

**Delayed gamma emission from
metastable nuclear de-excitation levels
using MARLEY for ν_e interactions in the
CCM experiment**

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on behalf of the CCM collaboration

Advisor: Dr. Juan Carlos D'Olivo Saez. ICN - UNAM

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Outline

- **Motivation**
- **The Coherent CAPTAIN-Mills (CCM) experiment**
- **Neutrino Production and Interaction**
- **De-excitation Gammas from ^{40}K**
- **Simulation**
- **Results**

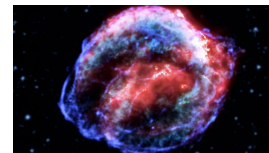
Motivation

Why study ν_e - Ar interactions at low Energies?

- Ton scale **liquid Argon** detectors are becoming central to neutrino physics (e.g. **DUNE, SBND**)
- A key physics target: detecting electron **neutrinos from core collapse supernovae** through the Charged Current interaction:



- **Cross section predictions** for this channel still have **large model uncertainties** at tens of MeV energies.
- Recent **DEAP-3600** results report evidence for ν absorption on Ar using ${}^8\text{B}$ solar neutrinos: averaged Total Xsec $(4.0^{+2.0}_{-1.6}(\text{stat})^{+0.8}_{-0.7}(\text{sys})) \times 10^{-41} \text{ cm}^2$ $2.4^{+1.3}_{-1.0}$ times greater than Bhattacharya prediction.
- **CCM** can provide a complementary measurement of ν_e -Ar CC in the **E<50 MeV** regime using **fast scintillation timing**.



piDAR and Supernova Neutrino Energy Spectrum

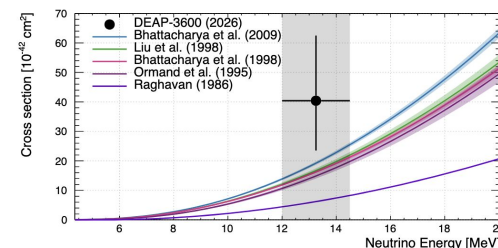
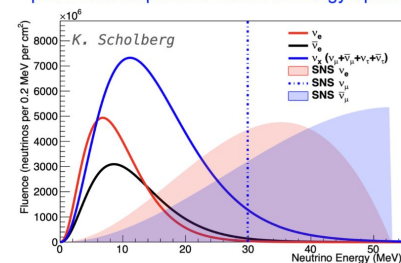
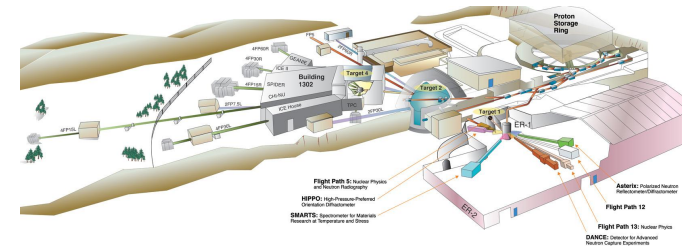
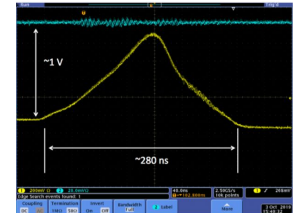
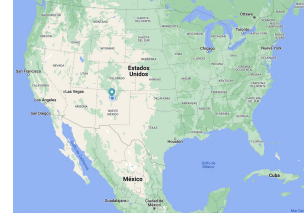


FIG. 2. Energy-averaged cross section result, compared with the energy-dependent cross section models Bhattacharya *et al.* [29][2], Liu *et al.* [30], Ormand *et al.* [31], and Raghavan [1].

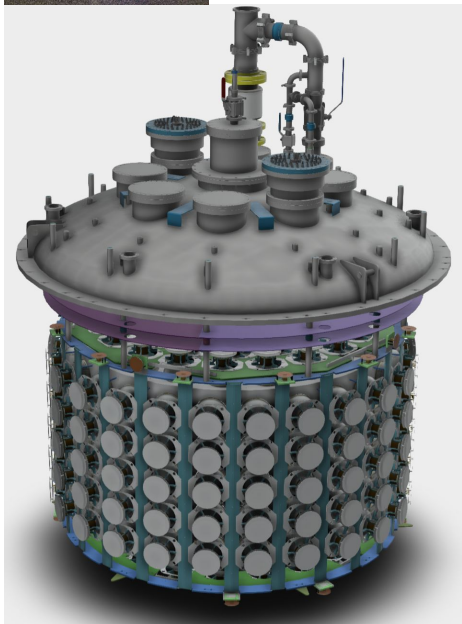
The Coherent CAPTAIN Mills (CCM) experiment

- 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

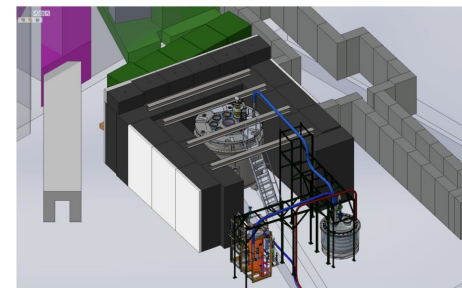
México (ICN-UNAM): Alexis Aguilar, Juan Carlos D'Olivo, Marisol Chávez



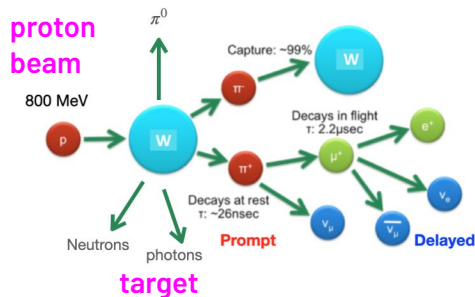
The CCM detector



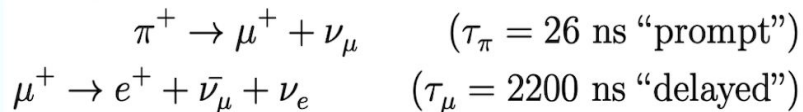
- Cylindrical cryostat with a **10 ton Liquid Argon (LAr)** capacity at 88K
- Located at **23 meters** from Tungsten target
- Instrumented with **200 8" Photomultiplier Tubes (PMTs)** inside the 7 ton fiducial region and 1" PMTs in a 3 ton veto region optically isolated.
- MIT Muon portable detectors "**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 ν_e -Ar interaction



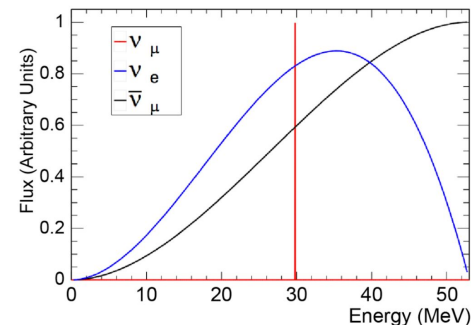
- Neutrons, photons, pions and other particles are produced **in target**
- π^- are absorbed
- π^+ DAR \rightarrow **prompt signal**.
- muon decays in flight \rightarrow **delayed signal**.



$$E_{\nu_\mu} \sim 30 \text{ MeV}$$

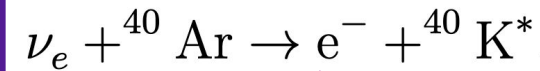
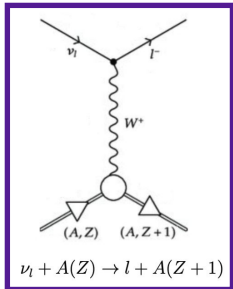
$$E_{\nu_e, \bar{\nu}_\mu} : 0 - 52.8 \text{ MeV}$$

Matches
supernova
range



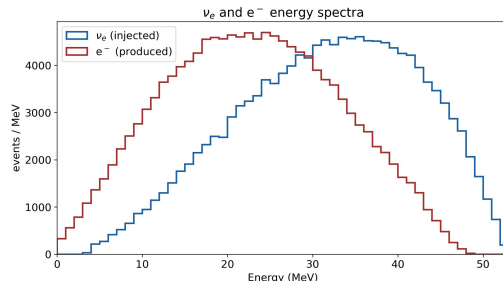
Neutrino production and ν_e -Ar interaction

- ν_e interaction in Liquid Argon:

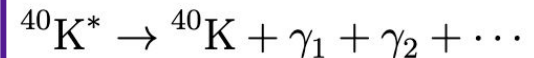


The outgoing e^- carries most of the energy ~20-50 MeV:
KEY SIGNATURE FOR SIGNAL ID
(Similar E range than Michel electrons)

Main prompt signal



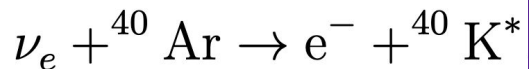
The excited Potassium decays to the ground level, leading to characteristic gamma emission cascades



Nuclear de-excitation gammas add visible energy to the signal

Key question: are these gammas prompt on CCM time scales?

