Recent MiniBooNE Results:

First Measurement of Monoenergetic Muon Neutrino Charged Current Interactions
and
A Search for Vector Portal Dark Matter

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May 31, 2018

for the MiniBooNE Experiment

UNIVERSITY OF MICHIGAN

SPITZ GROμP

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Editors' Suggestion Featured in Physics

First Measurement of Monoenergetic Muon Neutrino Charged Current Interactions

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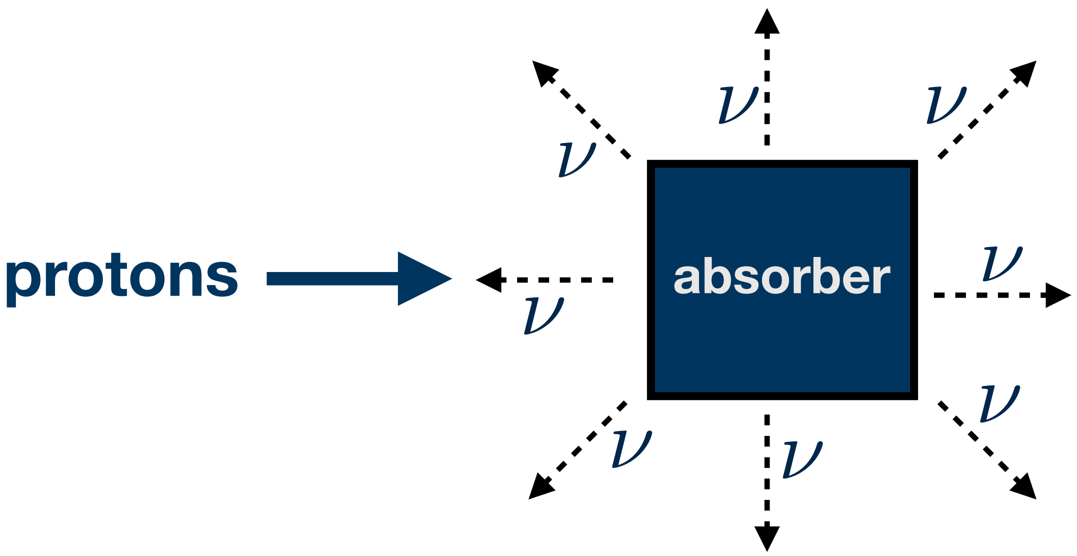
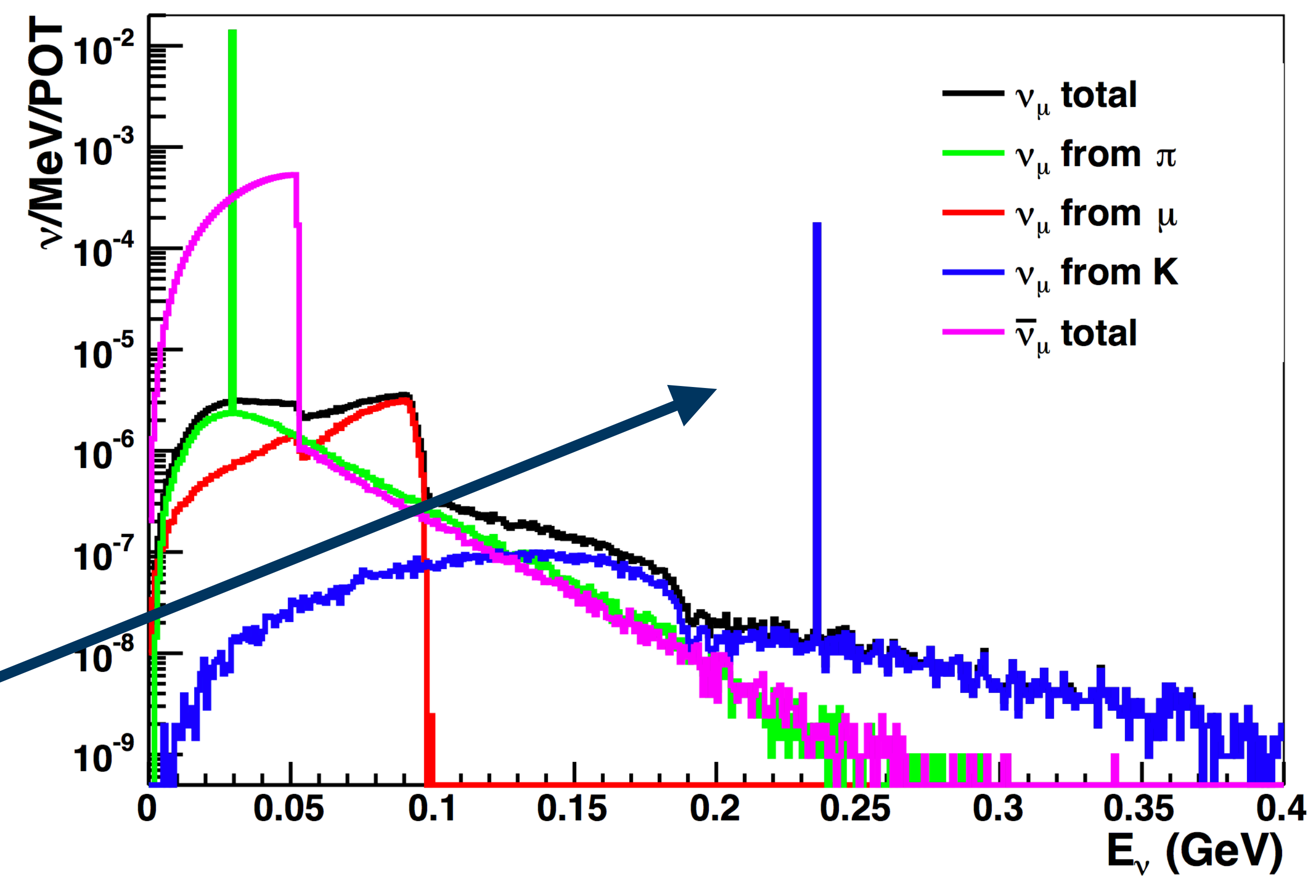
KDAR@MiniBooNE

Kaon Decay-at-Rest (KDAR) Neutrinos



ν_μ flux from the J-PARC spallation neutron facility

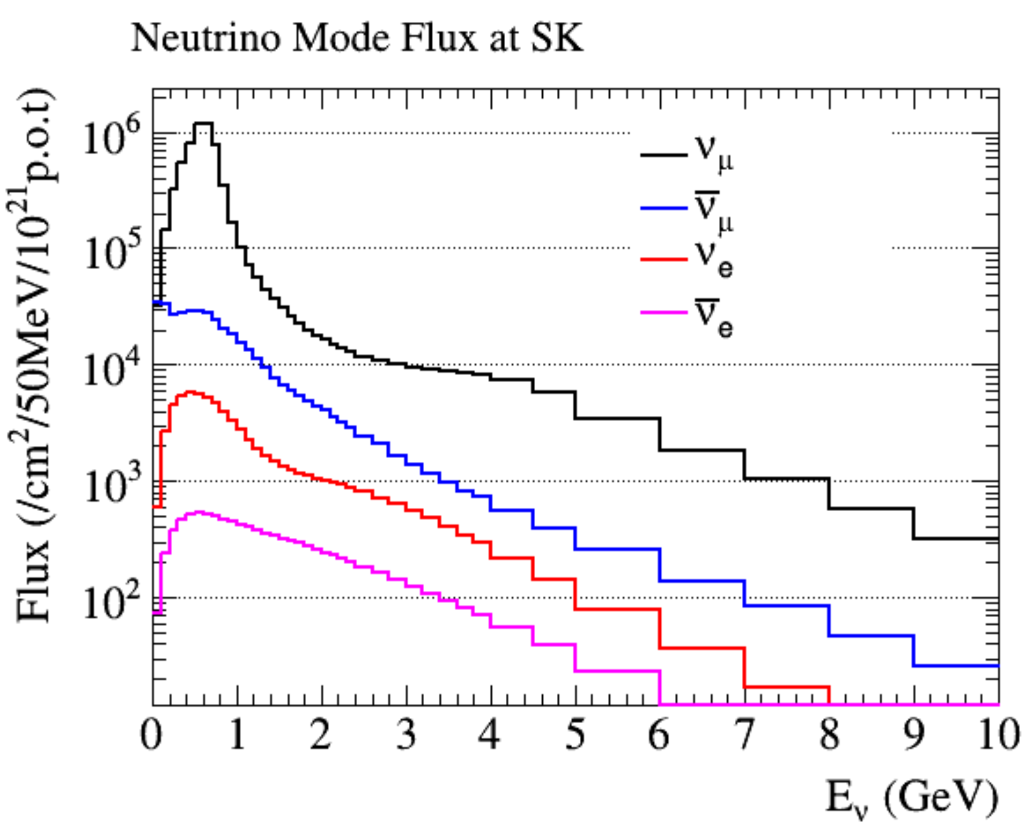


When a kaon decays at rest it produces a monoenergetic muon neutrino at 236 MeV 64% of the time.

$$K^+ \to \mu^+ \nu_\mu \quad [\mathrm{BR} = 64\%]$$

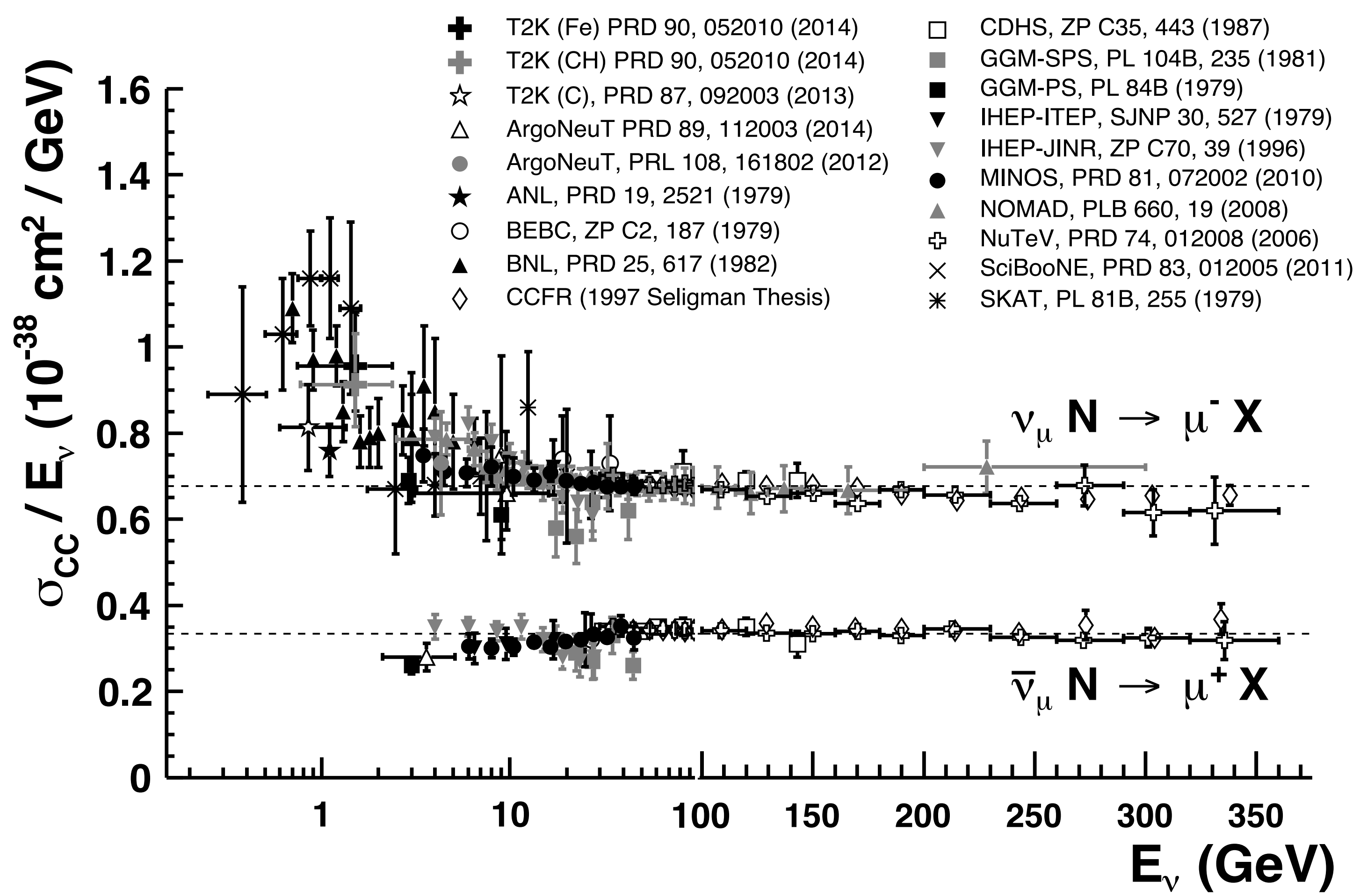
Cross Sections

Our knowledge of cross sections at low energies is not great.



T2K flux (unoscillated) peaks below 1 GeV.

CC Inclusive Cross Sections



K. Abe *et al.* (T2K Collaboration), Phys. Rev. D **96**, 092006 (2017)

C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C **40** 100001 (2016)

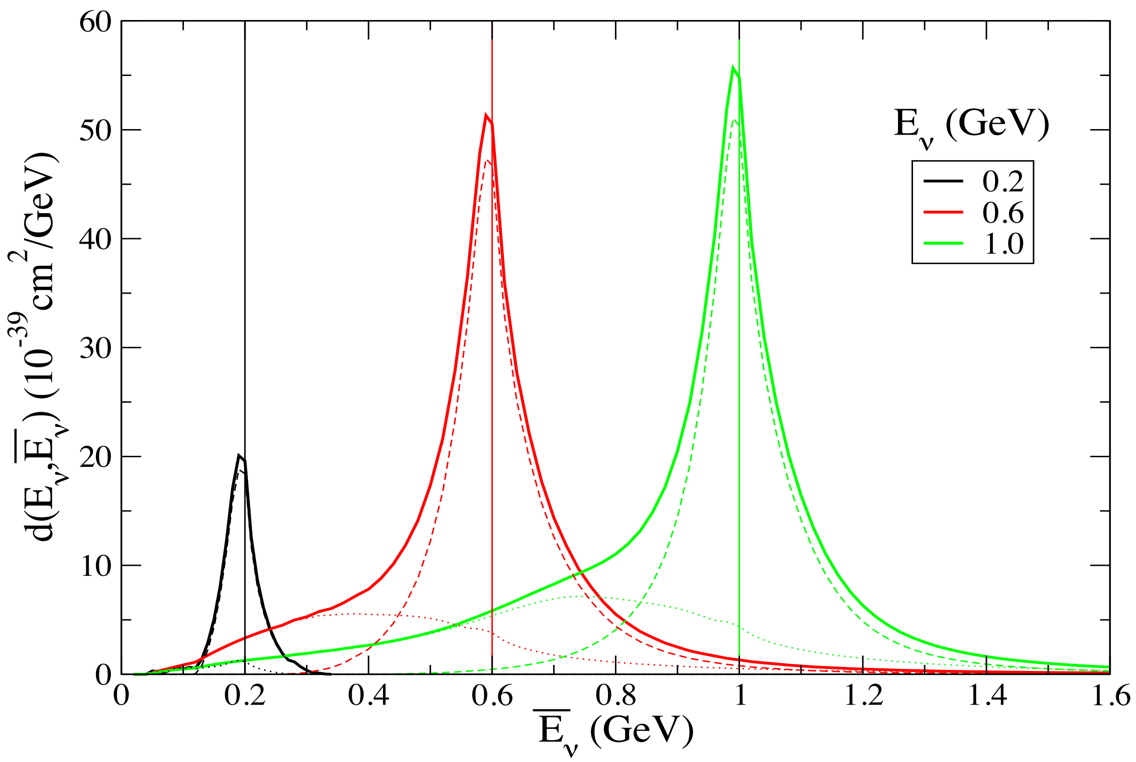
Energy Reconstruction

Neutrino energy reconstruction is complicated by:

- Invisible particles
- Detector thresholds
- Complicated final states

Solution: *Use KDAR neutrinos to benchmark energy reconstruction.*

Neutrino energy smearing for electron-only reconstruction.



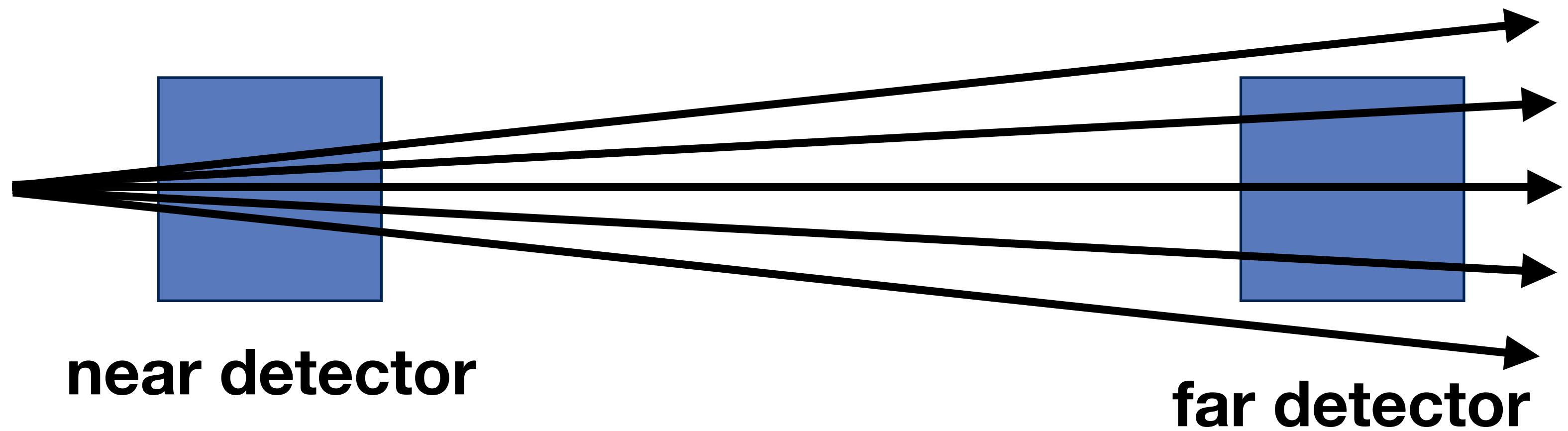
vertical lines = true energy
curves = reconstructed energy

M. Martini *et al.*, Phys. Rev. D **87**, 013009 (2013)

Oscillations

Near and far fluxes are inherently different…

…need cross section knowledge!



