# MiniBooNE Oscillation Results with Complete Dataset

**Adrien Hourlier**
on behalf of the MiniBooNE Collaboration
2020/11/24

Massachusetts Institute of Technology

**preprint available at arxiv:2006.16883**

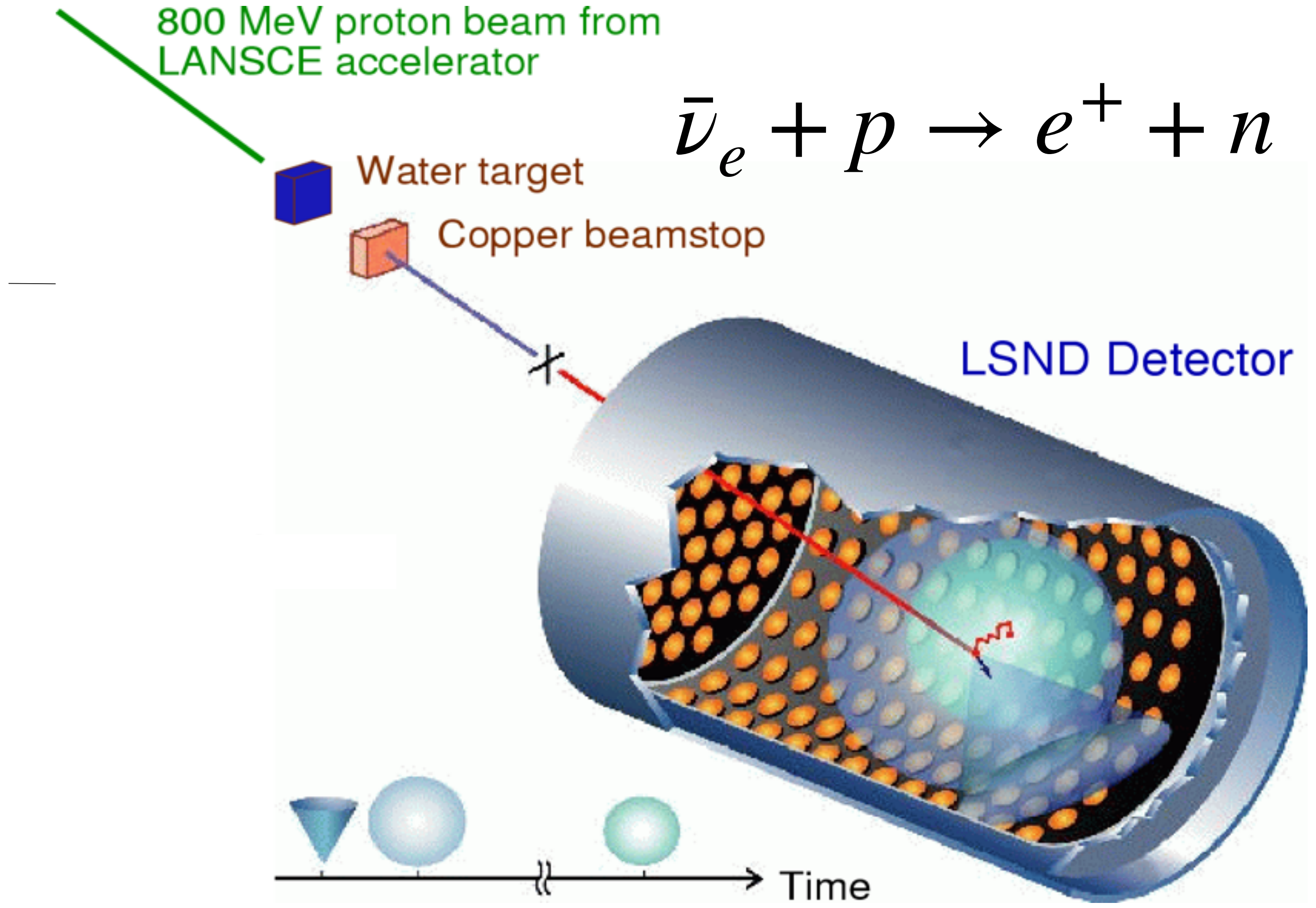
# Before MiniBooNE : The LSND Anomaly

- Stopped π beam at LANL

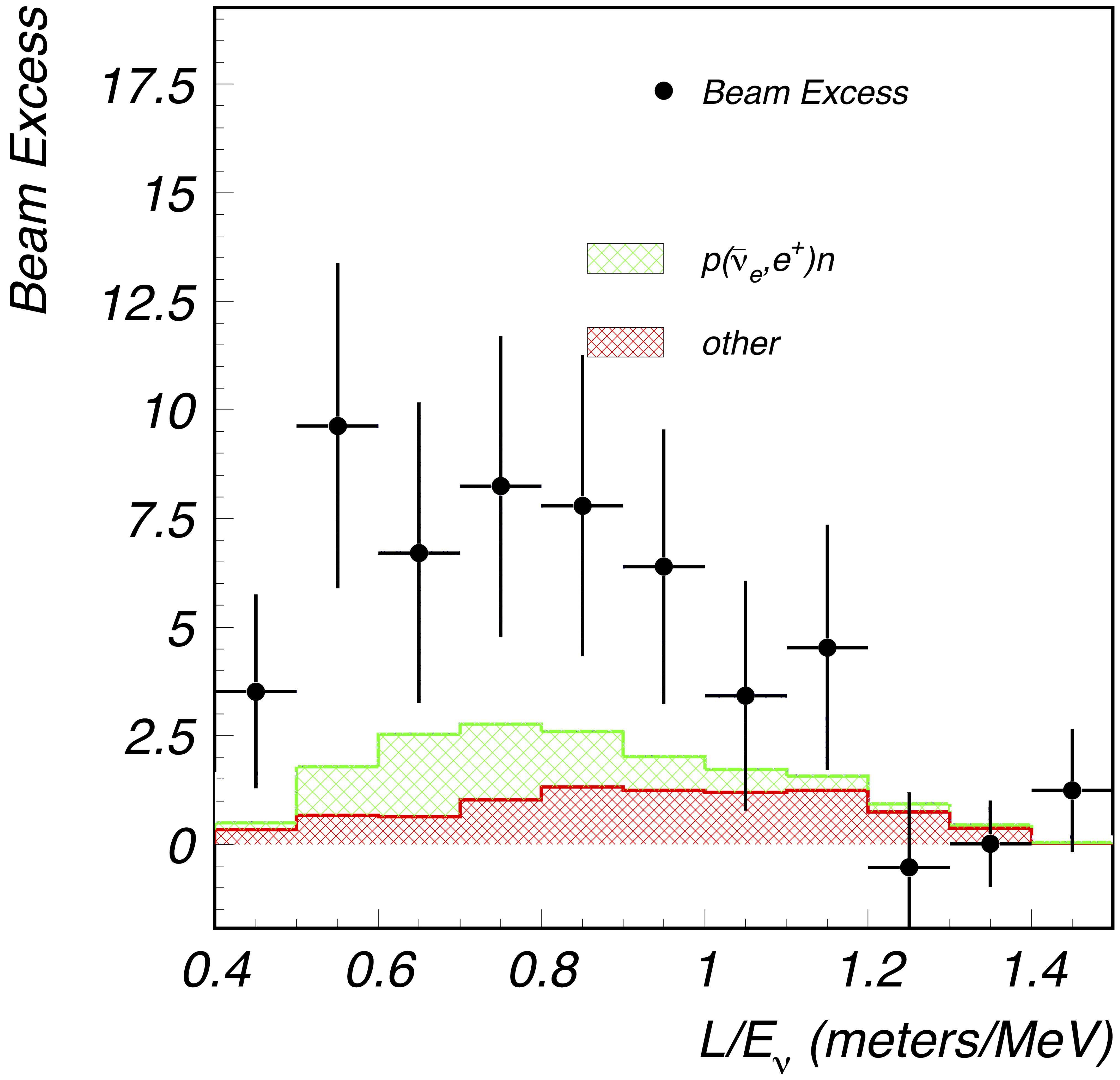
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\quad \hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

- appearance of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam
- $\bar{\nu}_e$ signature : Cherenkov light from $e^+$ with delayed n-capture
- Excess = 87.9 ± 22.4 ± 6 (3.8σ)

$$\bar{\nu}_e + p \to e^+ + n$$




Phys.Rev.D 64.112007



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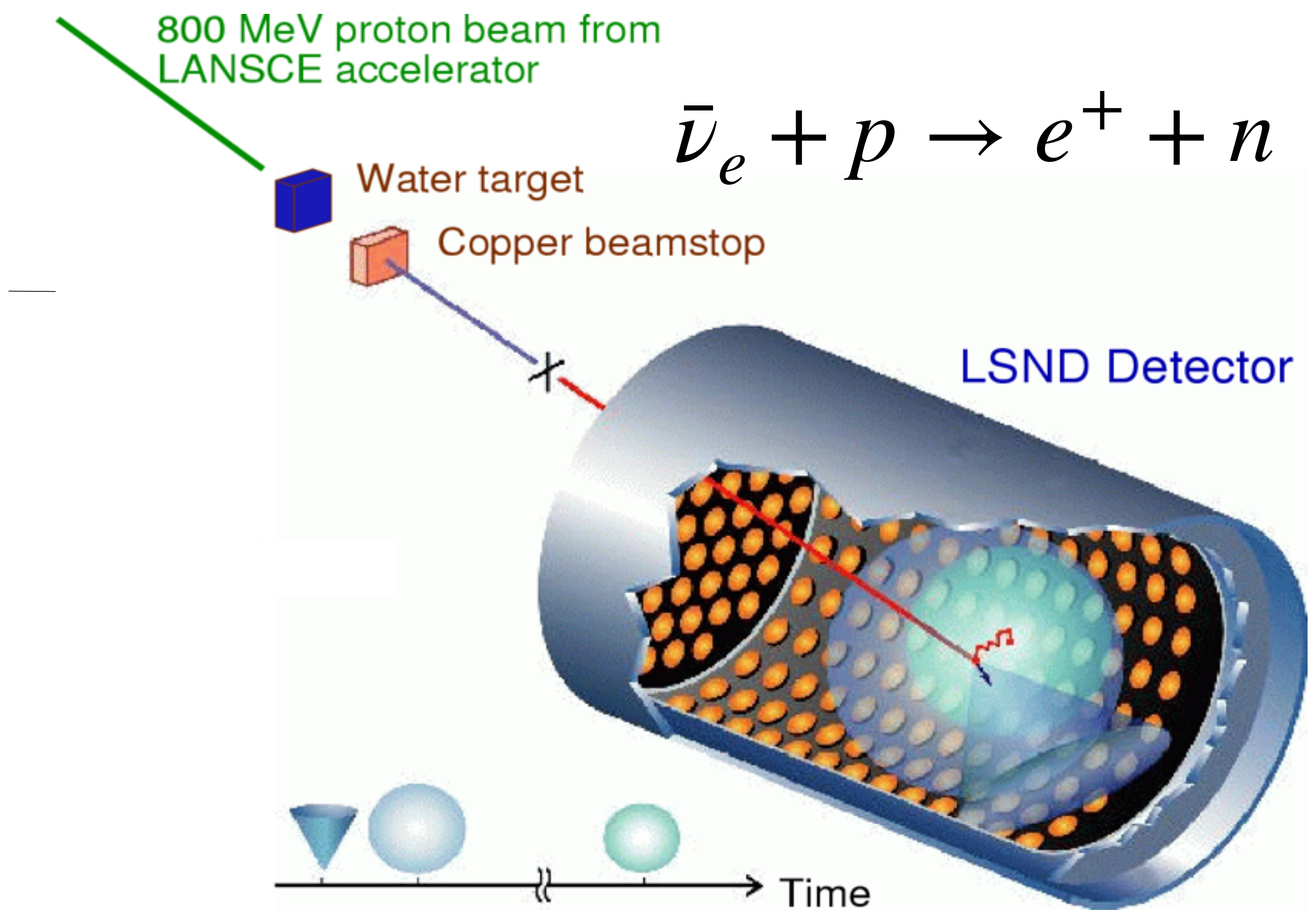


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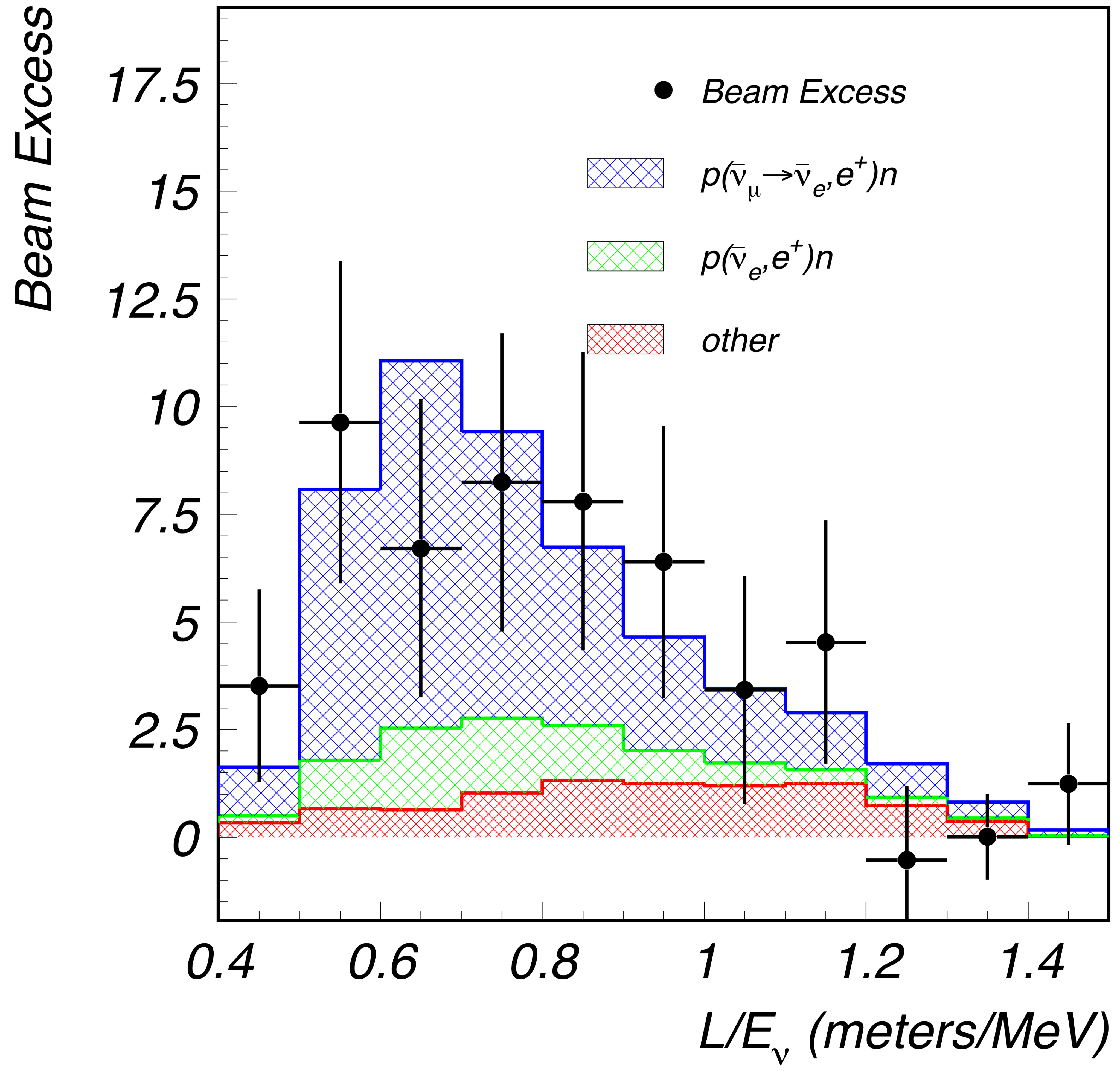

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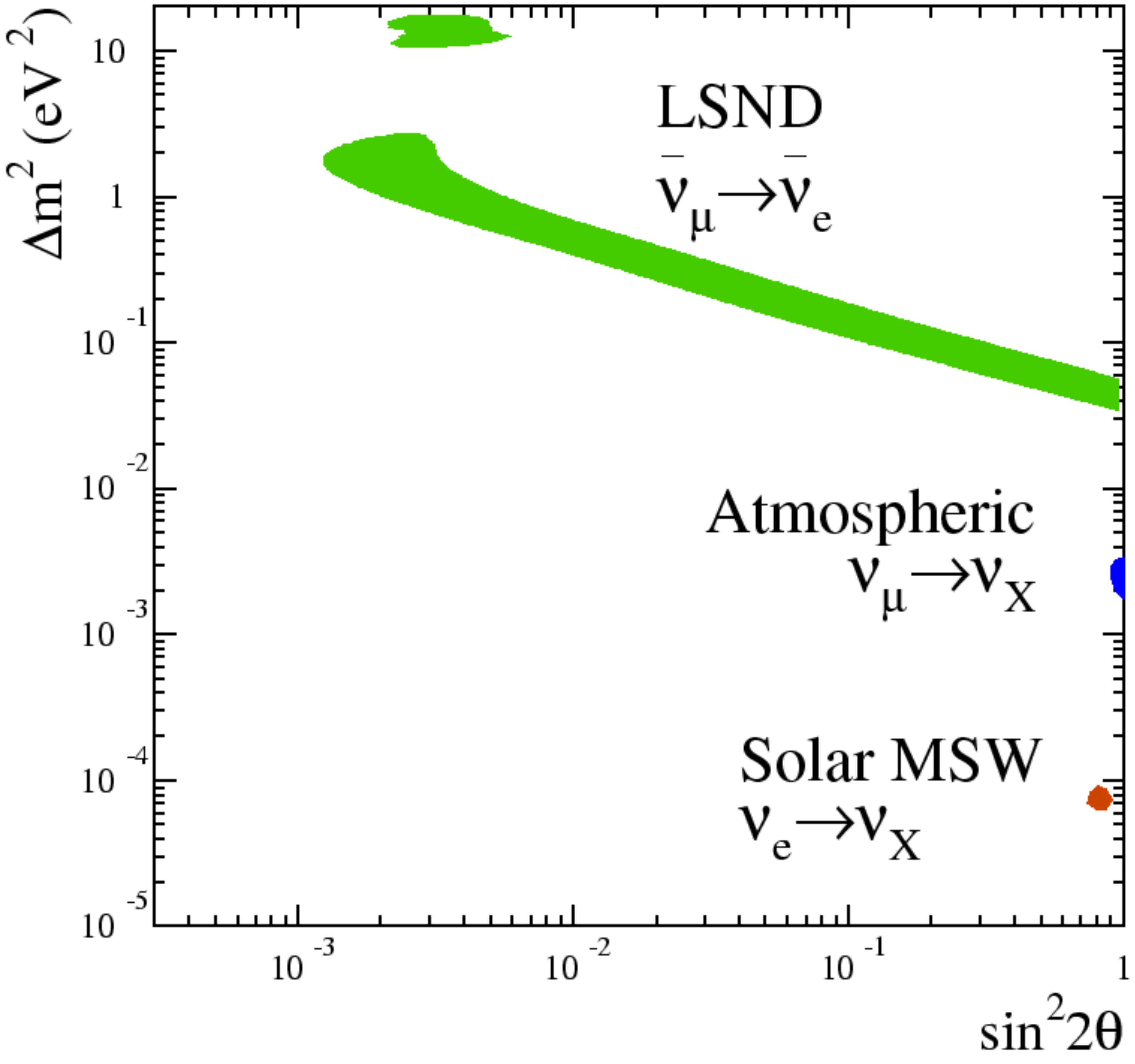
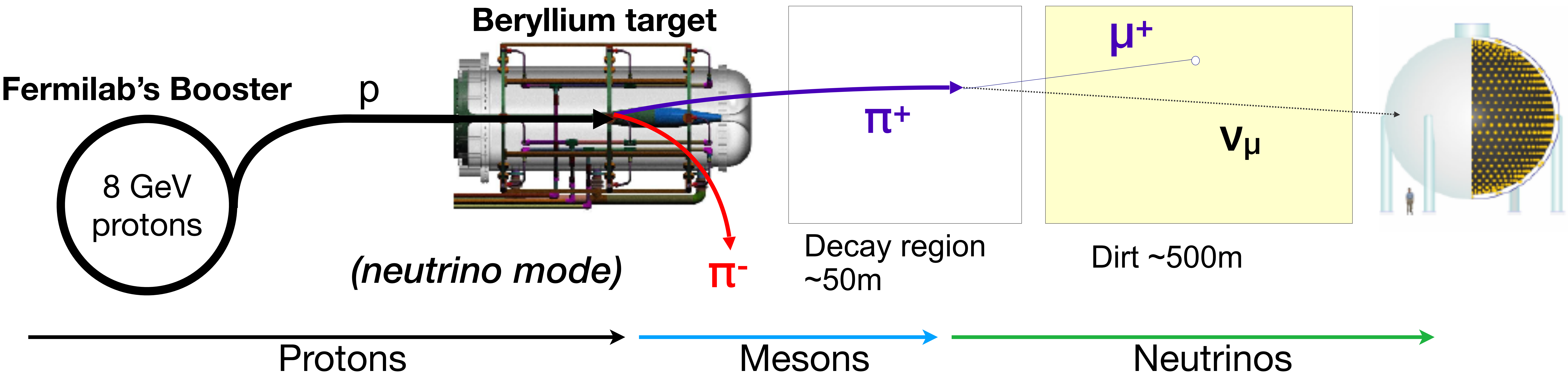