De-excitation gammas



- Each gamma corresponds to a **transition** between nuclear levels:

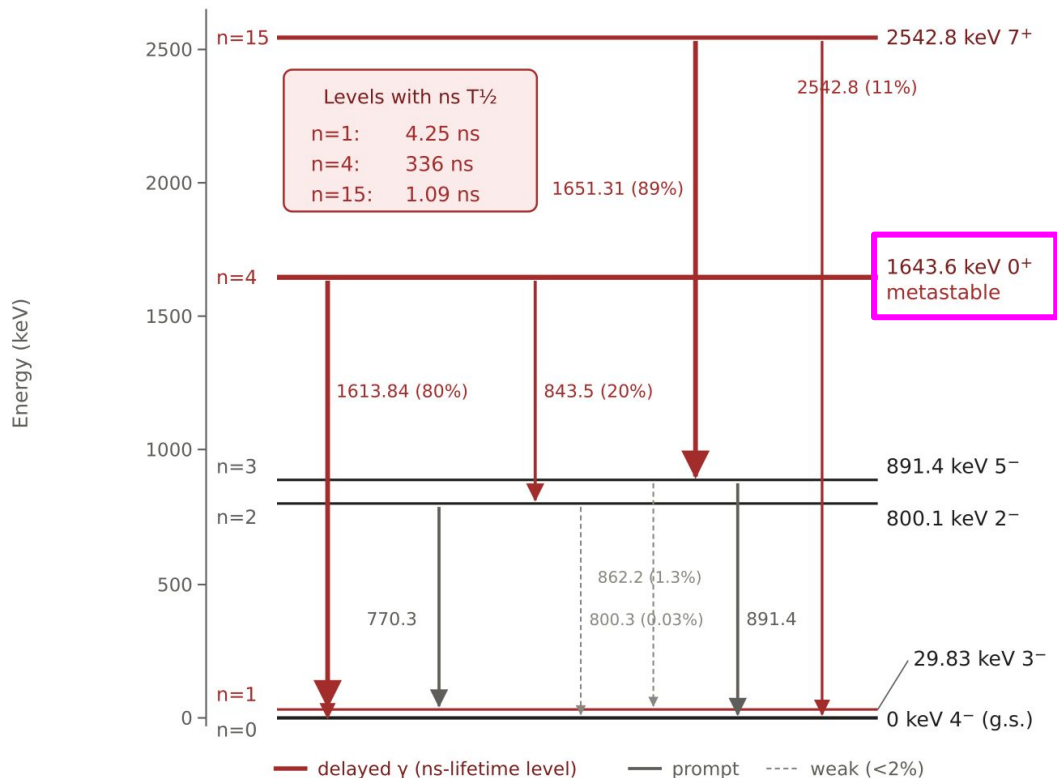
$$E_\gamma \simeq E_i - E_f$$

- Most levels decay in ps or fs: **prompt gammas** for CCM
- Metastable** or long-lived levels (ns) can delay subsequent gamma emission:

$$\Delta t \sim \text{Exp}(\tau), \quad \tau = \frac{T_{1/2}}{\ln 2}$$

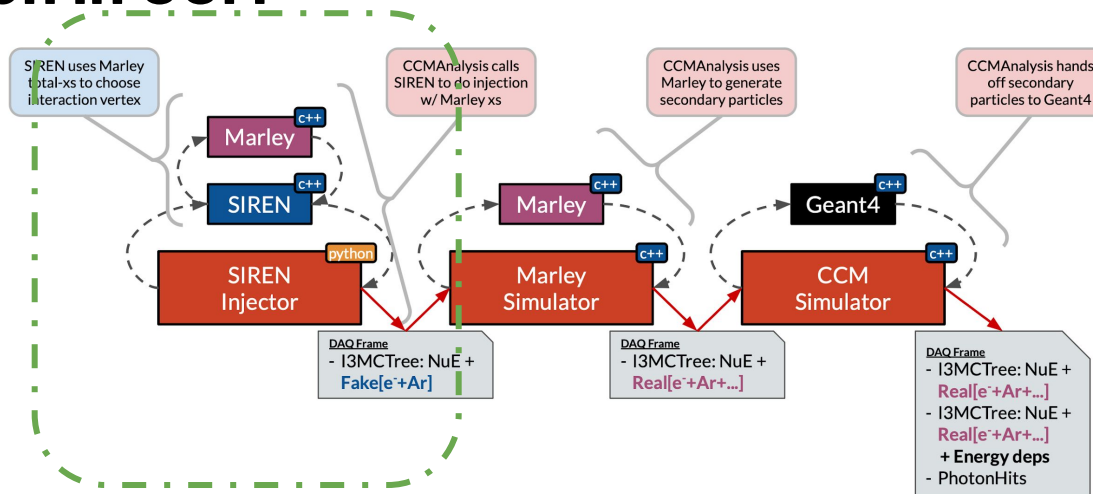
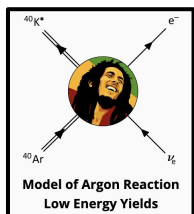
- This delayed component may be **observable with CCM fast timing**.

${}^{40}\text{K}$ de-excitation gammas from delayed (ns) levels



CC Signal Simulation in CCM

- 1.- Injection
- 2.- Ar interaction
- 3.- Energy depositions



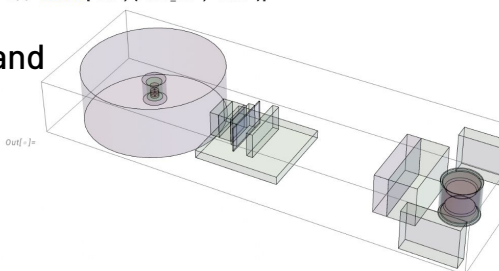
SIREN (Sampling and Injection for Rare Events)

- Injects and weights interaction final states,
- It makes use of the **total cross section** from MARLEY and the **neutrino flux**

MARLEY

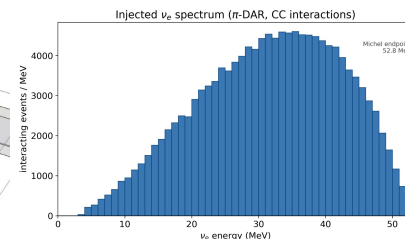
- Provides the cross section prediction.
- Developed by **Steven Gardiner (Fermilab)**

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in(-)- Visuals["CCM", {"surr_atr", "floor"}]
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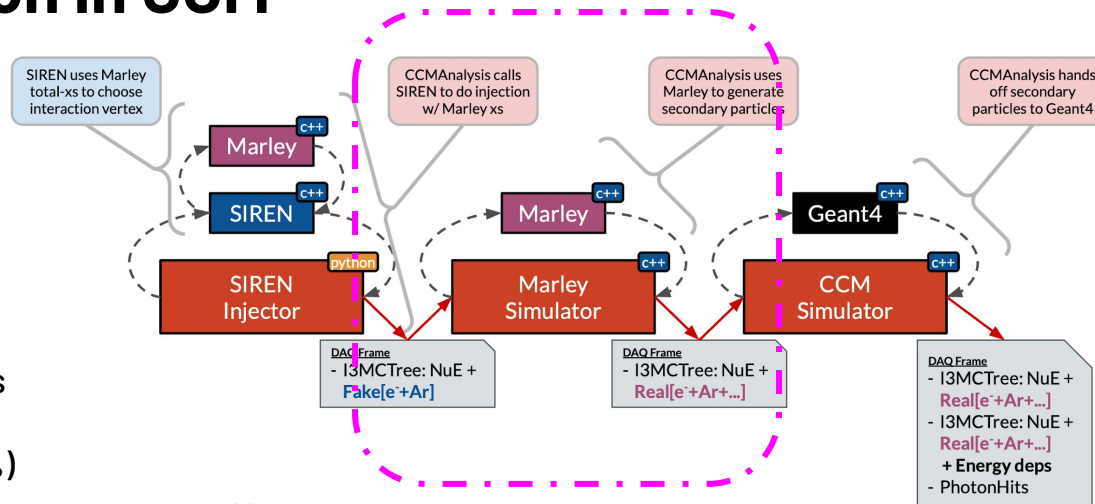
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A. Schneider



