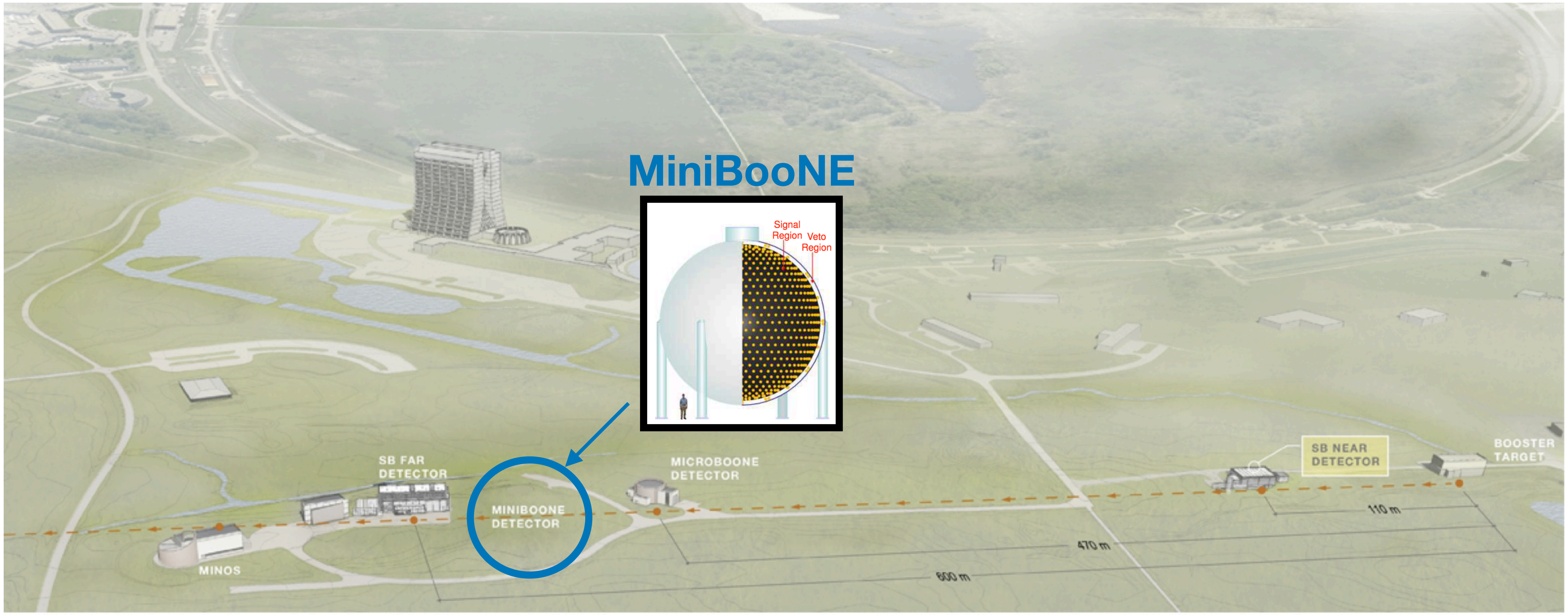
MiniBooNE in 10 Minutes

Nicholas Kamp for the MiniBooNE Collaboration

New Perspectives 2024

Overview

- Overview of the MiniBooNE experiment
- The electron-like excess
- Further MiniBooNE results



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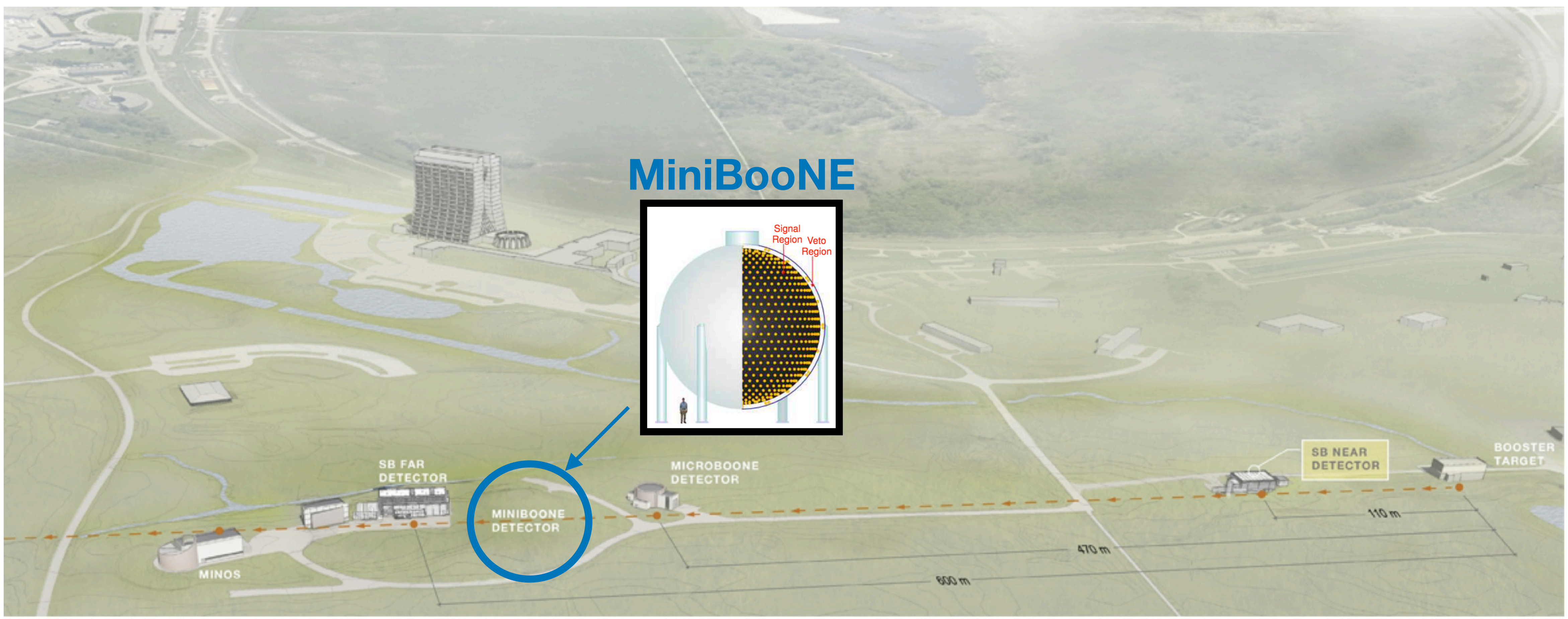
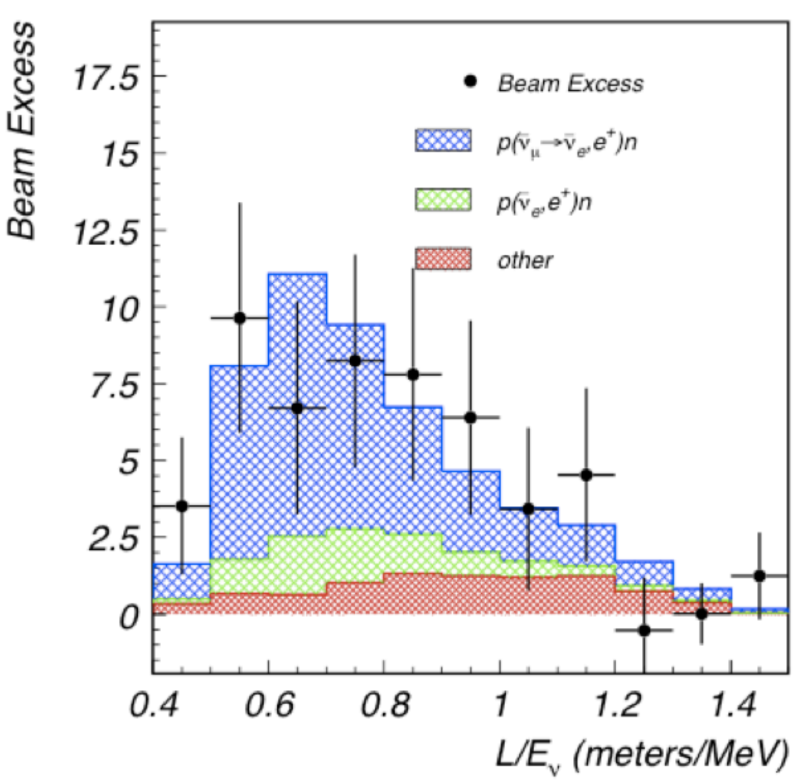
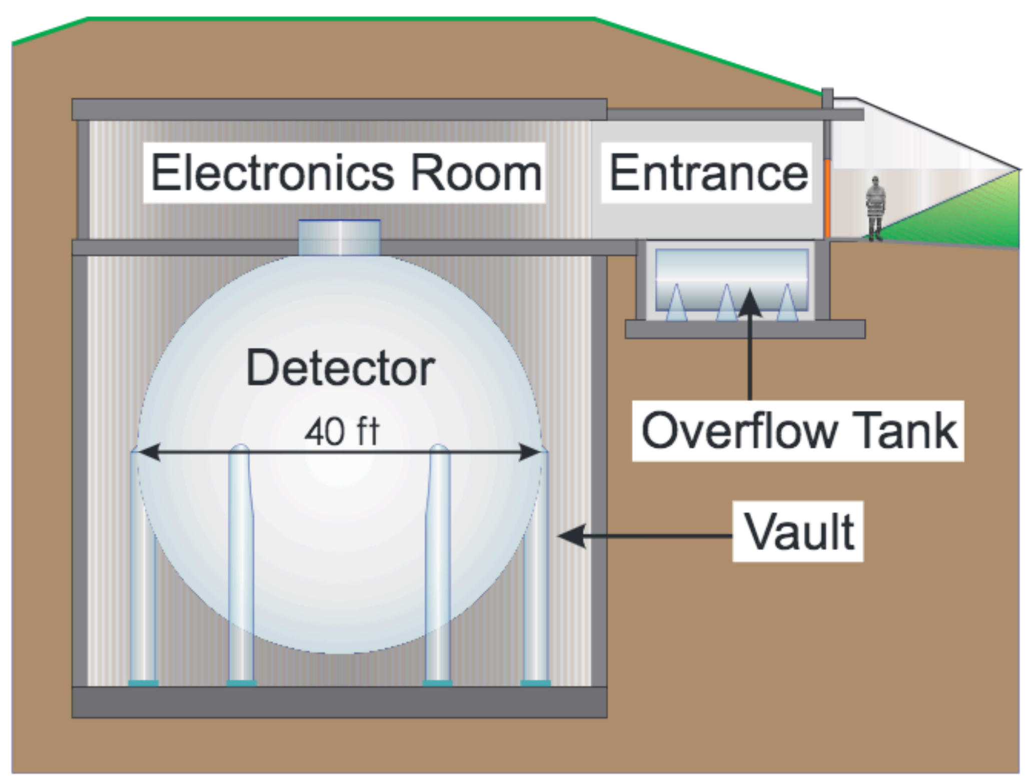


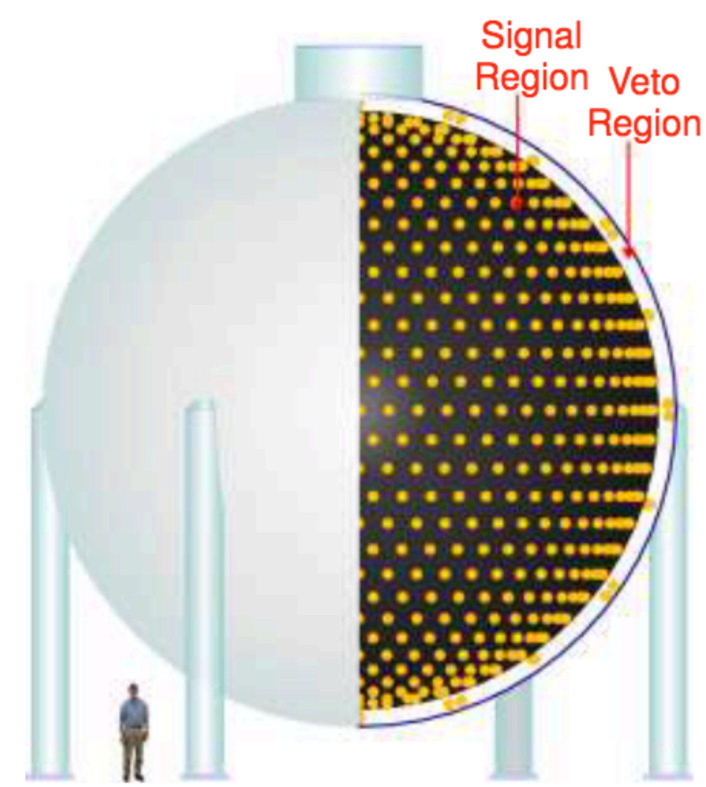
The MiniBooNE Experiment

- The MiniBooNE experiment uses a Cherenkov detector to measure the interactions of neutrinos produced in the Booster Neutrino Beam (BNB)

- Designed to look for muon-to-electron neutrino oscillations L/E ~ 1 km/GeV to test the oscillation interpretation of the LSND excess





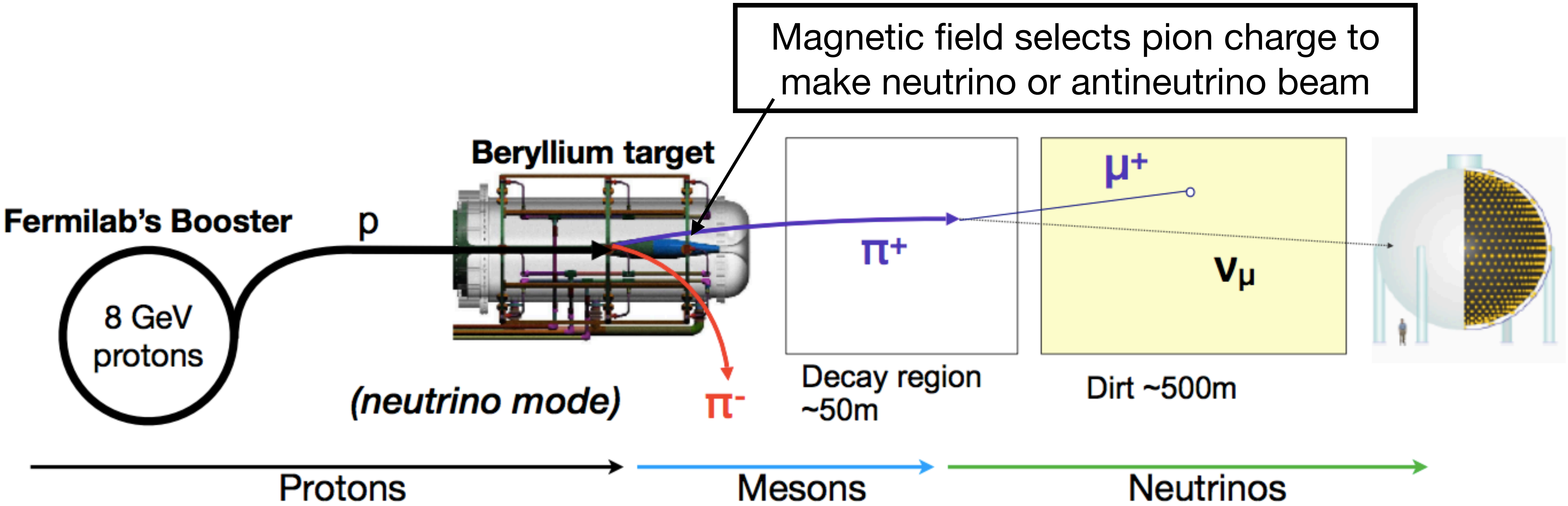


LSND Collaboration, PRD 64 112007. 2001

MiniBooNE Collab. Nucl. Inst. and Methods A. Volume 599. 2009

The Booster Neutrino Beam

- The Booster Neutrino Beam (BNB) is created by irradiating a beryllium target with 8 GeV protons
  - Neutrinos produced predominately in charged meson decay chains
- The MiniBooNE detector sits 541 m away from the BNB target



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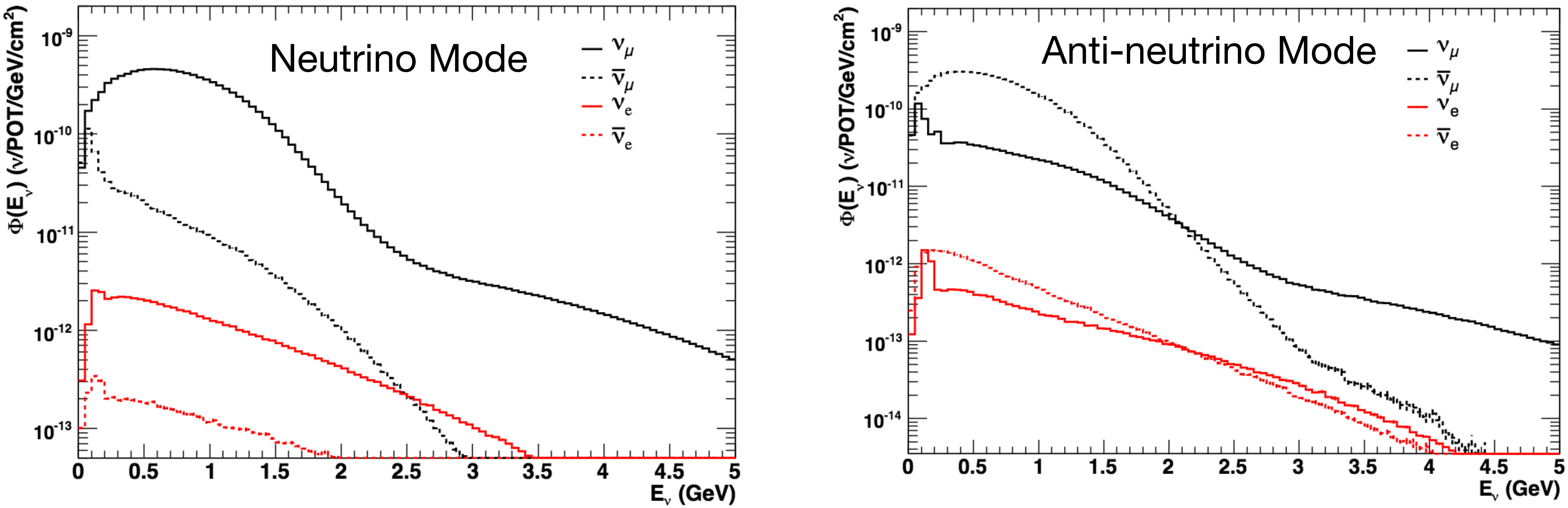
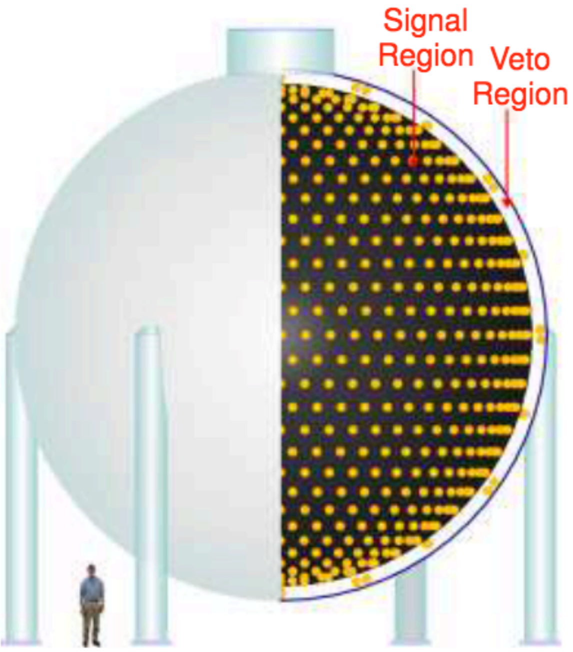


