Simulating low-energy charged-current electron neutrino interactions on argon in the CCM experiment

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on behalf of the CCM collaboration

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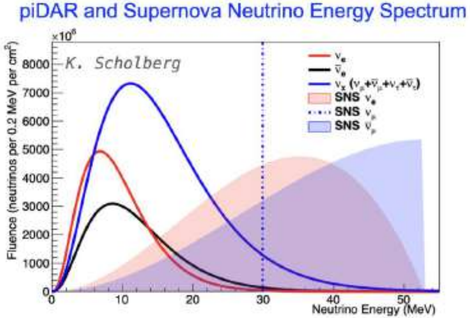
Outline

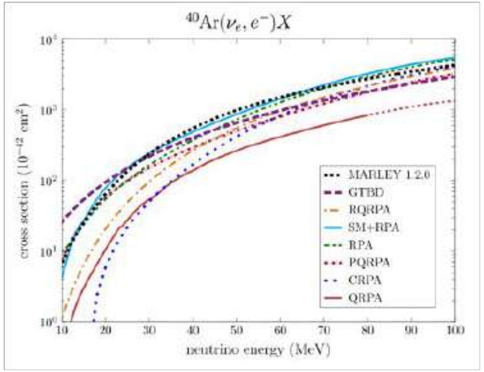
- Motivation
- The CCM experiment and detector
- Particle production and CC scattering
- Simulation
- Background
- Cherenkov light
- Takeaways

Motivation

Why study the interaction of ν_e with Ar at low Energies?

- Neutrinos: "**messengers of the universe"**.
- **Supernovae** emit millions of **neutrinos (E<50 MeV)** within a few seconds, which can reach the Earth and be detected.
- New generation of ton-scale particle detectors (e.g. **DUNE, SBND**) is based on **liquid Argon technology.** Aim to observe this signals
- **No measurements** of this cross section for low E in Ar! (KARMEN and LSND measurements (2001) in ^{12}C).
- **Model predictions** for the total Xsec vary up to a factor of 2: A measurement with 50% uncertainty would significantly improve constraints and help validate theoretical nuclear models.
- Measuring this XSec is critical for **DUNE** and multimessenger exploration via **SNEWS**, **core-collapse** supernova detection

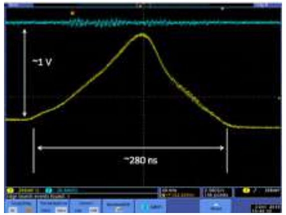




DEEP UNDERGROUND NEUTRINO EXPERIMENT

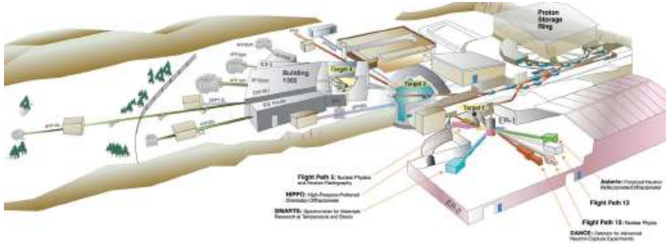
The Coherent CAPTAIN Mills (CCM) experiment

- Located at **Los Alamos,** New Mexico, USA. LANSCE, LANL.
- Accelerator experiment with **800 MeV proton pulsed beam** hitting a Tungsten Target from above (90° wrt beam) at 20 Hz.
- ~ 3.1×10^{13} protons per bunch in a **triangular time distribution** of 280 ns.



- **International collaboration** ~50 members

  México (ICN-UNAM): Alexis Aguilar, Juan Carlos D'Olivo,
  Cristian Macias, Marisol Chávez



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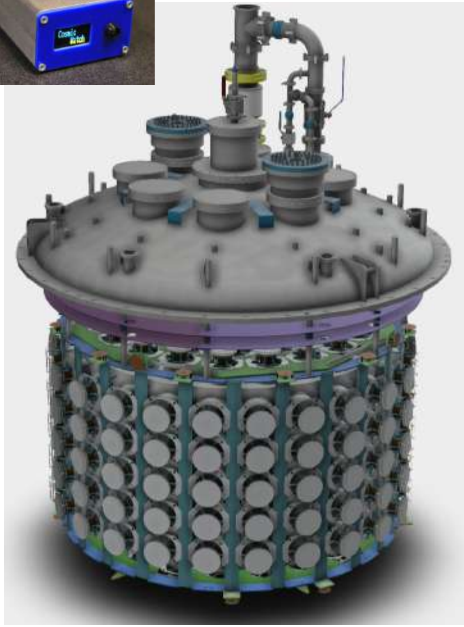
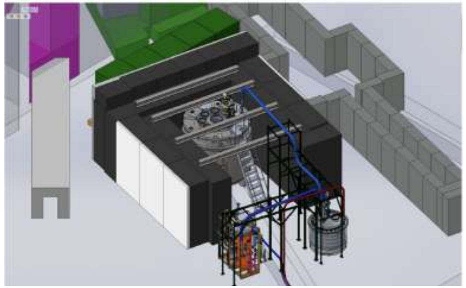
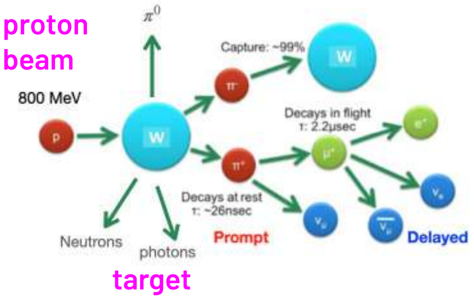
The CCM detector



- Cylindrical cryostat with a **10 ton Liquid Argon** (LAr) capacity at 88K
- Located at **23 meters** from Tungsten target
- Instrumented with **200 8" Photomultiplier Tubes** (PMTs) inside the 7 ton fiducial region and 1" PMTs in a 3 ton veto region optically isolated.
- MIT Muon portable detectors **"Cosmic Watches"** on top of the detector
- Detection system: **Scintillation and Cherenkov light.** No TPCs.
- Dynamic **energy range** from **~100 keV to 10 GeV**
- Resolution: **~2 ns (time), ~5 cm (position), 20% energy.**
- Surrounding **shielding:** lead, concrete,steel, borated polyethylene

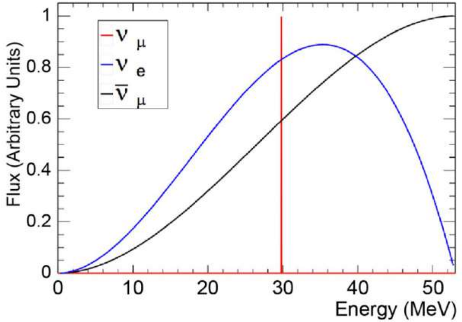


Neutrino production and Charged Current scattering



- Neutrons, photons, pions and other particles are produced **in target**

- π- are absorbed
- π+ DAR → **prompt signal**.
- muon decays in flight → **delayed signal**.



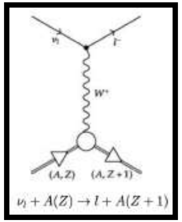
$$\pi^+ \to \mu^+ + \nu_\mu \qquad (\tau_\pi = 26 \text{ ns "prompt"}) \qquad E_{\nu_\mu} \sim 30 \text{ MeV}$$

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e \qquad (\tau_\mu = 2200 \text{ ns "delayed"}) \qquad E_{\nu_e,\bar{\nu}_\mu}: \ 0 - 52.8 \text{ MeV}$$

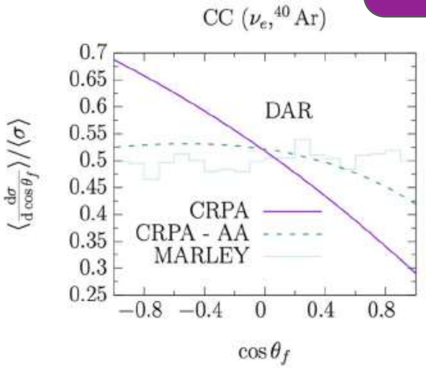
Matches supernova range

- ν_e **interact** in Liquid Argon:

$$\nu_e \ + \ ^{40}Ar \to e^- \ + \ ^{40}K^*$$

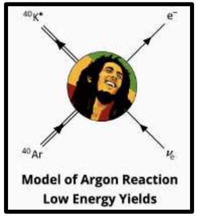


- CC Cross Section has **angular sensitivity.** Differences between models
- Reconstructing **electron direction** will help **constrain** xs models.



