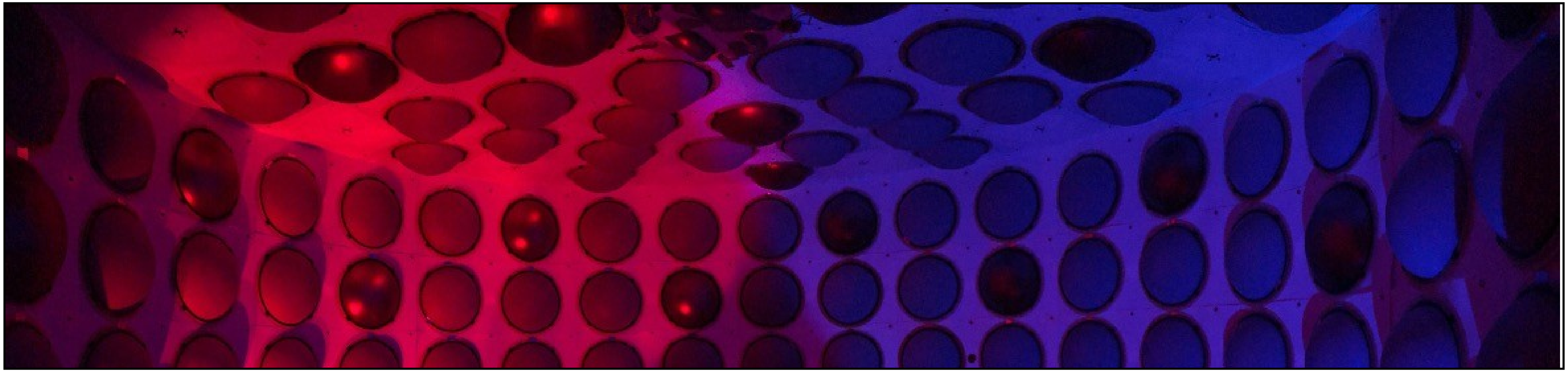
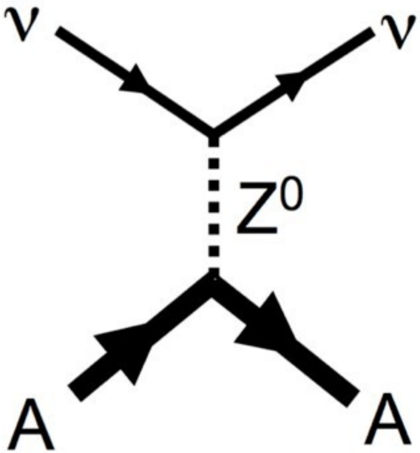


Dark Matter Searches and Neutrino Physics with the Coherent CAPTAIN-Mills experiment

Alexis A. Aguilar-Arévalo (ICN-UNAM)
for the CCM Collaboration

Colombian Meeting on High Energy Physics, Villa de Leyva, Colombia, 29 Nov, 2022

Coherent CAPTAIN-Mills (CCM)



CAPTAIN: “Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos”

EMBRY-RIDDLE Aeronautical University

Massachusetts Institute of Technology

Columbia University IN THE CITY OF NEW YORK

THE UNIVERSITY OF EDINBURGH

Fermilab

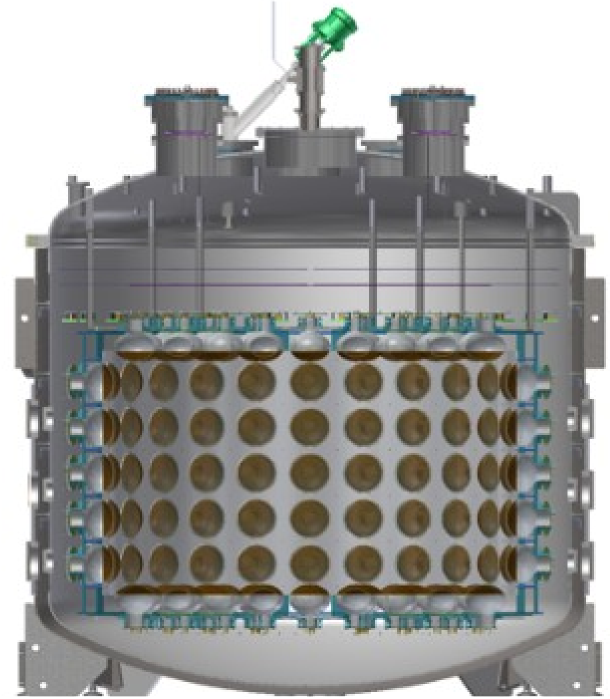
UNIVERSITY of FLORIDA

Los Alamos NATIONAL LABORATORY EST. 1943

UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO

Outline

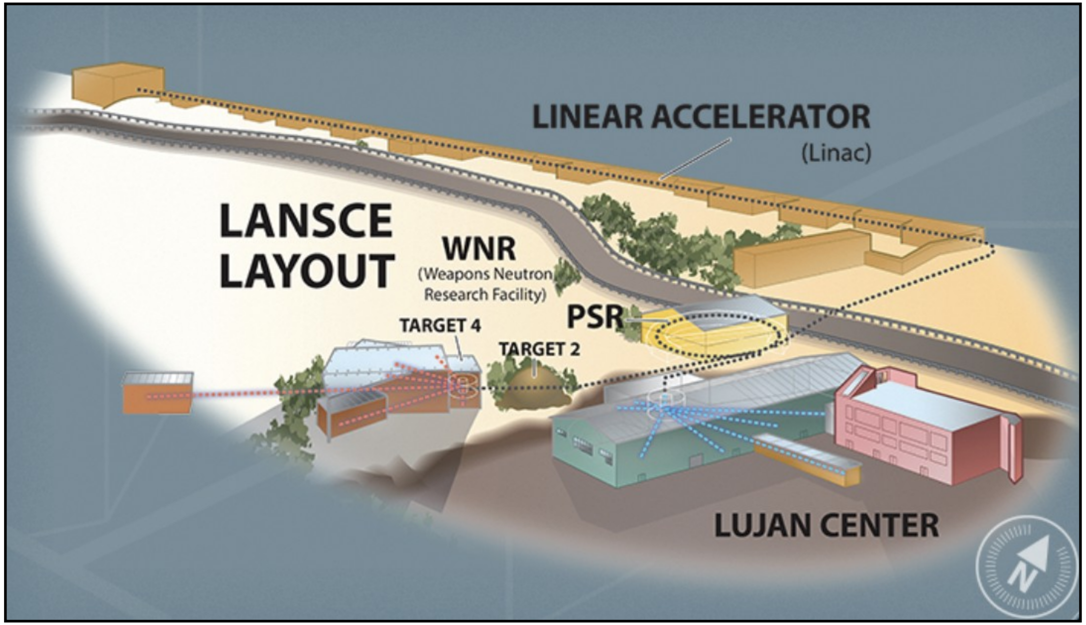
- The Lujan source and the CCM detector
- CCM Physics program
- CCM120 results
- CCM200
- Future upgrades
- Summary

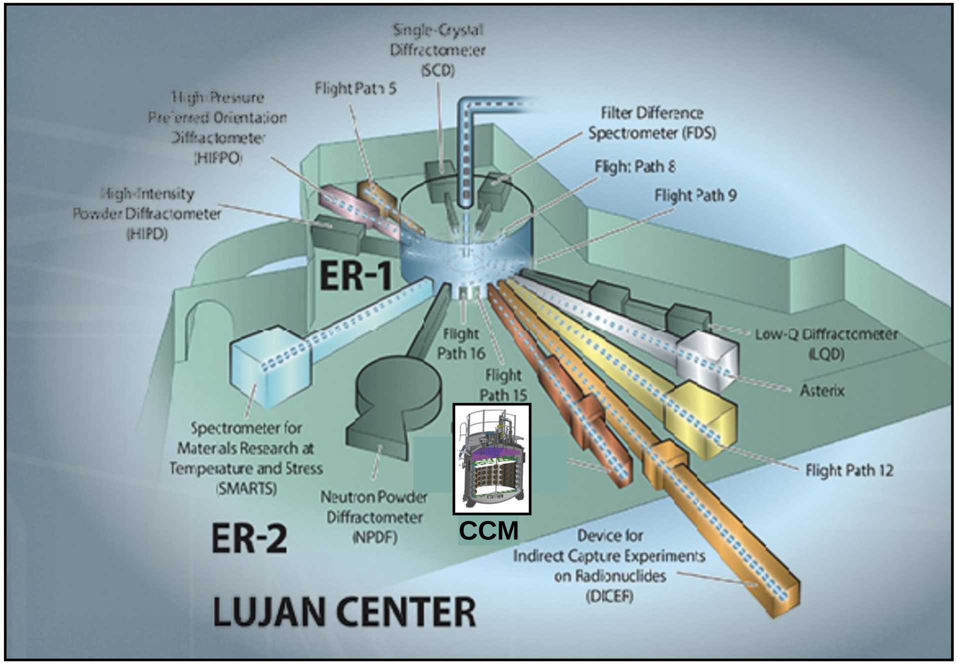


Lujan Center @ LANSCE

Los Alamos Neutron Science Center

Protons hit tungsten target in Lujan Center, pion decay at rest creates prompt flux of 30 MeV ν_μ and delayed flux of $\bar{\nu}_\mu$ and ν_e.

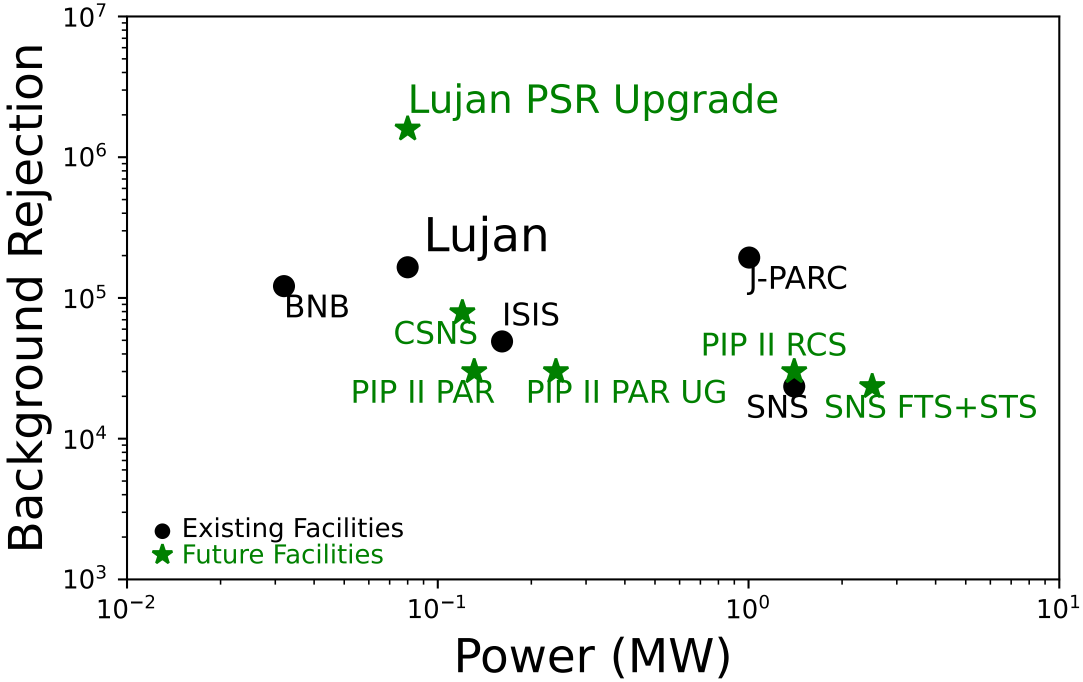




800 MeV proton beam bunched in the proton storage ring (PSR) with 100 μAmp current, 290 ns beam spill, and pulsed at 20 Hz

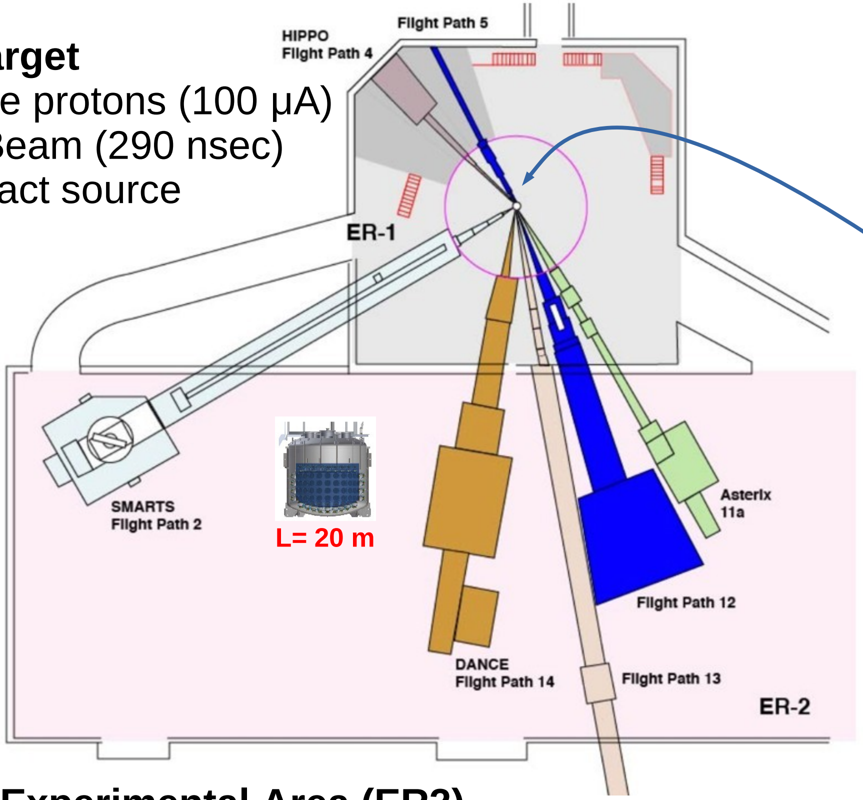
Lujan Facility capabilities

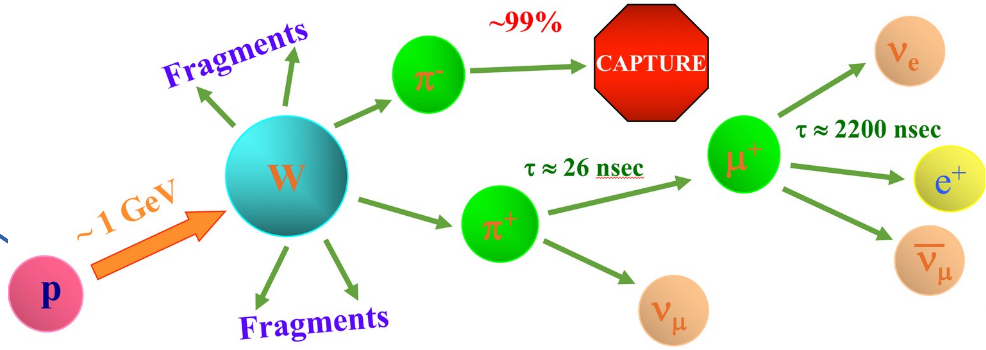
- Lower power compensated with a larger detector (CCM)
- Lujan Facility upgrades focusing on **background rejection**.
- 10 year upgrade to increase background rejection by an order of magnitude by shortening beam spill window from 290 ns to 30 ns



Particle production at Lujan

Lujan Target
- Intense protons (100 μA)
- Fast Beam (290 nsec)
- Compact source

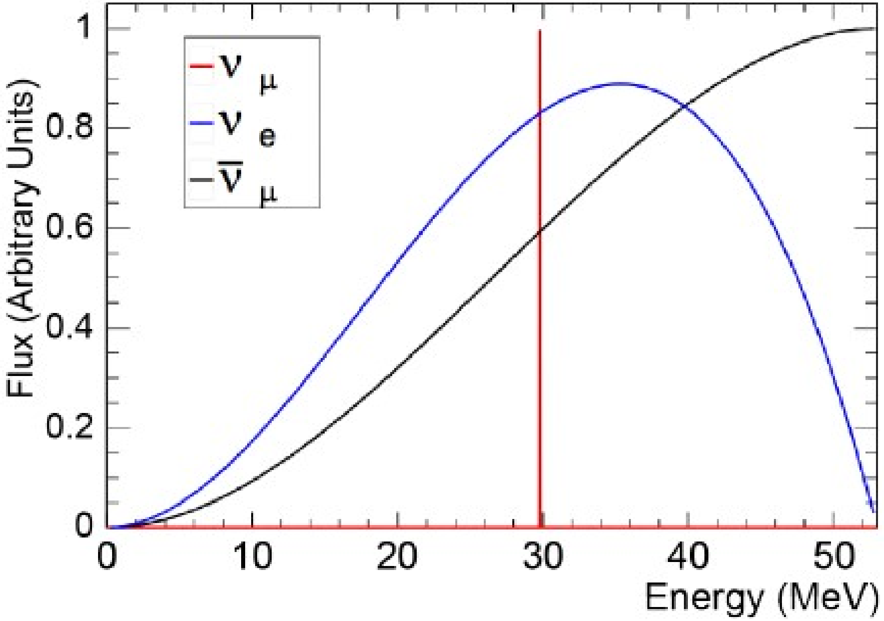


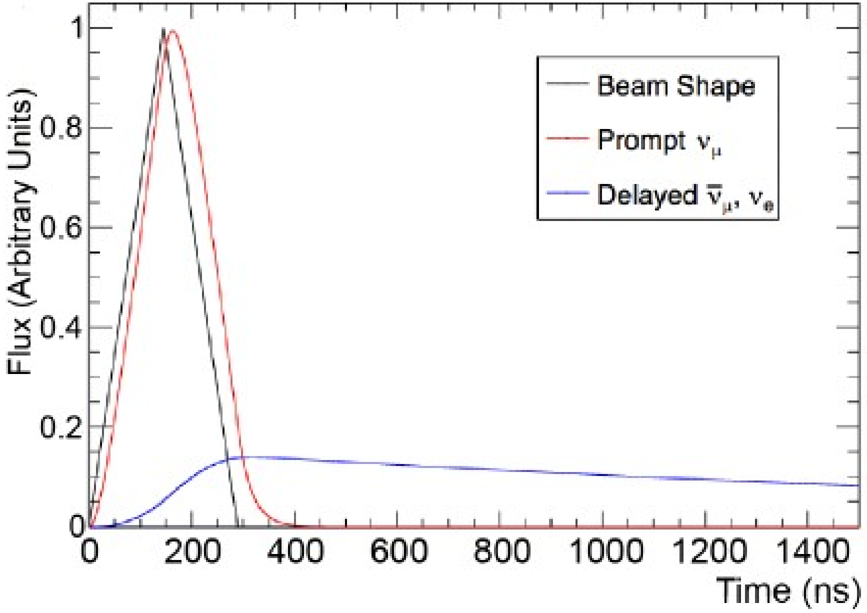


CCM120 beam and calibration run 2019

Lujan Experimental Area (ER2)
Space for large 10-ton liquid Argon ν detector.
Run detector in multiple locations.
Room to deploy shielding, large overhead crane, power, etc