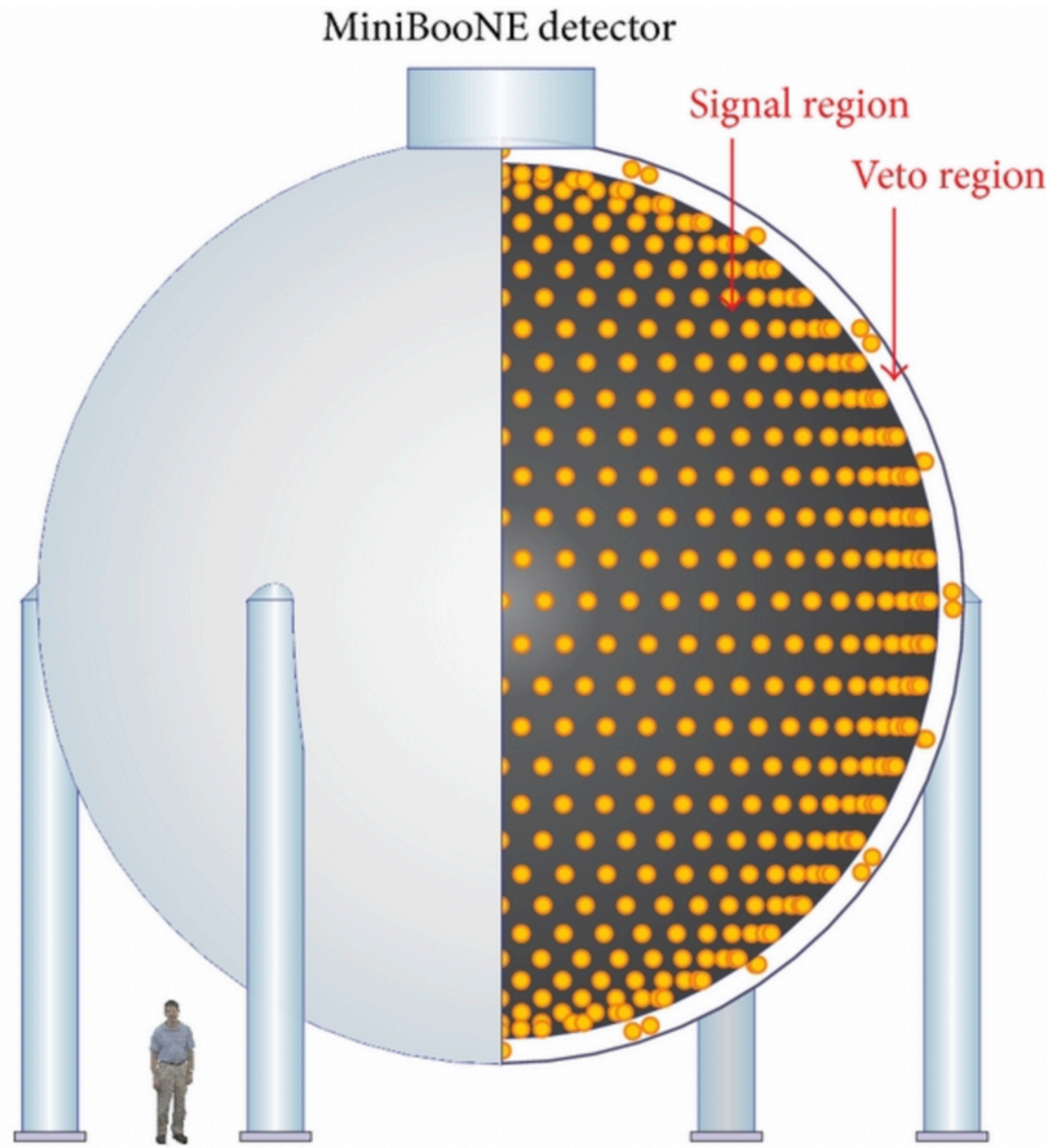

- LSND's oscillation fit yields parameter space that is not compatible with either atmospheric (Δm2~10-3 eV2) or solar (Δm2~1-5eV2) oscillations
- There cannot be three independent Δm2 in a 3v scheme
- LSND's result indicates a possible 4th generation of neutrino, but there are only 3 "active" flavors, that couple to the Z-boson.
- The additional neutrino must be "sterile" (not coupling to the Z and W bosons)

# The MiniBooNE Experiment

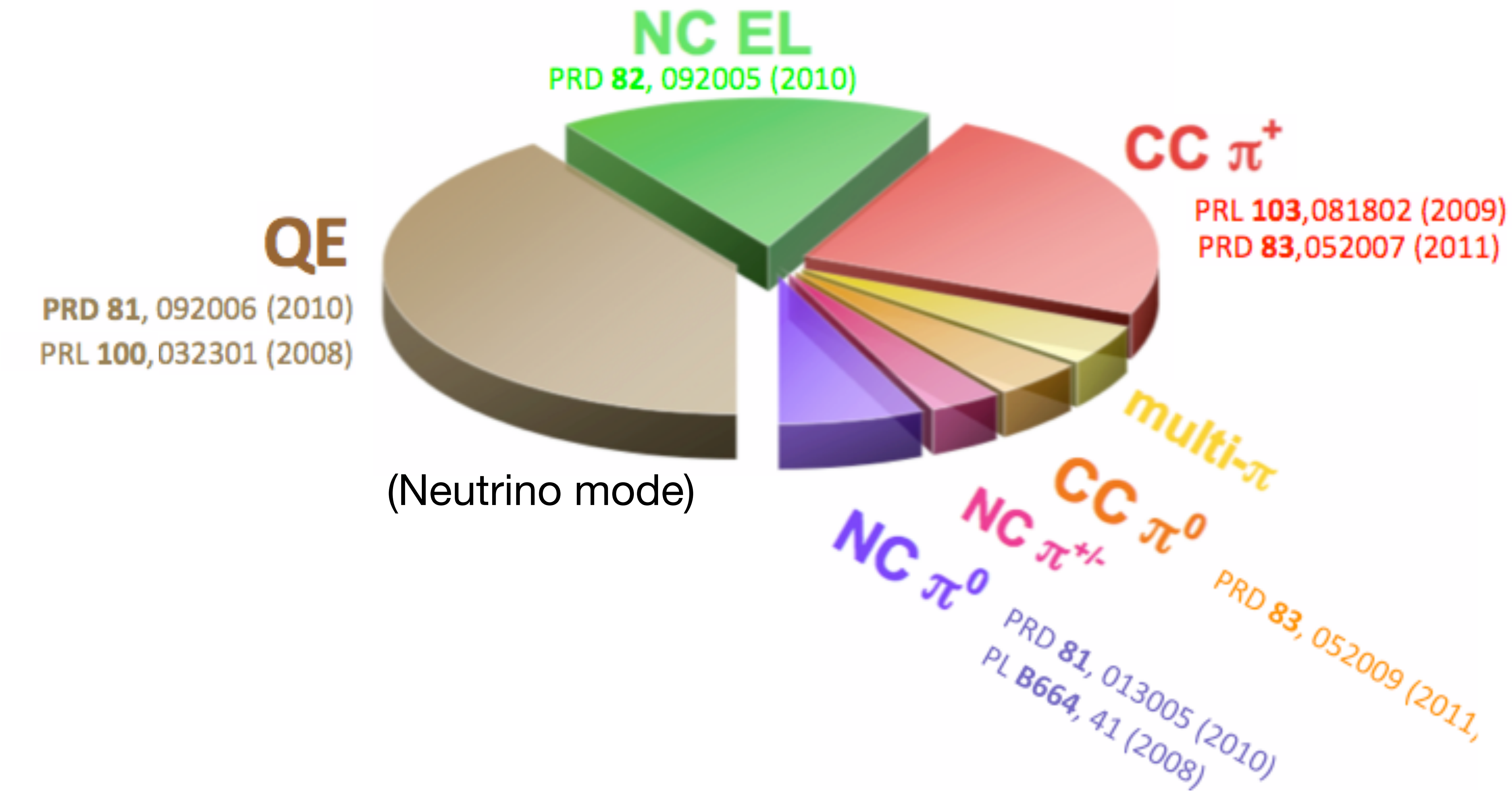



- Proposed to investigate the LSND anomaly, in search for sterile neutrinos
- Located on the Booster Neutrino Beam at Fermilab
- Single horn focused neutrino beam : Selection of neutrino/antineutrino modes
- Similar L/E as LSND :
  - MiniBooNE ~500 m / ~500 MeV
  - LSND ~30 m / ~ 30 MeV
- Different systematics due to different fluxes, event signatures and backgrounds

# The MiniBooNE Detector

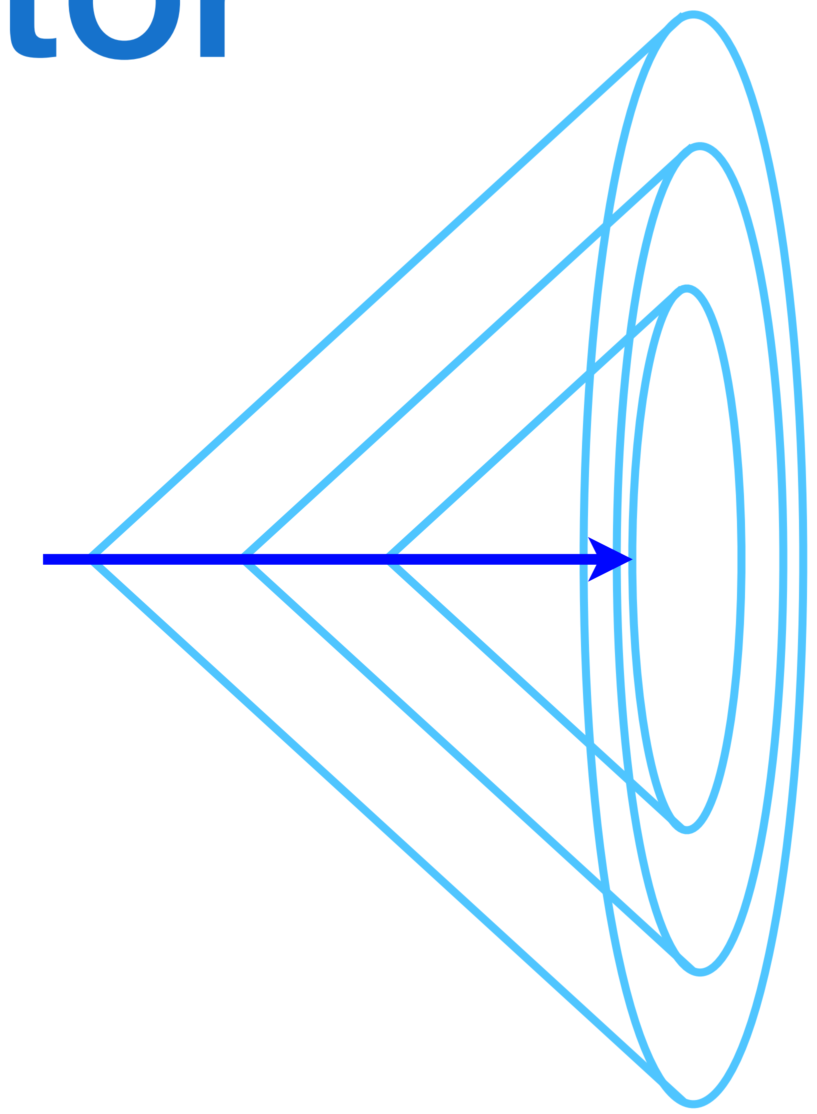


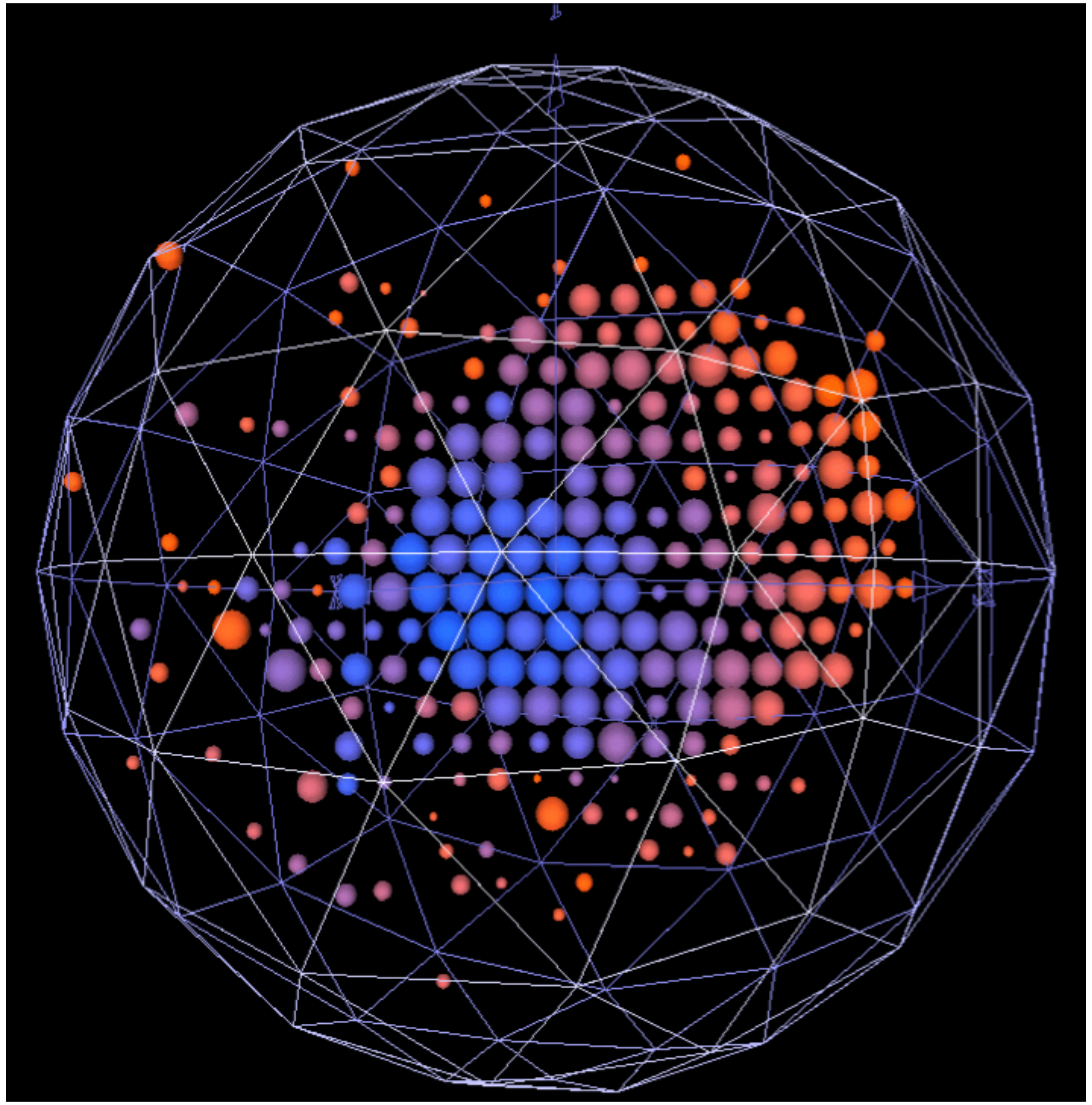

- ⌀12.2 m sphere, ⌀10m fiducial volume
- 800 tons of mineral oil, 450 tons fiducial mass
- 2 optically isolated volumes
- 1280 inner PMTs, 240 veto PMTs
- Very well understood detector
  - 3% change of the energy scale over 17 years of running
  - Measurements of cross sections for >90% of the neutrino and anti-neutrino processes



# Events in the Detector

- Muons
  - Long straight tracks
  - Sharp clean rings or disks





- Electrons
  - Multiple scattering
  - Radiative processes
  - Scattered fussy rings

- Neutral pions
  - Decay to 2 photons
  - Double fuzzy rings

- NC elastic scattering
  - No Cherenkov radiation
  - Isotropic scintillation hits

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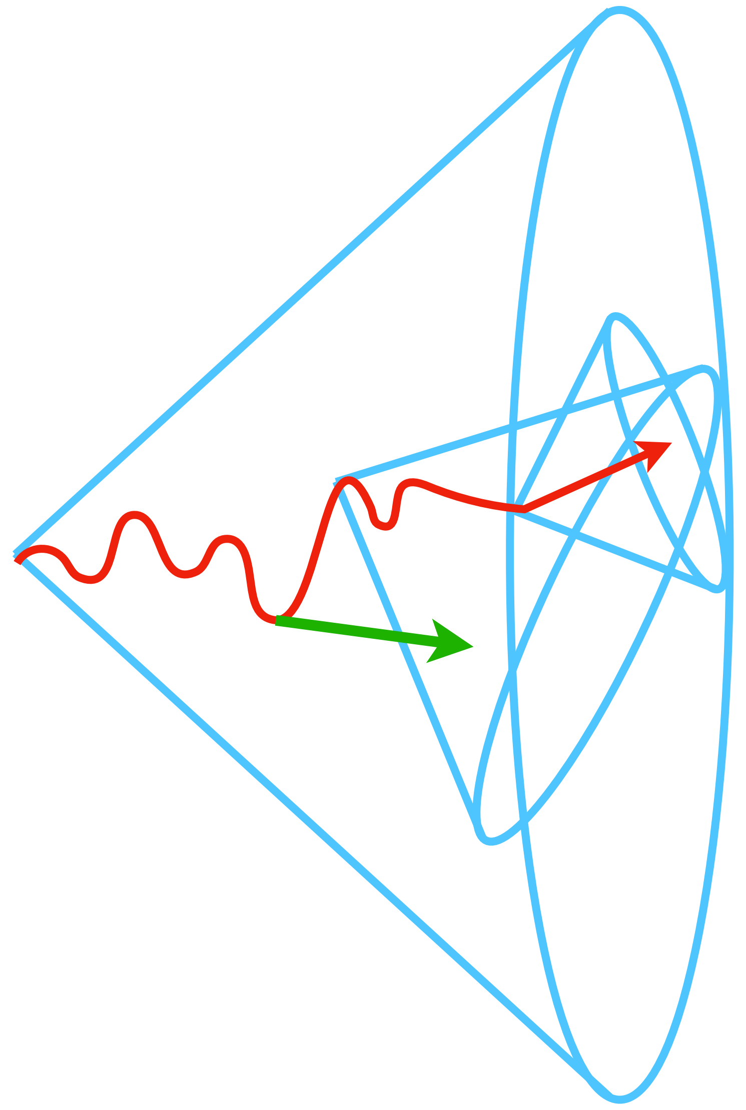

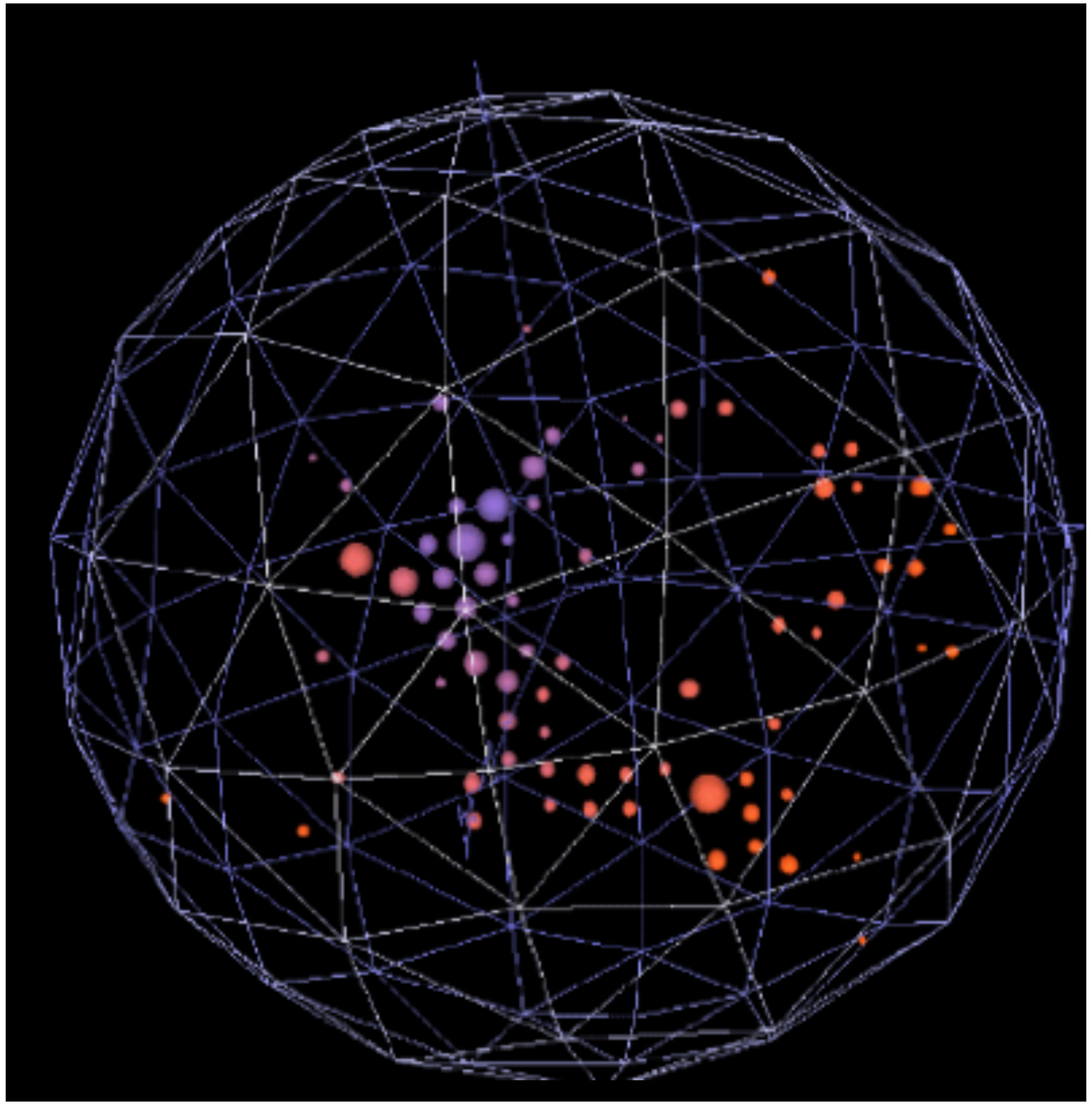

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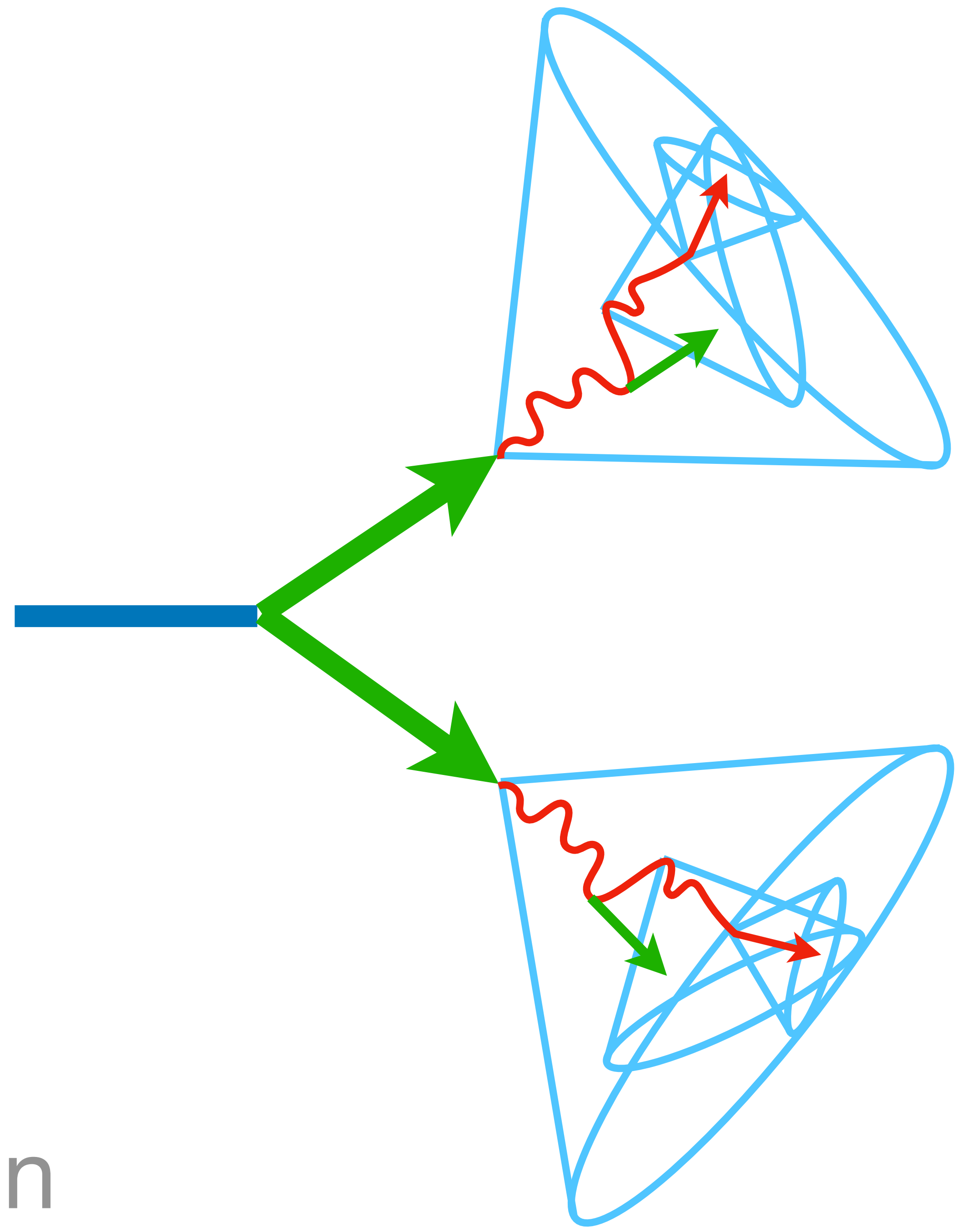