CC Signal Simulation in CCM

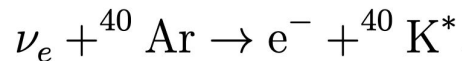
- 1.- Injection
- 2.- Ar interaction
- 3.- Energy depositions



A. Schneider

MARLEY

- Generates the interaction process
- Nuclear physics
- Many reactions but main one (70%)



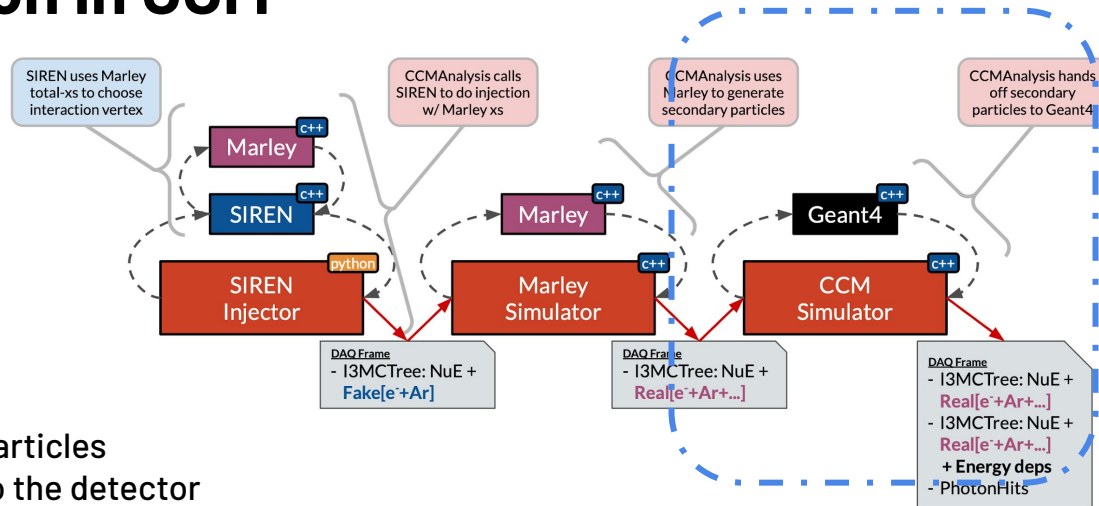
MARLEY v1.2.0 generates the de-excitation gammas with correct energies, but are placed at the same time as the primary interaction.

MARLEY gives the cascade content, but not its emission-time structure.

CCM adds the emission-time structure!!

CC Signal Simulation in CCM

- 1.- Injection
- 2.- Ar interaction
- 3.- Energy depositions



Geant4

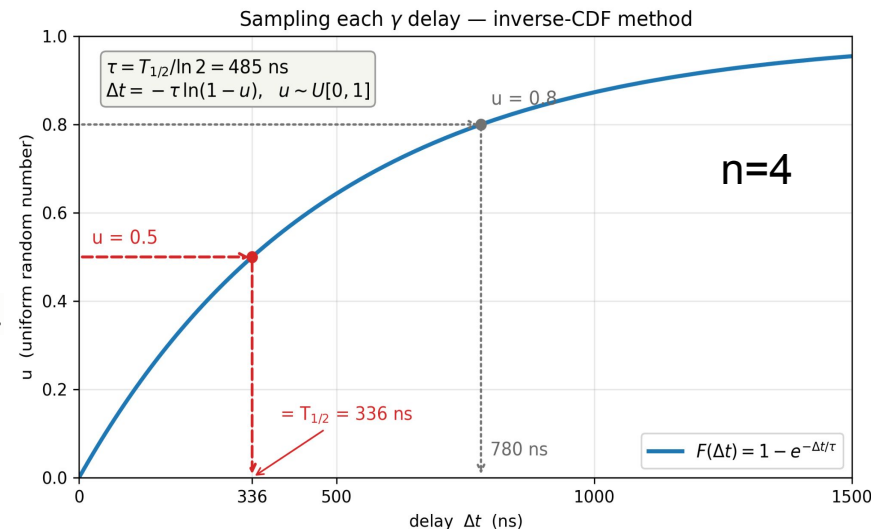


- Simulates **propagation** of all the particles produced previously by Marley into the detector
- **Detailed geometry** and **optical properties** of the detector, **PMT response**
- Retrieves **Energy depositions** in the detector and **photon production and propagation**

A. Schneider

Our modification: adding time to the de-excitation

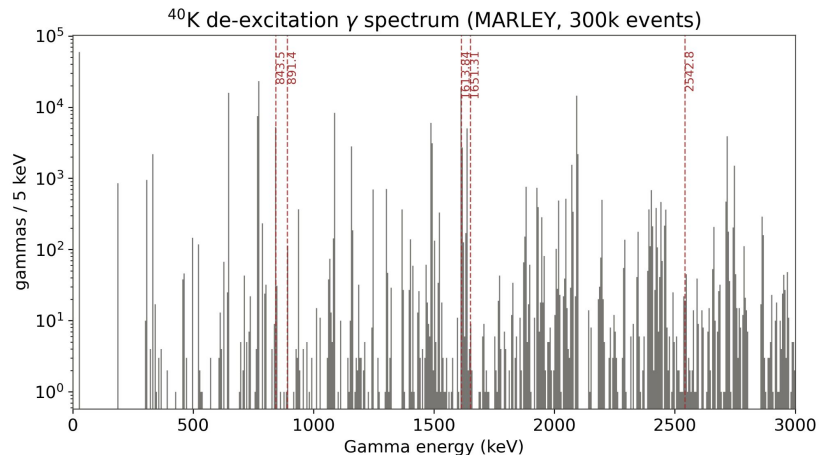
- **Extend MARLEY** assigning realistic emission times to de-excitation gammas from ^{40}K .
 - Implemented in “**MarleySimulator**”, before Geant4 propagation.
 - Input: **measured nuclear data** (NNDC/ENDSF): level energies, spins/parities, transitions (gamma energies + branching ratios), half lives $T_{1/2}$ of long-lived levels.
 - **Energies** of the gammas are known from MARLEY simulation.
 - With the information of the **transitions** it is possible to reconstruct the cascade (starting from the ground state)
 - For the long-lived levels (**1,4 and 15**) the emission delay is sampled from an exponential distribution. **Inverse CDF Sampling:**
- $$\Delta t = -\tau \ln(1 - u) \quad \tau = \frac{T_{1/2}}{\ln 2} \quad t_n = t_{\nu, \text{TOF}} + \sum_{k=1}^n \Delta t_k$$
- Delays are accumulated down the cascade



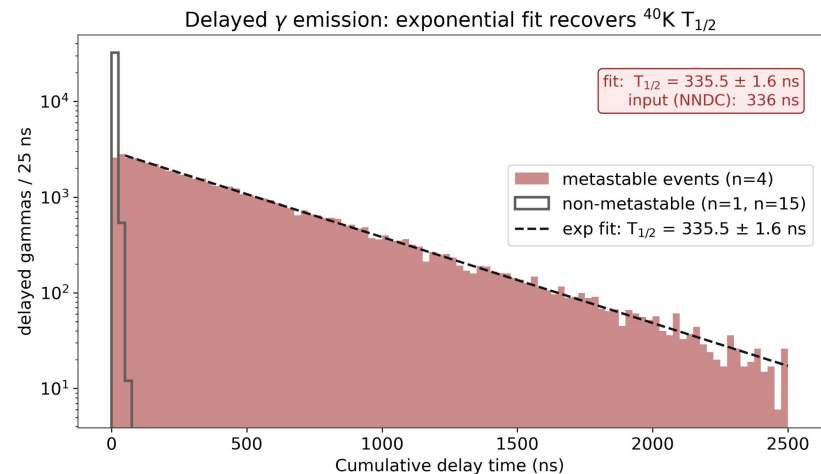
drawn per long-lived level · delays accumulate down the cascade

$n = 4$
 $T_{1/2} = 336 \text{ ns}$
 $\tau = 485 \text{ ns}$

Results: delayed gammas incorporated in simulation



- Gamma spectrum from MARLEY simulation.
- Discrete gamma energies from the nuclear cascade

