CALIBRATING COHERENT's FLUX NORMALIZATION DETECTOR

Karla R. Téllez Girón Flores

The Center for Neutrino Physics

Research Day 2023

Brookhaven National Laboratory

Blacksburg, VA, December 9th, 2023

VIRGINIA TECH

COHERENT SNS

· The COHERENT Collaboration ·

Brookhaven National Laboratory

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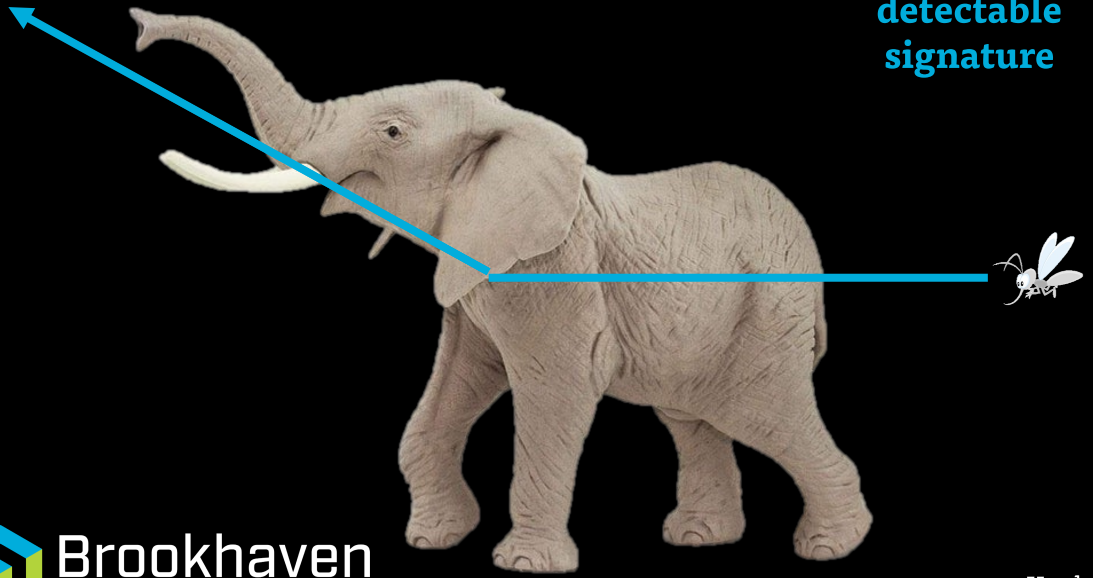
· INTRODUCTION ·

CEνNS: Coherent Elastic Neutrino-Nucleus Scattering

A neutrino scatters on a nucleus via exchange of a Z^0 boson, and the nucleus recoils as a whole.

The only detectable signature



- Coherent: $q \leq \sim R^{-1}$ is satisfied.
- Elastic: no new particles created.
- Clean prediction from the Standard Model (D.Z. Freedman, Phys. Rev. D 9 (1974)).
- Largest of all Standard Model (SM) neutrino cross-sections in 1-100 MeV range.
- Cross section $\propto N^2$.

· INTRODUCTION ·

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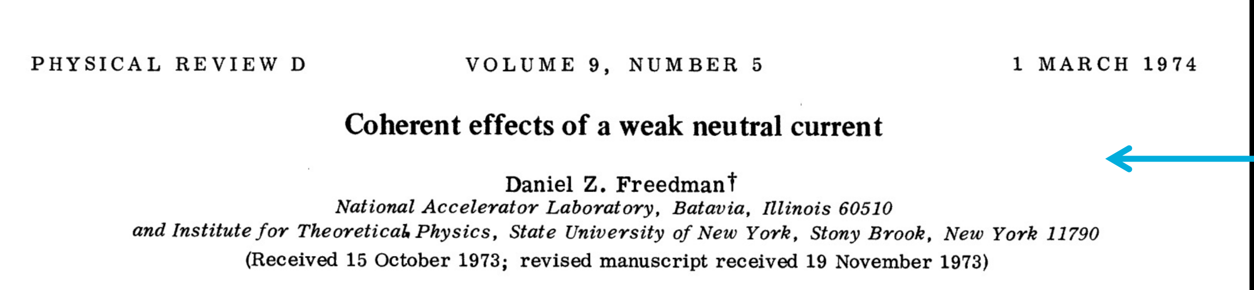
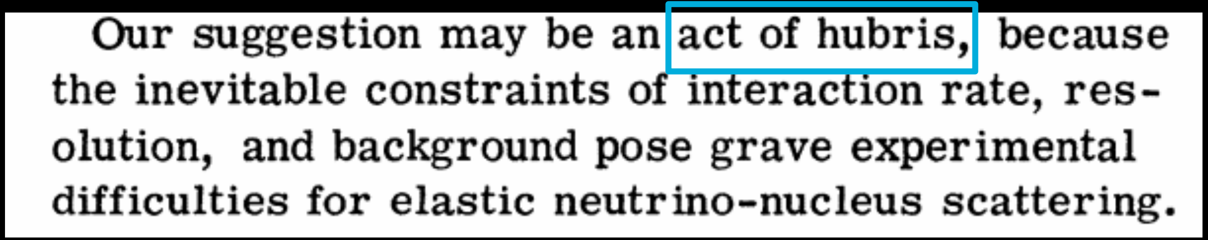


PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)



Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering.

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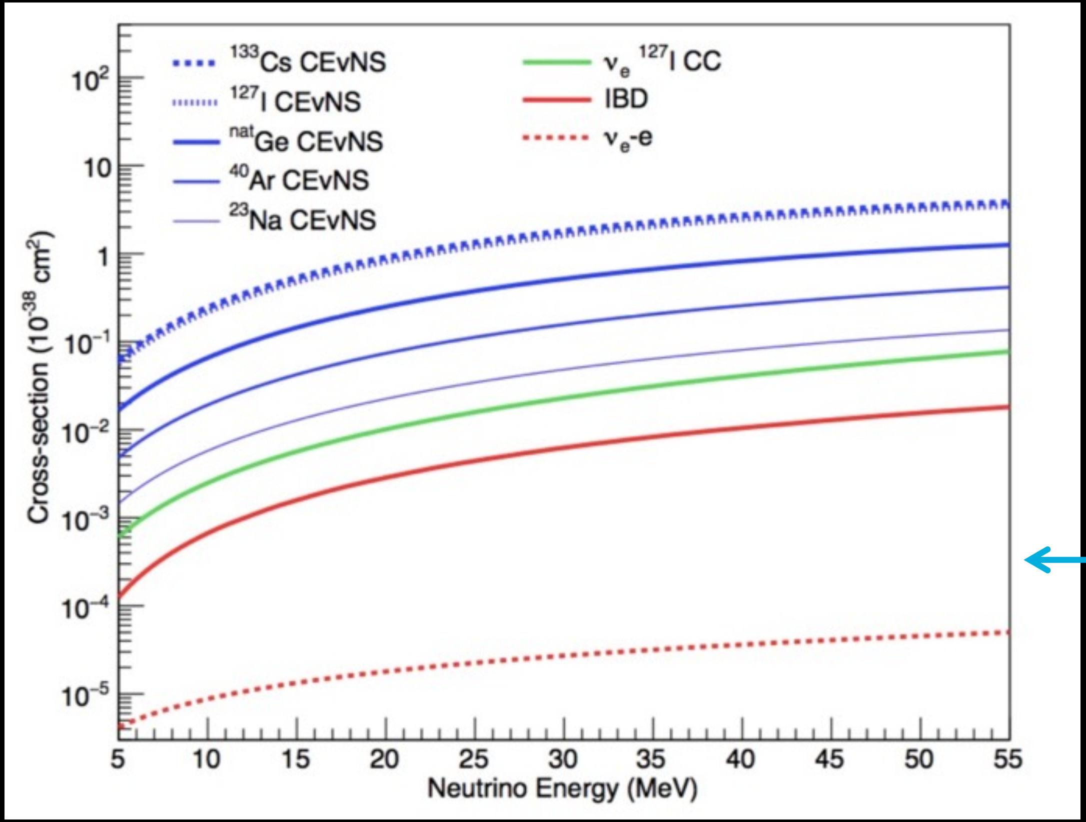

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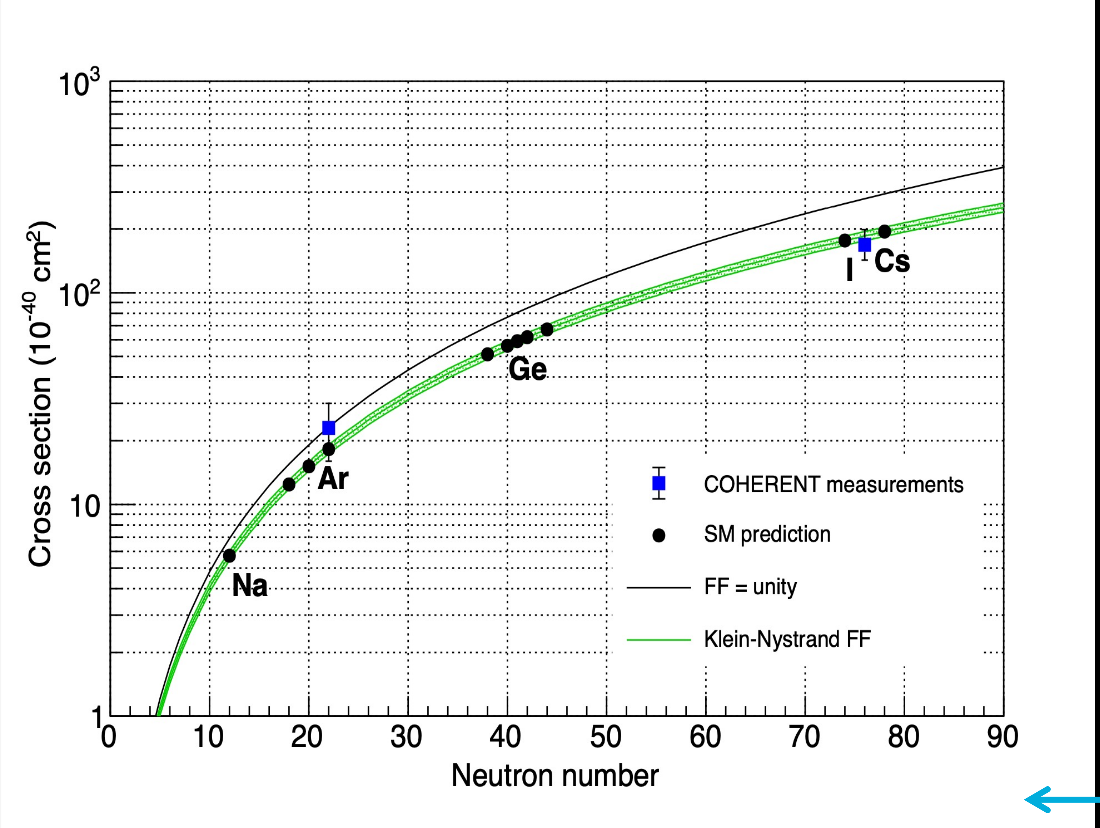

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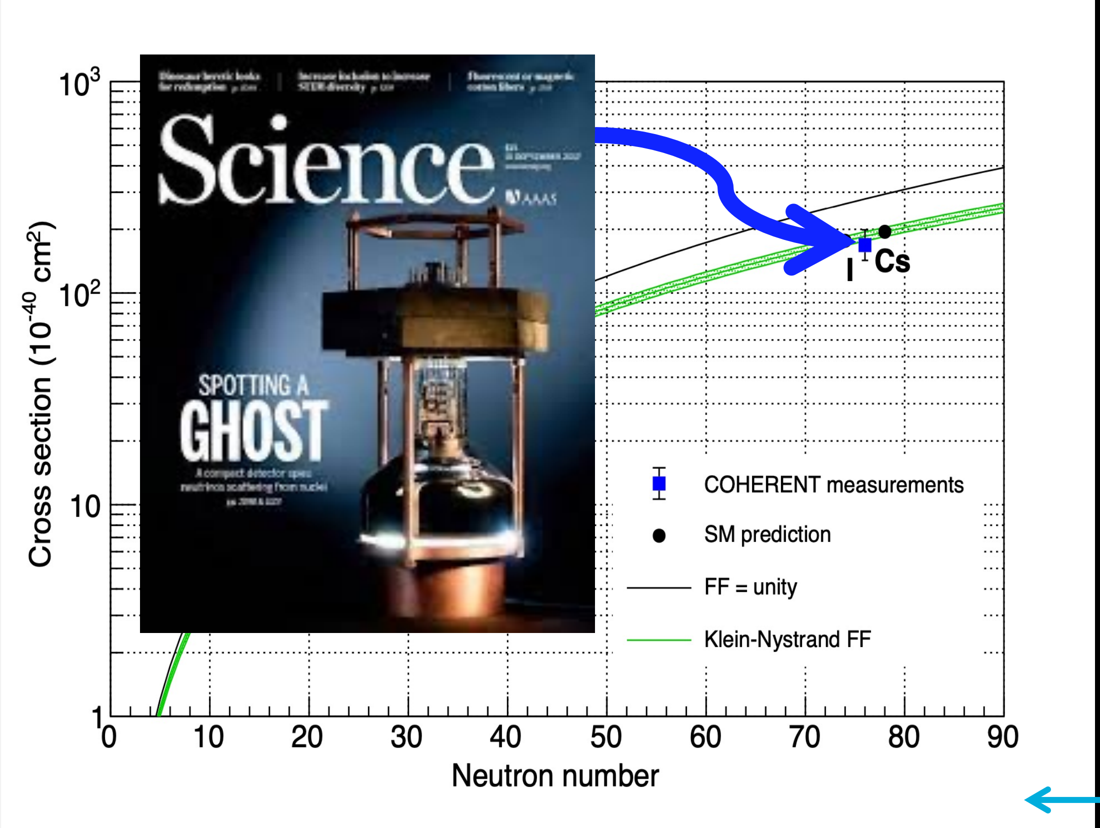

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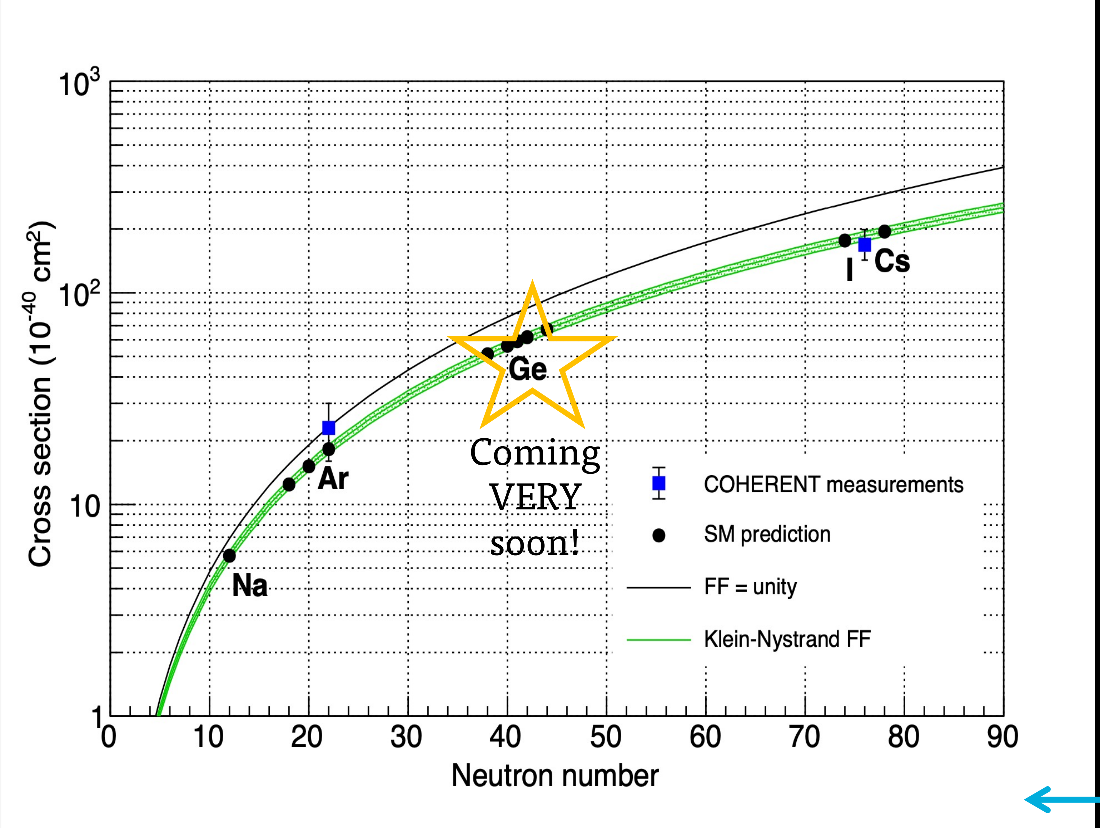

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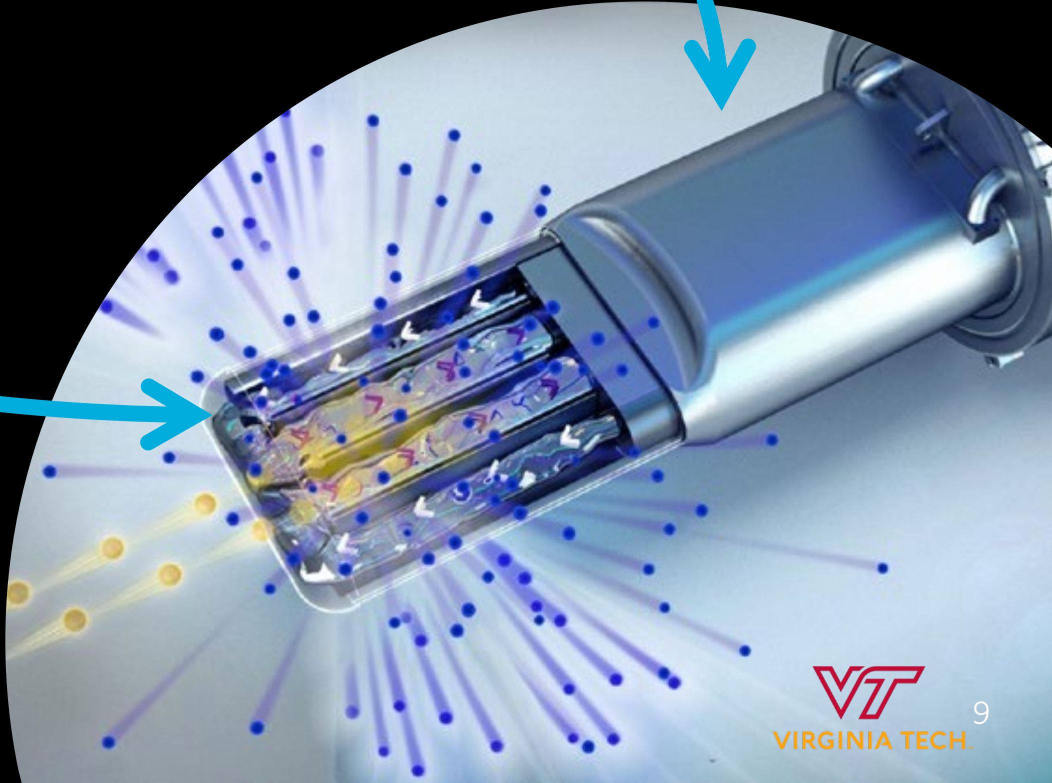
· COHERENT at the Spallation Neutron Source (SNS)·

- Proton beam energy: 0.9-1.4 GeV
- Total beam power: 1.4 MW
- Liquid Mercury target
- Frequency: 60 Hz



A high-intensity pulsed-neutron source!

COHERENT SNS

OAK RIDGE
National Laboratory

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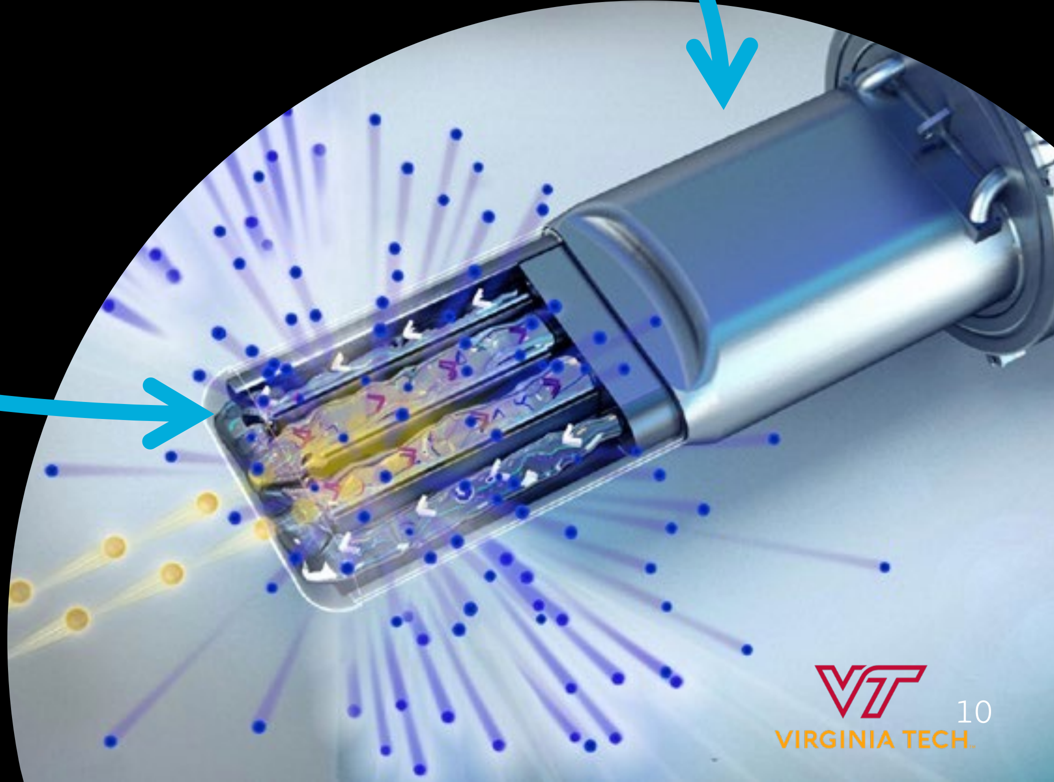

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Brookhaven
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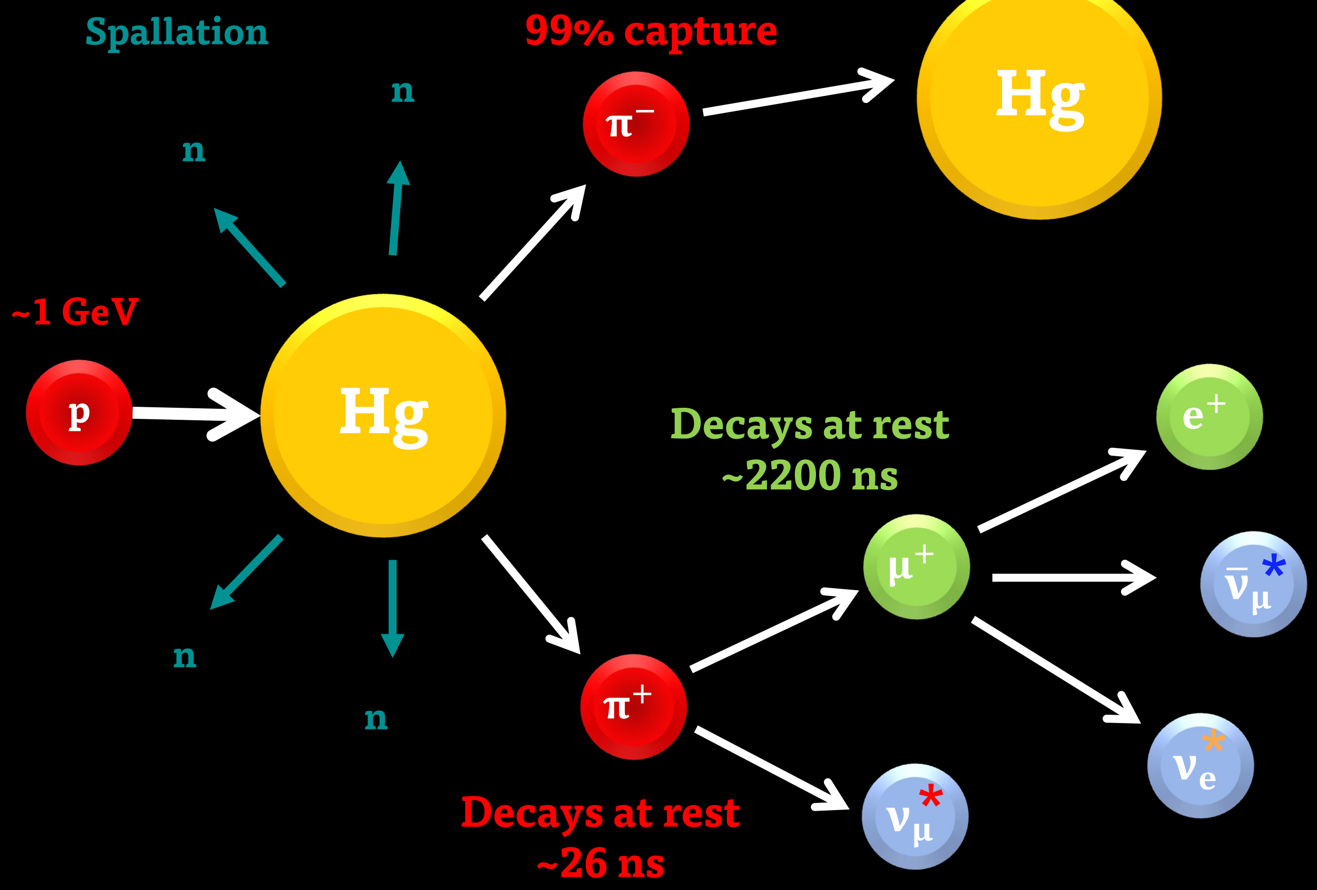
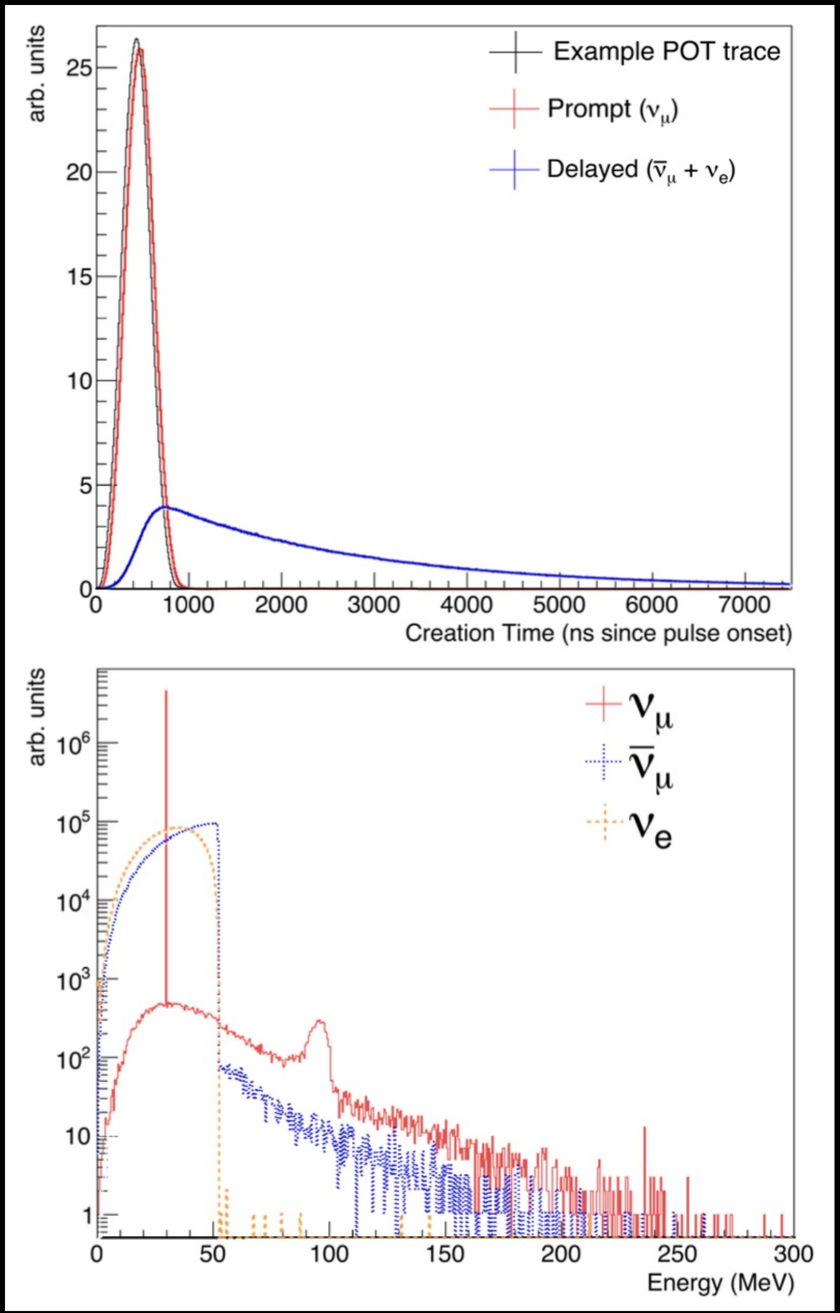
· SNS as a Neutrino Source ·

