BSM w/wo neutrino
@ Neutrino Beam Facilities

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PITT-PACC Workshop: Nu Tools for BSM at Neutrino Beam Facilities

Introduction

- New Physics: Dark matter(DM), neutrino masses and mixing, baryon abundance and various anomalies, g-2 of muon, LHCb, 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, astrophysical observations etc.

- LHC is mostly probing scales above 1 GeV

Introduction

Investigation of scales below 1 GeV

- This region is difficult to search
- Anomalies, and puzzles can be addressed
- There are many new ideas

Models (Many ongoing activities):
Light mediators: scalar/pseudo-scalar, vector; sub-GeV DM

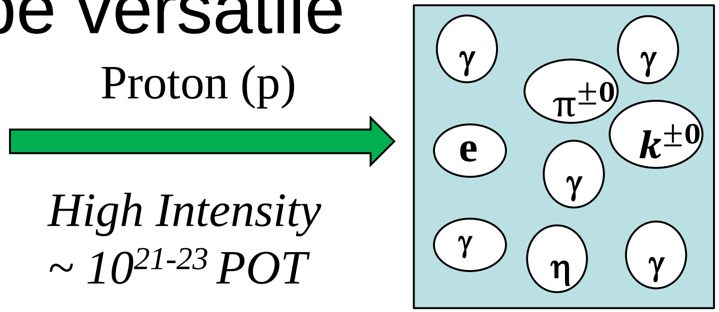
Low energy beam dump-based experiments, Forward physics facility at the LHC, Astrophysical observations, etc. can investigate low scale models

This talk will discuss: Exploration of various models at neutrino experiments: SBN and DUNE?

- High intensity beam, various production possibilities, large detectors, on/off axis coverages etc.

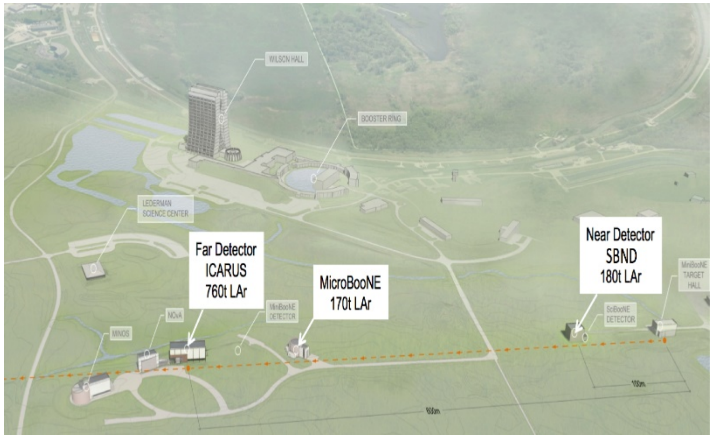
ν experiments

Neutrino experiments can be versatile

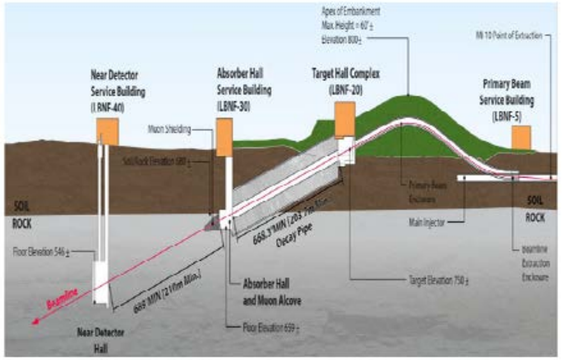


Beam dump-based (proton beam) [ongoing]: 800 MeV-3 GeV: COHERENT (Oakridge), CCM (LANL), JSNS2(JPARC) Detectors, CsI, LAr, NaI, Ge

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



DUNE (120 GeV)



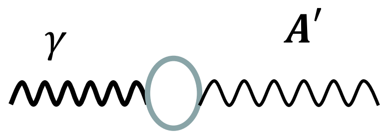
- Many experiments with proton beams have different beam energies using various detectors at different locations

- FASER, FASERν, SND are ongoing

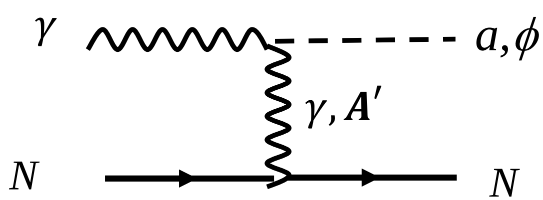
New physics at ν experiments

From γ:

A': Vector
ϕ=scalar
a=pseudo-scalar



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



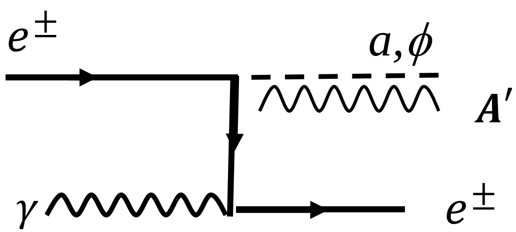
Primakoff

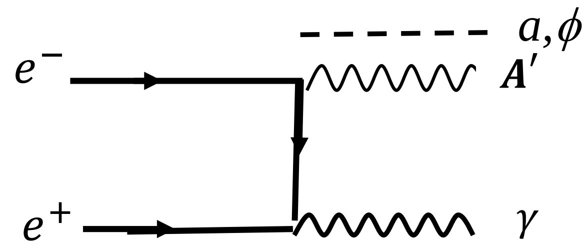
Coherent scattering for γ exchange

New physics at ν experiments

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

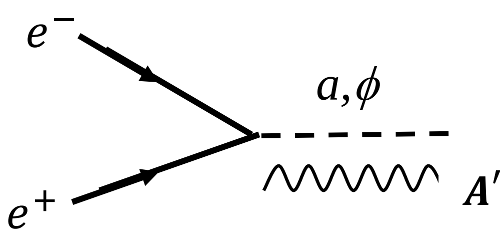
Compton

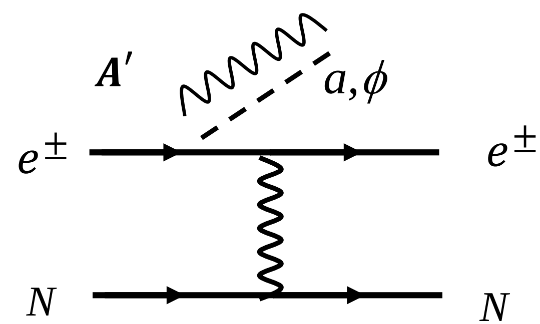




Associated

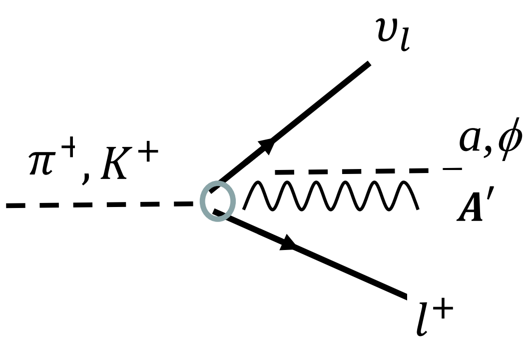
Resonance





Bremsstrahlung

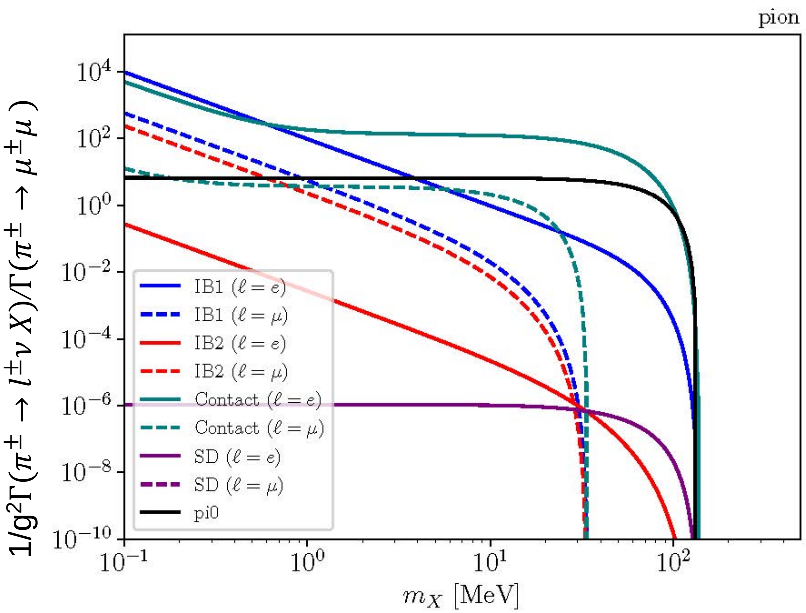
New physics at ν experiments



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

- *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)



