Anomalous ν_τ Appearance from Light Mediators in Short-Baseline ν Experiments

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Introduction

- New Physics: Dark Matter (DM), Neutrino masses and mixing, various anomalies, e.g., g-2 of muon, MiniBooNE etc

  Are they all correlated? Is there a model?

- Where is the new physics scale?

- Many experiments are probing new physics scales: DM direct and indirect detections, LHC, neutrino experiments, beam dump experiments, rare decays etc.

- LHC, direct and indirect detections are mostly probing scales with high sensitivities above 1 GeV

Introduction

This talk: Investigates scales below 1 GeV

- This region is not well searched
- Anomalies, puzzles can be addressed
- There are many new ideas

Models (a lot of ongoing activities):
Light mediators: scalar, pseudo-scalar, vector; sub-GeV DM

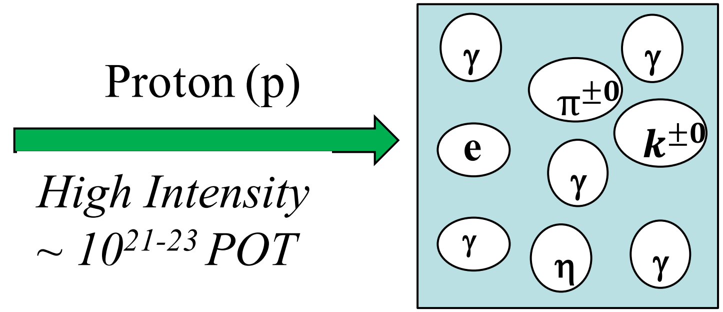
We will utilize: a few specific well-motivated scenarios

- involve tau neutrinos at short baseline neutrino experiments for probing

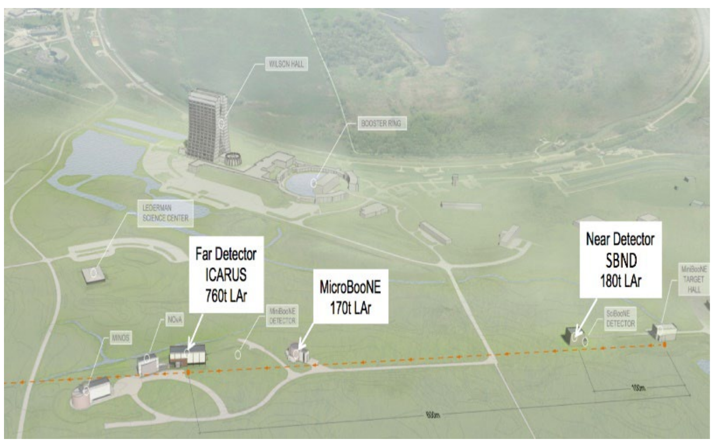
Light mediators and ν experiments

Beam dump-based Neutrino experiments can be versatile

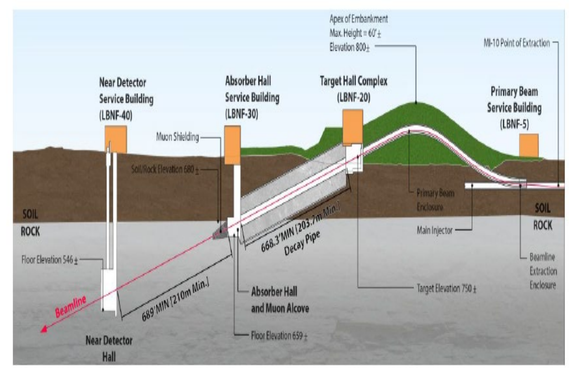
Beam dump-based (proton beam) [ongoing]: 800 MeV-3 GeV: COHERENT (Oakridge), CCM (LANL), JSNS2(JPARC) Detectors, CsI, LAr, NaI, Ge



Fermilab SBN program: 120 GeV NuMI, 8 GeV BNB beams (ongoing)



DUNE (120 GeV)

