LA-UR-24-31100

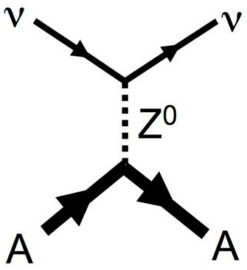
Beyond the Standard Model Interactions at Coherent CAPTAIN Mills

Dark Interactions 2024
Vancouver

Edward Dunton
On behalf of the CCM Collaboration

October 16, 2024

The Coherent CAPTAIN Mills (CCM) Experiment



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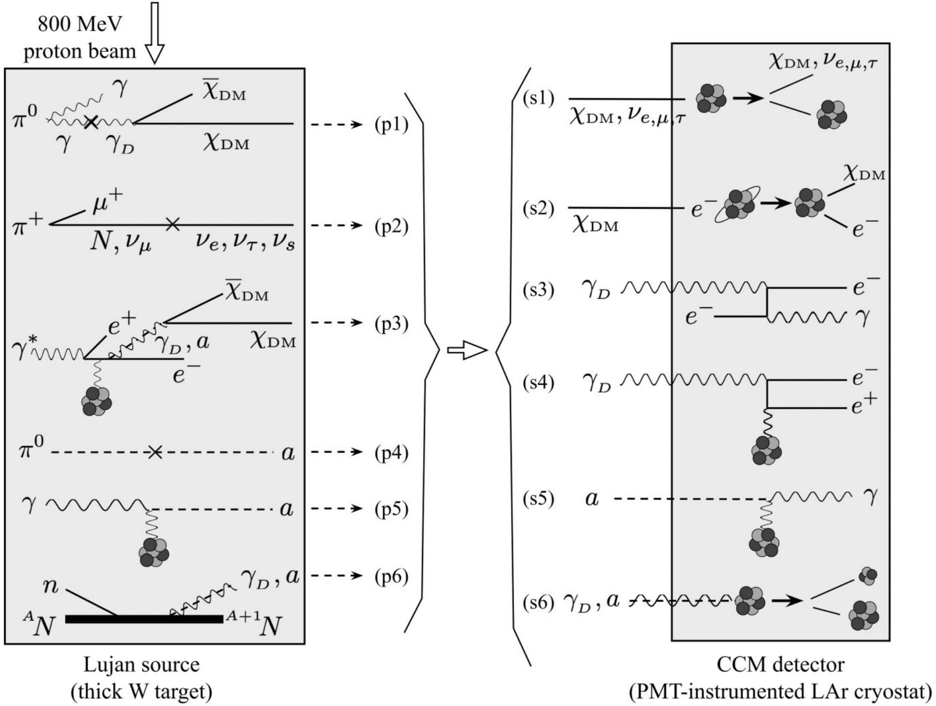
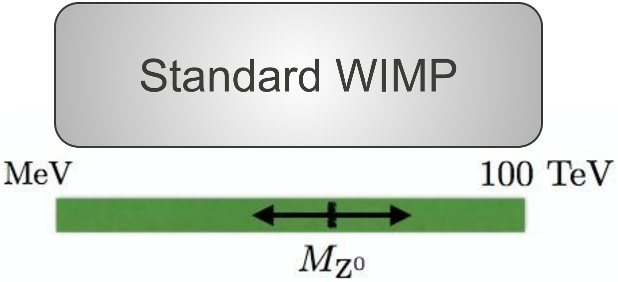
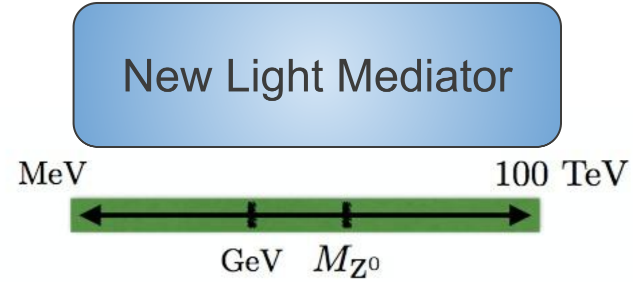


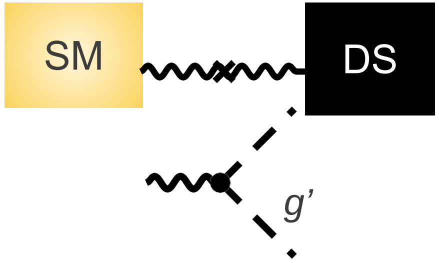
Vector Portal Light Dark Matter



- Assumes mediator is at the weak scale
- Strong constraints from cosmology, astrophysics, and colliders



- Does not assume mediator is the Z boson
- Simple parameterization of DM + Mediator:
  - 4 free parameters
    - Mass of the dark photon m_V
    - Mass of the dark matter m_χ
    - Mixing angle between SM and dark sector ε
    - Coupling between dark photon and dark matter α_D



Produce Dark Sector in Standard Model particle cascades in fixed target experiments

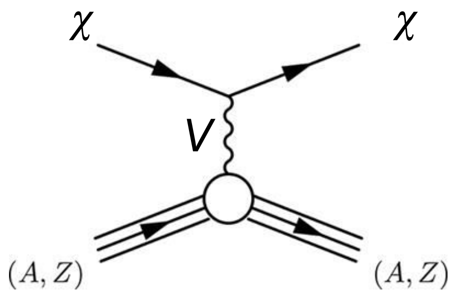
MiniBooNE beam dump mode first dedicated DM search in this way

Phenomenology: Vector Portal Light Dark Matter

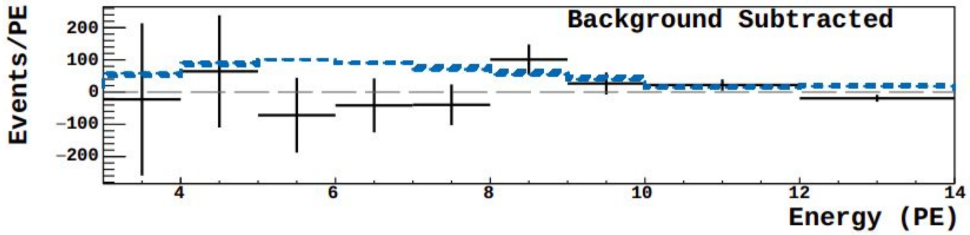
One example:

$$\mathcal{L}_B \supset -V_B^\mu \left(g_B J_\mu^B + g_\chi J_\mu^\chi + \epsilon_B e J_\mu^{\mathrm{EM}} \right)$$

$$J_\mu^B \equiv \frac{1}{3} \sum_i \bar{q}_i \gamma_\mu q_i$$

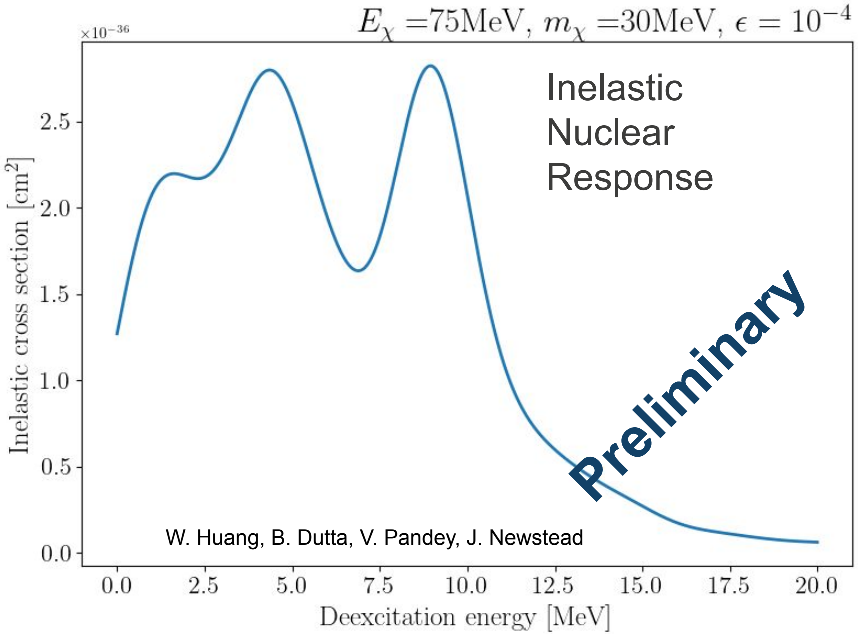


Coherent Elastic Scattering

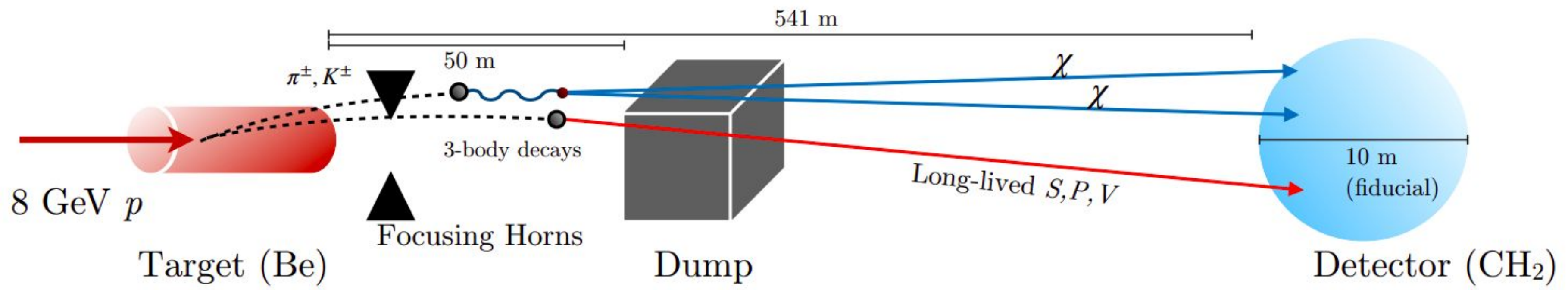


Phys. Rev. Lett. 129 (2022) 2, 021801 [2109.14146]

- Two Detection Modes:
- Elastic nuclear recoils → **keV** signature
- Inelastic response → **MeV** Argon nuclear de-excitations

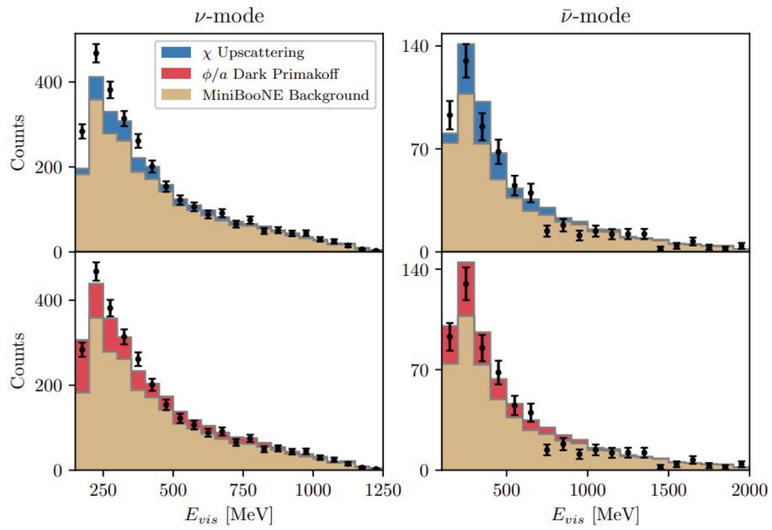


Dark Sector Explanations of the MiniBooNE Anomaly



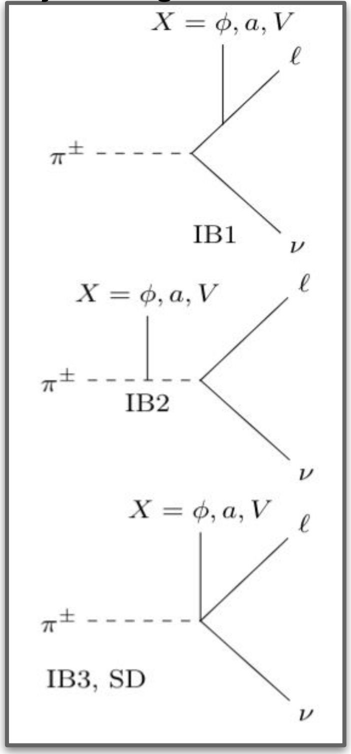
Phys.Rev.Lett. 129 (2022) 11, 111803

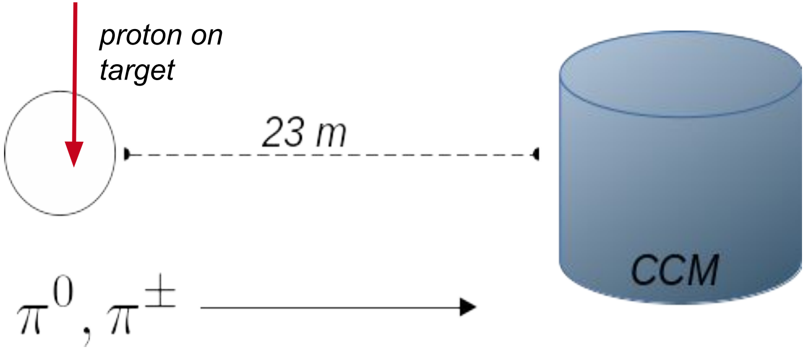
- 4.8σ excess at MiniBooNE target mode runs
- No excess in dump mode run
- If excess is due to new long-lived particles (**LLPs**) or light dark matter (**LDM**), it may be correlated to rare charged meson decays [*PRL* 129 (2022) 11, 111803]
- We can test this possibility at CCM



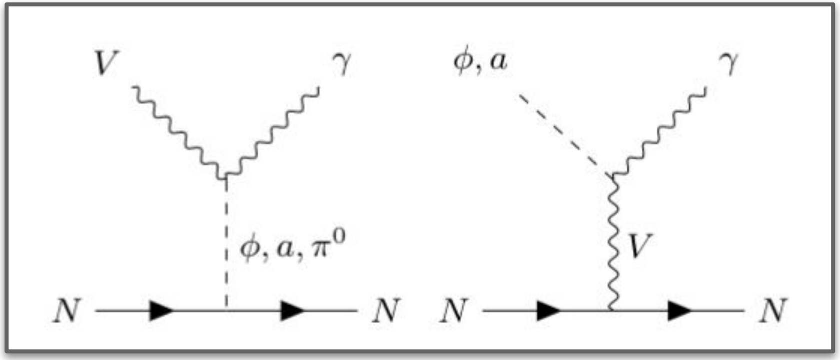
Phenomenology: Dark Sector Coupling to Meson Decays (DSCMD)

3-body pion decay in Lujan Target





Inverse-Primakoff like detection in CCM



Primakoff / Photoconversion Scattering Model

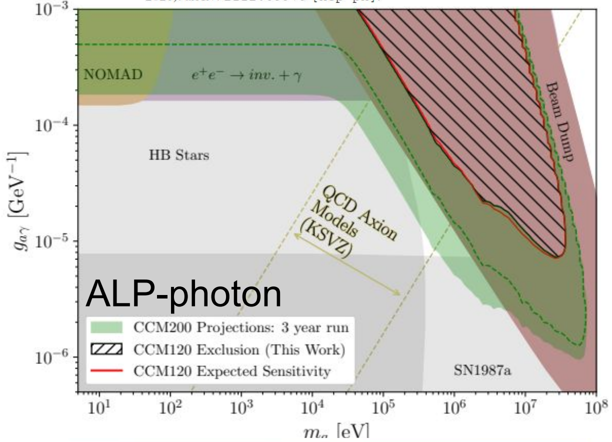
Decay Model	Scalar Mediator	Pseudoscalar Mediator	SM Pi0 Mediator	Vector Mediator
Scalar IB1 (e)	Dimension-4	Dimension-4	Dimension-4	✓
Scalar IB1 (mu)	Dimension-4	Dimension-4	Dimension-4	✓
Pseudoscalar IB1 (e)	Dimension-4	Dimension-4	Dimension-4	✓
Pseudoscalar IB1 (mu)	Dimension-4	Dimension-4	Dimension-4	✓
Vector IB1 (e)	✓	✓	✓	Anomalous
Vector IB1 (mu)	✓	✓	✓	Anomalous
Vector IB2 (e+mu)	✓	✓	✓	Anomalous
Vector contact (e+mu)	✓	✓	✓	Anomalous

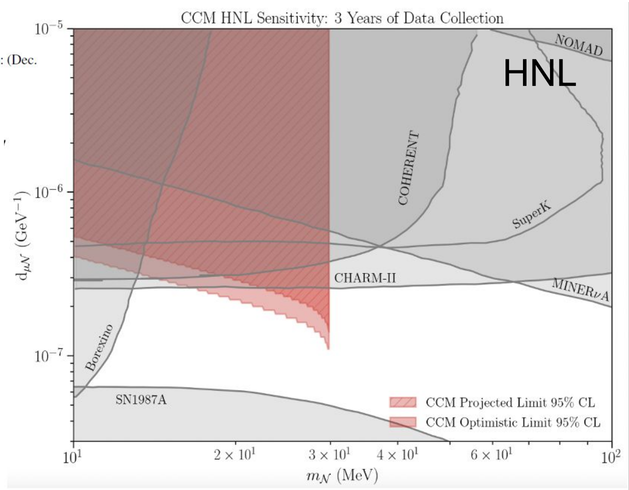
- Wide variety of models combining decay model and scattering model.
  - So far limited focus, but scope is total.
- CCM (stopped pion) tests in a complementary way to MiniBooNE (focused pion) and similar experiments.

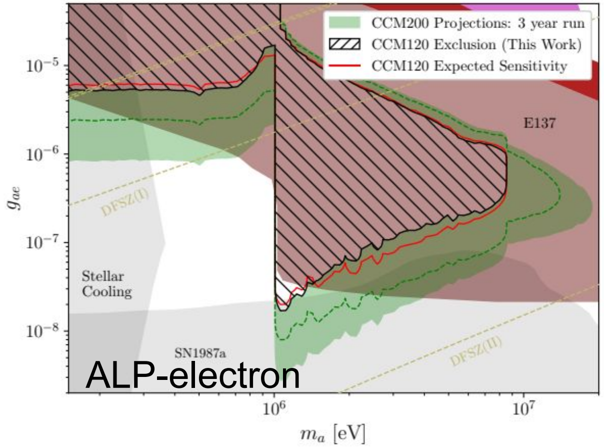
…and many more models!

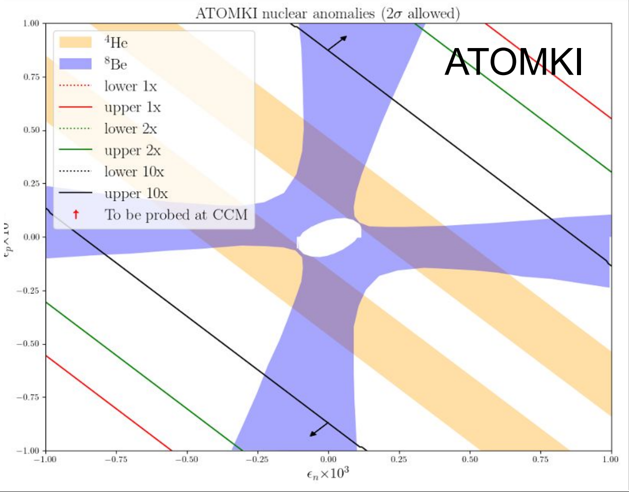
- Axion-Like Particles (ALPs)
- Heavy Neutral Leptons (HNL)
- ATOMKI Anomaly
- CEvNS neutrino search
- ν_eCCQE cross section measurements
- Mirror neutrons
- Etc…

A. A. Aguilar-Arevalo et al. "Axion-Like Particles at Coherent CAPTAIN-Mills". In: (Dec. 2021). arXiv: 2112.09979 [hep-ph].





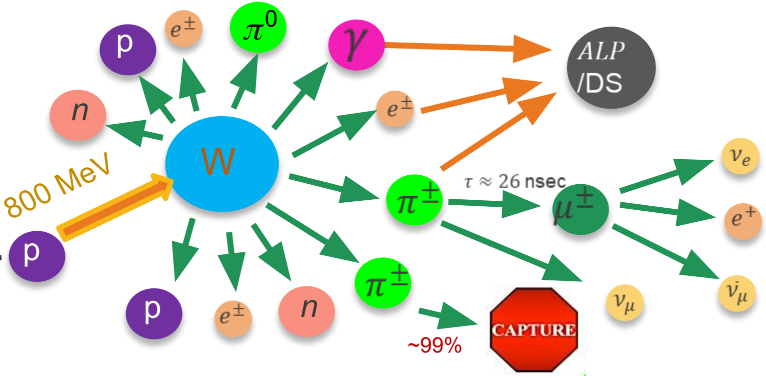




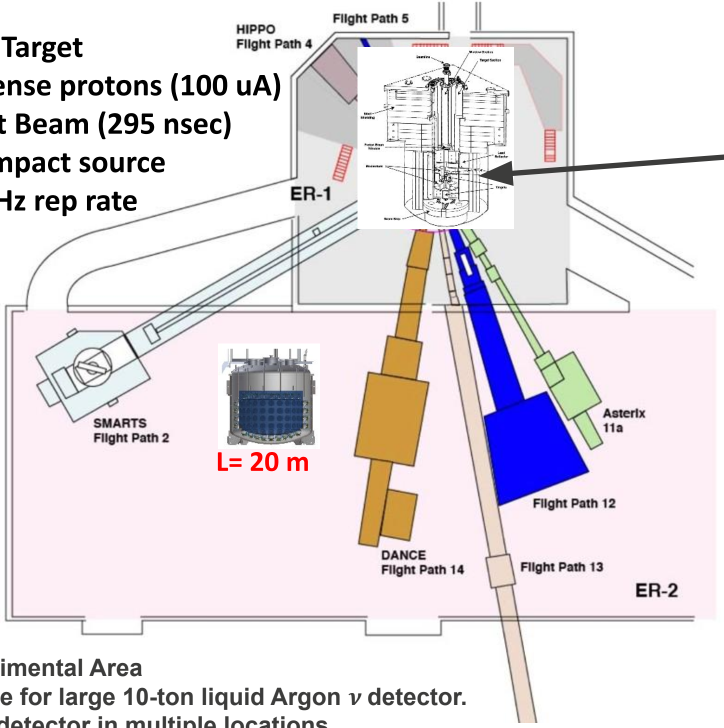
The CCM Experiment: LANSCE-Lujan Facility

Nuclear Instruments and Methods in Physics Research A 594 (2008) 373–381
Nuclear Instruments and Methods in Physics Research A 632 (2011) 101–108

Intense source muon neutrinos: target MCNP simulation flux 4.74x10^5 ν/cm^2/s at 20 m



Lujan Target
- Intense protons (100 uA)
- Fast Beam (295 nsec)
- Compact source
- 20 Hz rep rate



CCM120 beam and calibration run 2019 (L=20 m)

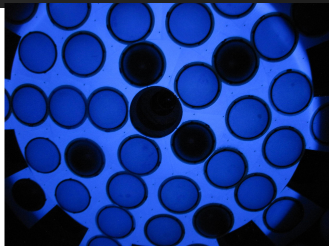
Lujan Experimental Area
- Space for large 10-ton liquid Argon ν detector.
- Run detector in multiple locations.
- Room to deploy shielding, large overhead crane, power, etc

The CCM120 Detector: 2019 run

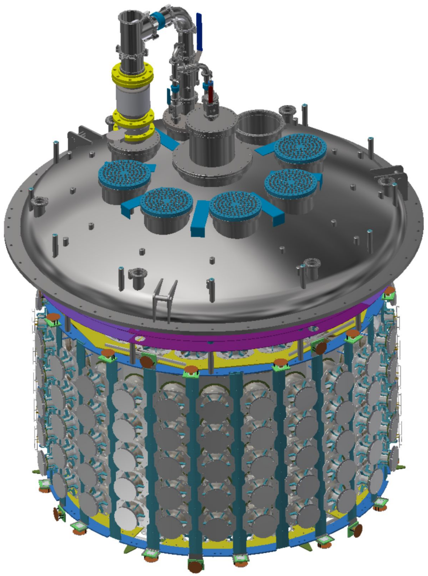
- Mounted in the 10 ton CAPTAIN cryostat.
- 7 tons LAr Fiducial volume, 3 tons LAr Veto (2-3 radiation lengths)
- 17 1” and 5 8” Veto PMTs instrument LAr Veto region.
- 120 R5912 PMT’s, wavelength shifting TPB foils
  - LAr cold test of the entire SBND PDS system: 96 TPB coated + 24 uncoated PMT’s, mounts, cables, feed thrus, HV, electronics, trigger, DAQ, calibration, simulations and data analysis. -> **now installed in SBND**

- 6-week Engineering run in 2019 collected **1.79×10^{21}** Protons on Target (POT).