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

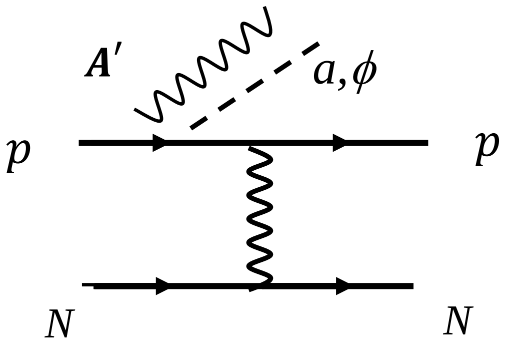
$\eta^0, \pi^0 \to \gamma A'_\mu$ *Neutral meson decays*

- Charged pion contribution can be larger than the neutral pion even without the focusing horns

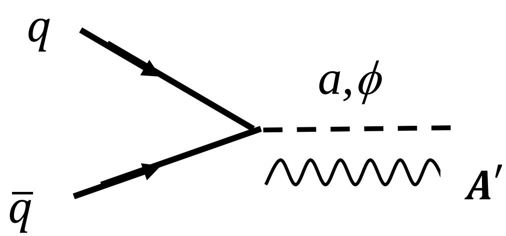
- Important for stopped pion and mesons decay-in-flight experiments

- *Satisfy the experimental constraint from* **PIENU and NA62***(Kaons)*

New physics at ν experiments



Proton bremsstrahlung



Parton interactions

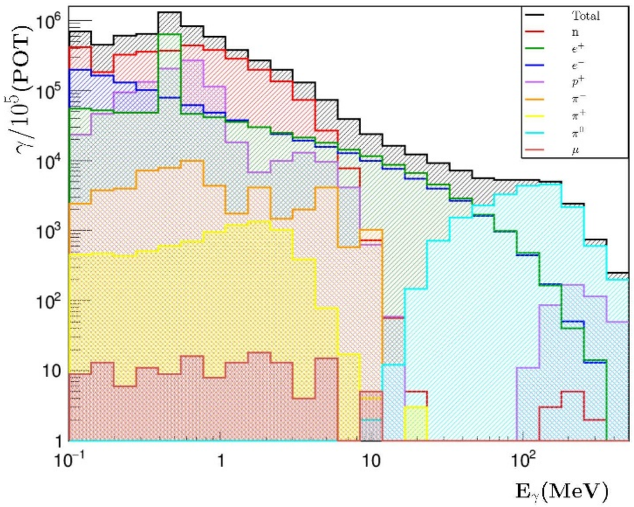
- There can be more production processes, e.g., $\nu + N \rightarrow \nu_s + N$ (coherently enhanced) using $\bar{\nu}_s \sigma_{\mu\nu} F^{\mu\nu} \nu$

- Nuclear de-excitation lines at lower mass target (lower beam energy)

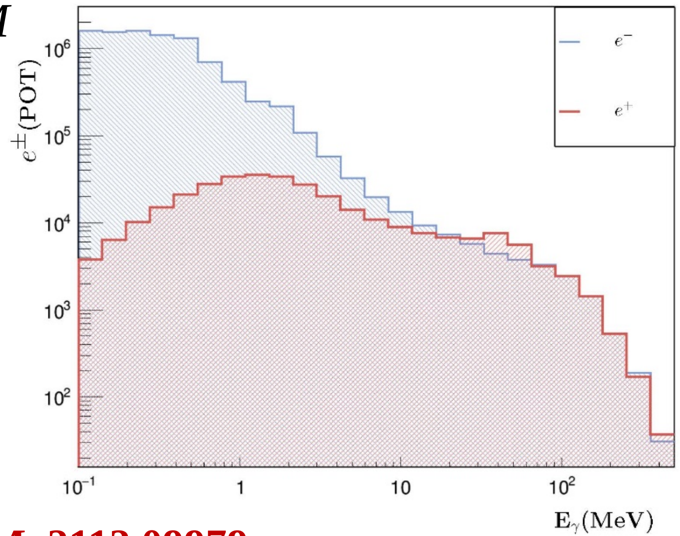
Waites, Thompson, Bungau, Conrad, Dutta, Huang, Kim, Shaevitz, Spitz, :2207.13659

Various flux spectra at ν experiments

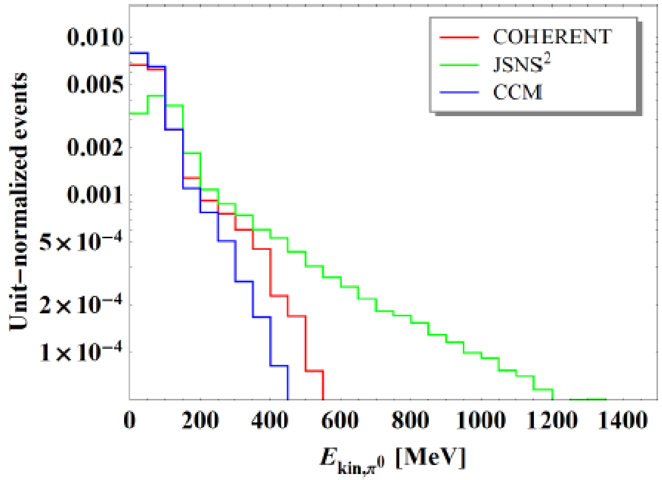
CCM/COHERENT: 0.1 π^+ per proton: $10^{22/23}$ POT, π^+ s are stopped



