Shedding light on low energy excess

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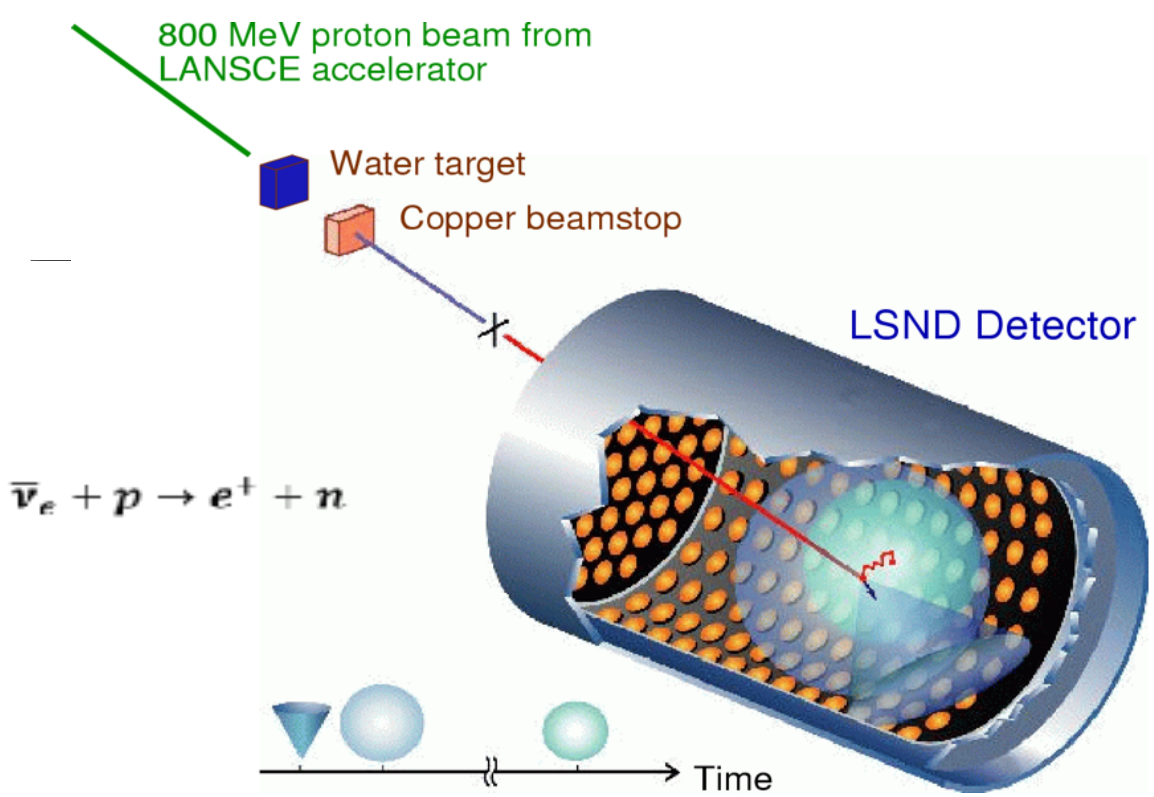
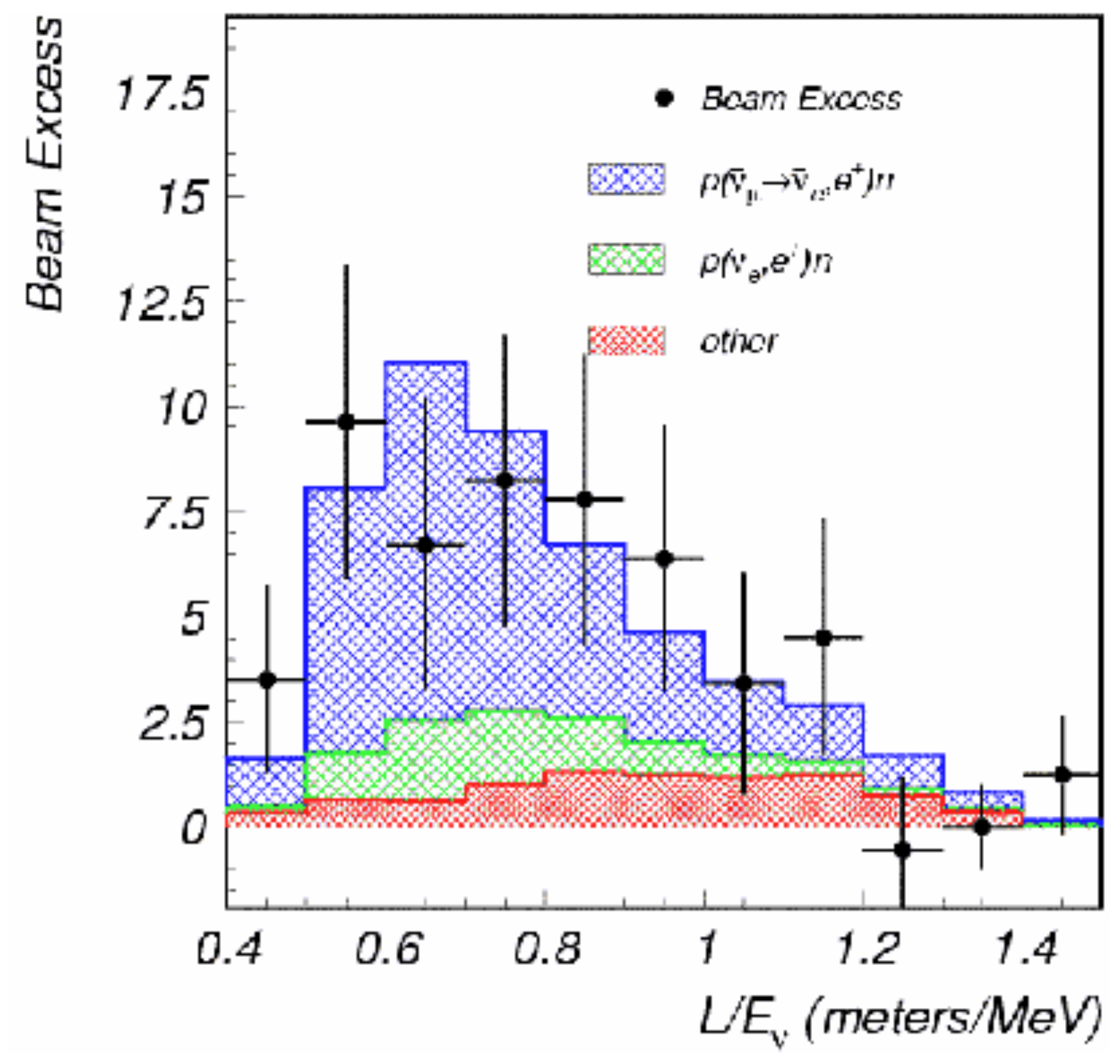
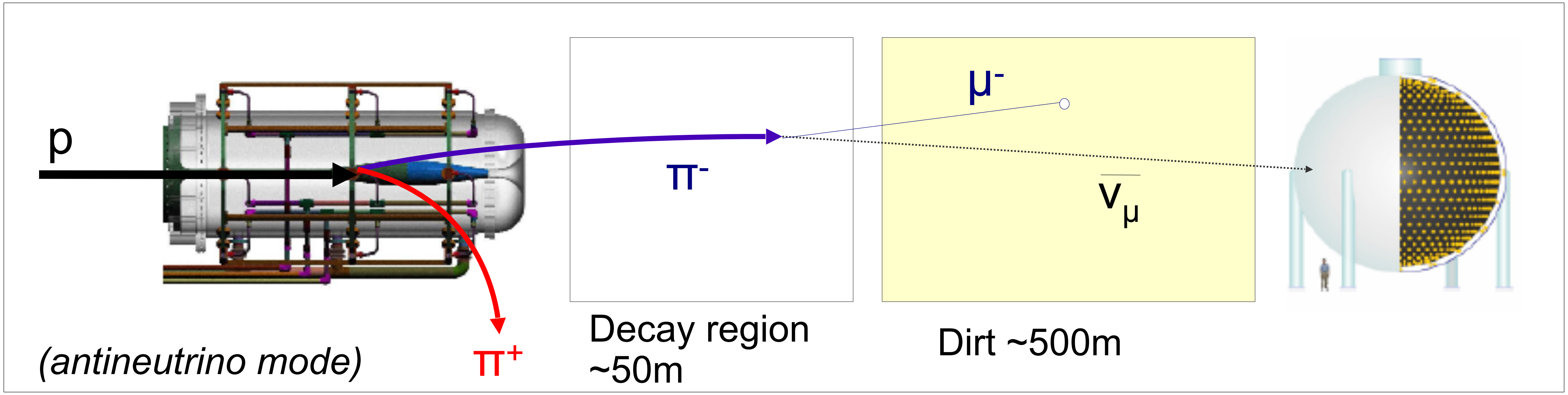
LSND experiment

- Stopped pion beam
  $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  $\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- $\bar{\nu}_e$ signature: Cherenkov light from e^+ with delayed n-capture
- Excess=87.9 ± 22.4 ± 6 (3.8σ)





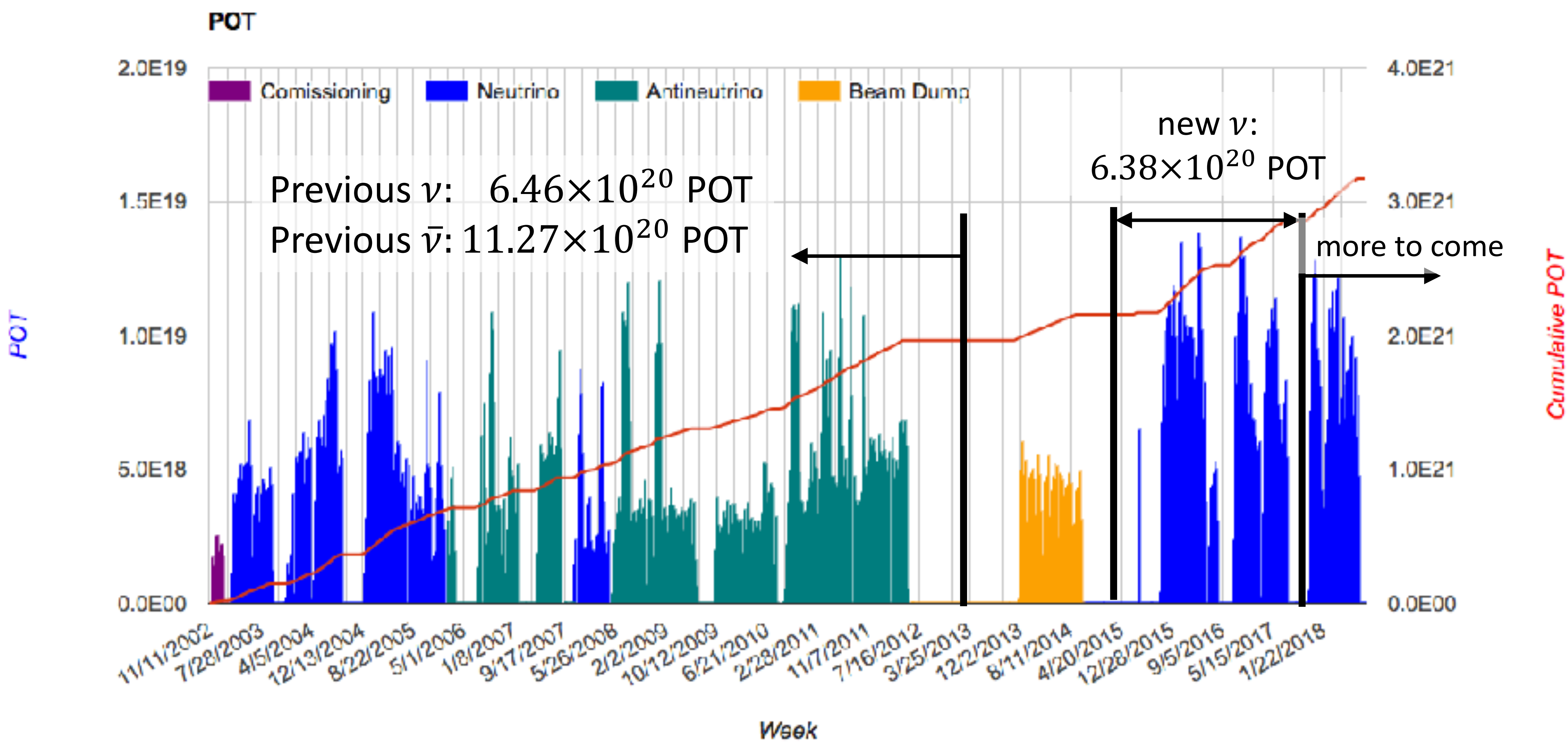
MiniBooNE experiment



- Similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

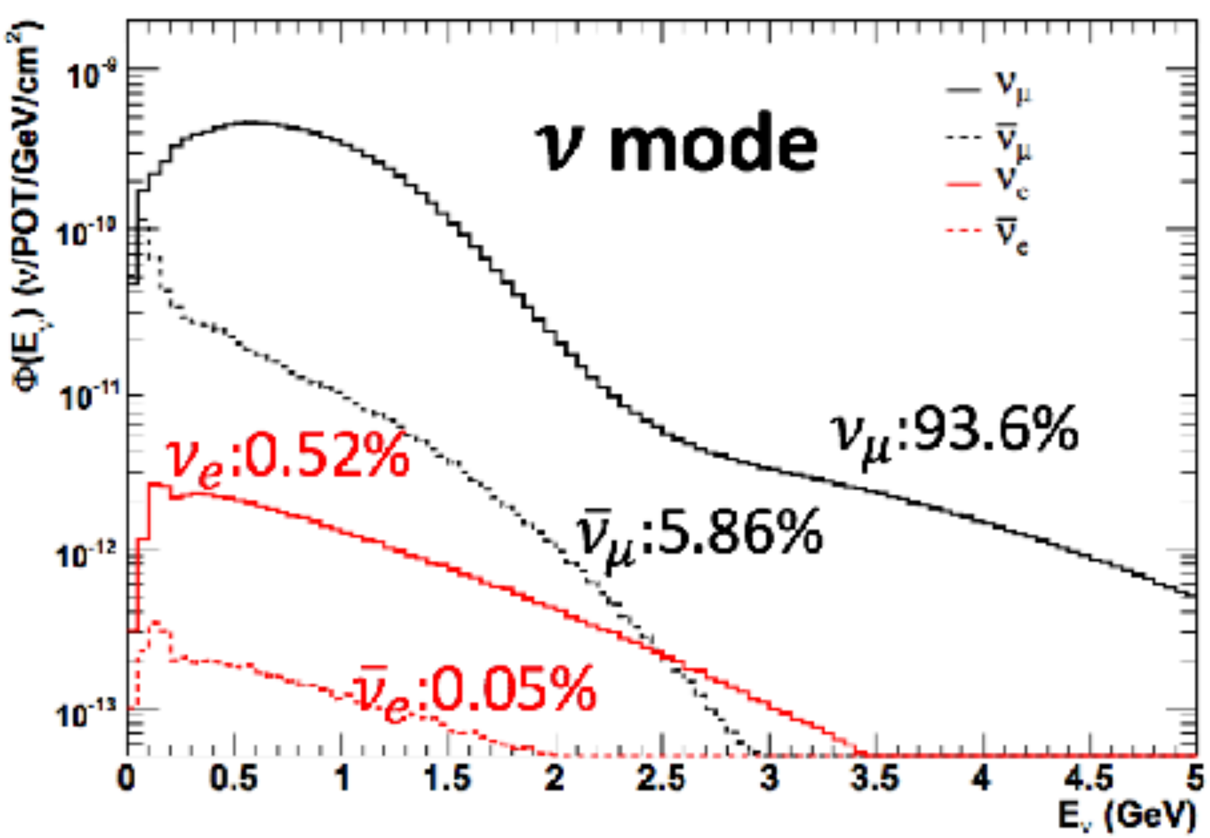
Data Set

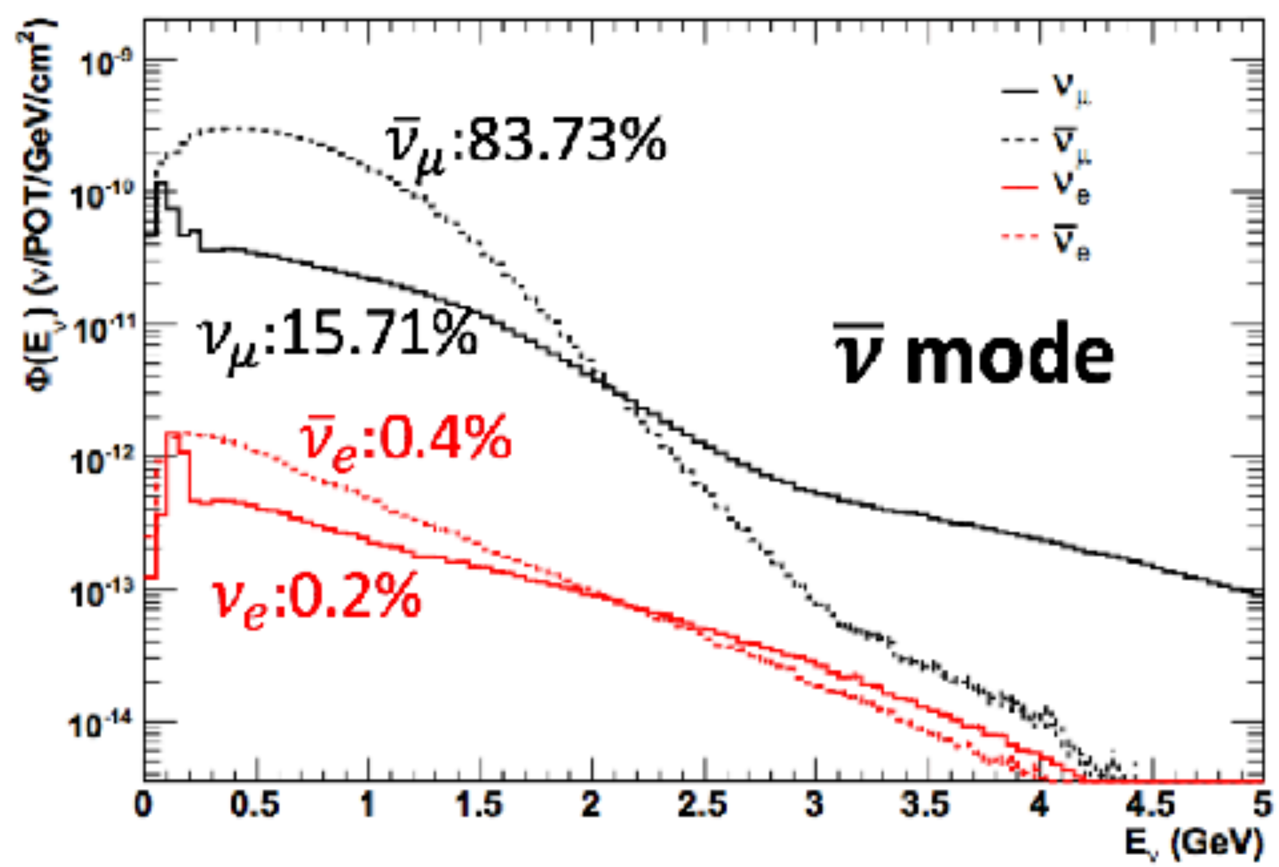
- 15+ years of running in neutrino, antineutrino, and beam dump mode. More than 30×10^{20} POT to date.
- New result of a combined 12.84×10^{20} POT in ν mode + 11.27×10^{20} POT in ν mode is presented in this talk



Booster Neutrino Beamline (BNB)

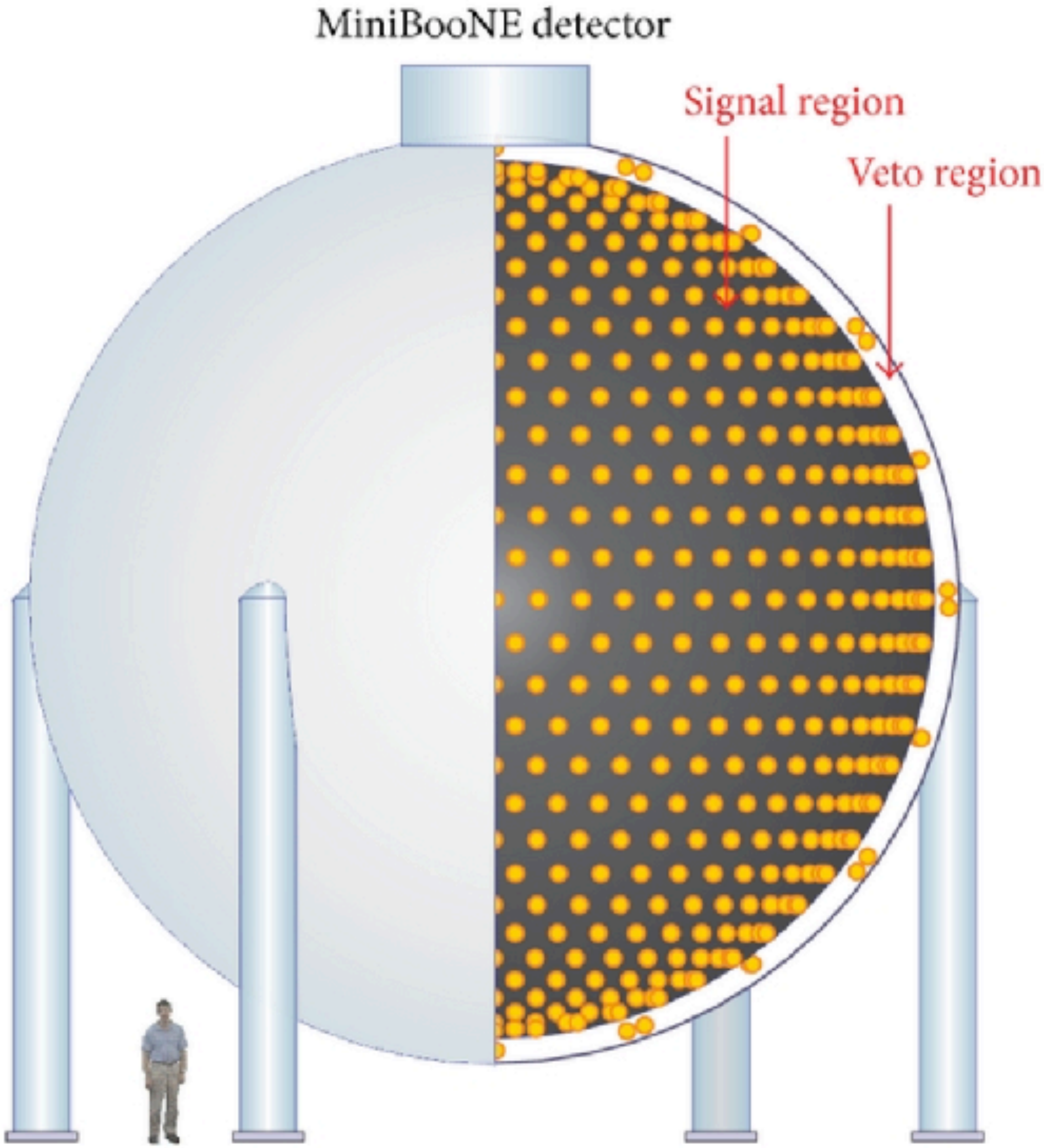
- Well understood neutrino beam
- Hadron production and interaction cross sections constrained by external data





