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Excess of Electron-Like Events in MiniBooNE

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on behalf of MiniBooNE collaboration

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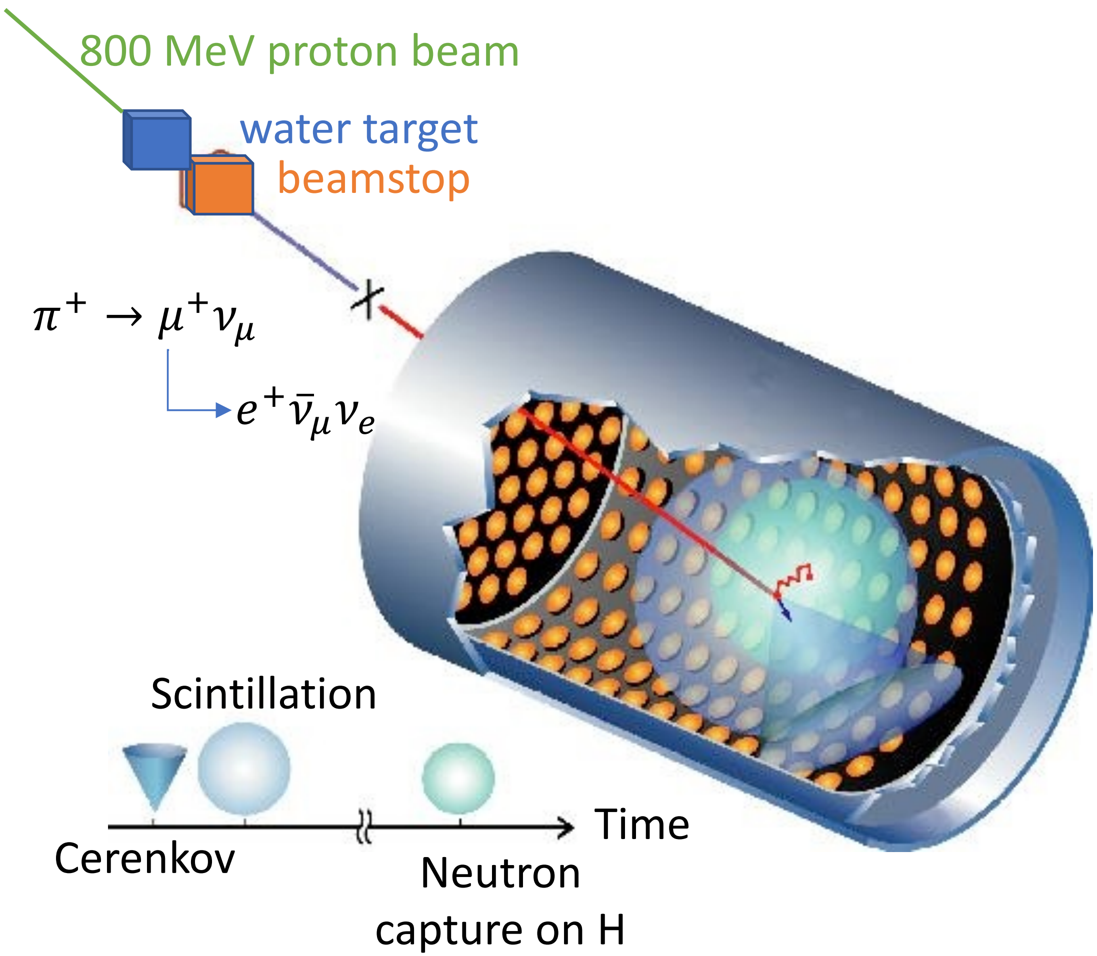
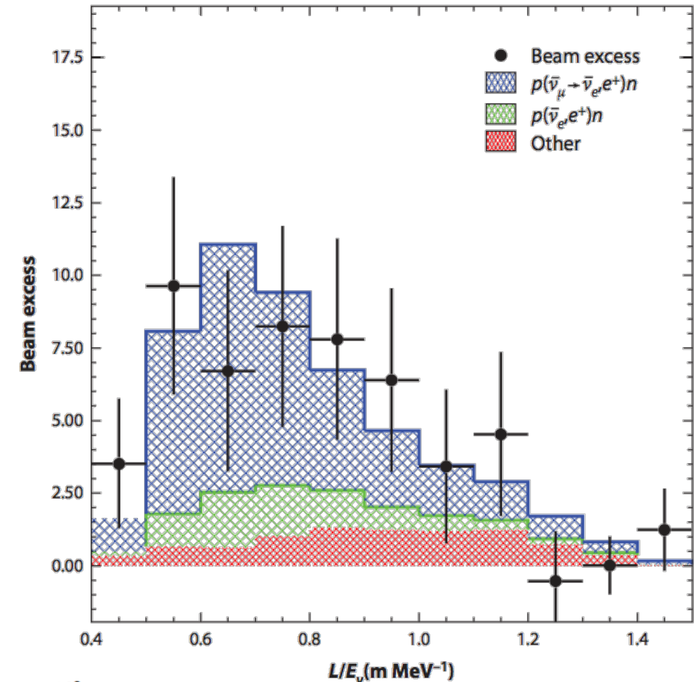
Neutrino 2018, Heidelberg, Germany

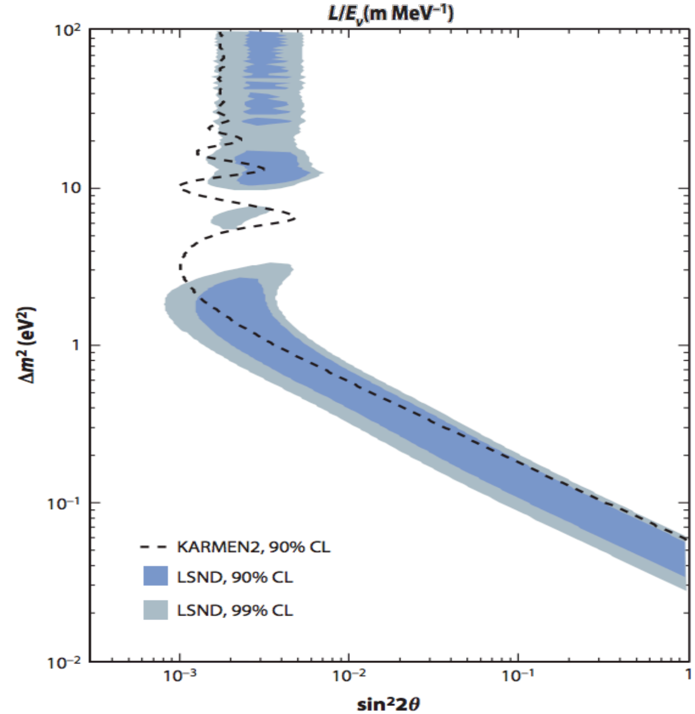
Outline

- The LSND Anomaly
- MiniBooNE experiment
- Observed excess
- Allowed region and other possibilities