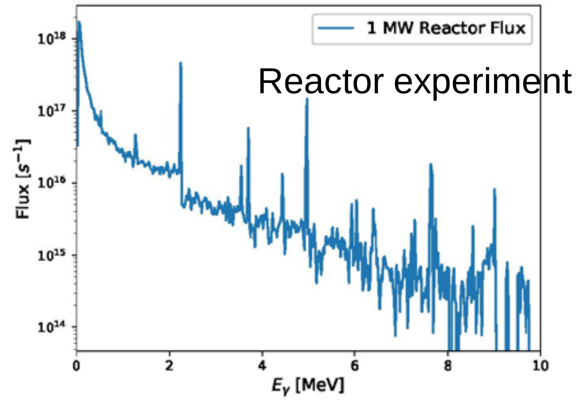
CCM



CCM, 2112.09979

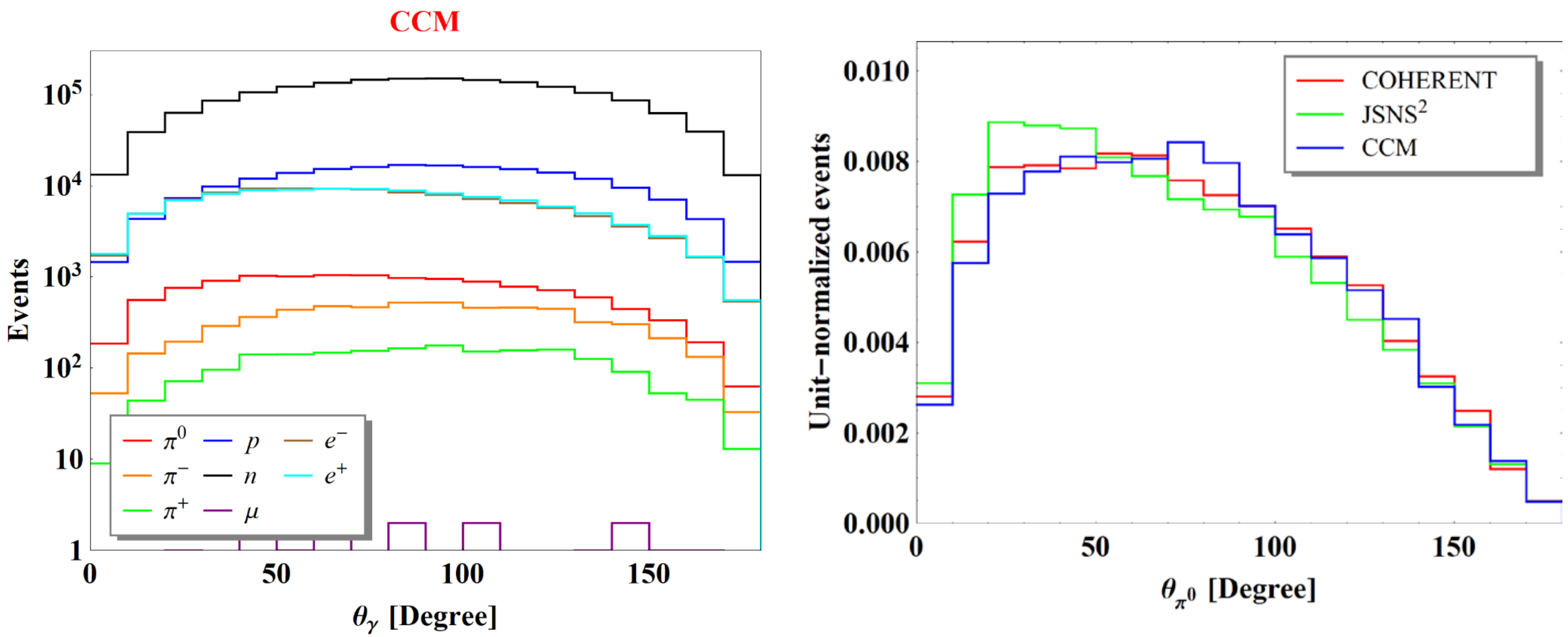


GEANT4, 10.7, QGSP_BIC_HP



Dutta, Kim, Liao, Park,Shin,Strigari, Thompson, JHEP 01 (2022) 144

Various flux spectra at ν experiments



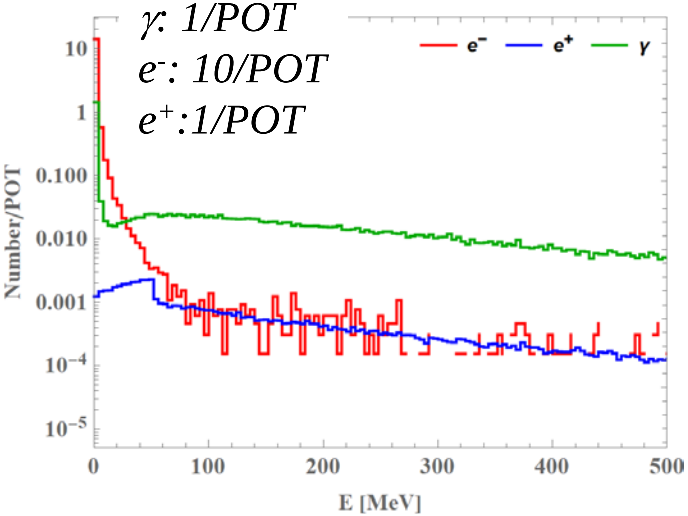
Photon, electron/positron, charged pion flux are isotropic for CCM/COHERENT/JSNS²

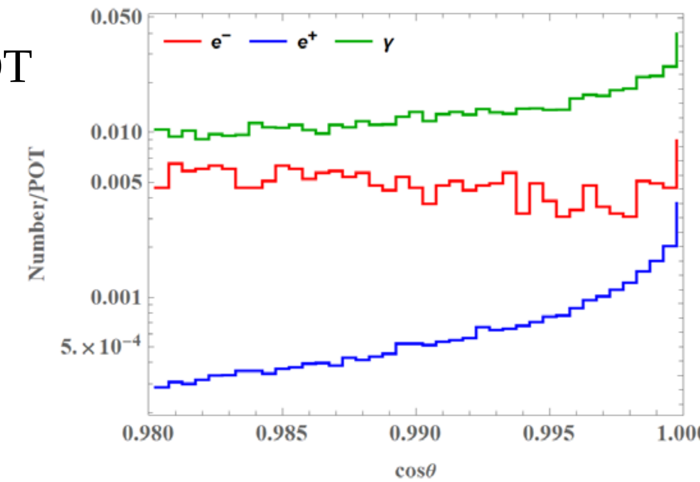
Dutta, Kim, Liao, Park,Shin,Strigari, Thompson, JHEP 01 (2022) 144

