Exploring low-energy charged-current scattering of electron neutrinos on argon with the CCM experiment

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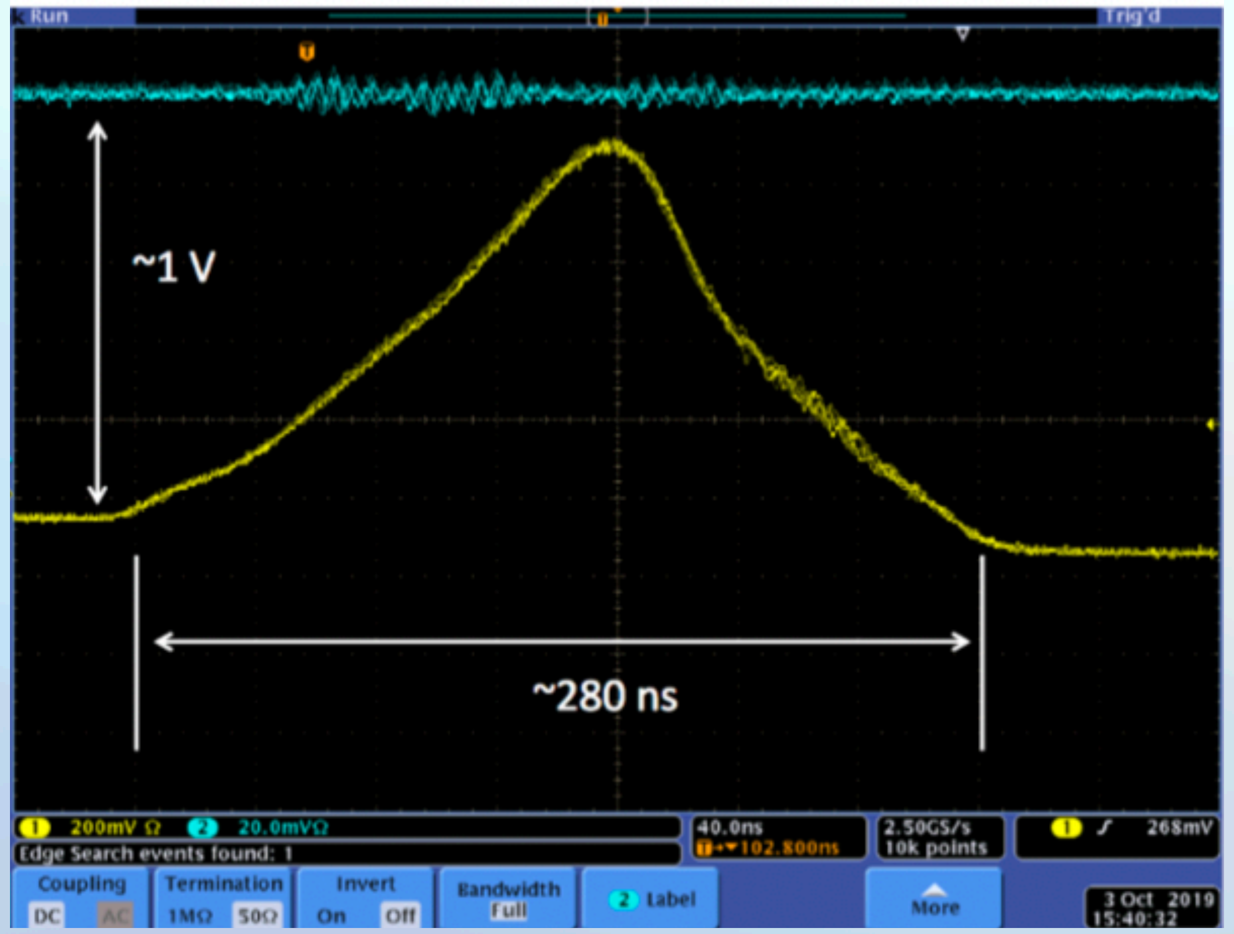
Outline

- The Coherent Captain Mills CCM experiment.
- Neutrino production and CC interaction.
- Cross Section prediction and background.
- Simulation with SIREN + MARLEY +G4LAr-sim in the CCMAnalysis framework.
- Future plans for the experiment.

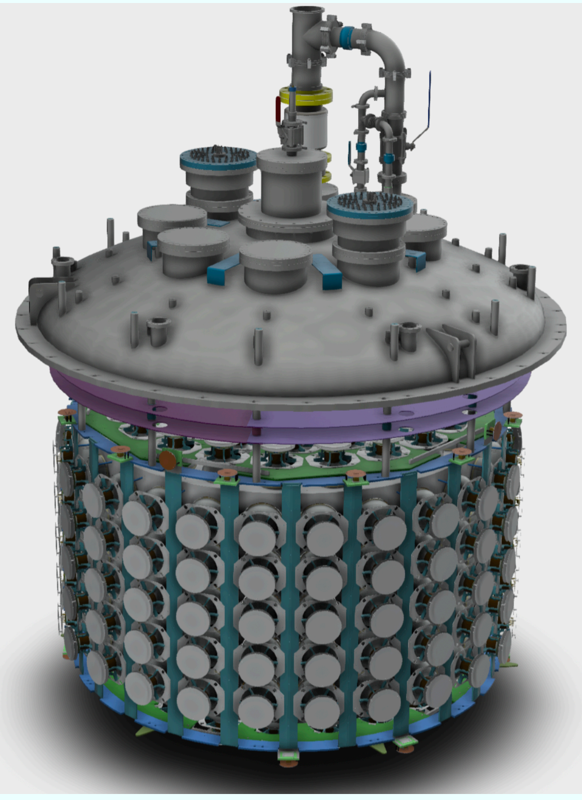
The Coherent Captain Mills experiment (CCM)

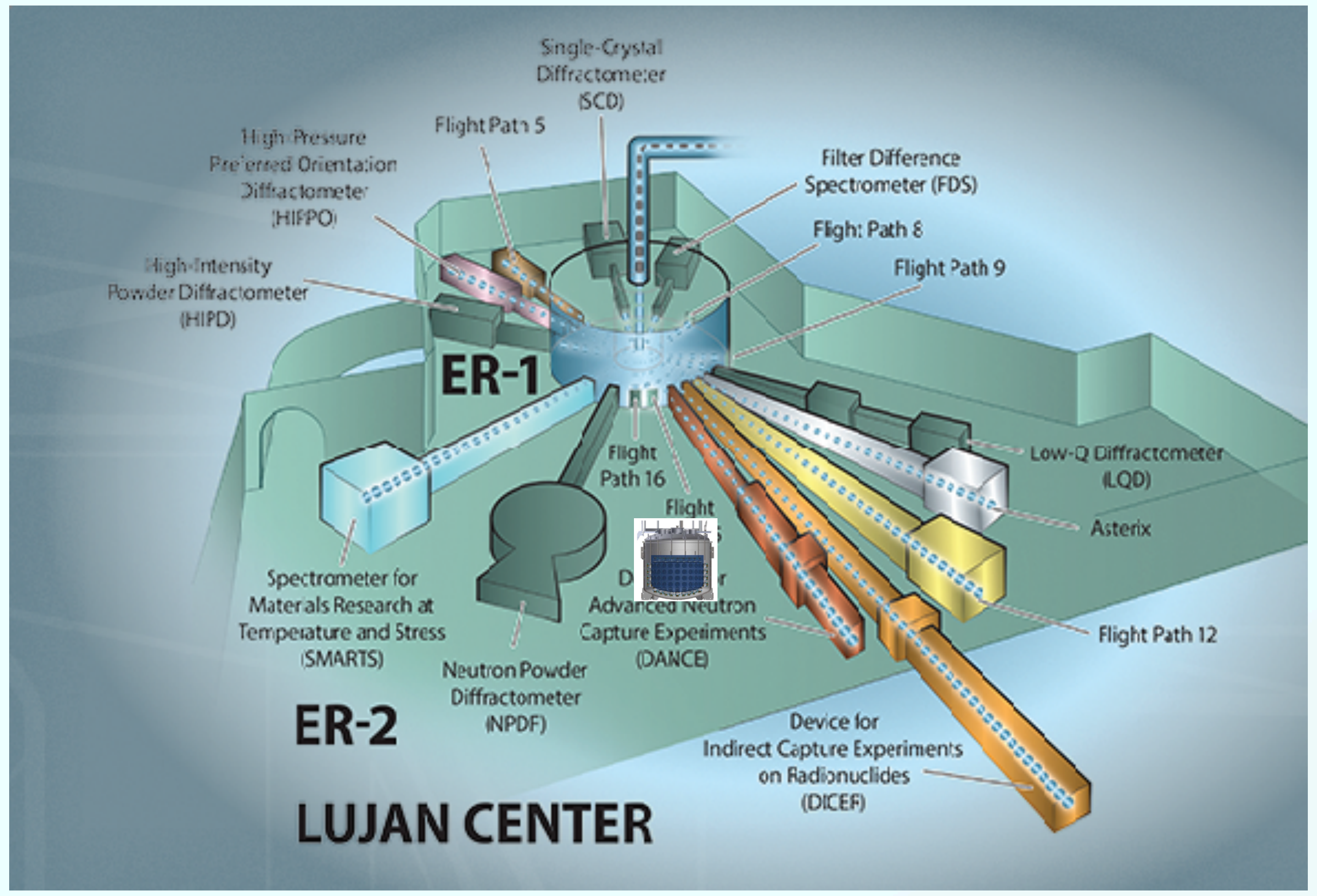
- Located at **Los Alamos**, New Mexico, USA. LANSCE, LANL.
- Accelerator experiment with **800 MeV proton pulsed beam** hitting a Tungsten Target from above (90° wrt beam) at 20 Hz.
- ~ 3.1×10^{13} protons per bunch in a **triangular time distribution** of 280 ns. 2.25×10^{22} POT (for a 3 year run).



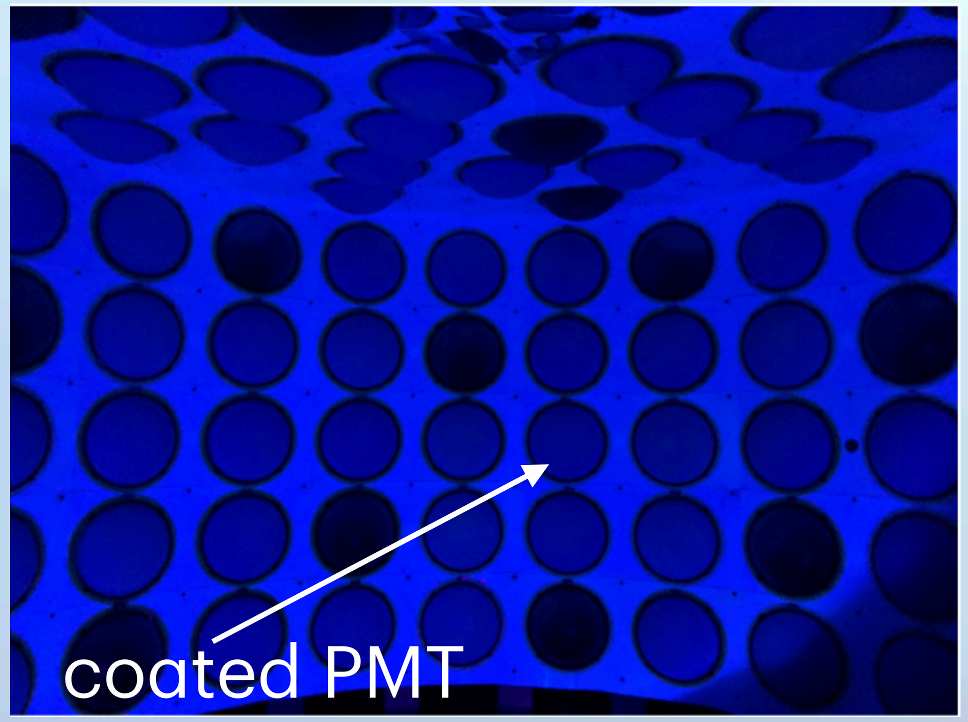
- Started engineering run in 2019 with **CCM120**
  120 Photo Multiplier Tubes (PMTs), that were tested and sent to **SBND.**
- Engineering run 2020-2021 with **CCM200**
  Completely new 200 PMTS, upgrades to shielding and electronics.
- Physics run 2022, 2023 with CCM200. No run in 2024.
- International collaboration ~**50 members**: including researchers, postdocs, Ph.D, post-bac, undergraduate students.
- **México** is the only Latin-American country at CCM:
  Juan Carlos D'Olivo, Alexis A. Aguilar, Cristian Macías (don't miss his poster session!), Marisol Chávez.

The CCM detector



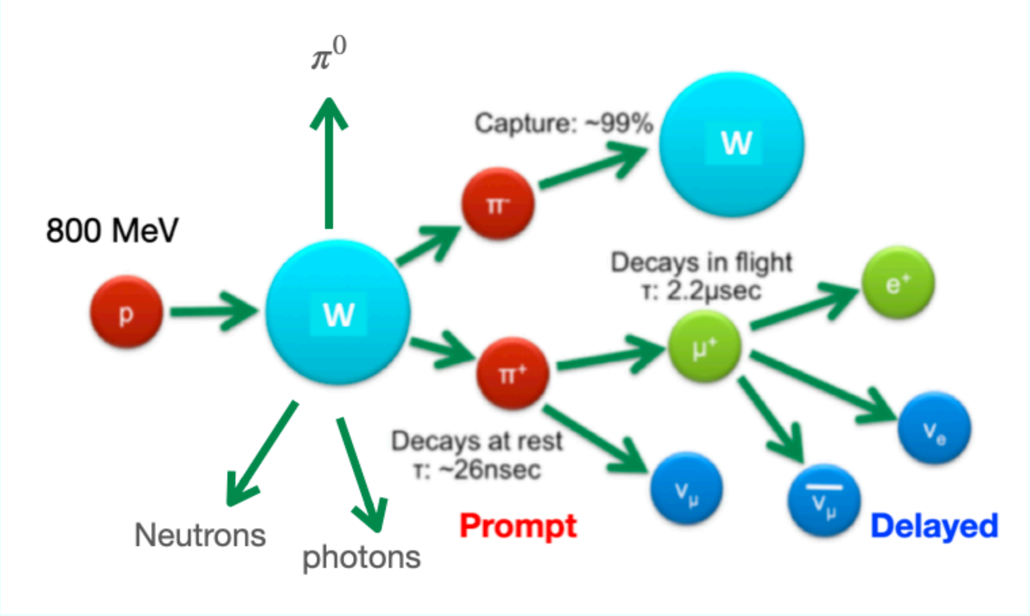


- Cylindrical cryostat with a **10 ton Liquid Argon (LAr)** capacity at 88K
- Located at **23 meters** from Tungsten target at Lujan Center (LANSCE)
- Instrumented with **200 8" Photo Multiplier Tubes** (PMTs) inside the 7 ton fiducial region and 1" PMTs in a 3 ton veto region optically isolated.