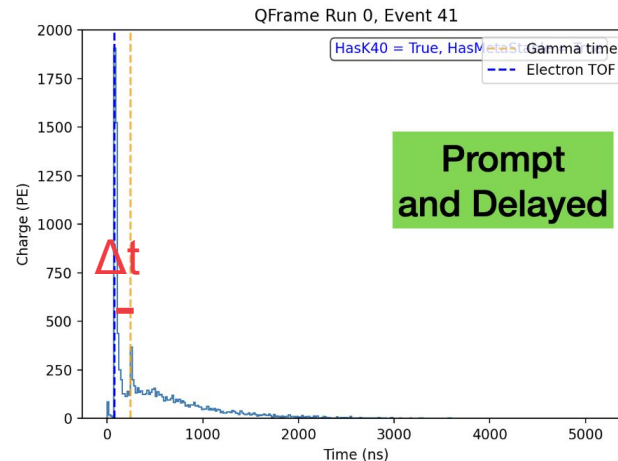
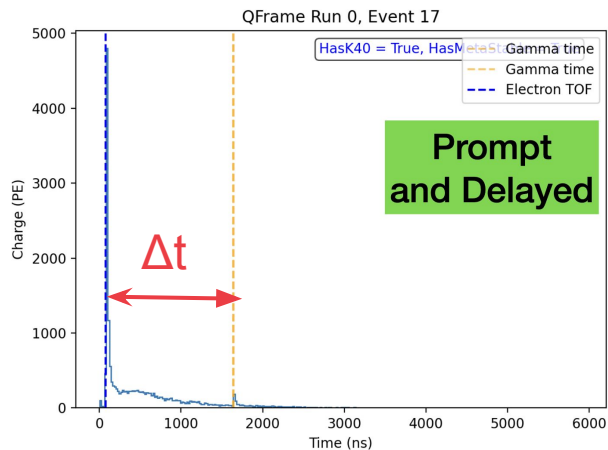


- Validation: Exponential fit recovers ⁴⁰K $T_{1/2}$

$$N(t) = Ae^{-t/\tau}$$

Results: A signal with gammas in CCM!

- From our simulated events:
 - ~70% of the CC interactions produced a ^{40}K in the final state
 - ~41% of them had de-excitations from **metastable** level
- The deposited charge is **measurable**
- Delayed coincidence signal end-to-end simulation in CCM



Takeaways

- **MARLEY** already generates the de-excitation gamma cascade in ν_e -Ar CC events, but the gammas are **emitted simultaneously** in the default CCM simulation.
- We implemented a **time-resolved** treatment: assigning gamma emission times from ^{40}K nuclear level lifetimes.
- Most nuclear levels are effectively prompt, but long-lived levels can produce delayed gamma emission at the ns scale. One **metastable** level: $T_{1/2} = 336$ ns.
- Validated: the **half-life** is recovered in the simulation $T_{1/2} = 335.5$ ns \pm 1.6 ns.
- This **delayed component** may provide a **characteristic timing** signature for ν_e -Ar CC events
- CCM could provide a **complementary measurement of** ν_e -Ar CC in the **E < 50 MeV** regime.



Thanks for listening!

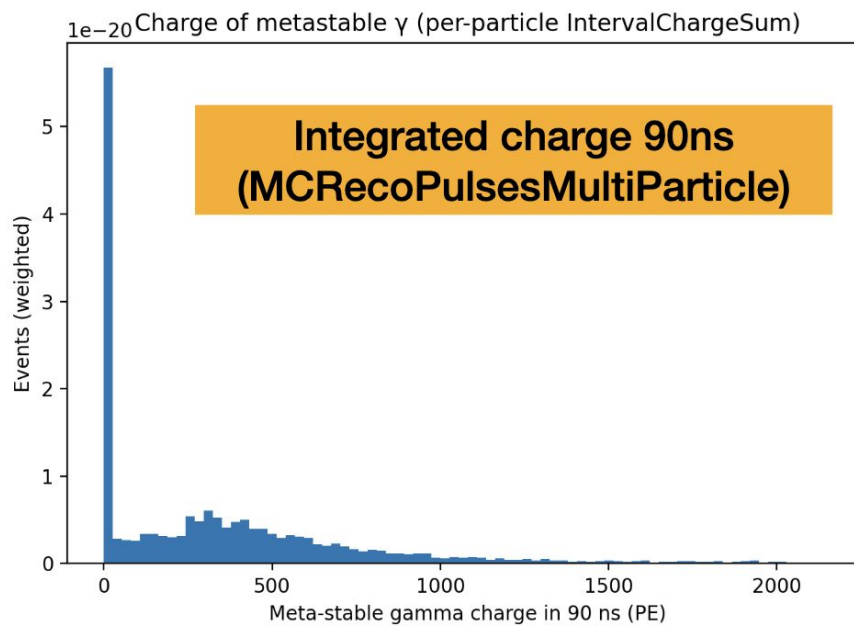


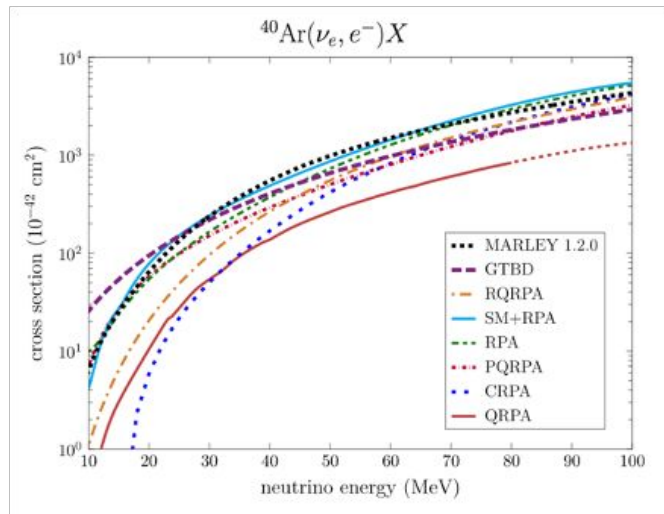
We acknowledge support of DGAPA
UNAM Grant PAPIIT-IN104723

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. Walker⁴

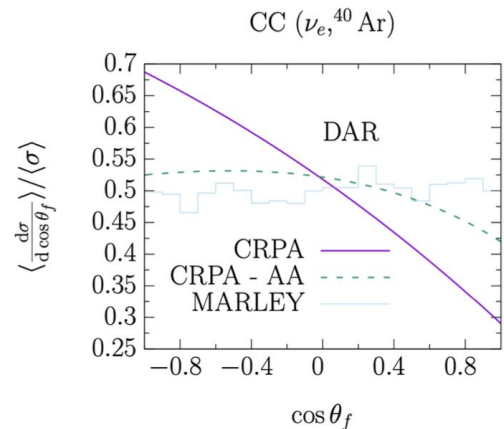
(The CCM Collaboration)