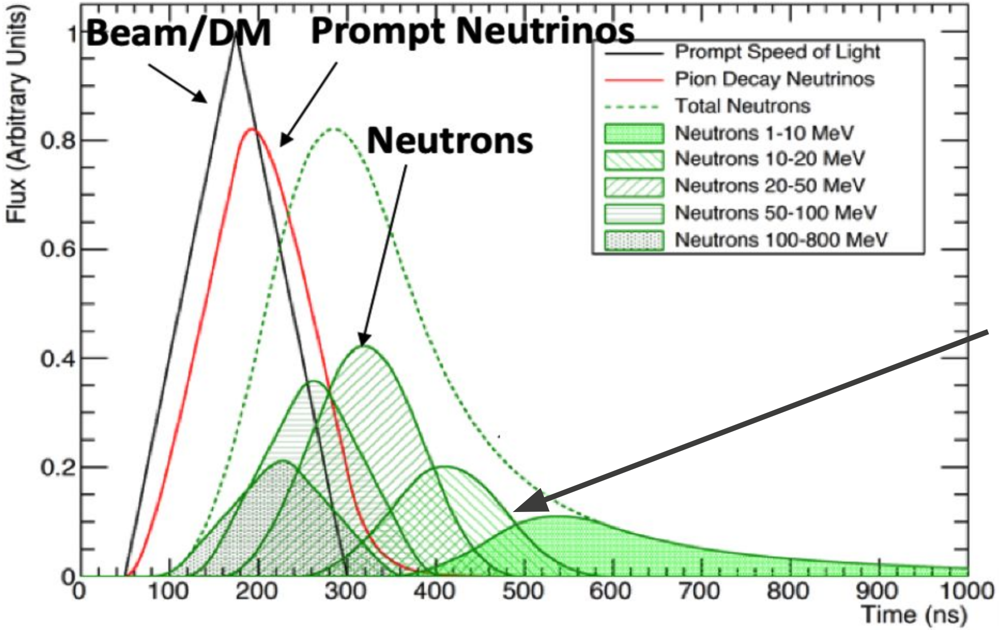
The CCM200 Detector: 2021 to 2025 runs.



- Instrument all 120 cylinder 8” PMTs with new PMTs
- + Instrument 40 8” PMTs on each end cap => total **200 new 8” PMT’s**.
- 40 1x1” vetos instrument outer region (double veto PMTs)
- Evaporative TPB foils (double efficiency of CCM120 foils) produced at U. Edinburgh.
- CCM200 detector built July 2021, initial test run done October-December 2021 collected $\mathbf{1.9 \times 10^{21}}$ POT.



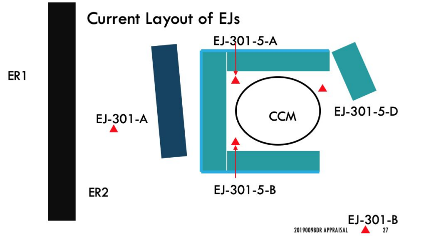
The CCM Detector: Using fast timing and shielding to remove beam-related neutrons



EJ301 MEASUREMENTS

Five EJ-301 detectors were used to detect neutrons at different locations around CCM

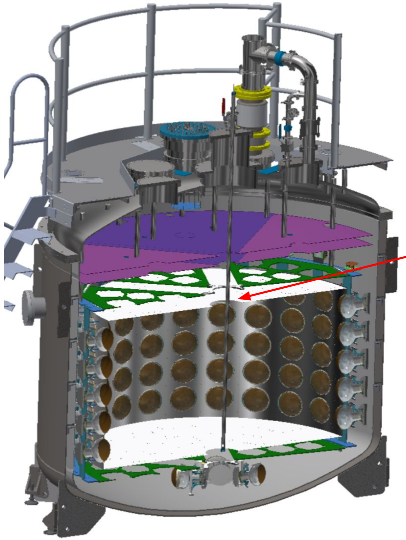
- EJ-301 liquid scintillator exhibits excellent pulse shape discrimination (PS) properties



External time of flight measurements with EJ301 detectors measure ~20 MeV fastest neutrons

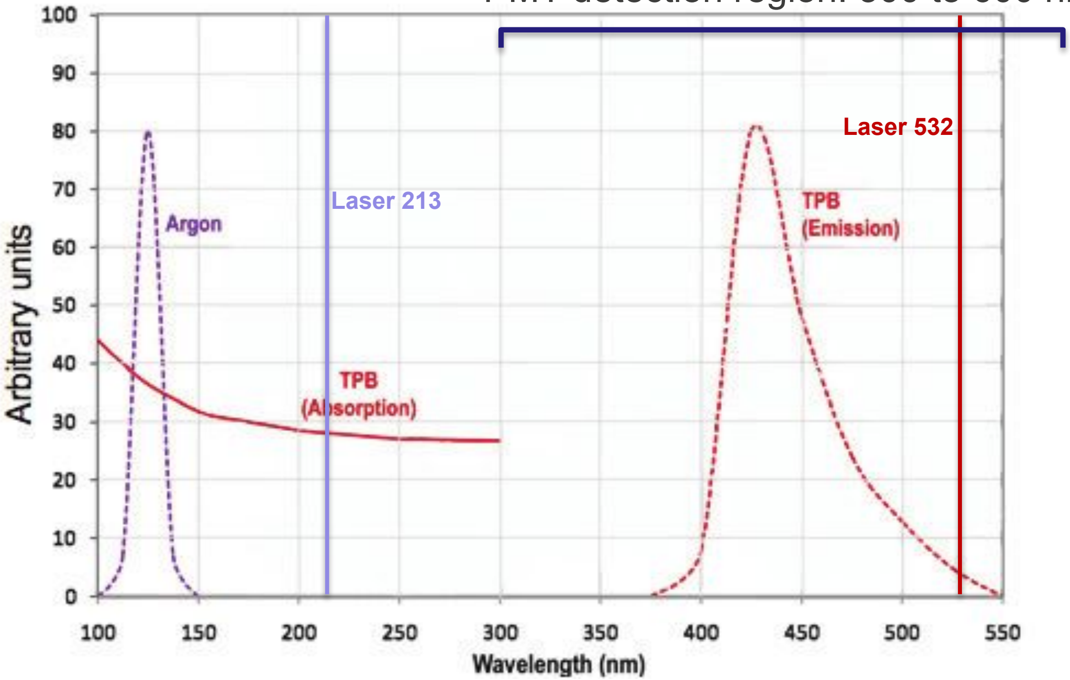
- Extensive 4m steel shielding around target and detector slows down neutrons
- EJ-301 n/γ detector time of flight measurements indicate fastest neutrons ~20 MeV.
- Analysis of CCM120 data shows 210 nsec signal region free of neutrons.

The CCM Detector: Calibrations



Inserted Source Calibration Rod down the center of the detector

PMT detection region: 300 to 600 nm

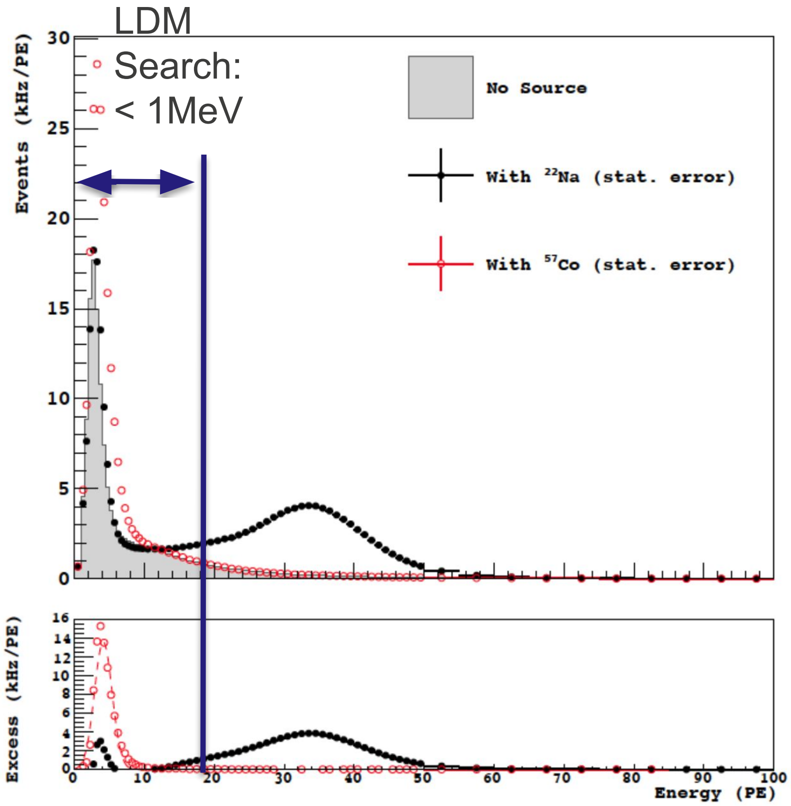


- Laser/Diffuser for 213/532 nm calibrations to test TPB response for foils and PMTs and the LAr properties.
- LED calibrations for PMT gain/timing
- Co-57 source provide energy scale calibration 122 keV gamma-ray.
- Na-22 source provide energy scale calibration 2.2 MeV gamma-rays.
- Radioactive sources provides position reconstruction calibration.

CCM=Optical Detector
Light Properties need to be very well known.

CCM120 Searches: Energy Regimes

- 2 Types of Searches: Electromagnetic and Nuclear Recoil
- 3 Energy Regimes for Searches:
  - **< 1 MeV** – Light Dark Matter (nr like)
    - Threshold 3 PE ≈ 200 keV up to Maximum 18 PE ≈ 2 MeV.



A. A. Aguilar-Arevalo et al. "First dark matter search results from Coherent CAPTAIN-Mills". In: *Physical Review D* 106.1 (July 2022).

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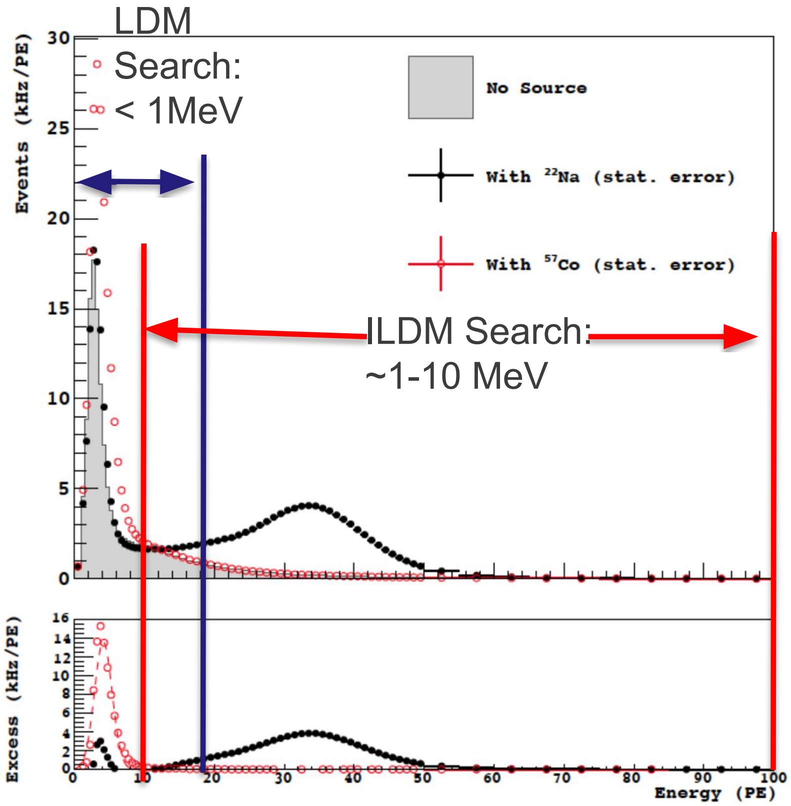
  - **~1-10 MeV** – Inelastic LDM (em like)
    - From minimum 10 PE ≈ 500 keV up to Maximum 200 PE ≈ 10 MeV.



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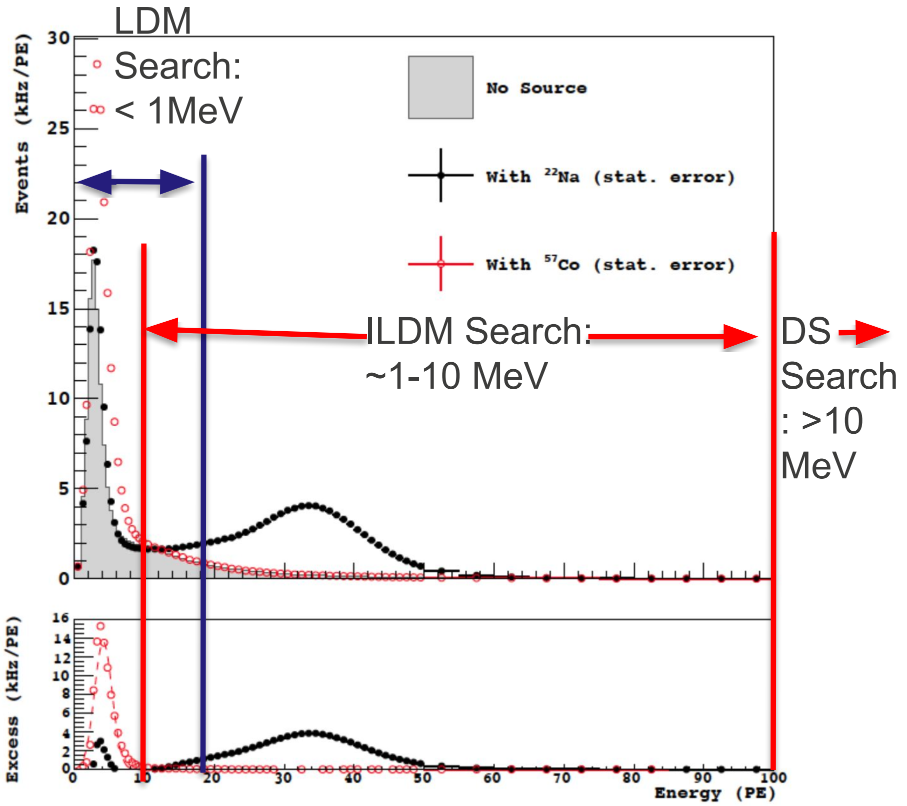
    - Threshold 3 PE ≈ 200 keV up to Maximum 18 PE ≈ 2 MeV.
  - **~1-10 MeV** – Inelastic LDM (em like)
    - From minimum 10 PE ≈ 500 keV up to Maximum 200 PE ≈ 10 MeV.
  - **> 10 MeV** – Dark Sector (em like)
    - From 200 PE ≈ 10 MeV.
- CCM200 uses similar energy regimes, with different PE scales and a lower threshold.



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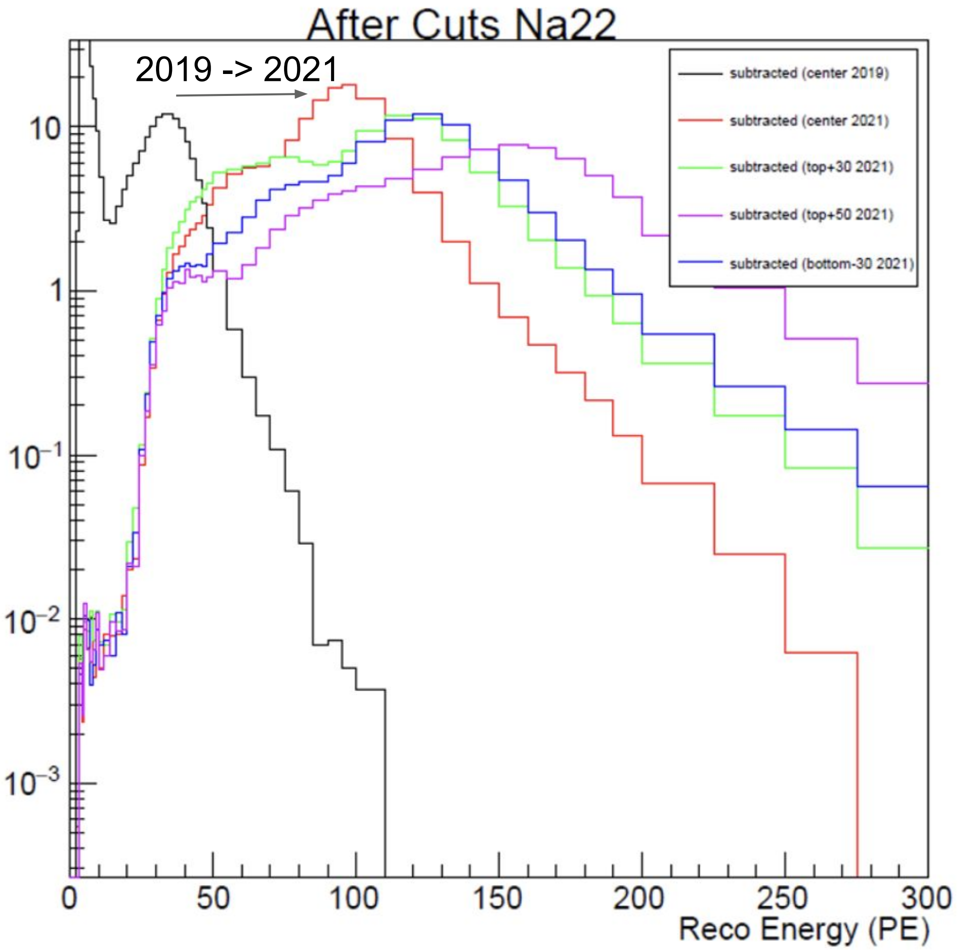
CCM200 2021 Searches: Energy Scale

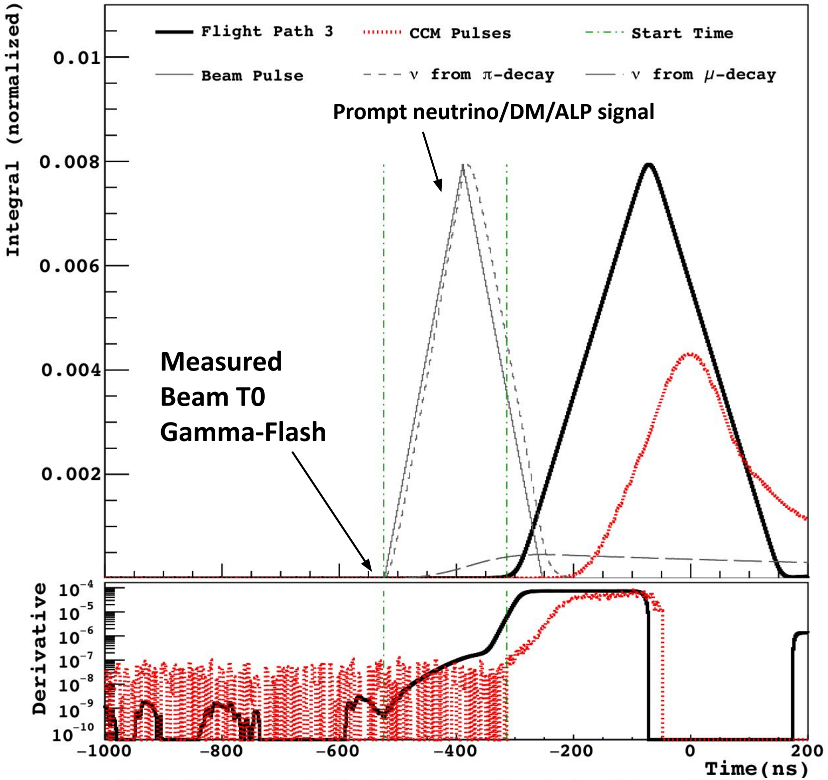
- The 2021 Data set had a very different energy scale from 2019.
- Using the Na22 calibrations at the center of the detector, we found a **3:1** improvement in energy scale for CCM200.
- We also mapped out various positions inside the detector along the central axis, giving us some information on the position-dependent smearing.

- Using a 40ns prompt integral, we found **~30 PE/MeV**.