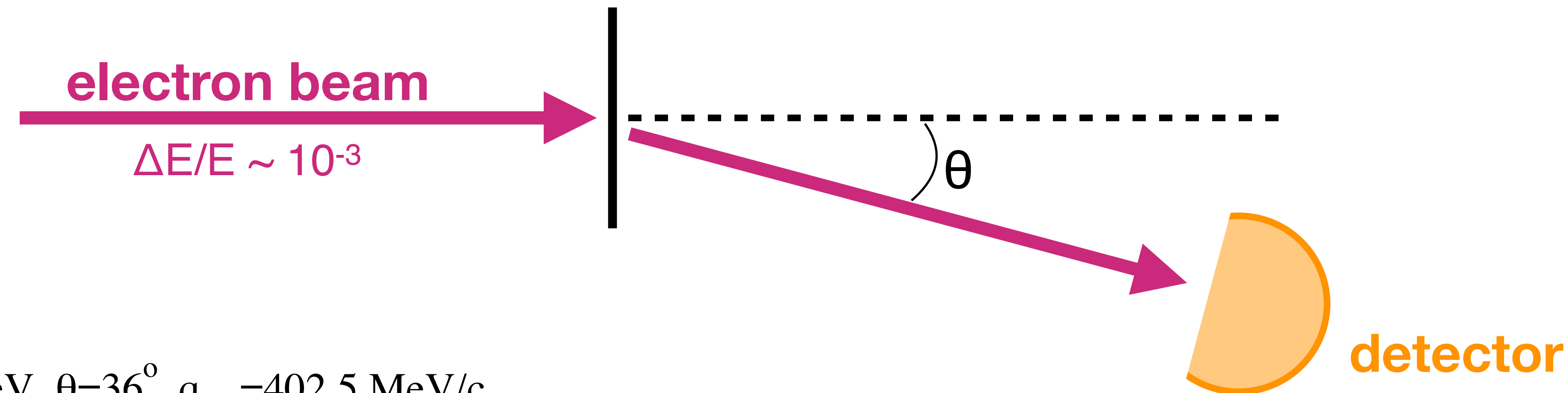
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{\text{GeV}}{\text{eV}^2\ \text{km}}\right)$$

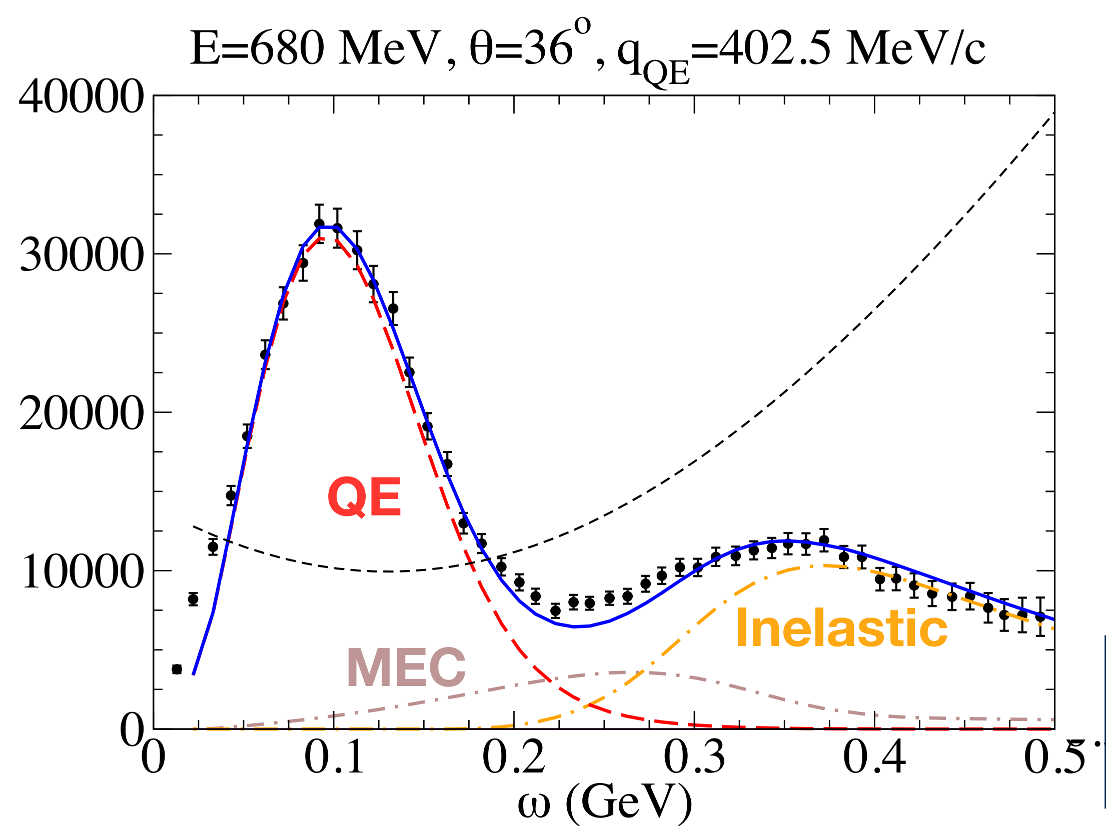
$$\frac{\Delta E}{E} \approx 20\% \text{ is typical}$$

Two-neutrino oscillation probability

Oscillation probability depends on energy!

Probing the Nucleus





Electron scattering has been our primary tool for understanding the nucleus.

electron scattering on carbon

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

FERMILAB-PUB-17-195-ND-T

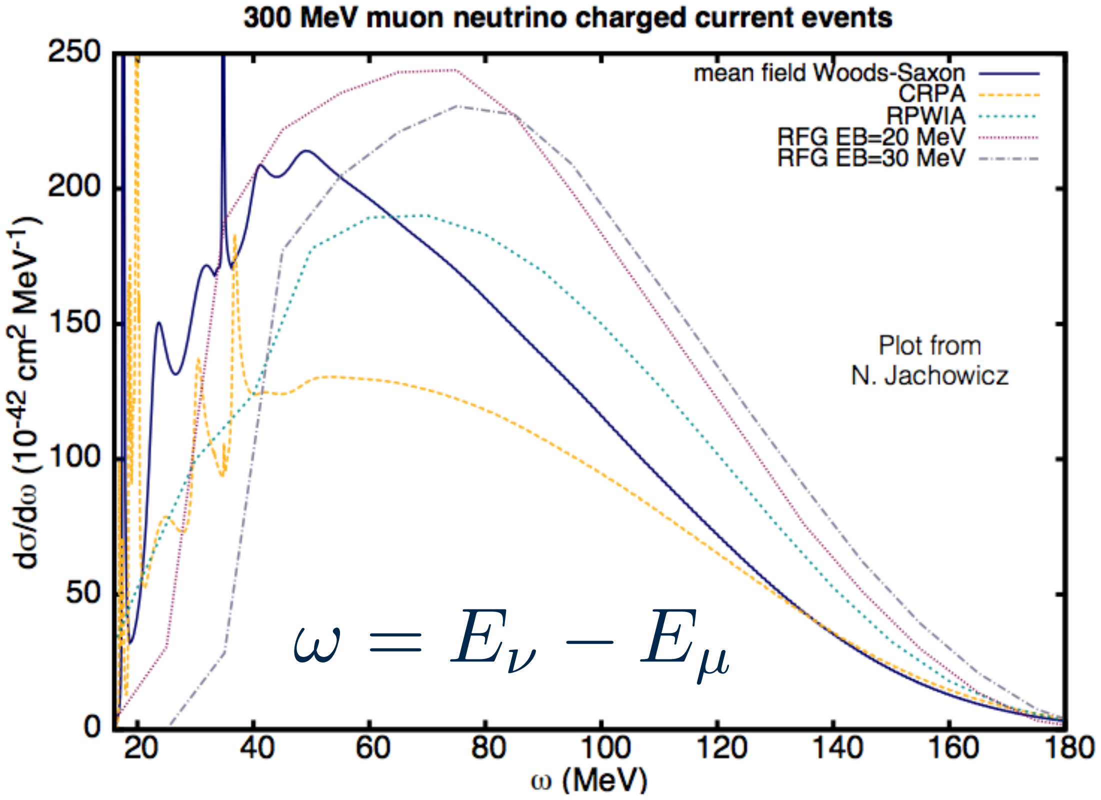
Probing the Nucleus

Which model of the nucleus, relevant to neutrinos, is correct?

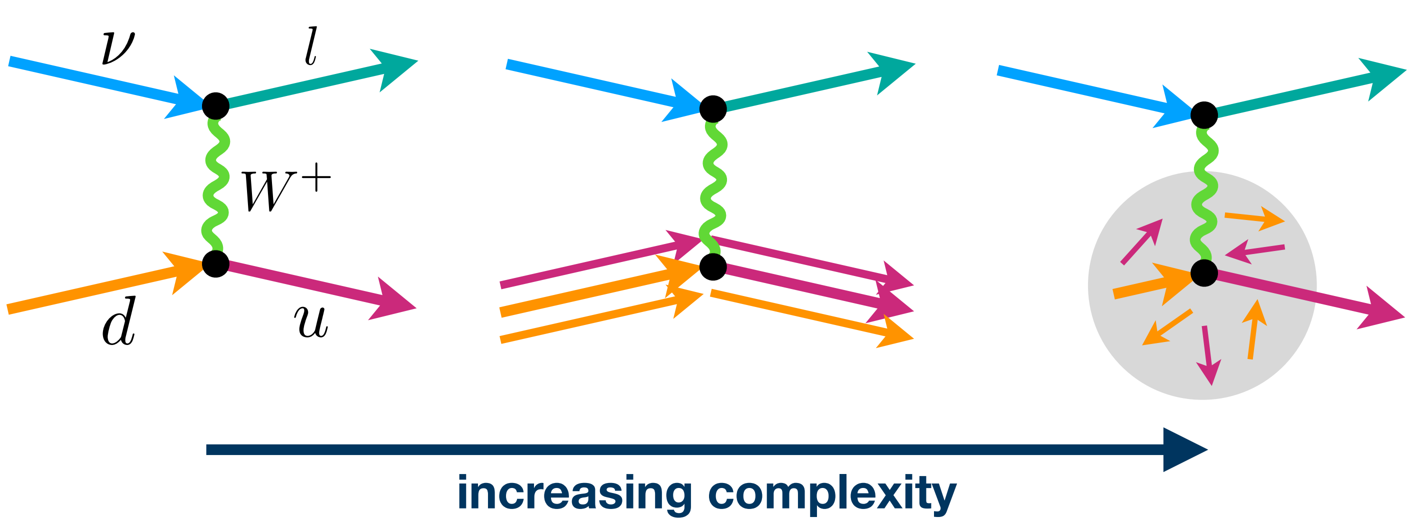
What is the correct way to treat the transition from on-nucleus to on-nucleon scattering?

How many final state neutrons are there as a function of energy transfer?

How large are the contributions of short-range correlations?



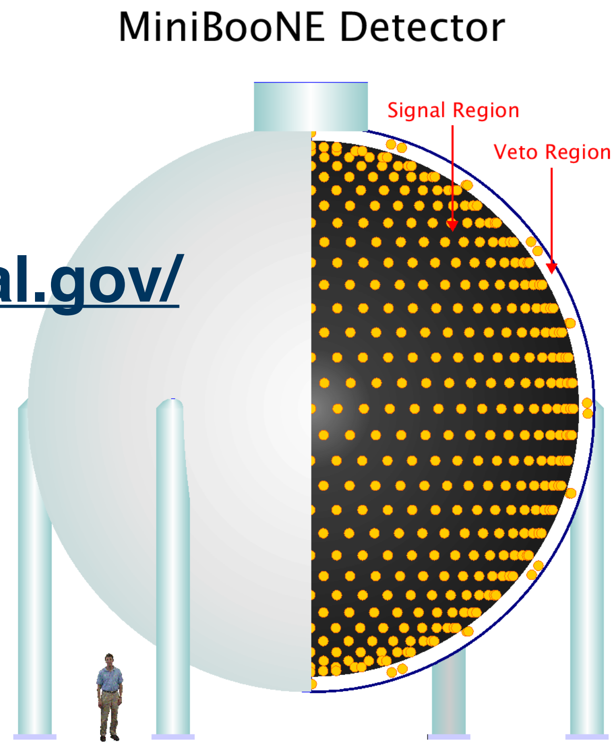
Can we do this measurement with neutrinos?

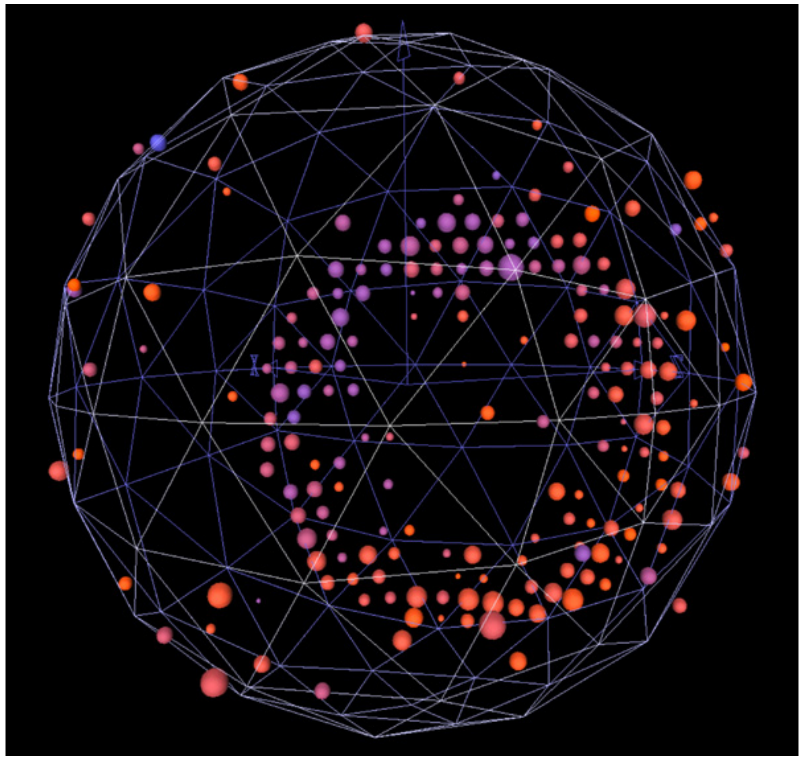


MiniBooNE

- Mineral oil detects scintillation and Cherenkov light in time using 1280 PMTs in the signal region and 240 PMTs in the veto region.
- MiniBooNE observes neutrinos from the BNB (on-axis) and NuMI (off-axis) neutrino sources at Fermilab.
- Taking data since 2002 — many oscillation, cross section, and exotic search results!

http://www-boone.fnal.gov/

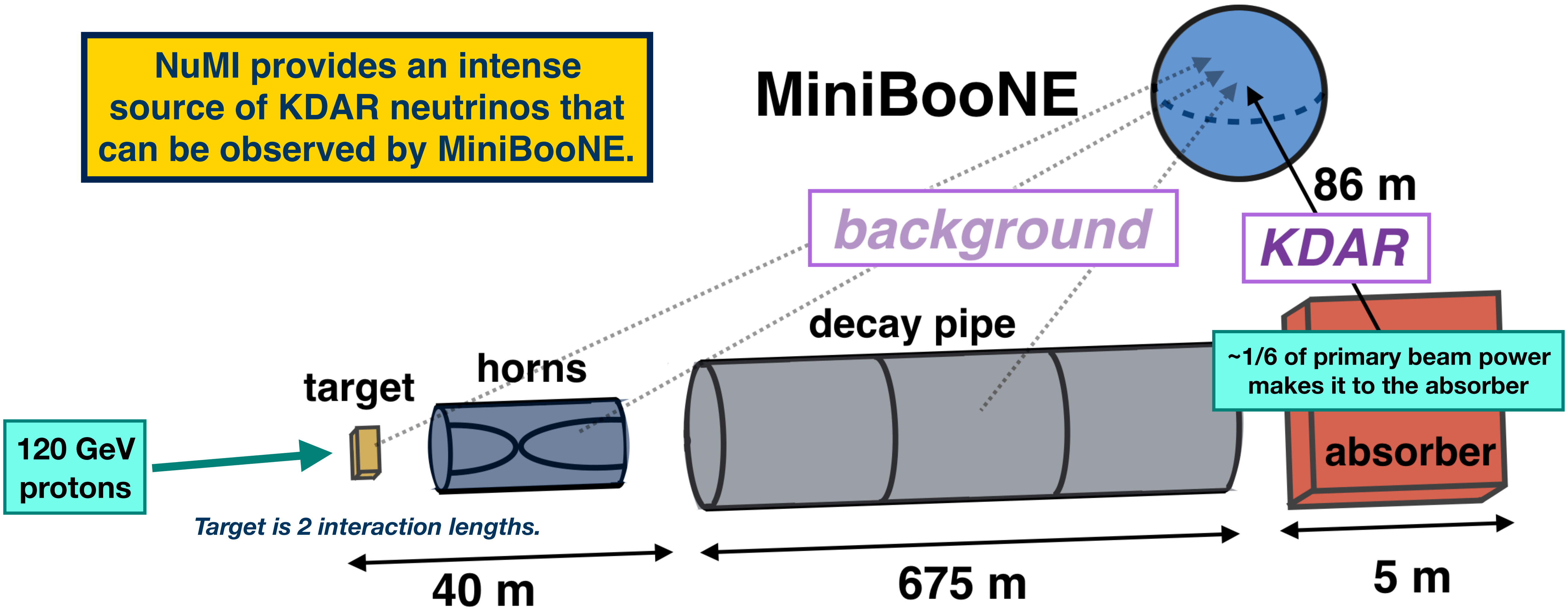




A typical muon in MiniBooNE

MiniBooNE and NuMI

NuMI provides an intense source of KDAR neutrinos that can be observed by MiniBooNE.



$$K^+ \to \mu^+ \nu_\mu$$

(at rest ➡ 236 MeV neutrino)

This analysis uses NuMI-LE antineutrino mode (2.62×10^{20} POT)

KDAR Events in MiniBooNE

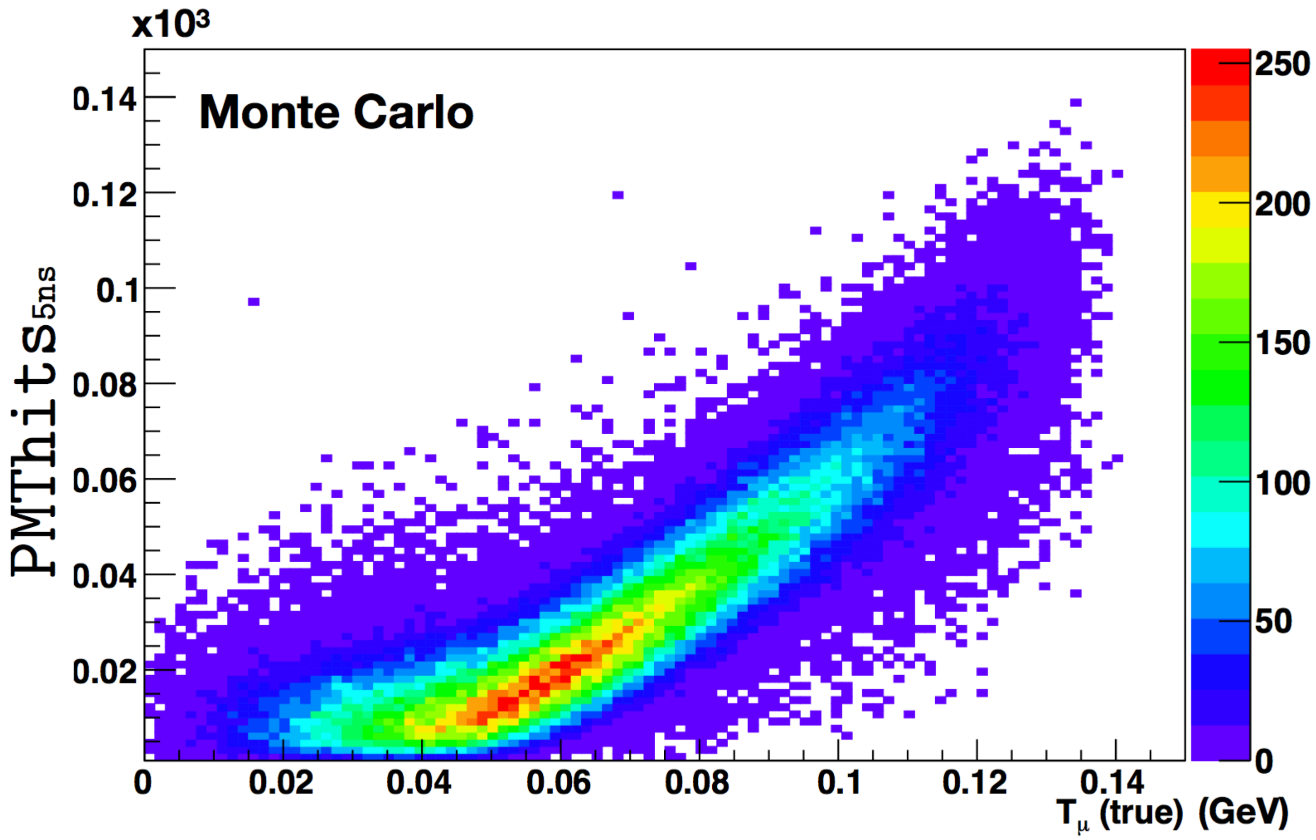
$$\nu_\mu \ {}^{12}\mathrm{C} \rightarrow \mu^- X$$

Use standard MiniBooNE muon neutrino selection:
two sub-events (muon + decayed electron), in fiducial volume, no veto activity.

