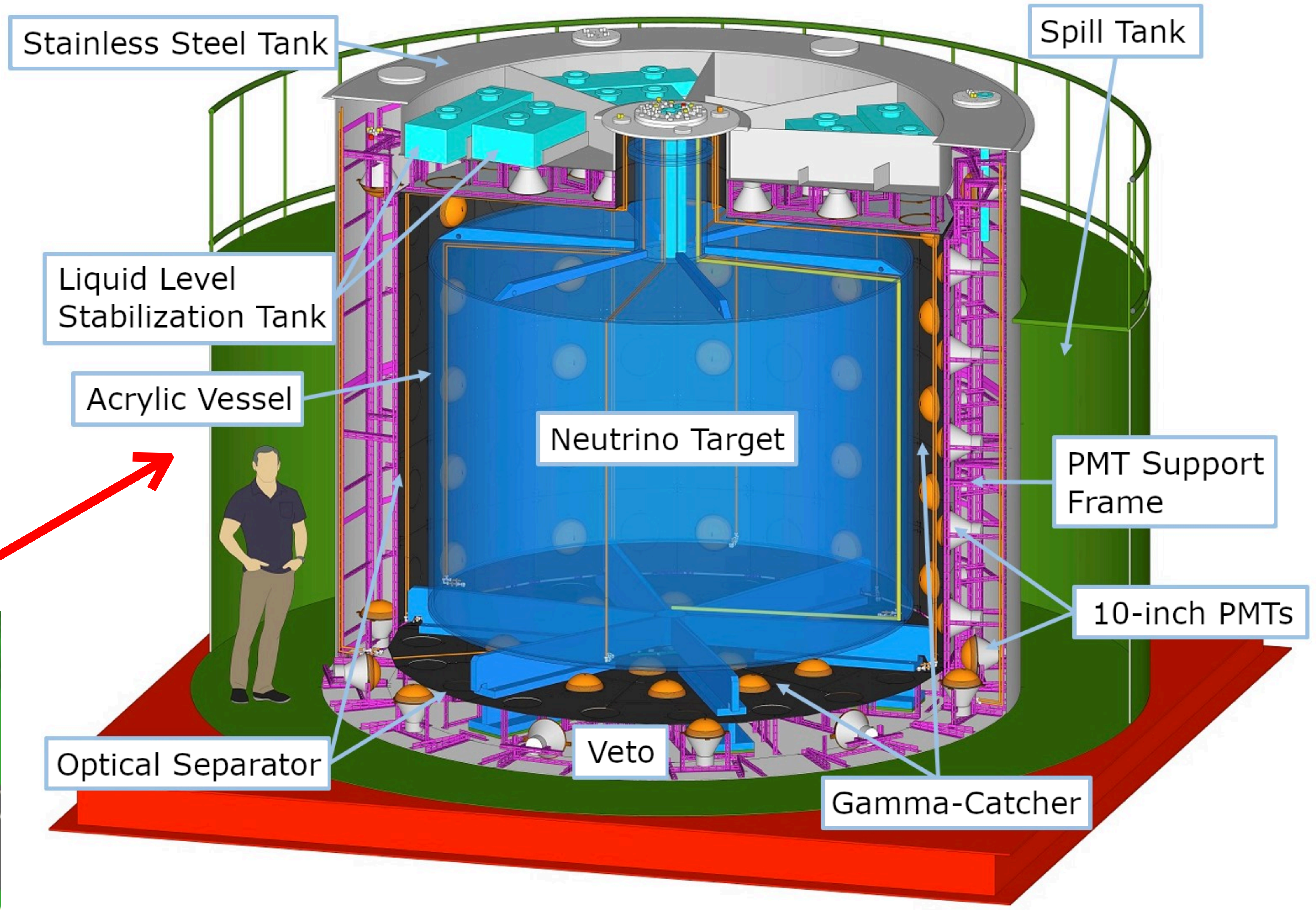
JSNS^2
Status & Results

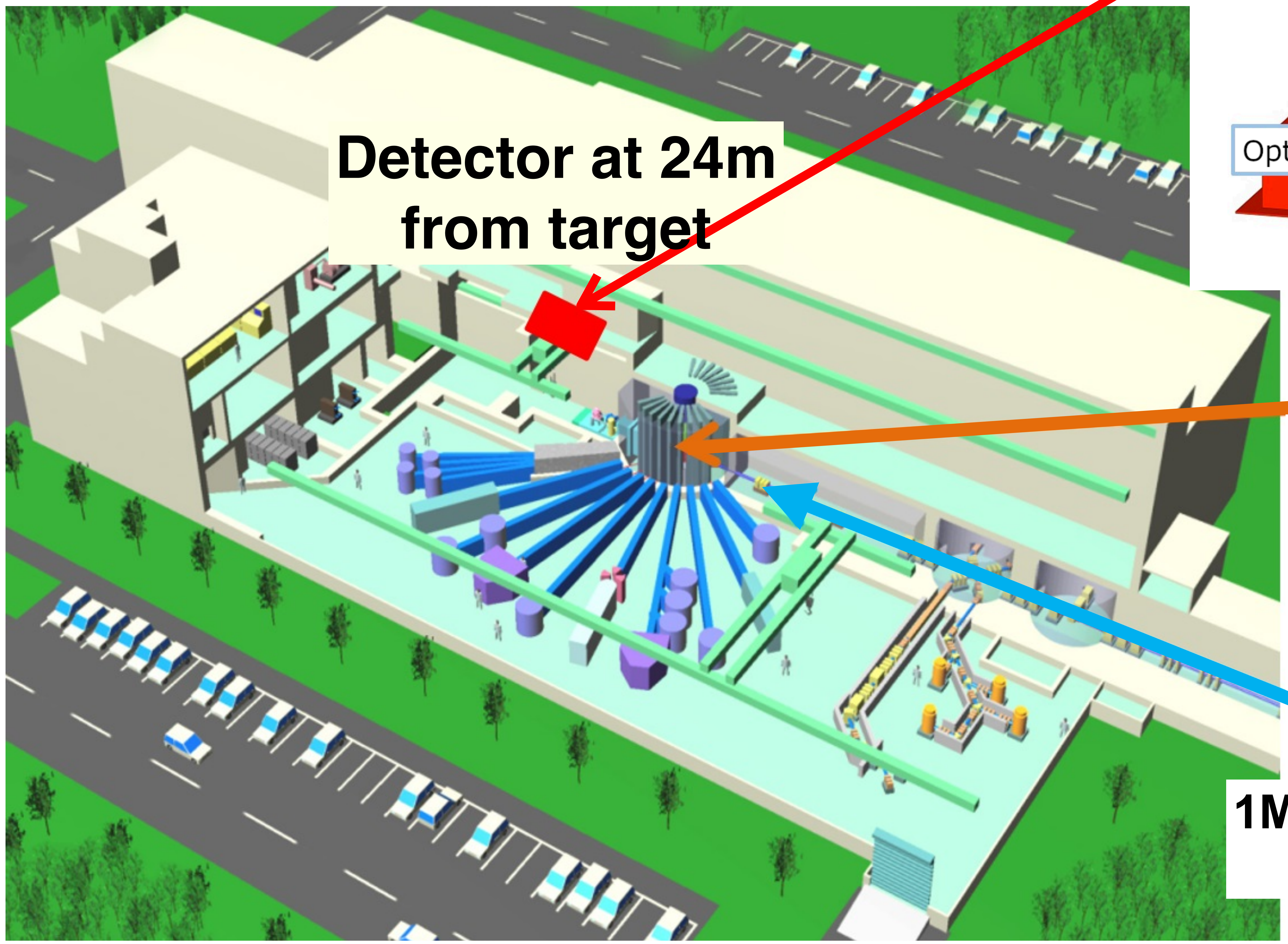
NEUTRINO 2024

Eric Marzec for the JSNS^2 Collaboration
University of Michigan
June 17 2024

Detector & Facility

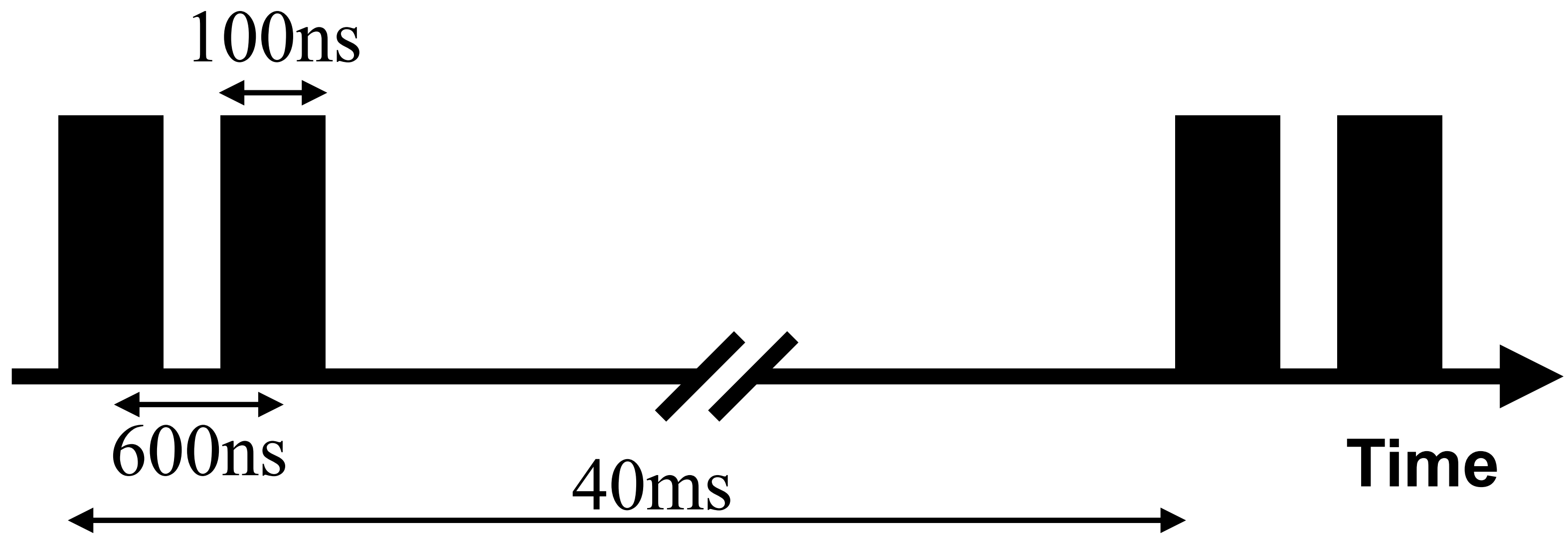
- Located at Materials & Life Sciences Facility (MLF) at J-PARC
- Detector is 17tons Gd-LS w/ 10% DIN & 31tons LS outer region
- Observed by 96 10-inch inner PMTs & 24 veto PMTs





Liquid Mercury Target

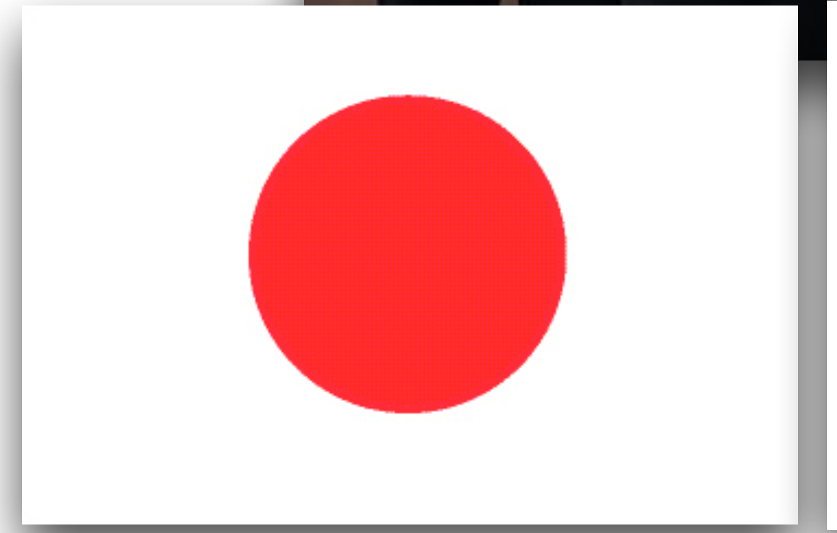
1MW, 3GeV pulsed Proton beam



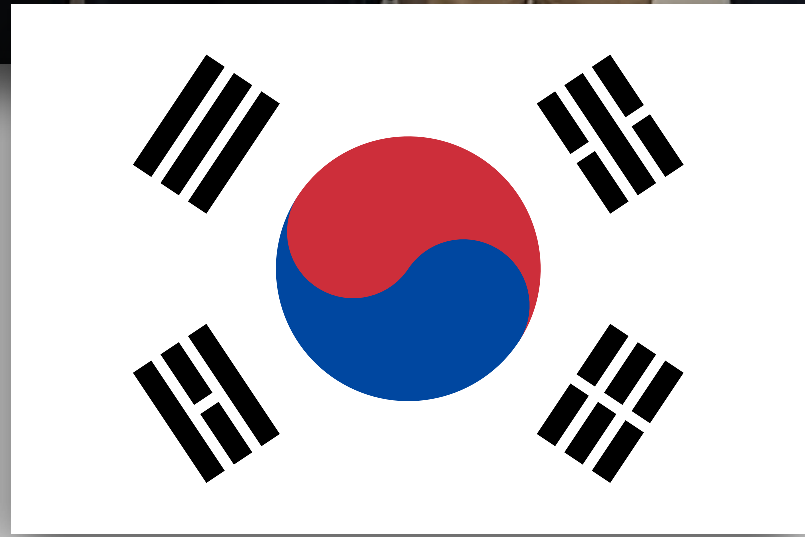
Low beam duty factor means excellent signal-to-noise.

JSNS^2 & JSNS^2-II Collaboration

JSNS^2 Collaboration - 61 Members across 23 institutions & 5 countries



KEK
JAEA
J-PARC
Tsukuba University
Osaka University
Tohoku University
Kitasato University
Kyoto Sangyo University



Soongsil University
Dongshin University
Seoyeong University
Kyung Hee University
Gwangju Institute of Science and Technology
Seoul National University of Science and Technology
Sungkyunkwan University
Chonnam National University
Jeonbuk National University
Kyungpook National University

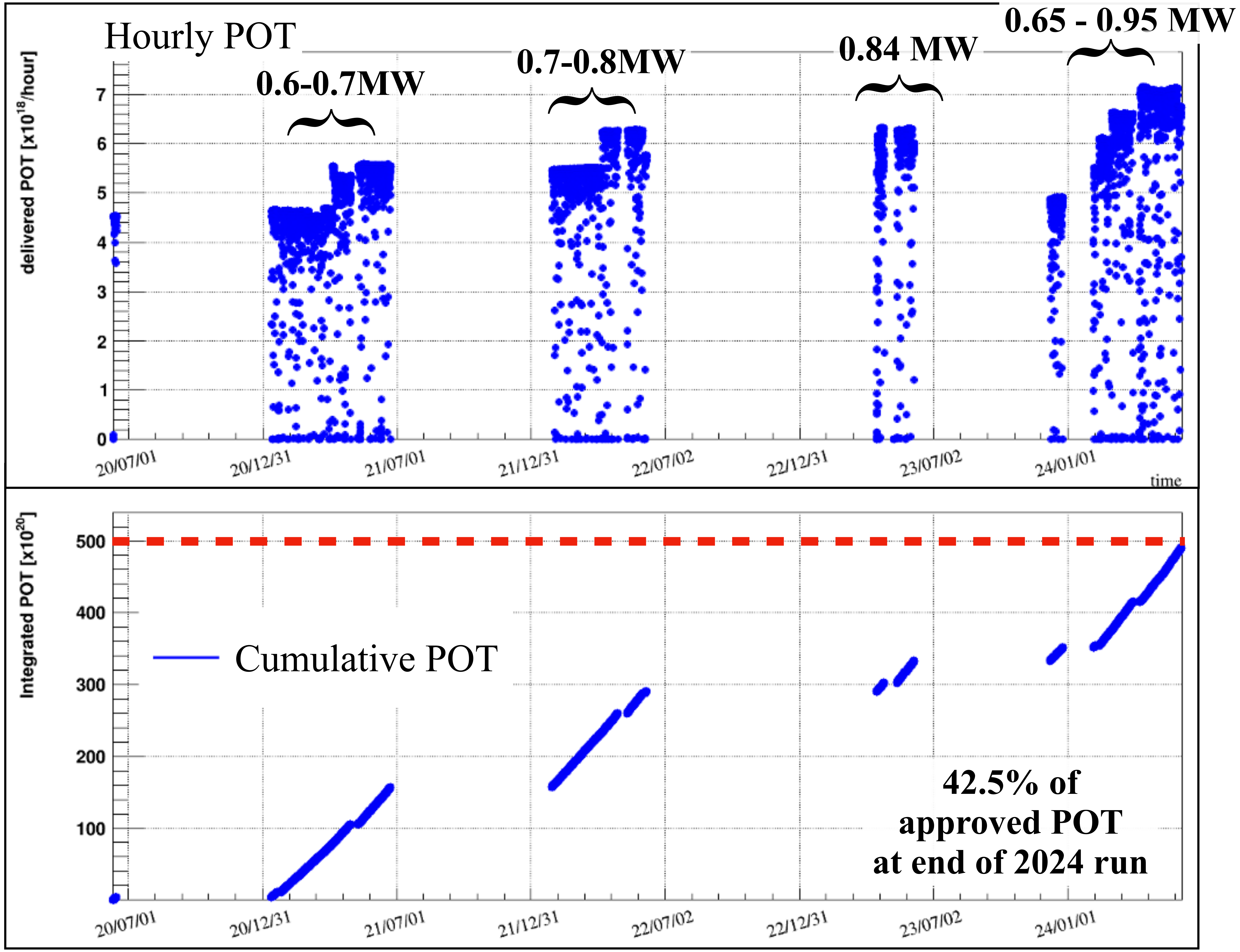
Brookhaven National Laboratory
University of Michigan
University of Utah