LSND Anomaly



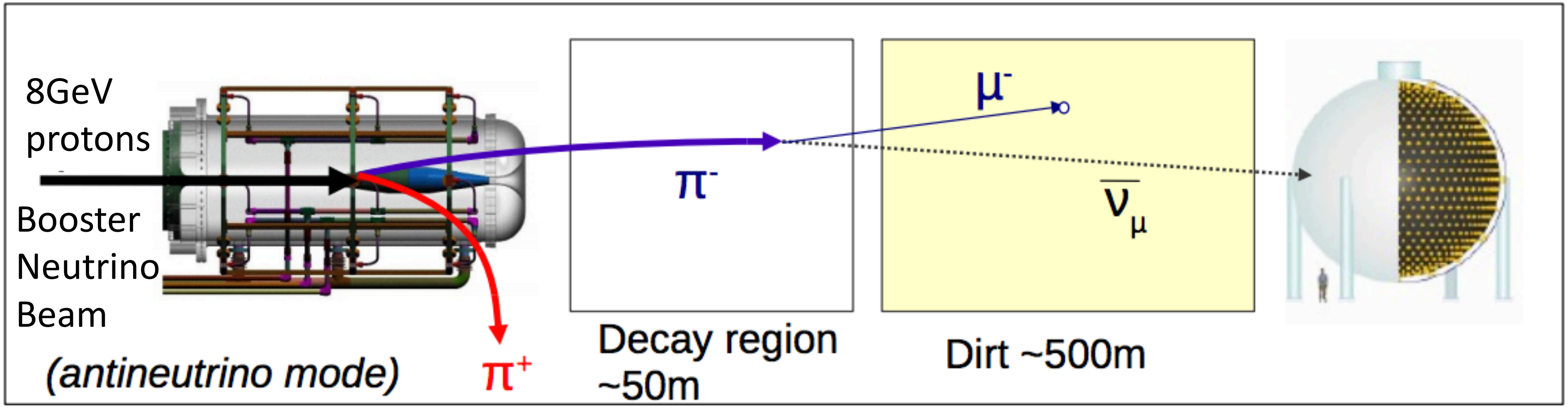




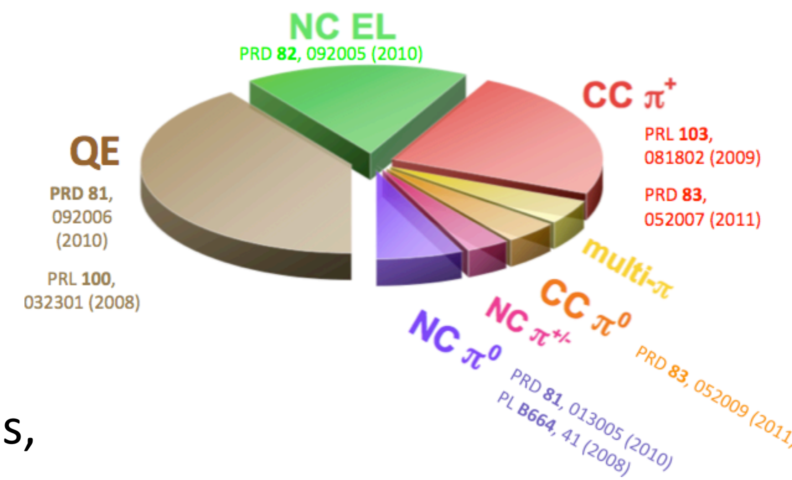
LSND observed a 3.8σ excess

Annu. Rev. Nucl. Part. Sci., *63*(1), 45–67.

MiniBooNE



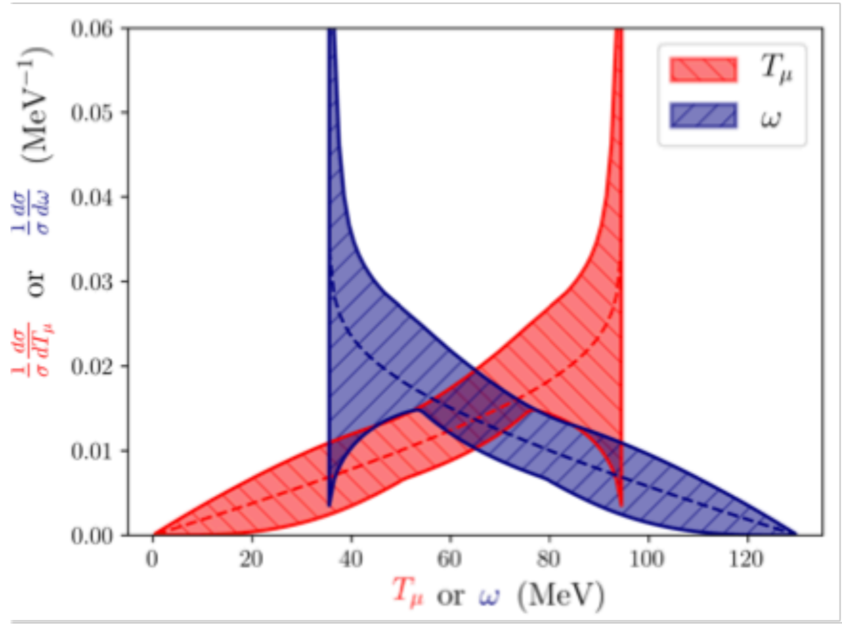
- Similar L/E
  - MiniBooNE ~500m/500MeV
  - LSND ~30m/30MeV
- 800-ton mineral oil Cherenkov detector
- Different systematics
  - Different flux, event signatures, and backgrounds from LSND
- Horn polarity determines ν or $\bar{\nu}$ mode
- Flux monitor for short baseline neutrino program (SBN)
- Well-understood detector with 26 publications(4900+ citations) in different channels, as well as recent
  - ν_μ from K^+ decay at rest from NuMI beam
  - Dark matter search

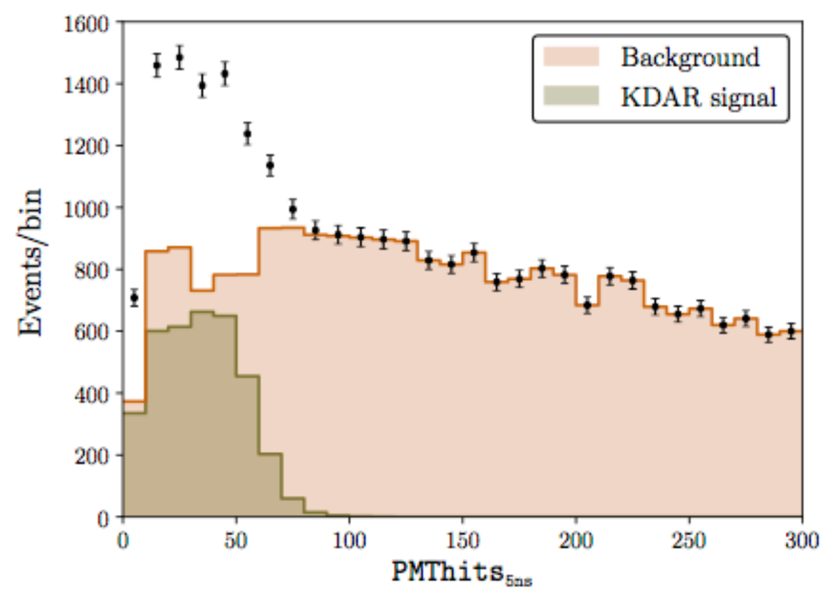


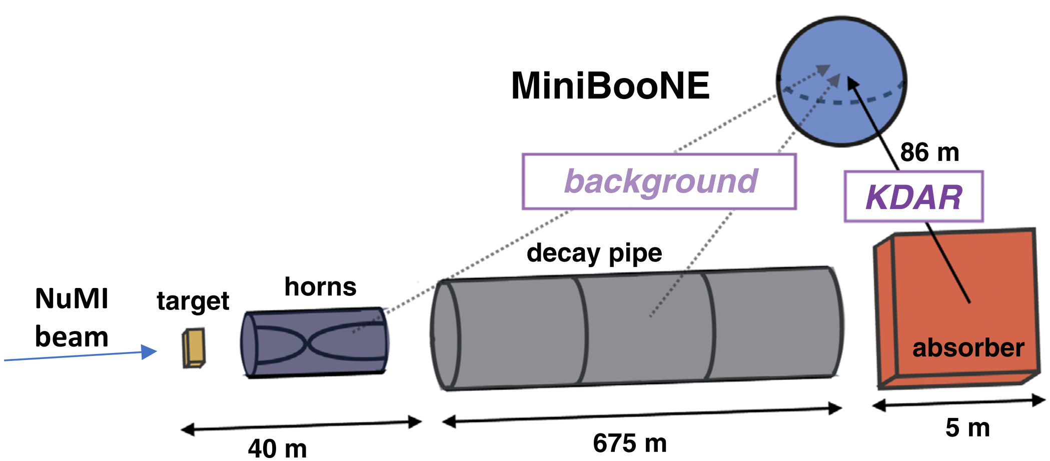
KDAR

"First Measurement of Monoenergetic Muon Neutrino Charged Current Interactions", PRL 120 141802 (2018) (Editor's 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.