CCM120 Analysis: Beam Related Background Free Region of Interest (ROI)

- Timing of massive importance to CCM efficiency.
- We define a **ROI** that includes only **steady state** (measurable in prebeam!) backgrounds.
- Directly measured T0 with the "FP3 detector."
- **T0 = -530 ns** DAQ time
  - Defines start of ROI for all searches.
- Determined speed of light particles from target to arrive 150 ns before neutron events seen in CCM



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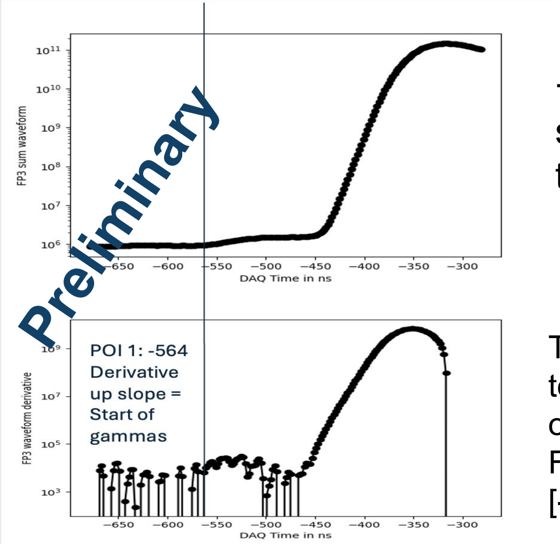
CCM200 2021 Analysis: Region of Interest (ROI)

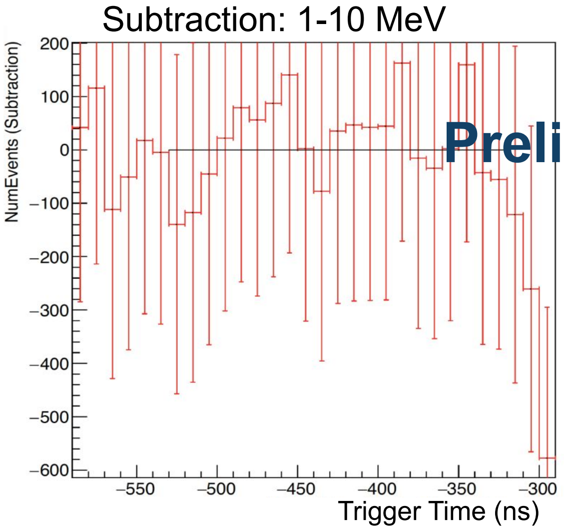
- The start of the 2021 ROI was the same as in 2019: -530 ns.
- The end, however, was delayed an additional 40-60 ns, depending on the T_0.
  - Determined by a significant change in cut efficiency and event rate (seen below)

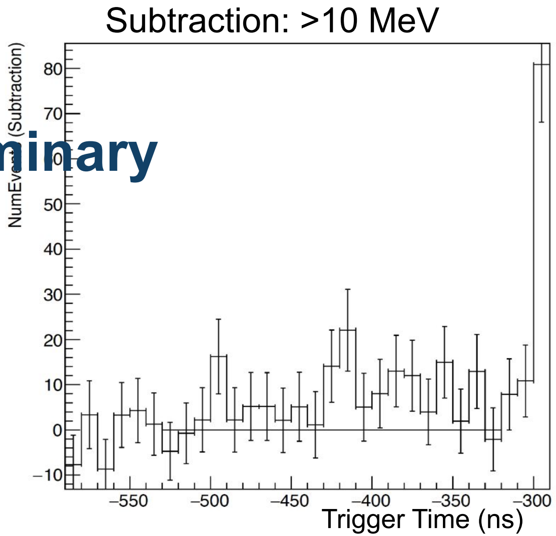
- 2021 had a final ROI of **210 ns** (representing 84% of prompt BSM signal), versus **150 ns** in 2019 (<50% of prompt BSM).



+38 ns
shift FP3
to CCM

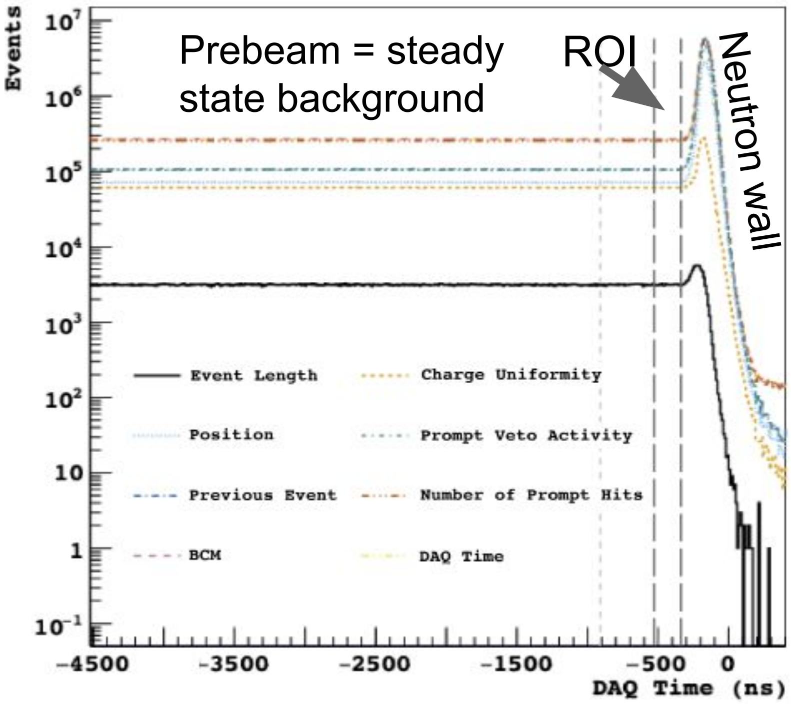
T_0 rounded to lower limit of uncertainty.
Full range = [-530,-504]





All Searches:
Data Quality / Pre-selection Cuts

- Data Quality cuts meant to ensure the events were useable.
  - Number of Hits
  - Previous Event
  - Veto
  - Fiducial Volume
  - Event Time
  - Beam Current Monitor (BCM)



(a) DAQ Time

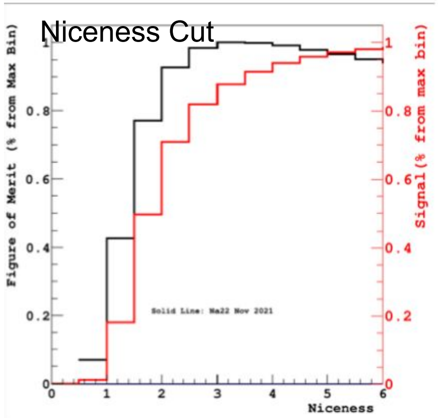
Data Quality Efficiency Table

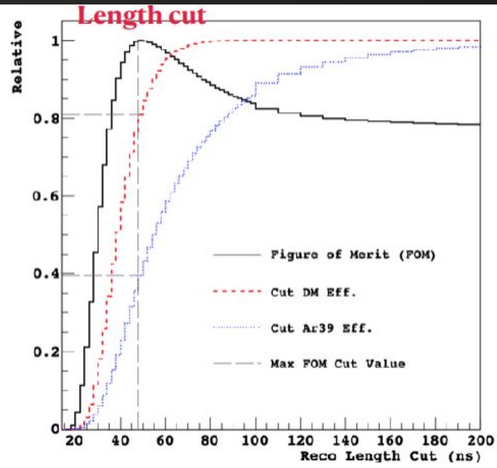
Cut	numHits	previousEvent	Veto	fiducialVolume	eventTime
Efficiency	0.510	0.238	0.236	0.149	0.0037

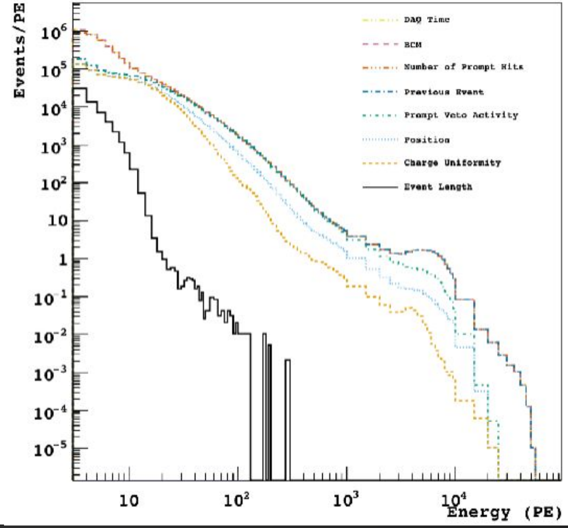
CCM NR Search: Event Characteristics

- In CCM, LDM events will involve coherent-like scattering of Argon nuclei
- Nuclear-recoil type events,
  - No triplet light
  - Additional nuclear recoil quenching factor of ~0.25.
- => Short in length and low in visible energy.

- Cuts:
  - **Length < 44ns**: a cut on the maximum length of the event (PID).
  - **Niceness/Charge Uniformity**: cut on charge distribution evenness between PMTs.



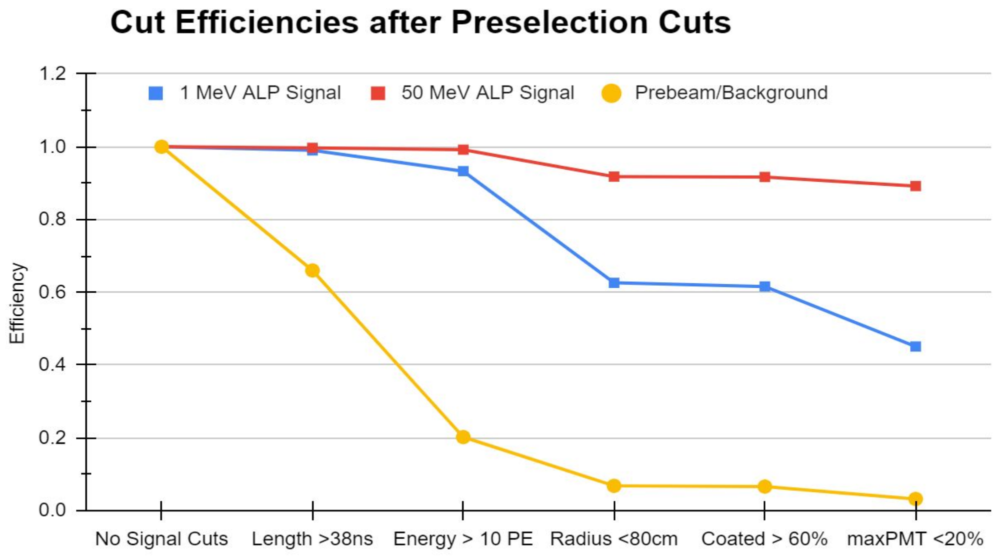




Black = LDM search final sample

CCM120 E/M Search: Signal Cuts

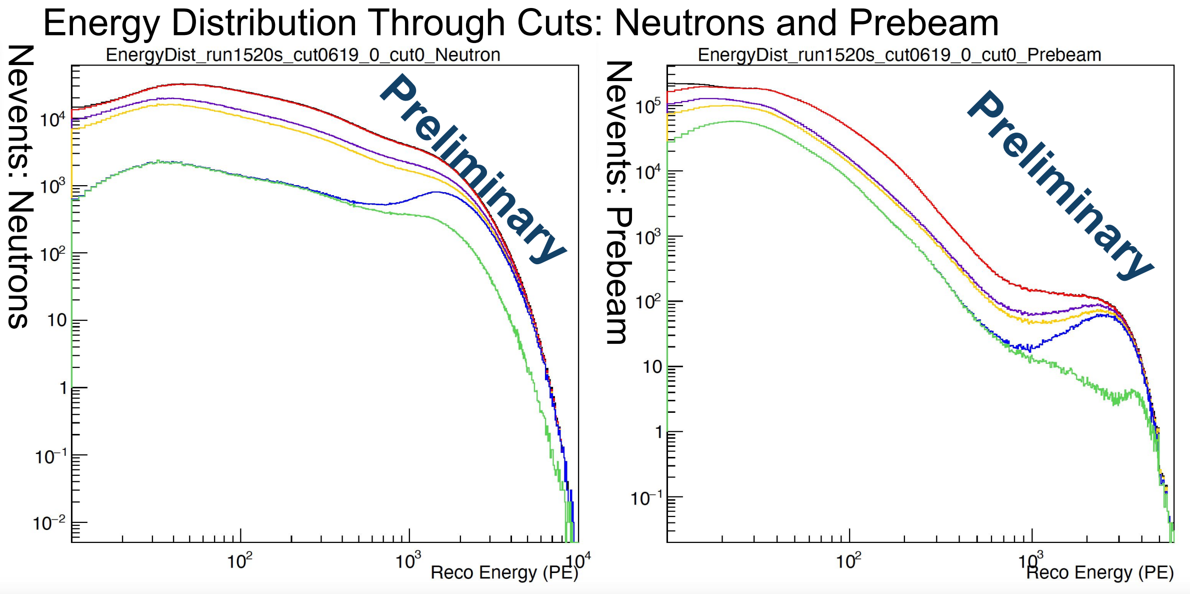
- In addition to the Data quality cuts from the LDM search (Previous Event, numHits, Veto, Niceness) we added 4 cuts for the E/M search based on signal characteristics.



- **Length > 38ns:** Electron like ALP events have triplet light and long length.
- **Radius < 80cm:** A stricter position cut due to the isotropic nature of the signal.
- **Coated > 60%:** More than 60% of the light seen is seen by TPB coated PMTs in scintillation events.
- **maxPMT < 20%:** No more than 20% of the total light is seen by a single PMT in simulated e/m like events or calibration source events..

CCM200 E/M Search: Signal Cuts

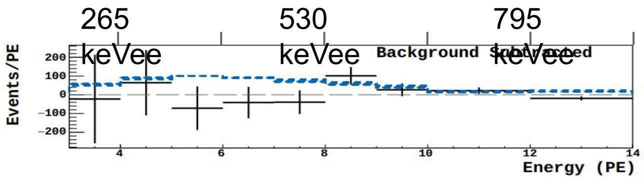
- The 2021 Analysis used the same data quality cuts as in 2019.
- However, the event selection cuts were slightly different.

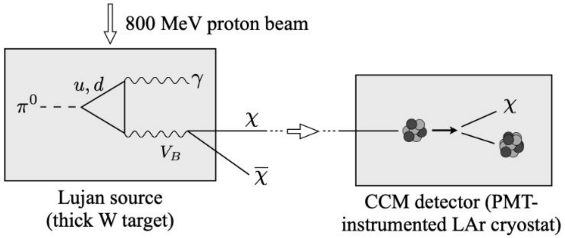


- **Length > 54 ns**: increased from 2019 but otherwise unchanged.
- **Radius < 80 cm:** repeat from 2019.
- **maxPMT < 20%:** repeat from 2019.
- **Cherenkov-light > 2%**: A new cut searching for potential Cherenkov light in the uncoated tubes in the first 10 ns of the event.
- **Prop20>10%:** A new cut removing events with too slow of a turn on, characteristic of neutron multiple scattering.

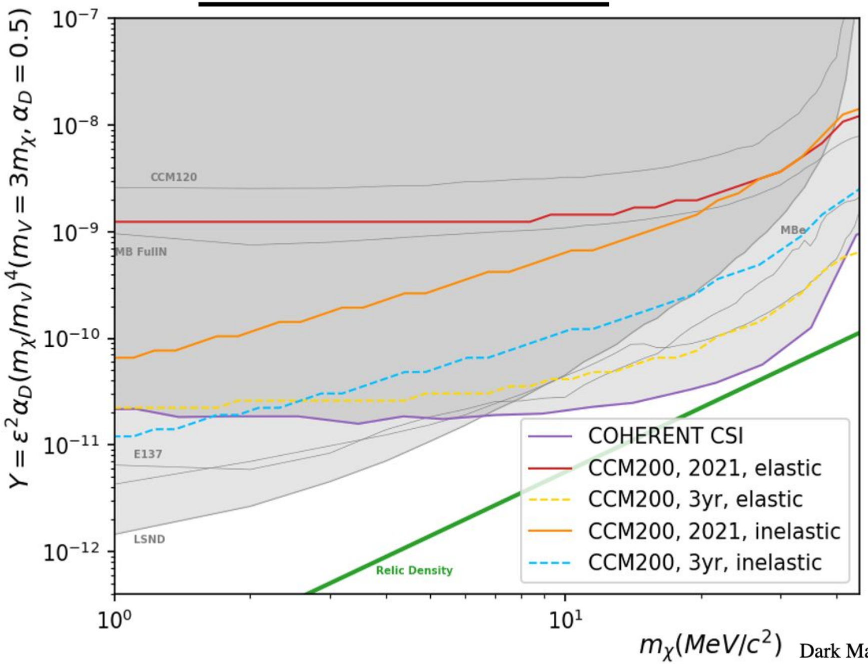
CCM LDM Sensitivities: Elastic and Inelastic

- Null result observed in both 2019 and 2021
- Exclusions produced for elastic and inelastic phenomenology

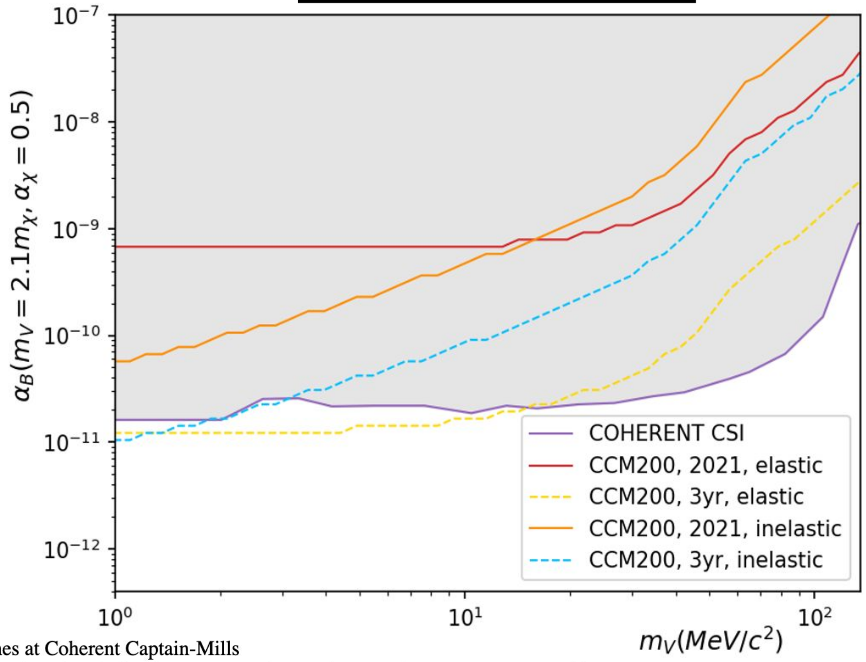




Vector Portal Model



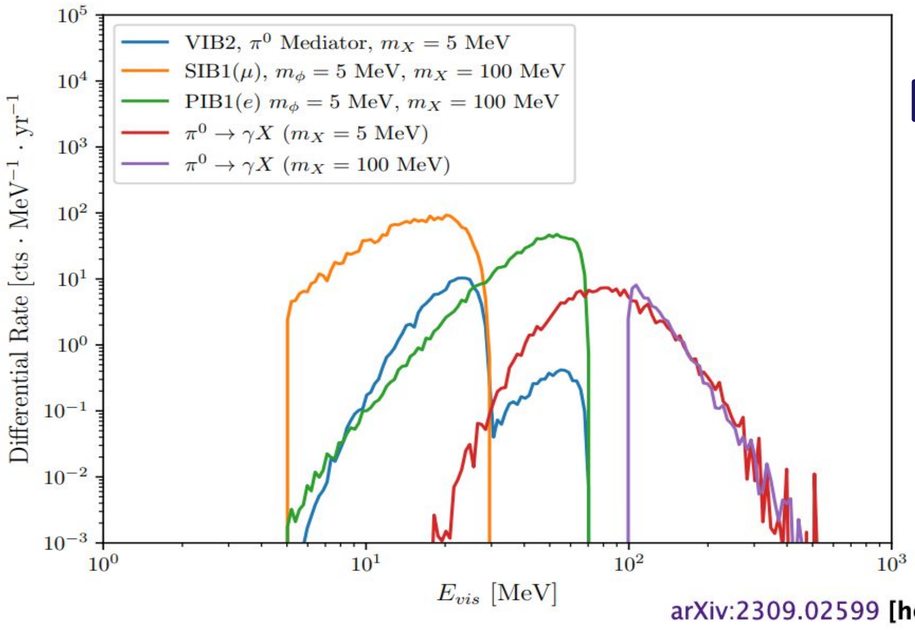
Leptophobic Model



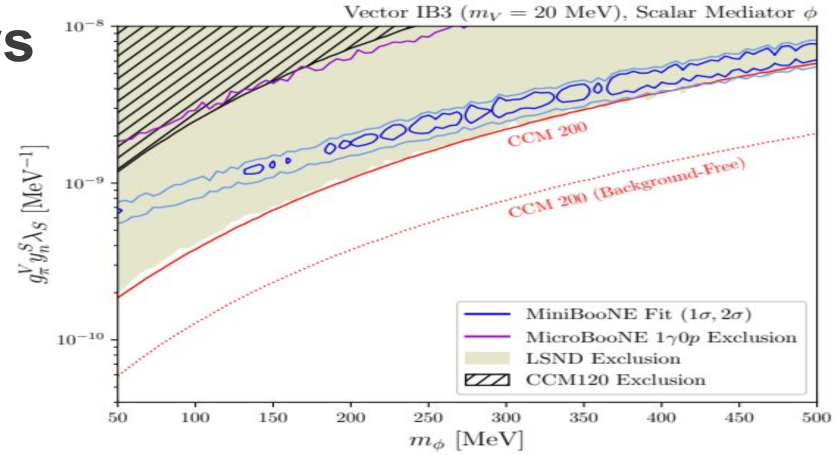
Dark Matter Searches at Coherent Captain-Mills
Tripathi, Mayank. University of Florida ProQuest Dissertations & Theses, 2024.31144965.