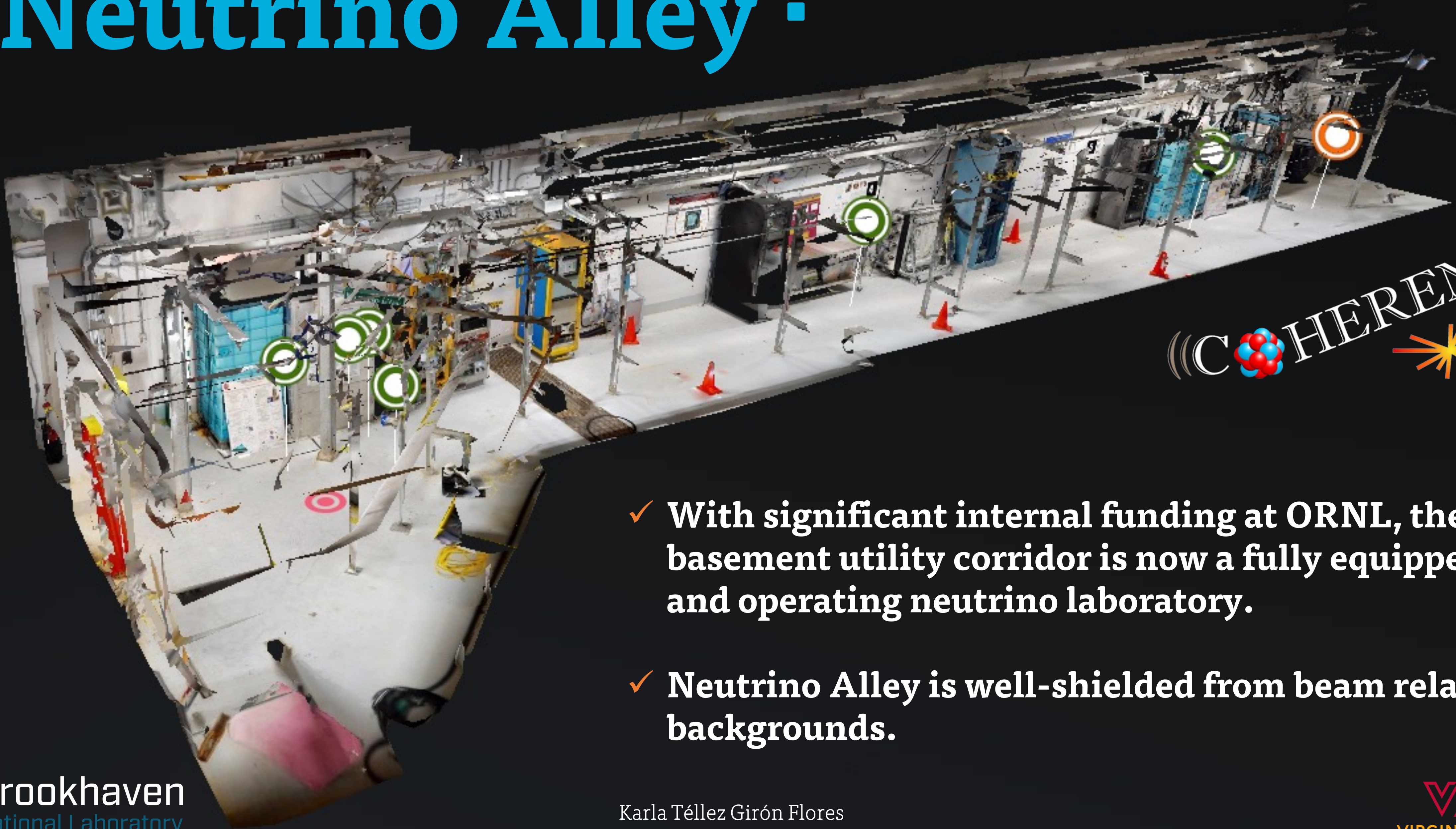


Energy and Time Distributions



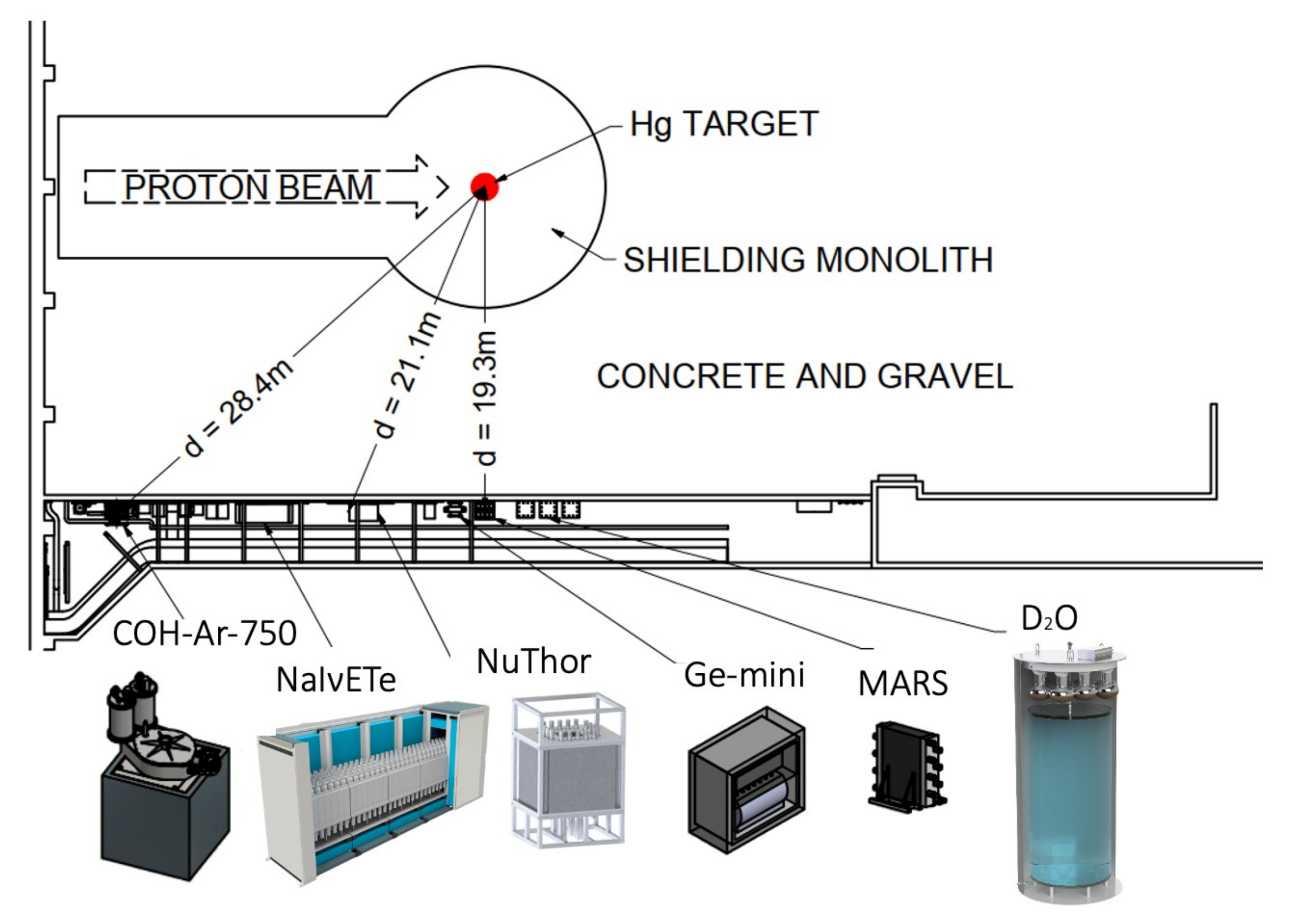
D. Akimov et. al. (COHERENT Collaboration) Phys. Rev. D 106, 032003

· Neutrino Alley ·



- ✓ **With significant internal funding at ORNL, the basement utility corridor is now a fully equipped and operating neutrino laboratory.**
- ✓ **Neutrino Alley is well-shielded from beam related backgrounds.**

· Neutrino Alley today ·



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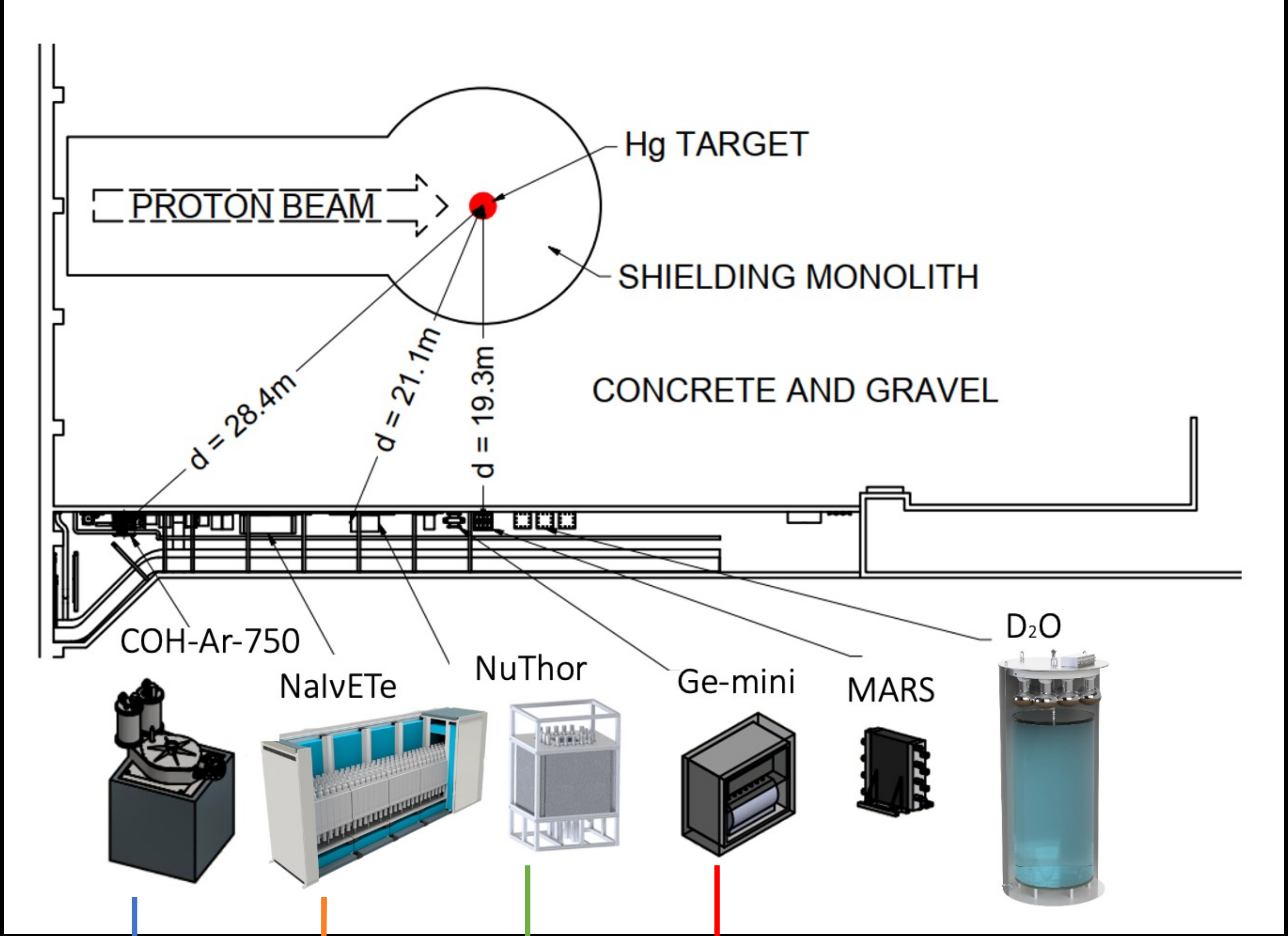

CENNS-750 (CEvNS)

- 610-kg of Liquid Argon
- Low-N observation of CEvNs to complement the first observation.

NaIvETe (CEvNS)

- An upgraded version of NaIvE, this will be a Ton-Scale detector to measure CEvNS on ^{23}Na (lightest nucleus yet!) and CC ν_e - ^{127}I cross section.

Ge-mini (CEvNS)

- A modular 16 kg array of Ge crystals for measuring CEvNS on Ge, a nucleus of moderate size.

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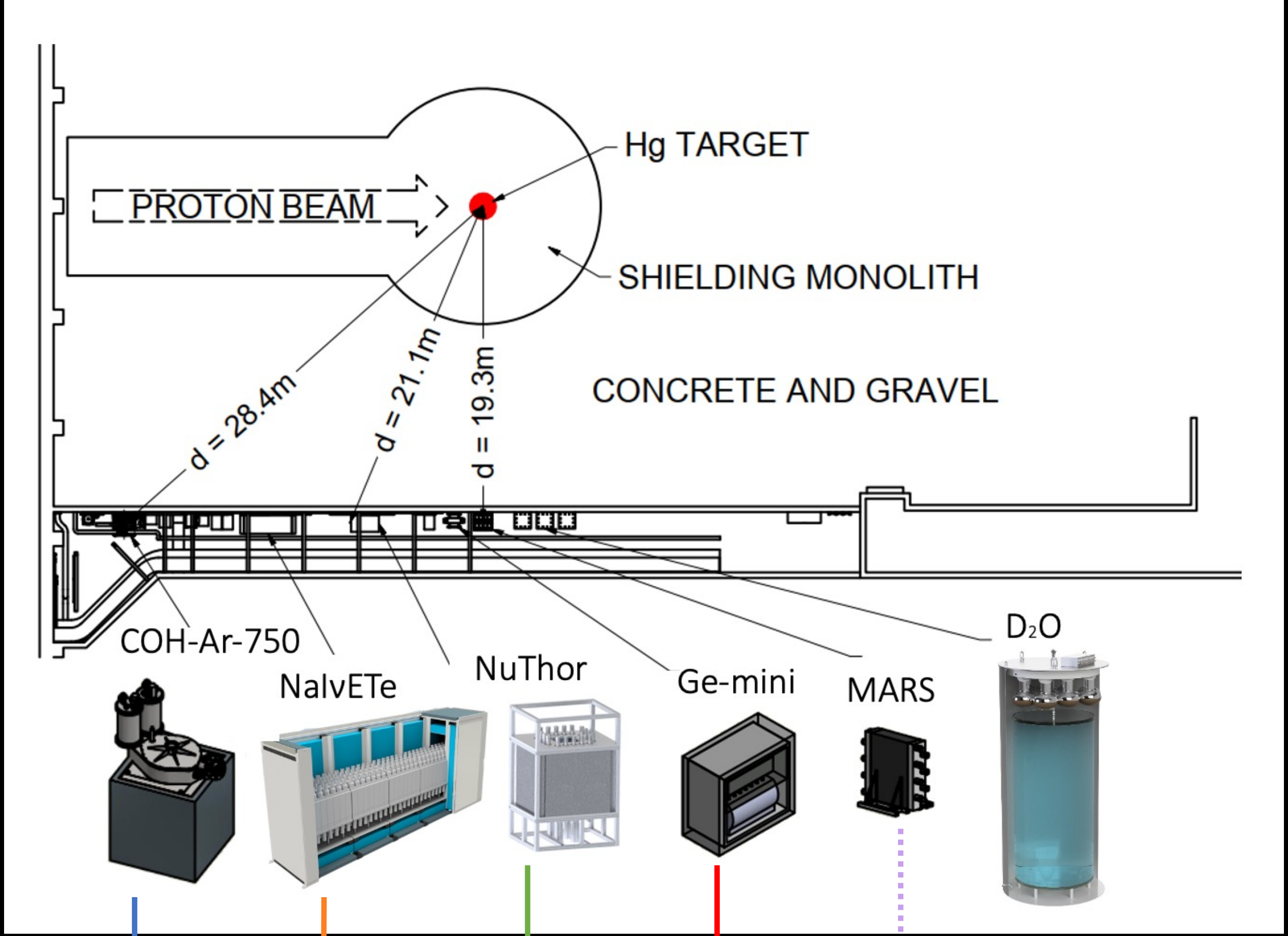

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NuThor (ν-induced fission)

- Looks for neutrons from neutrino-induced fission through capture of gadoliniated water.

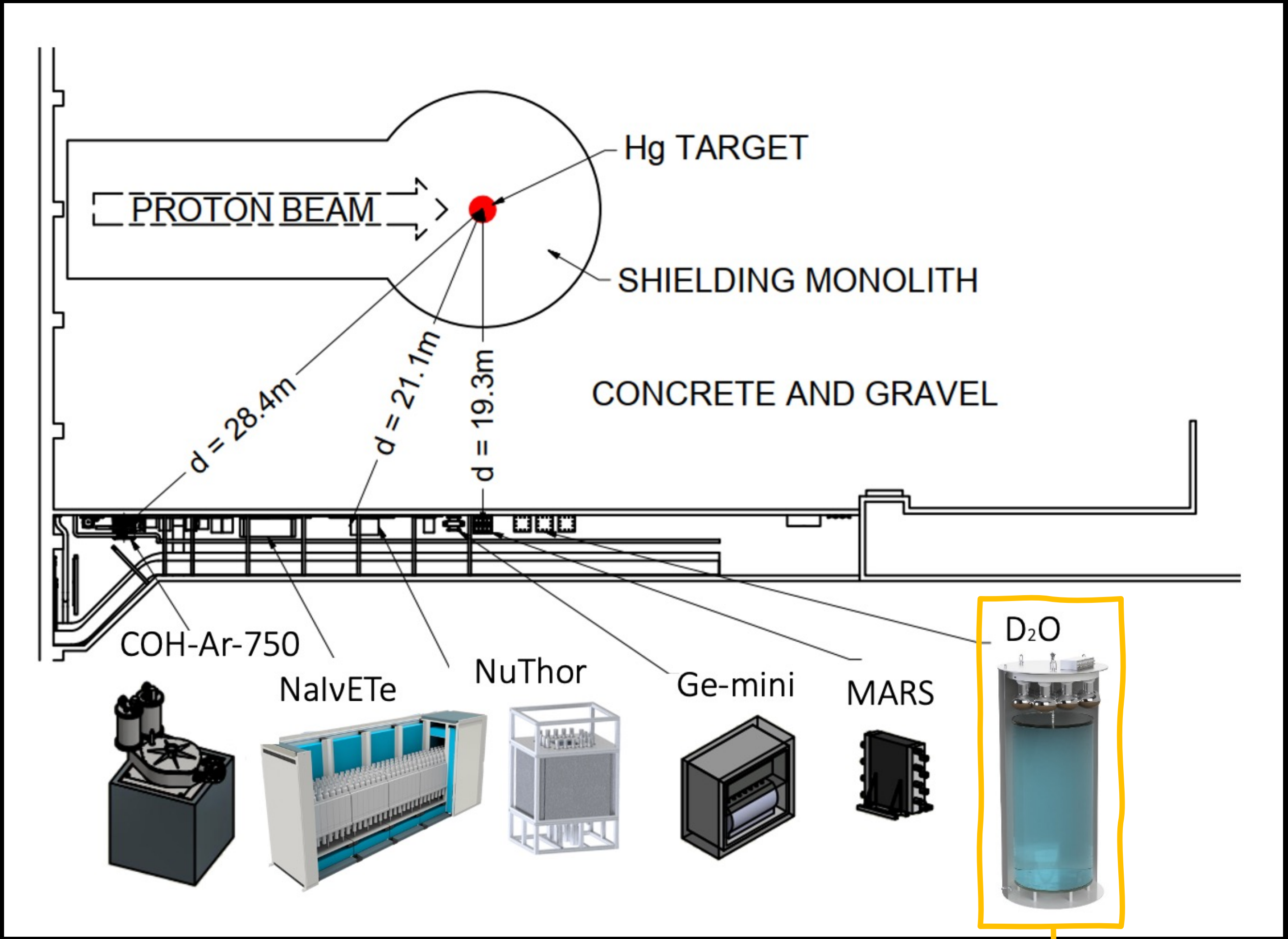
Ge-mini (CEvNS)

- A modular 16 kg array of Ge crystals for measuring CEνNS on Ge, a nucleus of moderate size.

MARS (backgrounds)

- A mobile detector to monitor de beam-related neutron rates in Neutrino Alley.

· Neutrino Alley today ·



Common for **all analyses** at COHERENT is the need for the lowest possible **neutrino flux uncertainty**, which is currently estimated to be **10%**.

We need better precision!

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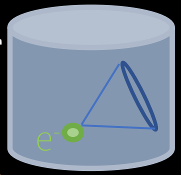
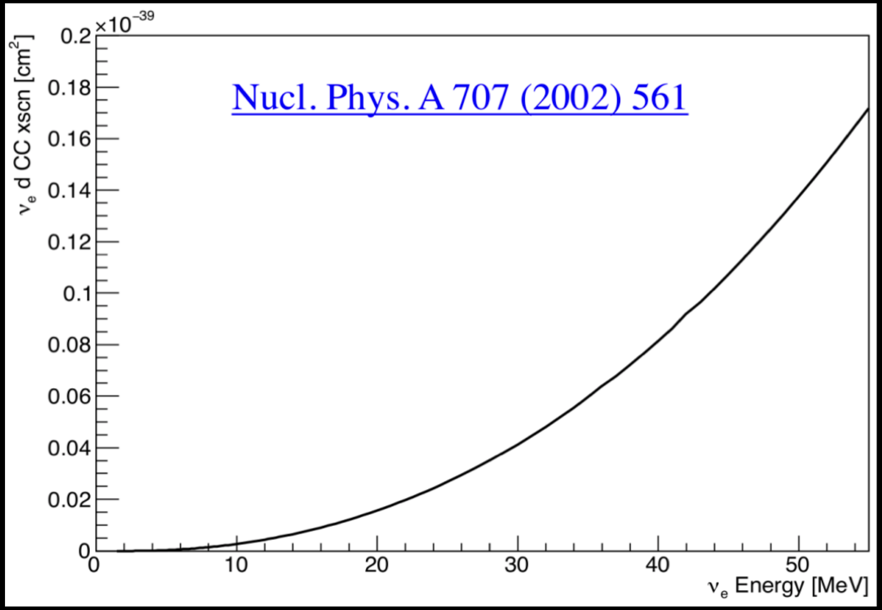
· Unlocking the High Precision CEνNS program ·

We need to improve the SNS ν flux estimate. We plan to do this via a well-understood process: the CC cross section for neutrino interactions with Deuterons:





Cross Section theoretically calculated at ~2-3% accuracy!

[Phys. Rev. C 101, 015505 (2020)]

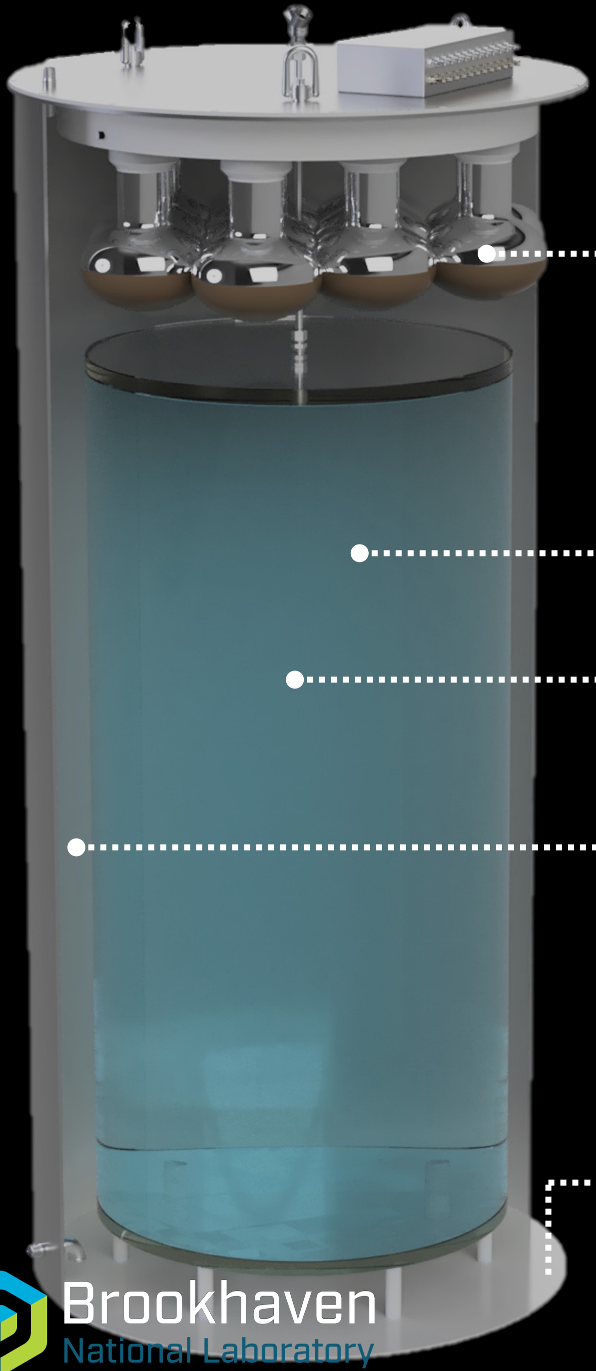
$$\nu_e + d \longrightarrow p + p + e^-$$

[Detectable Signature]

COHERENT
D_2O
SNS ν FLUX
MONITOR

A direct measurement of the neutrino flux will lower the uncertainty and improve precision for all current and future COHERENT analyses.

· D_2O: COHERENT's Neutrino Flux Normalization Detector ·



Twelve 8-inch Hamamatsu R-5912-100 PMTs

592 kg of Heavy Water

0.6-cm thick clear acrylic vessel

Light Water tail catcher

Stainless Steel Tank

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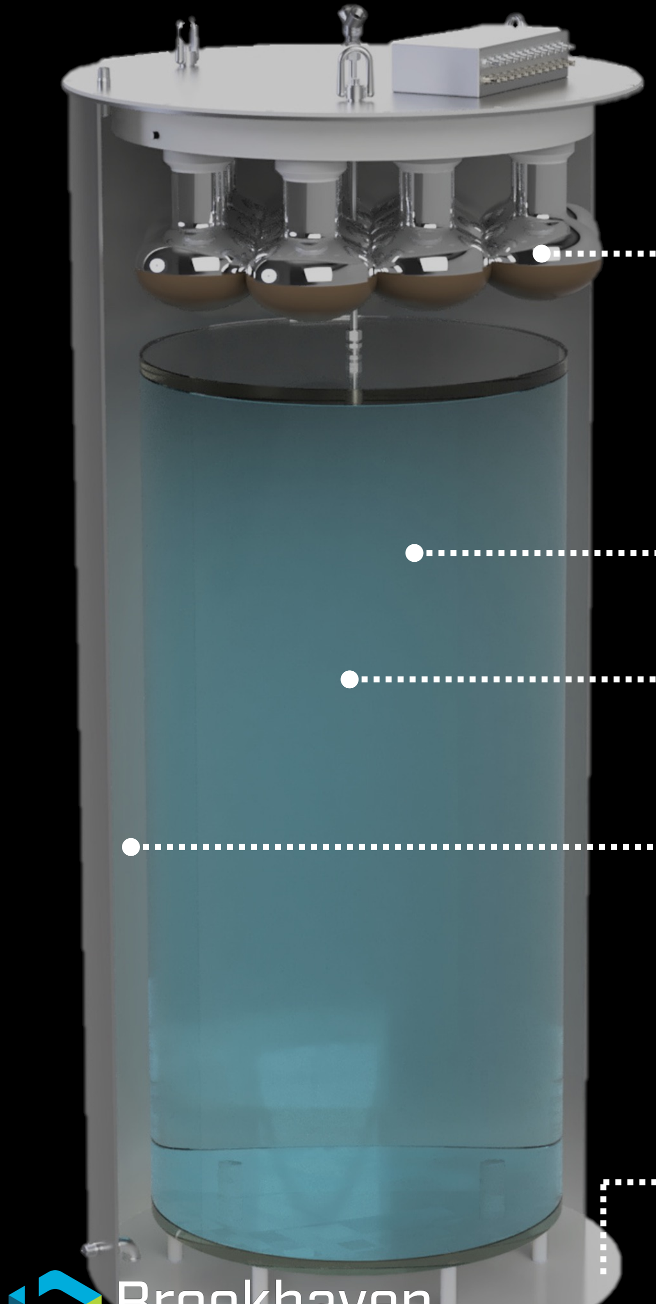
· D_2O: COHERENT's Neutrino Flux Normalization Detector ·



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0.6-cm thick clear acrylic vessel

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Not Pictured here:

- ✓ Reflective Tyvek® on the walls
- ✓ Lead Shielding
- ✓ Plastic Scintillator Muon Veto Panels
- ✓ A VERY COOL Calibration System built at VT.