PMThits$_{5ns}$ = (# of PMT hits) x (frac. of light det. in first 5 ns)

An attempt to isolate the muon Cherenkov light.

KDAR events produce muons with 0-120 PMThits$_{5ns}$.



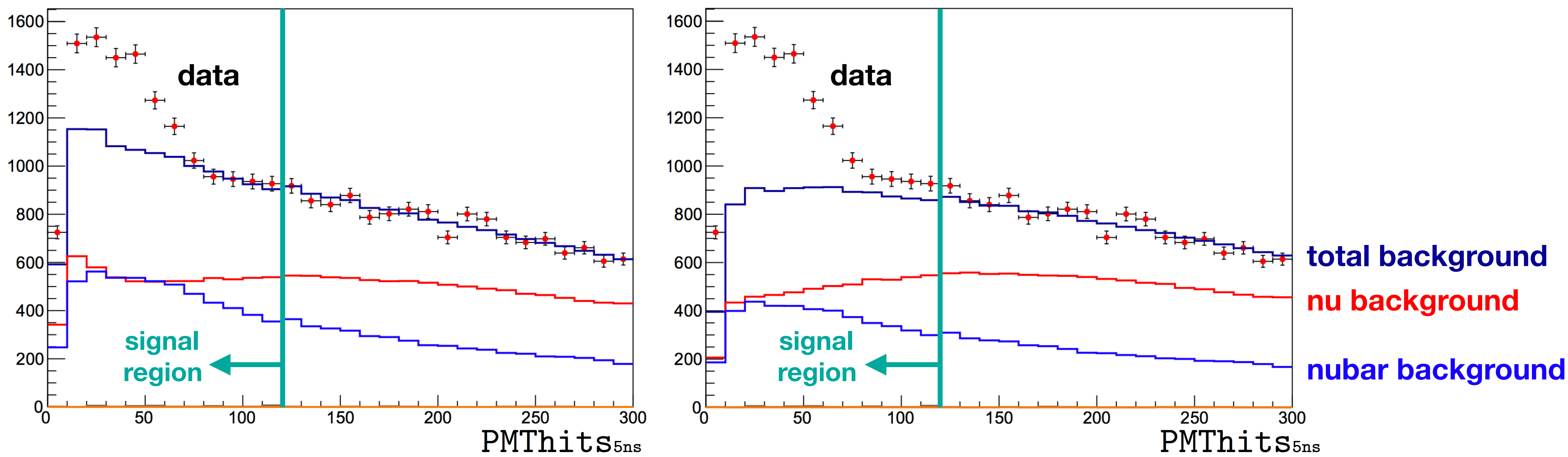
Cherenkov threshold for muons in mineral oil = 39 MeV

Challenge: Modeling Background

We observe an excess of events, but we want to be sure that it's real.

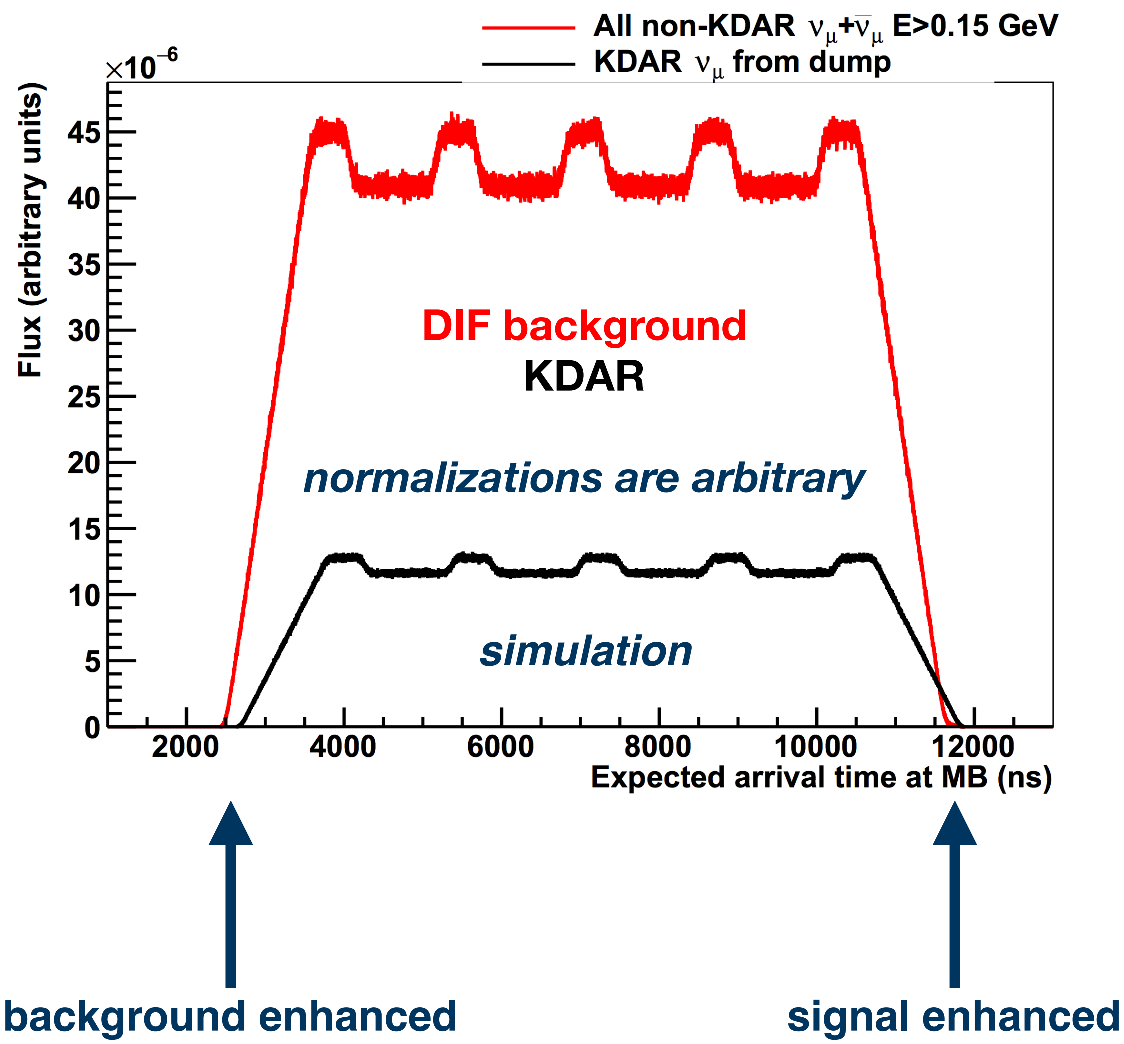
The size and shape of the excess depends highly on the selected background model.

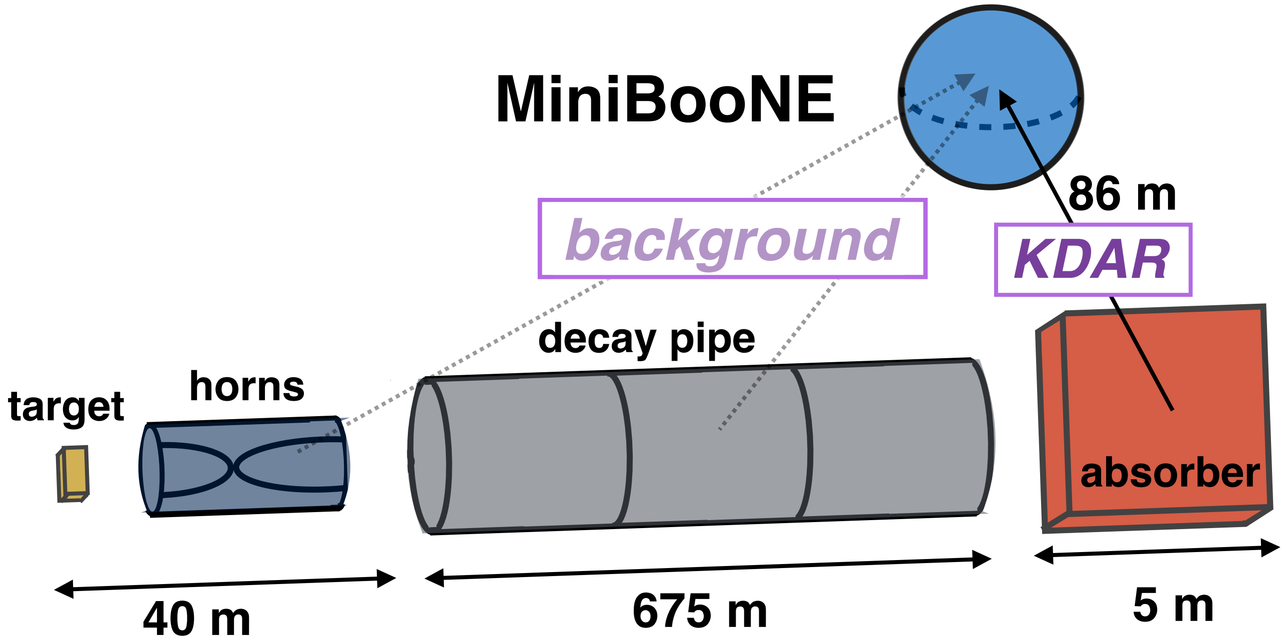
two neutrino event generator predictions for background



KDAR is not simulated and MC is scaled to data in background-only region ($PMThits_{5ns} > 120$)

Solution: Timing





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

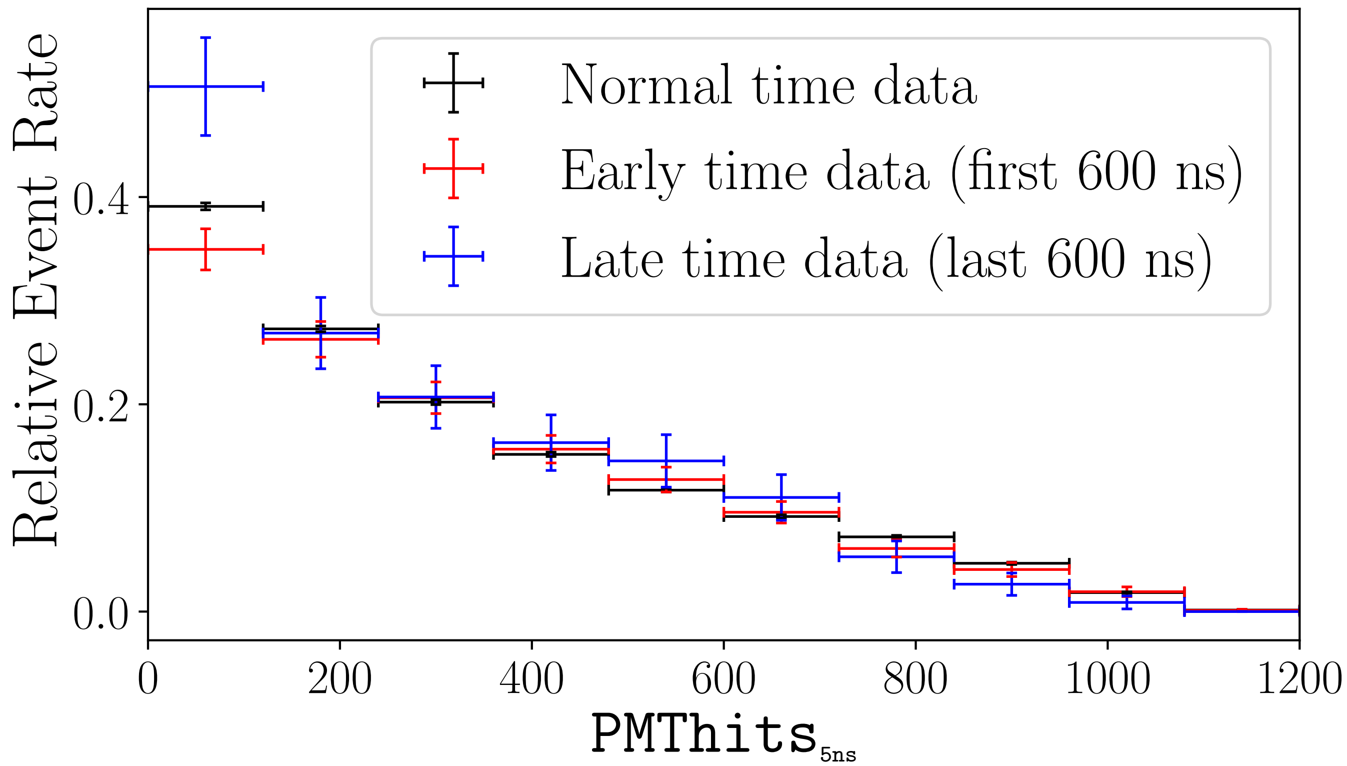
This means we can look at the evolution of signal and background over time!

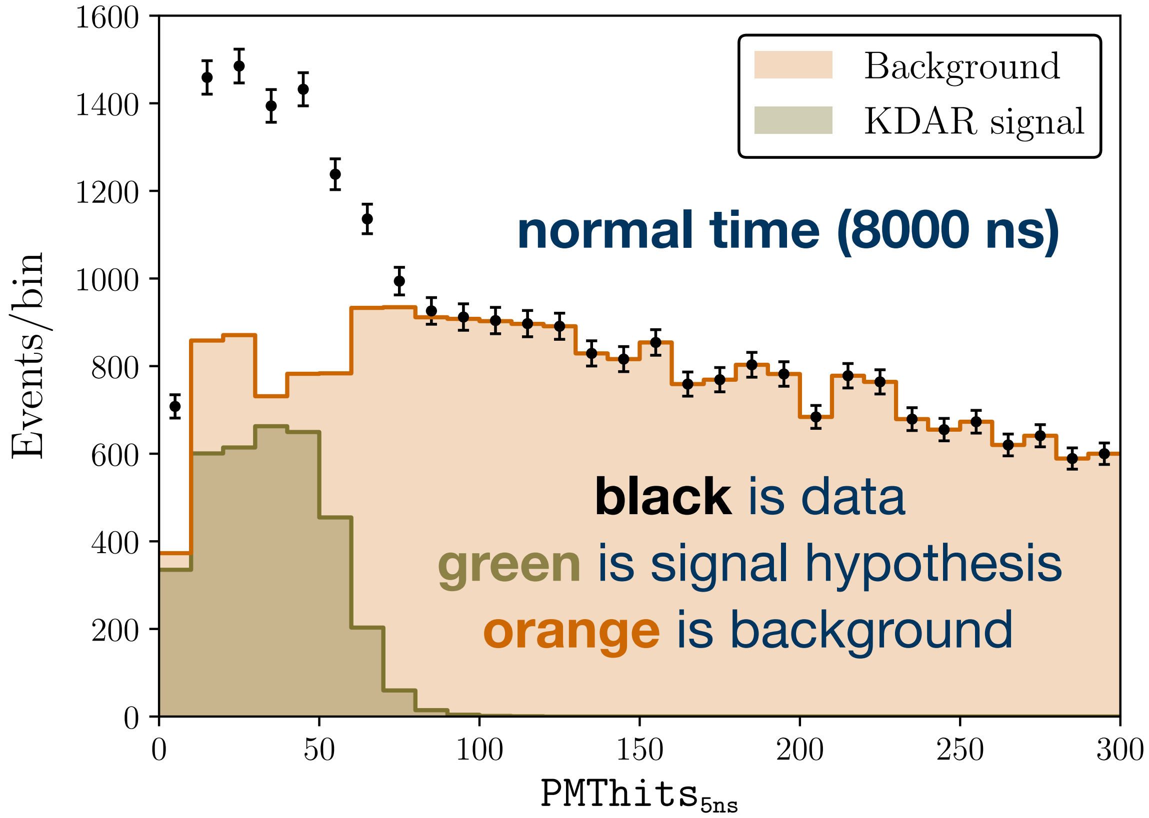
Solution: Timing

We expect KDAR here

2.1σ deficit at early time

2.4σ excess at late time





We can perform a 100% data-driven analysis that is independent of the uncertain flux and background predictions!

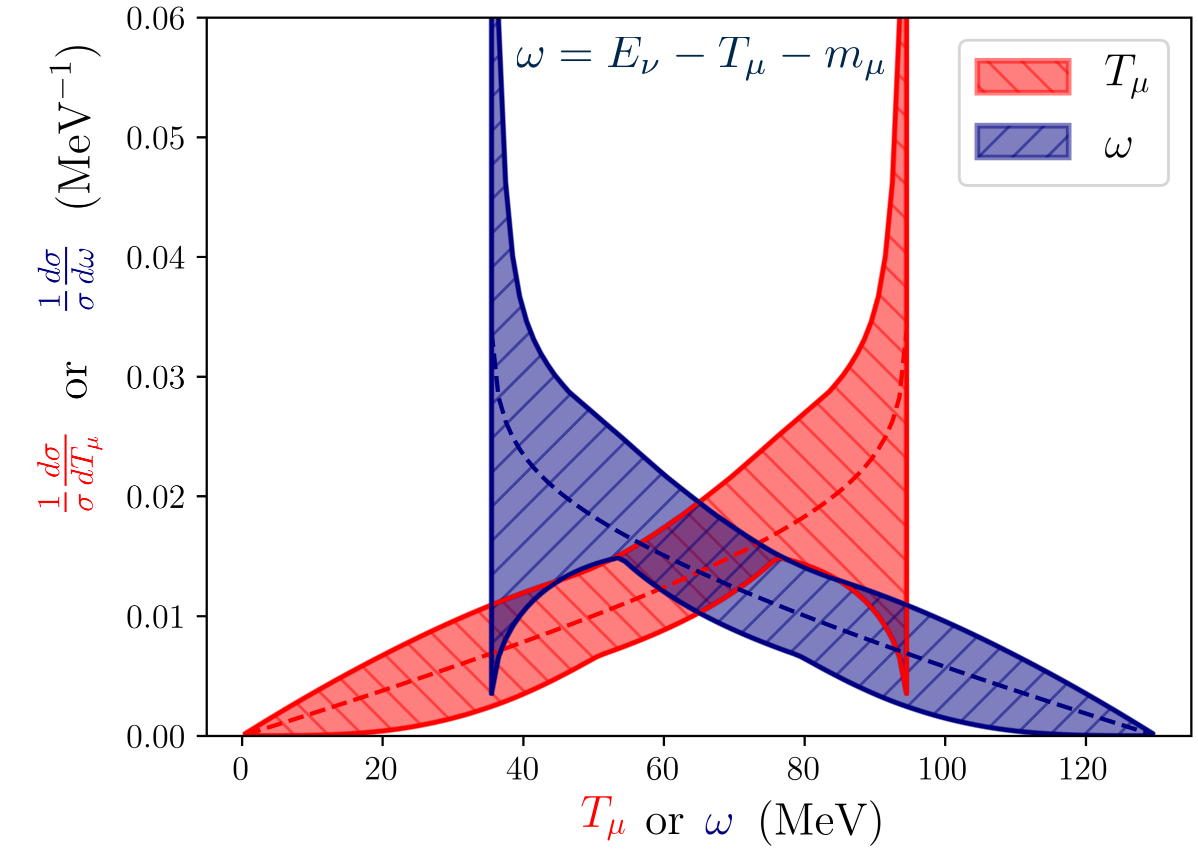
The Result

We observe the KDAR signal with 3.9σ significance.

