Joint IF-ICN High Energy Physics Seminar
Institute of Physics, UNAM, May 16th 2018

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for the MiniBooNE Collaboration

Measurement of CC interactions of mono-energetic ν_μ's with the MiniBooNE detector

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Medición de interacciones de CC de ν_μ's monoenergéticos con el detector MiniBooNE

Primary analyzers: Joshua Spitz, Rory Fitzpatrick, Johnathon Jordan (U. Mich.), Joe Grange (ANL),

Alexis A. Aguilar-Arévalo (ICN-UNAM)
por la Colaboración MiniBooNE

Seminario Conjunto de Física de Altas Energías IF-ICN
Instituto de Física, UNAM, 16 de Mayo 2018

Outline

- Motivation: Why is the KDAR neutrino important?
- The MiniBooNE detector & NUMI beamline
- KDAR neutrinos from the NUMI absorber in MiniBooNE
- Analysis
- Results
- Summary and outlook

This talk is based on this publication by the MiniBooNE Collaboration:

Phys. Rev. Lett. **120**, 141802 (2018)

PHYSICAL REVIEW LETTERS **120,** 141802 (2018)

Editors' Suggestion | Featured in Physics

First Measurement of Monoenergetic Muon Neutrino Charged Current Interactions

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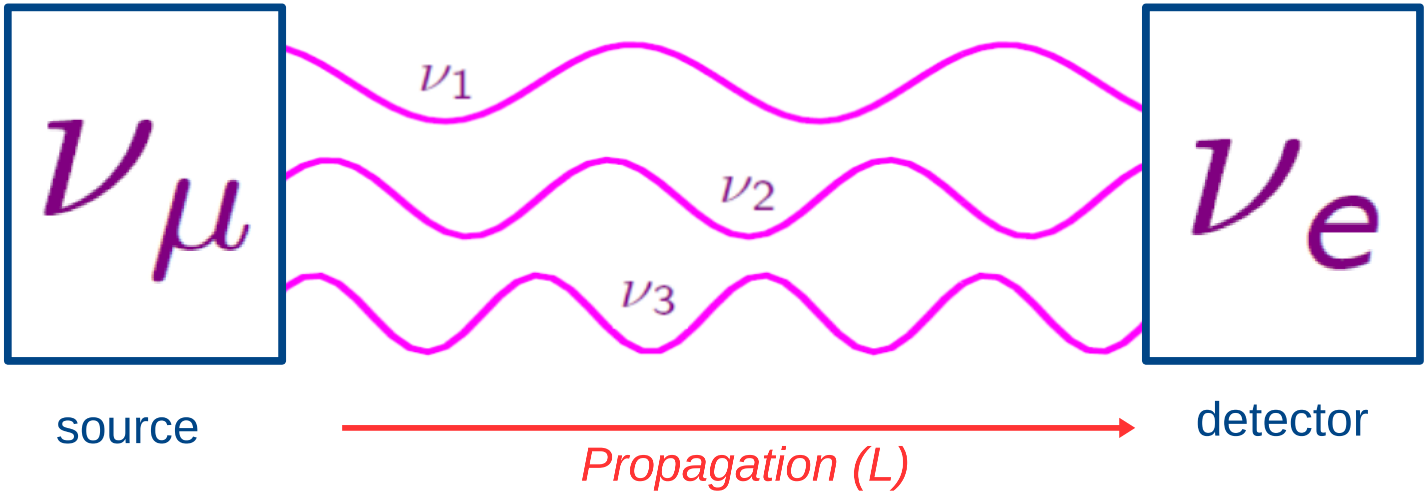
We report the first measurement of monoenergetic muon neutrino charged current interactions. MiniBooNE has isolated 236 MeV muon neutrino events originating from charged kaon decay at rest ($K^+ \rightarrow \mu^+ \nu_\mu$) at the NuMI beamline absorber. These signal ν_μ-carbon events are distinguished from primarily pion decay in flight ν_μ and $\bar{\nu}_\mu$ backgrounds produced at the target station and decay pipe using their arrival time and reconstructed muon energy. The significance of the signal observation is at the 3.9σ level. The muon kinetic energy, neutrino-nucleus energy transfer ($\omega = E_\nu - E_\mu$), and total cross section for these events are extracted. This result is the first known-energy, weak-interaction-only probe of the nucleus to yield a measurement of ω using neutrinos, a quantity thus far only accessible through electron scattering.

DOI: 10.1103/PhysRevLett.120.141802

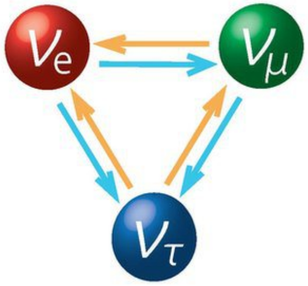
A charged kaon decays to a muon and a muon neutrino ($K^+ \rightarrow \mu^+ \nu_\mu$) 63.6% of the time [1]. In the case that the kaon is at rest when it decays, the emitted muon neutrino is monoenergetic at 236 MeV. The kaon decay at rest (KDAR) neutrino has been identified as a gateway to a number of physics measurements, including searches for high-Δm^2 oscillations [2,3] and as a standard candle for studying the neutrino-nucleus interaction, energy reconstruction, and cross sections in the hundreds of MeV energy region [4]. There are other ideas for using this neutrino, including as a source to make a precision measurement of the strange quark contribution to the nucleon spin (Δs) [4] and as a possible

Neutrino oscillation experiments

Measure the probability of neutrino flavor transformation



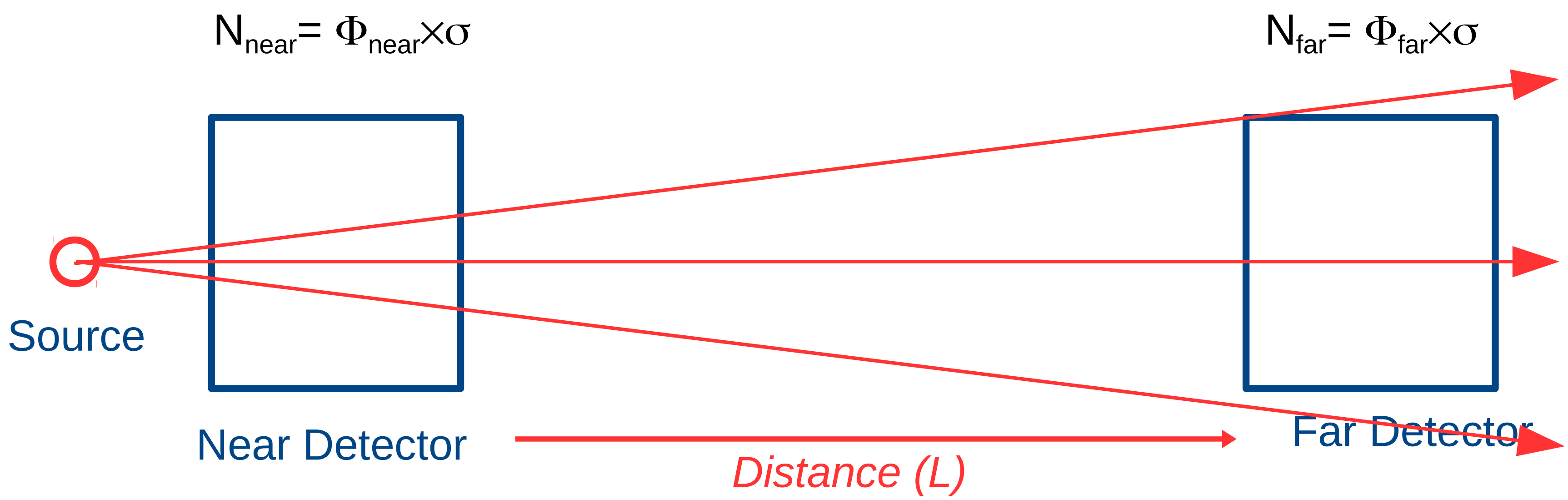
$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$



Must be able to compare the number of neutrinos of a given flavor between source and detector.

Neutrino oscillation experiments

… or between a near and a far detector.

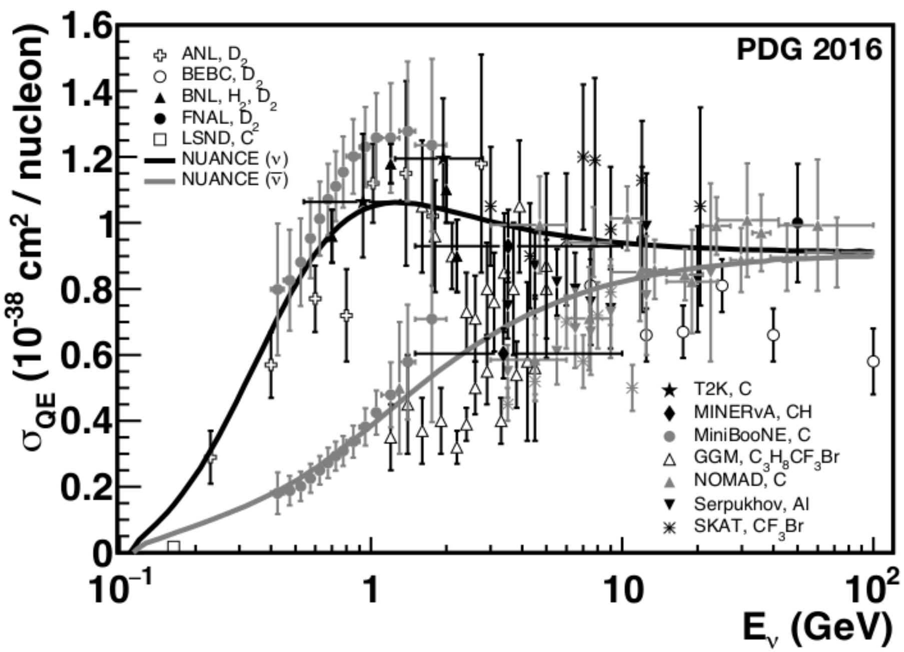


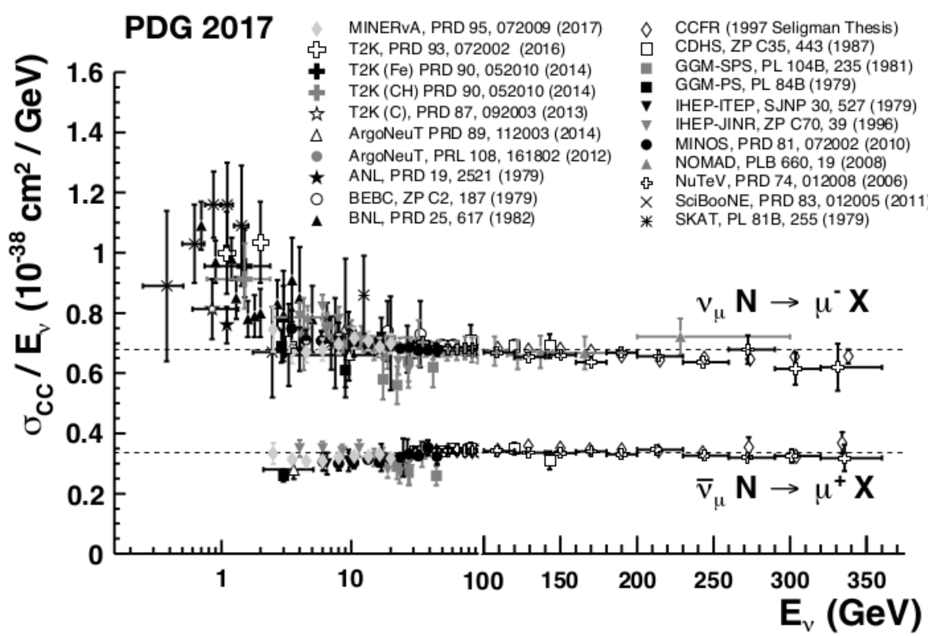
The near and far fluxes are different => must rely on cross section knowledge to do a proper comparison.

Problem 1- cross sections @ ~1 GeV

E~1 GeV is an important energy range to study neutrino oscillations, but ..

Muon neutrino cross sections

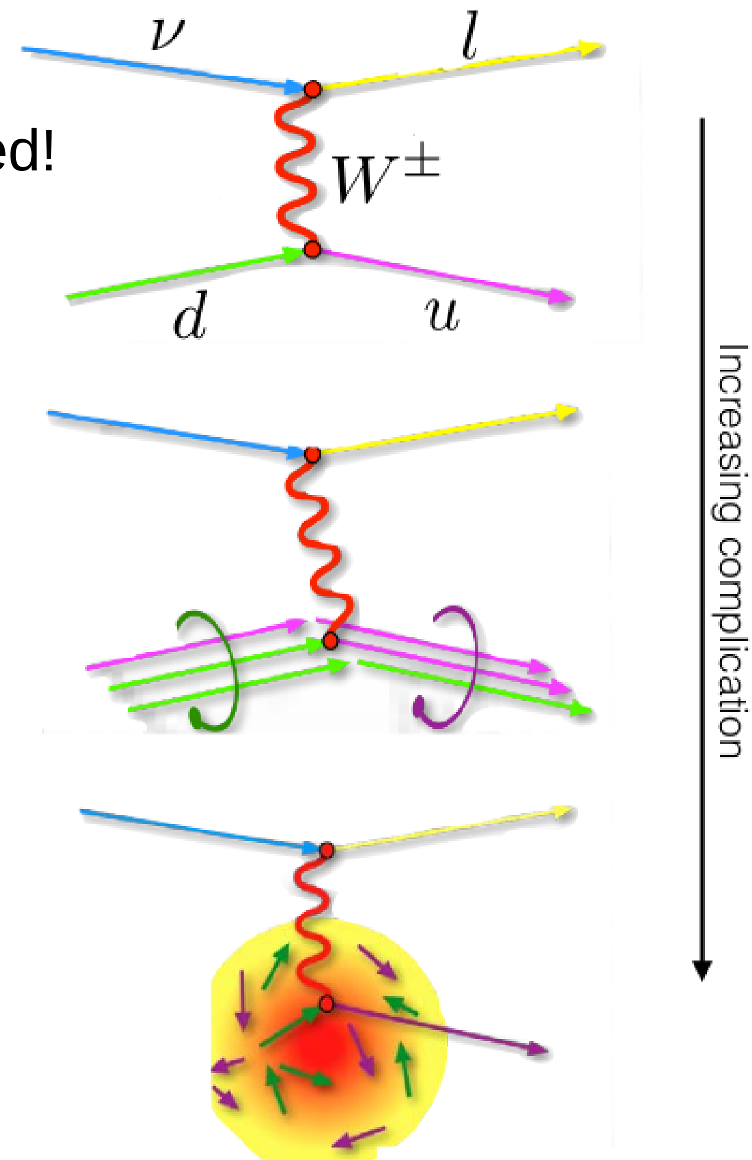




Our knowledge of cross sections around ~1 GeV is very weak

ν-energy reconstruction issues

- Neutrino interactions with nuclei are complicated!
  - Fermi motion.
  - Correlations between nucleons
  - Final state interactions
- Detector limitations
  - Energy resolution
  - Event classification issues
  - Cherenkov threshold