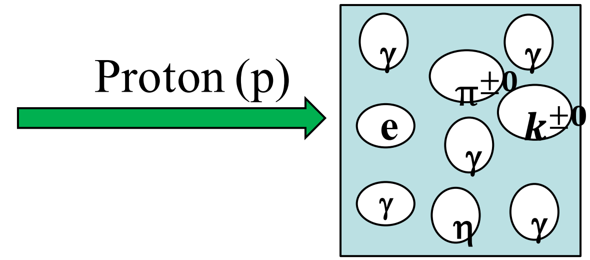


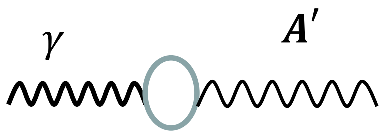
- Many experiments with proton beams have different beam energies using various detectors at different locations
- FASER, FASERν, SND are ongoing at the LHC

New physics at ν experiments

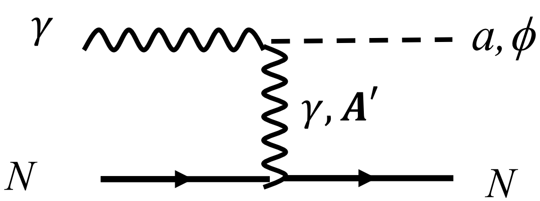
From γ:

A': Vector
ϕ=scalar
a=pseudo-scalar





$$L \supset -\frac{\varepsilon}{4} F^{\mu\nu} F^{(\prime)}_{\mu\nu} - g_{a,\phi\gamma(Z')} \frac{(a,\phi)}{4} F^{\mu\nu} \tilde{F}^{(\prime)}_{\mu\nu}$$



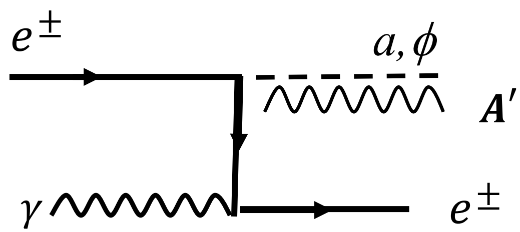
Primakoff

Coherent scattering for γ exchange

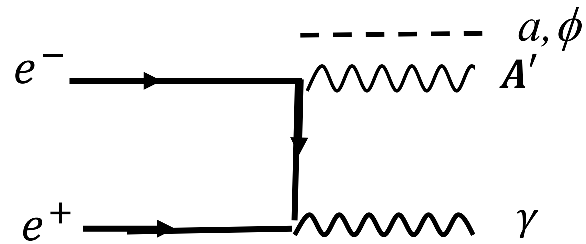
New physics at ν experiments

From $e^{\pm}$: $\quad L \supset -g_{\phi(a)ee}\bar{e}\,(i\gamma^5)e\,\phi(a) - g_{A'ee}\bar{e}\,\gamma^{\mu}e\,A'$

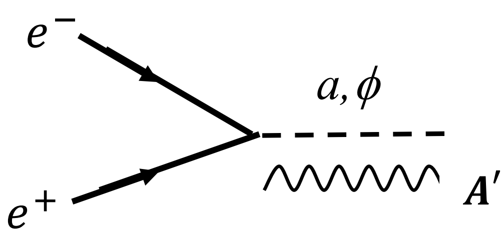
Compton



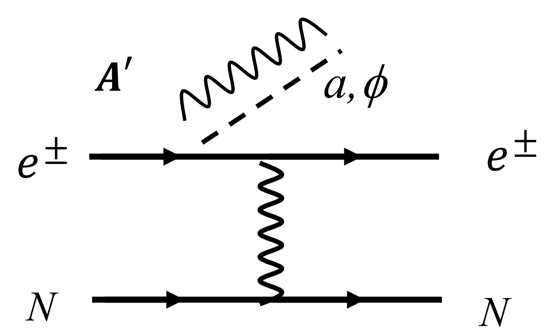
Associated



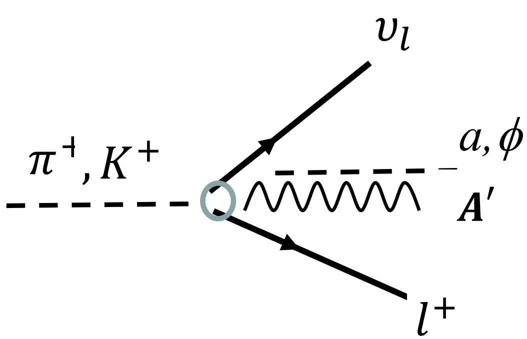
Resonance



Bremsstrahlung



New physics at ν experiments



PHYSICS REPORTS No. 3 (1962) 151-21)5.
Bandyopadhyay, Ghosh, Roy, PRD 105 (2022) 11, 115039.

