Searches for Physics Beyond the Standard Model with Coherent CAPTAIN Mills

Fermilab Wine and Cheese

TEXAS A&M UNIVERSITY
Physics & Astronomy

Los Alamos
NATIONAL LABORATORY
EST.1943

Adrian Thompson and **Edward Dunton**
on behalf of the
CCM Collaboration

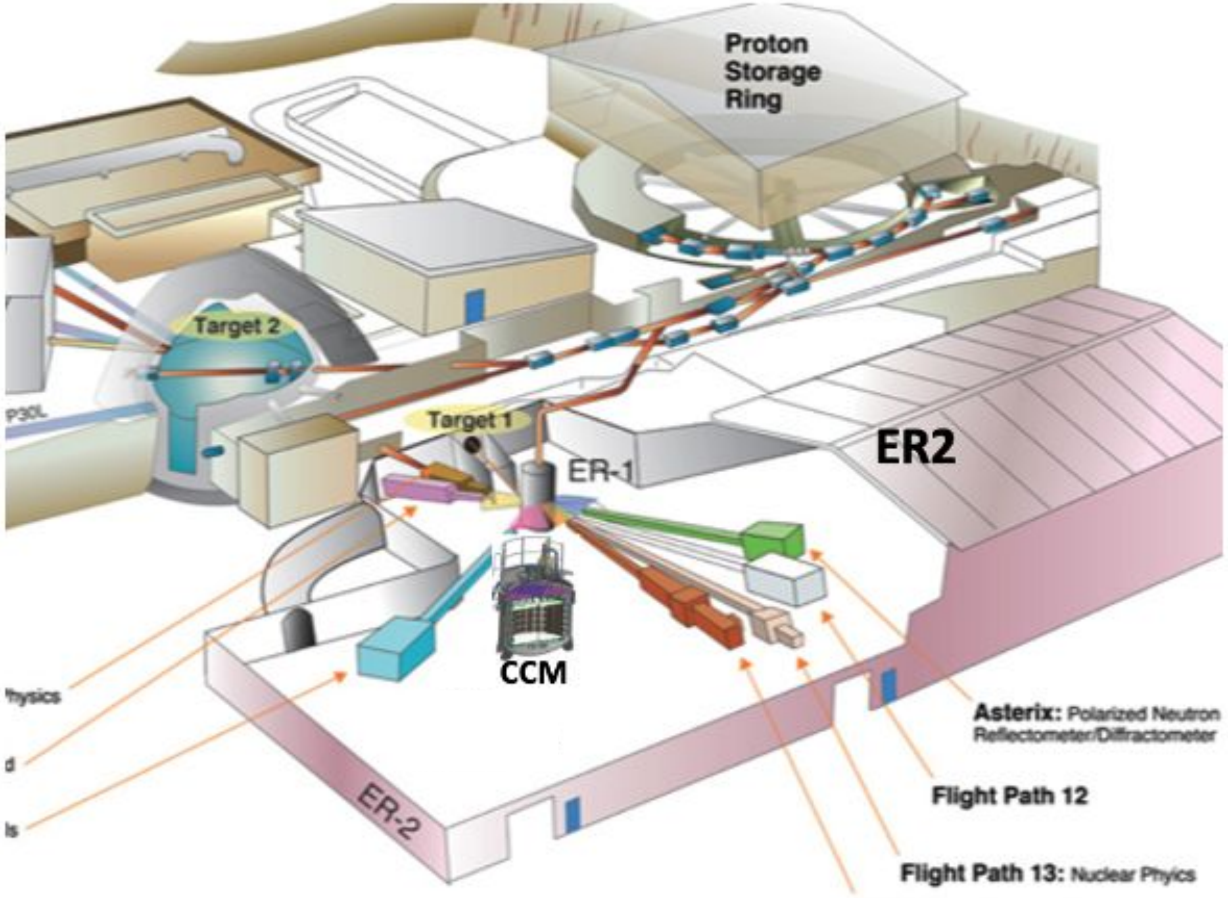
June 16, 2023

Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

Coherent CAPTAIN Mills (CCM) *at* LANSCE

(Los Alamos Neutron Science Center)

800 MeV protons, 100kW, 290 nsec pulsed beam



Agenda

I. Motivation and Theoretical Models:
   Searching for Dark Sector Physics with GeV Beam Dumps
II. The Coherent CAPTAIN Mills Experiment
III. Data Selection and Background Rejection in CCM
IV. Results and Future Sensitivities of CCM
V. Conclusion

Section I:
Motivation and Theoretical Models:
Searching for Dark Sector Physics with GeV Beam Dumps

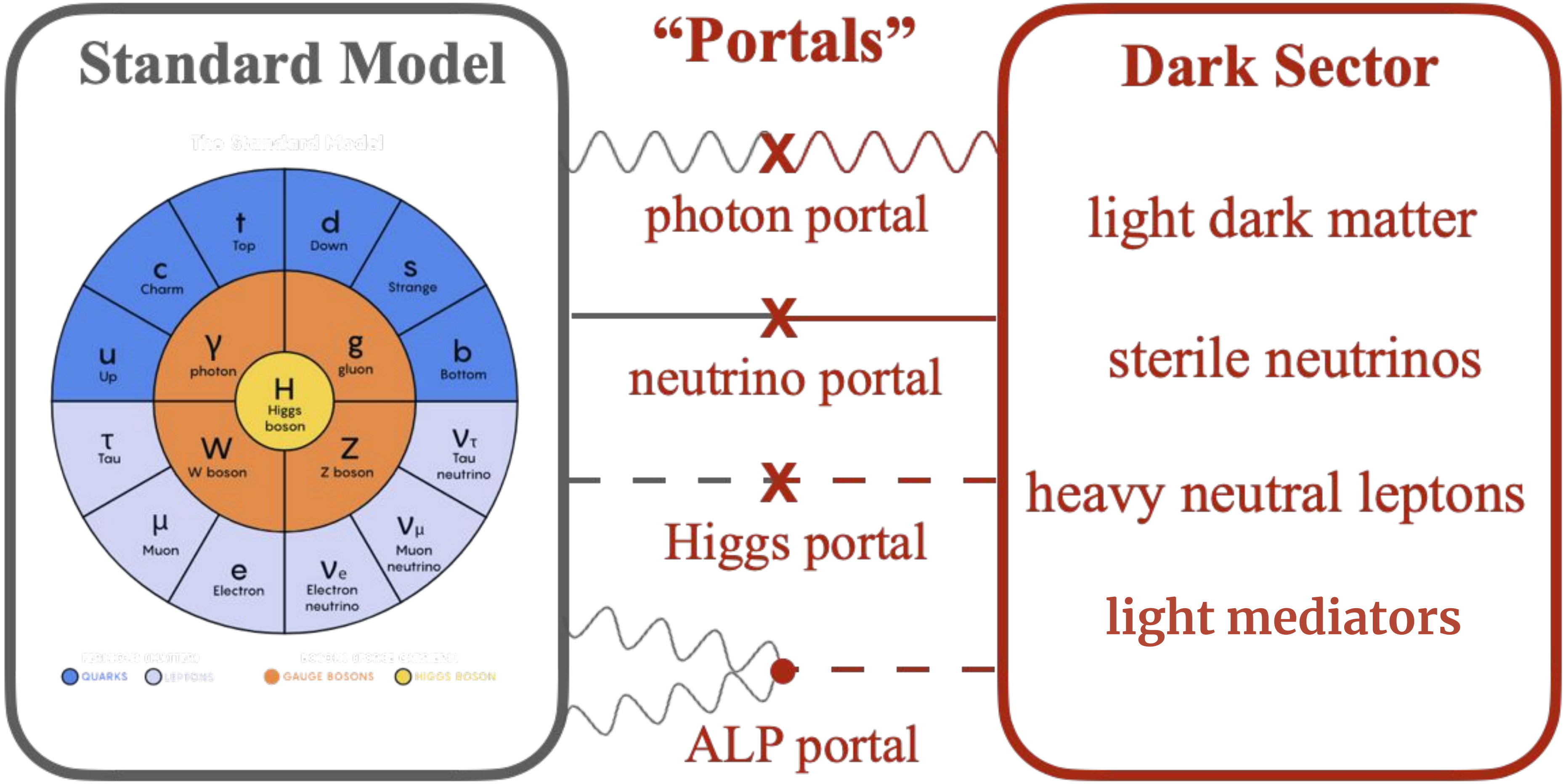
Outstanding Physics Puzzles

The Dark Matter Puzzle

Strong CP Problem

The Neutrino Mass Puzzle

Anomalies: MiniBooNE, Short Baseline…



Opportunities for Beam Dumps at sub-GeV Energies

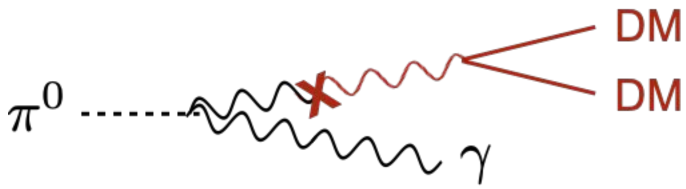
- Scarcity of new physics signals at colliders
- TeV scale WIMPs have been stringently constrained, but ***light DM*** targets are closer within reach
- The existence of ***light mediators*** inaccessible to colliders
- At CCM (800 MeV proton beam) we have access to ***energy and mass scales*** from the ***keV*** to ***hundreds of MeV***
- ***Unique physics signatures*** from the beam target

Physics Program at CCM with the Lujan Target

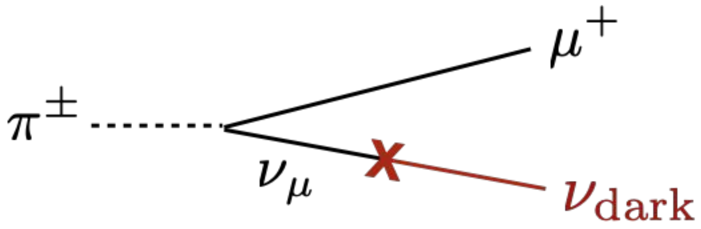
- Leptophobic Dark Matter: ***Phys. Rev. Lett.*** 129 (2022) 2, 021801 [2109.14146]
- First DM Search: ***Phys. Rev. D*** 106 (2022) 1, 012001 [2105.14020]
- Axion-like Particle Search: ***Phys. Rev. D*** 107 (2023) 9, 9 [2112.09979]
- *Testing Meson Portal Dark Sector Explanations for MiniBooNE at CCM* (forthcoming work)

CCM Physics Program: broad search for dark sector particles

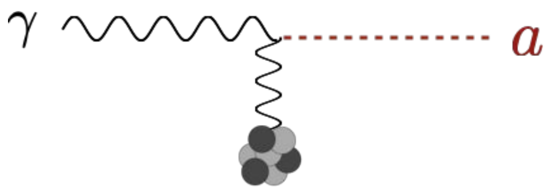
- **Dark matter production and detection via vector and (pseudo-)scalar portals**

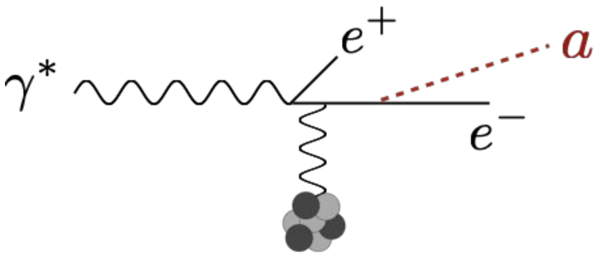


- **Neutrino Portals (sterile neutrinos, heavy neutral leptons)**

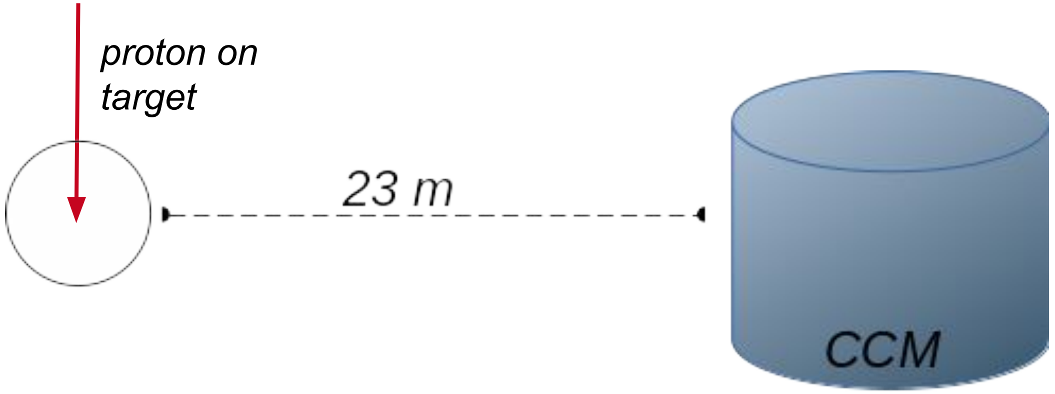


- **Dark Sector Mediators**



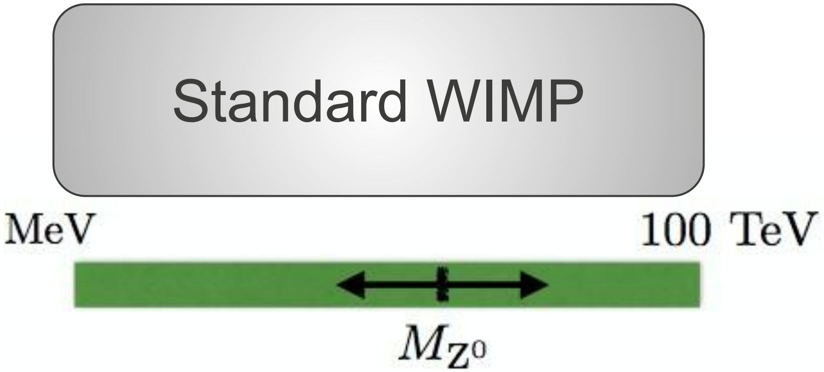


- ***Source***: Lujan beam at LANL
- ***Beam Energy:*** 800 MeV proton beam
- ***Target:*** Tungsten (W)
- ***Detector:*** LAr scintillator
- ***Baseline:*** 23 m

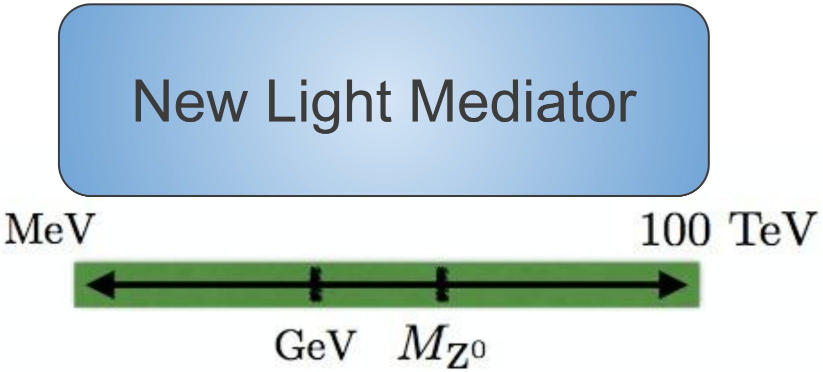


Proton beam dumps can probe all these portals

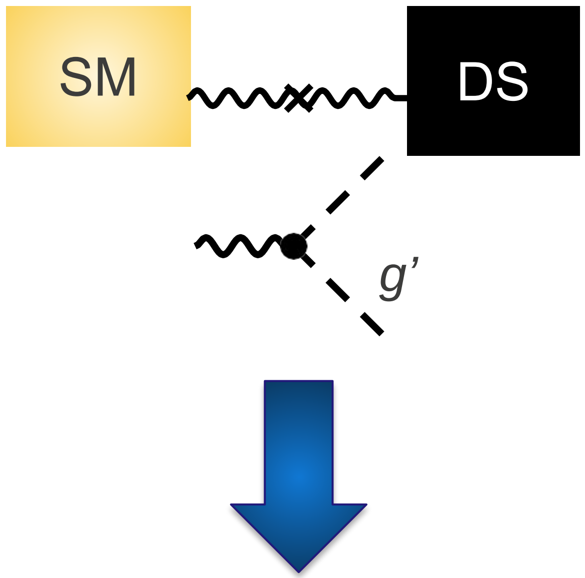
Vector Portal Light Dark Matter



- 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 **DS** in SM *particle cascades* in fixed target experiments

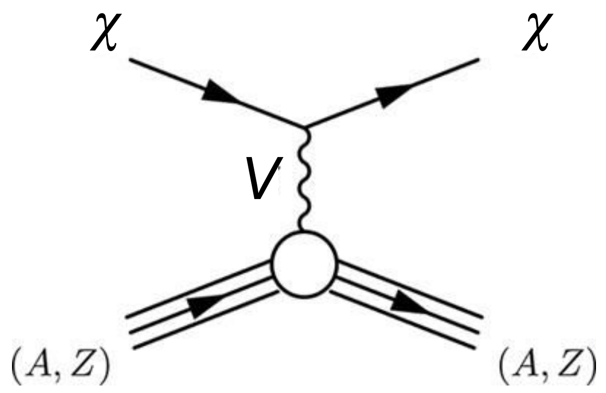
MiniBooNE beam dump mode first dedicated DM search in this way

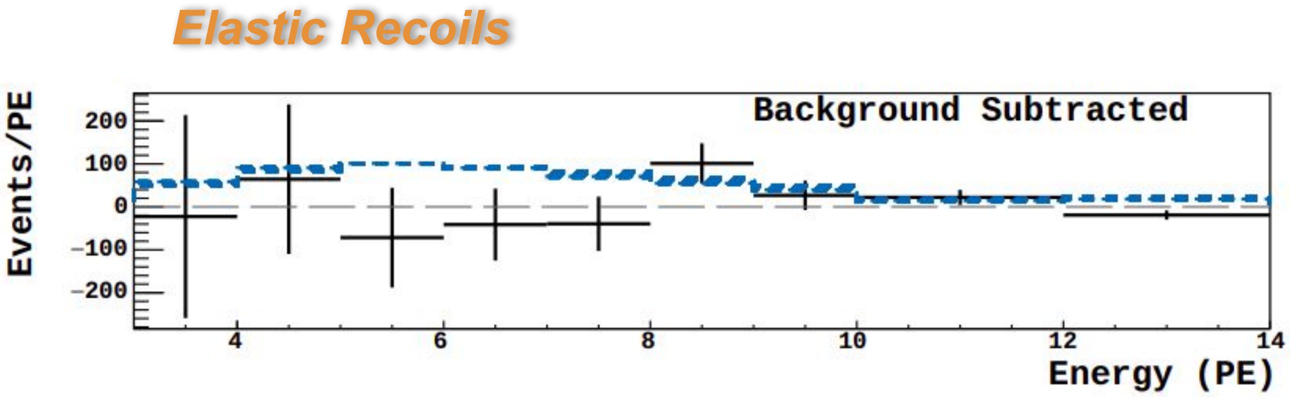
Phenomenology: Vector Portal Light Dark Matter

One example:

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

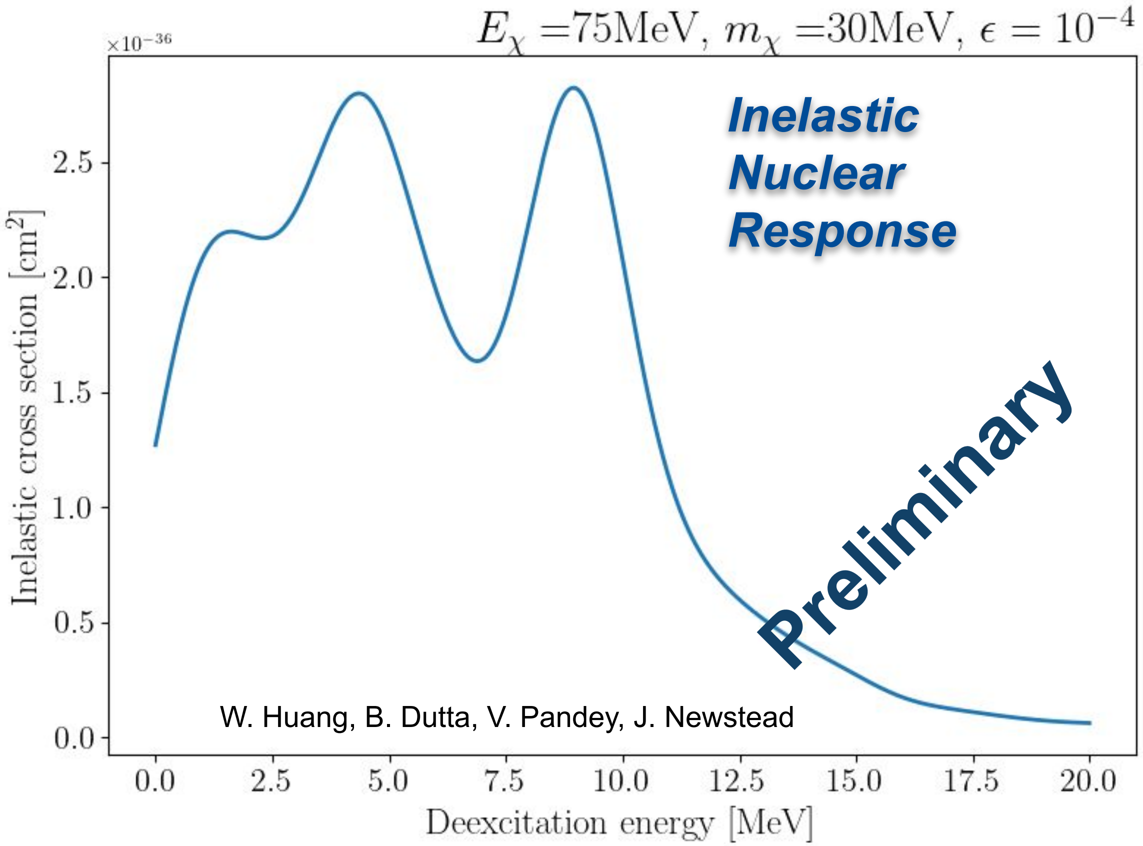
$$J_\mu^B \equiv \frac{1}{3}\sum_i \bar{q}_i \gamma_\mu q_i$$





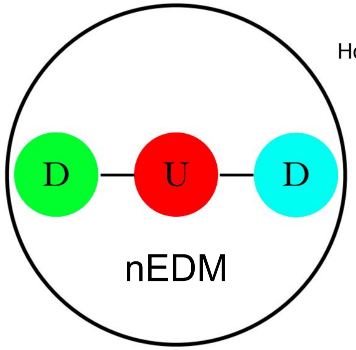
Phys. Rev. Lett. 129 (2022) 2, 021801 [2109.14146]

- Elastic nuclear recoils → **keV** signature
- Inelastic response: **MeV** Argon nuclear deexcitations



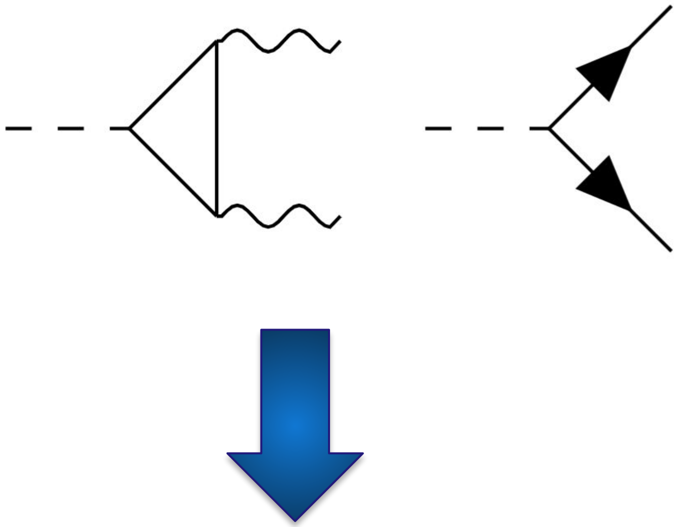
The QCD Axion and Axion-Like Particles (ALPs)

Hook [1812.02669]



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

  →*Why is the neutron dipole moment so small?* $d_n < 10^{-26}$ e cm
  - Related to *CP* violating term in QCD: $\mathcal{L} \supset \theta GG$
  - $U(1)_{PQ}$ broken → $a\mathbf{GG}$ term to dynamically conserve *CP*



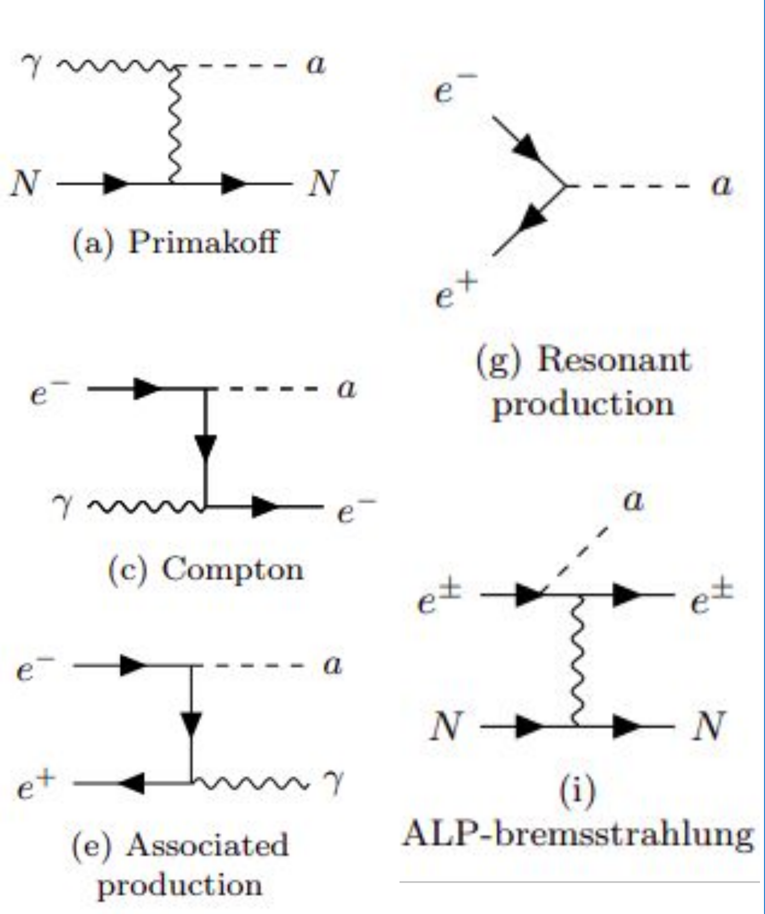
- But there are many other theories that predict pNGB pseudoscalars:
  - **generic goldstones** of broken global $U(1)_X$
  - String ***axiverse***
  - **Non-traditional** QCD axions
  - Axion **dark matter**

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

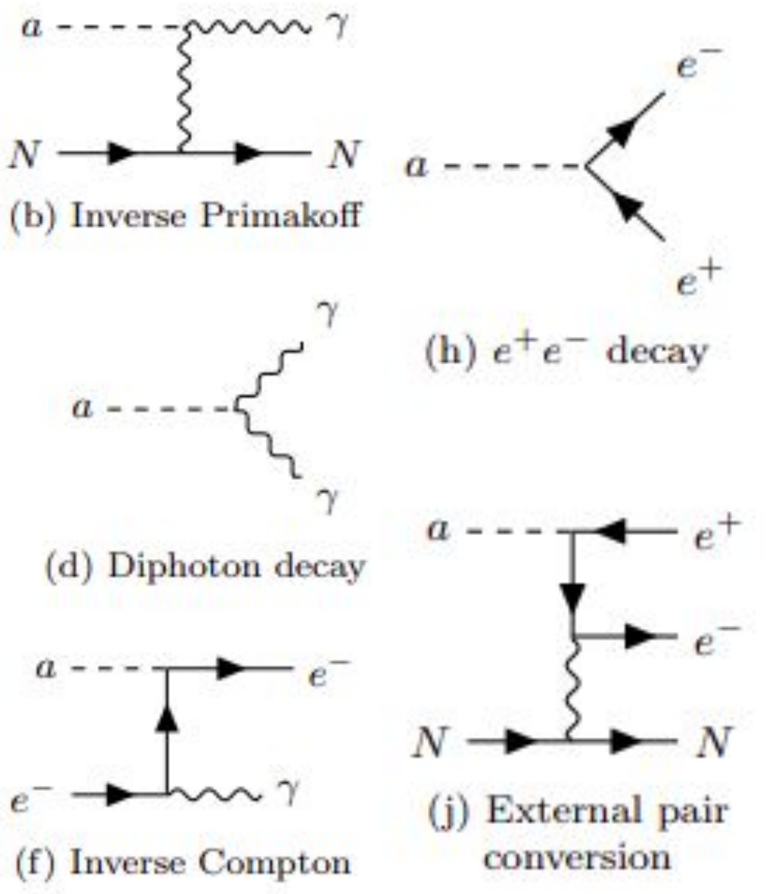
CCM is sensitive to ALPs with masses up to ~100 MeV

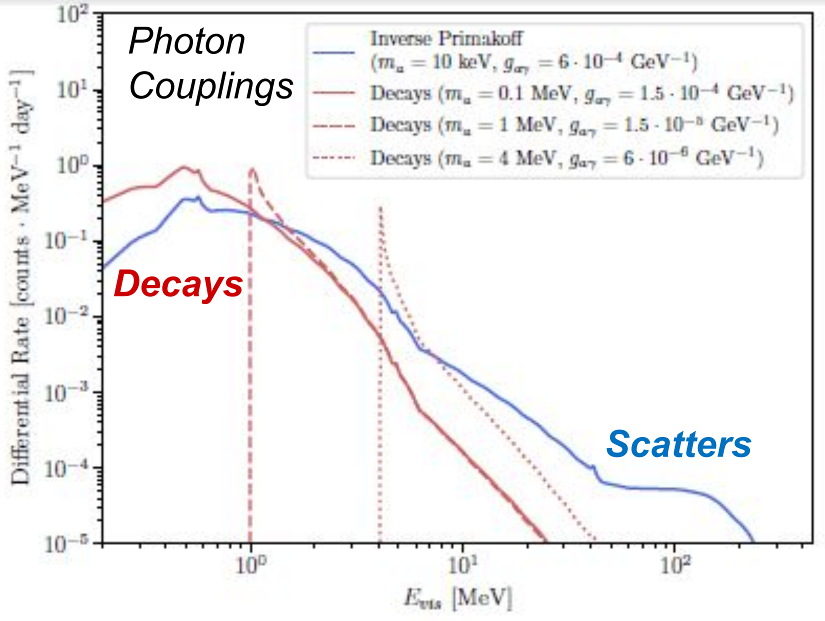
Phenomenology: ALP Detection in CCM

Production Channels in W Target

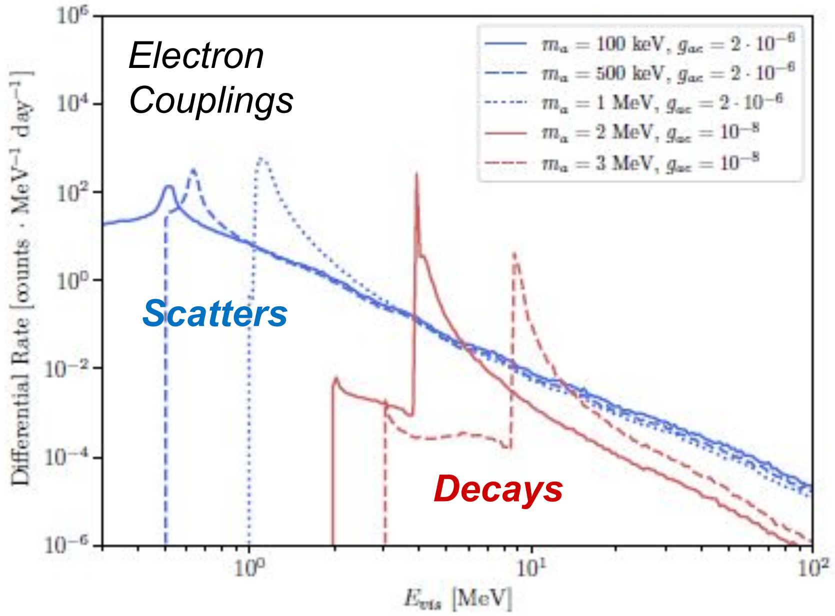


Detection Channels

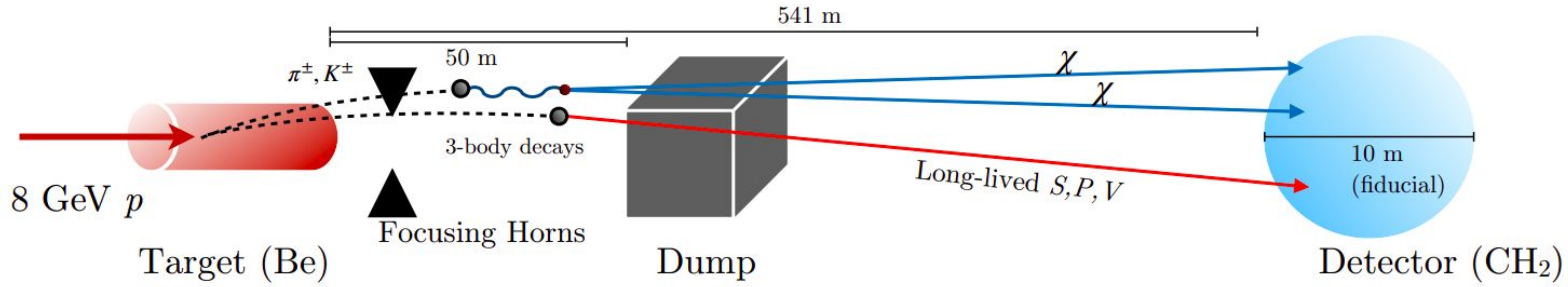




Phys. Rev. D 107 (2023) 9, 9 [2112.09979]

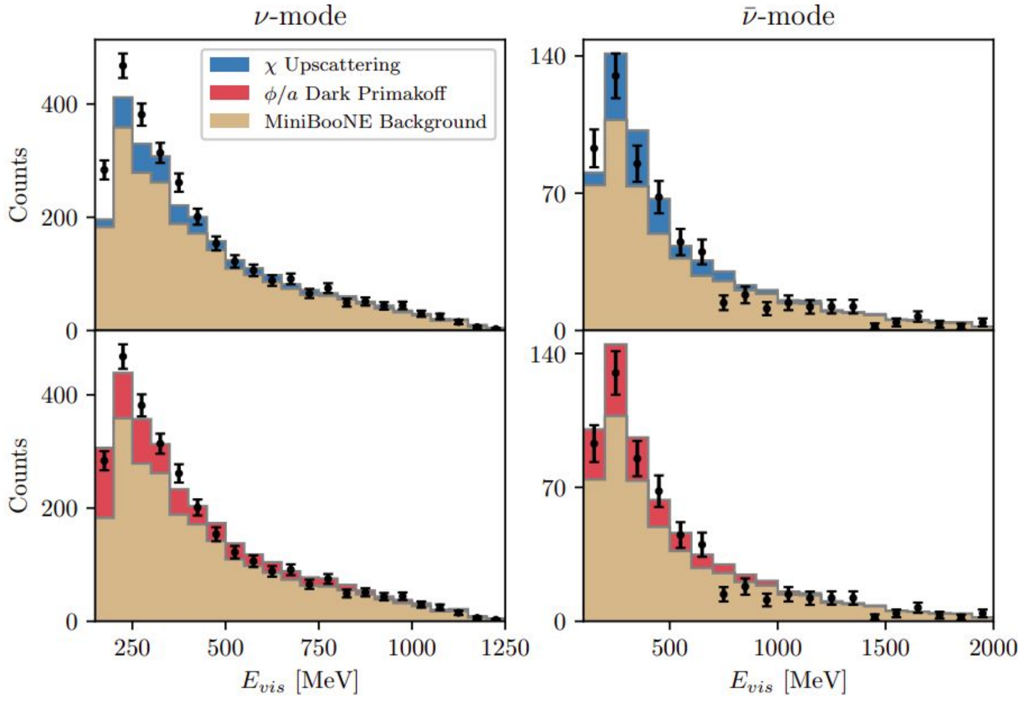


Dark Sector Explanations of the MiniBooNE Anomaly



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

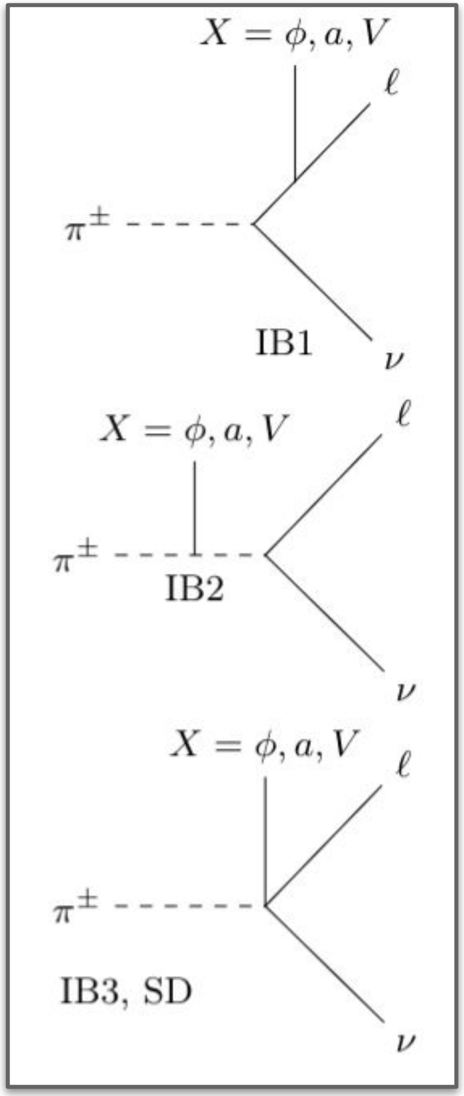
- 4.8σ excess at MiniBooNE **target mode** runs
- No excess in **dump mode** run
- If excess is due to new long-lived particles (**LLPs**) or light dark matter (**LDM**), it may be correlated to the charged meson decays [*PRL* 129 (2022) 11, 111803]
- We can test this possibility in a complementary way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

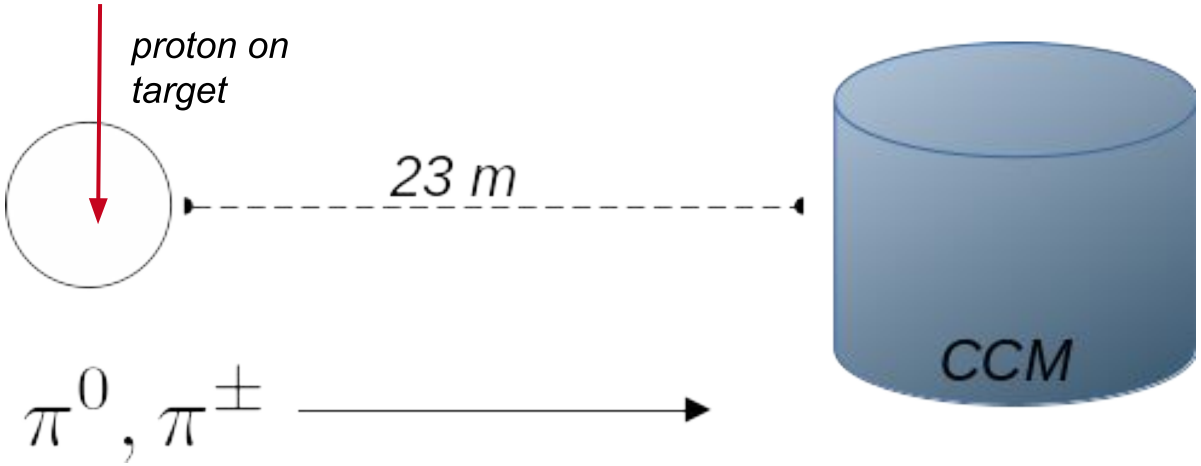


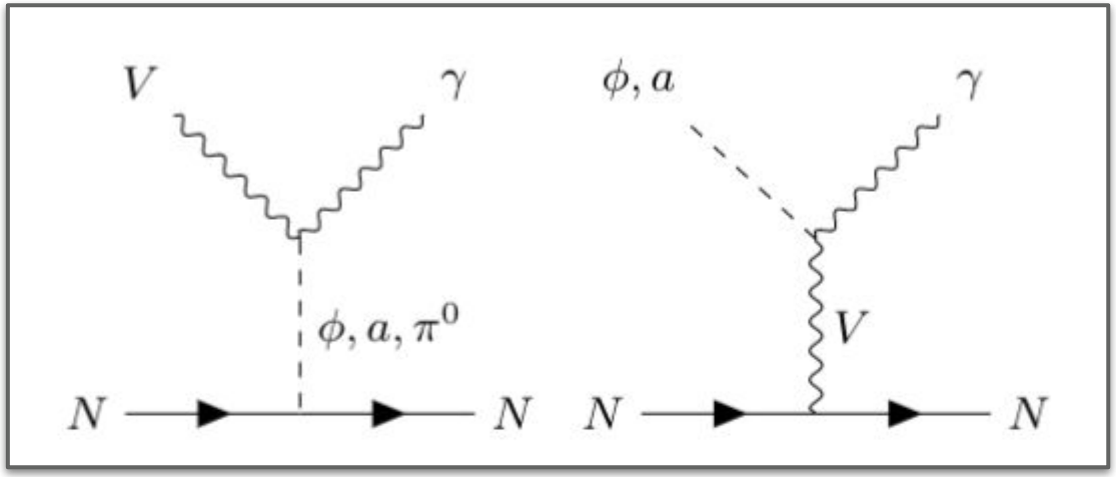
Phenomenology:
Dark Sector Charged Meson Decays (DSCMD)

Big picture: lots of possible operators to explain the MiniBooNE excess

We can test these systematically with both **charged** and **neutral** pion decays at CCM





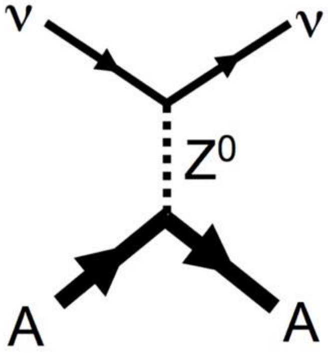


…and many more models!