Adapted from K. McFarland

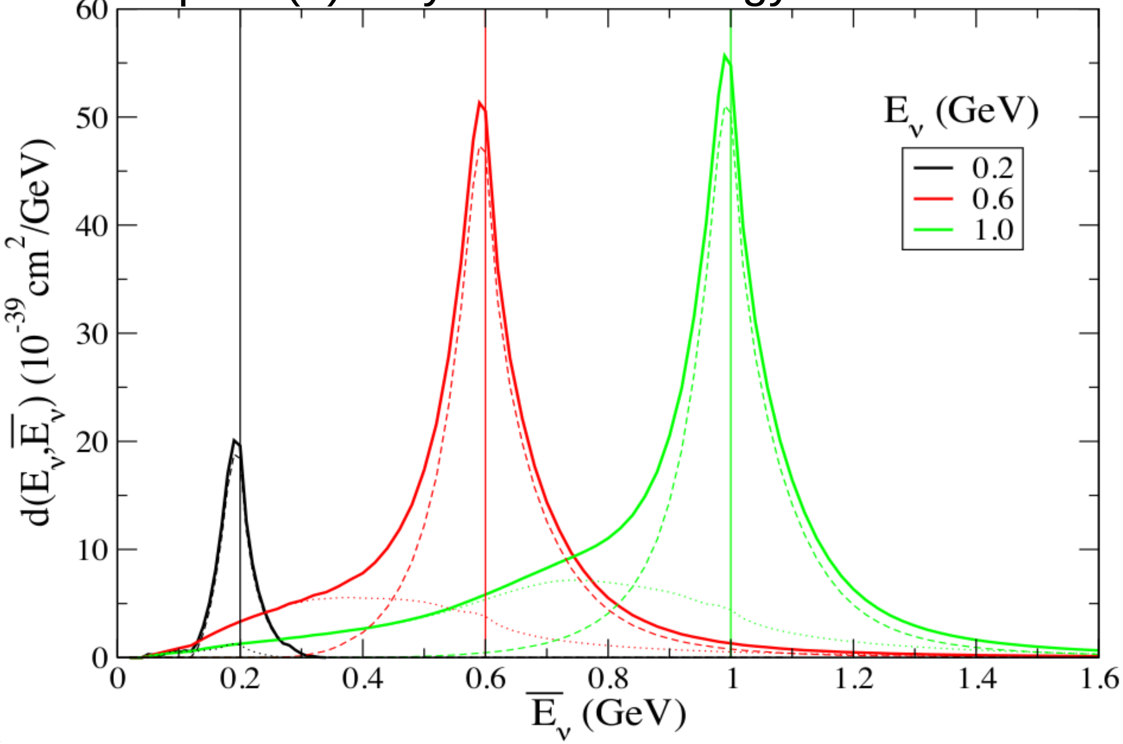
Problem 2- reconstructing E_ν is hard

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{\text{GeV}}{\text{eV}^2\,\text{km}}\right)$$

$$\frac{\Delta E}{E} > 20\% \quad \text{is typical}$$

The oscillation probability is a function of neutrino energy…
but it's hard to reconstruct the energy of the neutrino!

lepton (e)-only neutrino energy reconstruction



vertical lines=true neutrino energy
distributions=reconstructed neutrino energy

M. Martini, M. Ericson, and G. Chanfray, Phys. Rev. D 87, 013009 (2013)

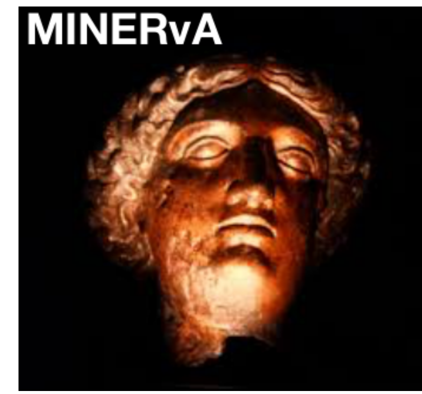
Efforts to study ν interactions

μBooNE

ArgoNeuT

MINOS

ANNIE
Accelerator Neutrino Neutron Interaction Experiment



SHORT-BASELINE NEAR DETECTOR
SBND

T2K

recision
eaction
ndependent
pectrum
easurement
NuPRISM:

NOvA

SciBooNE

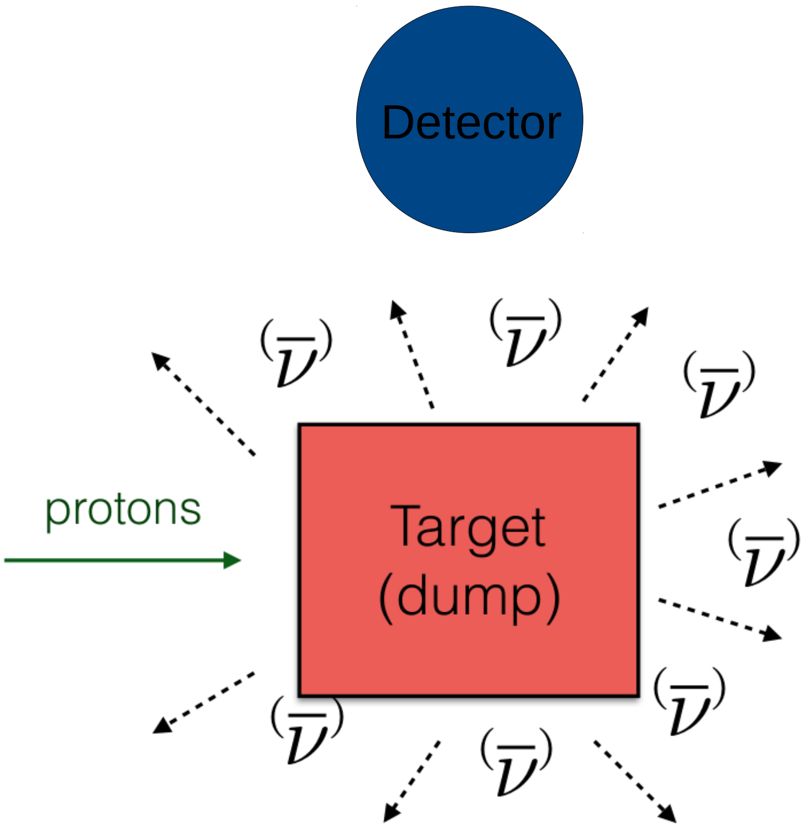
JSNS2

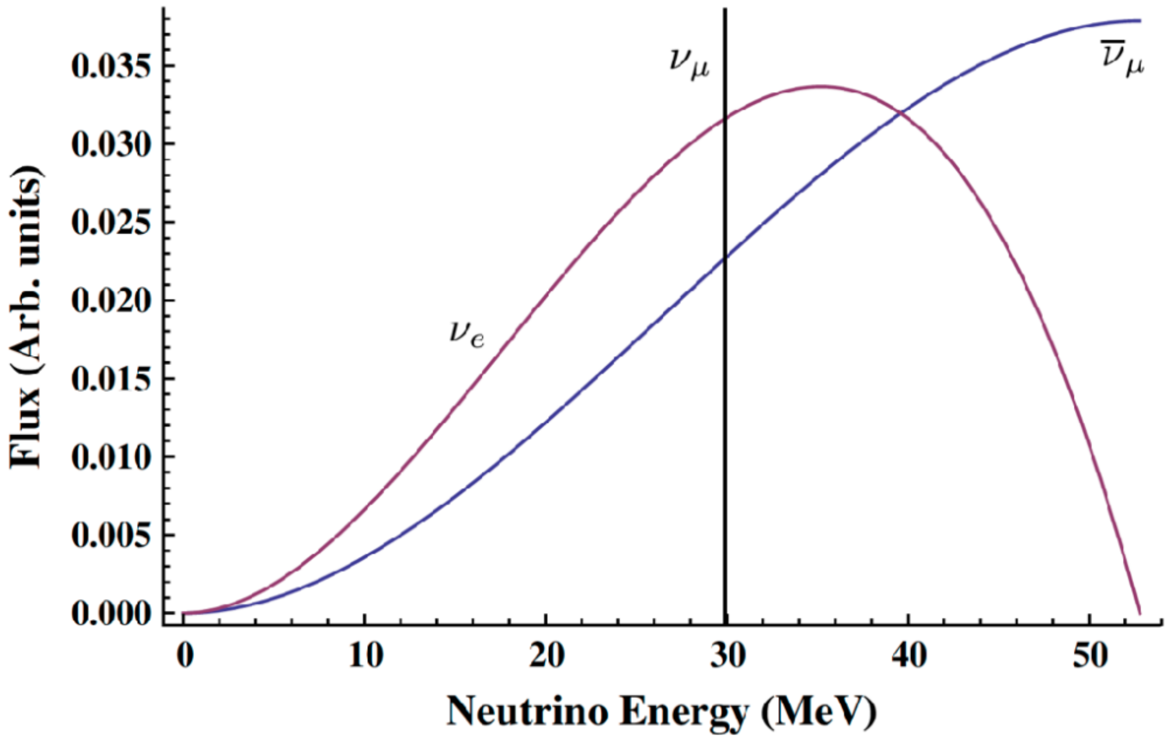
Monoenergetic neutrinos

- Accurate measurement of mono-energetic neutrinos has remained elusive.
- Achieving it would help to address **Problem 1** and **Problem 2** above.
- We are trying to measure the Kaon Decay at Rest (KDAR) neutrino for the first time.

Pion/Muon decay-at-rest neutrinos

Few hundred MeV proton beam walks into a dump ...



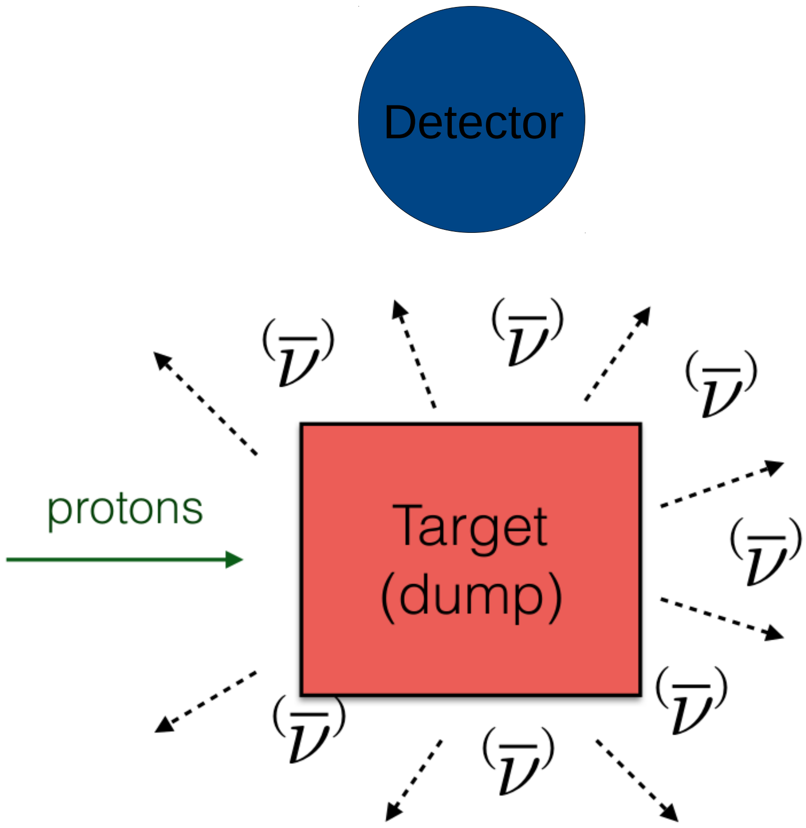


Used in several ν experiments

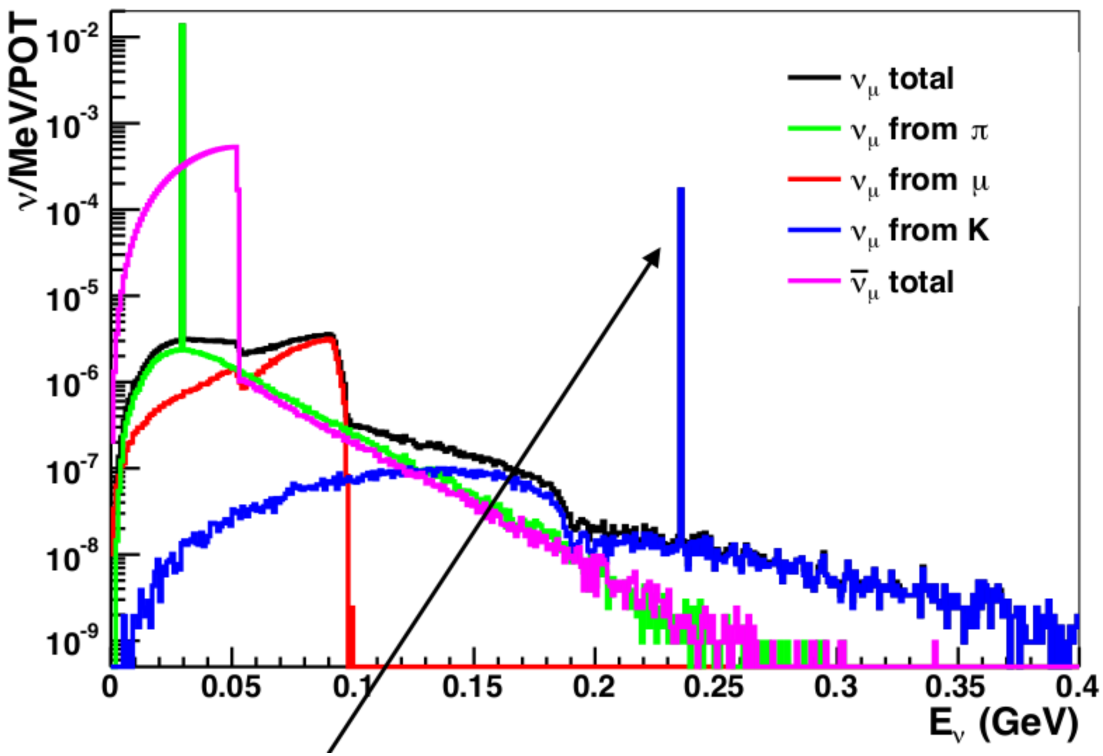
$$\pi^+ \to \mu^+ \nu_\mu$$
$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$

Kaon decay-at-rest (KDAR) neutrinos

Few GeV proton beam walks into a dump ...



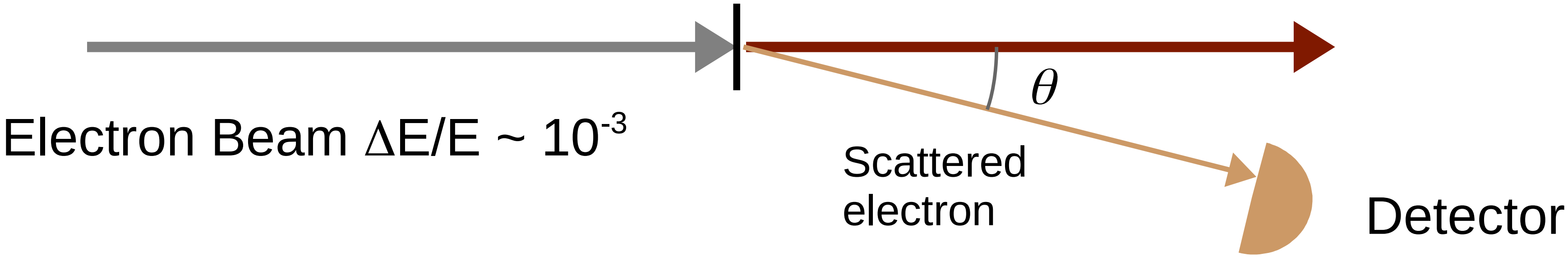
ν_μ flux at J-PARC spallation neutron facility



$$K^+ \rightarrow \mu^+ \nu_\mu$$ (branching ratio: 64%)

E=236 if kaon decays at rest

Probing the nucleus



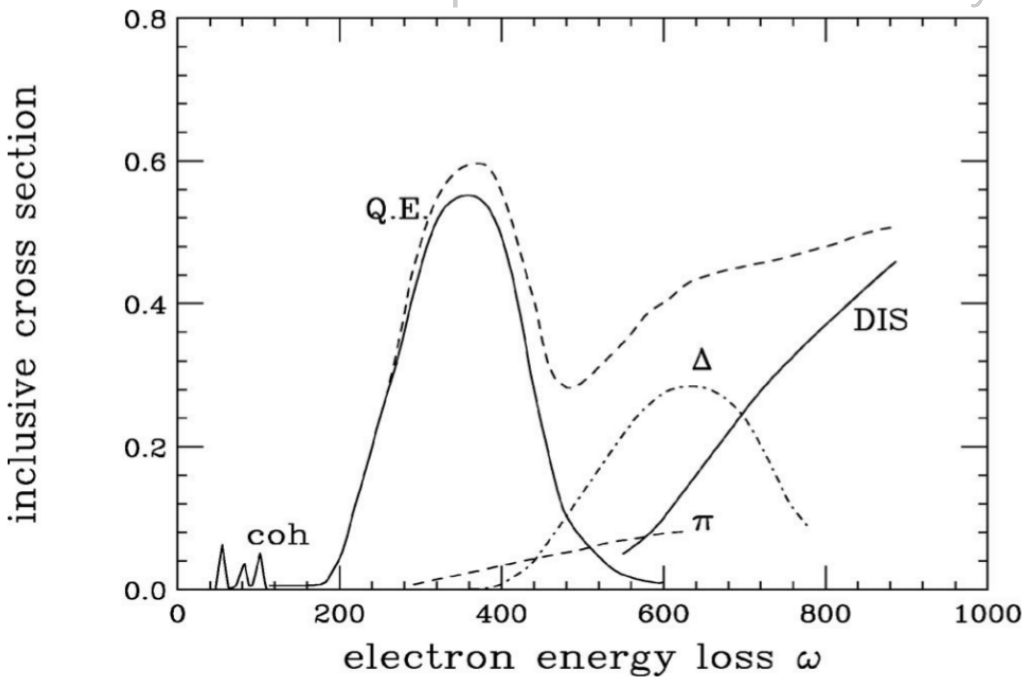
$$(E, 0, 0, p) \rightarrow (E', p' \sin\theta, 0, p' \cos\theta)$$