Form factor uncertainties associated with $\pi \rightarrow l_{\nu l} A'$ decay mode, Khodjamirian, Wyler, hep-ph/0111249

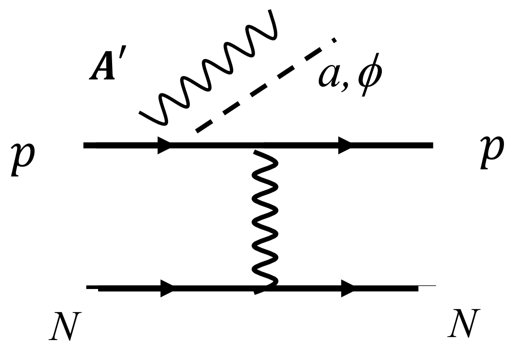
$$L \supset -g_{\phi(a)ff}\bar{f}(i\gamma^5)f\,\phi(a) - g_{A'ee}\bar{f}\,\gamma^\mu f\,A'_\mu$$

- *Charged meson decay: quarks and lepton couplings*
  - ➢ Not helicity suppressed ➔ both electron and muon final states contribute
  - ➢ Needs to include all the internal bremsstrahlung diagrams IB_i (i=1,23)
    - Satisfy the experimental constraint from **PIENU** (pions) and **NA62**(Kaons)

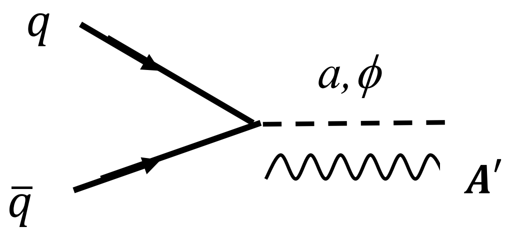
$\eta^0, \pi^0 \rightarrow \gamma A'_\mu$ *Neutral meson decays*

- ➢ Charged pion contribution can be larger than the neutral pion even without the focusing horns
- ➢ Important for stopped pion and mesons decay-in-flight experiments