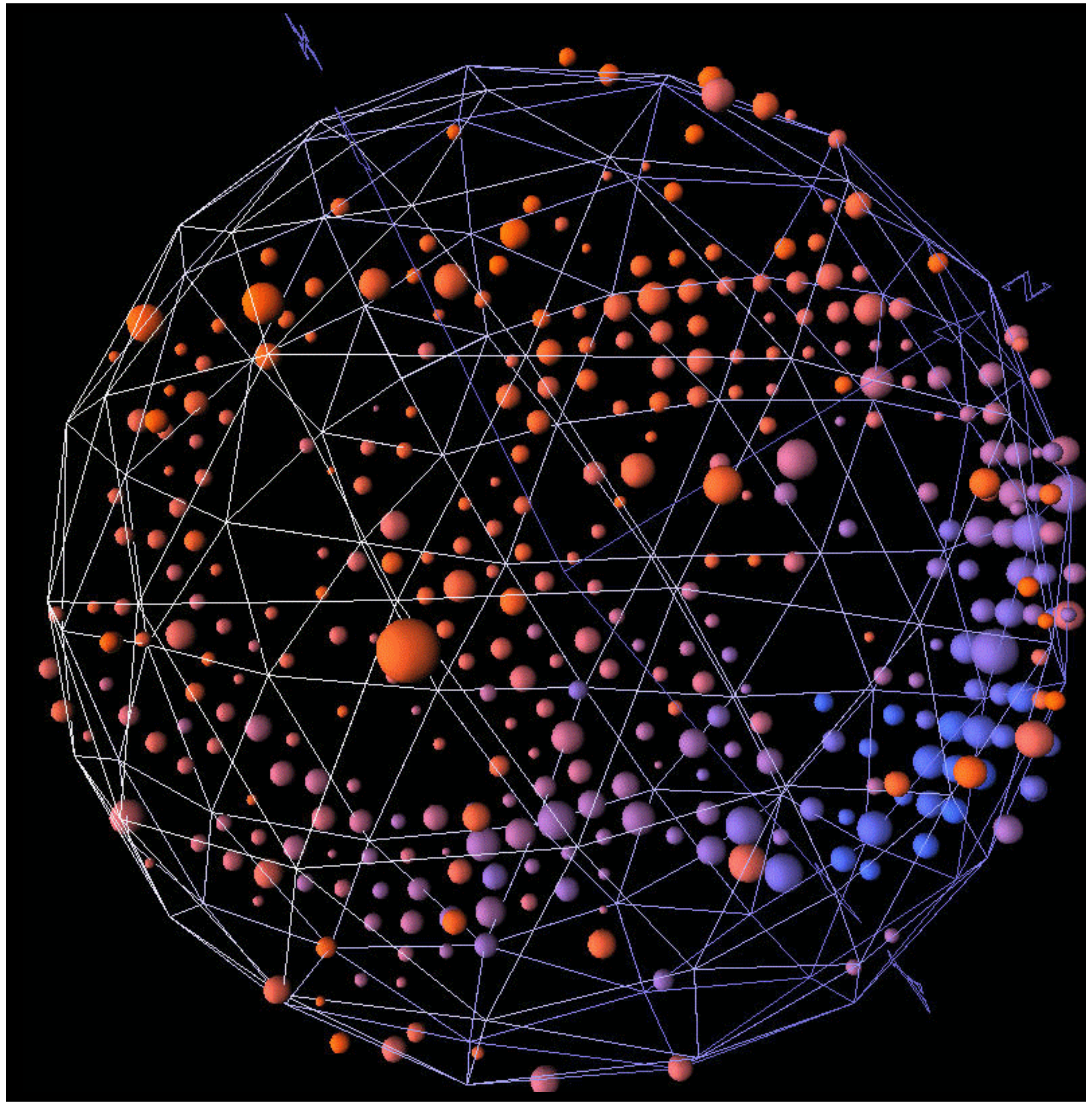

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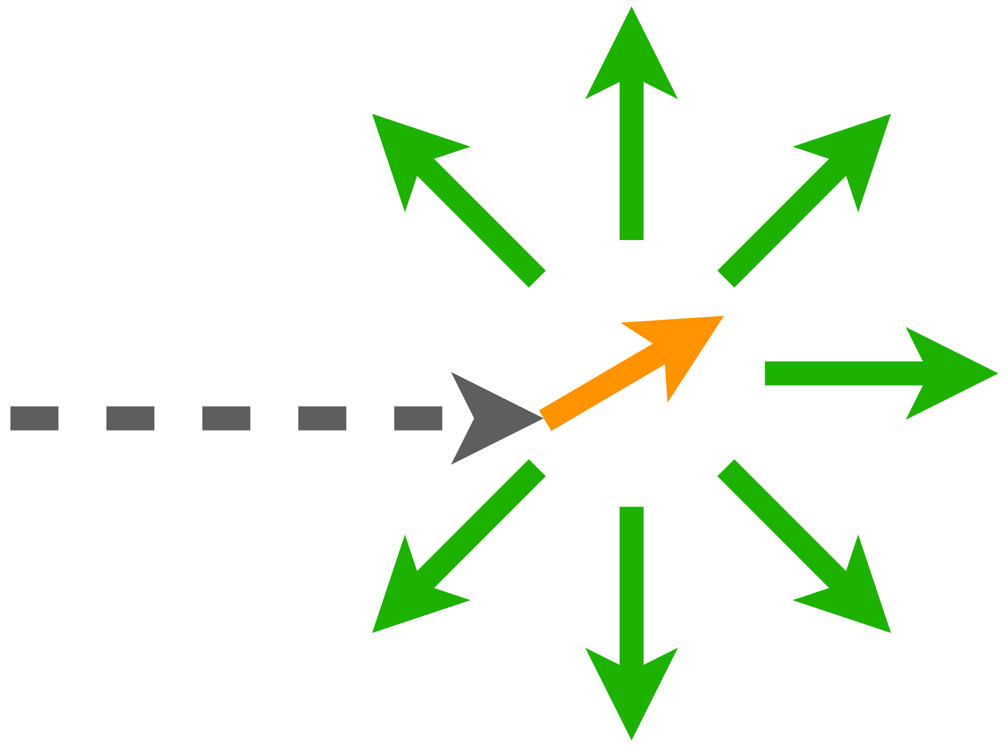
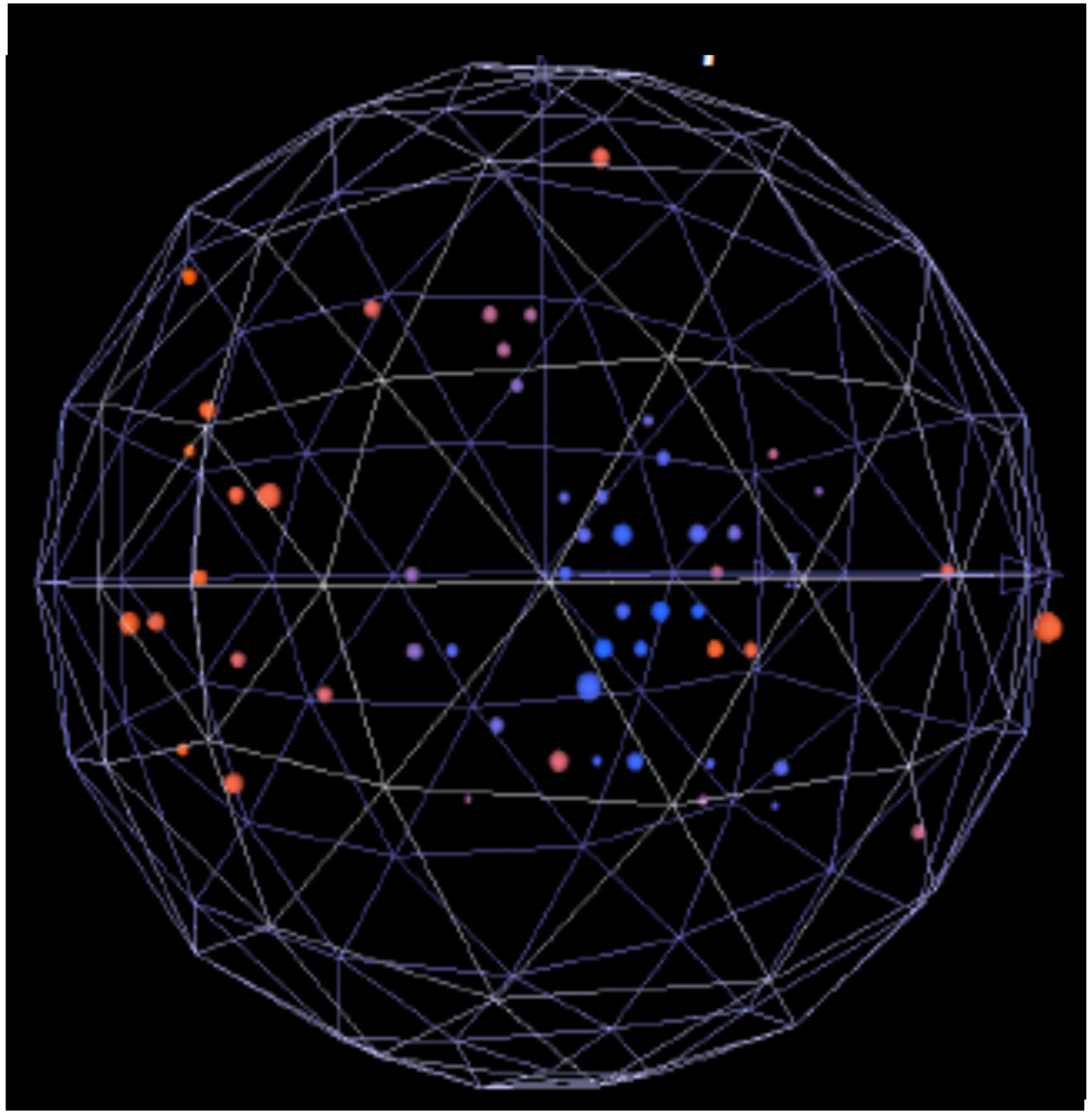
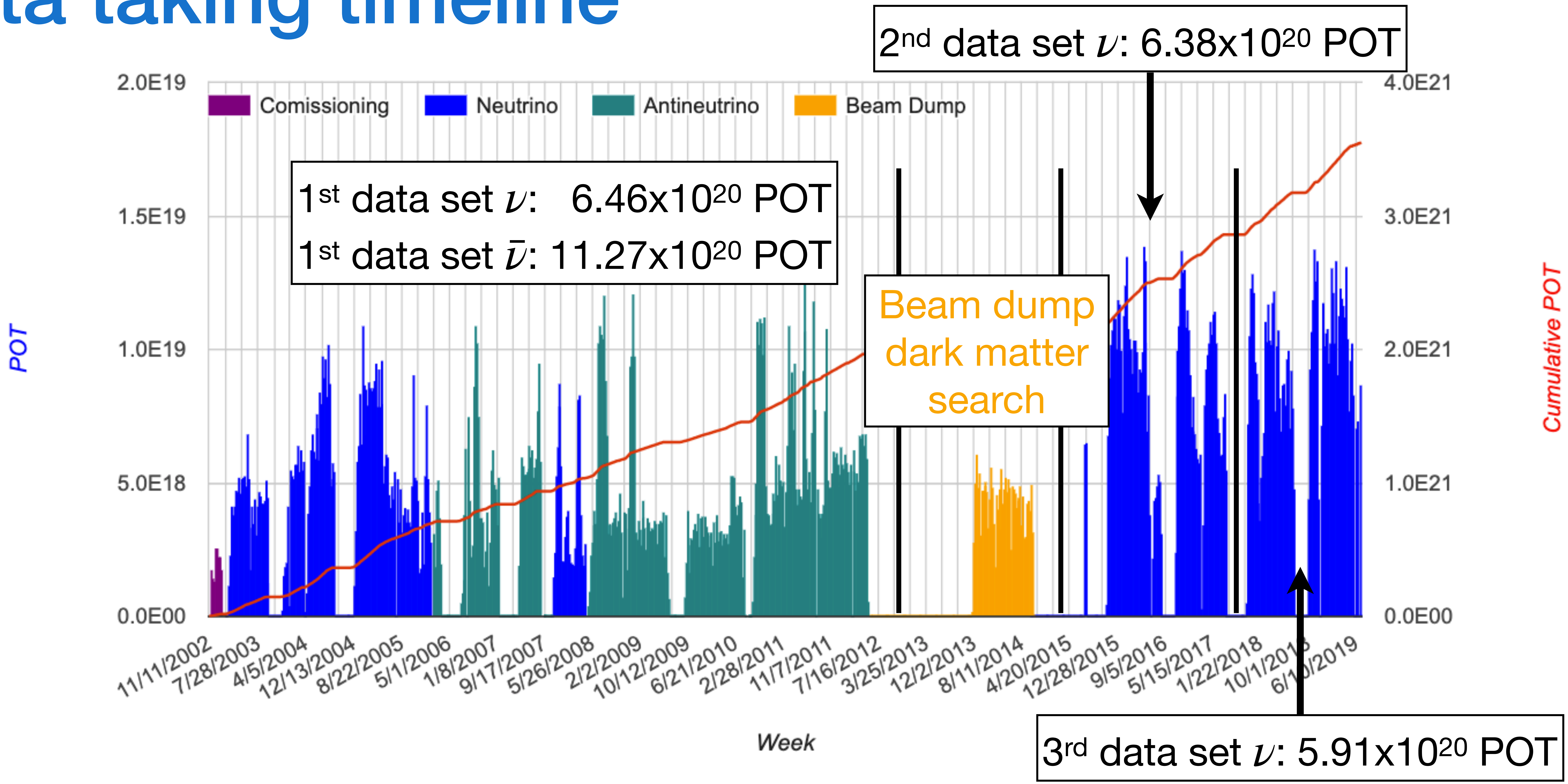




# Data taking timeline




- We have added another ~6x10$^{20}$ POT to the neutrino dataset since the previous data release.
- The detector was turned off at the end of summer 2019, mothballed and waiting for future use…
- Almost 17 years of running, or as much as 5 army ants worth of protons!

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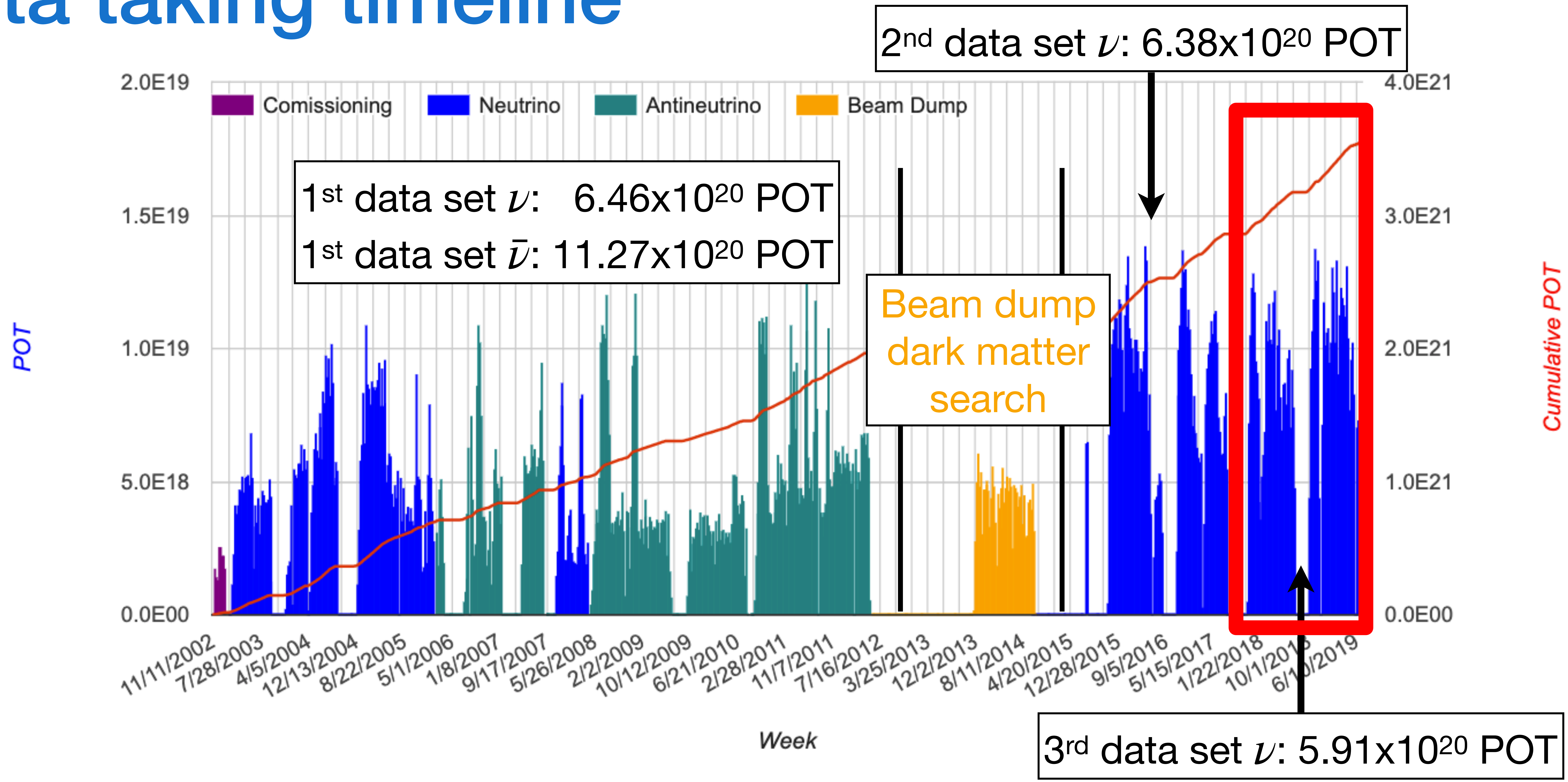