Slide adapted from G. Garvey

$$\omega \equiv E - E'$$

$$\mathbf{q} = \mathbf{p} - \mathbf{p}'$$

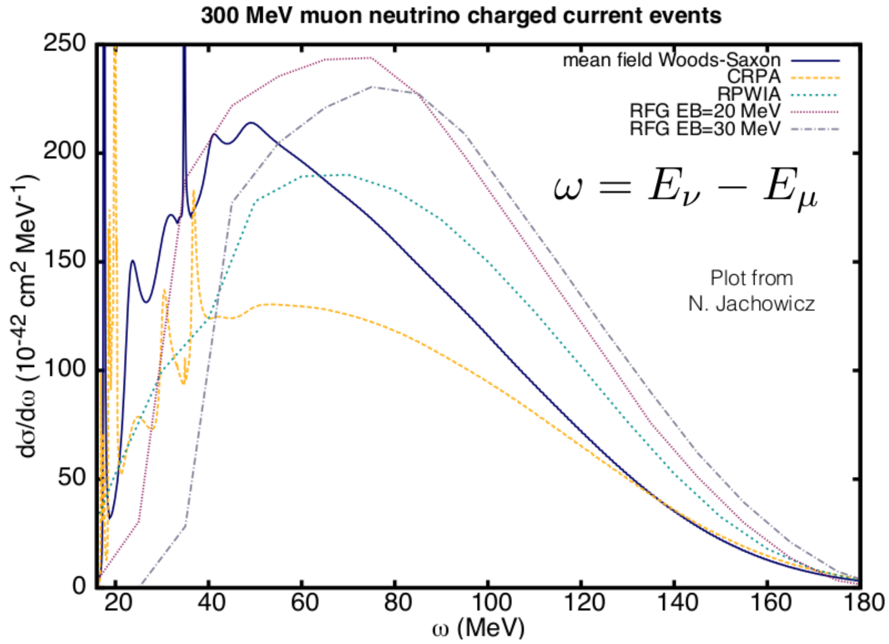
Thus, q and ω are precisely known <u>without any reference to the nuclear final state</u>



This measurement has not (yet) been possible with neutrinos.

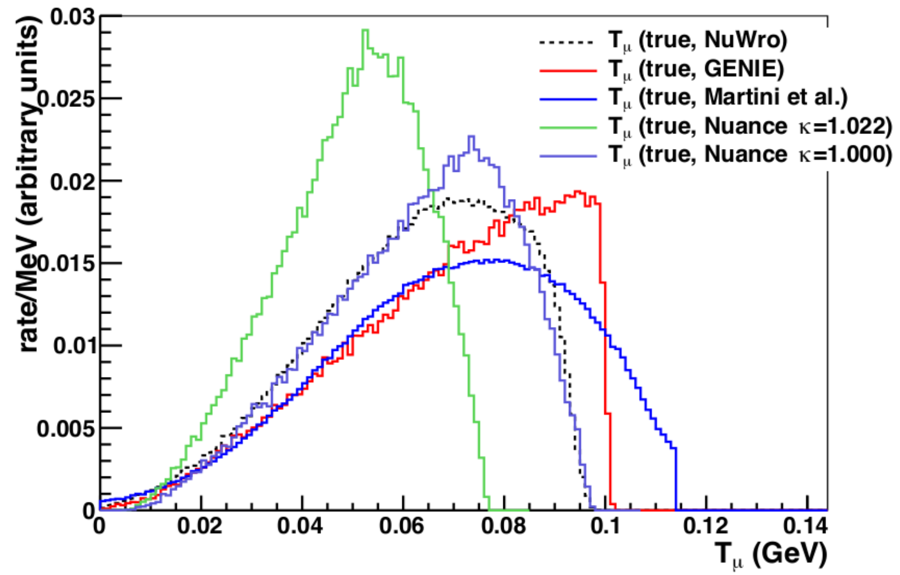
Why is the KDAR ν important?

- Can provide a measurement of ω with a known energy, weak-interaction-only nuclear probe.
- Standard candle for neutrino interactions @ 100s of MeV.
- Model predictions vary wildly



Open questions

- Which model of the nucleus, relevant to neutrinos, is correct?
- What is the correct way to treat the transition *on-nucleus* to *on-nucleon* scattering?
- How reliable is lepton-based energy reconstruction?
- How large arethe contributions of short-range correlations?



Other physics with KDAR neutrinos

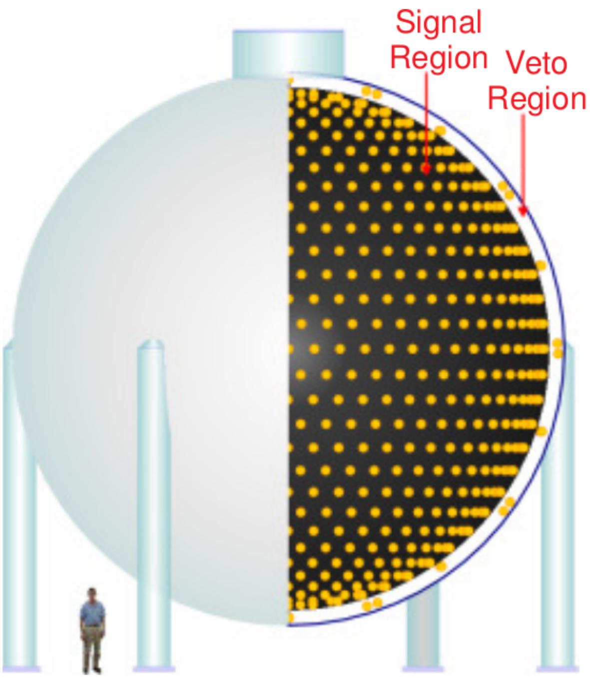
KDAR neutrinos open up many other physics measurements:

- Oscillation search for sterile neutrinos at short baselines
- Measure s quark contribution to nucleon spin (Δs)
- Look for dark matter annihilation in the Sun

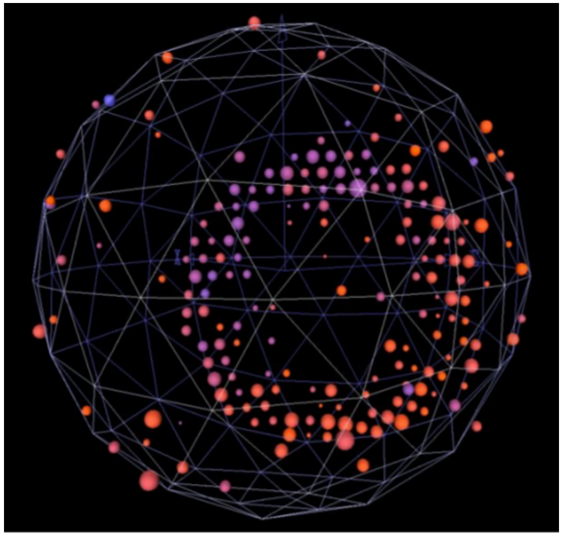
J. Spitz, Phys. Rev. D 85 093020 (2012).
S. Axani, et. al., Phys. Rev. D 92 092010 (2015)
C. Rott, et. al., J. of Cosmol. and Astropart. Phys. 11 039 (2015)
C. Rott, et. al., arXiv:1710.03822 [hep-ph].

MiniBooNE detector

- 12 m diameter sphere with 800 tons of mineral oil (CH_2).
- Cherenkov + scintillation detector, instrumented with 1280 (main) + 240 (veto) PMTs.



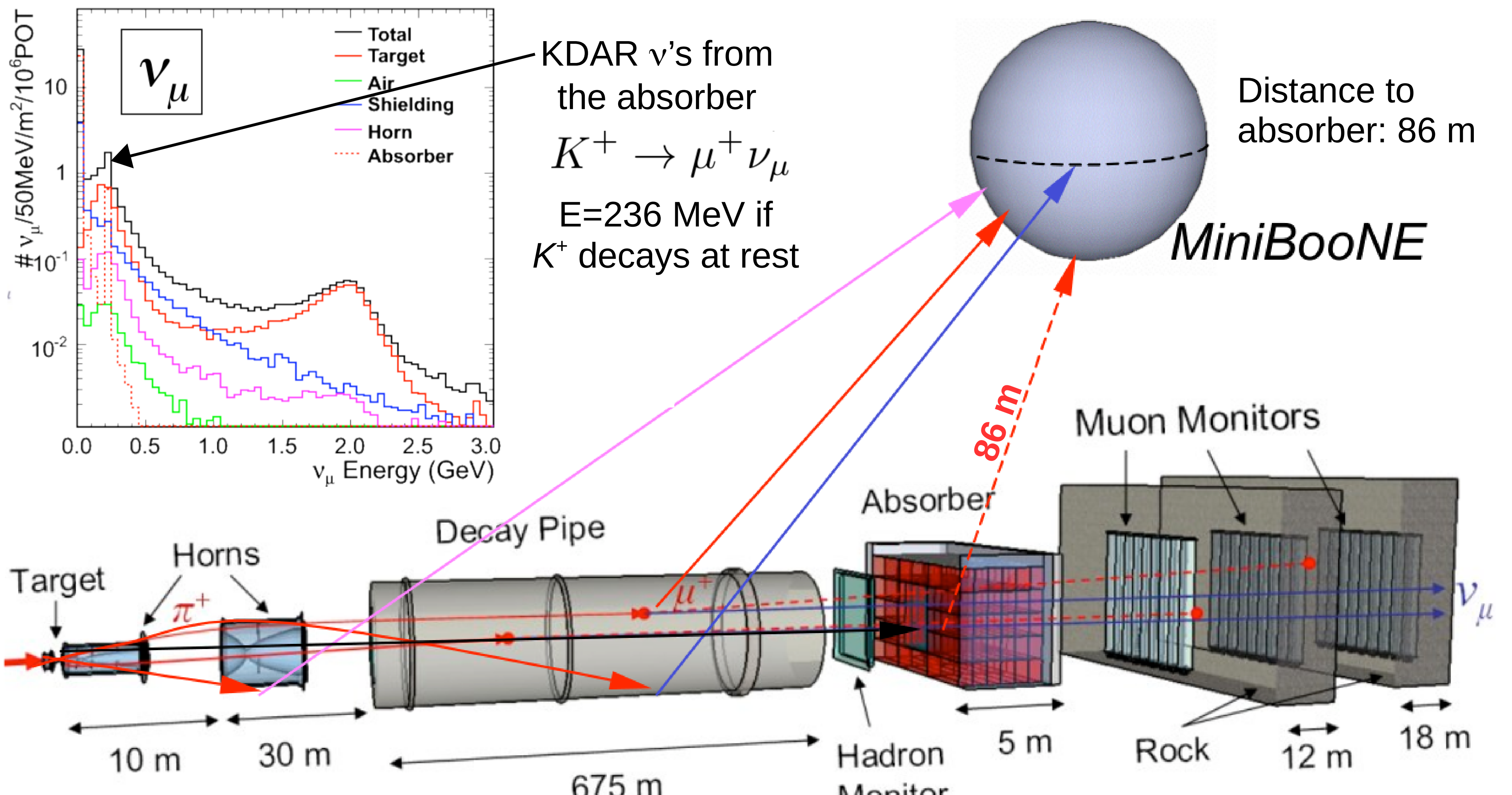
- Exposed to two neutrino beamlines at Fermilab:
  - Booster Neutrino Beam (on-axis)
  - NuMI neutrino beam (off-axis)
- Taking data **since 2002!**
- Many oscillation, cross section, and exotic search results! See www-boone.fnal.gov for more info.



A typical muon in MiniBooNE

MiniBooNE and the NuMI beamline

Neutrino (ν_μ) flux at MiniBooNE from the NUMI beamline

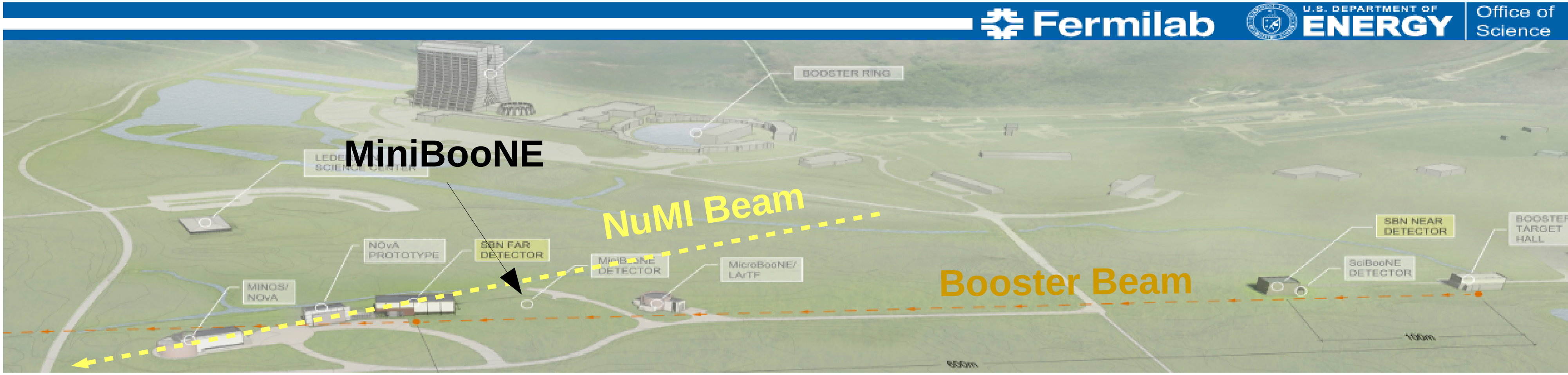


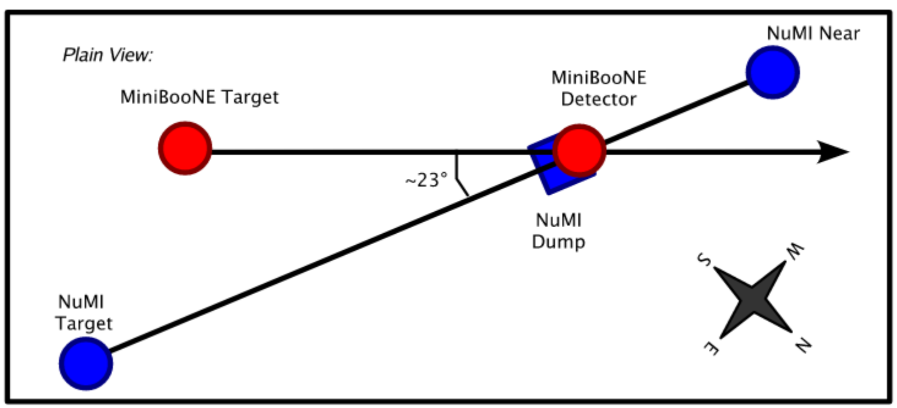
LE10 NUMI configuration ($2\lambda_{int}$ target)

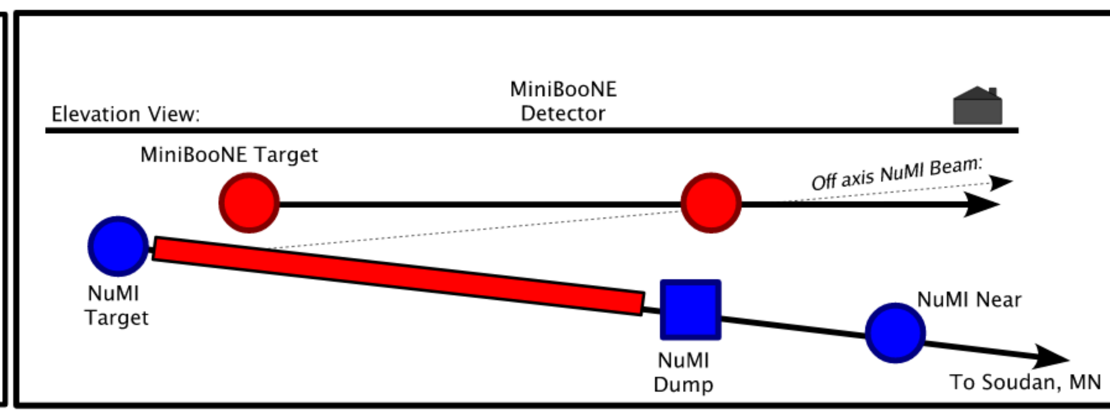
adapted from Z. Pavlovic PhD thesis

Short Baseline Neutrino (SBN) program

- Motivated by LSND/MiniBooNE to study ν oscillations. To begin operations in 2019.



