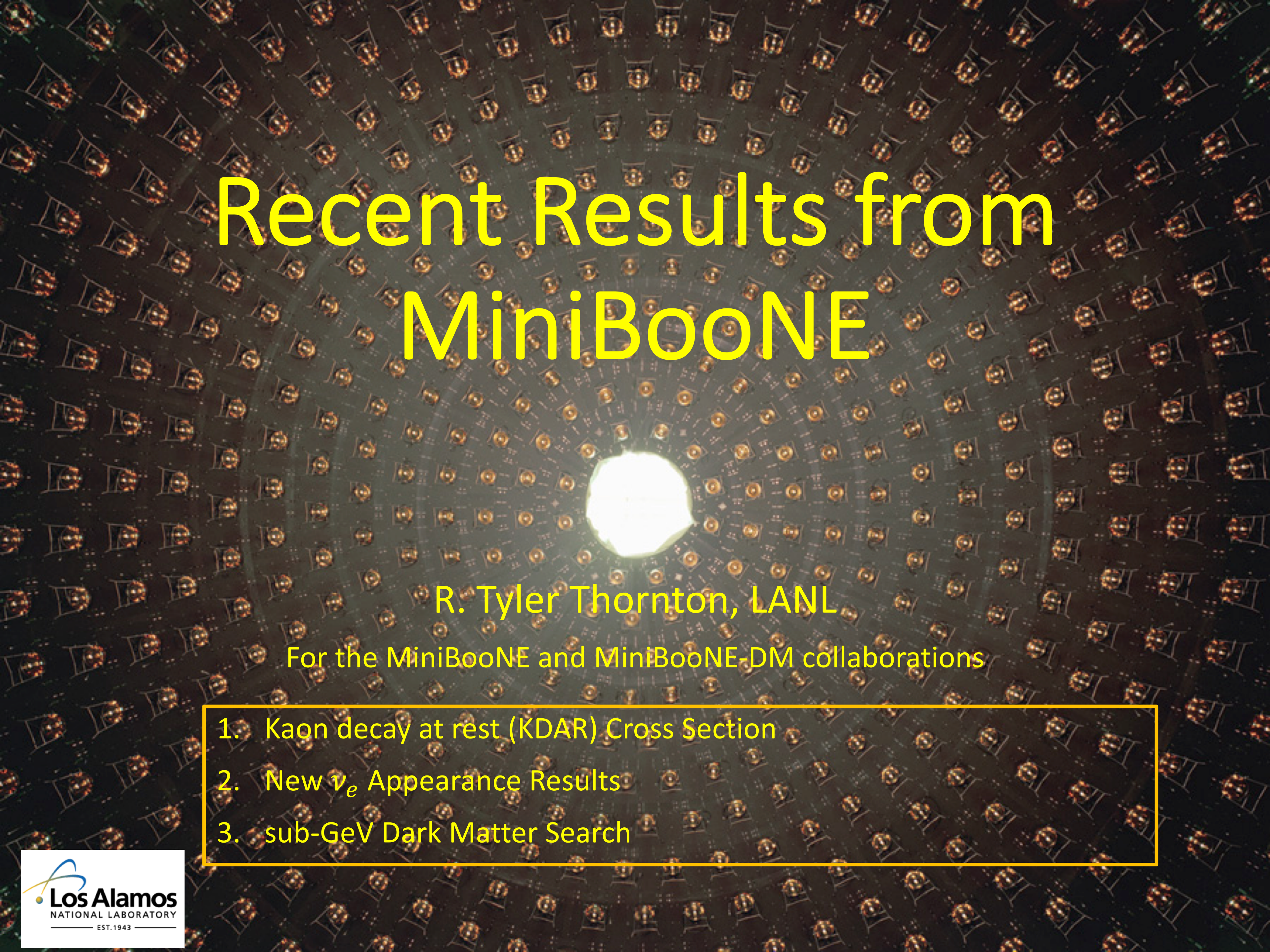


Recent Results from MiniBooNE

R. Tyler Thornton, LANL

For the MiniBooNE and MiniBooNE-DM collaborations

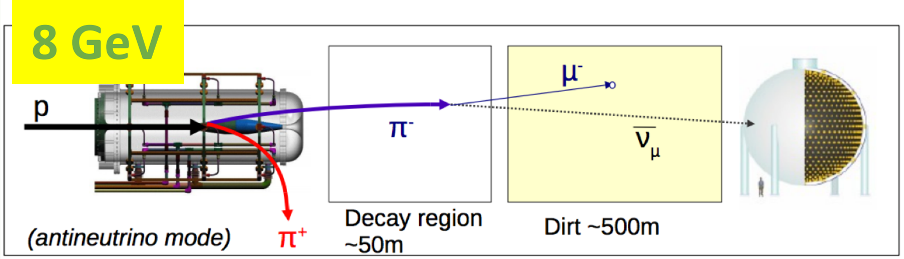
1. Kaon decay at rest (KDAR) Cross Section
2. New ν_e Appearance Results
3. sub-GeV Dark Matter Search

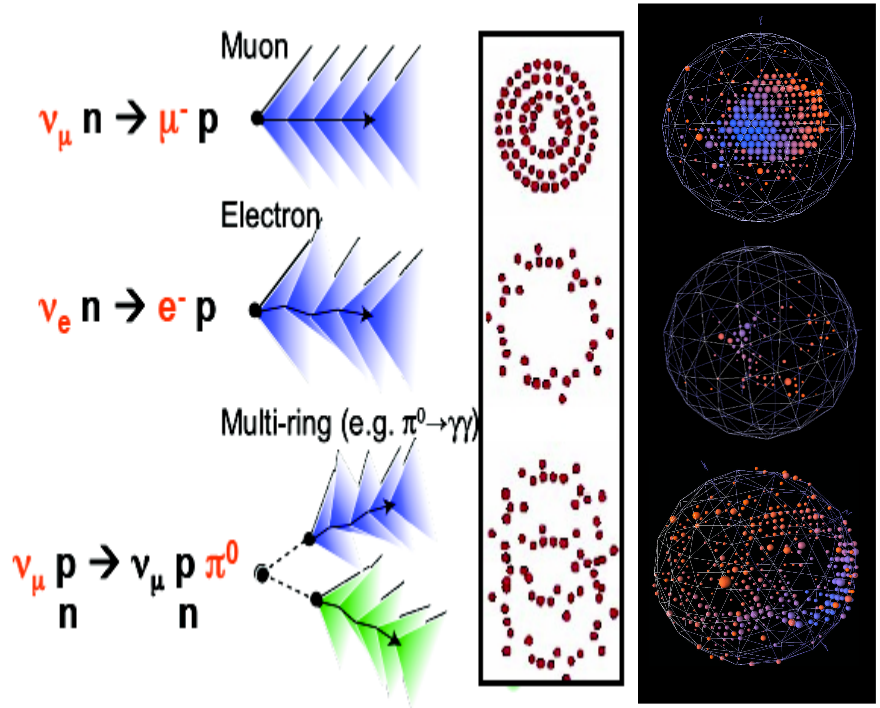
Los Alamos
NATIONAL LABORATORY
EST.1943

Comparing MiniBooNE and LSND

MiniBooNE

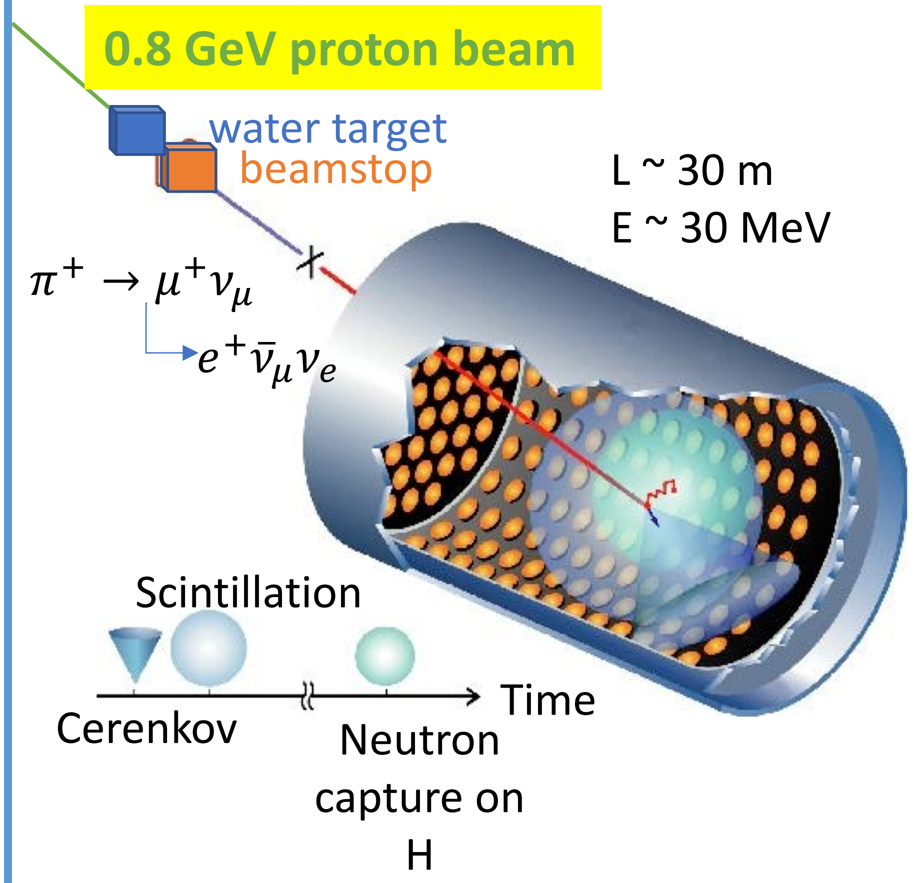
Cherenkov : Scintillation = 8:1





Liquid Scintillator Neutrino Detector (LSND)

Cherenkov : Scintillation = 1:5

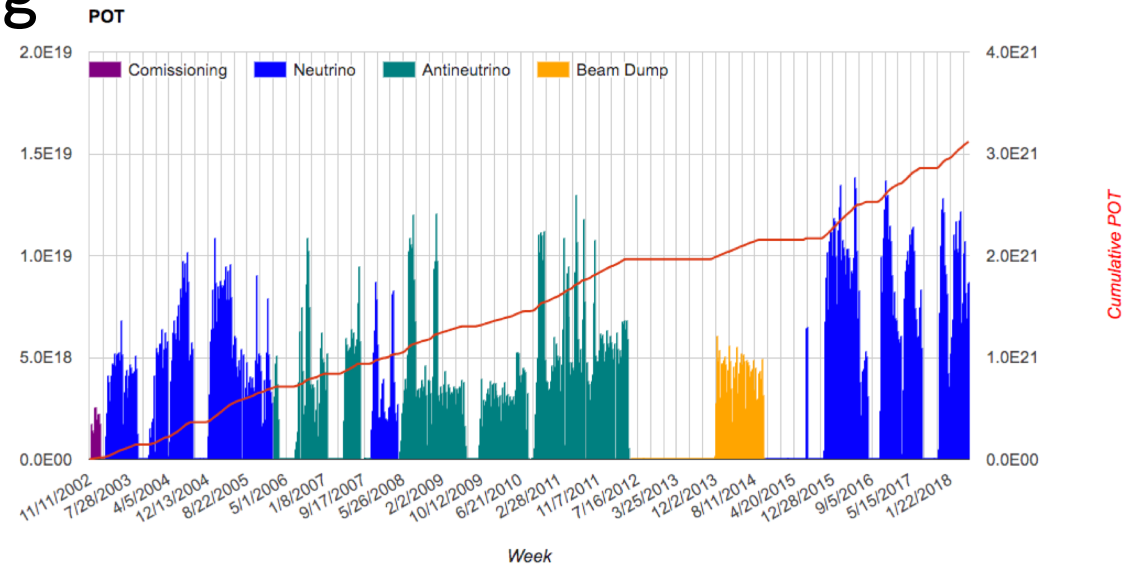


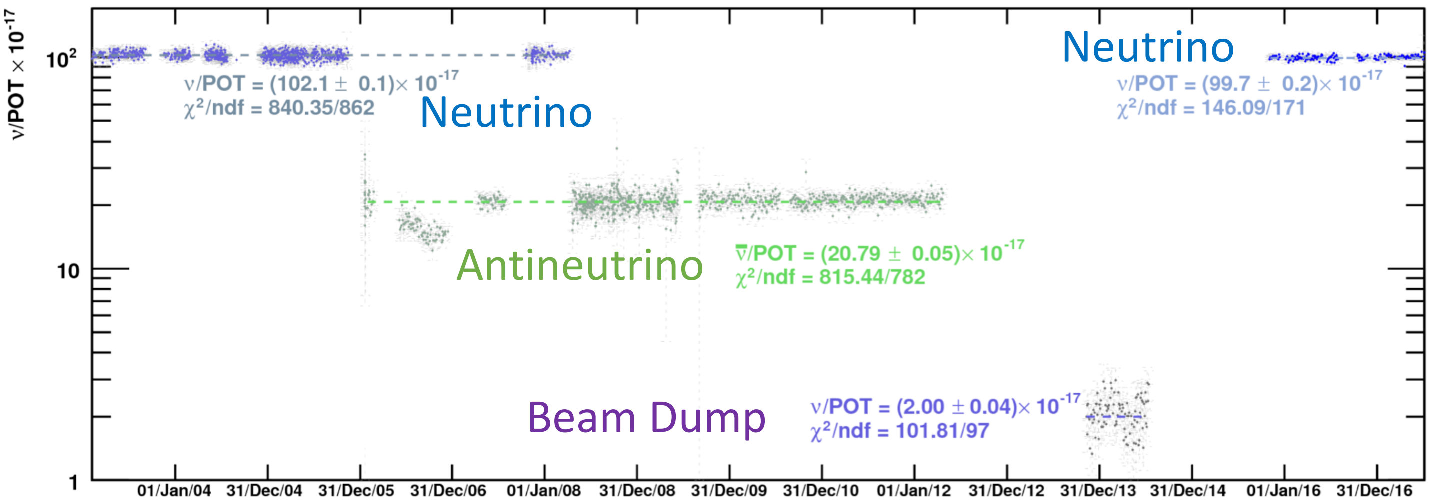
Different systematics. Same L/E baseline.

Booster Neutrino Beamline

15 years of running

- Accelerator has delivered more than $30{\times}10^{20}$ proton-on-target (POT)
- **Thanks Proton Source Department**
- **Thanks Accelerator Division**



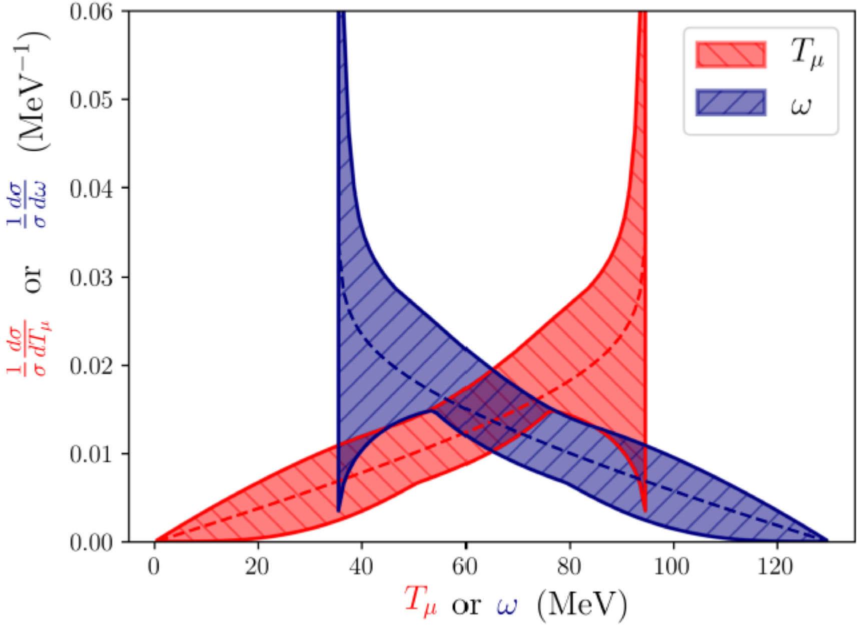


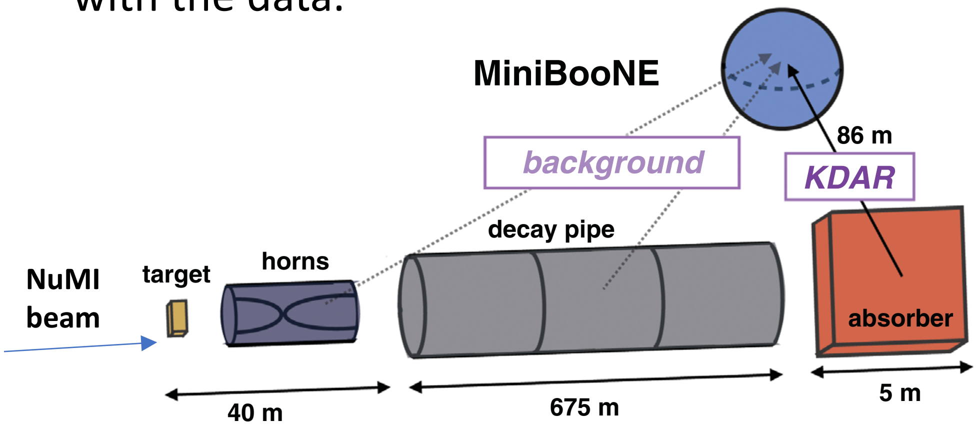
- Number of ν per POT
- Stable for ν Mode after ~8 years apart to within 2%

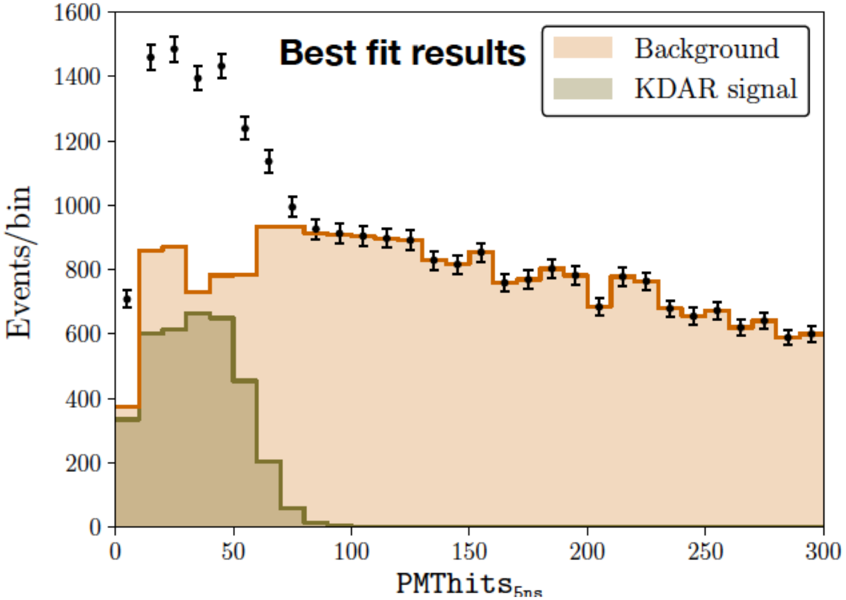
“First Measurement of Monoenergetic Muon Neutrino Charged Current Interactions”

PRL 120 141802 (2018) Editors’ Suggestion

- KDAR=Kaon Decay At Rest
- KDAR neutrinos from the NuMI beamline absorber have been isolated based on energy reconstruction and timing.
- First measurement of ω (energy transferred to the nucleus) with a known energy, weak-interaction-only nuclear probe.
- Results provide a standard candle for understanding ν_μ CC events at a known energy (236 MeV).
- An associated data release website allows any model prediction (T_μ or ω) to be compared with the data.

