Status of MiniBooNE Anomalous ν_e-like Excess & Non-Sterile Explanations

Lauren Yates
Massachusetts Institute of Technology

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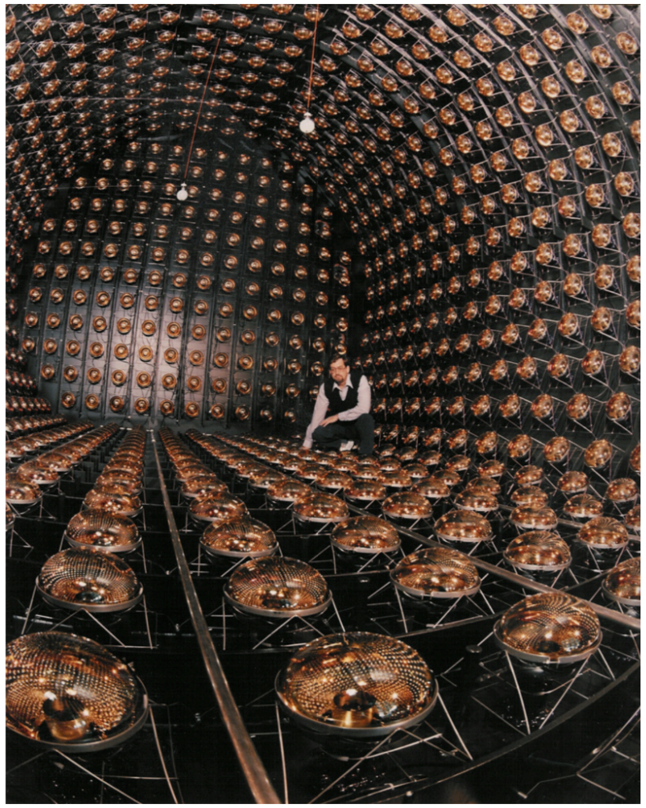
Disclaimers

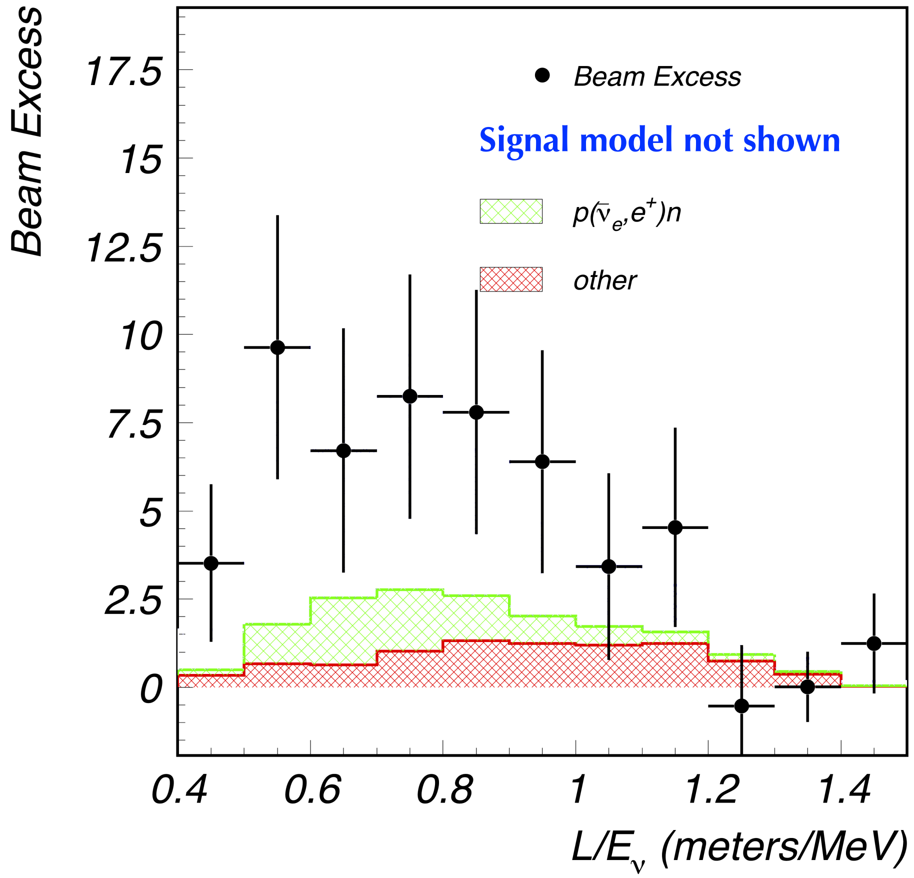
- I am not a MiniBooNE collaborator! And I don't play one on TV
  - But some of my friends and colleagues are…
- The views and opinions expressed in this talk are mine and do not necessarily reflect anyone else's

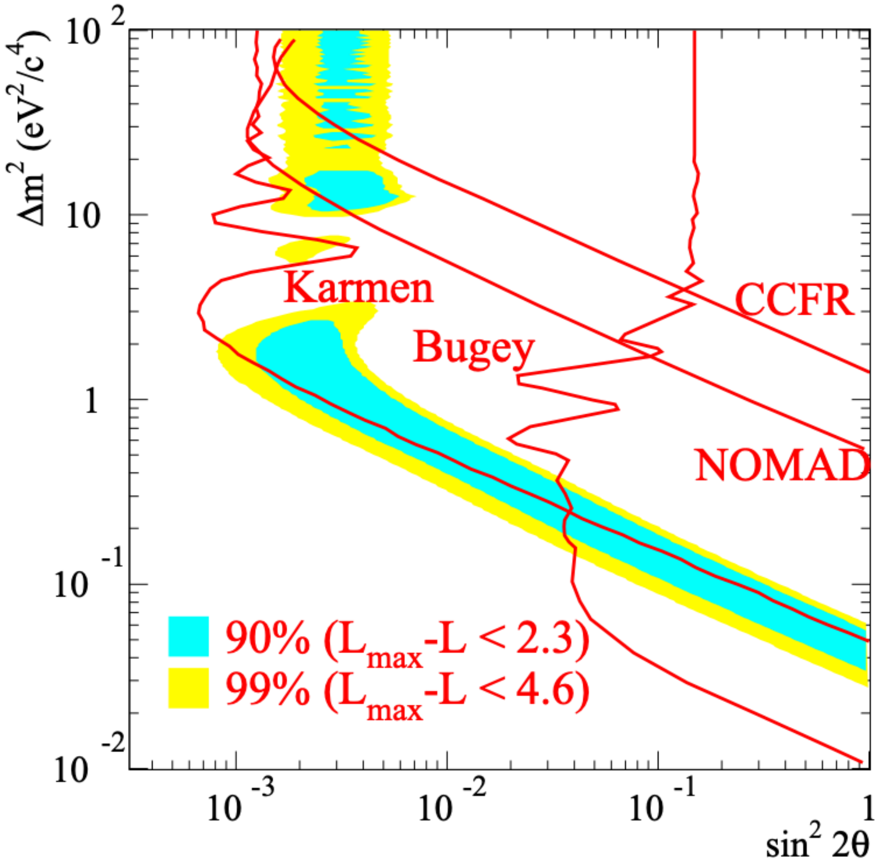
The LSND Anomaly

- LSND studied $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, using $\bar{\nu}_\mu$ from μ^+ decay at rest
- Detection mechanism: $\bar{\nu}_e + p \to e^+ + n$, then $n + p \to d + \gamma$ (2.2 MeV)
  - Observe Cherenkov and scintillation light from the positron, then delayed light from subsequent neutron capture — coincidence reduces backgrounds
- Observed a 3.8σ excess of $\bar{\nu}_e$-like events, which corresponds to an oscillation probability of P_{osc} ~ 0.26%

PRD 64, 112007 (2001)







The MiniBooNE Experiment

- The MiniBooNE experiment uses a mineral oil Cherenkov detector located in the Booster Neutrino Beam (BNB) at Fermilab
- Proposed to search for sterile neutrino oscillations suggested by LSND
- Located at a similar L/E as LSND
  - MiniBooNE at ~500m/500MeV
  - LSND at ~30m/30MeV

$$P_{\rm osc} \approx \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\rm eV^2]\cdot L[\rm m]}{E[\rm MeV]}\right)$$

- Experiments have different systematic uncertainties due to different fluxes, event signatures, and backgrounds

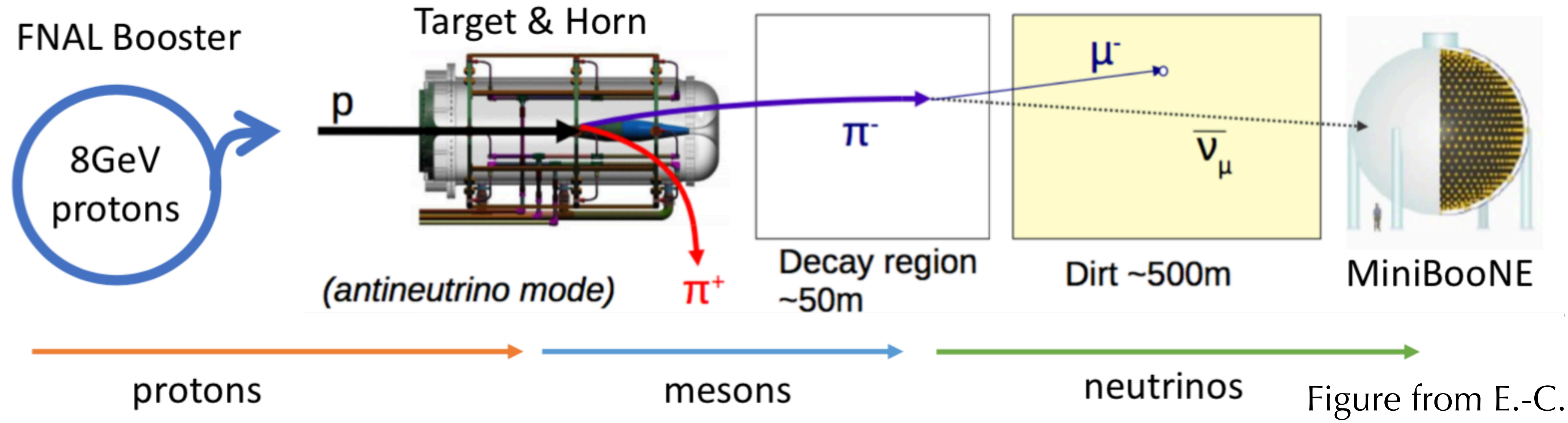
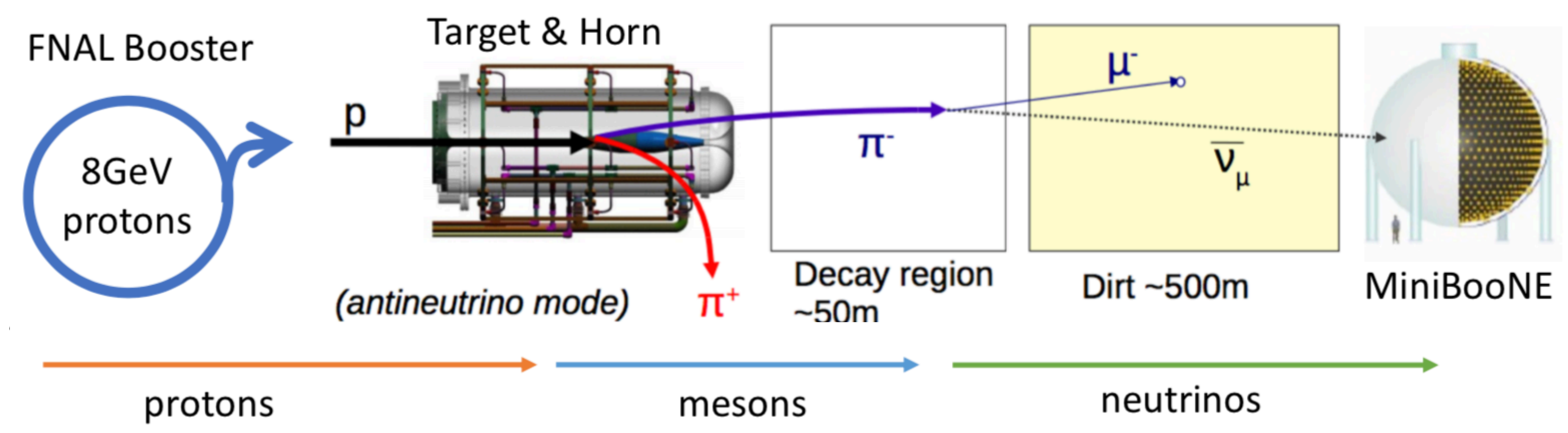