ν_μ, $\bar{\nu}_\mu$ and ν_e Energy and Timing

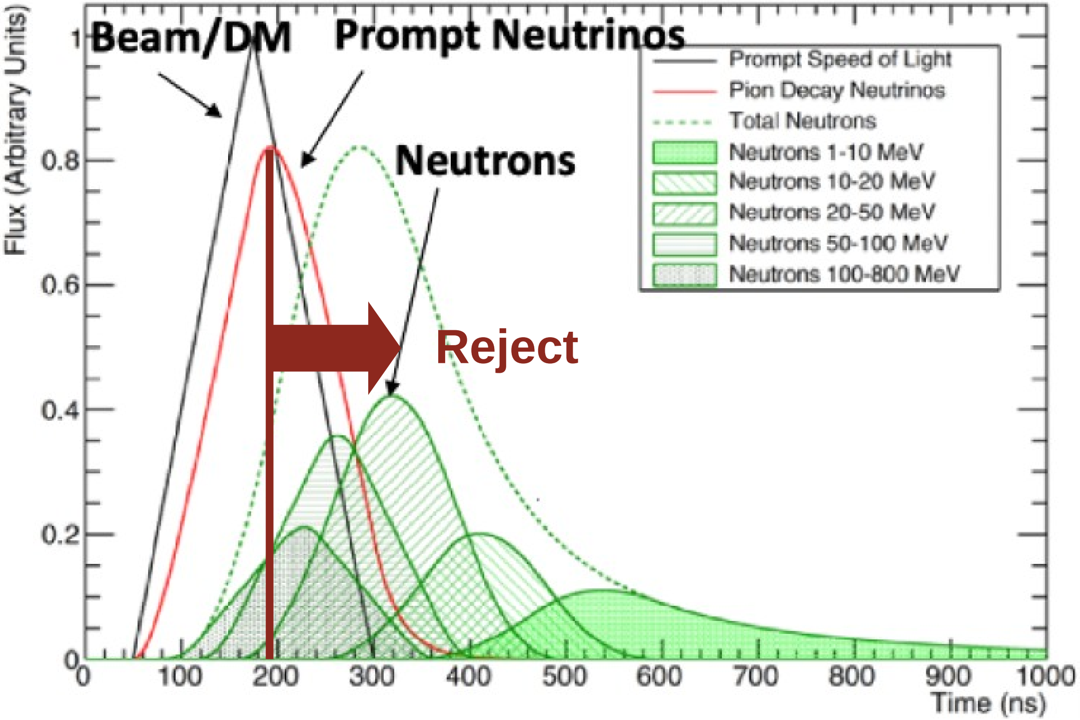




- Prompt 30 MeV mono energetic ν_μ component from π decay
- Delayed $\bar{\nu}_\mu$ and $\bar{\nu}_e$ from μ decay.

Neutron backgrounds & Timing cuts

- 190 nsec timing cut to remove neutron wall
- Primary neutron background with $E_n \approx$ 20-50 MeV reduced by timing cut (see arXiv:2105.14020 for discussion of timing cuts)
- Fast neutrons absorbed by shielding



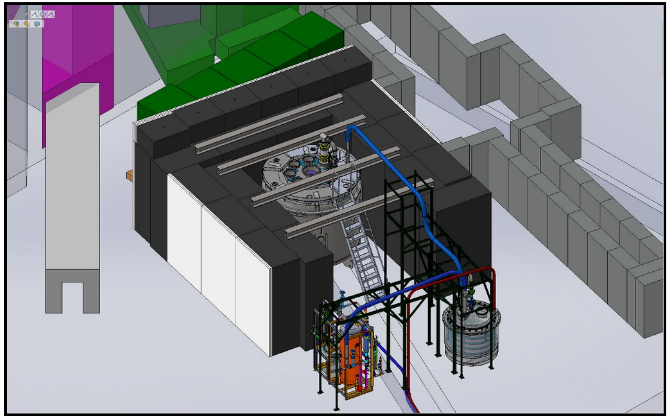
CCM at Lujan

- Detector at 90º off axis from the proton beam, and at 23 m from the tungsten target
- ~2.5 m diameter and ~2 m tall cylindrical cryostat instrumented with 200 8” PMTs.

  5 ton fiducial LAr volume

  5 ton optically isolated active veto region surrounding fiducial volume with 40 1” veto PMTs

- Lujan facility produces a ν flux of 5.28×10^{5} $cm^{-2}s^{-1}$
- A prototype with 120 PMTs (CCM120) operated in 2018-2019 collecting 17.9×10^{20} POT.
- CCM200 will receive 2.25×10^{22} POT in the upcoming 3 years.



Physics program overview

1) Search for light dark matter through coherent scattering off Argon

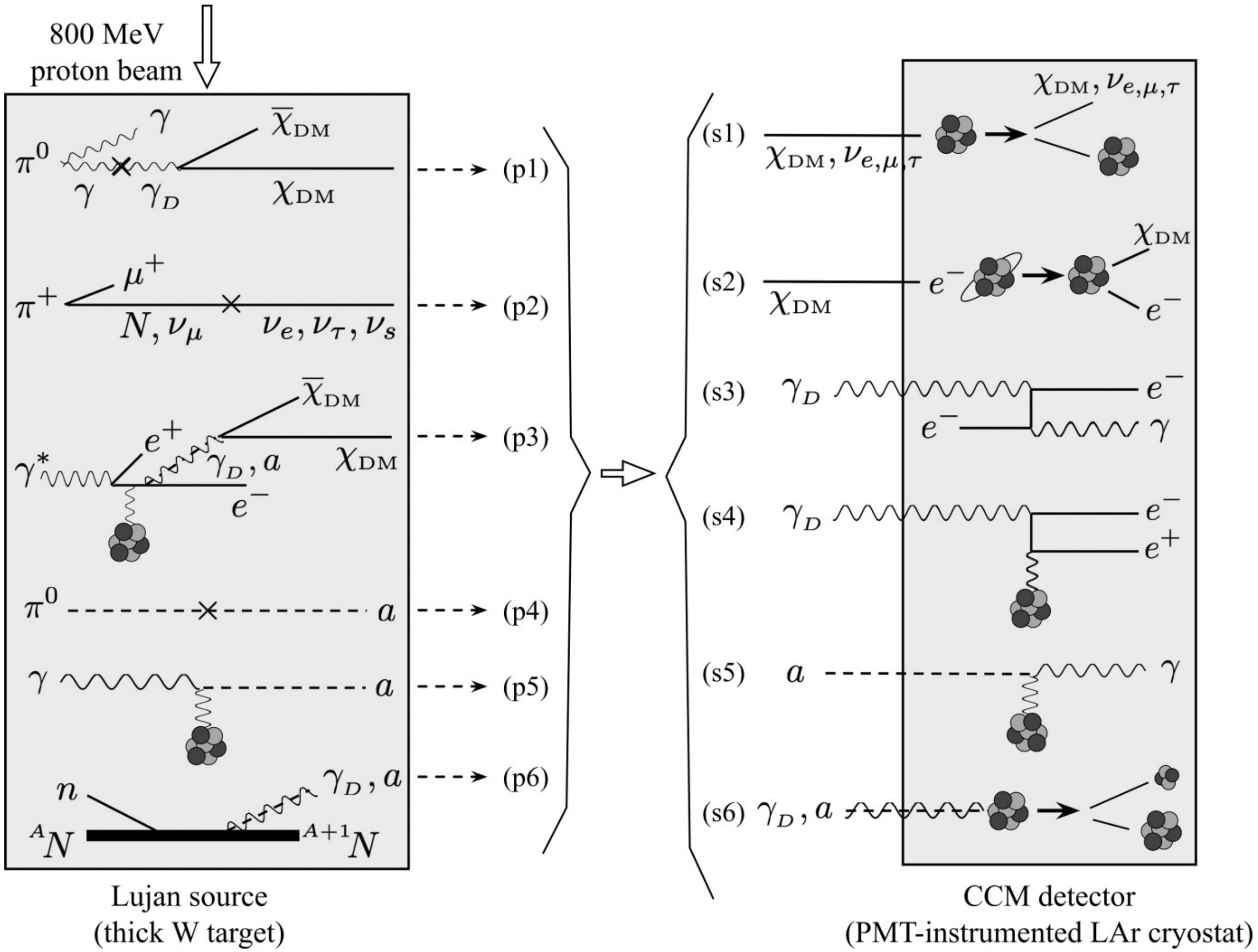
   Includes dark photon, leptophobic mediators, etc.

2) Search for longer lived dark particles

   Axion like particles and heavy neutral leptons, dark sector coupling to meson decay as explanation for MiniBooNE excess.

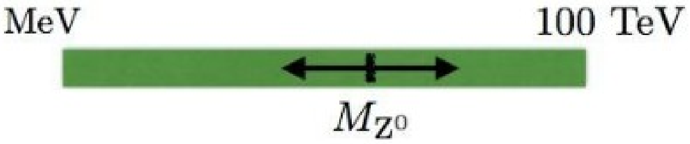
3) Precise measurements of neutrino-Argon cross sections *O*(10 MeV)

   CEvNS detection and CC cross sections relevant for DUNE supernovae measurements .



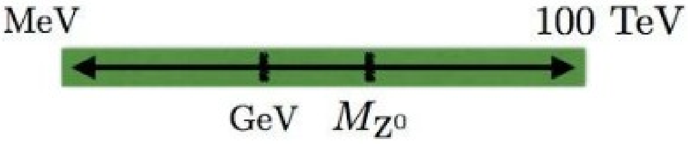
New Light Mediator (Vector Portal)

Standard WIMP



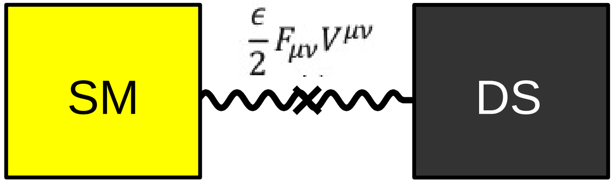
- Assumes mediator is the Z boson
- Strong constraints from cosmology, astrophysics, and particle physics

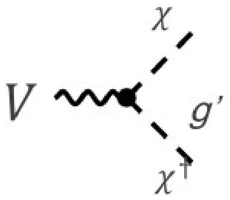
New Light Mediator



- Doesn’t assume mediator is the Z boson
- Simplest model: mediator is a vector (dark photon), has 4 free parameters:
  - Mass of the dark photon m_V
  - Mass of the dark matter m_χ
  - Mixing parameter between SM and dark sector ε
  - Coupling between dark photon and dark matter α’

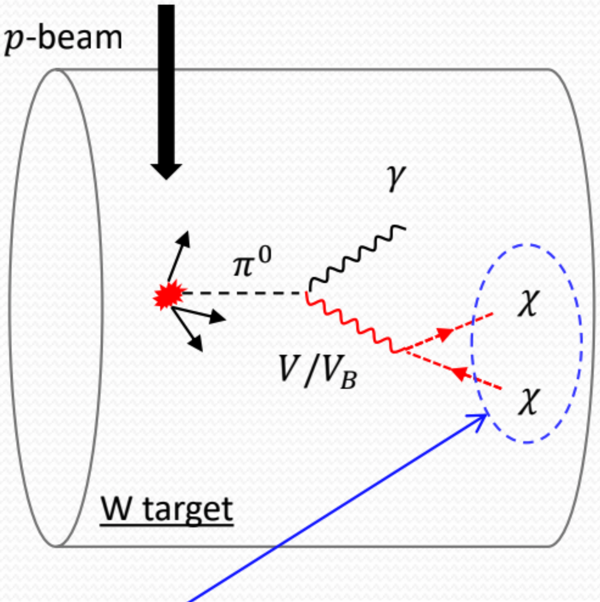
Pospelov, Ritz, Phys.Lett.B 671 (2009)





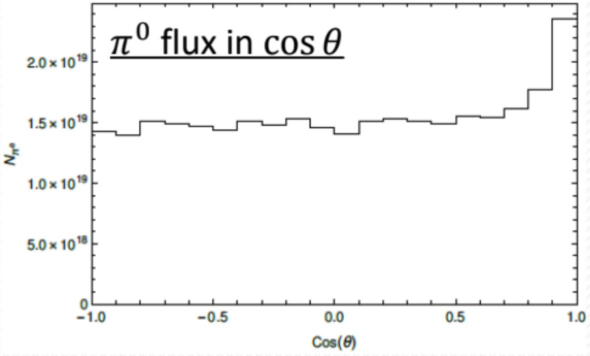
$$\alpha' = \frac{g'^2}{4\pi}$$

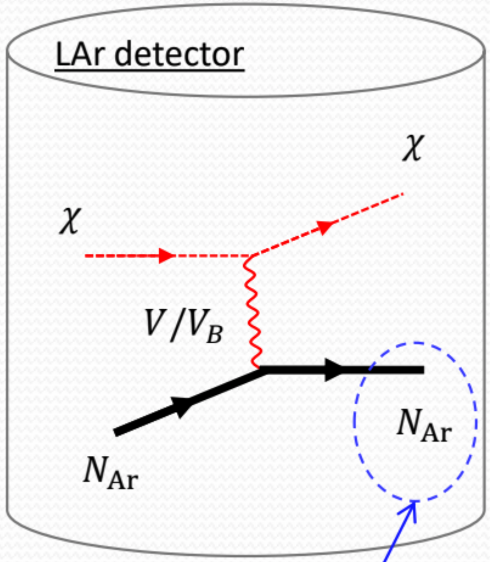
DM production and detection in CCM



π^0-induced DM flux widespread in angle

$$\boldsymbol{N_{\pi^0} = 0.115/\text{POT}}$$





Coherent scatter final state 1 - 100's keV

Observing a coherent scattering off an Ar nucleus

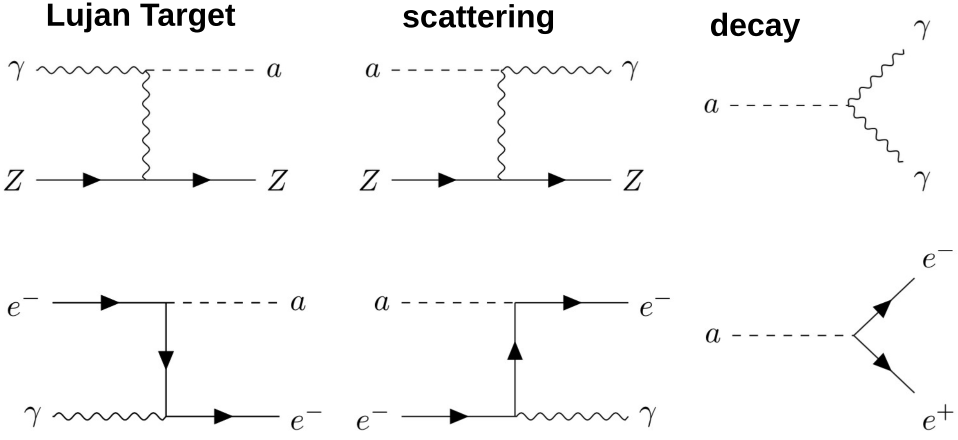
Axion Like Particles from γ and e-

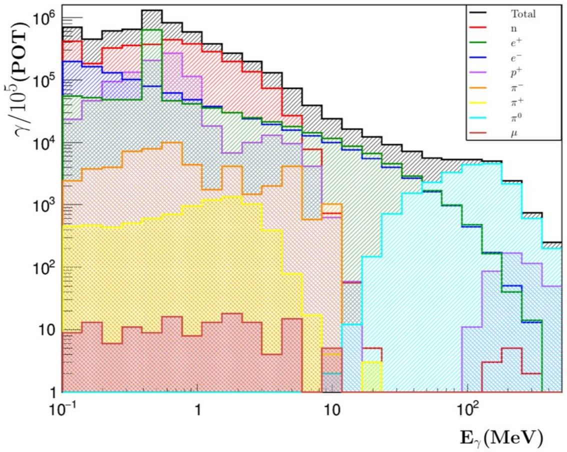
- Prolific Photon/electron production in Lujan target
- ALP Primakov production and inverse-Primakov scattering

