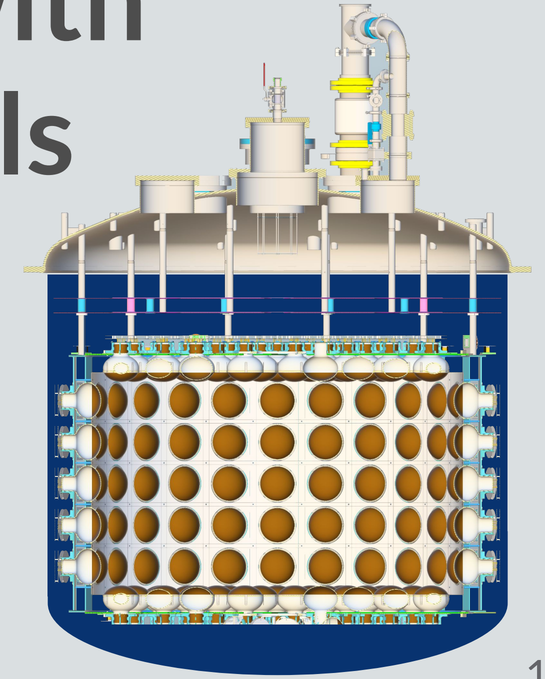
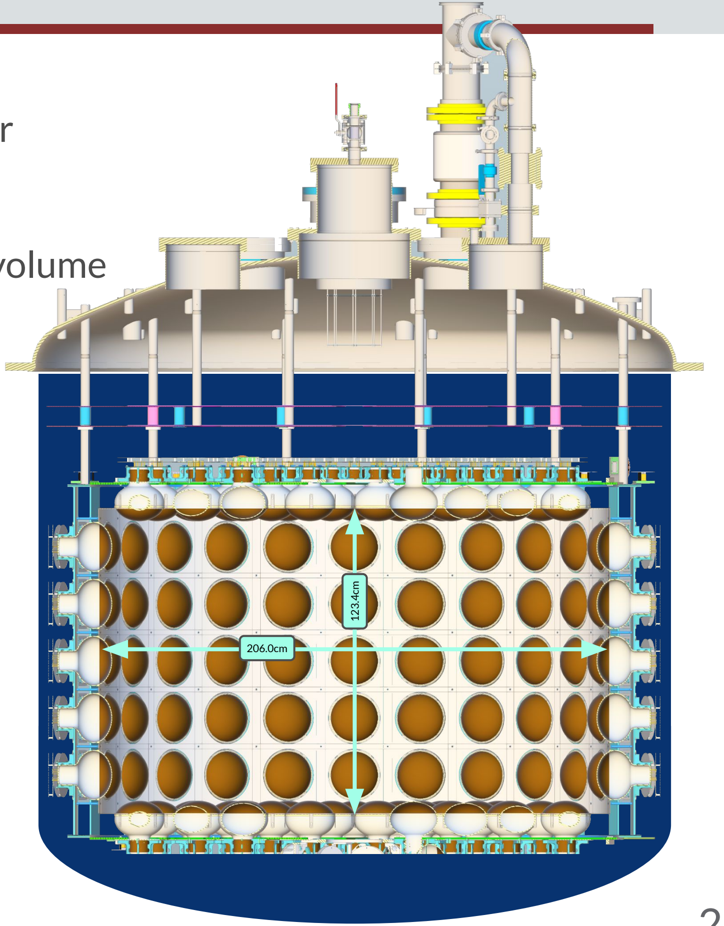
Dark Sector Searches with Coherent CAPTAIN Mills

Austin Schneider
CIPANP 2025 - Neutrino Masses, Mixing and Interactions
2025-06-12

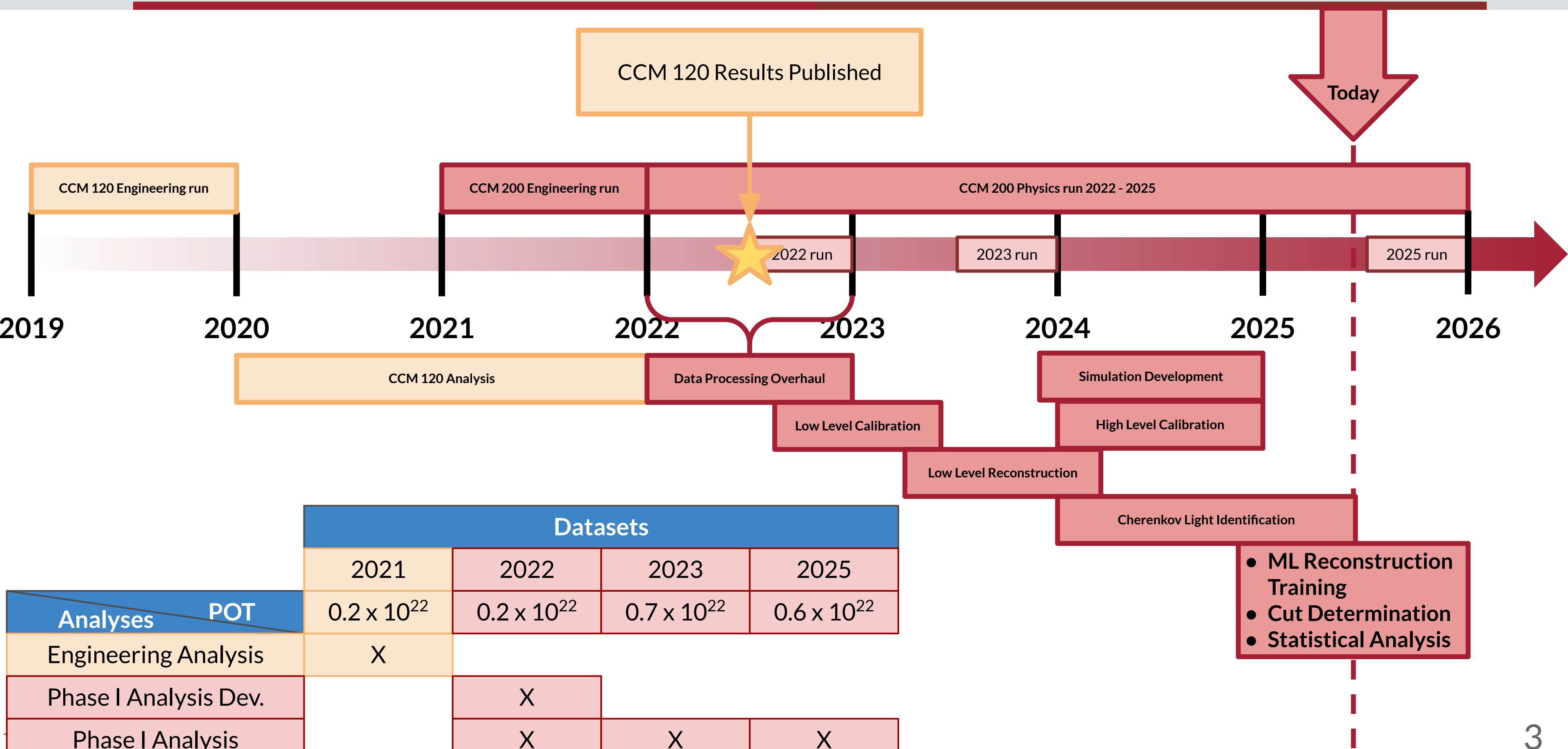


Coherent CAPTAIN-Mills (CCM)

- 10 ton liquid Argon (LAr) scintillation and Cherenkov detector
- Largest light-based LAr detector by photo-cathode area
- 200 8” PMTs provide 50% photo-coverage of a 5 ton fiducial volume
- 3 ton active veto region
- Mid-way through 3 year data taking period
  - 1.5×10^{22} POT



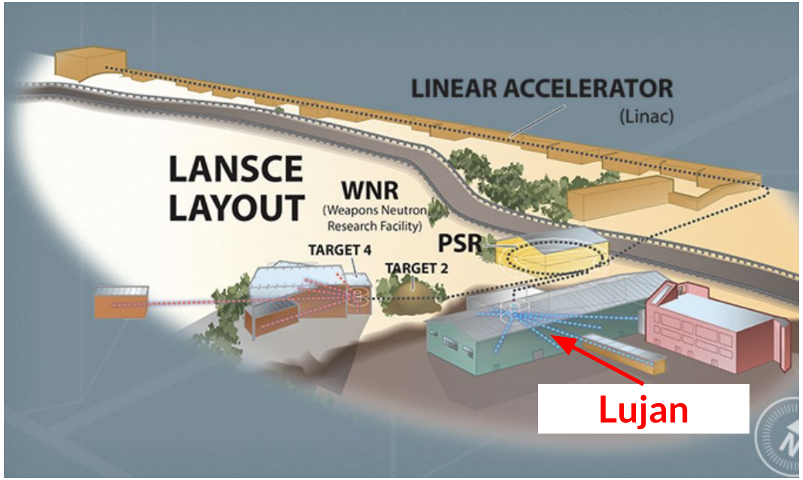
CCM Historical Timeline



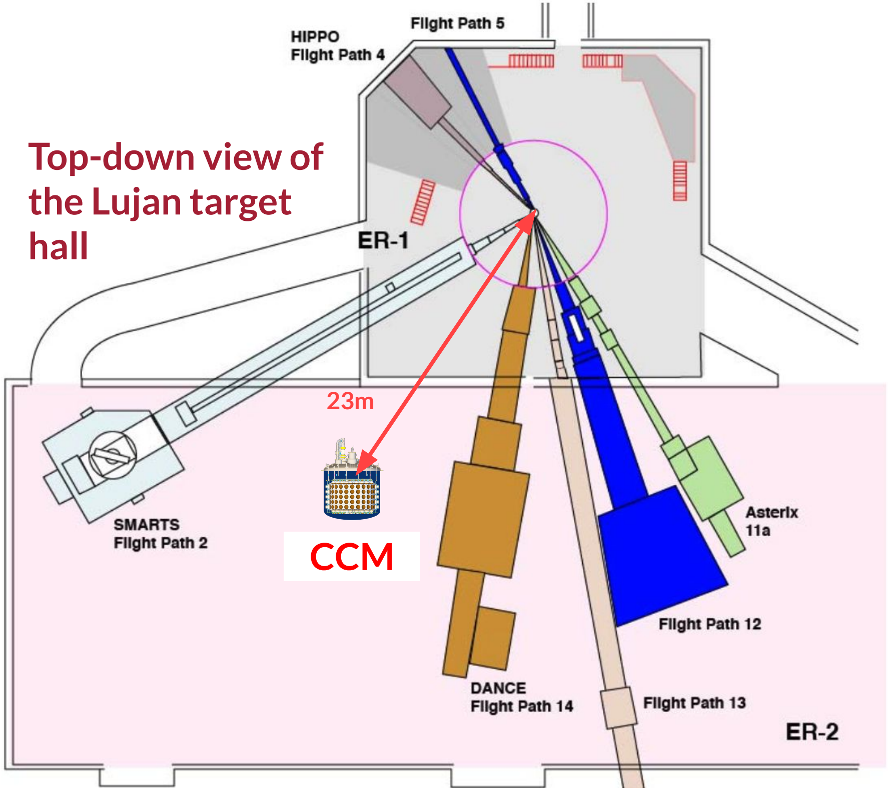
	Datasets			
	2021	2022	2023	2025
Analyses / POT	0.2×10^{22}	0.2×10^{22}	0.7×10^{22}	0.6×10^{22}
Engineering Analysis	X			
Phase I Analysis Dev.		X		
Phase I Analysis		X	X	X

CCM at Lujan

- CCM is 90° off axis from the beam
- Avoids decay-in-flight backgrounds
- 23m from target



Top-down view of the Lujan target hall

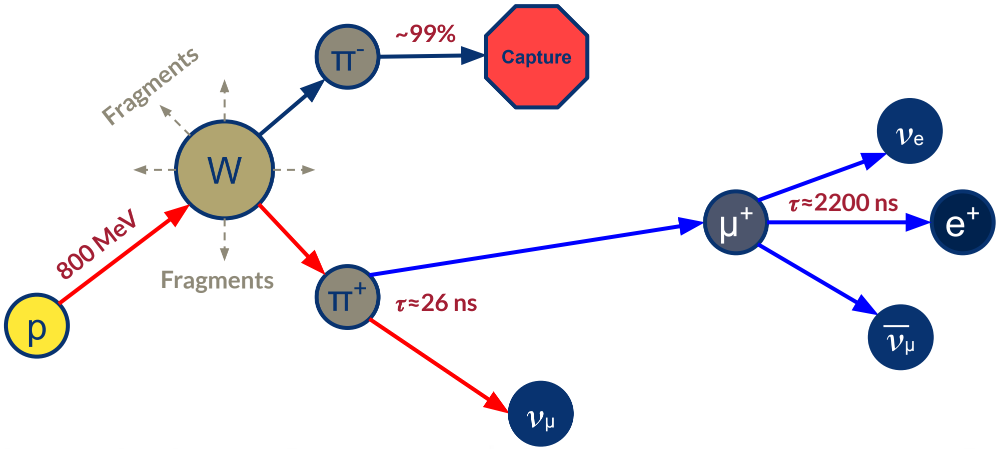


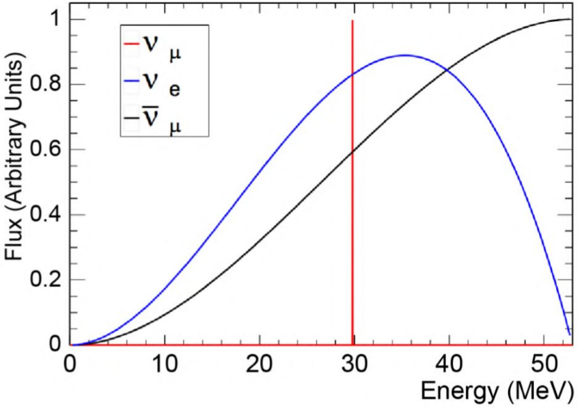
Lujan target neutrino production

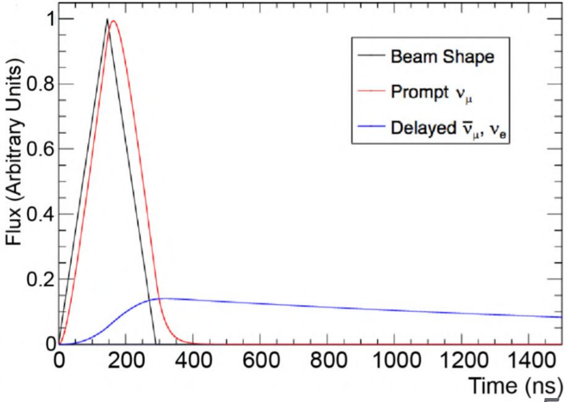
- 800 MeV pulsed proton beam
- 20 Hz | 100 micro-amps | 290 nsec spill

- π+ decay at rest is a prolific source of neutrinos
- Prompt NuMu neutrinos at 30 MeV
- Delayed NuE and NuMuBar

- Target environment has an intense flux of:
  - Charged pions
  - Neutral pions
  - Gamma-rays
  - Muons
  - Neutrinos
  - Neutrons