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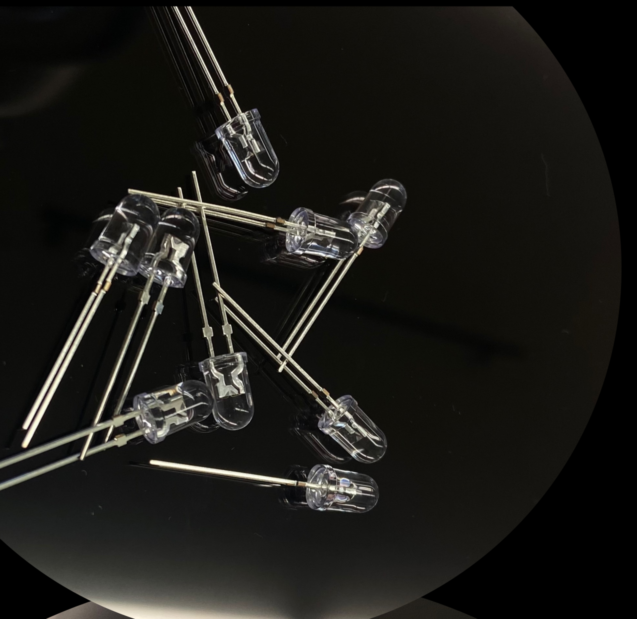

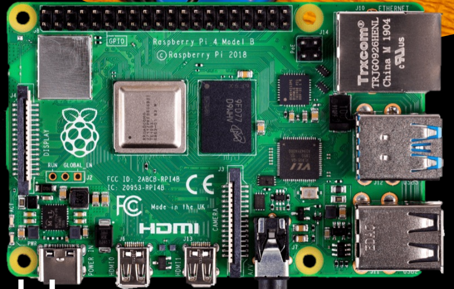

· Calibration HARDWARE ·

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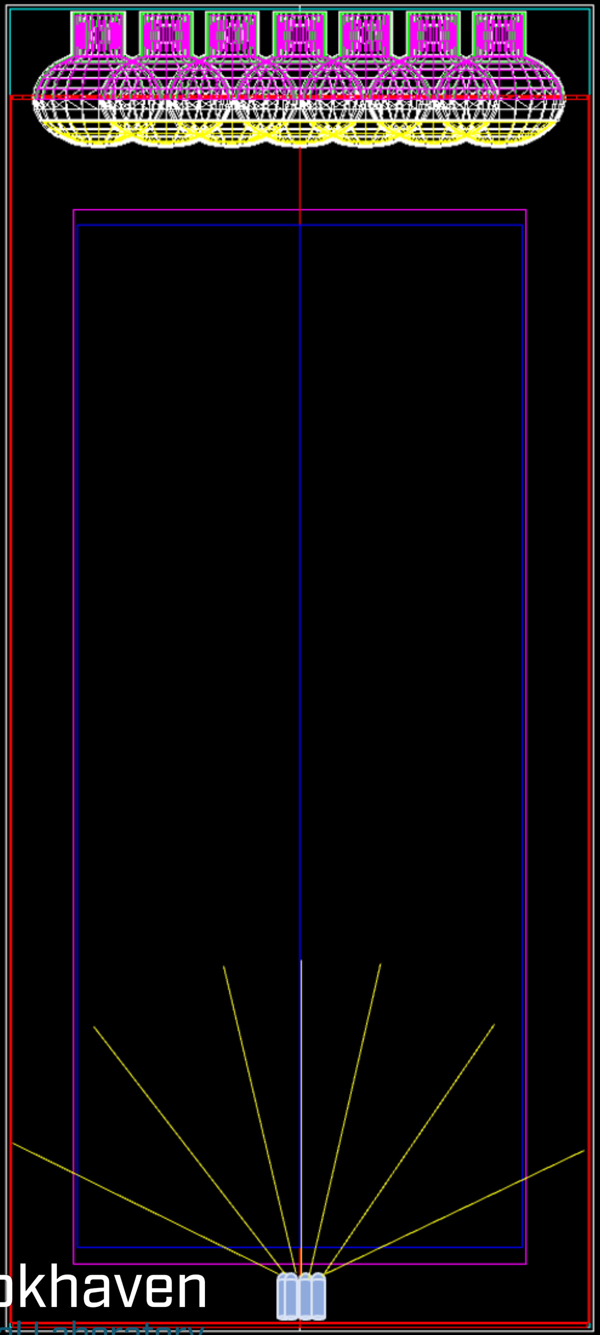


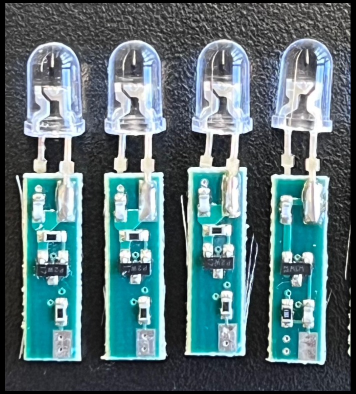
· LED Flasher System·

LEDs produce controlled pulses of light that hit the PMTs

- **Purposes:**
  1. Time-in PMTs
  2. Single P.E. Gain Calibration
  3. Track Water Attenuation

- **D_2O detector has 4 flashers:**

- *2x Low Light*
- *2x High Light*



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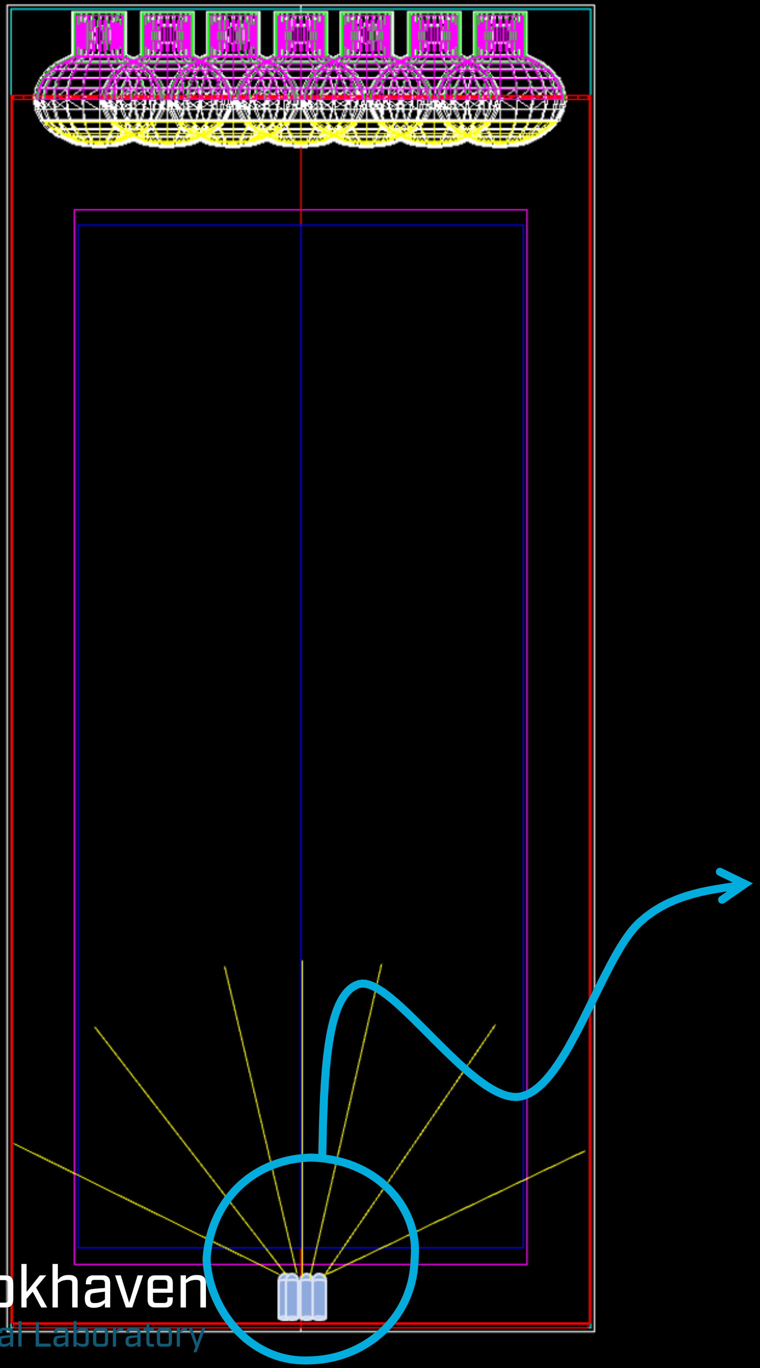

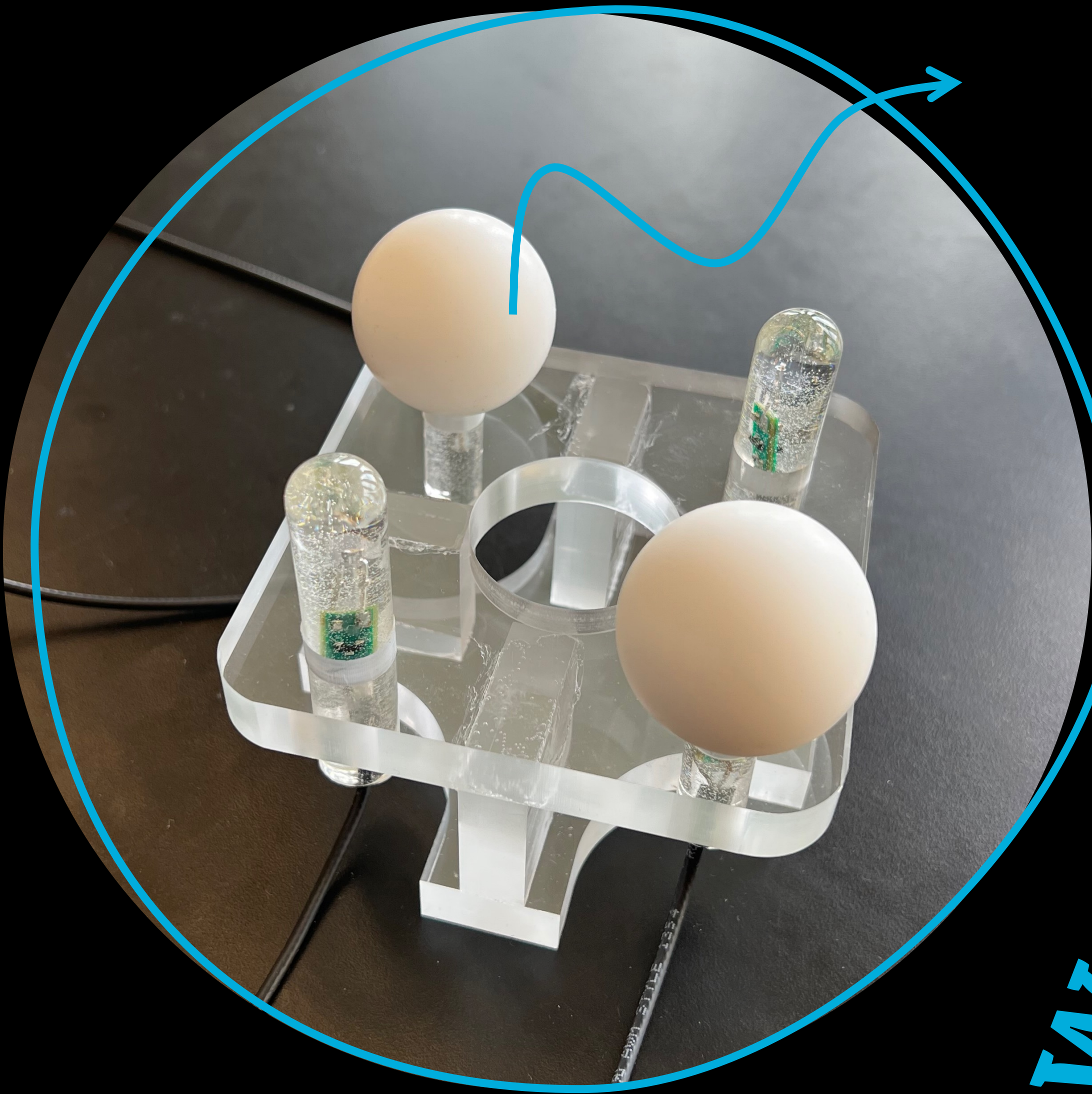

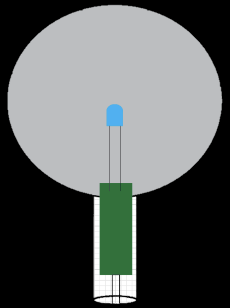

Waterproof!

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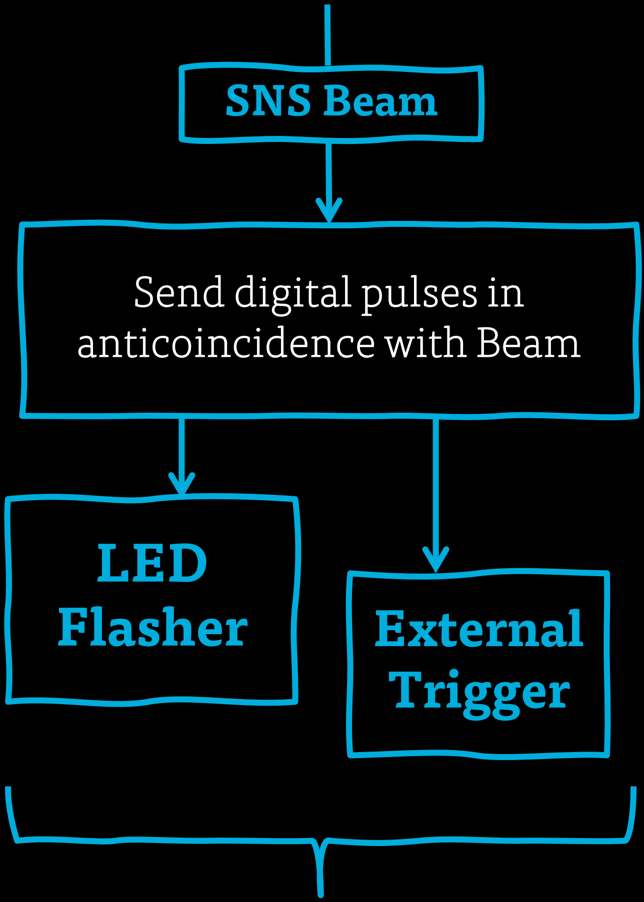
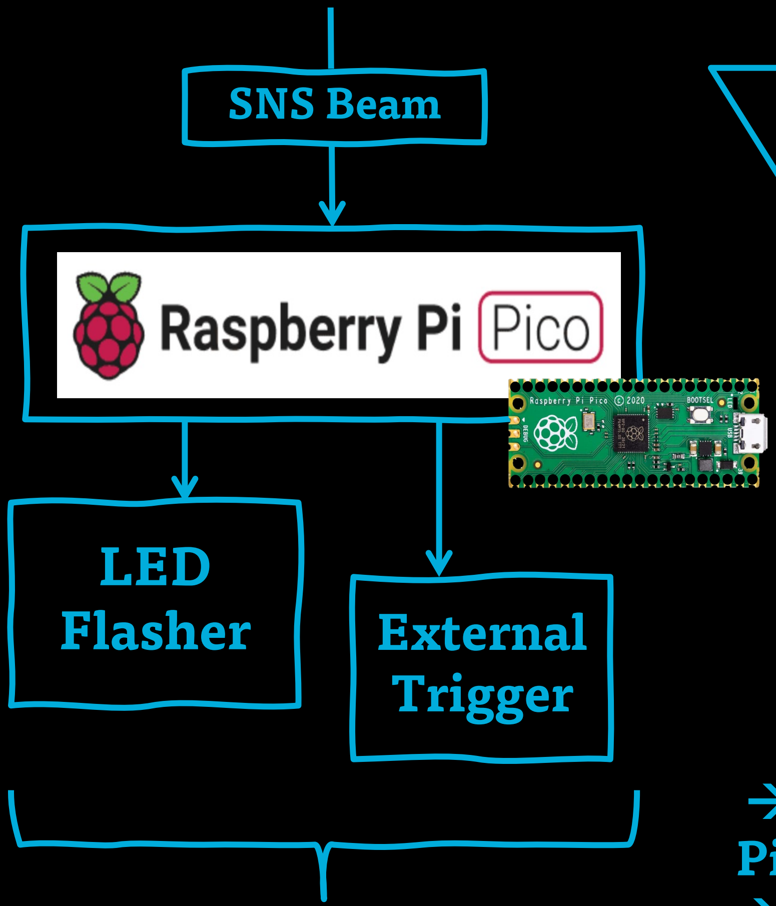
· LED Flasher System Operation ·



We need precise time separation between these two signals.

· LED Flasher System Operation ·



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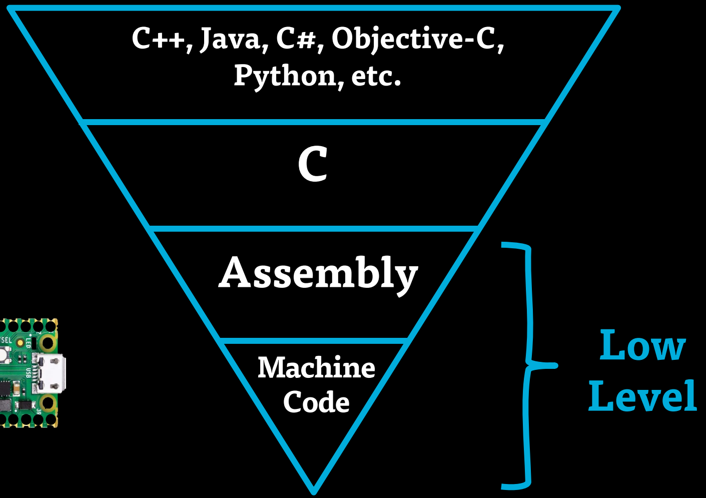
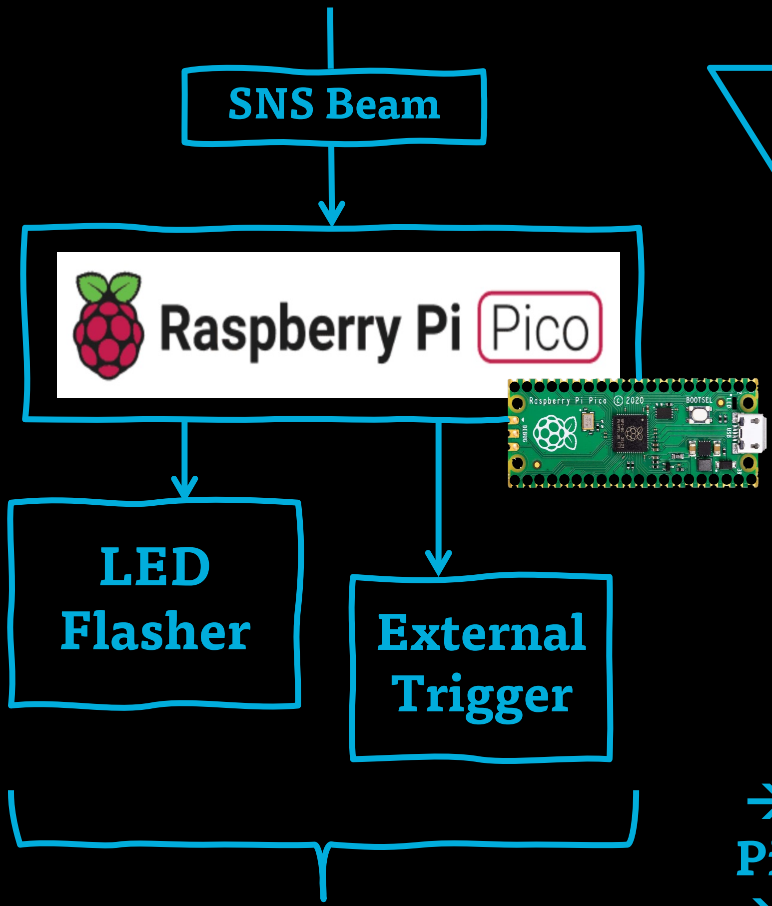


Pico is programmed in **PIO Assembly Language**

→ Interfacing directly with Pico pins
→ 125 MHz internal clock
→ No delays!

· LED Flasher System Operation ·



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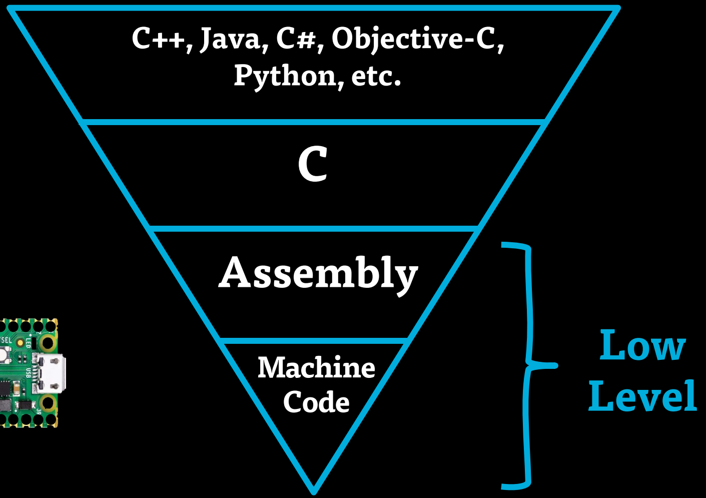

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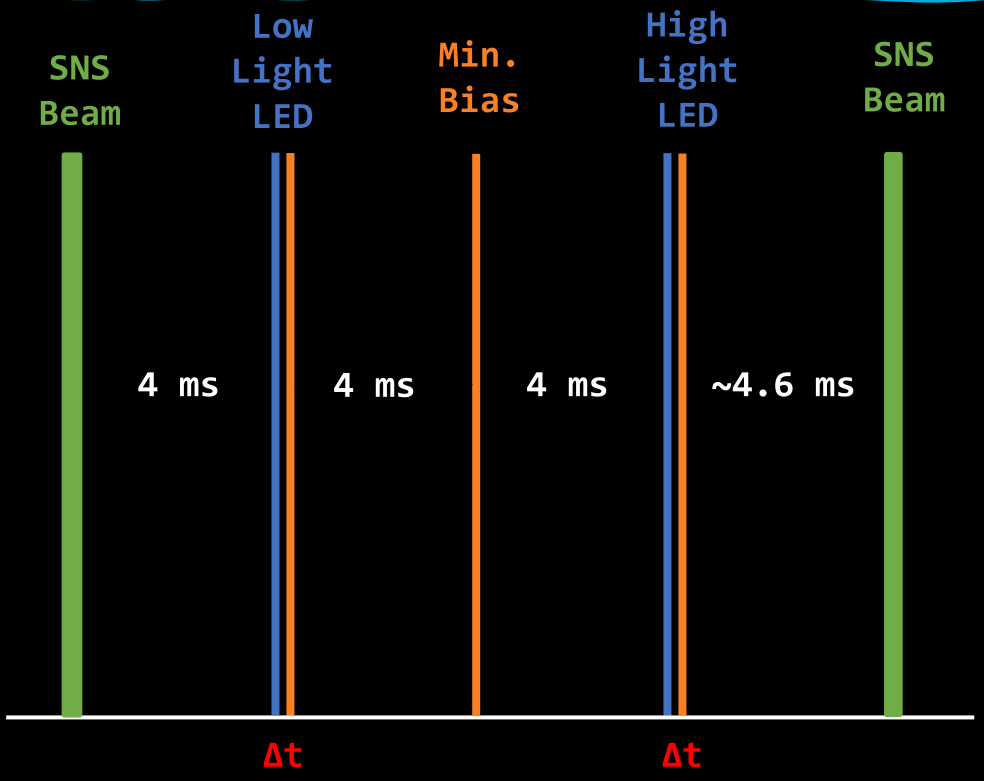
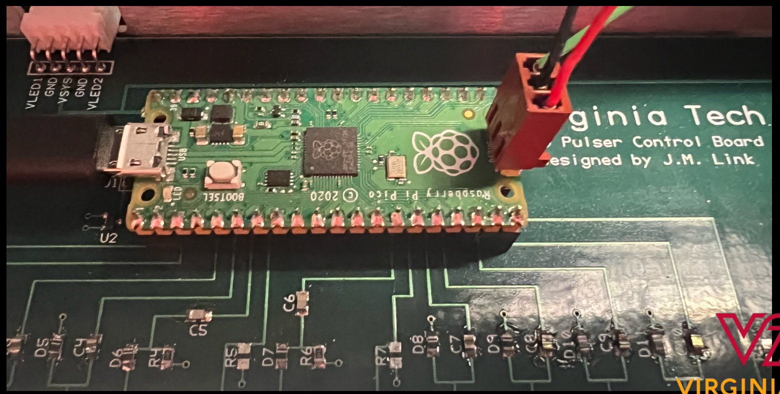
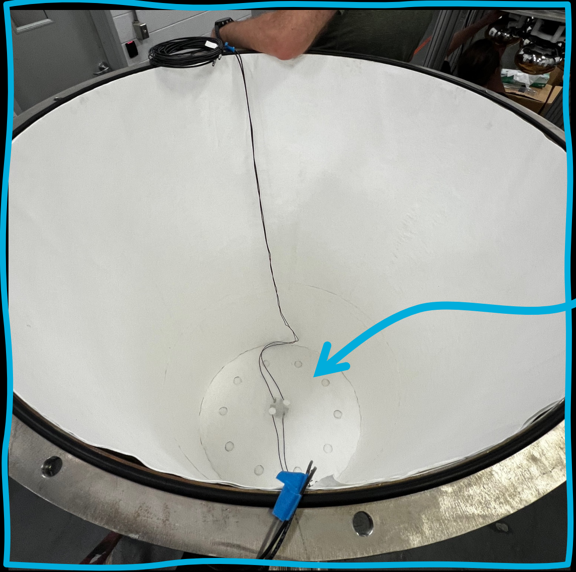
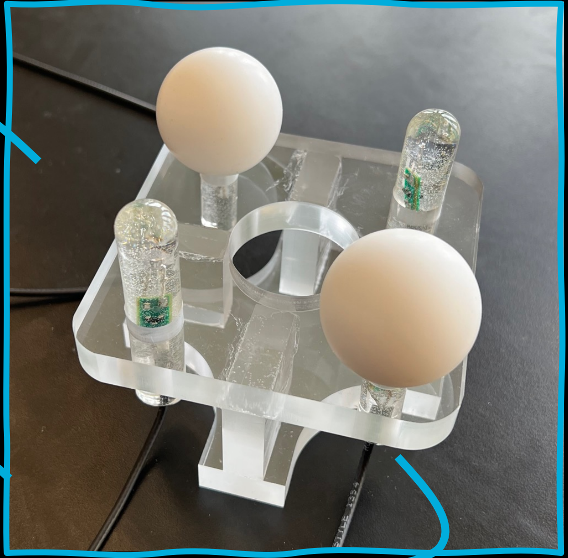


