New Physics at Accelerator-Based Short-Baseline Neutrino Experiments

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April 15, 2019

Atomic Nuclei as Laboratories for BSM Physics

ECT* - Trento, Italy

Outline

- Anomalies
  - Future oscillation experiments
  - New physics explanations
  - The MiniBooNE anomaly - a case study
- Searches
  - Models
  - Experimental constraints
- Neutrino Interaction Physics
  - Neutrinos as BSM backgrounds
  - KDAR neutrinos

Anomalies

Short-Baseline Anomalies

Experiment	Source	Oscillation Channel	Significance
LSND	Pion and muon decay-at-rest (DAR)	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8σ
MiniBooNE	Pion and kaon decay-in-flight (DIF)	$\bar{\nu}_\mu \to \bar{\nu}_e$	2.8σ
MiniBooNE	Pion and kaon decay-in-flight (DIF)	$\nu_\mu \to \nu_e$	4.5σ
Reactors	Beta Decay	$\bar{\nu}_e \to \bar{\nu}_e$	Varies
GALLEX/SAGE	Radioactive Source (Electron Capture)	$\nu_e \to \nu_e$	2.8σ

Future experiments are coming online to provide improved tests of the anomalies.

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I'll highlight two experimental programs designed to test the LSND and MiniBooNE anomalies.

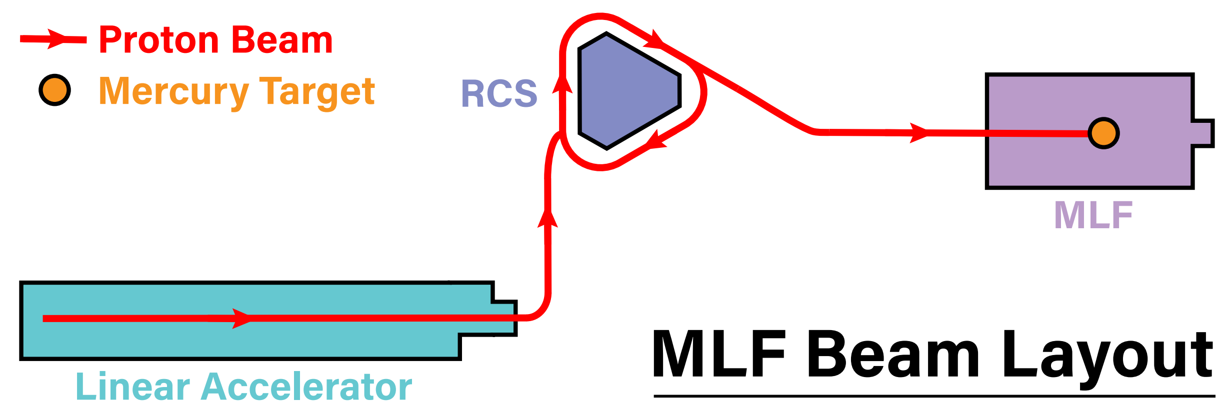
For a full review of eV-scale sterile neutrinos, see C. Giunti, T. Lasserre, arXiv:1901.08330

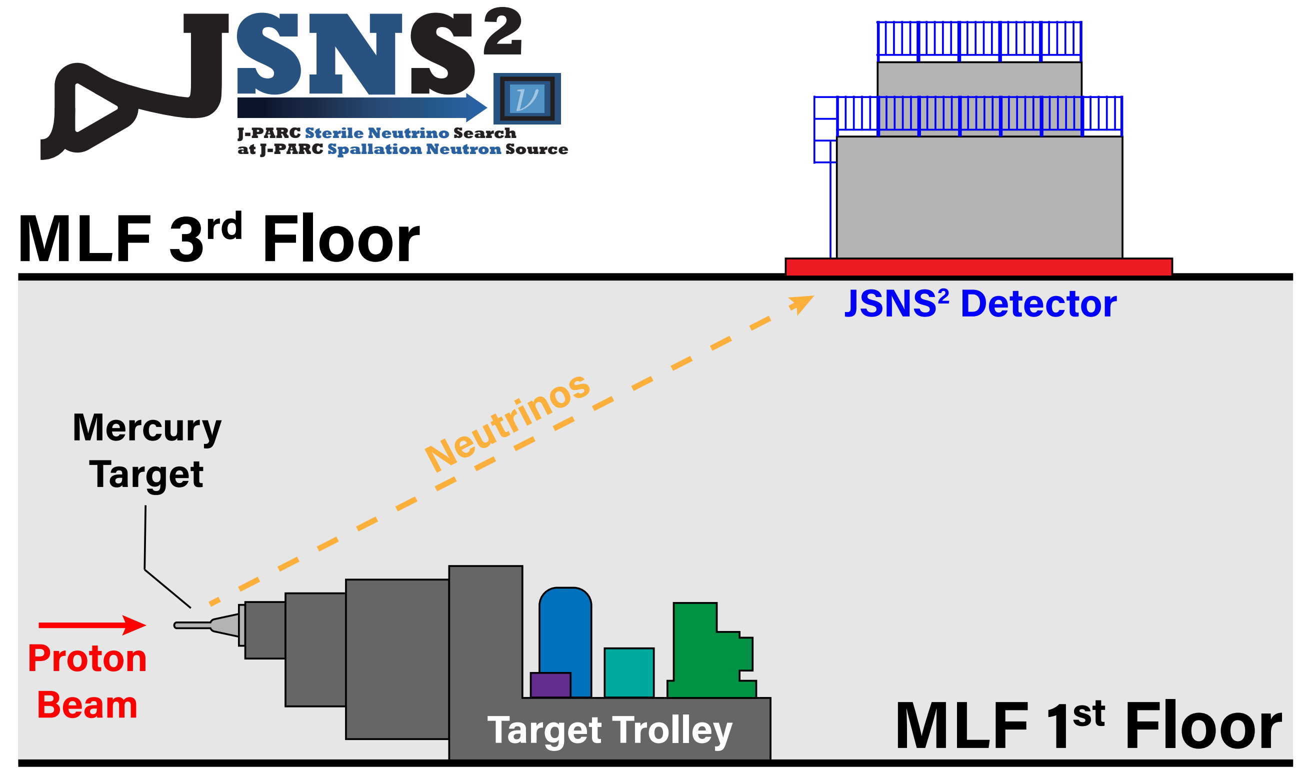
Future experiments are coming online to provide improved tests of the anomalies.

JSNS^2

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

- Direct test of LSND
- Target volume filled with Gd-doped liquid scintillator
  - Phase 0: 17 tons
  - Future Phases: Multiple detectors/baselines
- Uses a 3 GeV proton beam to generate a source of DAR neutrinos (~530 kW→1 MW)
- First data in 2019 (Phase 0)





JSNS² TDR arXiv:1705.08629

JSNS^2

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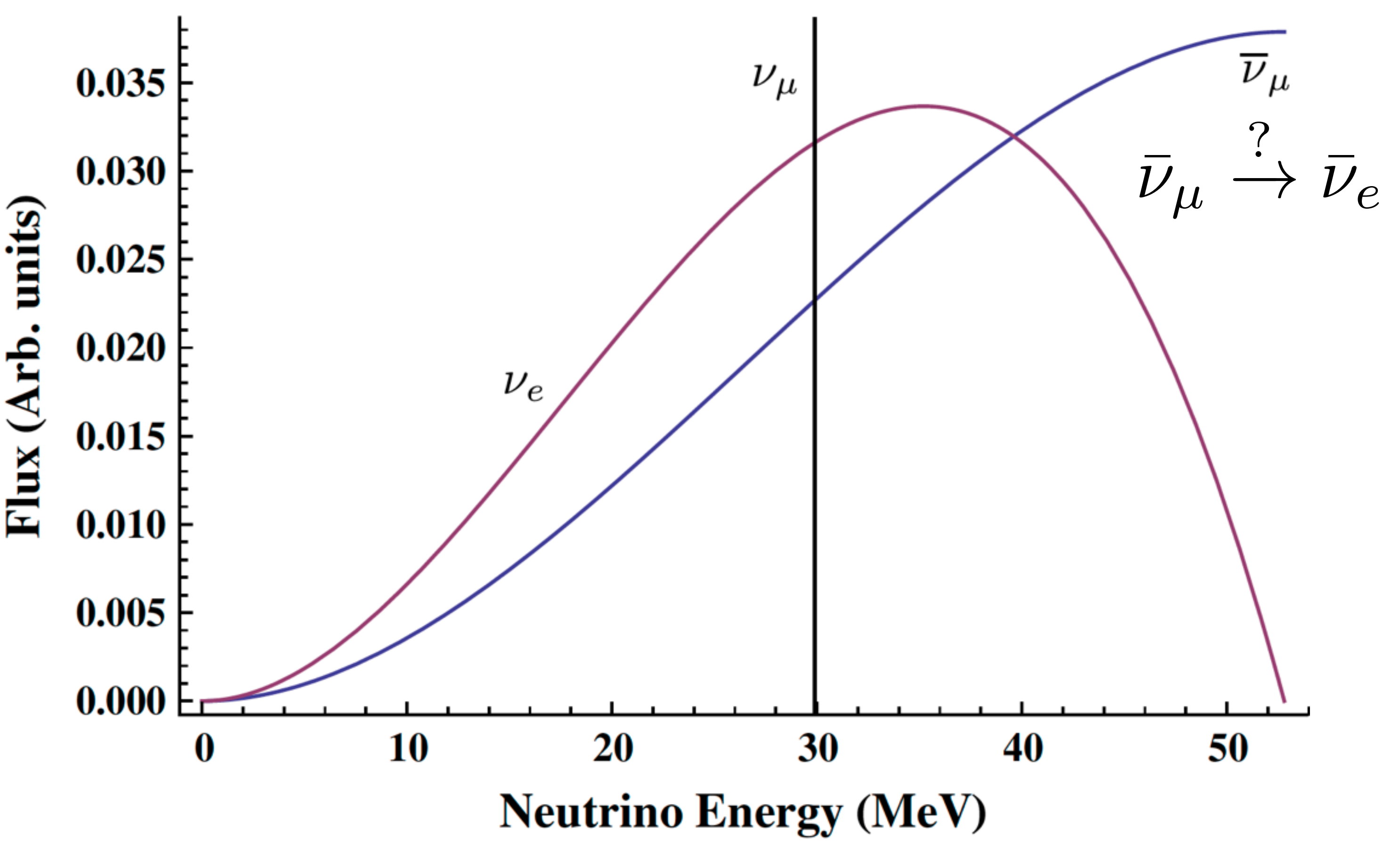
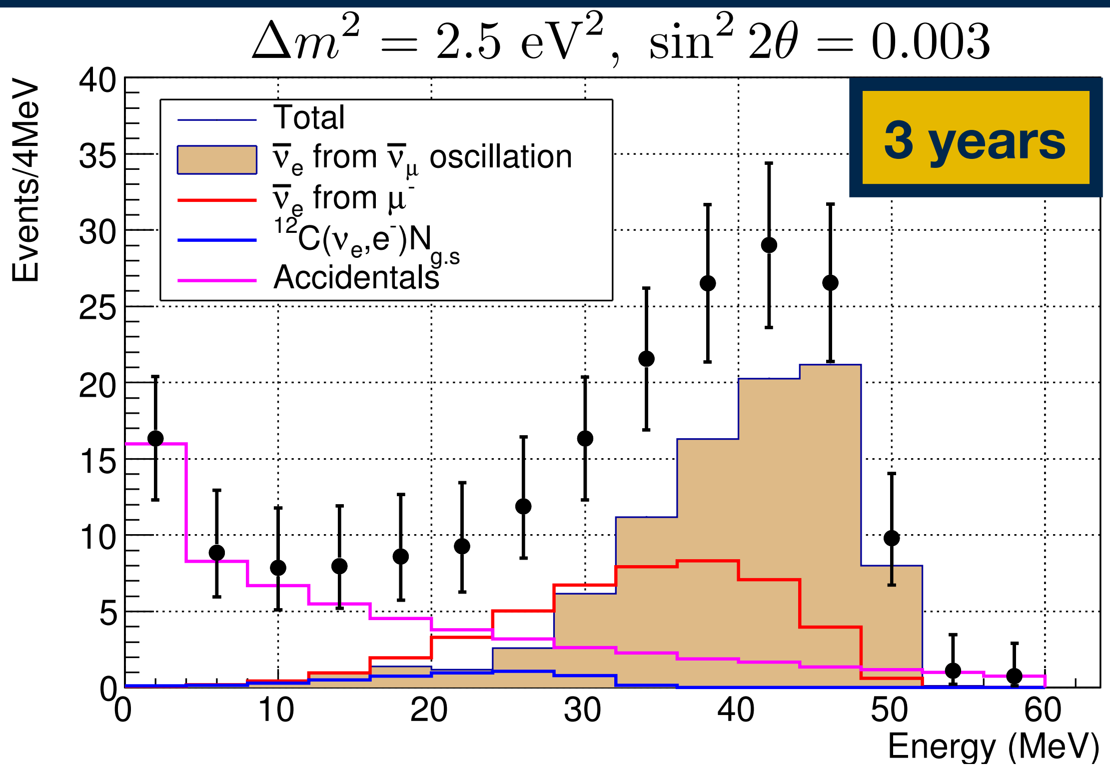
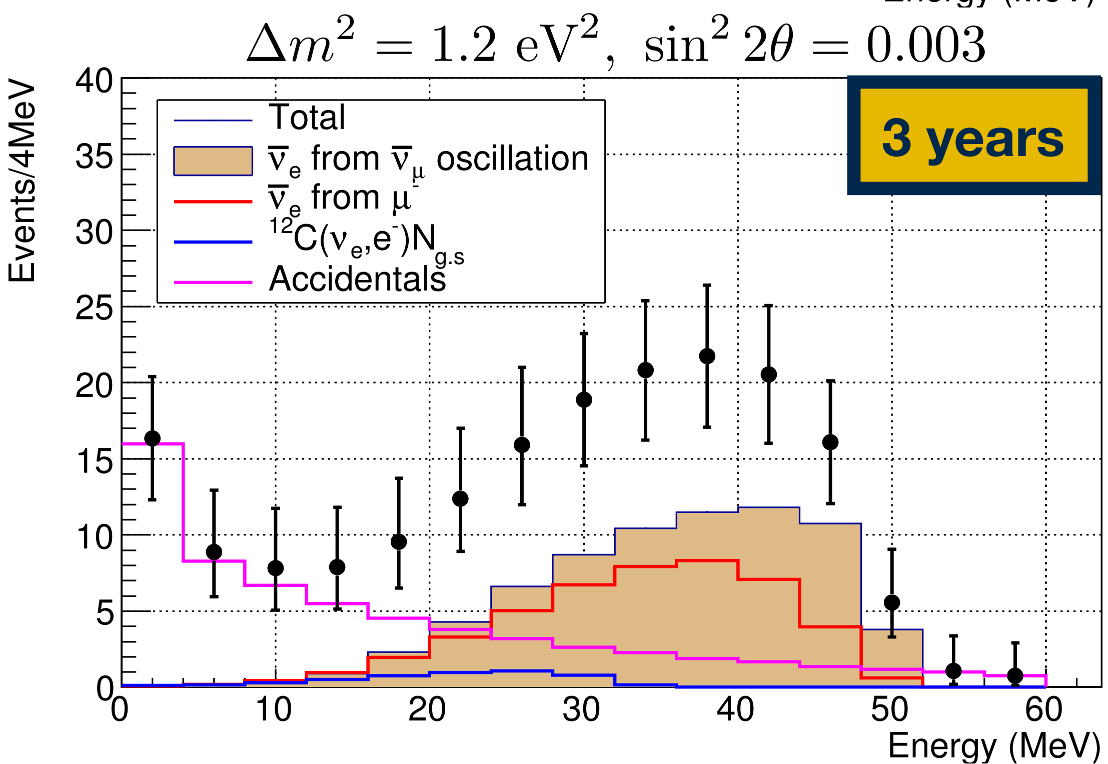
$$\pi^+ \to \mu^+ \nu_\mu \qquad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$





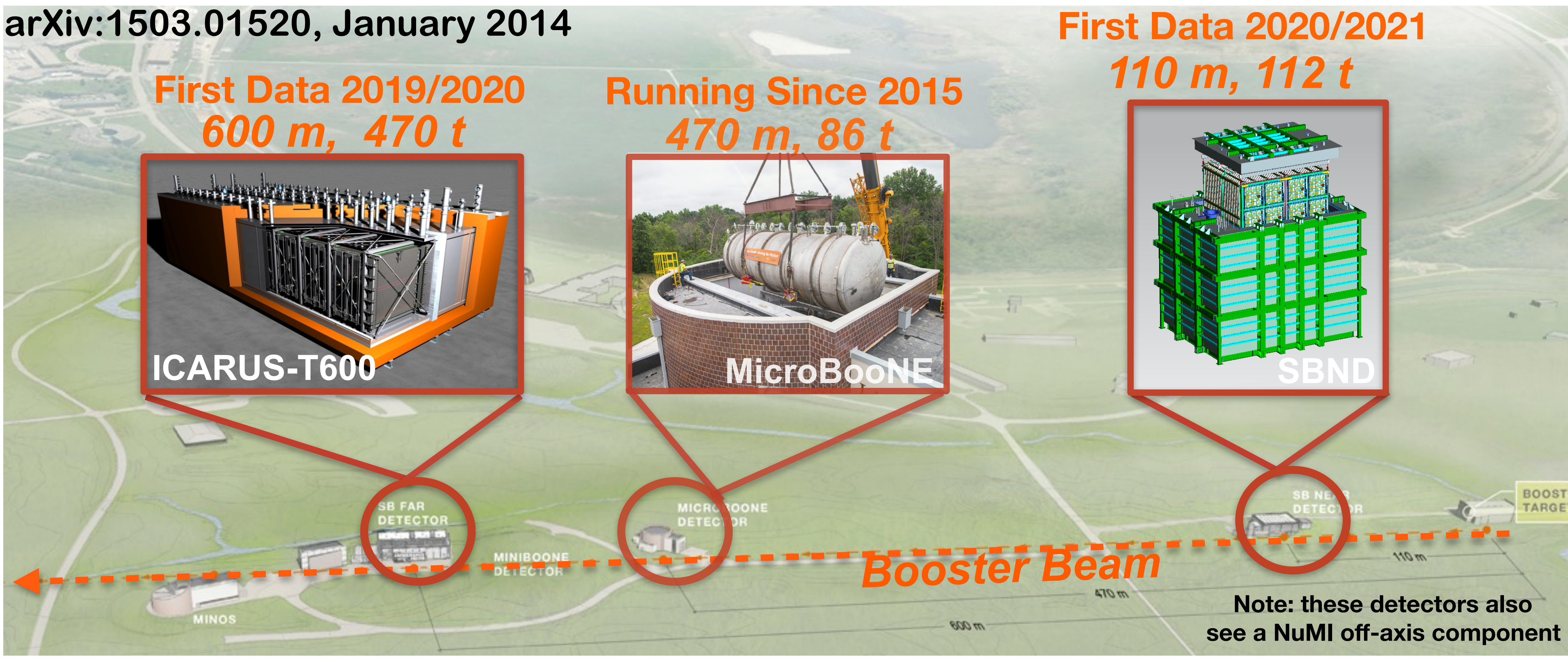


Oscillation candidates are identified by IBD double coincidences (positron, n-capture).

JSNS^2 TDR arXiv:1705.08629

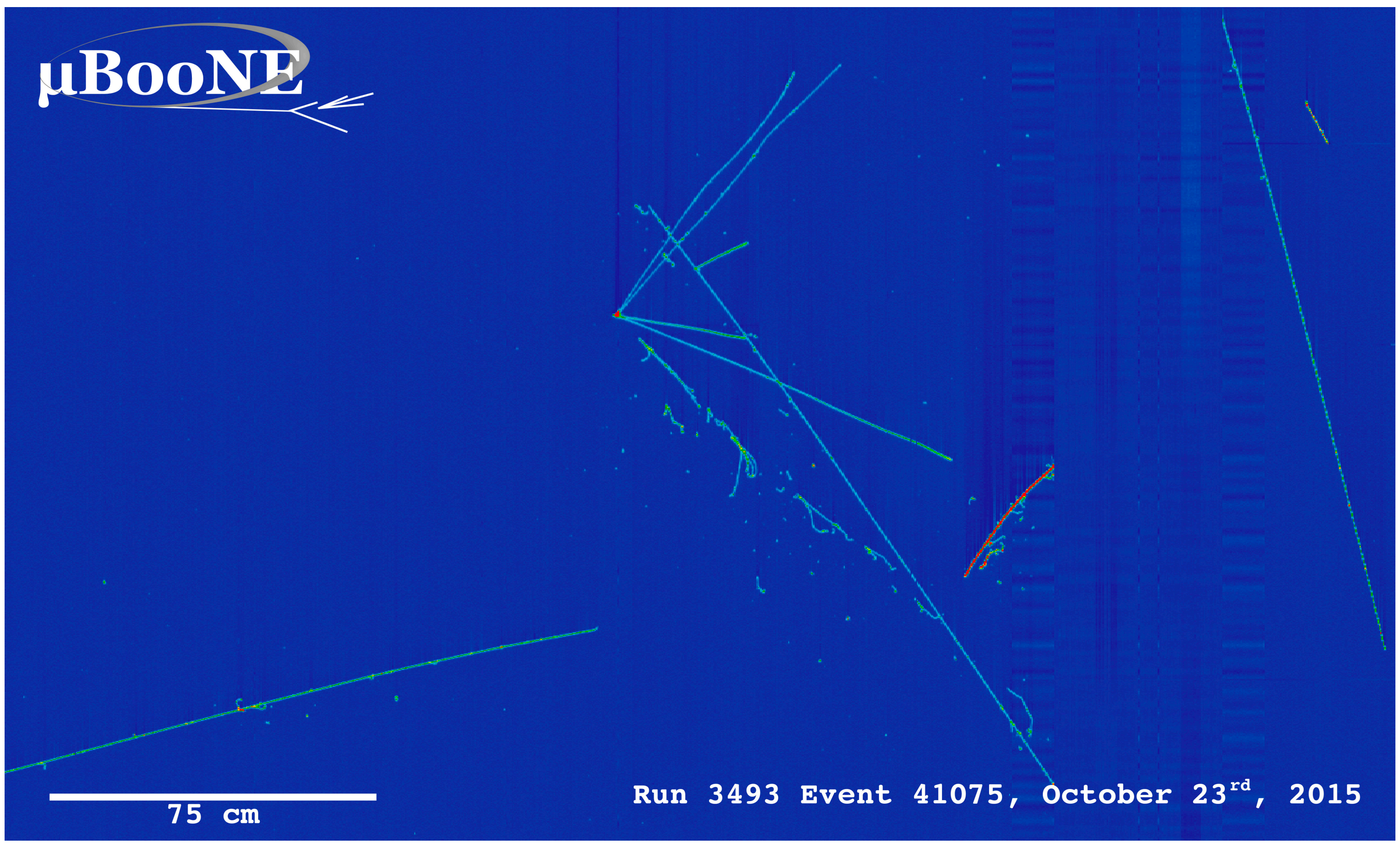
SBN

3 LArTPCs along the BNB at different baselines



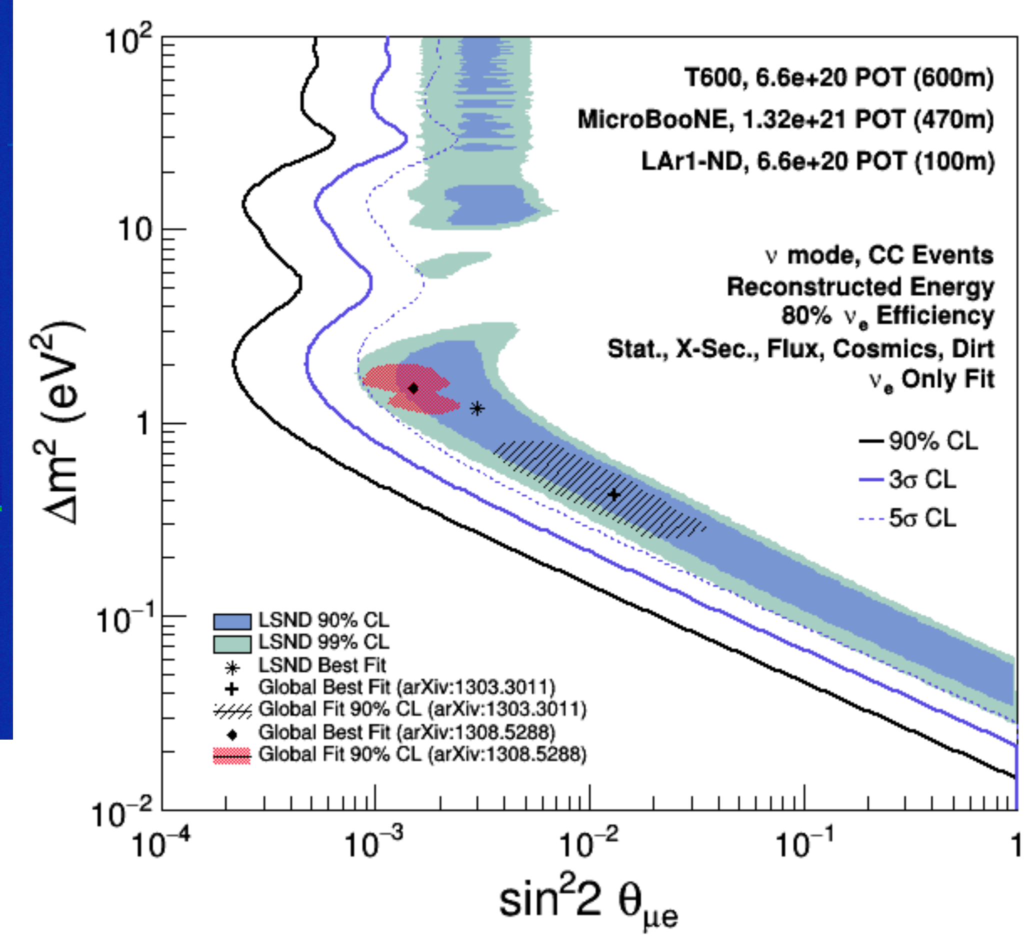
SBN Proposal: arXiv:1503.01520

SBN



The LArTPC technology produces exquisite images of neutrino interactions.

Sensitivity of the 3 detector SBN program



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Tension With Other Data

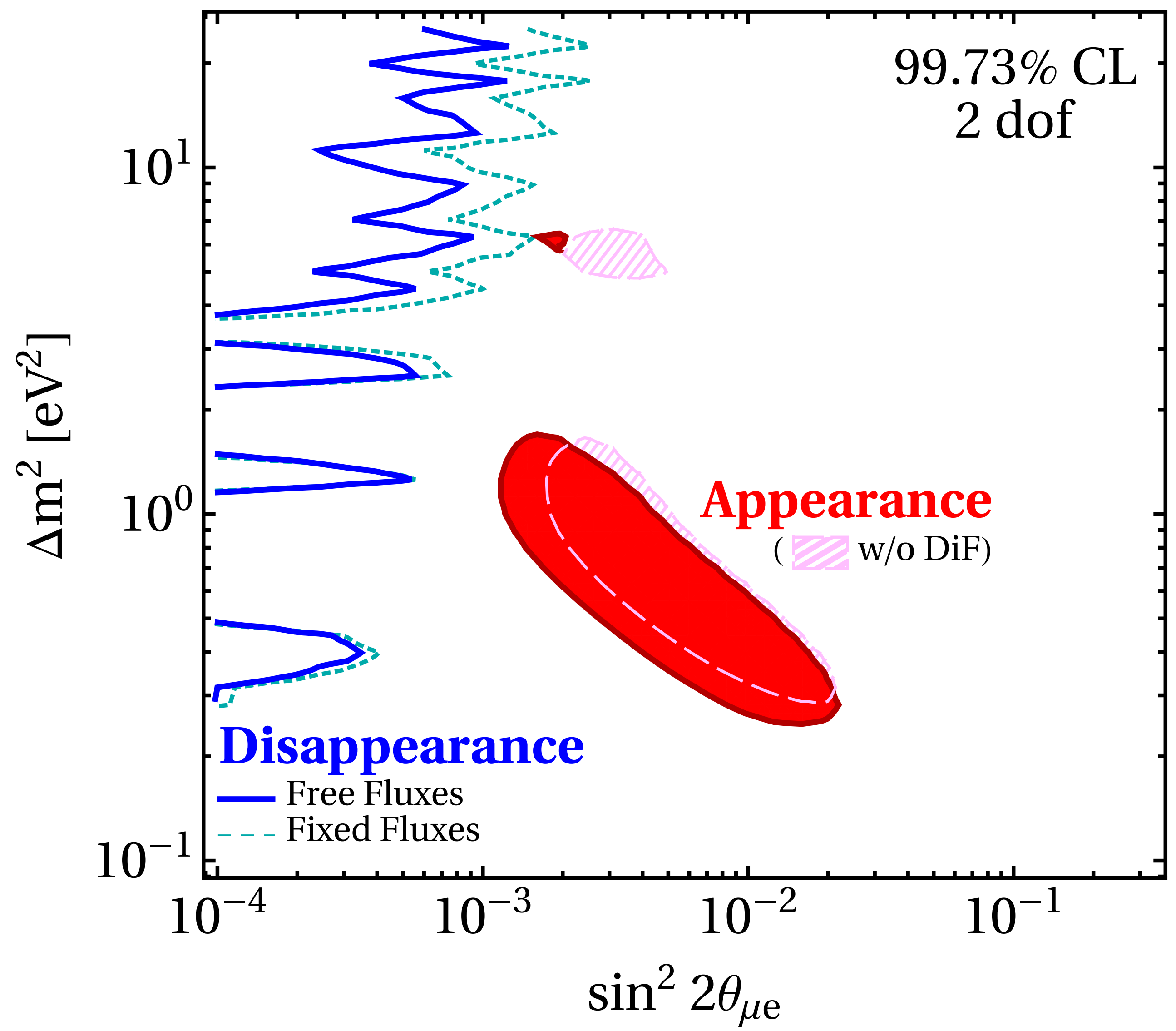
- There is tension between $\nu_\mu \rightarrow \nu_e$ appearance and ν_μ/ν_e disappearance
- In the short-baseline limit:

$$P_{ee} = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2)\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P_{\mu\mu} = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

This tension motivates other new physics explanations for the anomalies.



$$\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$$

M. Dentler et al., JHEP **08**, 010 (2018), 1803.10661

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Anomalies are a great place to start thinking about new physics at short baseline experiments.

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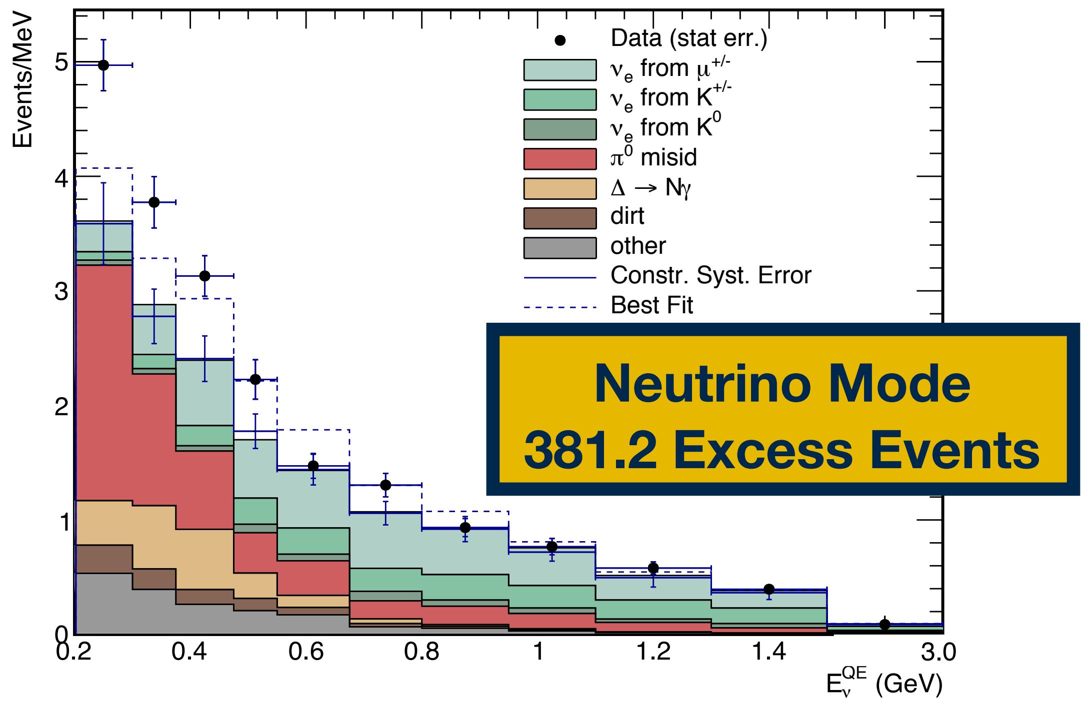
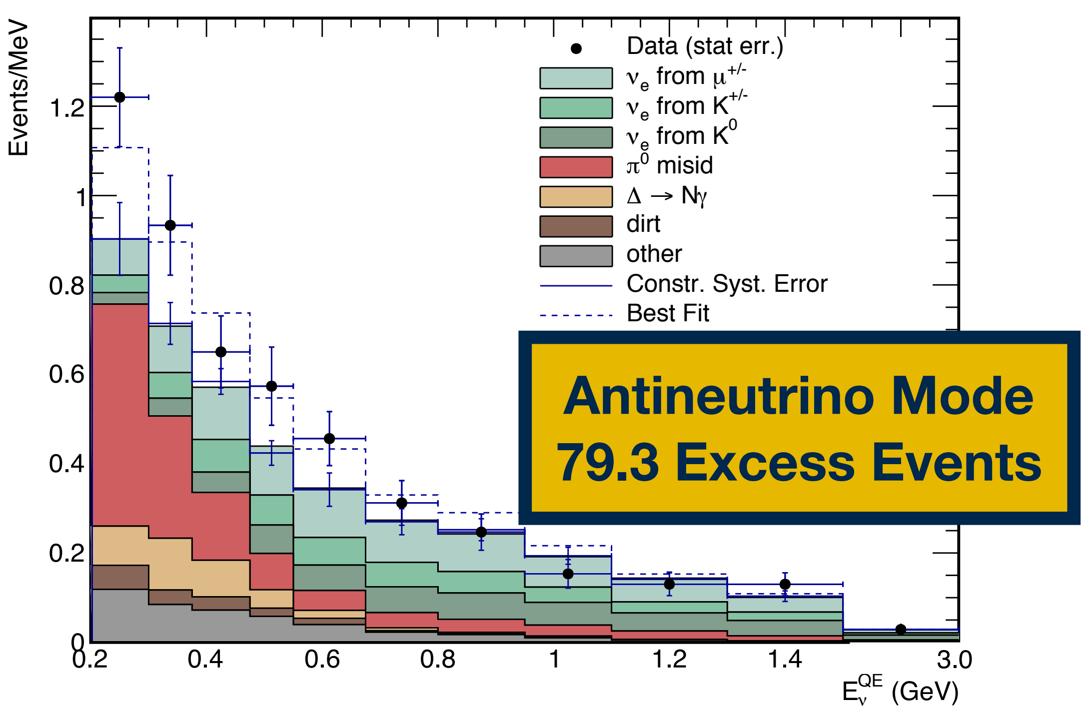
The MiniBooNE Excess

- MiniBooNE sees an excess of electron-like events at low energies
- A common interpretation is a new oscillation mode induced by an eV-scale sterile neutrino
- Consistent with the LSND anomaly in this picture





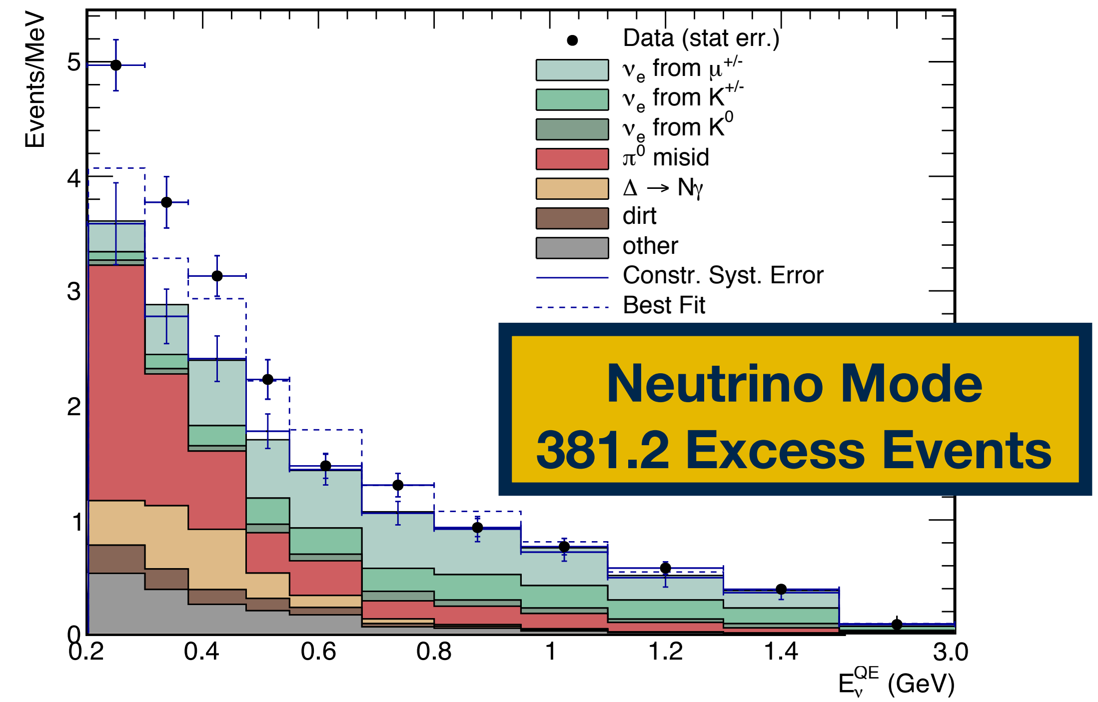
A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), (2018), 1805.12028

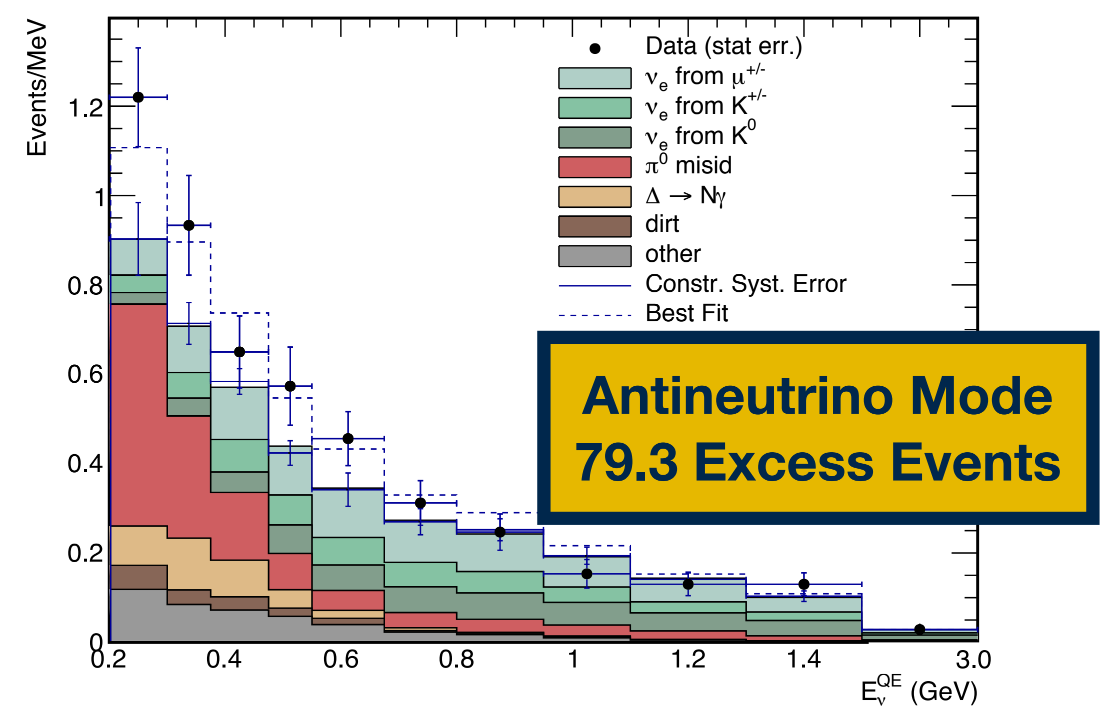
The MiniBooNE Excess

- MiniBooNE sees an
excess of electron-like

Can a BSM physics model produce the MiniBooNE excess without sterile neutrinos?

anomaly in this picture



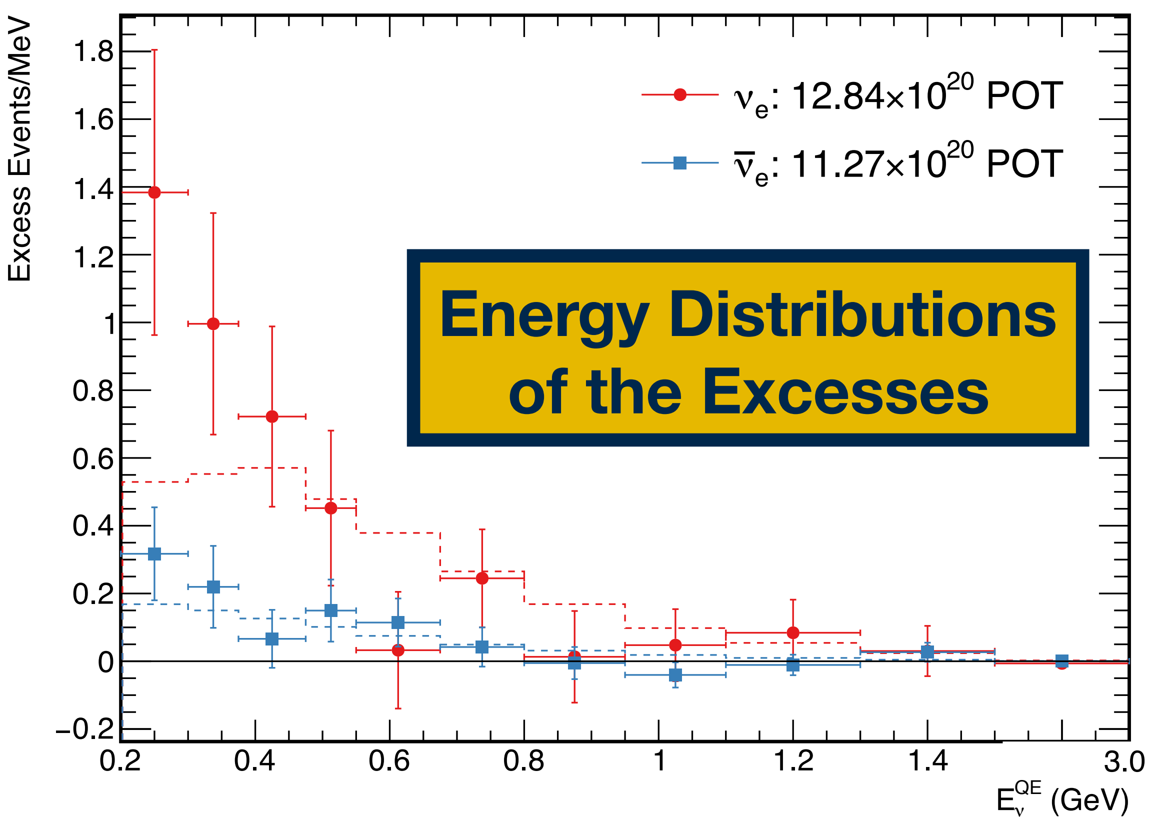


A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), (2018), 1805.12028

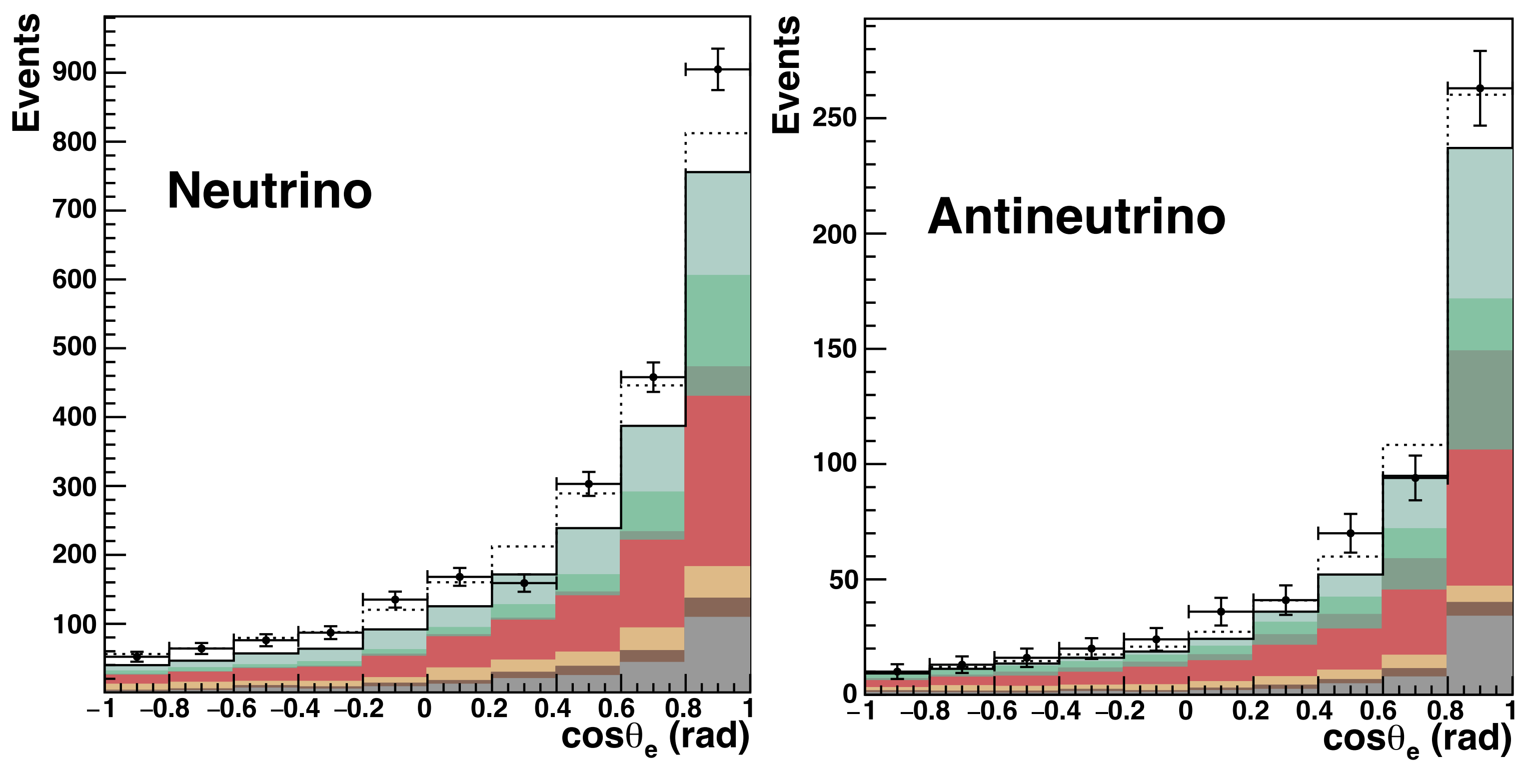
Models

- A new physics model (which may or may not involve neutrinos) for the low energy excess must specify two things:
  - A production mode for the new particle
  - An electron-like detector signature which fakes the ν_e CCQE signal ($\nu_e n \rightarrow e^- p$) in MiniBooNE:
    - Visible (e.g. $X \rightarrow e^+ e^-$) or semi-visible (e.g. $X \rightarrow X^` \gamma$) decays in the detector
    - Elastic or inelastic scattering off of particles in the detector
- The MiniBooNE data rules out entire production modes and detector signatures

Model Requirements



Energy Distributions of the Excesses

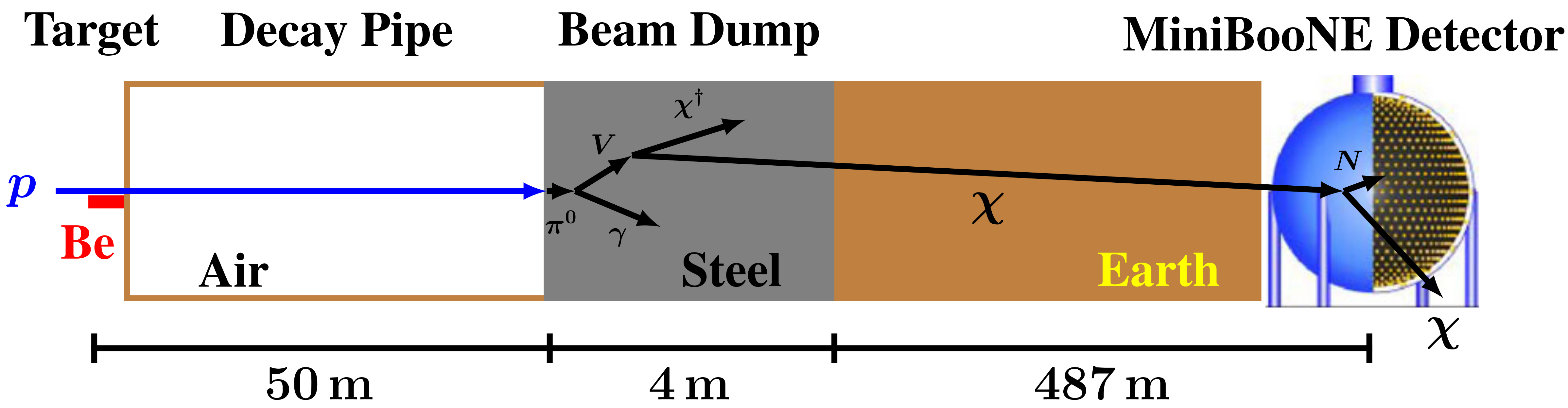


Angular Distributions of the Excesses

A good model for the excess must agree with all of these distributions simultaneously.

A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Phys. Rev. Lett. **121**, 221801 (2018), 1805.12028

Beam Dump Mode

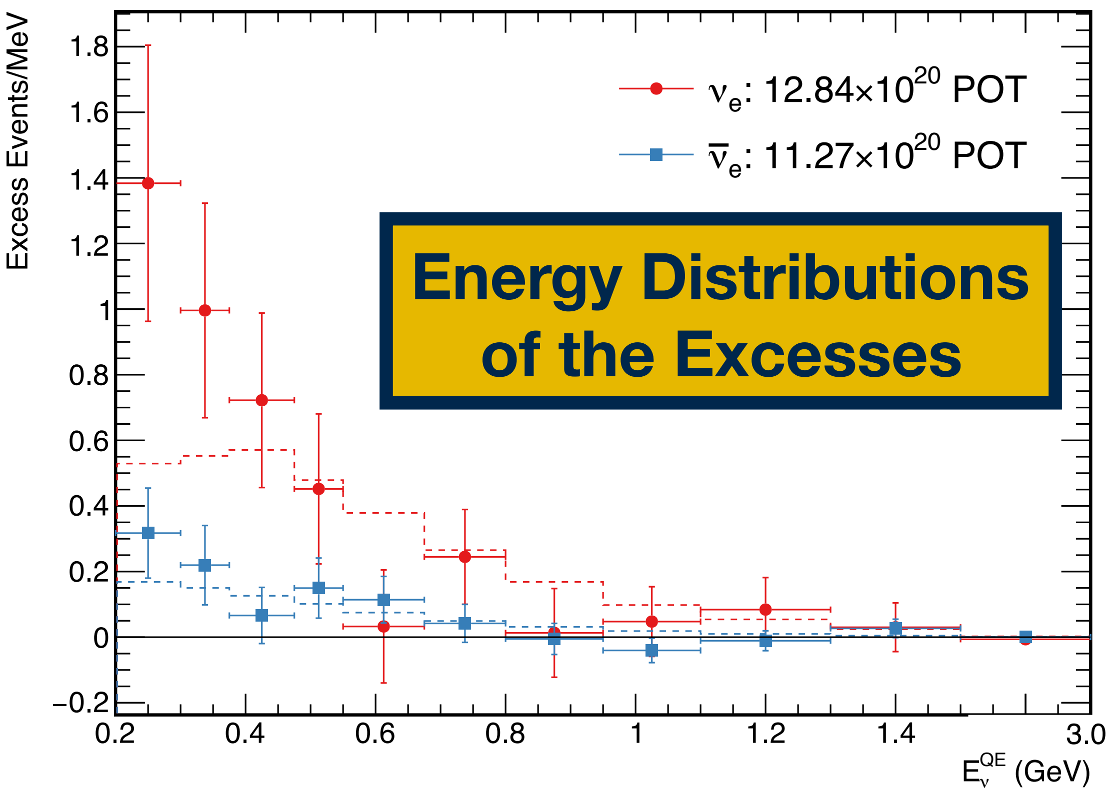


- MiniBooNE recently took data in beam dump mode where the beam is steered off target
- The goal was to search for new particles produced in the beam dump
- Reduced neutrino backgrounds (flux reduced by a factor of ~30, interaction rate by a factor of ~50) improve sensitivity

A. A. Aguilar-Arevalo et al. (MiniBooNE DM Collaboration) Phys. Rev. Lett. **118**, 221803, (2017), 1702.02688
A. A. Aguilar-Arevalo et al. (MiniBooNE DM Collaboration), (2018), PRD **98** 112004 (2018) 1807.06137

1.86×10^{20} POT in dump mode

Model Requirements



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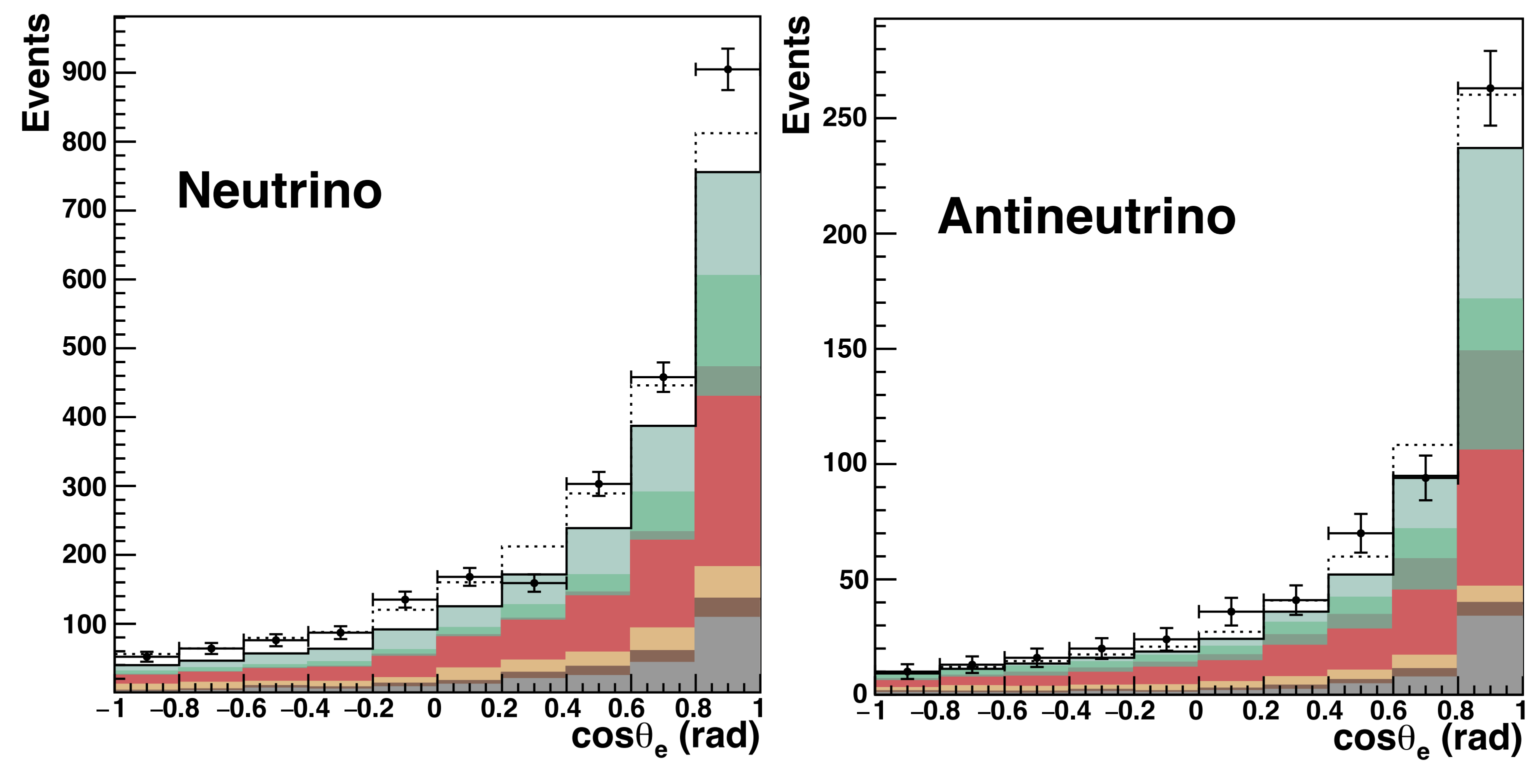

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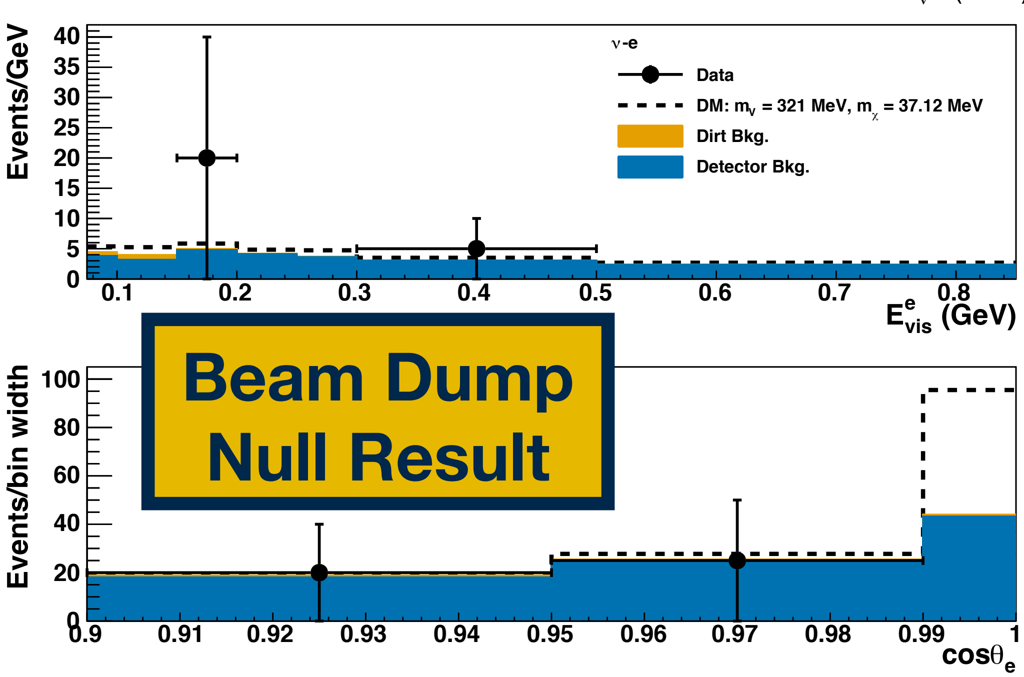

Beam Dump Null Result

How constraining are all of these results on new physics explanations of the excess?