New physics



Proton bremsstrahlung

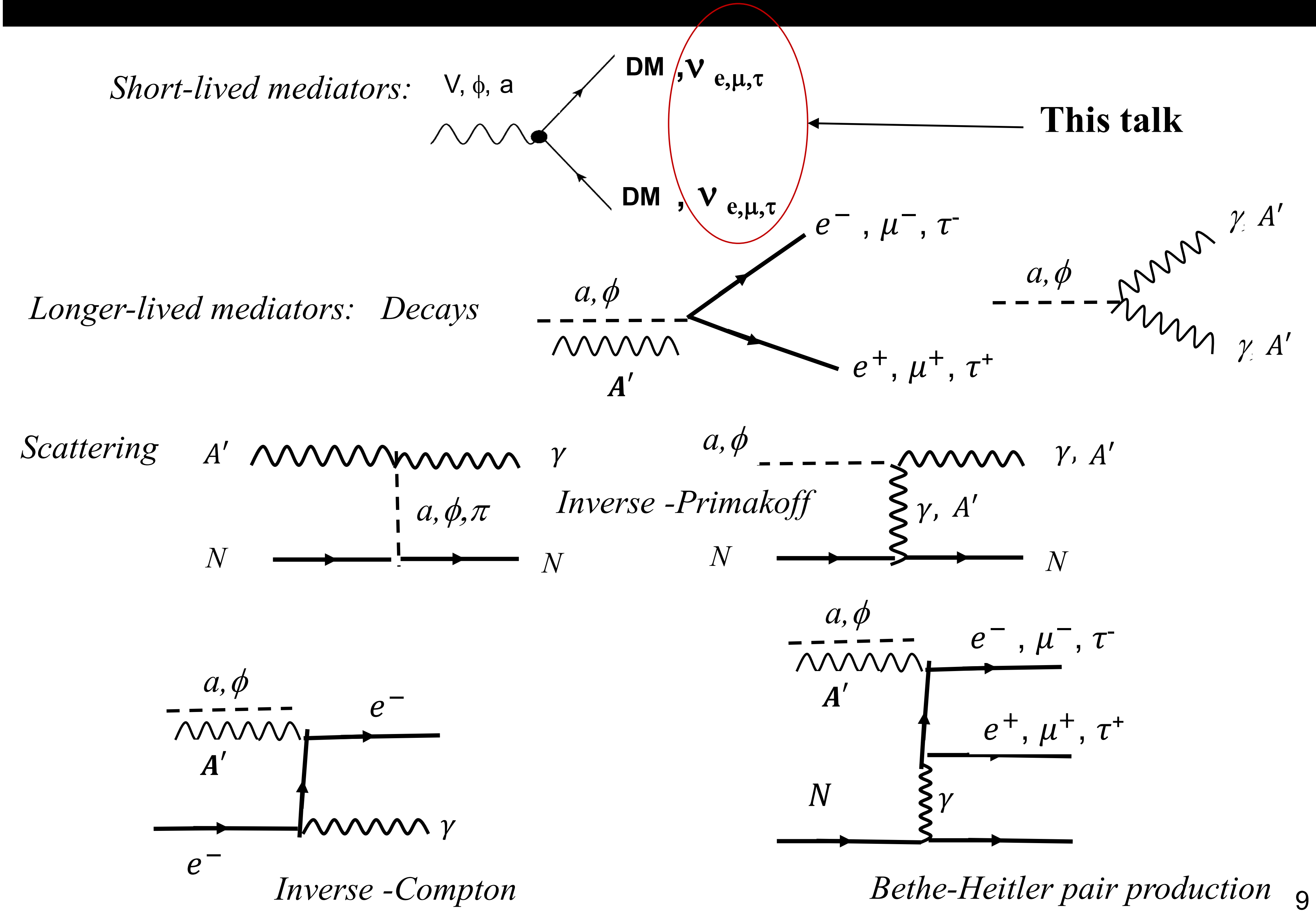


Parton interactions

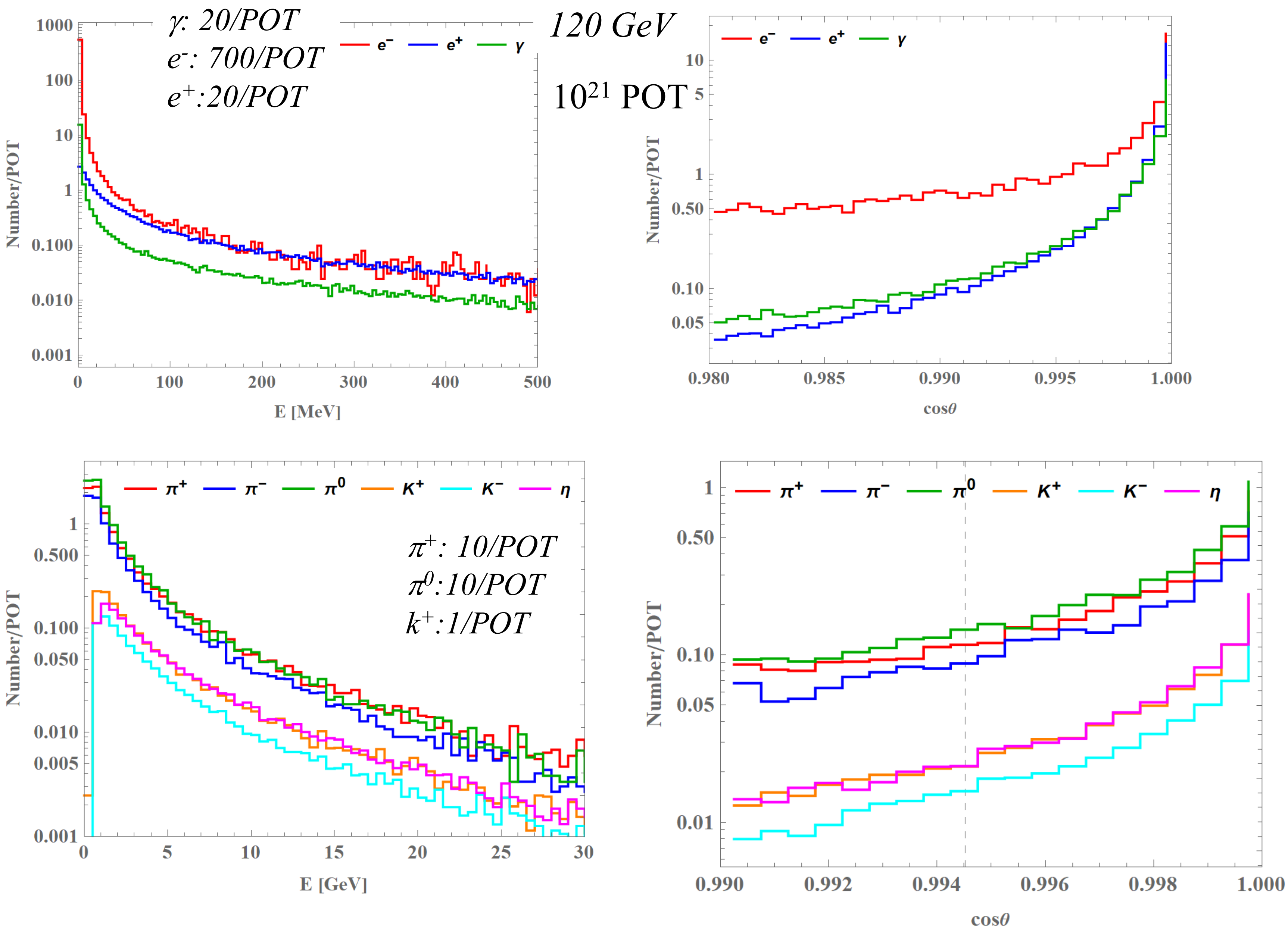
- There can be more production processes, e.g., $\nu + N \rightarrow \nu_s + N$ (coherently enhanced) using $\bar{\nu}_s \sigma_{\mu\nu} F^{\mu\nu} \nu$
- Nuclear de-excitation lines at lower mass target (lower beam energy)
- **Neutrons can be used: Bremsstrahlung, neutrons on target: light mediators**