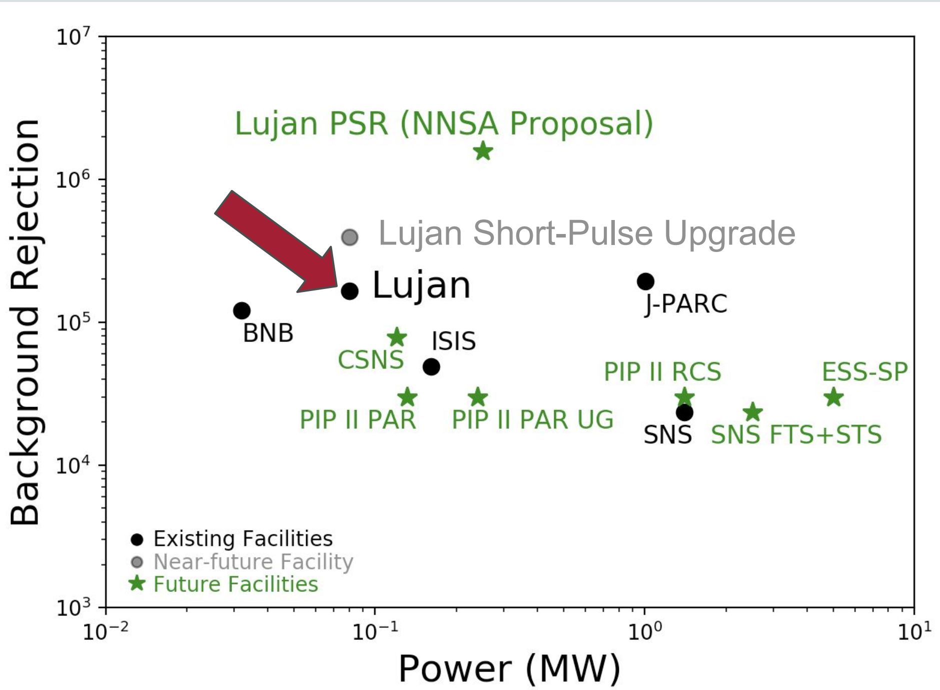


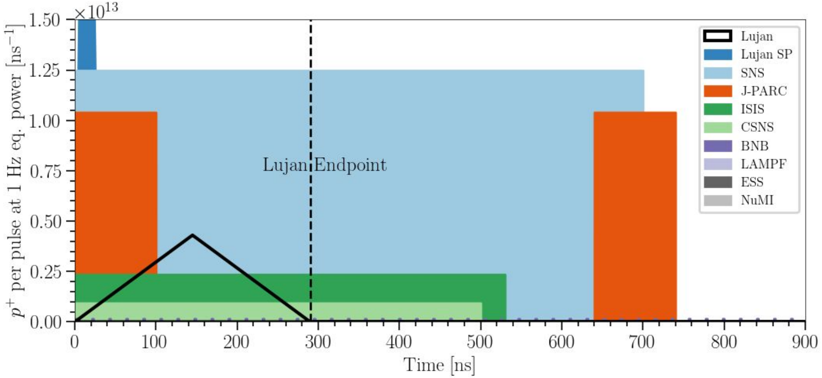


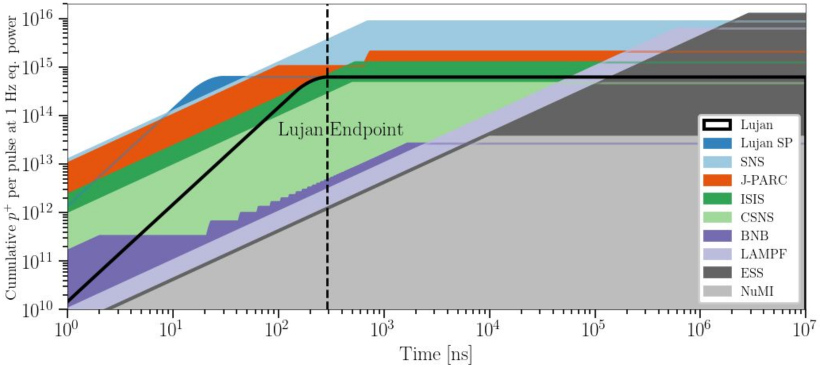


Proton Beam Dumps

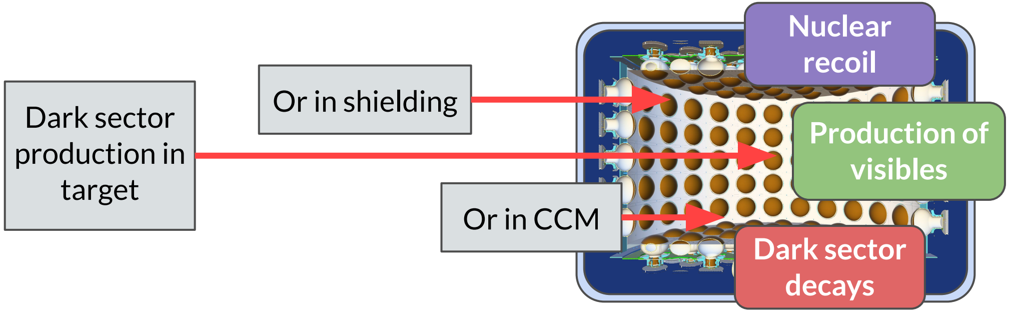
- piDAR provides a very clean flux of neutrinos
- Off-axis detection removes most backgrounds
- Primary background is neutrons
- Lujan's short 290 ns proton pulse allows us to remove neutrons through arrival time
    - Future upgrades will improve performance







Physics with Coherent CAPTAIN Mills



Broad program of dark sector searches

- Axion-Like-Particles and MeV-scale QCD axion [10.1103/PhysRevD.107.095036]
- Leptophobic MeV-scale dark matter [10.1103/PhysRevLett.129.021801]
- Light-dark-matter [10.1103/PhysRevD.106.012001]
- Meson Portal Dark Sector Solutions to the MiniBooNE Anomaly [10.1103/PhysRevD.109.095017]
- X17 ATOMKI particle [arXiv.2410.17968]
- Heavy Neutral Leptons
- Dark photons
- Scalar mediator DM

Standard Model measurements

- **Electron Neutrino Charged Current Cross Section on Argon at the MeV to 10's of MeV scale**
- Coherent Elastic Neutrino Nucleus Scattering (CEvNS) cross section measurement at the 10 keV to 100 keV scale

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Dark secto
production
target

Stand

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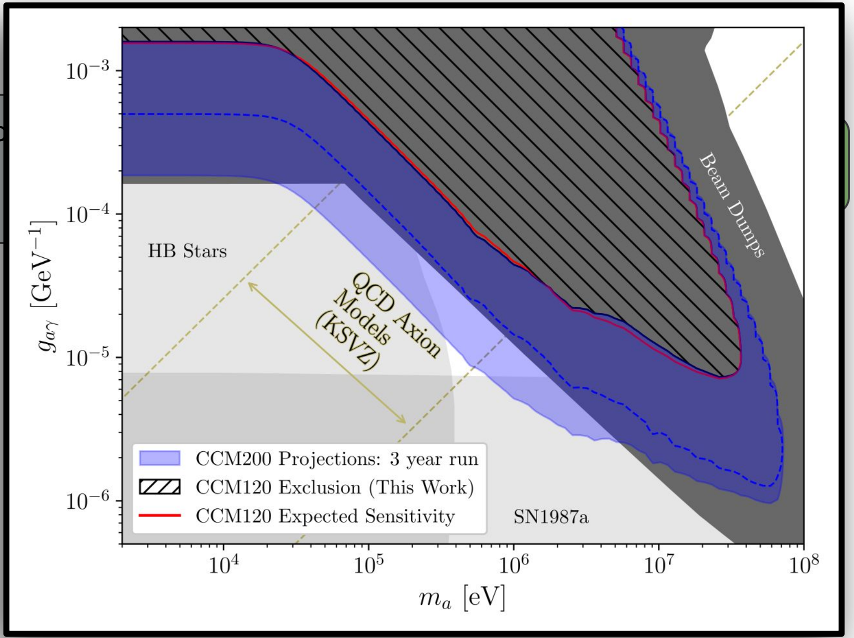

10 keV to 100 keV scale

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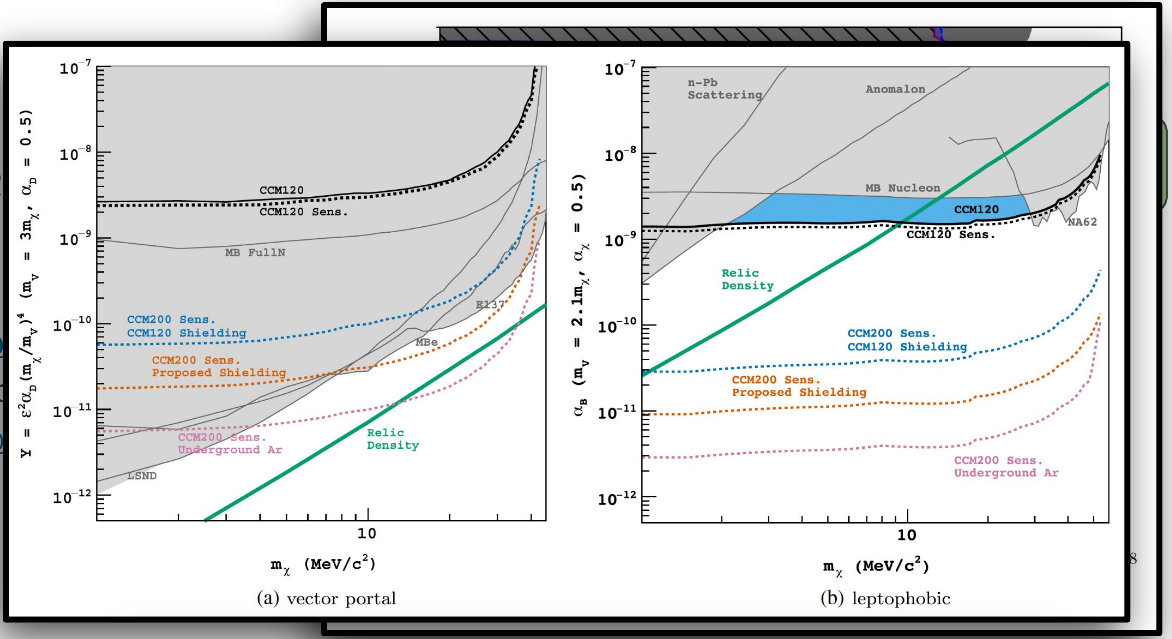
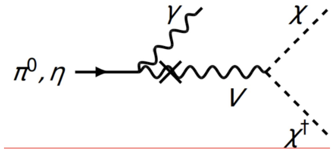
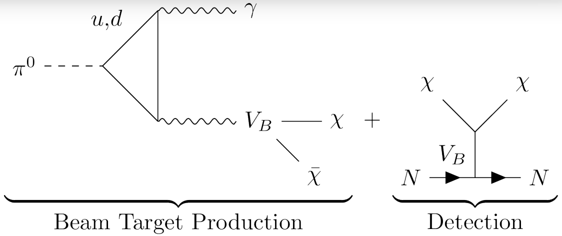


(a) vector portal (b) leptophobic

10 keV to 100 keV scale





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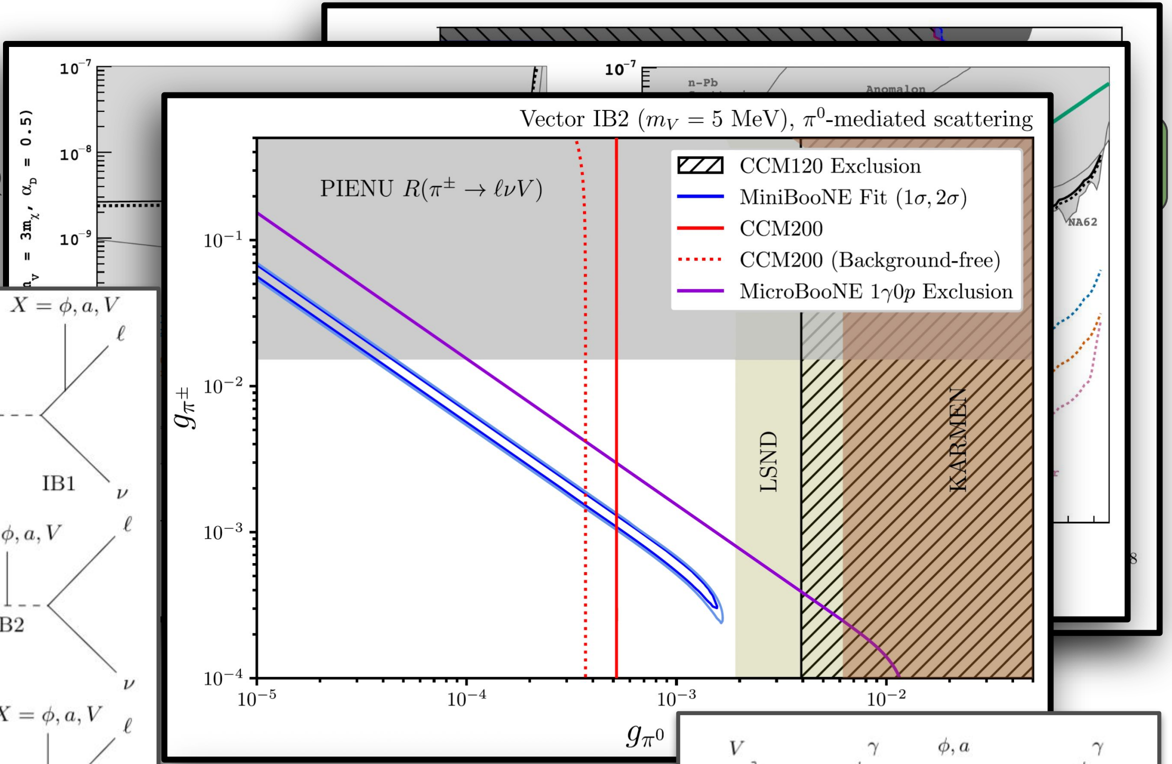