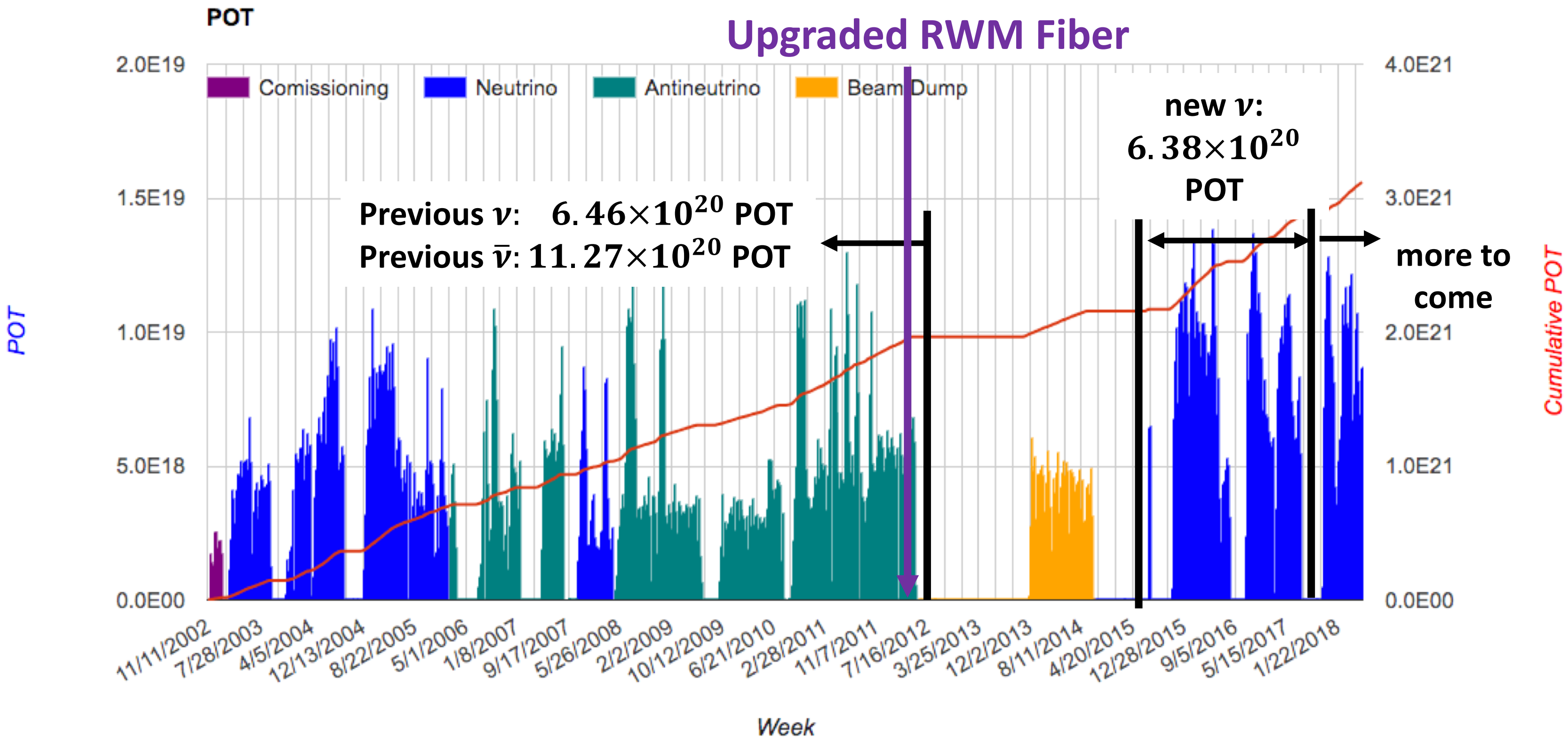






Updated MiniBooNE Oscillation Results: Doubled ν Mode data

- Extra data allows better calibrations and cross checks
- Second data set to look at consistency (~8 years apart)
- Improved background estimates from observed data and constraints
- Larger data set leads to smaller statistical uncertainty on signal and background measurements



Upgraded RWM Fiber

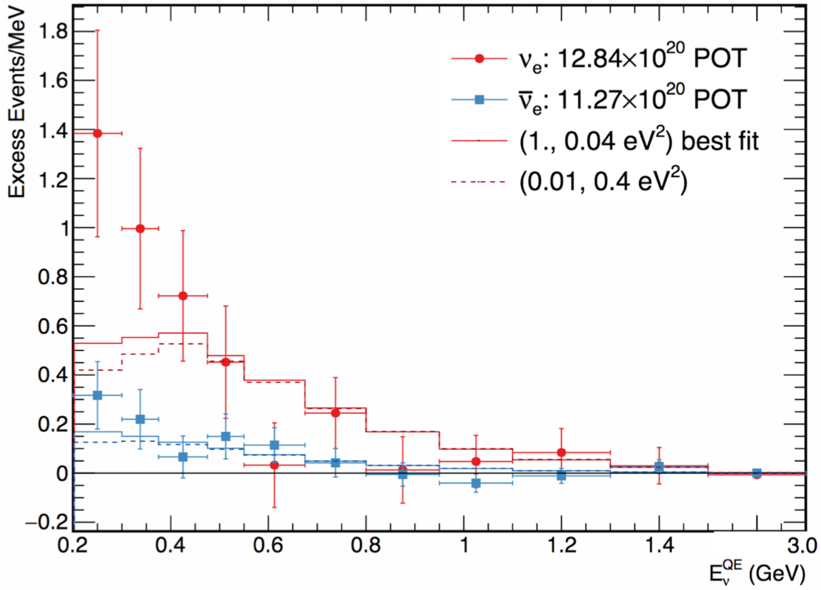
Previous ν: 6.46×10^{20} POT

Previous $\bar{\nu}$: 11.27×10^{20} POT

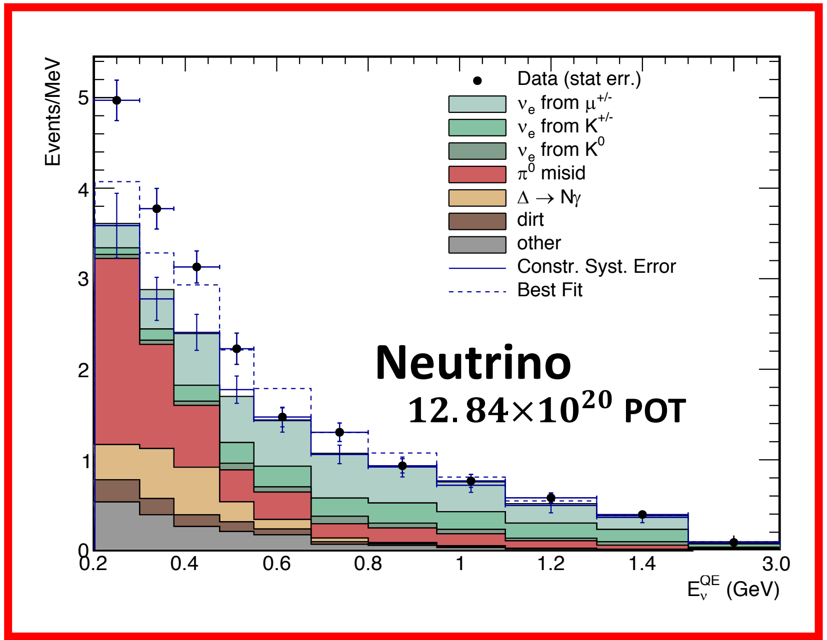
new ν: 6.38×10^{20} POT

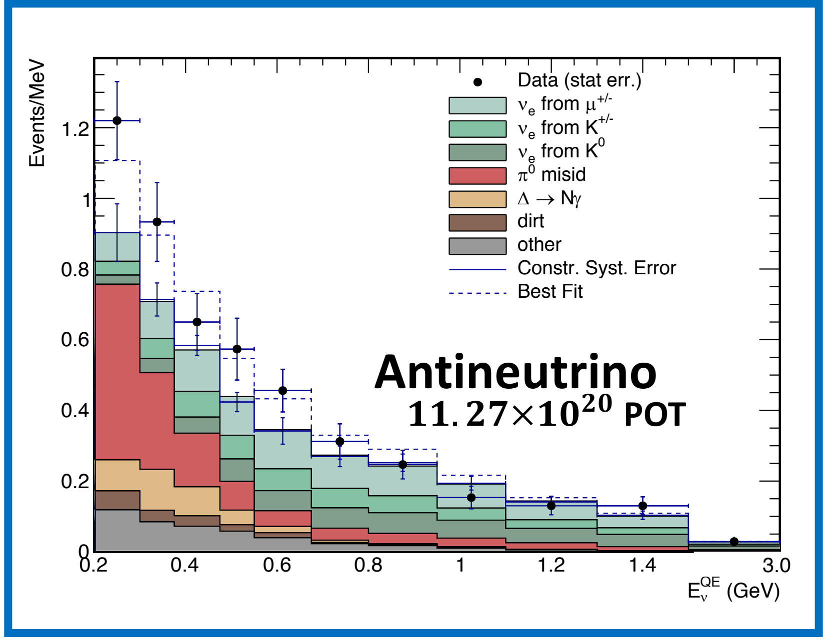
more to come

	ν mode	$\bar{\nu}$ mode	Combined
Data	1959	478	2437
Unconstr. Background	1590.5	398.2	1988.7
Constr.	1577.8	398.7	1976.5
Excess	381.2 ± 85.2 4.5σ	79.3 ± 28.6 2.8σ	460.5 ± 95.8 4.8σ
0.26% (LSND) $\nu_\mu \rightarrow \nu_e$	463.1	100.0	563.1

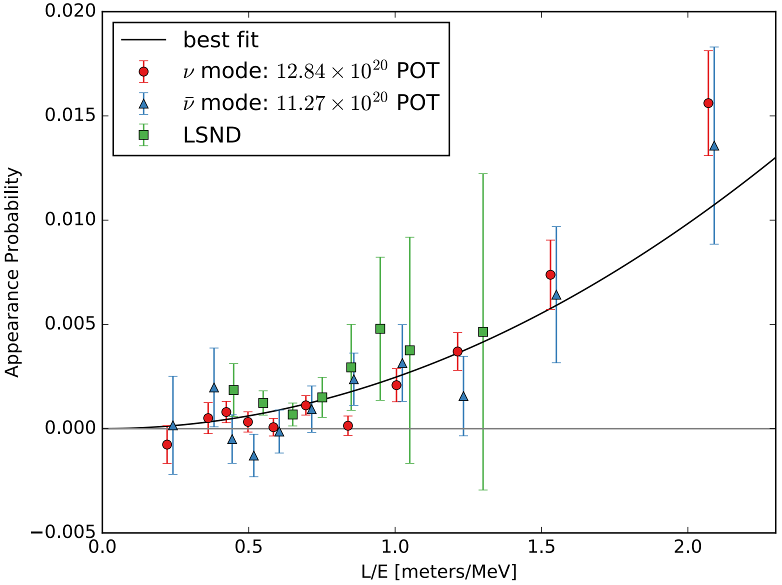


- Combined with LSND (3.8σ), total significance is at 6.1σ

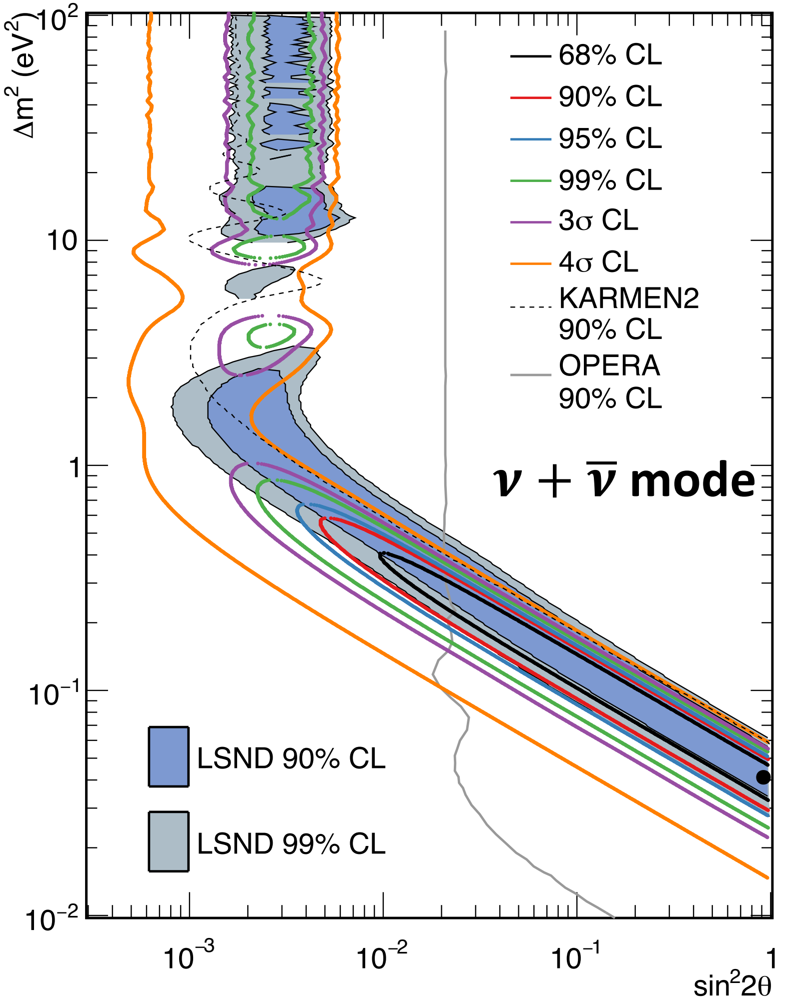




Summary of Oscillation Results



- MiniBooNE ν and $\bar{\nu}$ are **CONSISTENT** with LSND in L/E and appearance probability
- Simple 2ν fit
  - Best fit at maximum mixing
  - But 1σ region is large
  - Hints at more complicated model



$$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.958)$$

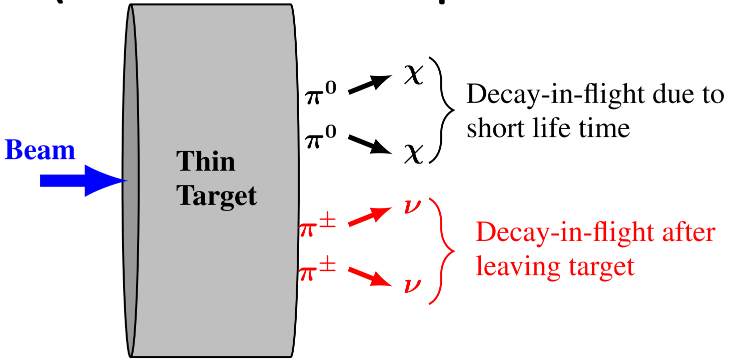
$$\chi^2/ndf = 19.5/15.4\ \text{(prob. = 20.1\%)}$$

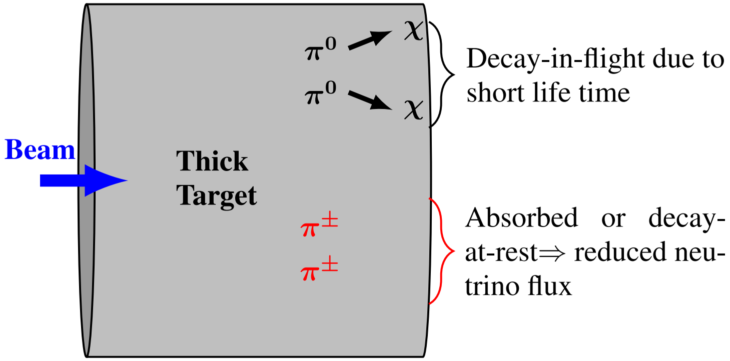
- For more information
  - arXiv:1805.12028, submitted to PRL
  - W&C Talk on July 27