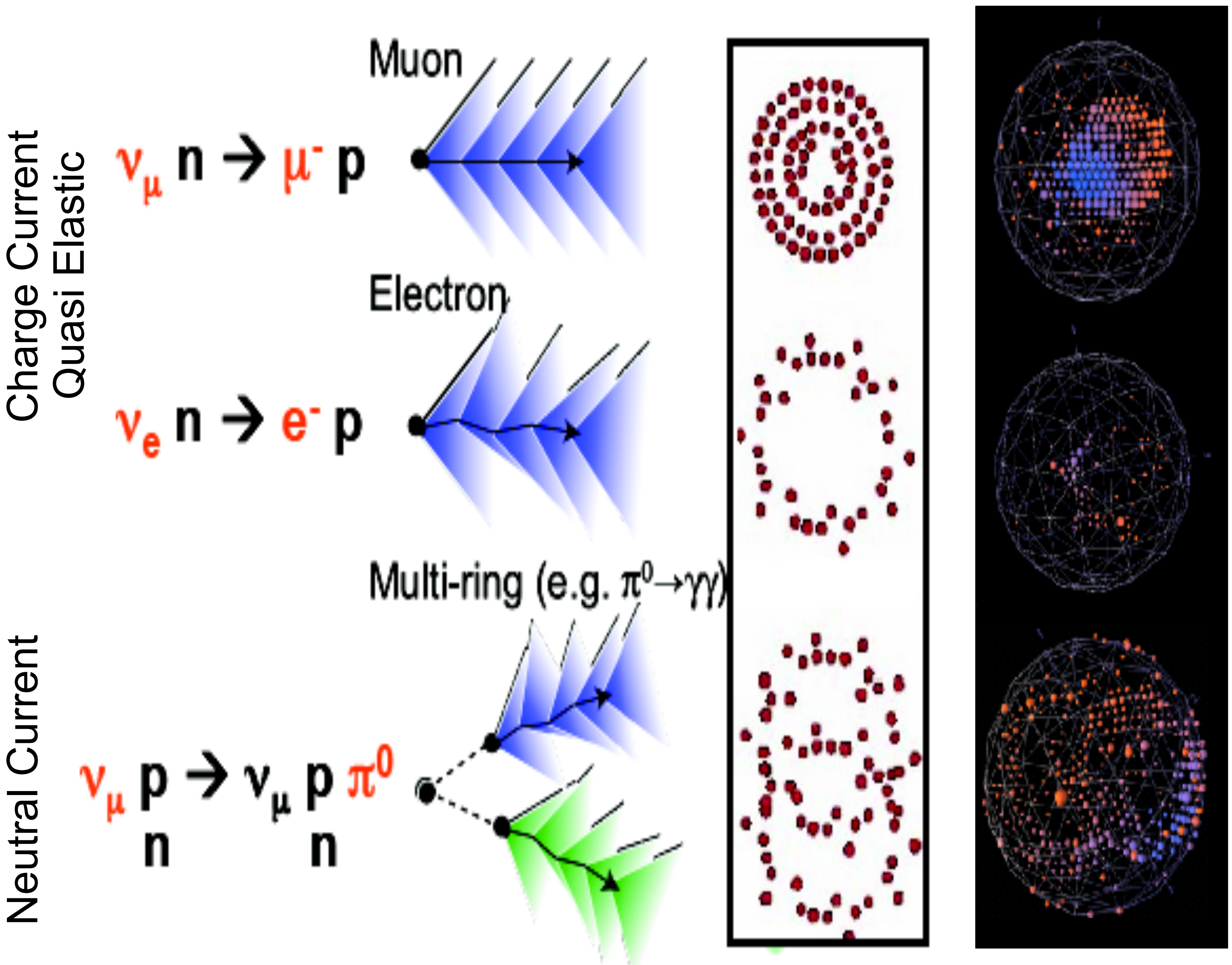
Phys. Rev. D79, 072002 (2009)

MiniBooNE detector



- 541 meters downstream from the target
- 12m diameter sphere with 10m fiducial volume
- 800 tons of pure mineral oil
- Two optically separated regions:
  - 1280 inner PMTs
  - 240 veto PMTS

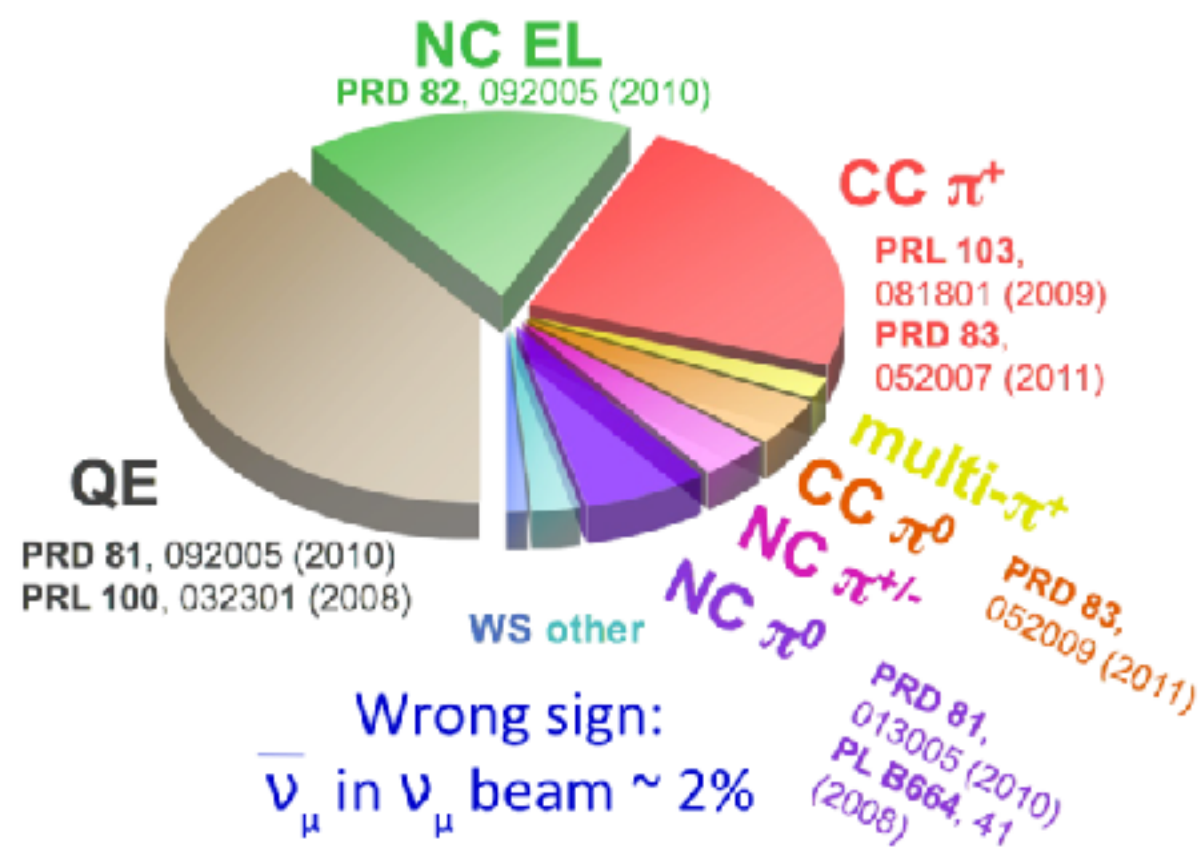
Events in MiniBooNE



- Identified using timing and hit topology
- Use primarily Cherenkov light
- ID based on ratio of fit likelihoods under different particles hypothesis

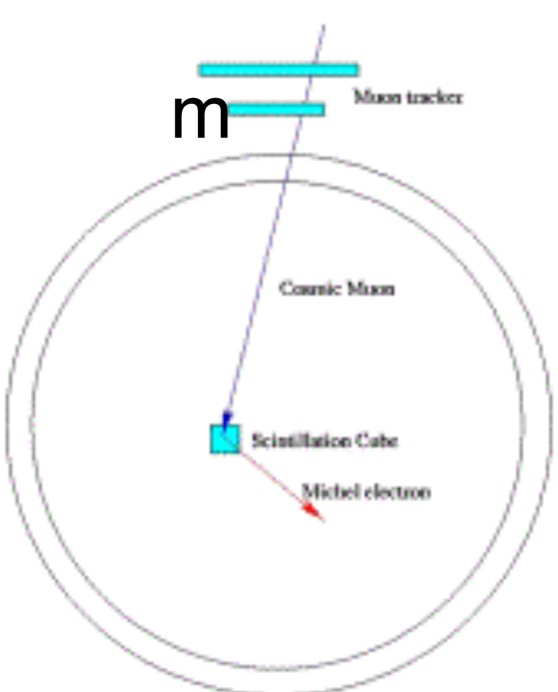
MiniBooNE detector

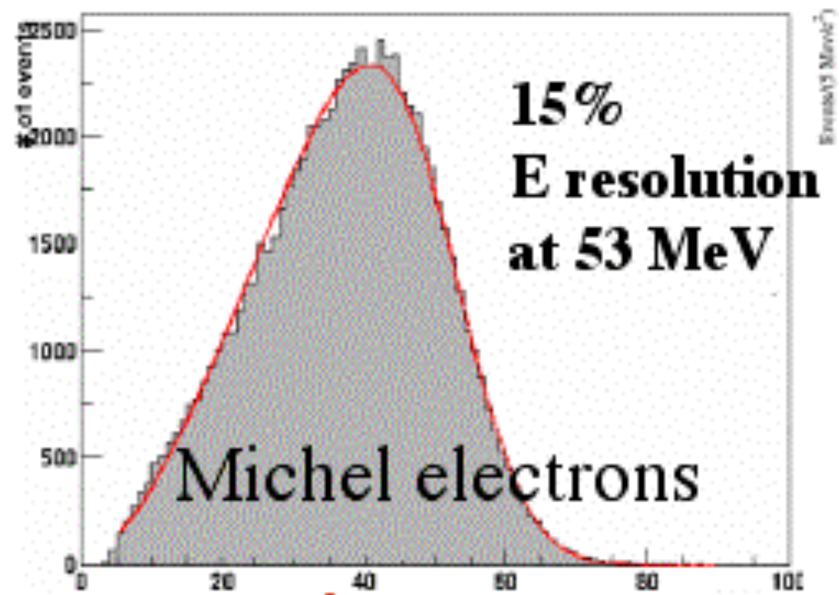
- Well understood detector
- Measured cross sections for most of the channels in neutrino and antineutrino mode
  - For neutrino mode MiniBooNE published cross sections for 90% of neutrino interactions and similarly for antineutrino mode