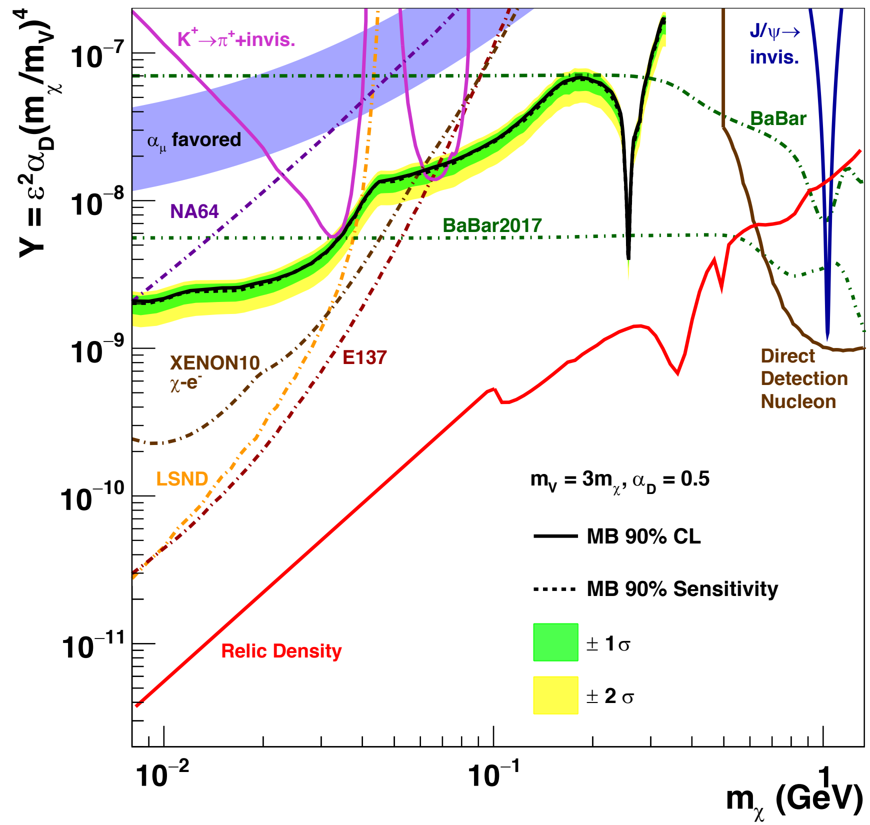


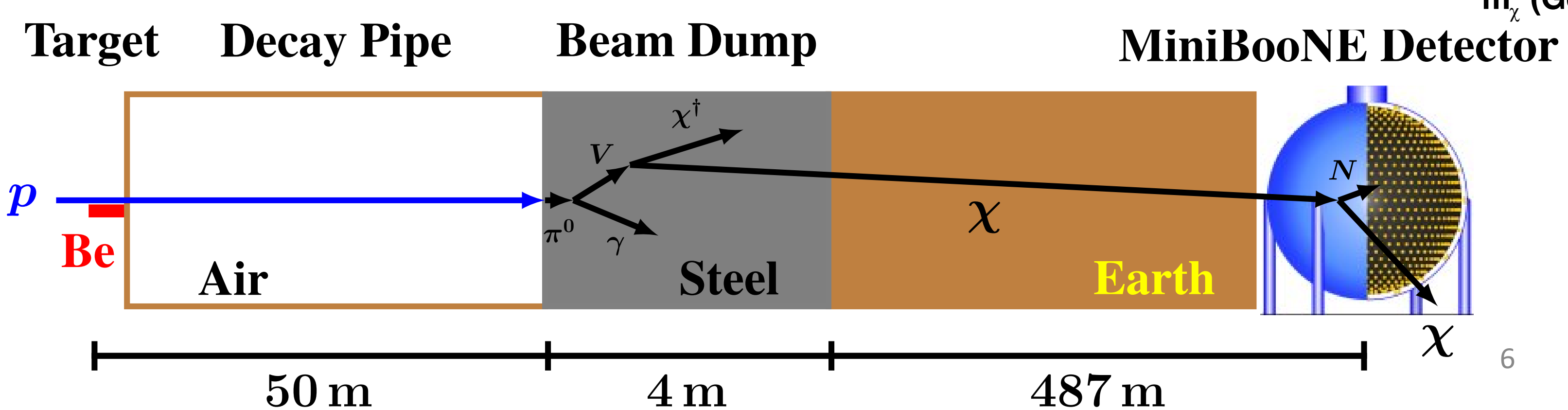
Dark Matter Search in Beam-Dump Mode

PRL 118, 221803 (2017)

Editor's Suggestion

- First dedicated search for direct detection of accelerator-produced dark matter in a proton beamline
  - Searched for the dark matter to elastically scatter off nucleons
- Beam-dump mode reduced the ν flux by ~50
- The goal was to test vector portal model interpretation of g-2 (ruled out)
- At time of publication: set world leading limits in the vector portal dark matter model with a dark matter mass between 0.01 and 0.3 GeV
- New results are expected later in 2018
  - Inelastic scatter to produce π^0s through Δ decay
  - Elastic scattering off electrons





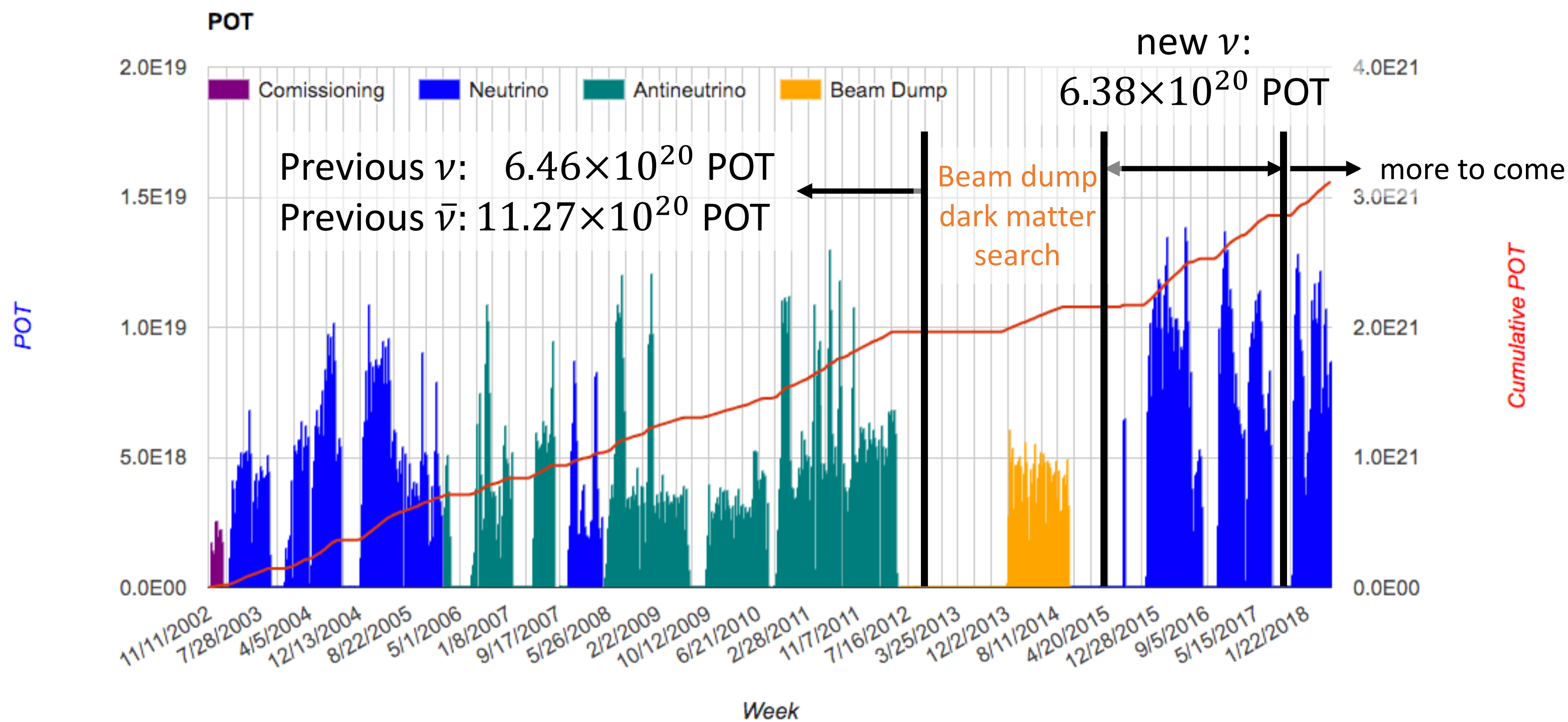
New MiniBooNE Oscillation Results with Neutrino Data Set Doubled

arXiv:1805.12028
submitted to PRL

- Extra data allows better calibrations and cross checks
- Second data set to look at consistency
- Improved background estimates from observed data and constraints
  - Dirt and π^0
- Larger data set leads to smaller statistical uncertainty on signal and background measurements

