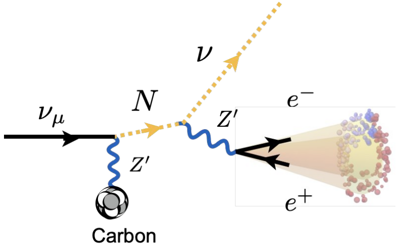






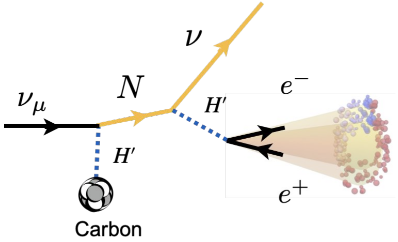
Transition Magnetic Moment

$$F^{\mu\nu}\left(\frac{\mu_\nu^{\alpha j}}{2}\overline{\nu_\alpha}\sigma_{\mu\nu}N_j + \frac{\mu_\nu^{ij}}{2}\overline{N_i}\sigma_{\mu\nu}N_j\right)$$



Dark Photon

$$Z'_\mu\left(V^{\alpha j}\overline{\nu_\alpha}\gamma^\mu N_j + V^{ij}\overline{N_i}\gamma^\mu N_j + d_V^\ell\,\overline{\ell}\gamma^\mu\ell\right)$$



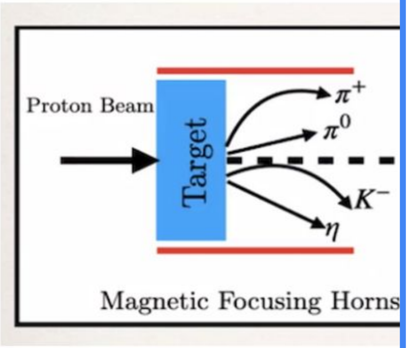
Dark Scalar

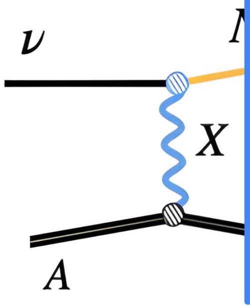
$$h'\left(S^{\alpha j}\overline{\nu_\alpha}N_j + S^{ij}\overline{N_i}N_j + d_S^\ell\,\overline{\ell}\ell\right)$$

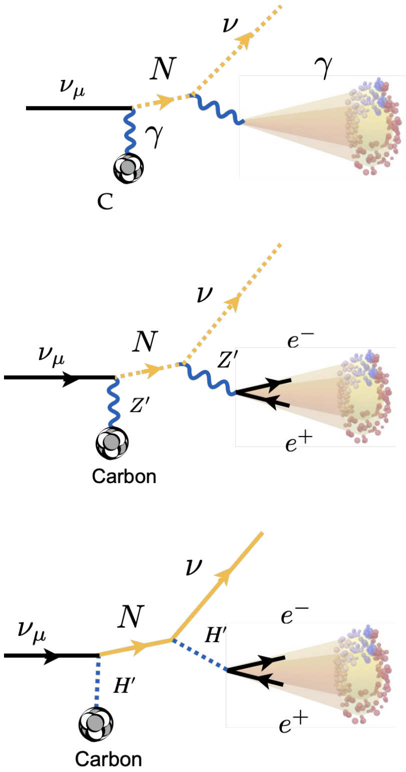
* **Model independent parameterization.**

HNLs: Light mediator

Option: Scattering

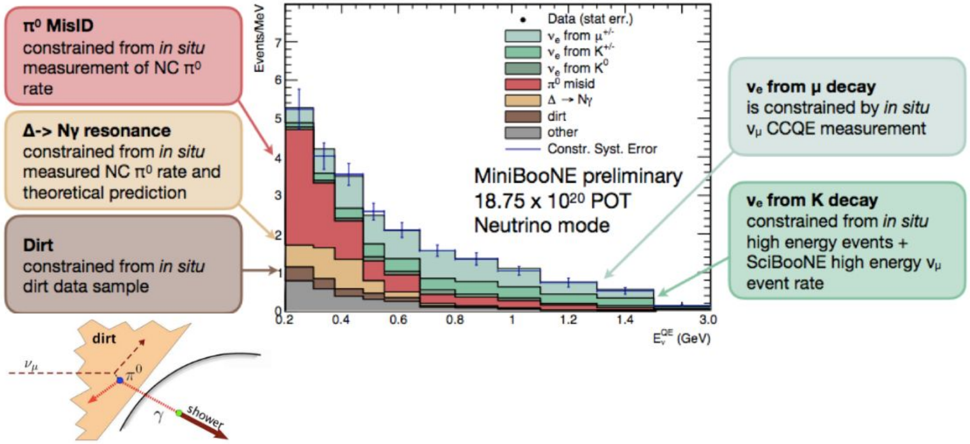






Studied in the context of the MiniBooNE anomaly where photon and e$^{\pm}$ were indistinguishable