- **80% coated** with Tetraphenyl butadiene **(TPB)** as wavelength shifter (128 nm -> visible light). TPB foils on internal walls.
- **Largest** LAr detector by photo-cathode **coverage area** in the world.
- Resolution: **~2 ns (time)**, ~**5 cm (position)**, **20% energy**.
- MIT Muon portable detectors **"Cosmic Watches"** added on top of the detector
- Detection system: **Scintillation and Cherenkov light (in progress).** (No TPCs).
- Dynamic **energy range** from **~100 keV to 10 GeV**
- 16 (18) us **DAQ Window** for 2022 (2023) run

Neutrino production and Charged Current scattering (CC)



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

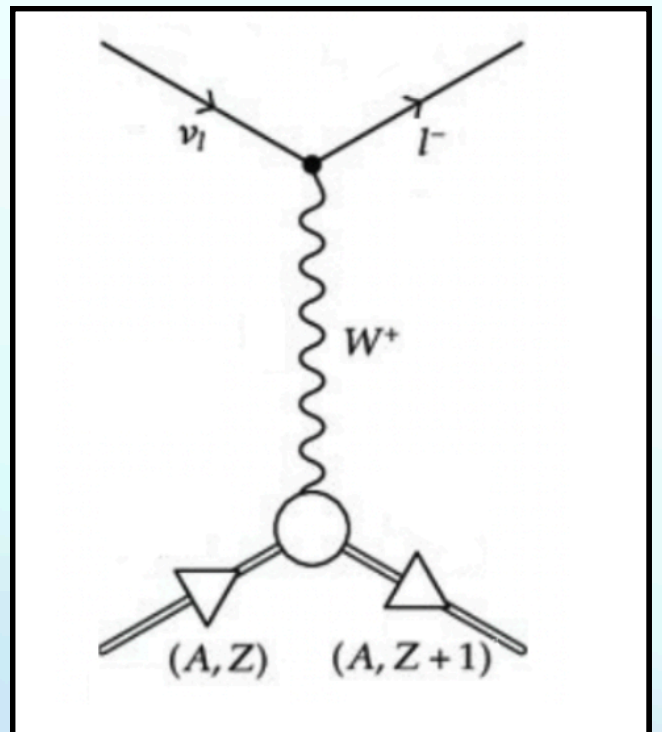
- When the **beam hits the target**, neutrons, photons, pions and other particles are produced.

- Most of the π^- are absorbed, the π^+ DAR, producing a **prompt signal.** The muon then decays in flight producing a **delayed signal**:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad (\tau_\pi = 26 \text{ ns "prompt"})$$
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \qquad (\tau_\mu = 2200 \text{ ns "delayed"})$$

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

$E_{\nu_e,\bar{\nu}_\mu} : 0 - 58.2$ MeV

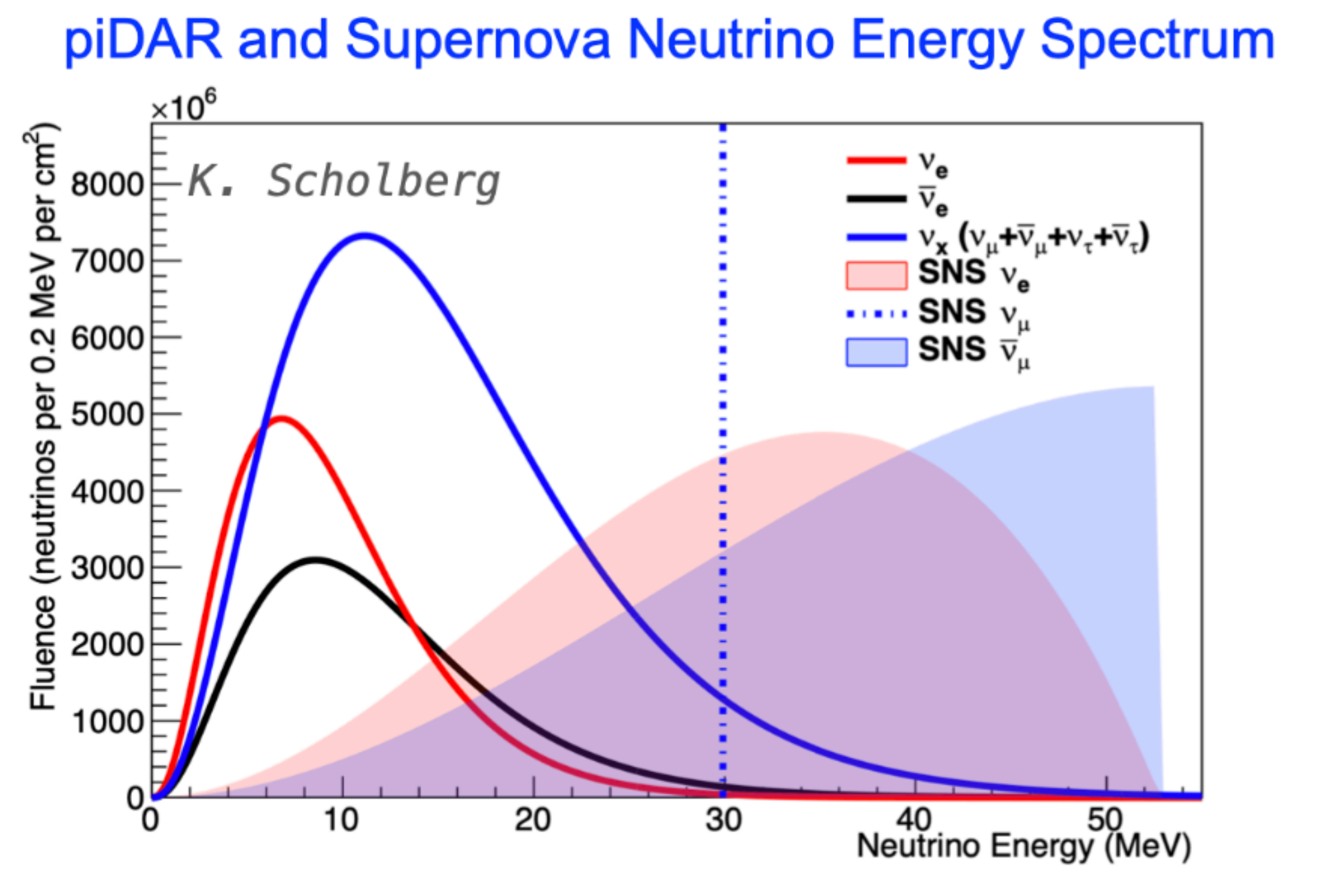


$\nu_l + A(Z) \rightarrow l + A(Z+1)$

- Neutrinos arrive to the detector and interact with the LAr. For ν_e scattered off Argon, this is the **main CC scattering reaction**:

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

- **LSND** and **KARMEN** measured (2001) the CC Cross Section for ν's with nuclei of ^{12}C.



- **CCM** could make the first measurement for CC in **Argon** in the range of $E < 50$ MeV.

- Understanding of CC Cross Section is relevant for **core-collapse supernova** detection and will be useful for the new generation of LAr detectors like **DUNE.**

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

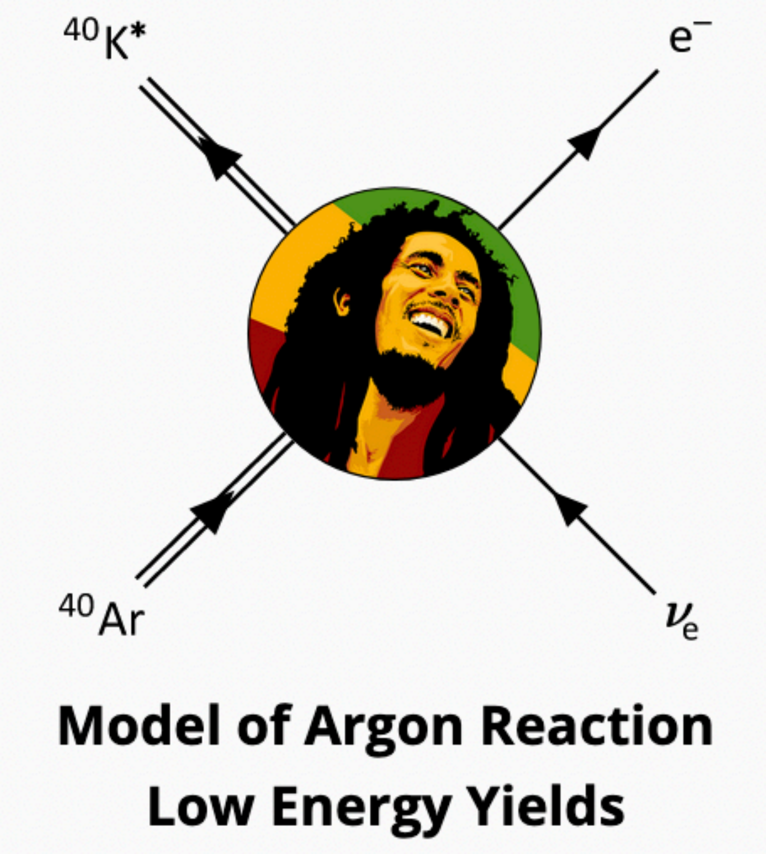
Photons VUV (128 nm)
Prompt component (singlet)~6 ns
Delayed component (triplet) ~1600 ns

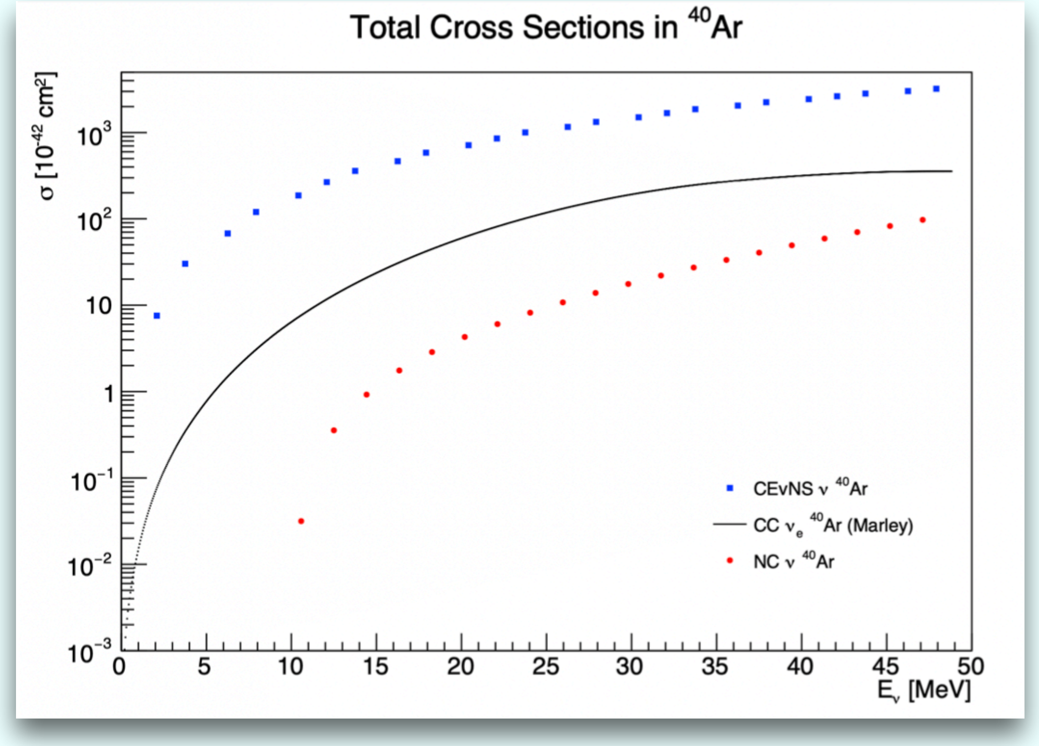
The $^{40}K^*$ returns to its **ground state** or can **ionize** Argon as it travels through the medium, producing light