CC Simulation in CCM

•**Stage 1:** Neutrino Primary **Vertex injection** (SIREN + MARLEY)



Fermilab

SIREN (Sampling and Injection for Rare EveNts)

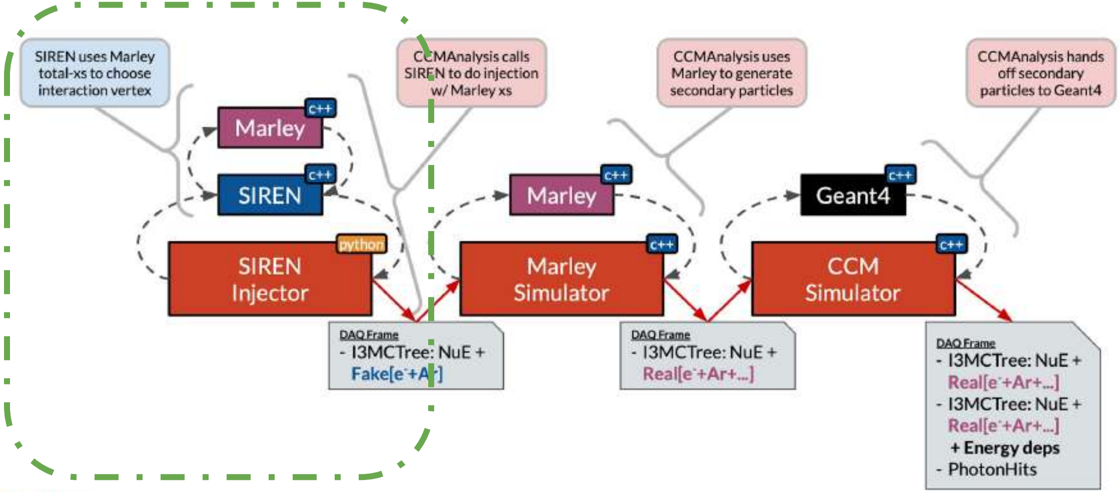
-**Injects and weights** interaction final states, with specific concern for the detector geometry.

-It makes use of the **total cross section** from MARLEY and the **neutrino flux**

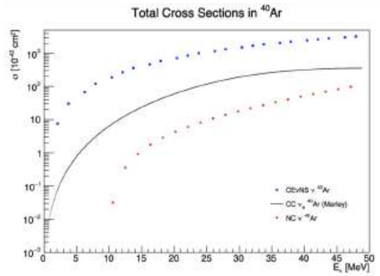
MARLEY

-Provides the cross section prediction.

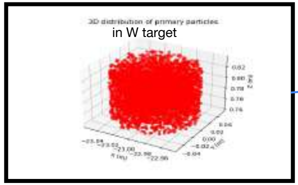
-Developed by **Steven Gardiner (Fermilab)**

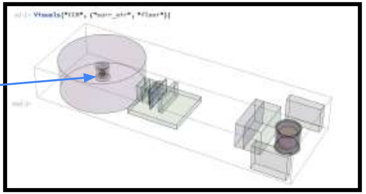


A. Schneider



$$\Phi_{\nu_e}(E_\nu) = \frac{192}{m_\mu}\left(\frac{E_\nu}{m_\mu}\right)^2\left(\frac{1}{2}-\frac{E_\nu}{m_\mu}\right)$$





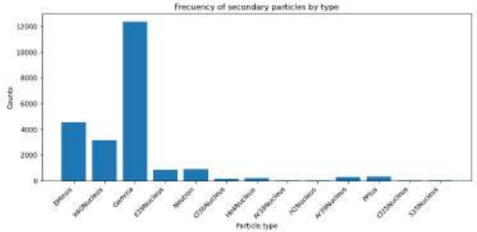
- Each of these stages are connected through the **CCMAnalysis framework**

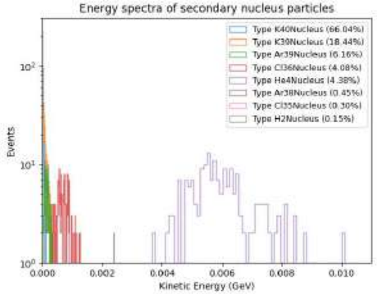
CC Simulation in CCM

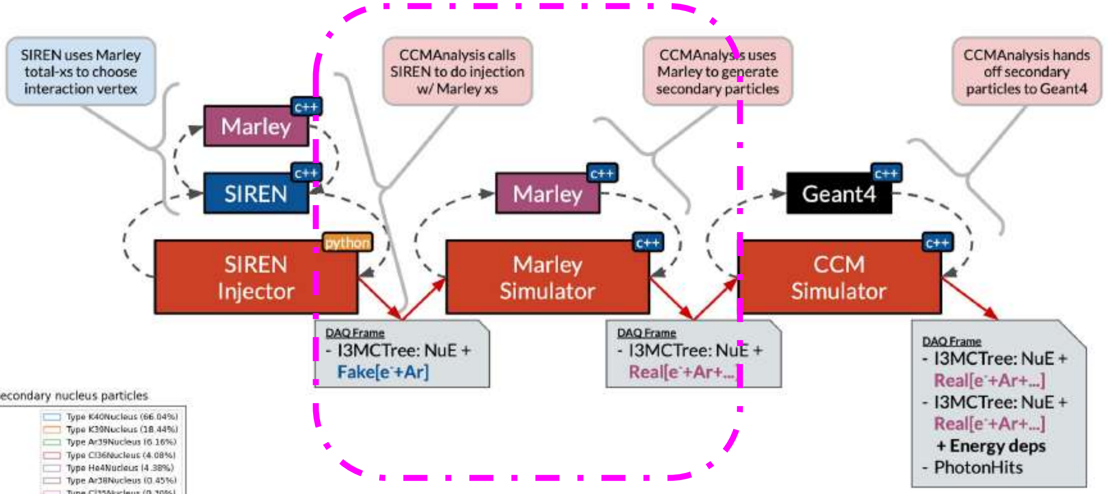
•**Stage 2:** Neutrino **Interaction with Argon** nuclei

-After electron neutrinos are injected in the CCM detector argon volume **MARLEY** generates the interaction process.

- For each interaction event, particles are produced. ^{40}K, e$^-$, γ, n, other nuclei, etc





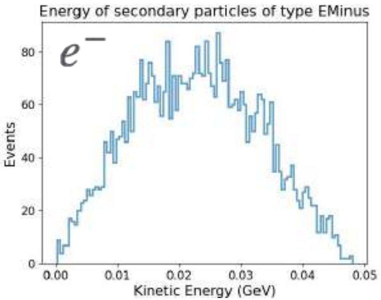


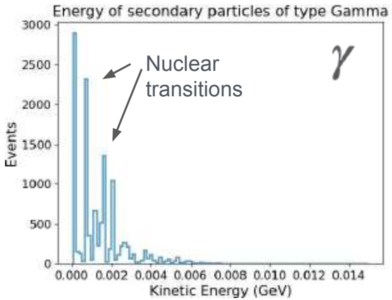
A. Schneider

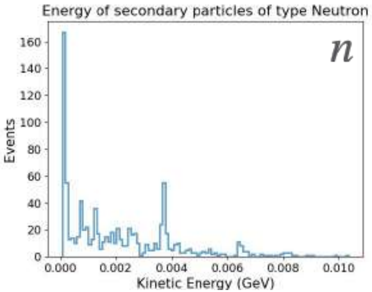
•Can **port** Injection (SIREN) and interaction with Ar (MARLEY) **to other detectors**