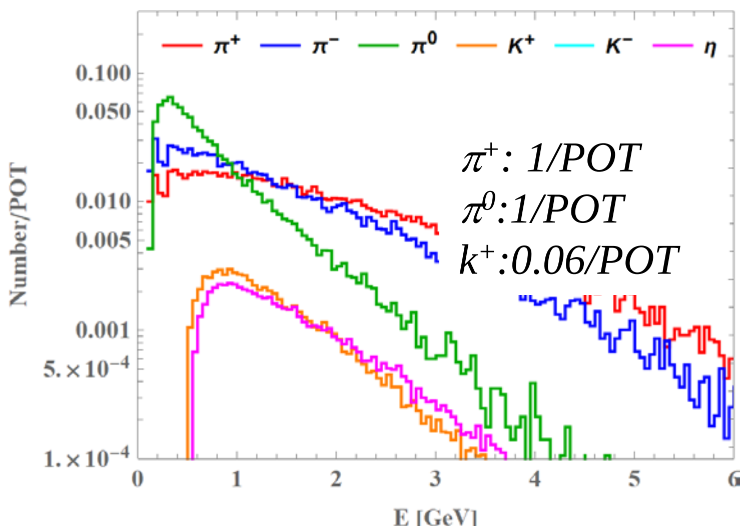
Various flux spectra at BNB

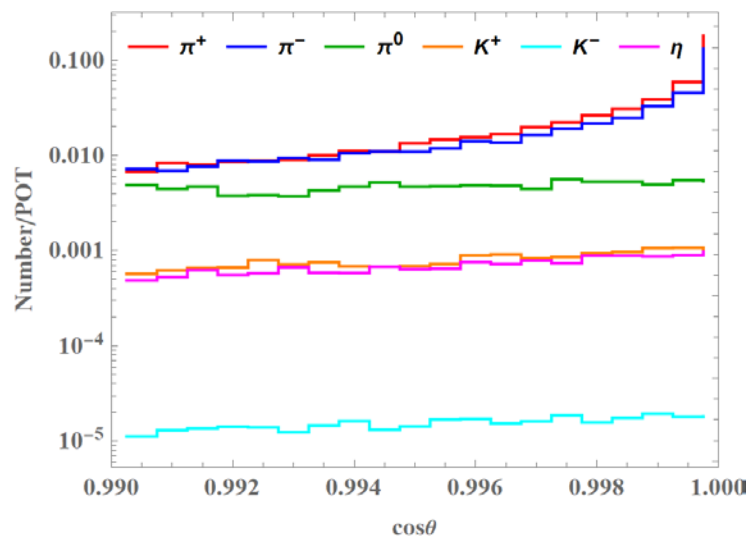
8 GeV beam

10^{21} POT





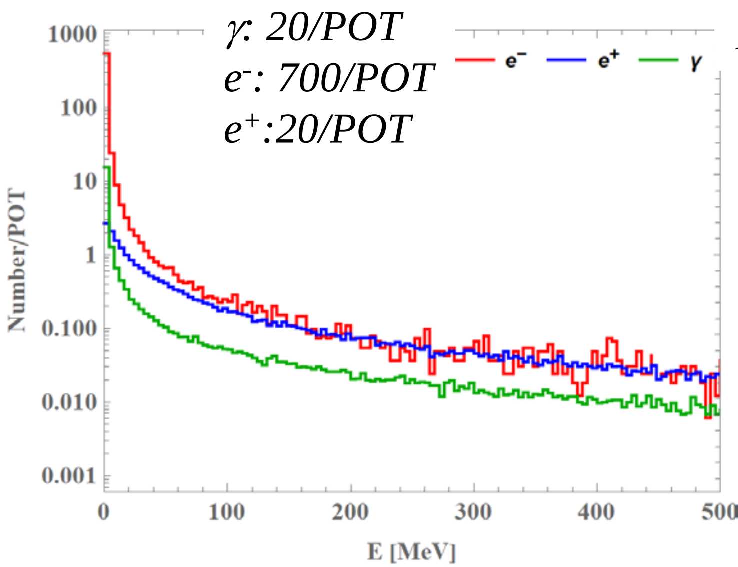


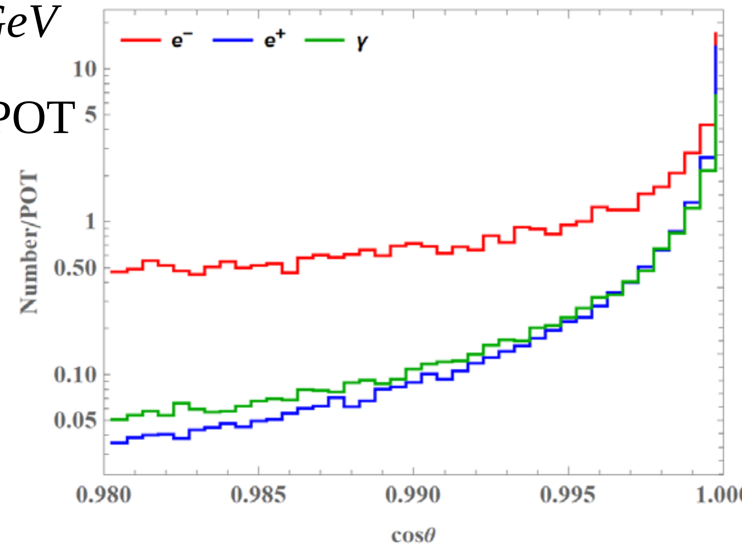


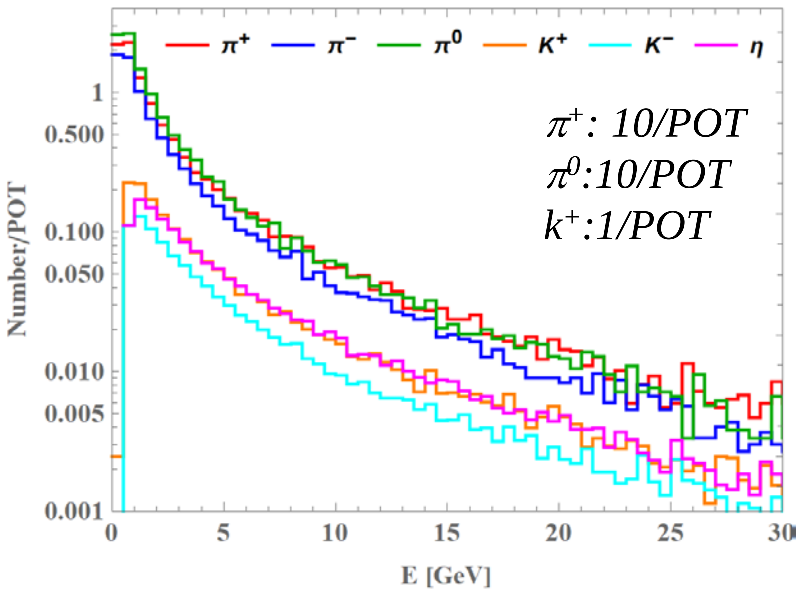
Due to the magnetic horns, charged meson flux will be enhanced in the beam direction

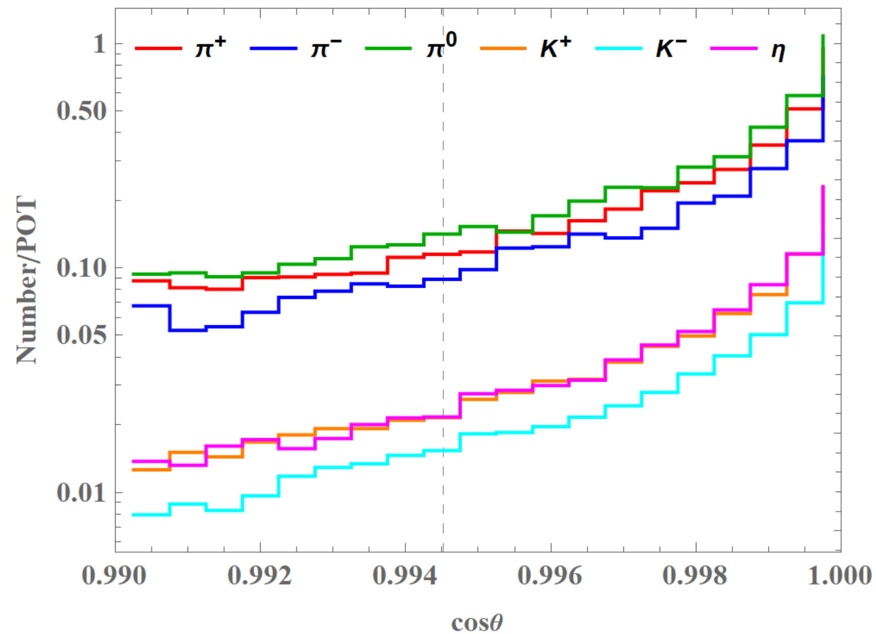
Doojin's talk

Various flux spectra at DUNE

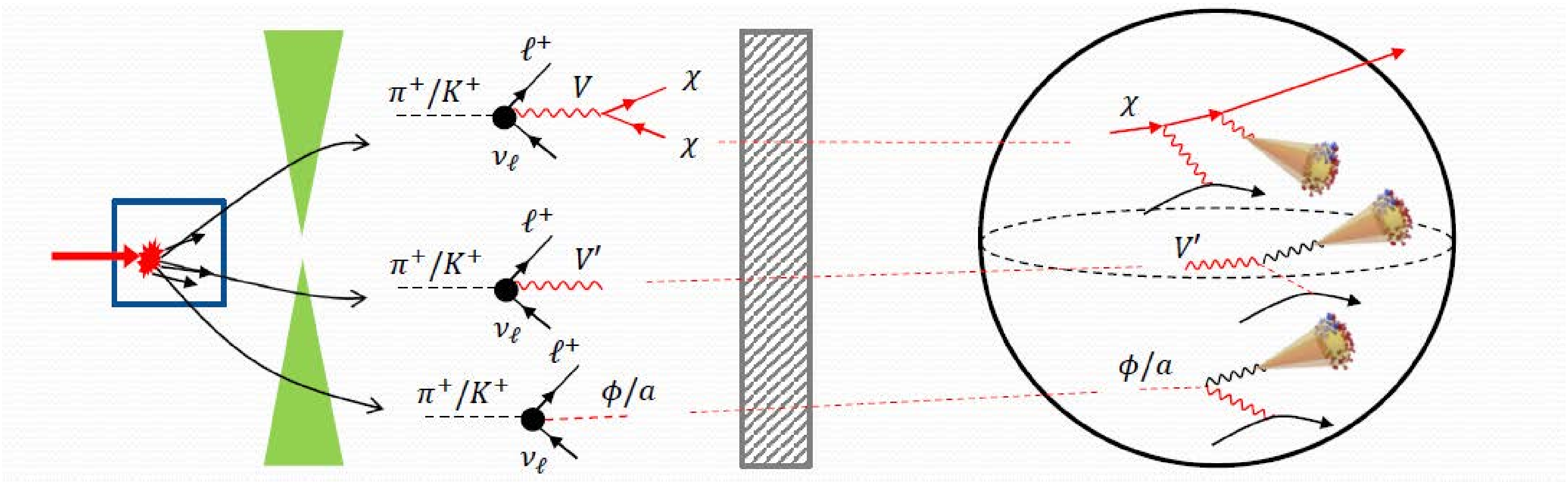








Focused flux spectra at DUNE/BNB



- More charged mesons in the direction of the detector

Adrian's talk
Doojin's talk

- Charged pion/neutral pion ~ 10: BNB; DUNE (This ratio allows the dark sector model to explain the MiniBooNE excess while satisfying the dump result)➔implications for models

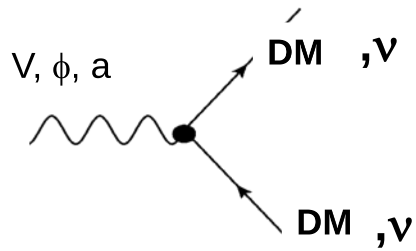
Dutta, Kim, Thompson, Thronton,Van de Water Phys.Rev.Lett. 129 (2022) 11, 111803

- Charged pion/neutral pion ~ 1 : Stopped pion experiments

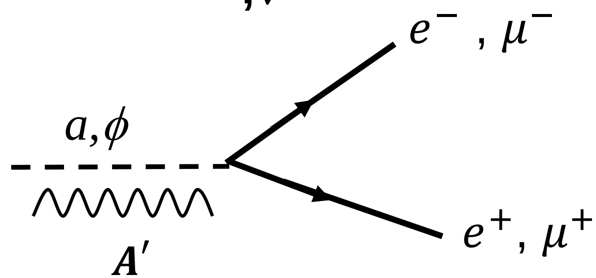
- Charge meson distributions (in decay volume) is important for BSM model contributions

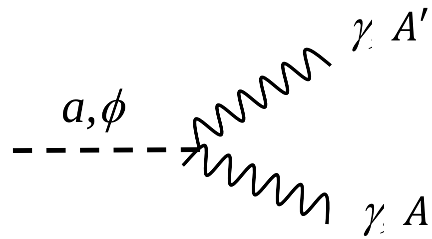
Final states at DUNE/BNB

Short-lived mediators:

