Dark Sector @ PIP2-BD

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Physics Opportunities at Beam Dump Facility in PIP-II and Beyond

Introduction

- New Physics: Dark matter(DM), neutrino masses and mixing, baryon abundance and various anomalies, 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, 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

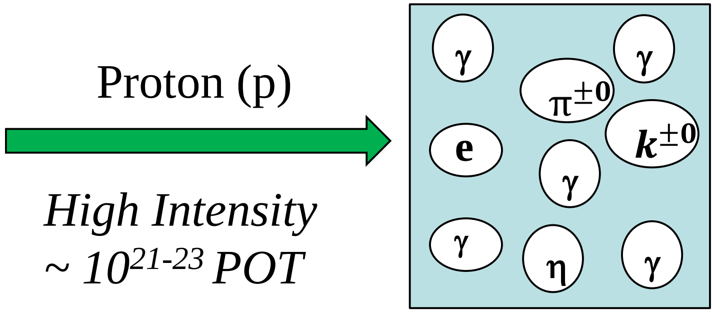
Models (Many ongoing activities):
Light mediators: scalar/pseudo-scalar, vector; sub-GeV DM

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 GeV scale proton beam dump-based stopped pion experiments:
High intensity beam, various production possibilities, large detectors

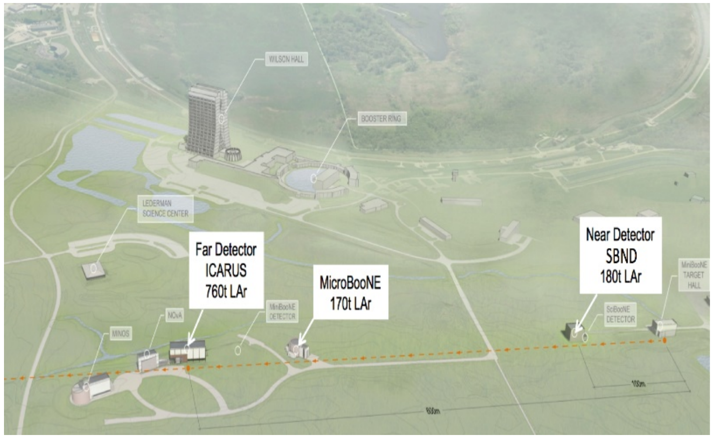
Proton beam-based experiments

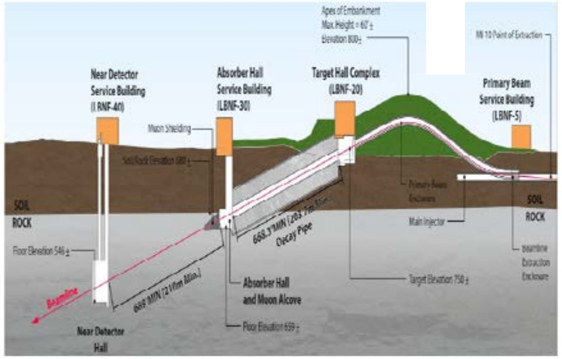
Beam dump-based (proton beam) [ongoing]: 800 MeV-3 GeV: COHERENT (Oakridge), CCM (LANL), JSNS2(JPARC) Detectors, CsI, LAr, NaI, Ge



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

DUNE (120 GeV)

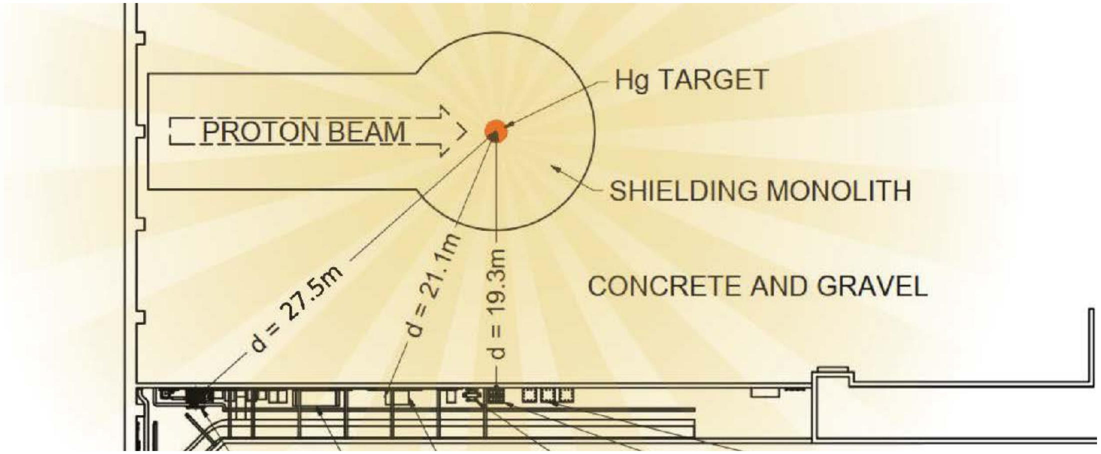




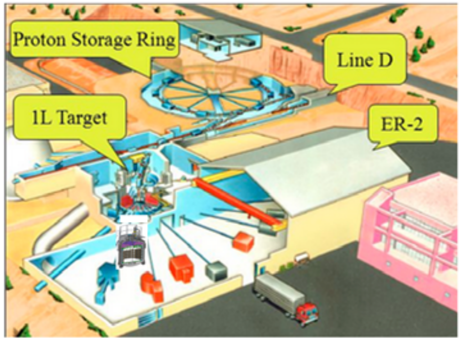
- FASER, FASERν, SND are ongoing

How complementary are these searches?

Stopped pion experiments



800 MeV protons, 100kW, 275 nanosecond pulsed beam



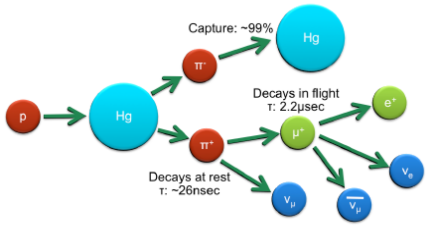
LANSCE-PSR-Lujan Target: Prolific source of charged/ neutral pions and photons that produce neutrinos and potential dark sector particles.

Creating a stopped-pion source with PIP-II: PIP2-BD

- PIP-II Accumulator Ring (PAR), Compact PIP-II Accumulator Ring (C-PAR), and Rapid Cycling Synchrotron Storage Ring (RCS-SR) are three accelerator scenarios we studied ahead of Snowmass 2022
- PAR and C-PAR are realizable in the timeframe of the start of the PIP-II accelerator and DUNE Phase I
- RCS-SR is a Booster Replacement scenario under ACE on the timescale of DUNE Phase II

Facility	Beam Energy (GeV)	Repetition Rate (Hz)	Pulse Length (s)	Beam Power (MW)
PAR	0.8	100	2×10^{-6}	0.1
C-PAR	1.2	100	2×10^{-8}	0.09
RCS-SR	2	120	2×10^{-6}	1.3

COHERENT



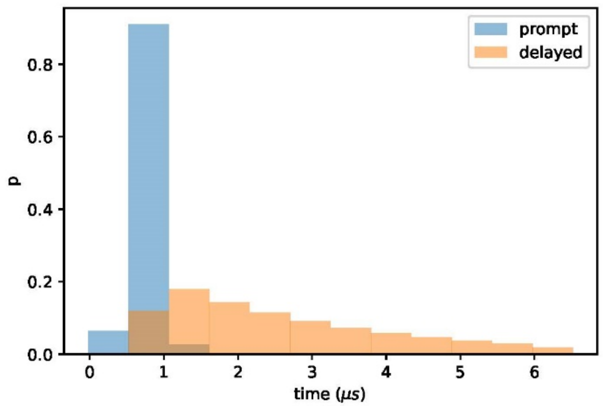
Proton beam hits a target Hg [COHERENT: 1 GeV]