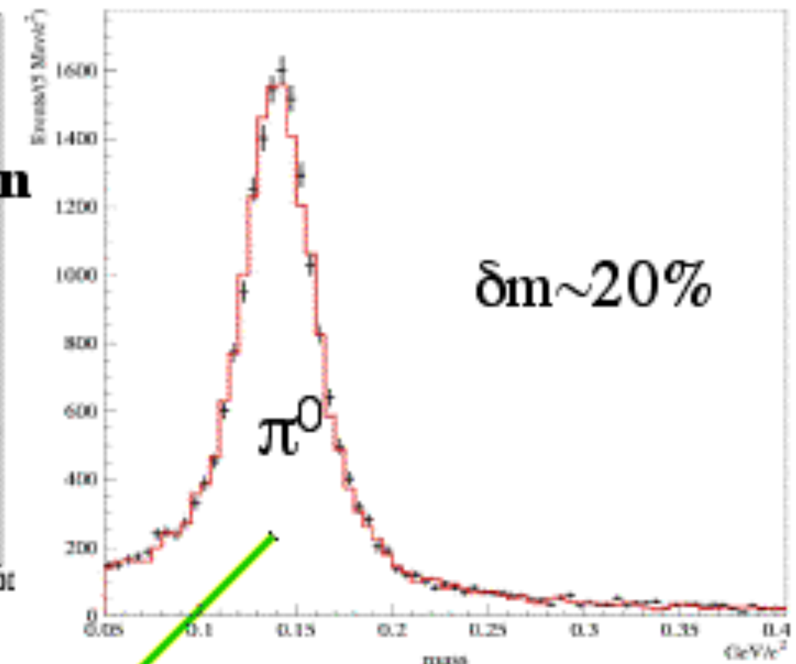


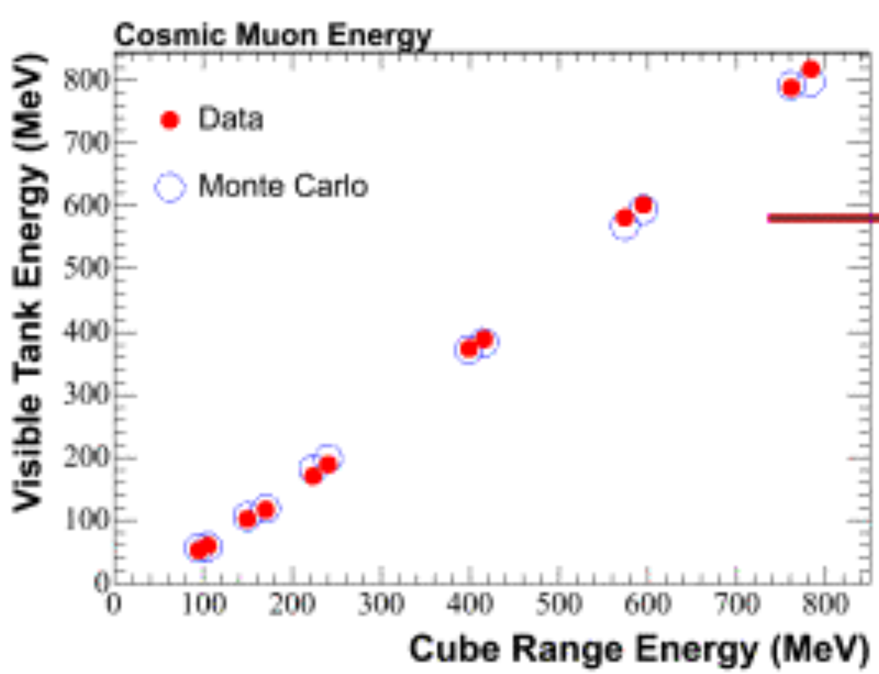
Detector calibration

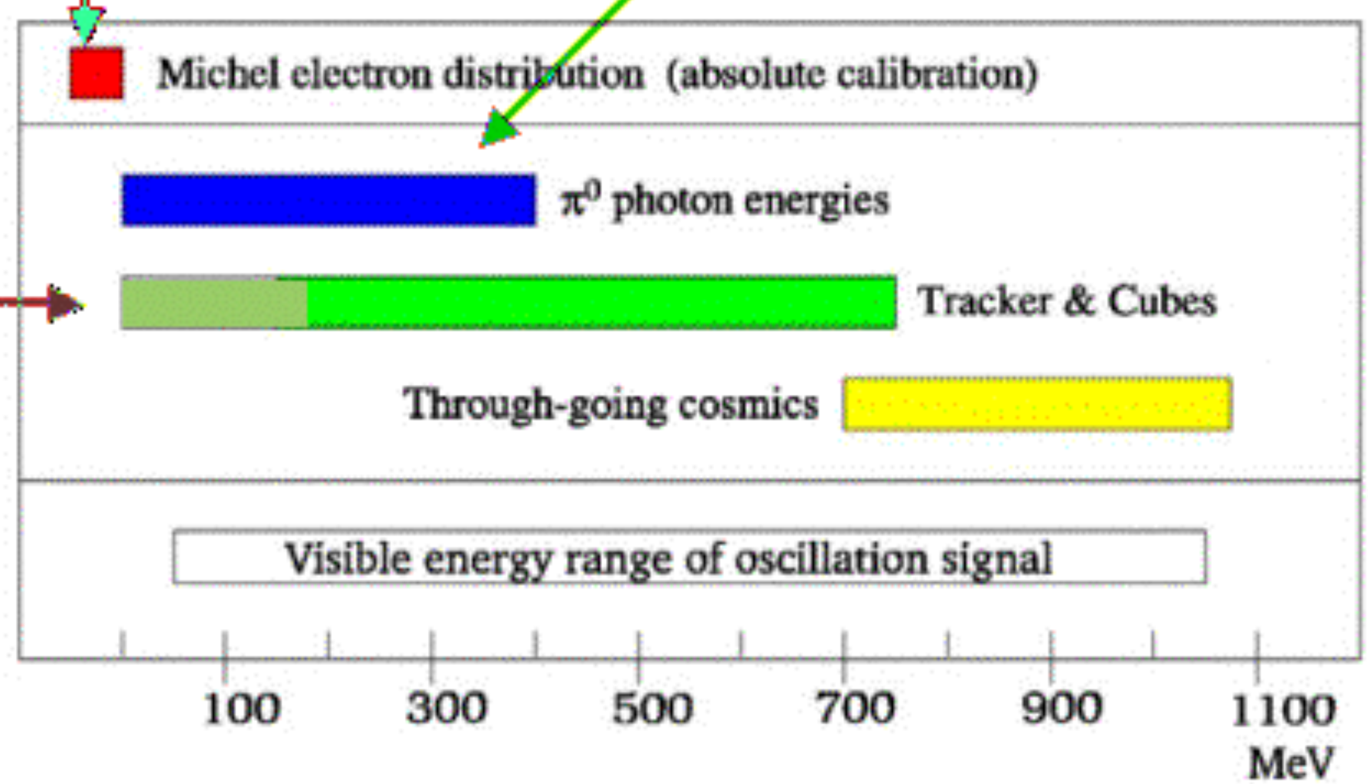
Tracker system



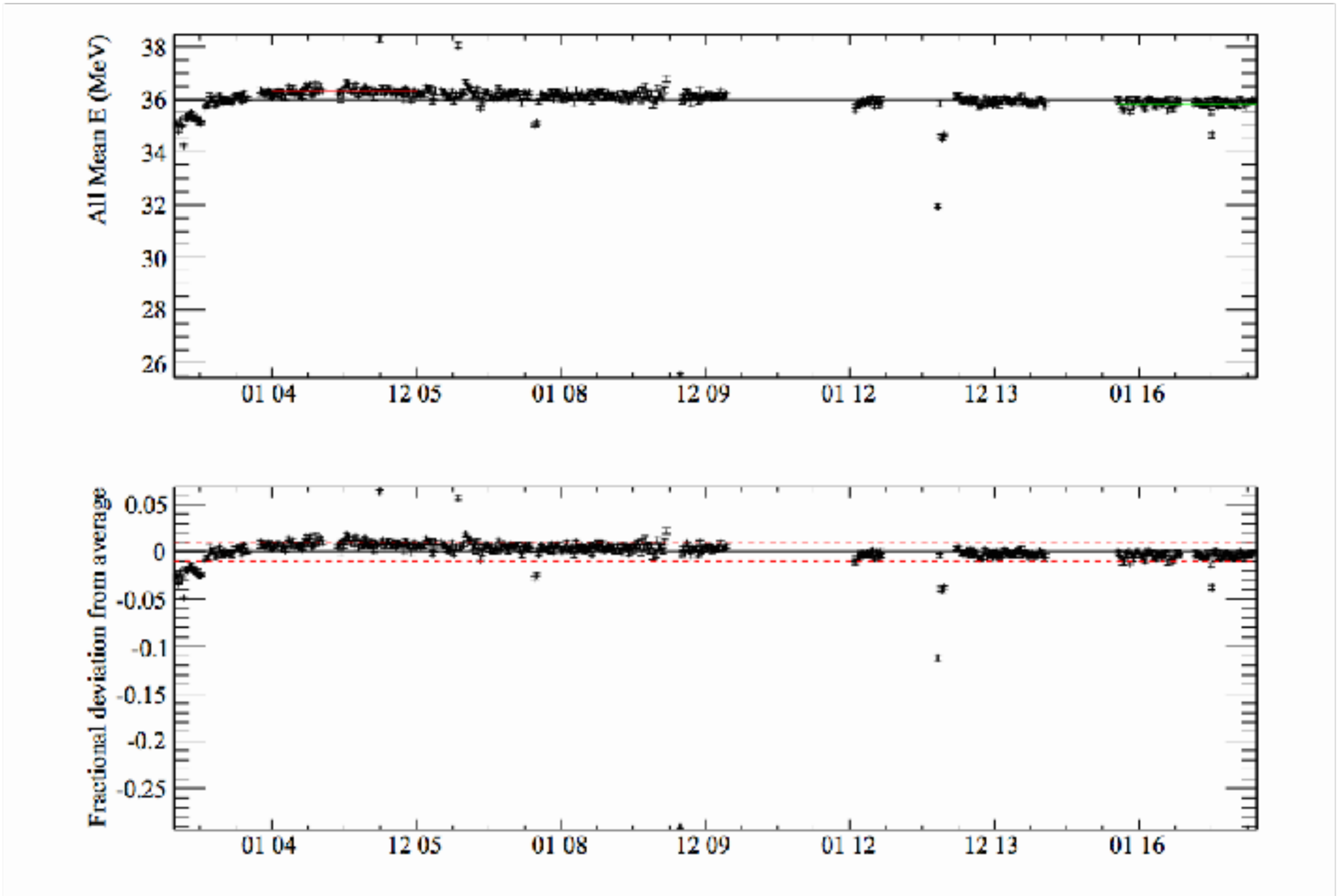






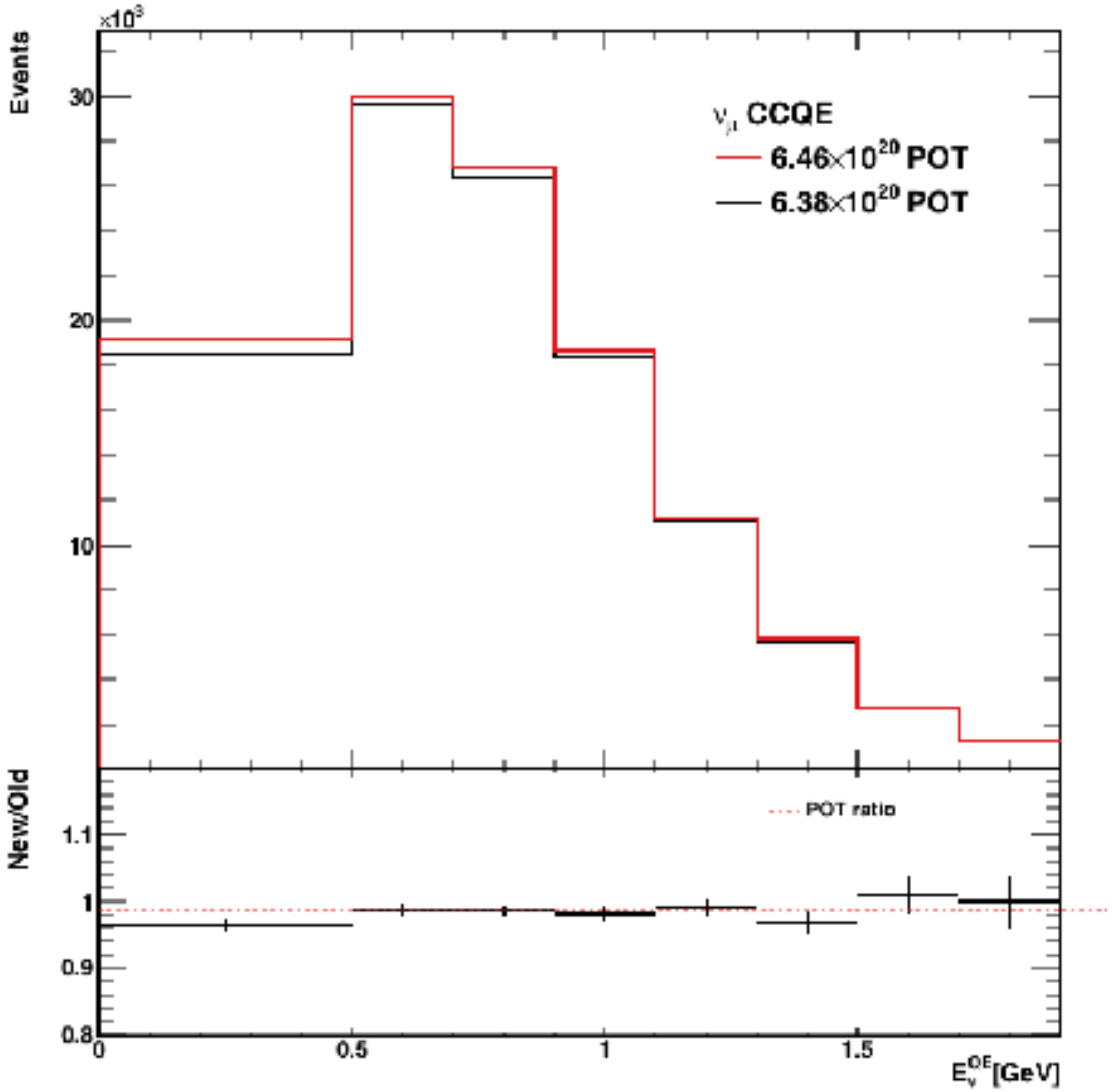


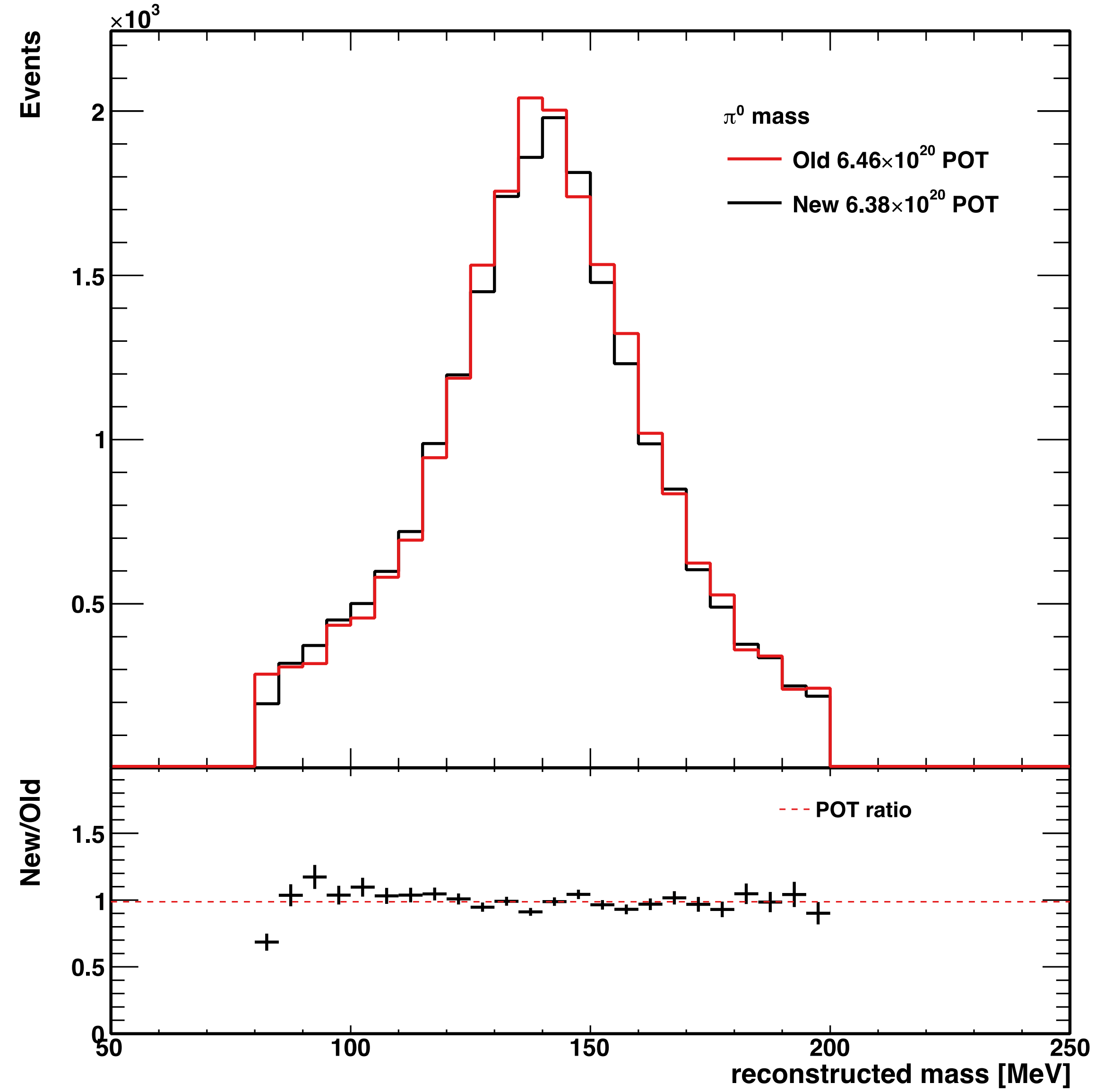
Michel electrons



- Michel electron mean energy over 15+ years of running
- New data set corrected for 2% shift over the whole run

ν_μ CCQE and π^0

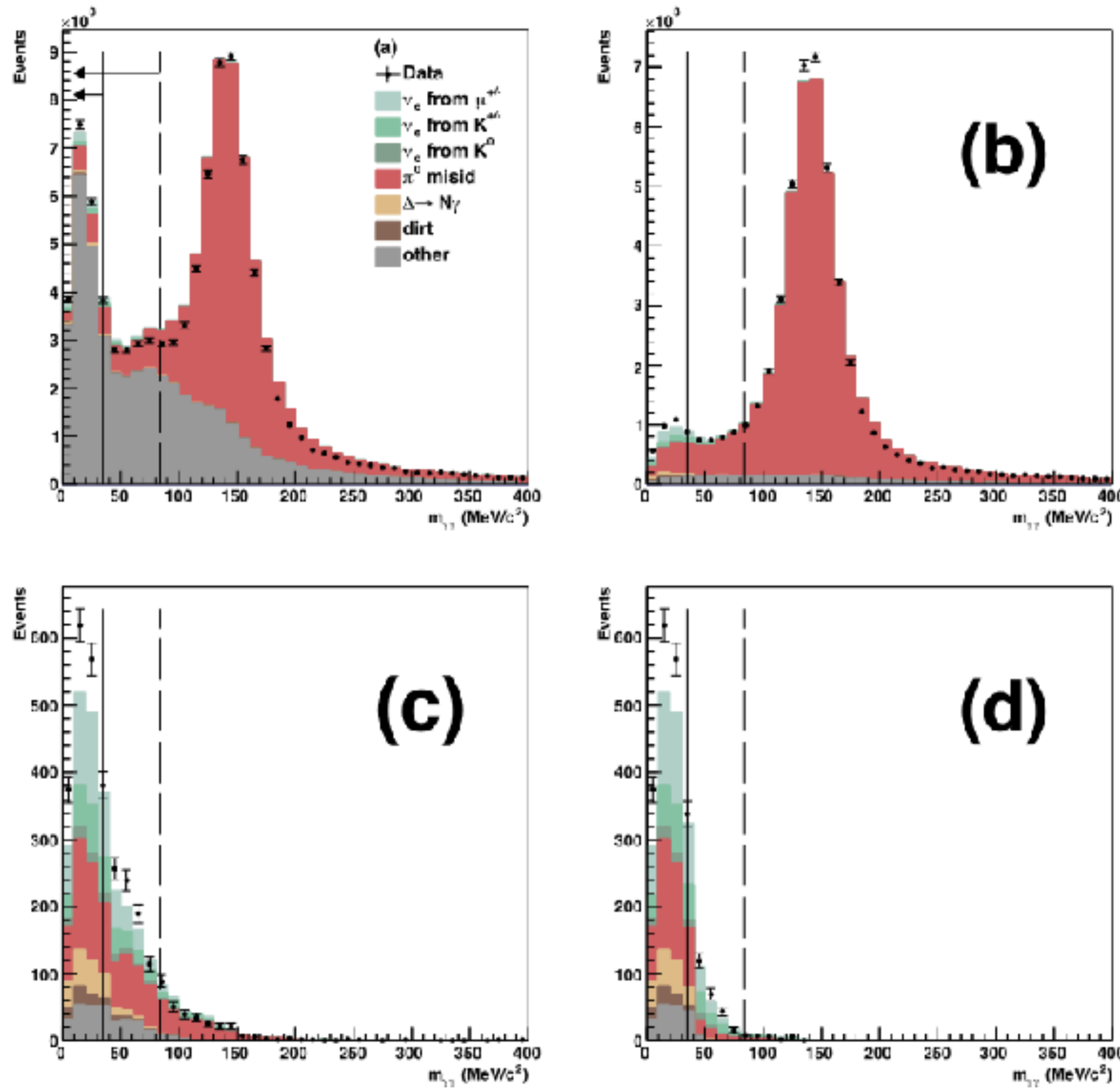




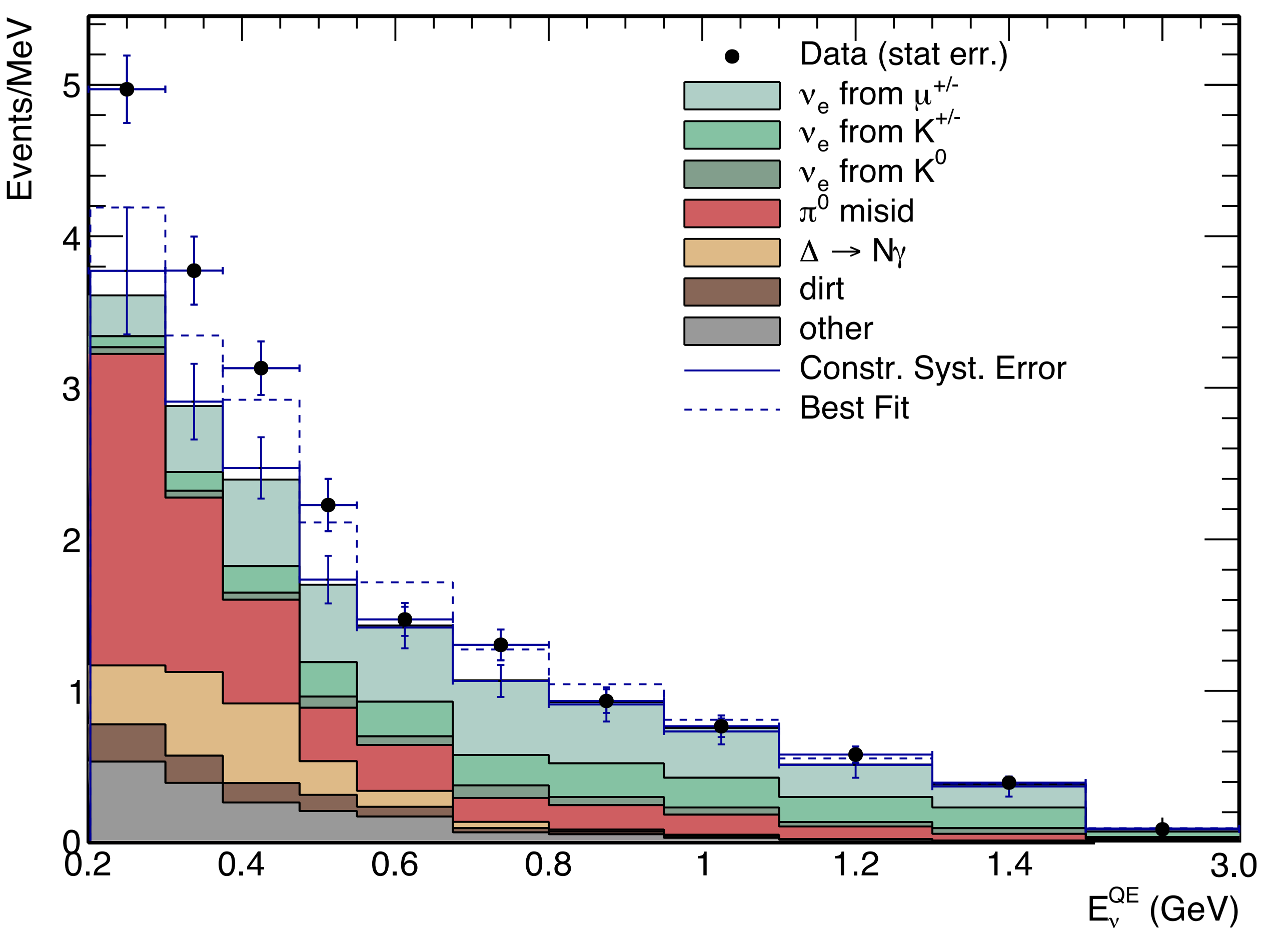
- Detector remains stable within 2% for data sets separated by ~8 years
- 2% energy shift applied to new data

ν_e event selection

- ν_e selection cuts
  a) precuts (remove cosmic backgrounds)
  b) e-μ likelihood
  c) e-π likelihood
  d) $m_{\gamma\gamma}$
- Background outside the oscillation cut window is well modeled by MC



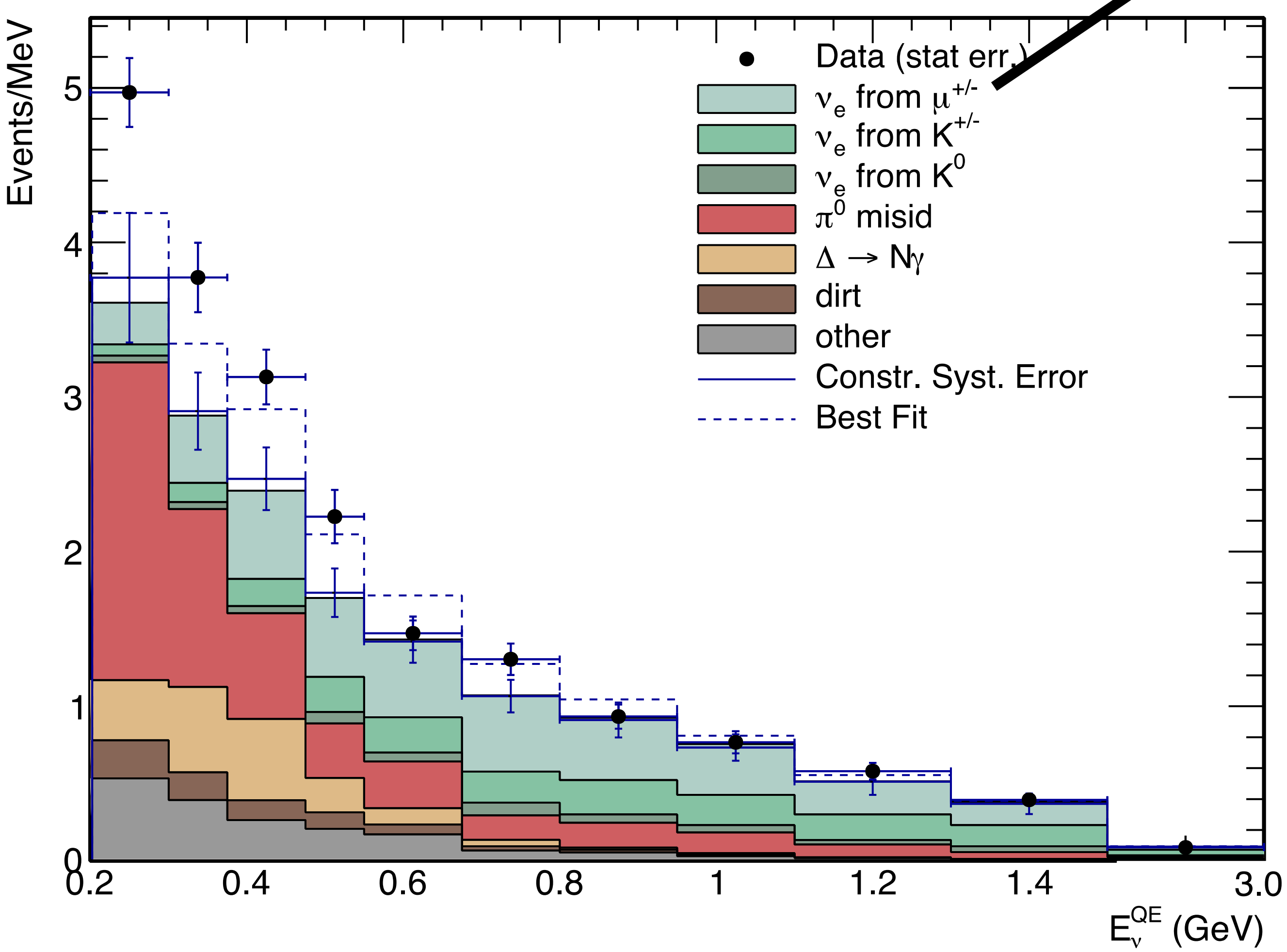
ν_e sample

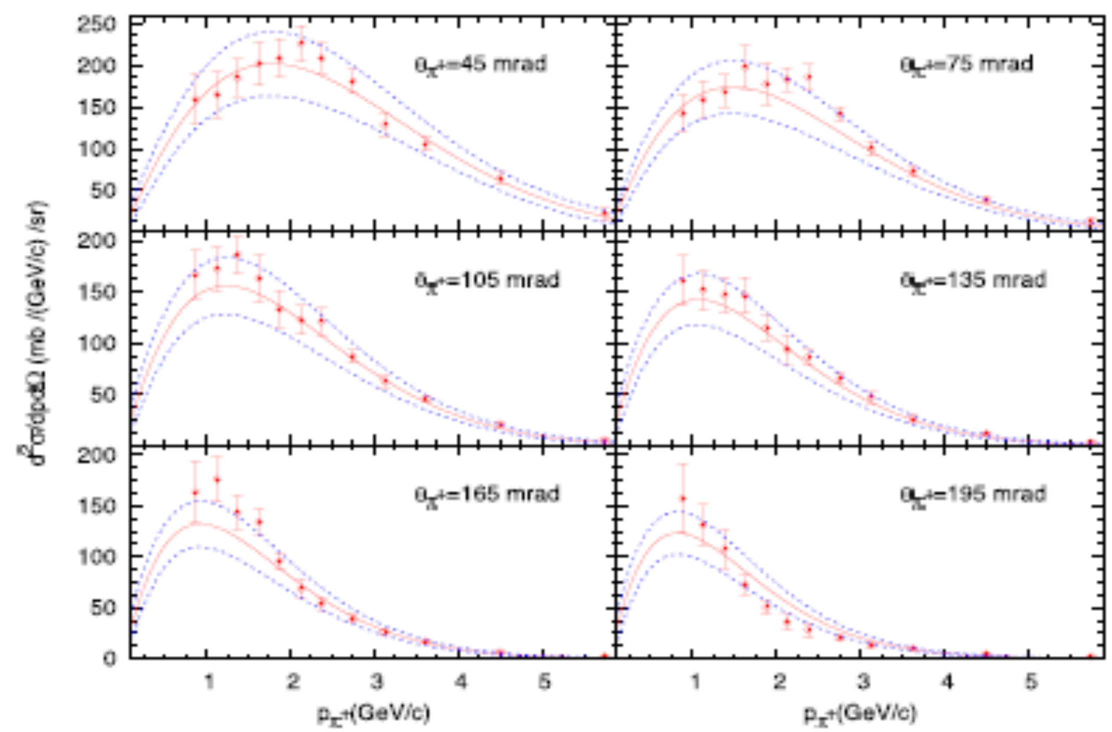


	Process	Neutrino Mode	Antineutrino Mode
misID	ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
	NC π^0	501.5 ± 65.4	112.3 ± 11.5
	NC $\Delta \rightarrow N\gamma$	172.5 ± 24.1	34.7 ± 5.4
	External Events	75.2 ± 10.9	15.3 ± 2.8
	Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
Intrinsic	ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	425.3 ± 100.2	91.4 ± 27.6
	ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	192.2 ± 41.9	51.2 ± 11.0
	ν_e & $\bar{\nu}_e$ from K^0_L Decay	54.5 ± 20.5	51.4 ± 18.0
	Other ν_e & $\bar{\nu}_e$	6.0 ± 3.2	6.7 ± 6.0
	Unconstrained Bkgd.	1590.5 ± 176.9	398.2 ± 49.7
	Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
	Total Data	1959	478
	Excess	381.2 ± 85.2	79.3 ± 28.6
	0.26% (LSND) $\nu_\mu \rightarrow \nu_e$	463.1	100.0

Background prediction

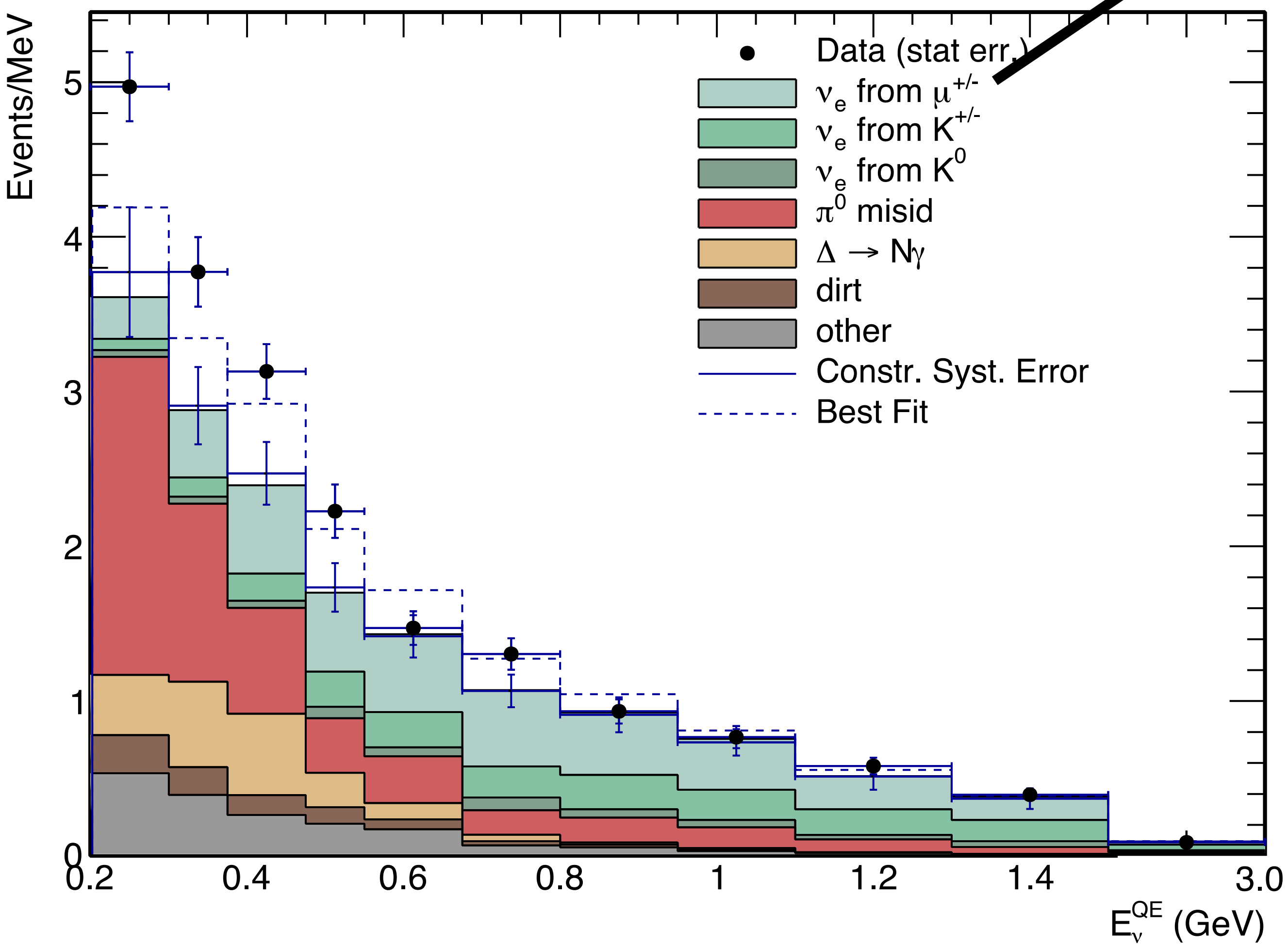
- External measurements - HARP & BNL E910 p+Be -> π±





Phys. Rev. D79, 072002 (2009)