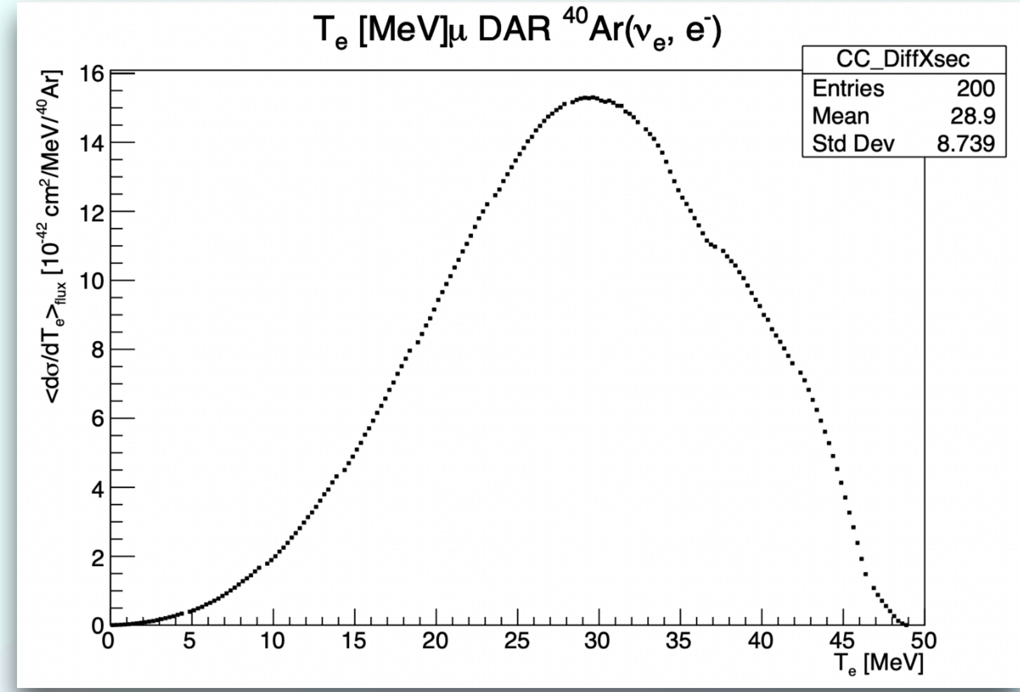
Cross section prediction

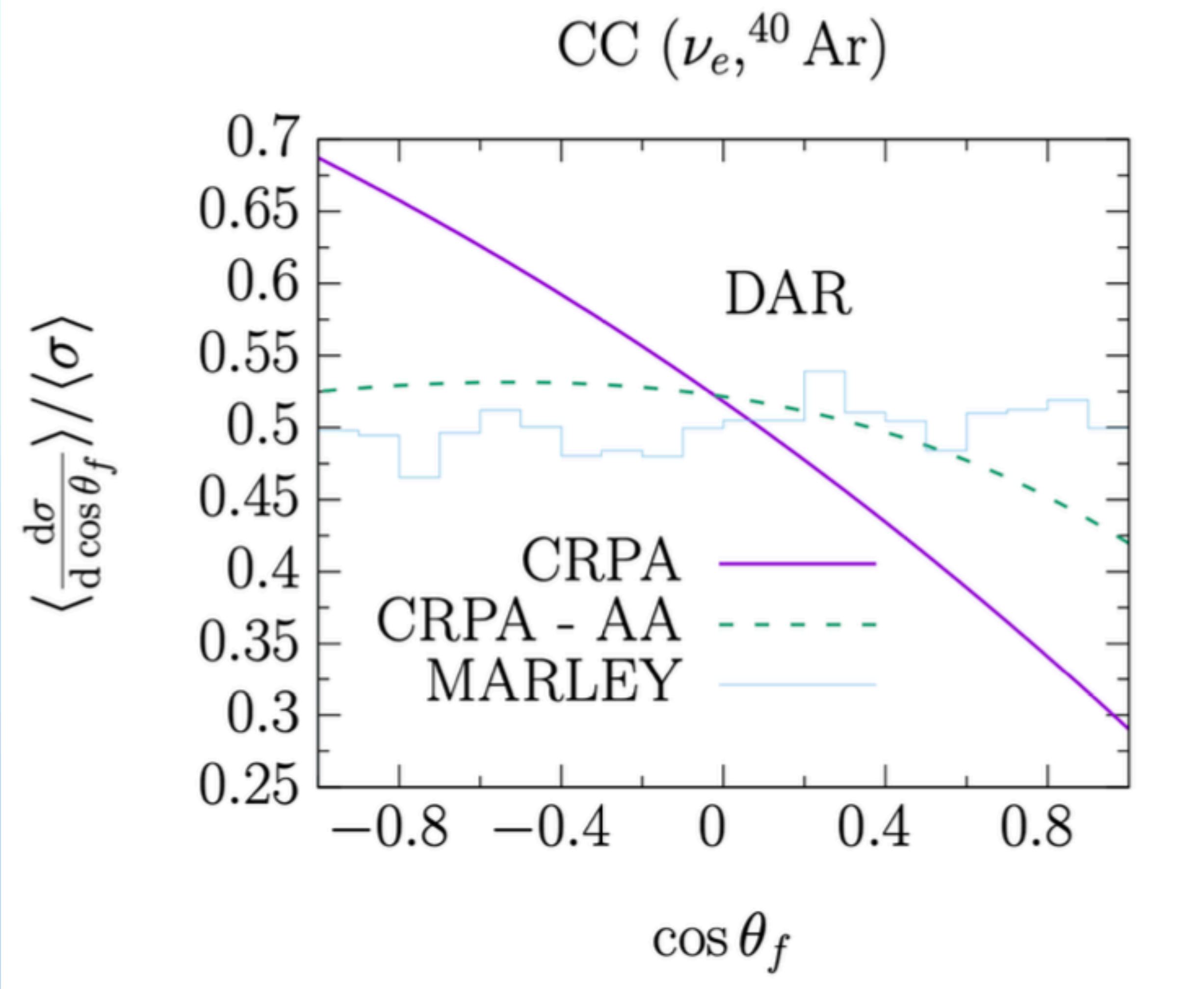
- We use the Cross Section prediction from the event generator **MARLEY** (Model of Argon Reaction Low Energy Yields) developed by S. Gardiner.

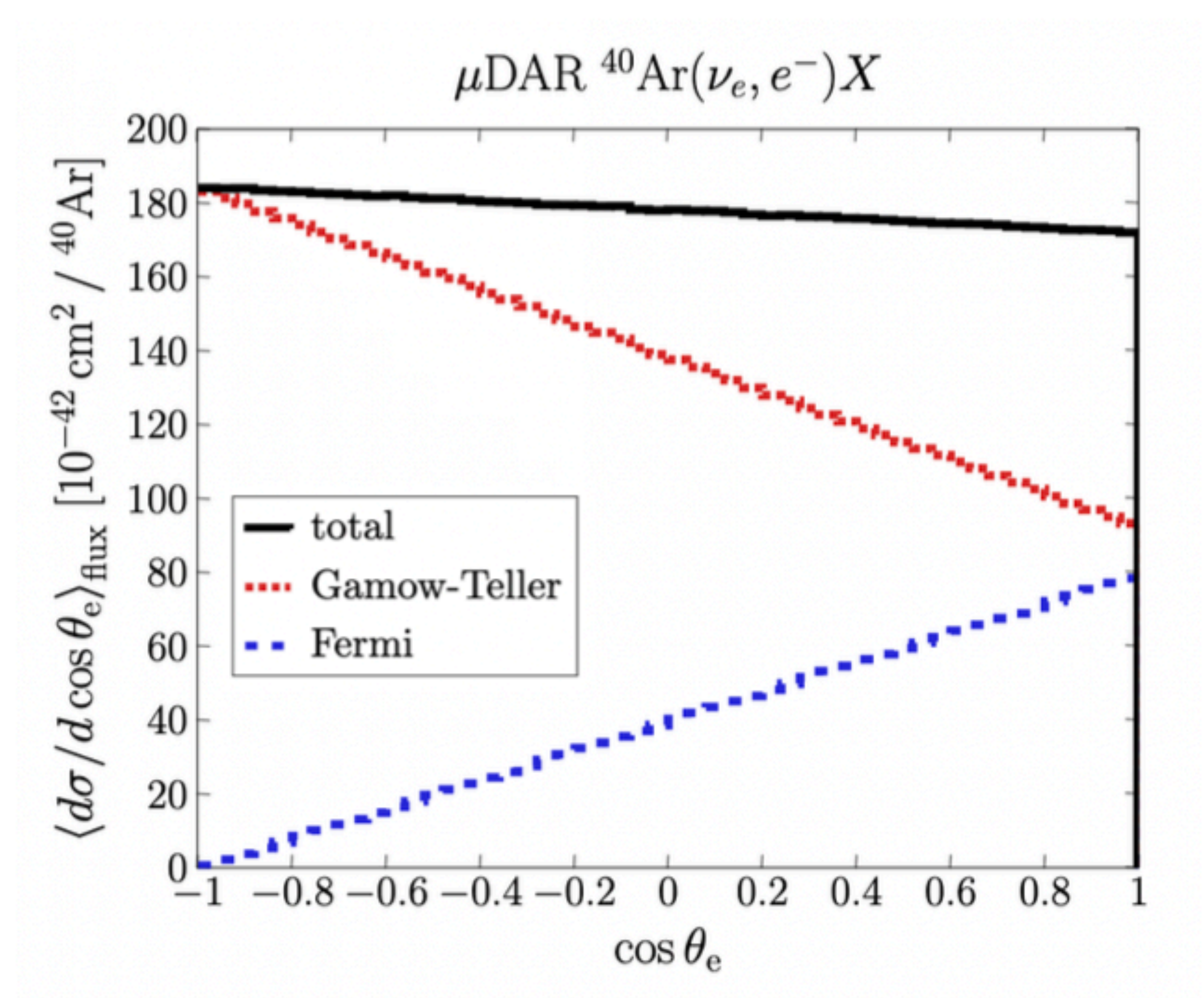
- The model includes the **allowed approximation** (long-wavelength ($q \to 0$) and slow nucleons ($p_N/m_N \to 0$) limit) and **Fermi and Gamow-Teller** matrix elements.











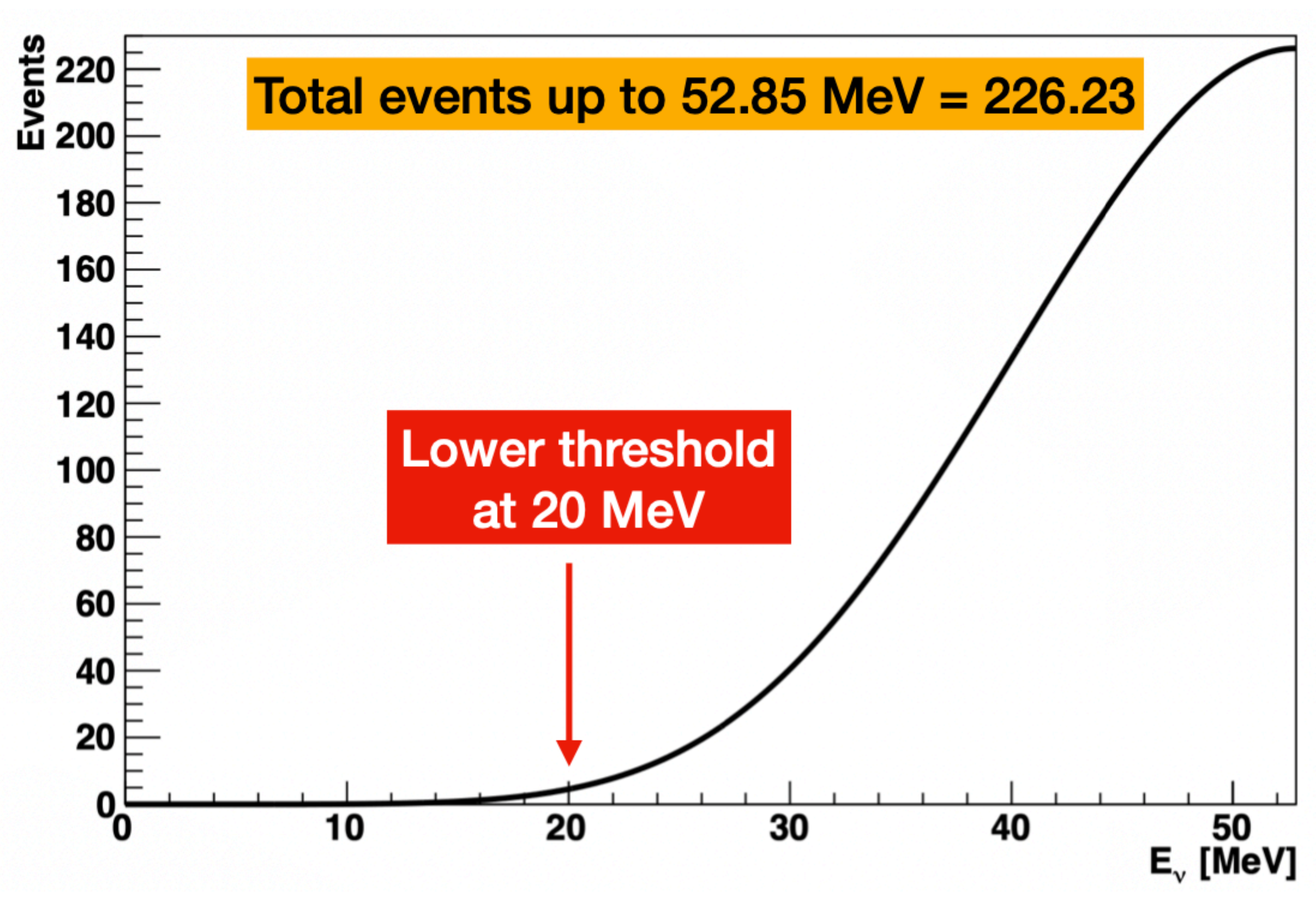
- MARLEY predicts a nearly **flat distribution.** Other models like CRPA include full expansion of nuclear matrix element (allowed as well as forbidden transition), predict more **backwards** strength.

- CC Cross Section has **angular sensitivity**, if the electron angle is known via Cherenkov light it will bring helpful information to constrain the models.

Total expected events

- Assuming **5 Tons** of Liquid Argon and a 75% of 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 (=$m_\mu/2$) MeV] .

Total events/3 years	Total events/ year	Total events/ year. (Eff=75%)
226.23	75.41	56.56

- Dominant source of error is the **uncertainty in the neutrino flux** ~10% is expected, based on the 7% error from LSND experiment (similar stopped pion source but different target type). This error derives from the number of pions/proton produced.

- A **4% systematic error** will stem from the uncertainty on the energy threshold due to our 20% energy resolution.

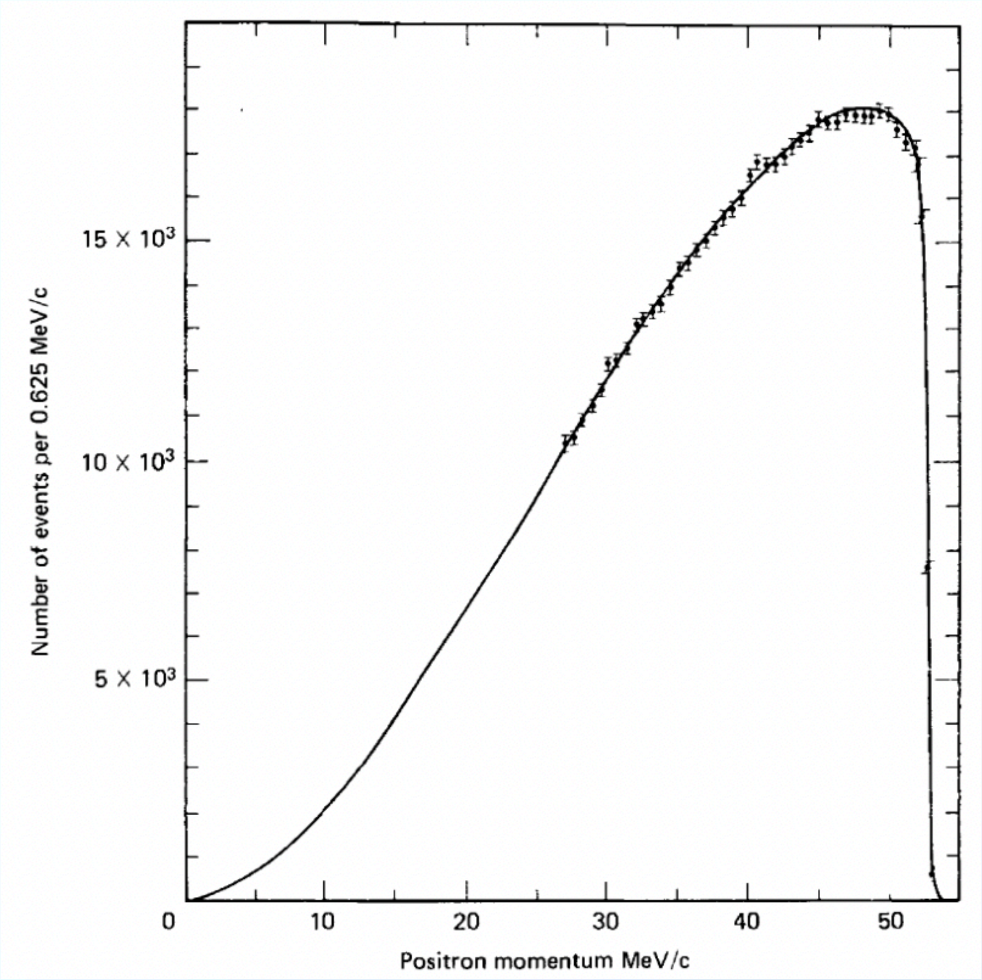
- These errors combined with the statistical contribution will result in a **16% total error on the ν_e CC cross section.**