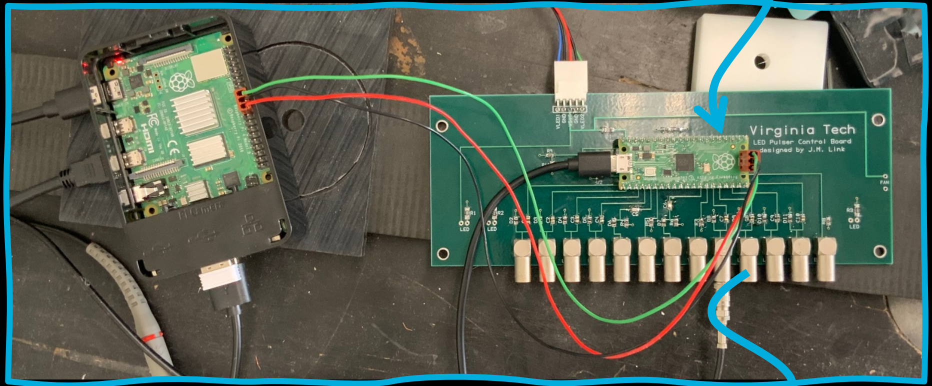


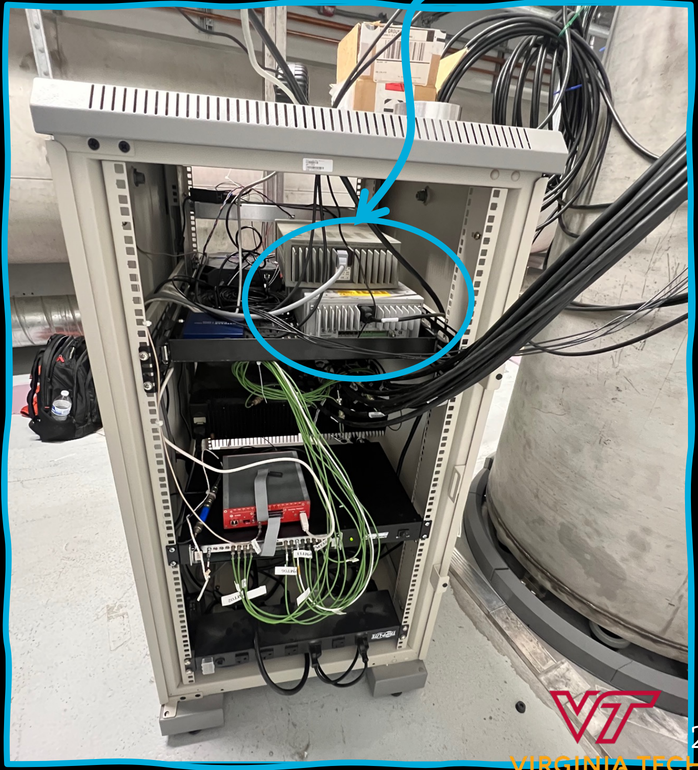
· D_2O Calibration System · ✅

```
; Feed me PIO Assembly
```

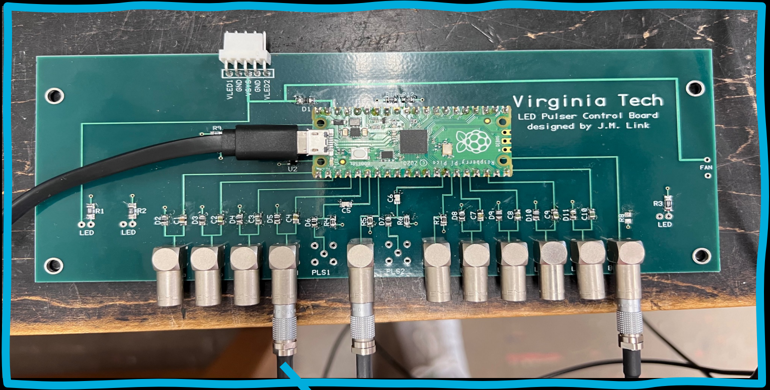


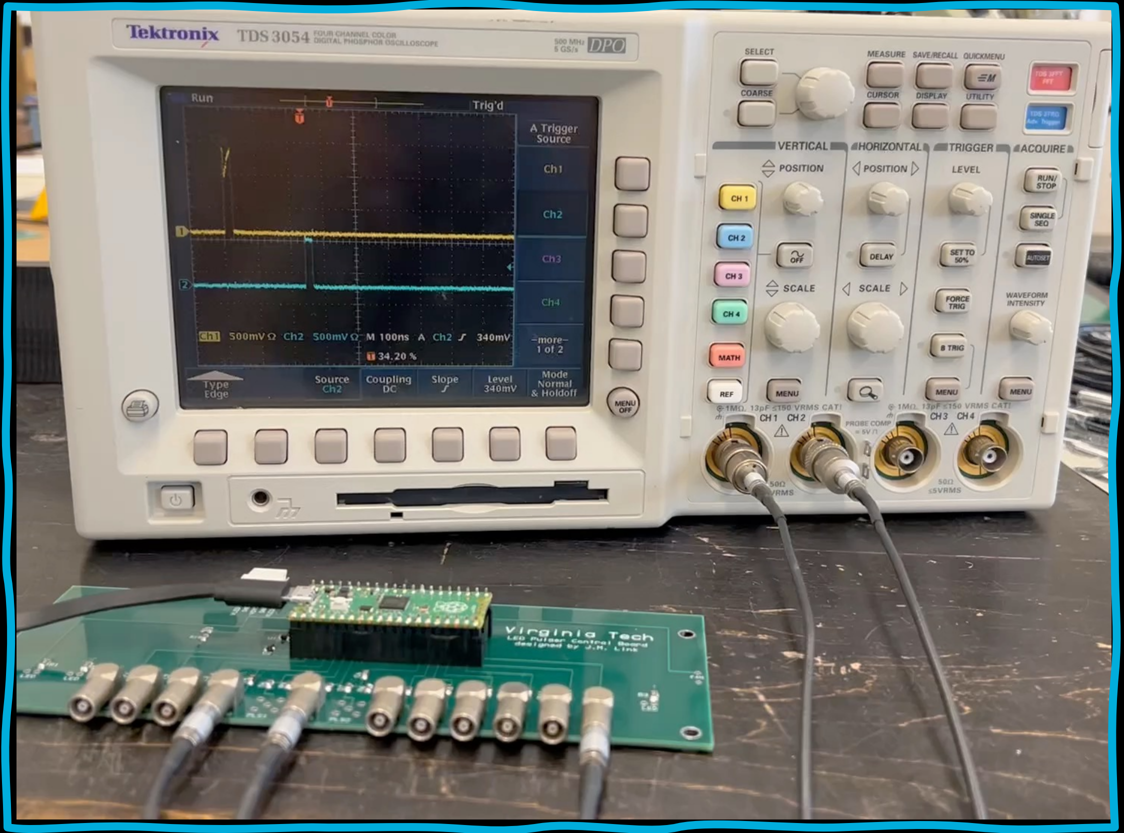


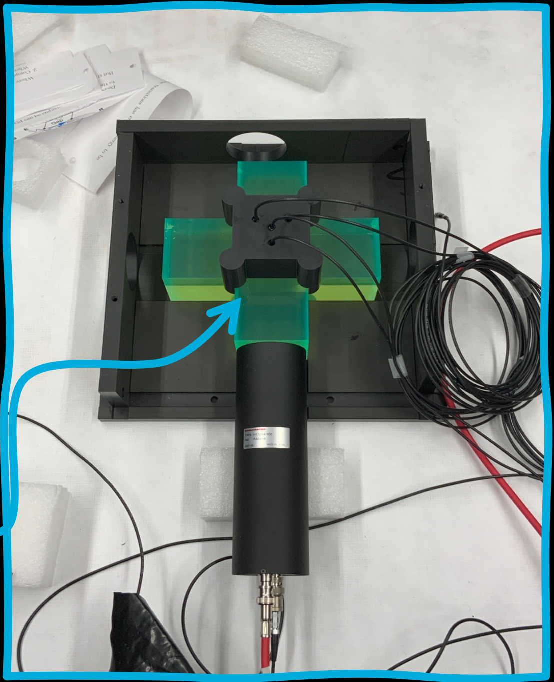




· Something Similar will be used in MAD ·







Similar pulsing structure as that for D_2O

· Raspberry Pi Pico, highly recommended ·

★★★★★

- ✓ Cheap
- ✓ User-friendly
- ✓ Lots of documentation
- ✓ Small but powerful

- ✓ The only device that serves to both calibrate a neutrino detector AND play Pac-Man.

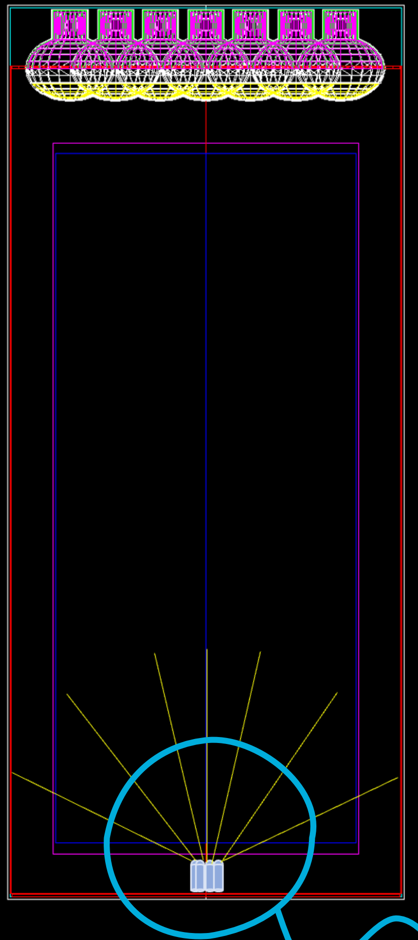
· Calibration ANALYSIS ·

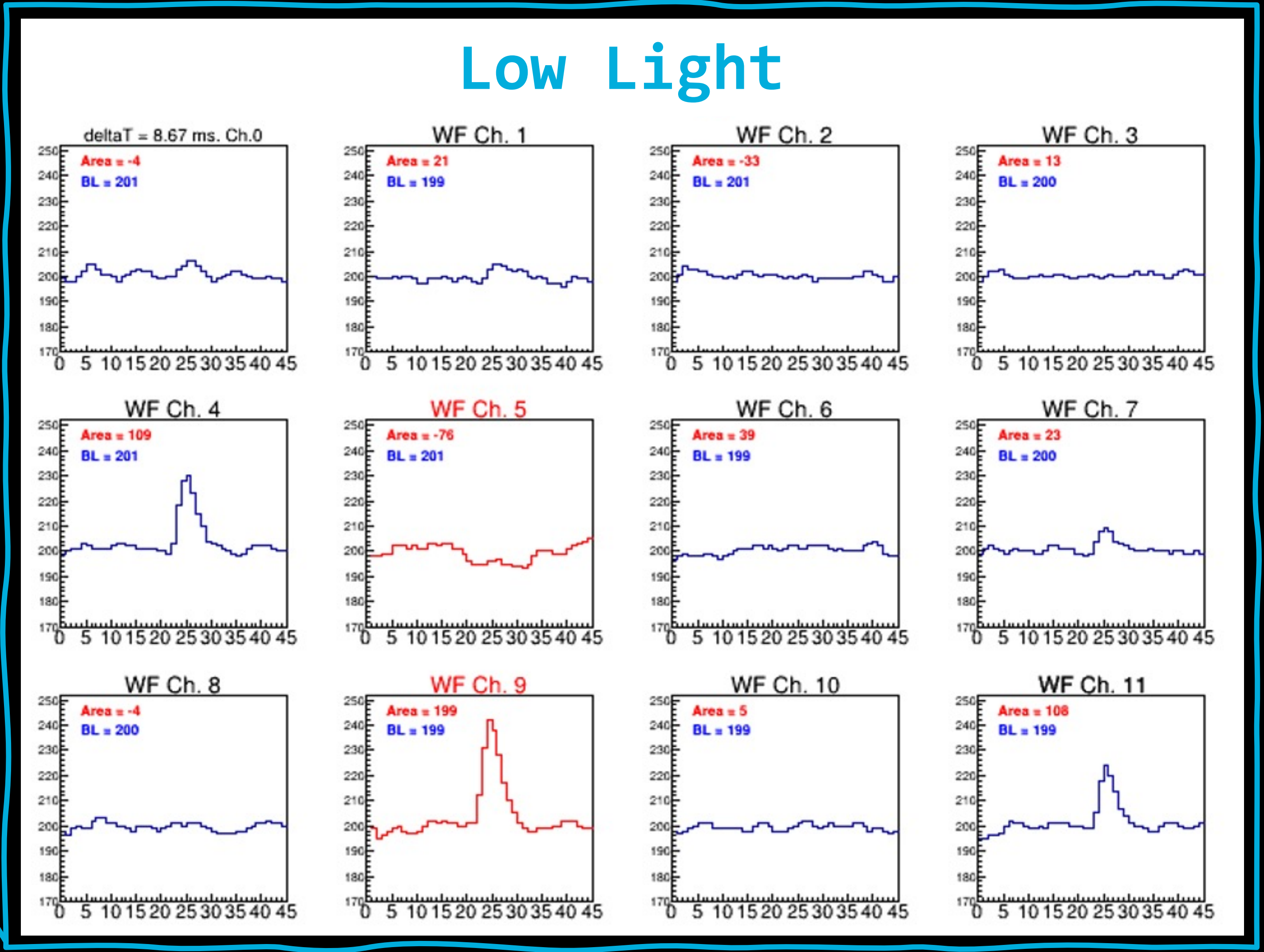
1) SPE Analysis
2) Michel Electrons
3) M.C.-to-Data matching → **ENERGY SCALE**

```
    0;
    baseline_size = nSamples[i]-35;
   baseline_size = nSamples[i]-25;    //NEW!

pulse_area[i] = 0.0;
pulse_height[i] = 0.0;

if(adcVal[i][peakPosition[i]] >= 4095) n_saturate_pmt++; //Ad

//-------- some quantities to calculate baseline r.m.s.-------

for(int j=0; j<baseline_size; j++){
    sum_wf = sum_wf + adcVal[i][j];
    sum_wf_sq = sum_wf_sq + (adcVal[i][j])*(adcVal[i][j]);
} //ENF FOR j

baseline_mean = 1.0*sum_wf/baseline_size;
baseline_rms = sqrt(1.0*sum_wf_sq/baseline_size - baseline_mea

cout << "Baseline Mean: " << baseline_mean << endl;
cout << "Baseline RMS: " << baseline_rms << "\n" << endl;

for(int j=baseline_size; j<nSamples[i]; j++){ // for samples b
    if(adcVal[i][j] > max_pmt[i]){
        max_pmt[i] = adcVal[i][j]; // make max_pmt = maximum
        peak_position[i] = j;

     e_area[i] = pulse_area[i] + adcVal[i][j] - baseline_me

        e Areas for diagnostics:
          l(pulse_area[i]);
                 line mean
```

· 1) Single Photoelectron (SPE) Analysis ·

Started by looking at Waveforms for Low Light Triggers only



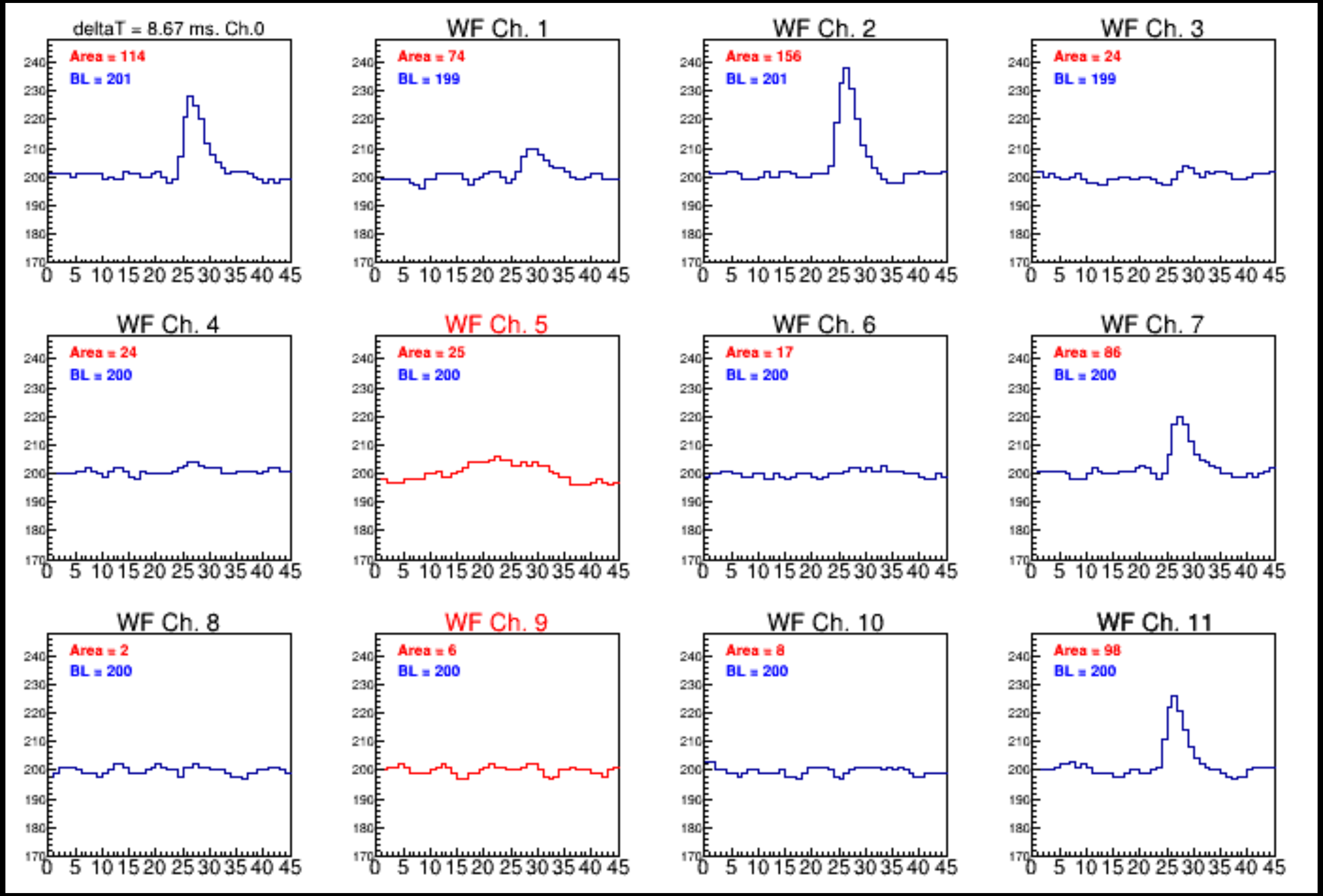


Low Light

Minimum Bias

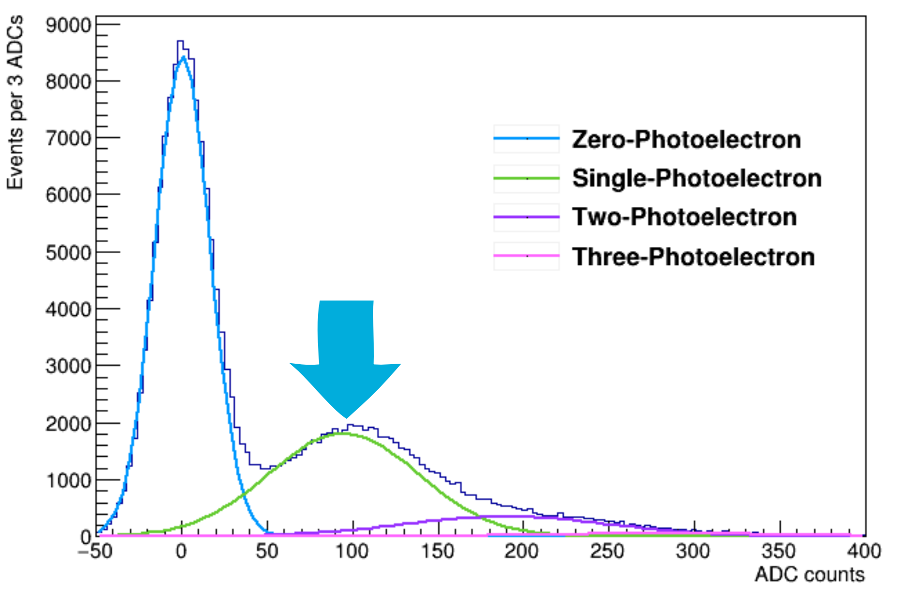
High Light

· 1) Single Photoelectron (SPE) Analysis ·



Get the Pulse Integral for each Channel per event and fill a histogram.

⇨ Single p.e. Distribution:



· SPE Analysis: A Multi-Gaussian Fit Function ·

$$\boxed{f(x)} = A_0 * e^{-\frac{1}{2}\left(\frac{x-\mu_0}{\sigma_0}\right)^2} \longrightarrow \text{Zero-p.e.}$$

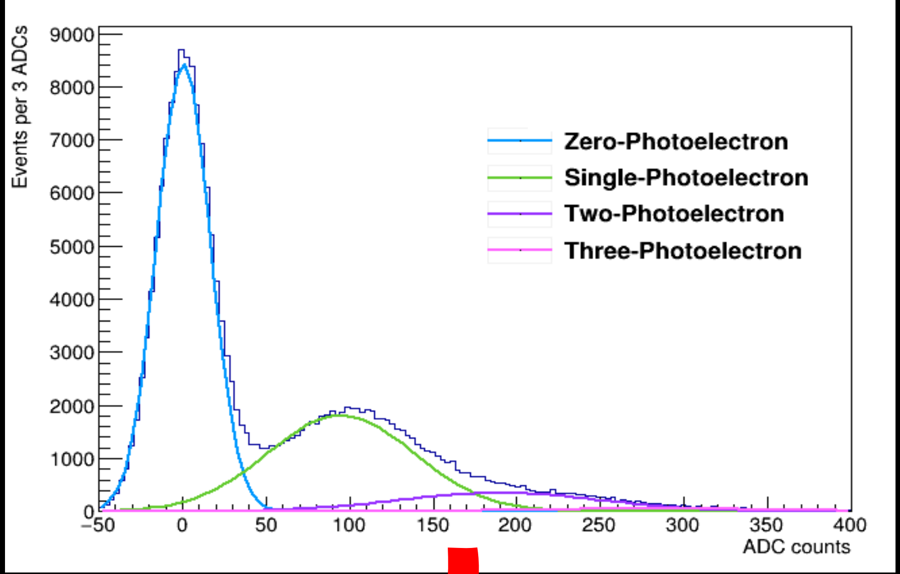
$$+ A_1 * e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_1}\right)^2} \longrightarrow \text{Single-p.e.}$$

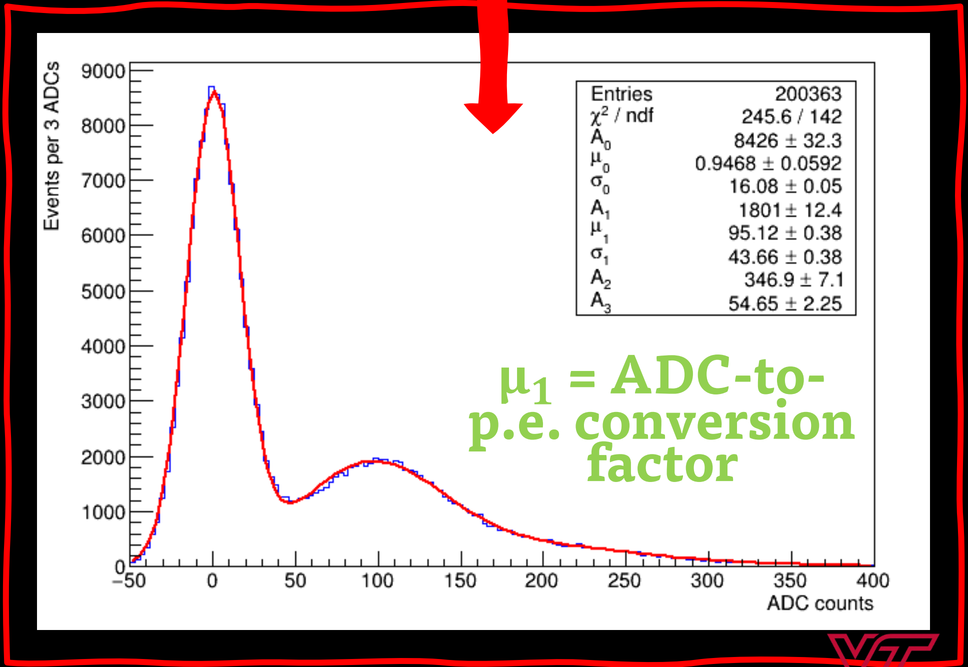
$$+ A_2 * e^{-\frac{1}{2}\left(\frac{x-2\mu_1}{\sqrt{2\sigma_1{}^2-\sigma_0{}^2}}\right)^2}$$

Two-p.e.

$$+ A_3 * e^{-\frac{1}{2}\left(\frac{x-3\mu_1}{\sqrt{3\sigma_1{}^2-2\sigma_0{}^2}}\right)^2}$$

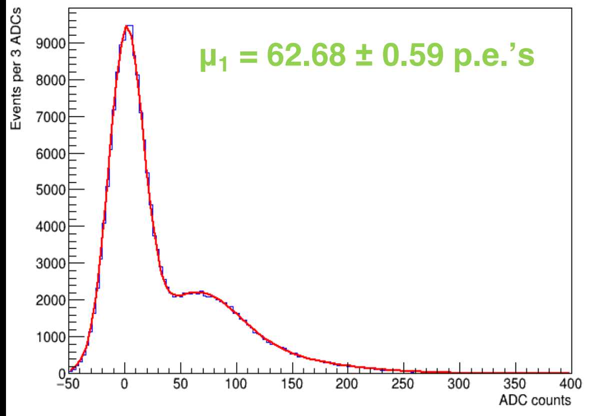
Three-p.e.