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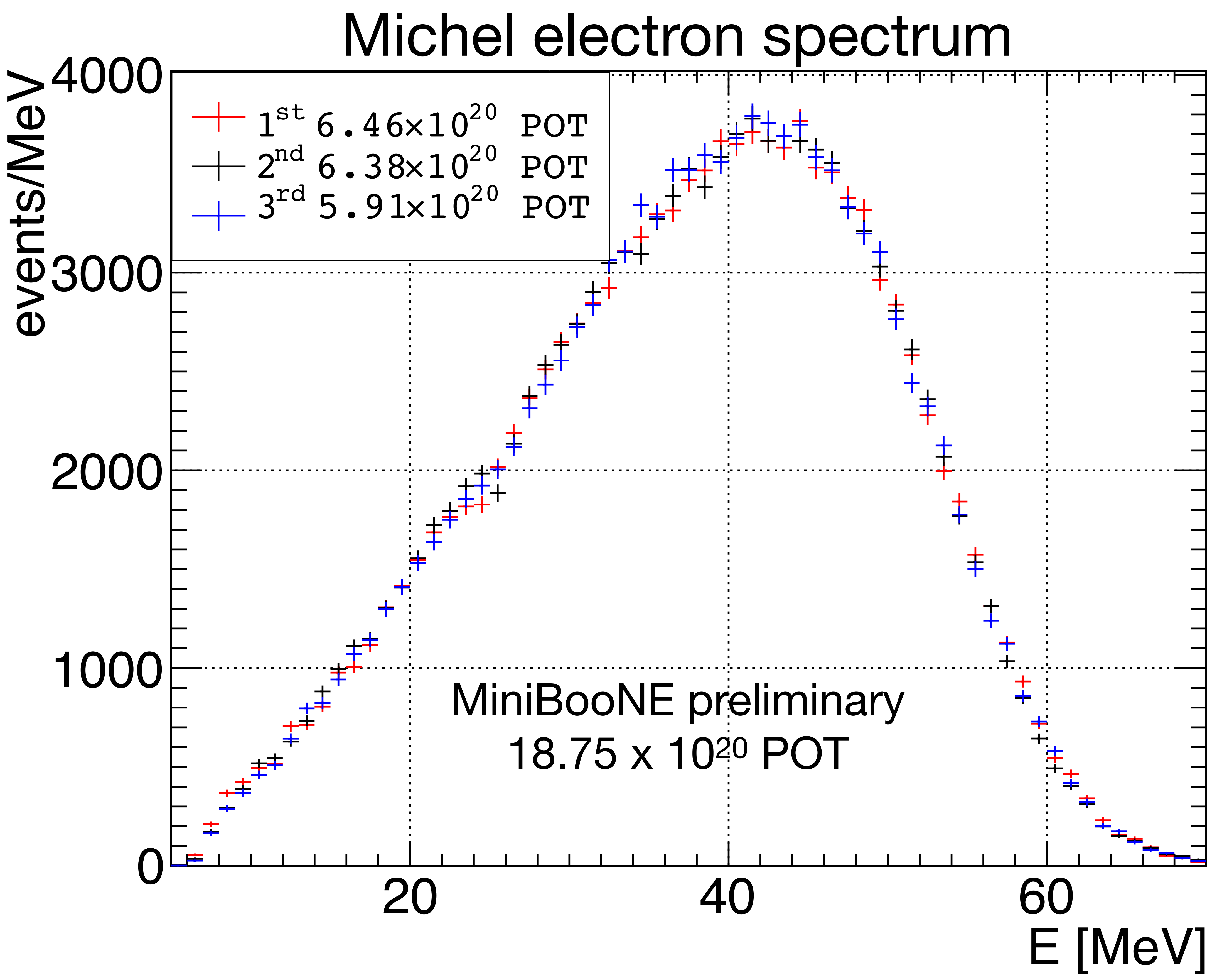
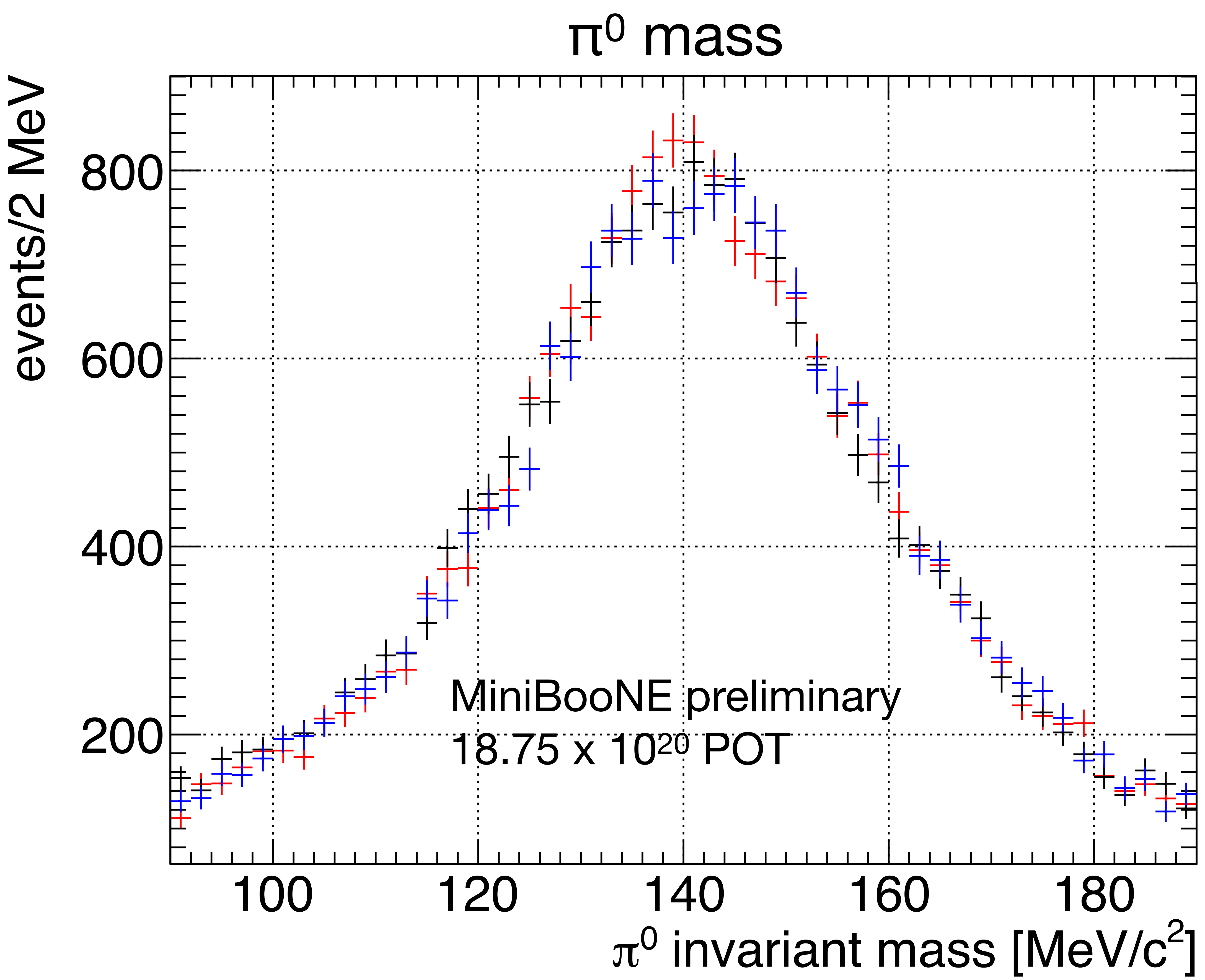
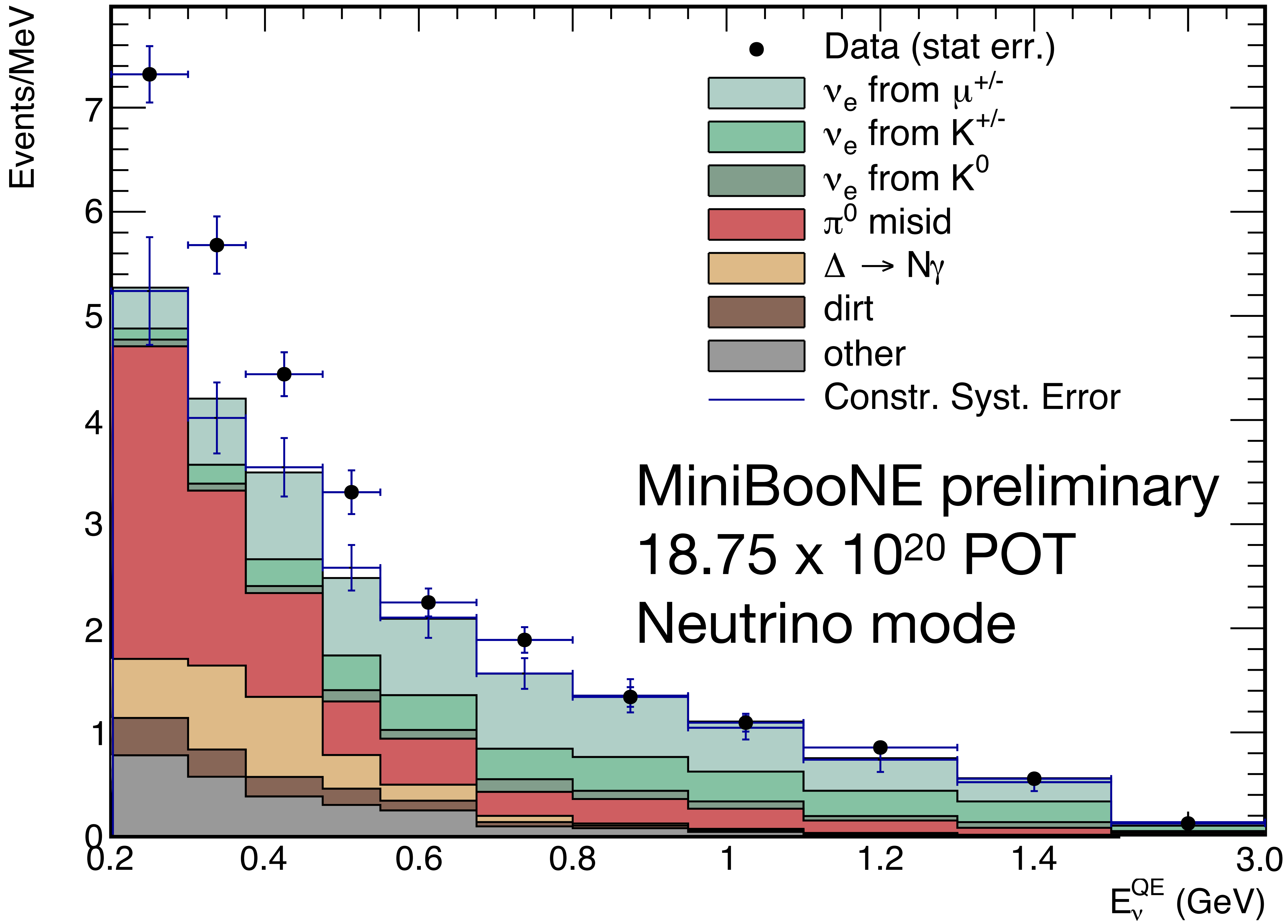
# Excellent long term detector stability over 3 run periods




- We can use two standard candles to calibrate the energy scale over the different data sets
- Scale up the energy response to match the original 2007 data release:
  - 2015-2017 neutrino data => 2% energy scaling
  - 2017-2019 neutrino data => 3% energy scaling

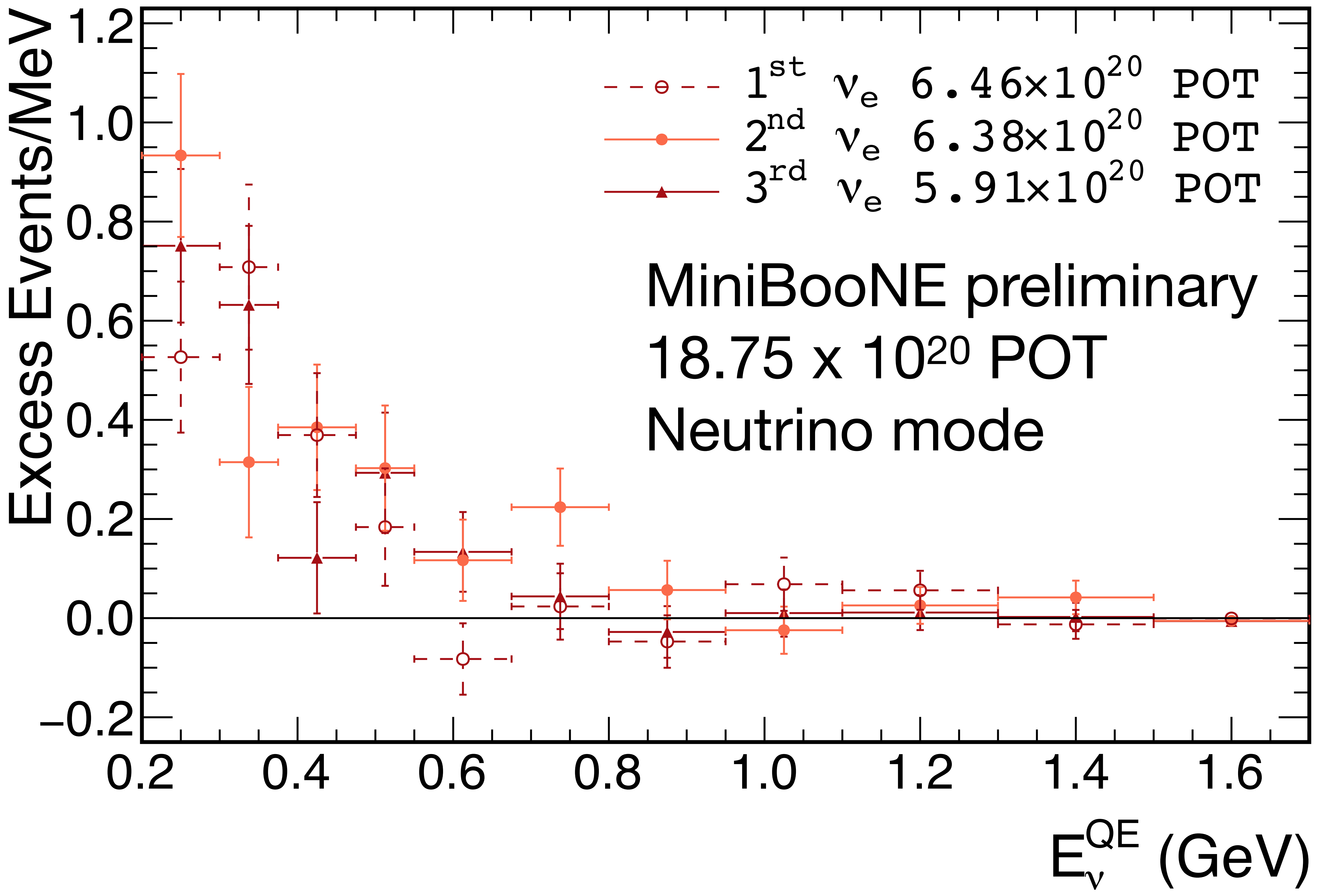
# Neutrino energy and 3ν prediction




- Excess of data events with respect to our background prediction
- We report an excess of 560.6 ± 119.6 electron-like events (neutrino mode)

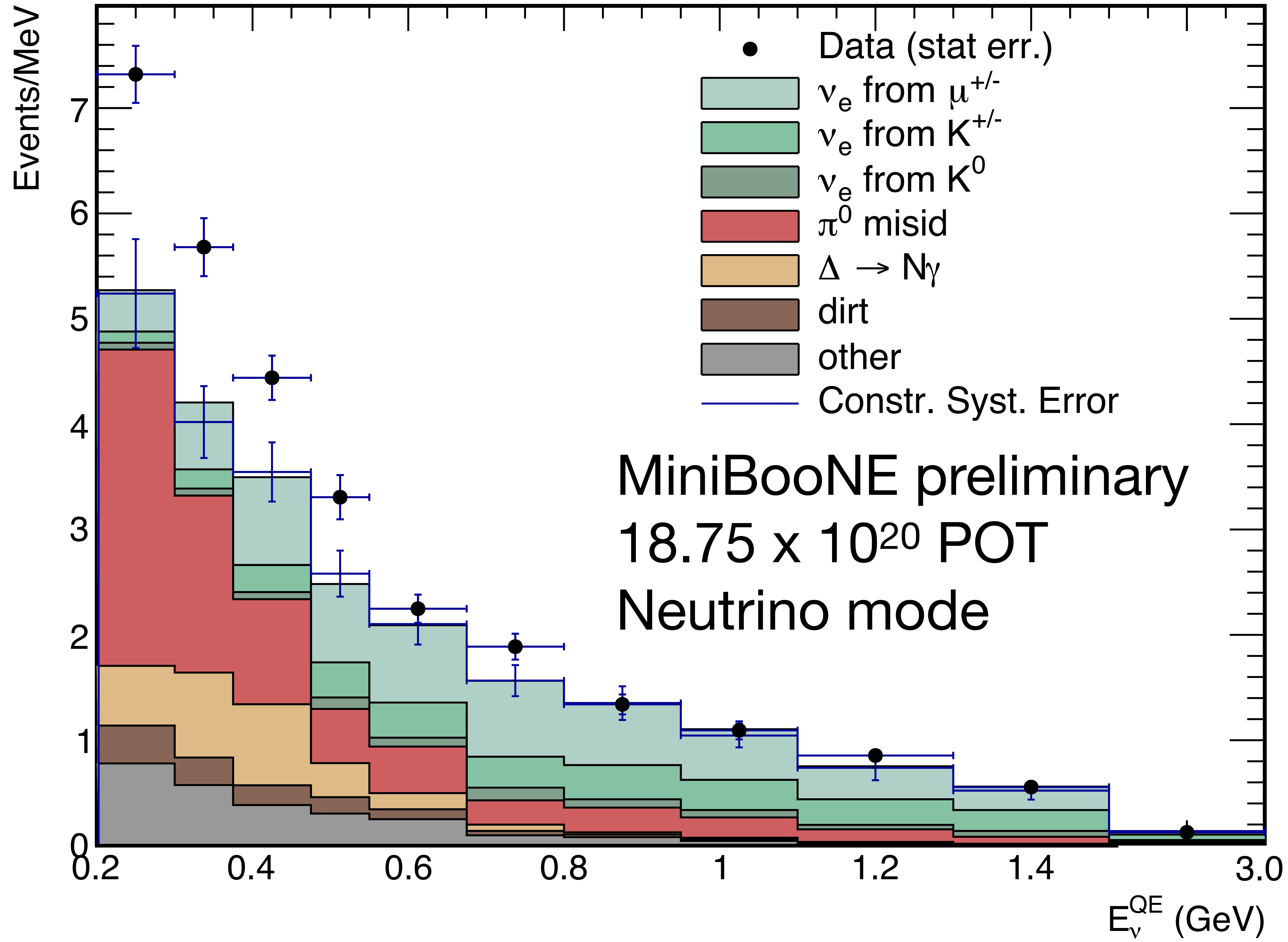
- **Significance : 4.7 σ in neutrino mode only**

# $\nu_e$-like excess stable across 3 runs




- Comparing the data-prediction excess for three data taking periods in neutrino mode
- Comparable statistics between the three data releases
- **The observed excess remains well compatible between the three data sets**

# Constraining the backgrounds



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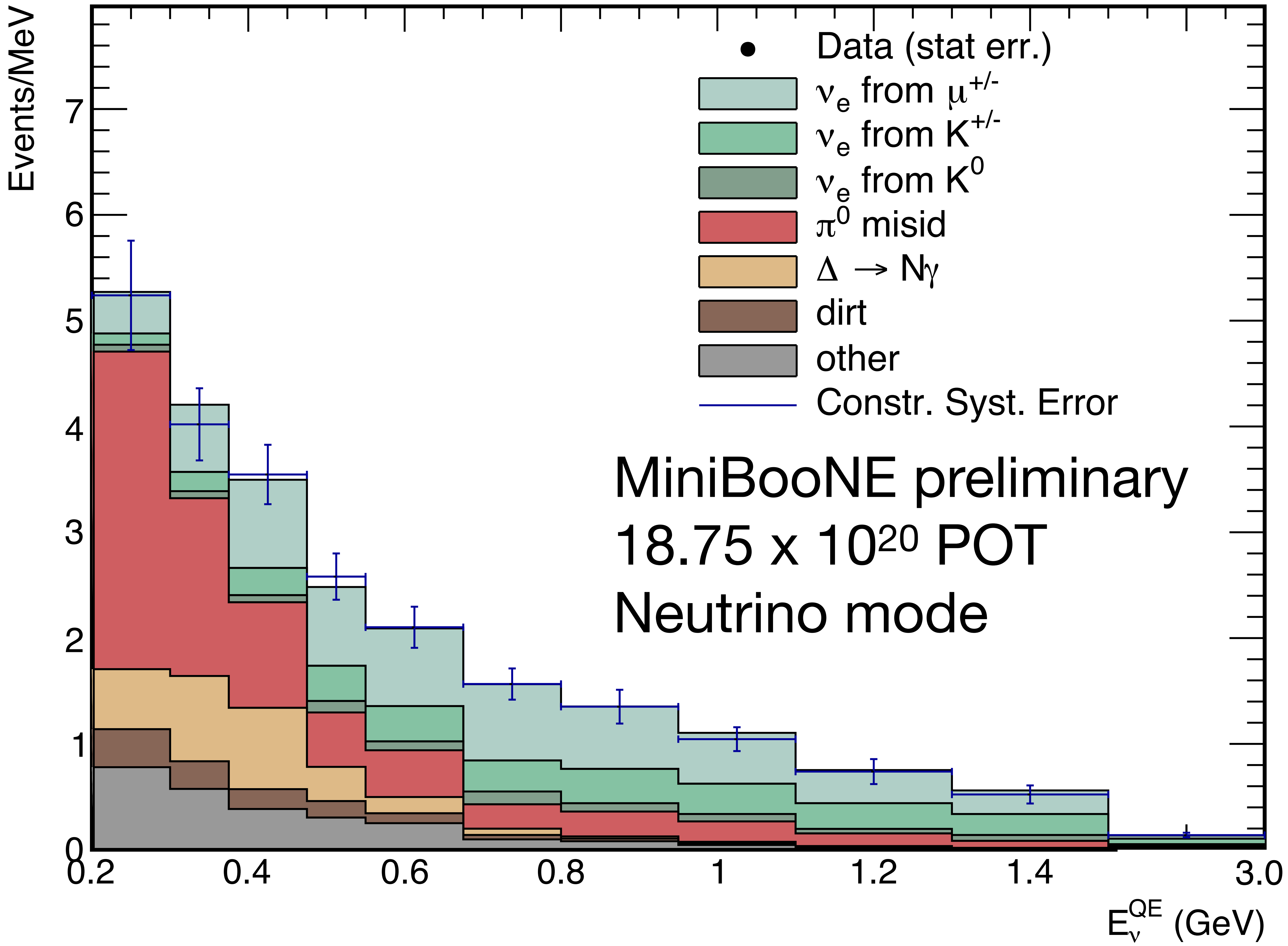
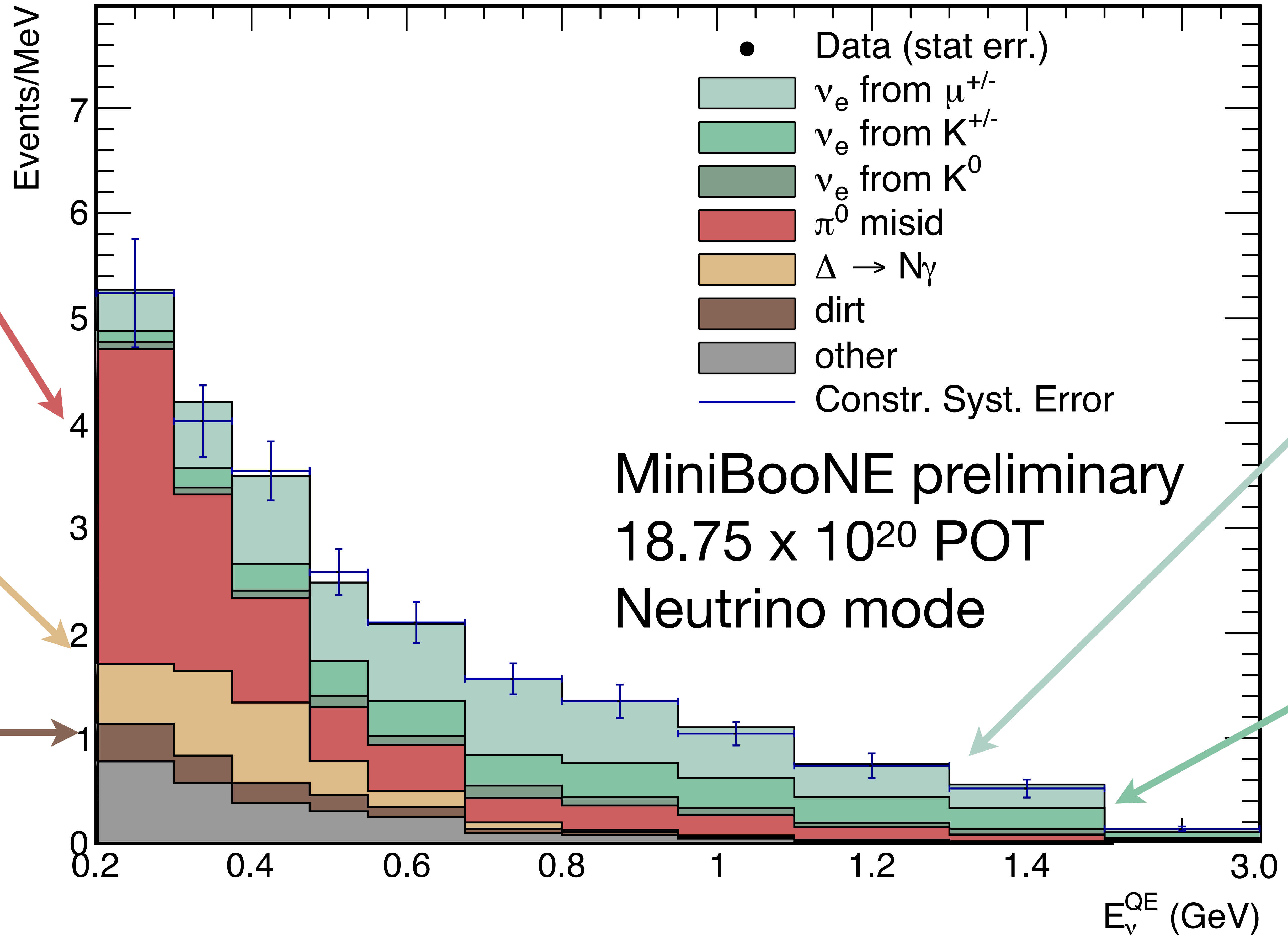