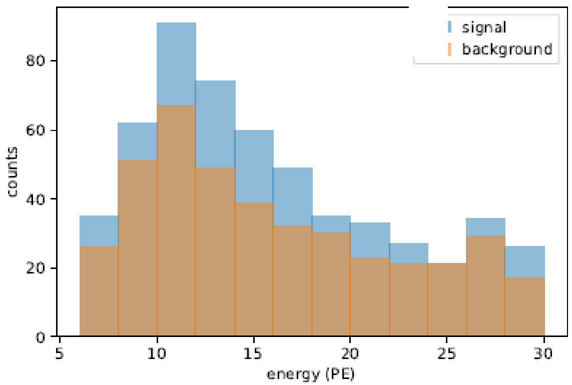
Prompt: $\pi^+ \to \mu^+ + \nu_\mu$

Delayed: $\mu^+ \to e^+ + \overline{\nu_\mu} + \nu_e$

CEvNS: Coherent elastic neutrino nucleus scattering, Nuclear recoil~ O(KeV)

COHERENT: CsI data:2018





COHERENT (2017) **No CEvNS rejected at 6.7σ: CsI (2020): 11.6σ**

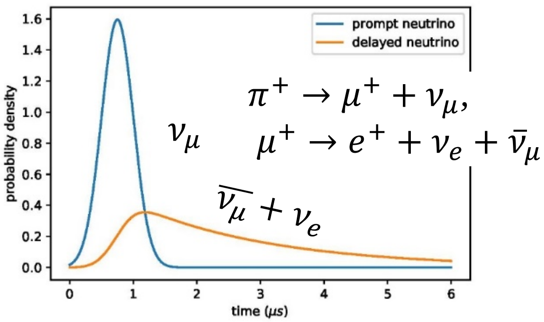
COHERENT (2020) **No CEvNS rejected at 3.8σ : LAr**

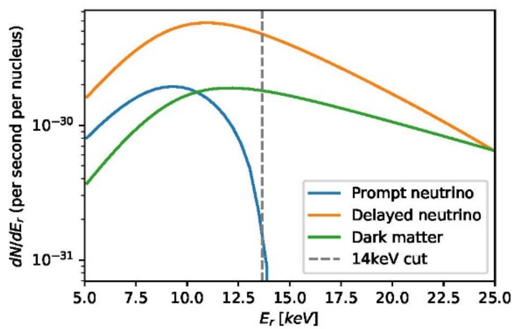
CENS-DM

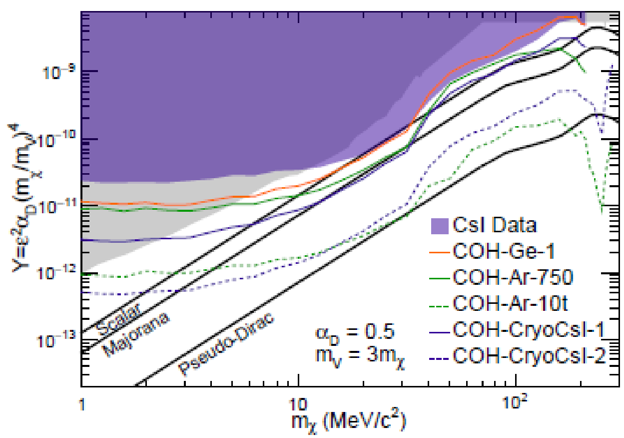
The ongoing CE νNS experiments, COHERENT, CCM etc. are probing light DM

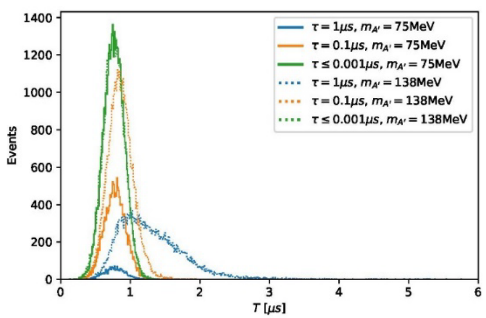
Deniverville, Pospelov, Ritz, PRD, 2015, Ge, Shoemaker, JHEP, 2018, Dutta, Kim, Liao, Park, Shin, Strigari, PRL, 2020

- Both neutrinos, DM produce nuclear recoils: how to distinguish them?
- The timing and energy recoil measurement at COHERENT, CCM, $JSNS^2$ can be used









- For $t < 1.5\mu$ s, we have mostly prompt ν
- For E_r >14 KeV (CsI) we remove the prompt ν

➔ We can remove the SM/NSI ν backgrounds

➔ Similar strategies apply to CCM, $JSNS^2$

CCM: KeV to MeV

CCM recently showed sensitivities to energies from KeV to 100 MeV

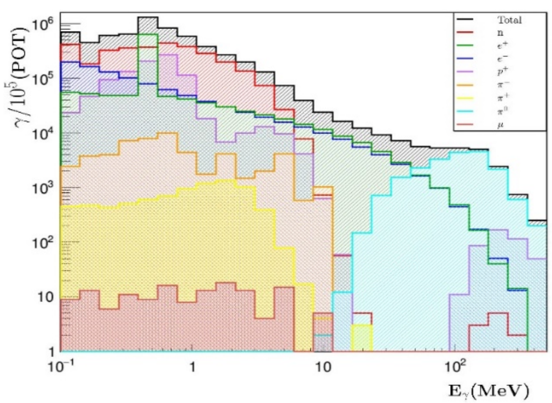
CCM, 2112.09979 (PRD)

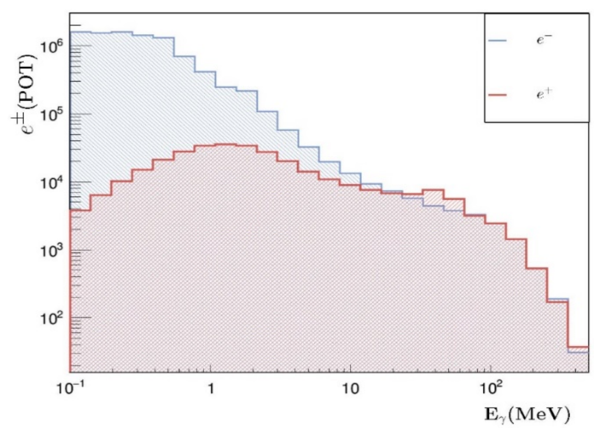
This opens up various new possibilities:

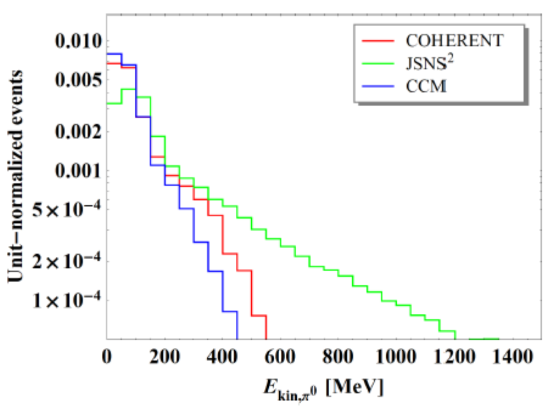
Axion, Inelastic DM-nucleus scattering, Dark photons,
Light mediators: MiniBooNe anomaly, HNL, Mirror Neutrons etc.