Backup slides

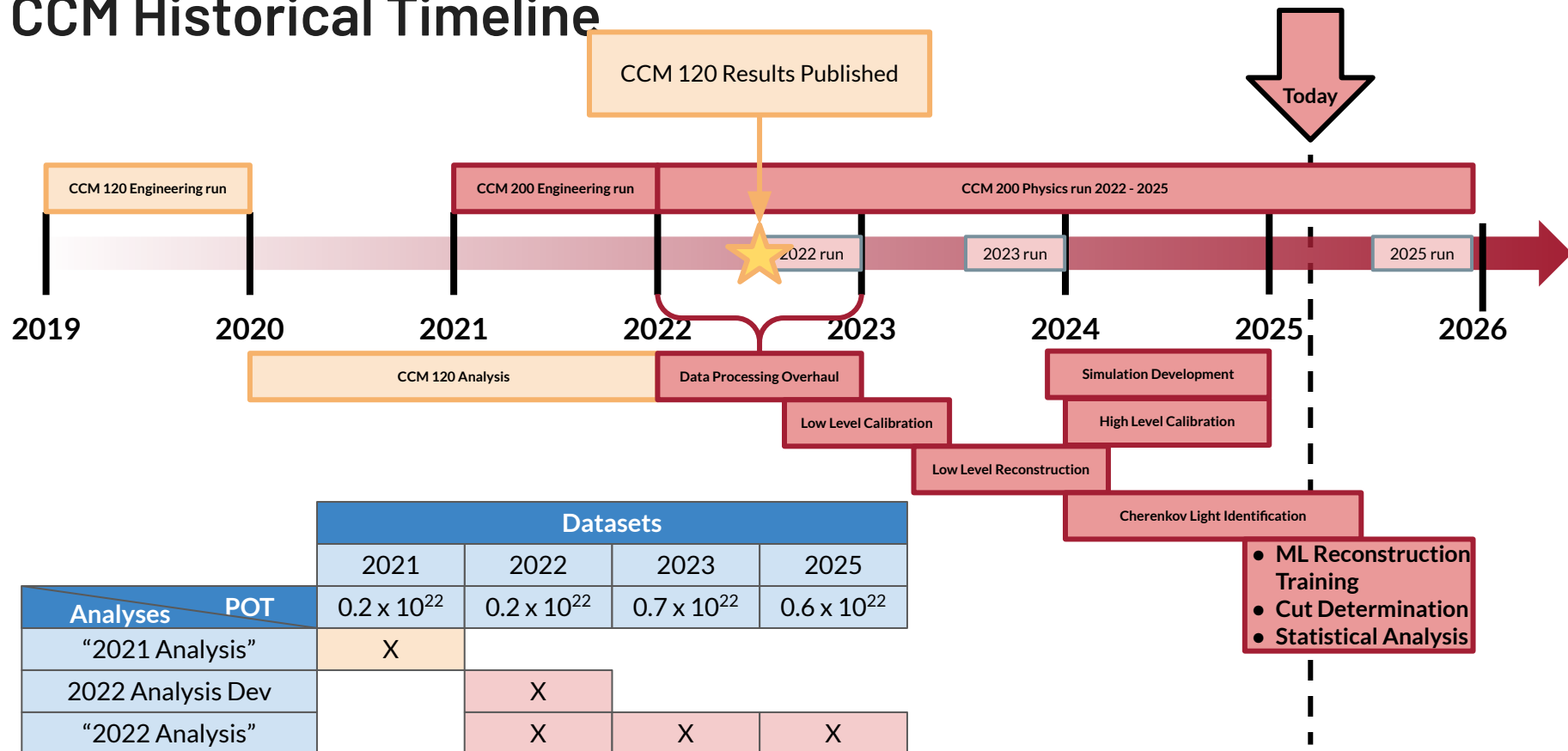




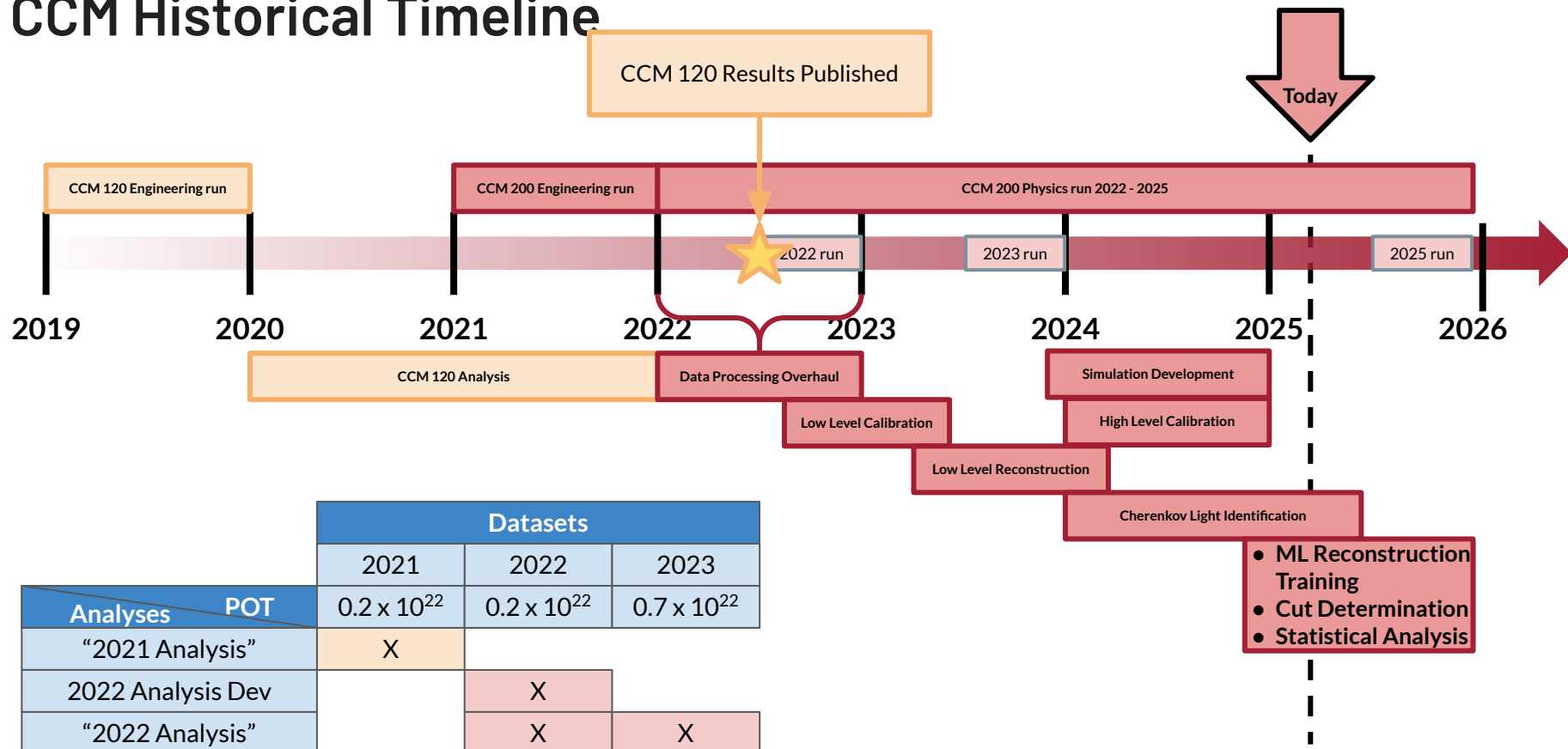
- CC Cross Section has **angular sensitivity**. Differences between models
- Reconstructing **electron direction** will help **constrain** xs models.

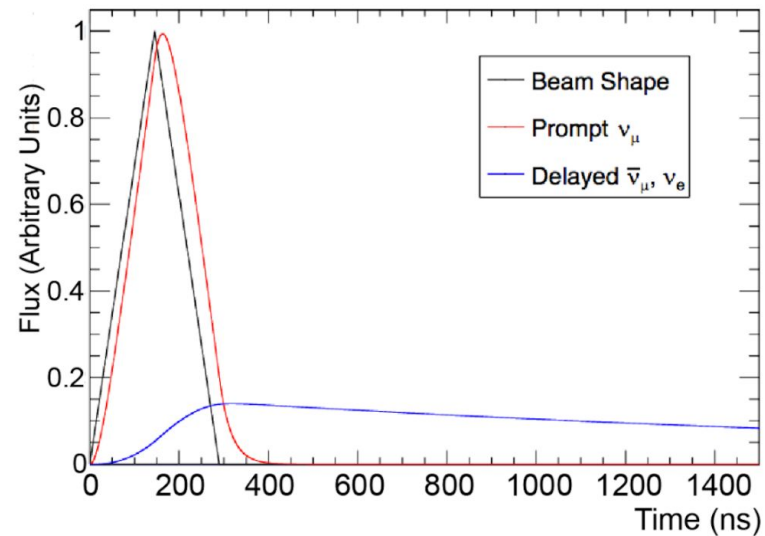
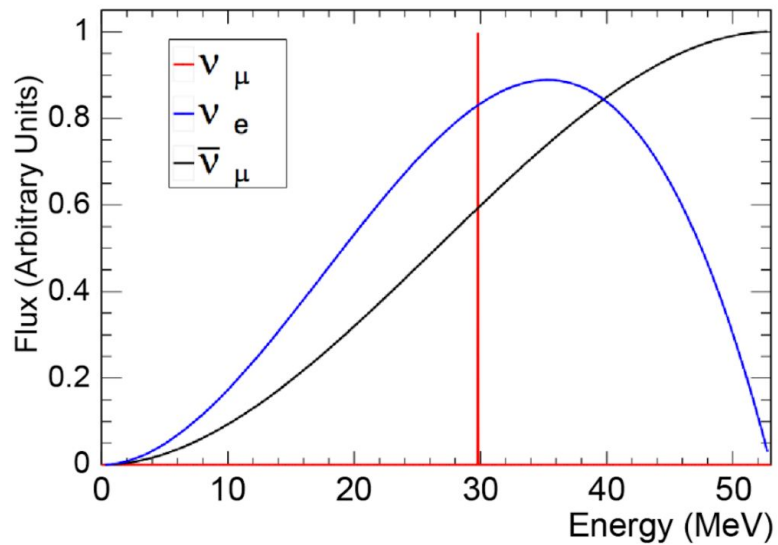