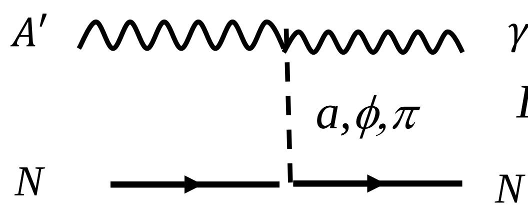


Longer-lived mediators: *Decays*

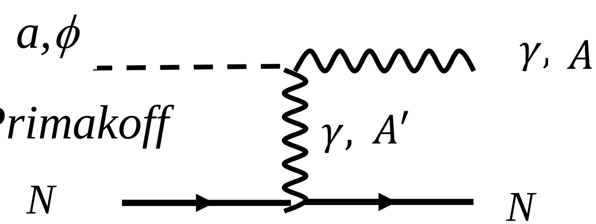


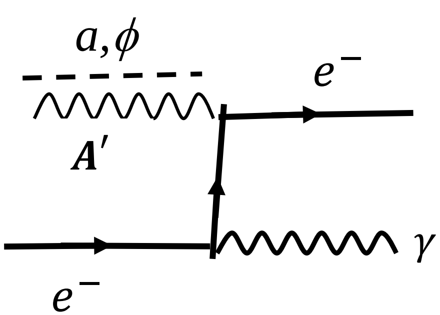


Scattering

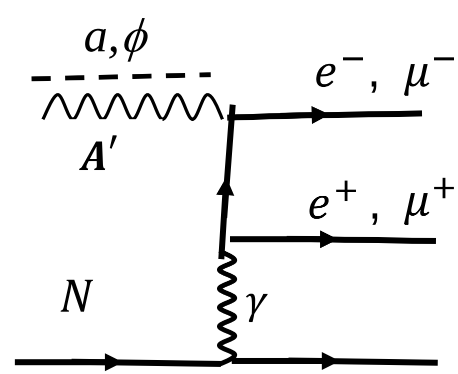


Inverse -Primakoff





Inverse -Compton



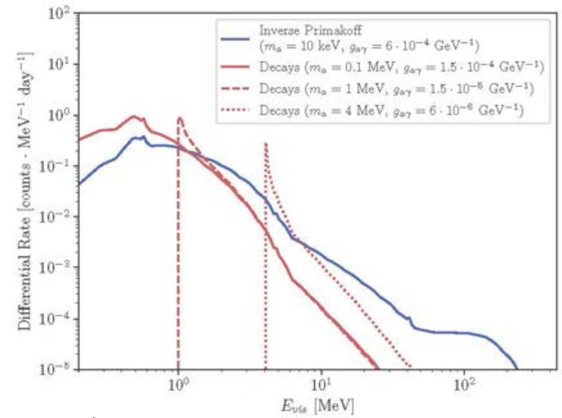
Bethe-Heitler pair production

Example: ALP at CCM

- $\gamma, e^{\pm}$ fluxes, Primakoff/Compton productions, inverse Compton/Primakoff, decays final states are used by CCM(LANL) to explore new physics

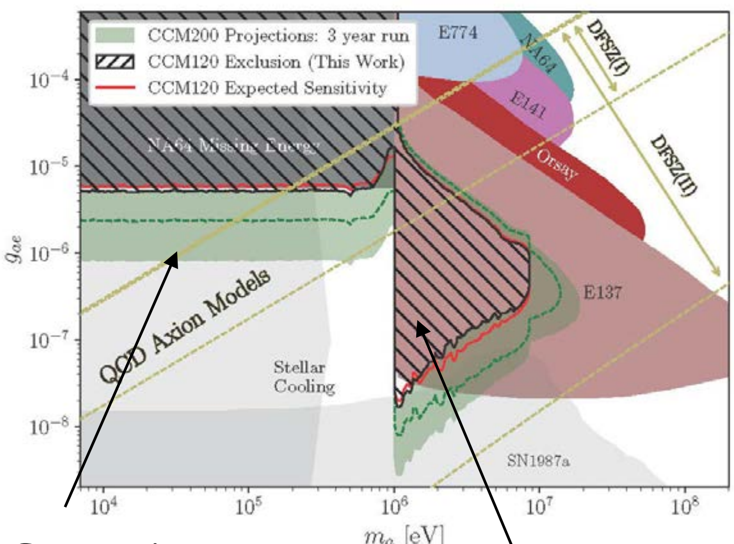
- CCM established the feasibility of searching for new physics in the MeV region ➔1-100 MeV

CCM, 2112.09979



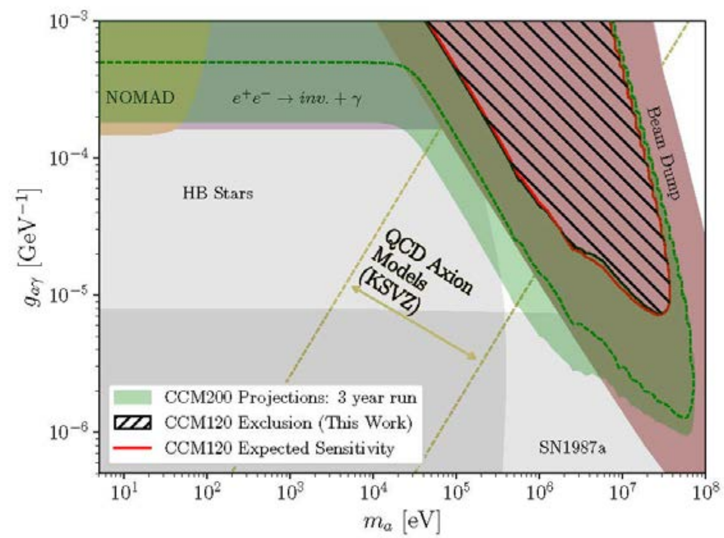
$$L \supset - -g_{a,\phi\gamma}\frac{a}{4}F^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$L \supset -g_{aee}\bar{e}\,(i\gamma^5)ea$$