# Constraining the backgrounds

**$\pi^0$ MisID**
constrained from *in situ* measurement of NC $\pi^0$ rate

**Δ-> Nγ resonance**
constrained from *in situ* measured NC $\pi^0$ rate and theoretical prediction

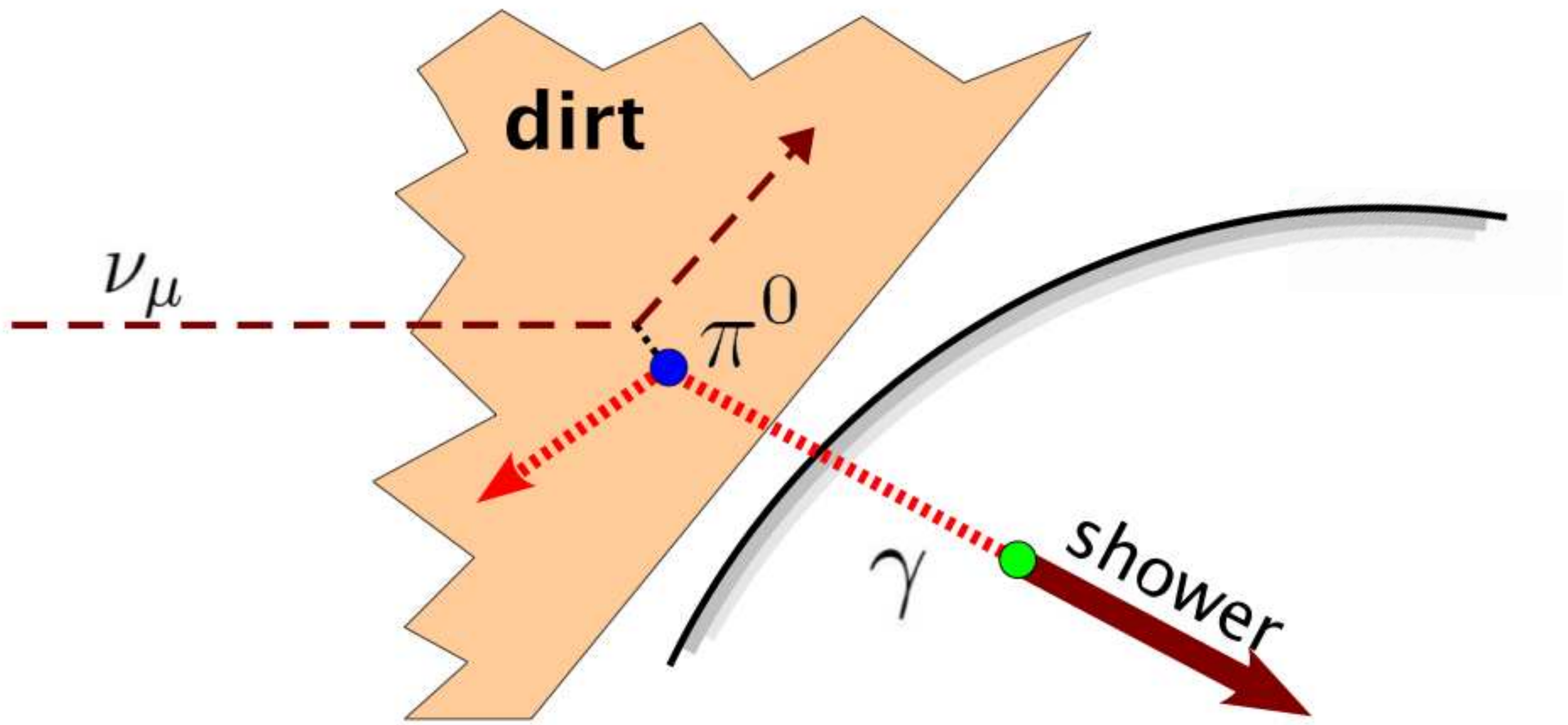
**Dirt**
constrained from *in situ* dirt data sample




**$\nu_e$ from μ decay**
is constrained by *in situ* $\nu_\mu$ CCQE measurement

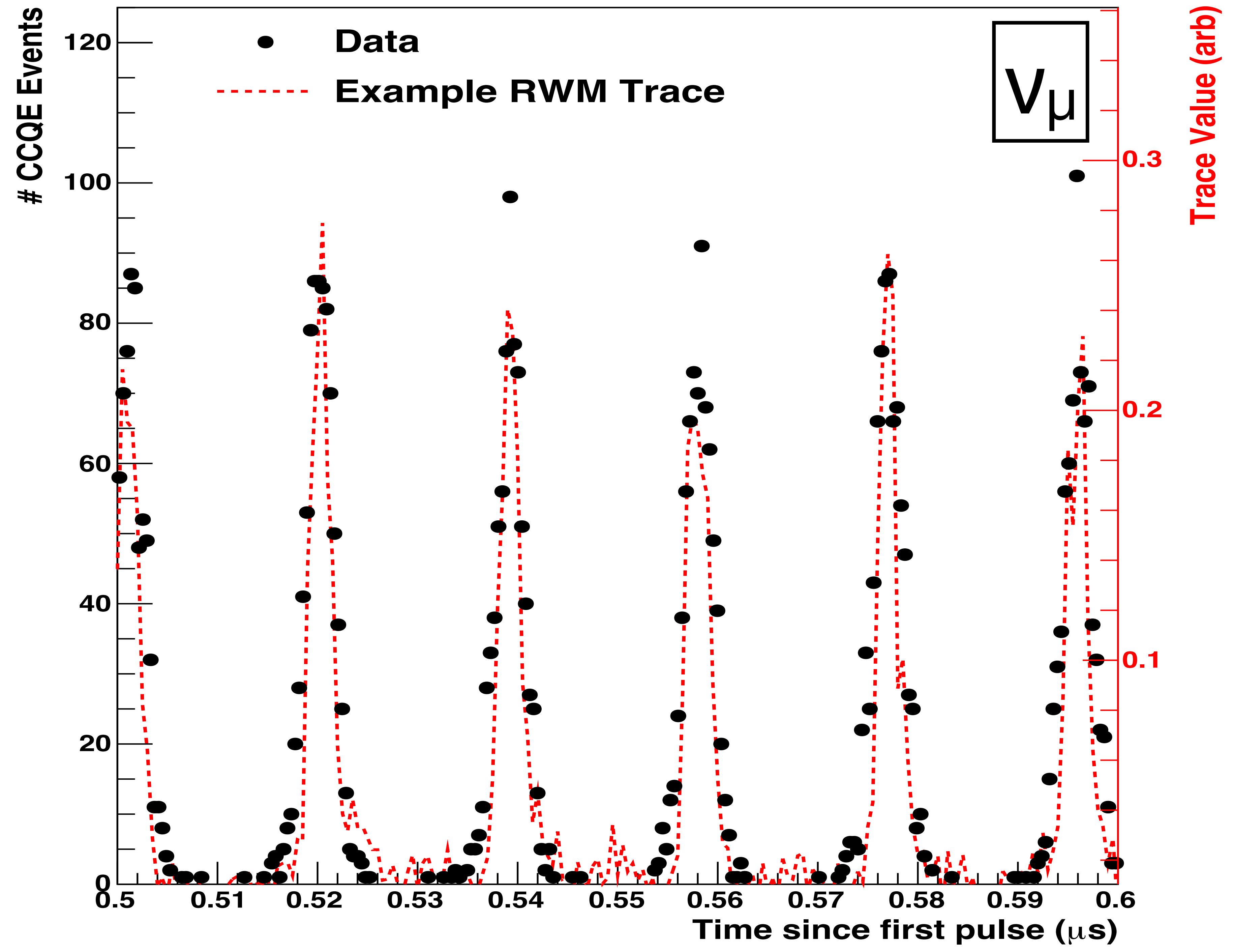
**$\nu_e$ from K decay**
constrained from *in situ* high energy events + SciBooNE high energy $\nu_\mu$ event rate

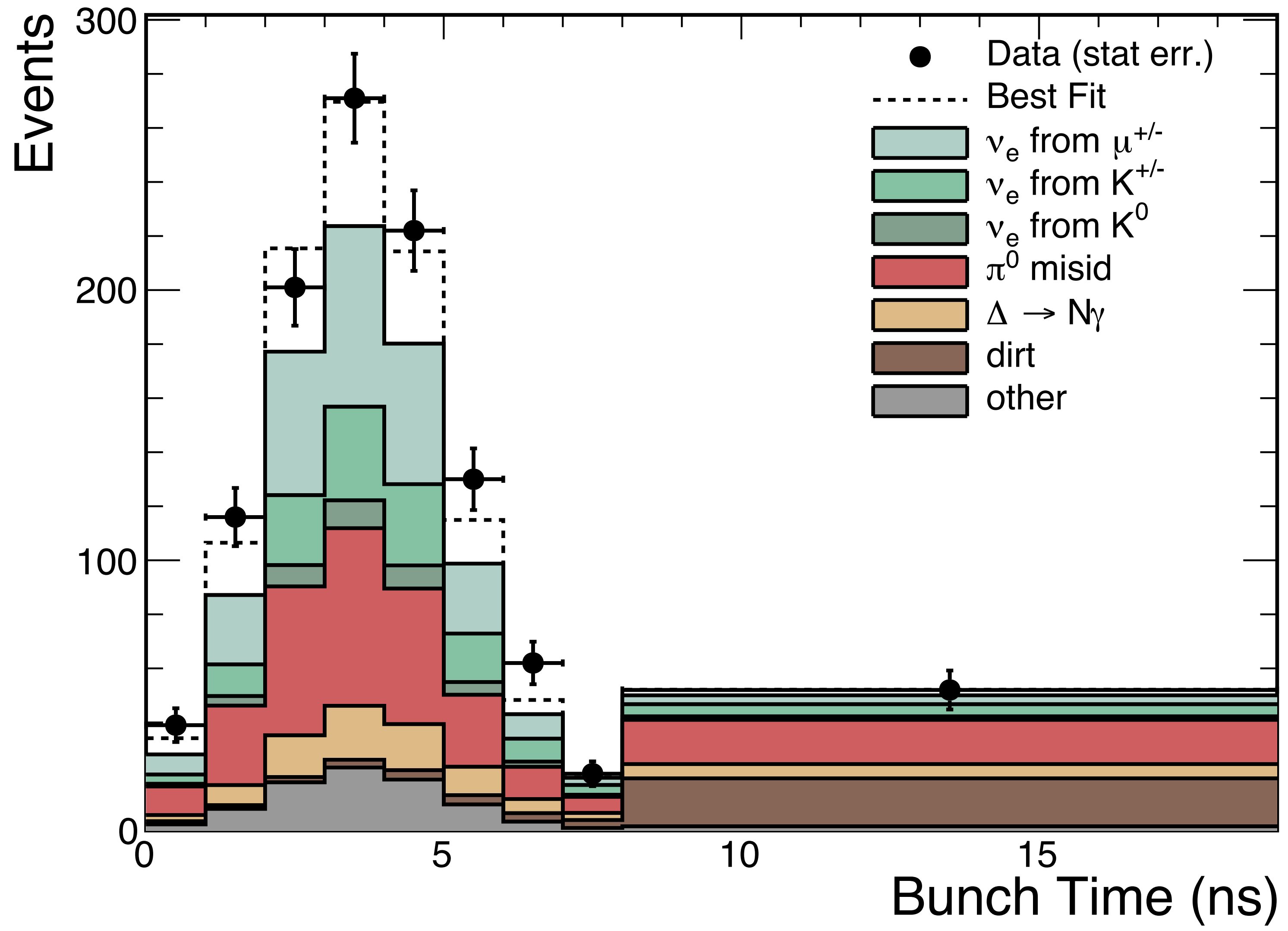
# Dirt constraint with timing




- Dirt events:
  - ➡ beam-related neutrino interactions in the rocks surrounding the detector
  - ➡ time shift due to extra flight path before particles enter the detector
- No cut on the event timing within the beam spill (RF cavity structure of 52.81 MHz)
- Event timing shows no significant excess of off-bunch data
  - ➡ **dirt constrained to better than 5σ**

Phys. Rev. D 98, 112004



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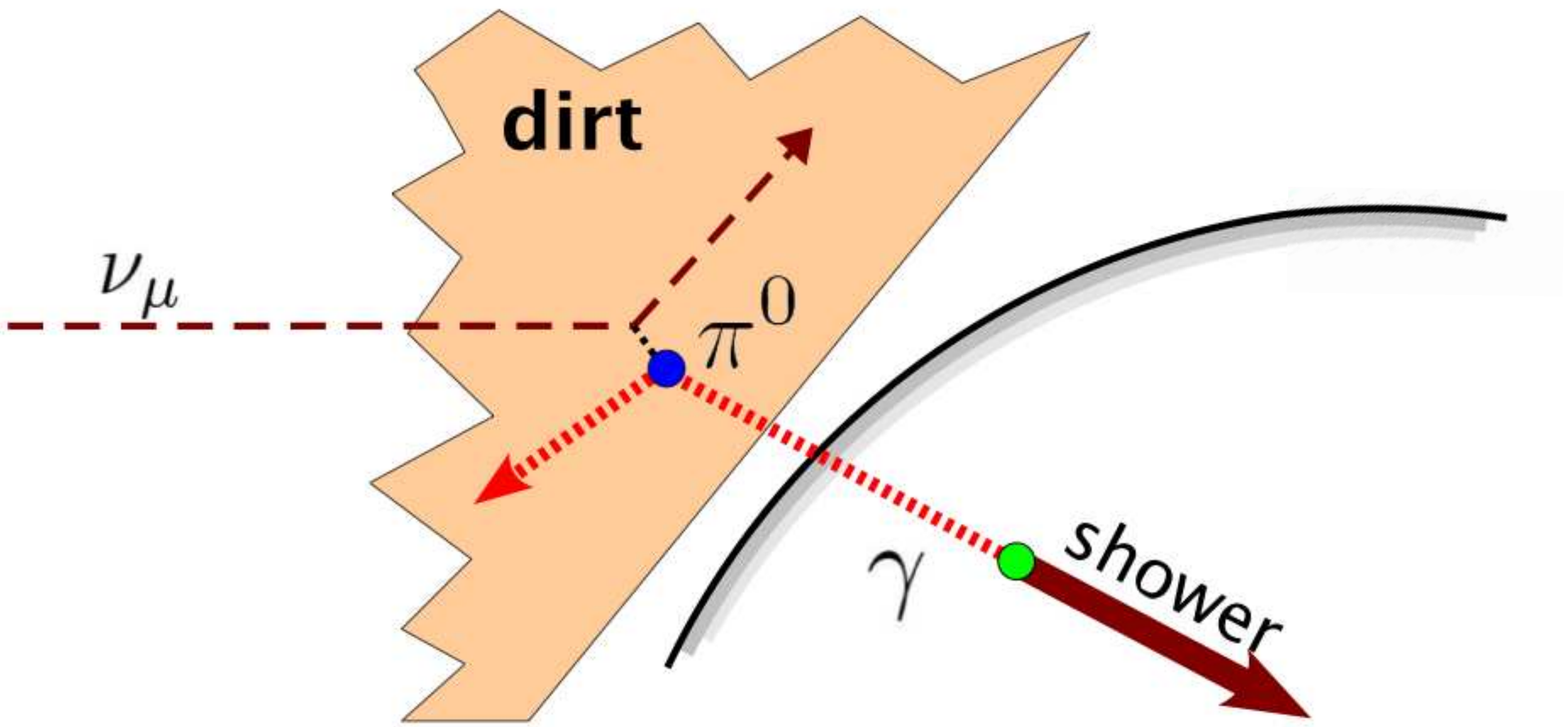


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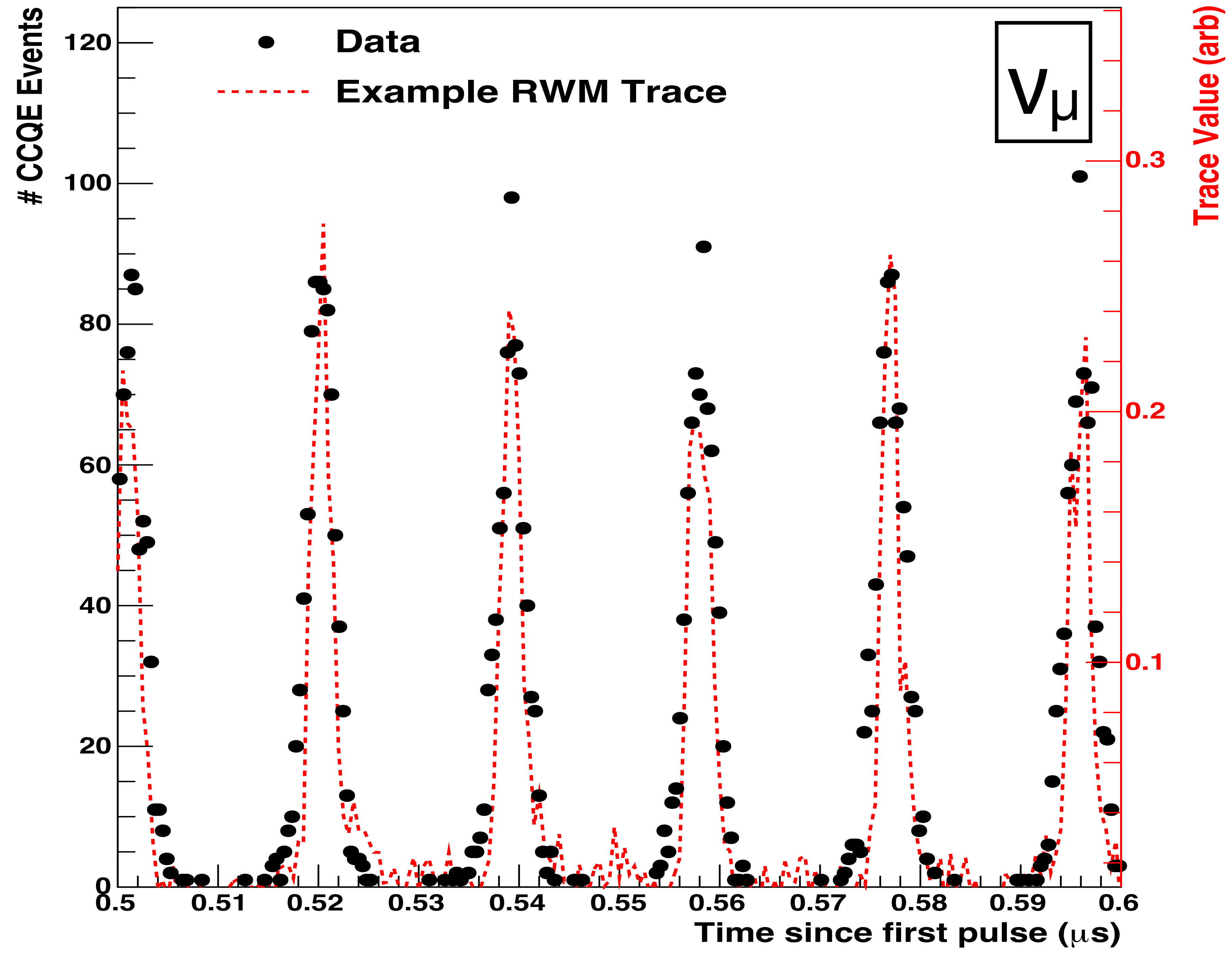