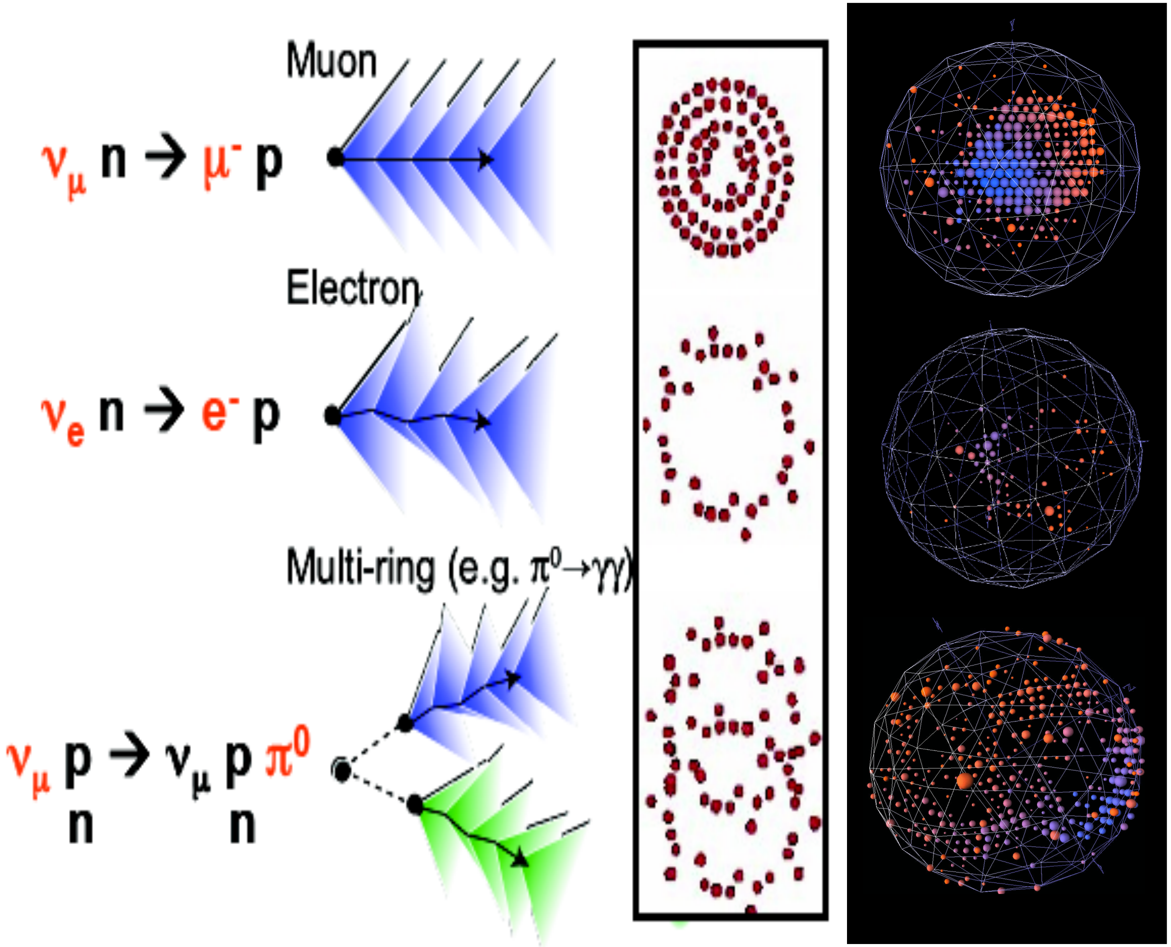
Data Set

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



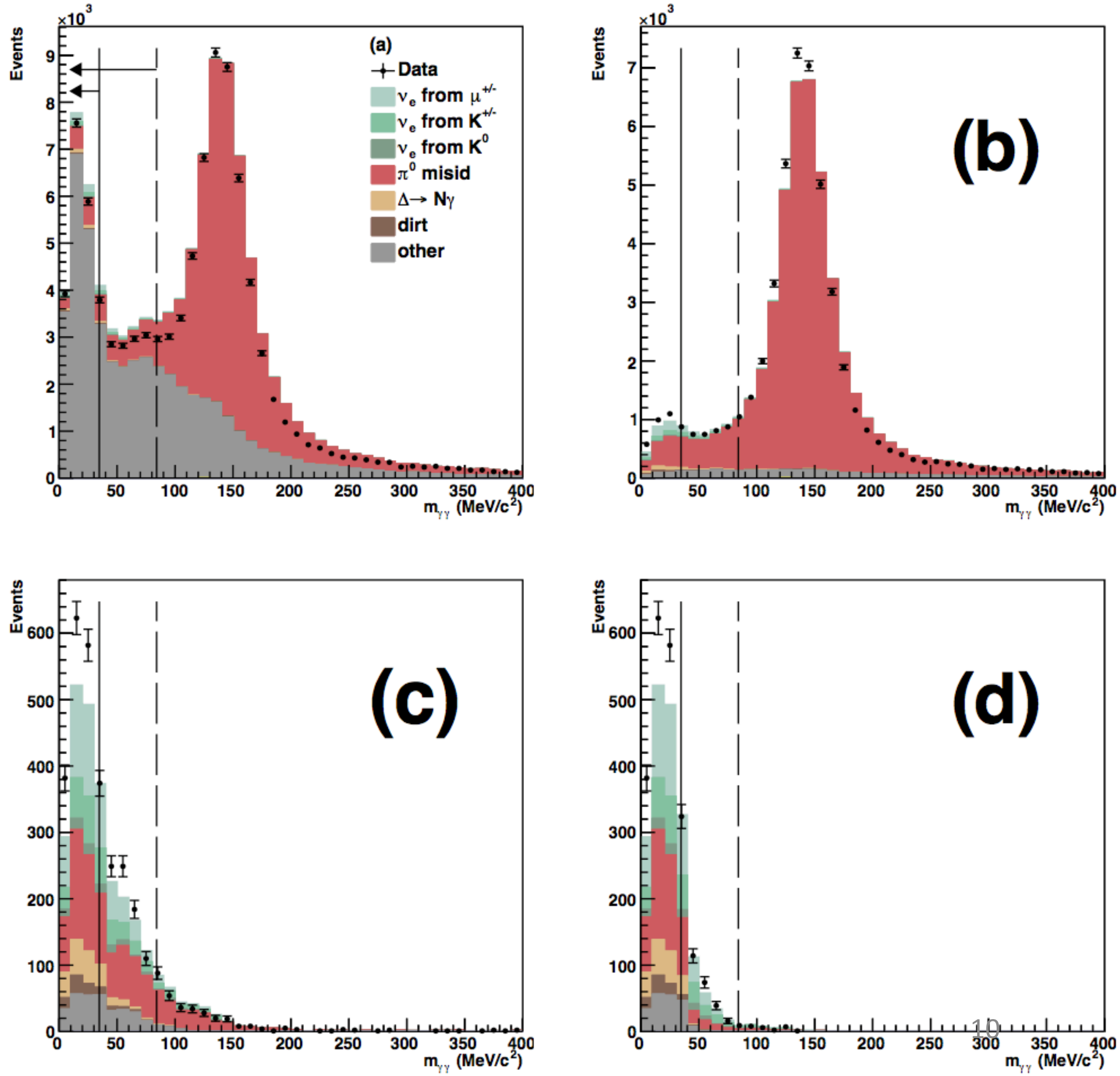
Event Signatures

- Examples of ν_μ CCQE ν_e CCQE, and NCπ^0 event topologies
- Use primarily Cherenkov light
- Compare fits of different track reconstruction hypotheses for PID
- Insensitive to the difference between single photon and single electron (time of flight might help)

