MeV-scale BSM Physics at Stopped-Pion Facilities

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The Strong CP Problem, pNGBs, and the Axiverse

Axion-like Particle Models

Strong CP Problem:

Introducing a PQ scalar $\phi \sim \rho e^{ia/f_a}$ with goldstone boson a that couples through aGG will dynamically remove CP violation in the strong sector

Dark Matter:

axionic DM solutions very popular for sub-eV masses, but can also exist at the keV-MeV

Axiverse:

string theory compactifications generically predict up to $o(100)$ pseudoscalar axion-like particles (ALPs)

High Quality ALPs:

making the axion solution to strong CP robust usually asks for heavier axion mass

$$\mathcal{L} \supset aG\tilde{G} + aF\tilde{F} + \sum_f a\bar{f}\gamma^5 f$$

Axion-like Particles @ Coherent CAPTAIN Mills (CCM)

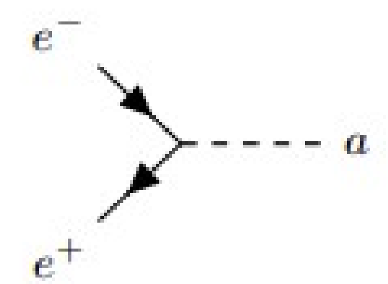
$$\mathcal{L} \supset -i g_{ae} a \bar{e} \gamma^5 e - \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Source: Lujan beam at LANL

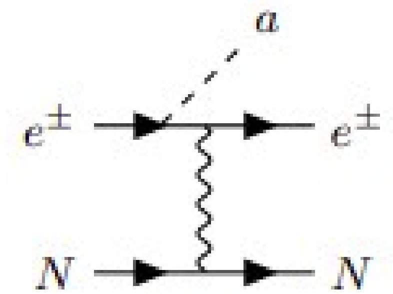
- 800 MeV proton beam

Target: Tungsten (W)

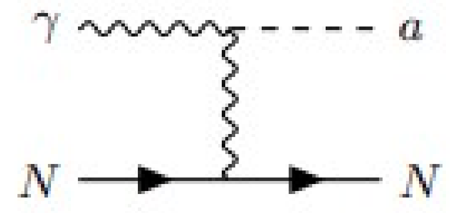
- Electromagnetic particle fluxes in the target in the 0.1-100 MeV range are sensitive to ALP production
- Consider photon and electron couplings



