



Michel Electron Studies in the DUNE Far Detector Prototypes

Shuaixiang (Shu) Zhang
Particle Physics Seminar
Brookhaven National Laboratory
Jul 16, 2026 (Thu)

Outline

□ Introductions

1. Introduction to DUNE & ProtoDUNE_s
2. Photon detection system (PDS) of ProtoDUNE-HD
3. Michel electrons

□ Optical Michel electron signal finding

1. Light yield estimation of Michel electrons
2. Single Michel electron candidate finding

□ Preliminary μ^- lifetime measurement

1. Selection and purification of Michel electrons
2. Muon lifetime reconstruction
3. Lifetime fitting

Outline

□ Introductions

1. Introduction to DUNE & ProtoDUNE
2. Photon detection system (PDS) of ProtoDUNE-HD
3. Michel electrons

□ Optical Michel electron signal finding

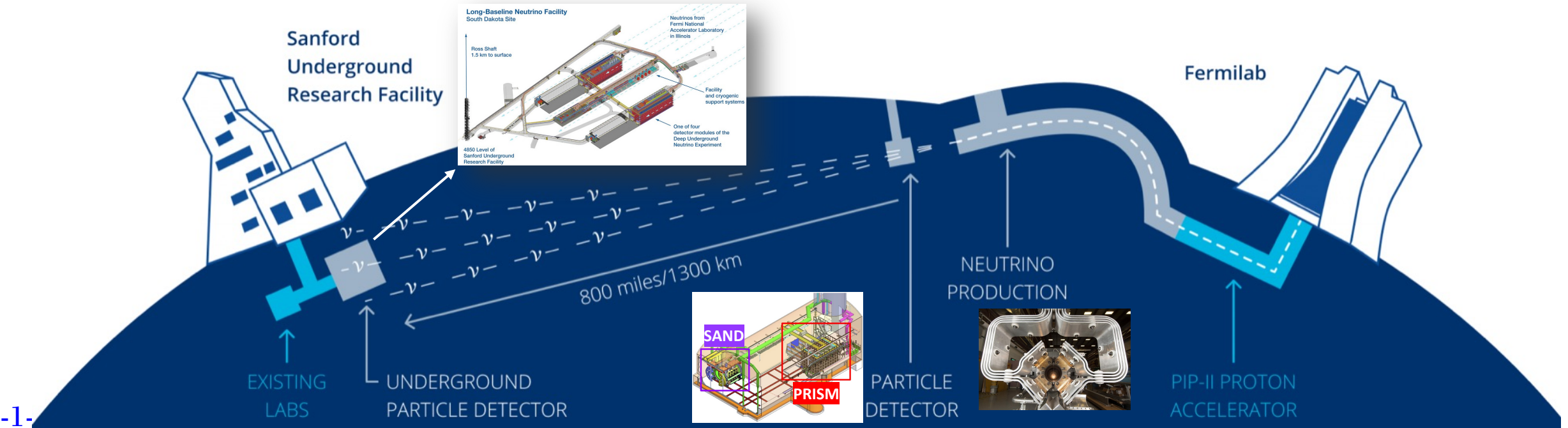
1. Light yield estimation of Michel electrons
2. Single Michel electron candidate finding

□ Preliminary μ^- lifetime measurement

1. Selection and purification of Michel electrons
2. Muon lifetime reconstruction
3. Lifetime fitting

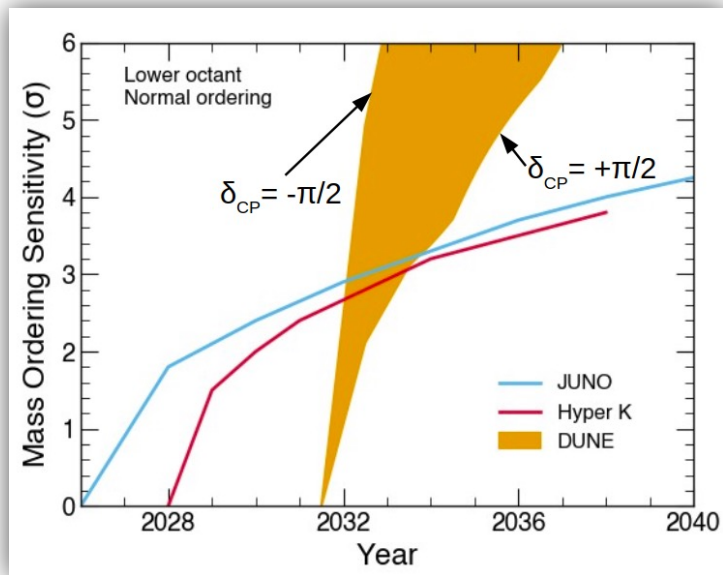
Introduction to DUNE

- ❖ DUNE: Deep Underground Neutrino Experiment
- ❖ Components: 1. Beam (1.2MW [phase I] → 2.4MW [phase II])
2. Near Detectors (SAND, ND-LAr + TMS (PRISM)) [Phase II: TMS ⇒ ND-GAr]
3. Far Detectors (FD1 & FD2 & FD3 [Phase II] : LArTPC, FD4 [Phase II] : “module of opportunity”)
- ❖ Timeline: start of science @ 2030

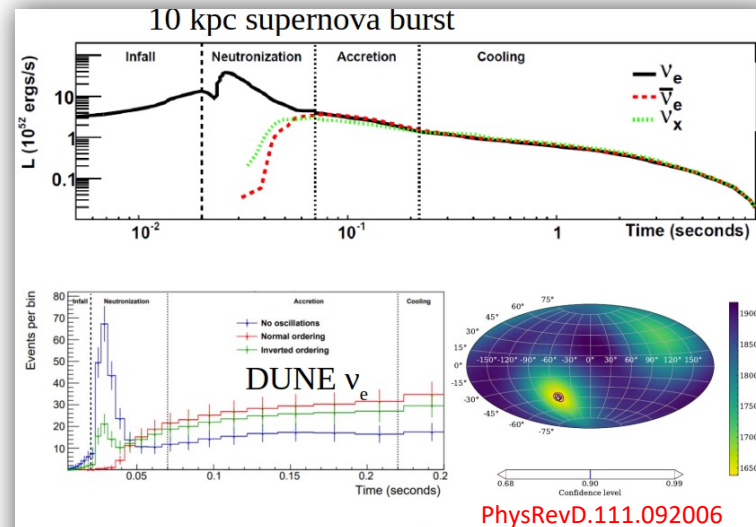


DUNE Physics

- ❖ Neutrino oscillations: δ_{CP} , mass ordering, mixing angles, test 3-flavor oscillation model
- ❖ Supernova physics: particularly sensitive to ν_e ($\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$)
- ❖ Broad BSM programs: proton decay, low-mass dark matter, neutrino tridents, heavy neutral lepton ...



Credit to Chris Marshall (DUNE oscillation-physics convener)
Talk during DUNE Sep 2025 CM



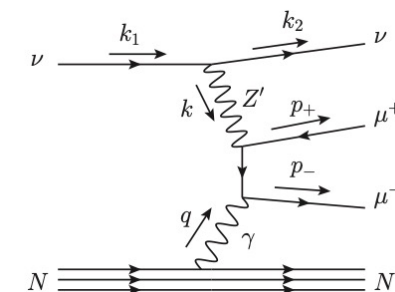
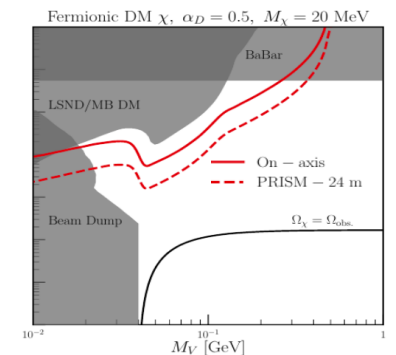
PhysRevD.111.092006

	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK ¹	10%	87%	3%
JUNO ²	1%	72%	27%

¹Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)

²Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

De Romeri, Kelly, and
Machado,
Phys. Rev. D 100 no. 9,
(2019) 095010

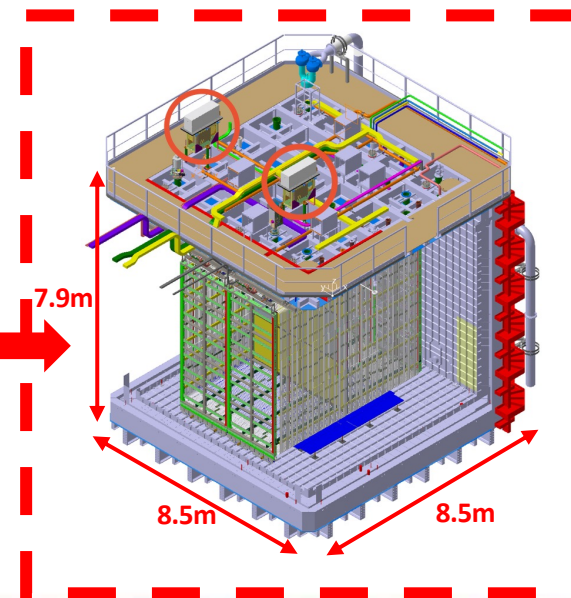
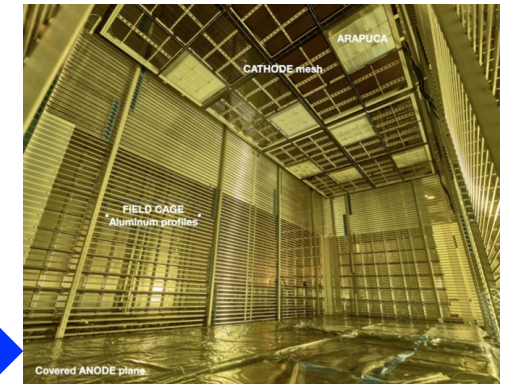
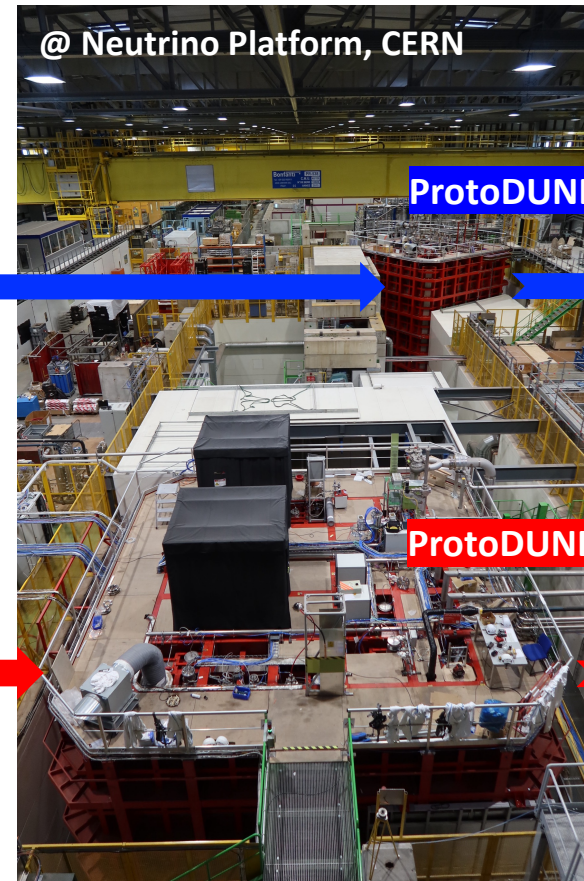
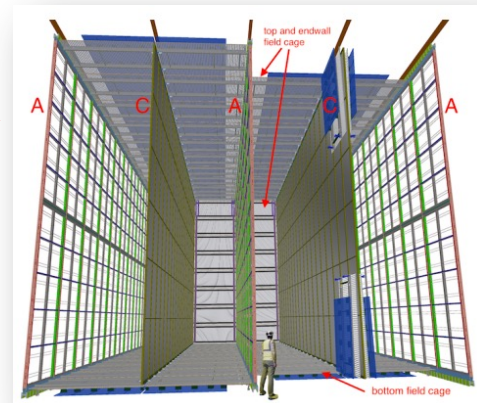
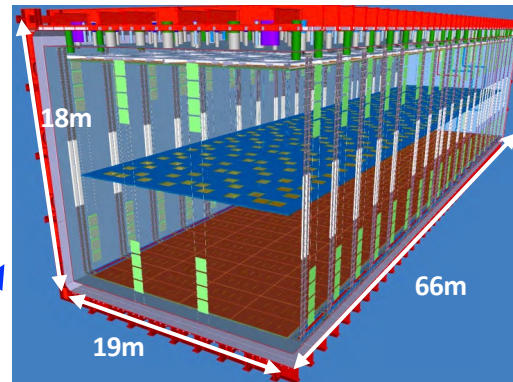
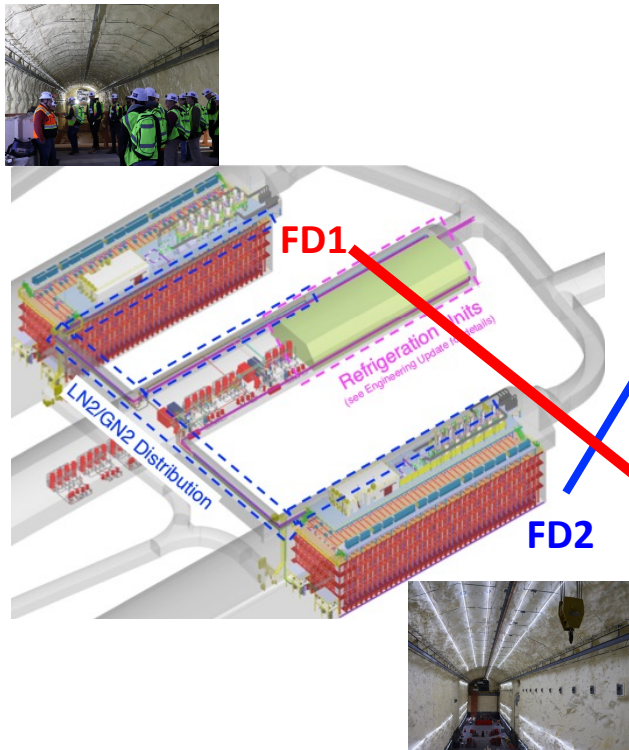


Wolfgang Altmannshofer
Stefania Gori, Maxim Pospelov
and Itay Yavin
Phys. Rev. Lett. **113**, 091801

...

ProtoDUNE_s: DUNE FD Prototypes

- ❖ **FD1 / FD2** ➡ ProtoDUNE- **HD** / **VD**: **horizontal** / **vertical**-drift **LArTPC**
- ❖ ProtoDUNE-HD data taking: May 2024 ~ Dec 2024 [(10 weeks of charged beam) + cosmic rays]

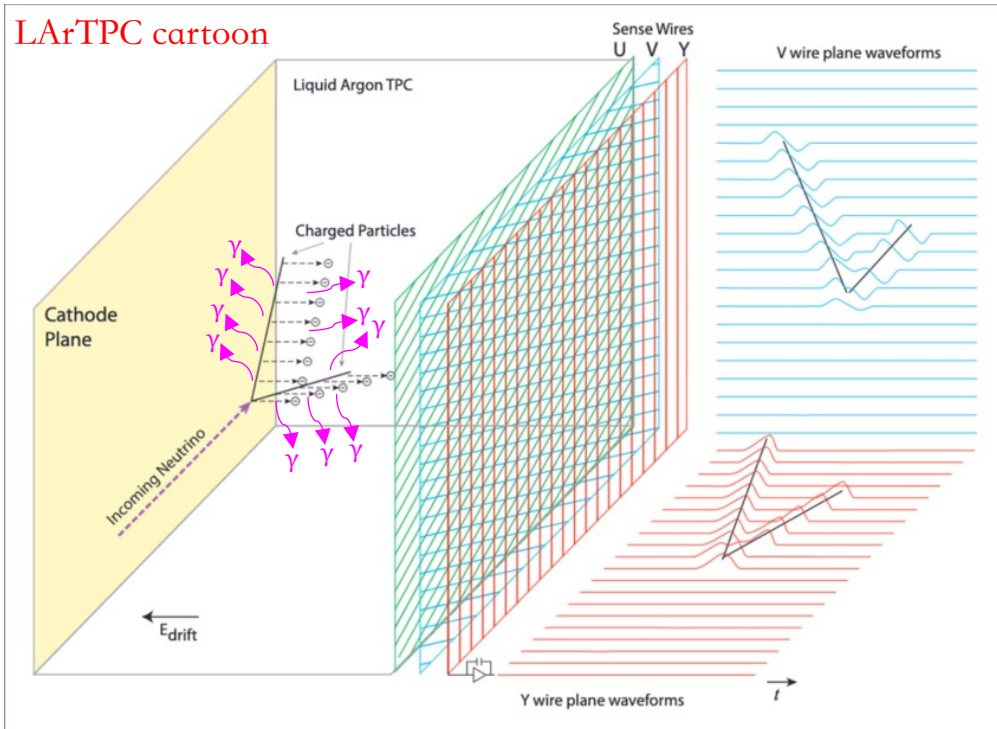


LArTPC & Scintillation Light

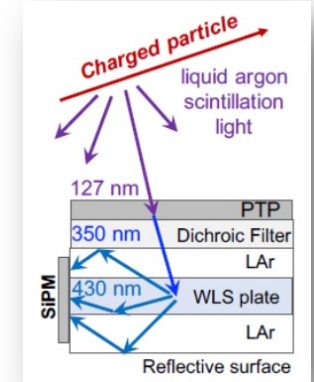
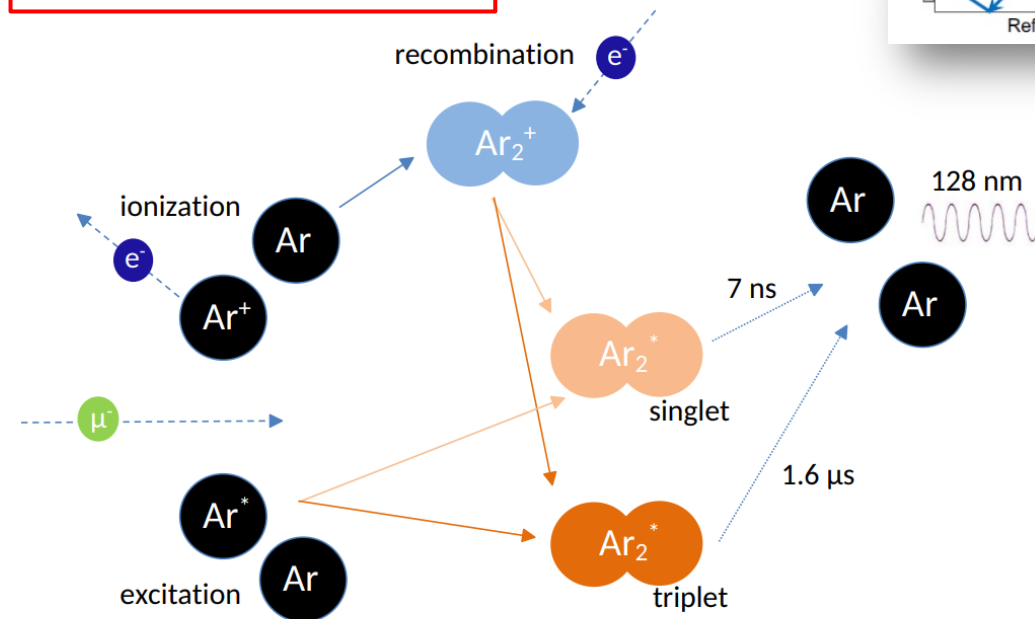
X-ARAPUCA (Photon detector of DUNE)

- ❖ LArTPC: Liquid Argon Time Projection Chamber
- ❖ Scintillation light: $\sim 24,000 \gamma/\text{MeV}$ @ 500V/cm, isotropic, 128nm
- ❖ Light components: fast photons ($\sim 7\text{ns}$), delayed photons ($\sim 1600\text{ns}$)

LArTPC cartoon

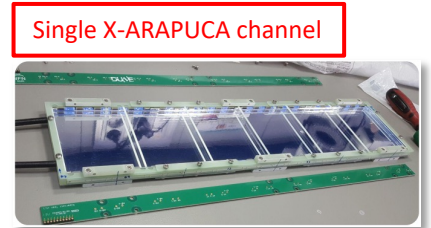
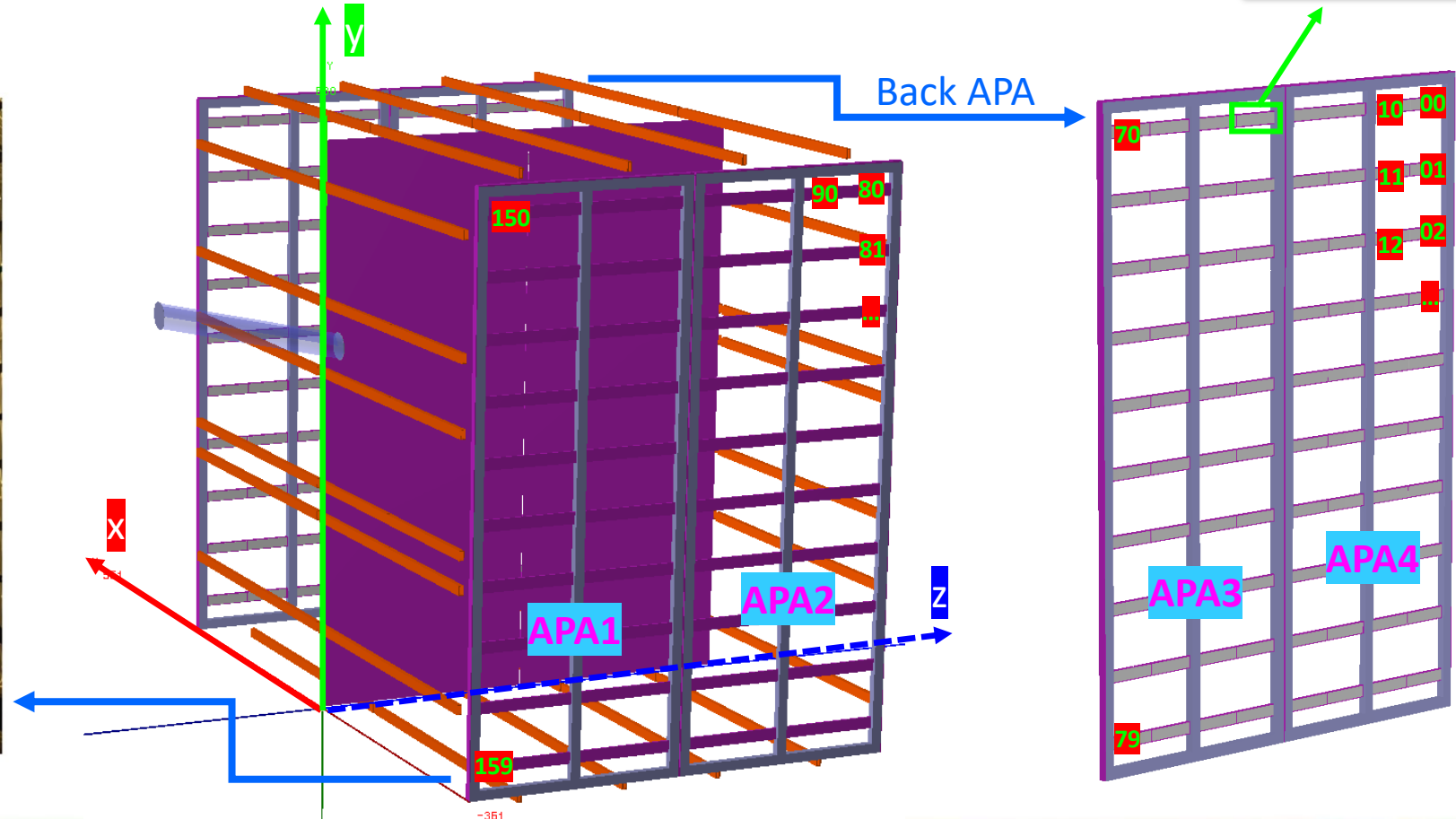
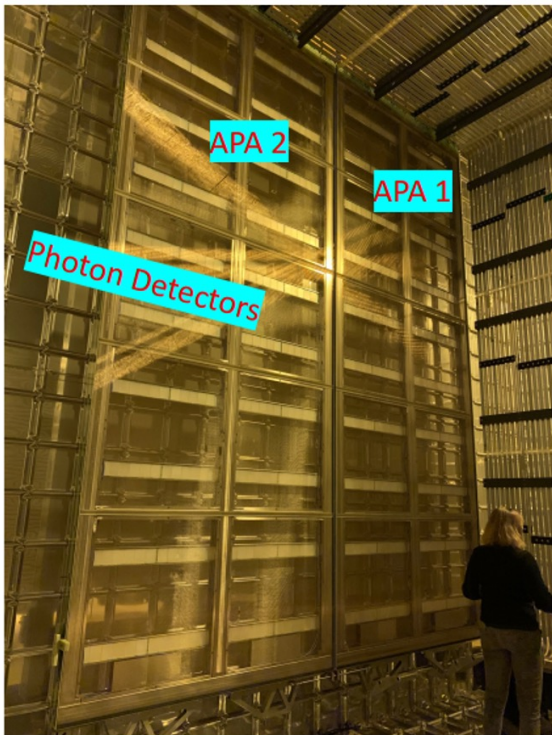


LAr scintillation mechanism



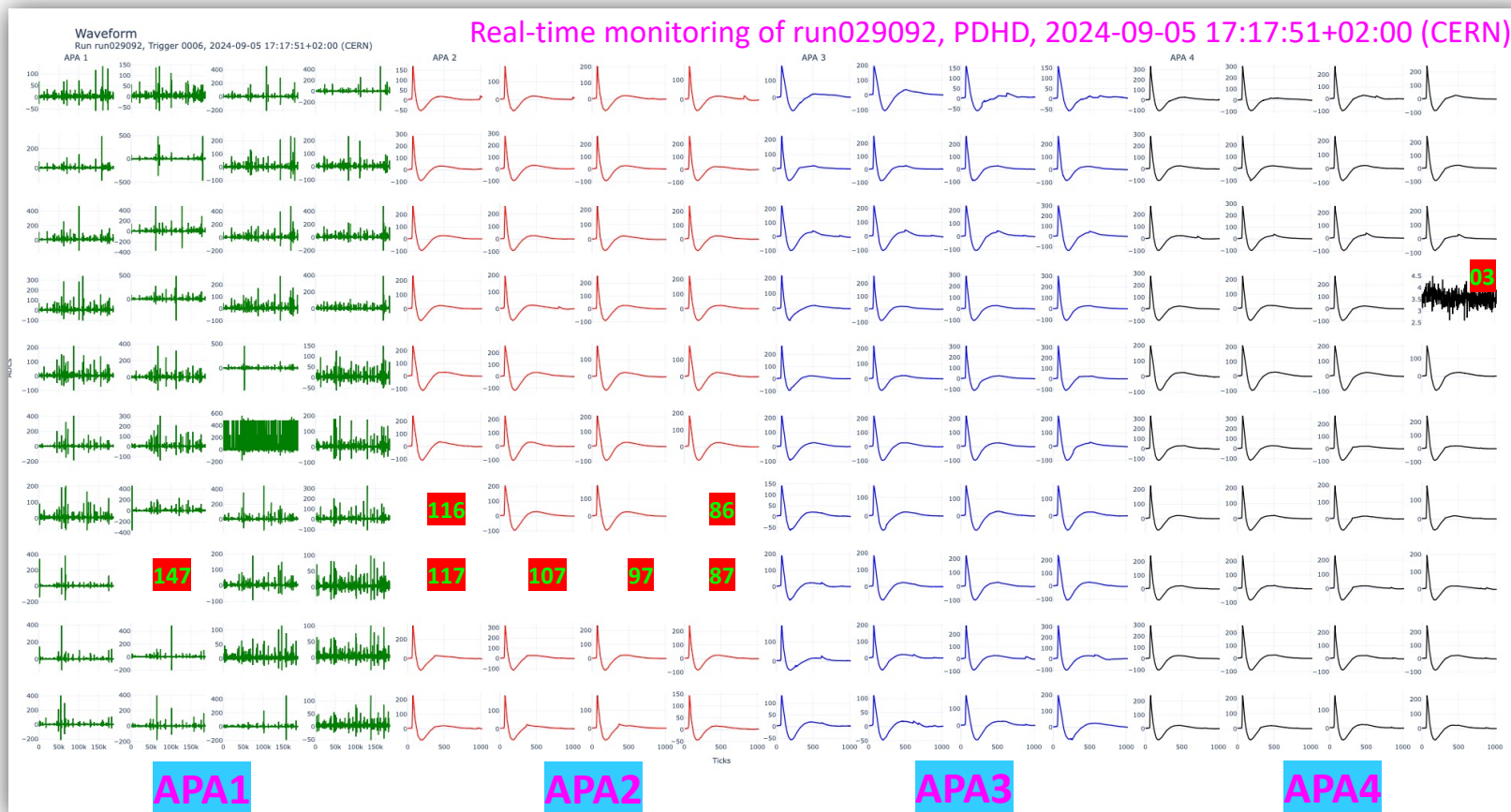
ProtoDUNE-HD PDS

- ❖ Photon Detection System (PDS) installed behind TPC wires
- ❖ X-ARAPUCA technology: large-scale (48cm×10cm); SiPM-based; high photon detection efficiency ($\sim 3\%$)
- ❖ 160 channels in total



Performances of PDS

- ❖ Details of optical channels: [dune_opdet_channels.fcl](https://dune-opdet-channels.fcl)
- ❖ APA1: full-streaming optical channels – readout window: $\sim 3\text{ms}$
- ❖ APA2, 3 & 4: self-triggered channels – readout window: $\sim 16\mu\text{s}$ (**Focus of this talk**)



Michel Electrons in Liquid Argon

❖ Michel electron: decay daughter of muon at rest

$$\begin{cases} \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{cases}$$

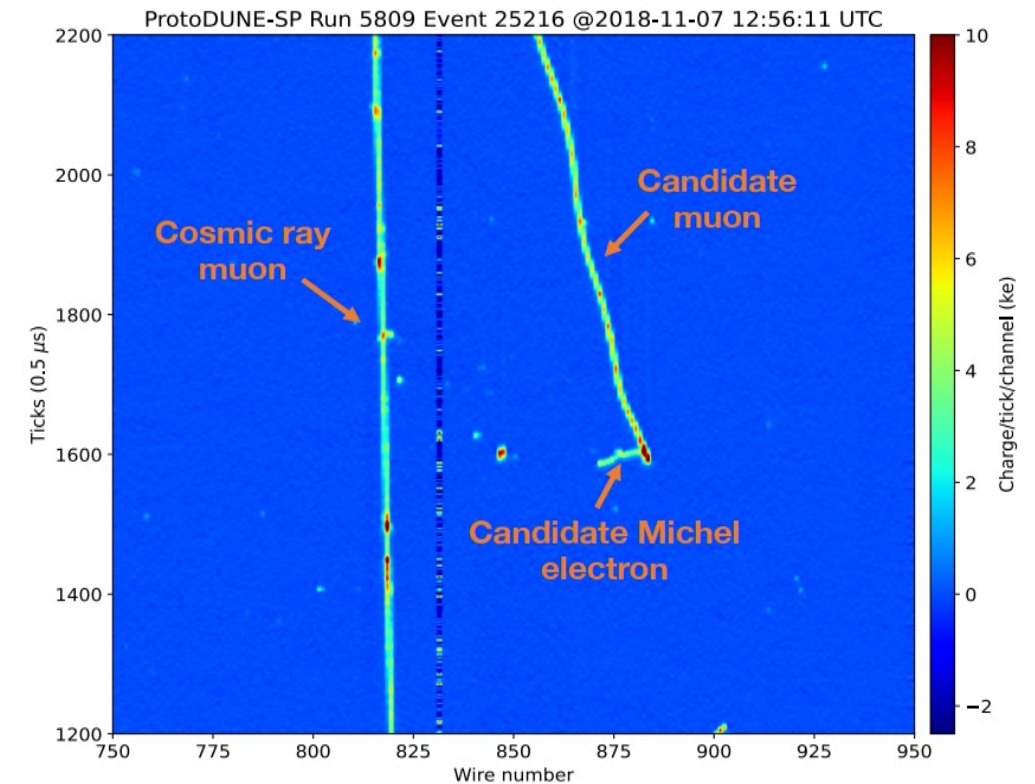
❖ In LAr:

- Stopping μ^+ : 100% decay
- Stopping μ^- : ~25% decay, ~75% captured by nucleus

❖ Stopping rate:

$$\begin{cases} \frac{1}{\tau_{\mu^+}} = \frac{1}{\tau_0} \\ \frac{1}{\tau_{\mu^-}} = \frac{R_H}{\tau_0} + \frac{1}{\tau_c} \end{cases}$$

- τ_0 : muon decay lifetime in vacuum
- R_H : Huff factor, characterize μ^- decay in orbit
- τ_c : μ^- capture



<https://journals.aps.org/prd/abstract/10.1103/PhysRevD.107.092012>

<https://iopscience.iop.org/article/10.1088/1748-0221/5/06/P06003/pdf>

Huff factor: <https://journals.aps.org/prc/abstract/10.1103/PhysRevC.35.2212>

M. Sorel: <https://iopscience.iop.org/article/10.1088/1748-0221/9/10/P10002/pdf>

Motivations & Goals

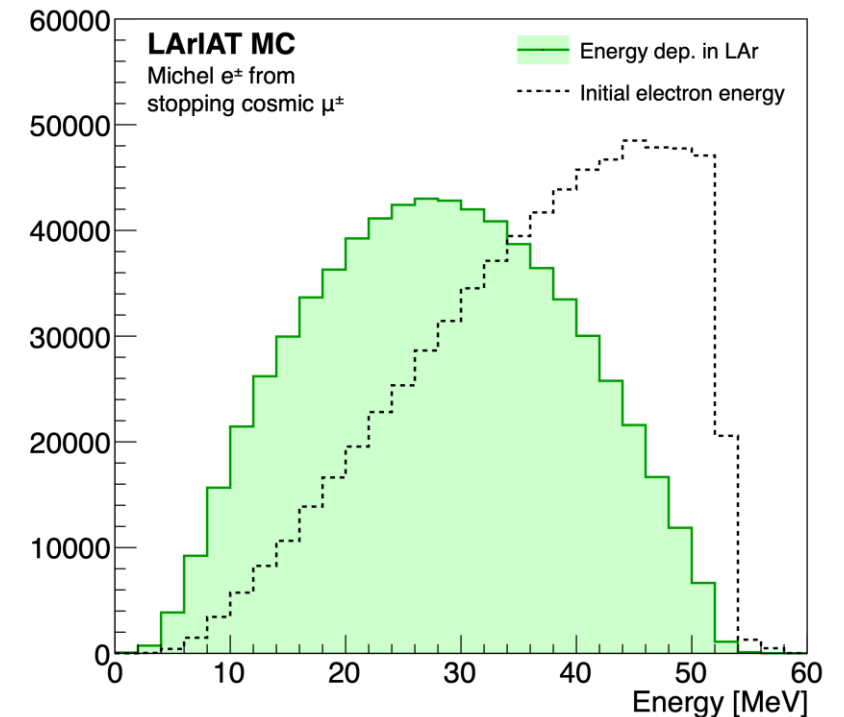
- ❖ In ProtoDUNEs: Michel electrons provide a $O(100)$ Hz source of $O(10)$ MeV electrons with characteristic spectrum
- ❖ ProtoDUNE-SP: [Identification and reconstruction of low-energy electrons in the ProtoDUNE-SP detector](#) [Charge]
[Evaluating the low-energy response of the ProtoDUNE-SP detector using Michel electrons](#) [Charge]

Motivations:

1. Understand detector response to $O(10)$ MeV electrons
2. Improve low-E event reconstruction (position, energy, etc)
3. Solar ν , supernova ν (triggering, reconstruction, etc)
4. Discrimination of μ^+ and μ^- ($\bar{\nu}_\mu$ and ν_μ)

Goals:

1. Explore PDS (Light) responses to $O(10)$ MeV electrons
2. Integrate TPC & PDS (Charge + Light) w.r.t. μ^- lifetime study



Outline

□ Introductions

1. Introduction to DUNE & ProtoDUNE_s
2. Photon detection system (PDS) of ProtoDUNE-HD
3. Michel electrons

□ Optical Michel electron signal finding

- 1. Light yield estimation of Michel electrons**
2. Single Michel electron candidate finding