Production in Lujan Target

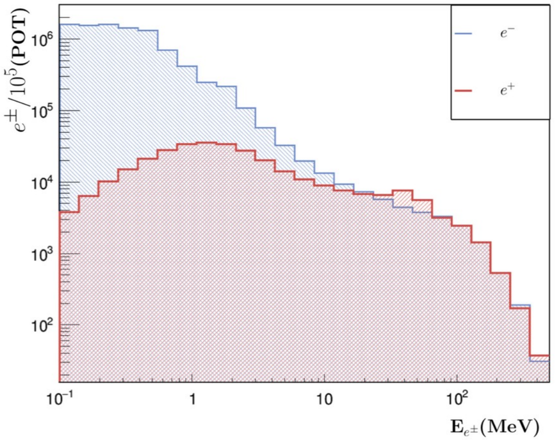
Detection via scattering

Detection via decay



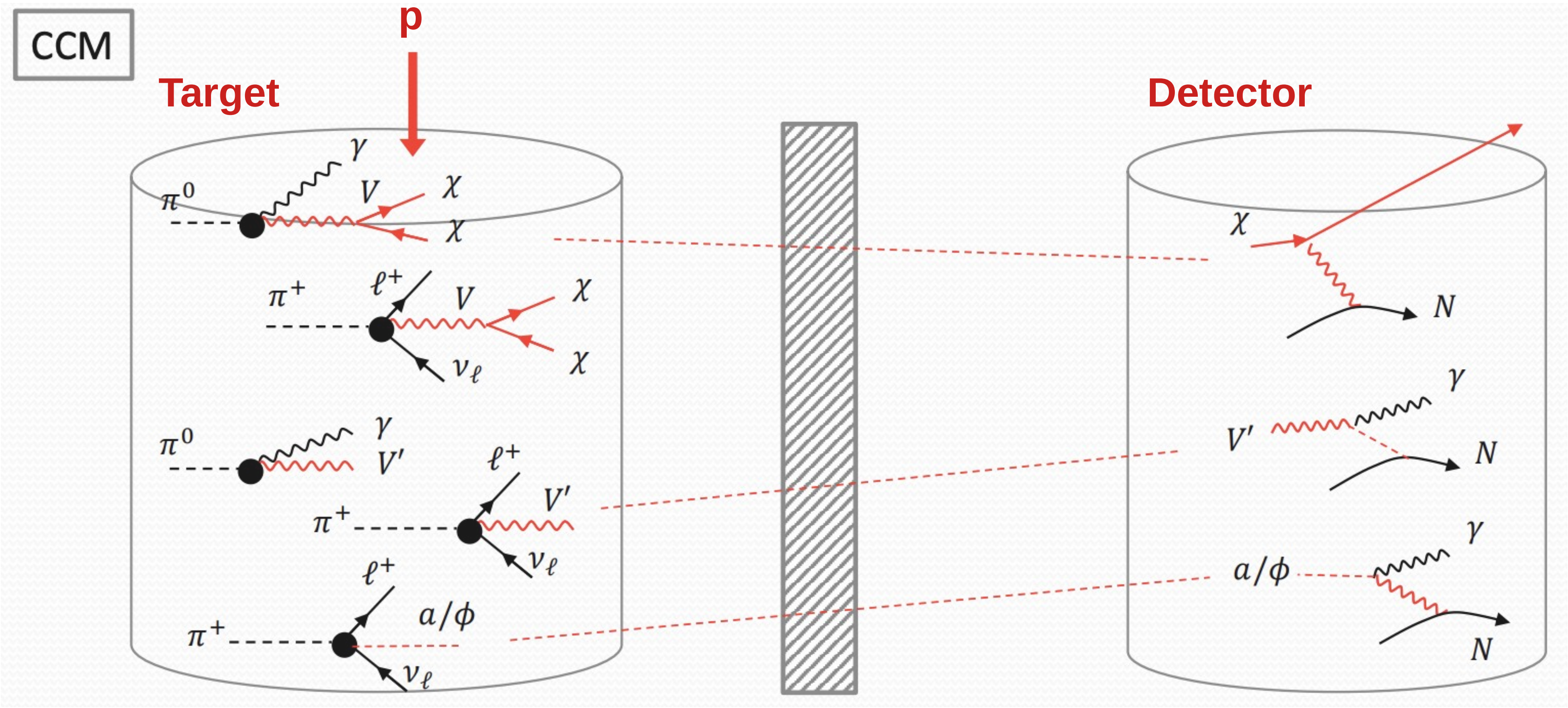


Final state scatter
0.1 – 10's MeV



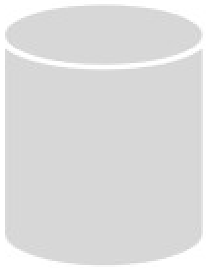
"Axion-Like Particles at Coherent CAPTAIN-Mills",
arXiv: 2112.09979

Dark Sector Coupling to Meson Decay



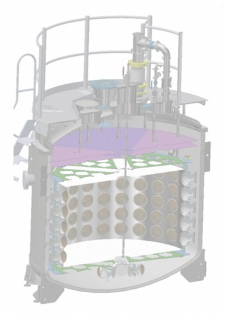
Possible explanation to the MiniBooNE Low Energy Excess arXiv:2110.11944

CCM Timeline



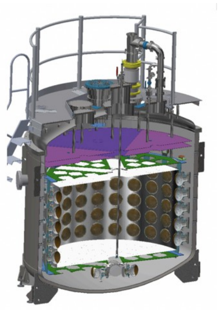
CCM120 Engineering Run

- Prototype detector
- Testing 120 PMTs for SBND
- Produced physics results



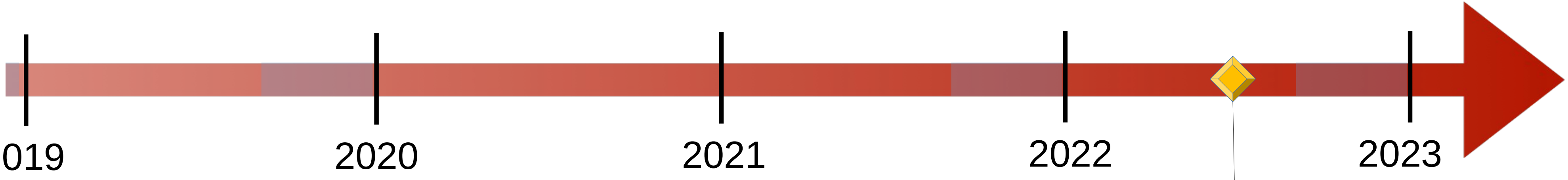
CCM200 Engineering Run

- Upgraded detector to 200 8” PMTs
- Doubled veto PMT coverage
- Increased forward shielding



CCM200 Physics Run

- Improved DAQ to handle more calibration streams
- Installed additional top-shielding
- New filtration system



CCM120 physics results published *here* and *here*!

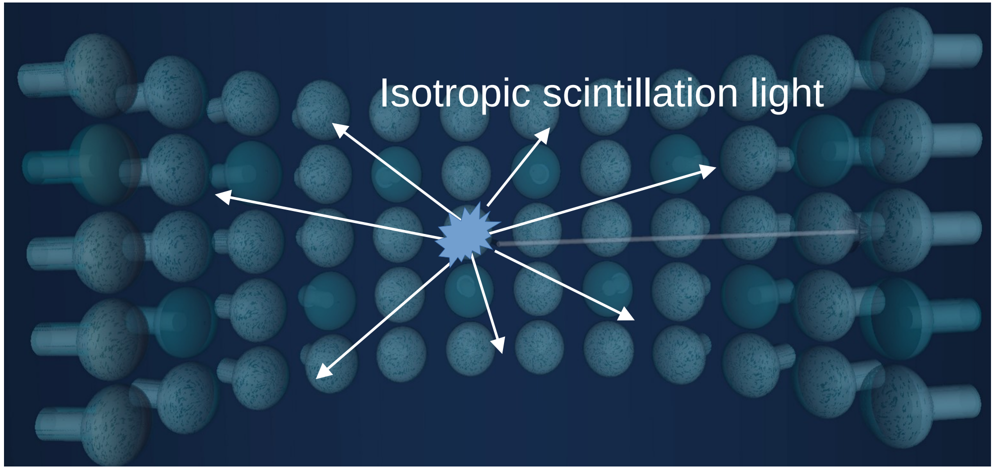
Scintillation light in CCM

Liquid Argon scintillation

- 40 photons/keV, $\lambda=128$ nm
- Fast 6 nsec (singlet) and slow ~1.6 μsec (triplet) time constants.

PMTs + TPB

- 120 (200) PMT’s provide 25% (50%) photocathode coverage.
- TPB WLS coating on PMT’s and foils converts 128 nm photons to visible light.
- TPB foils provide rest of coverage + optical barrier with veto region.

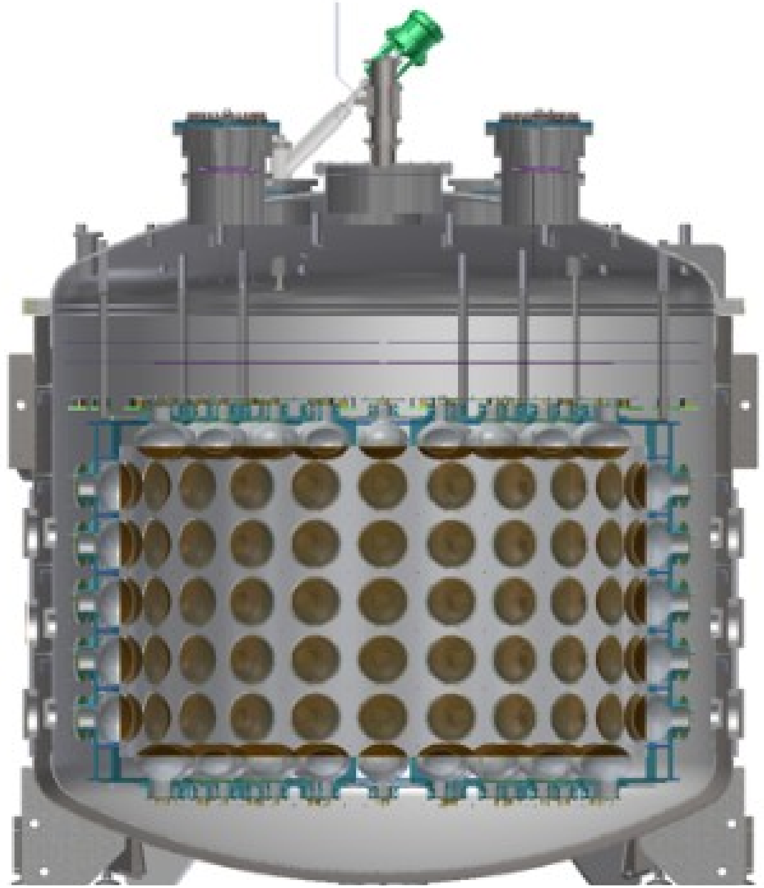


CCM is unique

- Big detector (5 ton fiducial)
- Fast timing capabilities allow to reach low backgrounds.
- Simulations predict resolutions:

  time~1 ns, position~20cm, energy~20%

- Sensitive to low Energy depositions (10-20 keV detection threshold, 1 PE/keV$_{nr}$)
- Wide energy dynamic range - from nuclear recoil events at ~10 keV to electromagnetic events around 100s MeV.
- Unique capabilities open up many different possibilities to do interesting physics.



The CCM120 detector

- 10 ton of LAr: 5 ton fiducial volume + 5 ton Veto (2-3 radiation lengths).
- 120 R5912 PMT’s (96 TPB coated + 24 uncoated). Wavelength shifting TPB foils.

TPB coated PMTs **Uncoated PMTs**

TPB painted reflector foils. Maximize light output

LAr cold test of the entire SBND photon dedection system (PDS):

PMT’s, mounts, cables, feedthroughs, HV, electronics, trigger, DAQ, calibration, simulations and data analysis.

CCM120 event building

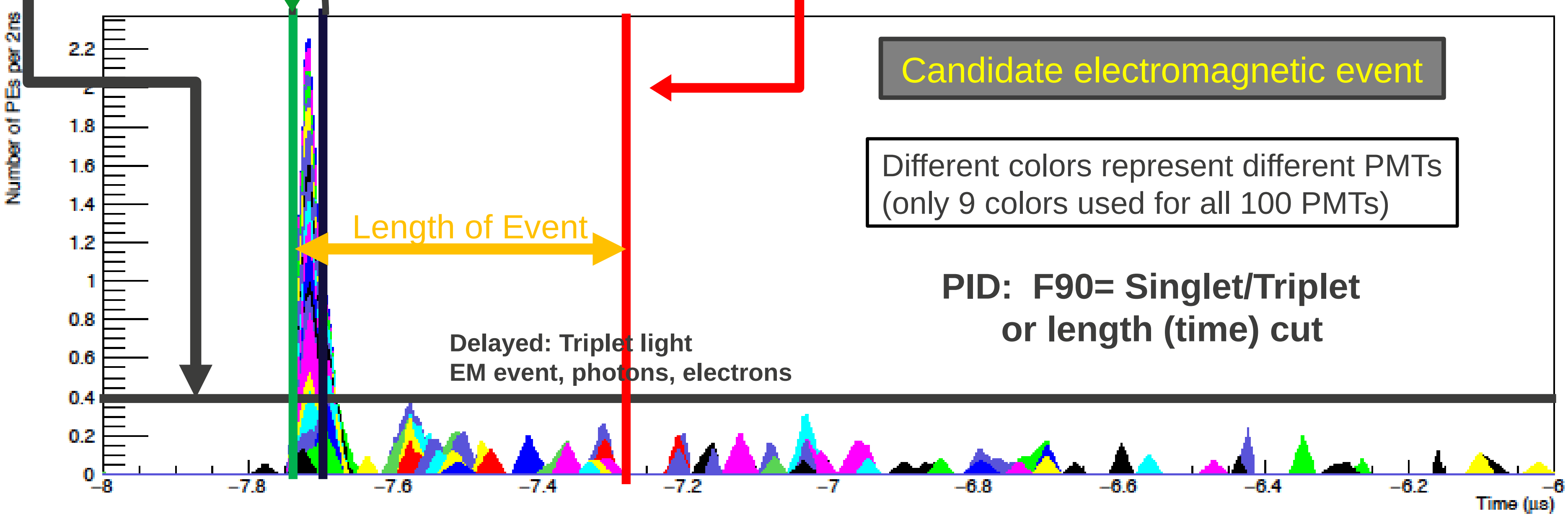
- Threshold is set to 0.4 PE

Event ends where there are 10 empty bins

Start of event is the first bin above threshold

Parameters Calculated

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



Prompt Region

Singlet light
Coherent neutrino/DM scatter

Candidate electromagnetic event

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

Length of Event

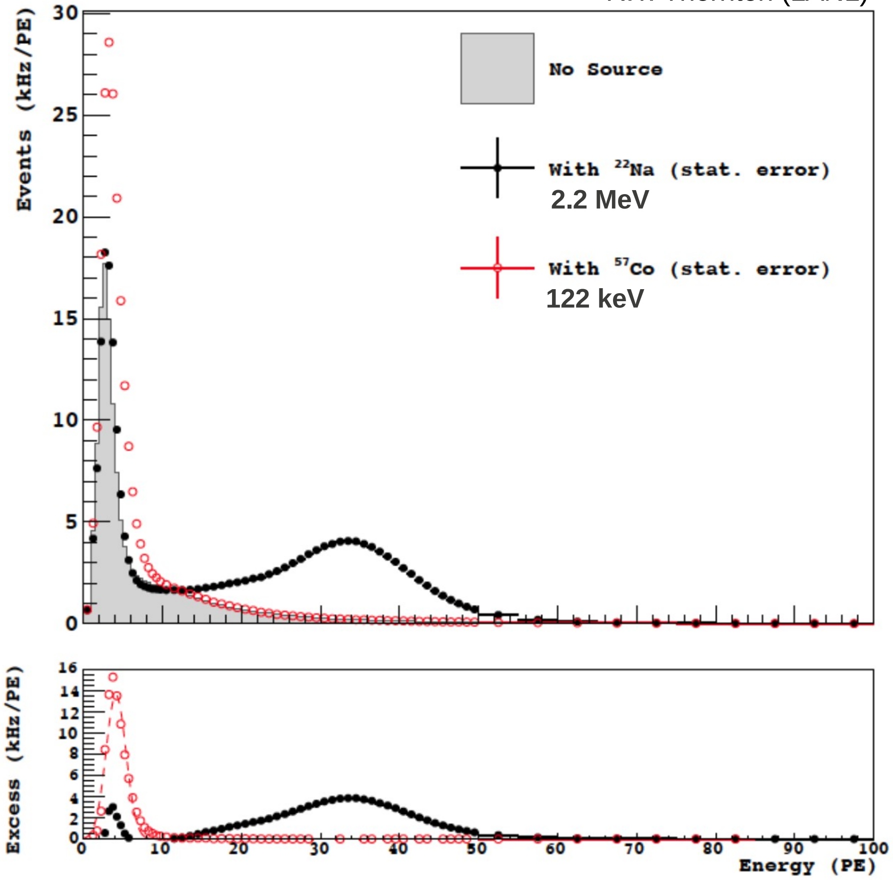
PID: F90= Singlet/Triplet or length (time) cut

Delayed: Triplet light
EM event, photons, electrons

CCM120 calibration

- Low light levels from impurities in LAr (no recirculating/filtering).
- ~2 ppm O_2 reduced the 128 nm light attenuation length from ~20 m to ~50 cm.
- **Na22 peak at (33.2 ± 8.9) PE for 2.2 MeV.**
- Peak at 4.7 PE is artifact of selection cuts.
- Co57 peak was expected at ~1.8 PE.
- Both, Co57 and Na22 rates are within 25% of simulation prediction.
- Full optical model developed using sources and two-freq laser (213 nm and 532 nm) for 2019 run.