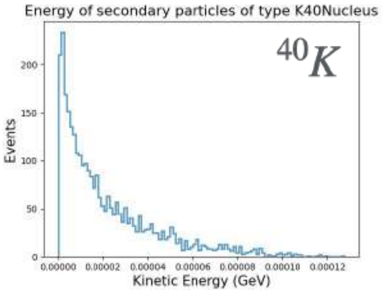
CC Simulation in CCM

- **Energy spectra** of some of the secondary particles (e, gammas, neutrons, K40)

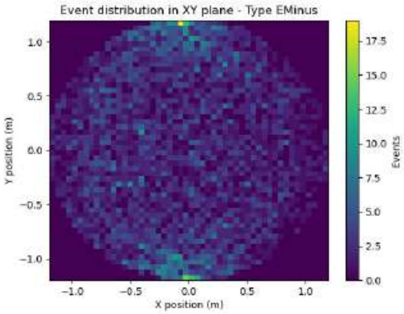


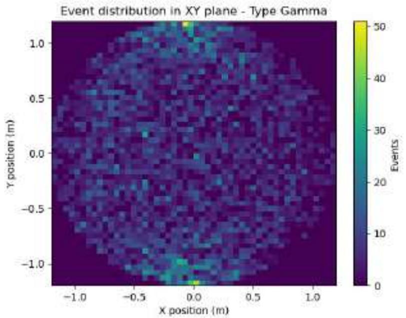


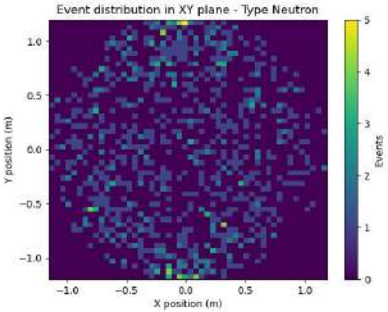


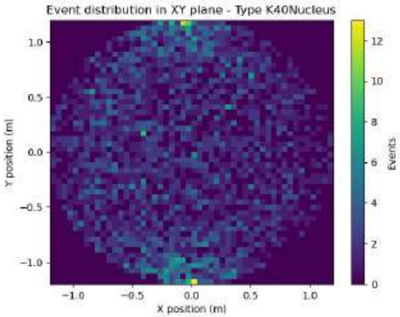


- **Spatial Distribution (XY)** in the CCM detector









CC Simulation in CCM

•**Stage 3:** MC simulation with Geant 4

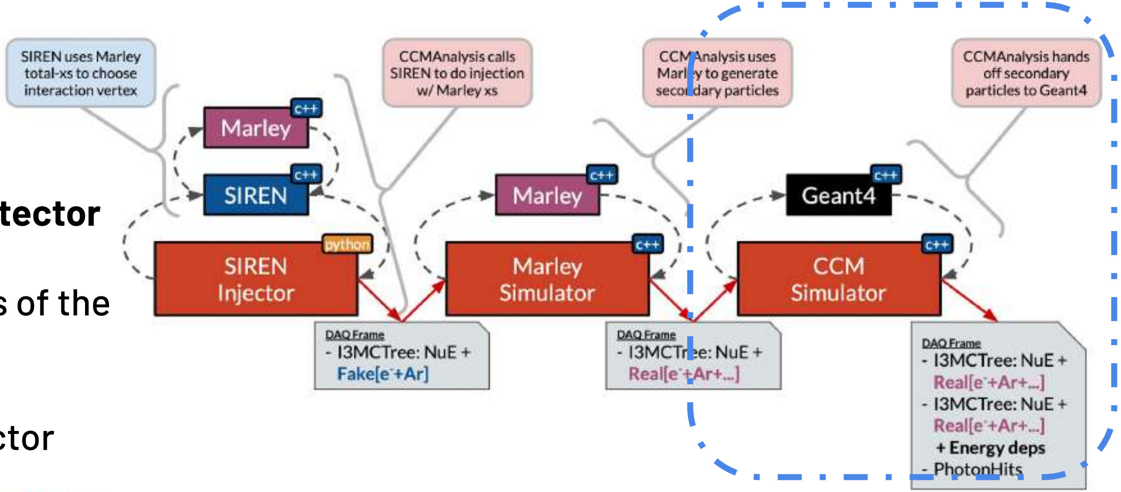
Geant4

-Simulates **propagation** of all the particles produced previously by Marley into the **detector**

- **Detailed geometry** and **optical** properties of the detector , **PMT response**

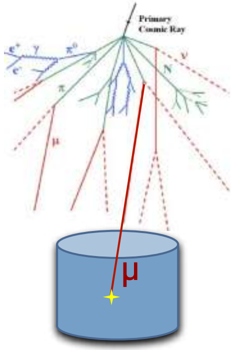
-Retrieves **Energy depositions** in the detector and **photon production and propagation**

- Developed by Darcy Newmark and Austin Schneider (CCM)



A. Schneider

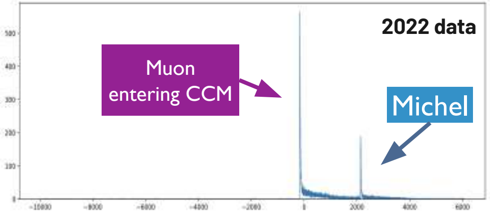
Background - Michel electrons



- **Cosmic Muons** constantly arrive to CCM, some of them enter the detector and stop

Cosmic watches are used for tagging muons

μ^- Decay in Orbit (DIO) : 24%
-Muon binds to the 1S (K-Shell) atomic orbital forming a **muonic atom**
-Decays via: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$
-Produces Michel electrons

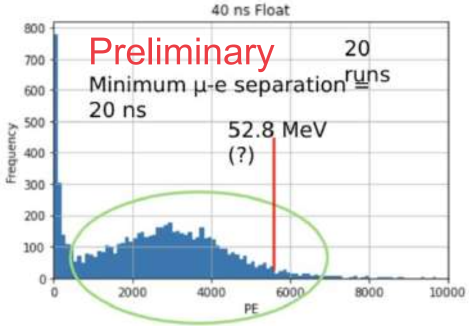


- Michel electrons can **mimic the CC signal** in the detector
  -Irreducible background for searching low E CC-neutrino interactions
  -Differentiate at the distribution level
  -Reduce rate with **muon veto**

- ~**1%** of muons that enter the detector **stop** and decay

- **2.18 x 10^{-7} Michels/trigger** in the detector within a **6 μs** region of interest

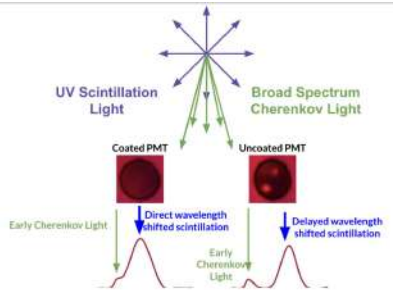
- **Simulation** (Cristian Macías) and **data analysis** (Darrel Smith) efforts in progress for **energy calibration.**

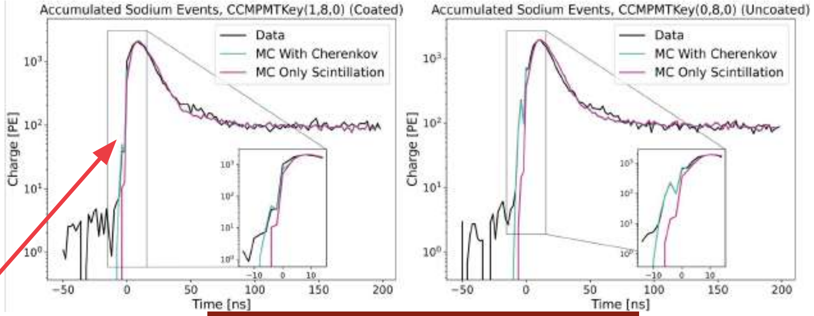


Michel Energy spectra (2022 Data)

Reconstruction with Cherenkov light in CCM

- Allows us to **discriminate between different particle types** (PID)
  - Present in **E/M events**, but not in nuclear recoils, and less in hadronic activity
- **Electron neutrino** (ν_e) CC interactions: can reconstruct outgoing electron direction
- **Michel electrons** have an **isotropic angular distribution**
  - Uncorrelated with beam or source direction, unlike true neutrino-induced electrons
- Cherenkov-based angular distribution:
  - **Statistically distinguish signal (directional) from background (isotropic)**
  - Improving the overall signal-to-background ratio
- Training ML reconstruction to reproduce electron energy, position, and direction
- **CCM did the First observation of Cherenkov light in liquid argon produced from sub-MeV particles !! D. Newmark**





D. A. Newmark, dnewmark@mit.edu

Takeaways

- The CC ν_e-Ar interaction **cross section** at low energies **remains unmeasured.**
Critical for supernova detection and future LAr experiments like **DUNE**.