Sun Yat-sen University

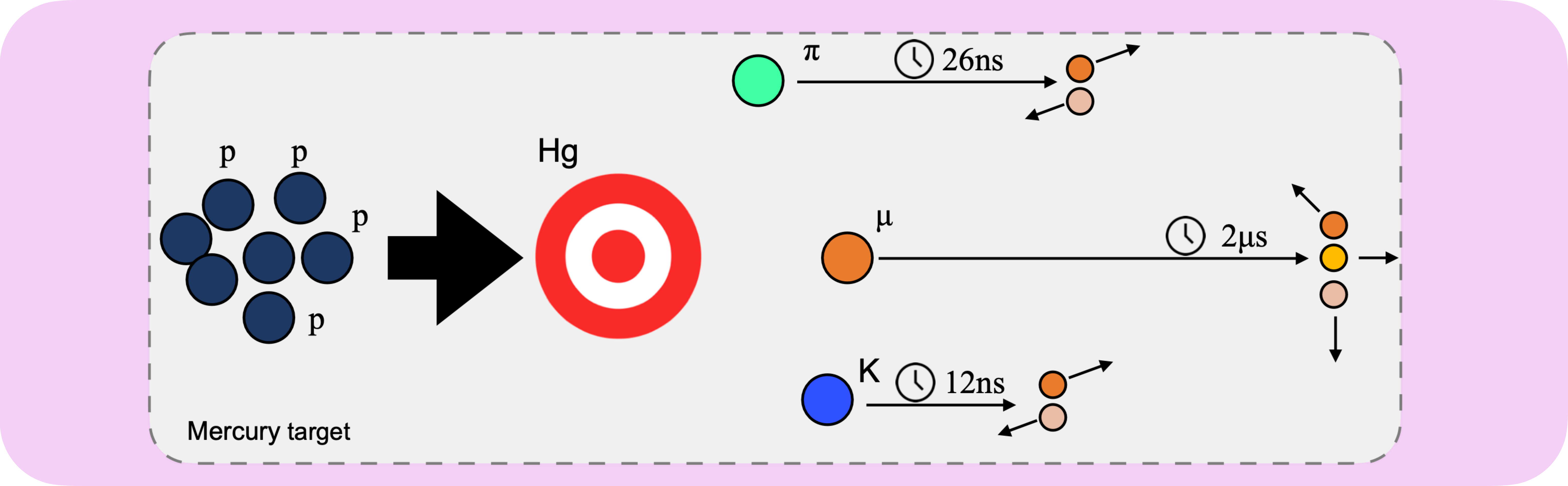
University of Sussex

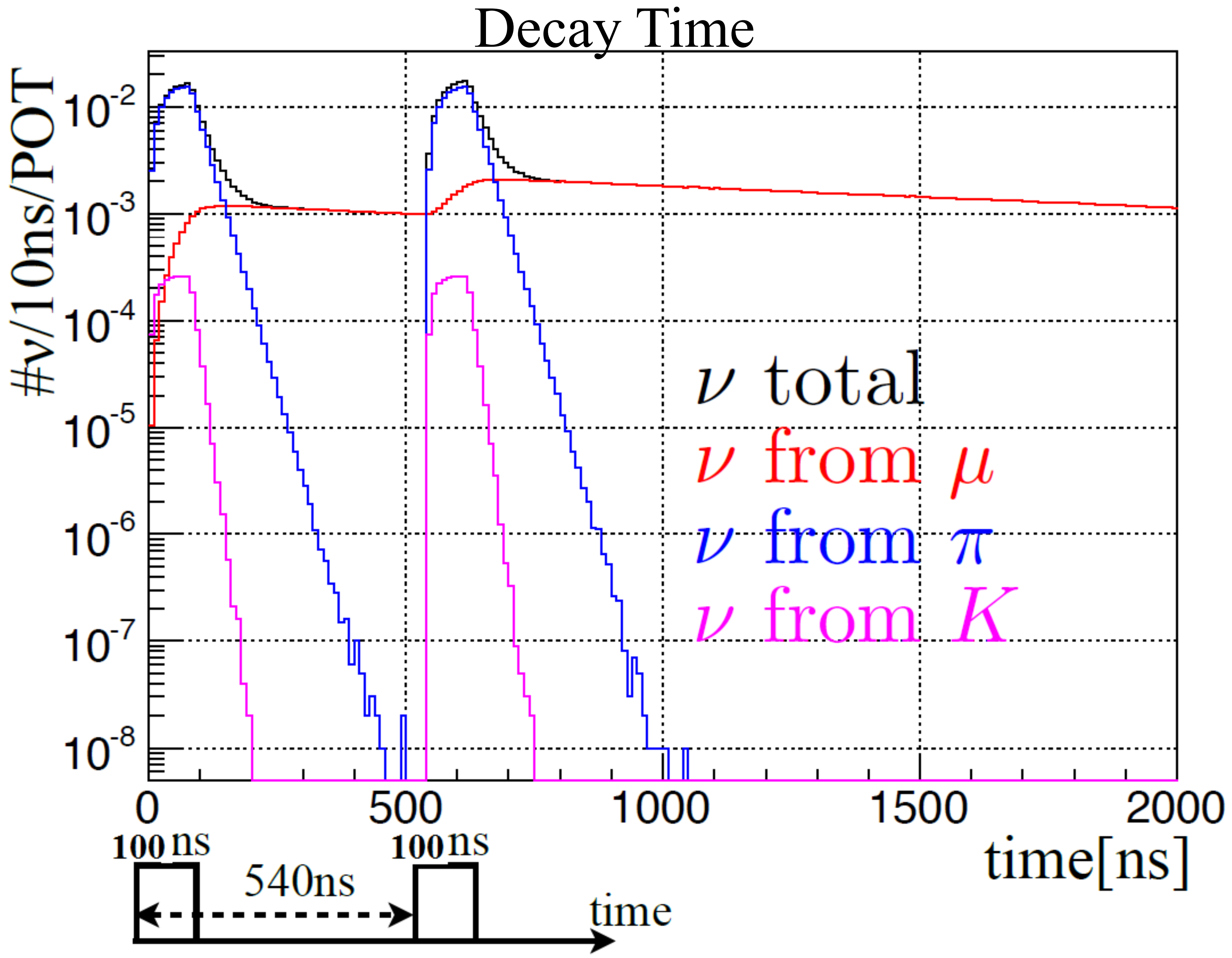
JSNS^2 Data Taking

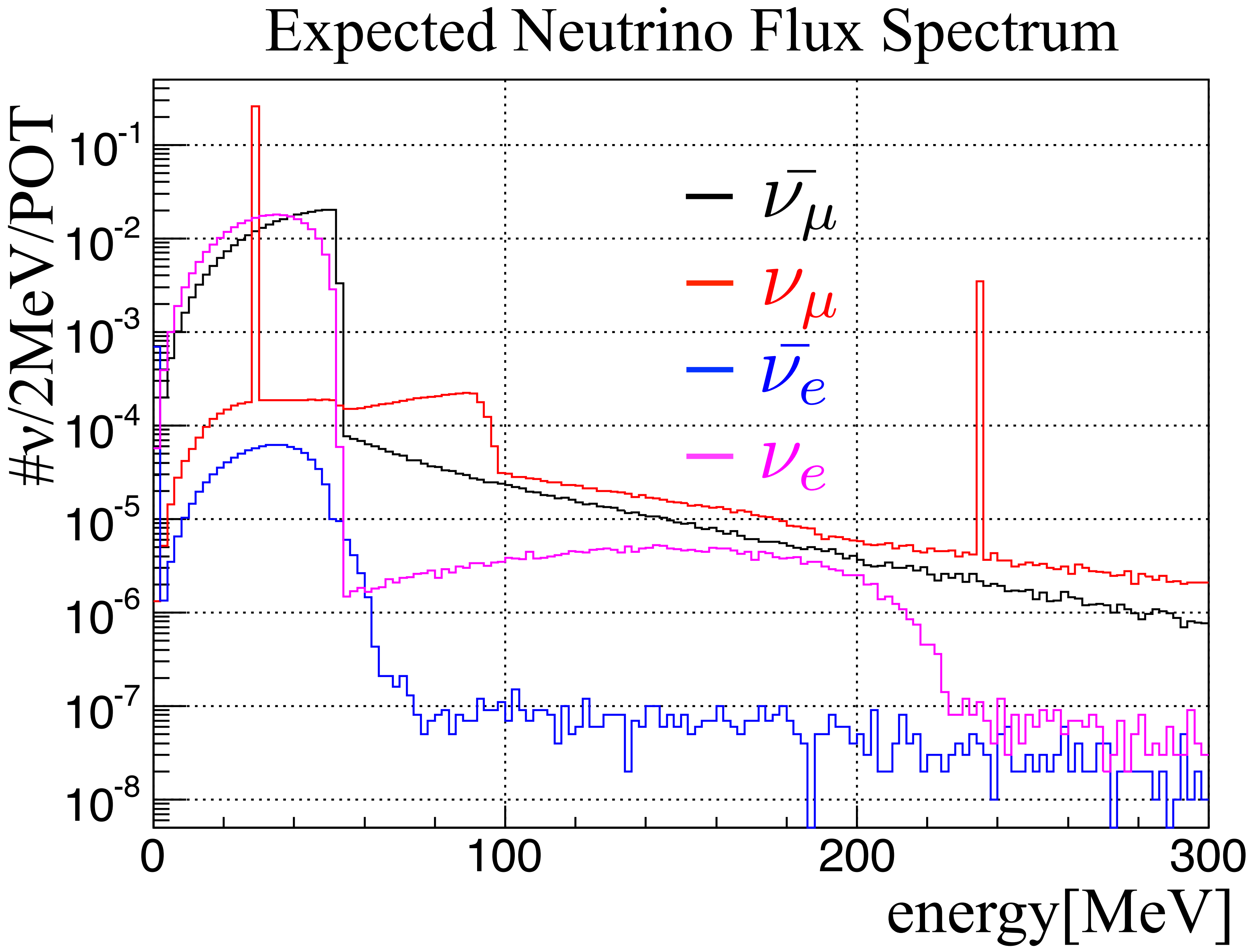
- Data taking began in spring 2020. First physics run was in 2021.
- Recently finished our 2024 data taking
- 1MW beam power design goal
- **Consistent 950kW beam delivery!**
- Data taking will resume in December



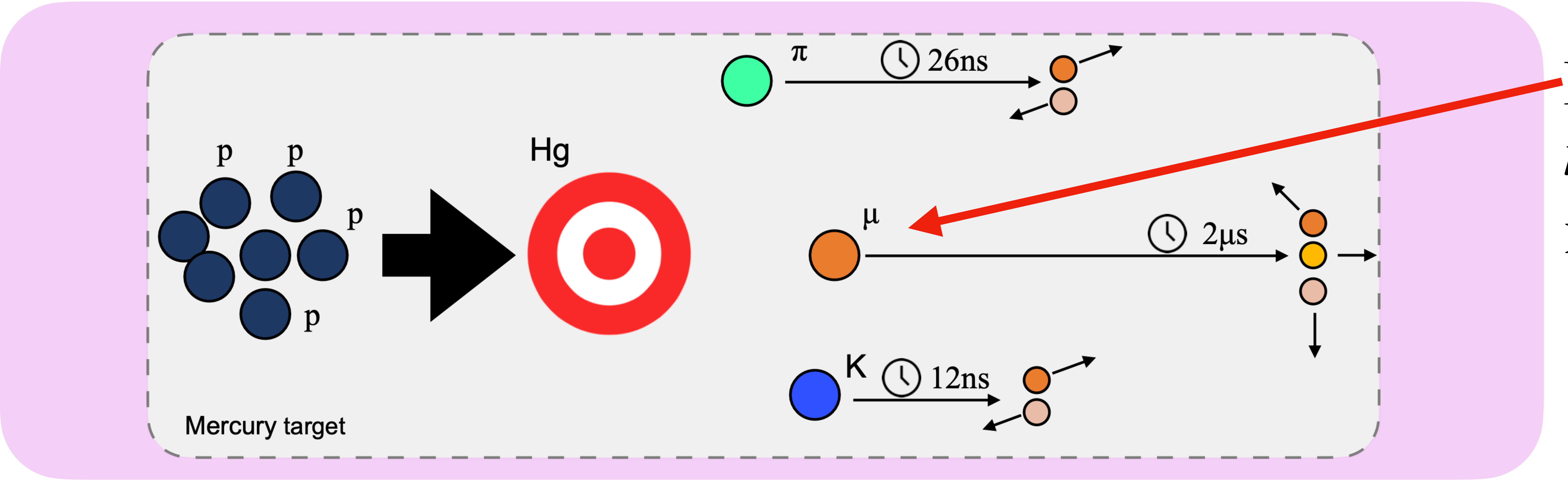
Neutrino Signals



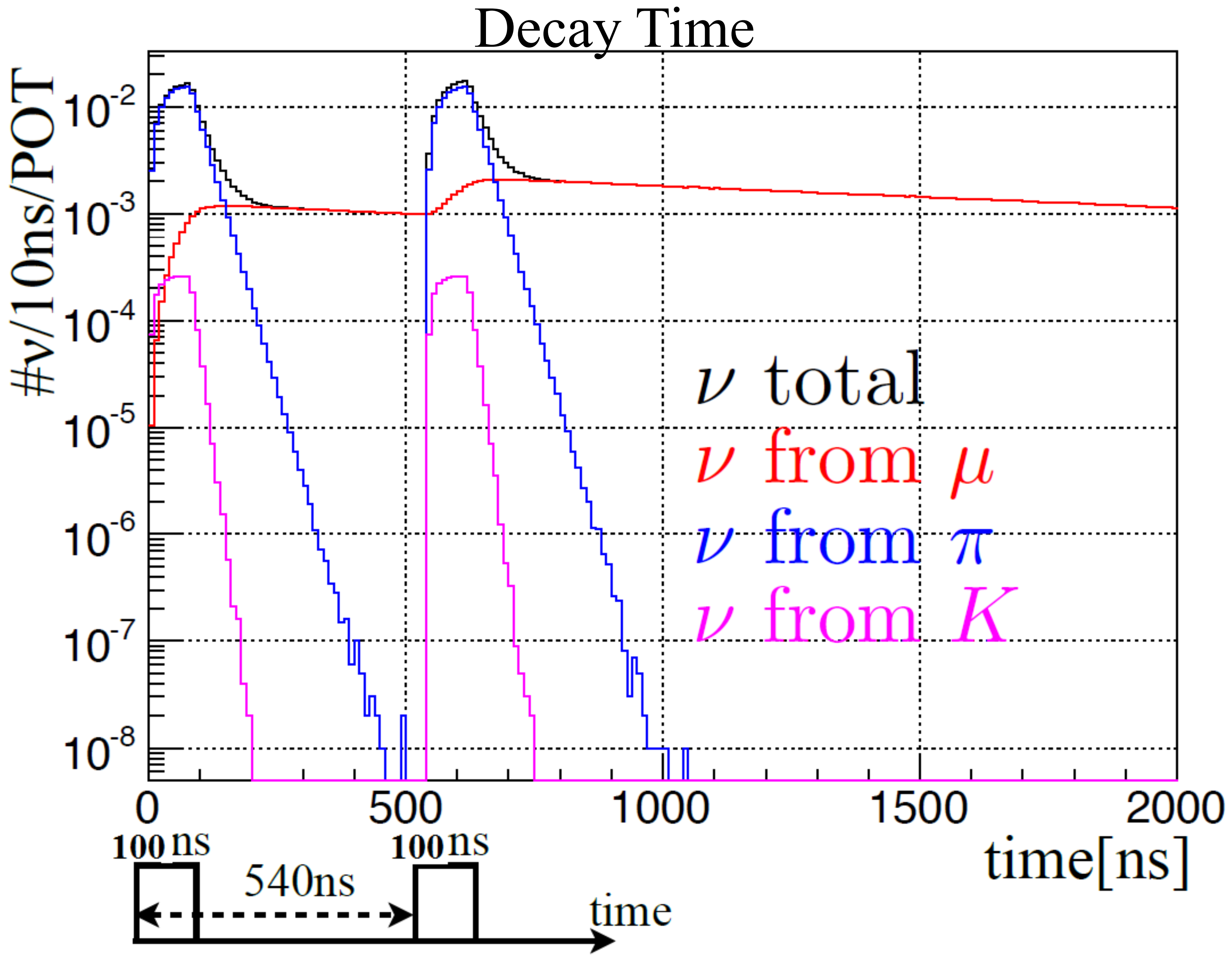


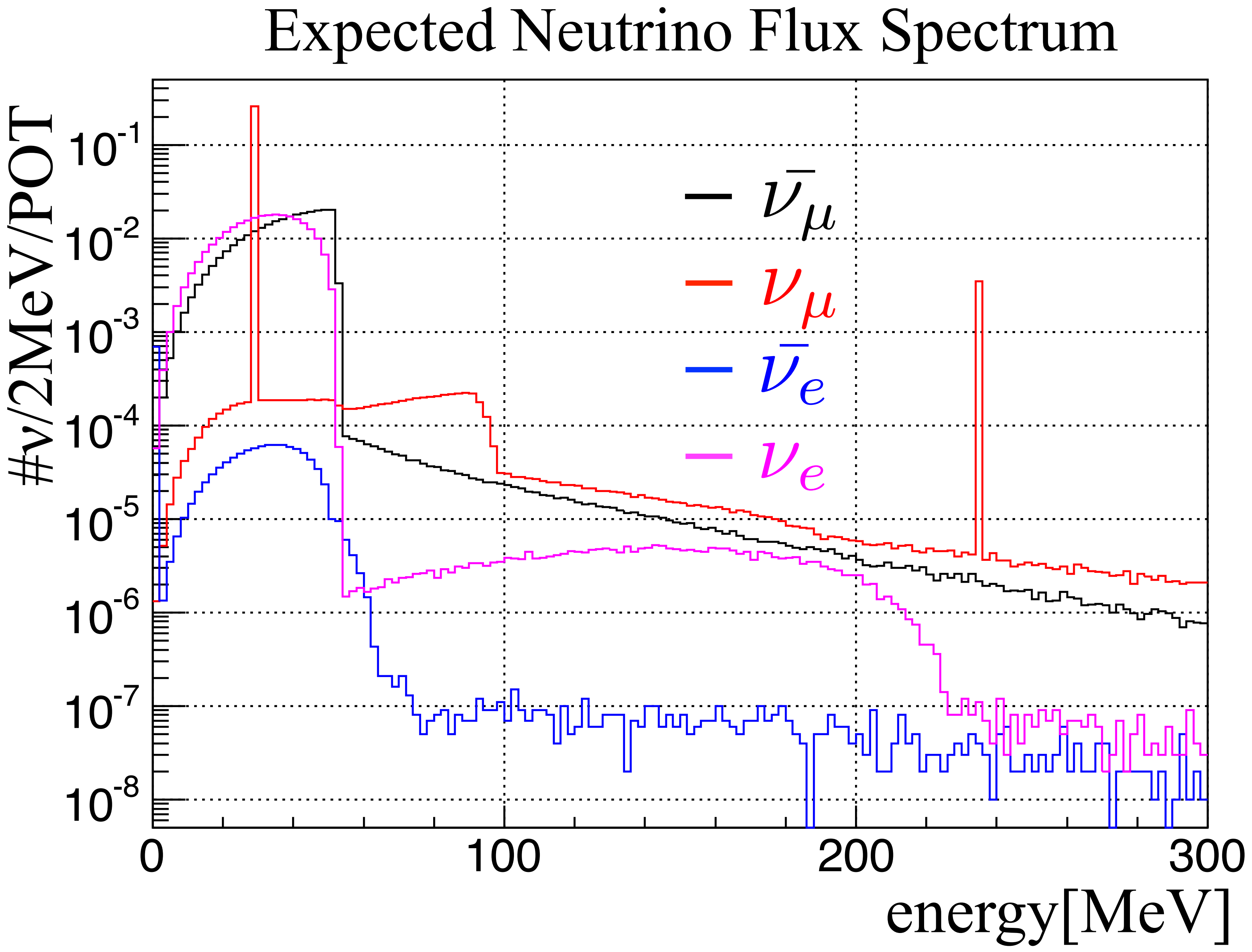


Neutrino Signals

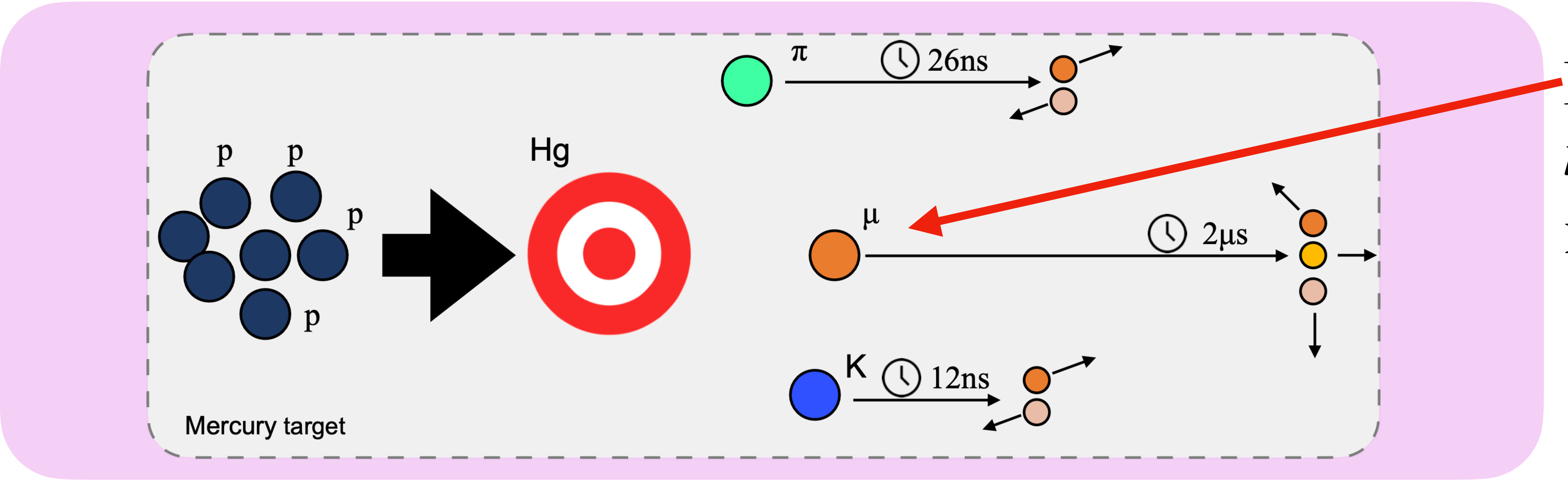


Look for short baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with neutrinos from muon decay



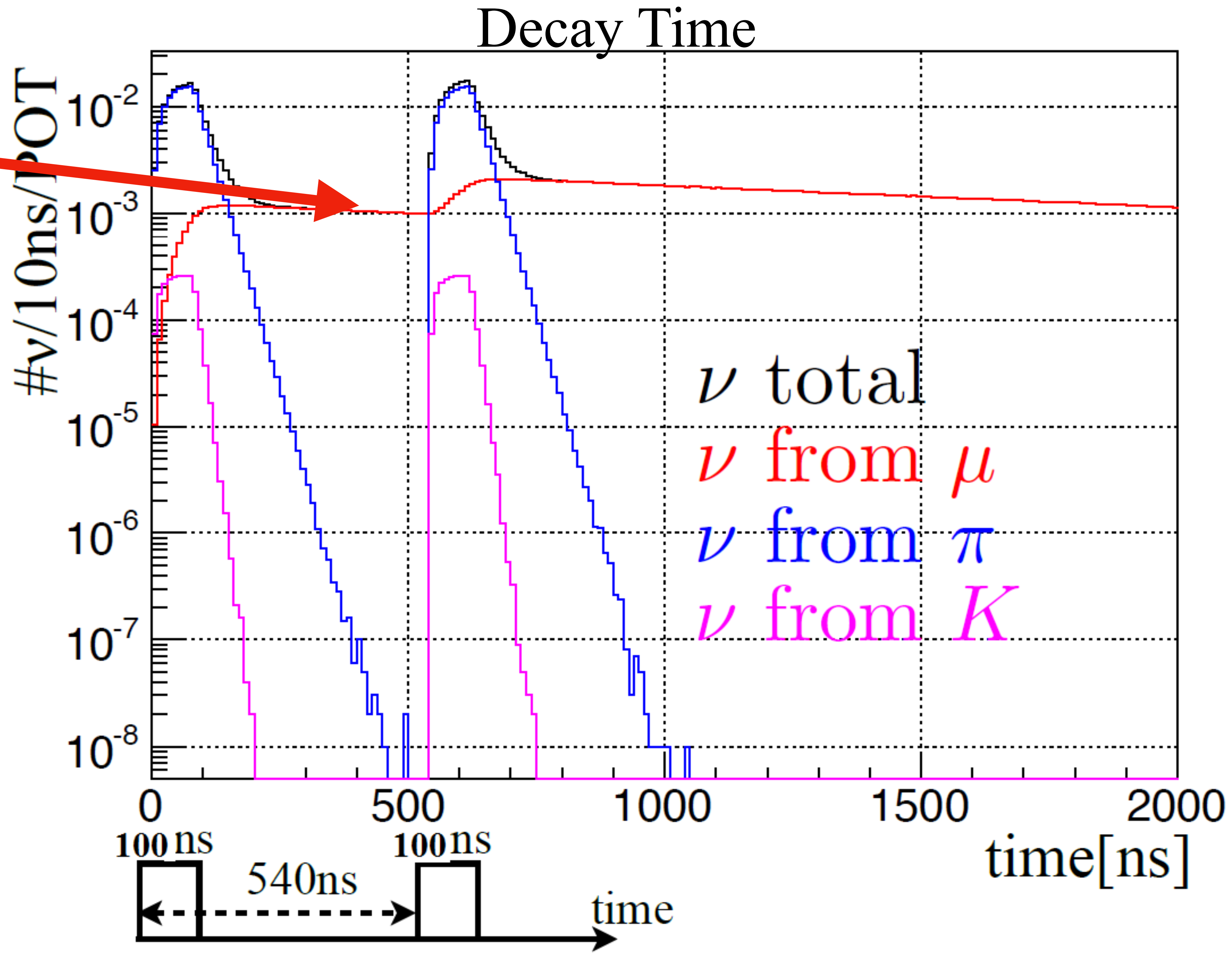


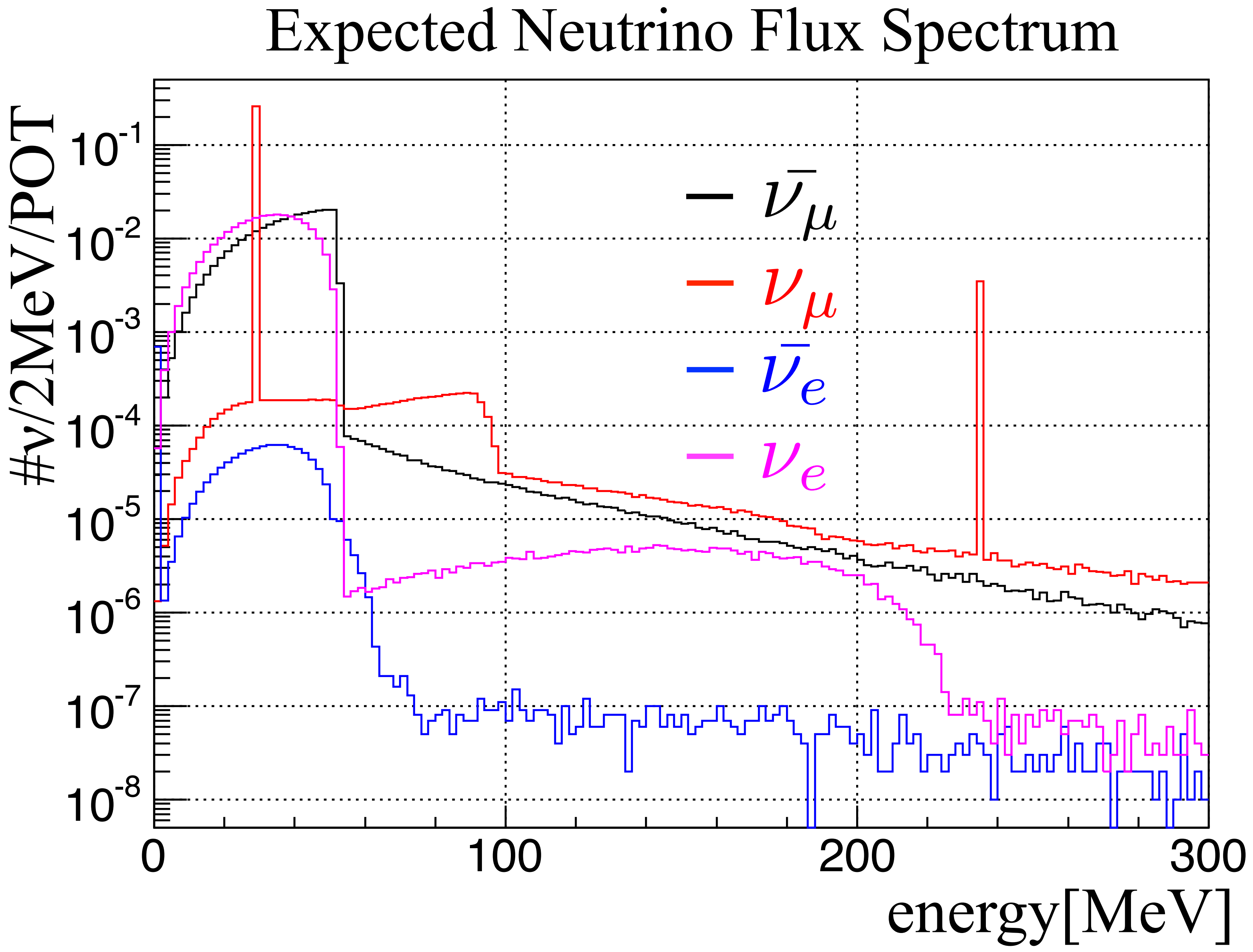
Neutrino Signals



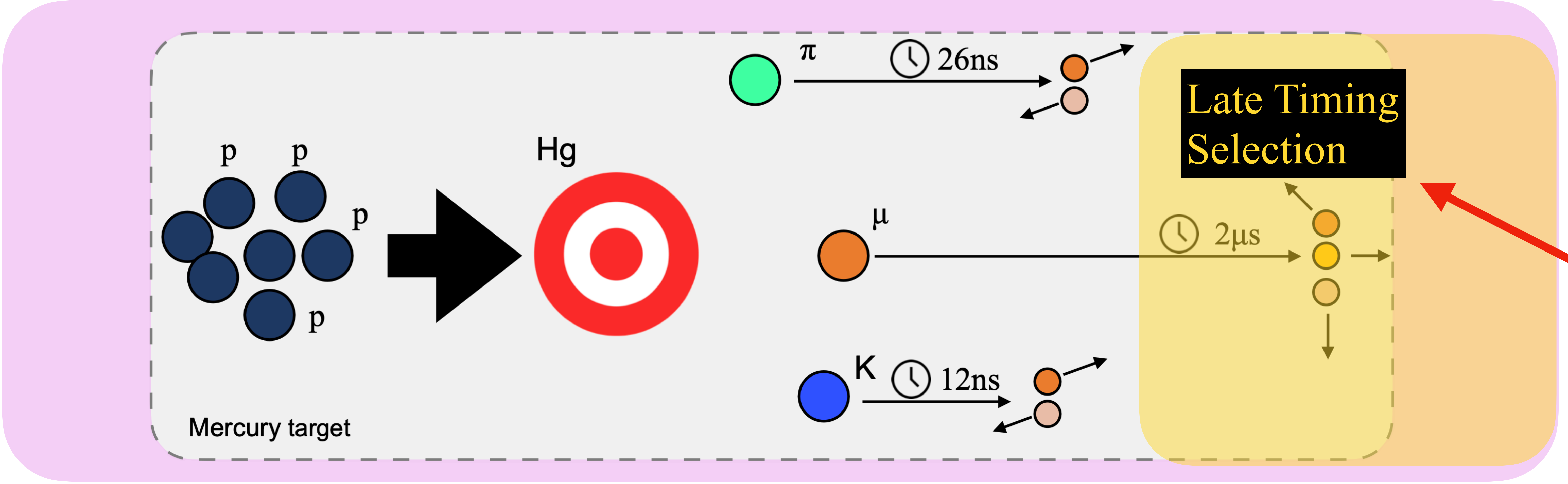
Look for short baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with neutrinos from muon decay