Determined significance by comparing simulated data to the background-only hypothesis.

Systematics only contribute at the 1-2% level and are not shown.

Shape-only differential cross section in T_μ and ω with 1σ error bands.



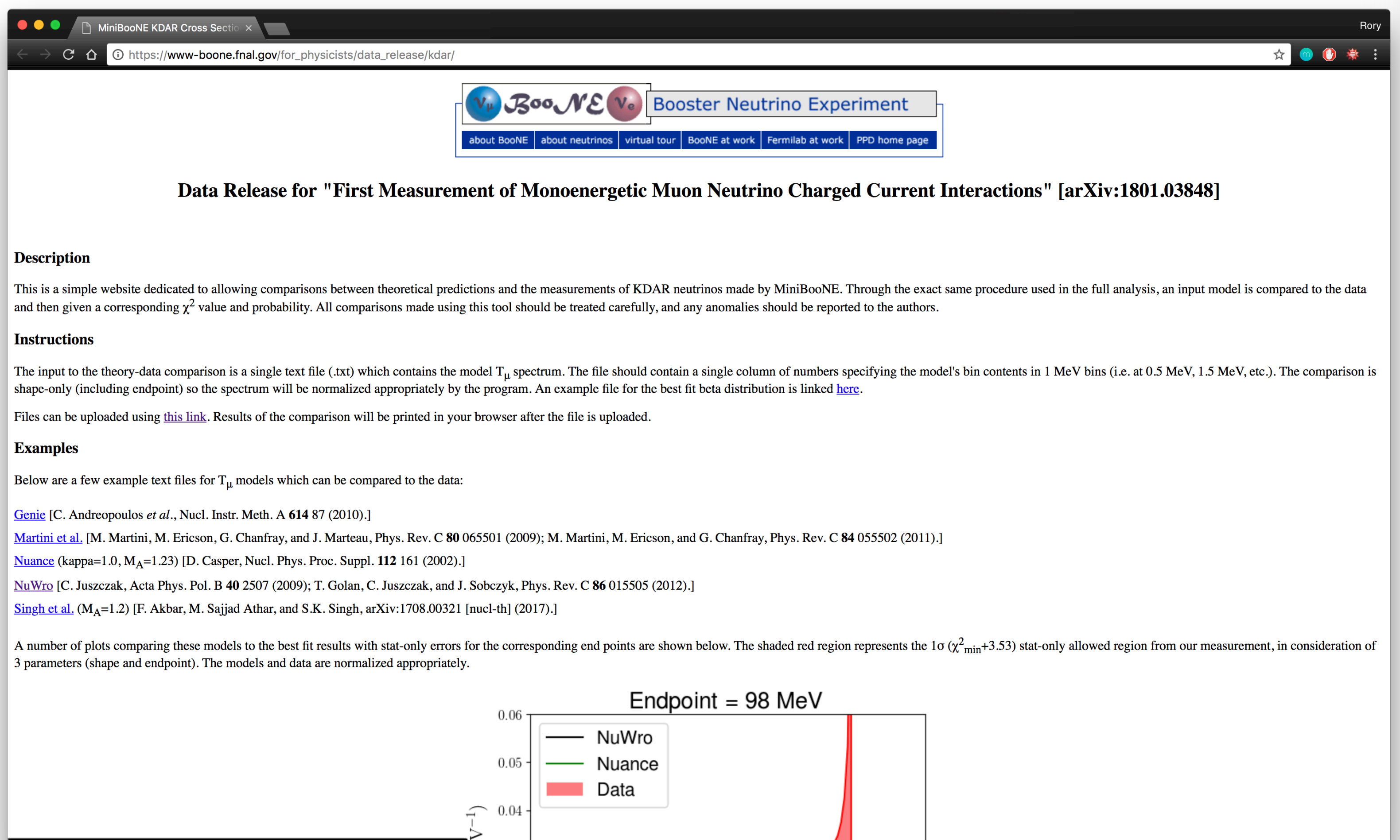
measurement flux (30%)

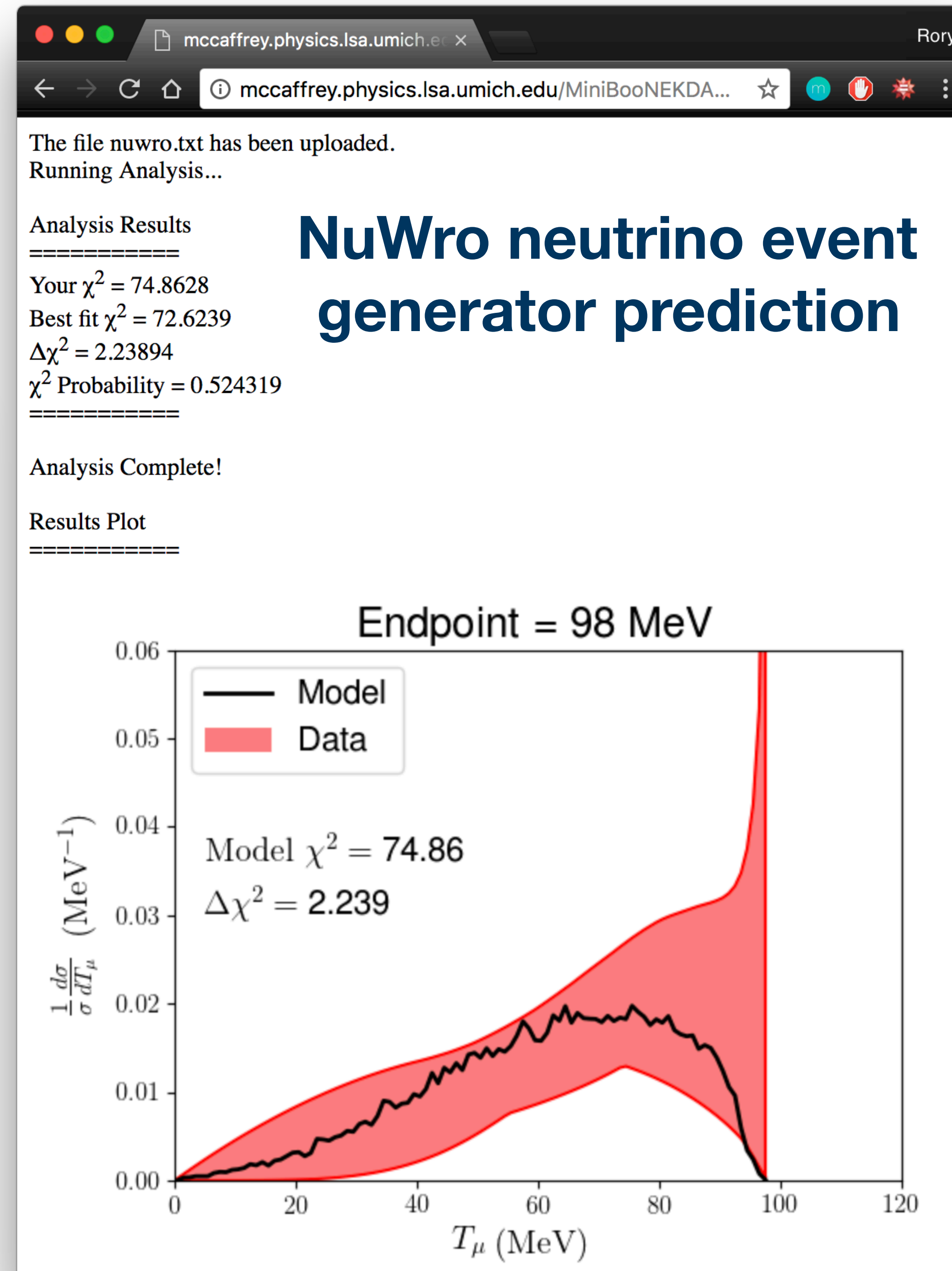
$$\text{Total } \nu_\mu \text{ CC cross section at } E_\nu = 236 \text{ MeV} \;:\; \sigma = (2.7 \pm 0.9 \pm 0.8) \times 10^{-39} \text{cm}^2/\text{neutron}$$

Theory Comparisons

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

Data release allows comparisons between our result and any arbitrary theoretical model.





NuWro neutrino event generator prediction

Outlook of KDAR Physics

- MiniBooNE has used KDAR neutrinos to measure energy transfer (ω) for the first time using neutrinos.
- Provides a standard candle for neutrino-nucleus interactions, cross sections, and energy reconstruction in the few-hundreds of MeV region.
- In the next few years:

  MicroBooNE (taking data since 2015)**:** can study both muon and hadronic outgoing components of KDAR interaction on argon with LArTPC technology.

  JSNS^2 (first data in 2019)**:** will collect 10-20k KDAR events/year on carbon.

- **Other published ideas:** muon neutrino disappearance, electron neutrino appearance, DM annihilation signature, strange quark contribution to nucleon spin…

PRL **118,** 221803 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

Dark Matter Search in a Proton Beam Dump with MiniBooNE

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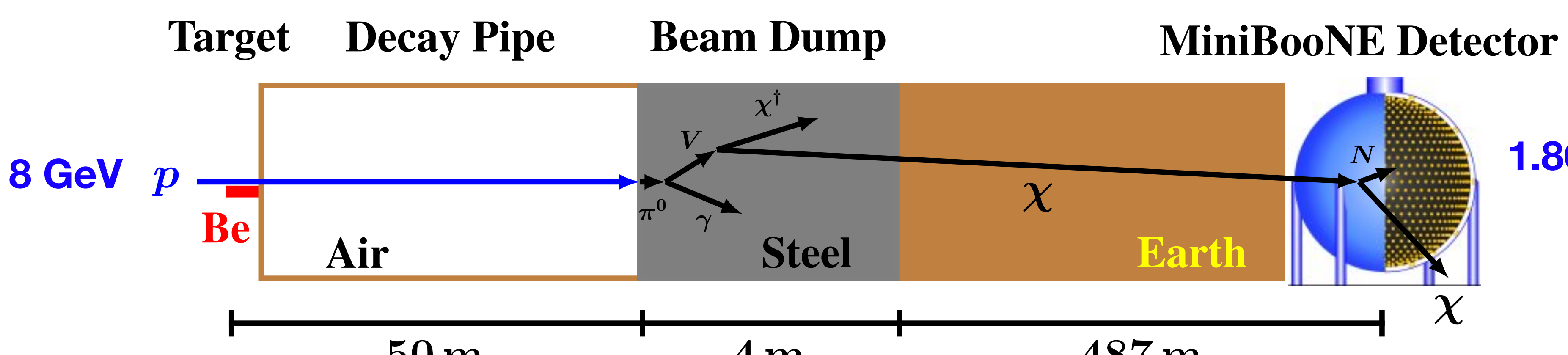
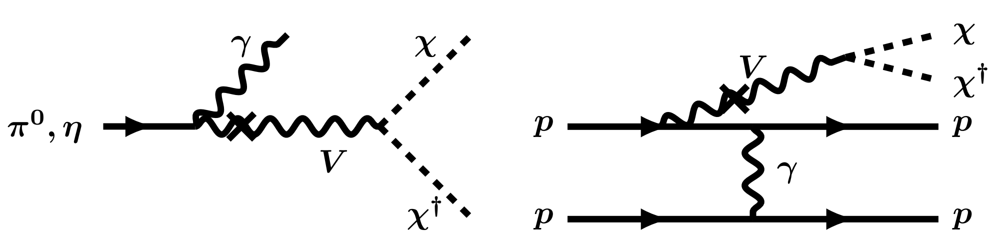
MiniBooNE-DM

Setup and DM Model

Searching for vector-boson mediated dark matter production.

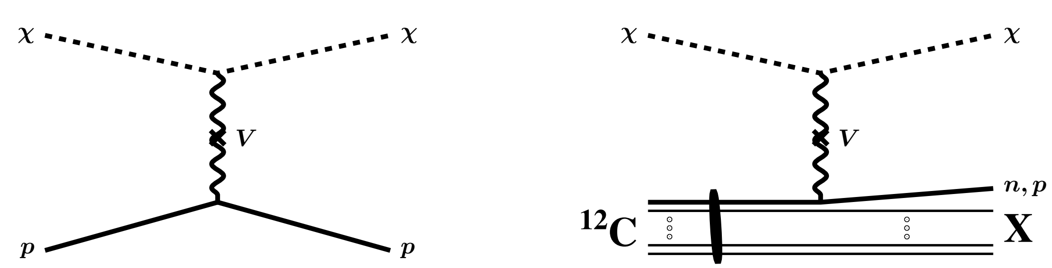


1.86 x 10^{20} POT collected from BNB protons



(a) π^0, η Decay (b) Proton Bremsstrahlung

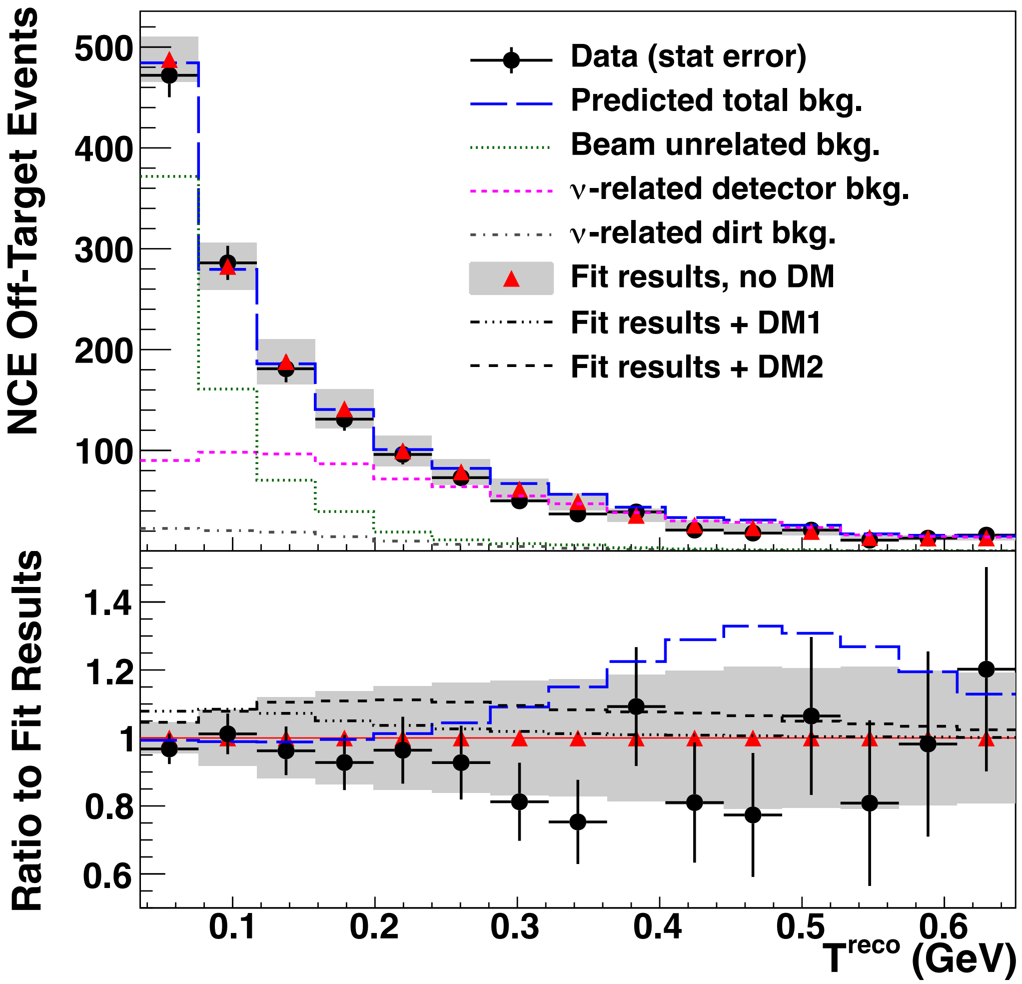
production channels

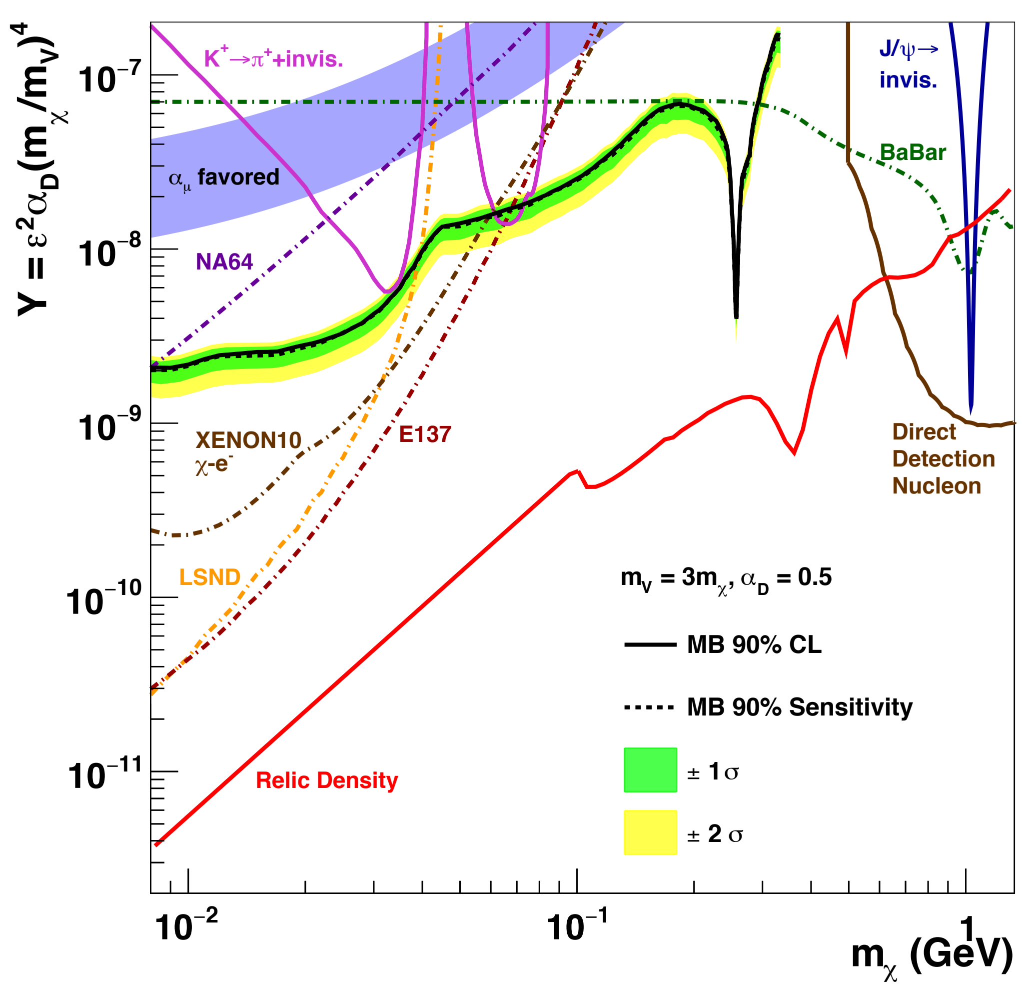


(a) Free protons (b) Bound nucleons in ^{12}C.