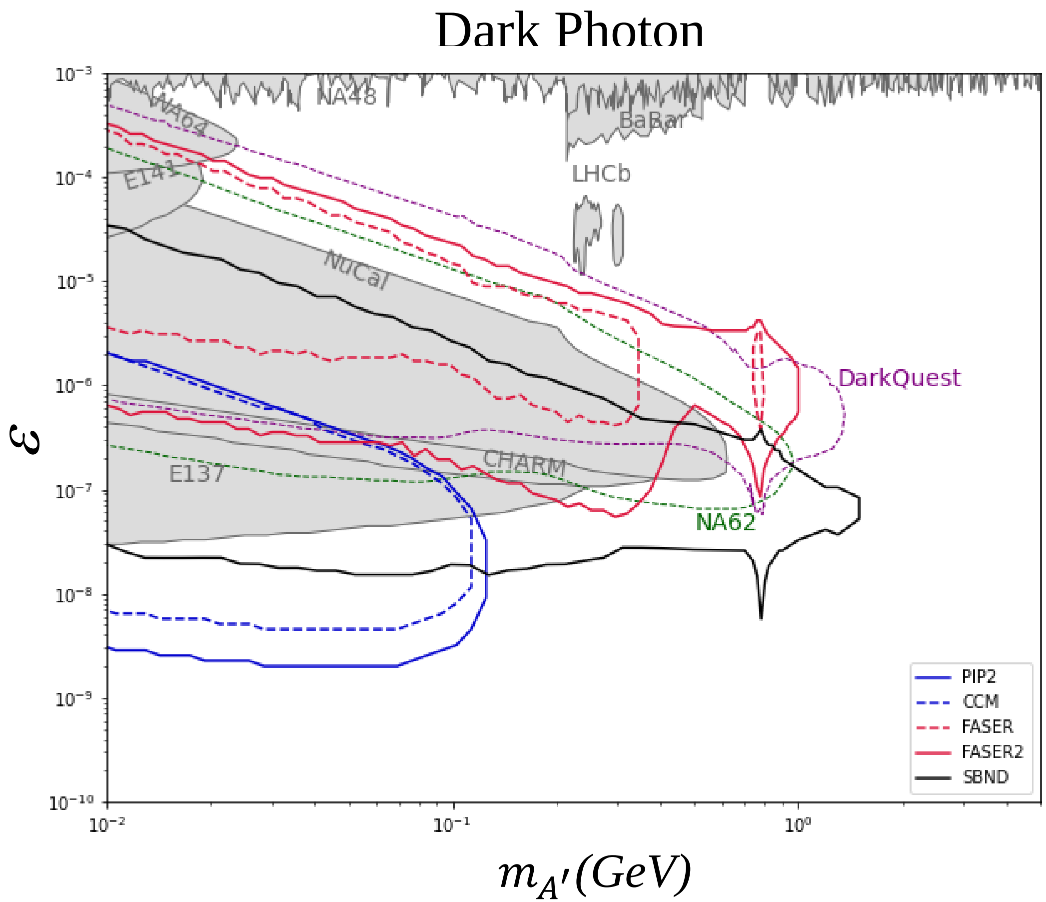


Scattering

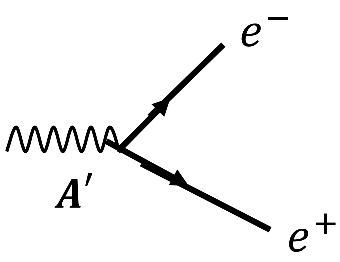
Decay



Example: SBND



Decay final states



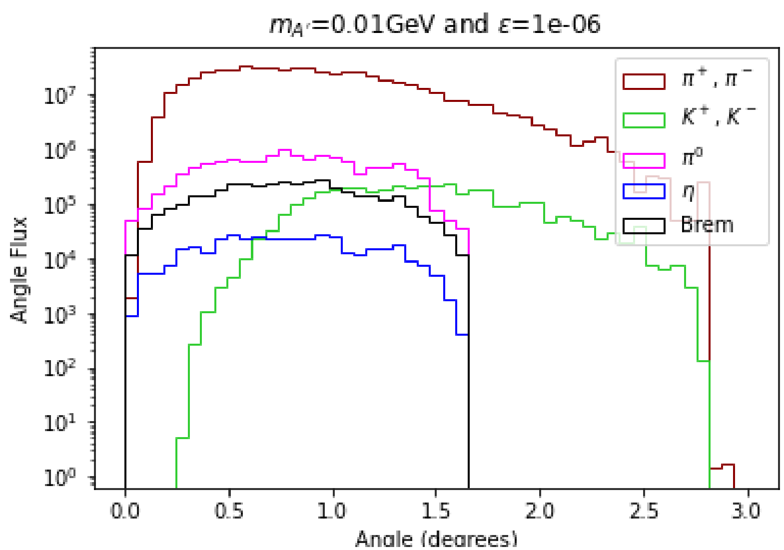
Scattering final states (ongoing)

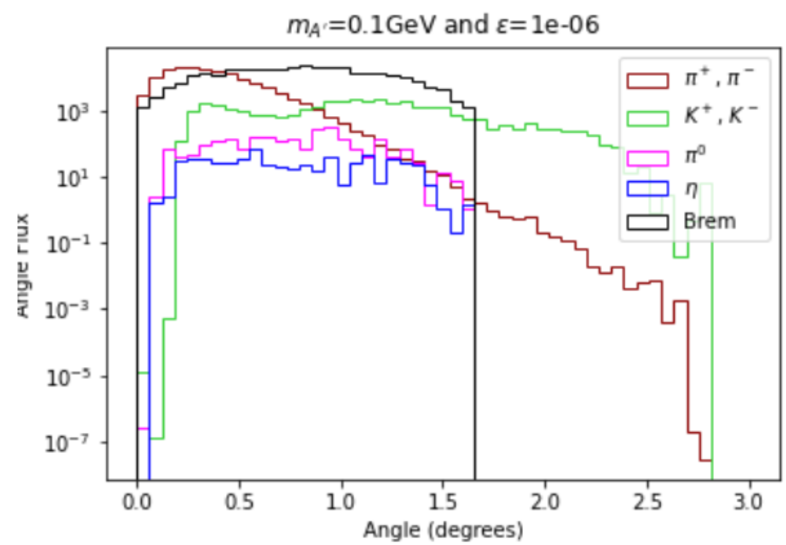
ılasubramanium, Dutta, Coyle, Kim, ırthikeyan, Pandey, Palamara, SchuKraft

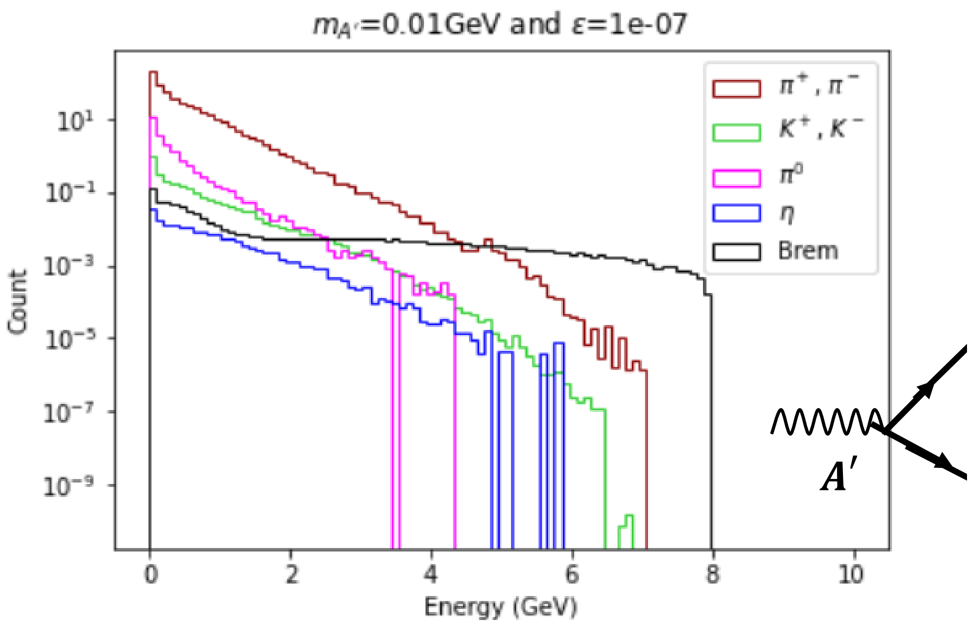
Productions involve: Charged and neutral meson decays, protons, electron/positron flux induces bremsstrahlung and various other production processes

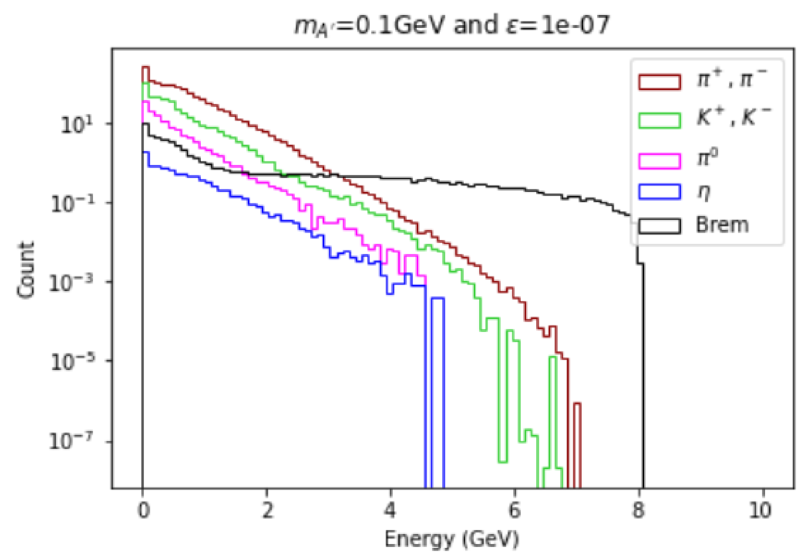
Example: SBND

A'