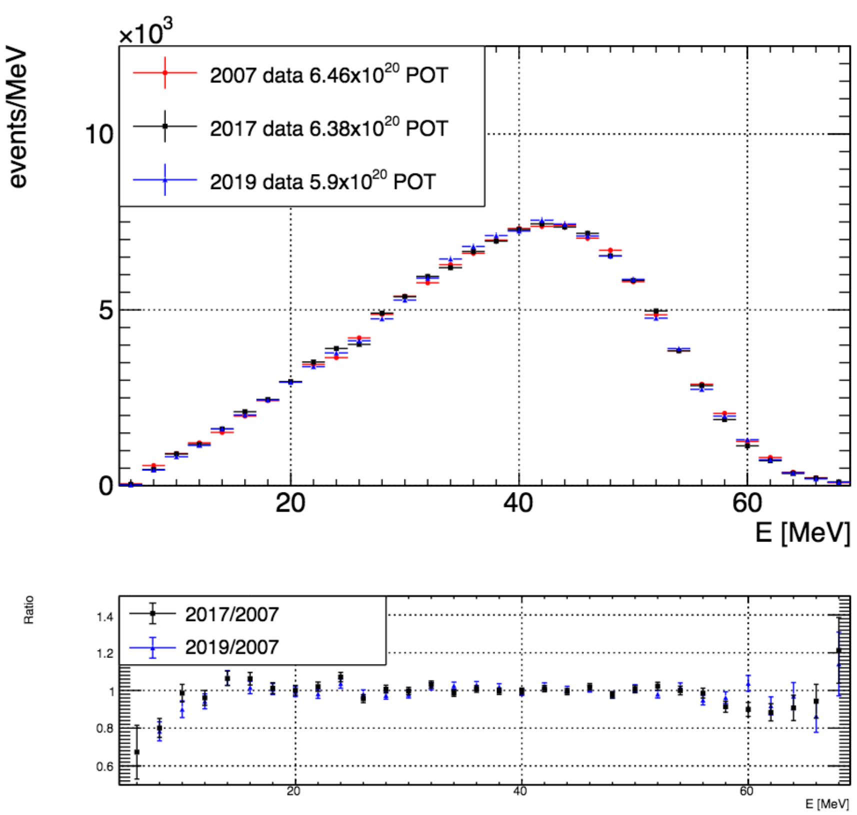
MiniBooNE Collab. Phys. Rev. D 79, 072002. 2009

The MiniBooNE Detector

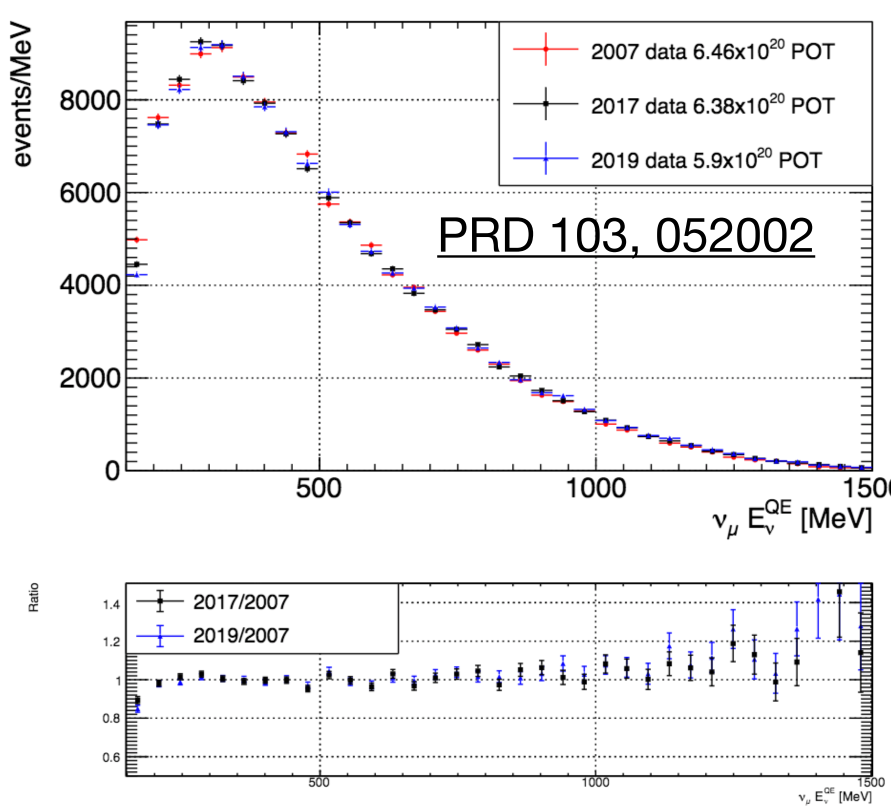
- 6.1m radius spherical mineral oil (CH_2) detector (high *n*, low Cherenkov threshold)
- 1520 photo-multiplier tubes covering the inner surface of the spherical detector
- Remarkable stability in the detector response over the 17 year lifetime



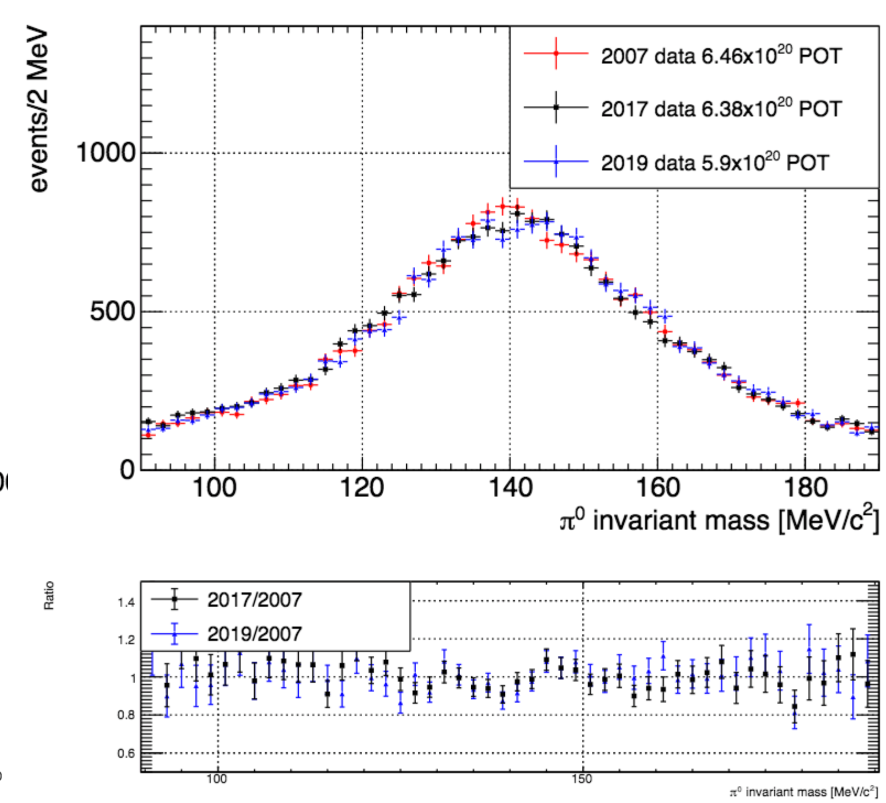
Michel Electron Energy



ν_μ CCQE Muon Energy

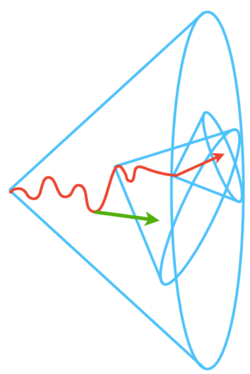


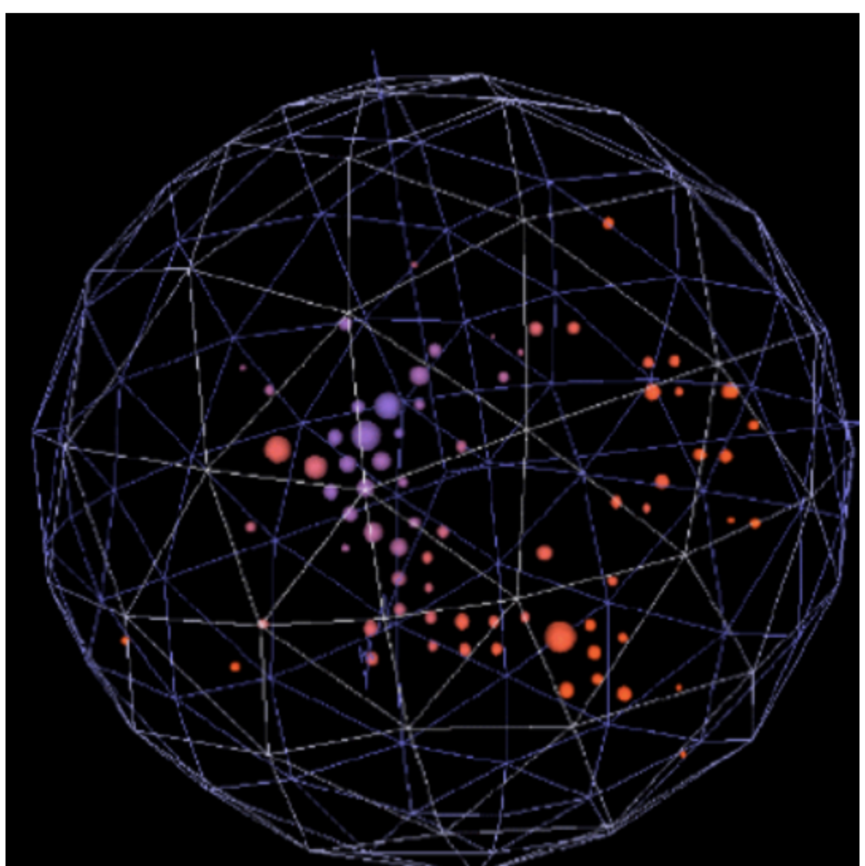
π^0 Mass Peak



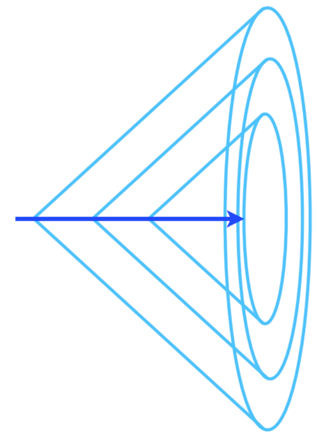
The MiniBooNE Detector

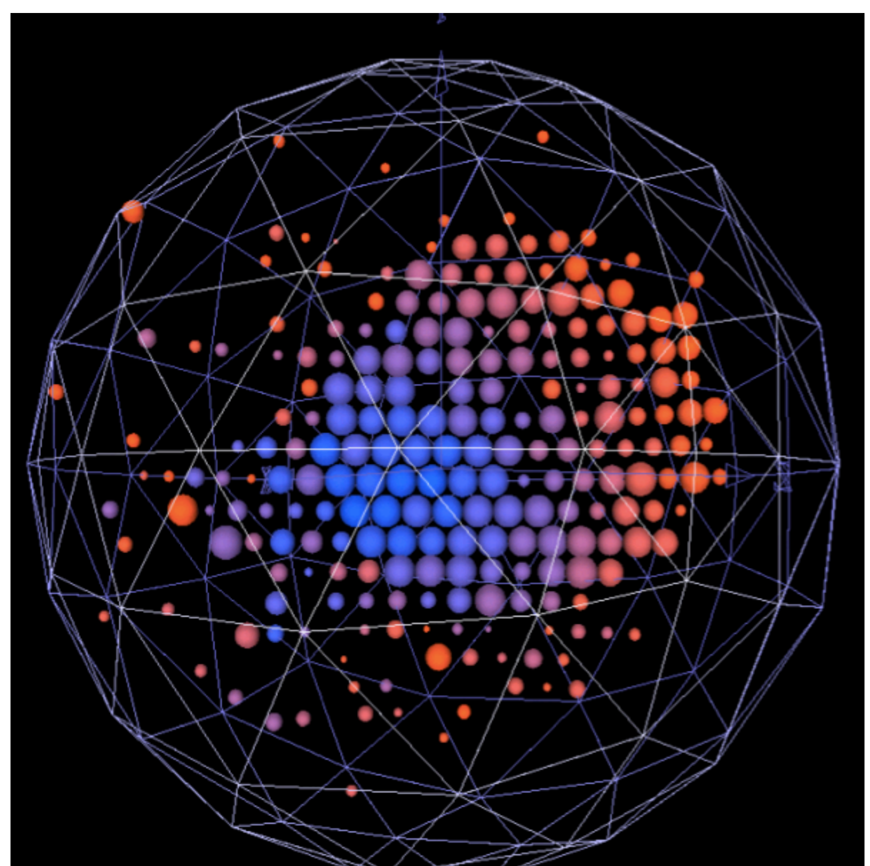
Electrons: "fuzzy" rings from multiple scattering and bremsstrahlung radiation



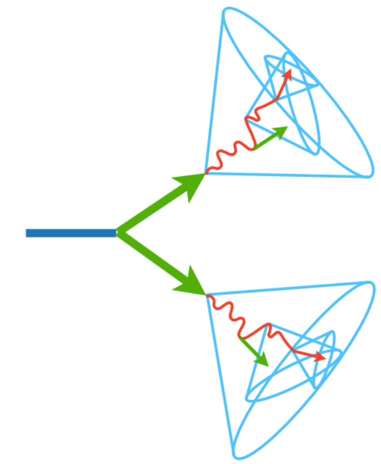


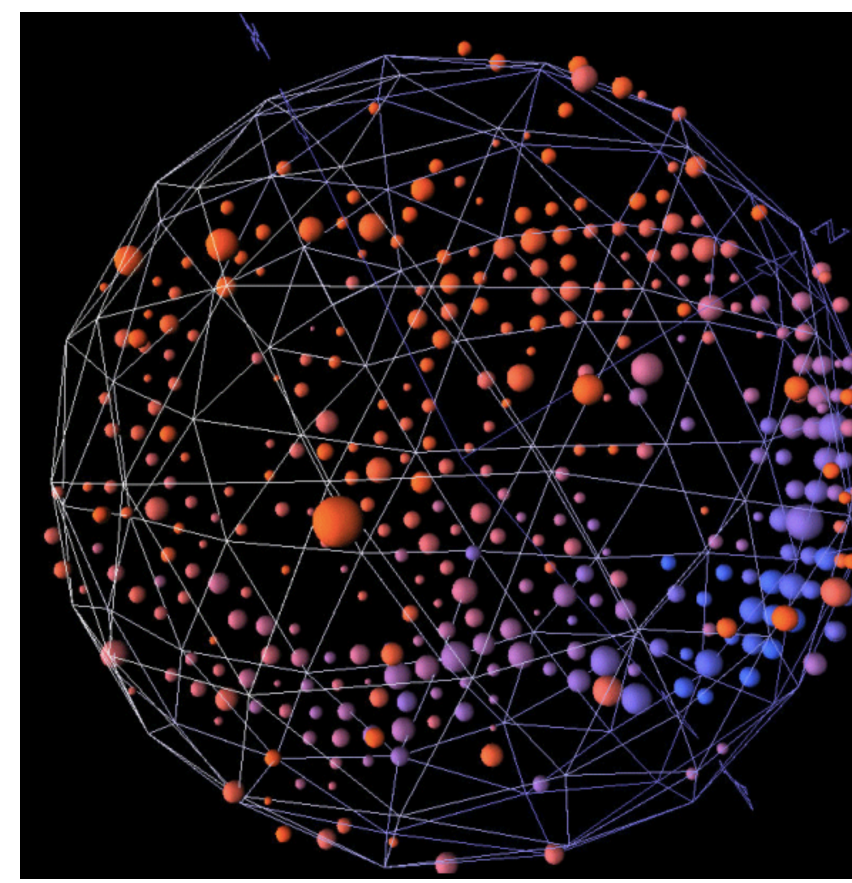
Muons: "clean" rings from long, straight minimum ionizing tracks