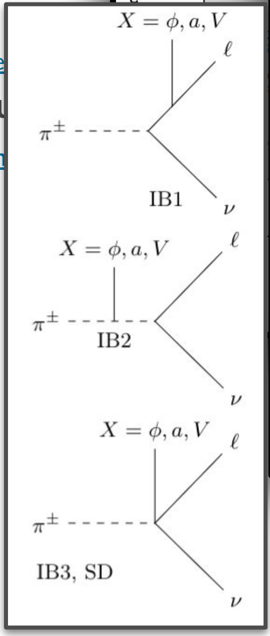

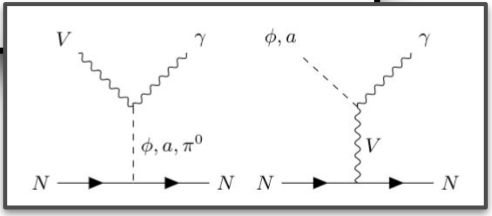

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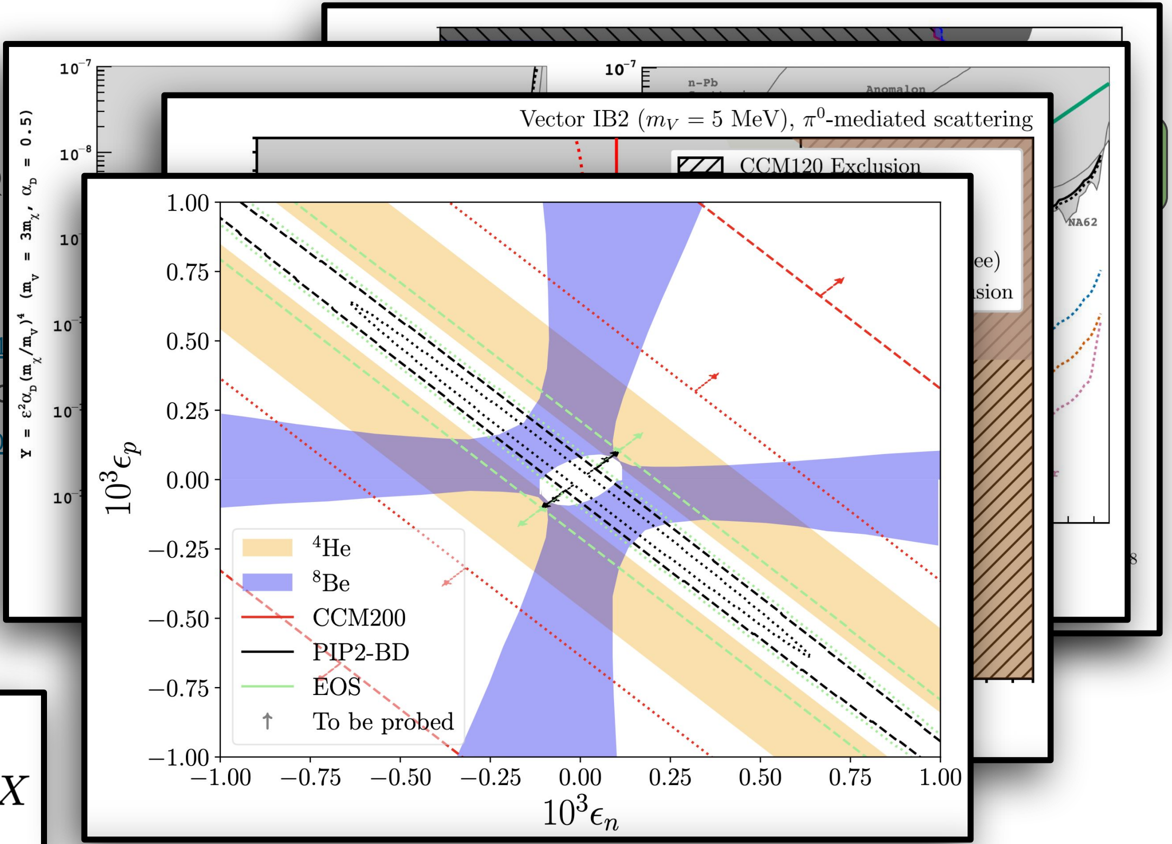

$$n + \mathcal{N} \to n + \mathcal{N}^*$$
$$\mathcal{N}^* \to \mathcal{N} + \gamma/X$$
$$X \to e^+ + e^-$$

Physics with Coherent CAPTAIN Mills

Broad progr

- Axio
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- Lept
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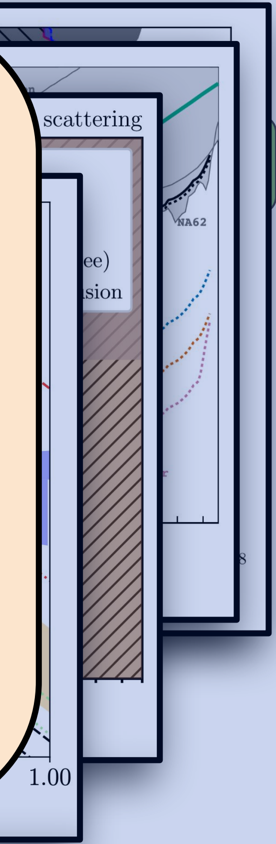
- Ligh
- Mes
  Mini
- **Sear**
  [arXiv
- Hea
- Dark

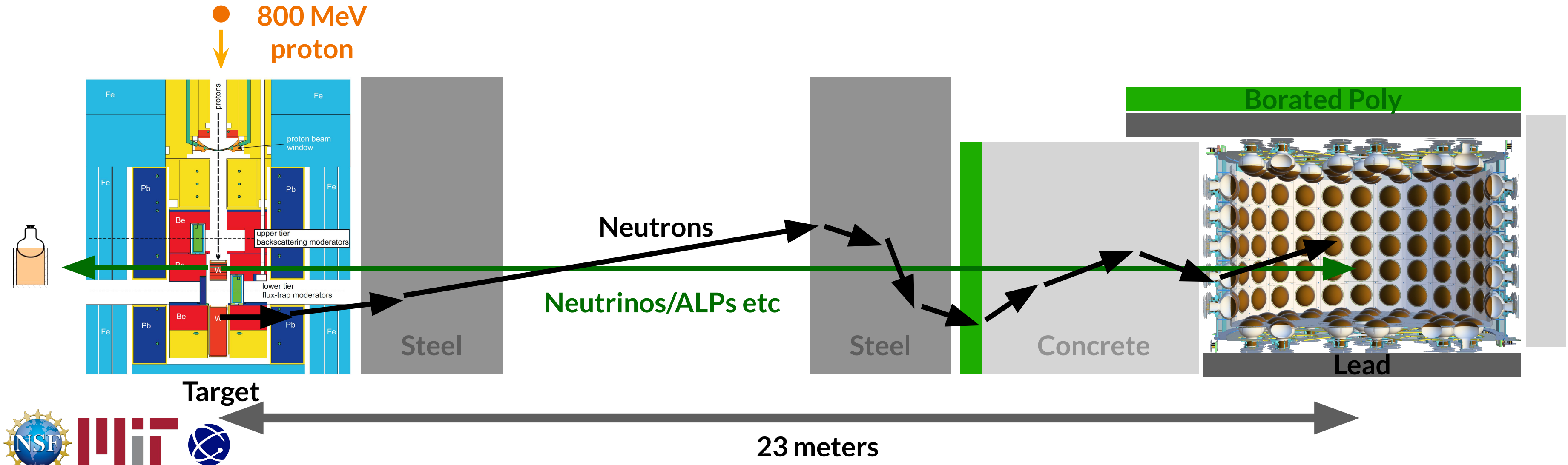
Currently probing:
- **O(1-10) MeV** electromagnetic signatures
- **O(100) keV** nuclear recoil signatures

Sensitive to:
- Axions
- Short baseline scenarios
- Accelerator produced Dark Matter
- and others…



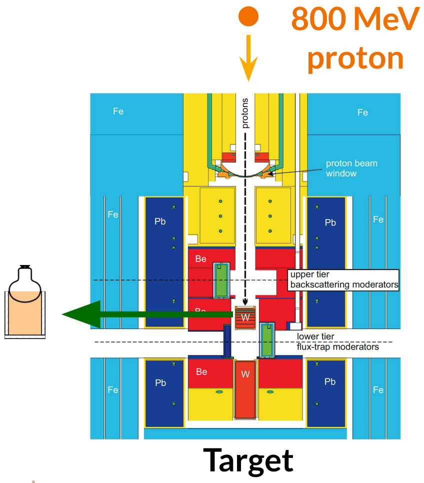
Backgrounds

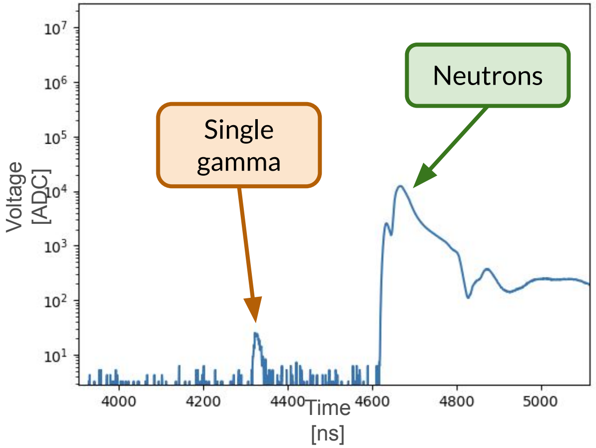
- 90 degrees off axis → no decay-in-flight contamination
- Primary backgrounds are fast neutrons
- Shielding attenuates neutrons, active veto allows us to tag neutrons entering our detector

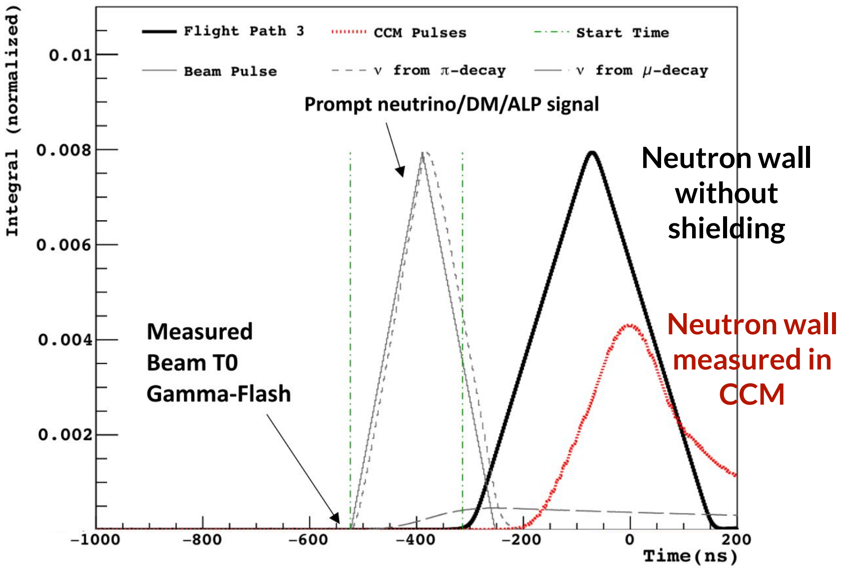


Backgrounds

- Precise timing using measured gamma flash allows us to isolate speed of light particles
- Can measure steady state backgrounds using pre-beam region of data collection

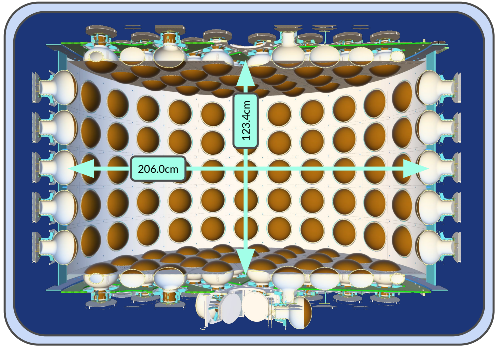


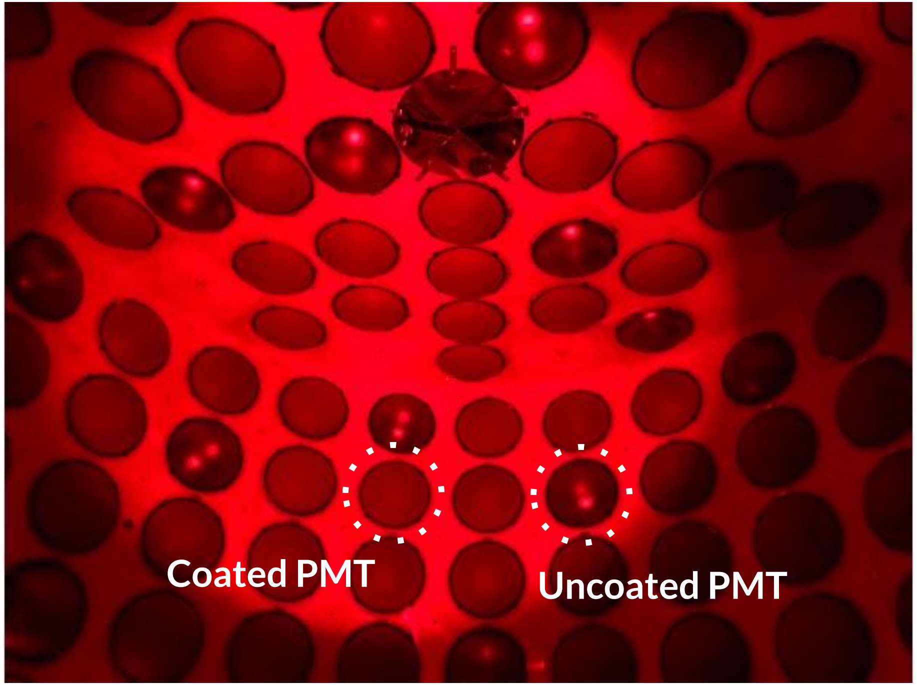




Coherent CAPTAIN-Mills (CCM)

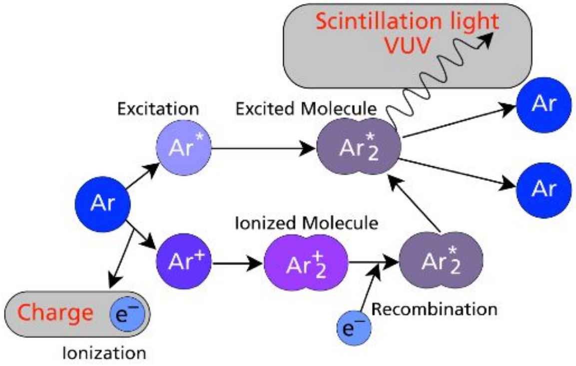
- Electronics have **2ns** sampling time
- Sensitive between ~100 keV and ~2 GeV
- 80% of PMTs coated in 1,1,4,4-Tetraphenyl-1,3-butadiene (TPB) to **wavelength shift LAr scintillation light**
- TPB foils cover detector walls



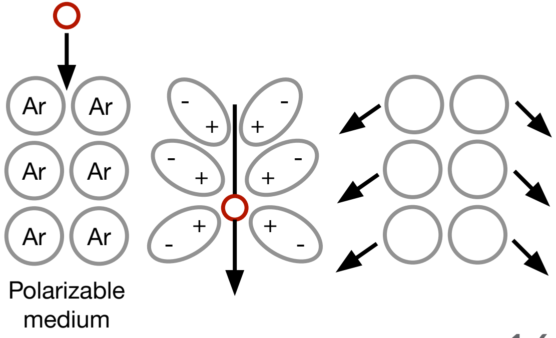


Light production in Liquid Argon

Quality	Scintillation Light	Cherenkov Light
Intensity	~ 40k photons/MeV	~700 photons/MeV (above 100 nm)
Direction	Isotropic	Directional
Timing	Fast component (ns) and slow component (μs) EPJC-s10052-020-7789-x	Prompt (ps)
Wavelength	Spectrum peaks at 128nm	Broad spectrum