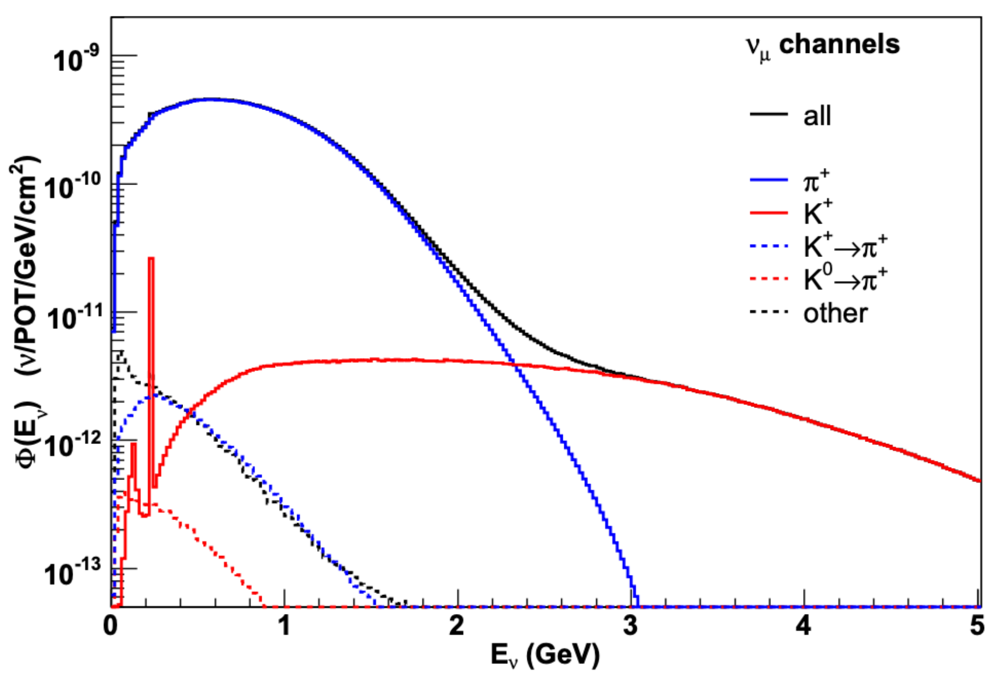
Figure from E.-C. Huang

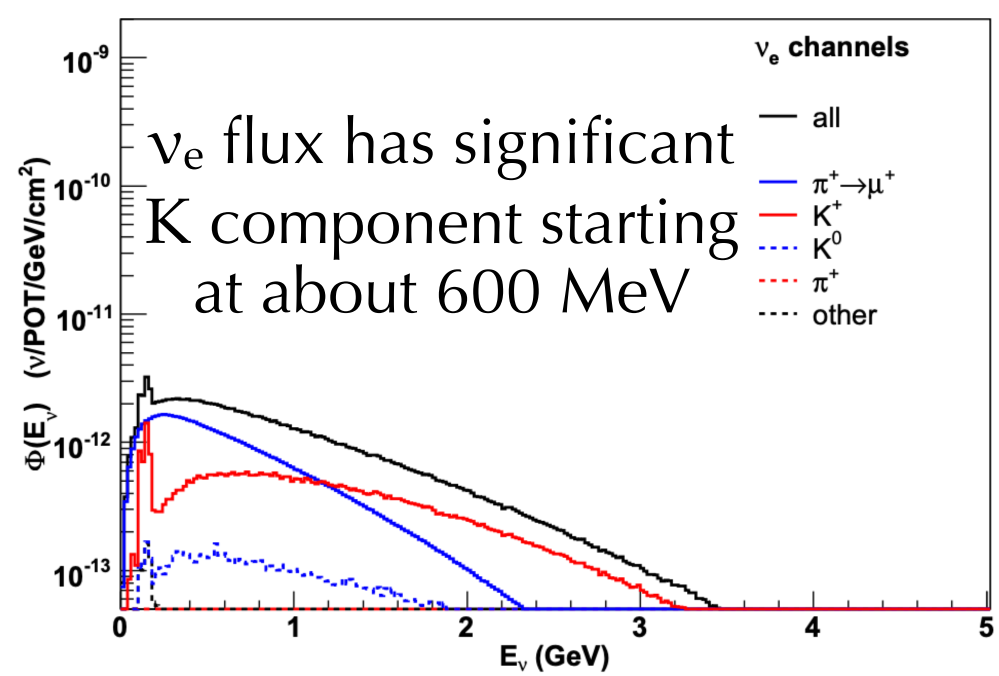
The Booster Neutrino Beam



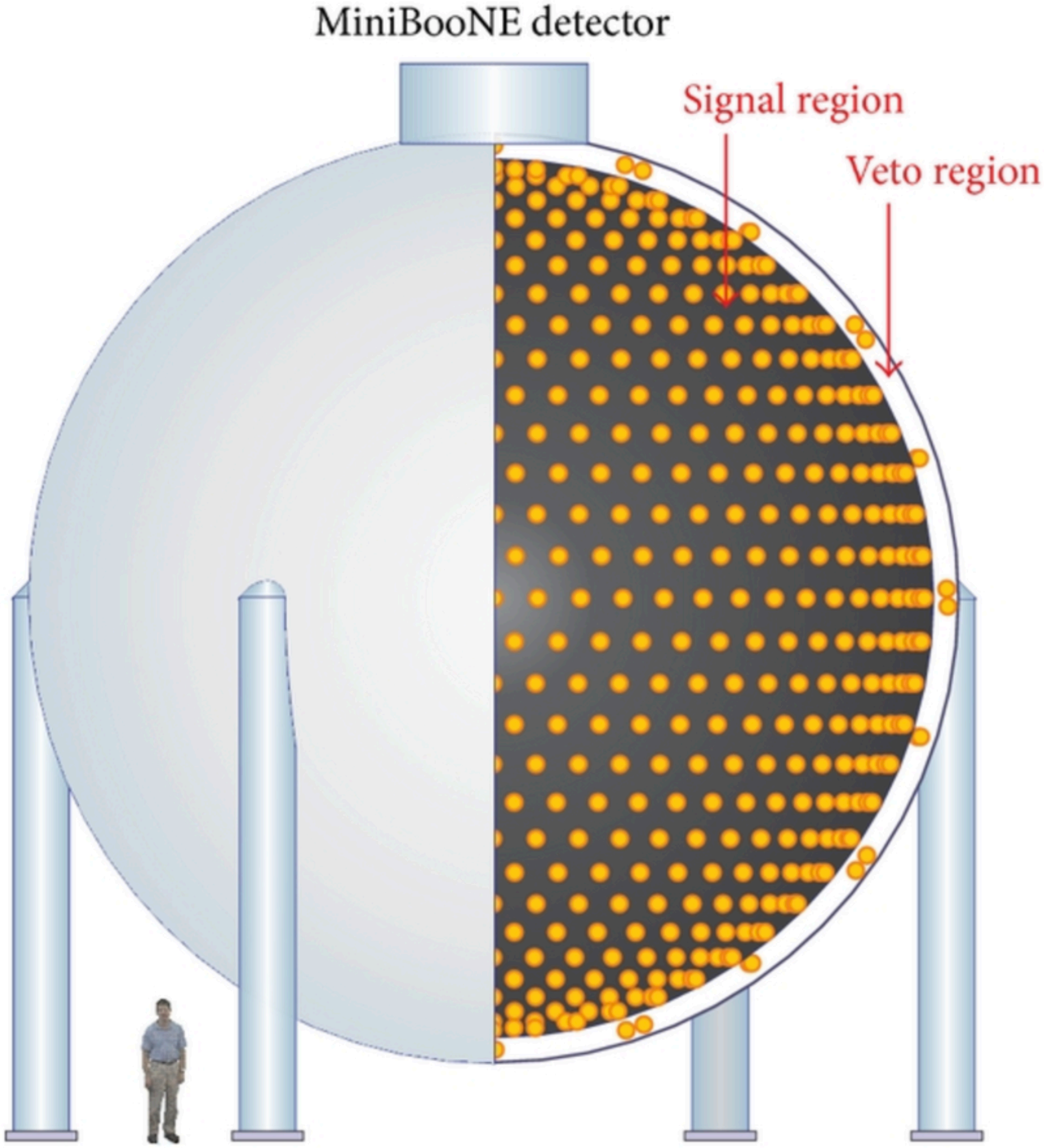
- Neutrinos from decays of hadrons created by 8 GeV protons on a beryllium target inside a focusing horn
- Horn polarity can be reversed, allowing MiniBooNE to run in both neutrino and antineutrino mode

"Neutrino Flux Prediction at MiniBooNE"
PRD 79, 072002 (2009)