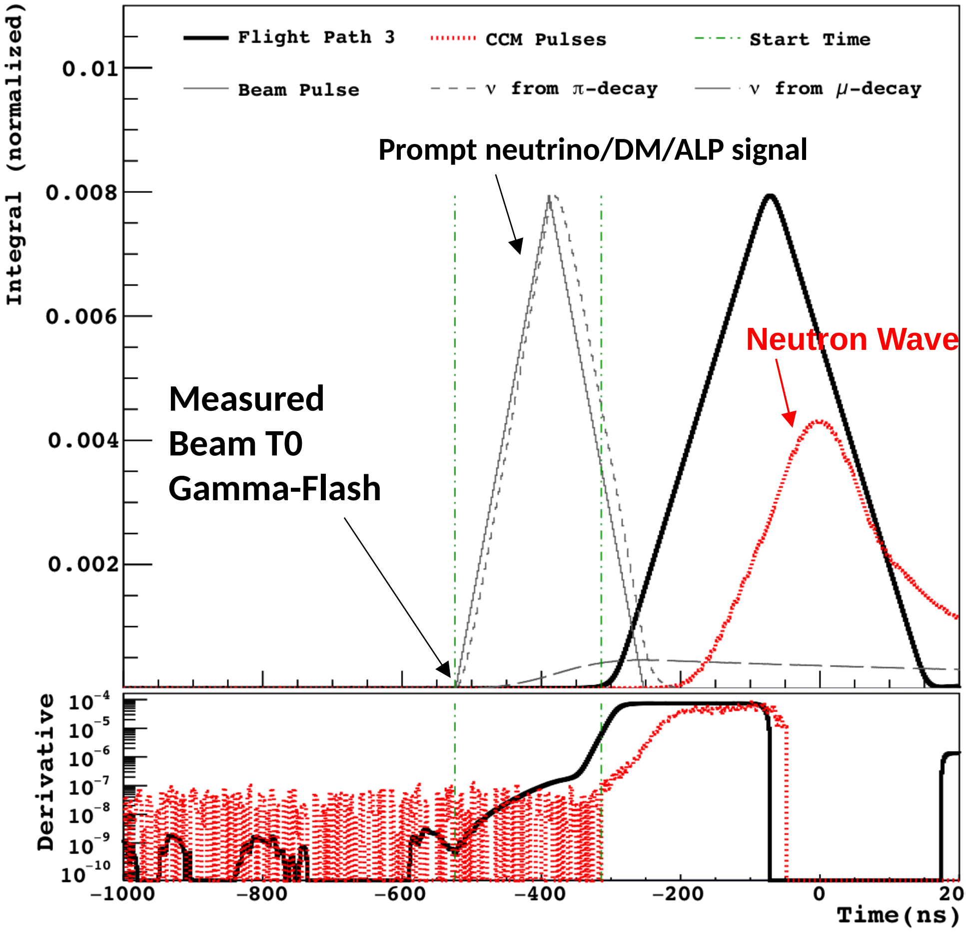
R.T. Thornton (LANL)



CCM120 Bkgd free time region

- Based on measurements, expect speed of light particles from source to arrive 210 ns before the events seen in CCM.
- Because of change in efficiencies of cuts near the CCM turn on the signal region will be 190 ns. (ROI: -530 to -340 ns)
- 190 ns window contains:
  - 80% of π^0-decay events
  - 74% of $\pi^\pm$-decay events
  - 4% of $\mu^\pm$-decay events

R.T. Thornton (LANL)



Prompt neutrino/DM/ALP signal

Neutron Wave

Measured Beam T0 Gamma-Flash

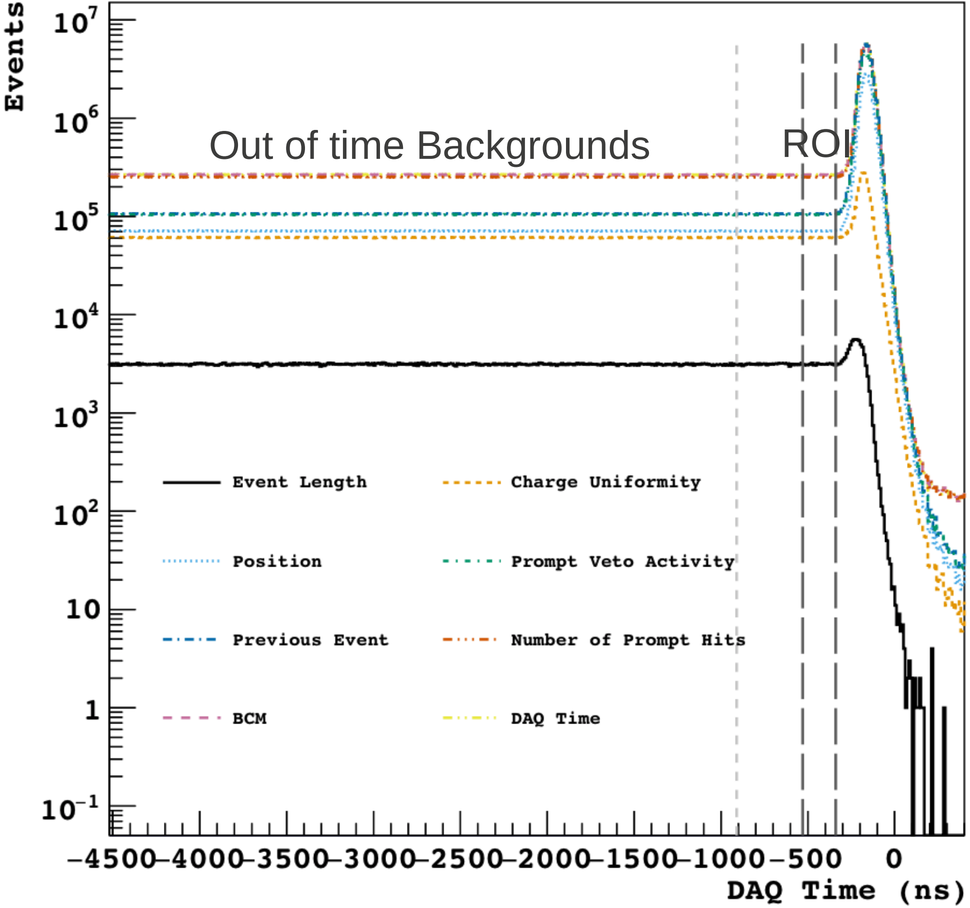
CCM120 Analysis: Measuring backgrounds

- Prompt light only analysis.
- Cuts: DAQ Time – BCM – Prompt Hits – Previous Event – Prompt Veto – Position – Q uniformity - Event Length
- Dynamic event lengths → rudimentary PID

    - LDM search: Event Length < 44 ns
    - ALP search: Event Length > 38 ns

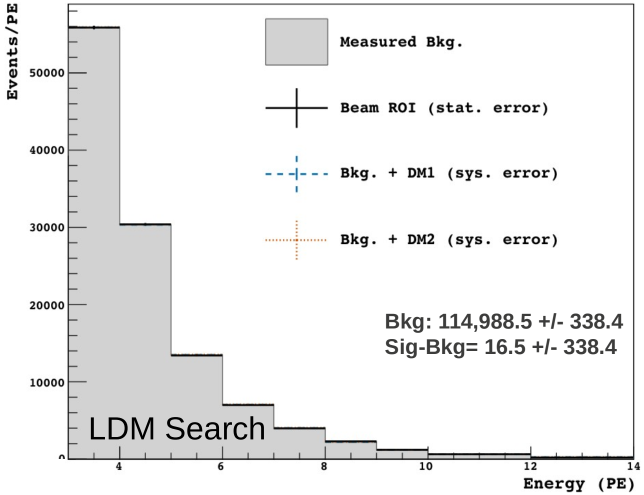
- Pre-beam is flat in time (no bias) → Good prediction for prompt speed of light window (ROI)
- ROI is free of *beam-related-backgrounds*, → the prediction on the number of events has only statistical errors. (systematics will be on DM signal).
- Ideal for Machine Learning techniques

R.T. Thornton (LANL)

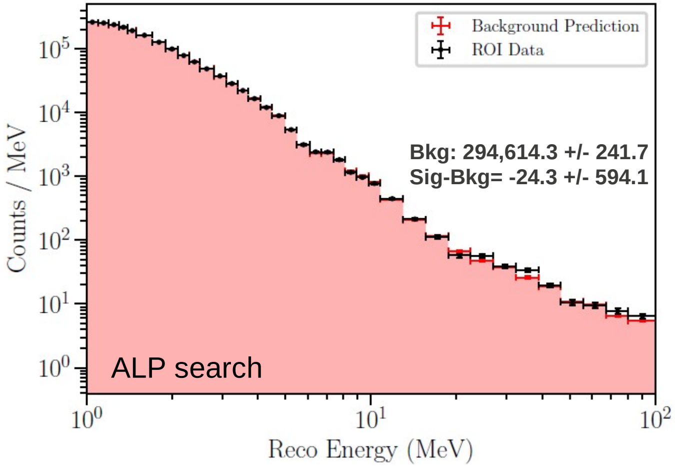


CCM120 run results

- Based on 2 primary data sets:
- Nuclear (Light DM) like events of short duration(<44ns) and low energy (<2 MeV).
- Electromagnetic (ALP) like events of long duration (>38 ns) and high energy (>1 MeV).
- Many different models tested between these 2 data sets!



Bkg: 114,988.5 +/- 338.4
Sig-Bkg= 16.5 +/- 338.4

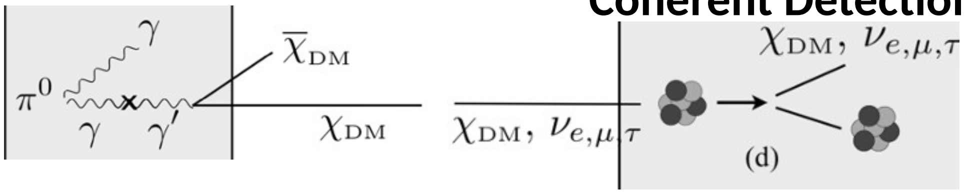


Bkg: 294,614.3 +/- 241.7
Sig-Bkg= -24.3 +/- 594.1

CCM120 Vector Portal DM

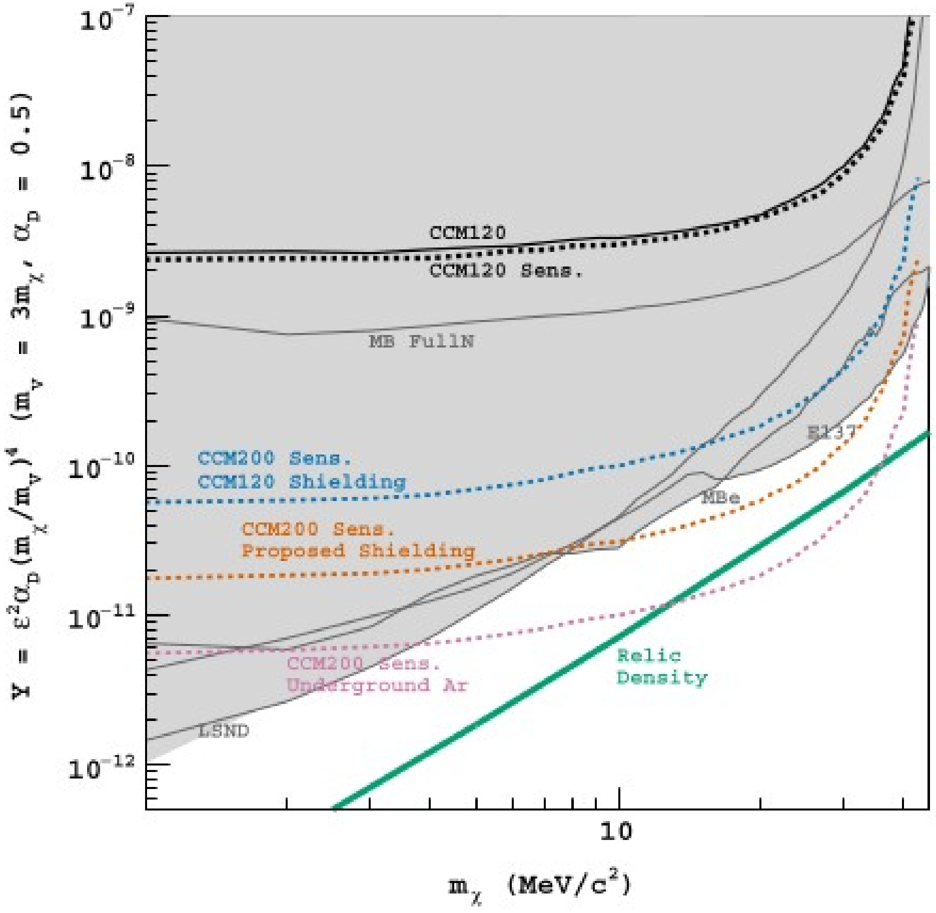
Source

Coherent Detection

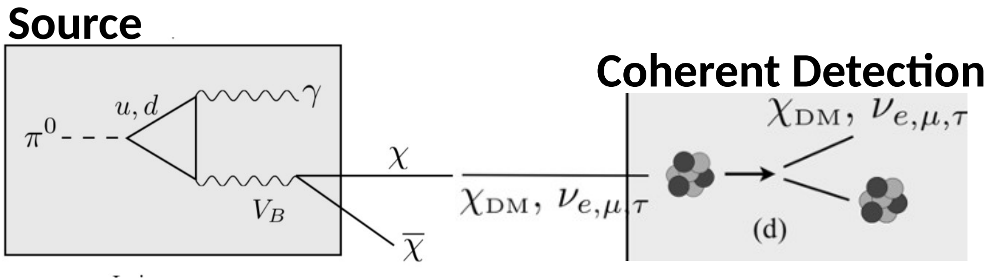


- Plot is for $m_V/m_\chi = 3.0$.
- Projection: CCM200 will cover new parameter space.
- Will probe relic density with isotopically pure Ar.

Phys. Rev. D 106,012001 (2022)



CCM120 Leptophobic DM

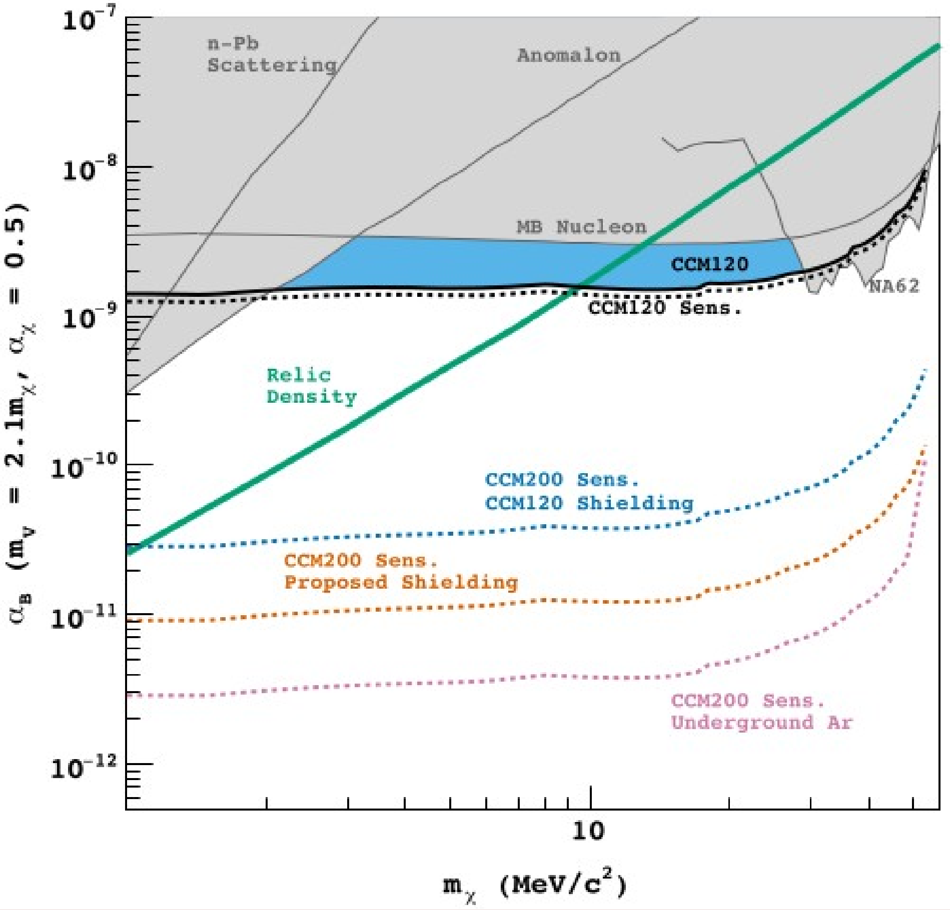

Source

Coherent Detection

- Plot is for $m_V/m_\chi = 2.1$. Community standard 3.0
- Projection: CCM200 will cover the relic density in the range of m_χ from 1 to 60 MeV/c^2.

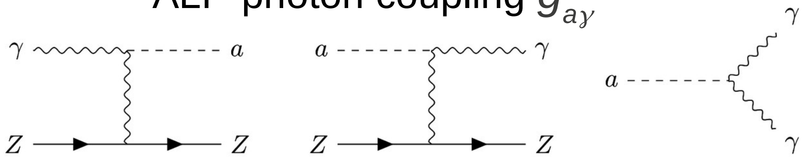
- Competitive despite: only 1.5 mo data, contaminated LAr, non op timal shileding!