Muon's long lifetime separates its neutrinos from pion/kaon neutrinos

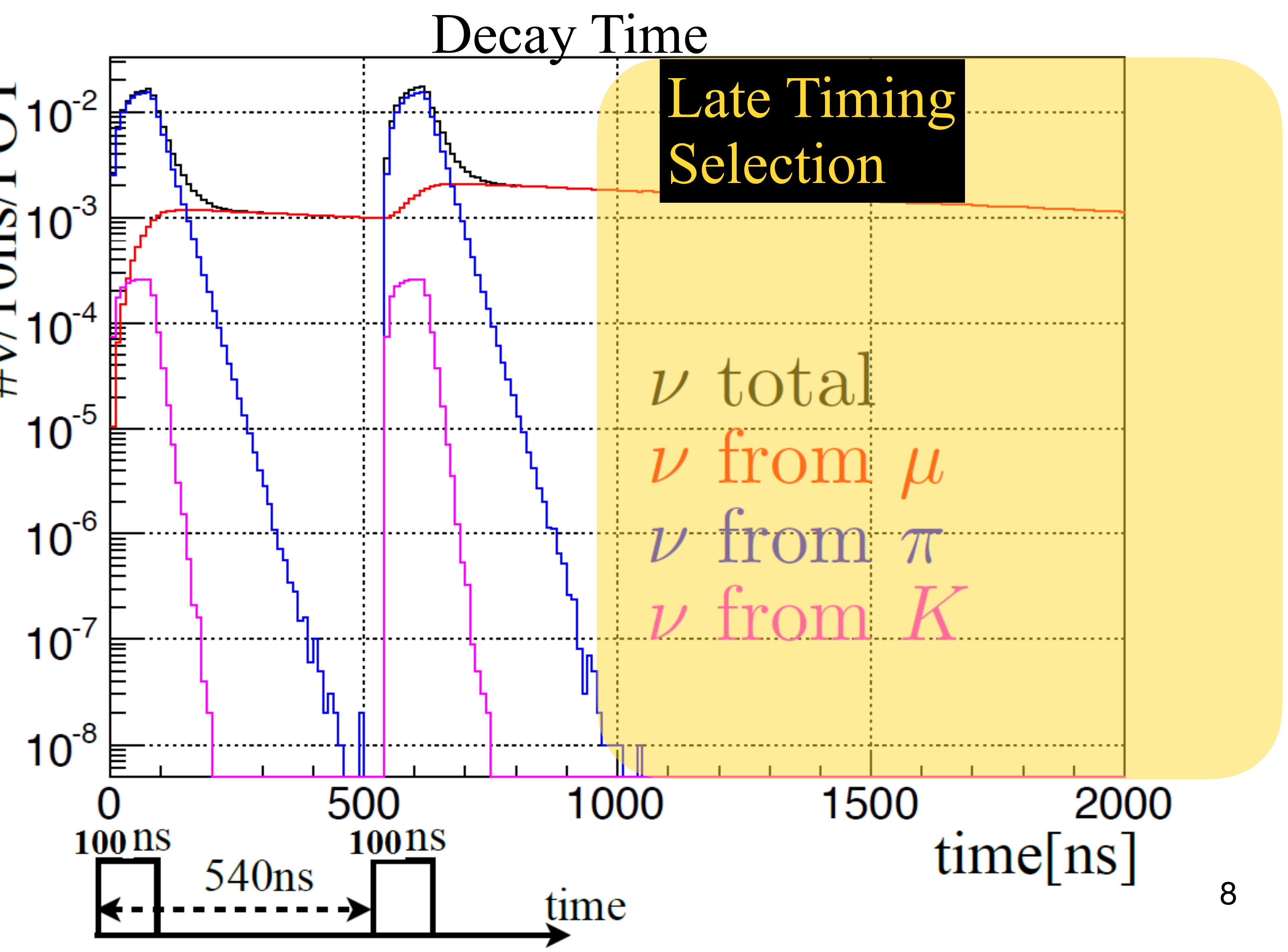


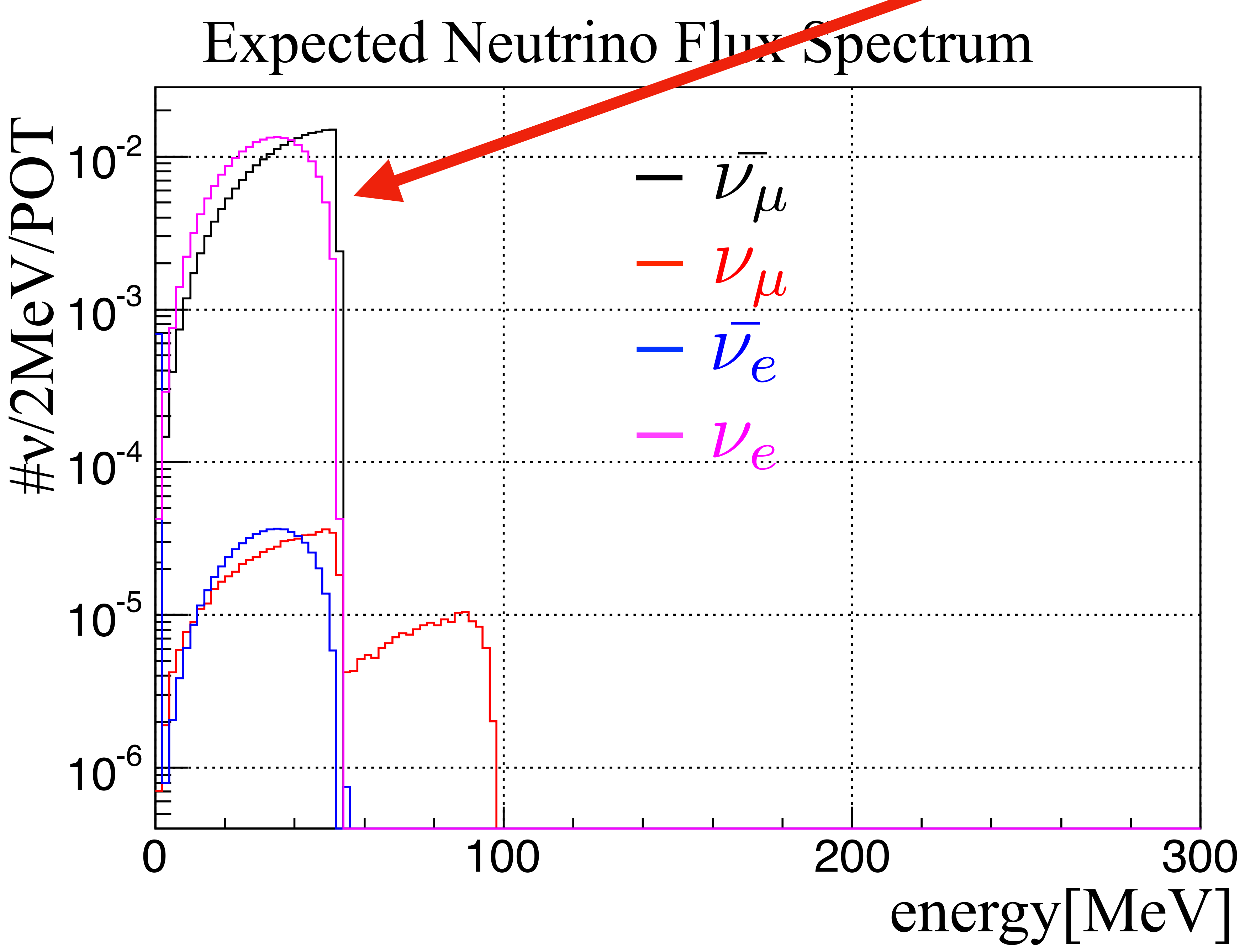


Neutrino Signals



Selecting for late times only removes decay-in-flight & pion/kaon neutrinos





Sterile Neutrino Signal

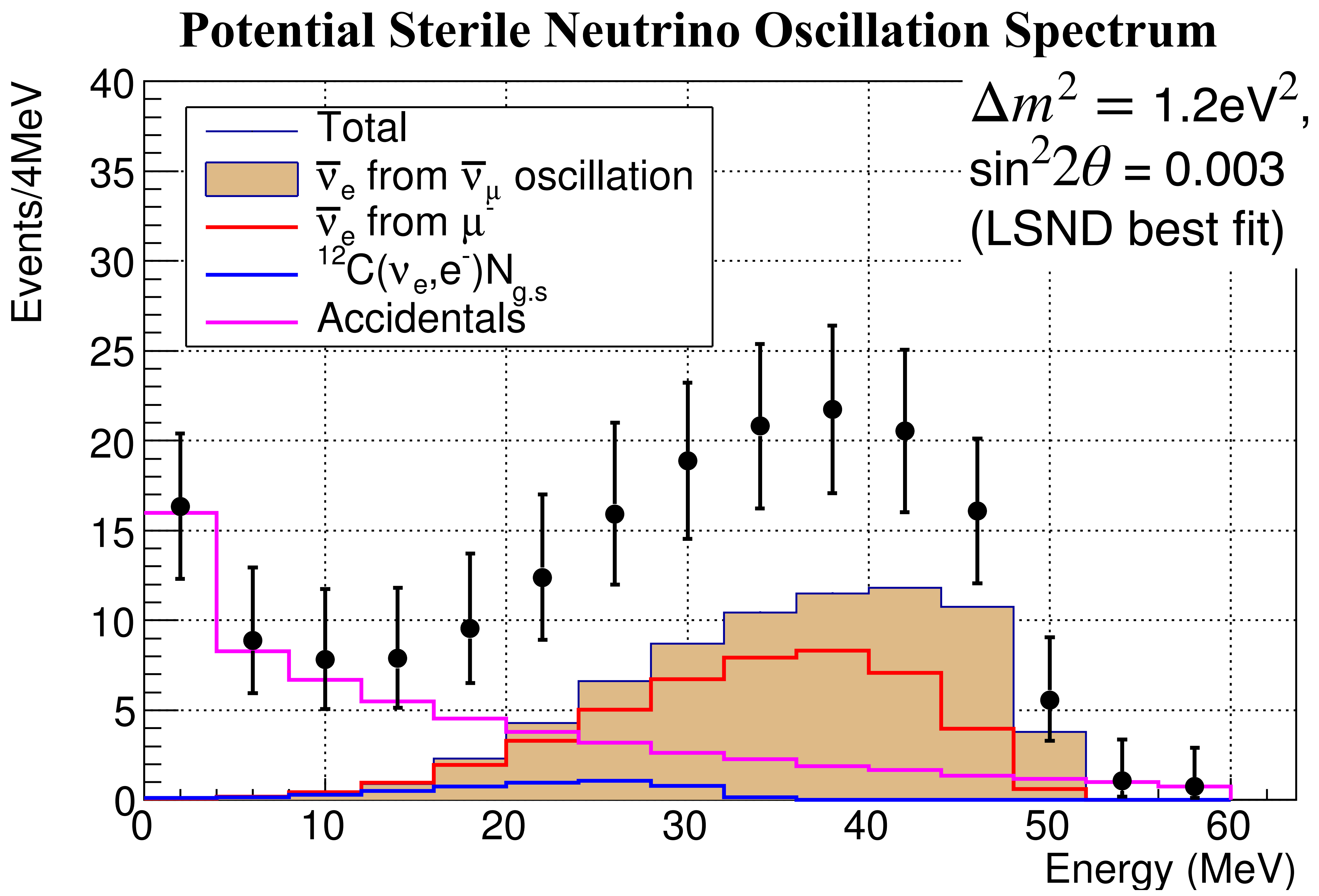
- Detect $\bar{\nu}_e$ via inverse beta decay (IBD) interactions.

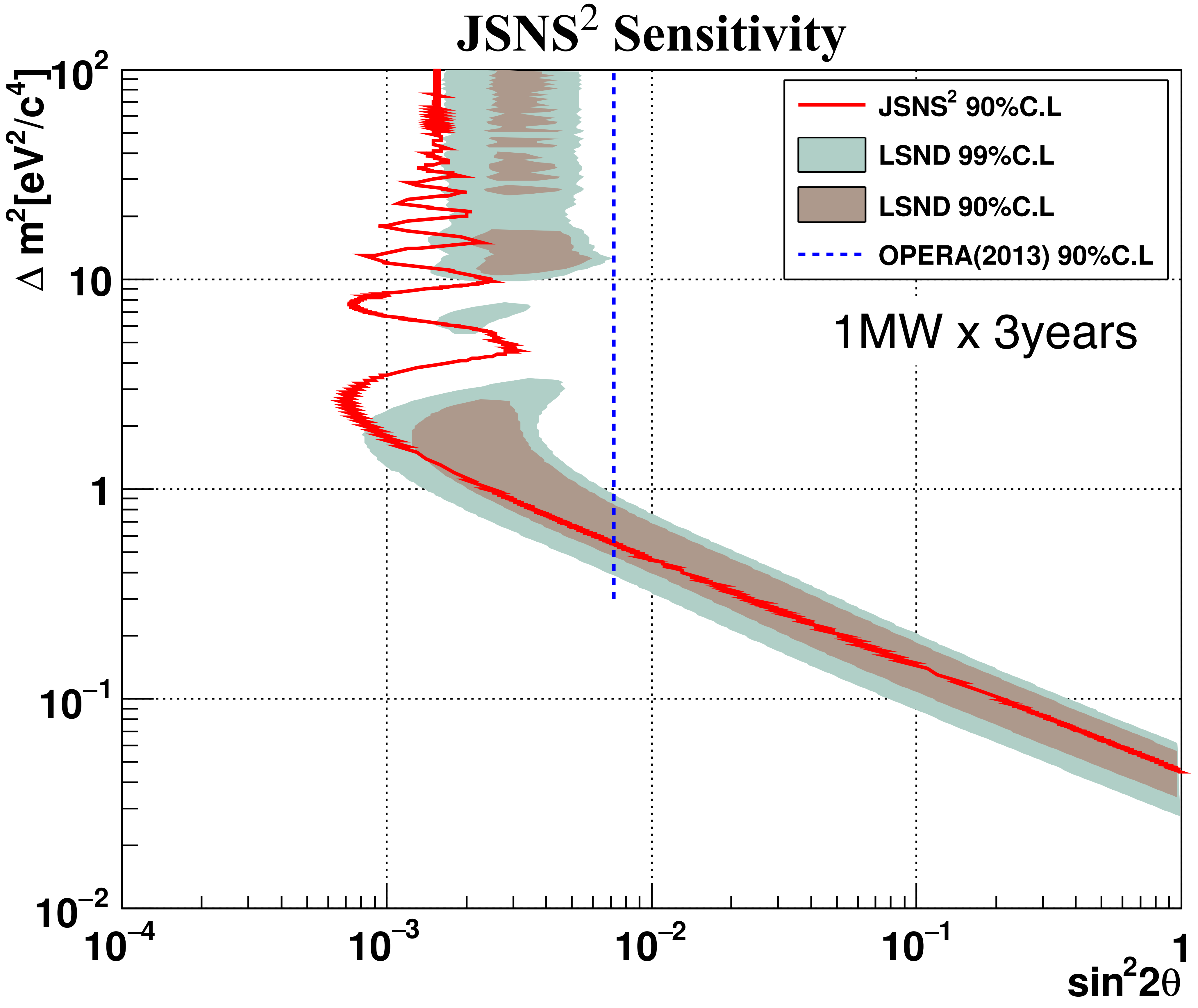
- Coincidence selection…

	Timing	Energy
Prompt	1.5 < t < 10μs	20 < E < 60 MeV
Delayed	Δt < 100μs	7 < E < 12 MeV

Expected Sterile Neutrino Sensitivity

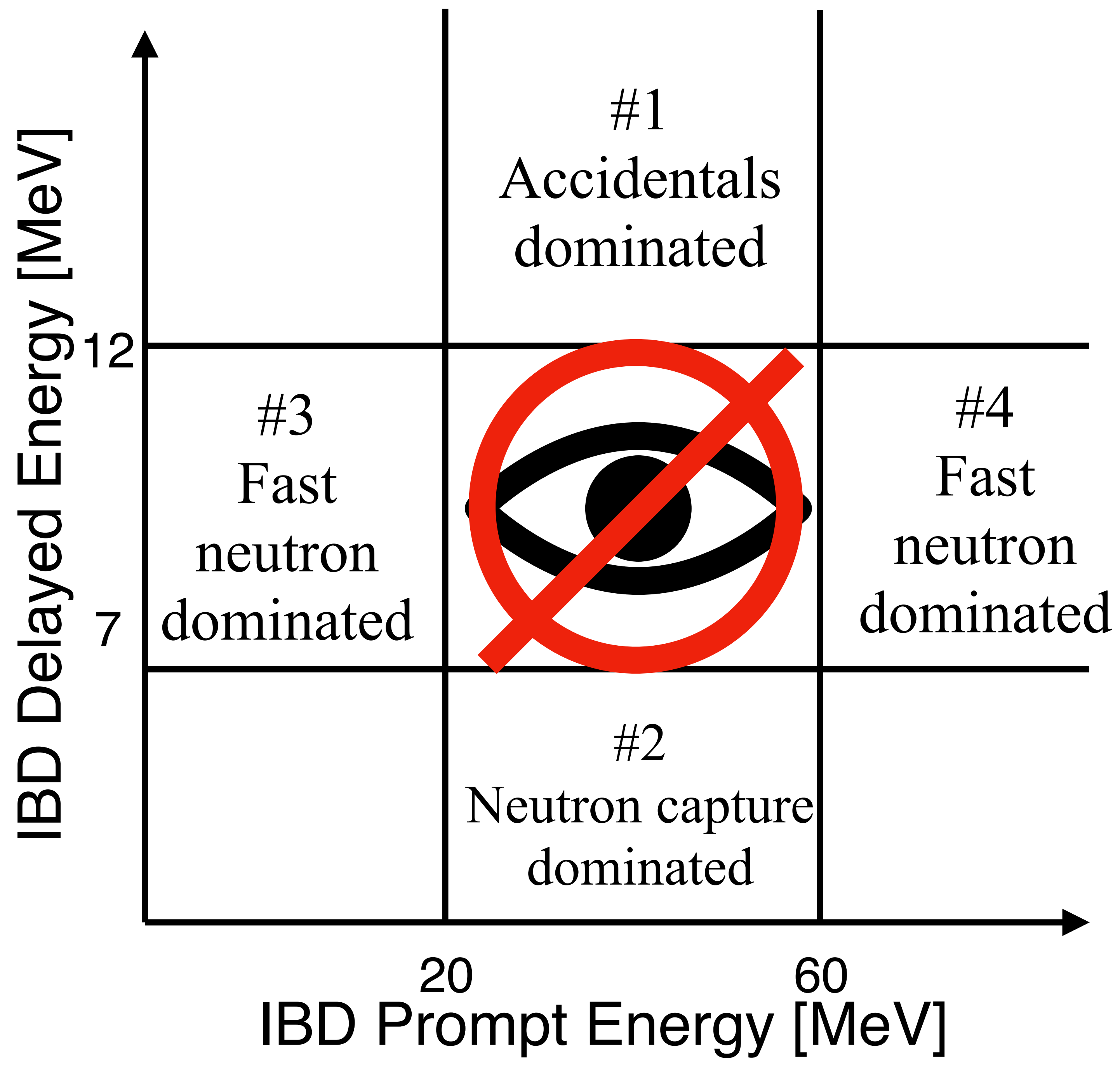
- With 1MW x 3years observed POT (currently acquired 42.5%) we'll cover the majority of the LSND observation region at 90%CL