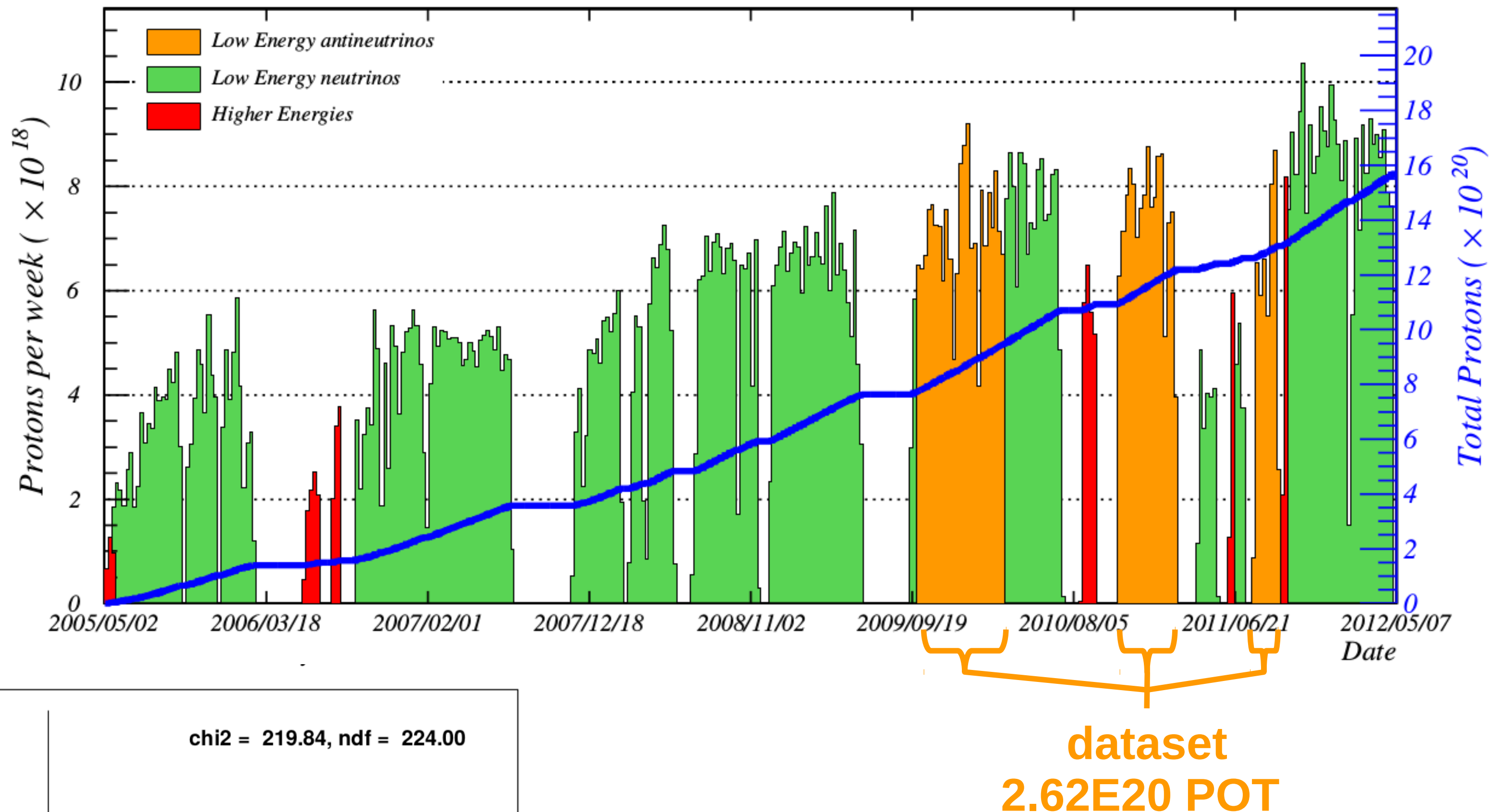


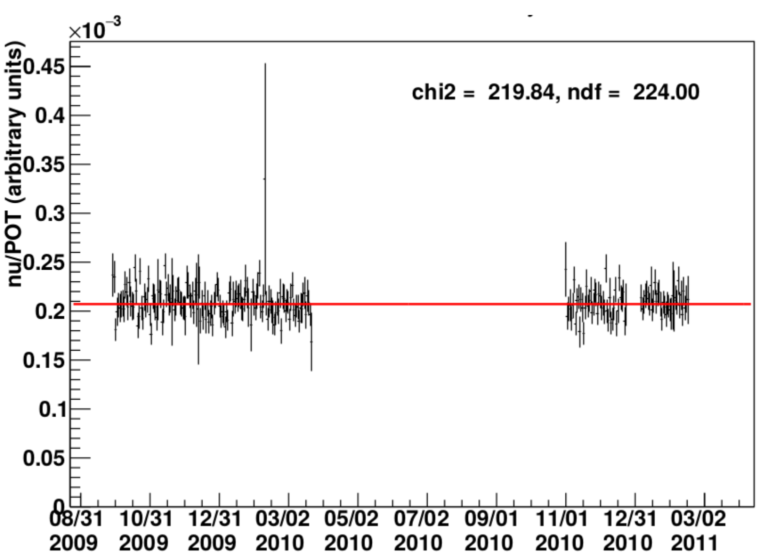


AIP Conf.Proc. 842 (2006) 834-836

BNB and NUMI beamline elements with MiniBoonE and MINOS Near Detector.

Dataset





- NuMI LE antineutrino mode
- higher signal:bkgd than neutrino-mode

- ~0.21 nu/POT candidate event rate
- 2.62E20 POT

KDAR neutrinos in MiniBooNE

$$\nu_\mu {}^{12}\mathrm{C} \rightarrow \mu^- X$$

KDAR events feature a low energy muon (T_μ ~0-120 MeV, 2 sub-event , including Michel decay).

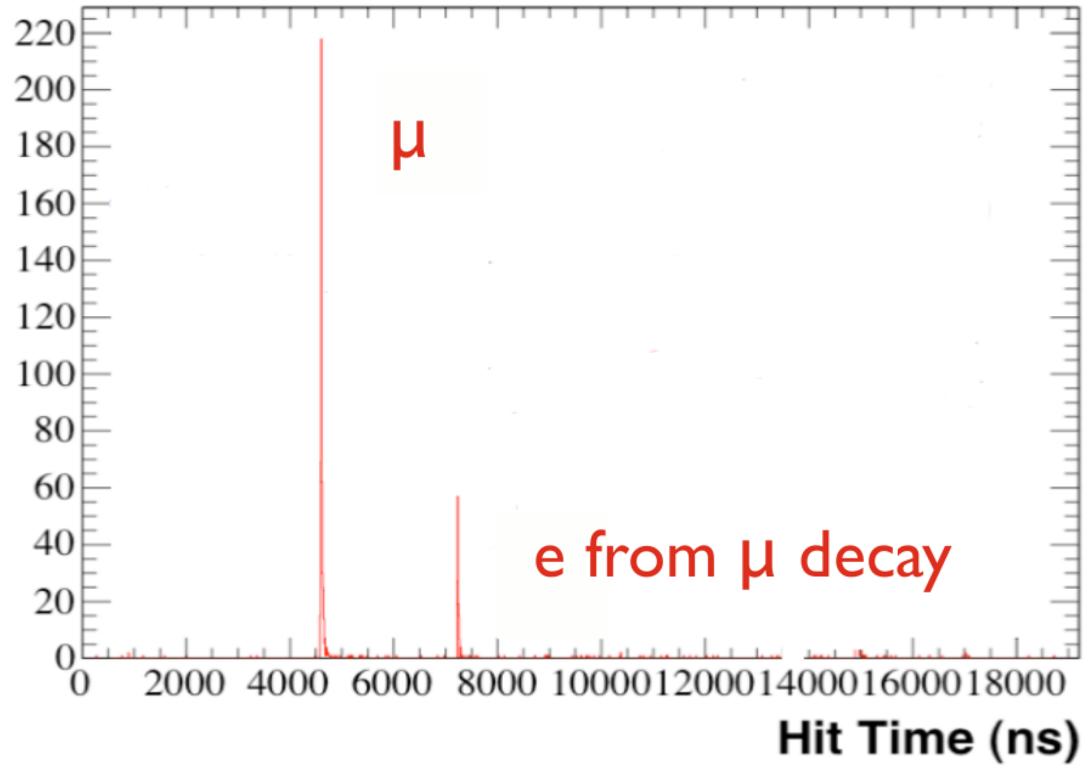
We use the standard MiniBooNE muon neutrino selection to isolate KDAR-like events (2 sub-event, in fiducial volume, no veto activity).

$$\nu_\mu {}^{12}\mathrm{C} \rightarrow \mu^- X$$

$$\downarrow$$

$$\mu^- \rightarrow e^- \nu_\mu \overline{\nu}_e$$

Typical two "subevents" event



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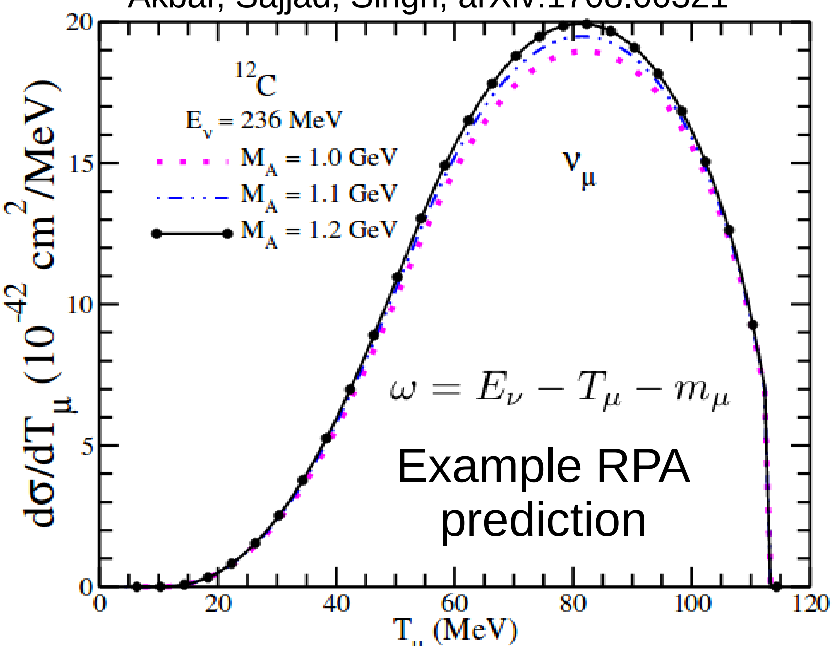
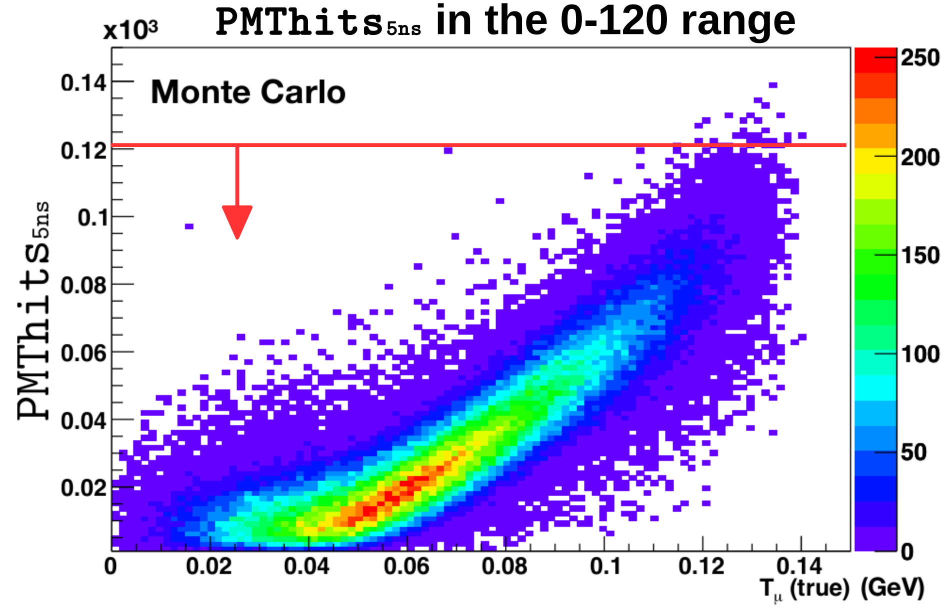
In order to isolate the muon KDAR events we consider the Cherenkov-dominated light in the first 5 ns of the event (after correcting for vertex location) ⟶ $\mathtt{PMThits}_{5ns}$

Akbar, Sajjad, Singh, arXiv:1708.00321



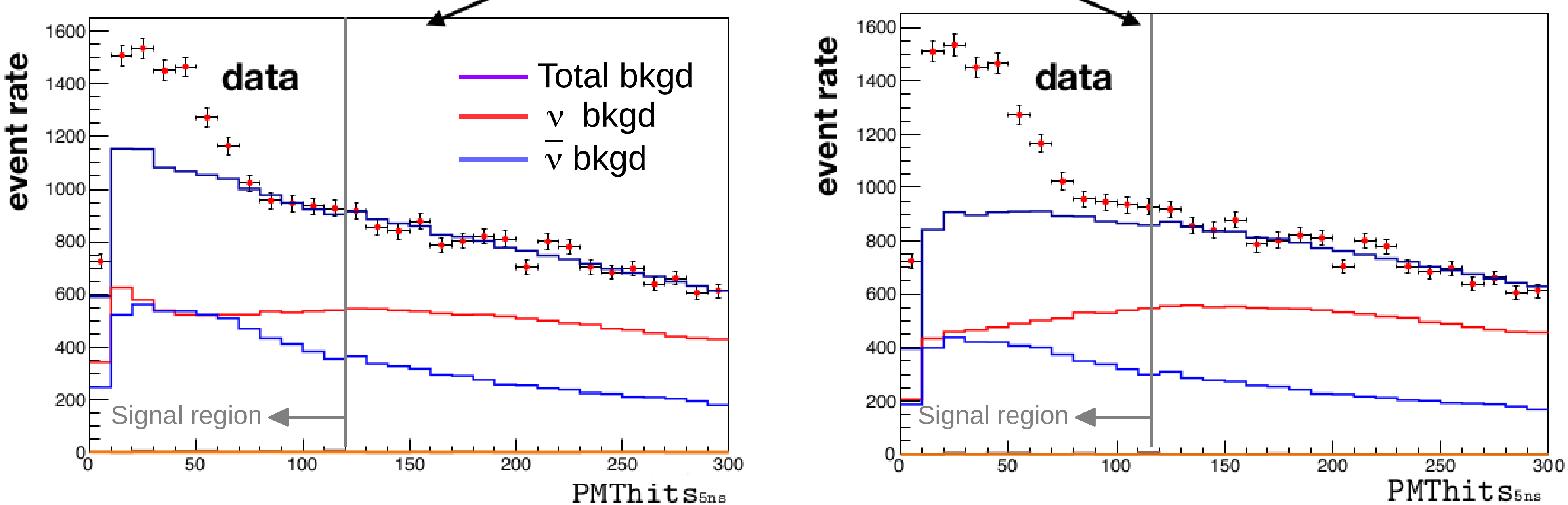
KDAR muons produce $\mathtt{PMThits}_{5ns}$ in the 0-120 range



KDAR signal vs Bkgd prediction

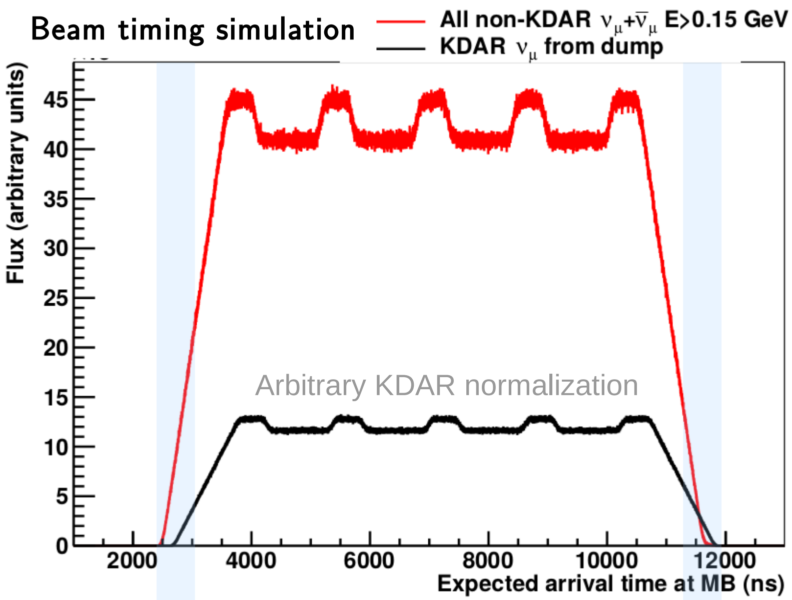
After-cuts, event sample shows clear excess at low energies where KDAR is expected!
but ...
large flux uncertainties and choice of input event generator
⇨ large variations in bkgd shape and normalization predictions.