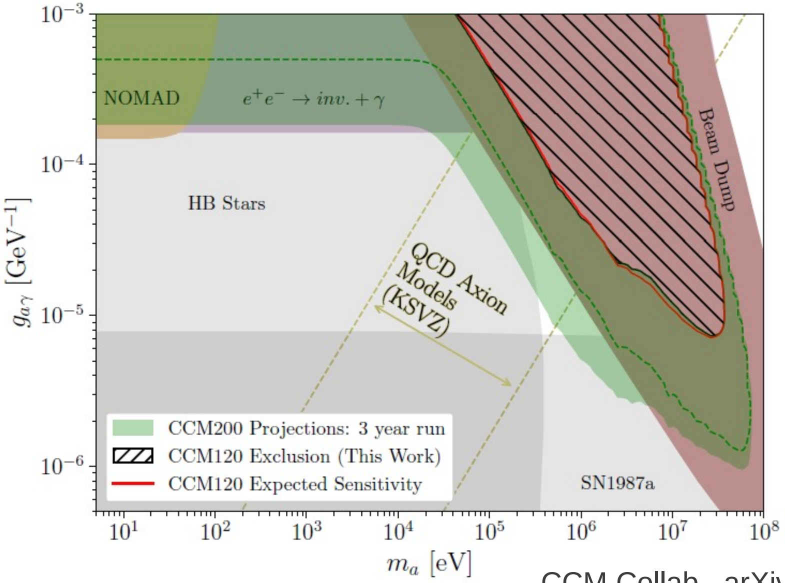
Phys. Rev. Lett. 129,021801 (2022)



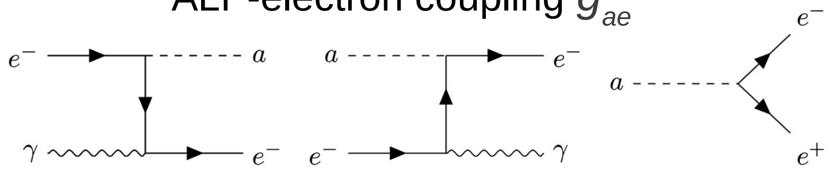
CCM120 Axion Like Particle search

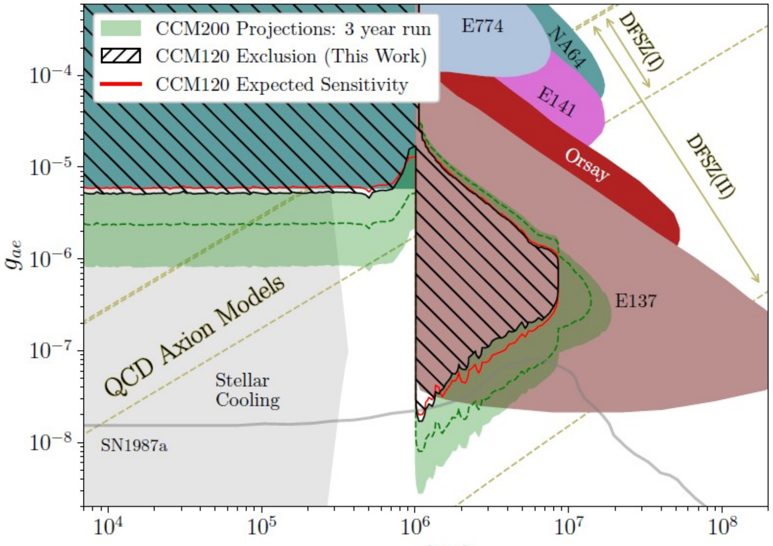
ALP-photon coupling $g_{a\gamma}$





ALP-electron coupling g_{ae}





CCM Collab. arXiv: 2112.09979 [hep-ph]

Analysis led by Dutta &Thompson (TAMU)

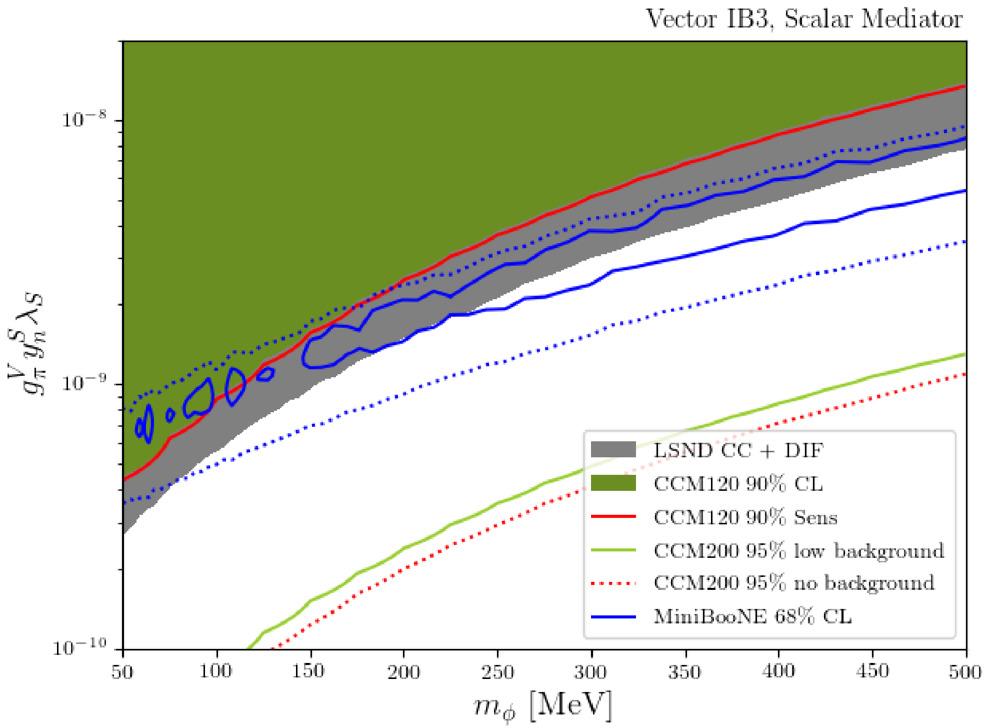
- Projected CCM200 region for a three year run with CCM120 bkgd estimates and conservative improvements (dashed green line). Background free assumption (extent of shaded green region).

Dark Sector Coupling to Meson Decay

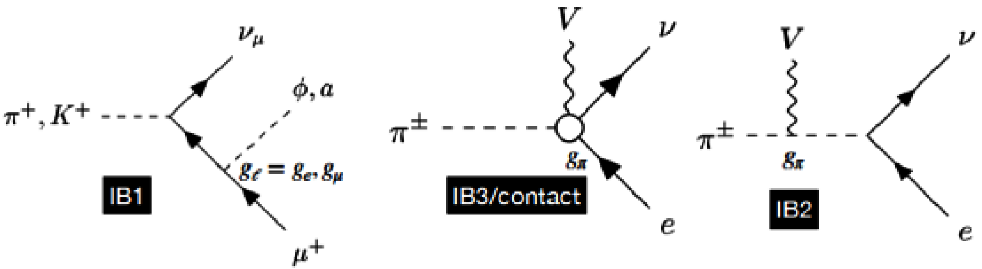
- Alternative solution to the MiniBooNE LEE is DSCMD from pion decay.

  Explains *i) higher excess in neutrino mode (more π^+ than π^- per incident proton)* and *ii) the beam-dump run results with neutral π^0.*

- 16 potential models depending on mediator type, dark particle type, and decay/production model.
- Fits to MiniBooNE excess give the predictions for CCM to test.



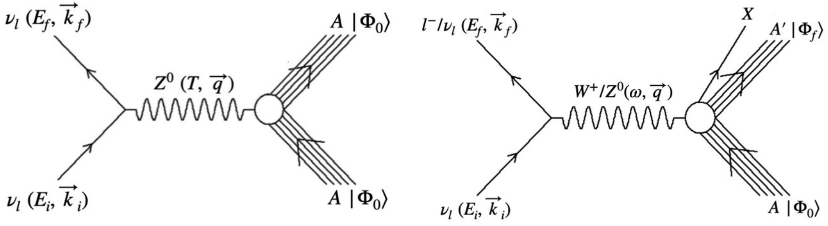
CCM can test most of the MiniBooNE solution space in a 2-3 yr run.



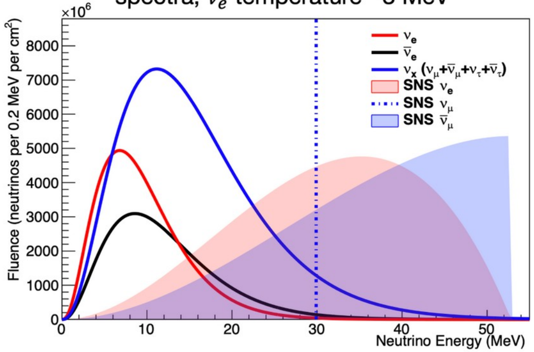
3-body charged meson decays $\pi \rightarrow l \nu X$, for $l=e,\mu$

CEvNS, Sterile ν's and Xsec's on Ar

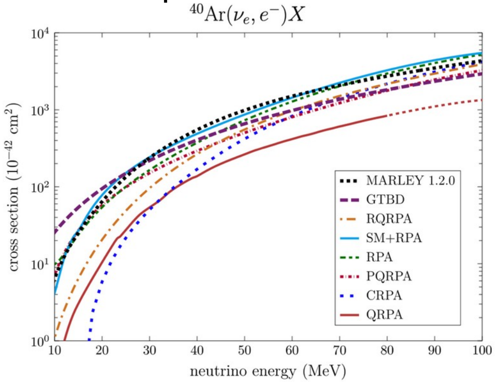
Limited data on Ar CEvNS and CC/NC cross sections



Supernova flux (10 kpc): pinched spectra; ν_e temperature ~3 MeV

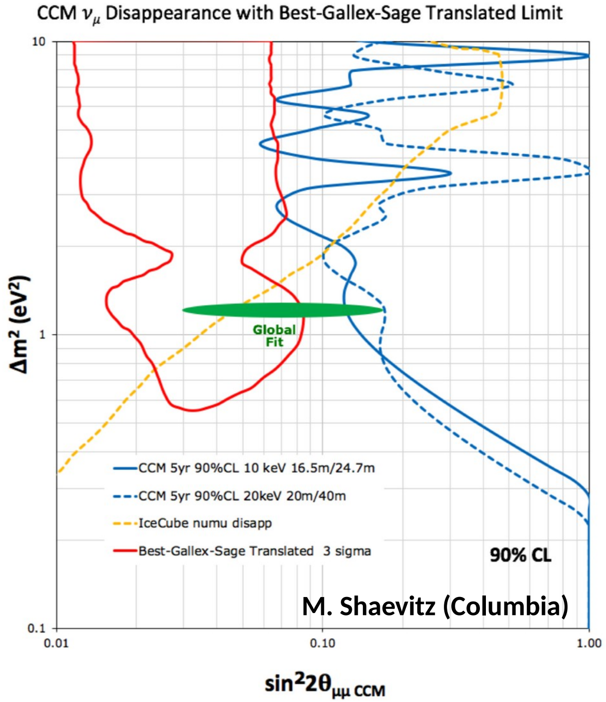


~25% spread on CC models



- DUNE Supernova Physics requires CC and NC measurements on Argon.
- CCM can make ~16% cross section measurement on LAr at Supernova energies for DUNE => theory currently at ~30%.

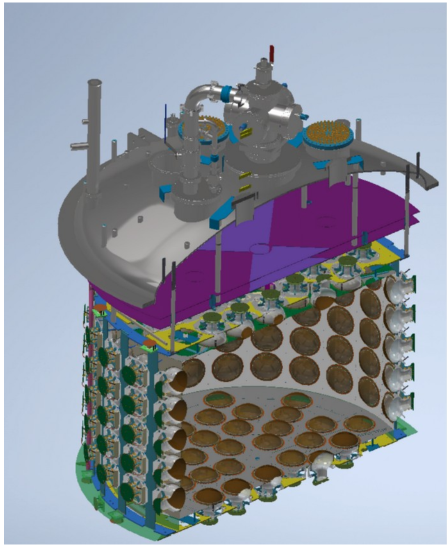
Need to first observe CEvNS before embarking on sterile neutrino search (two detectors ideal)

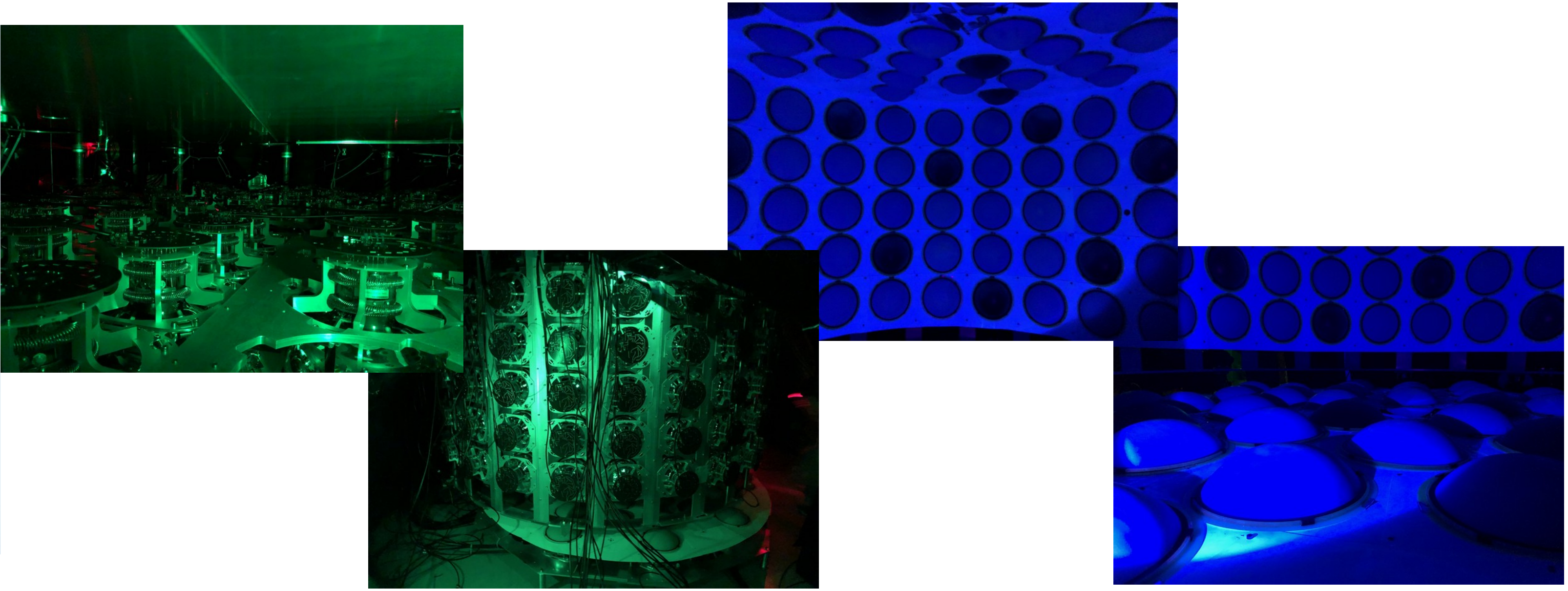


- Need to first establish 10 keV threshold and observe CEvNS.
- Sterile ν sensitivity is marginal. But global situation can change, and could make a smoking gun measurement.

Upgraded detector CCM200

- 120 cylinder + 40 x 2 end cap 8” PMTs => Total 200 PMT’s.
- 48 1x1” veto PMTs instrument outer region (double veto PMTs)
- New TPB evaporative foils (x2 efficiency of CCM120 foils) produced at U. Edinburgh.
- New CCM200 detector built July 2021, initial test run done September-December 2021.
- Improved shielding and LAr filtration system. Started 2022 beam run in October 2022.



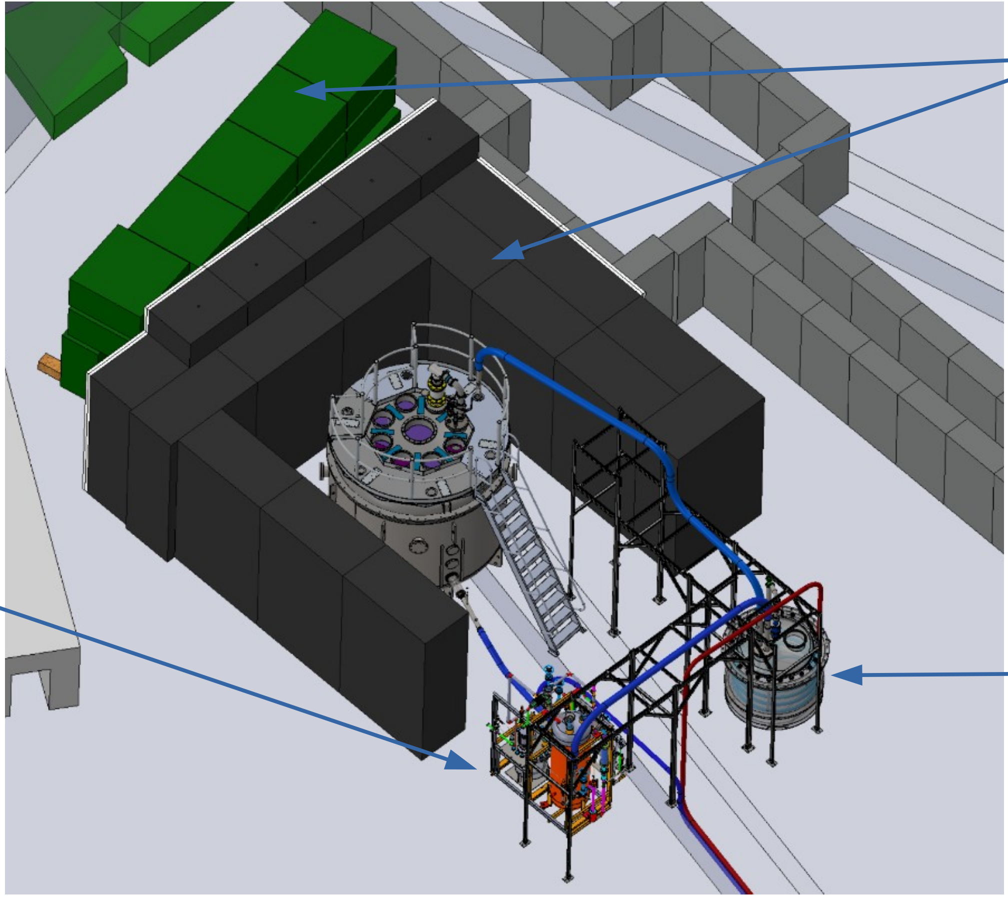


CCM200 layout @ LUJAN

Filter Skid (MicroBooNE design):

- 4A molecular sieve material removes H_2O.
- Cu alumina removes O_2.
- 10 ton LAr recirculation turn over time of ~3 hr.

Began Beam Running in October 2022!