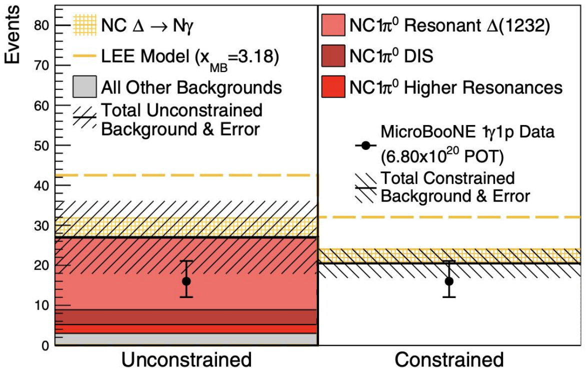
Hourlier. Adrien. MiniBooNE Coll. Neutrino2020



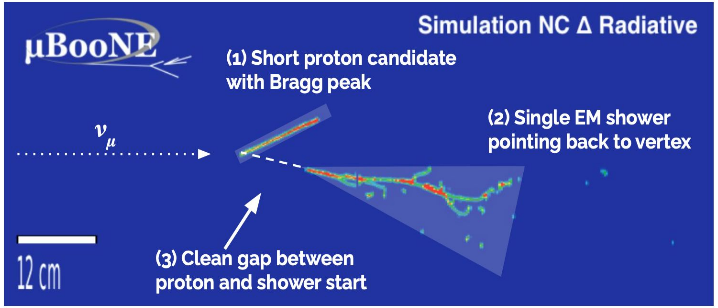
MicroBooNE Single γ Searches

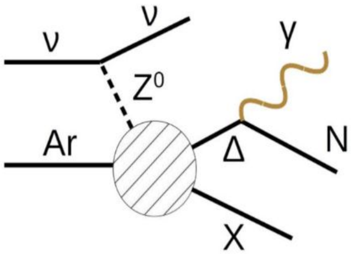
Search for photon-like LEE has already been performed

SM NC Δ → Nγ (PRL 128, 111801 2022)



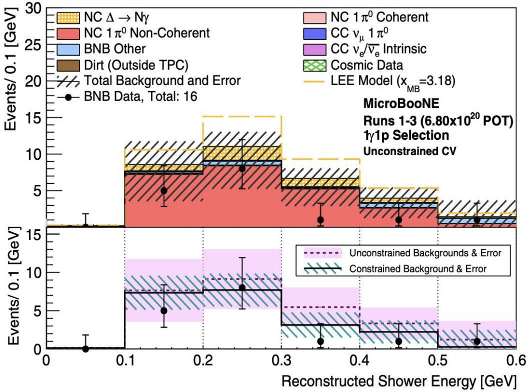
With no excess observed compatible with MiniBooNE!

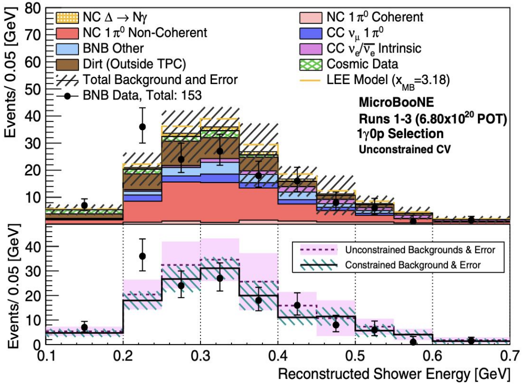




1. $\Delta^+ \rightarrow p\,\gamma \;\rightarrow 1\gamma\ 1p$

2. $\Delta^0 \rightarrow n\,\gamma \;\rightarrow 1\gamma\ 0p$

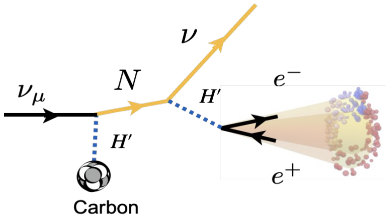


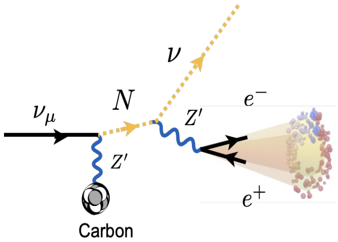


Signal prediction for selected models

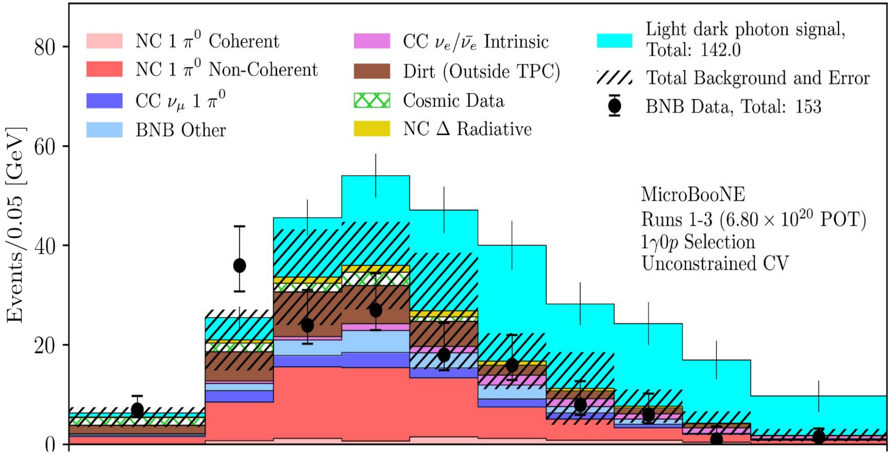
Contribution to 1g0p selection sizeable suggesting the search for NC Δ radiative decays is highly constraining for coherent-like benchmarks