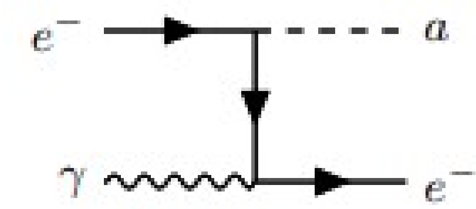
(g) Resonant production



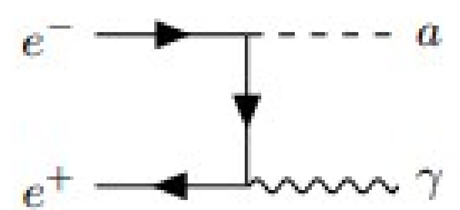
(i) ALP-bremsstrahlung



(a) Primakoff

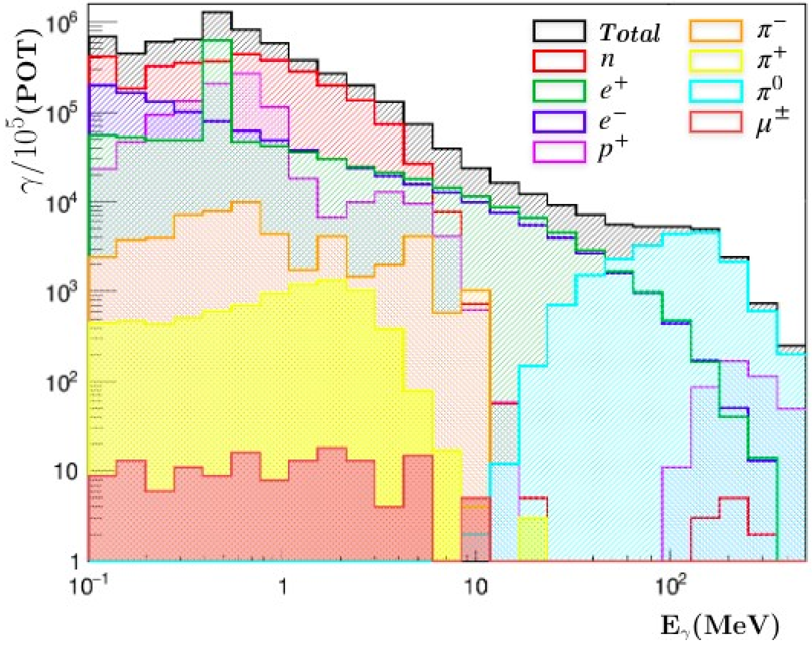


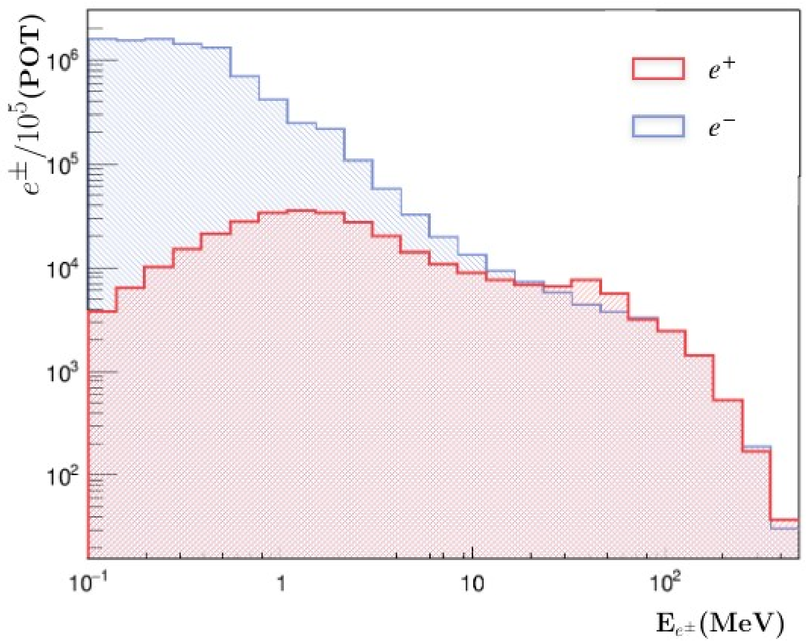
(c) Compton



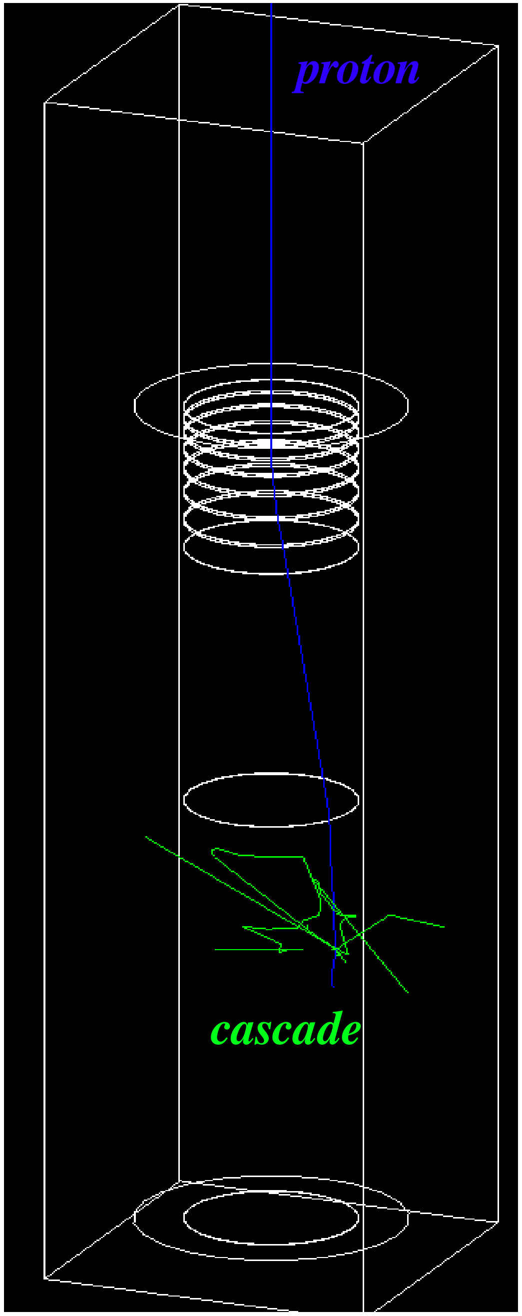
(e) Associated production

Electromagnetic Cascades: Fluxes at the W Target





- **GEANT4** simulated fluxes from 800 MeV protons on W target geometry
- **Physics list**: QGSP_BIC_HP
- Production of secondary e^+, e^-, photons sourced by:
  - e^+e^- Pair production
  - Bremsstrahlung
  - π^0 decays
  - Neutron/proton scattering
  - etc…
- Can evaluate flux uncertainties by comparing results of different physics lists: ~1-5% uncertainty at MeV range



Detection Channels in LAr

CCM Detector:

- 7t LAr PMT-instrumented cryostat
- 90 degrees off-axis
- 23m to target

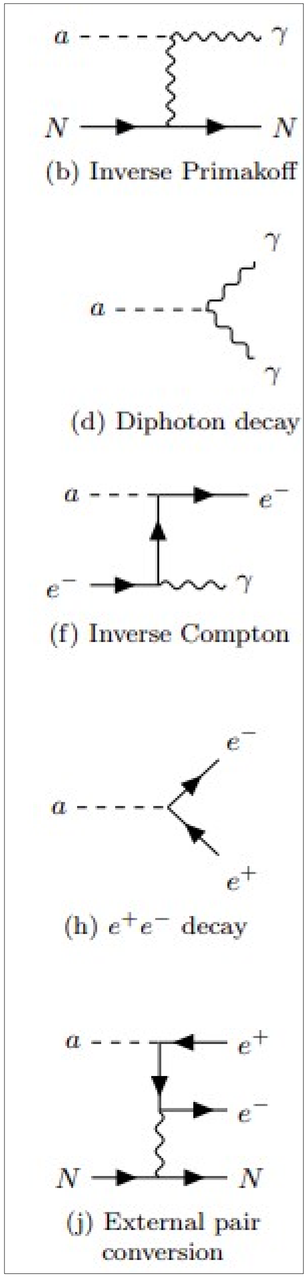
Visible Energy Final States:

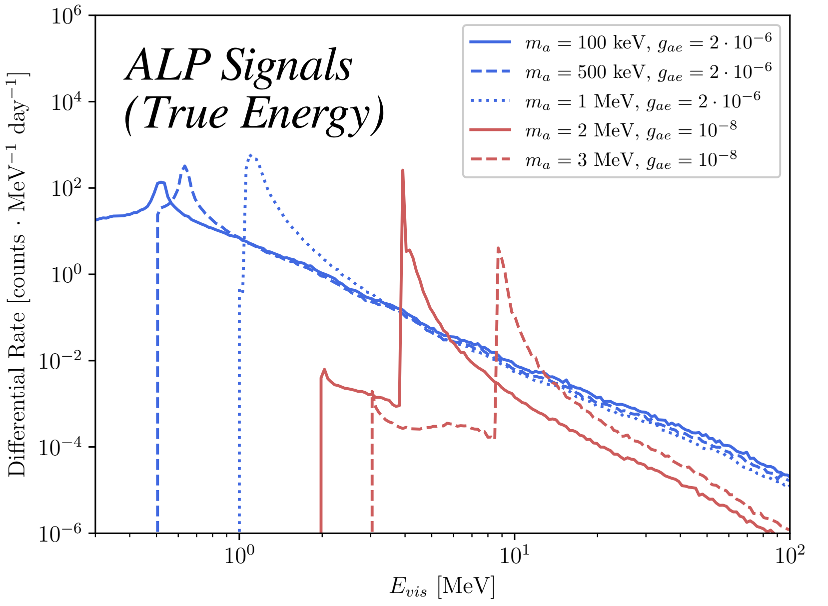
- 1 γ (inverse Primakoff)
- 2 γ (di-photon decays)
- $1\gamma 1e^-$ (inverse Compton)
- e^+e^- (pair conversion, decays)