□ Preliminary μ^- lifetime measurement

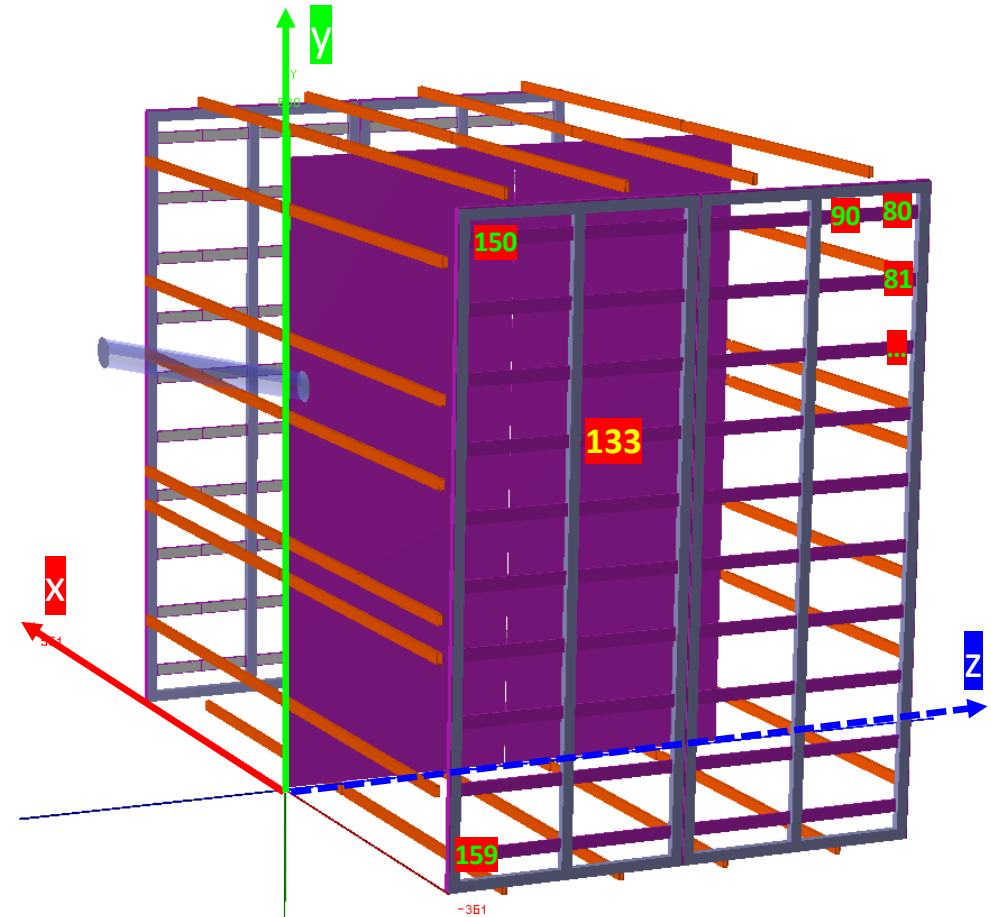
1. Selection and purification of Michel electrons
2. Muon lifetime reconstruction
3. Lifetime fitting

Light Yield Estimation (I)

- ❖ Expected Light yield (# of scintillation photons) of Michel electron:

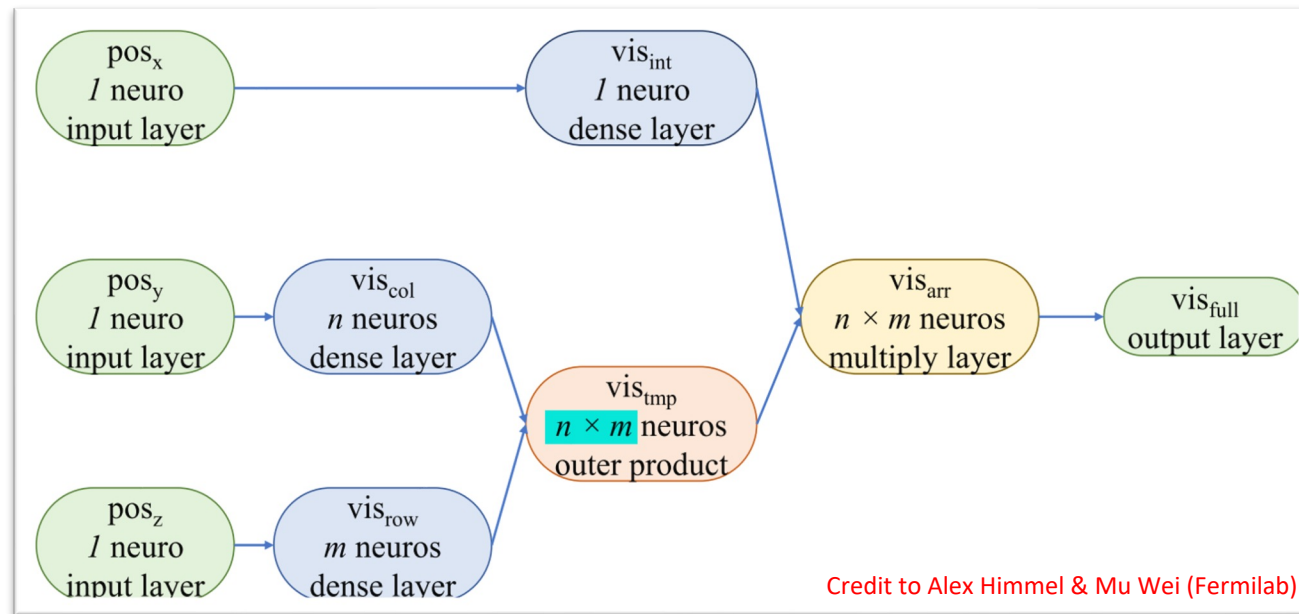
$$L = 9.1 \times 10^5 \quad \text{for } E_{\text{ME}} = 36.7 \text{ MeV under } 500 \text{ V/cm}$$

- ❖ Fast photon propagation module: [Computable Graph Model](#)
- ❖ Transmission efficiency through TPC wire planes: $T = 0.68$
- ❖ Photon detection efficiency (PDE): $A = 0.02$
- ❖ Final optical signal: $N_{\text{PE}} = L \times R_{\text{propagation}} \times T \times A$
- ❖ Focus example: optical channel **133**



Computable Graph Model (I)

- ❖ Computable graph model: machine-learning-based fast optical simulation model
- ❖ Traditional scintillation light simulation (GEANT4): track and simulate every photon
Giant computational cost & very **slow** for $\mathcal{O}(\text{GeV})$ energy deposition in LAr detector ($\mathcal{O}(10^6)$ photons)
- ❖ Machine-learning-based method: Input(photon emission vertex) $\rightarrow$ direct Output(optical channel responses)
Small computational cost & 20~50 times **faster**

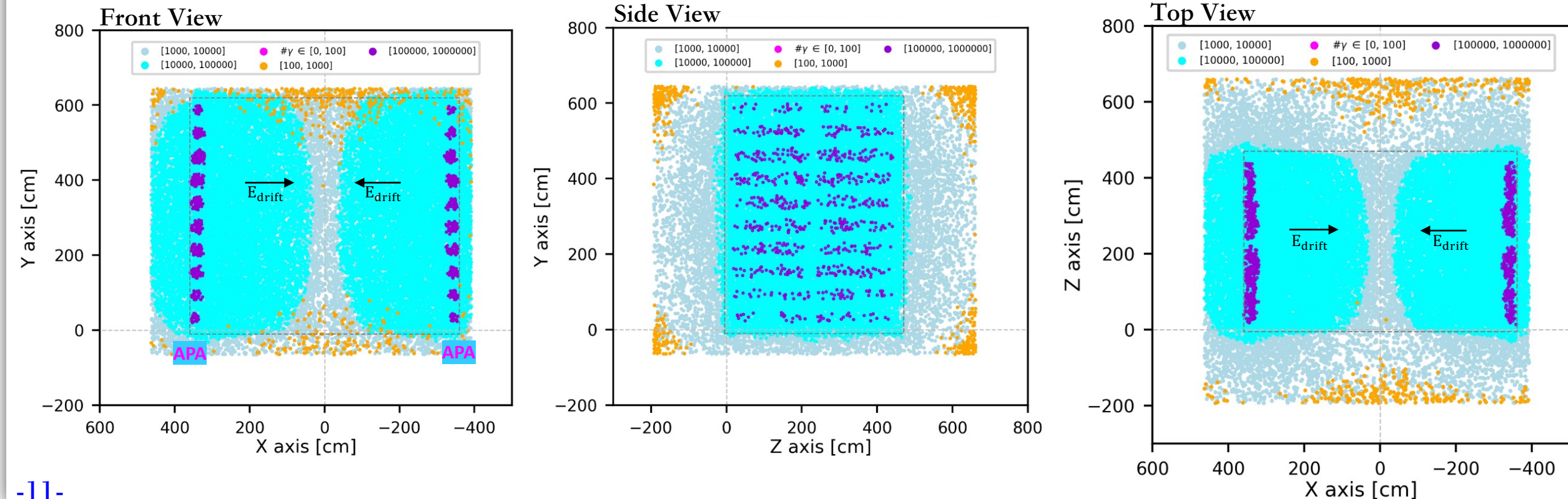


Computable Graph Model (II)

❖ Performance of computable graph model for ProtoDUNE-HD detector

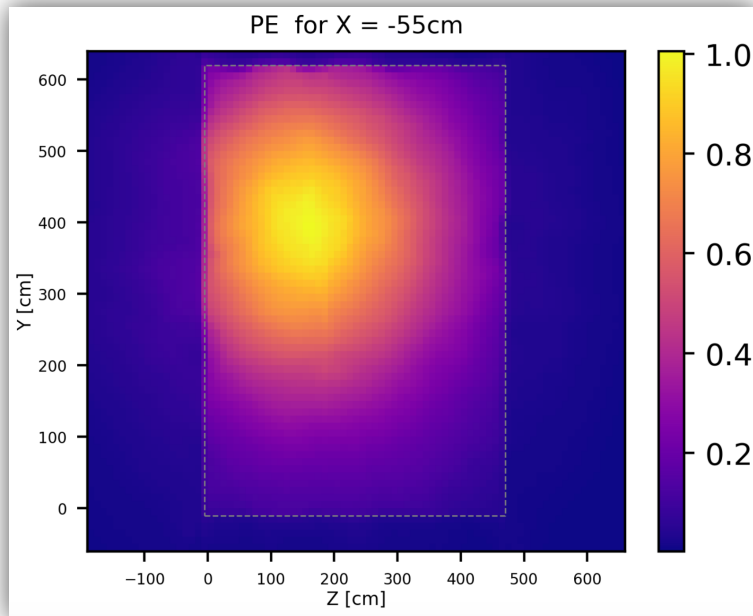
Responses of optical channels to different photon emission vertices in space

(Each vertex emits 10^6 photons isotropically)

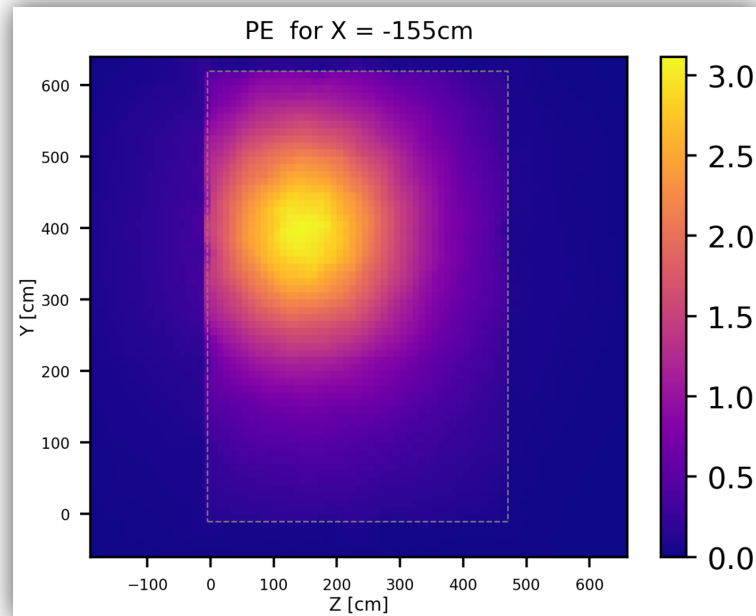


Light Yield Estimation (II)

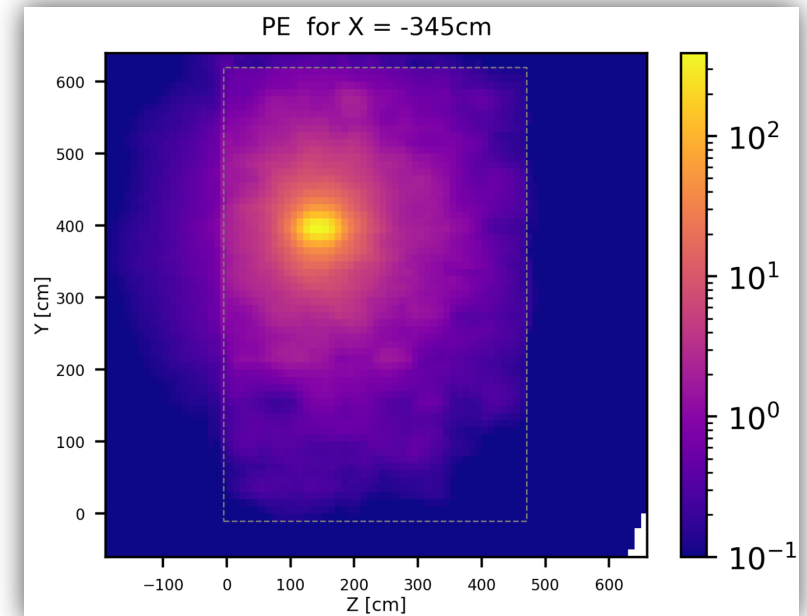
- ❖ Position of optical channel 133: $(Y, Z) = (396.7, 145.9)\text{cm}$ @ plane of $X = -356\text{cm}$
- ❖ Only fast component of argon light considered here: around [25% of total yield](#)
- ❖ Strong optical signal expected when Michel electron $\leq 2\text{m}$ away from X-ARAPUCA



Distance = 301cm



Distance = 201cm



Distance = 11cm

Outline

□ Introductions

1. Introduction to DUNE & ProtoDUNE_s
2. Photon detection system (PDS) of ProtoDUNE-HD
3. Michel electrons

□ Optical Michel electron signal finding

1. Light yield estimation of Michel electrons
- 2. Single Michel electron candidate finding**

□ Preliminary μ^- lifetime measurement

1. Selection and purification of Michel electrons
2. Muon lifetime reconstruction
3. Lifetime fitting

Michel e Identification Strategy

DATA

- ❖ Strategy: Using TPC tagging, then look at corresponding PDS responses
- ❖ Request cosmic muons passing cathode / anode (provide muon arrival time [T0])
- ❖ Example of TPC reconstructed Michel electron candidate:

Michel e evaluation: [Separation of track- and shower-like energy deposits in ProtoDUNE-SP using a convolutional neural network](#)

Muon decay point (in unit of cm)
(reconstructed by [Pandora](#))

Optical channels
closest to decay point

```
=====Michel e CAND! (score>0.1) COUNT (DECON)=====
Michel score: 0.793756, Michel hits: 16
Run: 28116, Event: 38472, TrackID: 1
Vertex(x, y, z) = (-18.6684, 584.512, 232.632)
End(x, y, z) = (278.942, 175.902, 121.775)

Distance to APA plane (+/-): 77.4044 cm

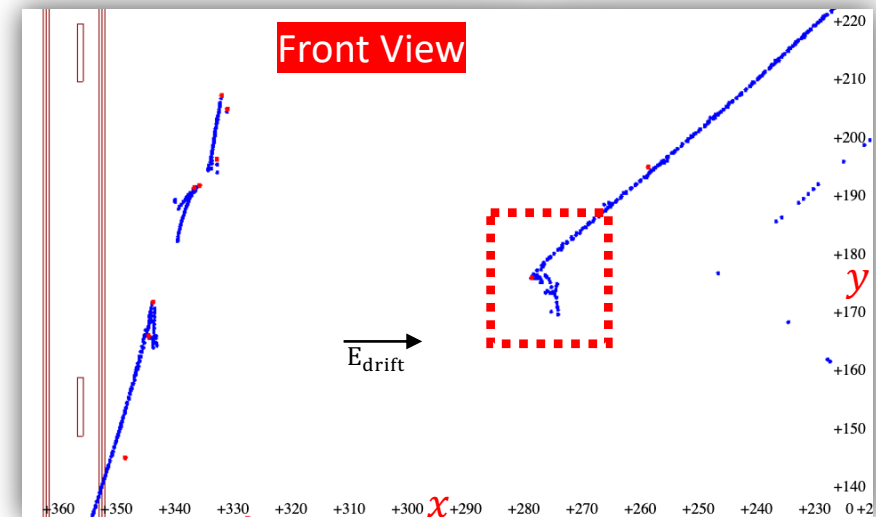
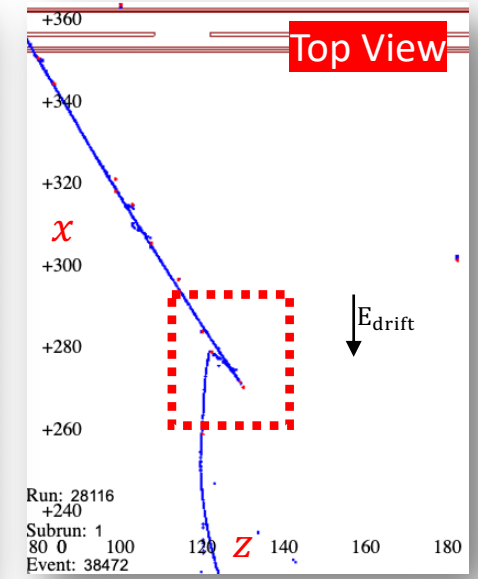
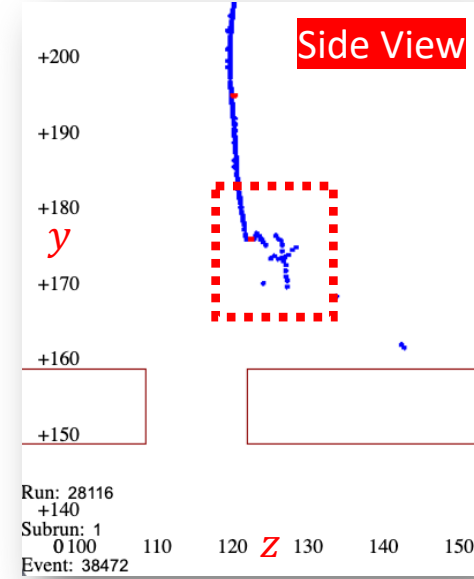
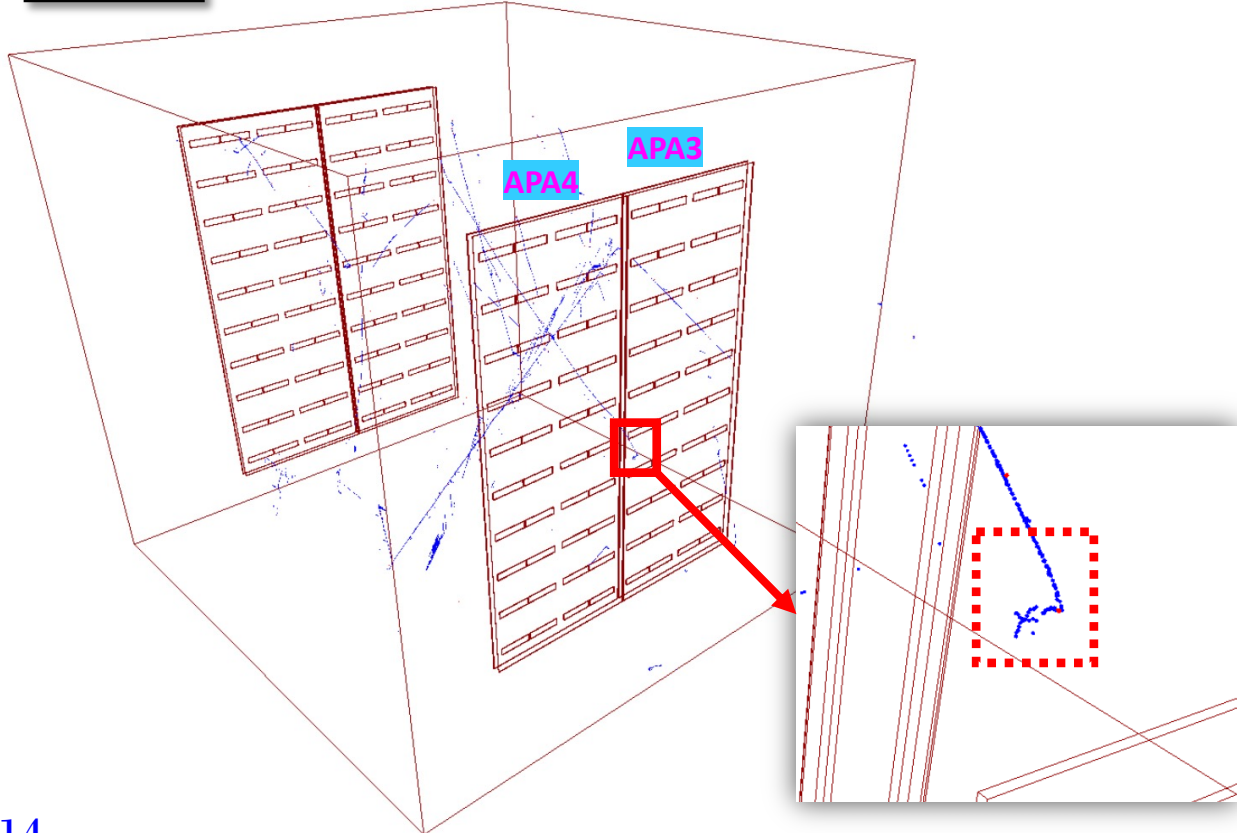
Closest OpCh (y, z): (153.66, 145.861); Label: 57
46 56 66
47 57 67
48 58 68
```

Distance between decay point
and APA plane
(photon detector arrays)

Pandora Reconstructed Tracks

DATA

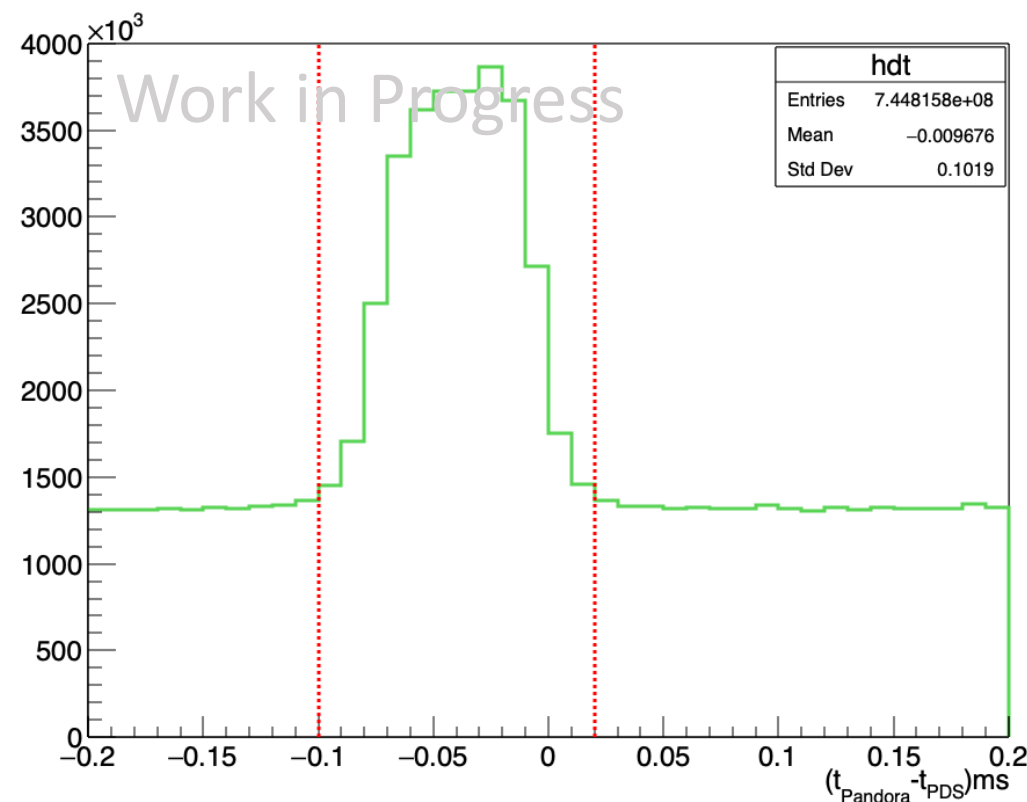
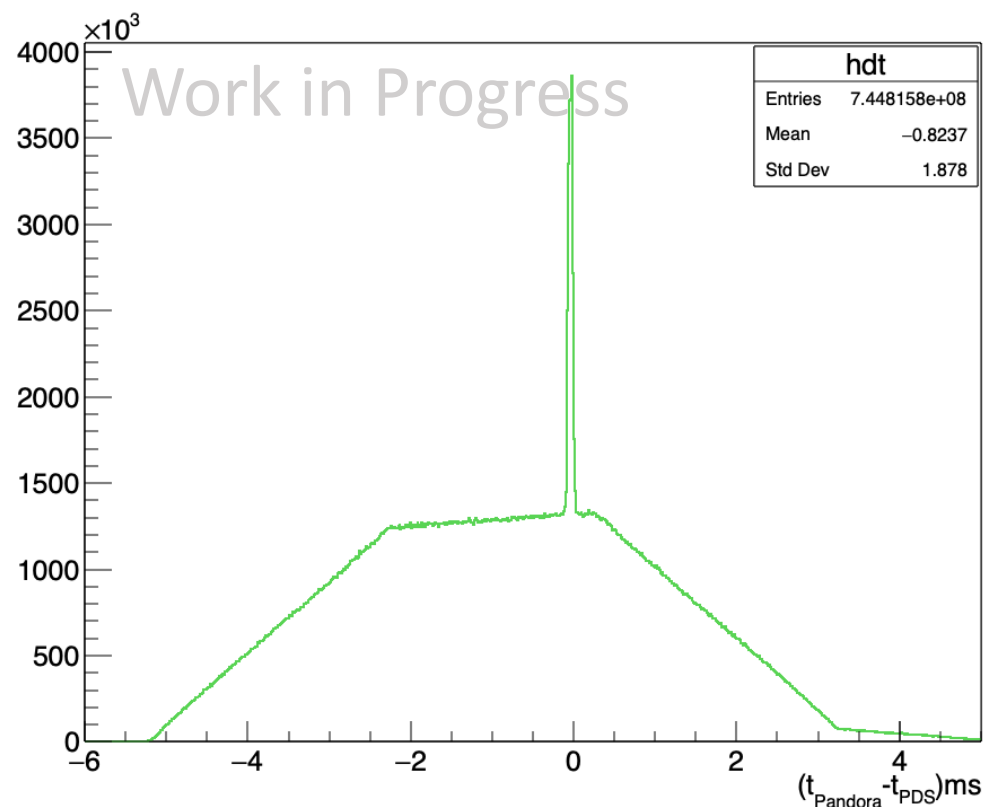
Run: 28116
Subrun: 1
Event: 38472



TPC-PDS Timing Matching

DATA

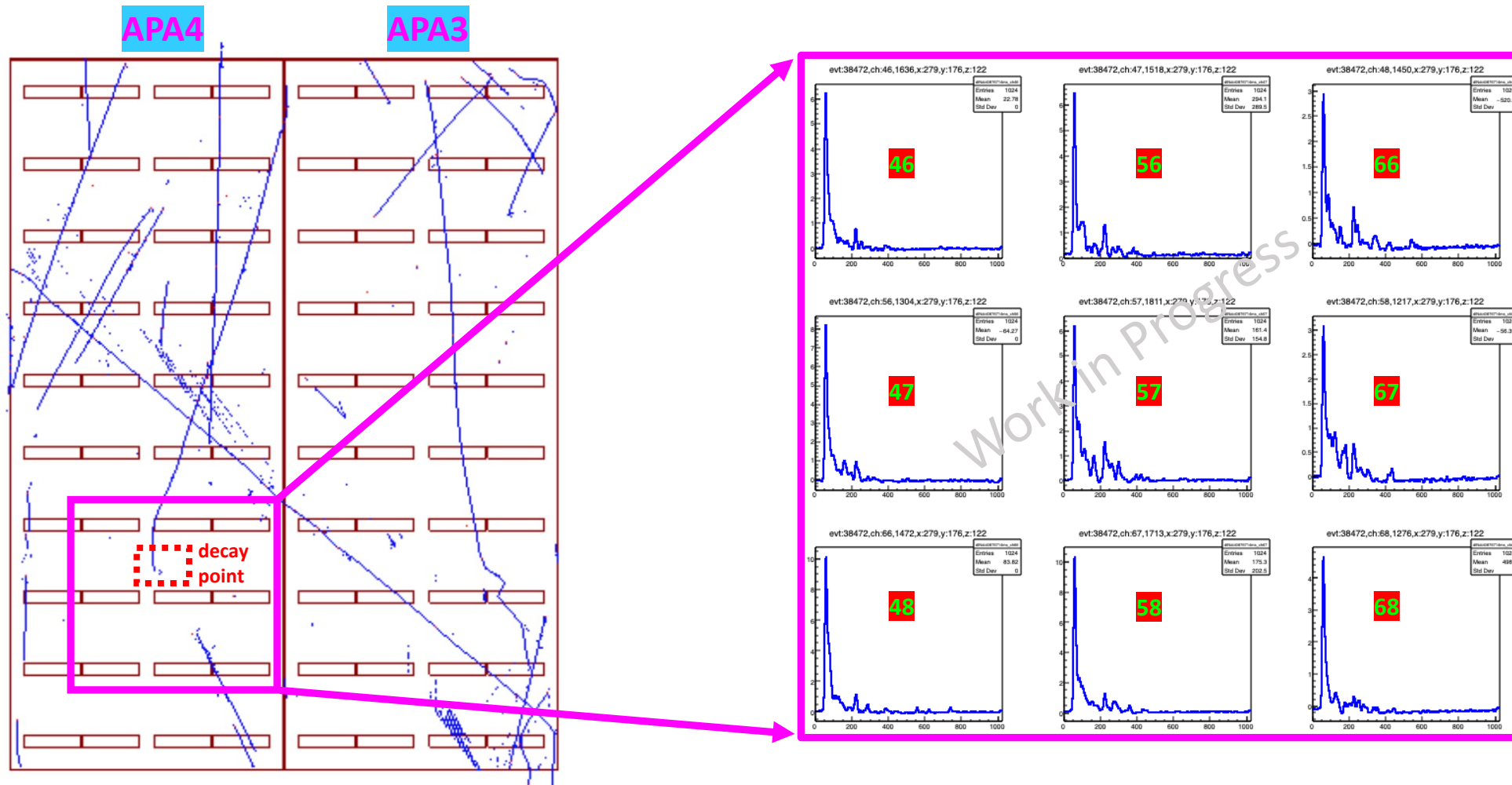
- ❖ Matching between TPC T0s with self-triggered PDS T0s
- ❖ Full list of cosmic run 28116 (208,667 events)
- ❖ Peak window: $[-0.1, 0.02]$ ms



Responses of Optical Channels

DATA

- ❖ Look at responses of nearby optical channels within above time window



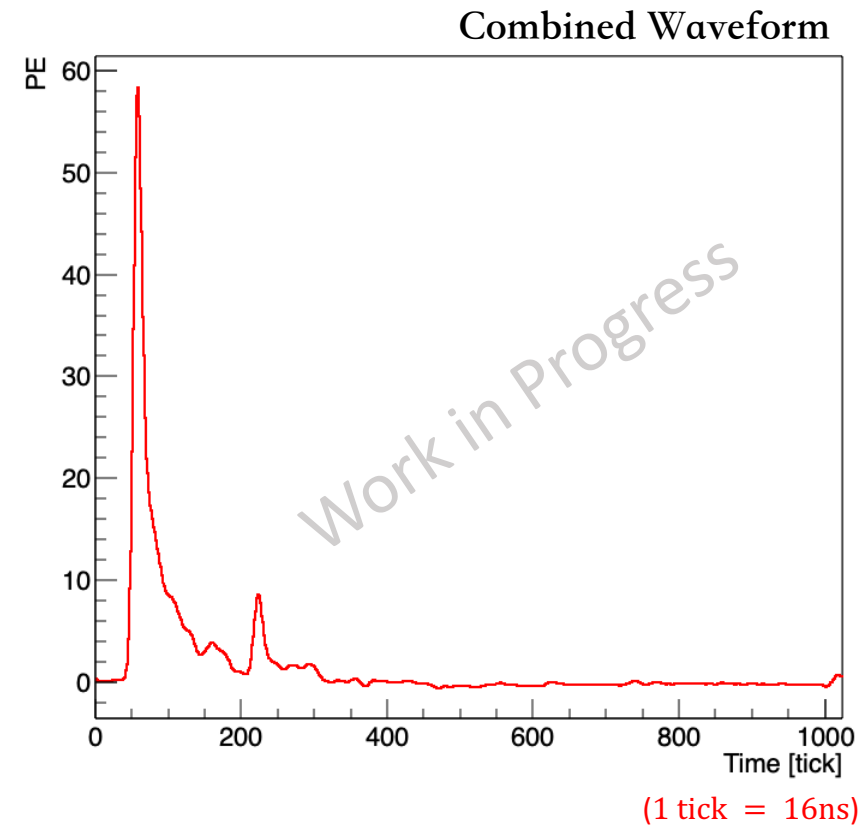
Combine Single Waveforms

DATA

❖ Combine single optical waveforms to flatten statistical fluctuations

❖ Expectation of typical Michel optical signal:

The fast light signal of Michel electron lies on the delayed-light tail of the muon signal
(A small sharp peak after the large muon peak)



Note: "PE" here refers to the differential photoelectron count w.r.t. time.