30 MeV mediators

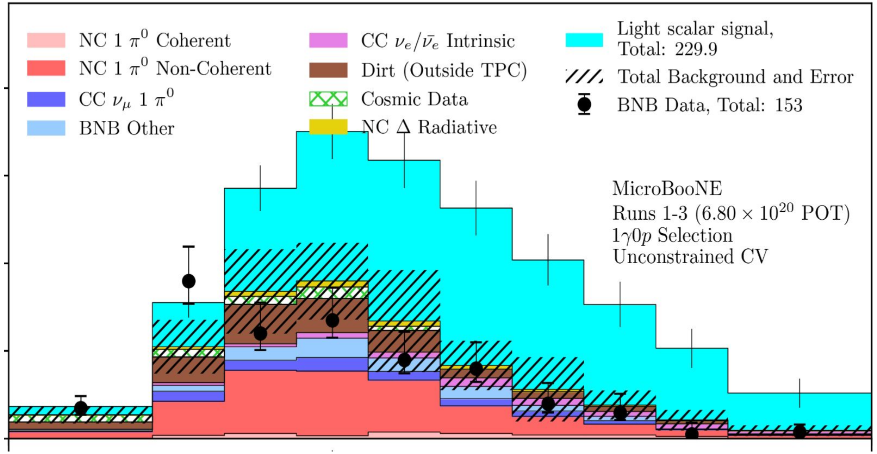




142 predicted signal events (on top of 153 total events)



229.9 predicted signal events (on top of 153 total events)



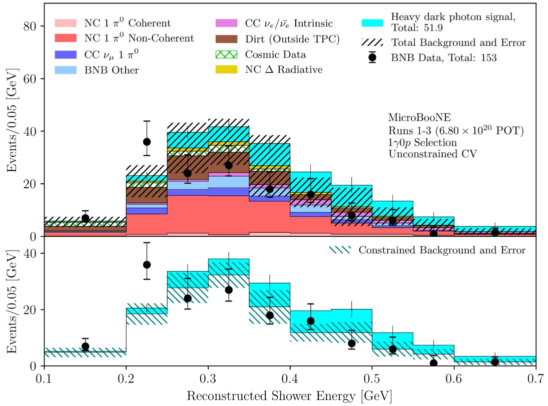
Signal prediction for selected models

Contribution to 1g0p selection sizeable suggesting the search for <u>NC Δ radiative decays is highly constraining for coherent-like benchmarks</u>

What is the impact of improved selection cuts? e.g. improved angular resolution for e^+e^-

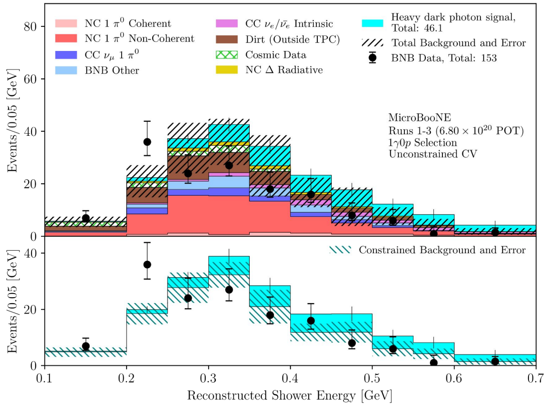
e.g. heavy dark photon model (1 GeV mediator)

$\theta_{sep.}$ < 35 deg.



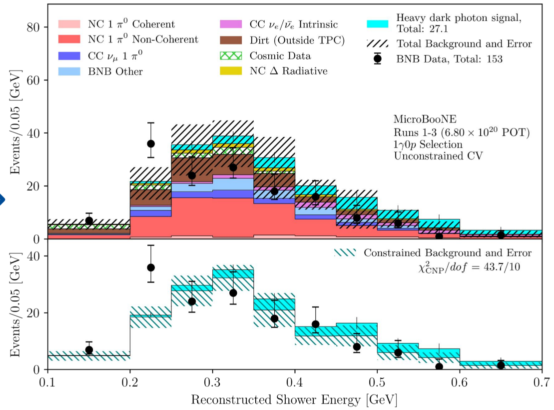
51.9 events

$\theta_{sep.}$ < 25 deg.



46.1 events

$\theta_{sep.}$ < 15 deg.



27.1 events

Main Takeaways

- Neutrino experiments are excellent place to search for new physics

  → *large flux of charged and neutral mesons*

- Minimal HNL models face strong mixing suppression

- Enhanced HNL production rate by:
  - Decoupling the production and detection
    - flavour insensitive
  - Introducing new light mediators

- Potentially strong constraints from existing searches
- Potentially strong sensitivities as DUNE ND-like experiments


Thank you for your attention!