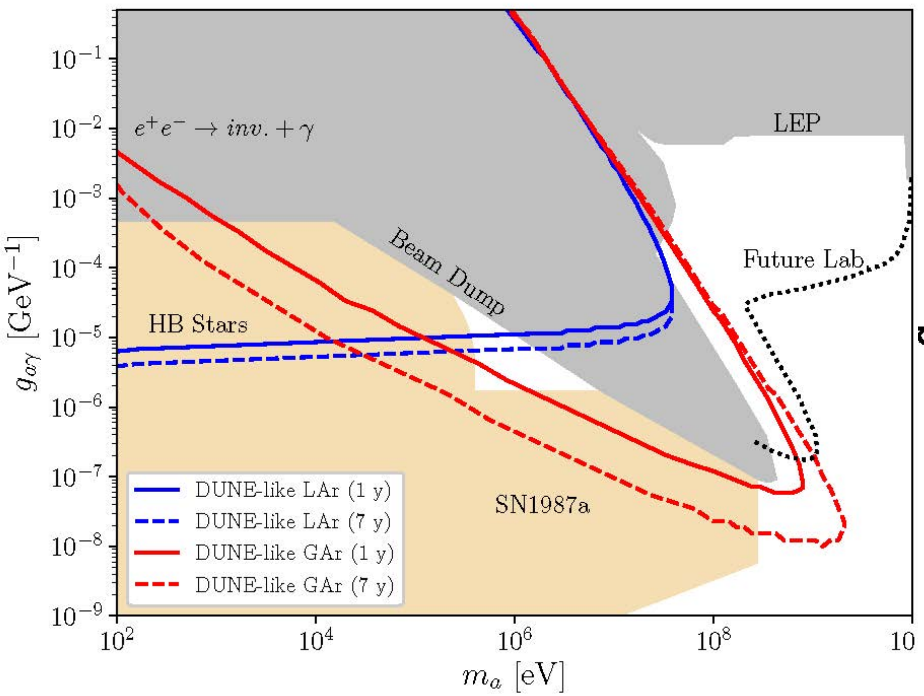


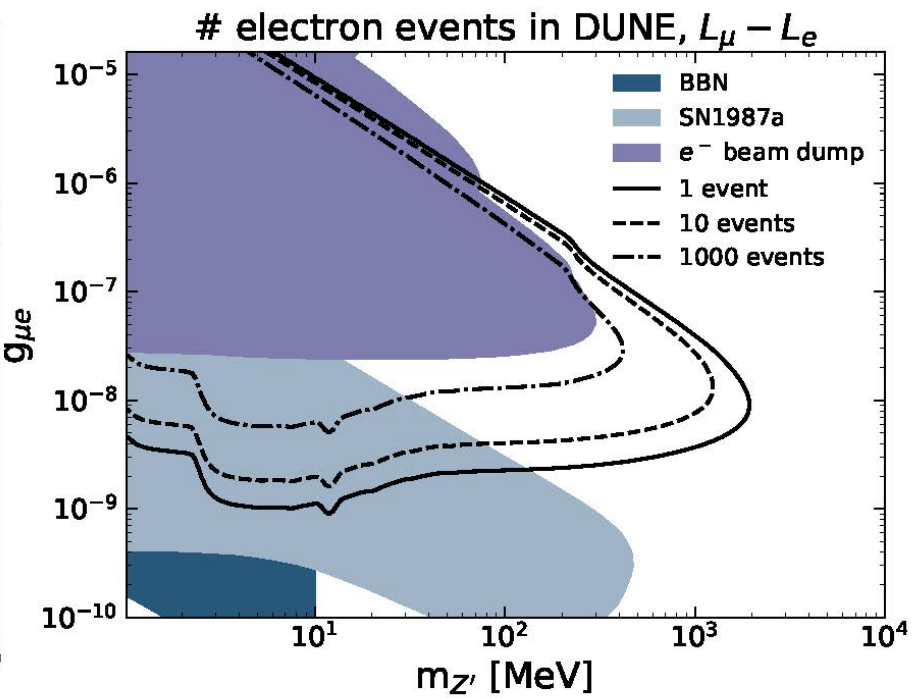




Balasubramanium, Dutta, Coyle, Kim, Karthikeyan, Pandey, Palamara, SchuKraft

Example: DUNE





$$L \supset -\bar{e}\, \gamma^\mu e\, A'$$

ALP at DUNE using photon, electron/positron flux

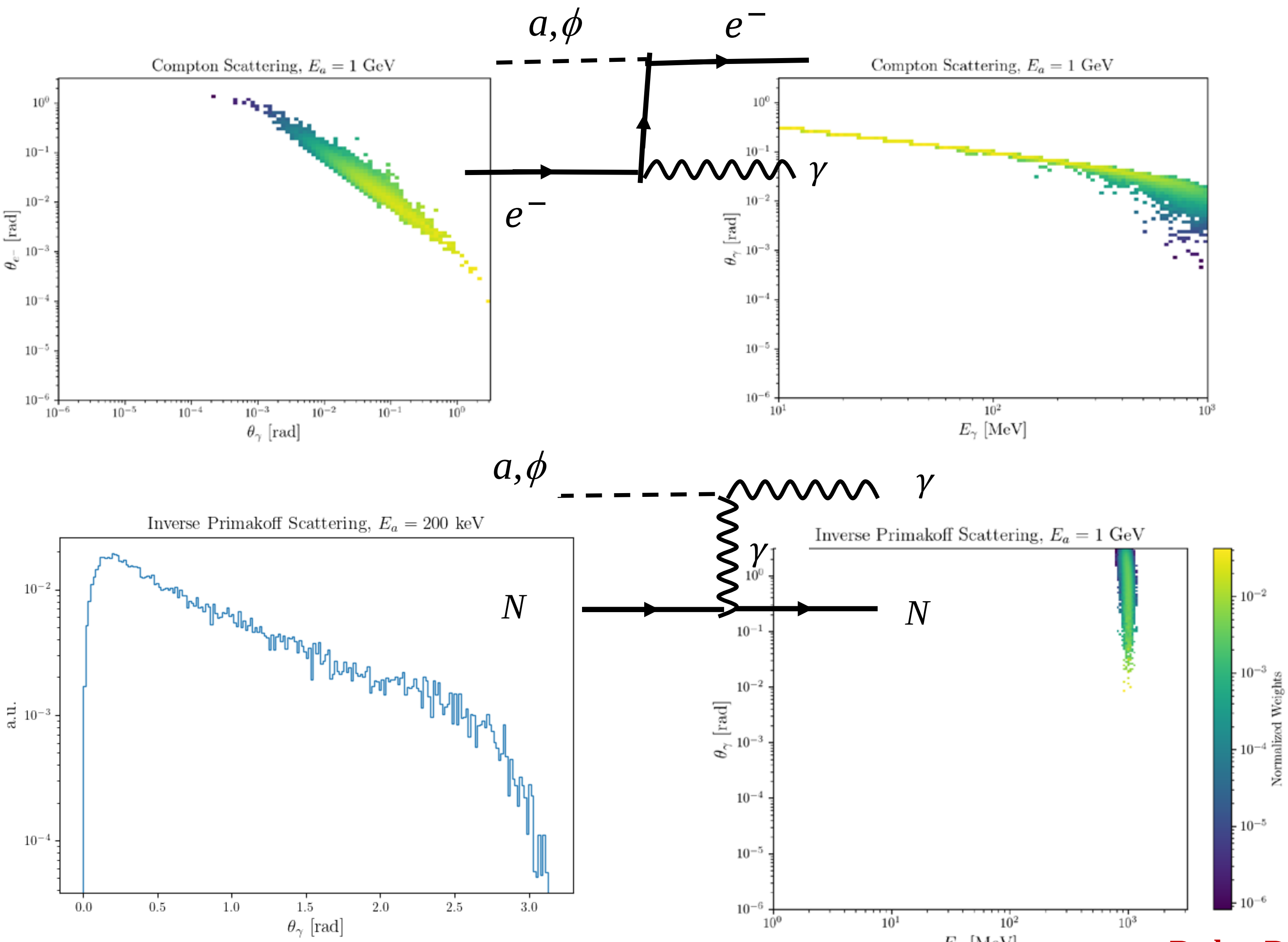
(includes scattering and decay)

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

Z' at DUNE using photon, electron/positron flux [bremsstrahlung + resonance] (includes decay)

Capozzi, Dutta, Gurung, Jang, Shoemaker, Thompson, Yu, Phys.Rev.D 104 (2021) 11, 115010

Example: DUNE

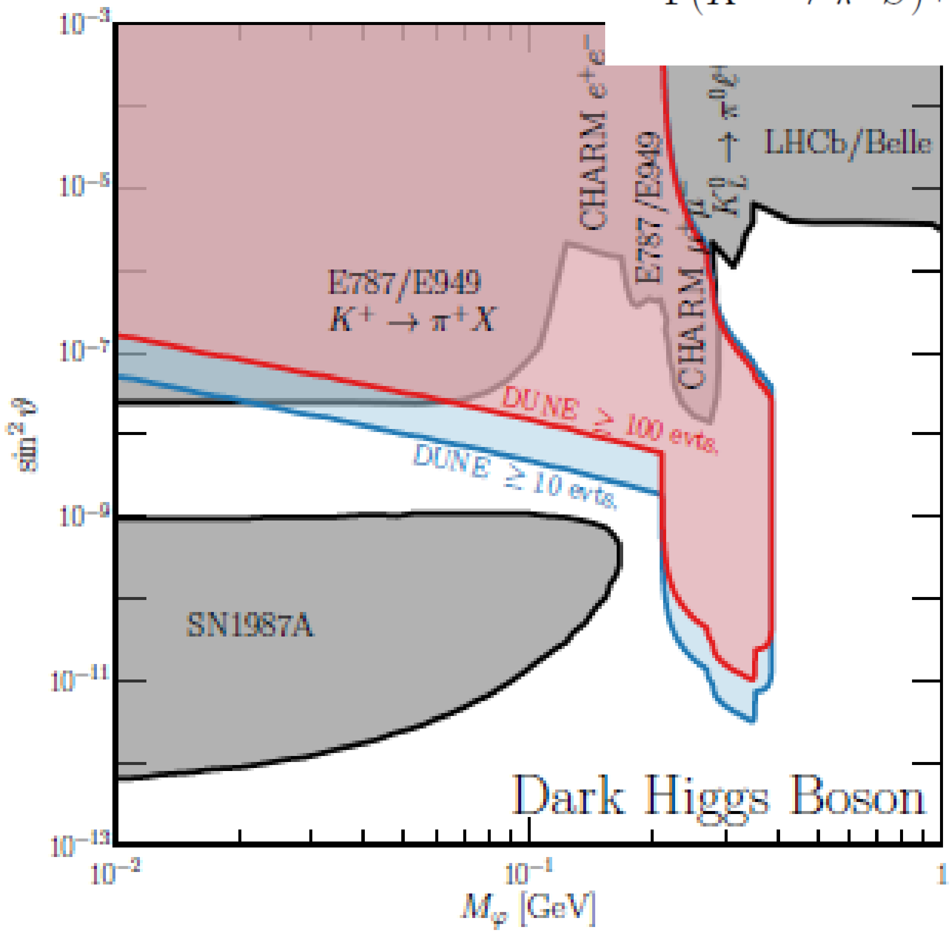


- *Correlation among different final observables*
- *ALP couplings, masses can be determined*