- Milli-charged particles (**mCPs**)
- Mirror neutrons, dark QCD
- Heavy Neutral Leptons (**HNL**s)
- Long-lived particles (**LLP**s), e.g. higgs portal scalars, pseudoscalars, dark photons
- Neutron-anti-neutron Oscillations
- High-stats CEνNS and ν_eCCQE cross section measurements

Section II:
The Coherent CAPTAIN Mills Experiment

The CCM Experiment



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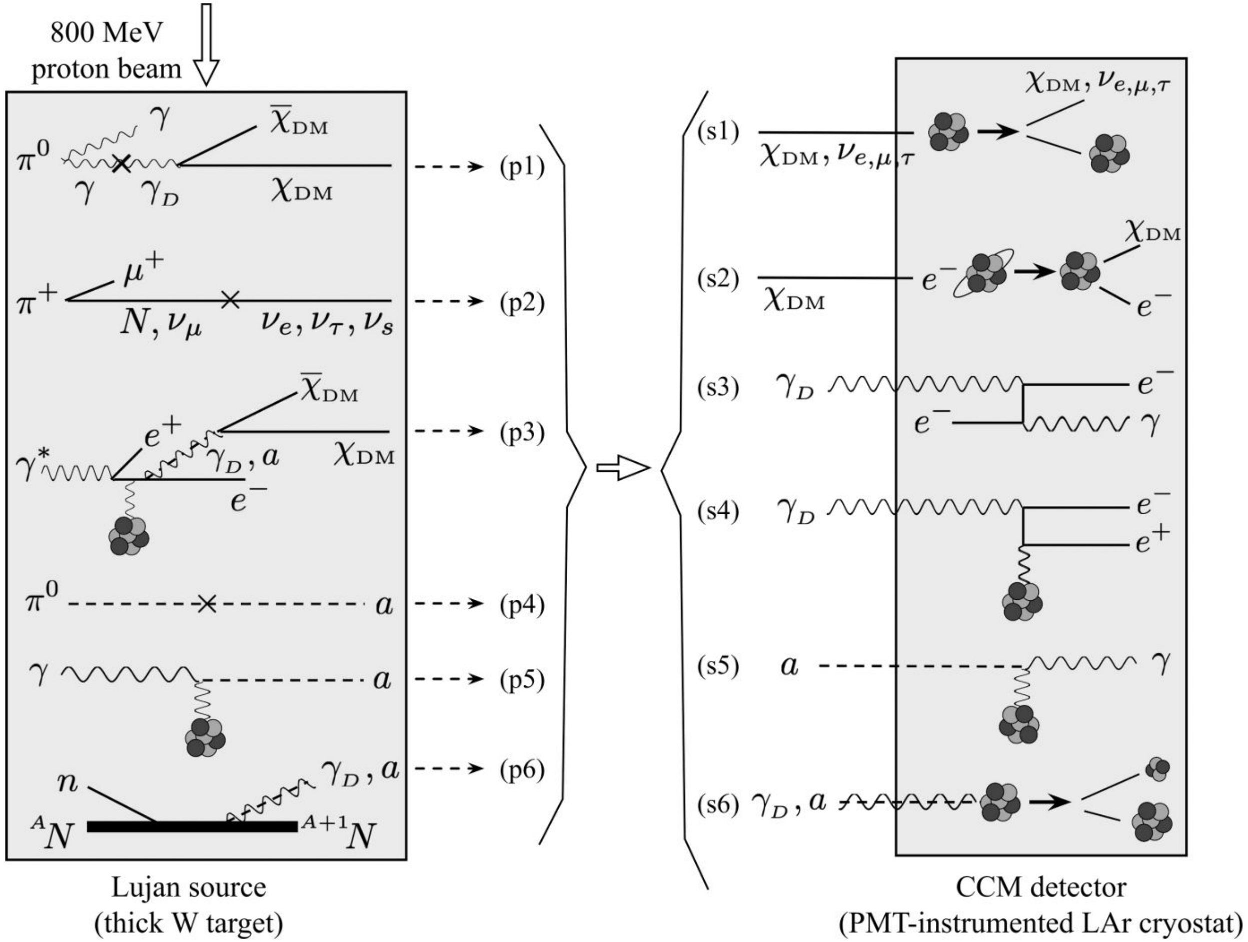
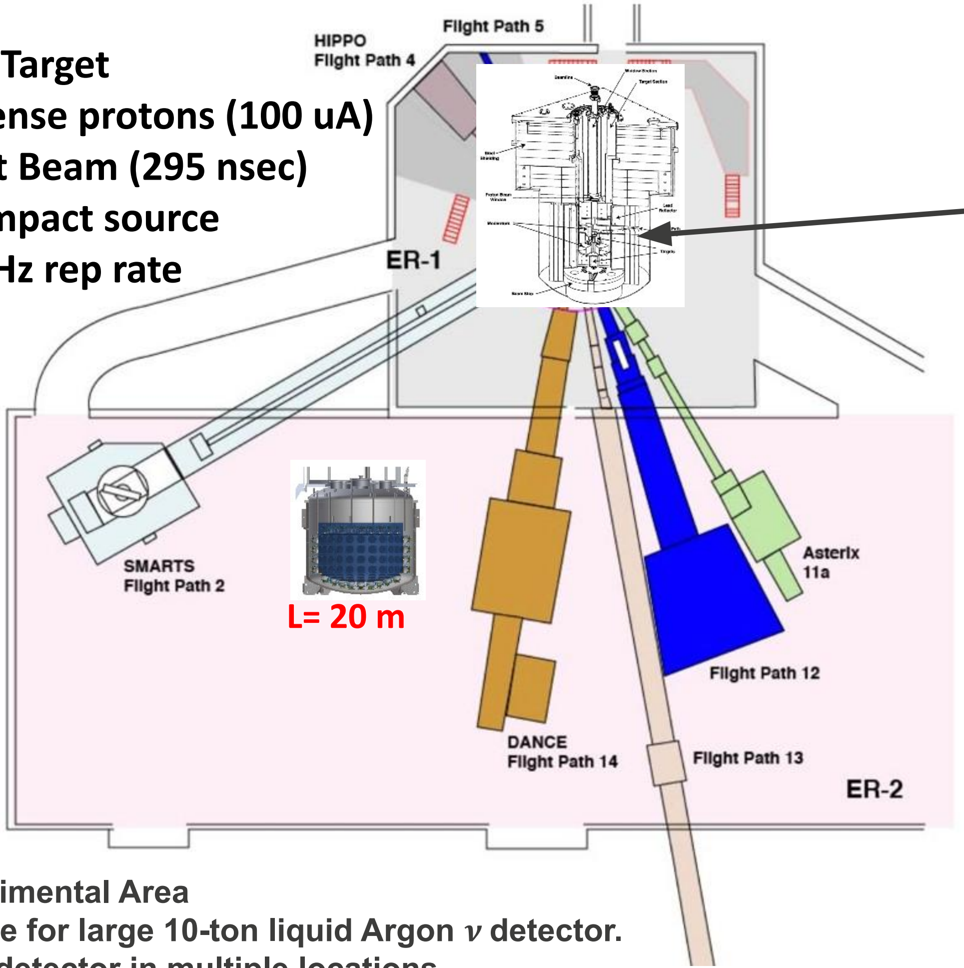


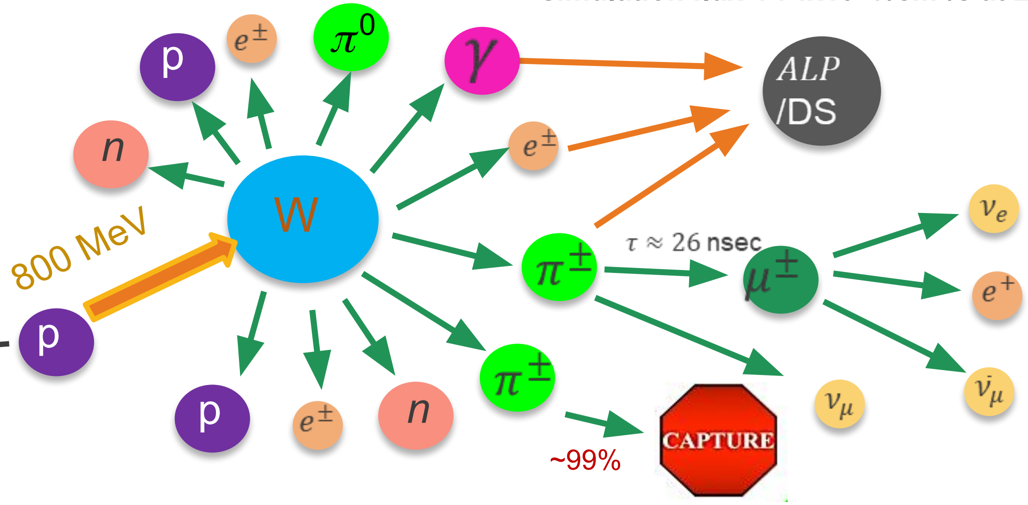
The CCM Experiment: LANSCE-Lujan Facility

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

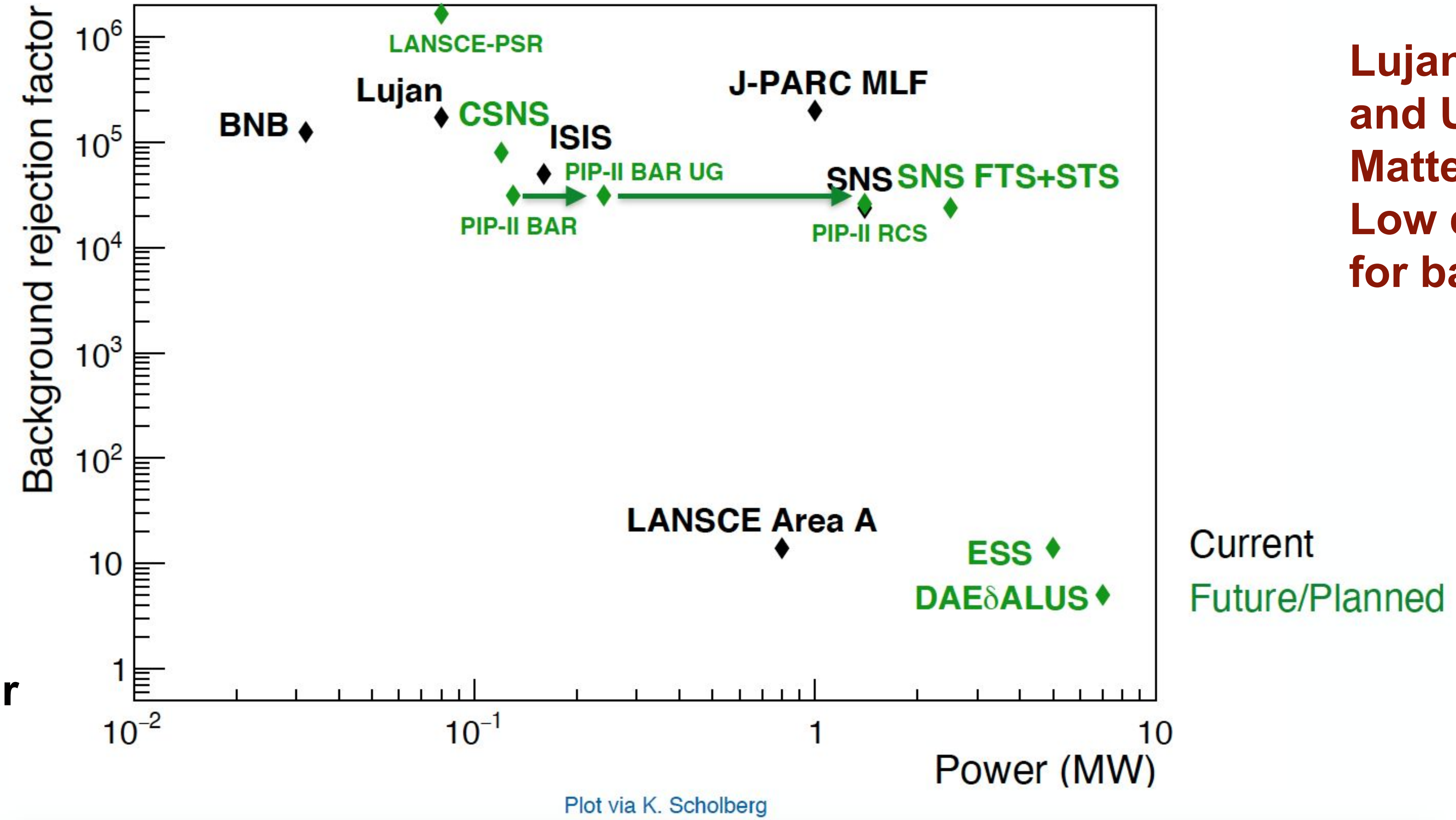




CCM120 beam and calibration run 2019 (L=20 m)

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 CCM Experiment: LANSCE-Lujan Beam



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

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

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

- **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

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

Complex target tuned for neutron production

Beamlines controlled by Hg window

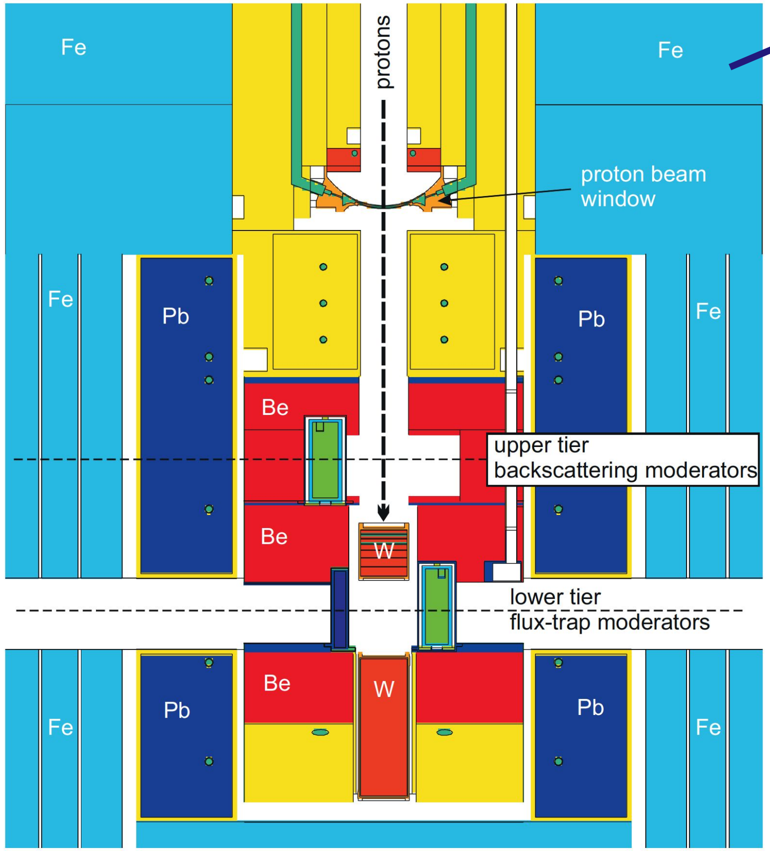
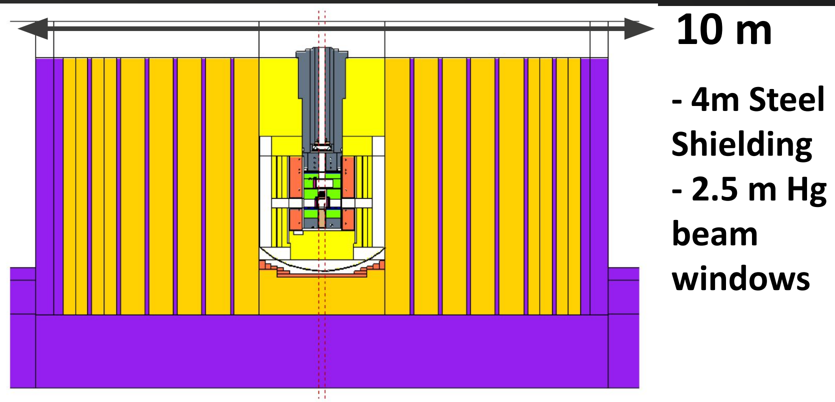
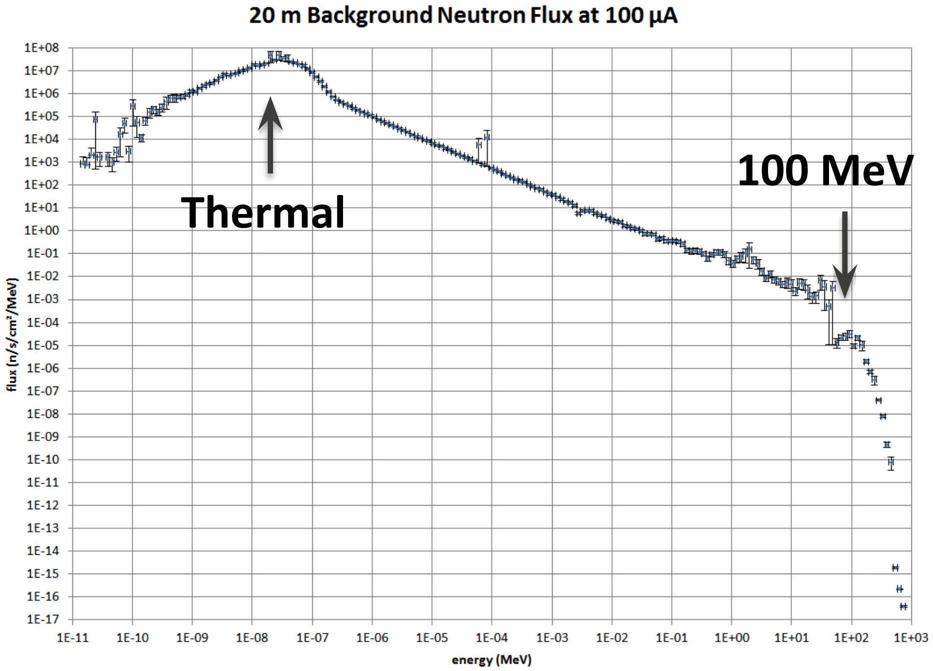


Fig. 1. Elevation view of the Lujan Center's TMRS geometry used in our calculations. The main components are labeled: split tungsten target (W), beryllium reflector (Be), lead reflector–shield (Pb), and the steel reflector–shield (Fe).

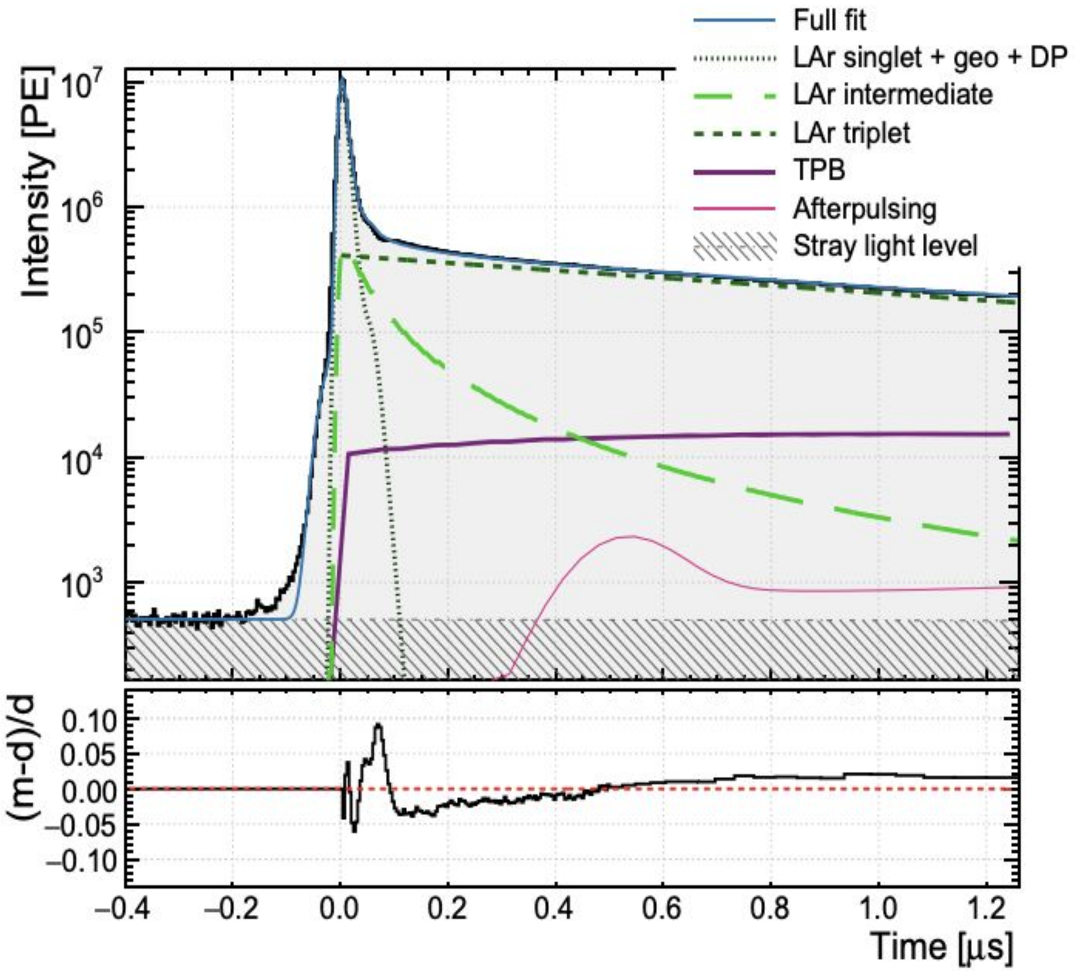


- Extensive shielding around target
- Simulations has confirmed hand calculated neutrino flux of ~4.74×10^5 nu/cm^2/s at 20 m
- MCNP simulation of target and ambient neutron flux

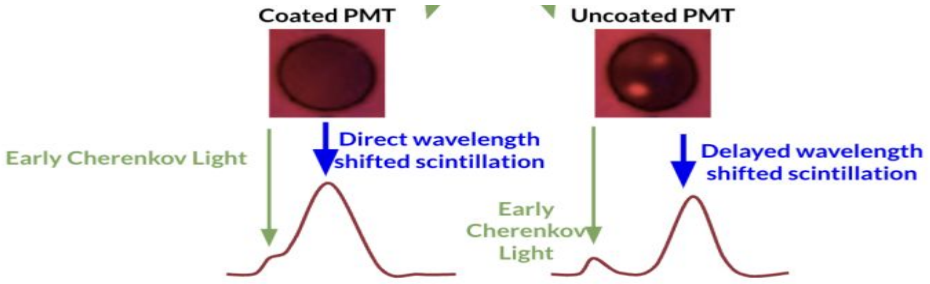


Scintillation/WLS mechanics

- 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 CCM120 Detector: 2019 run

- Mounted in the 10 ton CAPTAIN cryostat.
- 7 tons LAr Fiducial volume, 3 tons LAr Veto (2-3 radiation lengths)
- 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, feedthrus, HV, electronics, trigger, DAQ, calibration, simulations and data analysis. -> **now installed in SBND**

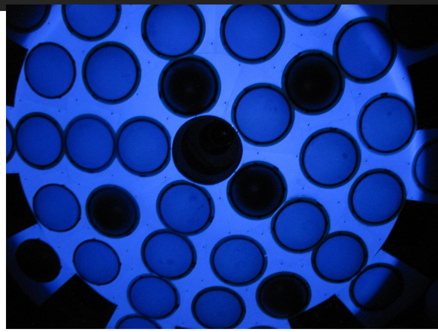
TPB coated PMTs

Uncoated PMTs

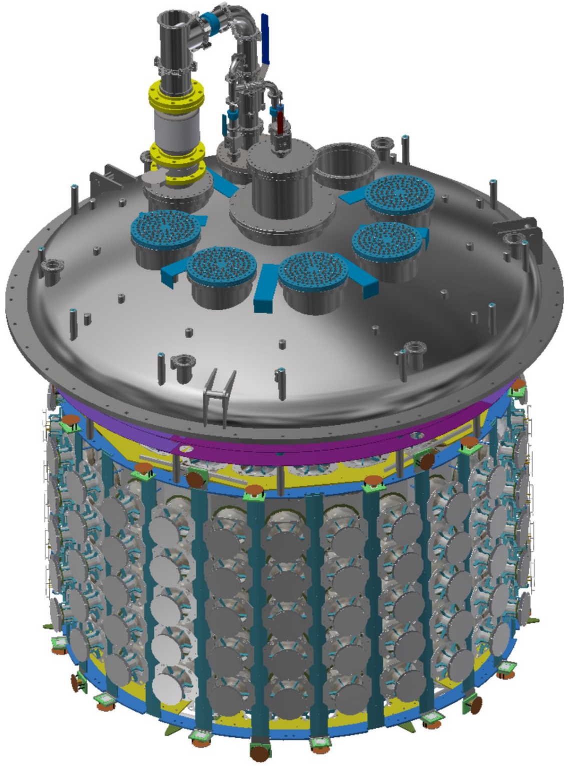
TPB coated reflector foils. Maximize light output to detect coherent neutrino-nucleus scattering

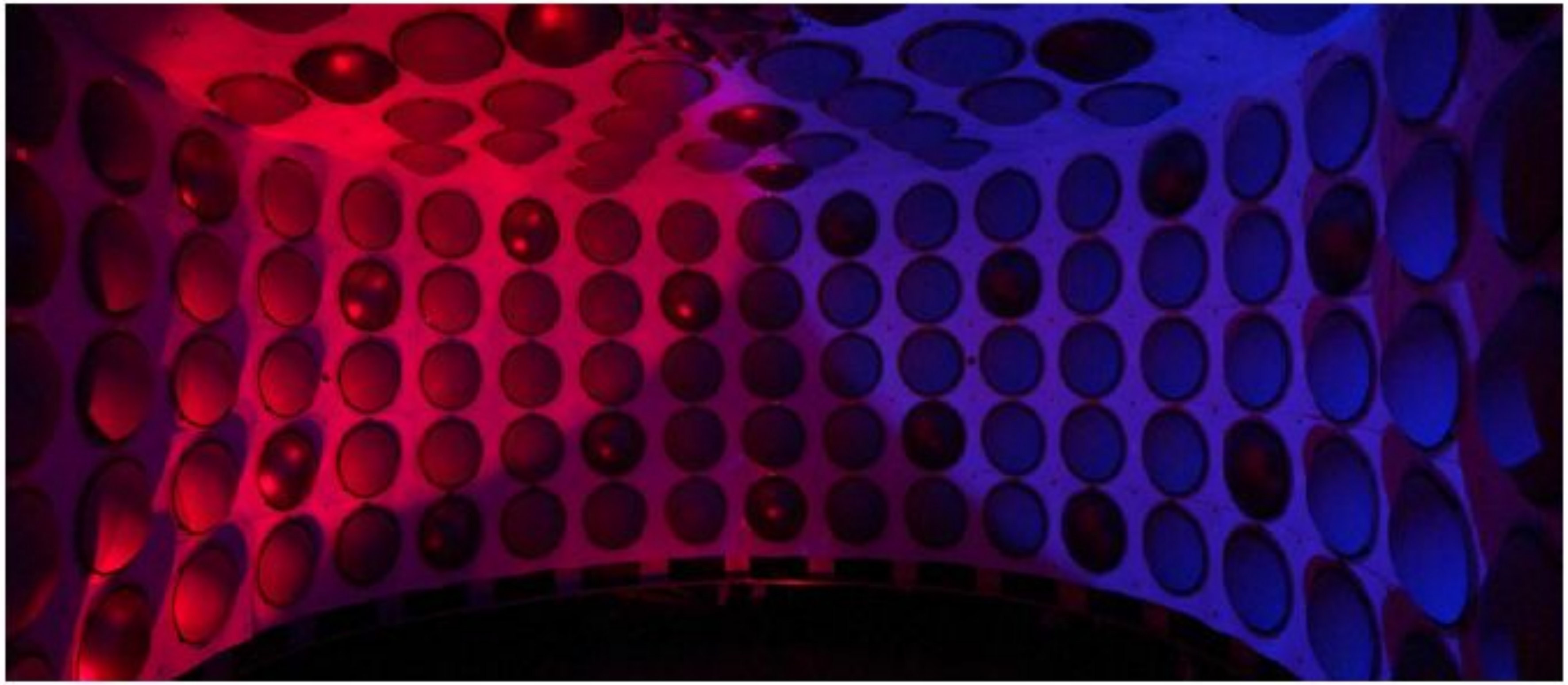
- 6-week Engineering run in 2019 collected **1.79×10^{21}** Protons on Target

The CCM200 Detector: 2021 to 2025 runs.



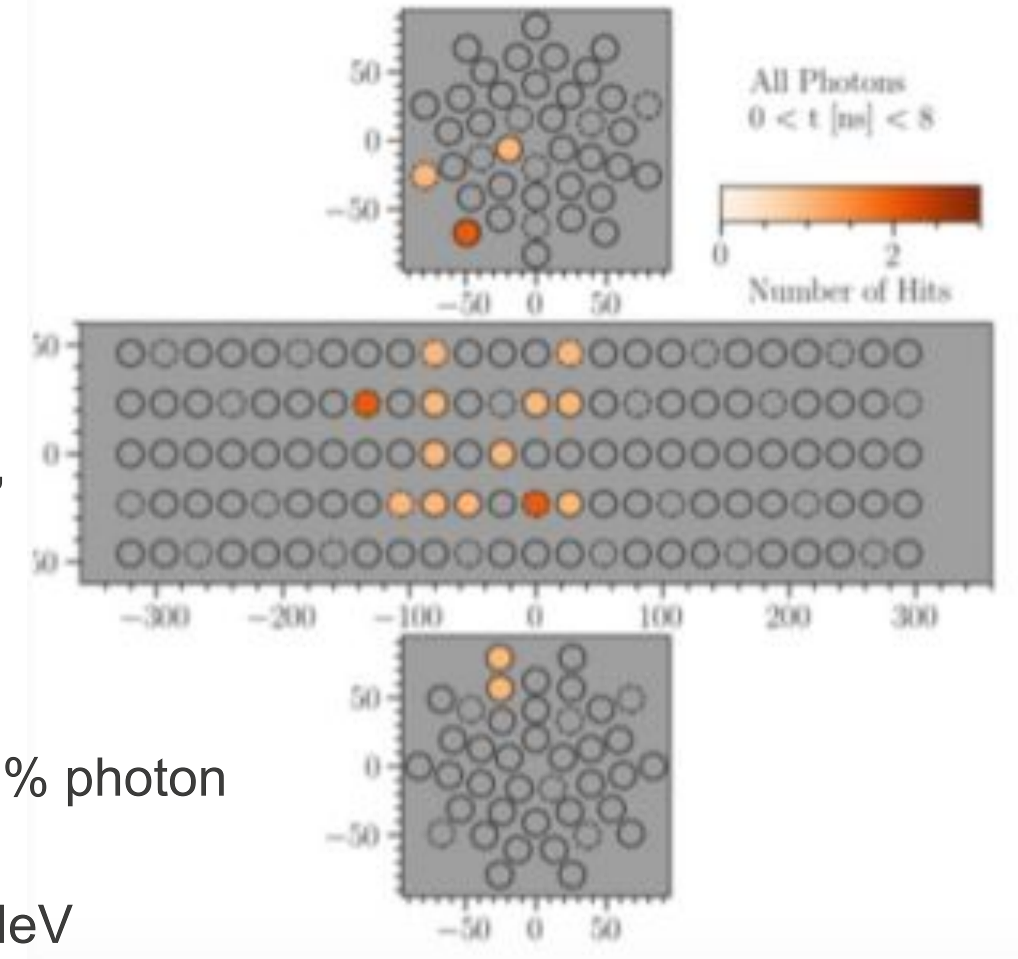
- Instrument all 120 cylinder 8” PMTs with new PMTs
- + Instrument 40 8” PMTs on each end cap => total **200 new 8” PMT’s**.
- 40 1x1” vetos instrument outer region (double veto PMTs)
- New evaporative TPB foils (double efficiency of CCM120 foils) produced at U. Edinburgh.
- New CCM200 detector built July 2021, initial test run done September-December 2021.





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.

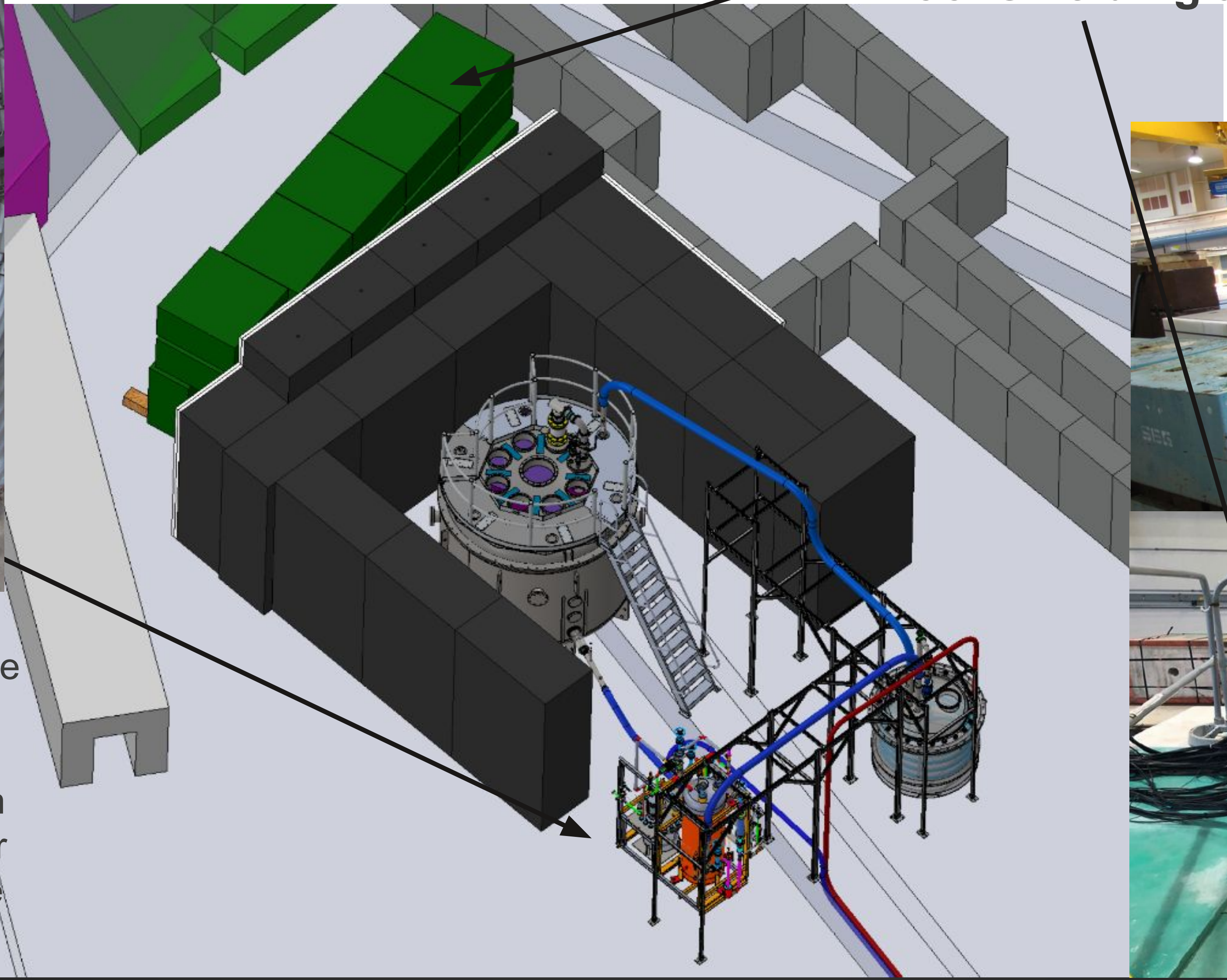


Simulated hits from Cherenkov light in CCM200 detector. Visible Cherenkov light precedes scintillation by up to 8 ns.

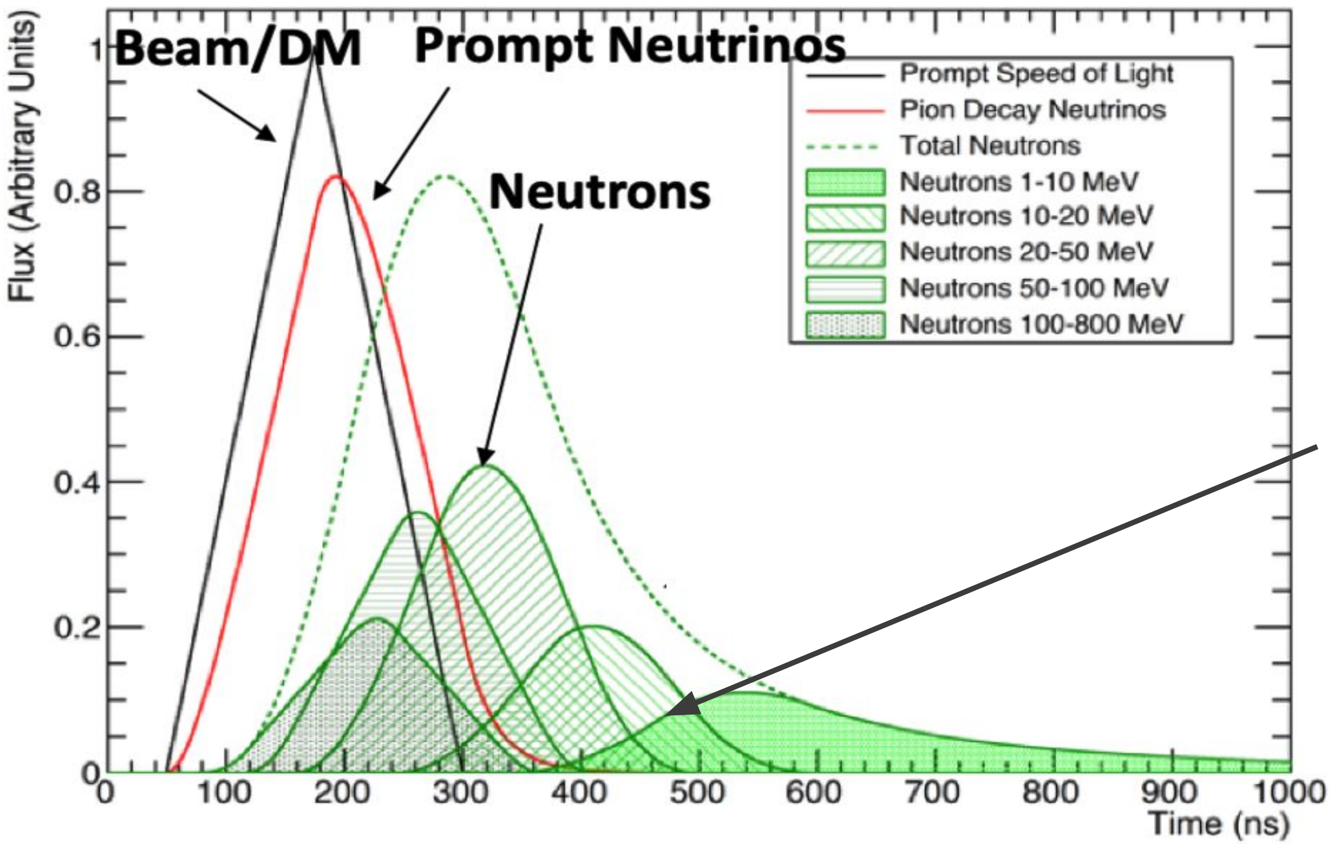
CCM200 Shielding Layout at Lujan (23 m from target)

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.



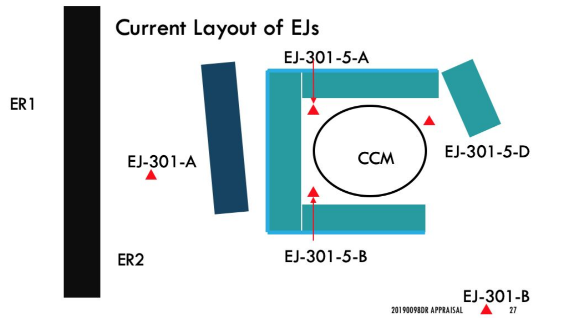
The CCM Detector: Using fast timing and shielding to remove beam-related neutrons



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

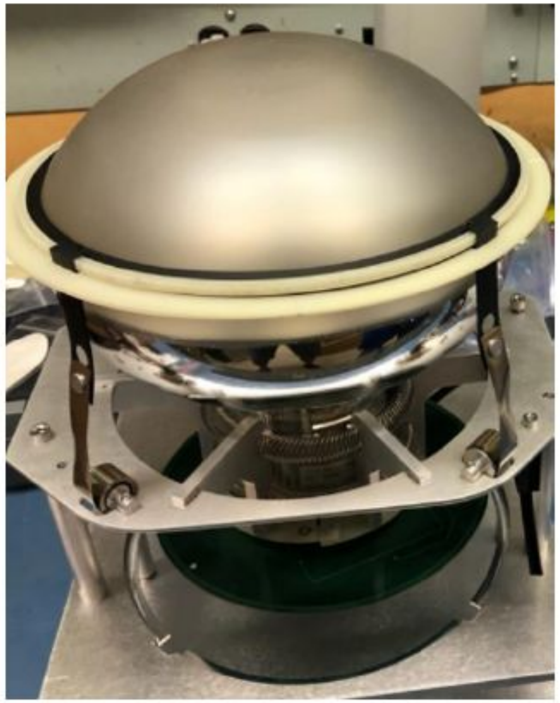


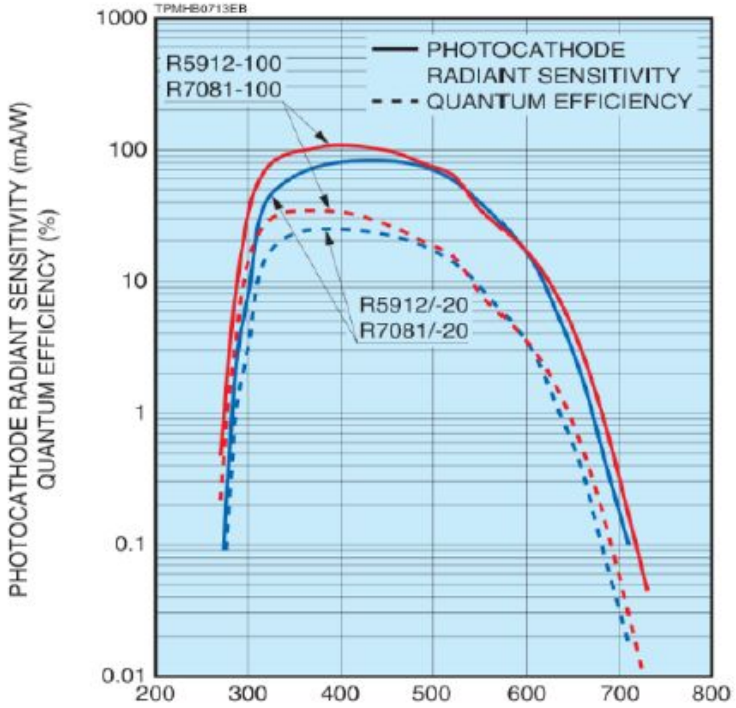
External time of flight measurements with EJ301 detectors measure ~20 MeV fastest neutrons

- 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.