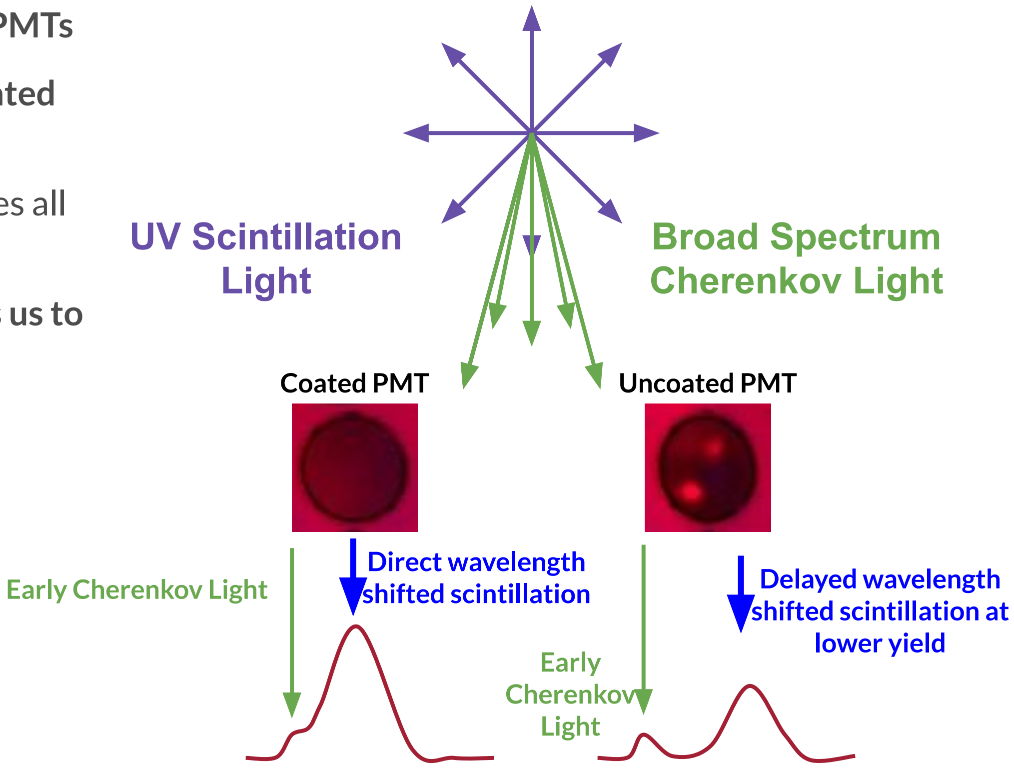


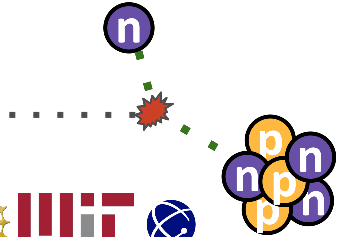
Charged particle

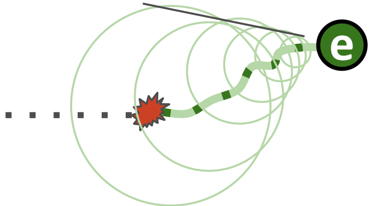


CCM light collection

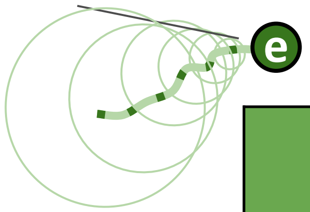
- UV scintillation light is “direct” to **only coated PMTs**
- Cherenkov light is “direct” to **coated and uncoated PMTs**
- Wavelength shifted light is isotropic and reaches all PMTs after some additional delays
- **Fast timing and coated/uncoated tubes allows us to identify Cherenkov light**
- Provides a handle for differentiating nuclear-recoil-like and electron-like events

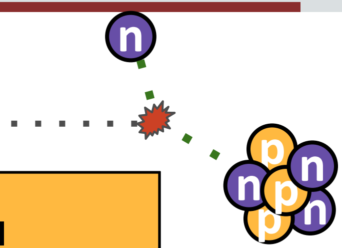






Basic signatures in CCM

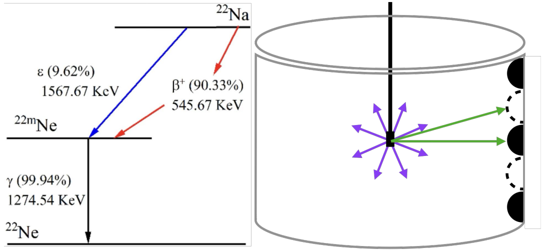


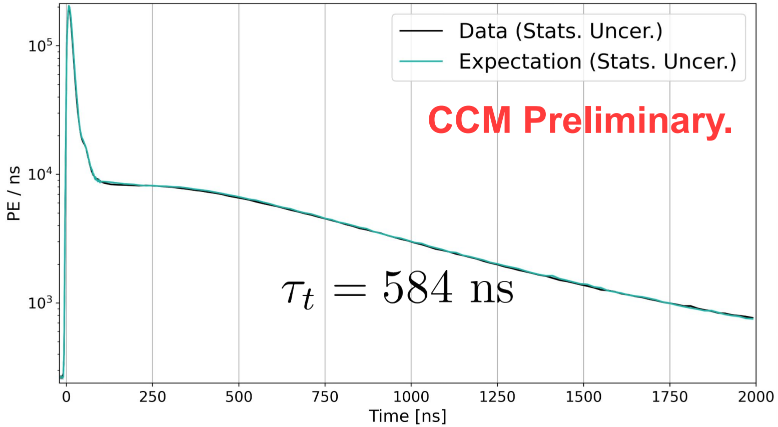


	Electron/Photon	Nuclear Recoil
Energy Range	~1 - 15 MeV	~100 keV
Light Produced	**Scintillation + Cherenkov**	**Scintillation / ~~Cherenkov~~**
Primary background	Neutron scatters	Low energy beta decays (^{39}Ar)
Background signal	**Scintillation / ~~Cherenkov~~**	**Scintillation + Cherenkov**

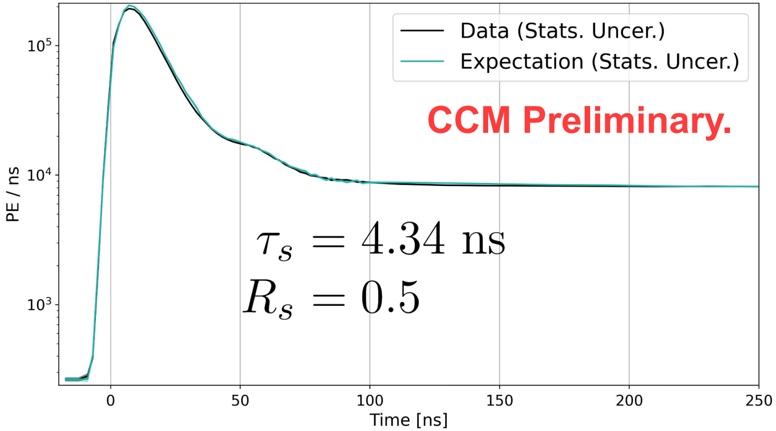
Calibration of light propagation & timing

- Radioactive ^{22}Na deployed in center of detector
- 1.2 MeV de-excitation γ-ray and e^+





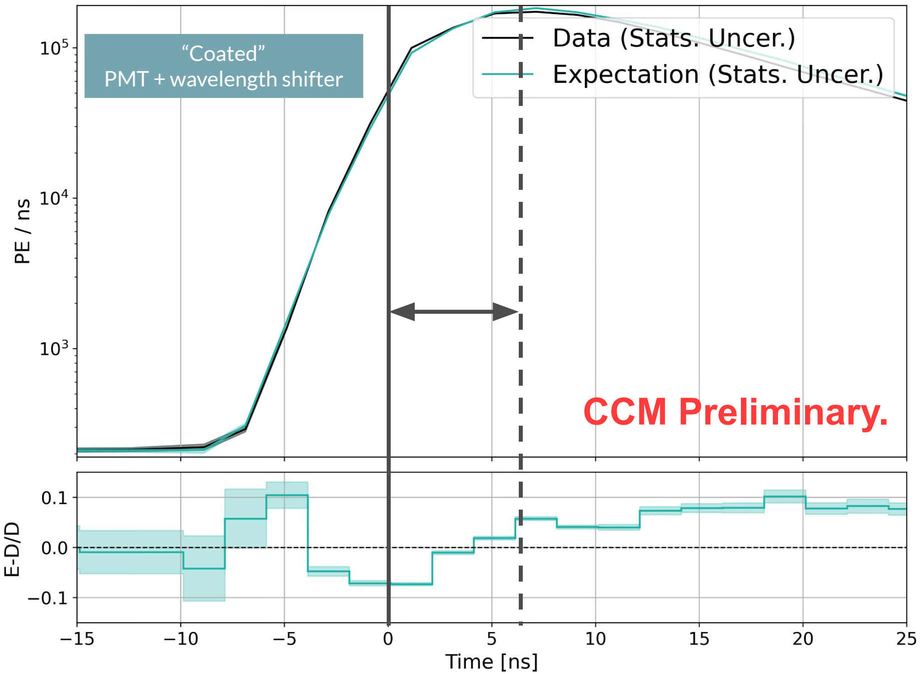
- **Differentiable detector simulation** used to tune light propagation
- Challenges:
  - Large volume, contaminants in LAr, heterogeneous detector response, degenerate parameter space, poorly constrained material properties
- Long timescales: better than 5% agreement
- Short timescales: better than 10% agreement

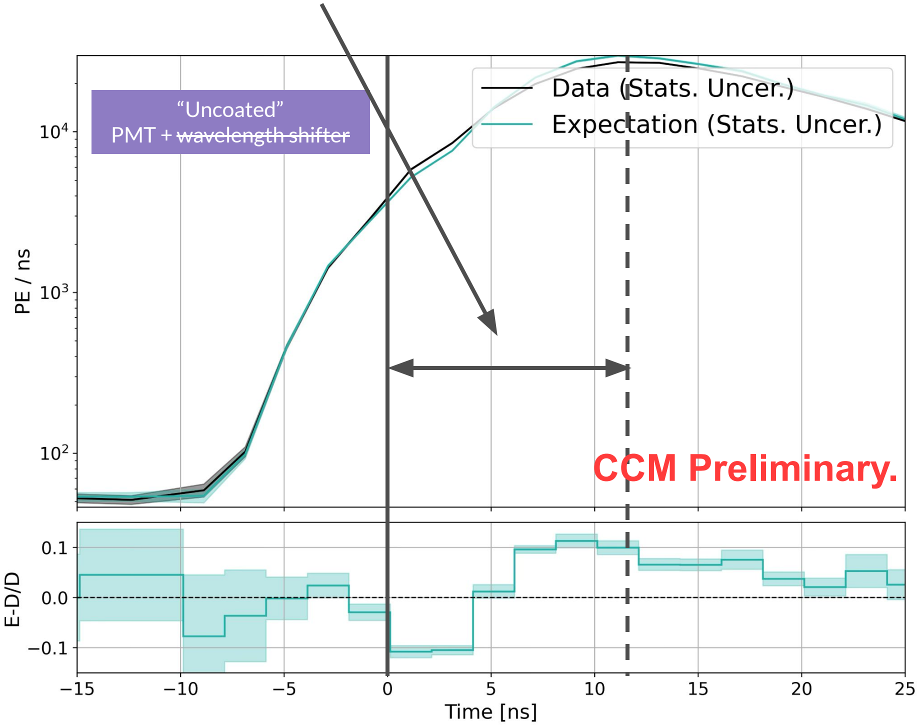


Work by: **D. Newmark [MIT]**

Very early time region

Scintillation light is delayed in the **"uncoated" PMTs** ⇒ broader time distribution





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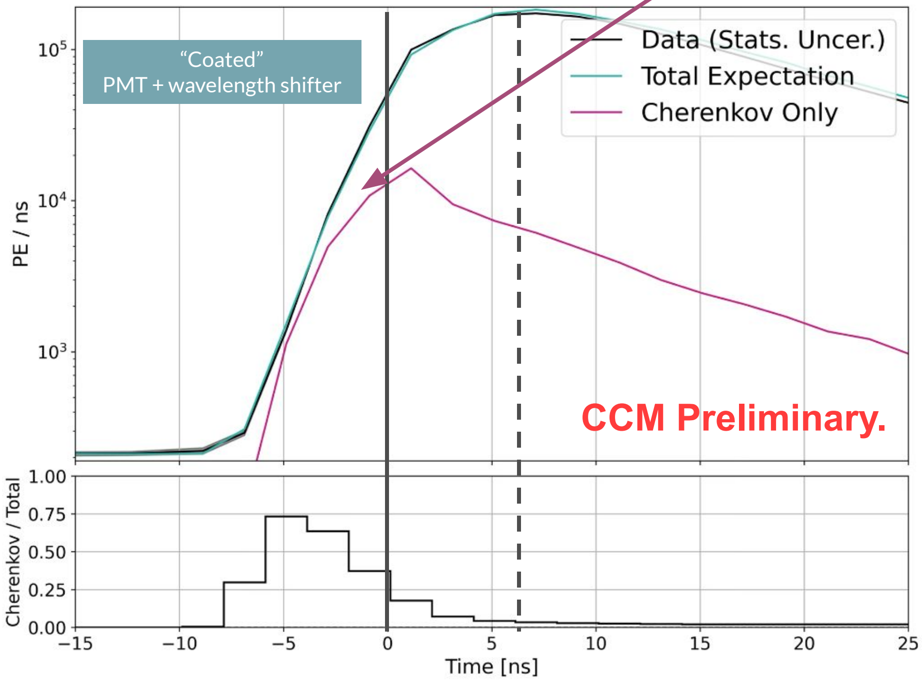
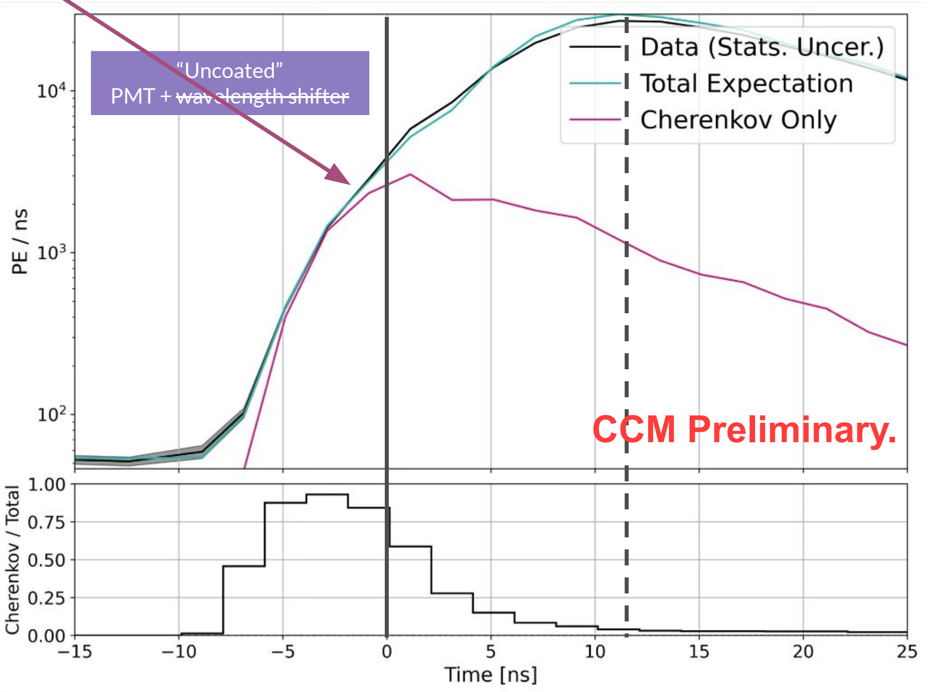
Very early time region

Early time regions are dominated by **Cherenkov light** / very high purity in **"uncoated" PMTs**