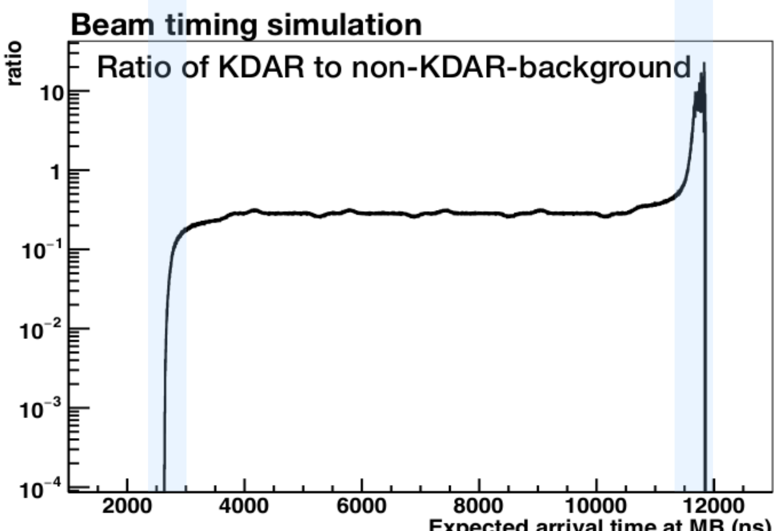
two possible (extreme) background predictions from the Nuance event generator



notes: (1) KDAR is not simulated; (2) MC prediction is normalized to data in background region

Timing to the rescue!

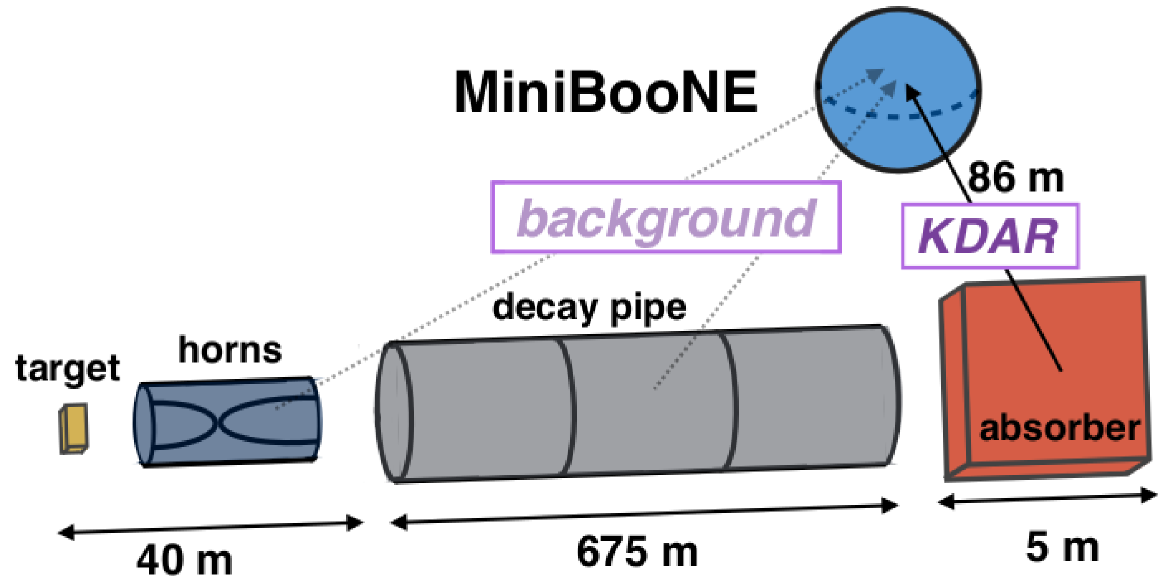




Bkgd-enhanced

Signl-enhanced

KDAR and background events arrive at MiniBooNE at different times

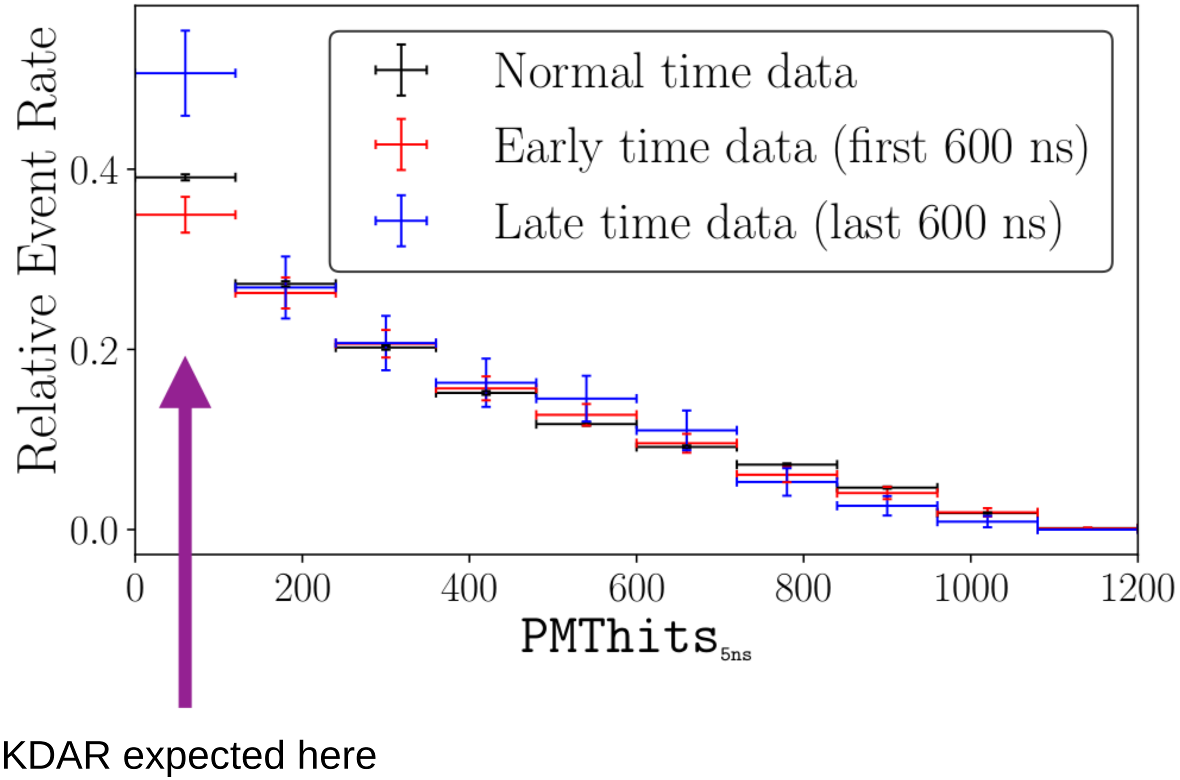


Signal events take a longer path to the detector than background events.

- Bkgd-enhanced region: first ~600 ns after beam start.
- Signl-enhanced region: last ~600 ns of beam window.

Sign of KDAR events

Deficit (excess) of KDAR-like data at early (late) times seen in the overall $\texttt{PMThits}_{5ns}$ distribution, but with low significance.



- Early time deficit: 2.1σ
- Late time excess: 2.4σ

We want to extract information about the muon kinematics in KDAR events.

Analysis overview

We extract the true T_μ distribution by studying how the data (signal and background) evolve in time.

Analysis procedure:

1. Specify a candidate signal model by choosing a shape, normalization, and end point.

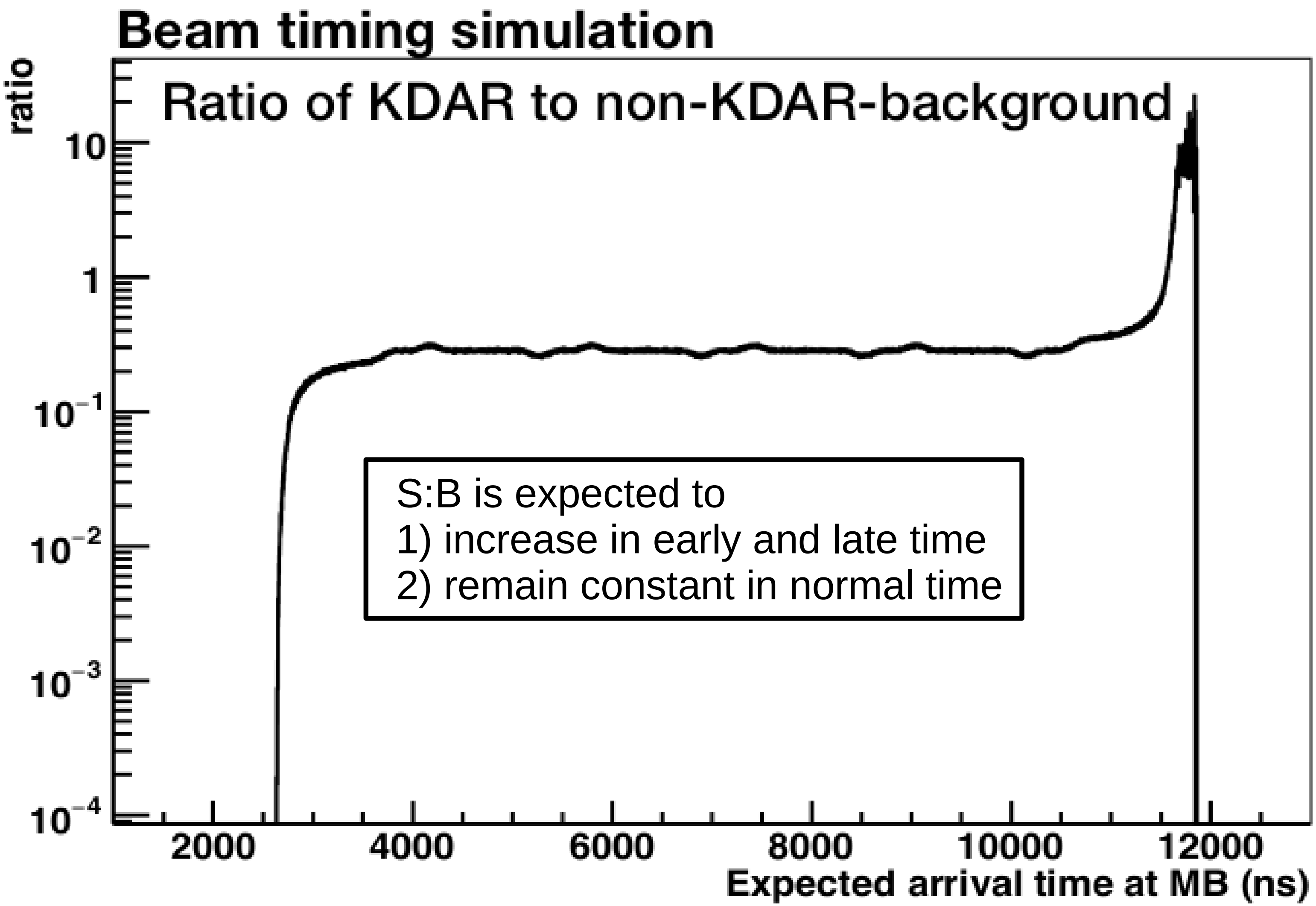
2. Use this signal model to construct a background model using a high-statistics region where signal:background is constant.

3. Compare the signal+background model to data in the signal- and background-enhanced regions to determine how well the model matches the data.

4. Repeat for each physically allowed signal model.

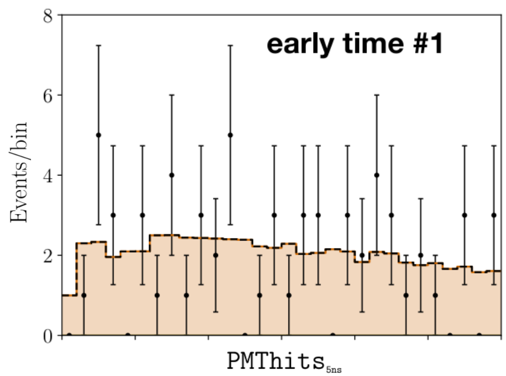
100% data-driven analysis

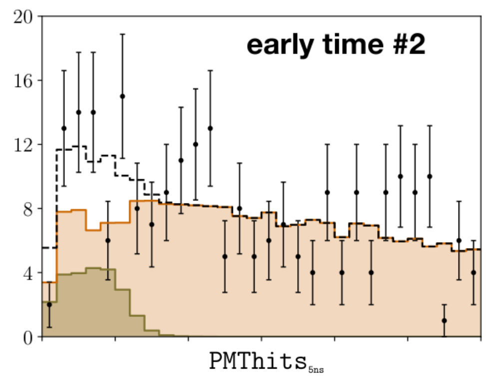
Extracting the KDAR T_μ distribution

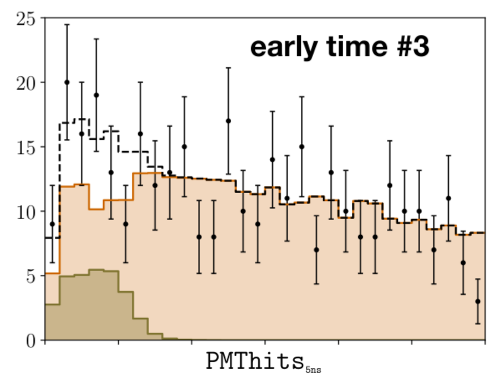


Extracting the KDAR T_μ distribution

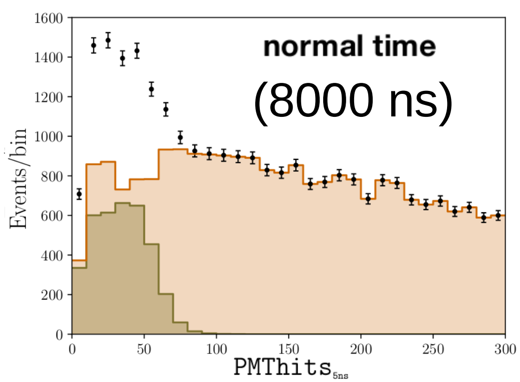
Data split into 7 time windows: 3 “early time”, 3 “late time”, and 1 high-stats “normal time”)





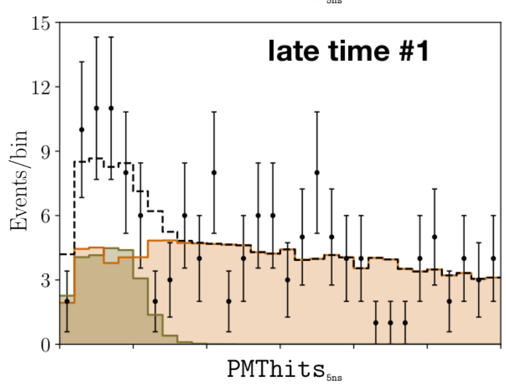


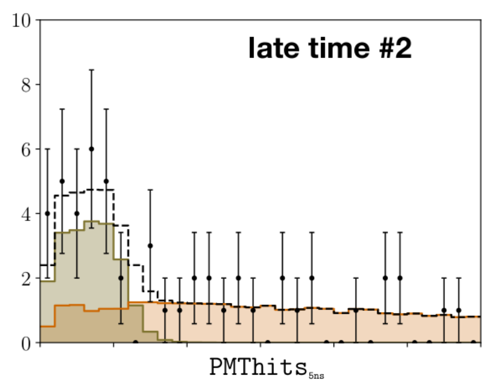
3 early time
(200 ns each)