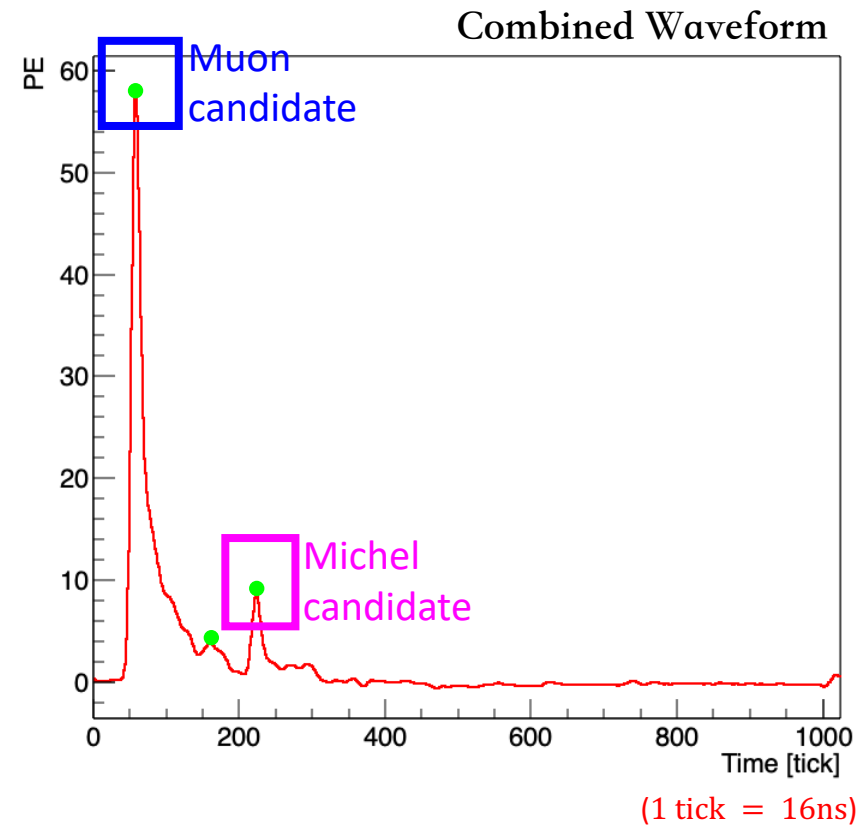
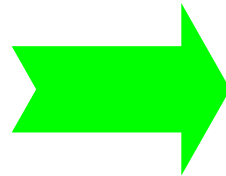
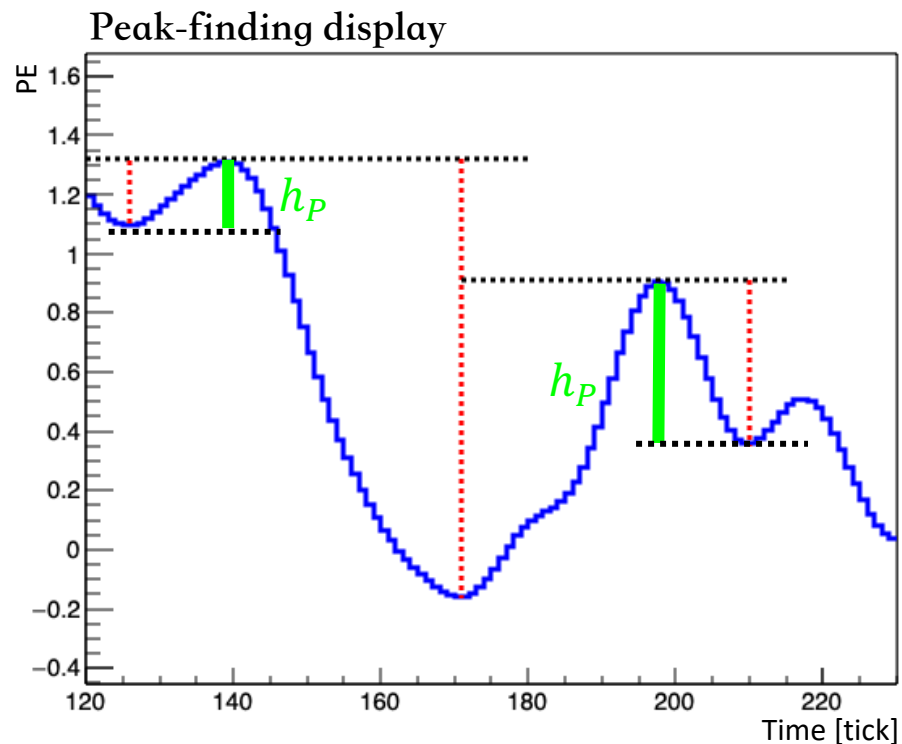
The Gaussian post-filter of the [Deconvolution Module](#) smears a single photoelectron into a single Gaussian distribution.

Apply Peak Finding

DATA

❖ Peak-finding algorithm:

- h_L / h_R : height difference between peak and left /right turning points
- Height of peak (h_P) $\equiv \min\{h_L, h_R\}$; Threshold: $h_P \geq 0.3$ (adjustable)
- Logic: highest peak: muon, 2nd-highest: Michel candidate



More Michel electron Candidates

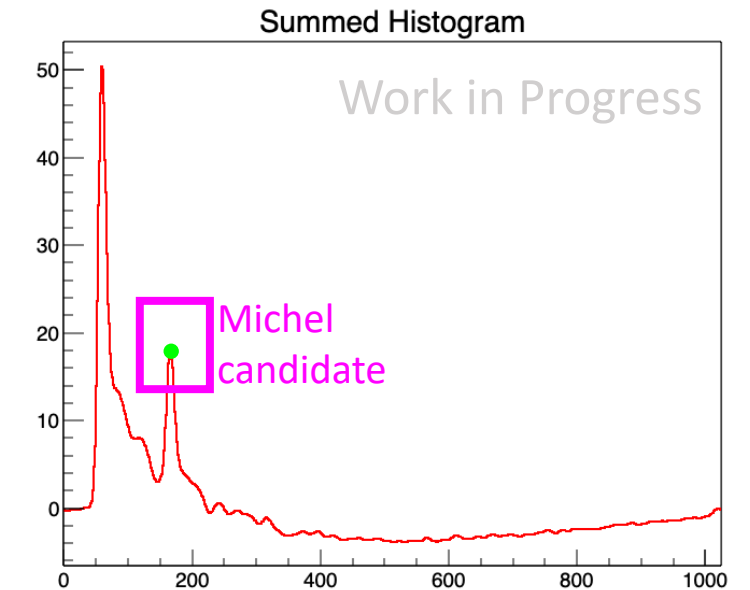
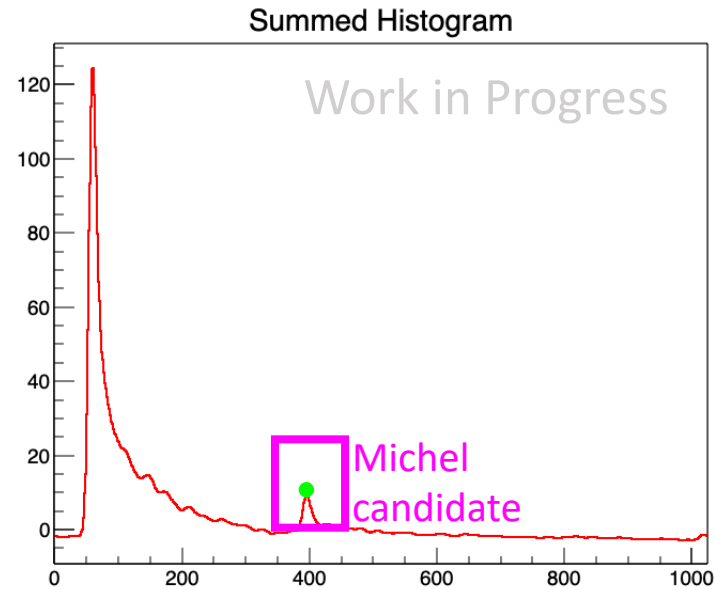
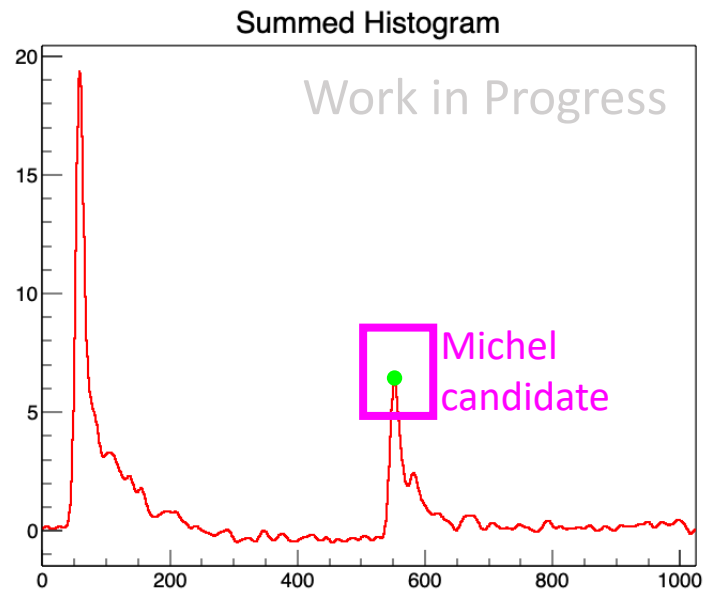
DATA

❖ More candidates:

```
=====Michel e CAND! (score>0.1) COUNT (DECON)=====
Michel score: 0.823544, Michel hits: 6
Run: 28116, Event: 102192, TrackID: 4
Vertex(x, y, z) = (-46.3183, 335.449, 441.312)
End(x, y, z) = (77.1776, 192.433, 195.932)
```

```
=====Michel e CAND! (score>0.1) COUNT (DECON)=====
Michel score: 0.409392, Michel hits: 14
Run: 28116, Event: 103897, TrackID: 15
Vertex(x, y, z) = (361.771, 221.324, 279.901)
End(x, y, z) = (327.638, 68.1718, 301.77)
```

```
=====Michel e CAND! (score>0.1) COUNT (DECON)=====
Michel score: 0.517771, Michel hits: 13
Run: 28116, Event: 10477, TrackID: 13
Vertex(x, y, z) = (365.249, 588.363, 276.762)
End(x, y, z) = (339.137, 450.635, 215.792)
```



Outline

□ Introductions

1. Introduction to DUNE & ProtoDUNE_s
2. Photon detection system (PDS) of ProtoDUNE-HD
3. Michel electrons

□ Optical Michel electron signal finding

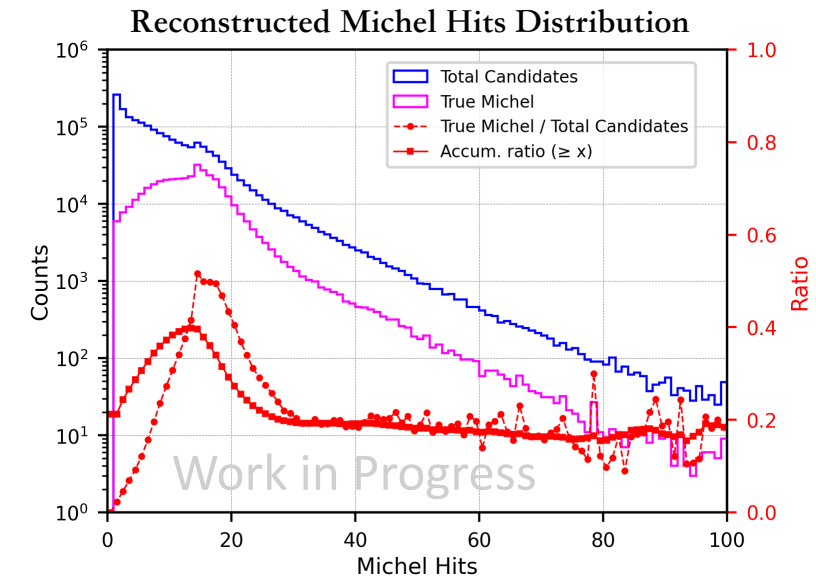
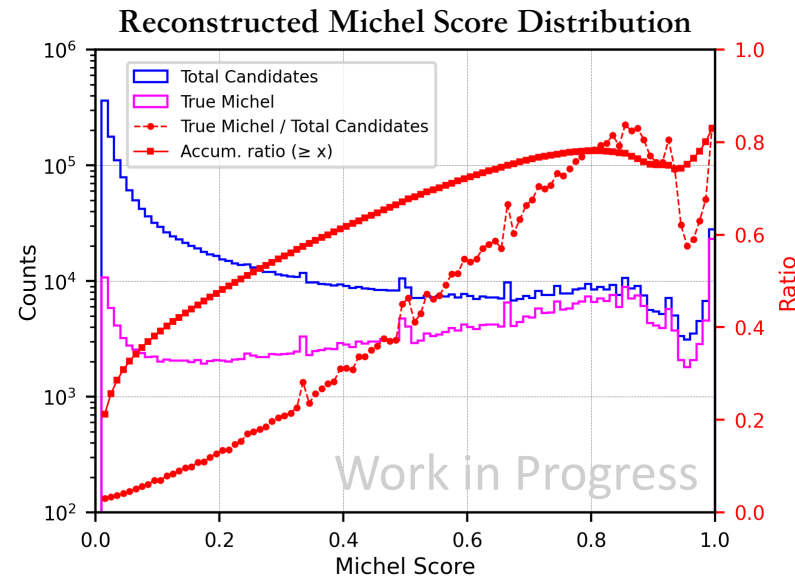
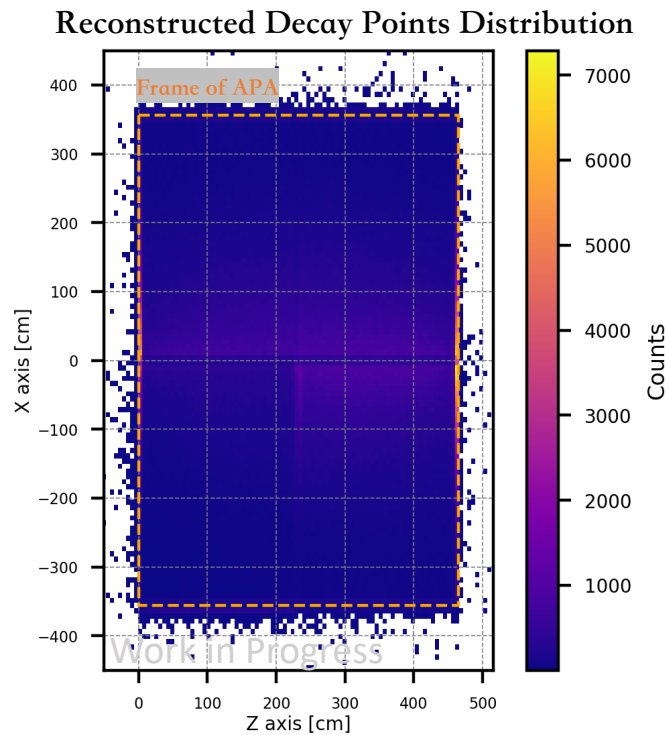
1. Light yield estimation of Michel electrons
2. Single Michel electron candidate finding

□ Preliminary μ^- lifetime measurement

- 1. Selection and purification of Michel electrons**
2. Muon lifetime reconstruction
3. Lifetime fitting

MC Cosmic Simulation

- ❖ Dataset: 1,926,732 cosmic events ([prod_cosmics_radiologicals_protodunehd](#))
- ❖ Num of Michel candidates (Michel score > 0.01): 1,868,962



Apply TPC Cuts to MC Dataset:



❖ Preliminary TPC cuts:

Space cut (remove edge candidates): $x \in [-356, 356]$, $y \in [30, 580]$, $z \in [30, 435]$ (in unit of cm)

Michel score cut (**MS**): $MS > 0.3$

Michel hits cut (**MH**): $MH > 3$

❖ Final results:

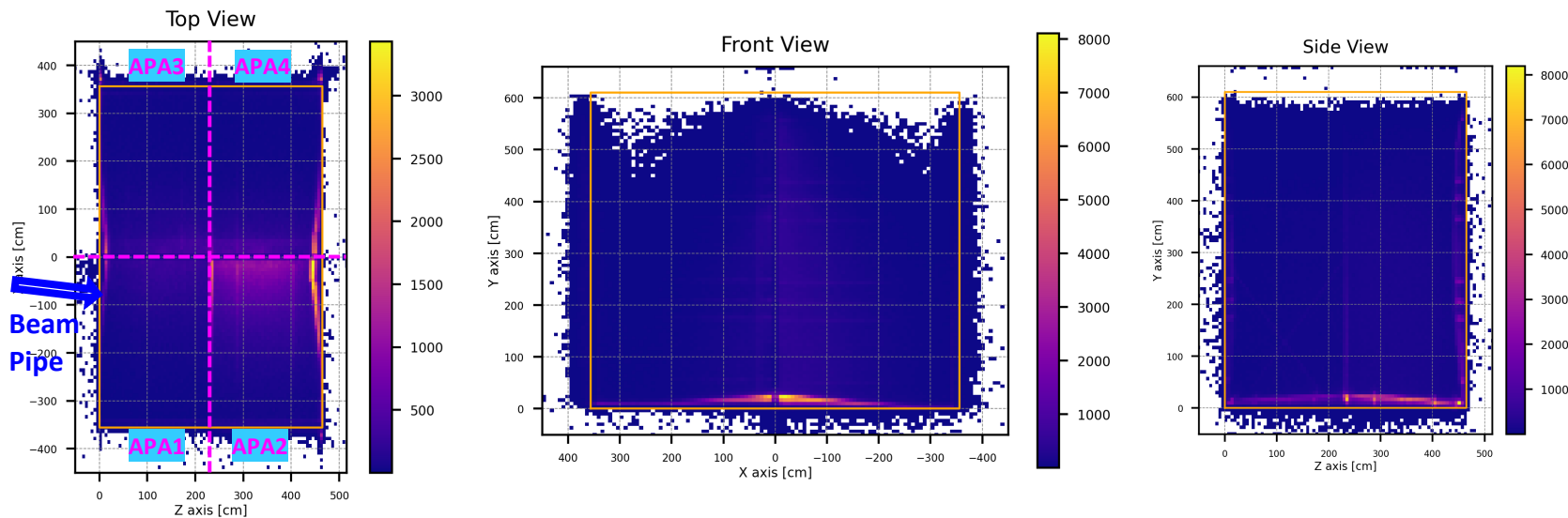
TPC Cuts	#(Total Candidates)	#(True Michels)	#Purity (True/Total)
Initial	1,868,962	397,144	21.2%
Space	893,456 (47.8%)	343,890 (86.6%)	38.5%
Space && MS	369,437 (19.8%)	276,792 (69.7%)	74.9%
Space && MS && MH	335,128 (17.9%)	264,479 (66.6%)	78.9%

Apply TPC Cuts to DATA (I)

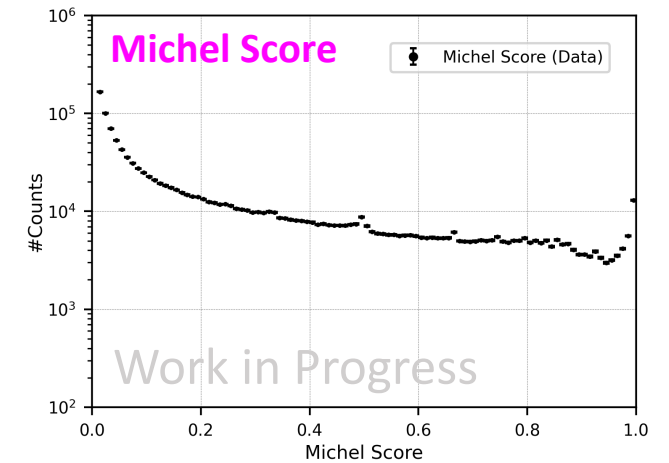
DATA

- ❖ Dataset: 2,127,801 events (~167h of data taking)
- ❖ Num of Michel candidates (Michel score > 0.01): 1,257,997

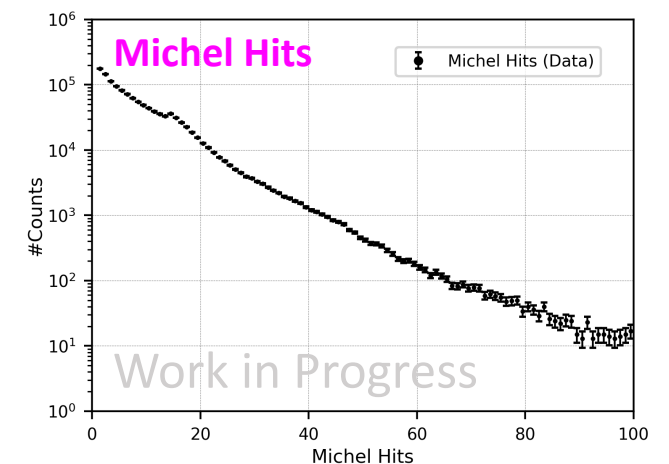
Distribution of Pandora Reconstructed Decay Vertices



Work in Progress



Work in Progress



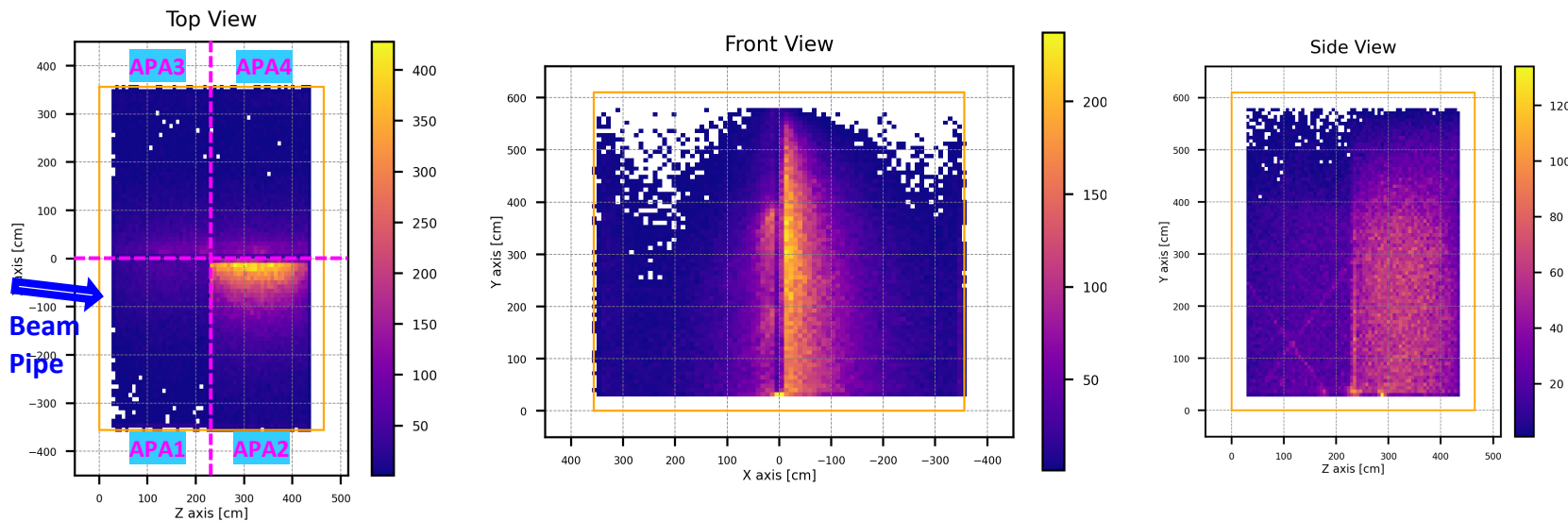
Work in Progress

Apply TPC Cuts to DATA (II)

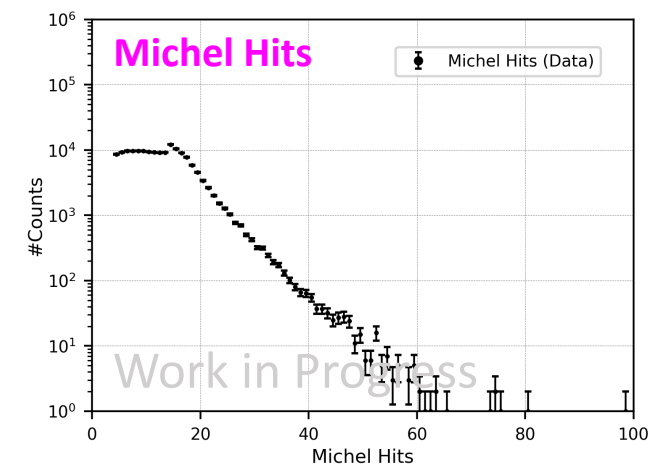
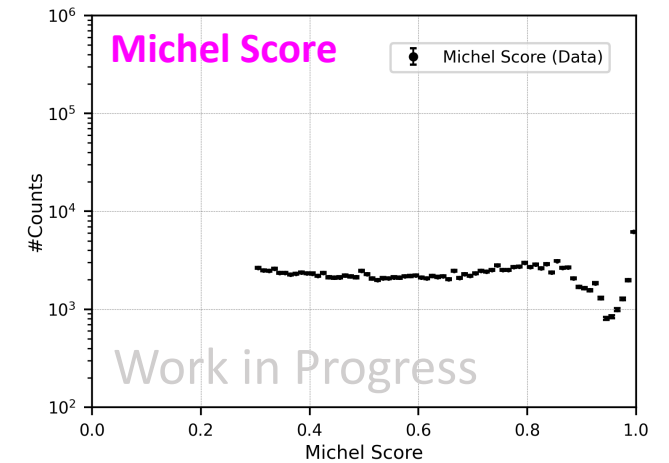
DATA

❖ Survived Michel candidates after TPC cuts: 159,651 (12.7%)

Distribution of Pandora Reconstructed Decay Vertices



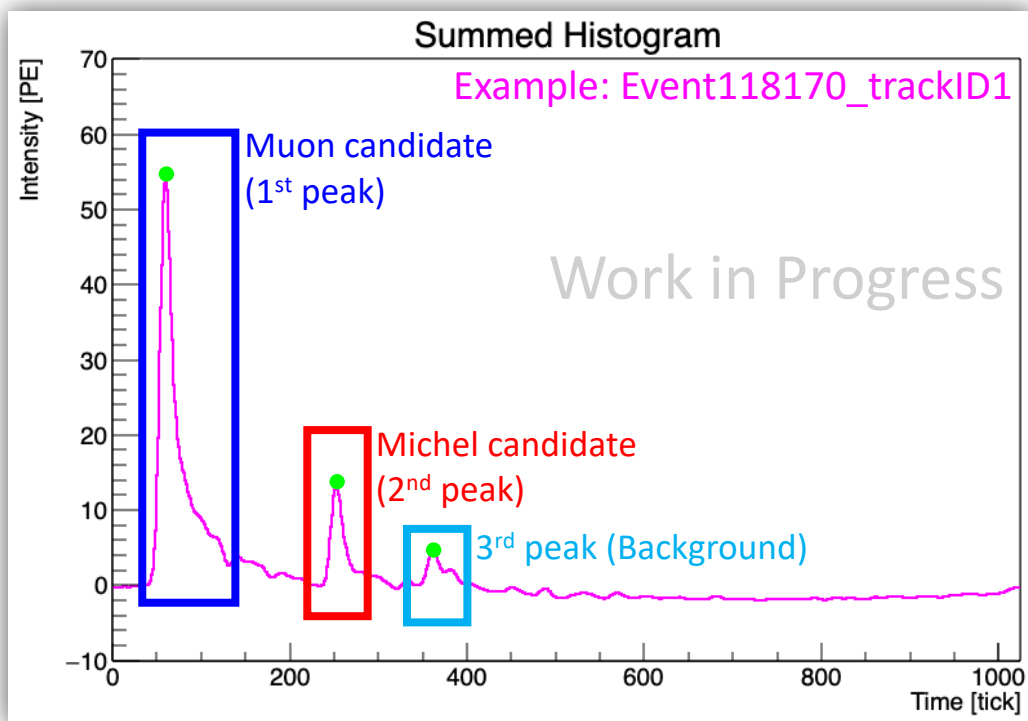
Work in Progress



Optical Waveform Processing (I):

DATA

- ❖ Robust-signal criterion: ≥ 3 **responsive optical channels** per Michel candidate
- ❖ Apply peak-finding algorithm to summed waveform of Michel candidate
- ❖ Primary threshold of peak finding: **0.3PE** $\Rightarrow$ If no 2nd or 3rd peak, record 0



Recorded info of selected peaks

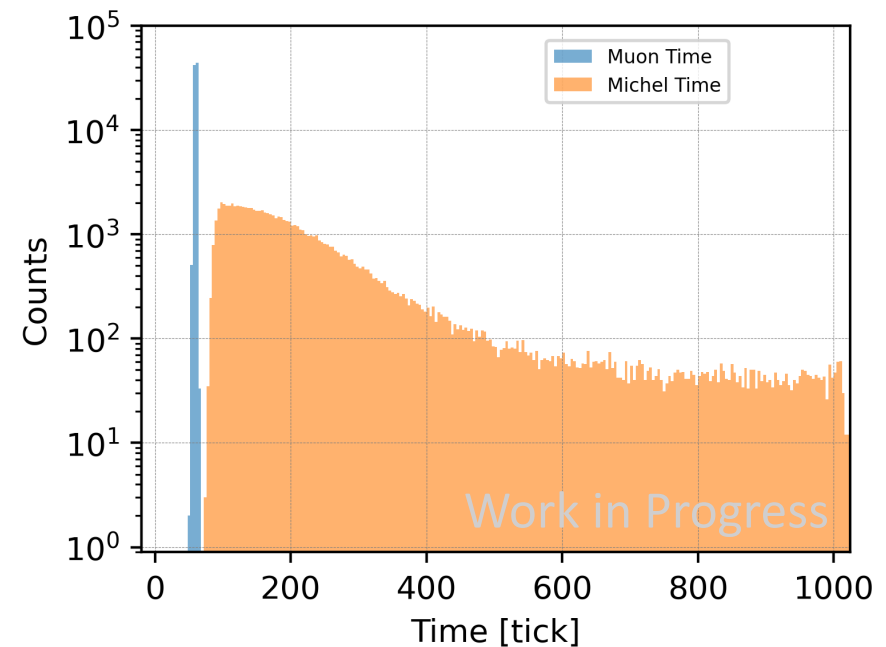
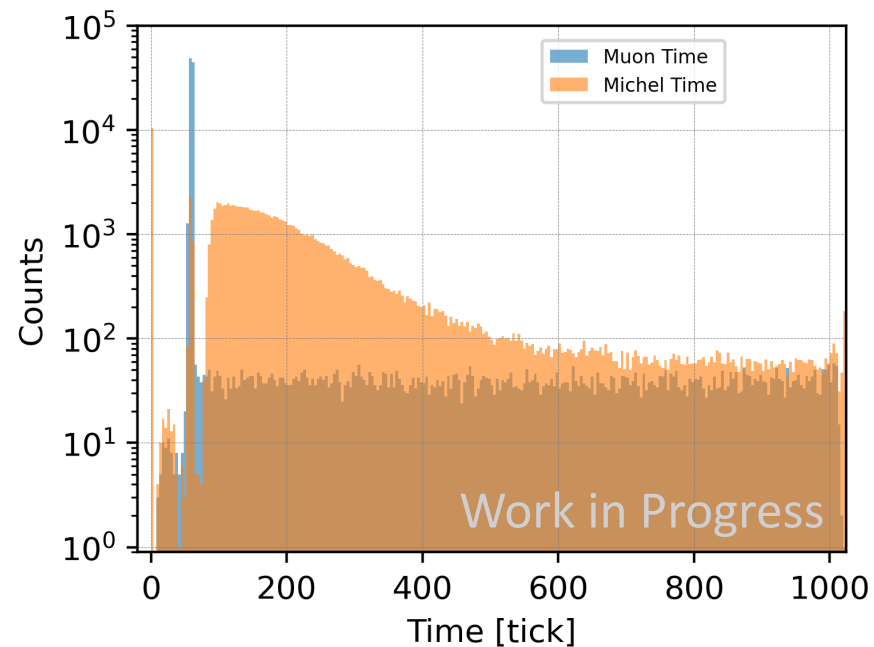
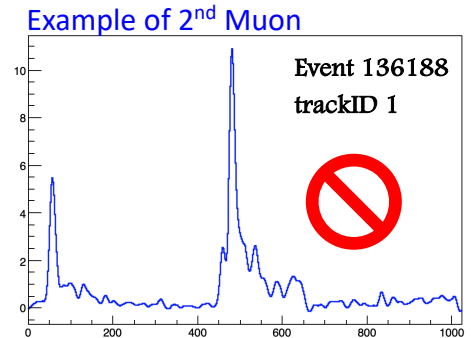
```
----Info of muon, Michel and 3rd candidates ----  
[Saved] Muon time peak: 60  
        Final intensity (min side): 51.8314  
        Left turn: 37 (height=54.4773)  
        Right turn: 132 (height=51.8314)  
[Saved] Michel time peak: 253  
        Final intensity (min side): 11.8037  
        Left turn: 234 (height=13.6318)  
        Right turn: 277 (height=11.8037)  
[Saved] Third time peak: 362  
        Final intensity (min side): 2.68379  
        Left turn: 344 (height=4.48533)  
        Right turn: 375 (height=2.68379)
```

Optical Waveform Processing (II):

DATA

❖ Michel candidate (2nd peak) should be after Muon candidate (1st peak): $t_{2nd} > t_{1st}$ ←

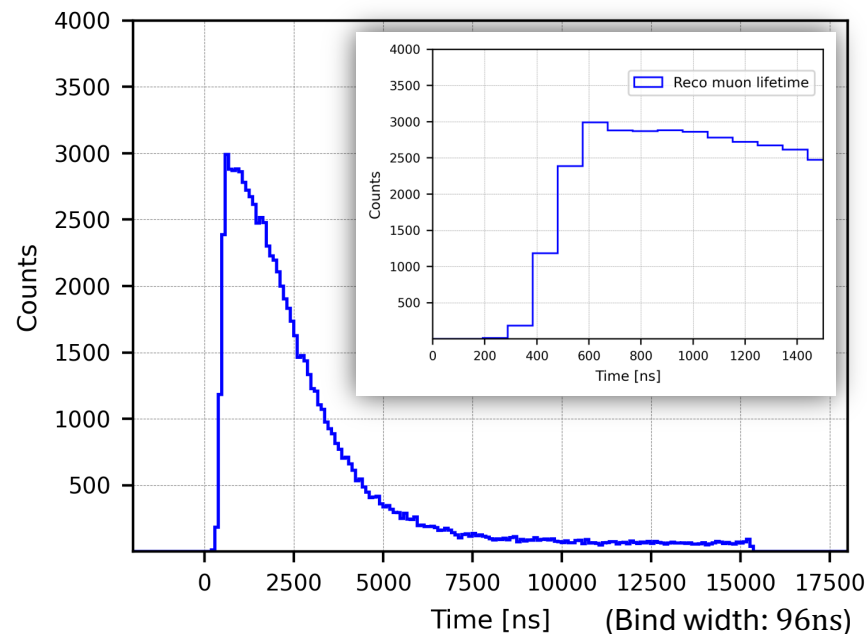
❖ Waveform should be triggered by muon candidate (1st peak): $t_{1st} \in [50, 65](\text{tick})$



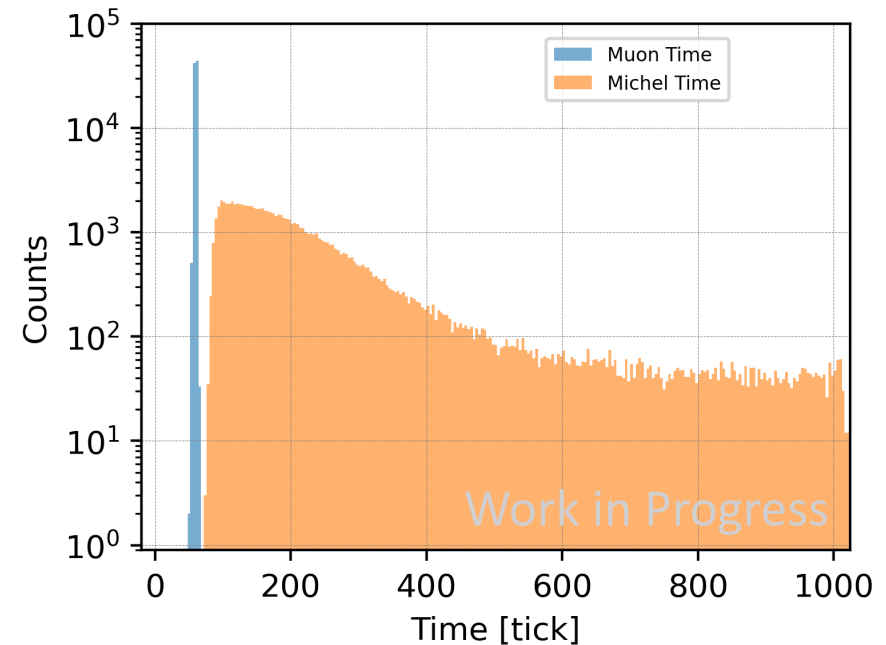
Preliminary Lifetime Distribution

DATA

- ❖ Lifetime calculation: $(t_{2nd} - t_{1st})$
- ❖ PDS Limitation: difficult to identify events with reconstructed lifetime $< 384\text{ns}$
- ❖ Limited reliability of lifetime distribution: false Michel electron events,
misidentified optical Michel signals (Ex: delayed light signals of muons)...