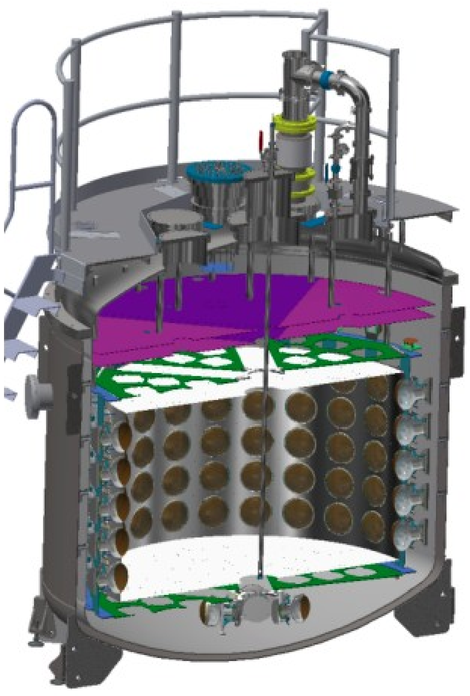
Selection Cuts and Backgrounds:

- T_0 determined from gamma flash
- Steady state background subtraction
- Timing cut → remove slow neutron wall
- ...radius cuts, coated PMT cuts, etc., see:

Axion-Like Particles at Coherent CAPTAIN-Mills
2112.09979



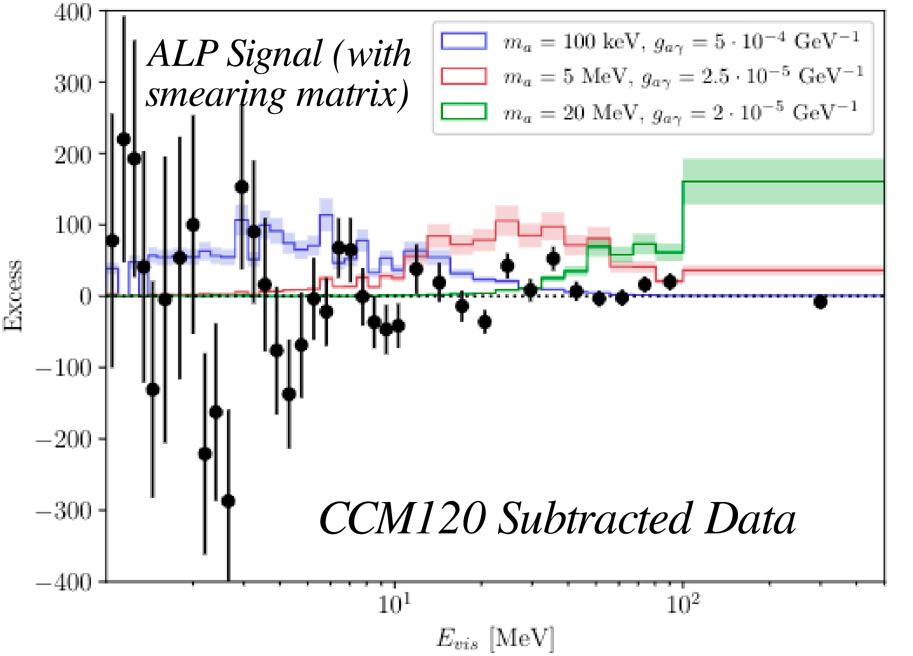




Limits with CCM120 and the Future

CCM120: 1.8e21 POT collected
CCM200: Taking data ***now***, planned 2.25e22 POT

- **CCM120 data:** 294590 observed events
- **Backgrounds**: 294614.3 ± 241.7 (syst) ± 542.8 (stat)
- Projected sensitivities also test traditional **QCD axion** parameter space and constraints from **astrophysics**
- Projected sensitivity to the "**cosmological triangle**" region of ALP parameter space $0.5 < m_a < 1$ MeV



Axion-Like Particles at Coherent CAPTAIN-Mills
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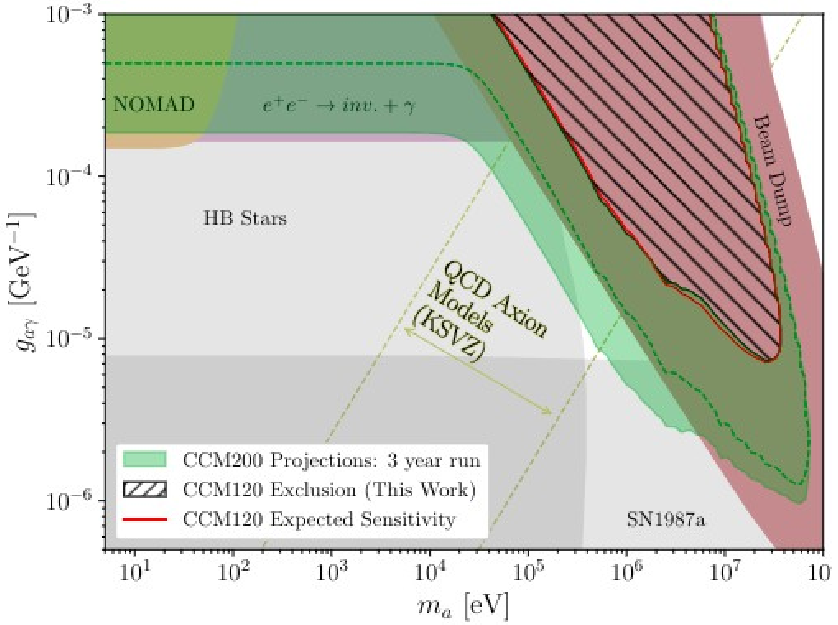