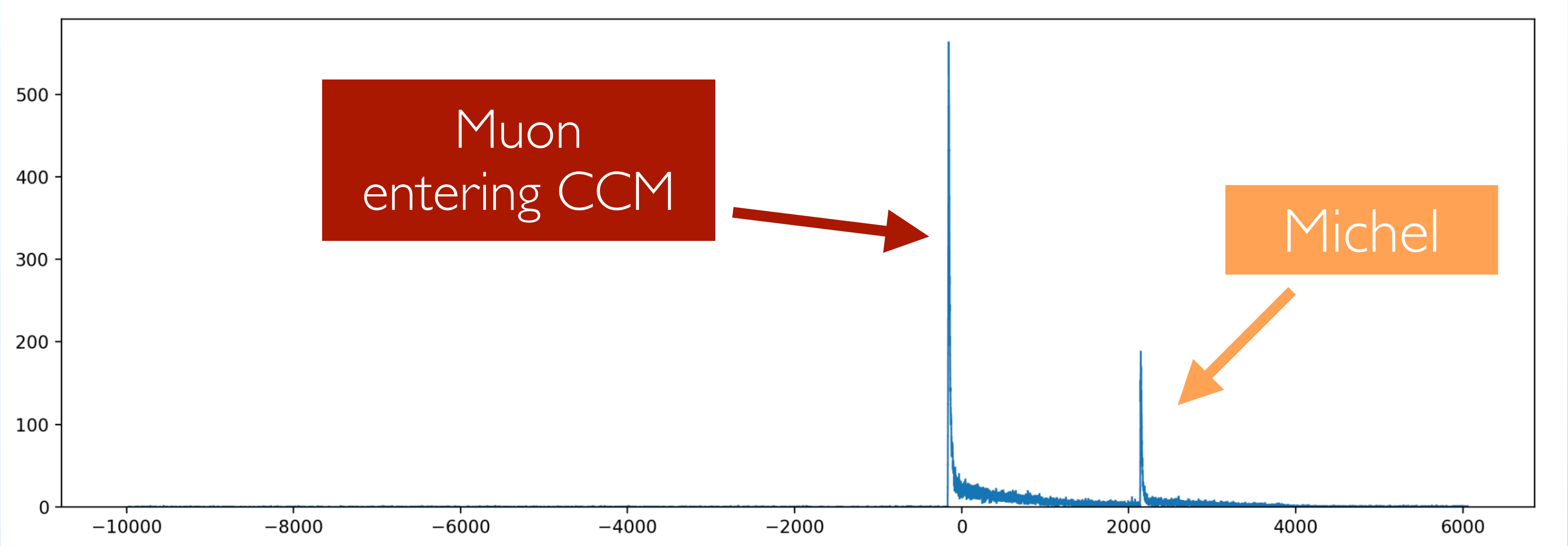
Main background for CC interaction in CCM

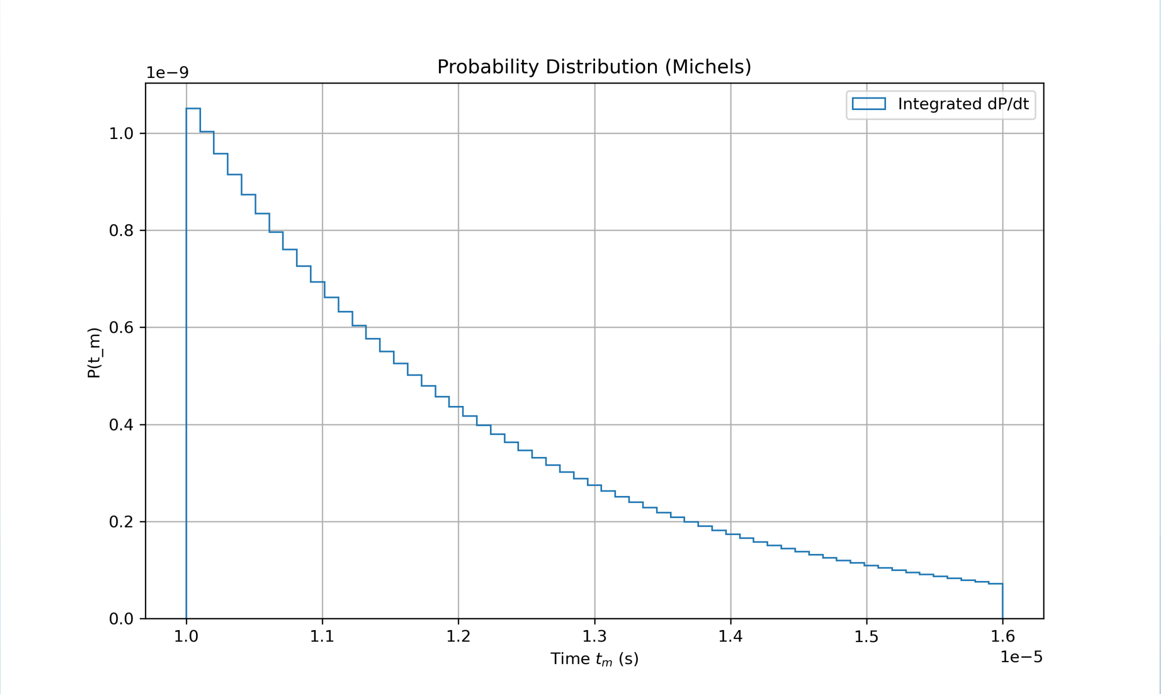
- **Cosmic muons** are constantly arriving to the Earth, they can go through the detector and decay, producing a **Michel electron**: $\mu \rightarrow e + \nu_e + \nu_\mu$

- Identifying Michel electrons is crucial as they can mimic the CC signal in the detector. They are our **main background** for searching CC-neutrino interactions.

- Estimating that only **1%** of the muons that enter the detector **stop** and produce a Michel, the calculated number of Michels in the LAr volume in a Region of Interest of $6\ \mu s$ is 2.18×10^{-7} events/trigger







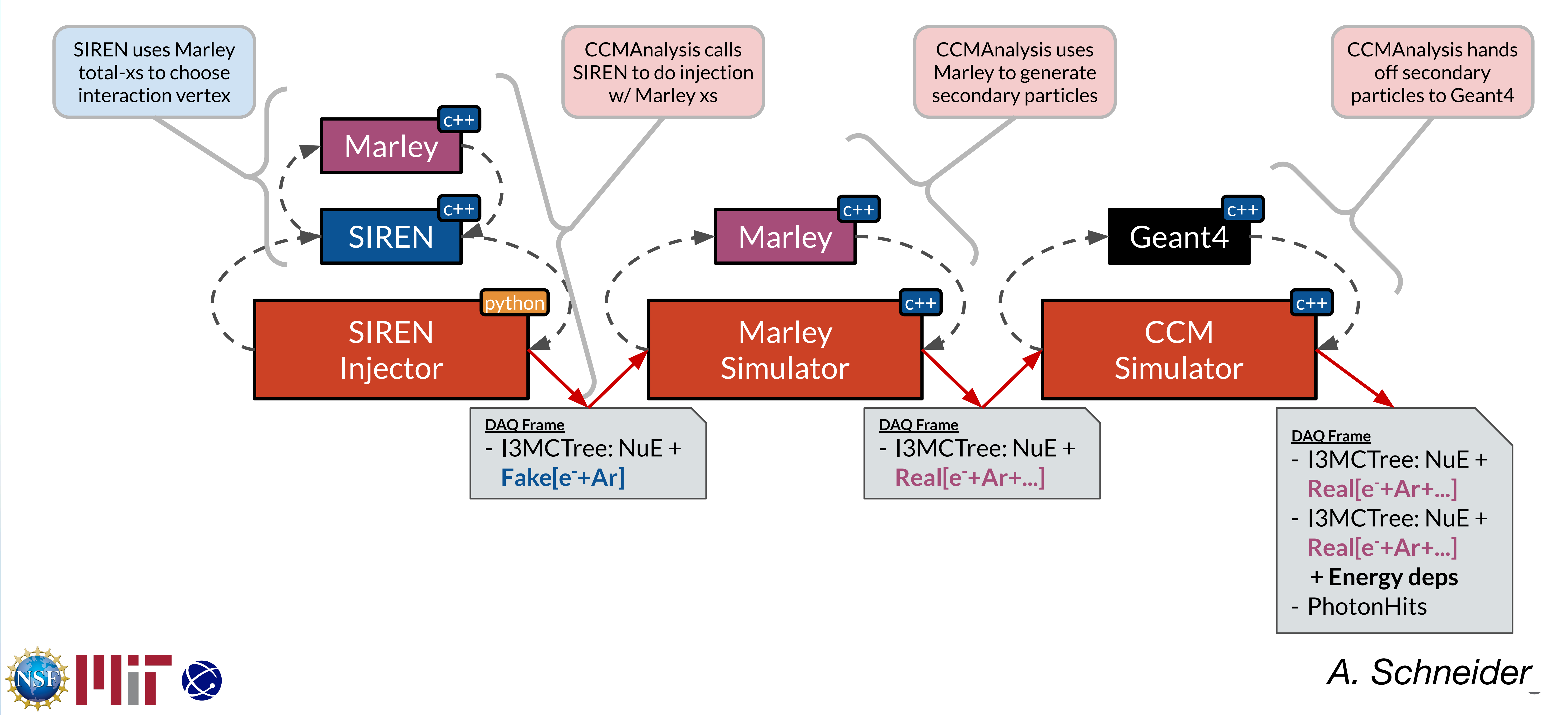
CC Simulation in CCM

- **3 stages of simulation**:

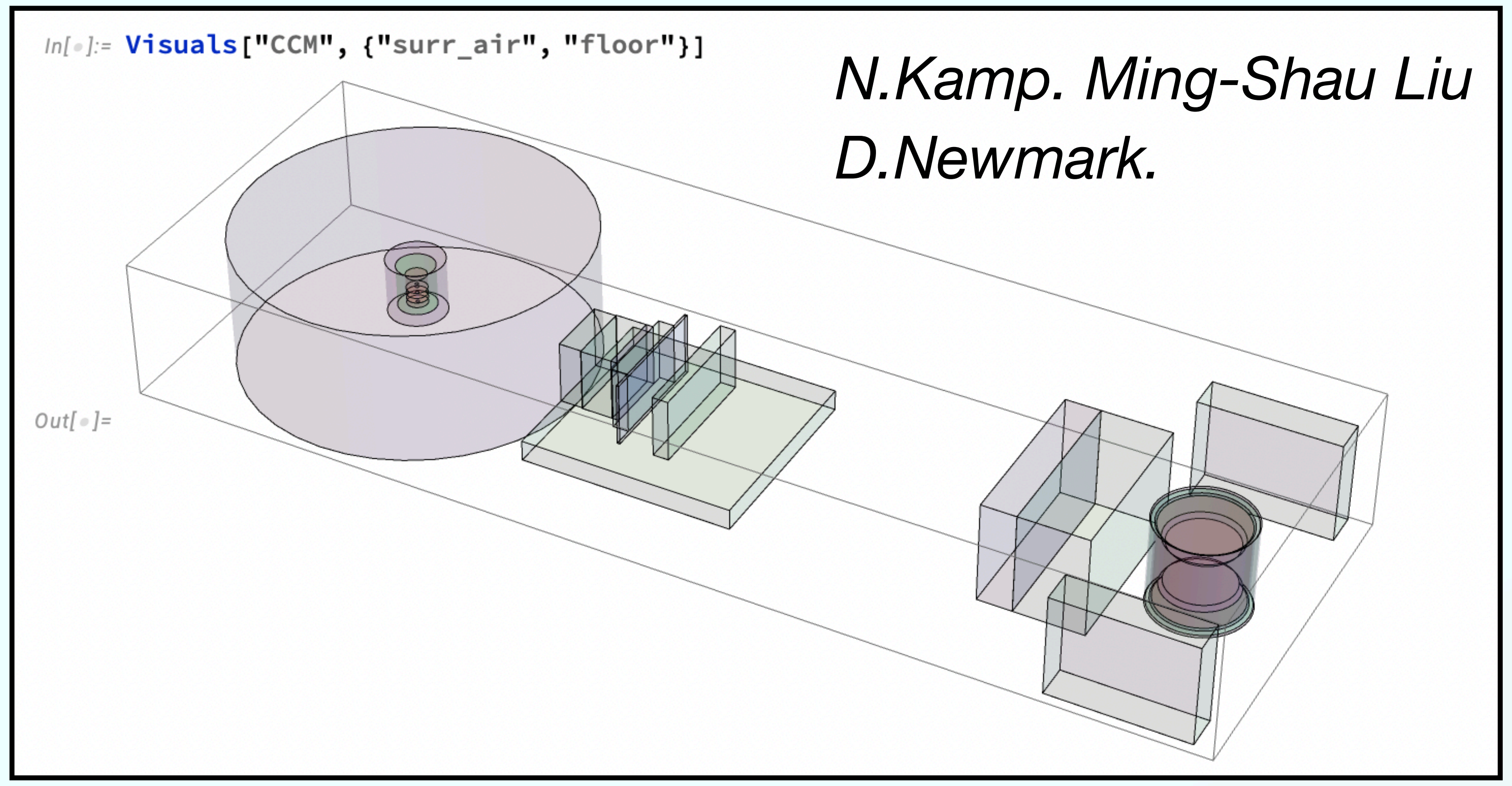
  - Primary **Vertex injection** (SIREN + MARLEY)
  - Production of **secondary particles** from CC interaction inside the Argon (MARLEY)
  - **Energy depositions** in the detector (Geant 4) *(In process)*

- All the simulation is being processed by the HPC- **Chicoma LANL** and **subMIT** clusters

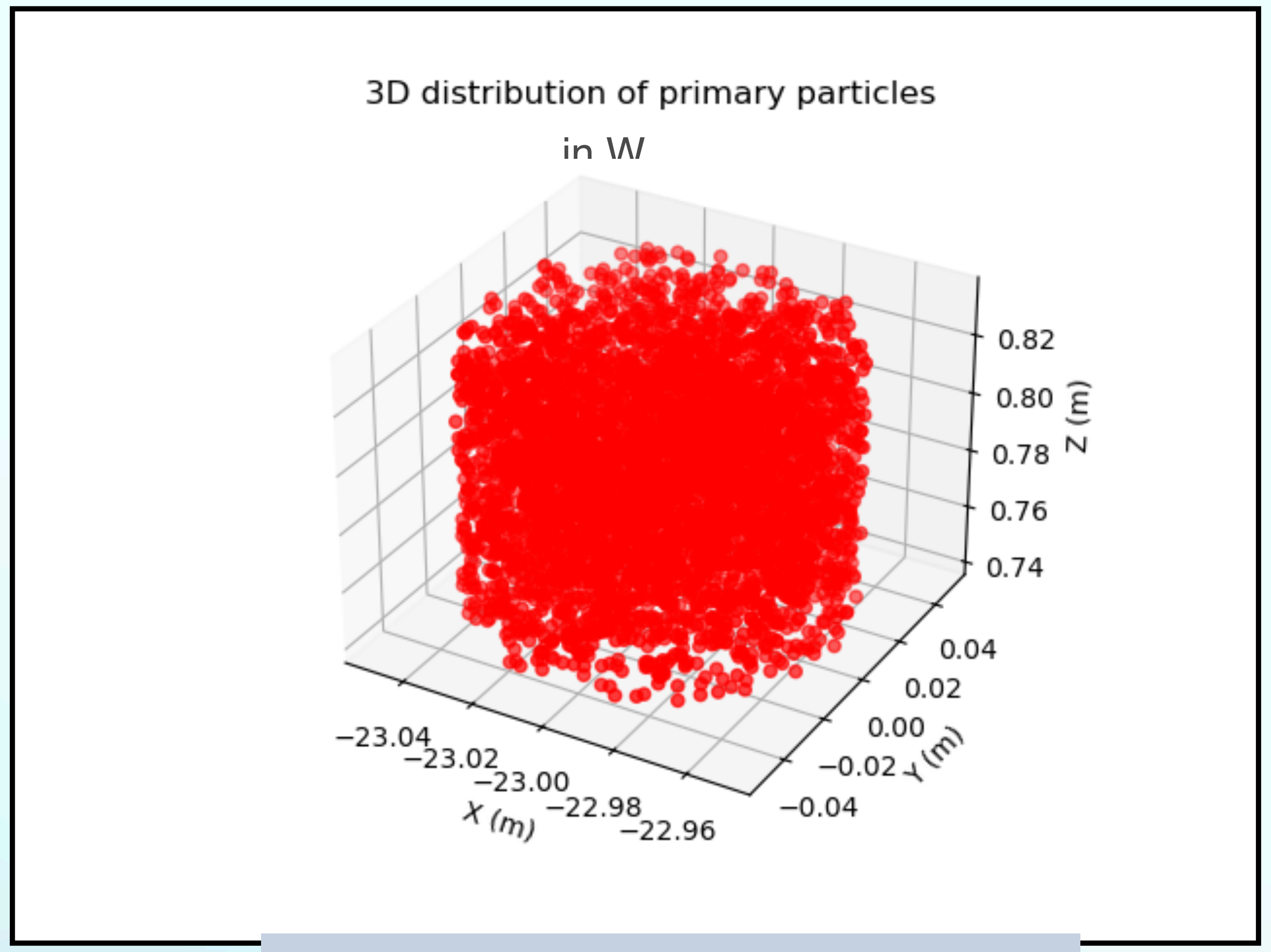
- Each of these stages are connected through the **CCMAnalysis framework**