interaction channels

Results





No events observed over background

Summary

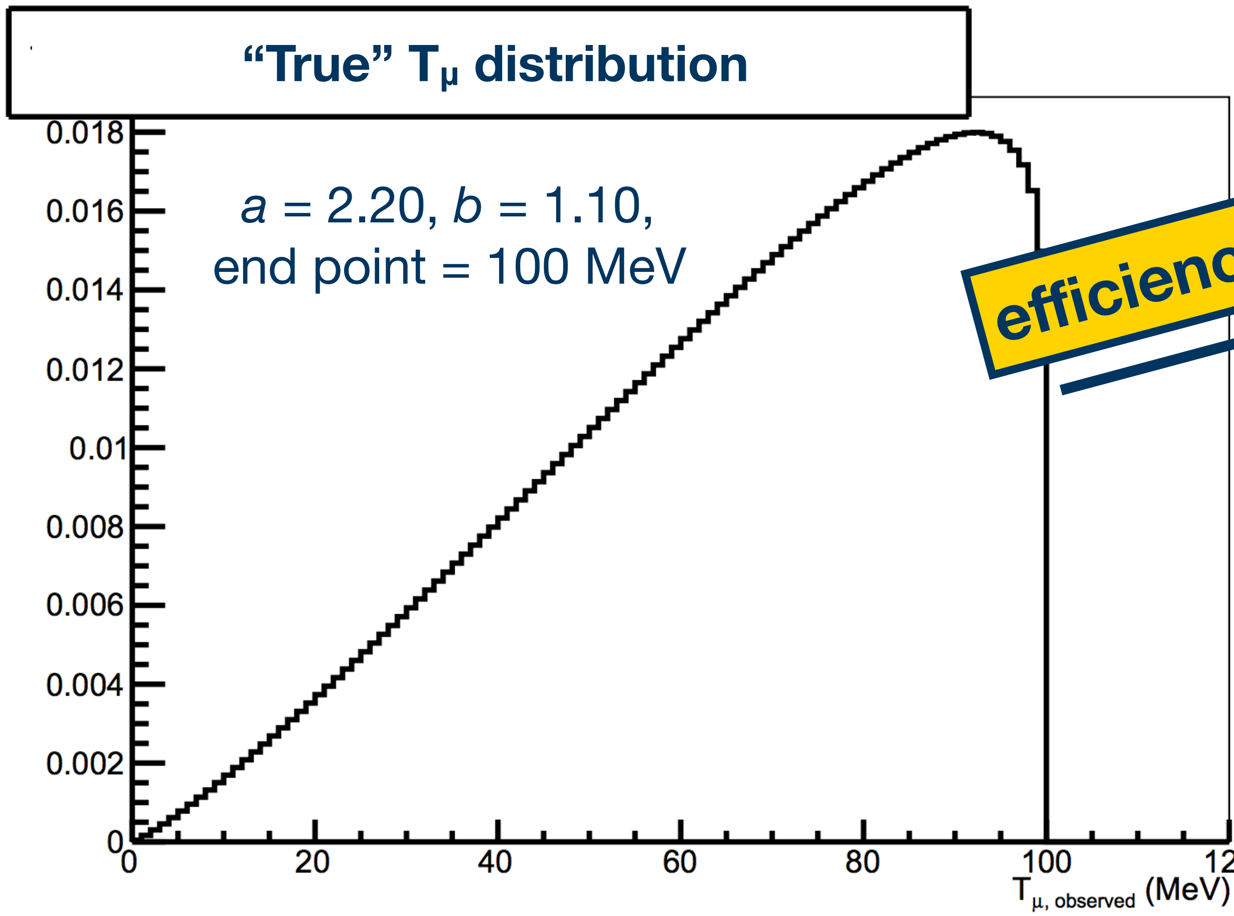
MiniBooNE's recent (and upcoming) physics results include:

- **The first observation of monoenergetic neutrinos from kaon decay at rest and a measurement of energy transfer using neutrinos.**
- **New limits on sub-GeV dark matter, setting globally most stringent limits for $0.08 < m_{\chi} < 0.3$ GeV.**
- **DM π0 and electron scattering channels are being analyzed and will have better sensitivity. Look for these results in the coming months!**

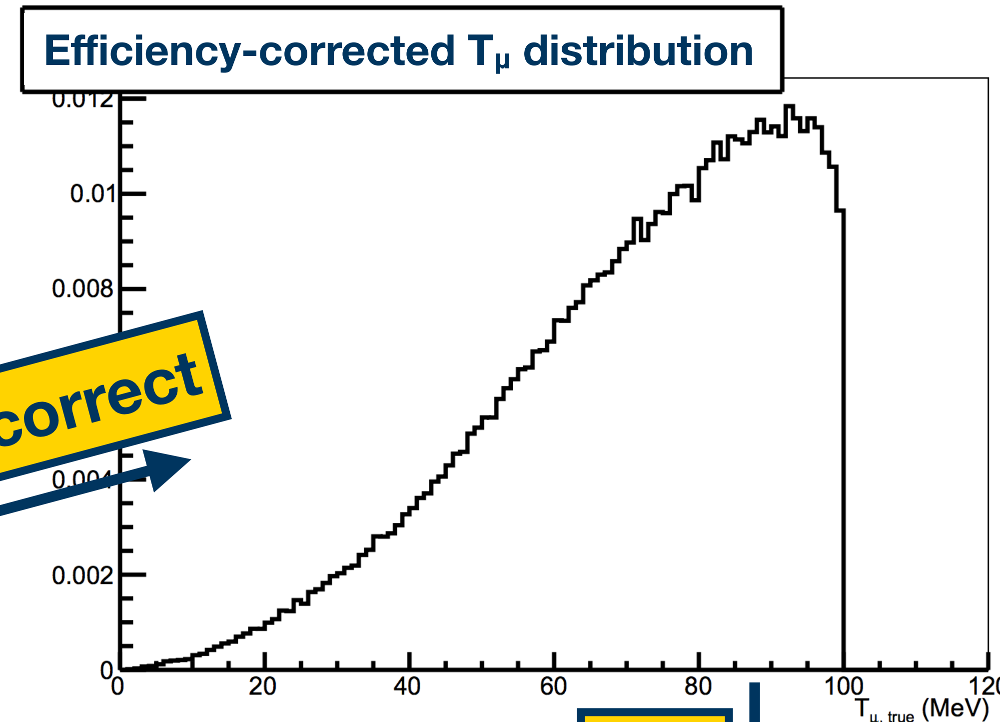

Questions?

Backup

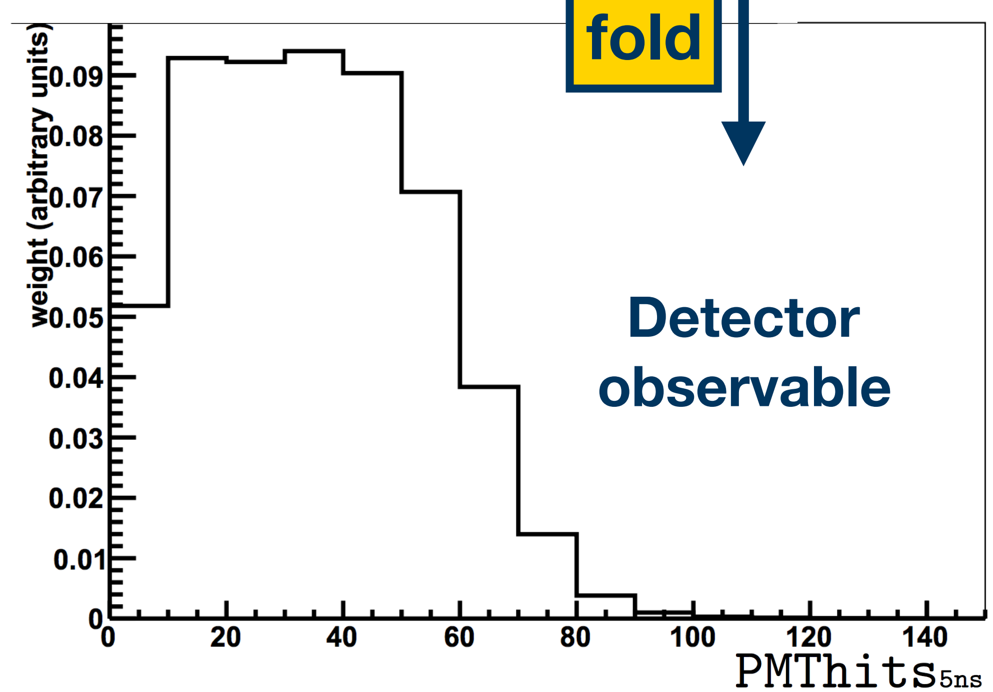
Signal Model Construction



efficiency correct



fold



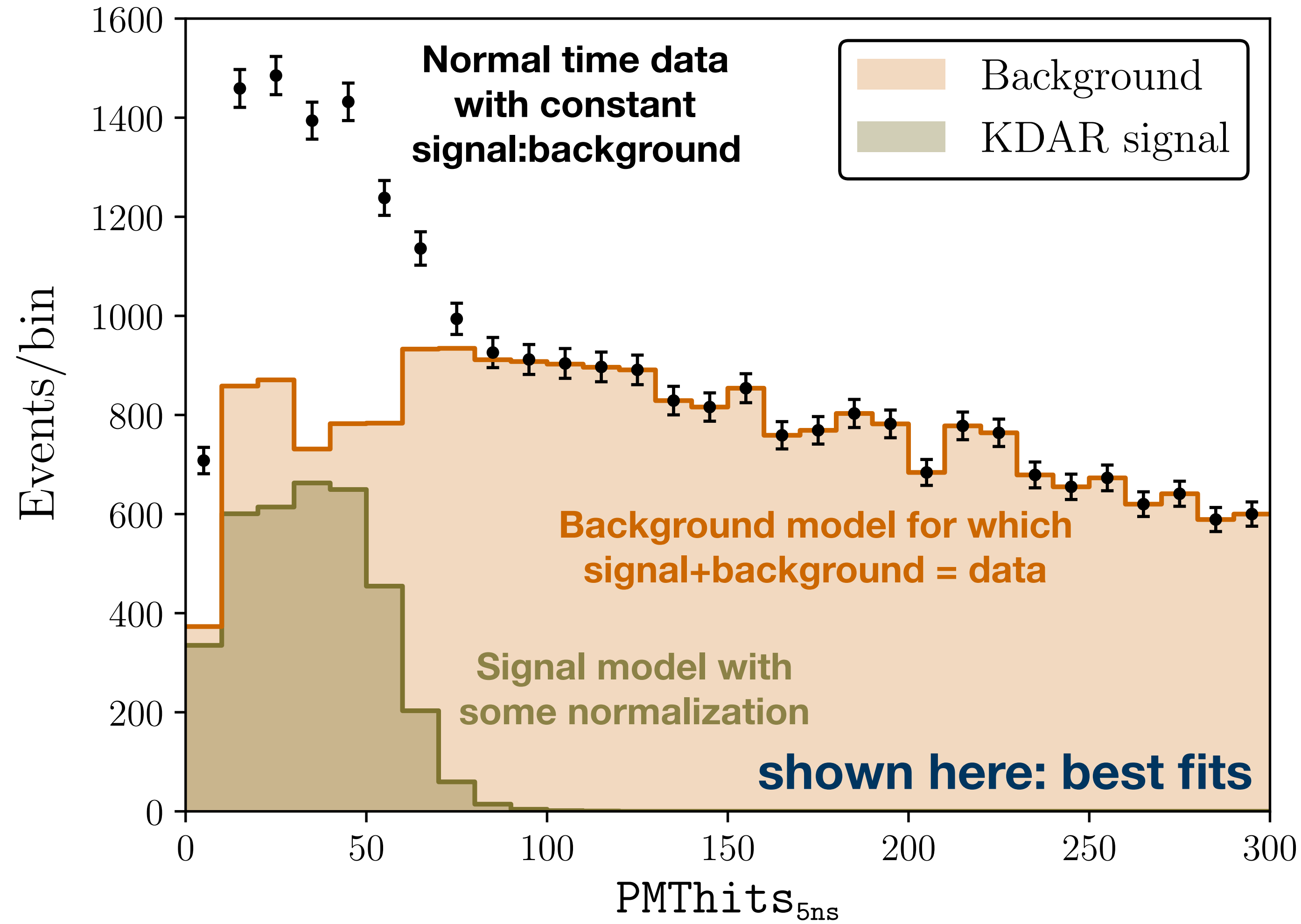
Step 1: Construct signal model.

Background Model

Now we assign a normalization to the **signal model** (yet another parameter we have to vary to find the best fit).

Define the **background model** such that **signal** + **background** = **data** in the high-statistics normal time region.

normal time (8000 ns)



Step 2: Construct background model.

Data Comparison

Each plot represents 200 ns of data.

Divide the early (**signal-enhanced**) and late (**background-enhanced**) time regions into three time bins each.

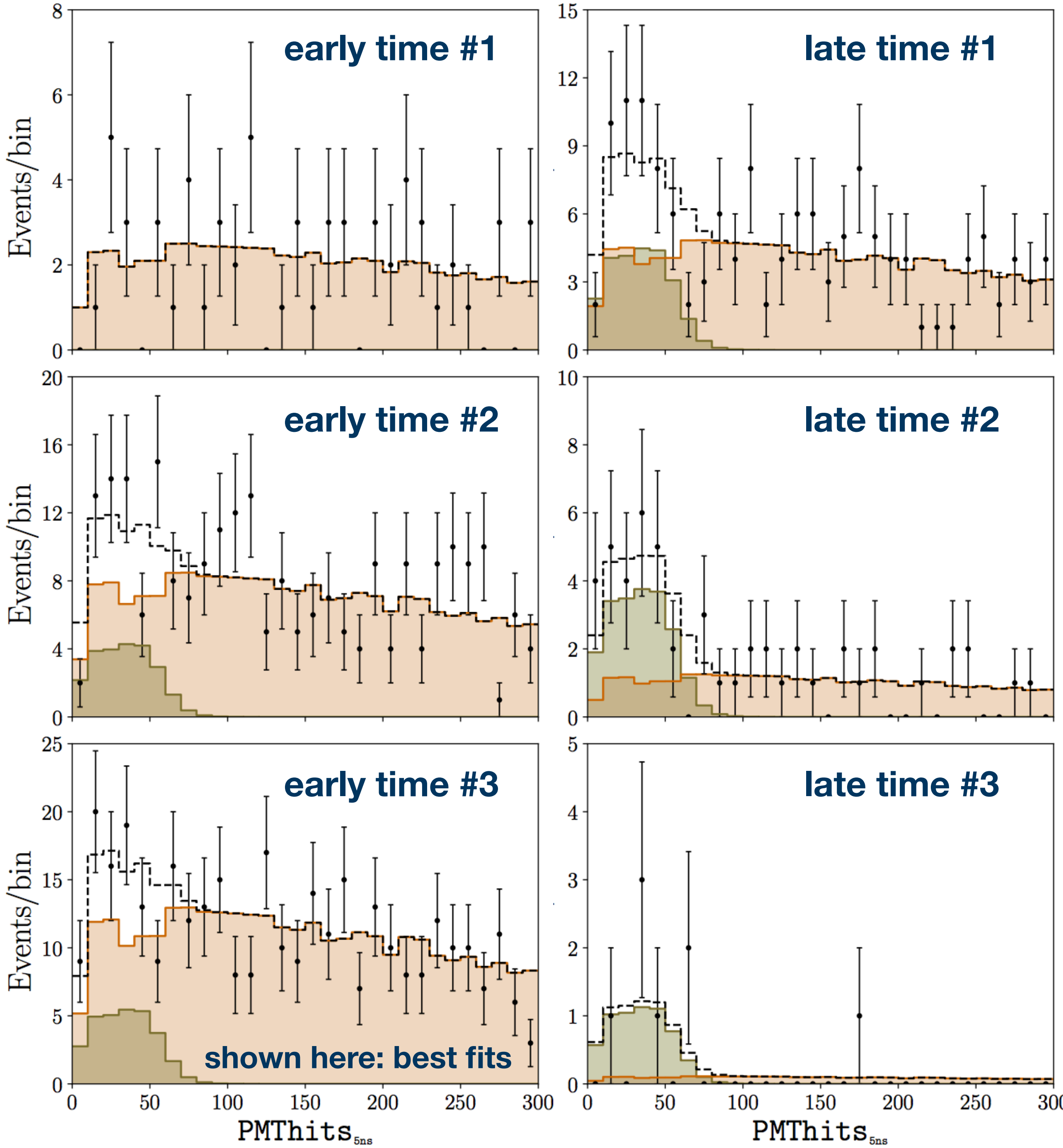
Normalize the **background model** to match the **background-only** region.

Allow **signal** normalization to float.

Signal and **background** shapes are constant at all times, only normalization can change.

Compute agreement between **data** and **signal**+**background** in each time bin using a Poisson χ^2.

Step 3: Compare signal+background to data in early and late times.