- **CCM** is **capable** of **measuring** it!!

- Theoretical **models disagree** by up to a factor of 2, simulation helps constrain and validate them.

- Our **full simulation chain** is implemented: SIREN + MARLEY + Geant4 + CCMAnalysis. The injection and interaction stages are **portable to other detectors** with LAr.

- **Cherenkov** light in LAr offers **directional separation** between **signal** and **background** , and CCM achieved the **first observation from sub-MeV particles using Cherenkov!**

- This work lays the **foundation** for a **future cross section measurement** of ν_e-Ar in the tens-of-MeV regime.

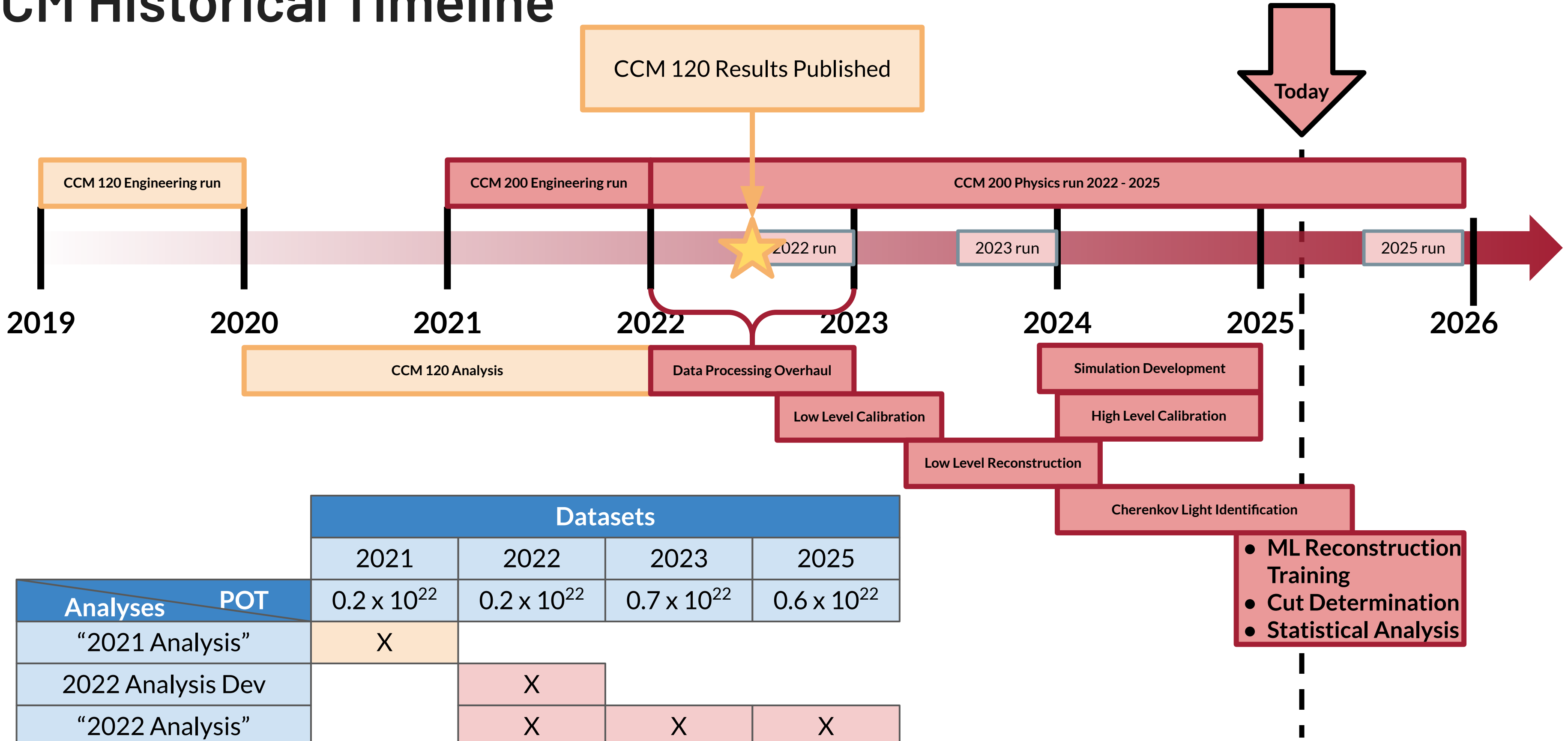
Thanks for listening!

We acknowledge support of DGAPA UNAM Grant PAPIIT-IN104723

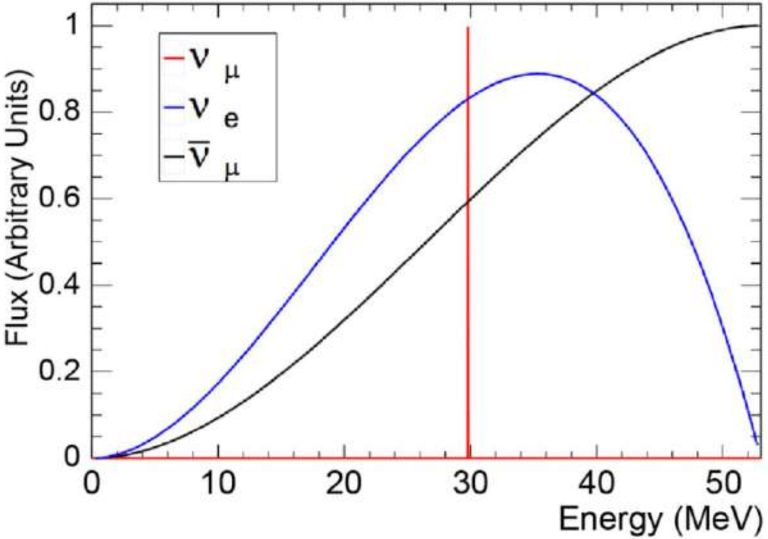
A.A. Aguilar-Arevalo,[8] D. S. M. Alves,[6] S. Biedron,[9] J. Boissevain,[1] M. Borrego,[6] M. Chavez–Estrada,[8] A. Chavez,[6] J.M. Conrad,[7] R.L. Cooper,[6,10] A. Diaz,[7] J.R. Distel,[6] J.C. D'Olivo,[8] E. Dunton,[2] B. Dutta,[11] A. Elliott,[4] D. Evans,[6] D. Fields,[9] J. Greenwood,[4] M. Gold,[9] J. Gordon,[4] E. Guarincerri,[6] E.C. Huang,[6] N. Kamp,[7] C. Kelsey,[6] K. Knickerbocker,[6] R. Lake,[4] W.C. Louis,[6] R. Mahapatra,[11] S. Maludze,[11] J. Mirabal,[6] R. Moreno,[4] H. Neog,[11] P. deNiverville,[6] V. Pandey,[5] J. Plata–Salas,[8] D. Poulson,[6] H. Ray,[5] E. Renner,[6] T.J. Schaub,[9] M.H. Shaevitz,[2] D. Smith,[4] W. Sondheim,[6] A.M. Szelc,[3] C. Taylor,[6] W.H. Thompson,[6] M. Tripathi,[5] R.T. Thornton,[6] R. Van Berg,[1] R.G. Van de Water,[6] S. Verma,[11] and K. Walker[4]
(The CCM Collaboration)