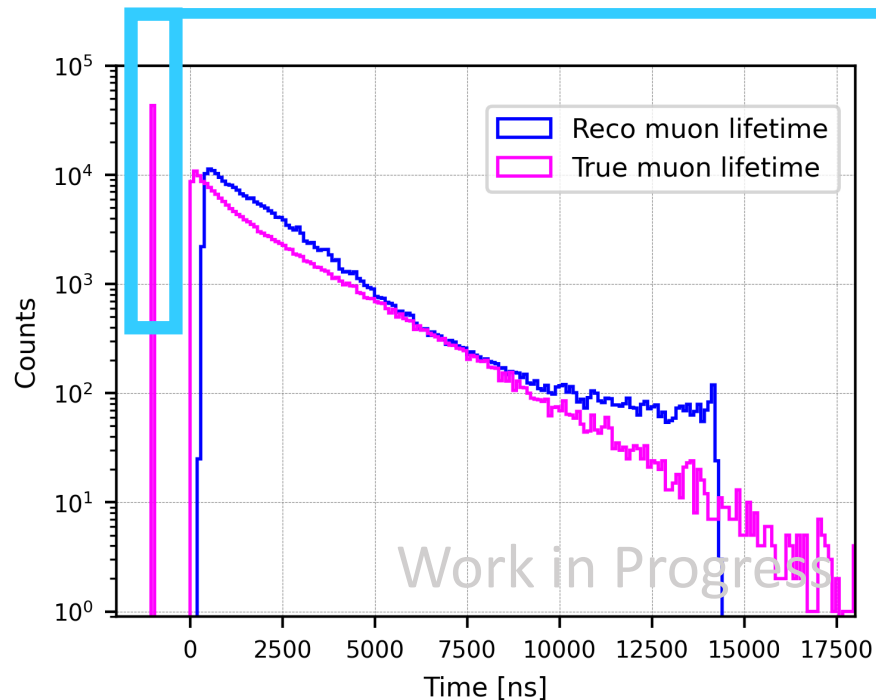
Event-by-event
subtraction



Lifetime Distribution in MC (I)

- ❖ Apply the same analysis procedure to MC dataset
- ❖ Every event has both reco and true lifetime values
- ❖ Significant discrepancy between reco and true lifetime distributions

Efficiency	Michel Purity
186900/264479 (70.7%)	186900/230076 (81.2%)



False Michel:
The lifetime (MC truth) will be labeled as -1000ns

Lifetime Distribution in MC (II)

MC

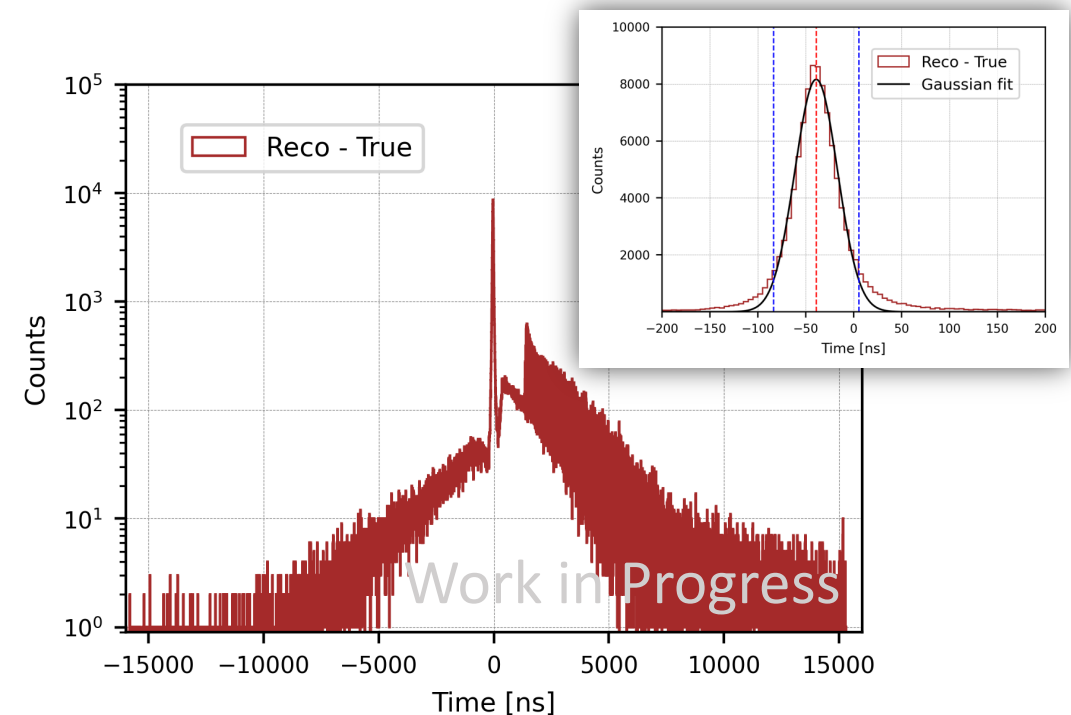
- ❖ Calculate event-by-event reco and MC truth difference
- ❖ (Reco – True) peak: @ –40ns with range [–120, 40]ns
- ❖ Define **PDS Recognition Rate**:

$$[(\text{Reco} - \text{True}) \text{ peak}] / \text{True Michel}$$

Efficiency	Michel Purity	PDS Recognition Rate
186900/264479 (70.7%)	186900/230076 (81.2%)	96212/186900 (51.5%)



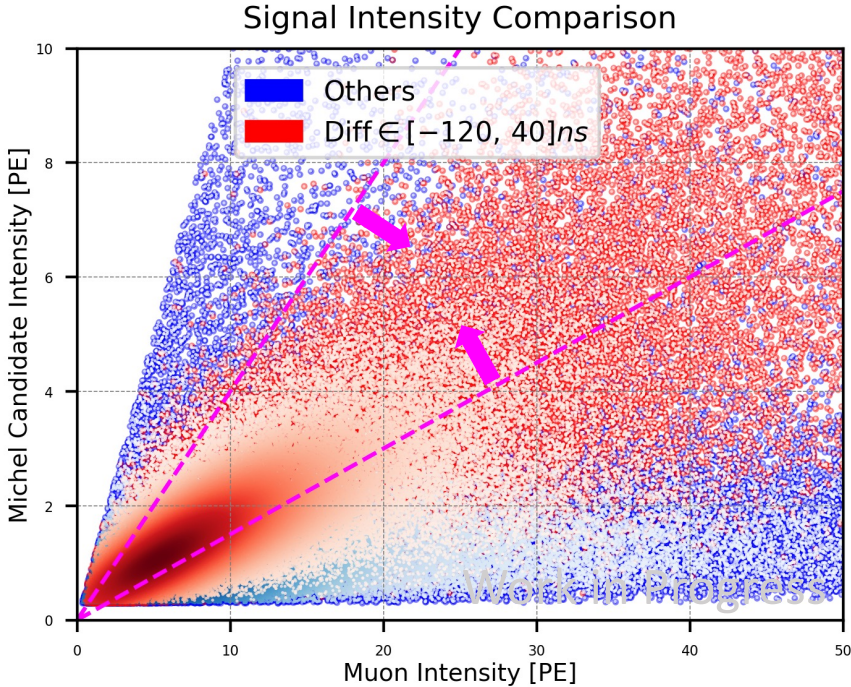
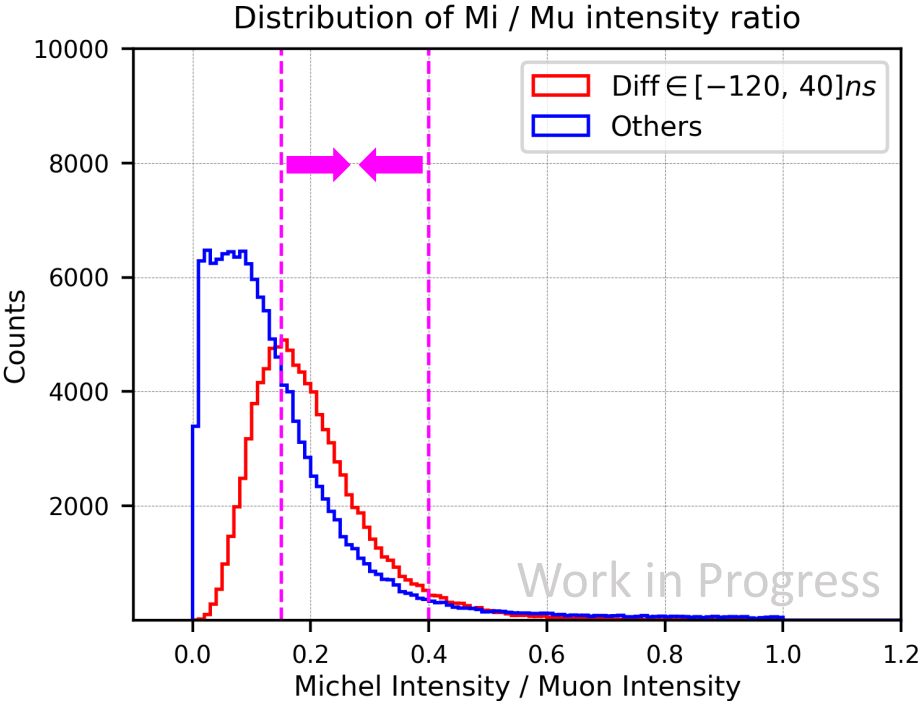
Reco – True



Optical Wvf Purification (I)

- ❖ Target: improve PDS Recognition Rate
- ❖ Constrain the intensity ratio of Michel candidate and muon candidate

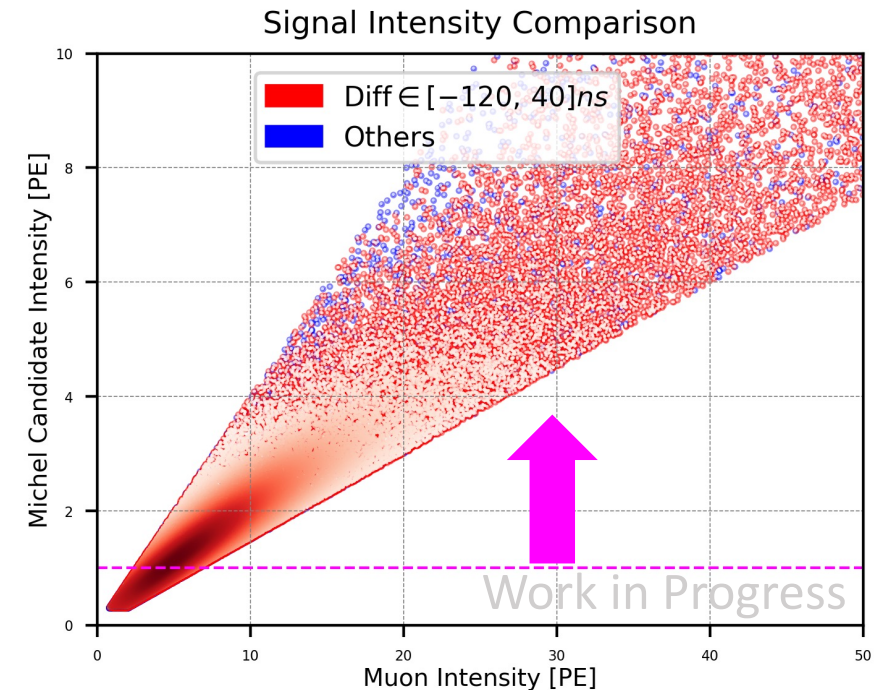
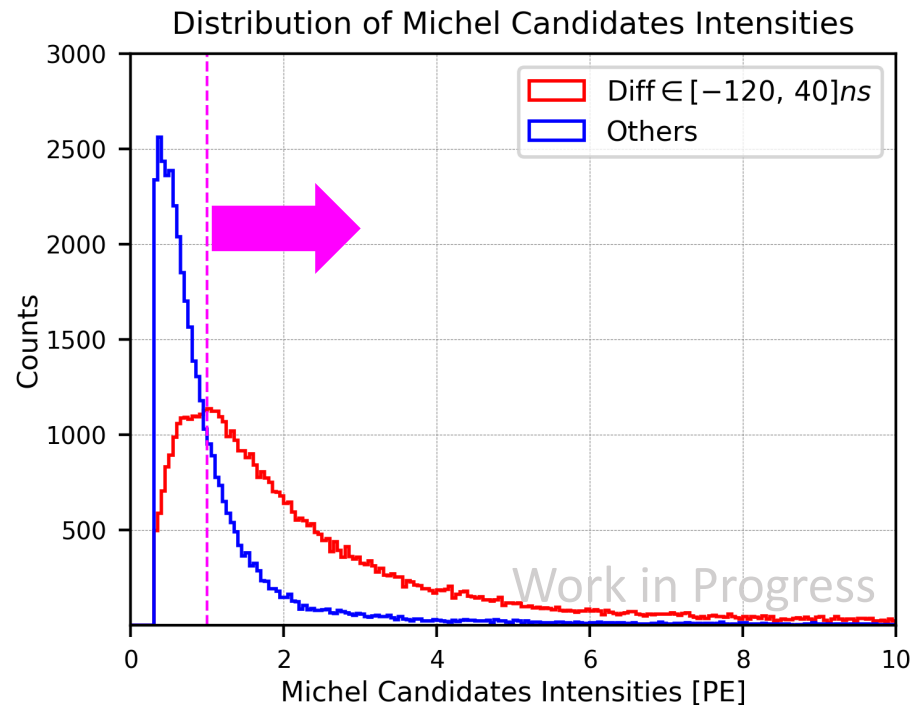
Cut	Efficiency	Michel Purity	PDS Recognition Rate
$\frac{I_{2nd}}{I_{1st}} \in [0.15, 0.4]$	91177/186900 (48.8%)	91177/98779 (92.3%)	58600/91177 (64.3%)



Optical Wvf Purification (II)

- ❖ Signal intensity cut for Michel candidates (I_{2nd})

Cut	Efficiency	Michel Purity	PDS Recognition Rate
$1.0 < I_{2nd}$	54632/91177 (59.9%)	54632/59175 (92.3%)	45339/54632 (83.0%)

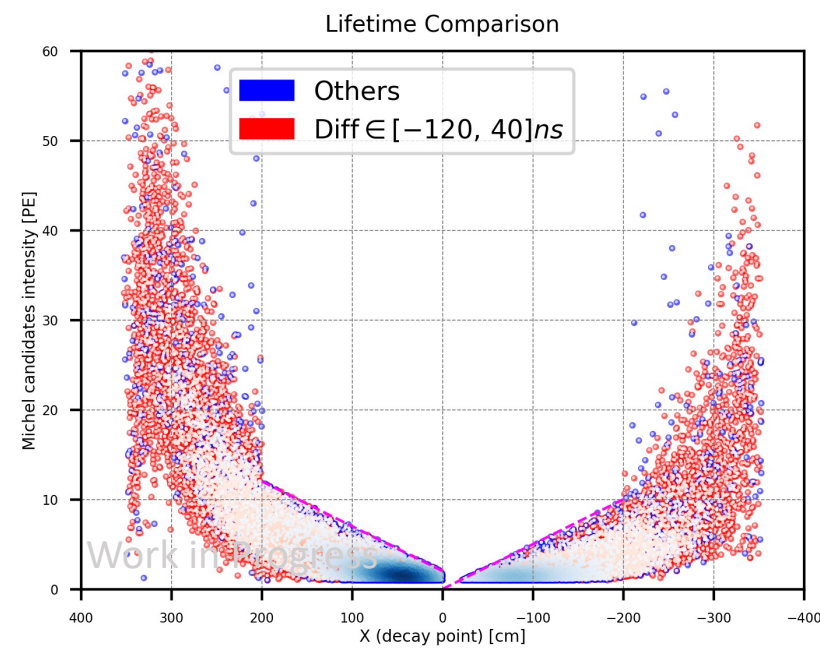
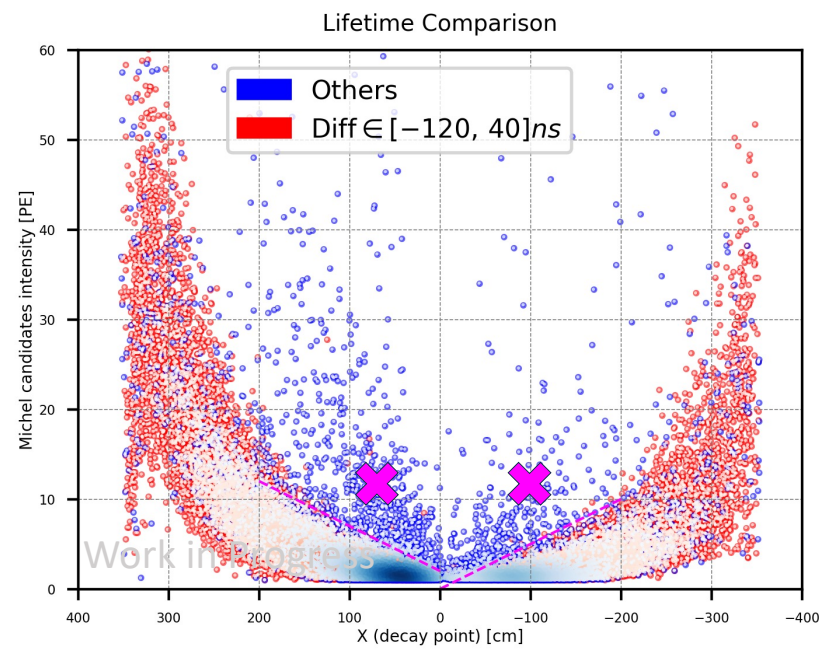


Optical Wvf Purification (III)

MC

- ❖ Cut on (Michel candidate signal, Muon decay position)
- ❖ Asymmetric distribution along drift direction:
Beam chamber: only PDS in APA2 considered
- ❖ Boundaries:
 - Slope = 5/100 [PE/cm]
 - Beam chamber ($X < 0$): $I_{2nd}(X = 0) = 2$
 - Non-beam chamber ($X > 0$): $I_{2nd}(X = 0) = 0$

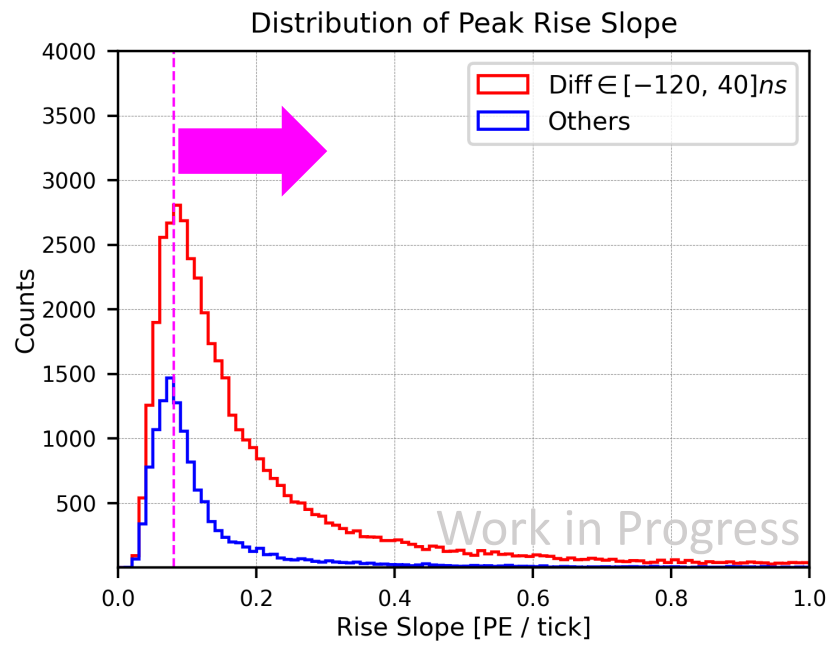
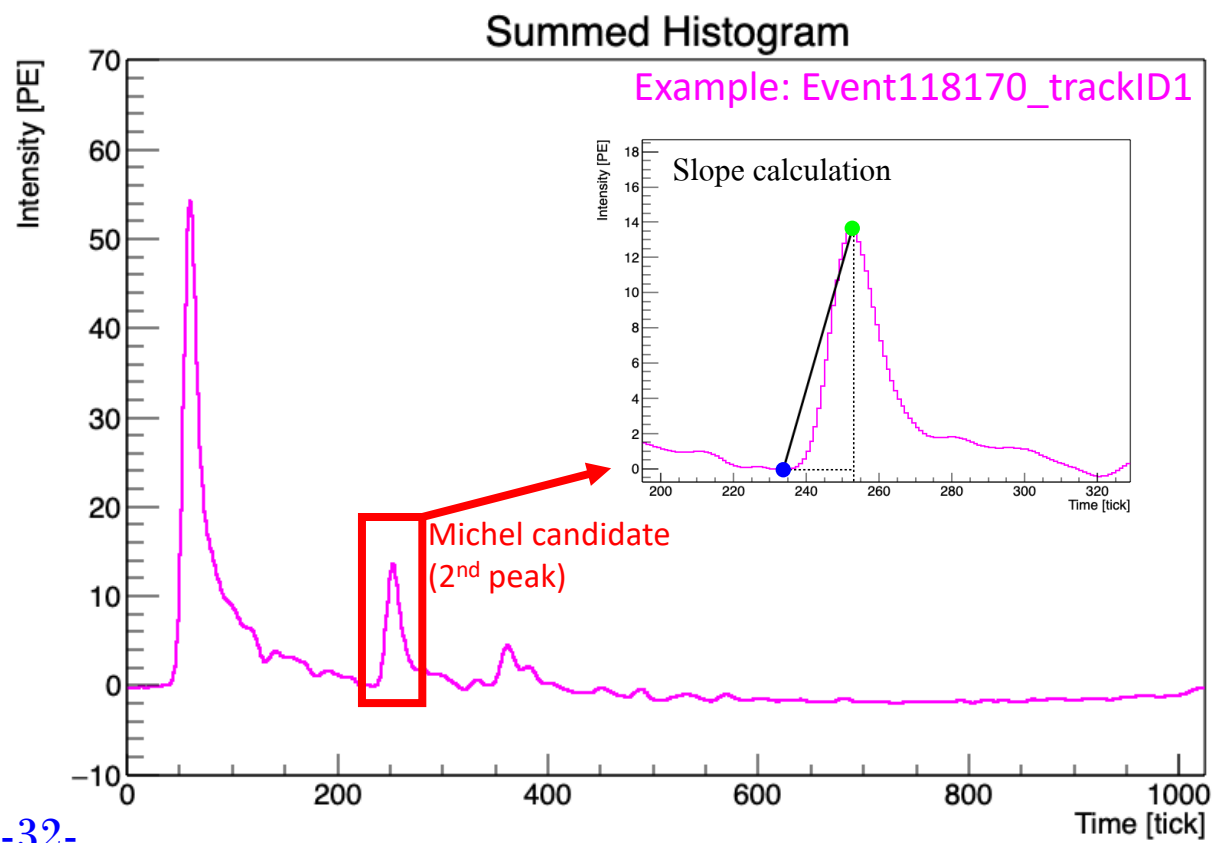
Cut	Efficiency	Michel Purity	PDS Recognition Rate
(I_{2nd}, X)	53725/54632 (98.3%)	53725/57855 (92.9%)	45149/53725 (84.0%)



Optical Wvf Purification (IV)

- ❖ Request peak of Michel candidate has sharp rise (r_{2nd})
- ❖ Simplified slope: peak point and left turning point
- ❖ $[r_{2nd}] = PE/(16ns)$

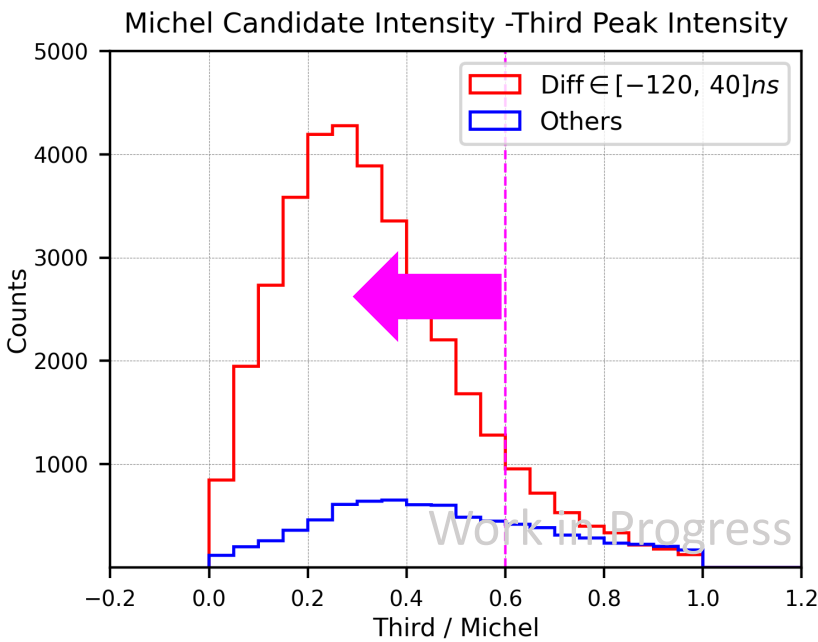
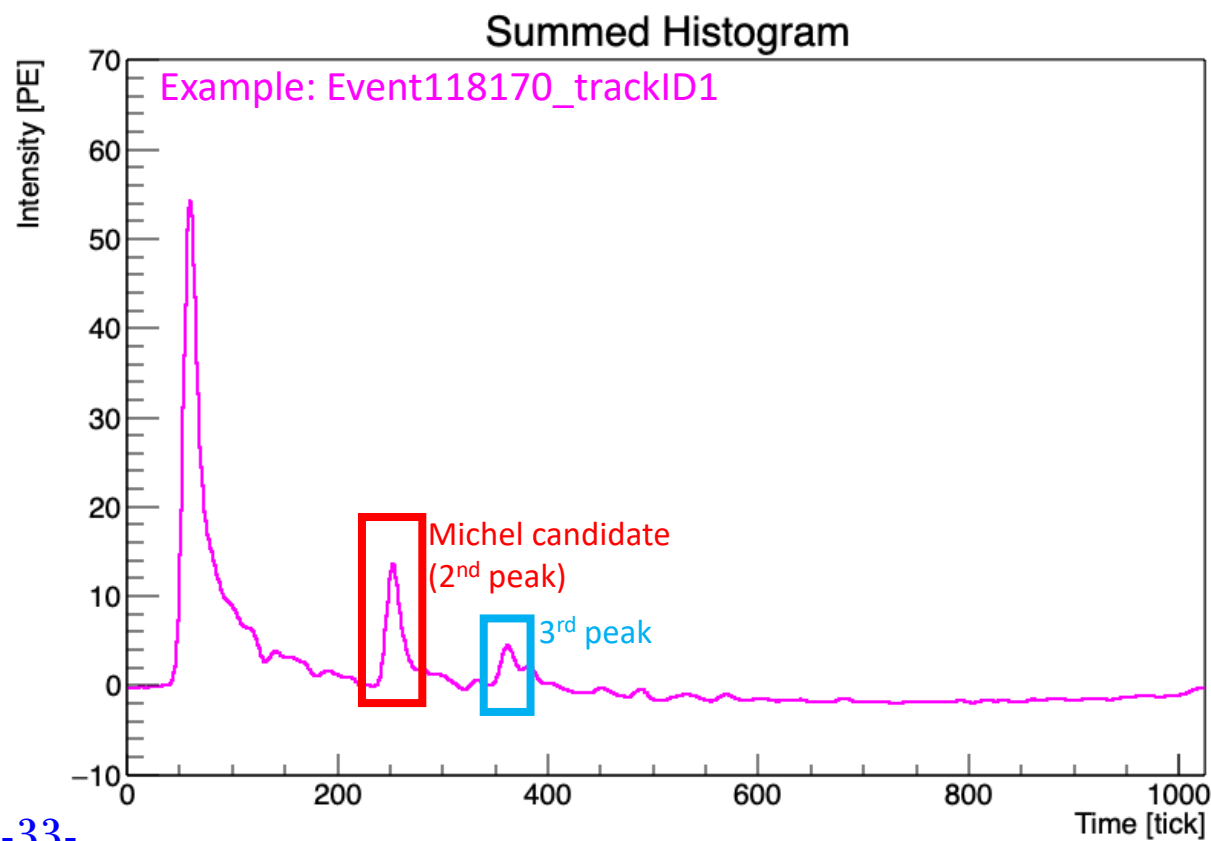
Cut	Efficiency	Michel Purity	PDS Recognition Rate
$0.09 < r_{2nd}$	40699/53725 (75.8%)	40699/43830 (92.9%)	36136/40699 (88.8%)



Optical Wvf Purification (V)

- ❖ 2nd (Michel candidate) and 3rd peak intensities ratio
- ❖ Request Michel candidates appear against background

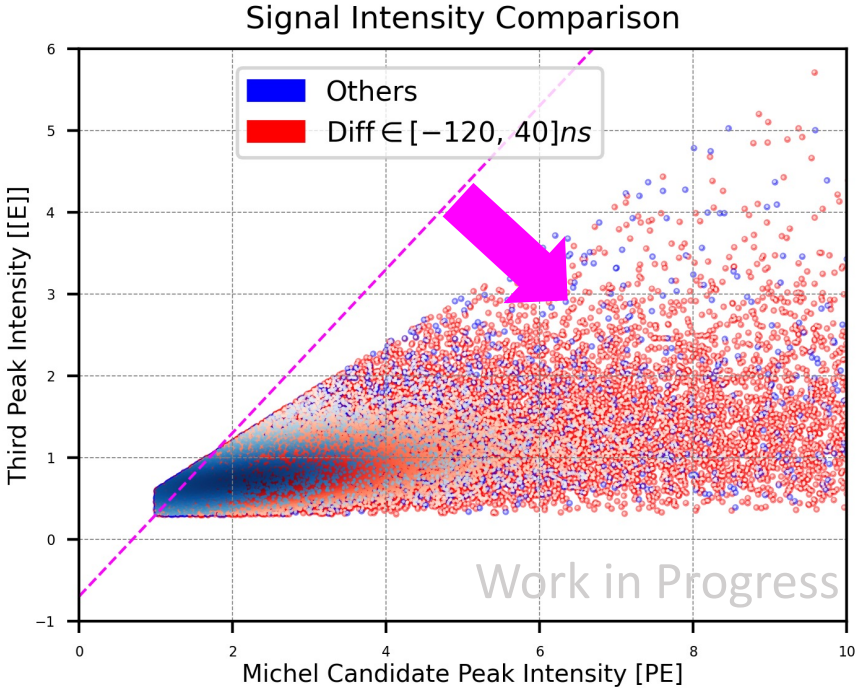
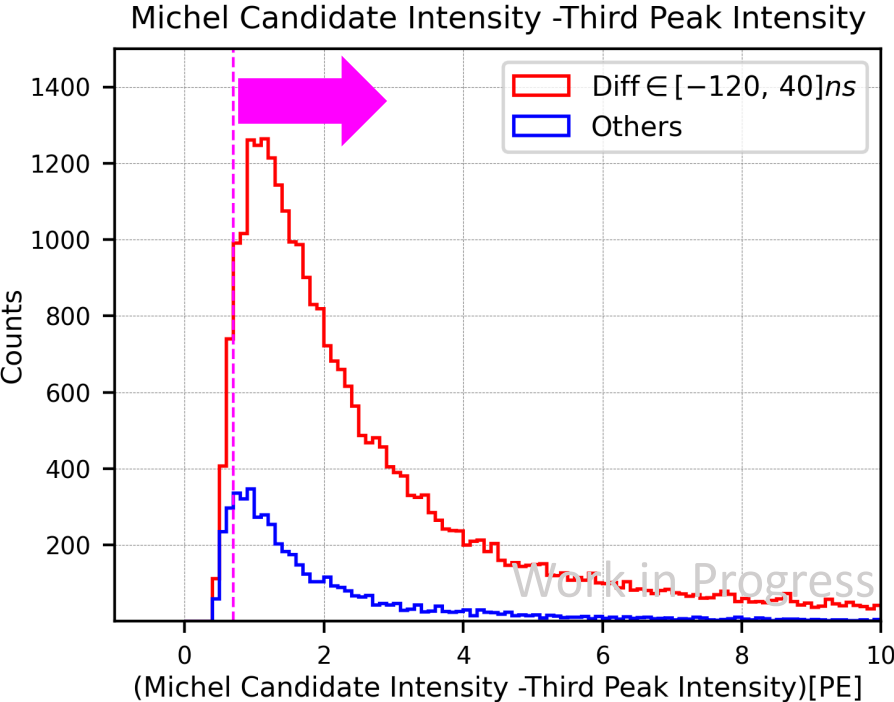
Cut	Efficiency	Michel Purity	PDS Recognition Rate
$\frac{I_{3rd}}{I_{2nd}} < 0.6$	35140/40699 (86.3%)	35140/37818 (92.9%)	32407/35140 (92.2%)



Optical Wvf Purification (VI)

❖ Absolute difference of 2nd and 3rd peak intensities

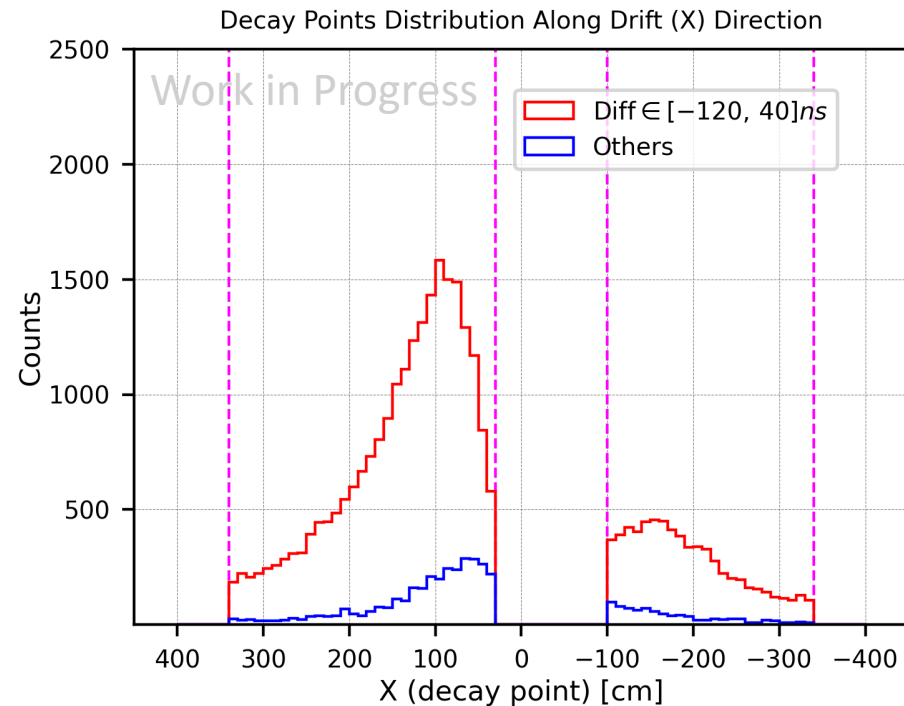
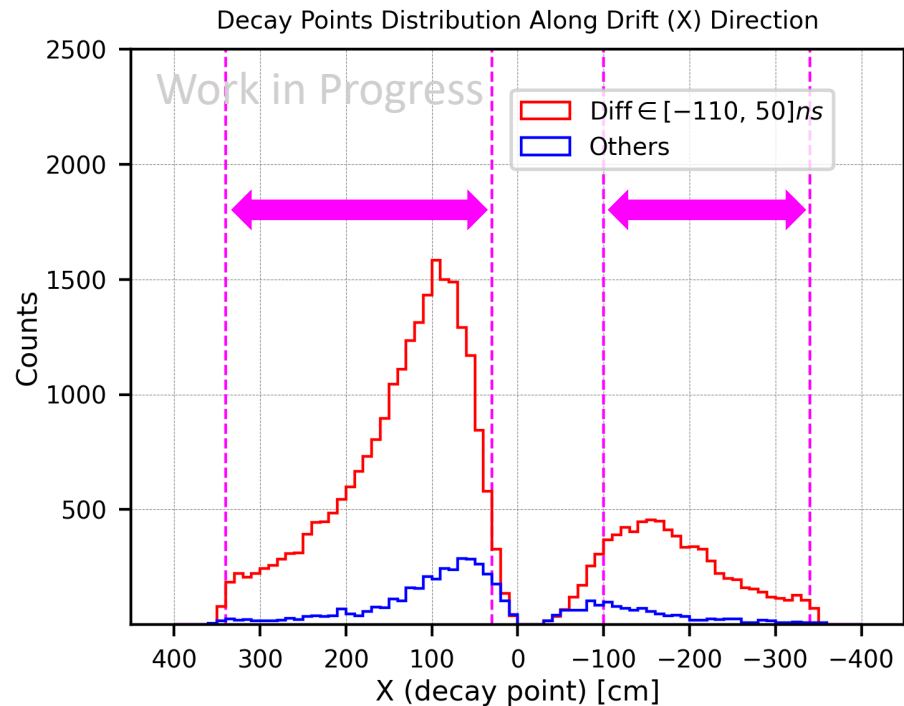
Cut	Efficiency	Michel Purity	PDS Recognition Rate
$0.7 < (I_{2nd} - I_{3rd})$	33425/35140 (95.1%)	33425/35968 (92.9%)	31148/33425 (93.2%)