New particles can be produced at the target using γ, $e^{\pm}$, pion flux

CCM/COHERENT: 0.π^+ per proton: $10^{22/23}$ POT





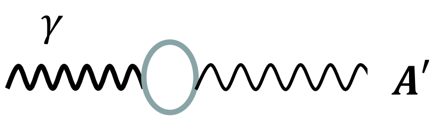


CCM, 2112.09979

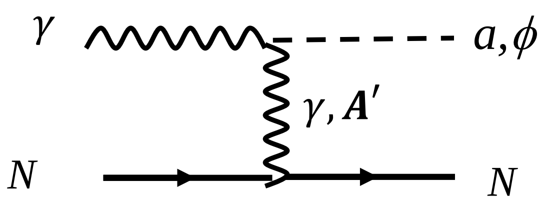
New physics at ν experiments

From γ:

A': Vector
ϕ=scalar
a=pseudo-scalar

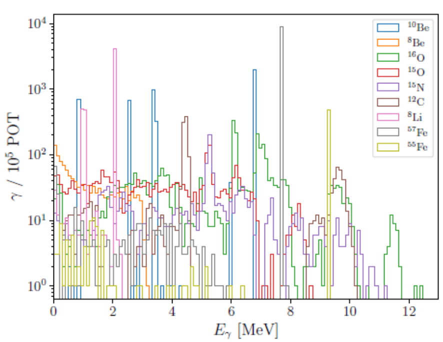


$$L \supset -\frac{\varepsilon}{4} F^{\mu\nu} F^{(\prime)}_{\mu\nu} - g_{a,\phi\gamma(Z')} \frac{(a,\phi)}{4} F^{\mu\nu} \tilde{F}^{(\prime)}_{\mu\nu}$$



Primakoff

Coherent scattering for γ exchange



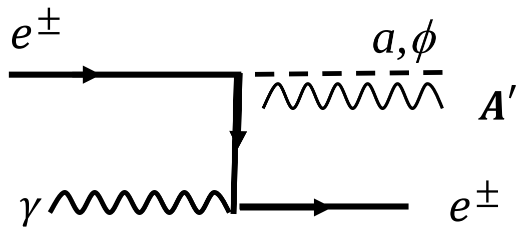
Deexcitation of N to N: produce a, s, A′*

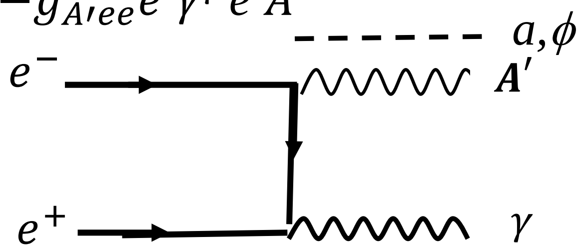
L. Waites, A. Thompson, A. Bungau, J. Conrad, B. Dutta, W. Huang, D. Kim, M. Shaevitz, J. Spitz, arXiv:2207.13659

New physics at ν experiments

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

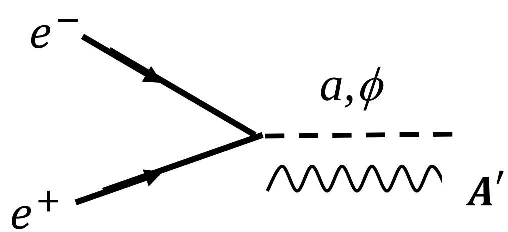
Compton

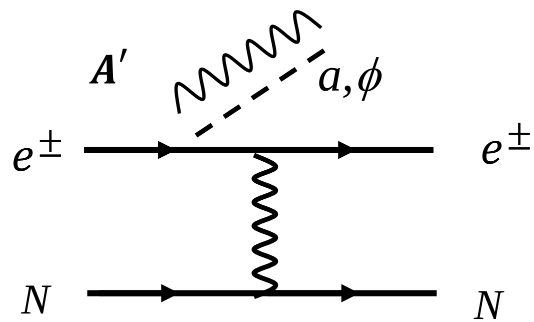




Associated

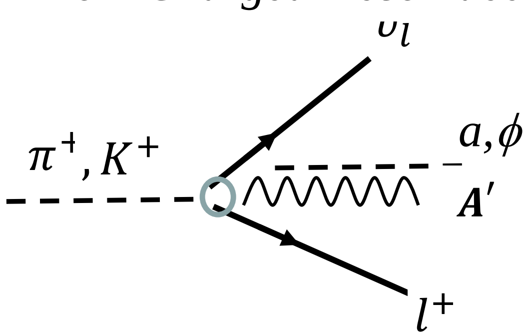
Resonance





Bremsstrahlung

- *Neutral meson decays* $\eta^0,\ \pi^0 \to \gamma A'_{\mu}$
- *From Charged meson decay: quarks and lepton couplings*

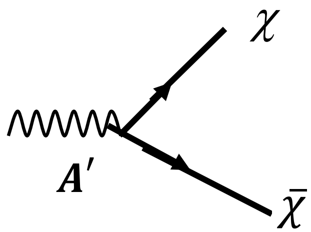


$L \supset -g_{\phi(a)ff}\bar{f}(i\gamma^5)f\,\phi(a) - g_{A'ee}\bar{f}\,\gamma^{\mu}f\,A'_{\mu}$

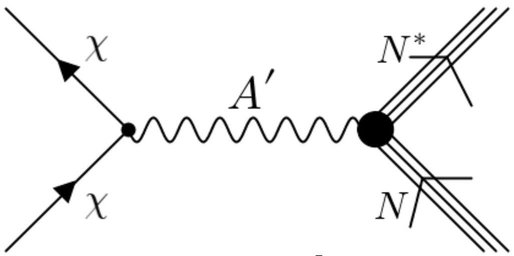
- ➢ Not helicity suppressed ➔ both electron and muon final states contribute
- ➢ Needs to include all the internal bremsstrahlung diagrams IB_i (i=1,23)

Example 1: MeV signal - DM

$$\begin{aligned}\pi^- + p &\to n + A' \\ \pi^0 &\to \gamma + A' \\ \eta^0 &\to \gamma + A' \\ e^{\pm *} &\to e^{\pm} + A'\end{aligned}$$



DM (χ) can be scalar/fermion



$N^* \to N\,\gamma$

$$\frac{d\sigma^{DM}_{\text{inel}}}{dE_r} = \frac{2e^2\epsilon^2 g_D^2 E'^2_\chi}{p_\chi p'_\chi (2m_N E_r + m_{A'}^2)^2}\frac{m_N}{2\pi}\frac{4\pi}{2J+1}\Bigg\{\sum_{J\geqslant 1, spin}\left[\frac{1}{2}(\vec{l}\cdot\vec{l}^* - l_3 l_3^*)\left(|\langle J_f||\hat{\mathcal{T}}_J^{mag}||J_i\rangle|^2 + |\langle J_f||\hat{\mathcal{T}}_J^{el}||J_i\rangle|^2\right)\right]$$

$$+ \sum_{J\geqslant 0, spin}\left[l_0 l_0^*\,|\langle J_f||\hat{\mathcal{M}}_J||J_i\rangle|^2 + l_3 l_3^*\,|\langle J_f||\hat{\mathcal{L}}_J||J_i\rangle|^2 - 2\,l_3 l_0^* Re\left(\langle J_f||\hat{\mathcal{L}}_J||J_i\rangle\langle J_f||\hat{\mathcal{M}}_J||J_i\rangle^*\right)\right]\Bigg\}$$

We use Bigstick: Shell Model code for this calculation

$$\frac{d\sigma^{DM}_{\text{el}}}{dE_r} = \frac{e^2\epsilon^2 g_D^2 Z^2}{4\pi(E_\chi^2 - m_\chi^2)(2m_N E_r + m_{A'}^2)^2}F^2(q^2)$$

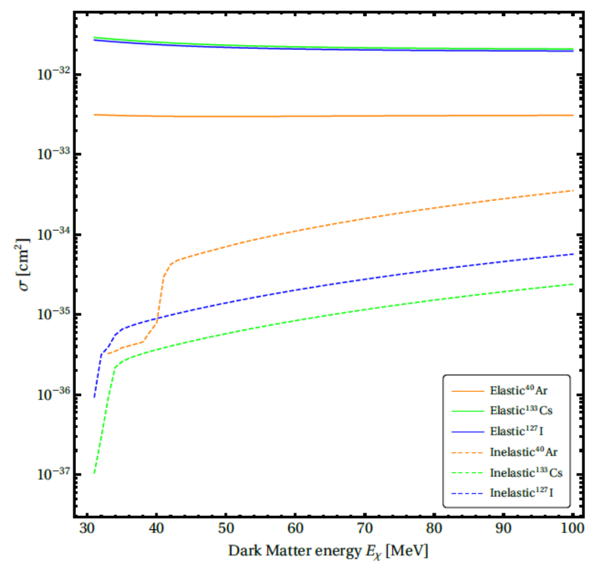
$$\times\left[2E_\chi^2 m_N\left(1 - \frac{E_r}{E_\chi} - \frac{m_N E_r}{2E_\chi^2}\right) + E_r^2 m_N\right]$$