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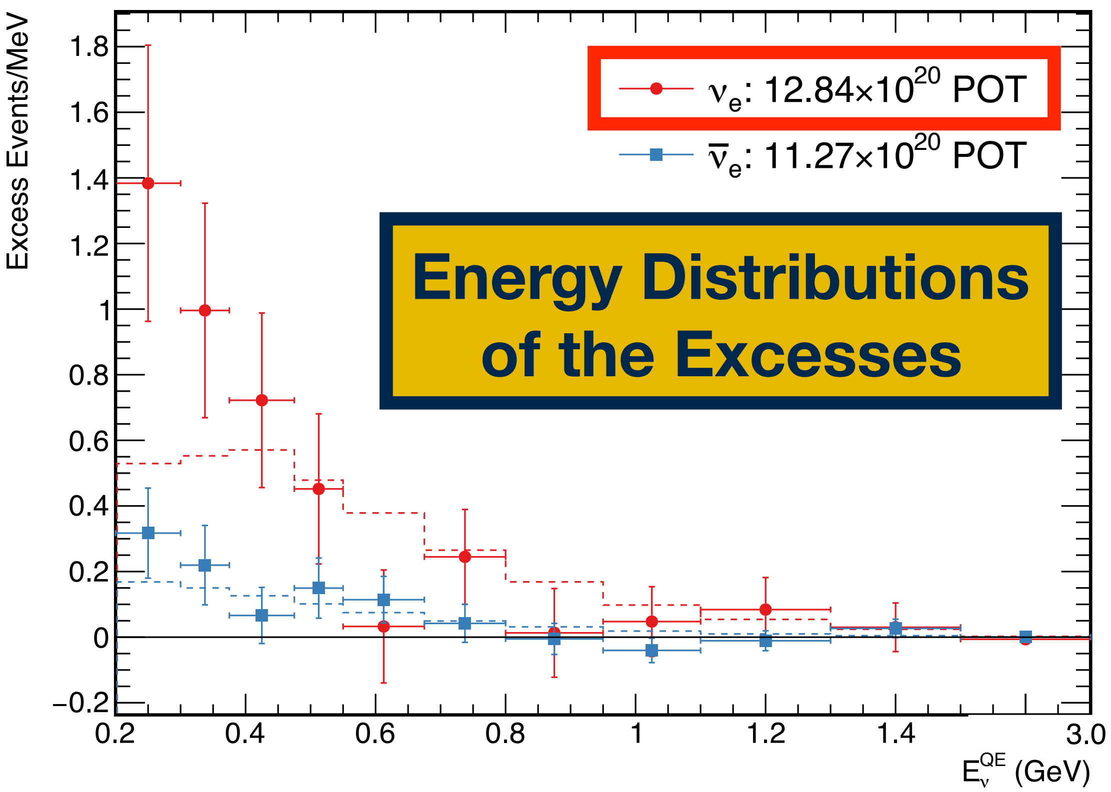

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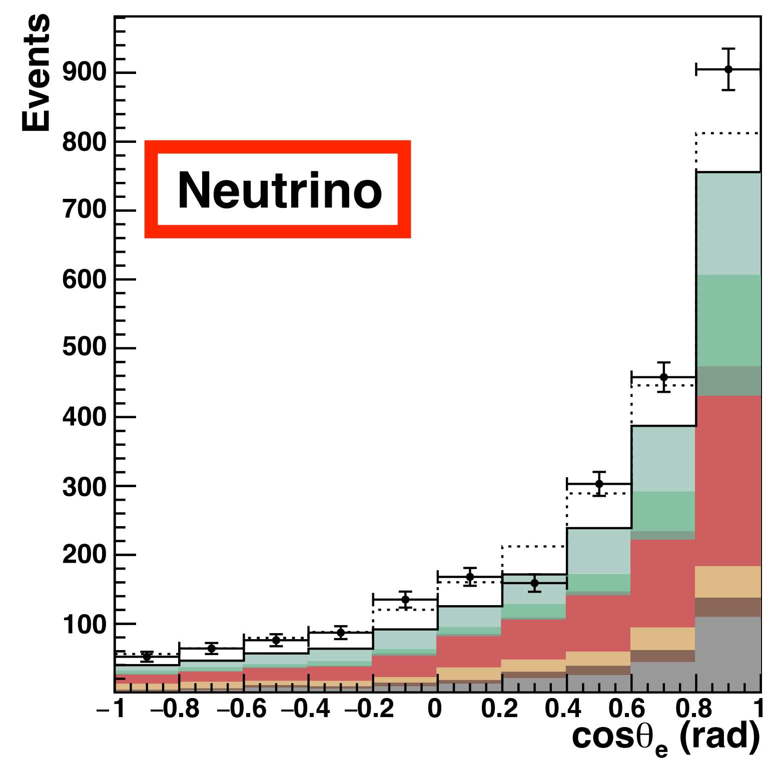
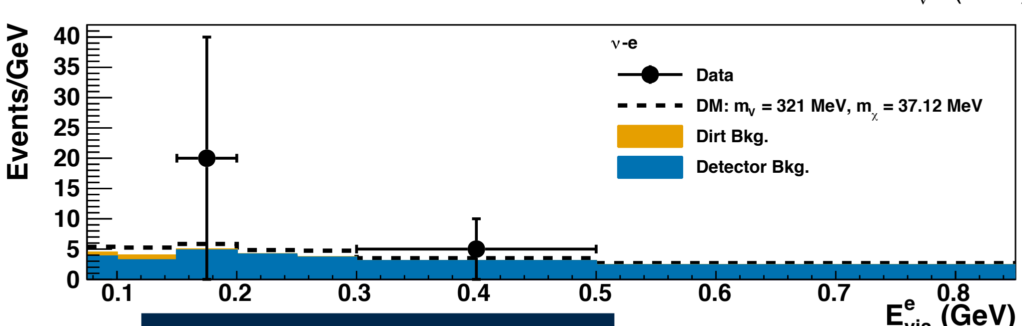
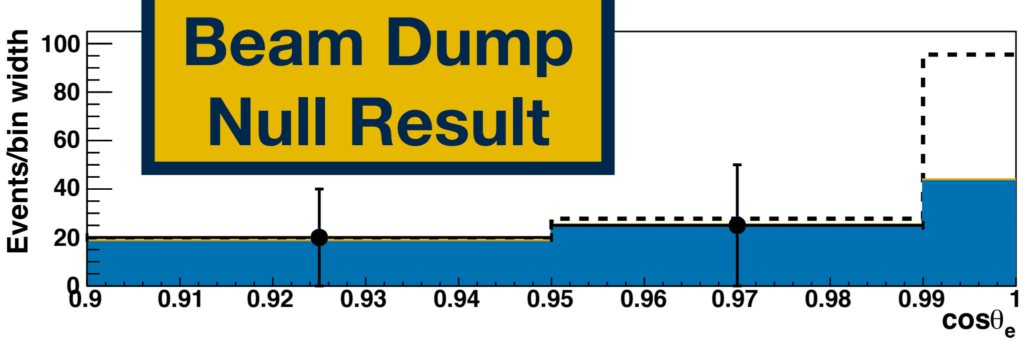


We will consider neutrino mode representative to simplify this discussion.

Angular Distributions of the Excesses





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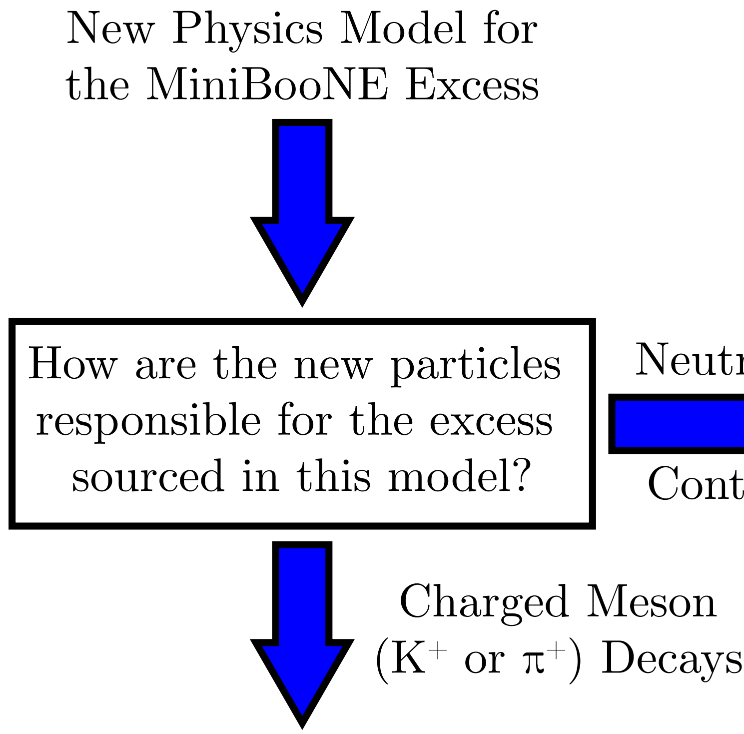
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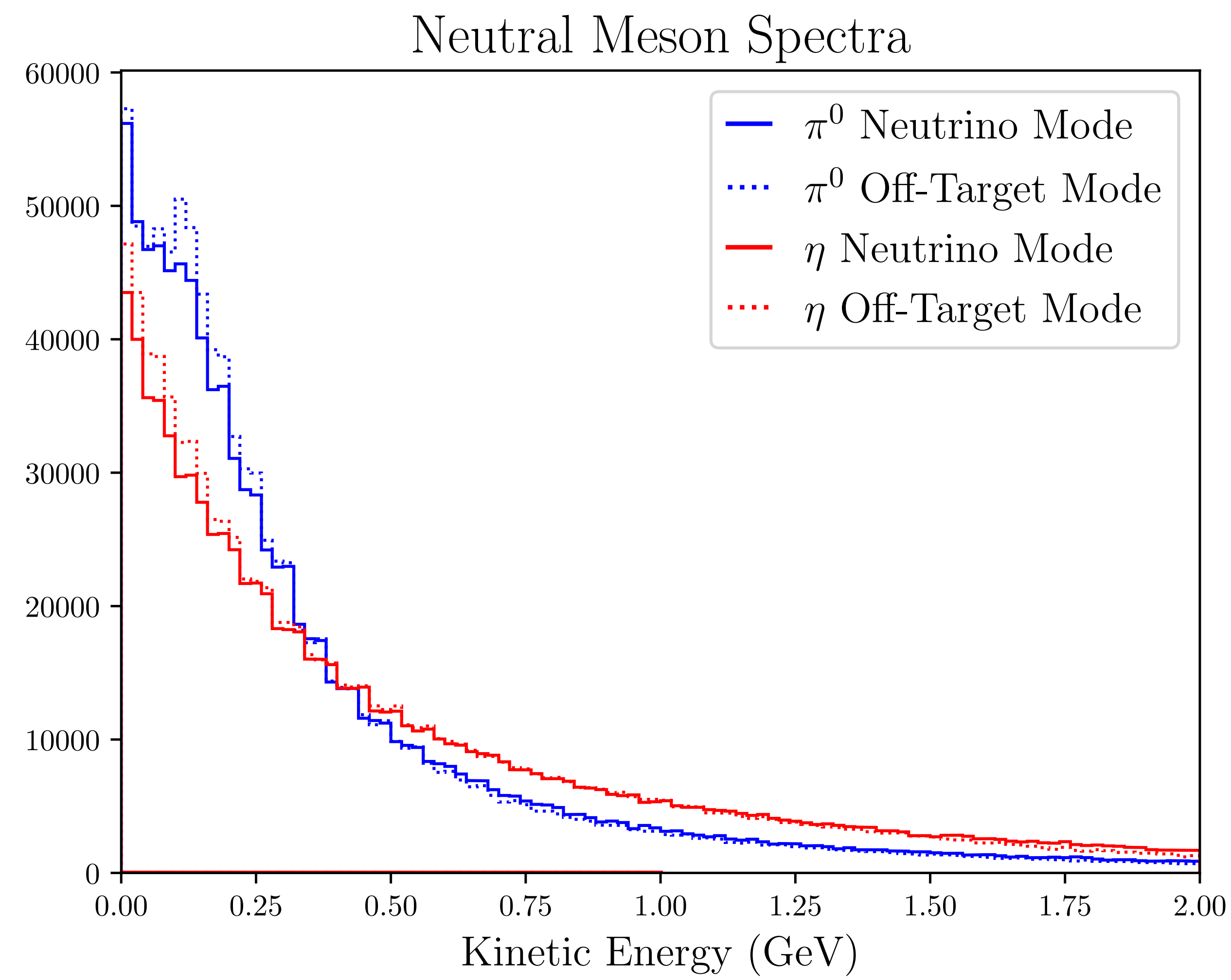
How are the new particles responsible for the excess sourced in this model?
Neutral Meson Decays
Continuum Processes
Charged Meson (K^+ or π^+) Decays

Production Constraints

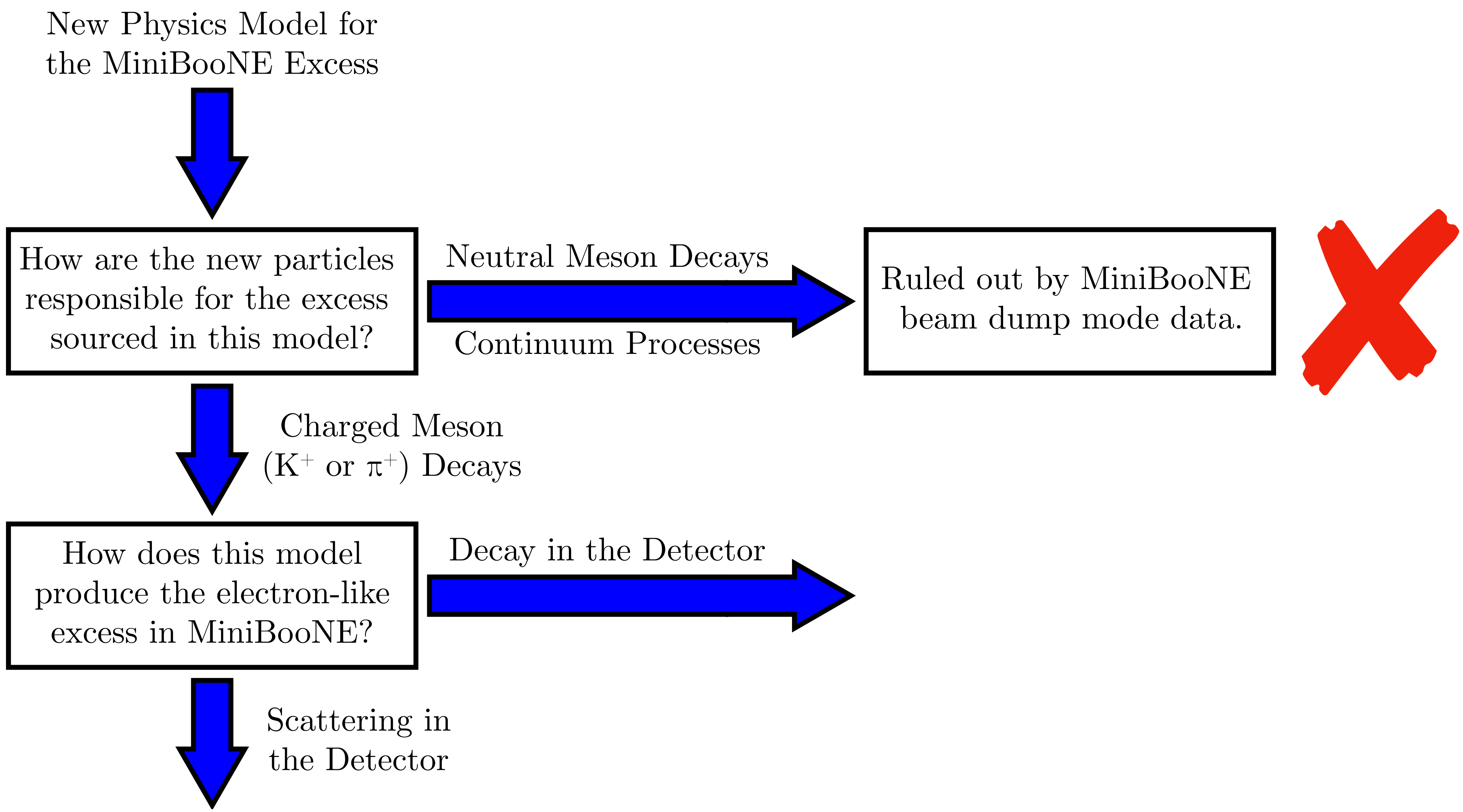
- The neutral meson kinematics and production rates are almost identical in neutrino mode and beam dump mode
- The number of events in beam dump mode will just depend on the ratio of POT:

$$\frac{1.86 \times 10^{20}\ \mathrm{POT}}{12.84 \times 10^{20}\ \mathrm{POT}} \times 381.2\ \mathrm{events} \approx 55\ \mathrm{events}$$



- Beam dump null result rules out new particle production that scales with POT (e.g. dark bremsstrahlung)

2 events observed on a predicted background of 2.4 ± 1.5 events. No elastic scattering candidates.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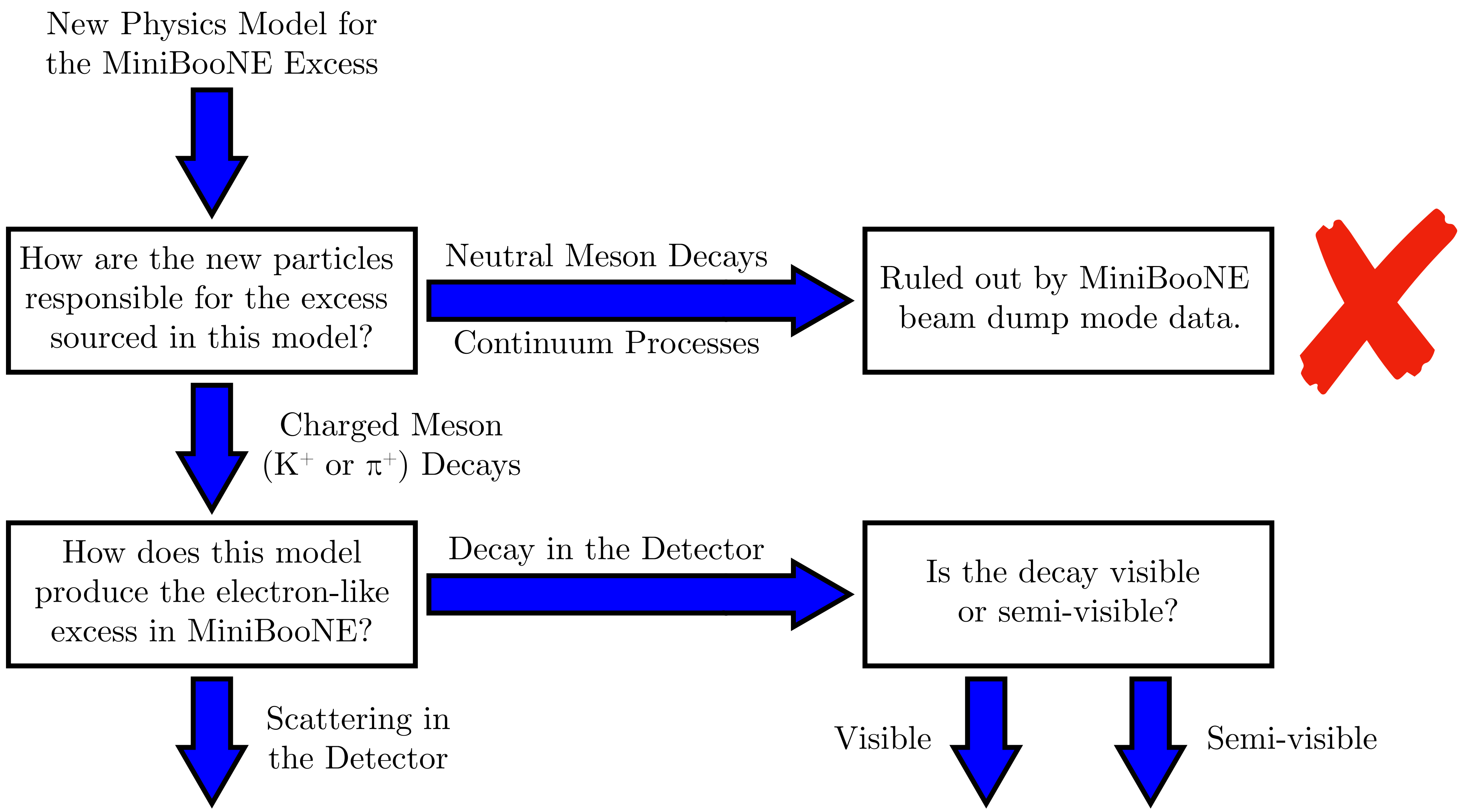
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Is the decay visible or semi-visible?
Scattering in the Detector
Visible
Semi-visible

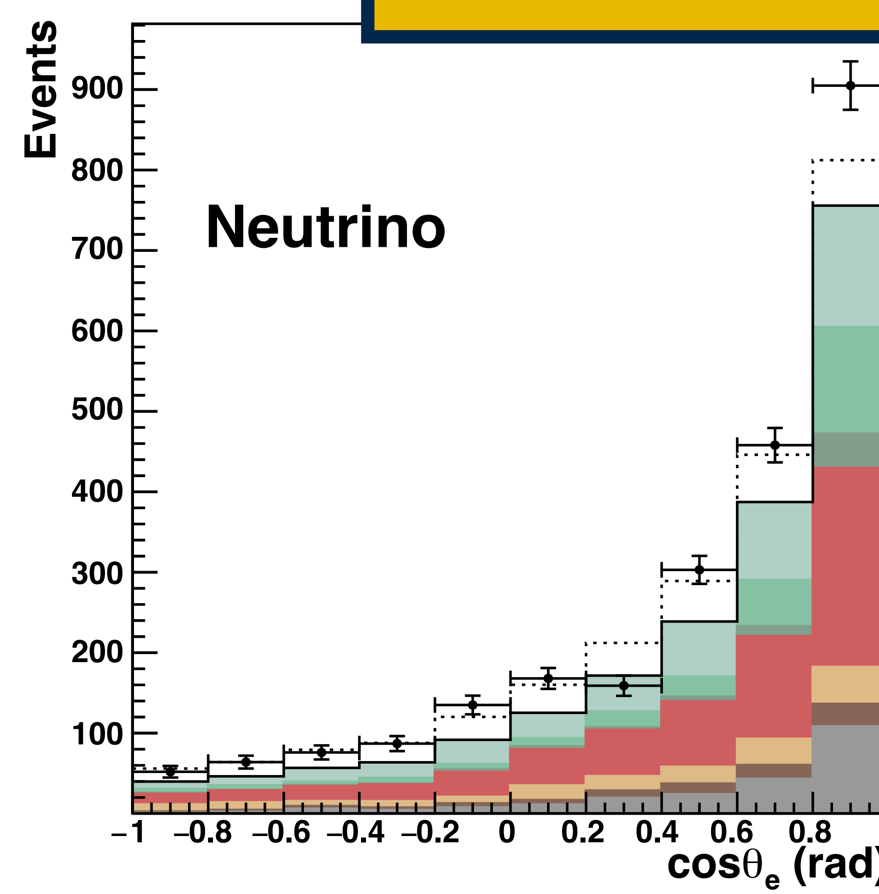
Visible Decays

- Consider a visible decay in the detector (e.g. X→e⁺e⁻ or X→$\gamma\gamma$)
- Overlapping tracks can look like a single electron in MiniBooNE
- Based on the invariant mass:

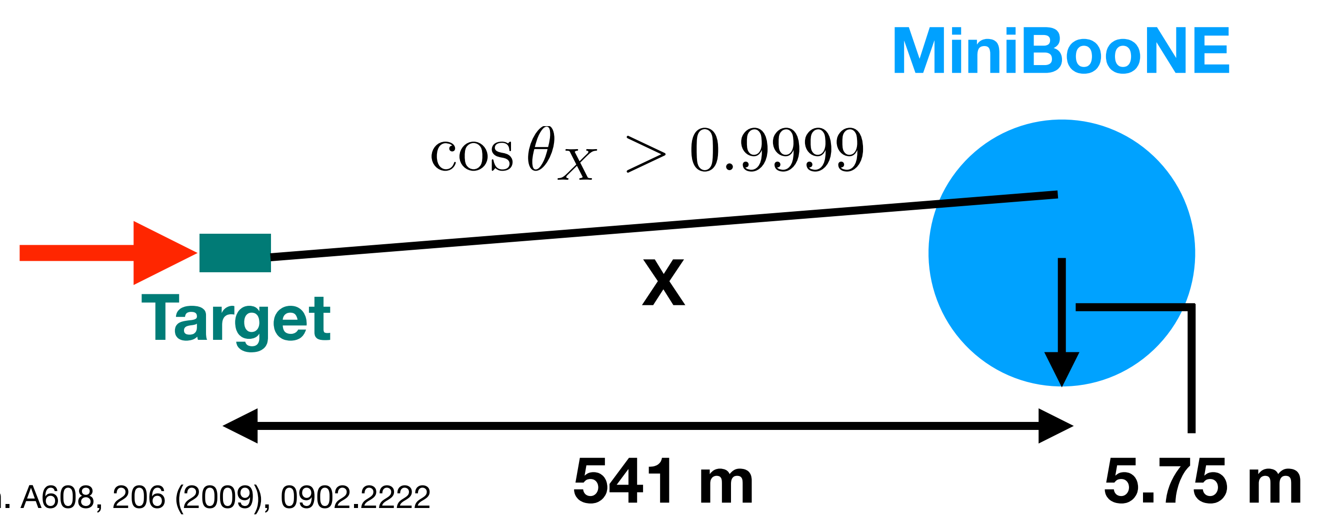
$$m_{track} \equiv \sqrt{2E_1E_2(1-\cos\theta_{12})}$$

- Two tracks are distinguishable if m_{track} > 30 MeV so m_X < 30 MeV
- The decay products must be highly boosted along the beam direction
- This cannot explain the angular distribution of the excess

Angular resolution is 3-5° for 100-600 MeV electrons



Excess for cosθ > 0.8 is ~150 events



R. B. Patterson, E. M. Laird, Y. Liu, P. D. Meyers, I. Stancu, and H. A. Tanaka, Nucl. Instrum. Meth. A608, 206 (2009), 0902.2222

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A similar argument works for semi-visible decays (e.g. $X \rightarrow X^{`} + \gamma$).

direction

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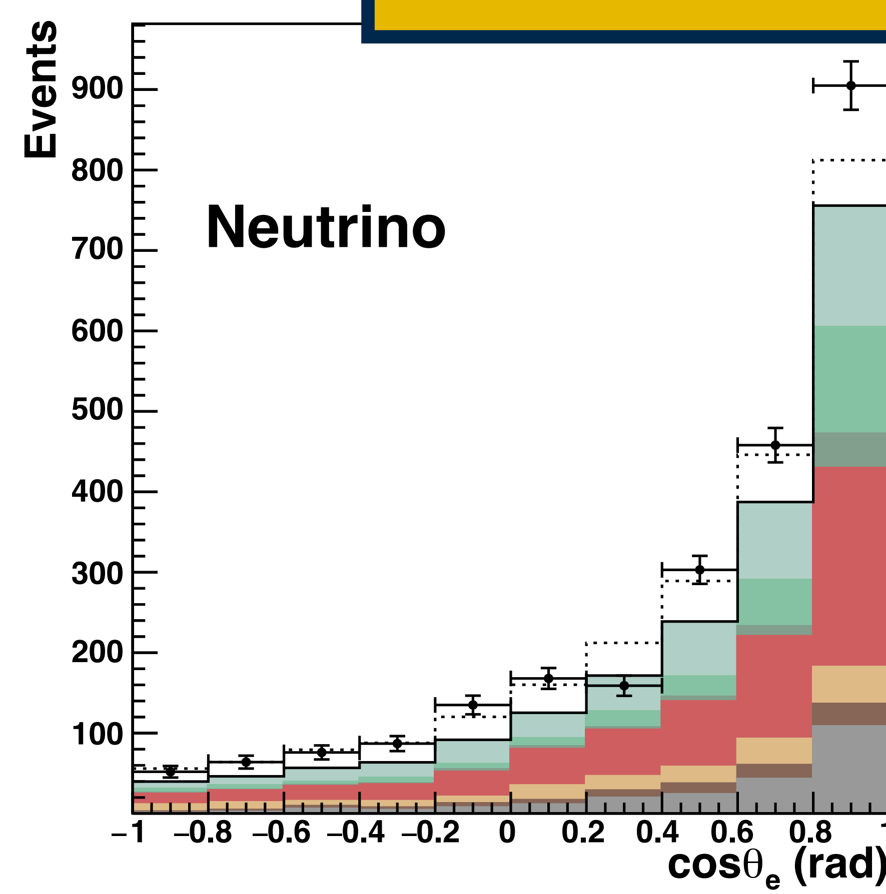

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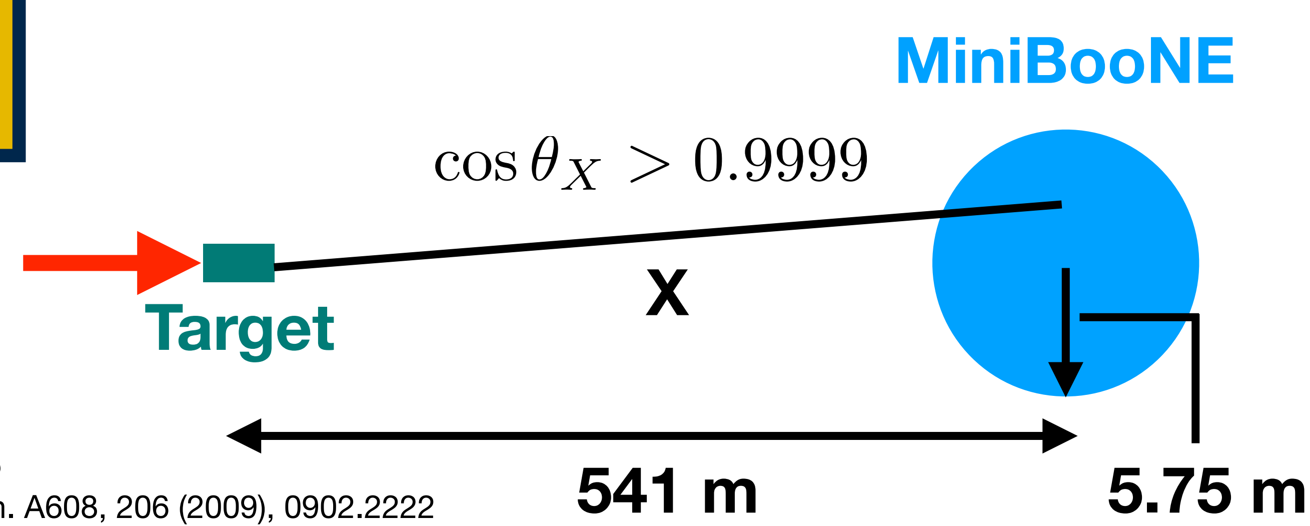

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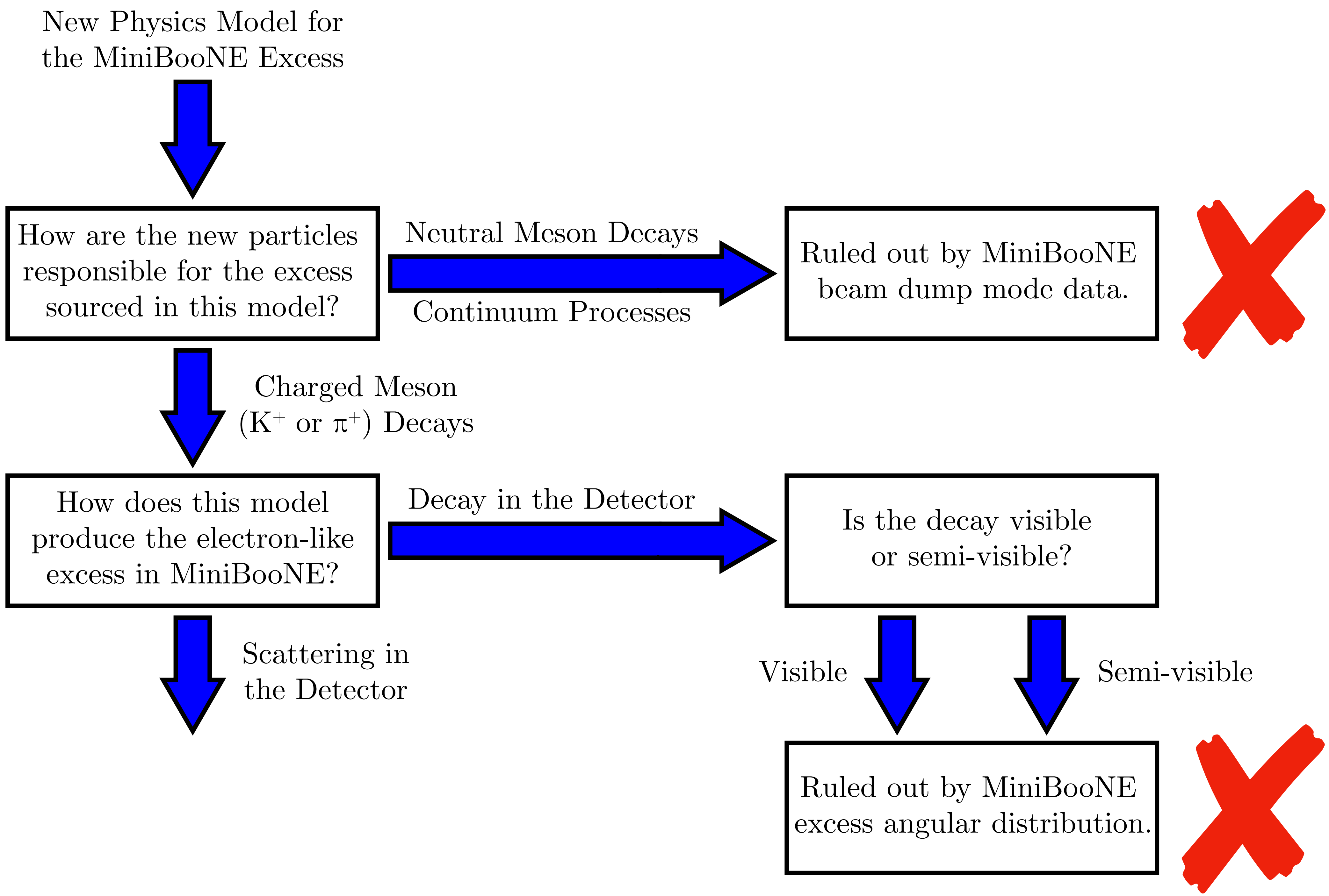
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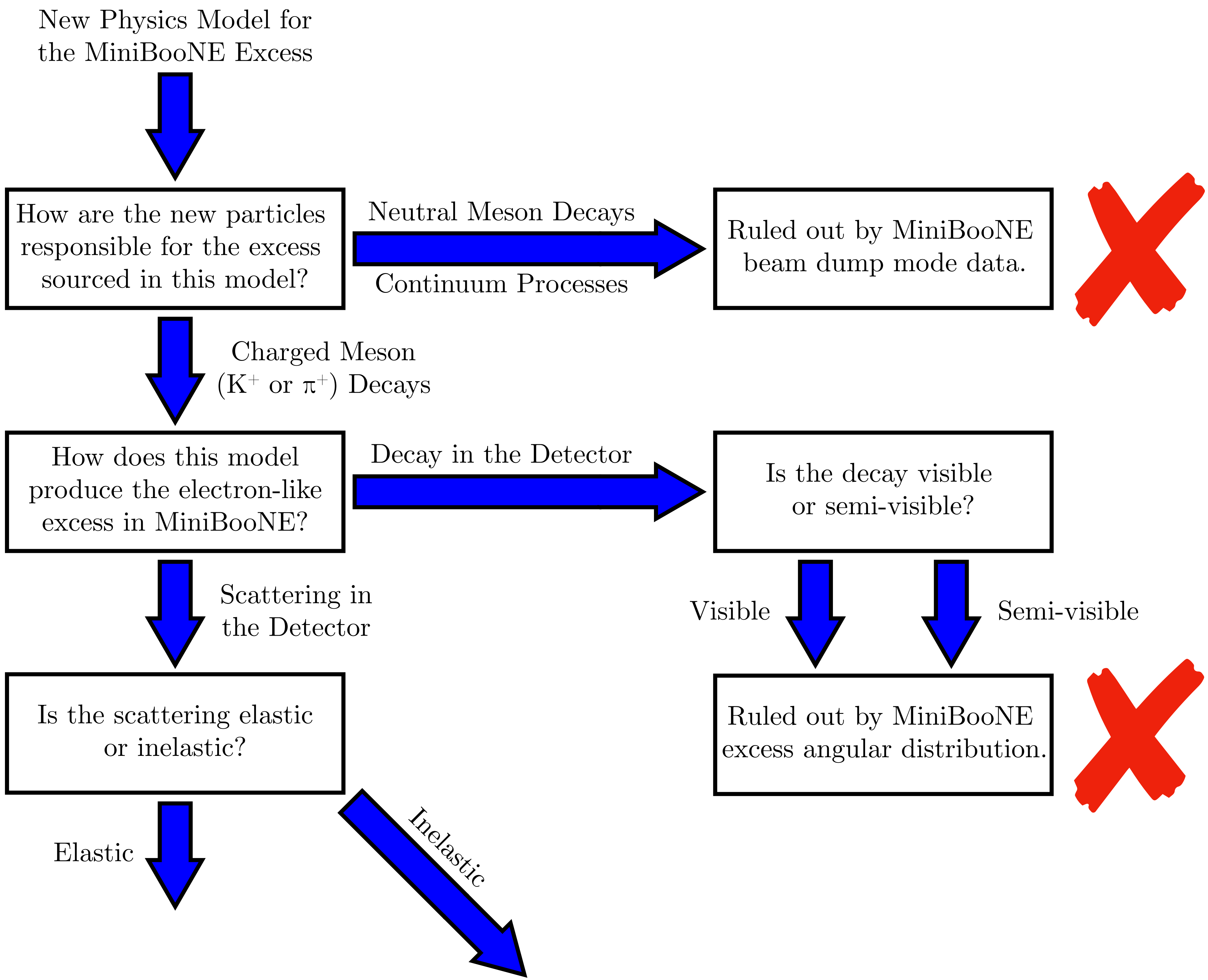

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Visible
Semi-visible
Is the scattering elastic or inelastic?
Ruled out by MiniBooNE excess angular distribution.
Elastic
Inelastic

Elastic Scattering

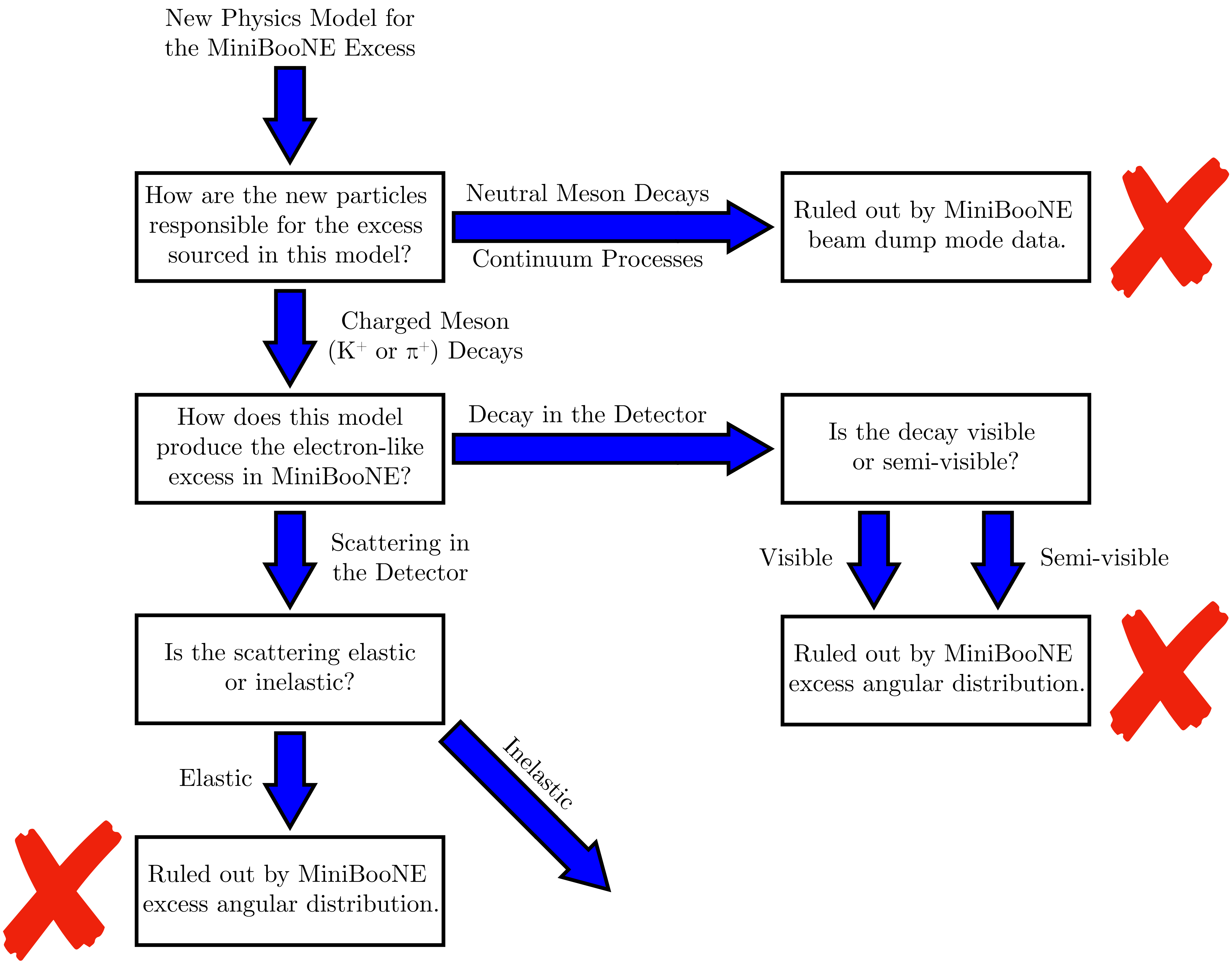
- Suppose the excess is produced by elastic scattering of a new particle off of detector electrons:

$$Xe^- \to Xe^-$$

- The track angle of the scattered electron is

$$\cos\theta_e = \frac{E_X E_e - m_e(E_X + m_e - E_e)}{\sqrt{(E_X^2 - m_X^2)(E_e^2 - m_e^2)}} \approx 1 - m_e\left(\frac{E_X - E_e}{E_X E_e}\right) + \mathcal{O}\left(\frac{m_e^2}{E_e^2}\right)$$

- This always gives a highly forward distribution since $E_e > 140$ MeV and $E_X > E_e$
- Possible loophole: non-relativistic X where this expansion fails, but this loophole is ruled out: to get $\cos\theta_e \sim 0$ you still need $E_e \approx m_e$ which fails the cuts
- Furthermore, heavy X has to be produced by a continuum process which is ruled out by the beam dump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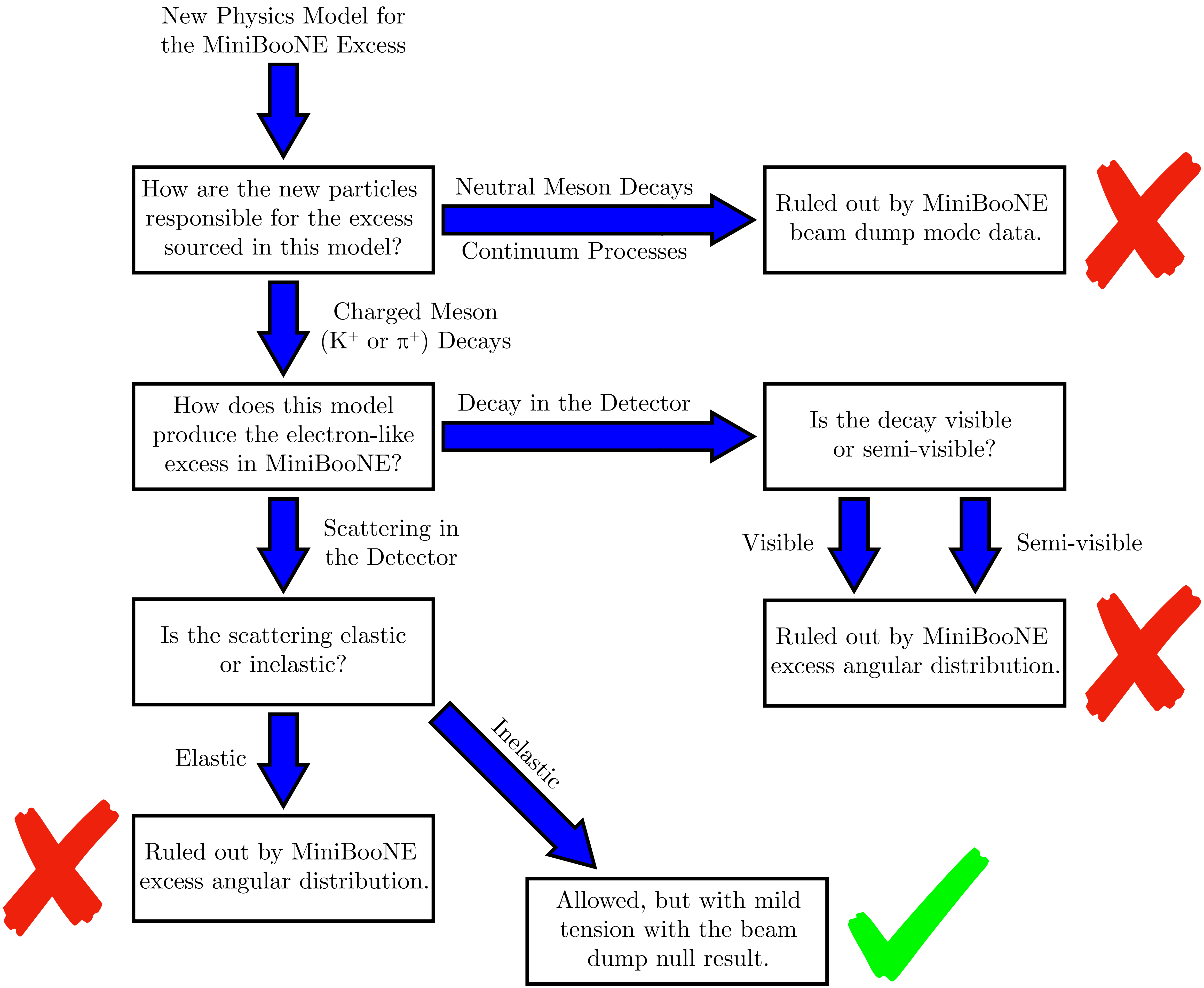
Is the scattering elastic or inelastic?
Elastic
Inelastic
Ruled out by MiniBooNE excess angular distribution.

Inelastic Scattering

- The only remaining option for generating the detector signature is through inelastic scattering
- Inelastic scattering off of the nuclei in the detector can easily accommodate the angular distribution of the excess
- In this way, inelastic scattering looks a lot like the ν_e CCQE interactions in the standard sterile neutrino interpretation of the excess ($\nu_\mu \rightarrow \nu_e$ oscillations)
- There is very weak tension with the beam dump mode null result, but more data is needed to be definitive



JJ, Y. Kahn, G. Krnjaic, M. Moschella, J. Spitz, arXiv:1810.07185, Phys. Rev. Lett. 122, 081801

New Physics Model for the MiniBooNE Excess

How are the new particles responsible for the excess

Neutral Meson Decays

Ruled out by MiniBooNE beam dump mode data.

The MiniBooNE excess is broadly consistent with something to do with neutrinos sourced from charged pion/kaon decays. New physics or systematics?

Final point: it's very hard to come up with a new physics explanation for both LSND and MiniBooNE simultaneously without oscillations.

Ruled out by MiniBooNE excess angular distribution.

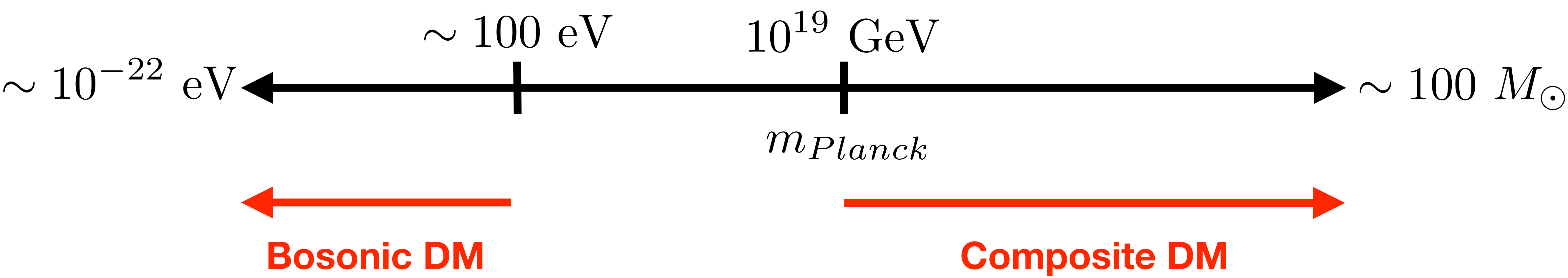
Allowed, but with mild tension with the beam dump null result.

JJ, Y. Kahn, G. Krnjaic, M. Moschella, J. Spitz, arXiv:1810.07185, Phys. Rev. Lett. 122, 081801

Dark Matter at
Neutrino Experiments

Dark Matter Models

What is the dark matter mass?

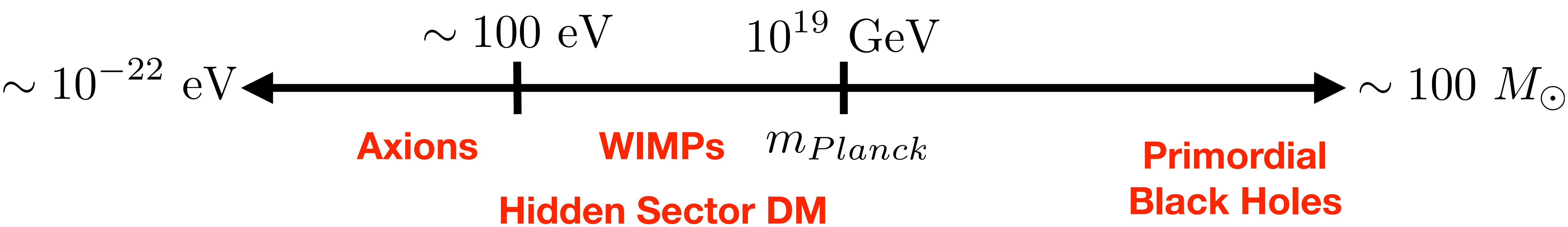


We don't have any idea what the right scale is.
Possible values span ~90 orders of magnitude.

S. Tremaine and J. E. Gunn, Phys. Rev. Lett.**42**, 407–410 (Feb 1979)
A. Boyarsky, O. Ruchayskiy and D. Iakubovskyi, Journal of Cosmology and Astroparticle Physics, (03), 005 (2009)

Dark Matter Models

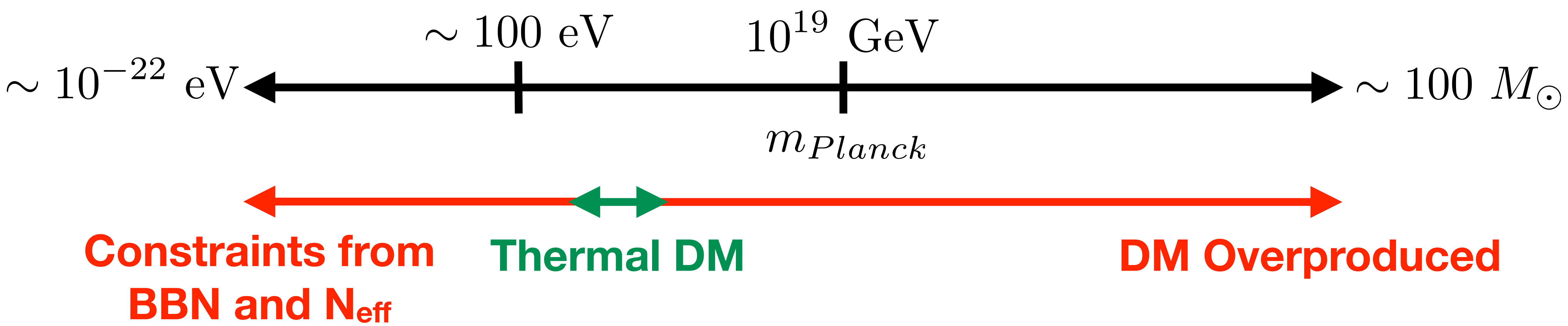
What is the dark matter mass?



Many candidates exist which span the full range.

Dark Matter Models

What is the dark matter mass?

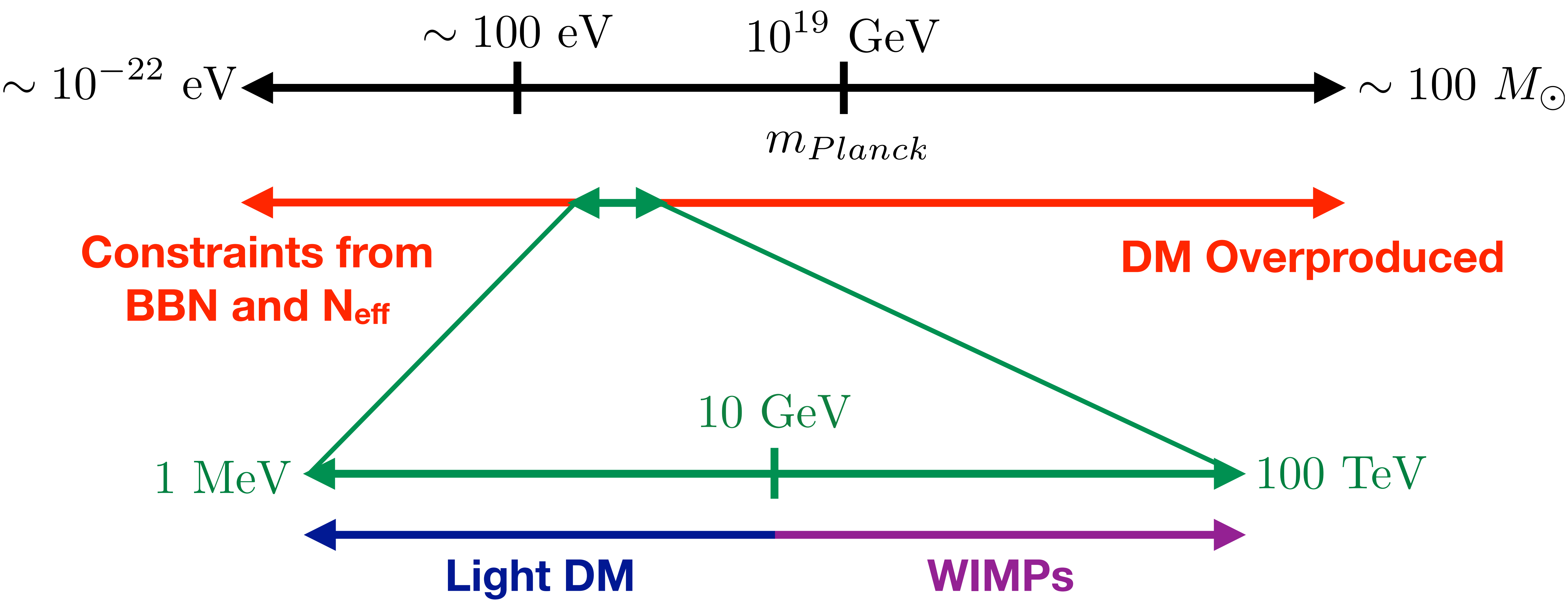


Thermal dark matter gives us much more information about allowed dark matter masses.

C. M. Ho and R. J. Scherrer, Phys. Rev. **D87**, 023505 (2013), arXiv:1208.4347
K. Griest and M. Kamionkowski, Phys. Rev. Lett. **64**, 615 (1990)

Dark Matter Models

What is the dark matter mass?



C. M. Ho and R. J. Scherrer, Phys. Rev. **D87**, 023505 (2013), arXiv:1208.4347
K. Griest and M. Kamionkowski, Phys. Rev. Lett. **64**, 615 (1990)

Light Dark Matter at Neutrino Experiments

Light Scalars and Dark Photons in Borexino and LSND Experiments

Observing a light dark matter beam with neutrino experiments

DAEδALUS and Dark Matter Detection

Detecting Dark Photons with Reactor Neutrino Experiments

Testing Light Dark Matter Coannihilation With Fixed-Target Experiments

Exploring Portals to a Hidden Sector Through Fixed Targets

Millicharged particles in neutrino experiments

Signatures of sub-GeV dark matter beams at neutrino experiments

Signatures of Pseudo-Dirac Dark Matter at High-Intensity Neutrino Experiments

Hunting sub-GeV dark matter with NOνA near detector

Probing New Physics with Underground Accelerators and Radioactive Sources

Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP

Light Dark Matter at Neutrino Experiments

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neutrino experiments

DAEδALUS and Dark Matter Detection

Detecting

Experiments

Explori

eriments

Signatures

ear detector

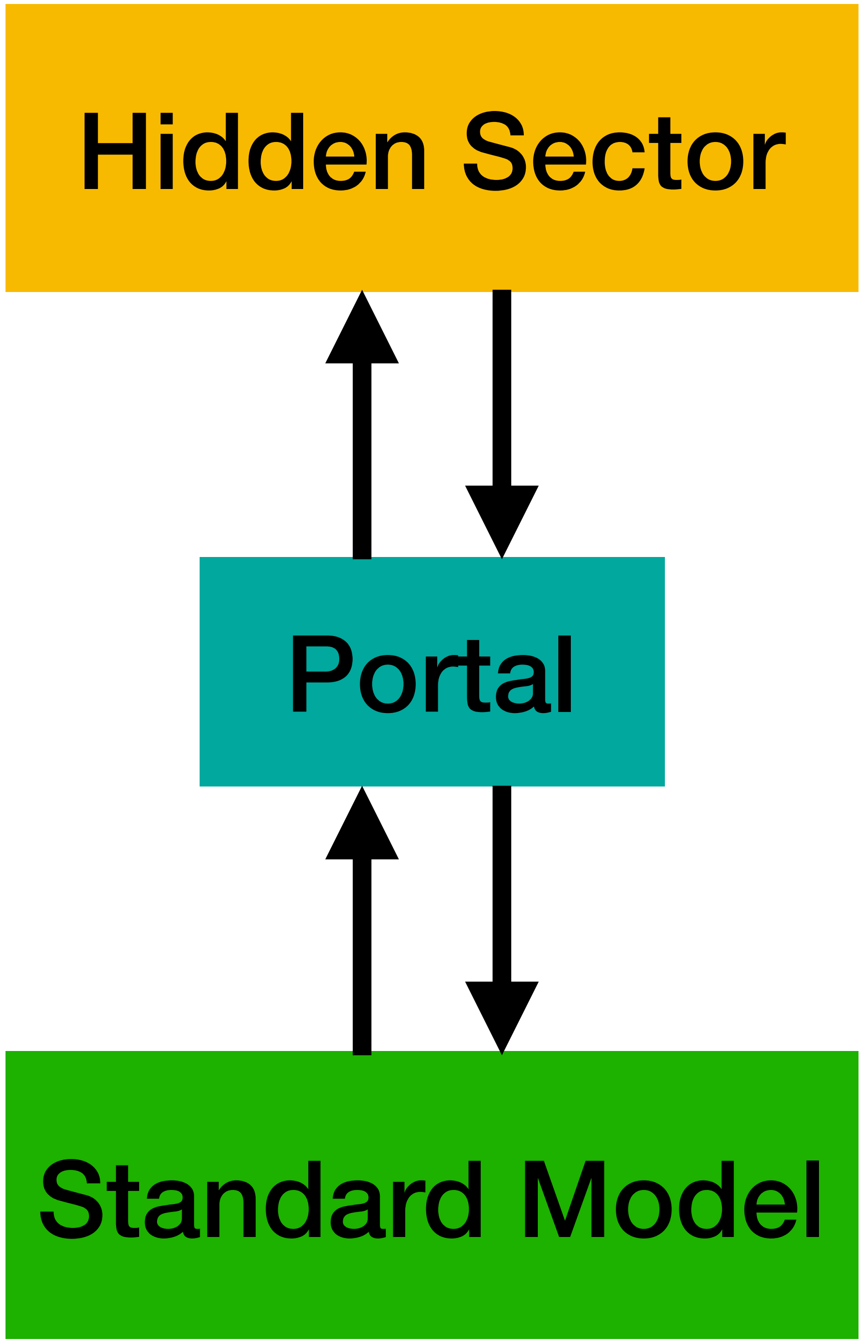
Many models of light, weakly-coupled dark matter candidates exist and can be tested at neutrino experiments.