Optical Wvf Purification (VII)

❖ Throw events close to cathode ($X = 0$) or anode

Cut	Efficiency	Michel Purity	PDS Recognition Rate
$X \in [30, 340] \cup [-340, -100]$	31278/33425 (93.6%)	31278/33532 (93.3%)	29511/31278 (94.4%)



Wvf Purification Summary

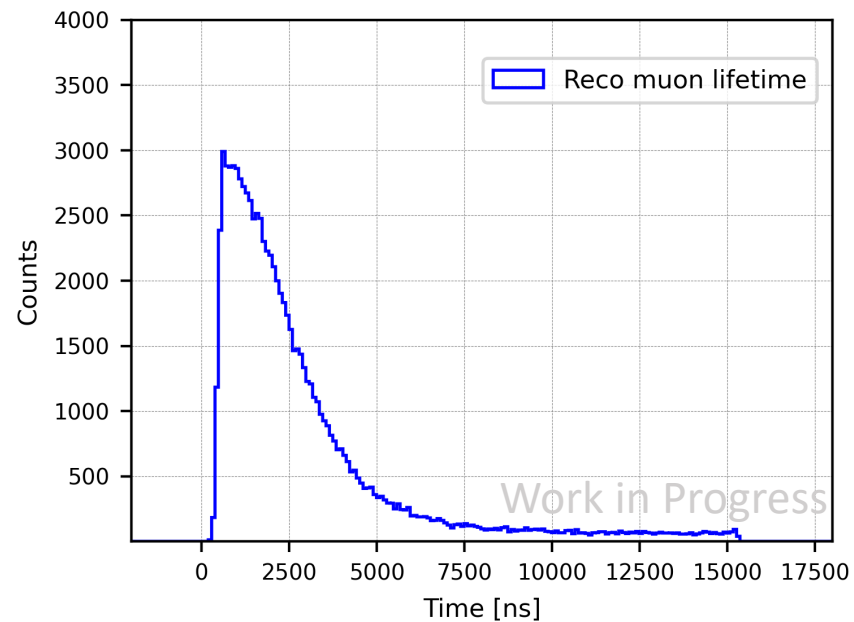
- ❖ PDS helps Michel identification (purity 78.9% $\rightarrow$ 93.3%)
- ❖ A sample of Michel electrons with both charge and optical signals has been successfully selected

PDS Cuts	Efficiency	Michel Purity	PDS Recognition rate
Initial PDS Processing	70.7%	81.2%	51.5%
$\frac{I_{2\text{nd}}}{I_{1\text{st}}} \in [0.15, 0.4]$	48.8%	92.3%	64.3%
$1.0 < I_{2\text{nd}}$	59.9%	92.3%	83.0%
$(I_{2\text{nd}}, X)$	98.3%	92.9%	84.0%
$0.09 < r_{2\text{nd}}$	75.8%	92.9%	88.8%
$\frac{I_{3\text{rd}}}{I_{2\text{nd}}} < 0.6$	86.3%	92.9%	92.2%
$0.7 < (I_{2\text{nd}} - I_{3\text{rd}})$	95.1%	92.9%	93.2%
$X \in [30, 340] \cup [-340, -100]$	93.6%	93.3%	94.4%
Final (accumulated)	11.8%	93.3%	94.4%

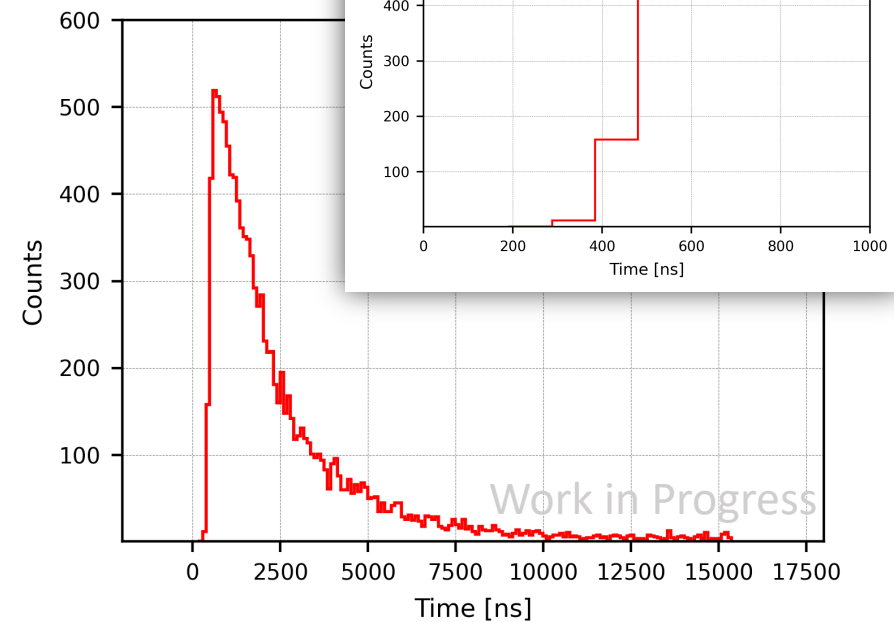
Apply PDS Cuts to DATA

DATA

- ❖ #Candidates: 159,651 $\Rightarrow$ 11,579
- ❖ PDS exhibits limited ability to identify events with reconstructed lifetime < 384 ns



Apply PDS cuts



Outline

□ Introductions

1. Introduction to DUNE & ProtoDUNE_s
2. Photon detection system (PDS) of ProtoDUNE-HD
3. Michel electrons

□ Optical Michel electron signal finding

1. Light yield estimation of Michel electrons
2. Single Michel electron candidate finding

□ Preliminary μ^- lifetime measurement

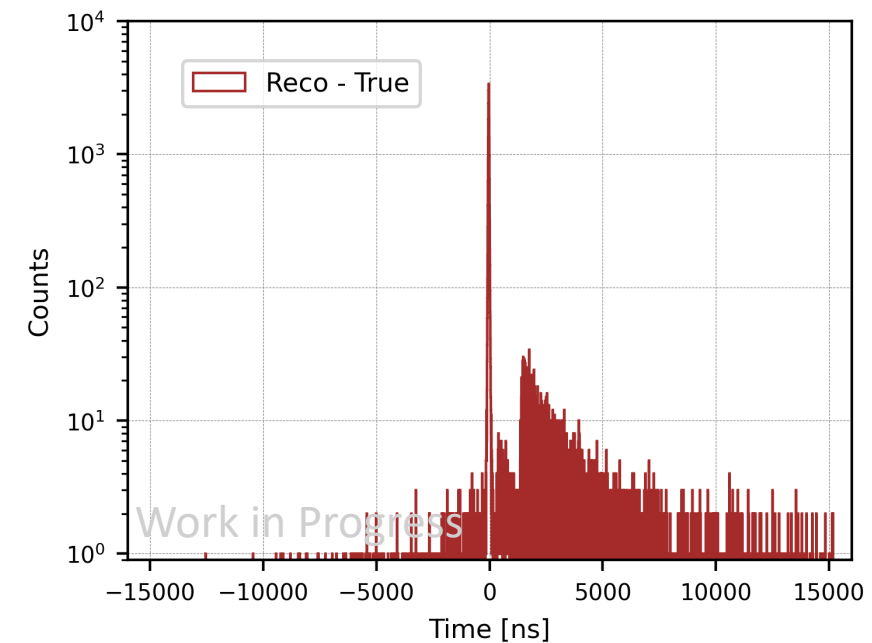
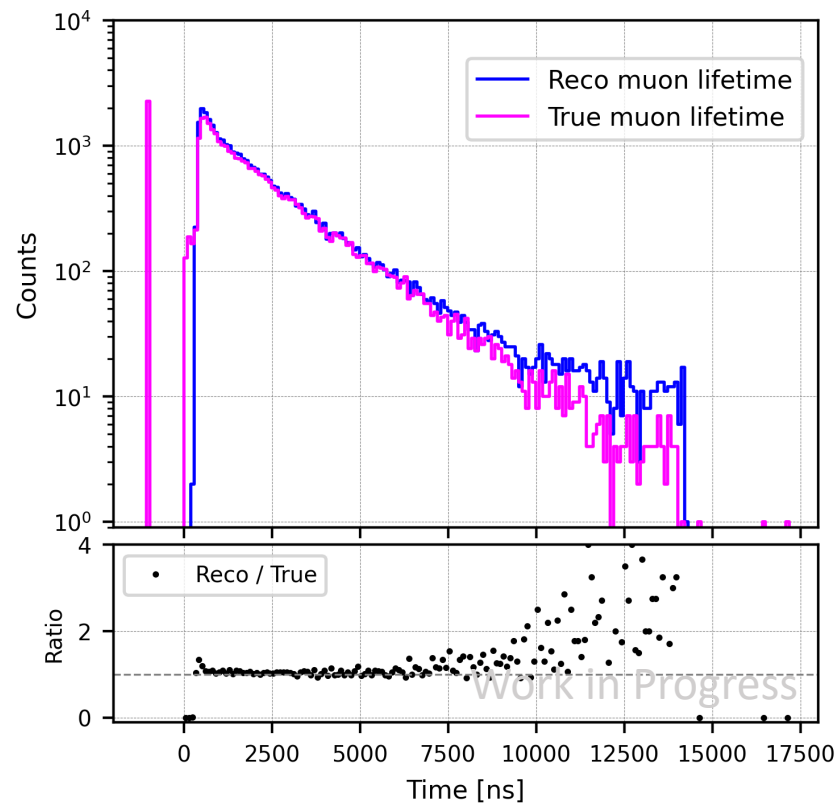
1. Selection and purification of Michel electrons
- 2. Muon lifetime reconstruction**
3. Lifetime fitting

Final Lifetime Distribution (I)

❖ Good consistency between final reconstructed and MC Truth lifetime distributions

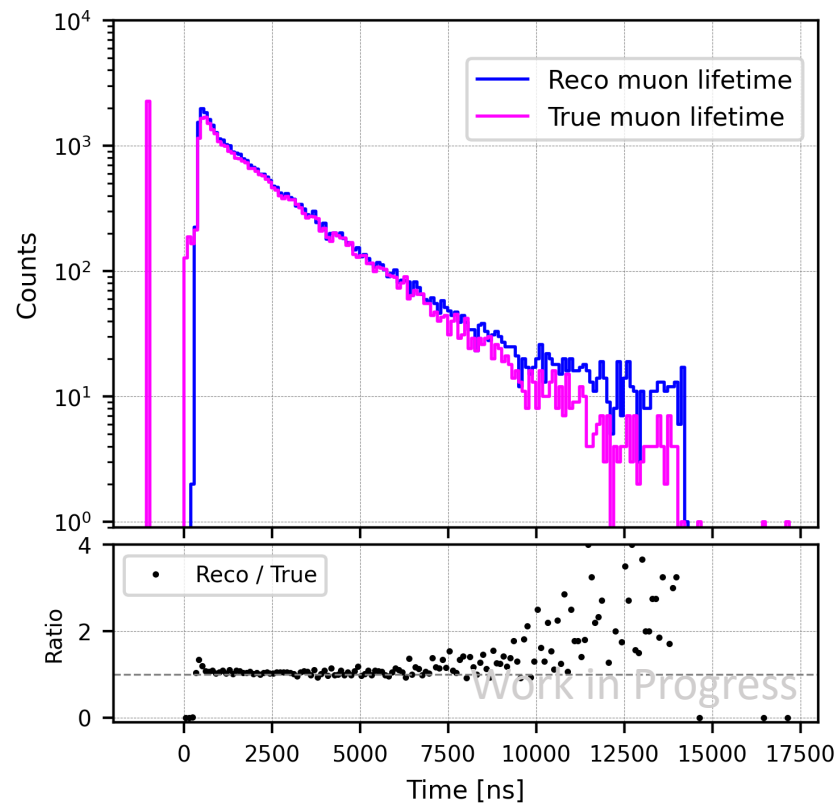
❖ Events with ill-reconstructed lifetimes: 11.9% ($1 - 93.3\% \times 94.4\%$)

False Michel electrons (6.7%); Misidentified true Michel electrons (5.2%)

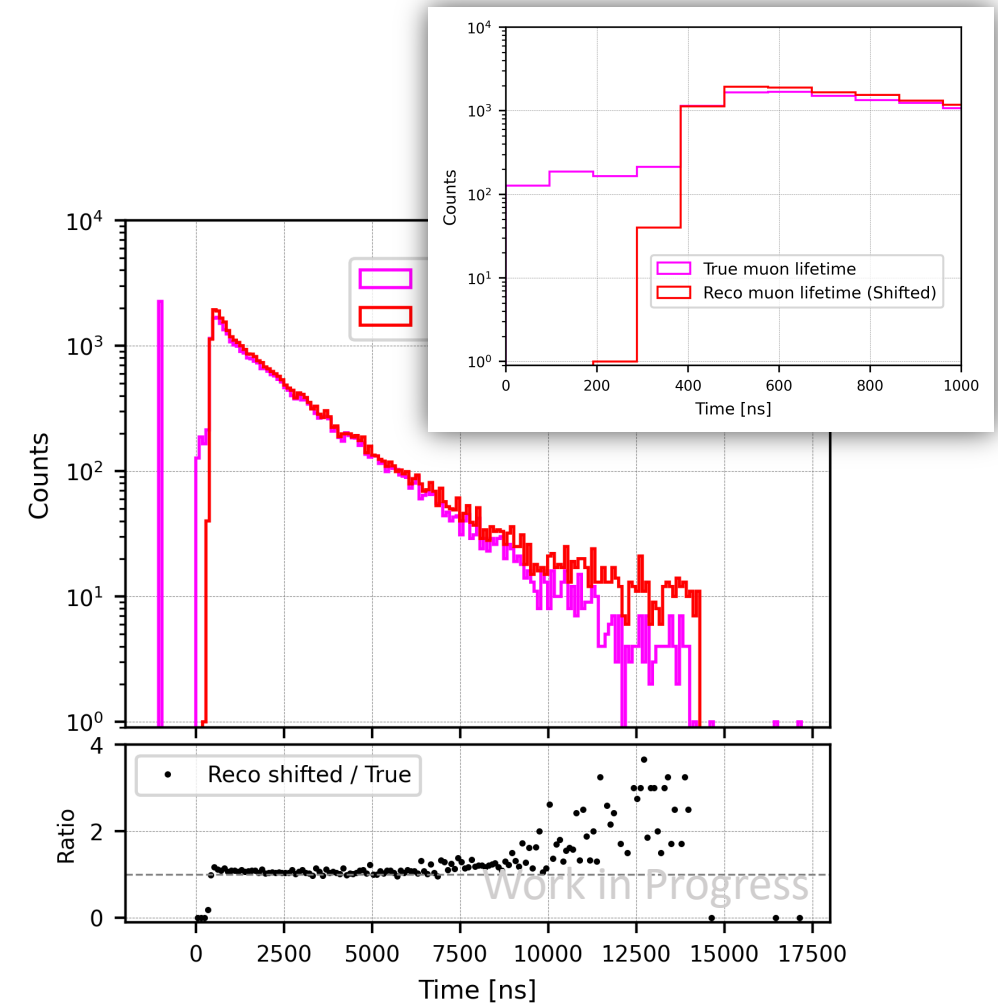


Final Lifetime Distribution (II)

- ❖ Add 40ns to reco lifetimes to compensate biased distribution of (Reco – True)
- ❖ Further improved agreement between reco and MC truth lifetimes

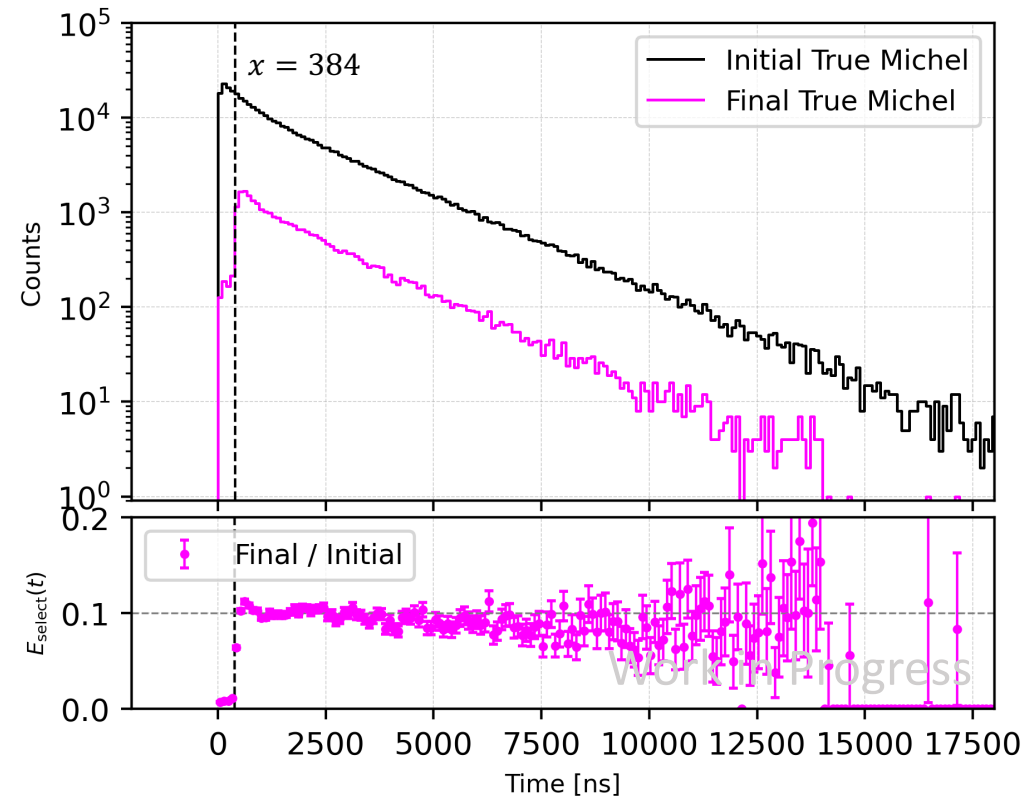


Reco Time +40ns



Efficiency W.R.T. Lifetime

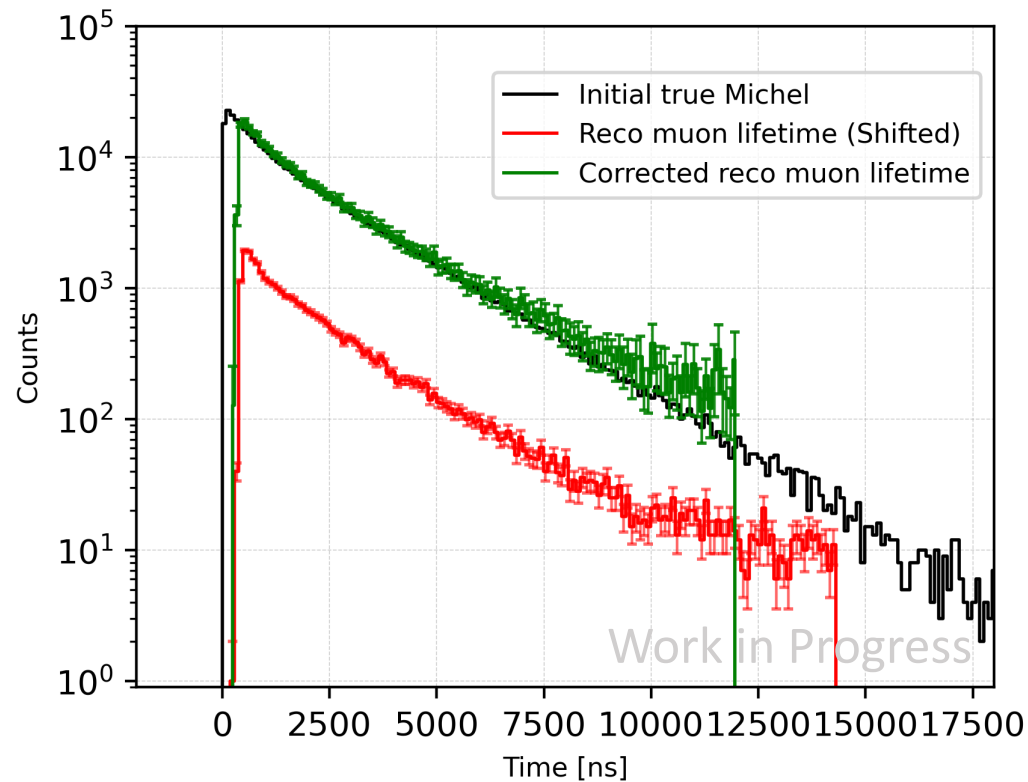
❖ Final selection efficiency w.r.t. lifetime: $E_{\text{select}}^{\text{MC}}(t) = \frac{D_{\text{Final True}}^{\text{MC}}(t)}{D_{\text{Initial True}}^{\text{MC}}(t)}$



Reconstructed Lifetime [MC]

MC

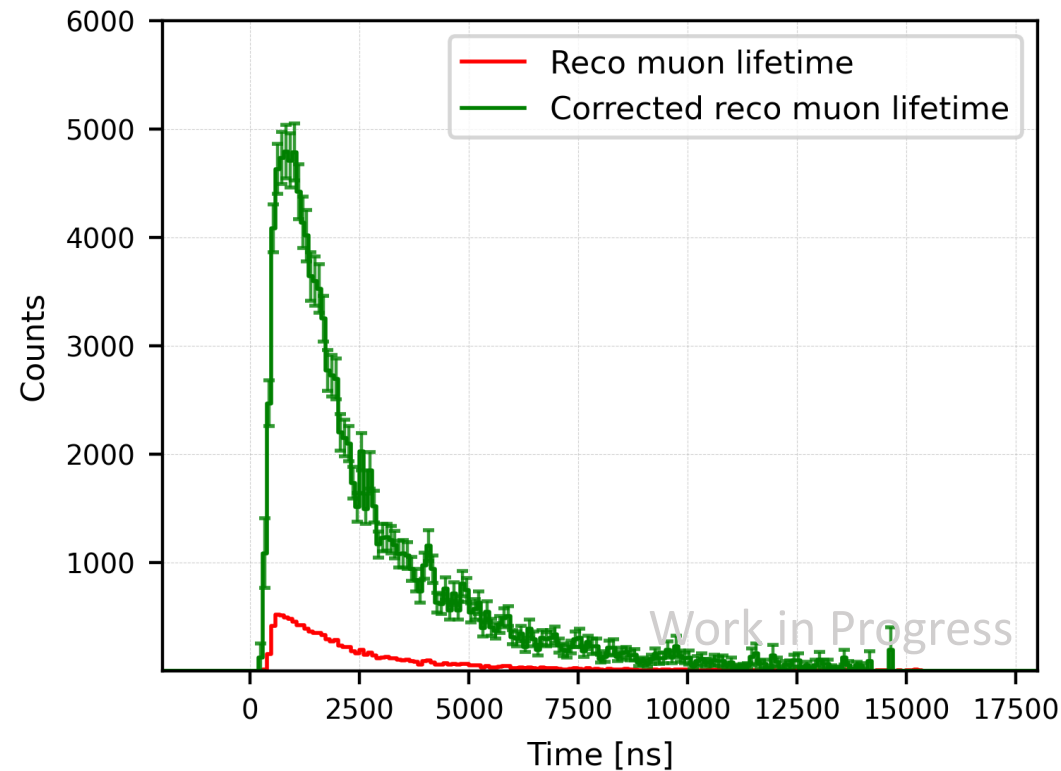
❖ Corrected reconstructed lifetime distribution: $D_{\text{Corr Reco}}^{\text{MC}}(t) = \frac{D_{\text{Final Reco}}^{\text{MC}}(t)}{E_{\text{select}}^{\text{MC}}(t)}$



Reconstructed Lifetime [DATA]

DATA

❖ Corrected reconstructed lifetime distribution: $D_{\text{Corr Reco}}^{\text{DATA}}(t) = \frac{D_{\text{Final Reco}}^{\text{DATA}}(t)}{E_{\text{select}}^{\text{MC}}(t)}$



Outline

□ Introductions

1. Introduction to DUNE & ProtoDUNE_s
2. Photon detection system (PDS) of ProtoDUNE-HD
3. Michel electrons

□ Optical Michel electron signal finding

1. Light yield estimation of Michel electrons
2. Single Michel electron candidate finding

□ Preliminary μ^- lifetime measurement

1. Selection and purification of Michel electrons
2. Detection efficiency calculation
- 3. Lifetime fitting**

Fitting Model (I)

❖ Muon decay rate:

$$f(t) = N^+ \cdot \left[\frac{1}{\tau_{\mu^+}} e^{-t/\tau_{\mu^+}} + \frac{R_H}{\tau_{\mu^+} \cdot R_\mu} e^{-t/\tau_{\mu^-}} \right]$$

- N^+ : initial number of μ^+
- τ_{μ^+} : lifetime of μ^+ , fixed as 2197.0 μ s
- R_H : Huff factor
- R_μ : the flux ratio μ^+/μ^-
- τ_{μ^-} : lifetime of μ^- , including both capture and decay

❖ Integrated formula: number of decay events in time window $[a, b]$:

$$\mu(a, b) = N^+ \left[\left(e^{-a/\tau_{\mu^+}} - e^{-b/\tau_{\mu^+}} \right) + \frac{R_H \tau_{\mu^-}}{\tau_{\mu^+} R_\mu} \left(e^{-a/\tau_{\mu^-}} - e^{-b/\tau_{\mu^-}} \right) \right]$$

❖ Huff factor (R_H) and muon ratio (R_μ) are completely degenerate

Fitting Model (II)

❖ A simplified formula:

$$f(t) = \frac{Nr}{\tau_{\mu^+}} e^{-t/\tau_{\mu^+}} + \frac{N}{\tau_{\mu^-}} e^{-t/\tau_{\mu^-}}$$

▪ N : normalization factor

▪ r : the ratio of normalization factors for μ^+ and μ^-

❖ Integrated form:

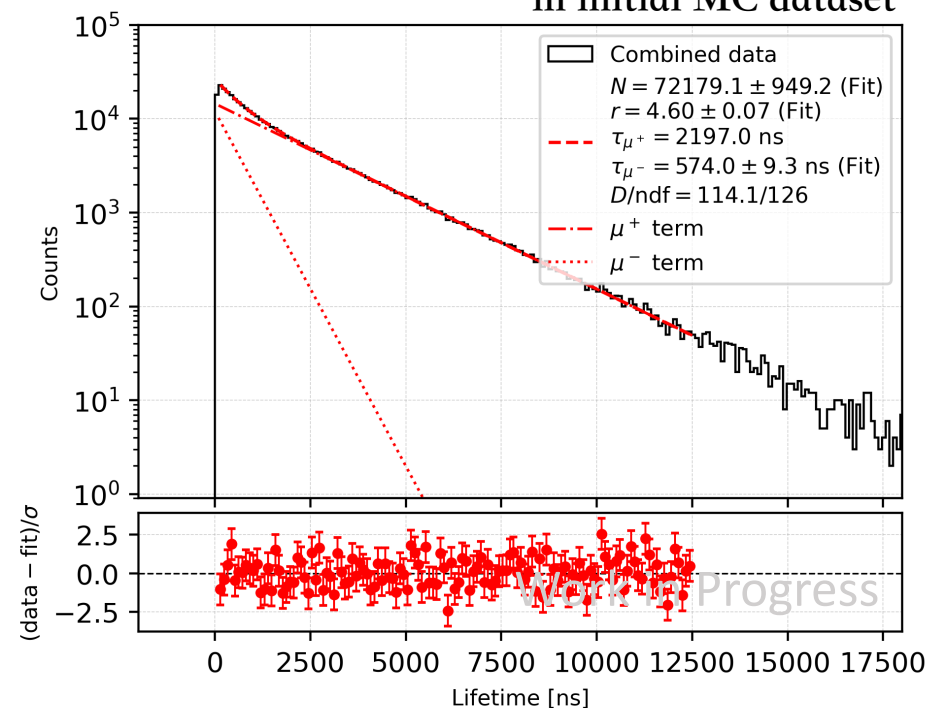
$$\mu(a, b) = Nr \left(e^{-a/\tau_{\mu^+}} - e^{-b/\tau_{\mu^+}} \right) + N \left(e^{-a/\tau_{\mu^-}} - e^{-b/\tau_{\mu^-}} \right)$$

❖ Two formulas are equivalent given:

$$N = N^+ \cdot \frac{R_H \cdot \tau_{\mu^-}}{R_{\mu} \cdot \tau_{\mu^+}}, \quad r = \frac{R_{\mu} \cdot \tau_{\mu^+}}{R_H \cdot \tau_{\mu^-}}$$

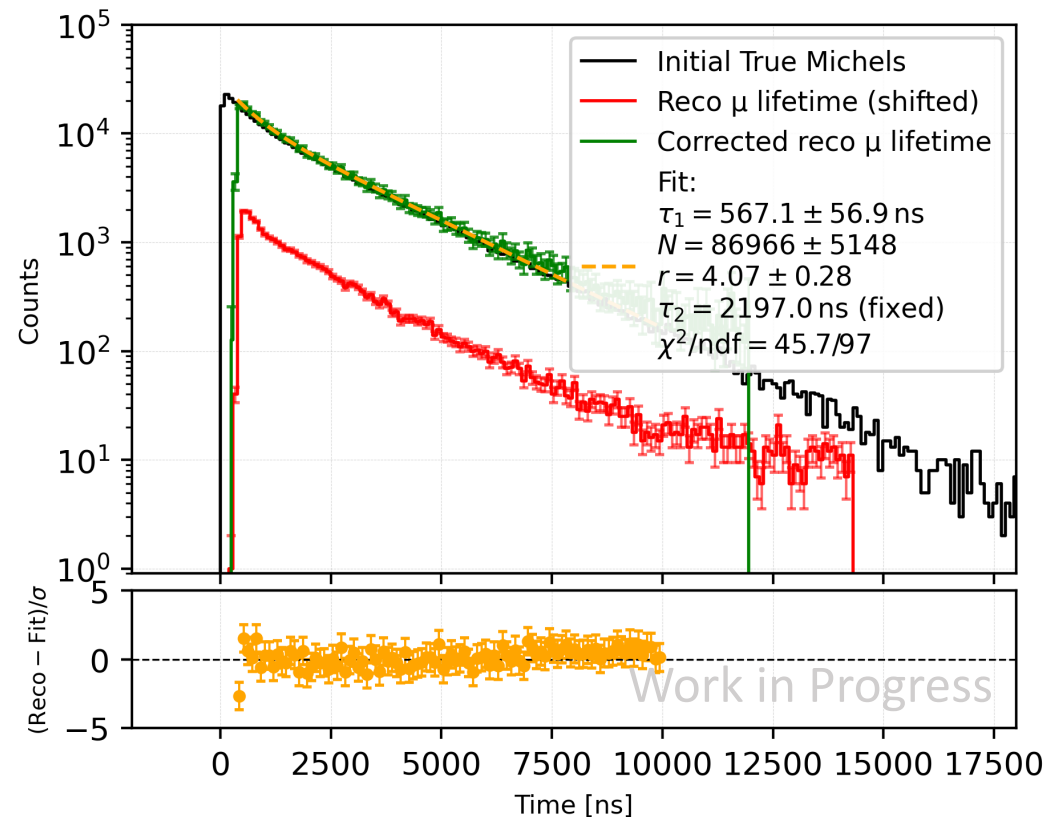
❖ The simplified formula accurately describes the lifetime distribution of decayed muons in the initial MC dataset prior to any event selections

Lifetime distribution of decayed muons
in initial MC dataset



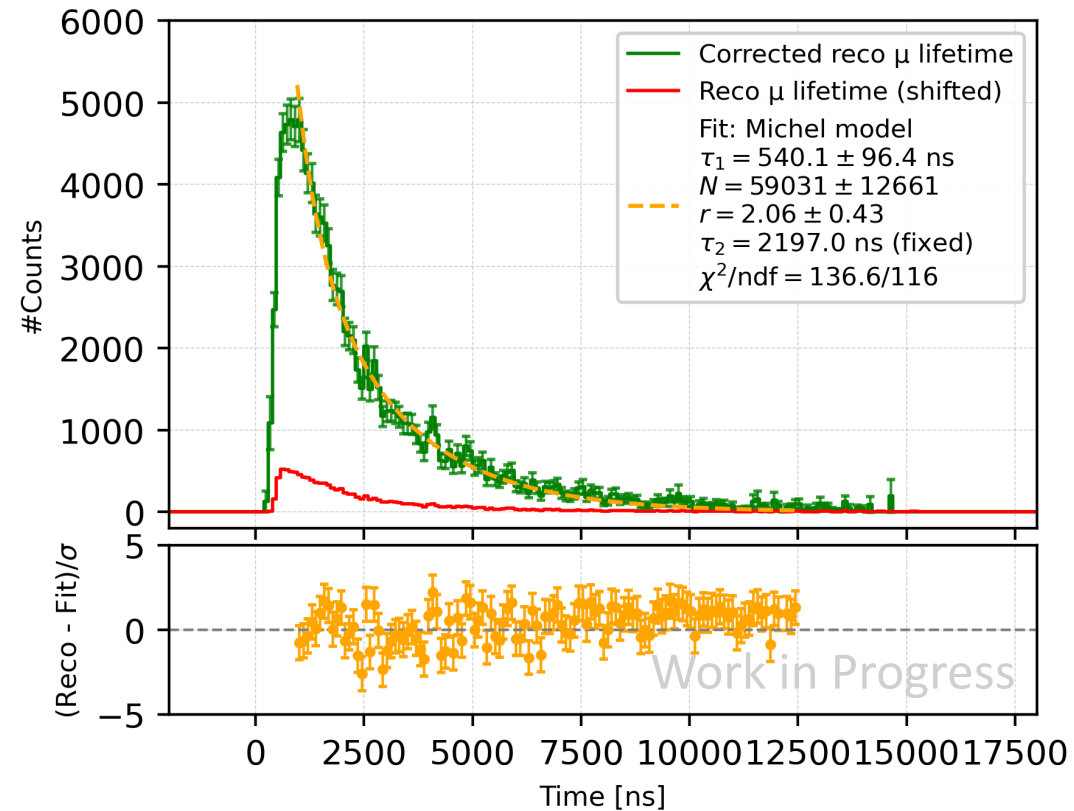
Lifetime Fitting in MC

- ❖ Apply the fitting formula introduced in the previous page (fix $\tau_{\mu^+} = 2197.0\text{ns}$):
- ❖ The fitted value of τ_{μ^-} agrees well with the MC input value of 579ns within uncertainties



Lifetime Fitting in Data

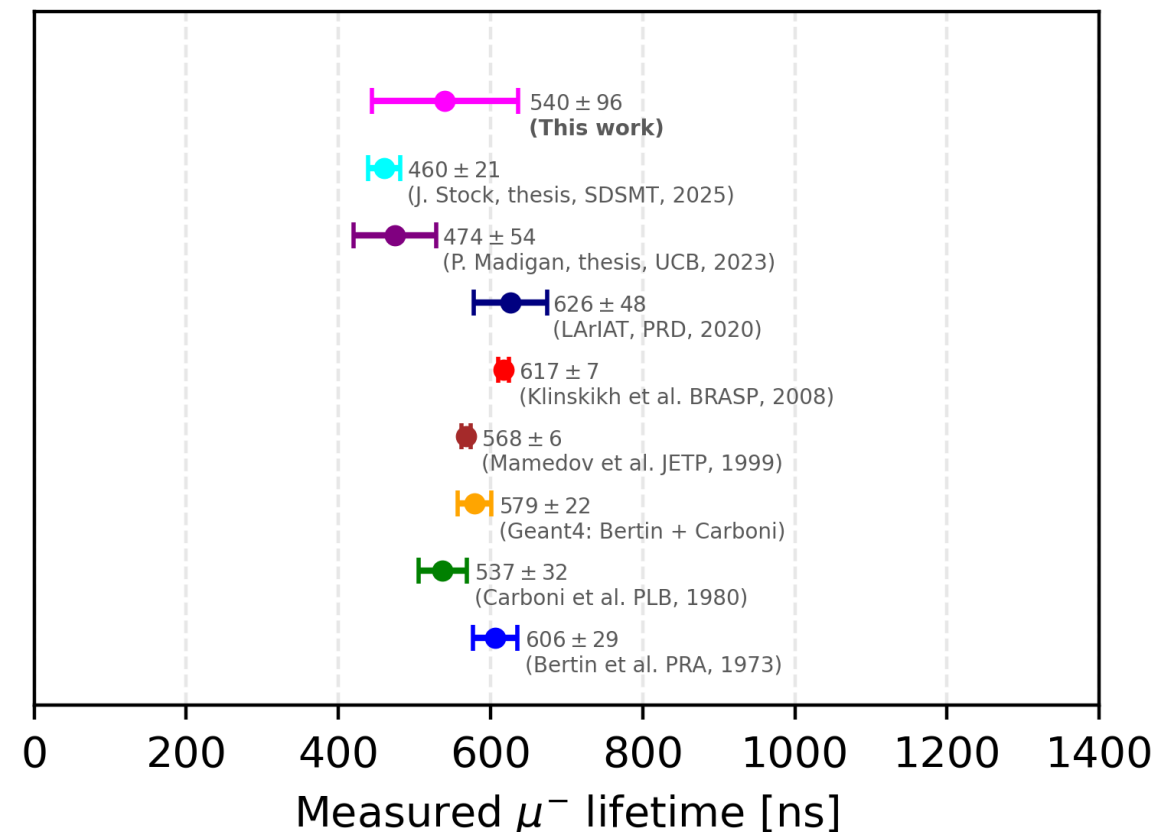
- ❖ The lifetime fitting yields $\tau_{\mu^-} = 540.1 \pm 96.4 \text{ ns}$