Background prediction



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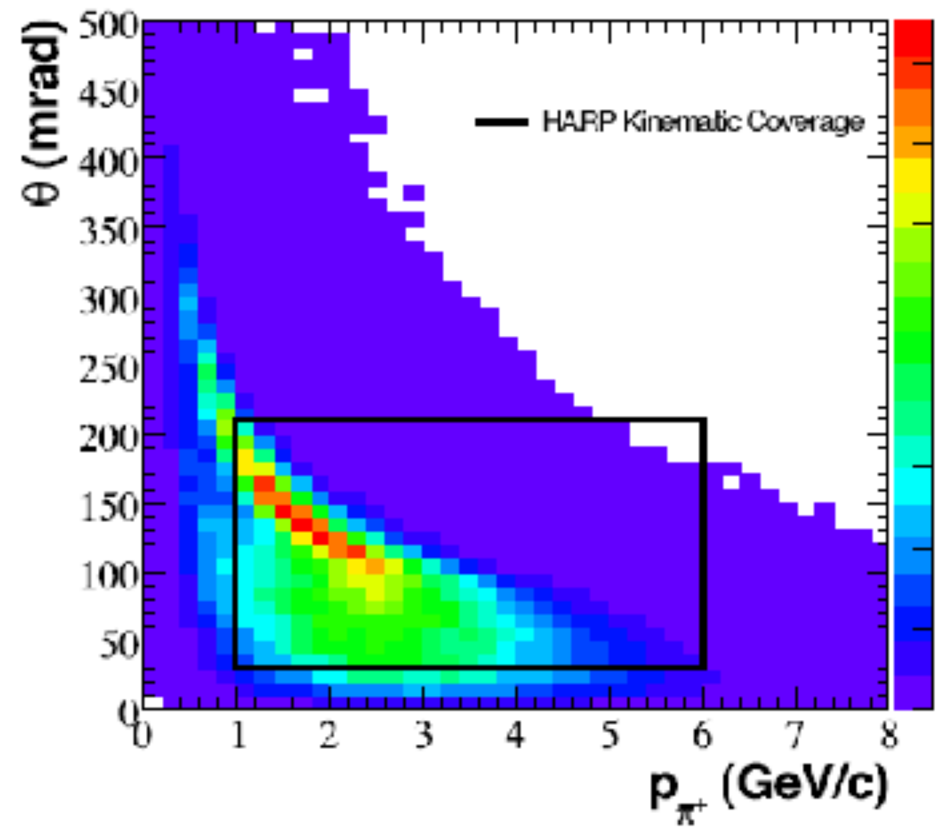
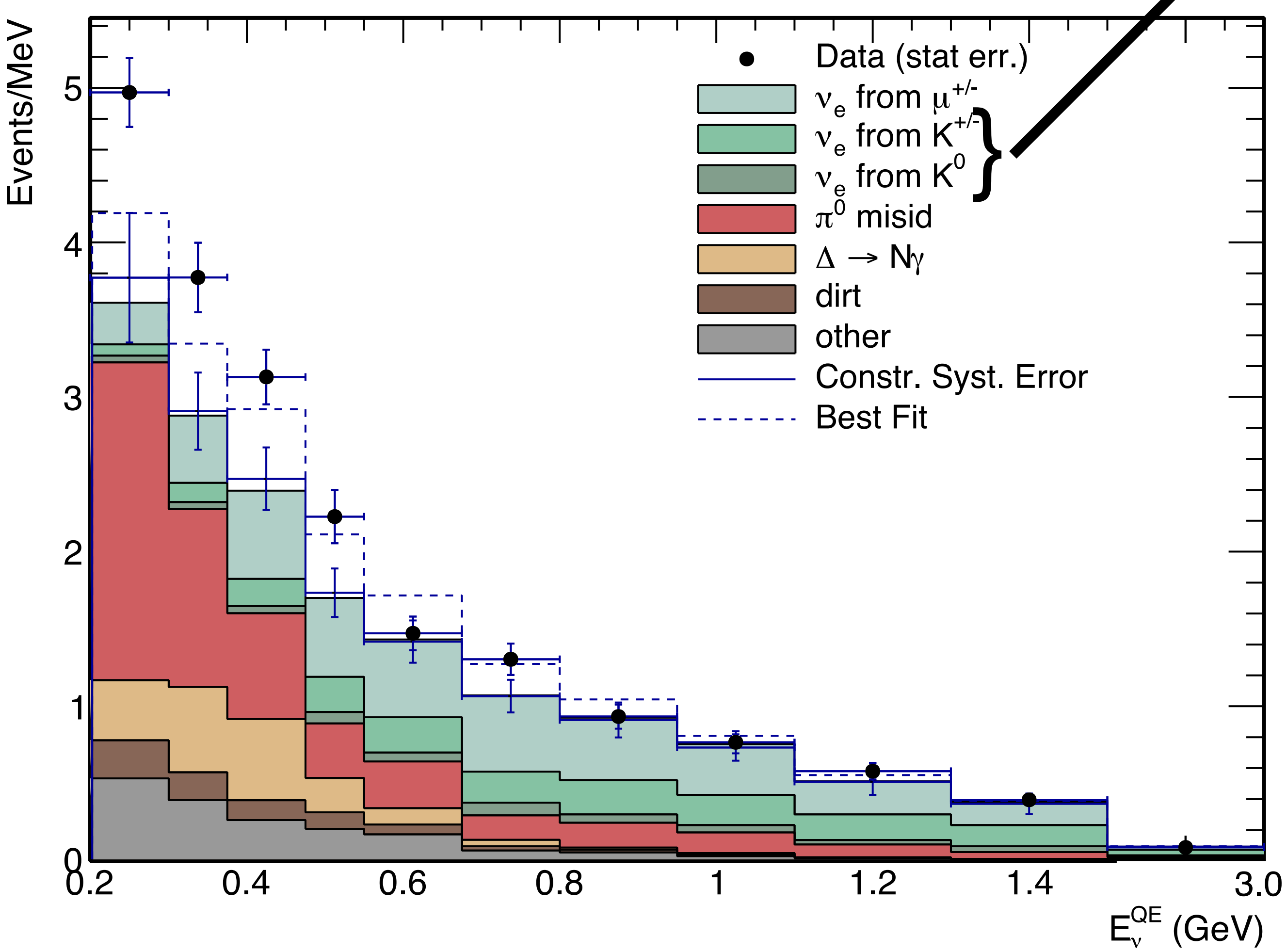


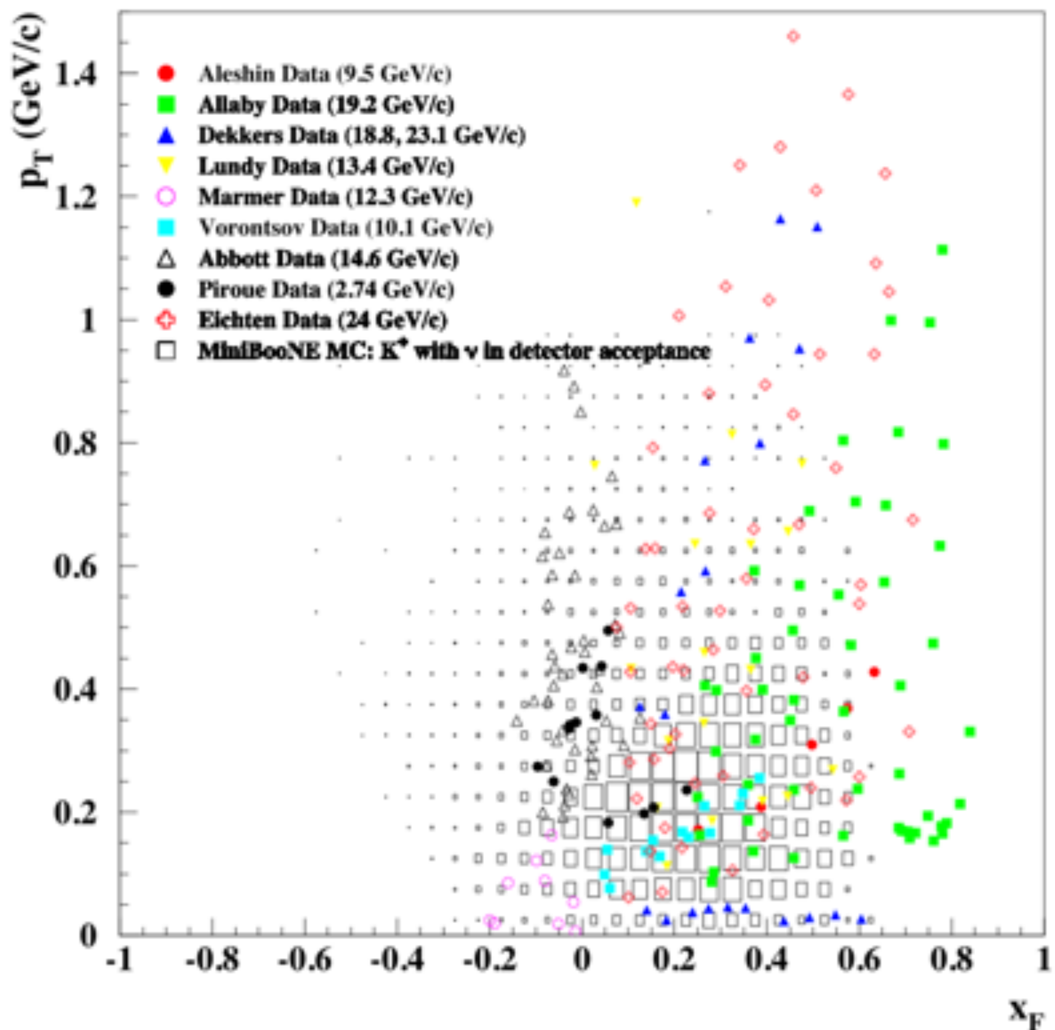
- Covers phase space contributing to 78% of neutrino flux from pi+ (76% from pi- in antineutrino mode)

Phys. Rev. D79, 072002 (2009)

Background prediction



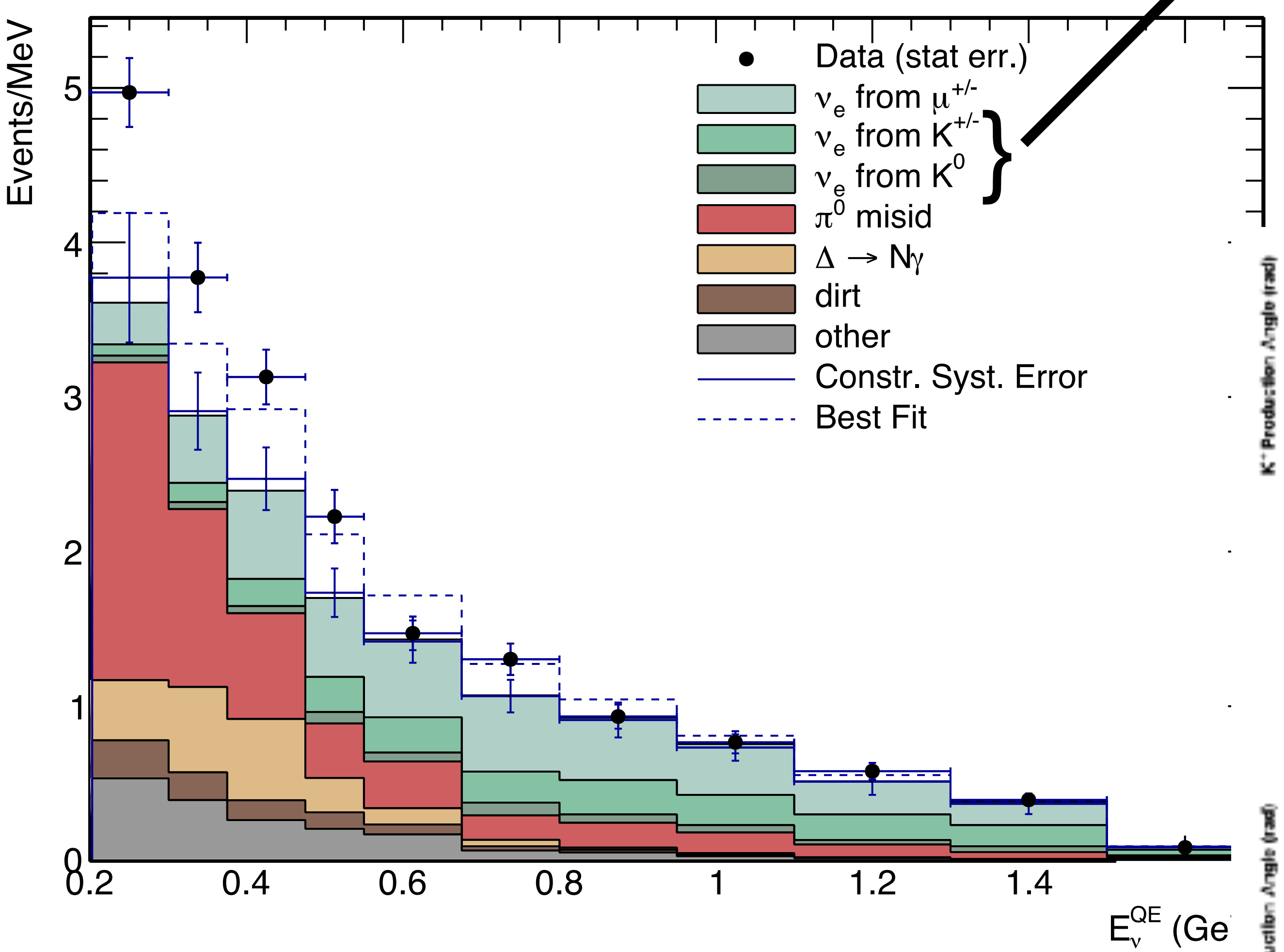
- Feynman scaling and Sanford-Wang fits to world K^+/K^0 data

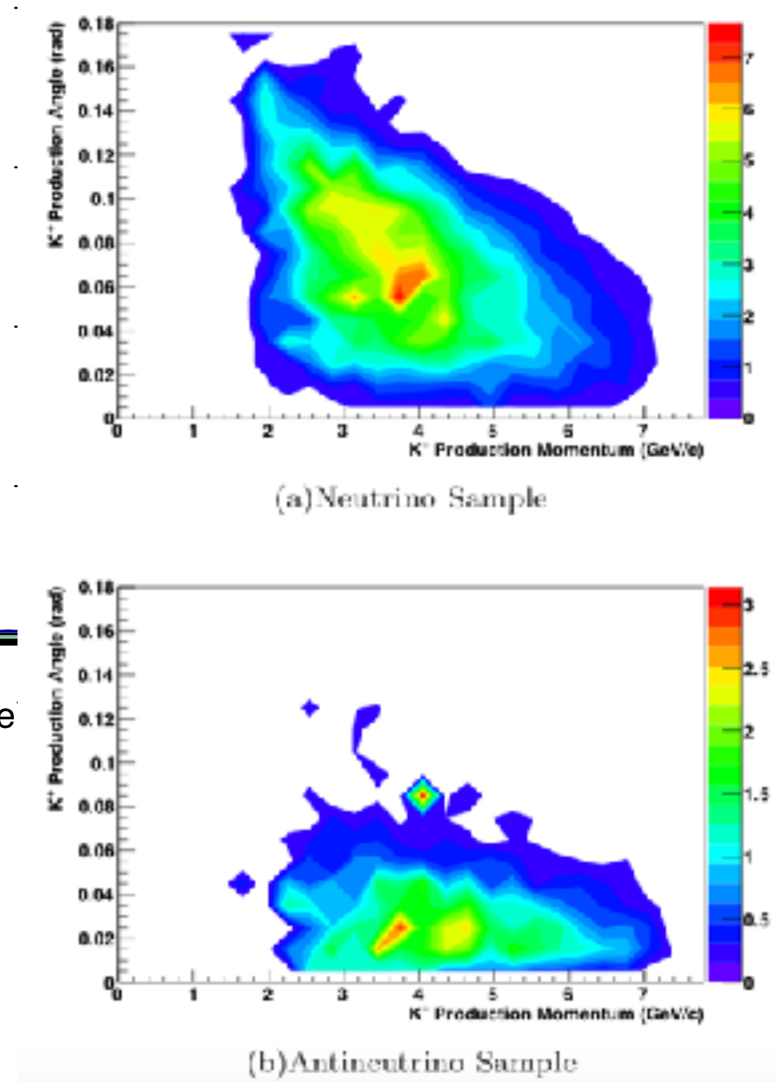


Phys. Rev. D84, 012009 (2011)

Background prediction

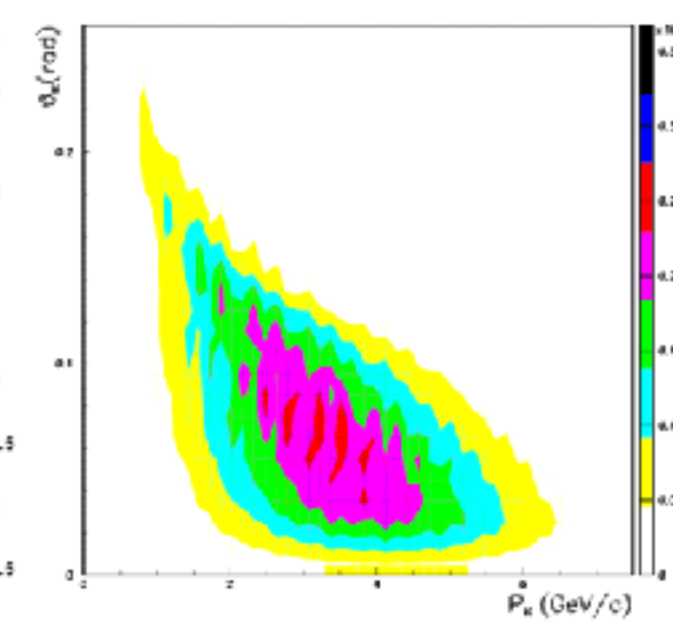
- Feynman scaling and Sanford-Wang fits to world K^+/K^0 data
  - Including the SciBooNE measurement of charged kaons in BNB





(a) Neutrino Sample

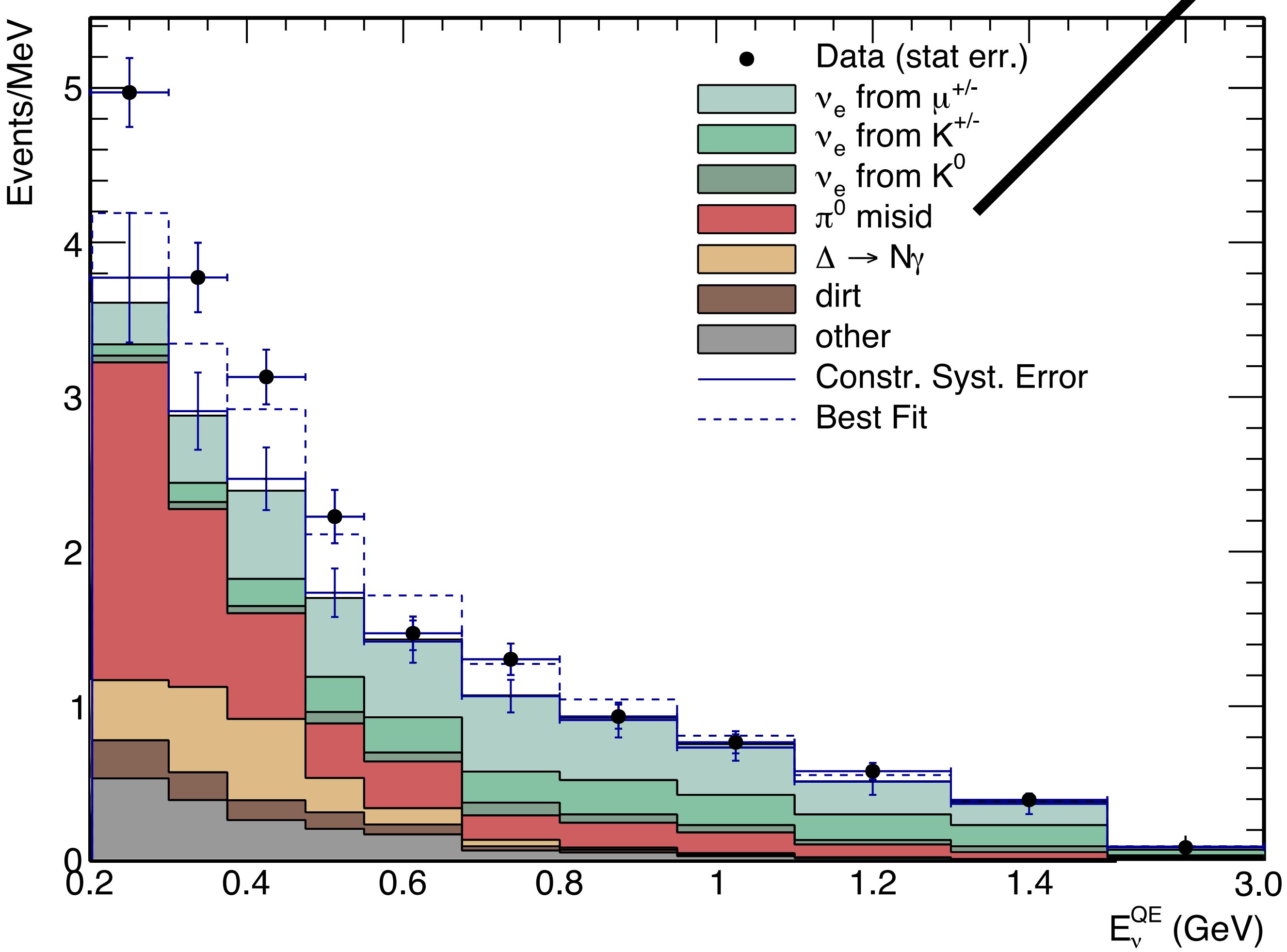
(b) Antineutrino Sample

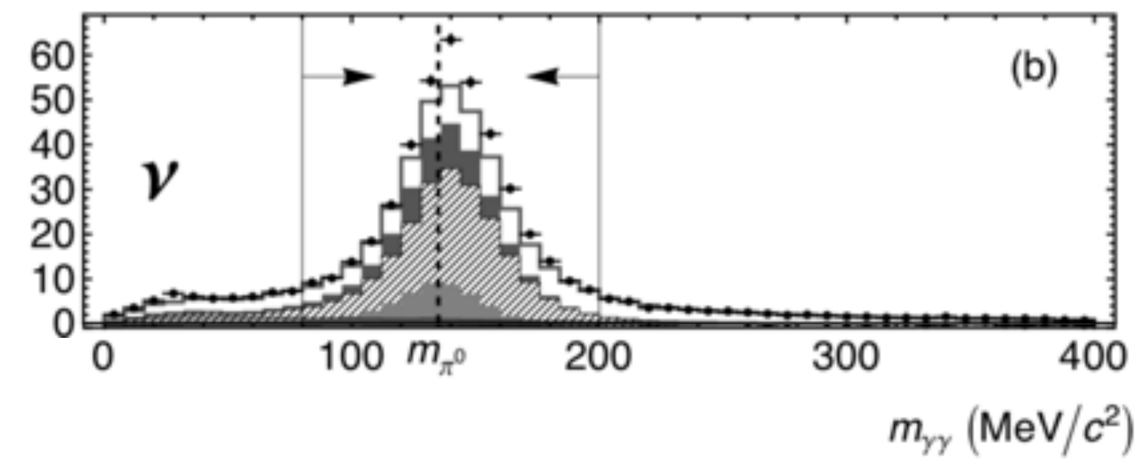


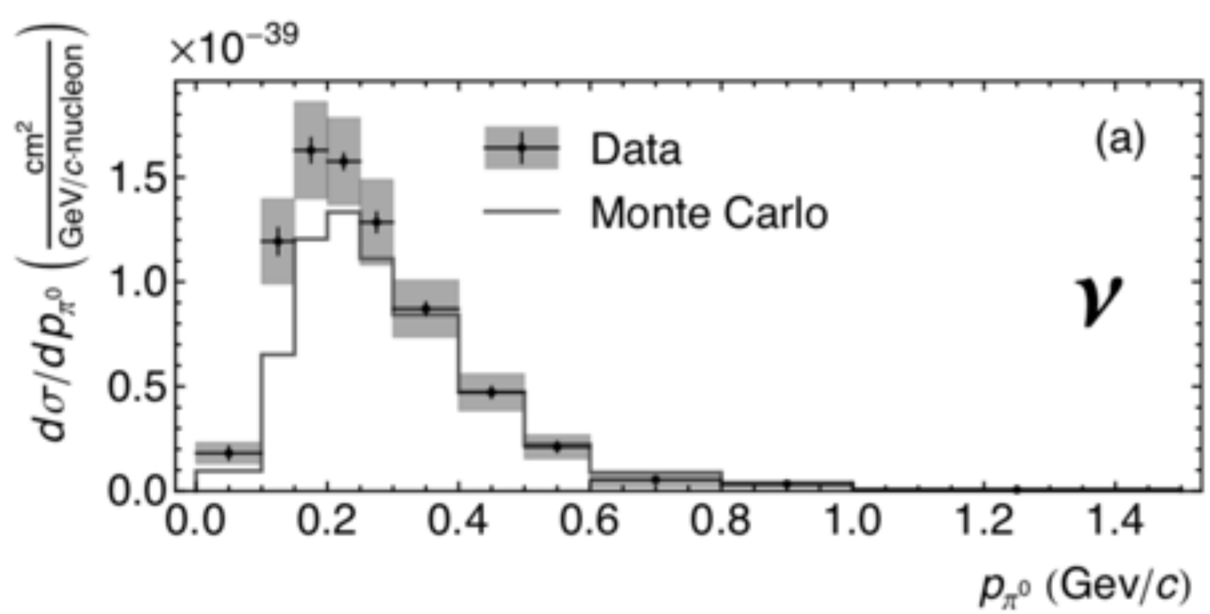
Phys. Rev. D84, 012009 (2011)