Probing New Physics with Underground Accelerators and Radioactive Sources

Light dark matter in neutrino beams: production modelling and scattering signatures
at MiniBooNE, T2K and SHiP

Light Dark Matter

- Light (sub-GeV) dark matter has come into vogue the past few years
- Motivated by absence of results in WIMP searches
- Of particular interest are "hidden sector" ("dark sector") models
- Several portals are possible; we will be interested in the vector portal



M. Battaglieri et al., (2017), arXiv:1707.04591

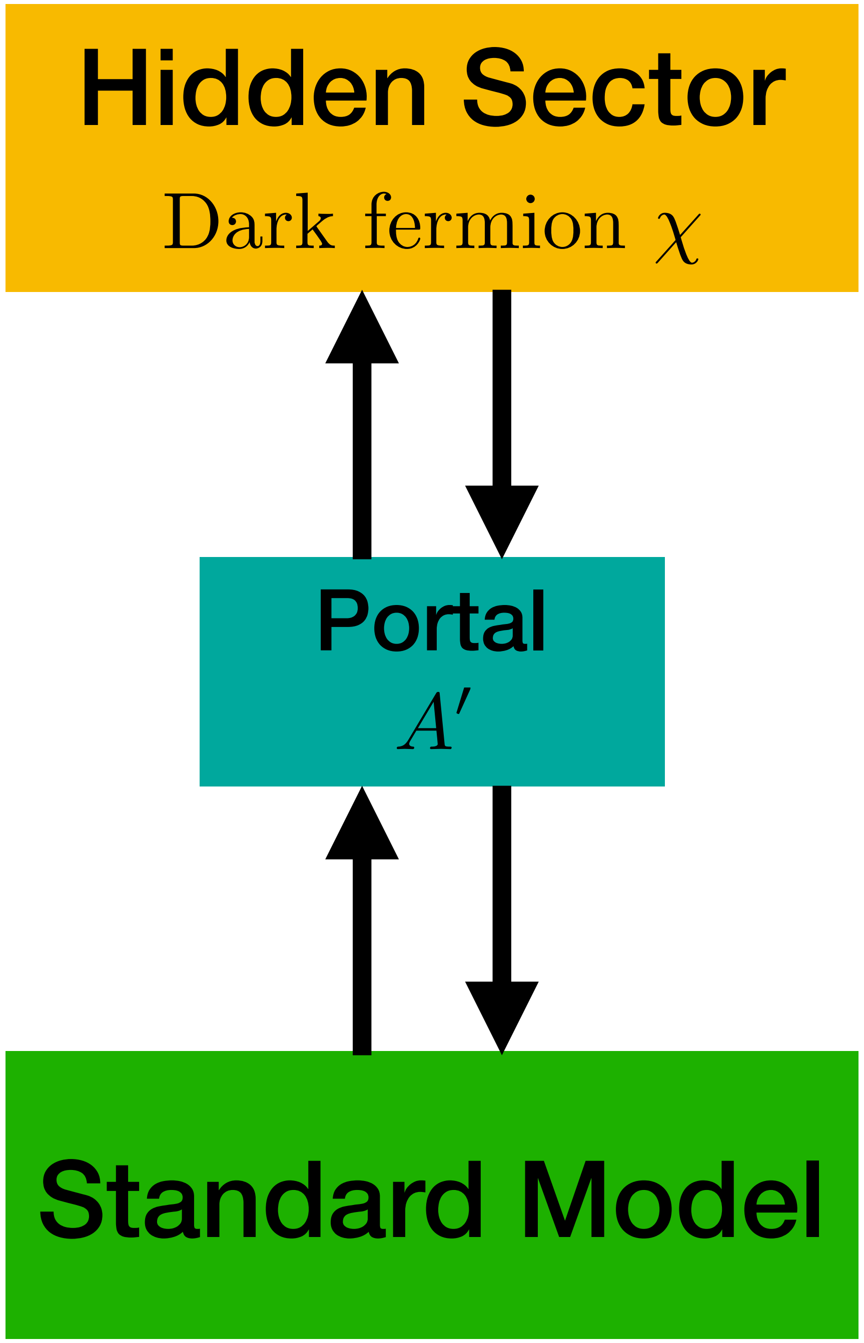
Dark Photon Model

- Add a new vector boson (dark photon) that connects the dark sector to the SM through “kinetic mixing”

$$\mathcal{L} \supset \frac{\epsilon_Y}{2} F'_{\mu\nu} B^{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu + \bar{\chi}(i\not{D} - m_\chi)\chi$$

- The dark photon gets terms which couple it to the SM EM current

$$\epsilon e A'_\mu J^\mu_{\rm EM}$$



TWO Z's OR NOT TWO Z's? ☆

Peter GALISON
Physics Department, Stanford University, Stanford, CA 94305, USA

and

Aneesh MANOHAR [1]
Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

B. Holdom, Phys. Lett. **B178** (1986) 65.

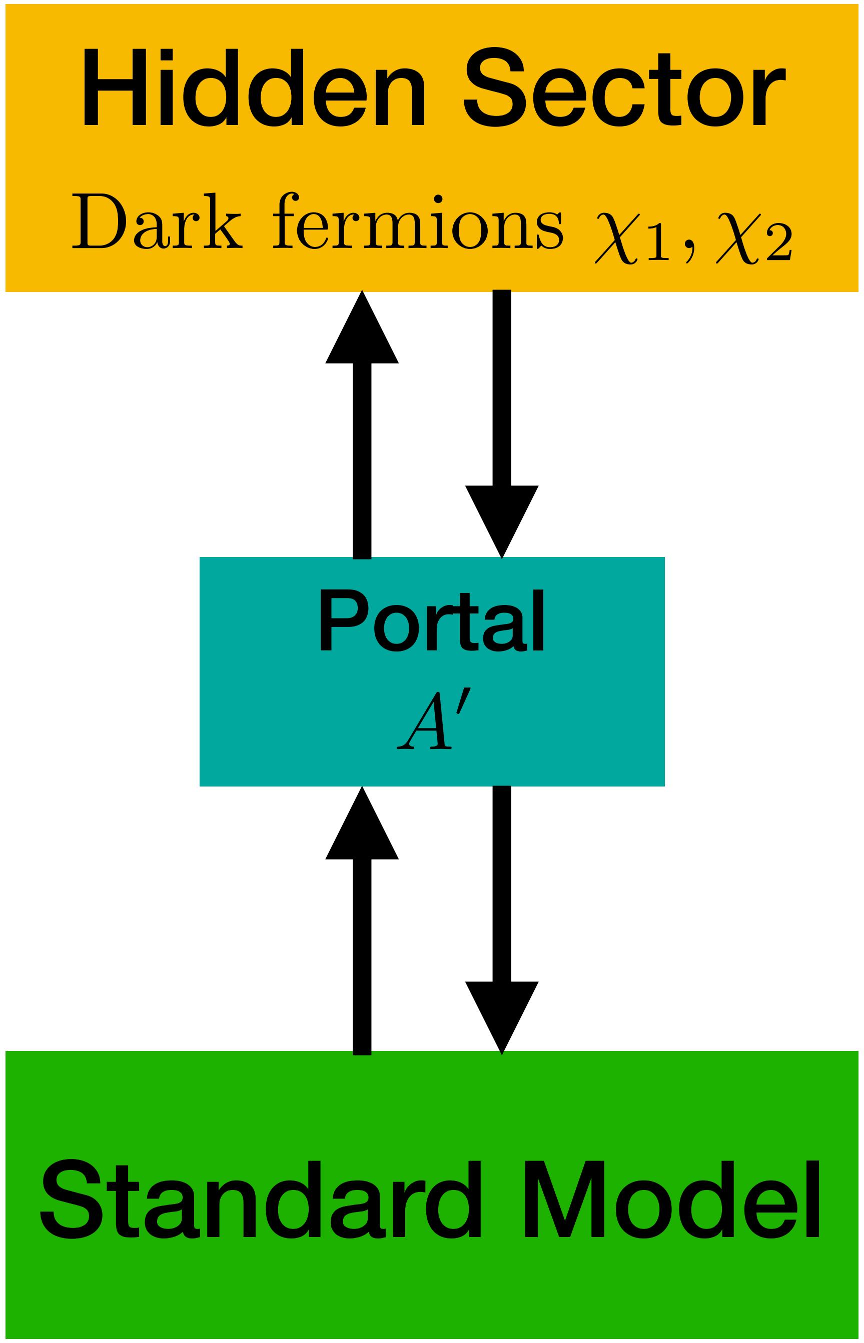
Coannihilating DM

- Now consider a slightly more complicated hidden sector
- We couple the dark fermions to the dark photon inelastically via an off-diagonal coupling

$$\mathcal{L} \supset g_D A'_\mu \bar{\chi}_2 \gamma^\mu \chi_1 + \text{h.c.}$$

- There is a natural mass splitting between the two dark fermions

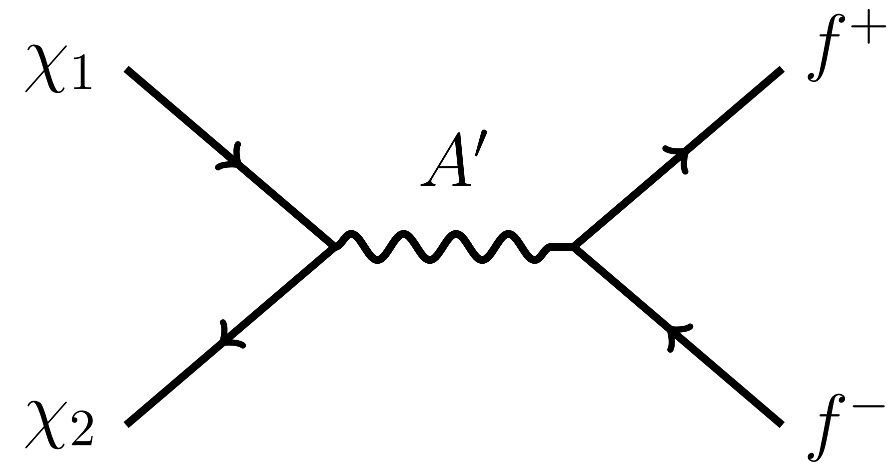
$$\Delta = m_2 - m_1$$

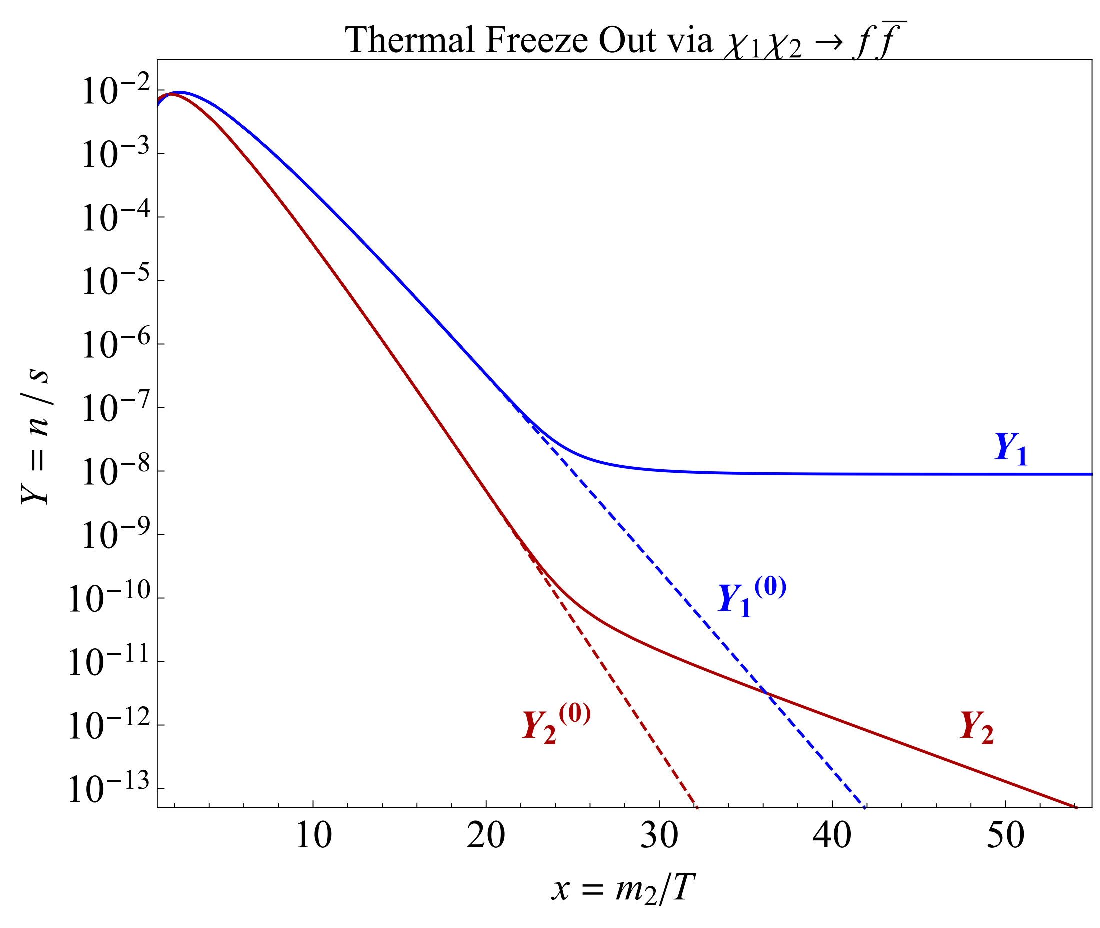


E. Izaguirre, Y. Kahn, G. Krnjaic, and M. Moschella, Phys. 11 Rev. **D96**, 055007 (2017), arXiv:1703.06881

The Case for Coannihilation

- **Large Viable Couplings**
  - Relic abundance set by coannihilation
  - Boltzmann suppression of heavier state requires higher cross section
- **Indirect Detection Shuts Off**
  - Also safe from CMB constraints
- **Direct Detection Forbidden**
  - Not enough energy to upscatter

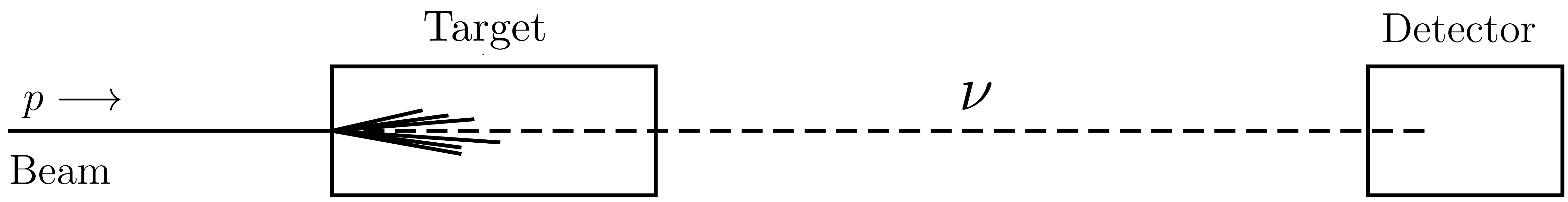




E. Izaguirre, Y. Kahn, G. Krnjaic, and M. Moschella, Phys. 11 Rev. **D96**, 055007 (2017), arXiv:1703.06881

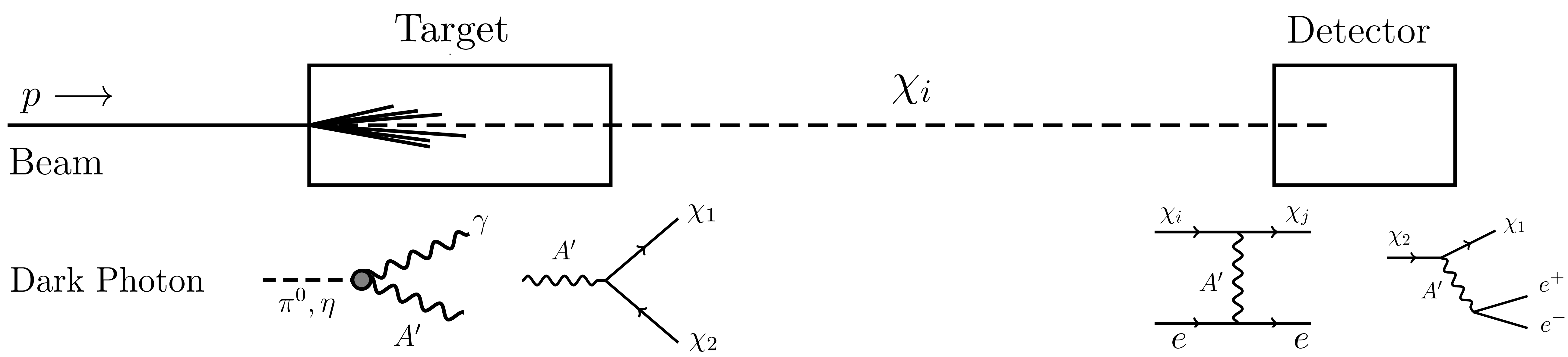
Production and Detection of Dark Matter

High Luminosity Proton Beam (100’s of MeV to 10’s of GeV)



Production and Detection of Dark Matter

High Luminosity Proton Beam (100's of MeV to 10's of GeV)



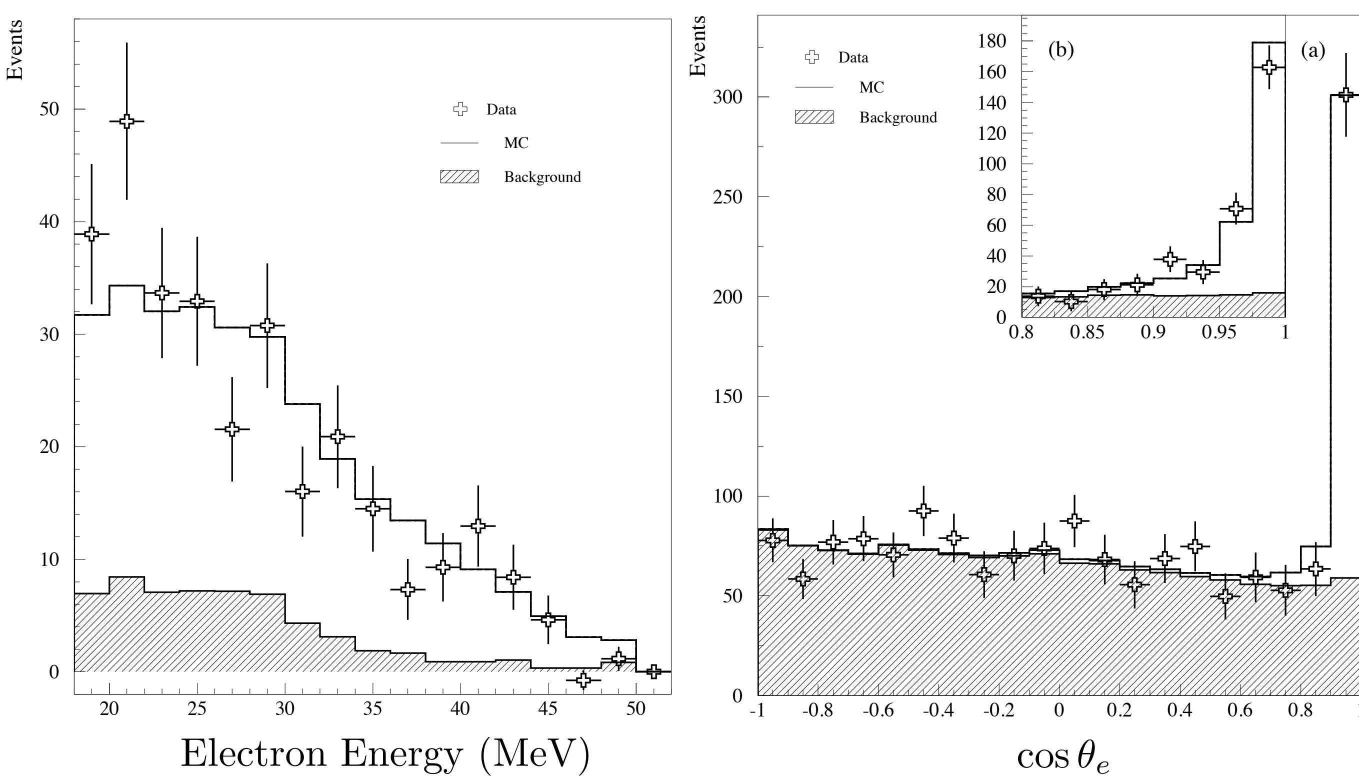
Scattering **Decay**

$$\mathrm{Br}(\pi^0 \to \gamma\gamma) \approx 0.99$$
$$\mathrm{Br}(\eta \to \gamma\gamma) \approx 0.39$$

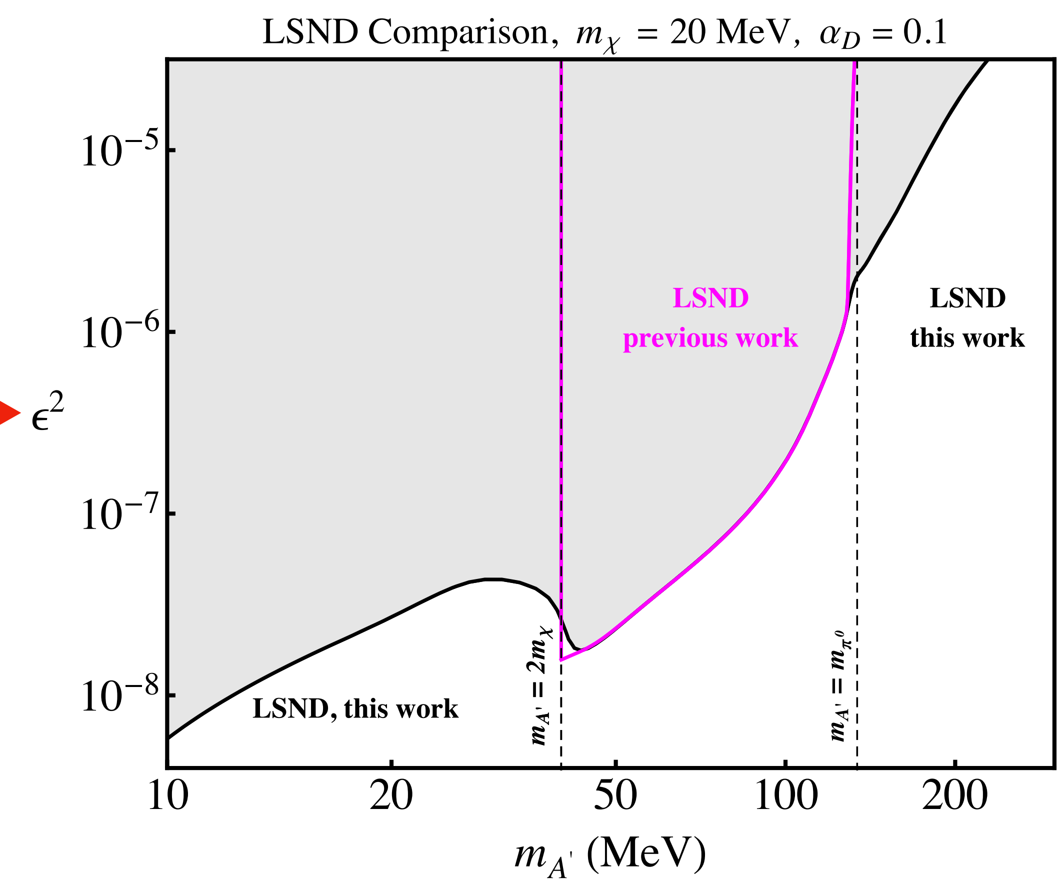
Large boosts mean there are no kinematic constraints on the scattering like in traditional direct dark matter searches.

LSND Constraints

A dark photon scattering signature would show up in measurements of neutrino scattering in LSND.



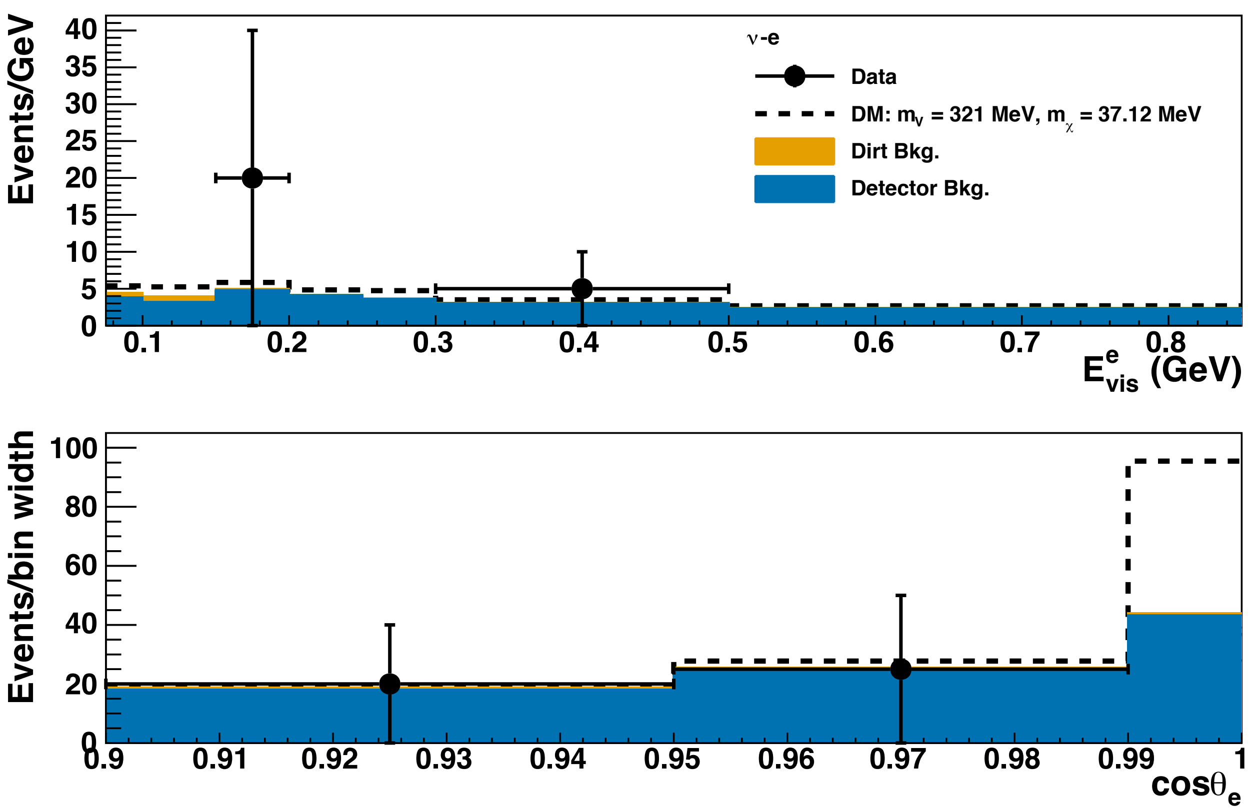
LSND ν-e elastic scattering measurement

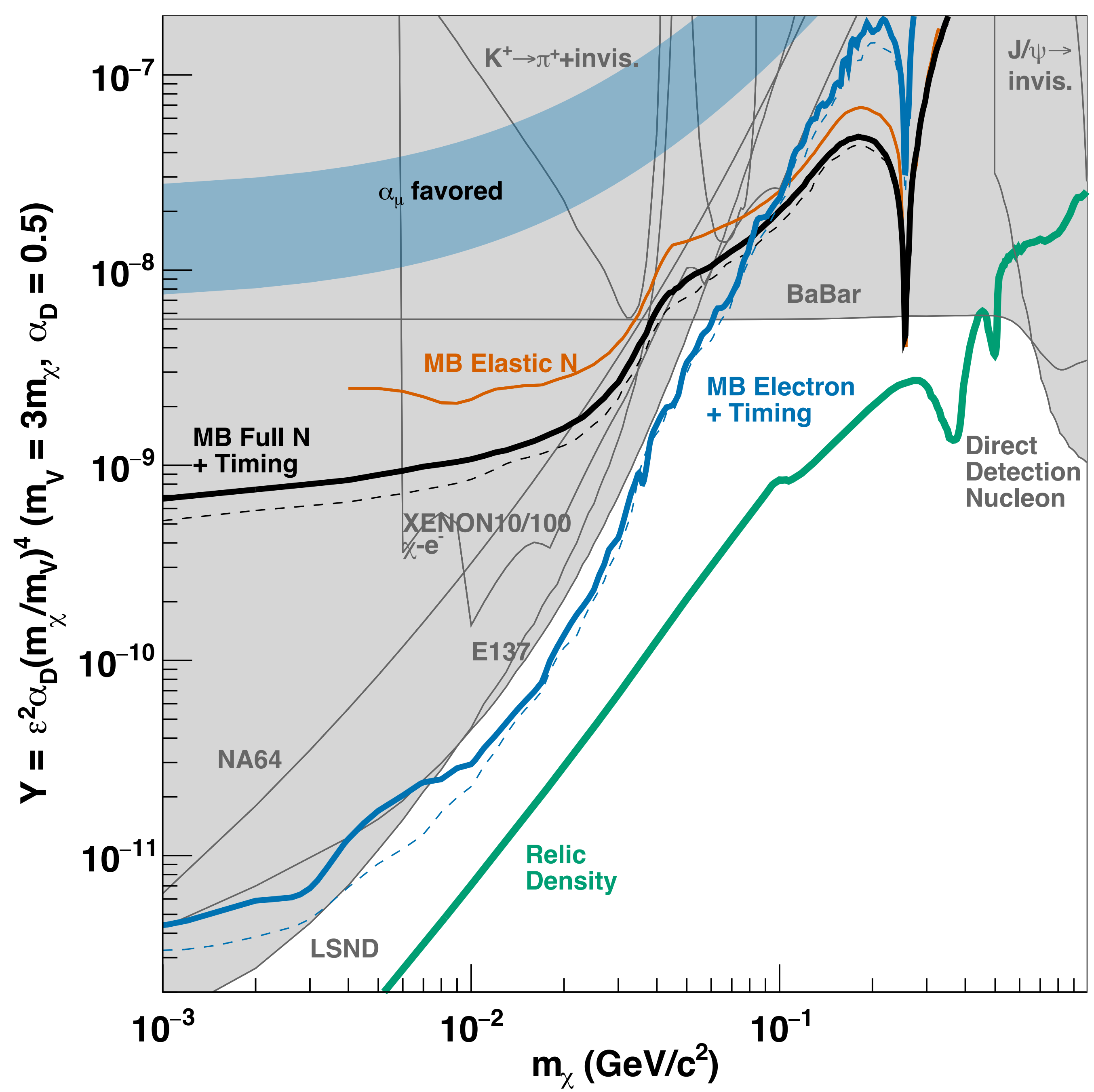


Dark photon constraint

Y. Kahn, G. Krnjaic, J. Thaler, and M. Toups, Phys. Rev. **D91**, 055006 (2015), arXiv:1411.1055
L. Auerbach et al. (LSND Collaboration), Phys.Rev. **D63**, 112001 (2001), arXiv:hep-ex/0101039

MiniBooNE Results





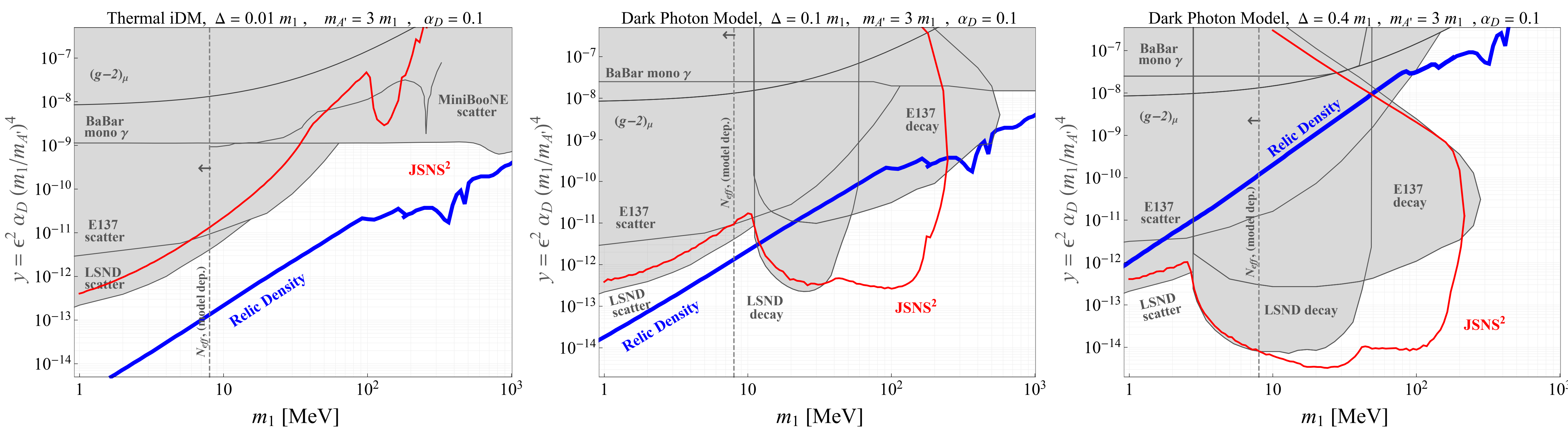
2 events observed on a predicted background of 2.4 ± 1.5 events. No elastic scattering candidates.

A. A. Aguilar-Arevalo et al. (MiniBooNE DM Collaboration), (2018), 1807.06137

JSNS² Sensitivity

$$\sigma v \propto \left(\epsilon^2 \alpha_D \frac{m_1^4}{m_{A'}^4}\right)\frac{1}{m_1^2} \equiv \frac{y}{m_1^2}$$

Cast constraints/sensitivity in terms of y and m_1 which govern the relic density.



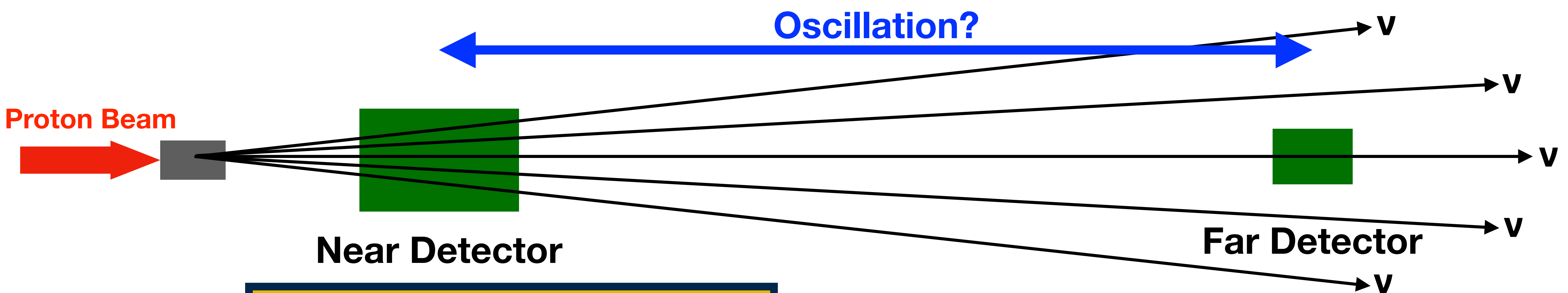
Increasing Δ

JSNS2 sensitivity assumes additional shielding

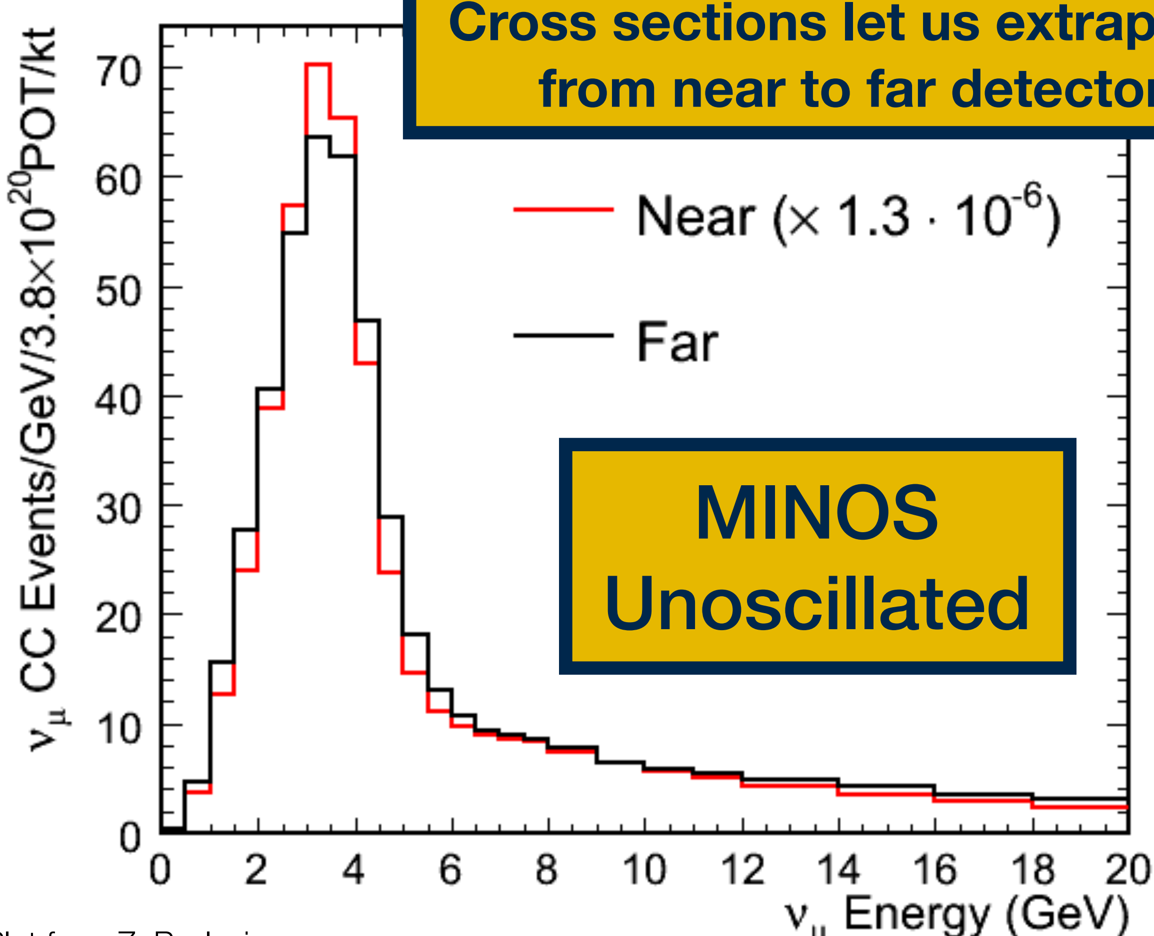
JJ, Y. Kahn, G. Krnjaic, M. Moschella, J. Spitz, arXiv:1806.05185, Phys. Rev. D 98, 075020

KDAR Neutrinos

Cross Sections

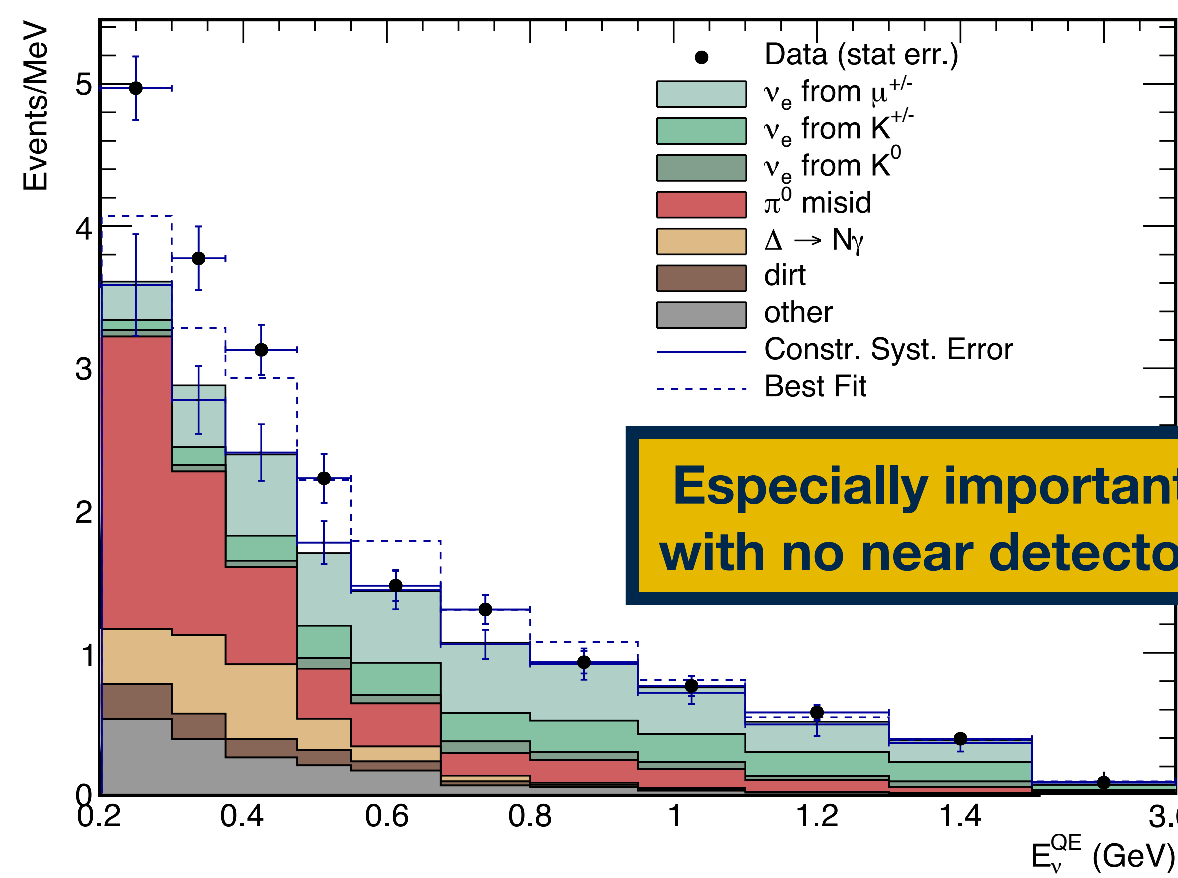


Cross sections let us extrapolate from near to far detectors



MINOS Unoscillated

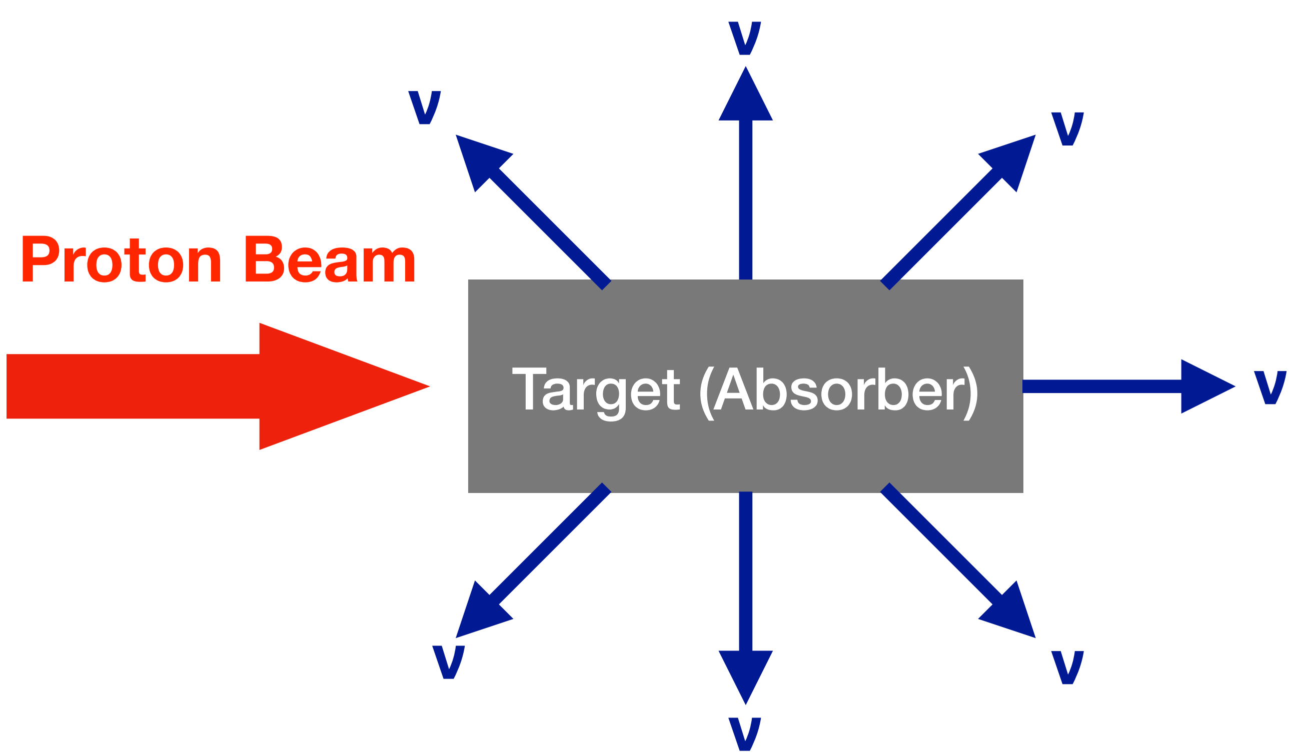
Plot from Z. Pavlovic

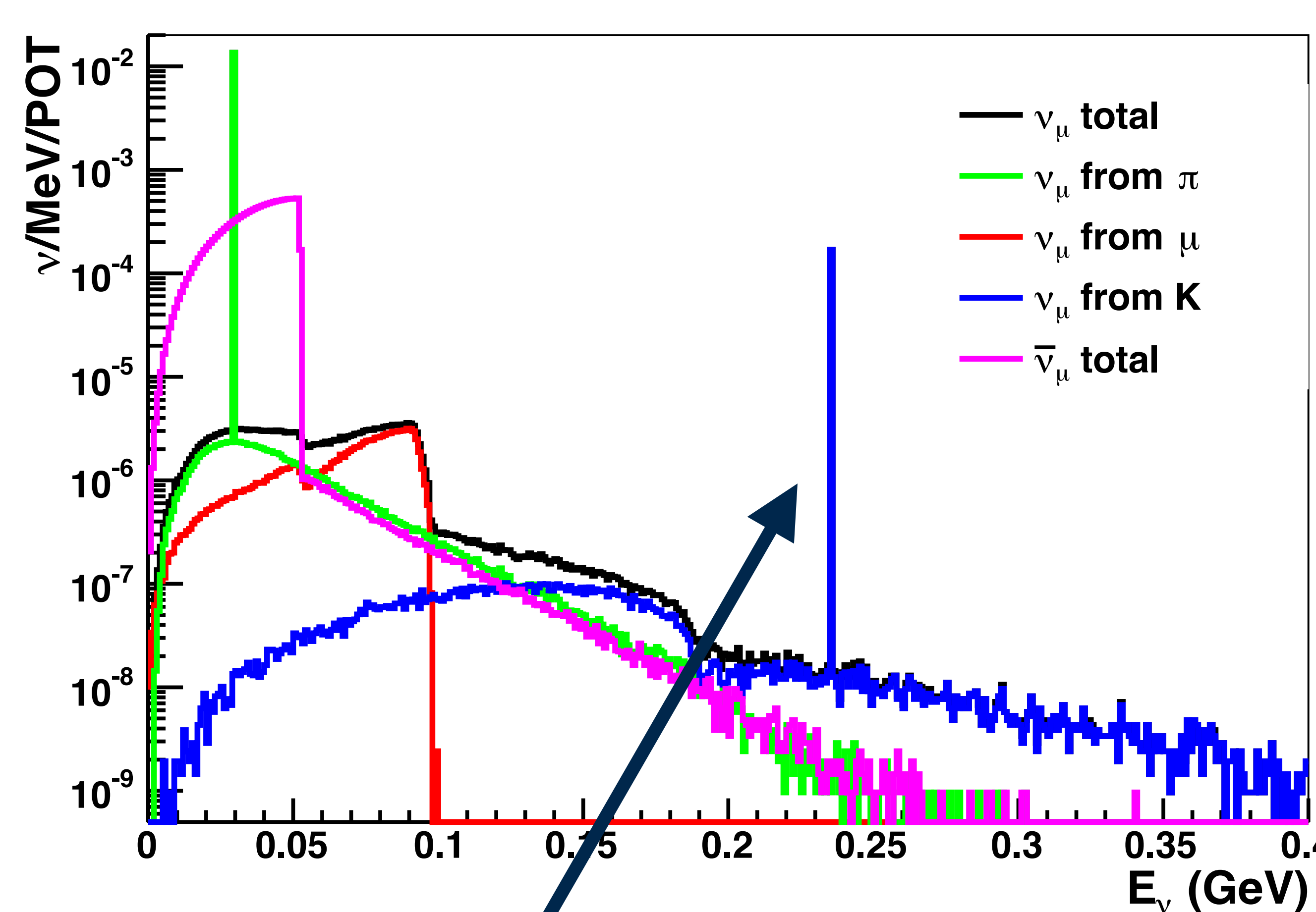


Especially important with no near detector

The KDAR Neutrino

KDAR = kaon decay at rest





$$K^+ \to \mu^+ \nu_\mu \quad [BR = 63.6\%]$$

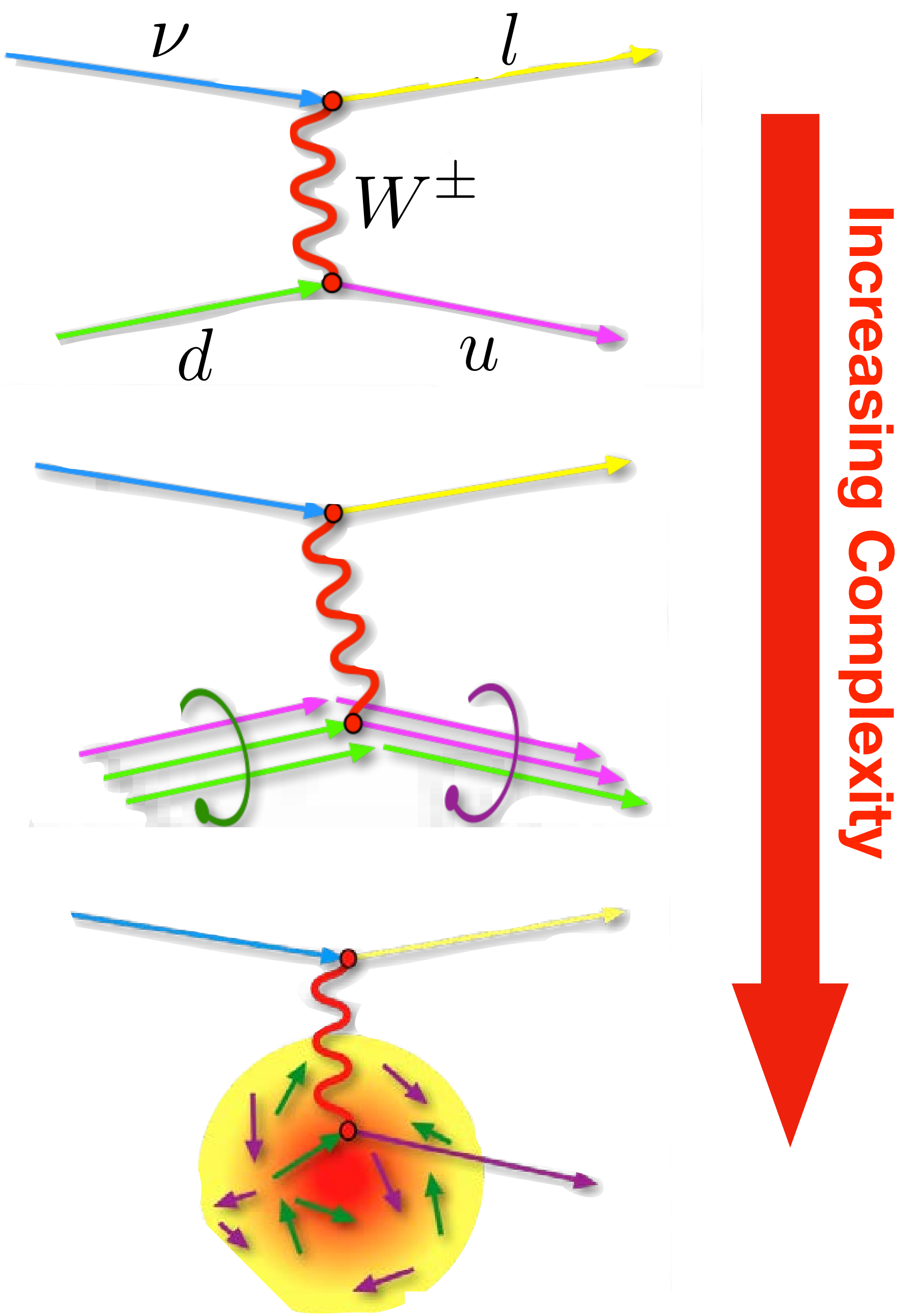
$$E_\nu = 236 \text{ MeV if } K^+ \text{ is at rest}$$

The 236 MeV KDAR ν_μ in the J-PARC MLF flux.

arXiv:1705.08629

Probing the Nucleus

- Calculations are difficult:
  - Fermi motion
  - Correlated nucleon pairs
  - Final state interactions
- Measurements are difficult:
  - Energy resolution
  - Event classification issues
  - Cherenkov threshold/invisible particles (neutrons)



Adapted from K. McFarland

Probing the Nucleus

We would like to do something analogous to electron scattering with neutrinos.

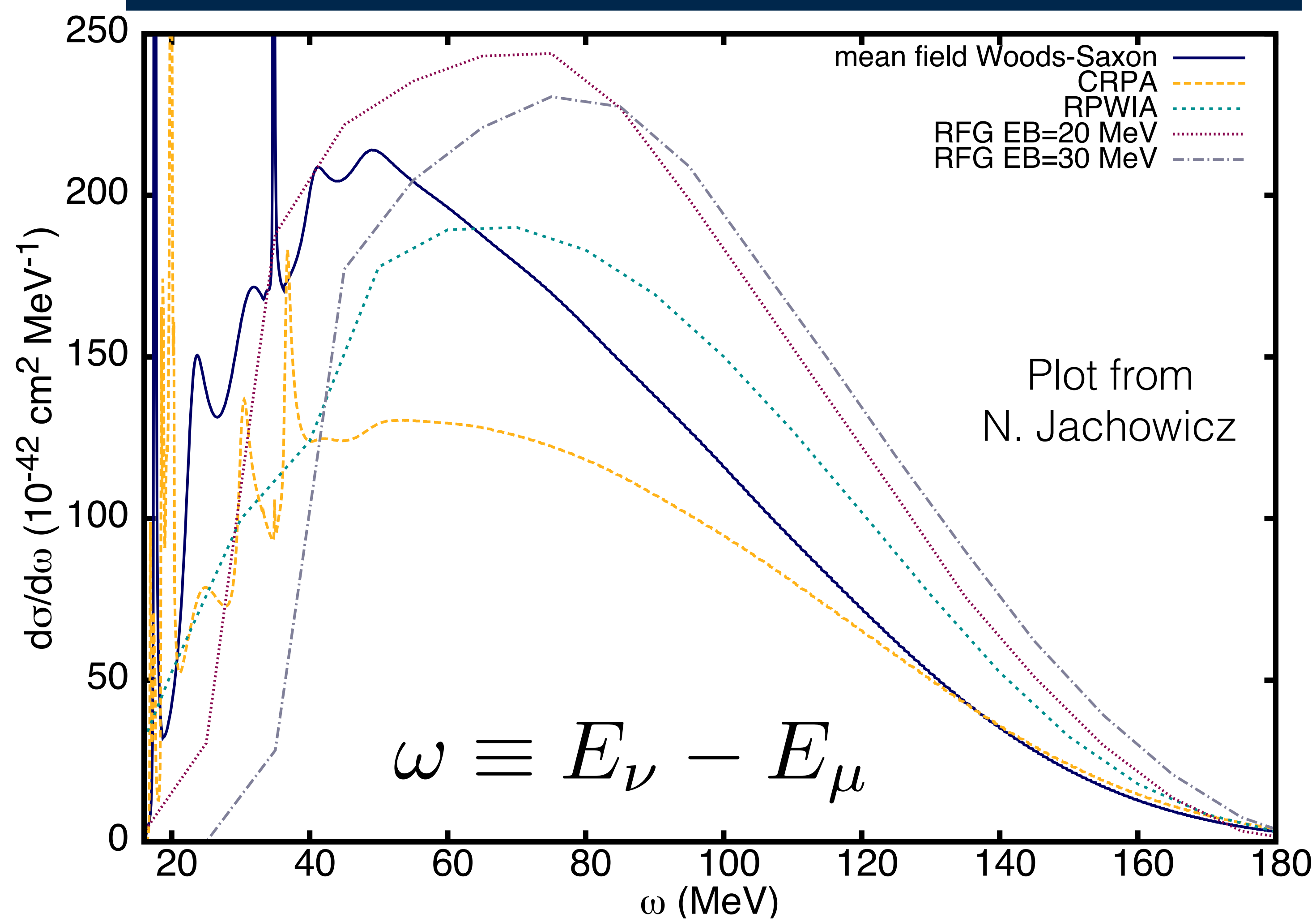
Problems:

1. Knowing neutrino energies is difficult.
2. Neutrino CC interactions are complicated

Solution: KDAR neutrinos

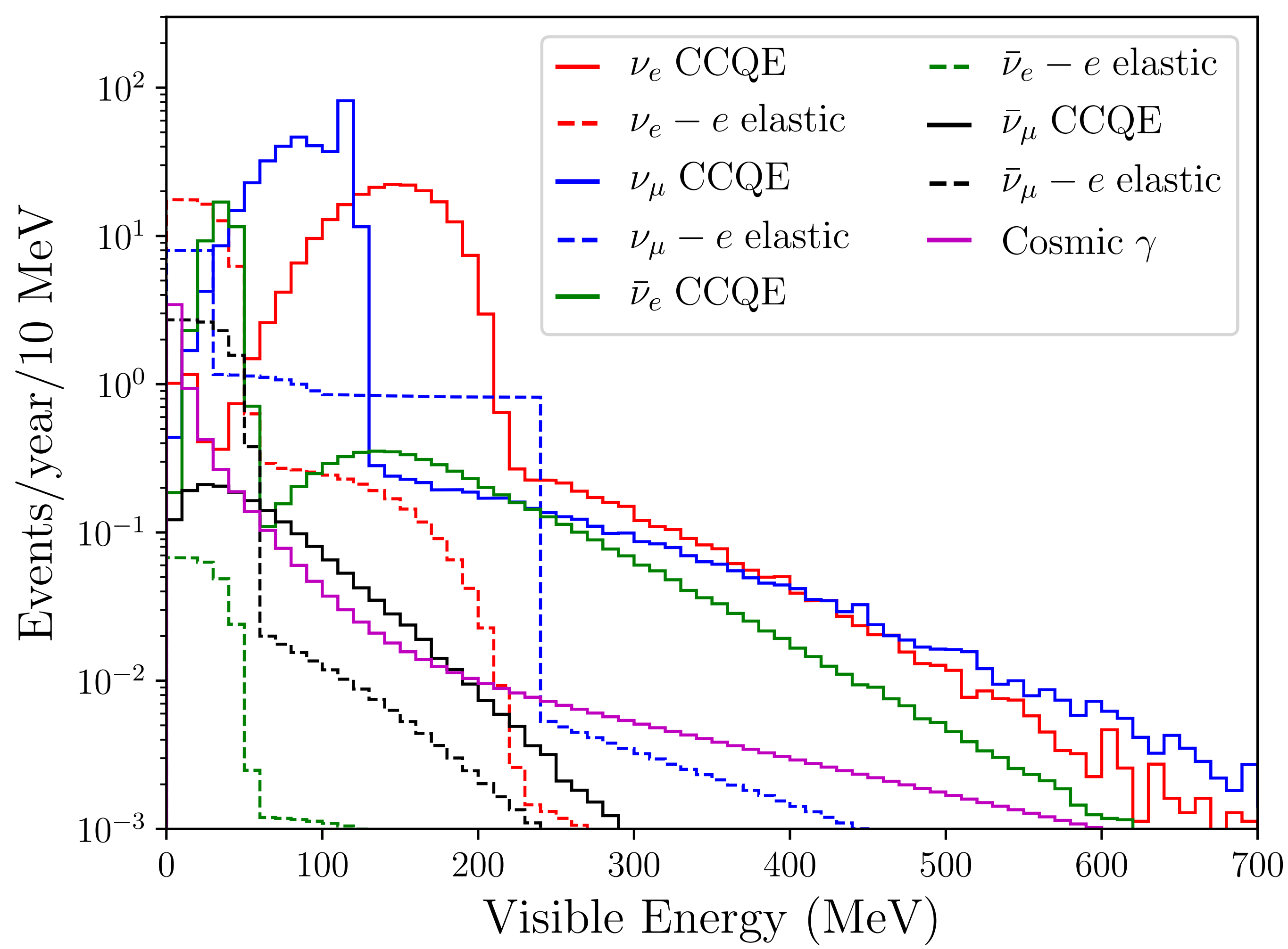
- Known energy
- Measure ω with neutrinos
- Standard candle for few 100's of MeV neutrinos

300 MeV ν_μ interactions on carbon

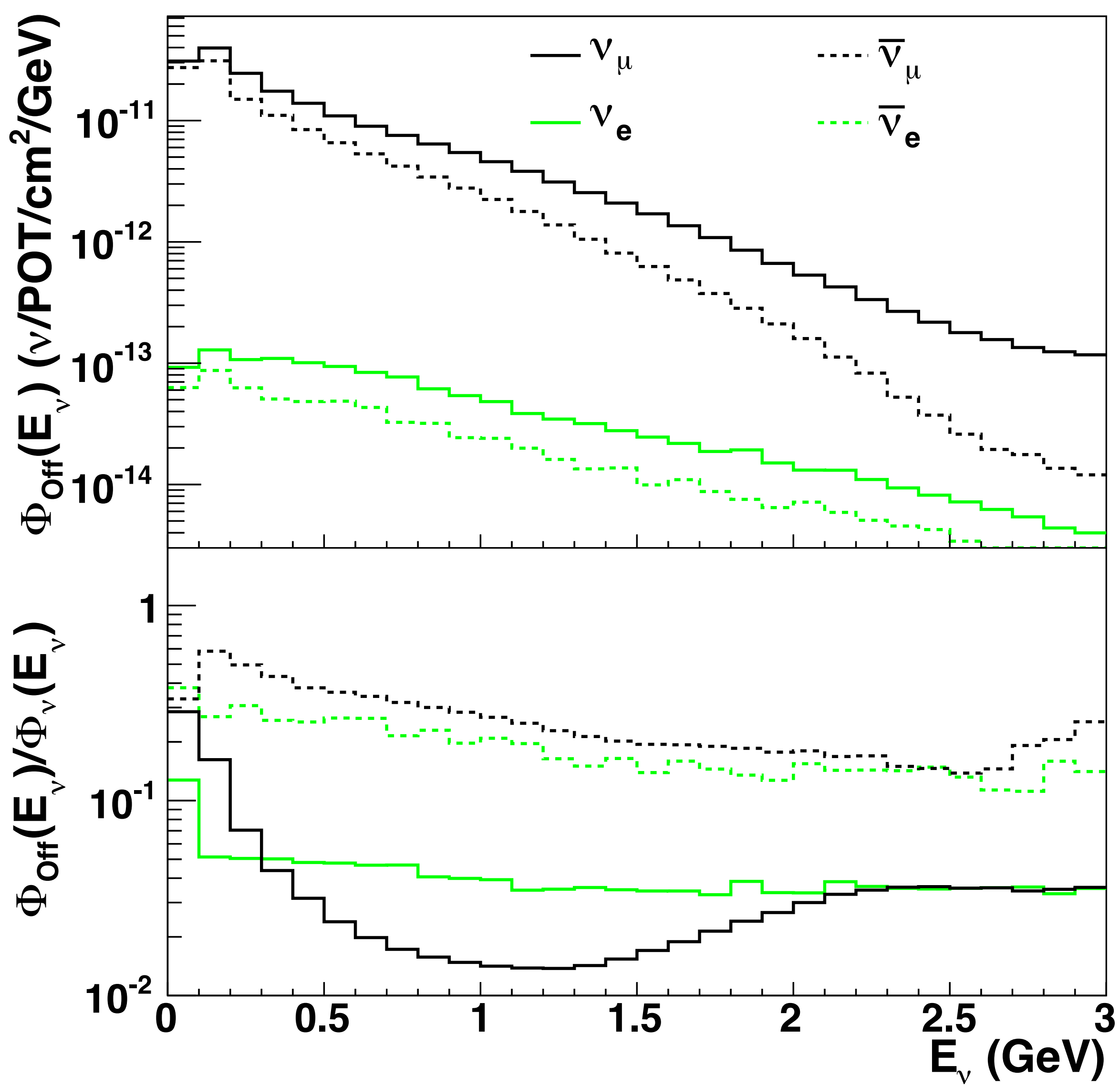


Model predictions are all over the place.