For Ar40

$$\left(\frac{Inelastic}{Elastic}\right)_{signal} = 10^{-2} - 10^{-1}$$

$$\left(\frac{Inelastic}{Elastic}\right)_{bkg} = 10^{-4} - 10^{-3}$$

B. Dutta, W. Huang, J. Newstead, V. Pandey, Phys.Rev.D 106 (2022) 11, 113006

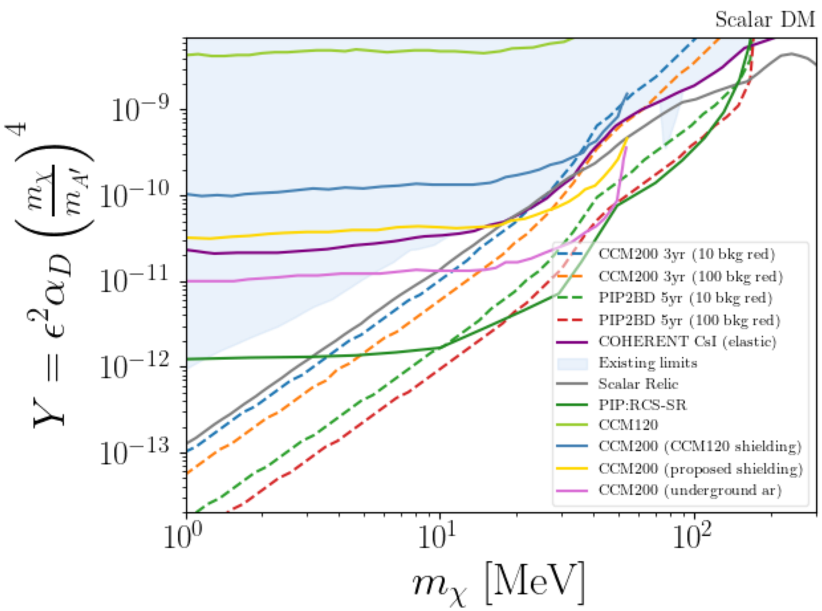


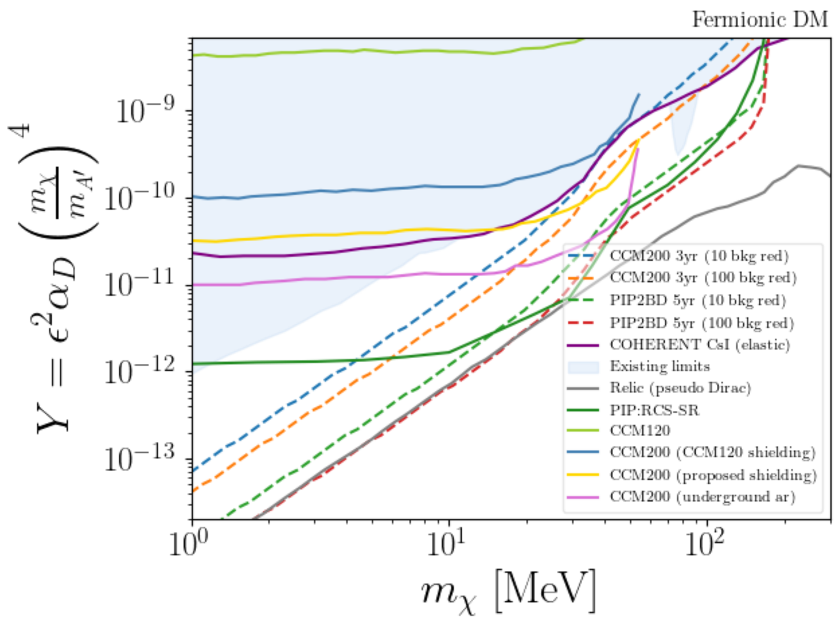
MeV signal - DM

$g_D = \sqrt{2\pi}$, $\frac{M_{A'}}{M_\chi} = 3$

$$\sigma_{\text{elastic}} \sim 1/(2m_N E_r + m_{A'}^2)^2$$
$$\approx 1/(2m_N E_r)^2 \text{ if } m_{A'}^2 < 2m_N E_r$$

B. Dutta, W. Huang, J. Newstead, arXiv:2302.10250



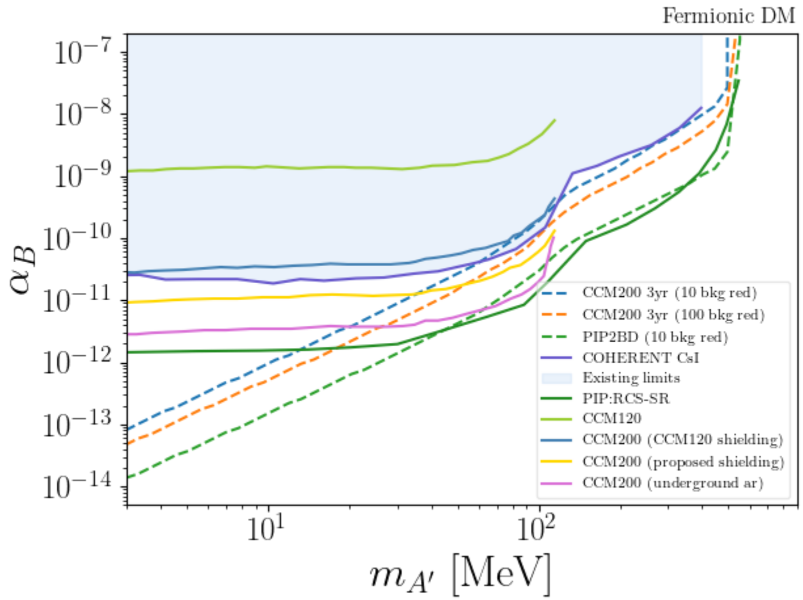


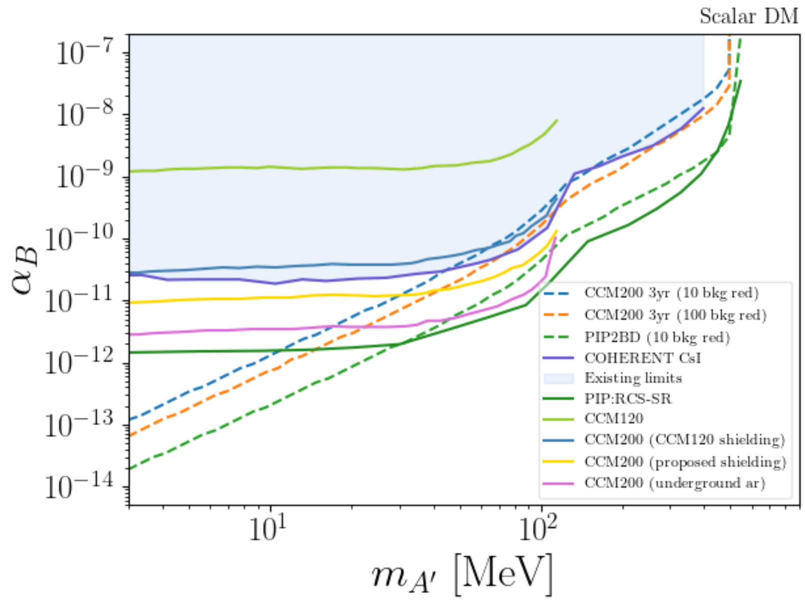
- We use CCM background measurements and projections
- $t < 200$ ns, prompt window reduces the neutrino background down to O(1) events
- Rescale the shell model prediction to be consistent with the experiment, **W. Tornow et al., 2210.14316**
- A lower threshold detector will help to improve the sensitivity in the elastic channel
  - Signal: Recoil (KeV), deexcitation photon