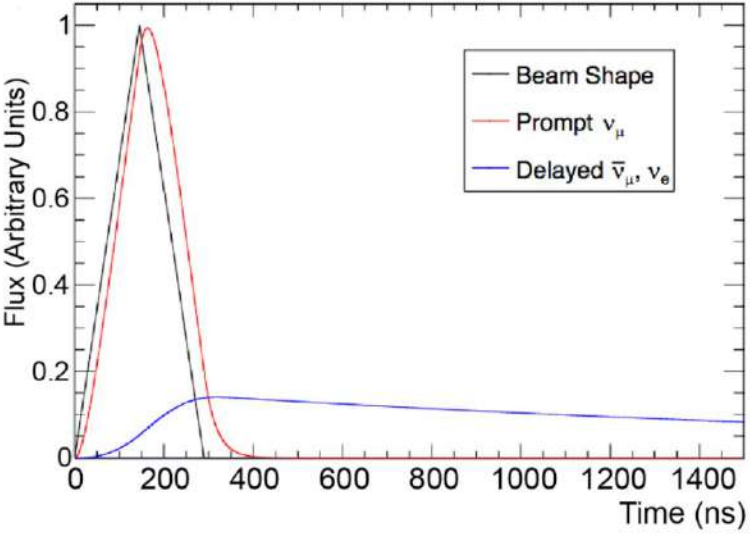
Backup slides

CCM Historical Timeline



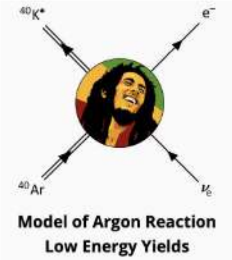
	Datasets			
	2021	2022	2023	2025
Analyses / POT	0.2×10^{22}	0.2×10^{22}	0.7×10^{22}	0.6×10^{22}
“2021 Analysis”	X			
2022 Analysis Dev		X		
“2022 Analysis”		X	X	X





Estimated ν flux: $3.9 \times 10^5\ \nu\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at 23 m for each neutrino flavor.

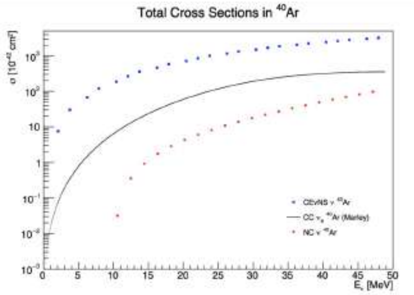
Cross section prediction



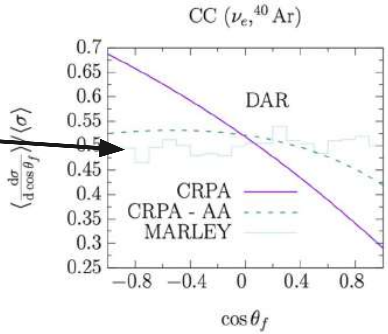
- **MARLEY** (Model of Argon Reaction Low Energy Yields) provides the cross section prediction.
  Developed by **Steven Gardiner**

Fermilab

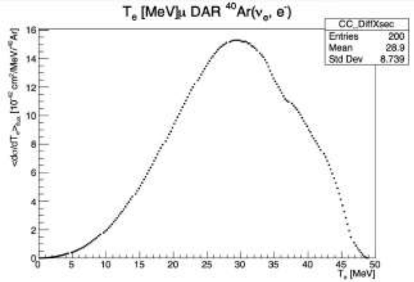
- Includes the **allowed approximation** (long-wavelength (q->0) and slow nucleons ($p_N/m_N \rightarrow 0$ limit) and **Fermi and Gamow-Teller** matrix elements.



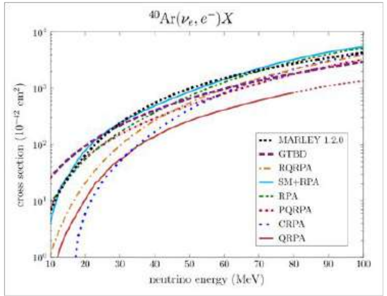
- MARLEY predicts a nearly **flat angular distribution.**
- Other models like CRPA include full expansion of nuclear matrix element (allowed as well as forbidden transition), predict more **backwards** strength.



CC xs has angular sensitivity. Reconstructing electron direction will help constrain xs models.
Critical for DUNE: Multimessenger exploration via SNEWS



- **Model predictions for the total cross section vary by up to a factor of 2** (~100%) → even a measurement with **50% uncertainty** would significantly improve constraints and help validate theoretical models.



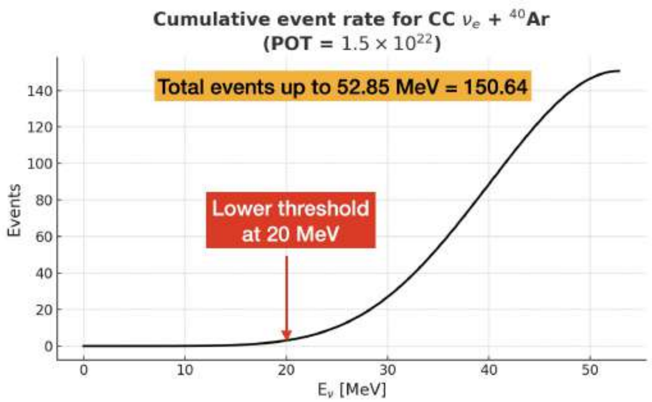
Total expected events in CCM

- Assuming **5 Tons** of LAr, **1.5 x 10^{22} POT** (2022+2023+ 2025 data) , and a **75% efficiency** in the CCM detector:

$$N_{ev} = \int N_T \cdot \phi \cdot \sigma \cdot \epsilon \, dE_\nu$$

CC Events in CCM at 23 m, for 5 tons of LAr, E_ν :[0, 52.85 (=$m_\mu/2$) MeV] .

Total events/3 years	Total events/ year	Total events/ year. (Eff=75%)
150.64	50.21	37.7

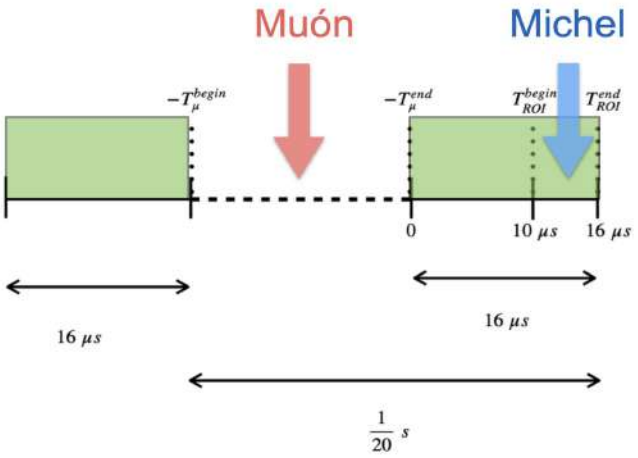


- Dominant source of error:
  - **Uncertainty in neutrino flux** ~10%.
    (Based on LSND-like source 7%)
    Derived from pions/proton production
- **Detector systematic error:**
  - Uncertainty on energy threshold: 4%
    Due to 20% energy resolution
- **Total estimated error on CC cross section: 16%**
  Includes systematic and statistical errors

- There is an extra **0.9 x 10^{22} POT** on disk currently (2021 data)
  Total events: 150.64 -> 180.766

Michel electrons Background estimation

- We assume that the muon entering the detector does in between two DAQ windows, making it impossible to observe directly.
- This muon produces a Michel electron within the DAQ window, particularly in a Region of Interest (ROI) relevant to our analysis.