SIREN + MARLEY injection

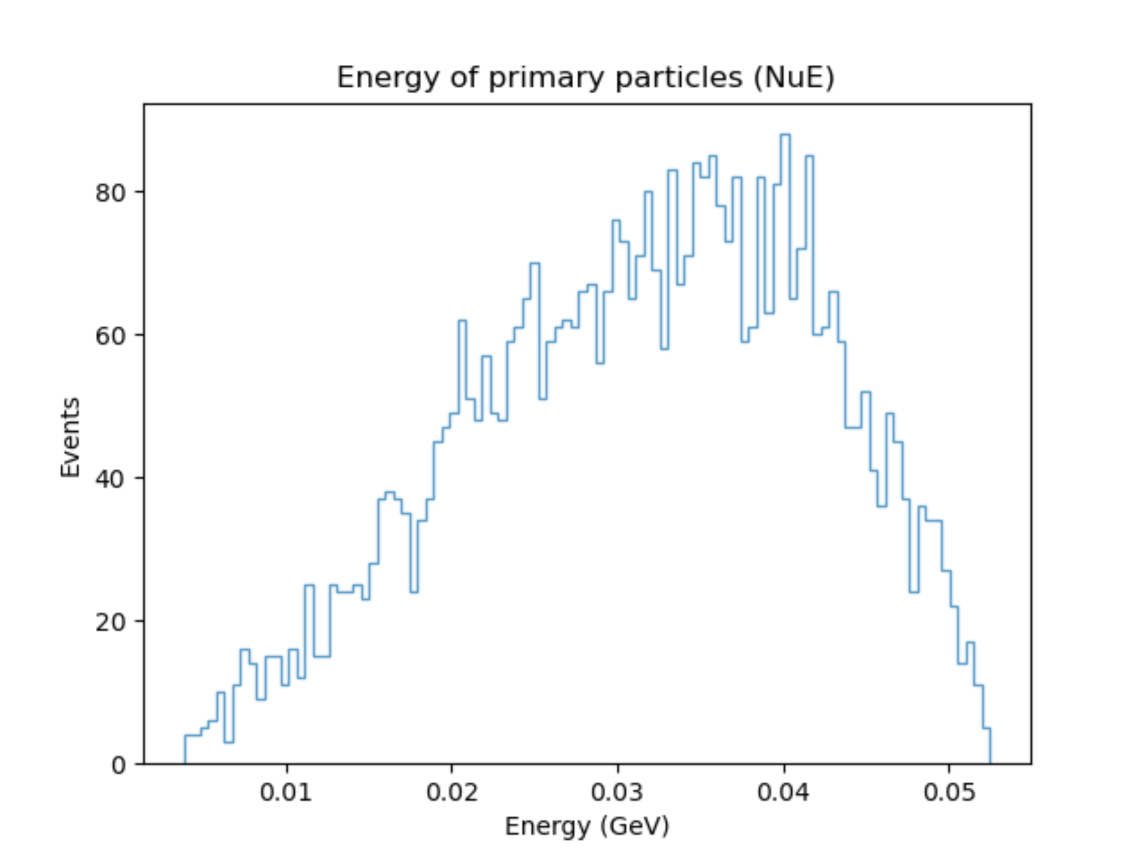


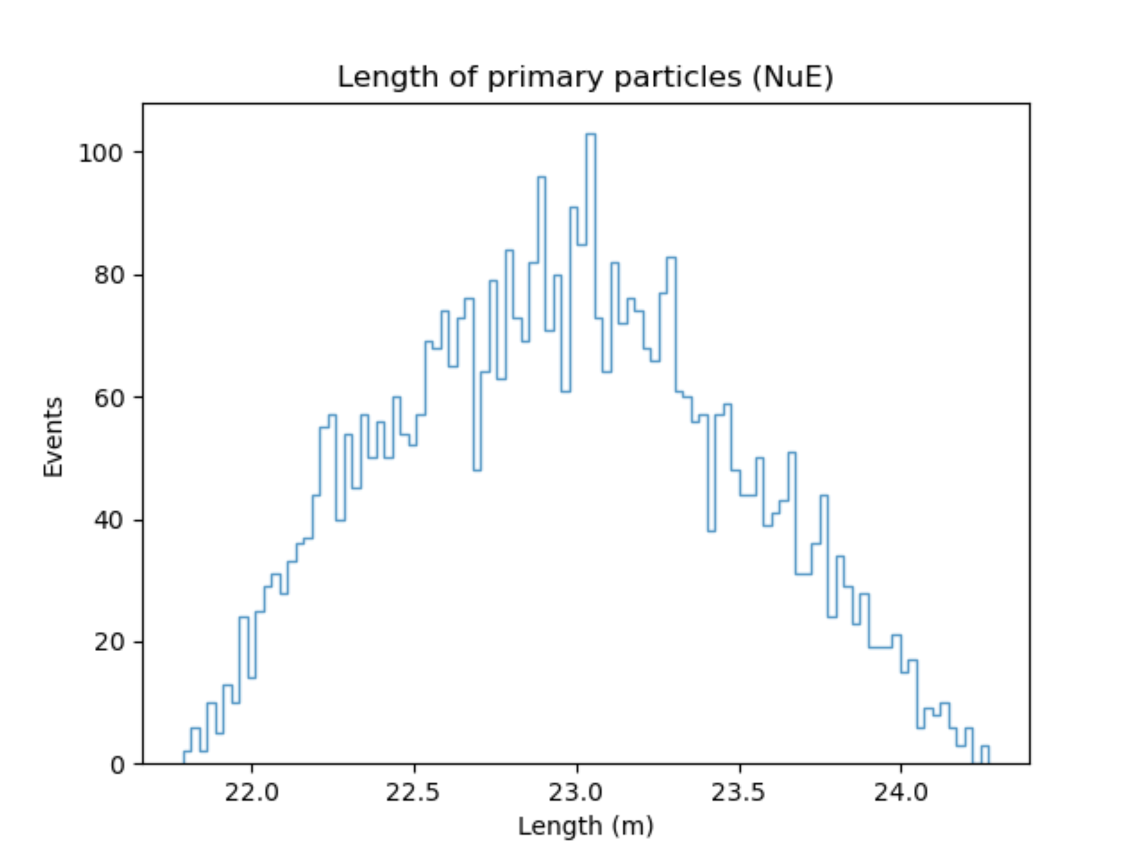
- **Electron Neutrinos** (primary particles) **are created** in the upper Tungsten target in Lujan Center using SIREN and the total Cross section from MARLEY:

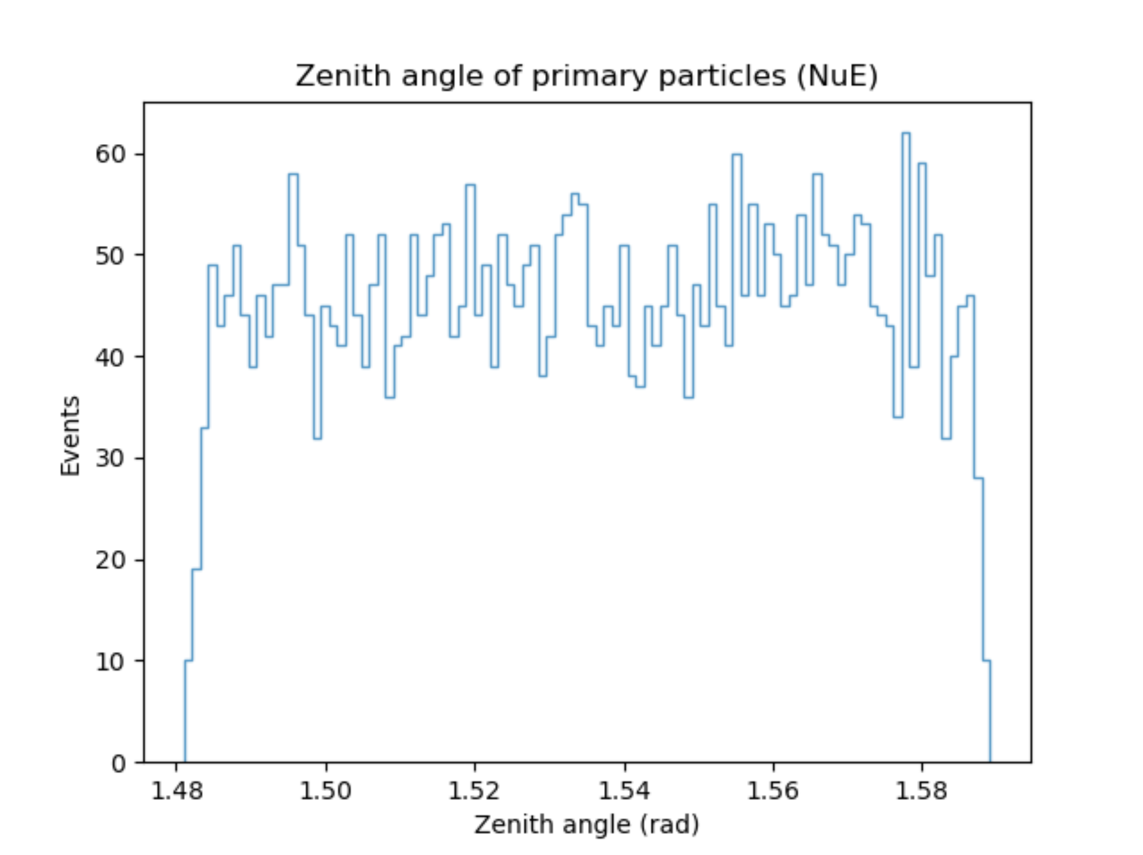


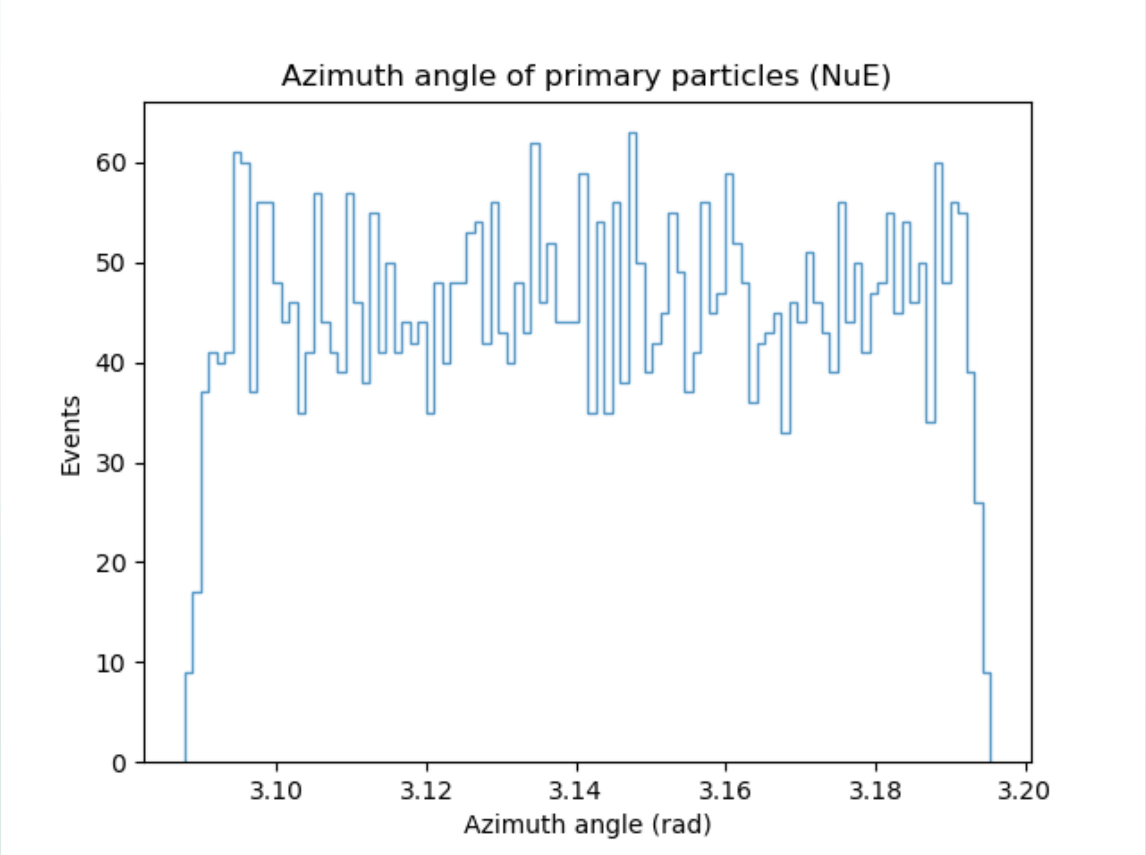
Upper W target dim:
radius 0.05 m, height 0.091 m