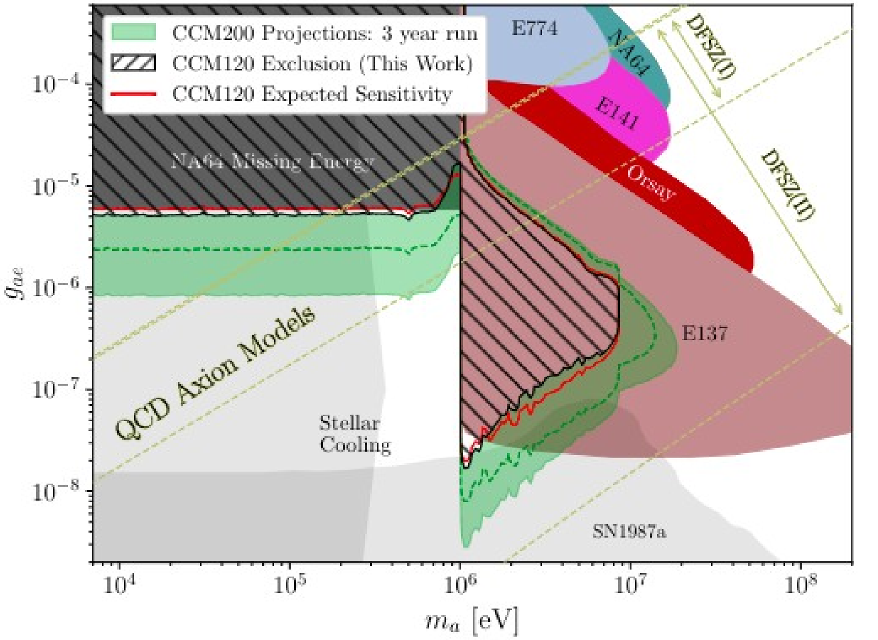

The MiniBooNE Anomaly

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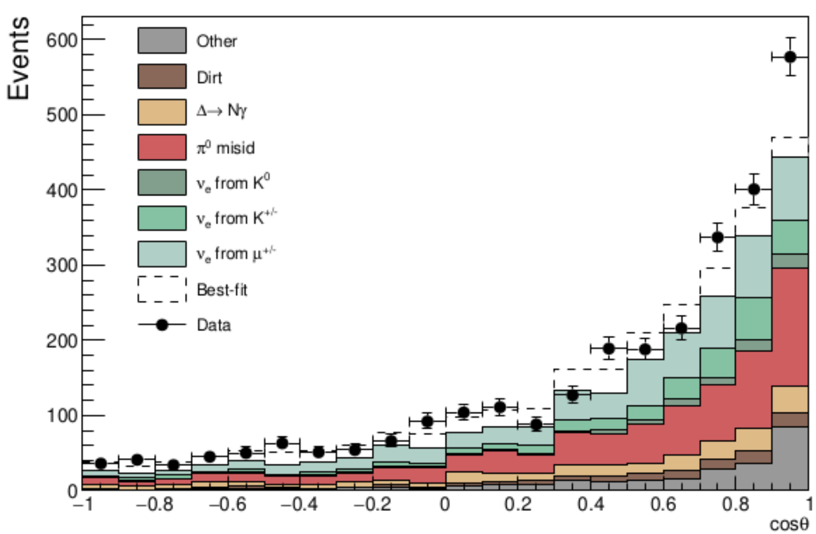
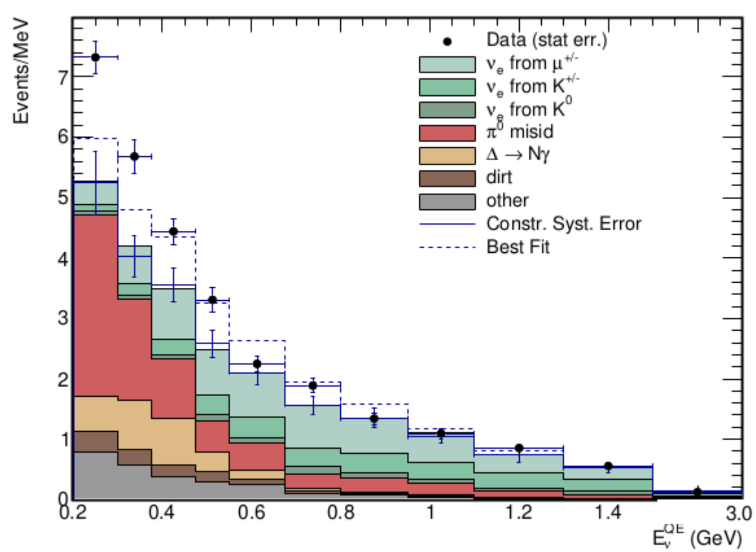
- MiniBooNE, 2021 [2006.16883]
- MiniBooNE, 2019 [1807.06137]
- MiniBooNE, 2018 [1805.12028]

Two main features of the excess:

1. Excess in the target-mode runs, no observed excess in the dump-mode run
2. Excess shows distinct angular and energy spectra

		Excess	POT	Charged Mesons Focused?
Target Mode	*Neutrino Mode*	560.6±119.6	1.875E+21	π^+, K^+
	Anti-neutrino Mode	77.4±28.5	1.127E+21	π^-, K^-
Dump Mode		None	1.86E+20	Isotropic

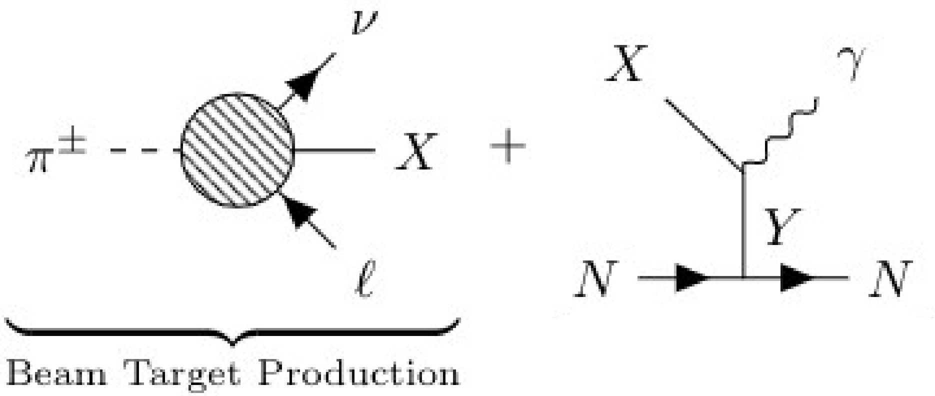


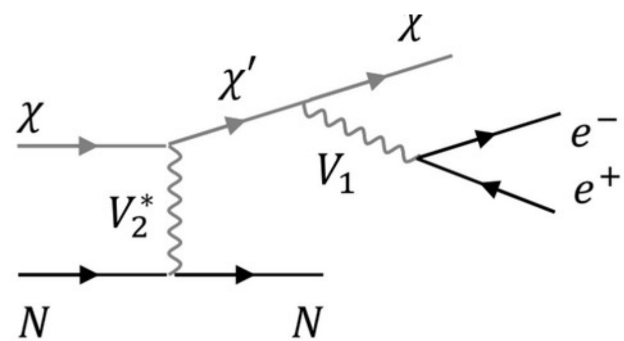


How can we explain this anomaly with a dark sector?