Neutral Pions: two fuzzy rings from decay to two photons





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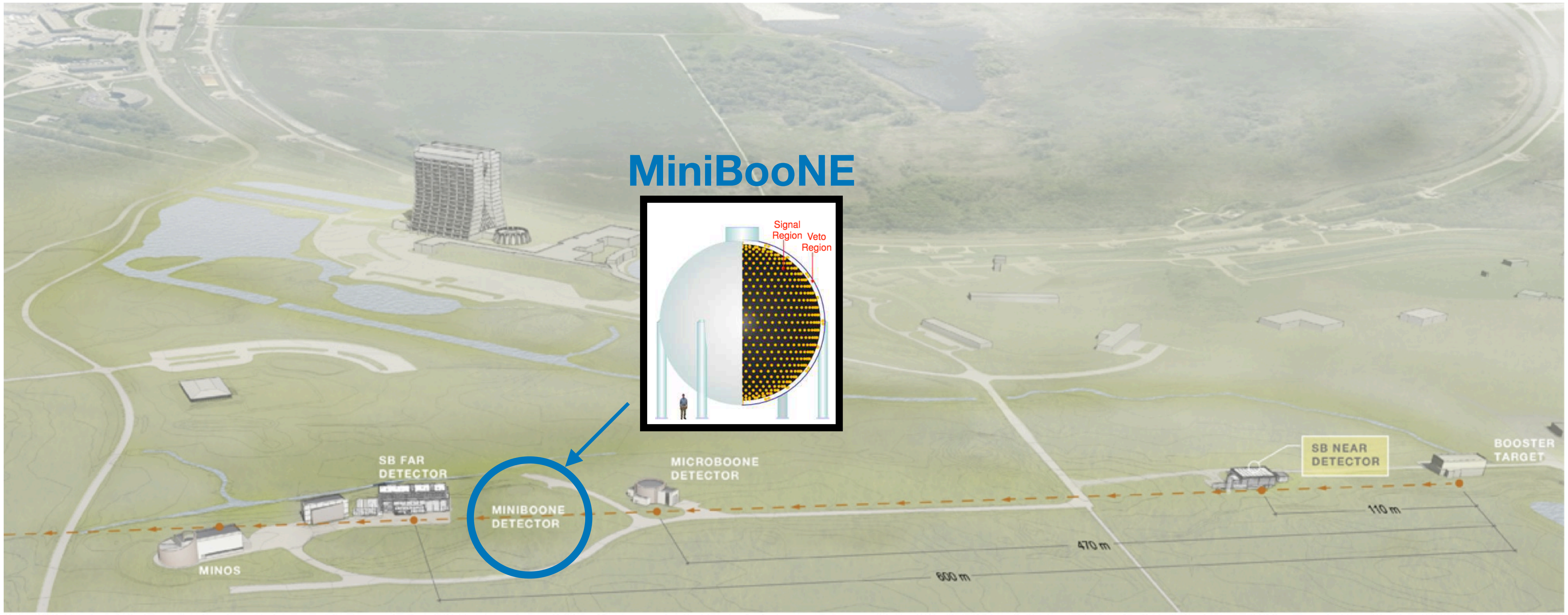
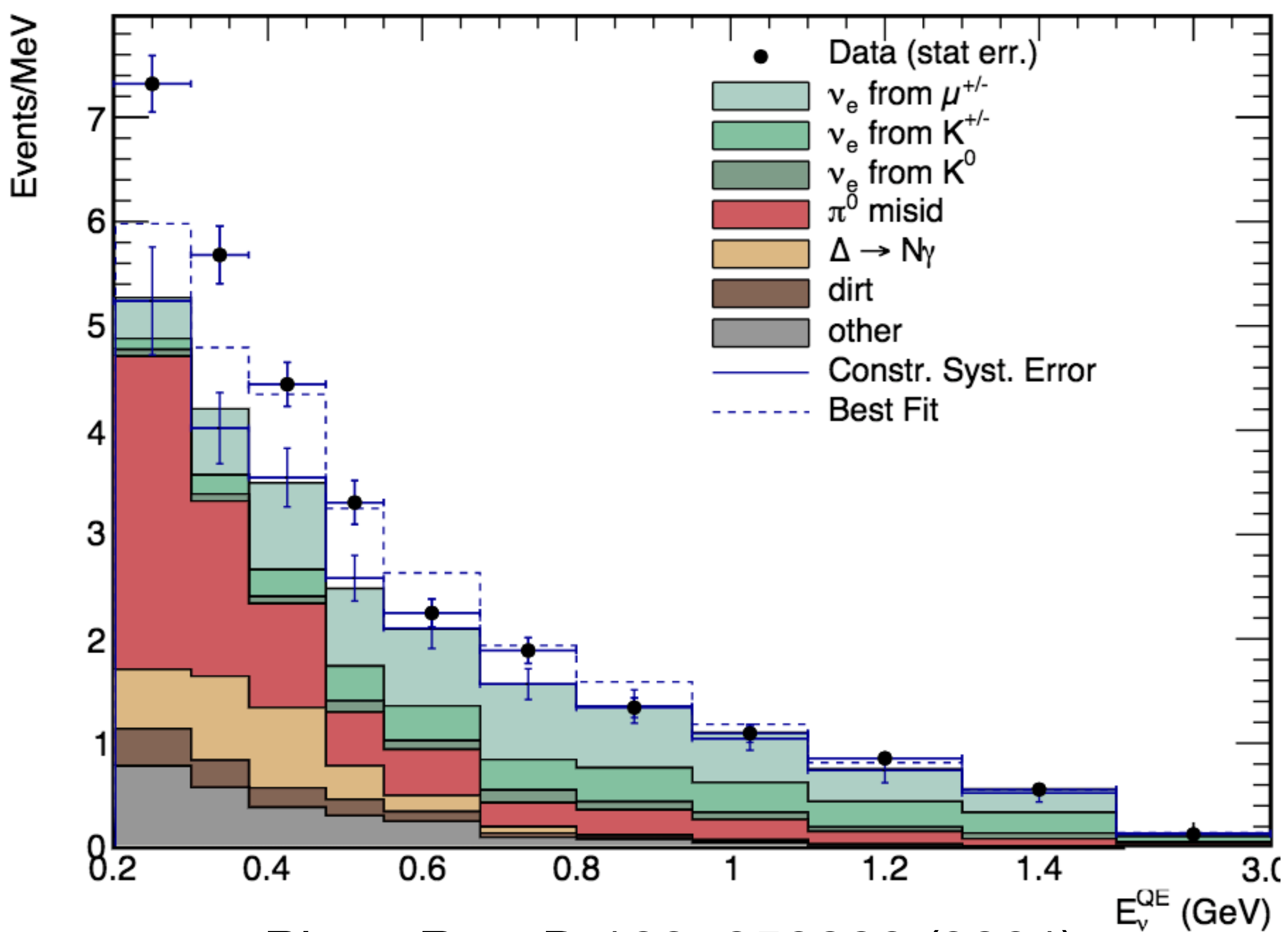
- **The electron-like excess**
- Further MiniBooNE results



Final Electron-Like Excess

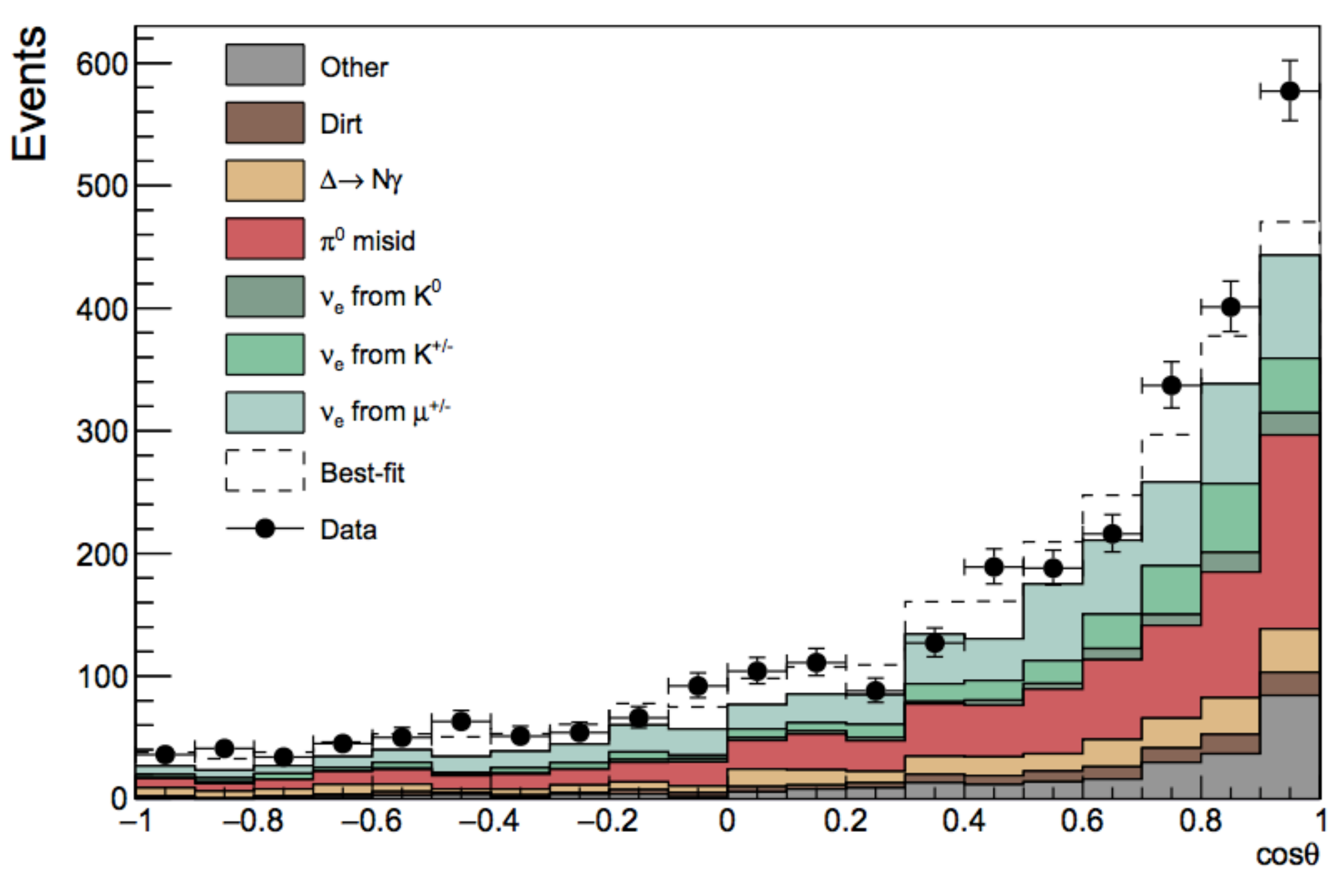
- With the complete dataset, the excess of electron-like events is: 638.0 ± 52.1 (stat) ± 122.2 (sys) events (4.8σ significance)
- Excess is consistent across the lifetime of the detector

Neutrino Mode

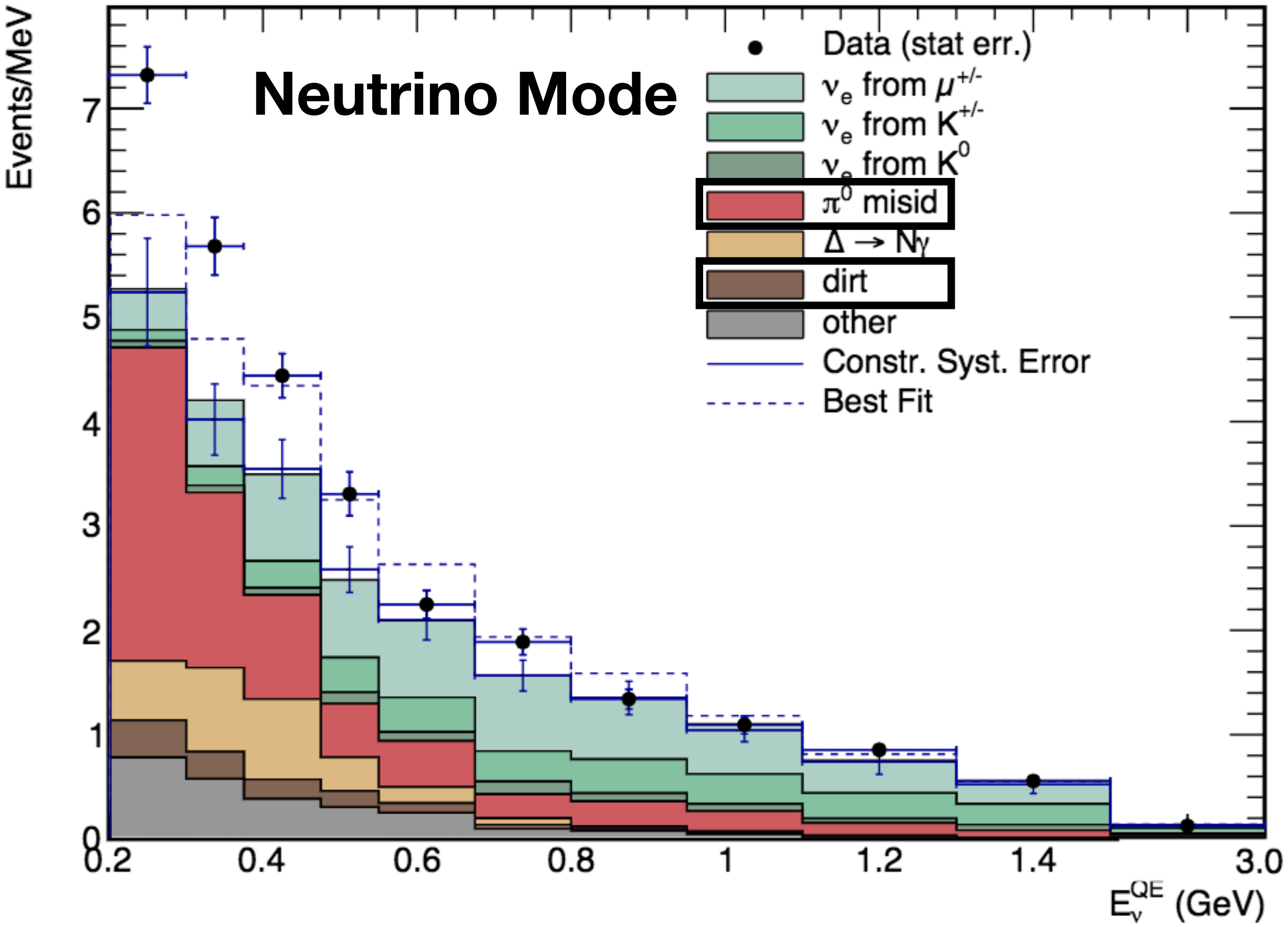


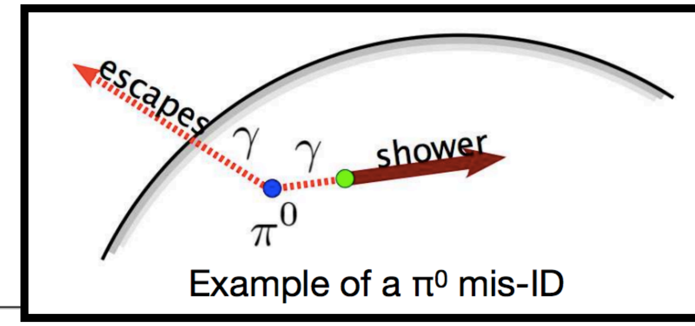
Phys. Rev. D 103, 052002 (2021)