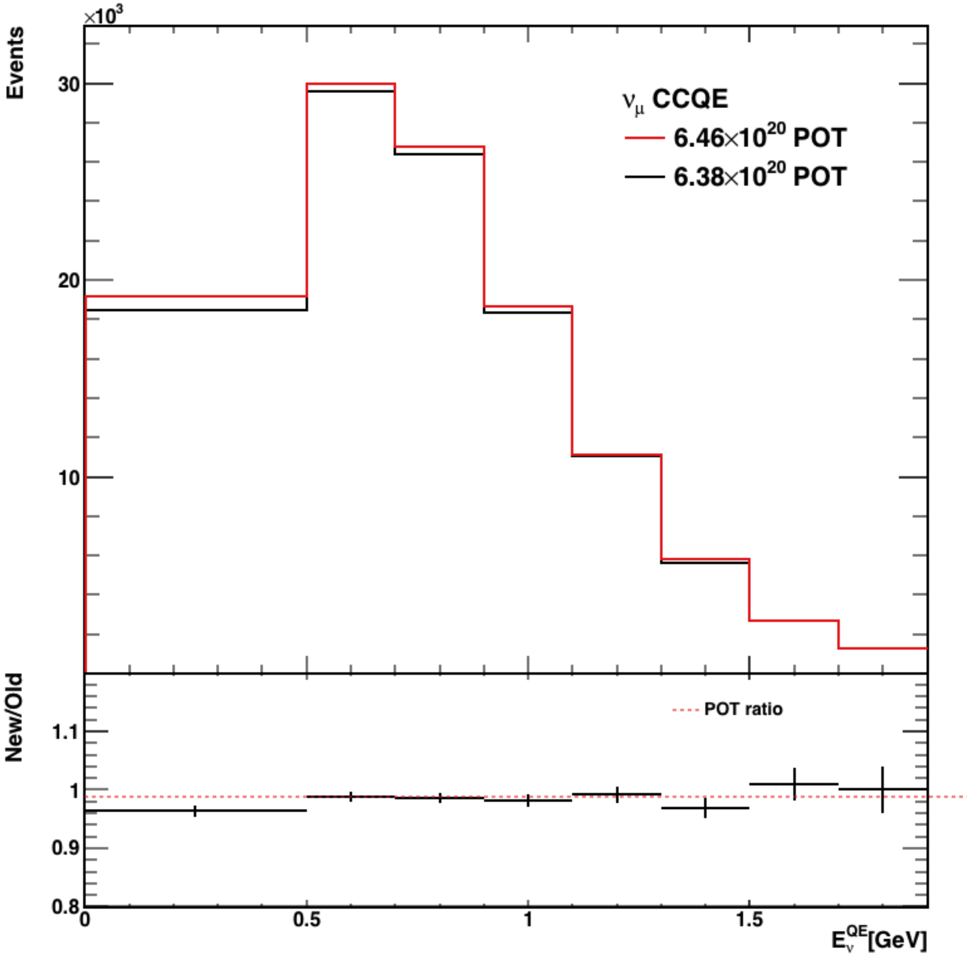


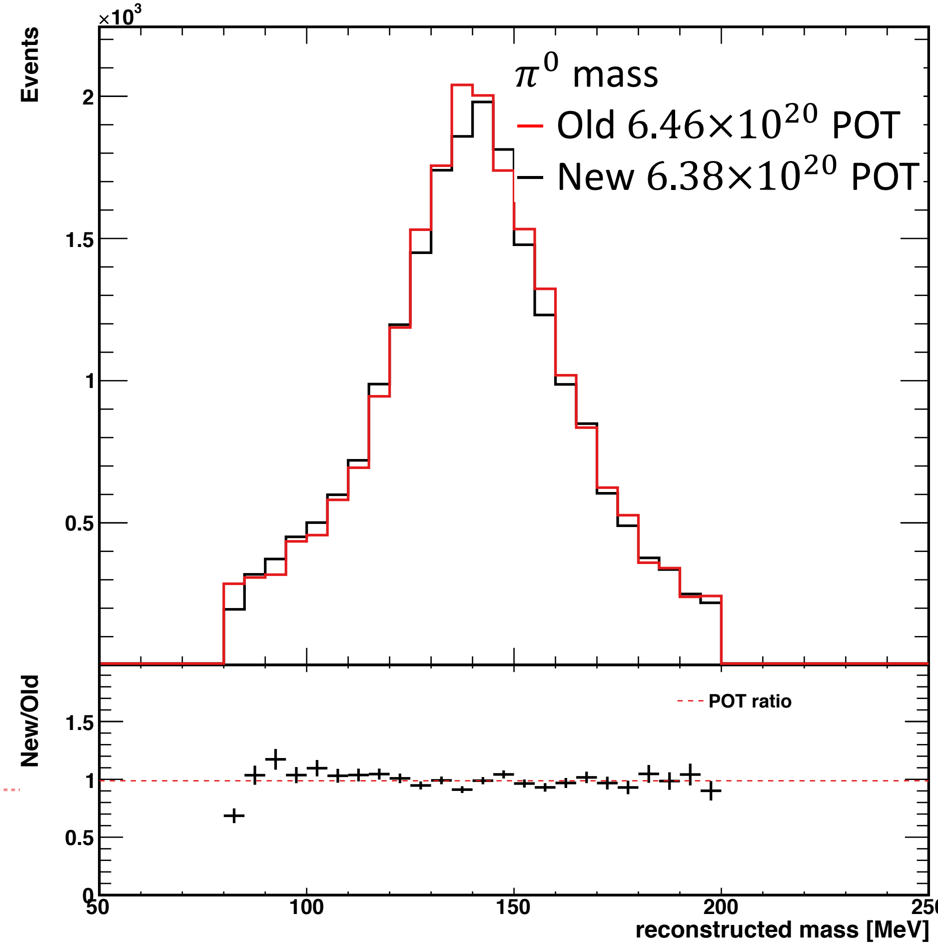
Data vs MC (Selection Process)

- $m_{\gamma\gamma}$ is shown
- Cuts are applied in the order of
  a. Only precuts (no PID cut)
  b. e-μ Likelihood cut
  c. e-π Likelihood cut
  $d.$ $m_{\gamma\gamma}$ cut
- Background outside the oscillation cut window is well understood by MC
- Other two PID distributions are in the backup slides



Detector Stability





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

MiniBooNE Analysis

- Standard $2{-}\nu$ oscillation model is used:
  $$P(L,E) = \sin^2 2\theta \times \sin^2(1.267\Delta m^2 L/E)$$
- $\sin^2 2\theta \equiv \sin^2 2\theta_{\mu e} \approx 4\left|U_{\mu 4}\right|^2 |U_{e4}|^2$ at the MiniBooNE mass splitting range
  - In a $3(\text{active}) + 1(\text{sterile})$ model, $\sin^2 2\theta_{\mu e}$ is assumed small
- ν_e CCQE-like events are constrained by the ν_μ CCQE-like events
- Maximum likelihood is used
  - For a $\nu + \bar{\nu}$ analysis, a simultaneous fit was conducted for $\nu_e, \nu_\mu, \bar{\nu}_e$, and $\bar{\nu}_\mu$ distributions

Excess

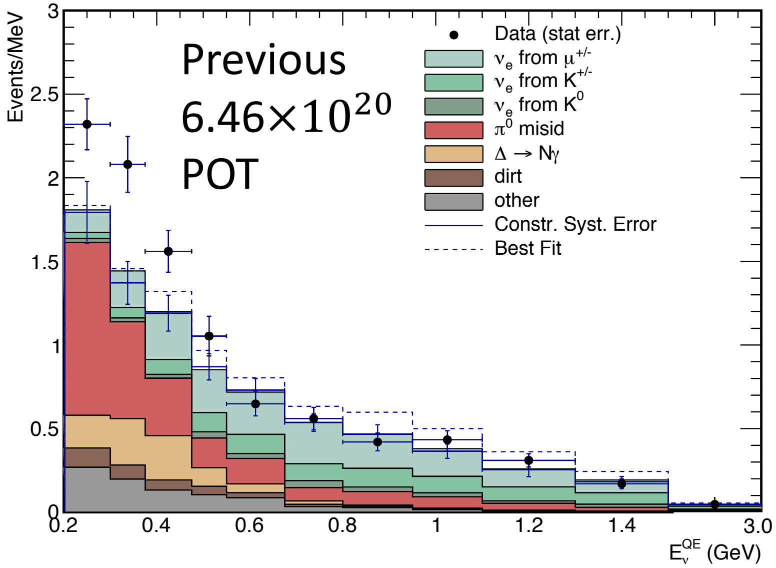
	ν **mode** $12.84{\times}10^{20}$ **POT**	$\overline{\nu}$ **mode** $11.27{\times}10^{20}$ **POT**	**Combined**
Data	1959	478	2437
Unconstrained Background	1590.5	398.2	1988.7
Constrained Background	1577.8	398.7	1976.5
Excess	381.2 ± 85.2 4.5σ	79.3 ± 28.6 2.8σ	460.5 ± 95.8 4.8σ
0.26% (LSND) $\nu_\mu \to \nu_e$	463.1	100.0	563.1

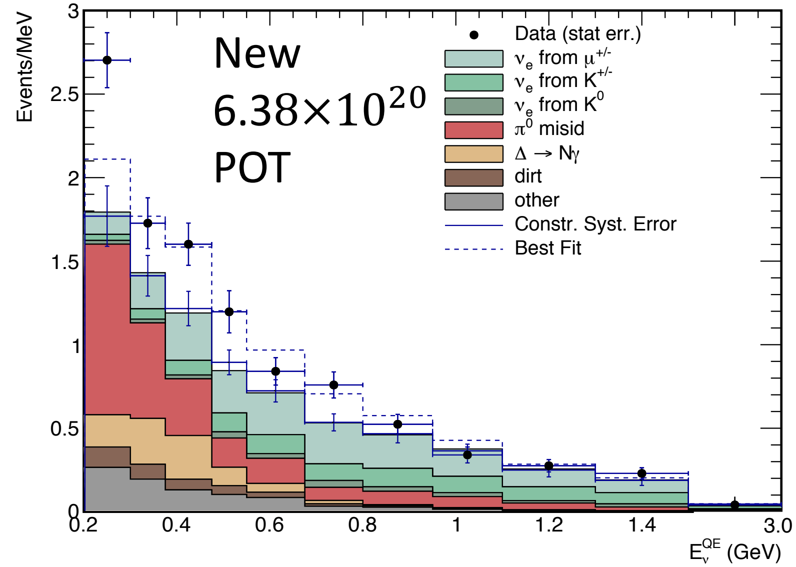
- Total excess for neutrino + antineutrino:

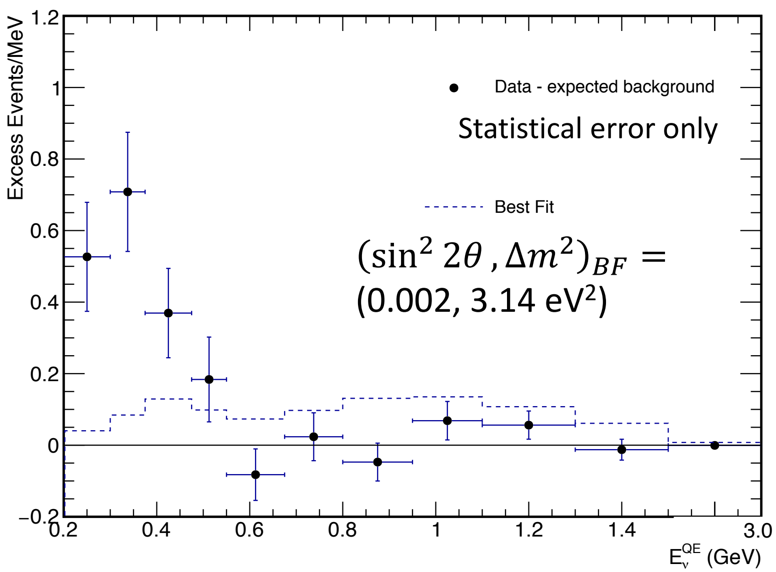
$$460.5 \pm 95.8(4.8\sigma)$$

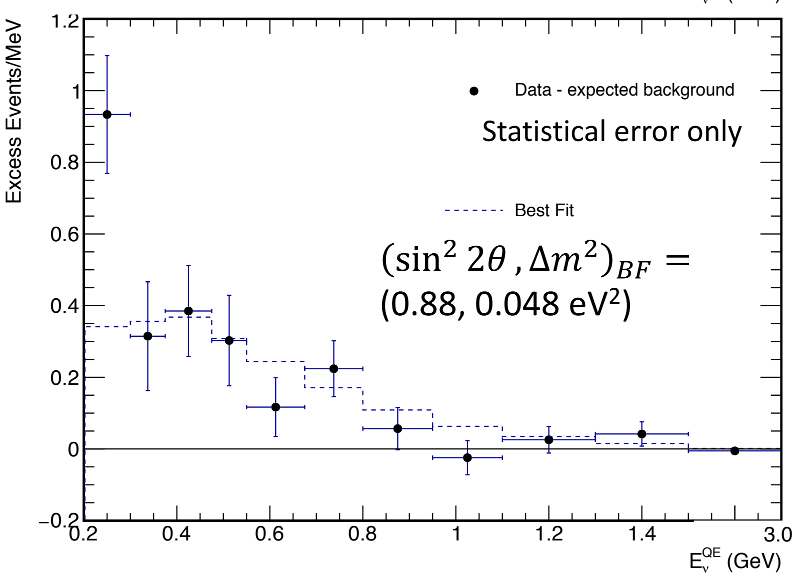
- Combined with LSND (3.8σ), total significance is at 6.1σ

Excess: Old vs New in ν Mode



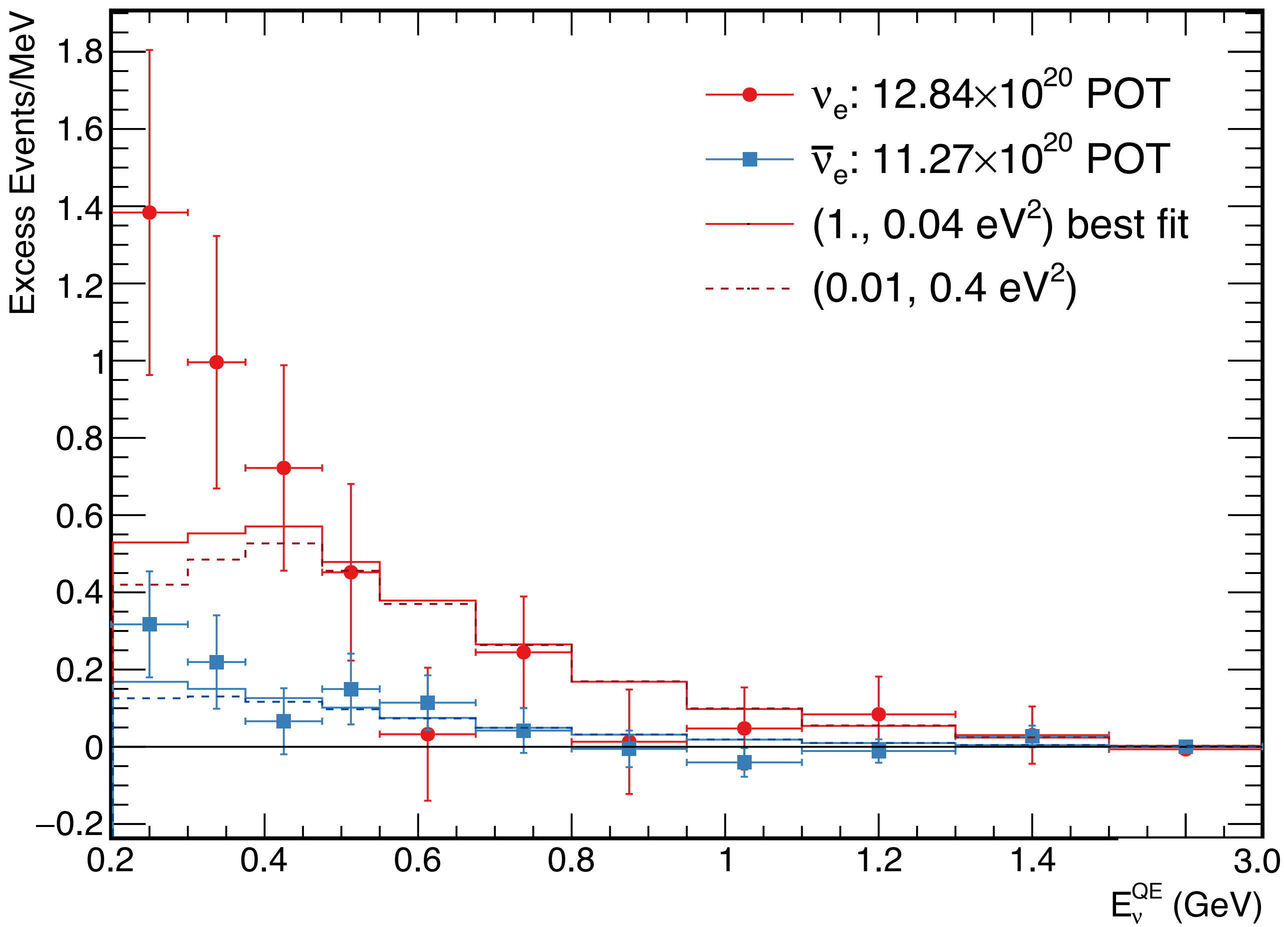






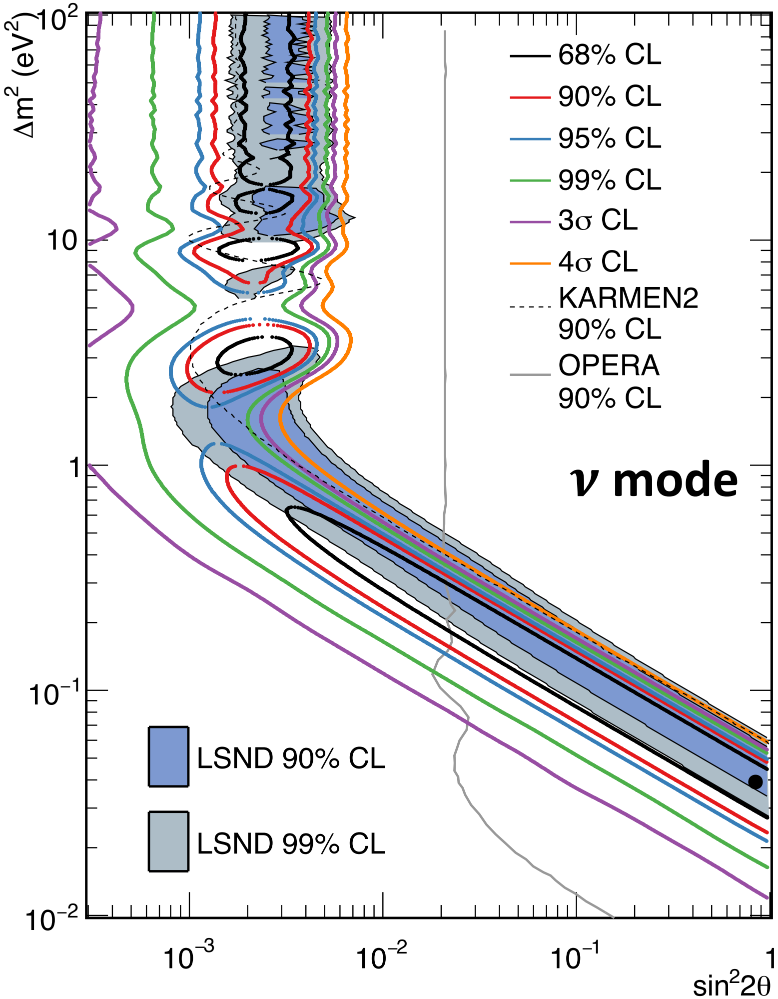
The observed ν_e spectra are statistically consistent between the new and previous data sets (KS prob =76%)