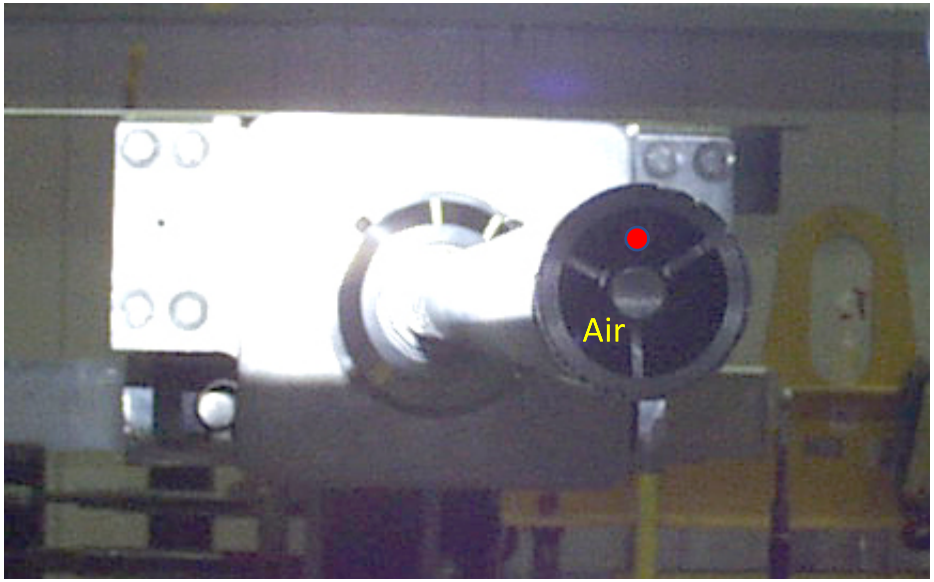
Beam-Dump Mode

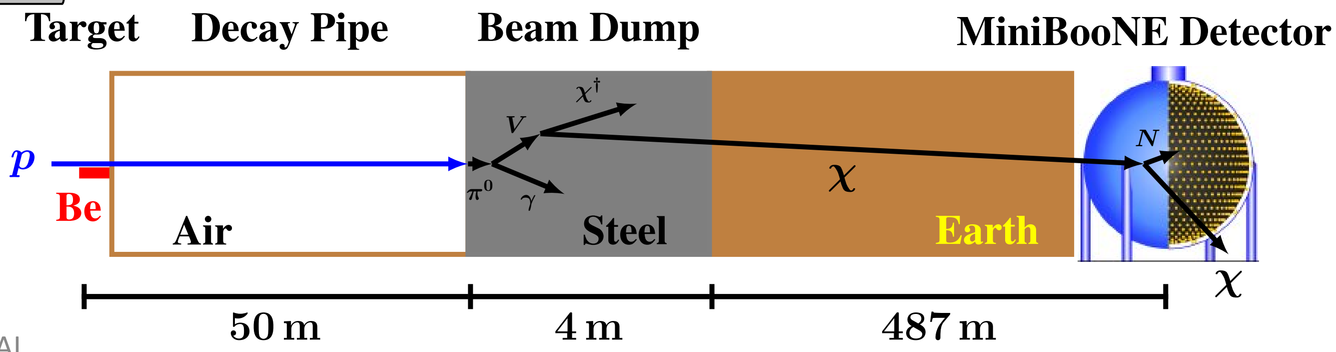
(Nov 2012 – Sep 2013 $\mathbf{1.86\times10^{20}}$ POT)

ν event rate in MiniBooNE decreased by a factor of 50 compared to ν Mode







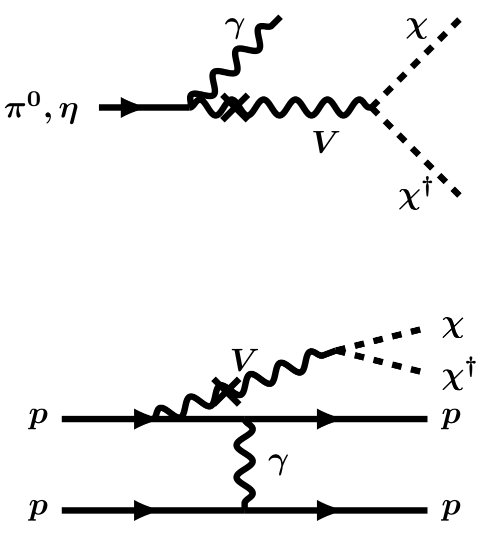


First Results: sub-GeV

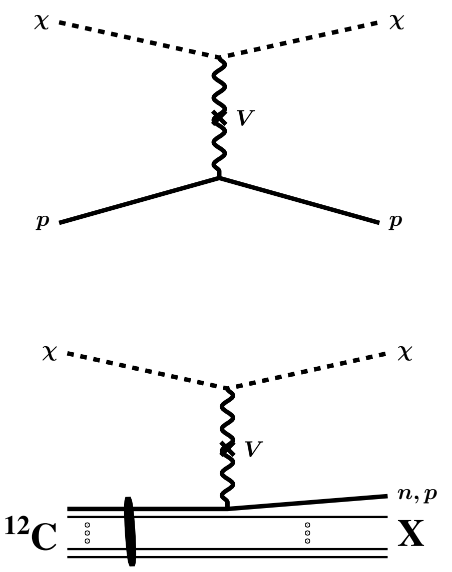
PRL 118, 221803 (2017)
Editors' Suggestion

- First dedicated search for direct detection of accelerator-produced dark matter in a proton beamline

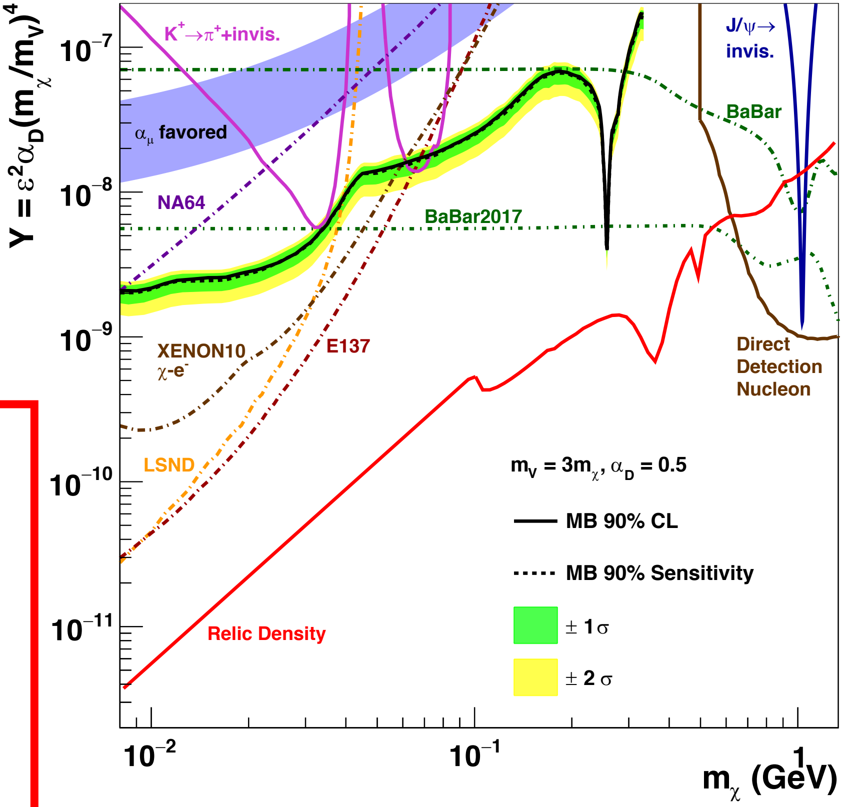
Production



Detection

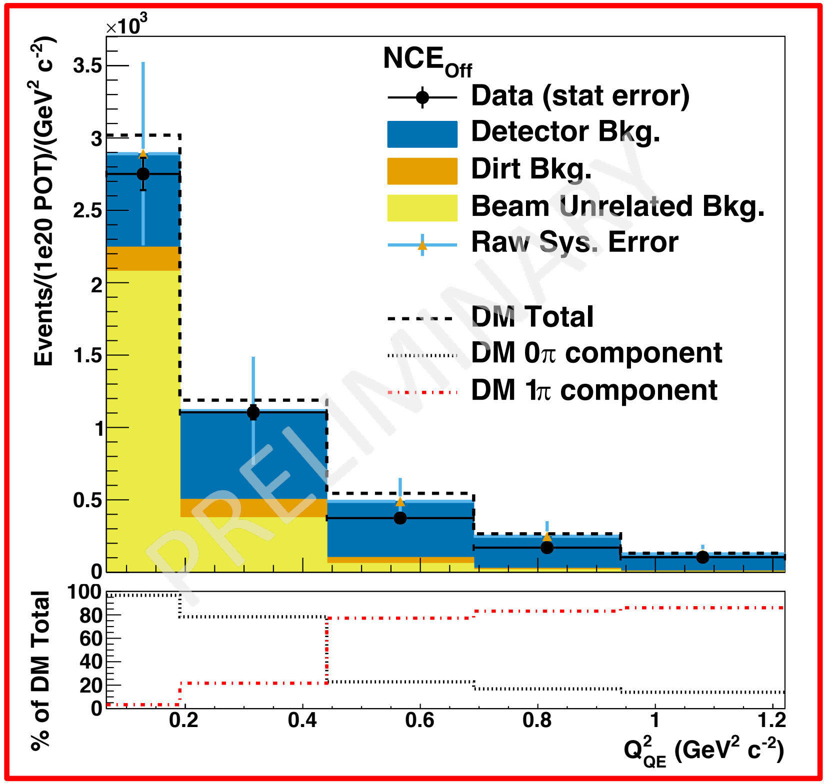


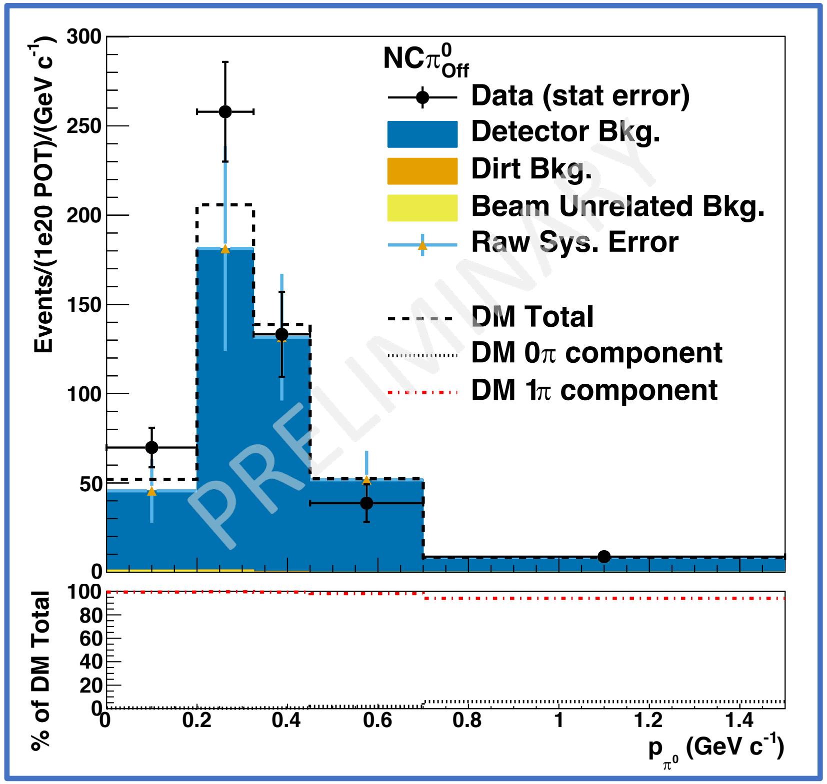
- The goal was to test vector portal model interpretation of g-2 anomaly **(ruled out)**



- $Y \propto$ DM annihilation cross section
- m_V = vector mediator (dark photon) mass (not assumed to equal m_Z)
- m_χ = dark matter mass
- ε = kinetic mixing between V and γ, or Z
- α_D = gauge coupling between V and χ

New To Nucleon Analysis (Full Nucleon)



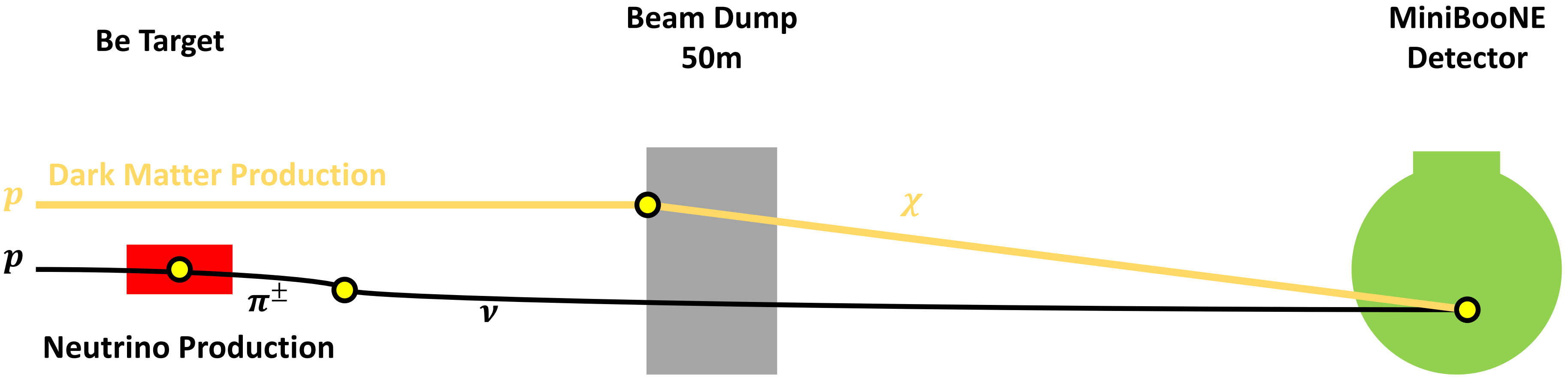


- **Neutral-Current elastic nucleon cut**
  - Large beam unrelated bkg. (BUB)
  - DM at high Q^2_{QE} has large % of true 1 π^0 sample

- **Neutral-Current single π^0 cut**
  - Reduced to almost no dirt and BUB

- Simultaneous fit of NCE and NCπ^0 cuts
- Constrained by ν and $\bar{\nu}$ data

New To Nucleon Analysis (“Time-of-Flight”)



Be Target

Beam Dump
50m

MiniBooNE
Detector

Dark Matter Production

p

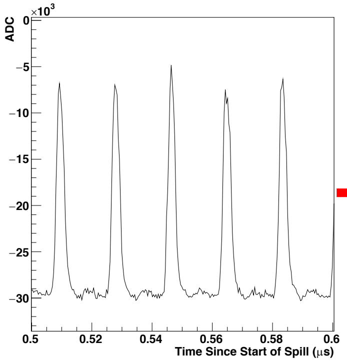
χ

p

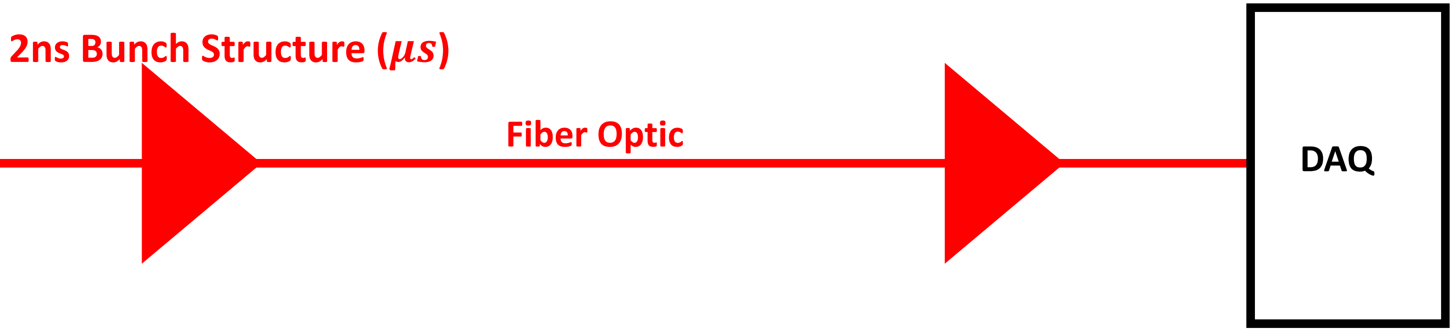
$\pi^{\pm}$

ν

Neutrino Production



RWM Timing Signal



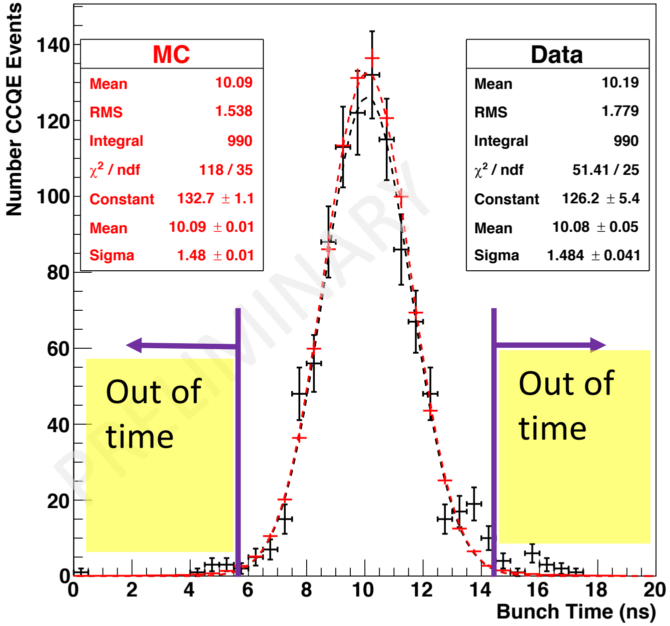
2ns Bunch Structure (μs)

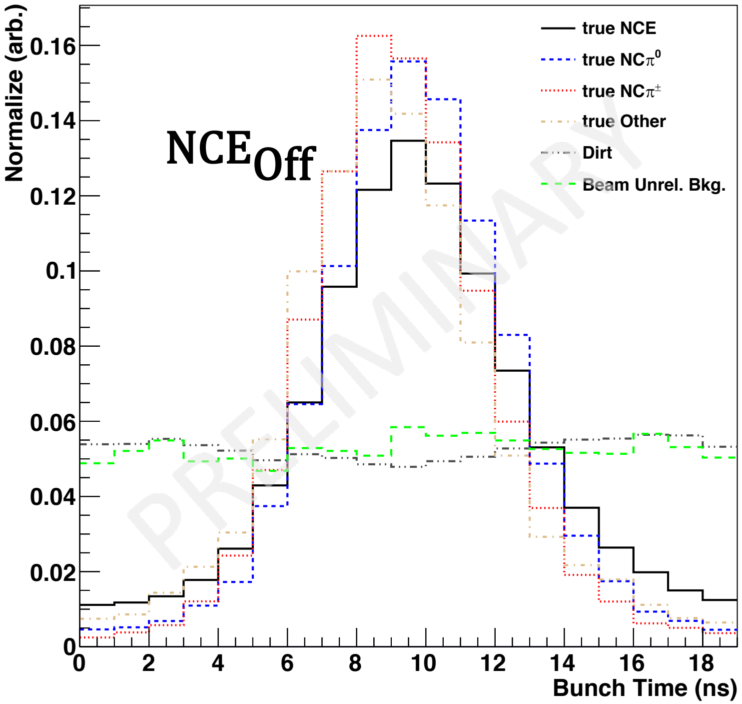
Fiber Optic

DAQ

New To Nucleon Analysis ("Time-of-Flight")

ν_μ CCQE$_{\mathrm{Off}}$ Bunch Time (ns)