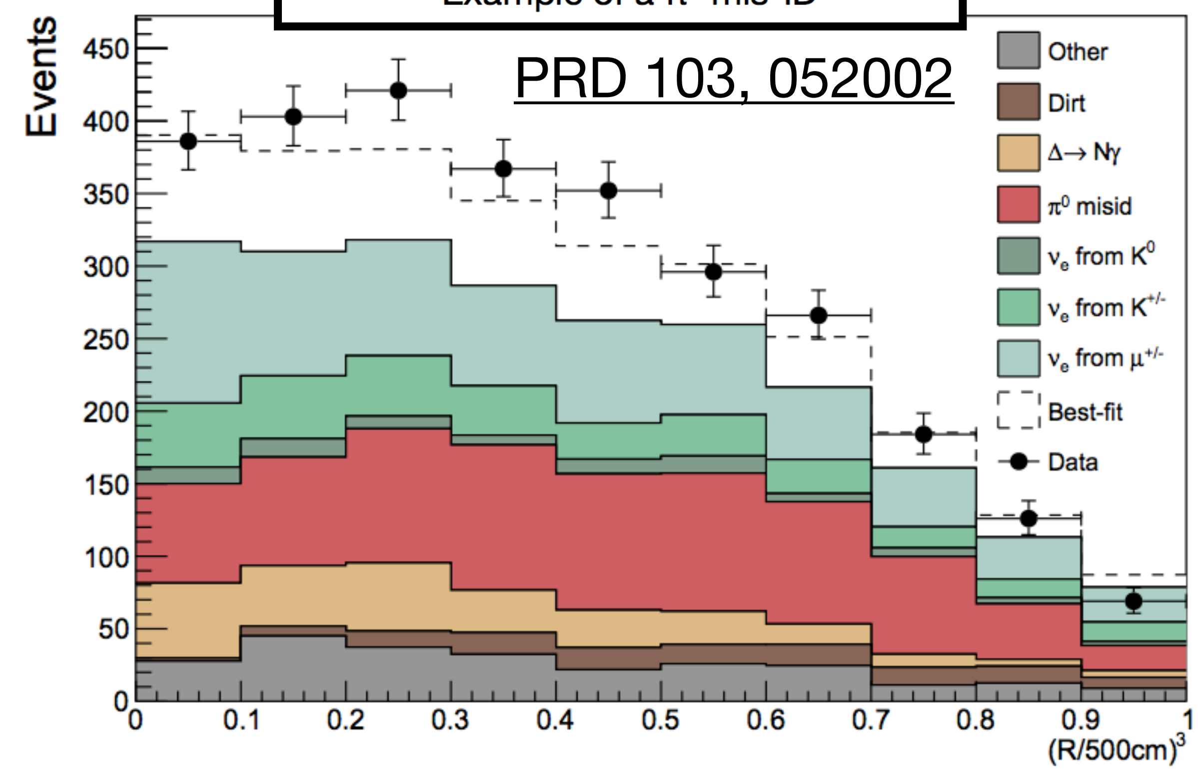
Neutrino Mode



Final Electron-Like Excess

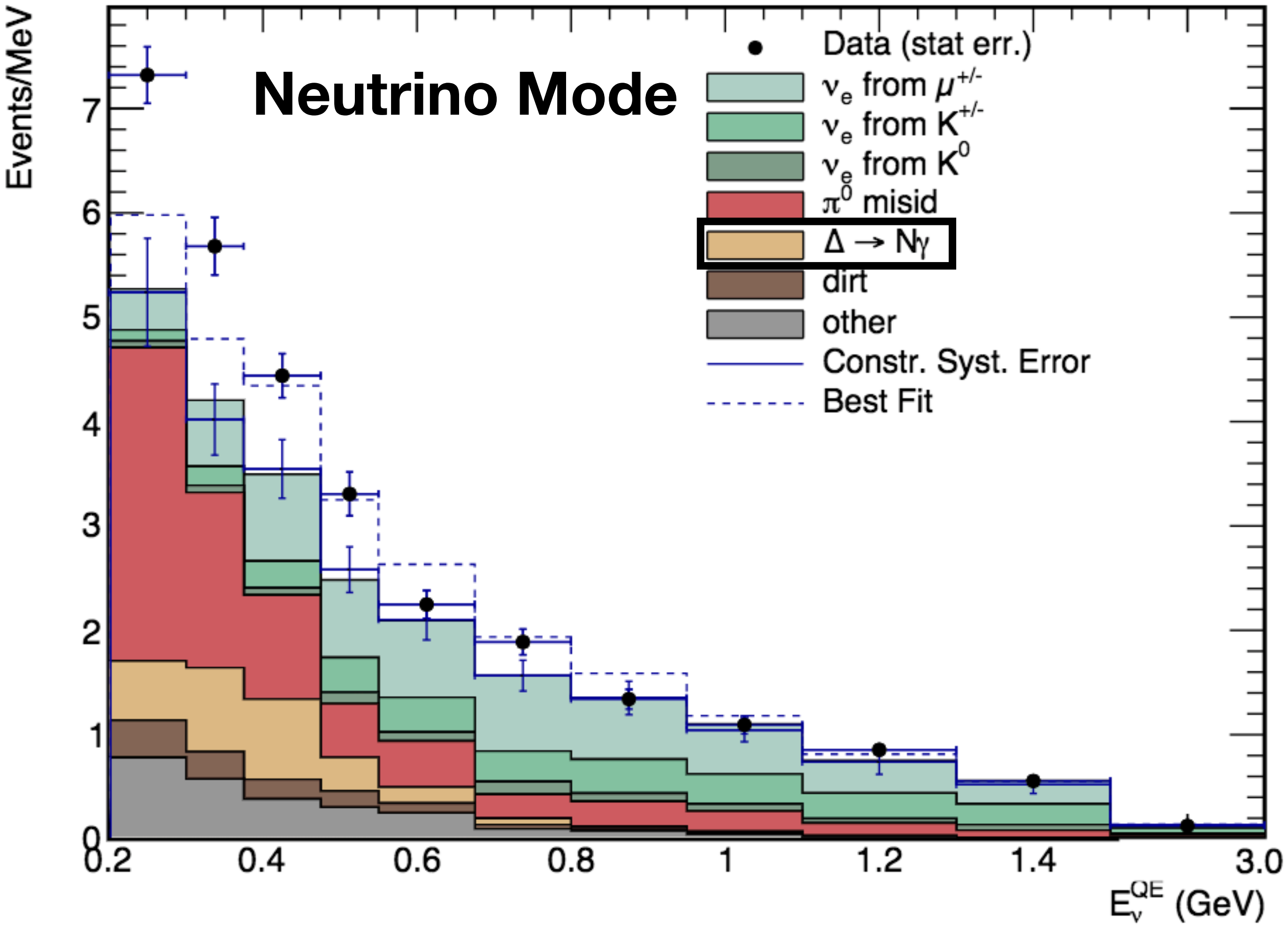




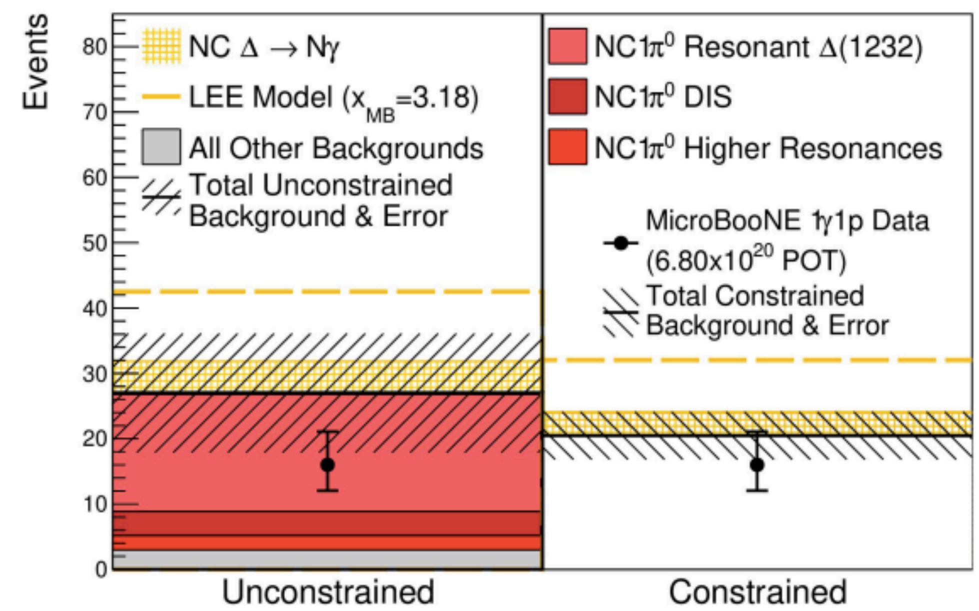


Neutral Pion and dirt backgrounds constrained *in situ*; disfavored by radial/timing distributions of excess

Final Electron-Like Excess



1γ1p



1γ1p

Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \rightarrow N\gamma$	+4.88
LEE ($x_{MB} = 3.18$)	+15.5

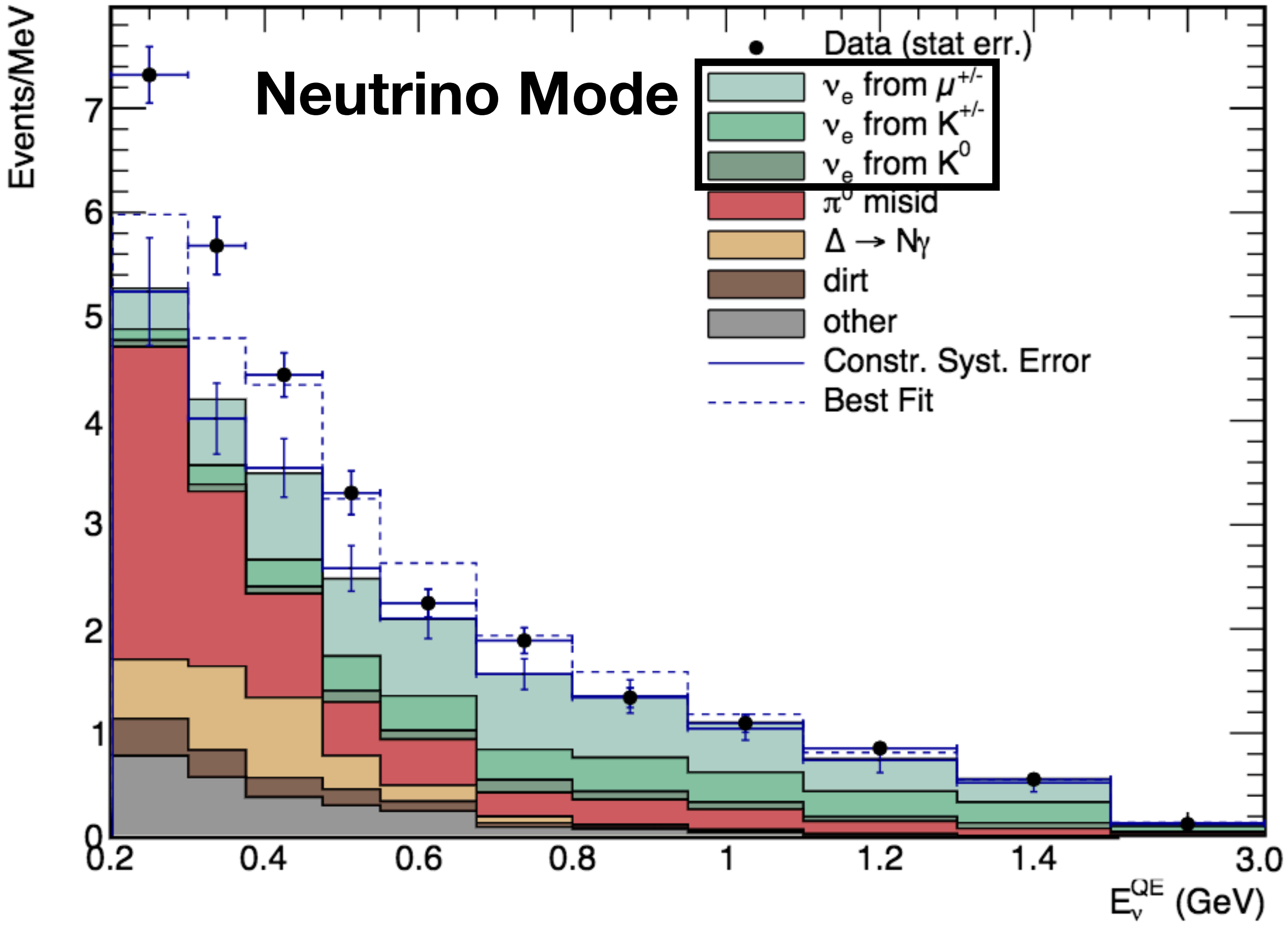
16
Data Events Observed

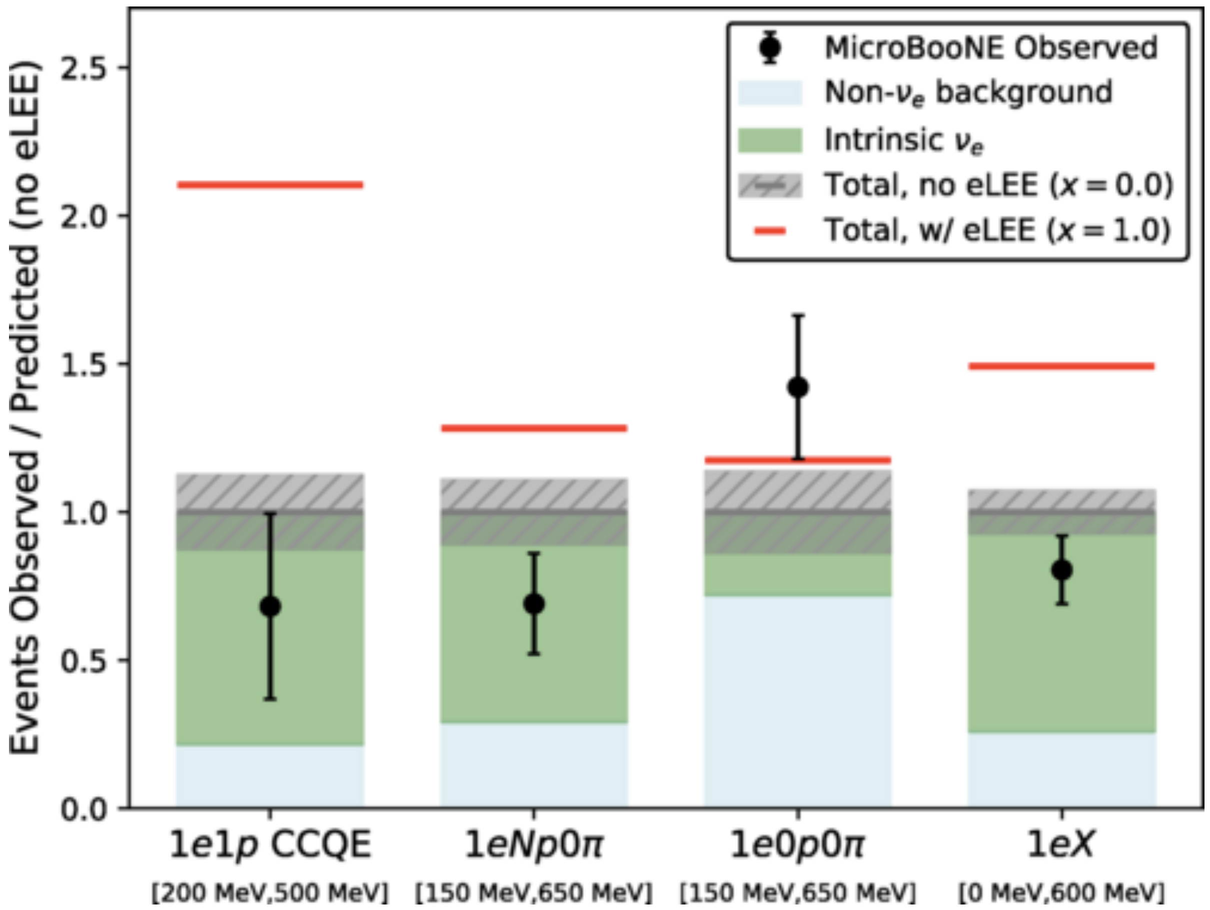
Phys. Rev. Lett. 128, 111801

Neutral Pion and dirt backgrounds constrained *in situ*; disfavored by radial/timing distributions of excess

Delta decay background would need be scaled by factor of ~3 to explain excess; disfavored by recent MicroBooNE results

Final Electron-Like Excess





MicroBooNE Phys. Rev. Lett. 128, 241801 (2022)

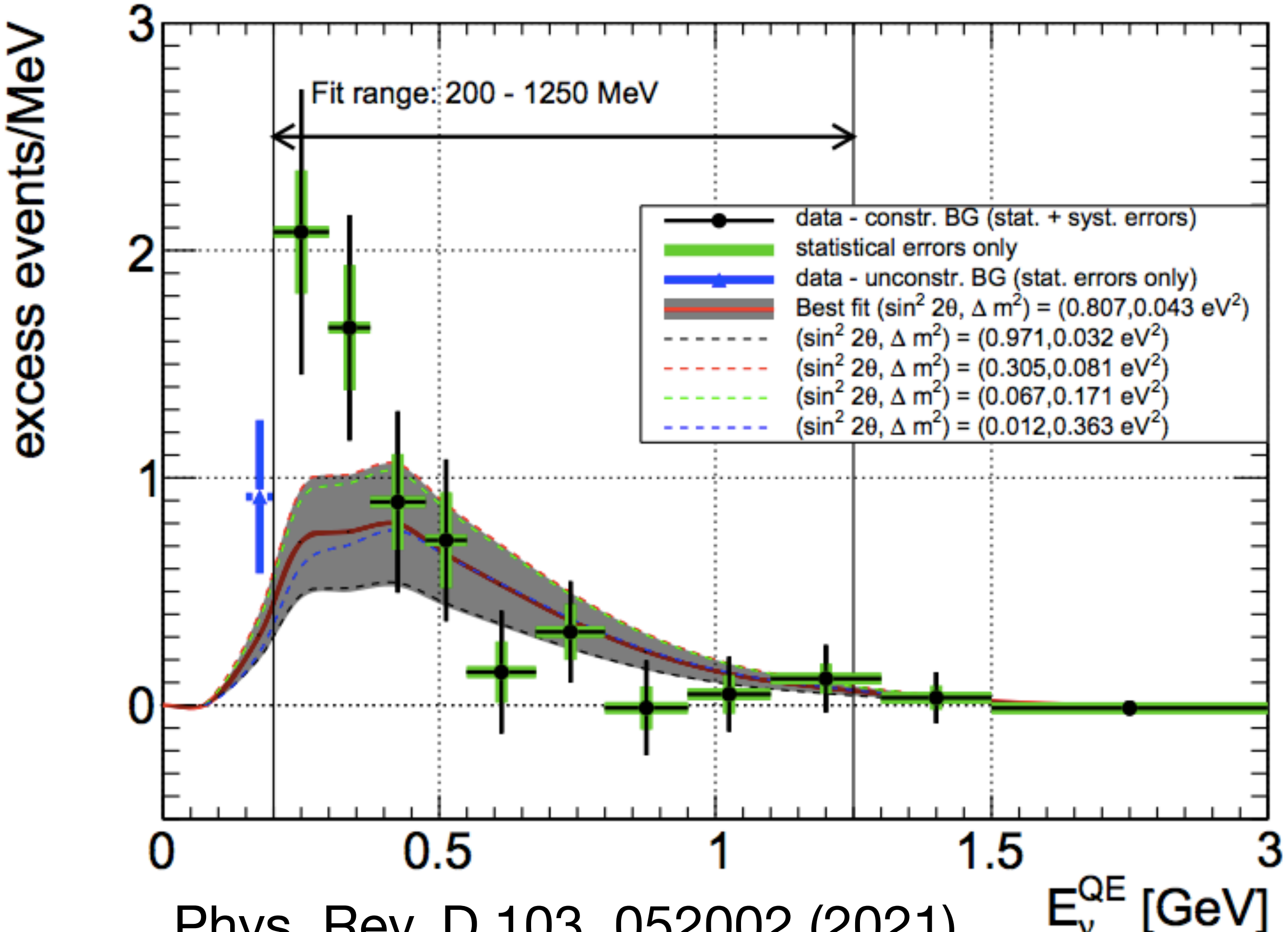
Neutral Pion and dirt backgrounds constrained *in situ*; disfavored by radial/timing distributions of excess

Delta decay background would need be scaled by factor of ~3 to explain excess; disfavored by recent MicroBooNE results