- Considering that only 1% of muons entering the detector stop and decay into a Michel electron:

2.18×10^{-7} events/trigger

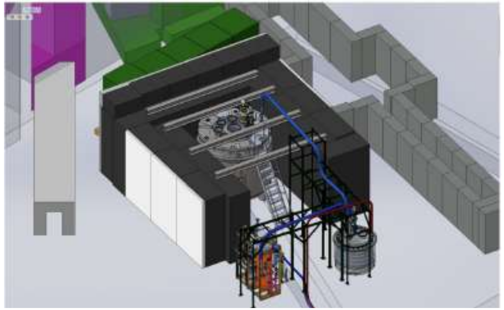
Backgrounds for CC search

Beam related	Solution
Time Related: **Neutrons from the beam**	Shielding, time cuts in data
Non time related: **Neutron activation**: emission of gamma, alpha, beta, neutrons, and fission products	Quality cuts, energy cut, measurement

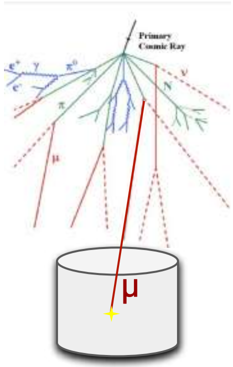
Non beam related	Solution
Cosmogenic neutrons	PID
Michel electrons: from cosmic muons	Veto cuts, Muon identification

W target shielded : surrounding 5m of steel, 2 m of concrete.

CCM Shielded: surrounding walls, roof and under the cryostat
Concrete, Steel, Borated Polyethylene, Lead



Michel electrons



- **Muons** constantly arrive to CCM, some of them enter the detector and stop:

μ^+
Experience repulsion from the nucleus
They are not captured
Decays freely $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
Lifetime: 2.197 us

Cosmic watches are used for tagging muons

μ^-
Captured by an atom.
Two possible processes:

Decay in Orbit (DIO) : 24%
-The muon binds to the 1S (K-Shell) atomic orbital forming a muonic atom
-Decays via:
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$
-This is not a free decay!!

Michel electrons

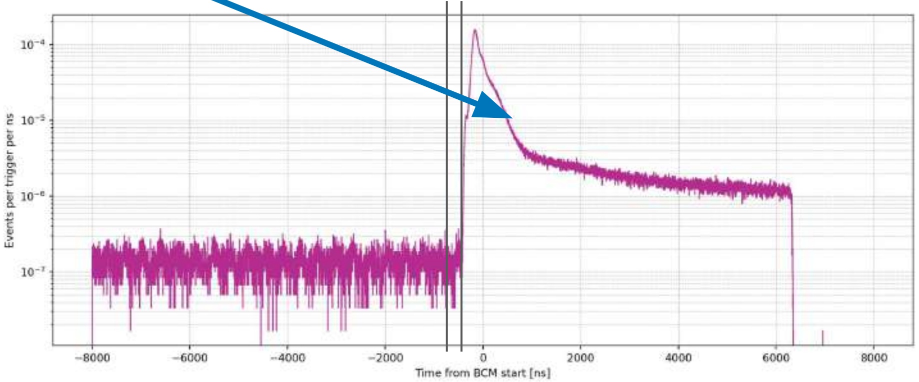
Nuclear capture: 76%
-The muon is absorbed by a proton In the nucleus:
$$\mu^- + p \rightarrow n + \nu_\mu$$
-No Michel electron is produced

μ- Lifetime in Argon: 537 ns

Neutrons

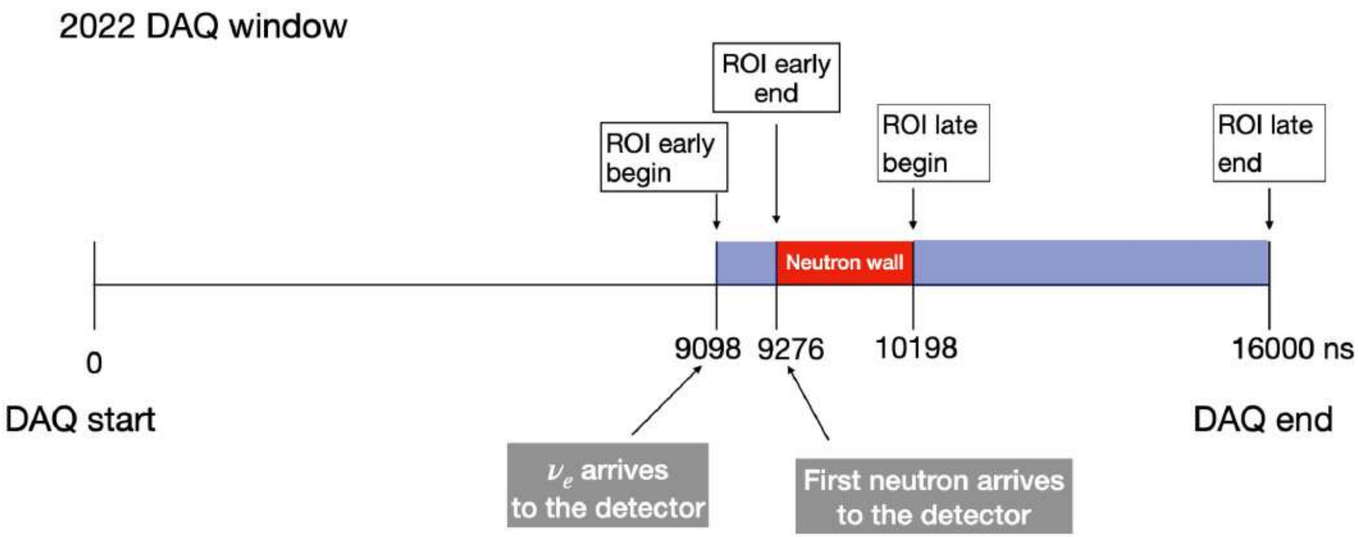
- Large number of neutron interactions post-beam
- Combination of cuts will remove most of these
  - Fiducial volume cuts
  - Event quality cuts
  - Triplet to singlet ratio cuts
  - Particle identification
    - Leveraging Cherenkov light
- Need a reduction of ~10^3 to get to 20% xs. sens.

Events between 1500PE and 2000PE. Before any cuts



Data Selection

- If neutron rate is too high post-cuts, we can leverage timing to reduce backgrounds
- Defining two ROI: early and late

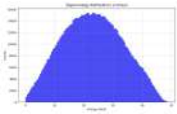


Early ROI length: 178 ns
Late ROI length: 5802 ns

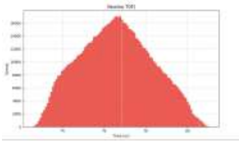
Statistical Analysis (MC)

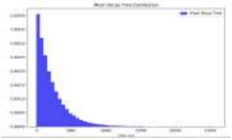
Signal distribution

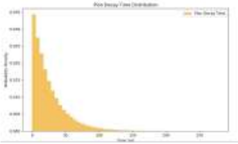
- Energy dist:
  - Energy of the outgoing electron produced after the interaction in LAr (SIREN+MARLEY)

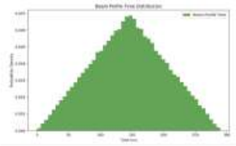


- Time dist combines:
  - Time when neutrino hits the detector (SIREN+MARLEY)
  - Time of pion decay
  - Time of muon decay
  - Triangular beam profile (pulse width =290 ns)