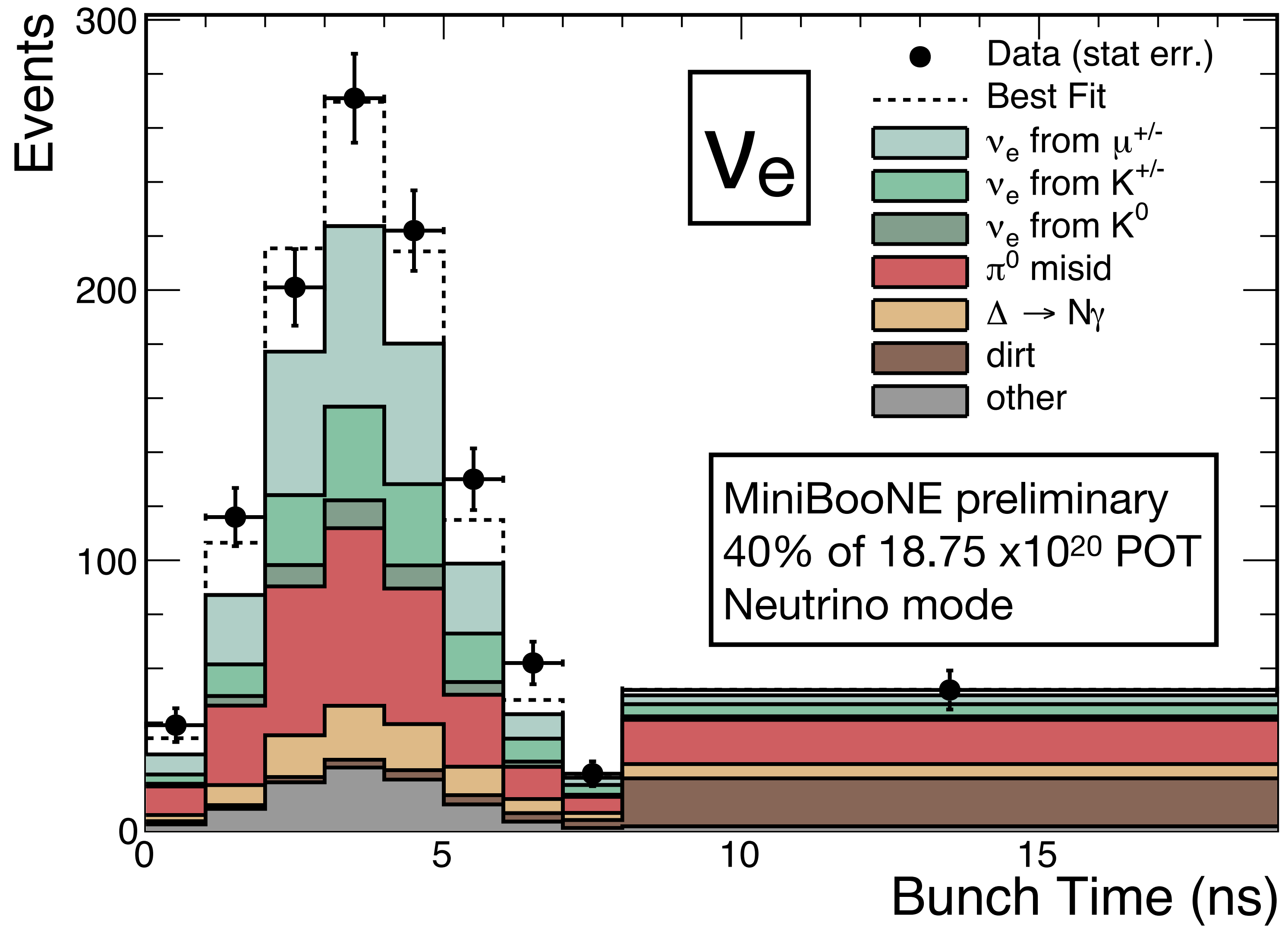


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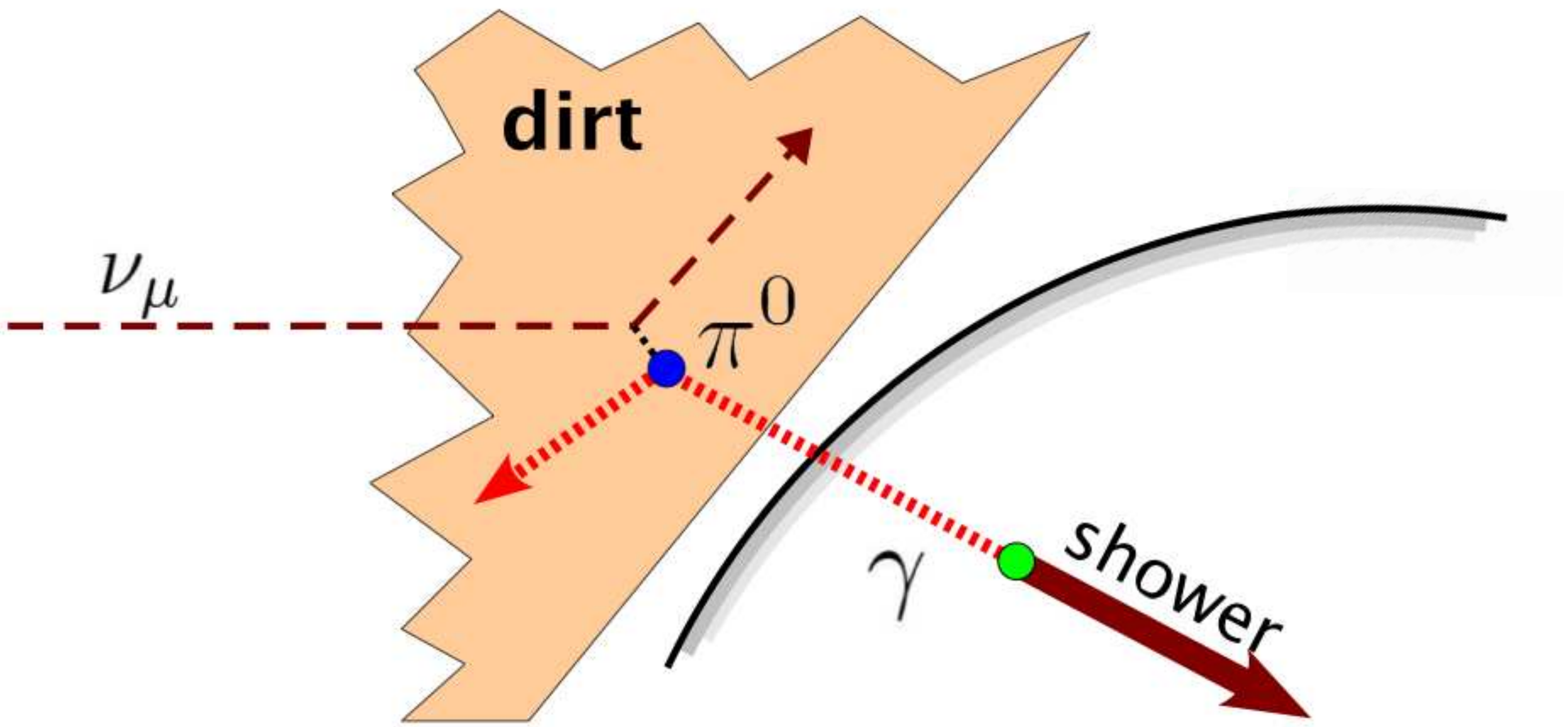


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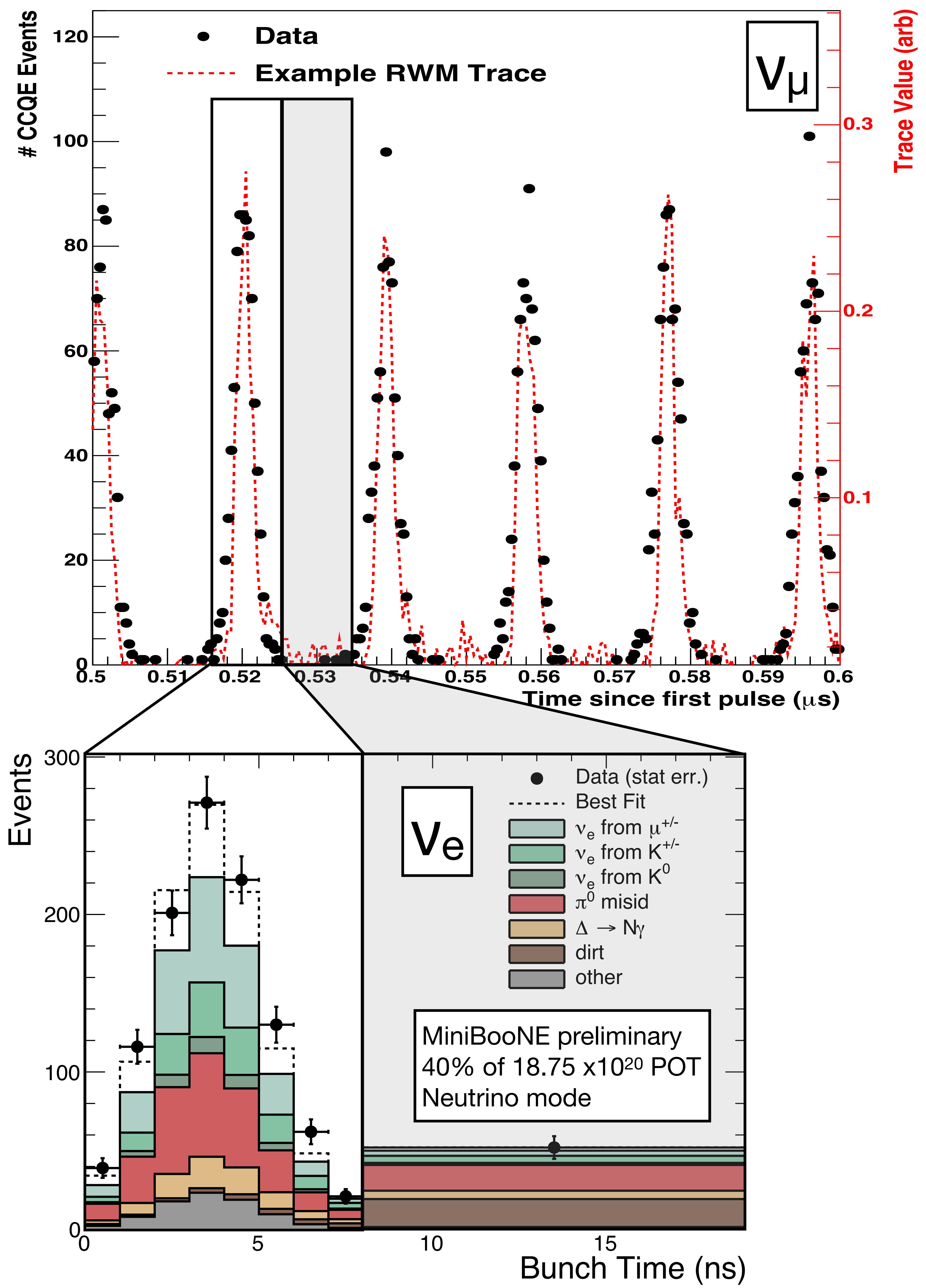


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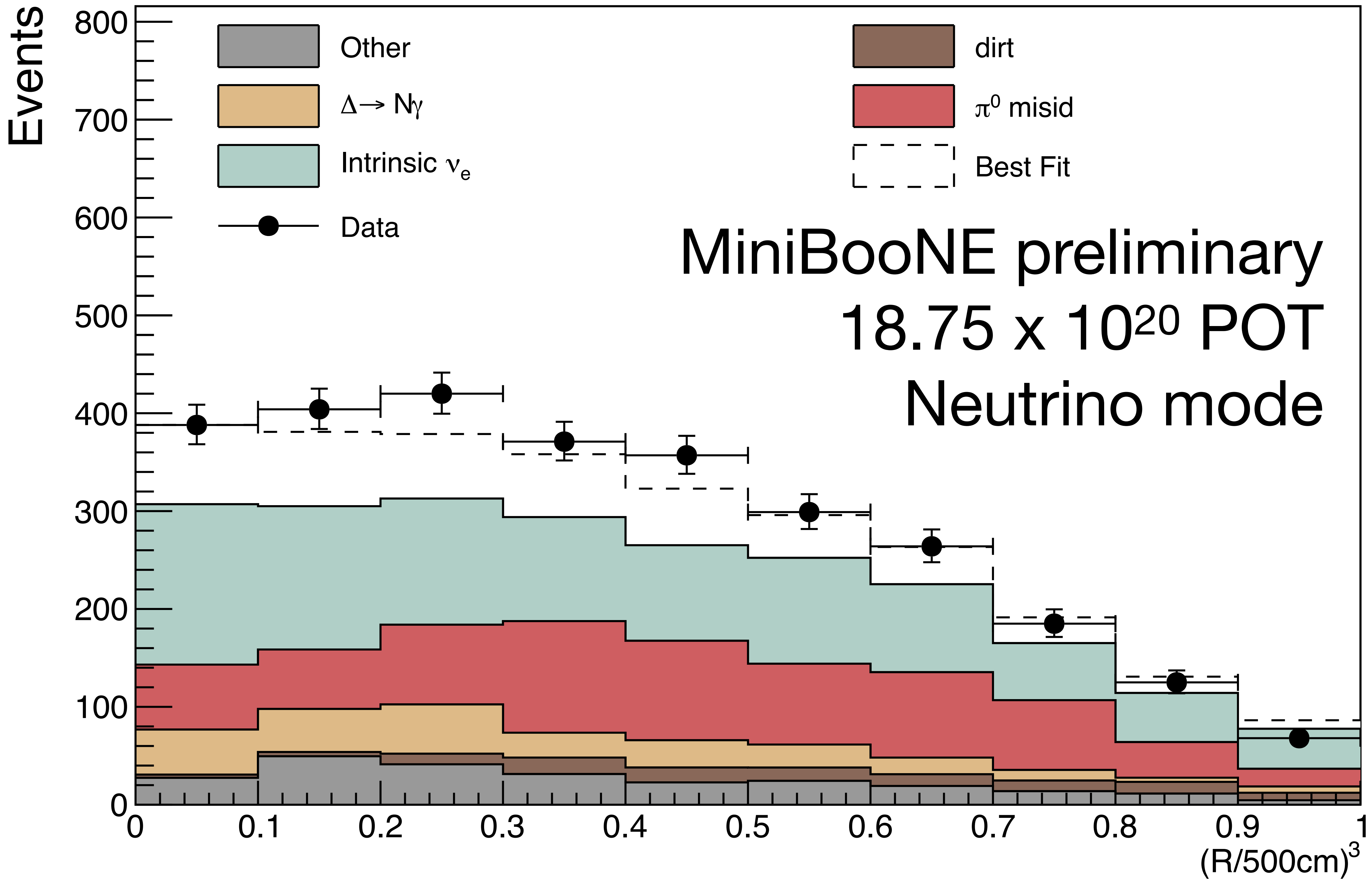
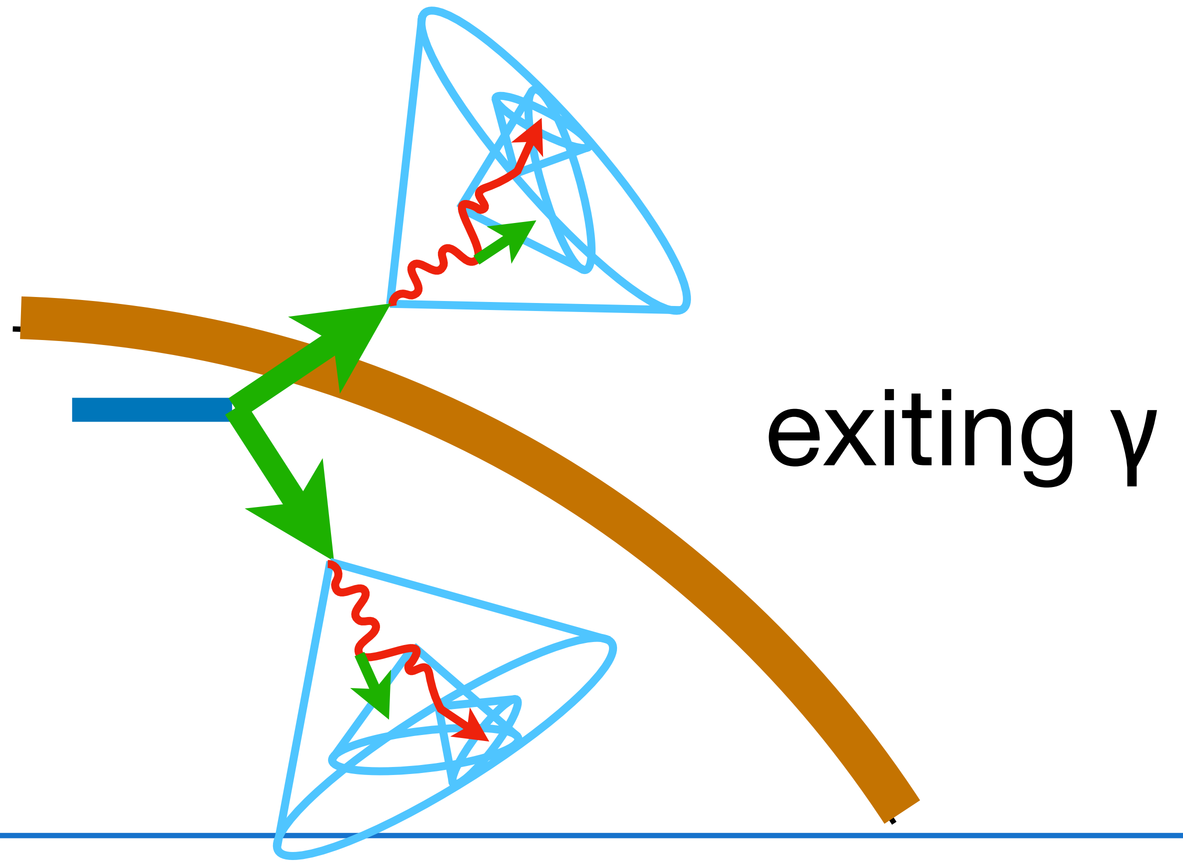



- Improved statistics allow for more distributions to be investigated
- Radial distribution shows that the excess is spread evenly within the volume of the detector
- An excess of $\pi^0$ background would have peaked near the edge (higher probability of missing one of the $\gamma$)
- Similar approach to SNO's CC/NC constraint
- Second best candidate : NC$\gamma$ background




Excess shape tests

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

Statistics only $\chi^2$

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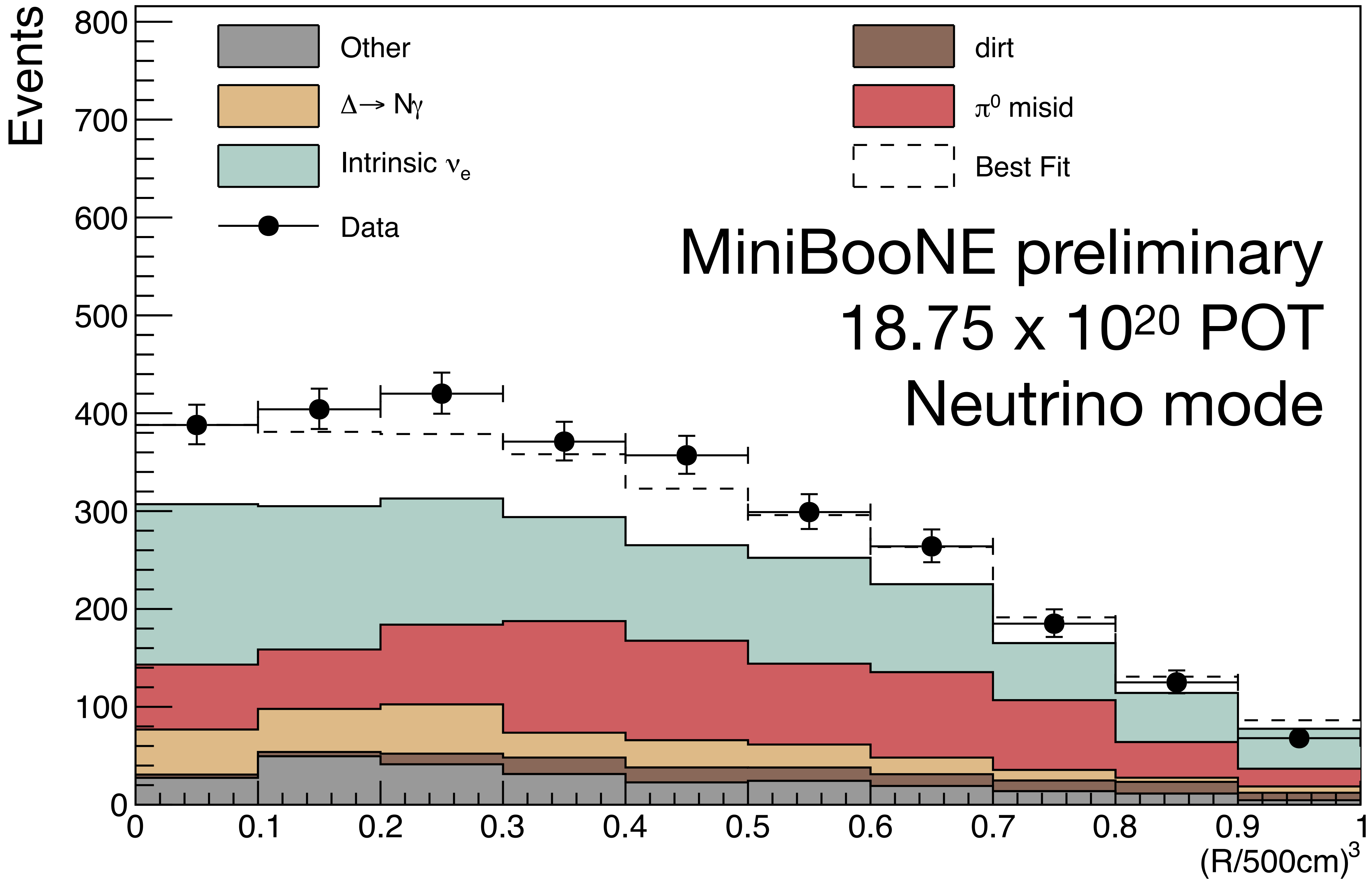


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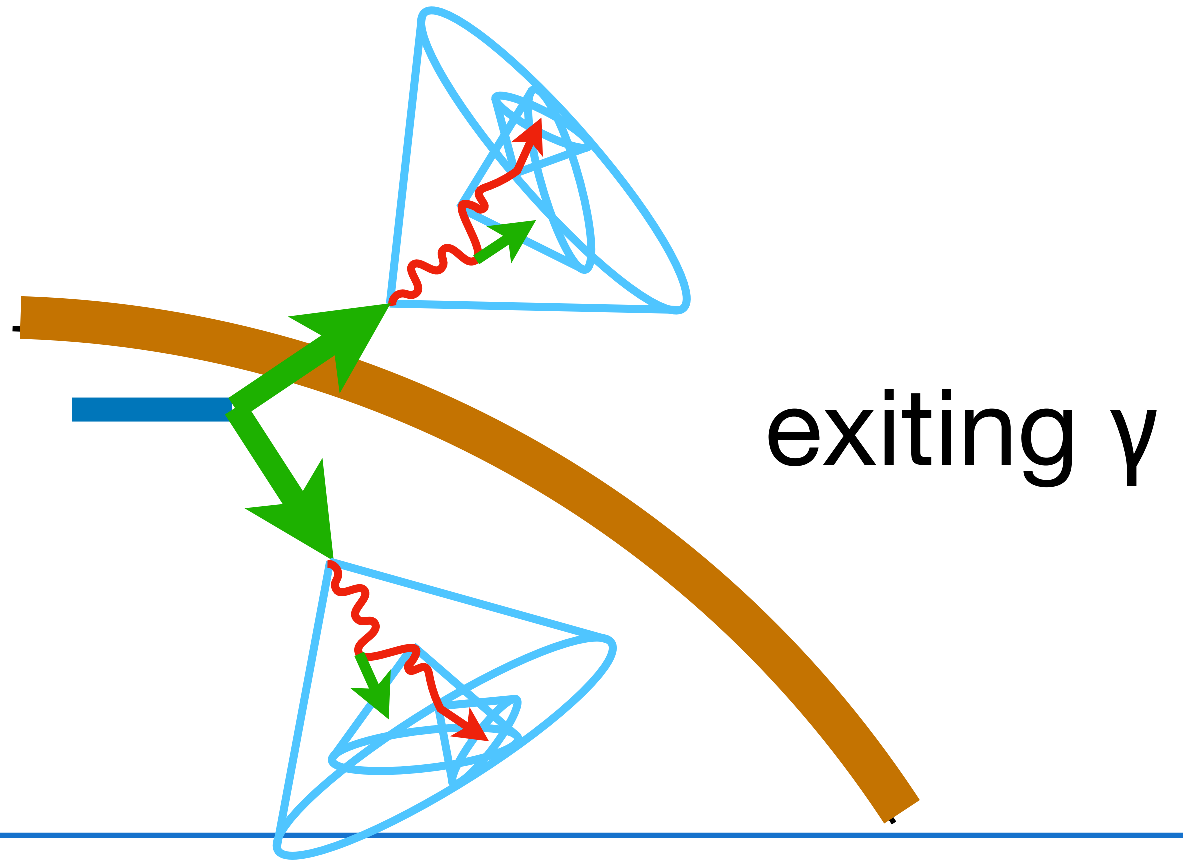