(1): Dark boson photoconversion

(2): $X \to \chi\chi$ into DM upscattering





Examples:

$$\mathcal{L}_S \supset g_\mu \phi \bar{\mu}\mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4}\phi F'_{\mu\nu}F^{\mu\nu} + \text{h.c.},$$

$$\mathcal{L}_P \supset i g_\mu a \bar{\mu}\gamma^5 \mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4} a F'_{\mu\nu}\tilde{F}^{\mu\nu} + \text{h.c.}$$

$$\mathcal{L}_V \supset e(\epsilon_1 V_{1,\mu} + \epsilon_2 V_{2,\mu})J^\mu_{\text{EM}} + (g_1 V_{1,\mu} + g_2 V_{2,\mu})J^\mu_D + (g'_1 V_{1,\mu} + g'_2 V_{2,\mu})J'^\mu_D$$

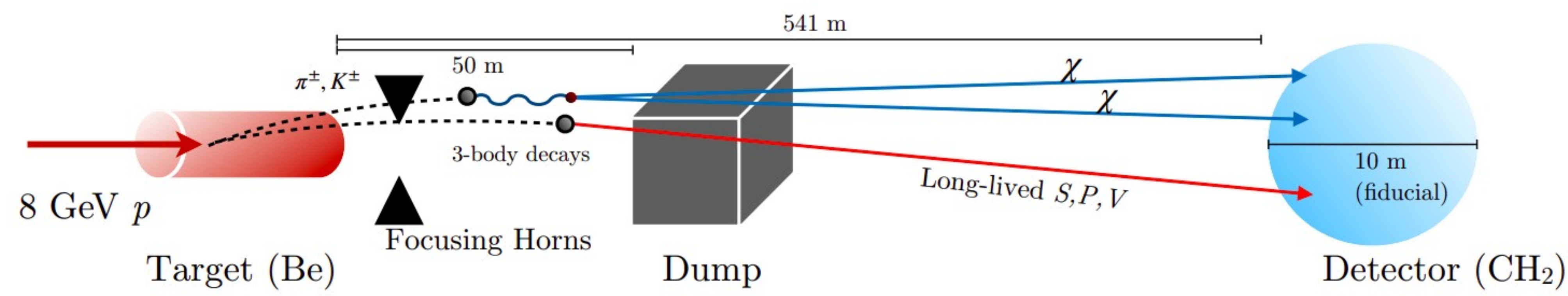
Correlates dark boson flux to target-mode excess

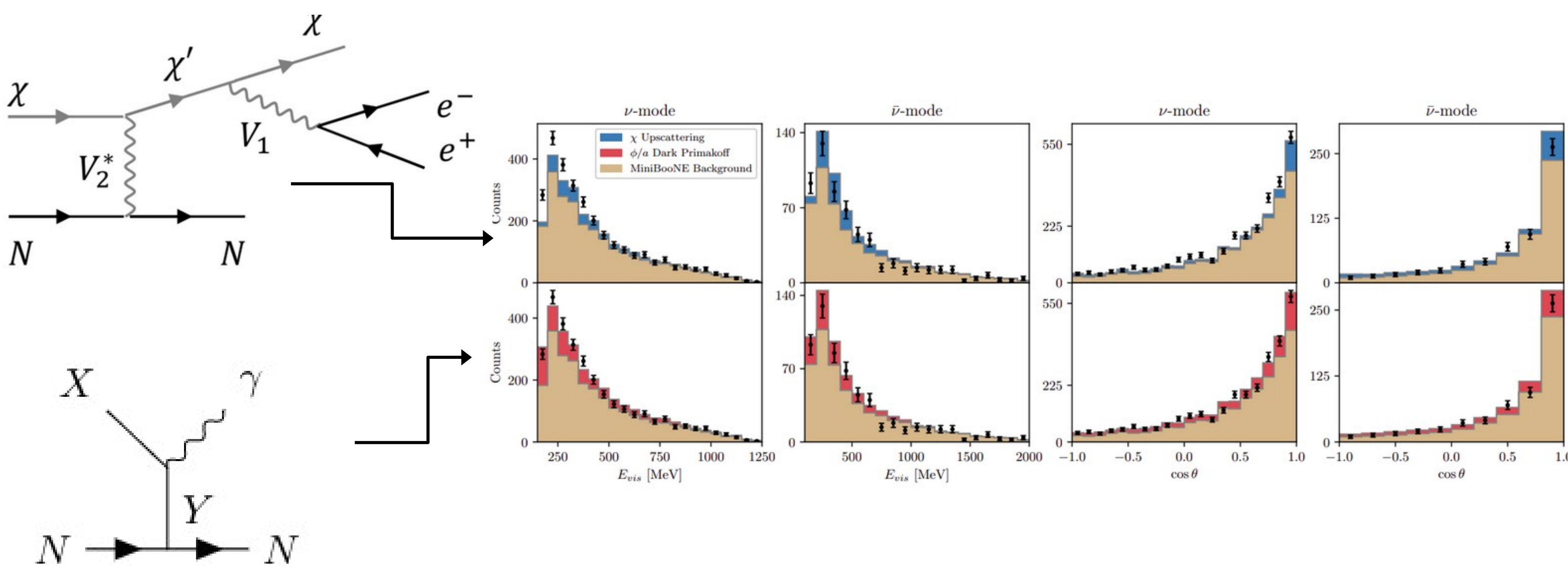
Massive particle in *t*-channel accounts for observed off-forward cosine distribution

We explored these scenarios here: arXiv:110.11944

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

Accomodating the MiniBooNE Observation





Dark Sector Chiral Perturbation Theory: What is the larger picture?

$$\mathcal{L} \supset \sum_q g_q V_\mu \bar{q}\gamma^\mu q$$

$$\mathcal{L}_{hp}^{\chi PT} \supset \frac{f_\pi^2}{4}\mathrm{Tr}\left[(\partial_\mu \mathbf{U} - iV_\mu\{\mathbf{g}_X, \mathbf{U}\})(\partial^\mu \mathbf{U} + iV^\mu\{\mathbf{g}_X, \mathbf{U}\})\right] \quad (2)$$

where the octet of meson states are contained in the Goldstone field Φ in the 3-flavor quark basis,

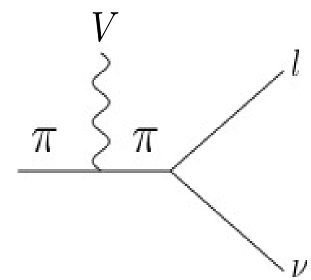
$$\mathbf{U} = e^{i\sqrt{2}\Phi/f_\pi},\ \Phi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \overline{K}^0 & -\frac{2\eta_8}{\sqrt{6}} \end{pmatrix}. \quad (3)$$