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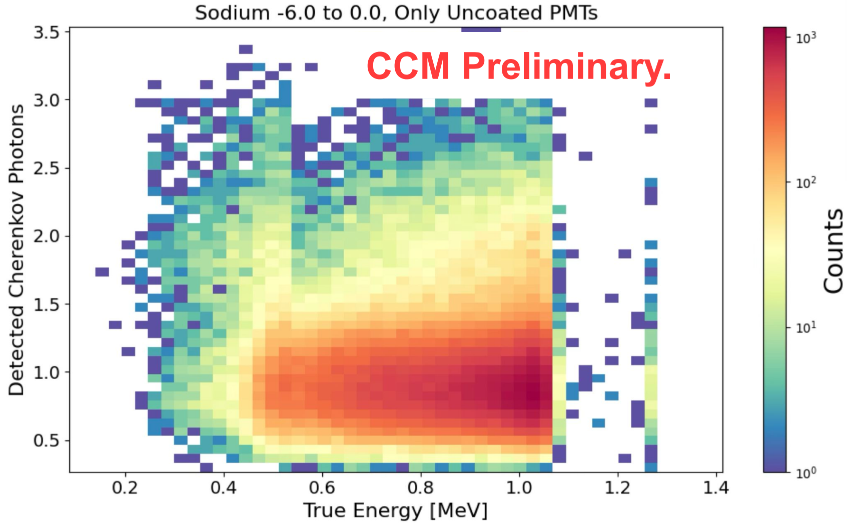
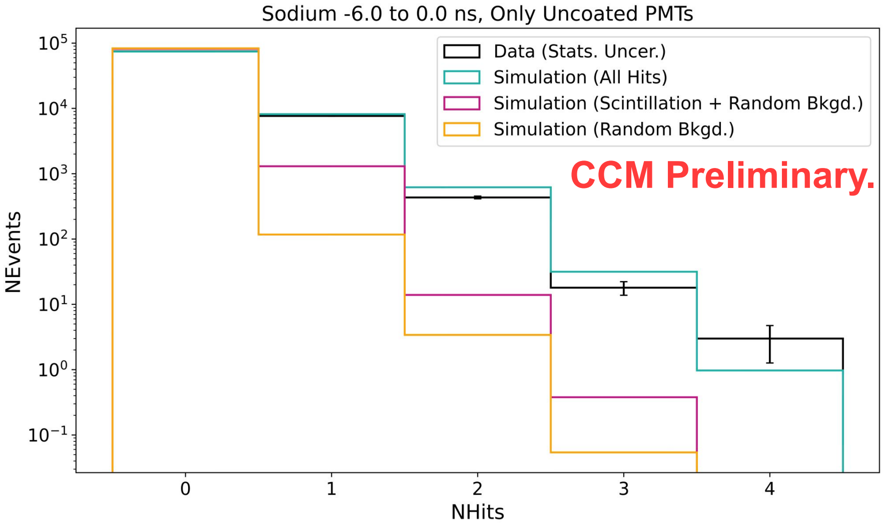
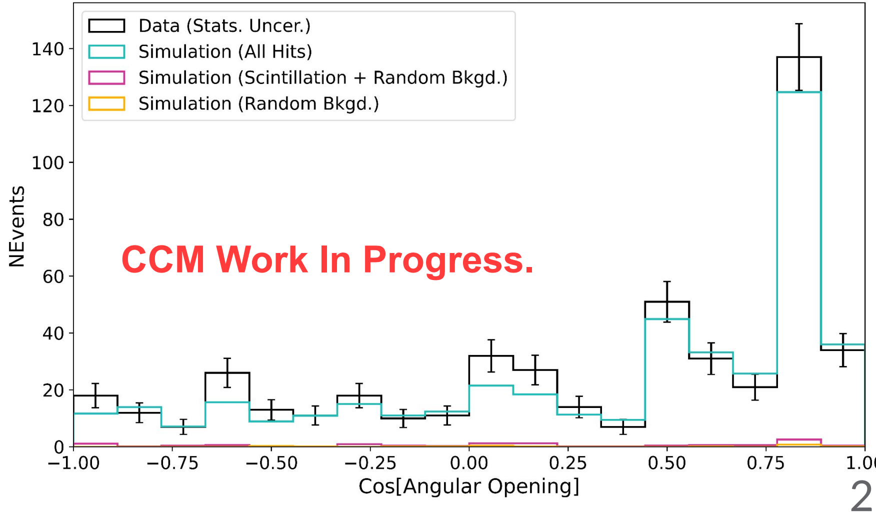
Isolating Cherenkov light

- ^{22}Na selection: sub-MeV electrons
- Simple cut (NHit >= 1) in early time region can isolate Cherenkov light
  - 86% purity of Cherenkov light
  - 10% efficiency







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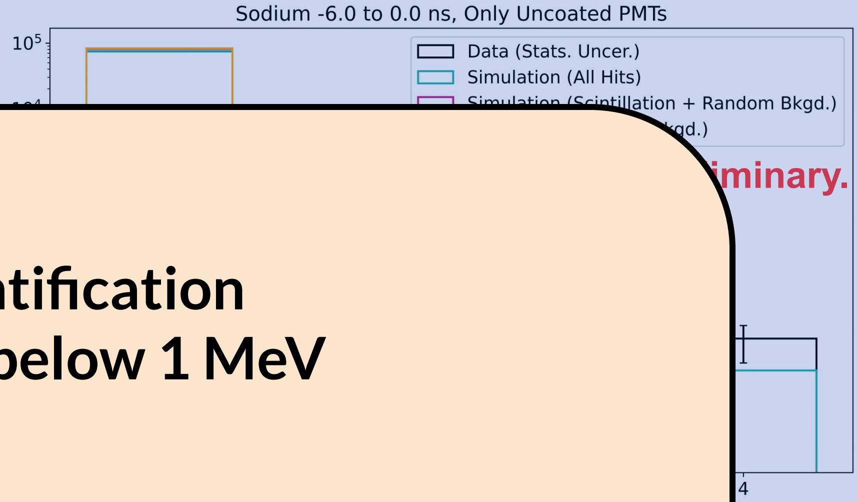


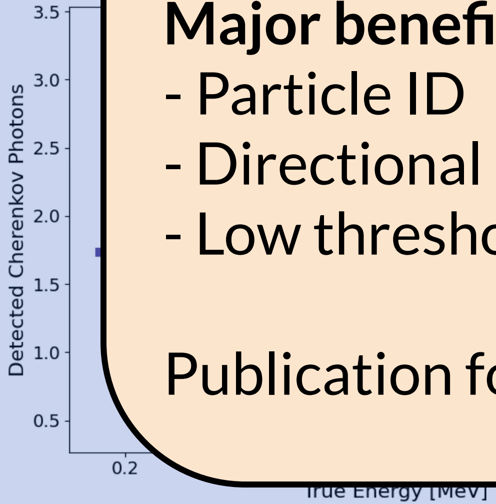
Two firsts in liquid argon:

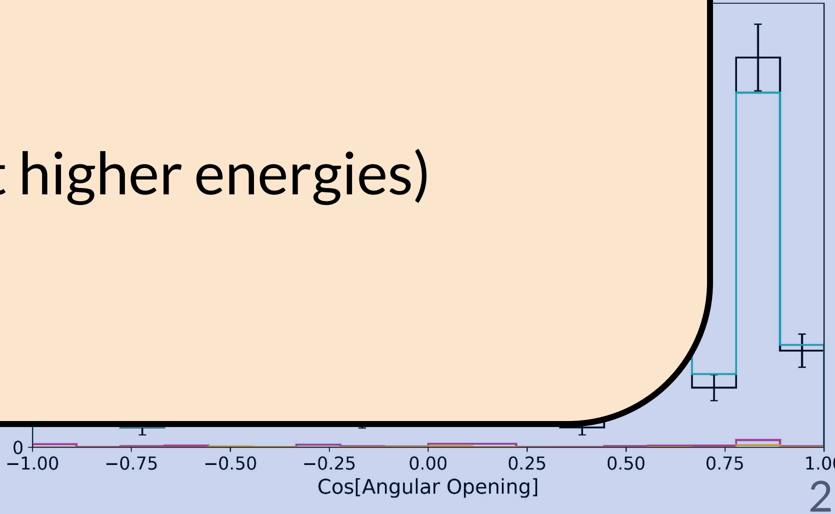
1. **Per-event Cherenkov identification**
2. **Cherenkov identification below 1 MeV**

Major benefits:

- Particle ID
- Directional reconstruction
- Low threshold (will improve at higher energies)

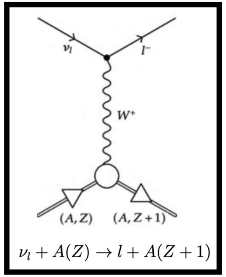
Publication forthcoming.





Work by: D. Newmark [MIT]

ν_e-Ar Charged Current Scattering

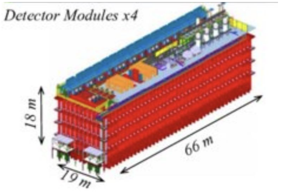


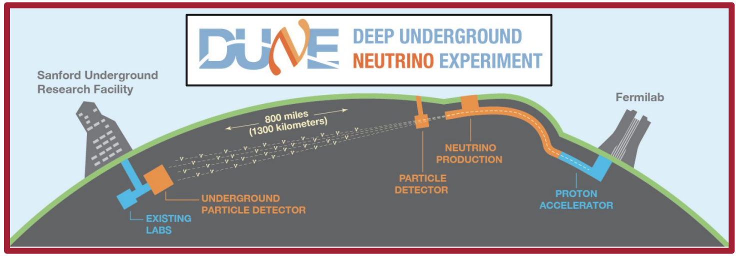
- Neutrinos interact in Liquid Argon
- νe CC scattering on Argon → main reaction: $\nu_e + {}^{40}Ar \to e^- + {}^{40}K^*$

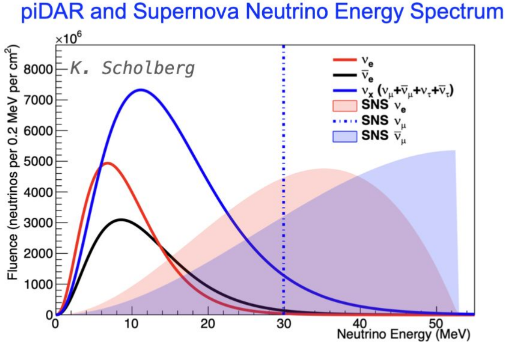
- **LSND and KARMEN** measured (2001) the CC Cross Section on ^{12}C

CCM can make the first measurement for CC in Argon in the range of E<50 MeV

- CC Cross Section relevant for core-collapse supernova detection
- Useful for the new generation of LAr detectors (DUNE)

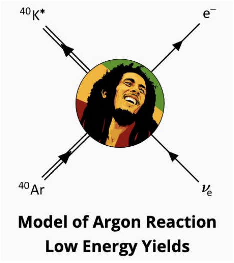






Work by: **M. Chávez Estrada [UNAM]**

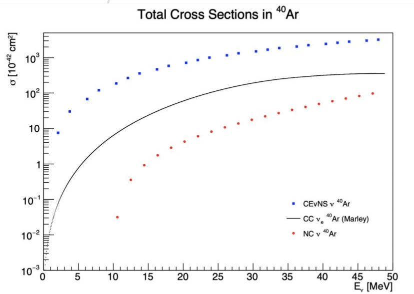
Cross section prediction



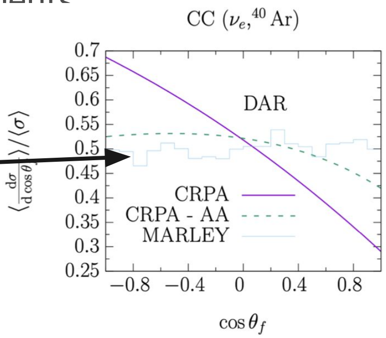
- **MARLEY** (Model of Argon Reaction Low Energy Yields) provides the cross section prediction.
  Developed by **S. Gardiner**

Fermilab

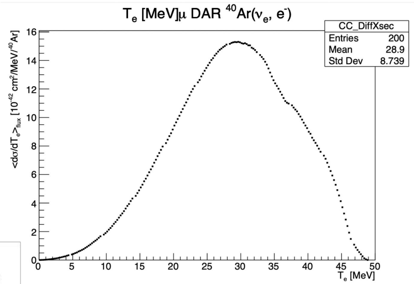
- Includes the **allowed approximation** (long-wavelength (q->0) and slow nucleons ($p_N/m_N \rightarrow 0$ limit) and **Fermi and Gamow-Teller** matrix elements



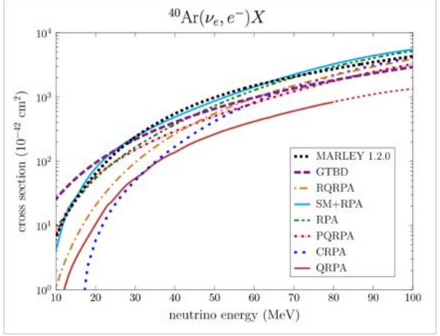
- MARLEY predicts a nearly **flat angular distribution**
- Other models like CRPA include full expansion of nuclear matrix element (allowed as well as forbidden transition), predict more **backwards** strength



ν_e CC 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%) → measurements needed to constrain/validate theoretical models



Work by: **M. Chávez Estrada [UNAM]**

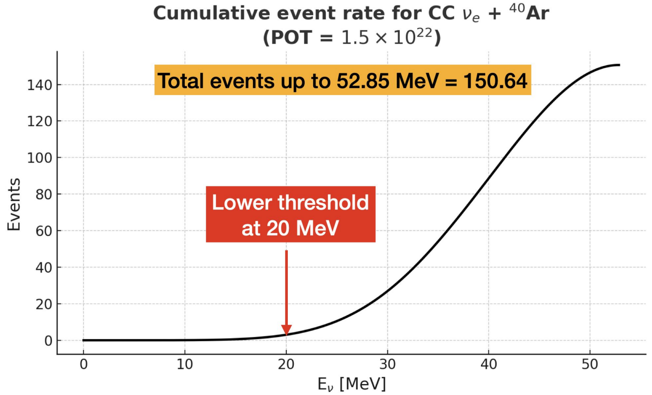
Total expected events in CCM

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

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

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%)
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 from energy threshold: 4%
    Due to 20% energy resolution

- There is an extra **0.2 x 10^{22} POT** on disk currently (2021 data)
  Total events: 150.64 -> 170.72

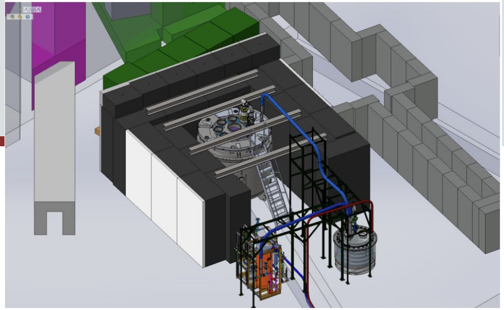
Work by: **M. Chávez Estrada [UNAM]**

Backgrounds for CC search

Beam related	Solution
Prompt neutrons from the beam	Shielding, time cuts in data
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



Work by: **M. Chávez Estrada [UNAM]**

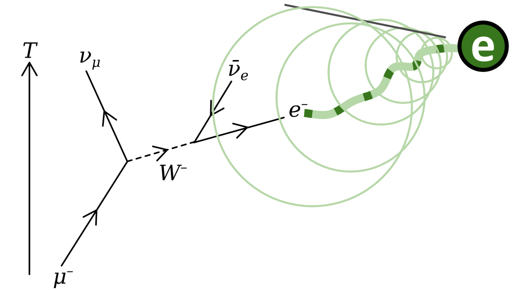
Backgrounds for CC search: Michel electrons

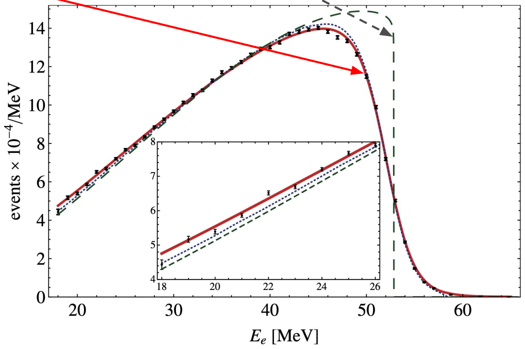
- High energy cosmic ray muons enter the detector