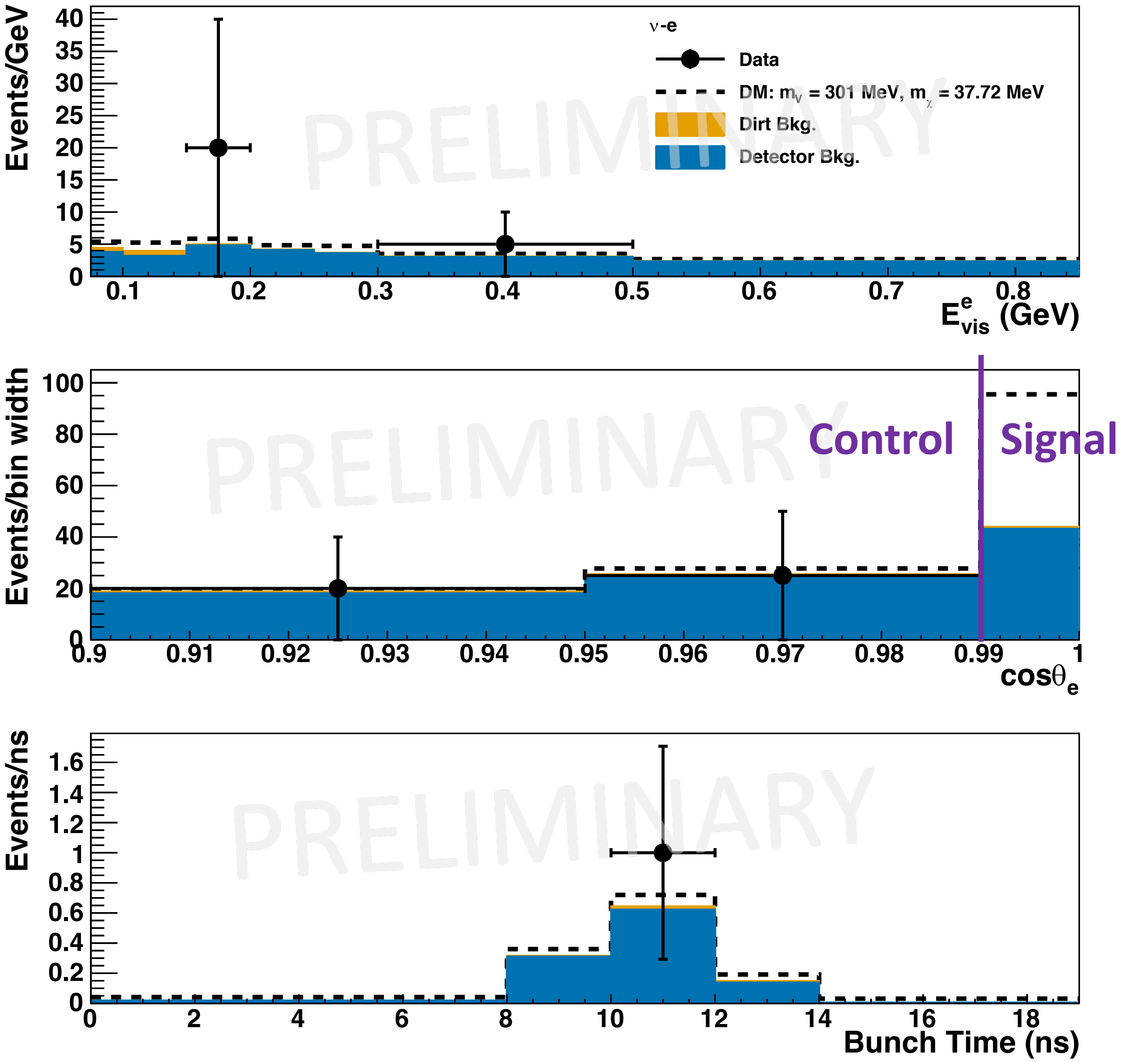
- **Time resolution of detector**
  - **Cherenkov ~1 ns**
  - **Scintillation ~4.5 ns**

For Full N Analysis:

- **Fit in "energy" and time to increase sensitivity to heavier masses**

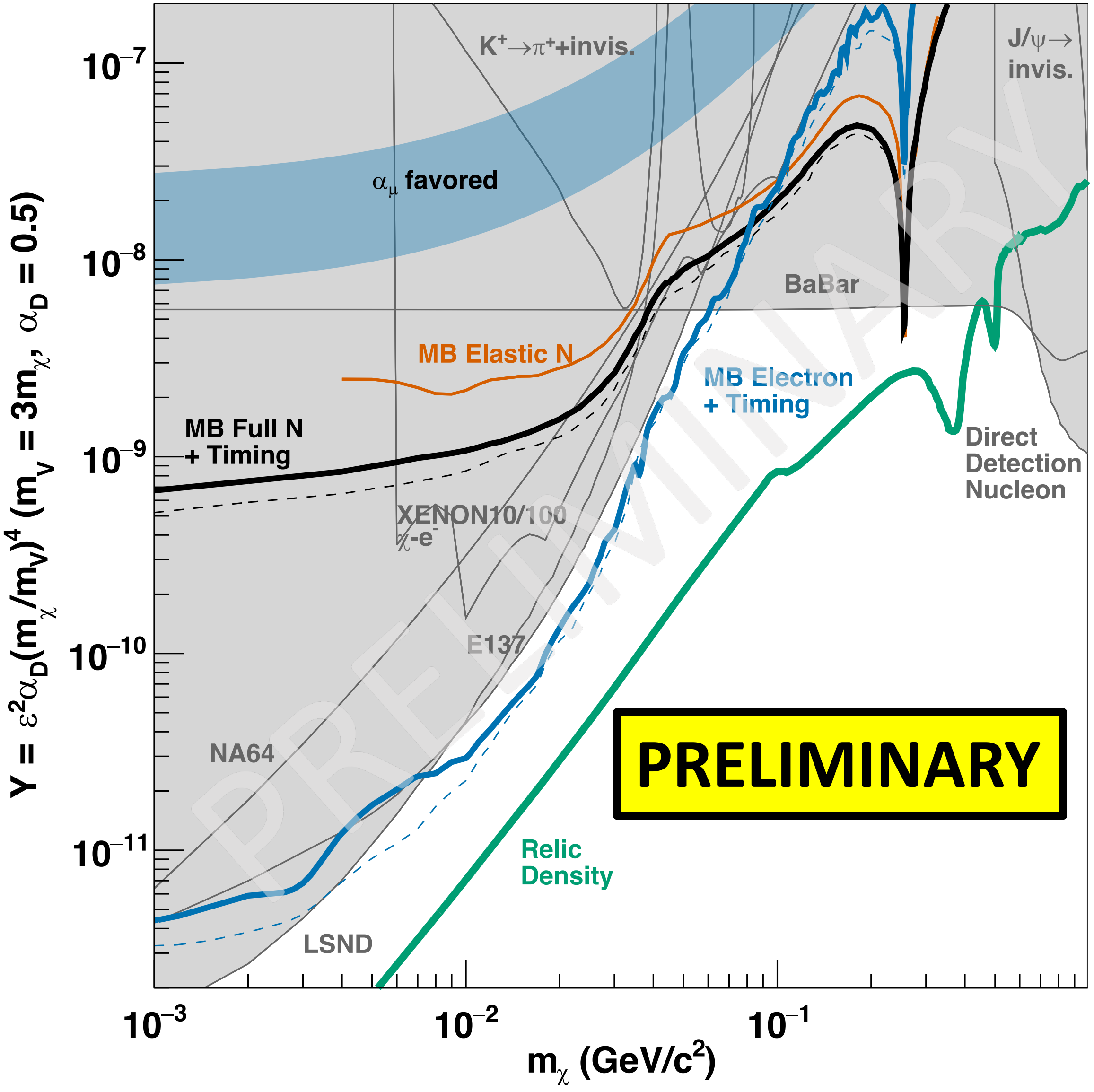
Electron Analysis

- Search for ν—electron neutral-current like interactions
- Outgoing electrons are very forward ($\cos\theta_e > 0.99$)
- Low Evis cut to remove Beam unrelated bkg.
- Beam related bkg. constrained by $0.9 \leq \cos\theta_e < 0.99$
- Statistical only fit in 3D
  - Evis
  - $\cos\theta_e$
  - Bunch Time



New 90% Confidence Limits

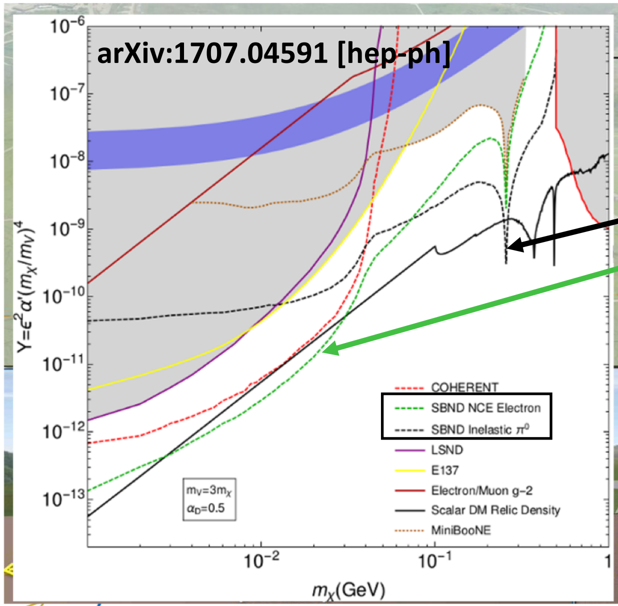
- No significant excess observed
- Results improved from 2017 PRL (MB Elastic N)
- Set world leading limits
- Sensitivity
  - Low mass ⇒ **Electron**
  - High mass ⇒ **Full N**
- **Paper under collaboration review**



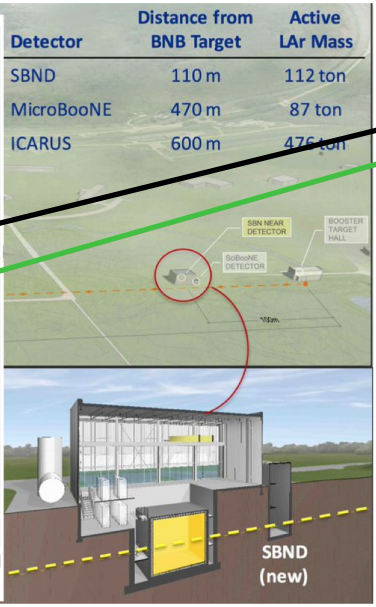
Dedicated SBN “Beam-Dump” Target

(Expression of Interest to 2017 PAC)

- A dedicated SBN “beam-dump” target would decrease the ν rate by another factor of 20
- Adding an extra target to the BNB in the dog leg region would allow simultaneous ν/beam-dump running
- **Increase SBN physics output at low cost**
- Positive response from PAC, seeking DOE funding

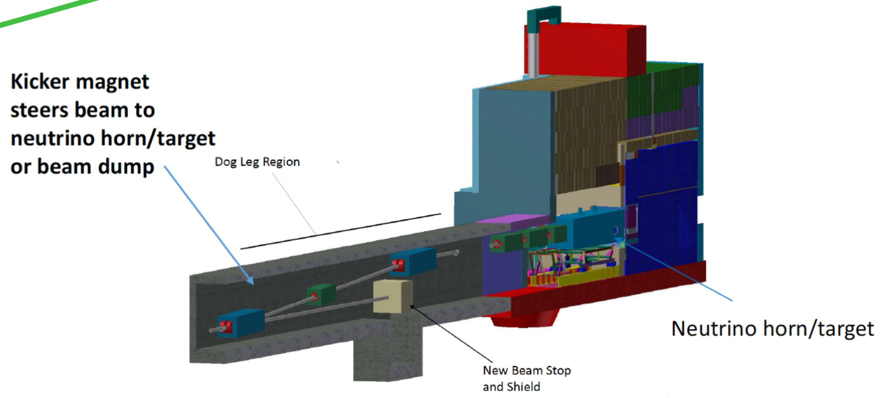


arXiv:1707.04591 [hep-ph]



Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

SBND: Start testing relic density line



Kicker magnet steers beam to neutrino horn/target or beam dump

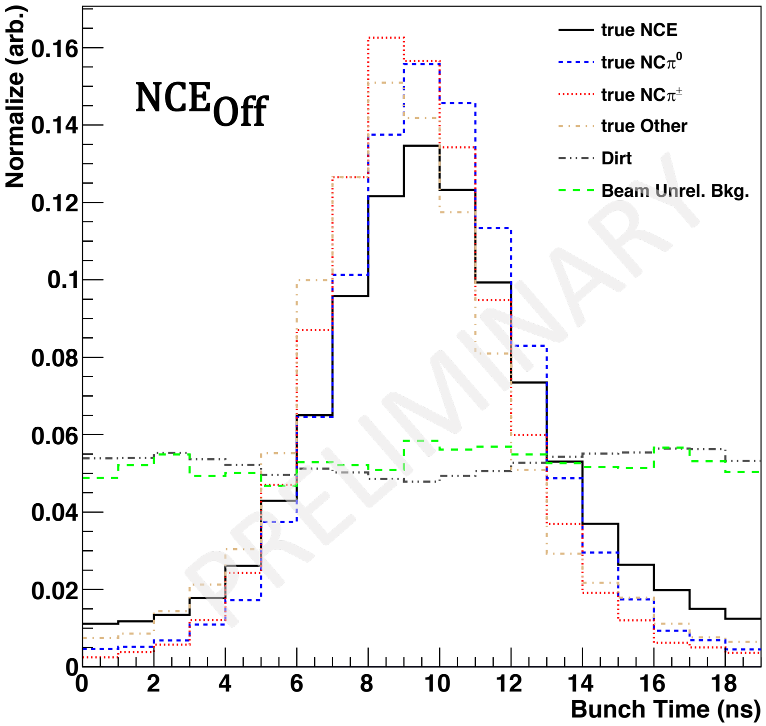
Summary

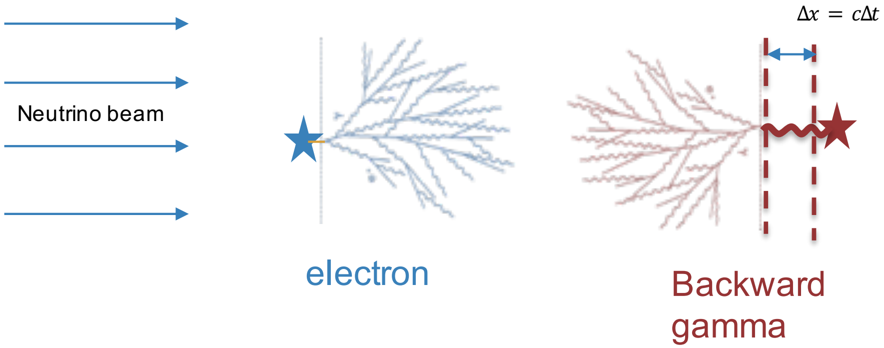
- The MiniBooNE detector has been running for ~ 15 years
- Accelerator division has provided $> 30\times10^{20}$ POT
- First cross-section measurement of a monoenergetic charged-current muon neutrino interaction (Kaon decay at rest)
- Doubled neutrino data
- Oscillation analysis now **CONSISTENT** in L/E and appearance probability with LSND
- Repurposed a neutrino beamline/detector to search for sub-GeV dark matter
- DM search sets new world limits with DM masses between 5 and 50 $\mathrm{MeV}/\mathrm{c}^2$
- Seeking DOE funds for dedicated SBN "beam-dump" target
- FNAL in great position to continue being world leaders in searches for accelerator-produced dark matter

Backup Slides

“Time-of-Flight” Constraining Backgrounds

- Different true event types have different timing structure
- Gammas travel before interacting
- Beam unrelated background and dirt are “flat” in time because they are uncorrelated with the beam
- Can use this info to constrain or remove background

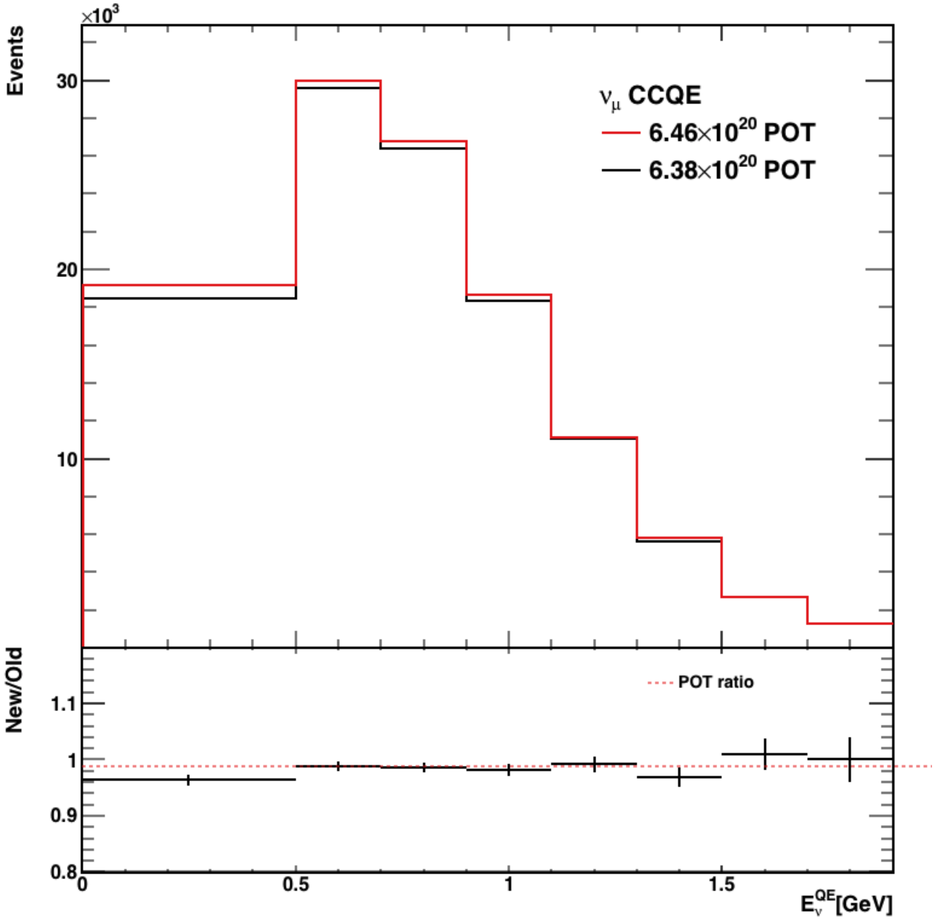


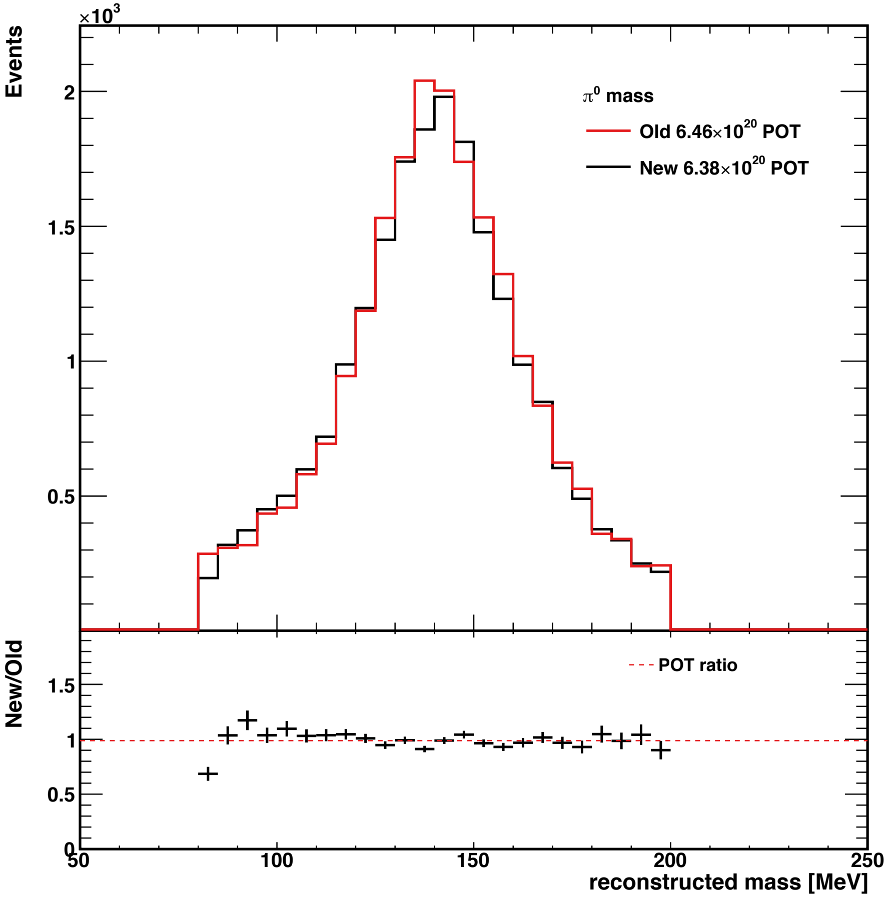


For Full N Analysis:

- **Fit in “energy” and time to increase sensitivity to heavier masses**

ν_μ CCQE and m_{π^0} Stability Checks

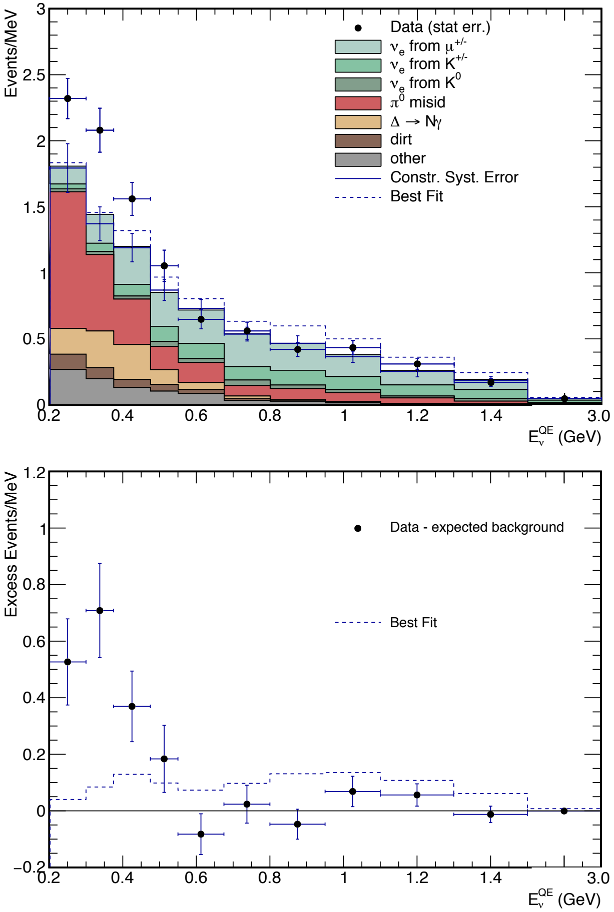




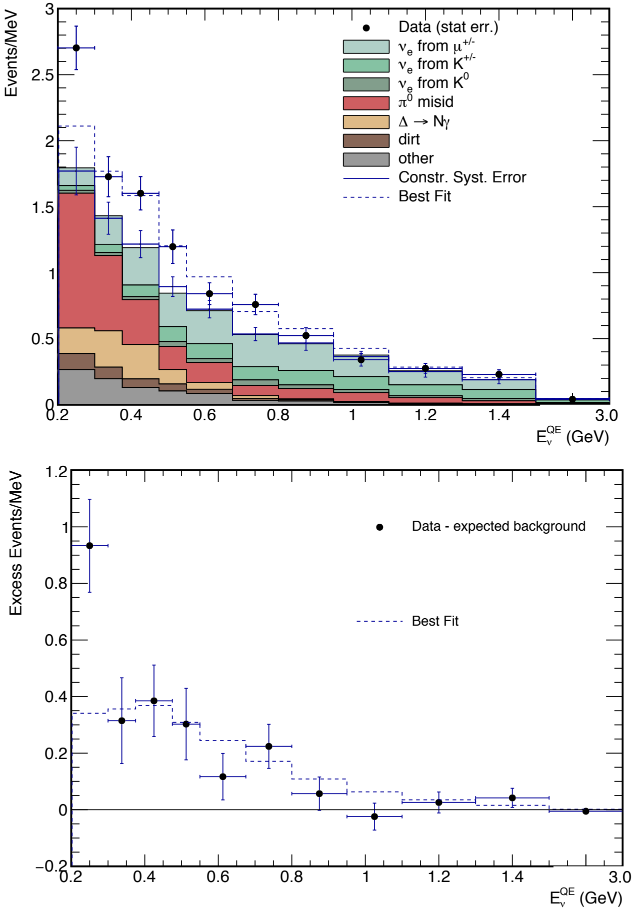
- Detector remains stable within 2% for data sets separated by ~8 years
- Similar check is done for Michel electrons

Comparing New and Old ν Data

Old: 6.46×10^{20} POT



New : 6.38×10^{20} POT



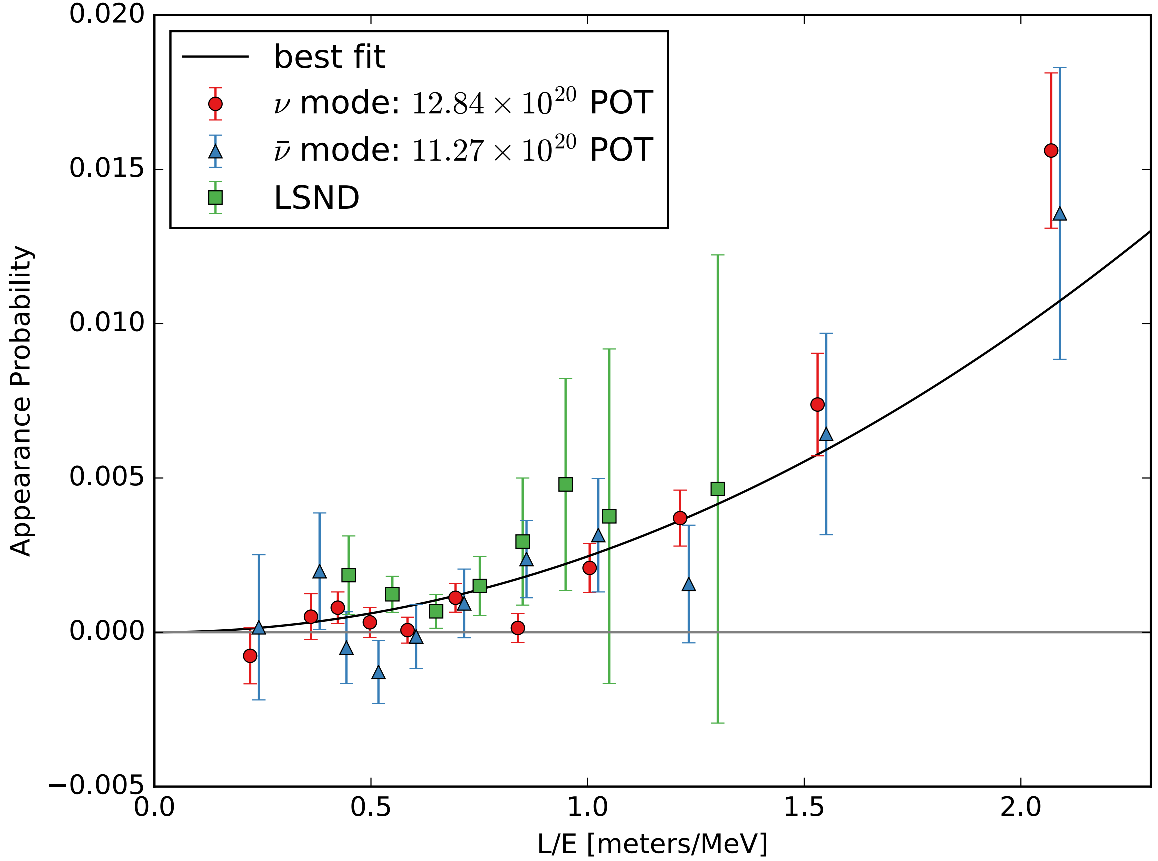
New Data is during MicroBooNE running

Compare to average excess

- Old ~ 1σ low
- New ~ 1σ high

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

Compare L/E to LSND



- Average E_ν^{QE} of each bin is used
- MiniBooNE neutrino, MiniBooNE antineutrino and LSND are **CONSISTENT** in appearance probability and L/E

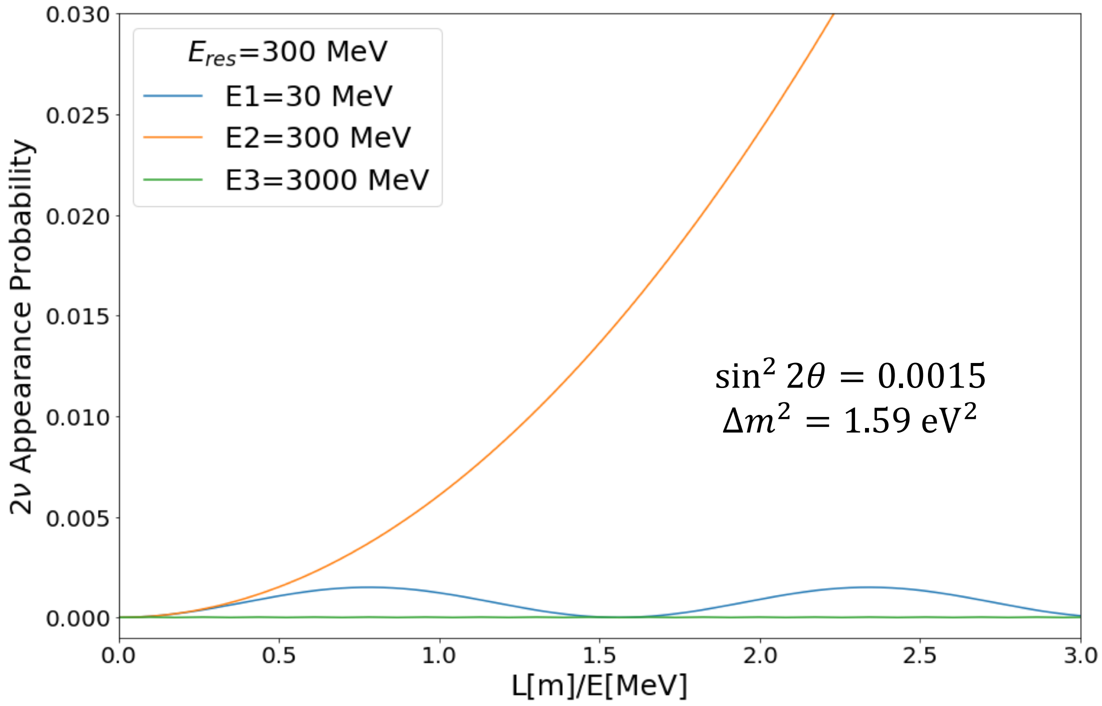
Example of an Empirical Exotic Model: An MSW-Like Resonance

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

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

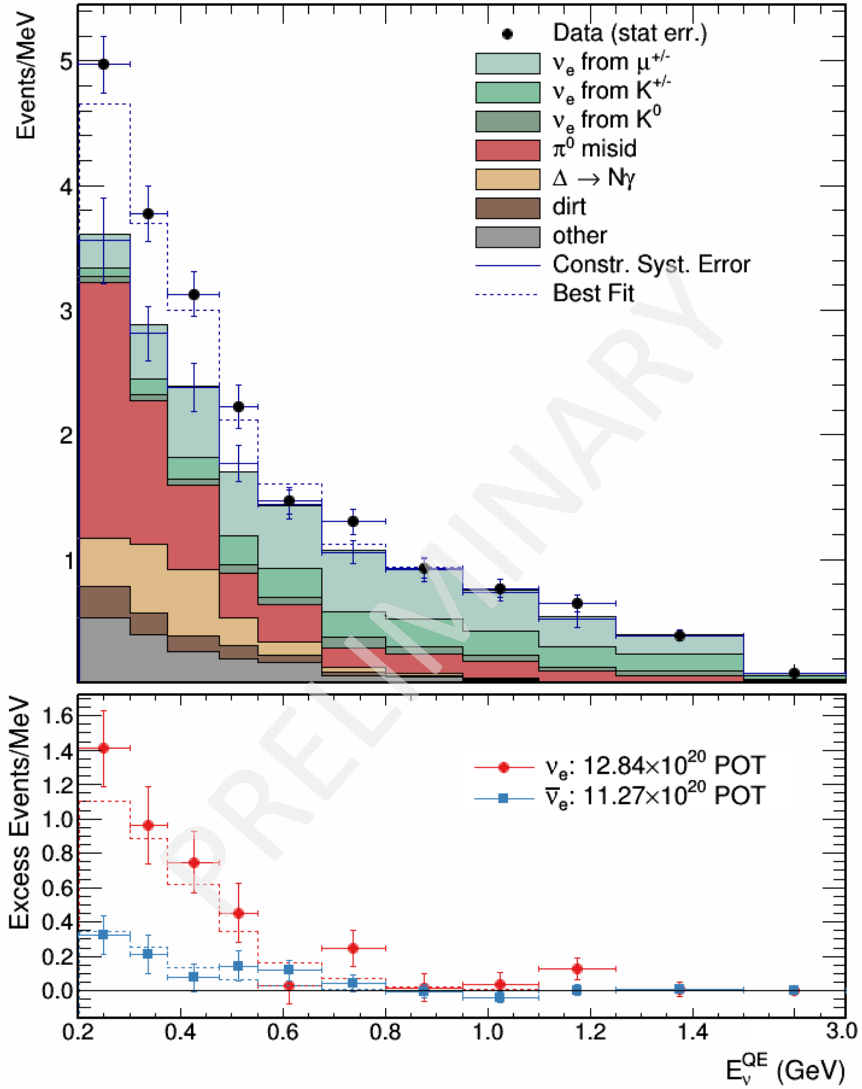
$$P(E \ll E_{res}, L) \approx \sin^2 2\theta \times \sin^2(1.267 \Delta m^2 L/E)$$