CCM Historical Timeline



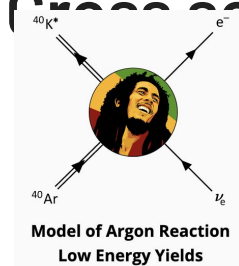
CCM Historical Timeline





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

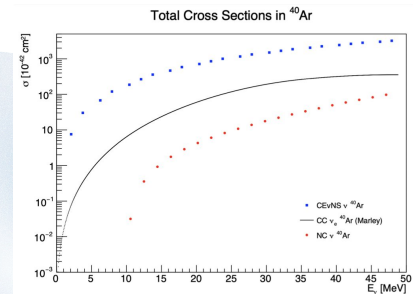
Cross section prediction



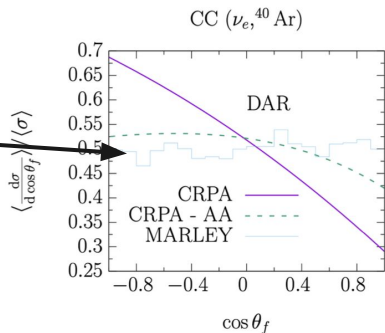
MARLEY (Model of Argon Reaction Low Energy Yields) provides the cross section prediction.
 Developed by **Steven Gardiner**



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

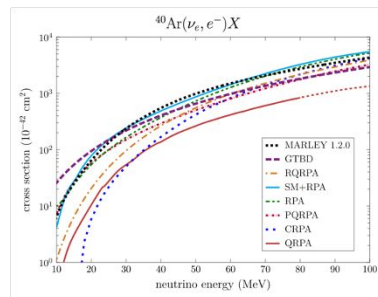
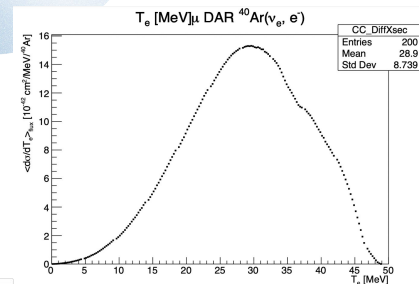


- MARLEY predicts a nearly **flat angular distribution**.
- Other models like CRPA include full expansion of nuclear matrix element (allowed as well as forbidden transition), predict more **backwards** strength.



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%)** \rightarrow even a measurement with **50% uncertainty** would significantly improve constraints and help validate theoretical models.



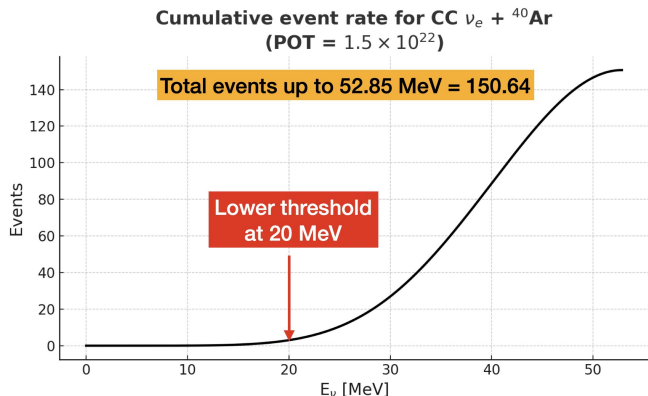
Total expected events in CCM

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

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

CC Events in CCM at 23 m, for 5 tons of LAr, E_ν :[0, 52.85 (=m _{ν} /2) MeV] .

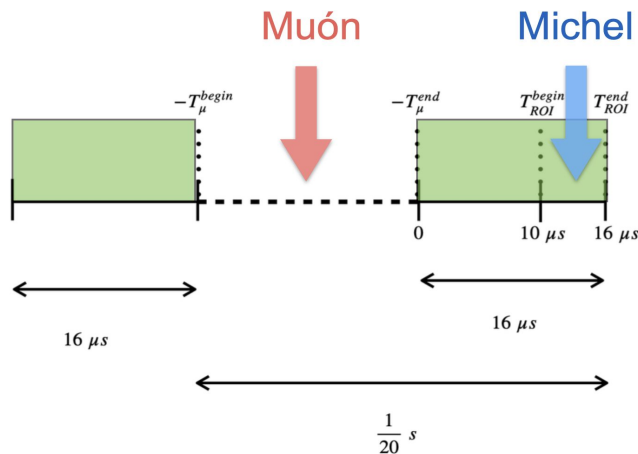
Total events/3 years	Total events/year	Total events/year. (Eff=75%)
150.64	50.21	37.7



- 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 **0.9×10^{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:

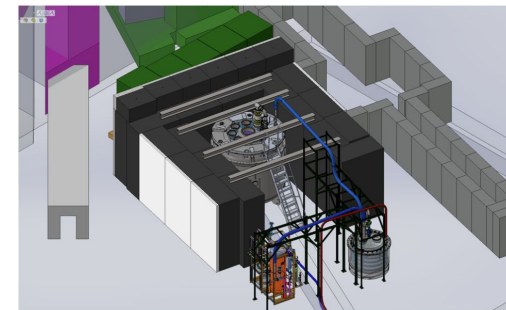
$$2.18 \times 10^{-7} \text{ events/trigger}$$

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

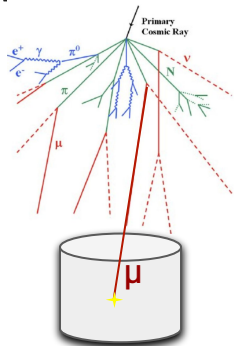
W target shielded : surrounding 5m of steel, 2 m of concrete.

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



Michel electrons

Neutrinos constantly arrive to CCM, some of them enter the detector and stop:



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



Captured by an atom.
Two possible processes:

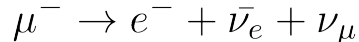


Cosmic watches are used for tagging muons

Decay in Orbit (DIO) : 24%

-The muon binds to the 1S (K-Shell) atomic orbital forming a muonic atom

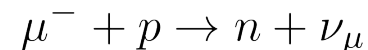
-Decays via:



-This is not a free decay!!

Nuclear capture: 76%

-The muon is absorbed by a proton
In the nucleus:



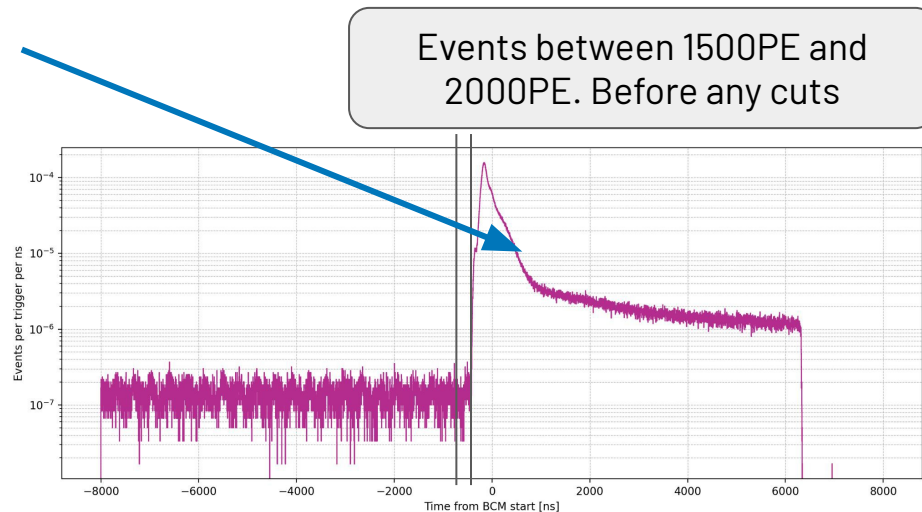
-No Michel electron is produced

Michel electrons

μ^- Lifetime in Argon: 537 ns

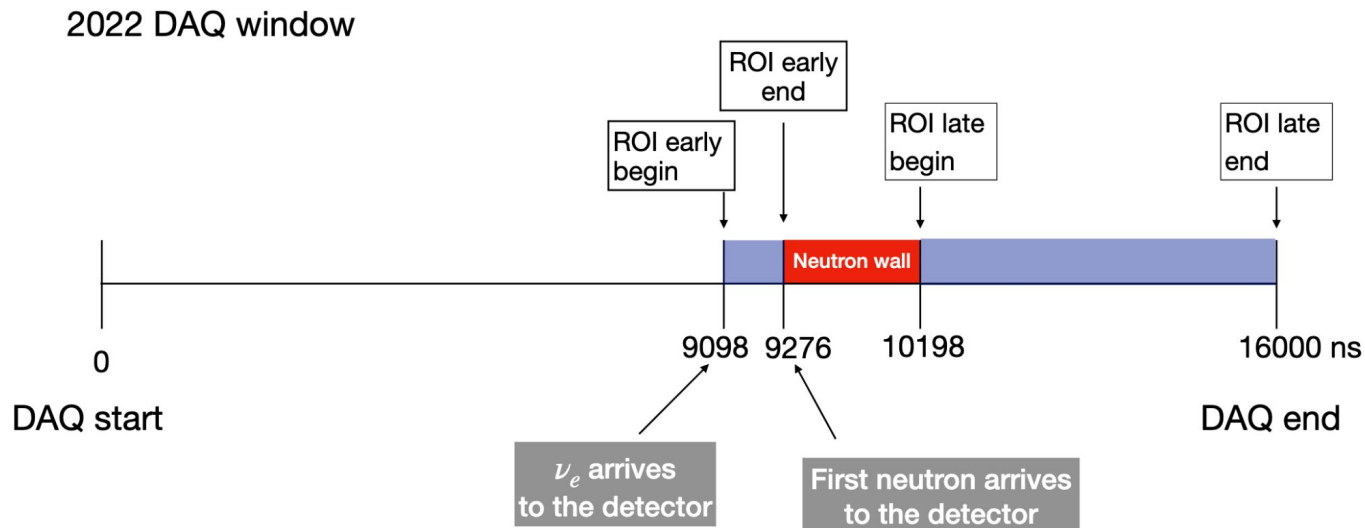
Neutrons

- 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 $\sim 10^3$ to get to 20% xs. sens.