Neutrino Backgrounds to BSM Searches



Neutrino backgrounds to DM searches in JSNS²

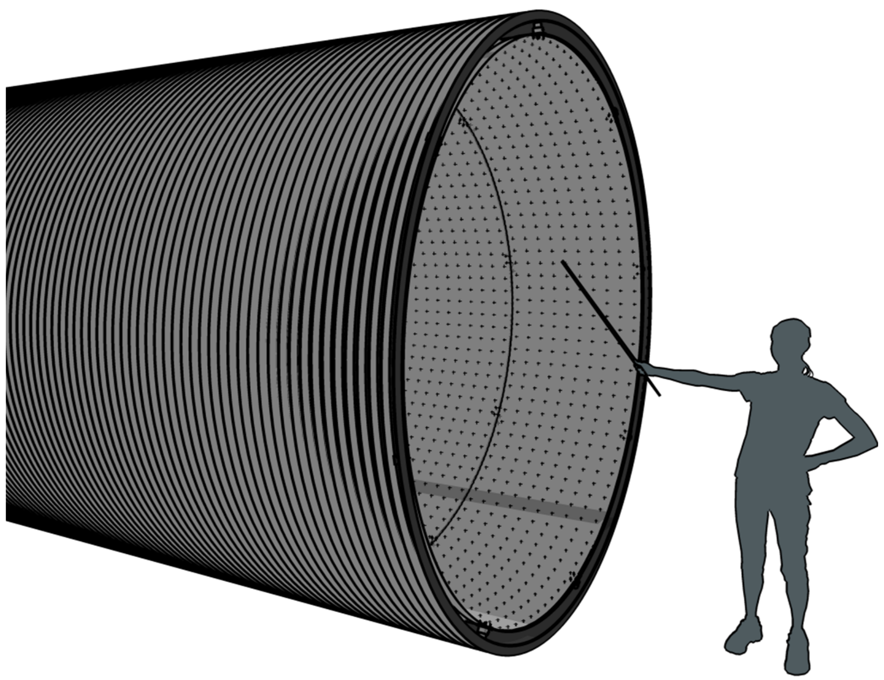


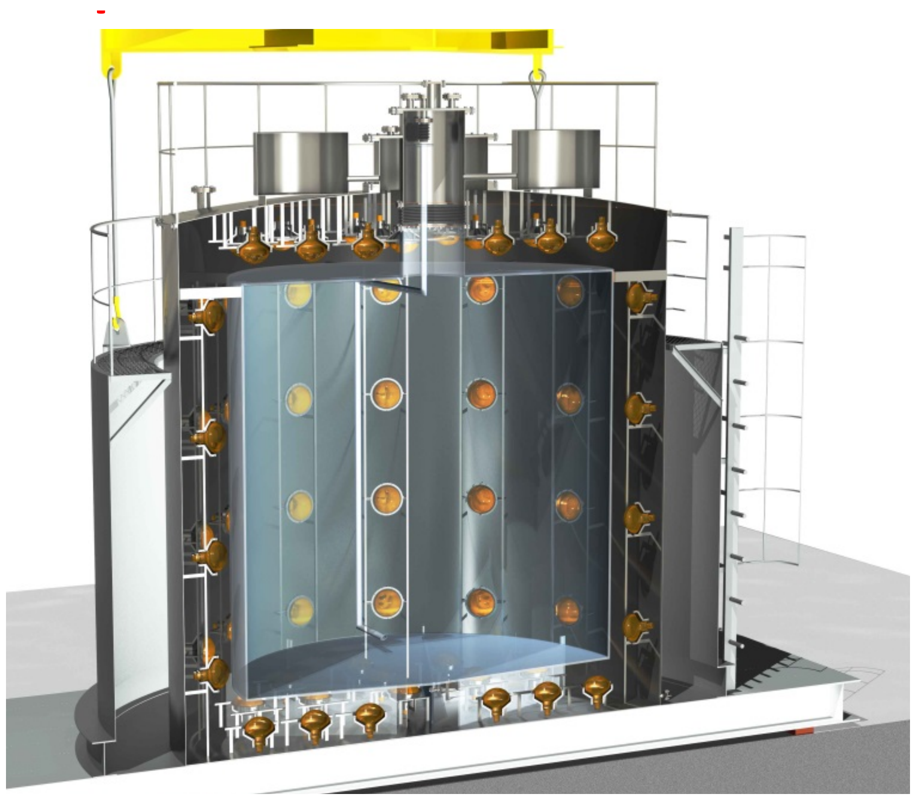
MiniBooNE off-target/neutrino mode flux ratios

A. A. Aguilar-Arevalo et al. (MiniBooNE DM Collaboration), (2018), 1807.06137
JJ, Y. Kahn, G. Krnjaic, M. Moschella, J. Spitz, arXiv:1806.05185, Phys. Rev. D 98, 075020

Other KDAR Physics

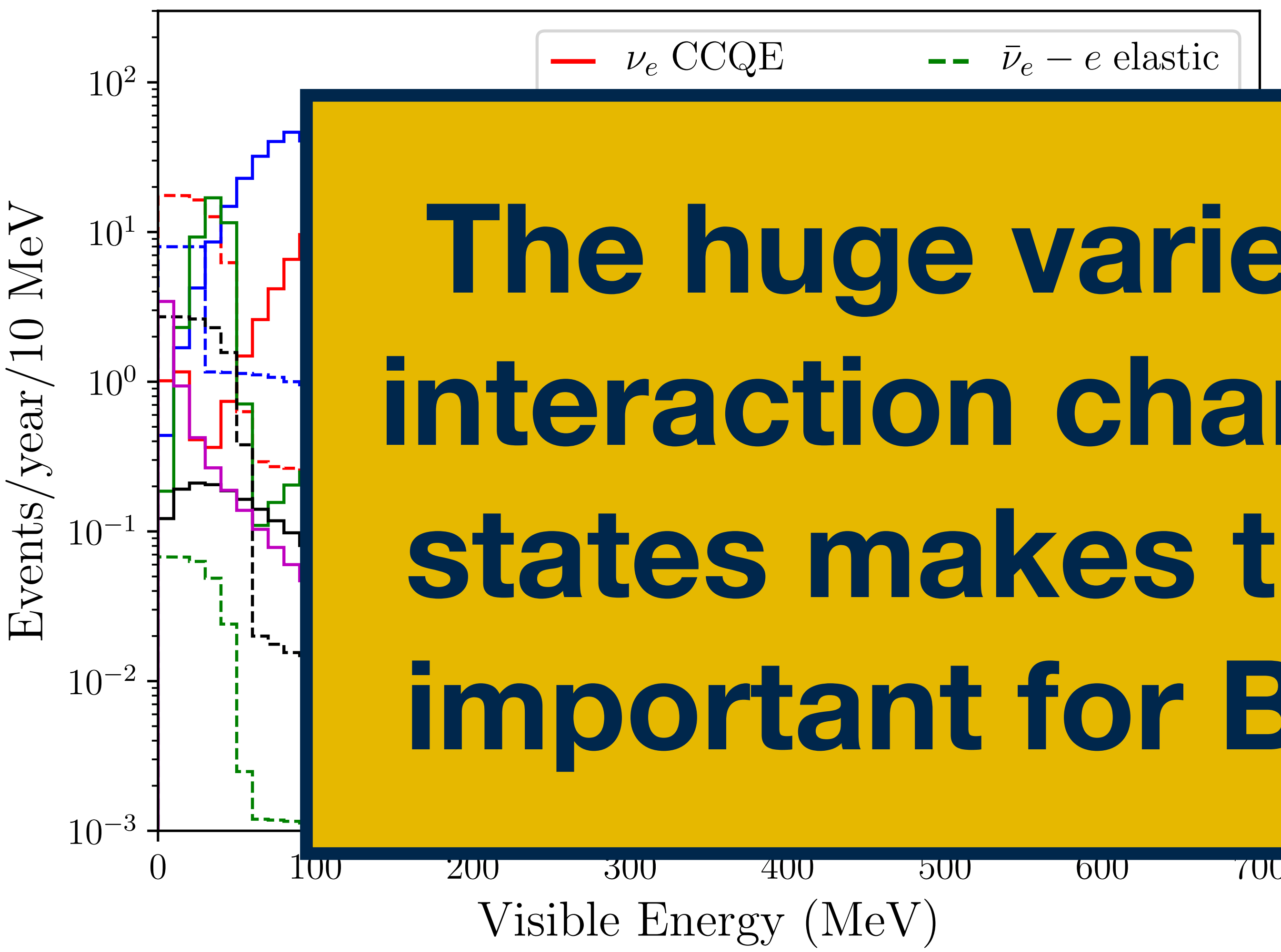
- KDAR neutrinos open up many other physics measurements:
  - Oscillation search for sterile neutrinos at short baseline
  - Measure Δs for nucleon spin
  - Look for dark matter annihilation in the sun
  - Measure the CC neutron yield

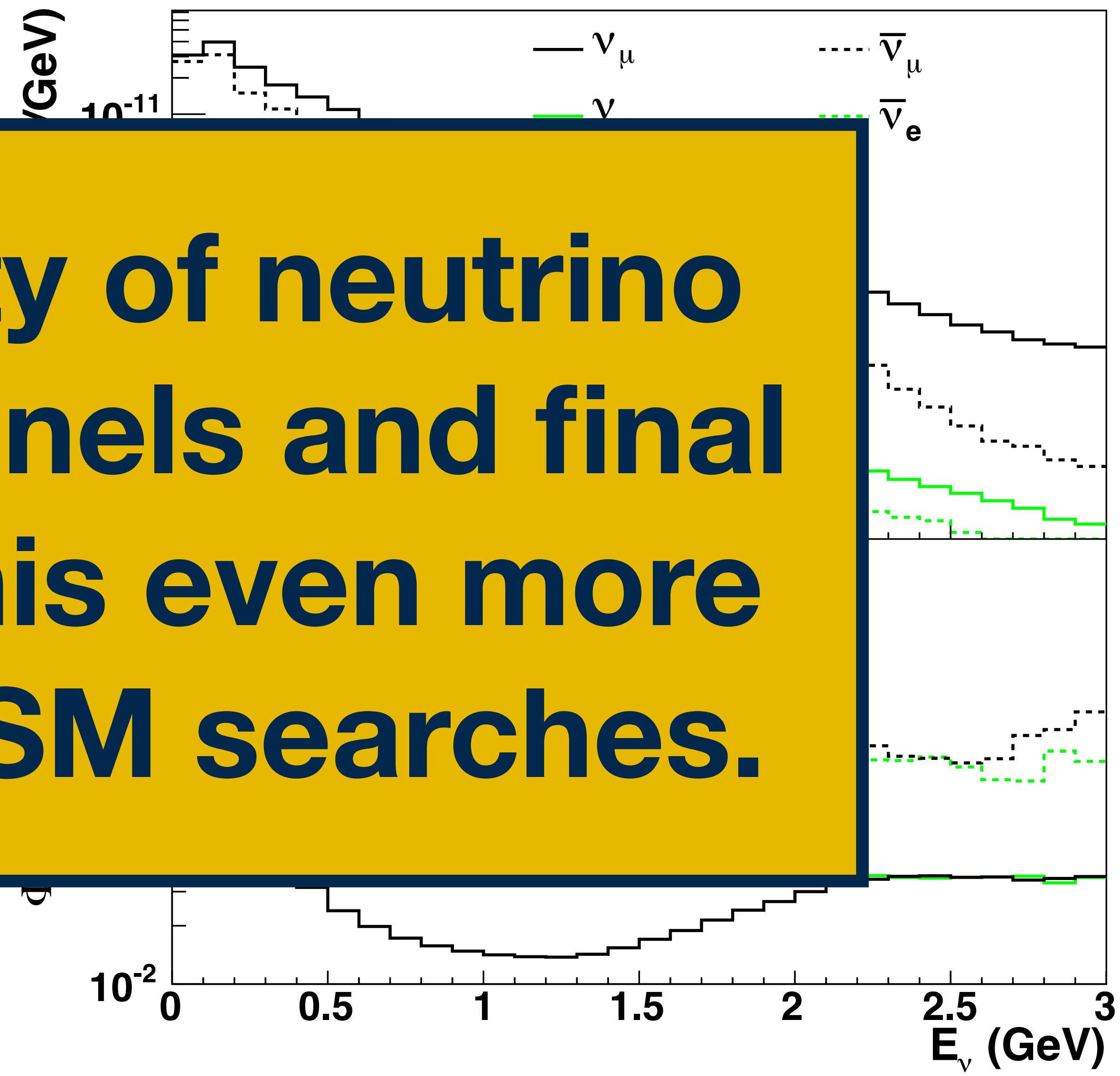




J. Spitz, Phys. Rev. D 85 093020 (2012).
S. Axani, et. al., Phys. Rev. D 92 092010 (2015).
C. Rott, et. al., J. of Cosmol. and Astropart. Phys. 11 039 (2015).
C. Rott, et. al., arXiv:1710.03822 [hep-ph].

Neutrino Backgrounds to BSM Searches





The huge variety of neutrino interaction channels and final states makes this even more important for BSM searches.

Neutrino backgrounds to DM searches in JSNS²

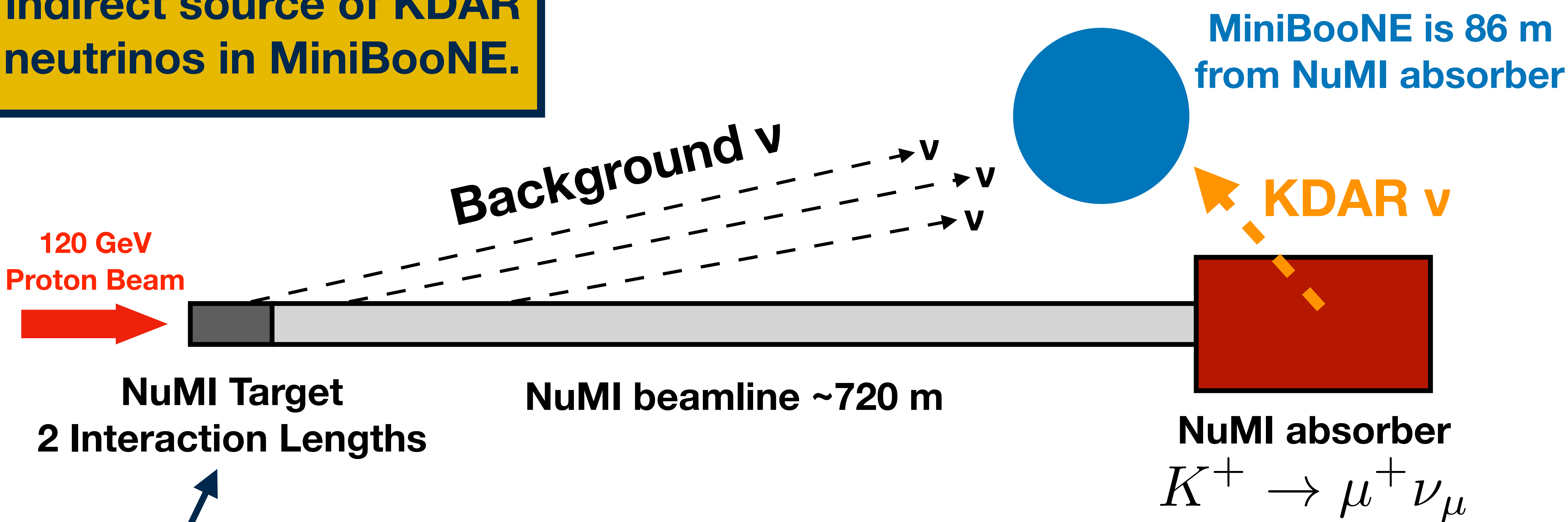
MiniBooNE off-target/neutrino mode flux ratios

A. A. Aguilar-Arevalo et al. (MiniBooNE DM Collaboration), (2018), 1807.06137

JJ, Y. Kahn, G. Krnjaic, M. Moschella, J. Spitz, arXiv:1806.05185, Phys. Rev. D 98, 075020

MiniBooNE and NuMI

NuMI provides an indirect source of KDAR neutrinos in MiniBooNE.



~1/6 of the primary beam power makes it to the dump.

We consider NuMI low energy mode.

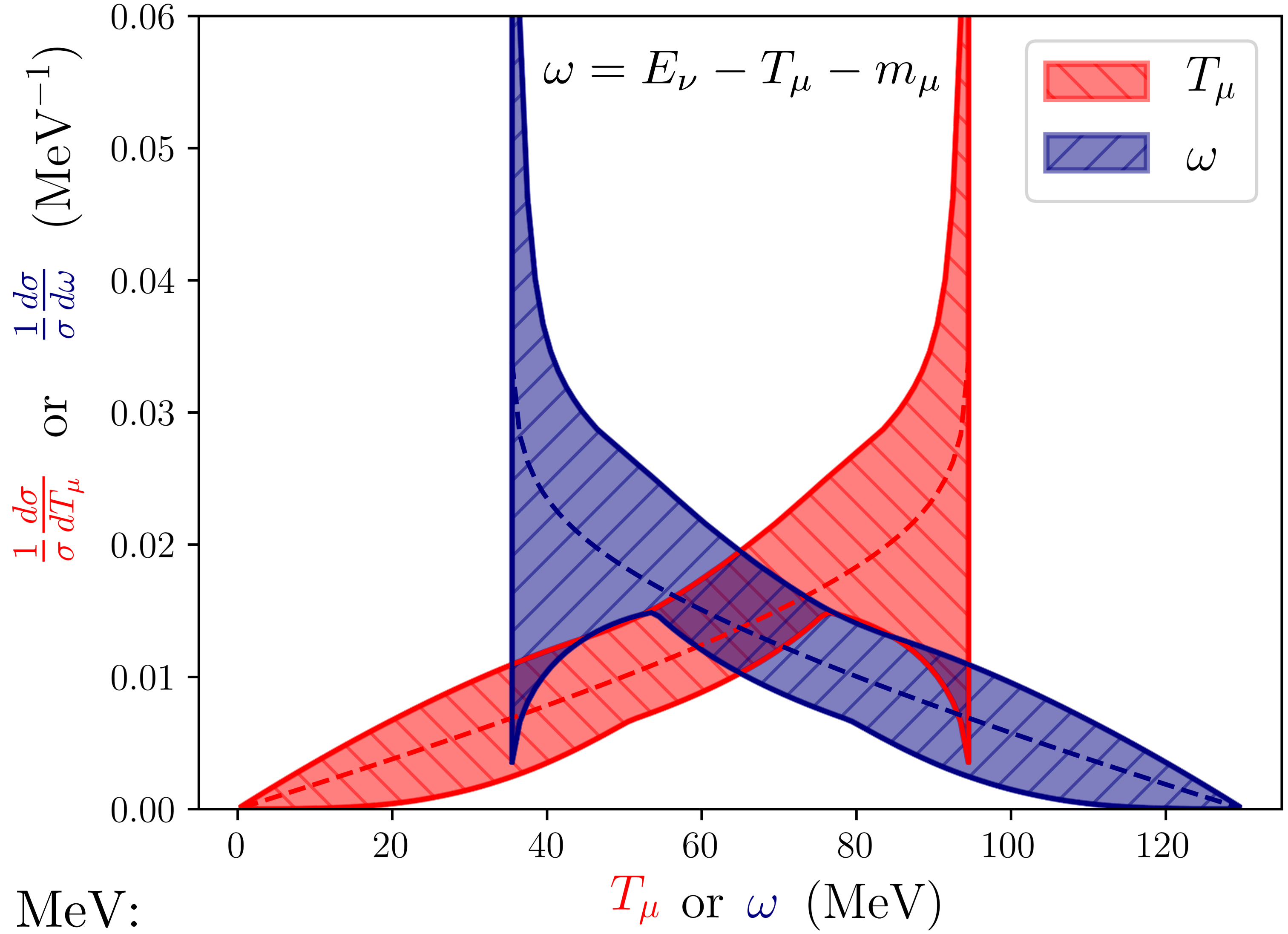
P. Adamson et al., Nucl. Instr. Meth. Phys. Res. A 806 (2016) 279–306

The Result

We observe the KDAR signal with 3.9σ significance.

Determined using a fake data comparison to the background-only hypothesis.

Endpoint = 95 MeV



Total ν_μ CC cross section at $E_\nu = 236$ MeV:

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

Measurement Flux (30%)

Shape-only differential cross sections in terms of T_μ and ω with 1σ error bands.

Theory Comparisons

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).]

Nuance (kappa=1.0, M_A=1.23) [D. Casper, Nucl. Phys. Proc. Suppl. **112** 161 (2002).]

NuWro [C. Juszczak, Acta Phys. Pol. B **40** 2507 (2009); T. Golan, C. Juszczak, and J. Sobczyk, Phys. Rev. C **86** 015505 (2012).]

Singh et al. (M_A=1.2) [F. Akbar, M. Sajjad Athar, and S.K. Singh, arXiv:1708.00321 [nucl-th] (2017).]

A number of plots comparing these models to the best fit results with stat-only errors for the corresponding end points are shown below. The shaded red region represents the 1σ (χ^2_{min}+3.53) stat-only allowed region from our measurement, in consideration of 3 parameters (shape and endpoint). The models and data are normalized appropriately.

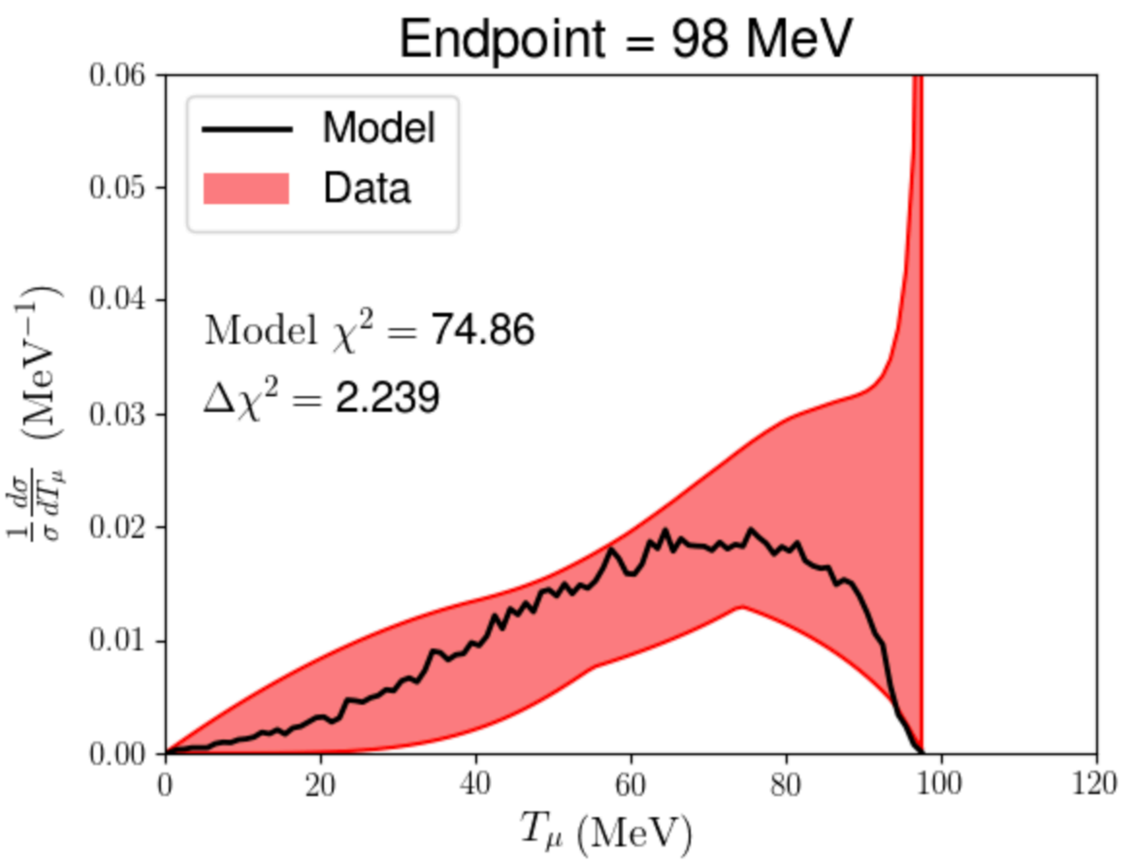
Website allows you to upload an arbitrary model prediction to be compared to our result.

The file nuwroData.txt has been uploaded.
Running Analysis...

Analysis Results
===========
Your χ^2 = 74.8628
Best fit χ^2 = 72.6239
$\Delta\chi^2$ = 2.23894
χ^2 Probability = 0.524319
===========

Analysis Complete!

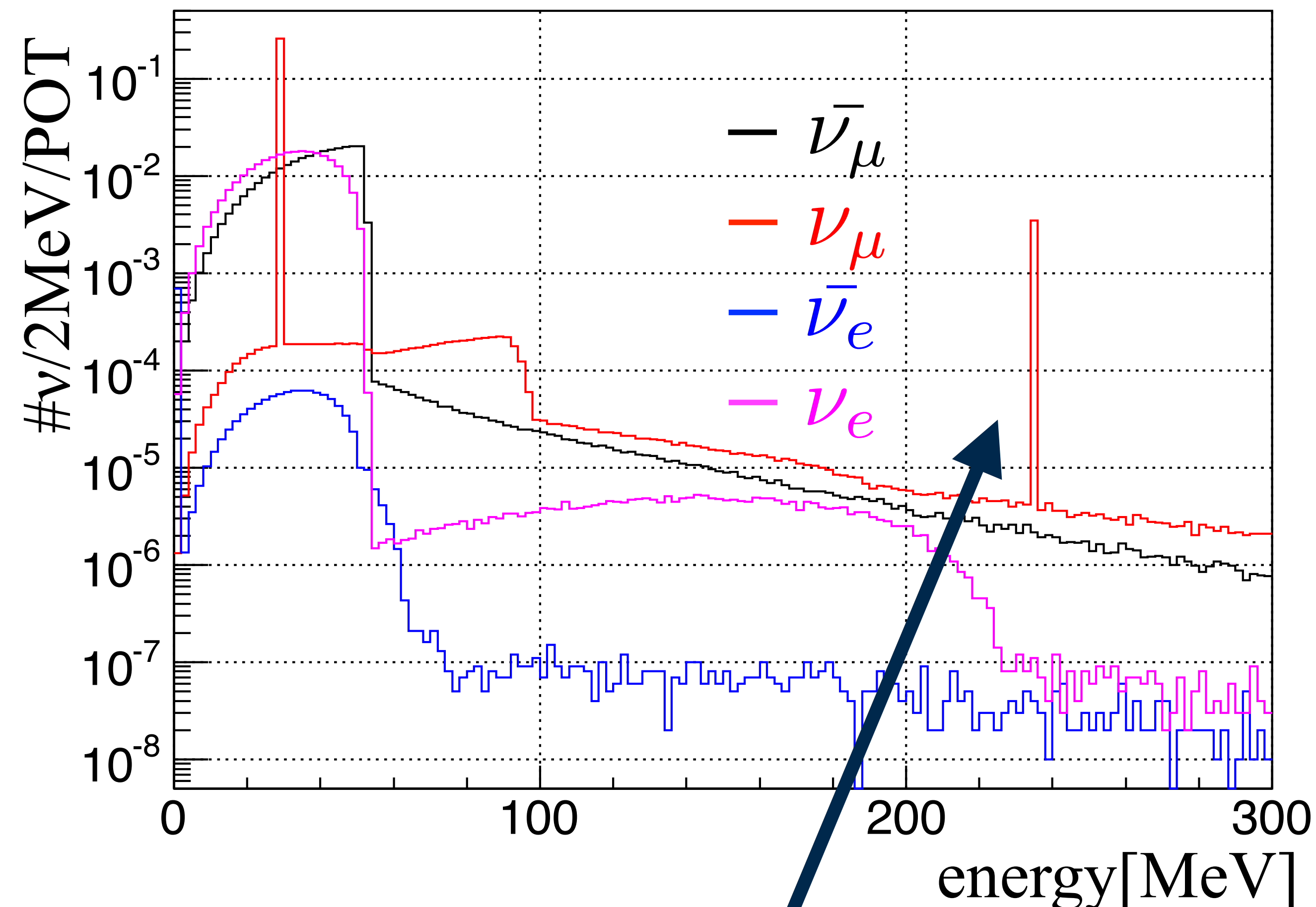
Results Plot
===========



Example comparison with NuWro prediction.

KDAR in JSNS²

- JSNS² can improve the KDAR measurement from MiniBooNE
- **Higher statistics**
  - 3 years of data will yield between 30,000 and 60,000 KDAR interactions
- **Better energy resolution**
  - The energy resolution of JSNS² will be a few percent at these energies
- **Lower backgrounds**
  - The KDAR measurement in JSNS² is essentially background free
- **Neutron counting**
  - JSNS² can tag final state neutrino from the neutrino interactions



The 236 MeV KDAR ν_μ in the J-PARC MLF flux.

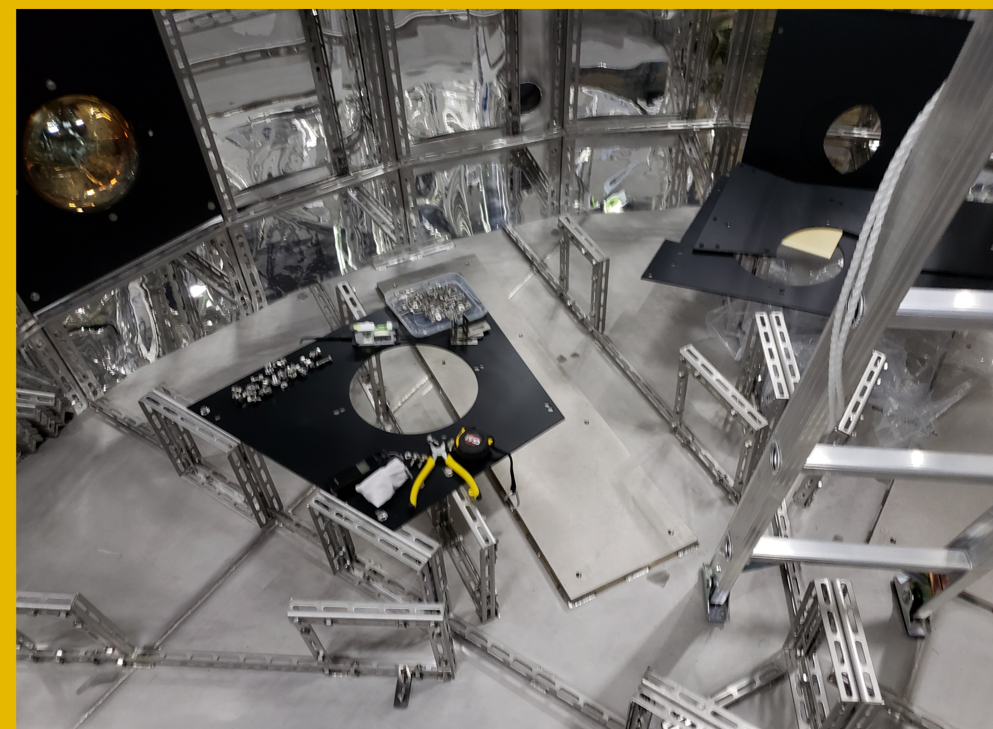
Conclusion

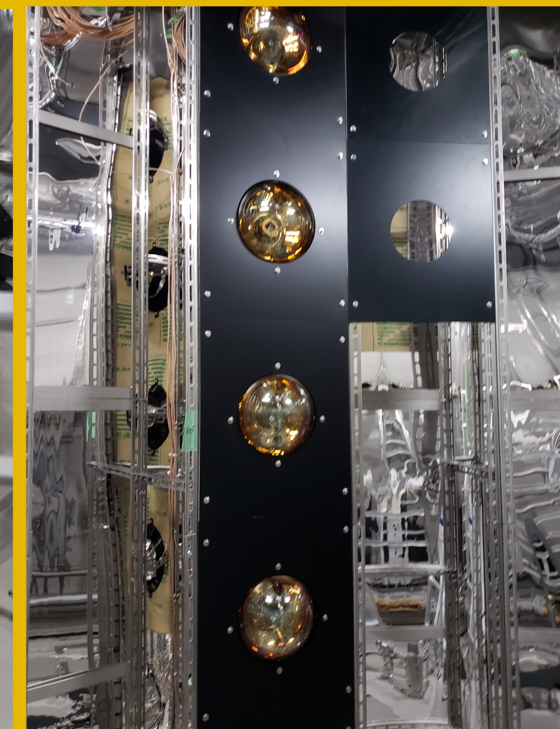
- Short-baseline neutrino experiments are great laboratories for studying new physics
- The short baseline anomalies will be tested with next generation experiments and motivate new thinking about the anomalies
- New models of light dark matter can be directly constrained by neutrino experiments
- Ongoing work on neutrino experiments will improve our BSM physics capabilities

Backup

Short Baseline Anomalies

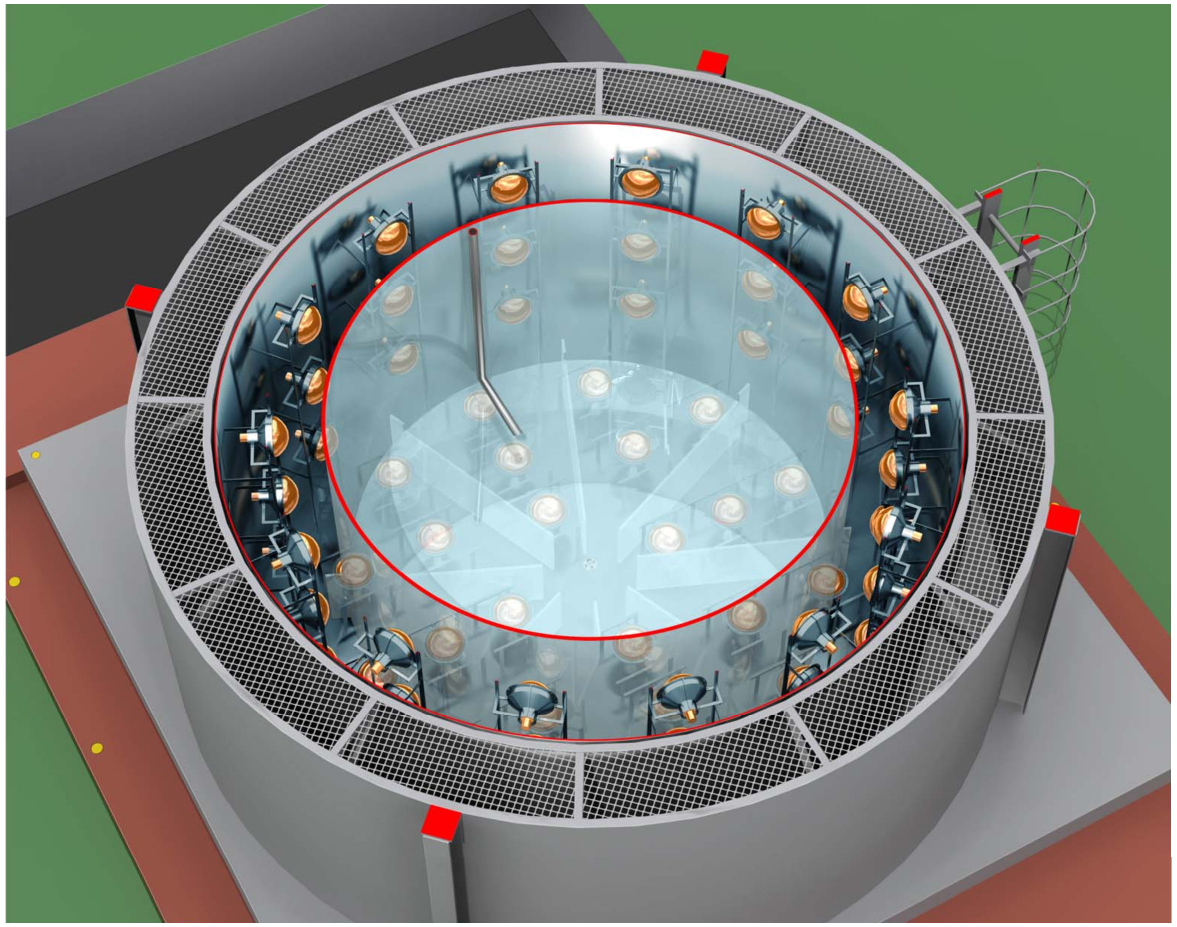
JSNS^2 Construction

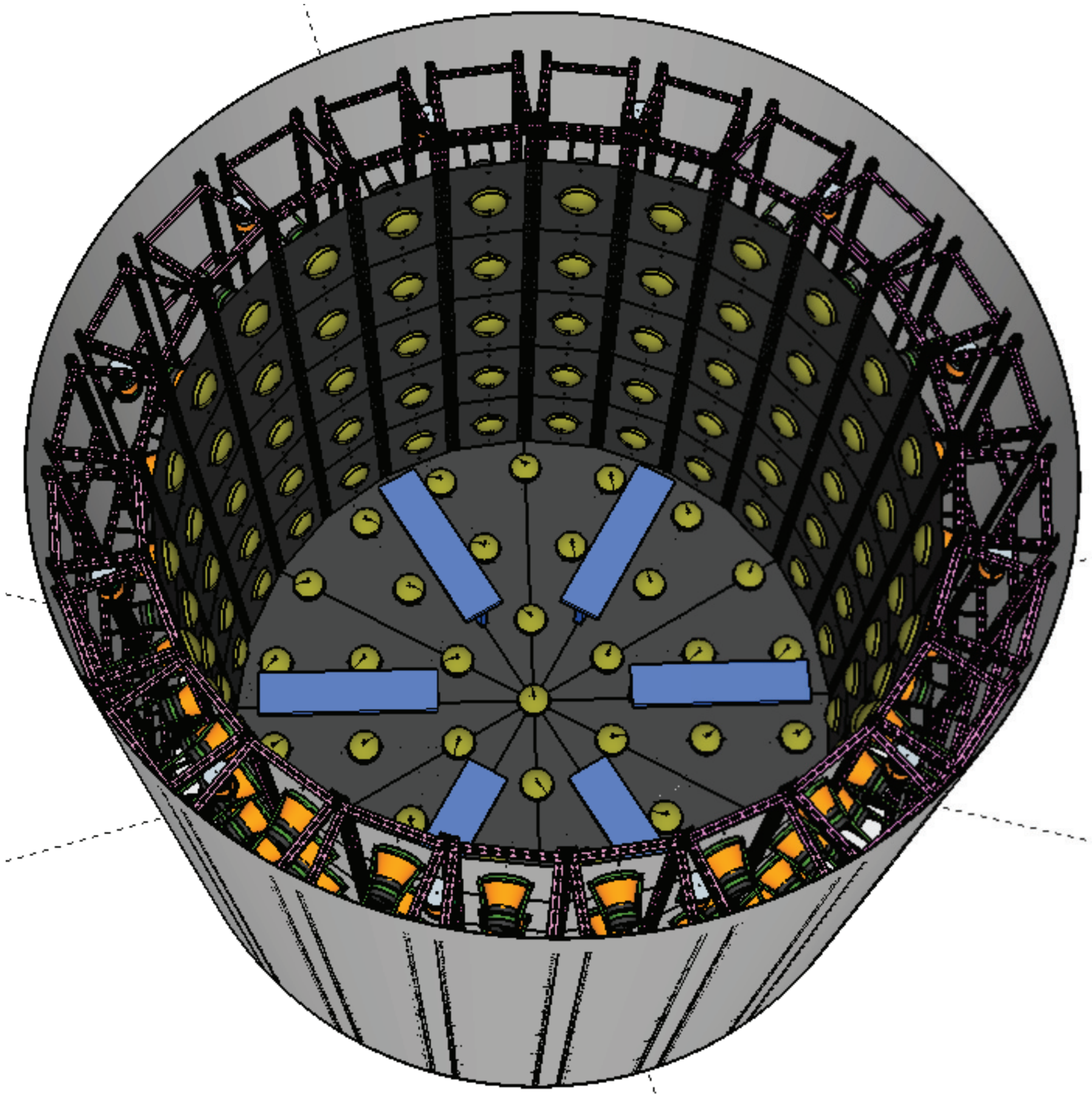




Detector is currently under construction. Expect construction to be finished in spring 2019 with first data in the fall.

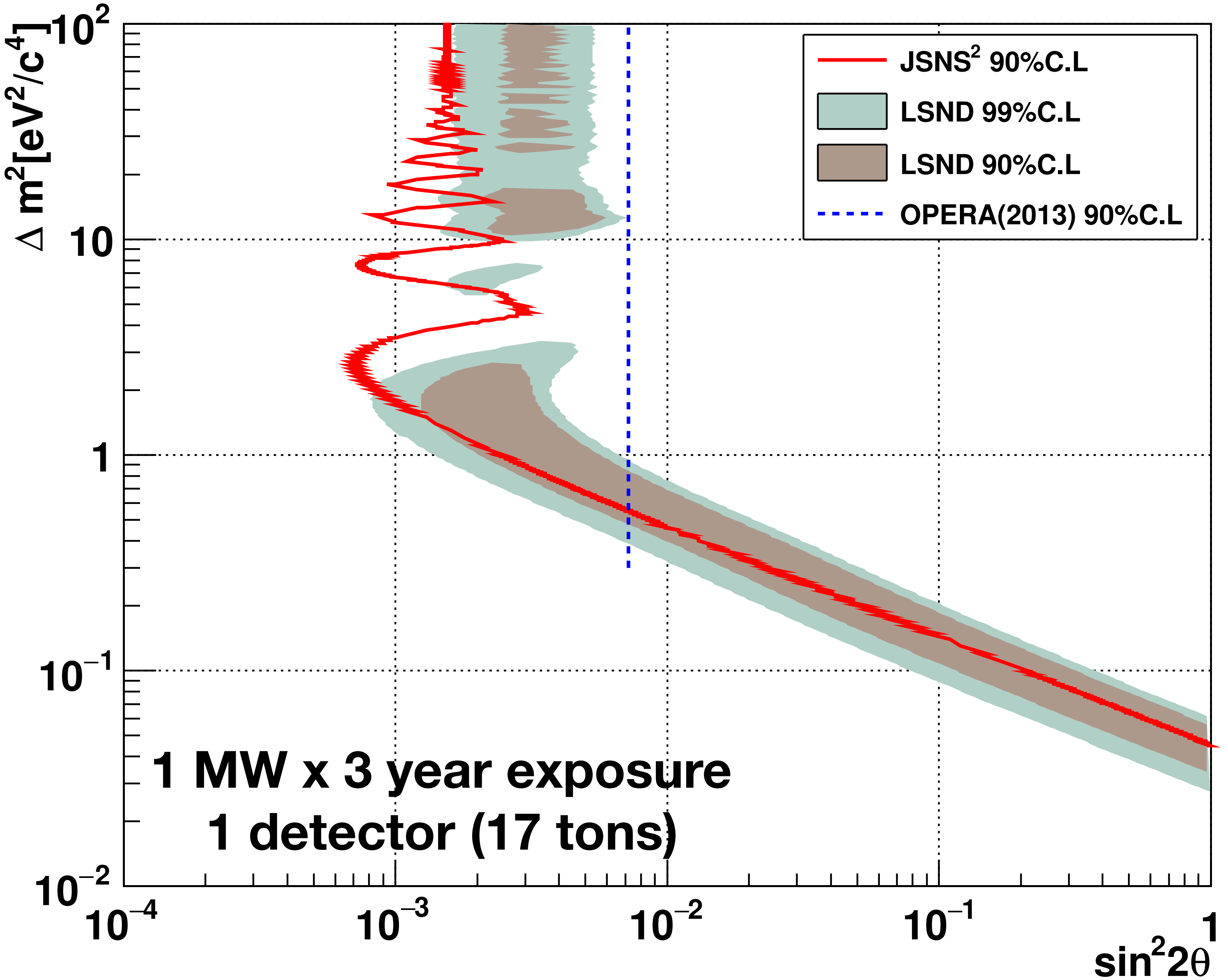
JSNS^2 Detector





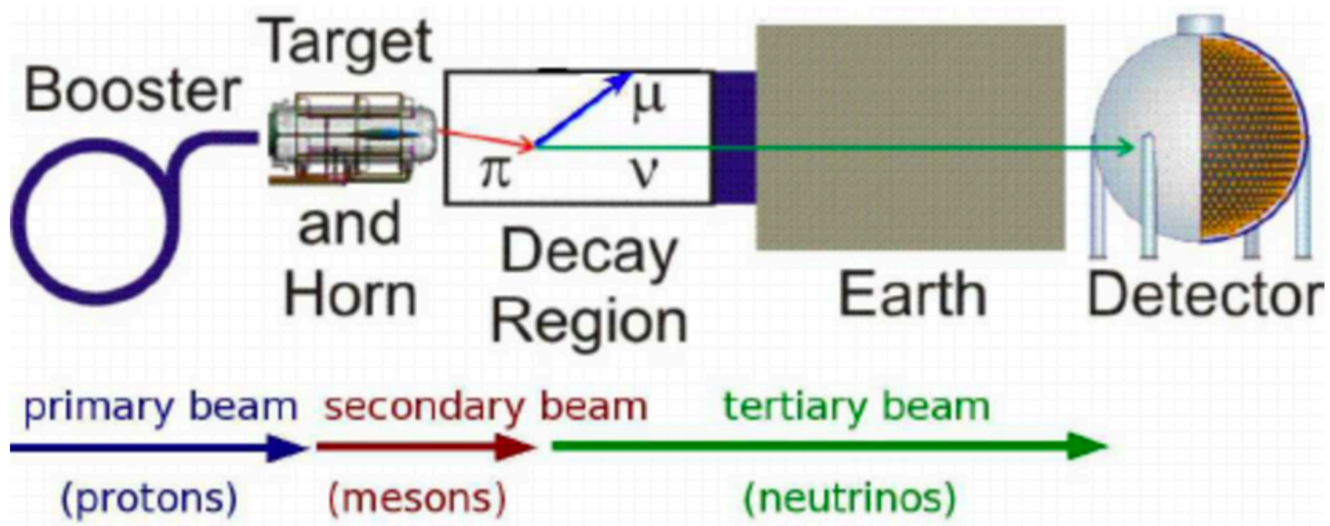
The detector consists of an inner acrylic vessel, a buffer region, and a veto region. There are 192 PMTs viewing the inner vessel and 48 PMTs in the veto region.

JSNS² Sensitivity



The MiniBooNE Experiment

- MiniBooNE is a neutrino experiment at Fermilab
- Neutrinos are produced in the Booster Neutrino Beamline
- Can run in two modes depending on the magnetic horn polarization
- Originally designed to test the LSND anomaly



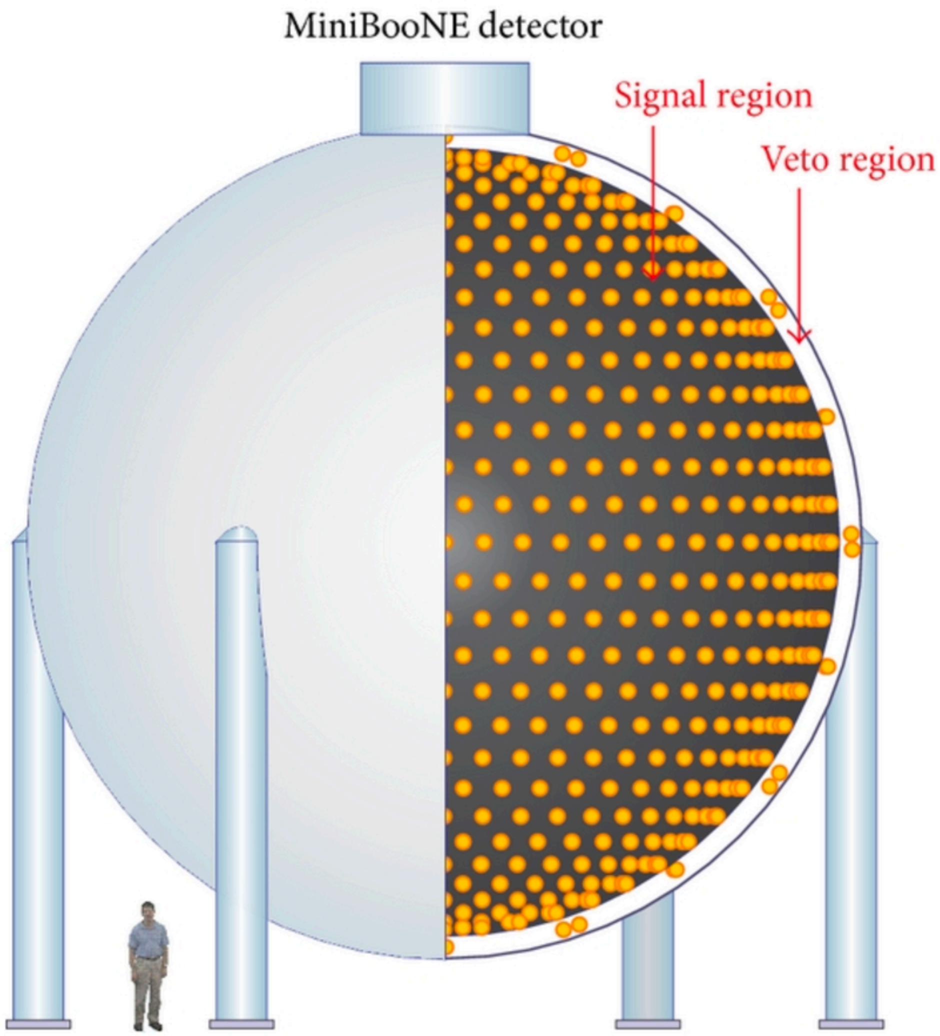
MiniBooNE has been collecting data since 2002. The total accumulated data in the two run modes is:

Neutrino Mode: 12.84×10^{20} POT

Antineutrino Mode: 11.27×10^{20} POT

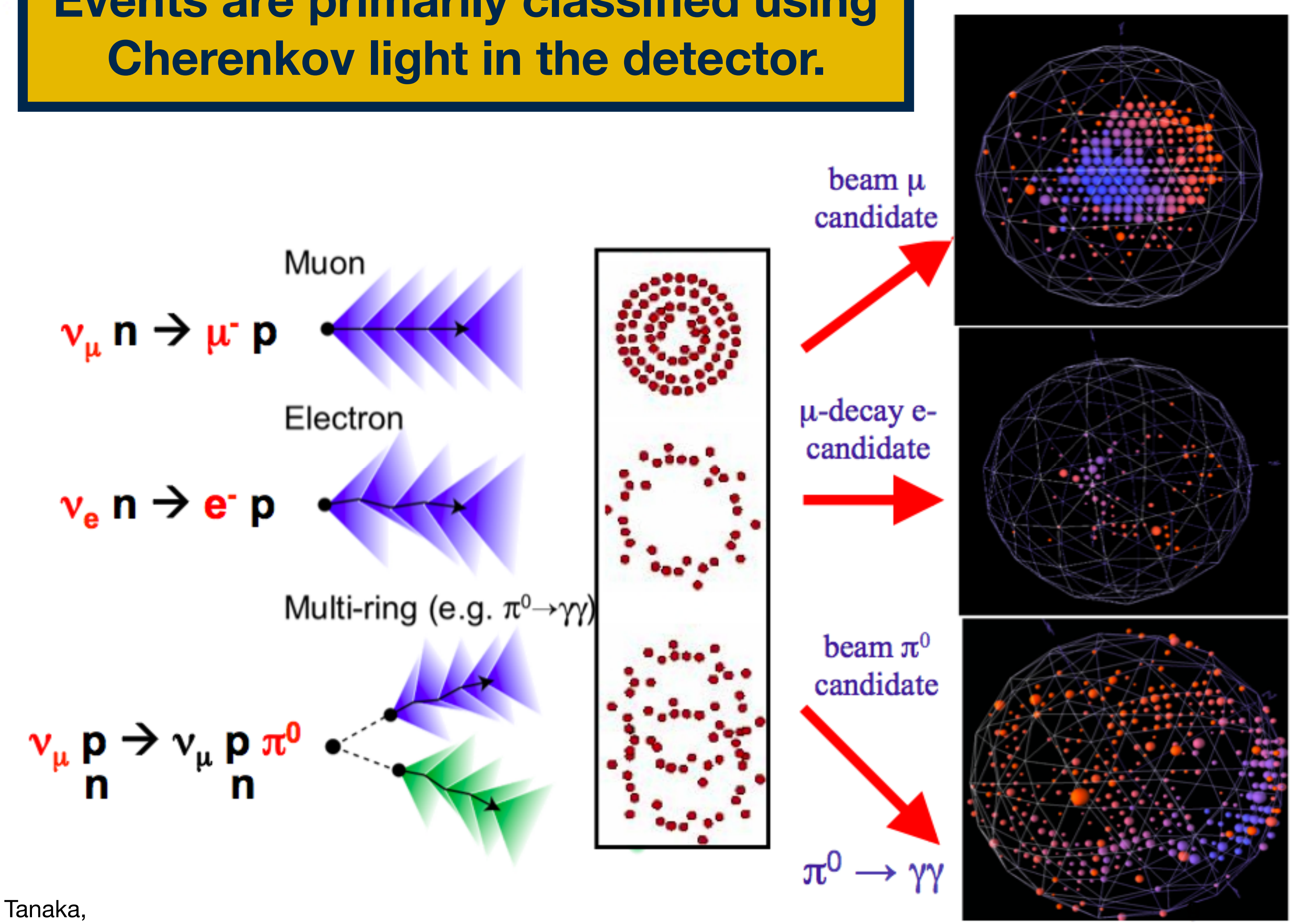
A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Nucl. Instrum. Meth. **A599**, 28–46 (2009), 0806.4201

Events in MiniBooNE



1280 inner PMTs
240 veto PMTs

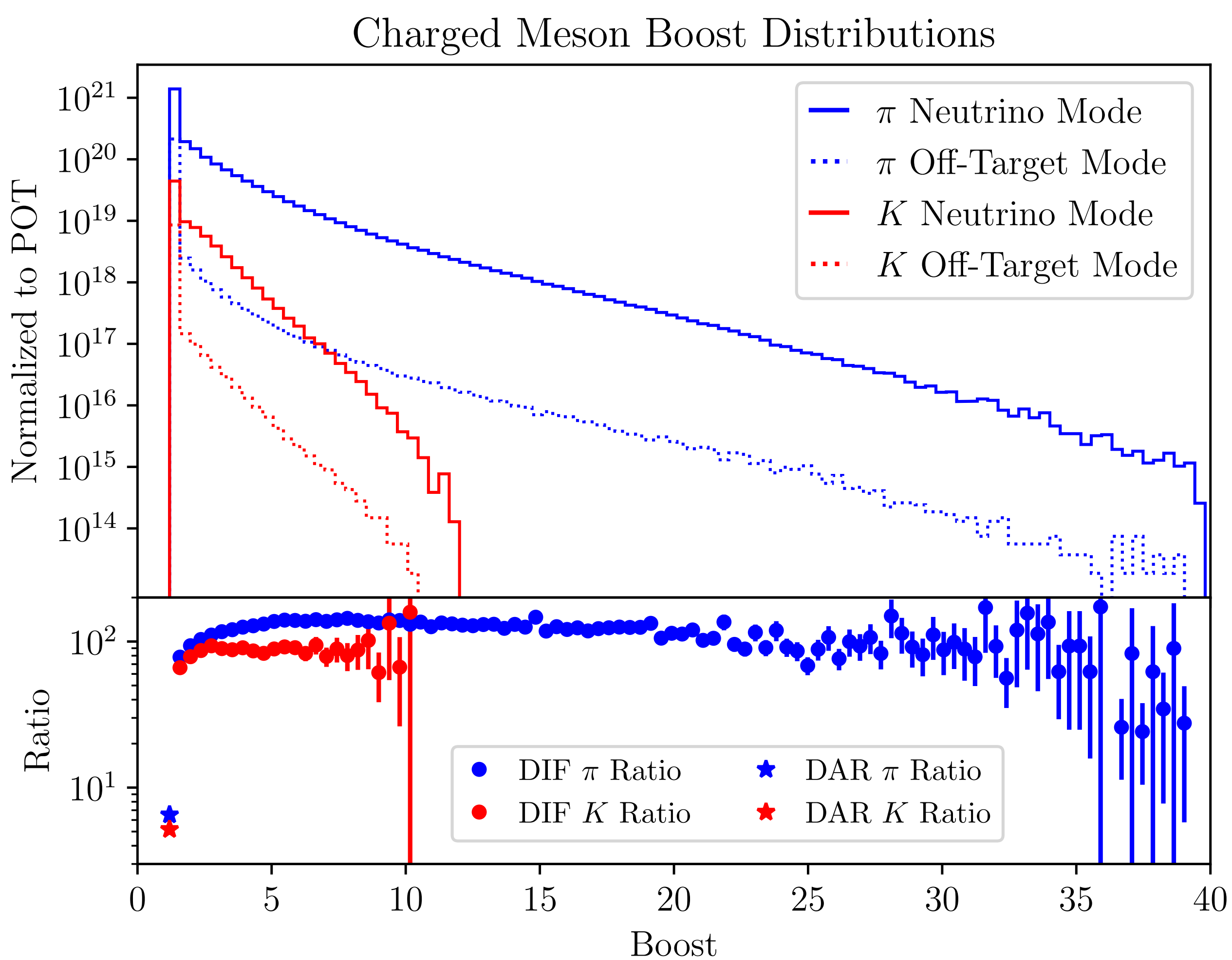
Events are primarily classified using Cherenkov light in the detector.