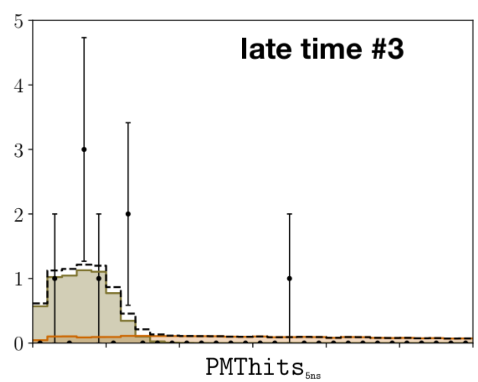


S:B is expected to
1) increase in early and late time
2) remain constant in normal time

black - data
green & **orange**
explained in next slides



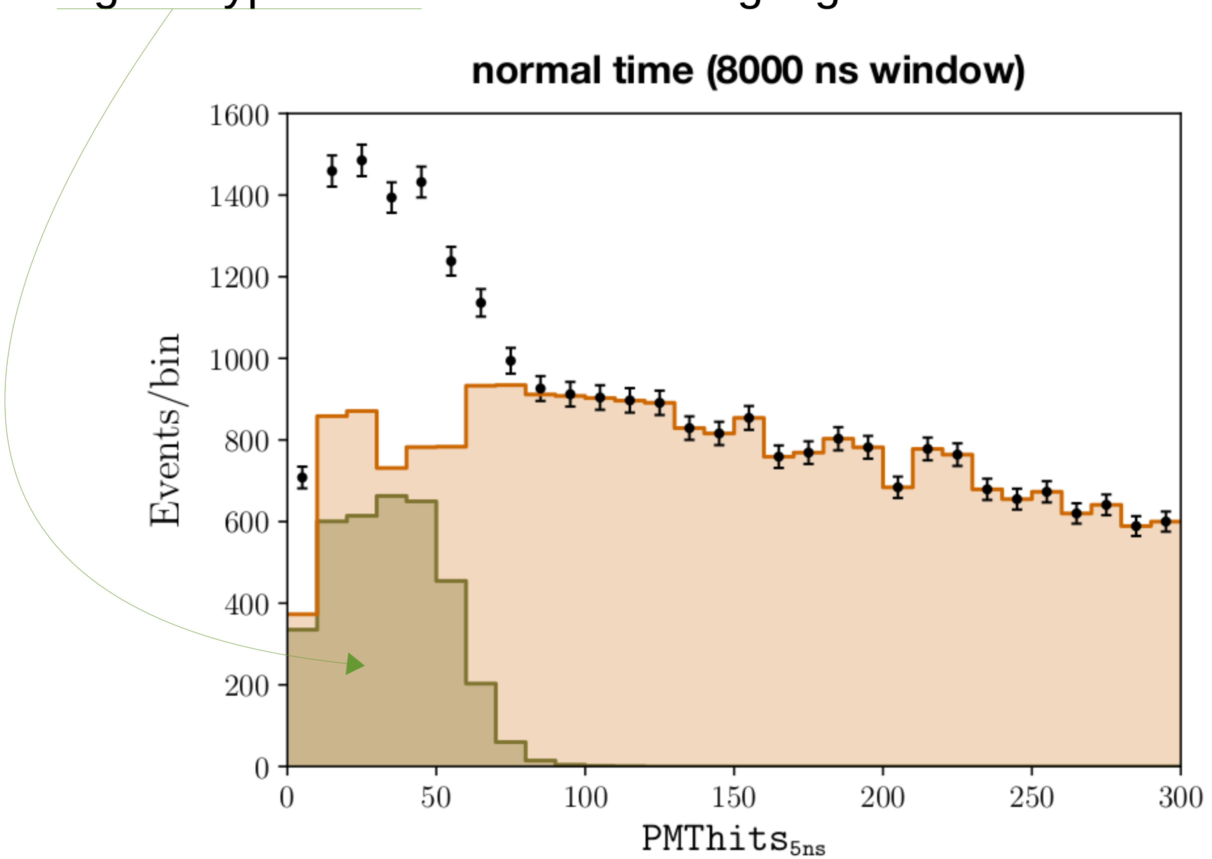




3 late time
(200 ns each)

Basic analysis idea

A signal hypothesis is formed using high-statistics normal time data

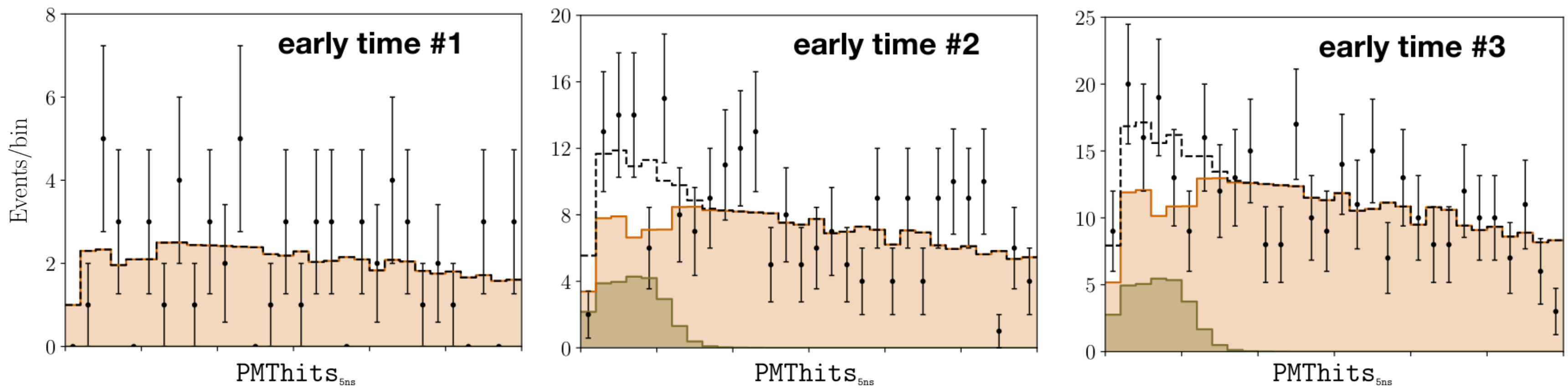


black - data
green - a signal hypothesis
orange - background

signal+background = data (in normal time)

Basic analysis idea (cont.)

Compare this hypothesis to data in early and late times, noting that:

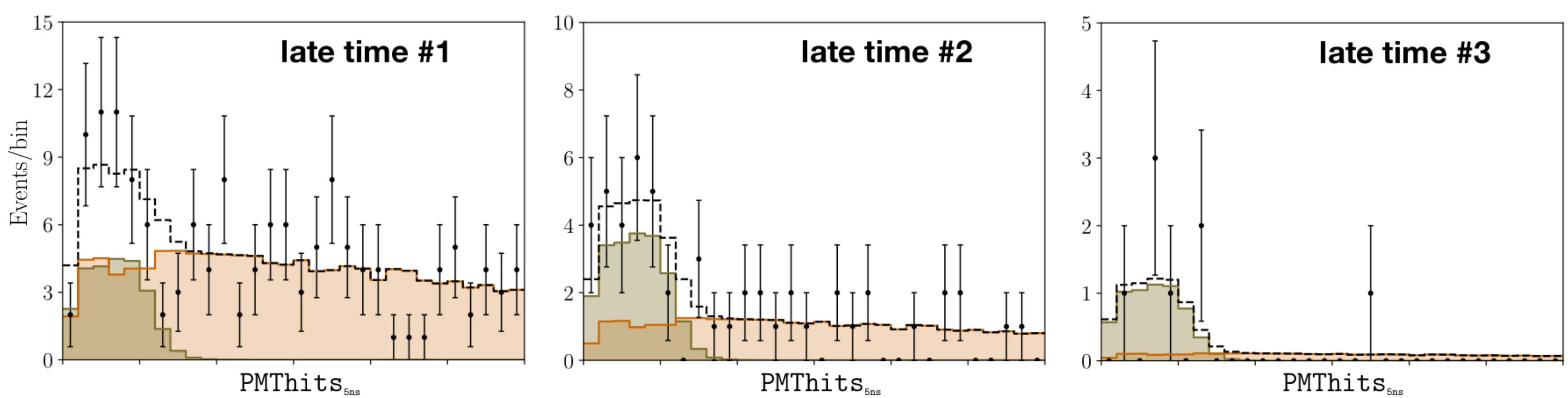


3 early time
(200 ns each)

(1) the underlying (true) signal and background shapes remain constant over the time scales considered.

(2) the background normalization can be determined using a region where no signal is expected.

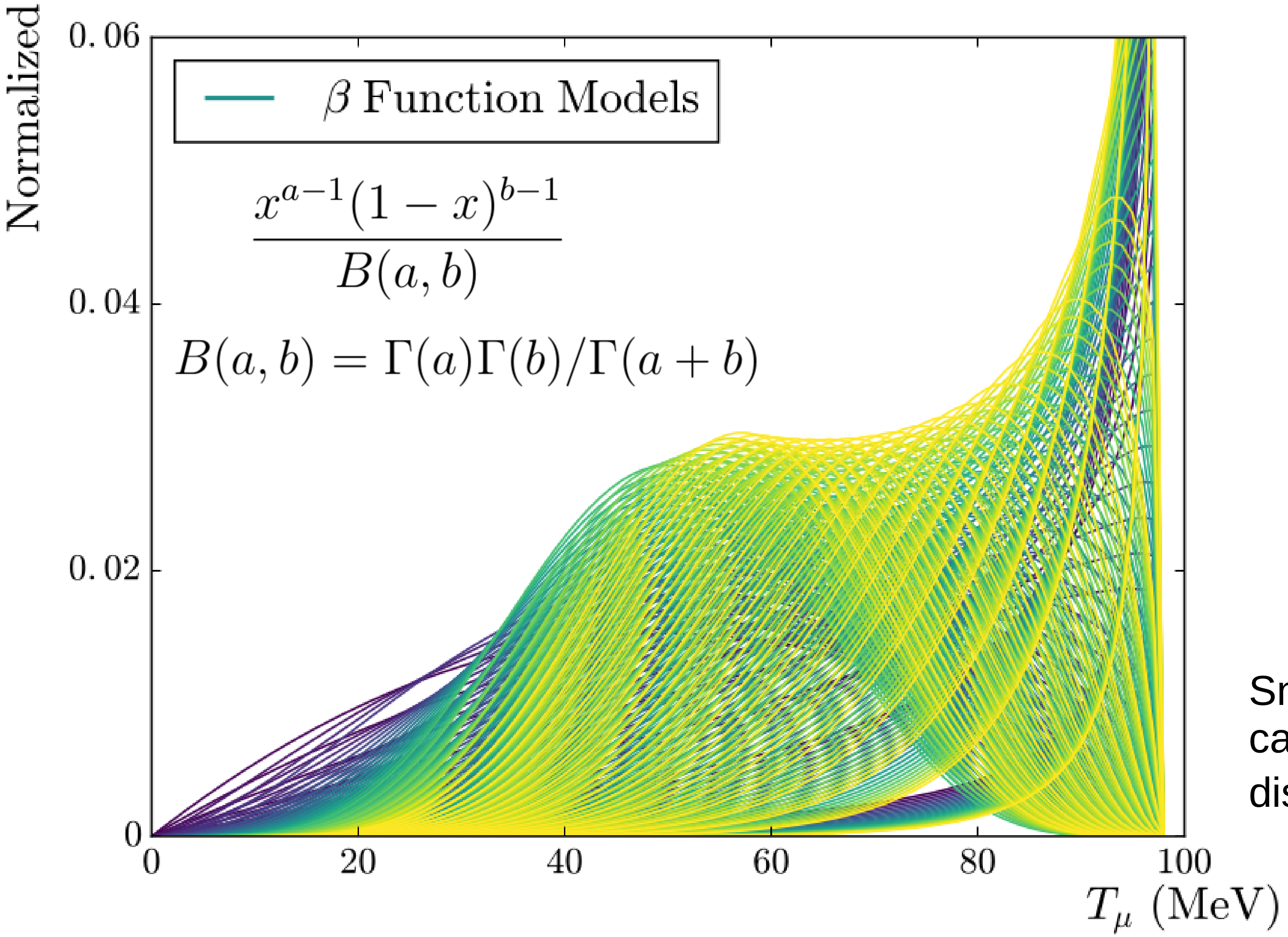
black - data
green - a signal hypothesis
orange - background



3 late time
(200 ns each)

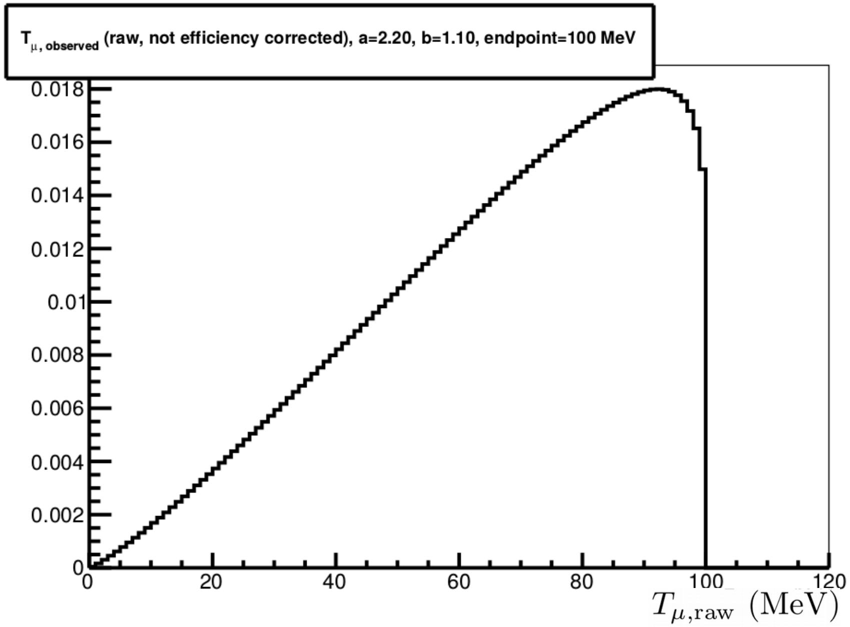
Generating signal candidates

Two-parameter shape templates (based on a beta distribution):
normalization and **endpoint** (95-115 MeV)



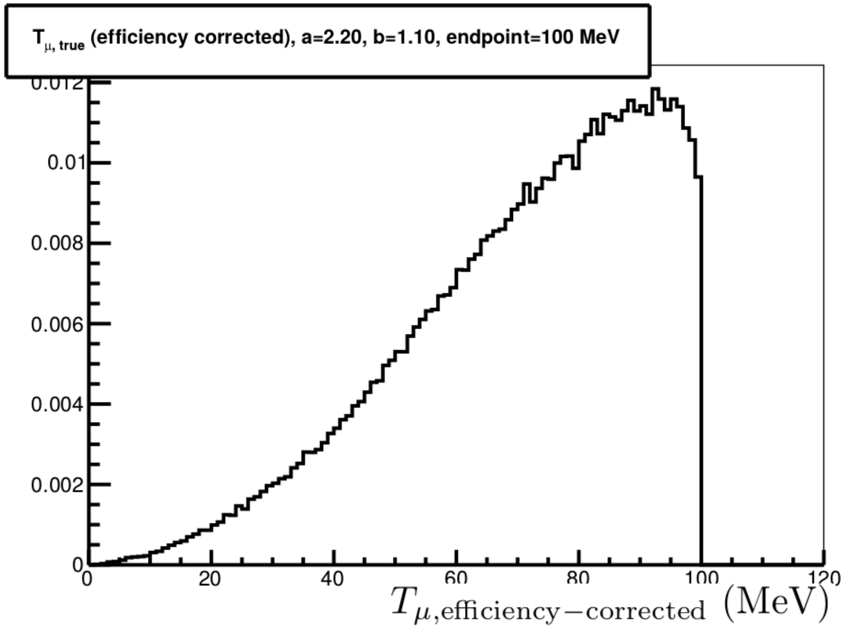
Small subset of shape candidates for the KDAR T_μ distribution.