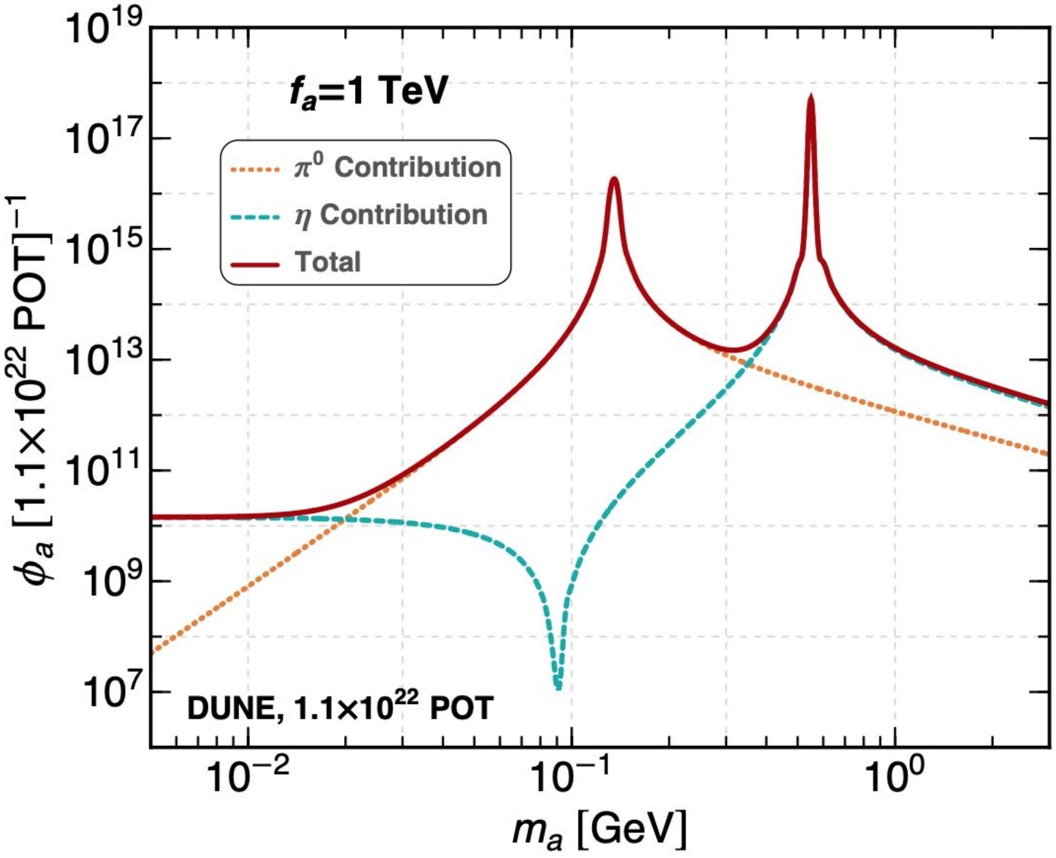
ALP flux

Contributions from:

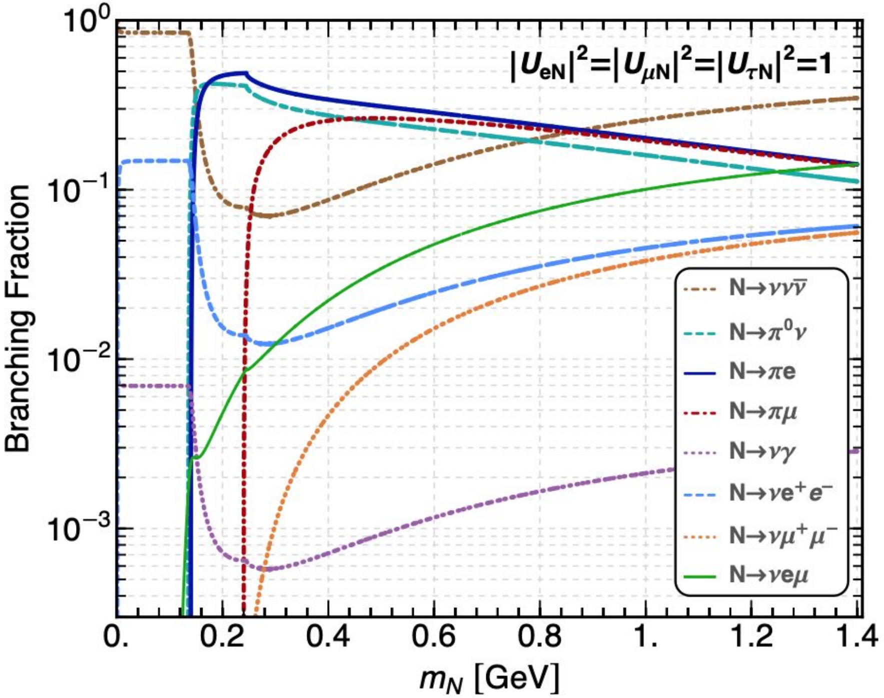
$$\pi^0 \to \pi^0 + g_{\pi a} a\,,$$
$$\eta \to \eta^0 + g_{\eta a} a\,,$$