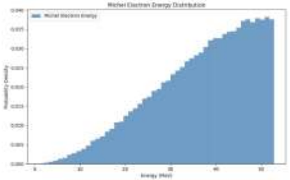




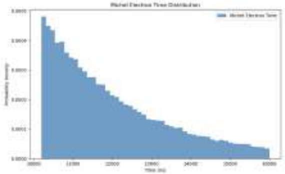
Background distribution

Considering only Michel electrons

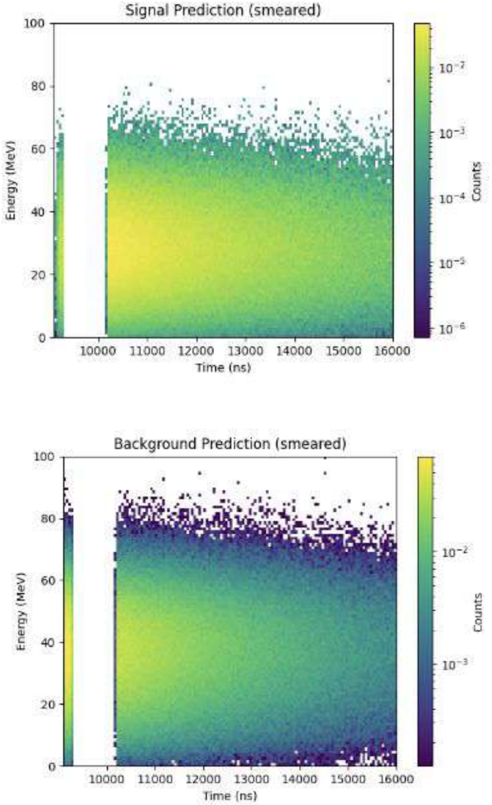
- Energy dist:

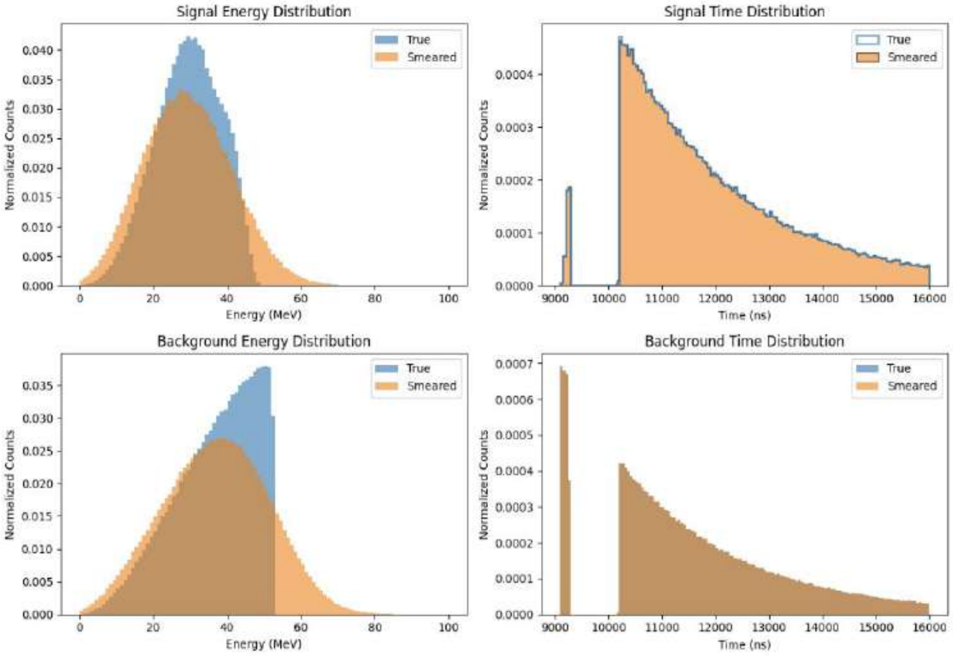


- Time dist:



Statistical Analysis (MC) (cont)





Data Selection

- Signal $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

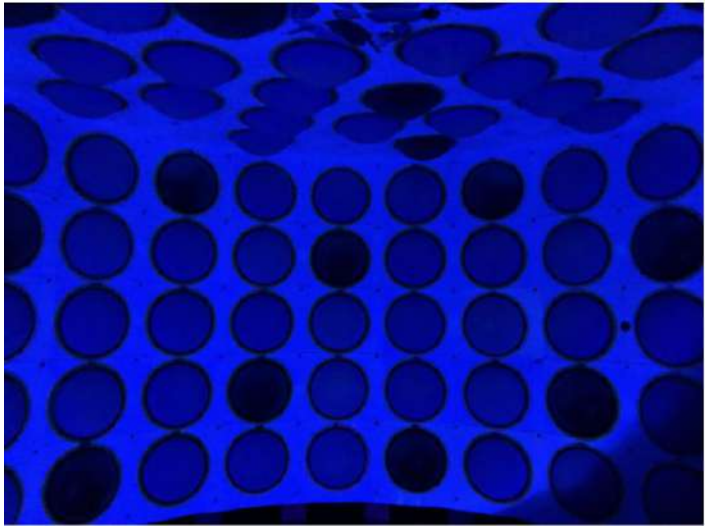
The outgoing electron usually carries most of the energy ~ 20–50 MeV : KEY SIGNATURE FOR SIGNAL ID (Similar E range than Michel electrons)

A non-negligible fraction of the neutrino energy is lost to nuclear binding energy, nuclear excitation, and the kinetic energy of emitted particles (protons, neutrons).

- Starting cuts in data:

Time	Define early/late ROI’s
Energy	Focus on the 20-50 MeV range to match the electron signal
Fiducial volume	Reduce edge-related backgrounds
Muon Veto	Use PMT’s in veto region and cosmic watches to tag incoming muons
Cherenkov-based directionality	Exploit isotropic vs directional separation

Coated and uncoated PMTs



The cryostat

Physics program at CCM

- CCM is an experiment that explores the search for SM, BSM and Dark Sector physics, such as **leptophobic dark matter, axion-like particles, meson portal models, and neutrino interactions.**

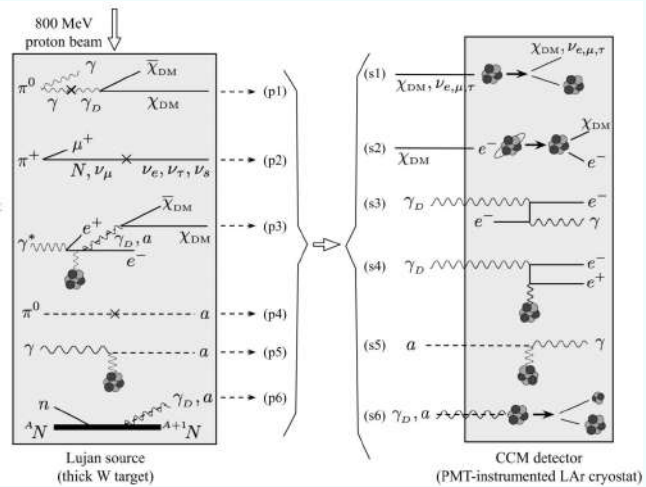
- **Publications:**
  -First Leptophobic Dark Matter Search from the Coherent–CAPTAIN-Mills Liquid Argon Detector (PRL)
  -First dark matter search results from Coherent CAPTAIN-Mills (PRD)
  -Prospects for detecting axionlike particles at the Coherent CAPTAIN-Mills experiment (PRD)