Data Selection

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



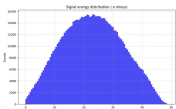
Early ROI length: 178 ns

Late ROI length: 5802 ns

Statistical Analysis (MC)

Signal distribution

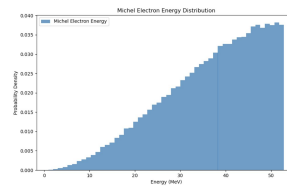
- Energy dist:
 - Energy of the outgoing electron produced after the interaction in LAr (SIREN+MARLEY)
- Time dist combines:
 - Time when neutrino hits the detector (SIREN+MARLEY)
 - Time of pion decay
 - Time of muon decay
 - Triangular beam profile (pulse width =290 ns)



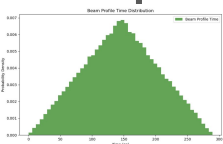
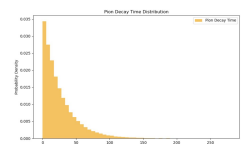
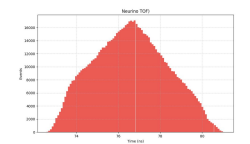
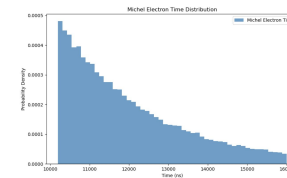
Background distribution

Considering only Michel electrons

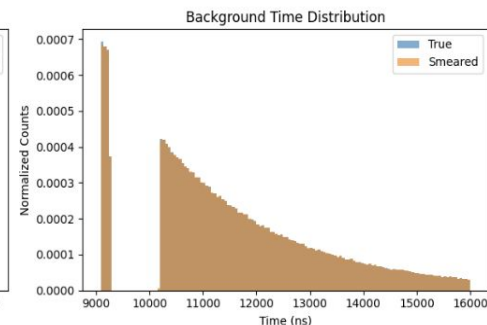
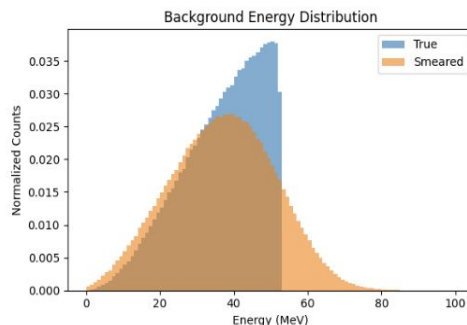
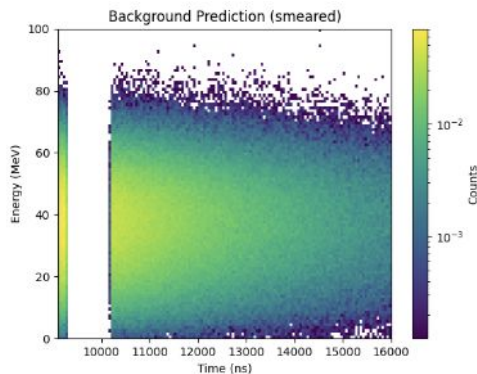
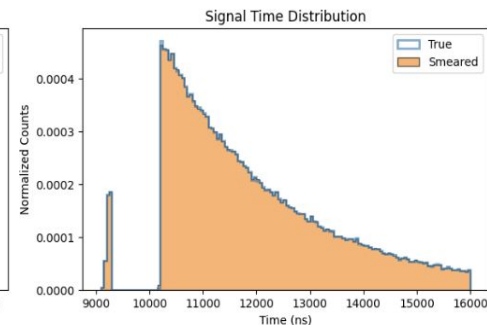
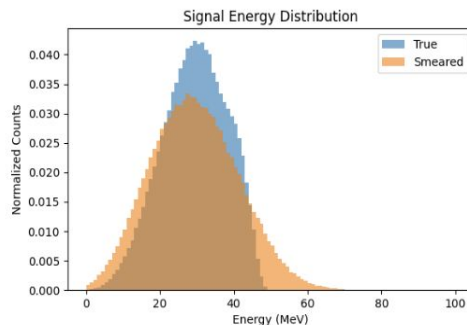
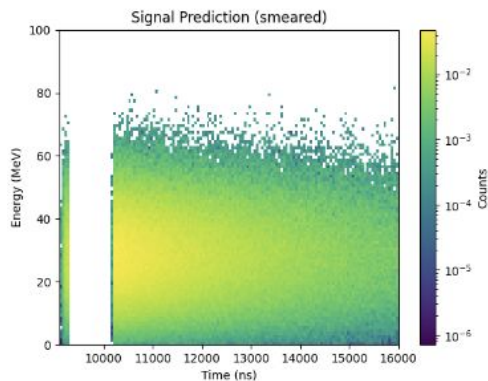
- Energy dist:



- Time dist:



Statistical Analysis (MC)(cont)



Data Selection

- Signal



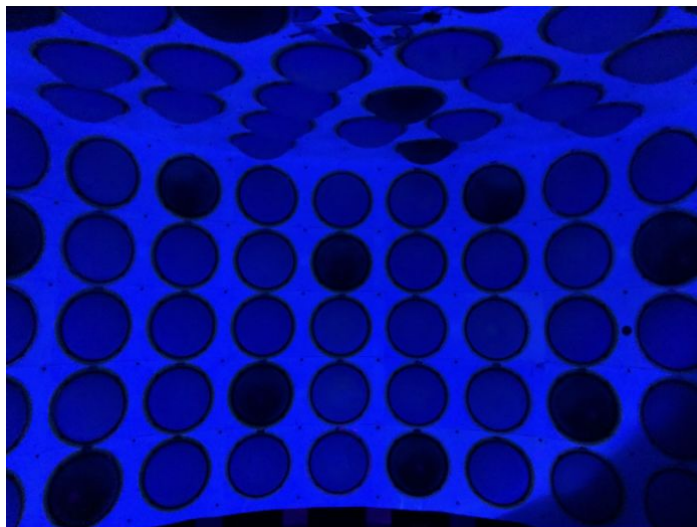
The outgoing electron usually carries most of the energy
~ 20–50 MeV : KEY SIGNATURE FOR SIGNAL ID
(Similar E range than Michel electrons)

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

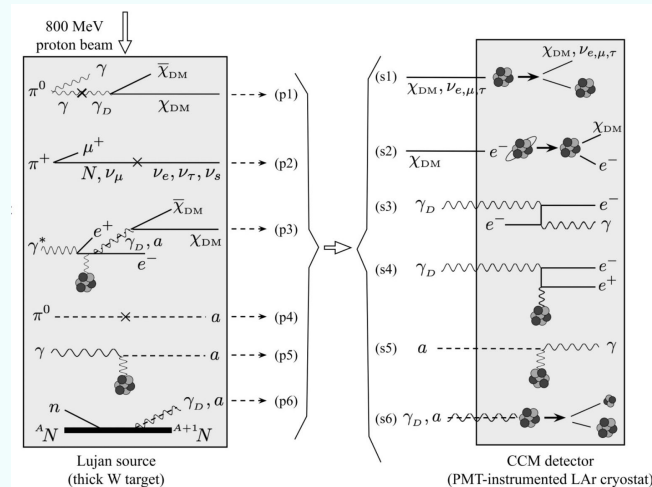
- CCM is an experiment that explores the search for SM, BSM and Dark Sector physics, such as **leptophobic dark matter, axion-like particles, meson portal models, and neutrino interactions.**
- **Publications:**
 - First Leptophobic Dark Matter Search from the Coherent-CAPTAIN-Mills Liquid Argon Detector (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