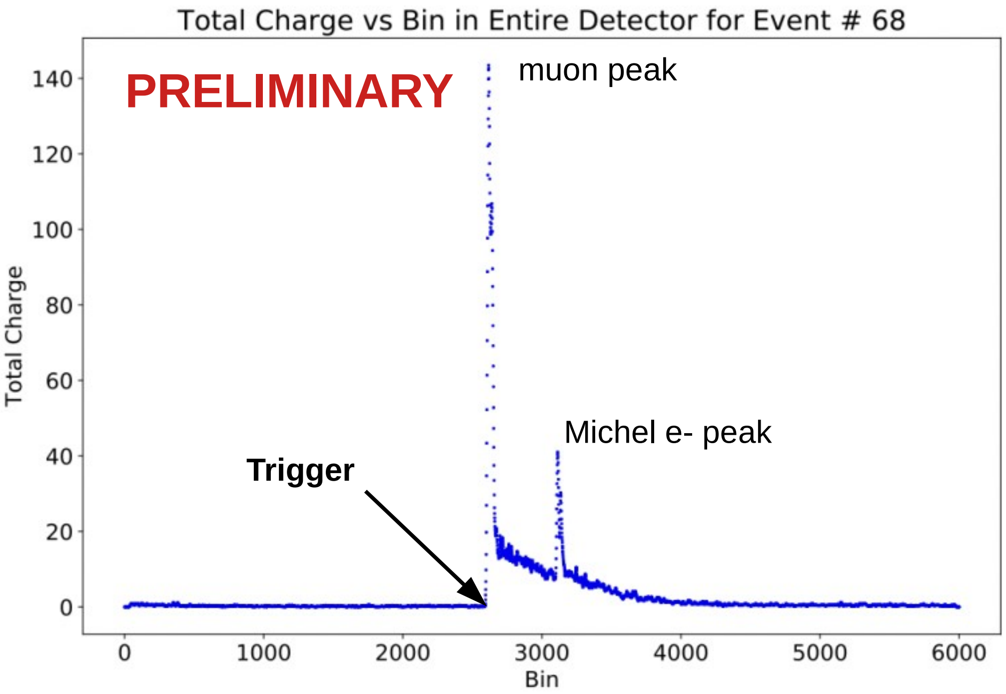


More steel and concrete shielding added to sides and roof.

LN2 heat exchanger to reduce LAr losses (especially important if we use isotopically pure U/G LAr in the future).

Cherenkov light detection

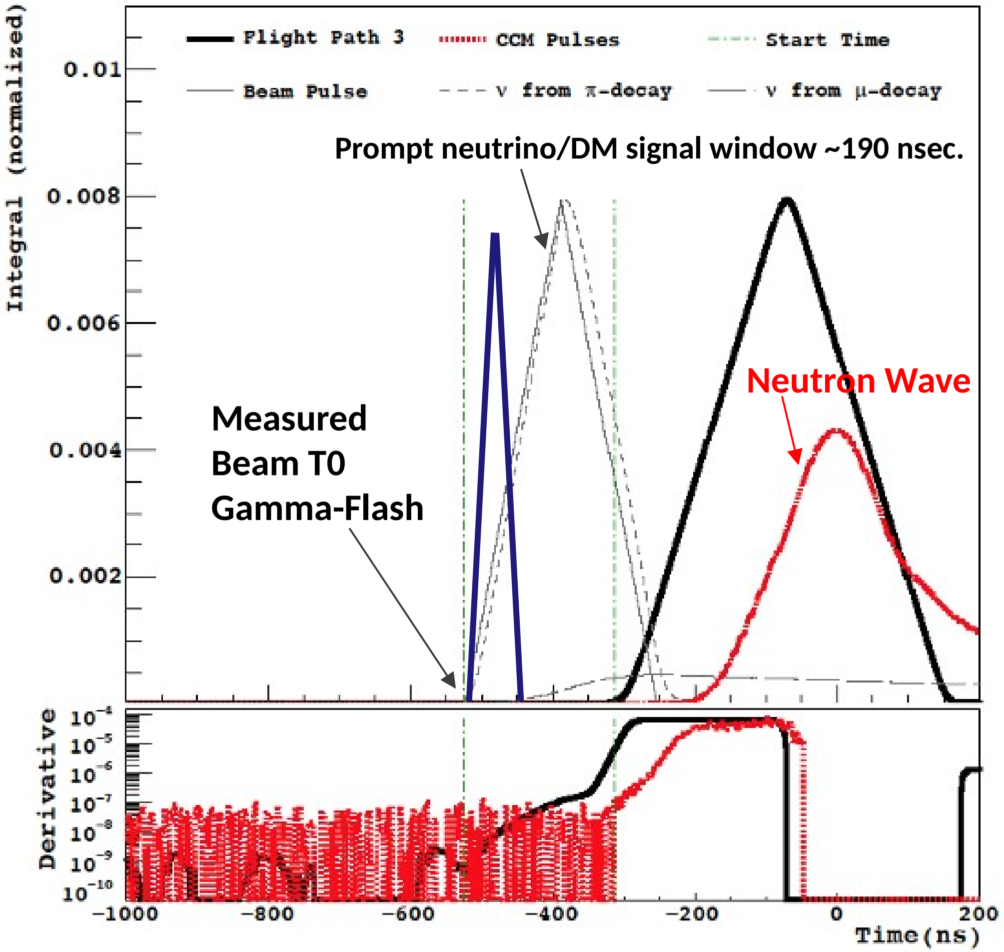
- **Analysis underway to identify Cherenkov light on event by event basis**
- Triggering on cosmic muon events using 5cm X 5cm external detectors that consist of two parallel scintillator panels and SiPM
- Using timing, direction, and uncoated PMTs to focus our search for Cherenkov light
- Provides Michel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



1 bin = 2 ns

Upgrade: Lujan 30 ns beam pulse

- TOF technique unique & 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 bkgd's from Ar39 decay and neutron activation.
- Shorten PSR pulse from 300 nsec to **30 nsec (Blue),** would increase signal efficiency and reduce random backgrounds. Estimated 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

- CCM200 is funded for a 3 year run cycle and will probe many new models/parameter space in the dark sector
- Once established the detection of CEVNS, a possible 2 detector configuration (20 m & 40 m) is ideal to study sterile neutrino oscillations ($\nu_\mu \rightarrow \nu_s$).
- Next generation CCM1000 detector is being considered to utilize future upgrades to Lujan proton source to reduce backgrounds by an order of magnitude

Summary

- **Coherent CAPTAIN-MILLS** is an accelerator-based experiment to search for dark-matter and other BSM physics in the **LANSCE Lujan Center** at LANL.
- Prototype **CCM120** already set new limits on Vector Portal Leptophobic dark matter candidates, as well as in ALP parameter space.
- In a three year run, the upgraded **CCM200** detector will:
  - → Search for sub-GeV dark matter with sensitivities that probe early Universe relic density.
  - → Probe new regions of the parameter space of Axion Like Particles (ALPs), beyond the reach of previous experiments and cosmological constraints.
  - → Test a new interpretation (DSCMS) of the legendary LSND and MiniBooNE excesses.
  - → Probe other BSM physics such as heavy neutral leptons, CEvNS, and sterile neutrinos.
- Big and sensitive detector with unique capabilities, opens up many possibilities.
- **Stay tuned!**

Thank you for your attention!

ATM

Massachusetts Institute of Technology

Los Alamos NATIONAL LABORATORY EST. 1943

Fermilab

NM

UF UNIVERSITY of FLORIDA

EMBRY-RIDDLE Aeronautical University

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

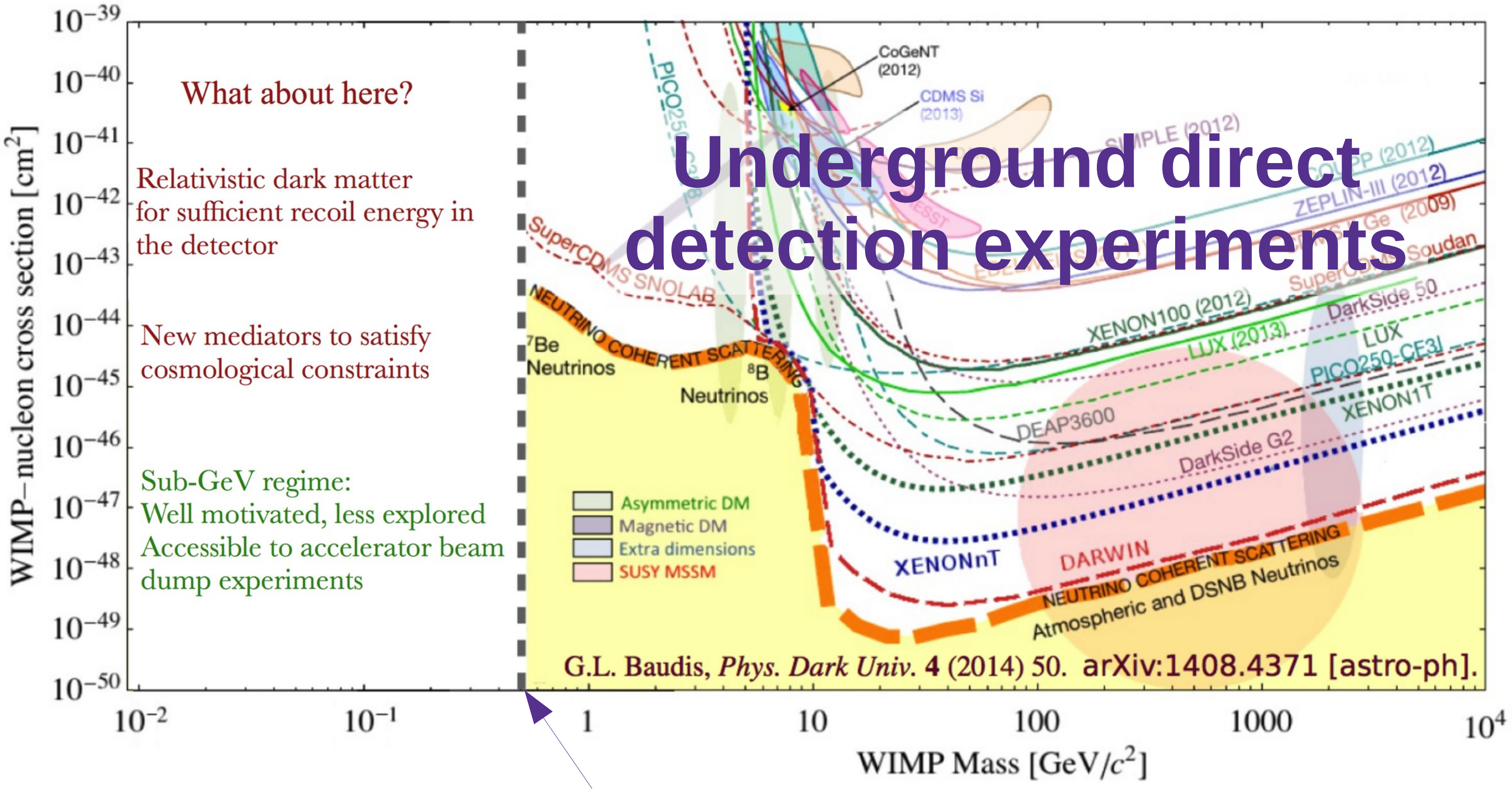
NEW MEXICO STATE UNIVERSITY 1888

THE UNIVERSITY OF EDINBURGH

UNIVERSIDAD NACIONAL AUTÓNOMA D MÉXICO

BACKUPS

Motivation Accelerator Sub-GeV Dark Matter searches



What about here?

Relativistic dark matter for sufficient recoil energy in the detector

New mediators to satisfy cosmological constraints

Sub-GeV regime:
Well motivated, less explored
Accessible to accelerator beam dump experiments

Underground direct detection experiments

G.L. Baudis, *Phys. Dark Univ.* **4** (2014) 50. arXiv:1408.4371 [astro-ph].

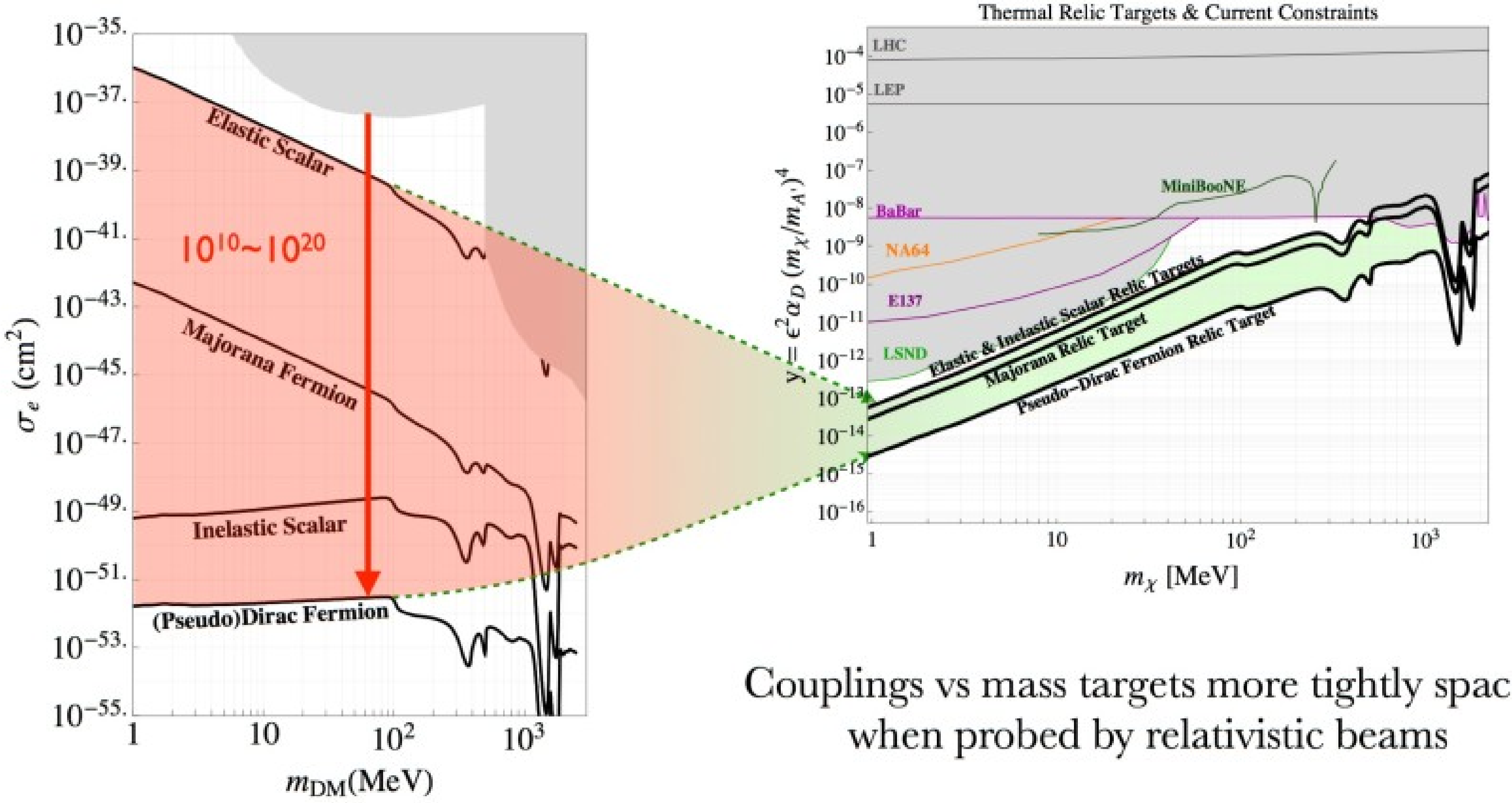
- Direct detection ~GeV mass threshold limit due to slow moving galactic halo DM.
- Access sub-GeV threshold with accelerator boosted DM. Method has experienced much recent theoretical and experimental activity.

Motivation Probing Sub-GeV DM thermal relic density

Boosted accelerator DM improves reach testing thermal relic density

Halo DM: non-relativistic probe

Accelerator DM beam: relativistic DM



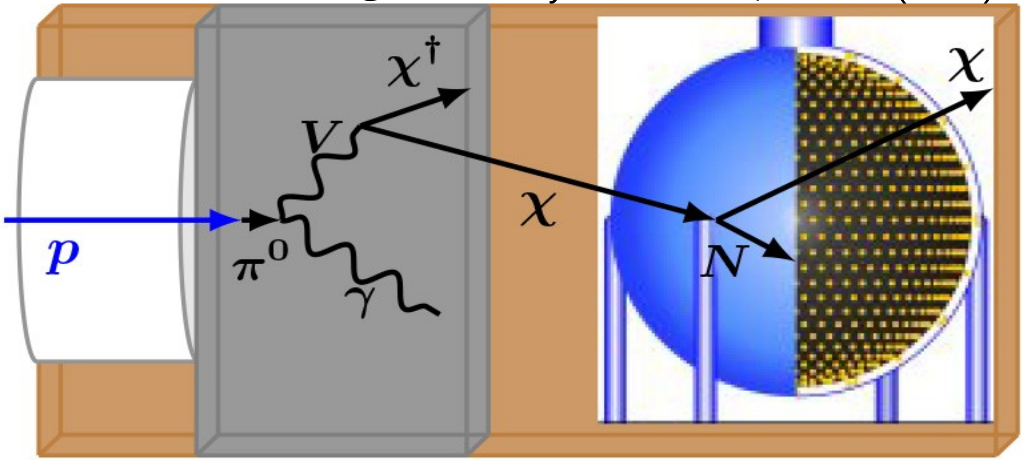
Couplings vs mass targets more tightly spaced when probed by relativistic beams

Accelerator produced DM

Method: produce DM with accelerator and detect with large near detectors.

- **Protons: high energy (> GeV) and high intensity beams (> 10 kW)** at FNAL, LANL, SNS, etc
- Searches also with electron machines Jlab, SLAC, etc.