From *true* T_μ to PMThits$_{5ns}$

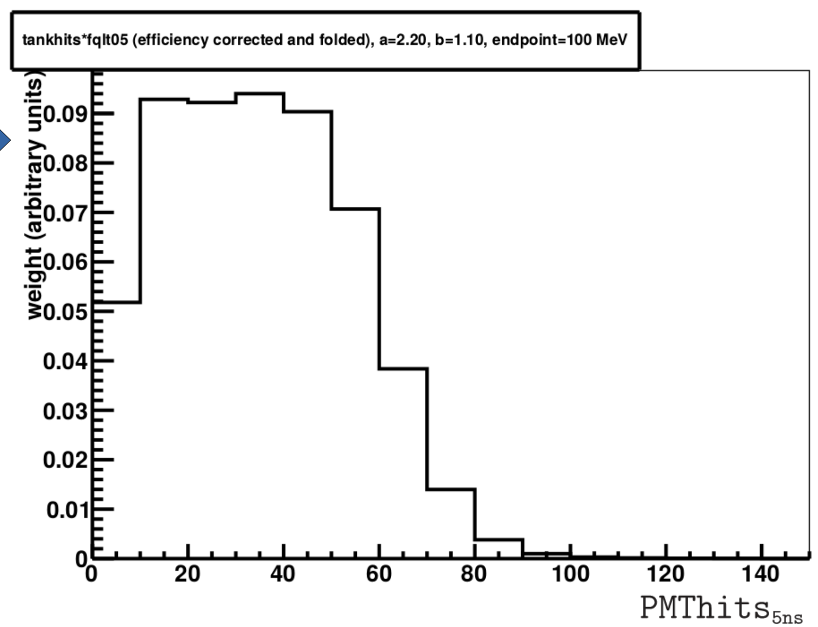


Candidate signal template
(“true” T_μ distribution)

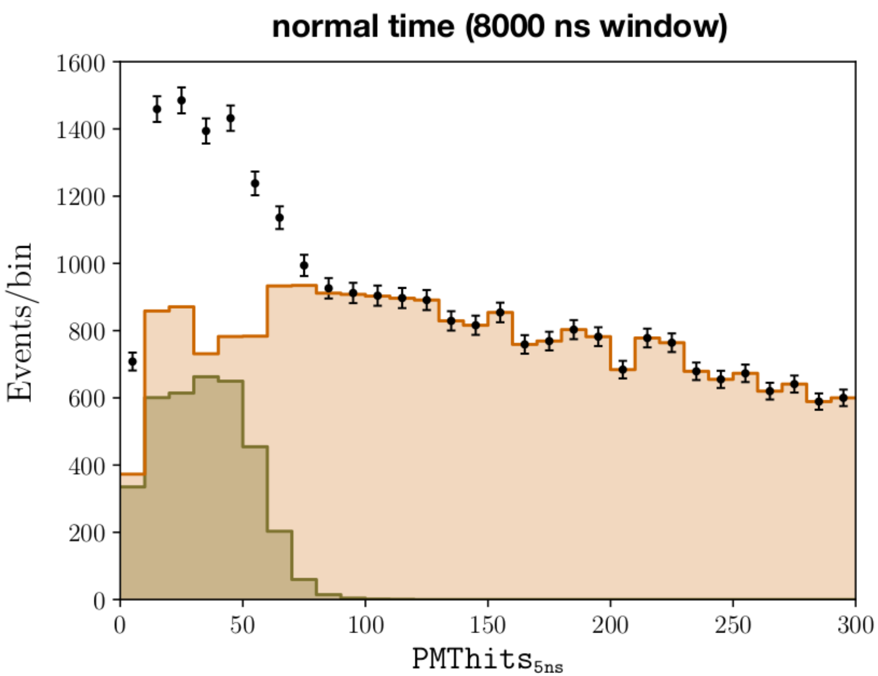
Efficiency correction

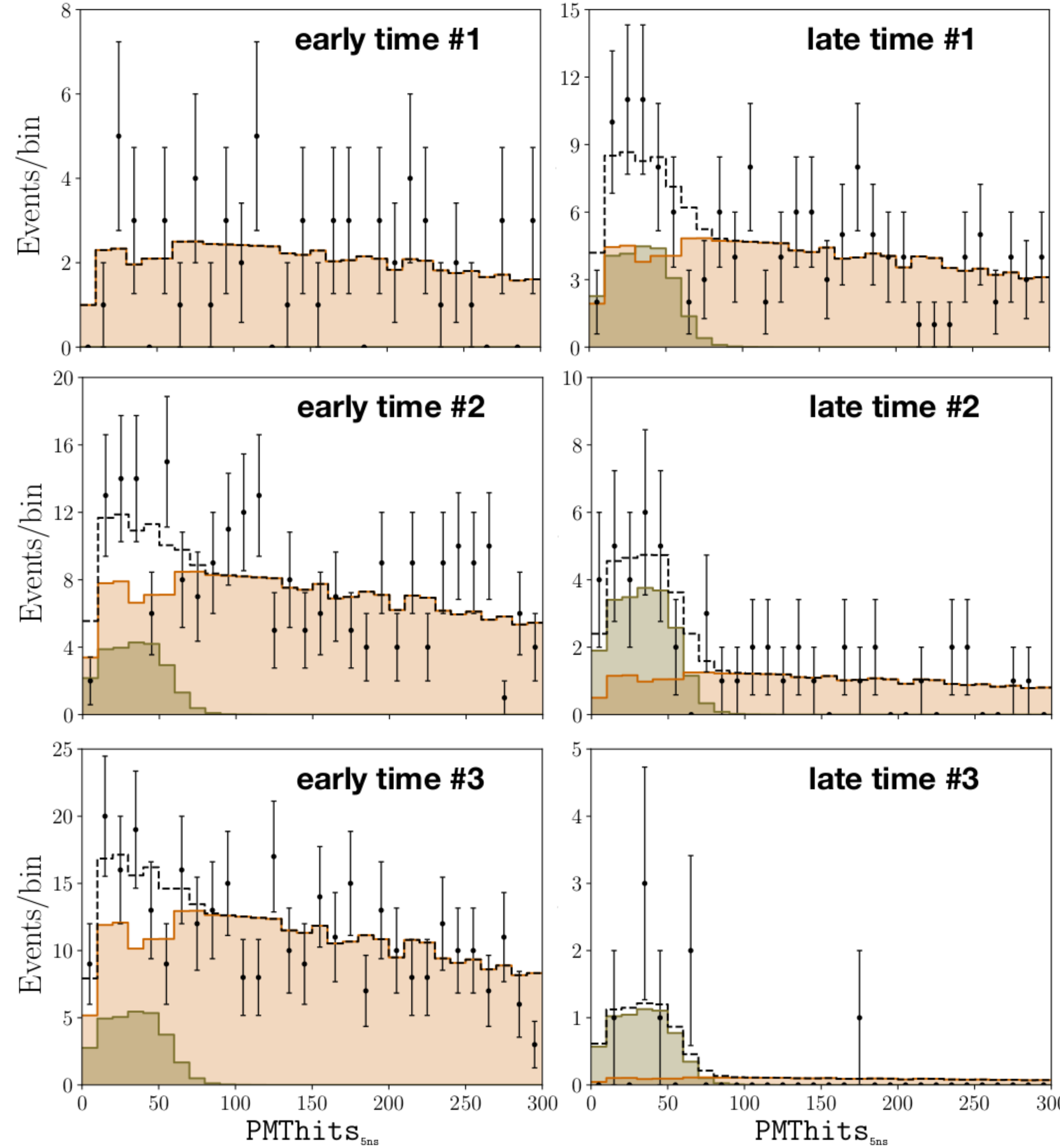


Folding



Best fit spectra



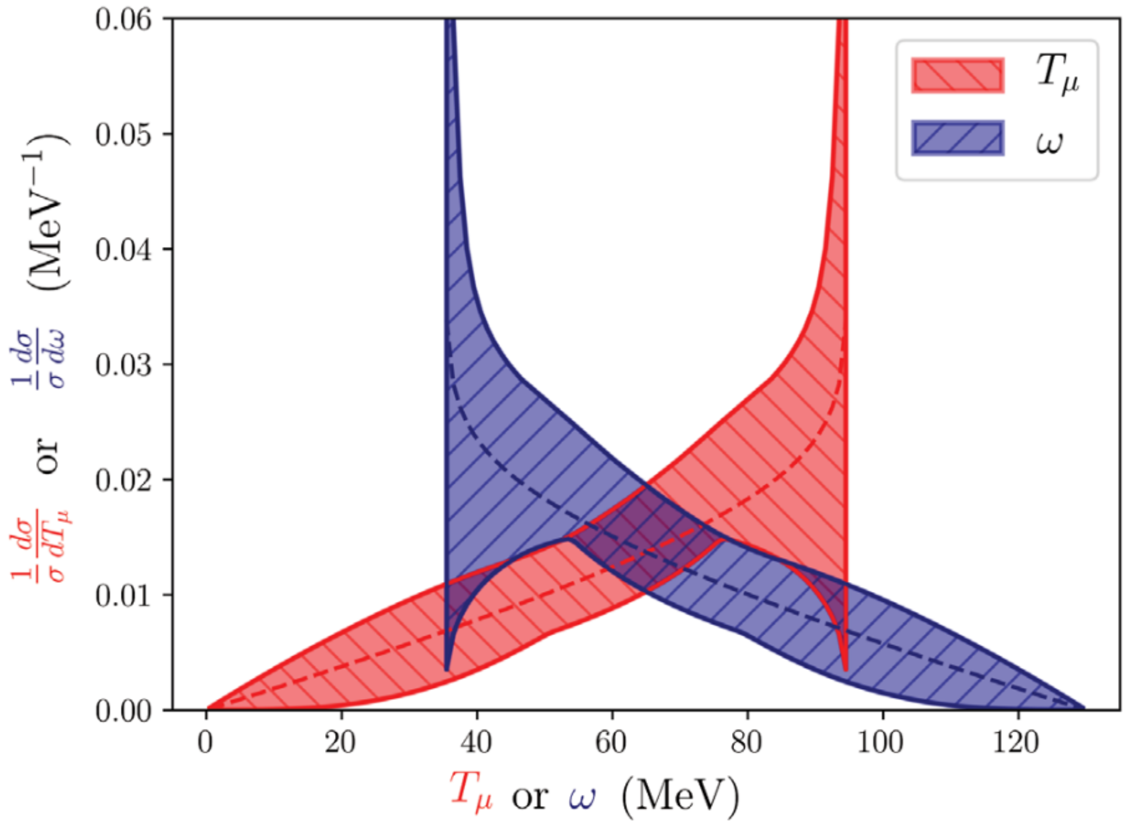


black - data
green - a signal hypothesis
orange - background

early & **late time** windows: 200 ns

Results

Endpoint = 95 MeV (best fit)



Shape-only differential cross section measurement in T_μ and ω (fully correlated) with 1σ error bands.

Statistical uncertainties dominant.

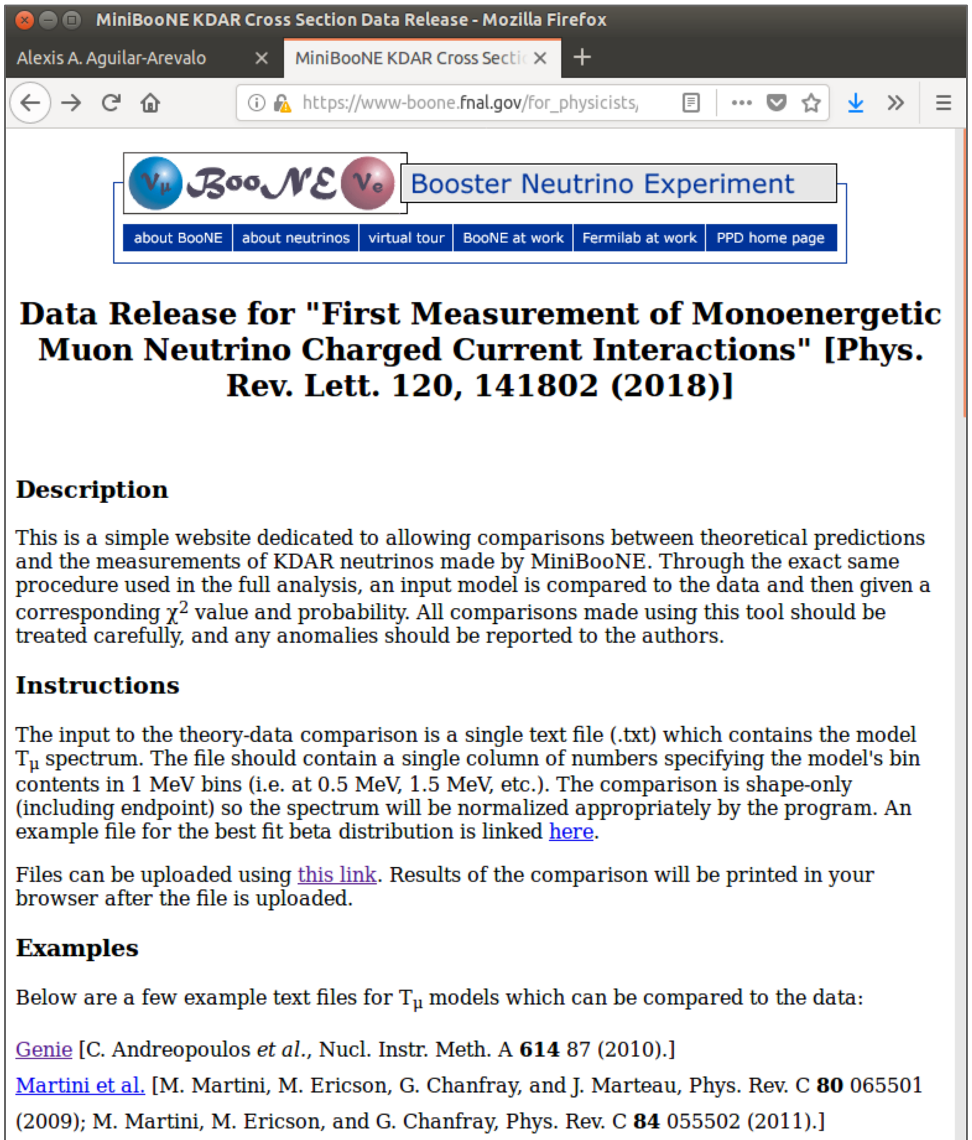
Total ν_μ CC Xsec at Eν = 236 MeV:

$$\sigma = (2.7 \pm 0.9 \pm 0.8) \times 10^{-39}\ \mathrm{cm}^2/\mathrm{neutron}$$

Measurement unc. flux unc.

Data release

https://www-boone.fnal.gov/for_physicists/data_release/kdar/


MiniBooNE KDAR Cross Section Data Release - Mozilla Firefox

Alexis A. Aguilar-Arevalo | MiniBooNE KDAR Cross Secti

https://www-boone.fnal.gov/for_physicists/

Booster Neutrino Experiment

about BooNE | about neutrinos | virtual tour | BooNE at work | Fermilab at work | PPD home page

Data Release for "First Measurement of Monoenergetic Muon Neutrino Charged Current Interactions" [Phys. Rev. Lett. 120, 141802 (2018)]

Description

This is a simple website dedicated to allowing comparisons between theoretical predictions and the measurements of KDAR neutrinos made by MiniBooNE. Through the exact same procedure used in the full analysis, an input model is compared to the data and then given a corresponding χ^2 value and probability. All comparisons made using this tool should be treated carefully, and any anomalies should be reported to the authors.

Instructions

The input to the theory-data comparison is a single text file (.txt) which contains the model T_μ spectrum. The file should contain a single column of numbers specifying the model's bin contents in 1 MeV bins (i.e. at 0.5 MeV, 1.5 MeV, etc.). The comparison is shape-only (including endpoint) so the spectrum will be normalized appropriately by the program. An example file for the best fit beta distribution is linked here.

Files can be uploaded using this link. Results of the comparison will be printed in your browser after the file is uploaded.