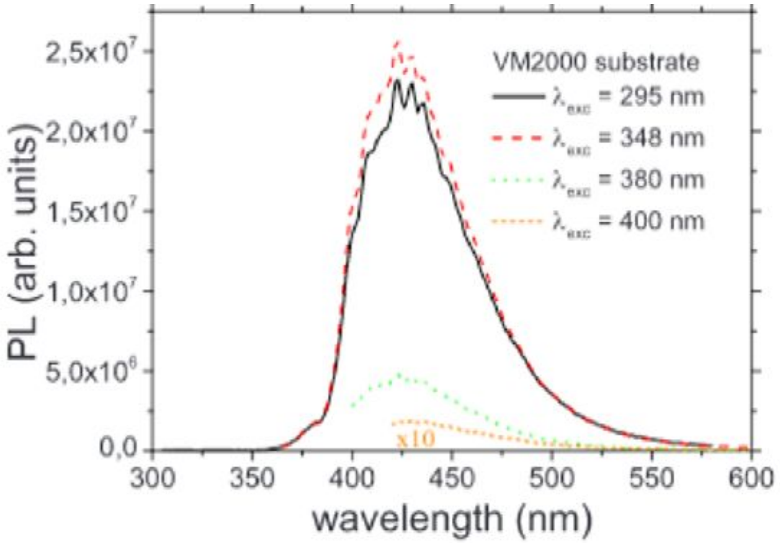
The CCM200 Detector: Hamamatsu R5912 PMTs

- **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.

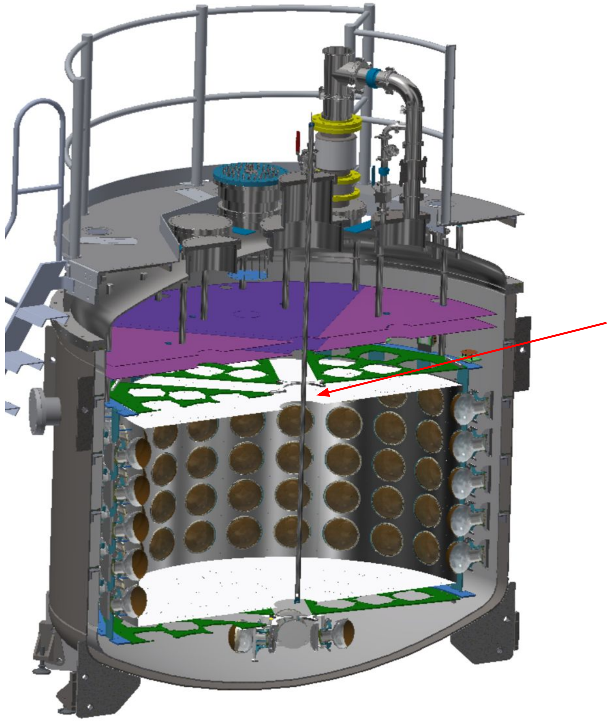




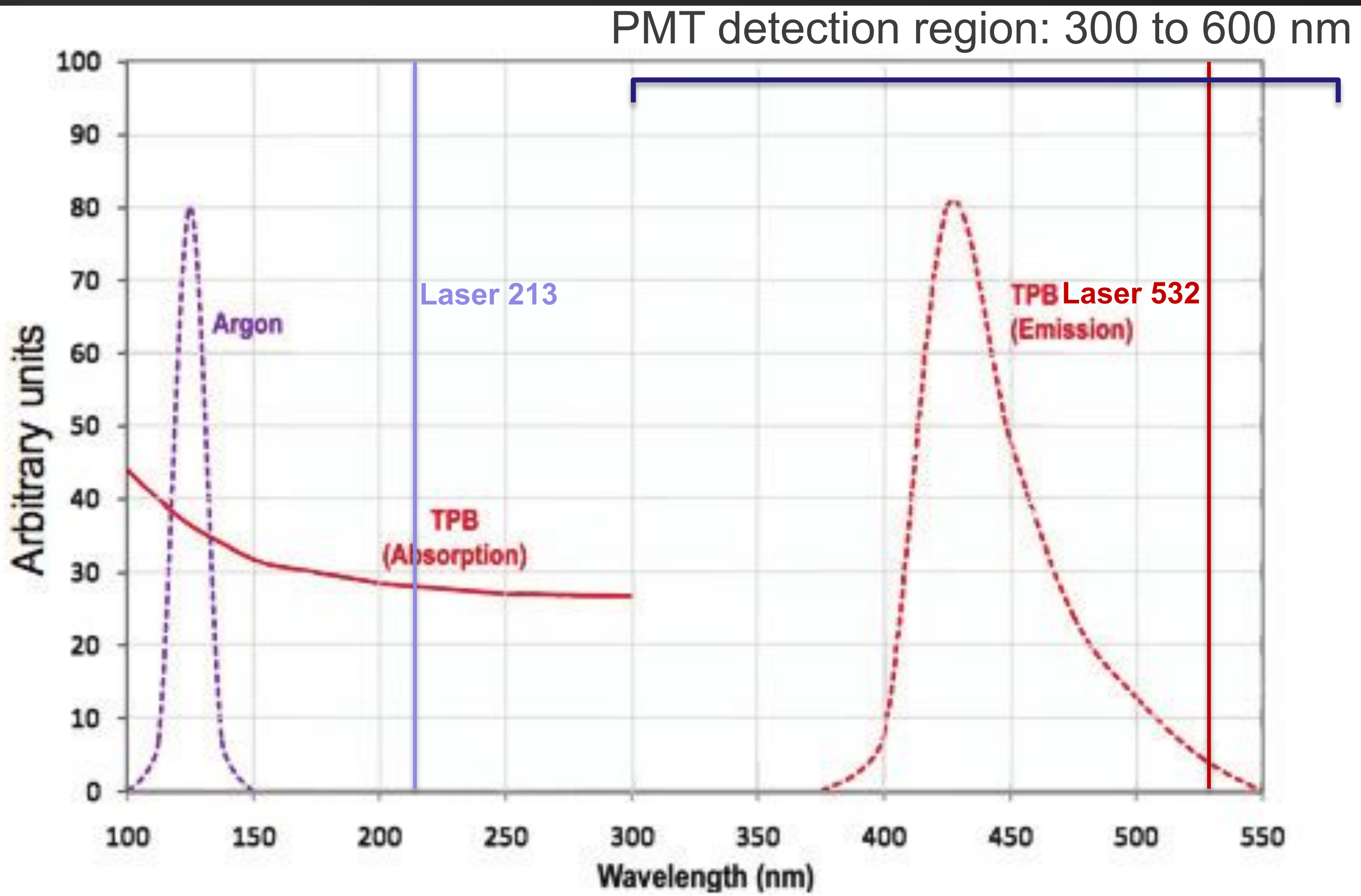
- Above: TPB-coated R5912 PMT
- Top Right: Hamamatsu Efficiency Spectrum
- Bottom Right: TPB Emission Spectrum



The CCM Detector: Calibrations



Inserted Source Calibration Rod down the center of the detector



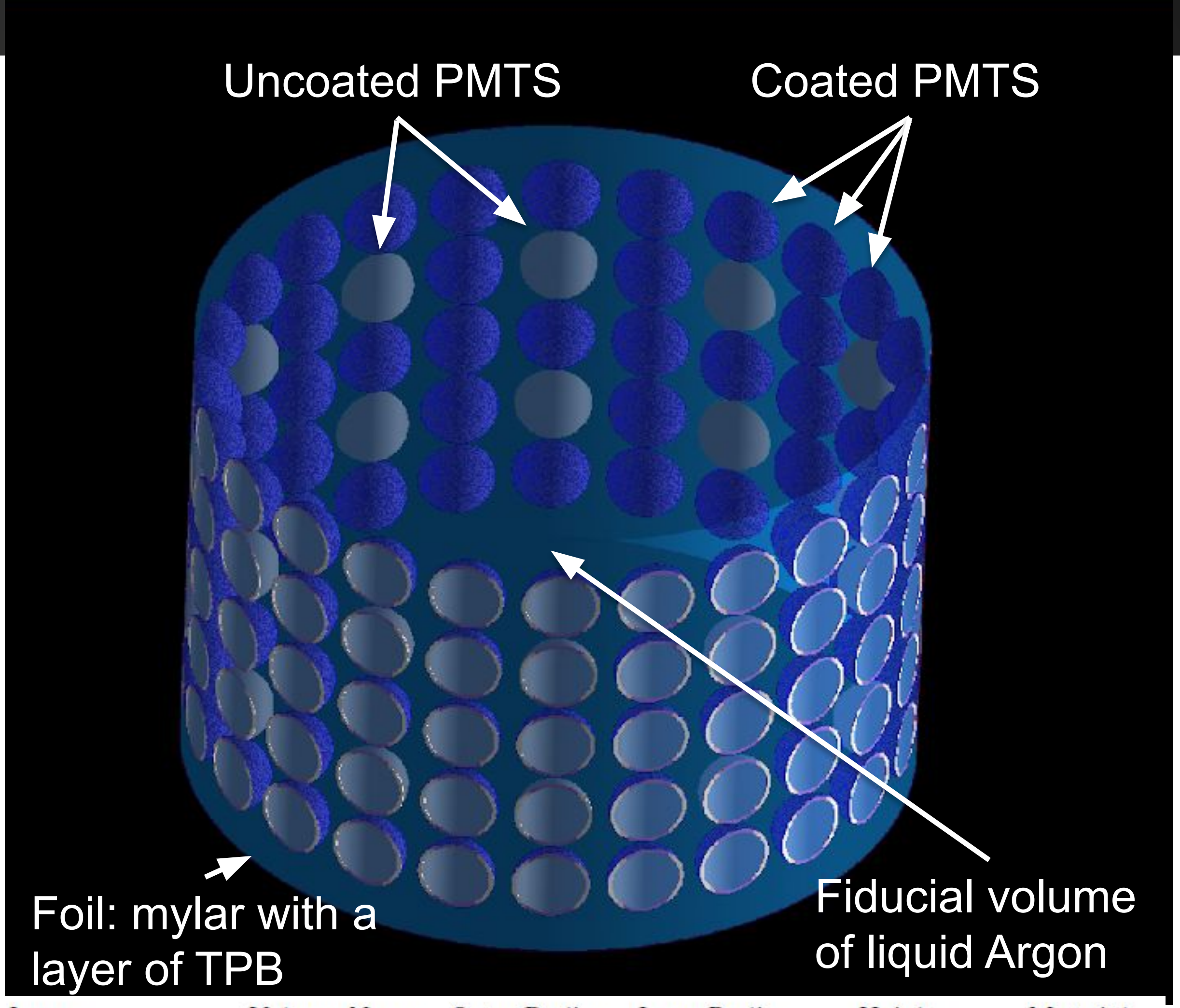
- Laser/Diffuser for 213/532 nm calibrations to test TPB response for foils and PMTs and the LAr properties.
- LED calibrations for PMT gain/timing
- Co-57 source provide energy scale calibration 122 keV gamma-ray.
- Na-22 source provide energy scale calibration 2.2 MeV gamma-rays.
- Radioactive sources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

CCM=Optical Detector

Light Properties need to be very well known.

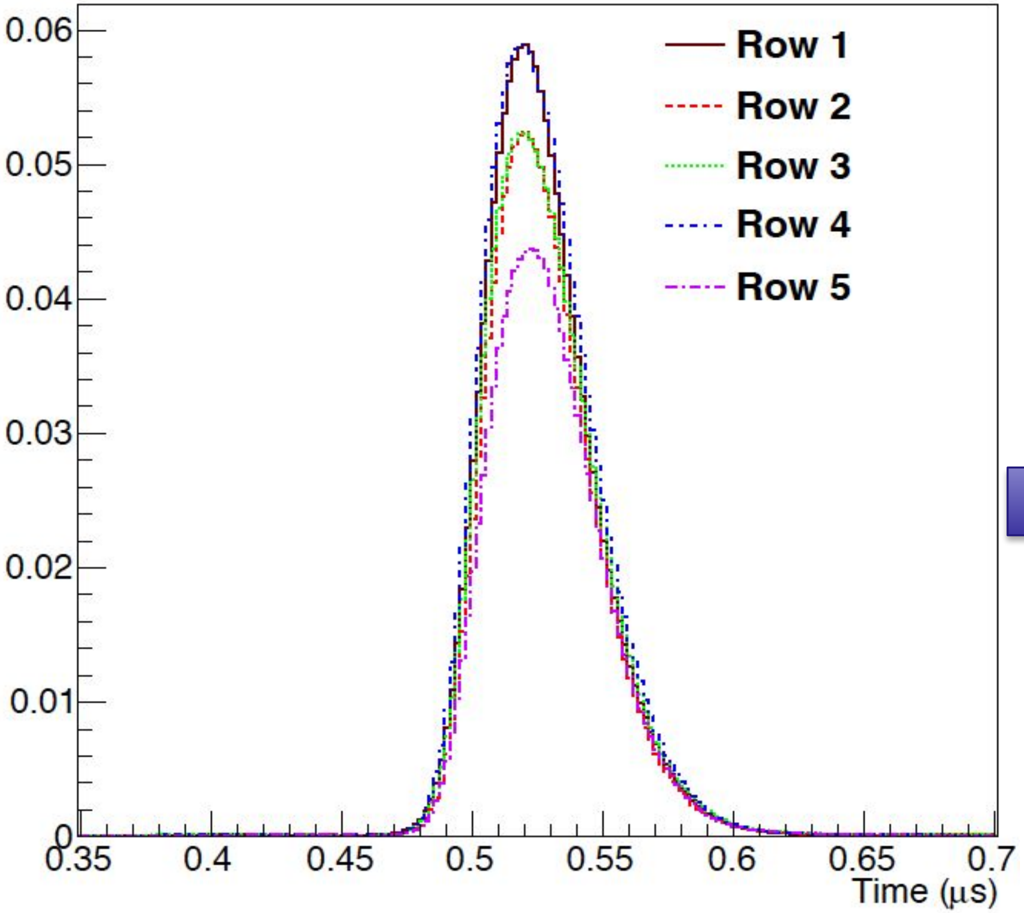
The CCM Detector Simulation

- Simulation built in **Geant4 simulation program** for nuclear and particle physics.
  - Detector composed of overlapping cylinders.
  - Fiducial volume included PMTs as semi-spheres with TPB coating.
  - **PMT Response** (including Quantum Efficiency, wavelength and angular efficiency, and pulse length and integral single photo-electron (SPE) uncertainty) modeled separately after Geant4 geometry for computing speed.
  - PMT Response converted simulation PEs into analysis pulses that could be analyzed **identically to data**.
- Full simulation needed **complex optical model** to correctly simulate CCM Events.
  - Built from calibration data.



Layer	Volume Name	Outer Radius	Inner Radius	Height	Material
Cryogen Outside	Cryogen	138 cm	135 cm	262 cm	Steel
Vacuum Insulator	Vacuum	135 cm	130 cm	252 cm	Vacuum
Inner Jacket	innerjacket	130 cm	127 cm	240 cm	Steel
Veto Argon	liquidArgon	127 cm	112 cm	230 cm	liquidArgon
PMT frame	Frame	112 cm	107 cm	142 cm	aluminum
Argon in frame	frame2foil	107 cm	102.076 cm	136.2 cm	liquidArgon
Reflective foil	ptfefoil	102.076 cm	102.0002 cm	136.142 cm	Mylar
TPB paint	TPBfoil	102.0002 cm	102.0 cm	136.0004 cm	TPB
Fiducial Argon	fiducial	102 cm	0 cm	136 cm	liquidArgon

The CCM Optical Model



χ^2 goodness of fit between data and simulation

Table of Material Properties not varied in the Optical Model

Parameter description	Simulation Value	Literature Value
Mylar reflectivity - visible	95%	95%
Mylar reflectivity - UV	10%	10%
LAr scintillation peak wavelength	128 nm	128 nm
LAr scintillation fast time constant	7 ns	7 ns
LAr scintillation yield	1.0/19.5 eV	1.0/19.5 eV
LAr Index of Refraction @ 128 nm	1.358	1.358
LAr Rayleigh Scattering Length @128 nm	100.78 cm	100.78 cm
LAr Visible (>400 nm) absorption length	2800 cm	2000 cm
TPB Index of Refraction	1.4	1.4
Evaporative TPB efficiency	96.27%	95%
TPB visible absorption	87.35%	90%
TPB thickness	1.91 μm	1.91 μm

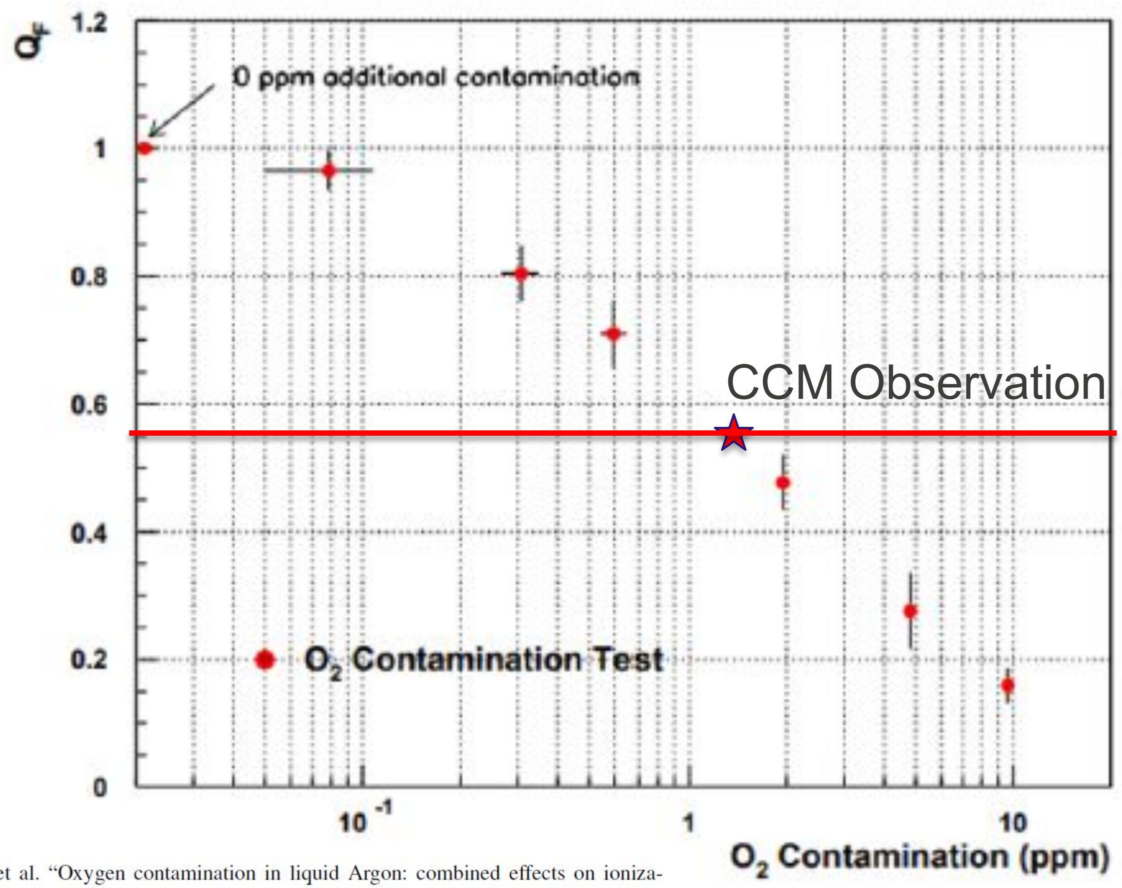
Table of best fit Parameters found for the Optical Model

Parameter	Best Fit Value	Best Fit Error	Units
Abs100	55.95	6.92	cm
R1Clouding	12.23	5.92	percent (%)
R1Radius	64.05	11.08	cm
FoilEff	45.55	7.97	percent (%)
Triplet Lifetime	400	100	ns
Conewide	7.555	1.488	cm
Conehigh	4.457	0.567	cm
Abs200	37.55	18.71	cm
Abs300	1310	172	cm
TopDivider	26.12	14.17	divider
Unsmooth	2.922	0.480	arbitrary

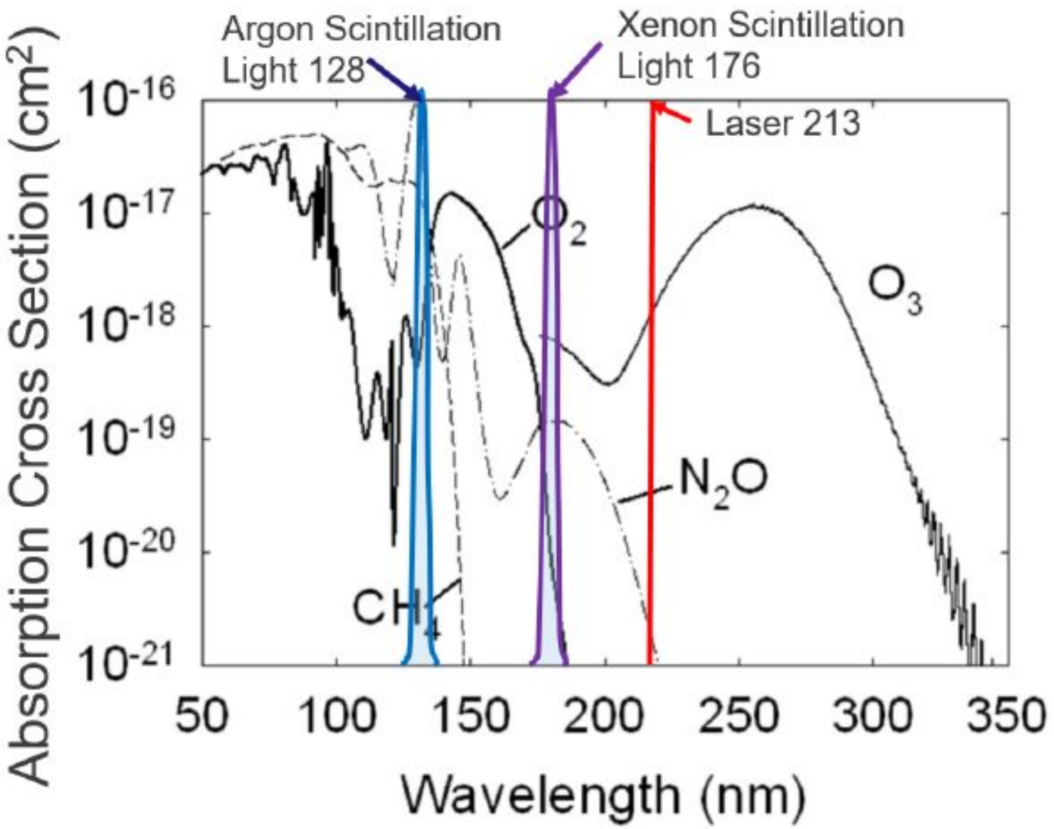
- **60** total vertically asymmetric row ratios (including uncoated/coated) from **laser** and **source** calibrations used to build simulation Optical Model

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

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.



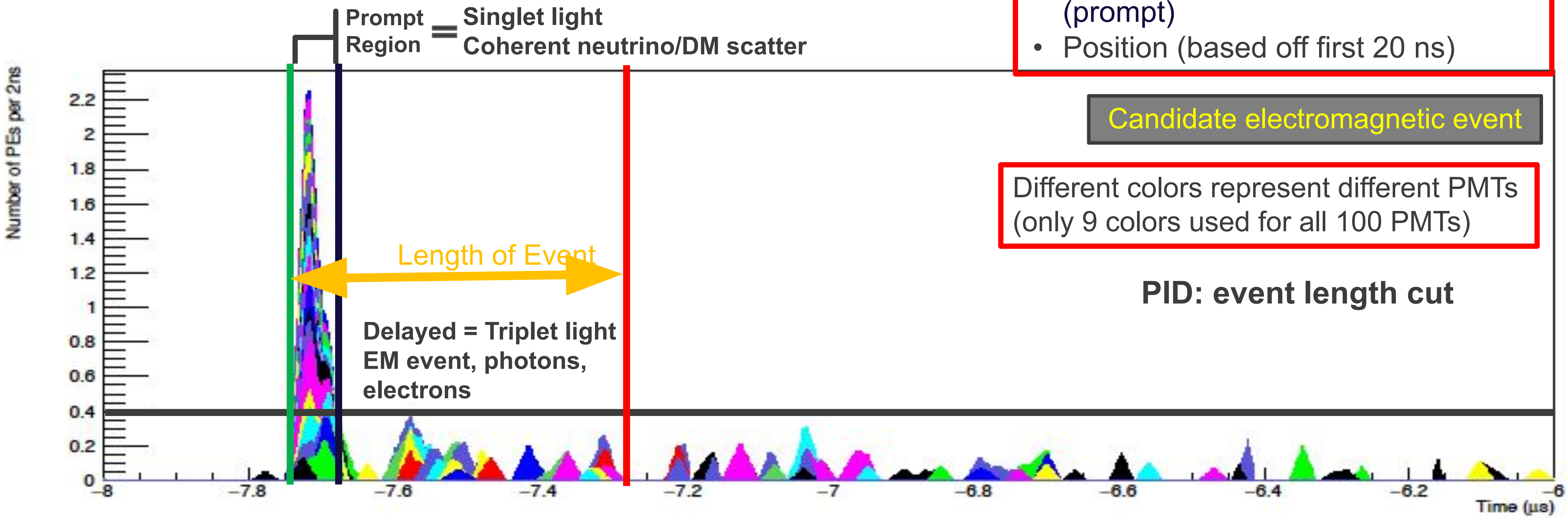
Concentration of O2	Absorption Length of 128nm light in LAr
0.0ppm	2,000 cm
0.002ppm	1,700 cm
0.02pm	1,000 cm
0.06ppm	500 cm
0.2ppm	180 cm
2ppm	20 cm *
20ppm	2 cm

- 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.

CCM120 Event Building Process

- CAEN electronics sampled at **500 MHz** rate with **2^14 bit** dynamic range
  - 2 ns wide charge bins, 16384 ADC maximum height
  - Typical SPE = 30 ADC
  - DAQ window = 16 us with 10 us prebeam
- PID capability using **event length** between e/m like (with triplet) and nuclear recoil (no triplet)

Parameters Calculated
• Start of Event • Length of Event • Integral of Charge in first 90 ns (prompt) • Position (based off first 20 ns)



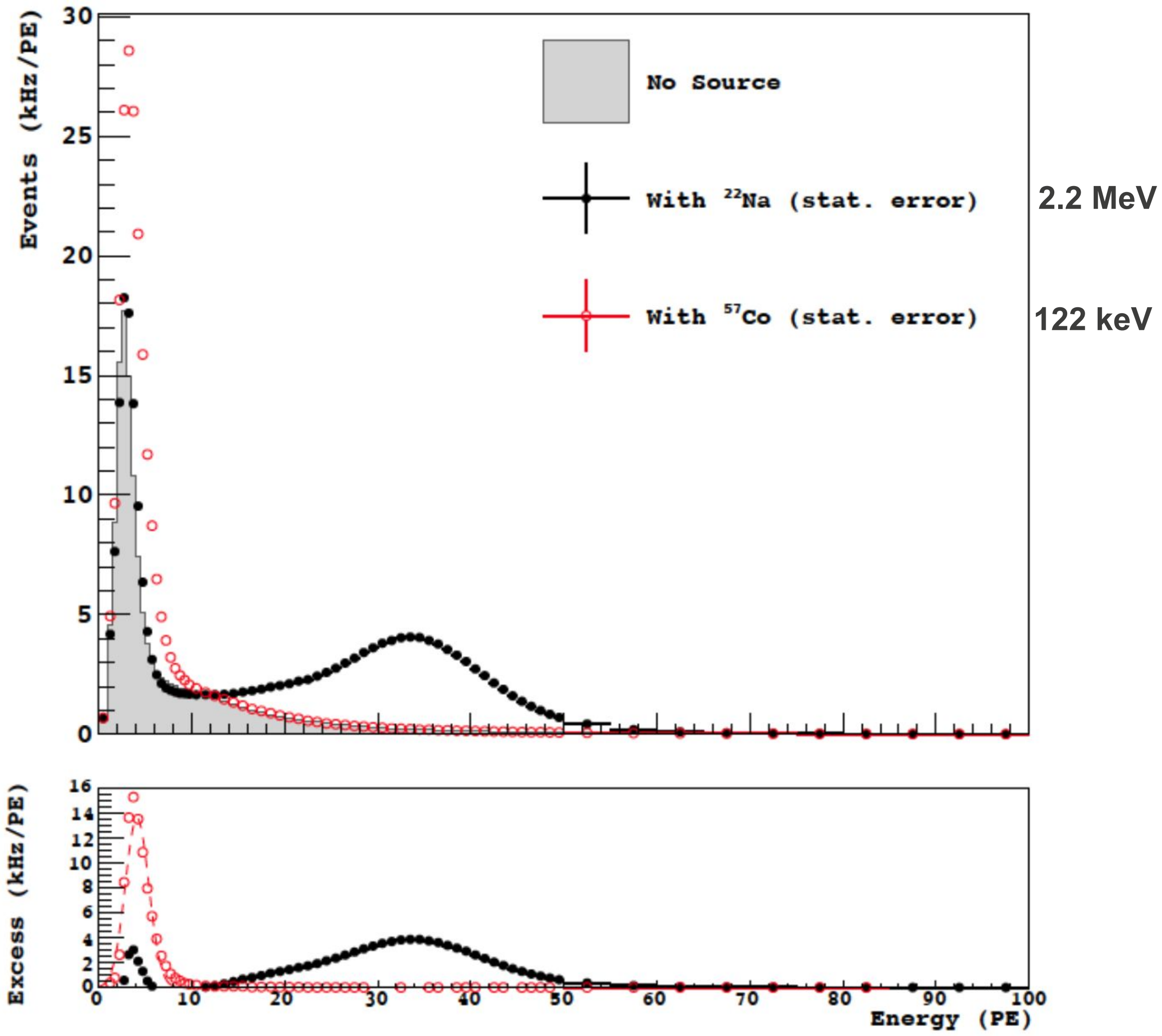
Different colors represent different PMTs (only 9 colors used for all 100 PMTs)

PID: event length cut

Section III:
Data Selection and Background Rejection in CCM120

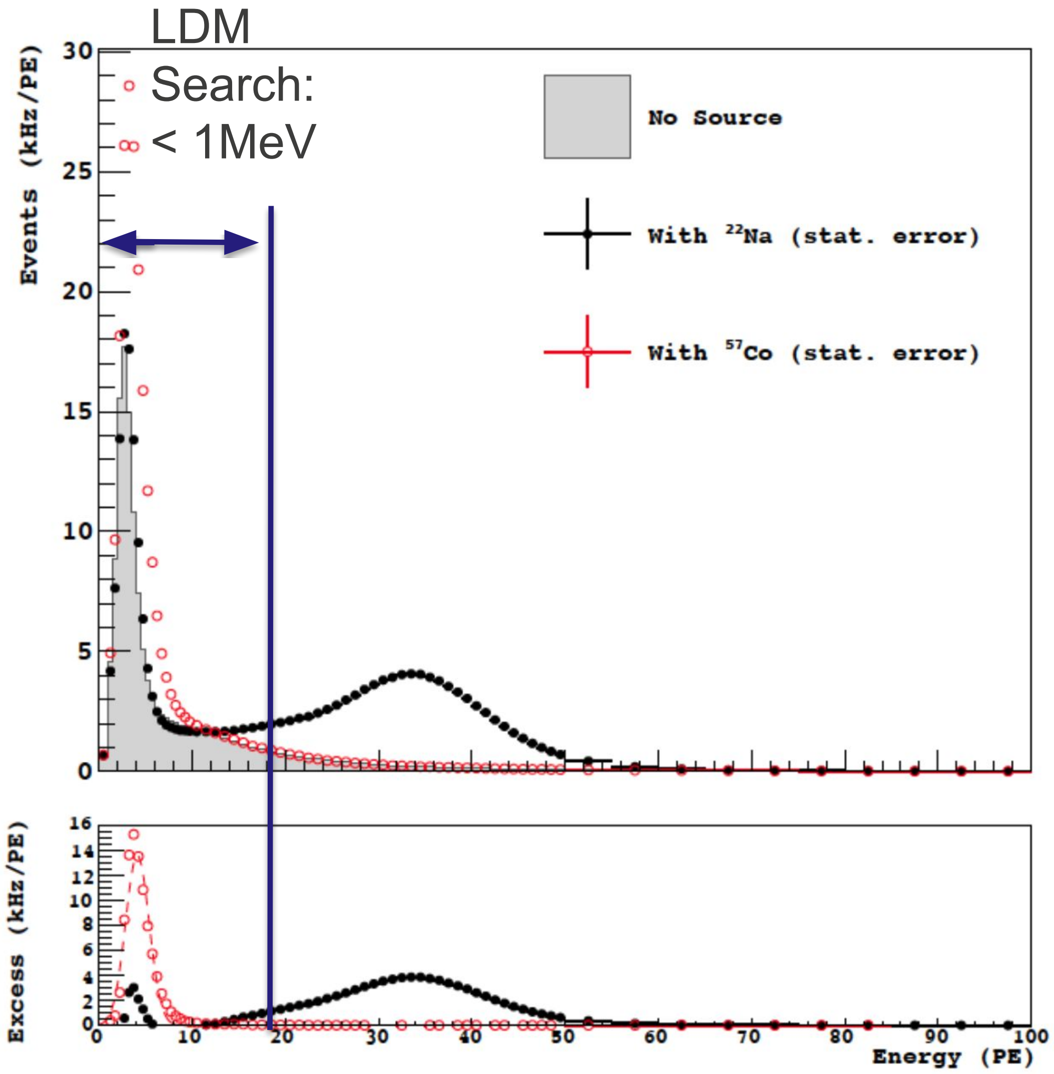
Data Selection: CCM120 Energy Scale from Radioactive Sources

- 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.



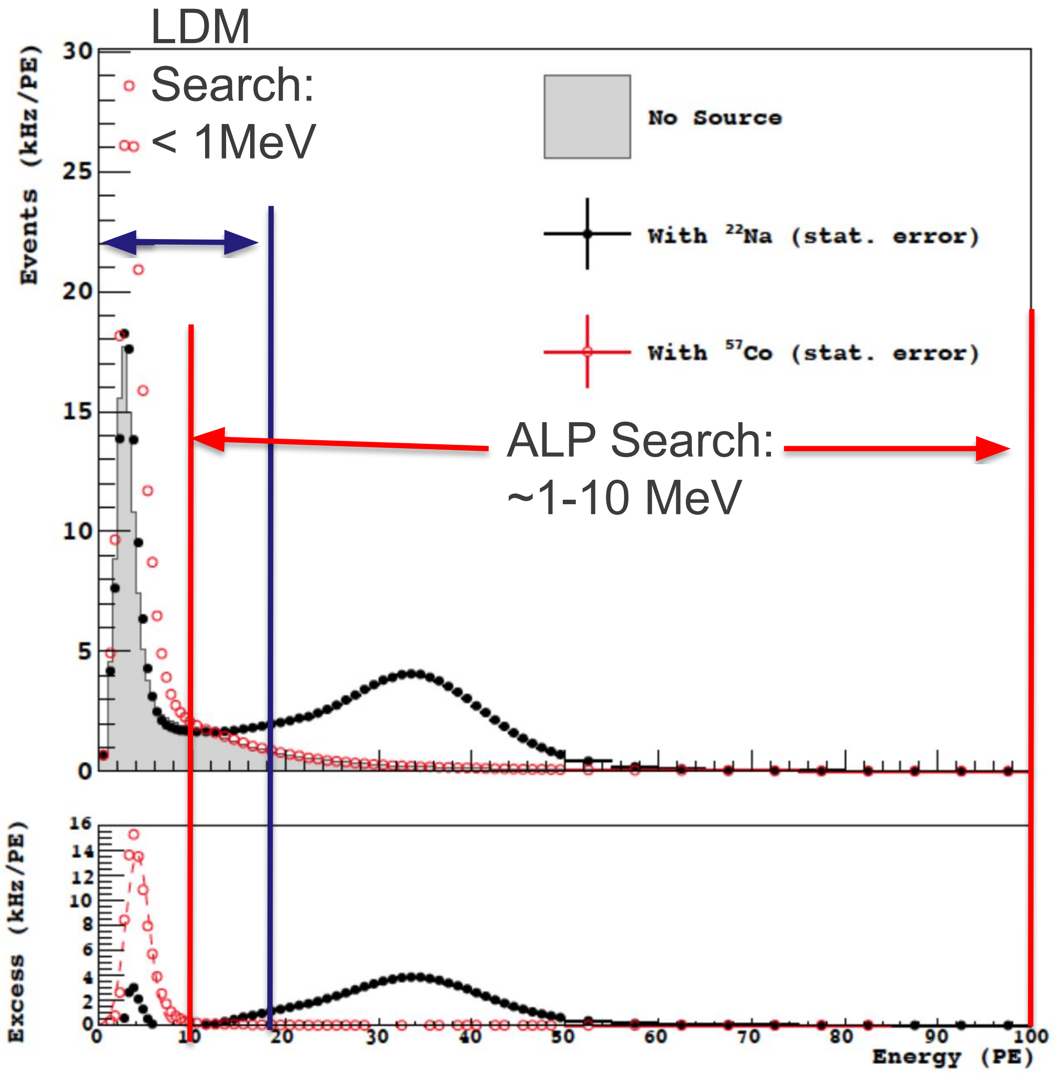
CCM120 Searches: Energy Regimes

- 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.



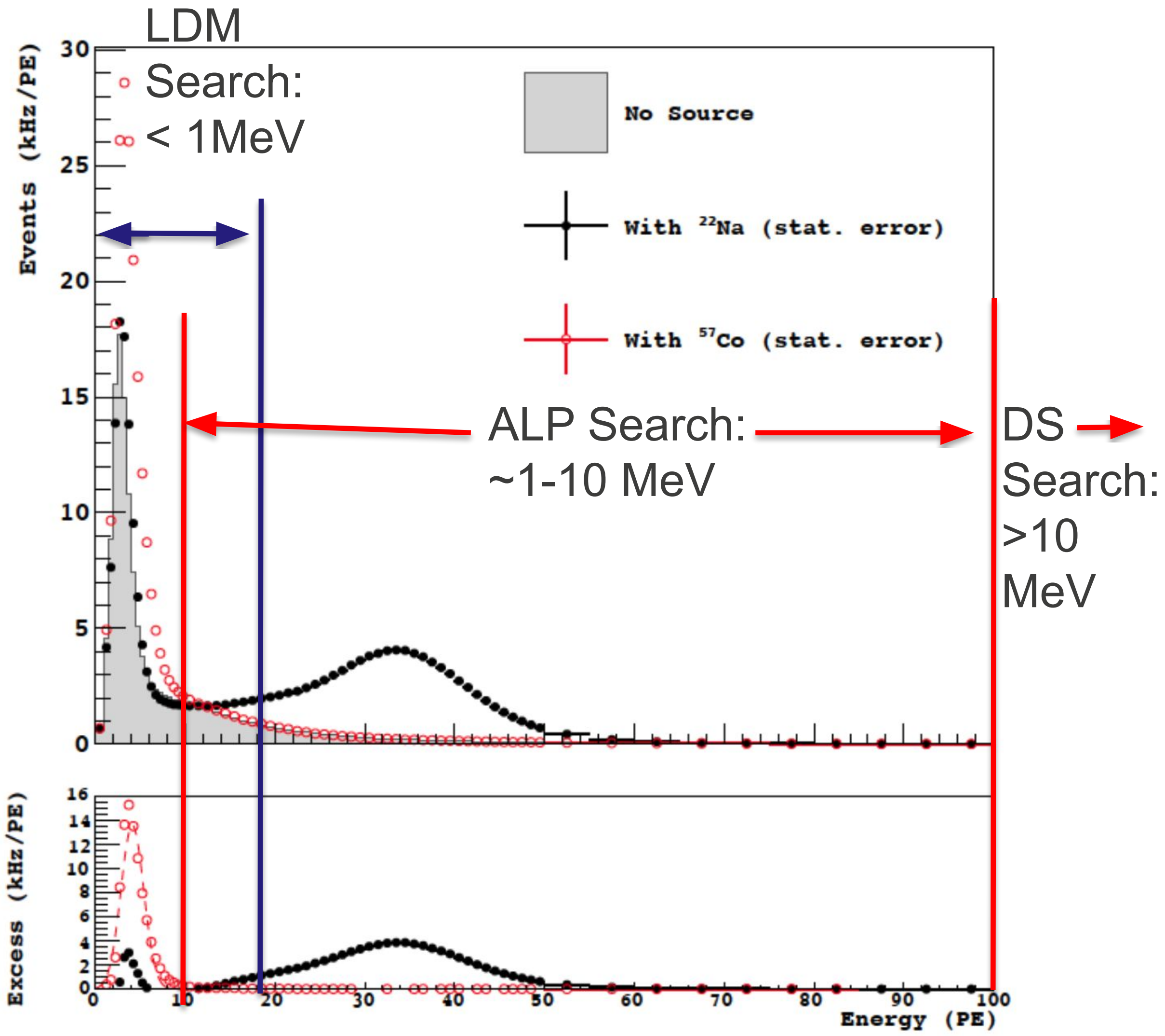
CCM120 Searches: Energy Regimes

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



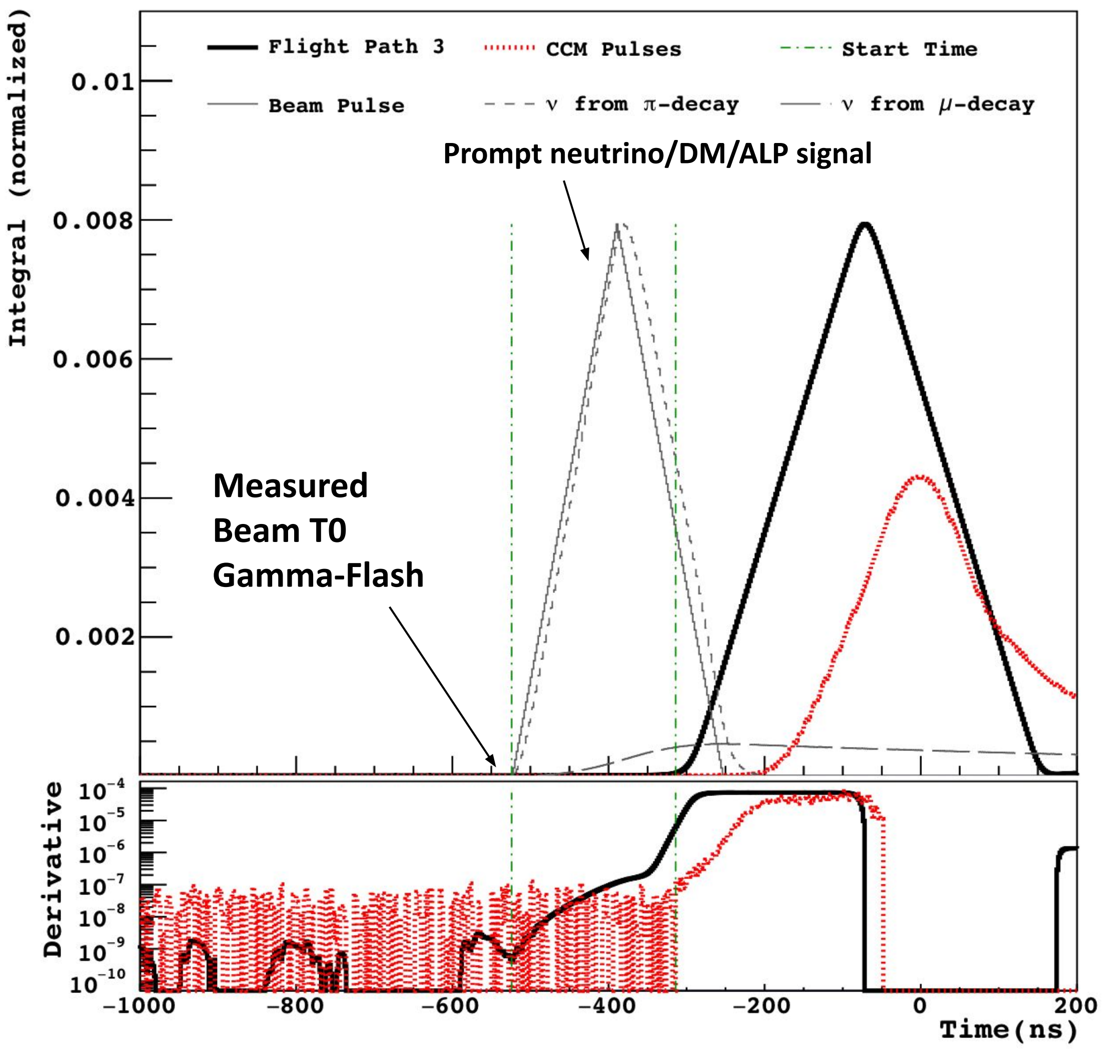
CCM120 Searches: Energy Regimes

- 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.
  - **~1-10 MeV** – QCD Axions (em like)
    - From minimum 10 PE ≈ 500 keV up to Maximum 200 PE ≈ 10 MeV.
  - **> 10 MeV** – Other Dark Sector (em like)
    - From 200 PE ≈ 10 MeV.
- CCM200 will use similar energy regimes, with different PE scales.