To obtain ALP flux

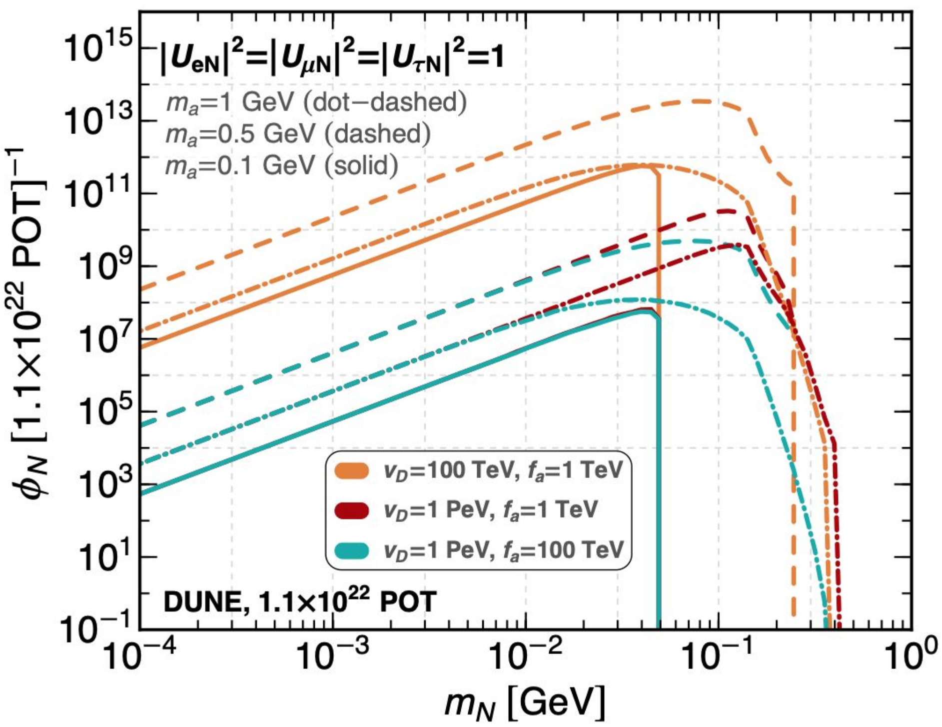
$$\frac{d^2\phi_a}{dE_a d\theta_a} = g^2_{\mathbf{m}a}\frac{E_a}{E_\mathbf{m}}\frac{d^2\phi_\mathbf{m}}{dE_\mathbf{m} d\theta_\mathbf{m}}$$



HNL flux



$|U_{eN}|^2=|U_{\mu N}|^2=|U_{\tau N}|^2=1$
Branching Fraction
m_N [GeV]
N→$\nu\nu\bar{\nu}$
N→$\pi^0\nu$
N→πe
N→$\pi\mu$
N→$\nu\gamma$
N→νe^+e^-
N→$\nu\mu^+\mu^-$
N→$\nu e\mu$

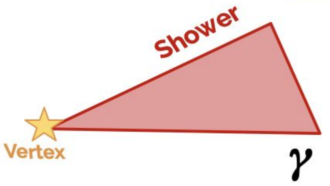


$|U_{eN}|^2=|U_{\mu N}|^2=|U_{\tau N}|^2=1$
m_a=1 GeV (dot−dashed)
m_a=0.5 GeV (dashed)
m_a=0.1 GeV (solid)
ϕ_N [1.1×10^{22} POT]$^{-1}$
v_D=100 TeV, f_a=1 TeV
v_D=1 PeV, f_a=1 TeV
v_D=1 PeV, f_a=100 TeV
DUNE, 1.1×10^{22} POT
m_N [GeV]

BSM in NC Δ-radiative search

In the meantime…

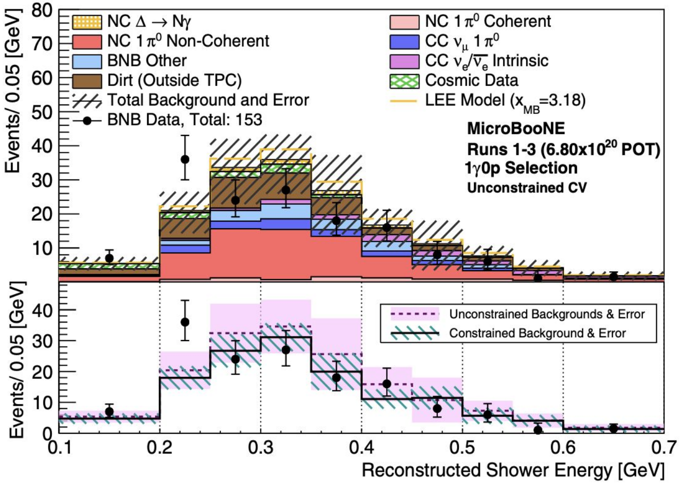
2. Find candidate vertices with topological selection