Background prediction

NC π^0 MiniBooNE measurement

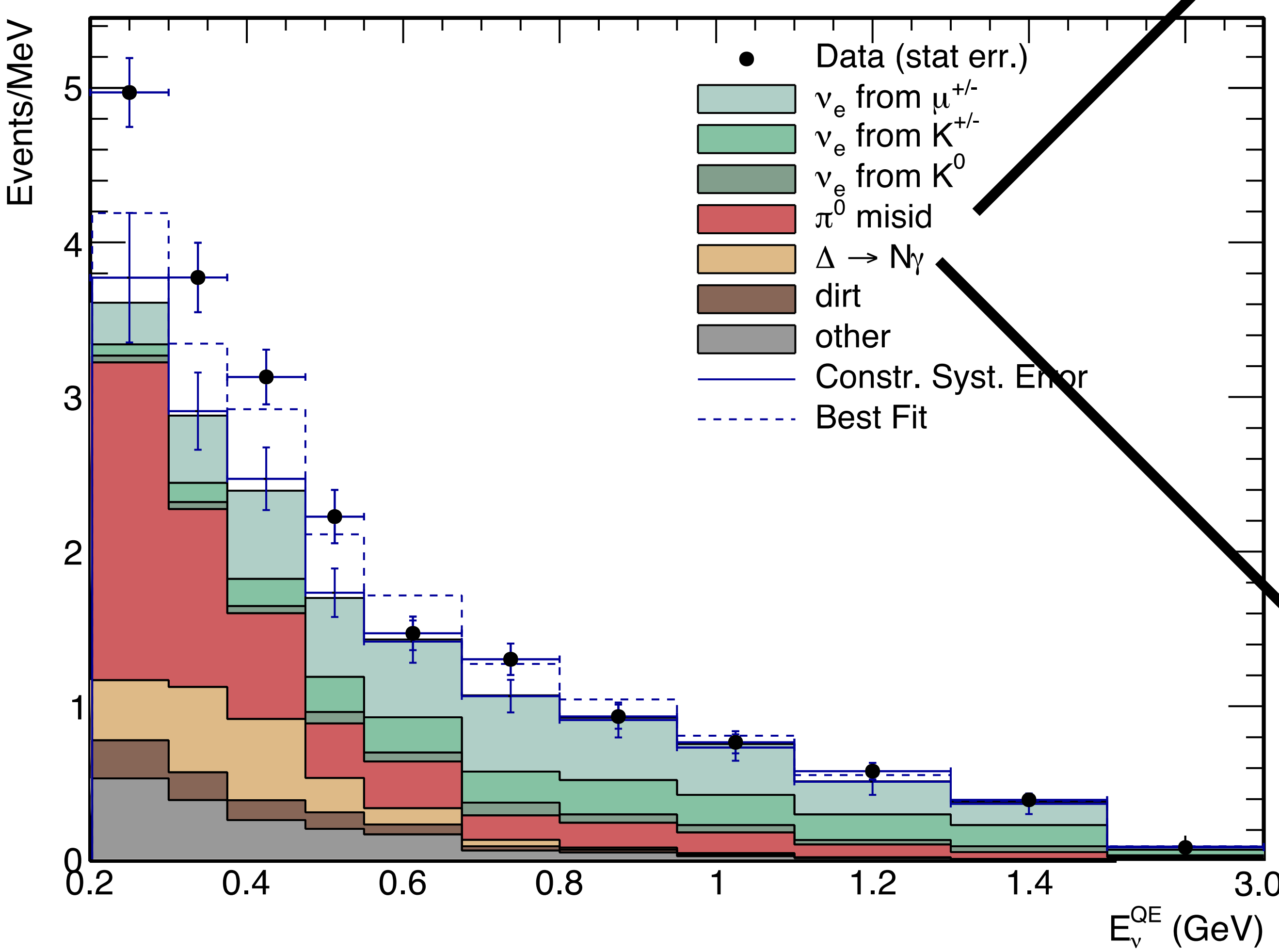






Phys. Rev. D81, 013005 (2010)

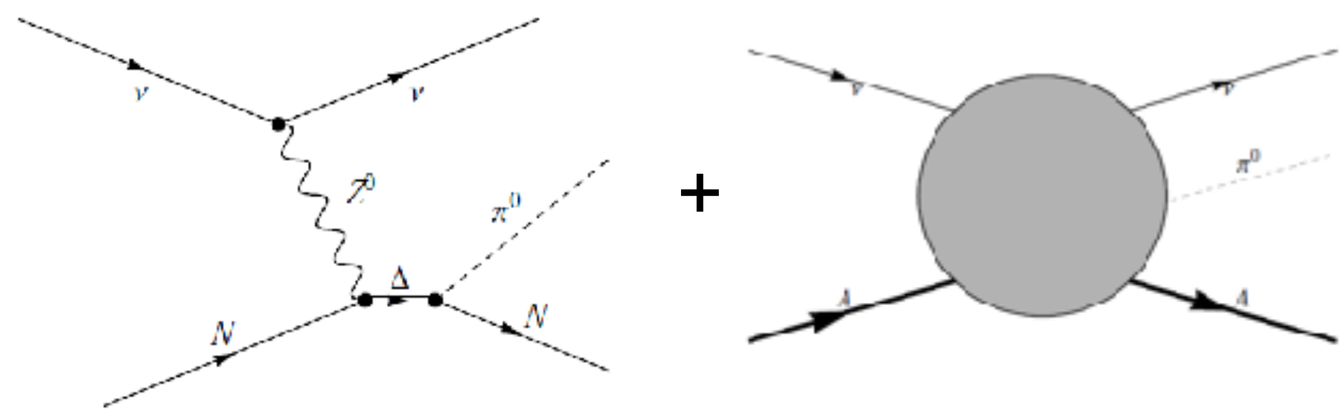
Background prediction



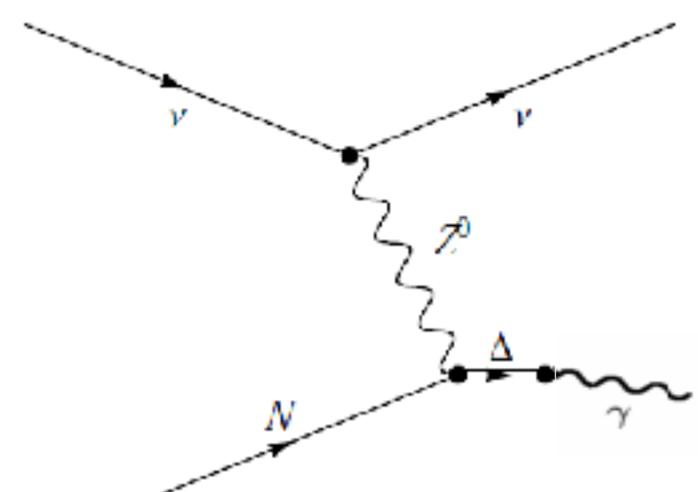
- NC π^0 MiniBooNE measurement

Resonant (~80%)

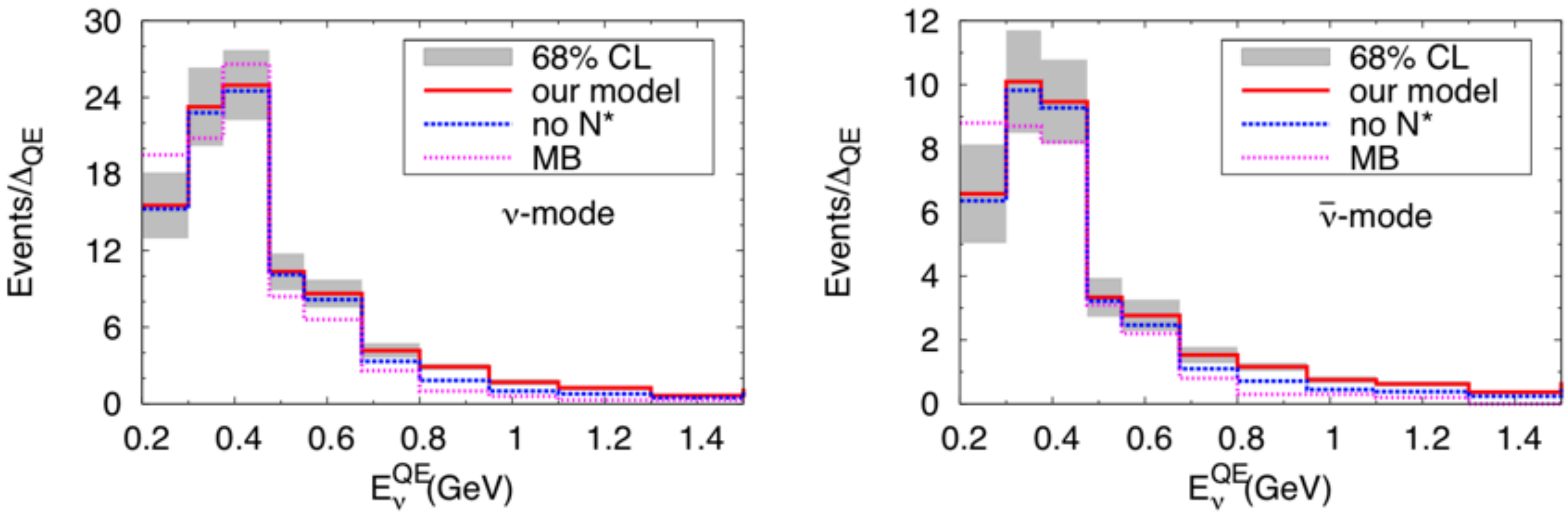
Coherent (~20%)



- Constrain radiative Δ decays



NC gamma

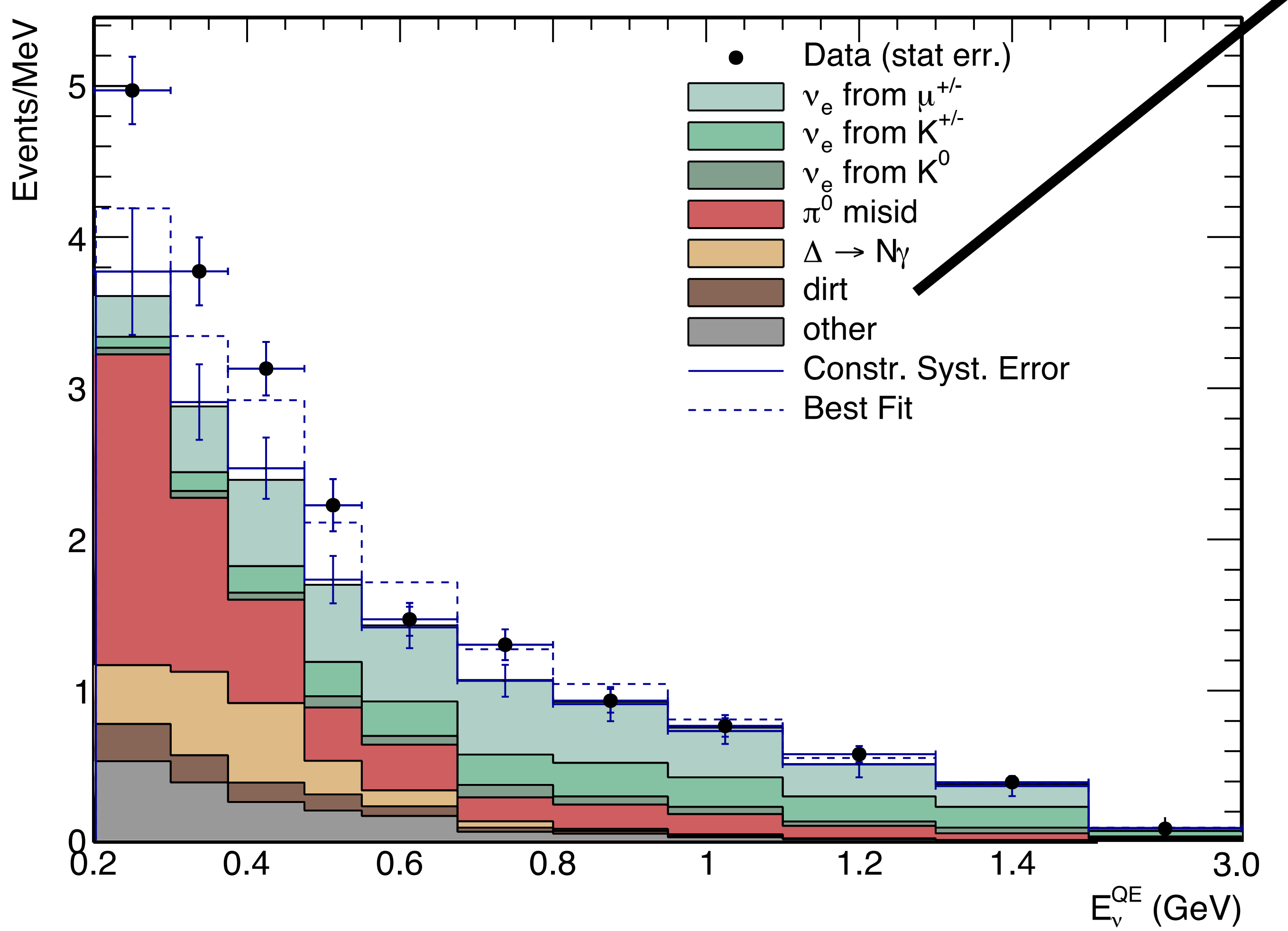


Phys. Lett. B740, 16 (2015).

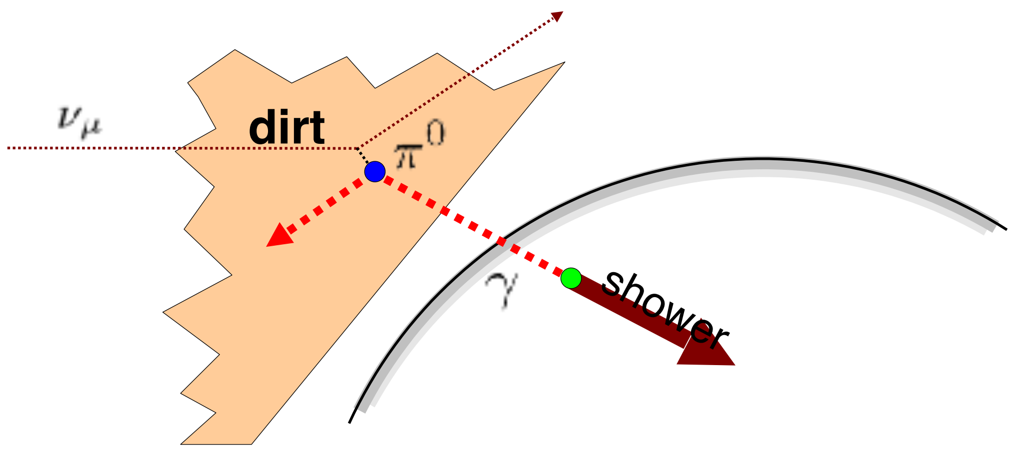
- Several theoretical calculations:
  - Computed event rates in neutrino and antineutrino mode consistent with MiniBooNE estimate

[2] E. Wang, L. Alvarez-Ruso and J. Nieves, Phys.Rev. C89, (2014)015503 [arXiv:1311.2151]
[3] R. J. Hill, Phys.Rev. D81, (2010)013008 [arXiv:0905.0291]
[4] X. Zhang, B. D. Serot, Phys.Lett. B719, (2013)409 [arXiv:1210.3610]
[10] Y. Hayato, Acta Phys.Polon. B40 (2009)2477
[11] C. Andreopoulos *et al.* Nucl.Instrum.Meth. A614 (2010)87 [arXiv:0905.2517]
[12] D. Casper, Nucl.Phys.Proc.Suppl. 112 (2002)161 [arXiv:0208030]

Background prediction



- Dirt:

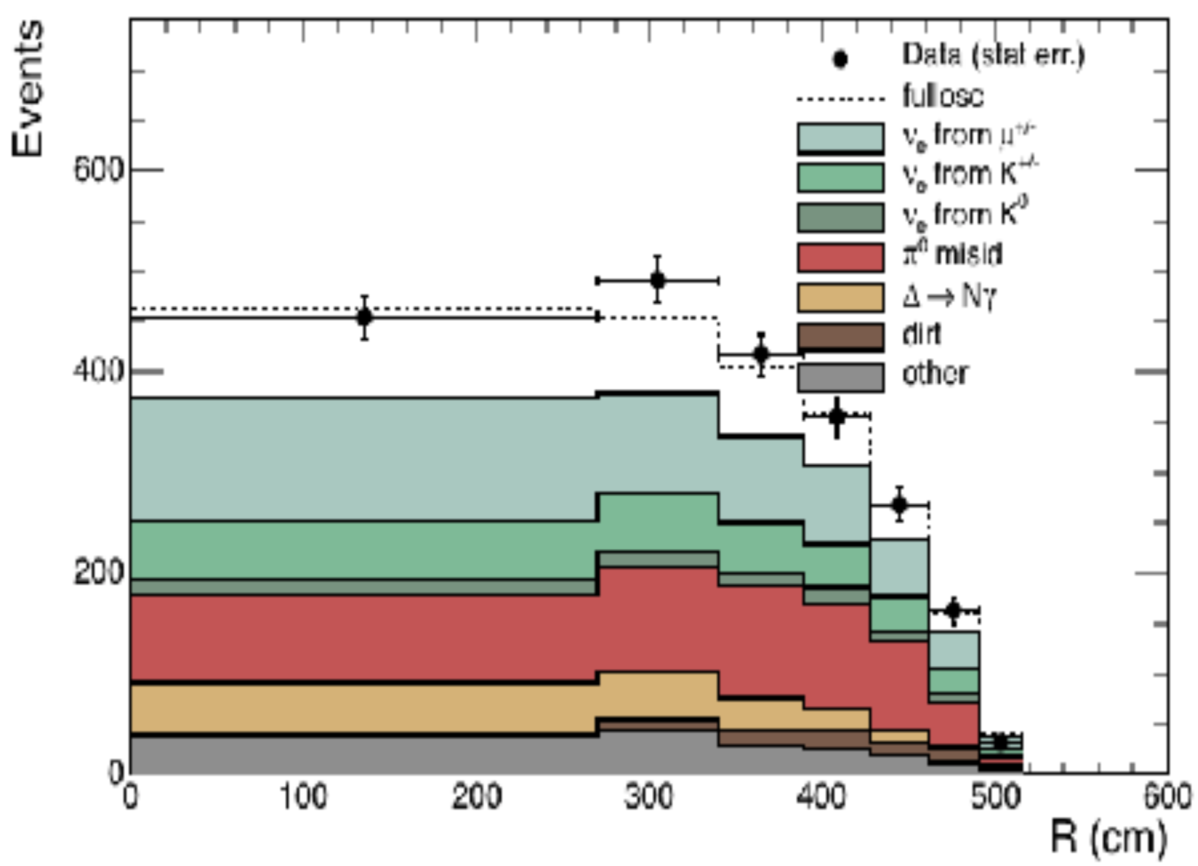


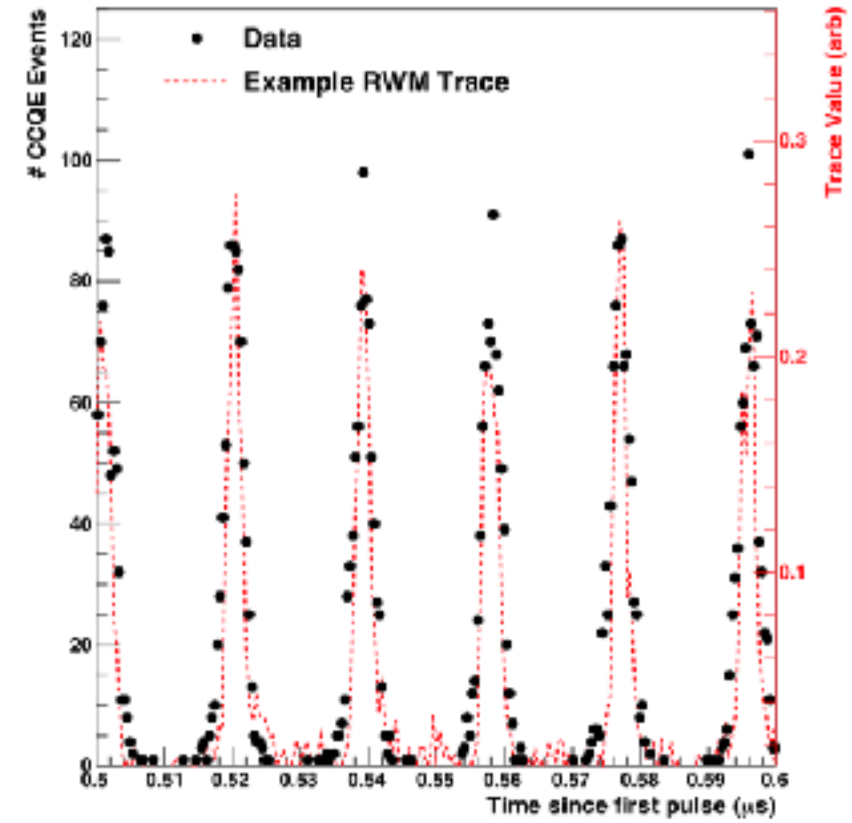
- Events at high R pointing toward center of detector
- MiniBooNE measurement using dirt enhanced sample