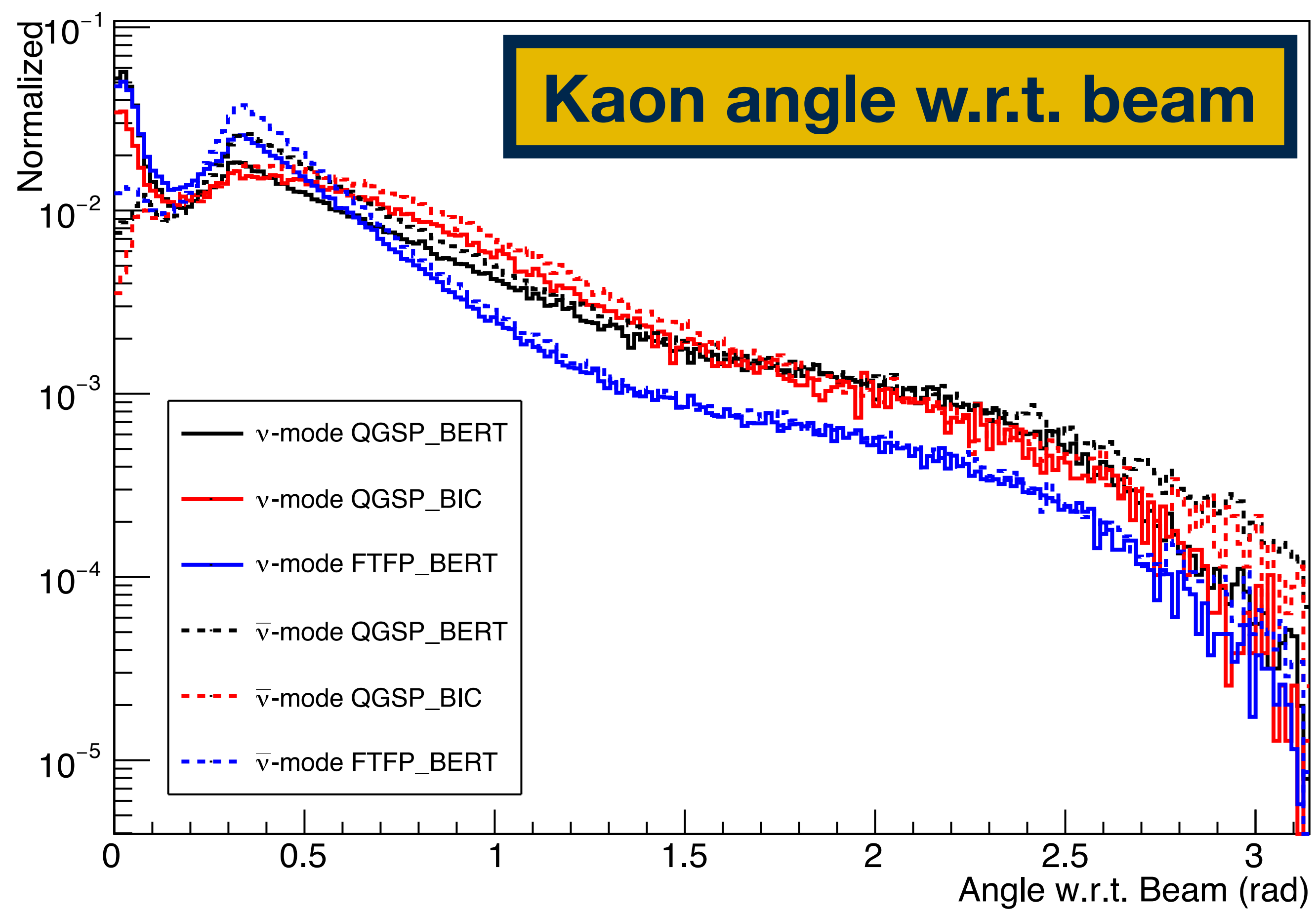


R. B. Patterson, E. M. Laird, Y. Liu, P. D. Meyers, I. Stancu and H. A. Tanaka, Nucl. Instrum. Meth. **A608**, 206–224 (2009), 0902.2222

A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Nucl. Instrum. Meth. **A599**, 28–46 (2009), 0806.4201

Charged Mesons





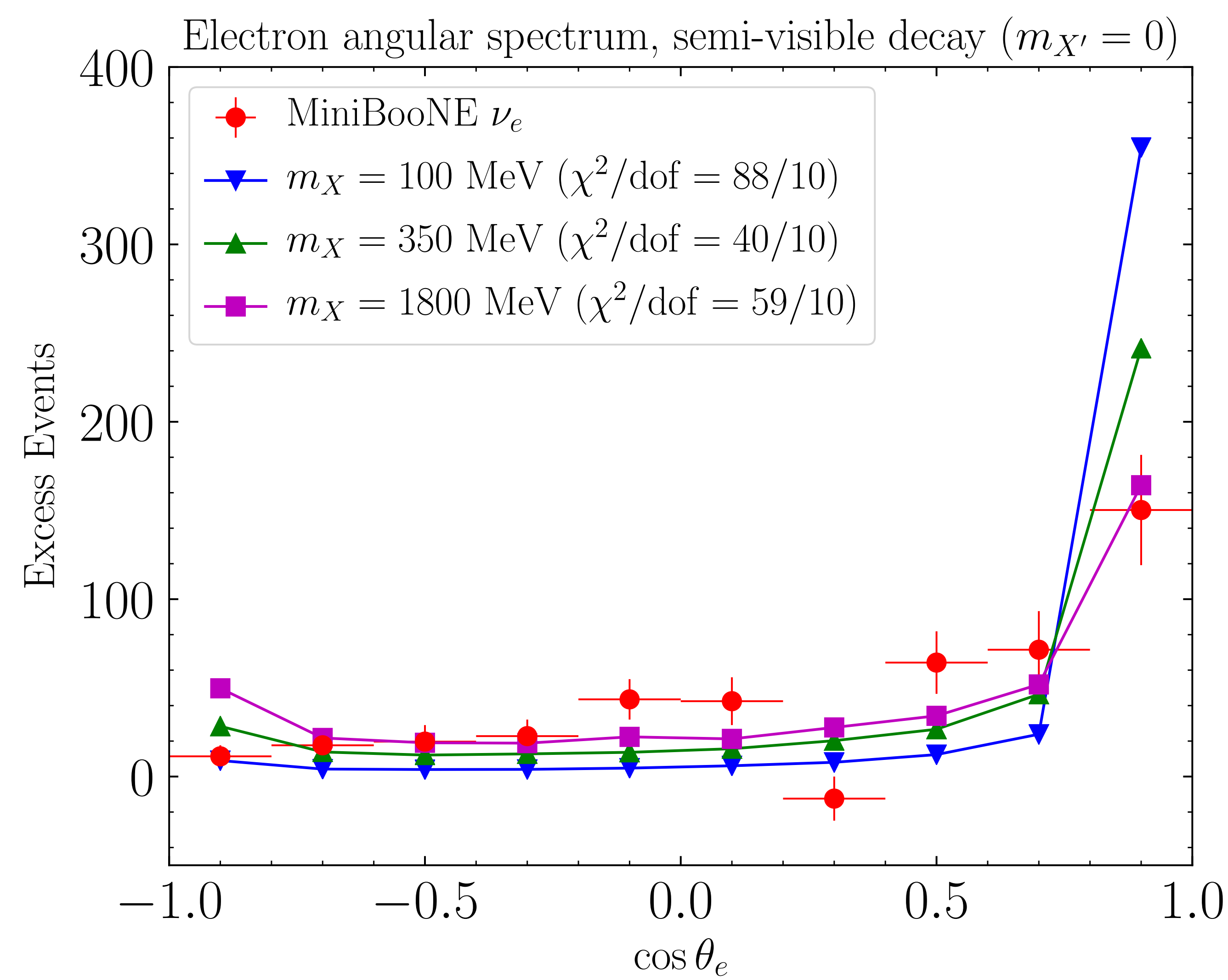
Charged meson production is lower by a factor of ~150 at high boosts.

Production from charged mesons is still compatible with the data.

This also helps explain the difference in the size of the excess between neutrino and antineutrino modes.

Semi-visible Decays

- Consider semi-visible decays of the general form
$$X \to X' + p_{EM}$$
- p_{EM} can represent any number of electromagnetic tracks as long as they are collimated
- In the lab frame particles emitted backwards have small energies,
$$E_{EM} \approx \frac{m_X^2 - m_{X'}^2}{2m_X}\gamma(1-\beta)$$
- We can engineer to the energy distribution exactly using
$$E_\nu^{reco} = \frac{2m_n E_e + m_p^2 - m_n^2 - m_e^2}{2(m_n - E_e + \cos\theta_e \sqrt{E_e^2 - m_e^2})}$$



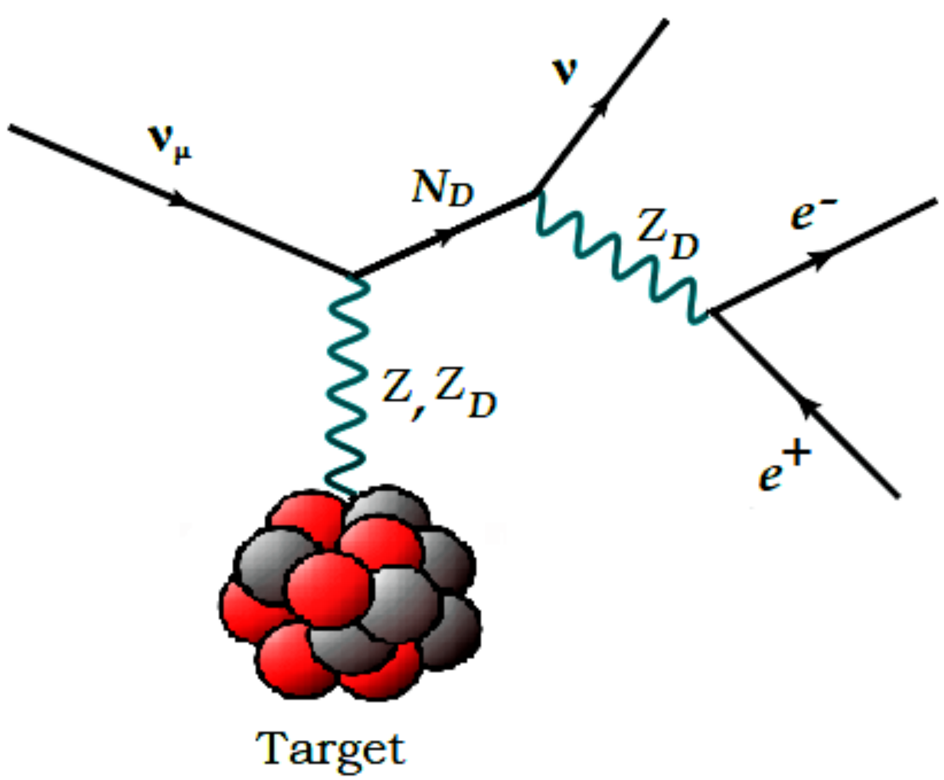
Tension is worse if we allow the lighter state to have nonzero mass.

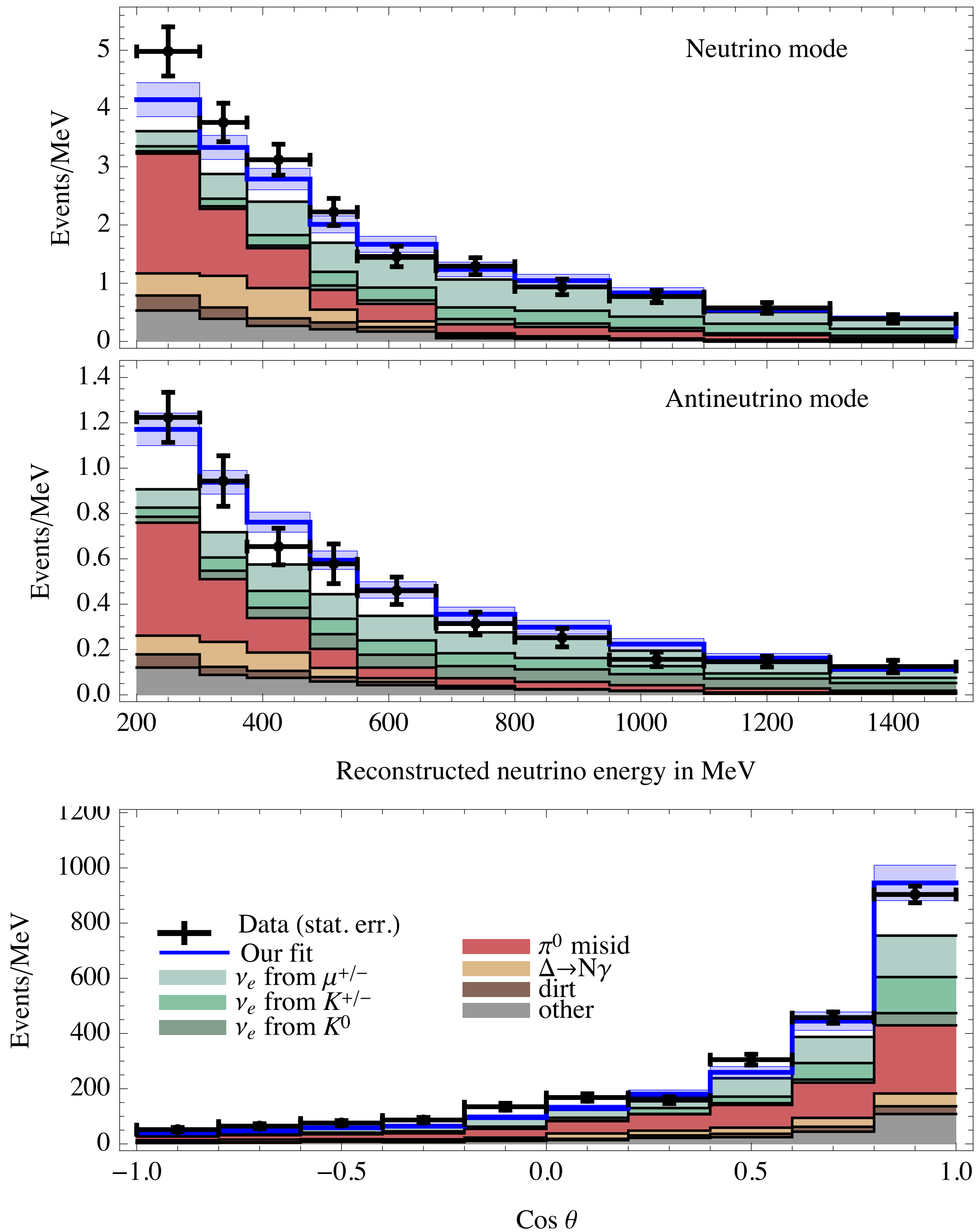
An Example Model

Dark Neutrino Portal Model

$$\mathcal{L} \supset \frac{m_{Z_\mathcal{D}}^2}{2} Z_{\mathcal{D}\mu} Z_\mathcal{D}^\mu + g_\mathcal{D} Z_\mathcal{D}^\mu \bar{\nu}_\mathcal{D} \gamma_\mu \nu_\mathcal{D}$$

$$+ e\epsilon Z_\mathcal{D}^\mu J_\mu^{em} + \frac{g}{c_W} \epsilon' Z_\mathcal{D}^\mu J_\mu^Z$$





E. Bertuzzo, S. Jana, P. A. N. Machado and R. Zukanovich Funchal, (2018), 1807.09877

MiniBooNE Allowed Regions

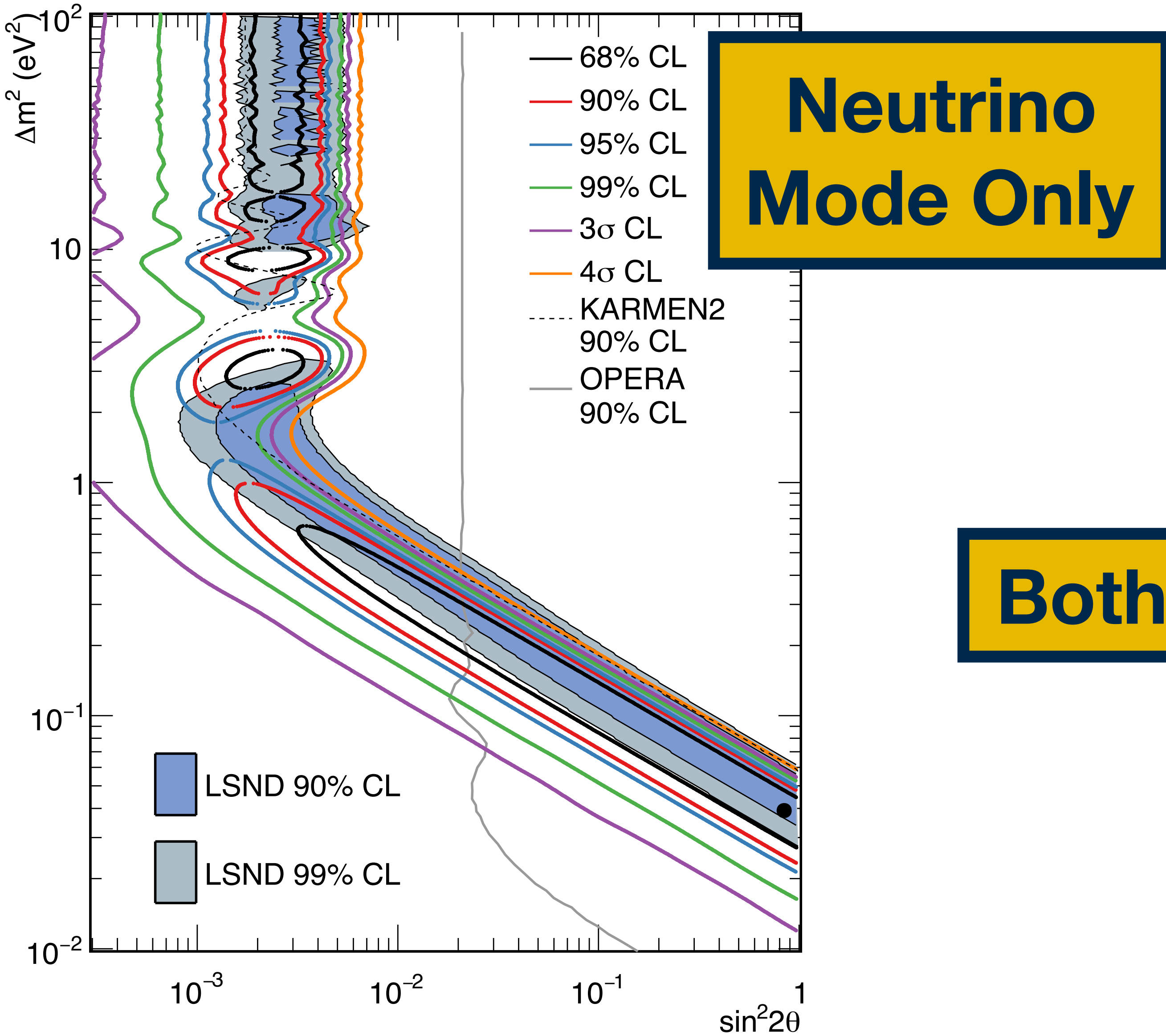


FIG. 4: MiniBooNE allowed regions in neutrino mode (12.84×10^{20} POT) for events with $200 < E_\nu^{QE} < 1250$ MeV within a two-neutrino oscillation model. The shaded areas show the 90% and 99% C.L. LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ allowed regions. The black circle shows the MiniBooNE best fit point. Also shown are 90% C.L. limits from the KARMEN [34] and OPERA [35] experiments.

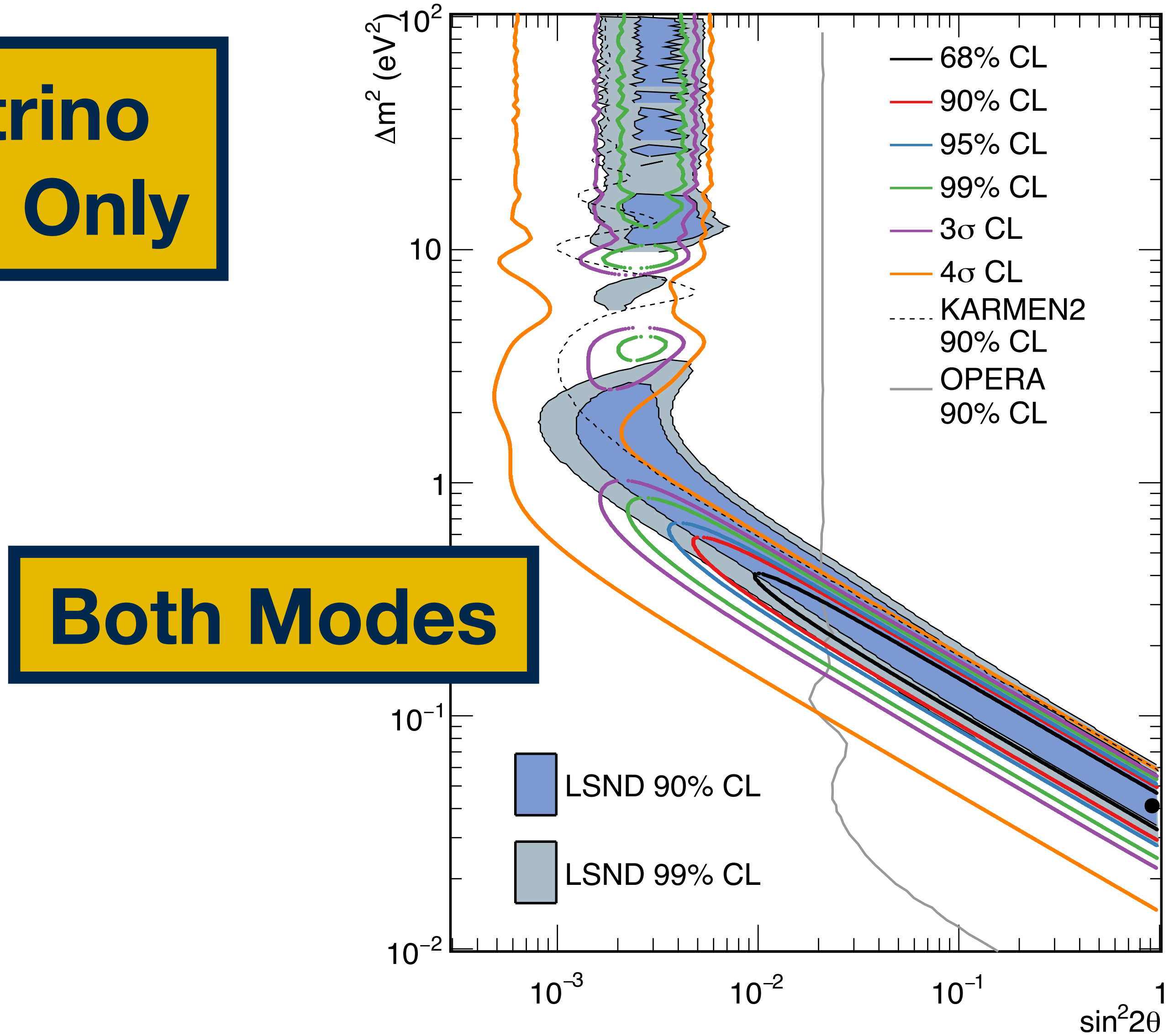
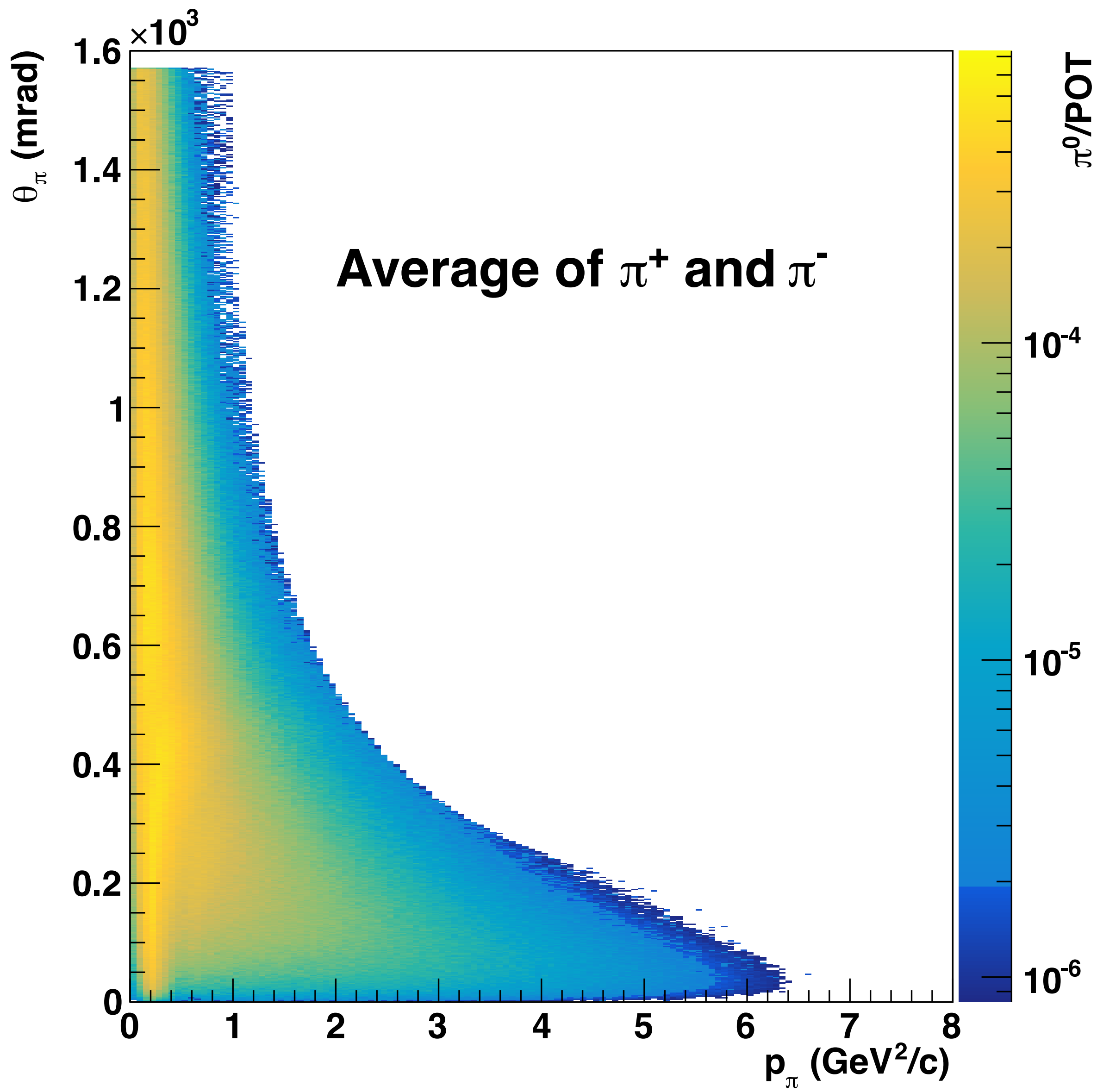
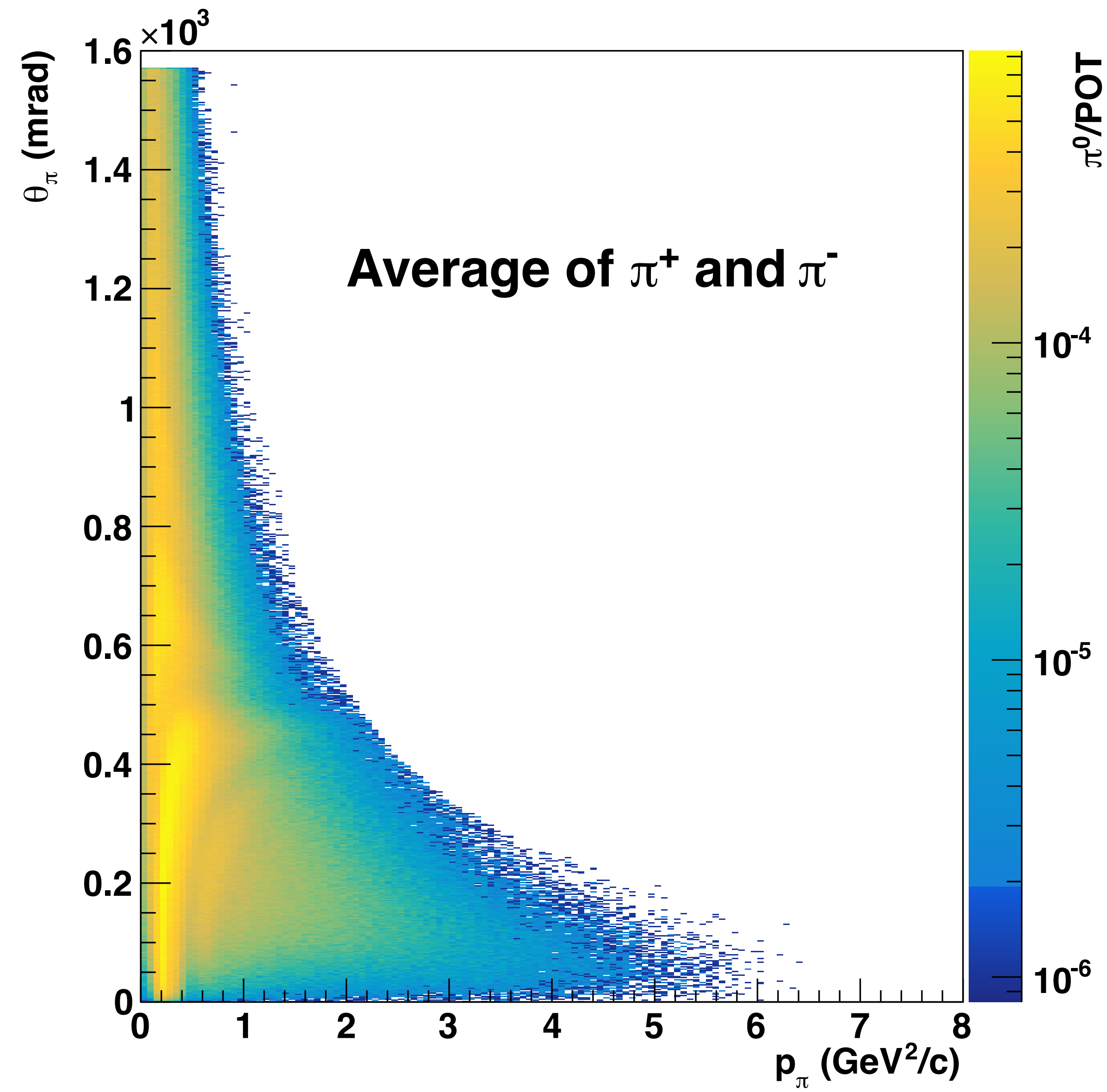


FIG. 5: MiniBooNE allowed regions for a combined neutrino mode (12.84×10^{20} POT) and antineutrino mode (11.27×10^{20} POT) data sets for events with $200 < E_\nu^{QE} < 1250$ MeV within a two-neutrino oscillation model. The shaded areas show the 90% and 99% C.L. LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ allowed regions. The black circle shows the MiniBooNE best fit point. Also shown are 90% C.L. limits from the KARMEN [34] and OPERA [35] experiments.

MiniBooNE Pion Kinematics

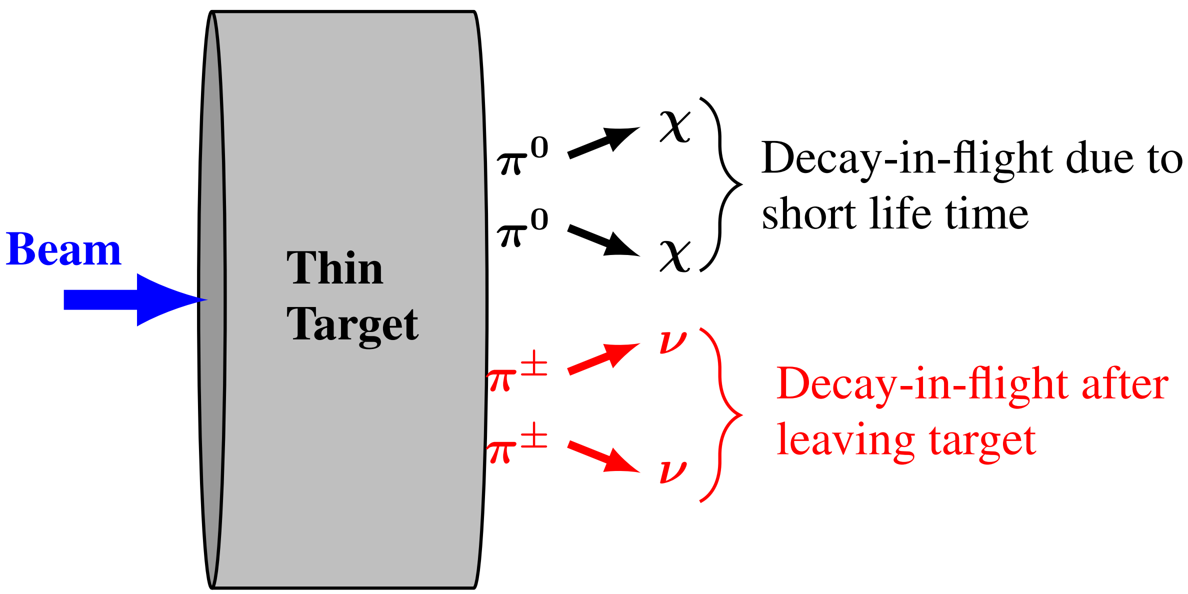


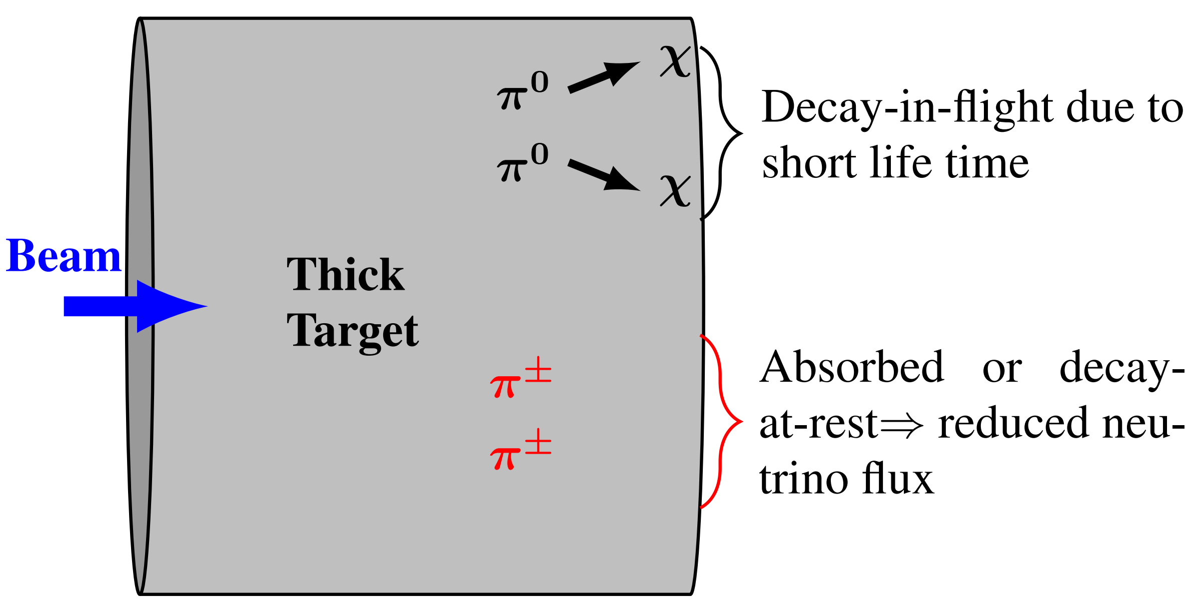
(a) neutrino-mode

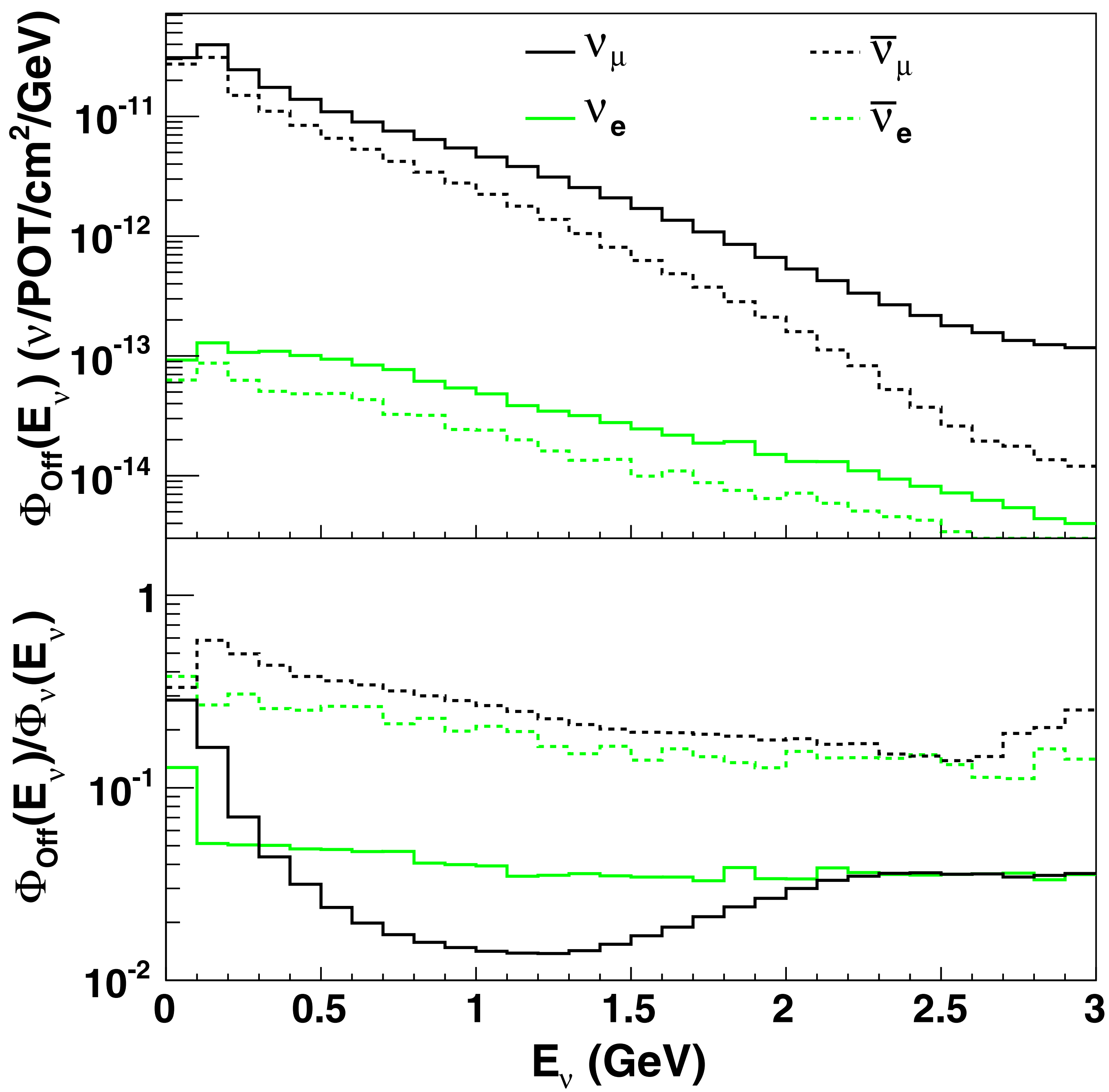


(b) off-target

Reduced Neutrino Flux

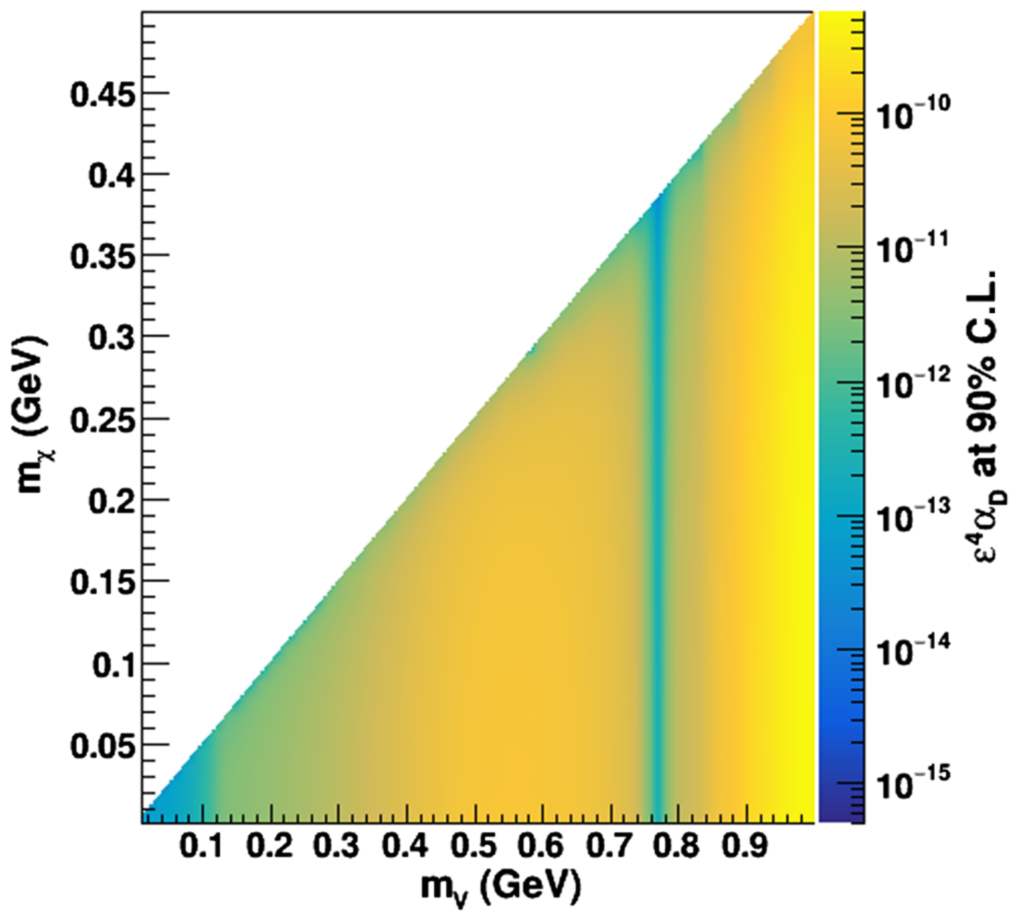


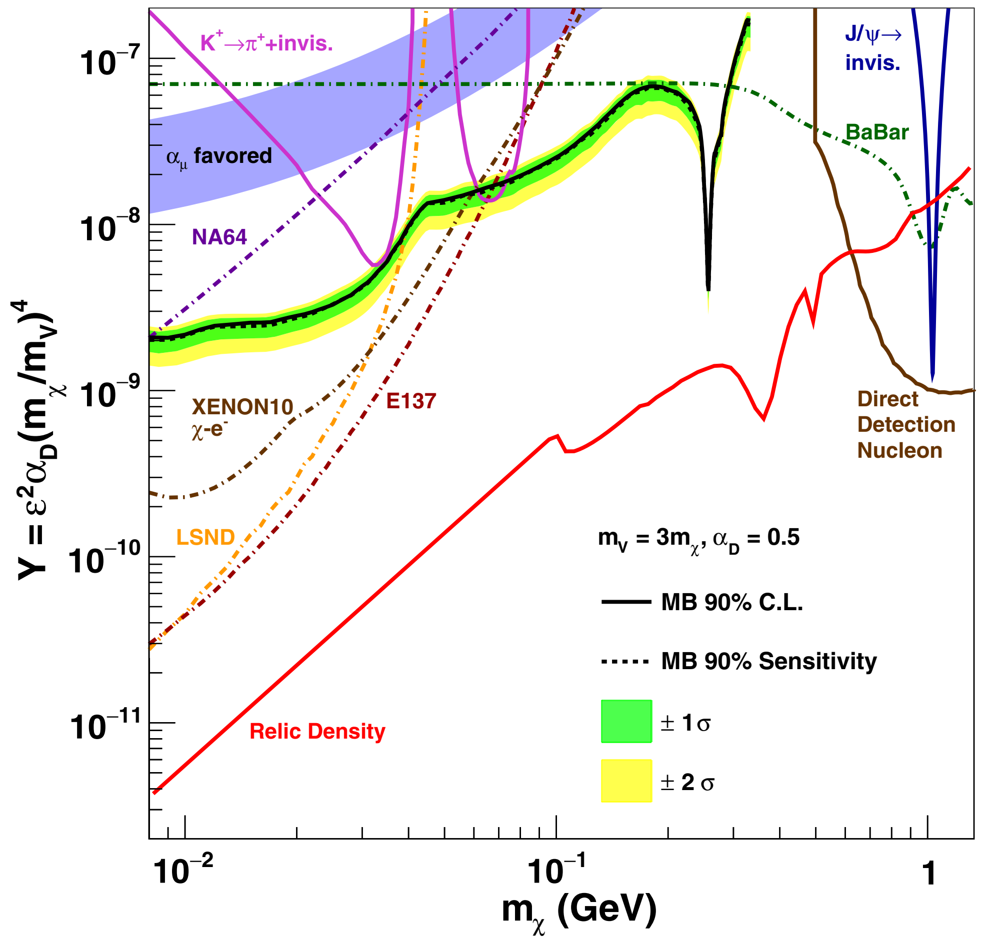


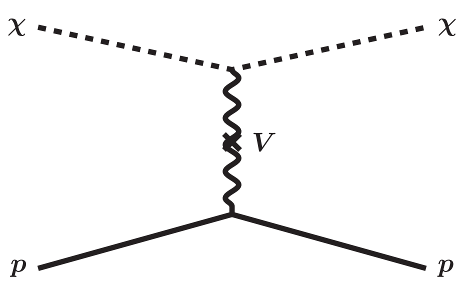


A. A. Aguilar-Arevalo et al. (MiniBooNE DM Collaboration) Phys. Rev. Lett. **118**, 221803, (2017), 1702.02688

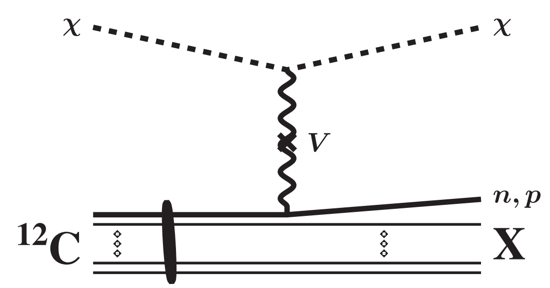
First Beam Dump Mode Results







(a) Free protons



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

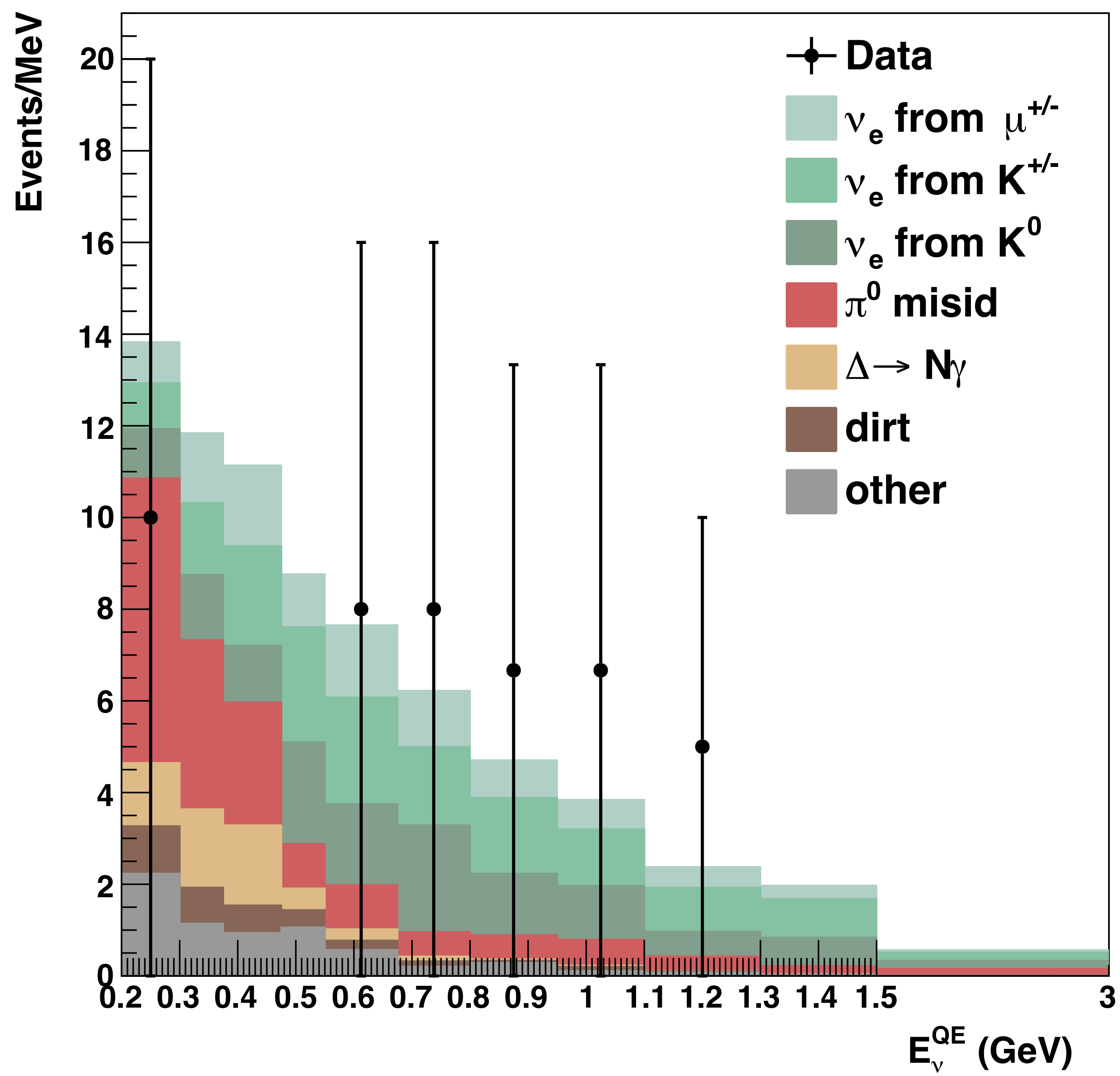
Beam Dump Mode Cuts

Cut #	Description
CCQE	
1	# subevents $= 2$
2	1st sub, # tank > 200 and all subevents, # veto hits < 6
3	1st sub, reconstructed vertex radius $< 500\,\mathrm{cm}$
4	1st sub, event time window $4.4 < T\,(\mu\mathrm{s}) < 6.4$
5	1st sub, μ/e log-likelihood ratio > 0
6	1st sub, kinetic energy $T > 200\,\mathrm{MeV}$
7	μ-e vertex distance $> 100\,\mathrm{cm}$ and $> (500T_\mu\,(\mathrm{GeV}) - 100)$ cm
NCE	
1	# subevents $= 1$
2	# tank hits > 12 and # veto hits < 6
3	Reconstructed vertex radius $< 500\,\mathrm{cm}$
4	event time window $4.4 < T\,(\mu\mathrm{s}) < 6.4$
5	p/e time log-likelihood ratio < 0.42
6	kinetic energy $35 < T\,(\mathrm{MeV}) < 650$
7	< 60 hits $10\,\mu\mathrm{s}$ before event trigger

Cut #	Description
NCπ^0	
1	# subevents $= 1$
2	# tank hits > 200 and # veto hits < 6
3	event time window $4 < T\,(\mu\mathrm{s}) < 7$
4	Reconstructed vertex radius $< 500\,\mathrm{cm}$ (e fit)
5	μ/e log-likelihood ratio > 0.05
6	e/π^0 log-likelihood ratio < 0
7	$80 < m_{\gamma\gamma}\left(\mathrm{MeV}\,c^{-2}\right) < 200$
ν-e	
1	# subevents $= 1$
2	# tank hits > 20 and # veto hits ≤ 2
3	event time window $4.4 < T\,(\mu\mathrm{s}) < 6.4$
4	Reconstructed vertex radius $< 500\,\mathrm{cm}$
5	visible energy $75 \leq E^e_{\mathrm{vis}}\,(\mathrm{MeV}) \leq 850$
6	reconstructed angle $\cos\theta_e \geq 0.9$
7	μ/e log-likelihood ratio: See text
8	e time log-likelihood ≤ 3.6
9	Scintillation / Cherenkov Ratio ≤ 0.55
10	Distance to wall $\geq 210\,\mathrm{cm}$
	For events with # tank hits > 200
11	e/π^0 log-likelihood ratio $> -6.25 \times 10^{-3}$
12	$m_{\gamma\gamma} \leq 80\,\mathrm{MeV}\,c^{-2}$

Beam Dump Data with Oscillation Analysis Cuts

- Oscillation search cuts were applied to the beam dump data
- The excess in this mode is -2.8 events, inconsistent with the expectation of 35.5 for a process which scales with POT
- This also tells us the beam dump cuts are a factor of 2-3 more stringent based on the number of events which pass



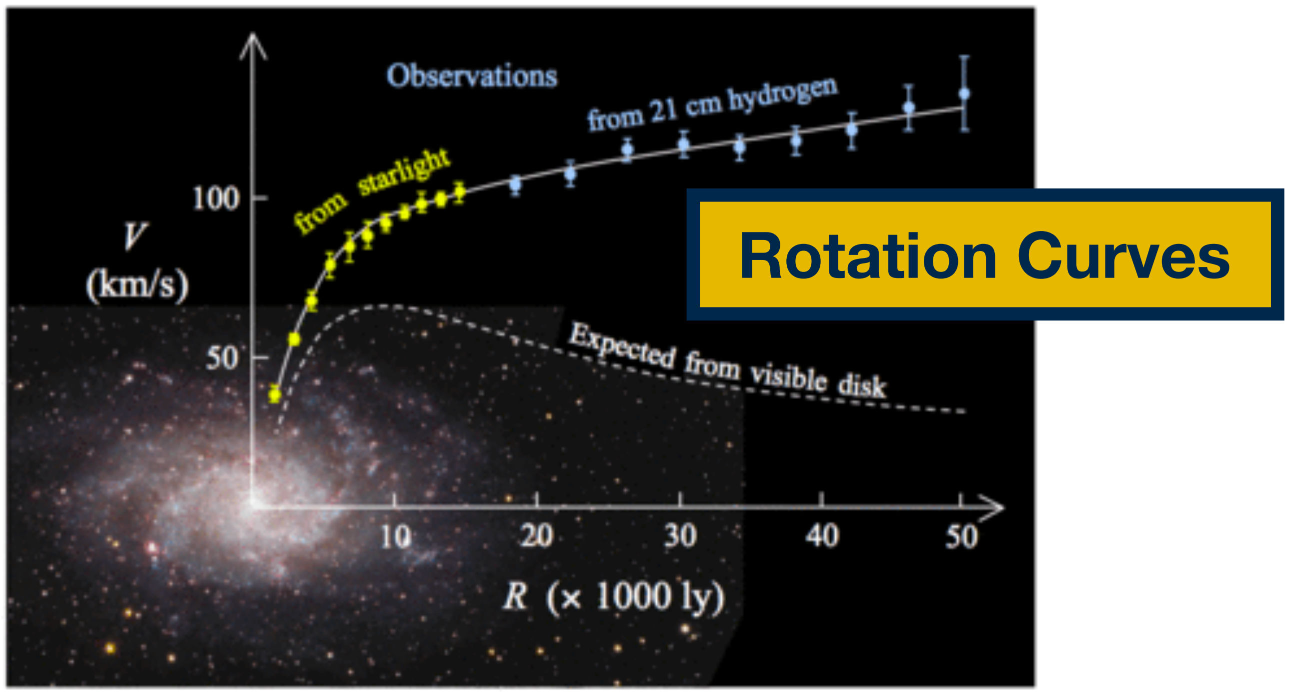
LSND and New Physics

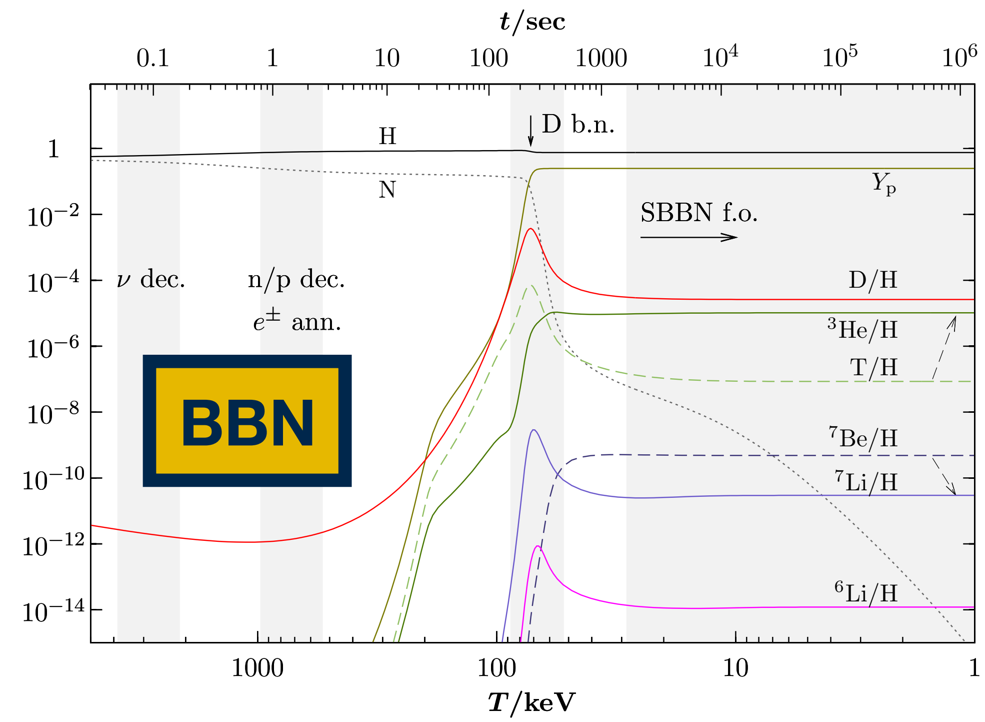
- A natural question is whether new physics can explain the LSND excess
- Hard to imagine the LSND and MiniBooNE excesses have the same non-neutrino new physics explanation
  - Different beam energies (800 MeV at LSND vs 8 GeV at MiniBooNE)
  - Different electron-like excess energies (< 50 MeV for LSND vs 100's of MeV for MiniBooNE)
  - Different detector signatures (single vs. double coincidence)
- The LSND excess is harder to fake because it involves a double coincidence consistent with inverse beta decay
  - Electron-like primary signal (order 10's of MeV)
  - Neutron capture on hydrogen (2.2 MeV) consistent with capture time (200 microseconds)
- Would require some sort of inelastic process

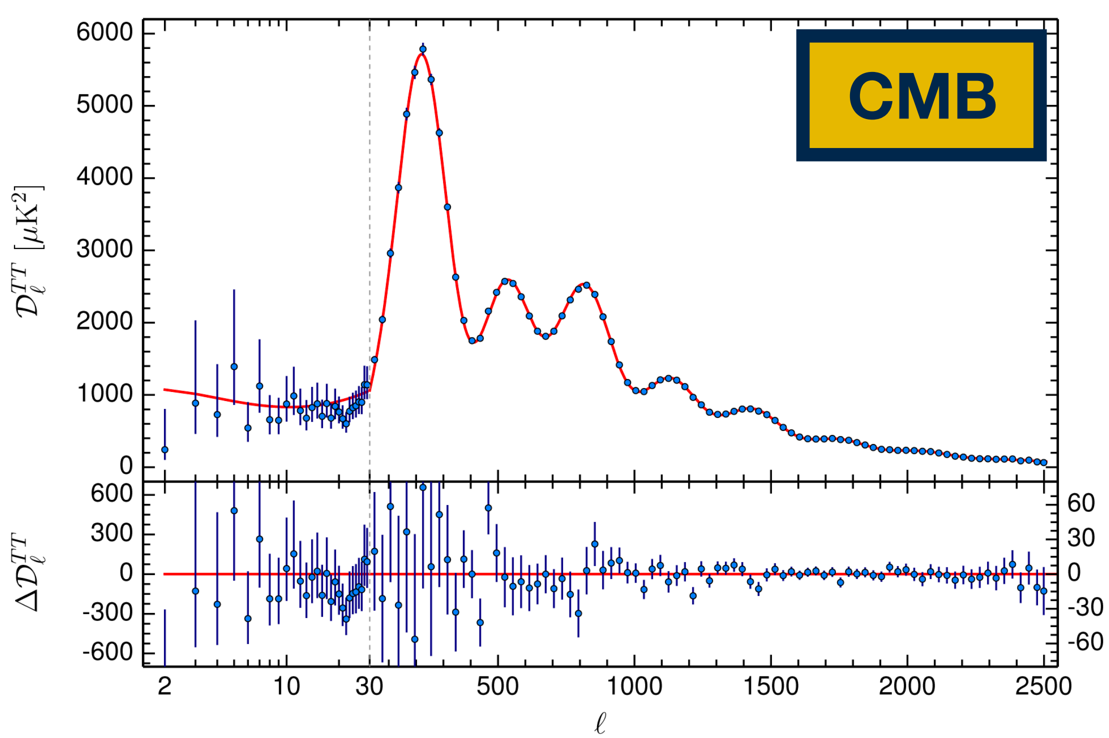
Backup

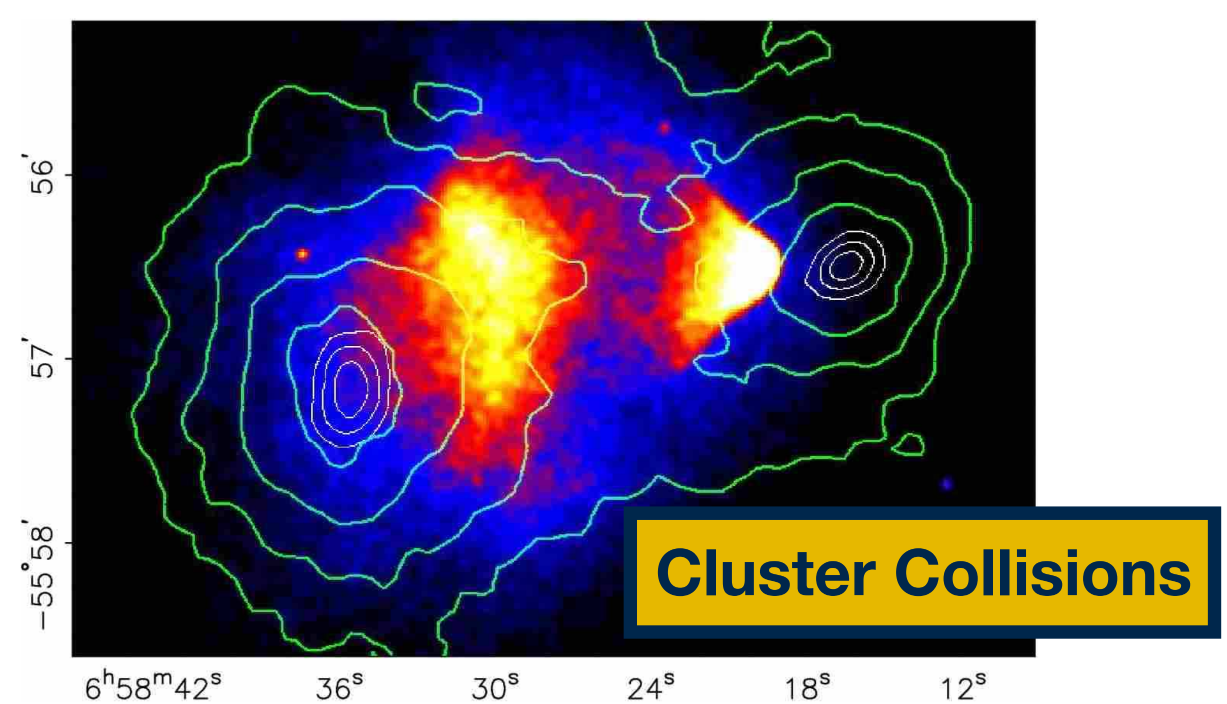
Dark Matter at Neutrino Experiments

Evidence for Dark Matter





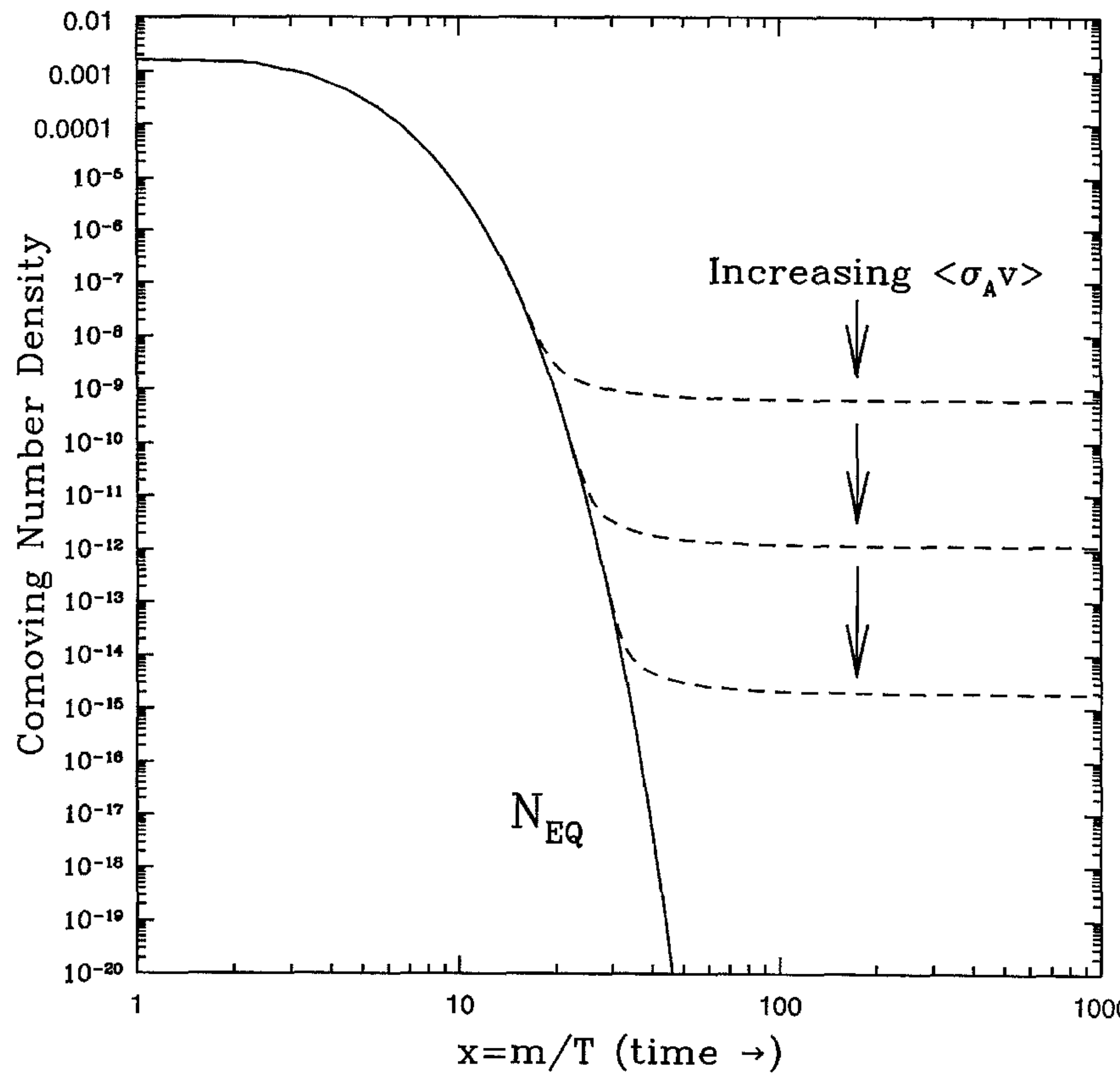




Thermal Dark Matter

- Consider DM in equilibrium with the SM in the early universe
- Abundance now is set by the mass and coupling of the dark matter
- Sets a minimum annihilation rate to get the correct abundance