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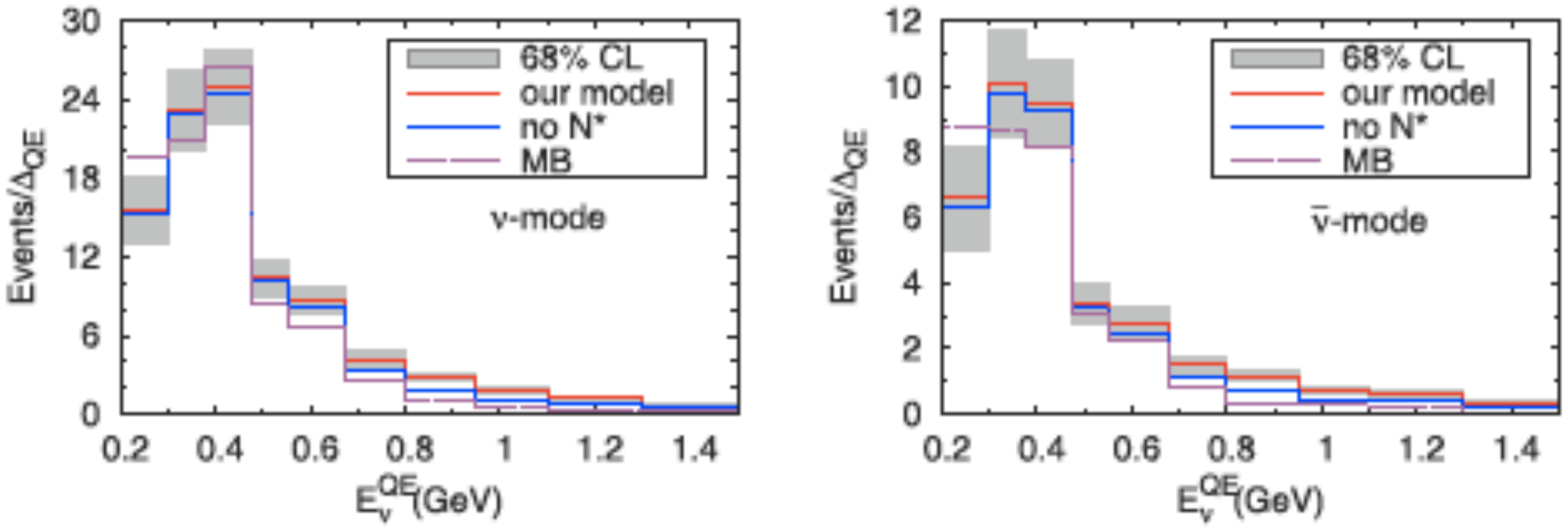
# $NC\ \Delta \rightarrow N\gamma$ resonance

- The production of $NC\ \Delta \rightarrow N\gamma$ is highly correlated to the measurement of $NC\ \pi^0$
- Same probability of a NC interaction, the difference in final state is the relative rate of resonant production.
  - ➡ Our predicted single $\gamma/\pi^0$ ratio is ~0.9%, which takes into account pion absorption in the nucleus, higher mass resonances, coherent scattering, and non-resonant processes
- Apply the same correction and fractional uncertainties to $NC\ \Delta \rightarrow N\gamma$ as $NC\ \pi^0$
- Additional uncertainty to account for final state interactions (FSI)
- The single gamma estimate agrees with theory



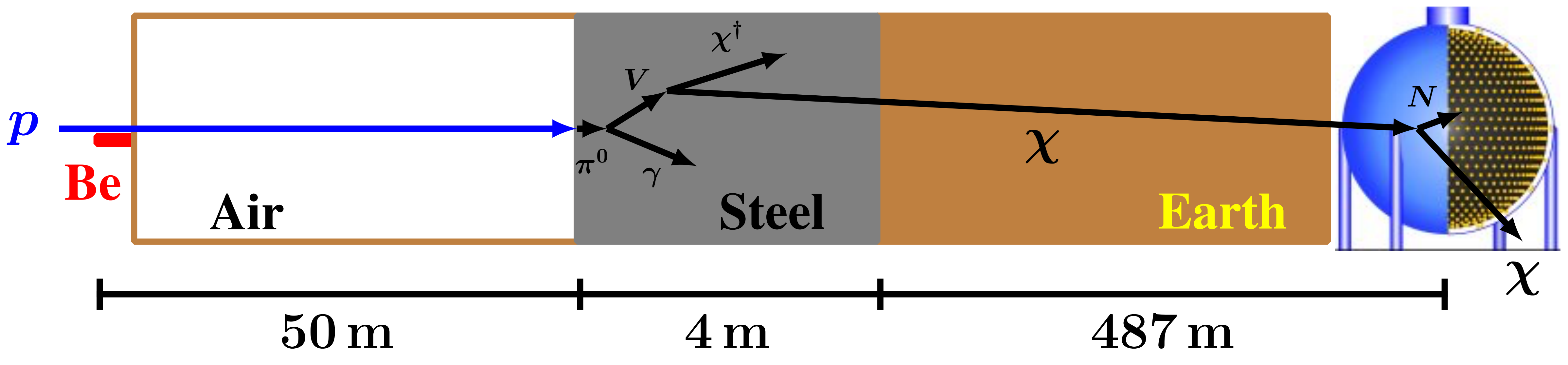

Single photon events from neutral current interactions at MiniBooNE

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

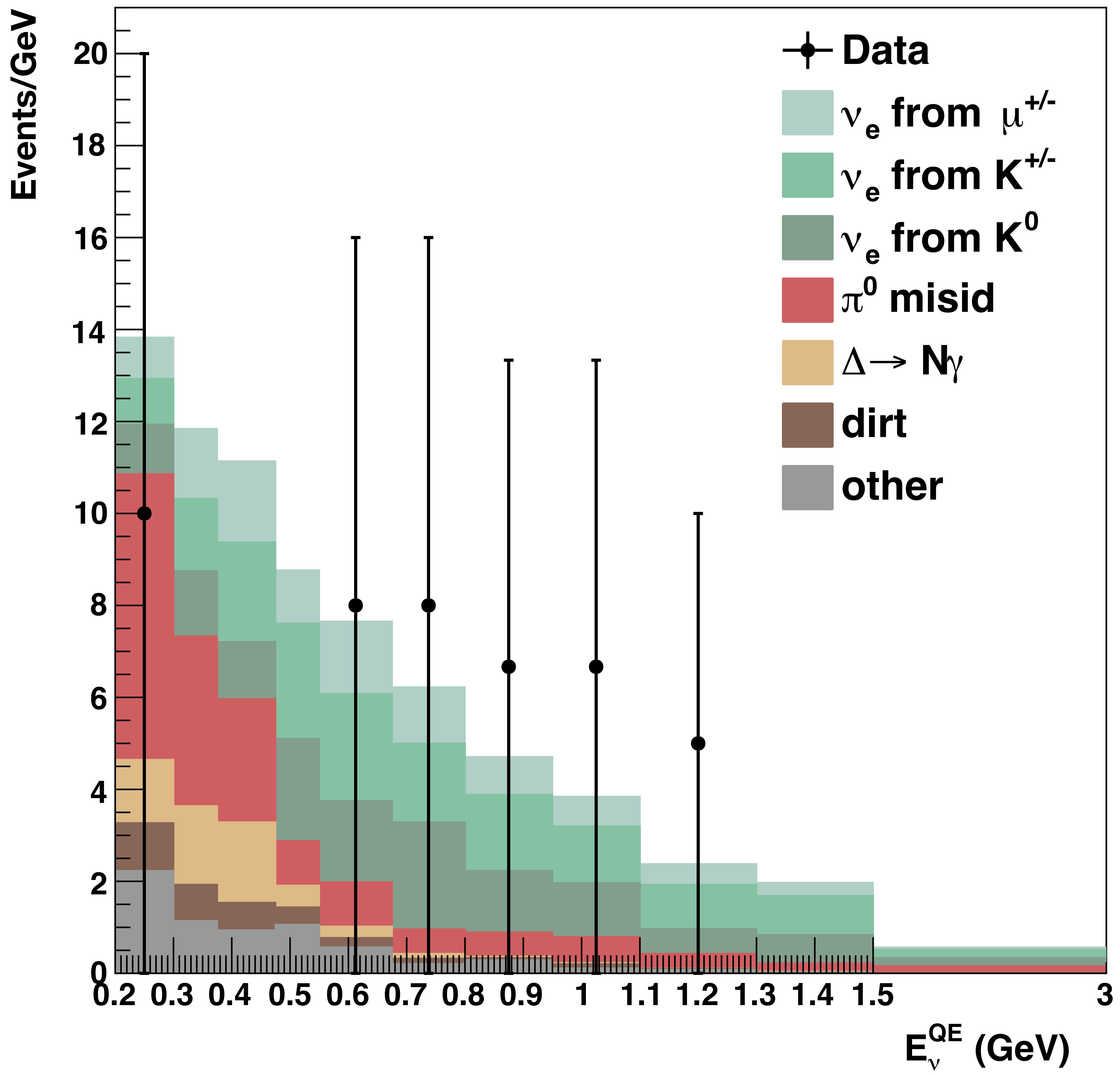
Phys. Lett. B 740 (2015) 16-22

# Constraints from the beam dump run




- Reduction in neutrino production by a factor of ~50
- No change to neutral meson production and proton bremsstrahlung to first order
  - ➡ Can directly test models that predict the oscillation excess does not scale as neutrino scales (e.g. vector portal, inelastic dark matter, …)

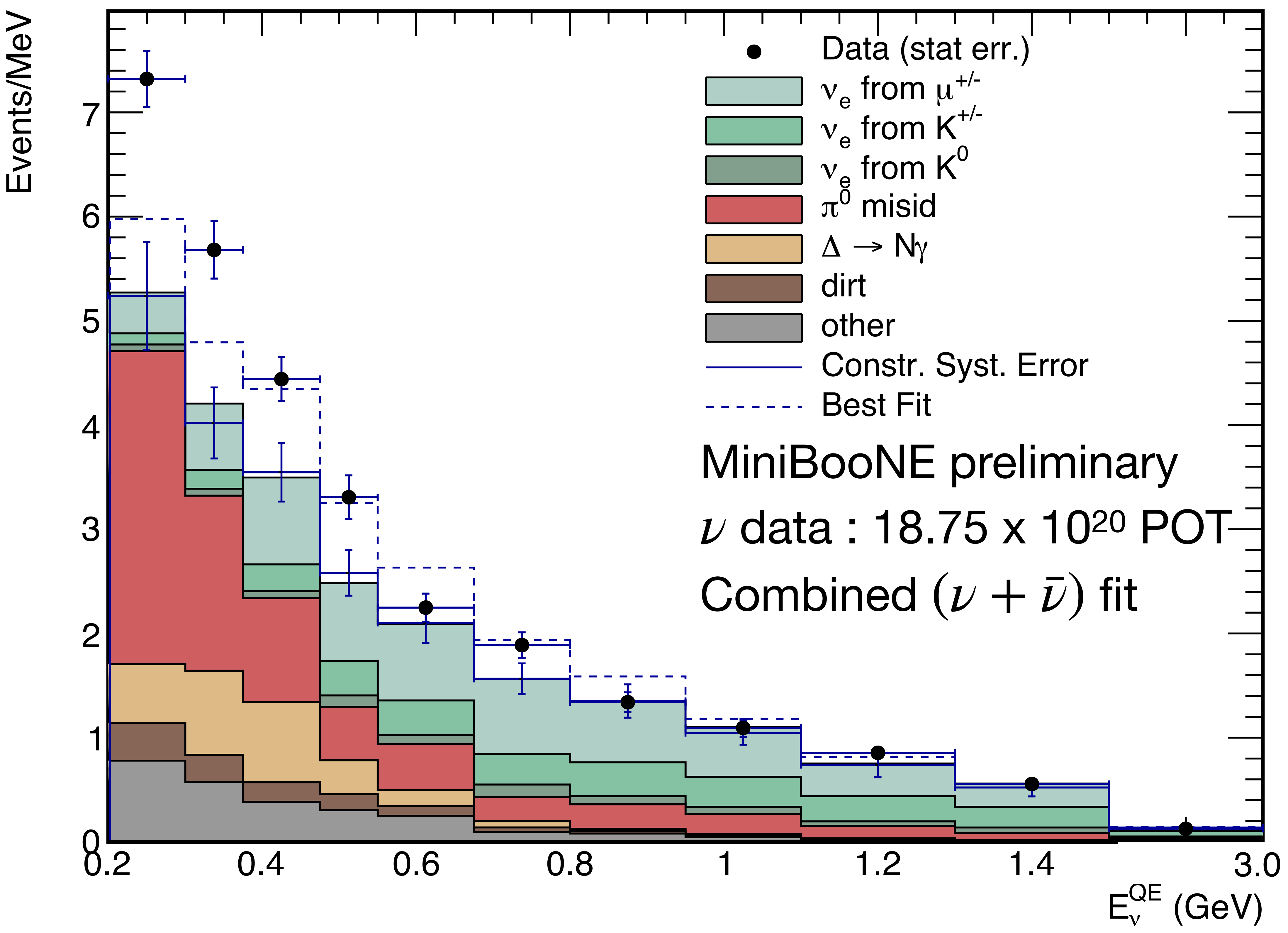
- **Expected :** 35.5±7.4 excess events in [200,1250] MeV for a POT-scaling excess
- **Measured :** 6 events, 8.8 backgrounds expected
  - ➡ -2.8 excess events
  - ➡ Explanation that scale only by POT instead of neutrino production are **disfavoured out at 4.6σ**

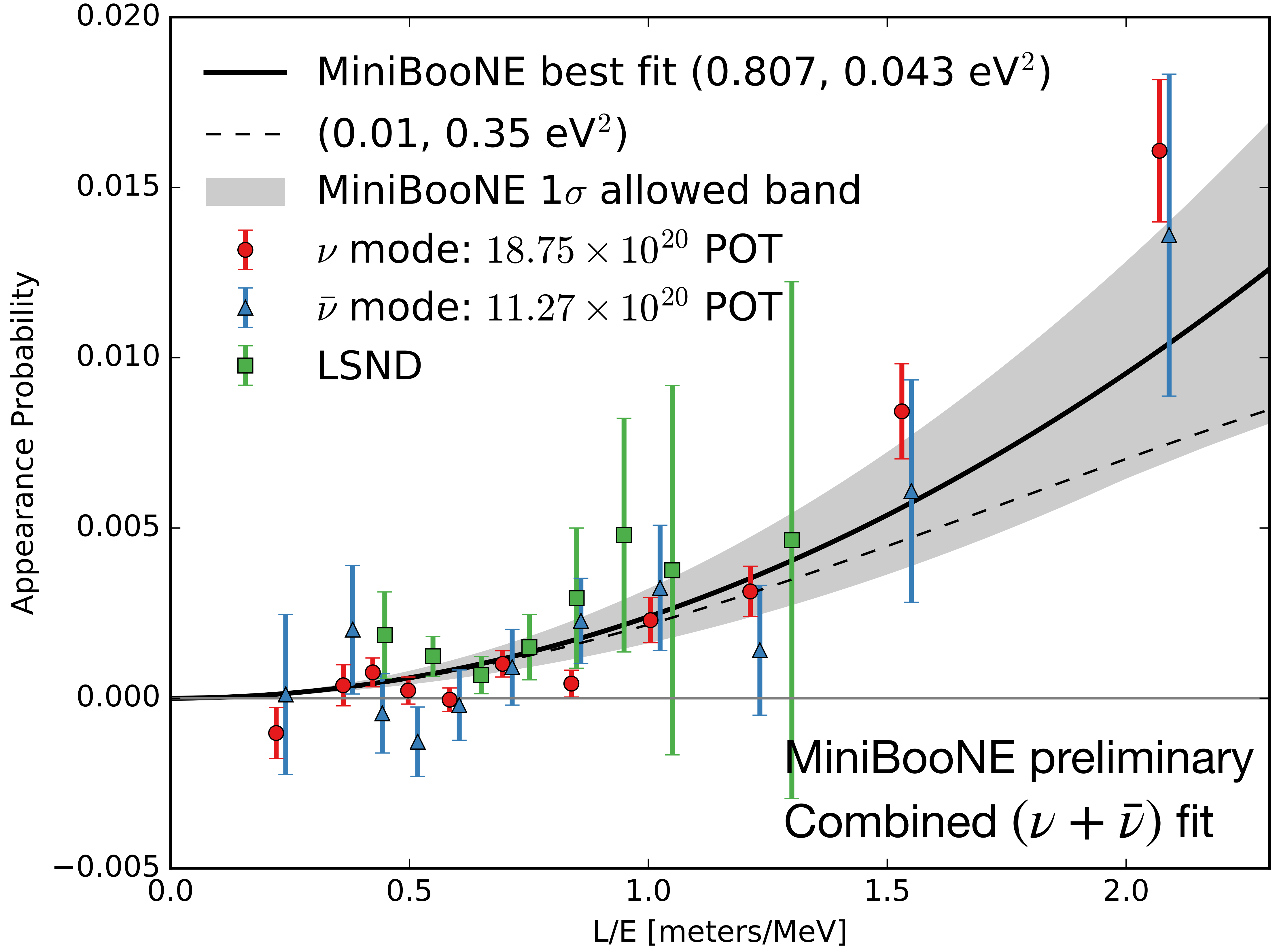



Phys. Rev. D 98, 112004

See Jordan et al. Phys. Rev. Lett. 122,081801 (2019) for constraints on different models

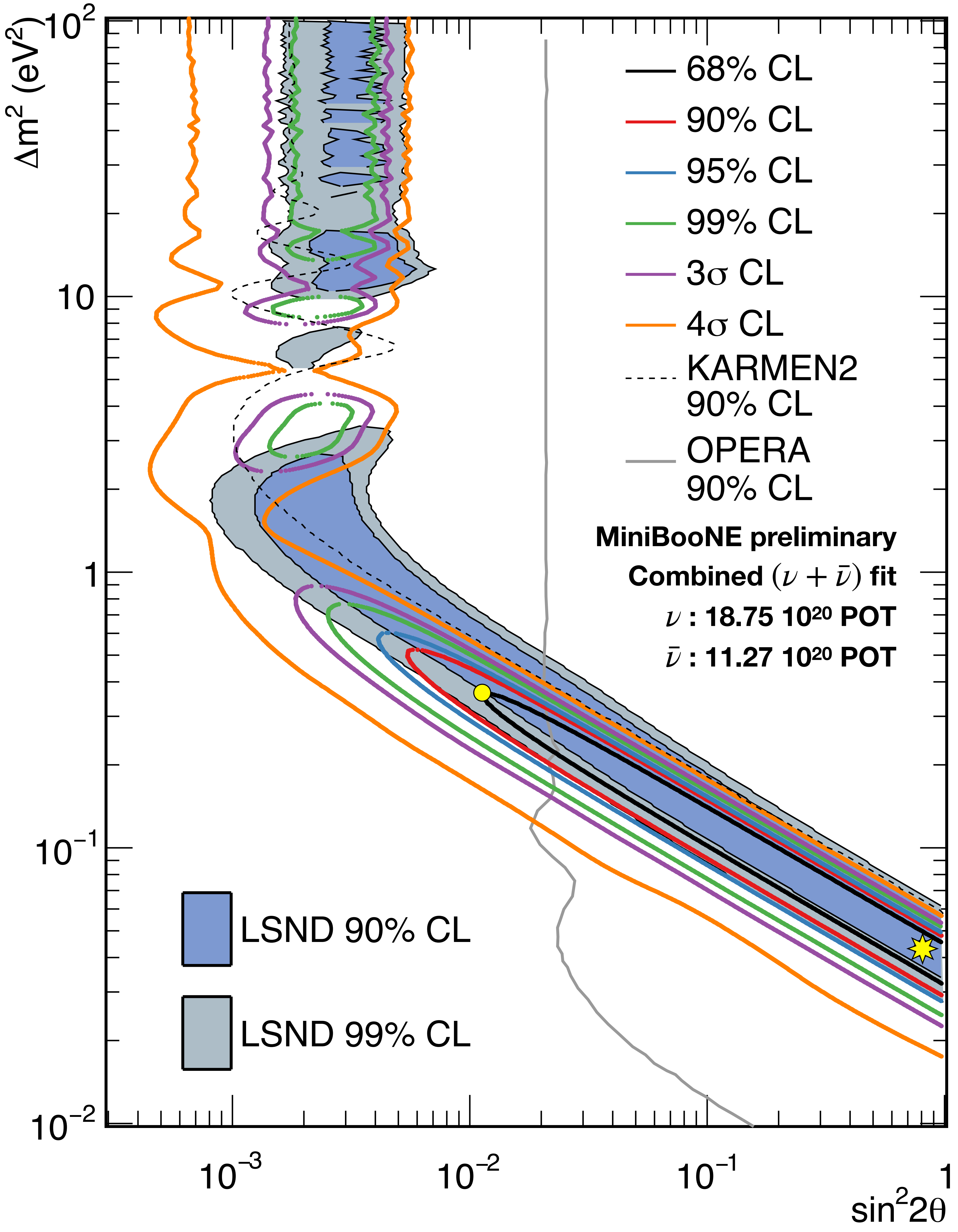
# Excess interpretation in a sterile neutrino hypothesis