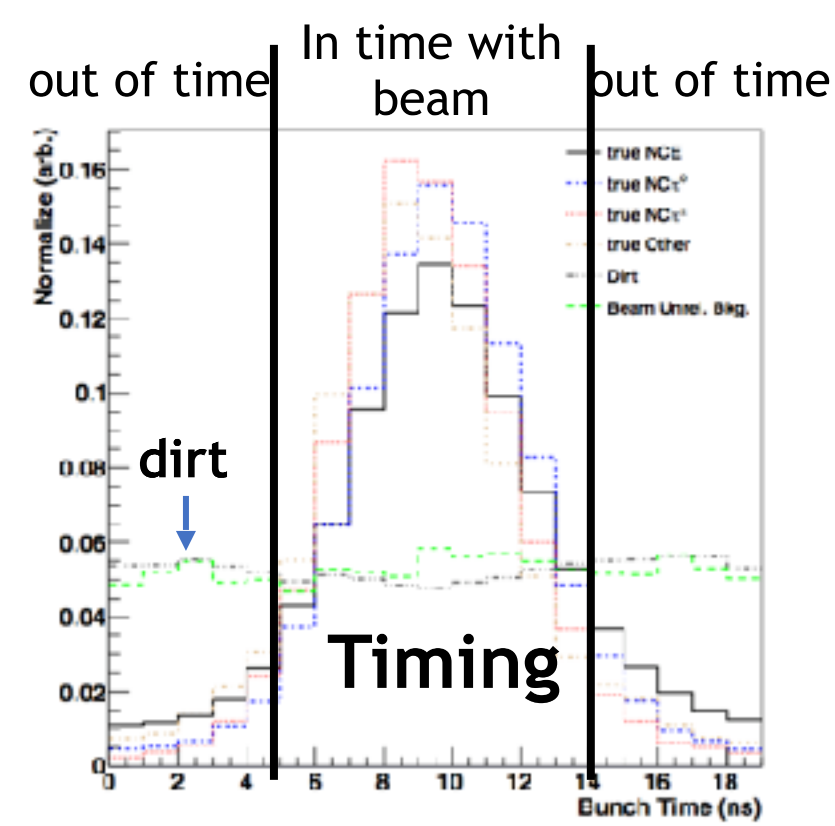
Dirt

- Inward going events on the boundary

- Excess spread over all the detector, not just edge of detector

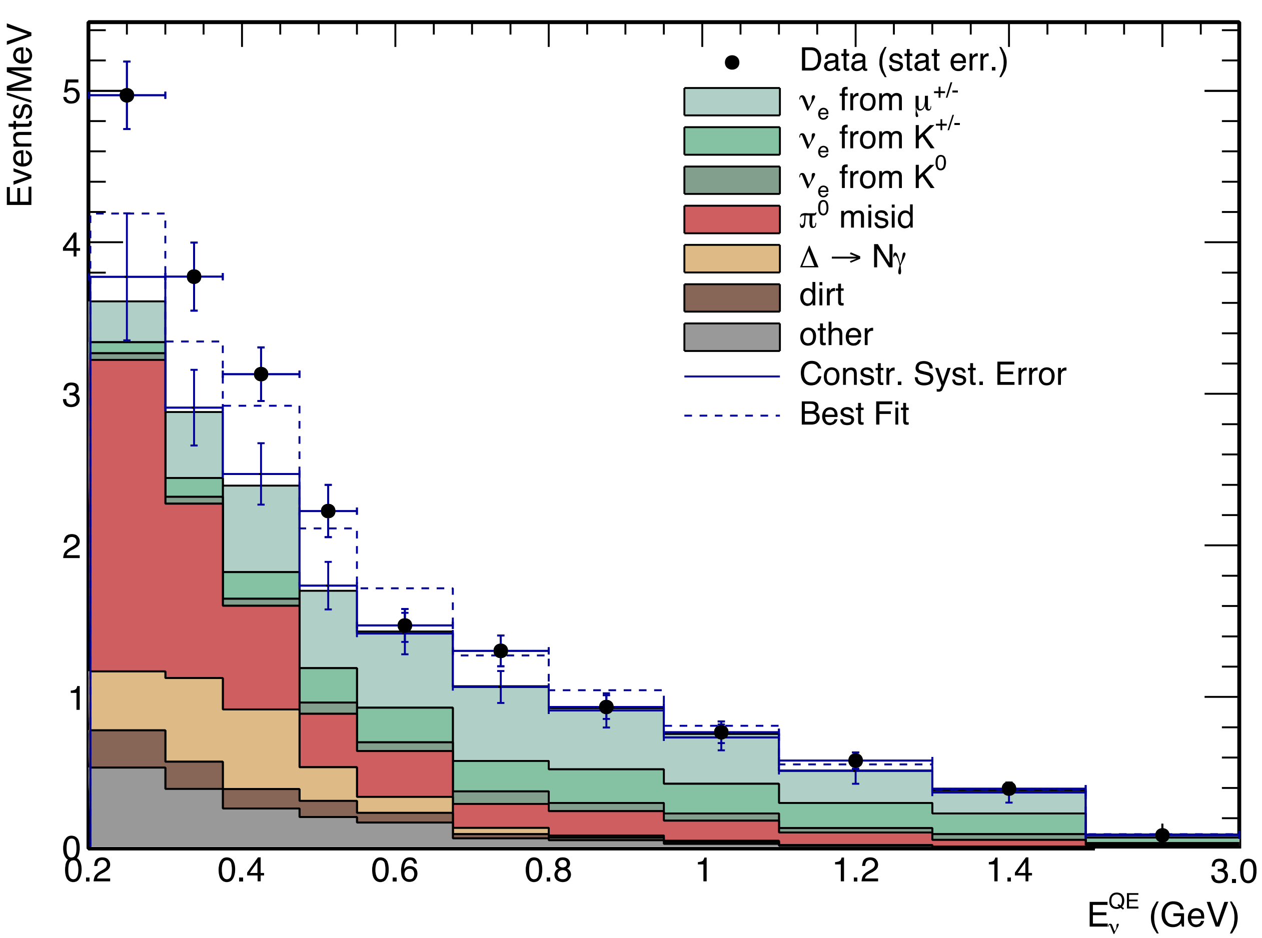






Background prediction

- With all the inputs listed so far systematic error on background is ~11% (unconstrained error)
- Dominant errors from cross-section, flux, and optical model
- Final constraint comes from simultaneous fit to ν_μ CCQE sample



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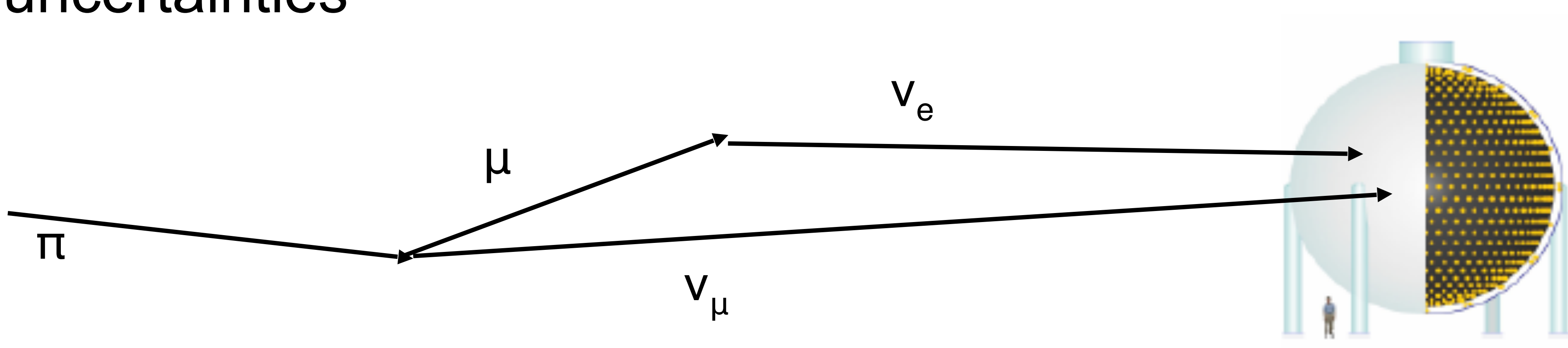
	Total Data	1959	478
	Excess	381.2 ± 85.2	79.3 ± 28.6
	0.26% (LSND) $\nu_\mu \to \nu_e$	463.1	100.0

Oscillation Fit Method

- Maximum likelihood fit:

$$-2\ln(L) = (x_1 - \mu_1, ...x_n - \mu_n)M^{-1}(x_1 - \mu_1, ...x_n - \mu_n)^T + \ln(|M|)$$

- Simultaneously fit
  - ν_e CCQE sample
  - High statistics ν_μ CCQE sample
- ν_μ CCQE sample constrains many of the uncertainties:
  - Flux uncertainties

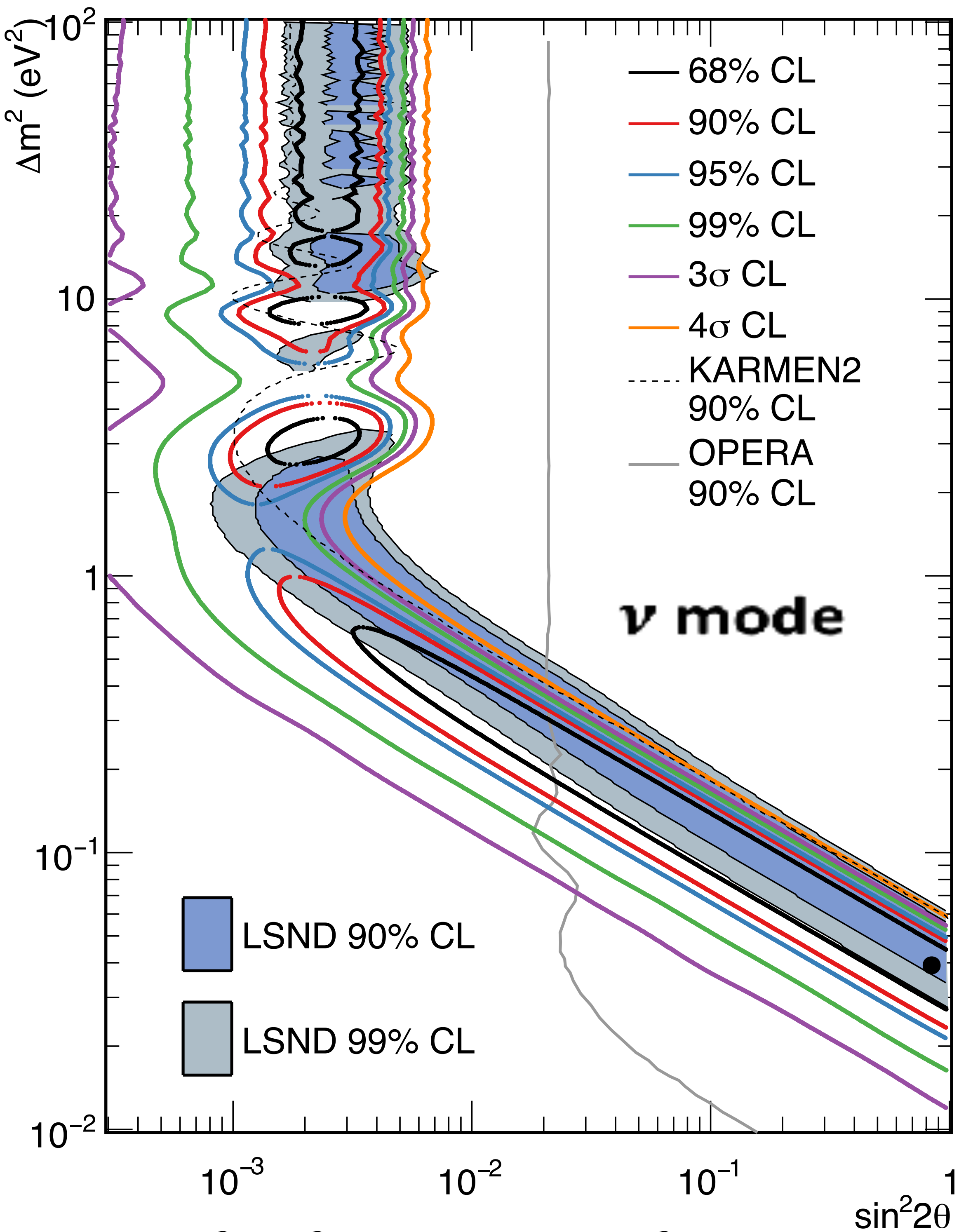


  - Cross section uncertainties

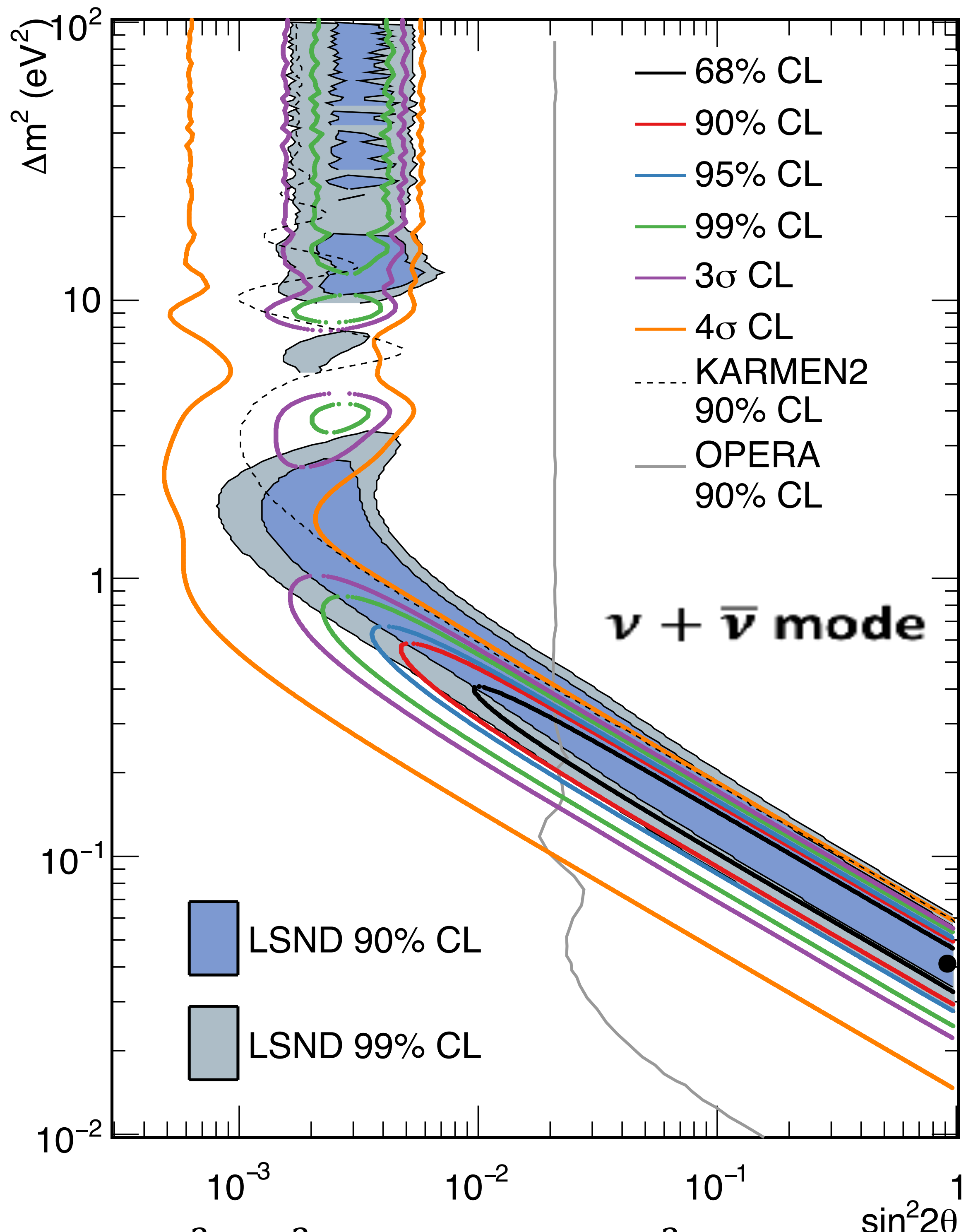
Event excess

	ν mode 12.84×10^{20} POT	$\bar{\nu}$ mode 11.27×10^{20} POT	Combined
Data	1959	478	2437
Unconstrained Background	1590.5	398.2	1988.7
Constrained Background	1577.8	398.7	1976.5
Excess	381.2 ± 85.2 4.5σ	79.3 ± 28.6 2.8σ	460.5 ± 99.0 4.7σ
0.26% (LSND) $\nu_\mu \rightarrow \nu_e$	463.1	100.0	563.1

Two-neutrino model

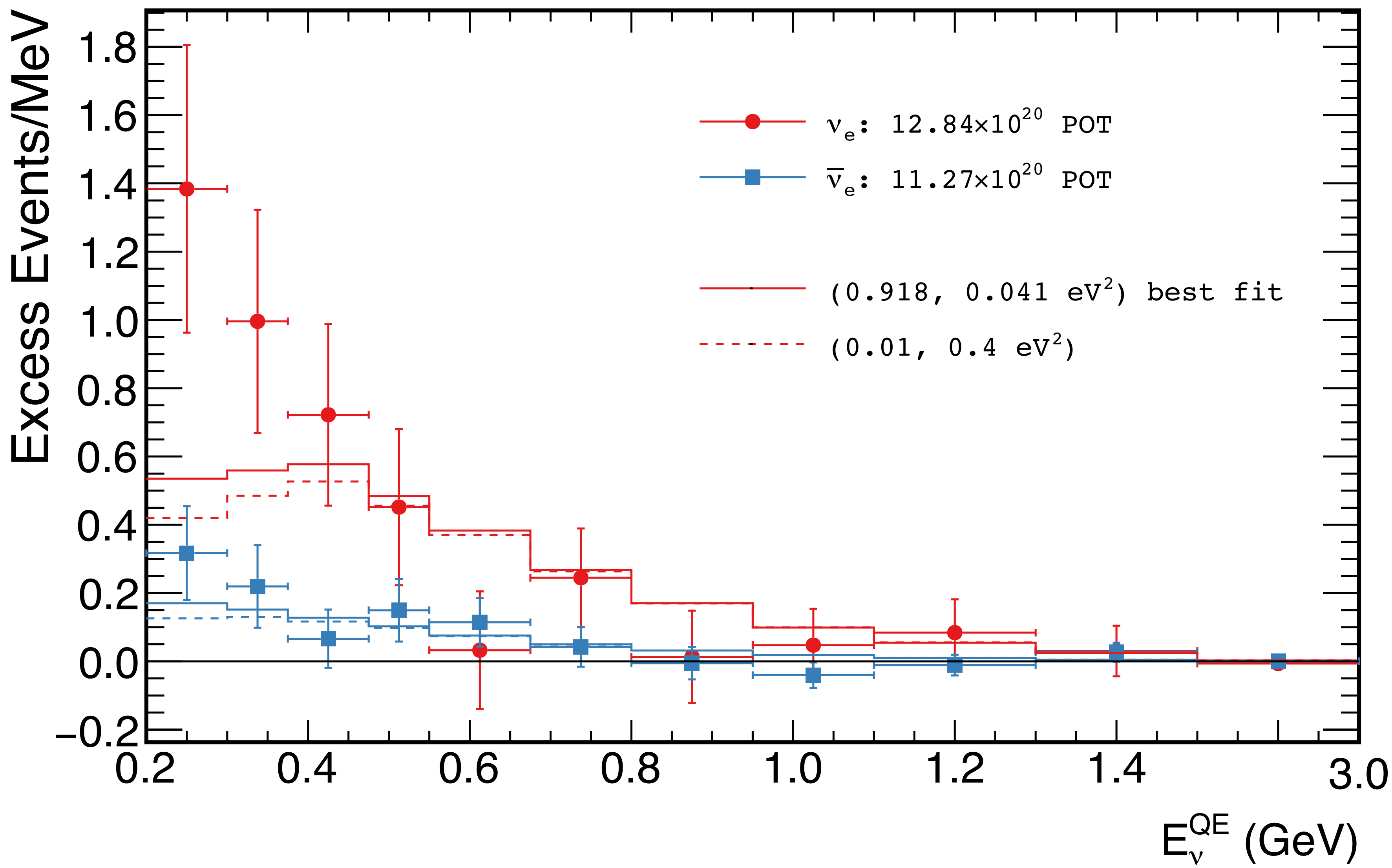


$(\Delta m^2, \sin^2 2\theta) = (0.039\ \mathrm{eV}^2, 0.842)$
$\chi^2/ndf\ = 9.9/6.7$ (prob = 15.5%)



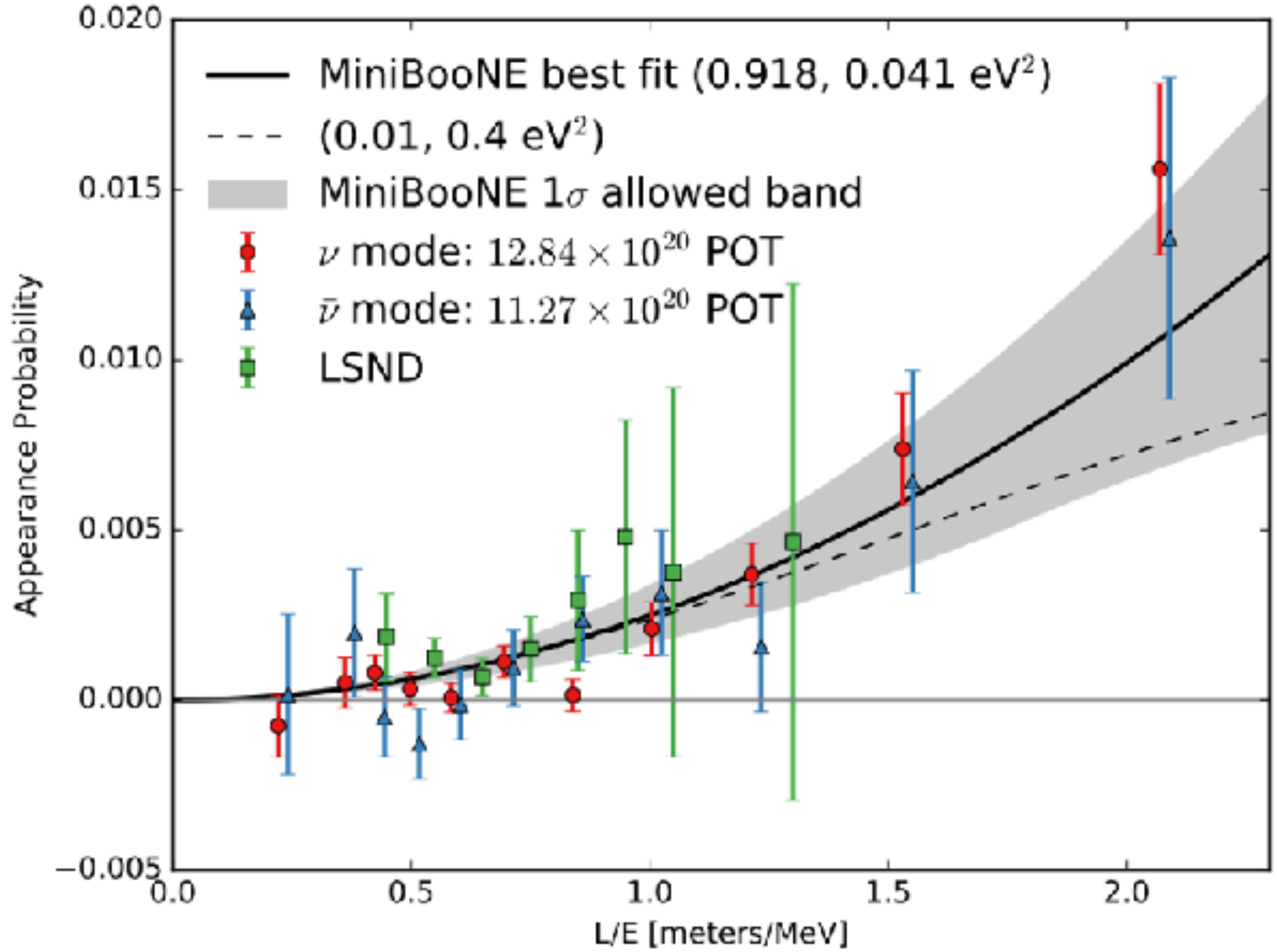
$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.918)$
$\chi^2/ndf\ = 19.4/15.6$ (prob = 21.1%)