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

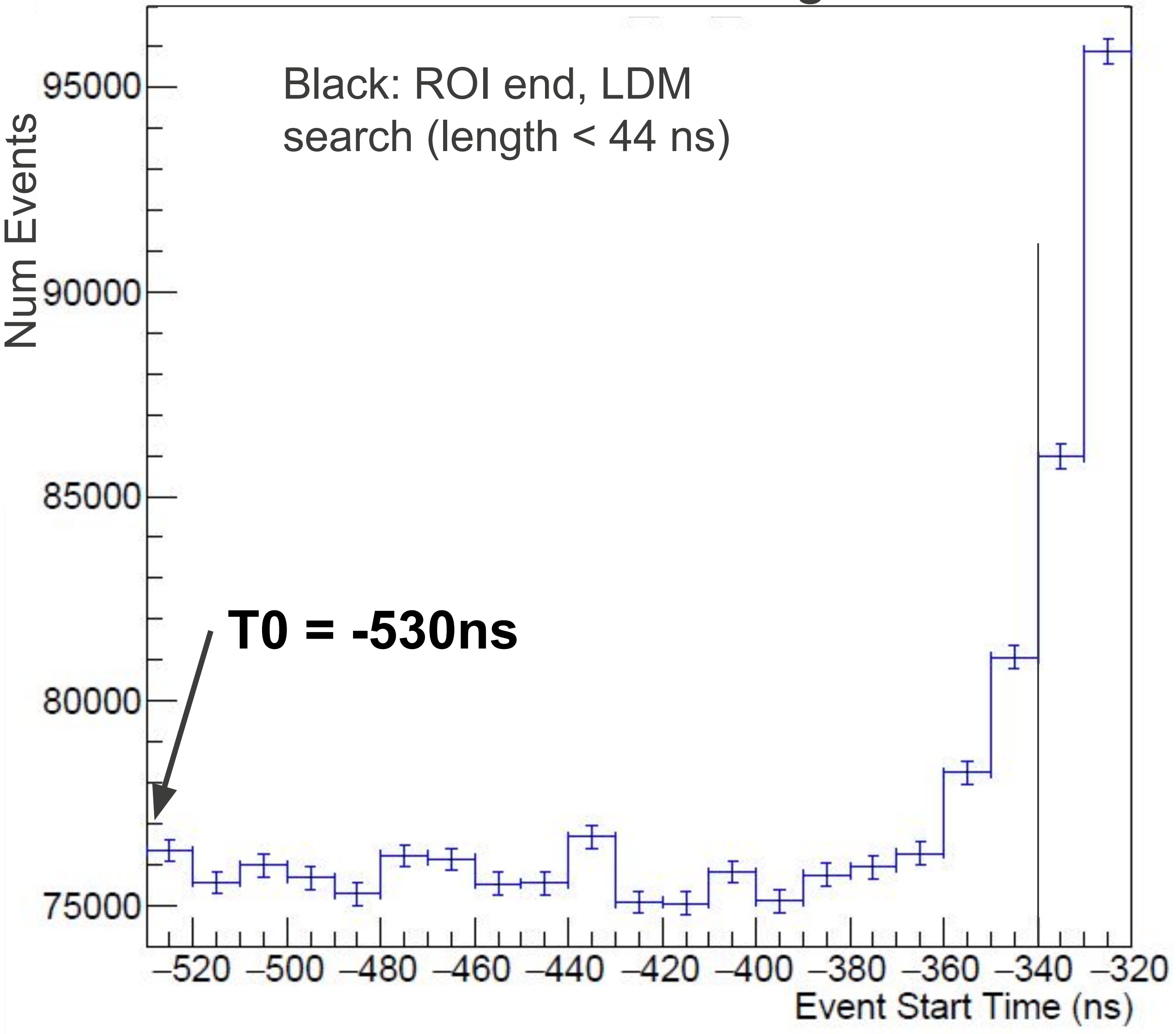
- Timing of massive importance to CCM efficiency.
- We define a **ROI** that includes only **steady state** (measurable in prebeam!) backgrounds.
- Directly measured T0 with the “FP3 detector.”
- **T0 = -530 ns** DAQ time
  - Defines start of ROI for all searches.
- Determined speed of light particles from target to arrive 210 ns before neutron events seen in CCM



ROI Determination: LDM Search

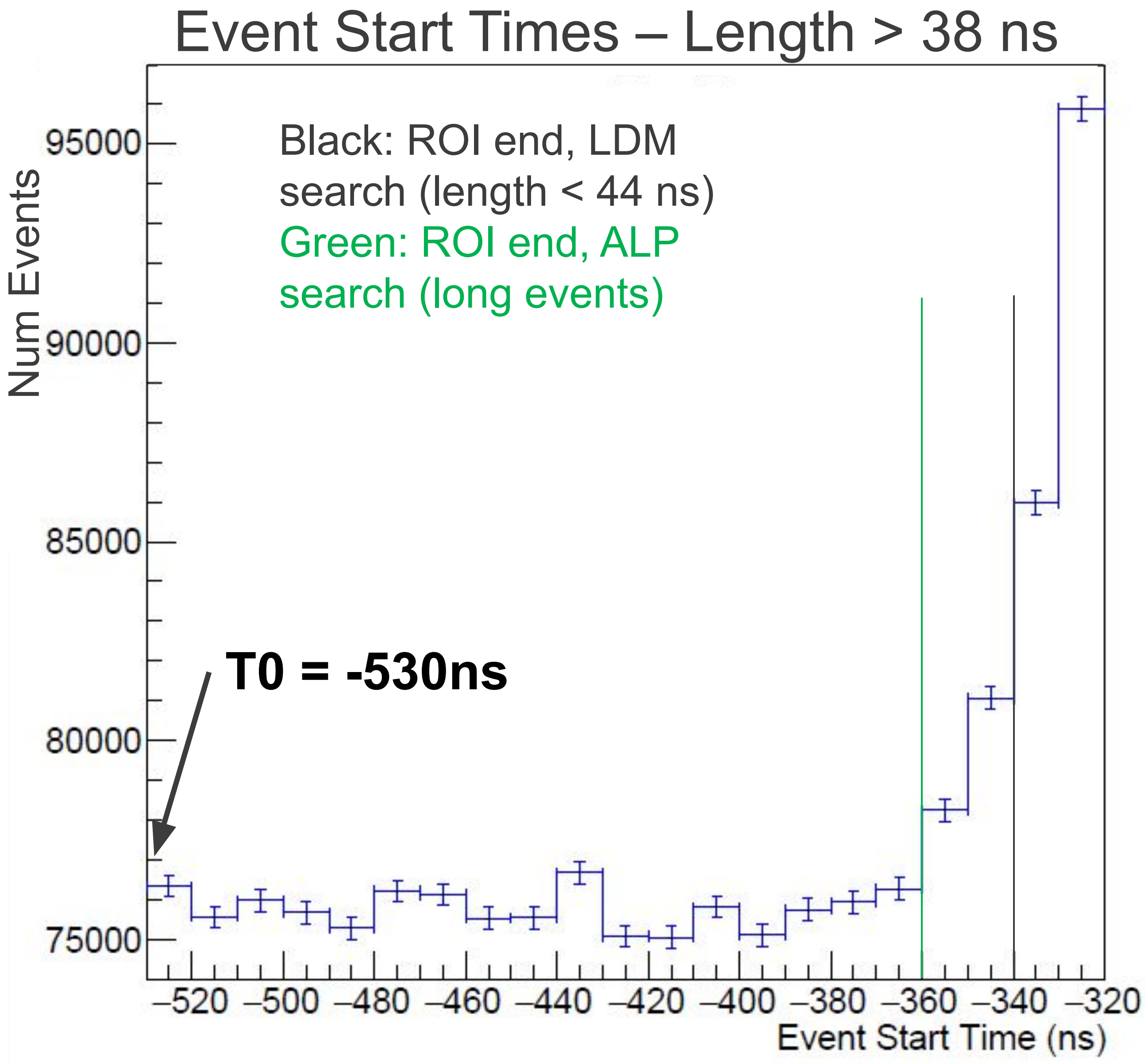
- ROI needs to only contain steady state (and thus measurable) background, even with other event types.
  - **LDM (short event)** cut changes began after 190 ns, which reduced the initial ROI

Event Start Times – Length > 38 ns



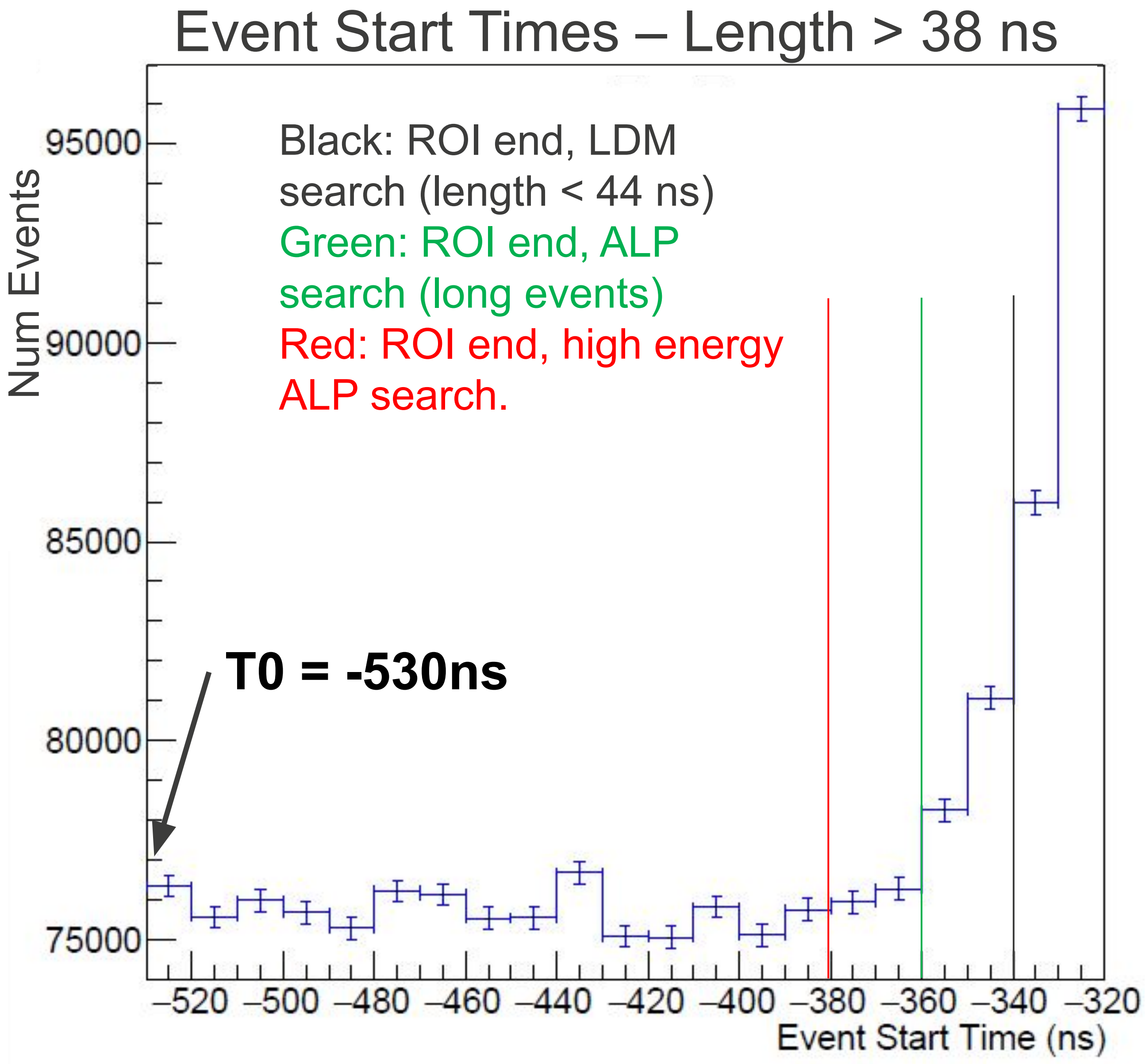
ROI Determination: ALP Search

- ROI needs to only contain steady state (and thus measurable) background, even with other event types.
  - **LDM (short event)** cut changes began after 190 ns, which reduced the initial ROI
  - **ALP (long events)** are affected earlier thanks to beam contamination, with cut changes after 170 ns.



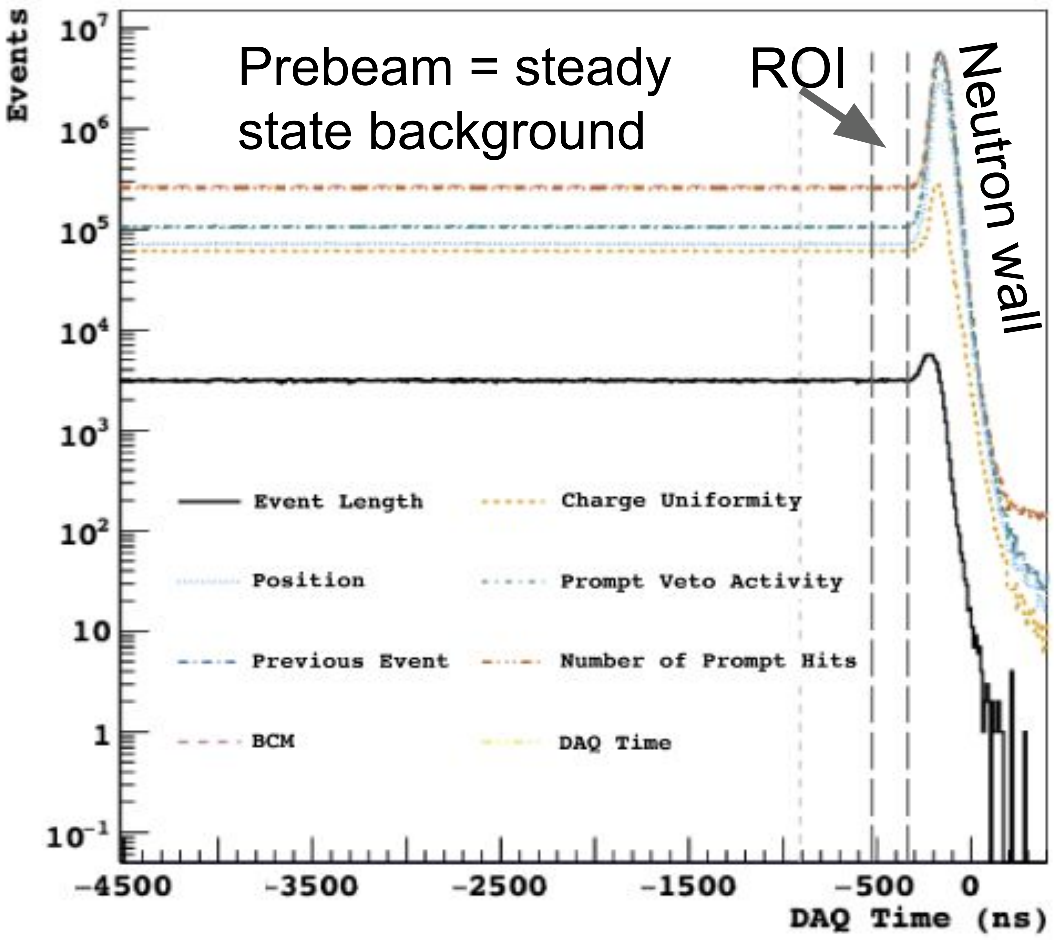
ROI Determination: High Energy Searches

- ROI needs to only contain steady state (and thus measurable) background, even with other event types.
  - **LDM (short event)** cut changes began after 190 ns, which reduced the initial ROI
  - **ALP (long events)** are affected earlier thanks to beam contamination, with cut changes after 170 ns.
  - **High energy ALP events** cut changes start even earlier, after 150 ns.
- Final ALP Search ROI totaled 150 ns, about half the beam pulse time.



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

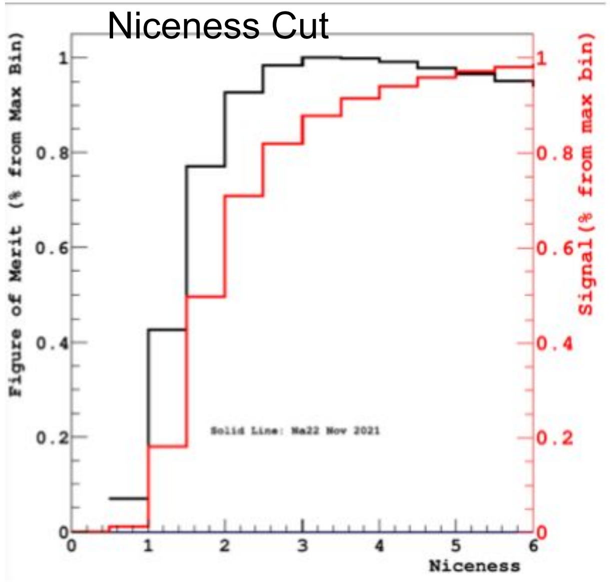
Data Quality Efficiency Table

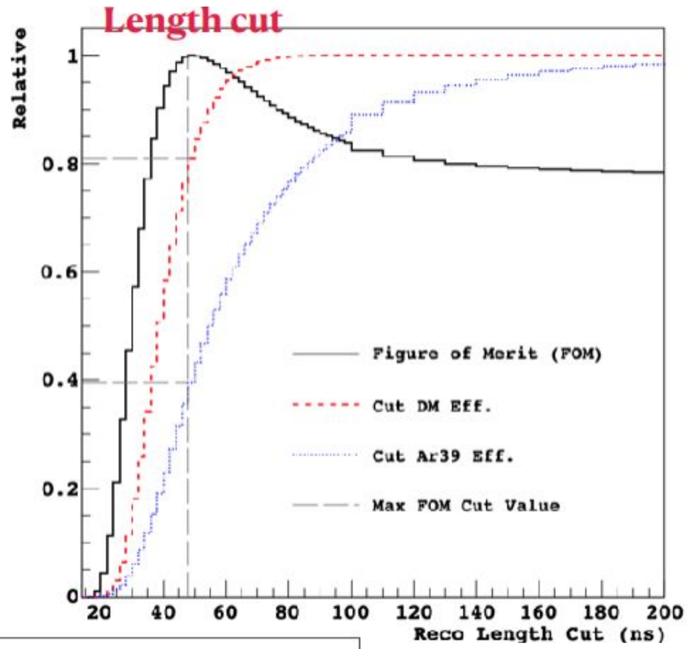
Cut	numHits	previousEvent	Veto	fiducialVolume	eventTime
Efficiency	0.510	0.238	0.236	0.149	0.0037

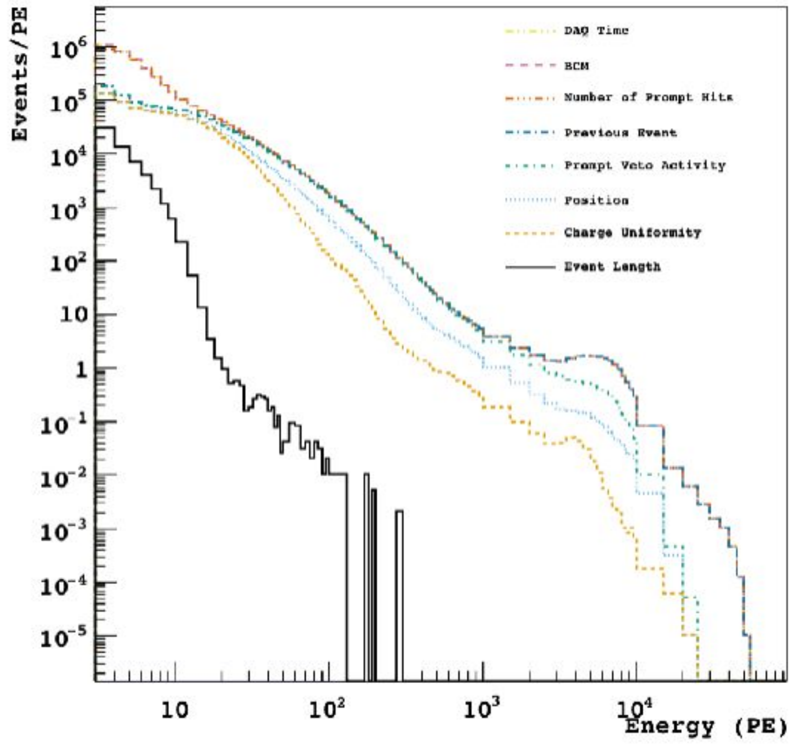
LDM Event Characteristics

- 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 energy.

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





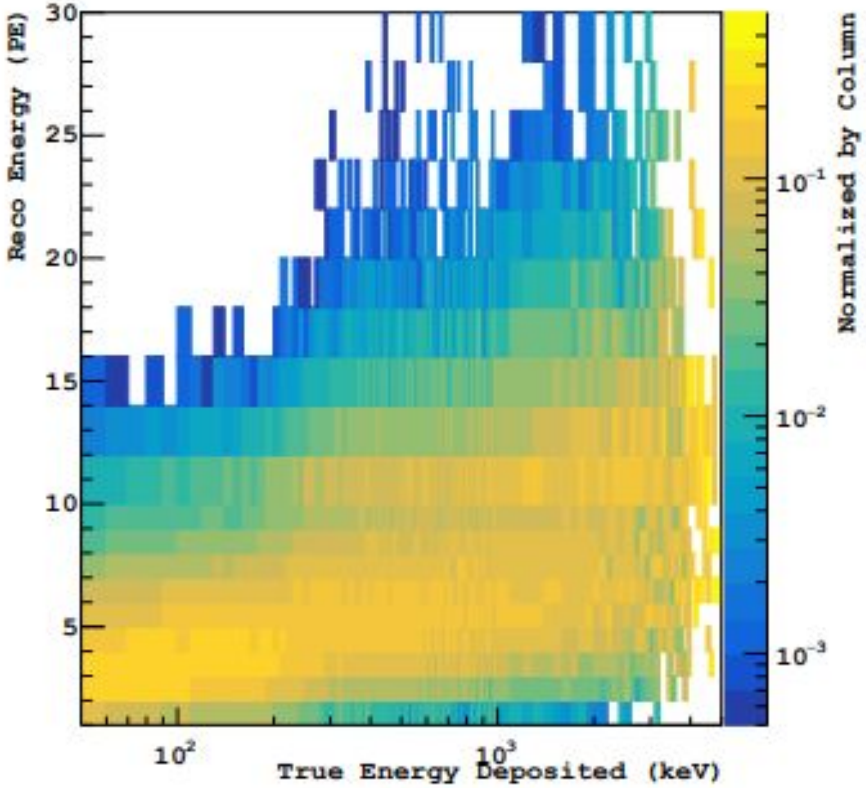


Black = LDM search final sample

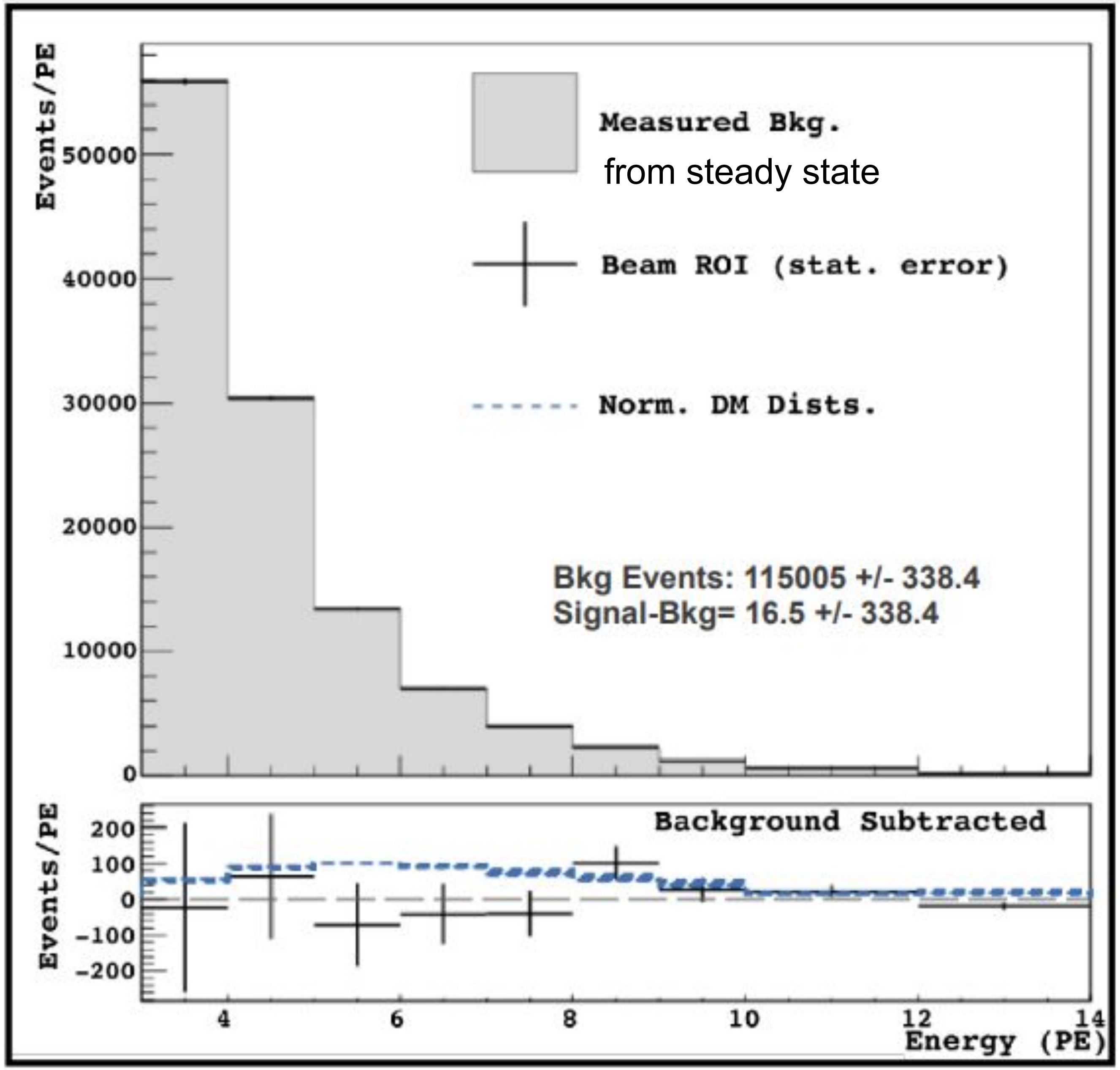
CCM120 LDM Search Results

[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).



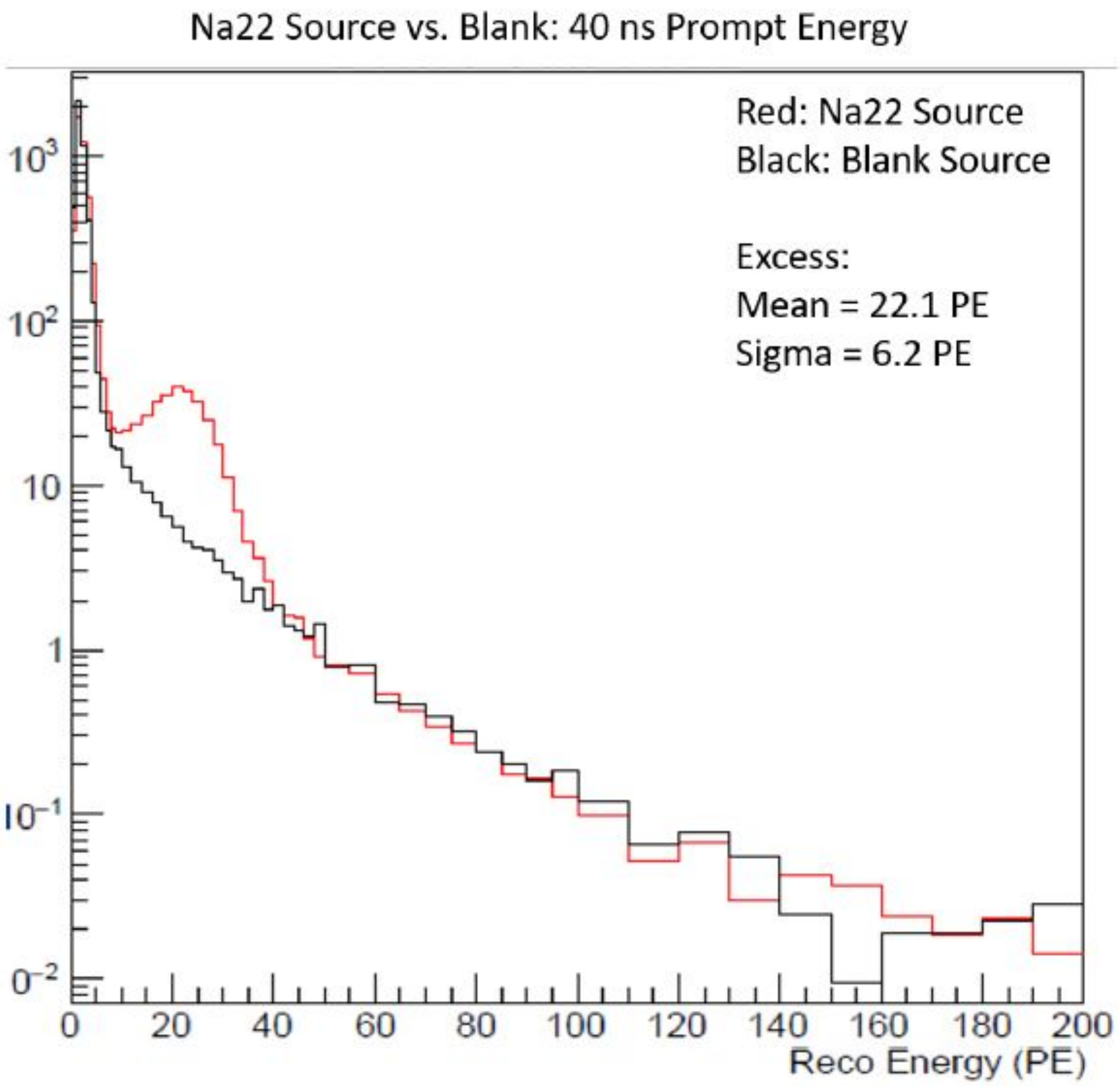
Signal smearing matrix created for the LDM search to relate between true energy deposited and reconstructed energy. This matrix was used to generate the DM predicted distribution shown in blue on the lower right.



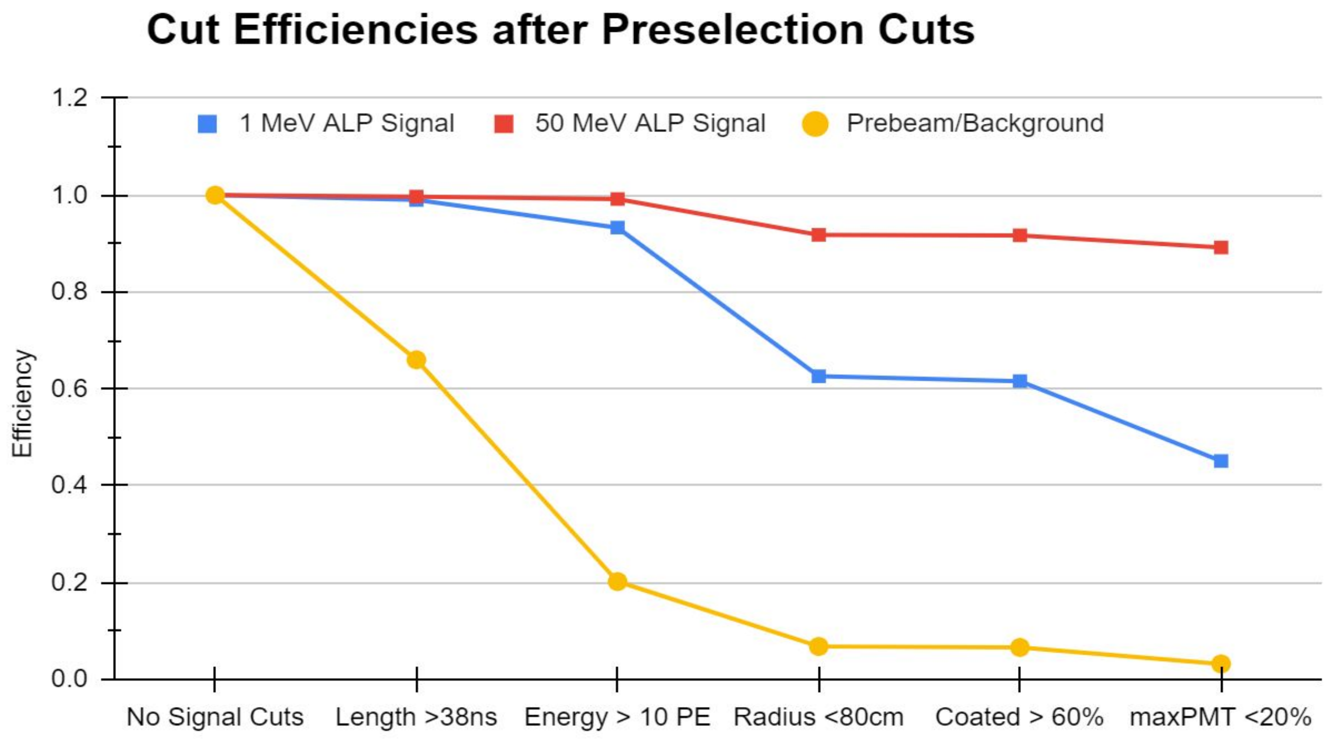
ALP Event Characteristics

- 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



ALP Search – Signal Cuts



- In addition to the Data quality cuts from the LDM search (Previous Event, numHits, Veto, Niceness) we added 5 cuts for the ALP search based on signal characteristics.

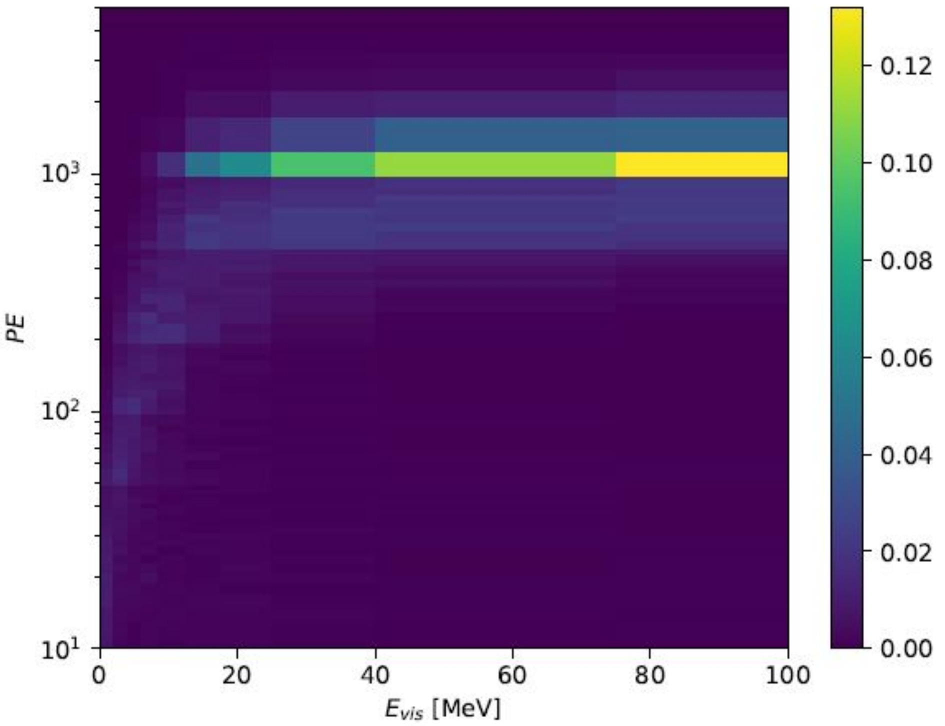
- **Length > 38ns:** Electron like ALP events have triplet light and long length.
- **Radius < 80cm:** A stricter position cut due to the isotropic nature of the signal.
- **Energy > 10PE:** ALP events are high energy (>1 MeV) while the backgrounds are mostly lower.
- **Coated > 60%:** More than 60% 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..

CCM120 Smearing Matrix And Efficiencies

- ALP signal cut efficiencies determined with respect to events which pass preselection cuts.
- CCM shows very **high background rejection (<0.01%)** while maintaining **high signal efficiency (>20%)**.
- Overall efficiency lowered mainly because of time cut (150ns ROI contains only half the 290 ns beam).