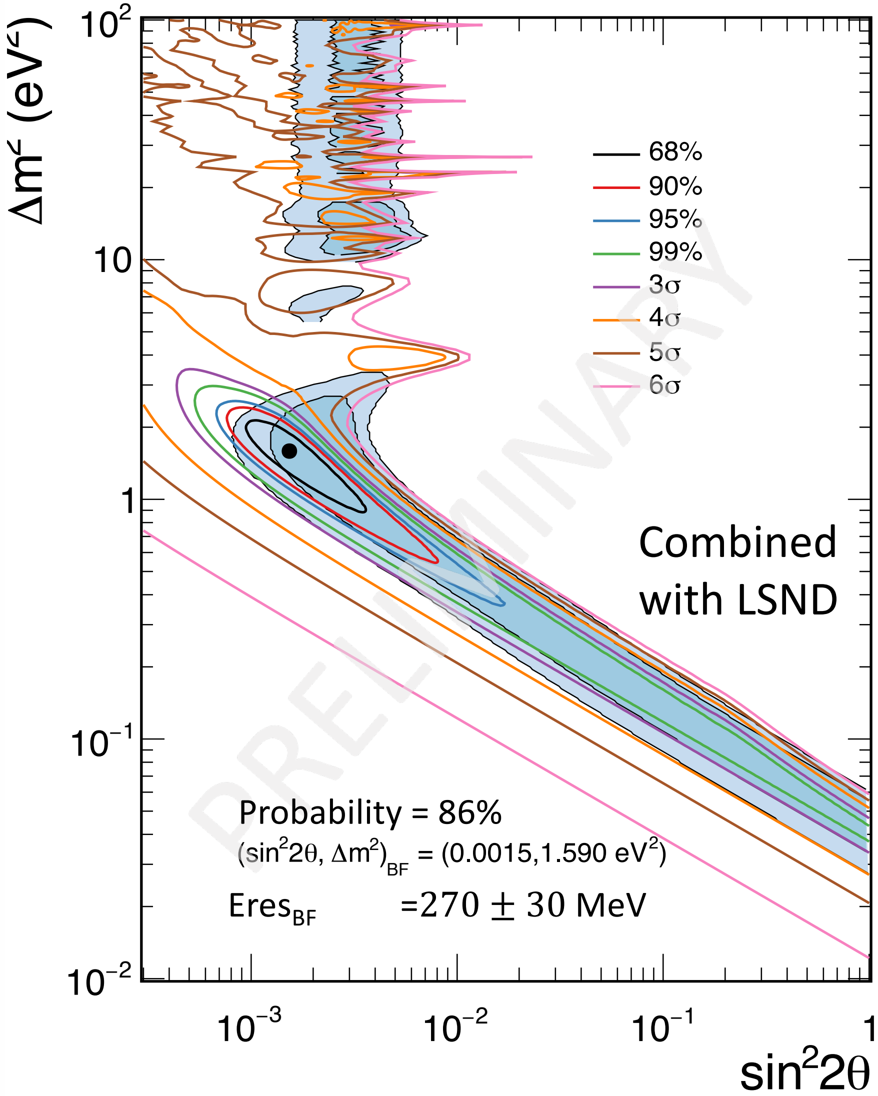
$$P(E \gg E_{res}, L) \approx 0$$



Similar to:
arXiv:1712.08019
arXiv:1202.1024

An MSW-Like Resonance Model





Combined with LSND

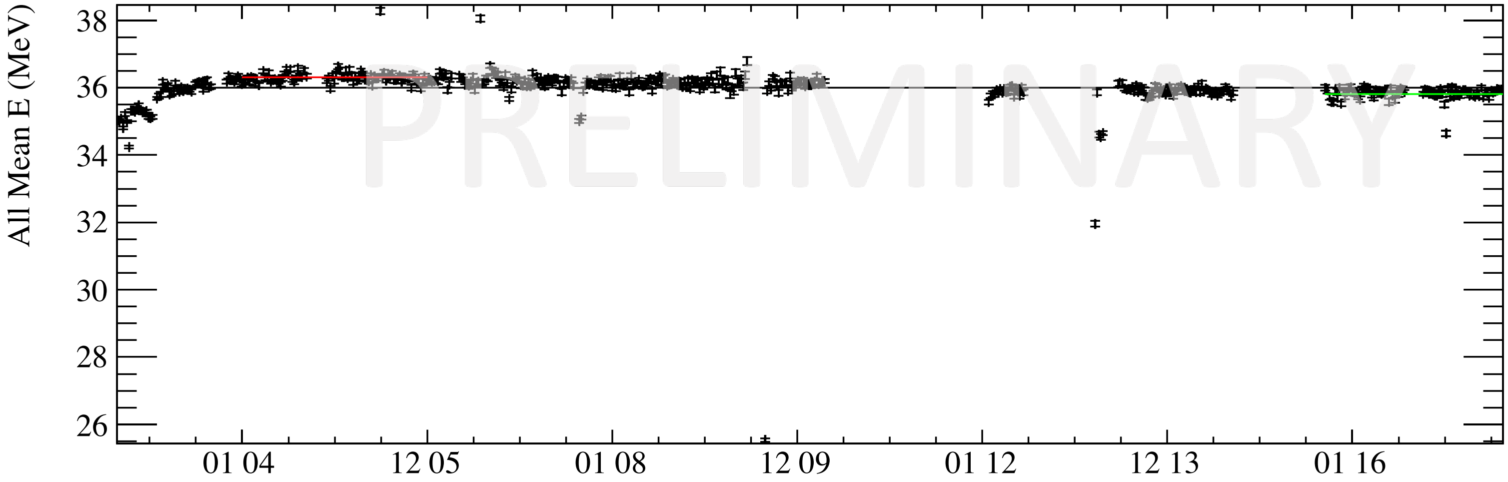
Probability = 86%

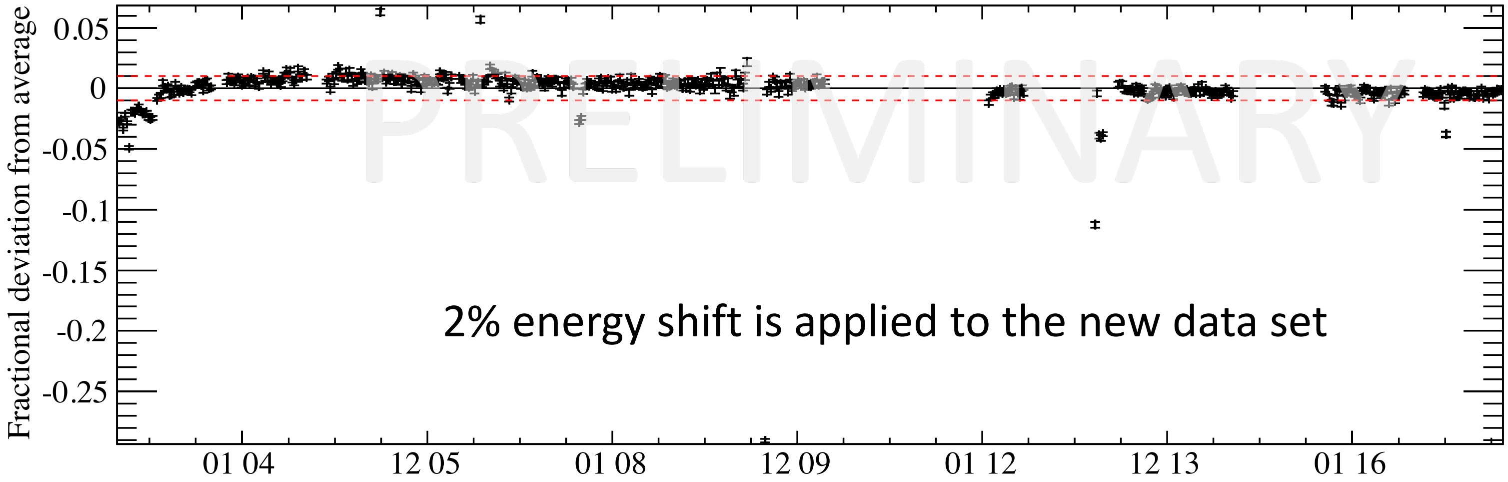
$(\sin^2 2\theta, \Delta m^2)_{BF} = (0.0015, 1.590\ \text{eV}^2)$

$\text{Eres}_{BF} = 270 \pm 30$ MeV

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

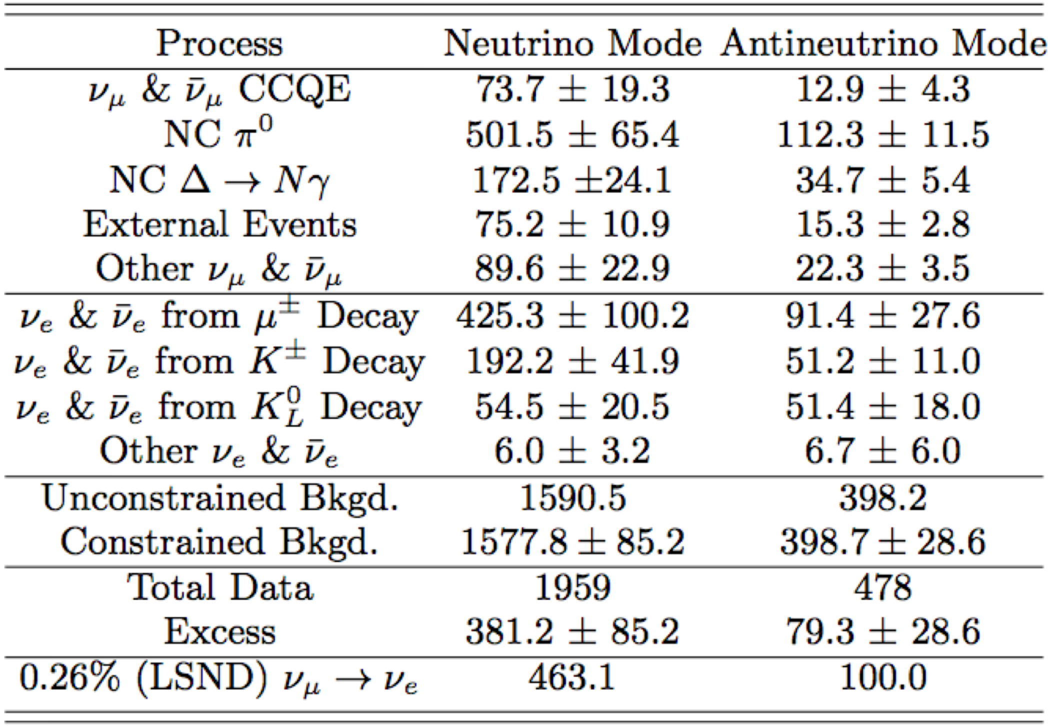
Michel electron





2% energy shift is applied to the new data set

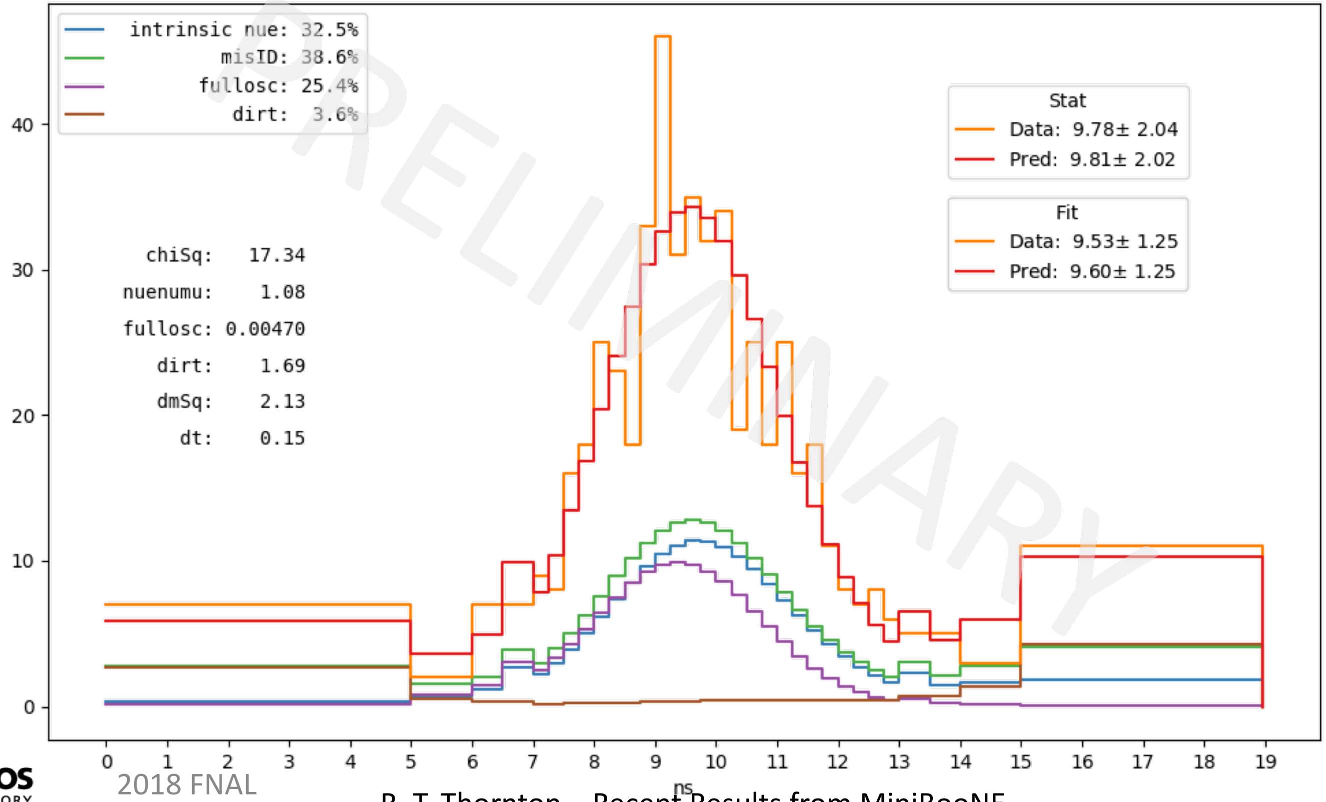
Excess



Process	Neutrino Mode	Antineutrino Mode
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
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	398.2
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

Could it be Dirt?

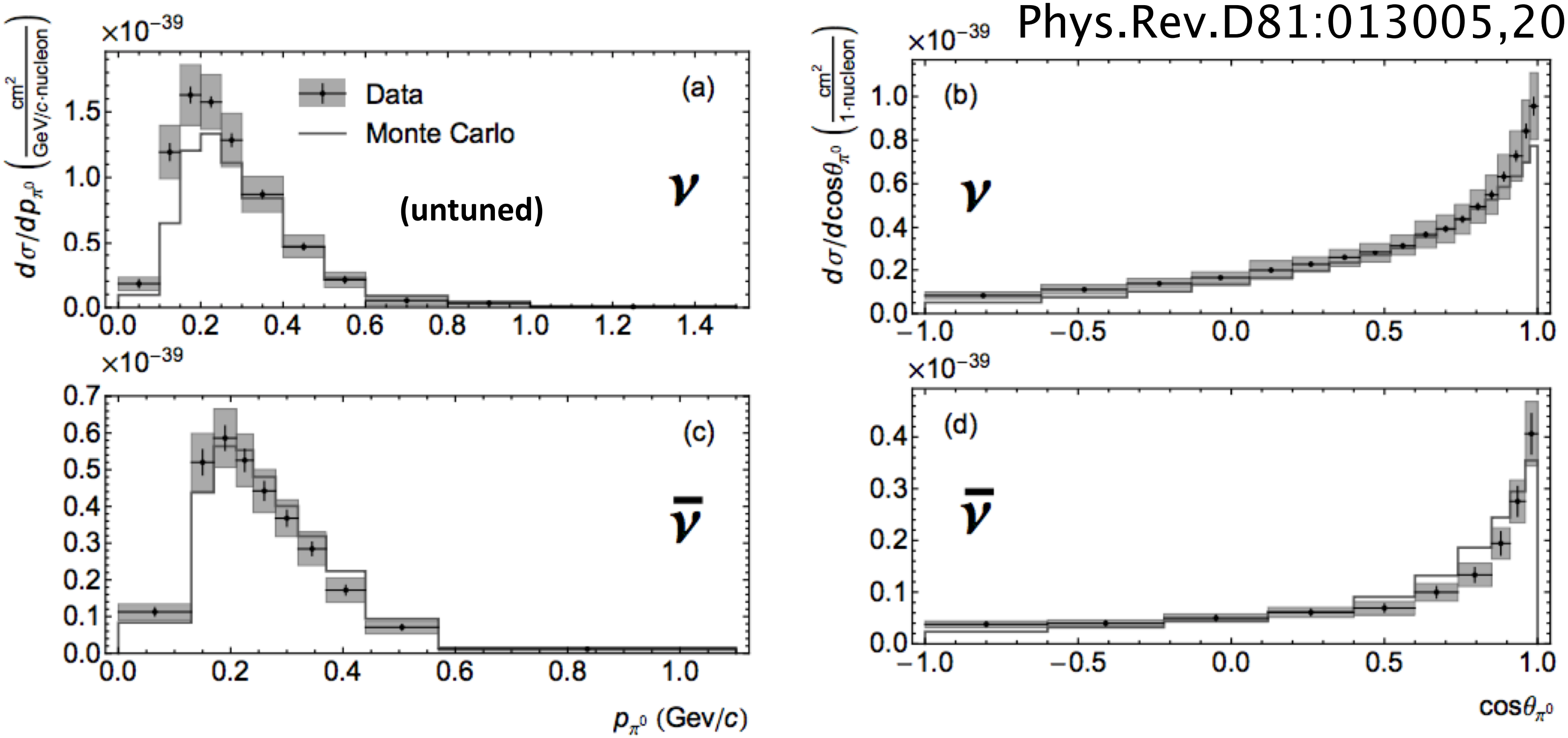
- Constrained at ~10% by internal measurements
- Time-of-flight measurement is consistent with dirt background estimate of 4%



Could it be misid π^0?

- π^0s are tuned to *in-situ* measurements

Phys.Rev.D81:013005,2010



(untuned)

FIG. 7: Flux-averaged absolute differential cross sections for NC $1\pi^0$ production on CH_2 including the effects of FSI. Data are shown as black dots with statistical error bars and systematic error boxes. The dark-gray line is the Monte Carlo prediction[33] using R-S models of single pion production[2, 5] modified as described in the text. (a) $\frac{d\sigma}{dp_{\pi^0}}$ for ν_μ-induced production. (b) $\frac{d\sigma}{d\cos\theta_{\pi^0}}$ for ν_μ-induced production. (c) $\frac{d\sigma}{dp_{\pi^0}}$ for $\bar{\nu}_\mu$-induced production. (d) $\frac{d\sigma}{d\cos\theta_{\pi^0}}$ for $\bar{\nu}_\mu$-induced production. The numerical values for the cross sections appear in Appendix C and are also available at the MiniBooNE website[43].

Could it be intrinsic ν_e?

- intrinsic ν_e has small contribution at low energy
- intrinsic ν_e is constrained by:
  - well-measured ν_μ CCQE data
  - SciBooNE measurement of ν_μ from kaon decay at the BNB

Phys.Rev.D81:092005,2010

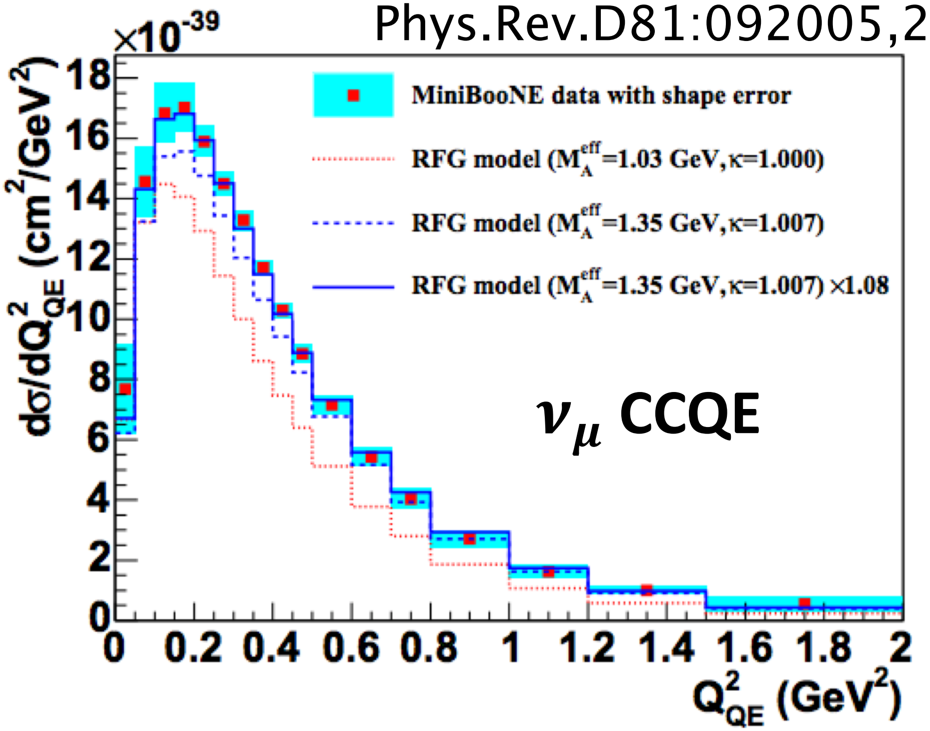


FIG. 14: (Color online). Flux-integrated single differential cross section per target neutron for the ν_μ CCQE process. The measured values are shown as points with the shape error as shaded bars. Calculations from the NUANCE RFG model with different assumptions for the model parameters are shown as histograms. Numerical values are provided in Table IX in the Appendix.

Could it be NC gamma?