Dev, Dutta, Han, Karthikeyan, Kim, Kim, 2311.10078

Final states

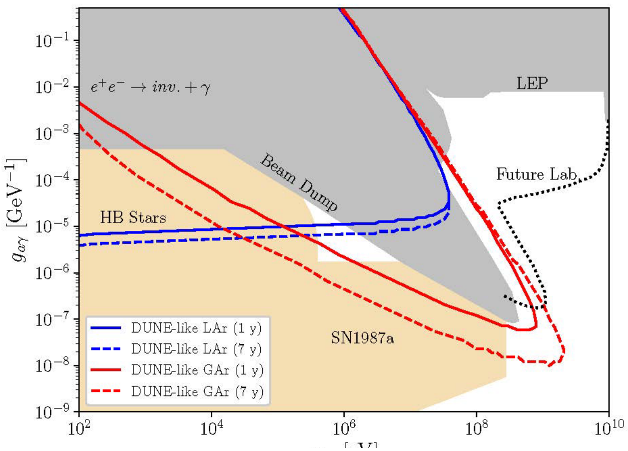


Various flux spectra at DUNE



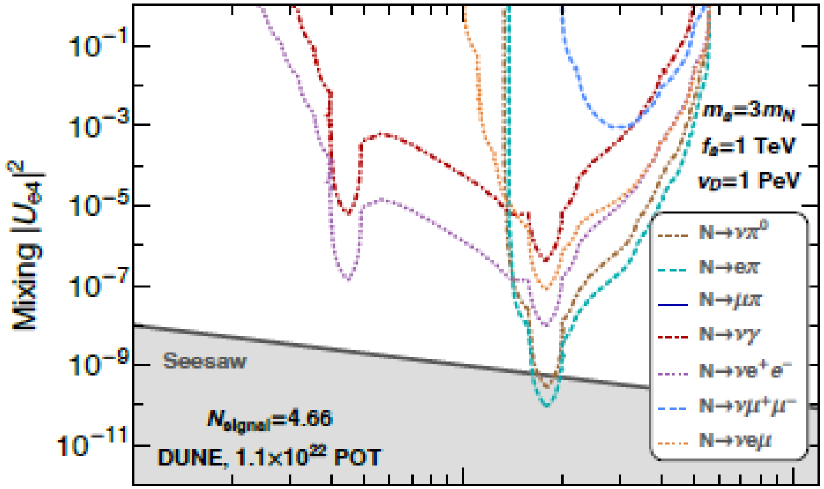
Example: DUNE, ICARUS…

ALP at DUNE using photon, electron/positron flux

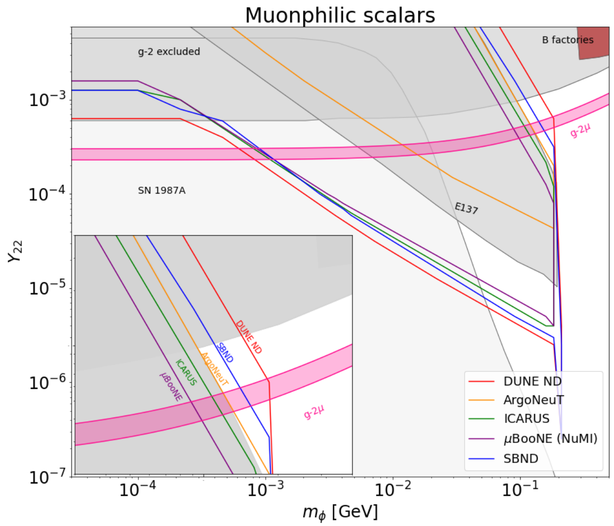


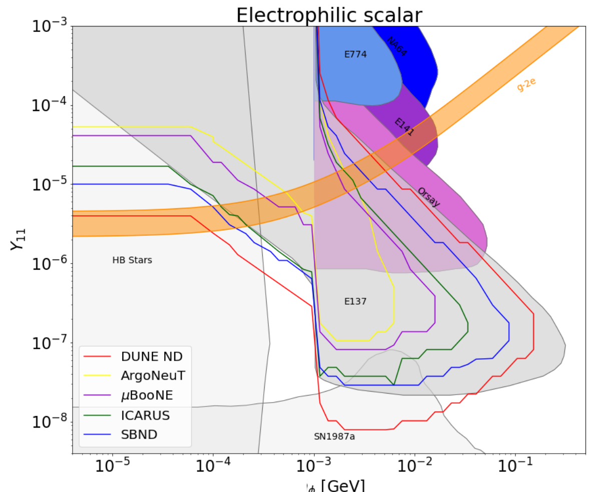
Brdar, Dutta, Jang, Kim, Shoemaker, Tabrizi, Thompson, Yu, Phys.Rev.Lett. 126 (2021) 20, 201801

HNLs via dark pions



Abdullah, De Gouvea, Dutta, Shoemaker, Tabrizi, arXiv:2311.07713





Dutta, Karthikeyan, Kim, 2308.01491

ν_τ final states

$$\mathcal{L}_{int} \supset \sum_f g_V x_f A'_\mu \bar{f} \gamma^\mu f$$

$$A' \to \nu_\tau \bar{\nu}_\tau$$

	DUNE	ICARUS-NuMI
Beam energy	120 GeV	120 GeV
Dist. to dump	204 m	715 m
Dist. to detector	575 m	800 m
Detector angle	On axis	$\sim 6^\circ$
Active volume ($w \times h \times l$) [m^3]	$3 \times 4 \times 5$	$2.96 \times 3.2 \times 18$ ($\times$ 2 modules)

A' productions: Charged mesons, neutral mesons, proton, neutron bremsstrahlung

(ν_τ-optimized mode can produce more events through charged mesons*)*

- ν_τ produces τ via charged current interactions
- τ leptons can be detected via hadronic (mesons), leptonic final states (e, μ etc.)

τ decay modes

Decay mode	Branching ratio (%)
$\pi^- \pi^0 \nu_\tau$	25.49
$e^- \bar{\nu}_e \nu_\tau$	17.82
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.39
$\pi^- \nu_\tau$	10.82
$\pi^- 2\pi^0 \nu_\tau$	9.26

Background

- $\nu_\mu \rightarrow \nu_\tau$ *oscillation*

$$P_{\mu\to\tau} = \sin^2(2\theta_{23})\sin^2\left[1.27\frac{\left(\frac{\Delta m^2_{23}}{\text{eV}^2}\right)\left(\frac{L}{\text{km}}\right)}{E/\text{GeV}}\right]$$