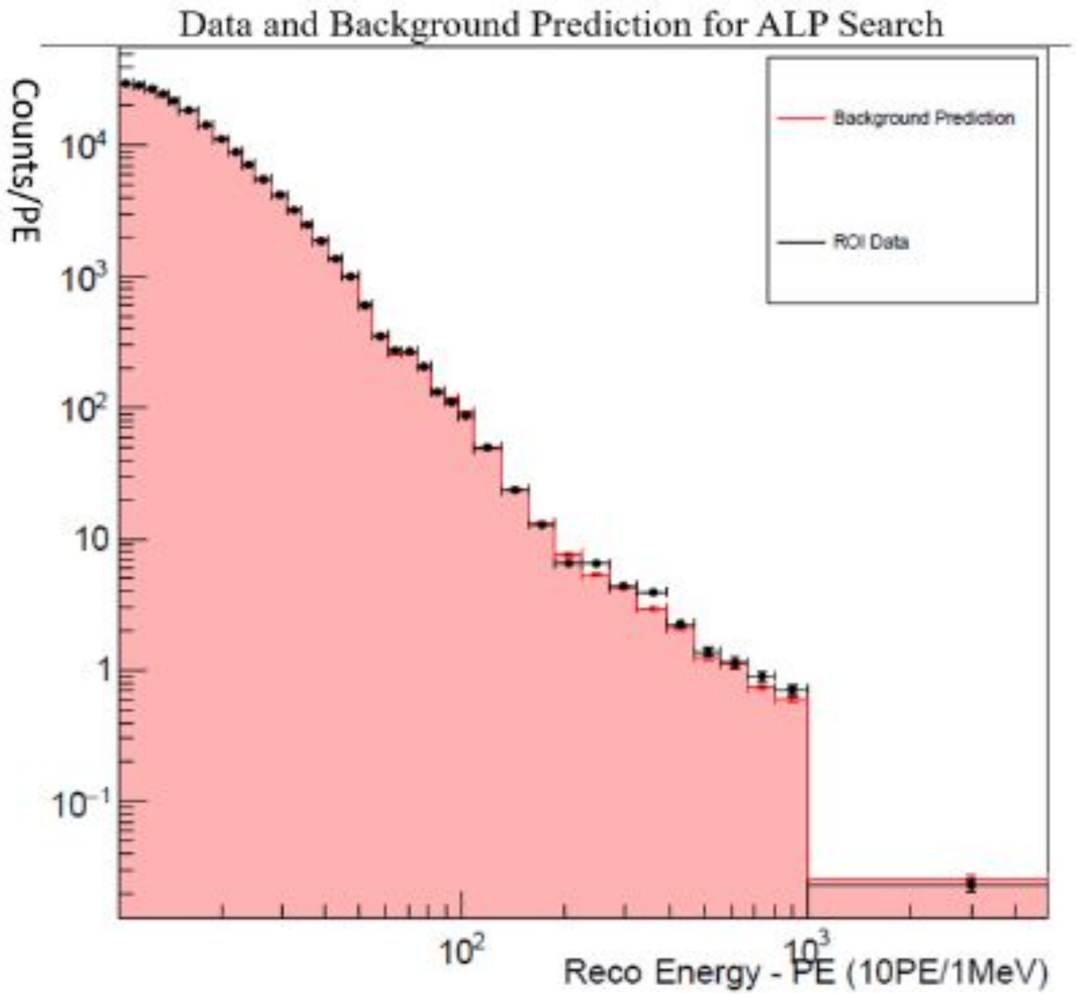
Table 5.2: ALP Search Efficiency Table

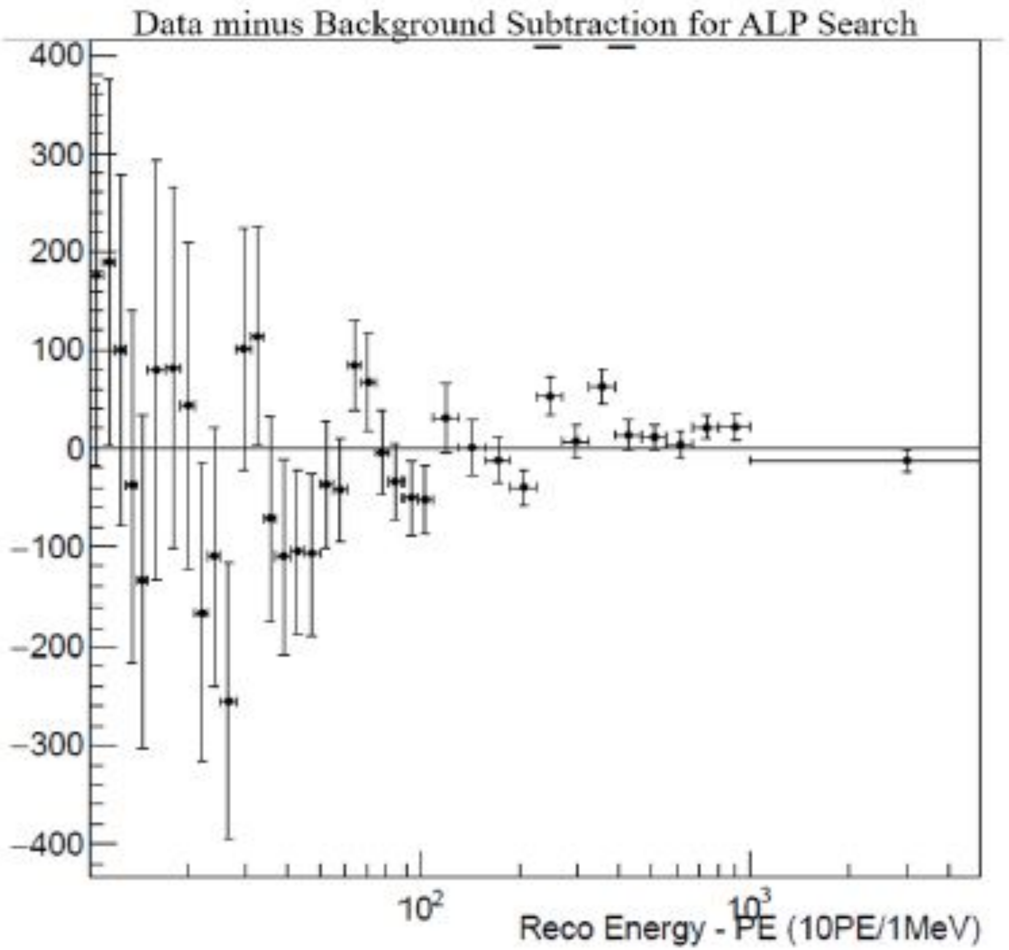
Cut	1MeV ALP	10MeV ALP	20MeV ALP	50 MeV ALP	Background
AllQuality	0.749	0.886	0.936	0.969	0.149
Time	0.393	0.447	0.451	0.458	0.0037
Length	0.990	0.998	0.998	0.997	0.660
Energy	0.933	0.990	0.991	0.992	0.202
Radius	0.626	0.658	0.753	0.918	0.068
Coated	0.616	0.656	0.751	0.917	0.066
maxPMT	0.451	0.588	0.711	0.892	0.032
Total	0.190	0.263	0.321	0.409	0.00012



Signal smearing matrix created for the ALP search to relate between true energy deposited and reconstructed energy. This matrix was used to generate the ALP predicted distributions and includes the efficiencies at various energies.

Data and Background Prediction: CCM120 Electromagnetic Search





(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.

Section IV:
Results and Future Sensitivities of CCM

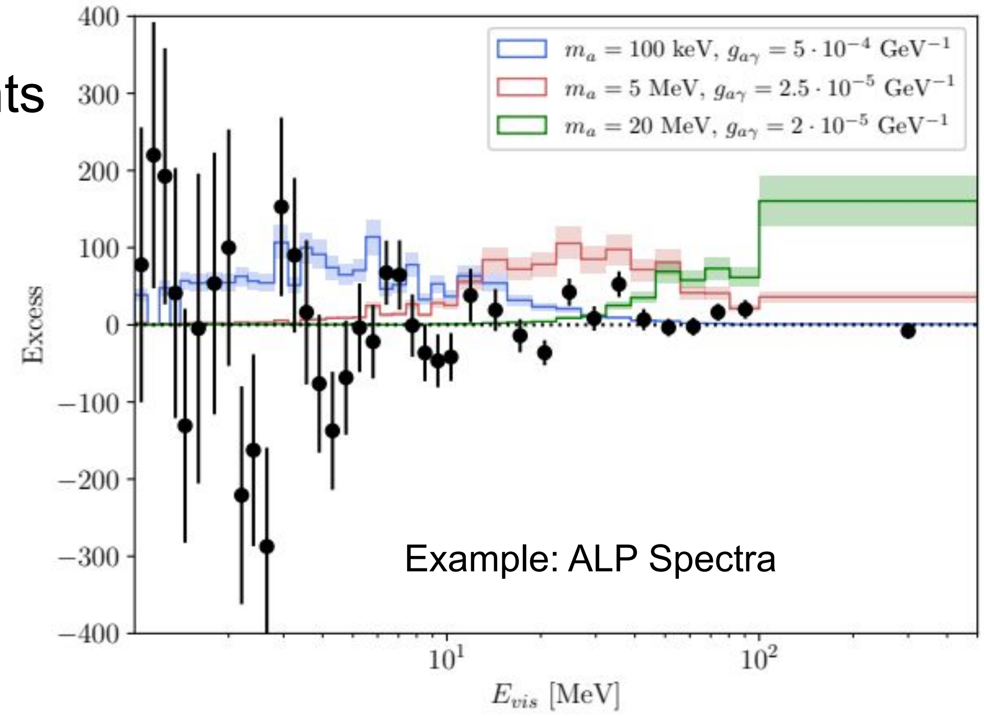
BSM Signal Prediction Pipeline

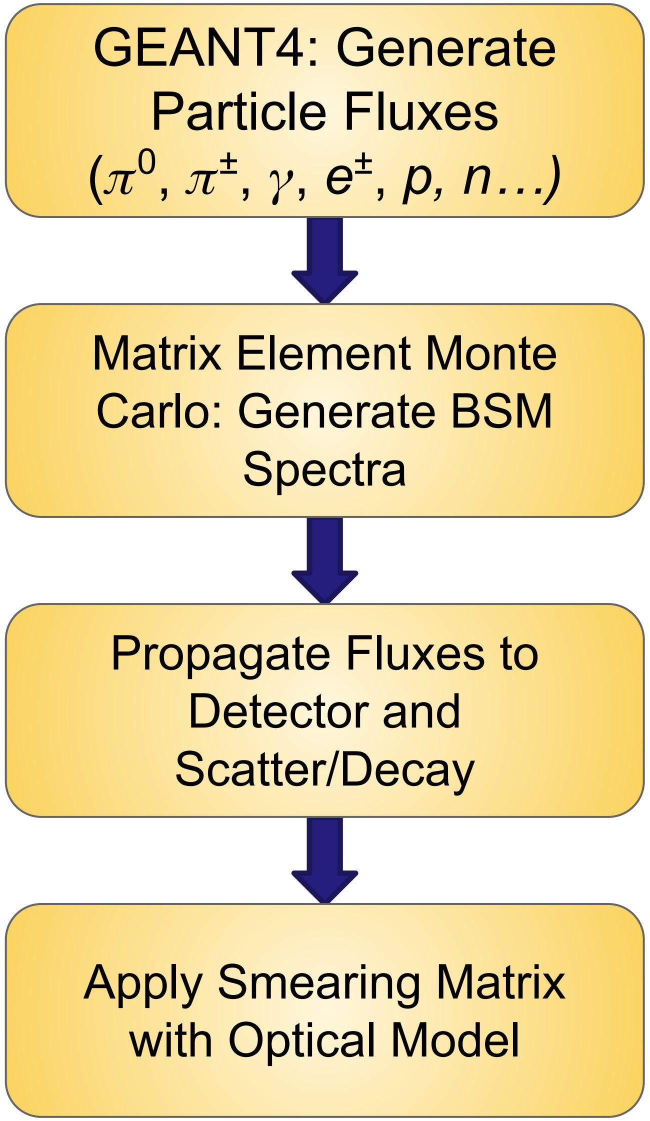
CCM120 Engineering 6-week Run

- 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

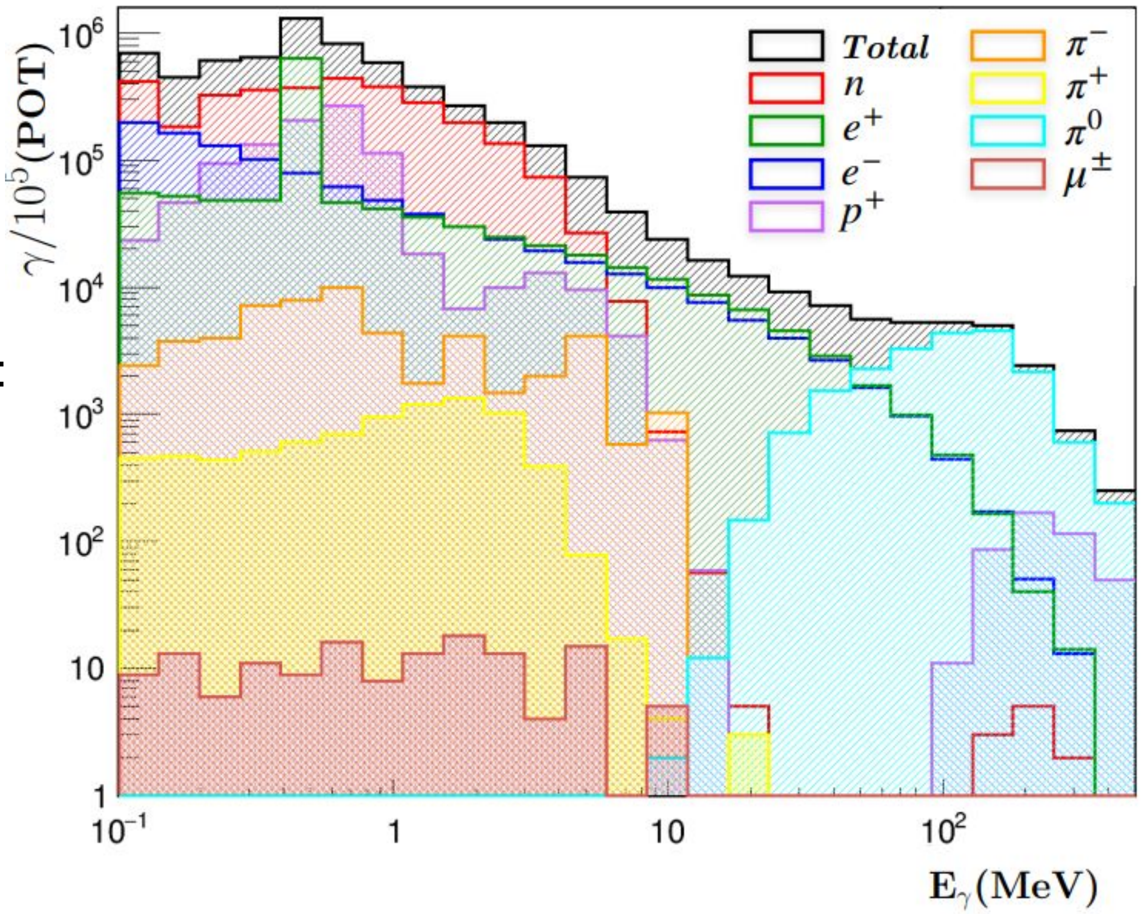
- 3 year run (2023-2025)
- 2.25 × 10^{22} POT

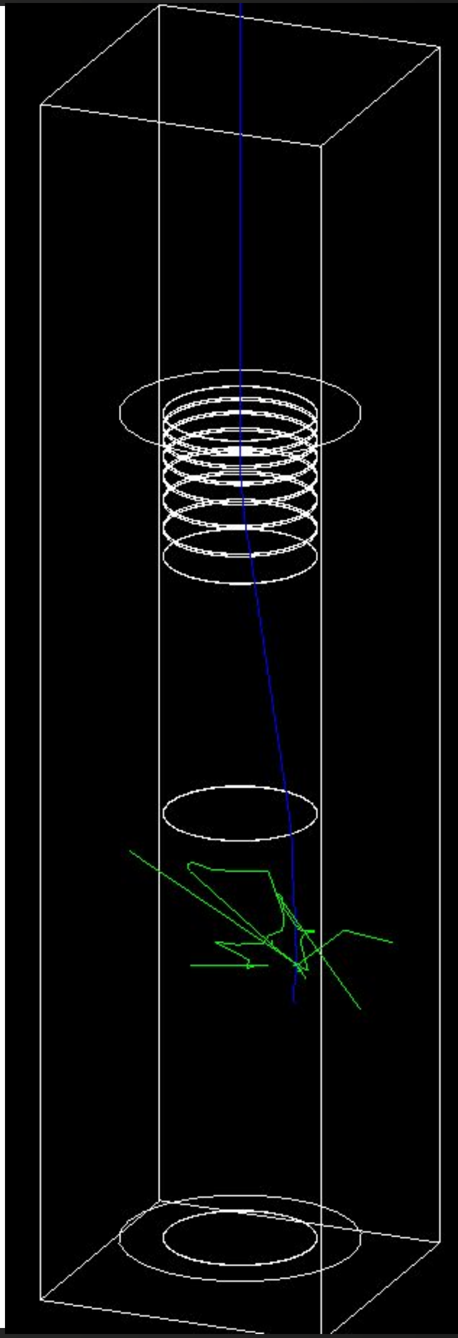




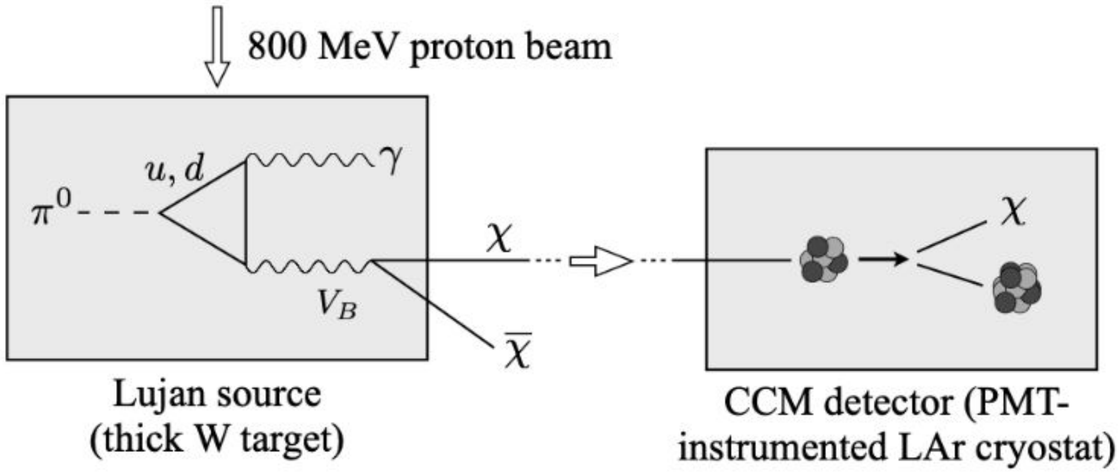
Lujan Target Physics: Electromagnetic and Hadronic Particle Showers

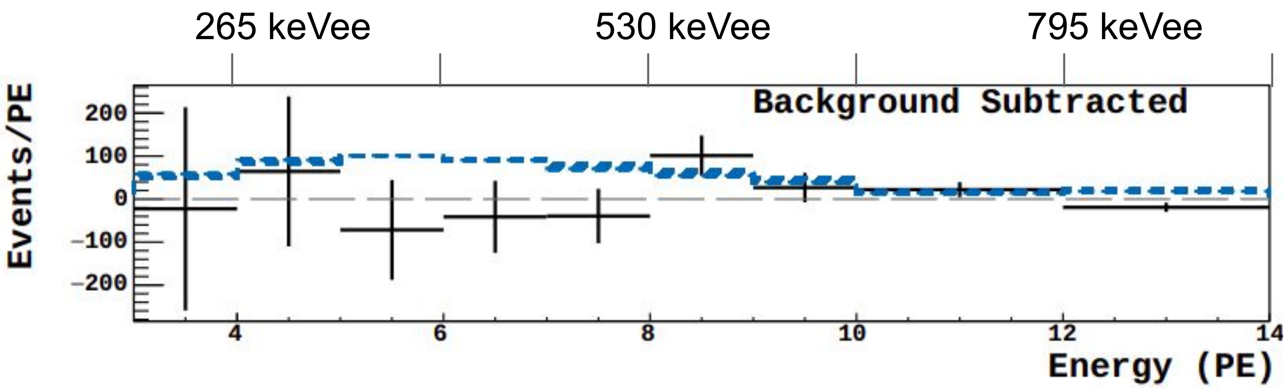
- **GEANT4** simulated fluxes from 800 MeV protons on W target geometry
- Physics list: `QGSP_BIC_HP`
- **Hadronic** cascades + **meson** production
  - π^0 , π^+ , π^-
- Production of **secondaries**: e^+, e^-, γ's:
  - e^+e^- Pair production
  - Bremsstrahlung
  - π^0 decays
  - Neutron/proton scattering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



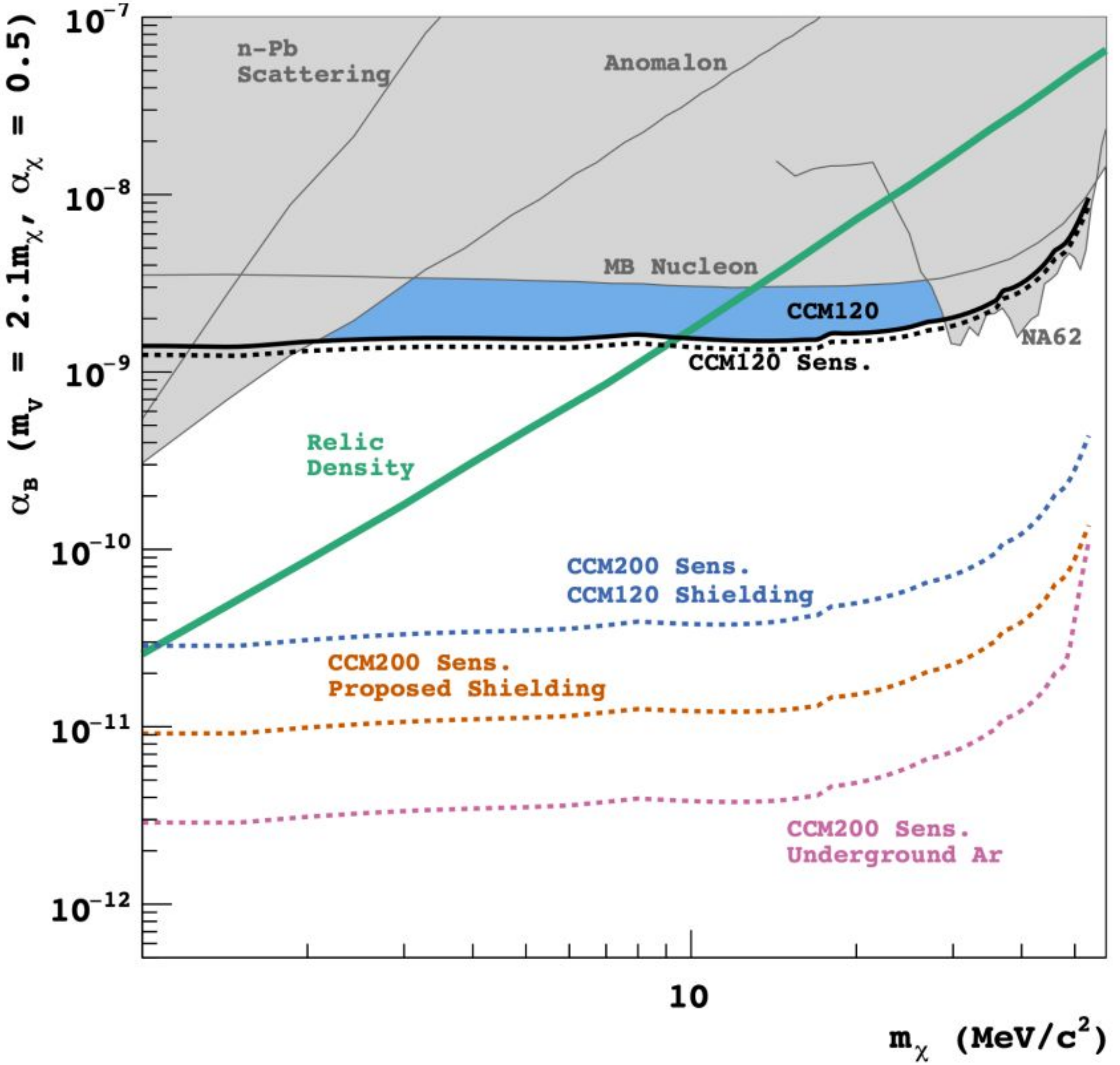


CCM120 Leptophobic Sensitivities: $m_V = 2.1m_\chi$



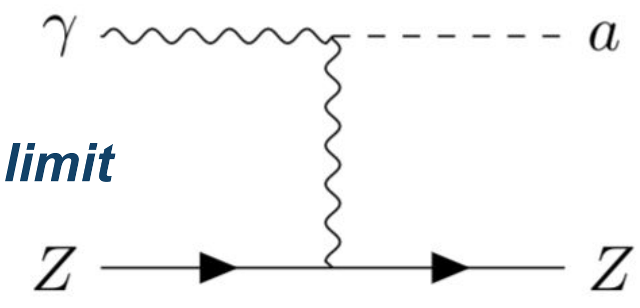


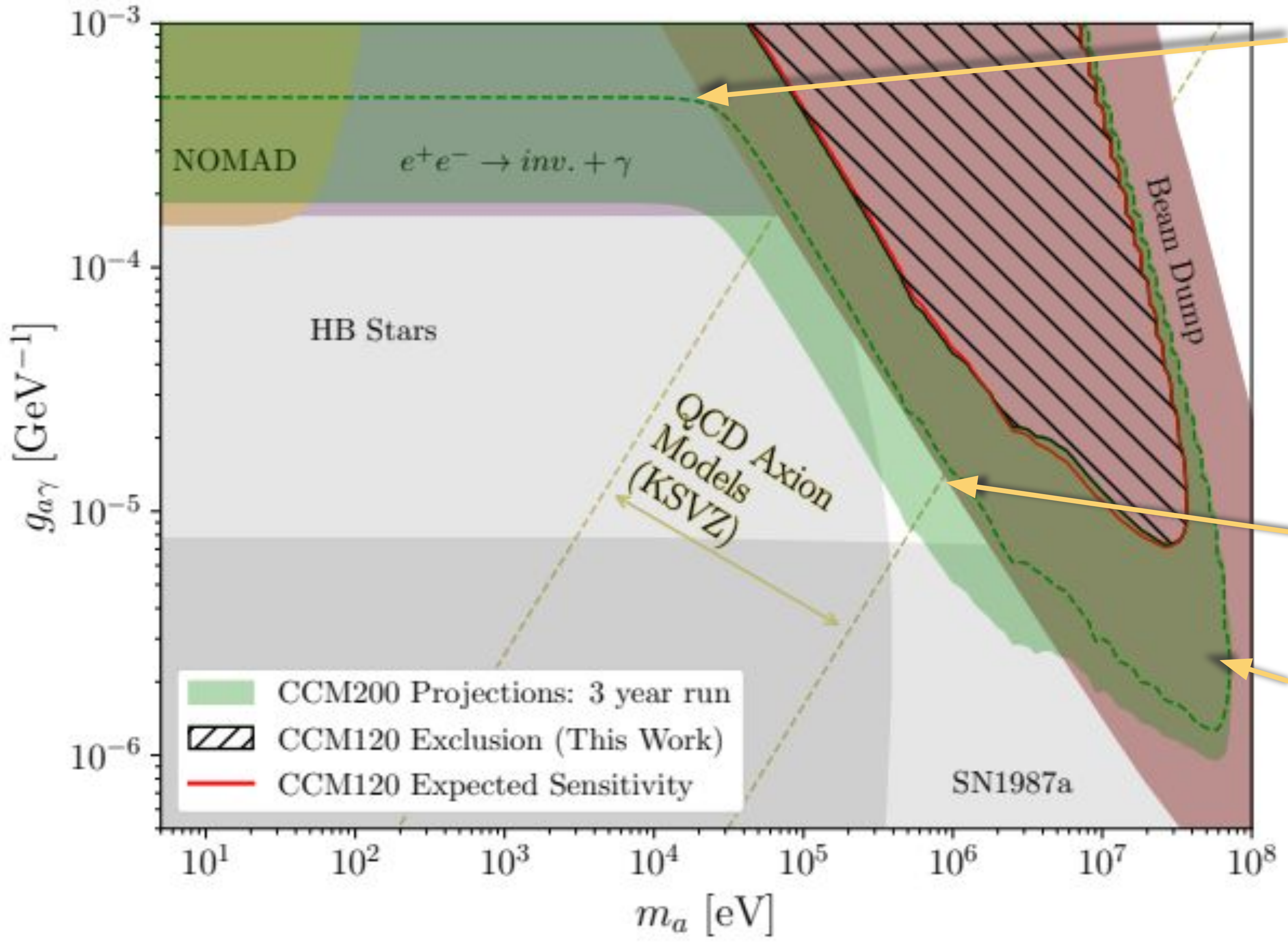
15.1±4.0 PEs/MeVee



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

2019 Search for QCD Axion: Photon Couplings

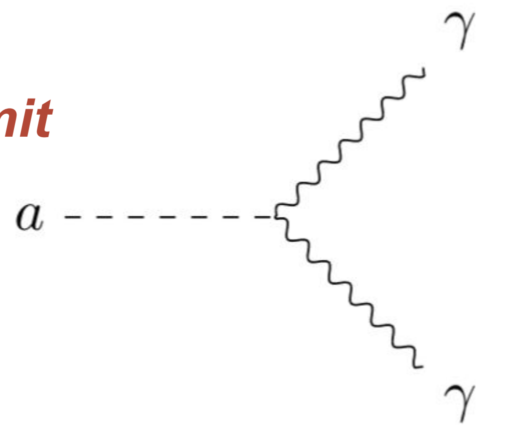




scattering limit

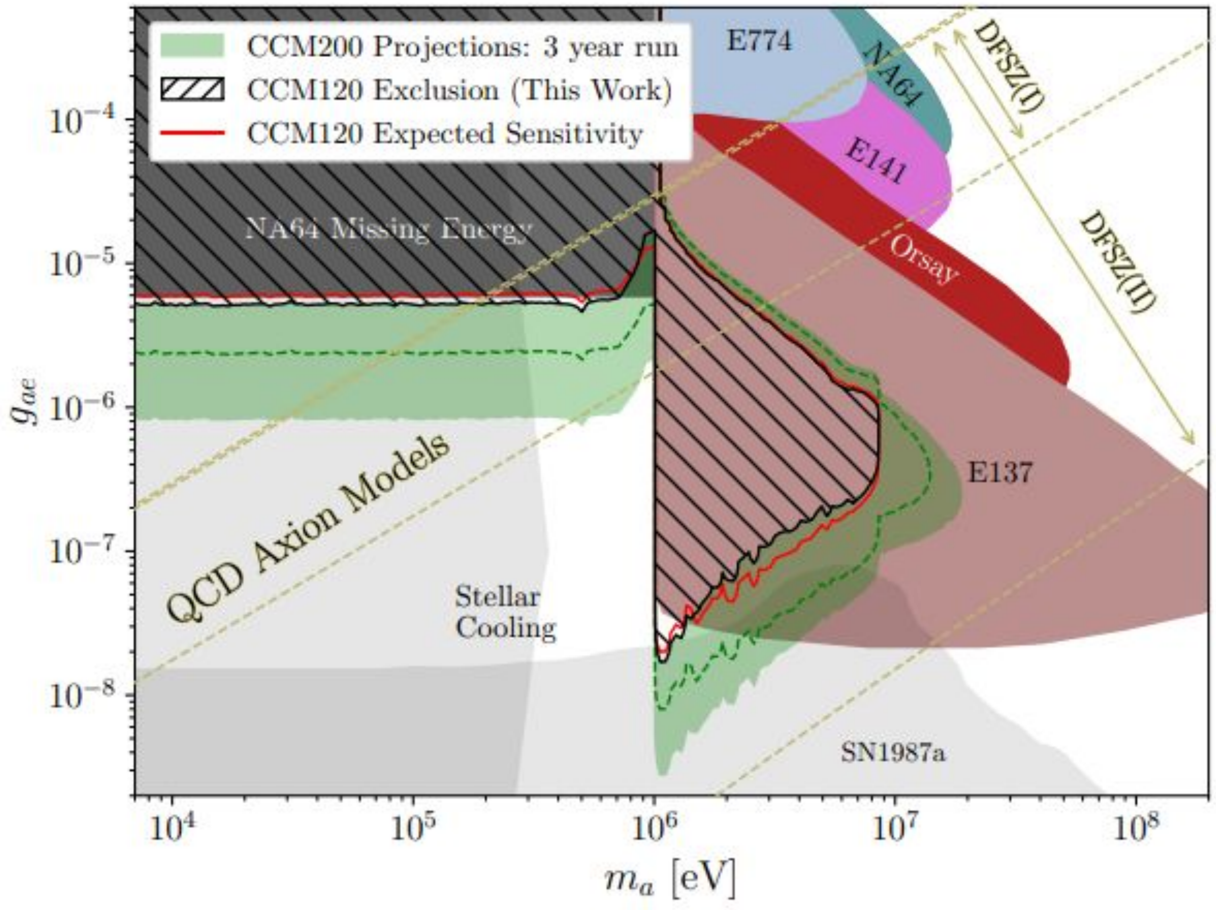
- We scan over ALP parameter space couplings to photons and electrons in a model-agnostic way (one coupling at a time turned on)
- Project sensitivity over the "cosmological triangle" at CCM200

decay limit

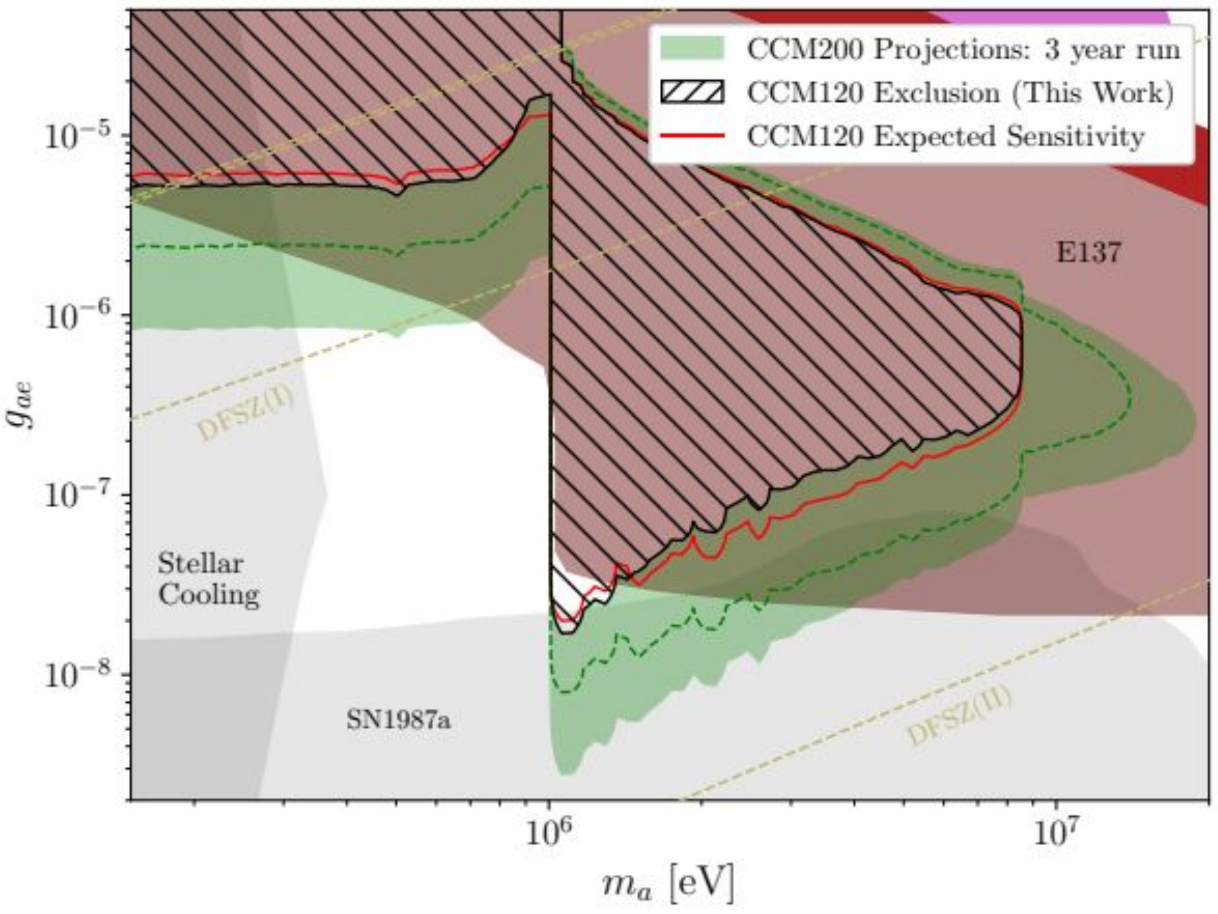


2019 Search for QCD Axion: Electron Couplings

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



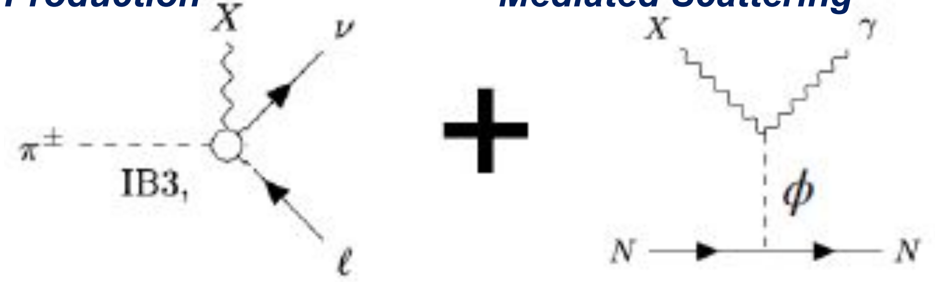
With electron loop-induced photon coupling and $a \rightarrow \gamma\gamma$

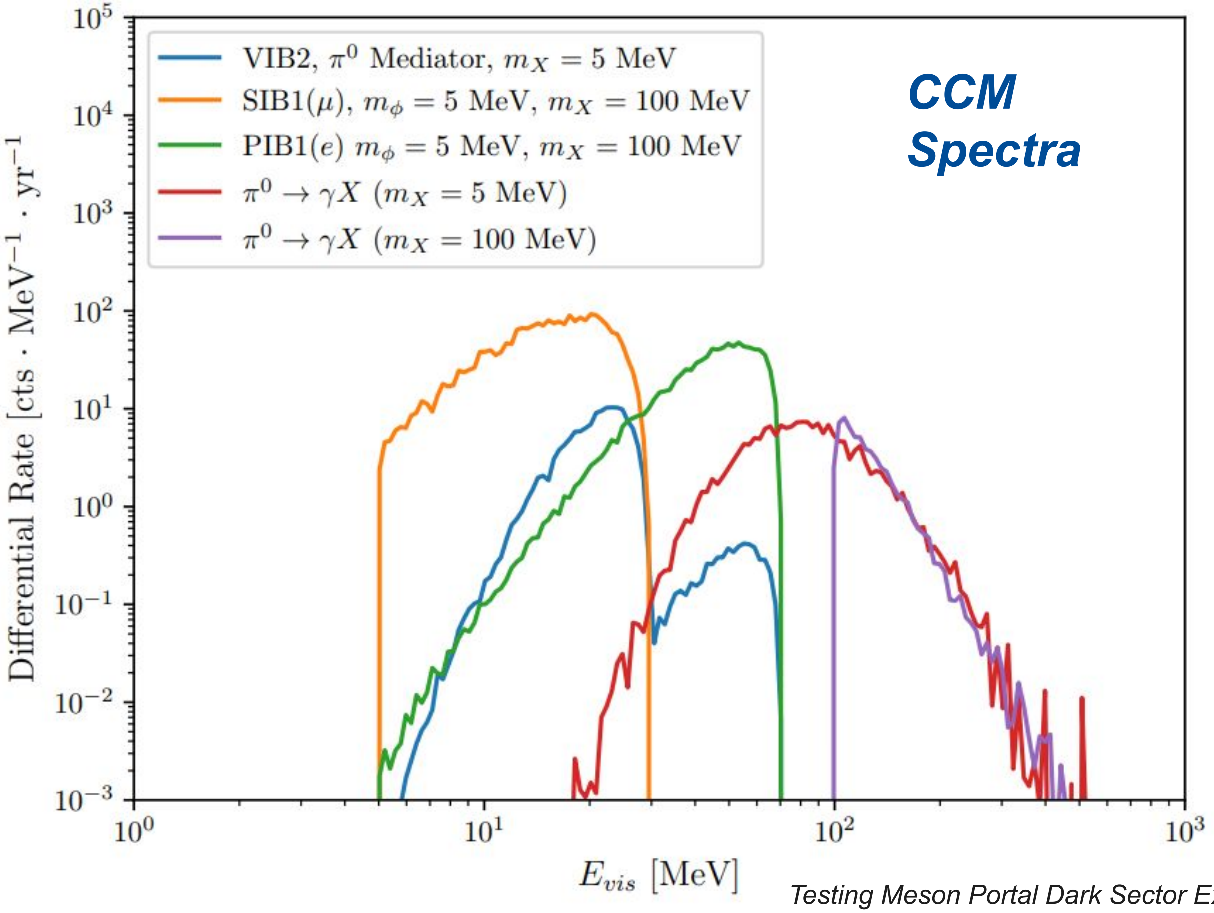
Dark Sector Charged Meson Decays (DSCMD): 2-Mediator Models

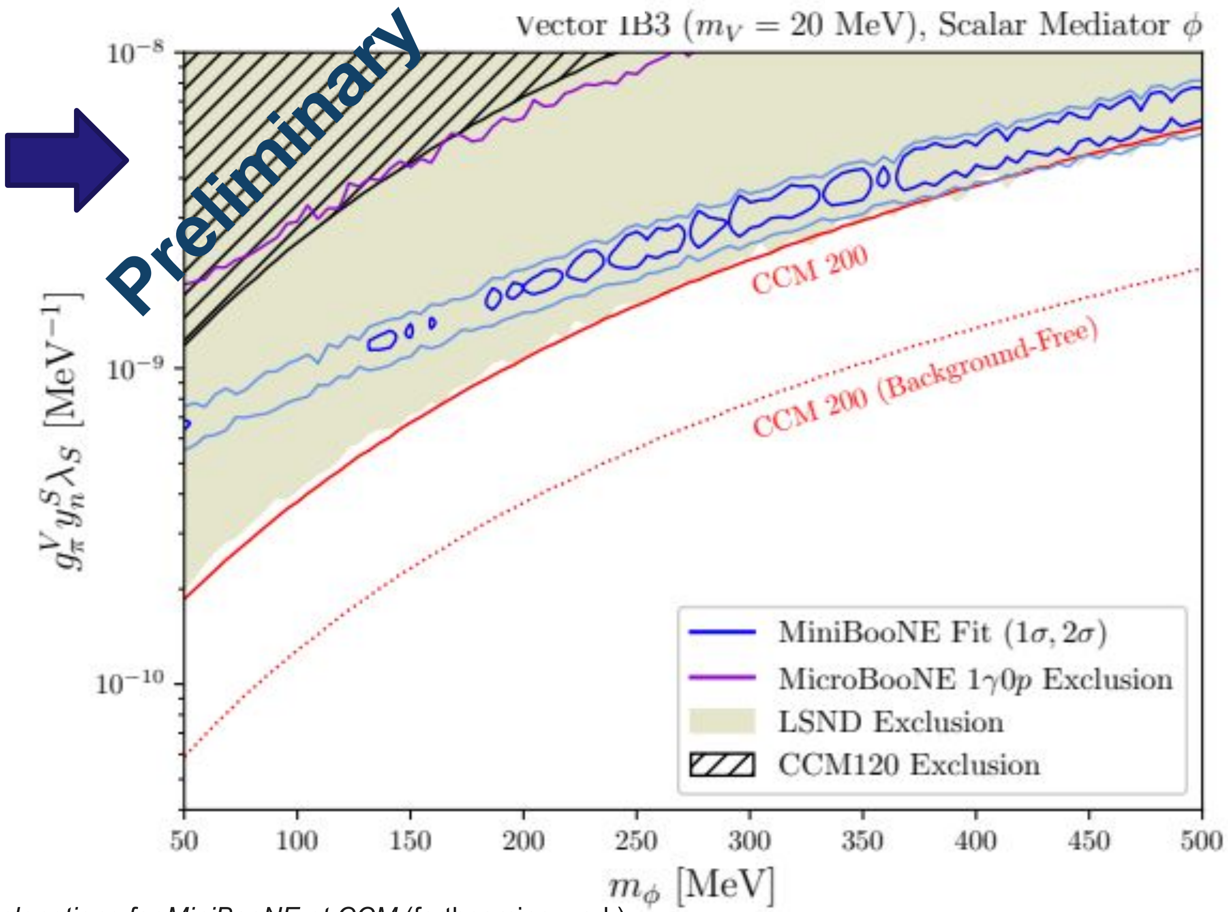
- DSCMD fits to MiniBooNE data for
  - ***Target Mode***: Neutrino + Antineutrino **excess**
  - ***Dump Mode***: null result as a constraint