MiniBooNE-DM @ FNAL. Phys. Rev. D 98, 112004 (2018)

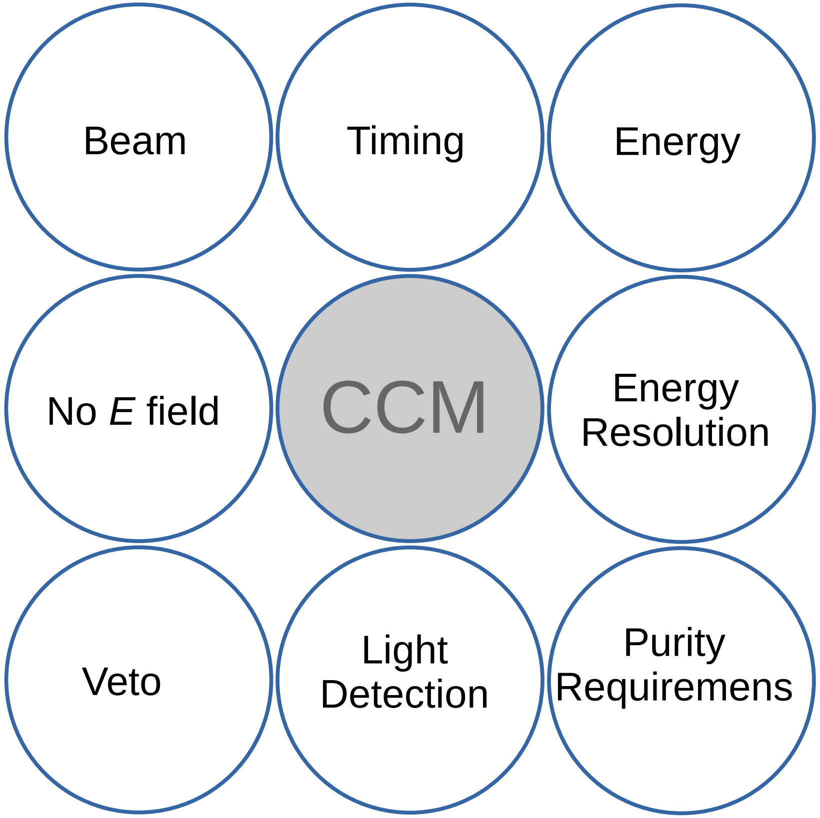


- Protons directly on beam dump produce **copious number of neutral particles** (π^0, η, etc.) which couple to dark matter.
- Boosted Dark Matter passes though dirt and interacts in detector.

- Large and sensitive detector required for high rates and good background rejection.
- **Final state particle energies ~MeV**

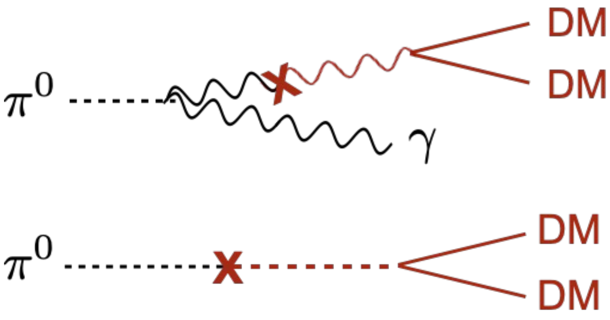
Pros of CCM design

- Short beam duty factor, ~10^{-6}
- Fast timing (2ns sampling)
- Wide energy dynamic range — from nuclear recoil events at ~10 keV to electromagnetic events around 100s MeV
- No electric field doubles photons detected compared to TPCs
- High photocathode density allows for energy resolution ~20% and detection of Cherenkov light
- Instrumented 5 ton veto region
- Purity requirements less stringent than for TPCs

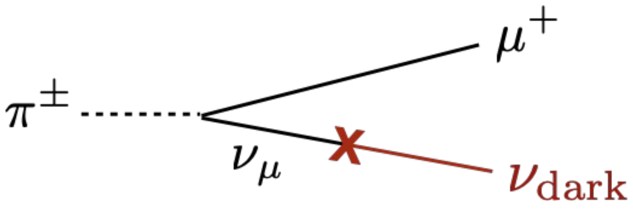


CCM Dark Sector program

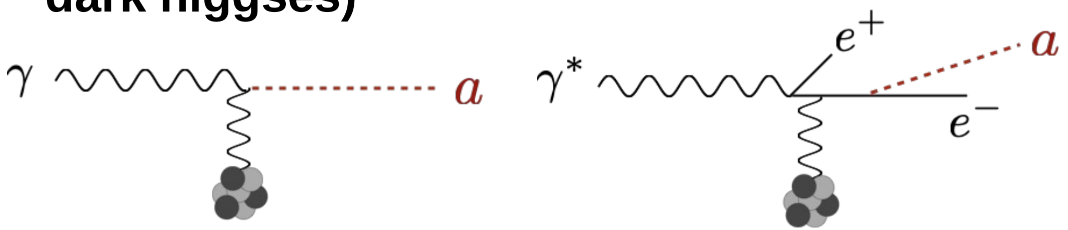
- **Dark matter production and detection via vector and (pseudo-)scalar portals**

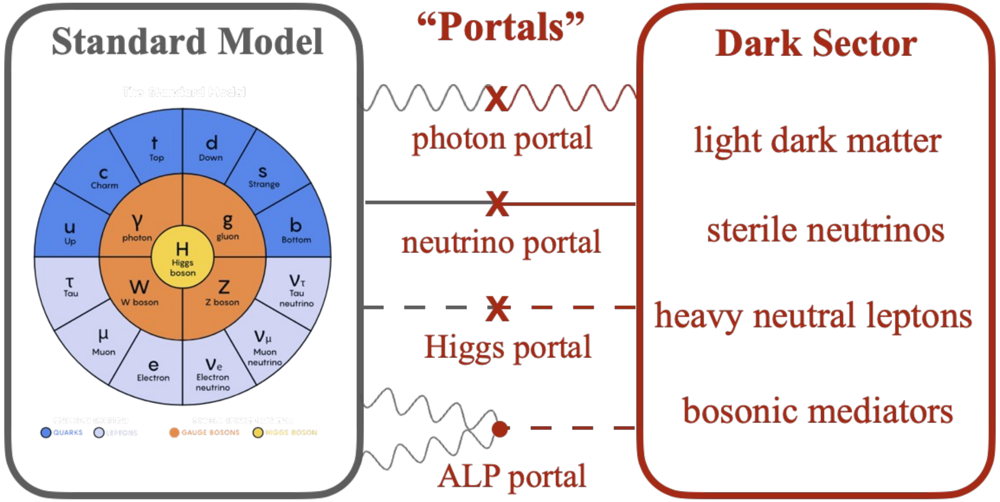


- **Neutrino Portals (sterile neutrinos, heavy neutral leptons)**



- **Dark Sector Mediators (ALPs, dark vectors, dark higgses)**

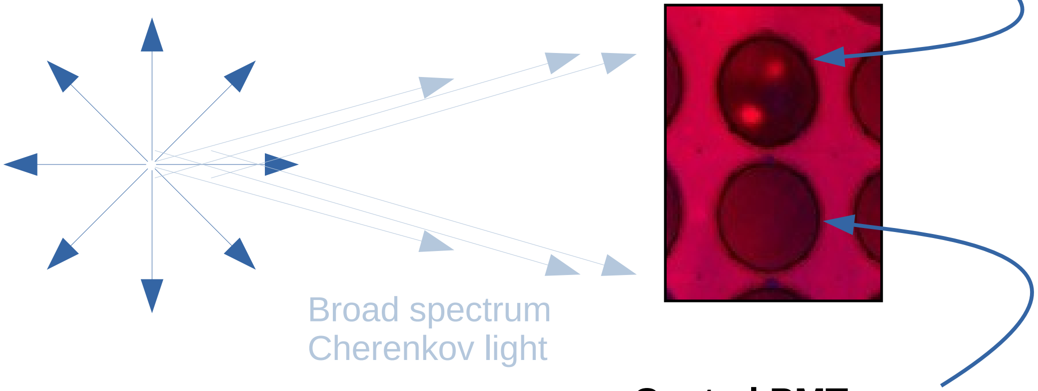




Proton beam dumps can probe all these portals

Light collection

- TBP foils shift 128 nm LAr scintillation light to the visible spectrum, allows better absorption by PMTs
- Combination of uncoated and coated PMTs allow for unique capabilities — simultaneous scintillation and Cherenkov light detection
- **Can isolate Cherenkov light in uncoated PMTs**

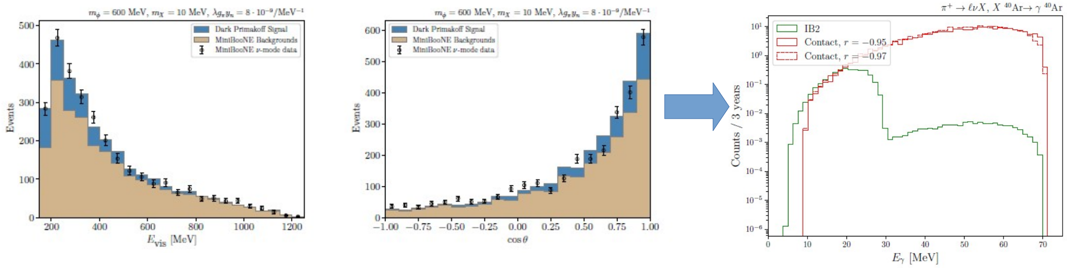


Uncoated PMTs
Detect visible component of Cherenkov light + small amount of light reflected from TBP foils on detector walls

Coated PMTs
Detect scintillation light and UV + most visible components of Cherenkov light

CCM120 DSCM Model search

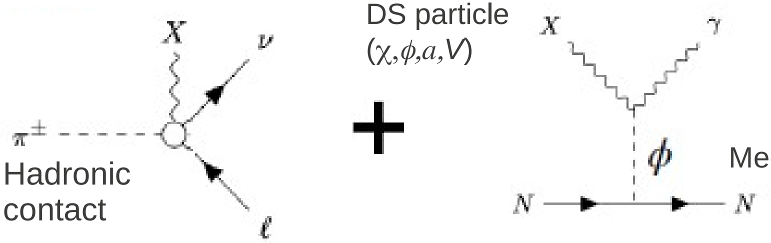
1. DSCMD fits to MiniBooNE excess used to determine predicted E_{vis} spectrum in CCM.



2. Predicted E_{vis} spectrum in CCM compared to measured excess in ROI to determine confidence limit and sensitivities.

Decay Model (leptonic, hadronic, hadronic contact)

Interaction Model

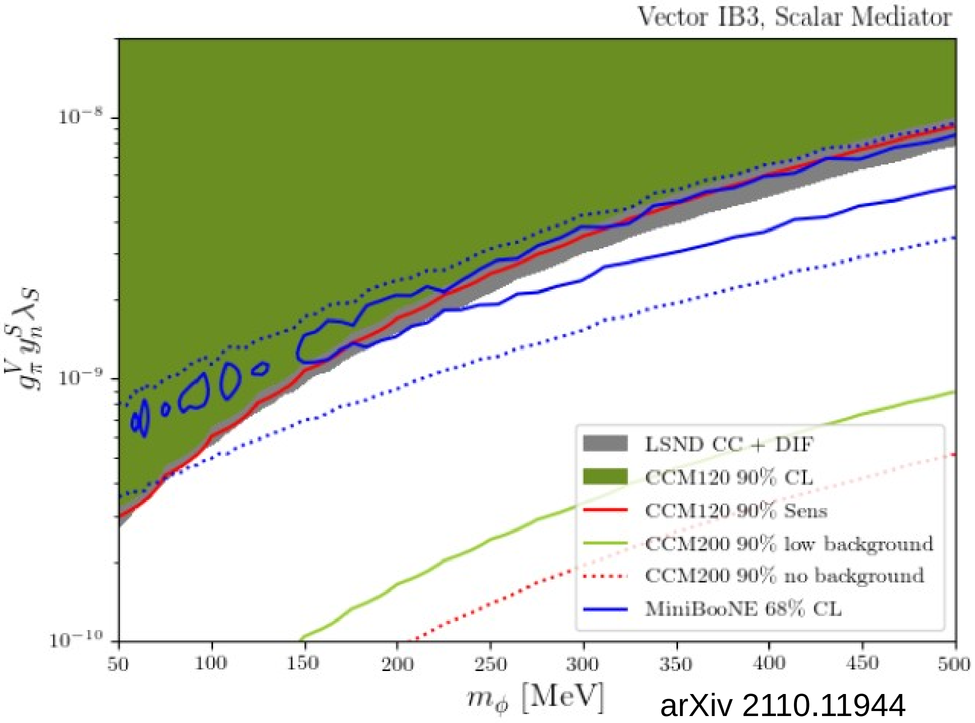


Hadronic contact

DS particle (χ,ϕ,a,V)

Mediator (ϕ,a,V,π^0)

Many (>16) potential models. CCM has tested 5.



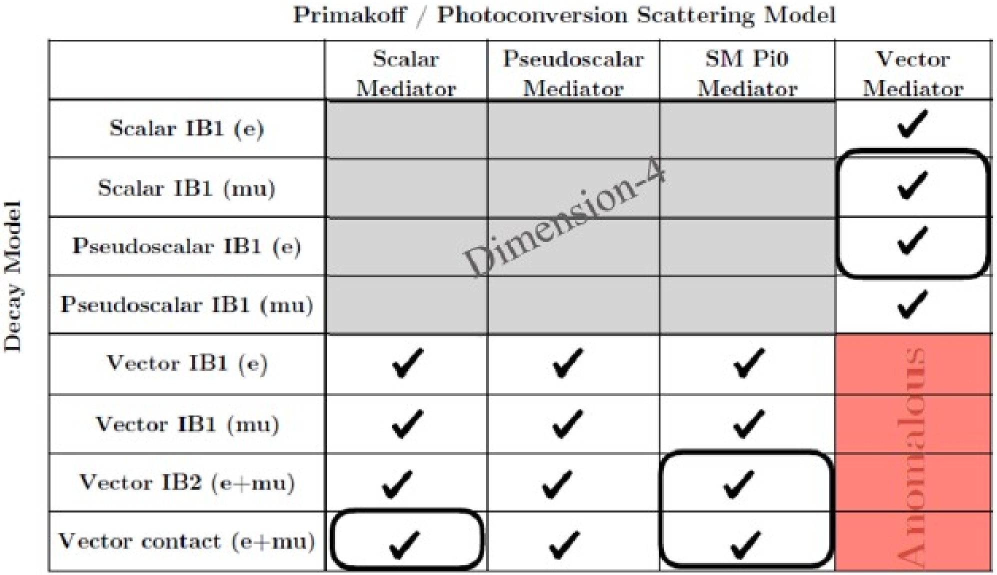
arXiv 2110.11944

Dark Sector Coupling to Meson Decay

- Alternative solution to the MiniBooNE LEE is DSCMD from pion decay.

  Explains *i) higher excess in neutrino mode (more π^+ than π^- per incident proton)* and *ii) the beam-dump run results with neutral π^0.*

- 16 potential models depending on mediator type, dark particle type, and decay/production model.
- Fits to MiniBooNE excess give the predictions for CCM to test.



Primakoff / Photoconversion Scattering Model

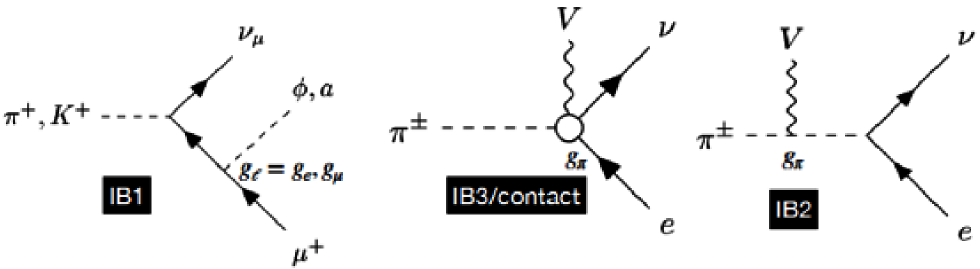
Decay Model

	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

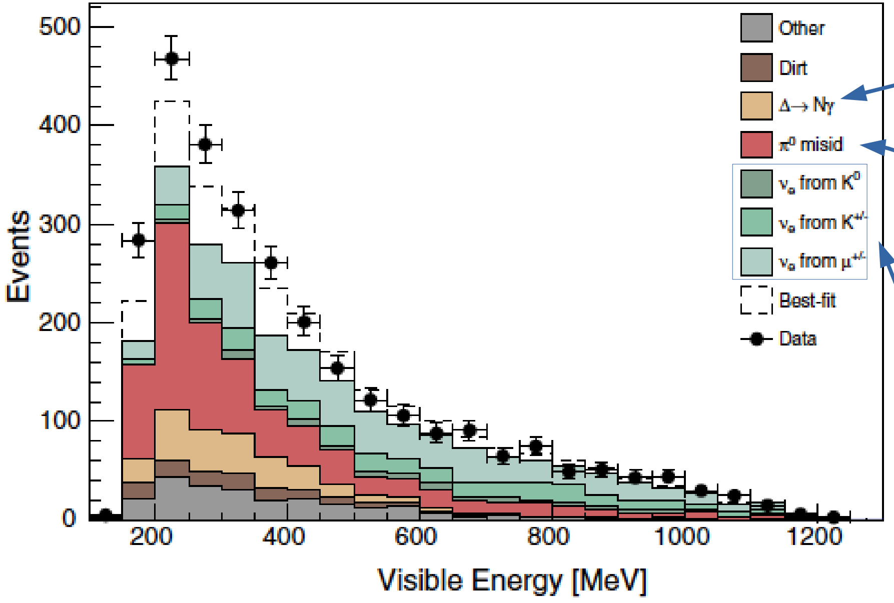
Combinations of DSCMS models. Check: solutions to MiniBooNE excess. Box: tested by CCM120.