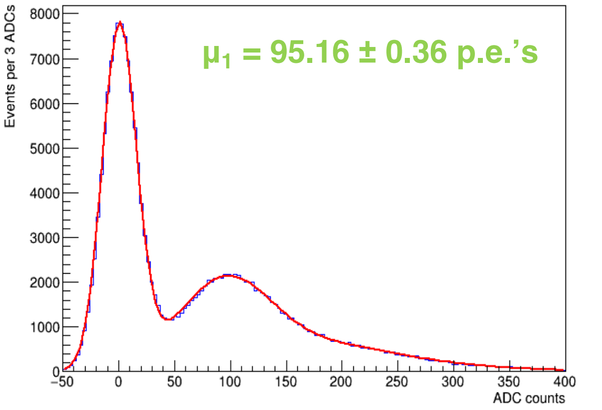


μ_1 = ADC-to-p.e. conversion factor

Ch. 0



Ch. 1



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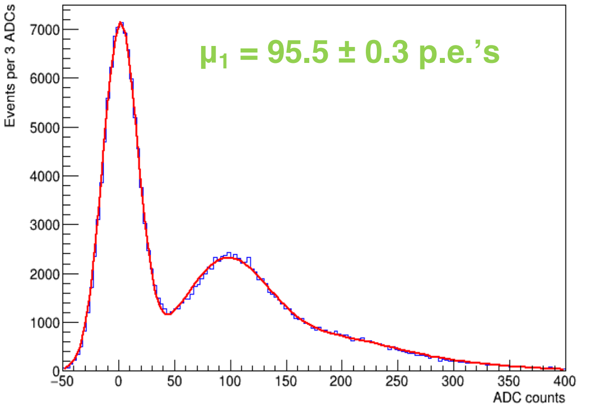

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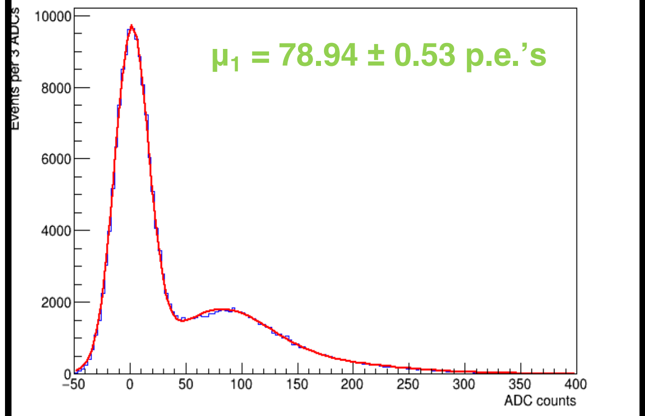

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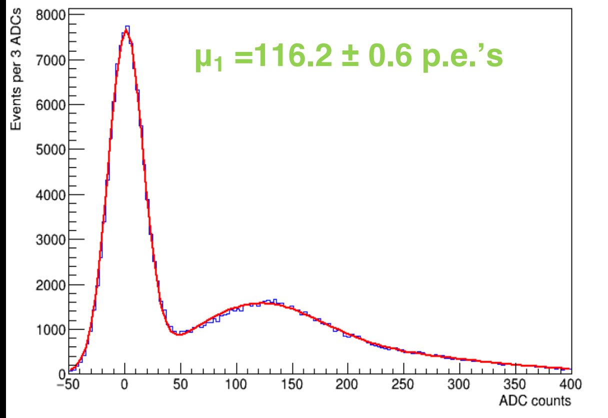

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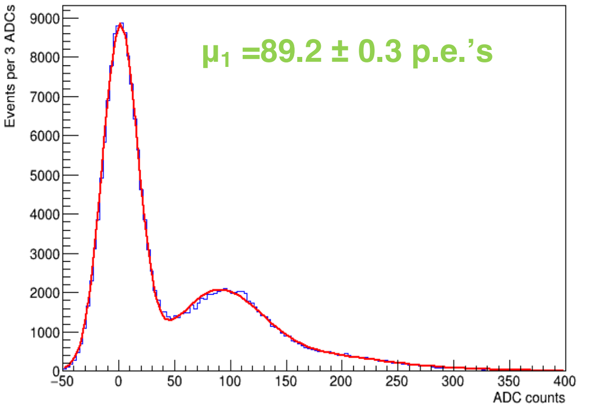

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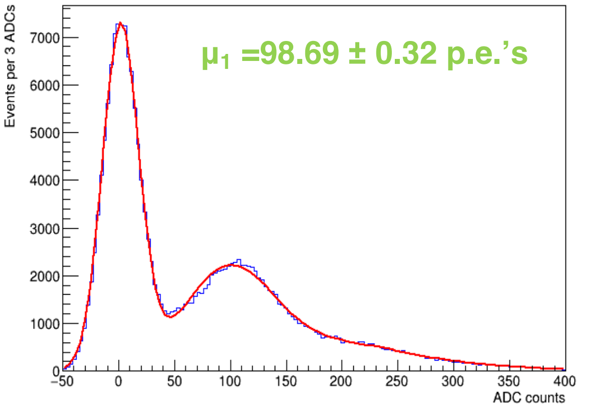

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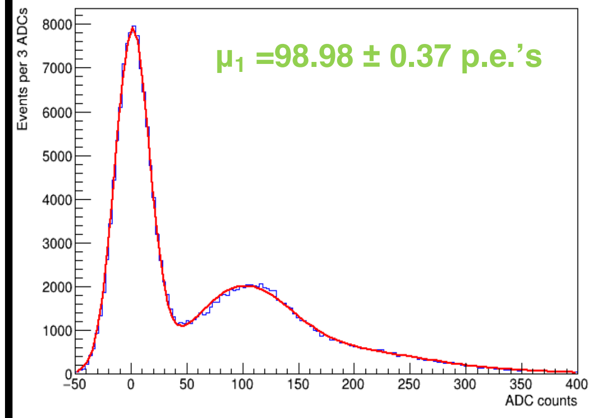

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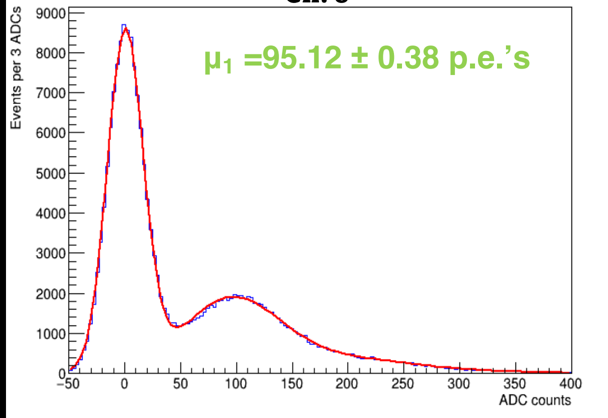

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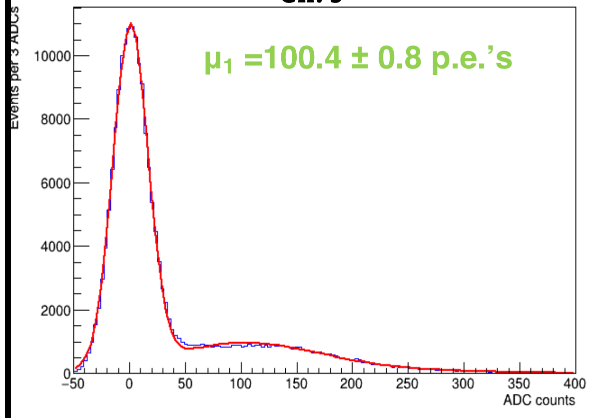

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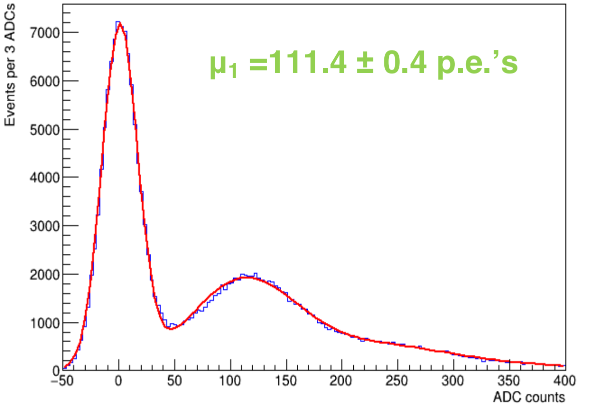
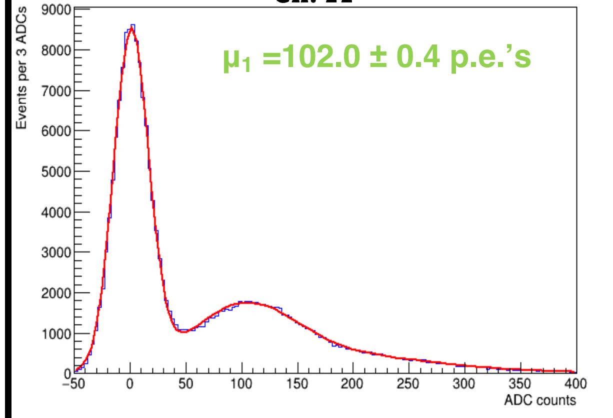
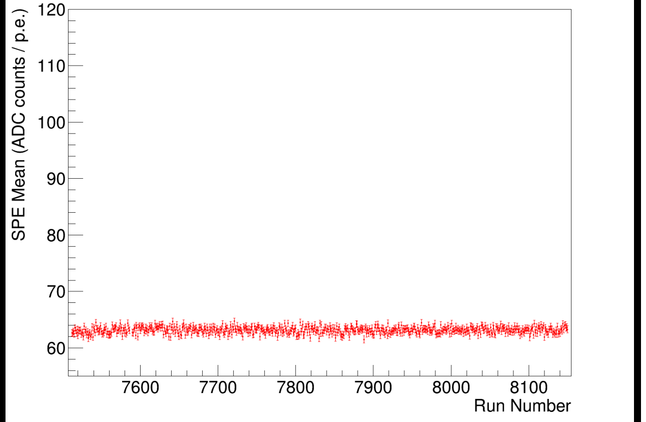


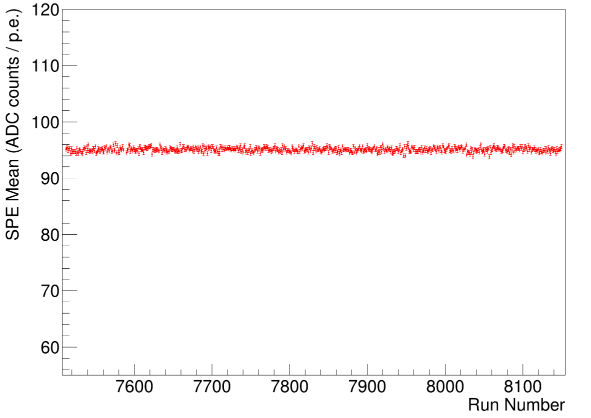
Ch. 11



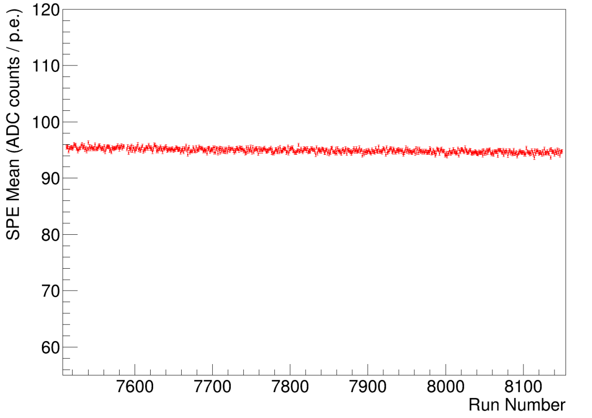
Ch. 0



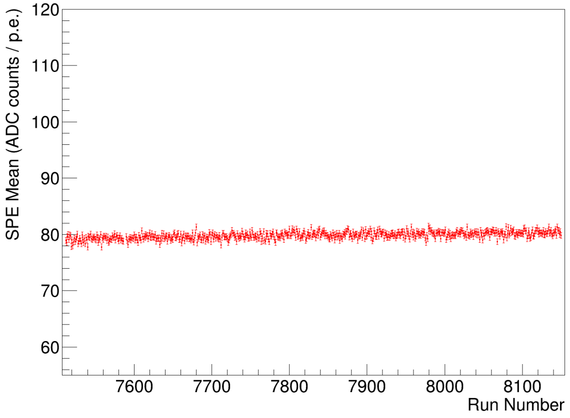
Ch. 1



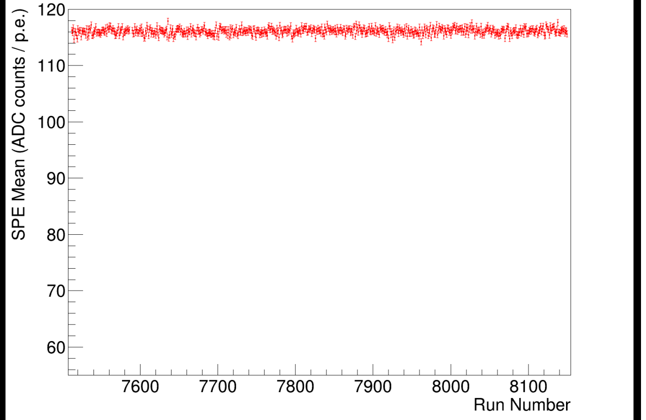
Ch. 2



Ch. 3



Ch. 4



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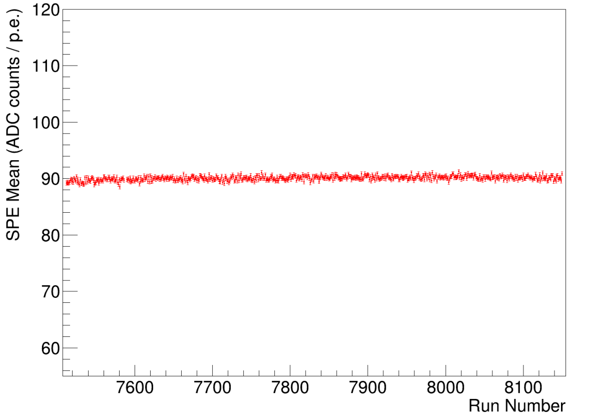
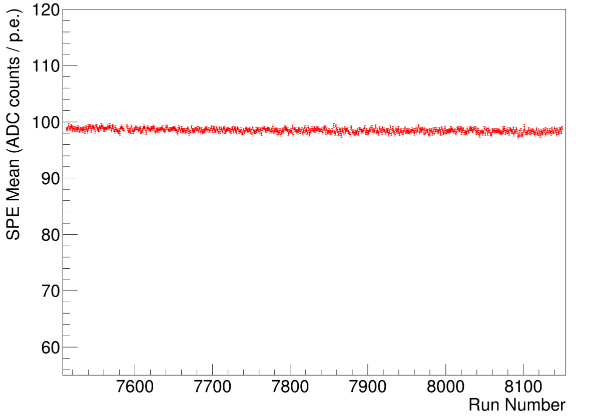
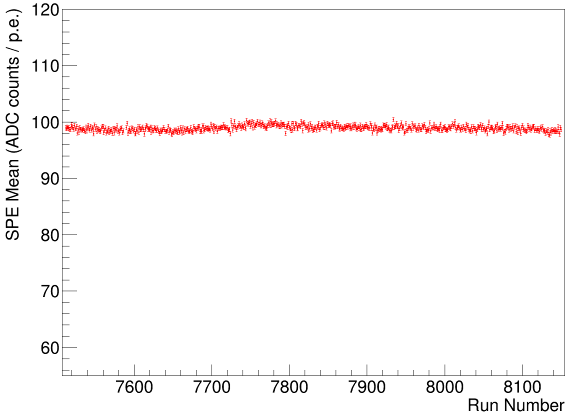


Ch. 6



Ch. 7



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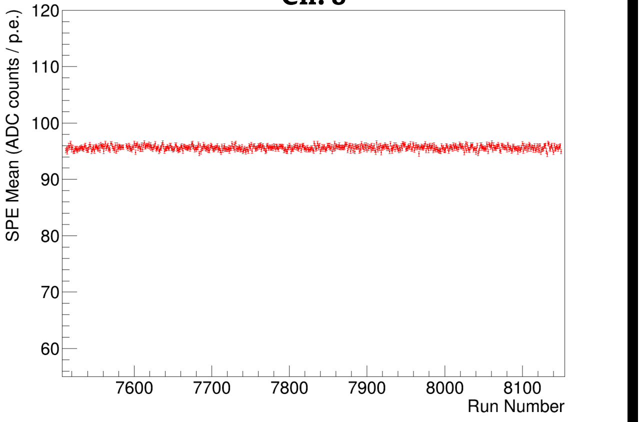
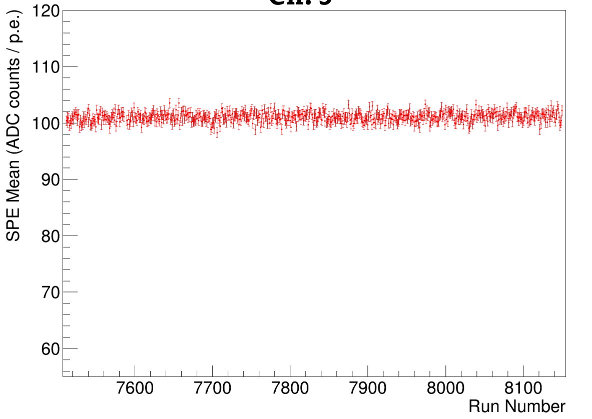
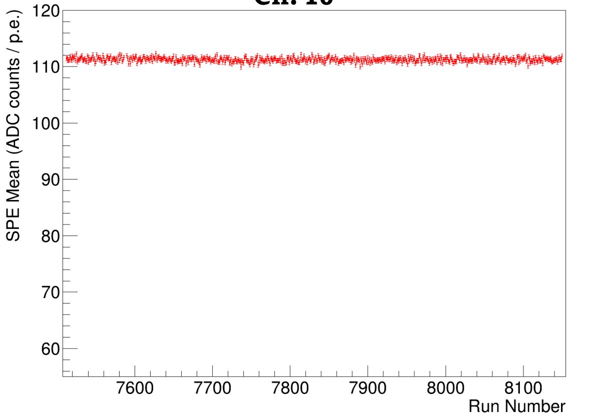


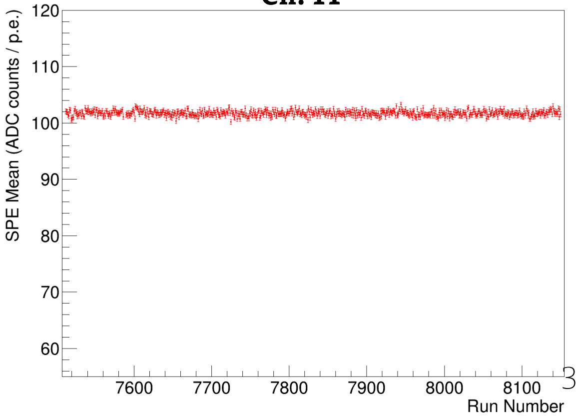
Ch. 9



Ch. 10

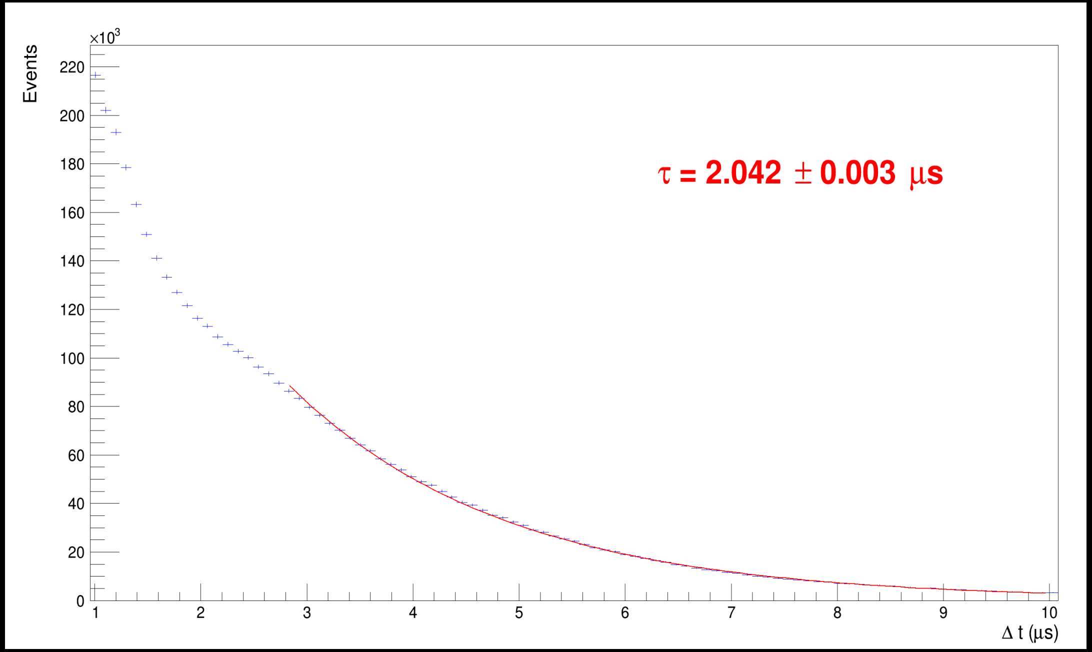


Ch. 11



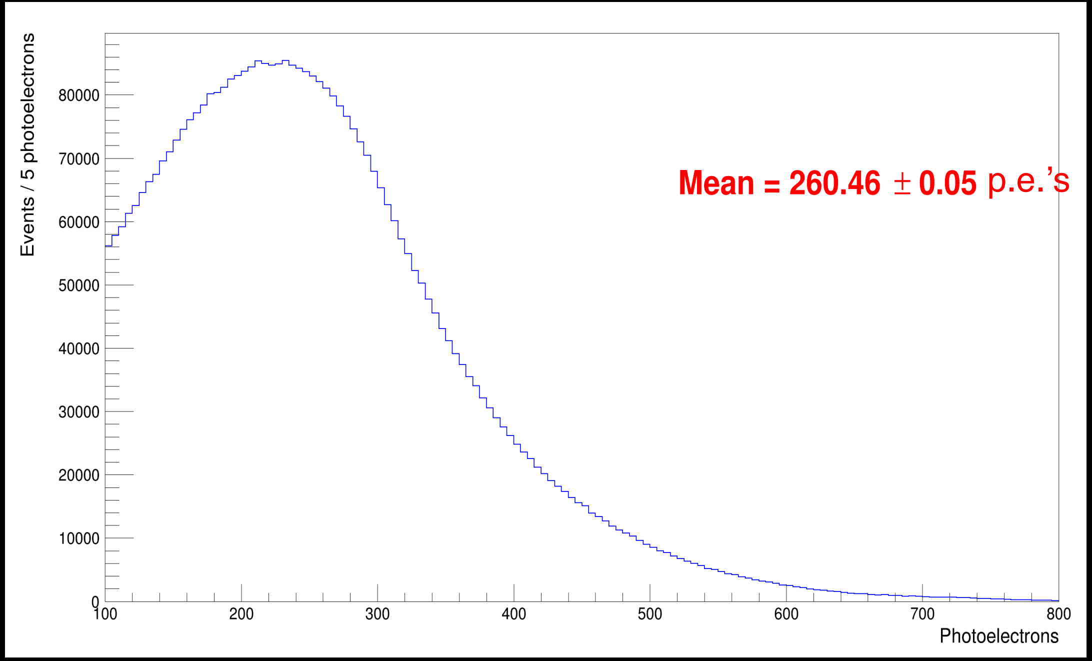
· 2) Search for Michel Electrons ·

Δt ≤ 10 μs distribution



- **Δt = time to previous event (muon).**
- **Distribution is consistent with decay/capture rate of muons.**

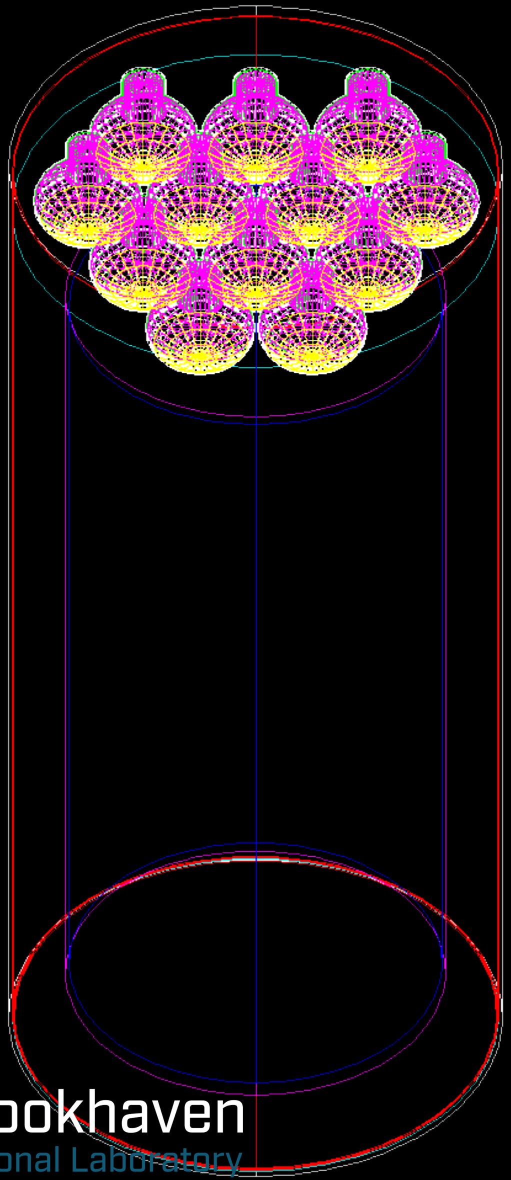
Michel Electron Spectrum as a function of p.e.'s



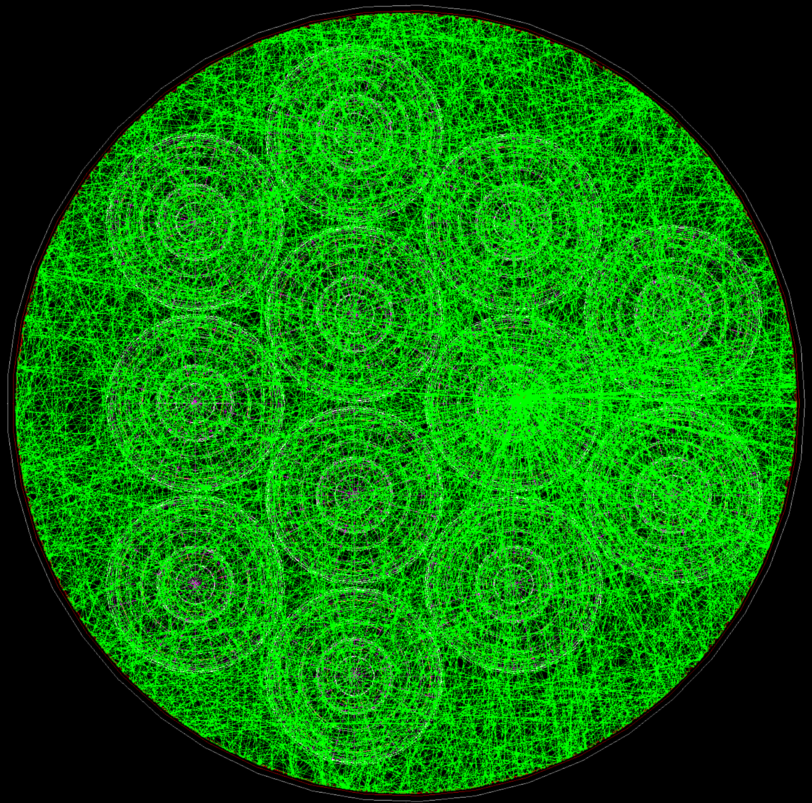
Take all internal trigger events within a 10 μs time window, all our afterpulsing filters on & apply our SPE Calibration Factor.

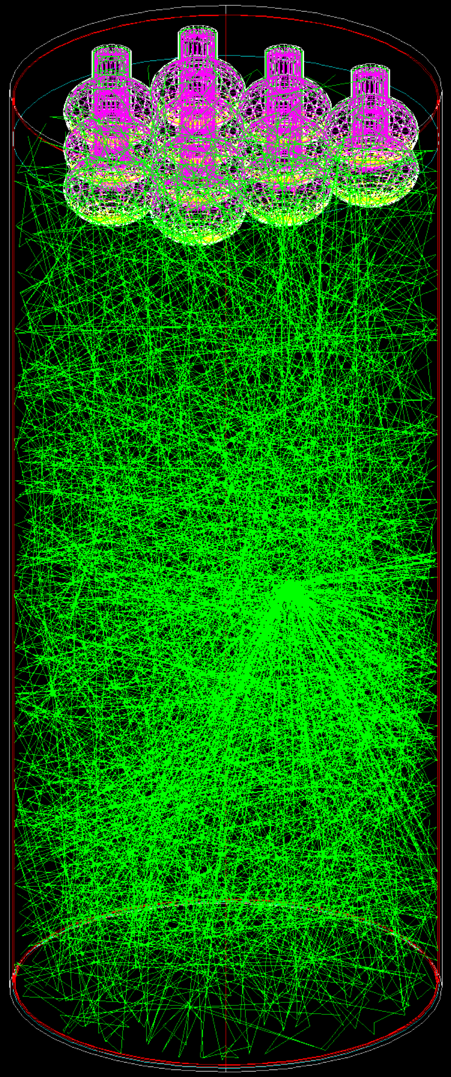
Karla Téllez Girón Flores

· 3) Data to Monte Carlo comparison ·



Back to G4 Simulations !