Decay Channel: Vector LLP Production

Detection Channel: Scalar Mediated Scattering







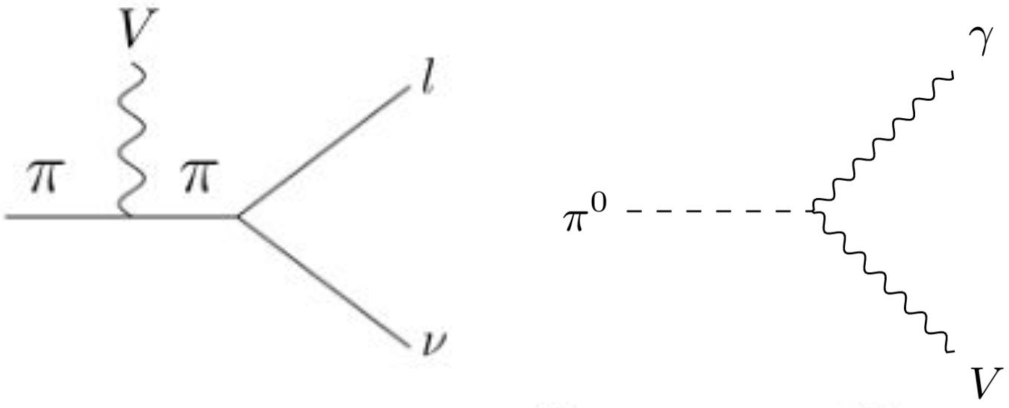
Testing Meson Portal Dark Sector Explanations for MiniBooNE at CCM (forthcoming work)

DSCMD: Single Vector LLP at CCM120 and Beyond

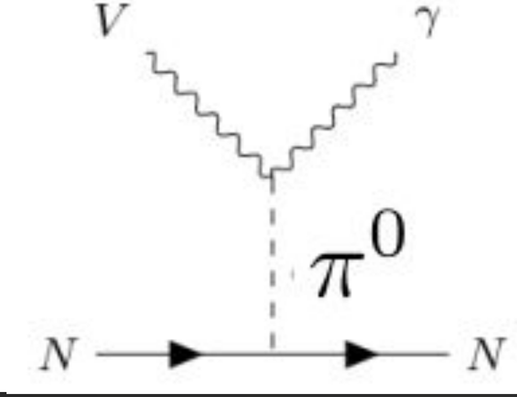
- We fit the **MiniBooNE target + dump** data for a *o*(5) MeV vector mass
- CCM200 slated to test this explanation using the neutral pion couplings

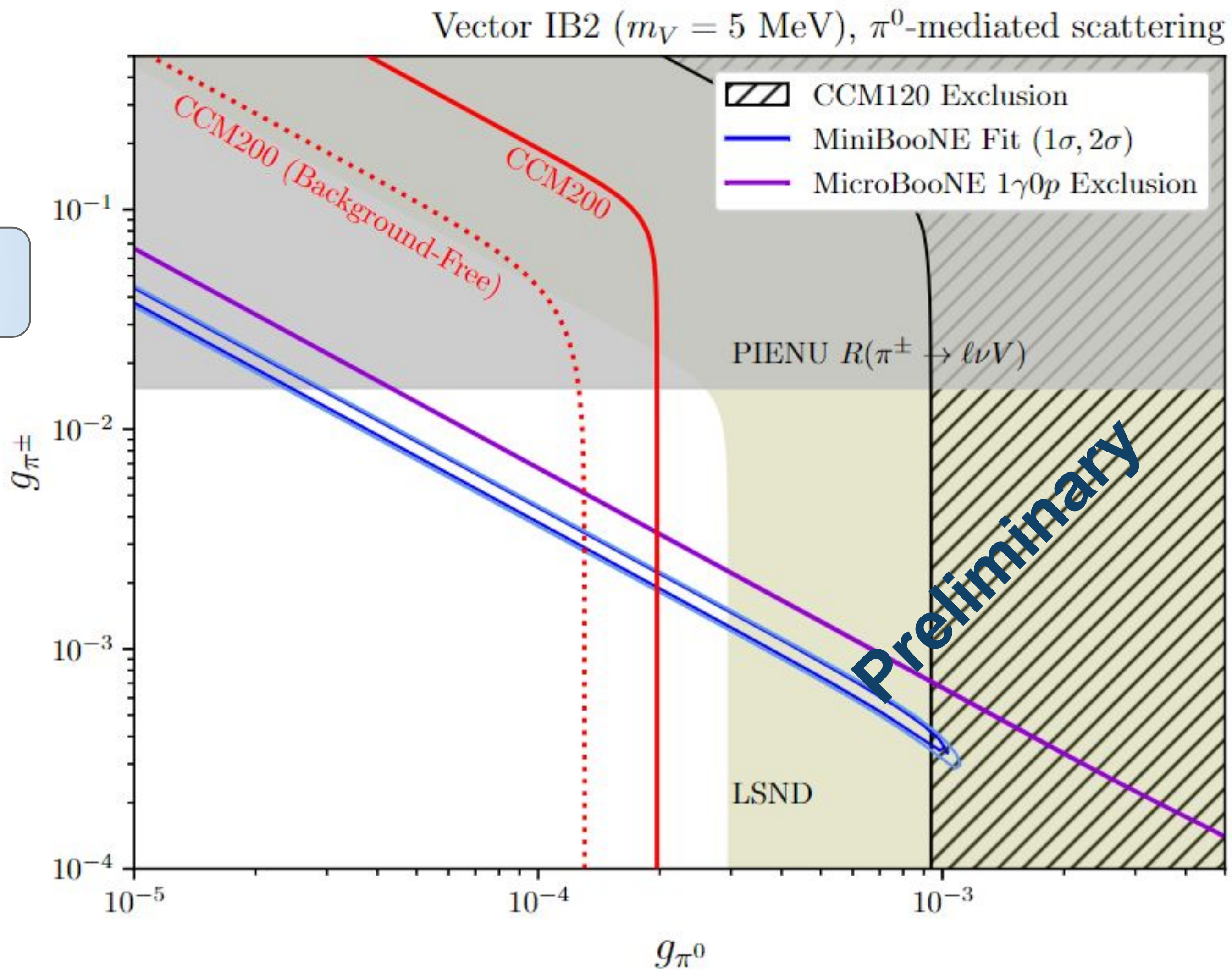
Single vector LLP coupling to π-doublet

Decay Channels



Detection Channel

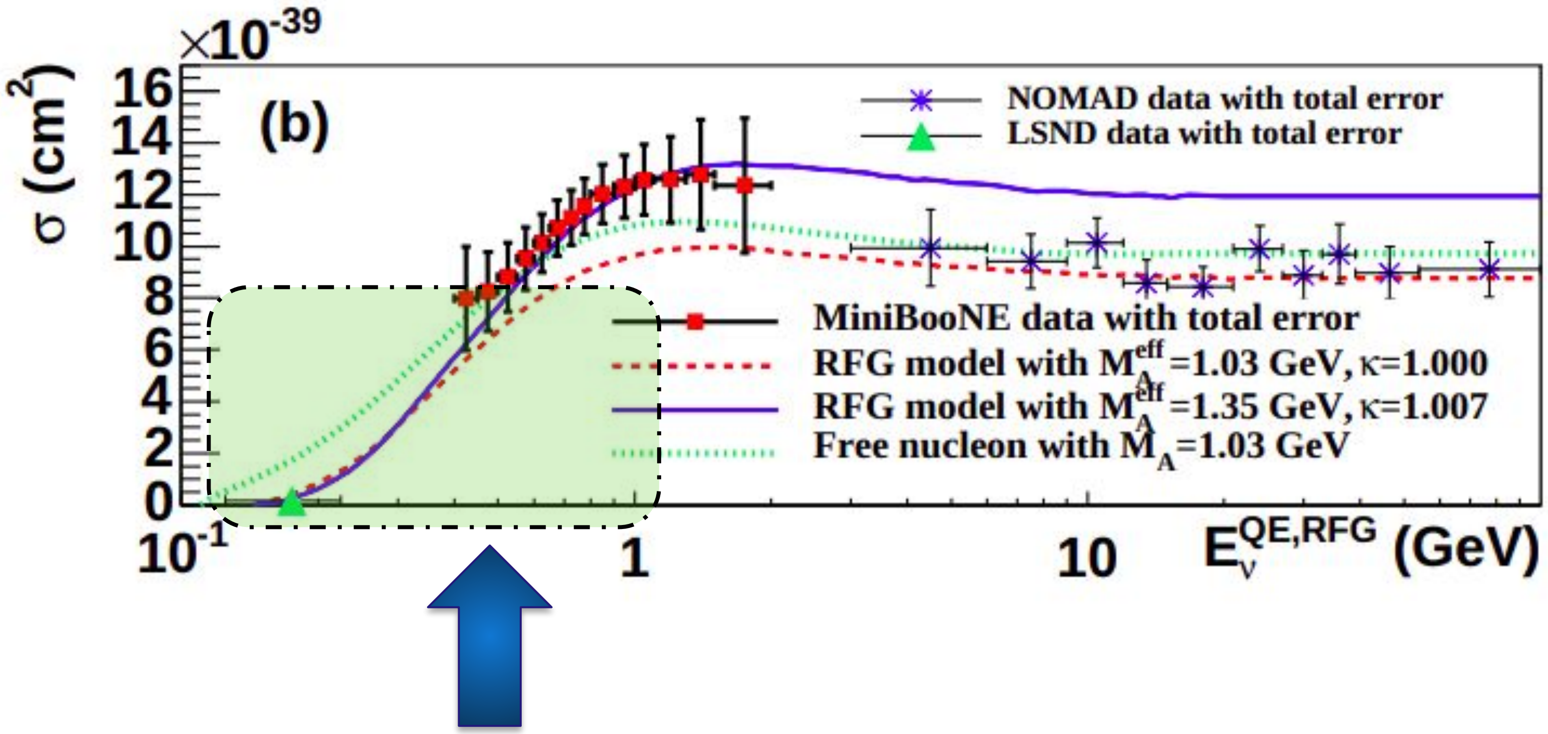




Testing Meson Portal Dark Sector Explanations for MiniBooNE at CCM (forthcoming work)

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**



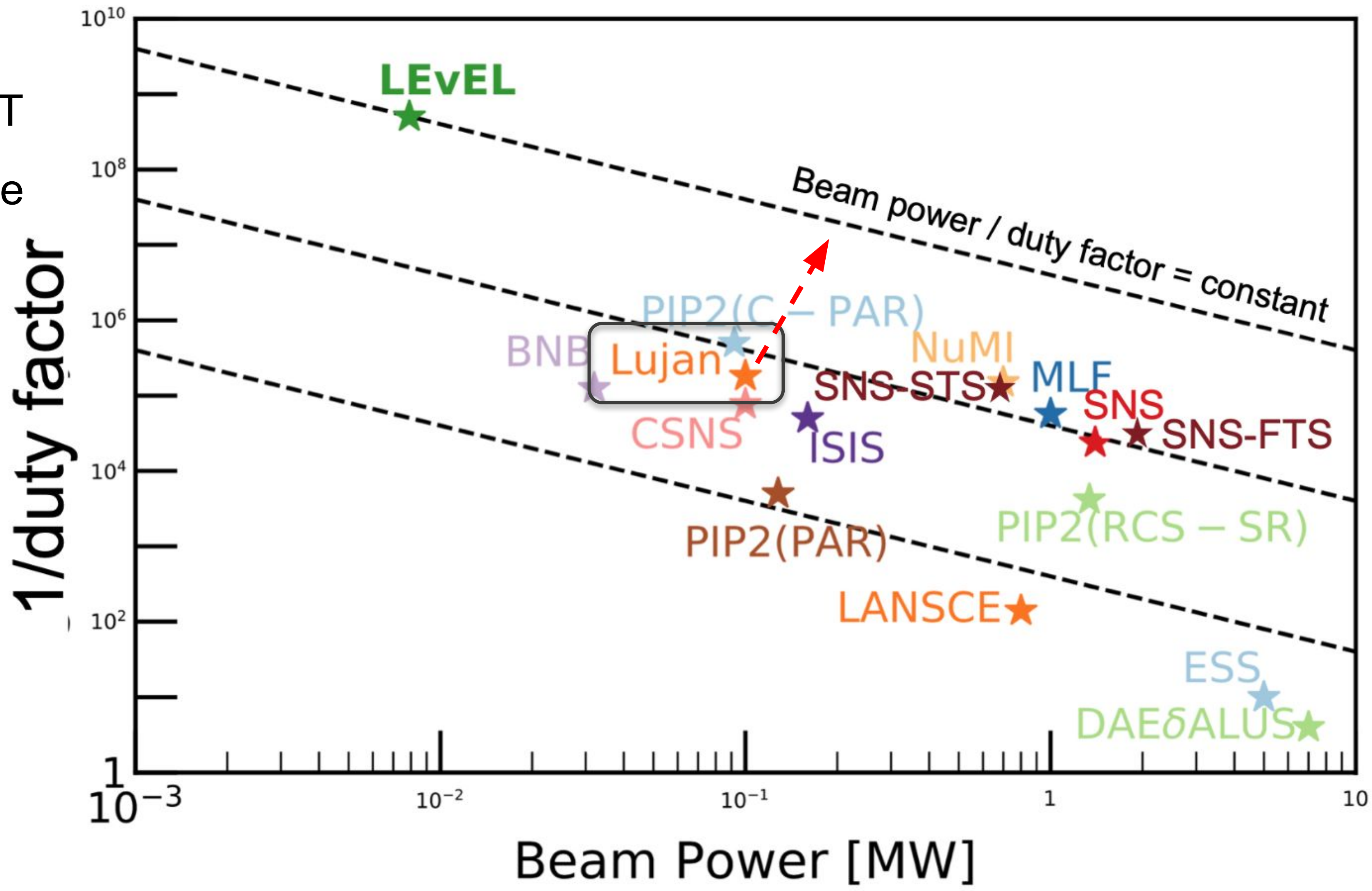
More measurements needed here!

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

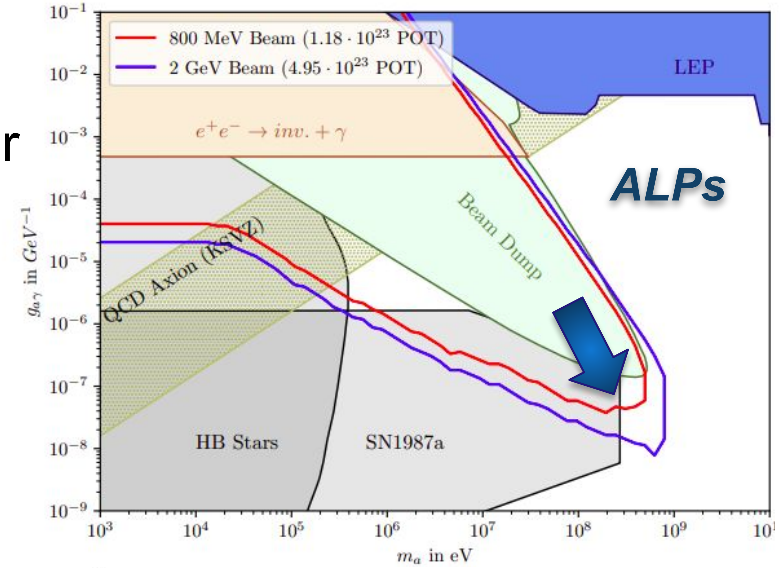
Lujan/CCM makes up for less power with large, sensitive, and fast 10-ton LAr detector!

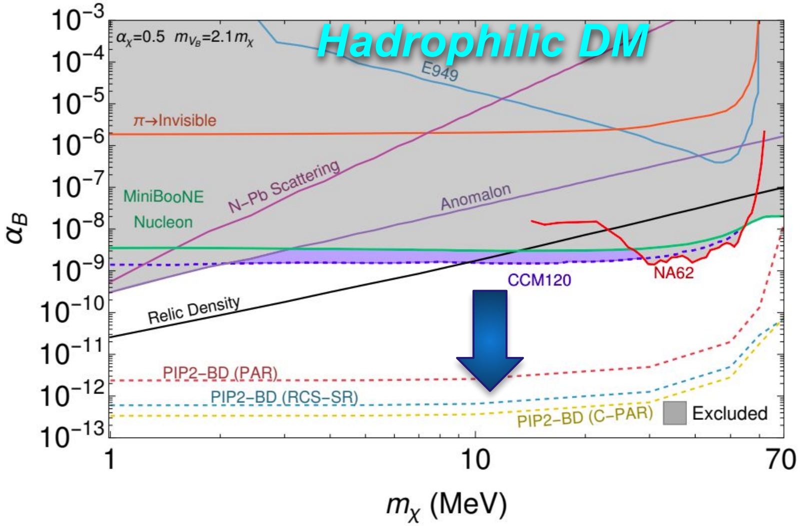


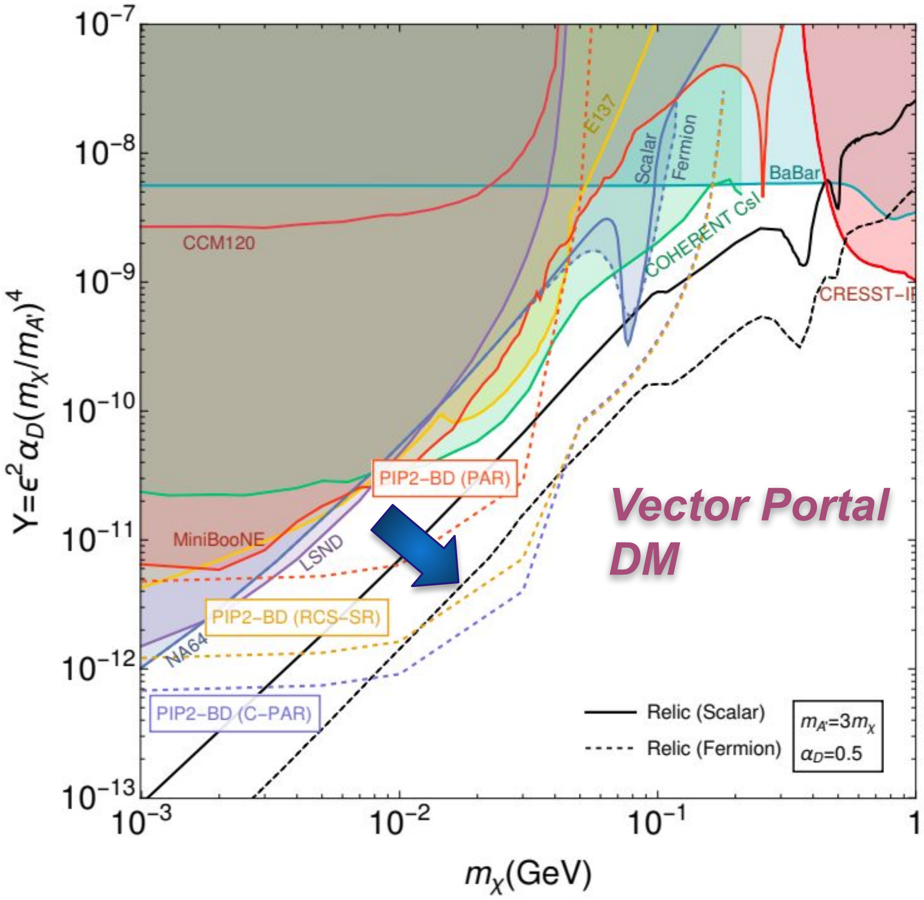
Proton Improvement Plan Beam Dump (PIP-II BD) [arXiv:2203.08079]

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.







Summary and Future Outlook

- CCM200 is taking data ***now*****, results forthcoming!**
- **Diverse physics program** for tests of BSM explanations to physics puzzles
- Energy window: keV to 100s of MeV
  - Broad set of BSM physics signals
    - *high intensity* source of ALPs, LDM, HNLs, etc.
    - Tests of short baseline anomalies and rare pion decay models
  - Orders of magnitude in parameter space sensitivity
- Upgrades ongoing to bring CCM's sensitivity to its fullest potential
- Working with theorists to cultivate new ideas

Acknowledgements

Los Alamos NATIONAL LABORATORY EST. 1943

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

TEXAS A&M UNIVERSITY Physics & Astronomy

U.S. DEPARTMENT OF ENERGY | Office of Science

HEP: Dark Matter New initiatives (DMNI)

Massachusetts Institute of Technology

UF UNIVERSITY of FLORIDA

THE UNIVERSITY OF EDINBURGH

Fermilab

EMBRY-RIDDLE Aeronautical University

UNM

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO

Backup Deck

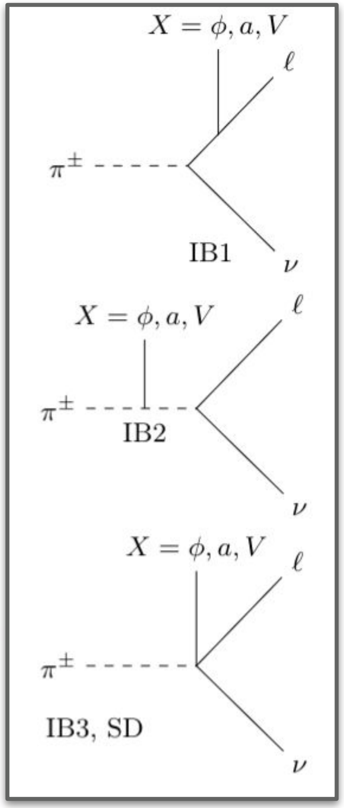
Dark Sector Coupling to Meson Decay : DSCMD models

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

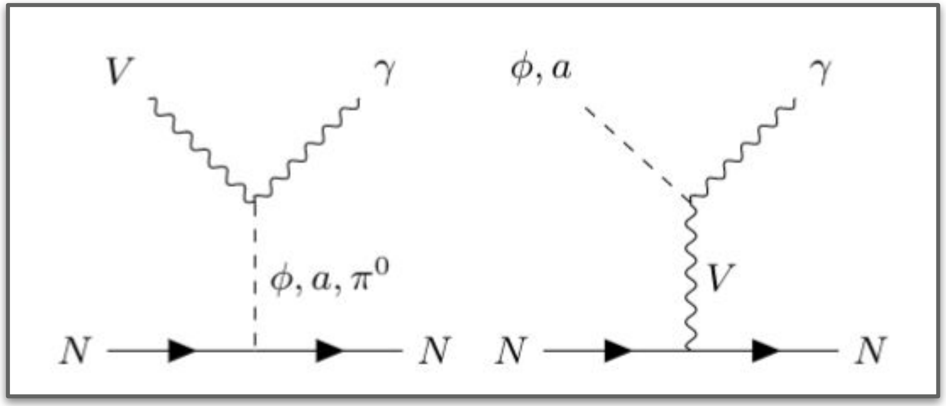
Focusing on these, but only for pragmatic purposes (scope is total)



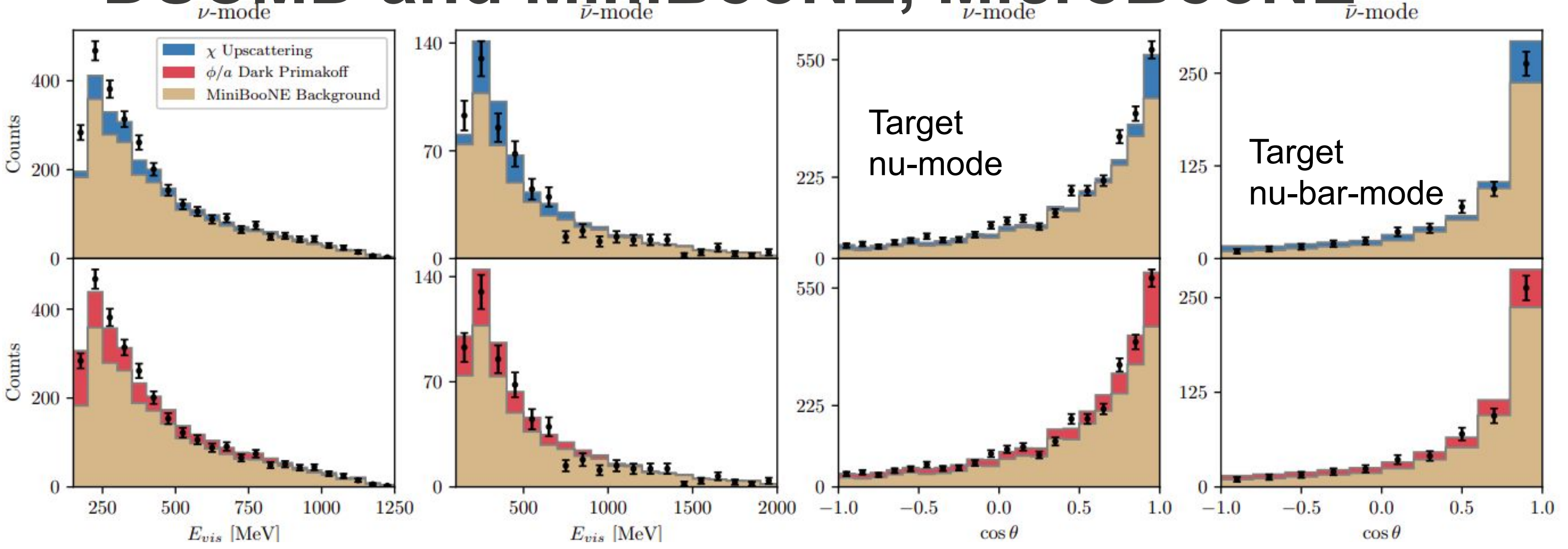
Decay Operator

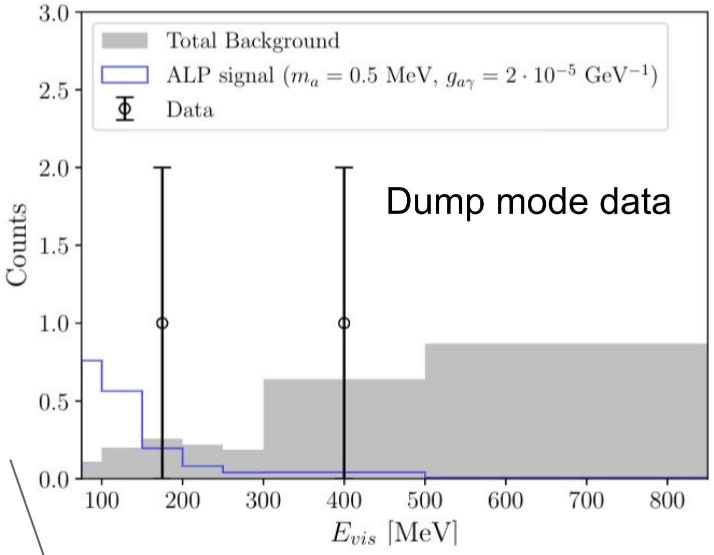
Scattering Operator

Combinatorics! Check which solve MB anomaly

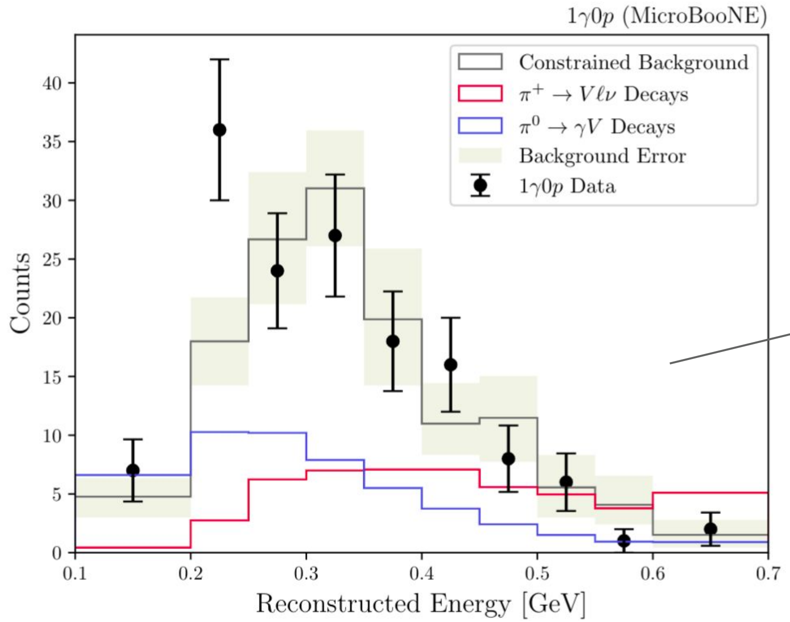


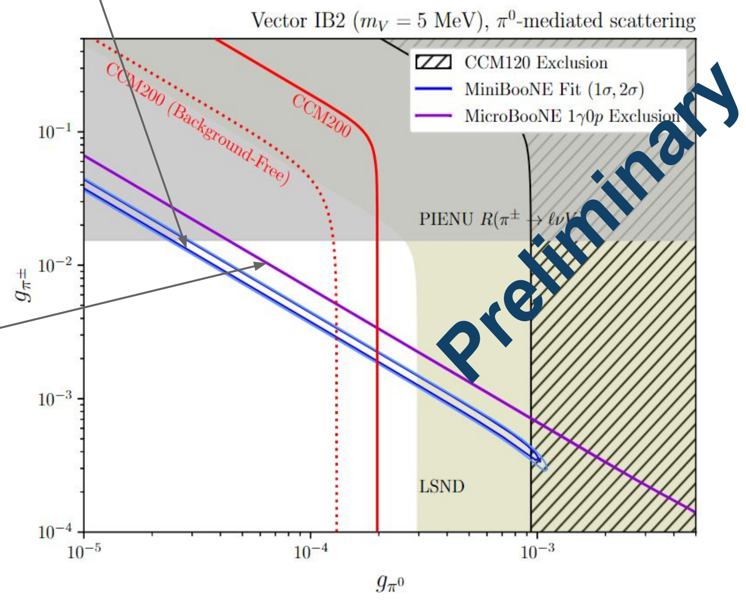
DSCMD and MiniBooNE, MicroBooNE





- 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!

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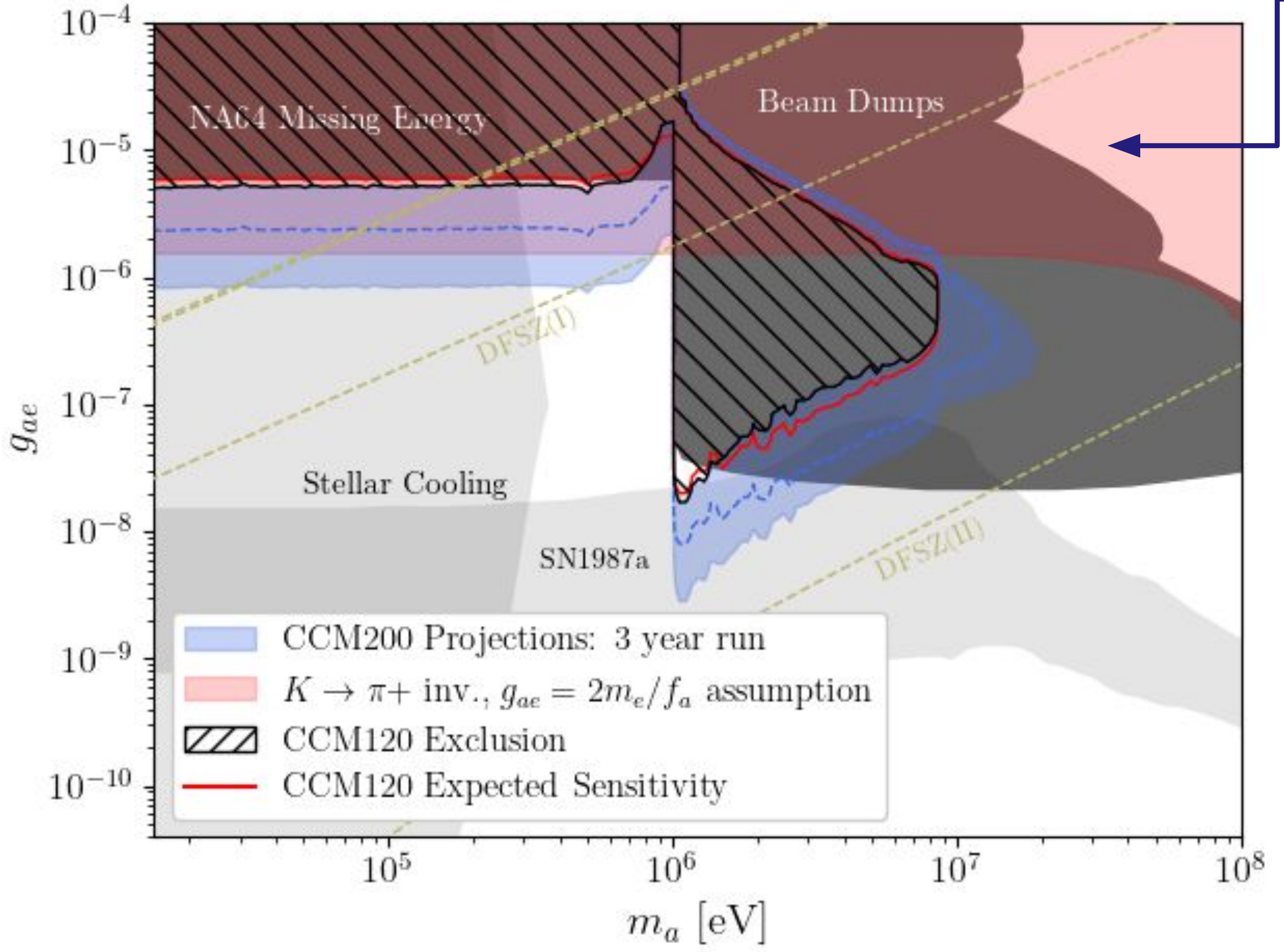
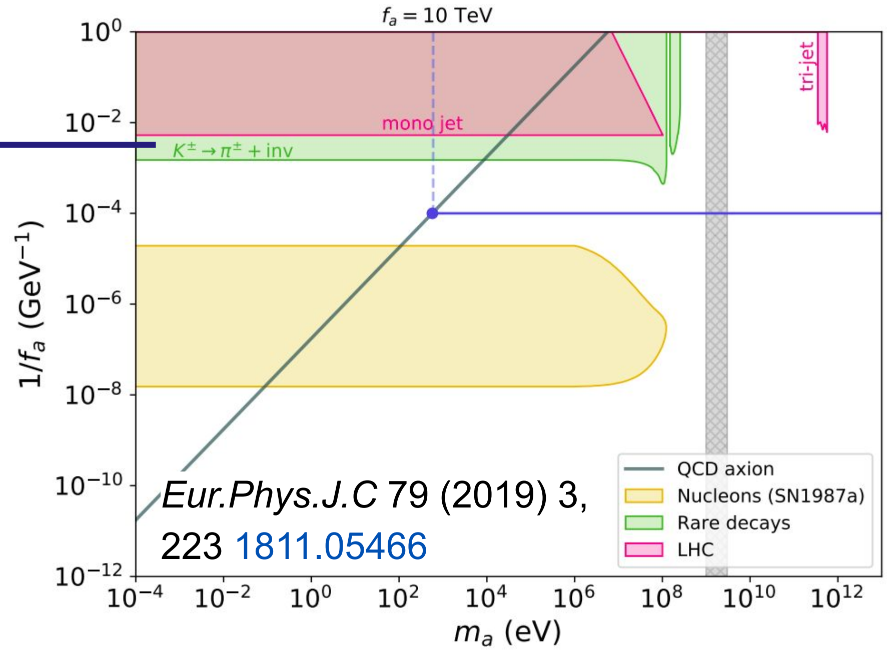
TABLE II. Relevant exotic decays of $\pi^{\pm}/K^{\pm}$ and existing upper limits at 90% confidence level X stands for invisibly decaying (massive) bosons. The predicted BRs (third though last columns) are based on the following parameter choices: $[\epsilon_1, (g_1^2/4\pi)] \simeq (6.0\times10^{-5}, 1)$ for the single-mediator scenario, $[\epsilon_1, \epsilon_2, (g_2^2/4\pi)] \simeq (7.0\times10^{-5}, 1.0\times10^{-4}, 0.5)$ for the double-mediator scenario, $(g_\mu, g_n, \lambda) \simeq (5\times10^{-3}, 10^{-2}, 4.4\times10^{-4}\ \text{MeV}^{-1})$ for the scalar scenario, and $(g_\mu, g_n, \lambda) \simeq (10^{-2}, 10^{-2}, 6.5\times10^{-3}\ \text{MeV}^{-1})$ for the pseudoscalar scenario.

		Model (i) ($\times10^{-12}$)		Model (ii) ($\times10^{-8}$)	
Channel (BR)	Limit ($\times10^{-8}$)	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	$\cdots$	$\cdots$
$K\to\mu(e)\nu_{\mu(e)}ee$ [54]	7.4(2.7)	500(530)	680(720)	$\cdots$	$\cdots$
$\pi\to\mu(e)\nu_{\mu(e)}X$ [88]	600(50)	0.12(25)	0.17(34)	120($\cdots$)	1.1($\cdots$)
$\pi\to\mu(e)\nu_{\mu(e)}ee$ [54]	–(0.37)	0.12(25)	0.17(34)	$\cdots$	$\cdots$

Constraints on Traditional QCD Axions





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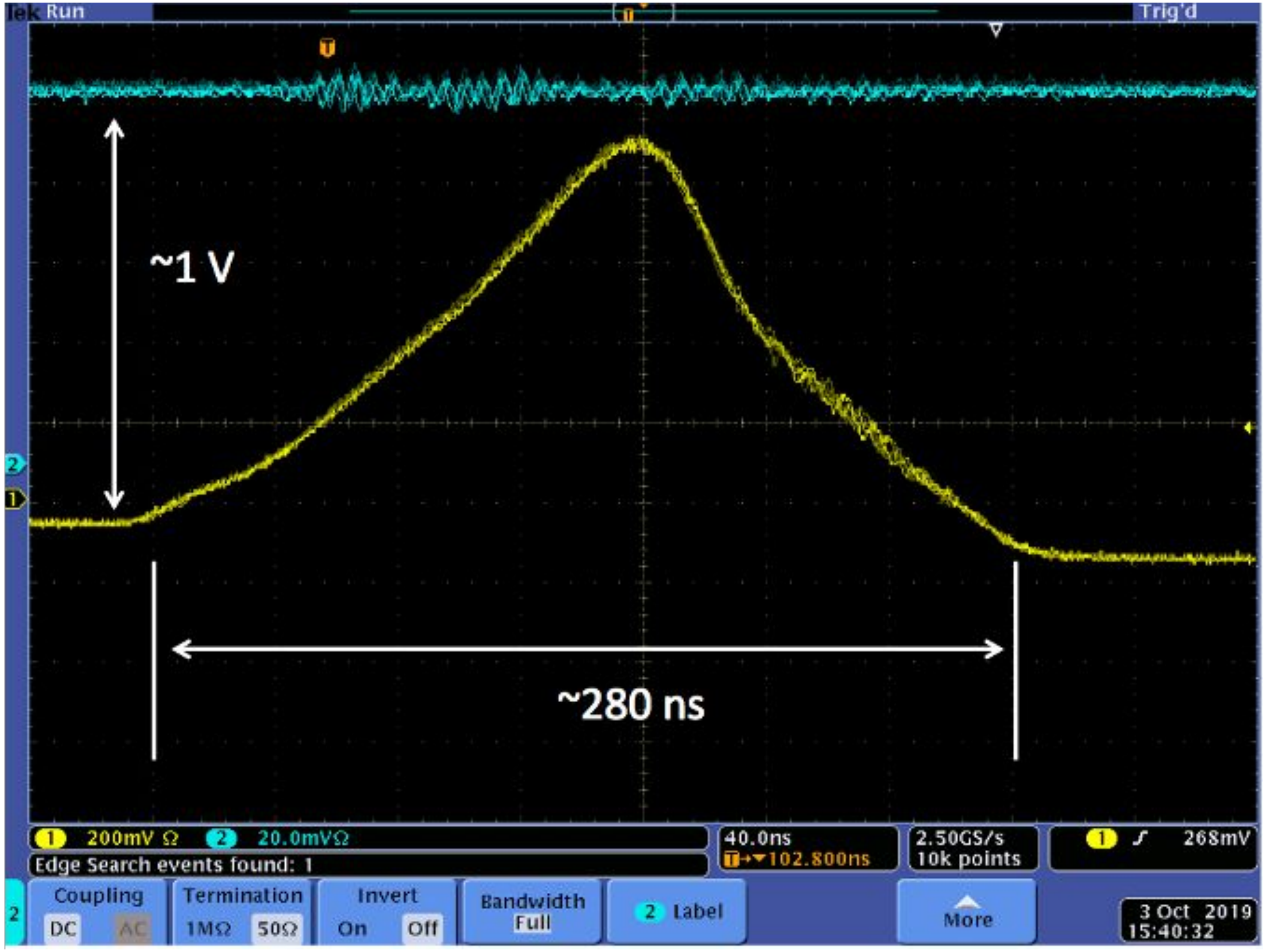
- ***pure Gluon*** coupling constraints set limits on axions that solve strong CP (here from rare Kaon decays)
  - sets indirect constraint on g_ae
- Other constraints from EW couplings could apply or be evaded depending on PQ charges

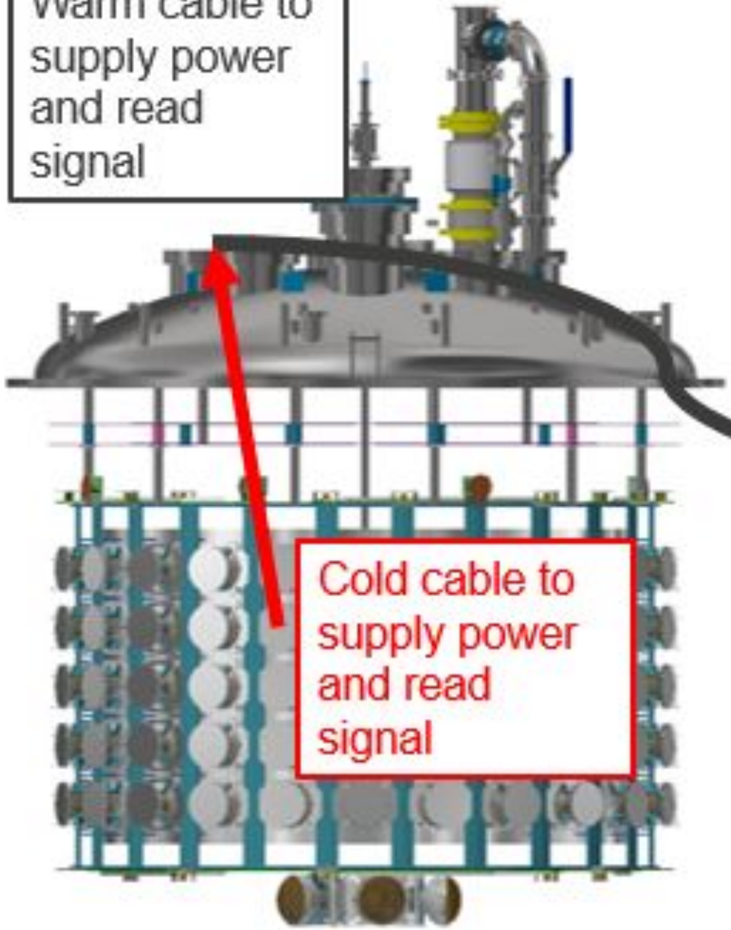
Trigger by Trigger measurement of the Beam through Integrated Beam Current Monitor

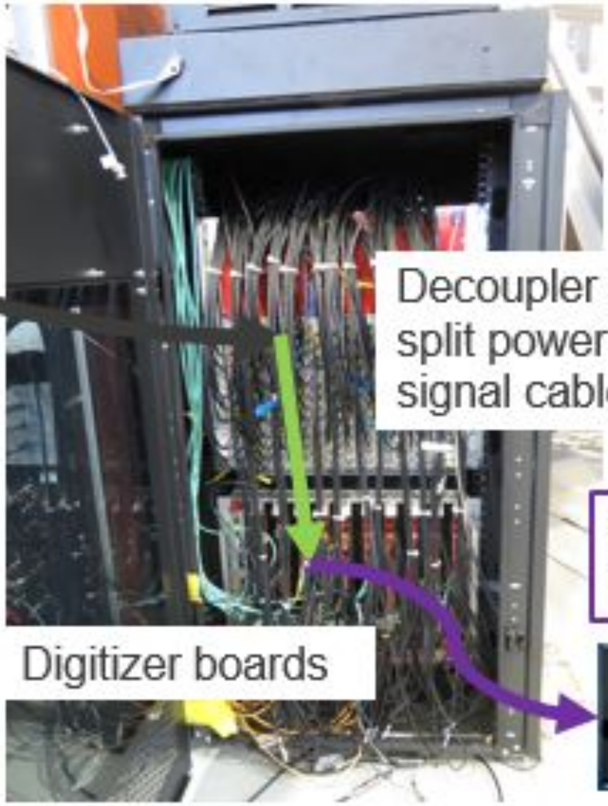
- CCM includes direct measurements of the beam proton pulse through a BCM integrated directly into the DAQ and data stream.
- This BCM can be used to analyze the protons per trigger, and ensure that only the best quality triggers are included in the final analysis.