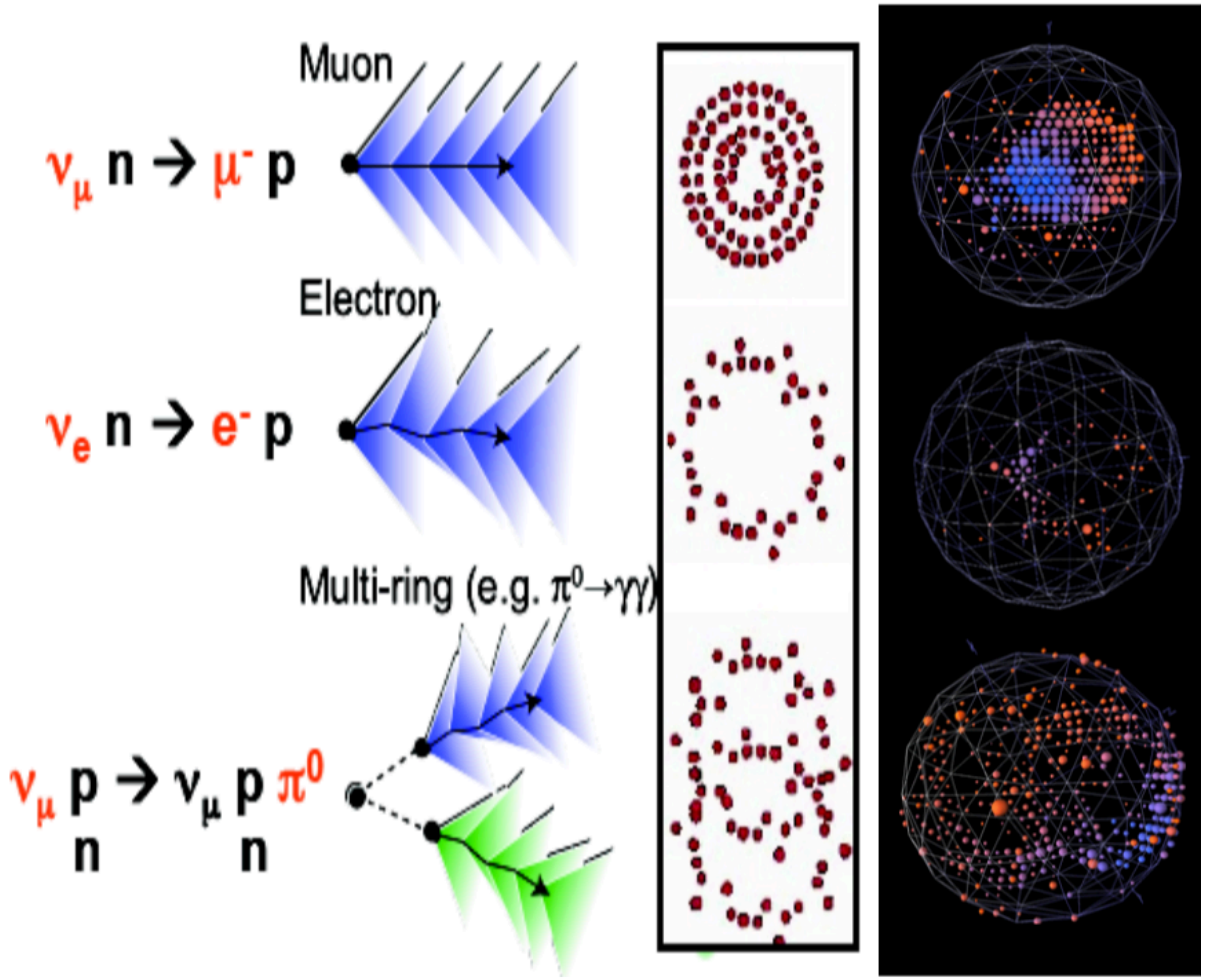
The MiniBooNE Detector



- 540m from the BNB target
- 12.2m diameter sphere, 10m diameter fiducial vol.
- 800 tons of mineral oil, 450 tons fiducial mass
- Signal region instrumented with 1280 PMTs, which give 10% photocathode coverage
- Veto region instrumented with additional 240 PMTs

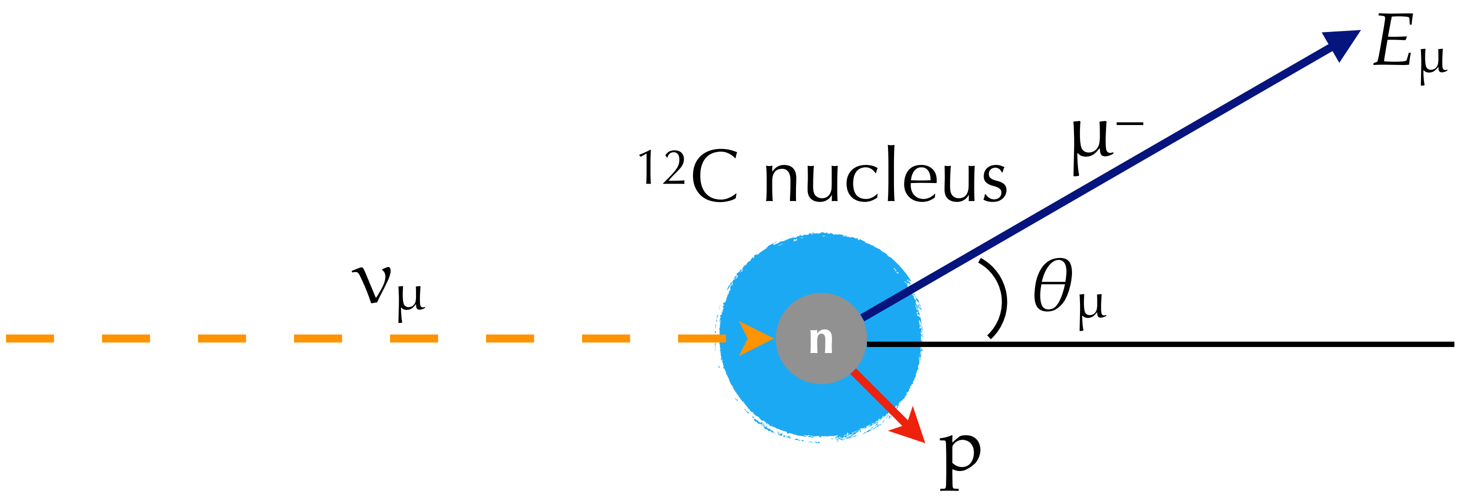
MiniBooNE Event Signatures

- MiniBooNE primarily uses Cherenkov light
- Compare fits for different track reconstruction hypotheses for PID
- Cannot distinguish a single photon from a single electron



MiniBooNE Energy Reconstruction

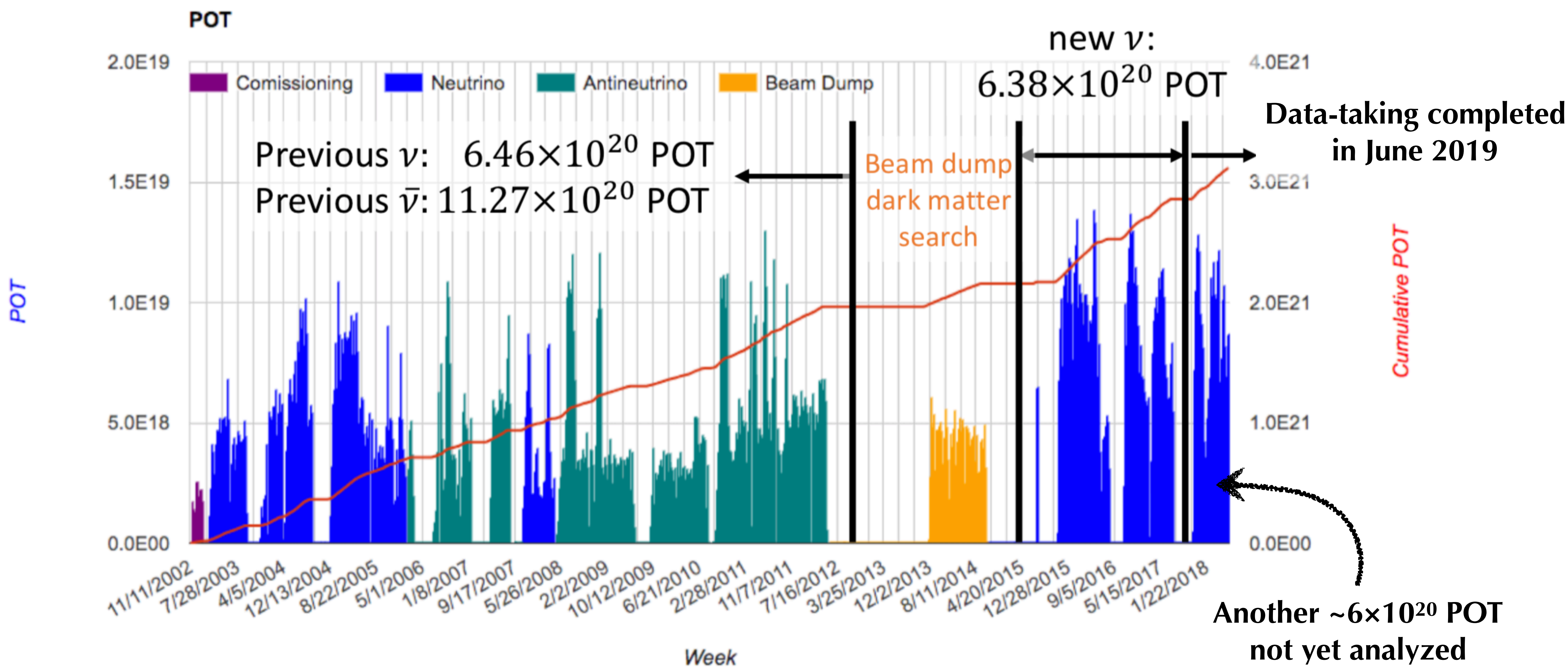
- Energy is reconstructed using the CCQE energy formula
- Assumes initial-state nucleon is at rest and interaction is CCQE, although does account for nuclear binding energy E_B
- However, in reality:
  - Initial state nucleon will have some Fermi momentum
  - Not all interactions will be CCQE