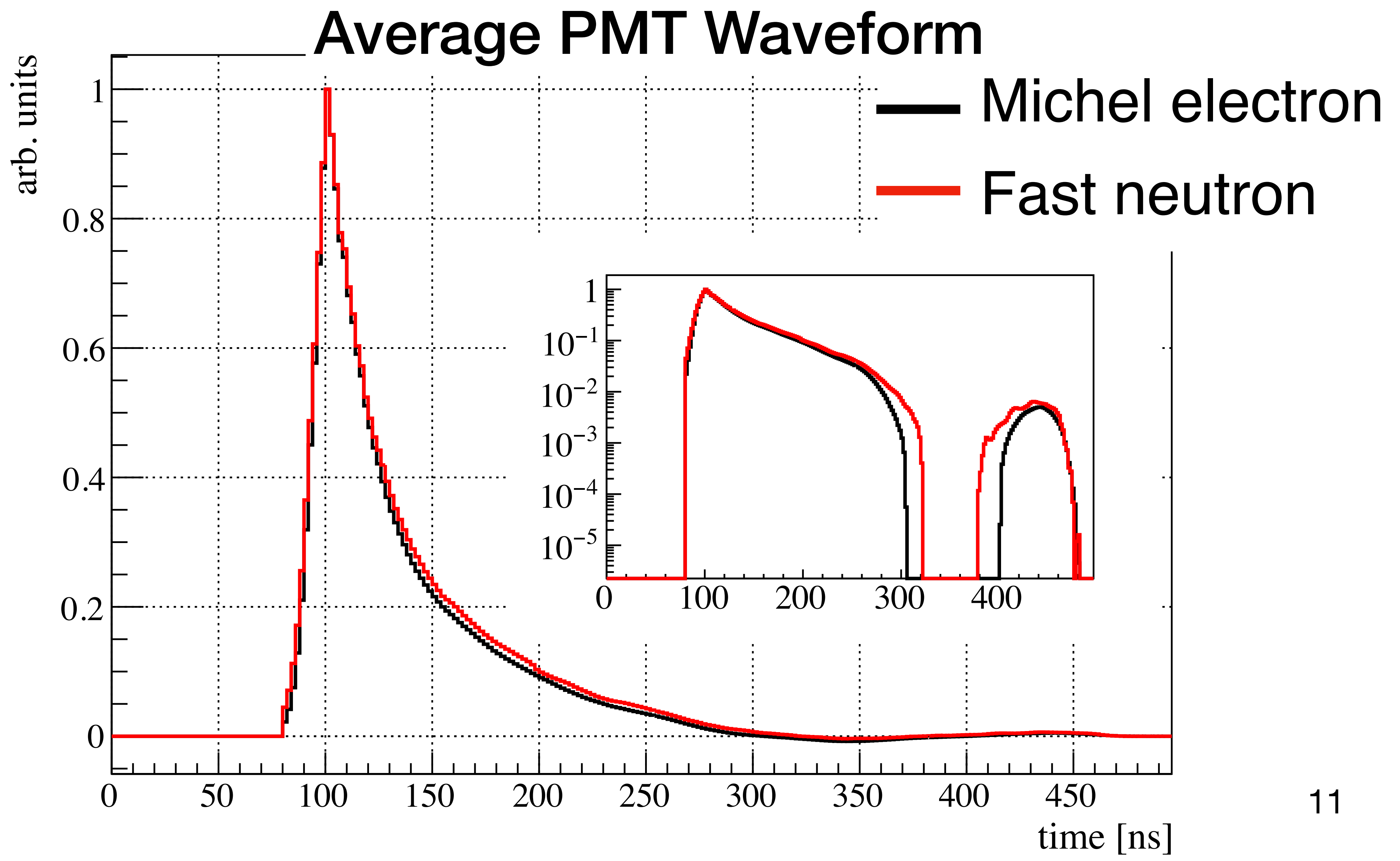


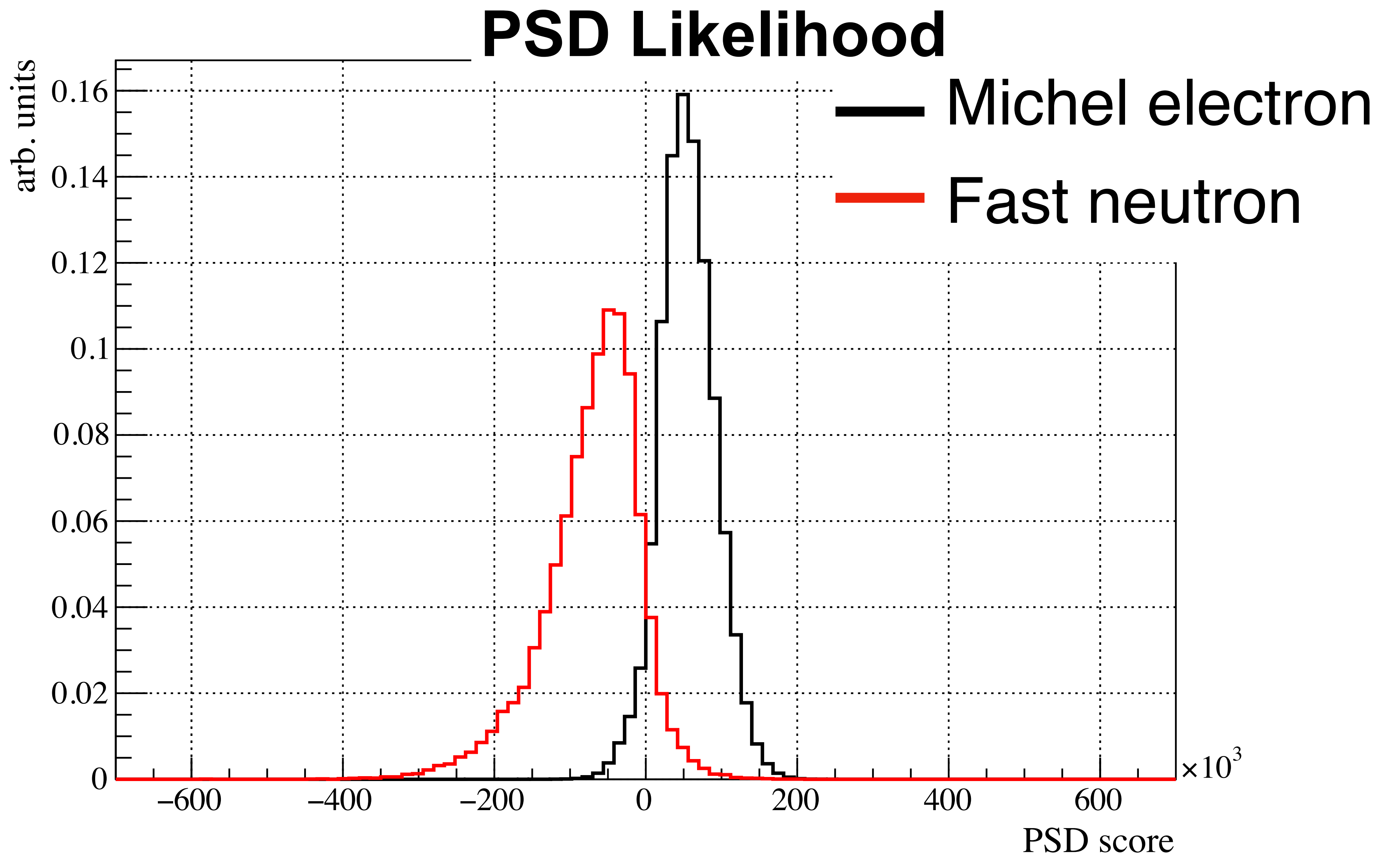


Sterile Neutrino Search Status

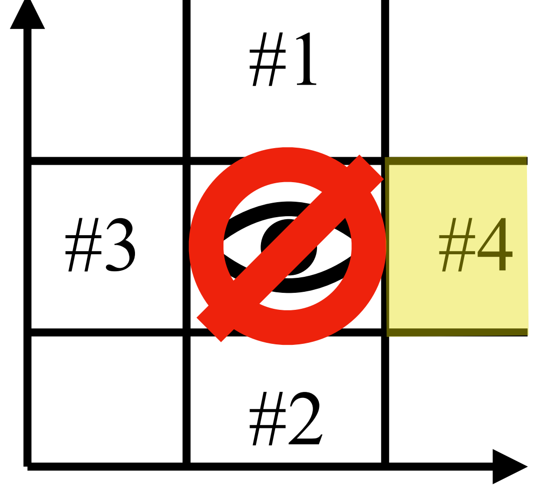
- We define a blinded signal energy window
- Sideband regions used to develop the background estimates and compare to observation
- Cosmic fast neutrons are our most pernicious background.
  - We can reject them using pulse-shape discrimination (PSD).
  - Achieves 95% rejection with only 10% signal loss (arXiv:2404.03679)





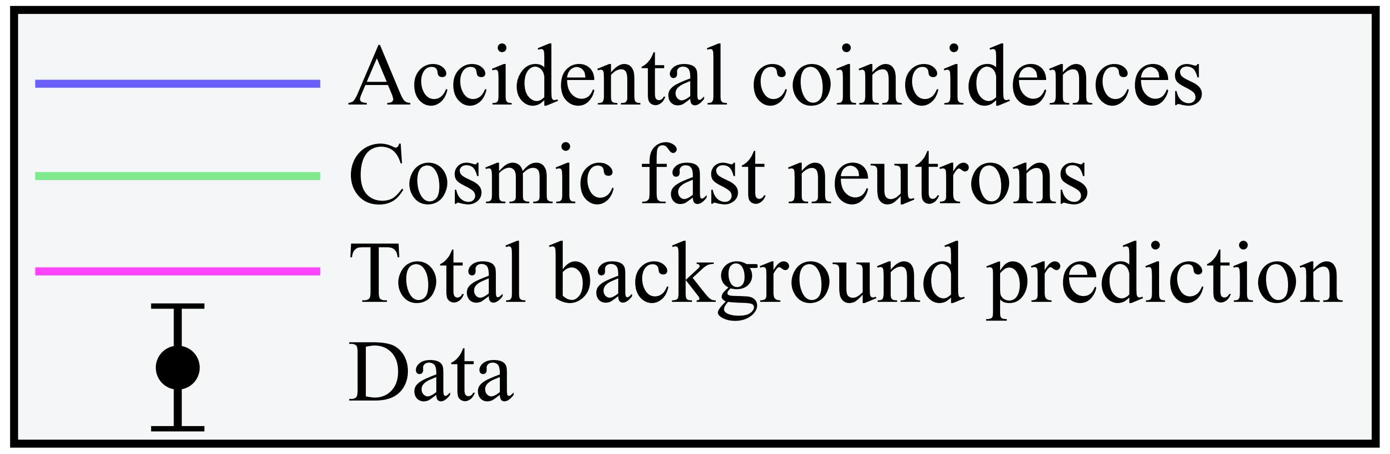


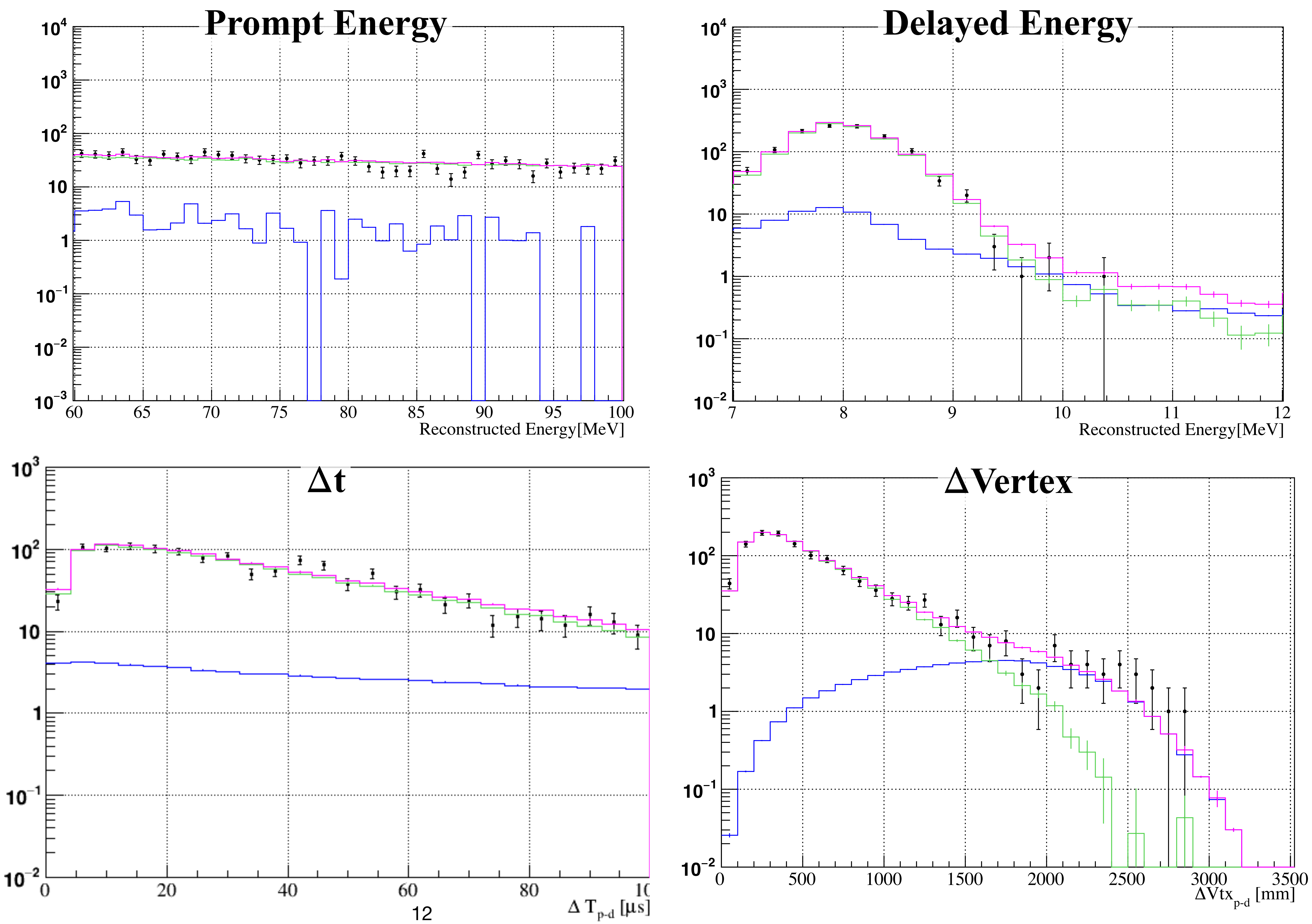
Side-band #4, Prompt Energy > 60 MeV Delayed Energy 7-12 MeV



- **All background estimates are data driven**
- Accidental rates are estimated via “spill-shift” method
  - Prompt-delayed pairs from different beam spills are purposefully mis-paired.
- Cosmic fast neutron rate is estimated by looking in late time window (>1ms after beam)
- **Observed data is consistent with accidentals+neutron background estimate**
- Other sidebands are being studied similarly

	Observed	Estimated
Accidentals	-	71.6±1.2
Fast Neutrons	-	1178±4.4
Total	1224±35.0	1250±4.6



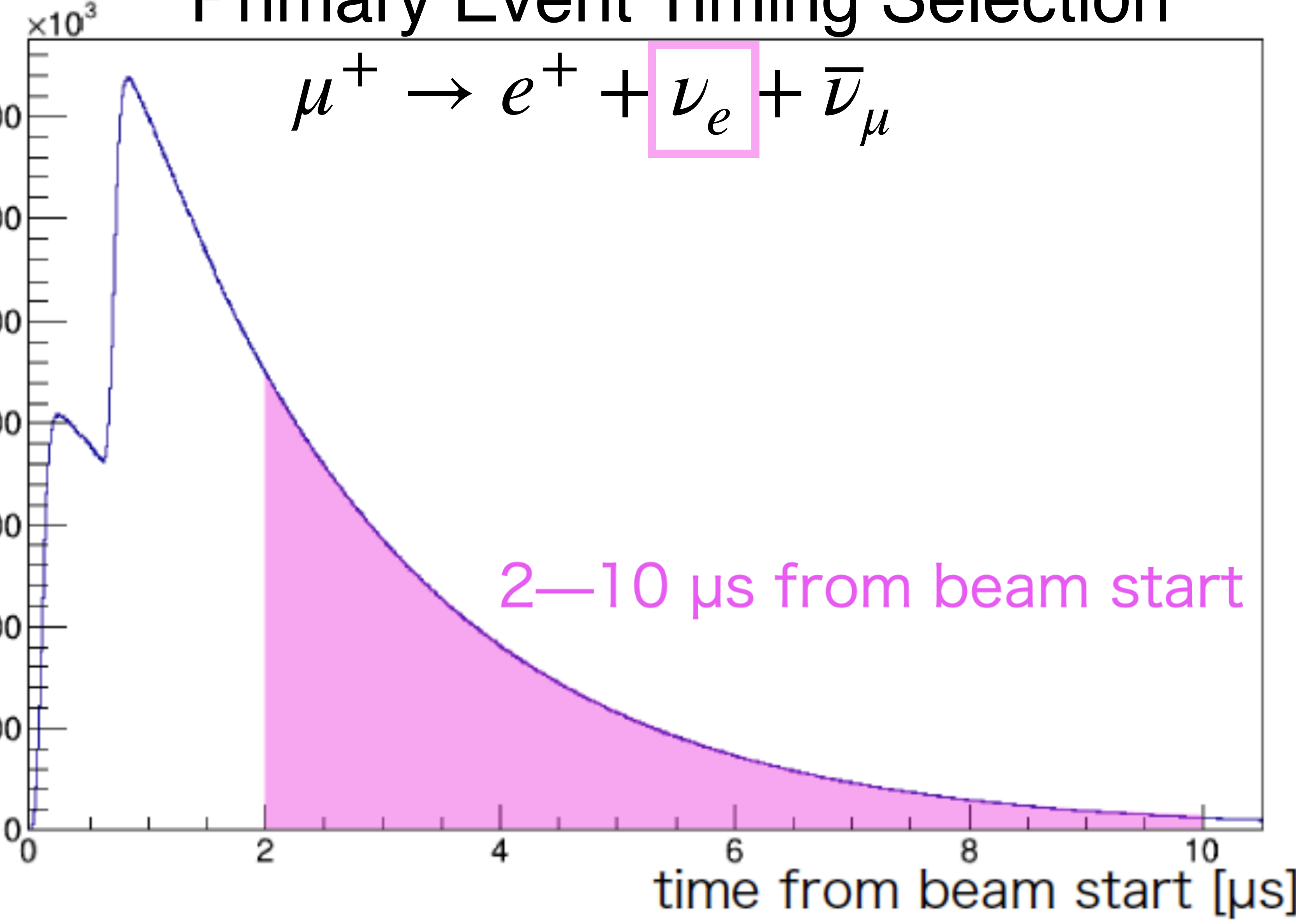


$\bar{\nu}_\mu$ Flux Normalization from Carbon to Nitrogen ground state (CNgs) Measurement

- Production: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ (CNgs: ν_e; IBD/Sterile: $\bar{\nu}_\mu$)
- Detection: $^{12}C + \nu_e \rightarrow {}^{12}N_{g.s.} + e^-$ followed by $^{12}N_{g.s.} \rightarrow {}^{12}C + \nu_e + e^+$
- **CNgs measurement provides a data-driven estimate of the $\bar{\nu}_\mu$ normalization**
- Avoid reliance on uncertain/complicated beam production calculations → improves sterile neutrino sensitivity

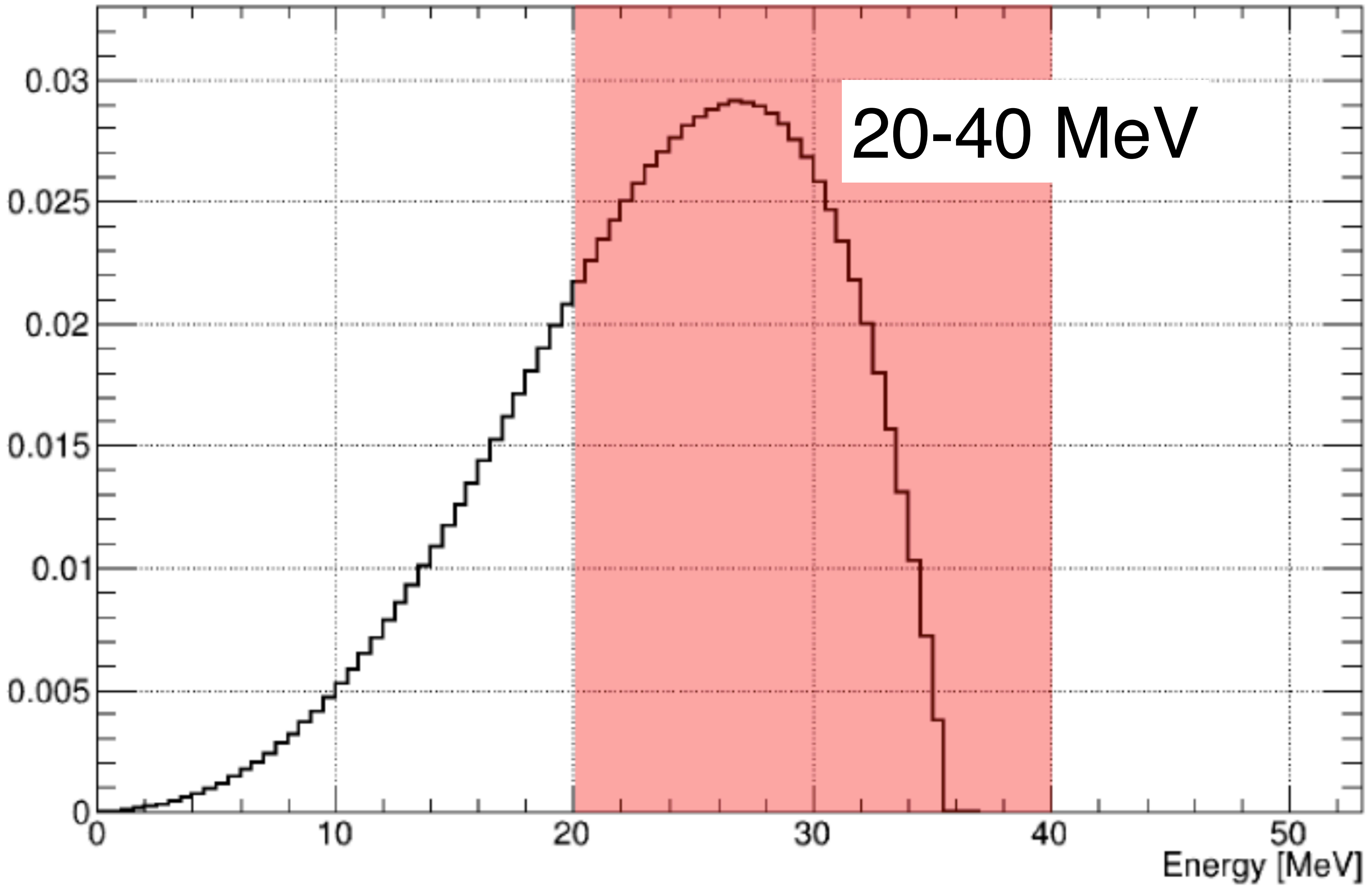
CNgs Dataset & Event Selection

Primary Event Timing Selection



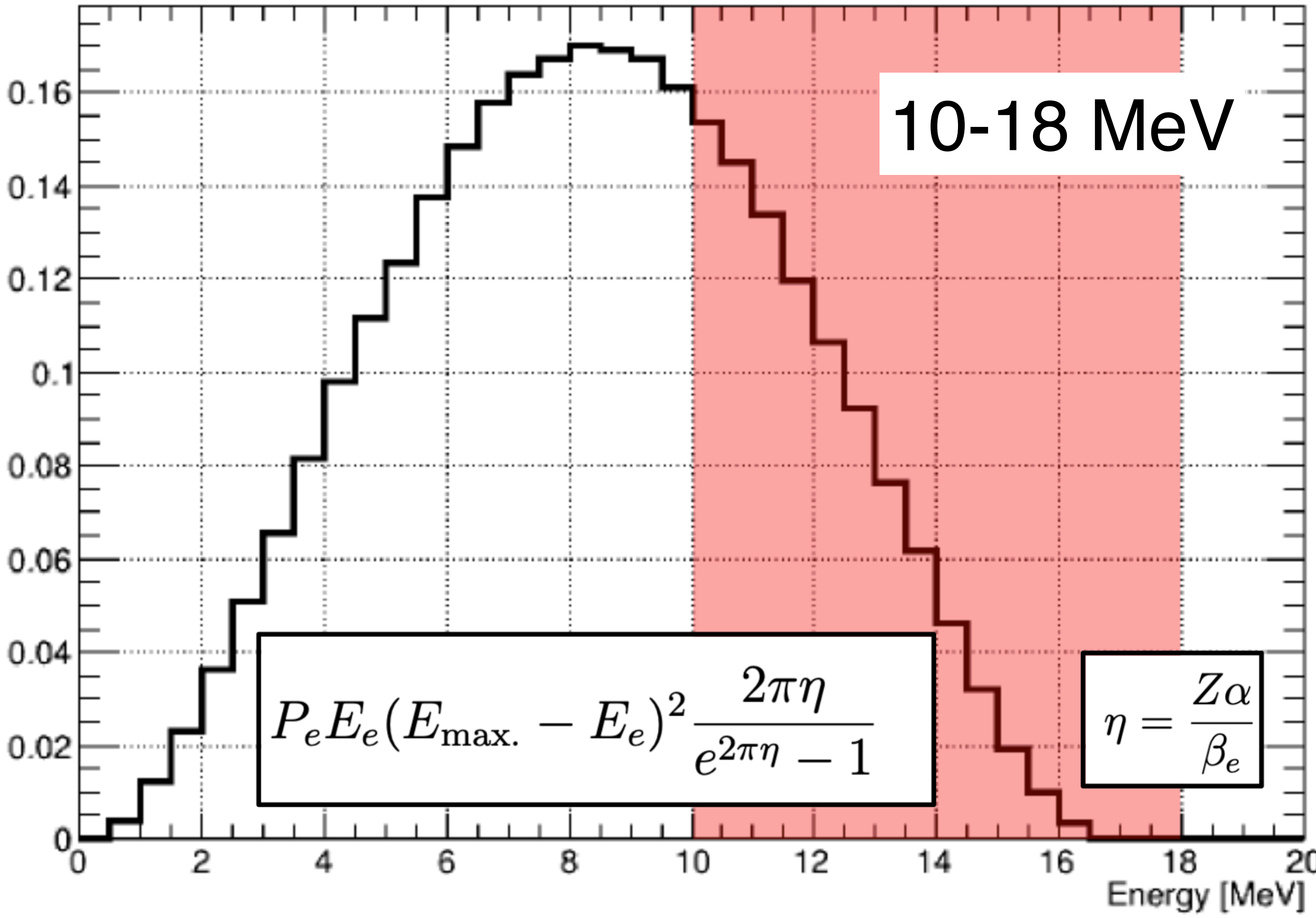
$^{12}C + \nu_e \rightarrow {}^{12}N_{g.s.} + e^-$