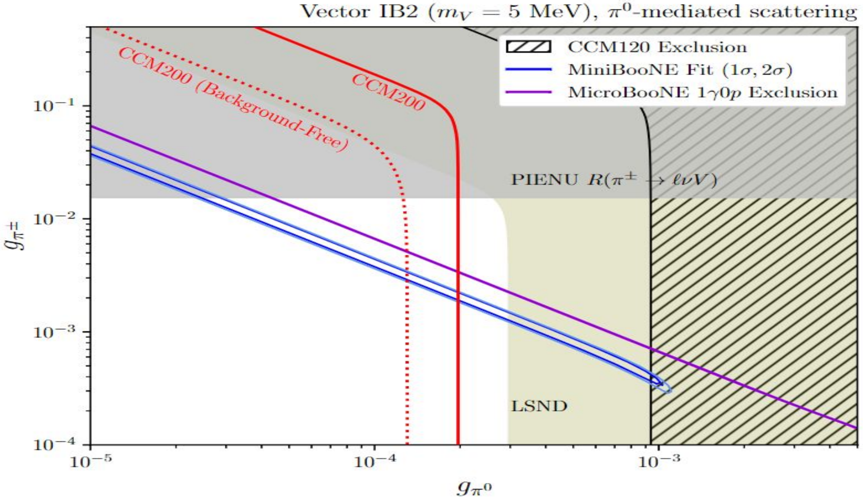
Dark Sector Coupling to Meson Decays (DSCMD): 2-Mediator Models

- DSCMD fits to MiniBooNE data for
  - Target Mode: Neutrino + Antineutrino excess
  - Dump Mode: null result as a constraint
- CCM tests this model using neutral pion couplings

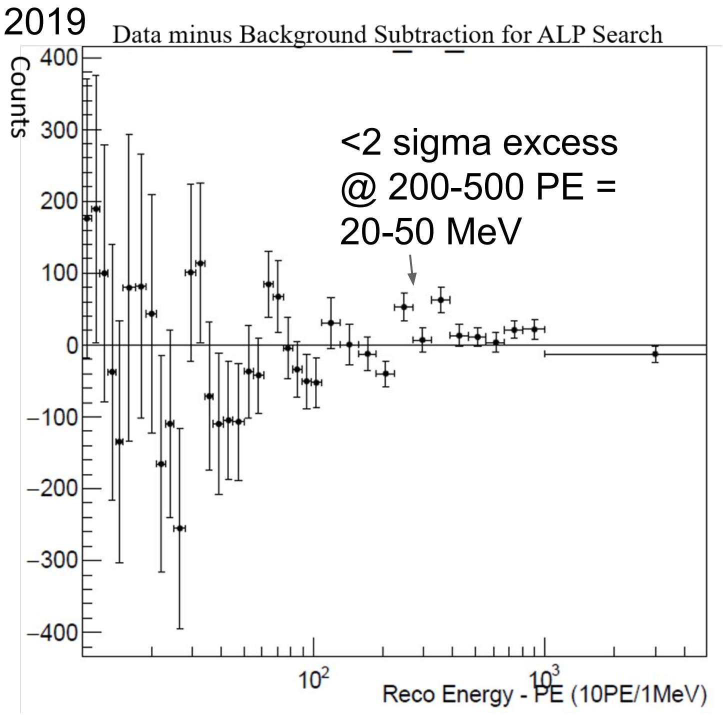


arXiv:2309.02599 **[hep-ph]**



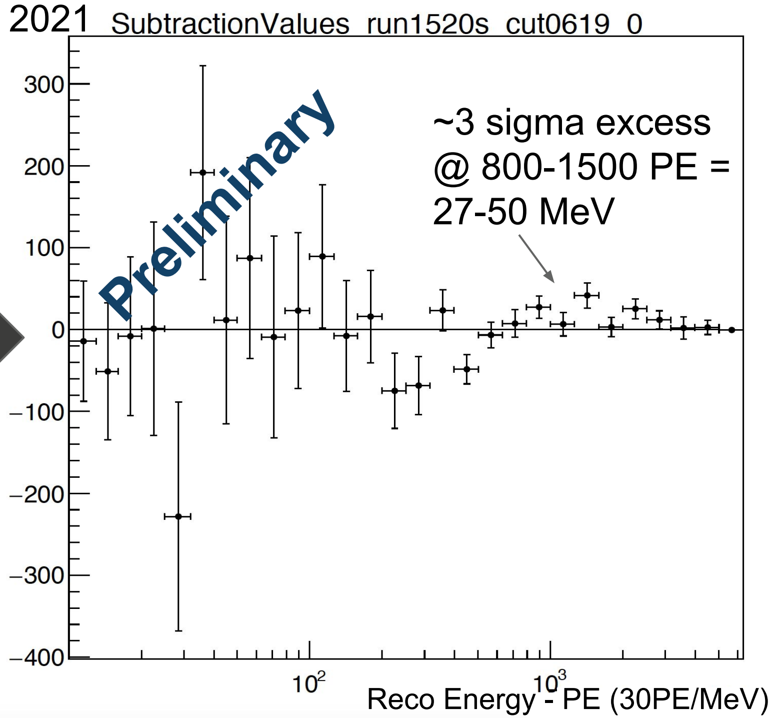


CCM120 2019 vs. CCM200 2021 Subtractions



+Added shielding, +3 m distance,

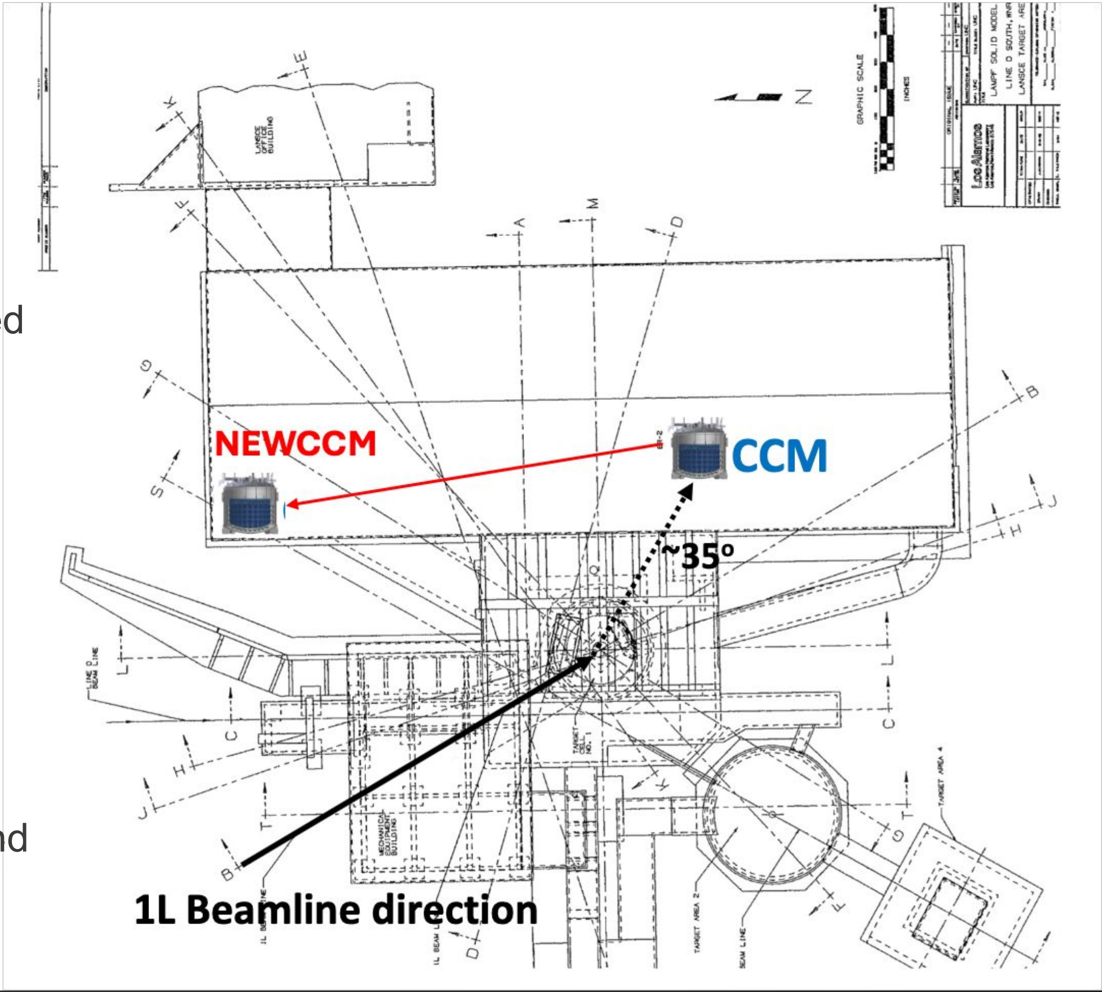
+80 PMTs, x3 energy scale



- There is one major deviation from the background prediction in both data sets.
- This excess manifests in the 20-50 MeV region, and is consistent in rate even after accounting for efficiency and background differences.

CCM200 2021 Analysis: Conclusions

- The consistent anomaly in the 2 runs so far directs CCM's future plans.
- We are currently operating under the hypothesis that this anomaly is caused by **very rare, very high energy neutrons**.
- 3 possible sources:
  - Direct from target
  - Bounce from other flight paths
  - From bend in beamline
- 2022 (other flight paths closed) and plan to move in 2025 address these possibilities.
- If not neutrons, we plan a larger detector (CCM1000) for better PID and signal identification.



Acknowledgements

HEP: Dark Matter New initiatives (DMNI)

Backup Deck

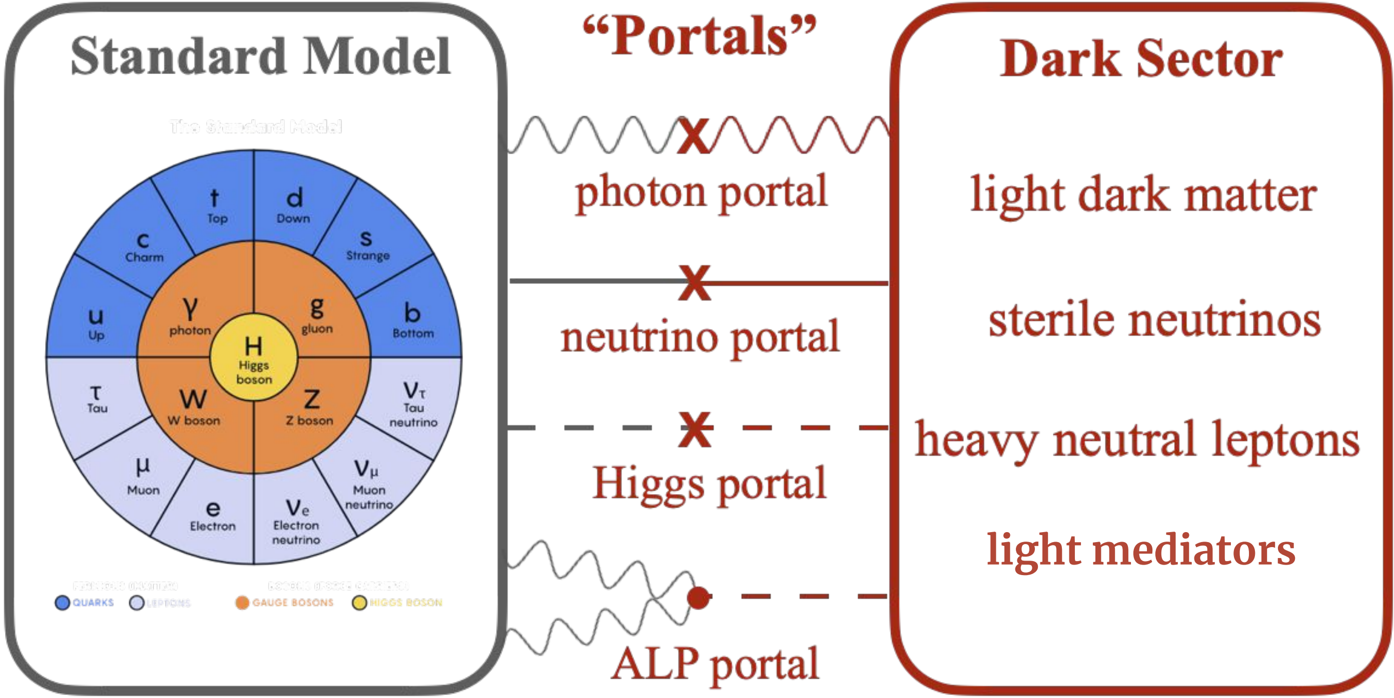
Outstanding Physics Puzzles

The Dark Matter Puzzle

Strong CP Problem

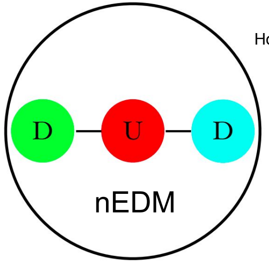
The Neutrino Mass Puzzle

Anomalies: MiniBooNE, Short Baseline…



The QCD Axion and Axion-Like Particles (ALPs)

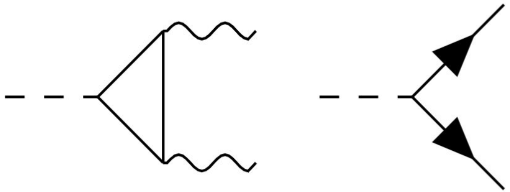
Hook [1812.02669]



- Axions are a proposed solution to the Strong-CP problem in QCD

  →*<u>Why is the neutron dipole moment so small?</u>* $d_n < 10^{-26}$ e cm

  - Related to *CP* violating term in QCD: $\mathcal{L} \supset \theta \boldsymbol{GG}$
  - $U(1)_{PQ}$ broken → ***a*GG** term to dynamically conserve *CP*



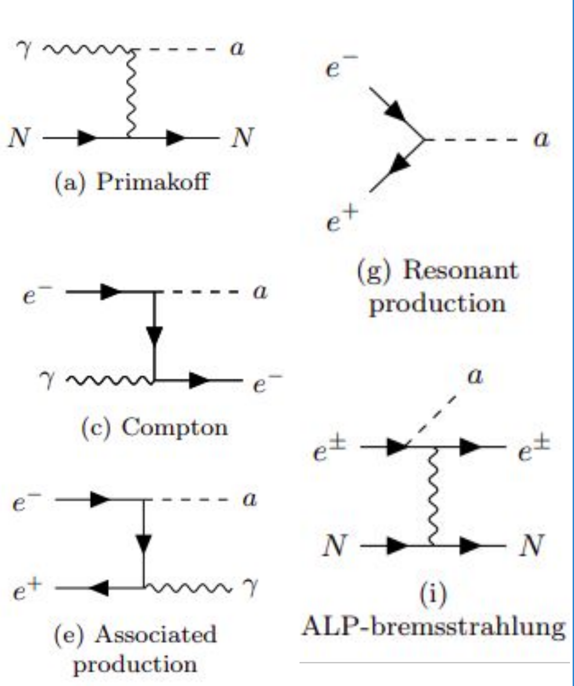
- But there are many other theories that predict pNGB pseudoscalars:
  - **generic goldstones** of broken global $U(1)_X$
  - String ***axiverse***
  - **Non-traditional** QCD axions
  - Axion **dark matter**

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

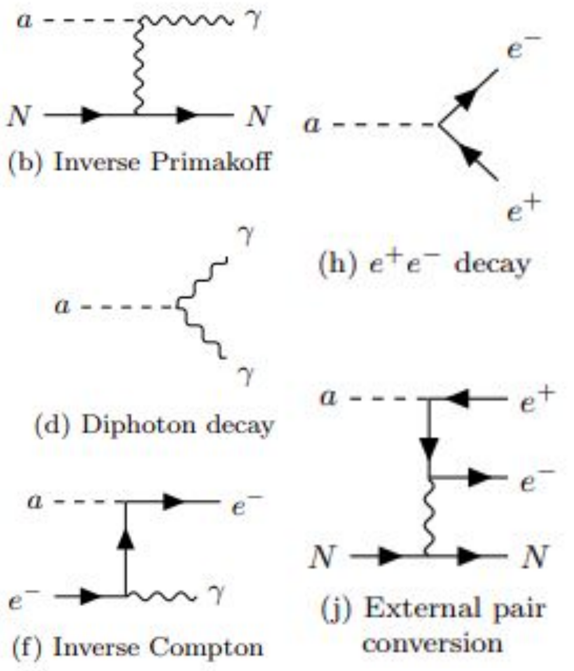
CCM is sensitive to ALPs with masses up to ~100 MeV

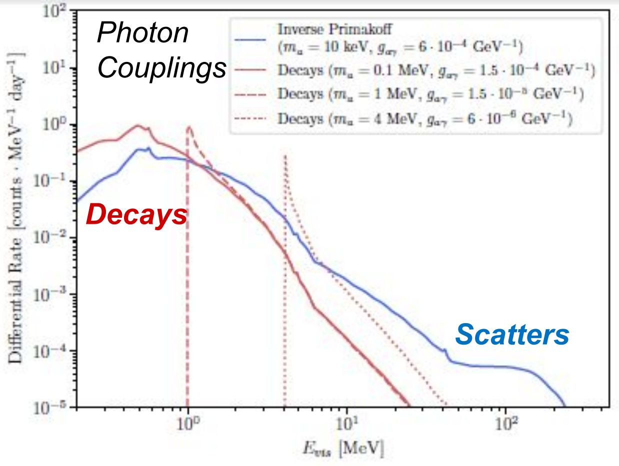
Phenomenology: ALP Detection in CCM

Production Channels in W Target

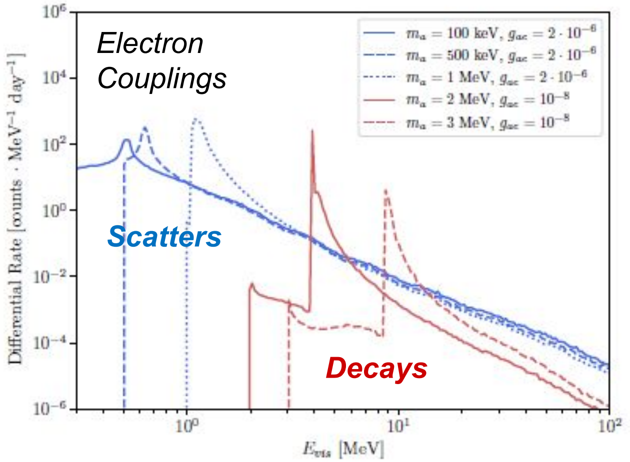


Detection Channels





Phys. Rev. D 107 (2023) 9, 9 [2112.09979]



Dark Sector Coupling to Meson Decay : DSCMD models

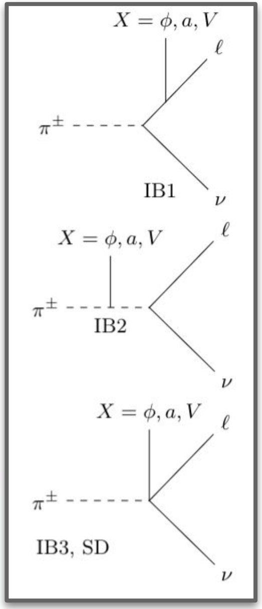
Primakoff / Photoconversion Scattering Model

Decay Model	Scalar Mediator	Pseudoscalar Mediator	SM Pi0 Mediator	Vector Mediator
Scalar IB1 (e)				✔
Scalar IB1 (mu)				✔
Pseudoscalar IB1 (e)				✔
Pseudoscalar IB1 (mu)				✔
Vector IB1 (e)	✔	✔	✔	
Vector IB1 (mu)	✔	✔	✔	
Vector IB2 (e+mu)	✔	✔	✔	
Vector contact (e+mu)	✔	✔	✔	

Dimension-4

Anomalous

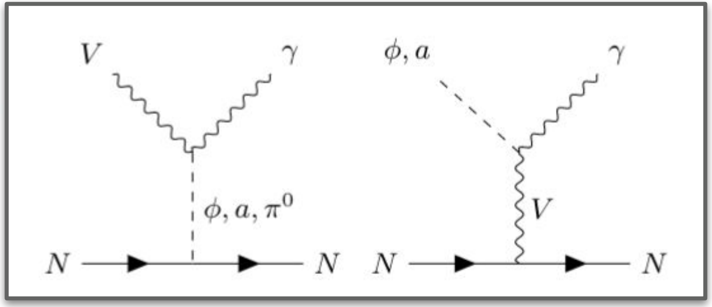
Focusing on these, but only for pragmatic purposes (scope is total)



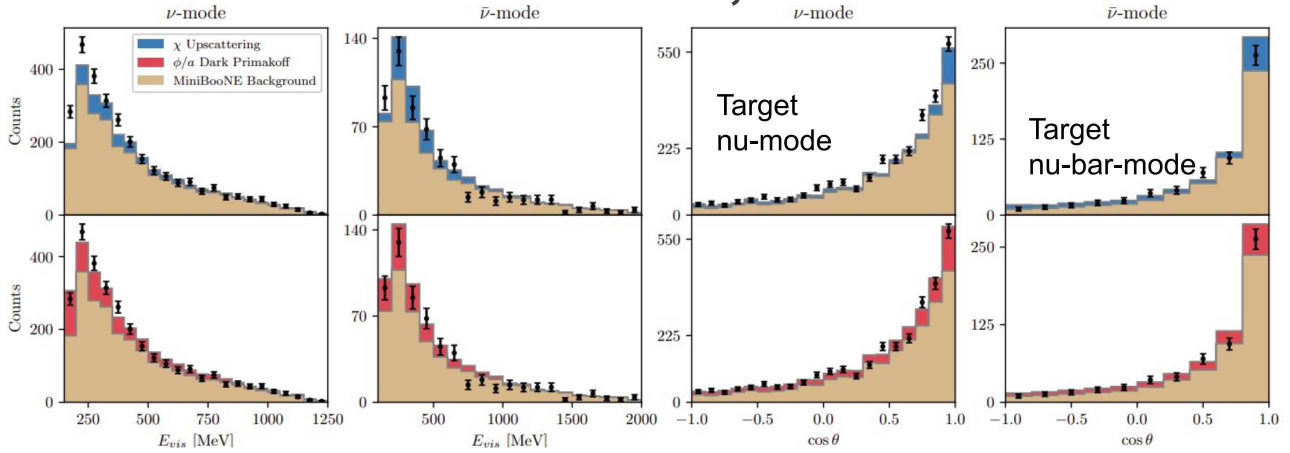
Decay Operator

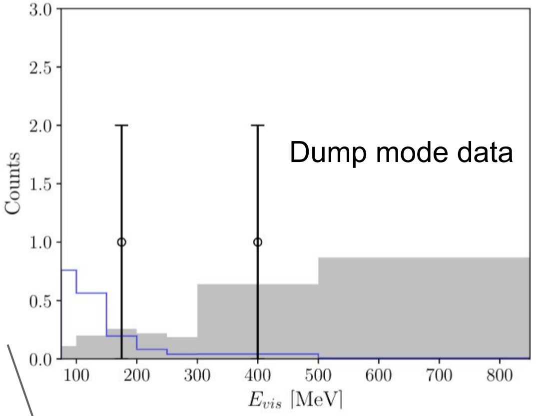
Scattering Operator

Combinatorics! Check which solve MB anomaly

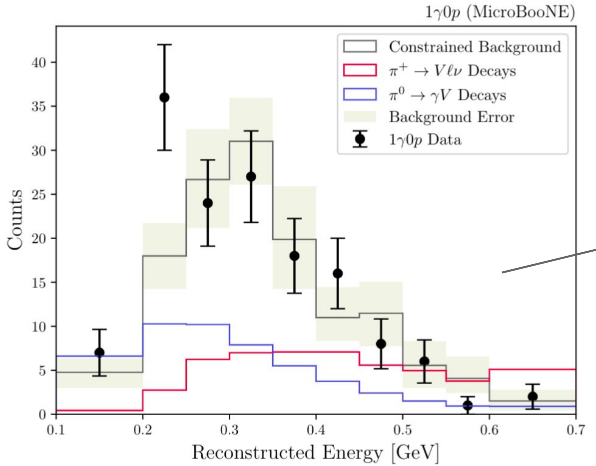


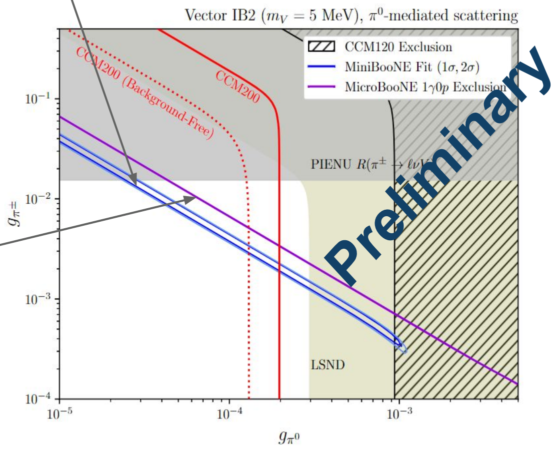
DSCMD and MiniBooNE, MicroBooNE





- We fit the **MiniBooNE target + dump** data with a combined log likelihood
- Derive constraint from MicroBooNE 1-gamma 0-proton analysis for Delta resonance production





Pion Decay Constraints versus DSCMD

- CCM and MiniBooNE much more sensitive to rare pion decays than normal searches
  - Many more pions produced.
  - Increased detector distance.
  - Appearance versus disappearance experiment.
- Neutrino search techniques highly sensitive to rare pion decay events!