Repeat

Models covered this parameter space:

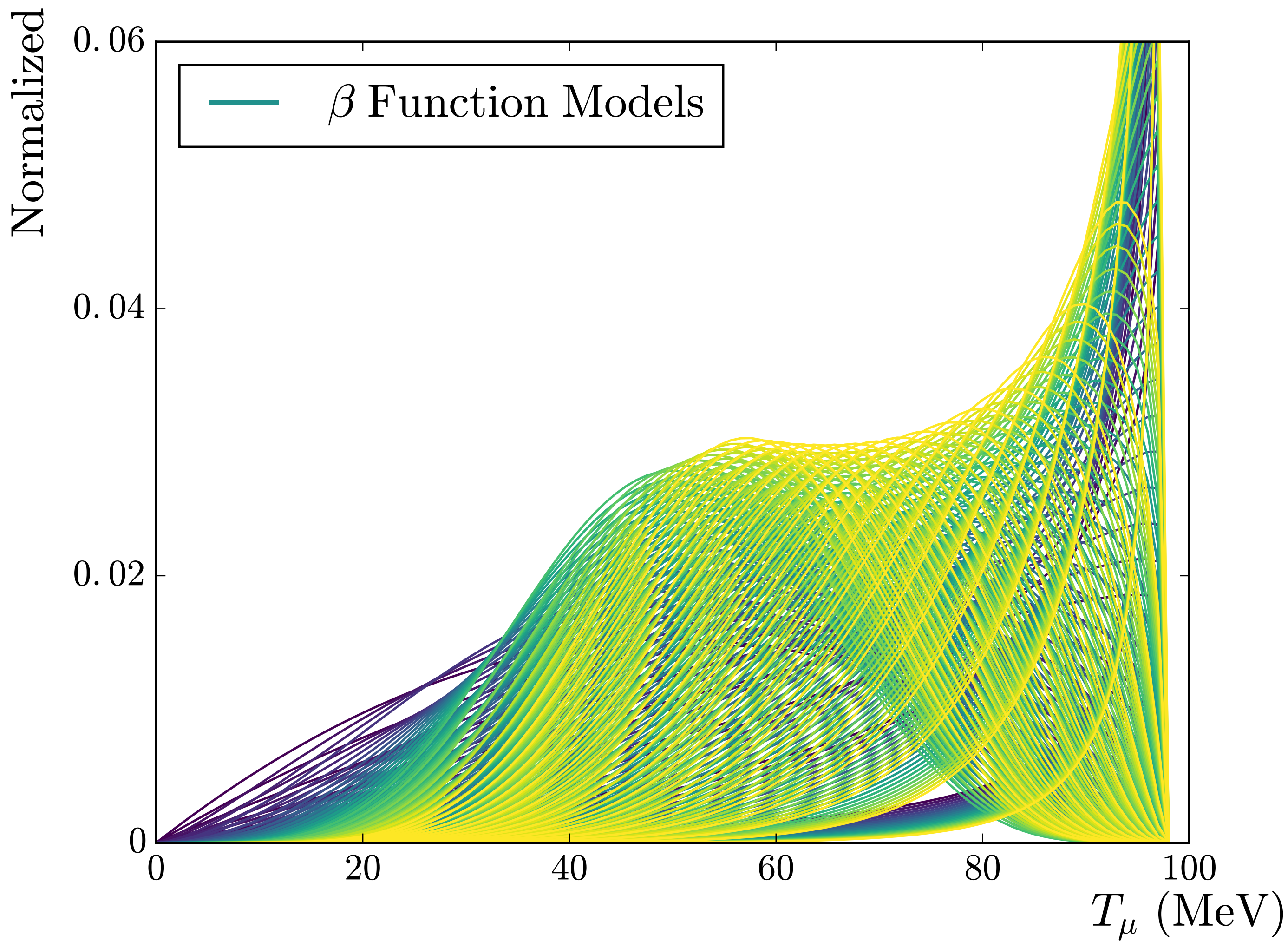
2.0 < *a* < 8.0
0.0 < *b* < 6.0

Models with *a* < 2.0 are unphysical.

We allowed the end point to vary from 95 MeV to 115 MeV to reflect variation among model predictions.

Signal normalization was varied from zero to the maximum value allowed by the data.

Step 4: Repeat for each possible signal model.



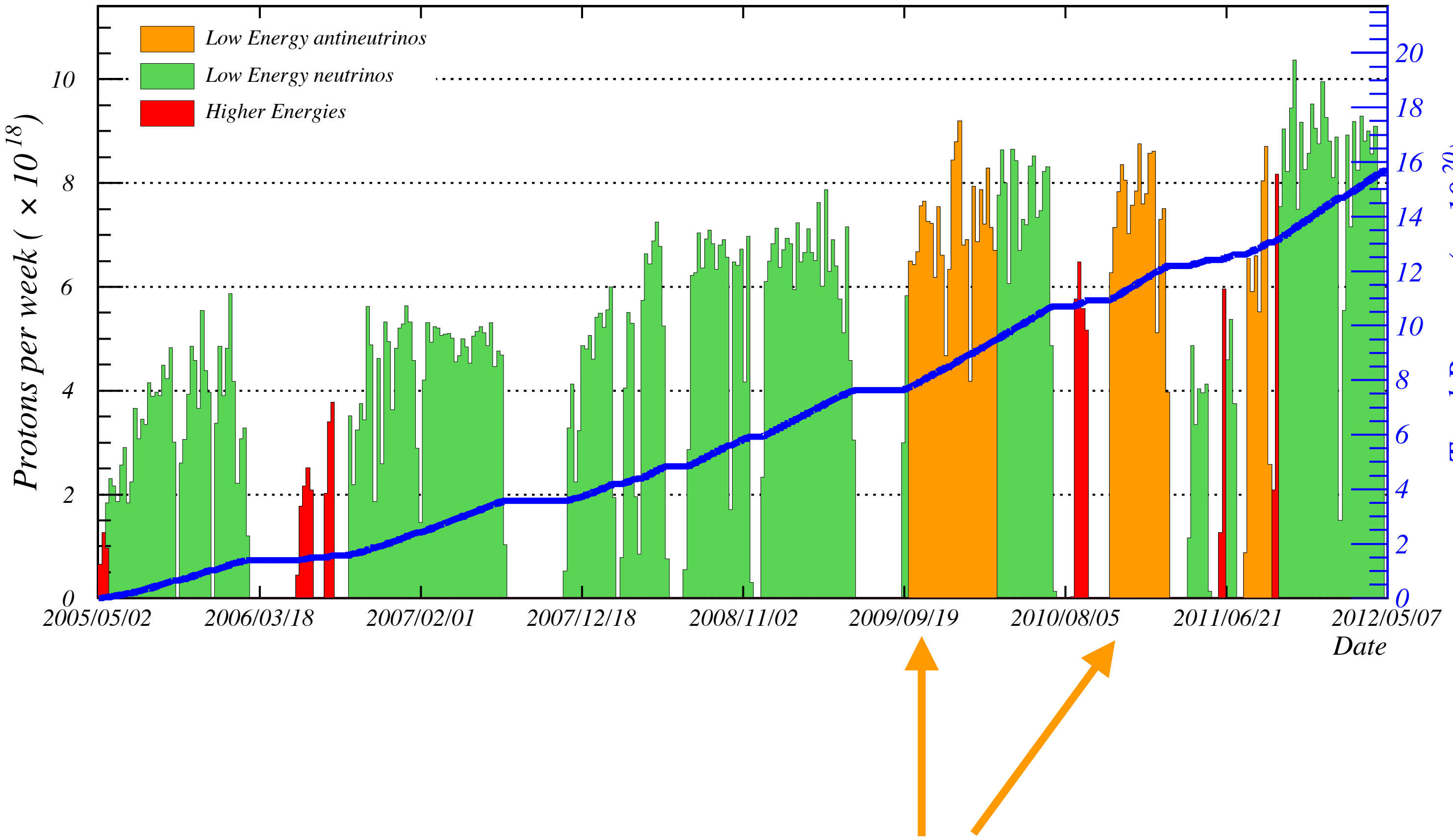
There exists a beta function within our parameter space that agrees reasonably with each neutrino generator model we could have picked.

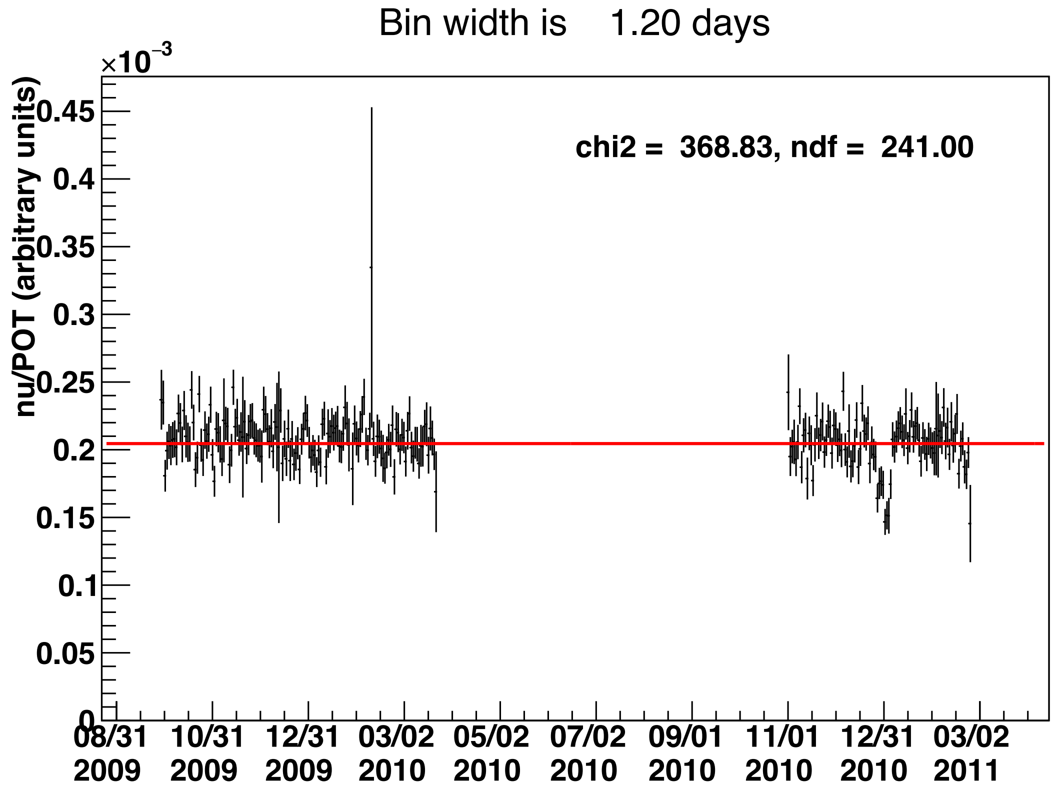
Other KDAR Physics

- Oscillation search for sterile neutrinos at short baseline.
- Precision measurement of strange spin component of the nucleon (Δs).
- Signature of dark matter annihilation in the sun.
- Measure charged current neutron yield.

J. Spitz, Phys. Rev. D 85 093020 (2012).
S. Axani, G. Collin, J.M. Conrad, M.H. Shaevitz, J. Spitz, T. Wongjirad, Phys. Rev. D 92 092010 (2015).
J. Spitz, Phys. Rev. D 89 073007 (2014).
C. Rott, S. In, J. Kumar, and D. Yaylali, J. Cosmol. and Astropart. Phys. 11 039 (2015).
C. Rott, S. In, J. Kumar, and D. Yaylali, arXiv:1710.03822 [hep-ph].

KDAR Dataset

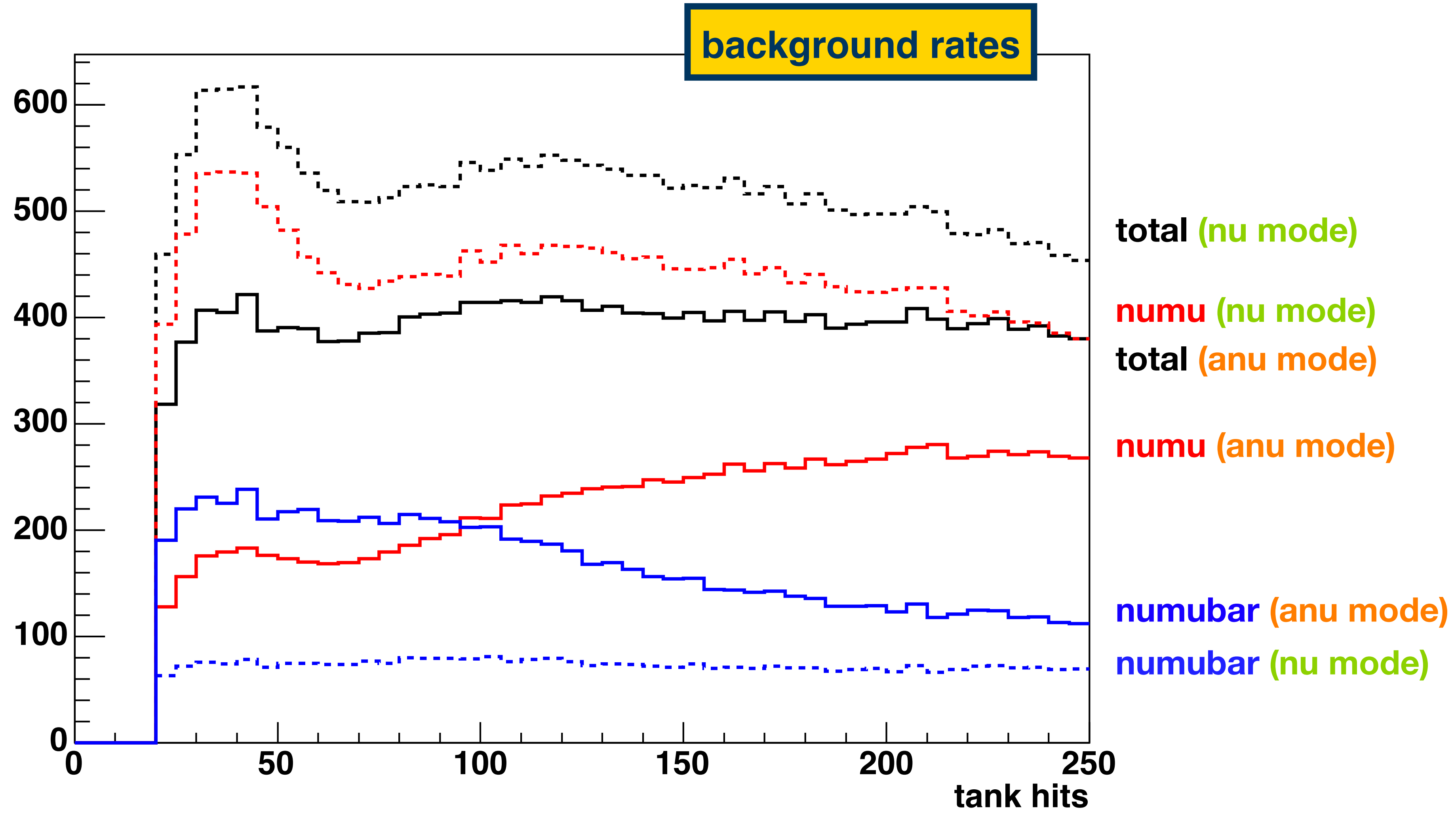




NuMI LE antineutrino mode has higher signal:background than neutrino mode

2.62 x 10^{20} POT

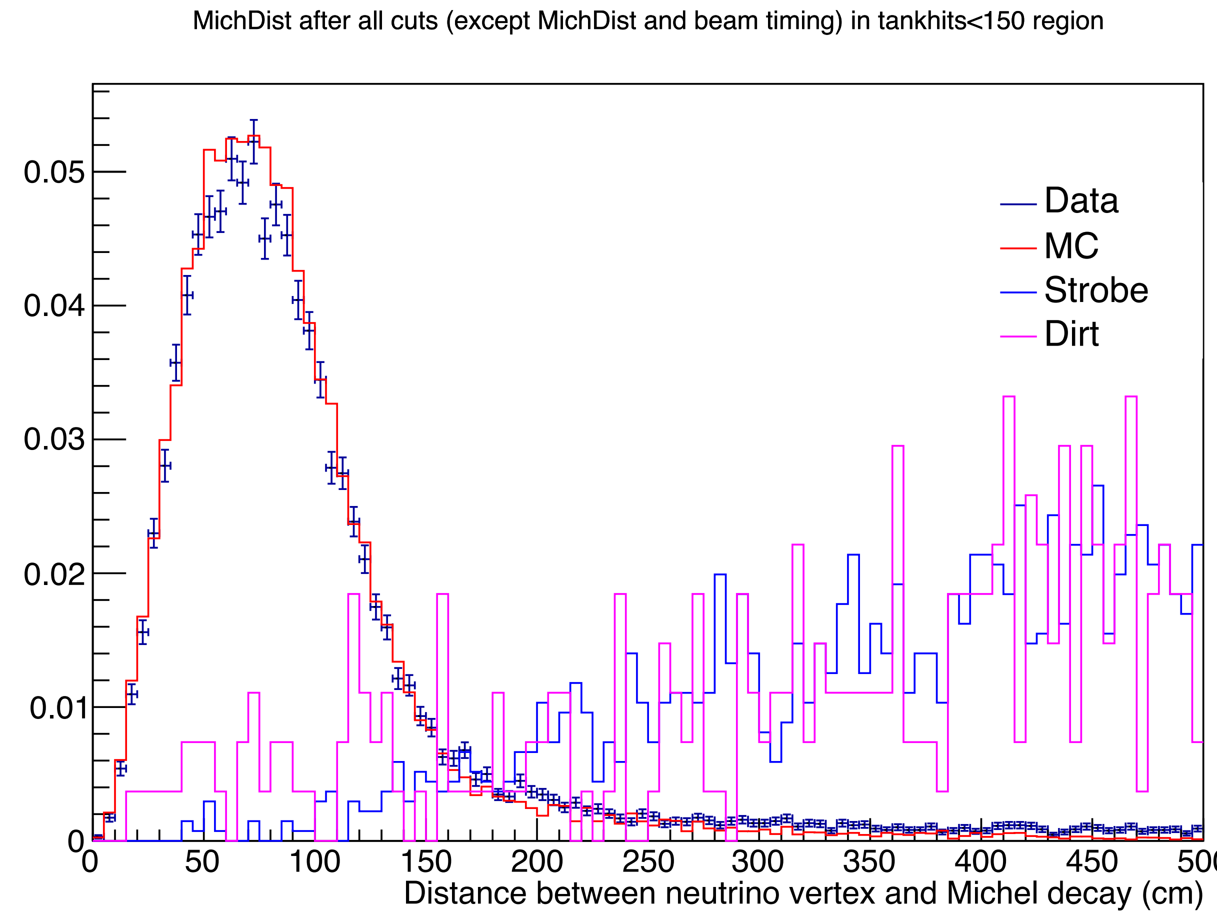
Why use antineutrino mode?



Background rates are lower in antineutrino mode.