Primary Event Energy Selection



$^{12}N_{g.s.} \rightarrow {}^{12}C + \nu_e + e^+$

Follower Event Energy Selection



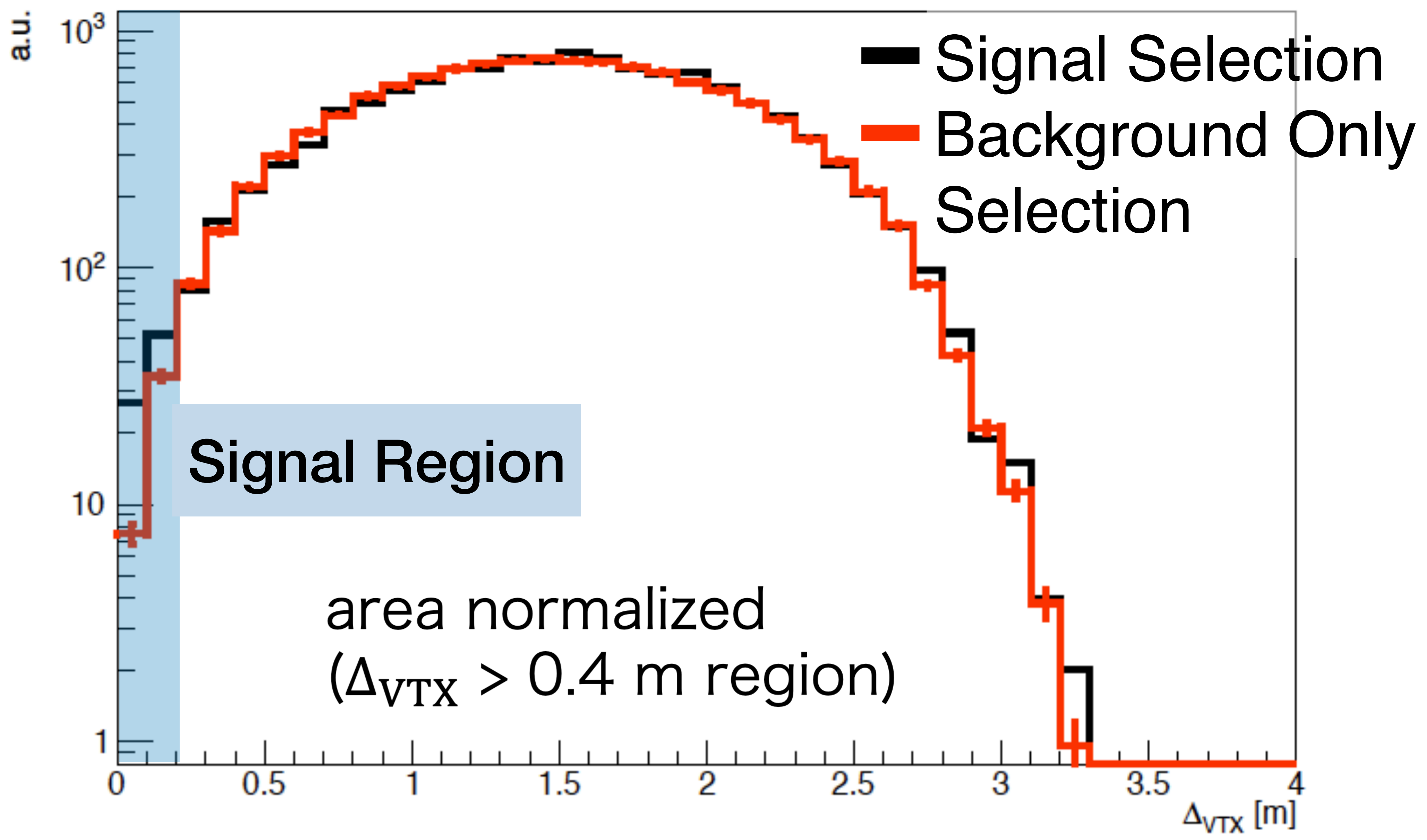
- 2021 & 2022 beam datasets are analyzed (2.2×10^{22} POT)
- Event pairing selection: $0.2\text{ms} < \Delta t < 12\text{ms}$ (2021), 25ms(2022), ΔVertex < 200mm

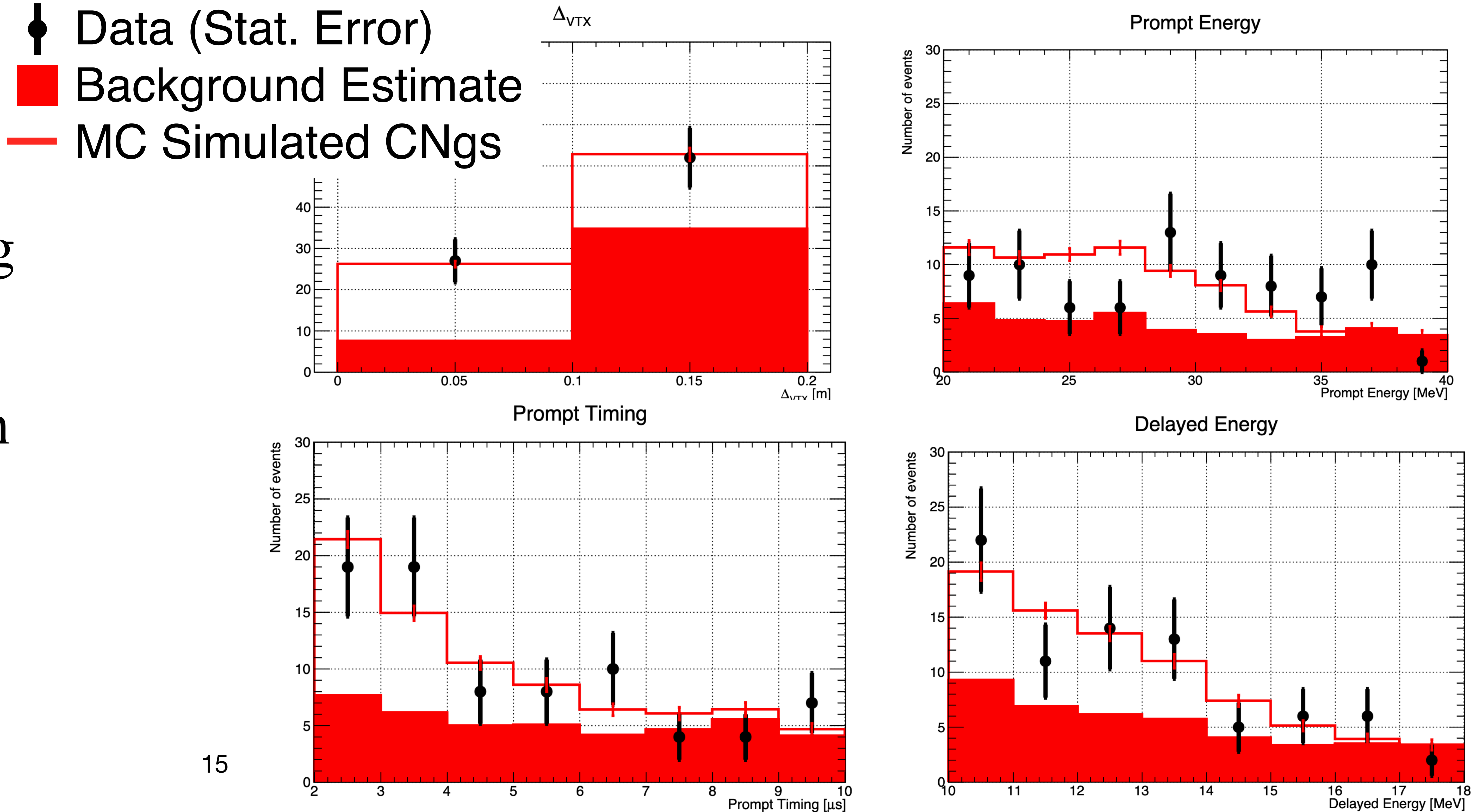
79 events pass selection

CNgs Backgrounds

Estimated background rate is:
42.2±6.5(stat.)±1.7(syst.)

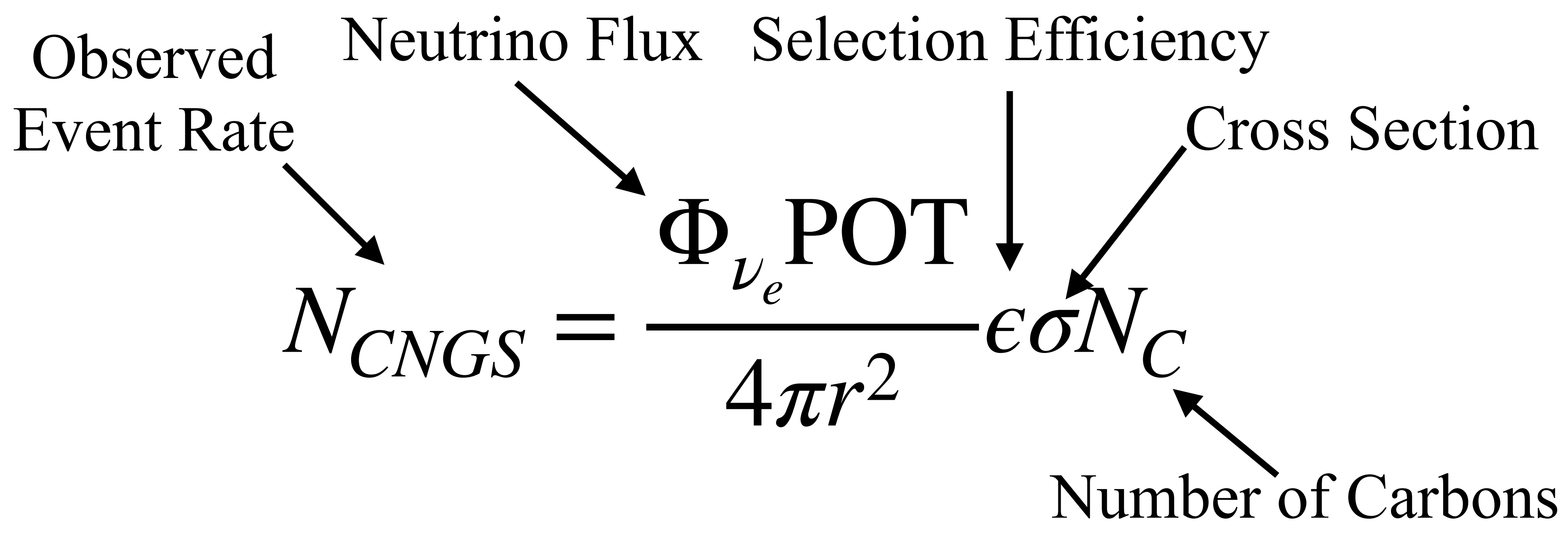
- Dominant background source is from accidental coincidences.
- Background PDFs are estimated by performing event selection in a late timing window (>1ms after beam)
- Normalization determined from fit in high ΔVertex region
- Reject background only hypothesis with $p=2.9\times10^{-7}$



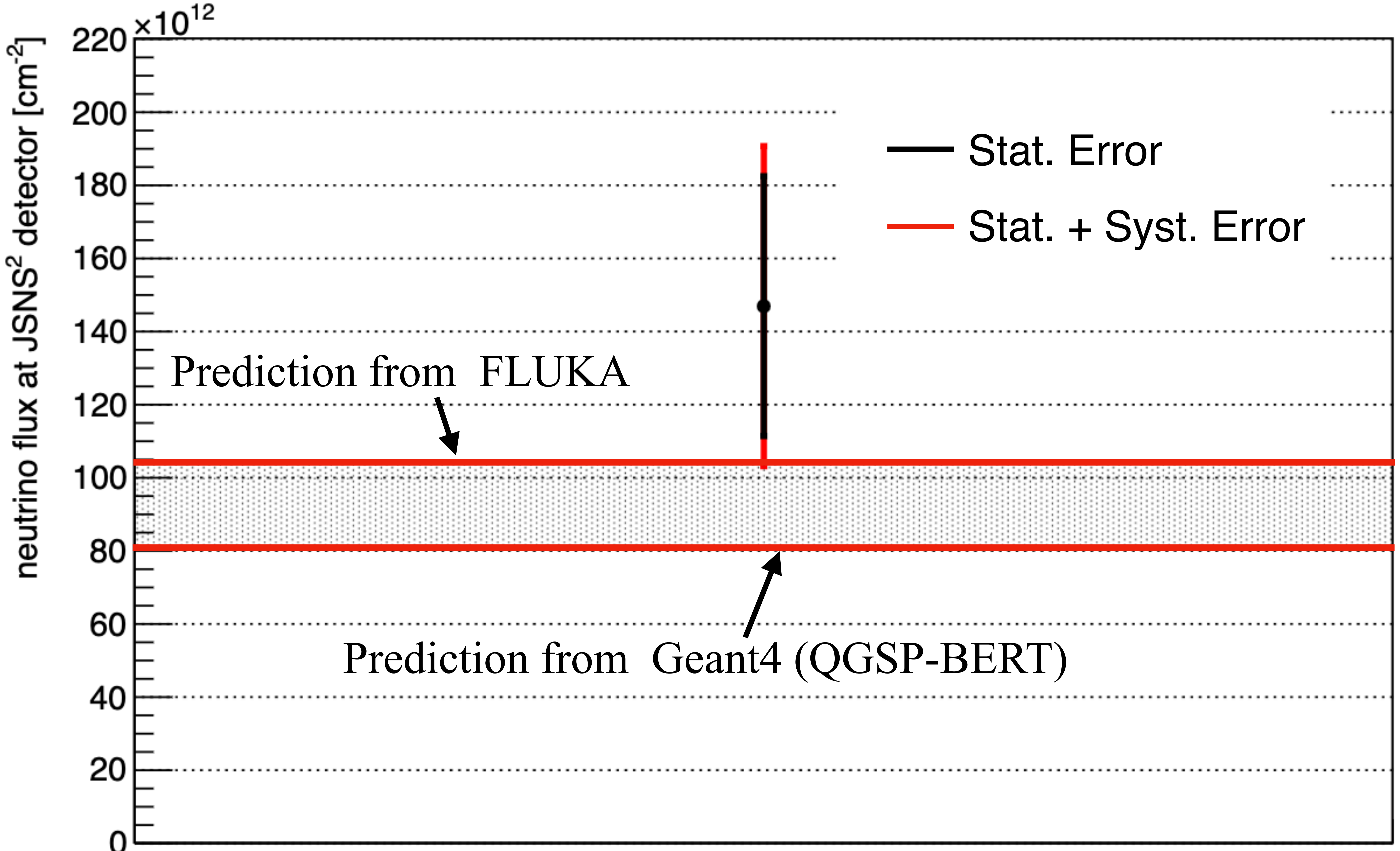


CNgs Results

- Estimated detection efficiency: **0.0588 ± 0.0021**
- Combined LSND[1] + KARMEN[2] cross section estimate: **$9.1 \pm 0.7 \times 10^{-42}$cm^2**
- JSNS^2 Measured neutrino flux: $\Phi_{\nu_e} = \Phi_{\bar{\nu}_\mu}$ = **1.47 ± 0.36(stat.)± 0.26(syst.) x10^{14}cm^{-2}**



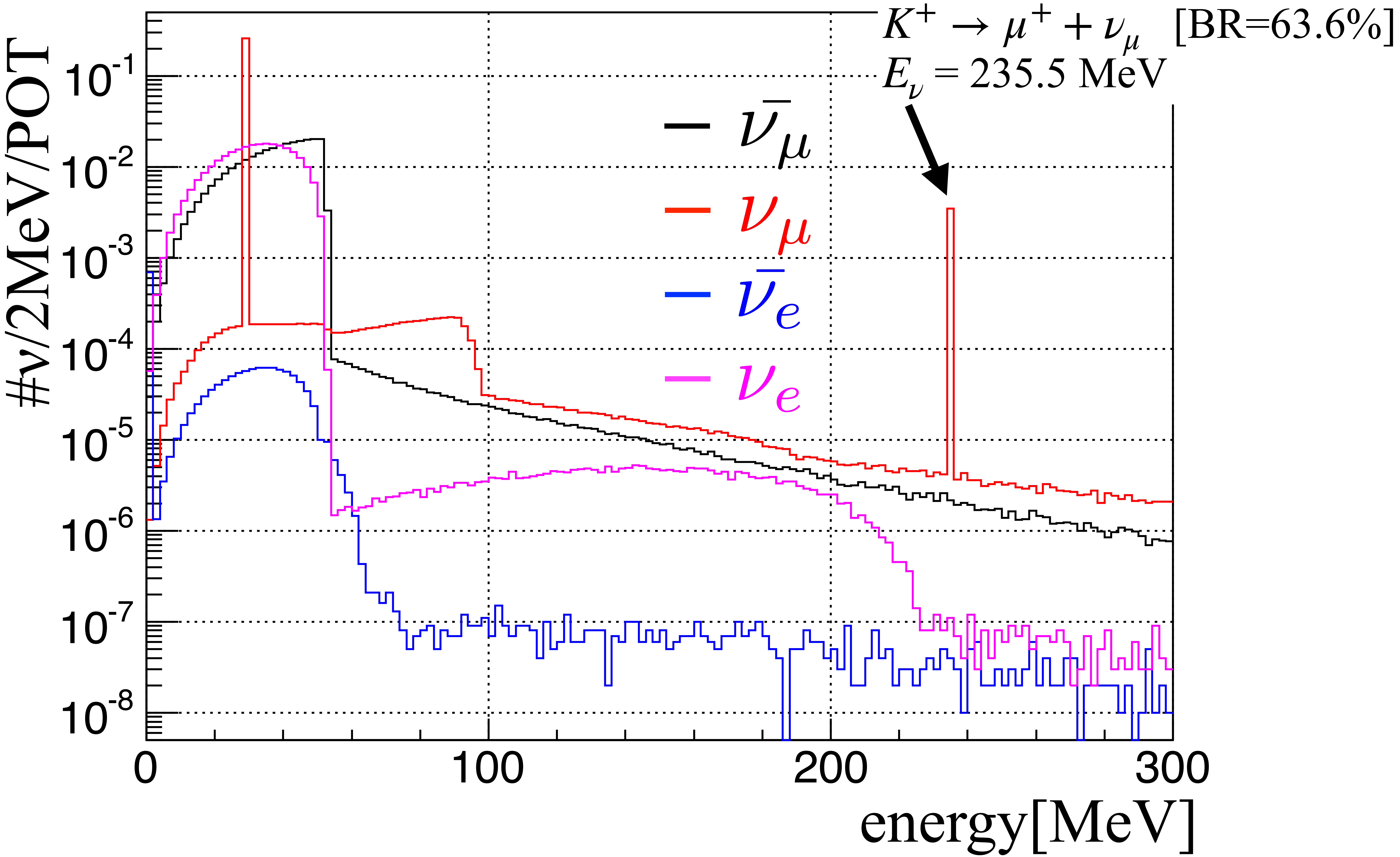
$$N_{CNGS} = \frac{\Phi_{\nu_e} POT}{4\pi r^2} \epsilon \sigma N_C$$



[1]LSND CNgs measurement: Phys. Rev. C 64:065501 (2001)

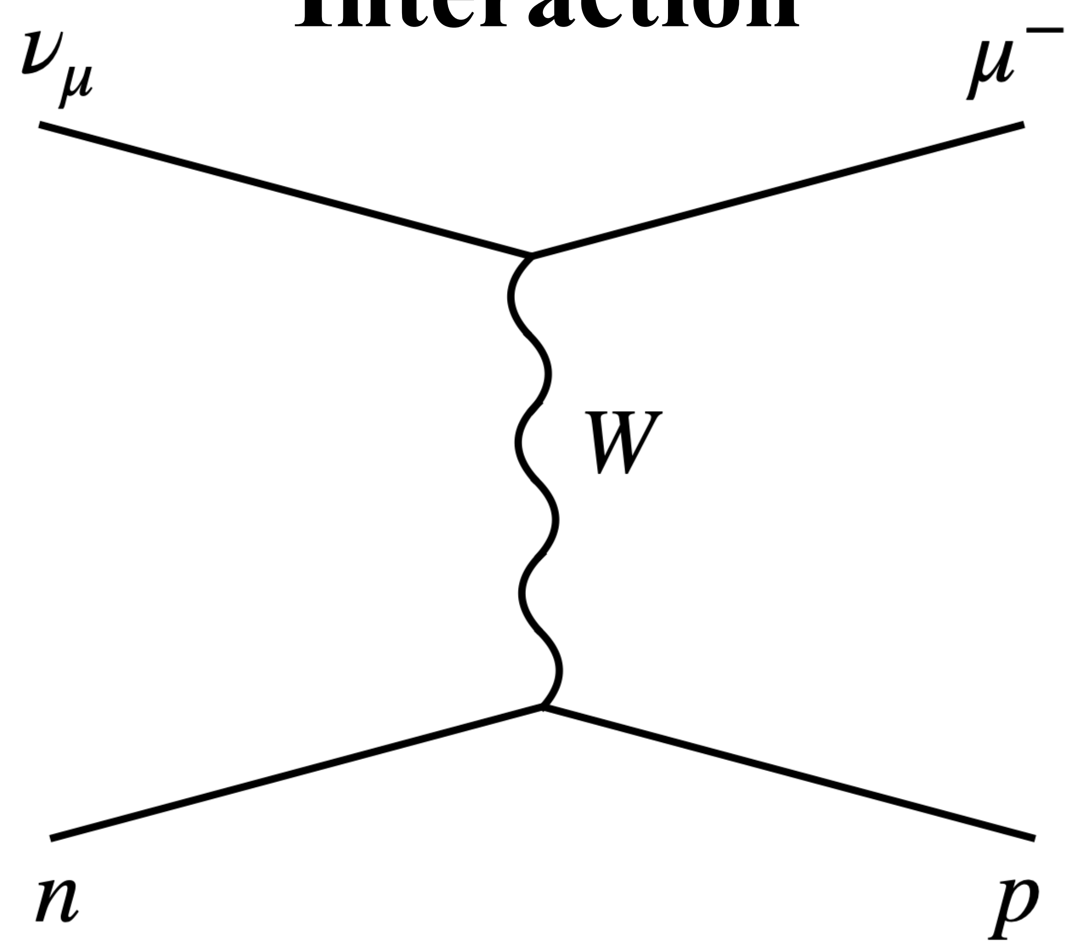
[2]KARMEN CNgs measurement: Nucl. Phys. 40, 183 (1998)