PHYSICAL REVIEW LETTERS **129,** 111803 (2022)

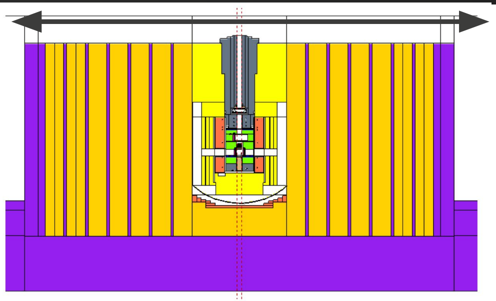
TABLE II. Relevant exotic decays of $\pi^{\pm}/K^{\pm}$ and existing upper limits at 90% confidence level X stands for invisibly decaying (massive) bosons. The predicted BRs (third though last columns) are based on the following parameter choices: $[\epsilon_1, (g_1^2/4\pi)] \simeq (6.0 \times 10^{-5}, 1)$ for the single-mediator scenario, $[\epsilon_1, \epsilon_2, (g_2^2/4\pi)] \simeq (7.0 \times 10^{-5}, 1.0 \times 10^{-4}, 0.5)$ for the double-mediator scenario, $(g_\mu, g_n, \lambda) \simeq (5 \times 10^{-3}, 10^{-2}, 4.4 \times 10^{-4}\ \text{MeV}^{-1})$ for the scalar scenario, and $(g_\mu, g_n, \lambda) \simeq (10^{-2}, 10^{-2}, 6.5 \times 10^{-3}\ \text{MeV}^{-1})$ for the pseudoscalar scenario.

		Model (i) ($\times 10^{-12}$)		Model (ii) ($\times 10^{-8}$)	
Channel (BR)	Limit ($\times 10^{-8}$)	Single	Double	ϕ	a
$K \to \mu\nu_\mu V(\phi)$ [87]	2000 (300)	500	680	230	100
$K \to e\nu_e\nu\nu$ [54]	6000	530	720	⋯	⋯
$K \to \mu(e)\nu_{\mu(e)}ee$ [54]	7.4(2.7)	500(530)	680(720)	⋯	⋯
$\pi \to \mu(e)\nu_{\mu(e)}X$ [88]	600(50)	0.12(25)	0.17(34)	120(⋯)	1.1(⋯)
$\pi \to \mu(e)\nu_{\mu(e)}ee$ [54]	–(0.37)	0.12(25)	0.17(34)	⋯	⋯

The CCM Experiment:
The Lujan Target and Source

Extremely well understood and modeled by AOT

Nuclear Instruments and Methods in Physics Research A 594 (2008) 373–381
Nuclear Instruments and Methods in Physics Research A 632 (2011) 101–108



10 m

- 4m Steel Shielding
- 2.5 m Hg beam windows

Complex target tuned for neutron production

Beamlines controlled by Hg window

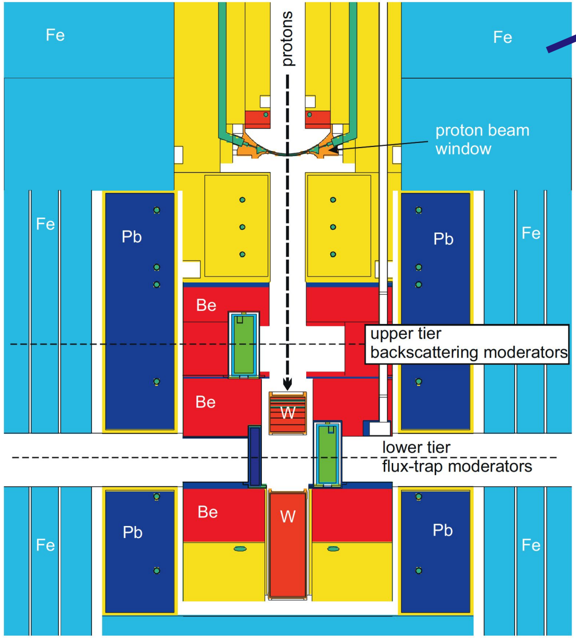
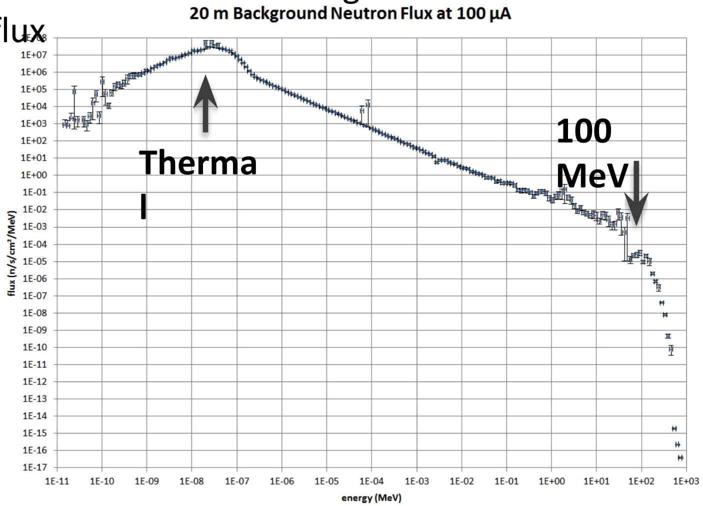
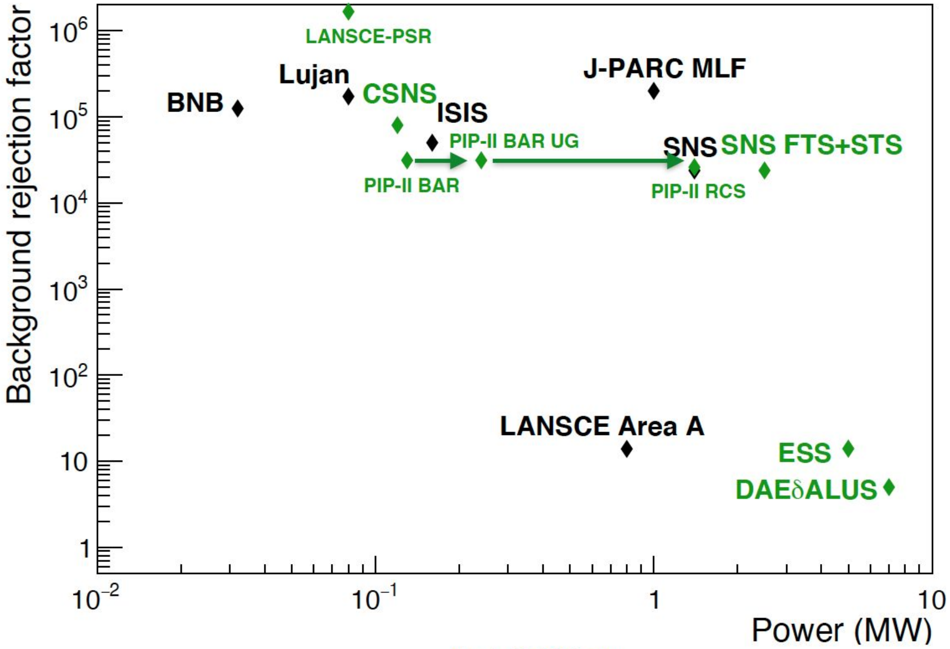


Fig. 1. Elevation view of the Lujan Center's TMRS geometry used in our calculations. The main components are labeled: split tungsten target (W), beryllium reflector (Be), lead reflector–shield (Pb), and the steel reflector–shield (Fe).

- Extensive shielding around target
- Simulations has confirmed hand calculated neutrino flux of ~4.74×10^5 nu/cm^2/s at 20 m
- MCNP simulation of target and ambient neutron flux



The CCM Experiment: LANSCE-Lujan Beam



Plot via K. Scholberg

Lujan is a Competitive and Unique Neutrino/Dark Matter Source
Low duty factor critical for background rejection!

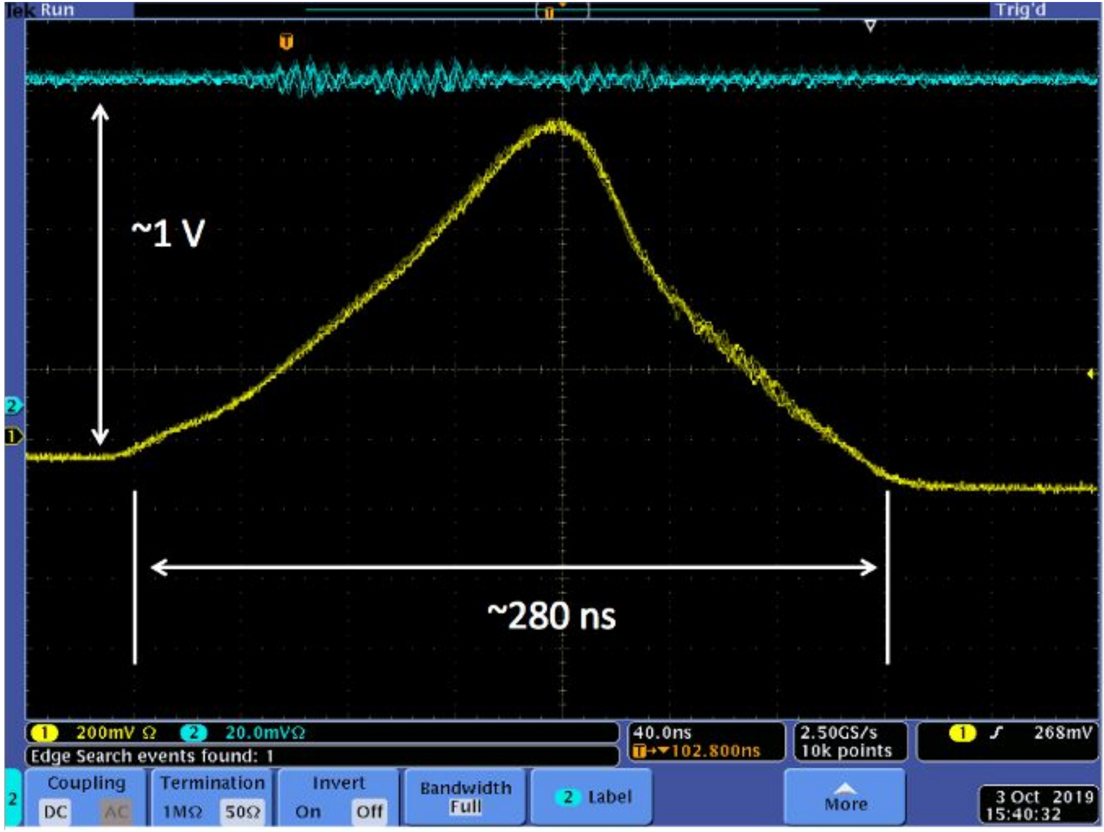
Lujan/CCM makes up for less power with large, sensitive, and fast 10 ton LAr detector!

Typical beam delivery of 7.5×10^{21} POT/year

- **Neutrino/DM experiments require high Instantaneous Power – measure of Signal/Background:**
  SNS (FWHM 350 nsec @ 60 Hz)= 0.060 kJ/nsec; Lujan(FWHM 138 nsec @ 20 Hz)= 0.031 kJ/nsec

Trigger by Trigger measurement of the Beam through Integrated Beam Current Monitor

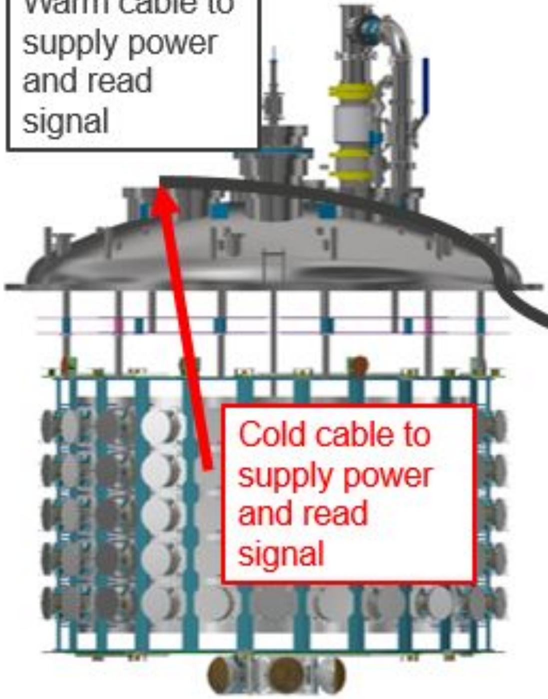
- CCM includes direct measurements of the beam proton pulse through a BCM integrated directly into the DAQ and data stream.
- This BCM can be used to analyze the protons per trigger, and ensure that only the best quality triggers are included in the final analysis.



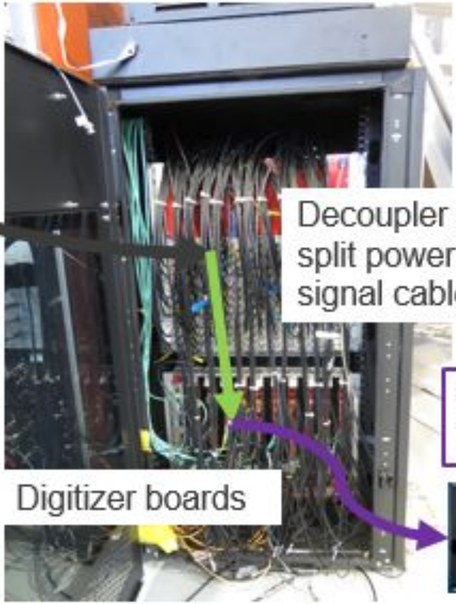
CCM120 Flow of Data

- CAEN V1730
- 500 MHz clock
- 16 Channels
- 2^{16} Bit ADC Chip per channel
- 2 V range
- 11 boards

Warm cable to supply power and read signal



Cold cable to supply power and read signal



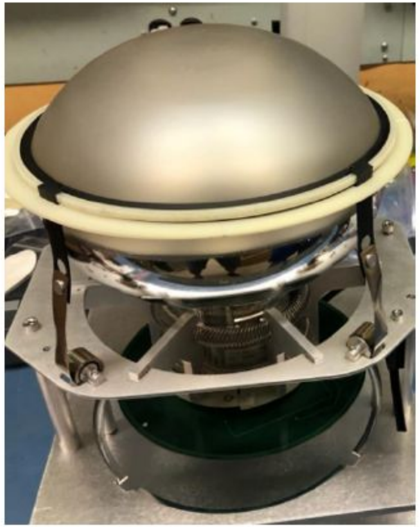
Decoupler box to split power and signal cables

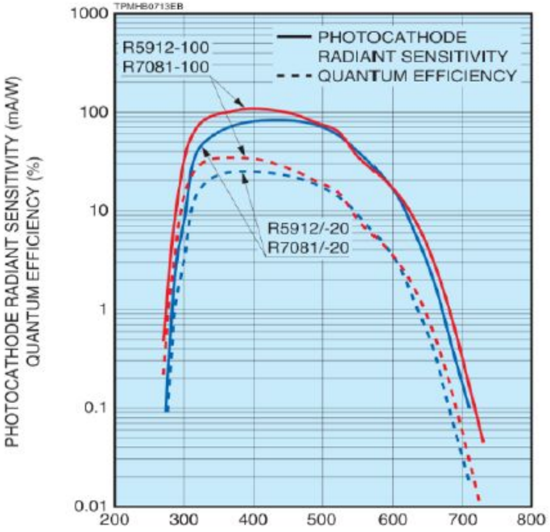
Digitizer boards

Fiber Optic connection to DAQ computer

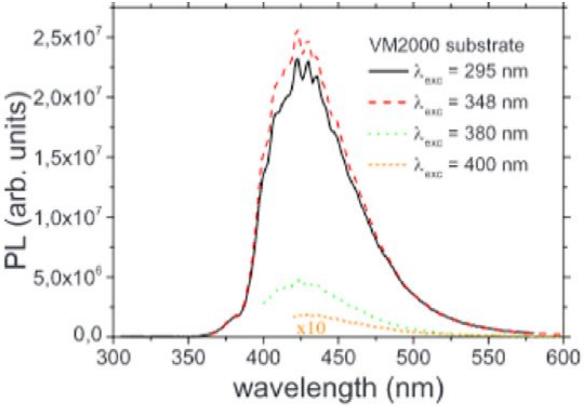
The CCM200 Detector: Hamamatsu R5912 PMTs

- **160 PMTs** evaporatively **coated** with Tetraphenyl Butadiene (TPB)
  - Overlap between PMT detection spectrum and TPB emission spectrum
- **40 PMTs uncoated**
  - Helpful for calibration purposes
- **40 Veto PMTs**
  - 8 1” PMTs on the bottom looking in
  - 10 1” PMTs on the top looking in
  - 22 1” PMTs on the columns looking up and down.



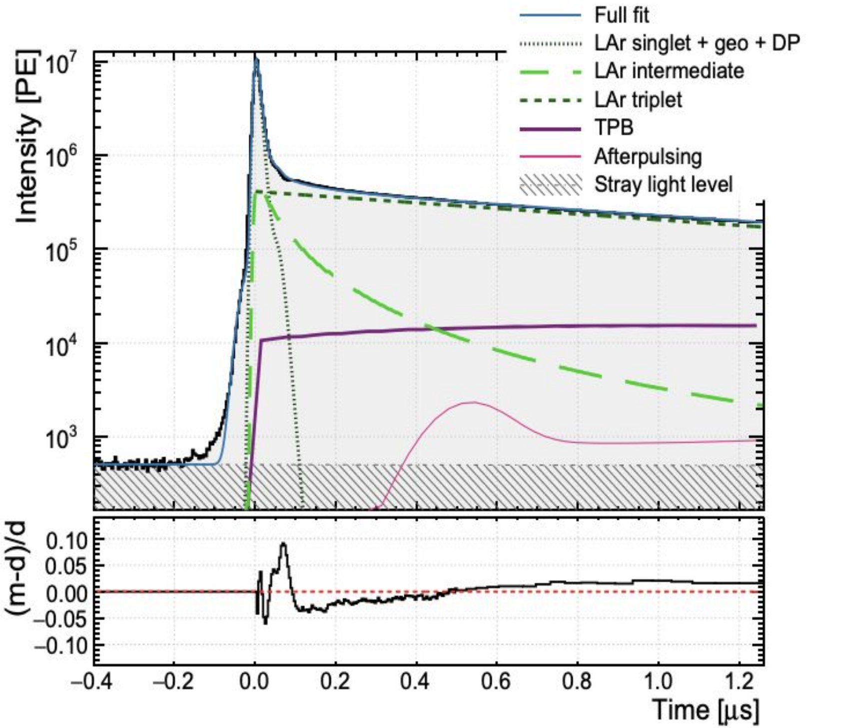


- Above: TPB-coated R5912 PMT
- Top Right: Hamamatsu Efficiency Spectrum
- Bottom Right: TPB Emission Spectrum

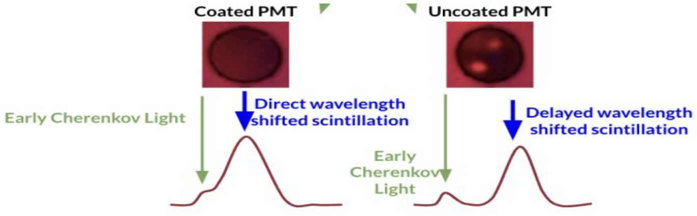


Scintillation/WLS mechanics

- Excited argon forms a dimer, de-excites releasing a **fast singlet** and **slower triplet** excitation components
- Scintillation light spectrum peaks at **128nm**
- Emits **$4*10^4$ photons/MeV** of deposited energy from scintillation
- Timing of prompt and delayed light components have been measured by the DEAP collaboration (right)
- Tetraphenyl Butadiene (TPB) **wavelength shifts** 128nm LAr scintillation light to the visible spectrum, allows better absorption by PMTs
- Combination Coated+Uncoated tubes allows separate detection of scintillation and Cherenkov light.