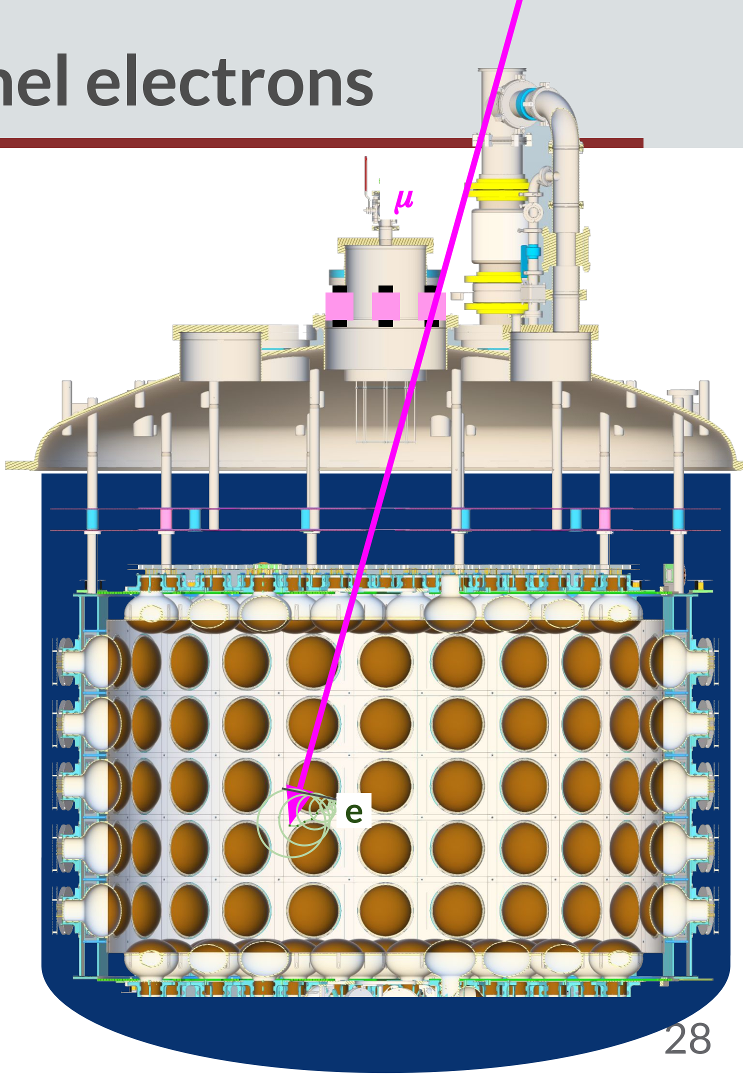
μ^+ Decay freely (repelled by nucleus) $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu_\mu}$

μ^- 76% undergo nuclear capture $\mu^- + p \rightarrow n + \nu_\mu$

24% decay-in-orbit around a nucleus $\mu^- \rightarrow e^- + \bar{\nu_e} + \nu_\mu$







Work by: **M. Chávez Estrada [UNAM]**

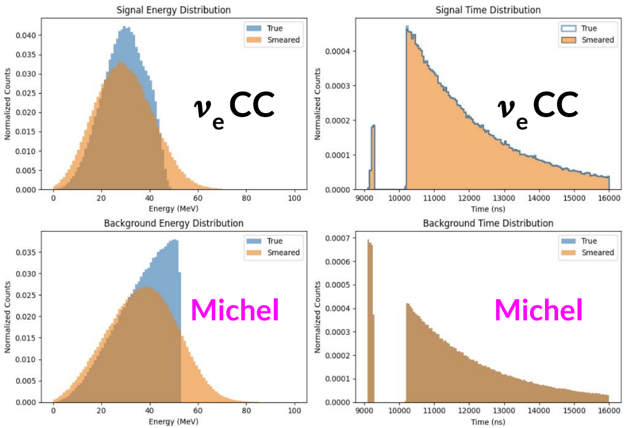
Backgrounds for CC search: Michel electrons

- High energy cosmic ray muons enter the detector

μ^+ Decay freely (repelled by nucleus)

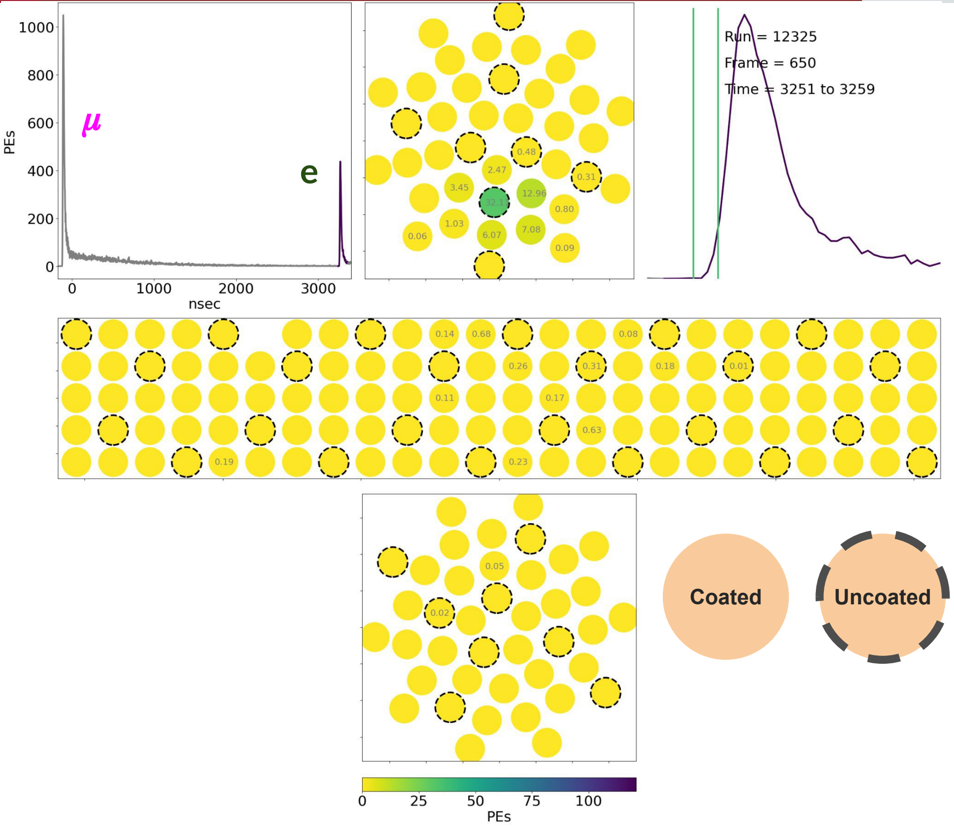
μ^- 76% undergo nuclear capture

24% decay-in-orbit around a nucleus



Energy

Time



Work by: **M. Chávez Estrada [UNAM]**

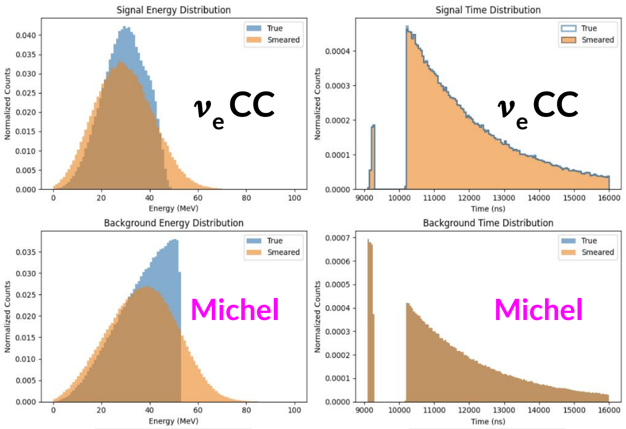
ν_e-Ar CC Search

- High energy cosmic ray muons enter the detector

μ^+ Decay freely (repelled by nucleus)

μ^- 76% undergo nuclear capture

24% decay-in-orbit around a nucleus



Energy Time

CCM can measure the flux integrated cross section to within 16%

Work by: **M. Chávez Estrada [UNAM]**

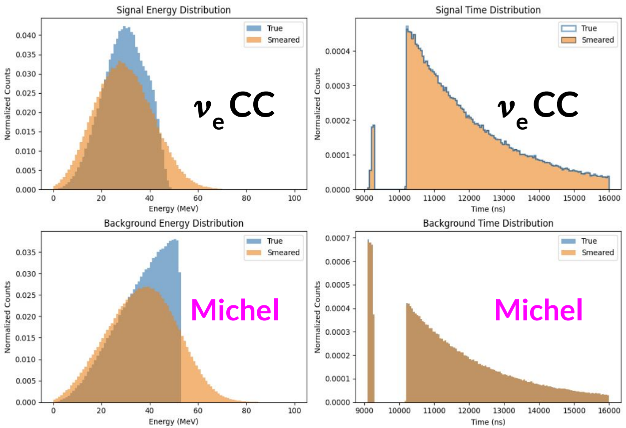
ν_e-Ar CC Search

- High energy cosmic ray muons enter the detector

μ^+ Decay freely (repelled by nucleus)

μ^- 76% undergo nuclear capture

24% decay-in-orbit around a nucleus



Energy   Time

CCM can measure the flux integrated cross section to within 16%

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

Tagging K* deexcitation gammas and reconstructing direction (w/ Cherenkov light) will provide additional background rejection

Work by: **M. Chávez Estrada [UNAM]**

In Summary

- CCM is sensitive to a variety of BSM scenarios
  - Relevant to Short Baseline anomalies & DM scenarios
  - Electromagnetic sensitivity O(1 MeV) - O(10 MeV)
- First per-event identification of Cherenkov light in Liquid Argon (& below 1 MeV)
  - Will provide improved sensitivity for BSM and Standard Model Searches
  - Including NuE CC xs measurements in the 1 - 50 MeV energy regime
- New searches and constraints are on the way!

Thank You For Listening!

LDRD
LABORATORY DIRECTED
RESEARCH & DEVELOPMENT

Los Alamos
NATIONAL LABORATORY
EST. 1943

UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO
POR MI RAZA HABLARA EL ESPIRITU

ATM

Massachusetts
Institute of
Technology

Fermilab

NM

EMBRY-RIDDLE
Aeronautical University

NSF

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

UF
UNIVERSITY of
FLORIDA

NEW MEXICO STATE UNIVERSITY
NMSU
1888

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

THE UNIVERSITY OF EDINBURGH

Bonus Slides

Simulating BSM processes

Simulation and Injection of Rare EveNts (**SIREN**)

- A new software tool for BSM event injection
- Rich injection and reweighting capabilities
- Near arbitrary extensibility for models and detectors
- Detailed geometric modeling
- Fast and lightweight

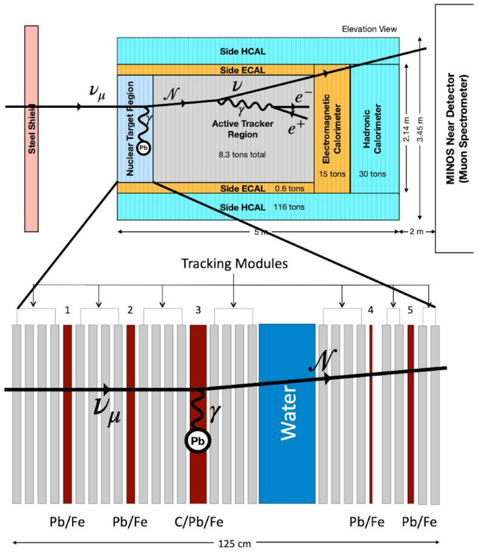
github.com/Harvard-Neutrino/SIREN

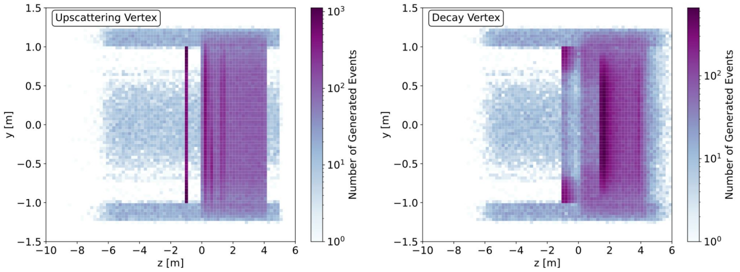
pypi.org/project/siren

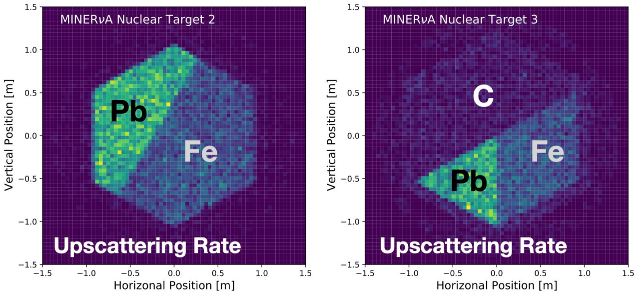
```
> pip install siren
```

[arXiv:2406.01745](https://arxiv.org/abs/2406.01745)