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







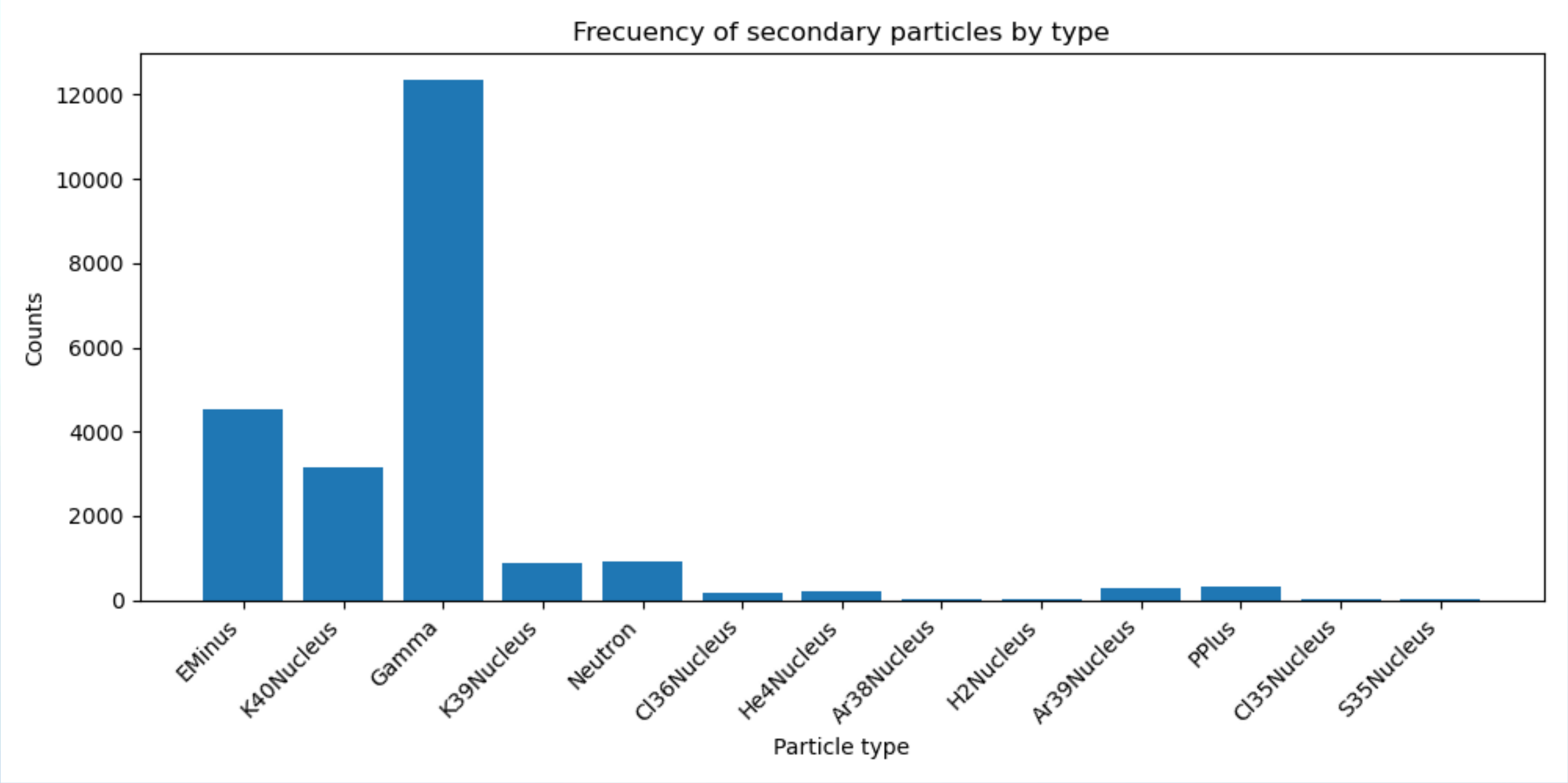


MARLEY CC simulation

- The neutrinos are injected in the CCM detector argon volume, **MARLEY generates the Charged Current events.** For each interaction event, secondary particles are produced.

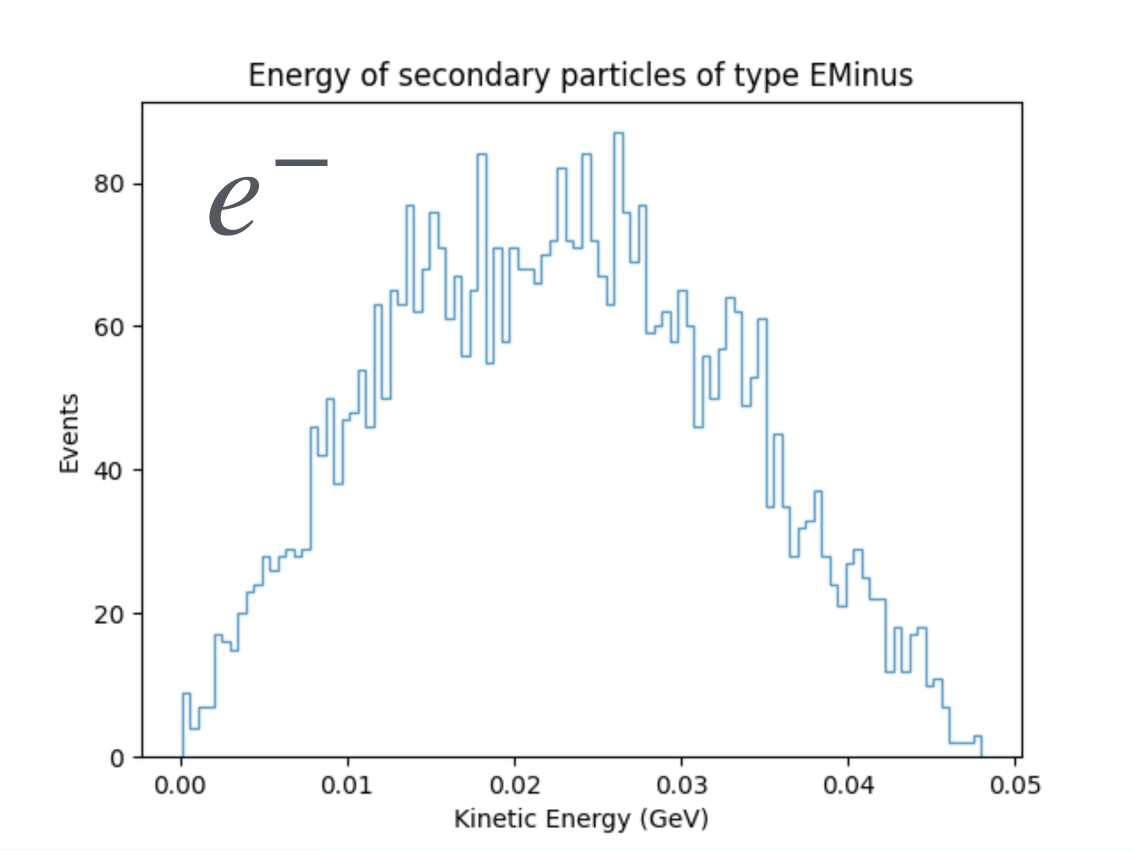
- This is the main reaction:

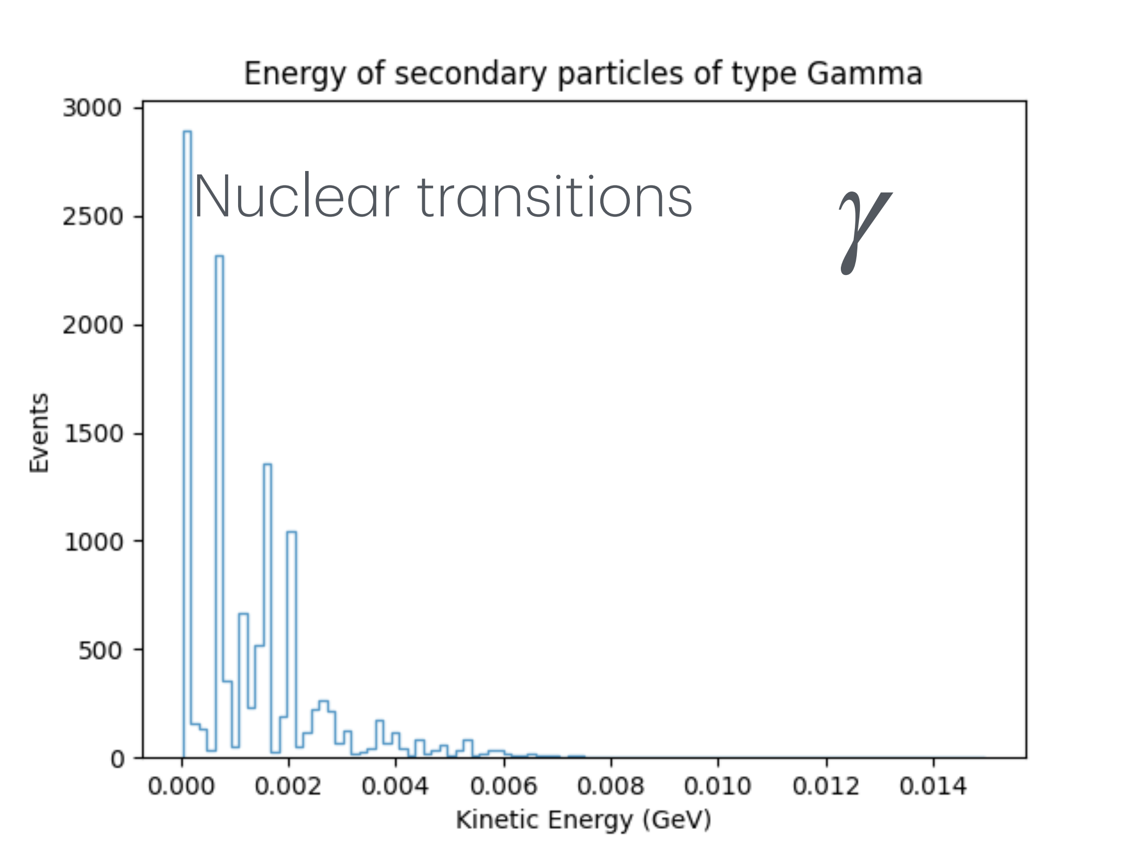
$$\nu_e \ + \ {}^{40}Ar \rightarrow e^- \ + \ {}^{40}K^*$$