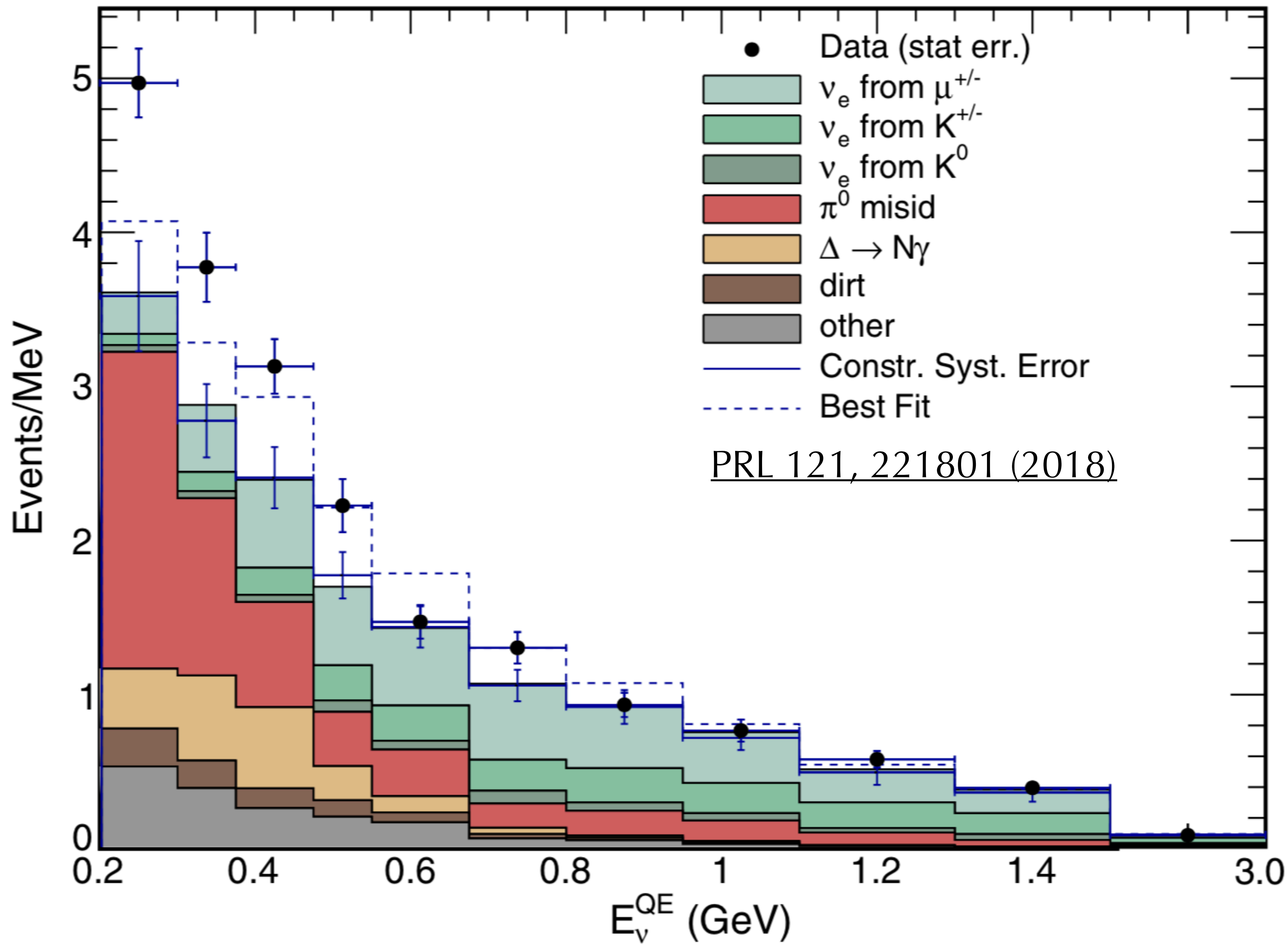
$$E_\nu^{\mathrm{QE}} = \frac{2(M_n - E_B)E_\ell - ((M_n - E_B)^2 + M_\ell^2 - M_p^2)}{2((M_n - E_B) - E_\ell + p_\ell \cos\theta_\ell)}$$

New Dataset: Double the νs!

- In 2018, MiniBooNE released an updated result with double the neutrino-mode data statistics: PRL 121, 221801 (2018)
- New data improves signal measurement and data-driven background constraints
- Increases neutrino-mode MiniBooNE excess to 4.5σ and gives a combined significance for the LSND and MiniBooNE excesses of 6σ



Status of the Excess

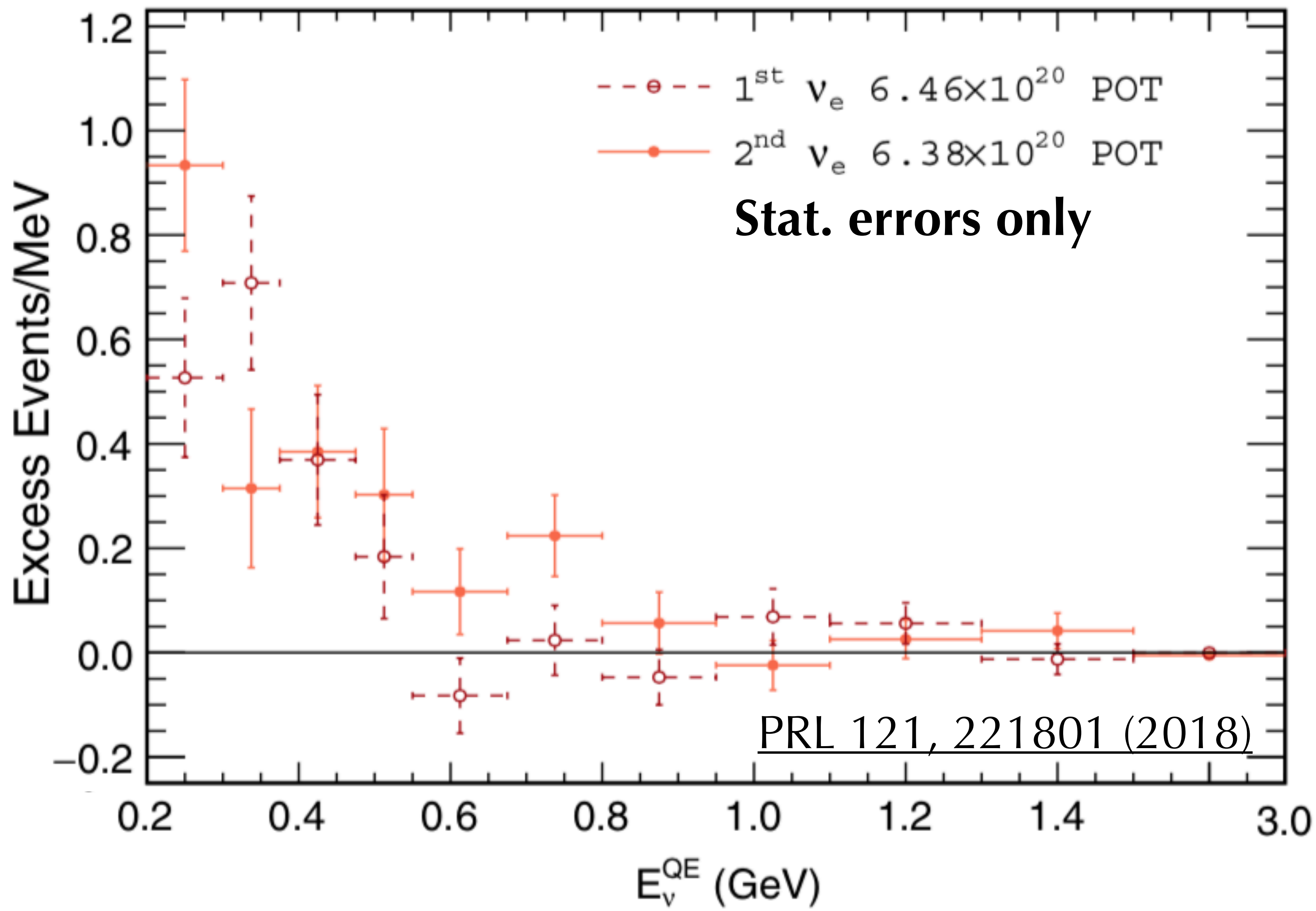


MiniBooNE E_ν^{QE} distribution for all neutrino mode data, 12.84×10^{20} POT

Status of the Excess

Is the new neutrino-mode data consistent with the previous result?

- MiniBooNE has done a many of checks detector stability
- Previous and new excesses are statistically consistent

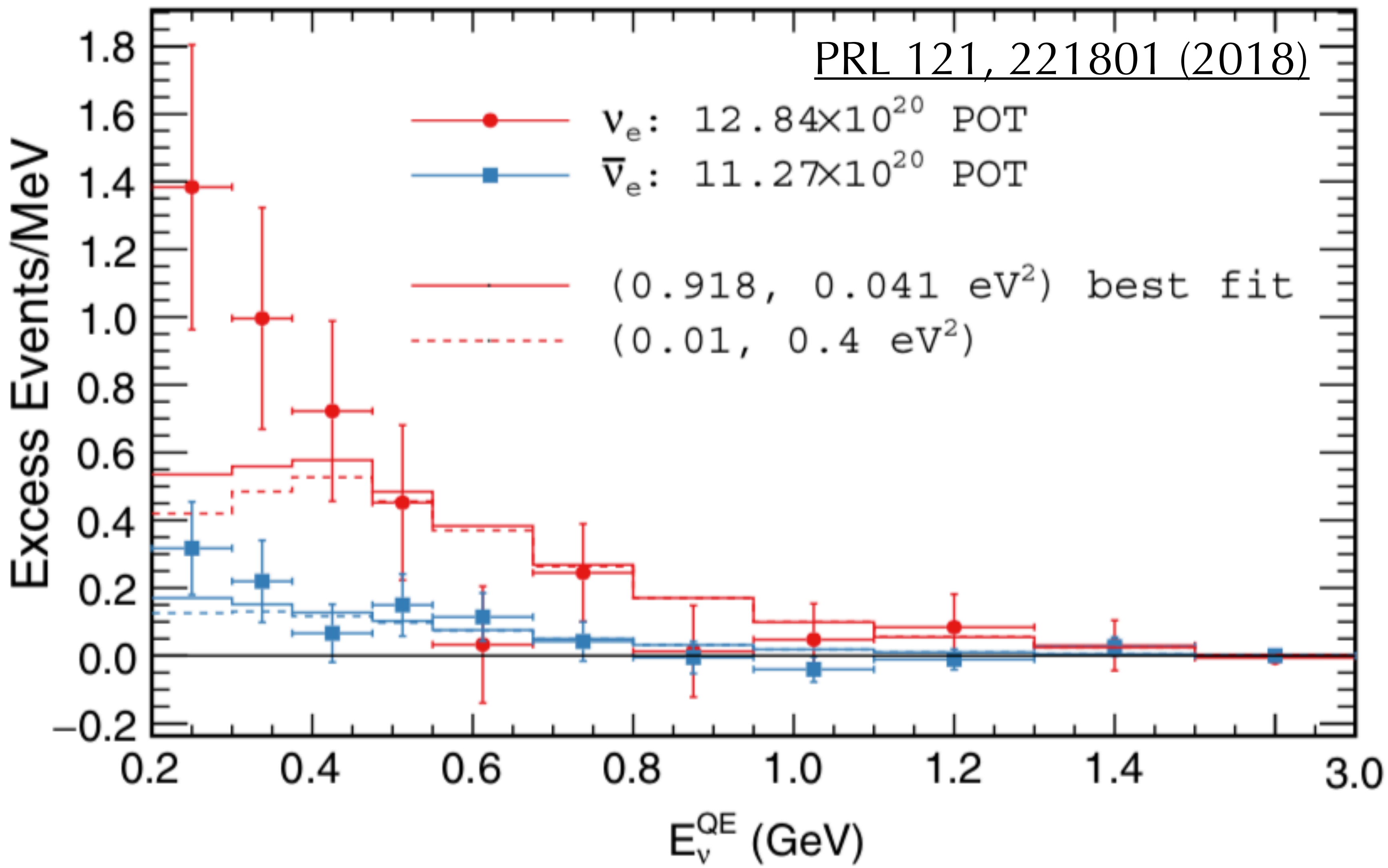


PRL 121, 221801 (2018)

Status of the Excess

Is the combined neutrino-mode excess consistent with the antineutrino-mode excess? How do these compare to oscillation predictions?