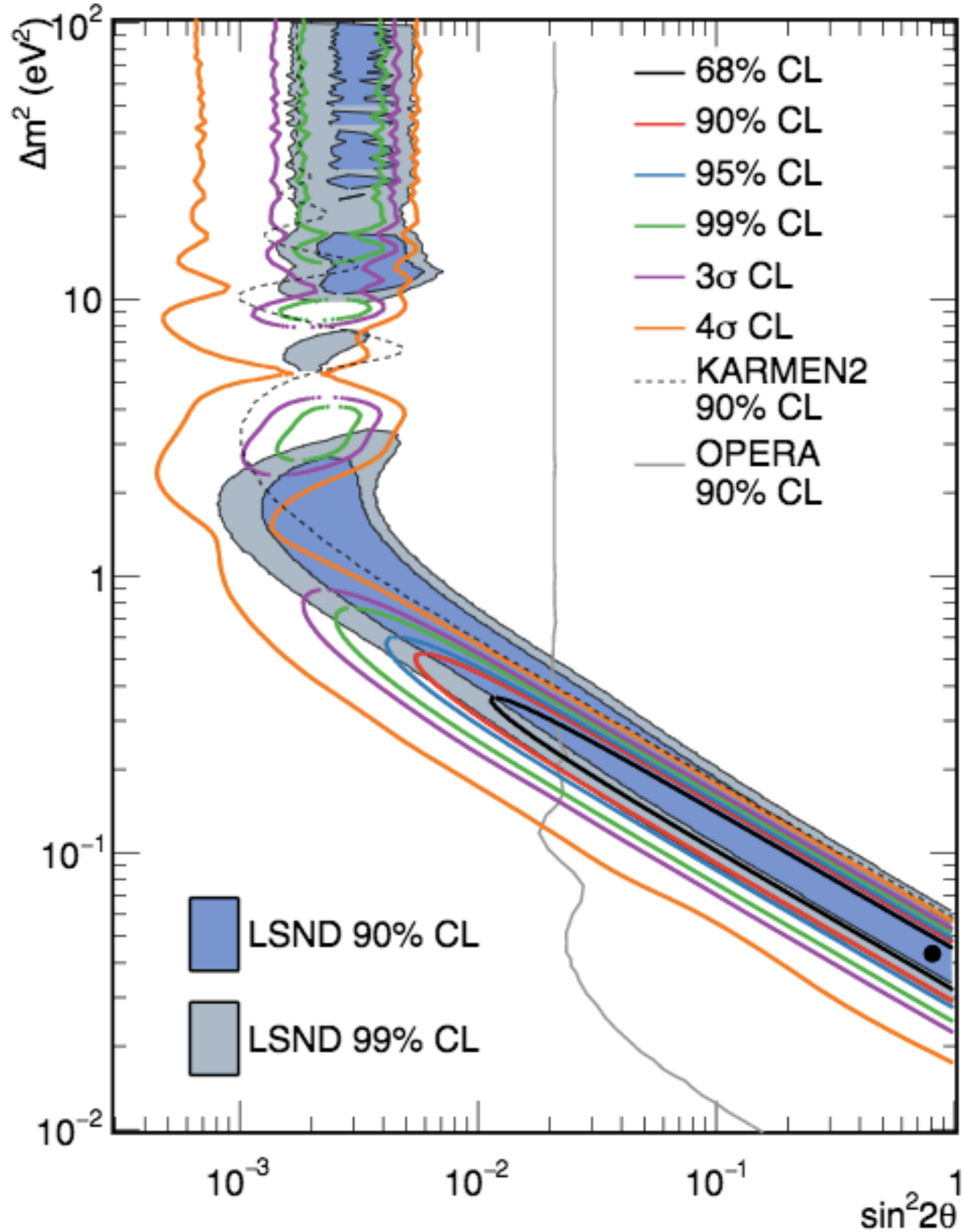
Excess consisting of entirely true electron neutrino events disfavored by recent MicroBooNE results

Oscillation Interpretation

- eV-scale sterile neutrino oscillation parameter space consistent with LSND allowed region
- Additional excess above best fit at lowest energies

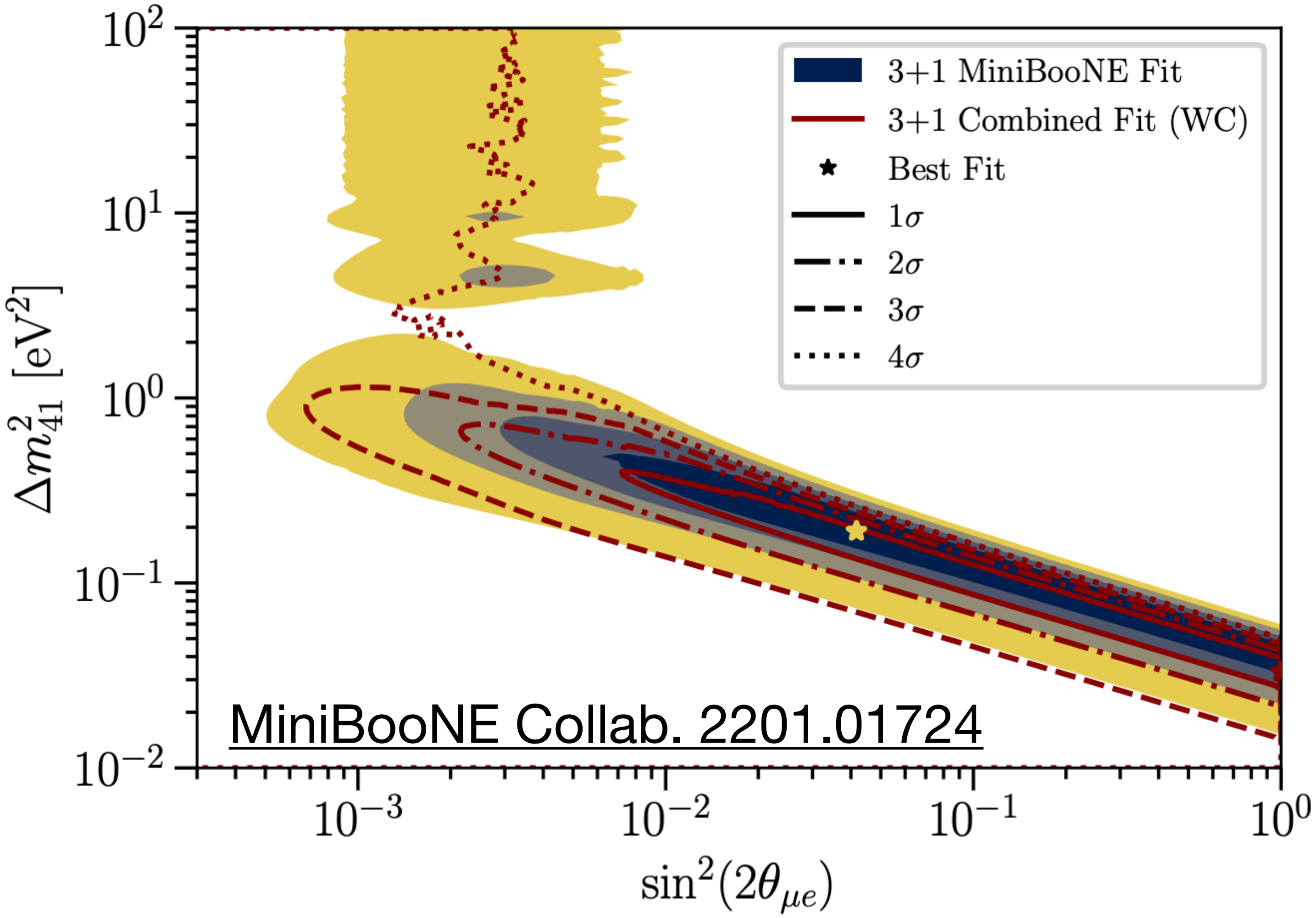


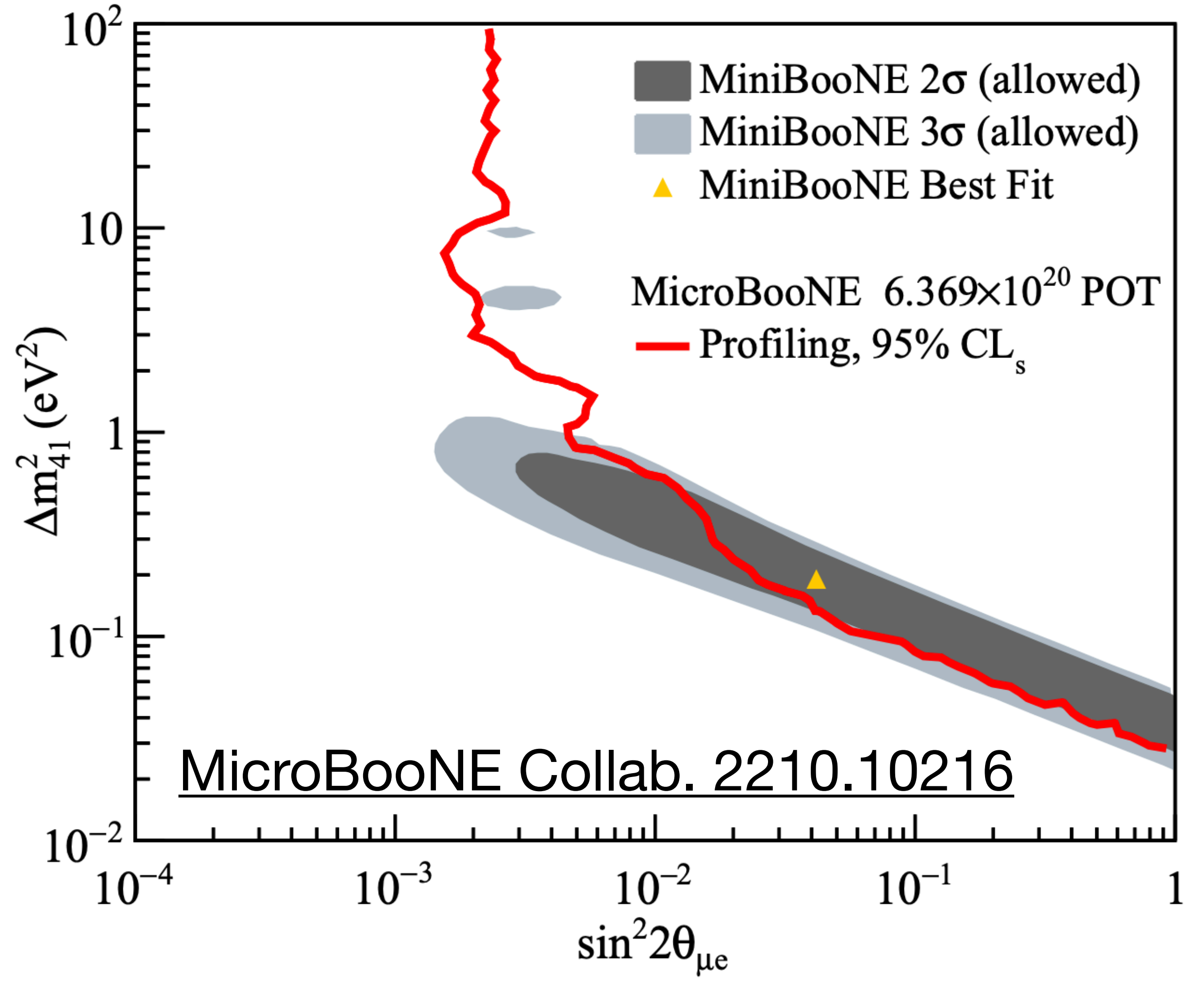
Phys. Rev. D 103, 052002 (2021)



Steriles and MicroBooNE

- MiniBooNE has performed a combined fit to the 3+1 model considering the MicroBooNE ν_e analyses—allowed regions remain at the 3σ C.L.
- MicroBooNE's own 3+1 analysis rules out a portion of MiniBooNE's allowed region at the 95% C.L.





Beyond Sterile Neutrinos

- Tension in sterile neutrino global fits [1] has led the community to explore alternative models to explain the MiniBooNE excess

Non-exhaustive list

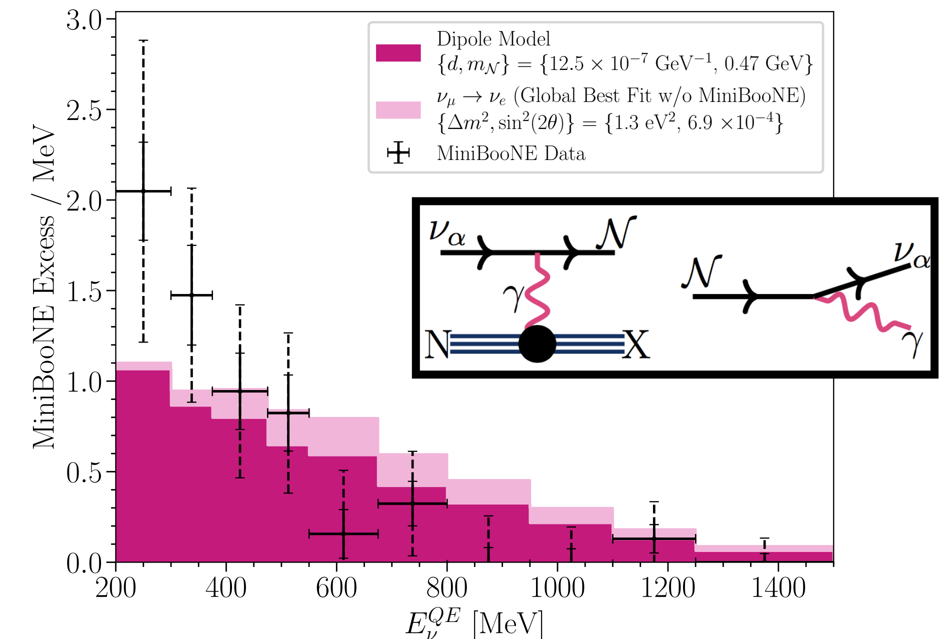
- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - *[13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)*
  - *[14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141*
- New resonance matter effects
  - *[5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)*
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - *[7] Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470*
- Decay of heavy sterile neutrinos produced in beam
  - *[4] Gninenko, Phys.Rev.D83:015015,2011*
  - *[12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)*
  - *[15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)*
  - *[11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)*
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - *[1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)*
  - *[2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531*
  - *[3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)*
  - *[10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)*
  - *[6] Abdallah, Gandhi, Roy, Phys. Rev. D 104, 055028 (2021)*
- Decay of axion-like particles
  - *[8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)*
- A model-independent approach to any new particle
  - *[9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)*

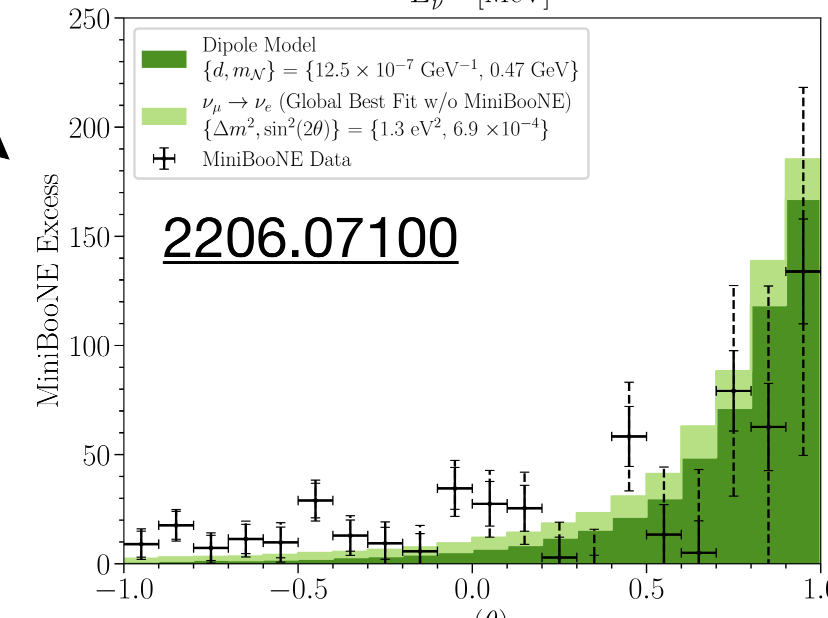
Produces true electrons

Produces true photons

Produces e^+e^- pairs

- BSM matter effects in sterile oscillations Alves et al. arXiv:2201.00876
- Charged meson decay to new physics Dutta et al. arXiv 2110.11944





2206.07100

[1] See 1803.10661 and 1906.00045

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  - [3] Ballett, Pas
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  - [6] Abdallah, C
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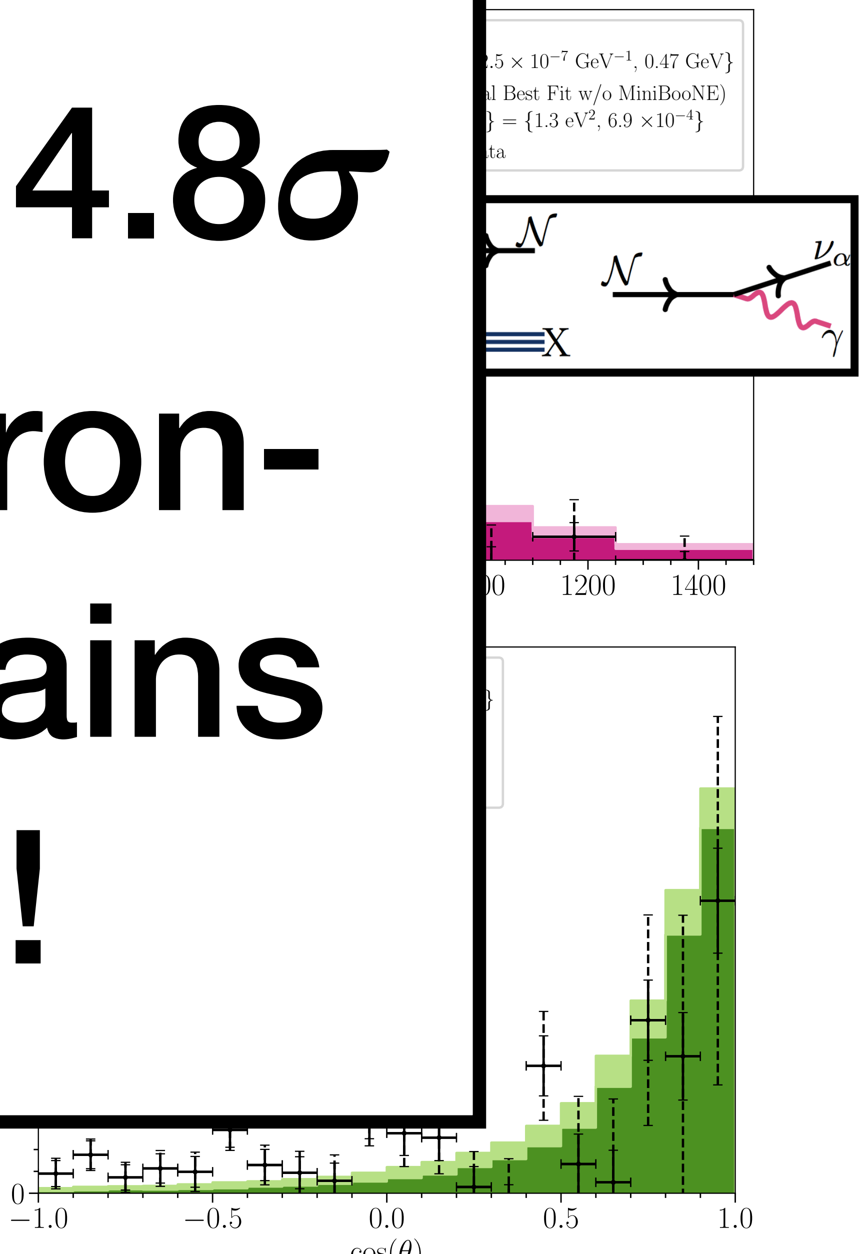
  - [9] Brdar, Fisc

The MiniBooNE 4.8σ excess of electron-like events remains unexplained!