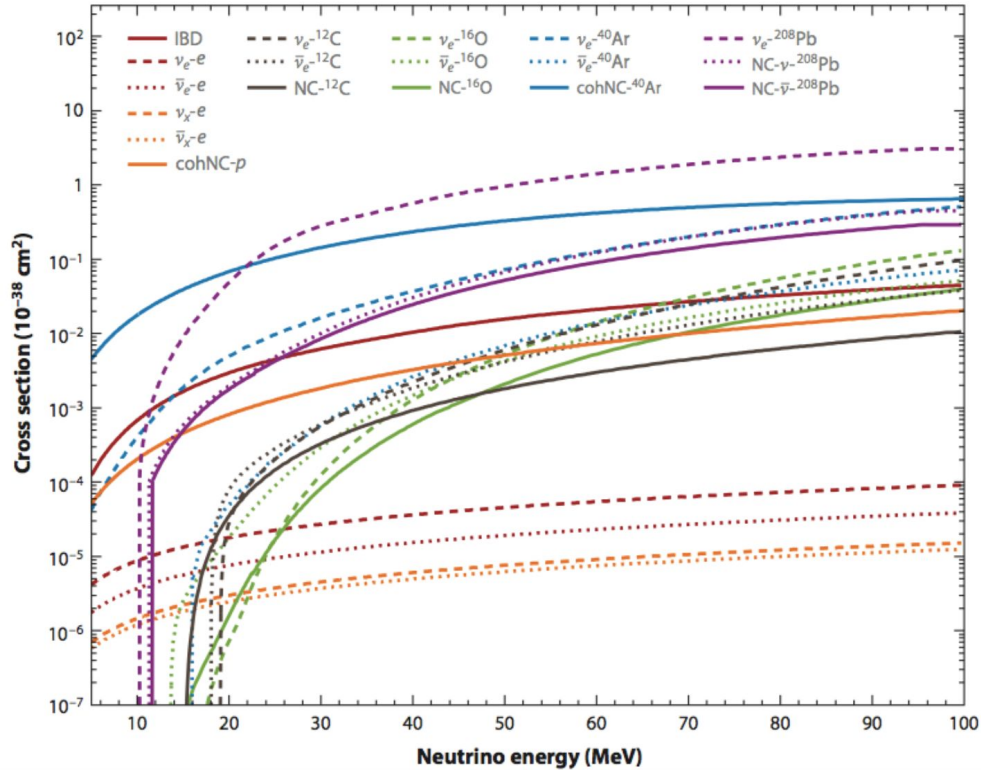
Axion like particles



Coherent scattering

Compton scattering

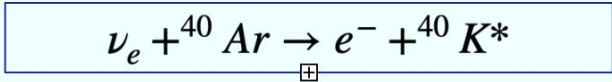
Cross Sections



Light production and detection in Argon

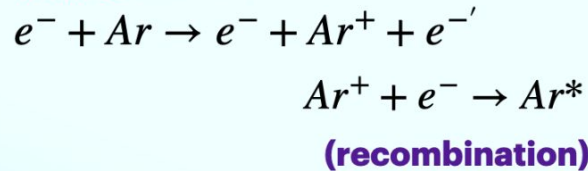
- **Detection mechanism: Scintillation light**

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

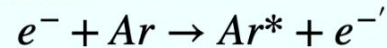


Electrons can:

Ionize the Ar :

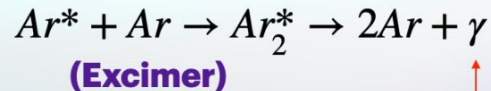


Excite the Ar:



Both process
lead to Ar^*

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



Detected by PMTs

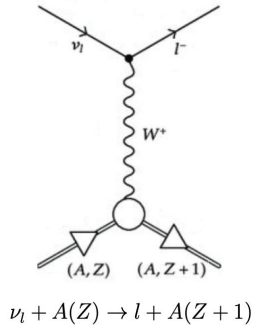
Photons VUV (128 nm)
Prompt component (singlet) ~6 ns
Delayed component (triplet) ~1600 ns

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

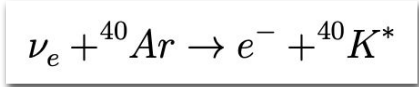
CC Scattering

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)



For scattered off with Argon:



Cross Section:

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

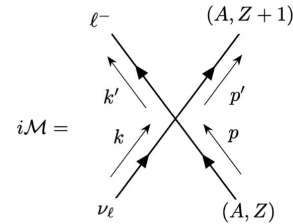
$L_{\mu\nu}$ Leptonic Tensor
 $W^{\mu\nu}$ Hadronic Tensor

$Q^2 \equiv -q^2$ 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)

Leptonic Tensor:

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

m_l Final lepton mass

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

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) Initial (final) nuclear spin

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

\mathcal{N}^μ 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 (λ) and the momentum of the nucleon y the momentum of the struck nucleon is neglected with respect to its mass

Temporal component:

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

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

Spatial component:

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

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

Fermi and
Gamow-Teller
operators

Under this approximation, the hadronic tensor:

$$\begin{aligned} W^{00} &= 4E_i E_f B(F) \\ W^{ab} &= \frac{4}{3} \delta_{ab} E_i E_f B(GT) \\ W^{0a} &= 4W^{a0} = 0 \end{aligned}$$

$$\begin{aligned} B(F) &\equiv \frac{g_V^2}{2J_i + 1} |\langle J_f | | \mathcal{O}_F | | J_i \rangle|^2 \\ B(GT) &\equiv \frac{g_A^2}{2J_i + 1} |\langle J_f | | \mathcal{O}_{GT} | | J_i \rangle|^2 \end{aligned}$$

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

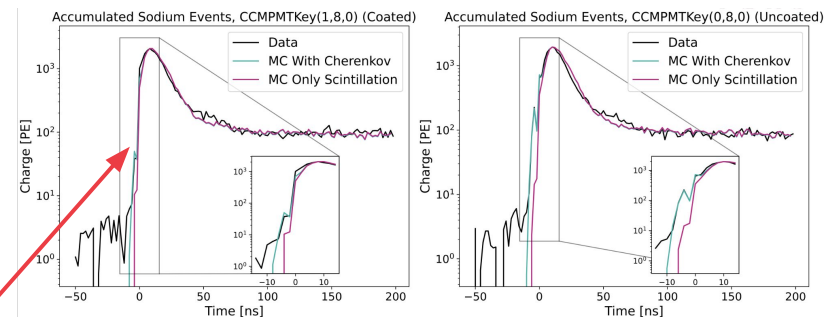
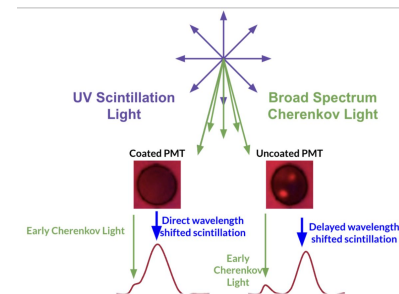
In the CM system the energies of the particle are independent of the scattering angle :

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

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

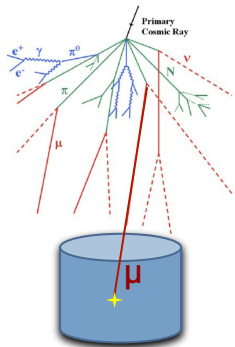
Reconstruction with Cherenkov light in CCM

- 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

Background - Michel electrons



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

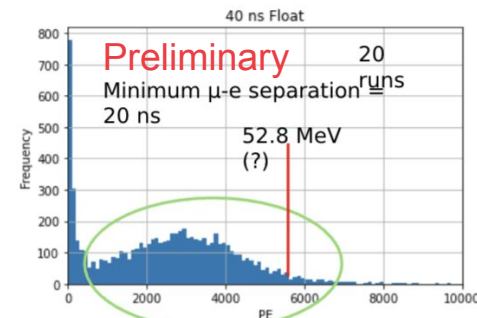
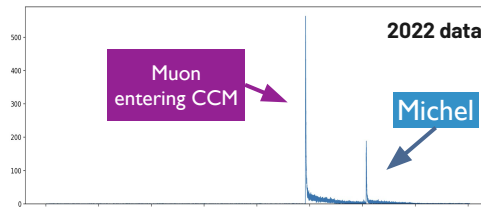
μ^- Decay in Orbit (DIO): 24%

- 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
- 2.18×10^{-7} Michels/trigger in the detector within a **6 μ s** region of interest
- **Simulation** (Cristian Macías) and **data analysis** (Darrel Smith) efforts in progress for **energy calibration**.



Cosmic watches are used for tagging muons



Michel Energy spectra (2022 Data)