- Excesses in neutrino and antineutrino mode are qualitatively consistent with each other, but not completely consistent with 3+1 model



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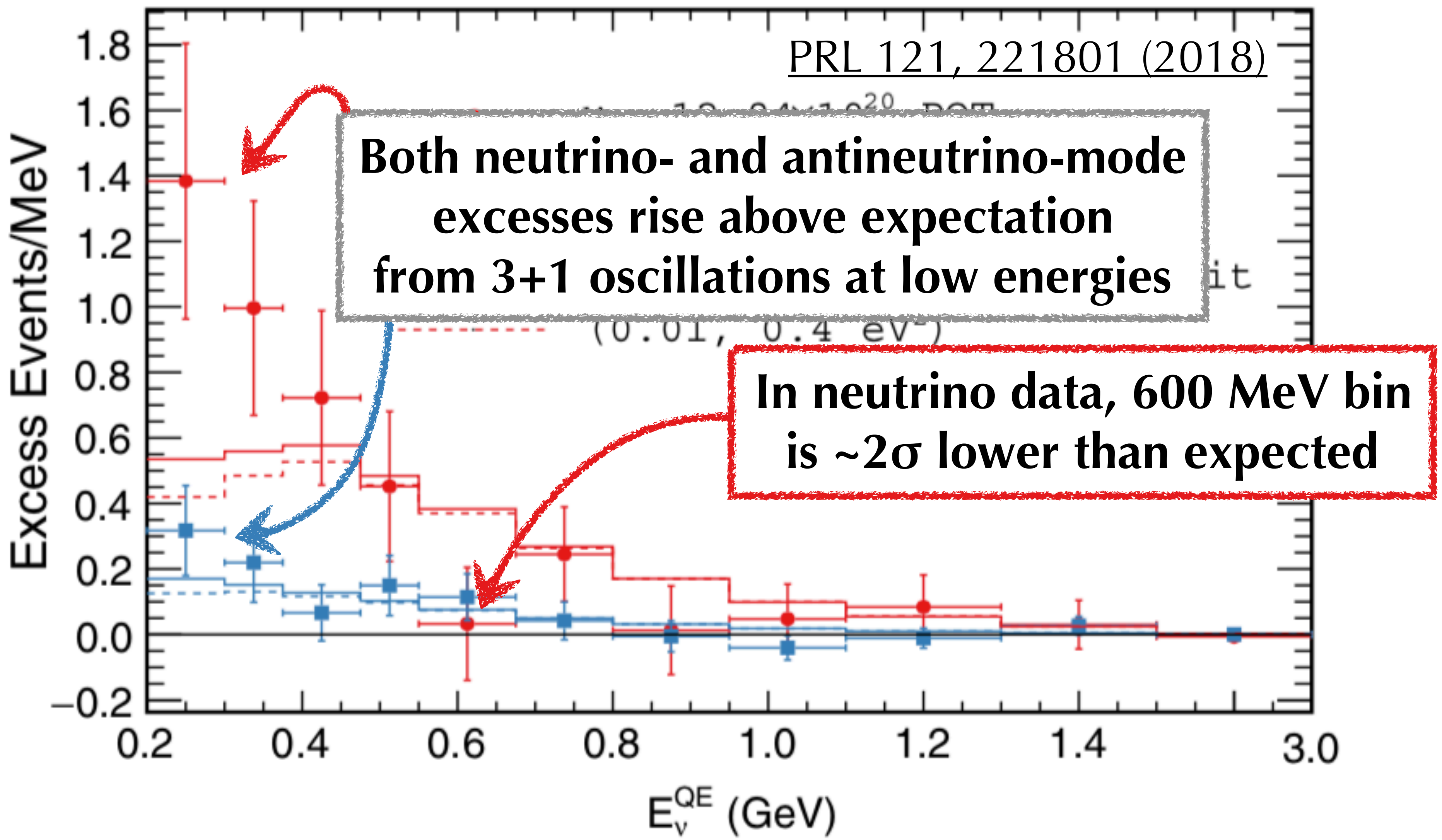

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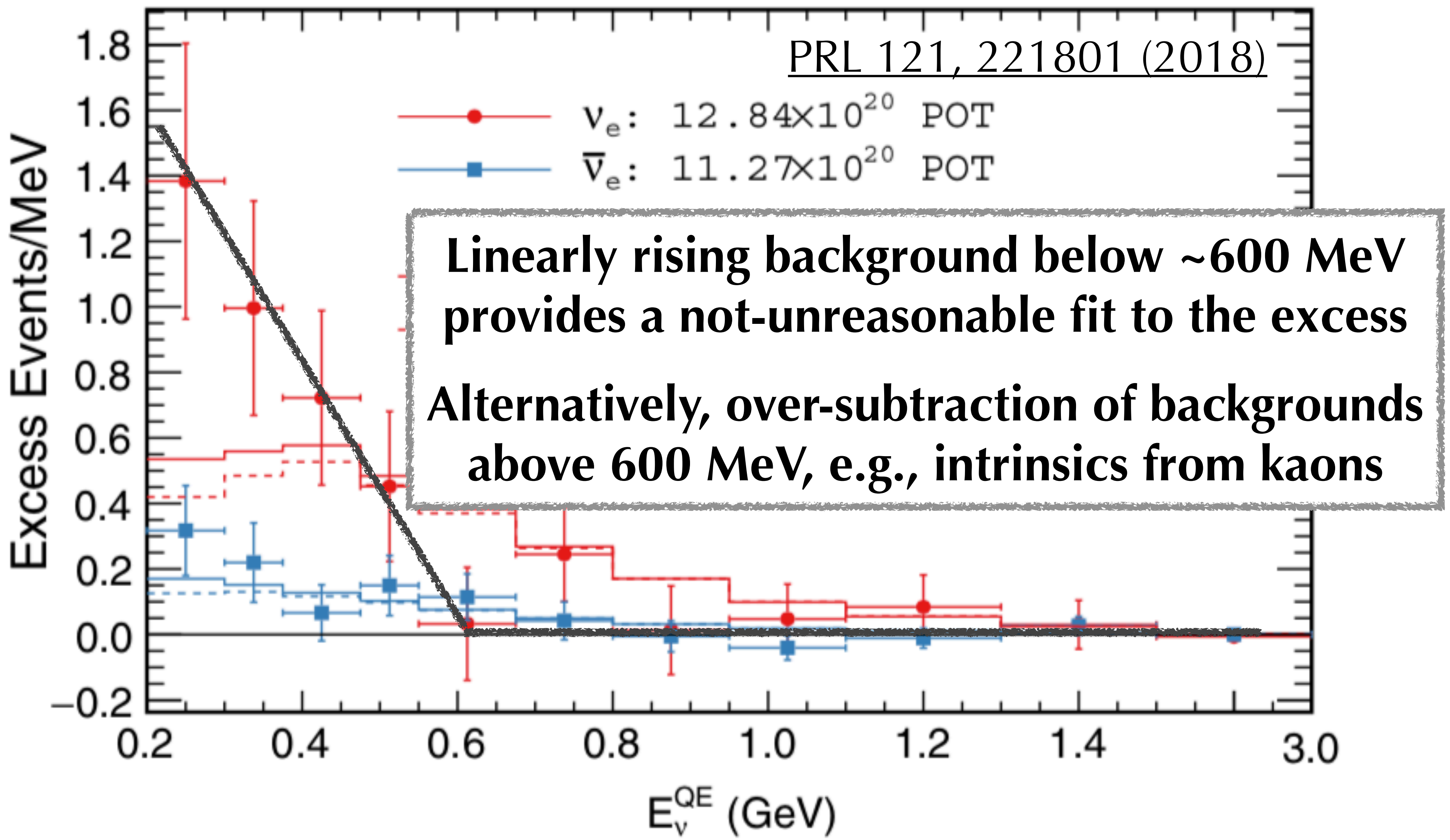


Possible Explanations for the Excess

- **Underestimation of systematic uncertainties on backgrounds**
  - Beam intrinsic ν_e events from either muon or kaon decays
  - Misidentified π^0 events
  - $\Delta \rightarrow N\gamma$ events
  - Dirt events
- **Nuclear effects, affecting energy reconstruction**

Standard Model

I have been asked to focus on the SM explanations

- Sterile neutrino oscillations (3+*N*)
- Resonant neutrino oscillations
- Lorentz violation
- Sterile neutrinos that decay
- Non-standard interactions of sterile neutrinos
- Sterile neutrinos propagating in large extra dimensions
- Dark neutrino portal
- … and more!