Comparison With Existing Results

DATA

- ❖ The fitted value is consistent with previous measurements, albeit with a larger uncertainty
- ❖ Accuracy limited by statistics



Summary:

- ❖ First observation of Michel-electron optical signals in the ProtoDUNE-HD detector
- ❖ A robust workflow developed for the identification and purification of Michel optical signals
- ❖ The PDS demonstrated the ability to identify Michel signals apart from the TPC
- ❖ A high-purity dataset of well-identified Michel optical signals selected
- ❖ A Preliminary measurement of the μ^- lifetime performed using experimental data

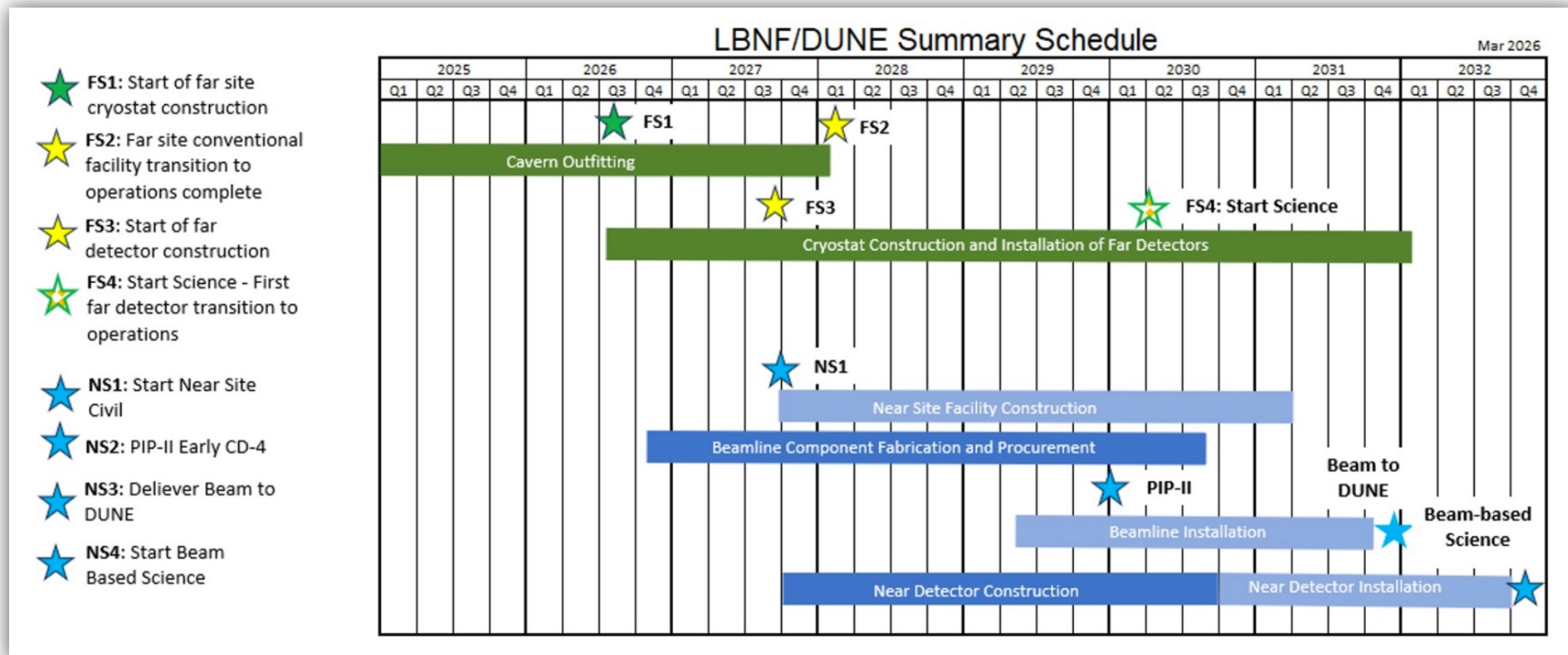
- ❖ Future work:
 1. Evaluate systematic uncertainties (e.g., selection efficiency w.r.t. time, sensitivity to TPC & PDS cuts)
 2. Await new production of MC samples and reproduced experimental data
 3. Extend to other Michel electron studies: TPC-PDS jointed energy reconstructions, position reconstruction, etc
 4. Apply the developed techniques to supernova neutrino studies

Thank you for listening! ☺

Backups

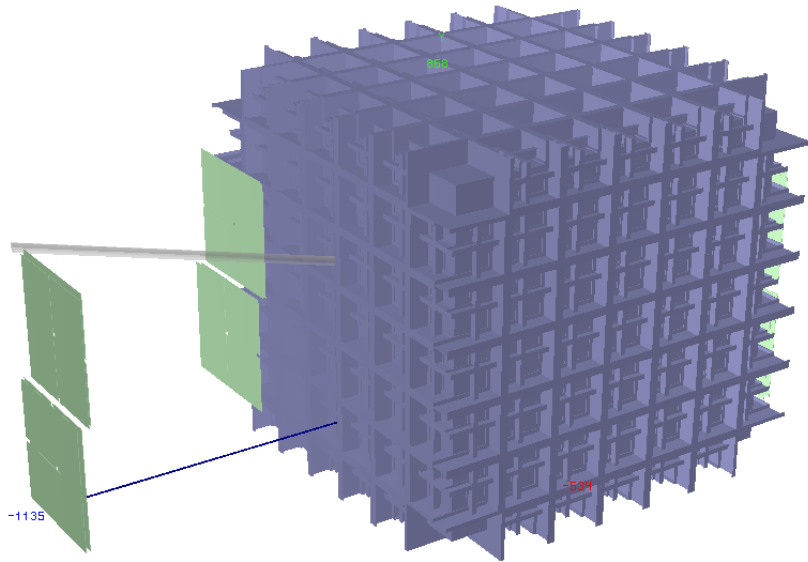
DUNE Timeline

❖ Sowjanya Gollapinni, DUNE Co-spokesperson, DUNE May 2026 collaboration meeting

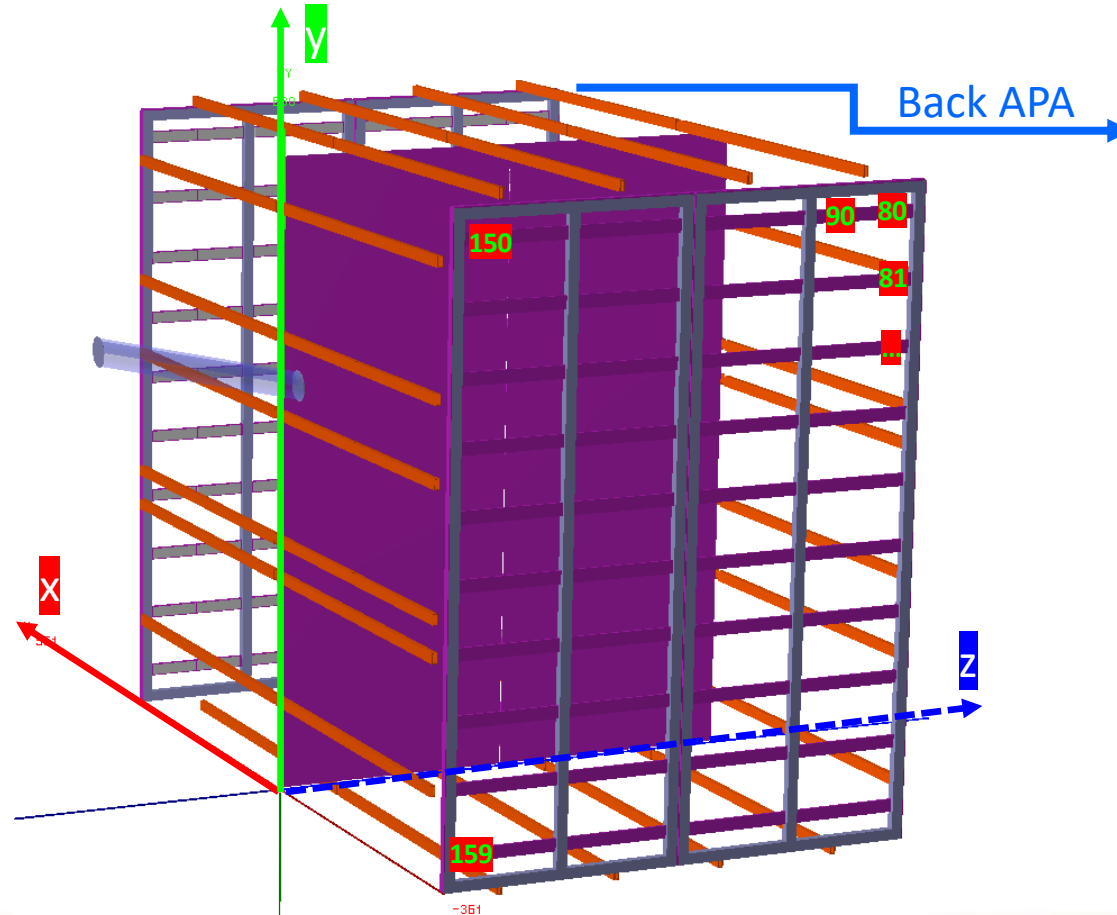
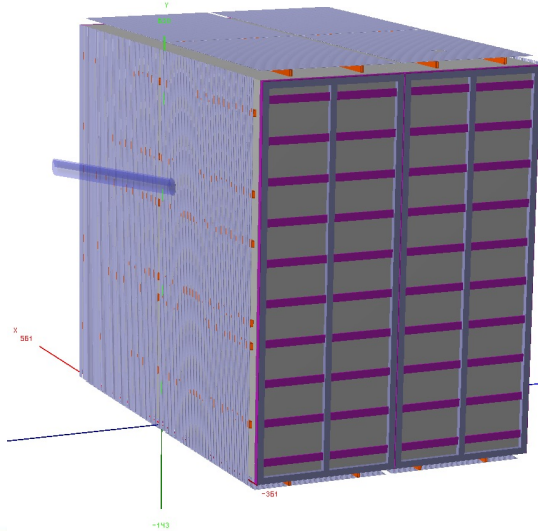


ProtoDUNE-HD Geometry Review

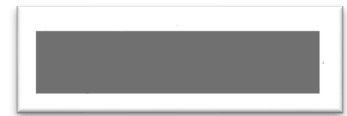
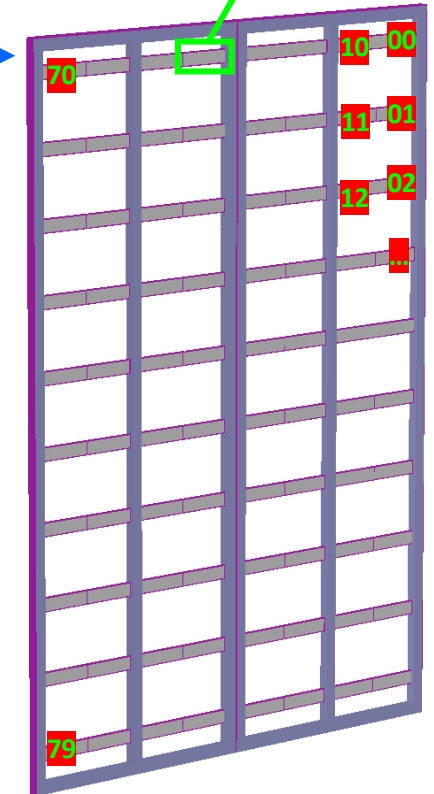
- ❖ [protodunehd v6 refactored nowires.gdml](#)
- ❖ 160 optical channels; All X-Arapuca bars; 48cm×10cm



-1135



Back APA



Optical Channel Labels (I):

❖ APA and Field cage bordery: $x \in [-360, 360]cm$, $y \in [-10, 620]cm$, $z \in [-5, 470]cm$

Cryo Boundaries

Xmin: -391.52 Xmax: 463.52 Ymin: -65.1706 Ymax: 725.069 Zmin: -193.854 Zmax: 661.186

Optical Channels positions: 160

0	356.246	578.909	427.071
1	356.246	518.159	427.071
2	356.246	457.409	427.071
3	356.246	396.659	427.071
4	356.246	335.909	427.071
5	356.246	275.159	427.071
6	356.246	214.41	427.071
7	356.246	153.66	427.071
8	356.246	92.9099	427.071
9	356.246	32.16	427.071

10	356.246	578.909	377.921
11	356.246	518.159	377.921
12	356.246	457.409	377.921
13	356.246	396.659	377.921
14	356.246	335.909	377.921
15	356.246	275.159	377.921
16	356.246	214.41	377.921
17	356.246	153.66	377.921
18	356.246	92.9099	377.921
19	356.246	32.16	377.921

20	356.246	578.909	316.671
21	356.246	518.159	316.671
22	356.246	457.409	316.671
23	356.246	396.659	316.671
24	356.246	335.909	316.671
25	356.246	275.159	316.671
26	356.246	214.41	316.671
27	356.246	153.66	316.671
28	356.246	92.9099	316.671
29	356.246	32.16	316.671

30	356.246	578.909	267.521
31	356.246	518.159	267.521
32	356.246	457.409	267.521
33	356.246	396.659	267.521
34	356.246	335.909	267.521
35	356.246	275.159	267.521
36	356.246	214.41	267.521
37	356.246	153.66	267.521
38	356.246	92.9099	267.521
39	356.246	32.16	267.521

40	356.246	578.909	195.011
41	356.246	518.159	195.011
42	356.246	457.409	195.011
43	356.246	396.659	195.011
44	356.246	335.909	195.011
45	356.246	275.159	195.011
46	356.246	214.41	195.011
47	356.246	153.66	195.011
48	356.246	92.9099	195.011
49	356.246	32.16	195.011

50	356.246	578.909	145.861
51	356.246	518.159	145.861
52	356.246	457.409	145.861
53	356.246	396.659	145.861
54	356.246	335.909	145.861
55	356.246	275.159	145.861
56	356.246	214.41	145.861
57	356.246	153.66	145.861
58	356.246	92.9099	145.861
59	356.246	32.16	145.861

60	356.246	578.909	84.6112
61	356.246	518.159	84.6112
62	356.246	457.409	84.6112
63	356.246	396.659	84.6112
64	356.246	335.909	84.6112
65	356.246	275.159	84.6112
66	356.246	214.41	84.6112
67	356.246	153.66	84.6112
68	356.246	92.9099	84.6112
69	356.246	32.16	84.6112

70	356.246	578.909	35.4612
71	356.246	518.159	35.4612
72	356.246	457.409	35.4612
73	356.246	396.659	35.4612
74	356.246	335.909	35.4612
75	356.246	275.159	35.4612
76	356.246	214.41	35.4612
77	356.246	153.66	35.4612
78	356.246	92.9099	35.4612
79	356.246	32.16	35.4612

Optical Channel Labels (II):

80	-356.446	578.909	427.071
81	-356.446	518.159	427.071
82	-356.446	457.409	427.071
83	-356.446	396.659	427.071
84	-356.446	335.909	427.071
85	-356.446	275.159	427.071
86	-356.446	214.41	427.071
87	-356.446	153.66	427.071
88	-356.446	92.9099	427.071
89	-356.446	32.16	427.071

90	-356.446	578.909	377.921
91	-356.446	518.159	377.921
92	-356.446	457.409	377.921
93	-356.446	396.659	377.921
94	-356.446	335.909	377.921
95	-356.446	275.159	377.921
96	-356.446	214.41	377.921
97	-356.446	153.66	377.921
98	-356.446	92.9099	377.921
99	-356.446	32.16	377.921

100	-356.446	578.909	316.671
101	-356.446	518.159	316.671
102	-356.446	457.409	316.671
103	-356.446	396.659	316.671
104	-356.446	335.909	316.671
105	-356.446	275.159	316.671
106	-356.446	214.41	316.671
107	-356.446	153.66	316.671
108	-356.446	92.9099	316.671
109	-356.446	32.16	316.671

110	-356.446	578.909	267.521
111	-356.446	518.159	267.521
112	-356.446	457.409	267.521
113	-356.446	396.659	267.521
114	-356.446	335.909	267.521
115	-356.446	275.159	267.521
116	-356.446	214.41	267.521
117	-356.446	153.66	267.521
118	-356.446	92.9099	267.521
119	-356.446	32.16	267.521

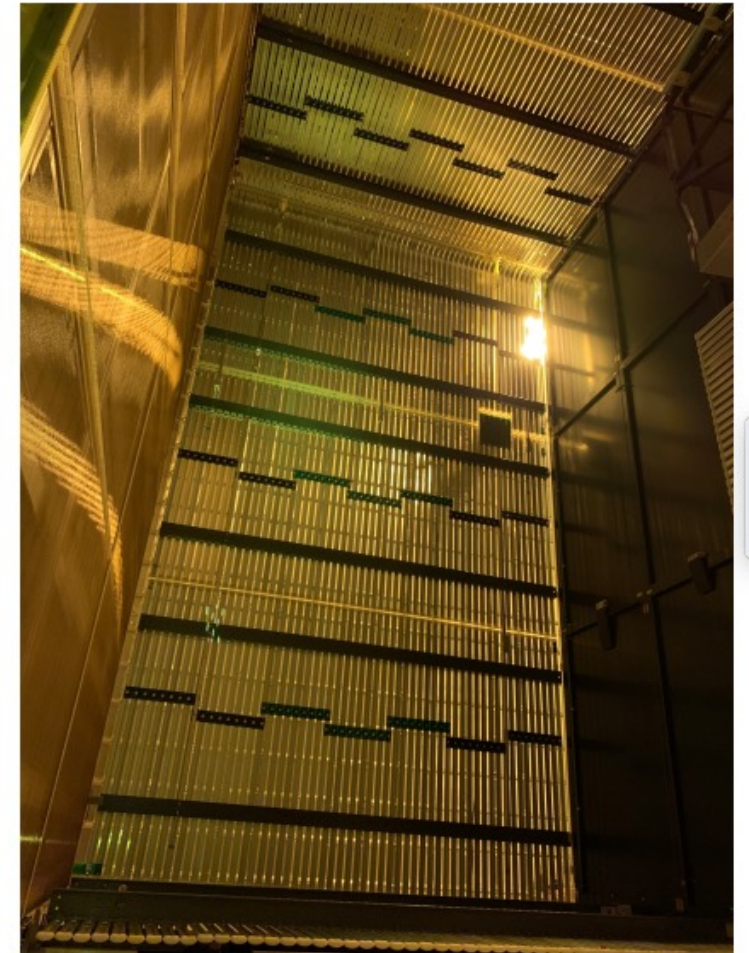
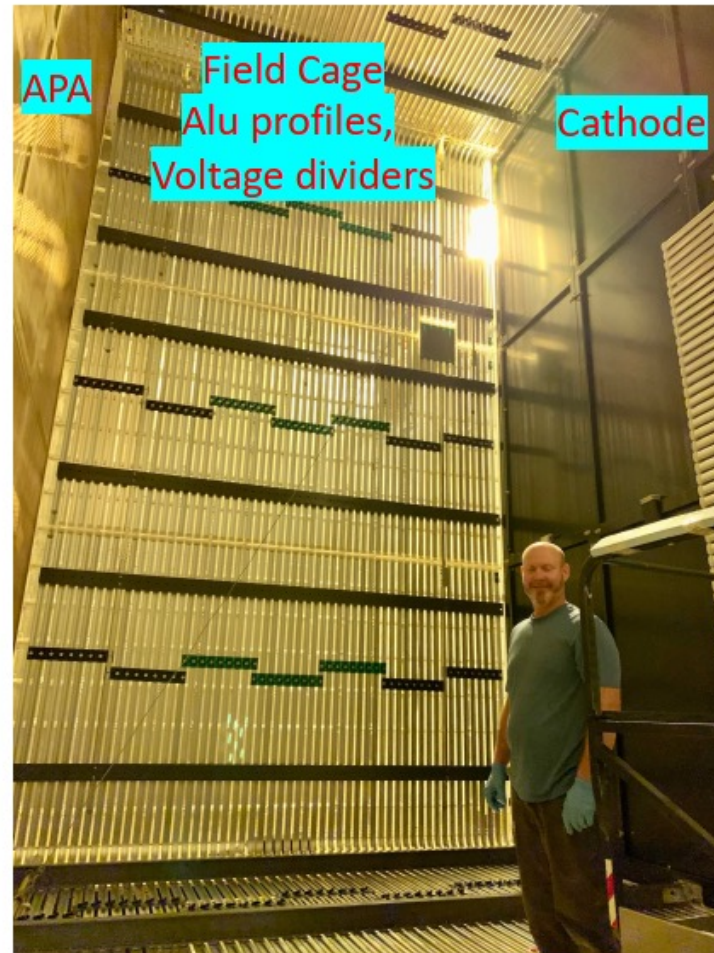
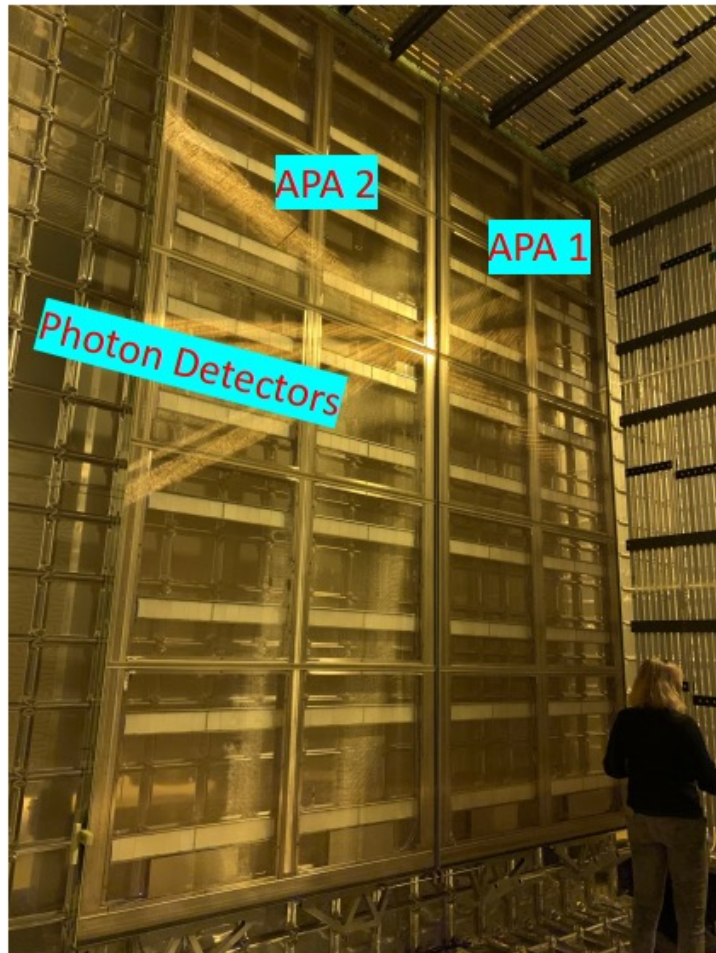
120	-356.446	578.909	195.011
121	-356.446	518.159	195.011
122	-356.446	457.409	195.011
123	-356.446	396.659	195.011
124	-356.446	335.909	195.011
125	-356.446	275.159	195.011
126	-356.446	214.41	195.011
127	-356.446	153.66	195.011
128	-356.446	92.9099	195.011
129	-356.446	32.16	195.011

130	-356.446	578.909	145.861
131	-356.446	518.159	145.861
132	-356.446	457.409	145.861
133	-356.446	396.659	145.861
134	-356.446	335.909	145.861
135	-356.446	275.159	145.861
136	-356.446	214.41	145.861
137	-356.446	153.66	145.861
138	-356.446	92.9099	145.861
139	-356.446	32.16	145.861

140	-356.446	578.909	84.6112
141	-356.446	518.159	84.6112
142	-356.446	457.409	84.6112
143	-356.446	396.659	84.6112
144	-356.446	335.909	84.6112
145	-356.446	275.159	84.6112
146	-356.446	214.41	84.6112
147	-356.446	153.66	84.6112
148	-356.446	92.9099	84.6112
149	-356.446	32.16	84.6112

150	-356.446	578.909	35.4612
151	-356.446	518.159	35.4612
152	-356.446	457.409	35.4612
153	-356.446	396.659	35.4612
154	-356.446	335.909	35.4612
155	-356.446	275.159	35.4612
156	-356.446	214.41	35.4612
157	-356.446	153.66	35.4612
158	-356.446	92.9099	35.4612
159	-356.446	32.16	35.4612

X-ARAPUCAs in APA:

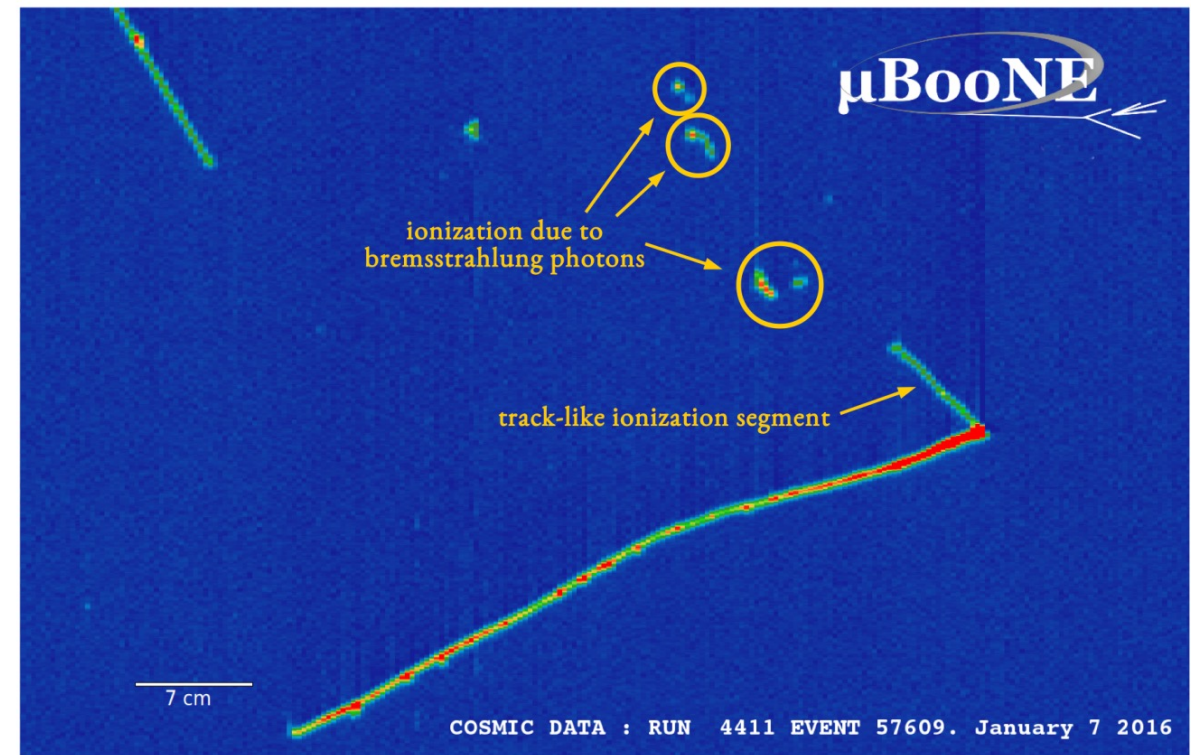
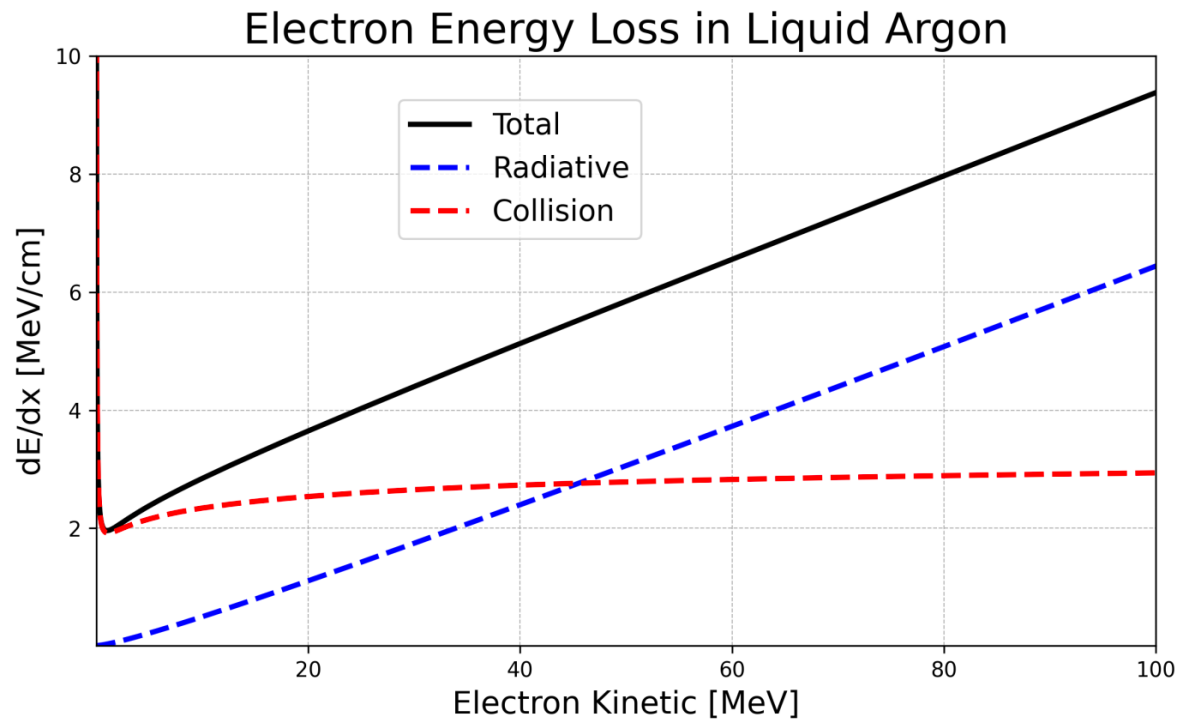


PDS Channels in PDHD:

- ❖ https://github.com/vpec0/duneopdet/blob/85501b4eab4a08bbef6ff17b3cc909a0459ef0c0/duneopdet/OpticalDetector/Deconvolution/dune_opdet_channels.fcl

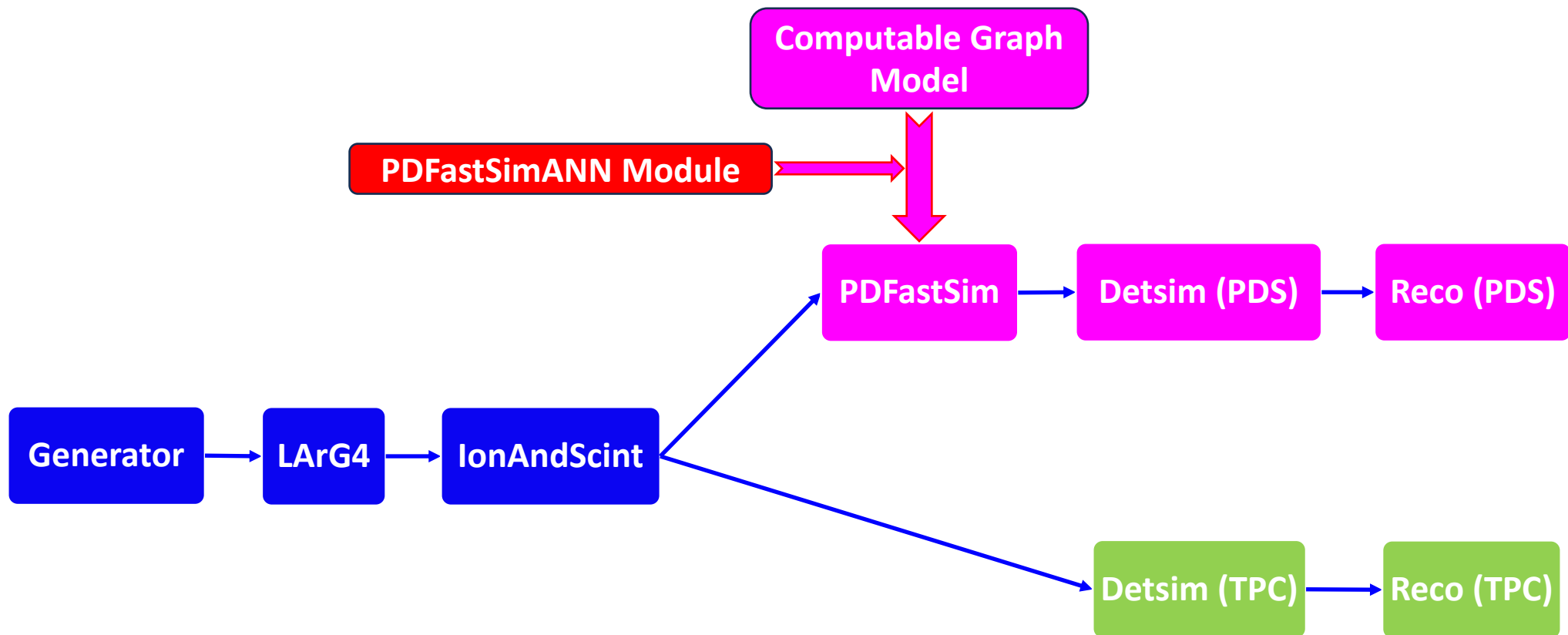
```
1   FBKChannels:      [4,14,24,34,40,42,45,46,47,49,50,52,55,56,57,59,60,62,
65,66,67,69,70,72,75,76,77,79,84,85,86,87,94,95,96,97,104,105,106,107,114,115,
116,117,120,121,124,125,127,129,130,131,134,135,137,139,140,141,144,145,147,14
9,150,151,154,155,157,159] # 68 channels
2
3   HPKChannels:      [0,
1,2,3,5,6,7,8,9,10,11,12,13,15,16,17,18,19,20,21,22,23,25,26,27,28,29,30,31,32
,33,35,36,37,38,39,41,43,44,48,51,53,54,58,61,63,64,68,71,73,74,78,80,81,82,83
,88,89,90,91,92,93,98,99,100,101,102,103,108,109,110,111,112,113,118,119,122,1
23,126,128,132,133,136,138,142,143,146,148,152,153,156,158] # 92 channels
4
5   Dead_channels: [86,87,97,107,117,116,147]
6   Noise_channels:[3,135]
```


Michel Electron Energy Loss



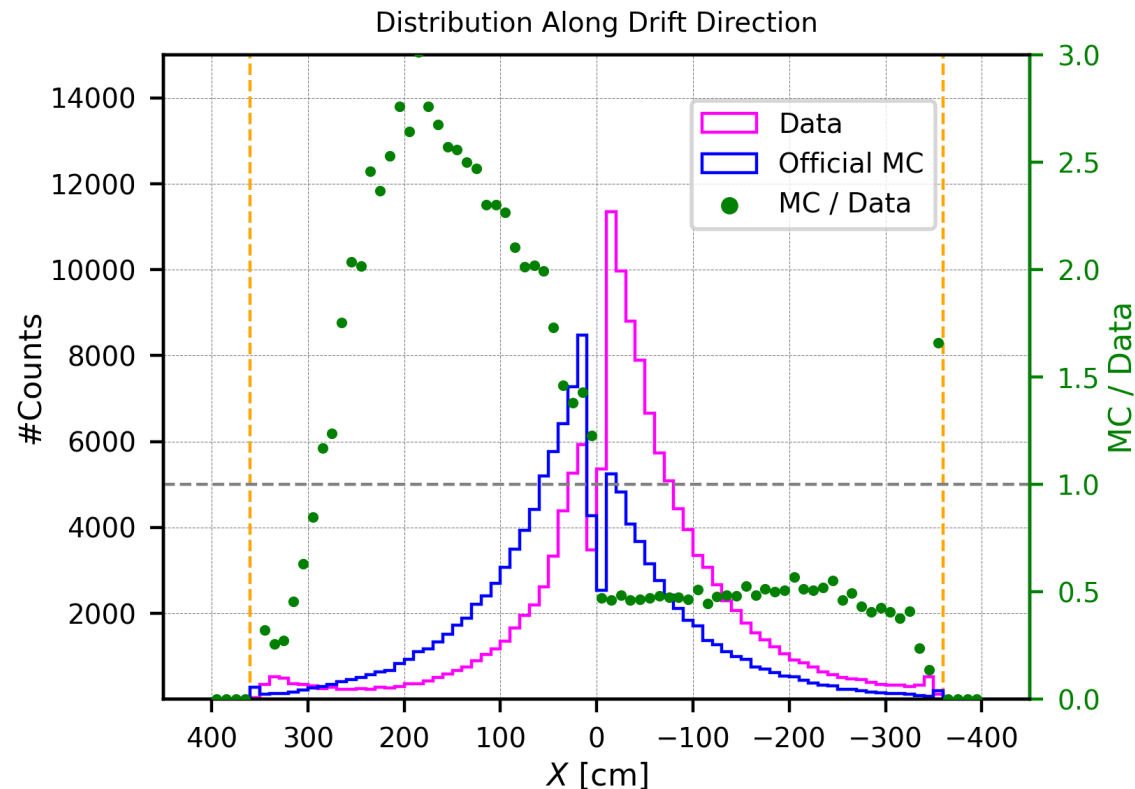
Function of PDFastSimANN Module

- ❖ [PDFastSimANN](#) was initially developed by Mu Wei (former postdoc of Fermilab) @ Aug 2020
- ❖ Function: invoke machine learning-based fast optical simulation module



MC DATA Comparison:

- ❖ Removing ending points in APA1 region: #track = 121669 (MC), #track = 141185 (Data) [After TPC cuts]
- ❖ In beam chamber ($X < 0$), MC and Data match well, ratio = ~ 0.5 , > 0.35 (740000/2130000)
- ❖ In non-beam chamber ($X \geq 0$), clear mismatch $\Rightarrow$ infer that **APA3 & APA4 might have some issues in Data**



Track Asymmetry (I)

- Matthew Siden (CSU):

Three Wire Problem

- This shift is likely impacting the T0 tagging efficiency.
 - Shifts on opposite sides of the cathode.
 - More difficult to stitch tracks when their cathode endpoints are farther apart.
- Repaired channel map has since been developed and implemented.