- *D mesons decays:* $B(D^+ \to \tau^+\nu_\tau) = (1.2 \pm 0.24) \times 10^{-3}$

Negligible number of ν_τ

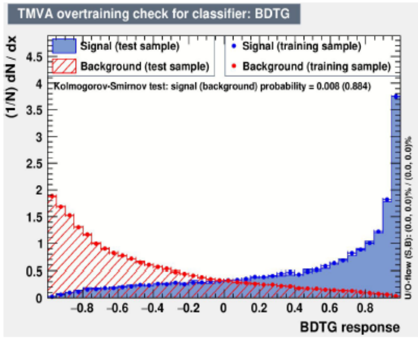
Berryman, de Gouvea, Fox, Kayser, Kelly, Raaf, JHEP 02 (2020) 174

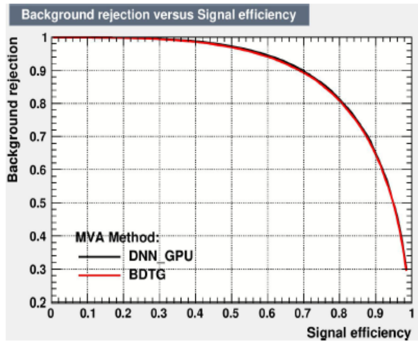
- Hadronic final states: background due to neutral current
- Leptonic final states: charged current

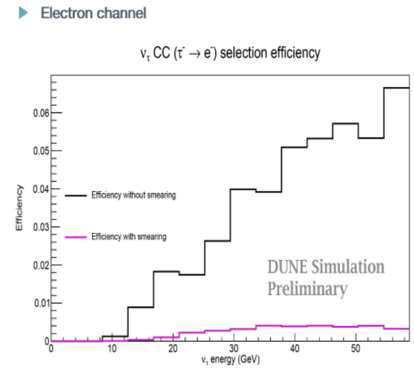
➢ Misidentification is a problem

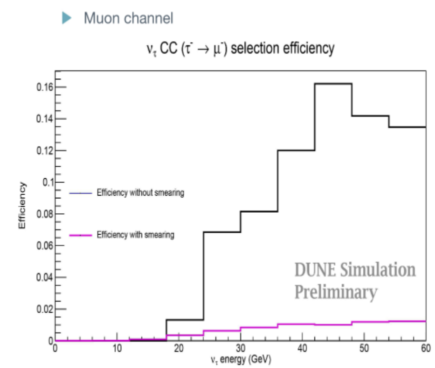
➢ What would be the signal detection efficiencies for τ–> e, μ, hadron final states?

Background







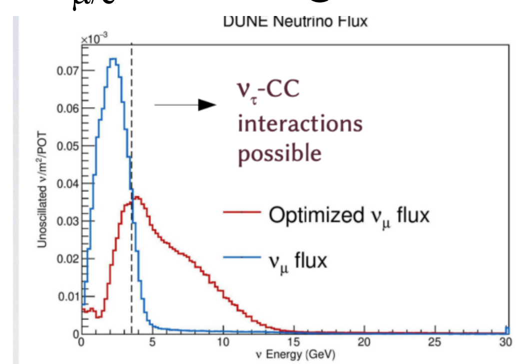


Reasonable separation of the ν_τ CC from their main backgrounds.

ND ν_τ studies, H. Razafinime, A. Sousa, 2022, B, Yaeggy Alvarez's talk

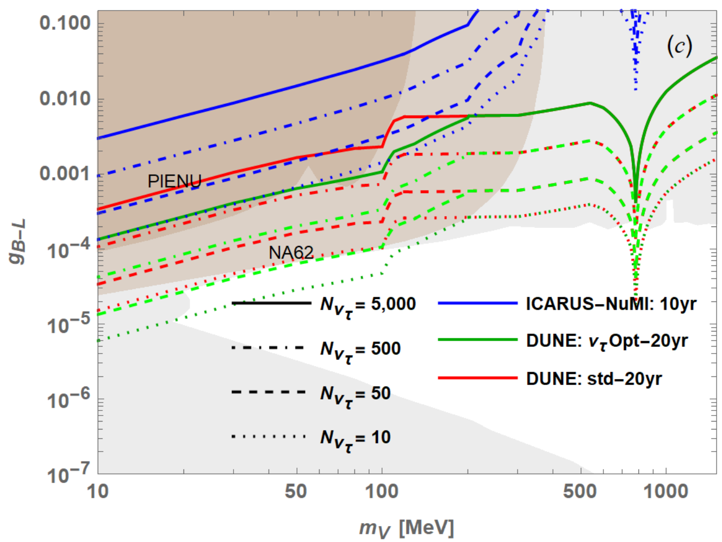
- Investigation of ν_τ -identification and related backgrounds in all three major τ -decay channels utilizing multivariable analysis, machine-learning techniques + additional event information from the SAND detector in the ND complex [ongoing]
- The level of hadronic activities induced by ν_τ scattering vs. $\nu_{\mu/e}$ scattering can be a good discriminator.
- The τ tagging and background rejection efficiencies perform better with increasing energy ➔ measurements in the ν_τ -optimized mode