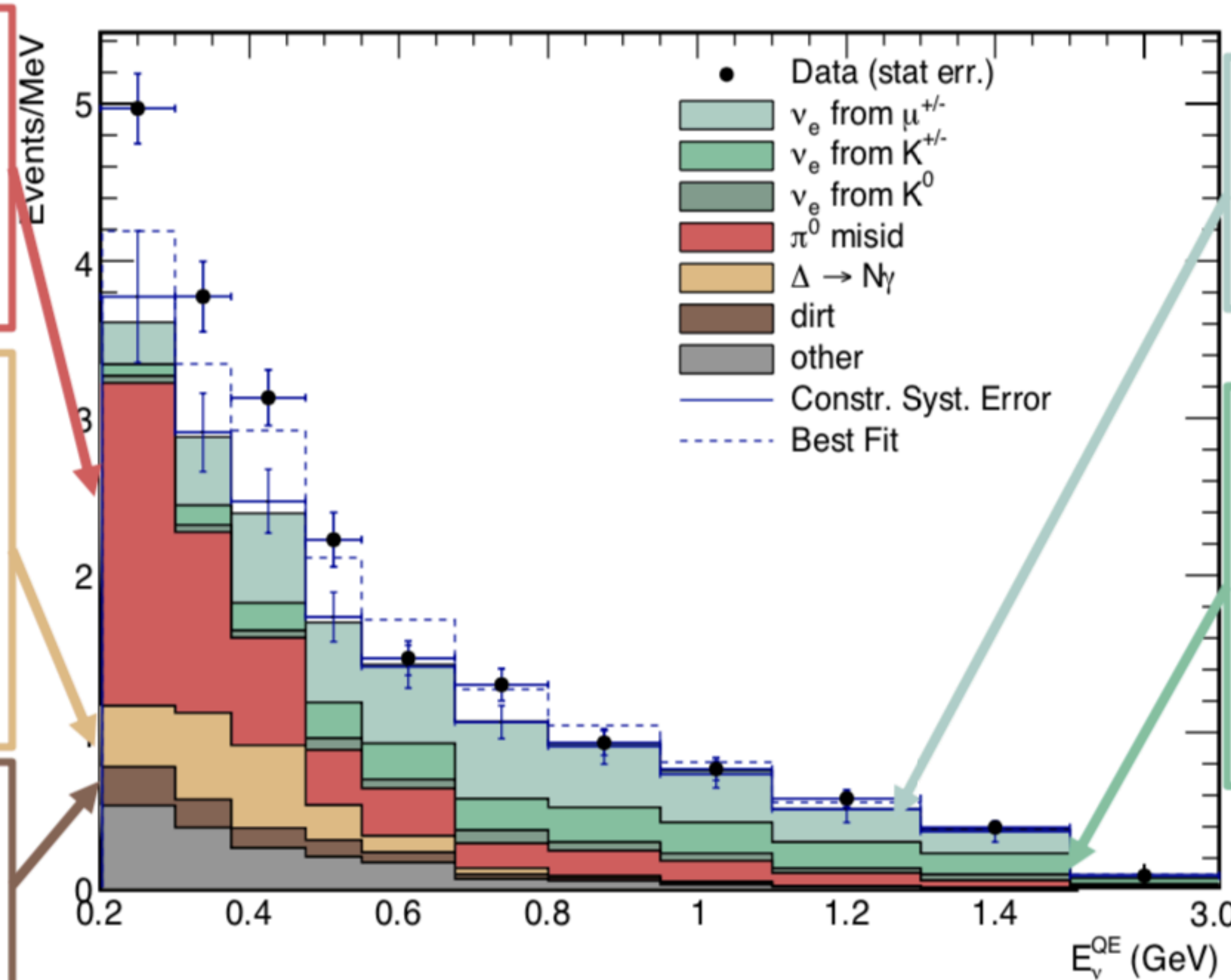
Beyond the Standard Model

Constraining the Backgrounds

MisID π^0 is constrained from *in-situ* measurement of NC π^0 rate

Δ resonance is constrained from measured NC π^0 rate and theoretical prediction

Dirt is rate is measured from *in-situ* dirt data sample

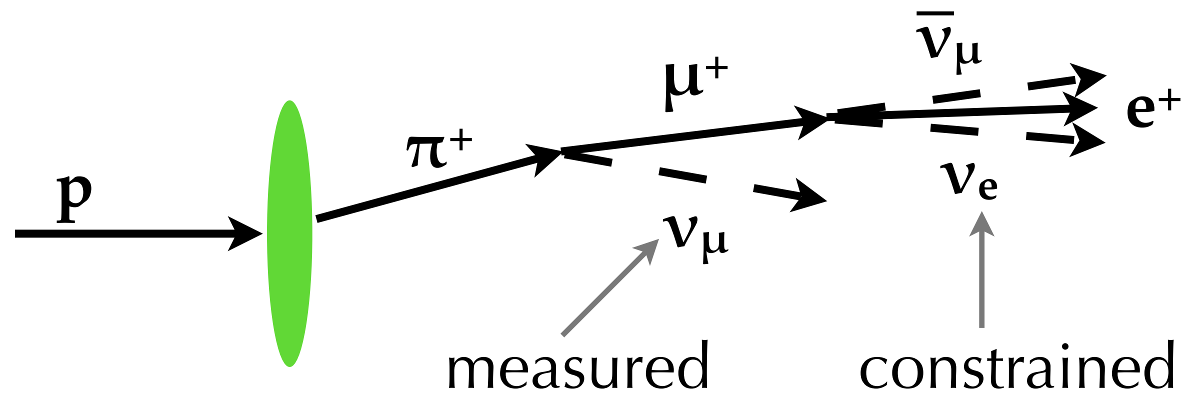


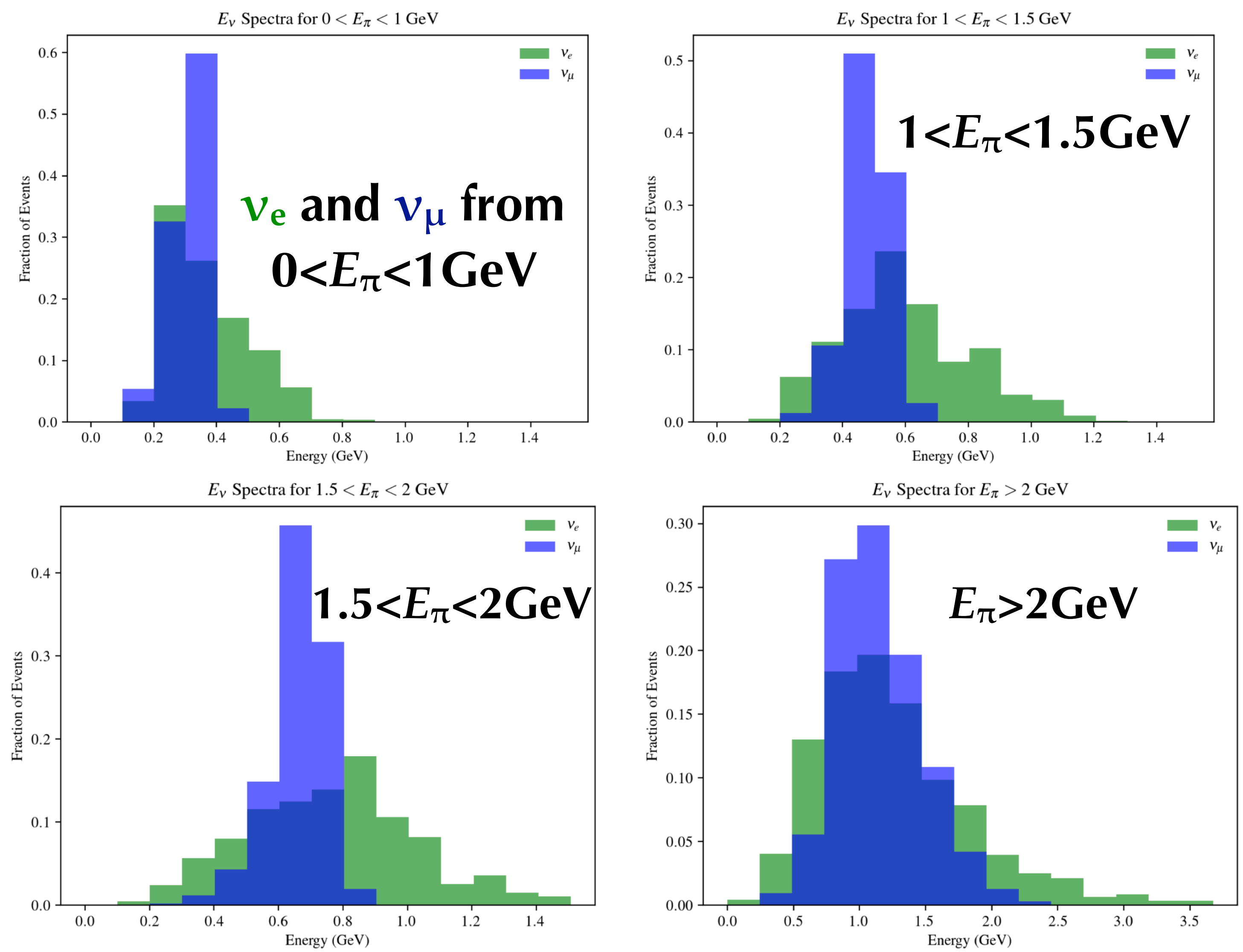
ν_e from μ decay is constrained by ν_μ CCQE measurement

ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

Constraining the Intrinsic ν_e Flux

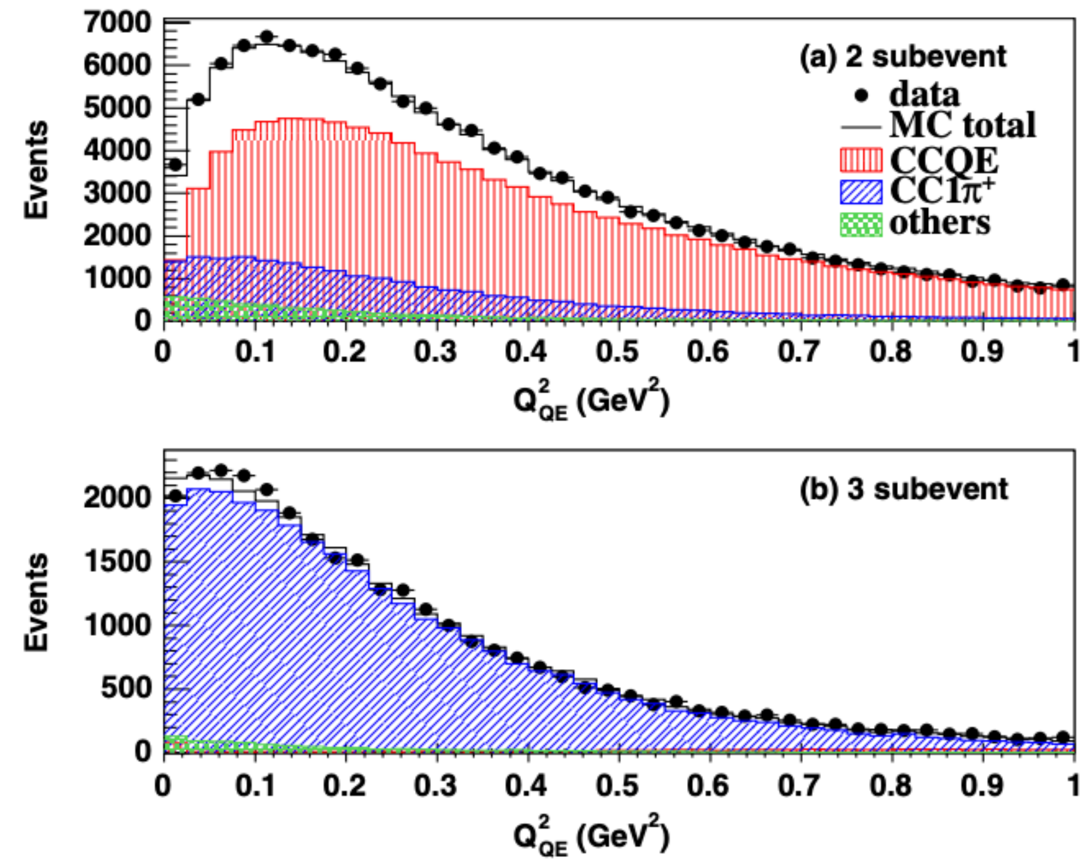
- The ν_e rate is small at low energies, so flux would have to be much higher than predicted
- MiniBooNE uses the measured ν_μ to constrain intrinsic ν_e prediction
- Both species of neutrinos come from same population of parent hadrons (mostly $\pi^\pm$)
- Also have constraints on kaons from SciBooNE