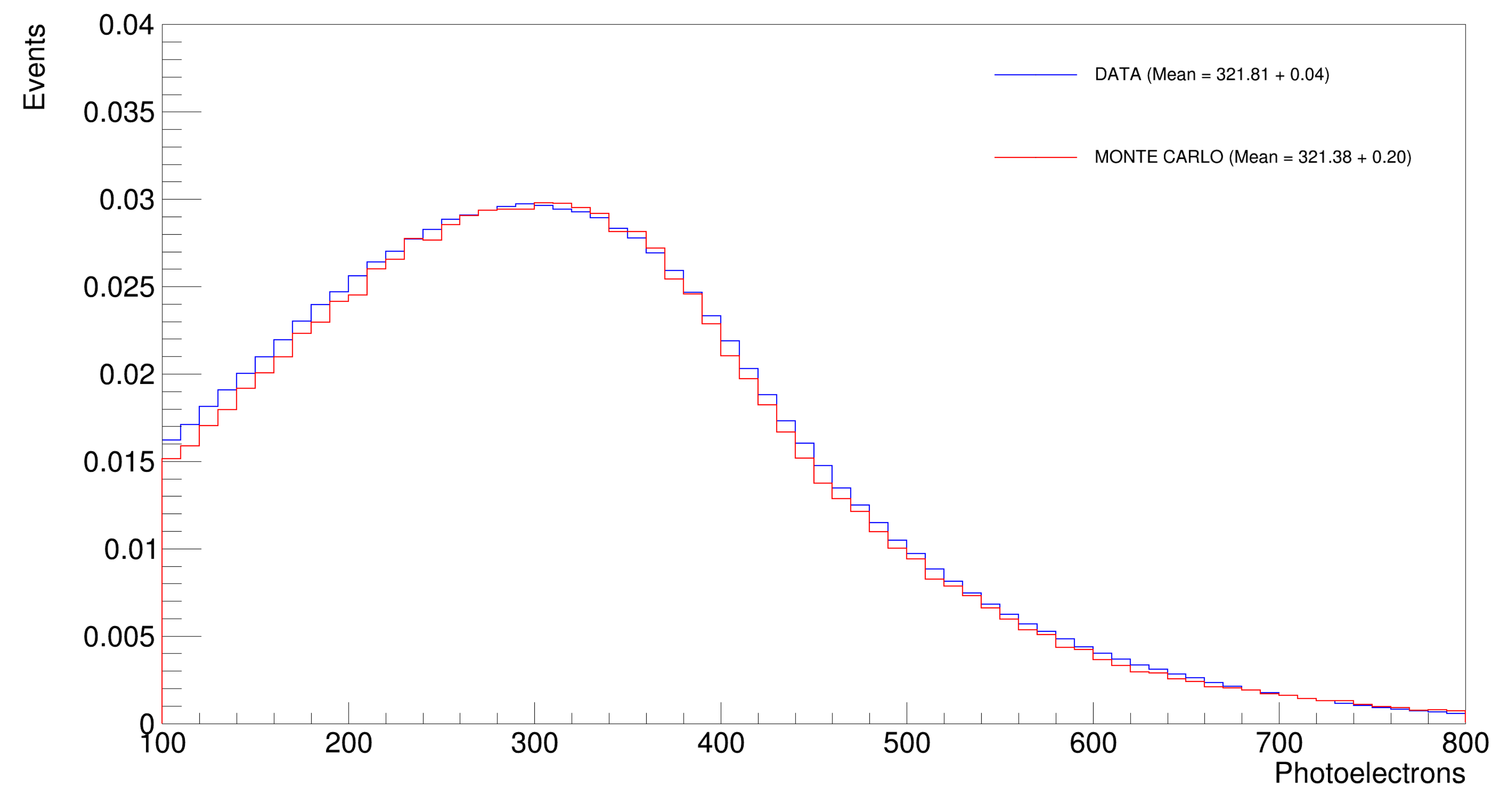


Generate Michel Electrons throughout our detector

· 3) Data to Monte Carlo comparison ·

Tweaking parameters to have simulations match our observations.

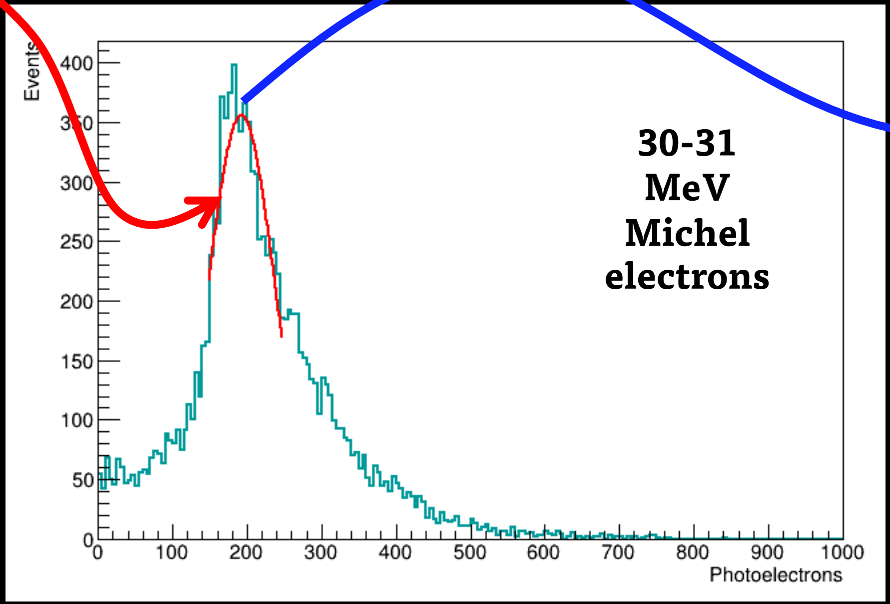
- ✓ **PMTs' Quantum Efficiency**
- ✓ **Tyvek Reflectivity**



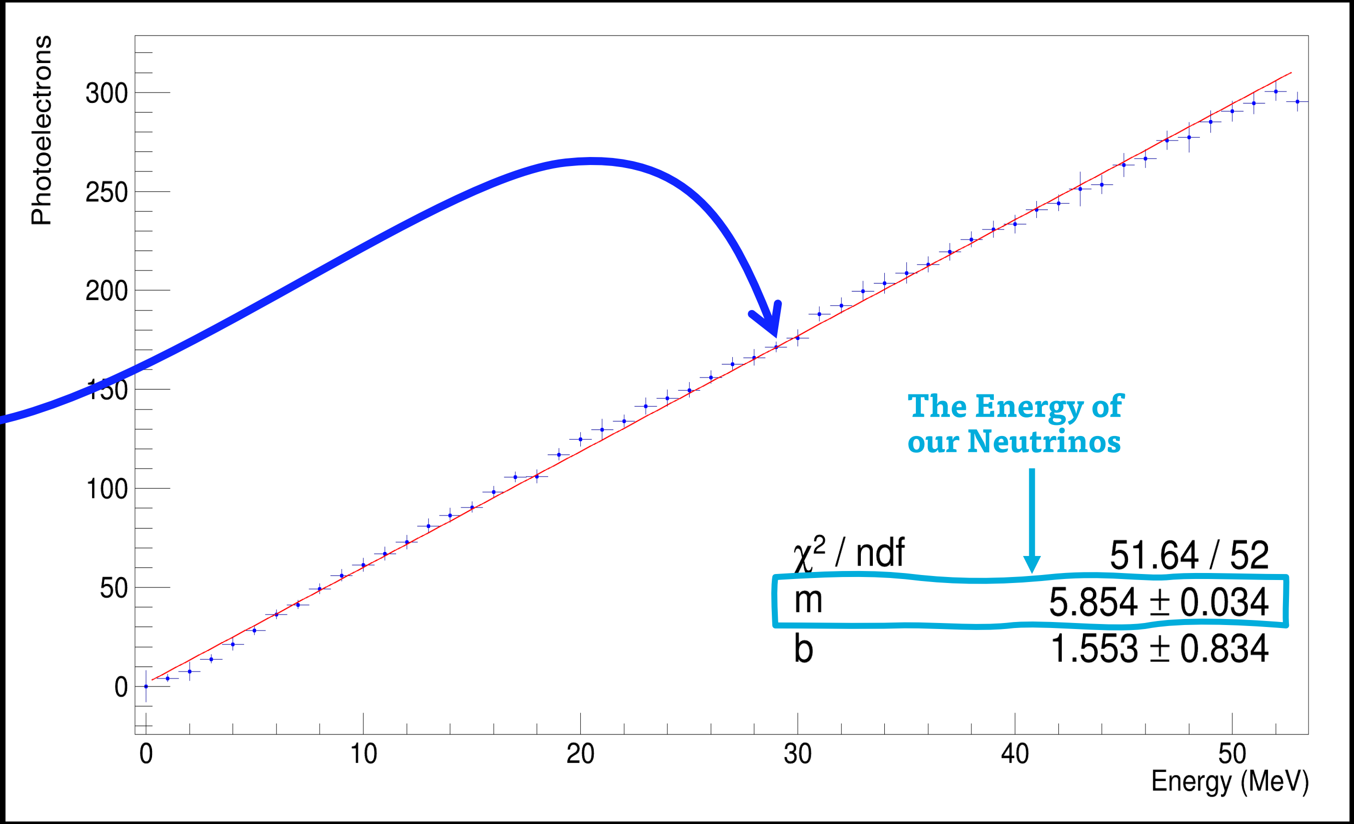
After matching, we generate lots of events in our detector…

· NEXT: Finding an Energy Scale ·

- Get Light Yield plots for all MC True Energies.
- Fit them with Gaussians.
- Plot the means of these fits.



30-31 MeV Michel electrons



The Energy of our Neutrinos

· Current Status and Future ·

- **Getting ready to see neutrinos!**
- **Fully-assembled detector has been up and running since July 2023.**
- **SNS beam went off on August 14, will be back in Summer of 2024.**

2nd Module coming in 2024!

THANK YOU!

· Backup Slides ·

· CEνNS Cross Section ·

Nuclear Form Factor

Klein-Nystrand:

$$\left|F(q)^2\right| = \left(\frac{3(\sin(qR) - qR\cos(qR))}{(qR)^3(1+a_{kn}^2 q^2)}\right)^2$$

$R = 1.2\,(N+Z)^{1/3}$

$a_{kn} = 0.7$

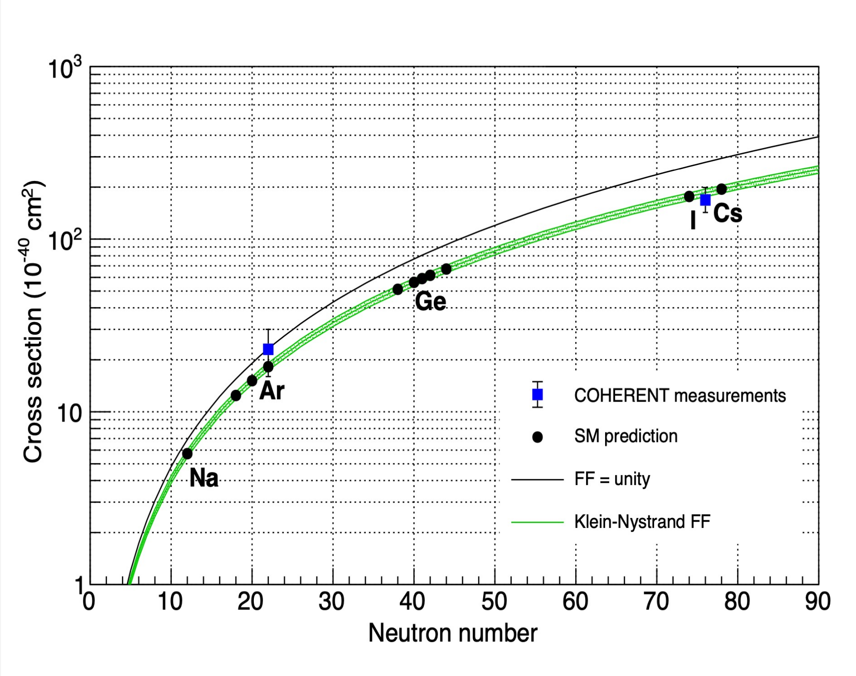
If $T \ll E_\nu$,

$$\left(\frac{d\sigma}{dT}\right) = \frac{G_F^2}{2\pi}\frac{\boxed{Q_W^2}}{4}\boxed{F^2(q)}M\left[2 - \frac{MT}{E_\nu^2}\right]$$

Weak Mixing Angle

$$Q_W = \boxed{N} - \left(1 - 4\sin^2\theta_W\right)Z$$

Neutron Number Dependence



Why CEνNS ?

A new portal to (non)standard particle and nuclear physics

… small but multicolor !

Signals of today are the backgrounds of tomorrow!

Neutrino EM Properties

Non-Standard Interactions

Crucial for DUNE

Weak Nuclear Form Factors

Direct Detection Dark Matter Experiments

Accelerator-produced Dark Matter

Supernova Detection Experiments

CEνNS with Reactor neutrinos?

CEνNS

new ν properties

dark matter

supernovae

new interactions

solar neutrinos

nuclear form factors

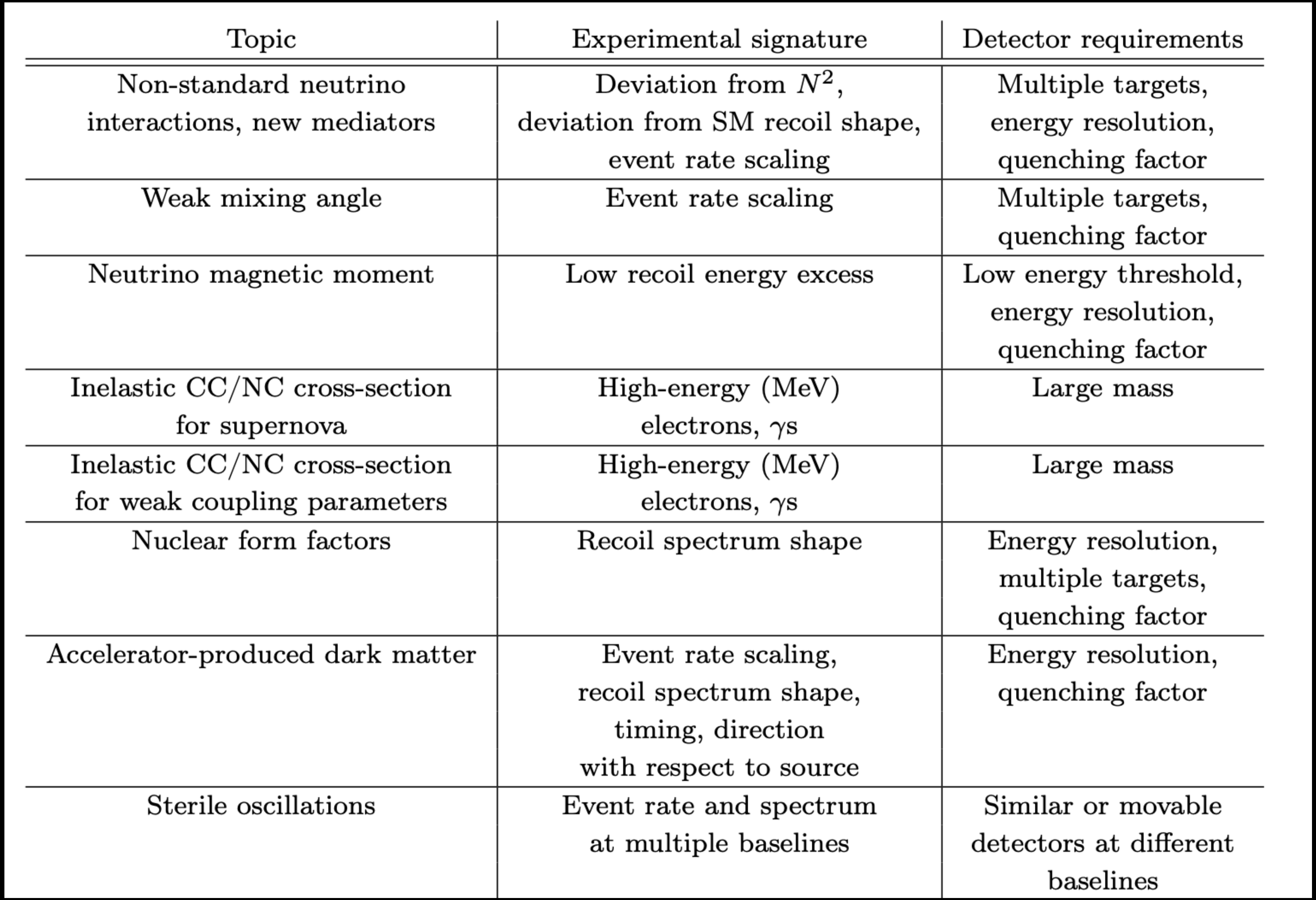
sterile neutrinos

EW precision tests

new detectors

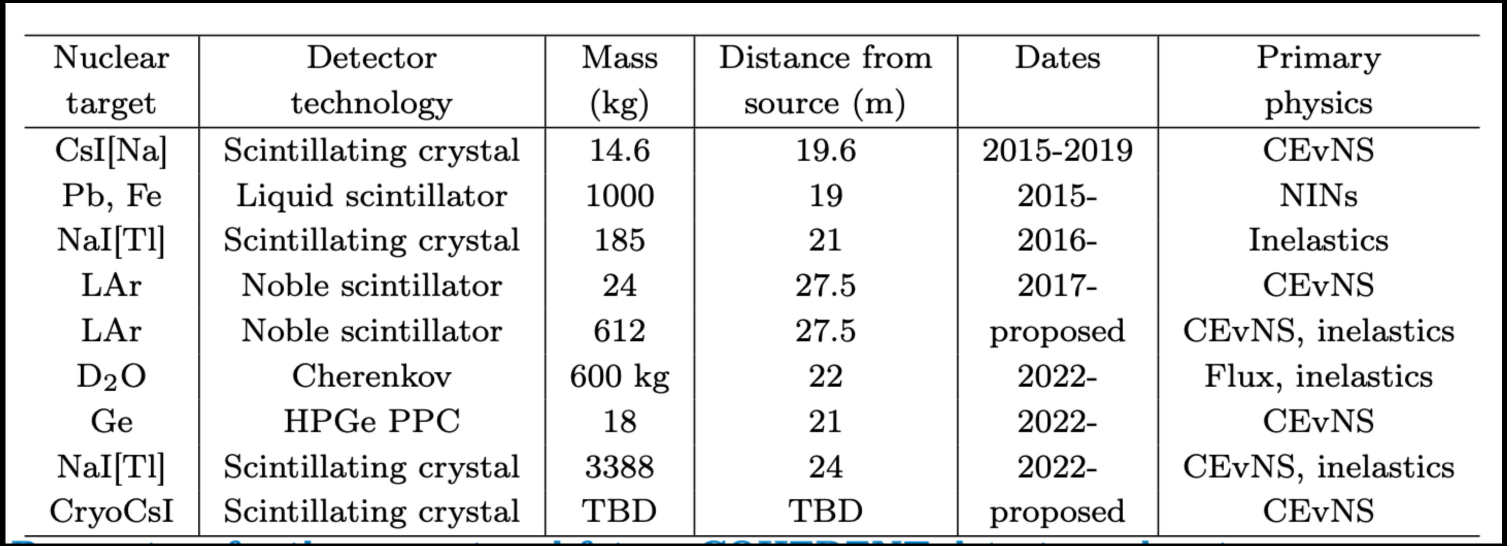
Slide from opening plenary talk by Eligio Lisi at NuInt 2018 https://indico.cern.ch/event/703880/

COHERENT Physics Topics



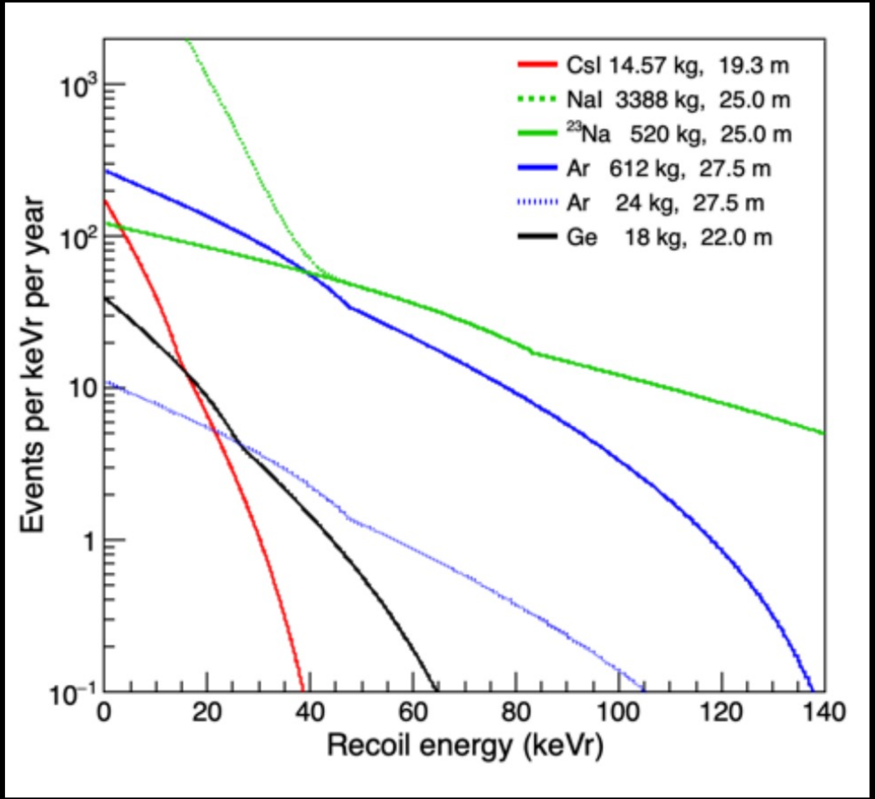
Topic	Experimental signature	Detector requirements
Non-standard neutrino interactions, new mediators	Deviation from N^2, deviation from SM recoil shape, event rate scaling	Multiple targets, energy resolution, quenching factor
Weak mixing angle	Event rate scaling	Multiple targets, quenching factor
Neutrino magnetic moment	Low recoil energy excess	Low energy threshold, energy resolution, quenching factor
Inelastic CC/NC cross-section for supernova	High-energy (MeV) electrons, γs	Large mass
Inelastic CC/NC cross-section for weak coupling parameters	High-energy (MeV) electrons, γs	Large mass
Nuclear form factors	Recoil spectrum shape	Energy resolution, multiple targets, quenching factor
Accelerator-produced dark matter	Event rate scaling, recoil spectrum shape, timing, direction with respect to source	Energy resolution, quenching factor
Sterile oscillations	Event rate and spectrum at multiple baselines	Similar or movable detectors at different baselines

COHERENT Past and Future

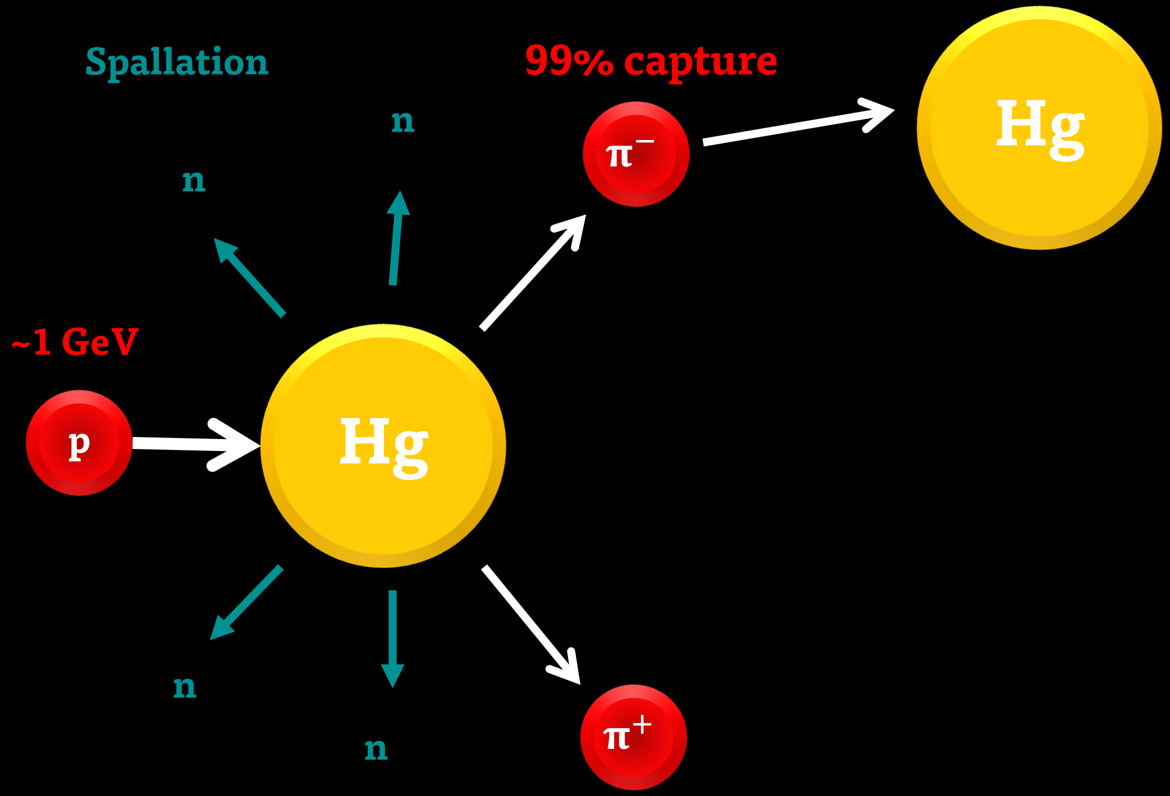


Nuclear target	Detector technology	Mass (kg)	Distance from source (m)	Dates	Primary physics
CsI[Na]	Scintillating crystal	14.6	19.6	2015-2019	CEvNS
Pb, Fe	Liquid scintillator	1000	19	2015-	NINs
NaI[Tl]	Scintillating crystal	185	21	2016-	Inelastics
LAr	Noble scintillator	24	27.5	2017-	CEvNS
LAr	Noble scintillator	612	27.5	proposed	CEvNS, inelastics
D_2O	Cherenkov	600 kg	22	2022-	Flux, inelastics
Ge	HPGe PPC	18	21	2022-	CEvNS
NaI[Tl]	Scintillating crystal	3388	24	2022-	CEvNS, inelastics
CryoCsI	Scintillating crystal	TBD	TBD	proposed	CEvNS