CCM120 Flow of Data

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





PMT Response

- PMT SPE characteristics determined through the use of 2 LEDs on top and bottom of detector.
- PMT response averaged between the 2 points to counteract solid angle effects.
- PMT modeled with pulses of varying length and integral as in plot right.
- SPE Pulses used to calibrate data ADC to PE value and create simulation pulses with the same behavior.

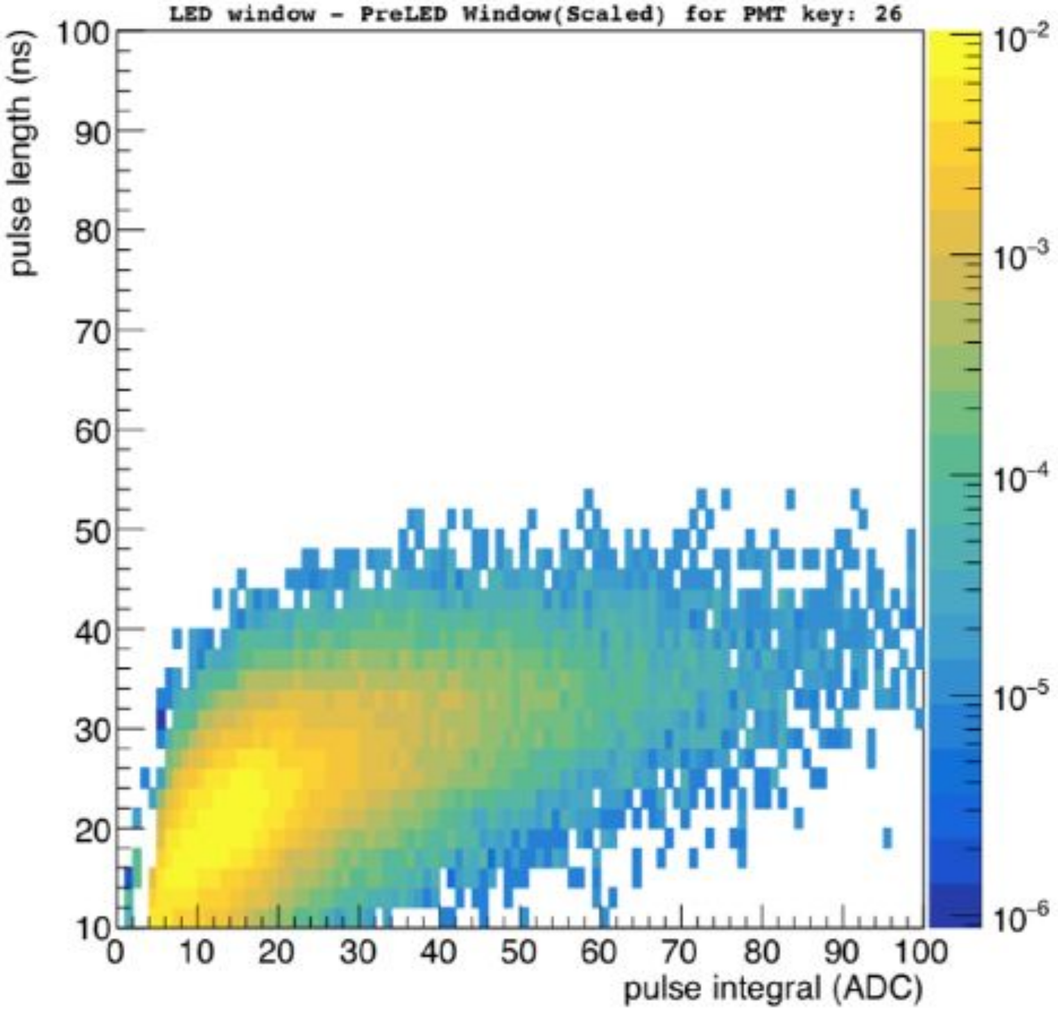
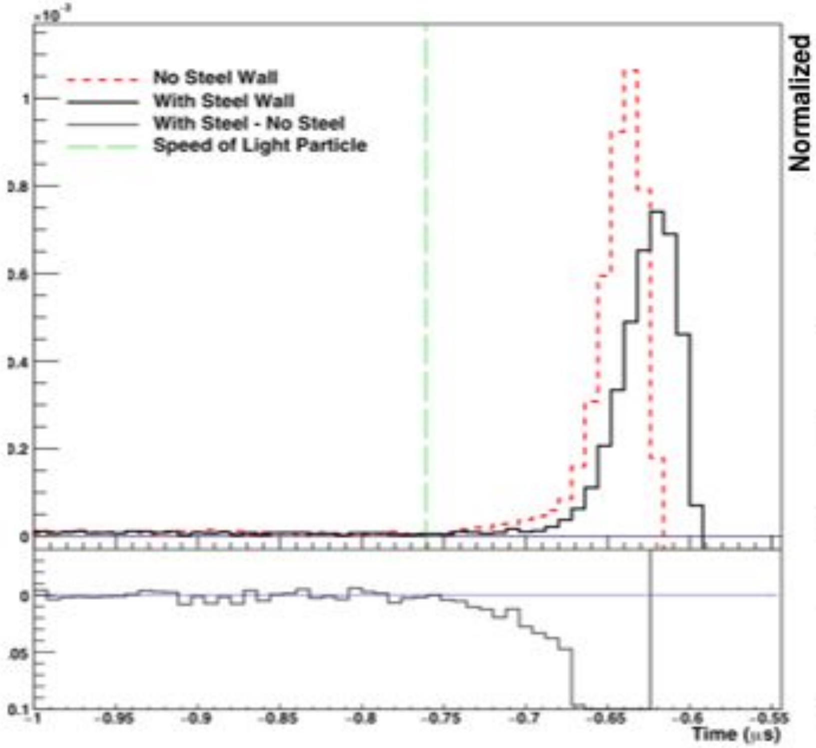
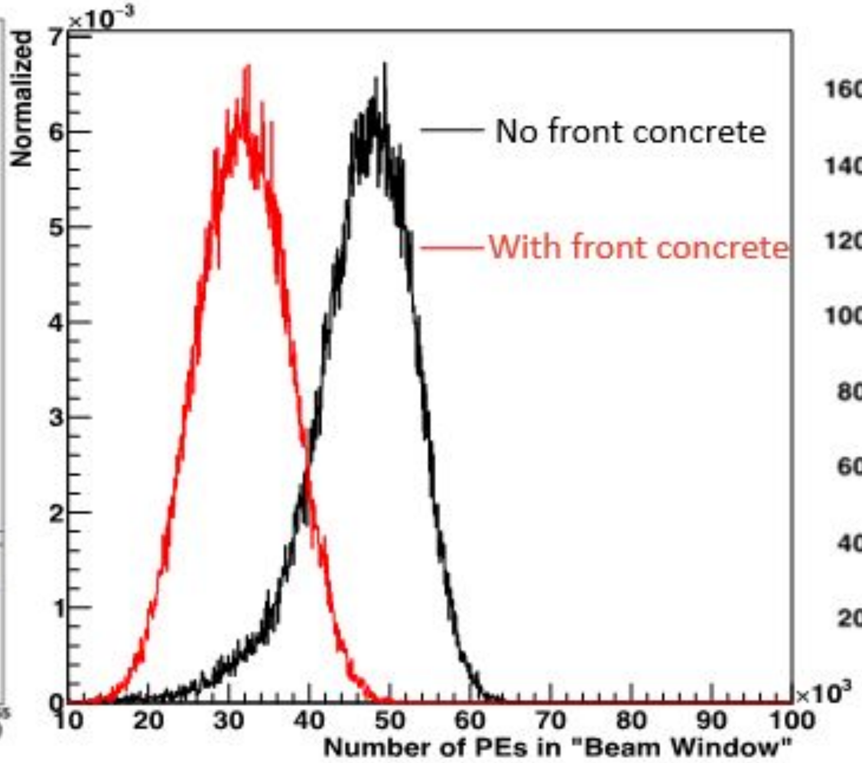


Figure 4.4: The SPE charge and length values from a single PMT, showing the distribution that was used to simulate the PMT response.

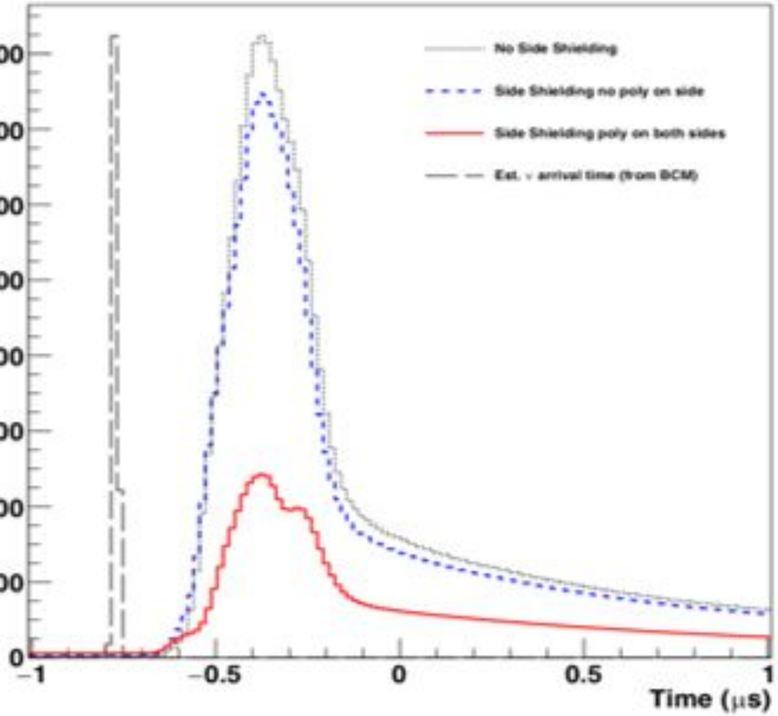
Effects of Shielding



Steel shield: decreases beam-related rate and increases delay



Front concrete: decreases bream-related energy deposition in CCM

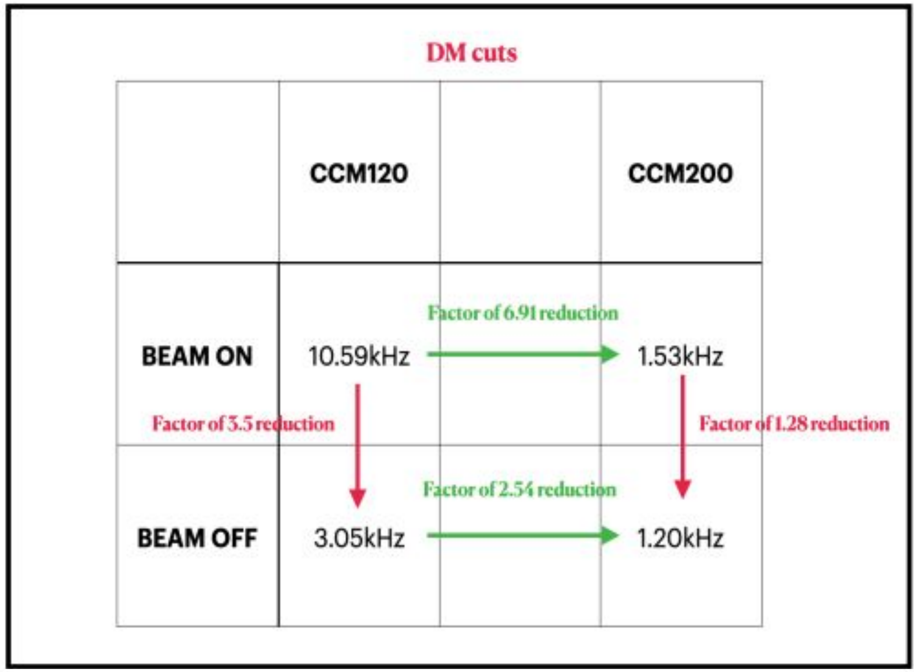


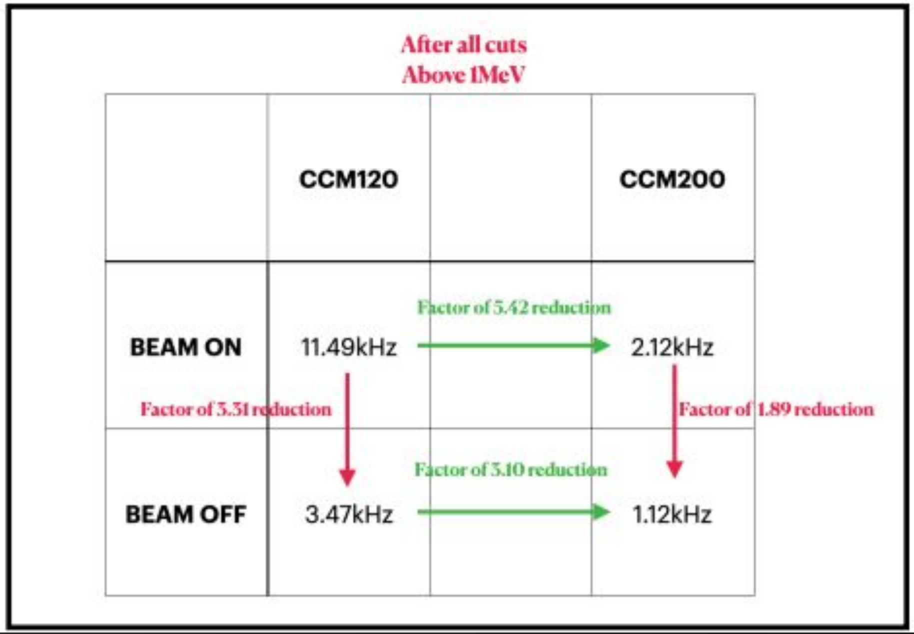
Side shielding: decreases beam-related rate

- Tested Shielding in Stages to see the effect on background

Background Rates: CCM120 and CCM200

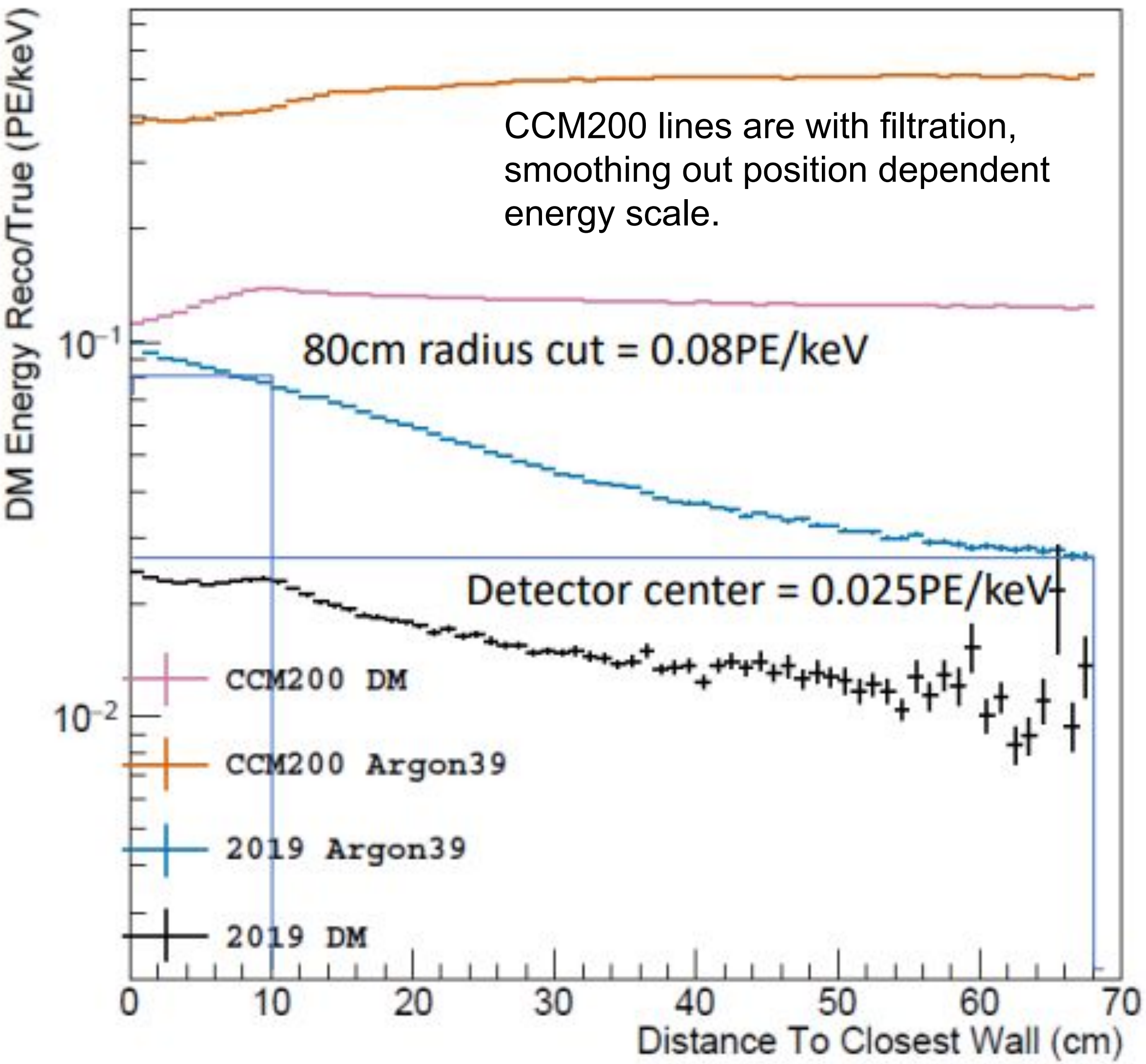
- Added Concrete and Roof shielding between CCM120 (2019) and CCM200 (2021) runs leads to reduced background rates
  - Nearly to level of eliminating beam-related background/activation, from comparison of beam-on vs. beam-off background.
- Factor of ~7 reduction in LDM search backgrounds.
- Factor of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



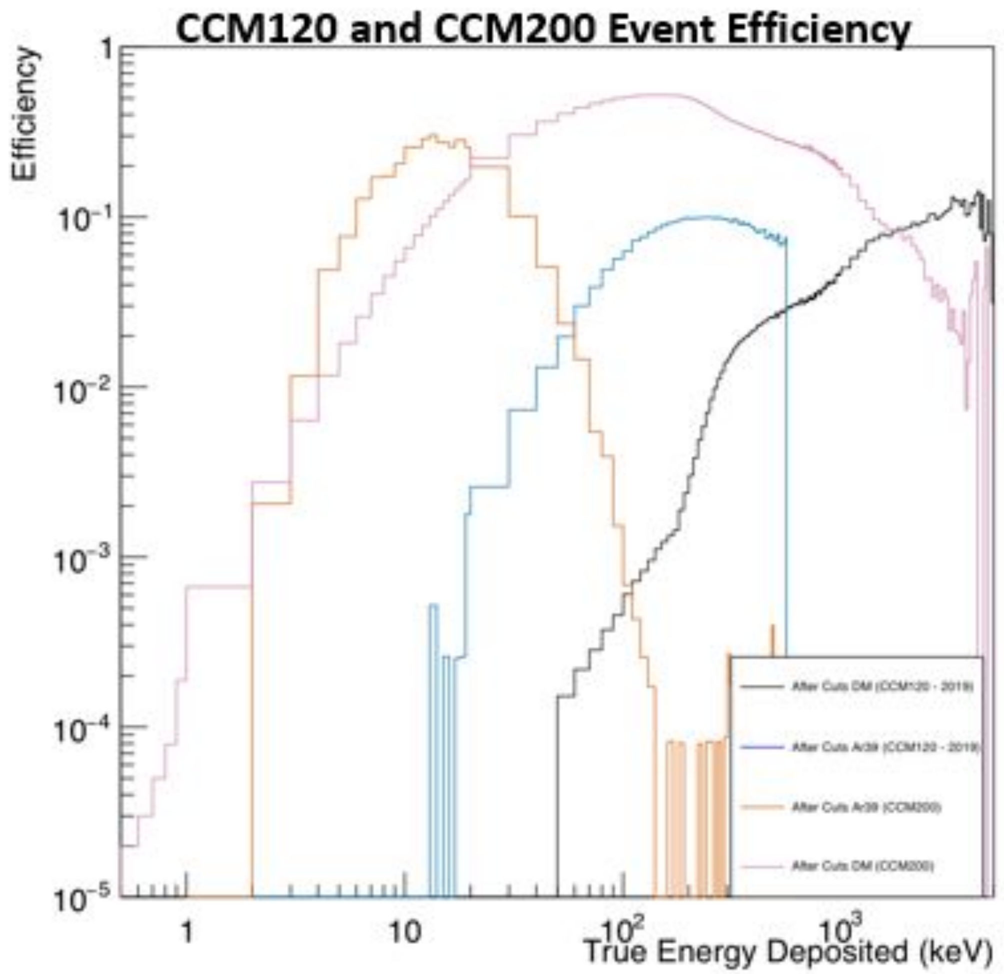


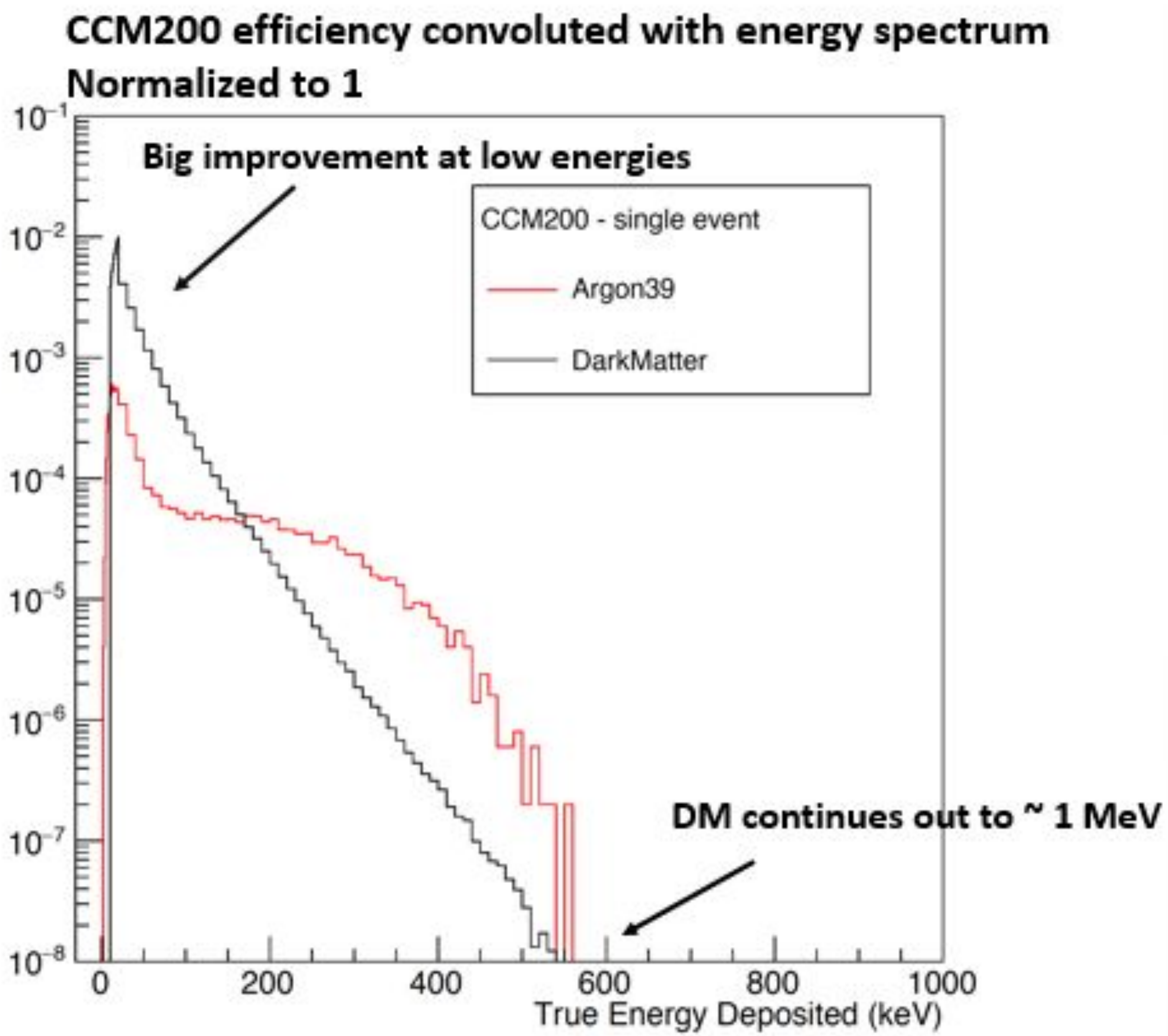
Reason for smearing distortion: Position

- ALP events occur isotropically throughout the detector.
- Na22 calibration occurs at center of detector.
    - Almost factor of 4 difference in Reco/true energy ratio based solely on position.
    - Average event around 30-40 cm from closest wall = 0.04-5 PE/keV
- Position smearing approx. doubles the energy scale and adds 50% uncertainty depending on where it is.



CCM 200 Efficiency Improvement



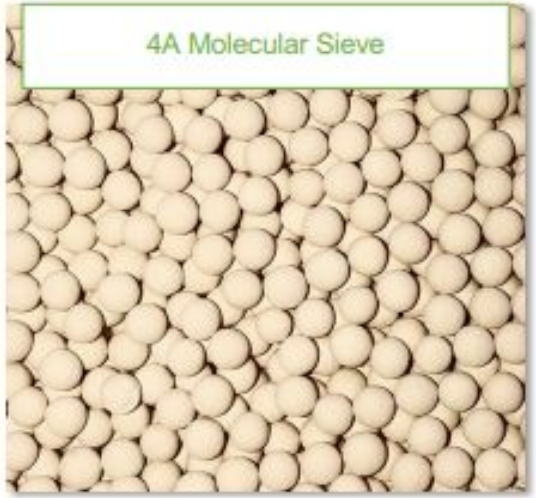


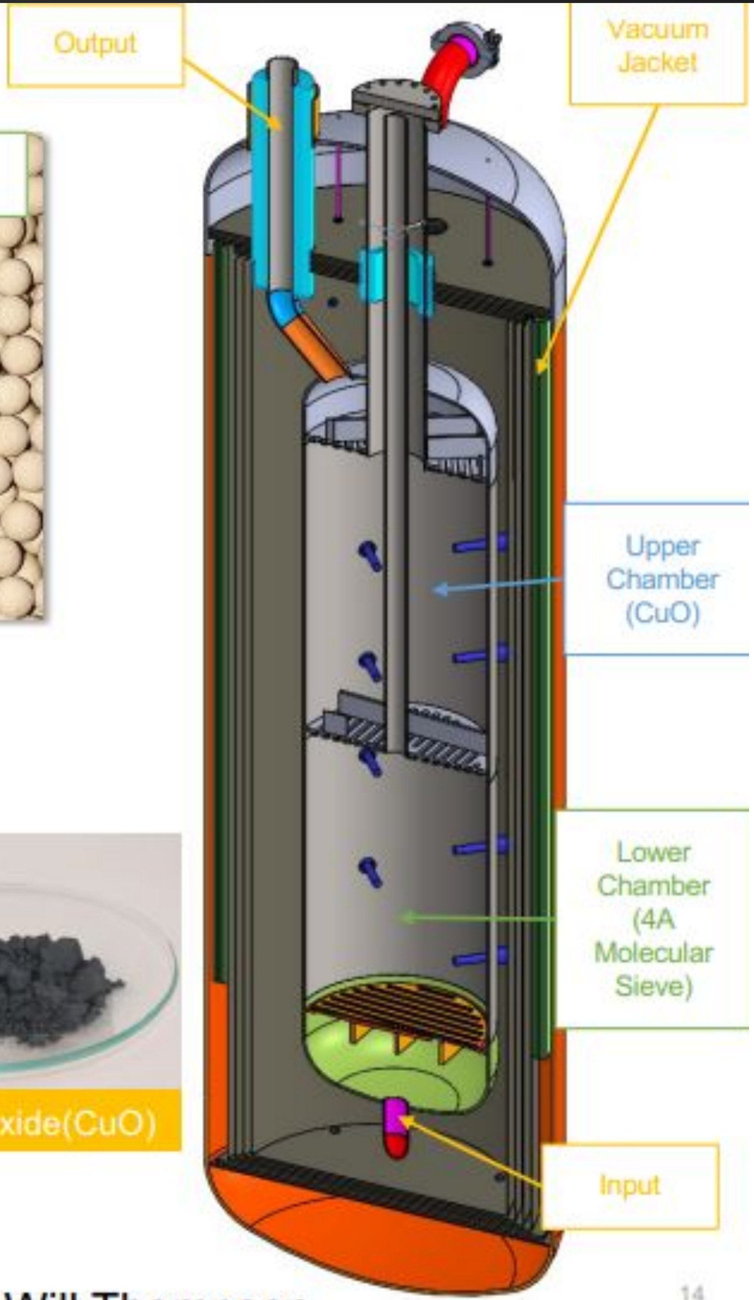
DM integral efficiency 1% => 25% with clean LAr

Ar39 integral efficiency 26% => 1% with clean LAr (better triplet light rejection)

Filter Skid – Filter Vessel

- **Upper Chamber**:
  - $2Cu + O_2 = 2CuO$
  - Copper (Cu) removes oxygen becomes contamination
  - 33kg of Cu -> **16.4g of O_2 capture capacity**
  - Goal of **60ppb** O_2 concentration
- **Lower Chamber**
  - 4A Molecular sieve material removes water concentration
  - 27.22kg of molecular sieve => **611g of H_2O** capture capacity
  - Goal of **0.01 ppm** H_2O concentration
- **Regeneration:**
  - Molecular Sieve: pass argon heated to 220C through sieve to vaporize water
  - Lower Chamber:
    - $CuO + H_2 \rightarrow Cu + H_2O$





Los Alamos NATIONAL LABORATORY

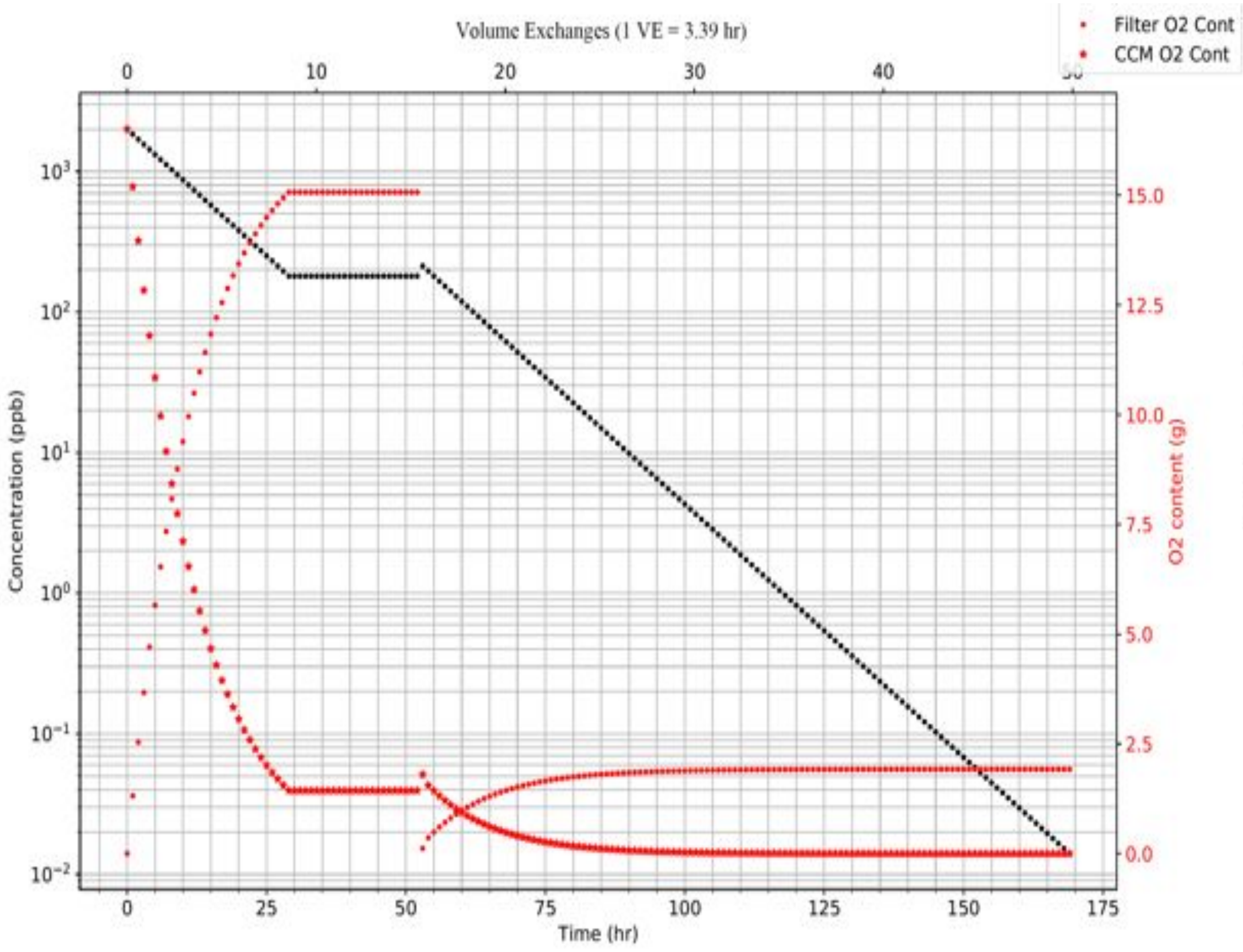
We have tested first part

Will Thompson

14

Filtration System Expected Performance

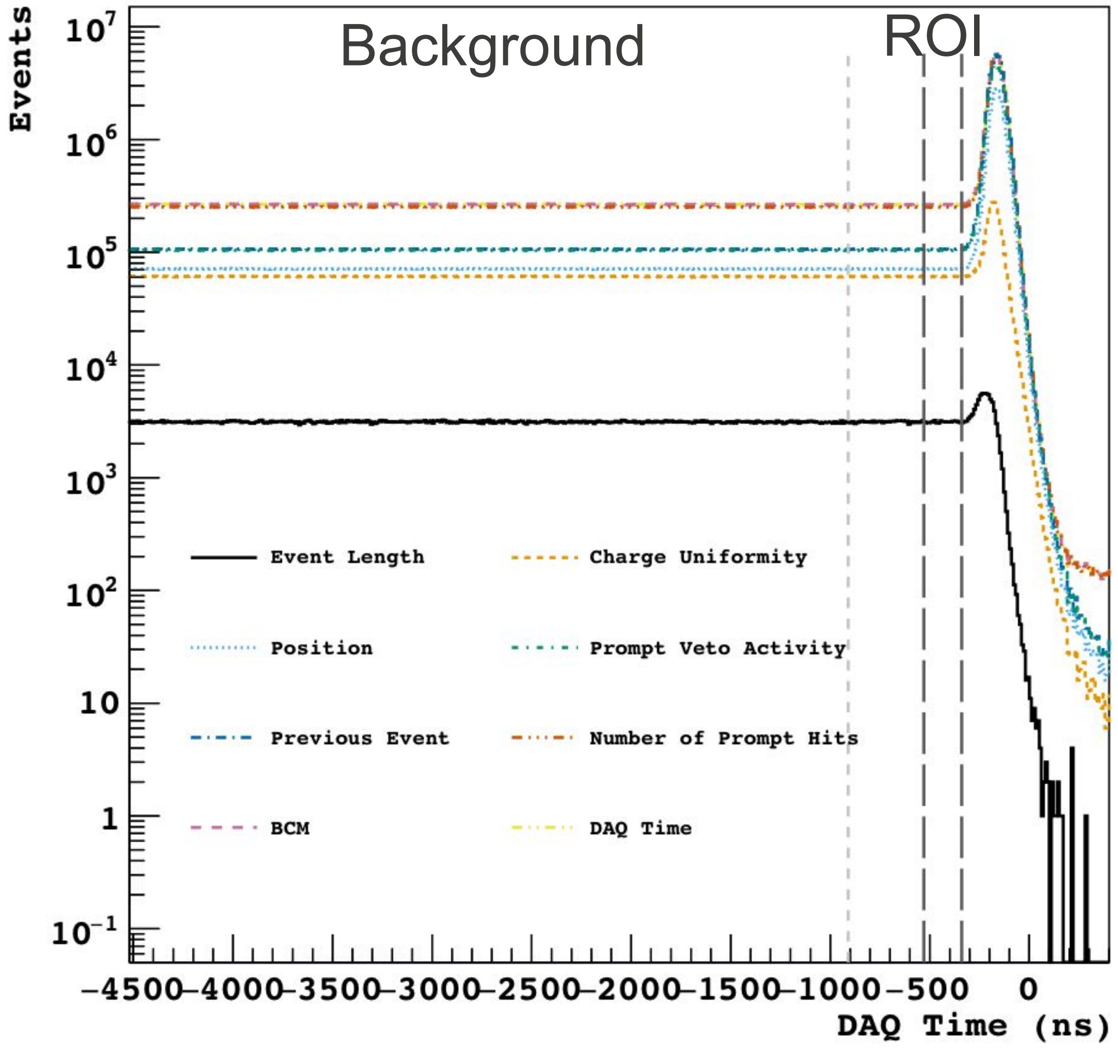
- MicroBooNE-designed filter skid can achieve oxygen levels below 10 ppb
- CCM only needs around 50 ppb for significant improvements
- From 2ppm this should take a little less than 3 days.



Achieve 10 ppb O_2 in about three days. For required efficiency need better than 50 ppb.