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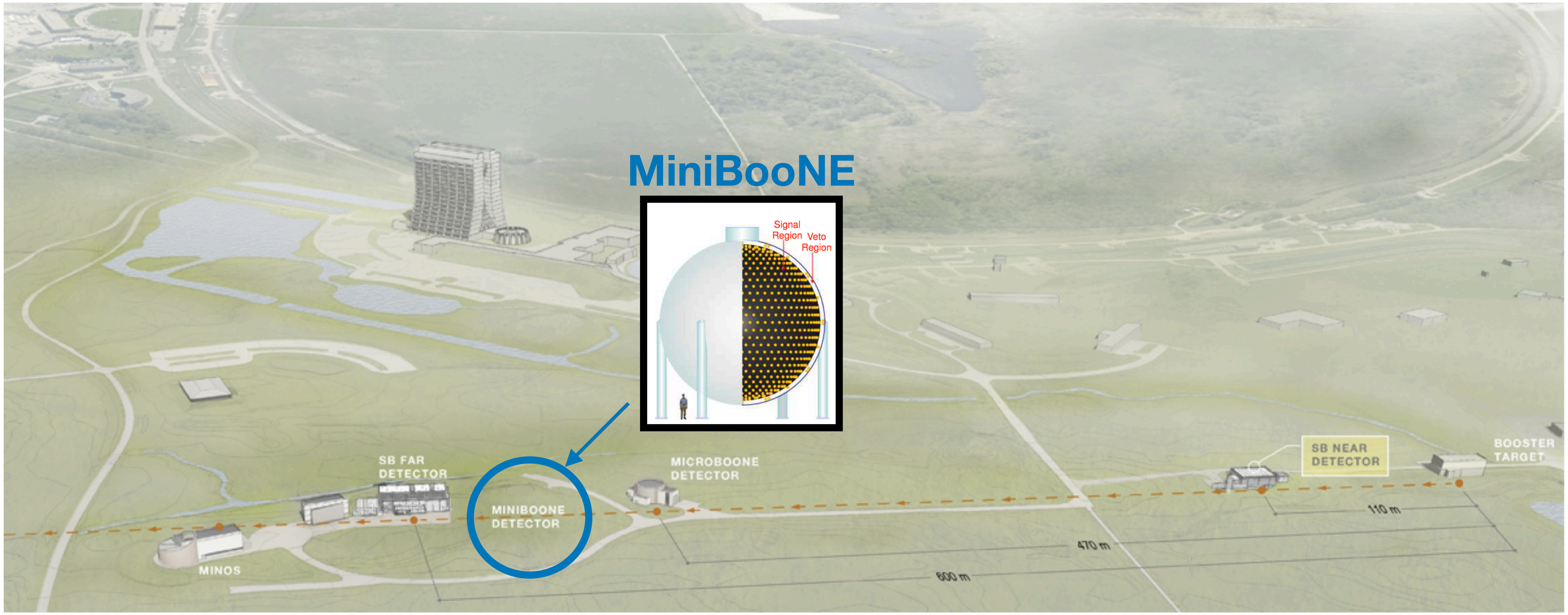
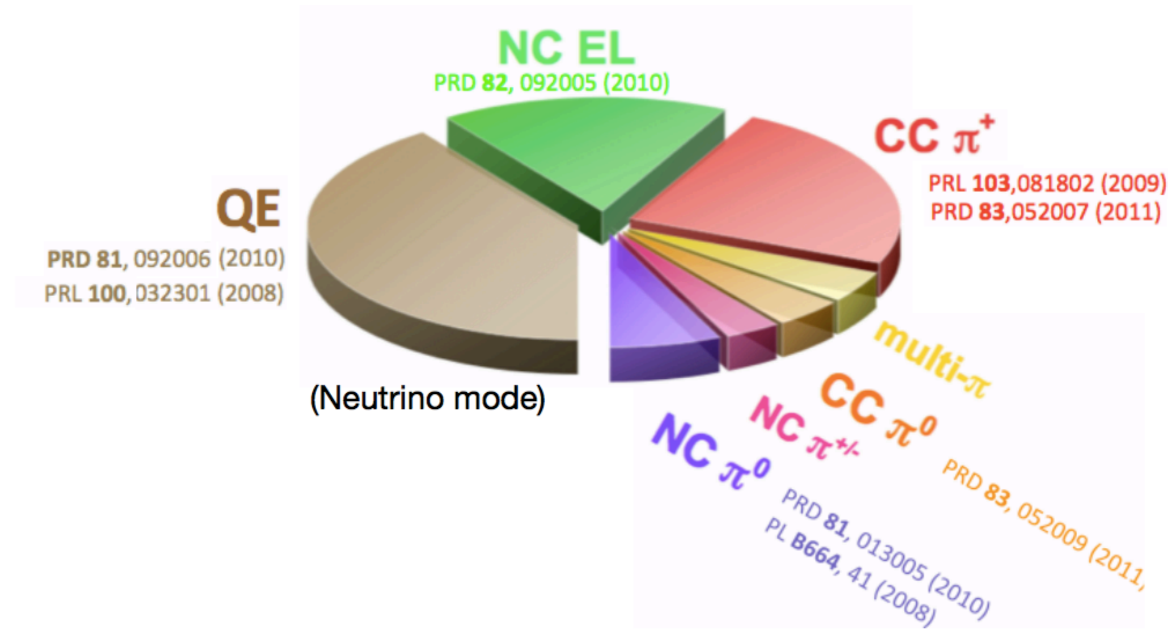
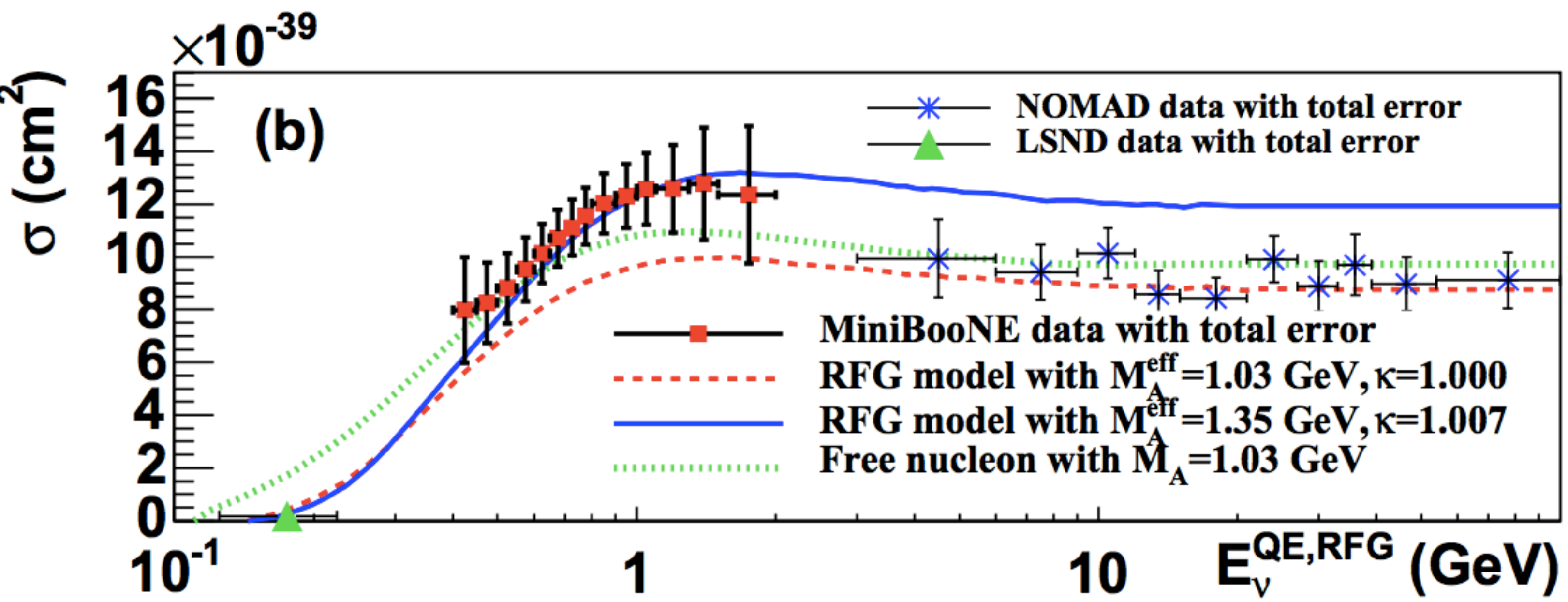


Cross Sections

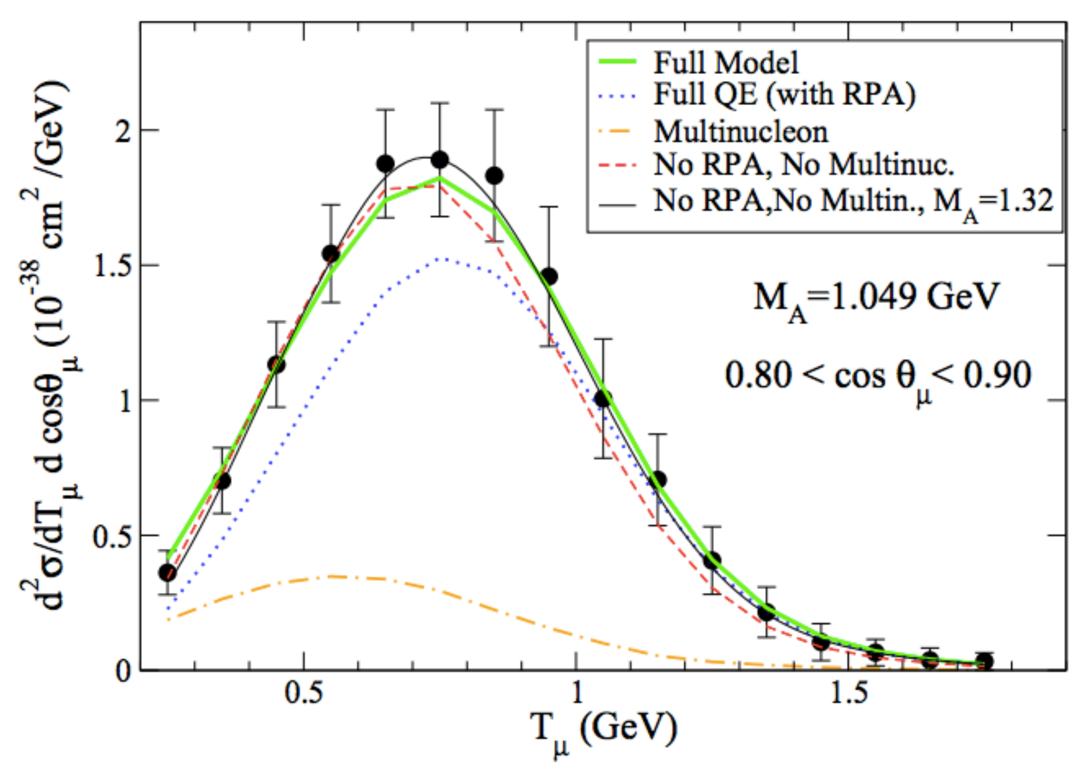
- Many cross section measurements across different neutrino interaction channels over the 17-year run
- Muon neutrino CCQE double-differential cross section established importance of multi-nucleon effects in accelerator neutrino experiments



Adapted from Adrien Hourlier



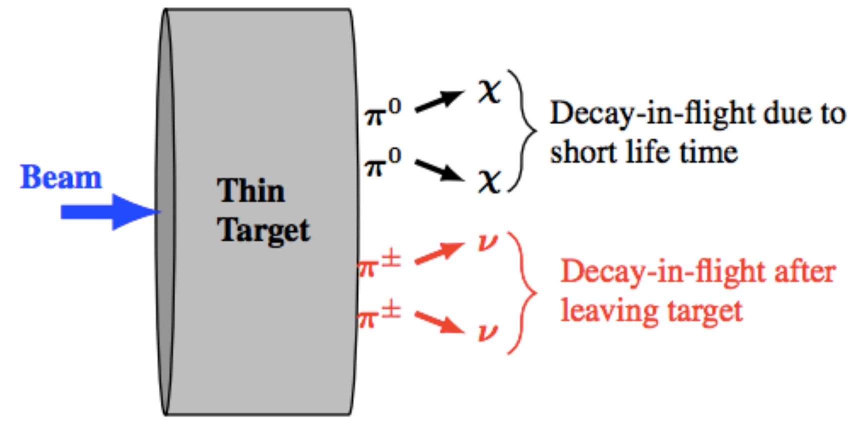
MiniBooNE Collaboration Phys. Rev. D 81, 092005 (2010)

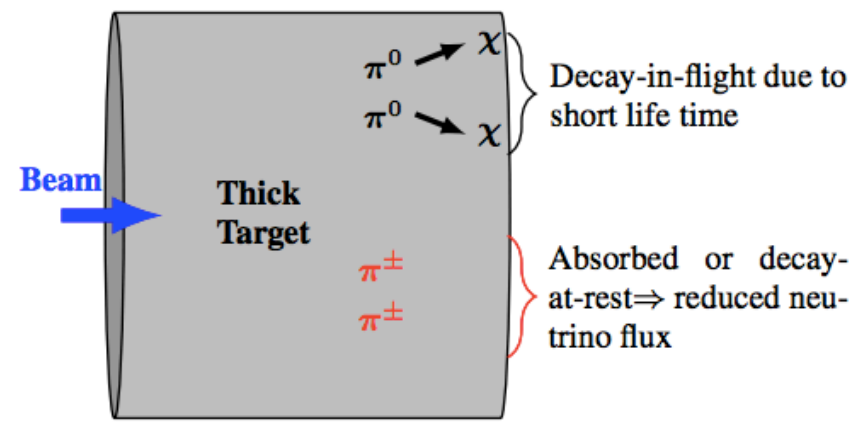


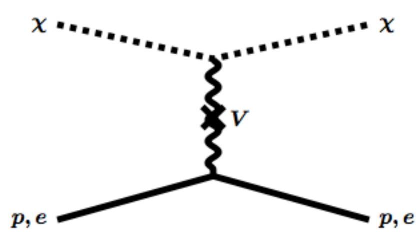
Nieves et al., Physics Letters B (2011)

Dark Matter

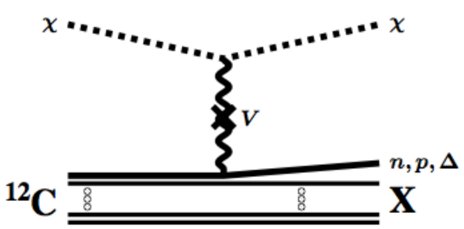
- MiniBooNE's beam dump run set strong constraints on sub-GeV vector-portal and leptophobic dark matter models