Two-neutrino model



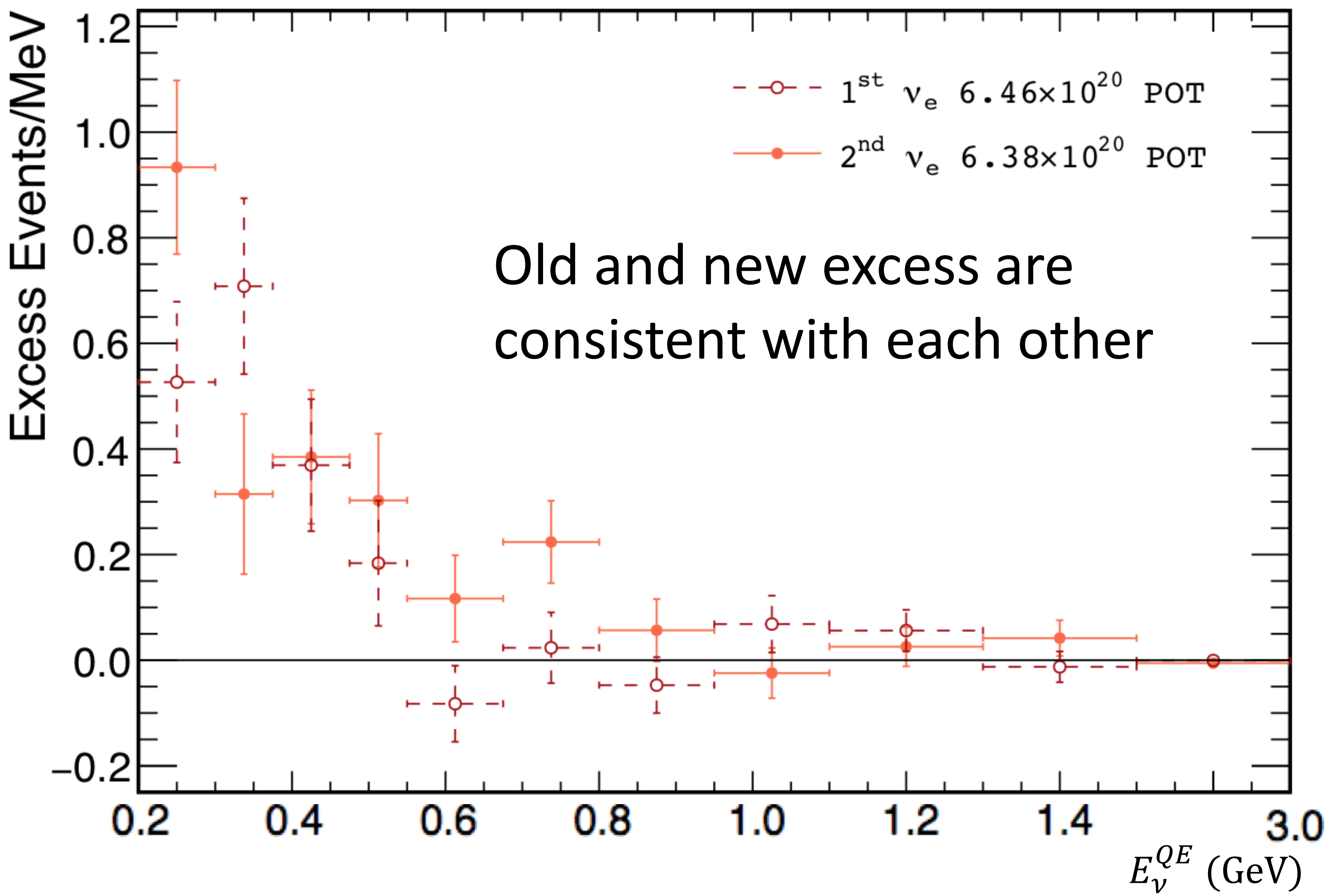
- Excess qualitatively consistent in neutrino and anti-neutrino modes

L/E dependence



- Excess L/E dependence consistent with LSND

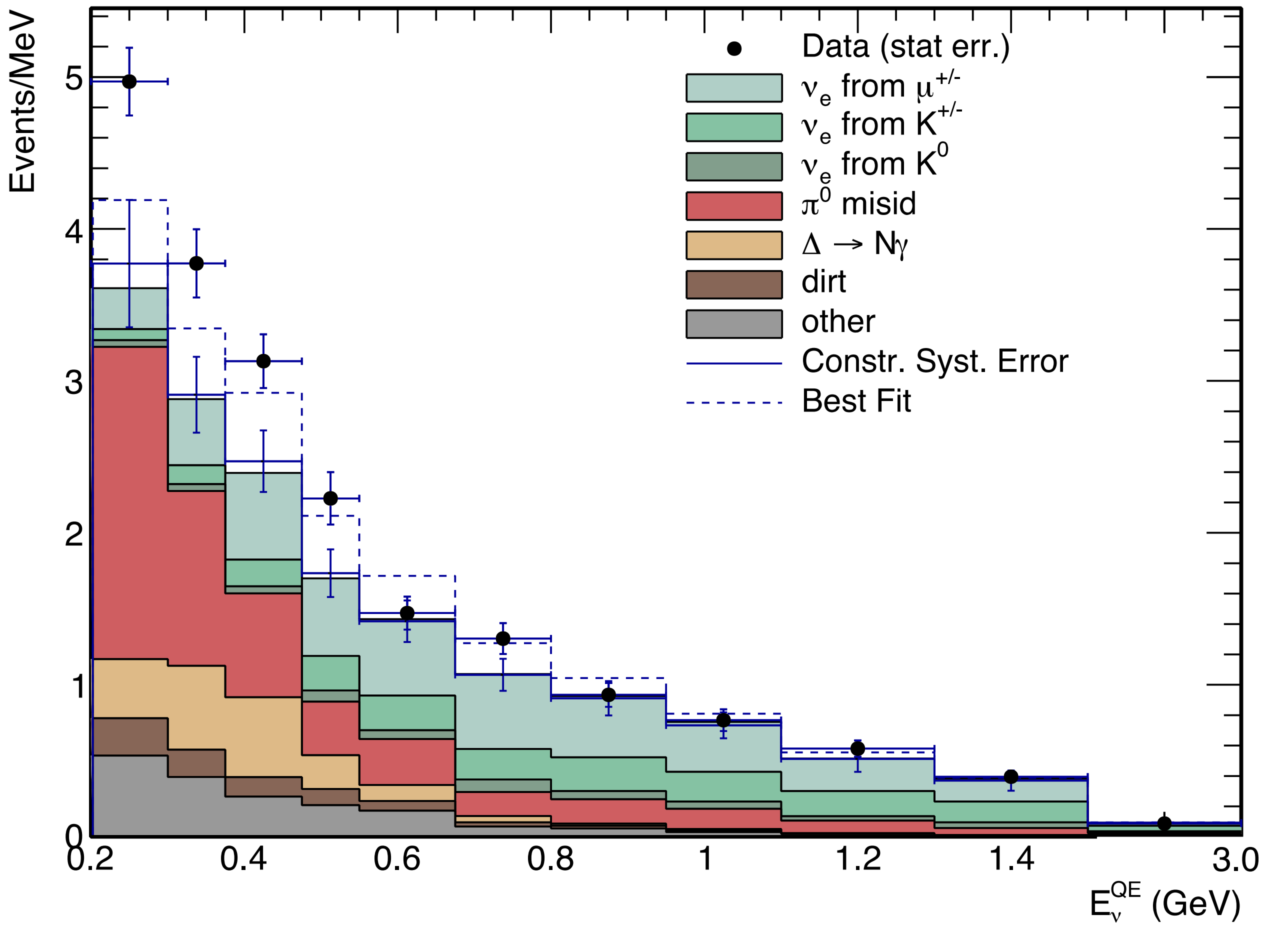
Old vs New



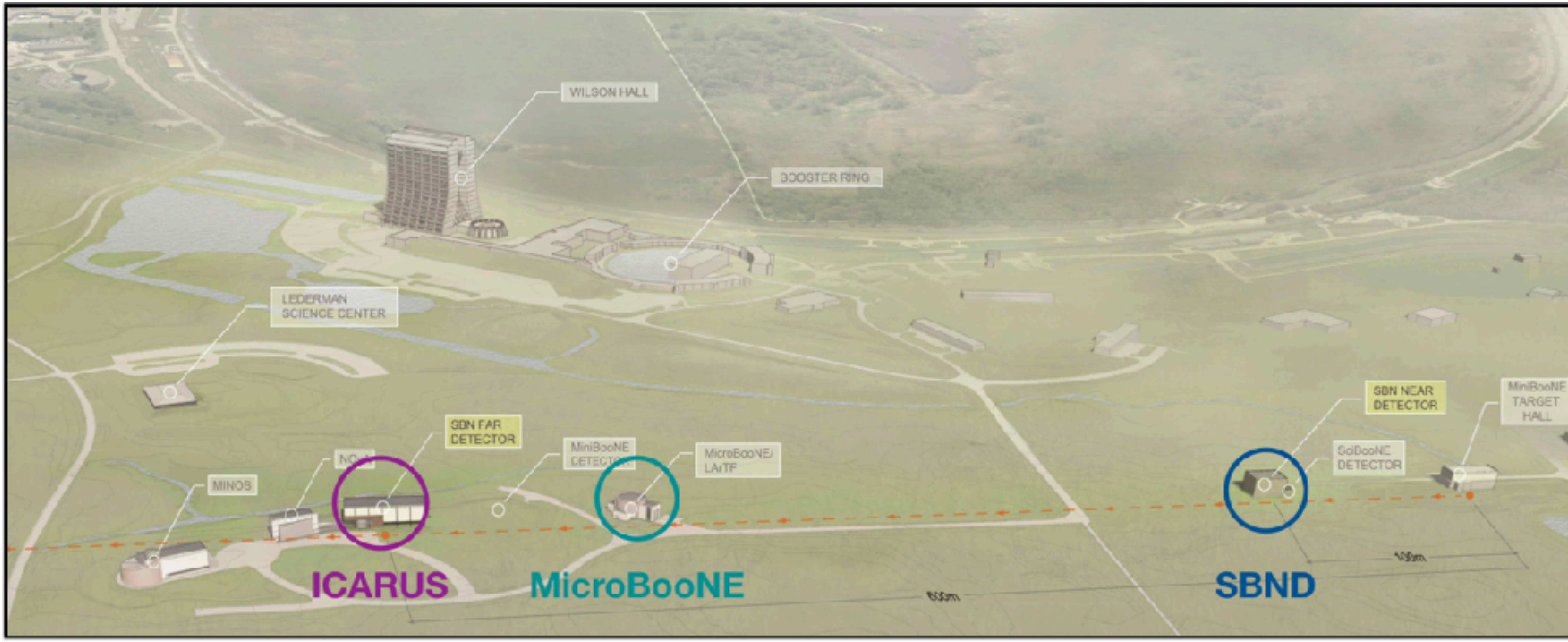
- The observed ν_e spectra are statistically consistent between the new and previous data sets (KS prob =76%)

Key questions

- Is the low energy excess electron like or gamma like?
- What is the L/E dependence? Are these sterile neutrino oscillations?

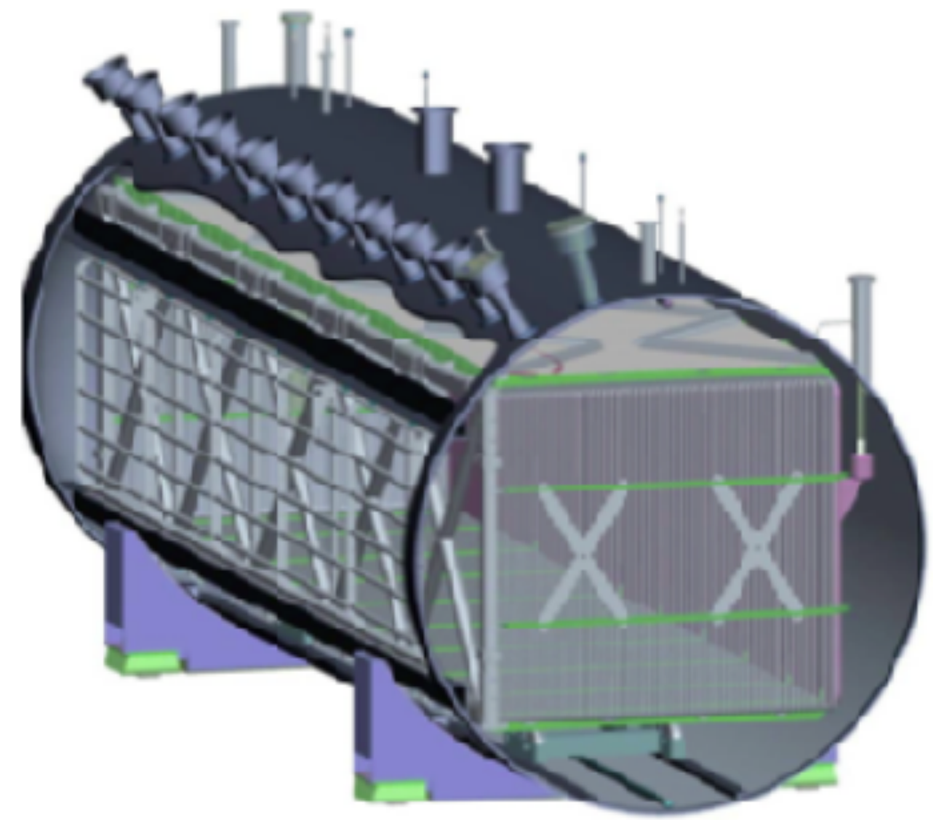


Fermilab's SBN program



- SBN program (see A. Fava's talk) takes phased approach
  - Phase 1: MicroBooNE
  - Phase 2 :SBND (see J. Zennamo's talk), ICARUS (see Y. T. Tsai's talk)

MicroBooNE



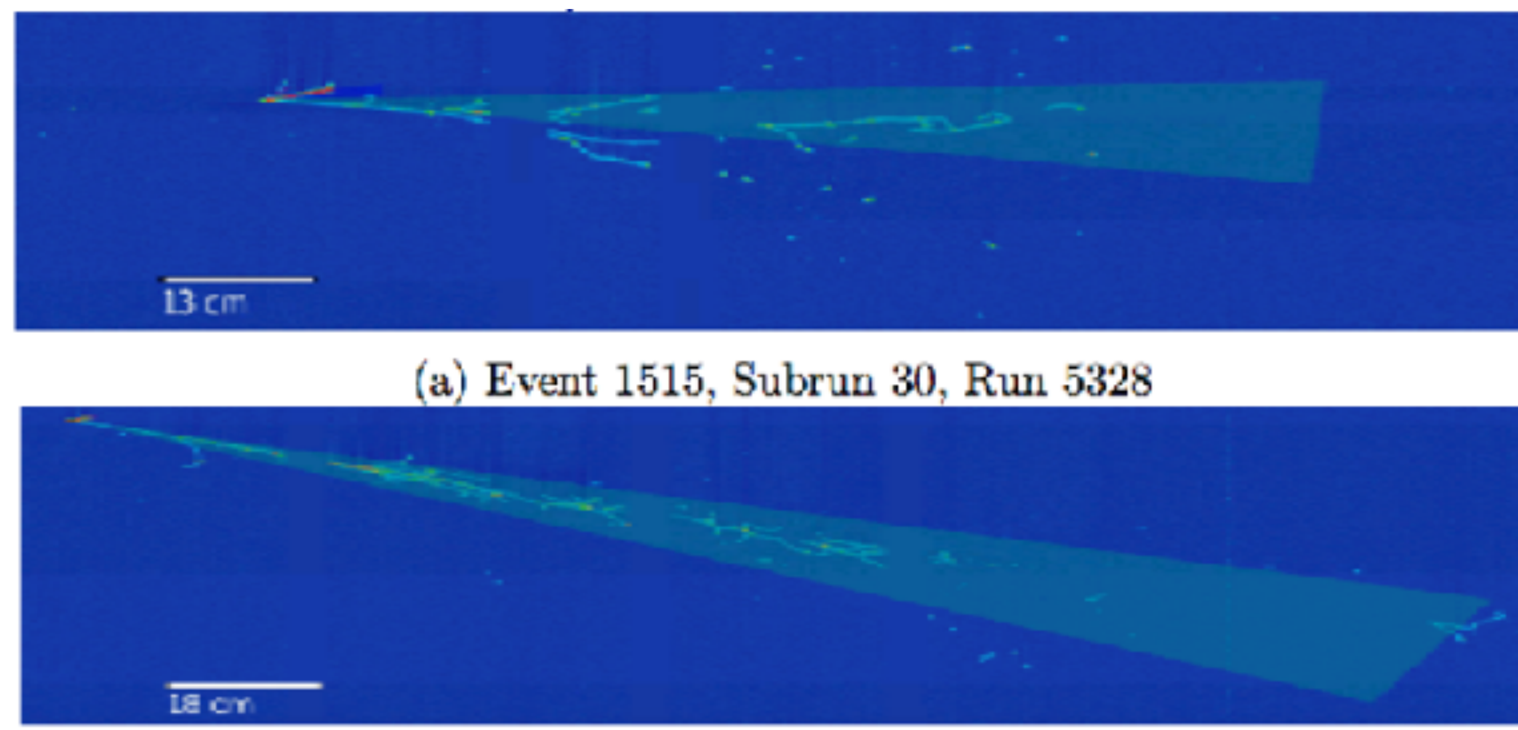
- Path to Low Energy Excess Analysis:
  - Detailed characterization of the detector (signal processing, noise characterization,…
  - Develop event reconstruction techniques
    - Deep learning (see talk by L. Yates)
    - Pandora
    - Wire cell
  - Neutrino interaction measurements (see talk by L. Jiang, poster by K. Woodruff)
  - Solid validation of ν_e and photon analyses

LEE analyses

- Several complementary LEE analysis:
  - ν_e analyses
    - 1e1p (Deep learning)
    - 1eNp (Pandora)
    - Inclusive (Pandora, WireCell)
  - Single photon analyses
    - 1γ0p (Pandora)
    - 1γ1p (Pandora)

- Crucial for testing different LEE models

Example of selected data events

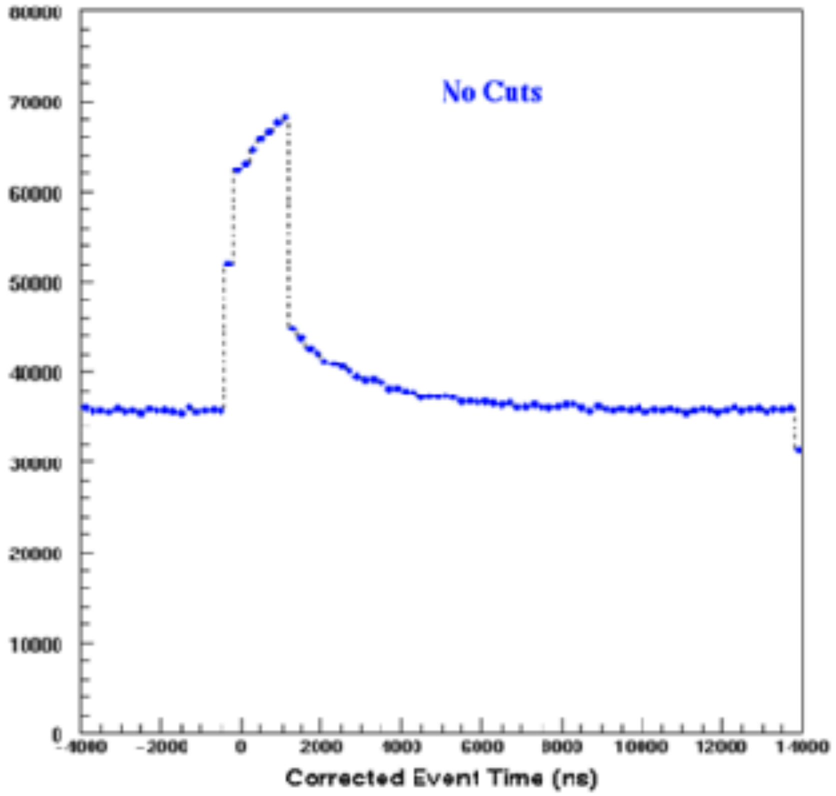


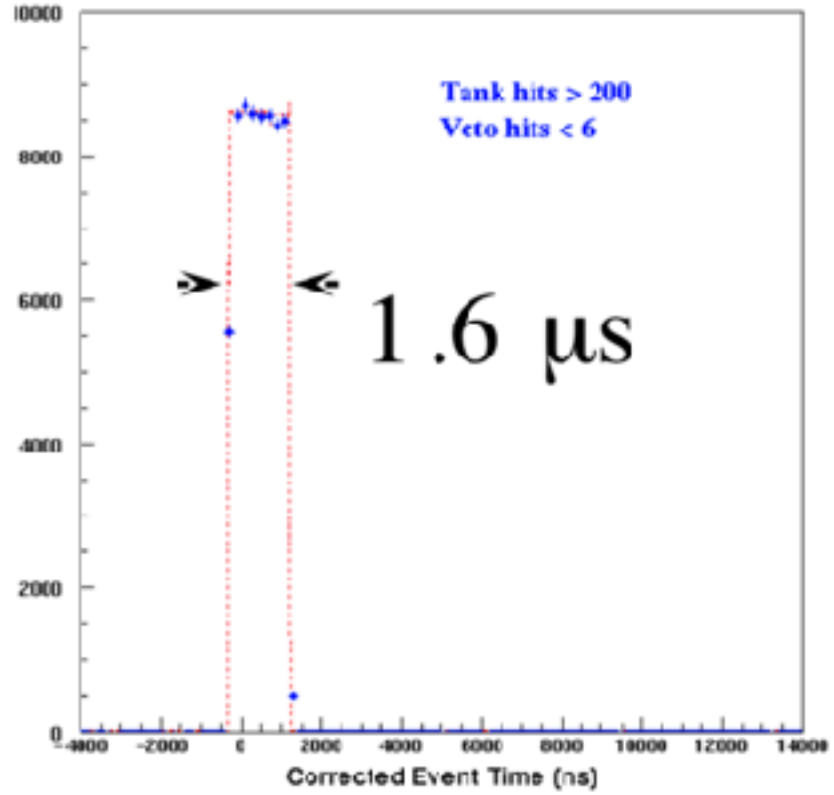
Conclusion

- MiniBooNE low energy excess in combined neutrino and antineutrino mode analysis is at 4.7σ level
- MiniBooNE continues to take data, and future analysis will include time-of-flight information to better constrain backgrounds
- Microboone making great progress on path toward LEE analysis in understanding detector effects, developing automated reconstruction
  - First physics results are coming out with many more underway
- Fermilab's SBN program under construction will probe the L/E dependence of excess events, and provide definitive answer on sterile neutrino