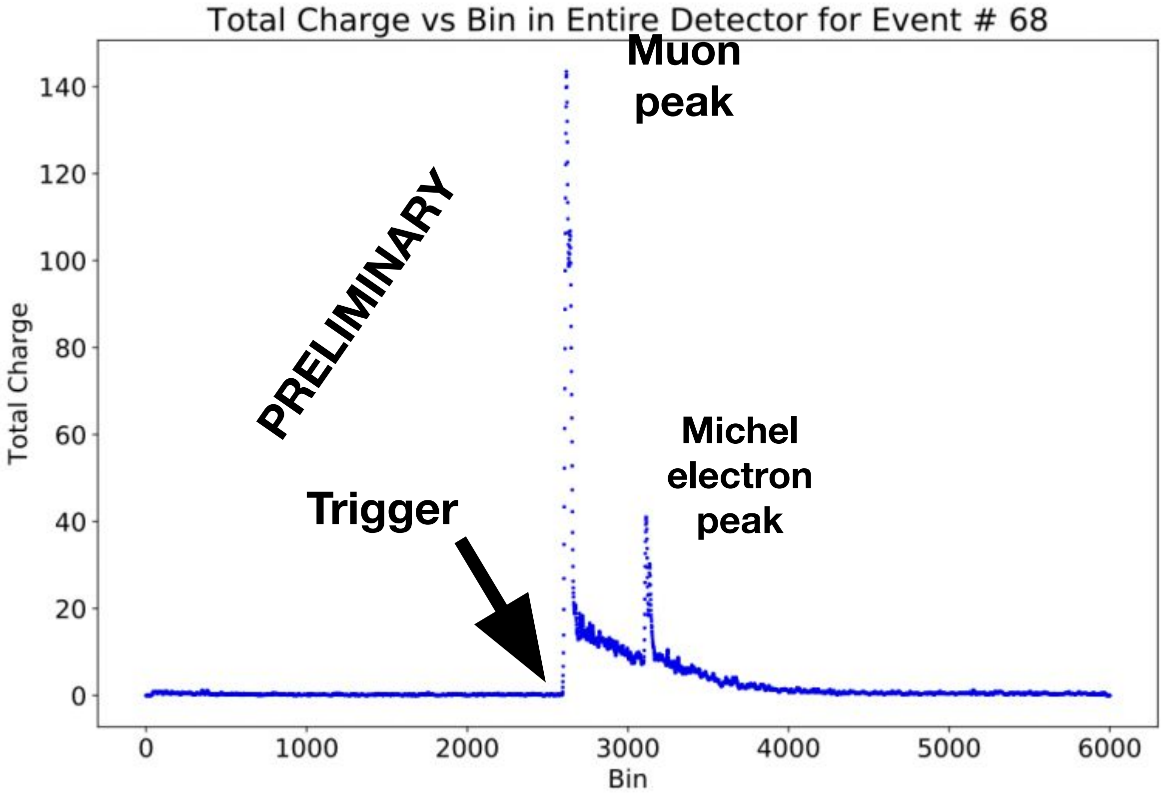
CCM120 Analysis: Measuring Steady State Backgrounds

- 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



Cherenkov Light Detection

- **Analysis underway to identify Cherenkov light on event by event basis**
- Triggering on cosmic muon events using 5cm X 5cm external detectors that consist of two parallel scintillator panels and SiPM
- Using timing, direction, and uncoated PMTs to focus our search for Cherenkov light
- Provides Michel electron sample for energy calibration up to 50 MeV



1 bin = 2 ns

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.

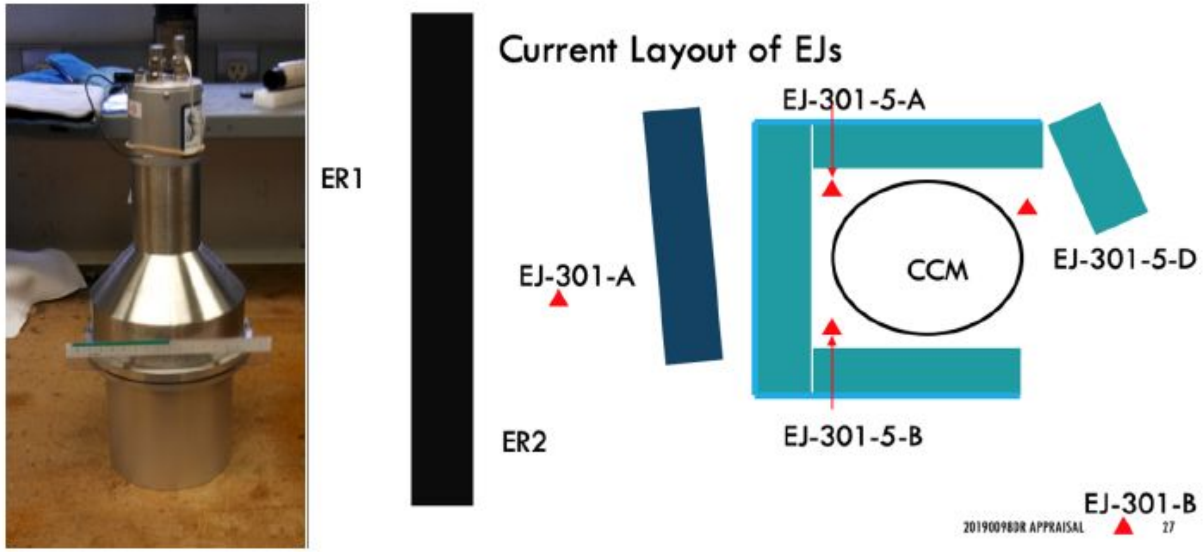


Figure 3.22: An EJ-301 detector (left) and the placement around CCM of 5 such detectors (right).

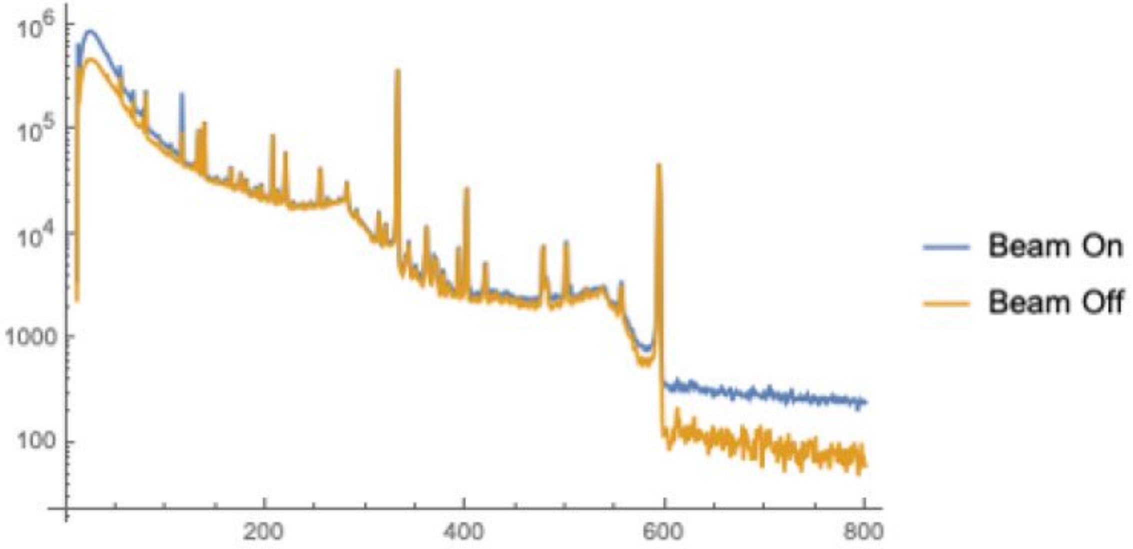
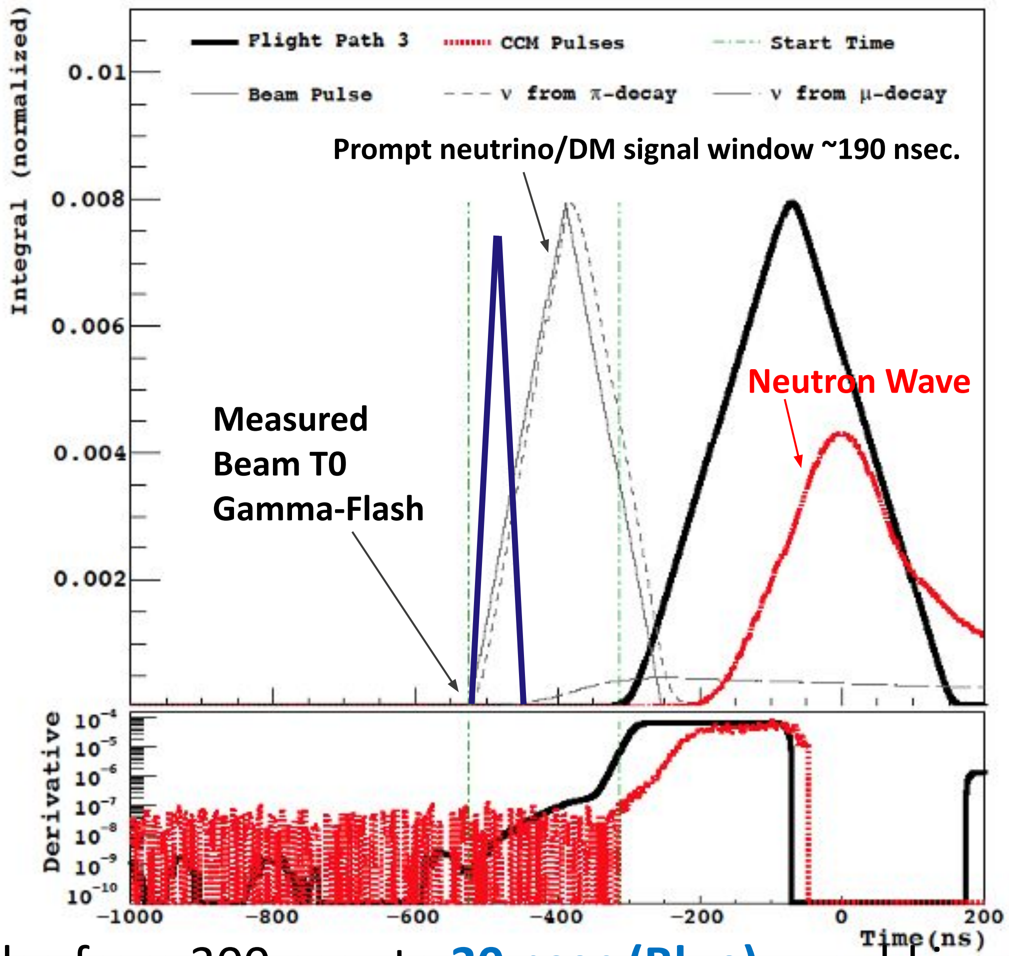


Figure 3.24: The gamma spectrum as determined by the germanium detector comparing beam on versus beam off

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.

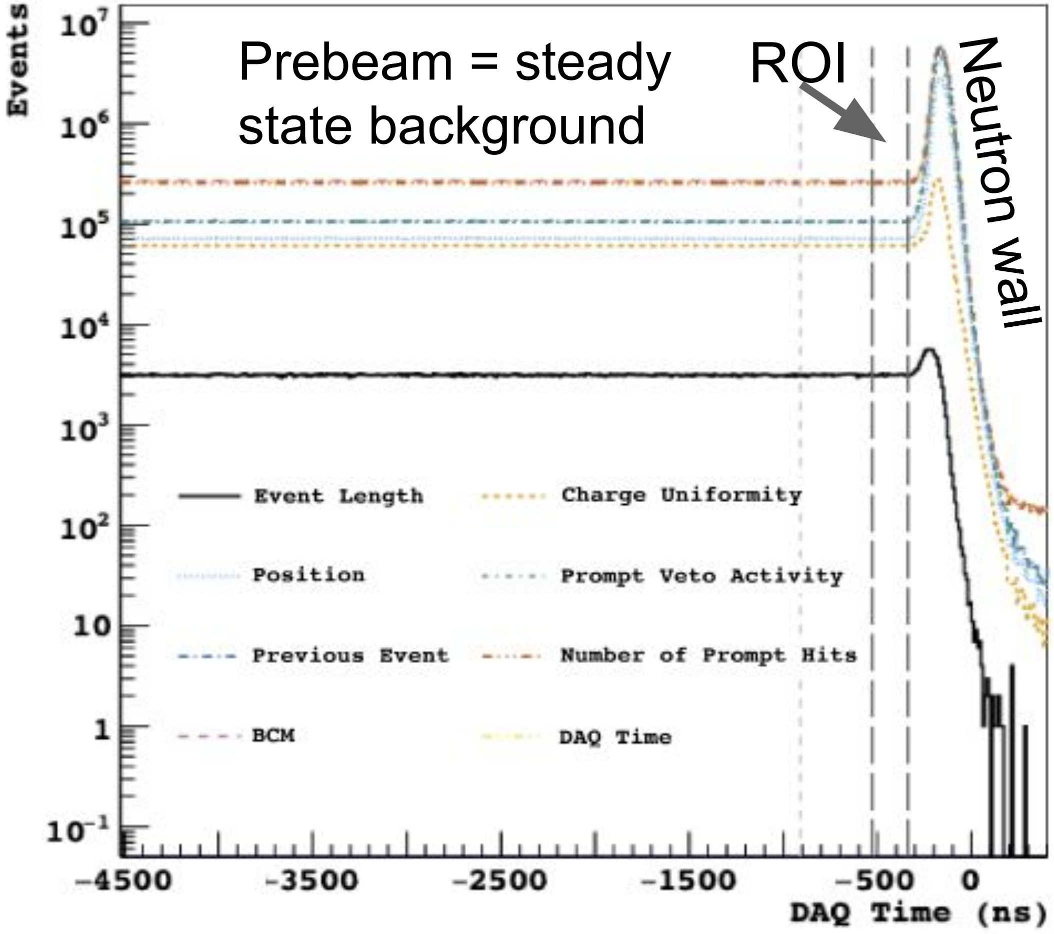


Shorter beam pulse reduces random backgrounds from Ar39 decay and neutron activation

- 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.

Data Quality / Pre-selection Cuts

- Data Quality cuts meant to ensure the events were useable.
  - **Number of Hits** – checked that there were at least 3 PMT hits in an event.
  - **Previous Event** – checked if there was an event before the event that could be the singlet to the triplet.
  - **Veto** – made sure the event began inside the fiducial volume.
  - **Fiducial Volume** – make sure the event was contained within the fiducial volume.
  - **Event Time** – checked event was in the ROI.
  - **Beam Current Monitor (BCM)** – checked that the BCM recorded a good beam pulse



(a) DAQ Time

Data Quality Efficiency Table

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

ALP Search – Signal Cuts

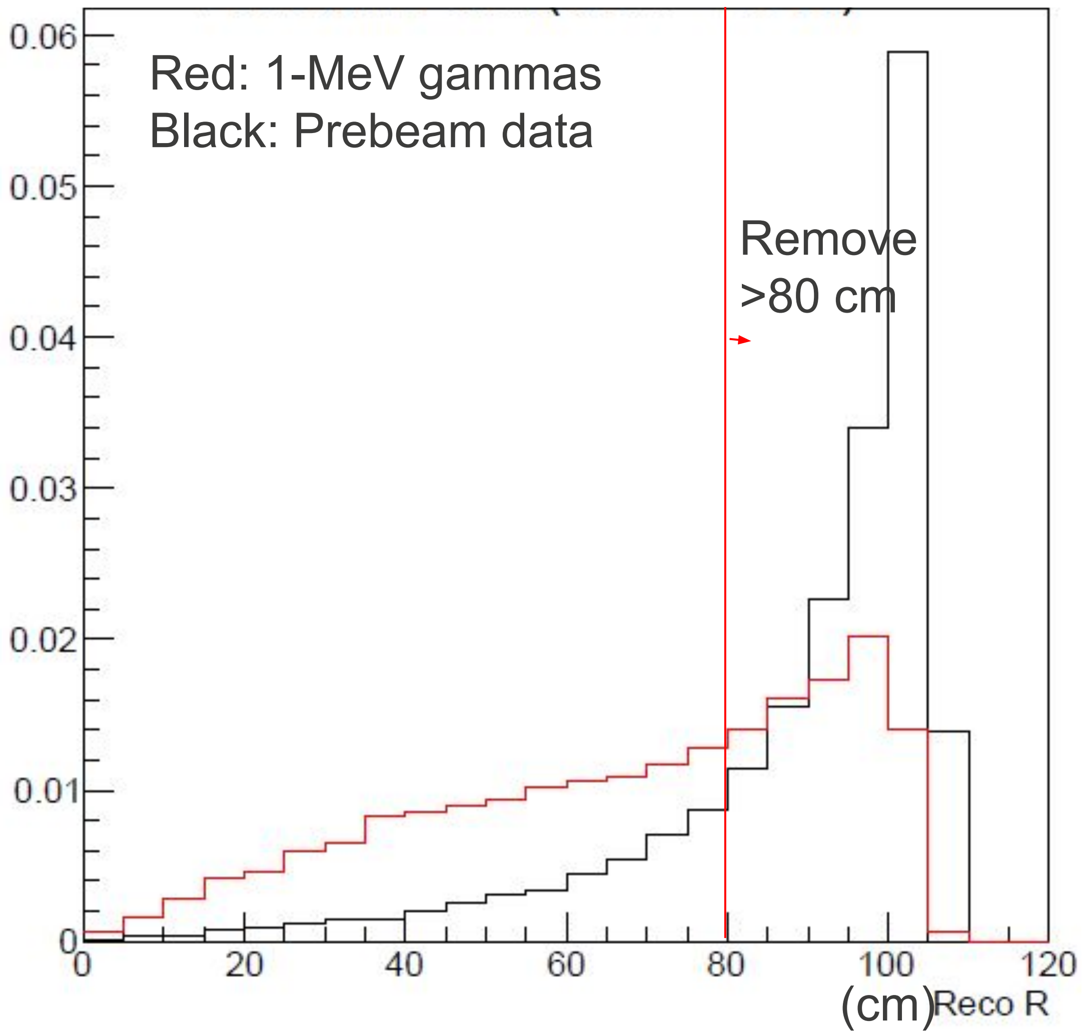


Figure 5.8: The ALP simulation vs. prebeam radius showing the preference for a tighter radius cut.

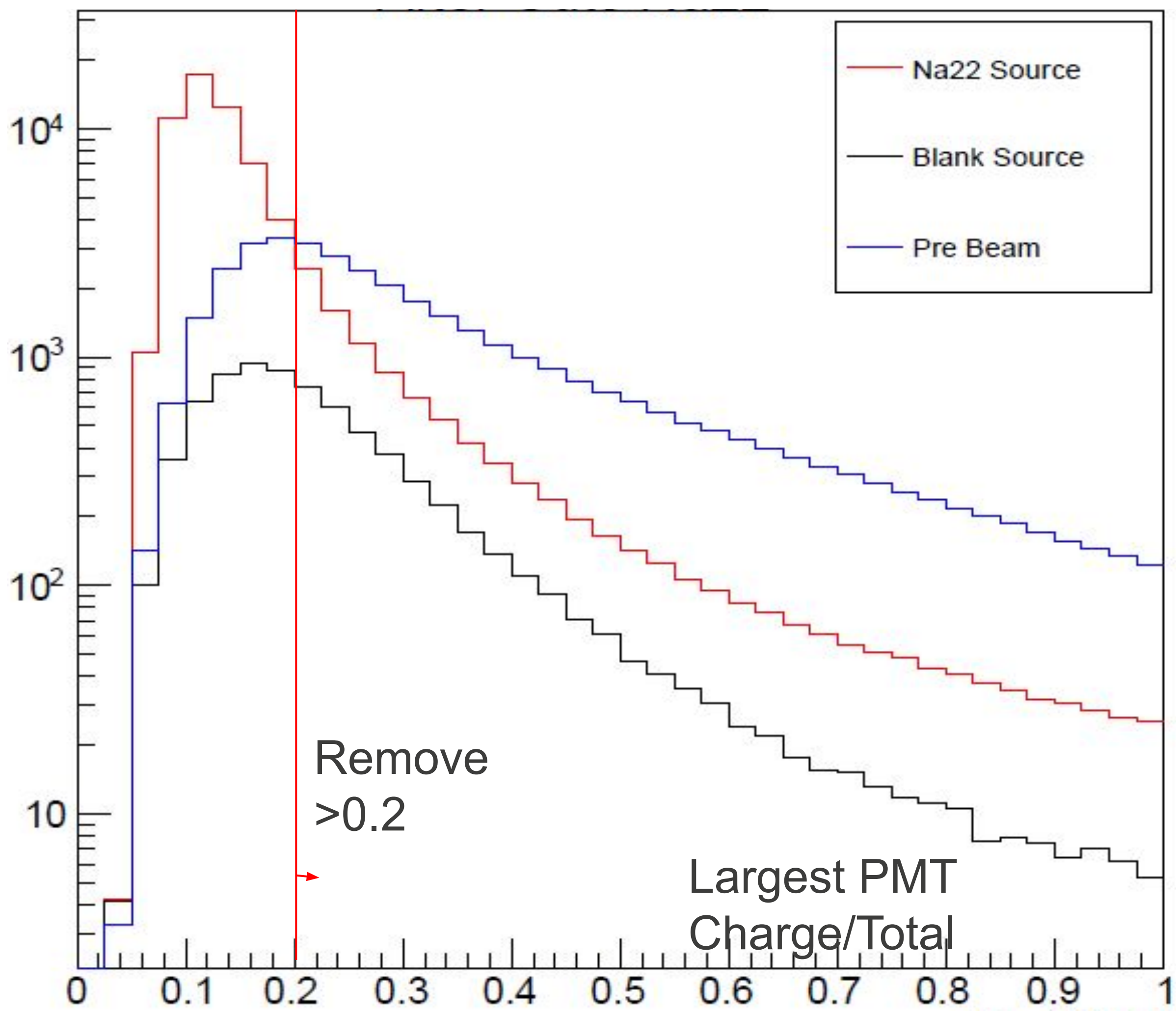
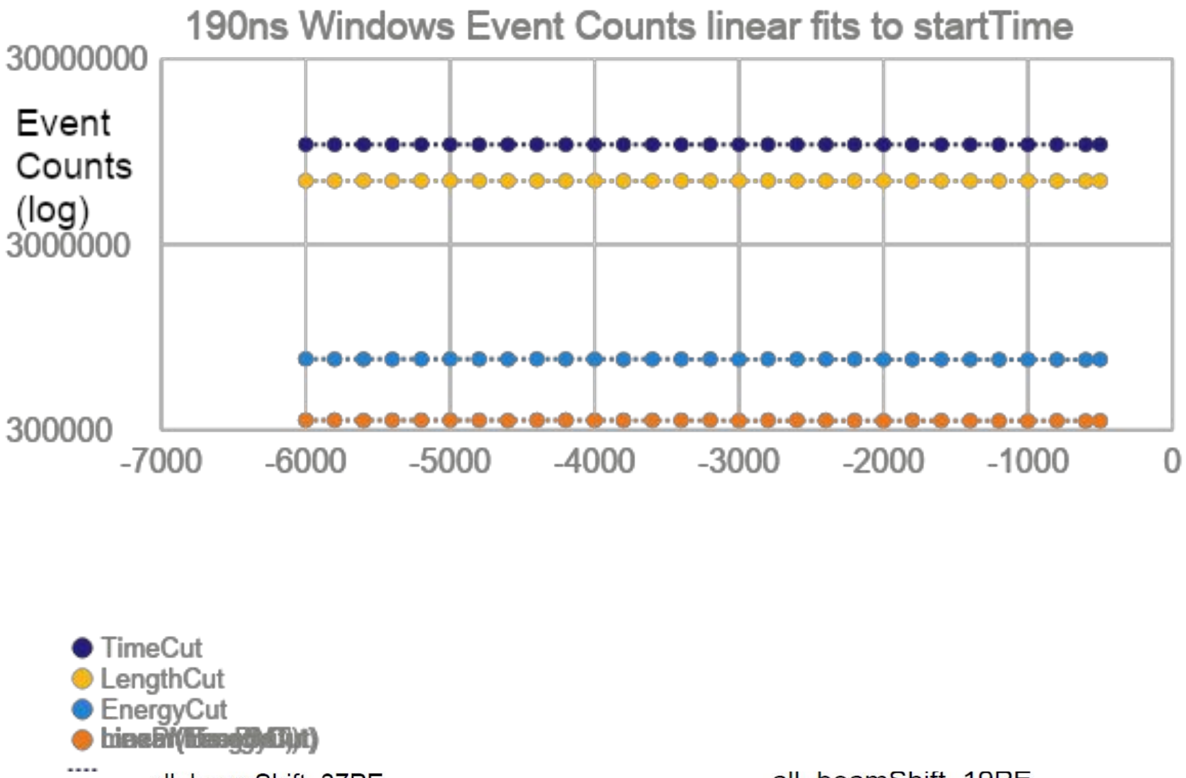
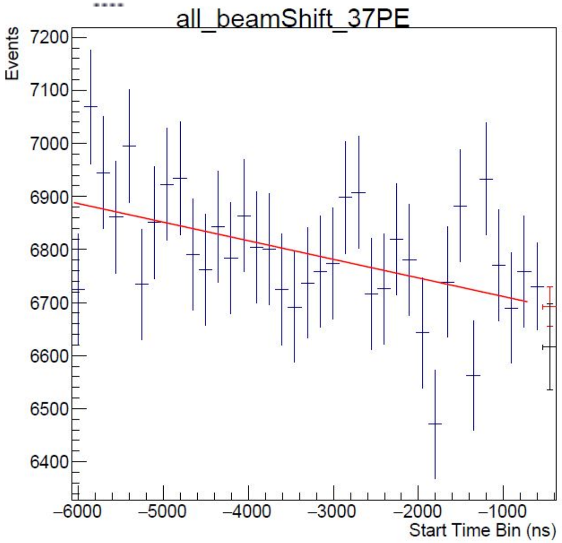


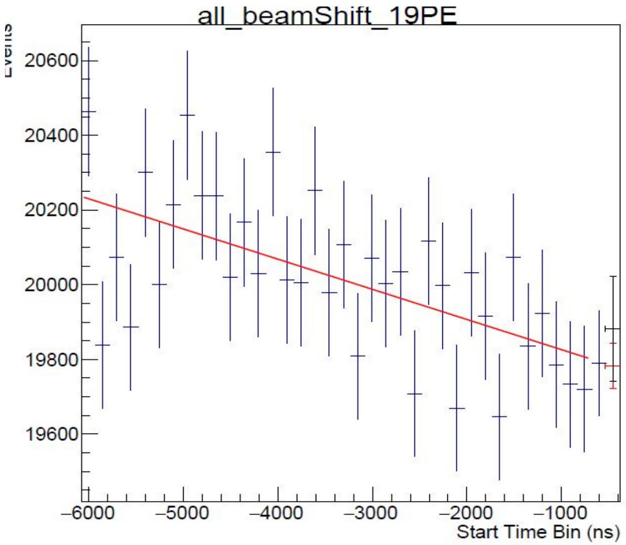
Figure 5.9: The shape difference between gamma-like ^{22}Na events and the overall prebeam in the maxPMT proportion variable.

Background Prediction

- When calculating the prebeam background for the ALP search, a significant and obvious decay in background rate was observed even on the scale of microseconds.
- This decay occurs across all cuts and all energies, and is a significant source of systematic error if left alone.
  - Additionally, this decay rate is different for different energies.
- This decay in Background Rate resembles that expected from radioactive decay of beam-related activation from the previous beam cycle.







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.

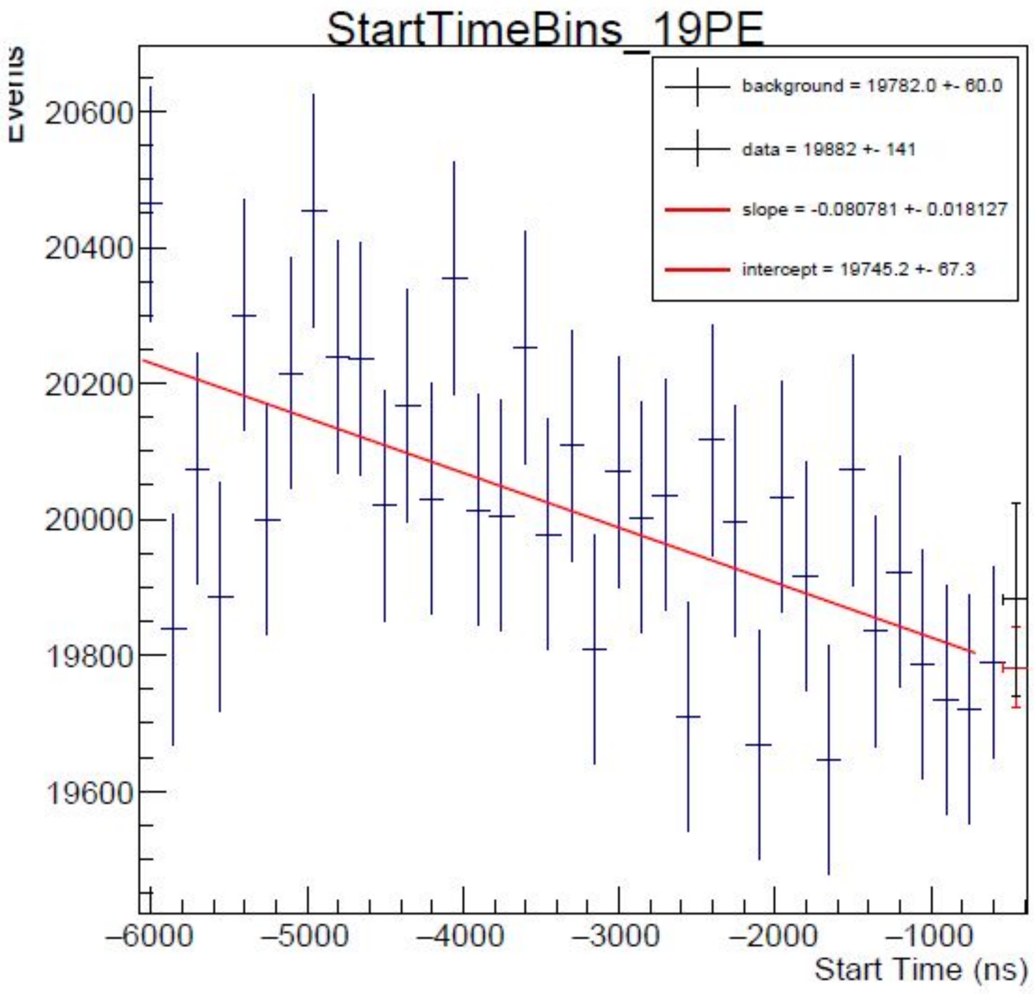
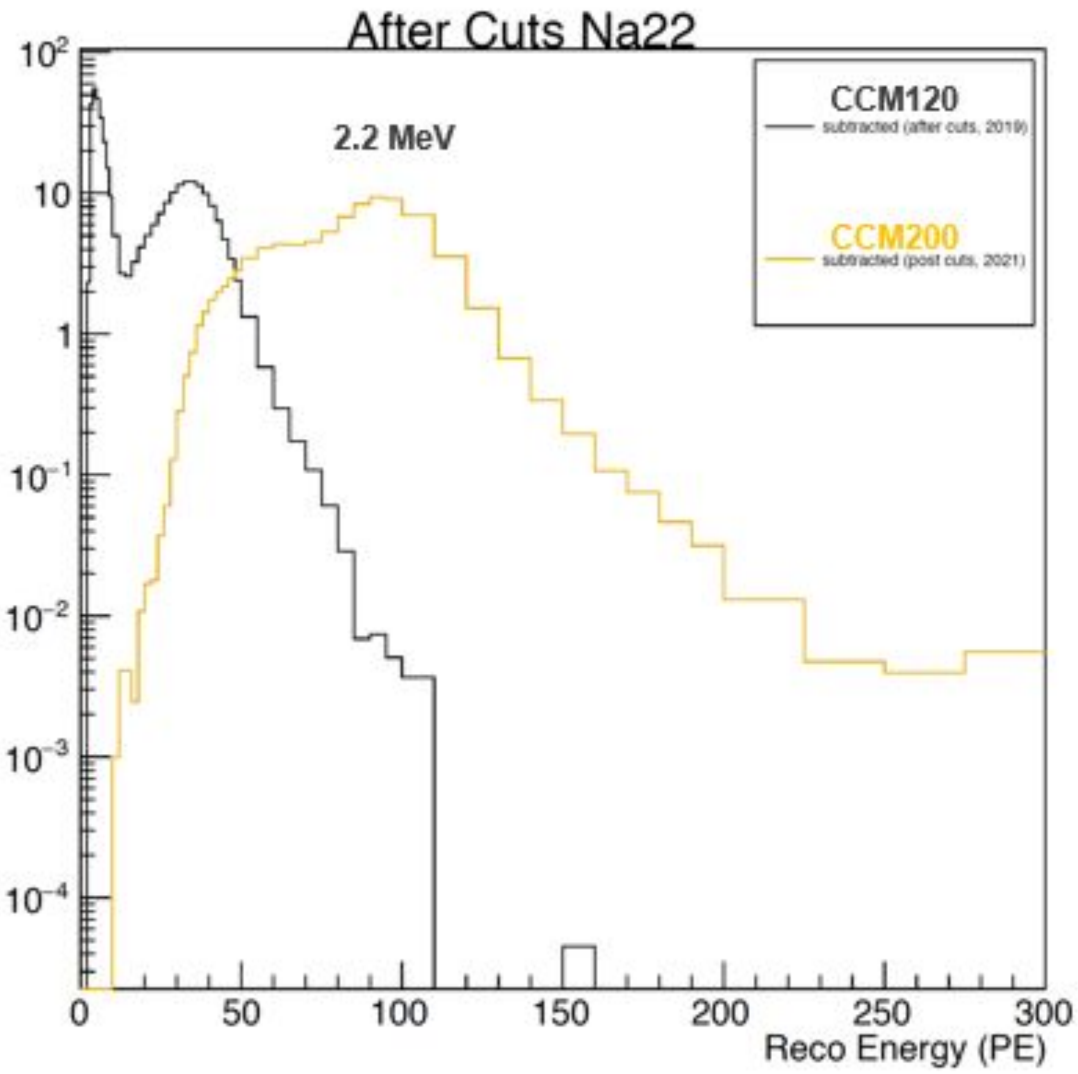


Figure 6.1: The 19PE bin's start time distribution. In blue are the prebeam ROI-length (150ns) time windows, black is the actual data value, and red is the background prediction from the linear fit (also in red).

CCM120/CCM200 Results from Energy Calibration

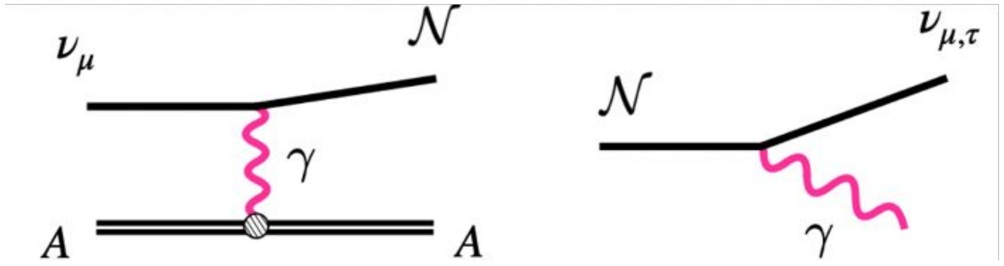
- Impurities from not recirculating or filtering the argon led to low light levels O(ppm) O_2 reduced the 128 nm light attenuation length from O(10 m) to ~50 cm
- CCM120: Na22 33.2 ± 8.9 PE for 2.2 MeV
- CCM200: 106 PE for 2.2 MeV
- CCM200 over three times more light detection efficiency.
- **Filtration of LAr will increase this by another factor of ~5 necessary for 10 keV thresholds.**



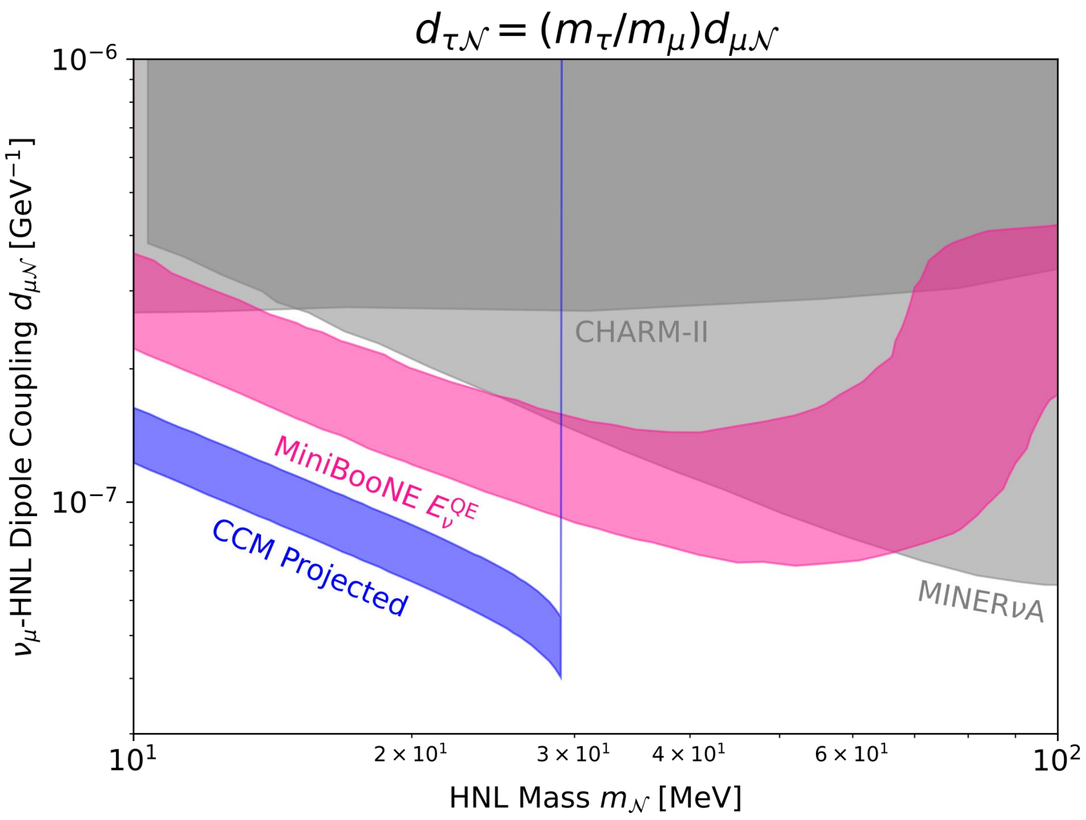
Ed Dunton (Columbia)

Heavy Neutral Lepton Search

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

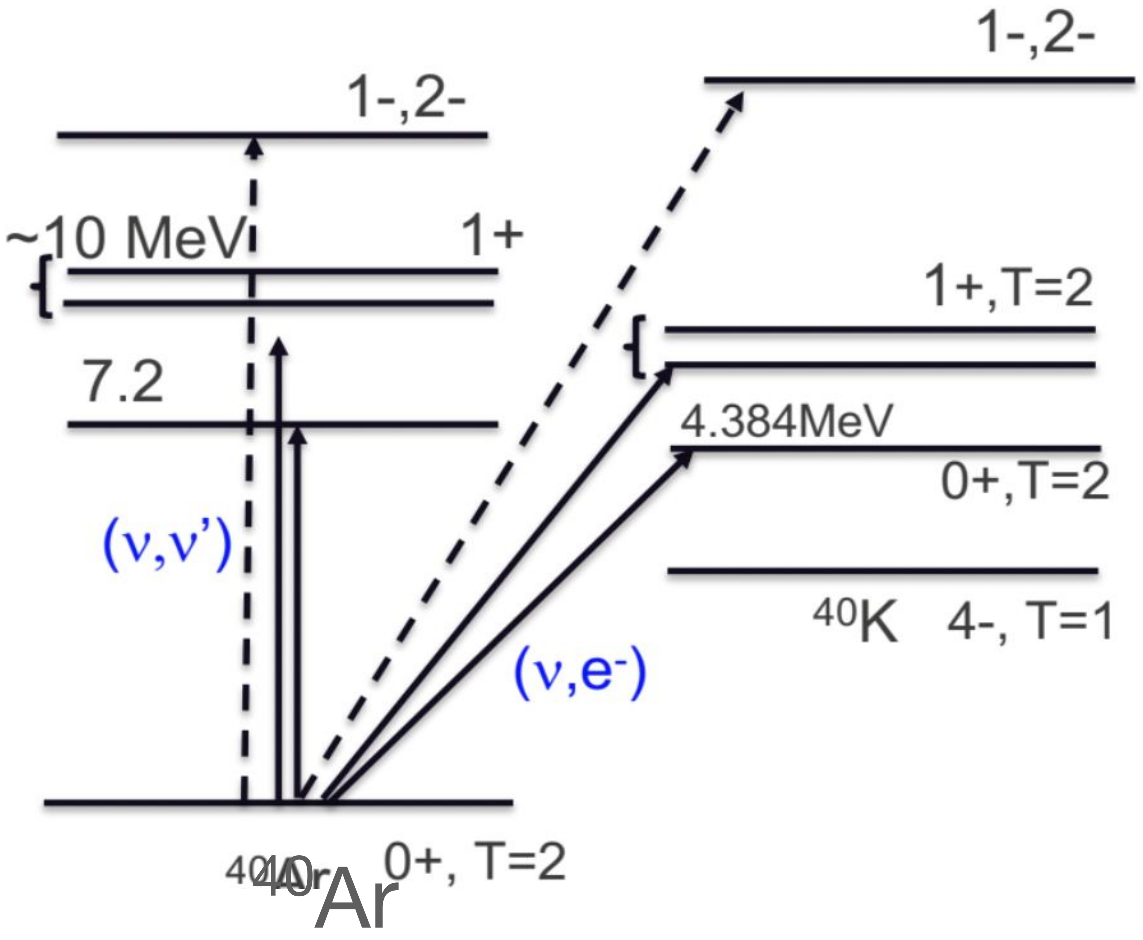


- Lujan facility is spacious enough to allow for increased shielding in future runs



Cross Sections

- CCM200 has sensitivity to charge current (CC) neutrino interaction on Argon nucleus cross section
- CC measurements are useful to constrain future supernovae neutrino measurements in DUNE and other LAr detectors
- Exploring CEvNS measurements using nuclear recoil signatures



Underground Argon

- There is a global need for low activity Argon (Ar-39 removed) such as Darkside, DEAP, CEvNS, LEGEND, FNAL, etc. (see https://arxiv.org/pdf/1901.10108.pdf)
- For CCM200 to reach relic density limits will require further suppression of random backgrounds by two orders magnitude, from ~10000+/-100 to levels of 100 +/- 10 events over three years.
- Darkside-50 (kg) acquired Argon from underground (UGA) source in southern CO with Ar-39 reduced by a factor of 1000.
- We are investigating ways to acquire larger volumes of UGA for CCM200. Need to demonstrate re-circulation and heat exchanger system reduces LAr losses to minimal levels.

Denver Post

NEWS

Colorado argon will be at the heart of dark matter experi

1 of 2

Kinder Morgan plant operator Joe Buffington, left, and operations supervisor Stan Mannis look over Fermilab's argon-extraction unit that they call "a little plant within our plant" north of Cortez.

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