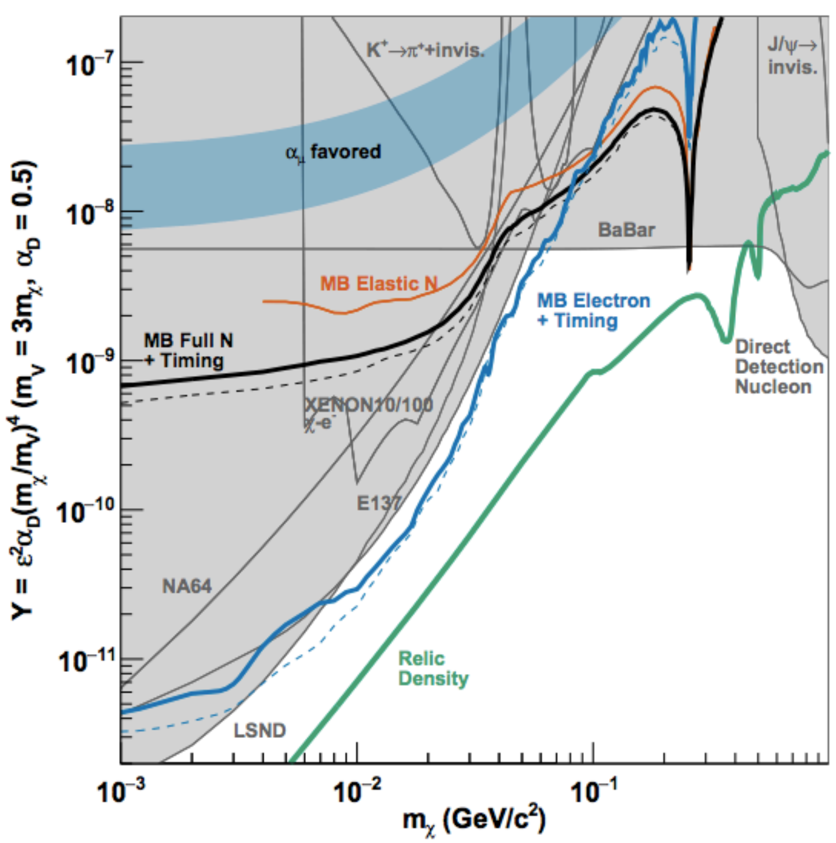




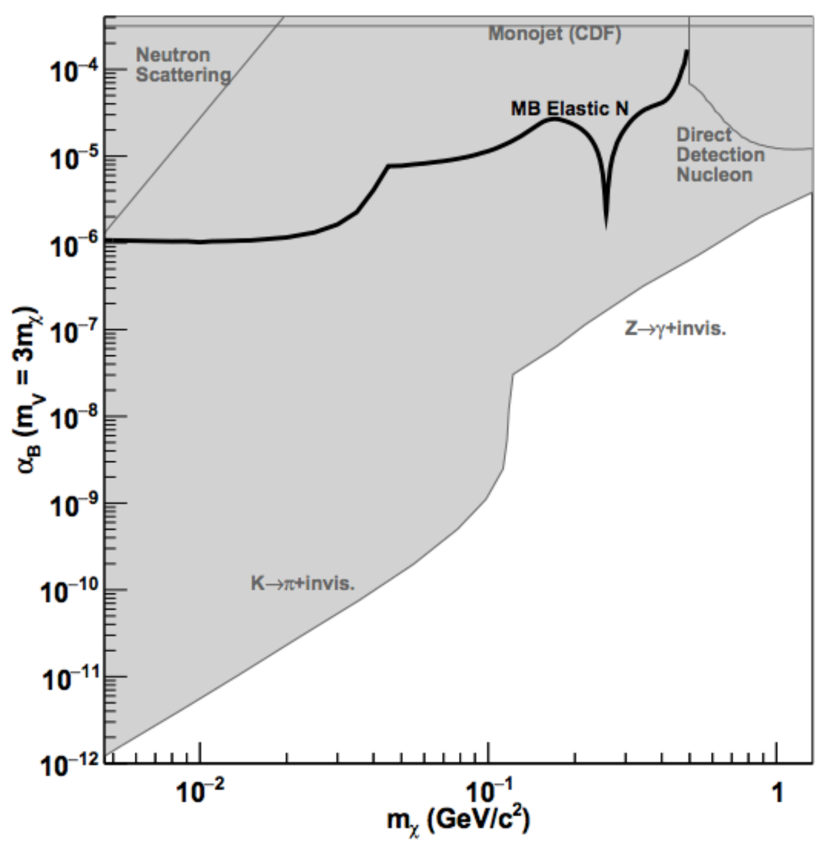
(a) Free Protons or Electrons



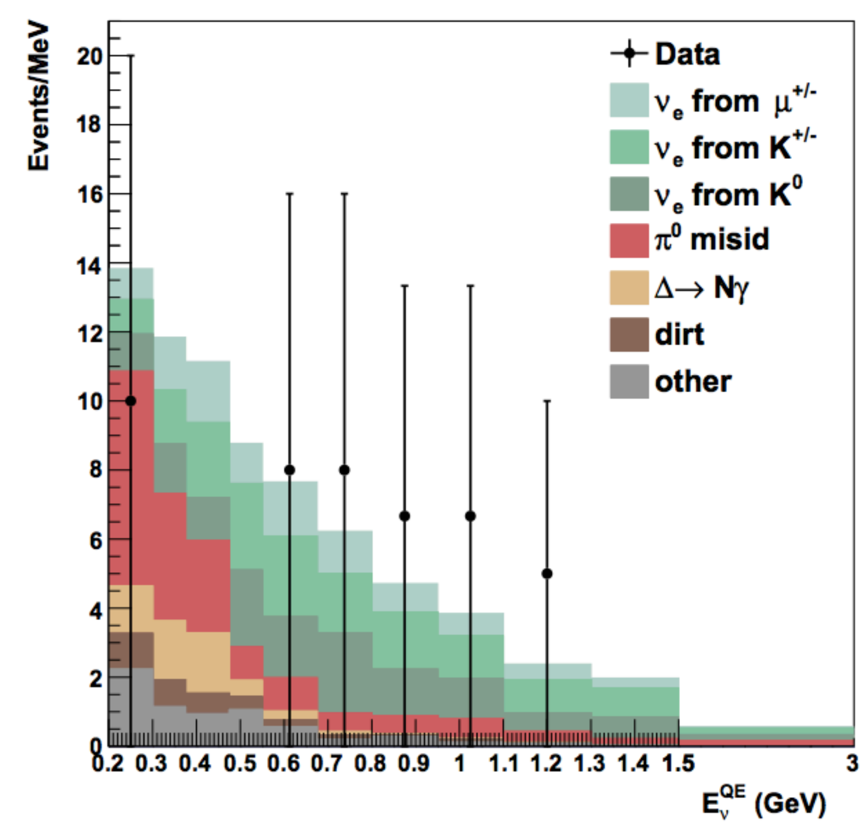
(b) Bound Nucleons



(a) vector portal



(b) leptophobic



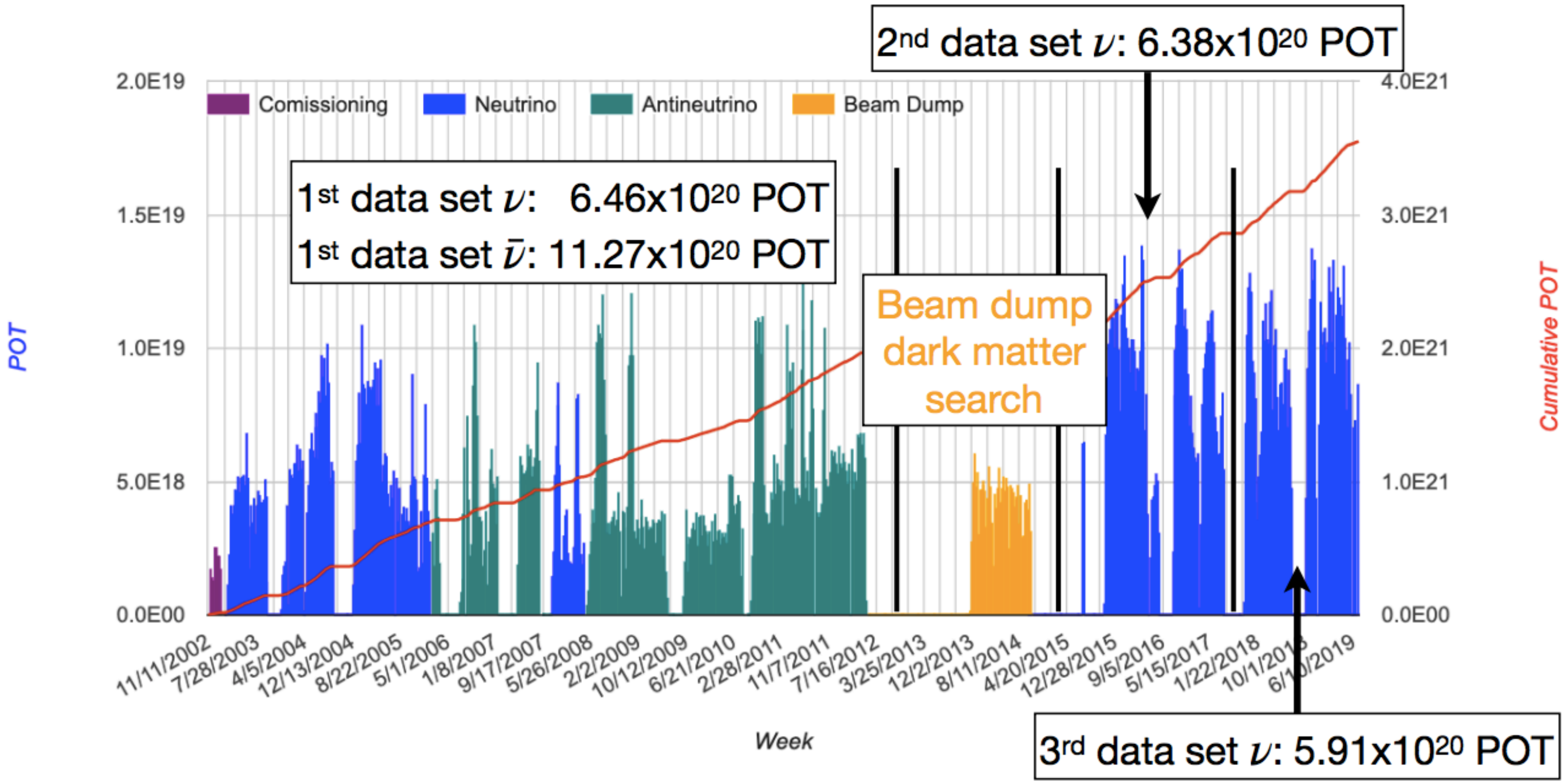
MiniBooNE-DM Collab. Phys. Rev. D 98, 112004 (2018)

Conclusion

- MiniBooNE's 818-ton mineral oil Cherenkov detector detector has taken 17 years of data at Fermilab's booster neutrino beam
- MiniBooNE observes a 4.8σ excess of electron-like events
  - Recent MicroBooNE results offer some insights into the nature of the excess, but it remains unexplained!
  - Community is exploring more exotic explanations
- Many other important MiniBooNE results, including cross section measurements and dark matter constraints

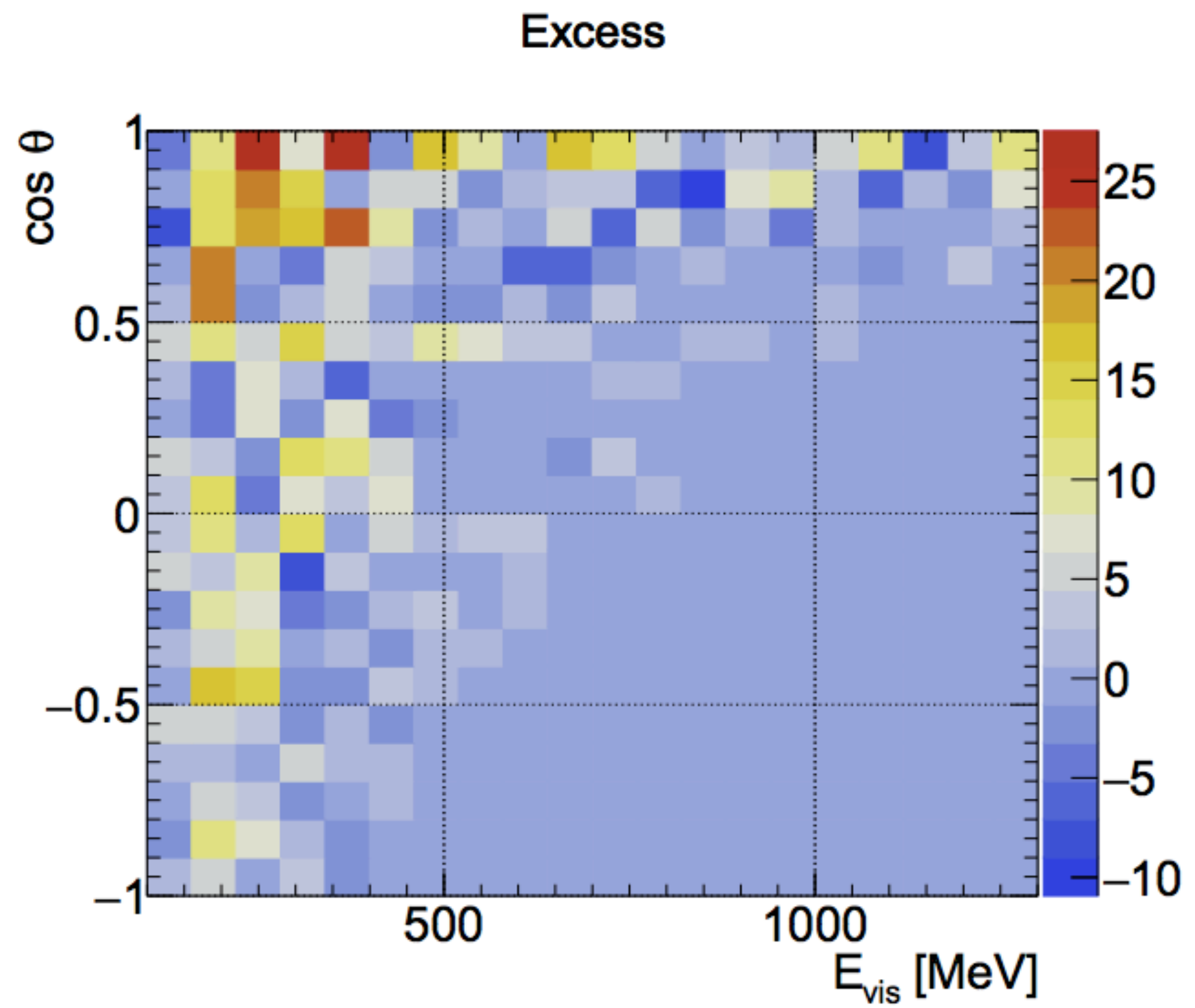
Backup

The Entire MiniBooNE Dataset

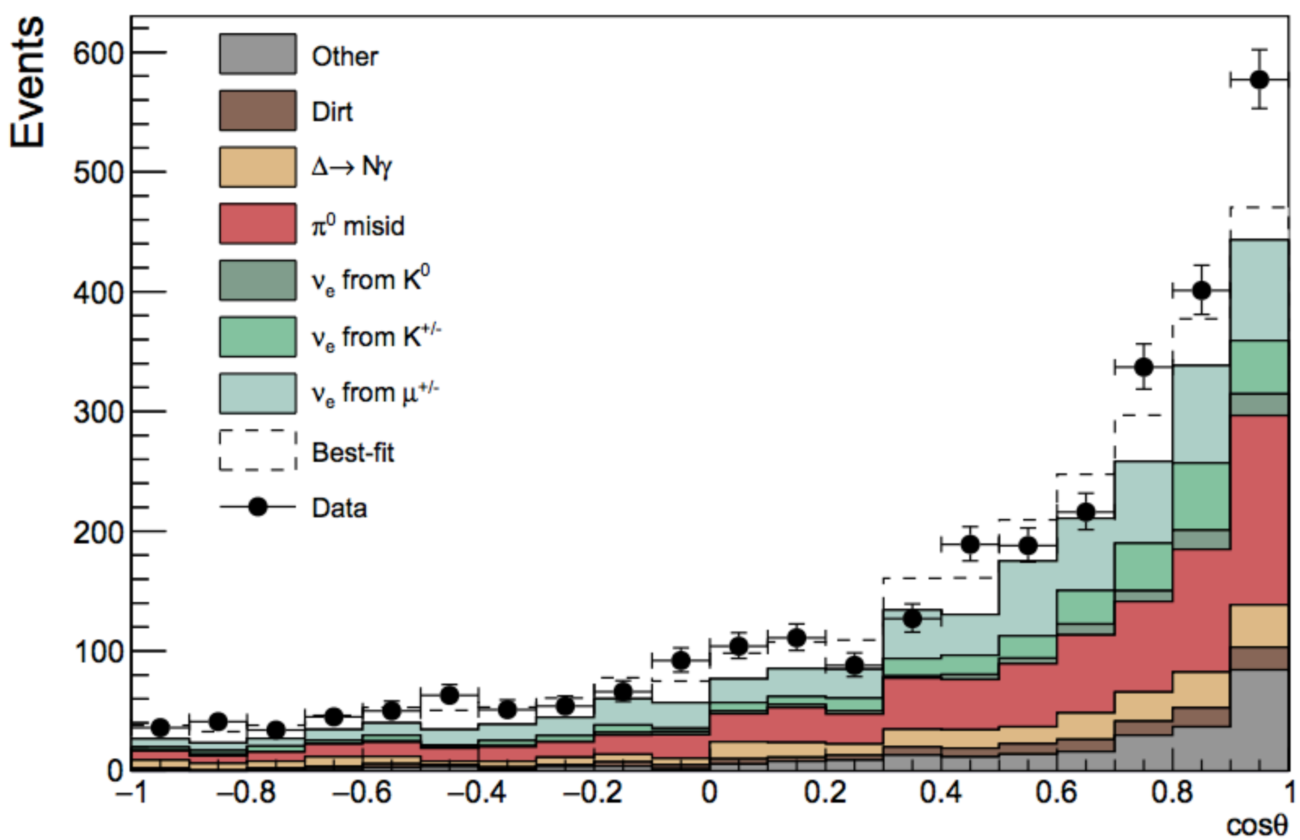


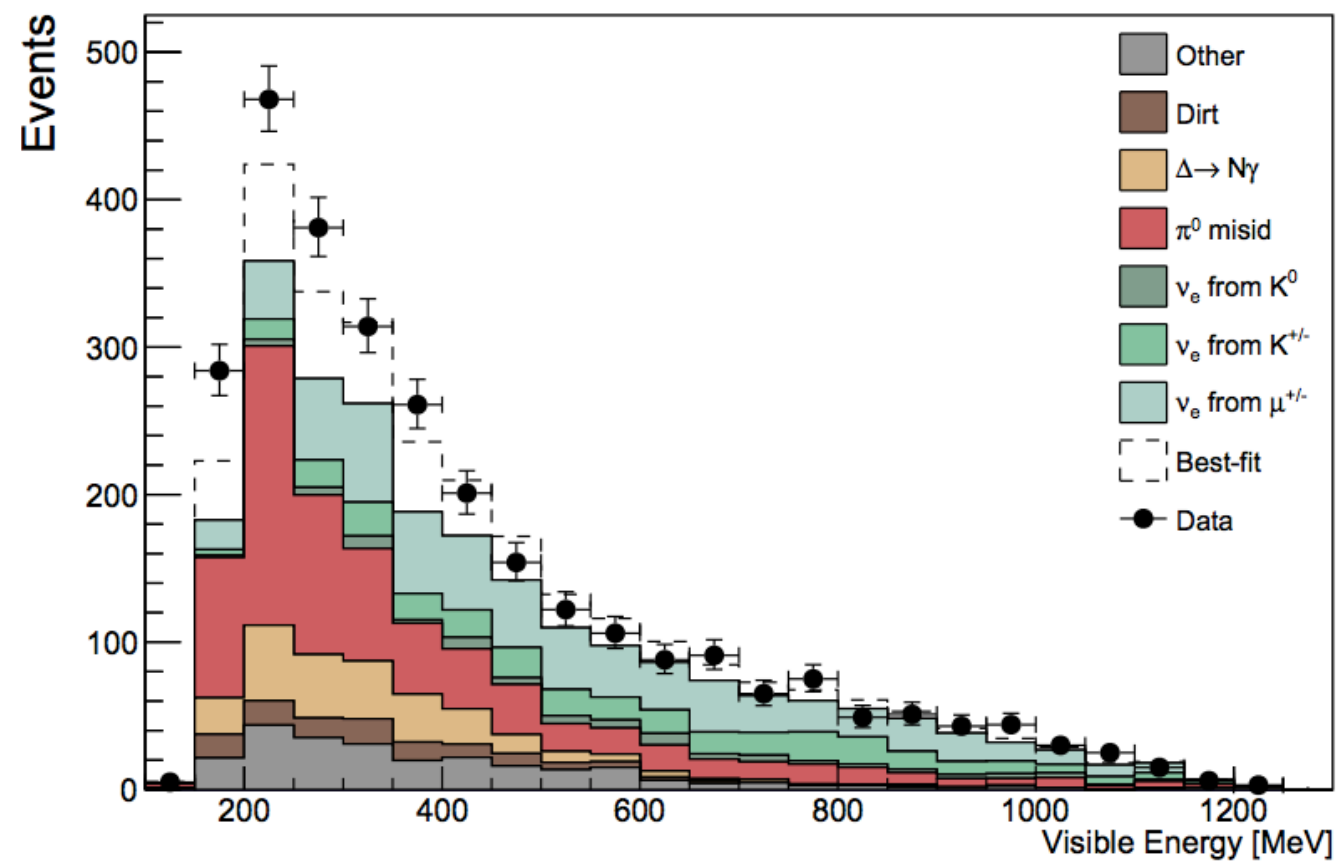
Neutrino mode total: 18.75e20 POT
Antineutrino mode total: 11.27e20 POT