1γ0p is more difficult, but provides a secondary dataset for comparison and verification

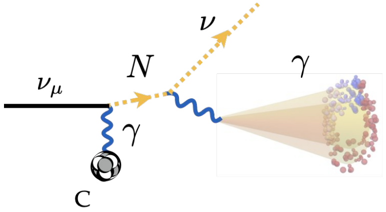
- **54.7%** of true 1γ events
- **9%** reconstruction efficiency with 0 track and 1 shower requirement and pre-selection cuts

2. $\Delta^0 \rightarrow n\,\gamma \rightarrow 1\gamma\ 0p$



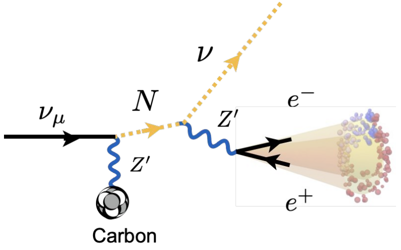
Caveat: **1γ 0p selection has larger bkg, as proton kinematics cannot be leveraged for bkg rejection**

BSM Benchmark models



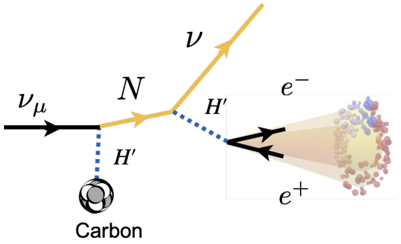
Transition Magnetic Moment

$$F^{\mu\nu}\left(\frac{\mu_\nu^{\alpha j}}{2}\overline{\nu_\alpha}\sigma_{\mu\nu}N_j + \frac{\mu_\nu^{ij}}{2}\overline{N_i}\sigma_{\mu\nu}N_j\right)$$



Dark Photon

$$Z'_\mu\left(V^{\alpha j}\overline{\nu_\alpha}\gamma^\mu N_j + V^{ij}\overline{N_i}\gamma^\mu N_j + d_V^\ell\,\overline{\ell}\gamma^\mu\ell\right)$$



Dark Scalar

$$h'\left(S^{\alpha j}\overline{\nu_\alpha}N_j + S^{ij}\overline{N_i}N_j + d_S^\ell\,\overline{\ell}\ell\right)$$

*** Model independent parameterization.**

We consider **three BSM models**

Where mediator is massive, we consider **light** and **heavy** scenarios

	Vector	Scalar
Light mediator	**A**	**B**
Heavy mediator	**C**	**D**

Transition mag. moment	**TMM**

DarkNews

Signal events generated by DarkNews

(A. Abdullahi, J. Hoefken, M. Hostert, D. Massaro, S. Pascoli)

DarkNews is a light-weight Python generator for neutrino-nucleus upscattering to heavy neutrinos.

```
import DarkNews as dn
my_gen = dn.GenLauncher(mzprime=1.25, m4=0.140,
↪   neval=1000, noHF=True, HNLtype="dirac",
↪   experiment="microboone",
↪   nu_flavors=["nu_mu","nu_mu_bar"])
df = my_gen.run()
```

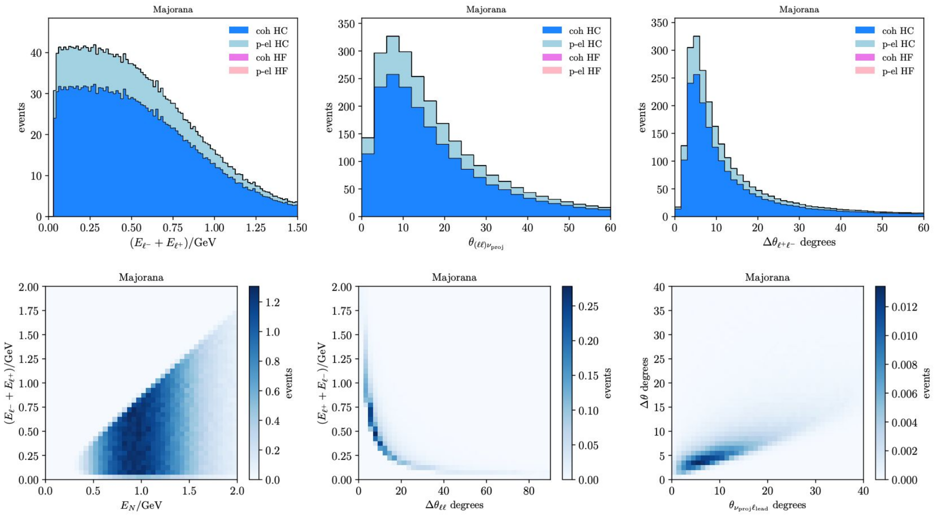
- *Supports up to 3 (Dirac or Majorana) HNLs*
- *Scalar, vector, or transition magnetic moment contributions.*
- *Event output weighted (fast) or unweighted (slower).*
- *Pandas or numpy, as well as HepEvt, HepMC2 and 3.*
- *Simple detector geometry for MiniBooNE and MicroBooNE.*
- *Several neutrino fluxes implemented.*

Public and documented!