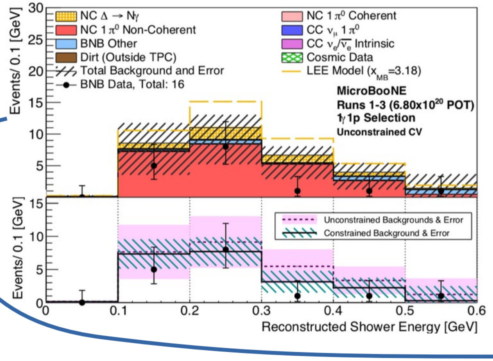


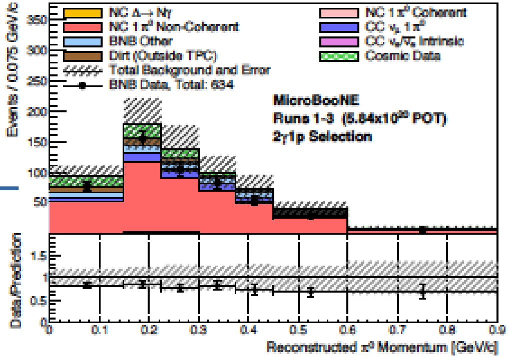
3-body charged meson decays $\pi\rightarrow l\nu X$, for $l=e,\mu$

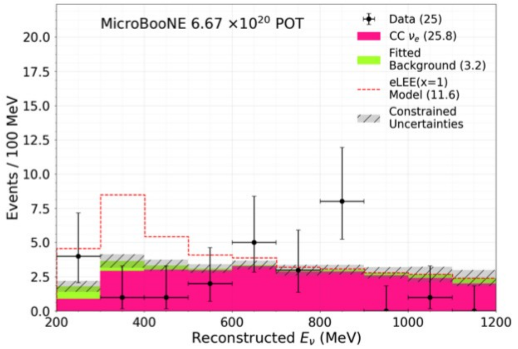
MiniBooNE excess and MicroBooNE

- Recent MicroBooNE results (arXiv 2110.00409 + 2110.14054 + other μB papers) demonstrate MB excess is robust.
- Confirmed background estimates for: Δ radiative decay, π^0 , and intrinsic ν_e.
- DSCMD can explain the MB excess.



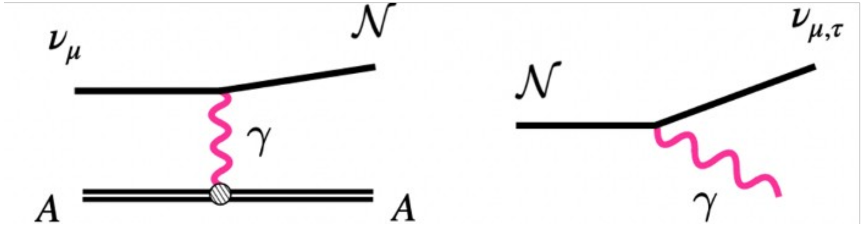




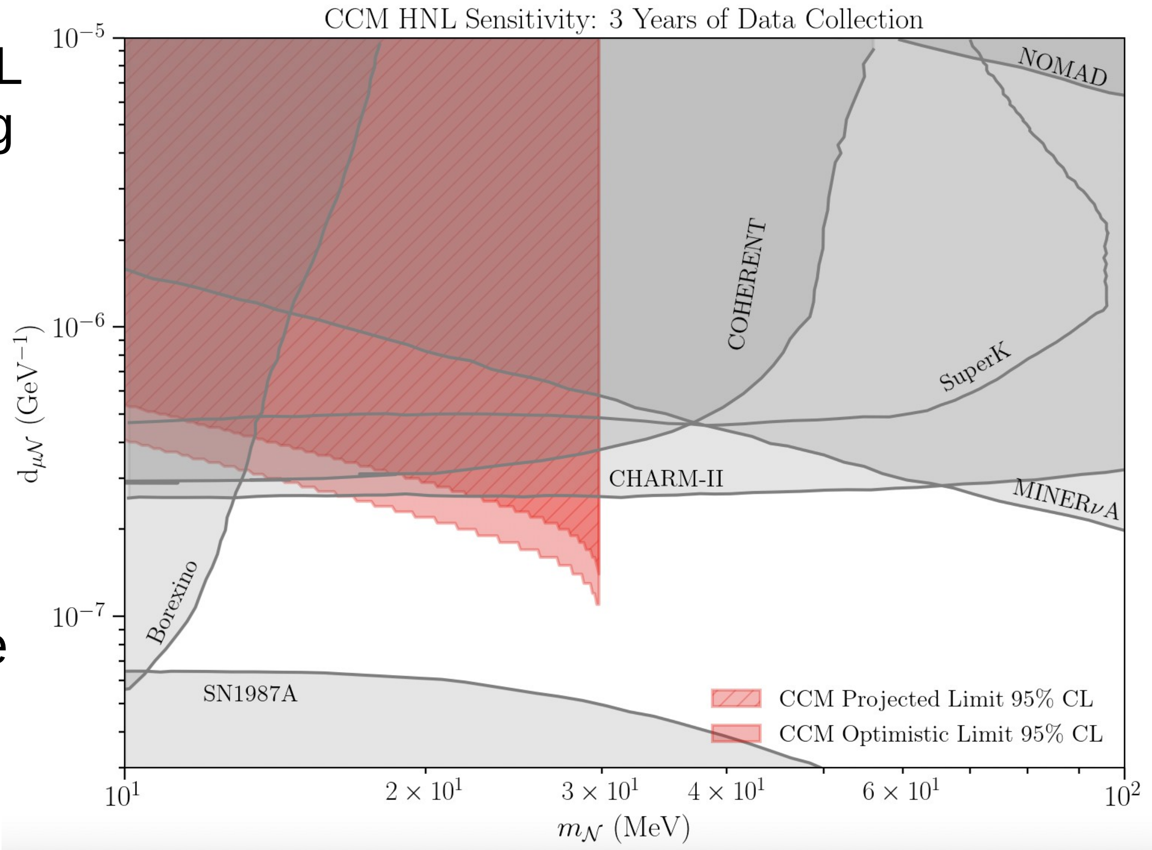


Heavy neutral lepton search

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

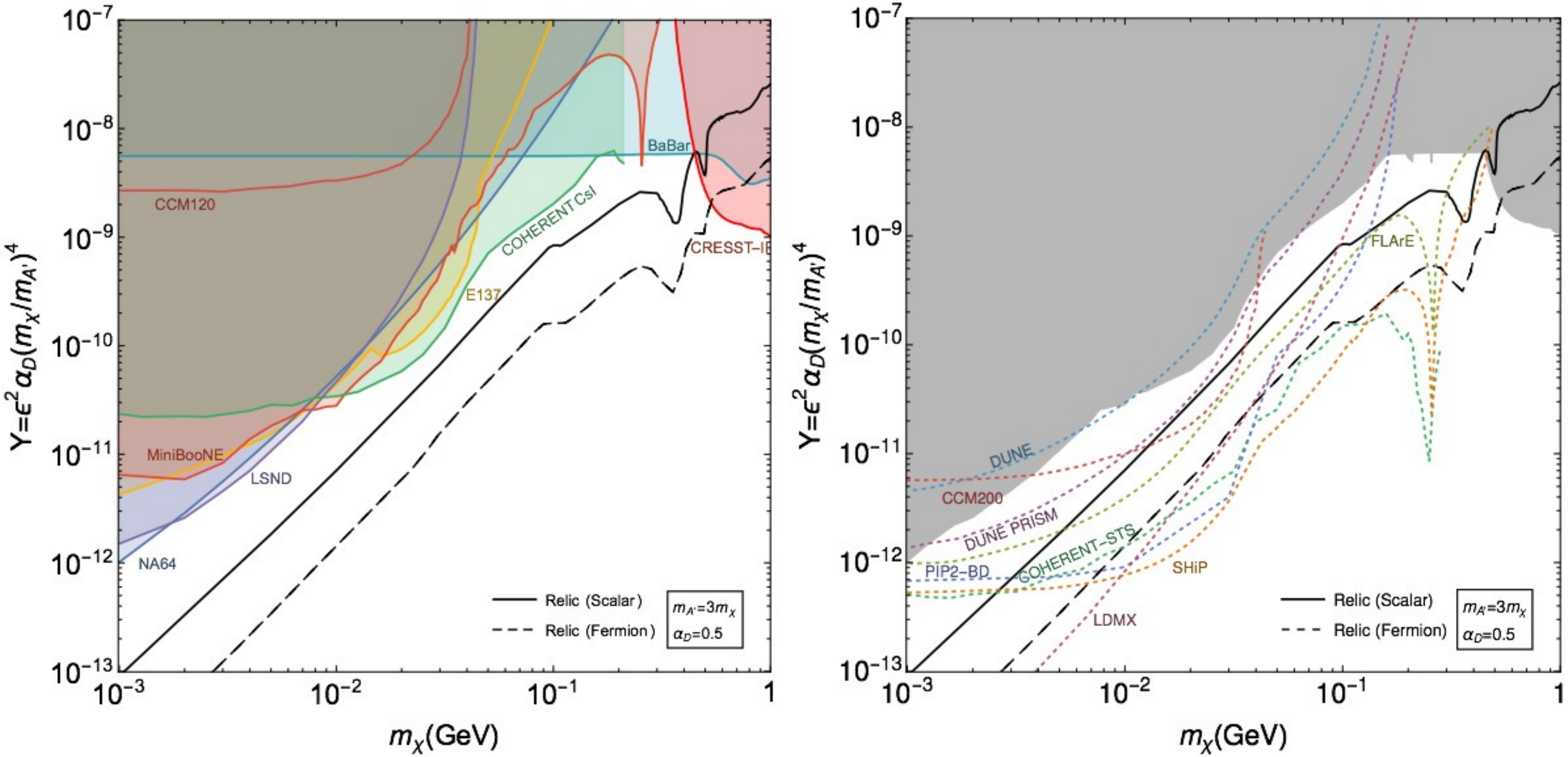


- Lujan facility is spacious enough to allow for increased shielding in future runs.



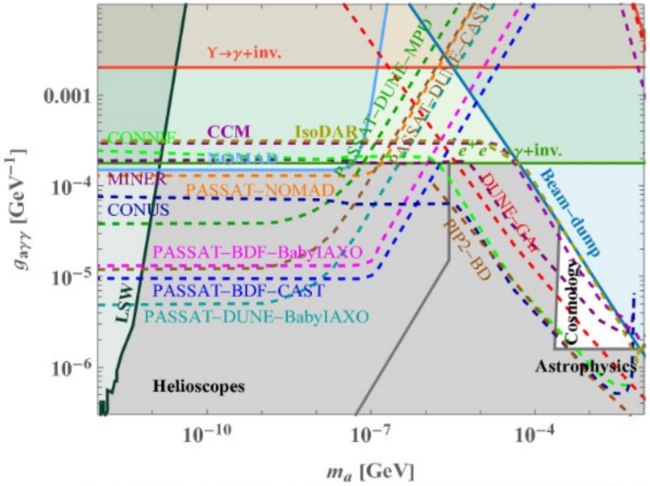
CCM at SNOWMASS 2022

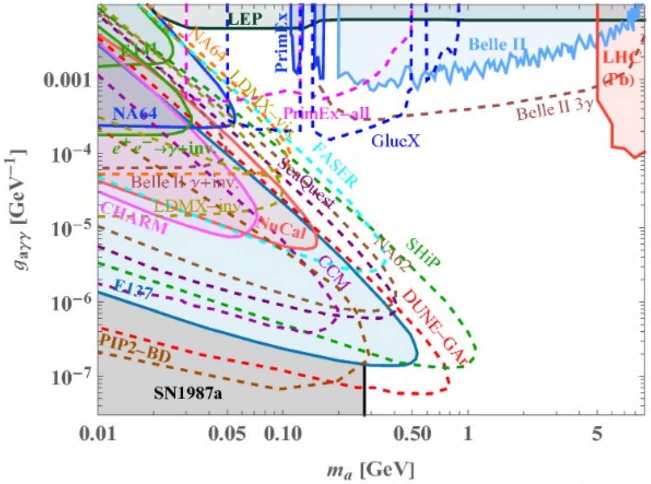
Vector Portal DM

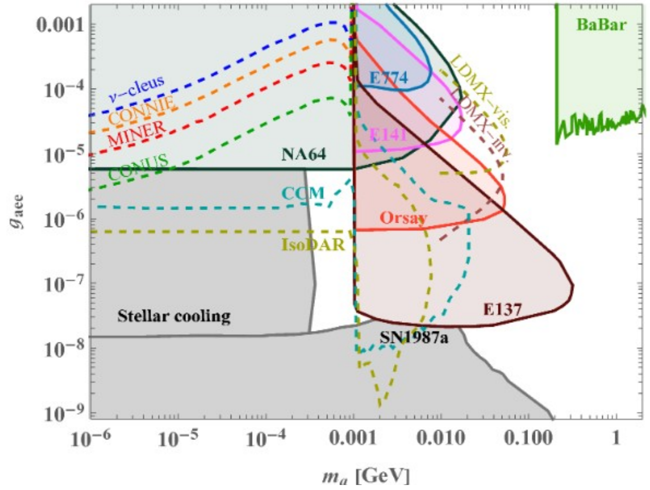


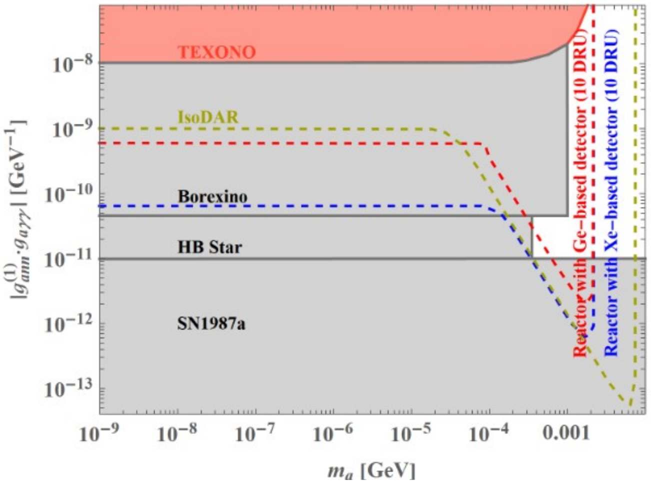
- **CCM (with UGAr) can cover new DM parameter space near term, other experiments further into the future.**
- **Lots of future searches!**

CCM at SNOWMASS 2022





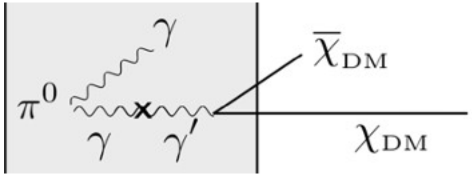




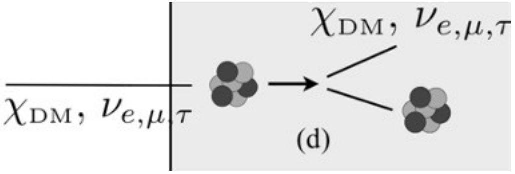
- CCM can cover new interesting axion parameter space now.
- No near-term competition in cosmic rectangle region (g_{ae}).
- Competition from reactor experiments in cosmic triangle region (g_a).
- Testing astrophysical limits.

CCM DM production and detection

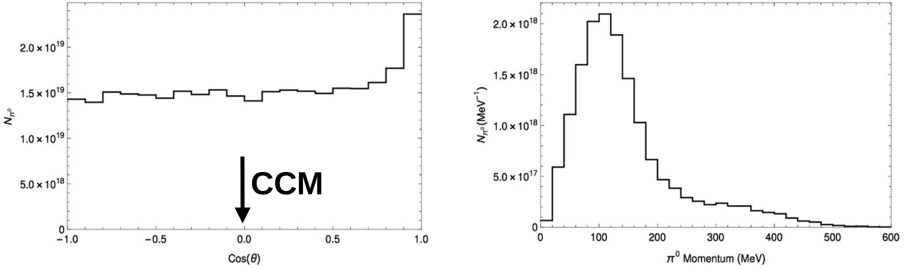
Production: DM couples to Lifetime – 8.5 x 10^{-8} nsec



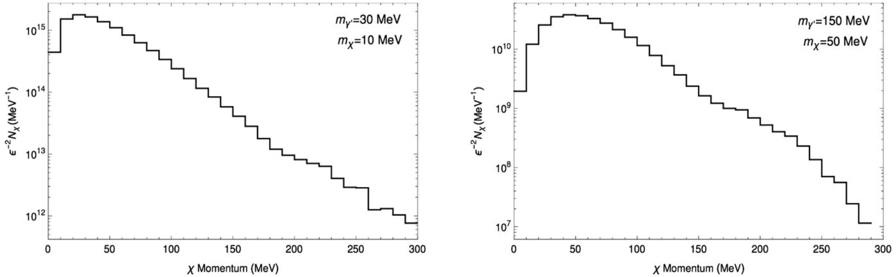
Detection: DM coherently scatters off Argon – 10 to 100s keV recoil



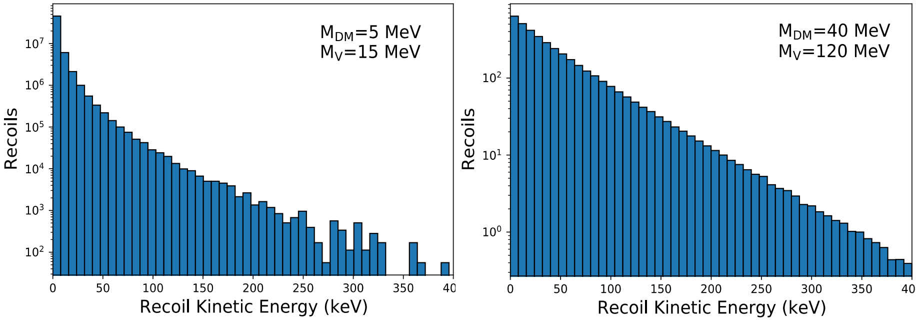
MCNP modeling of in Lujan Tungsten Target



Generated π⁰ kinematics



Generated dark matter momentum



DM recoil spectrum off Argon

Prompt neutrino endpoint 50 keV

BdNMC code, deNiverville, *et. al*. arXiv:1609.01770