Excess: Neutrino vs Anti-neutrino

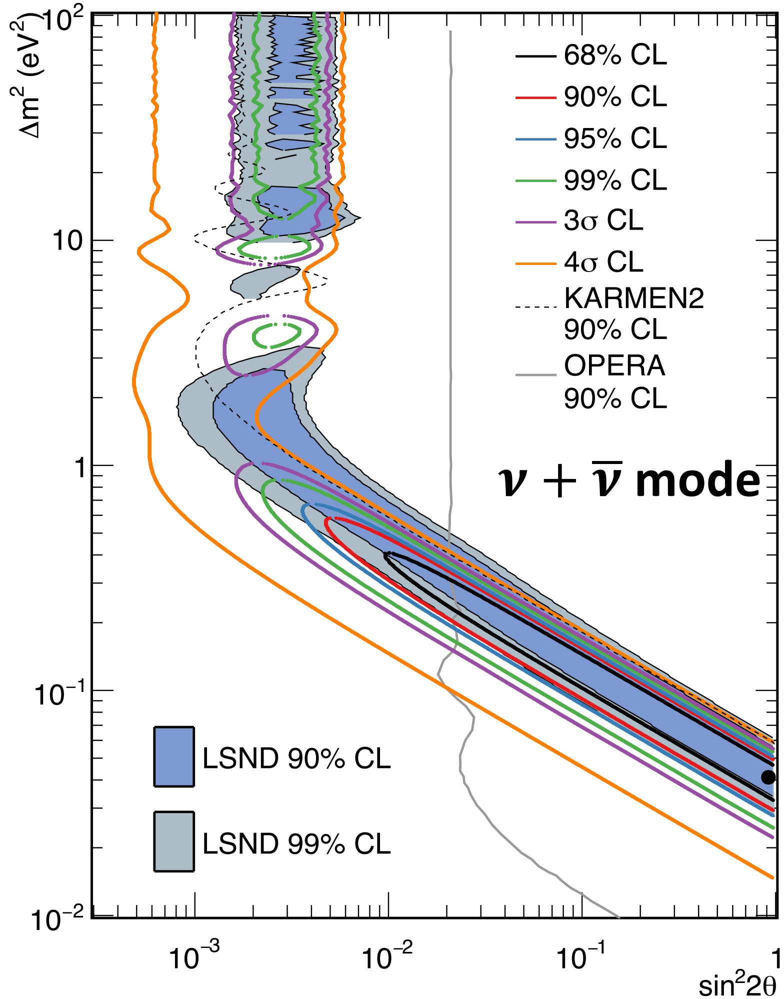


- Excess in neutrino and antineutrino mode is qualitatively consistent

Allowed Region

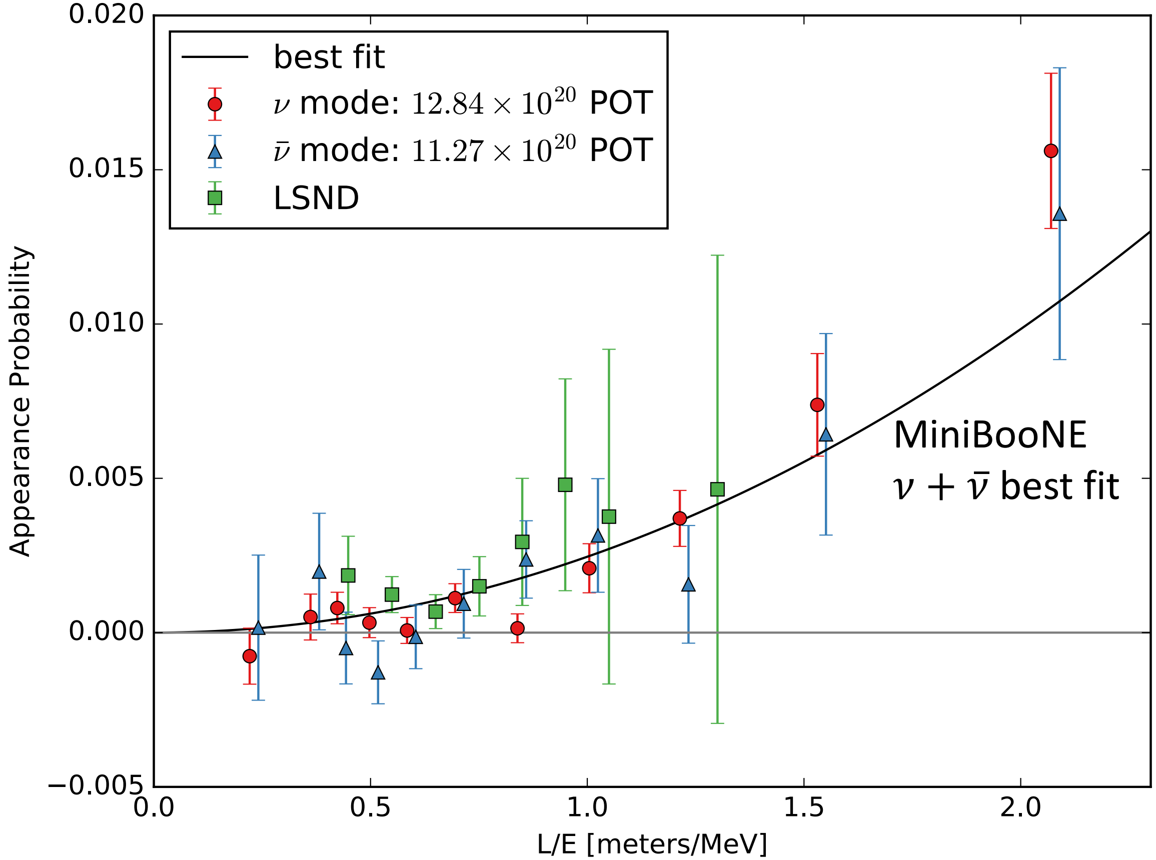


$(\Delta m^2, \sin^2 2\theta) = (0.037\ \mathrm{eV}^2, 0.958)$
$\chi^2/ndf = 10.0/6.6$ (prob = 15.4%)



$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.958)$
$\chi^2/ndf = 19.5/15.4$ (prob = 20.1%)

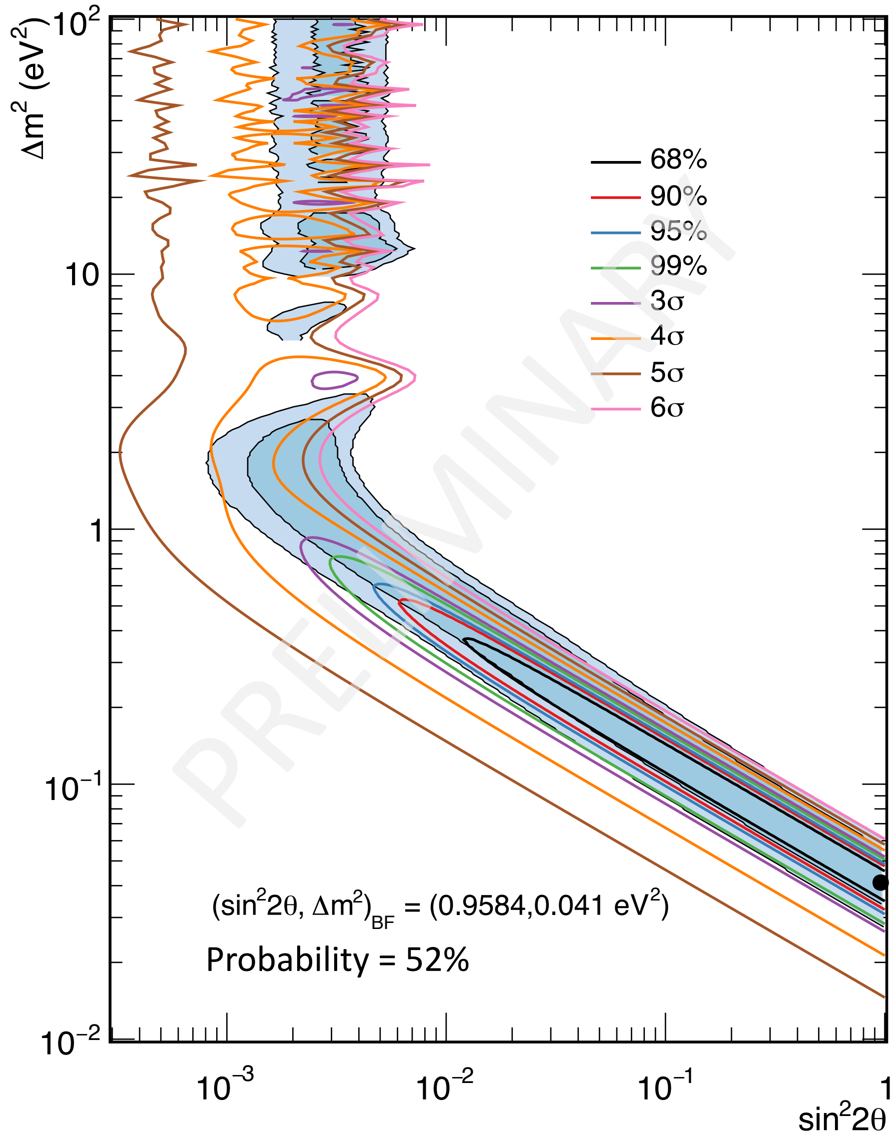
L/E



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

Combined Fit with LSND

- Combined fit of MiniBooNE $\nu + \bar{\nu}$ mode and LSND is at 6σ level
- Assuming no correlation between MiniBooNE and LSND
- Best fit of MiniBooNE and LSND combined is **consistent** with our latest result
- Note: a large $\sin^2 2\theta$ is unphysical for a pure 3+1 model