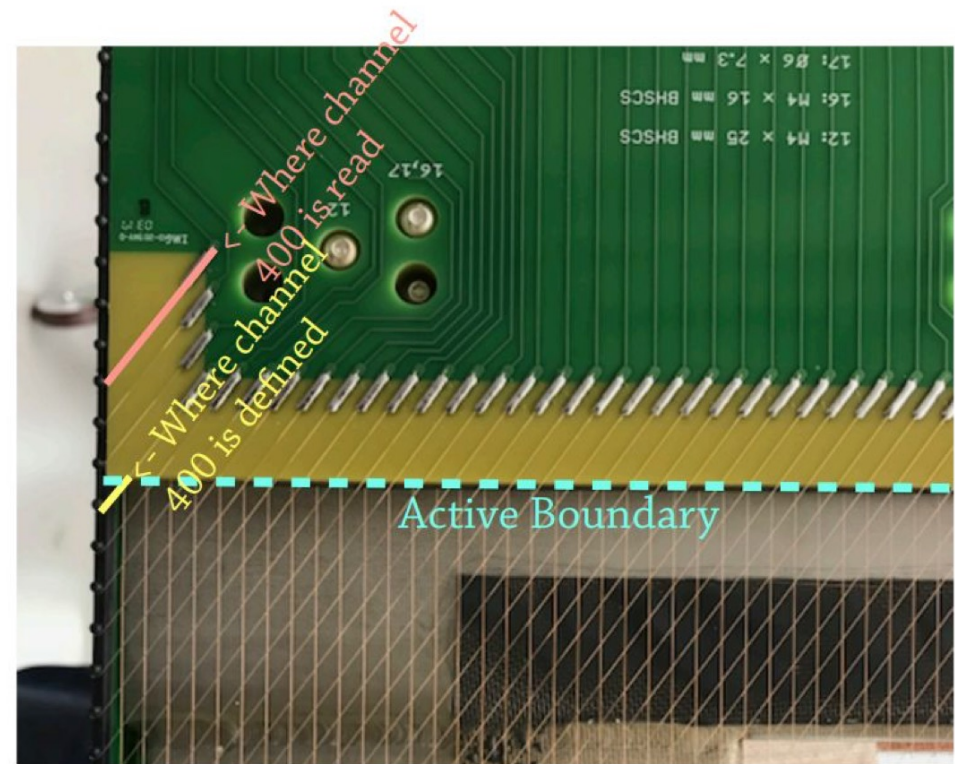


Image from Laura's presentation

Track Asymmetry (I)

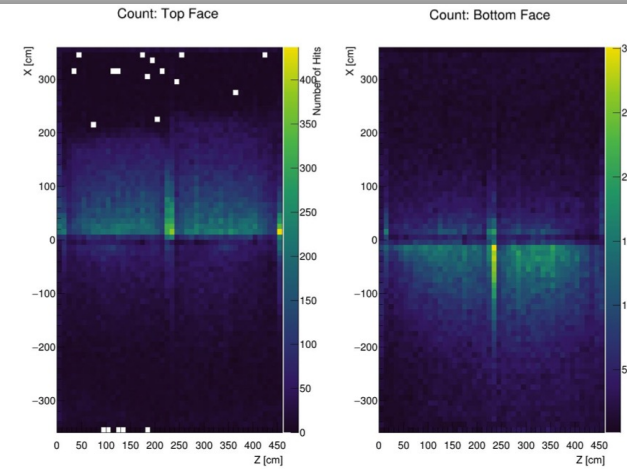
- Matthew Siden (CSU):

7

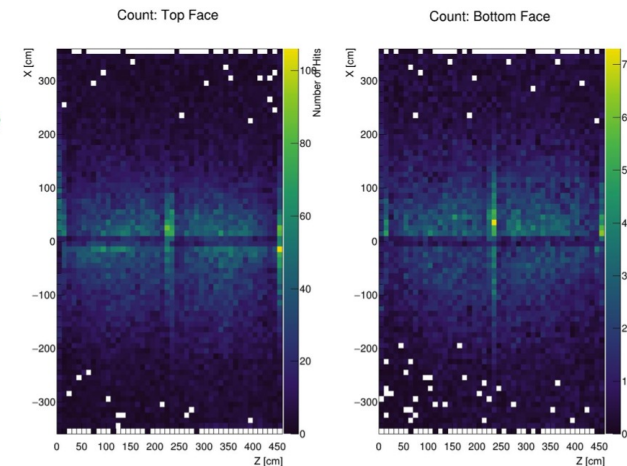
New Channel Map

- Roughly ~100,000 tracks ran with the new channel map.
- Eliminated the asymmetry in track direction.
- Some asymmetry in track density favoring the +x side of the detector.
- Broken tracks on the APA gap remain.
- Otherwise substantially better performance with the new channel maps.

Old Ch Map

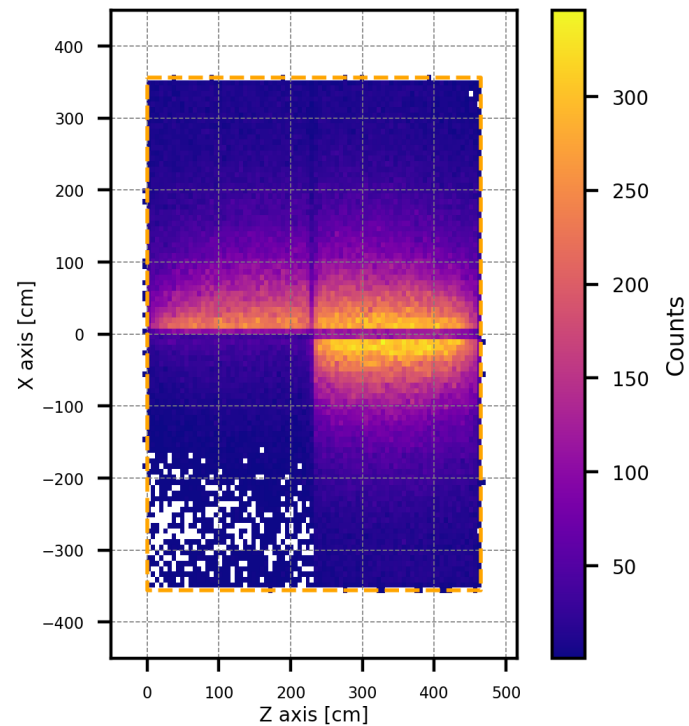


New Ch Map

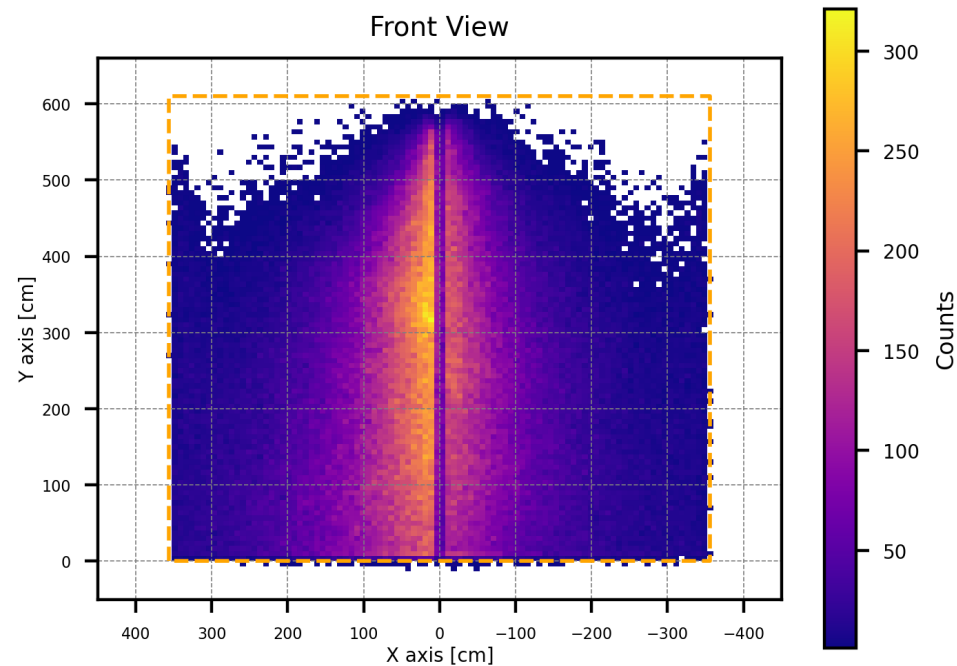


Space Distribution of True Michel:

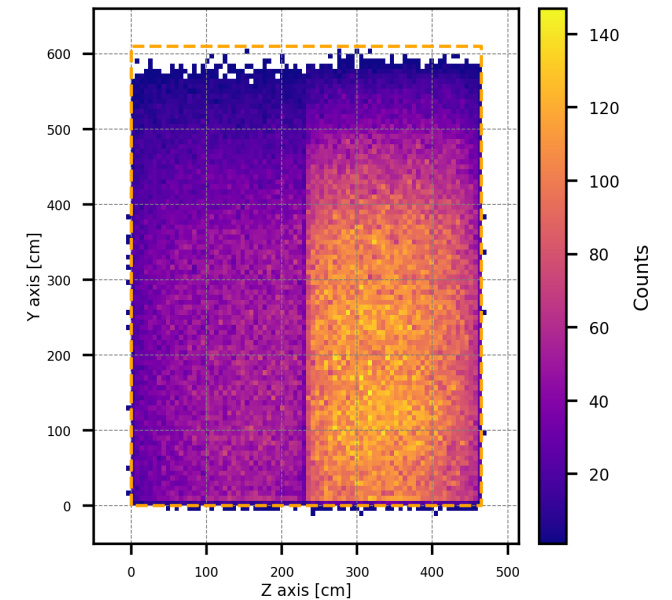
Top View



Front View



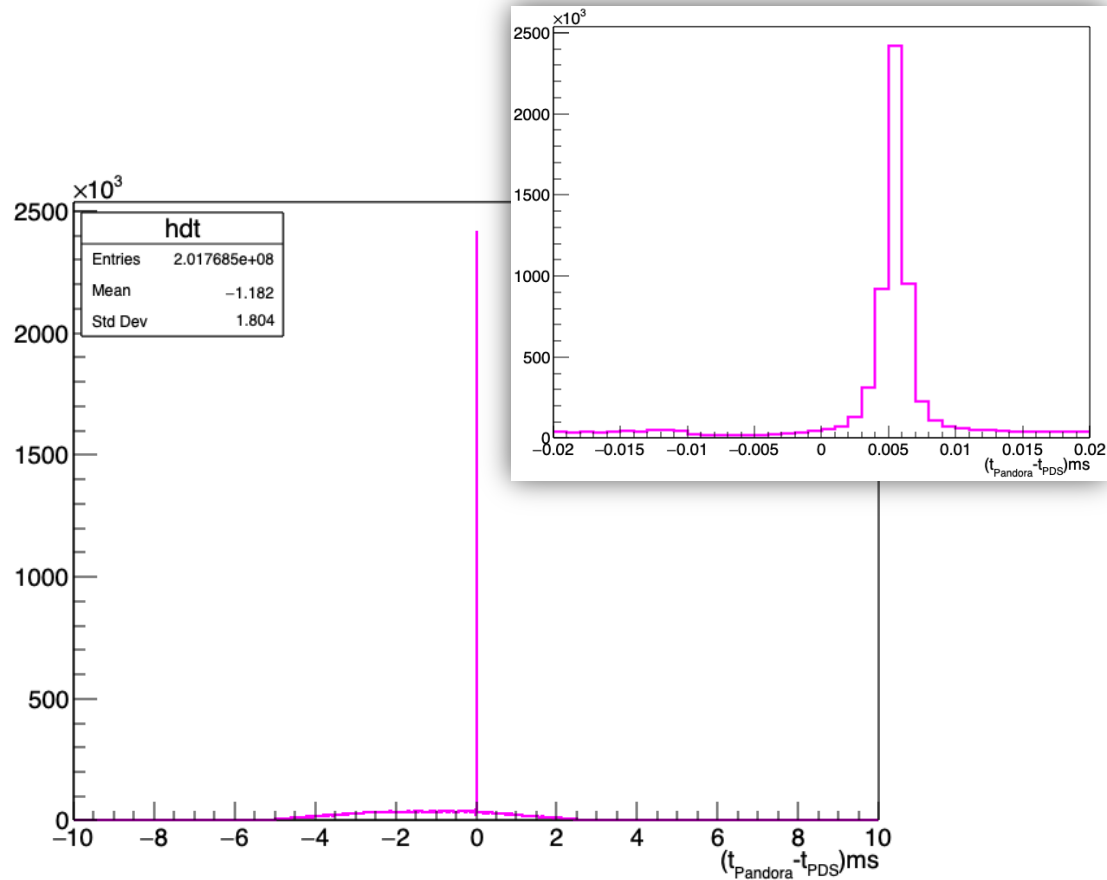
Side View



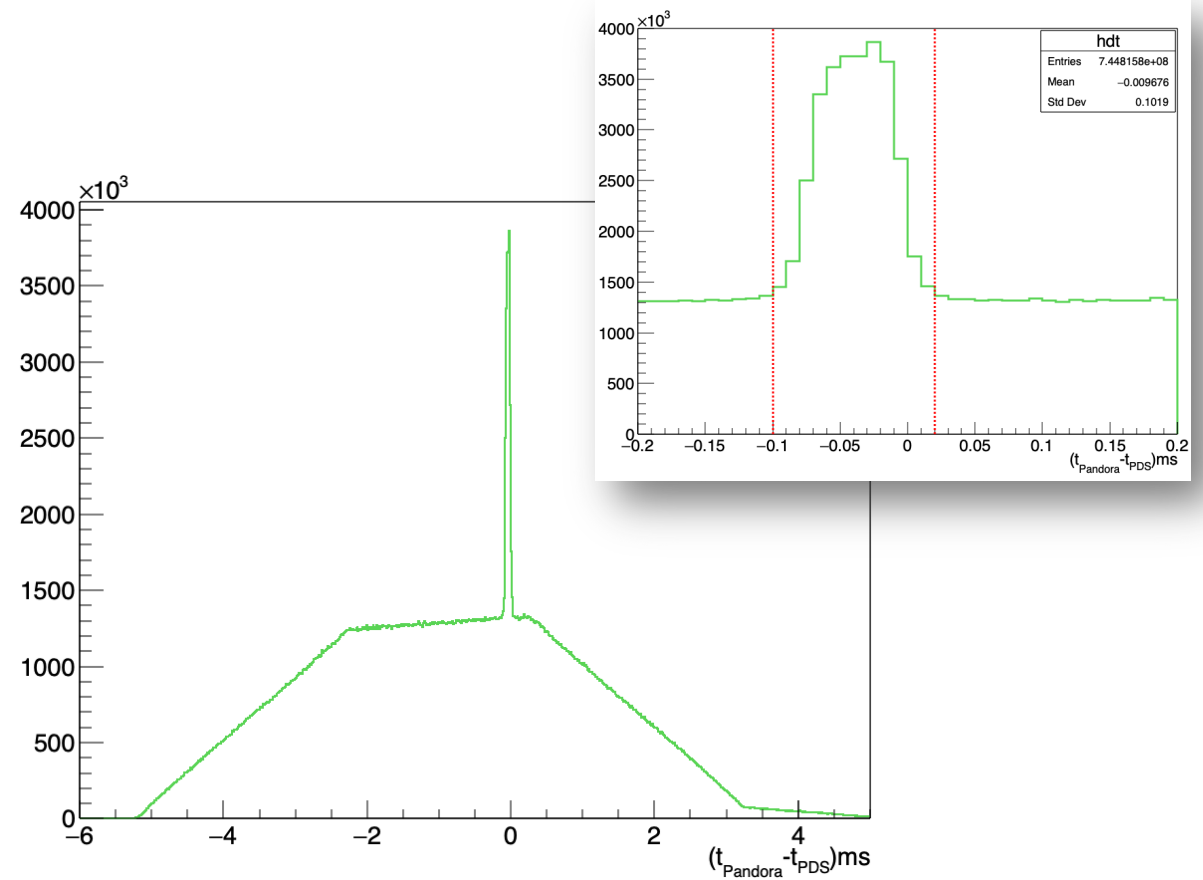
MC VS DATA Timing Matching:

MC DATA

MC, cosmic + radiological bkg

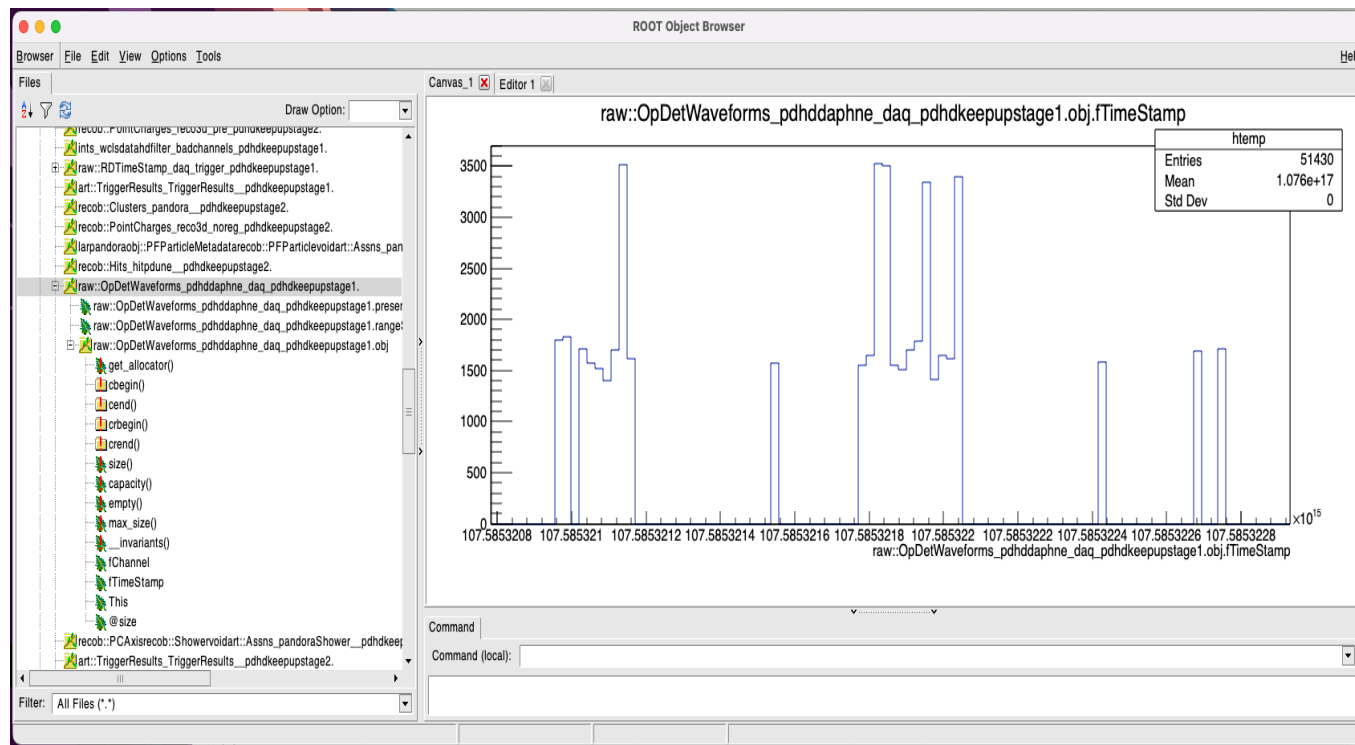


DATA, cosmic run 28116



PDS Timing Precision:

- ❖ Pdhd keepup data:
np04hd_raw_run028059_1633_dataflow2_datawriter_0_20240719T045856_reco_stage1_reco_stage2_20240719T114708_keepup.root
- ❖ Raw waveform: `raw::OpDetWaveforms_pdhddaphne_daq_pdhkeepupstage1`



- A `double` is a 64-bit floating-point number, which follows the IEEE 754 standard. It has:
 - 53 bits of precision (52 bits for the mantissa and 1 implicit leading bit).
 - A large range: roughly -10^{308} to 10^{308} .

chatGPT

$$107.5853228 \cdot 10^{15} = 1.07585323 \times 10^{17}$$

$$2^{57} = 1.44115188 \times 10^{17}$$

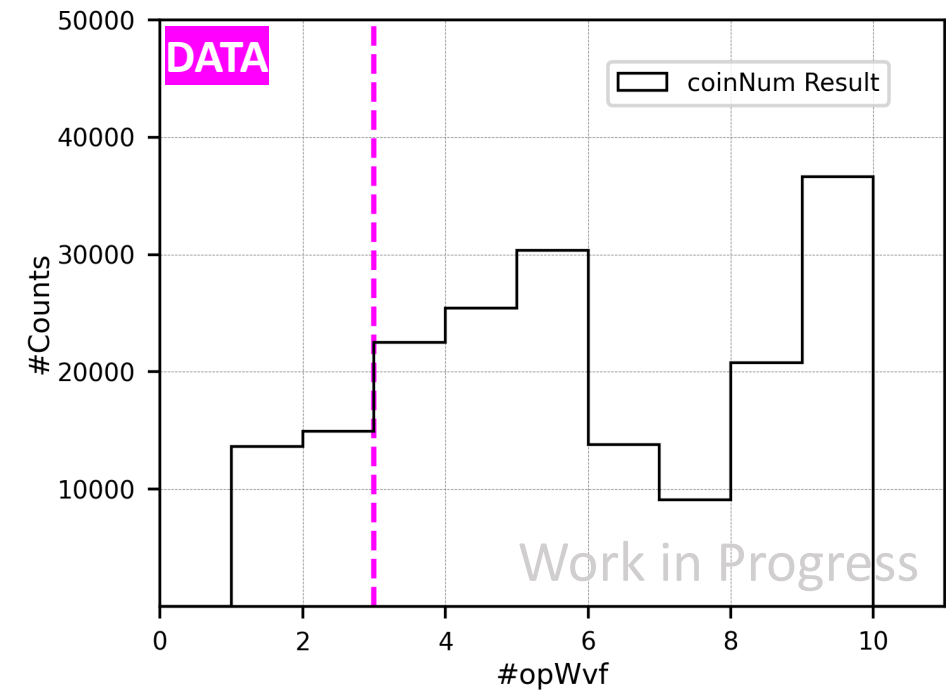
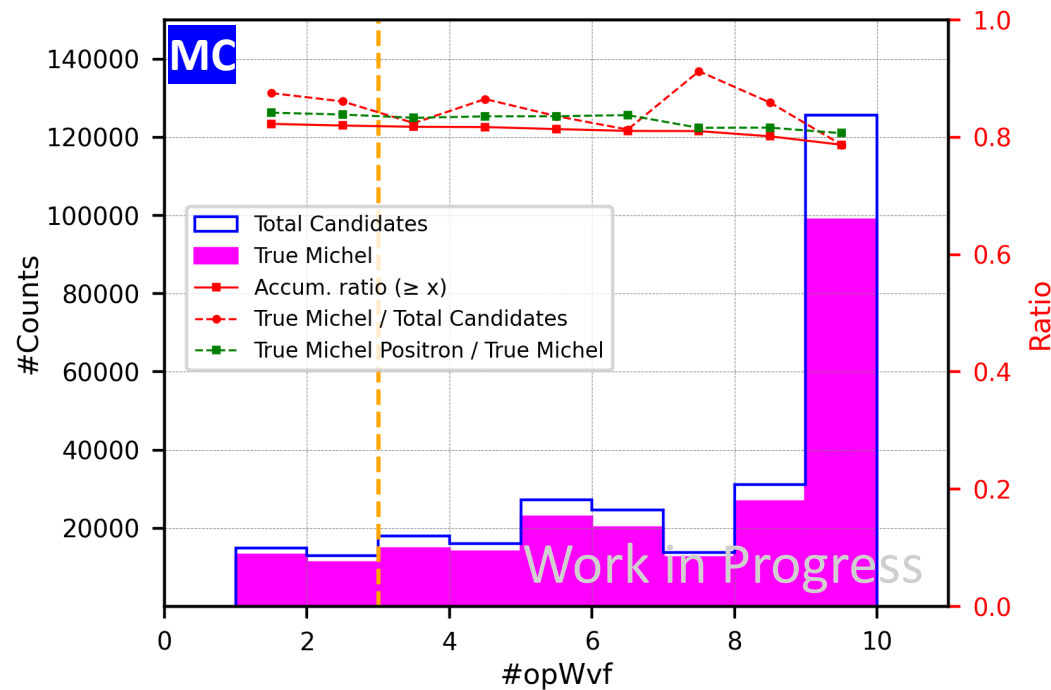
- ❖ So our accuracy is: 2^4 ticks: $256ns = 0.000256ms$

PDS Responses of Michel Candidates: MC DATA

❖ After TPC cuts

- #candidate with ≥ 1 wvfs : 284,529 (Purity: 82.3%)
- #opWvf ≥ 3 : 256,595 (Purity: 81.8%)

- Track candidate with ≥ 1 wvfs: 187,165
- #opWvf ≥ 3 : 158,615



Scale MC to DATA

Update!

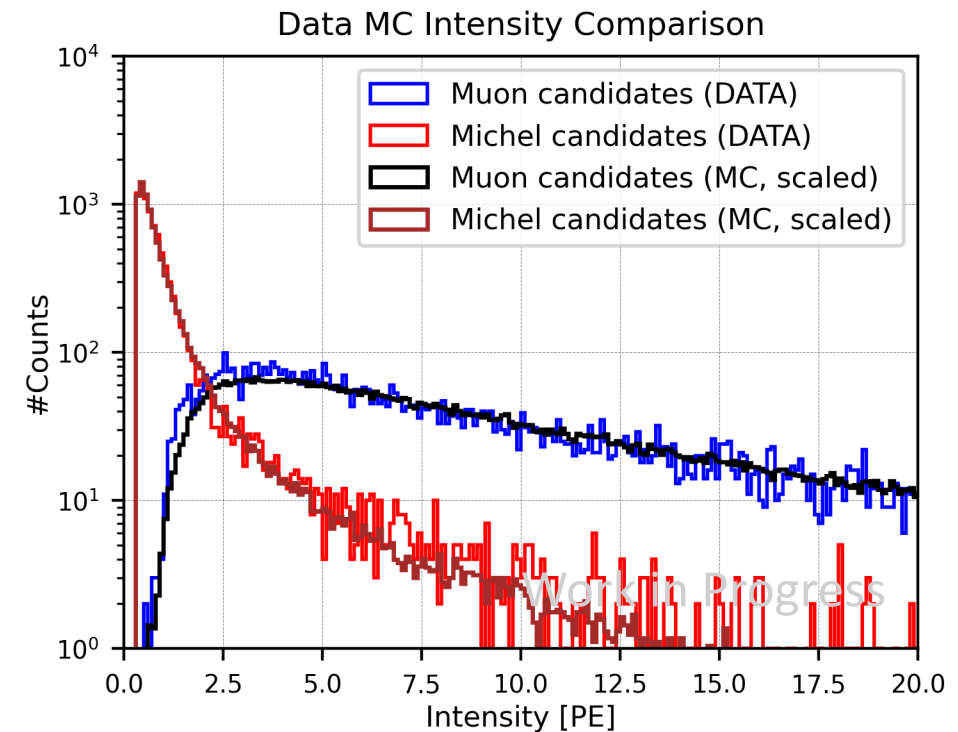
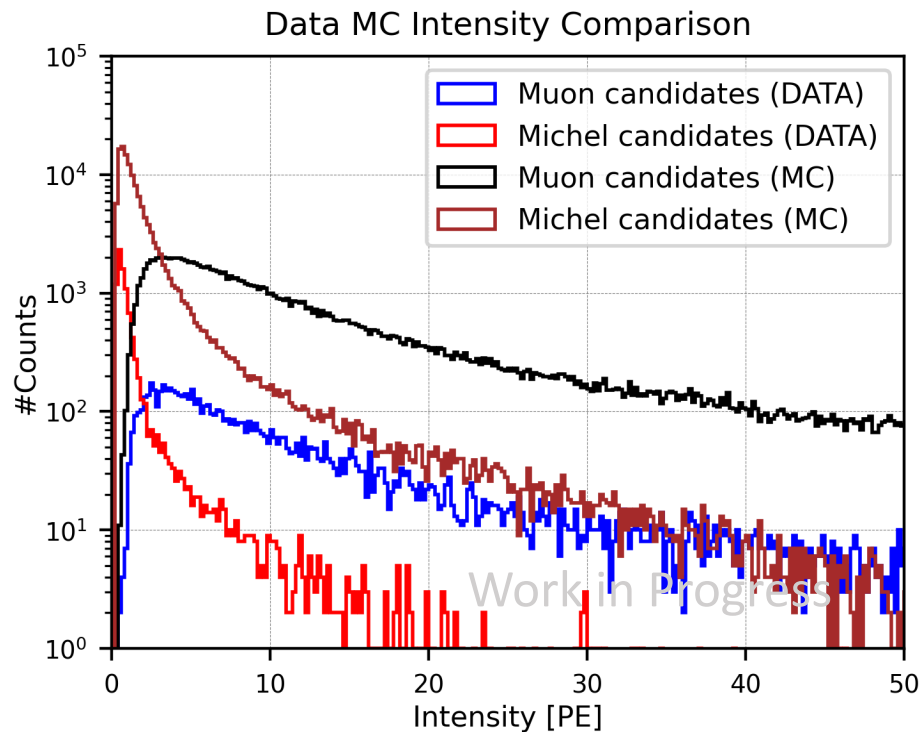
DATA MC

❖ Discrepancy w.r.t. signal intensity between MC and DATA observed

❖ Preliminary scaling: $N_{\text{MC}}^{\text{scaled}}(x) = 0.065 N_{\text{MC}}(x)$

$$I_{\mu}^{\text{MC, scaled}} = I_{\mu}^{\text{MC}}$$

$$I_{\text{ME}}^{\text{MC, scaled}} = 0.4 I_{\text{ME}}^{\text{MC}} + 0.18$$



ME/Muon Intensity Ratio for DATA

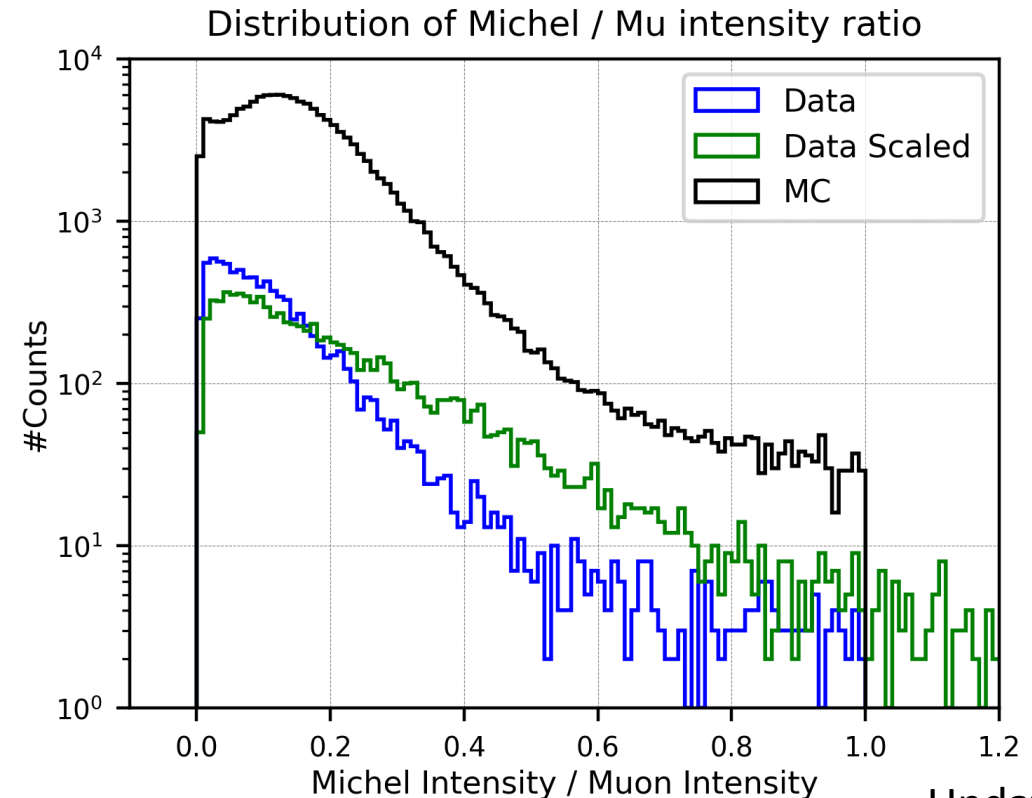
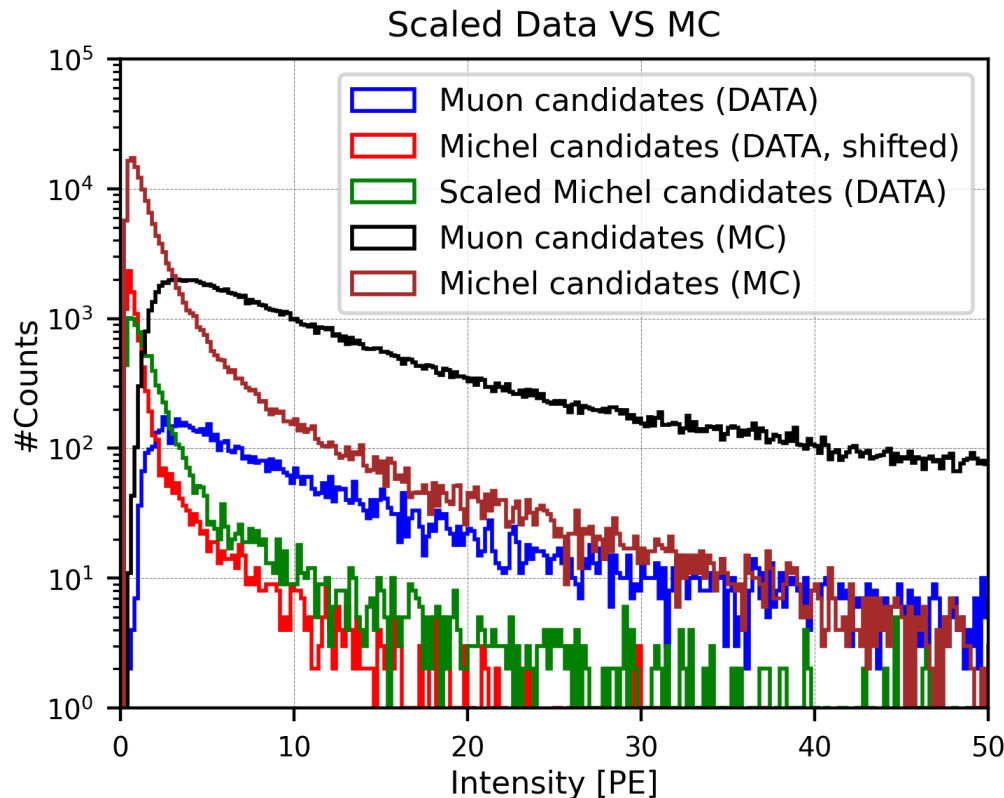
Update!