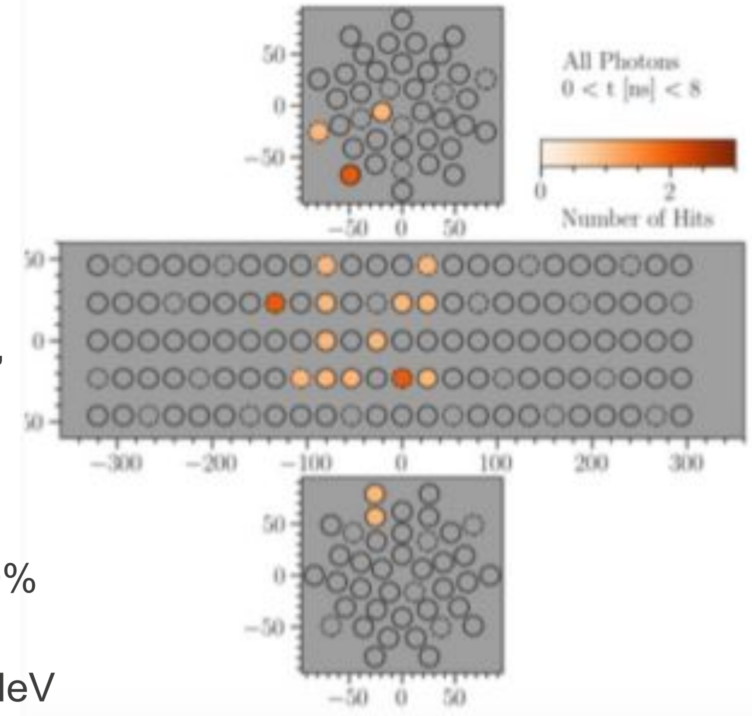


Eur. Phys. J. C (2020) 80:303, https://doi.org/10.1140/epjc/s10052-020-7789-x



The CCM Detector: Optical LAr Detector advantages

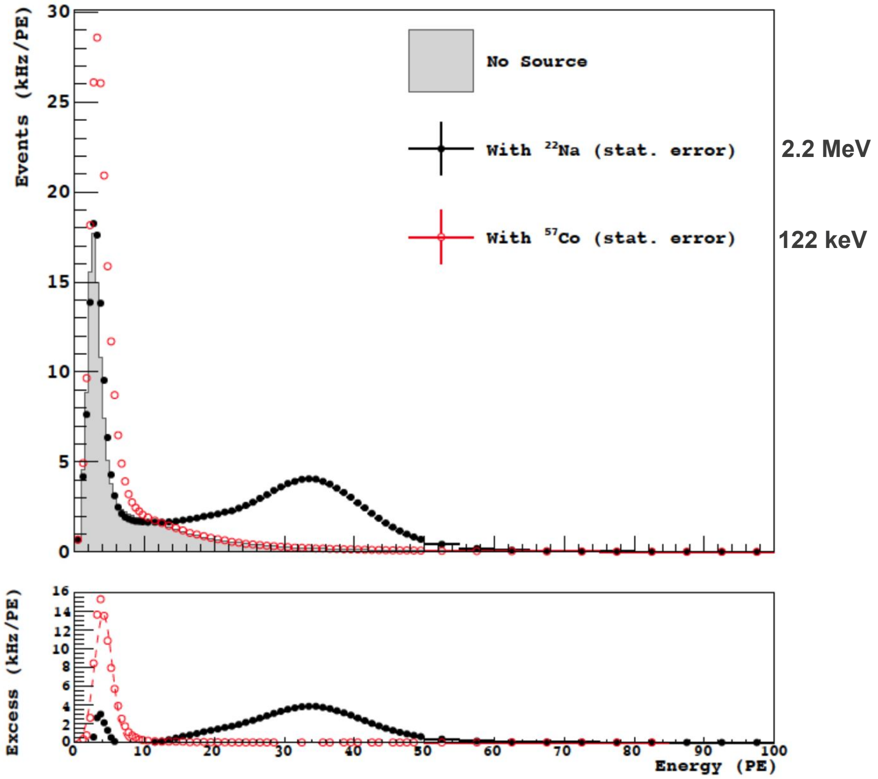
- Optical Detectors have response times at the **2 ns** level
  - LArTPCs have millisecond readouts
  - When trying to use timing-based background rejection, need FAST detector
- LAr scintillation produces **40,000 photons/MeV**
  - More than any organic scintillator
  - 40 photons/keV = theoretical threshold of 10 keV at 10% photon detection level
  - LArTPCs 3-5mm wire spacing reconstructs events > MeV
- LAr does not re-absorb **Cherenkov light**
  - Cherenkov can separate low energy electromagnetic events from nuclear recoil
  - Cherenkov can also provide directionality for e/m like events.



Simulated hits from Cherenkov light in CCM200 detector. Visible Cherenkov light precedes scintillation by up to 8 ns.

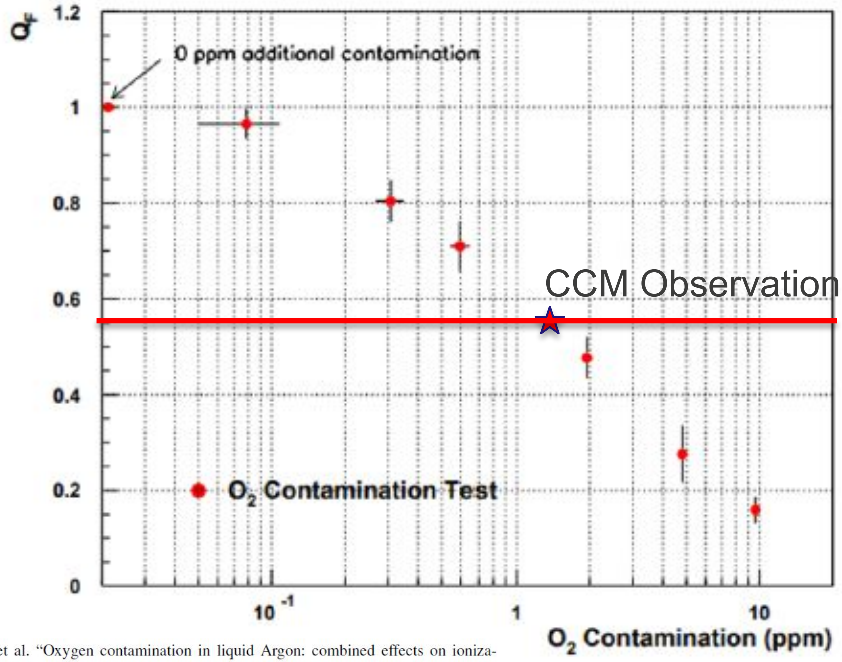
Data Selection: CCM120 Energy Scale from Radioactive Sources

- Impurities from not recirculating or filtering the argon led to low light levels. ~2 ppm O_2 reduced the 128 nm light attenuation length from ~20 m to ~50 cm
- According to simulations the 4.7 PE peak for Co57 is an artifact of the event cuts, the real peak is ~1.8 PE
- Na22 33.2 ± 8.9 PE for 2.2 MeV
- Both Co57 and Na22 rates are within 25% of simulation prediction
- Nuclear Recoil (neutron, LDM, CEvNS) energy scale approx. ½ of electron event (Na22, ALP) scale.



A. A. Aguilar-Arevalo et al. "First dark matter search results from Coherent CAPTAIN-Mills". In: *Physical Review D* 106.1 (July 2022).

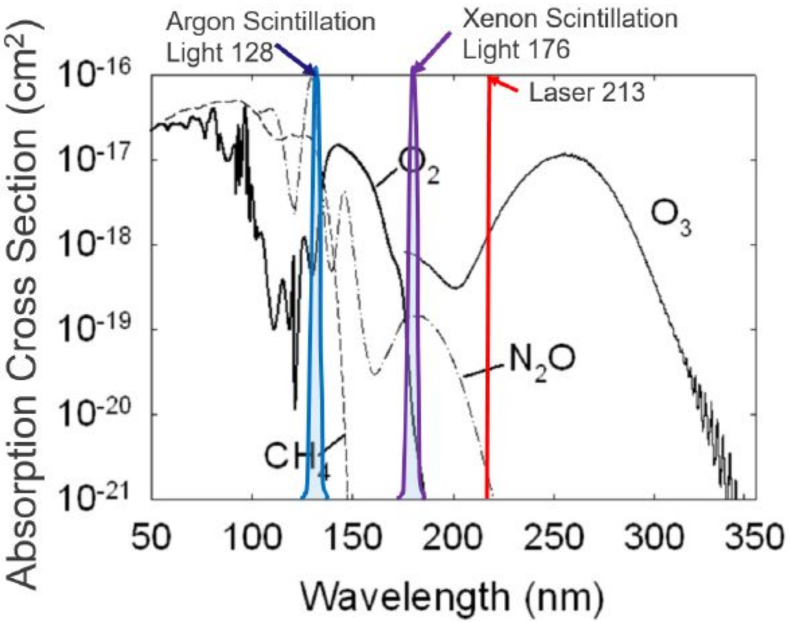
Contamination



R Acciarri et al. "Oxygen contamination in liquid Argon: combined effects on ionization electron charge and scintillation light". In: *Journal of Instrumentation* 5.05 (2010), P05003–P05003.

- CCM observed LAr absorption lengths at 128 nm of 55 cm, along with an additional quenching factor of 55%.
- Both Values are consistent with oxygen contamination just below the 2ppm level.

Antígona Segura et al. "Biosignatures from Earth-Like Planets Around M Dwarfs". In: *Astrobiology* 5 (Jan. 2006), pp. 706–25.

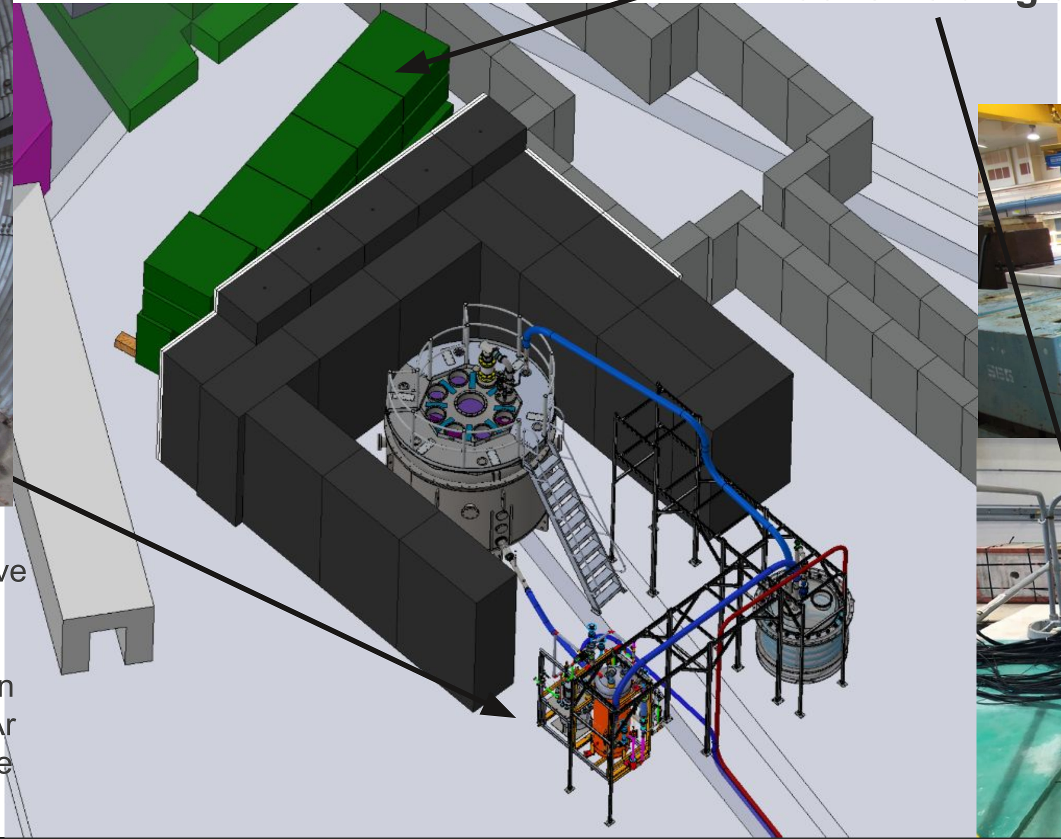


Concentration of O2	Absorption Length of 128nm light in LAr
0.0ppm	2,000 cm
0.002ppm	1,700 cm
0.02pm	1,000 cm
0.06ppm	500 cm
0.2ppm	180 cm
2ppm	20 cm *
20ppm	2 cm

CCM200 Shielding Layout at Lujan (23 m from target)

More steel and concrete shielding added. Roof shielding added in October 2021.

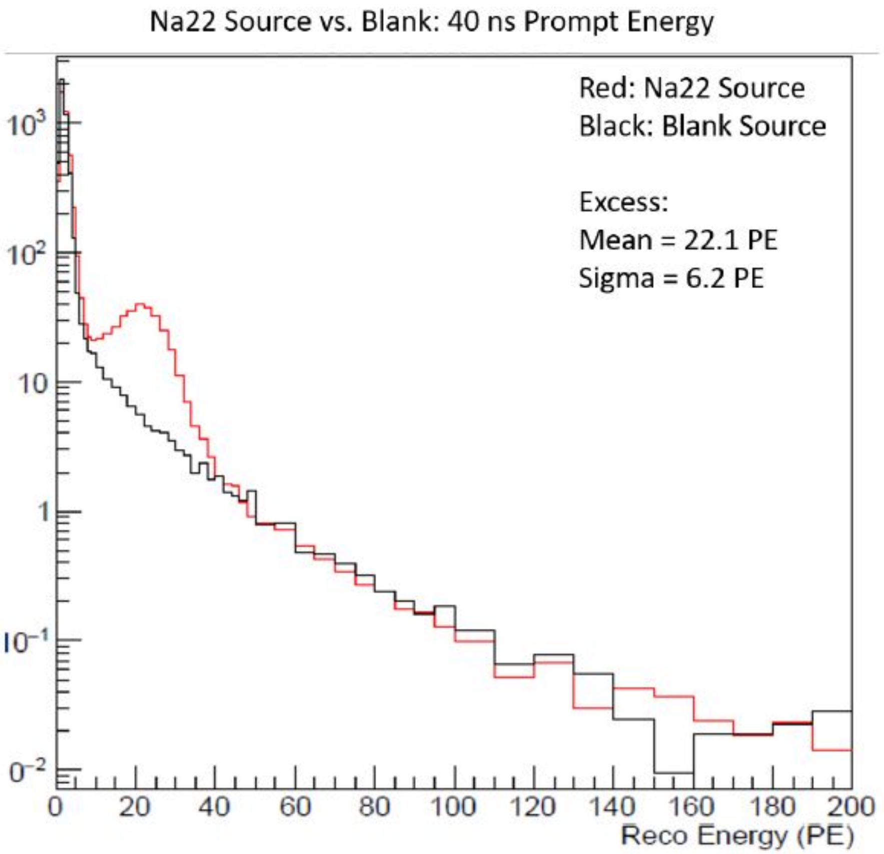
Filter skid (MicroBooNE design): 4A molecular sieve material to remove water contamination and Cu Alumina to remove oxygen contamination. Ten ton LAr recirculation turn over time of ~three hours.



ALP Event Characteristics

- In CCM, we expect ALPs to produce high energy photon or electron scatterings.
- Electromagnetic-like signature
  - Triplet light 75% of total scintillation output
  - Quenching Factor of 1 with pure argon
- => Long in length and high in energy

- Due to long length running into beam neutrons, prompt window set to 40ns (from 90) to avoid beam energy in long events.
  - The redone energy calibration for 40ns prompt window is shown to the right.
  - 2.2 MeV = 22.1 PE => 10 PE/MeV



Background Measurements

- CCM made several direct measurements of various background types.
- EJ-301 scintillation detectors measures neutron speed and comparative rate
- Thermal neutron detector measures steady state neutrons
- Germanium detector measures gamma rays at various energies.

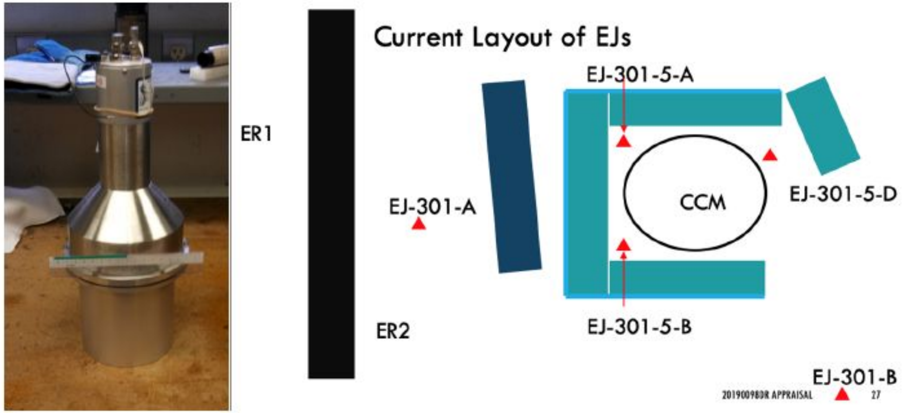


Figure 3.22: An EJ-301 detector (left) and the placement around CCM of 5 such detectors (right).

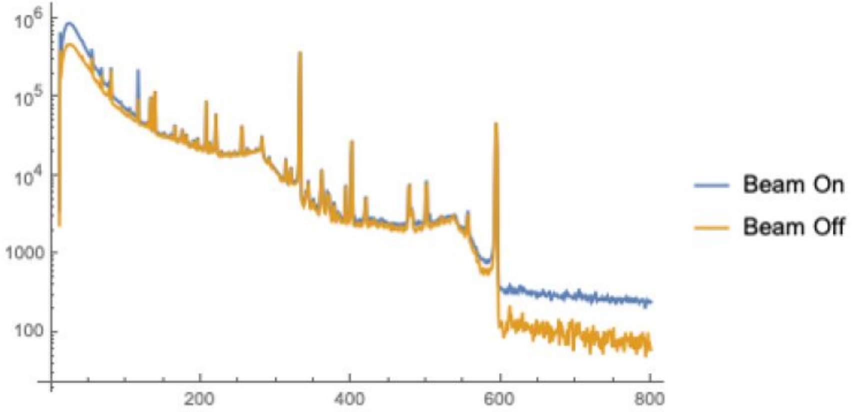
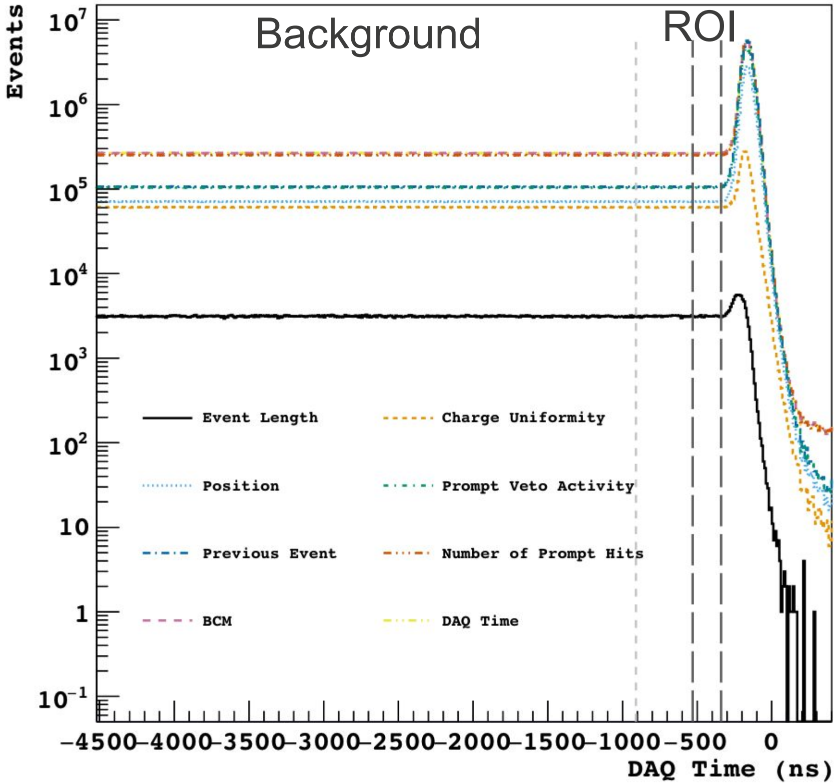


Figure 3.24: The gamma spectrum as determined by the germanium detector comparing beam on versus beam off

CCM120 Analysis: Measuring Steady State Backgrounds

- Prompt light only analysis
- Dynamic event lengths allow a poor-persons PID
  - Maximize dark matter over Ar39 puts the length cut at 44 ns
- Pre-beam is flat in time (no bias) allowing a good prediction of what to expect in the prompt speed of light window (ROI)
- ROI is a beam-related background free region, so the prediction on the number of events is statistical only (systematics will be on DM signal)
- Ideal for Machine Learning techniques



Background Prediction

- CCM uses direct measurements of the steady state background to predict the ROI background.
- However, the ‘steady state’ is not steady – checks revealed a background that was slightly decaying in rate across all energies, significant on the order of microseconds.
  - Beam activated radioactivity (known to exist from Germanium background measurements) was a possible candidate.
- Used linear fits of 6us of background to determine that expected within the ROI.

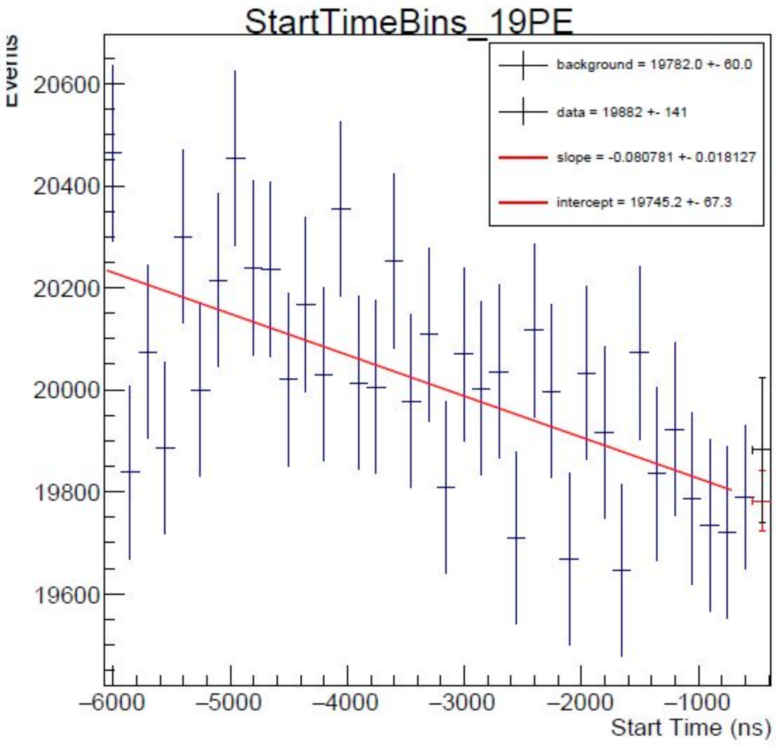
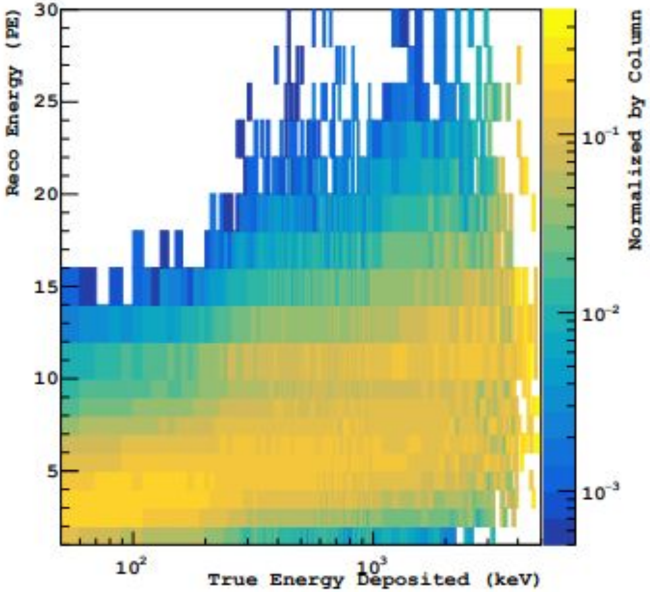


Figure 6.1: The 19PE bin’s start time distribution. In blue are the prebeam ROI-length (150ns) time windows, black is the actual data value, and red is the background prediction from the linear fit (also in red).