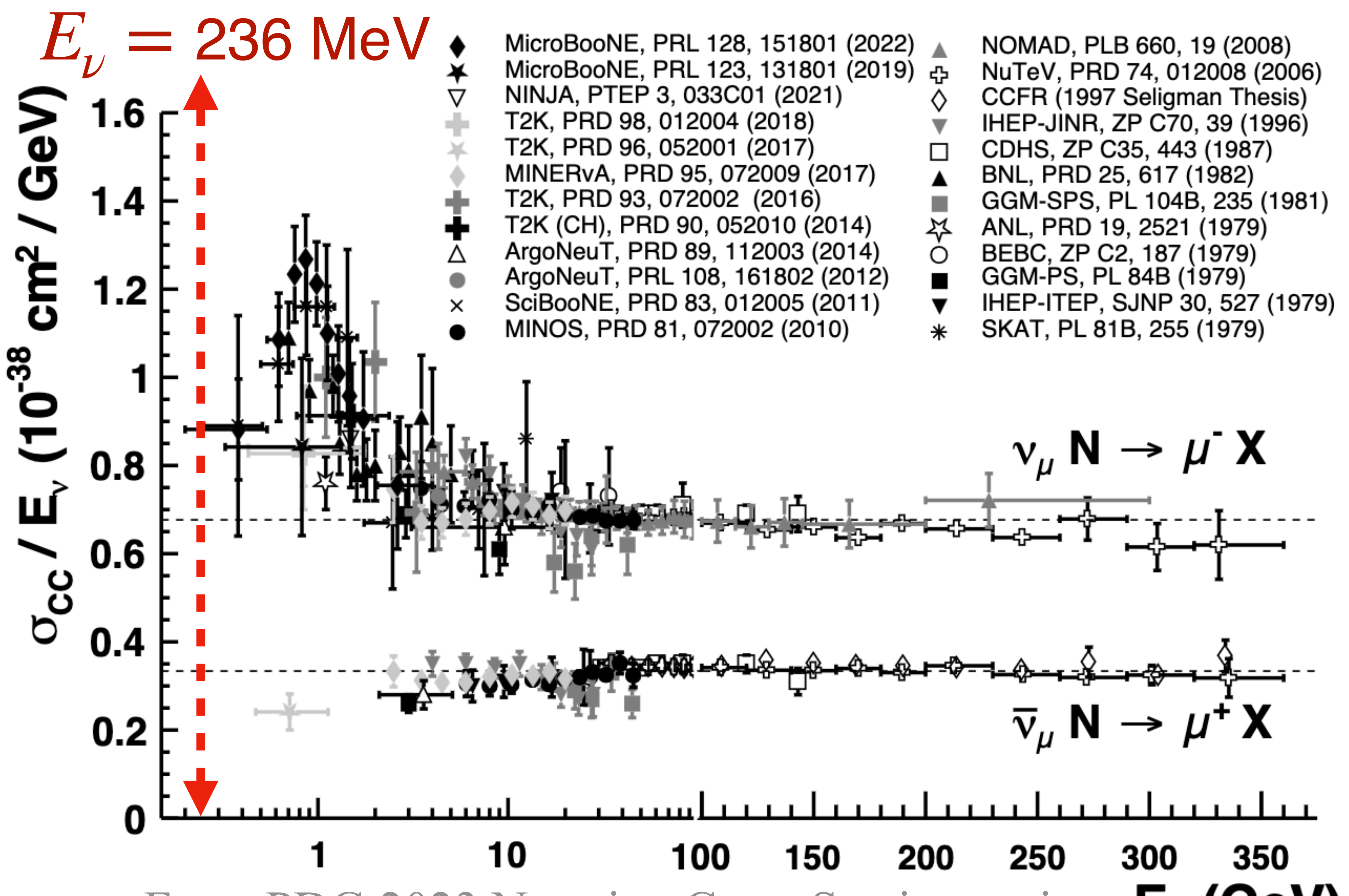
Kaon Decay At Rest (KDAR)



KDAR

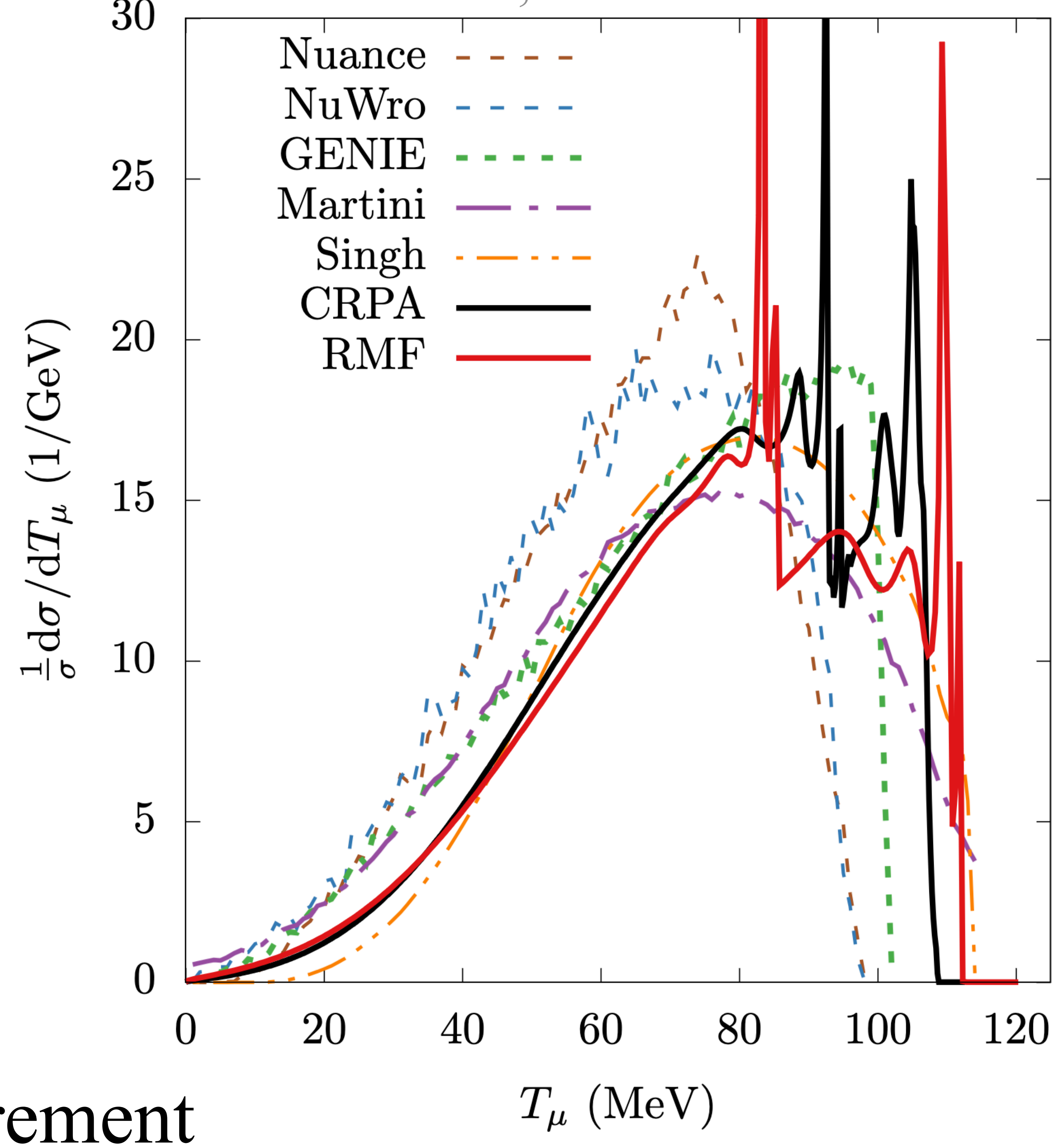
Charged Current Interaction





From PDG 2023 Neutrino Cross Section review

From PRC 103, 064603



- KDAR neutrinos have a KNOWN energy, ideal for a cross section measurement
- Few cross-section measurements below 1GeV
- Nuclear models disagree significantly about the expected cross section & kinematics
- Only one prior KDAR measurement exists from MiniBoone (PRL 120, 141802)

KDAR Neutrino Signal

- Kaons decay quickly (τ =12.4ns). KDAR interactions are prompt with the beam
- The prompt interaction produces a muon and (typically) 1 proton.
- Ensuing muon decay produces a secondary event

KDAR Neutrino Signal

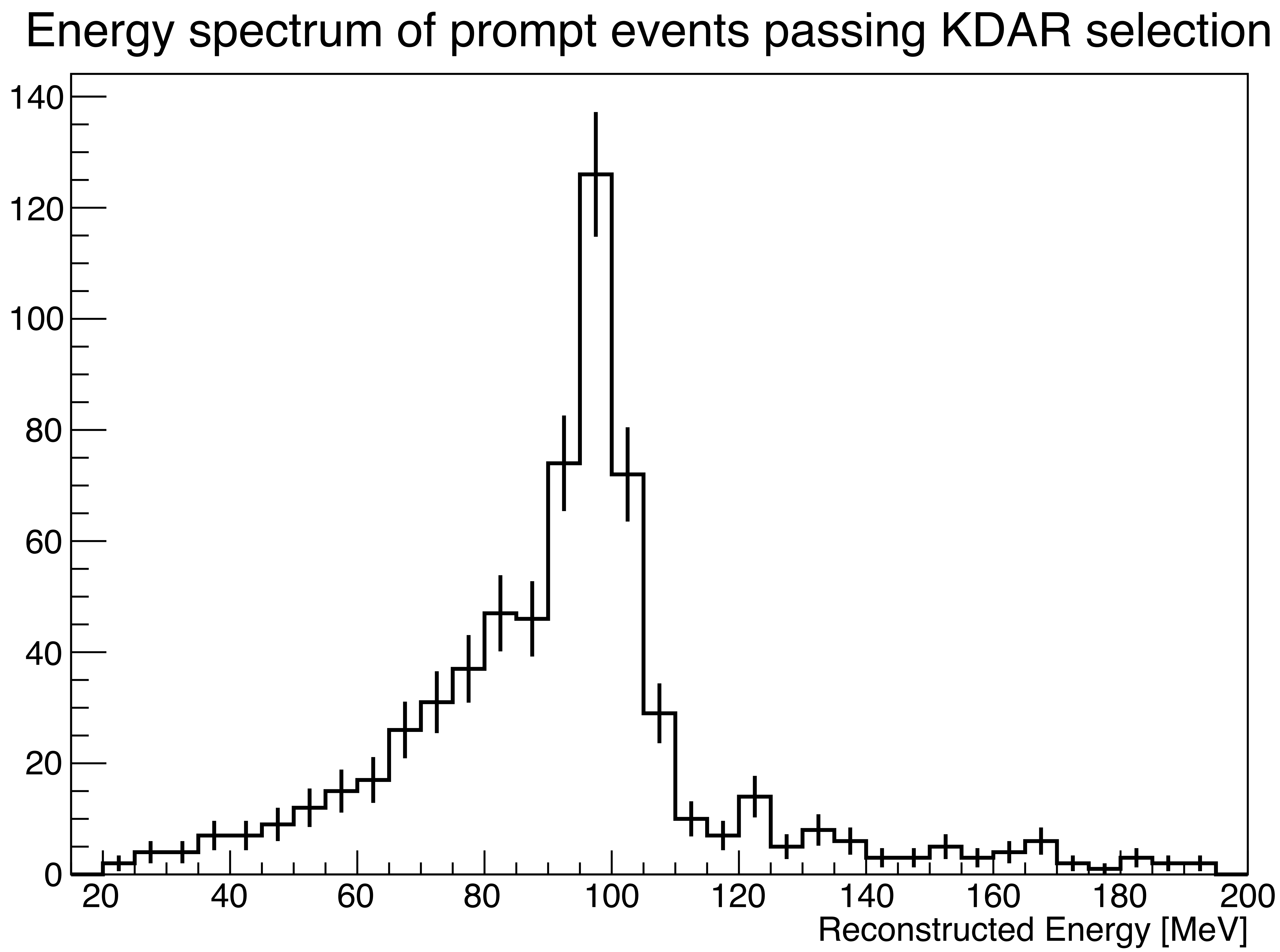
"Visible energy" is our observed variable

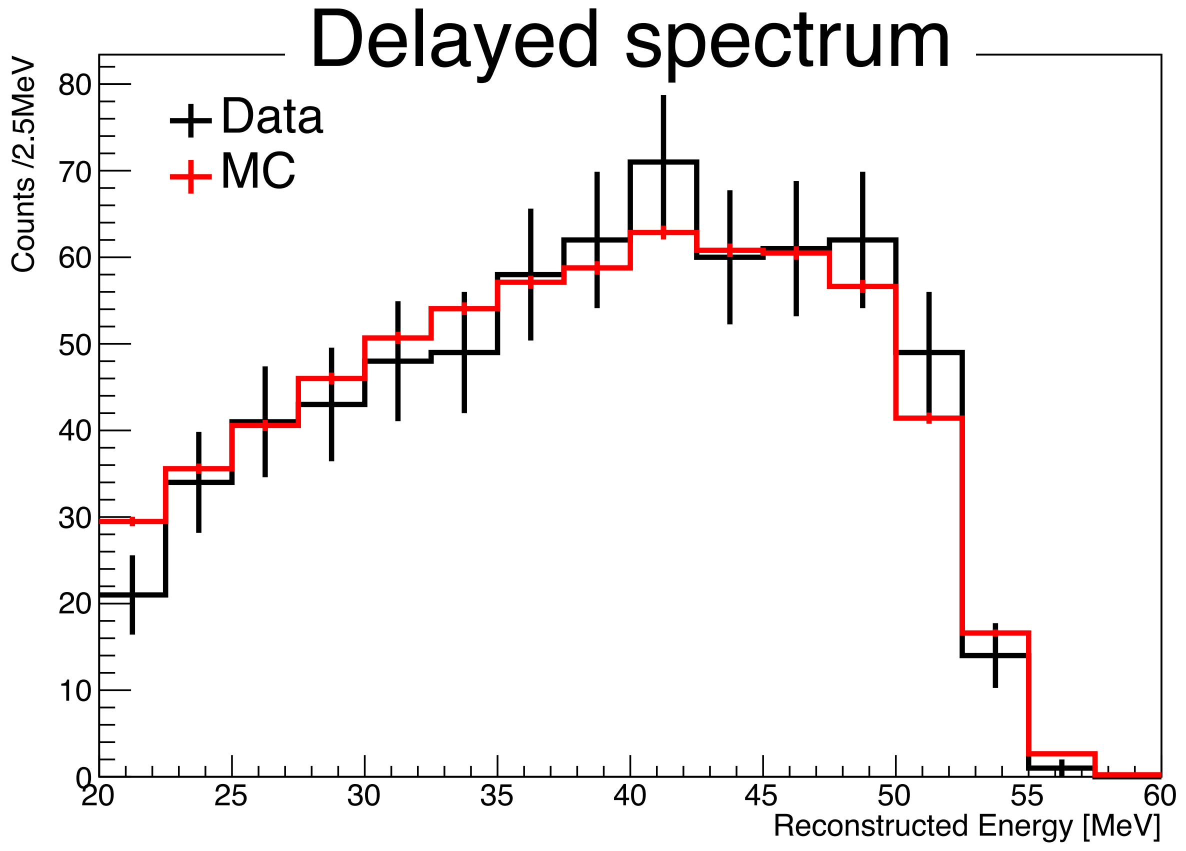
$$E_{\mathrm{vis}} = T_\mu + \sum T_p$$

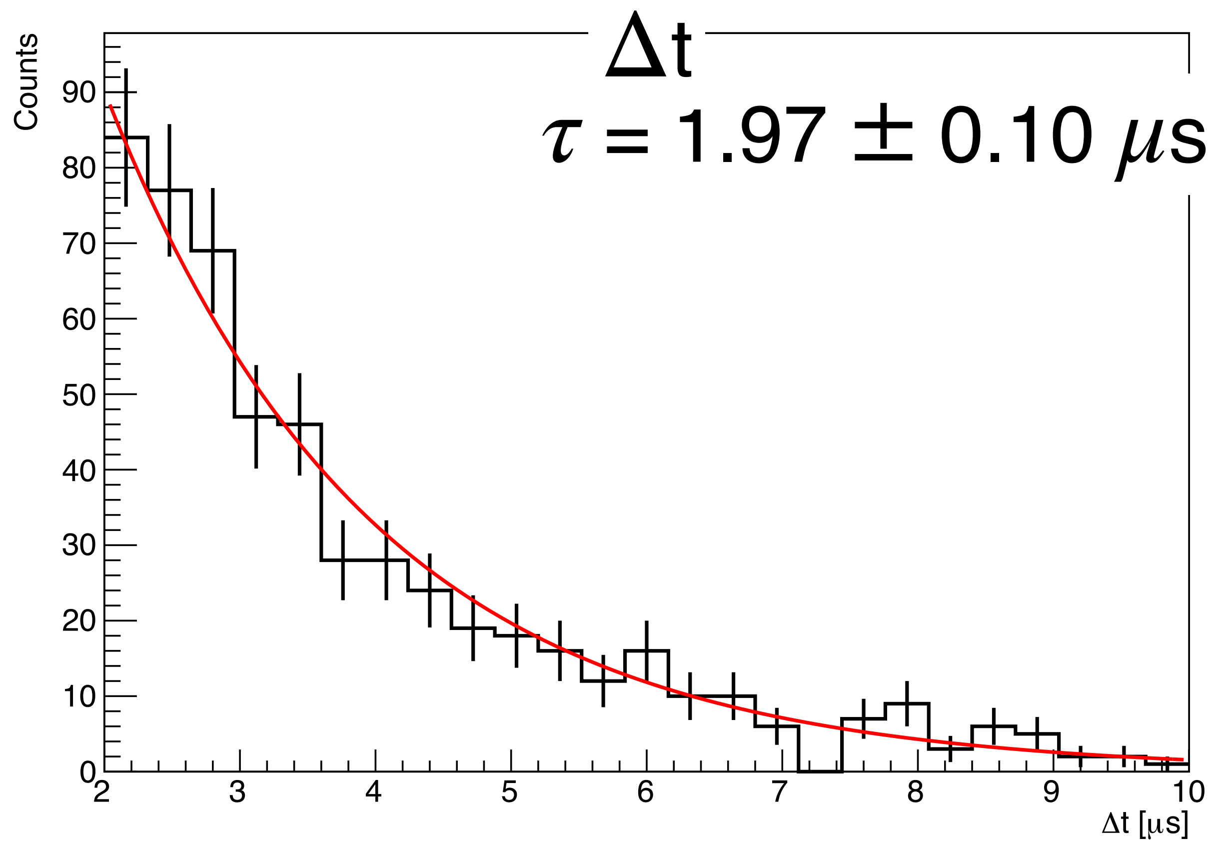
KDAR Dataset

- 2021 dataset analyzed, 1.4×10^{22} POT
- **<u>621 events pass all cuts</u>**
- Selection criteria…

	Prompt	Delayed
Energy	20-150 MeV	20-60 MeV
Timing	2x150ns Beam centered windows	Δt < 10μs
Position	Fiducial Volume: R<1400mm -1000mm < z < 500mm	ΔVertex< 300mm