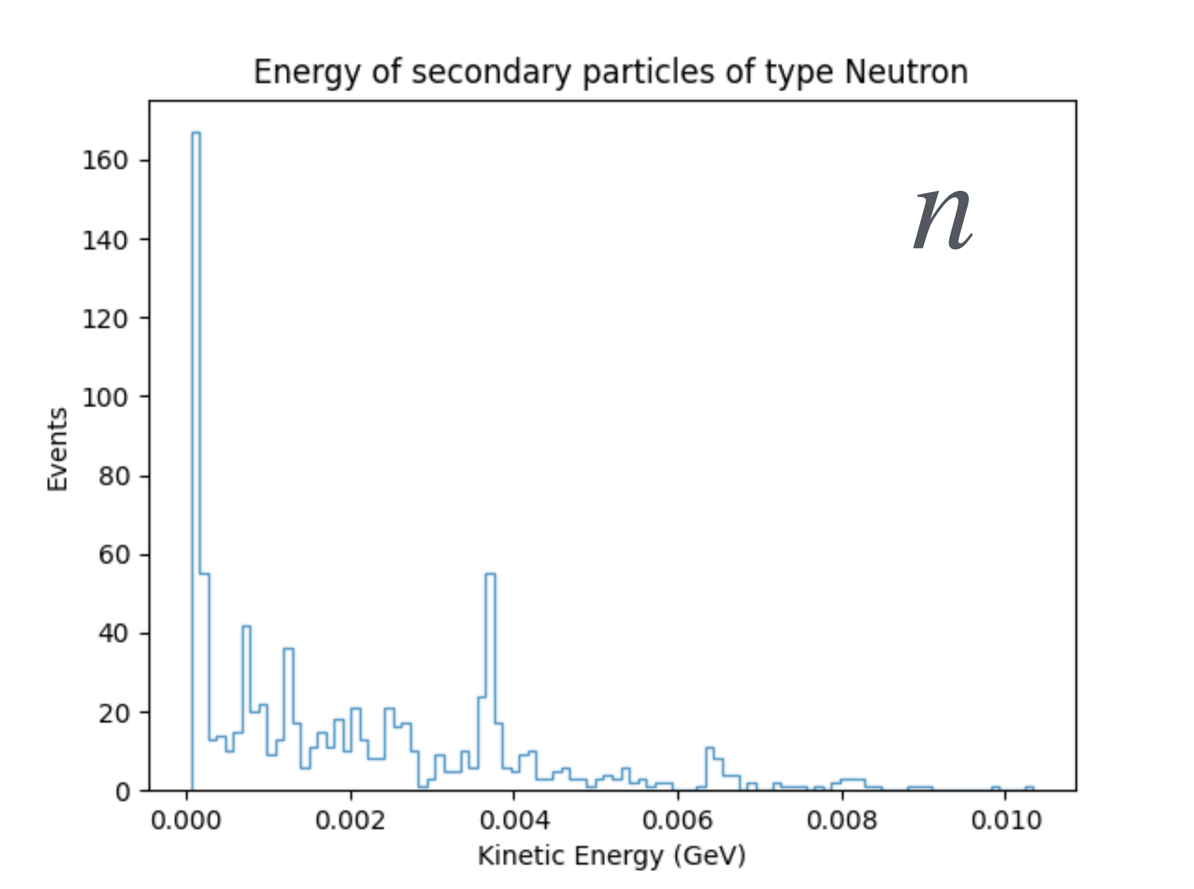


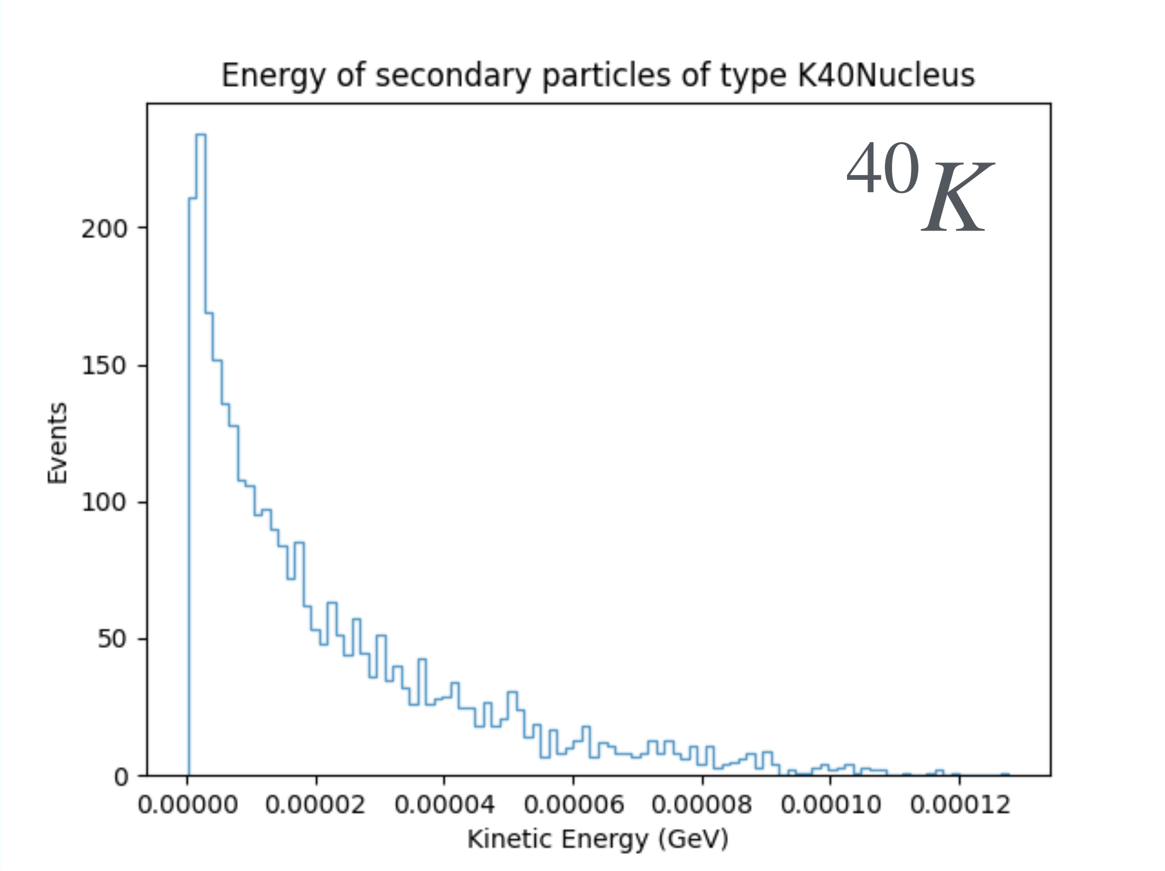
MARLEY CC simulation

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

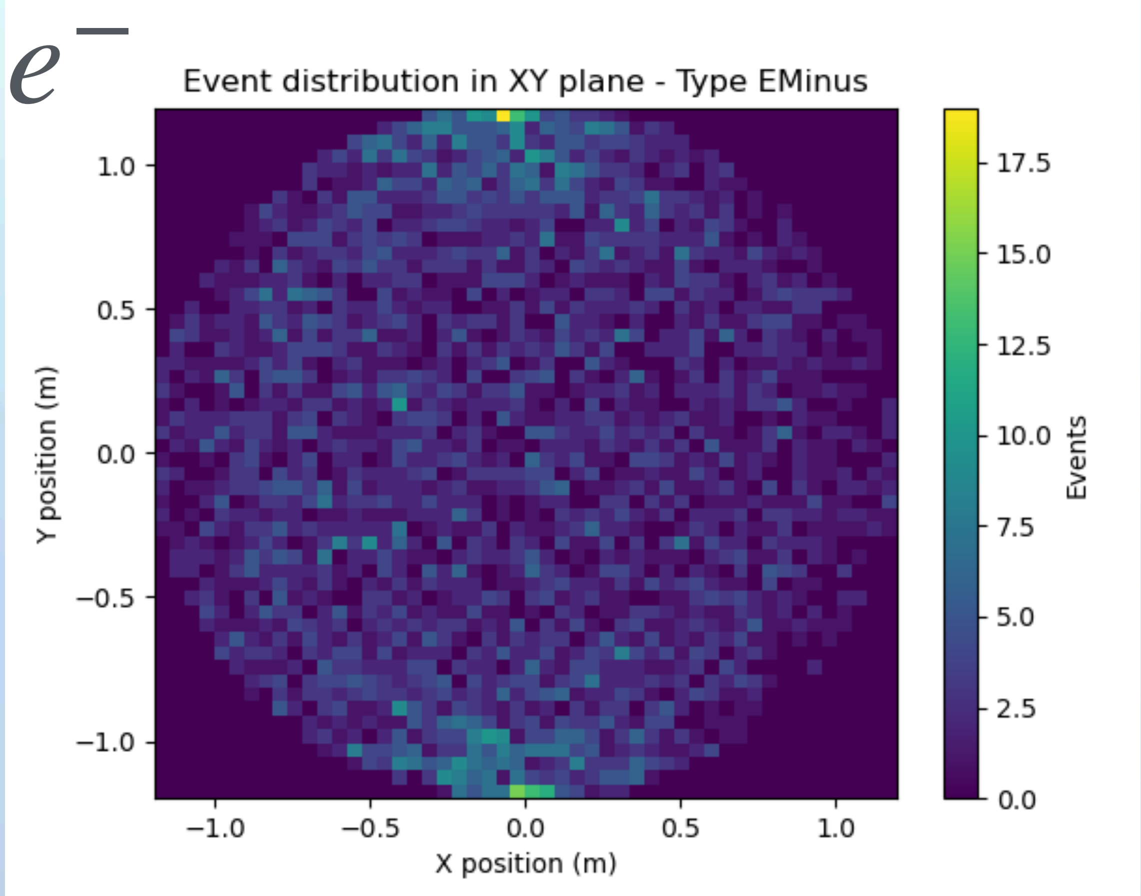


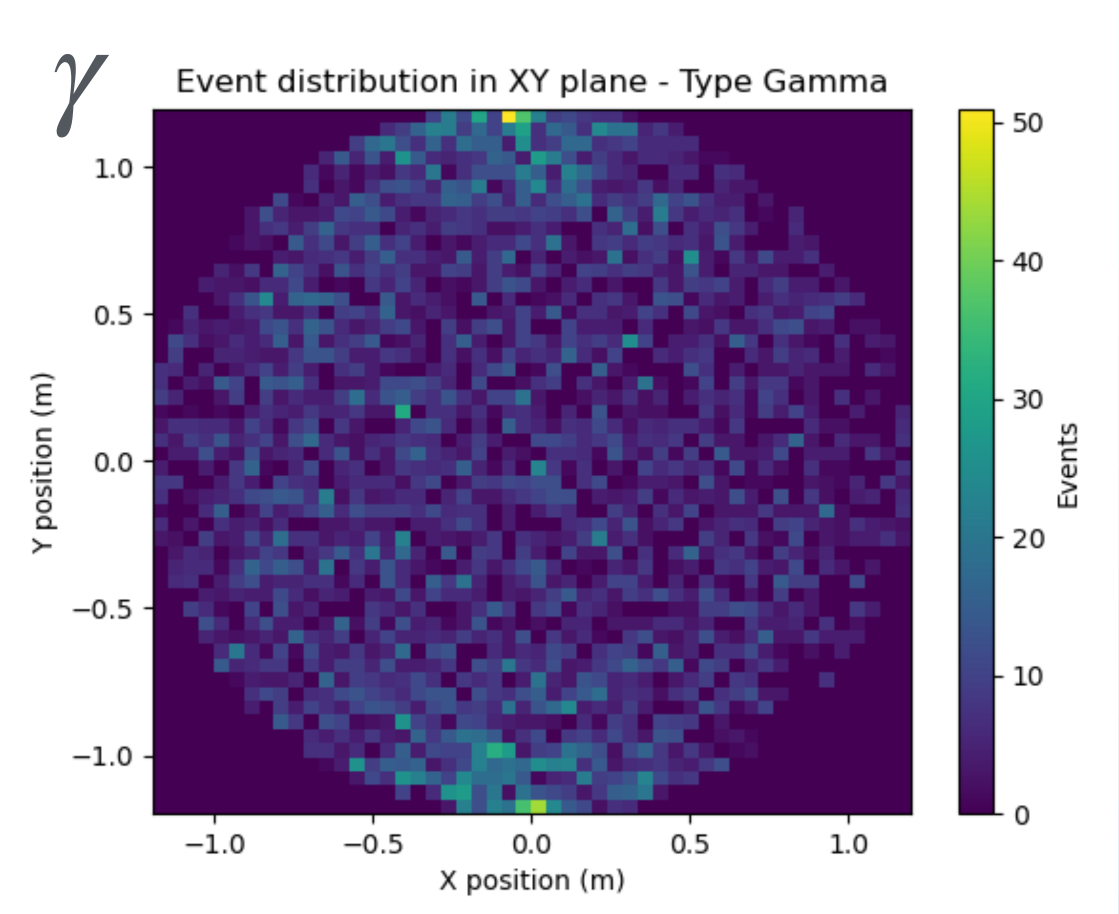


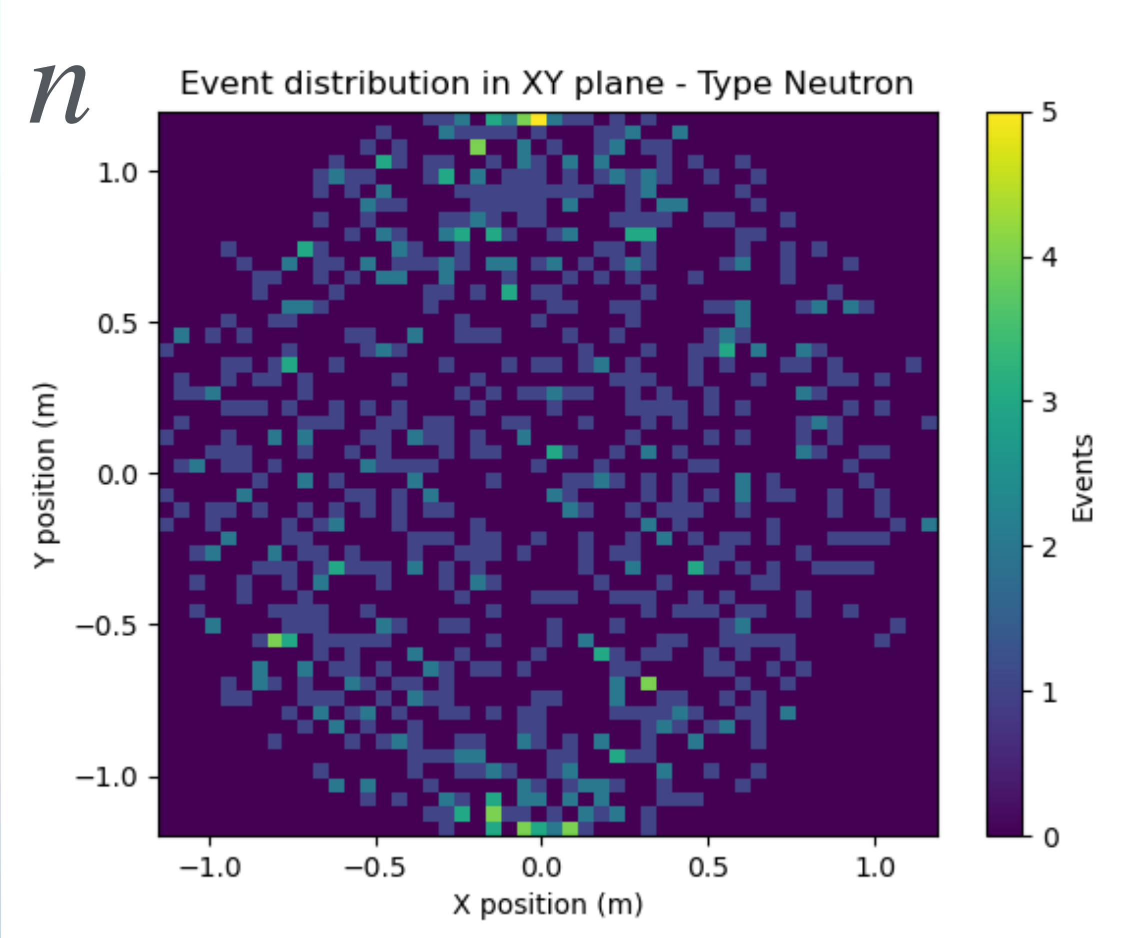


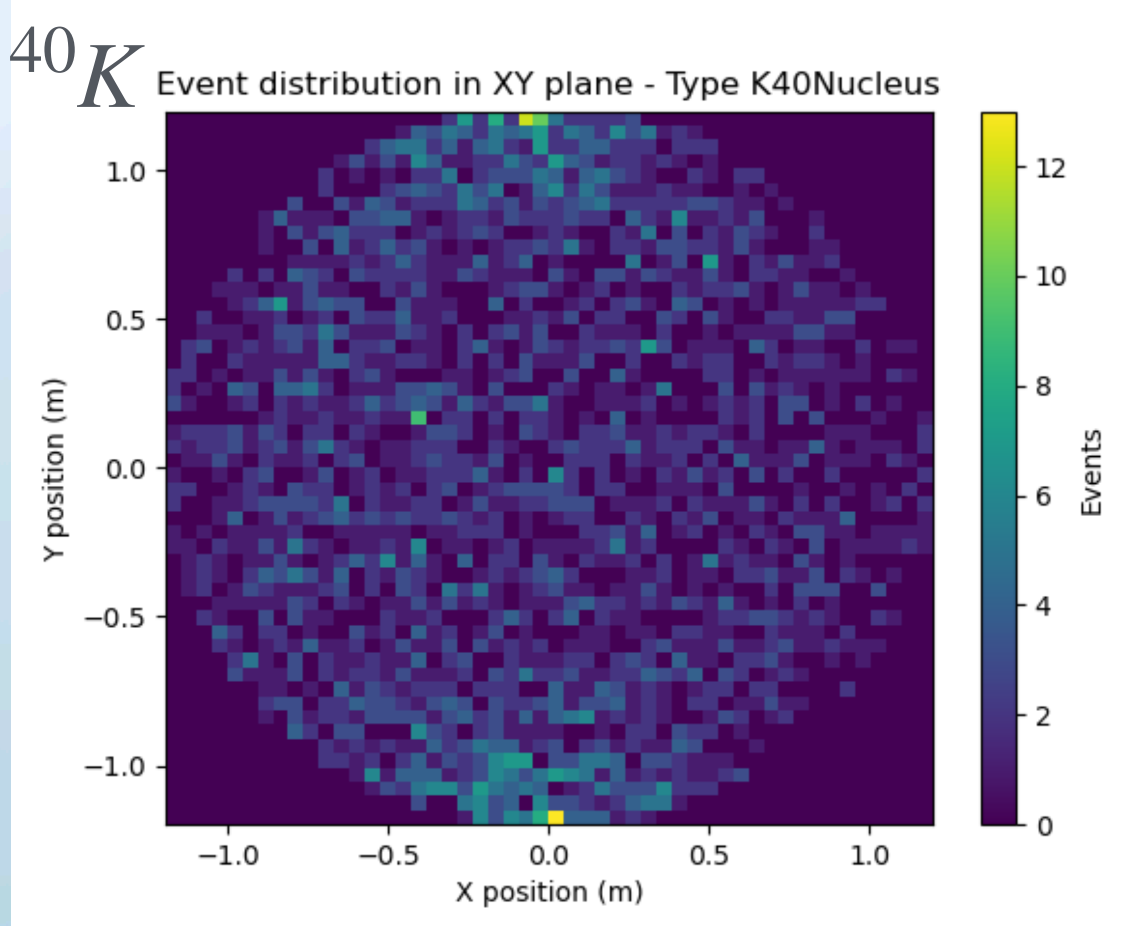


- **Spatial Distribution (XY)** in the CCM detector









Future and upgrade plans for CCM

- **Cherenkov** light PID.
- Implementation of a **high energy self-trigger**.
- Moving the detector away from **23m to 30m** in 2025.
- **CEvNS.**
- Start to collect new data in the **2025 run.**
- Doping of LAr with **Xenon.**
- **Recirculation** and **filtration** LAr system.

Stay tuned for the results!
Thank you!