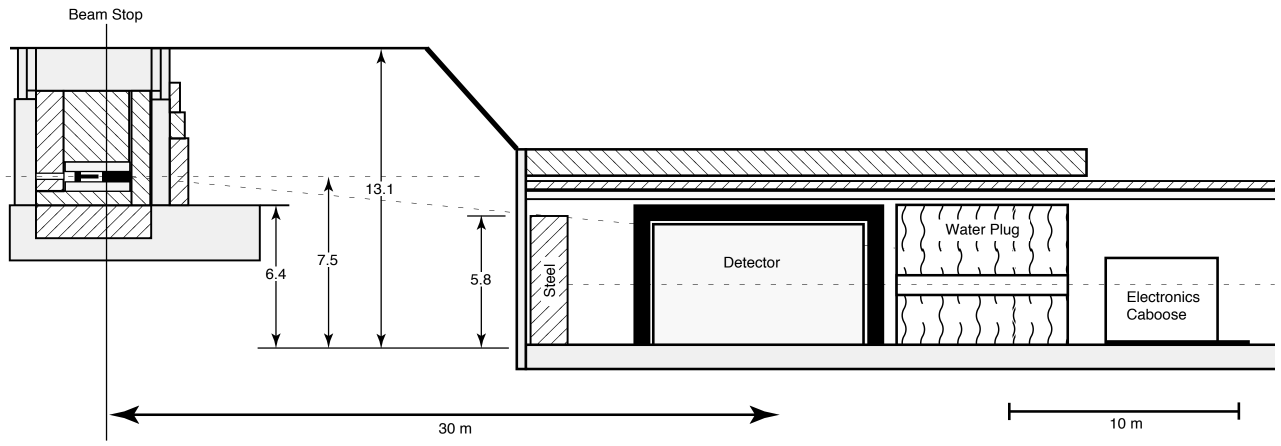
Thermal Freeze-out Picture

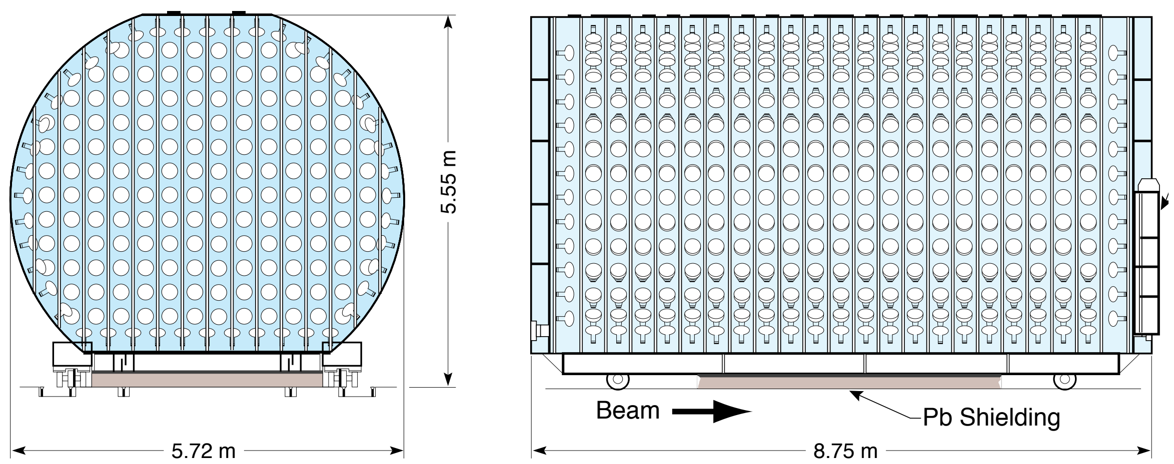


G. Jungman, M. Kamionkowski, K. Griest (1996)

LSND

- LSND was a neutrino oscillation experiment at Los Alamos
- Used a decay at rest source of neutrinos from an 800 MeV proton beam
- Used a combination of scintillation and Cherenkov light





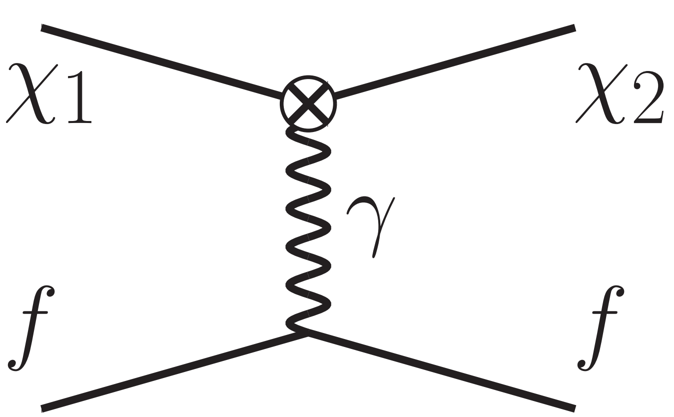
C. Athanassopoulos et al. (LSND Collaboration), Nucl. Instrum. Meth.**A388**,149–172 (1997), nucl-ex/9605002

Dipole Model

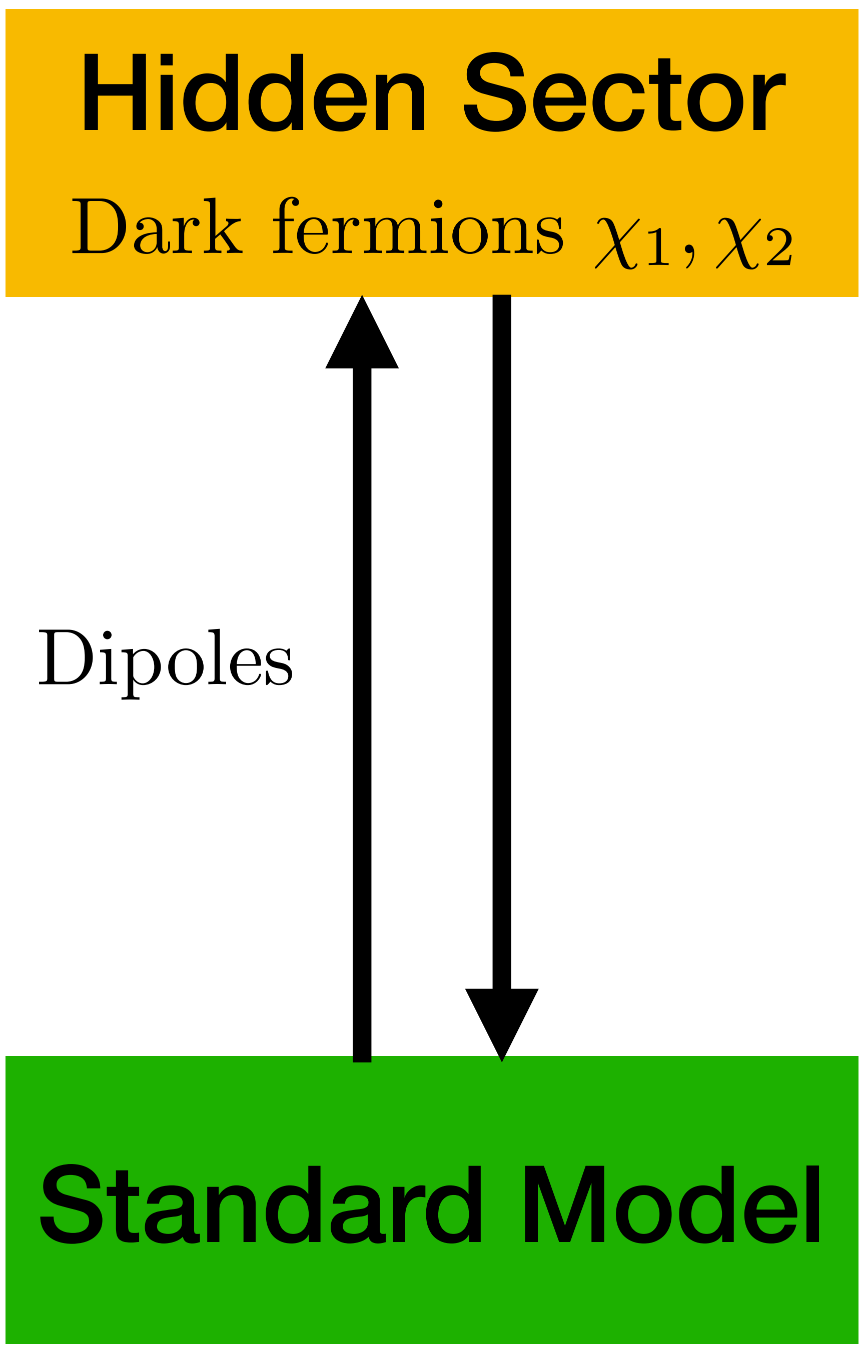
- We can also couple the dark fermions to the SM photon directly

$$\mathcal{L} \supset \frac{-i}{2\Lambda}\bar{\chi}_2\sigma^{\mu\nu}(c_M + ic_E\gamma^5)\chi_1 F_{\mu\nu}$$

- If the mass splitting is 3.5 keV, this model can explain the 3.5 keV excess via excitation and decay



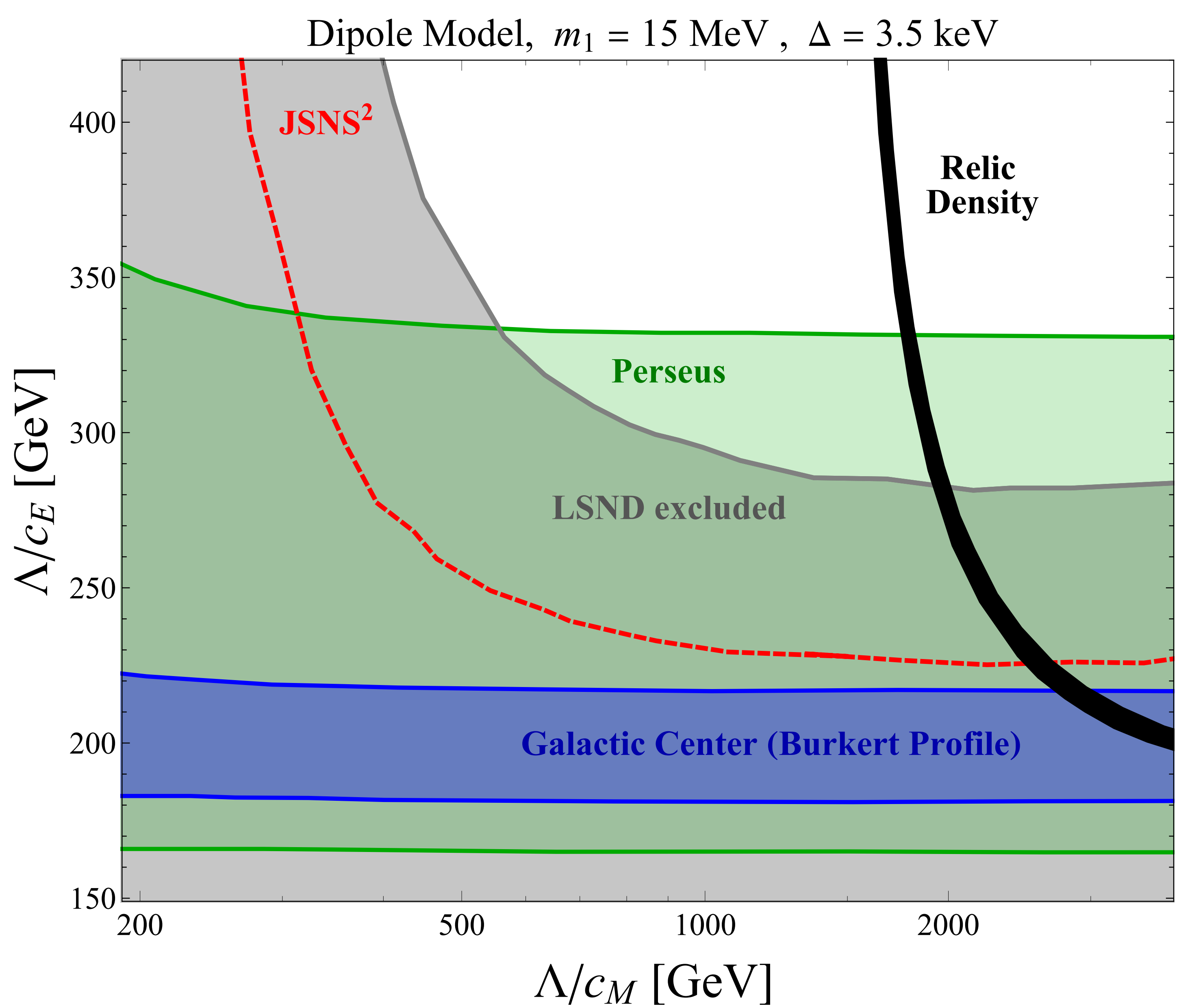
$$\chi_2 \to \chi_1 + \gamma$$



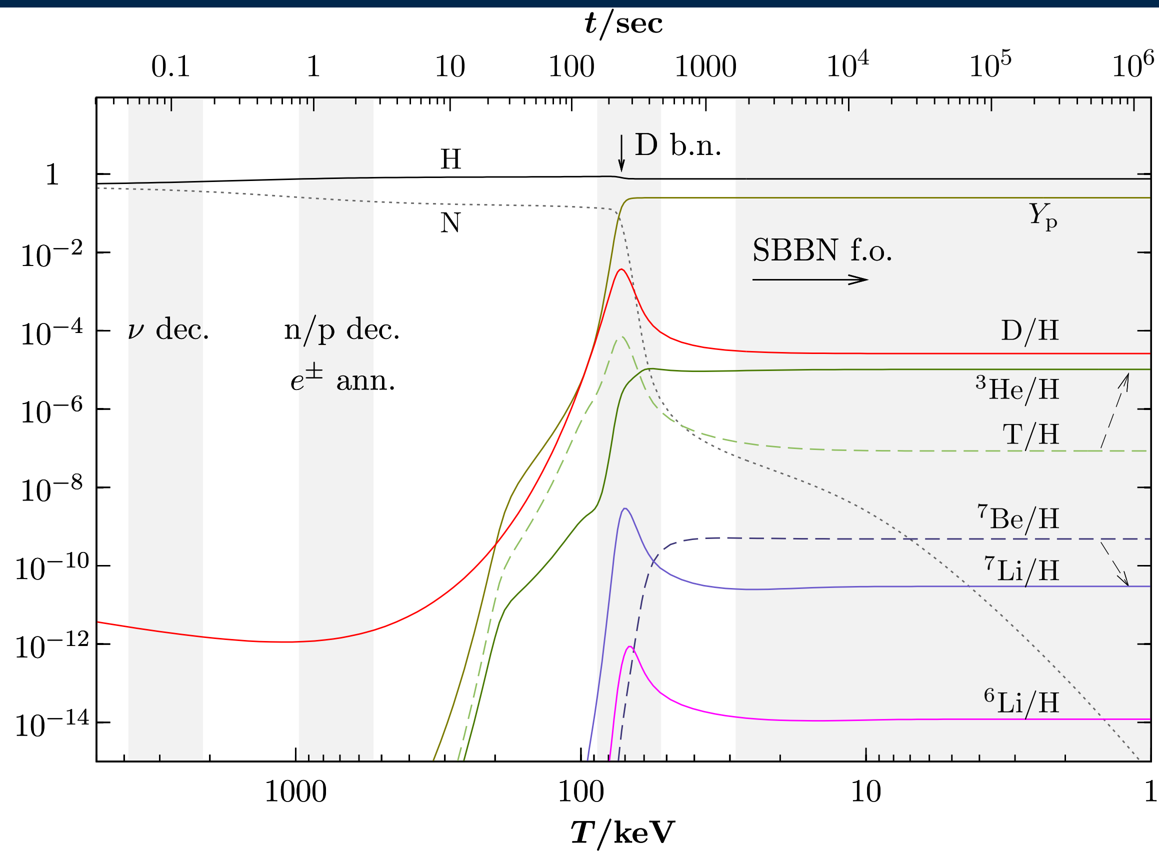
F. D'Eramo, K. Hambleton, S. Profumo, and T. Stefaniak, Phys. Rev. **D93**, 103011 (2016), arXiv:1603.04859

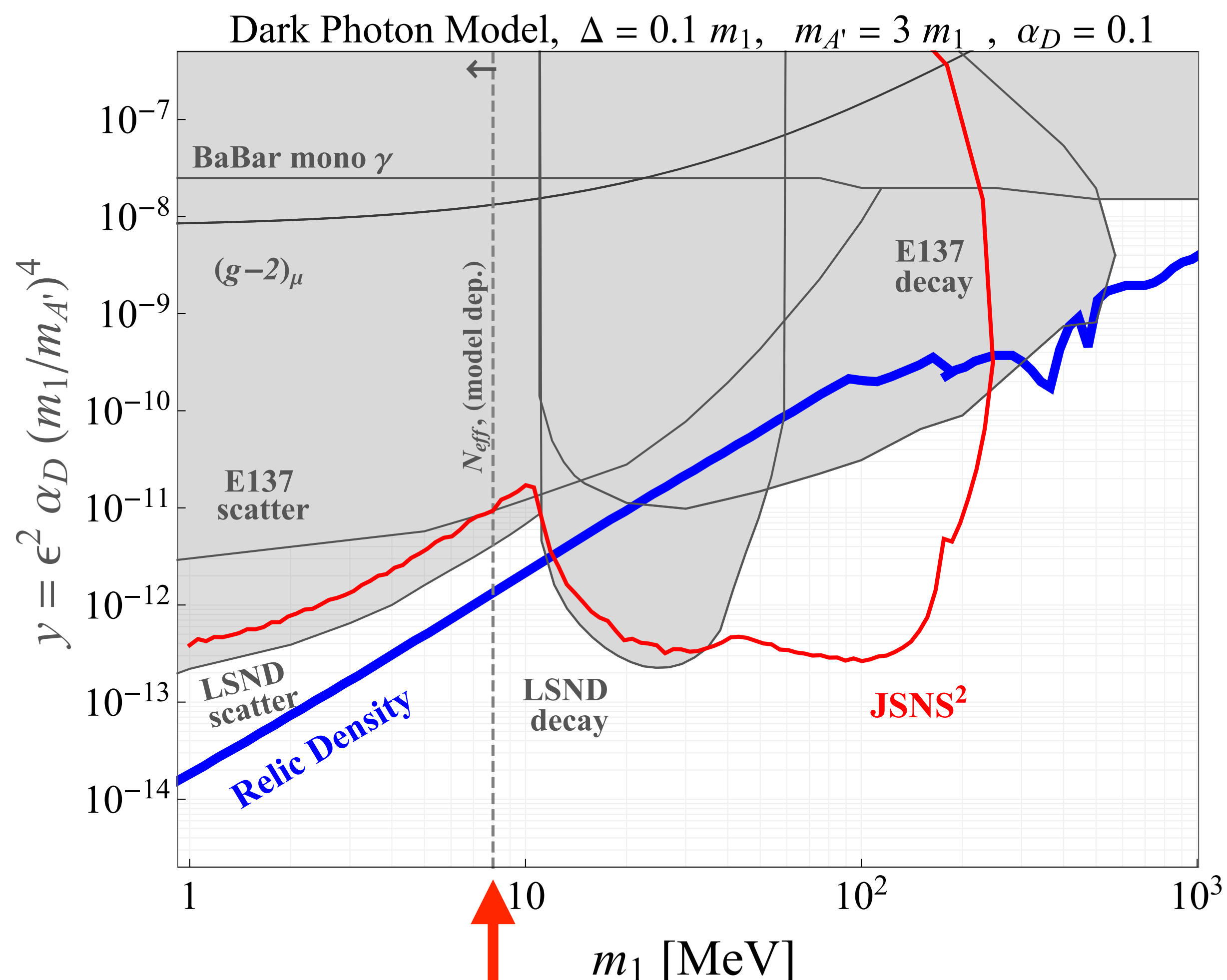
Dipole Model Constraints

- We present newly computed constraints on the preferred parameter space for this model
- Existing LSND data constrains the dipole model as an explanation for the 3.5 keV GCE



BBN Constraints





An electromagnetically coupled dark matter particle which is relativistic at neutrino decoupling can inject energy later, heating the photons relative to the neutrinos and modifying N_{eff}.

N_{eff} (BBN) constraint on dark matter

K. M. Nollett and G. Steigman, Phys. Rev. D89, 083508 (2014), arXiv:1312.5725
M. Pospelov, J.Pradler, Ann.Rev.Nucl.Part.Sci.60:539-568,2010

CMB Power Injection

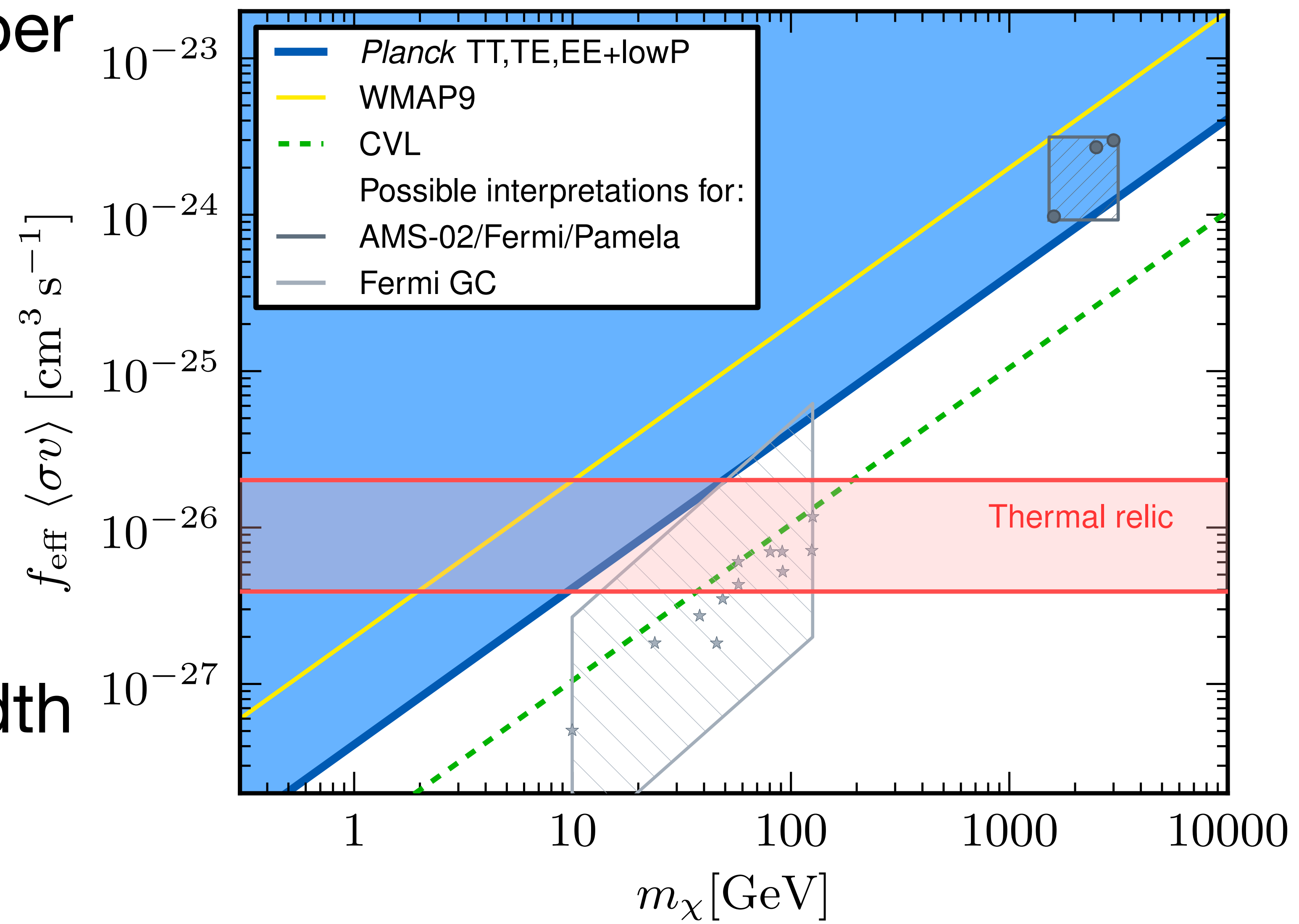
- The power injected per time per volume is given by

$$\frac{dE}{dtdV}(z) = 2\, g\, \rho^2_{\rm crit} c^2 \Omega^2_{\rm c} (1+z)^6 p_{\rm ann}(z)$$

where

$$p_{\rm ann}(z) \equiv f(z) \frac{\langle \sigma v \rangle}{m_\chi}$$

- Injected power from DM annihilation increases the width of last scattering and lowers peaks in the CMB spectrum
- Coannihilating DM avoids this constraint since χ_2 disappears



Planck Limits

P. A. R. Ade et al. (Planck), (2015), arXiv:1502.01589

Higgs Portal

- Add a new scalar which mixes with the SM Higgs and couples to the dark sector

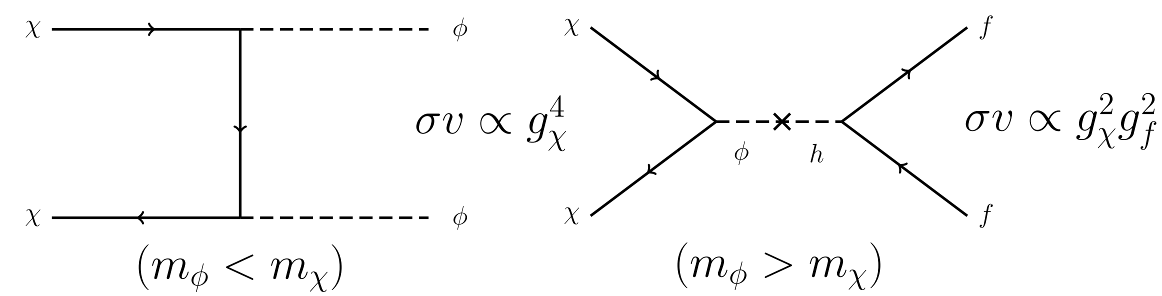
$$\mathcal{L}_{\Phi,H} = (A_{\Phi H}\Phi + \lambda_{\Phi H}\Phi^2)H^\dagger H$$

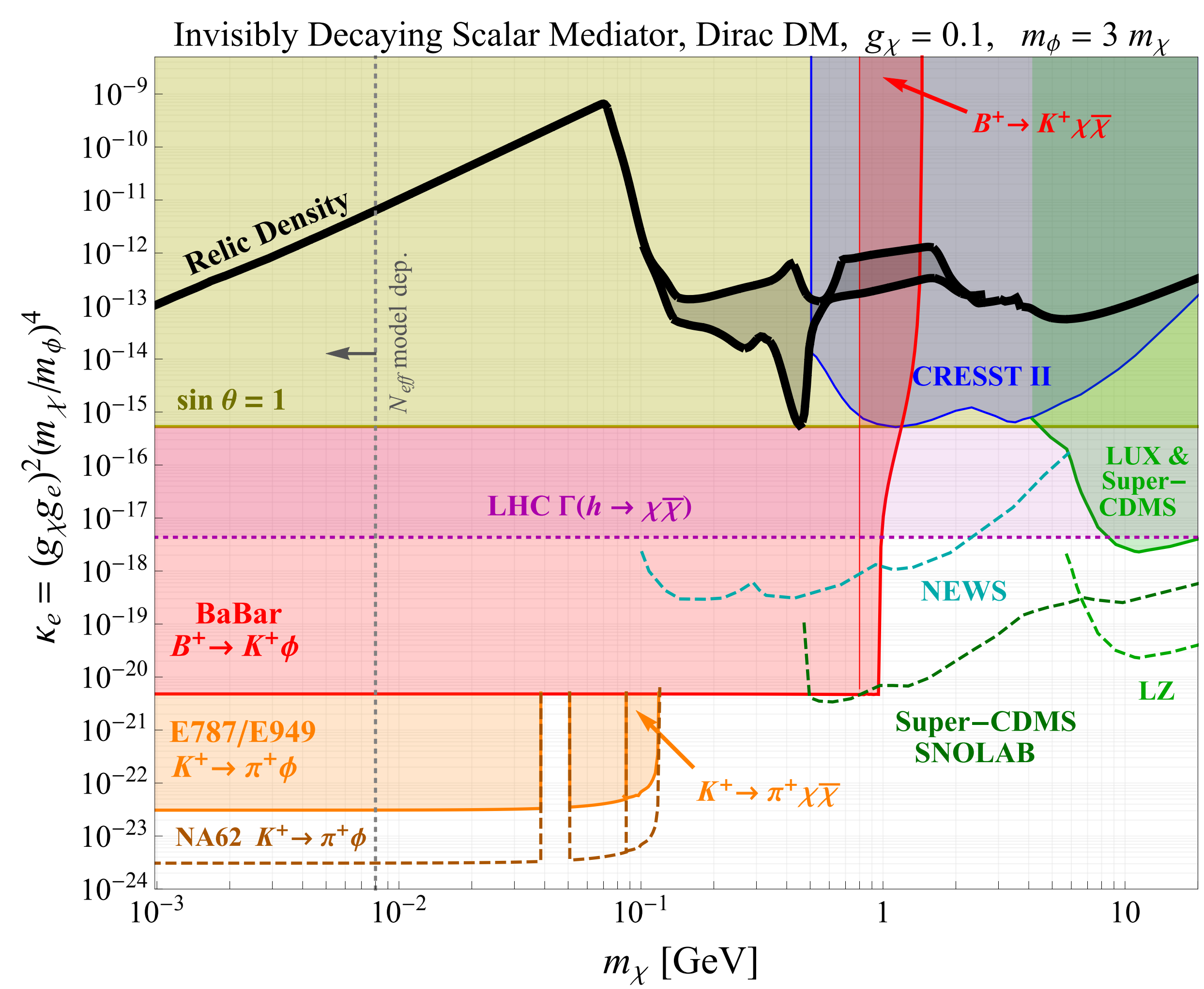
$$\mathcal{L}_{\phi,\mathrm{DM}} = \phi(g_\chi \bar{\chi}\chi + g'_\chi \bar{\chi}\gamma^5\chi)$$

- New scalar couples to the SM fermions through the mixing with the Higgs

$$\mathcal{L}_{\phi,\mathrm{SM}} = \phi \sin\theta \sum_f \frac{m_f}{v}\bar{f}f \quad , \quad g_f \equiv \frac{m_f}{v}\sin\theta$$

- Highly constrained by colliders, rare meson decays, and direct detection experiments





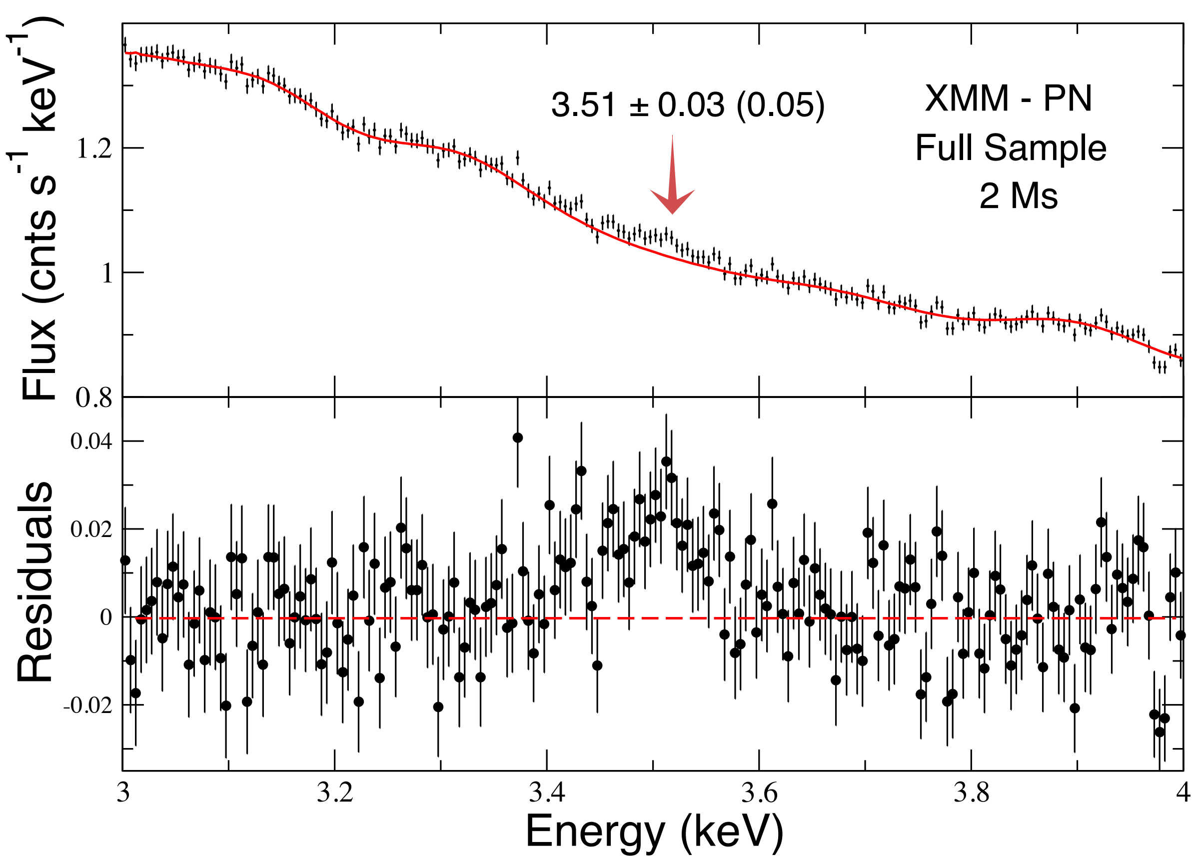
G. Krnjaic, Phys. Rev. D **94**, 073009 (2016)

3.5 keV Excess

- Observation of new ~3.5 keV line in observations of galaxy clusters and the galactic center
- One interpretation is sterile neutrino decay to a SM neutrino and a photon

$$\Gamma_\gamma(m_s,\theta) = 1.38 \times 10^{-29}\ \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

- Many other models of keV scale dark matter have been proposed to explain the line
- Still no resolution



A. Boyarsky, et al., Phys. Rev. Lett. 113, 251301 (2014)
E. Bulbul, et al., Astrophys.J. 789 (2014) 13
A. Boyarsky, et al., Phys. Rev. Lett. 115, 161301 (2015)
Dodelson, S., & Widrow, L. M. 1994, Physical Review Letters, 72, 17

Masses in the Coannihilation Model

- Our dark sector has a 4-component fermion ψ with the dark photon A' and a symmetry-breaking scalar ϕ whose vacuum expectation value gives the A' a mass:

$$\mathcal{L} = i\overline{\psi}\not{D}\psi + M\bar{\psi}\psi + \lambda\phi\,\overline{\psi^c}\psi + h.c. \qquad \psi = (\xi, \eta^\dagger)$$

- After symmetry-breaking, ψ gets a Majorana mass from the ϕ vev

$$-\mathcal{L}_{\mathrm{mass}} = m\xi\eta + \frac{\mu_\xi}{2}\xi\xi + \frac{\mu_\eta}{2}\eta\eta + h.c. \qquad \mu_\xi = \mu_\eta \equiv \mu$$

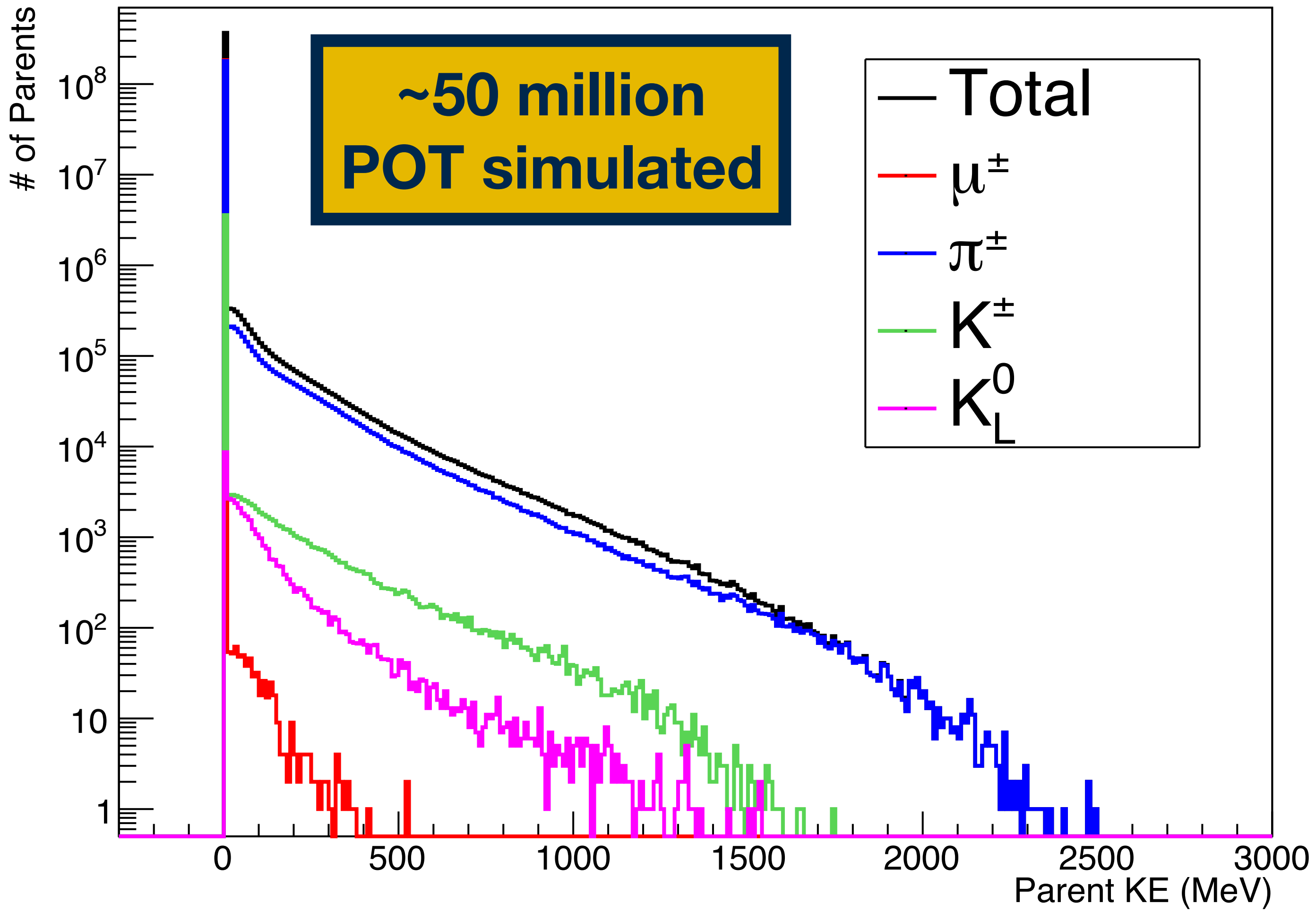
- We take the Majorana masses of the Weyl fermions to be the same. If they aren't, we will get subleading diagonal interactions as well. The mass eigenstates are

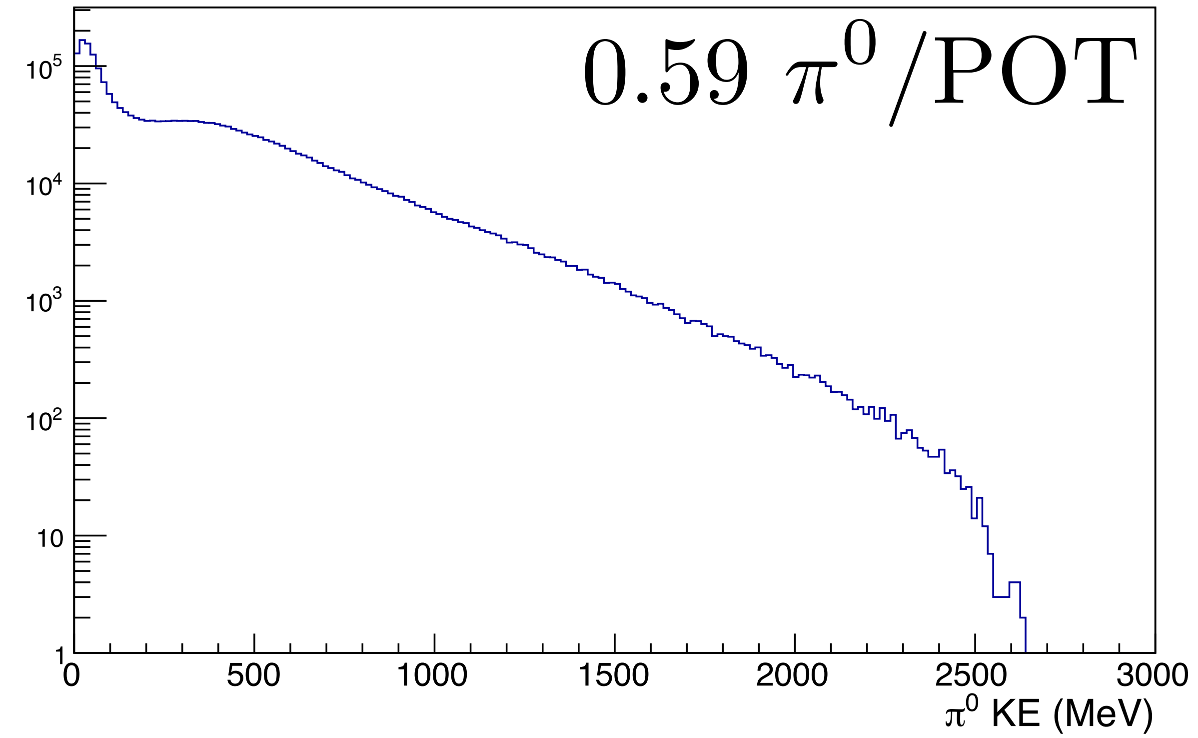
$$\chi_1 = \frac{i}{\sqrt{2}}(\eta - \xi) \quad , \quad \chi_2 = \frac{1}{\sqrt{2}}(\eta + \xi) \qquad m_{1,2} = m \mp \mu$$

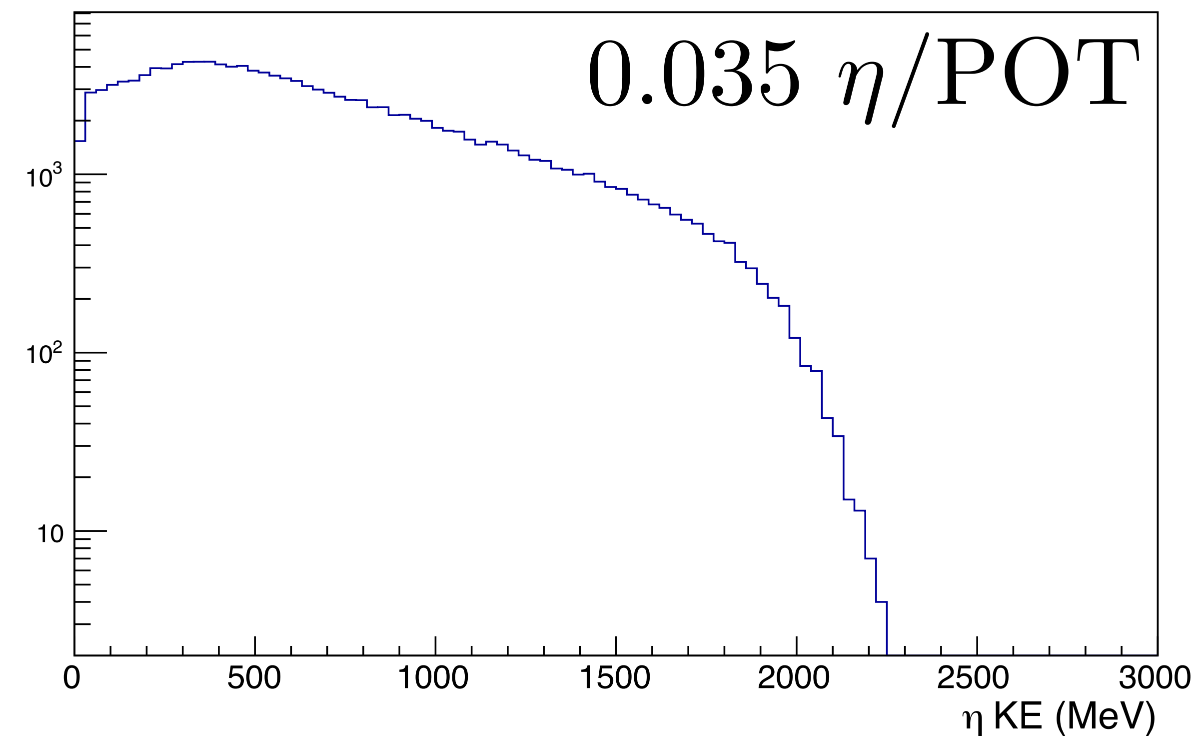
- It is technically natural to have M >> Δ since the Majorana mass terms break the global ψ-number symmetry.

MLF Parent Spectra

3.8×10^{22} POT/year

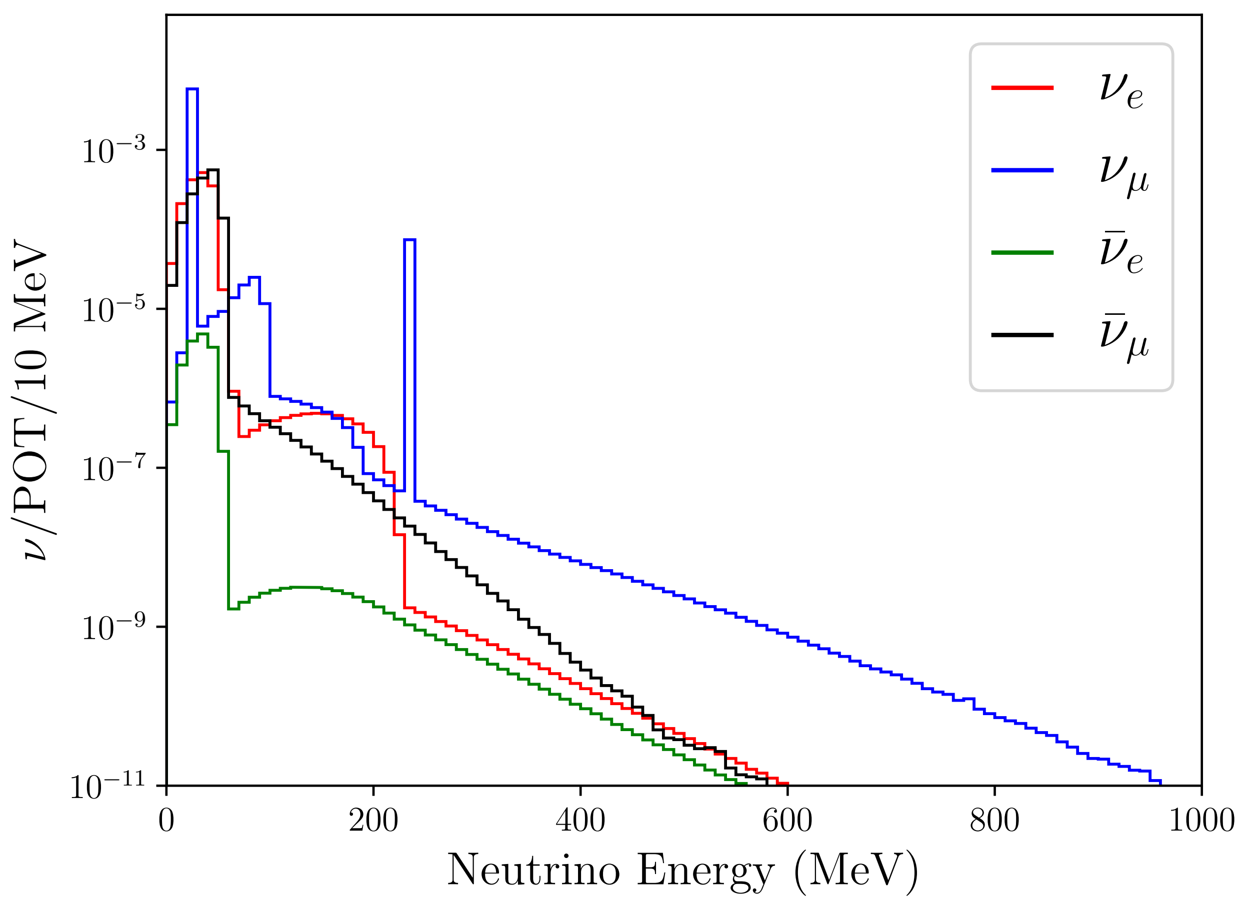


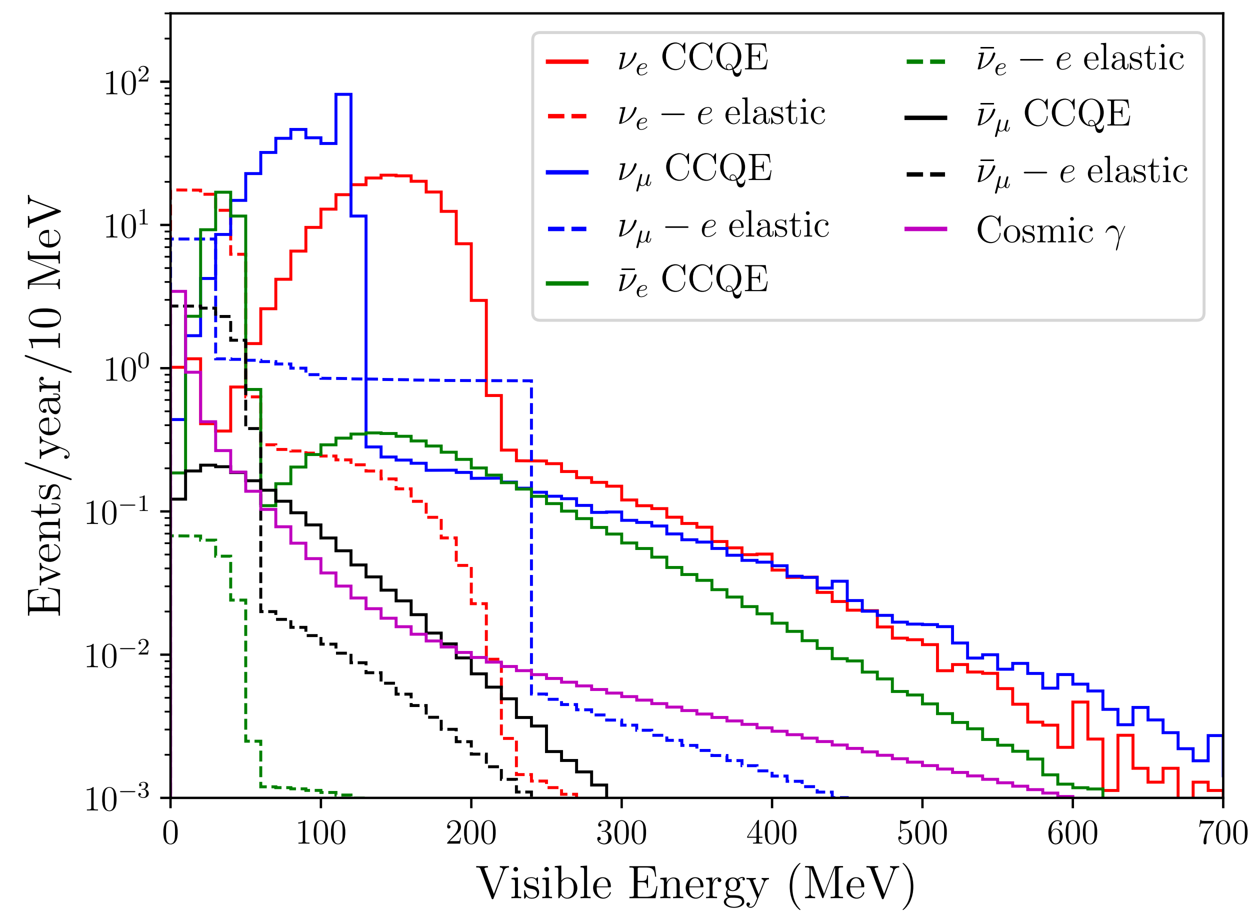




Neutral meson spectra come from the Liege Intranuclear Cascade Model

Backgrounds

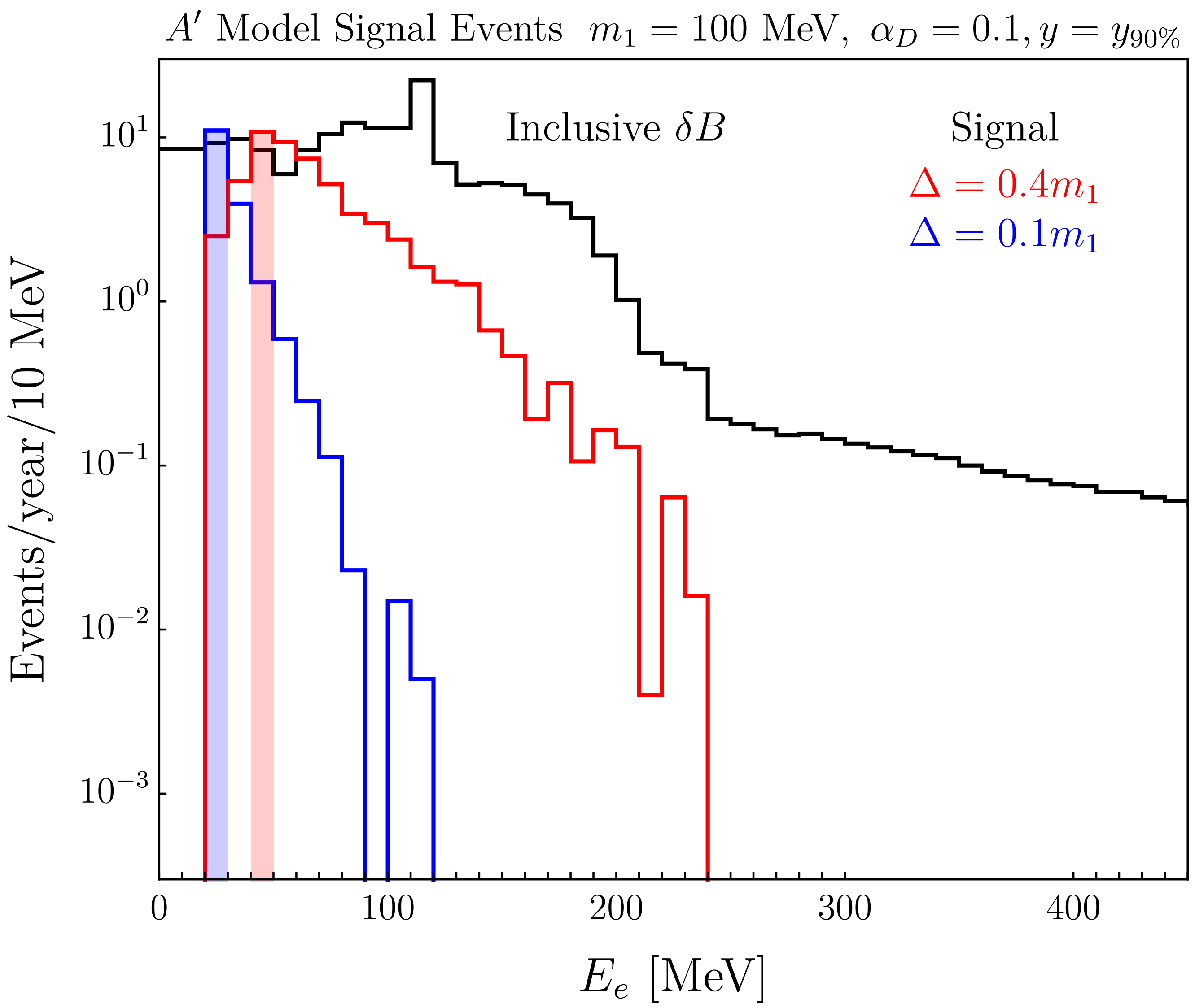


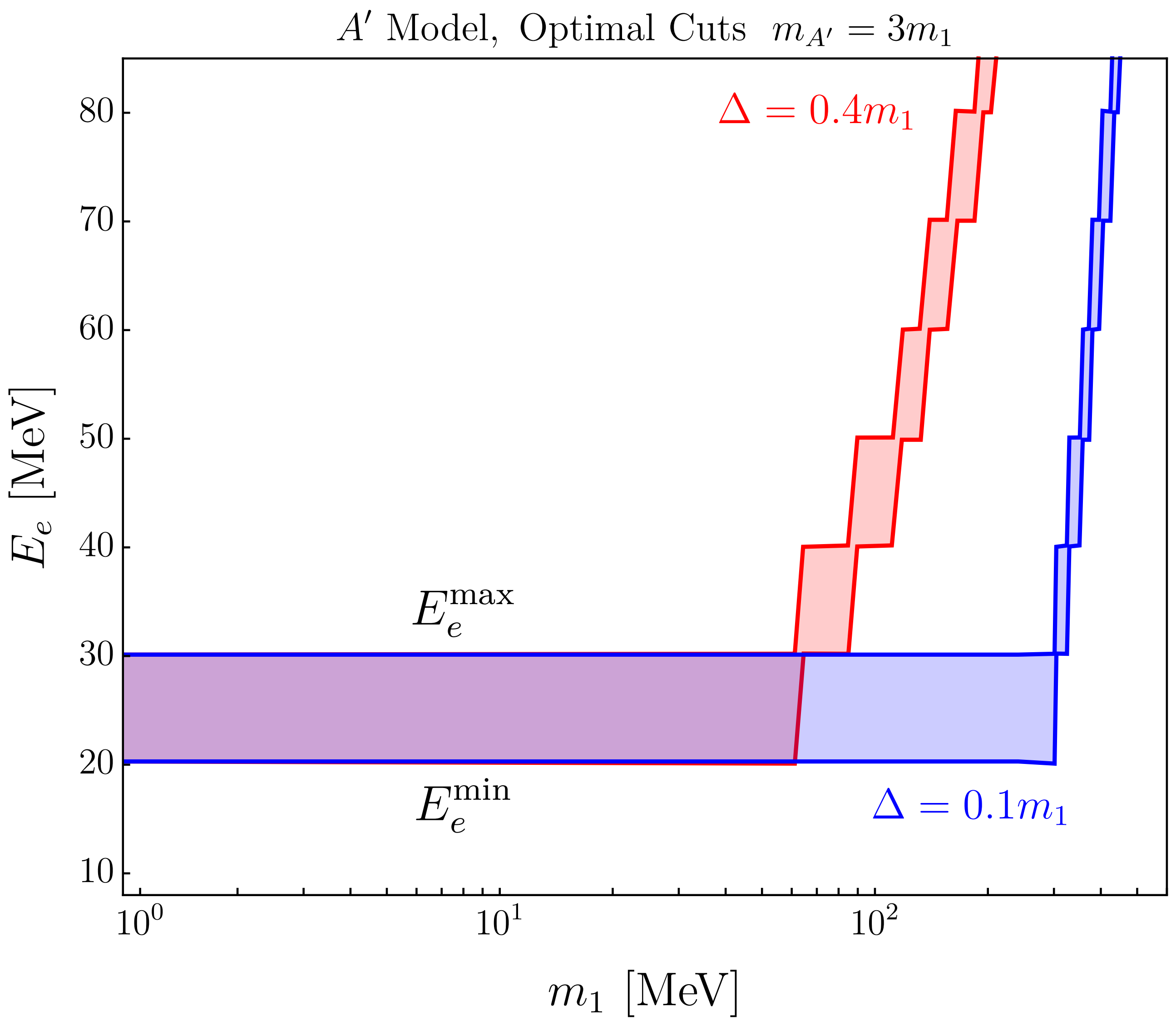


Backgrounds are reduced by:

- Beam timing (duty factor is ~5×10^{-6})
- Pulse shape discrimination for CCQE
- Michel electron cut (for muon flavor CCQE backgrounds)

Constraint Procedure

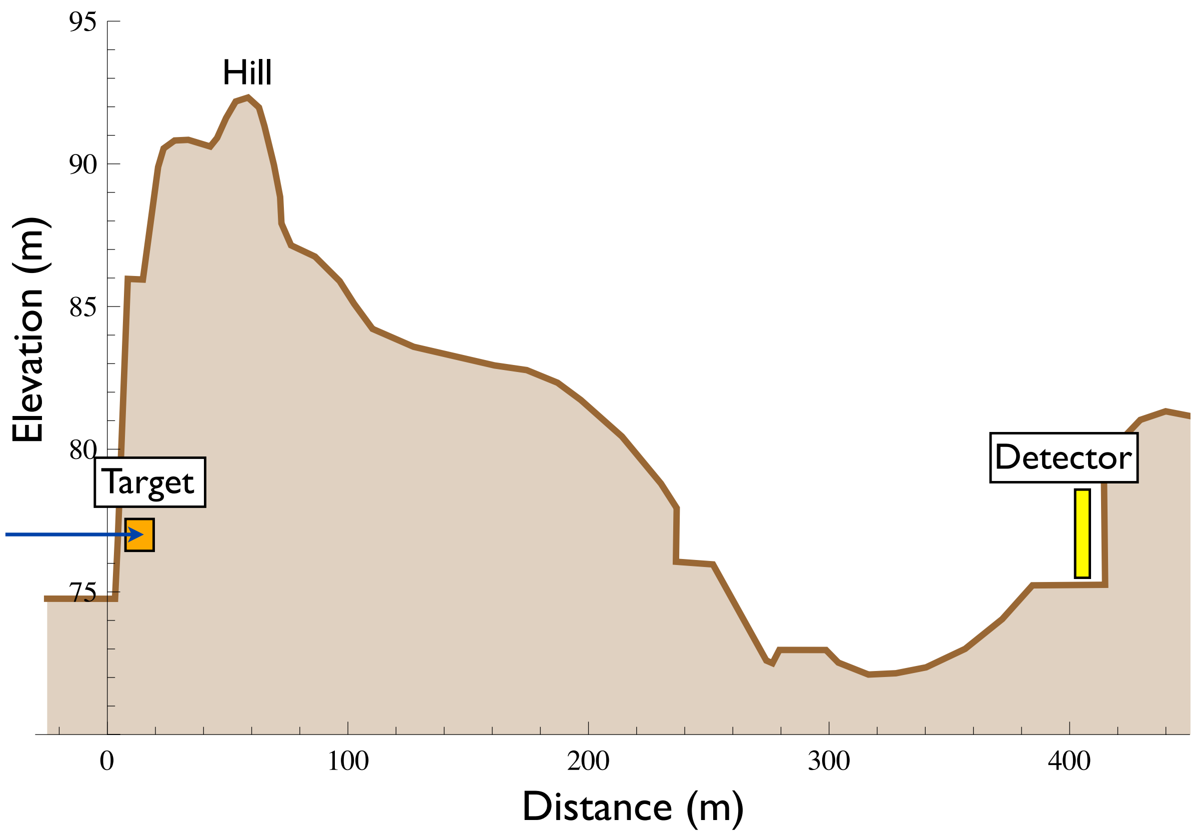


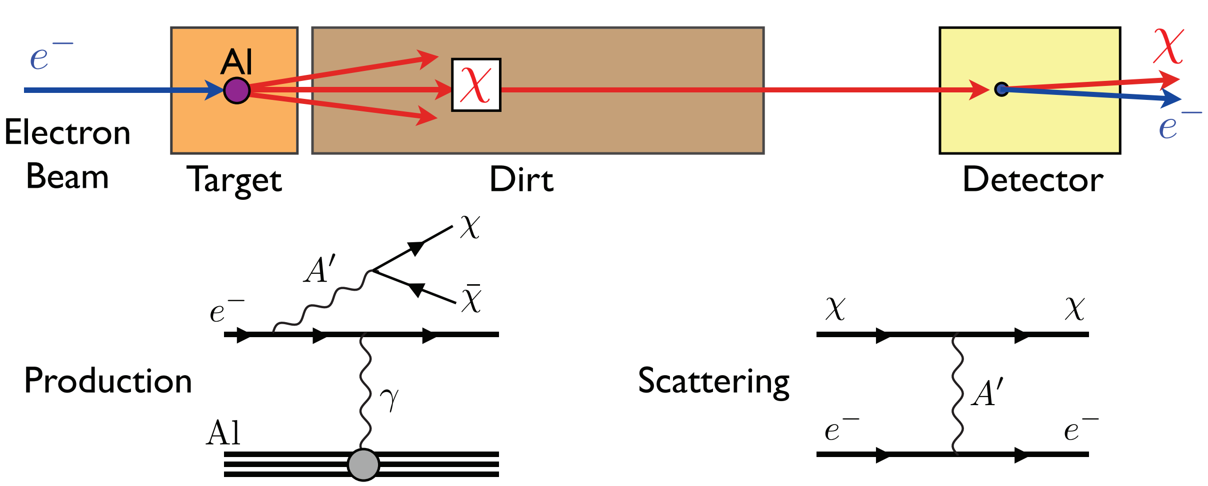


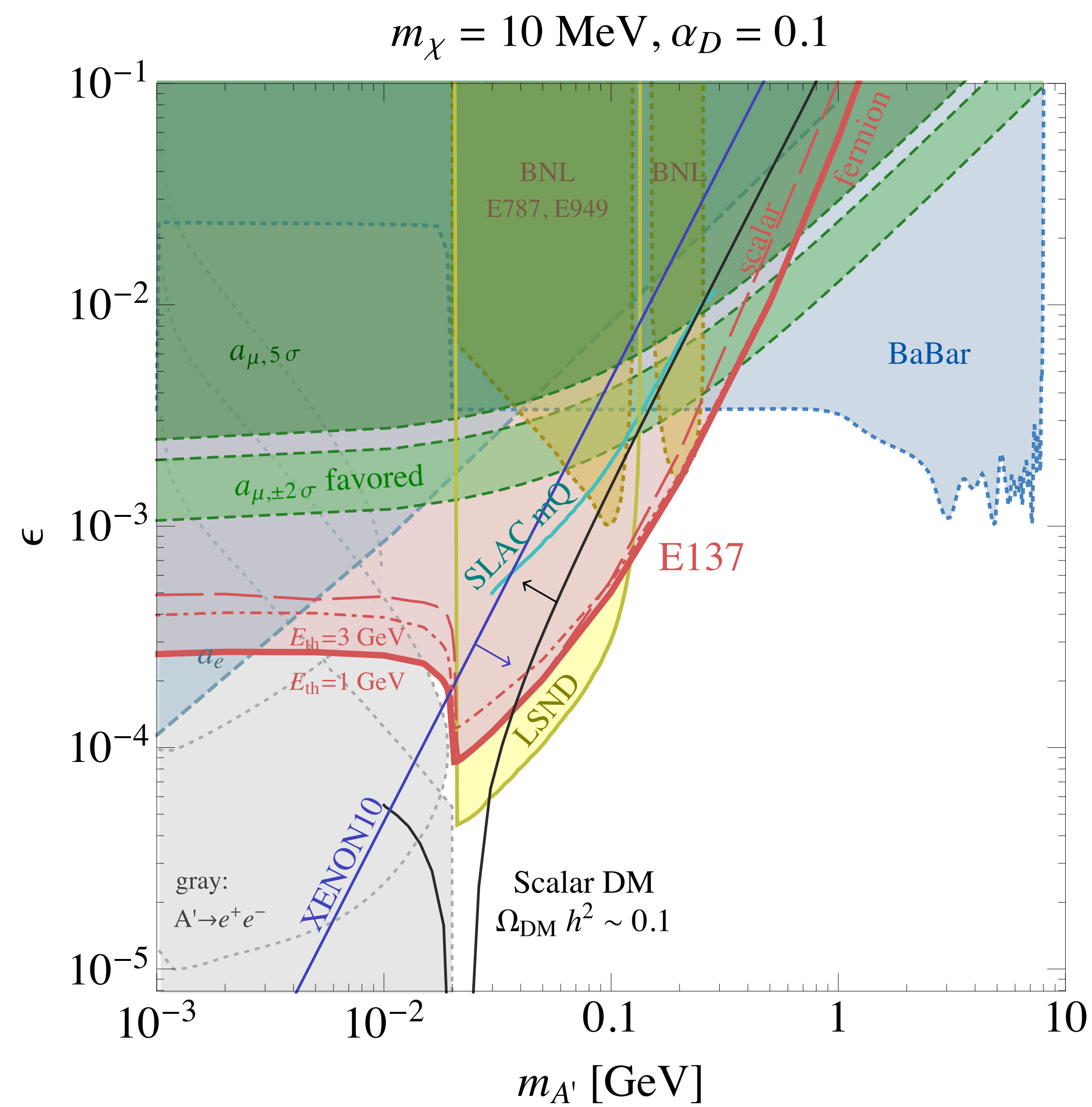
Choose optimal search region based on signal to background ratio

Choice of optimal region depends on the dark matter mass.

E137 Constraints







Originally designed to look for neutral, semi-stable new particles produced in a 20 GeV electron beam.

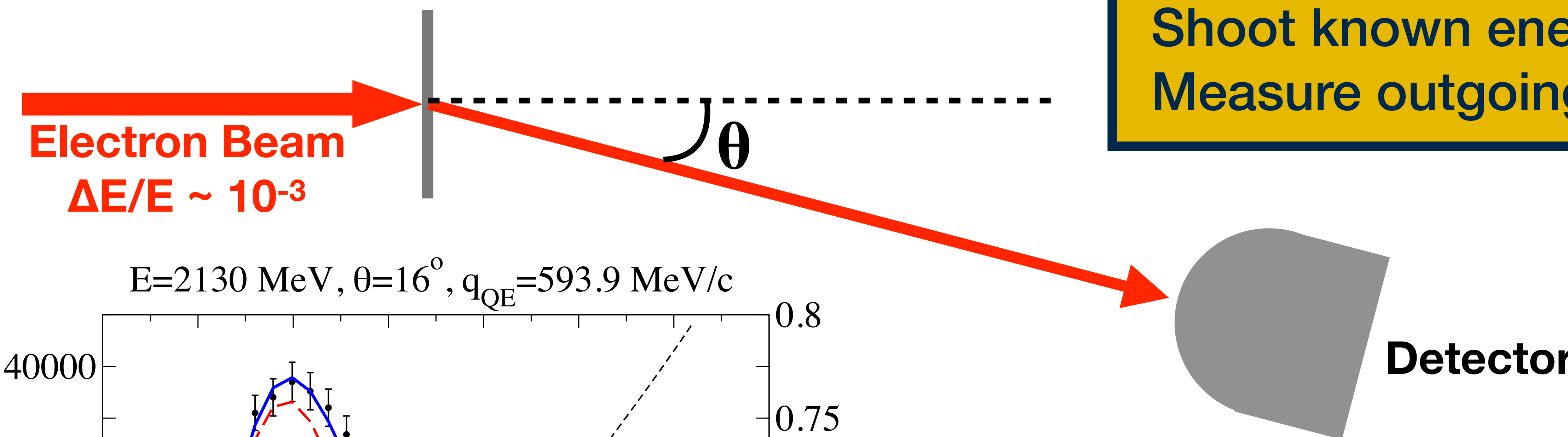
B. Batell, R. Essig, Z. Surujon, Phys. Rev. Lett. **113**, 171802, arXiv:1406.2698

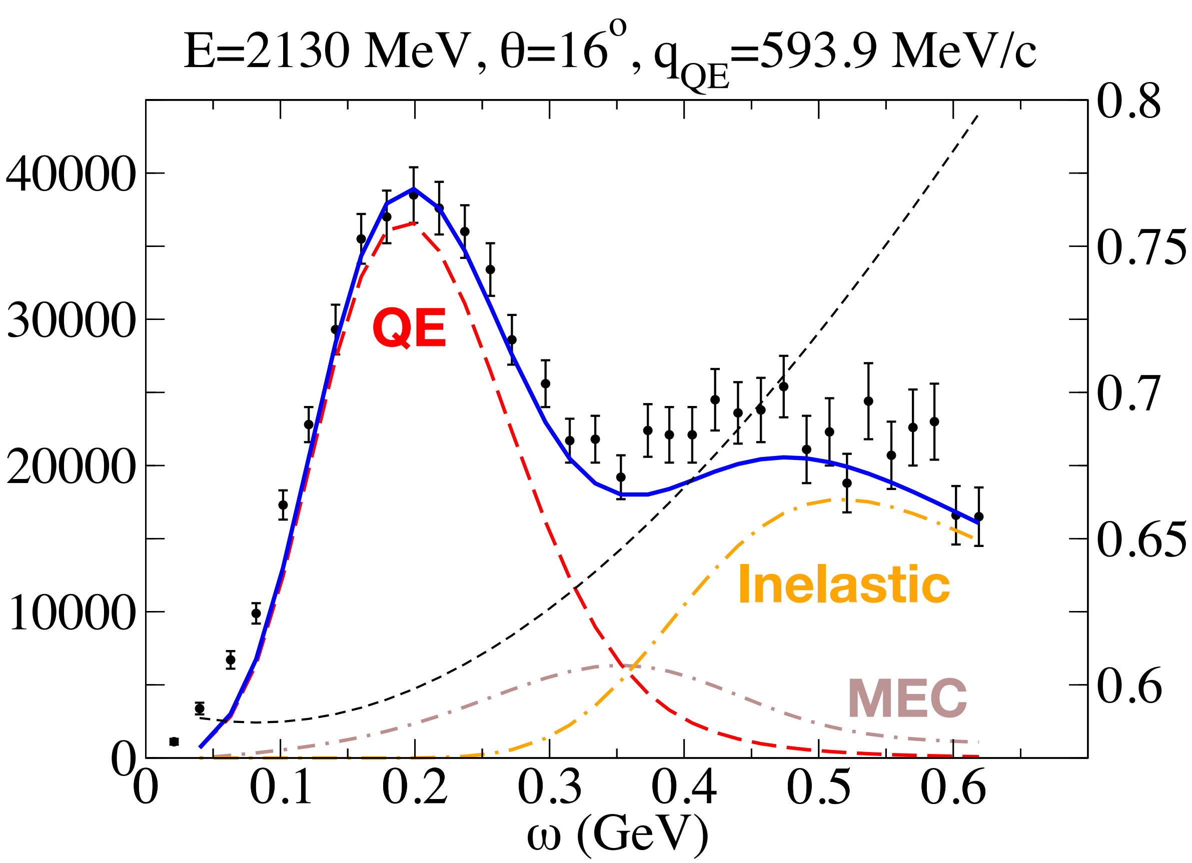
Backup

KDAR Neutrinos

Probing the Nucleus

Shoot known energy beam.
Measure outgoing electron.





Electron scattering on carbon

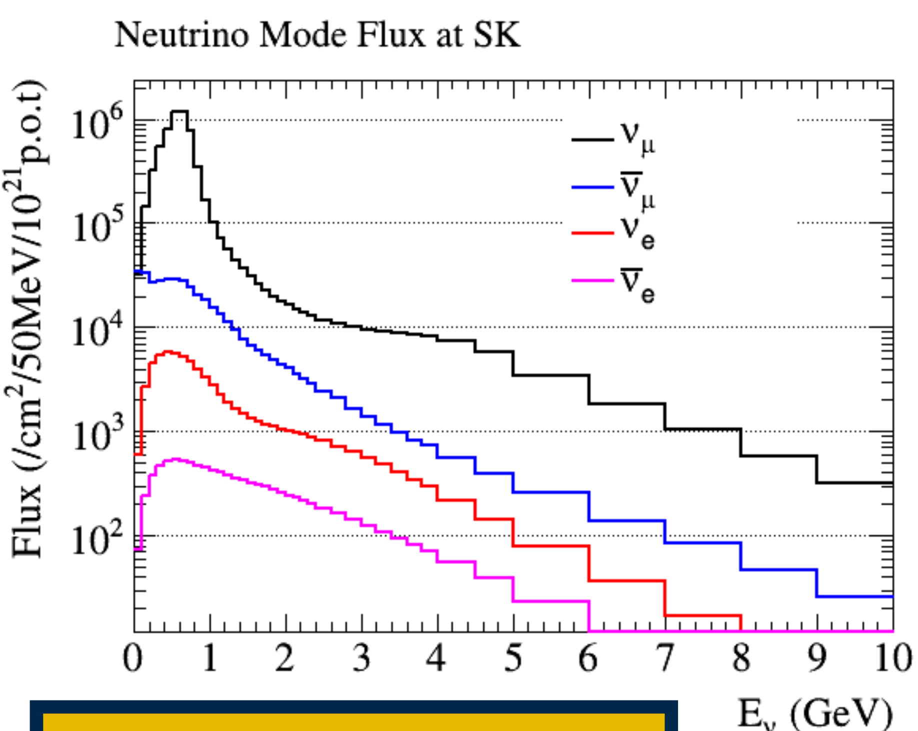
$\omega \equiv E - E'$

Electron scattering has been the dominant tool for understanding the nucleus up until this point.

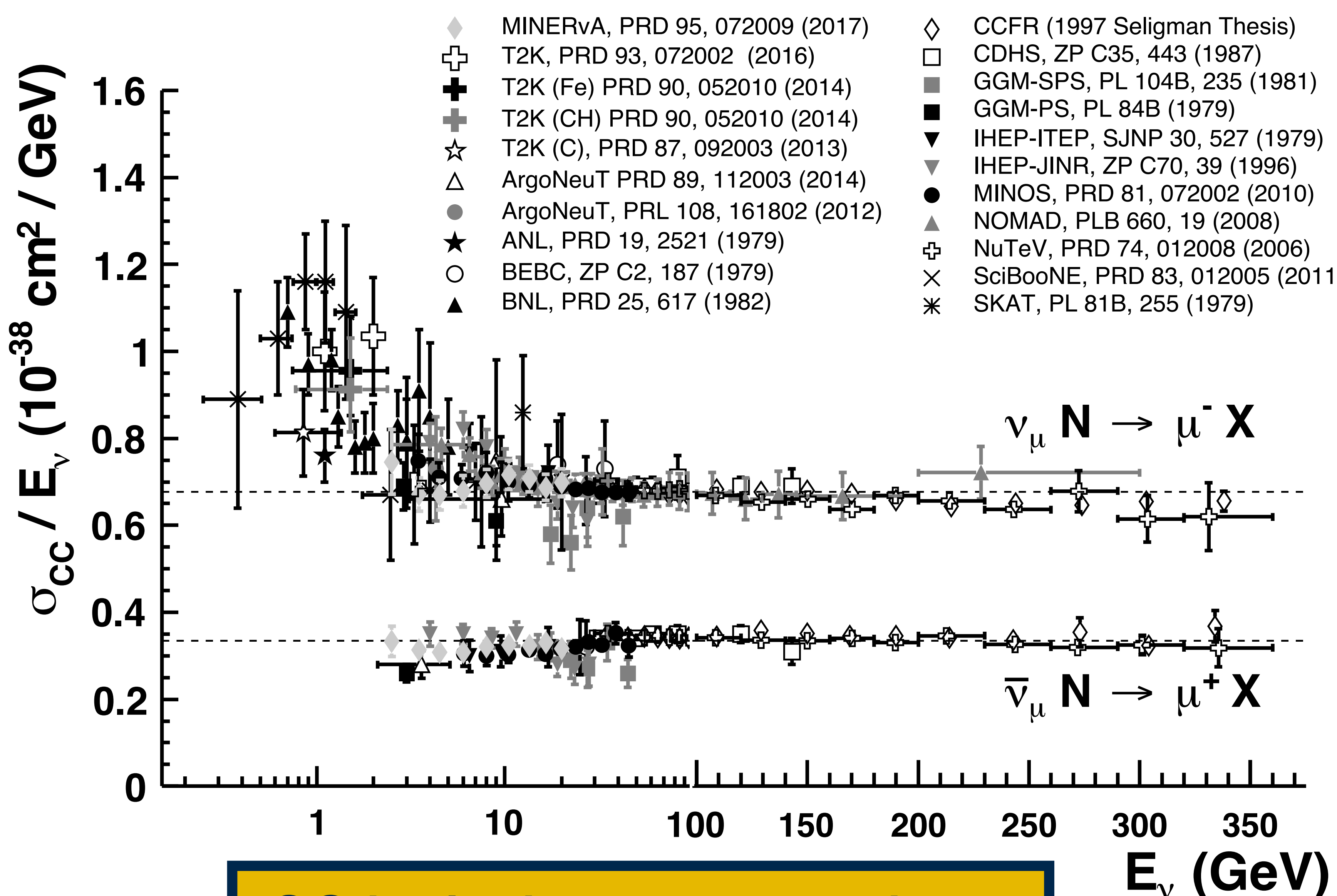
arXiv:1706.03621

Cross Sections

Our knowledge of cross sections at low energies is quite bad.



T2K flux peaks at below 1 GeV.



CC inclusive cross sections.

PDG Review of Neutrino Cross Section Measurements

Energy Reconstruction

The two-ν oscillation probability depends on the neutrino energy:

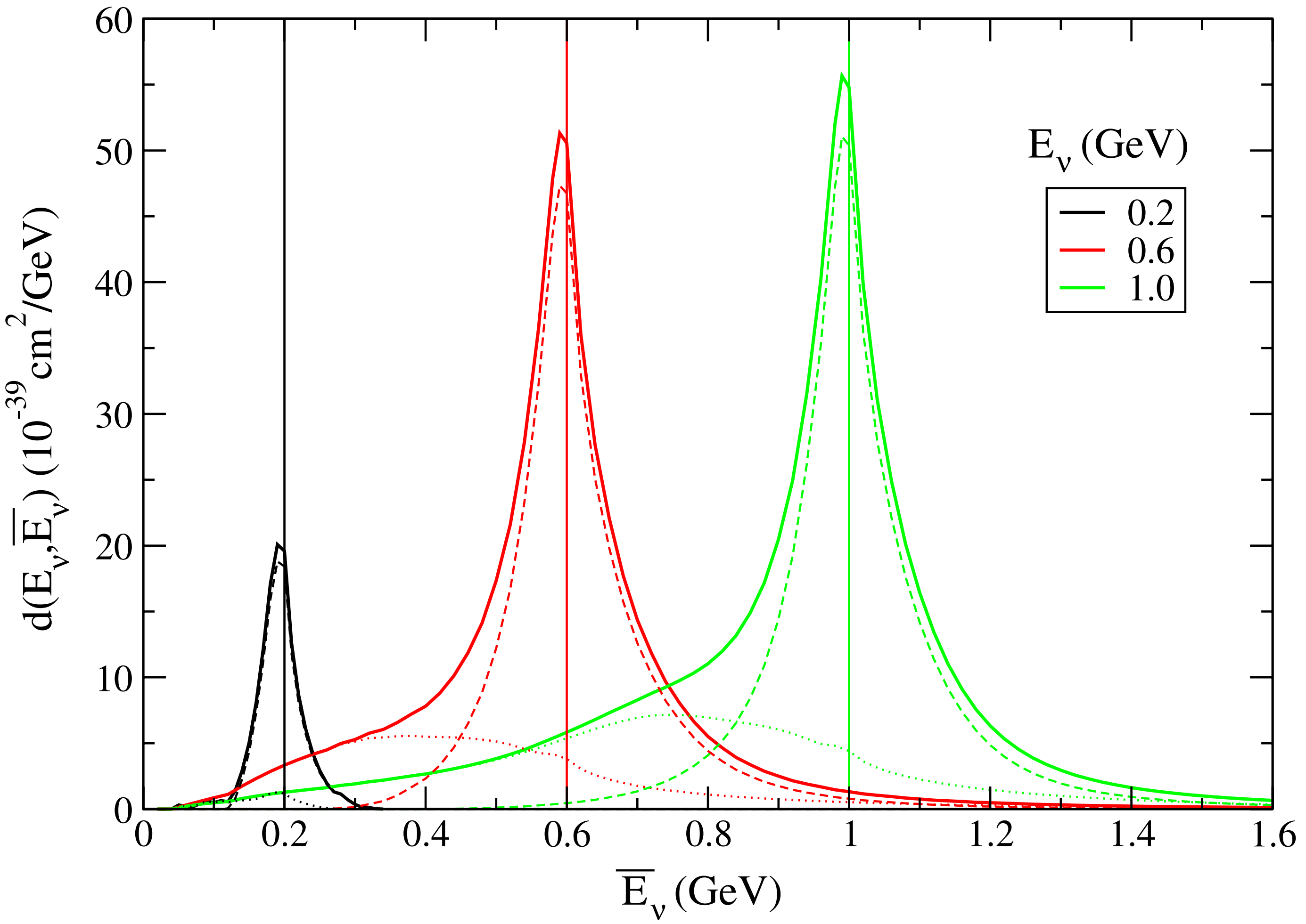
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{\text{GeV}}{\text{eV}^2\ \text{km}}\right)$$

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

Neutrino energy reconstruction is complicated by:

- Invisible particles
- Detector thresholds
- Complicated final states

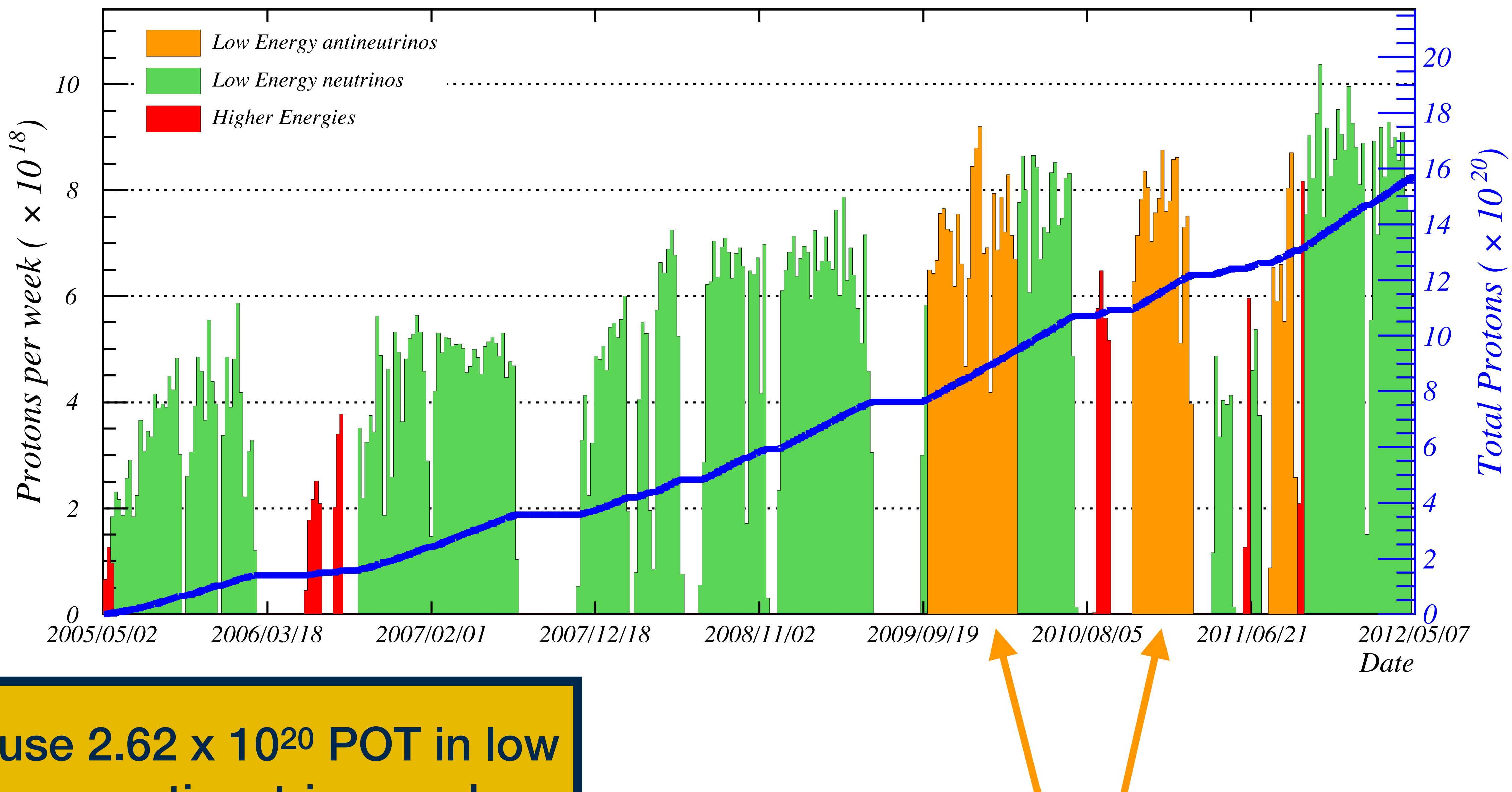
Solution: Use KDAR neutrinos to benchmark the reconstruction.



Neutrino energy smearing for electron only reconstruction.
Vertical lines = true energy
Curves = reconstructed energy

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

Data Periods



We use 2.62 x 10^{20} POT in low energy antineutrino mode. Signal to background ratio is higher in antineutrino mode.

KDAR Events in MiniBooNE

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

- KDAR neutrino CCQE events in MiniBooNE feature two sub-events:
  1. A low energy muon (T_μ < 120 MeV)
  2. An electron from the muon decay

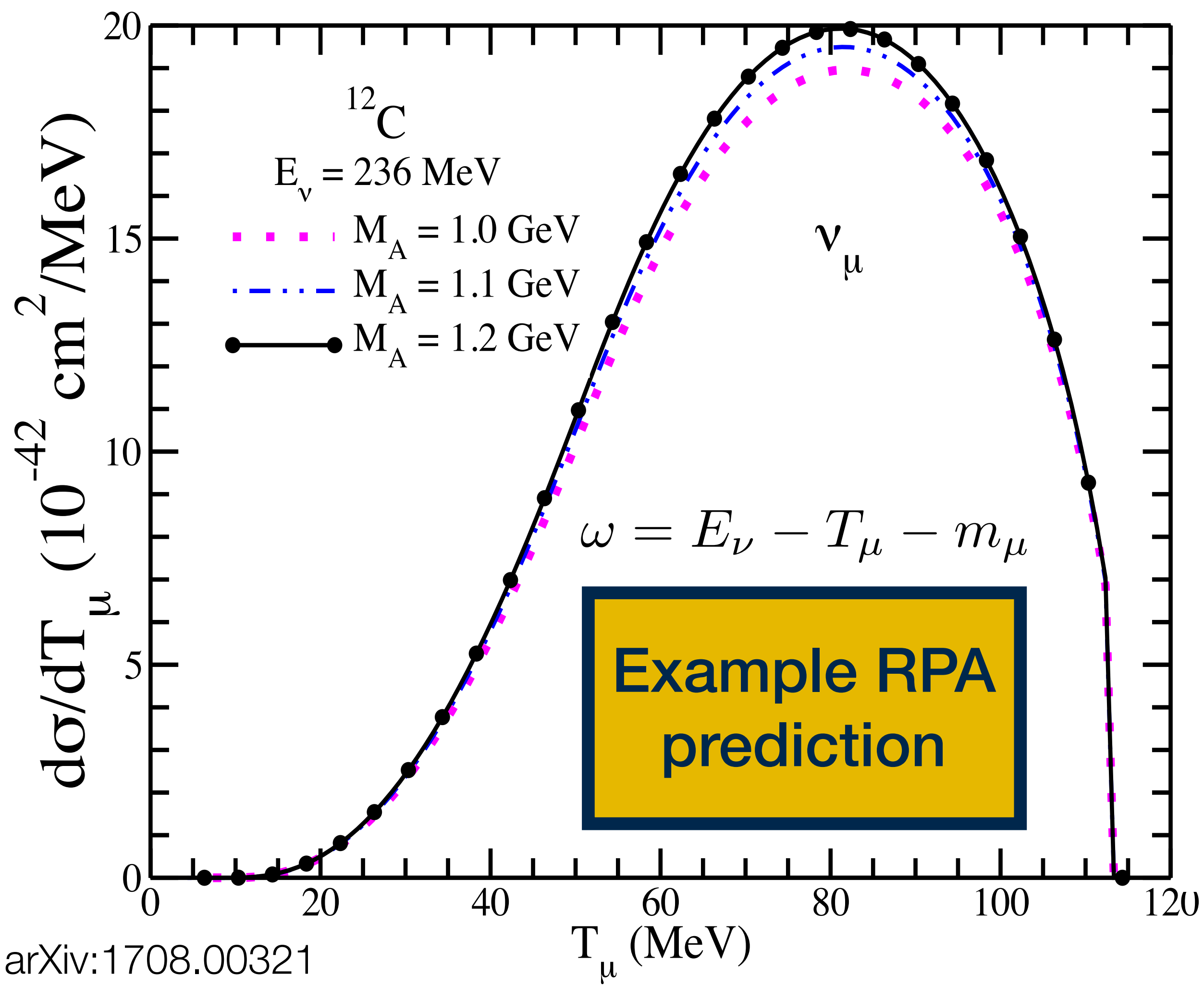
$$\begin{array}{l} \nu_\mu\,{}^{12}\mathrm{C} \rightarrow \mu^- X \\ \quad\quad\quad\quad\quad\; \downarrow \\ \quad\quad\quad\quad\quad\; \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \end{array}$$

- KDAR-like events are isolated using standard cuts:
  - 2 sub-events detected (Michel vertex within 150 cm of muon vertex)
  - Vertex inside the fiducial volume (r < 500 cm)
  - No veto activity

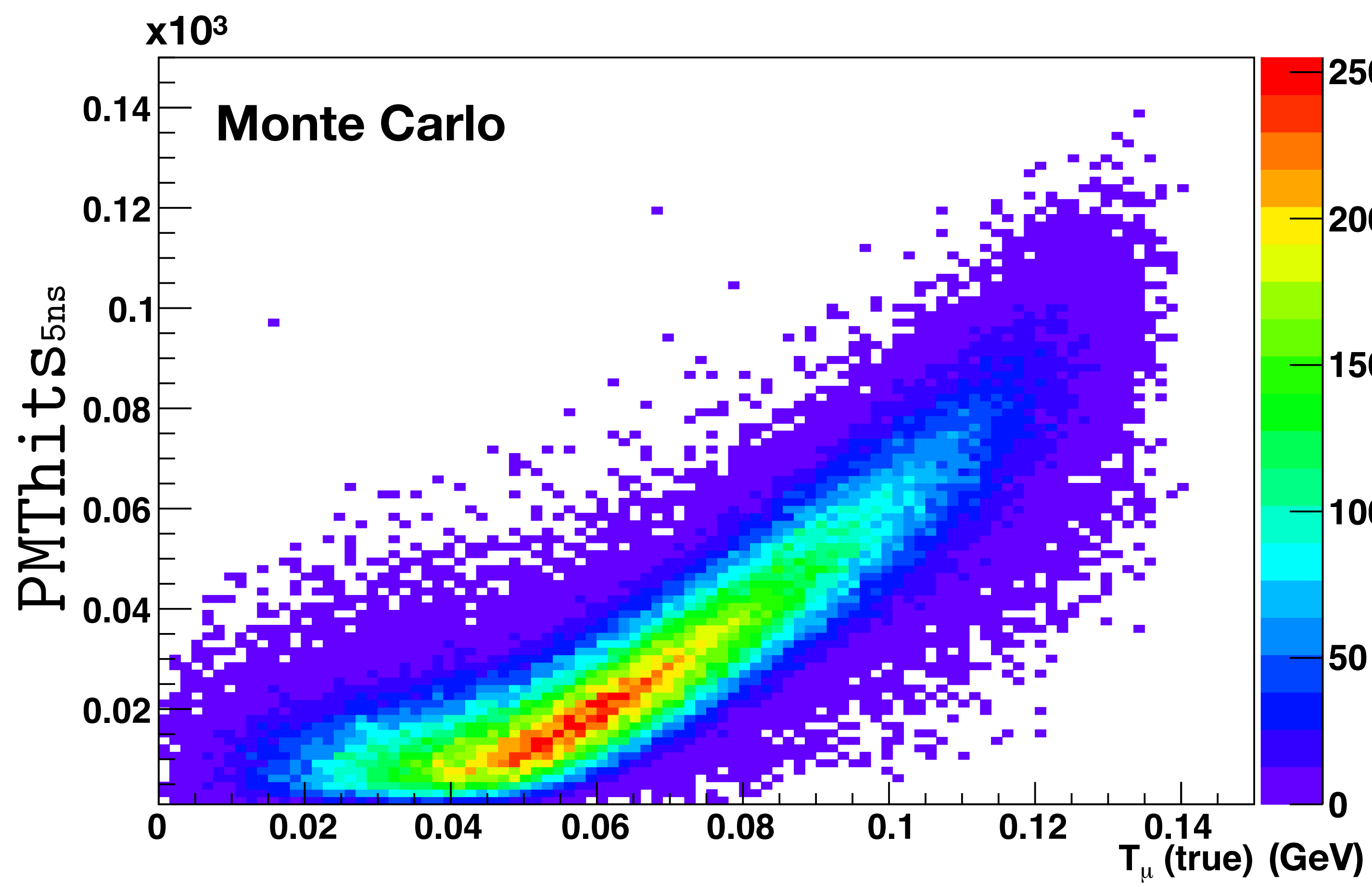
KDAR Muon Energy Reconstruction

We are interested in making comparisons with theoretical models in terms of the muon kinetic energy (T_μ) and neutrino-nucleus energy transfer (ω).

We use the Cherenkov light in the first 5 ns of the event to estimate the muon energy using a variable called $\mathrm{PMThits}_{5ns}$.



arXiv:1708.00321



KDAR muons have $\mathrm{PMThits}_{5ns}$ < 120

Solution: Templates

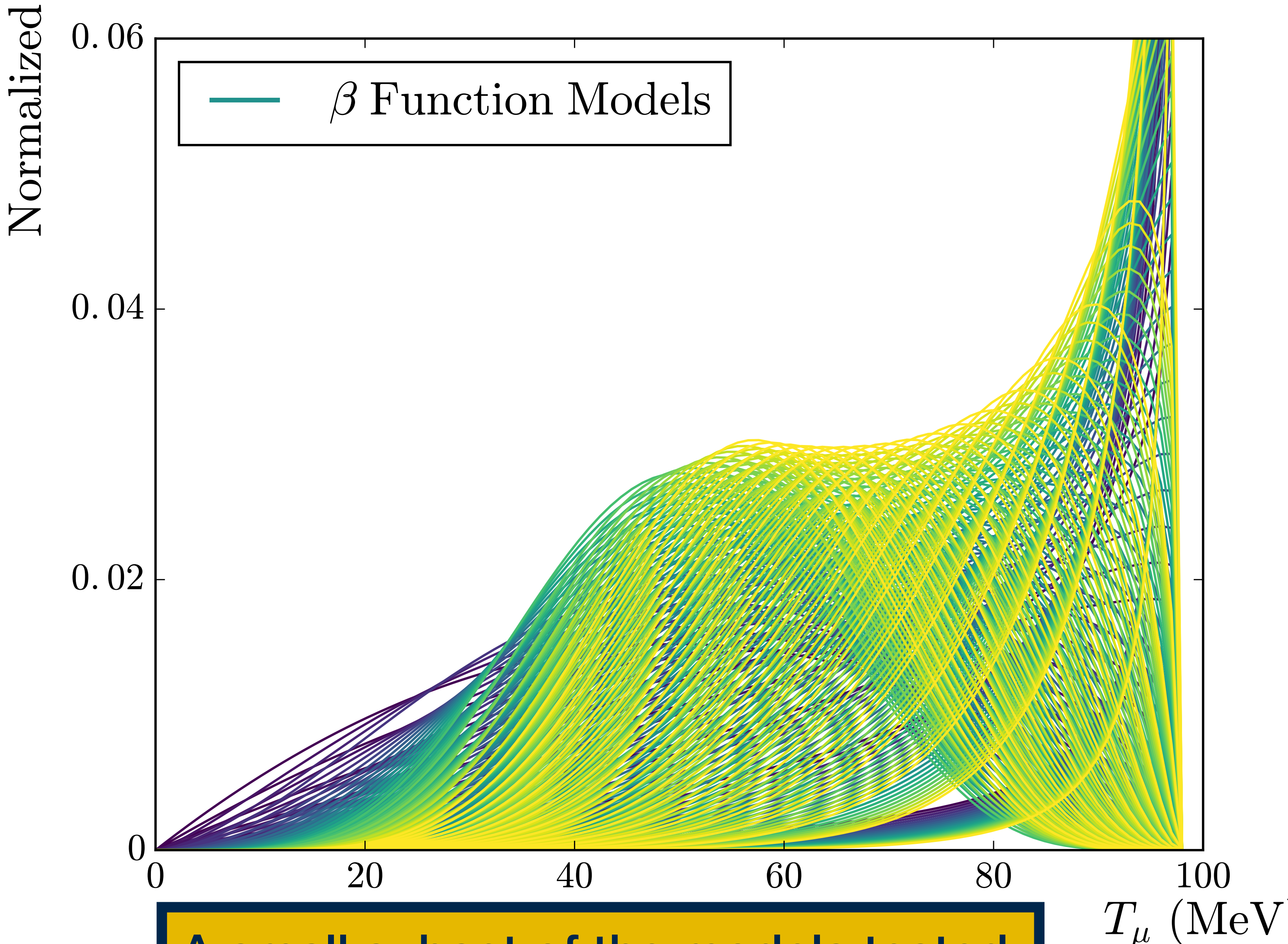
Rather than arbitrarily picking a single generator prediction, we chose to use a more general signal model.

We assume that the signal is be well-described by a beta distribution (2 parameters):

$$\beta(x; a, b) = \frac{x^{a-1}(1-x)^{b-1}}{B(a,b)}$$

$$B(a,b) = \Gamma(a)\Gamma(b)/\Gamma(a+b)$$

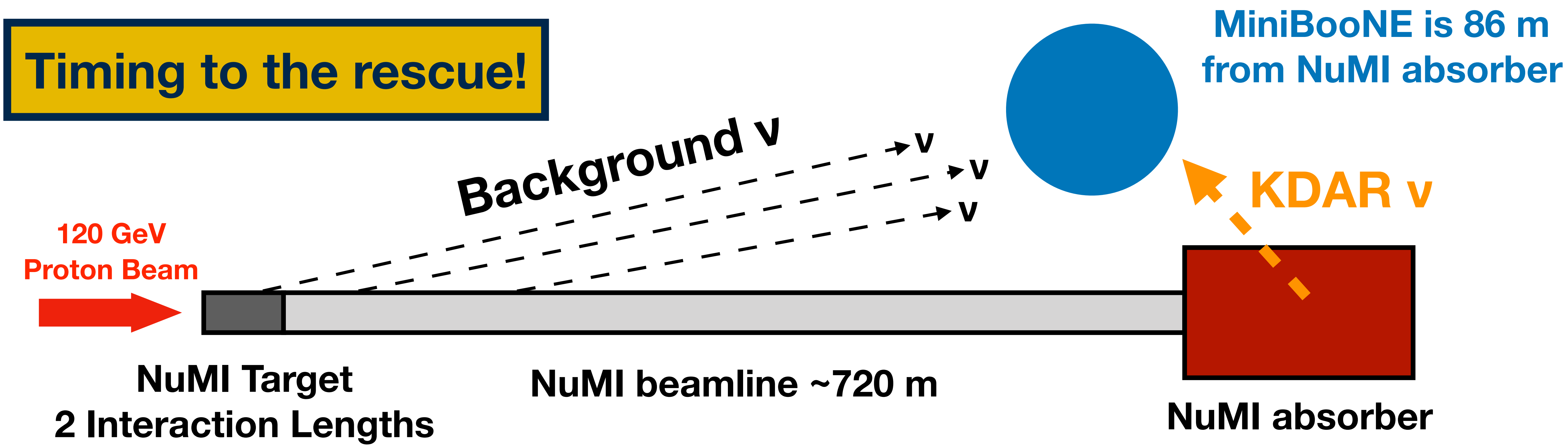
We test each model against the data to find the best fit.



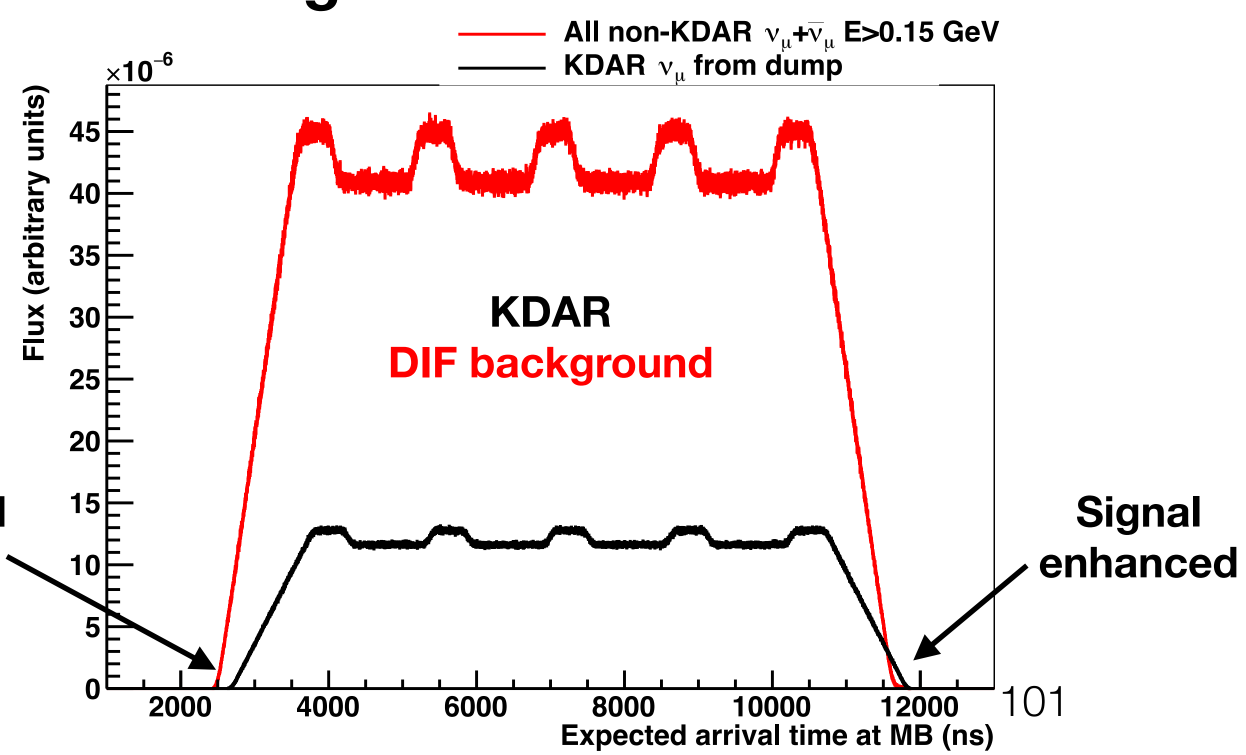
A small subset of the models tested.
Endpoint is fixed to 98 MeV.

Solution: Timing

Timing to the rescue!



Beam timing simulation. Normalizations are arbitrary.



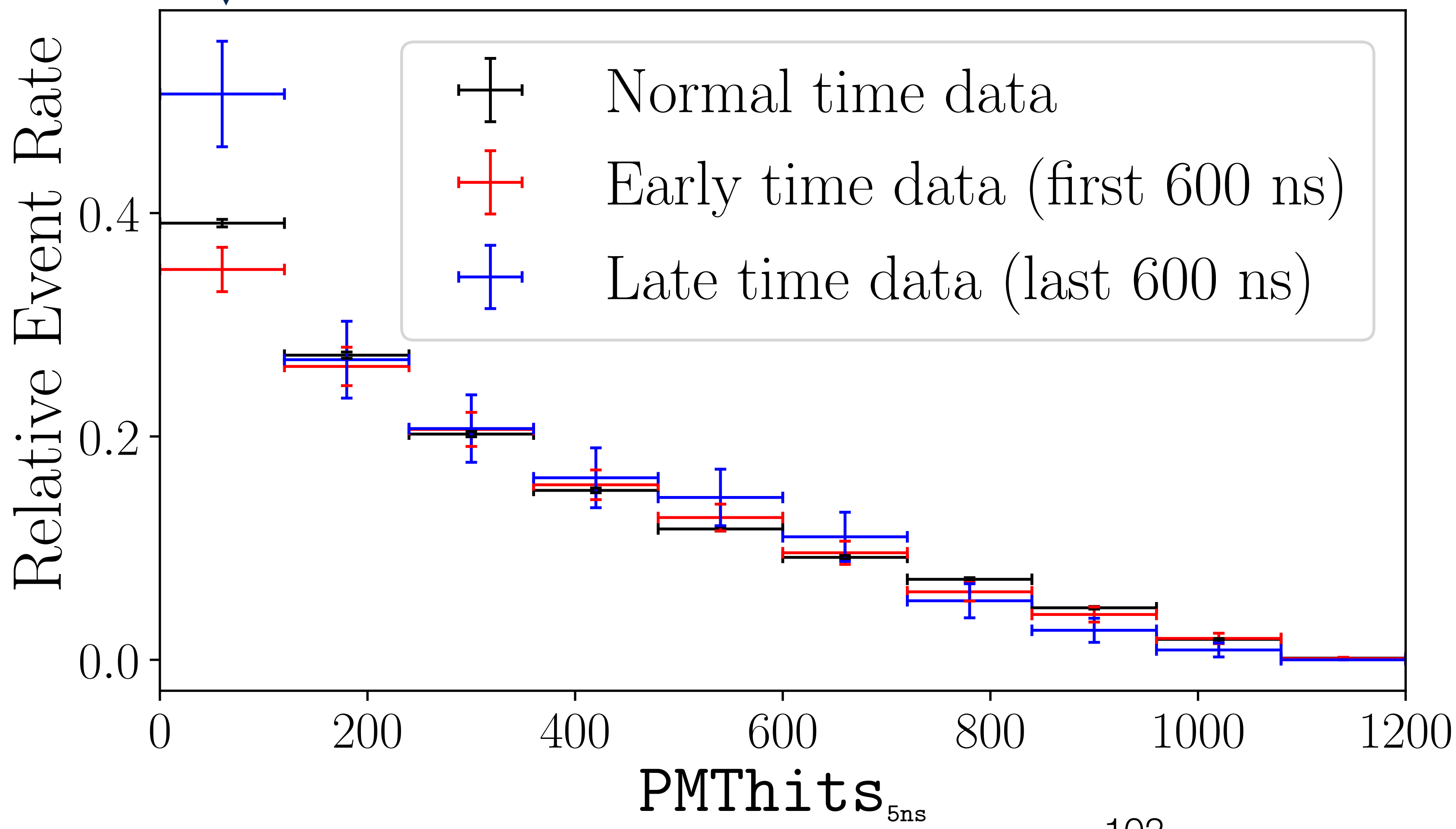
Signal arrives later than background due to the longer path it must take.

We can look for an evolution of signal and background over time.

Solution: Timing

Expect KDAR here

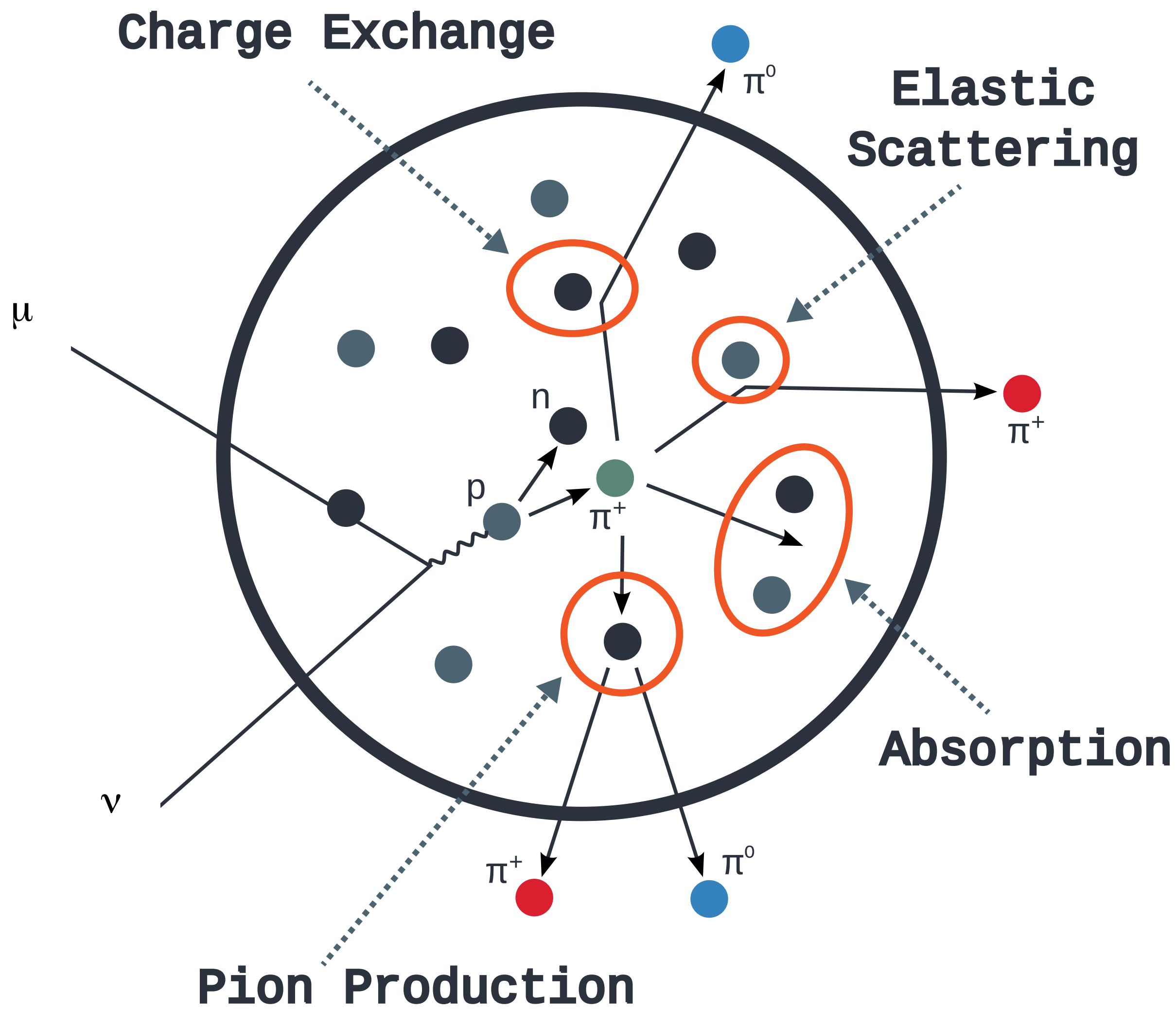
2.1σ deficit at early times
2.4σ excess at late times



In consideration of beam timing uncertainties, we divide the beam window into 3 pieces:

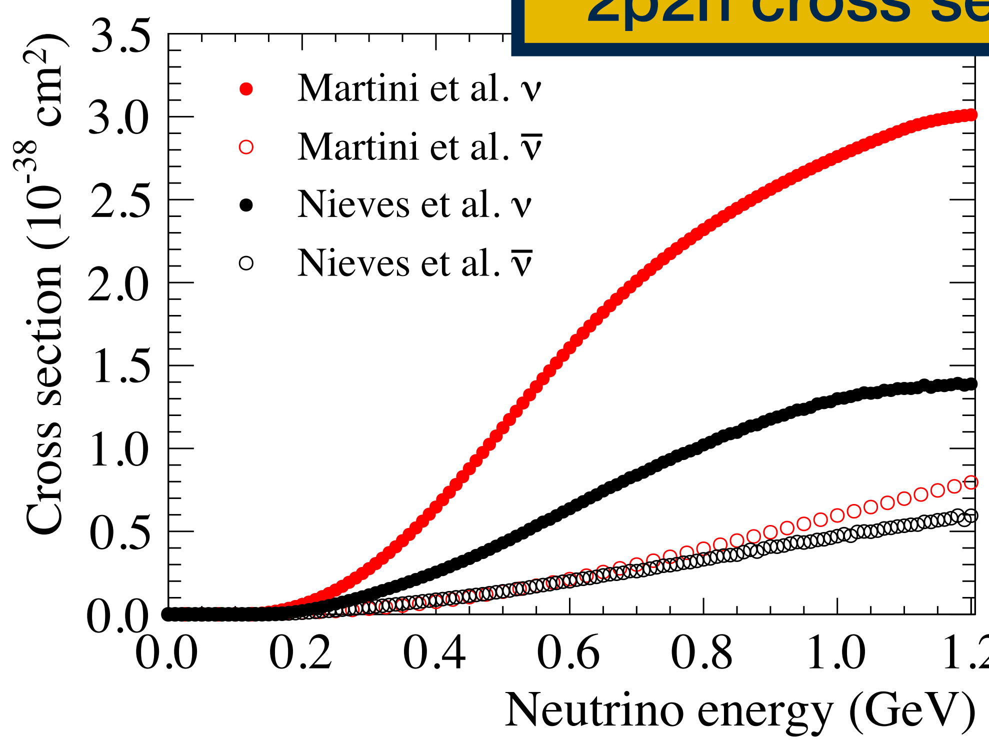
- Early time (first 600 ns)
  - Background-enhanced
- Late time (last 600 ns)
  - Signal-enhanced
- Normal time (8000 ns)
  - Constant signal to background ratio

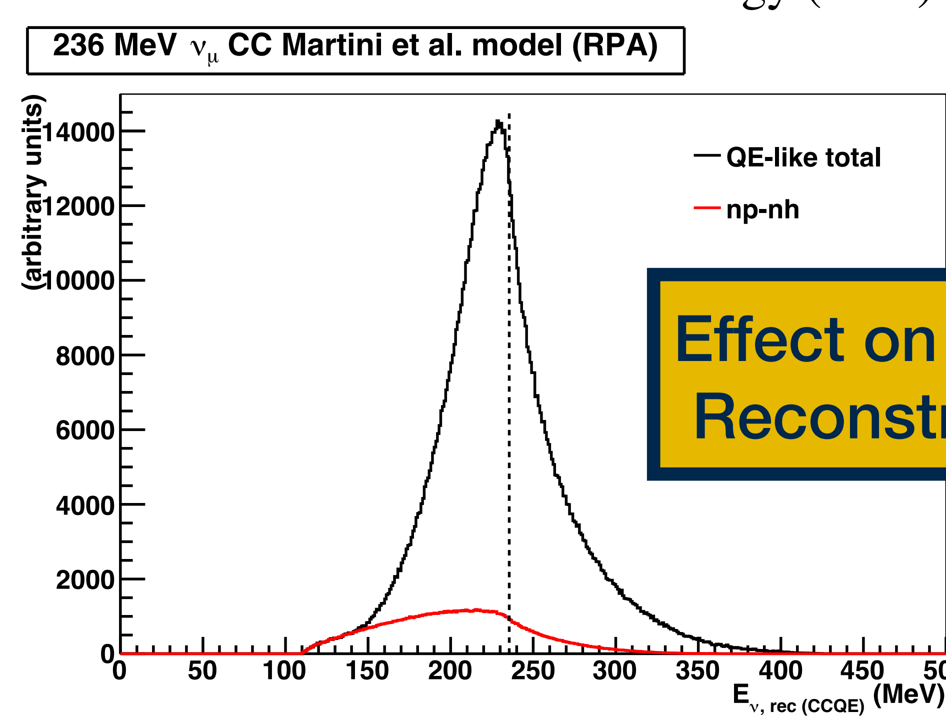
MEC + FSI



Schematic diagram of FSI.