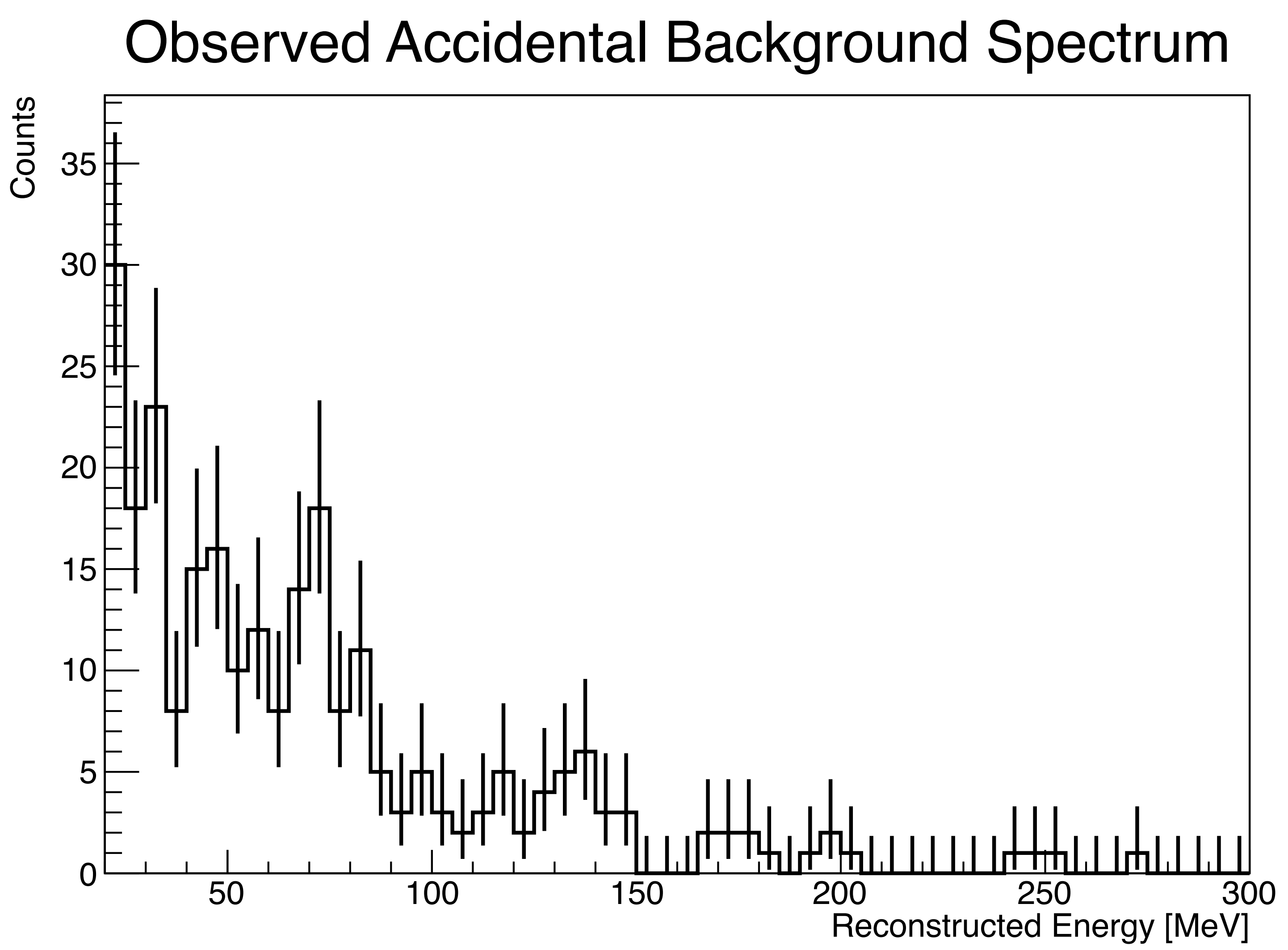




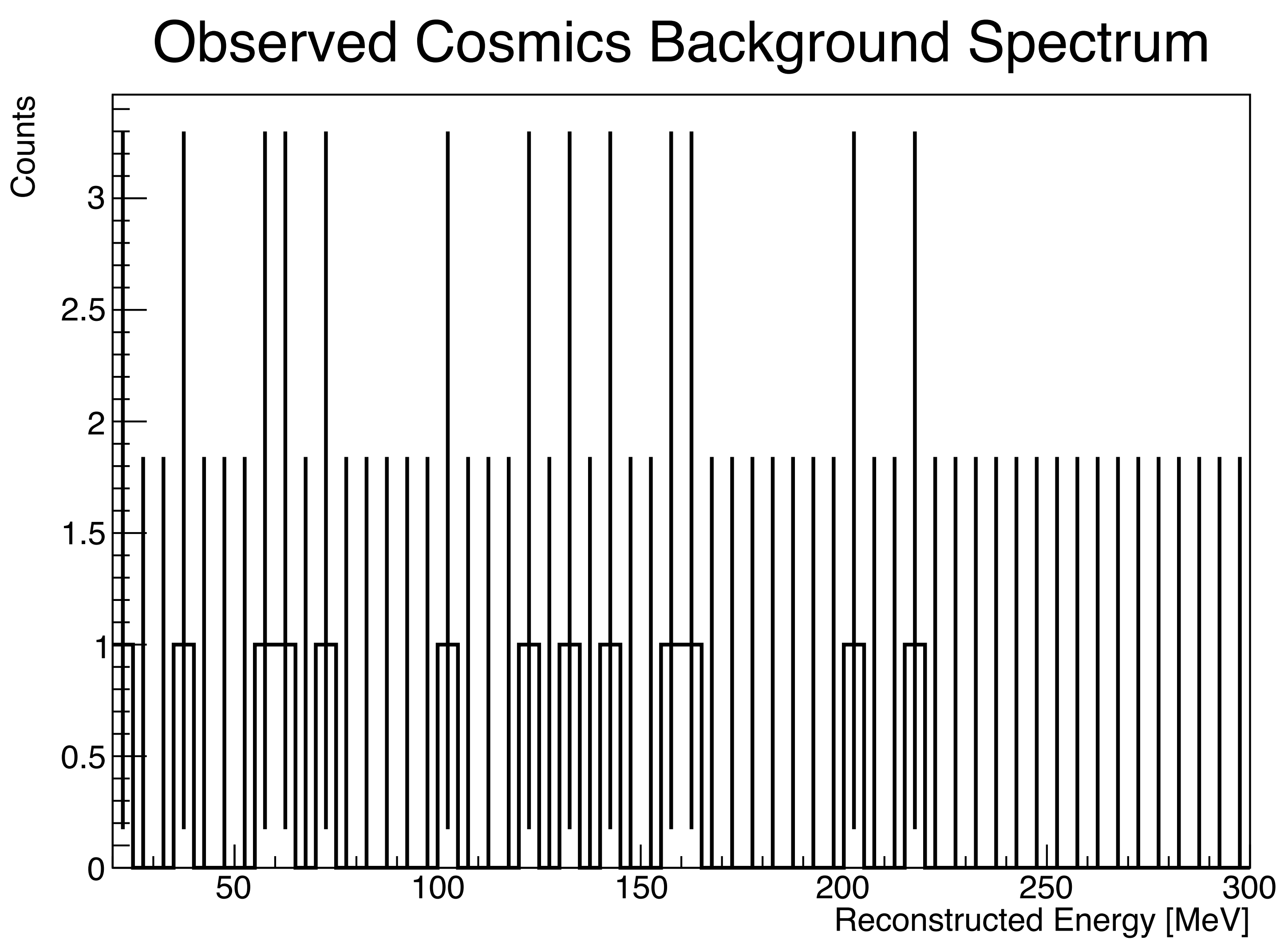


KDAR Backgrounds

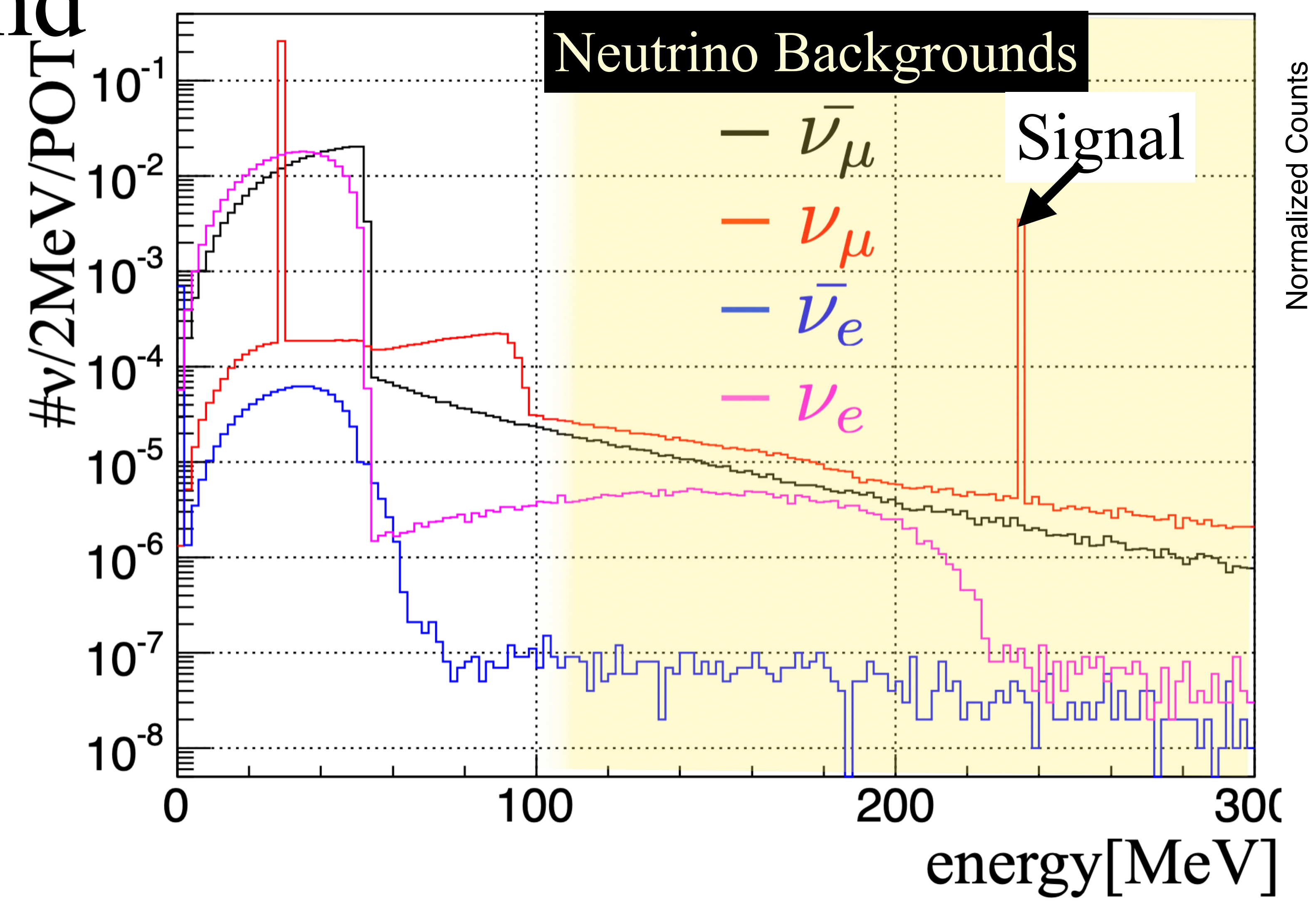
- **Dominant background source is pion decay-in-flight (DIF) neutrinos**
- DIF background spectral shape estimated with MC
- Both NuWro & GiBUU event generators are used for DIF background simulation
- Normalization estimated using the kinematically disallowed (>150MeV) portion of the KDAR spectrum

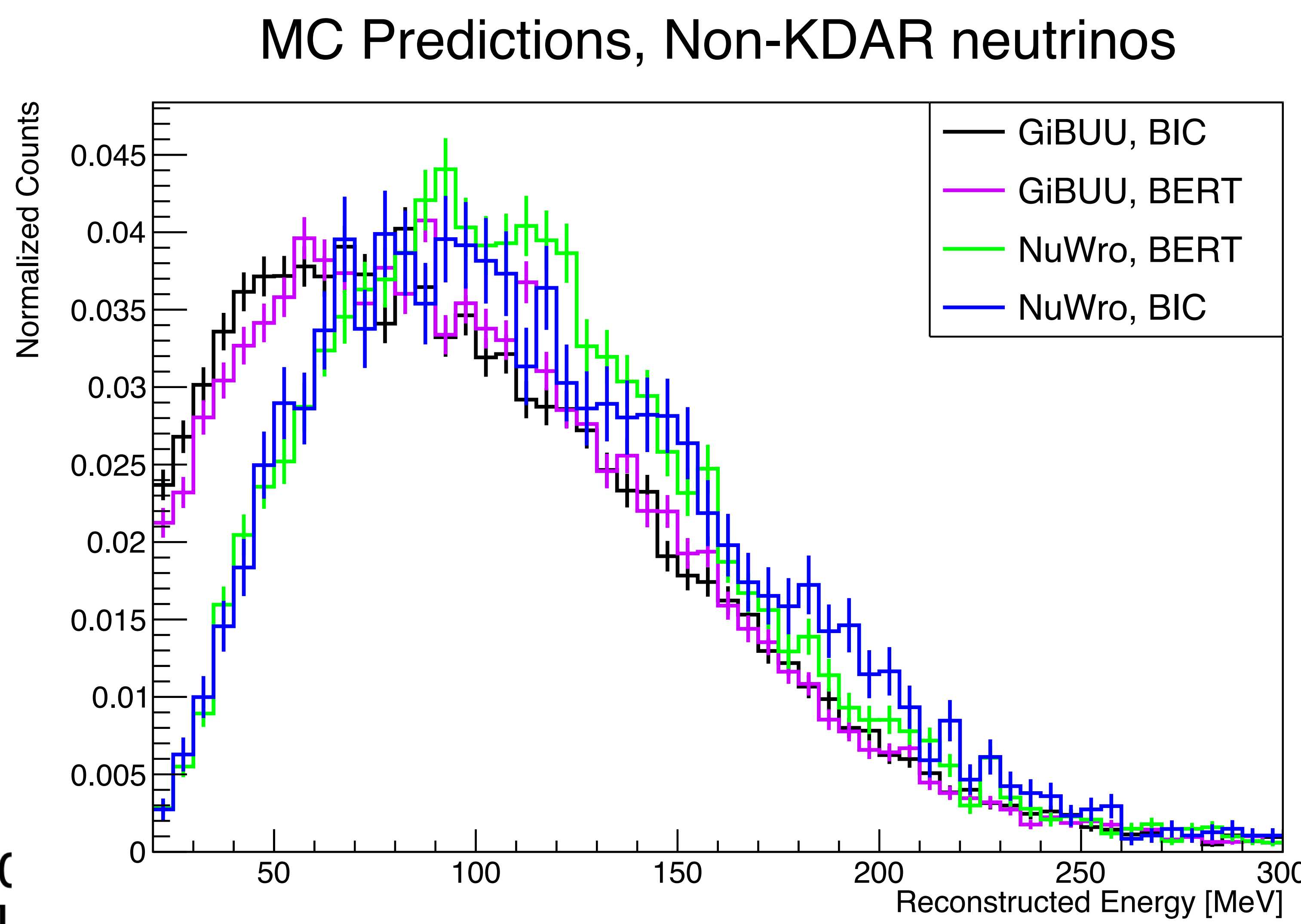


< 1.14 events in KDAR dataset



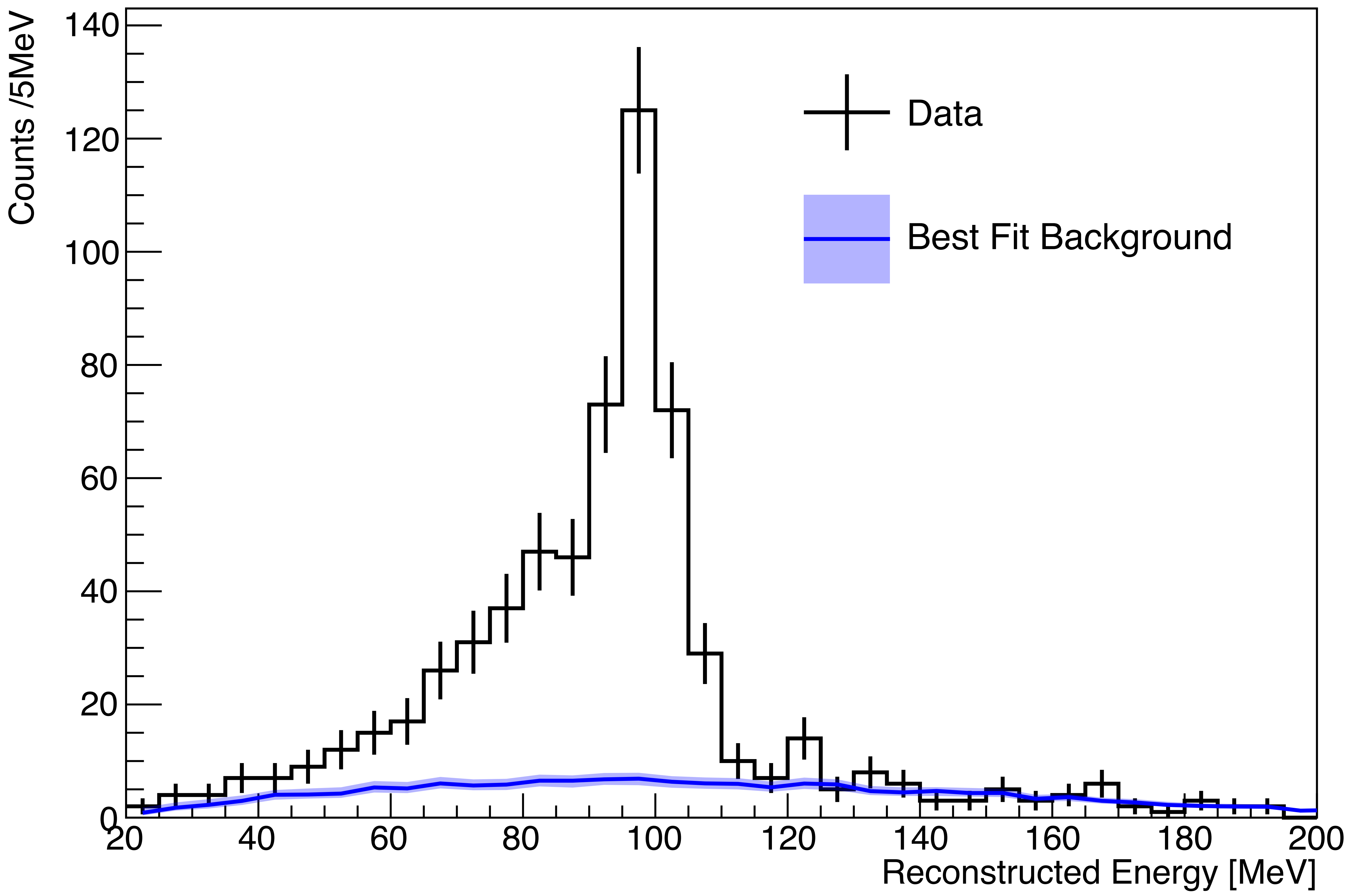
< 6.57 events in KDAR dataset

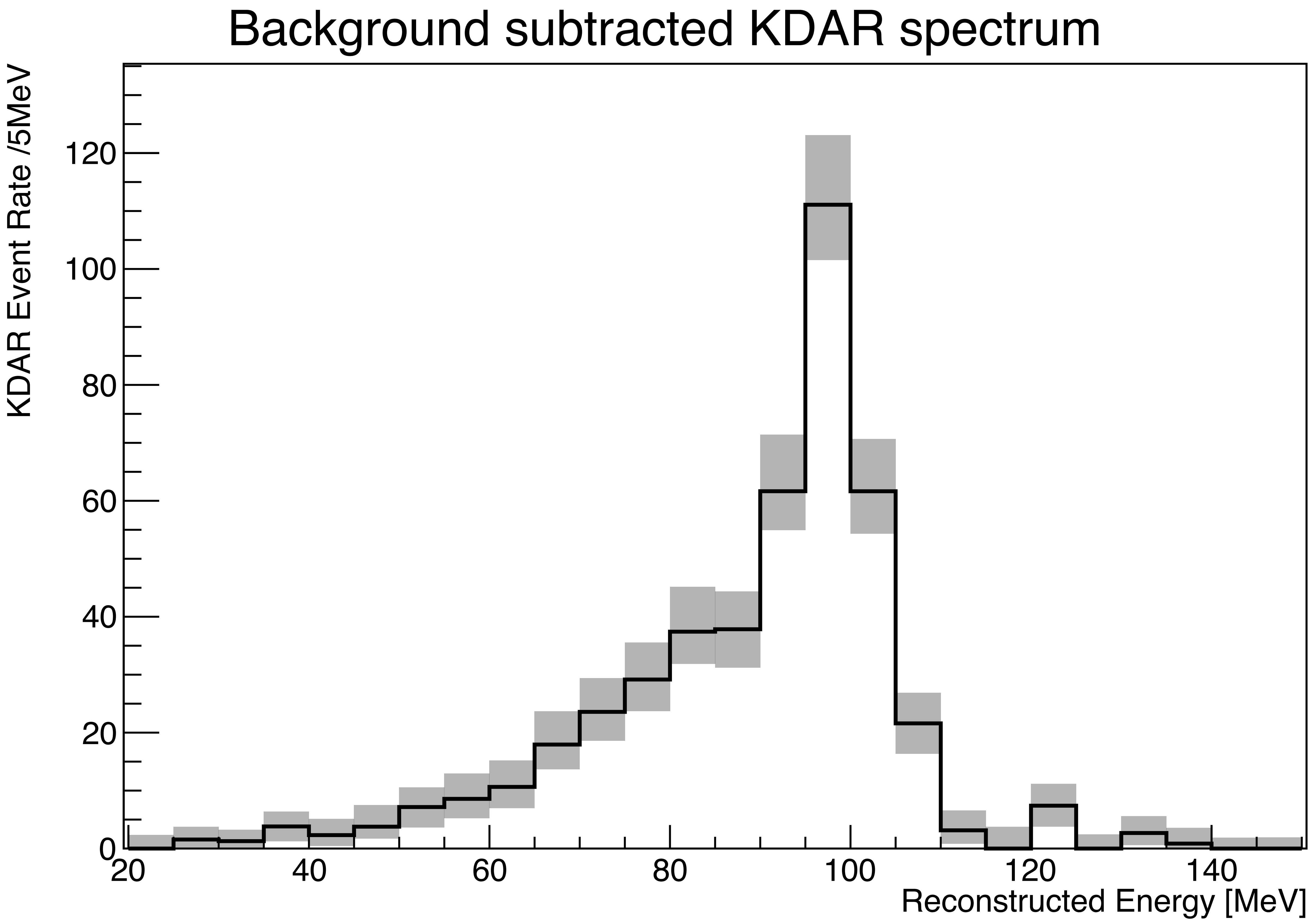




KDAR Signal Extraction

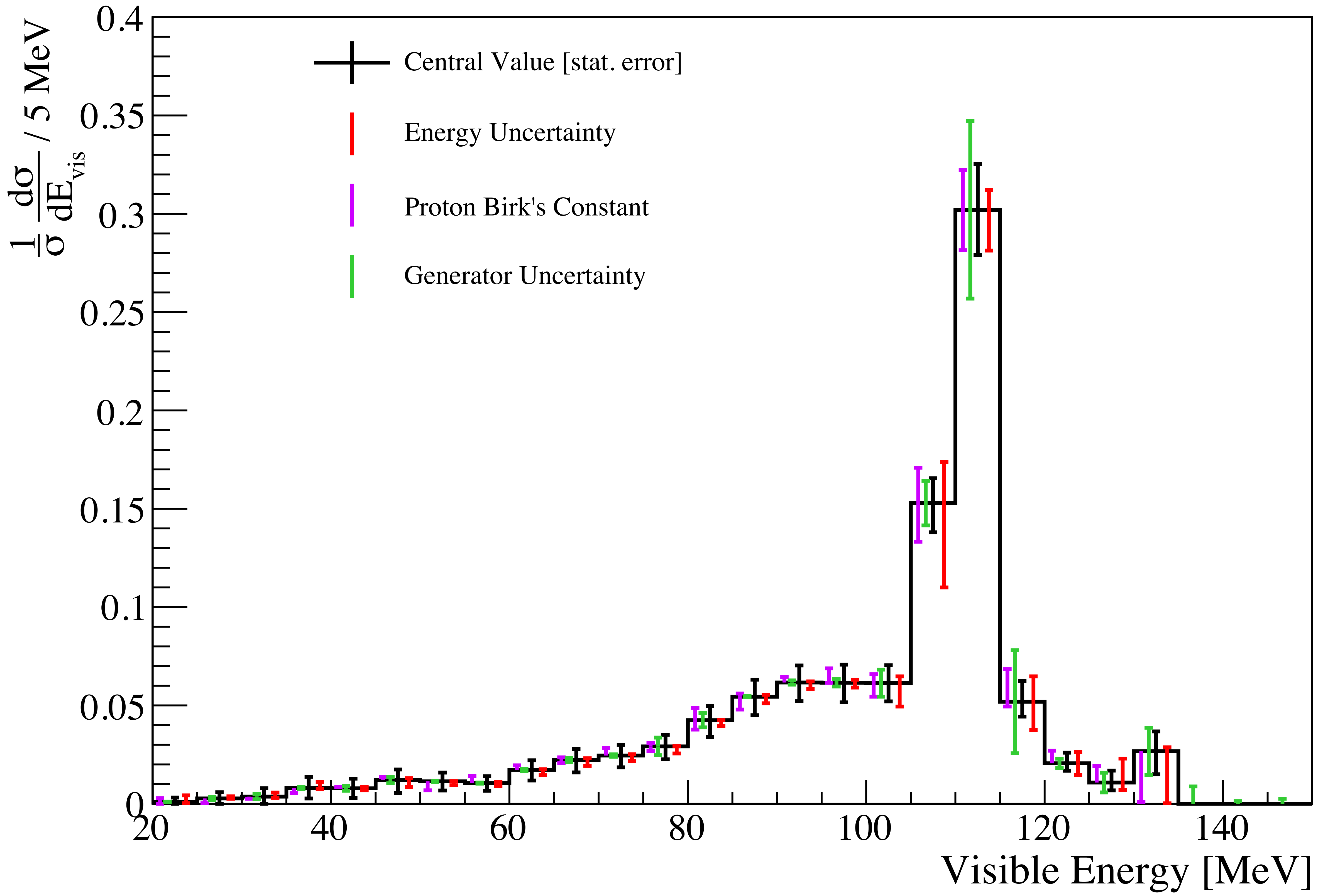
- Best fit signal rate: 492.2 ± 29.1 events
- Background rate: 131.1±19.2 events(20-150MeV)