MeV signal – DM: Leptophobic

U(1)$_B$ Model

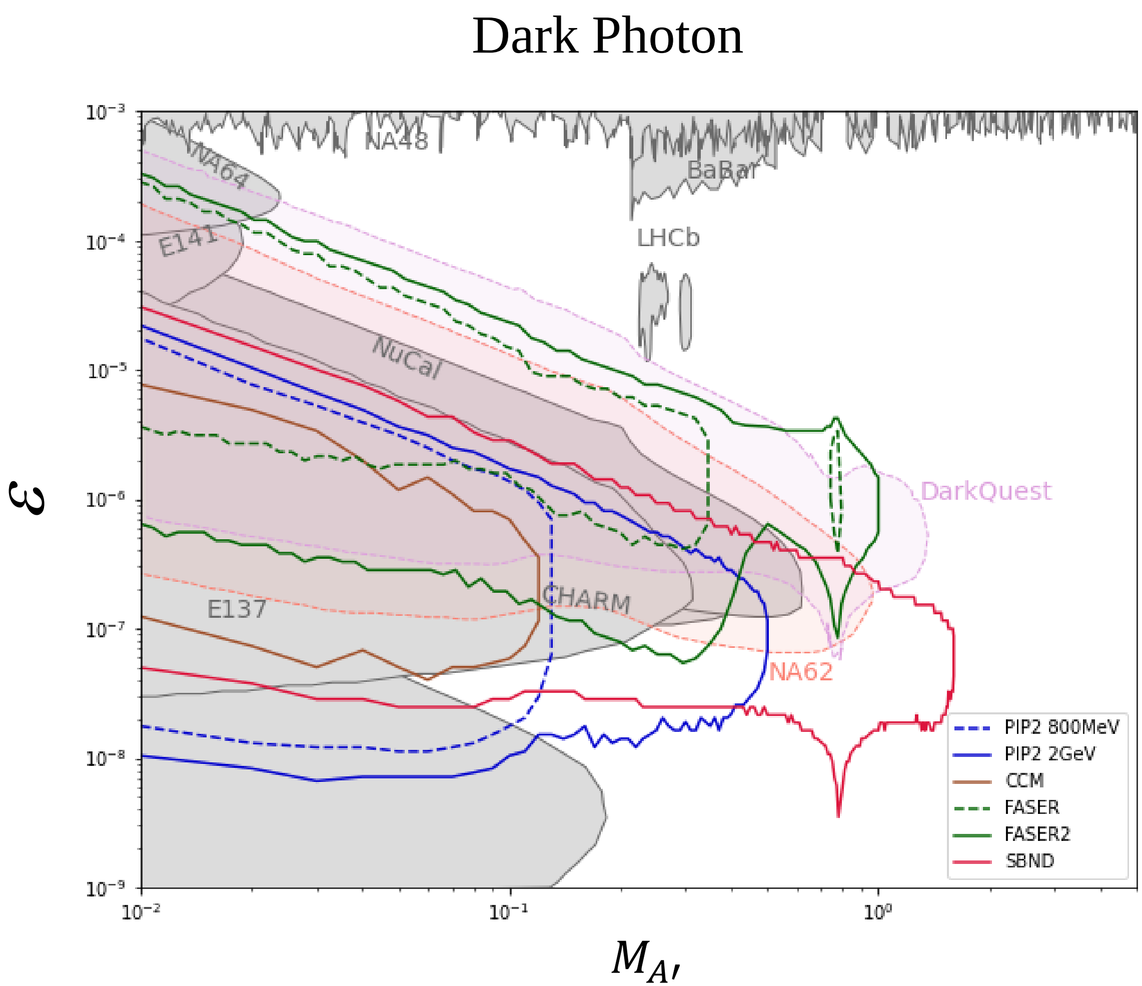
$$m_{A'}/m_\chi \approx 2$$



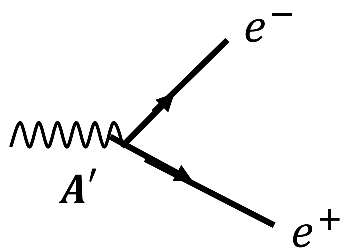


Can we implement inelastic scattering at SBN?

Example2: dark photon



Decay final states



Scattering final states (ongoing)

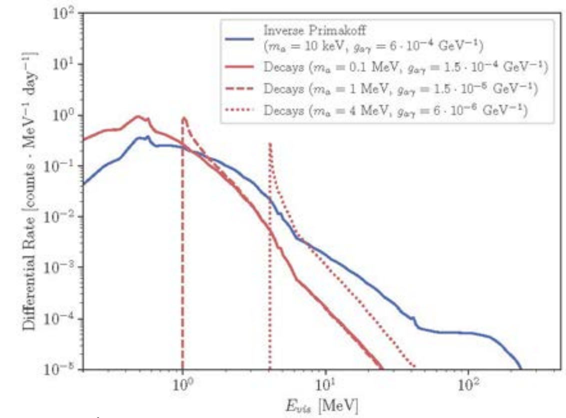
Dutta, Karthikeyan, Kim, to appear

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

Example 3: ALP

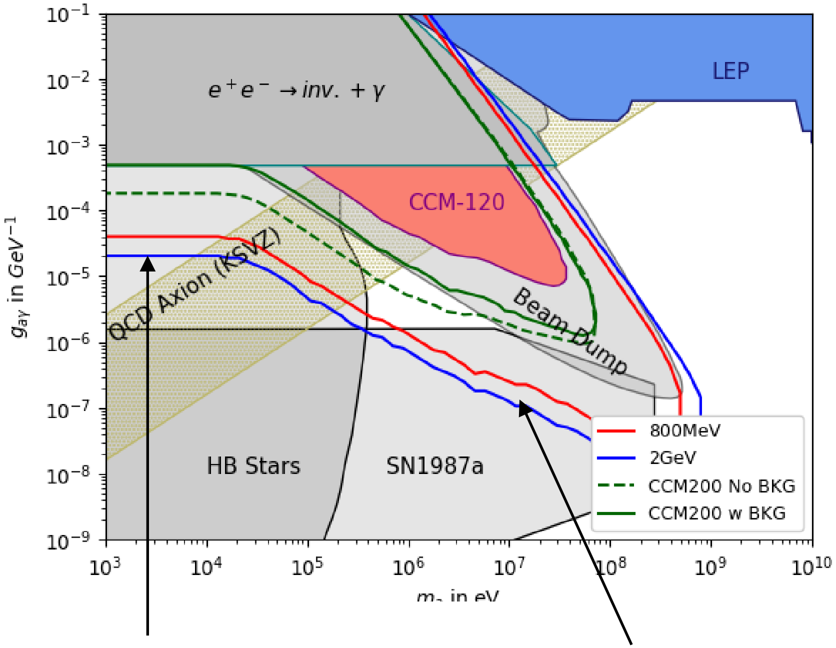
- $\gamma, e^{\pm}$ fluxes, Primakoff/Compton productions, inverse Compton/Primakoff, decays final states are used by CCM(LANL) to explore new physics

  - For g_{ae}, coupling, the CCM engineering run data has started exploring new parameter space