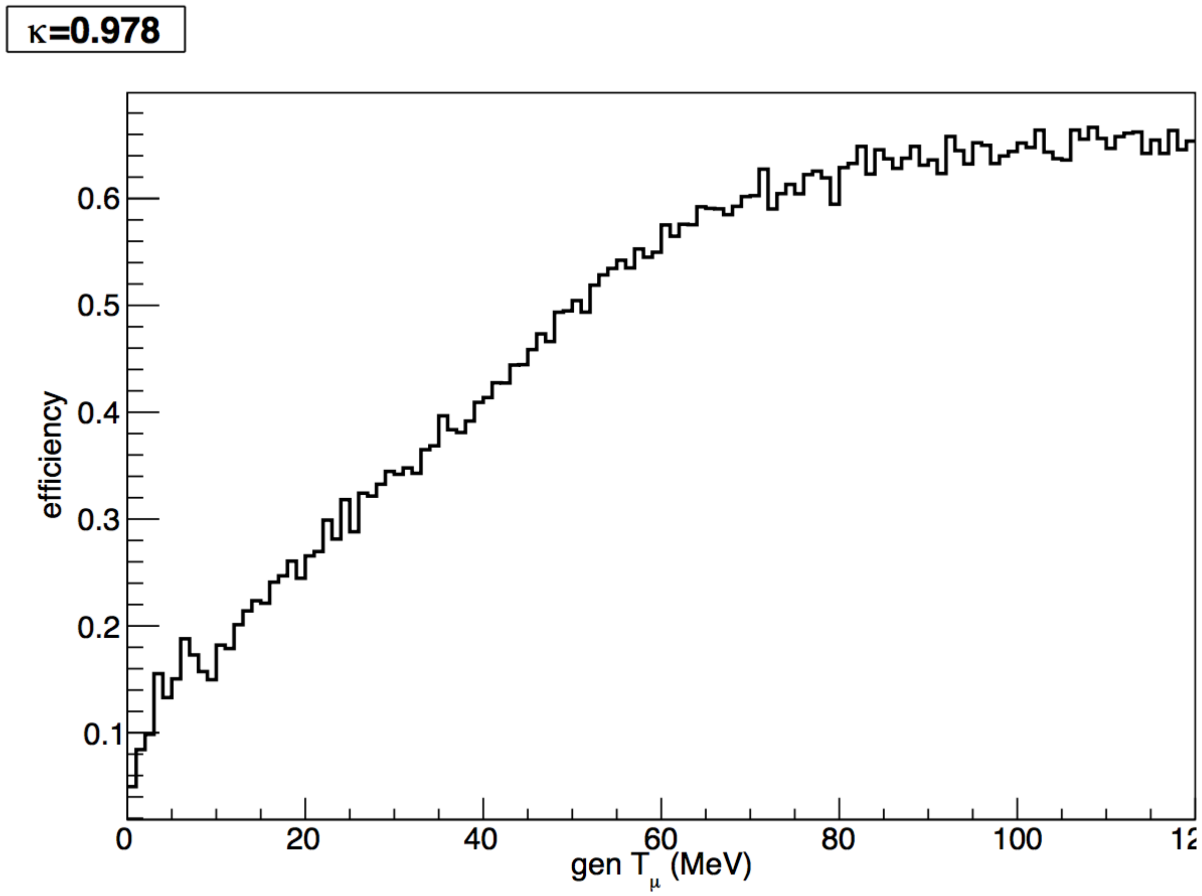
KDAR Cuts

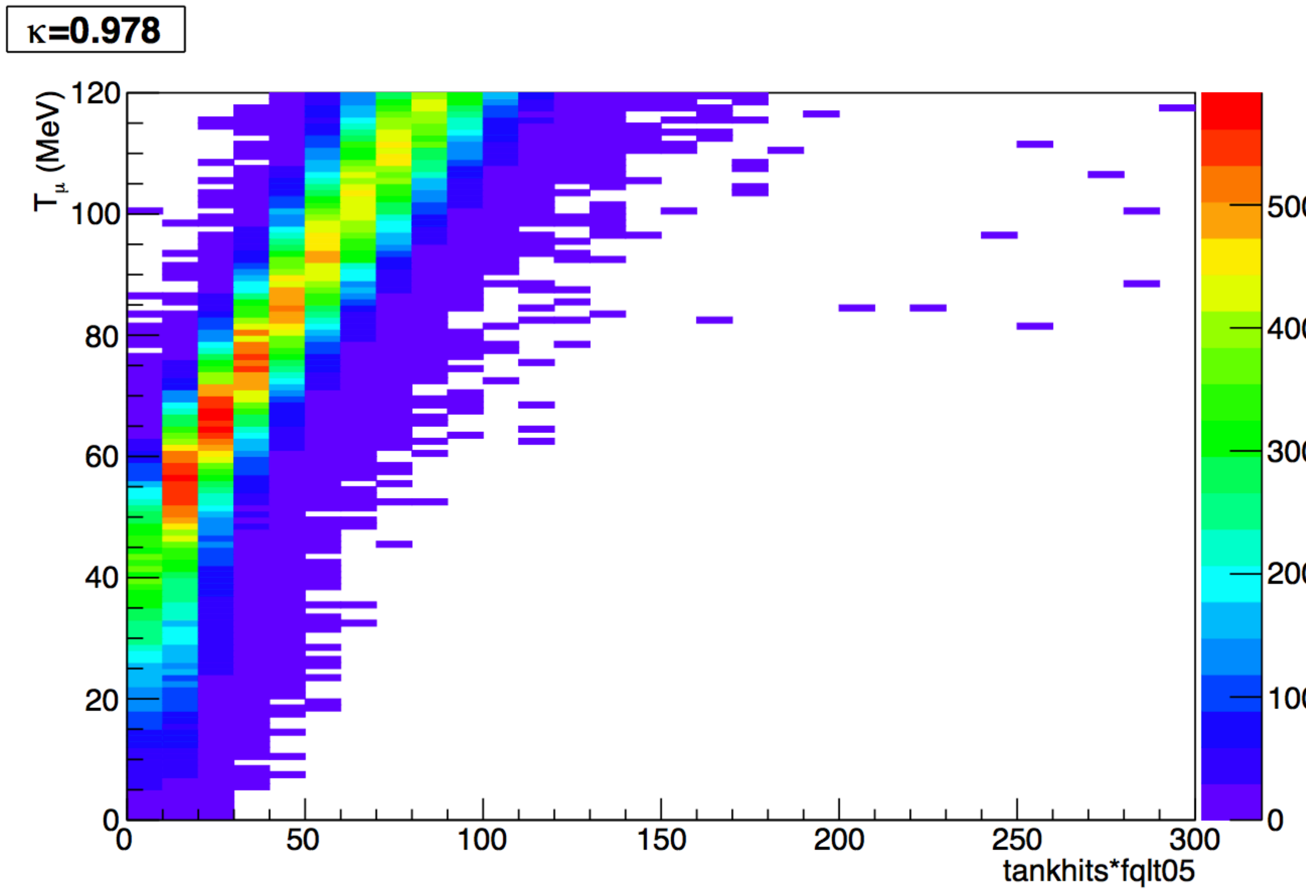
1. Two subevents (SE) and < 6 veto hits in each SE.
2. First SE in beam time window.
3. Second SE 20 < tank hits < 200.
4. r < 500 cm.
5. First SE tank hits > 20.
6. First SE PMT hit time RMS < 50 ns.
7. Michel distance < 150 cm.



Distance between primary track endpoint and reconstructed decay point (cm)

Efficiency and Folding Matrix

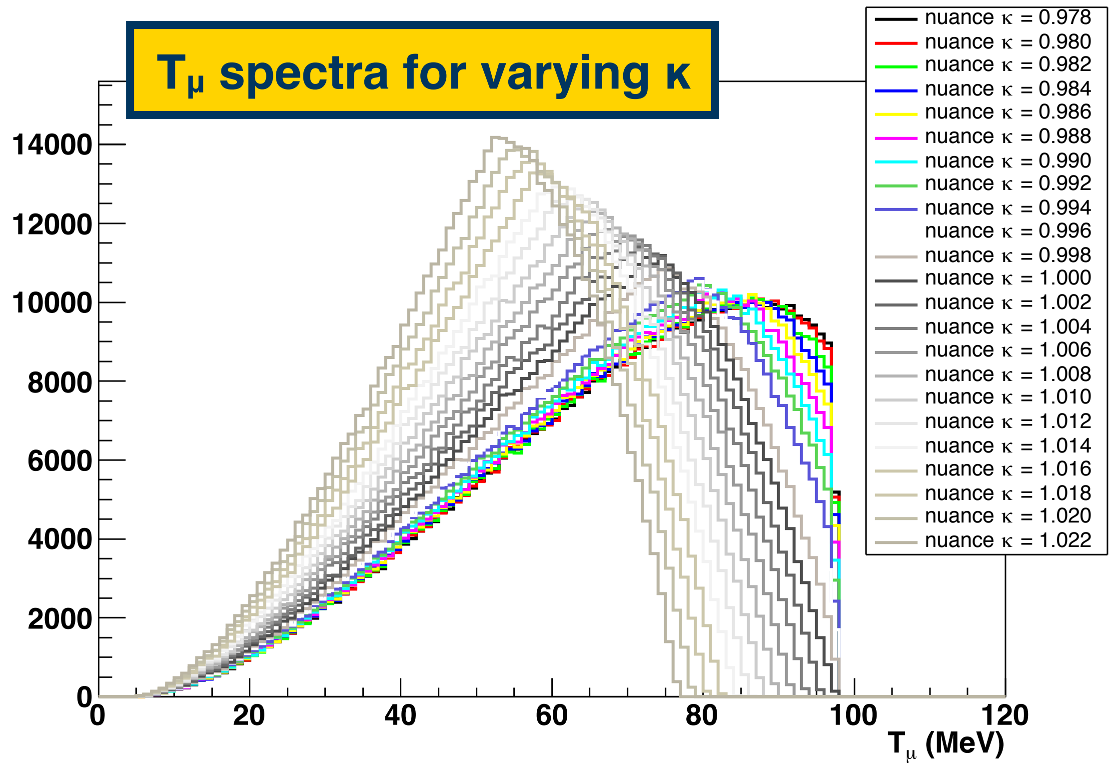


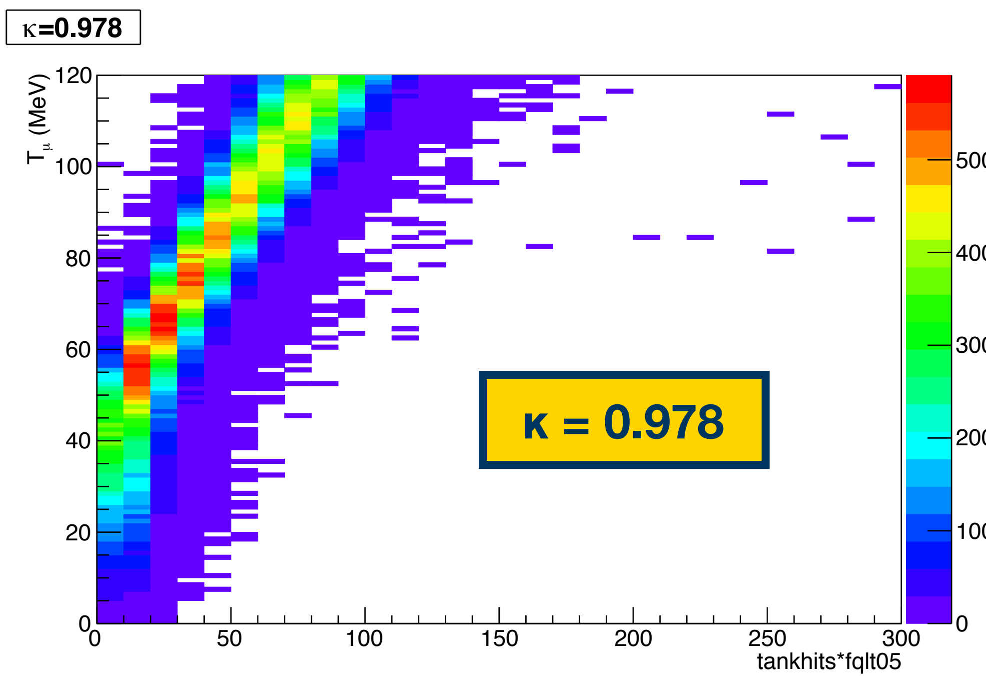


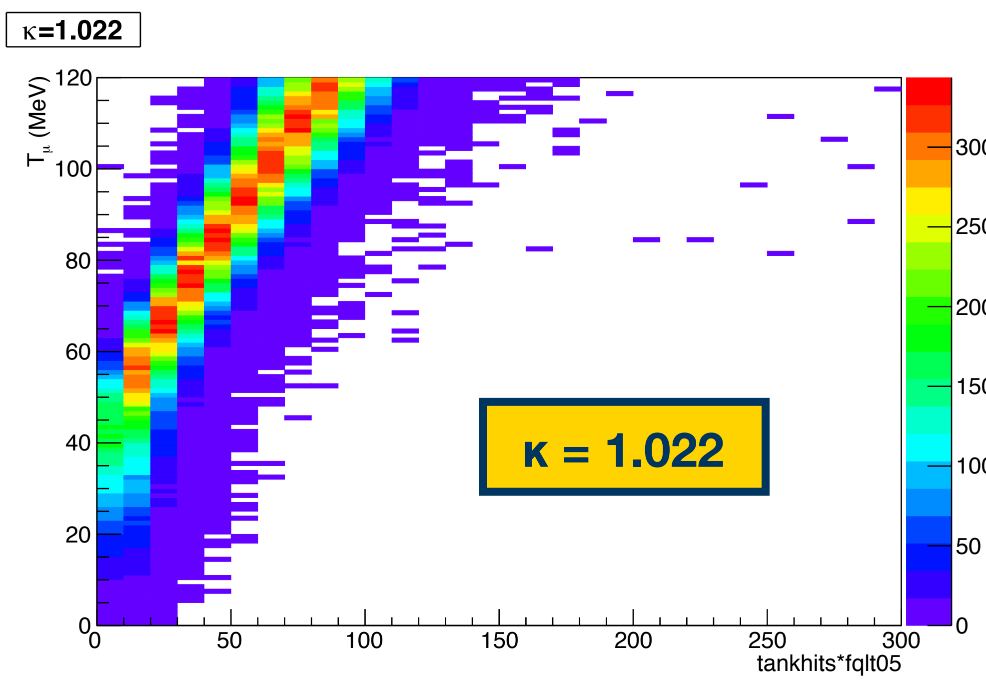
This result is *nearly* independent of the flux prediction, assumptions about low-energy neutrino kinematics and cross sections, and neutrino event generators!

The only, (demonstrably) *weak* dependence on these items is in forming the efficiency correction and folding matrix (see next slide).

Model Dependence of Folding

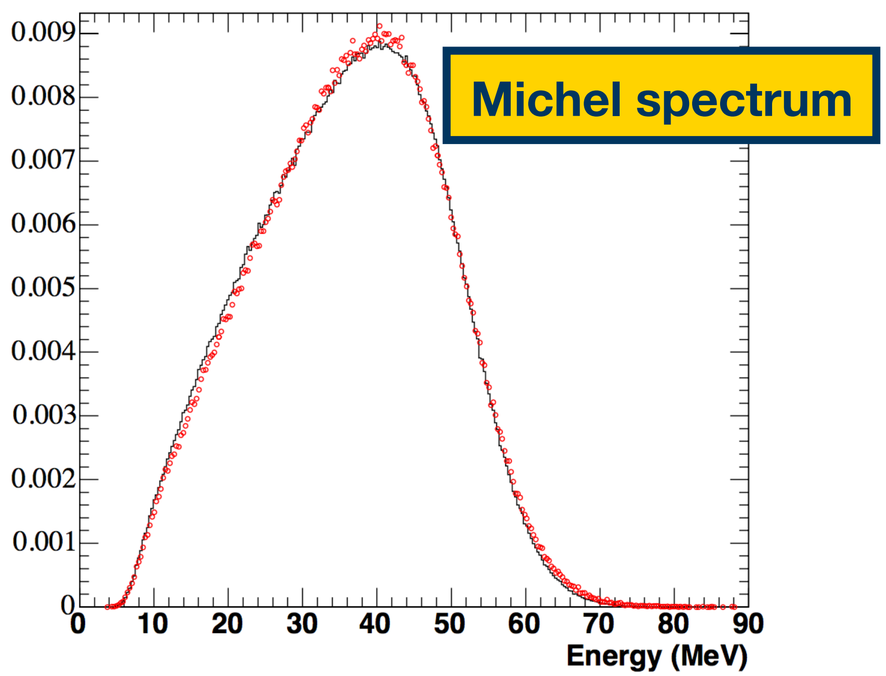


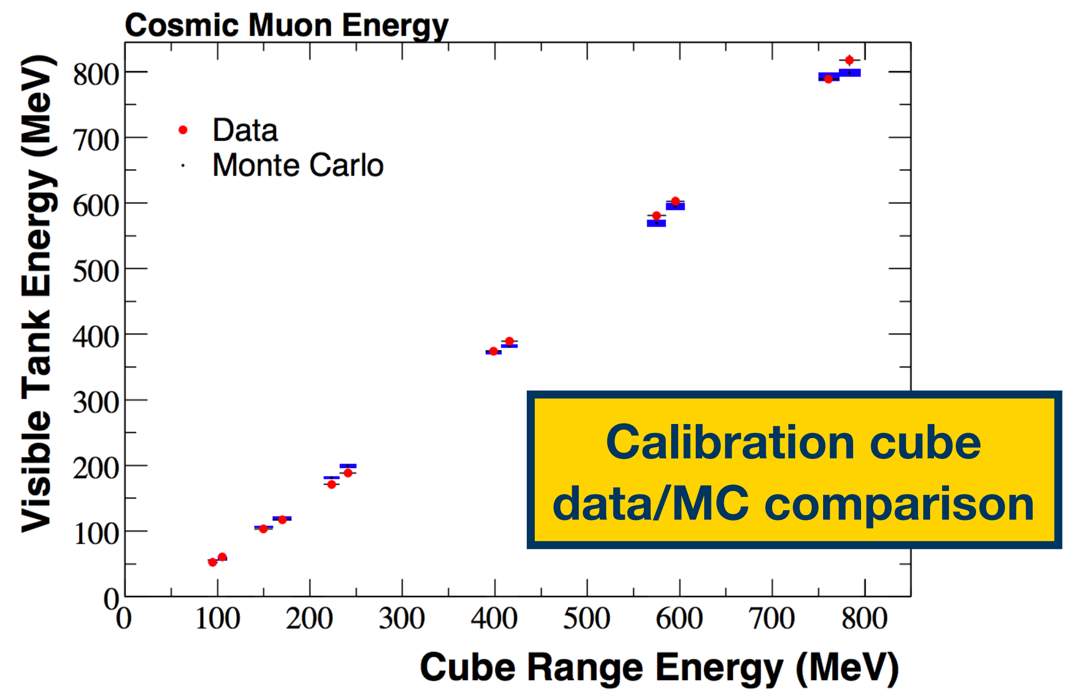


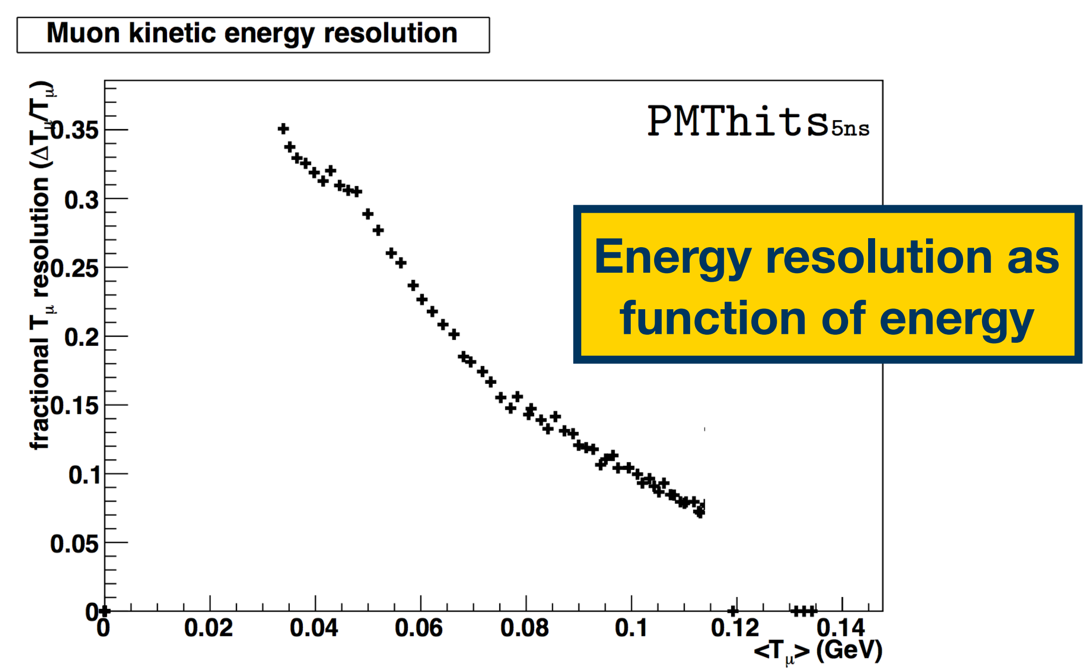


The analysis extracts the same best fit model using both the extreme options for creating the folding and efficiency matrices.