Electron Angle / Energy

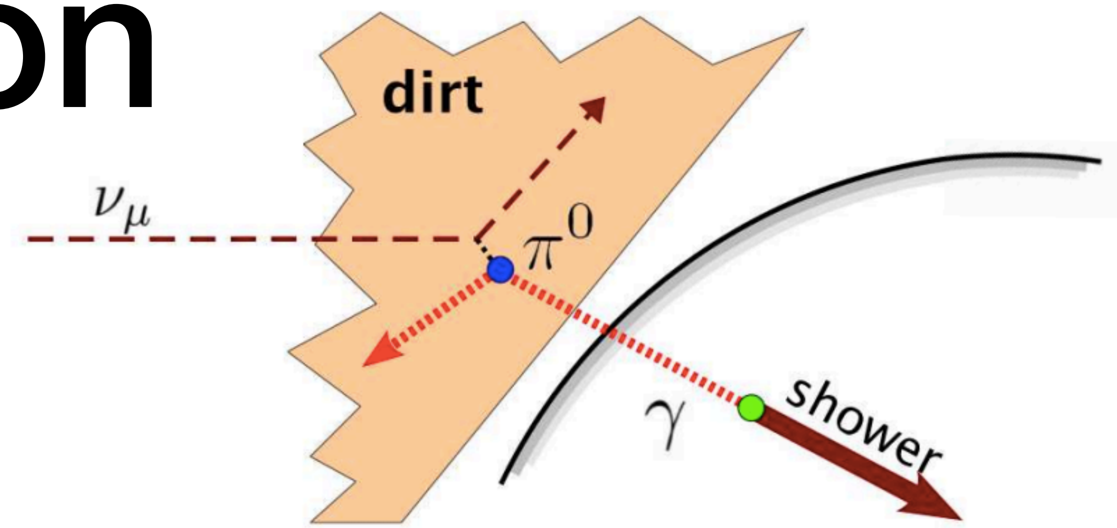


- Significant portion of the excess in the low electron visible energy / scattering angle region of phase space
- In the most forward peaked region, the excess extends to higher visible energy

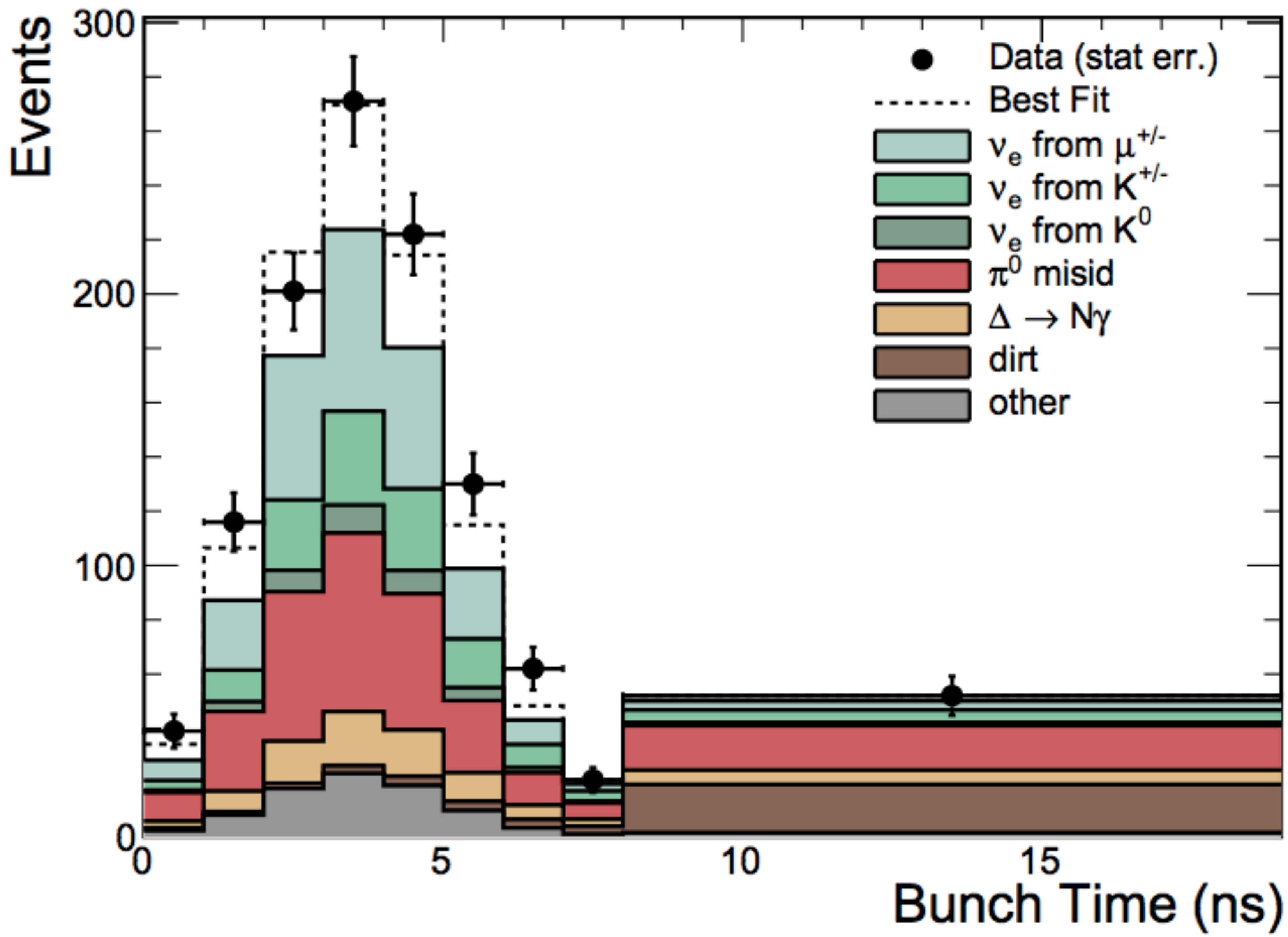




Timing Distribution

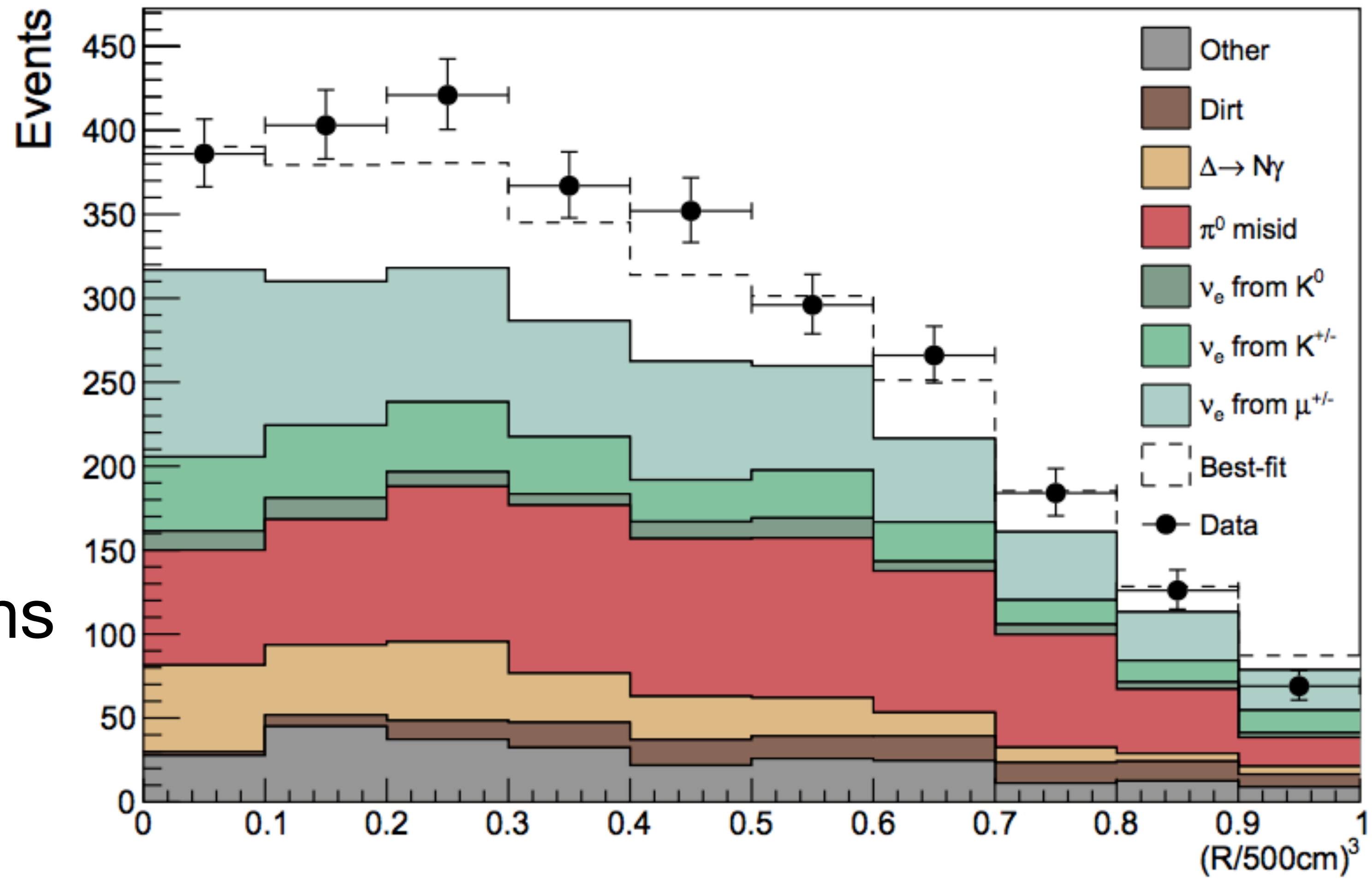


- The excess is contained within the expected 8 ns window around the beam bunch timing structure
- Disfavors interpretations involving external neutrinos or beam-off events
- Note: timing information available for second run period only

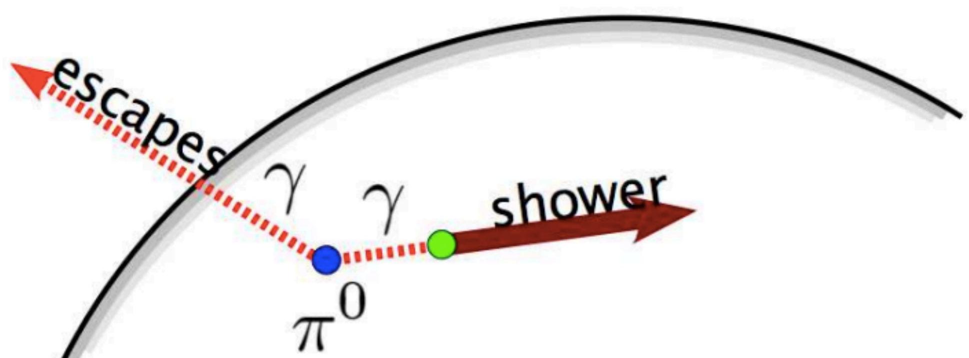


Radial Distribution

- Shape fits to the radial distribution disfavor explanations of the excess involving external events or neutral pions



Hypothesis	Multiplicative factor	$\chi^2/9ndf$
NC $\Delta \rightarrow N\gamma$ Background	3.18	10.0
External Event Background	5.98	44.9
ν_e & $\bar{\nu}_e$ from K_L^0 Decay Background	7.85	14.8
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay Background	2.95	16.3
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay Background	1.88	16.1
Other ν_e & $\bar{\nu}_e$ Background	3.21	12.5
NC π^0 Background	1.75	17.2
Best Fit Oscillations	1.24	8.4

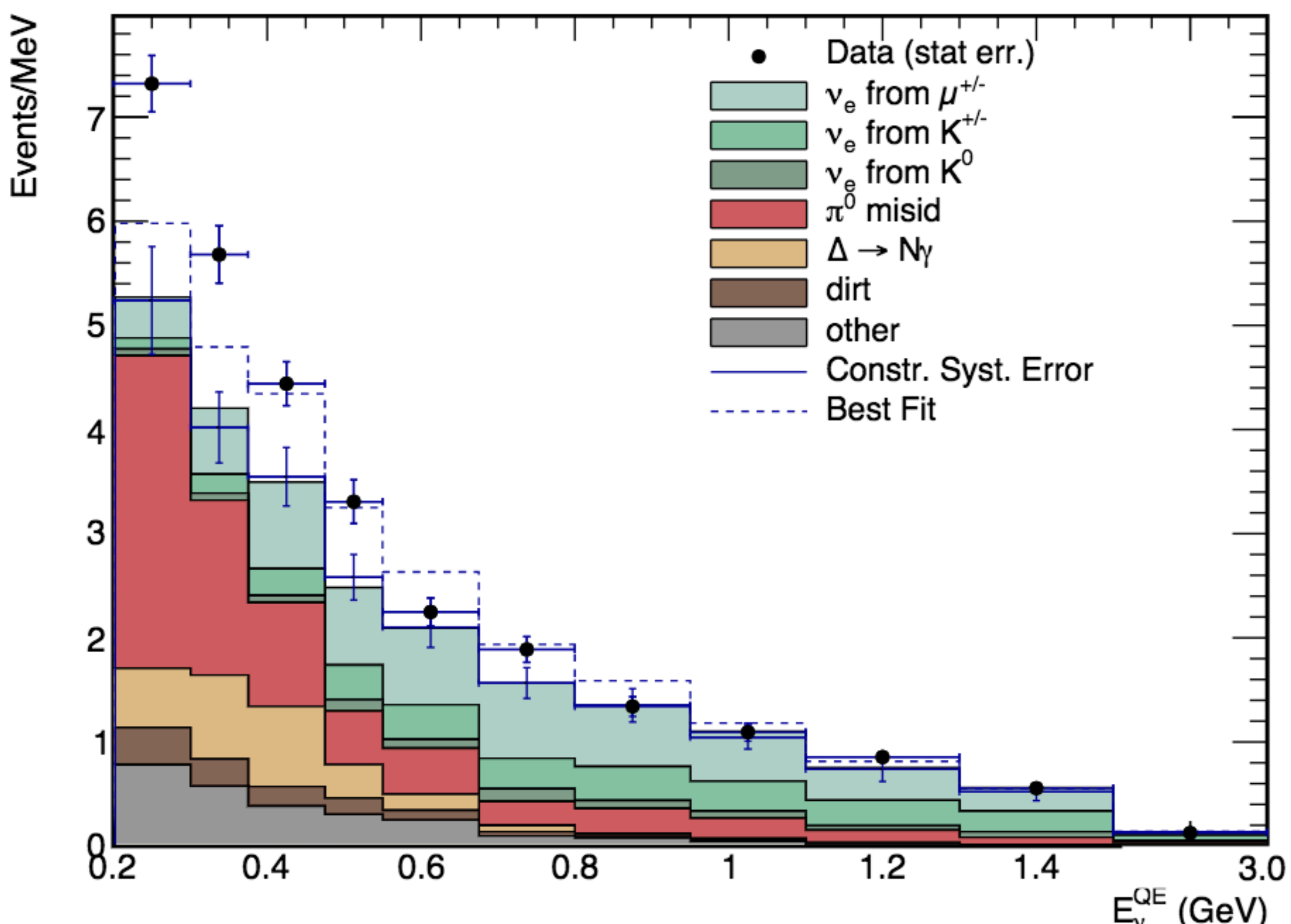


Example of a π^0 mis-ID

Final Electron-Like Excess

- With the complete dataset, the excess of electron-like events is: 638.0 ± 52.1 (stat) ± 122.2 (sys) events (4.8σ significance)
- Excess is consistent across the lifetime of the detector

Neutrino Mode



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Neutrino Mode