Backup

Event preselection

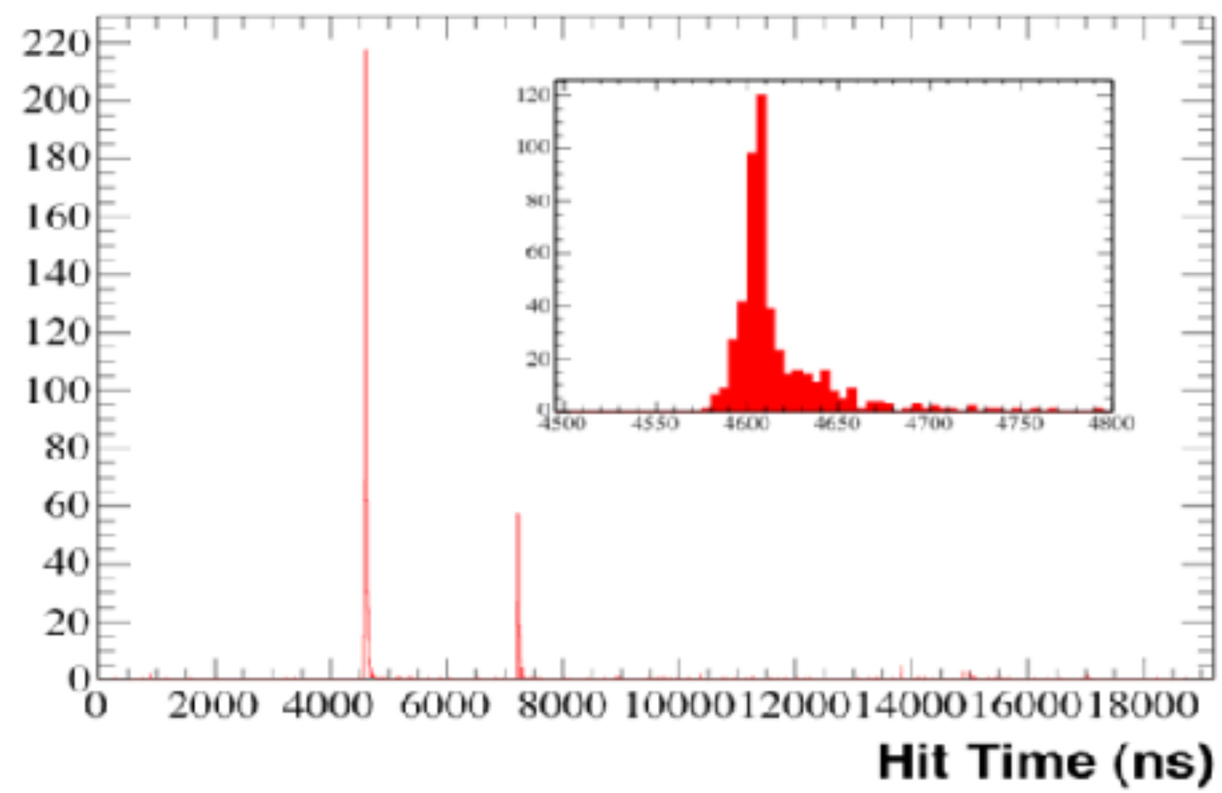




- Simple precuts remove cosmic backgrounds

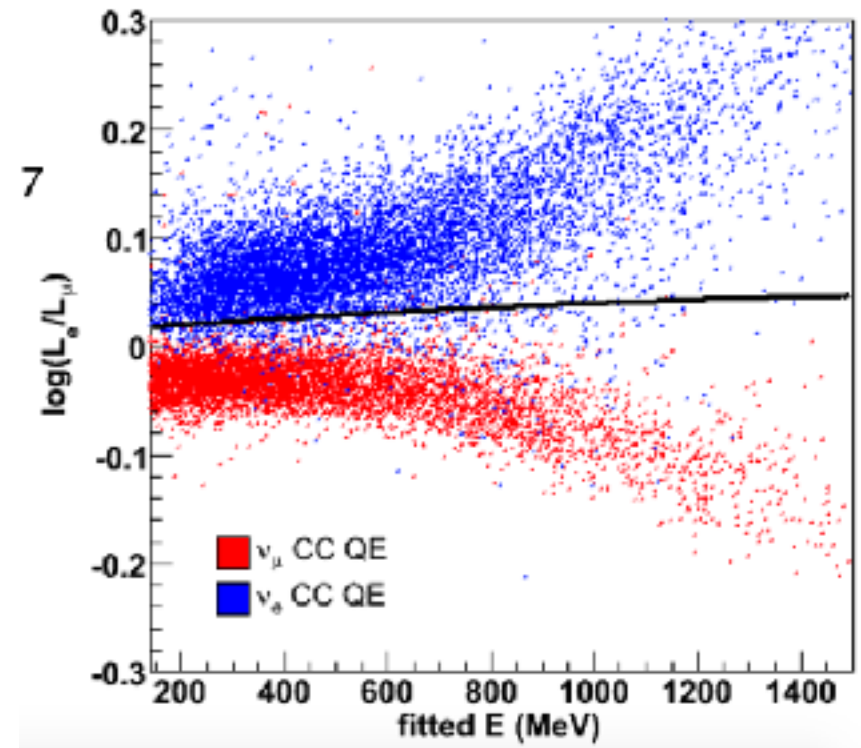
- Subevent structure (clusters in time) used for particle identification

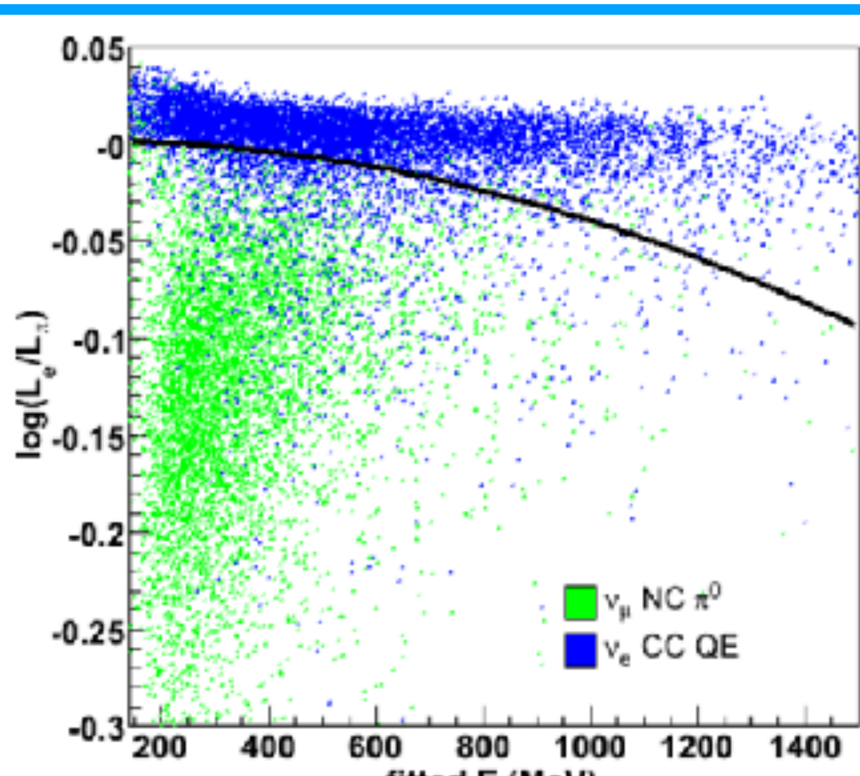
- Two subevent time structure expected for ν_μ CCQE

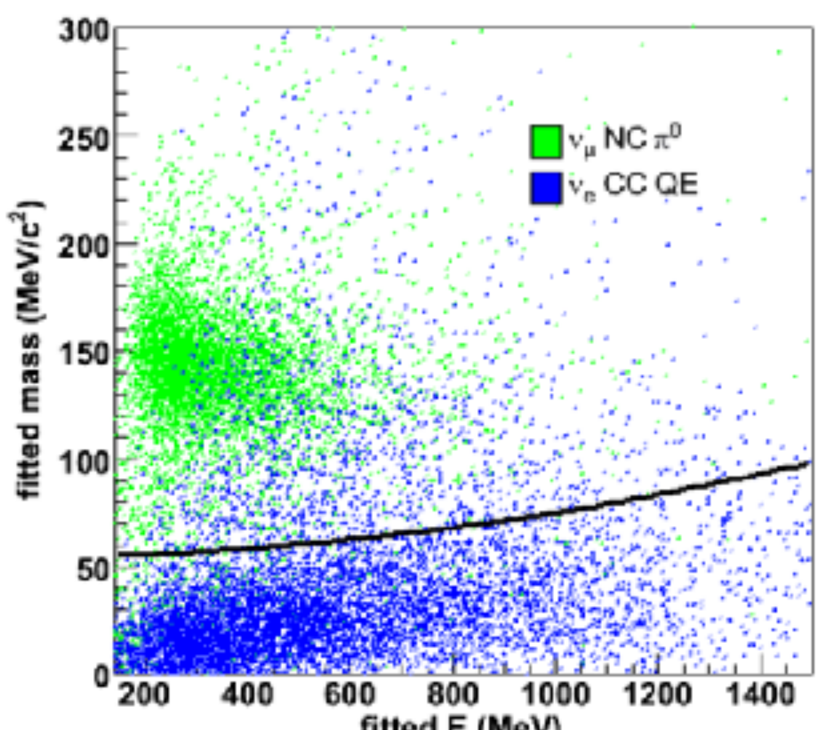


Electron like events

- Analysis pre-cuts
    - Only 1 subevent
    - Veto hits<6 & Tank hits>200
    - Radius<500
- Separate from numu
    - Fit tracks under electron and muon hypothesis





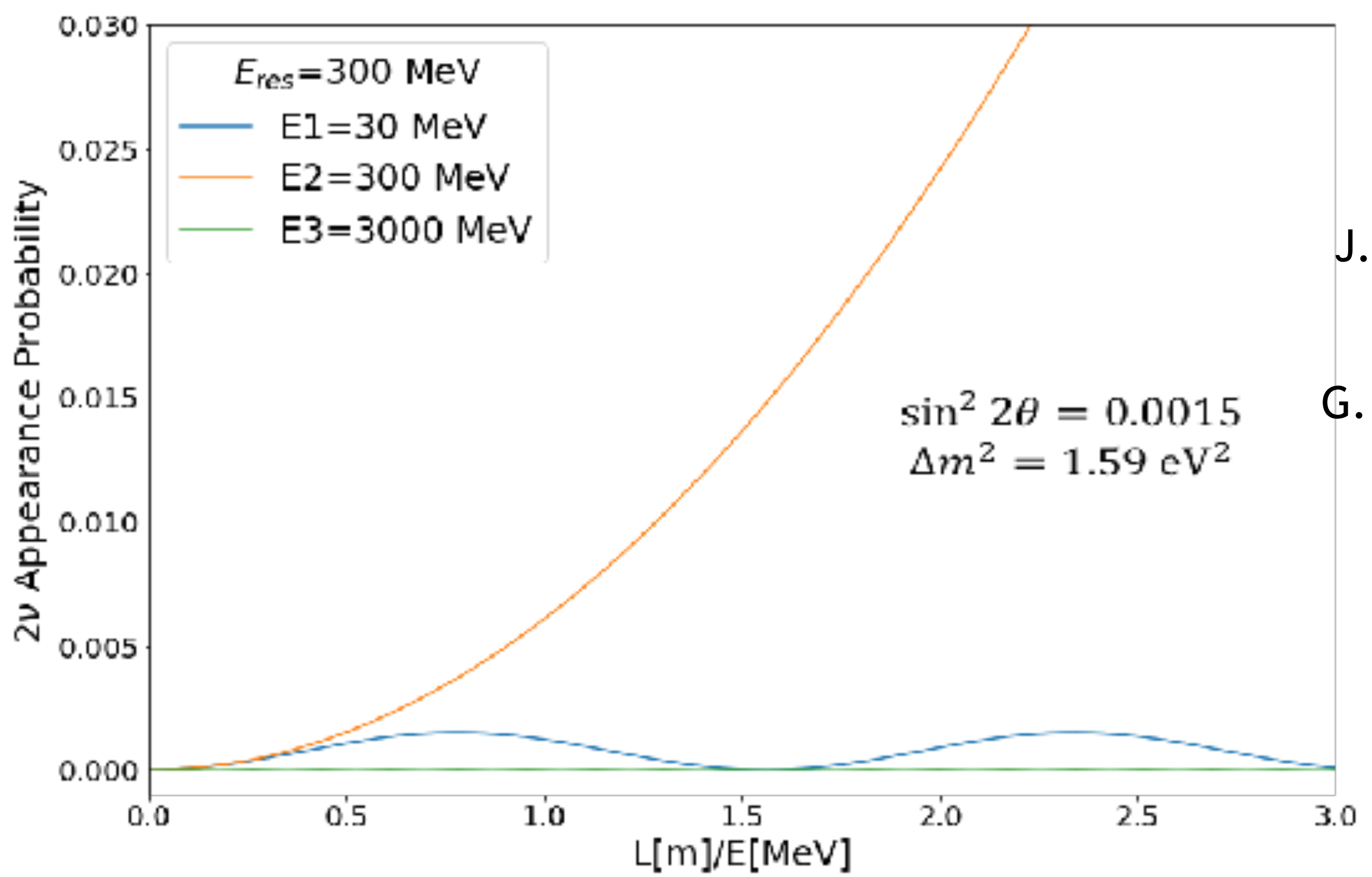


- Separate from pi0
    - Fit under two electron like tracks hypothesis

Example of an Empirical Exotic Model: An MSW-Like Resonance

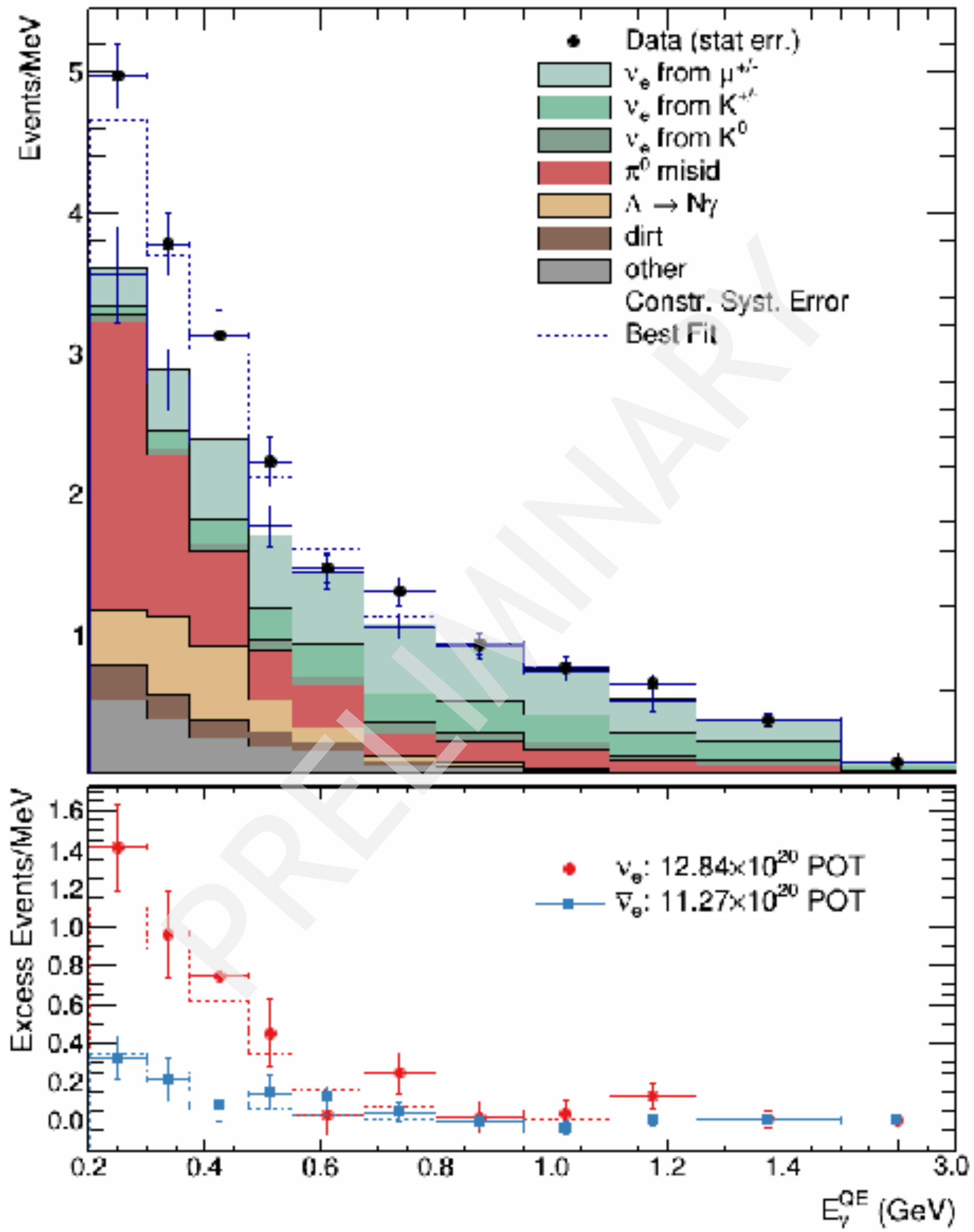
$$C = \sqrt{\cos^2 2\theta\,(1 - E/E_{res})^2 + \sin^2 2\theta}$$
$$\sin^2 2\theta_M = \sin^2 2\theta\,/C^2$$
$$\Delta m_M^2 = C\Delta m^2$$

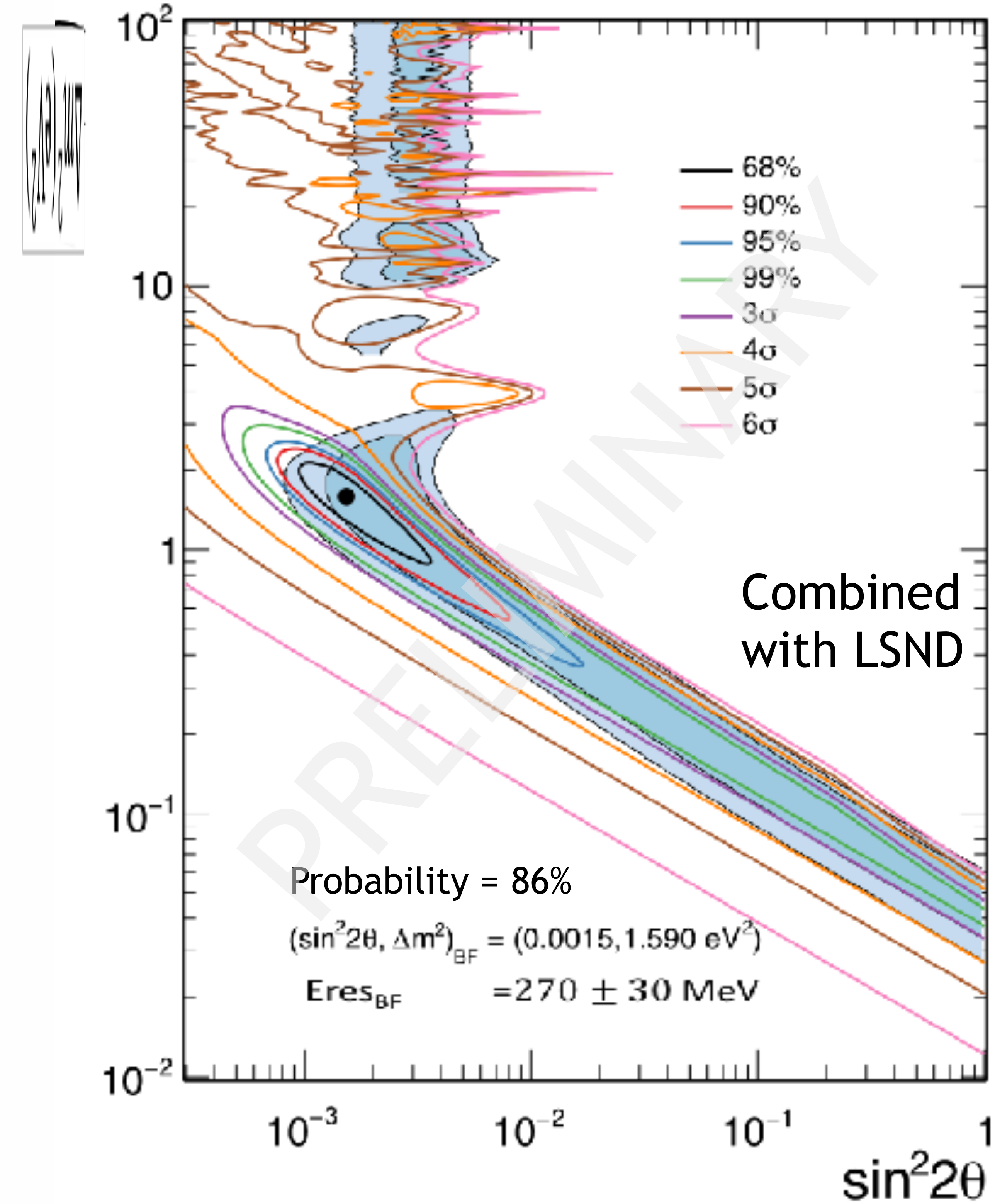
$$P(E \ll E_{res}, L) \approx \sin^2 2\theta \times \sin^2(1.267\Delta m^2 L/E)$$
$$P(E \approx E_{res}, L) = \sin^2 2\theta_M \times \sin^2(1.267\Delta m_M^2 L/E)$$
$$P(E \gg E_{res}, L) \approx 0$$



Inspired by:
J. Assadi, E. Church, R. Guenette, B. J. P. Jones, & A. M. Szelc, PRD 97, 075021 (2018);
G. Karagiorgi, M. H. Shaevitz, & J. M. Conrad, arXiv:1202.1024;
Heinrich Paes, Sandip Pakvasa, & Thomas J. Weiler, PRD 72, 095017 (2005).

An MSW-Like Resonance Model





A more exotic model could provide a better fit to the MiniBooNE/LSND data

Another Example

FERMILAB-PUB-18-336-T
OSU-HEP-18-04

A Dark Neutrino Portal to Explain MiniBooNE

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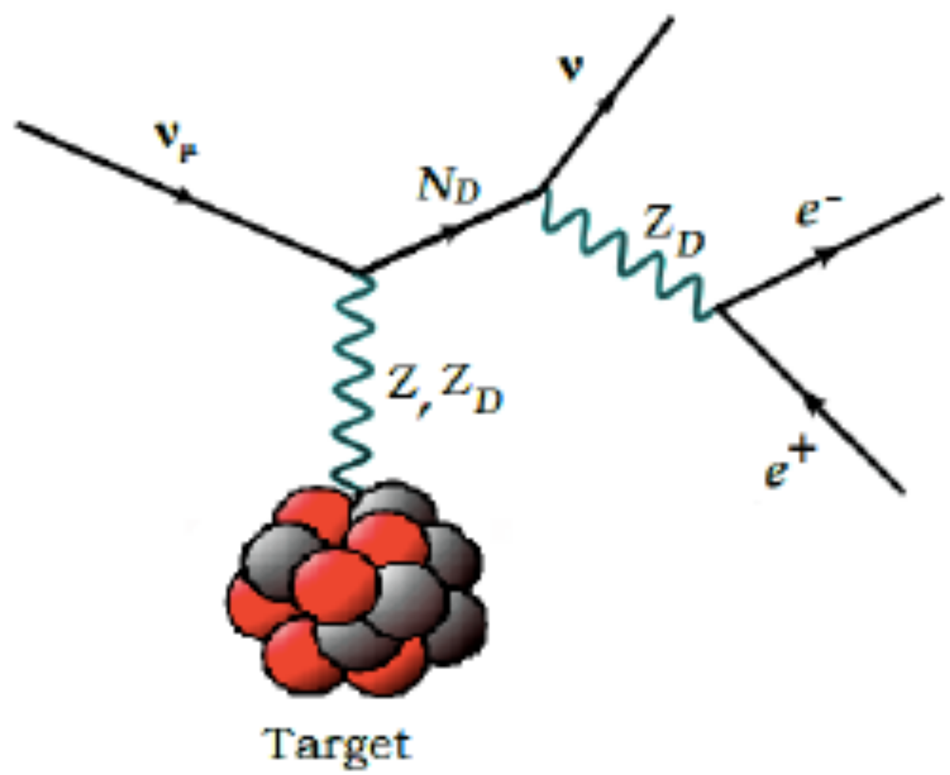
(Dated: July 25, 2018)

We present a novel framework that provides an explanation to the long-standing excess of electron-like events in the MiniBooNE experiment at Fermilab. We suggest a new dark sector containing a dark neutrino and a dark gauge boson, both with masses between a few tens and a few hundreds of MeV. Dark neutrinos are produced via neutrino-nucleus scattering, followed by their decay to the dark gauge boson, which in turn gives rise to electron-like events. This mechanism provides an excellent fit to MiniBooNE energy spectra and angular distributions.



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