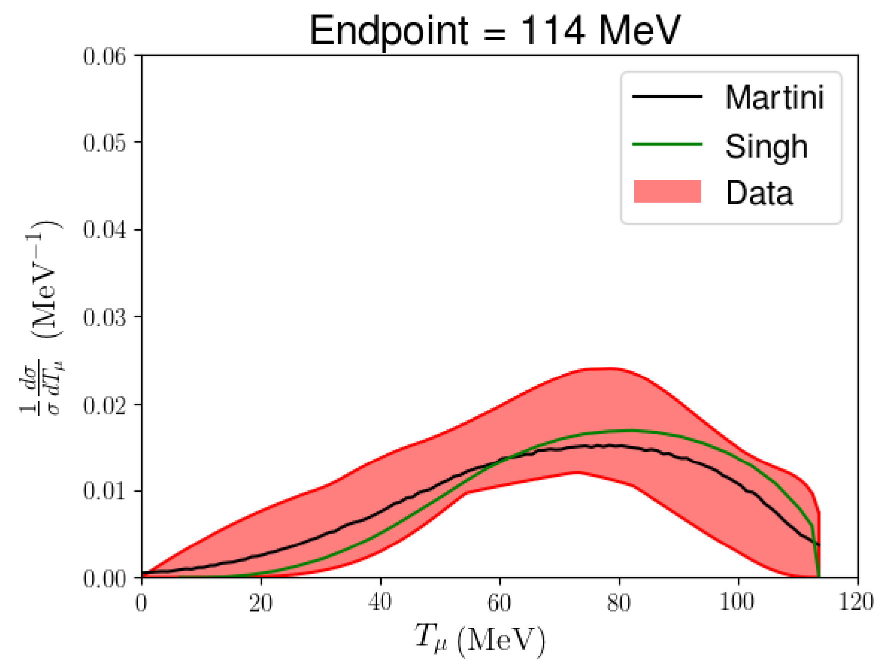
Examples

Below are a few example text files for T_μ models which can be compared to the data:

Genie [C. Andreopoulos *et al.*, Nucl. Instr. Meth. A **614** 87 (2010).]

Martini et al. [M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **80** 065501 (2009); M. Martini, M. Ericson, and G. Chanfray, Phys. Rev. C **84** 055502 (2011).]

Allows comparison between theoretical models for KDAR T_μ to MB data.



Example: Comparison to Martini and Singh models.

Summary and outlook

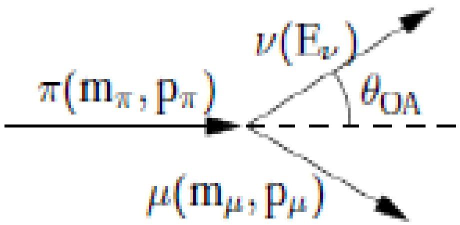
- Using neutrinos, MiniBooNE performed the *first known-energy, weak-interaction-only probe of the nucleus to yield a measurement of ω*, a quantity thus far only accessible through electron scattering.
- Result can be used to calibrate neutrino-nucleus interactions in the ~O(100) MeV region.
- First step towards full exploitation of the 236 MeV KDAR neutrino for other fundamental physics.
- Near future
  - MicroBooNE (runnig since 2015) will measure the same KDAR ν's.
  - J-PARC Sterile Neutrino Search at the J-PARC SNS will collect ~10-20k KDAR events/year on Carbon.
- Other uses of KDAR ν's: neutrino oscillation experiments, DM-annihilation signature, s-quark contribution to nucleon spin, ...

Thank you for your attention!

A.A. Aguilar-Arevalo et al.,Phys.Rev.Lett. **120**, 141802 (2018), arXiv:1801.03848 [hep-ex].

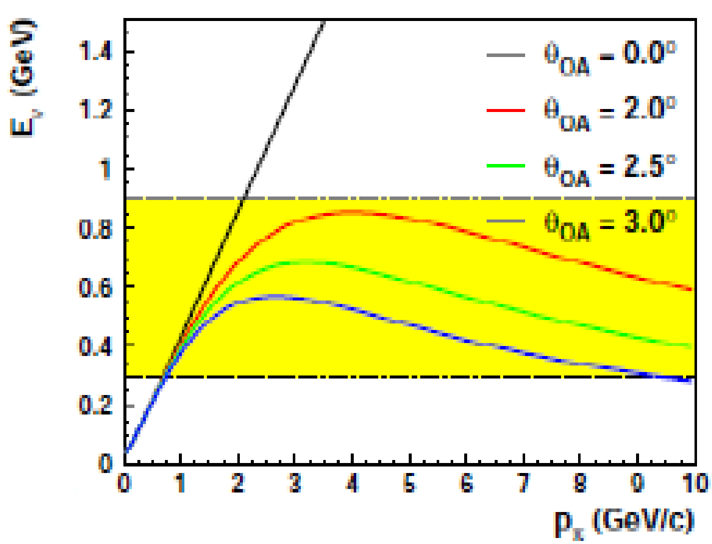
Backups

Experimentos “fuera del eje”

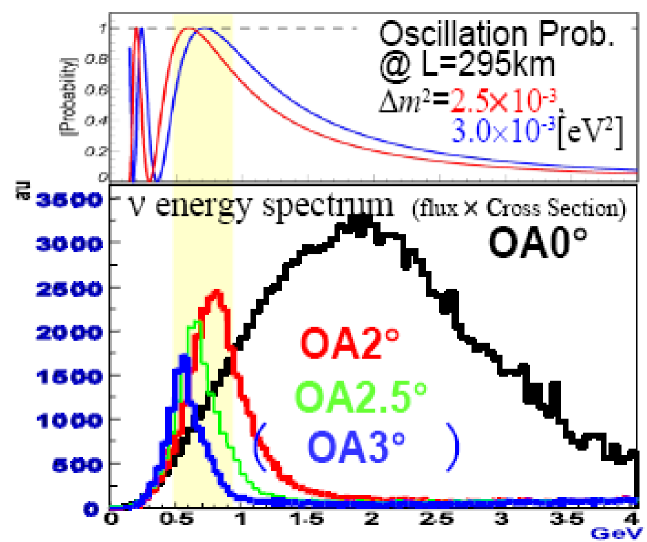


$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta_{OA})}$$

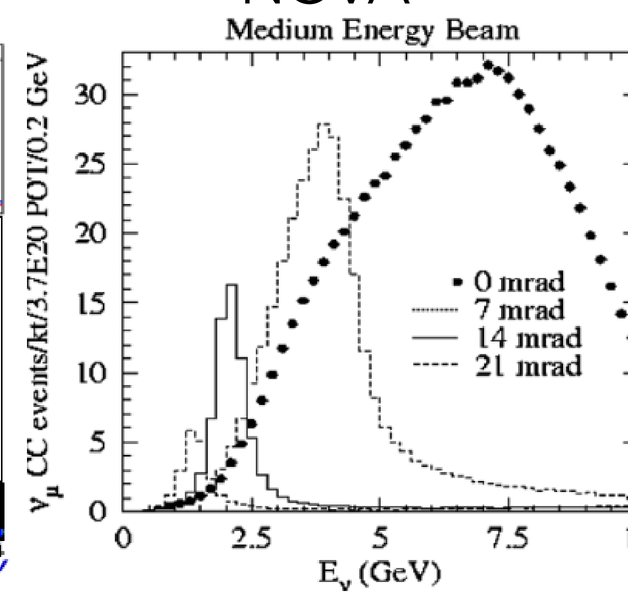
- haces enfocados con cornos magnéticos
- ν's a un ángulo θ≠0 respecto al eje.
- Espectro de E_ν pseudo-monocromático
- menor flujo, pero menor bkgd.
- NuMI-MiniBooNE: un ejemplo arXiv:0809.2447



T2K

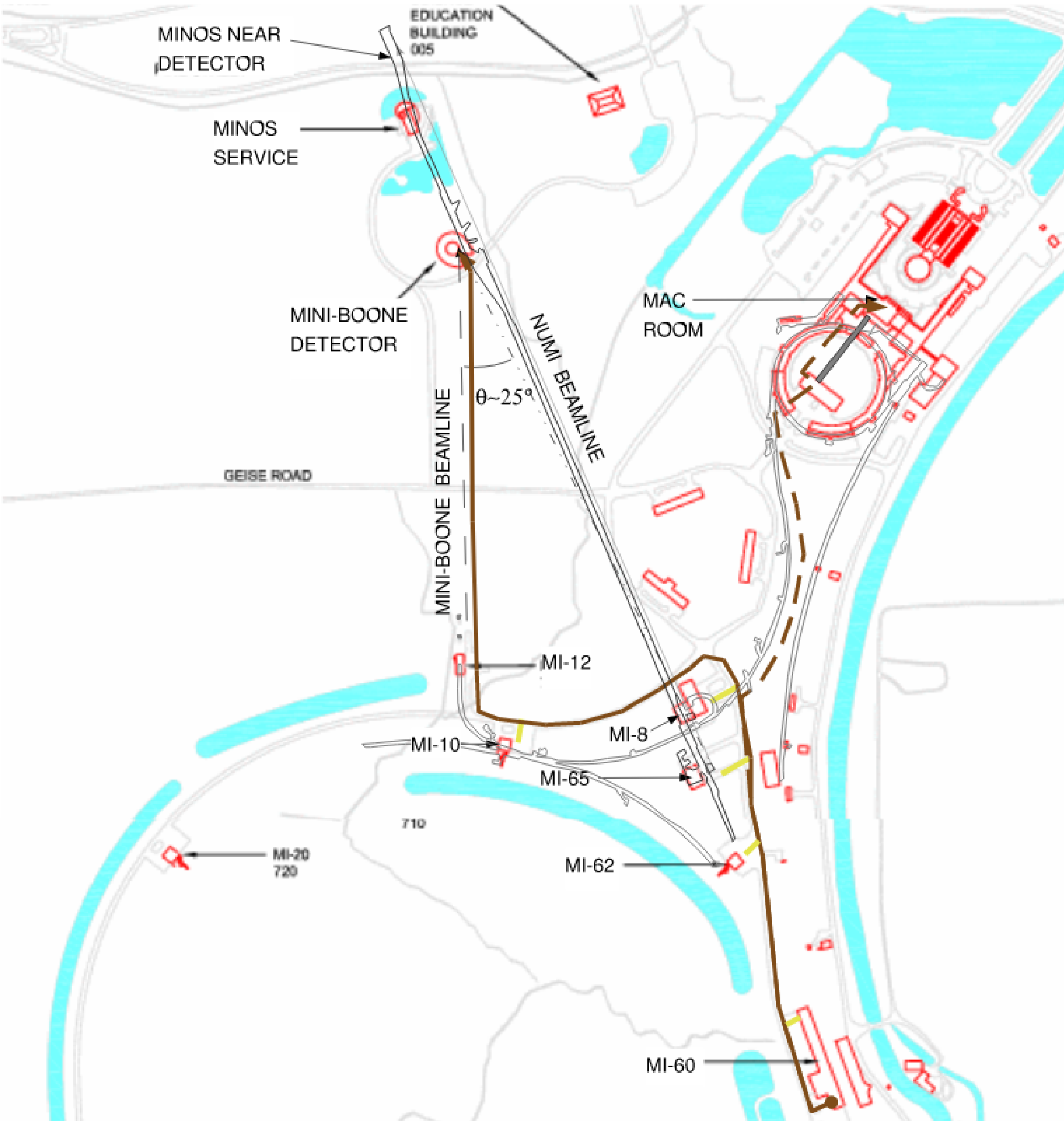


NOvA

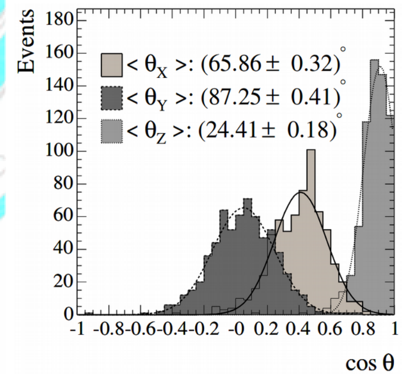


NuMI-MiniBooNE

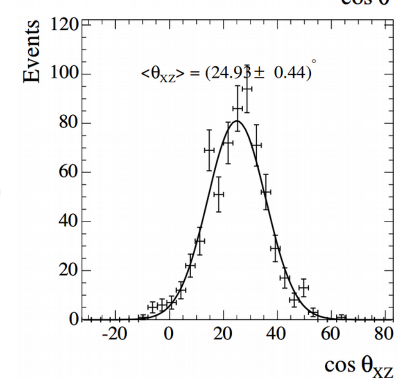
ca. 2005, LE10 neutrino configuration



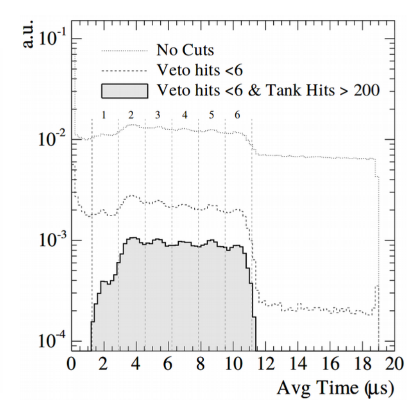
High energy events in MiniBooNE (from decay pipe)



Angular distributions

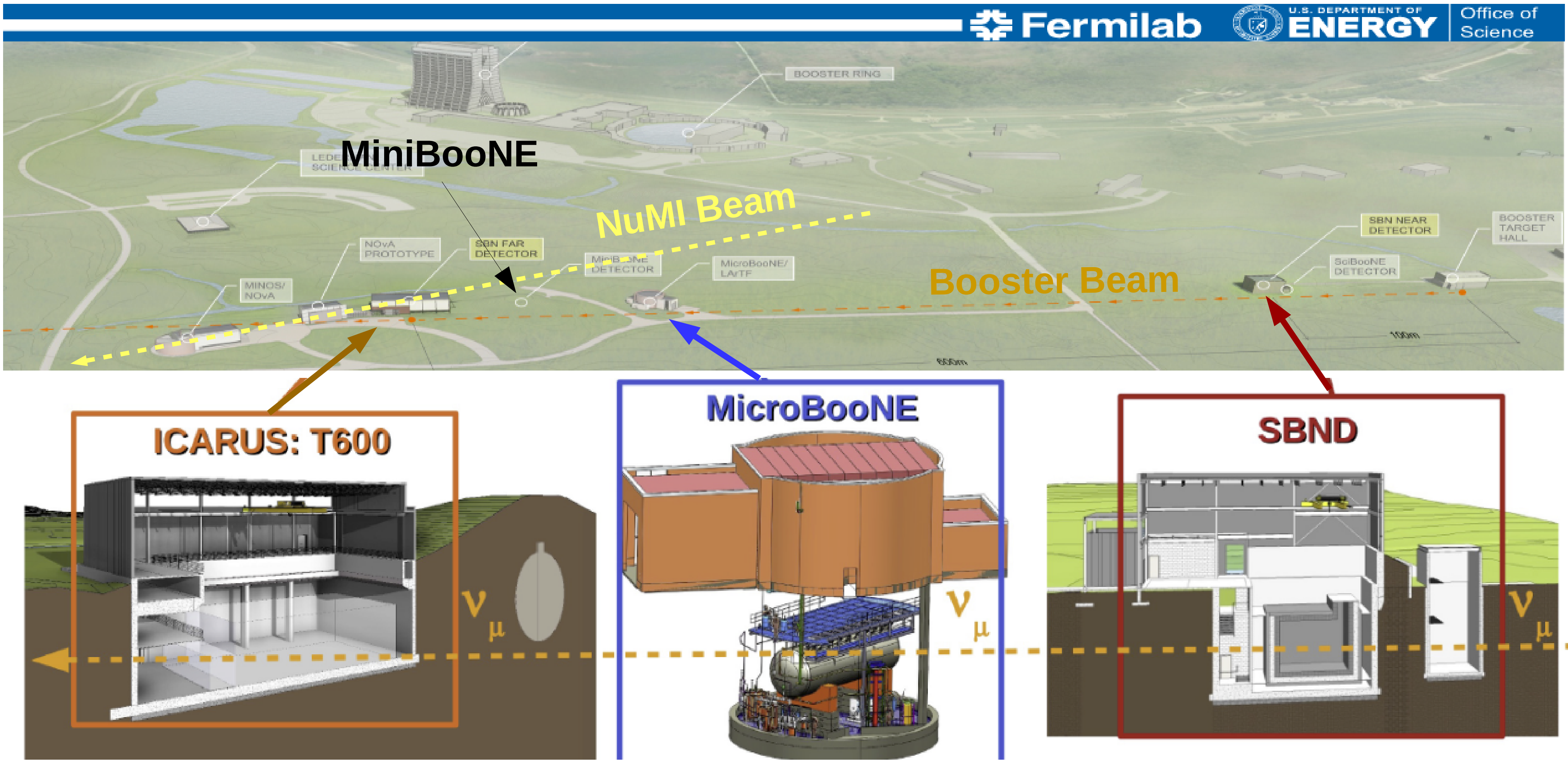


Horizontal projection angle



Timing

Short Baseline Neutrino (SBN) program



- Motivated by LSND/MiniBooNE to study ν oscillations. To begin operations in 2018.
- Short Baseline Near Detector (**SBND**) → Ideal for beam dump sub-GeV DM search.