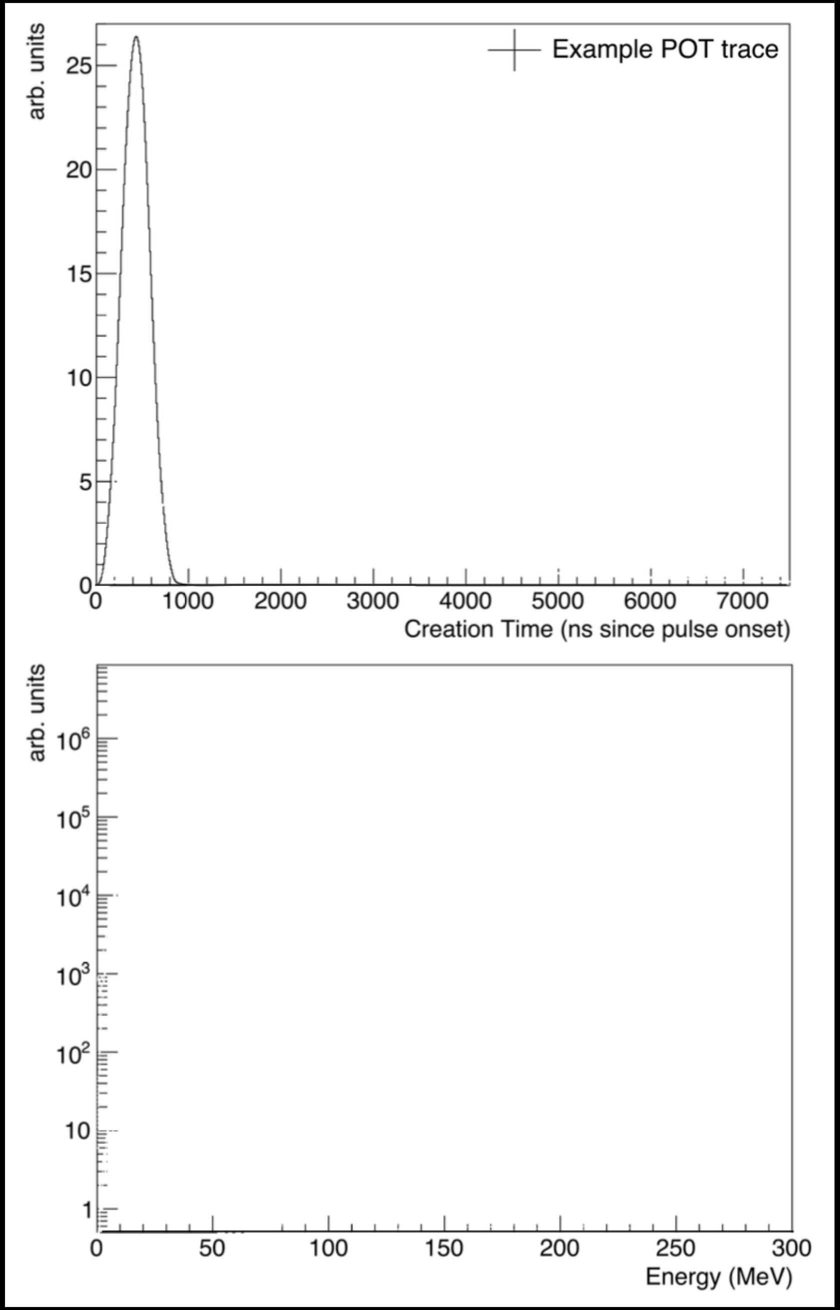
Recoil Spectra



· SNS as a Neutrino Source ·

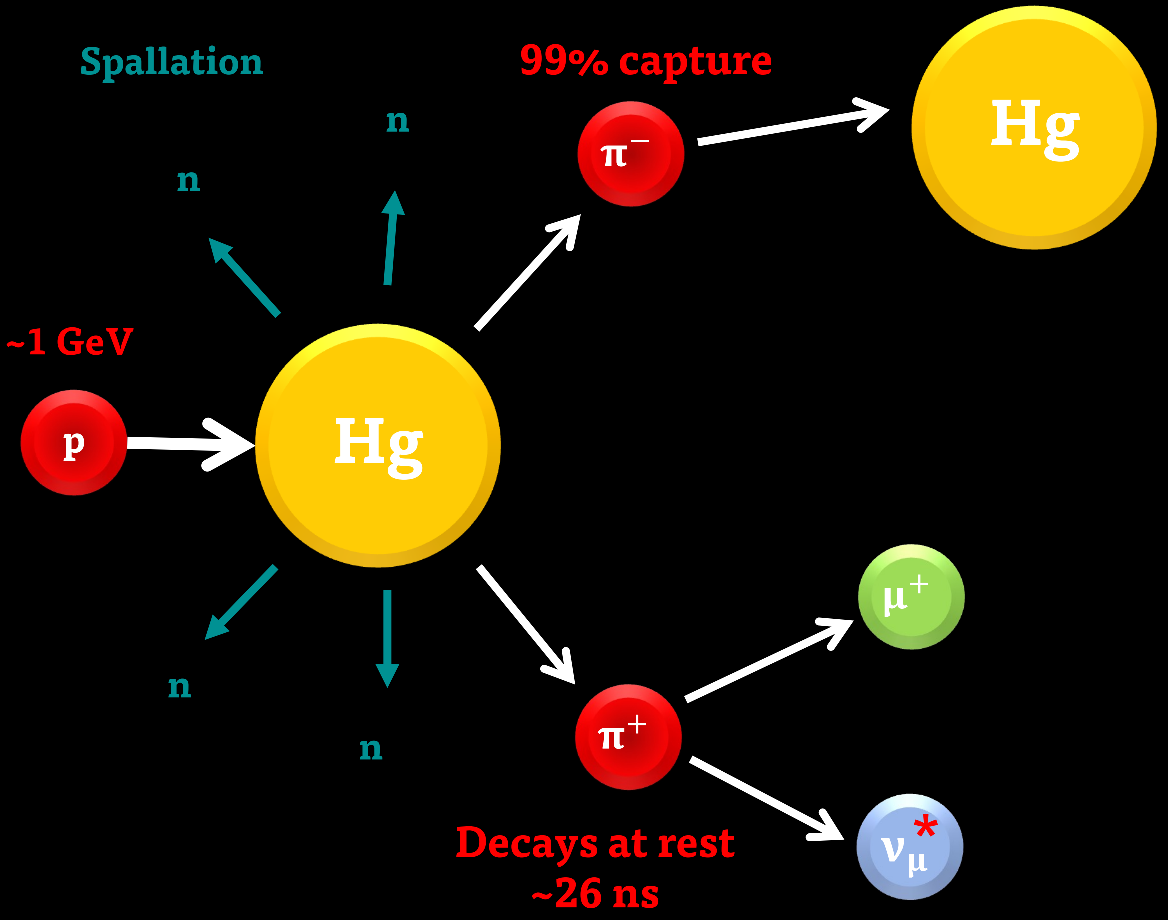


Energy and Time Distributions

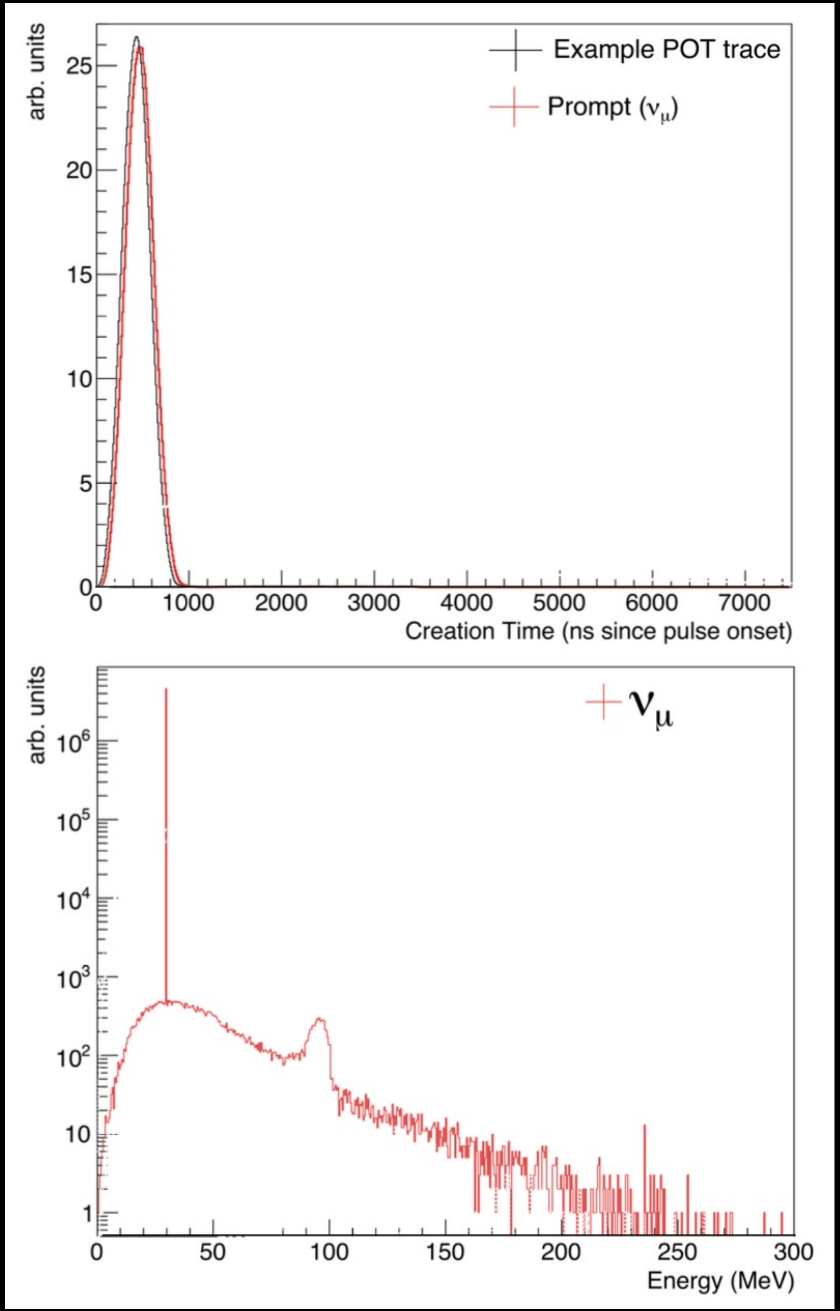


D. Akimov et. al. (COHERENT Collaboration) Phys. Rev. D 106, 032003

· SNS as a Neutrino Source ·

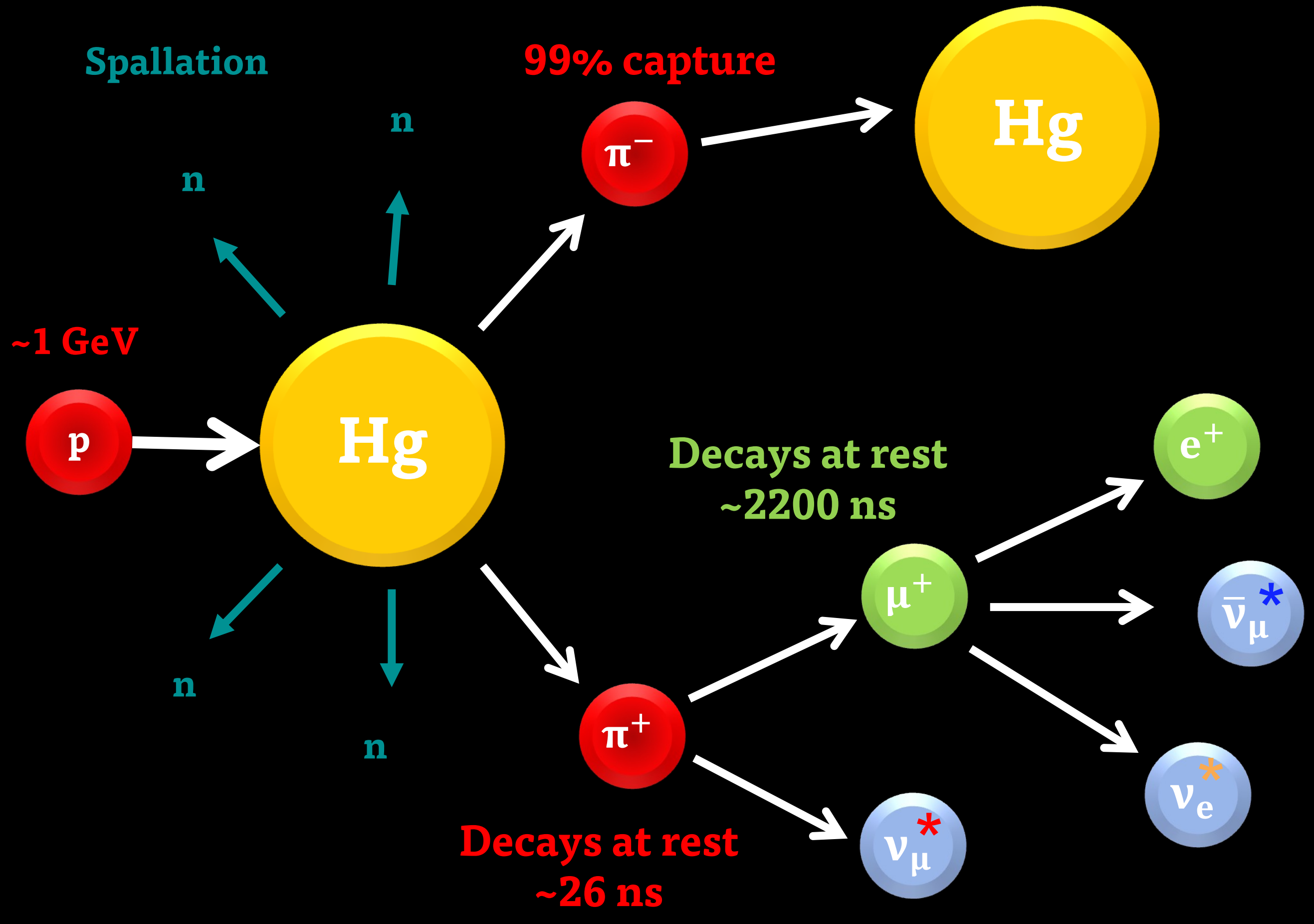


Energy and Time Distributions



D. Akimov et. al. (COHERENT Collaboration) Phys. Rev. D 106, 032003

· SNS as a Neutrino Source ·



Spallation

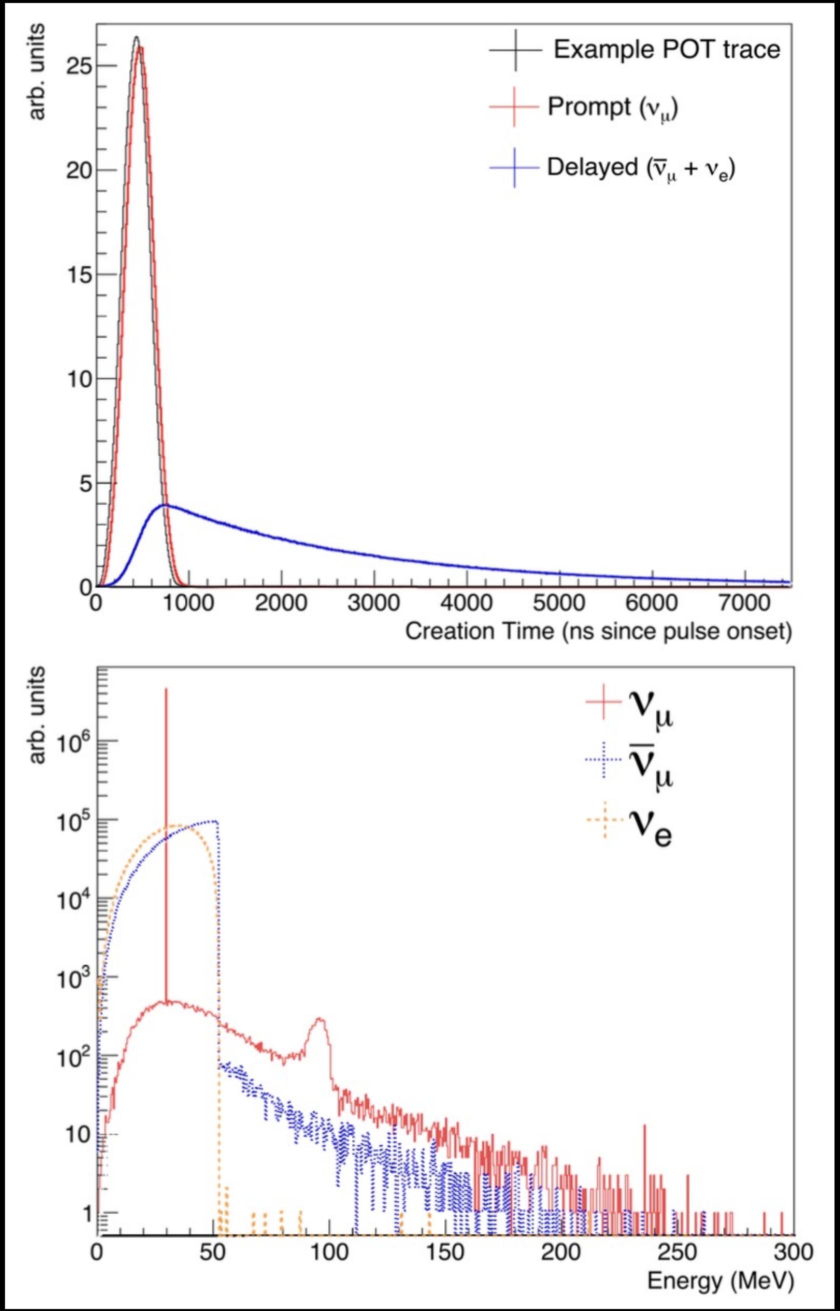
99% capture

~1 GeV

Decays at rest
~2200 ns

Decays at rest
~26 ns

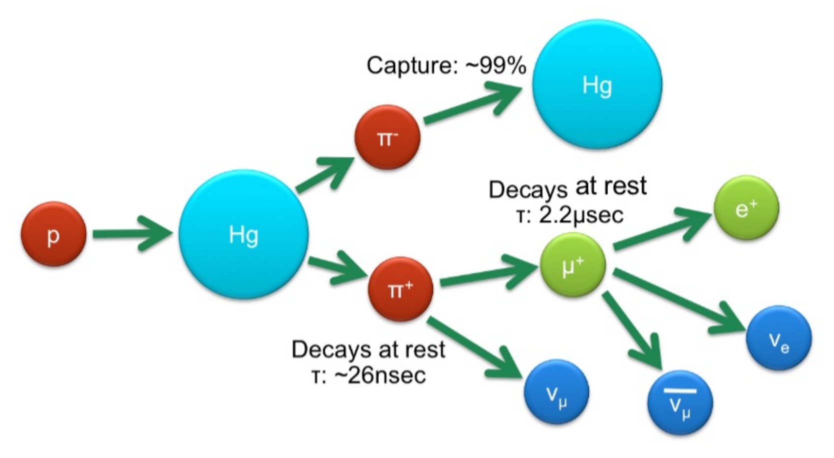
Energy and Time Distributions



D. Akimov et. al. (COHERENT Collaboration) Phys. Rev. D 106, 032003

Understanding the SNS Neutrino Beam

1. A pulsed 1.4-MW beam of approximately 1-GeV protons strikes a ~50 cm-long Hg Target.
2. These protons interact multiple times within the thick target, losing energy and spalling nuclei, and create neutrons and byproduct charged pions.
3. The majority of π^+ come to rest (less than 1% decay in flight) within the dense Hg target.
4. These stopped decays give rise to neutrinos with energies of the order of tens of MeV:



$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

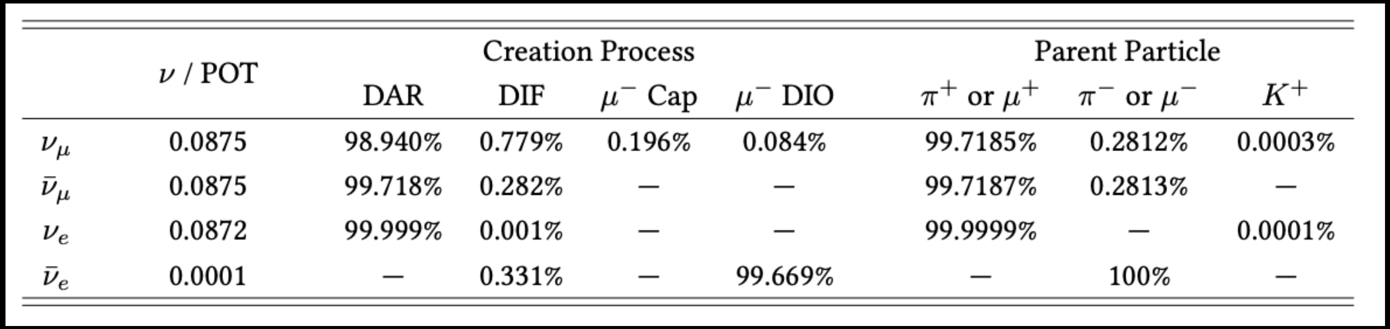
2-body decay:
monochromatic 29.9 MeV
(PROMPT)

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

3-body decay: energies
between 0-$m_\mu/2$
(DELAYED 2.2 μs)

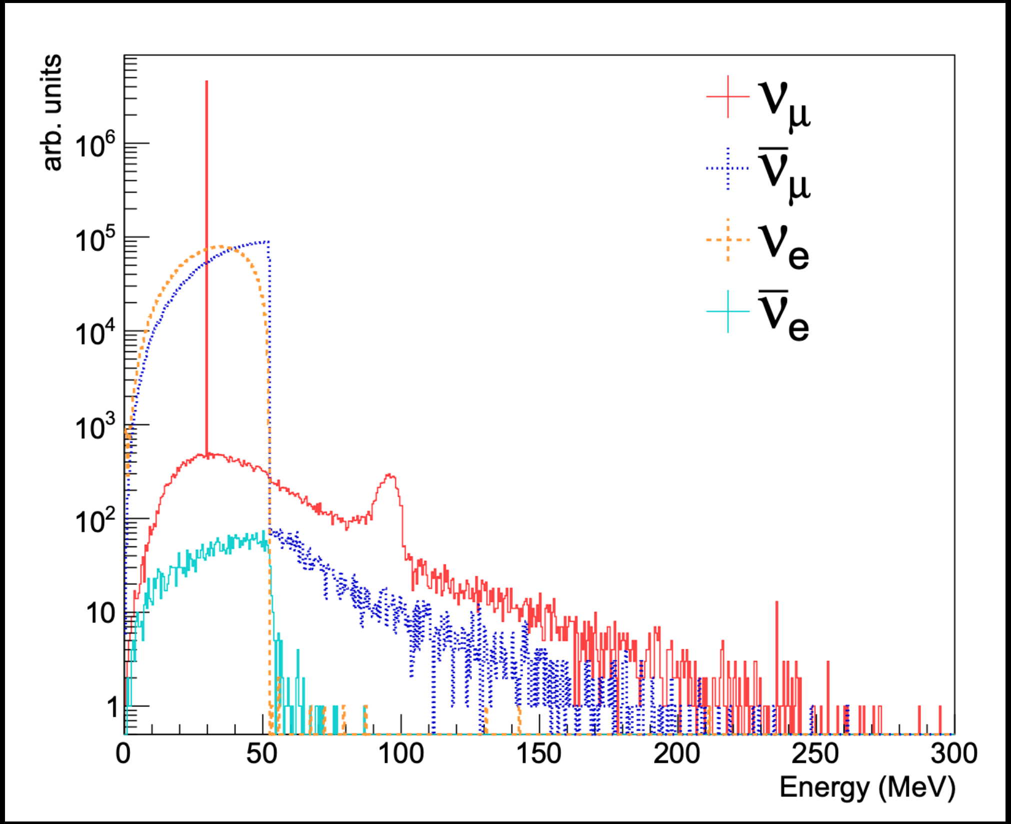
5. SNS interactions also produce copious quantities of π^-, but the vast majority (~ 99%) of these capture on nuclei in the target before decaying and rarely produce neutrinos.

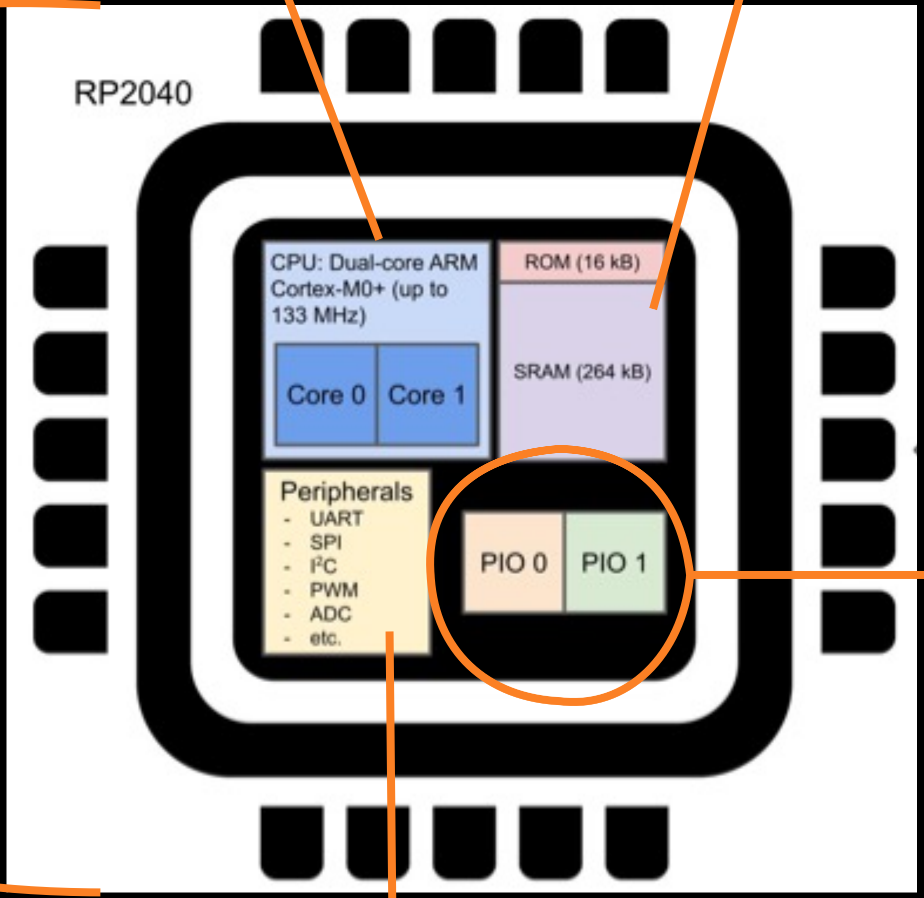
Understanding the SNS Neutrino Beam



	ν / POT	Creation Process				Parent Particle		
		DAR	DIF	μ^- Cap	μ^- DIO	π^+ or μ^+	π^- or μ^-	K^+
ν_μ	0.0875	98.940%	0.779%	0.196%	0.084%	99.7185%	0.2812%	0.0003%
$\bar{\nu}_\mu$	0.0875	99.718%	0.282%	—	—	99.7187%	0.2813%	—
ν_e	0.0872	99.999%	0.001%	—	—	99.9999%	—	0.0001%
$\bar{\nu}_e$	0.0001	—	0.331%	—	99.669%	—	100%	—

A breakdown of the processes and parent particles which create neutrinos for 1 GeV protons at the SNS with an aluminum PBW. Taken from R. Rapp's Doctoral Dissertation.





Dual CPU running at default 125 MHz

264 kB RAM

Built-in Peripherals

Two PIO instances to create tiny programs to emulate other peripherals

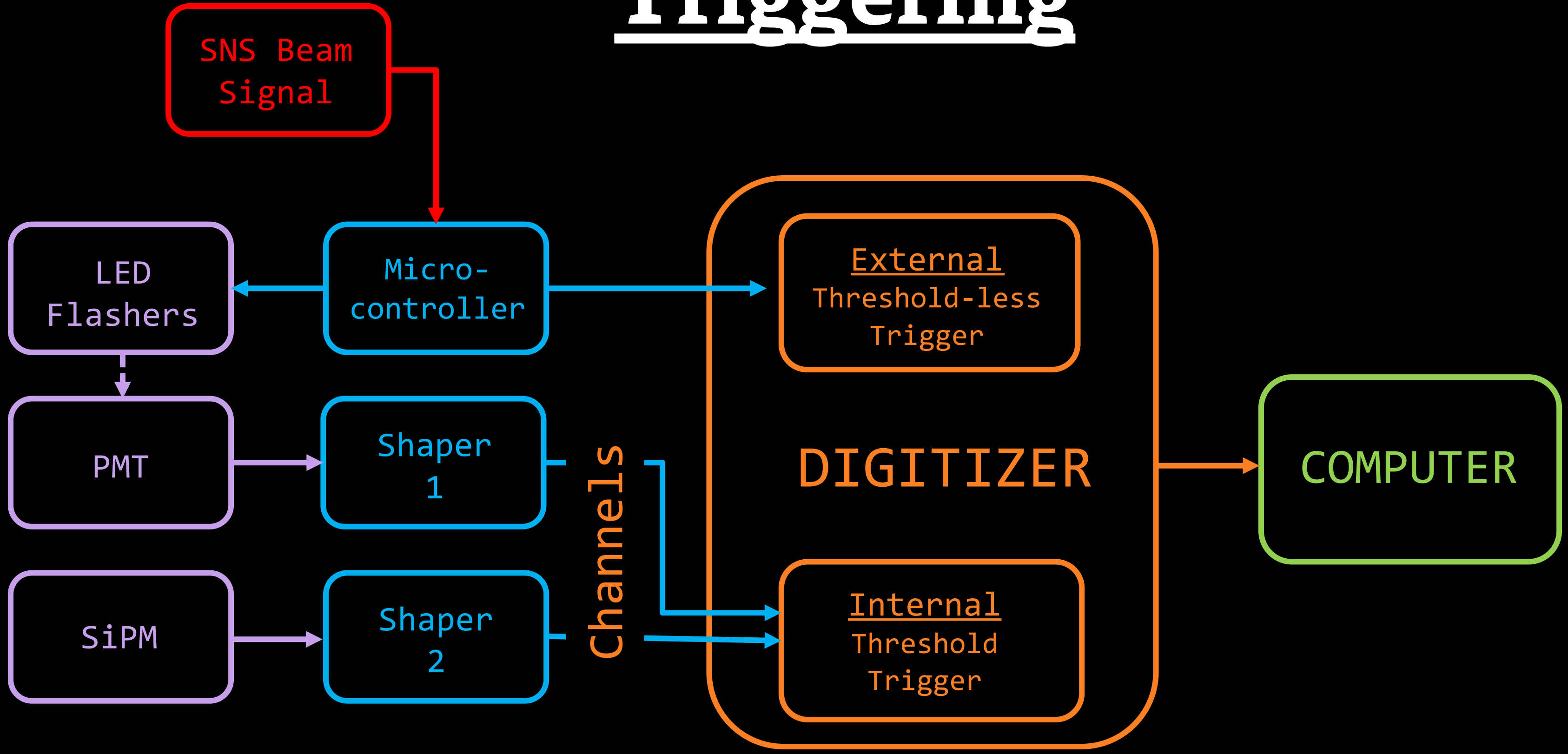
Each of these has 4 state machines (SM).