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(The CCM Collaboration)

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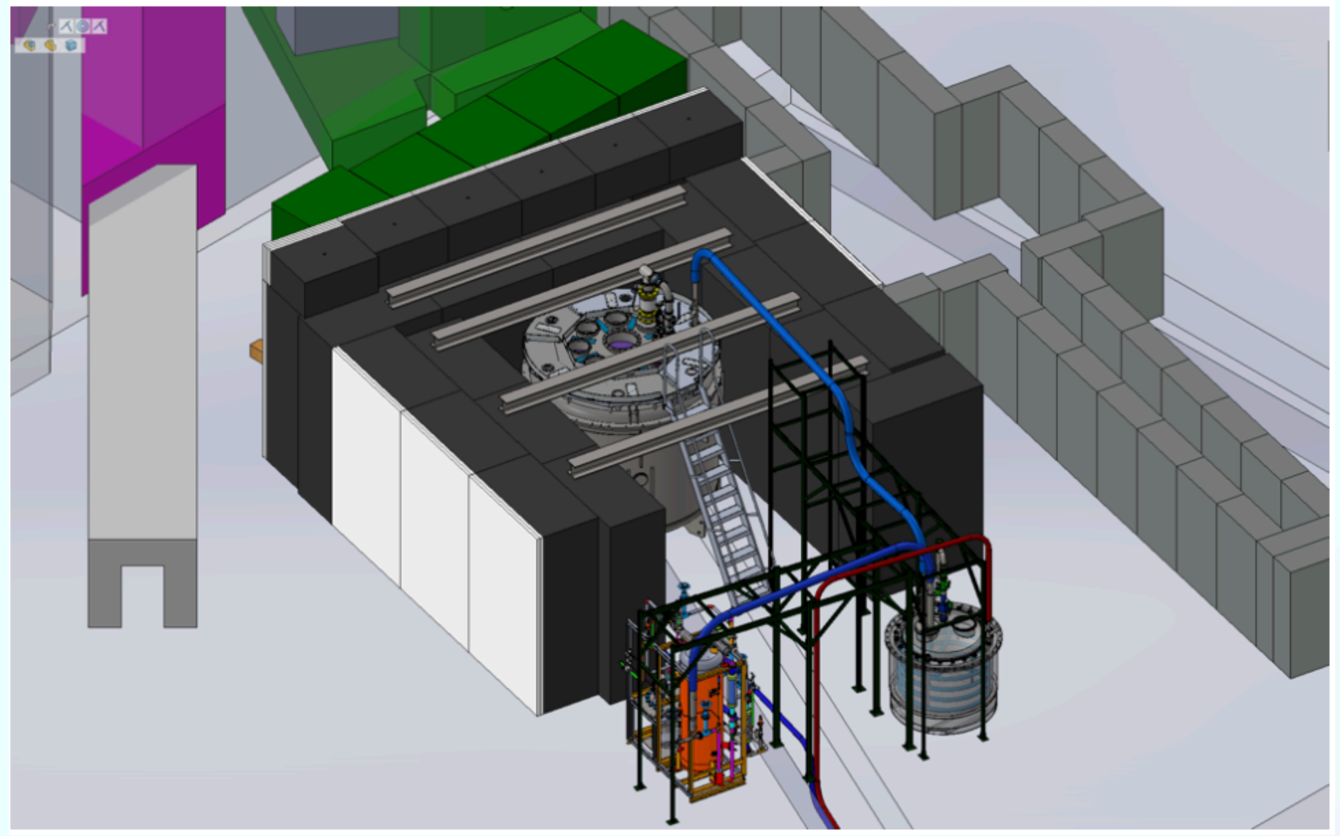
Extra slides

Sources of background and shielding at CCM detector

Beam related background	Solution
Time related: Neutrons from the beam	Time cuts in data
Non time related: Neutron activation (emission of γ, α, β ,n, and fission products)	Shielding

Non beam related	Solution
Ar39: emission of betas	Use of underground Ar, isotopically pure
Cosmic Muons	Veto cuts. Detection with cosmic watches

- 5m of steel, 2 m of concrete surrounding the W target.
- CCM Shielded in the surrounding walls, roof and under the cryostat: Concrete, Steel, Borated Polyethylene, Lead



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.**

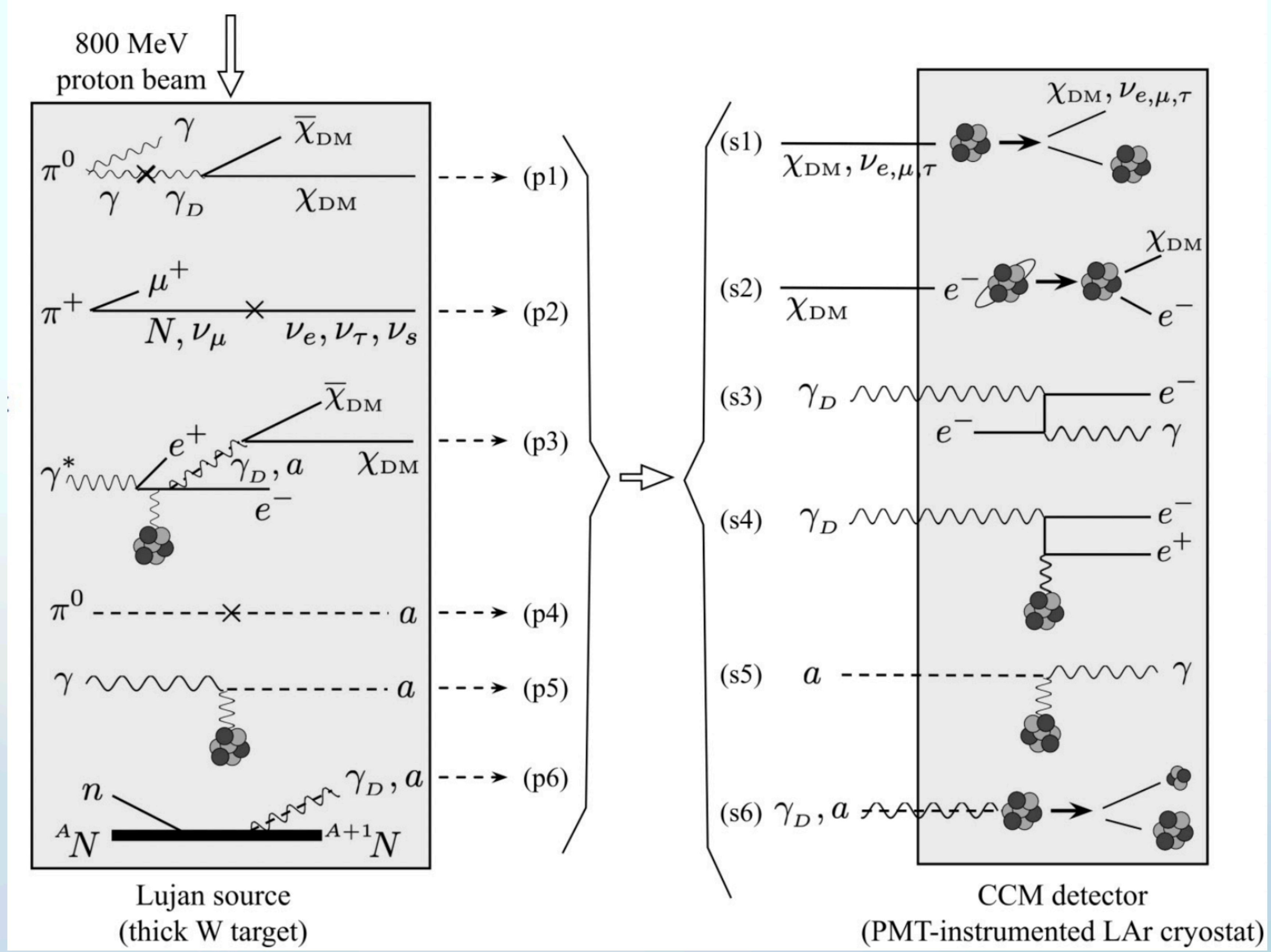
- **Publications:**
  -First Leptophobic Dark Matter Search from the Coherent–CAPTAIN-Mills Liquid Argon Detector (PRL)
  -First dark matter search results from Coherent CAPTAIN-Mills (PRD)
  -Prospects for detecting axionlike particles at the Coherent CAPTAIN-Mills experiment (PRD)

Dark photons decay into Dark matter

Sterile neutrinos, oscillations

Dark photons decay into Dark matter

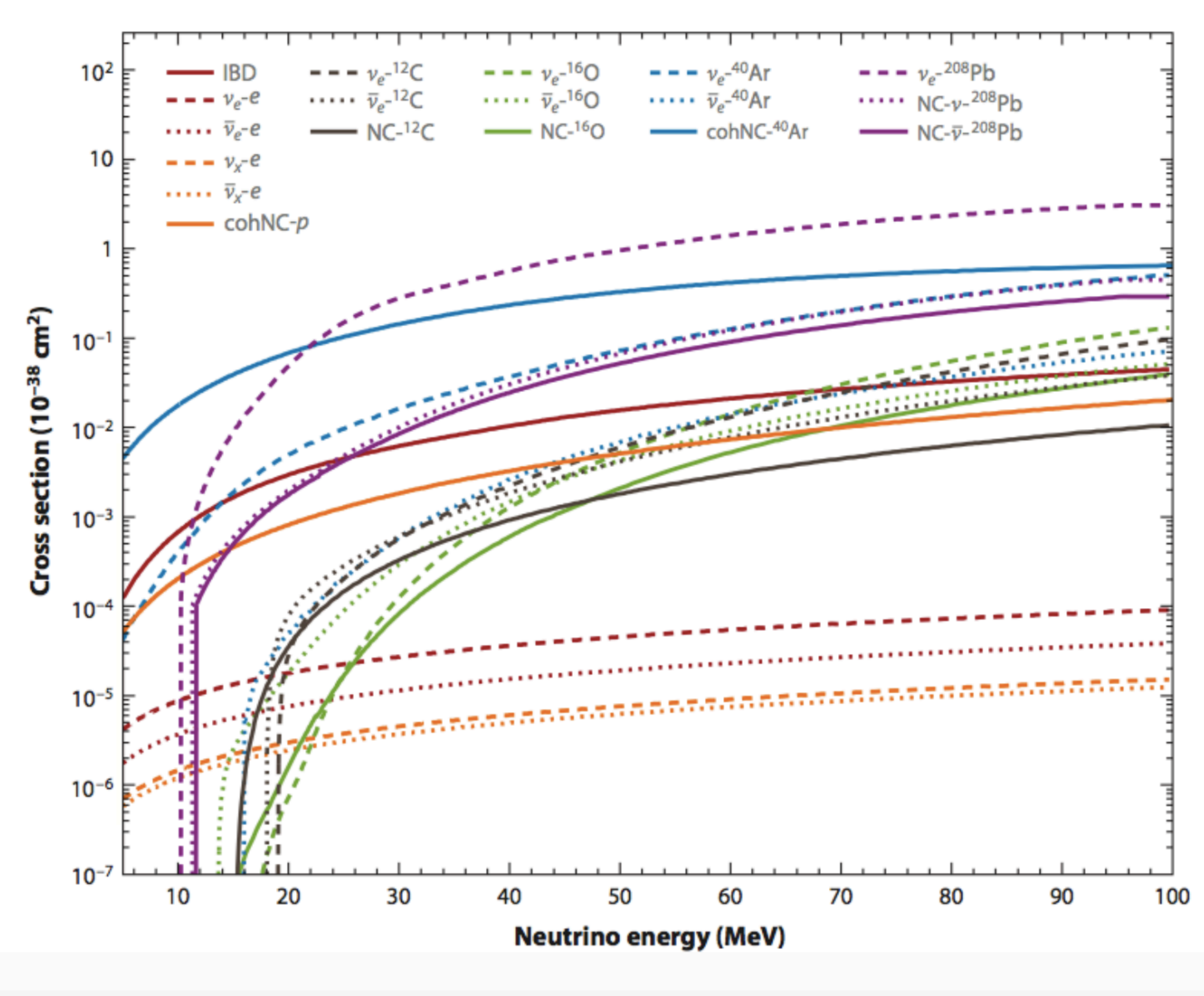
Axion like particles



Coherent scattering

Compton scattering

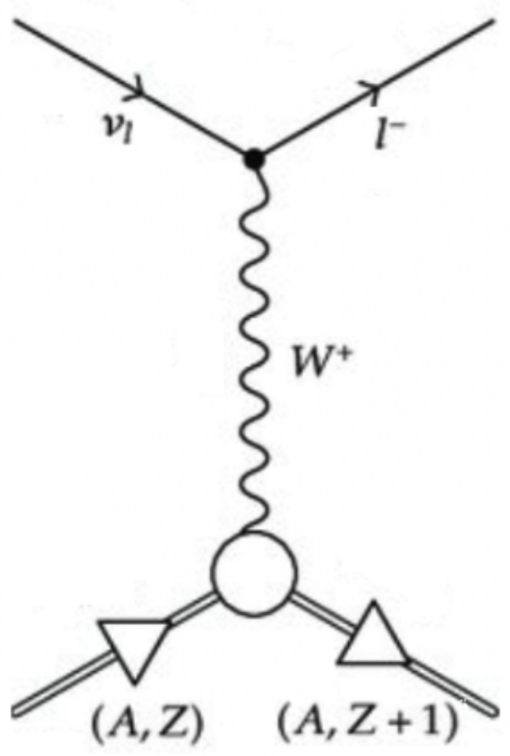
Cross Sections



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 ν_e 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

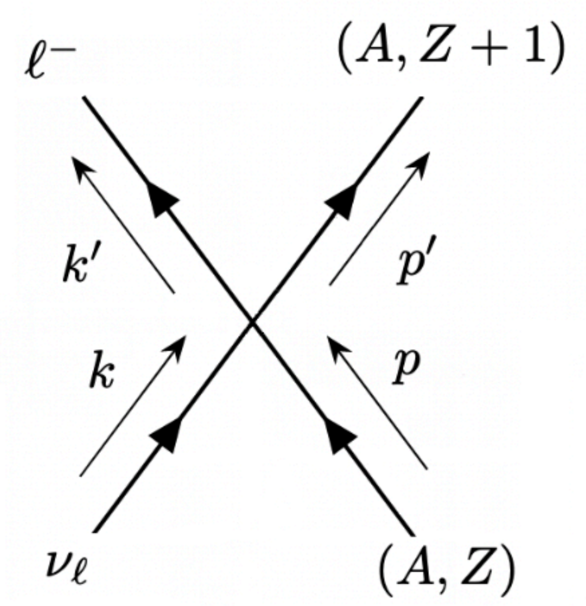
V_{ud} CKM Matrix element

$s = E_{CM}^2$

m_i Initial nucleus mass

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

$i\mathcal{M} =$



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

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

q 3-momentum transfer

j^μ weak current operator

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 $j^\mu(n)$ is evaluated under the allowed approximation:

Large wavelength ($q \to 0$) 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

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

CC Scattering (cont)

Therefore the cross section:

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

Angular dependence!

Fermi and Gamow-Teller Reduced matrix elements

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

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

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