➢ ν_τ from charged pion decays will benefit from this configuration

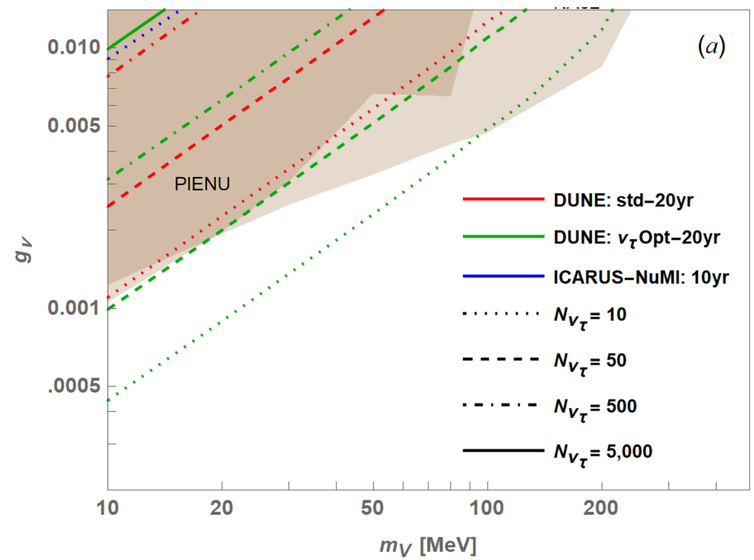


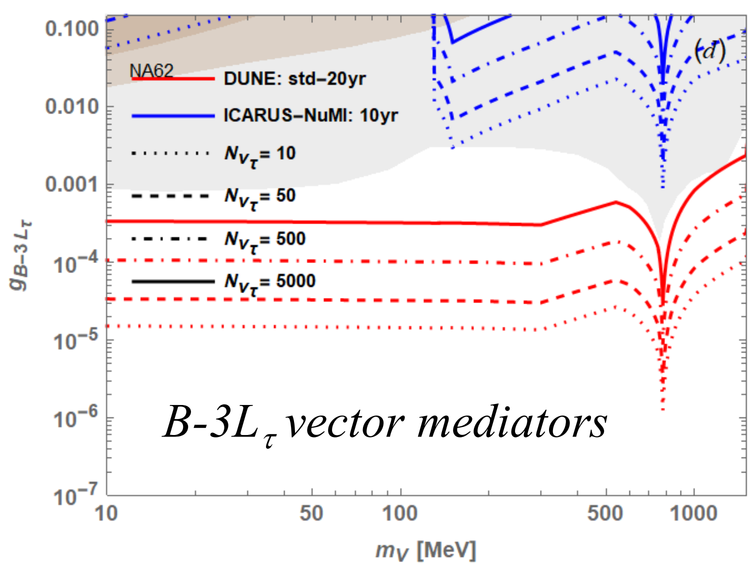
Various Models

B-L vector mediators



ν-philic mediators





$U(1)_{B-3L_\tau}$: J. Heeck, M. Lindner, W. Rodejohann, and S. Vogl, Sci Post, 2019

Similar parameter space also exists for $U(1)_{T3R}$ model

Dutta, Ghosh, Kumar, PRD2019

Dev, Dutta, Han, Kim, 2304.02031 [hep-ph]

Outlook

- Light mediator models can explain various anomalies and puzzles
- M(new physics) < GeV is not easy to probe, e.g., LHC, direct and indirect detection experiments mostly probe M> GeV
- Various experiments provide interesting possibilities for searching low-scale models
- Light mediators can be produced using photon, electron-positron, mesons, protons, neutrons and neutrino fluxes
- Light mediators can be probed using tau neutrinos
- The probing can be difficult at the near detector