Further, for simplicity we select only up- and down-type quark couplings in the coupling matrix $\mathbf{g}_X$;

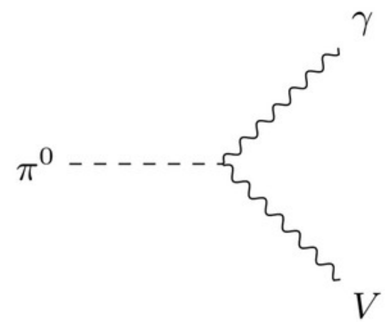
$$\mathbf{g}_X \equiv \begin{pmatrix} g_u & 0 & 0 \\ 0 & g_d & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (4)$$

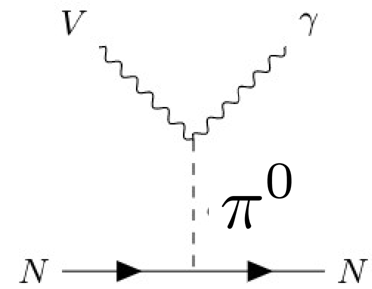
Quark couplings →
We generically expect couplings to both neutral and charged mesons!

$$\mathcal{L}_{hp}^{\chi PT} \supset i(g_u - g_d)V_\mu \pi^+(\partial^\mu \pi^-)$$



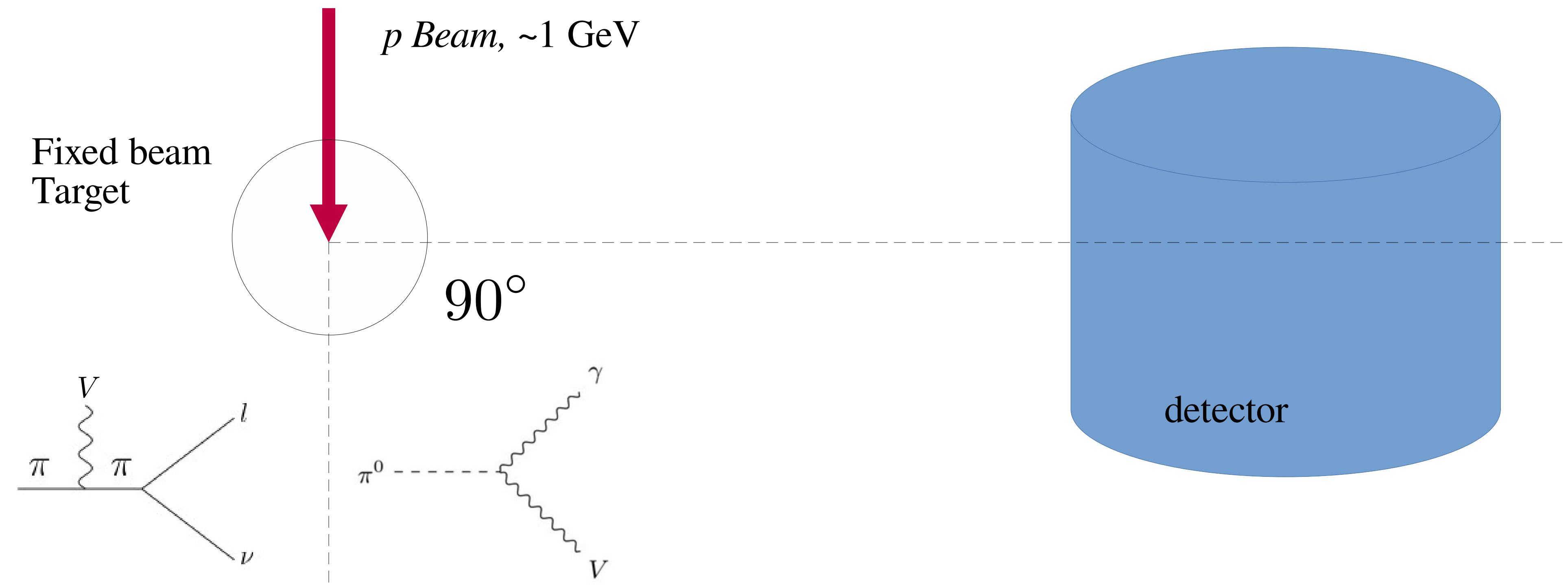
$$\mathcal{L}_{hp}^{\chi PT} \supset (2g_u + g_d)\frac{e}{16\pi f_\pi}\pi^0 F_{\mu\nu}\tilde{H}^{\mu\nu}$$





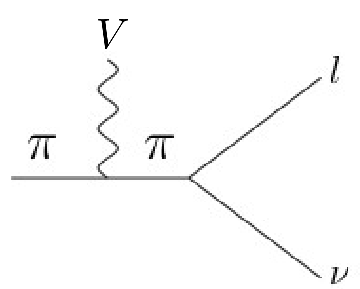
$g_{\pi NN} = 13$

Probing the Meson-portal Dark Sector at Stopped-Pion Facilities



- Beam targets with meson focusing: <u>charged pions dominate the signal</u>
- Stopped-pion beam target: <u>neutral and charged pion equity</u>
- If the dark sector enters the chiPT, we should test both **neutral** and **charged** meson couplings! → complementarity between stopped pion and high energy beam dump facilities

Testing this explanation at CCM (Coherent CAPTAIN-Mills)