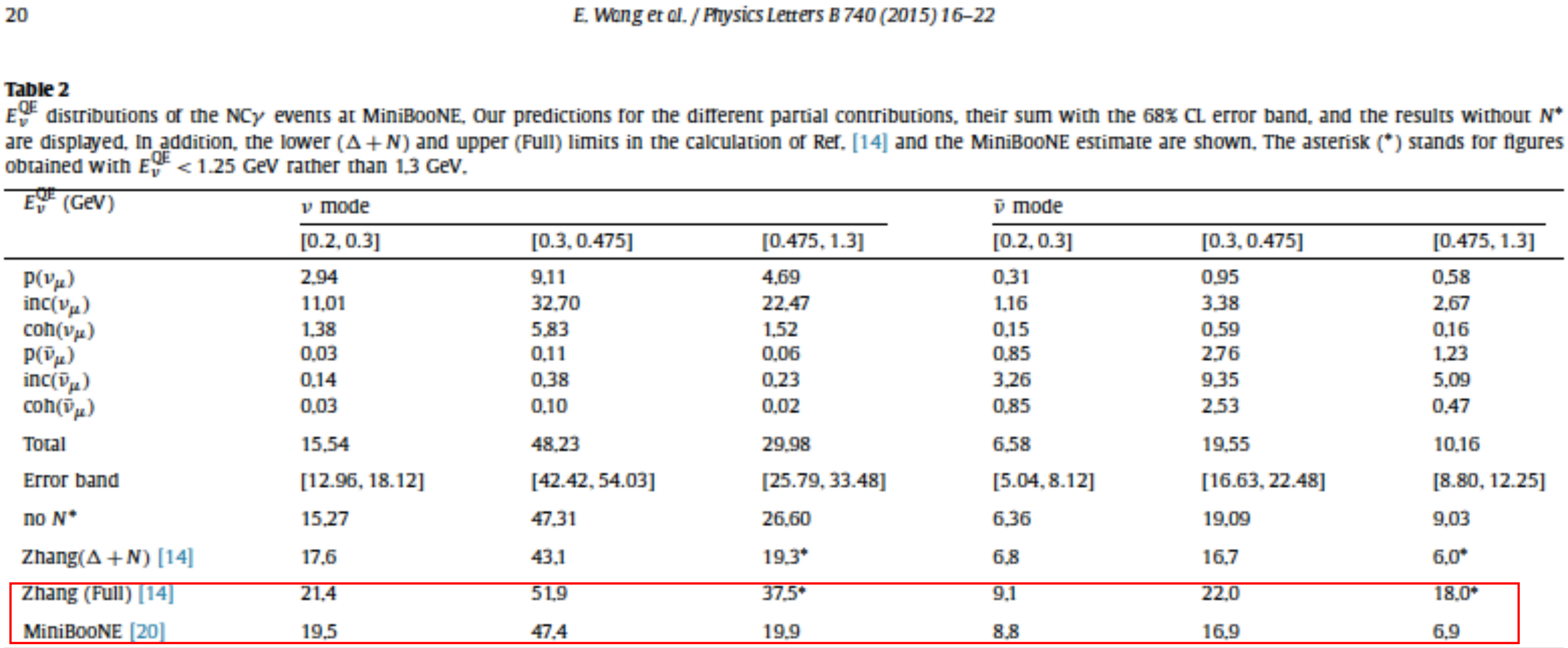


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Table 2
$E_\nu^{\rm QE}$ distributions of the NCγ events at MiniBooNE. Our predictions for the different partial contributions, their sum with the 68% CL error band, and the results without N^* are displayed. In addition, the lower ($\Delta + N$) and upper (Full) limits in the calculation of Ref. [14] and the MiniBooNE estimate are shown. The asterisk (*) stands for figures obtained with $E_\nu^{\rm QE} < 1.25$ GeV rather than 1.3 GeV.

$E_\nu^{\rm QE}$ (GeV)	ν mode			$\bar{\nu}$ mode		
	[0.2, 0.3]	[0.3, 0.475]	[0.475, 1.3]	[0.2, 0.3]	[0.3, 0.475]	[0.475, 1.3]
p(ν_μ)	2.94	9.11	4.69	0.31	0.95	0.58
inc(ν_μ)	11.01	32.70	22.47	1.16	3.38	2.67
coh(ν_μ)	1.38	5.83	1.52	0.15	0.59	0.16
p($\bar{\nu}_\mu$)	0.03	0.11	0.06	0.85	2.76	1.23
inc($\bar{\nu}_\mu$)	0.14	0.38	0.23	3.26	9.35	5.09
coh($\bar{\nu}_\mu$)	0.03	0.10	0.02	0.85	2.53	0.47
Total	15.54	48.23	29.98	6.58	19.55	10.16
Error band	[12.96, 18.12]	[42.42, 54.03]	[25.79, 33.48]	[5.04, 8.12]	[16.63, 22.48]	[8.80, 12.25]
no N^*	15.27	47.31	26.60	6.36	19.09	9.03
Zhang($\Delta + N$) [14]	17.6	43.1	19.3*	6.8	16.7	6.0*
Zhang (Full) [14]	21.4	51.9	37.5*	9.1	22.0	18.0*
MiniBooNE [20]	19.5	47.4	19.9	8.8	16.9	6.9

Theoretical Estimates for NC gamma production
agree well with MiniBooNE estimates

Could it be NC gamma?

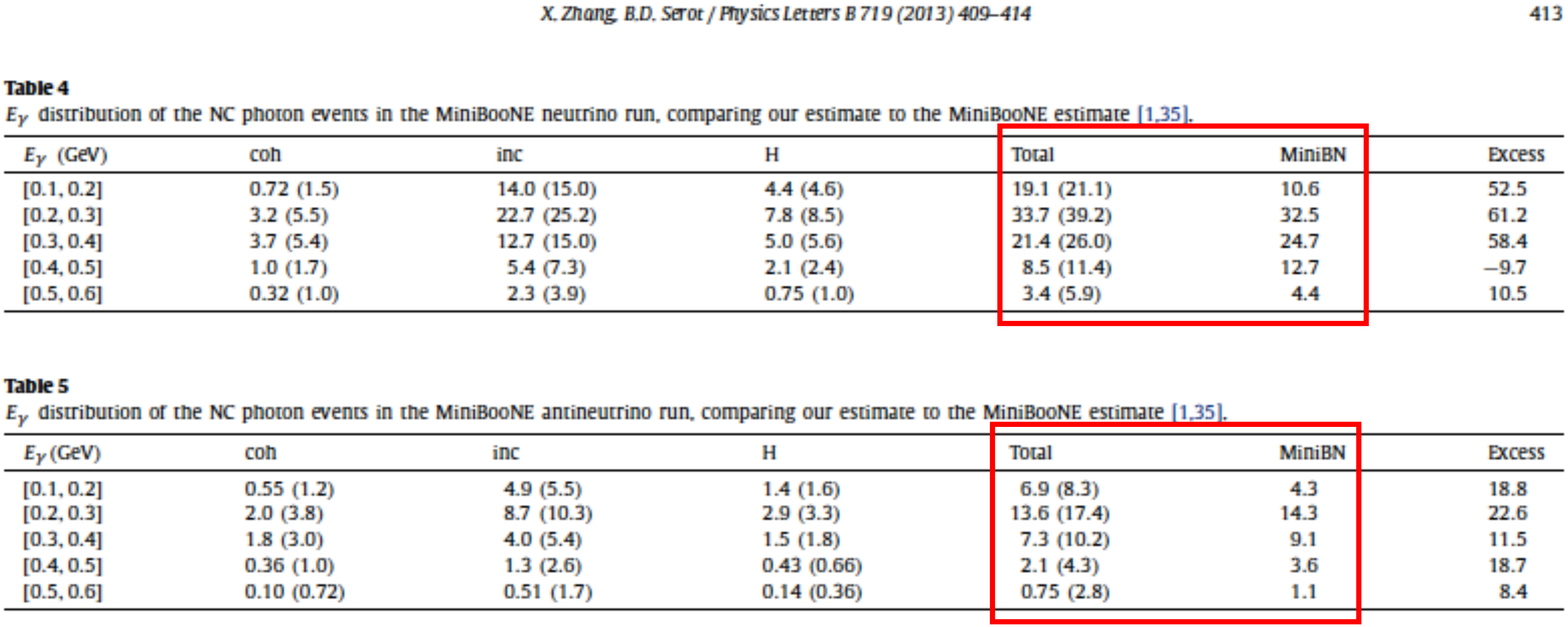

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Table 4
E_γ distribution of the NC photon events in the MiniBooNE neutrino run, comparing our estimate to the MiniBooNE estimate [1,35].

E_γ (GeV)	coh	inc	H	Total	MiniBN	Excess
[0.1, 0.2]	0.72 (1.5)	14.0 (15.0)	4.4 (4.6)	19.1 (21.1)	10.6	52.5
[0.2, 0.3]	3.2 (5.5)	22.7 (25.2)	7.8 (8.5)	33.7 (39.2)	32.5	61.2
[0.3, 0.4]	3.7 (5.4)	12.7 (15.0)	5.0 (5.6)	21.4 (26.0)	24.7	58.4
[0.4, 0.5]	1.0 (1.7)	5.4 (7.3)	2.1 (2.4)	8.5 (11.4)	12.7	−9.7
[0.5, 0.6]	0.32 (1.0)	2.3 (3.9)	0.75 (1.0)	3.4 (5.9)	4.4	10.5

Table 5
E_γ distribution of the NC photon events in the MiniBooNE antineutrino run, comparing our estimate to the MiniBooNE estimate [1,35].

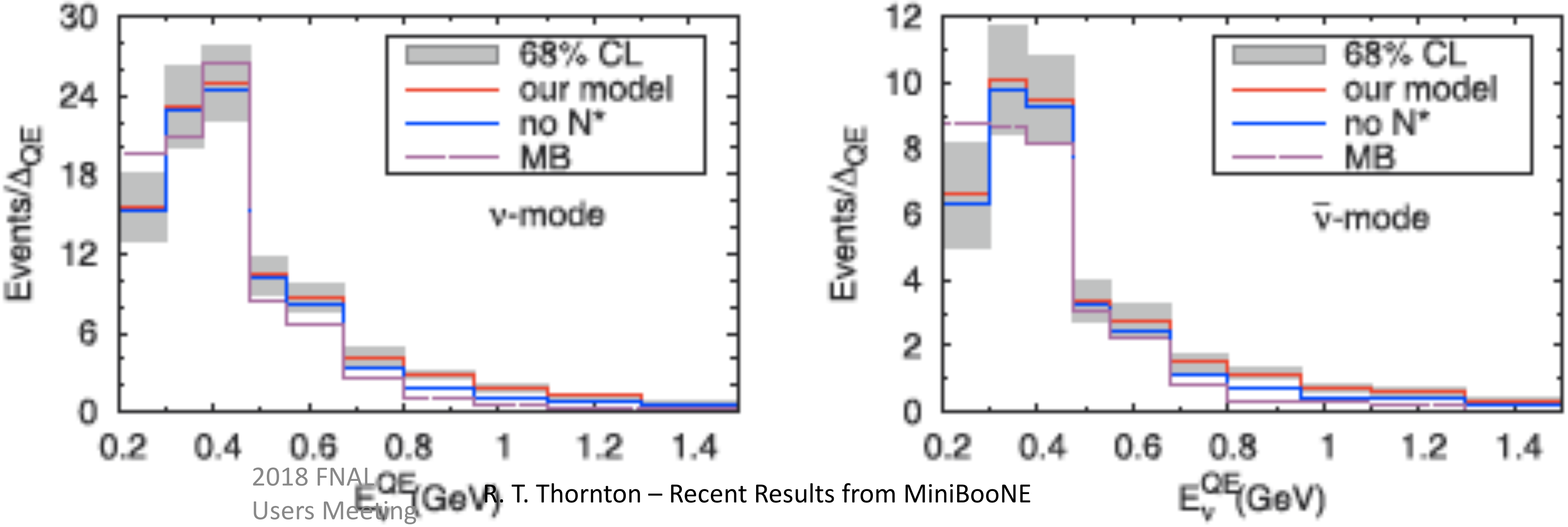
E_γ (GeV)	coh	inc	H	Total	MiniBN	Excess
[0.1, 0.2]	0.55 (1.2)	4.9 (5.5)	1.4 (1.6)	6.9 (8.3)	4.3	18.8
[0.2, 0.3]	2.0 (3.8)	8.7 (10.3)	2.9 (3.3)	13.6 (17.4)	14.3	22.6
[0.3, 0.4]	1.8 (3.0)	4.0 (5.4)	1.5 (1.8)	7.3 (10.2)	9.1	11.5
[0.4, 0.5]	0.36 (1.0)	1.3 (2.6)	0.43 (0.66)	2.1 (4.3)	3.6	18.7
[0.5, 0.6]	0.10 (0.72)	0.51 (1.7)	0.14 (0.36)	0.75 (2.8)	1.1	8.4

Could it be NC gamma?

Single photon events from neutral current interactions at MiniBooNE

En Wang, Luis Alvarez-Ruso*, Juan Nieves

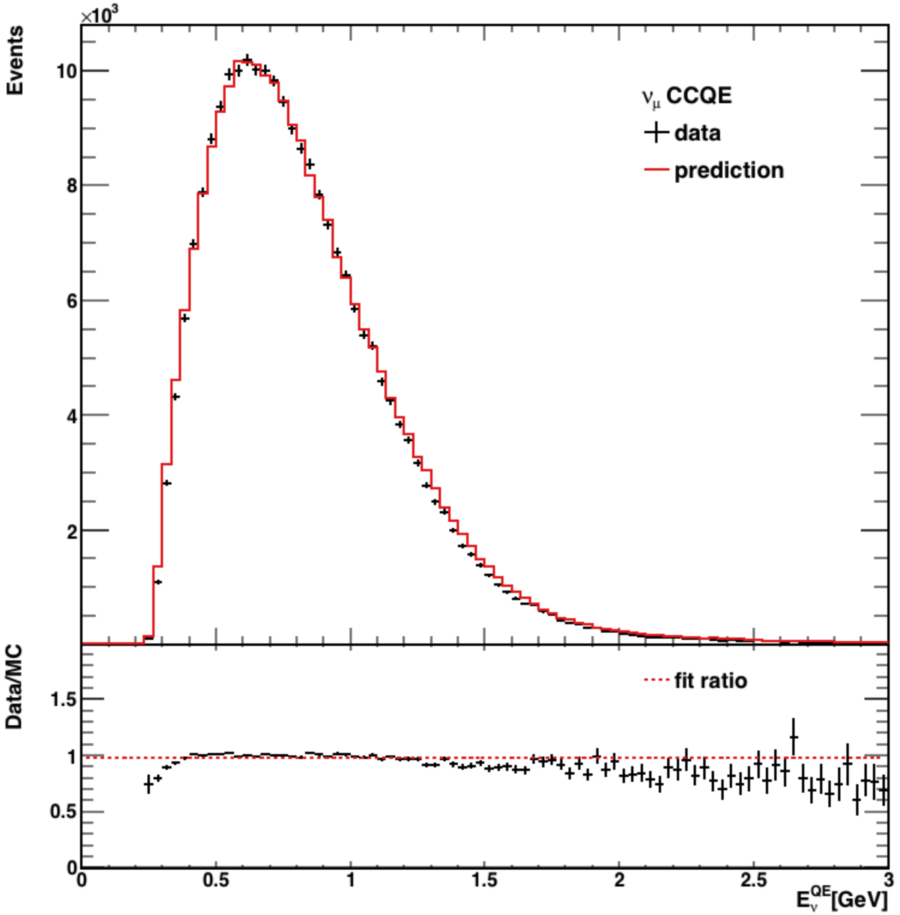
Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Universidad de Valencia, Institutos de Investigación de Paterna, Apartado 22085, E-46071 Valencia, Spain

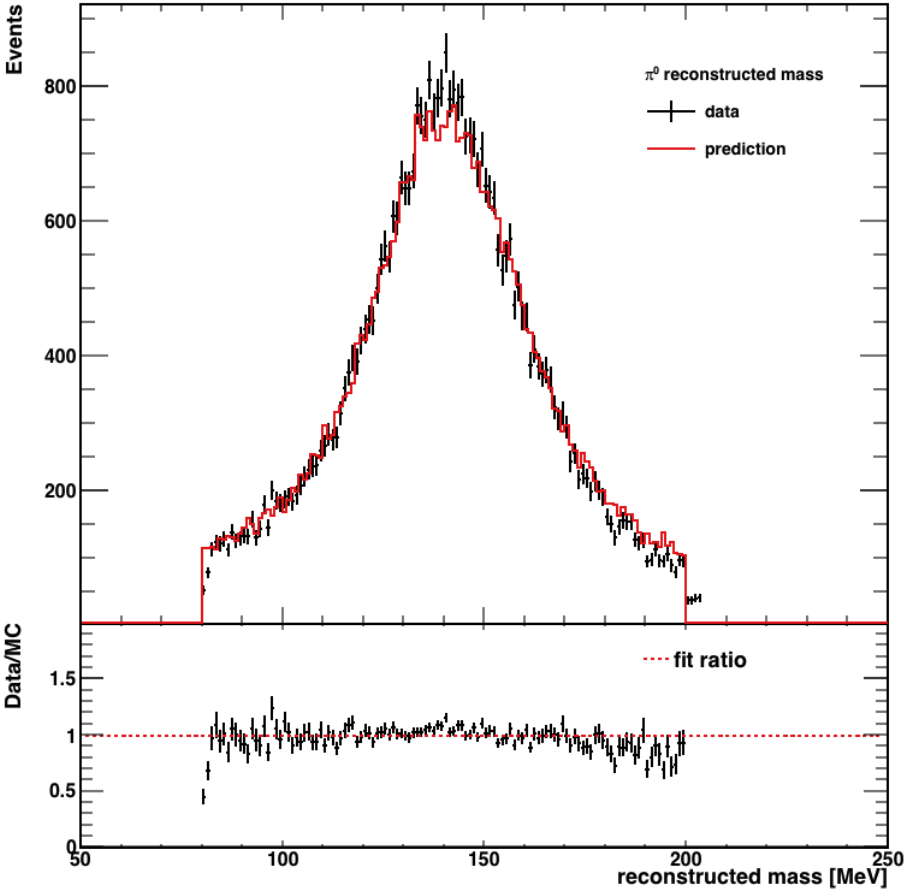


Could it be nuclear effects?

- Nuclear effect cannot explain the excess, since it’s normalized to Numu CC. However, it can affect the reconstructed energy.