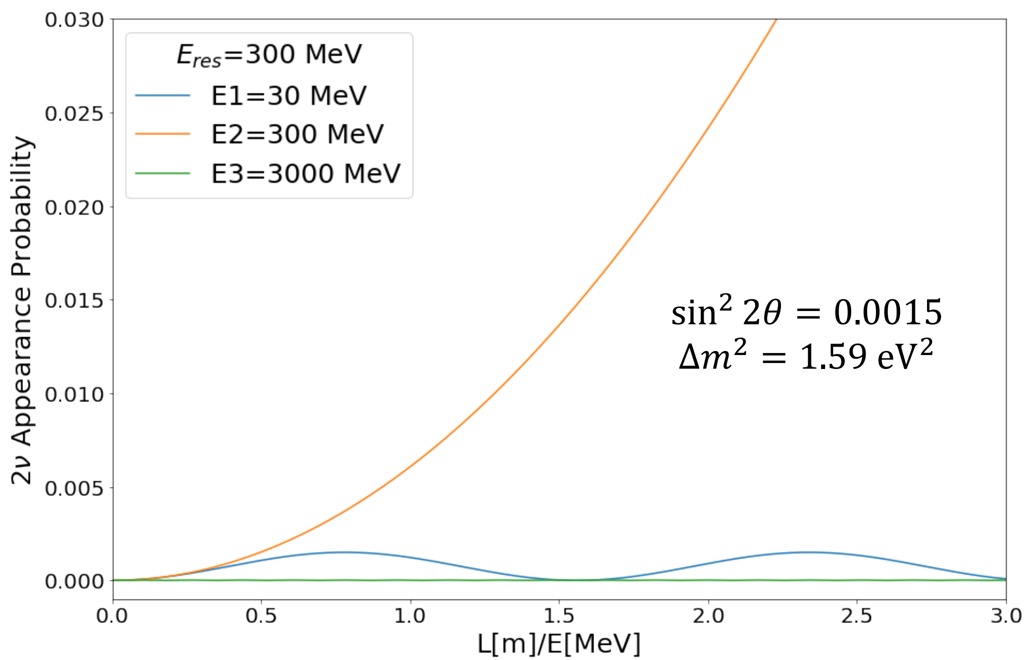
Example of an Empirical Exotic Model: An MSW-Like Resonance

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

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

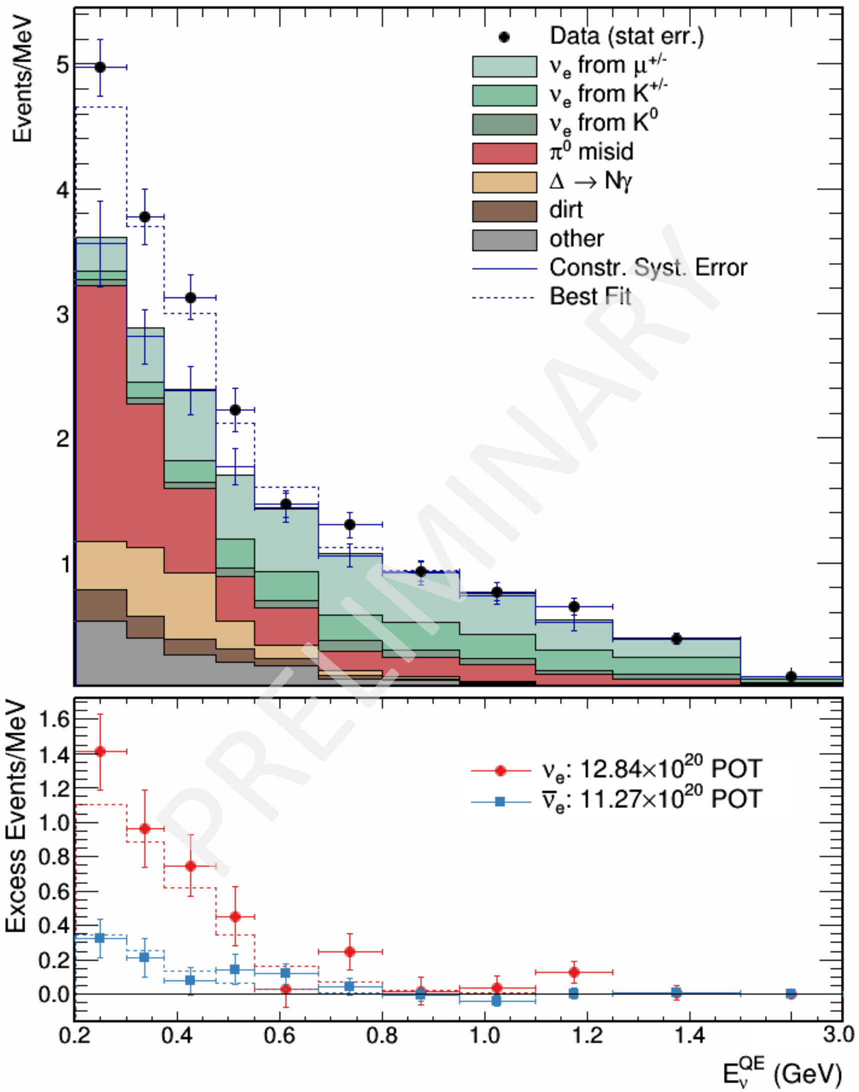
$$P(E \approx E_{res}, L) = \sin^2 2\theta_M \times \sin^2(1.267\Delta m_M^2 L/E)$$

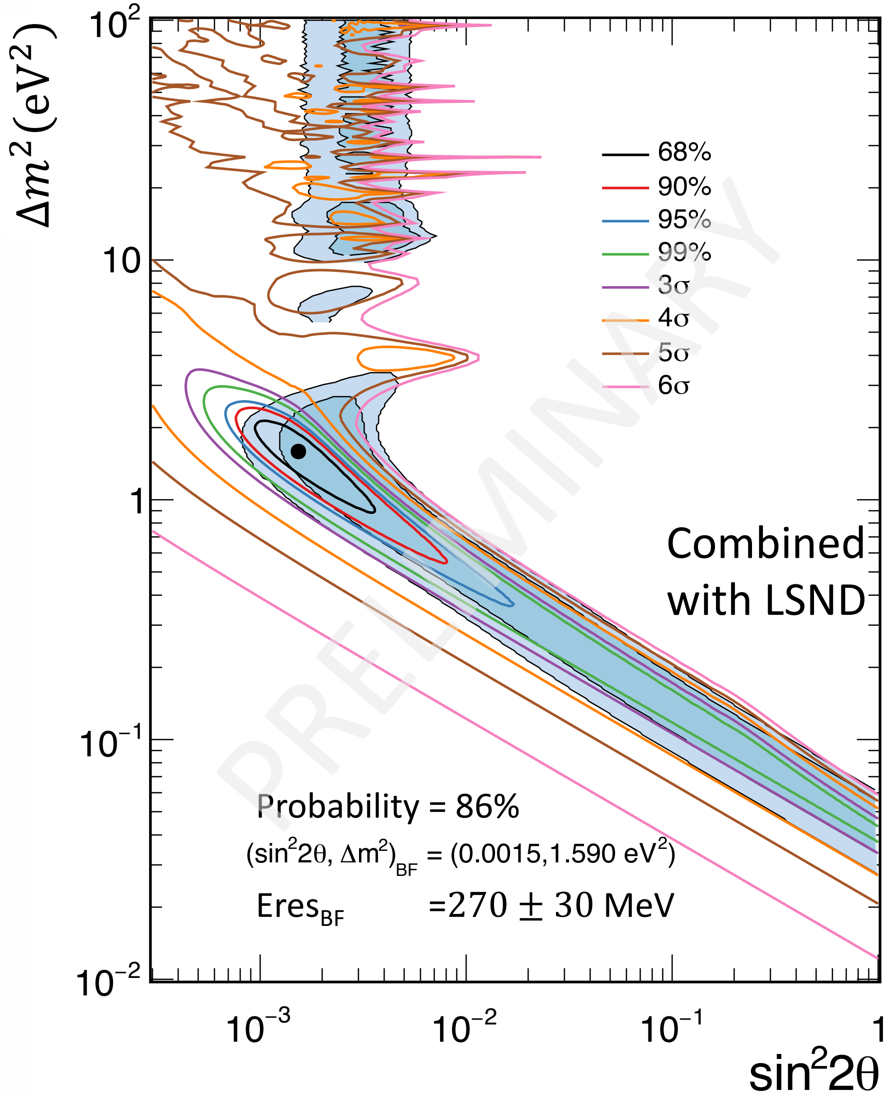
$$P(E \gg E_{res}, L) \approx 0$$



Insipred by J. Assadi *et al.*, arXiv:1712.08019 & G. Karagiorgi, M. H. Shaevitz, J. M. Conrad arXiv:1202.1024

An MSW-Like Resonance Model





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

Conclusion

- MiniBooNE confirms LSND excess at 4.8σ, with a combined significance at 6.1σ
- MiniBooNE continues data-taking, and analysis in the future will include time-of-flight information to better constrain backgrounds
- MicroBooNE will confirm whether excess is due to electrons or photons
- SBN will confirm whether the excess is due to neutrino oscillations
- Thanks to Fermilab for MiniBooNE operation (15 y) & for great beam delivery