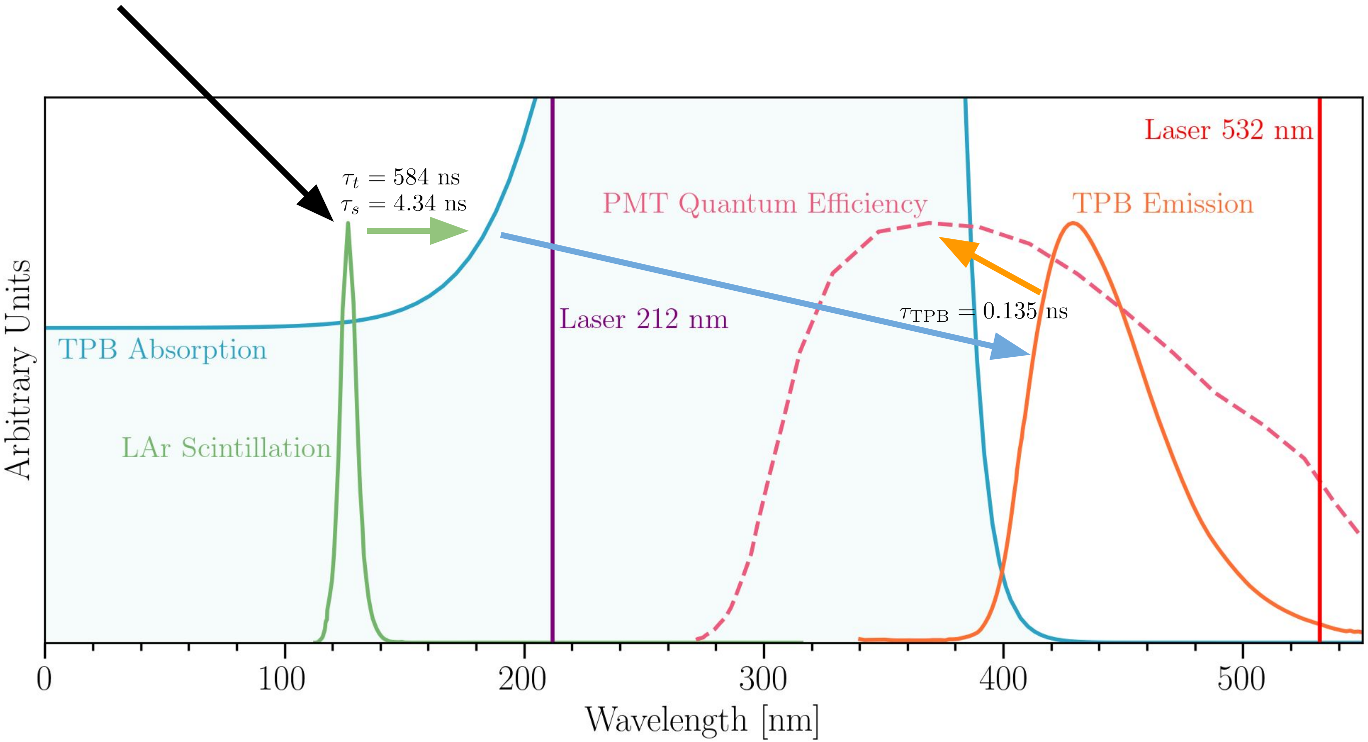
AS, N. W. Kamp, A. Wen





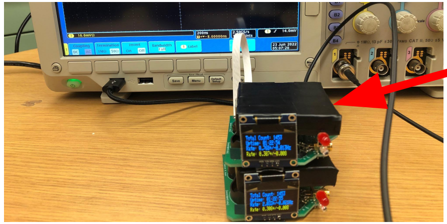


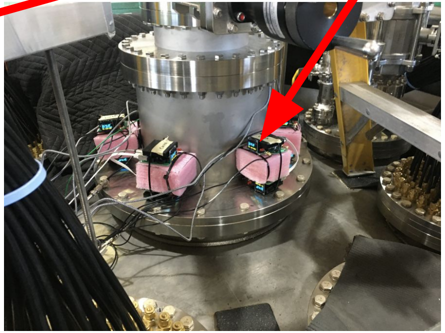
Wavelength dependence

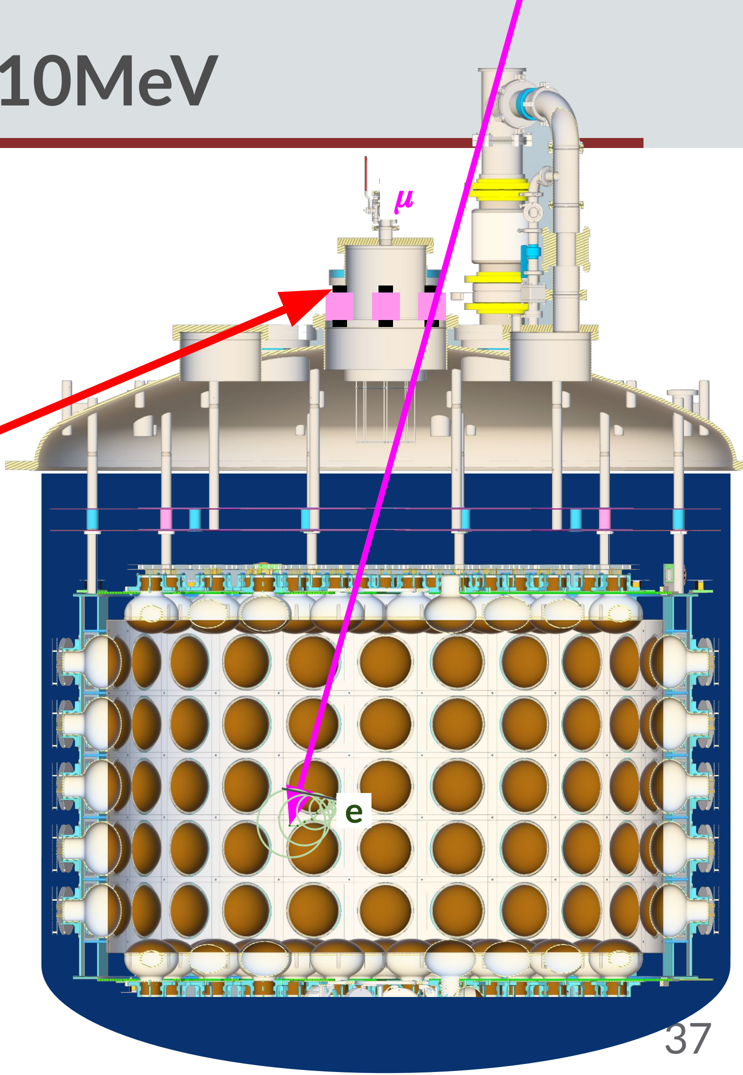


Developing Cherenkov light ID >10MeV

- Need a well known, bright source of Cherenkov light for refining the procedure
- Michel electrons from stopped cosmic ray muons have a well known spectrum and are up to 53 MeV
- Tag muons entering the detector with "[Cosmic Watch]" detectors

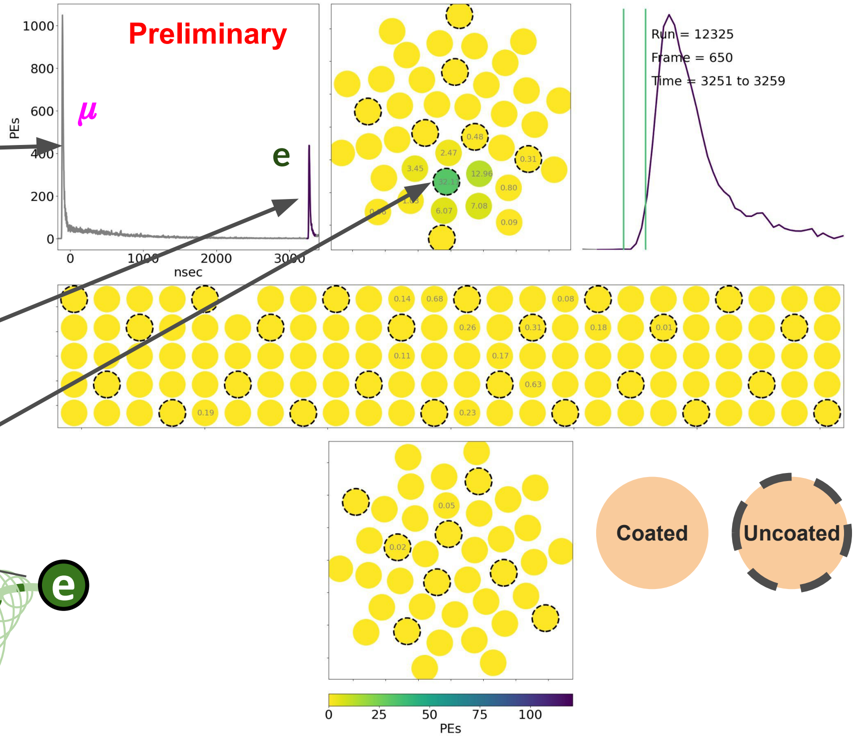


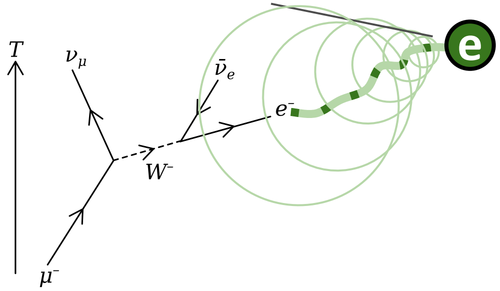




Cherenkov light with Michel electrons

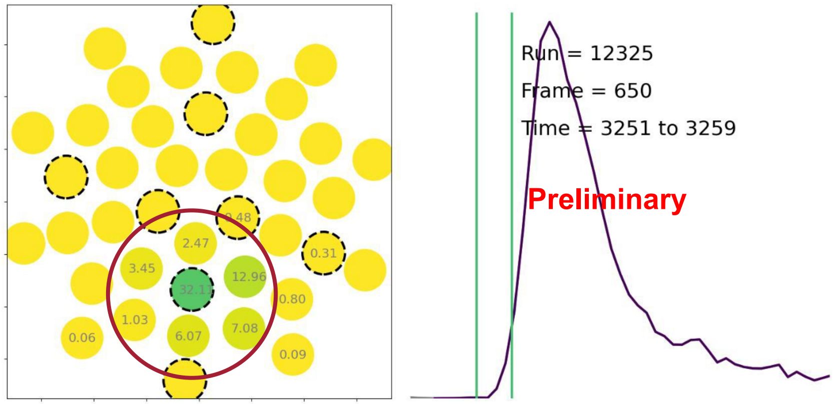
- Cosmic ray muon is tagged by external plastic scintillator detector
- Muon enters the detector causing bright scintillation, and coming to a stop (1/10 muons)
- Stopped muon subsequently decays, creating a Michel electron with energy up to 53 MeV
- Michel electron produces Cherenkov and scintillation light
- Uncoated tubes are efficient at picking up the early Cherenkov light

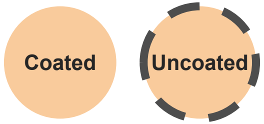


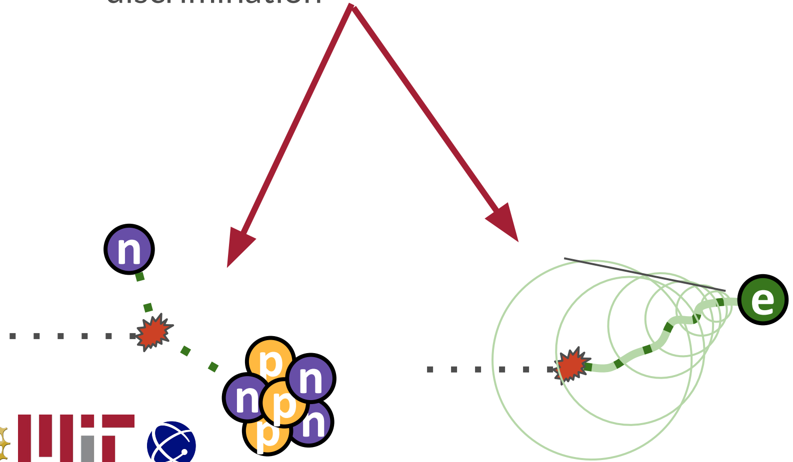


Cherenkov light with Michel electrons

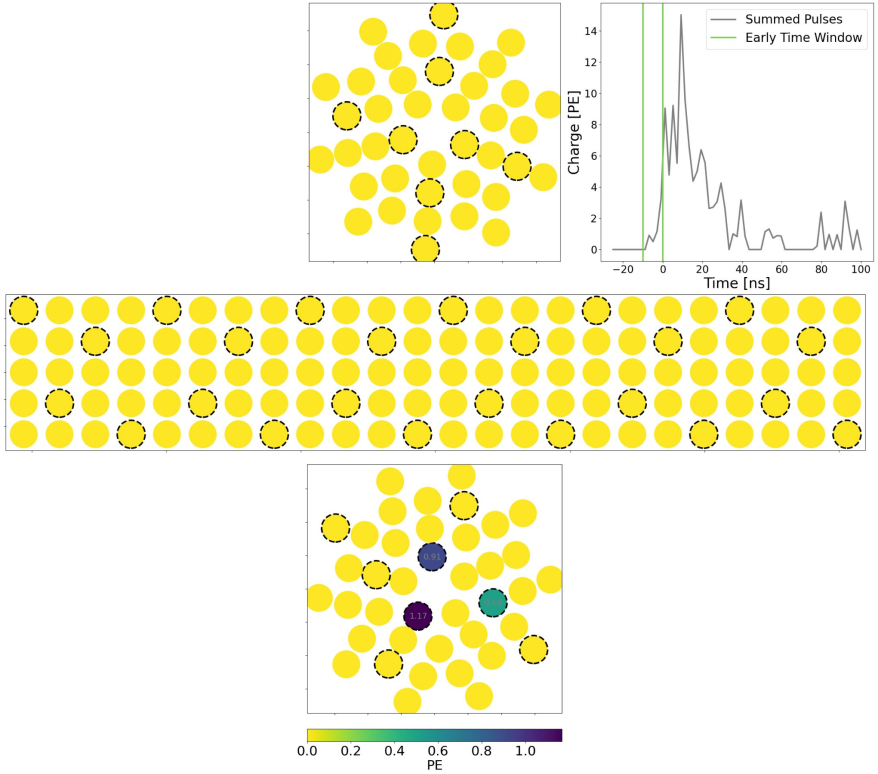
- First demonstration of event-by-event identification of Cherenkov light in liquid Argon
- Working now to incorporate Michel electrons into the calibration
- Will provide an important reference point for developing Cherenkov light based particle discrimination