MC DATA

$$I_{\mu, \text{DATA}}^{\text{corr}} = I_{\mu, \text{DATA}}$$

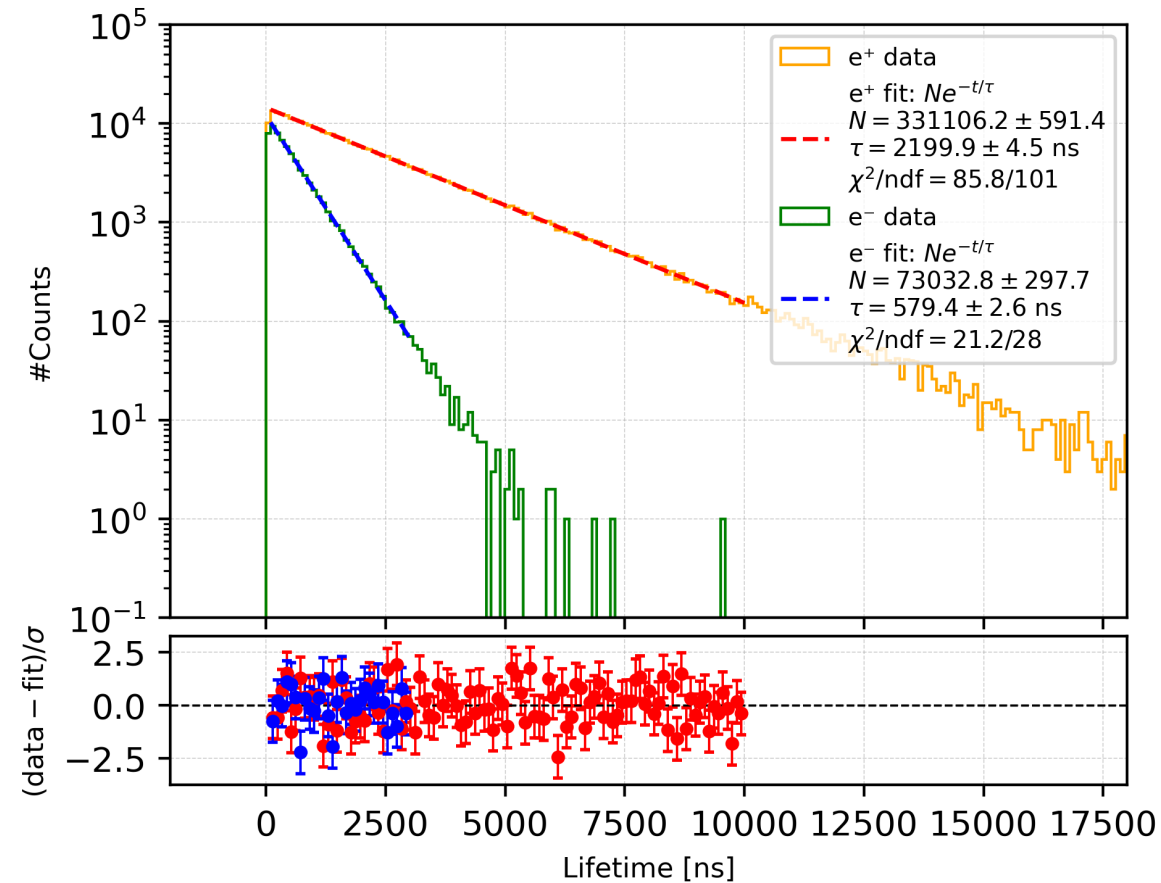
$$I_{\text{DATA}}^{\text{ME, corr}} = 2.5 I_{\text{DATA}}^{\text{ME}} - 0.45$$

$$R_{\text{DATA, corr}} = \frac{I_{\text{ME, DATA}}^{\text{corr}}}{I_{\mu, \text{DATA}}^{\text{corr}}} = \frac{2.5 I_{\text{DATA}}^{\text{ME}} - 0.45}{I_{\mu, \text{DATA}}}$$



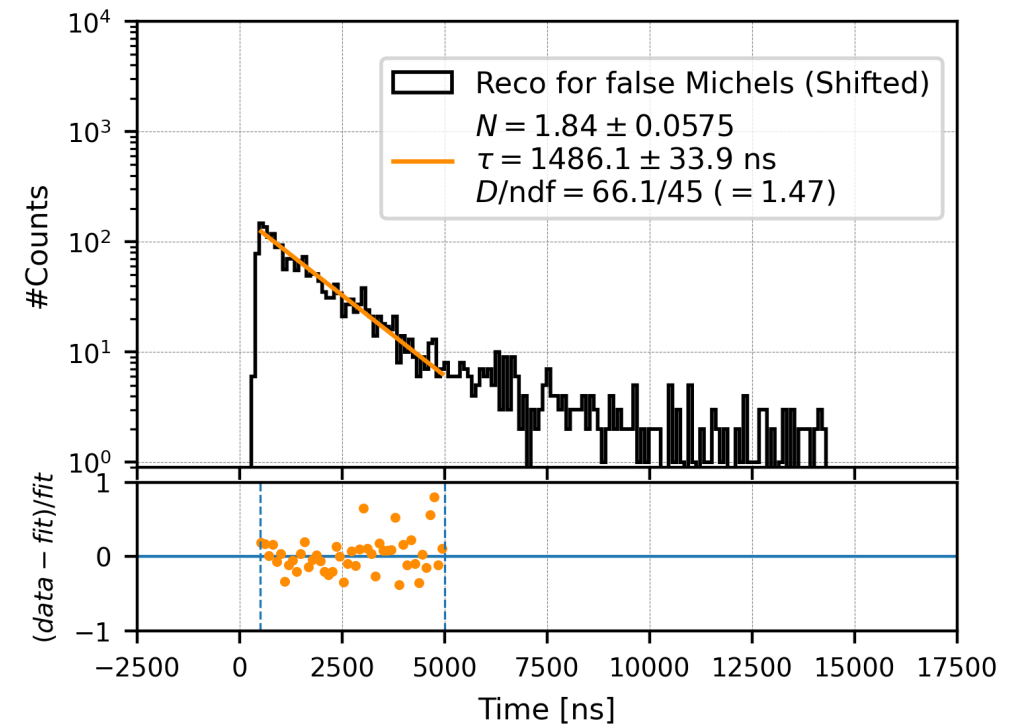
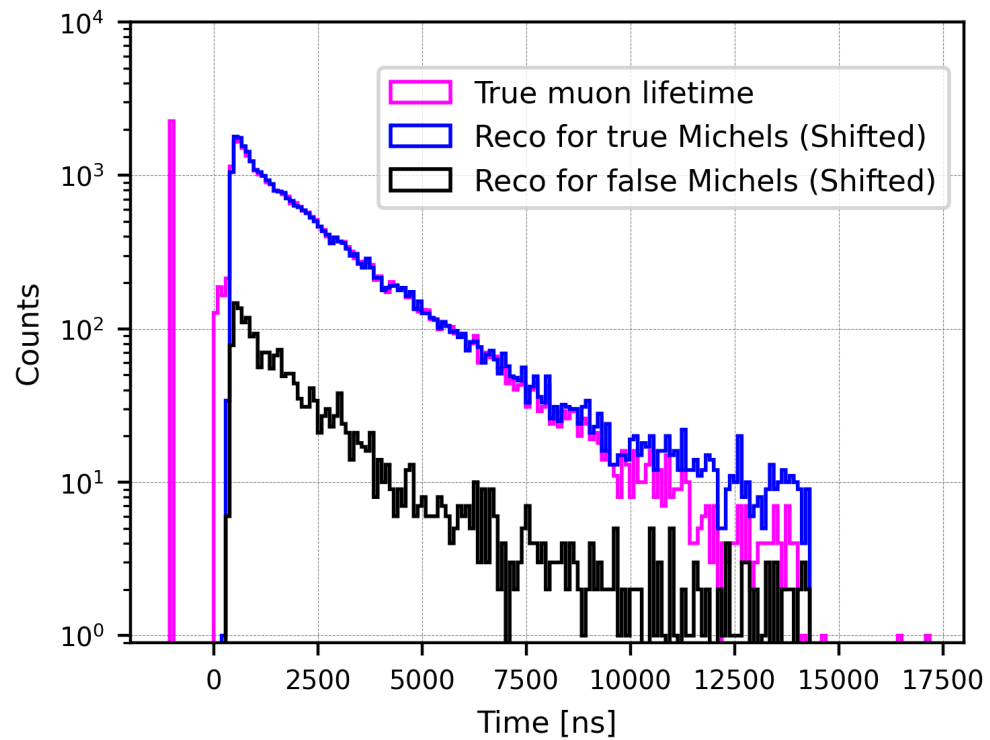
Update further

Separate Fittings of True Michels



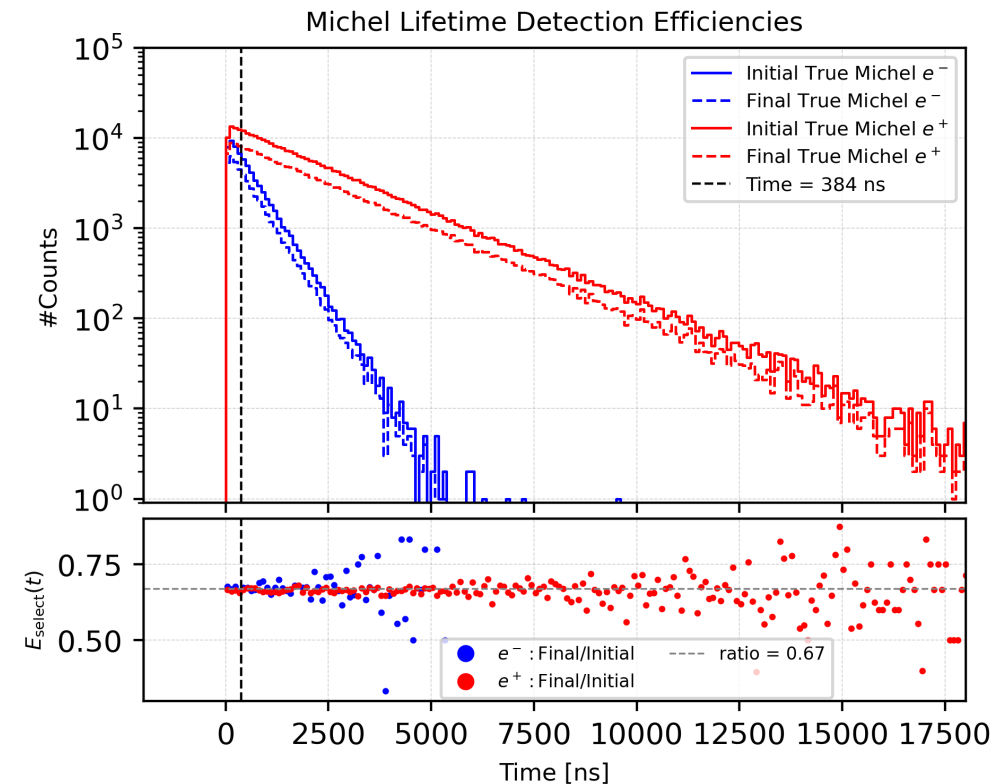
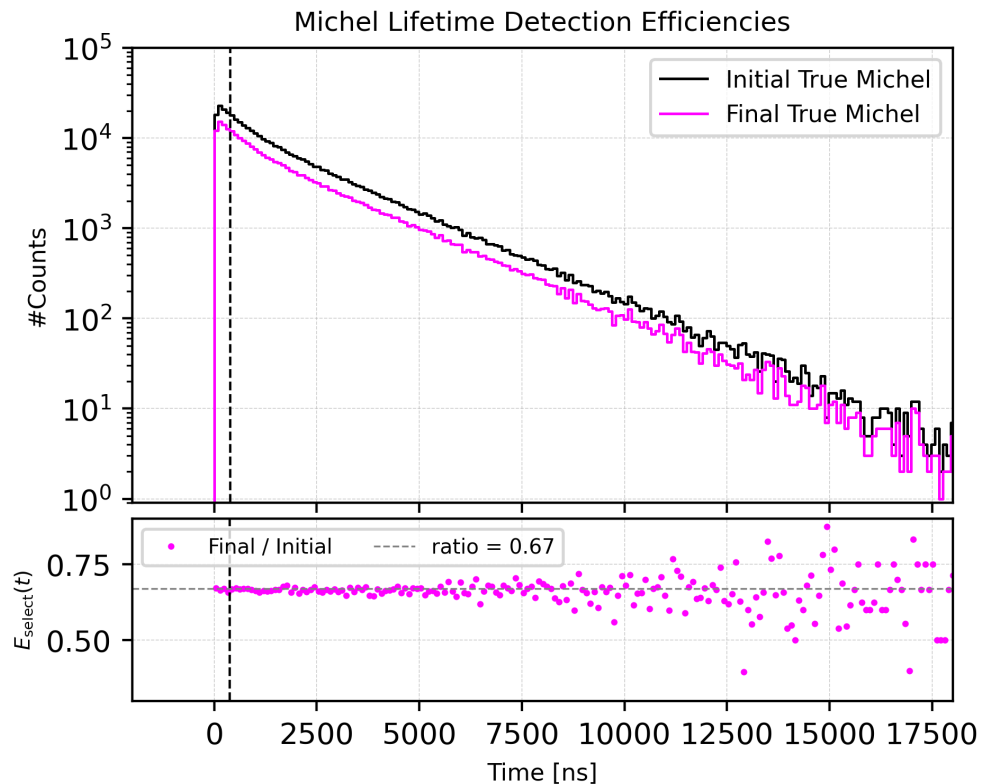
Background Fitting:

❖ After TPC & PDS cuts



Efficiencies After TPC Cuts:

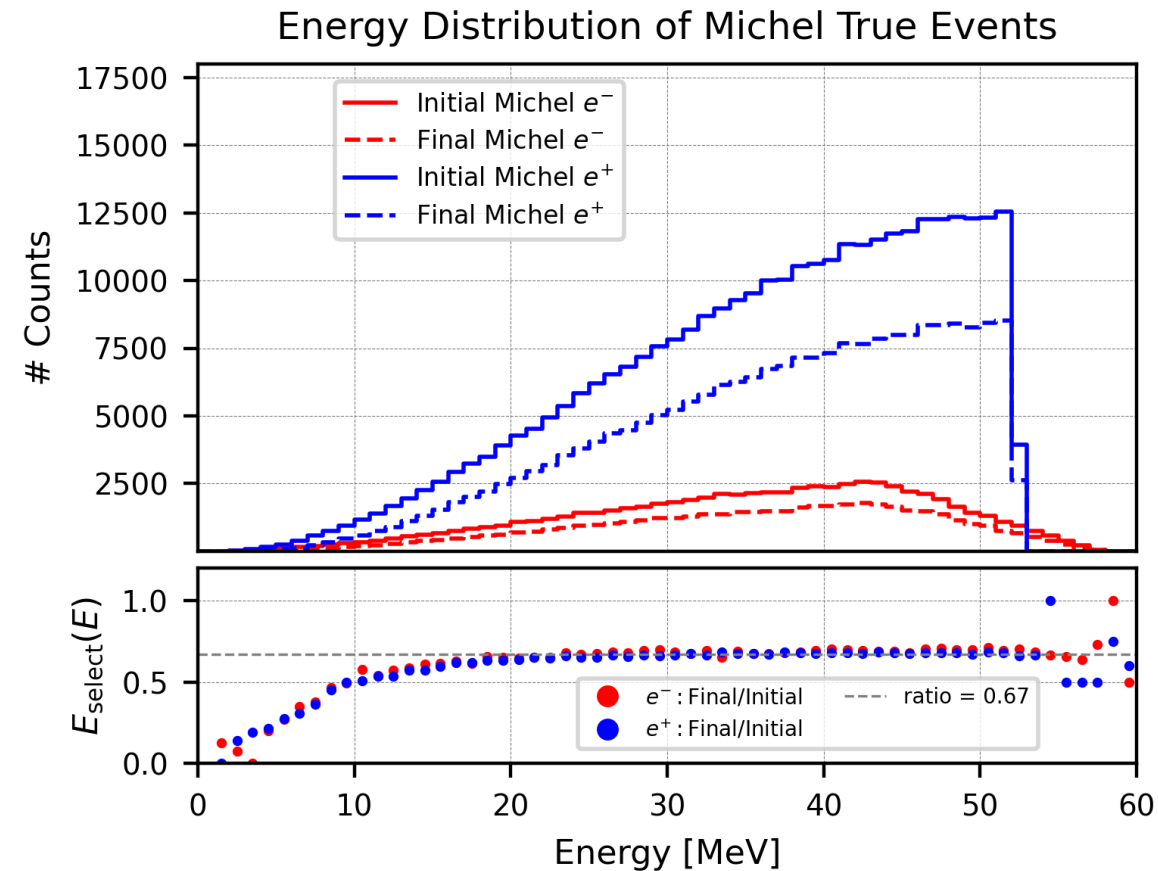
```
#(TPC_lifetime) / #(lifetime_trueMichel_initial): 264479 / 397145 (0.67)
#(TPC_lifetime_e) / #(lifetime_e): 47019 / 69862 (0.67)
#(TPC_lifetime_p) / #(lifetime_p): 217460 / 327283 (0.66)
```



Efficiency VS Energy [TPC Cuts]:

MC

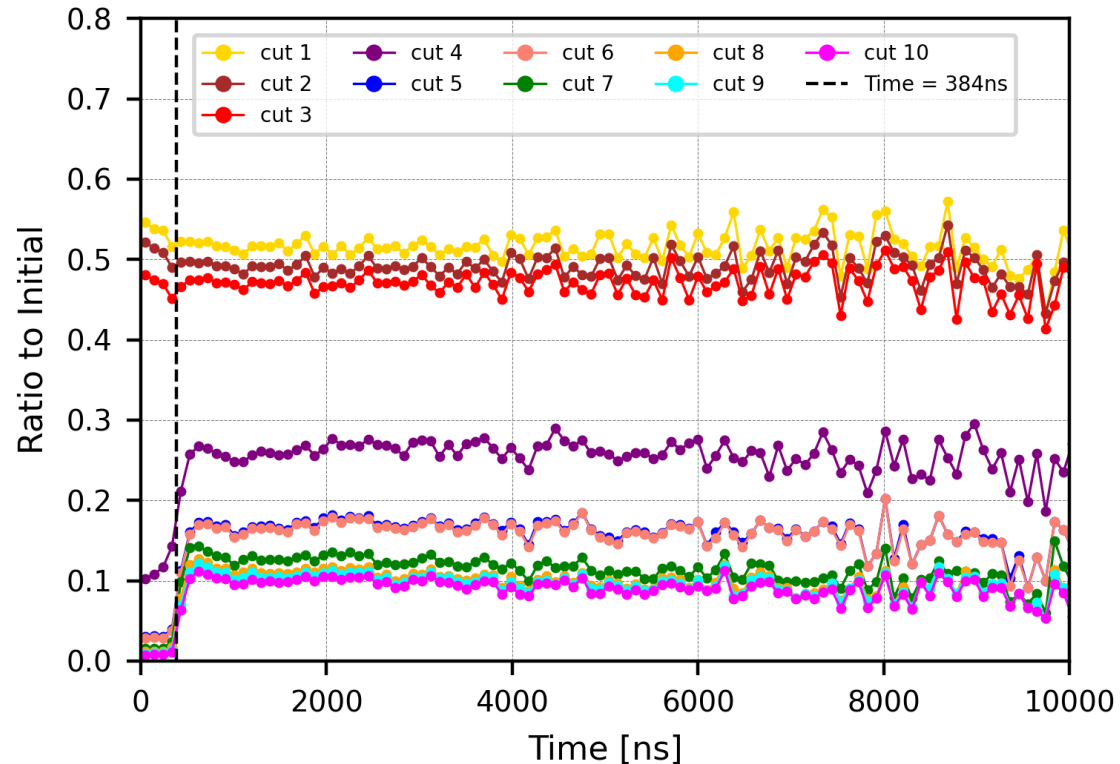
❖ $e^+ e^-$ separated



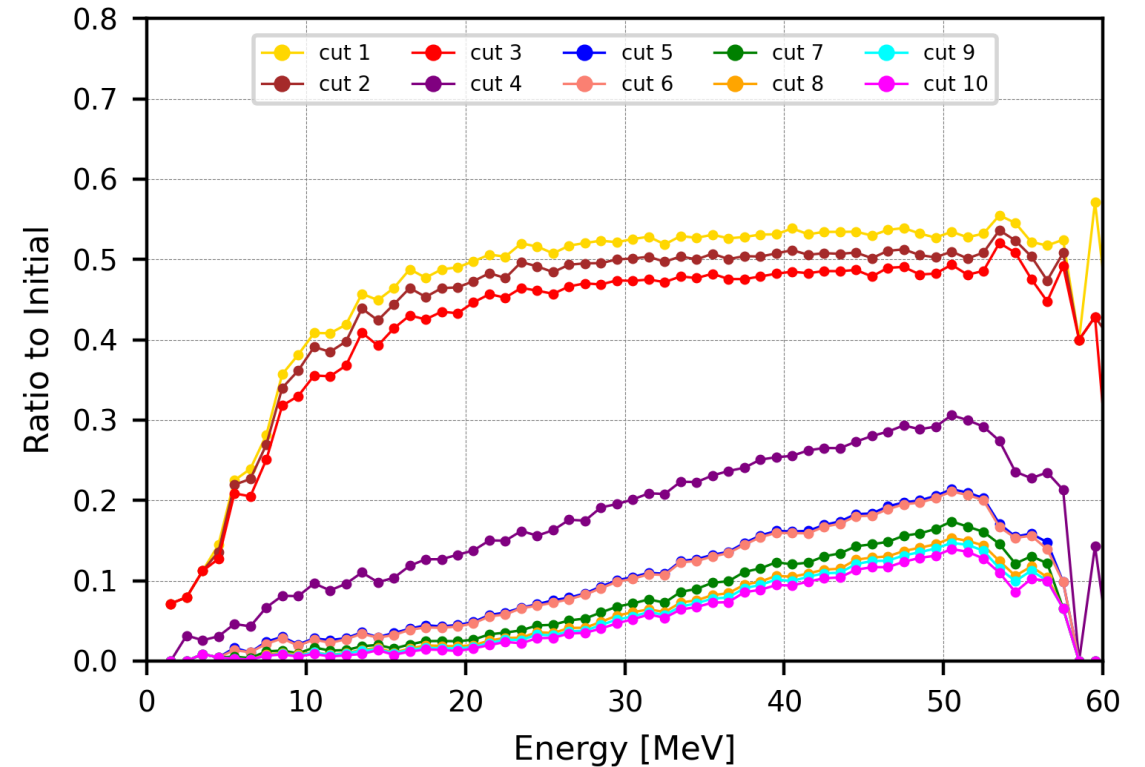
PDS Efficiencies [$e^\pm$ combined]:

❖ Combined efficiencies:

Michel Selection Efficiencies



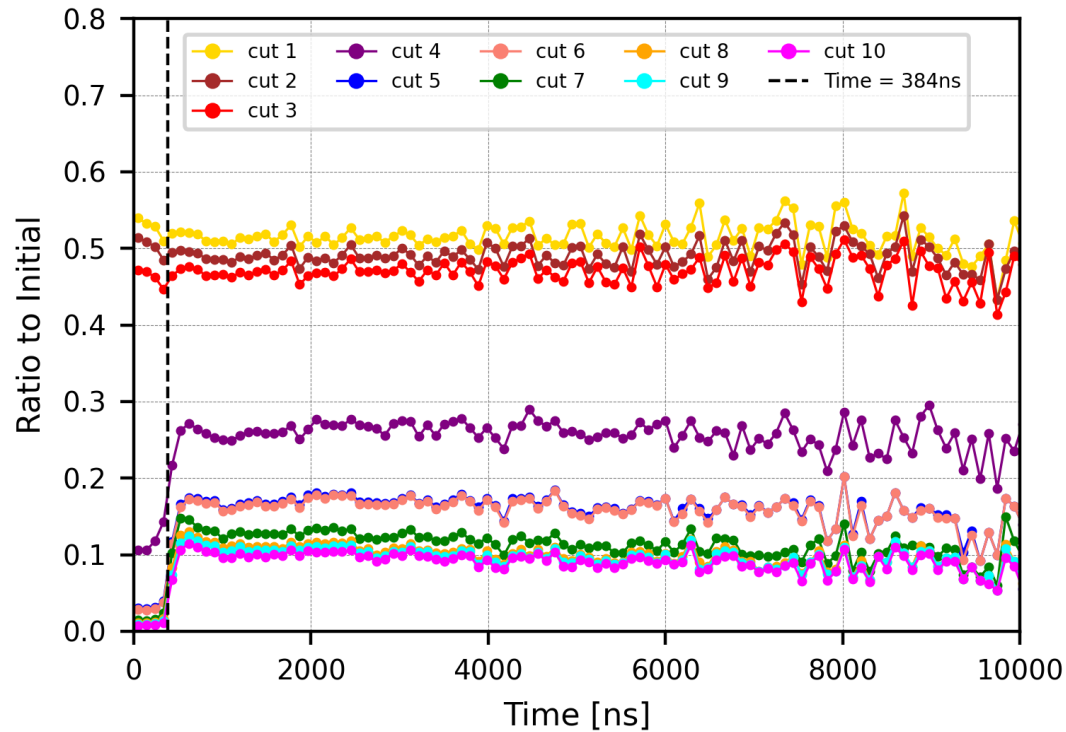
Michel Selection Efficiencies



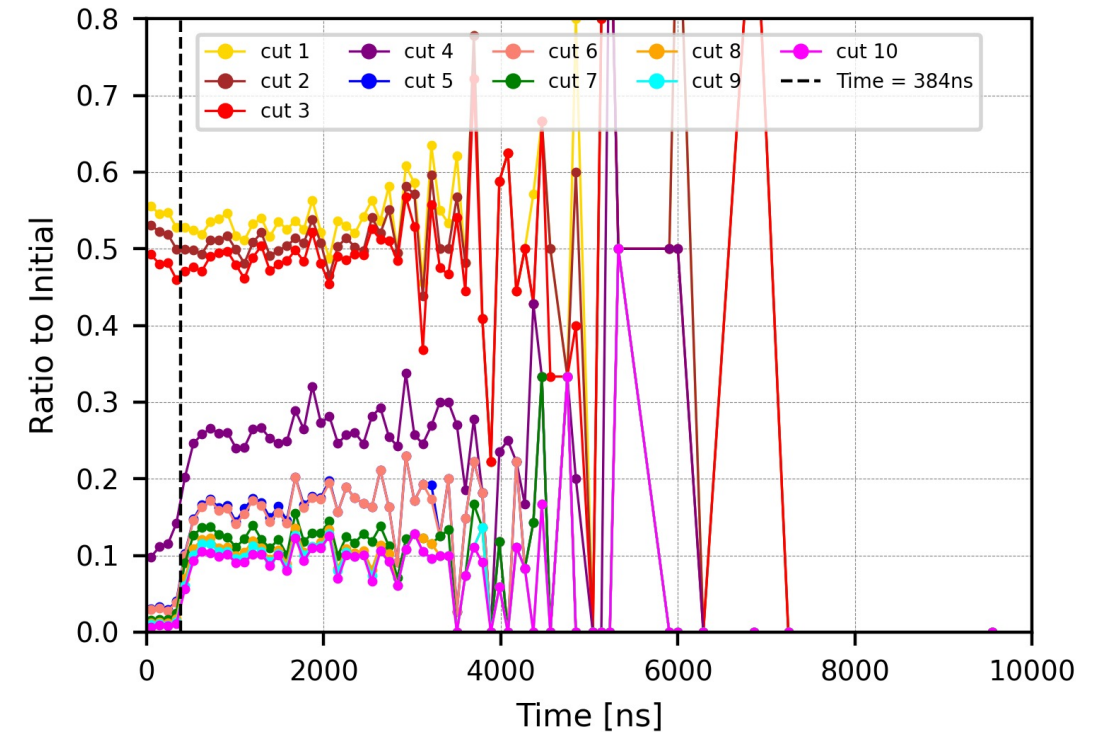
Efficiencies VS Time [$e^\pm$ separated]:

 e^+

Michel Selection Efficiencies

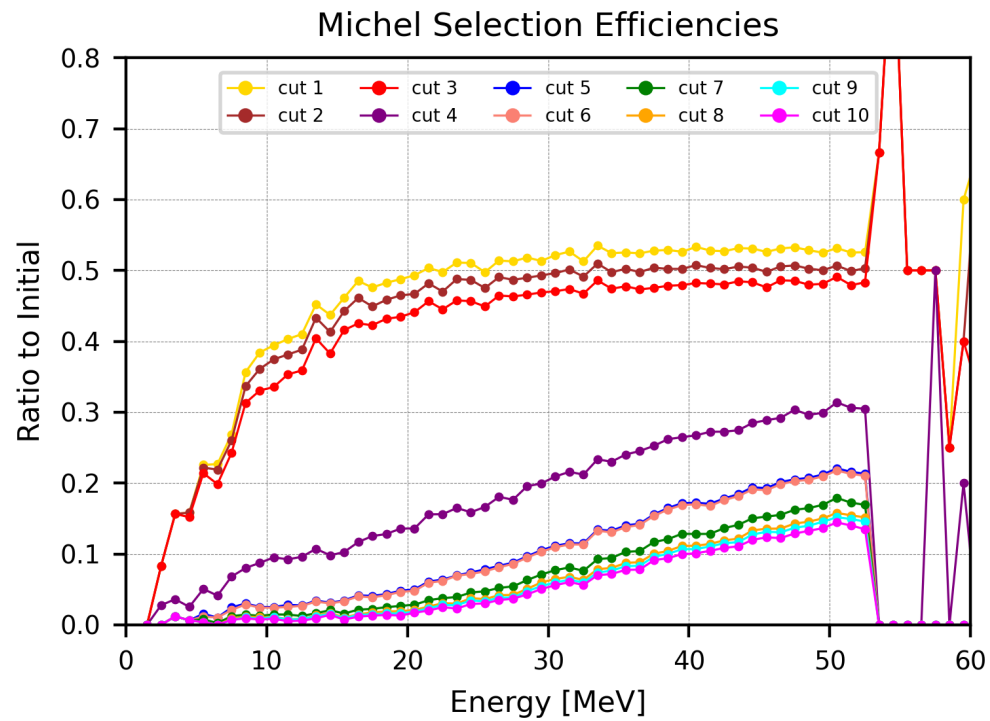
 e^-

Michel Selection Efficiencies

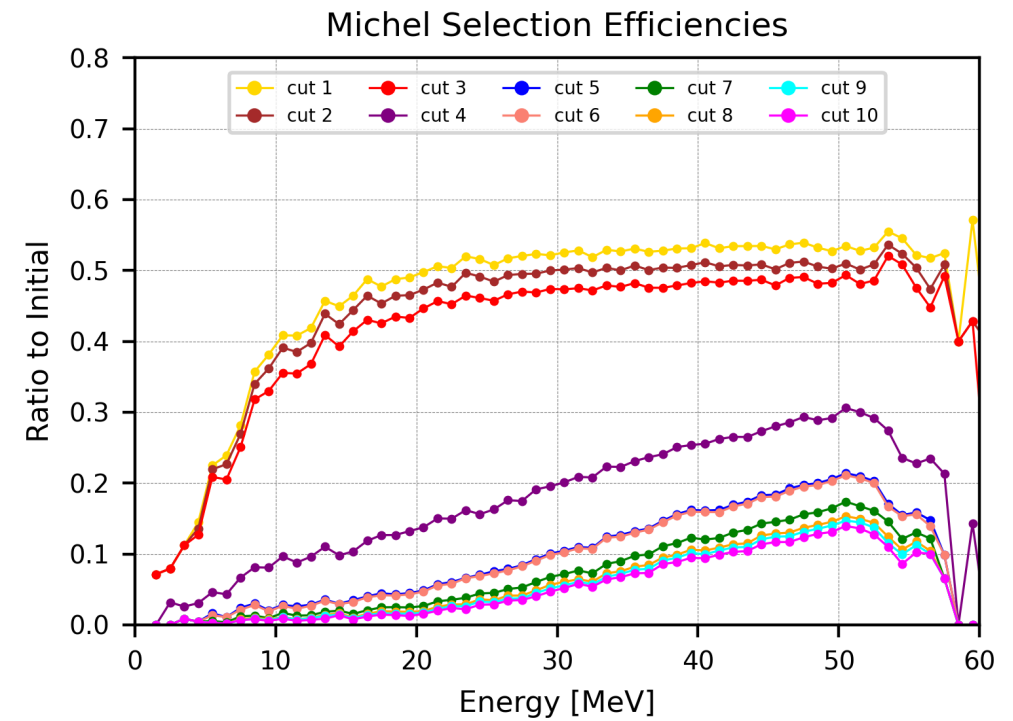


Efficiencies After TPC Cuts:

e^+



e^-



Muon Decay in Flight:

$$P_{\text{DIF}}(L) = 1 - \exp \left[-\frac{L}{\beta\gamma \cdot c\tau_\mu} \right] = 1 - \exp \left[-\frac{L m_\mu}{p_\mu c\tau_\mu} \right] \quad (4.14)$$

Assuming a propagation distance of $L = 10\text{m}$ and the free-muon lifetime $\tau_\mu = 2.2\mu\text{s}$, the probability becomes

$$P_{\text{DIF}}(10\text{m}) \approx 1 - \exp \left[-\frac{1.6 \times 10^{-3}}{p_\mu [\text{GeV}/c]} \right] \approx \frac{1.6 \times 10^{-3}}{p_\mu [\text{GeV}/c]} \quad (4.15)$$

For $p_\mu = 0.3\text{GeV}/c$, the probability is $P_{\text{DIF}}(10\text{m}) = 0.53\%$. For $p_\mu = 1.0, 10\text{GeV}/c$, the corresponding probabilities are 0.16% and 0.016% , respectively. Therefore, the contribution from **DIF** is expected to be small and can be neglected compared with **DIO**.

Michel-like Signal diagnosis:

Several signal / bkg checks:

Ex: third peak

True Michel

Very Michel-like

Big signal at the end of time window

Correlations of r , N , τ_{μ^-} :

Show both MC (initial) / final MC / final Data

X