2p2h cross section



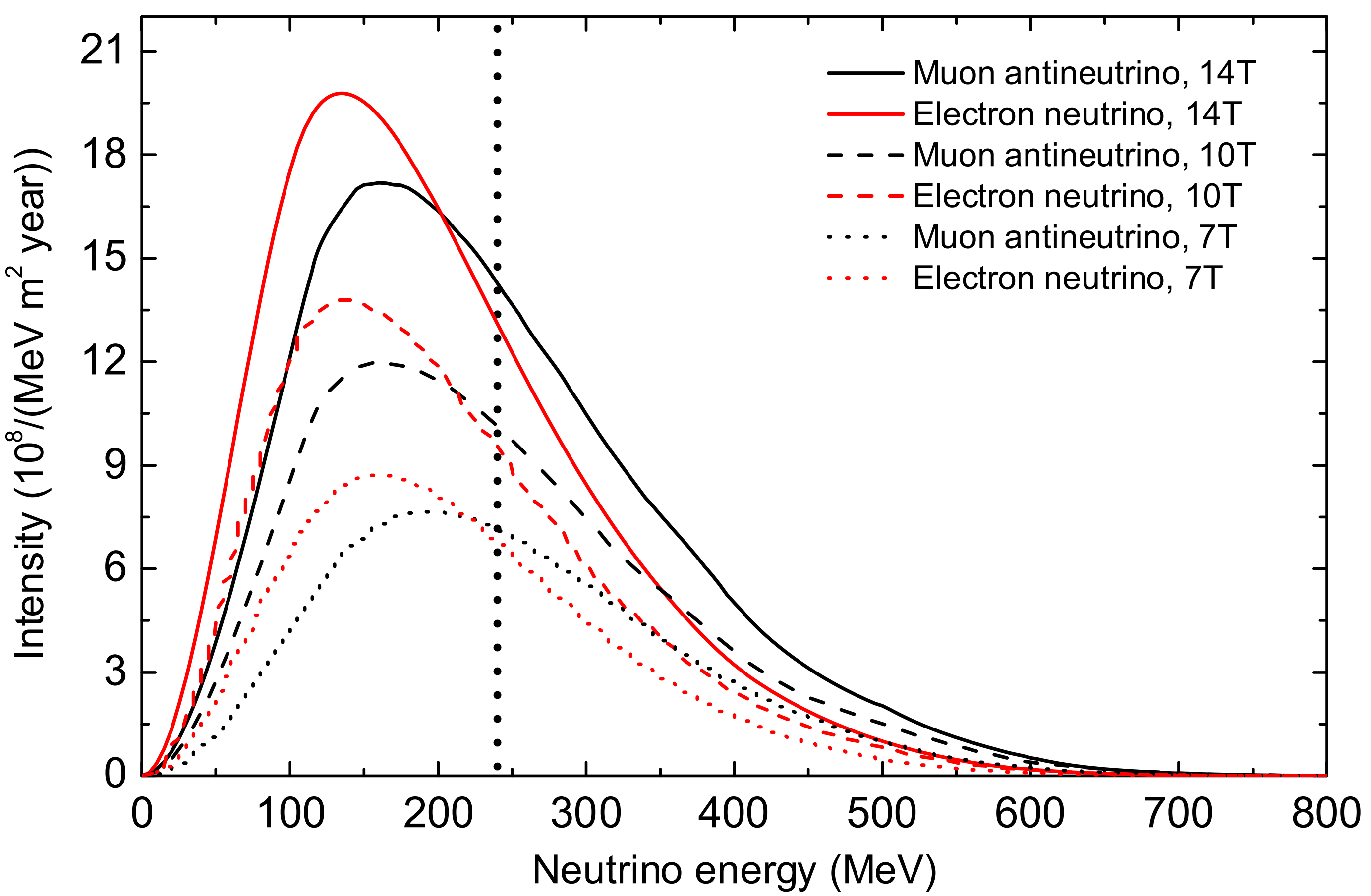


Effect on Energy Reconstruction

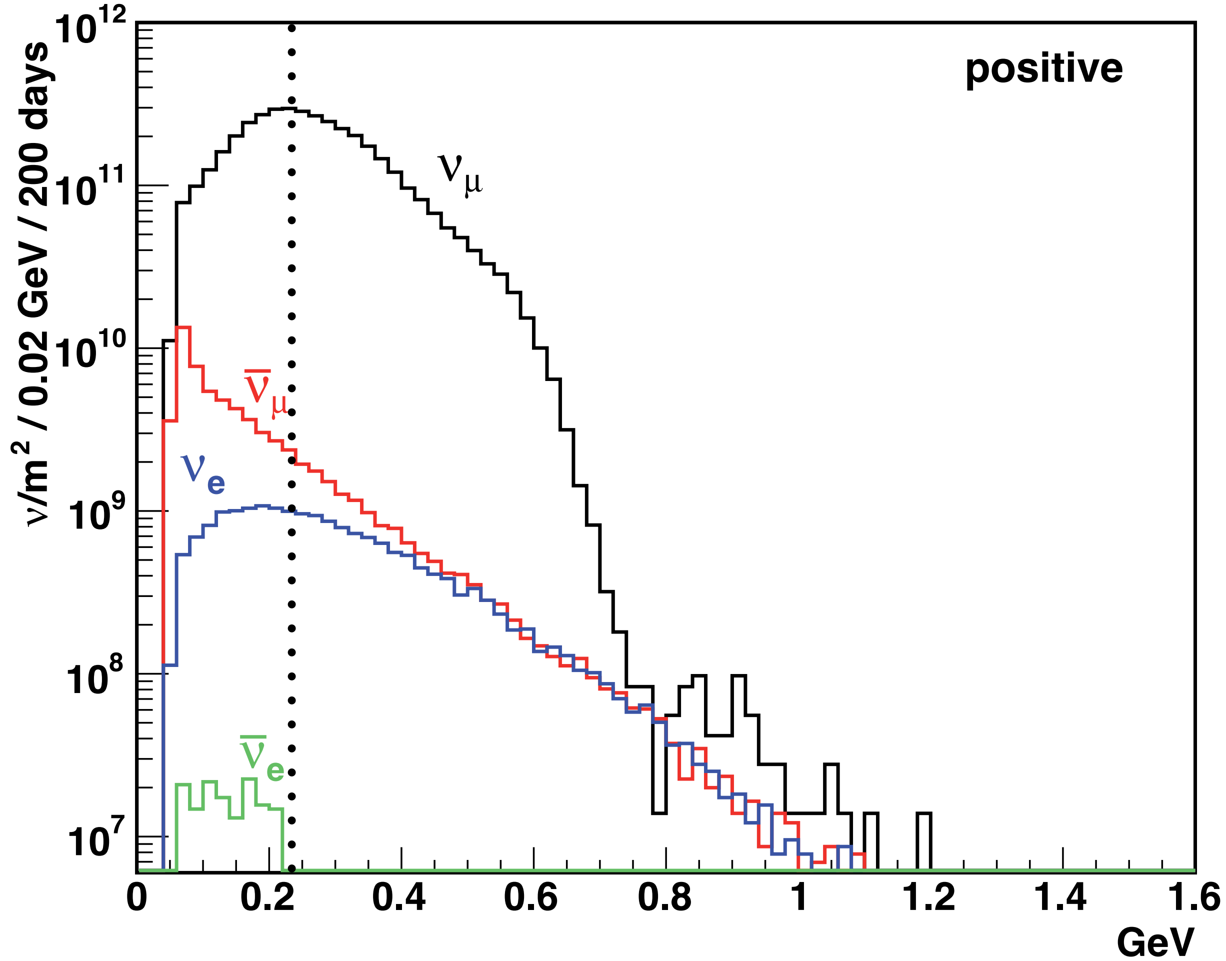
arXiv:1706.03621, arXiv:1707.01048

KDAR and δ_{CP}

MOMENT; δ_{CP} search in China

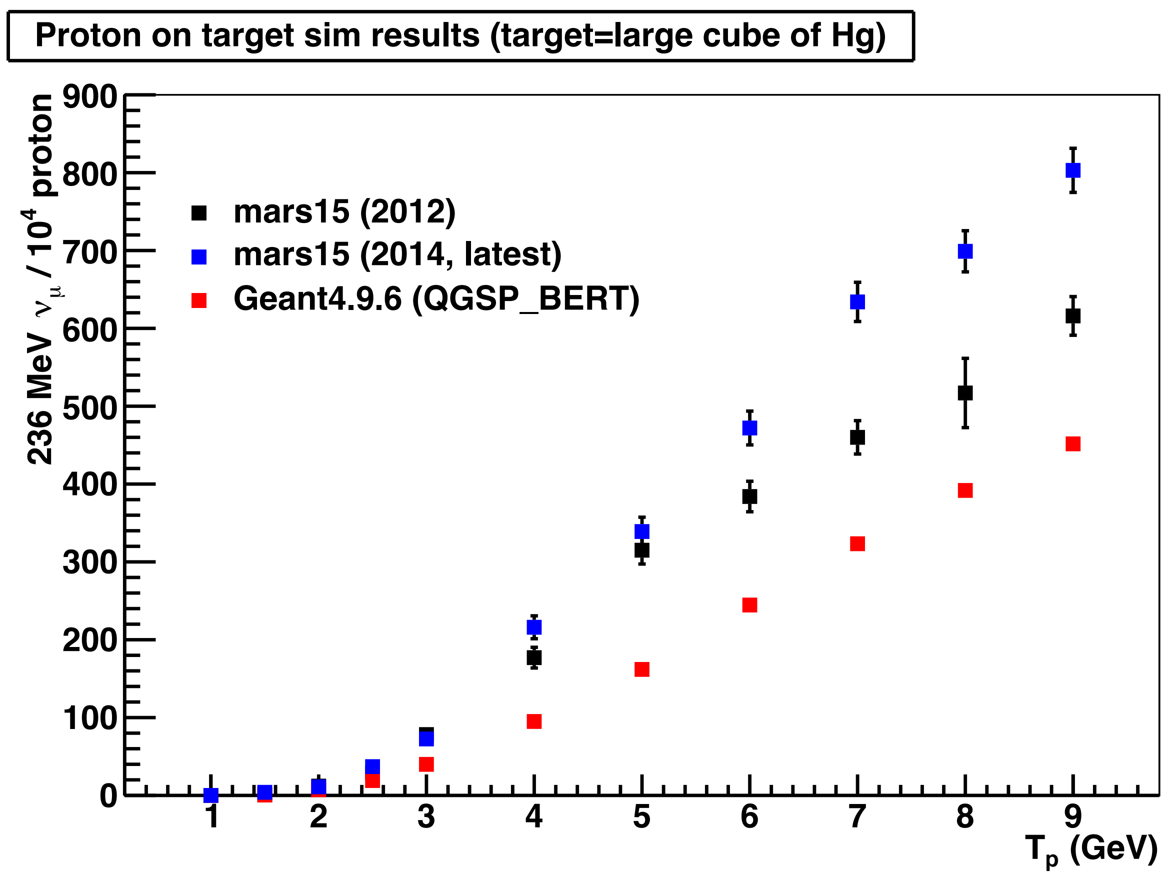


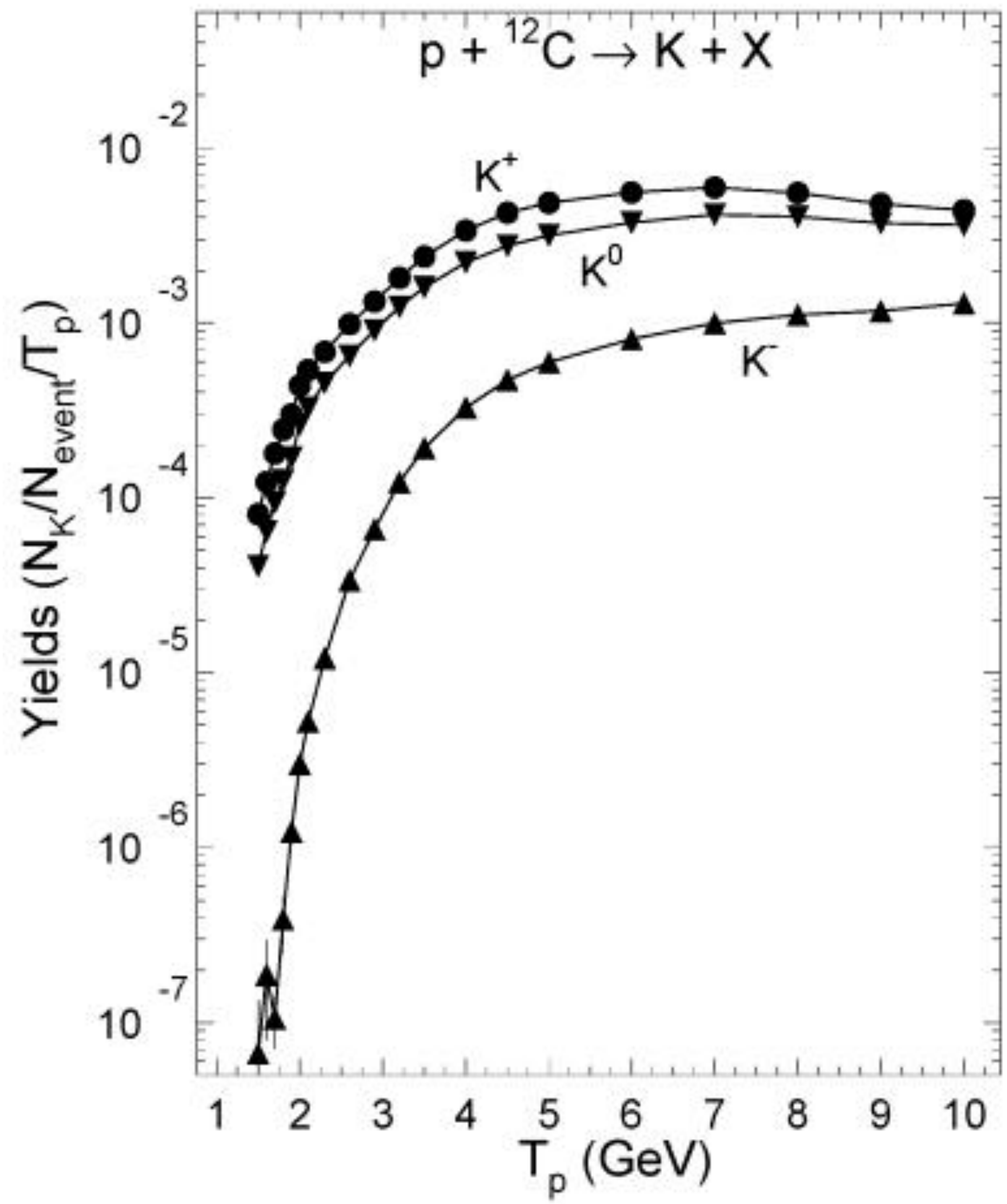
ESSνSB: δ_{CP} search in Europe



KDAR is relevant for the flux at these experiments!

Kaon Production

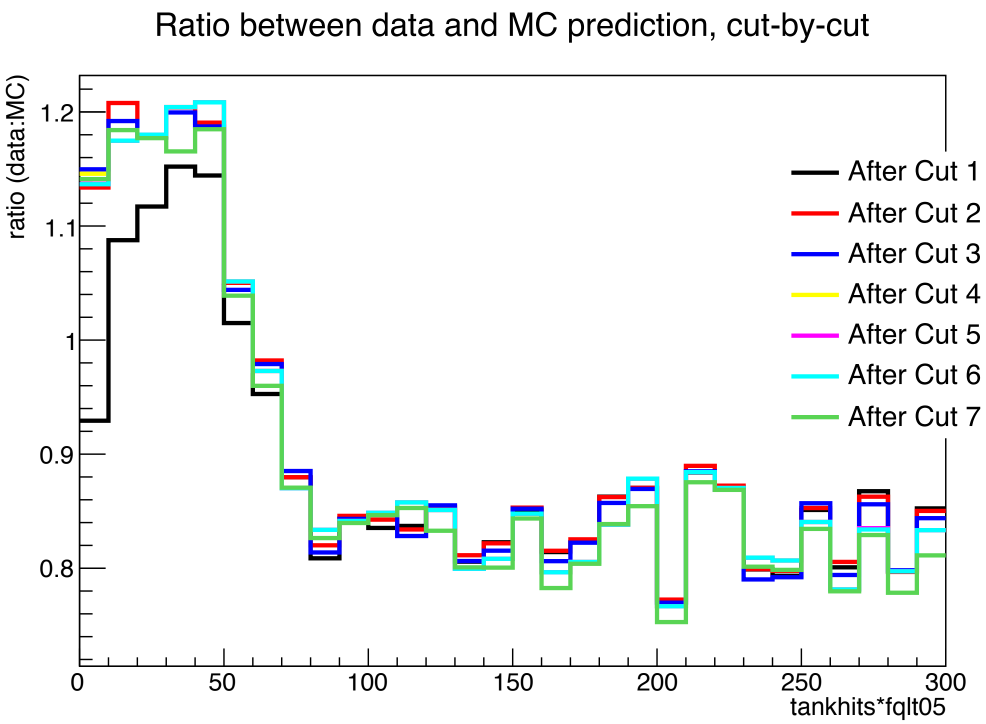


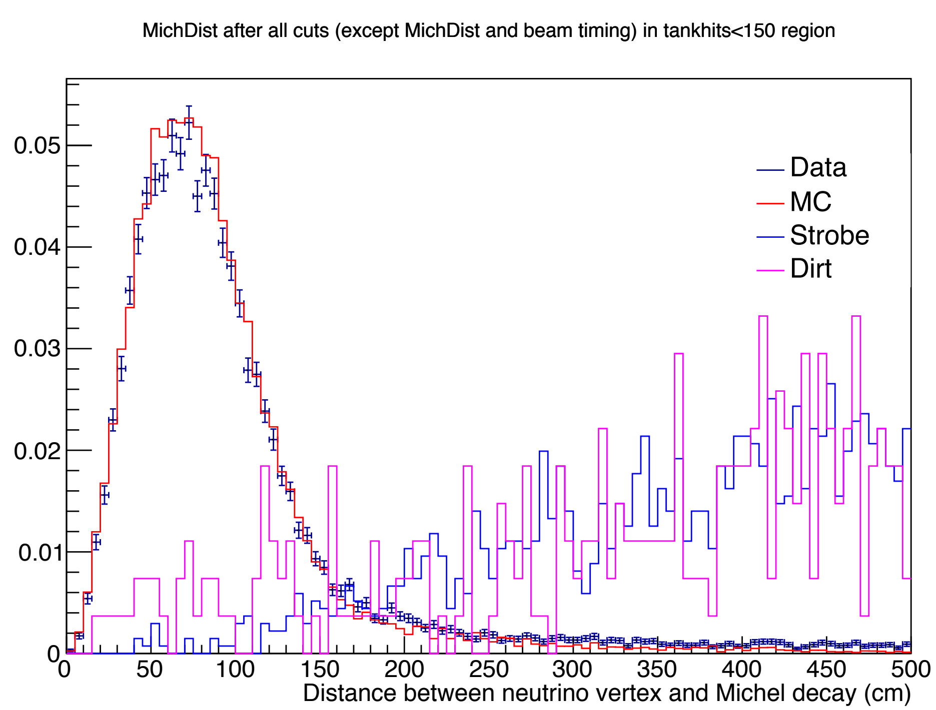


Kaon production is highly uncertain in proton-nucleus collisions.

MARS15, Fermilab-Conf-09-647-APC

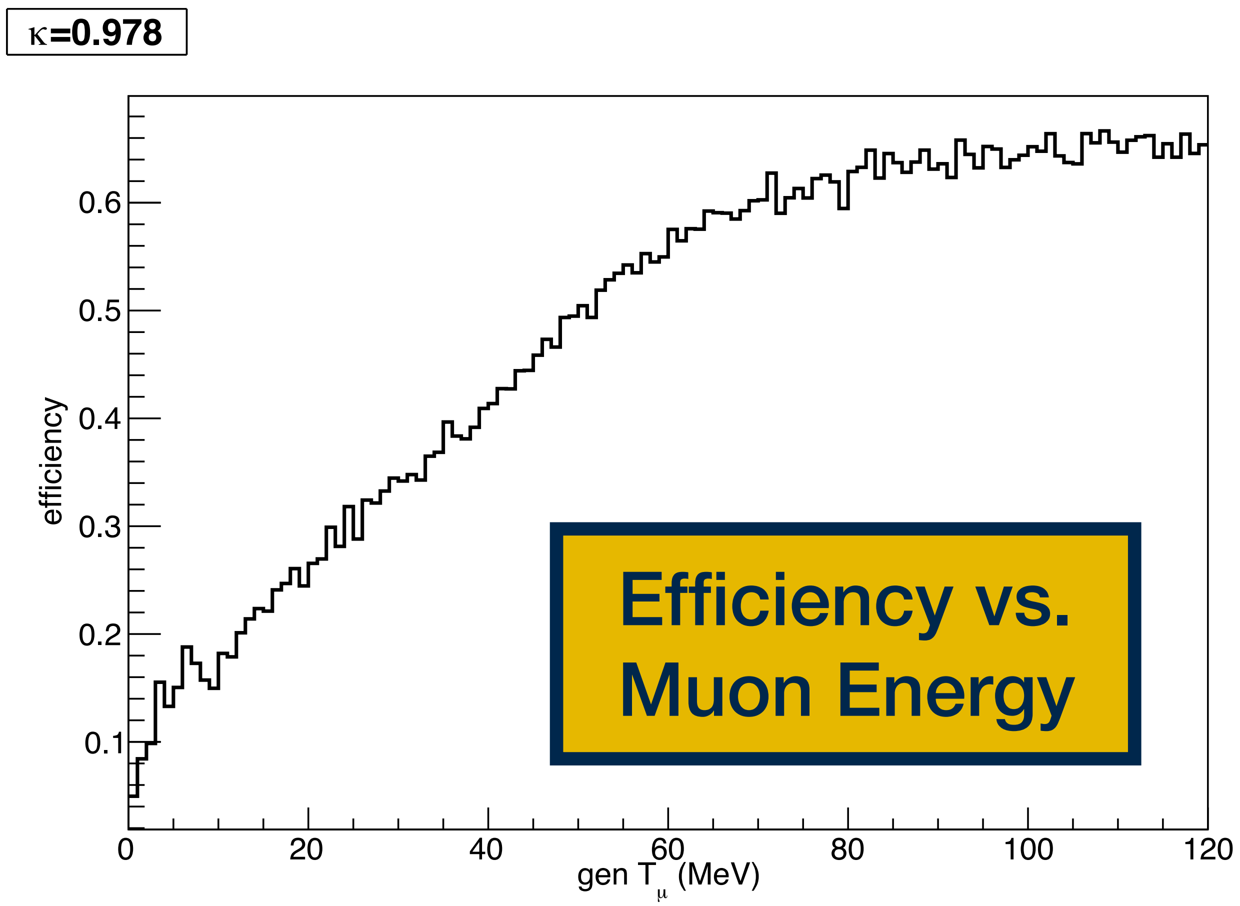
Full Cut List

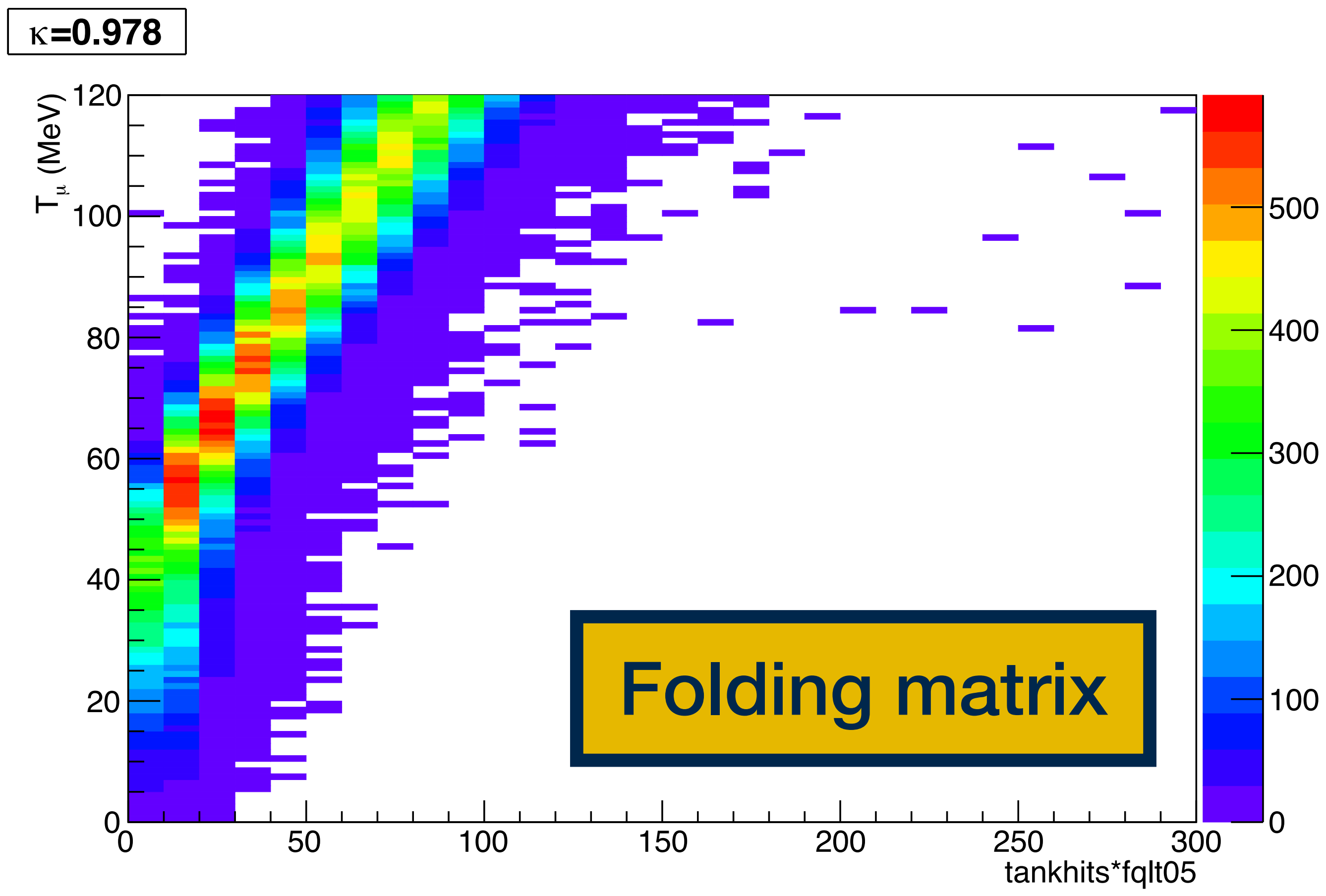




1. Two subevents with < 6 veto hits in each subevent.
2. Muon subevent in the beam window.
3. 2nd subevent TankHits < 200 and > 20.
4. Reconstructed vertex radius < 500 cm from center of the tank.
5. 1st subevent TankHits > 20.
6. 1st subevent hit time RMS < 50 ns.
7. Michel distance < 150 cm.

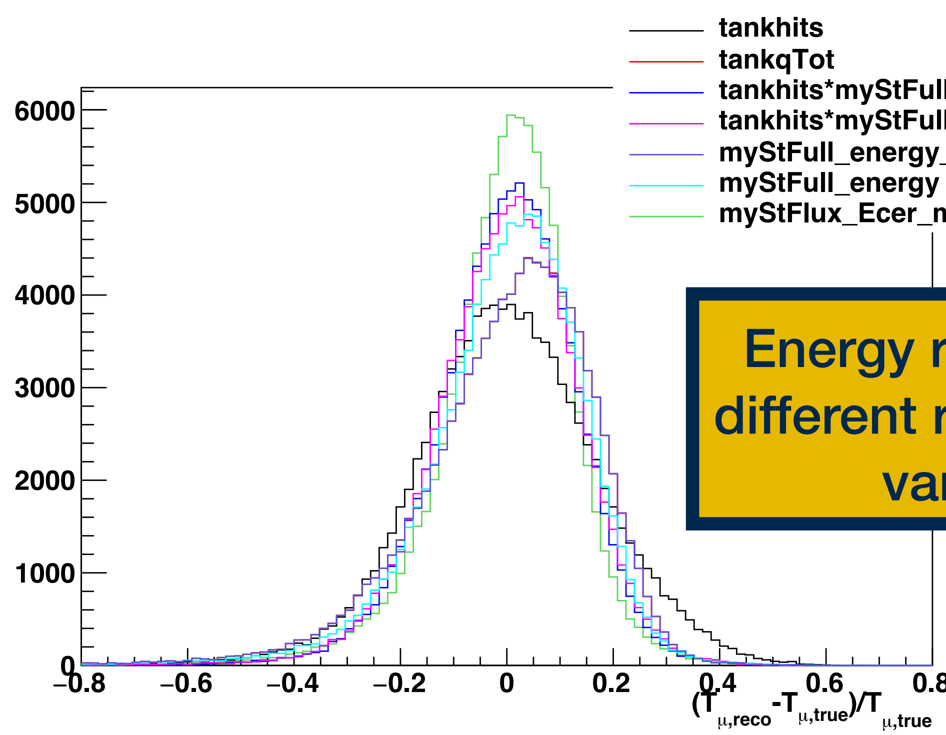
Efficiency + Folding



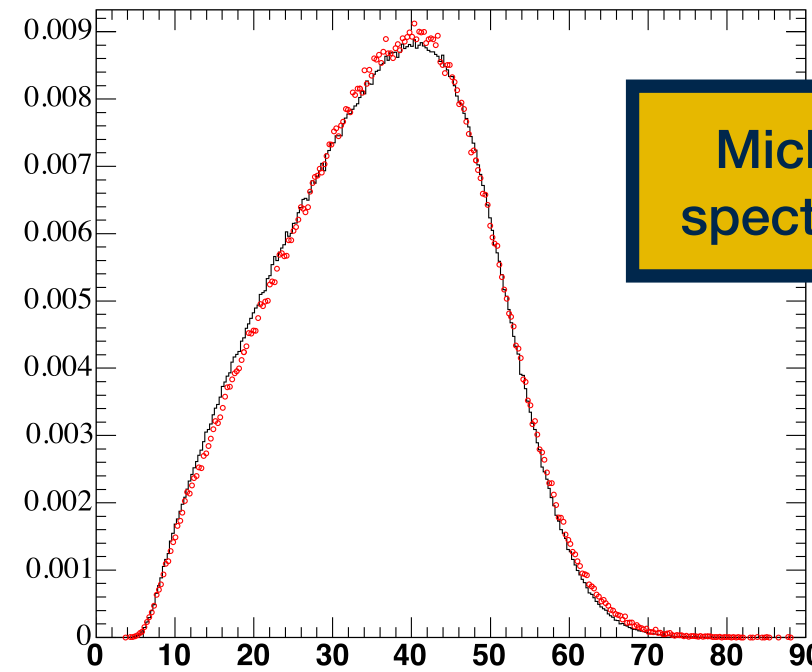


Weak dependence on the generator parameters enters via the flux used to generate the efficiency and the folding matrix.

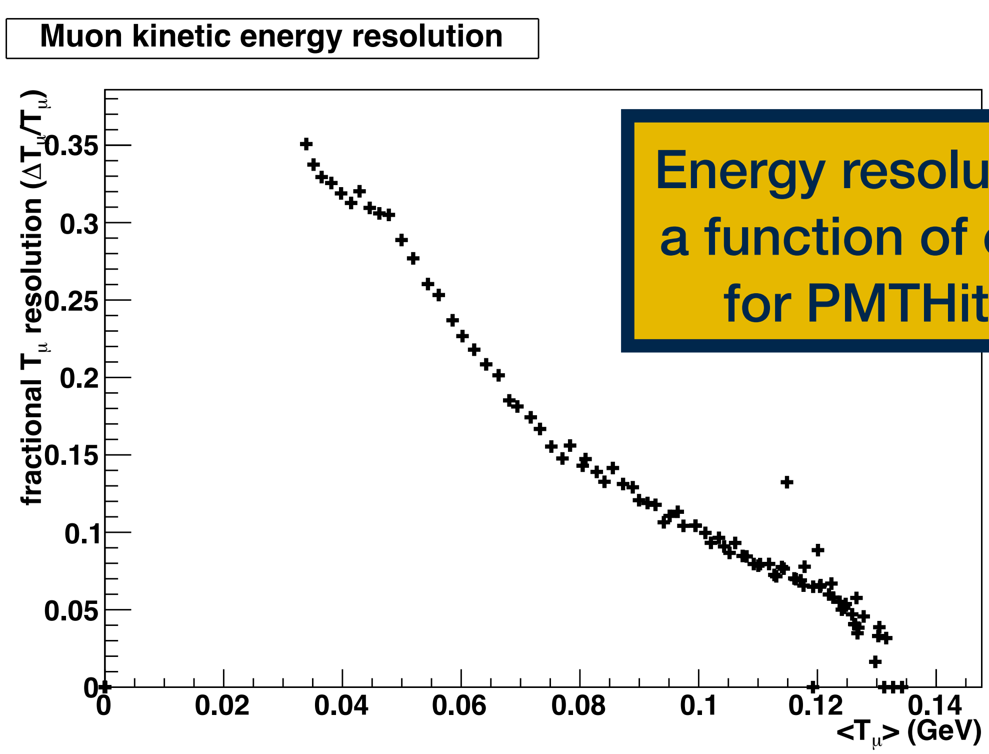
Energy Resolution



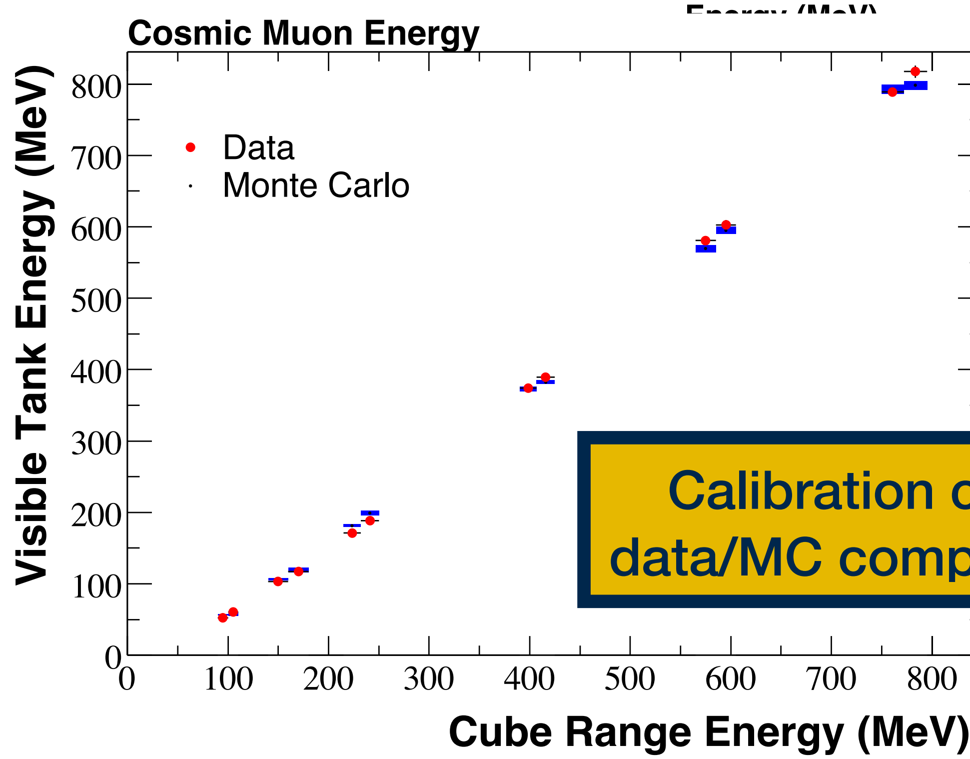
Energy resolution for different reconstruction variables.



Michel spectrum

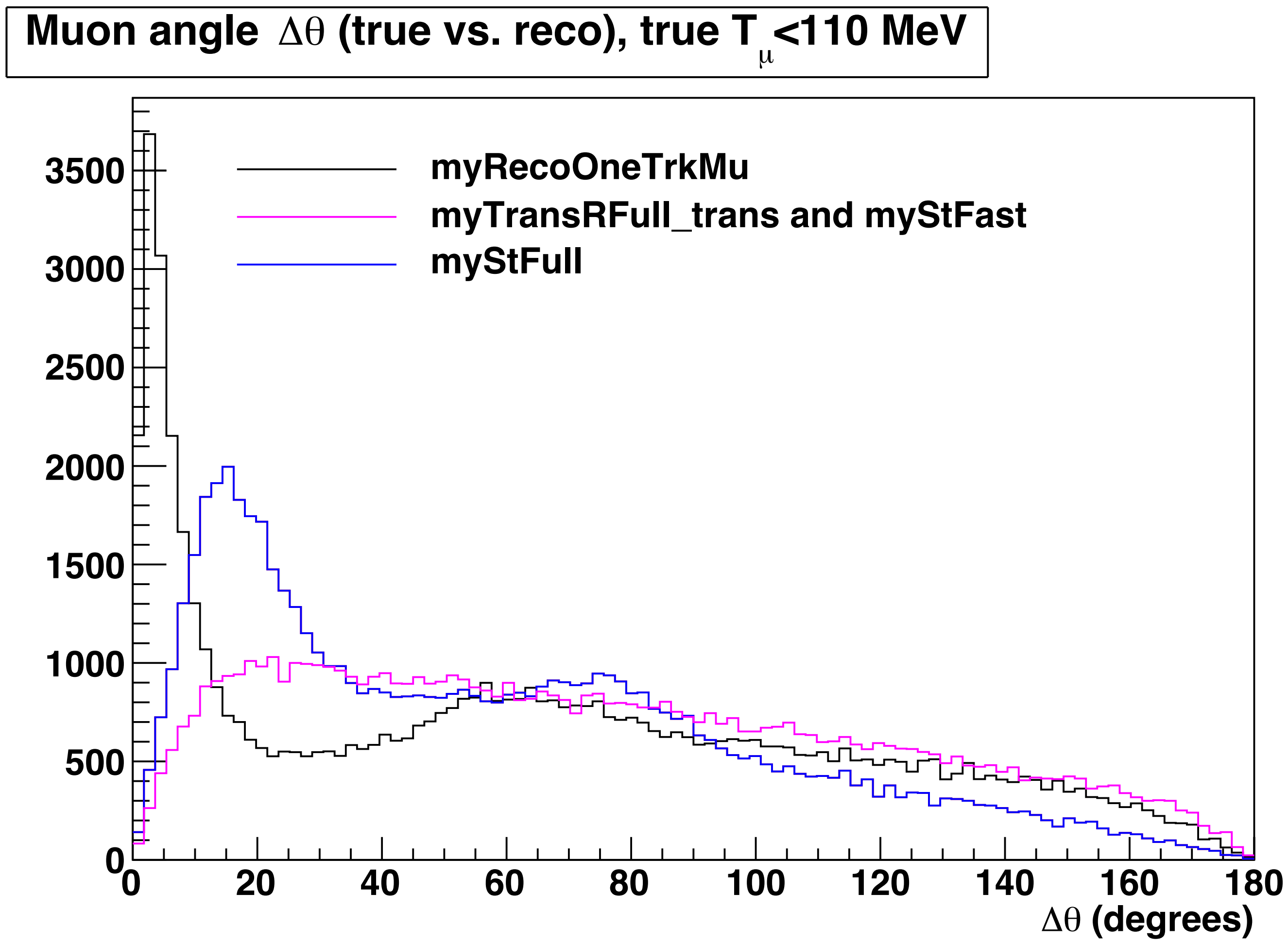


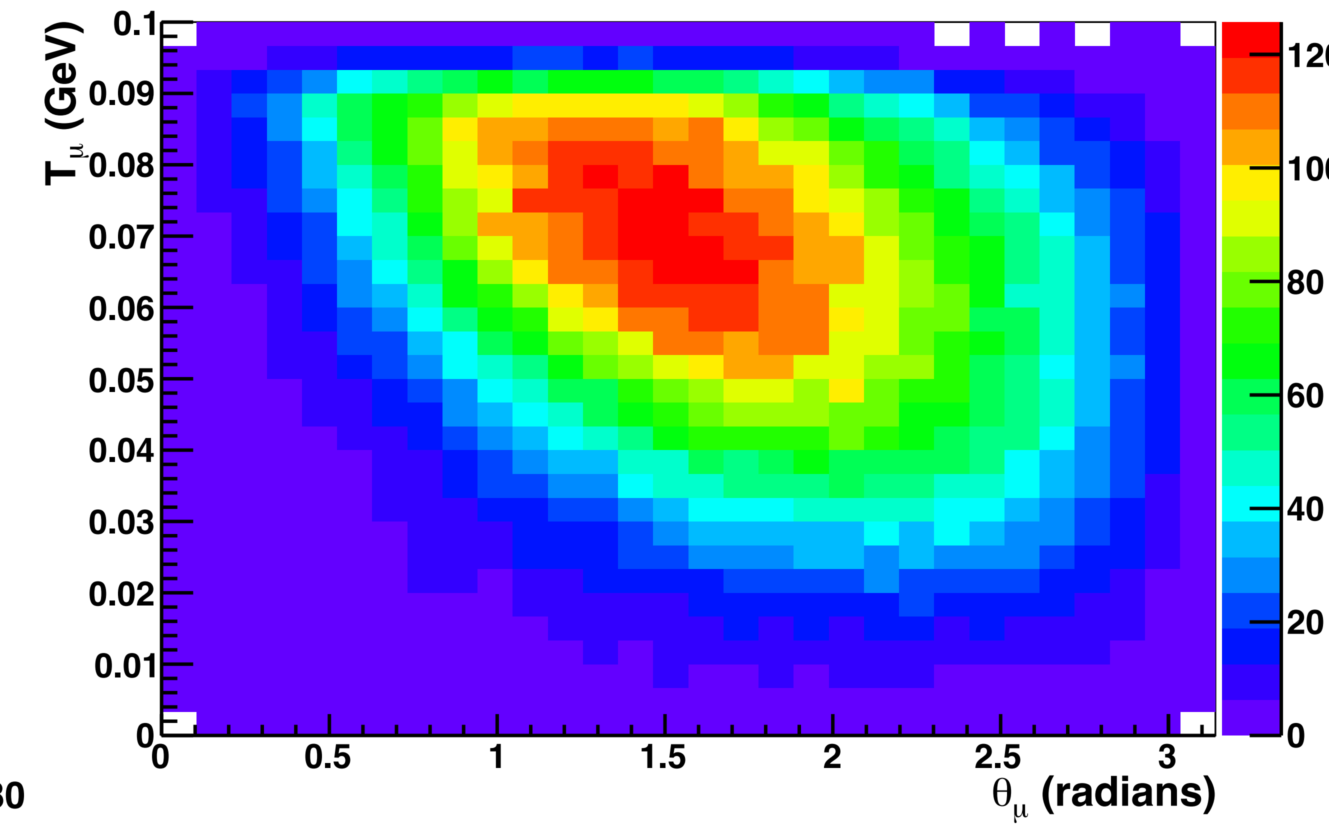
Energy resolution as a function of energy for $PMTHits_{5ns}$.



Calibration cube data/MC comparison

Muon Direction

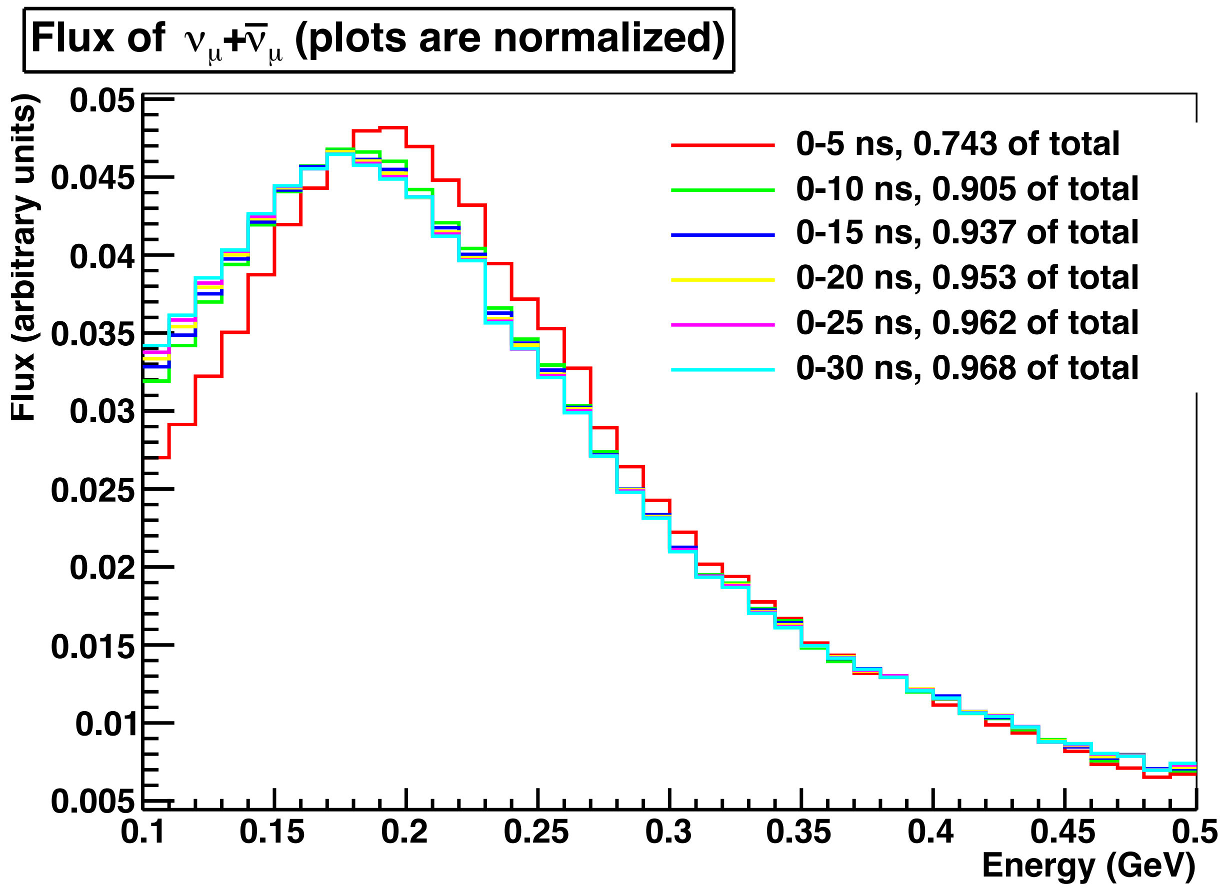


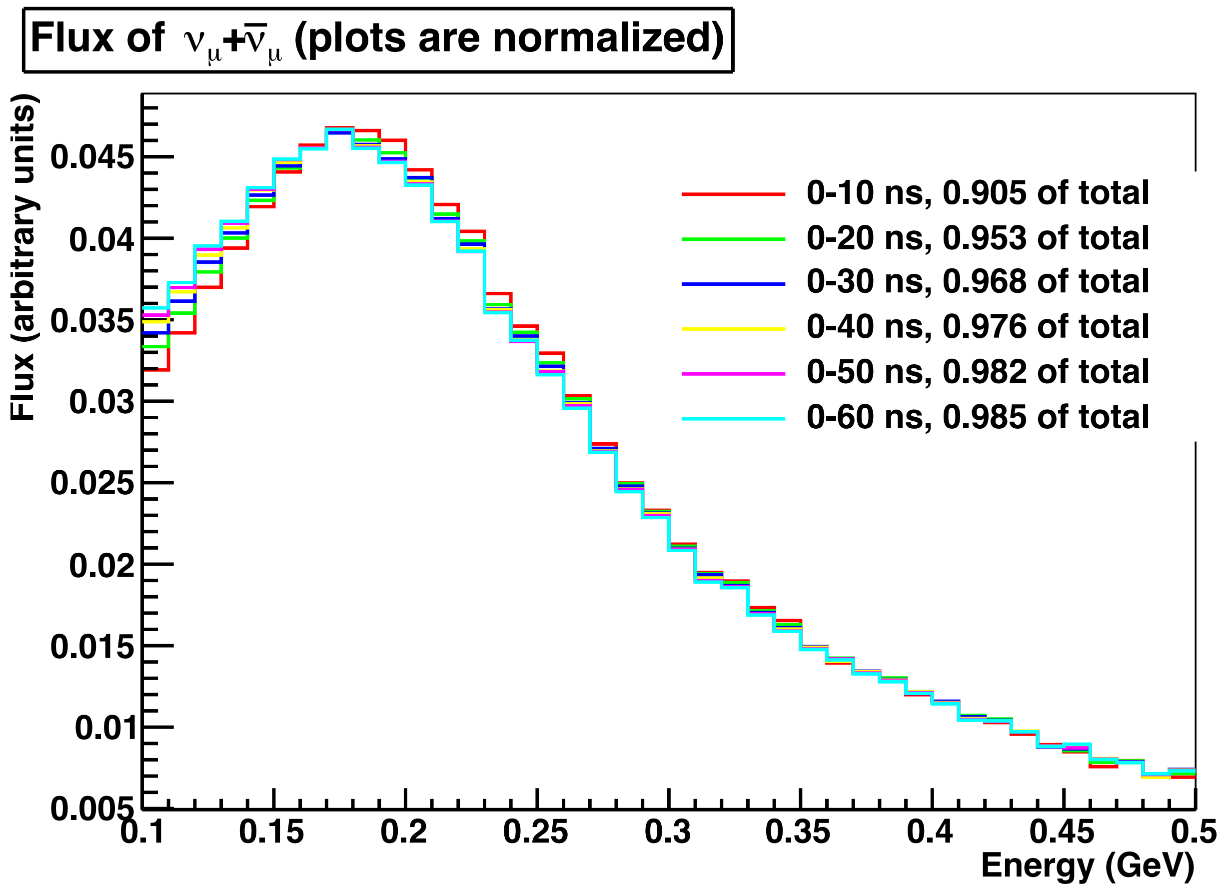


Long tails in the energy reconstruction at low energies.

Muon direction is uncorrelated with neutrino direction for KDAR neutrinos.

Background in Time

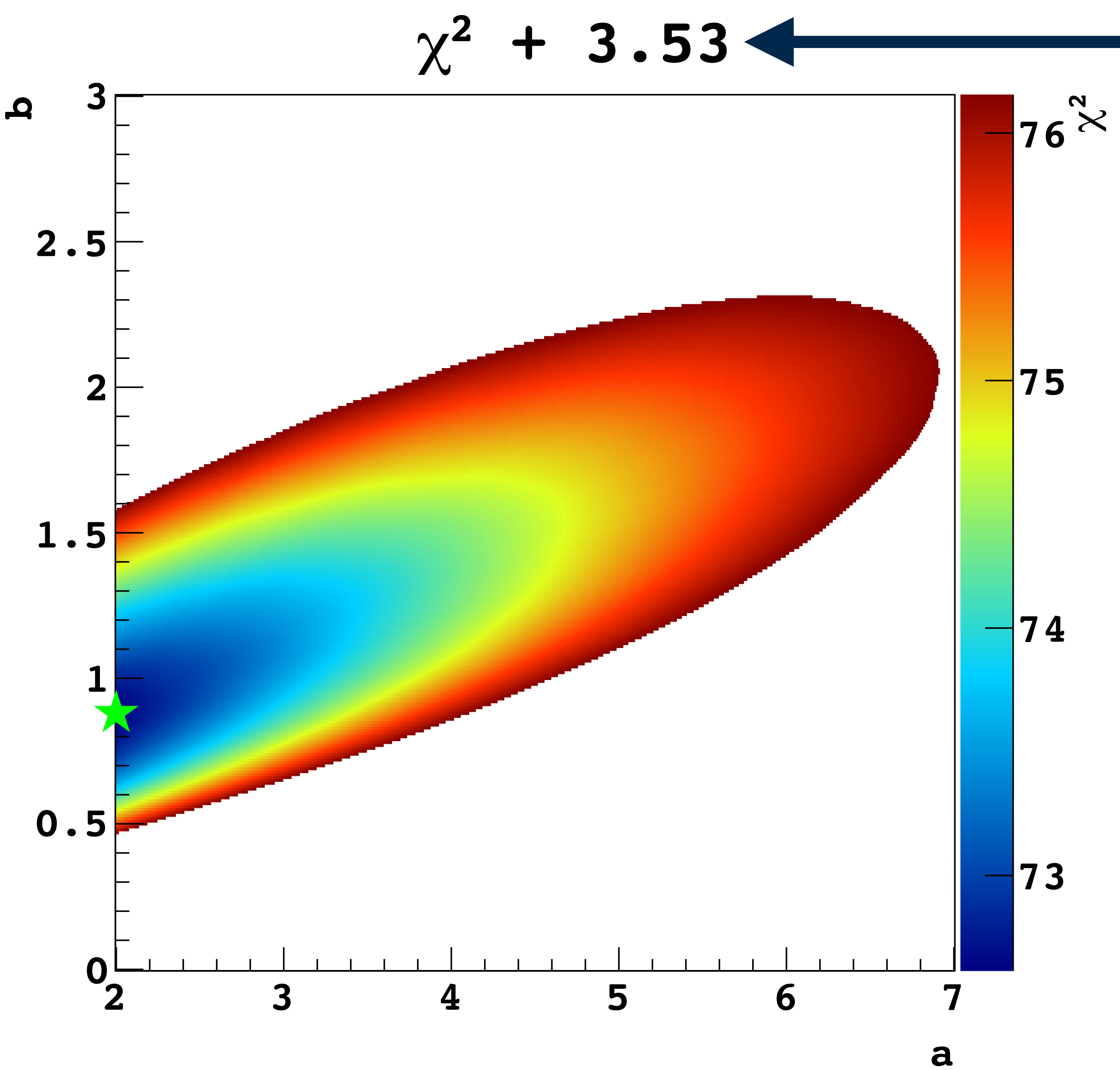


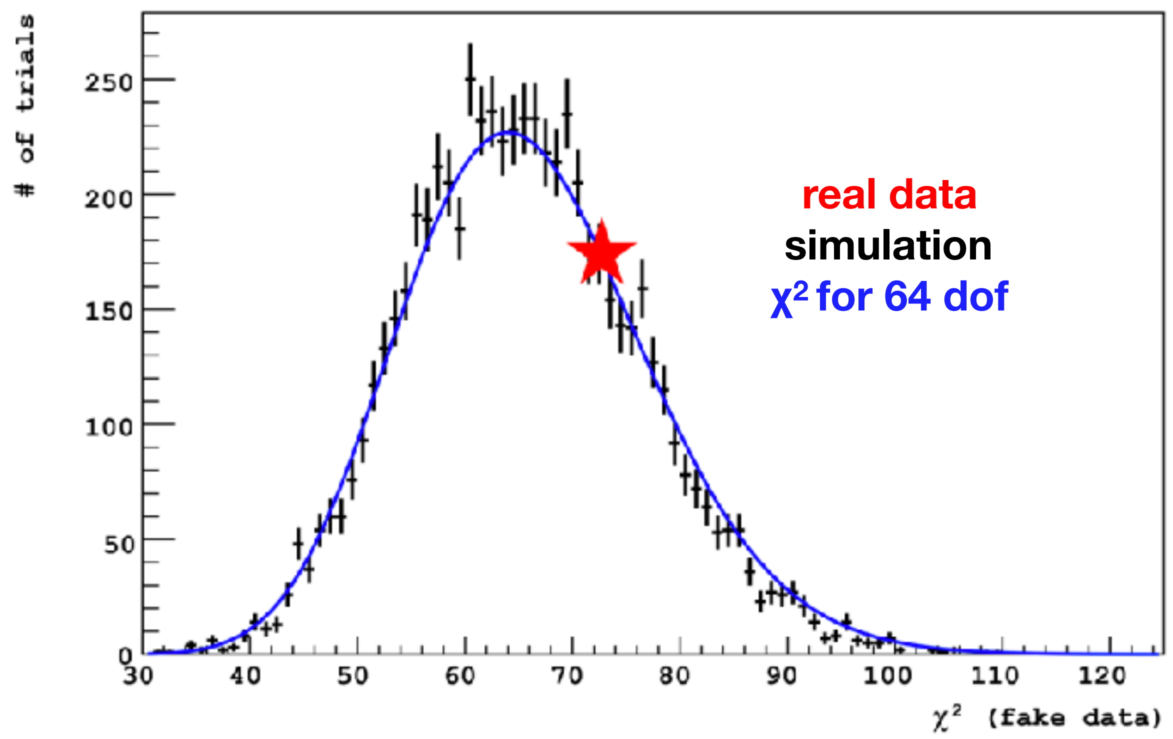


Variations on time scales of 5-10 ns.
Irrelevant for our 200 ns bins.

Shape Contours

3 parameters



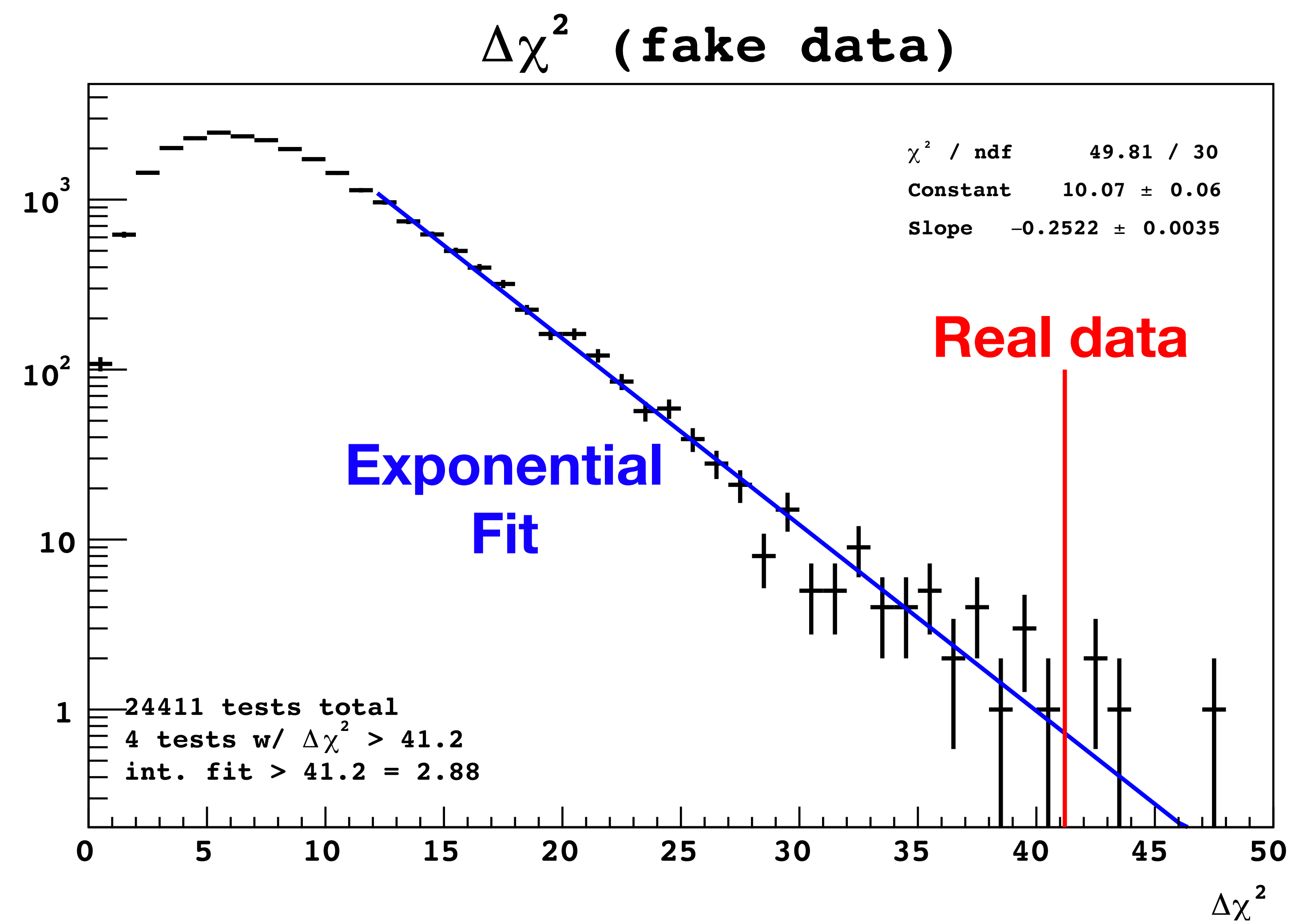


Shape parameter contour
Endpoint fixed to 95 MeV

Fake data confirms the χ^2 treatment of our statistic

Observation Significance

- We compute the significance of the KDAR observation using fake data.
- We generate fake data according to a background-only hypothesis
  - Shape = normal time shape
  - Normalization = integral of data in each time bin
- Find the minimum χ^2 for each fake data set.
- Determine the probability of finding a larger χ^2 for the background-only hypothesis.



Background only fake data χ^2 values