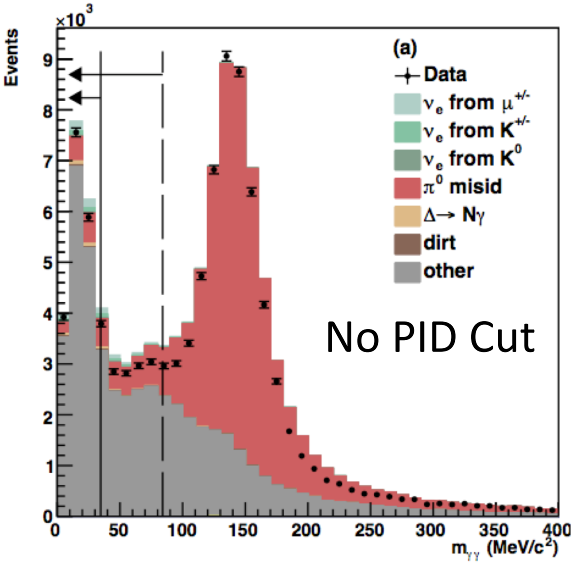
ν_μ CCQE and m_{π^0} : Data vs MC

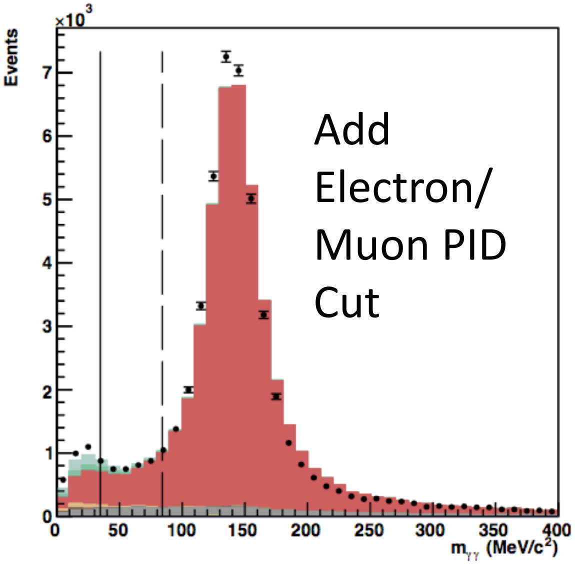


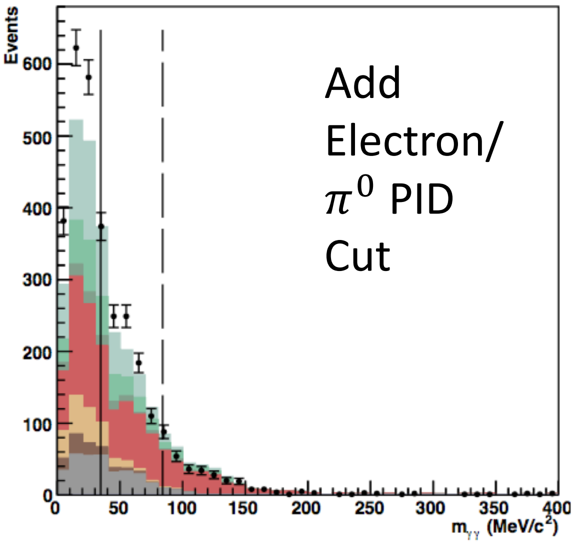


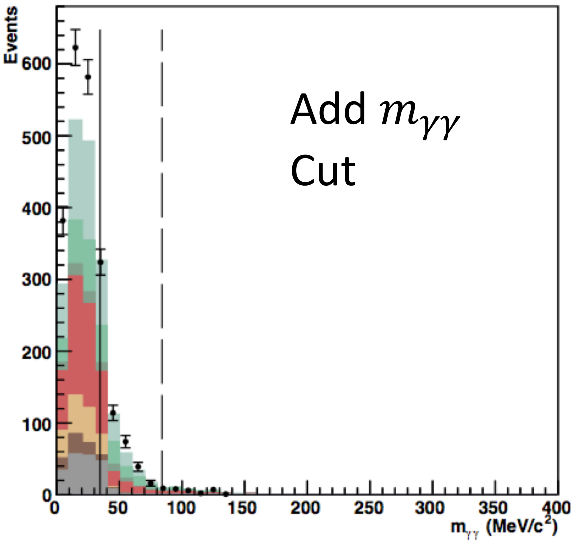
MiniBooNE Detector Well Understood

- 26 papers (4900+ citations)
- Measured cross section results used to constrain background channels to the oscillation analysis
- Example is the reconstructed $m_{\gamma\gamma}$
- Before any oscillation PID cuts, there is good agreement between data and simulation
  - After applying results from cross section analyses


No PID Cut


Add Electron/ Muon PID Cut


Add Electron/ π^0 PID Cut


Add $m_{\gamma\gamma}$ Cut

Data vs MC (Selection Process)

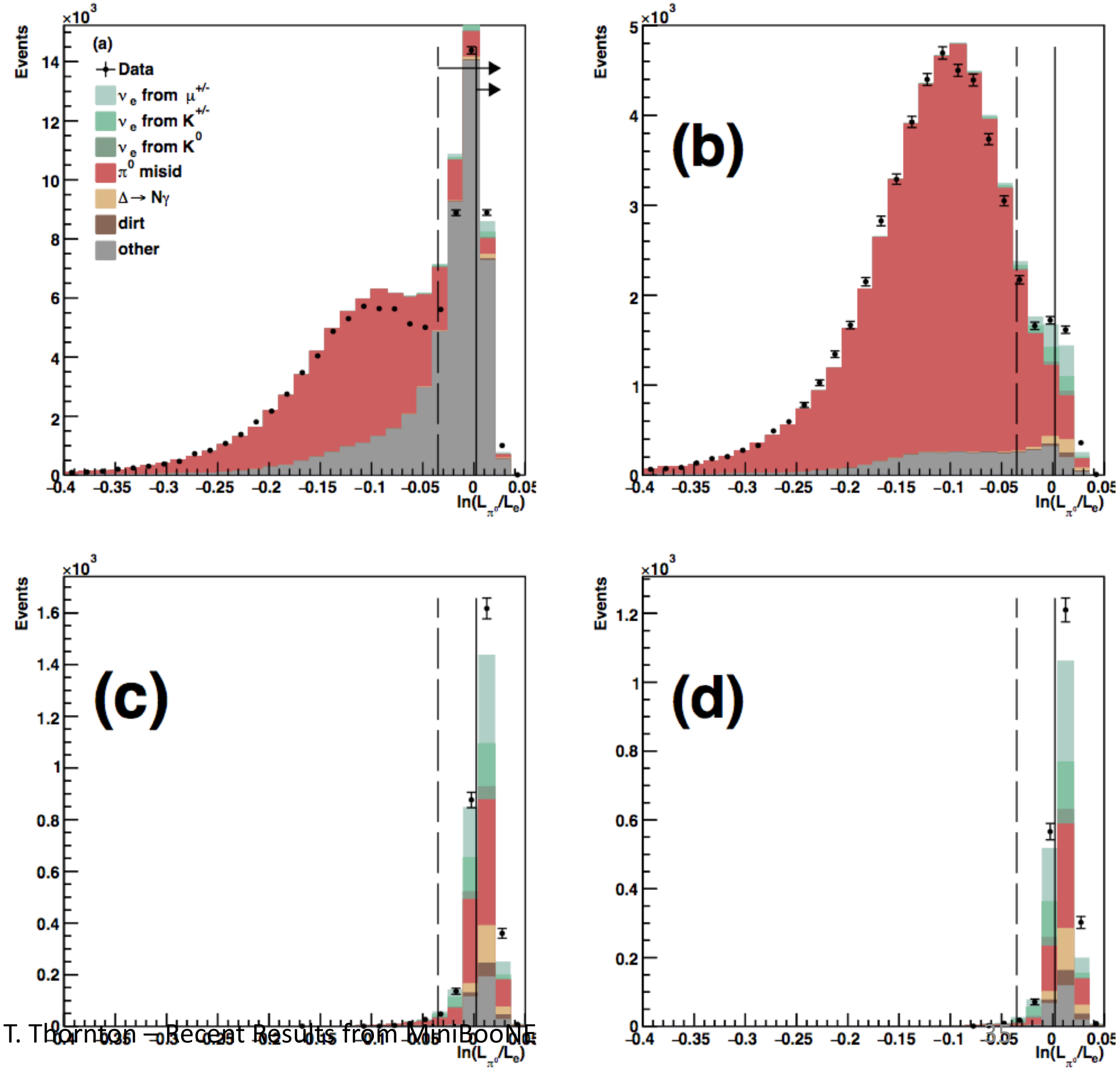
- e-π likelihood is shown
- Cuts are applied in the order of

a. no PID cut

b. e-μ cut

c. e-π cut

d. $m_{\gamma\gamma}$ cut



Data vs MC (Selection Process)

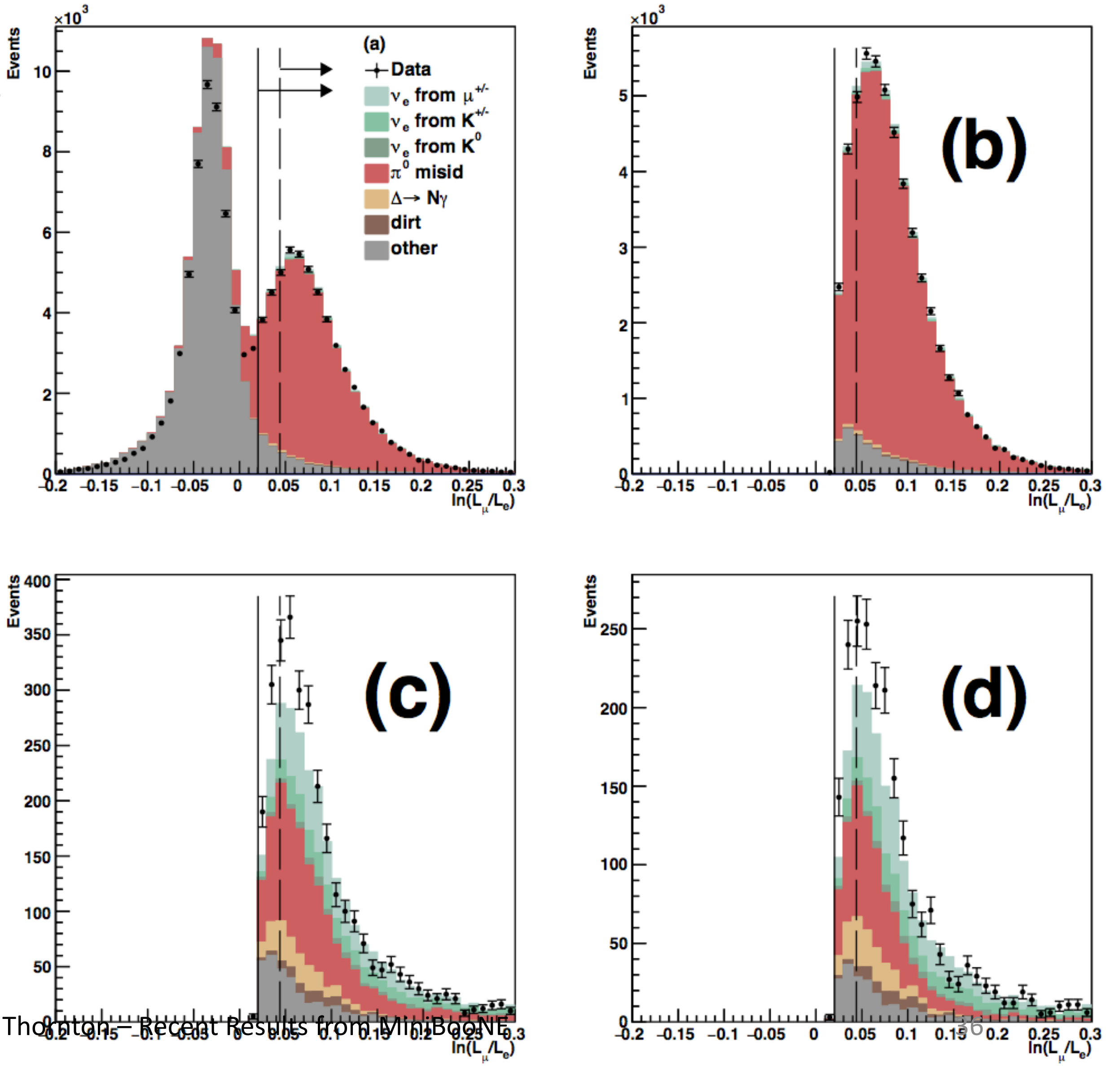
- e-μ likelihood is shown
- Cuts are applied in the order of

a. no PID cut

b. e-μ cut

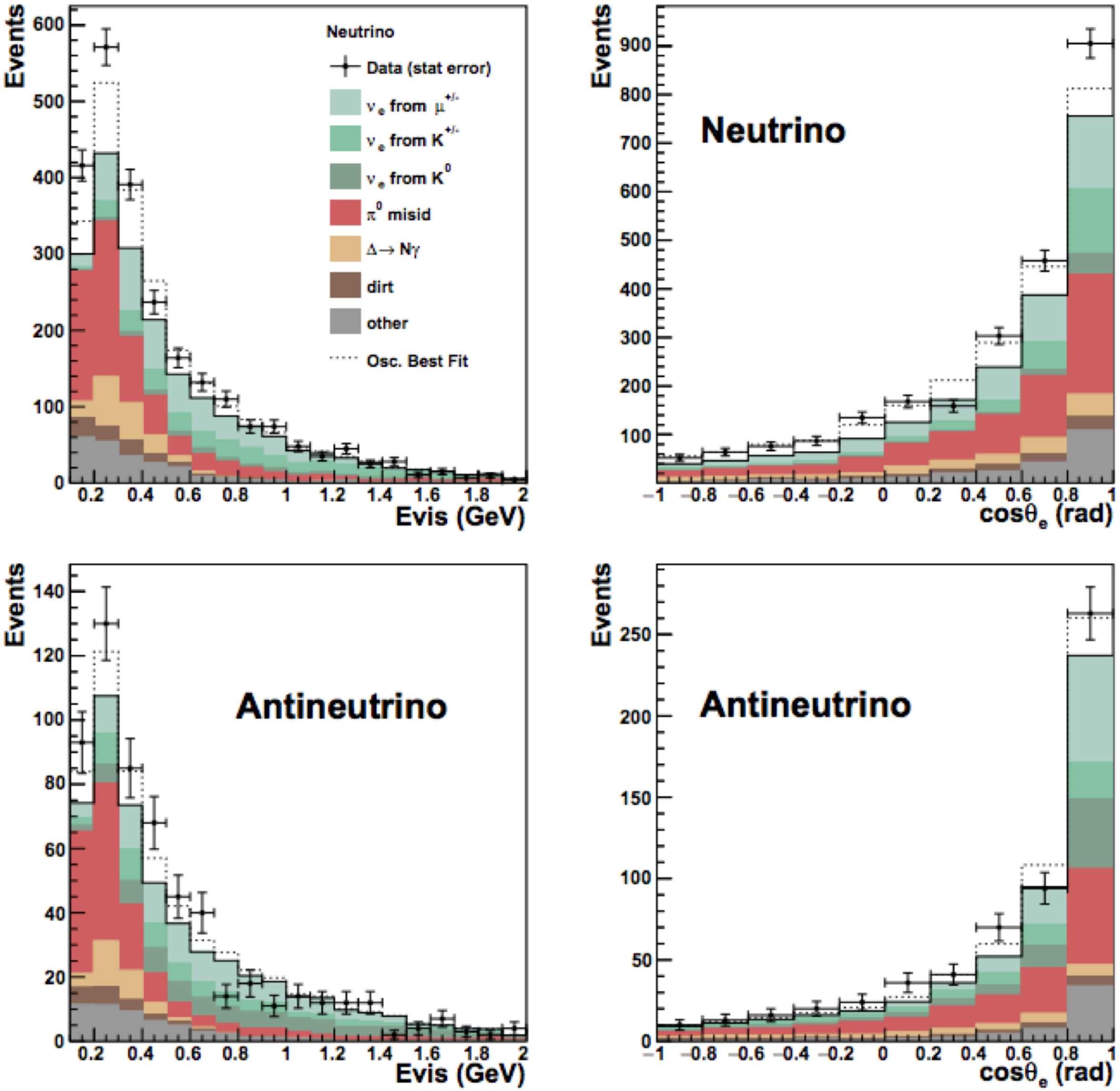
c. e-π cut

d. $m_{\gamma\gamma}$ cut

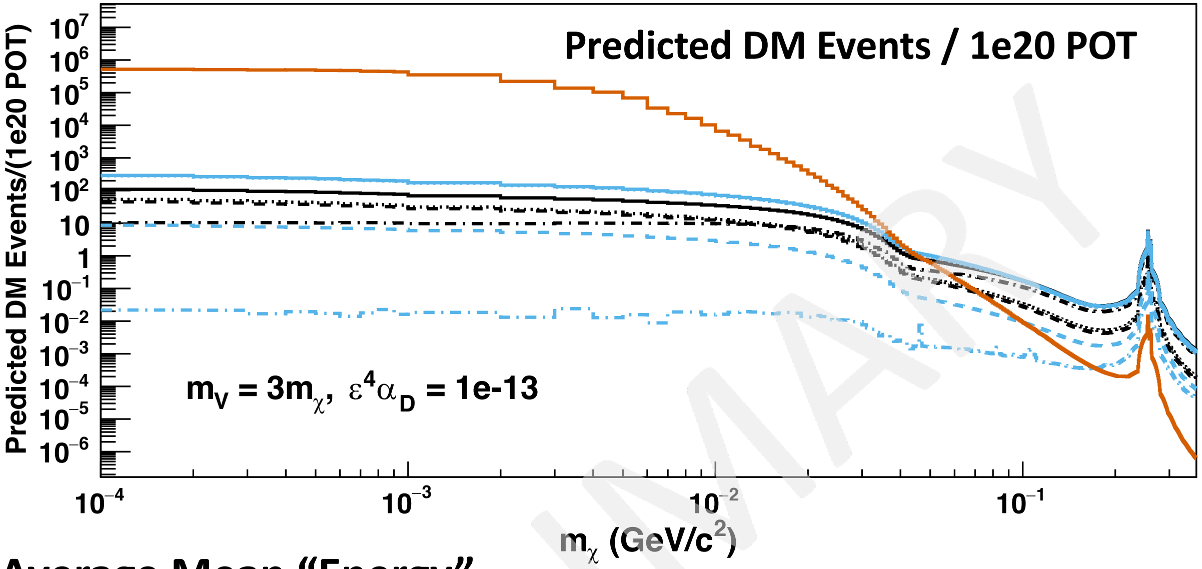


Evis vs UZ : Data vs MC

- E_ν^{QE} is a function of Evis and UZ
- Selection cuts are defined as function of Evis
- There is a low Evis cut in the analysis
- Low bound of E_ν^{QE} is above the low Evis cut



Predicted DM Distributions



Average Mean “Energy”