Muon Energy Resolution







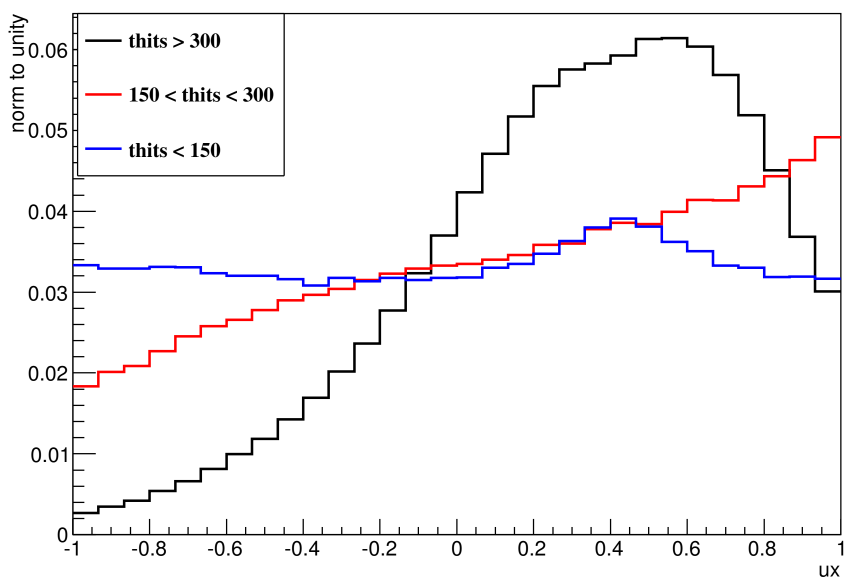
Large sample of Michel electrons provides calibration for detector response to scintillation and Cherenkov light at energies highly relevant for KDAR muons.

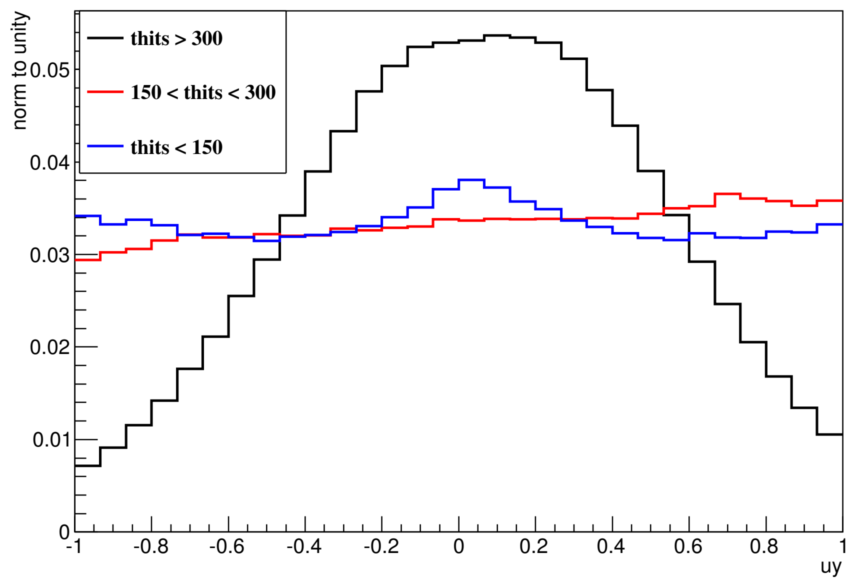
Further, a scintillator “calibration cube” inside the MiniBooNE tank provides an ultra-clean sample of tagged 95 MeV muons for understanding energy resolution and detector response.

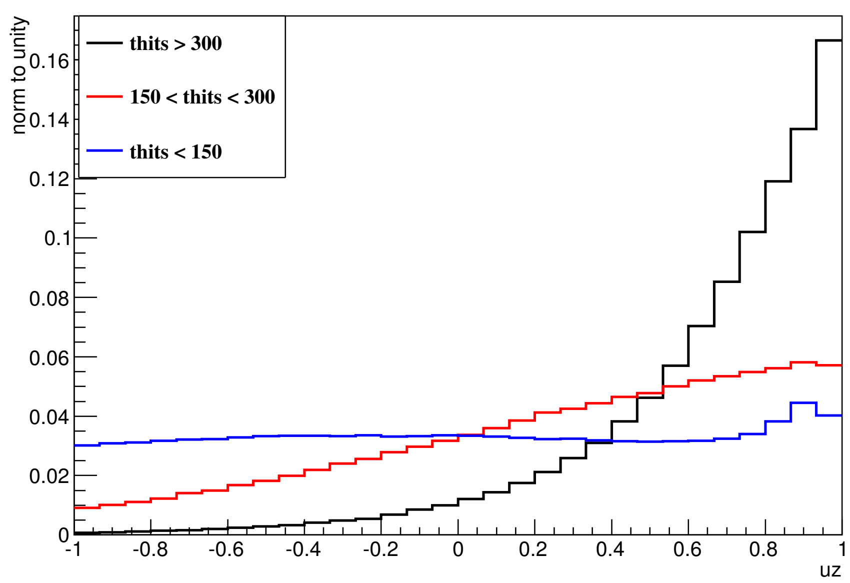
12% muon energy resolution at $T_\mu = 95$ MeV dropping to 25% for $T_\mu = 50$ MeV.

Muon Direction

Why can't we use neutrino direction to distinguish signal from background?







Correlation between neutrino direction and muon direction at KDAR energies is very weak — need to know something about hadronic component of interaction to reconstruct neutrino direction.

Poisson Extended Maximum Likelihood

time bin: i
energy bin: j

signal prediction

$$P_{i,j,\alpha} = T_{j,\alpha} + B_{i,j}$$

background prediction

$$\chi^2_{i,\alpha} = 2\sum_j \begin{cases} P_{i,j,\alpha} - d_{i,j} + d_{i,j}\ln(d_{i,j}/P_{i,j,\alpha}) & d_{i,j} > 0 \\ P_{i,j,\alpha} & d_{i,j} = 0\,. \end{cases}$$

data

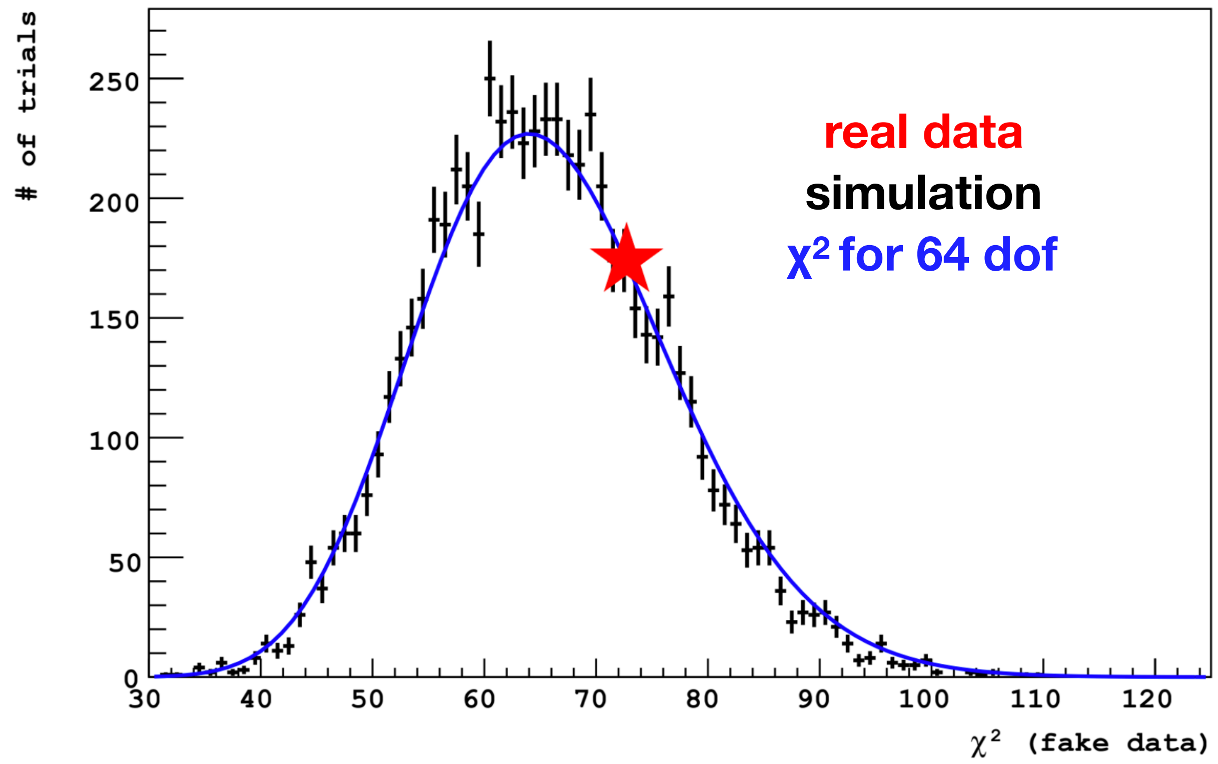
$$\chi^2_i = \min_\alpha(\chi^2_{i,\alpha})$$

Marginalize over signal normalization α in non-normal time bins.

$$\chi^2 = \sum_i \chi^2_i + f_{\mathrm{pull}}$$

Expect no signal in first time bin, so compare distribution of events in that time bin to background candidate to form pull term.

χ^2 Results



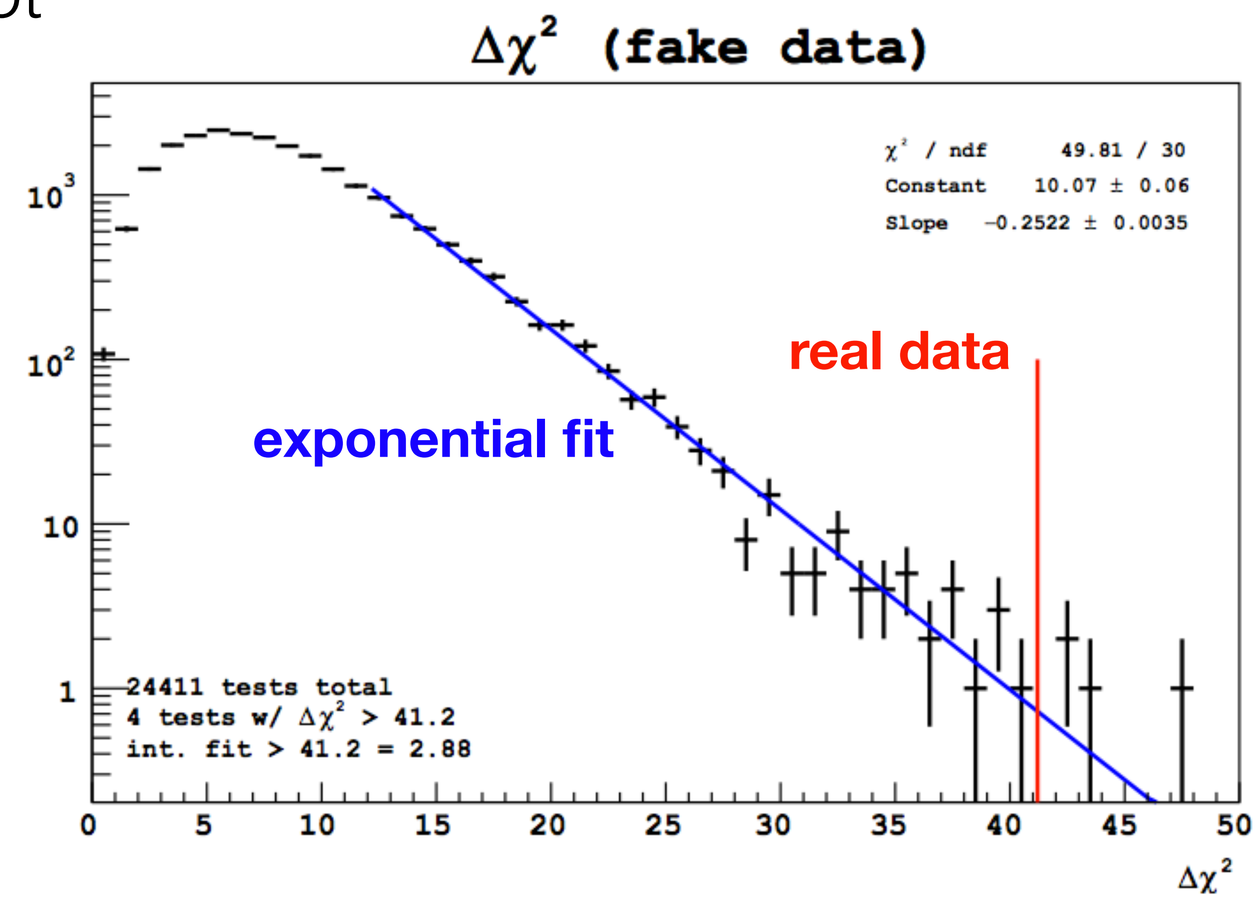
Test 10,000s combinations of shapes, normalizations, and endpoints.

Report χ^2 for each candidate signal, marginalizing over varying signal normalization in each time bin.

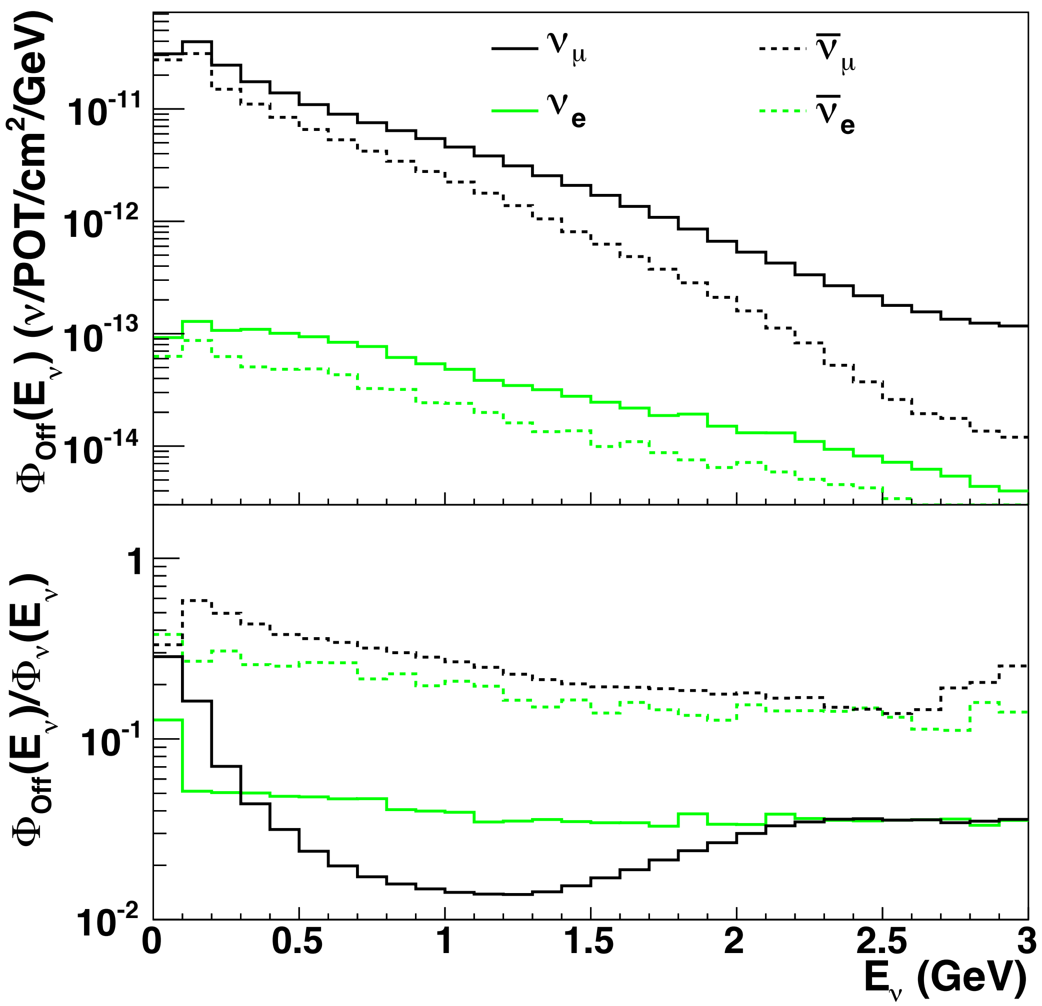
Simulated data demonstrates that extended maximum likelihood follows χ^2 distribution for (# bins - # of parameters) degrees of freedom

Observation Significance

- Calculate χ^2_{null} assuming no signal.
- Find: $\Delta\chi^2 = \chi^2_{\text{null}} - \chi^2_{\text{min}} = 41.2$
- We use a Poisson χ^2 statistic rather than the standard one, so we can not directly convert this $\Delta\chi^2$ to a probability.
- Instead, generate lots of fake data assuming no signal.
- Find χ^2_{min} of each fake dataset.
- Use this sample to find significance of observation: 3.9σ



MiniBooNE-DM Flux



Predicted flux (off-target)

Off-target flux ratio to nu-mode

MiniBooNE-DM Model

Minimal dark sector model.

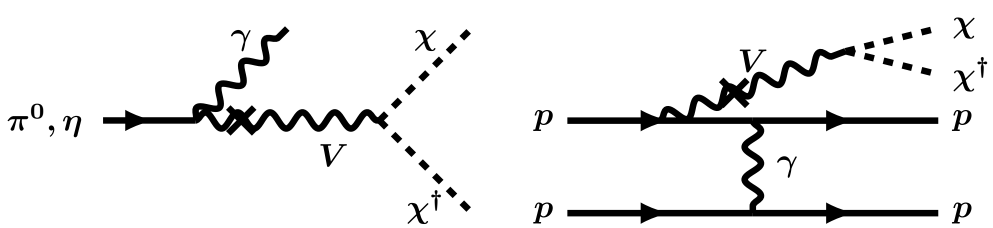
Interactions with χ mediated by U(1) gauge boson V_μ ("dark photon") that kinetically mixes with ordinary photon.

Four tunable physics parameters:

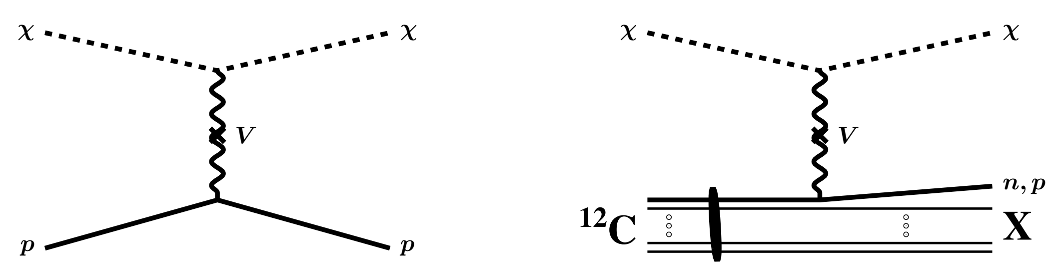
DM mass (m_χ), V_μ mass (m_V), kinetic mixing (ϵ), dark gauge coupling (g_D)

Dark matter particle is assumed to be a complex scalar.

Event rate scales as $\epsilon^4 g_D^2/(4\pi)$ for $m_V > 2m_\chi$.



(a) π^0, η Decay (b) Proton Bremsstrahlung



(a) Free protons (b) Bound nucleons in ^{12}C.

Production rates scale as ϵ^2

Scattering rate scales as $\epsilon^2 g_D^2/(4\pi)$