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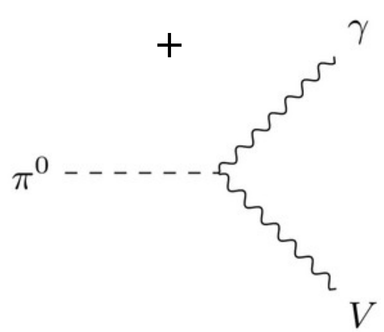
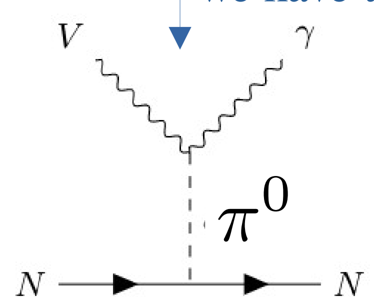
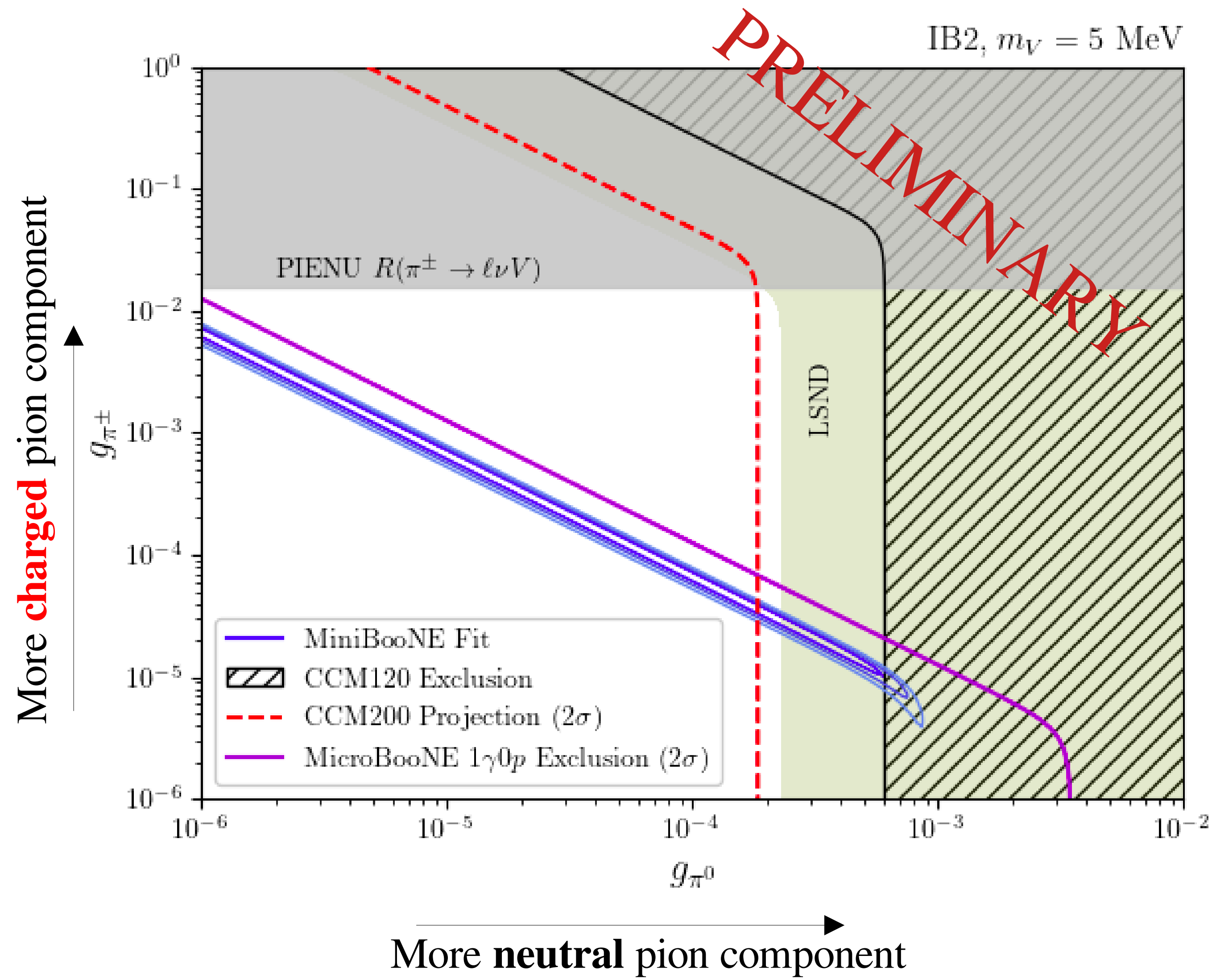


If we have one,
we have the other



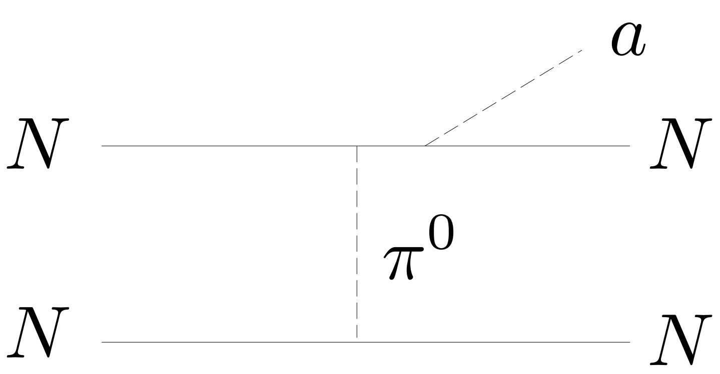


CCM120 Engineering run data
Paper forthcoming

The Neutron ~~Problem~~ *Solution*

(teaser for upcoming work)