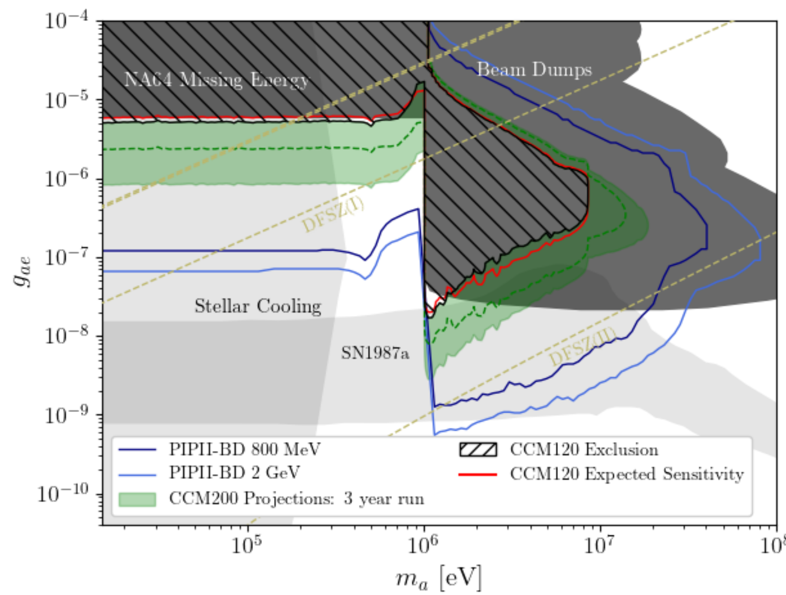
CCM, 2112.09979

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



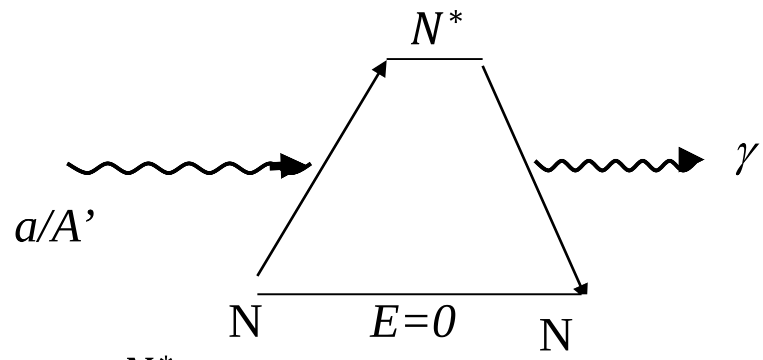
Scattering *Decay*

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

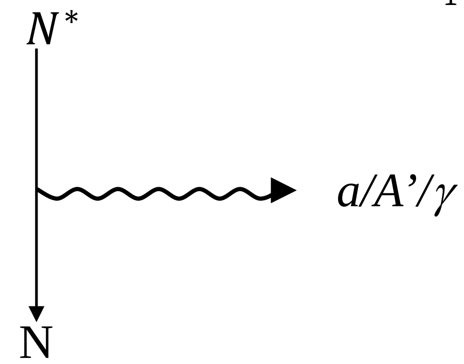


Example 3.1: Absorption

Additional detection and production modes:
MeV Lines from inelastic absorption,
e.g., axion absorption;



Axion productions from deexcitation
lines at the target



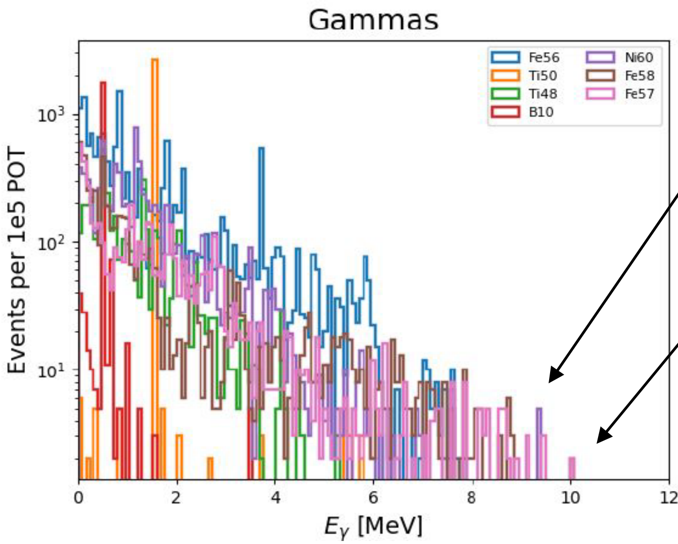
Primakoff/ Compton production
Inverse Primakoff/Compton detection

$g_{aee}, g_{a\gamma\gamma}$

Dexciation production
Inelastic Absorption

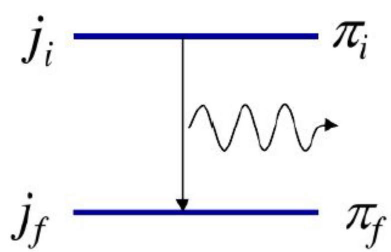
g_{ann}

CCM/PIP2: ALP

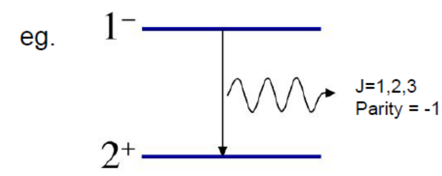


We use these lines to produce axions, dark photon production

$$\pi = (-1)^I \text{ for E transitions}$$
$$\pi = (-1)^{I+1} \text{ for M transitions}$$
$$\text{multipolarity} = 2^I$$



$$|J_i - J_f| \leq J \leq J_i + J_f$$
$$\pi = \pi_i \pi_f$$



$$J^\pi = 1^-(E1), 2^-(M2), 3^-(E3)$$

l	π_γ	Radiation type	Label
1	–1	Electric Dipole radiation	E1
1	+1	Magnetic Dipole radiation	M1
2	–1	Magnetic Quadrupole radiation	M2
2	+1	Electric Quadrupole radiation	E2
3	–1	Electric Octapole radiation	E3
3	+1	Magnetic Octapole radiation	M3

- These lines are also utilized at IsoDAR [60 MeV proton beam dump experiment with Be target]
- Can be utilized at PIP2 and DAMSA