Dark photons decay into Dark matter

Sterile neutrinos, oscillations

Dark photons decay into Dark matter

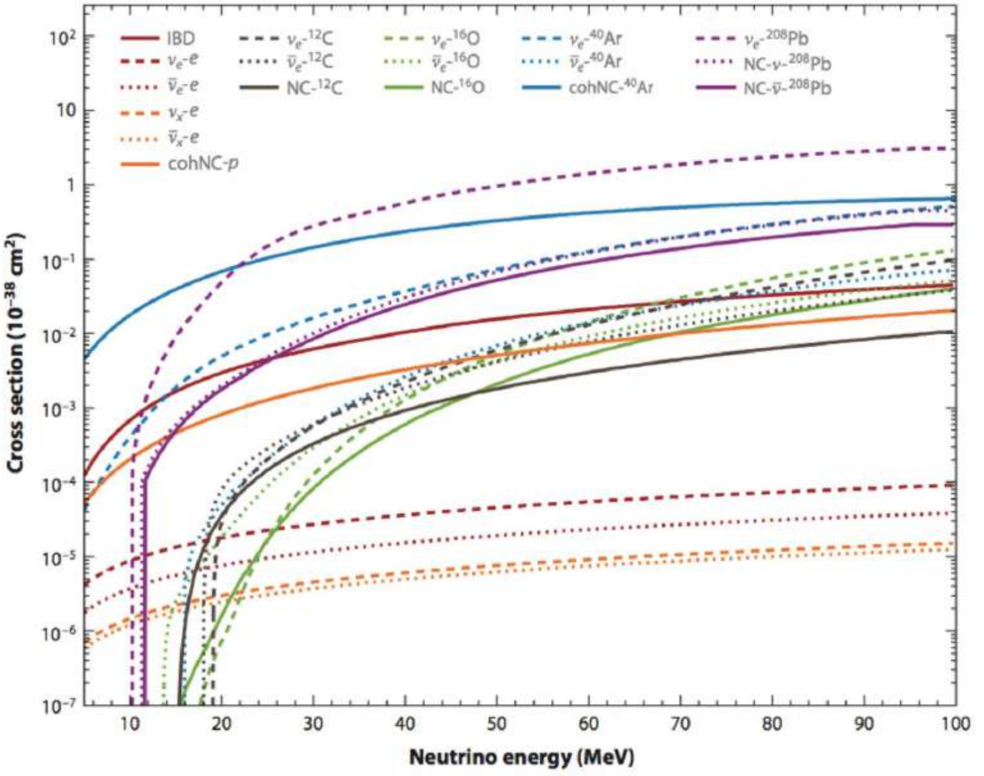
Axion like particles



Coherent scattering

Compton scattering

Cross Sections



Light production and detection in Argon

- **Detection mechanism: Scintillation light**

The ν_e is scattered by the Ar atom through the **CC** process:

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

Electrons can:

Ionize the Ar :

$$e^- + Ar \rightarrow e^- + Ar^+ + e^{-'}$$

$$Ar^+ + e^- \rightarrow Ar^*$$

(recombination)

Excite the Ar:

$$e^- + Ar \rightarrow Ar^* + e^{-'}$$

Both process lead to Ar^*

The excited Argon (Ar^*) combines with atoms of neutral Argon creating excimers:

$$Ar^* + Ar \rightarrow Ar_2^* \rightarrow 2Ar + \gamma$$

(Excimer)

Detected by PMTs

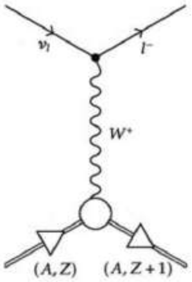
Photons VUV (128 nm)
Prompt component (singlet)~6 ns
Delayed component (triplet) ~1600 ns

The ${}^{40}K^*$ returns to its **ground state** or can **ionize** Argon as it travels through the medium, producing light

CC Scattering

Neutrino Charged Current Scattering

The scattering of the neutrino with the nucleus (A,Z) is mediated by a W boson, leading to a lepton and a nucleus (A,Z+1)



$\nu_l + A(Z) \rightarrow l + A(Z+1)$

For scattered off with Argon:

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

Cross Section:

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 |V_{ud}|^2}{32\pi (s - m_i^2)^2} F_C L_{\mu\nu} W^{\mu\nu}$$

$L_{\mu\nu}$ Leptonic Tensor

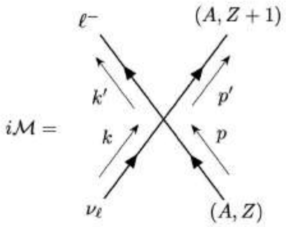
$W^{\mu\nu}$ Hadronic Tensor

$Q^2 \equiv -q^2$ 4-momentum transfer

$q^\mu = (k - k')^\mu = (p' - p)^\mu$

G_F Fermi constant

V_{ud} CKM Matrix element



m_i Initial nucleus mass

F_C Coulomb Factor (interaction of the e with the Coulomb field from the nucleus)

CC Scattering (cont)

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 |V_{ud}|^2}{32\pi(s - m_i^2)^2} F_C L_{\mu\nu} W^{\mu\nu}$$

Leptonic Tensor:

$$L_{\mu\nu} \equiv Tr[\gamma_\mu(1-\gamma_5)\not{k}\gamma_\nu(1-\gamma_5)(\not{k}' + m_l)]$$
$$= 8[k_\mu k'_\nu + k_\nu k'_\mu - g_{\mu\nu}(k \cdot k') - i\epsilon_{\mu\nu\rho\sigma}k^\rho k'^\sigma]$$

m_l Final lepton mass

Hadronic Tensor:

$$W^{\mu\nu} \equiv \frac{1}{2J_i + 1} \sum_{M_i} \sum_{M_f} \mathcal{N}^\mu \mathcal{N}^{\nu *}$$

J_i (J_f) Inicial (final) nuclear spin

M_i (M_f) Third component of the nuclear spin on its initial (final) state

$\mathcal{N}^\mu$ Nuclear matrix element

$$\mathcal{N}^\mu = \langle f | \sum_{n=1}^{A} e^{i\mathbf{q}\cdot\mathbf{x}(n)} j^\mu(n) | i \rangle$$

CC Scattering (cont)

$$\mathcal{N}^{\mu} = \langle f | \sum_{n=1}^{A} e^{i\mathbf{q}\cdot\mathbf{x}(n)} j^{\mu}(n) | i \rangle$$

$$W^{\mu\nu} \equiv \frac{1}{2J_i + 1} \sum_{M_i} \sum_{M_f} \mathcal{N}^{\mu} \mathcal{N}^{\nu *}$$

The current operator is evaluated under the allowed approximation:

Large wavelength () and the momentum of the nucleon y the moment of the struck nucleon is neglected with respect to its mass

Temporal component:

$$\mathcal{N}^{0} = \frac{g_V}{\sqrt{2J_i + 1}} \delta_{J_i J_f} \delta_{M_i M_f} \langle f || \mathcal{O}_F || i \rangle$$

Spatial component:

$$\mathcal{N}^{\omega} = \frac{-g_A (-1)^{J_i - M_i}}{\sqrt{3}} (J_f \; M_f \; J_i \; - M_i | 1 \; \omega) \langle f || \mathcal{O}_{GT} || i \rangle$$

$$\mathcal{O}_F \equiv \sum_{n=1}^{A} t_{-}(n)$$

$$\mathcal{O}_{GT} \equiv \sum_{n=1}^{A} \sigma(n) t_{-}(n)$$

Fermi and Gamow-Teller operators

Under this approximation, the hadronic tensor:

$$W^{00} = 4 E_i E_f B(F)$$

$$W^{ab} = \frac{4}{3} \delta_{ab} E_i E_f B(GT)$$

$$W^{0a} = 4 W^{a0} = 0$$

$$B(F) \equiv \frac{g_V^2}{2J_i + 1} \left| \langle J_f || \mathcal{O}_F || J_i \rangle \right|^2$$

$$B(GT) \equiv \frac{g_A^2}{2J_i + 1} \left| \langle J_f || \mathcal{O}_{GT} || J_i \rangle \right|^2$$

Fermi and Gamow-Teller Reduced matrix elements

Total energy of the nuclei in the initial (final) state

CC Scattering (cont)

Therefore the cross section:

Angular dependence!

$$\frac{d\sigma}{d\cos\theta_l} = \frac{G_F^2|V_{ud}|^2}{2\pi} F_C \left[\frac{E_i E_f}{s}\right] E_l |\mathbf{p}_l| \left[(1+\beta_l\cos\theta_l)\, B(F) + \left(1-\frac{1}{3}\beta_l\cos\theta_l\right) B(GT)\right]$$

Fermi and Gamow-Teller Reduced matrix elements

In the CM system the energies of the particle are independent of the scattering angle :

$$\sigma = \frac{G_F^2|V_{ud}|^2}{\pi} F_C \left[\frac{E_i E_f}{s}\right] E_l |\mathbf{p}_l| \left[B(F) + B(GT)\right]$$

To date there are no experimental data available for CC scattering of in argon in the MeV range.