Neutron / Nucleon Bremsstrahlung of Axions and Dark Photons

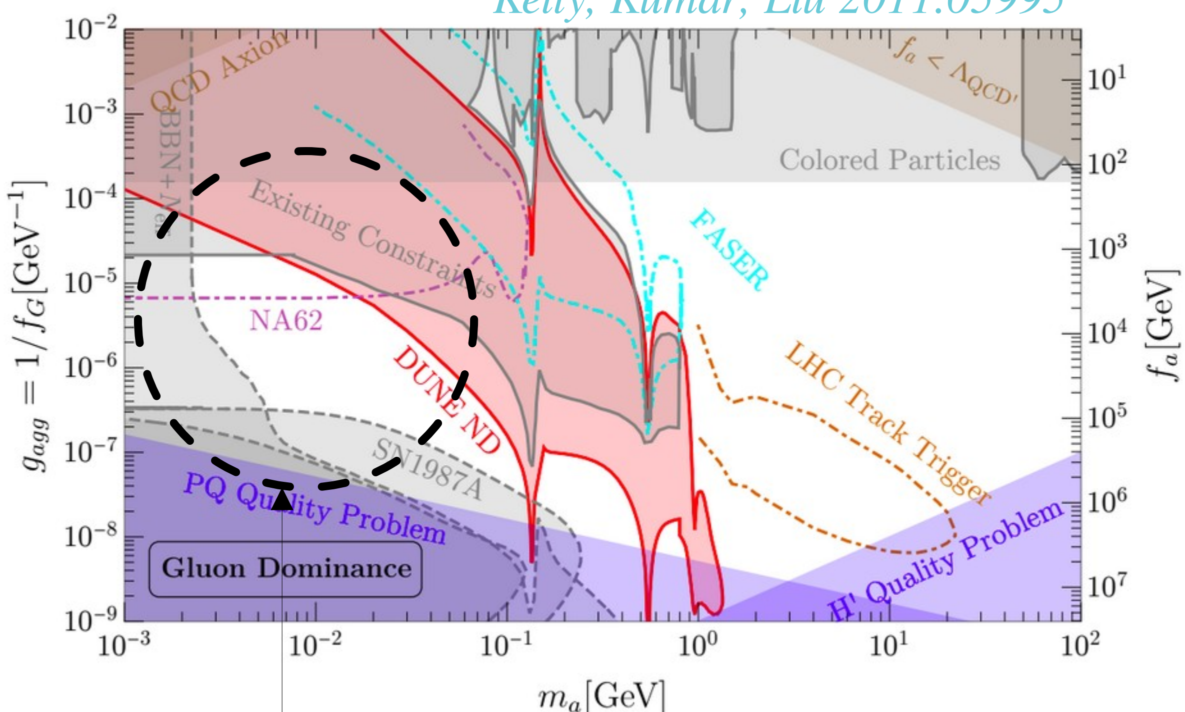


Spallation neutron sources have high intensity neutrons interacting with high-Z environments could make for *good intensity frontier probes* of QCD ALPs

- Nucleon bremsstrahlung of dark bosons studied intensely in stellar environments (neutron stars!)
- Sensitive to difference between derivative (pNGB) and yukawa-type couplings;

$$g_{an} a \bar{n} \gamma^5 n \quad \textit{vs.} \quad \frac{\partial_\mu a}{f_a} \bar{n} \gamma^\mu \gamma^5 n$$

Kelly, Kumar, Liu 2011.05995



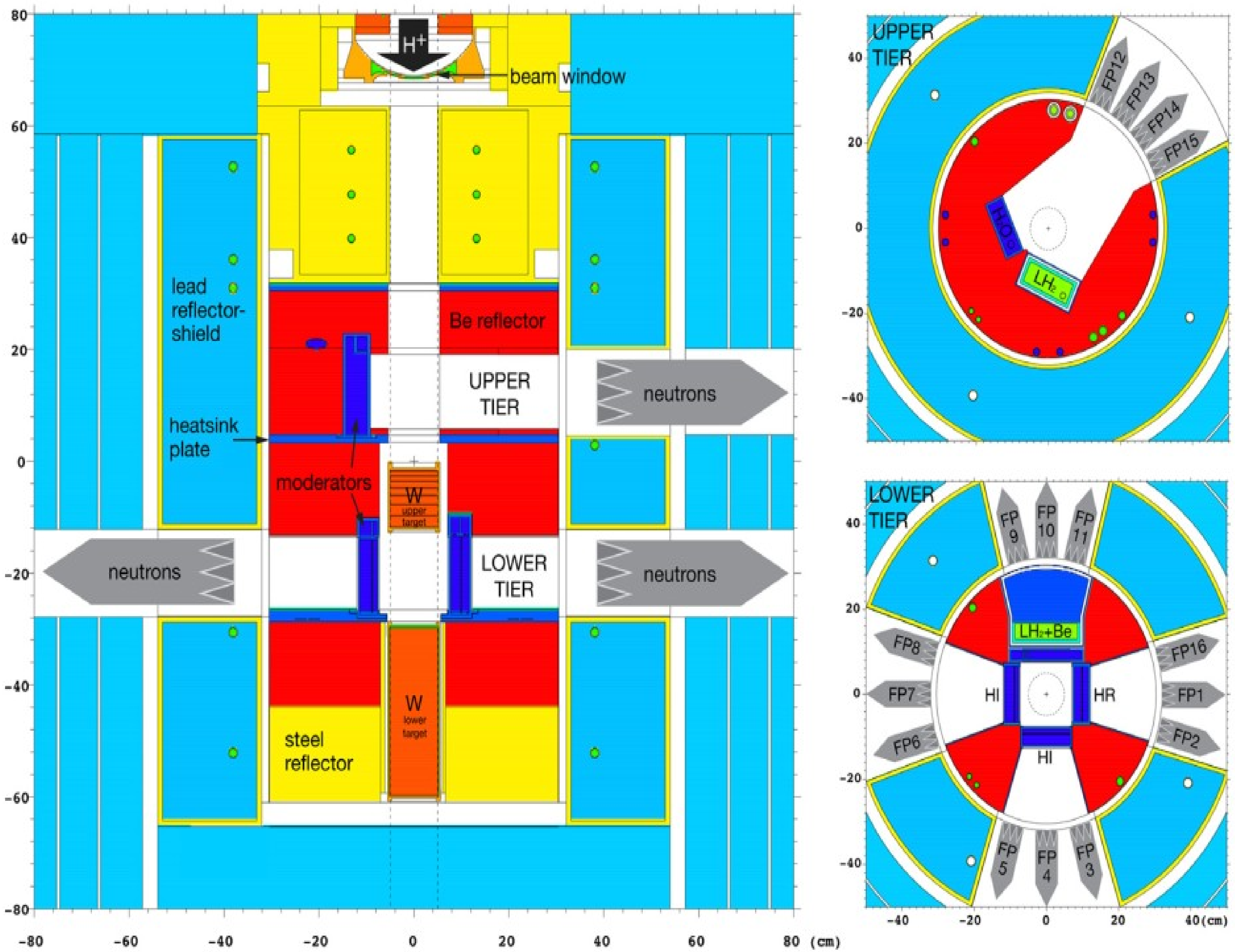
Target space for MeV probes: Can we test this space with neutron sources?

Outlook

- Significant hints that if the MB anomaly is explained by BSM, it should be correlated to the charged mesons (and possibly entire meson octet?) and testable at stopped pion facilities
- We need to understand the proton beam target environment and particle shower pheno → many portals for BSM studies
- More progress on understanding neutron fluxes is being made → good for background estimation + leveraging for new BSM production channels
- There are a multitude of exciting BSM probes available to us at CCM and stopped-pion experiments at MeV energy scales, prompting a complimentary BSM program to the CEνNS program

Backup Deck

CCM Target Geometry and Neutron Production



CCM120 Engineering Run

800 MeV protons, 100kW, 290 nsec pulsed beam