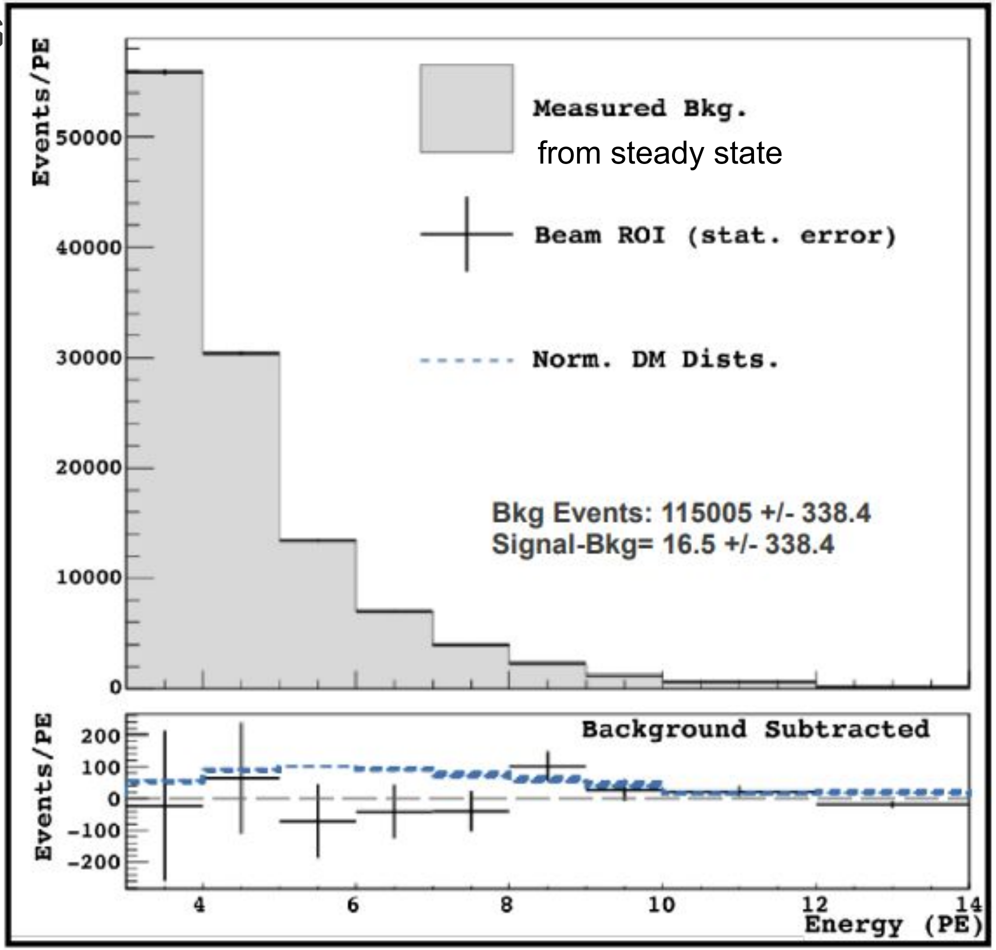
CCM120 LDM Search Results

[1] A. A. Aguilar-Arevalo et al. "First dark matter search results from Coherent CAPTAIN-Mills". In: *Physical Review D* 106.1 (July 2022).

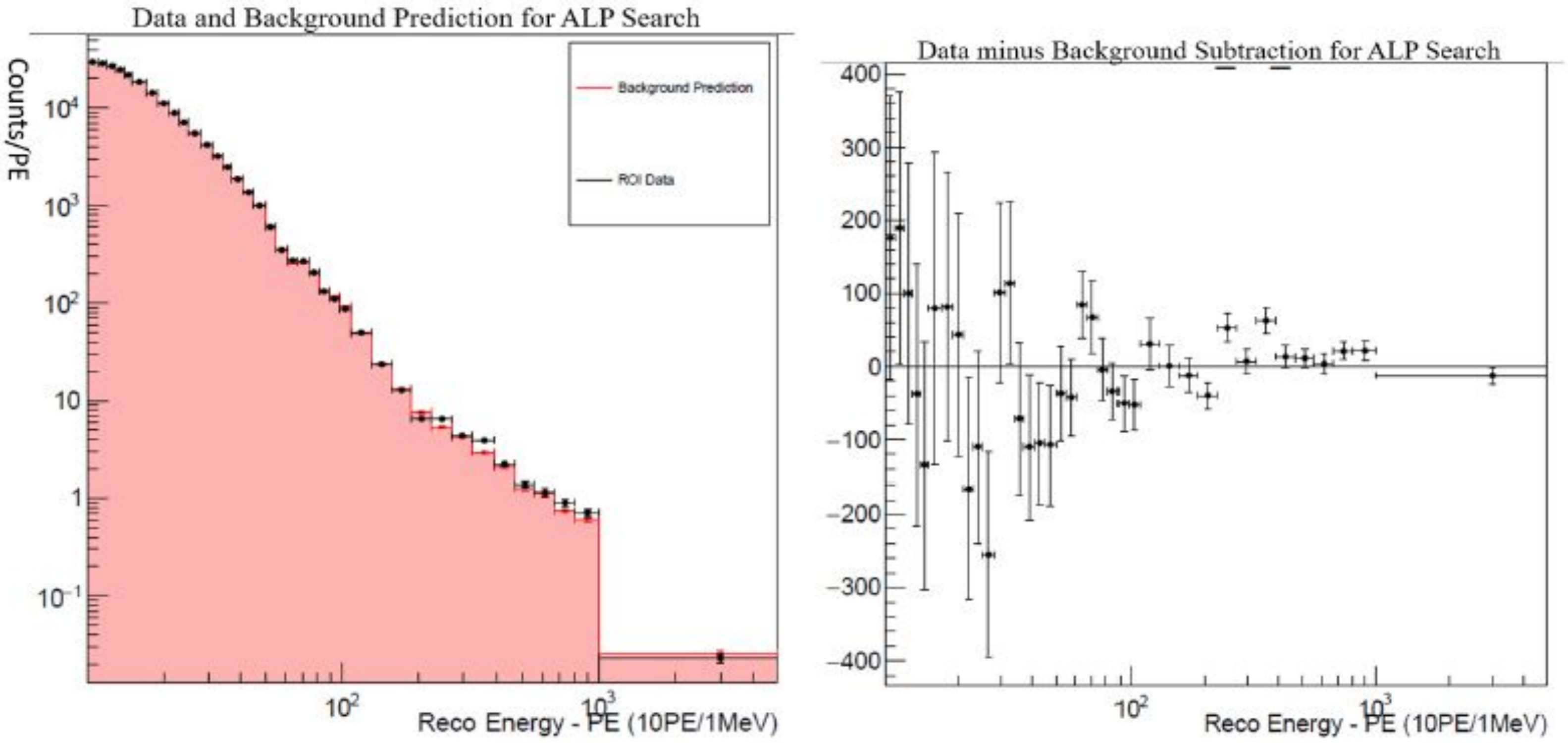
[2] A. A. Aguilar-Arevalo et al. "First Leptophobic Dark Matter Search from the Coherent–CAPTAIN-Mills Liquid Argon Detector". In: *Physical Review Letters* 129.2 (July 2022).



Signal smearing matrix created for the LDM search to relate between true energy deposited and reconstructed energy. This matrix was used to generate the DM predicted distribution shown in blue on the lower right.



CCM120 Electromagnetic Search: Data and Background Prediction

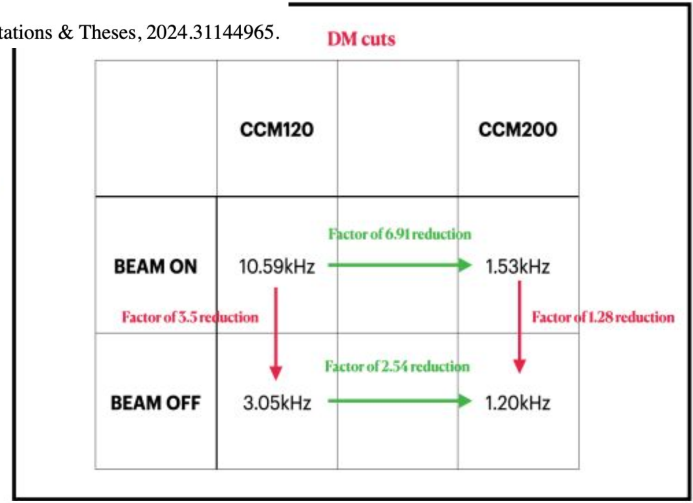


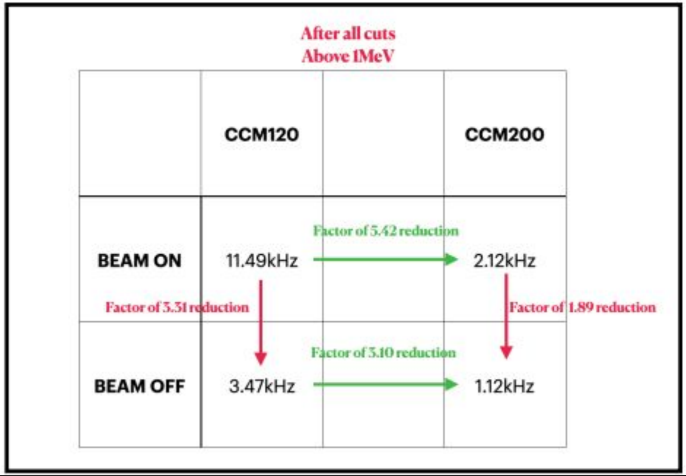
(Left) The data and background spectra from the background prediction and the measured data in the beam ROI. (Right) The subtraction between data and background prediction about 0.

Background Rates: CCM120 and CCM200

Dark Matter Searches at Coherent Captain-Mills
Tripathi, Mayank. University of Florida ProQuest Dissertations & Theses, 2024.31144965.

- Added Concrete and Roof shielding between CCM120 (2019) and CCM200 (2021) runs leads to reduced background rates
  - Nearly to level of eliminating beam-related background/activation, from comparison of beam-on vs. beam-off background.
- Factor of ~7 reduction in LDM search backgrounds.
- Factor of ~5 reduction in E/M search backgrounds.
  Reduction greatest at low energy, reducing as energy increases.





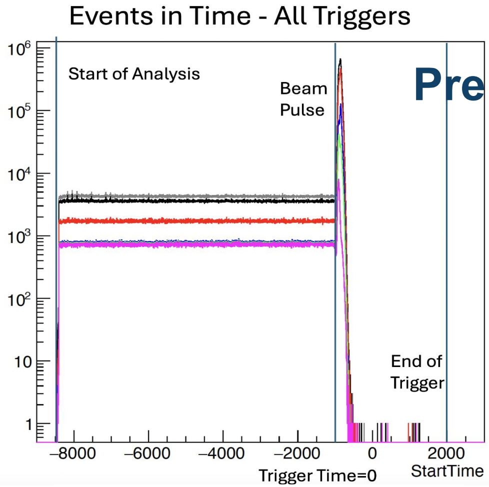
2021: Prebeam Modeling

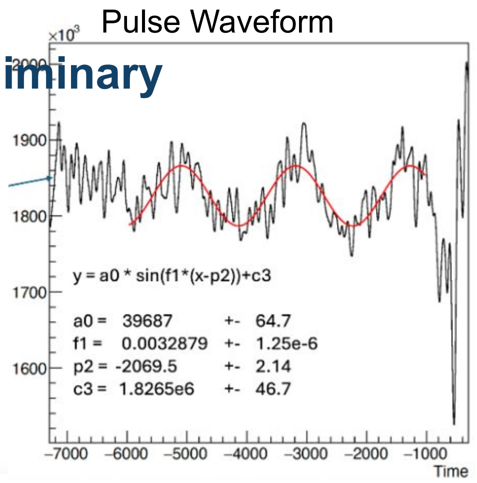
- In the 2021 data set, the prebeam used for background prediction was not simple. Effects included:
  - An oscillation
  - Sharp dips
  - An overall trend
  - Issues near the window start
  - And overall higher error
- We compensated with a full fit function on a limited prebeam:

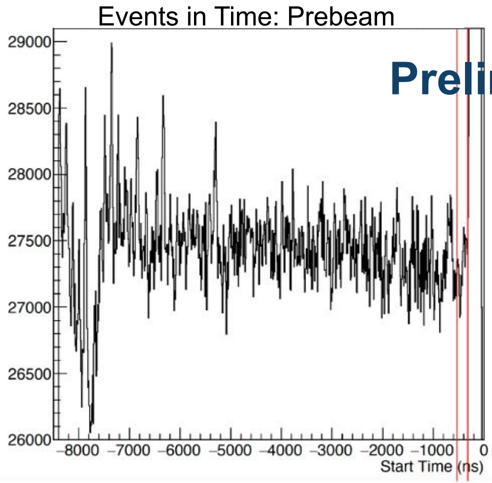
Oscillation Term

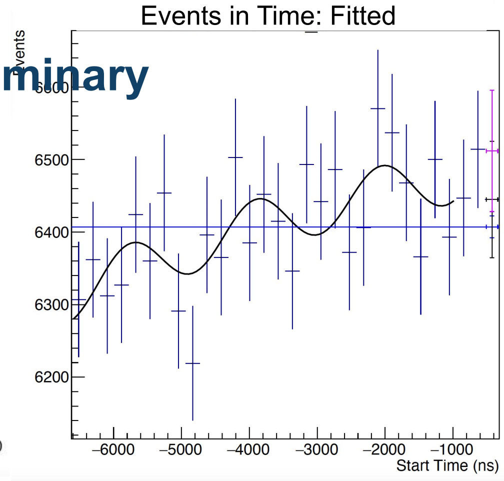
$$y = a0 * sin(a1 * (x - a2)) + exp(a3 + a4 * x) - exp(a5 + a6 * x) + a7$$

Radioactive Decay Terms

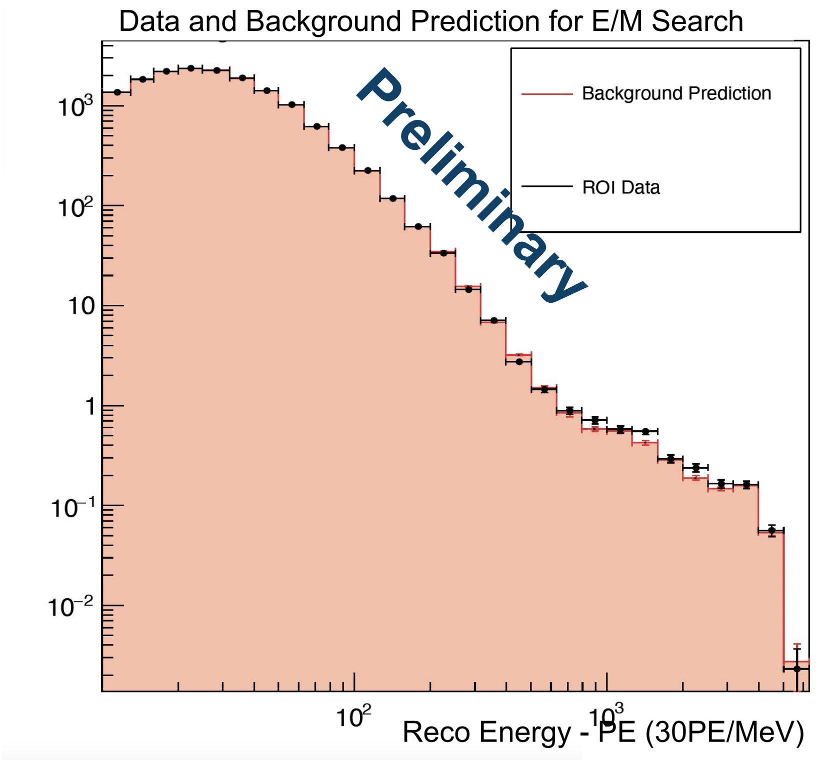


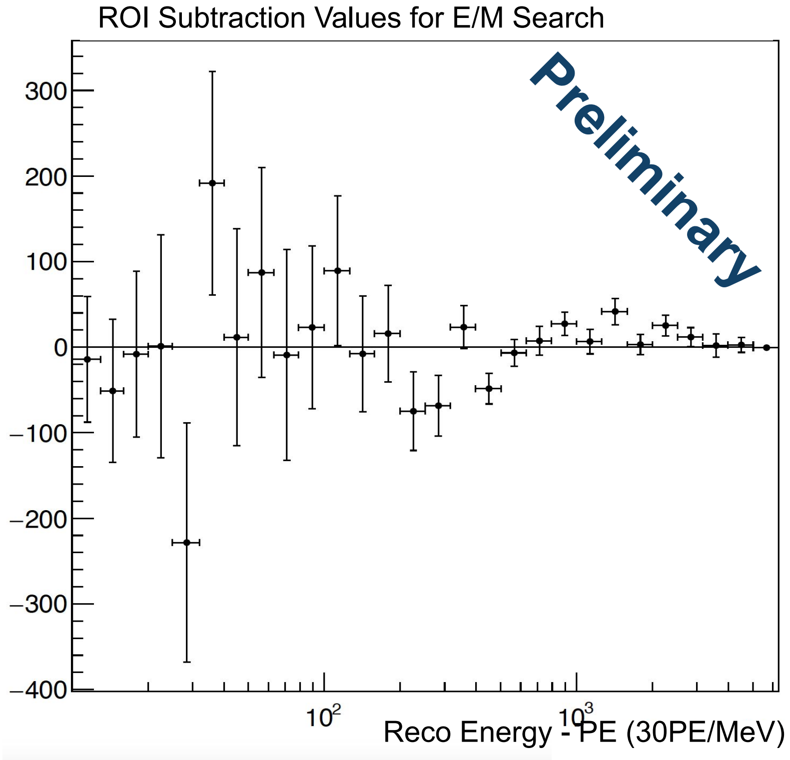






CCM200 2021 Analysis: Data Subtraction



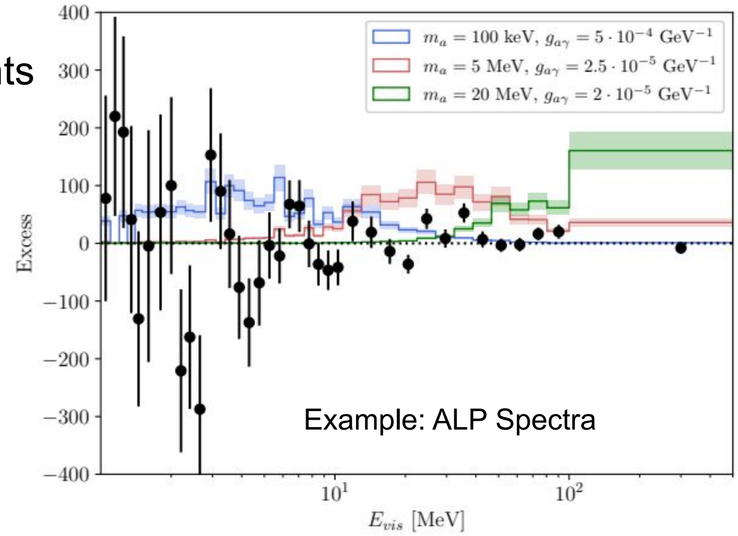


The background prediction and measured data in the ROI (left) and the data - background subtraction (right) for the 2021 electromagnetic search of CCM.