CCM/PIP2: ALP

- $g_{ann} g_{a\gamma\gamma}$

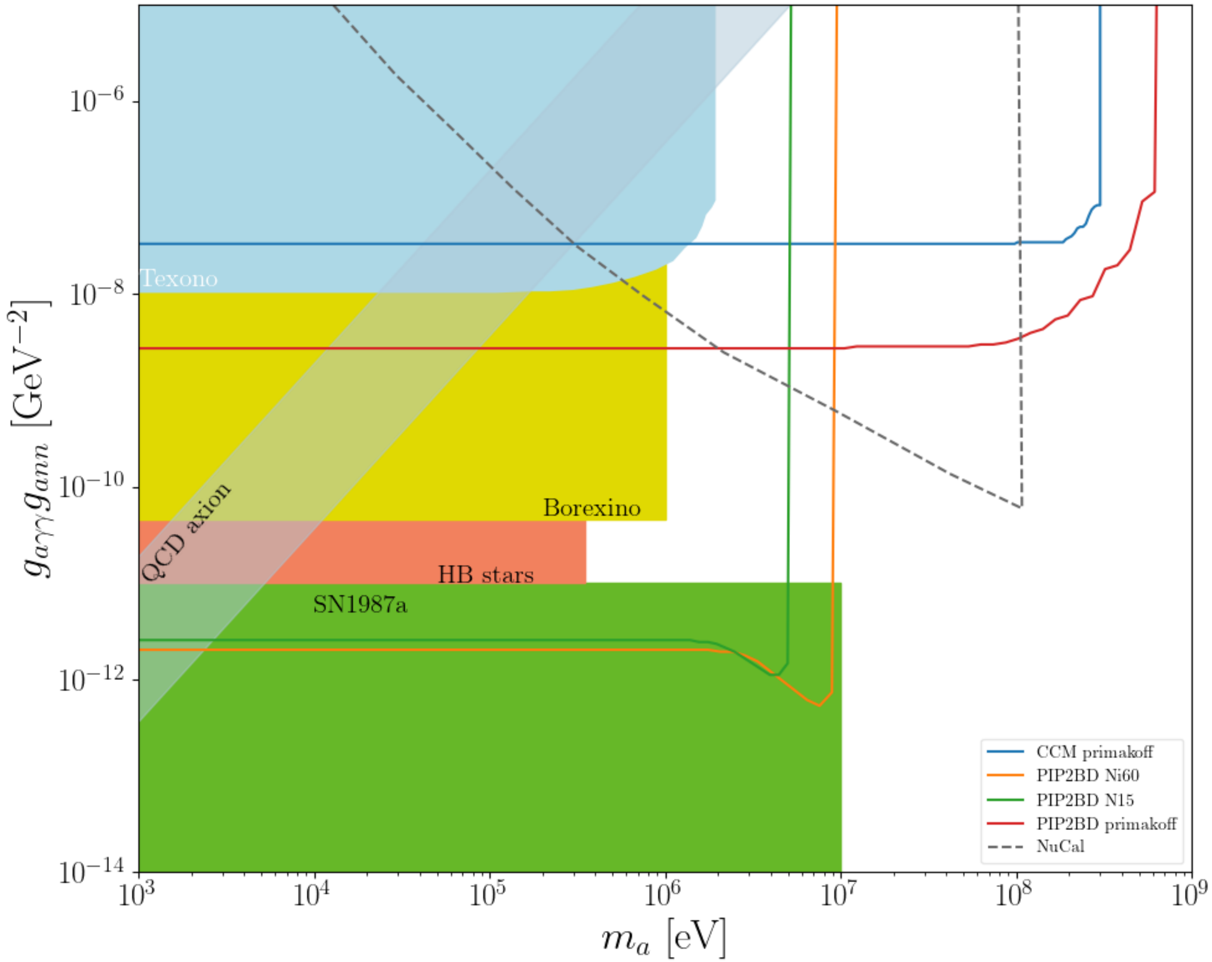
deexcitation line (target)+ inverse Primakoff/Compton (detector); Primakoff/Compton (Target) +excitation (detector)

- g_{ann}

deexcitation line (target)+) +excitation (detector)

$$\mathcal{L}_{\text{int}} \supset \frac{\partial_\mu a}{f_a} \bar{N} \gamma^\mu \gamma^5 N$$

$$g_{ann} = \frac{1}{f_a}$$



Dutta, Newstead, Huang, to appear

- De-excitation line at the target is due to absorption:

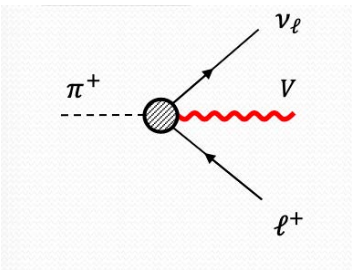
$$\sigma_{\text{abs}}(E_a, \Delta_2) = \frac{g_A^2 \pi}{6(2J+1)} g_{ann}^2 \delta(E_a - E_r - \Delta_2)\, p_a \, |\langle J_f || \sum_{i=1}^{A} \frac{1}{2} \hat{\sigma}_i \hat{\tau}_0 || J_i \rangle|^2$$

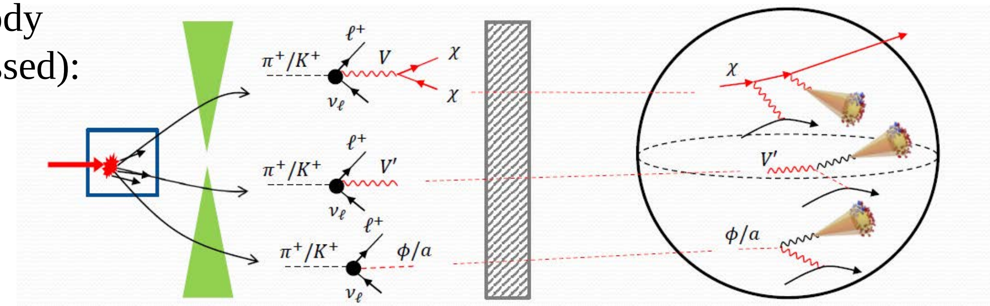
Example4: Dark Sector

MiniBooNE anomaly: Dark sector

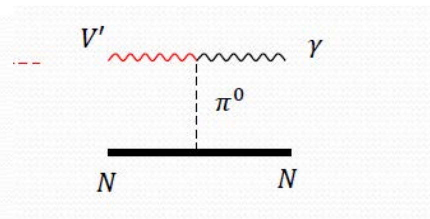
- For dark sector appearing from π^0->V γ only: ruled out by MB dump

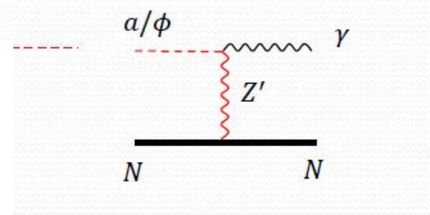
Use the charged pion 3 body Decay (helicity unsuppressed):