Each SM:

- **can be used to control a set of consecutive pins.**
- **has a Program Counter, to execute code independently from other SM.**
- **Clock Divider to run an individual SM between 2 kHz and 133 MHz**
- **Two working registers, X & Y to store data.**
- **Control Logic to run the instructions.**

▪ D_2O: COHERENT's Neutrino Flux Normalization Detector ▪

Triggering



SNS Beam Signal

LED Flashers

Micro-controller

PMT

Shaper 1

SiPM

Shaper 2

Channels

External
Threshold-less
Trigger

DIGITIZER

Internal
Threshold
Trigger

COMPUTER

Separate Modules

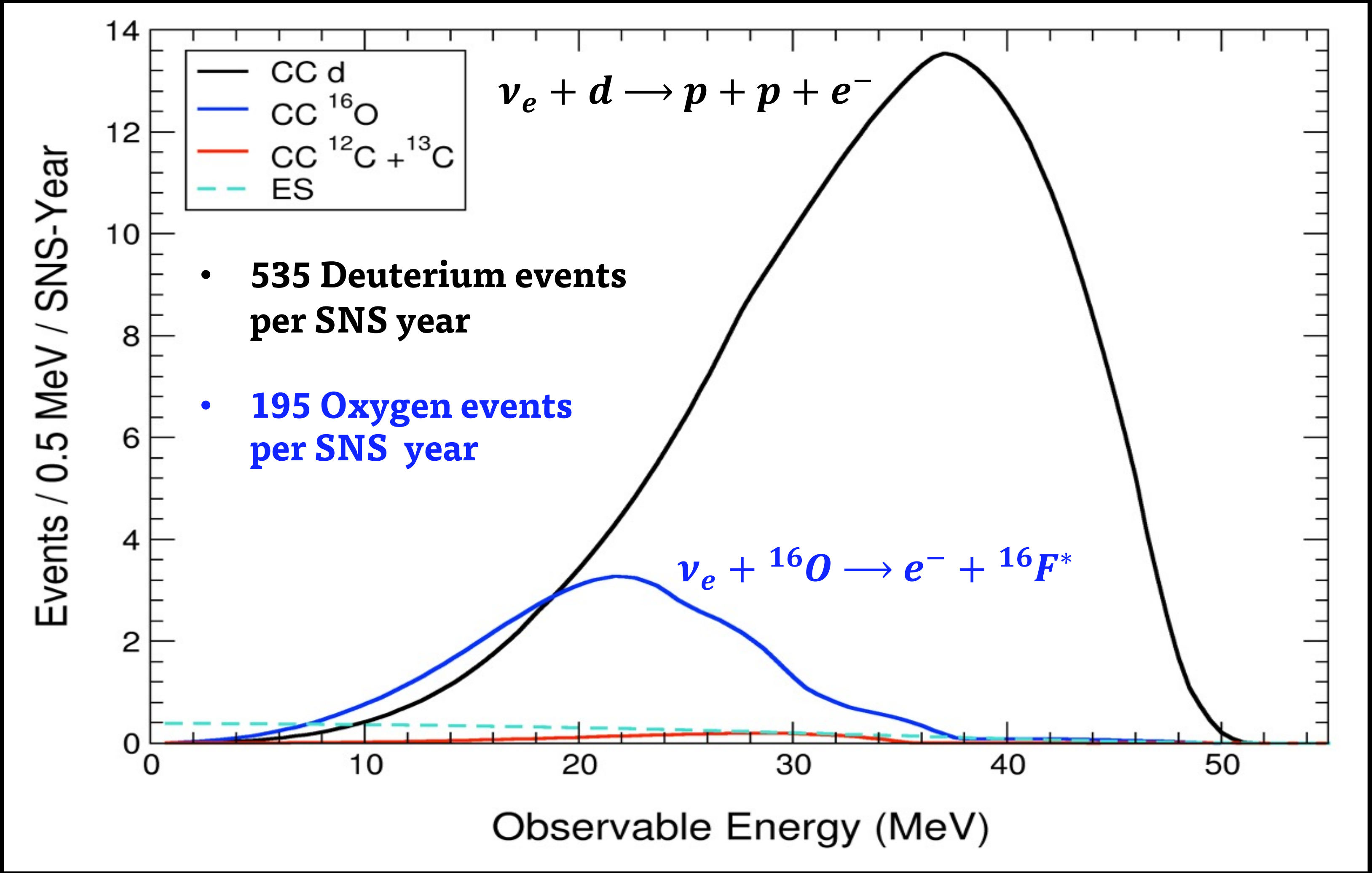
1. A D_2O detector with Oxygen + Deuterium interactions.
2. An H_2O detector with Oxygen interactions only.

Same Michel Electron Spectra and Rates in both.

- We can get a pure-Deuterium spectrum by doing a subtraction of the H_2O detector!

✓ We cut all backgrounds.
✓ No energy cuts! We use all available Deuterium spectrum for our flux error measurement.
✓ No MC systematic errors.

D_2O: COHERENT's NEUTRINO FLUX-NORMALIZATION DETECTOR



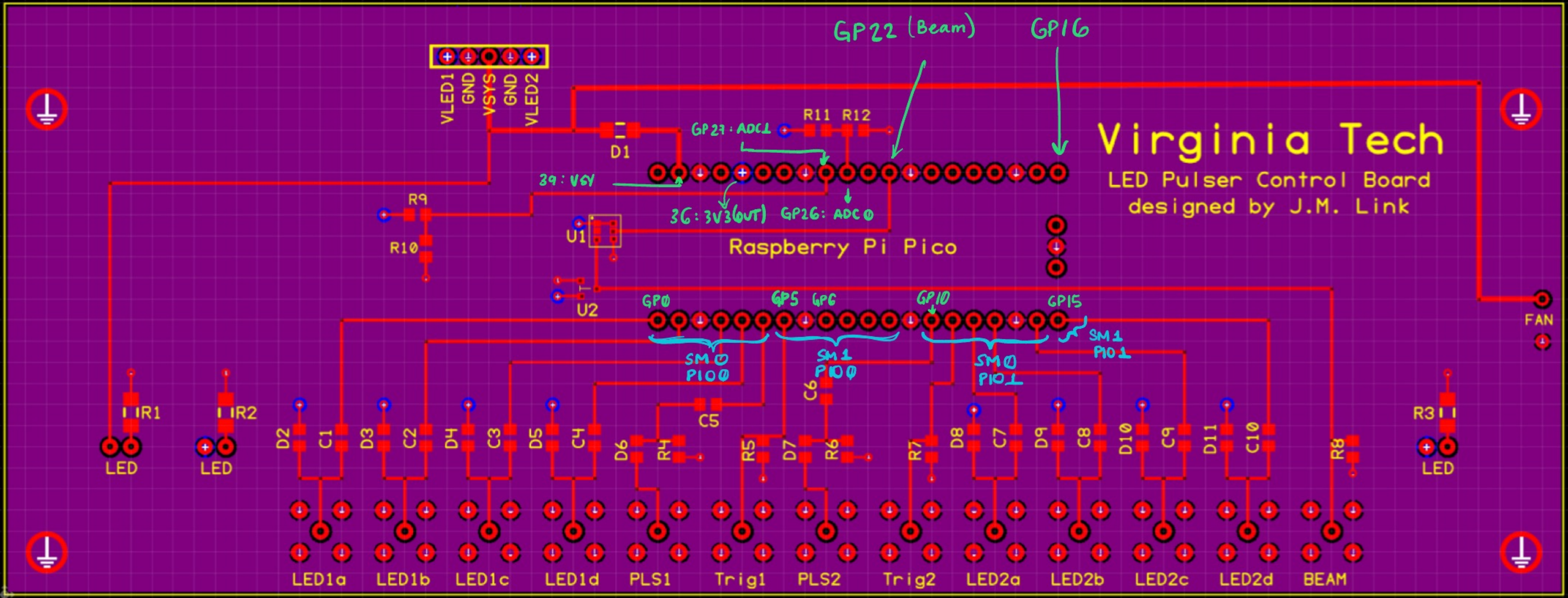
$\nu_e + d \longrightarrow p + p + e^-$

- **535 Deuterium events per SNS year**
- **195 Oxygen events per SNS year**

$\nu_e + {}^{16}O \longrightarrow e^- + {}^{16}F^*$

Expected Count Rates from SNOwGLoBES

Control Board:



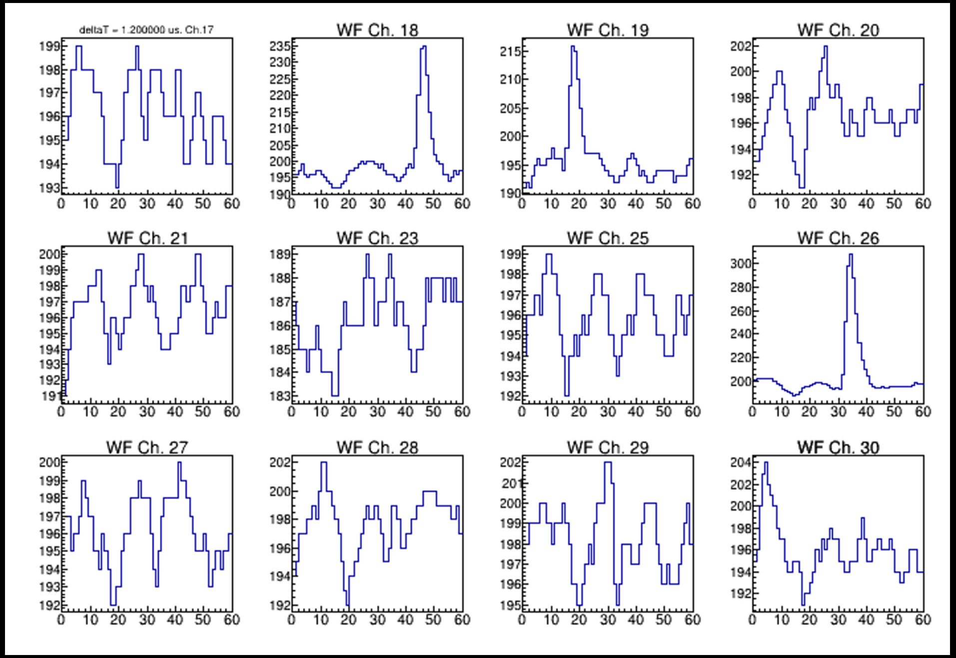
· Data Analysis ·

First: Afterpulsing Removal

Afterpulsing is due to ionization happening inside the PMTs. We can't get rid of it and constitutes ~86% of our data.

Looked at waveforms, searching for:

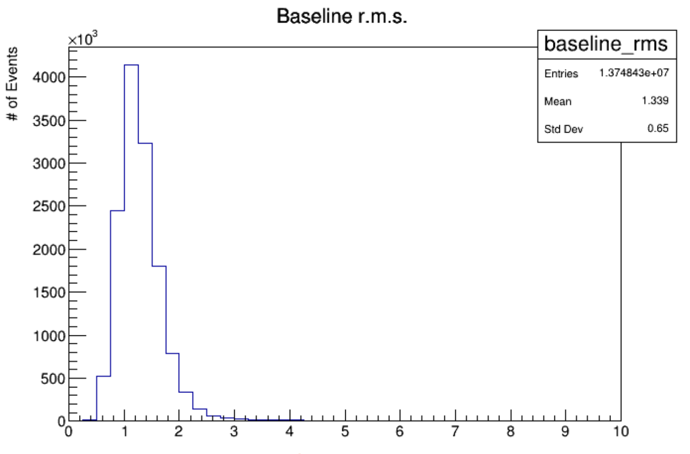
- Baseline fluctuations
- Saturation
- Cross Talk
- Multiple peaks

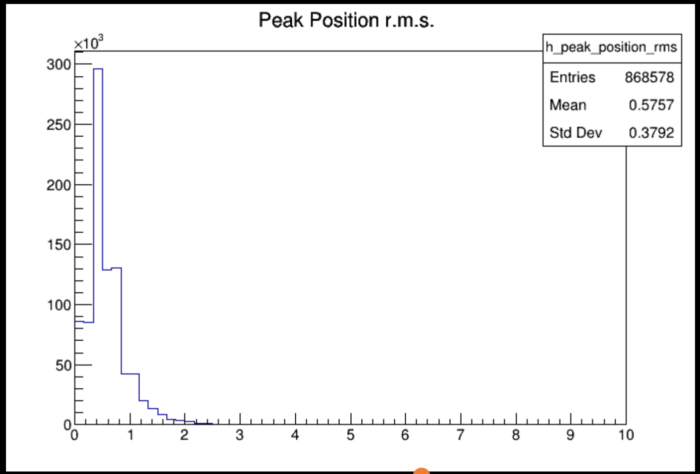


CUTS:

- Pulse Height > 2 p.e.
  - Pulse Height > 3*(Baseline r.m.s.)
  - Pulse Area / Pulse Height > 1
- # Hit PMTs > 3, so
- Peak Position r.m.s. < 2.5

Selecting Good Events
Afterpulsing Filters





1. Pulse Height > 2 p.e.?

NO
Check if lower-amplitude conditions are satisfied:

YES
Calculate pp_mean and r.m.s when PMT Hit > 3
[Calculate sum_ADC.]

2. Pulse Height > 3*(Baseline r.m.s.)
+
3. Pulse Area / Pulse Height > 1?

NO
Thanks for participating!

YES
If it's consistent with pp_mean, [count it in sum_ADC]

4. Then, pp_rms <2.5 rejects afterpulsing!

VIRGINIA TECH

The Center for Neutrino Physics

▪ Something to know before we proceed to fit Gaussians ▪

- At the beginning, our analysis was based on a stochastic model where $\sigma_2^2 = 2\sigma_1^2$ This seemed to overpredict the number of 2-p.e. (and 3 p.e.) events
- We can model these widths by including non-stochastic component, σ_{nS} and adding it in quadrature to the statistical component, $\sigma_{N,stat}$.
- As σ_0 is associated to baseline noise, it is non-stochastic. However, it contributes to the 2 p.e. and 1 p.e. widths as well, so we take it to be our non-stochastic component.

non-Stochastic

Stochastic

$$\sigma_1^2 = \sigma_{1,stat}^2 + \sigma_{nS}^2 \rightarrow \sigma_{1,stat}^2 = \sigma_1^2 - \sigma_{nS}^2$$

$$\sigma_2^2 = \sigma_{2,stat}^2 + \sigma_{nS}^2$$

recall

$\sigma_{nS} = \sigma_0$

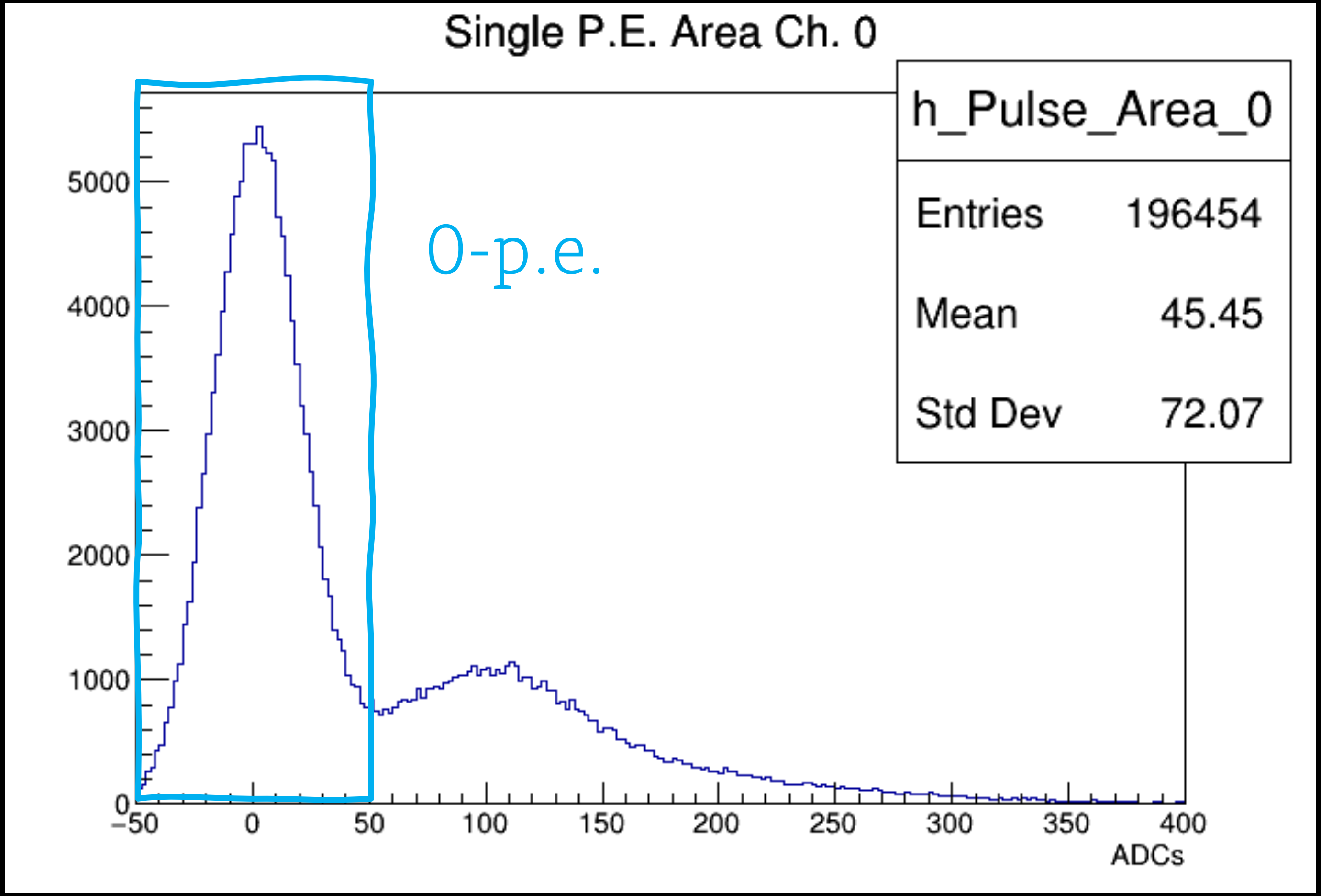
$\sigma_{2,stat}^2 = 2\sigma_{1,stat}^2$

$$\boxed{\sigma_2^2 = 2\sigma_1^2 - \sigma_0^2}$$

And a similar approach leads to

$$\boxed{\sigma_3^2 = 3\sigma_1^2 - 2\sigma_0^2}$$

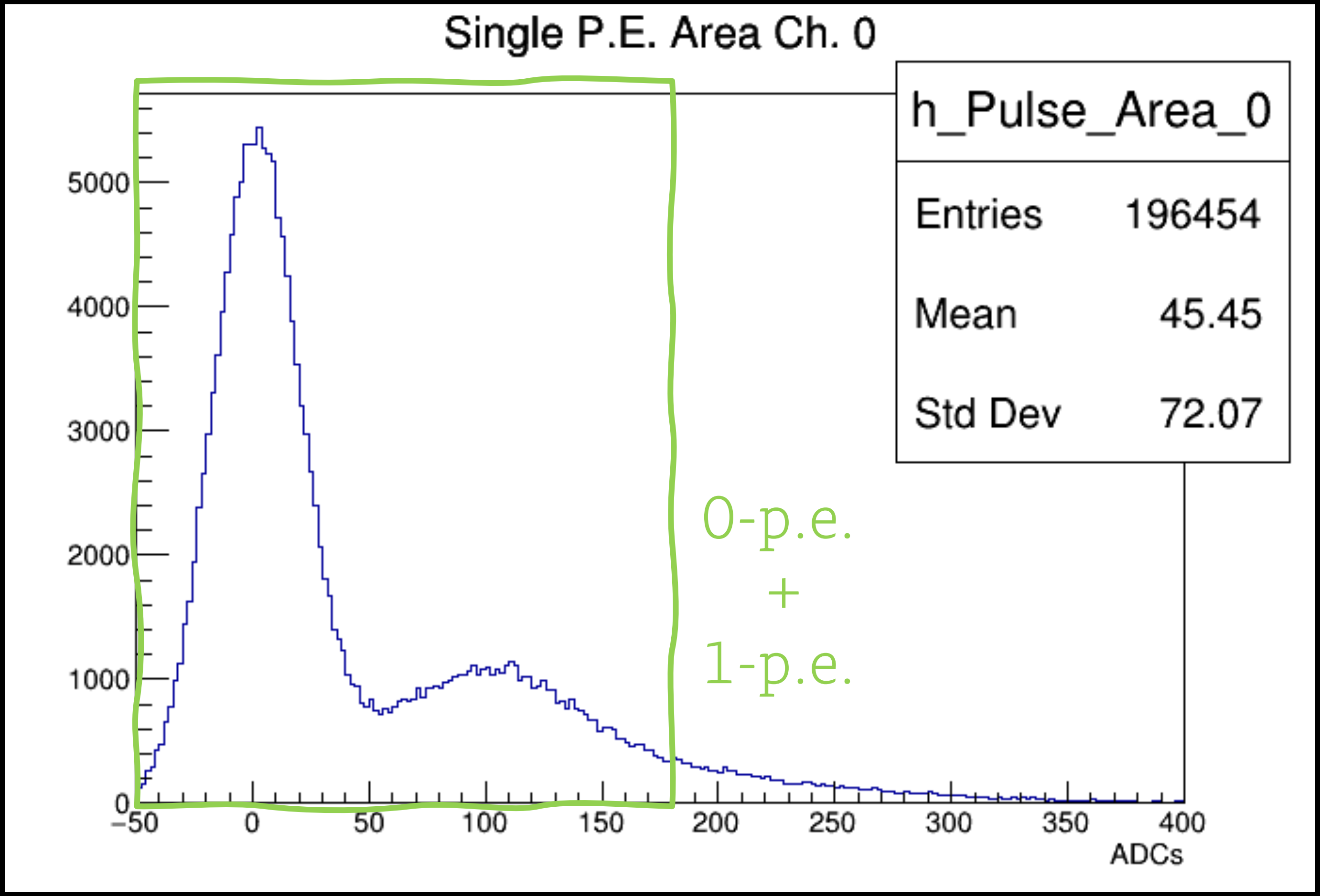
· Performing a Multi-Gaussian Fit ·



First, we fit the peak of the *0-p.e. Gaussian*, and we retrieve the fit parameters from here.

$$f_1(x) = p_0 * e^{-\frac{1}{2}\left(\frac{x-p_1}{p_2}\right)^2}$$

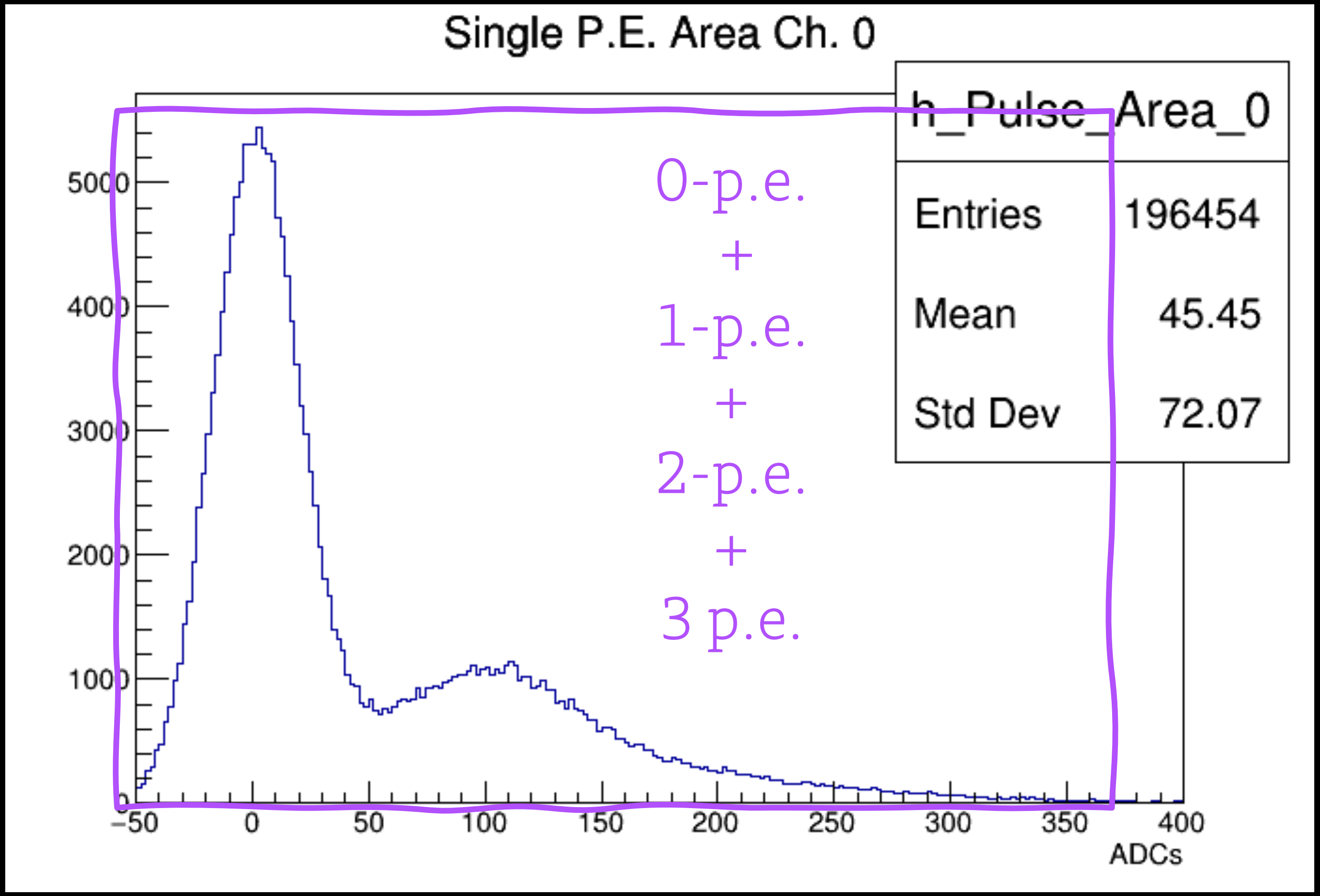
Performing a Multi-Gaussian Fit



Then we use a double Gaussian fit for 0-p.e and 1-p.e.

$$f_6(x) = p_0 * e^{-\frac{1}{2}\left(\frac{x-p_1}{p_2}\right)^2} + p_3 * e^{-\frac{1}{2}\left(\frac{x-p_4}{p_5}\right)^2}$$

· Performing a Multi-Gaussian Fit ·



Finally, we use a Four-Gaussian fit for 0,1,2,3-p.e.

$$f_8(x) = p_0 * e^{-\frac{1}{2}\left(\frac{x-p_1}{p_2}\right)^2} \longrightarrow \text{0-p.e.}$$

$$+\, p_3 * e^{-\frac{1}{2}\left(\frac{x-p_4}{p_5}\right)^2} \longrightarrow \text{1-p.e.}$$

$$\text{2-p.e.} \longleftarrow +\, p_6 * e^{-\frac{1}{2}\left(\frac{x-2p_4}{\sqrt{2p_5^2-p_2^2}}\right)^2}$$

$$\text{3-p.e.} \longleftarrow +\, p_7 * e^{-\frac{1}{2}\left(\frac{x-3p_4}{\sqrt{3p_5^2-2p_2^2}}\right)^2}$$

Our model

SOON

Extraction of Neutrino Events

Energy Cuts

Get smeared spectra and cut away the Oxygen events.

- We also cut lots of Deuterium events.

Fit to Monte Carlo

Generate a separate set of Oxygen and Deuterium events in MC.

- Non-quantifiable MC error.

Separate Modules

H_2O and D_2O separate detectors!