Brdar, Dutta, Kim, Shoemaker, Tabrizi, Thompson,Yu

Example: DUNE

$$\Gamma(K^\pm \to \pi^\pm S) \approx \frac{\sin^2\theta}{16\pi m_K}\left|\frac{3V_{td}^* V_{ts} m_t^2 m_K^2}{32\pi^2 v^3}\right|^2 \lambda^{1/2}\left(1, \frac{m_S^2}{m_K^2}, \frac{m_\pi^2}{m_K^2}\right)$$



Using $K^\pm \to \pi^\pm\phi$

$\phi \to l^+l^-, \pi^+\pi^-$

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

Model Varieties

High intensity sources allow us to probe many new physics mediators!

- Quark couplings: meson decays (charged and neutral), proton brem, Parton interactions,
  Detection: scattering, decays
  → $U(1)_B$, $U(1)_{B\text{-}L}$, $U(1)_{T3R}$, QCD axion, Scalar quark couplings
- *Electron couplings: electron bremsstrahlung, resonance, Compton, associated, charged meson decays,*
  Detection: Inverse Compton, BH pair production, decays
  → $U(1)L_e\text{-}L_{\mu,\tau}$, $U(1)_{B\text{-}L}$, $U(1)_{T3R}$, leptophilic scalar, pseudoscalar
- *Muon couplings: charged meson decays, muon brem*
  Detection: *BH muon pair production, decays*
  → $U(1)L_\mu\text{-}L_{e,\tau}$, $U(1)_{B\text{-}L}$, $U(1)_{T3R}$, muonphilic scalar, pseudoscalar
- *Photon couplings: photon flux, neutral meson flux,*
  Detection: *Scattering, decays*
  → $L \supset -\frac{\varepsilon}{4} F^{\mu\nu} F^{(\prime)}_{\mu\nu} - g_{a,\phi\gamma} \frac{(a,\phi)}{4} F^{\mu\nu} \tilde{F}_{\mu\nu}$
- *Neutrinophilic mediator: : charged meson decays, Detection: decays into* ν_τ

➔ *Complete models of ALP, U(1)' models, g-2 allowed parameter spaces, MiniBooNE explanation*

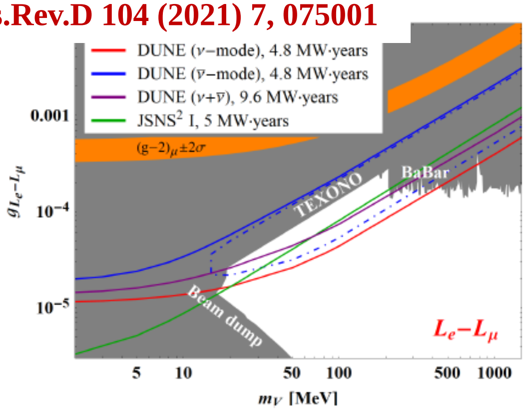
Model Varieties

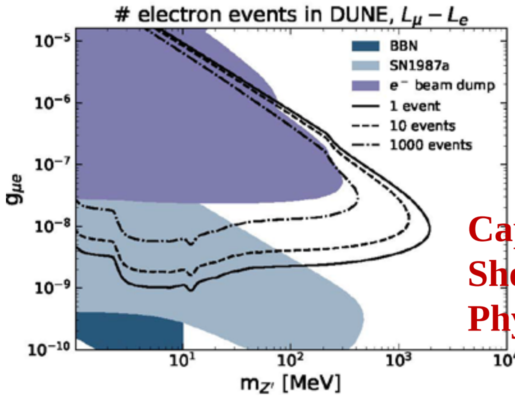
- Light mediators models with neutrino-quark/lepton interactions, e.g., $U(1)L_e$-$L_{\mu,\tau}$, $U(1)_{B-L}$ can also be probed by scattering at the detector(NSI search):

  $\nu + e,N \rightarrow \nu + e,N$ ➔ *Similar to SM neutrino* scattering

➔A complimentary probe of the parameter space , e.g., using decay:

Dev, Kim, Sinha, Zhang, Phys.Rev.D 104 (2021) 7, 075001



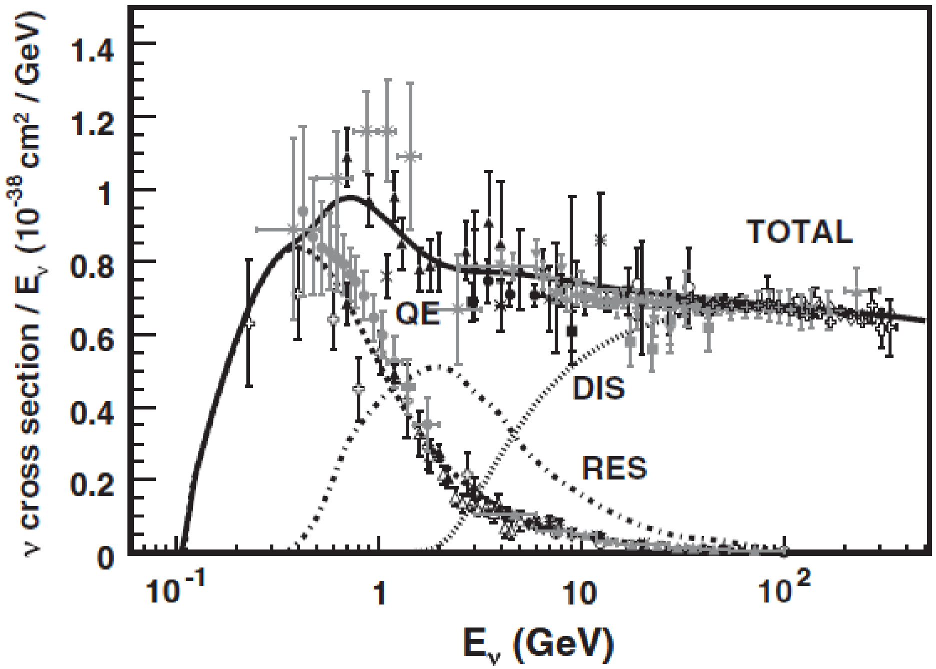


Scattering needs to be included

Capozzi, Dutta, Gurung, Jang, Shoemaker, Thompson, Yu, Phys.Rev.D 104 (2021) 11, 115010

- HNL production from charged pion decays can also be probed from the HNL decays into lepton pair, photon etc. **Coloma, Fern´andez-Mart´ınez, Gonz´alez-L´opez, Hern´andez-Garc´ıa, Pavlovic, Eur. Phys. J. C, 81(1):78, 2021**
- HNL produced the neutrino up scattering at the detector can produce lepton pairs, photons etc. **Kamp, Hostert, Schneider, Vergani, Argüelles, 2206.07100** **Bertuzzo, Jana, Machado, Funchal, Phys.Rev.Lett. 121 (2018) 24, 241801**
- All these mediators can decay into DM: All production modes need to be combined, i.e., charged, neutral meson decays, bremsstrahlung etc.

Backgrounds



- *μ, e, γ in the final states*

New physics

- *Angular and energy distributions of the final state particles along with various correlations*

Questions?

- *Do the neutrino flux adjustment affect BSM physics?*
- *How do different generators impact?*
- *Is there any low-hanging fruit for BSM models?*

Outlook

- Light mediator models can explain various anomalies and puzzles
- Many model possibilities
- M(new physics) < GeV is not easy to probe, e.g., LHC, direct and indirect detection experiments mostly probe M > GeV
- Neutrino experiments provide interesting possibilities to search for low-scale models without any interaction with neutrinos
- New physics can be searched using neutrino and γ, $e^{\pm}$, meson fluxes at the accelerator-based experiments
- Ongoing neutrino experiments are already providing interesting results