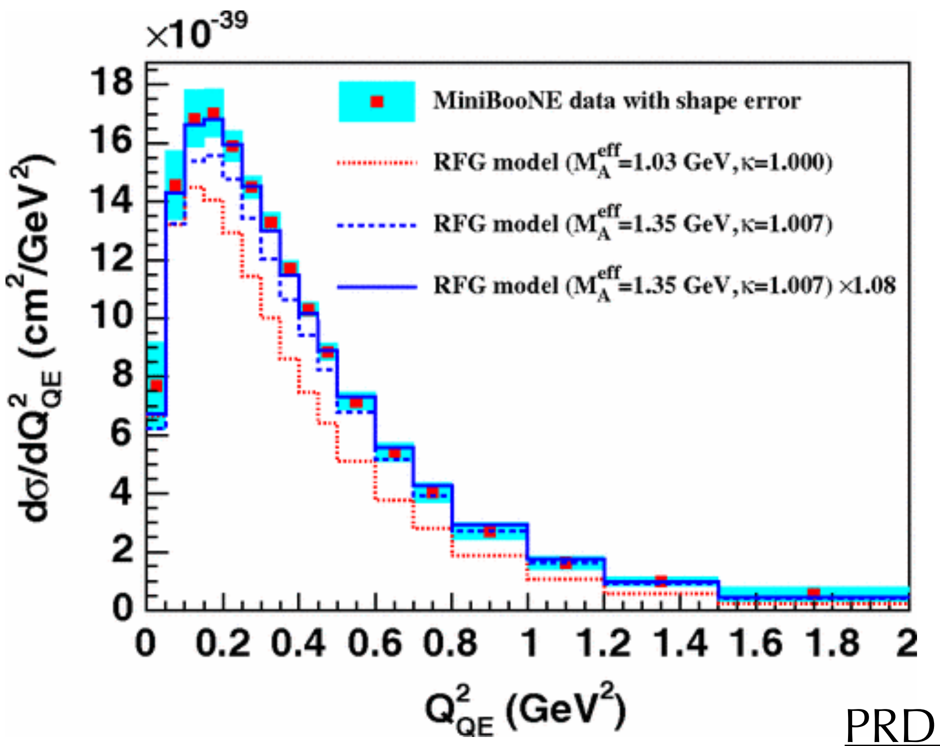


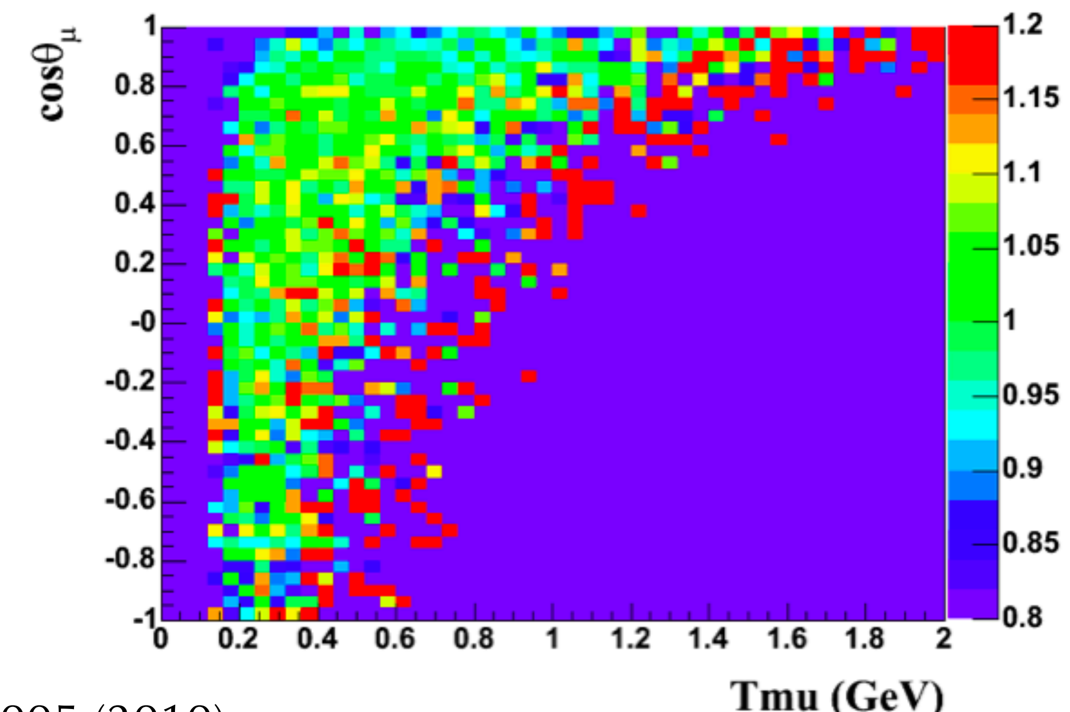


Constraining the Intrinsic ν_e Cross Section

- MiniBooNE tuned cross section model based on their high-statistics ν_μ data
  - Fit for a scale factor for CC $1\pi^+$ using a dedicated CC $1\pi^+$ sideband
  - Fit for model parameters M_A^{QE} and κ using their CCQE data
- After tuning, ν_μ data shows reasonable agreement with prediction, including in double-differential distribution



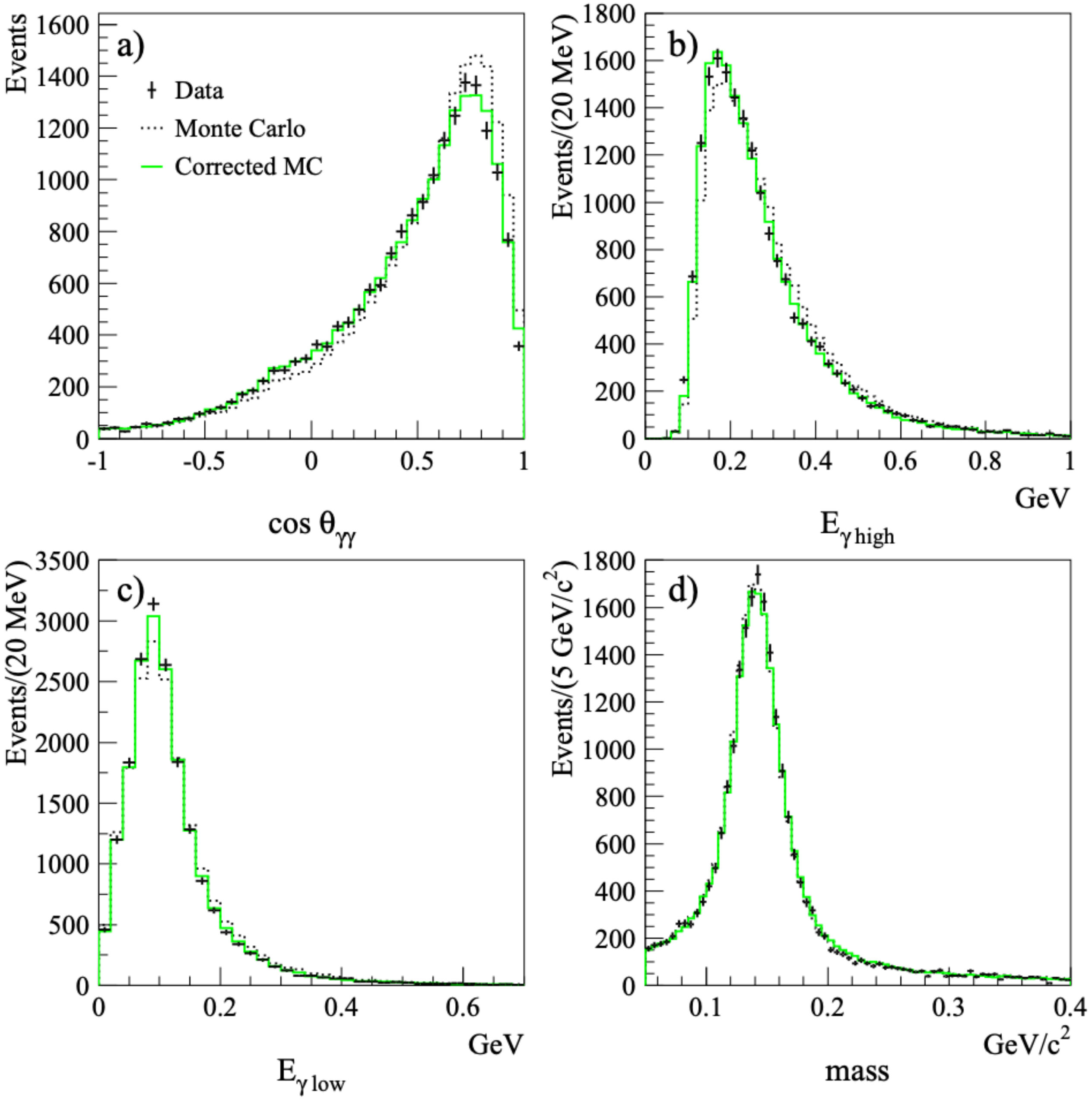




PRD 81, 092005 (2010)