Paper: arxiv.org/abs/2207.04137
GitHub: github.com/mhostert/DarkNews-generator
PyPI: pypi.org/project/DarkNews/

`pip install DarkNews`

Example of e^+e^- kinematics at MiniBooNE (Majorana HNL)



Single Photon Analysis Overview

Kathryn Sutton, DPF 2019

1. Take Pandora **reconstructed tracks and showers**

2. Find candidate vertices with **topological selection** and pre-selection cuts

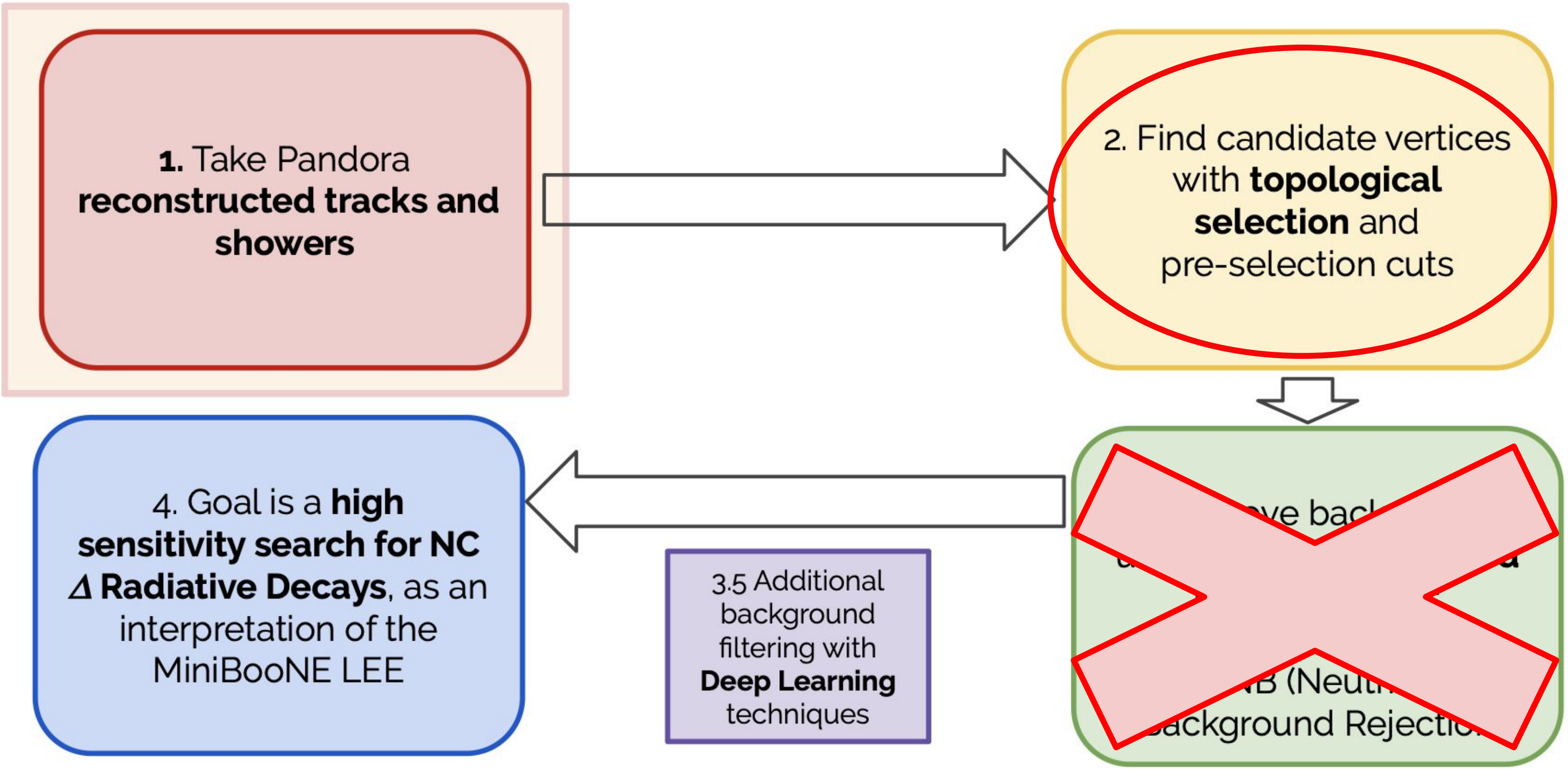
3. Remove background using **2 tailored Boosted Decision Trees**:
-Cosmic Rejection
-BNB (Neutrino) Background Rejection