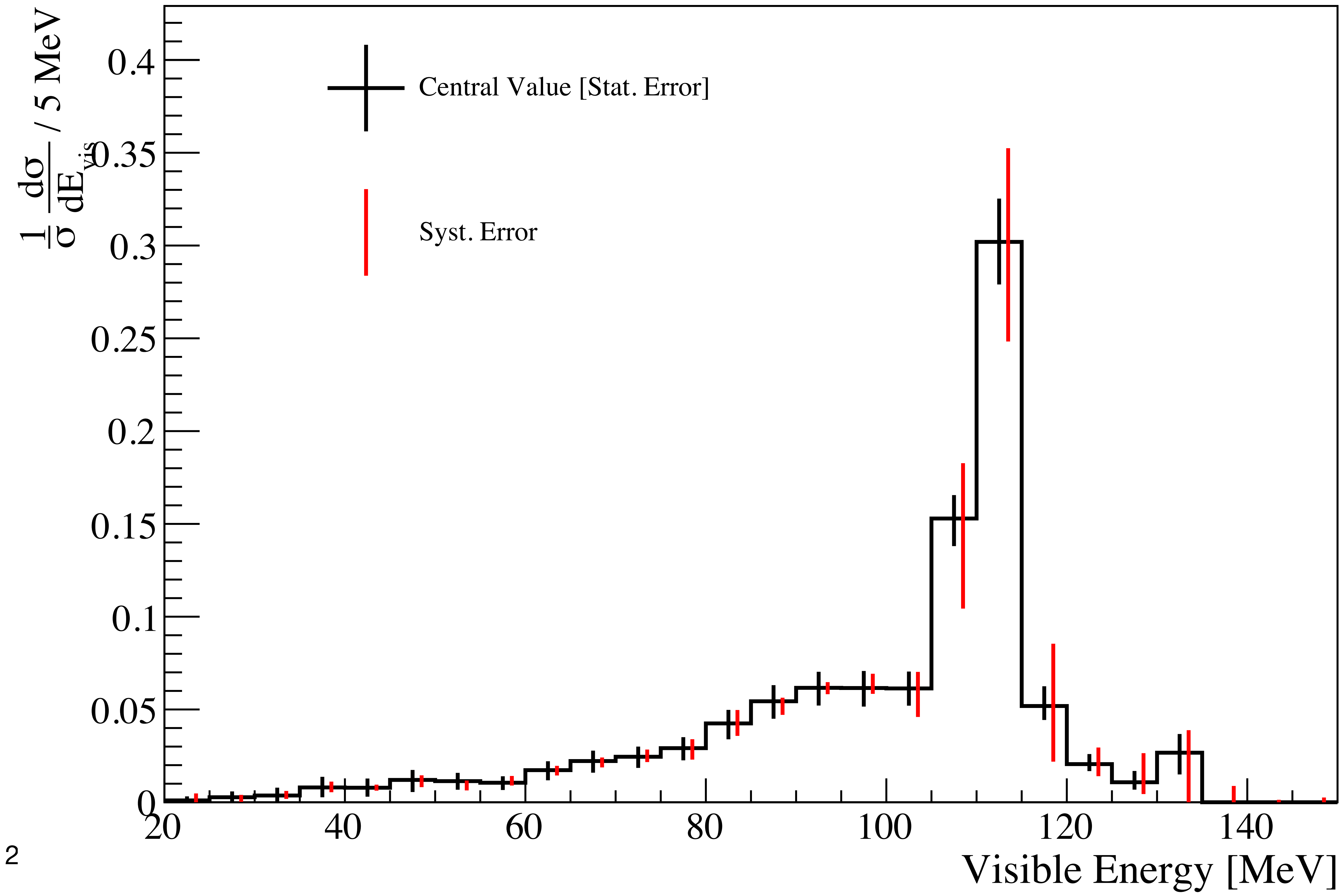




KDAR Results

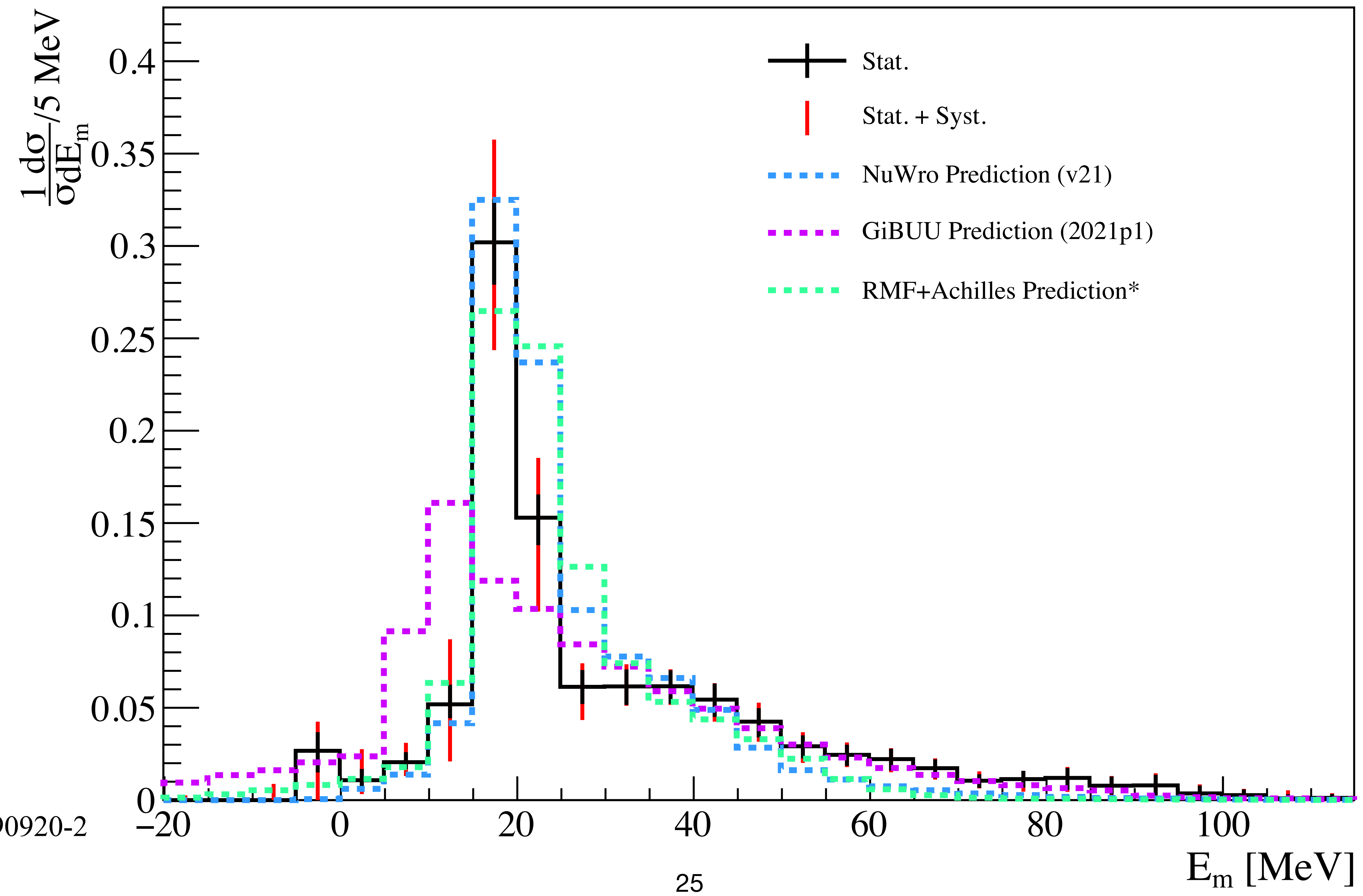
- We use Iterative Bayes (D'Agostini) unfolding, detector response estimated using NuWro & GiBUU event generators.
- **Shape only measurement.** Kaon production rates are too uncertain to estimate the integrated cross section.
- The largest source of error is the "generator" systematic.
- Measurement will improve with better modeling and additional statistics





First KDAR Missing Energy Measurement

- This result can also be in terms of "missing energy"
- $E_{miss} = E_{\nu} - m_{\mu} - E_{\text{vis}}$
- The neutrino energy is KNOWN. Any unobserved/extra energy was absorbed/provided by the nucleus



*Provided by Alexis Nikolakopoulos[1-4].

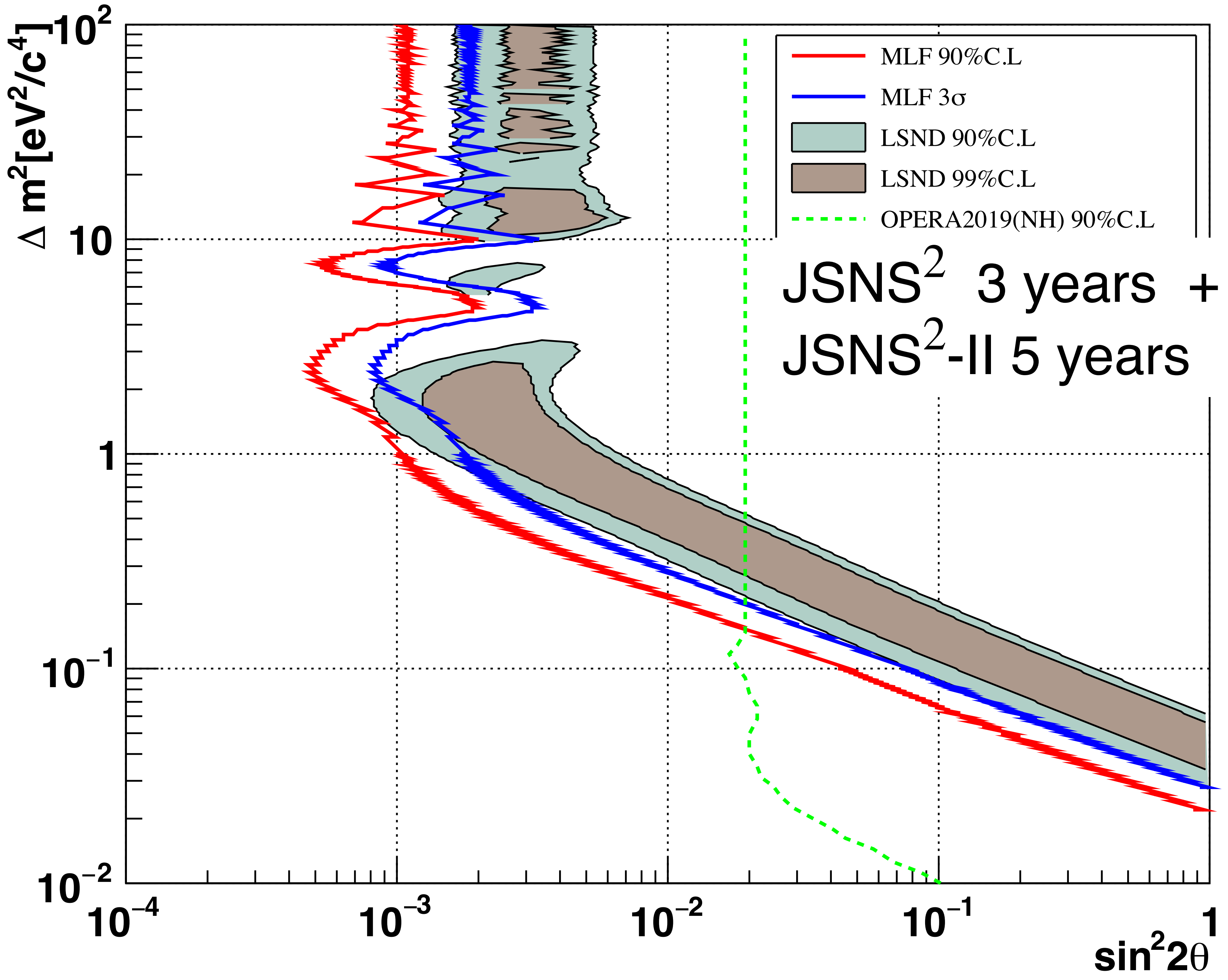
[1] RMF: arxiv:1904.10696, arxiv:2104.01701
[2] Spectral Function: doi.org/10.1016/0375-9474(94)90920-2
[3] INC: arxiv:2007.15570
[4] Achilles: arxiv:2205.06378

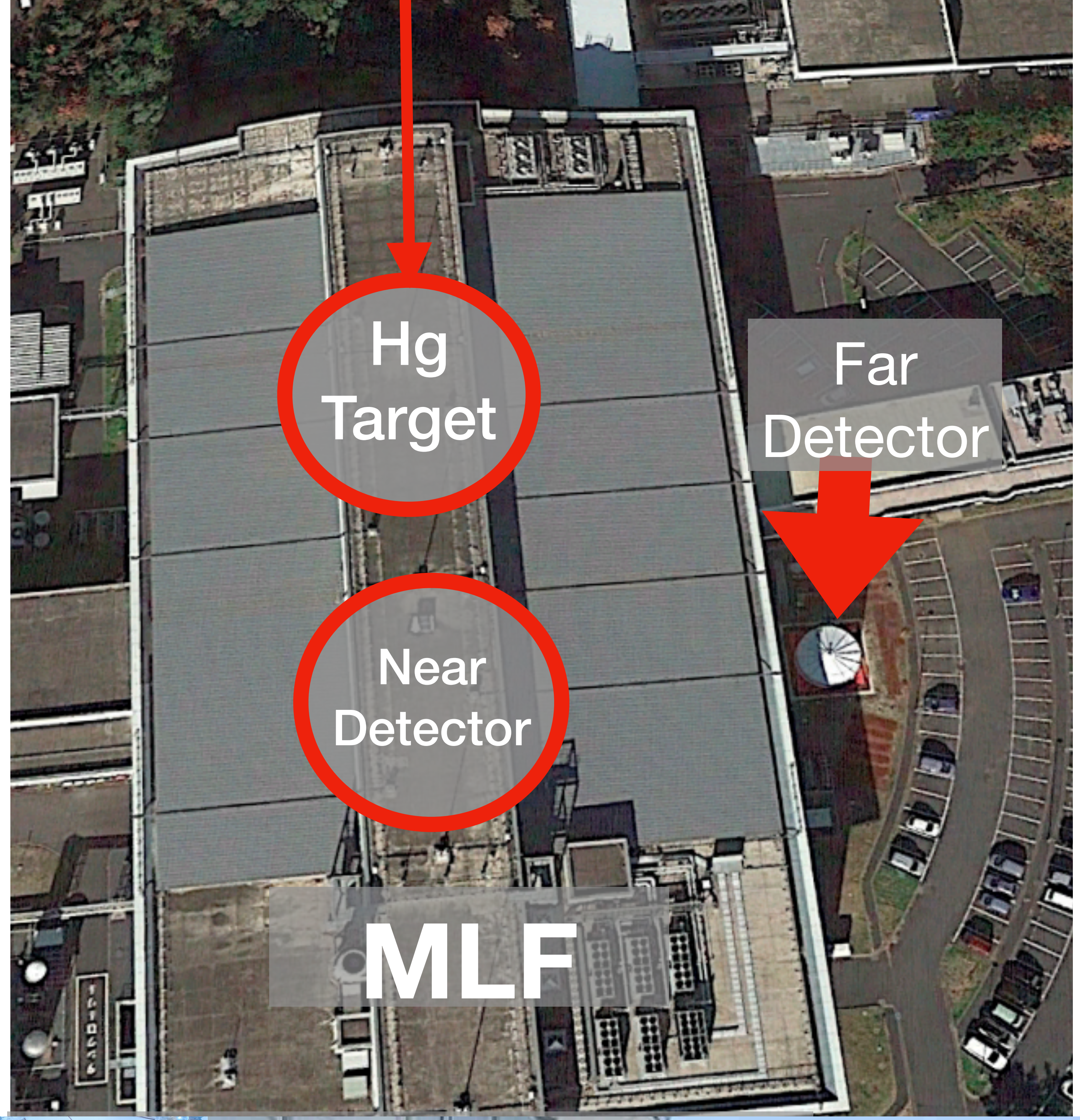
JSNS²-II

J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source

(arXiv:2012.10807)

- Target volume 32-tonnes, **baseline is 48m**
- Construction began in 2021, expected to begin **data taking in the 2024-2025 run period**
- A second baseline allows observation of "smoking gun" oscillation signature
- Improves sensitivity across parameter space, especially at low Δm^2 values





Thank you for your attention

JSNS²

J-PARC Sterile Neutrino Search
at J-PARC Spallation Neutron Source

THE ROYAL SOCIETY

JAPAN SOCIETY FOR THE PROMOTION OF SCIENCE
日本学術振興会

NRF National Research Foundation of Korea

HEISING-SIMONS FOUNDATION

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Backup

$JSNS^2$ vs. LSND

	LSND	$JSNS^2$	Notes
Detector Mass	167t	17t	-
Baseline	30m	24m	-
Beam Proton Energy	0.8GeV	3GeV	Allows for KDAR measurement. Expect ~10x higher pion production
Beam Power	800kW	1MW	-
Beam Duty Factor	600μs x120Hz	100ns(x2) x25Hz	Expect ~300x fewer ambient IBD backgrounds
Detector Medium	Dilute LS	Gd-LS	-
Neutron Capture	Hydrogen, ~0.2ms, 2.2MeV	Gadolinium, ~26μs, 8MeV	Shorter capture time & higher energy mean fewer backgrounds
Particle ID	Cherenkov	PSD	-

CNgs Efficiencies and Cross Section

- Neutrino flux estimate requires we carefully estimate our detection efficiency
  - **Estimated average efficiency: 0.0588 ± 0.0021**
- We use a combined Karmen+LSND cross section measurement

$$N_{CNGS} = \frac{\Phi_{\nu_e} \mathrm{POT}}{4\pi r^2} \epsilon \sigma N_C$$

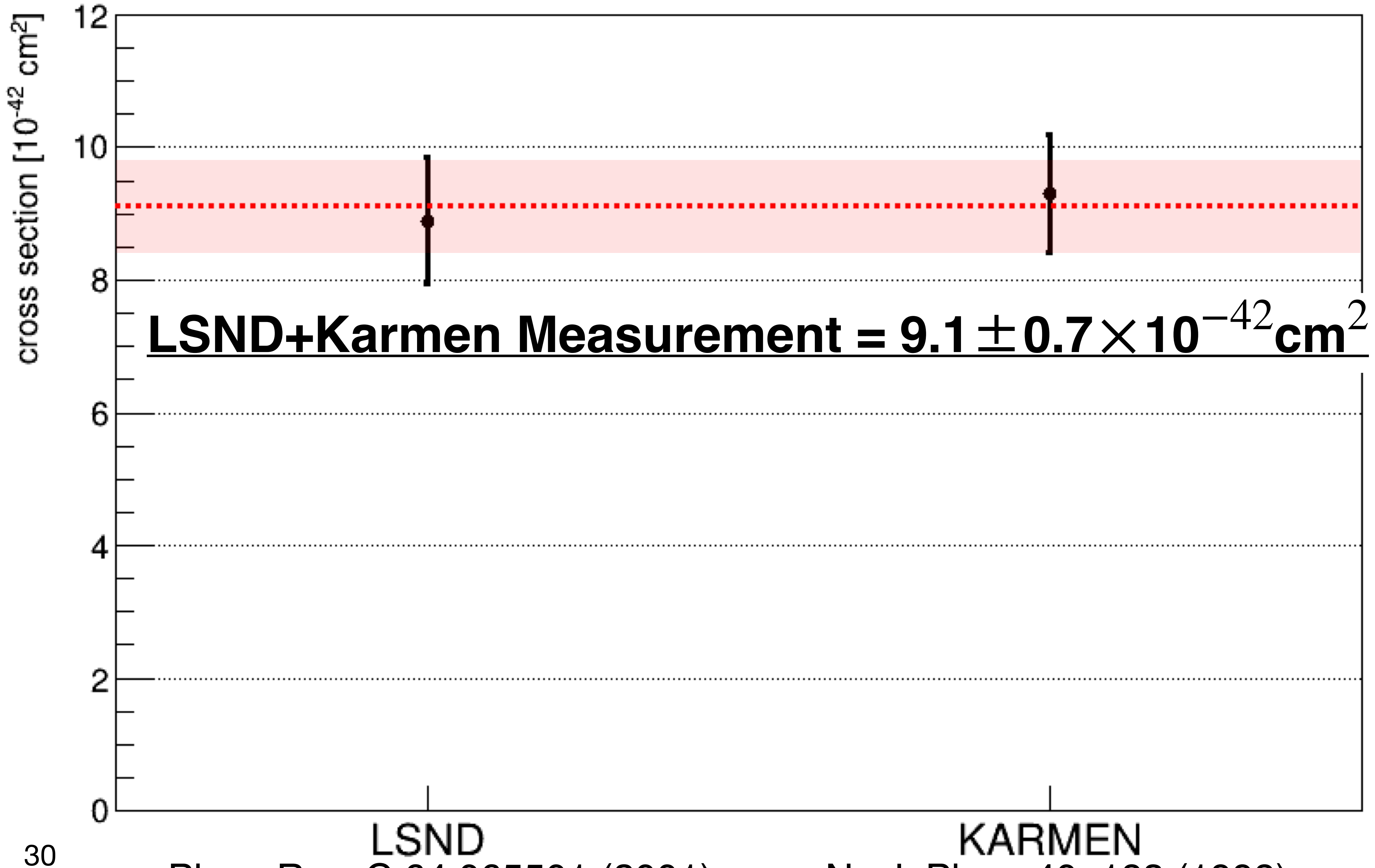
Observed Event Rate (N_{CNGS}), Neutrino Flux (Φ_{ν_e}), Selection Efficiency (ϵ), Interaction Cross Section (σ), Number of Carbons (N_C)

Efficiency Estimates

item		efficiency	error (%)
bkg estimation (MST vs SS)		-	10.7 %
Energy		2021: 0.255 2022: 0.255	2021: 4.6 % 2022: 5.0 %
(FADC) Timing	prompt	2021: 0.498 2022: 0.468	2021: 0.4 % 2021: 0.2 %
(FADC) Timing	Δ_t	2021: 0.5180 2022: 0.7805	2021: 0.08 % 2022: 0.05 %
muon veto		2021: 0.885 2022: 0.901	2021: 0.4 % 2022: 0.3 %
Michel electron veto	prompt	0.9930	0.01 %
Michel electron veto	delayed	0.9768	0.03 %
Δ_{VTX}		0.881	0.8 %
fiducial		- (related to the number of ^{12}C)	8 %

item	value and error
The number of ^{12}C	$(4.68 \pm 0.37) \times 10^{29}$ (PSD fiducial volume)
Cross section	$(9.1 \pm 0.7) \times 10^{-42}$ cm^2

Cross Section Estimates



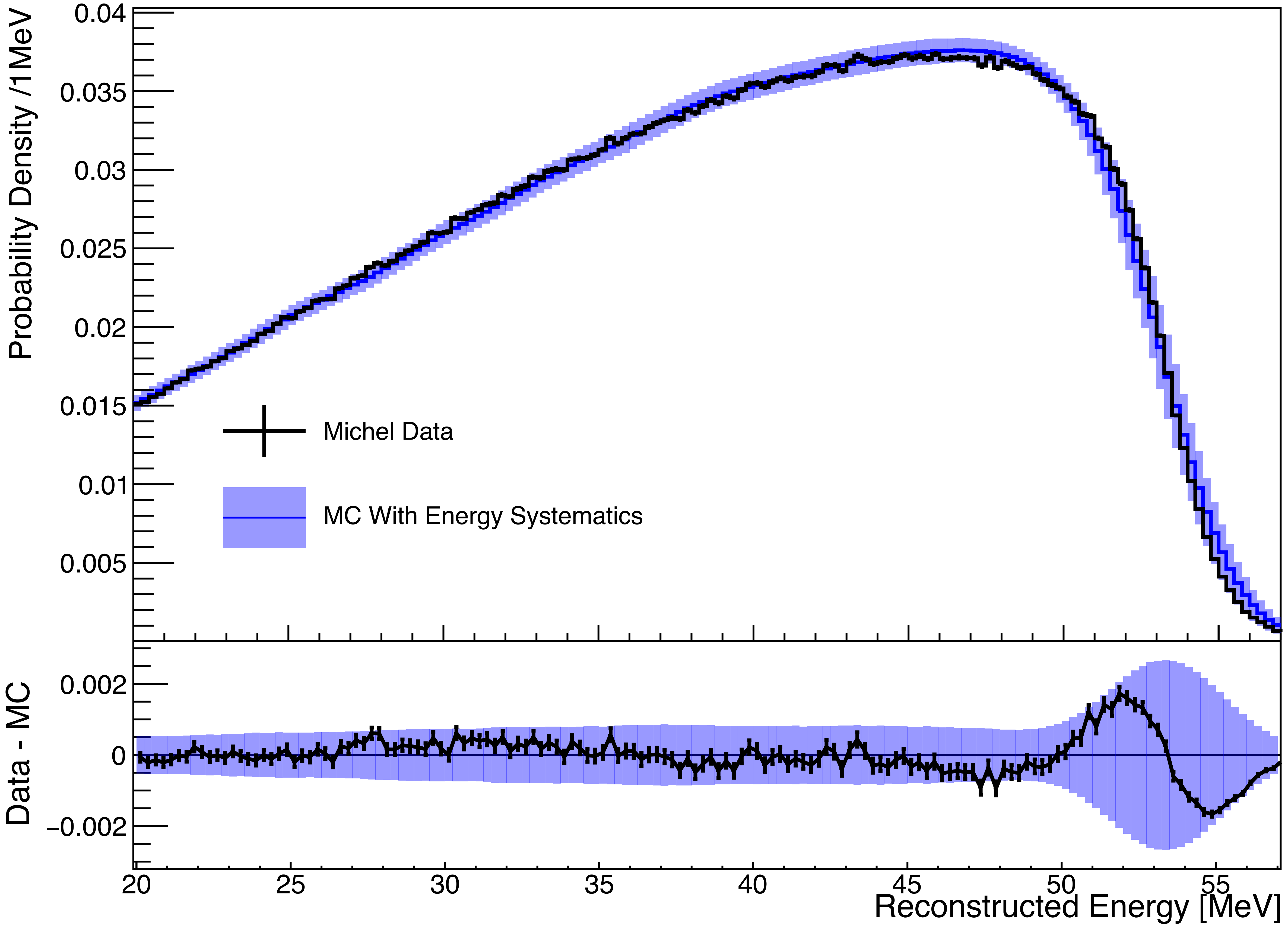
Phys. Rev. C 64:065501 (2001)   Nucl. Phys. 40, 183 (1998)

KDAR Energy Calibration

- Energy reconstruction is calibrated & systematics are determined using Michel MC & data.

- Additional systematics from the comparison of the energy scale observed from neutron capture (8MeV) and from Michel (~53MeV).

- The energy scale systematics are constrained to 0.68% uncertainty.



^{252}Cf Calibration

arXiv:2404.04153

- We developed a 3D calibration arm for our ^{252}Cf source
- It was used to improve our optical model used for reconstruction