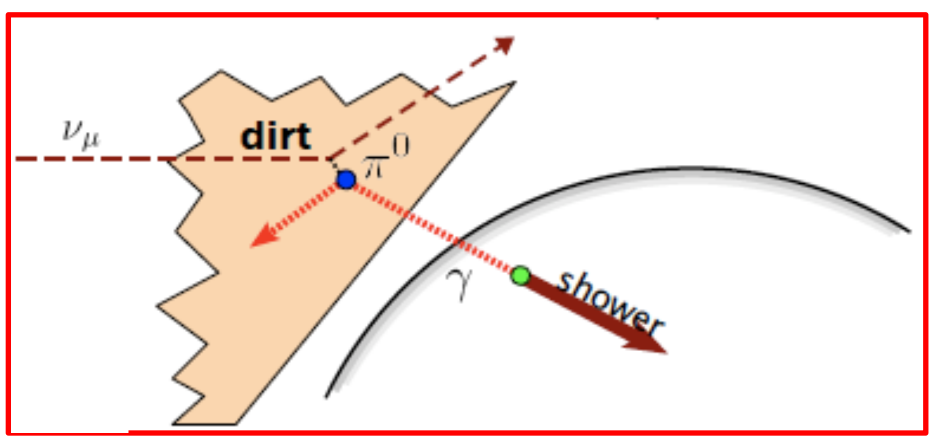
Constraining π^0 Misidentification

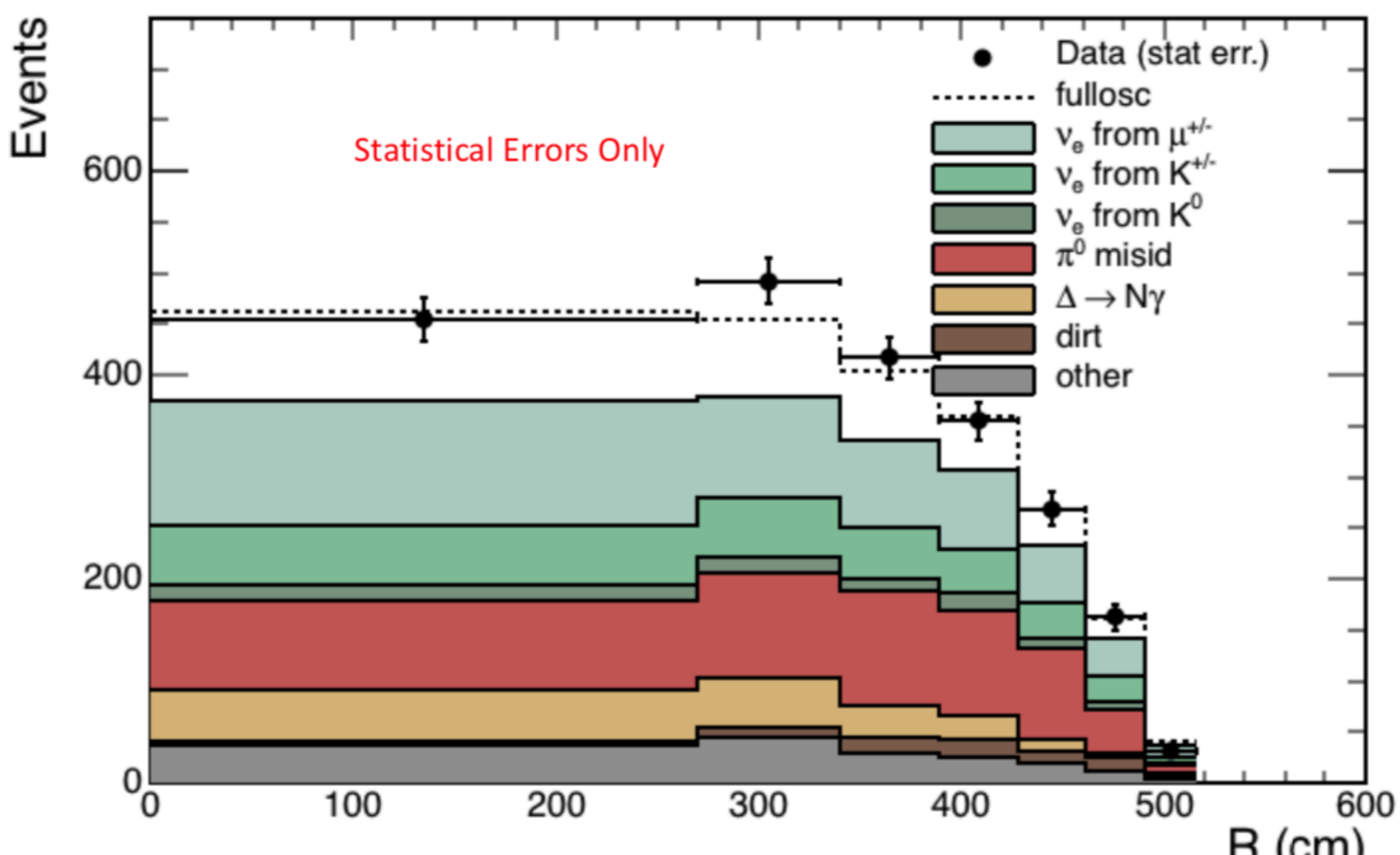
- The NC π^0 background rate is constrained by MiniBooNE's high-statistics measurement of NC π^0 production
- Two main sources:
  - One **photon exits** or is **absorbed** — well-constrained by the measured rate of two-photon π^0 events, the interaction length in mineral oil, and knowledge of photo-nuclear absorption
  - **Weak second photon** — constrained by measurement of kinematics of two-photon π^0 events, used to tune simulation



Constraining Dirt

- Increased data statistics has allowed better measurement of dirt backgrounds and reduced the associated uncertainty
- Contribution is estimated by isolating events where the vertex is near the boundary and the shower is inward-going — constrained at the ~10% level
    - Better constraint based on using timing information is in progress
- Excess is consistent over the entire radius of the detector





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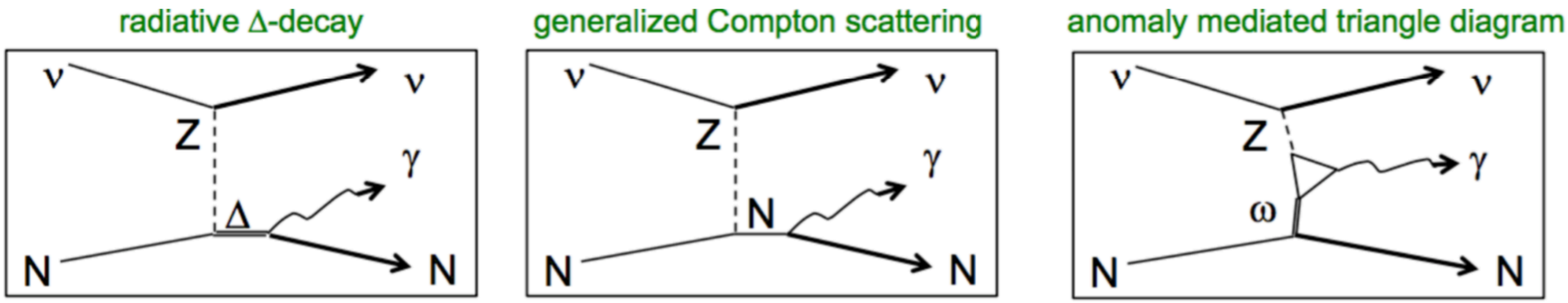
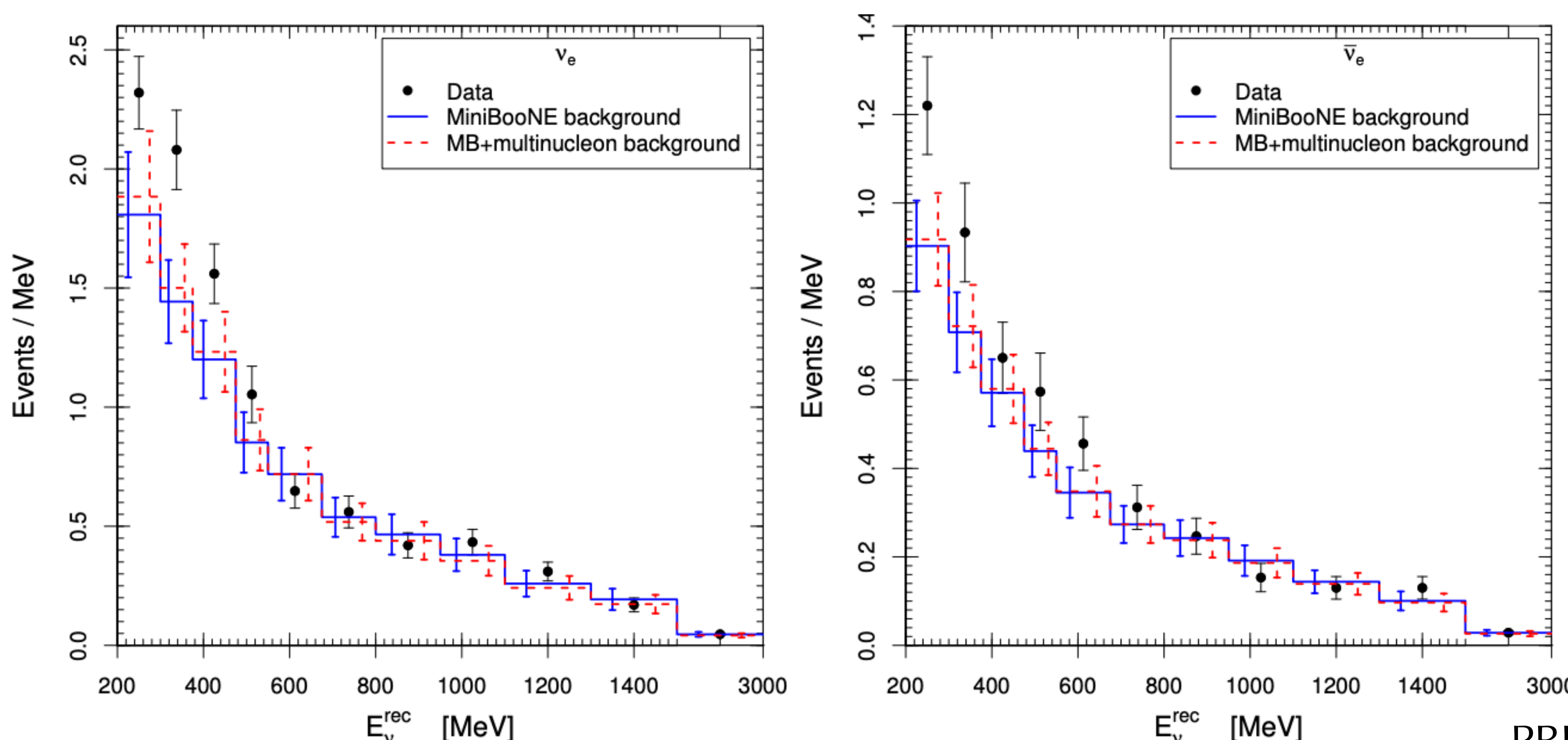


- Current theoretical predictions match well with MiniBooNE's simulation for NC Δ radiative decay (NC $\Delta \to N\gamma$)
  - Other NC processes that produce a single γ in the final state are plausible
- MiniBooNE's simulation is tuned on their measurement of NC π^0
  - Most NC π^0 come from NC Δ events where the Δ decays via $\Delta \to N\pi$, so the NC π^0 events give some information about Δ production
- However, theoretical uncertainties are large and the process has never yet been measured by a neutrino experiment
  - T2K set a limit; MicroBooNE will measure it on argon

Nuclear Effects & Energy Reconstruction

- The MiniBooNE neutrino interaction generator does not have multi-nucleon effects
- The detector is not sensitive to the final-state protons that might allow one to distinguish multi-nucleon events
- When reconstructing multi-nucleon events with the CCQE energy formula, one tends get an underestimate of the neutrino energy
- This is an un-modeled background in MiniBooNE that would tend to reconstruct at low energies! This could help explain pile up of excess at low energies



PRD 93, 073008 (2016)

Aside: Reconstruction in LArTPCs

- LArTPCs provide additional handles for energy reconstruction, because they allow us to reconstruct the proton
- In this case, can calculate the neutrino energy in three different ways and check for consistency

$$E_\nu^{\text{range}} = \text{KE}_\ell + \text{KE}_p + M_\ell + M_p - (M_n - E_B)$$

$$E_\nu^{\text{QE, }\ell} = \frac{2(M_n - E_B)E_\ell - ((M_n - E_B)^2 + M_\ell^2 - M_p^2)}{2((M_n - E_B) - E_\ell + p_\ell \cos\theta_\ell)}$$

$$E_\nu^{\text{QE, p}} = \frac{2(M_n - E_B)E_p - ((M_n - E_B)^2 + M_p^2 - M_\ell^2)}{2((M_n - E_B) - E_p + p_p \cos\theta_p)}$$

- This should allow LArTPC experiments to isolate a purer sample of CCQE events and reduce misconstruction of other interactions

More on LArTPCs in my other talk!

Summary

- The MiniBooNE anomaly remains puzzling, especially with the release of new data that strengthens the significance of the excess
- Many Standard Model explanations can be ruled out based on MiniBooNE's own data-driven constraints
- Other explanations remain plausible
  - Unexpected behavior from NC events with a single γ in the final state
  - Mis-modeling of nuclear effects that change the energy reconstruction
- 3+1 model for sterile neutrinos is already over-constrained and shows inconsistencies with world data (including MiniBooNE)
- Ideas for BSM explanations beyond just sterile neutrinos would be helpful inputs from the theory community

Thank you!