3.5 Additional background filtering with **Deep Learning** techniques

4. Goal is a **high sensitivity search for NC Δ Radiative Decays**, as an interpretation of the MiniBooNE LEE

Single Photon Analysis Overview

Kathryn Sutton, DPF 2019



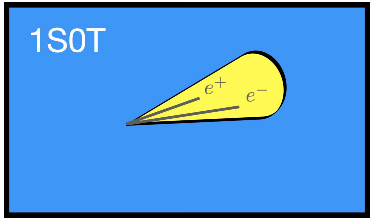
Single Photon Analysis Overview

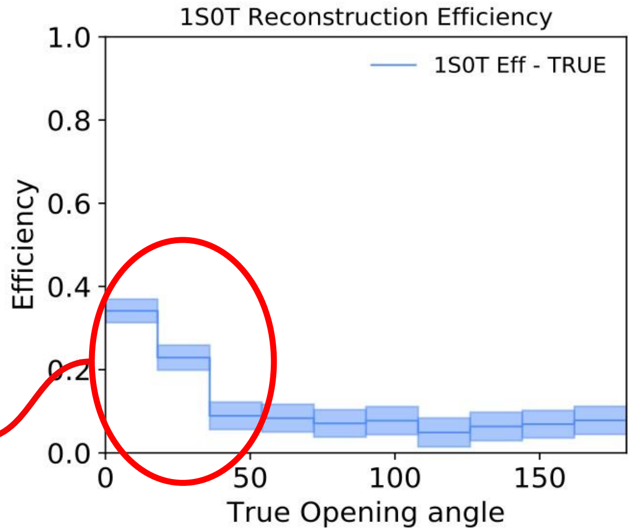
2. Find candidate vertices with **topological selection** and pre-selection cuts

Topological Selection

1γ 0p selection requires exactly one shower to be reconstructed alongside the neutrino vertex

...recall that for





Maximum efficiency to reconstruct *single shower* below 35°

Single Photon Analysis Overview

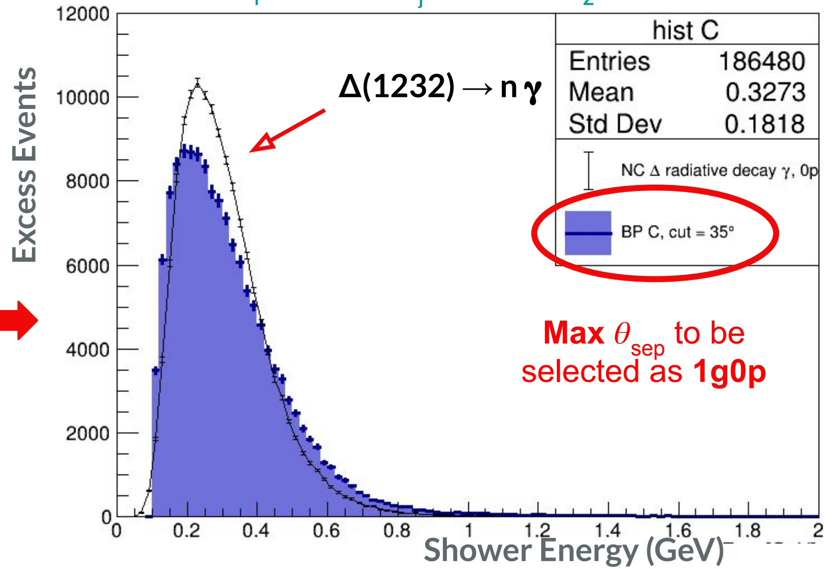
2. Find candidate vertices with **topological selection** and pre-selection cuts

Pre-selection Cuts

1. Reconstructed shower energy
2. ~~Shower start position from SCB~~

Taking light dark photon model as an example, *energy distribution* of the e^+e^- *approaches that of NC Δ photon for > 20°*

m_i=150 MeV, m_j=107 MeV, $m_{Z'}$ = 30 MeV



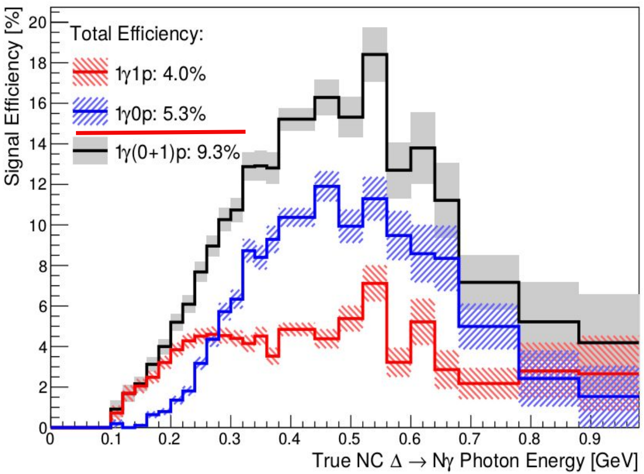
Single Photon Analysis Overview

2. Find candidate vertices with **topological selection** and pre-selection cuts

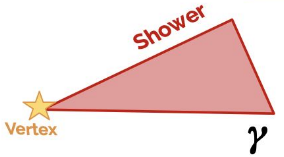
Pre-selection Cuts

1. Reconstructed shower energy → apply signal efficiency
2. ~~Shower start position from SCB~~

Note: 5.3% is doubled to 10.6% as generated events contain only 0p events



2.Find candidate vertices with topological selection



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