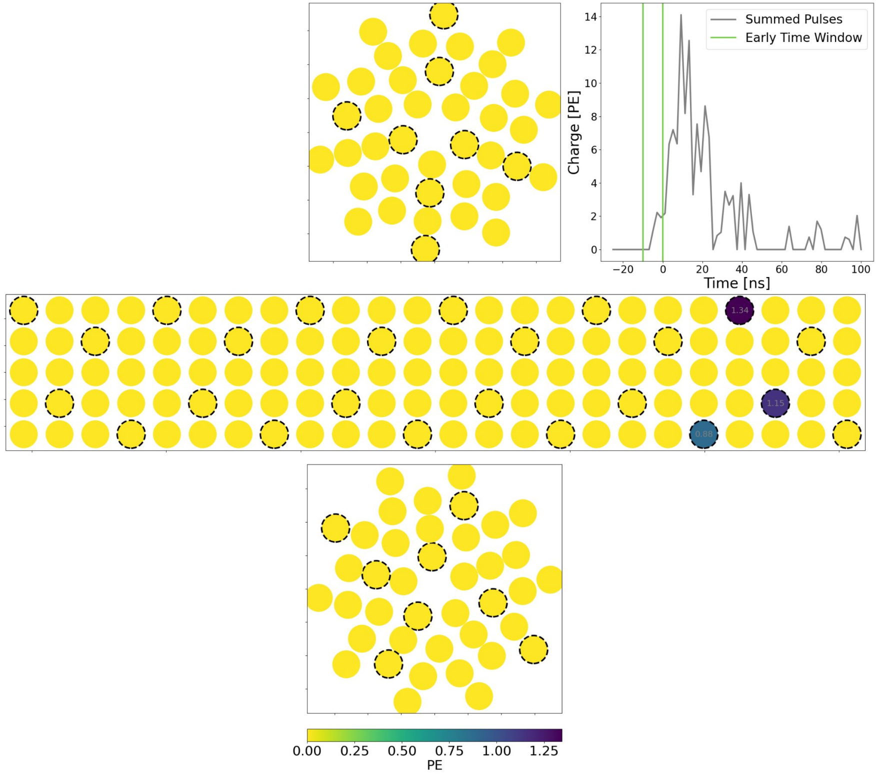




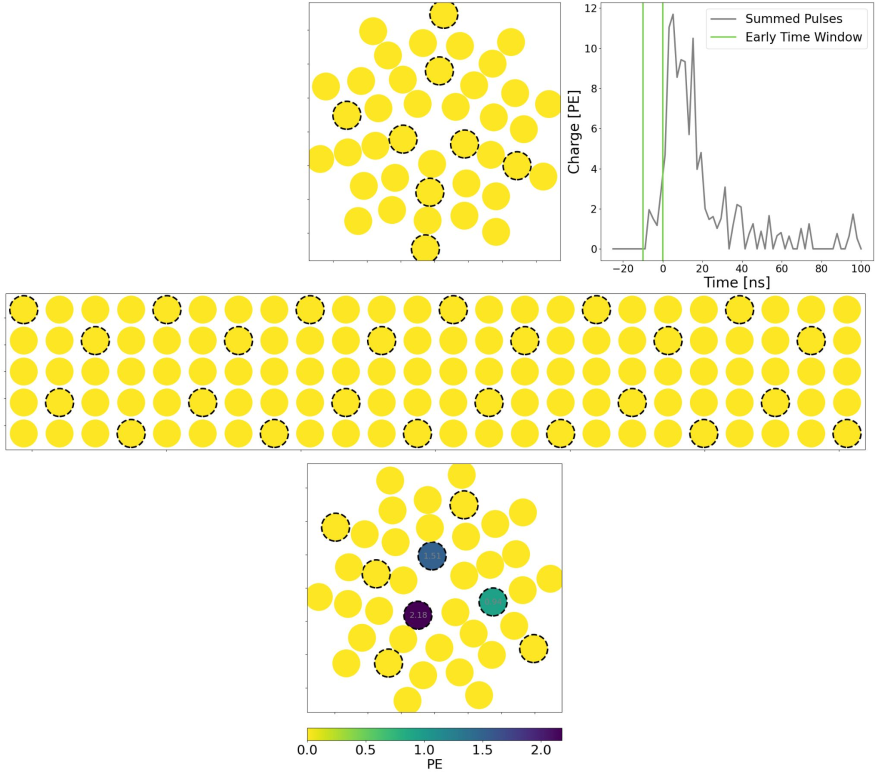


Na22 Simulation

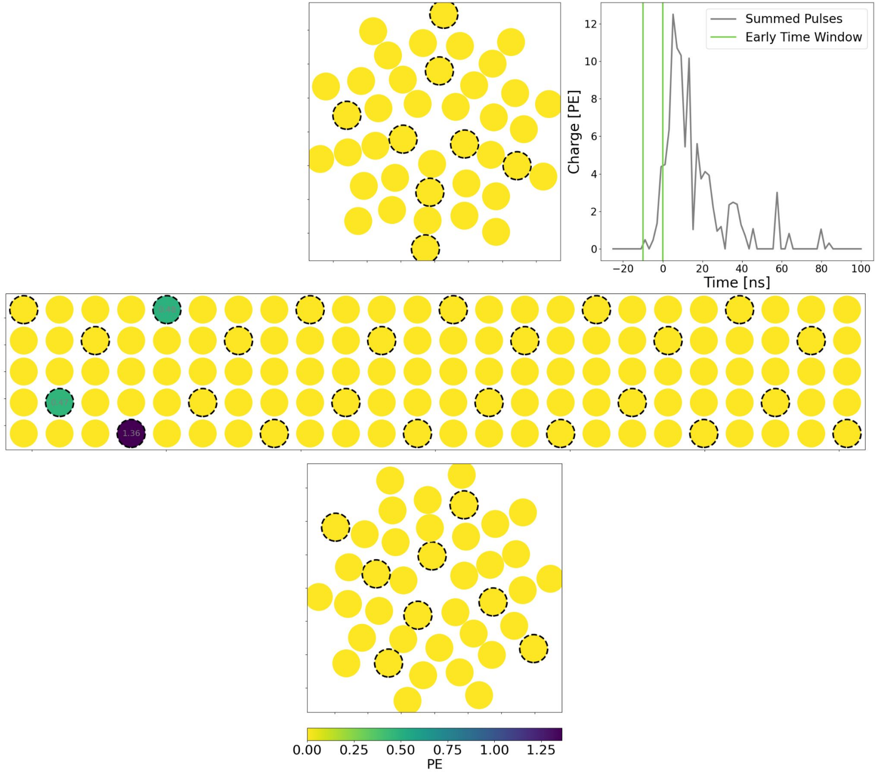




Na22 Data



Summed Pulses
Early Time Window
Charge [PE]
Time [ns]
1.51
2.18
PE

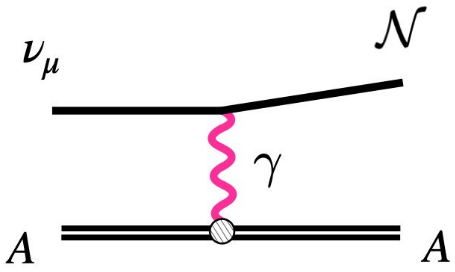


Summed Pulses
Early Time Window
Charge [PE]
Time [ns]
1.36
PE

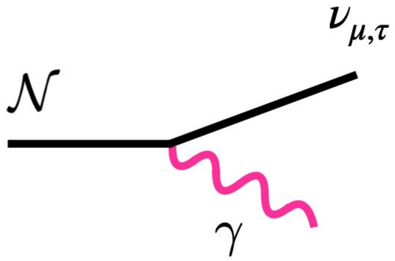
Neutrissimos - Oscillation and decay

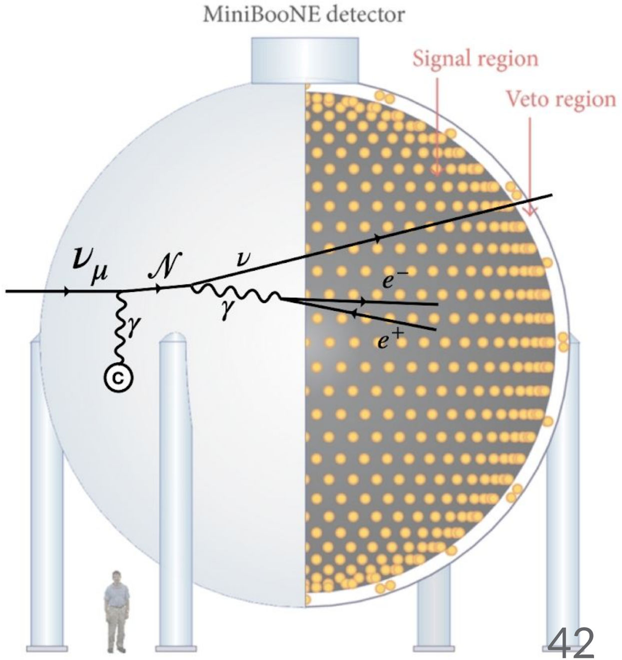
Introduce an MeV-scale heavy neutral lepton with a transition magnetic moment, or neutrissimo

Upscattering from SM neutrinos to neutrissimos occurs in transit from beam



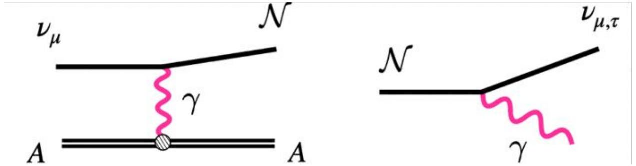
Subsequent decay of neutrissimo to a photon can produce the MiniBooNE signature

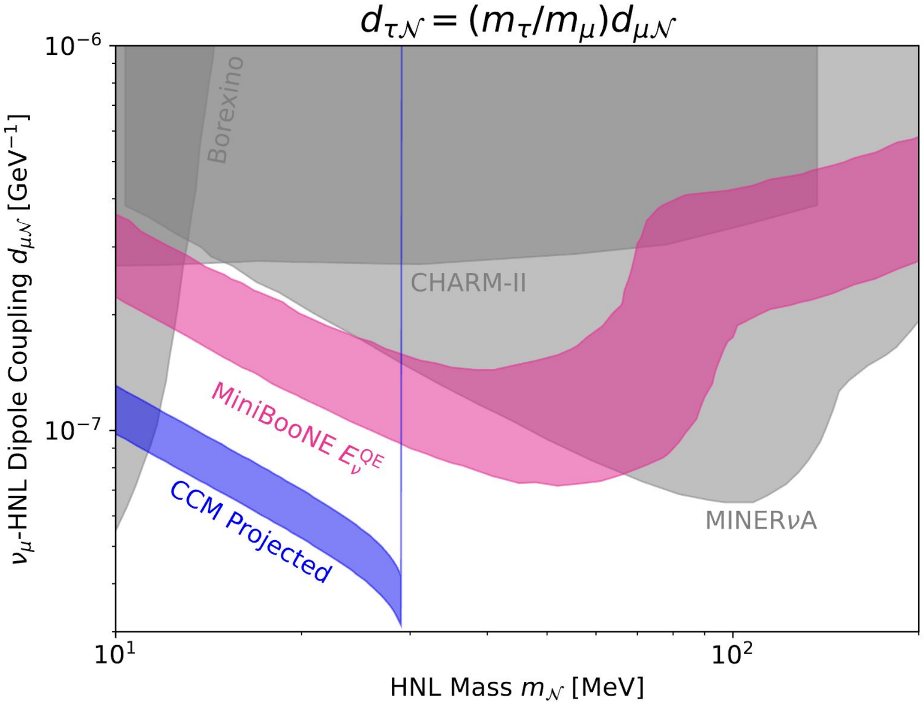




Heavy Neutral Leptons

- Heavy neutral leptons
- Using dipole portal transition model [https://doi.org/10.1103/PhysRevD.107.055009]
- Considering HNL production from upscattering in shielding and detector materials
- Detection from ~10 MeV photon





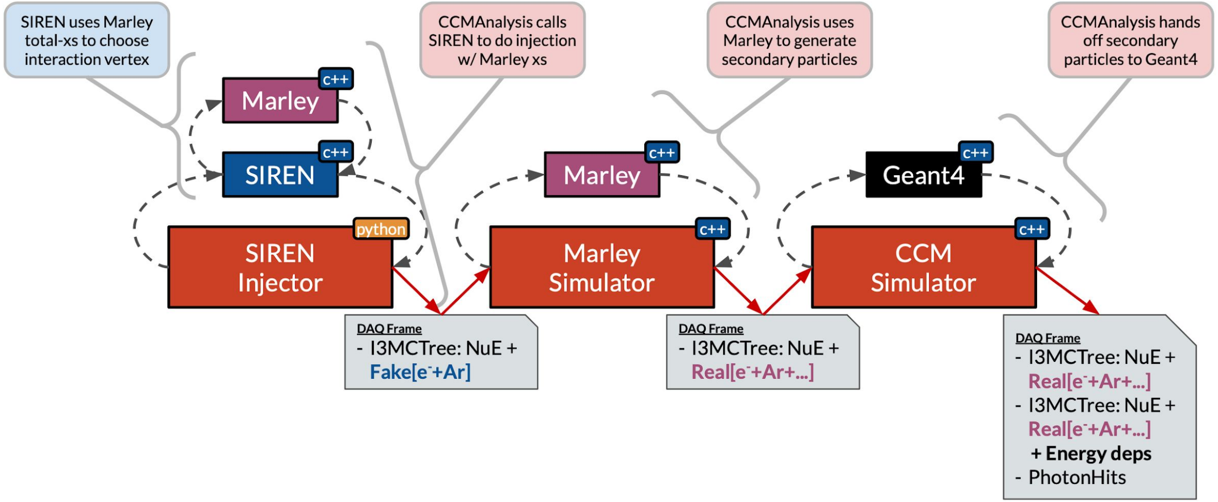
CC simulation in CCM

- **Stages of simulation:**
  - Primary **Vertex injection** (SIREN + MARLEY)
  - Production of **particles** product of CC interaction inside the Argon (MARLEY)
  - **Energy depositions** in the detector and **photon propagation** (Geant 4)
  - PMT response

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

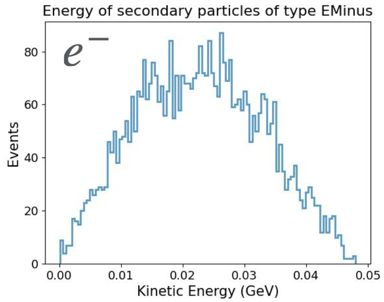
- Each of these stages are connected through the **CCMAnalysis framework**

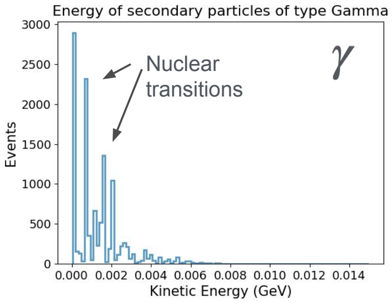
- Can **port** Injection (SIREN) and interaction with Ar (MARLEY) **to other detectors**

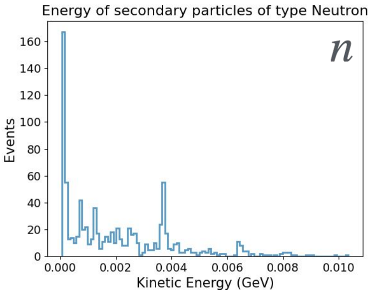


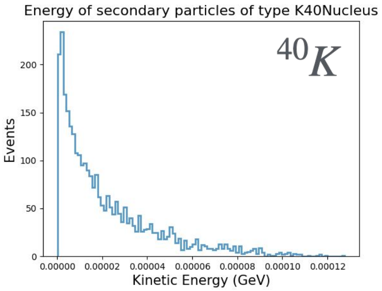
MARLEY CC Simulation (cont.)

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

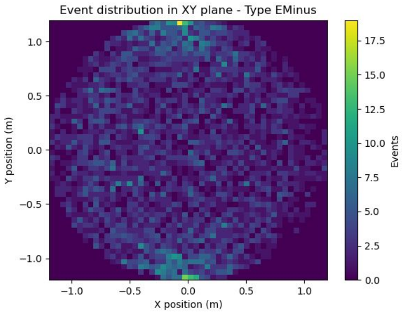


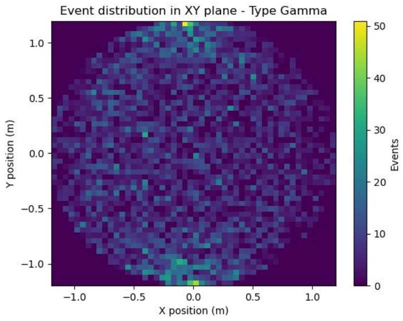


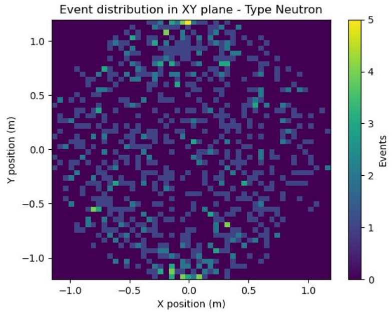


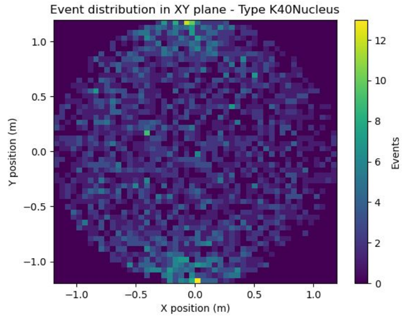


- **Spatial Distribution (XY)** in the CCM detector



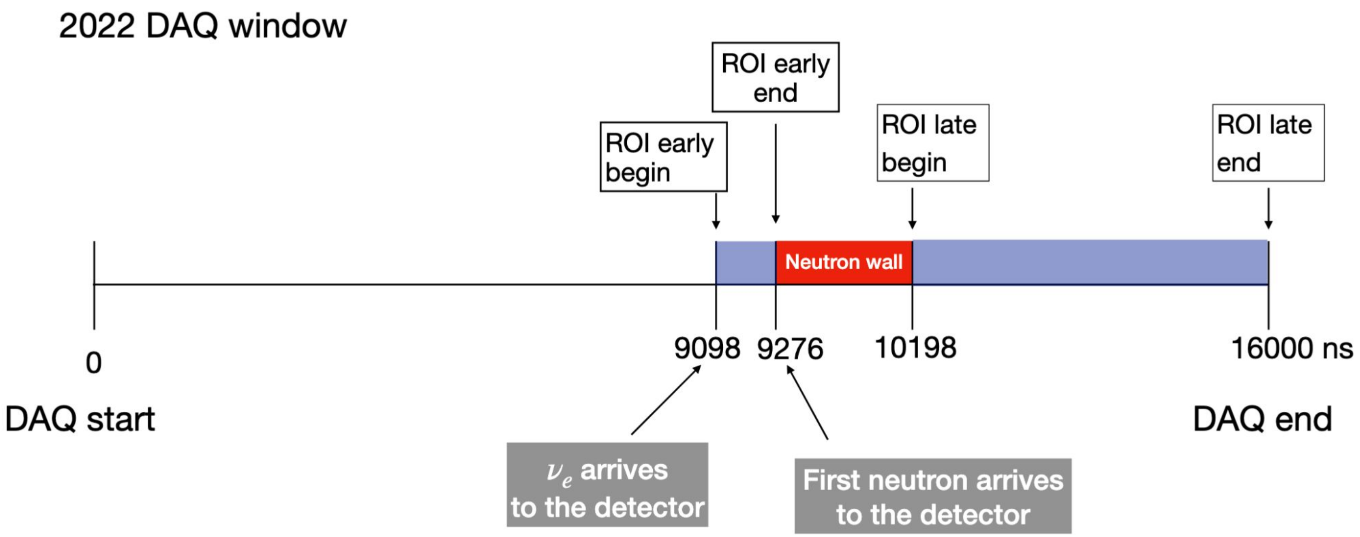






Data Selection

- 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) (cont)