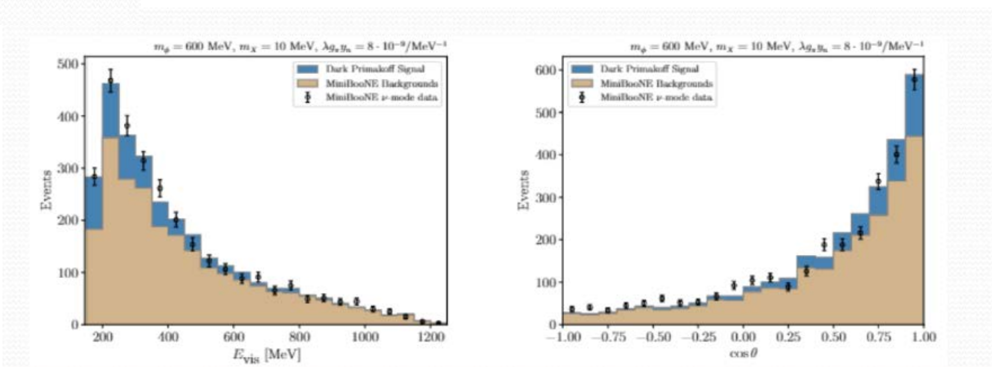


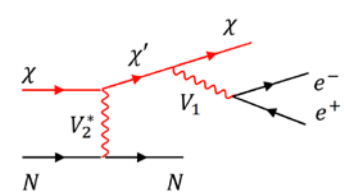


Detection







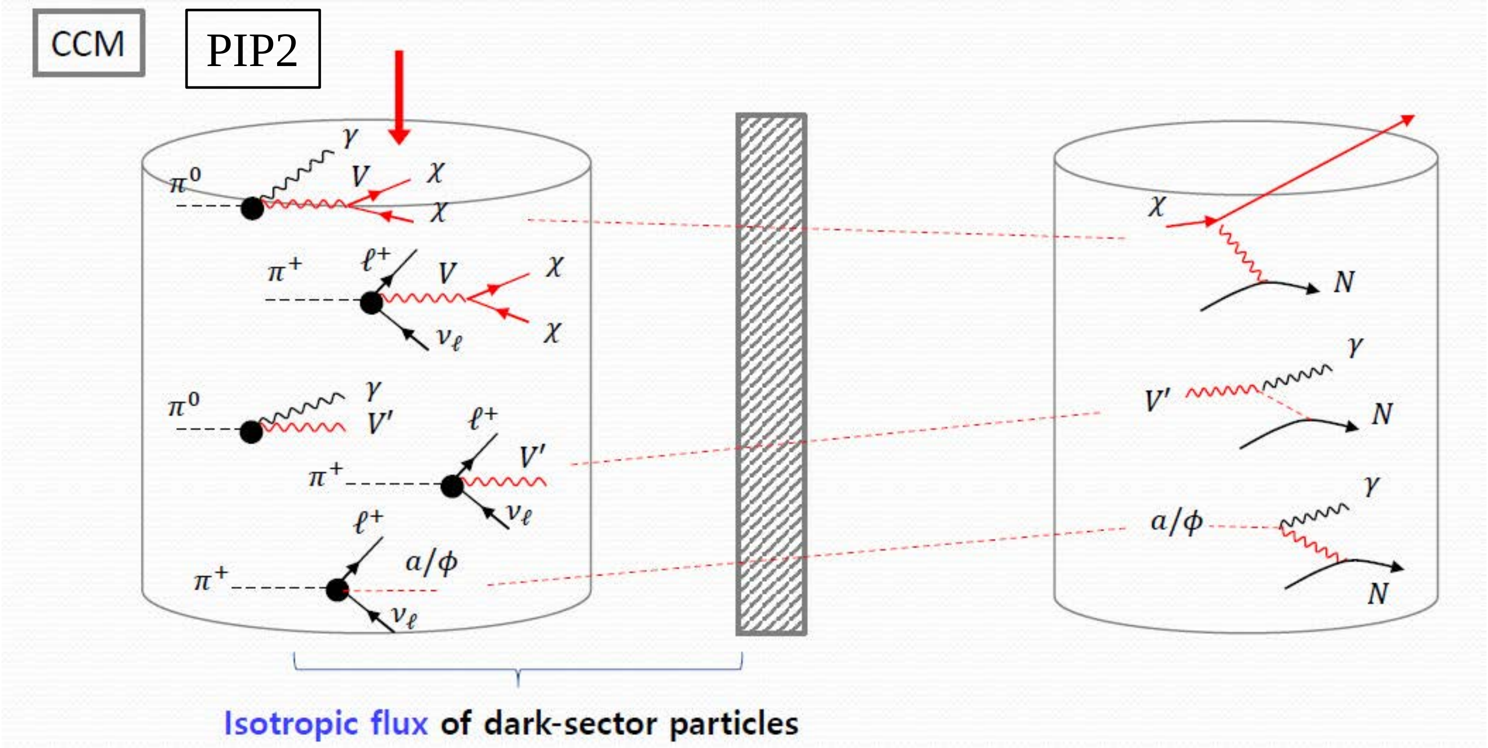


Can be probed at CCM, MicroBooNE, SBND, DUNE

Dutta, Kim, Remington, Thompson, Van de Water, PRL 129 (2022) 11, 111803

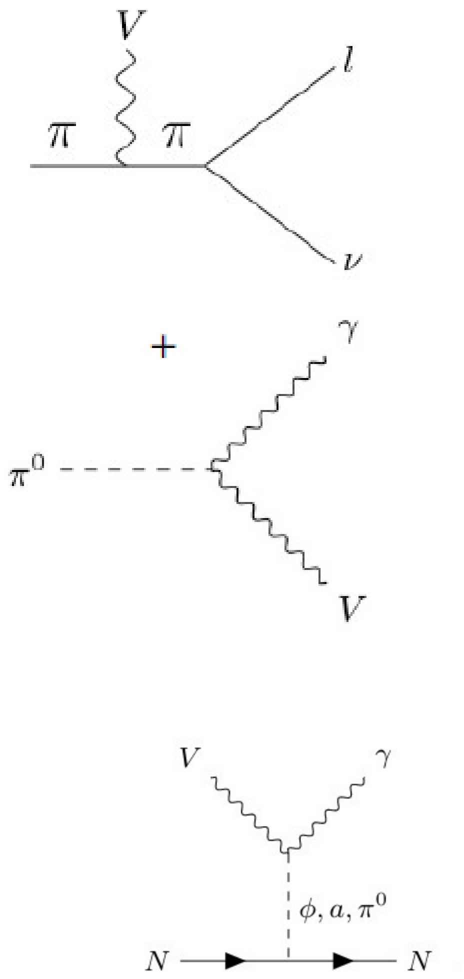
Dark Sector

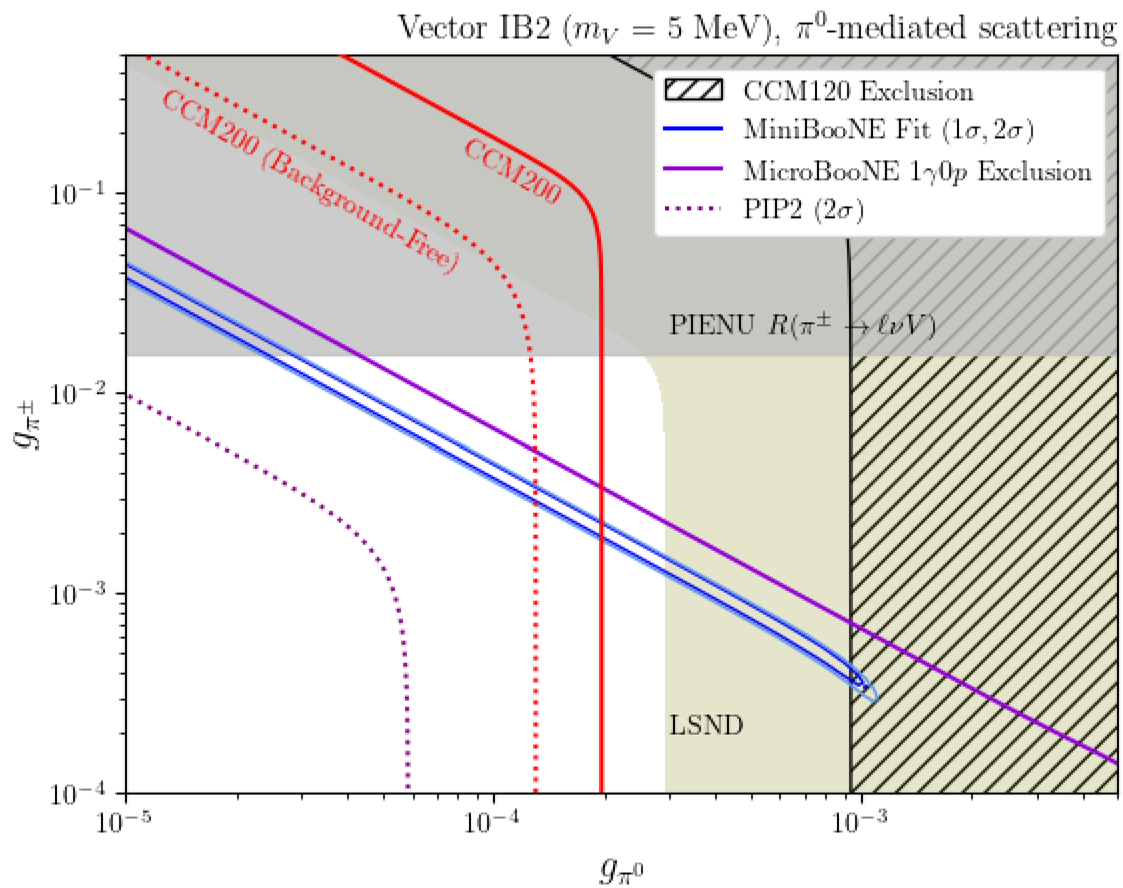
MiniBooNE puzzle at CCM/PIP2



Productions via π^0 and π^+ can be investigated ➔ *would help to discern light mediator models*

Dark Sector





A. Thompson, CCM collaboration, to appear

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
- Stopped pion based proton beam dump experiments have unique opportunities to probe the dark sector with MeV e, γ final states
  neutrino-related background is small
- New physics can be searched using pion, γ, $e^{\pm}$, meson fluxes, Lower mass scales can be probed efficiently
- Ongoing CCM is already providing interesting results on dark sector model parameter space
- PIP2-BD can investigate a larger range of parameter space of various models