BSM Signal Prediction Pipeline

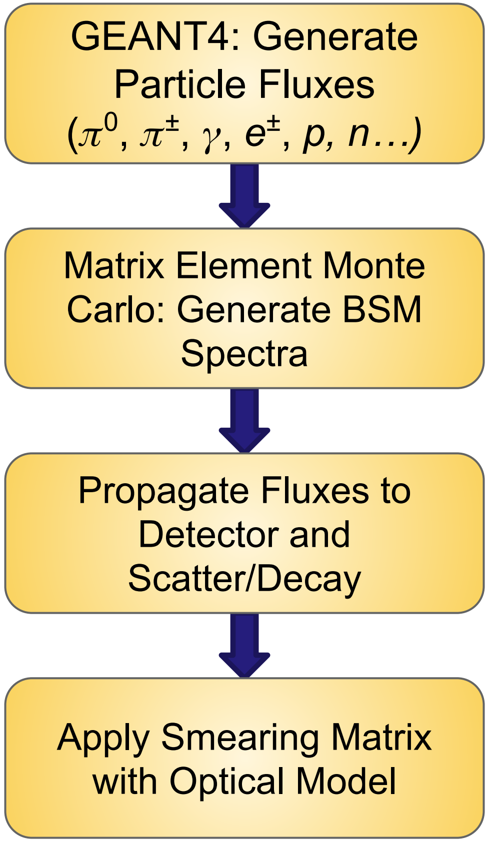
CCM120 Engineering 6-week Run

- 1.79 × 10^{21} Protons on Target (**POT**)
- Electromagnetic / ALP Search
  - 294590 **observed** EM events in ROI
  - **Backgrounds**: 294614.3 ± 241.7 (syst) ± 542.8 (stat)
- Nuclear Recoil / LDM Search
  - 115005 **observed** in ROI
  - 16.5±338.4 subtraction events
- Separation of energy spectra from keV to *o*(100) MeV across different models



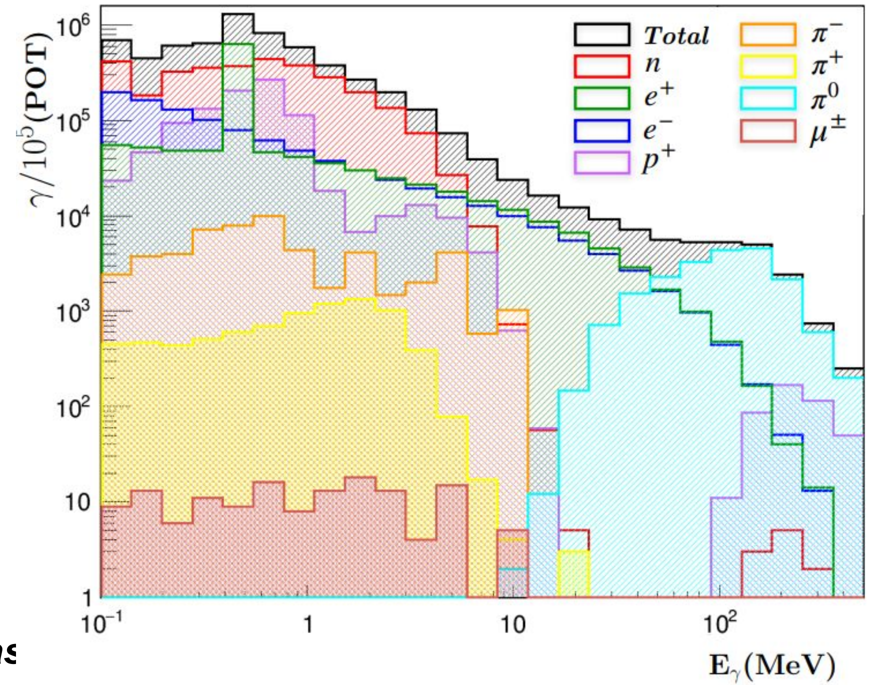
CCM200 Projection

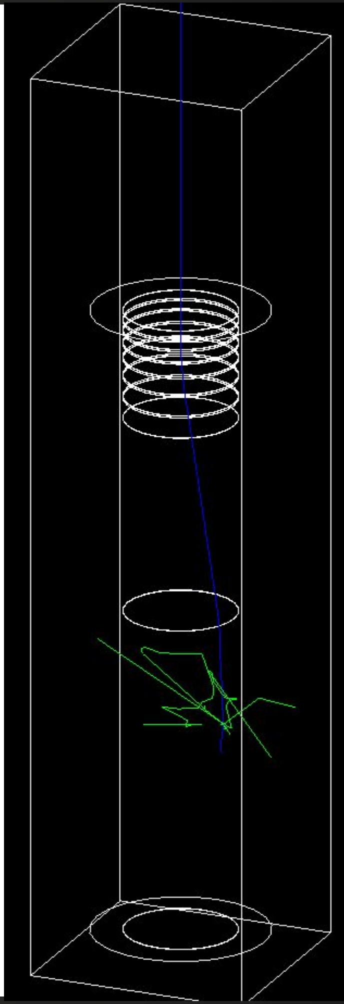
- 3 year run (2023-2025)
- 2.25 × 10^{22} POT



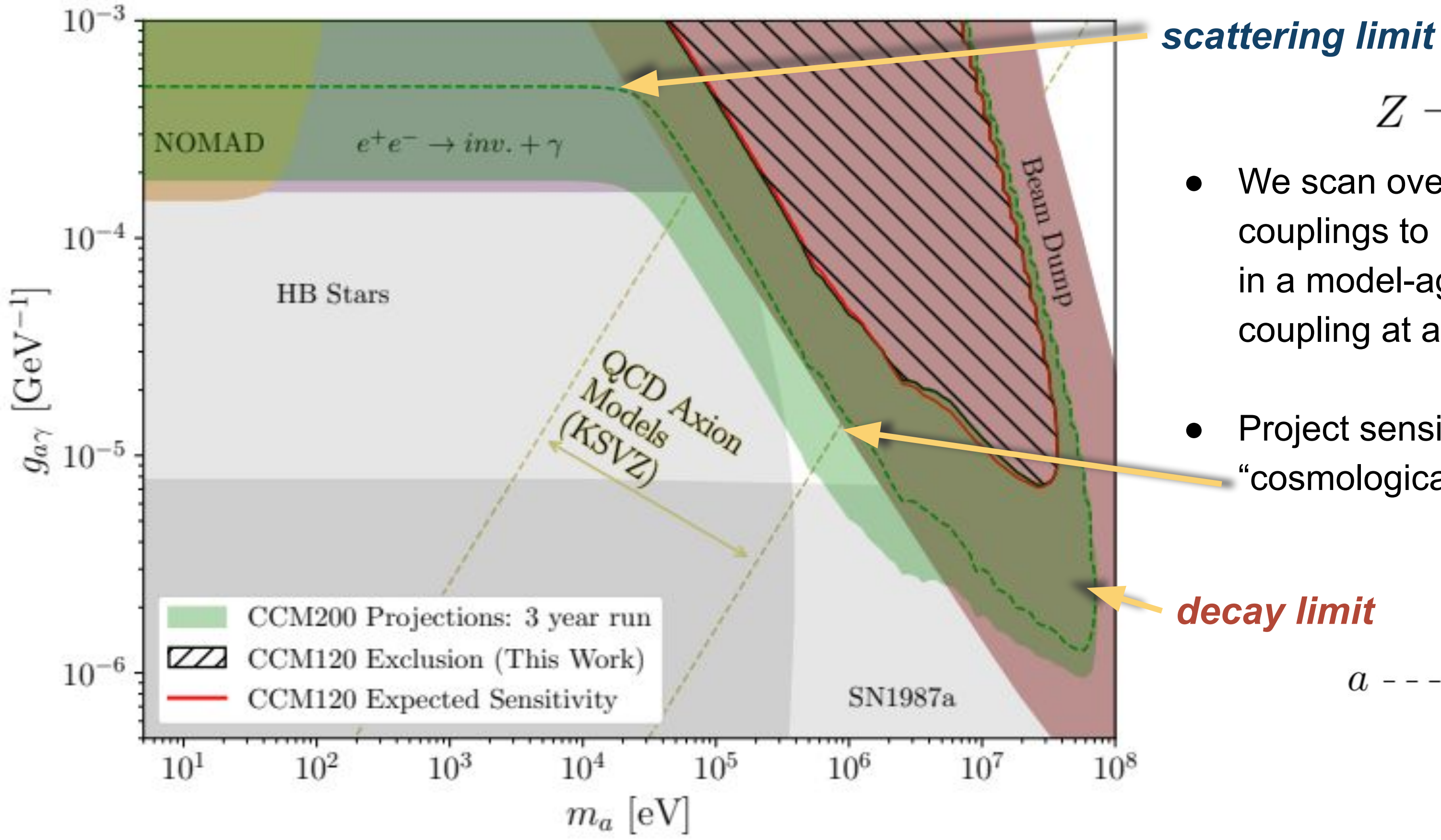
Lujan Target Physics: Electromagnetic and Hadronic Particle Showers

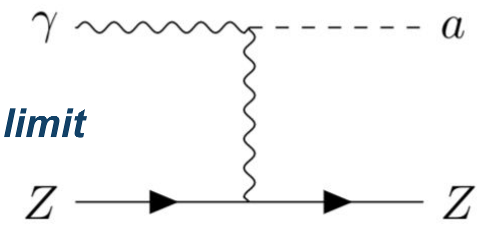
- **GEANT4** simulated fluxes from 800 MeV protons on W target geometry
- Physics list: `QGSP_BIC_HP`
- **Hadronic** cascades + **meson** production
  - π^0 , π^+ , π^-
- Production of **secondaries**: e^+, e^-, γ's:
  - e^+e^- Pair production
  - Bremsstrahlung
  - π^0 decays
  - Neutron/proton scattering
  - etc…
- ***Each of these processes serves as a potential dark sector flux source***



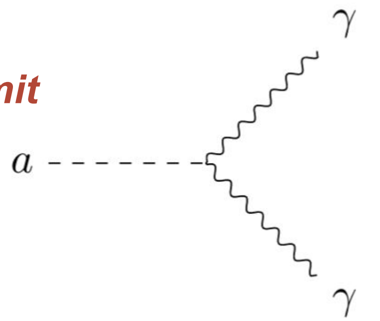


2019 Search for ALPs: Photon Couplings



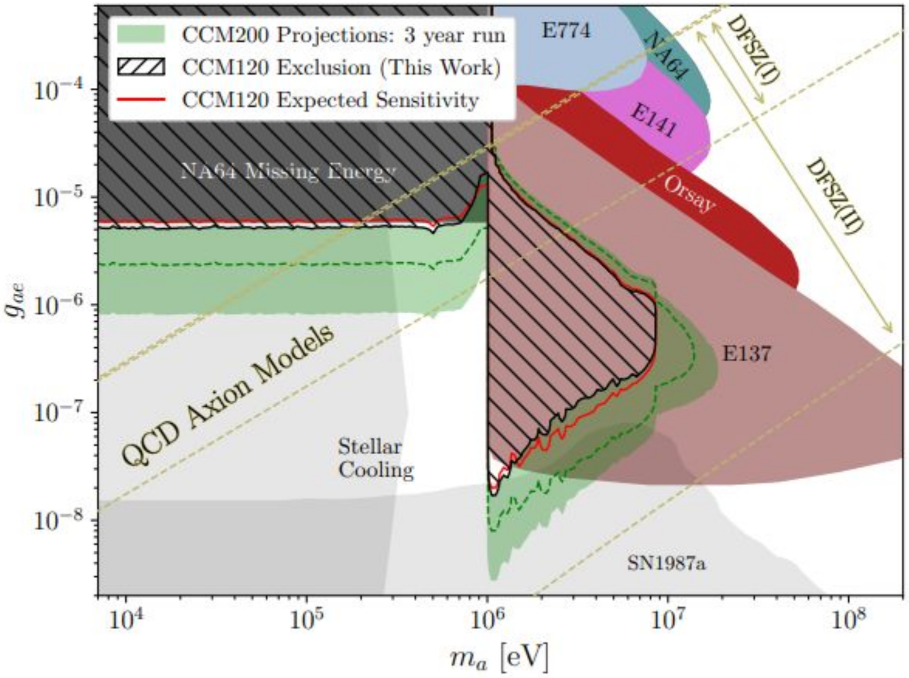


- We scan over ALP parameter space couplings to photons and electrons in a model-agnostic way (one coupling at a time turned on)
- Project sensitivity over the "cosmological triangle" at CCM200

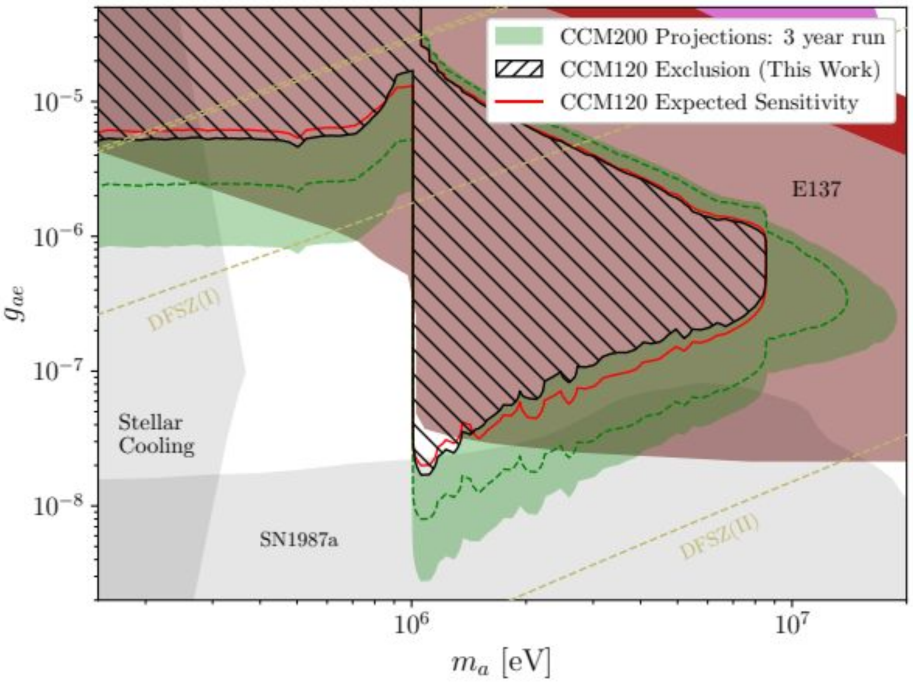


2019 Search for ALPs: Electron Couplings

A. A. Aguilar-Arevalo et al. "Axion-Like Particles at Coherent CAPTAIN-Mills". In: (Dec. 2021). arXiv: 2112.09979 [hep-ph].



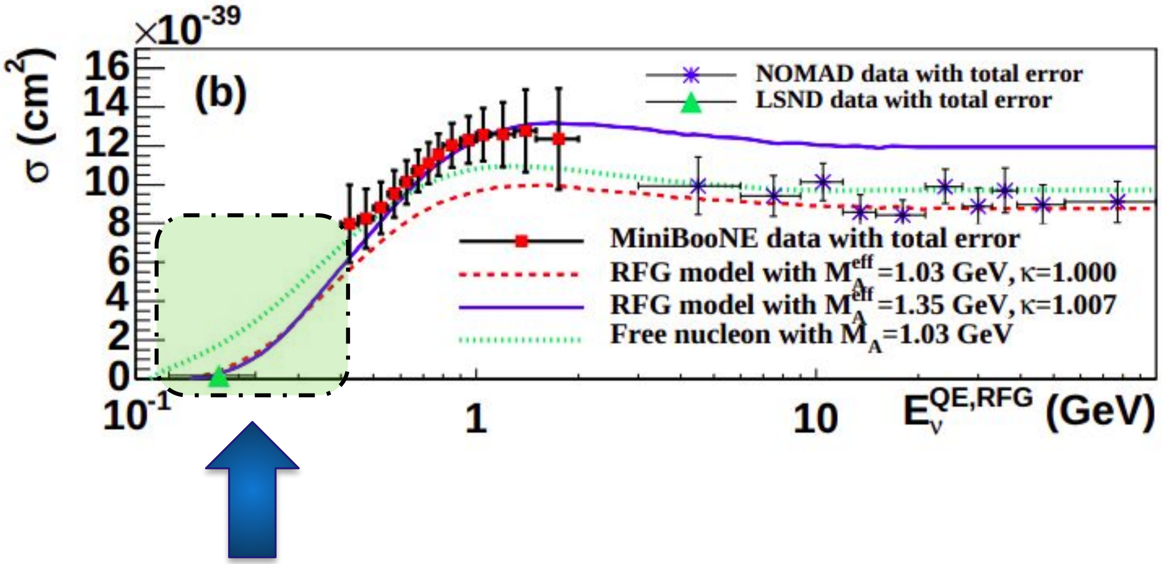
Pure ALP-electron coupling



With electron loop-induced photon coupling and $a \to \gamma\gamma$

Neutrino Physics at CCM

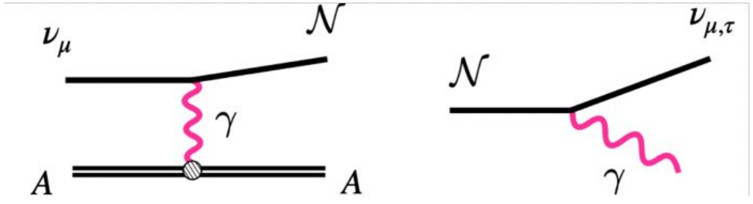
- **CEvNS** measurements
- Charged-current quasi-elastic (**CCQE**) cross section measurement
- Relevant for physics @DUNE:
  - **Supernovae** neutrino physics
  - sub-GeV **atmospheric neutrinos**



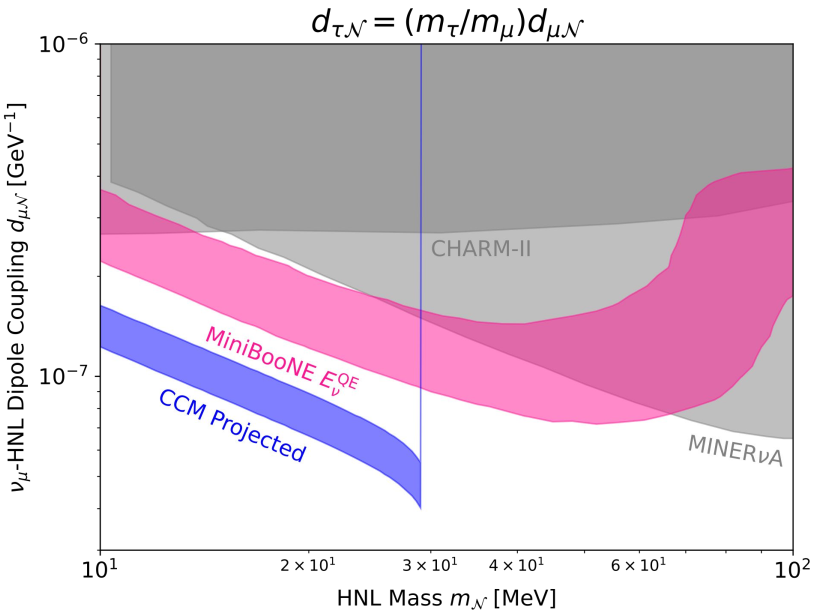
More measurements needed here!

Heavy Neutral Lepton Search

- CCM200 3 year run sensitivity to HNL production from neutrino upscattering in shielding and detector materials only

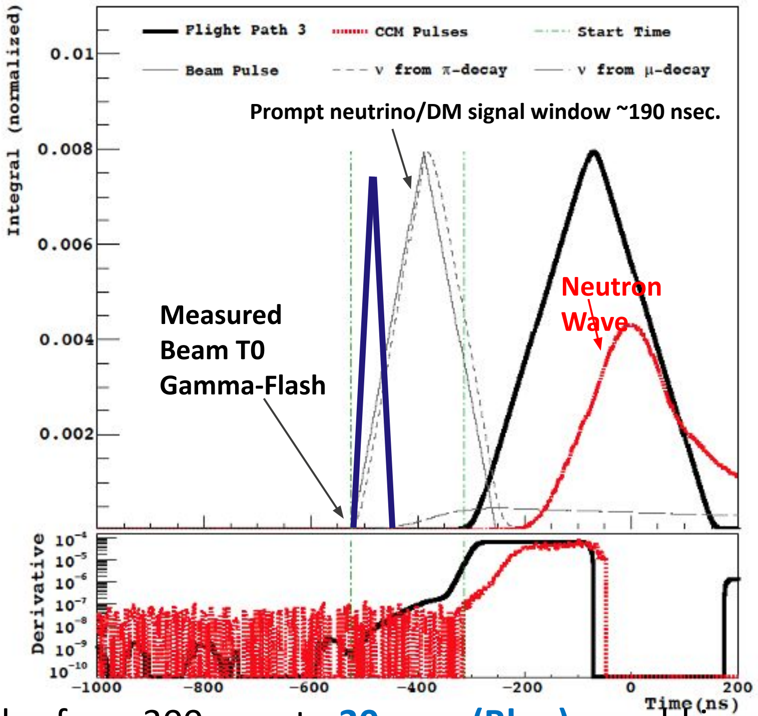


- Lujan facility is spacious enough to allow for increased shielding in future runs



Lujan Improved S/B with Upgrade 30 nsec Beam

TOF technique unique and powerful for isolating prompt signal and measuring backgrounds and errors from pre-beam. Key is to shorten the beam width.



Shorter beam pulse reduces random backgrounds from Ar39 decay and neutron activation

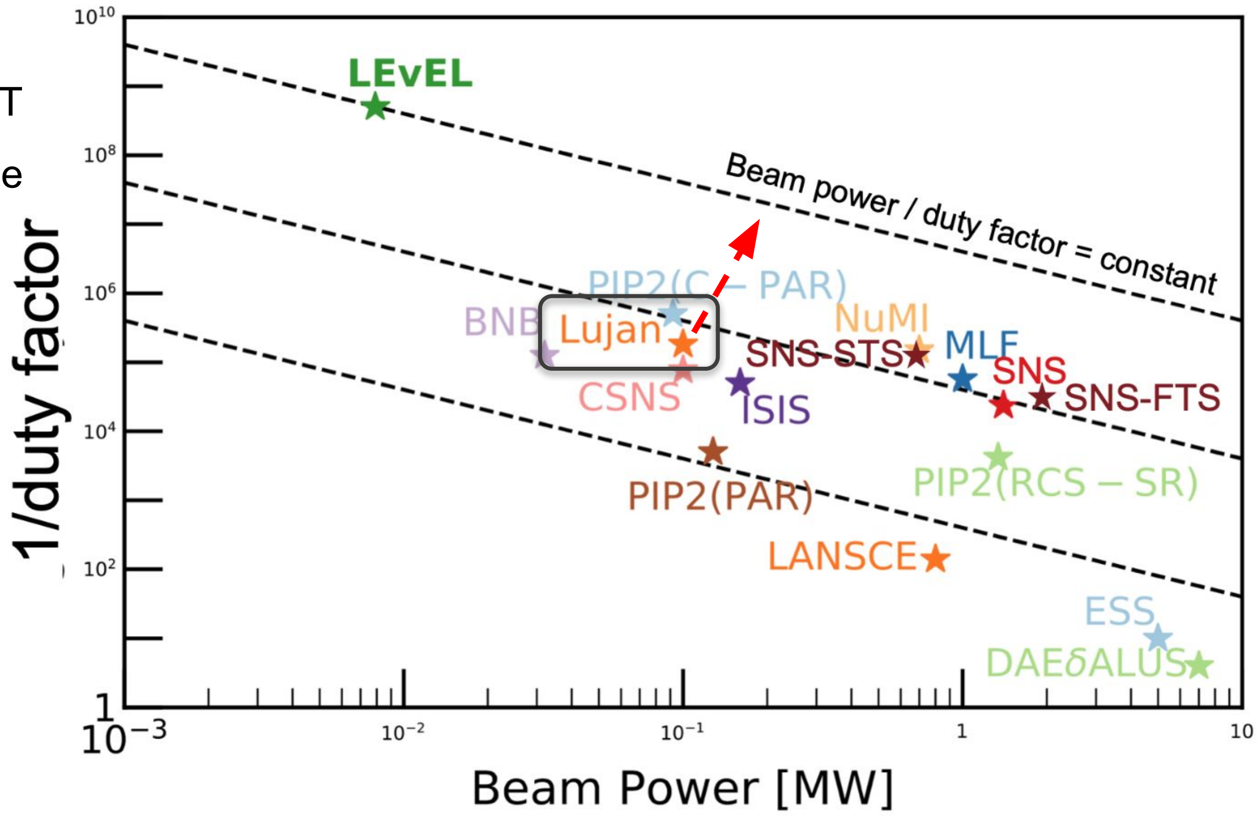
- If we shorten PSR pulse from 300 nsec to **30 nsec (Blue),** would increase signal efficiency and reduce random backgrounds, estimate increase **S/B (30 nsec) > 100**.
  - Factor ~10 reduction in random backgrounds from Ar39 and neutron activation
  - Factor ~10 reduction of EM events relative to nuclear scattering using Singlet/Triplet light PID.

Future Upgrades at CCM

Upgrades can greatly reduce backgrounds to improve sensitivity:

- **Short Pulse** from LANSCE AOT
  - Working toward 120ns pulse
- **Cherenkov** light
  - Direction reconstruction
- **Underground Argon**
- CCI (coherent Cesium Iodide second detector)
  - tonne-scale

Lujan/CCM makes up for less power with large, sensitive, and fast 10-ton LAr detector!



Proton Improvement Plan Beam Dump (PIP-II BD) [arXiv:2203.08079]

New Dedicated Facility: FNAL Proton Beam Dump @ 1 GeV

- Single-phase, **100 ton** scintillation-only **LAr** detector *o*(20 m) proximity to target
  - Same tech as CCM200
  - 800 MeV - 2 GeV beam possibilities
- Projected **world-leading sensitivity**;
  - Dark matter
  - ALPs
  - Sterile Neutrinos
  - ν cross section measurements, etc.