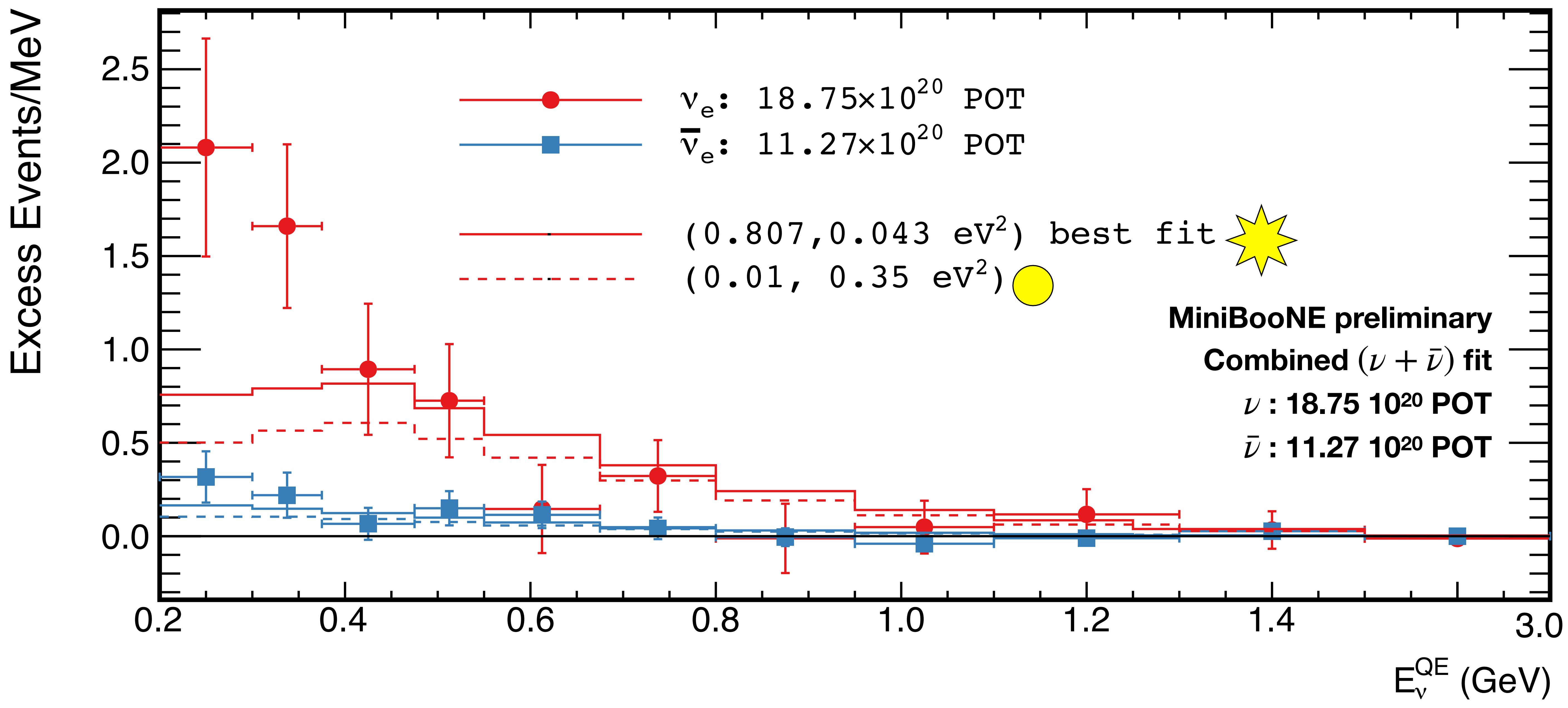




- Combined $(\nu + \bar{\nu})$ fit
- LSND and MiniBooNE points follow the same best fit 2v oscillation interpretation

# Preferred regions in sterile neutrino hypothesis



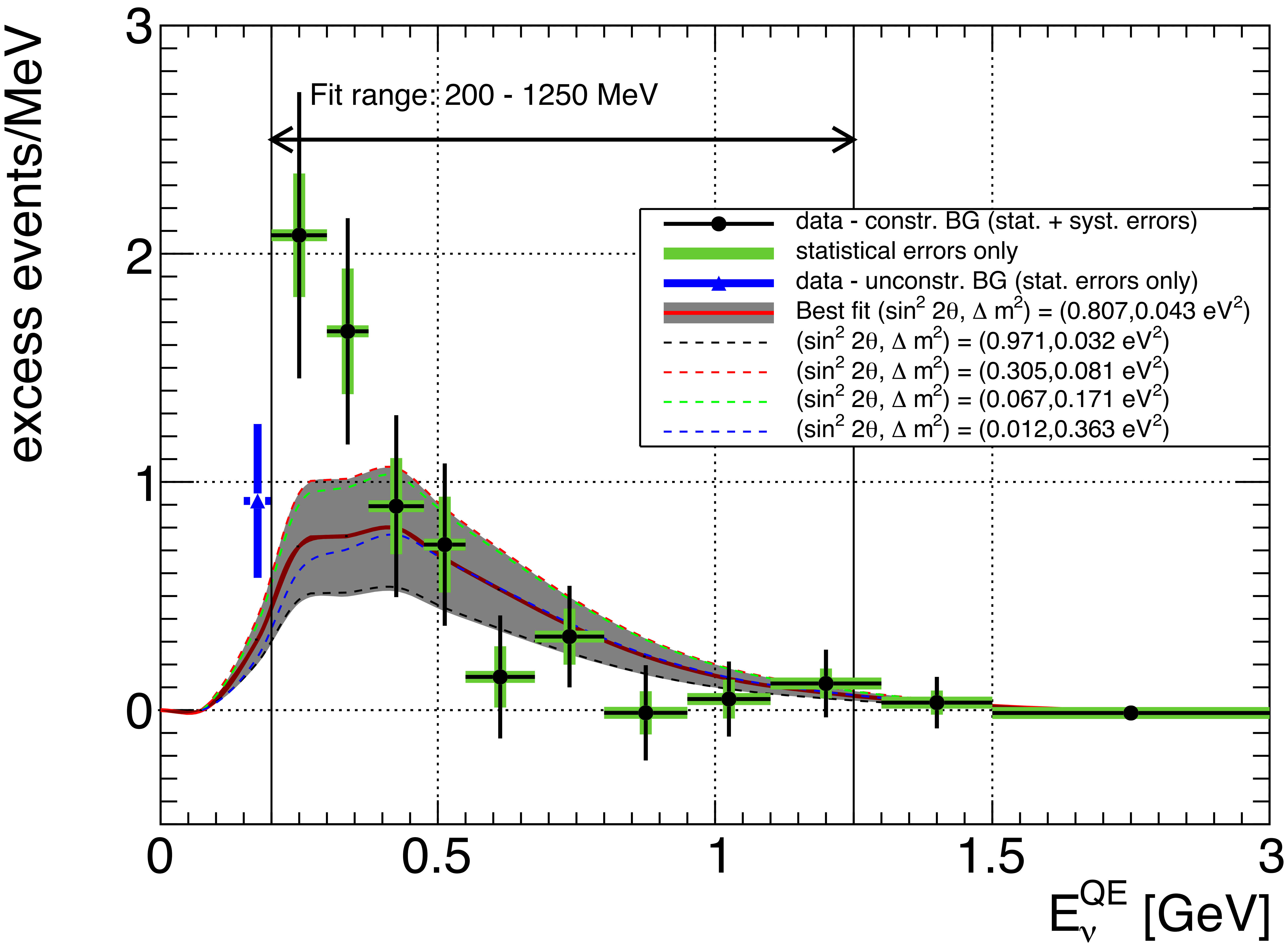

- Neutrino mode excess 4.7σ,
- **Neutrino+Anti-neutrino modes excess : 4.8σ**




## Neutrino + Anti-Neutrino Mode

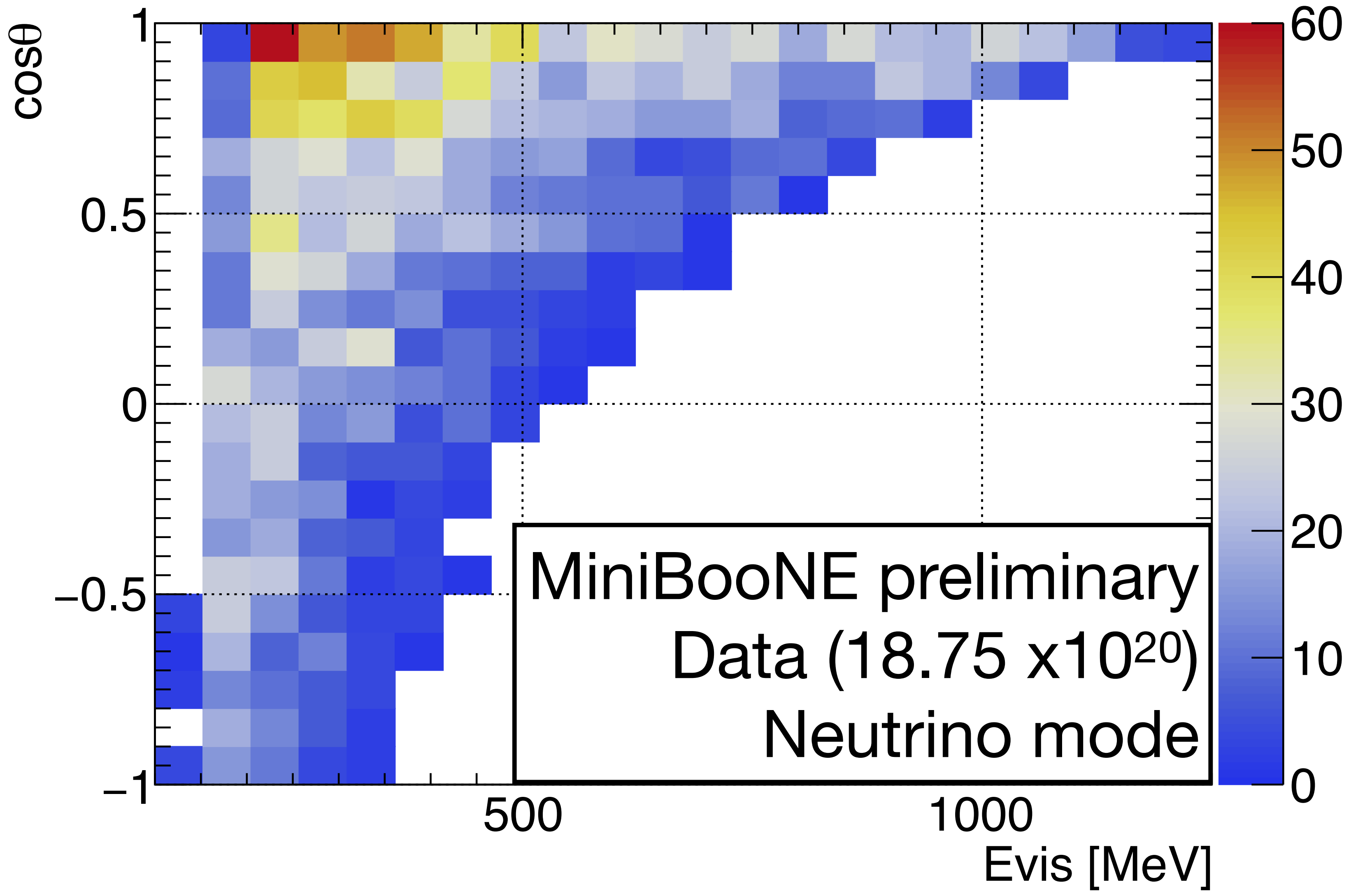
$$(\Delta m^2, \sin^2 2\theta) = (0.043\ \text{eV}^2, 0.807)$$
$$\chi^2/ndf = 21.7/15.5\ (\text{prob} = 12.3\%)$$

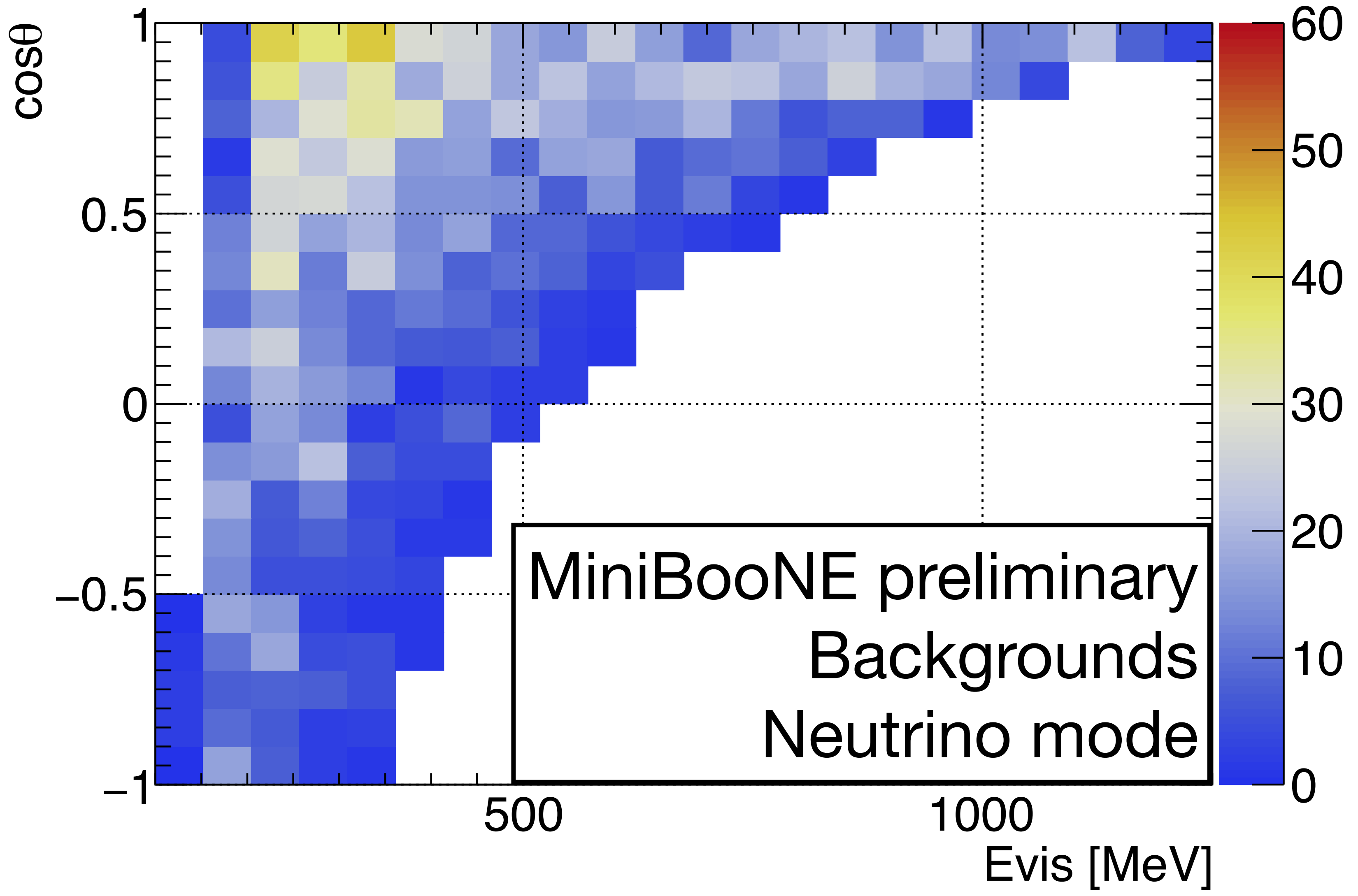
# Full $\nu_e$ statistics excess plot

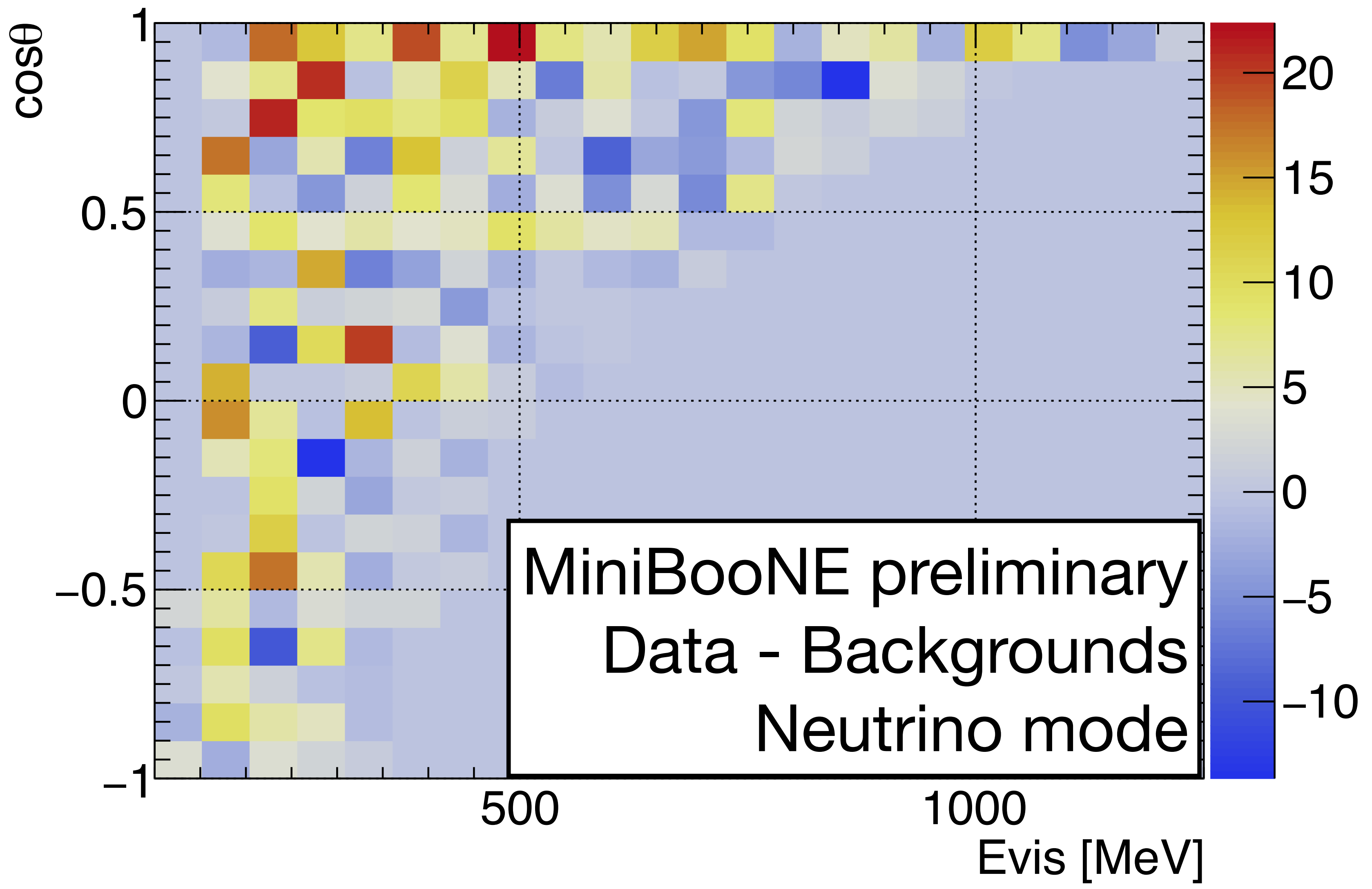



- The grey area corresponds to the allowed 1σ region of the oscillation fit
- The excess is well explained at high E (> 300 MeV) by a simple oscillation model
- Need an additional explanation for the first two bins
- Value in the 150-200 MeV bin is with statistical error only, and unconstrained backgrounds

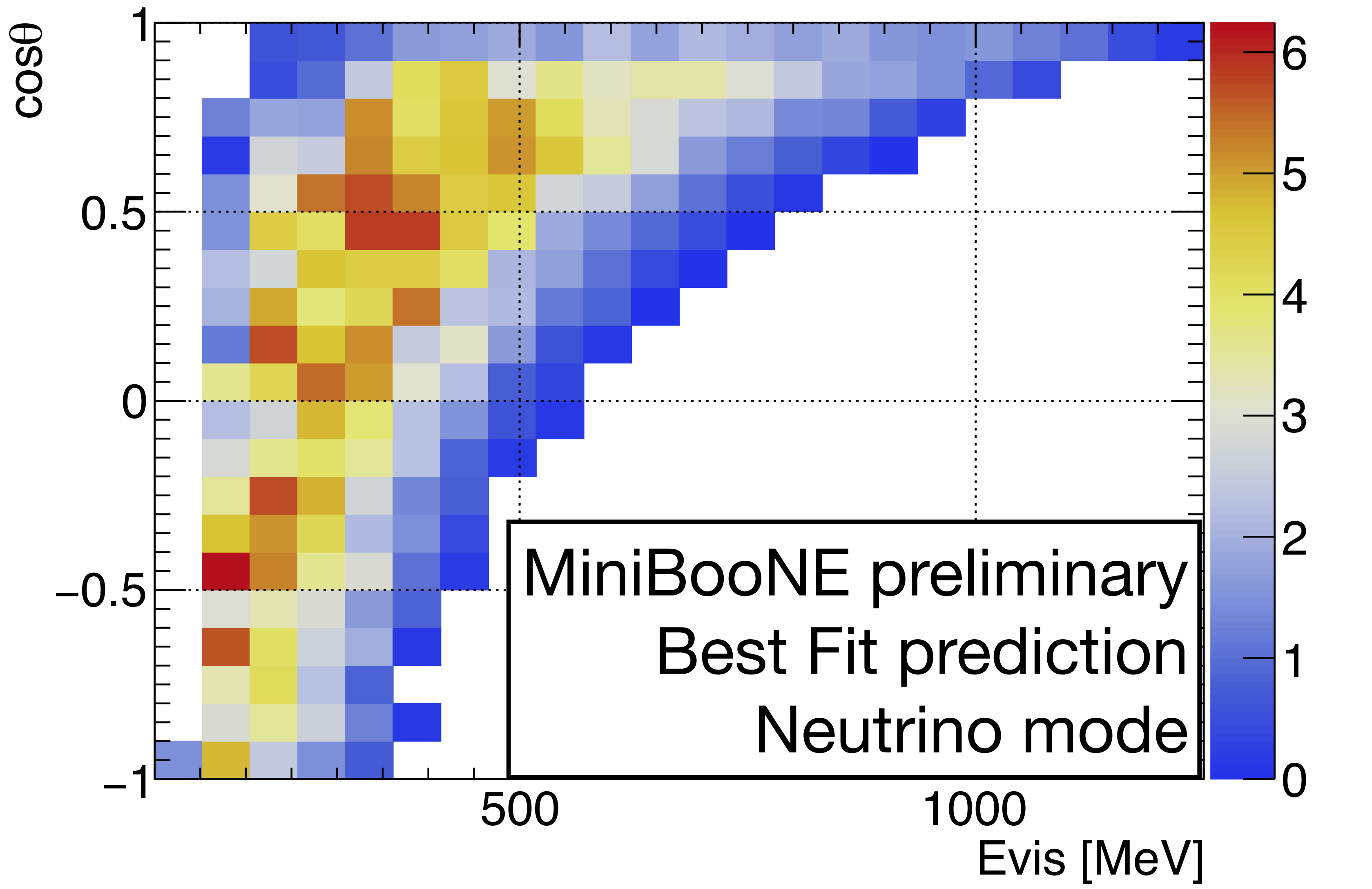
# cos(θ) VS $E_{vis}$ Distributions for $\nu_e$ samples



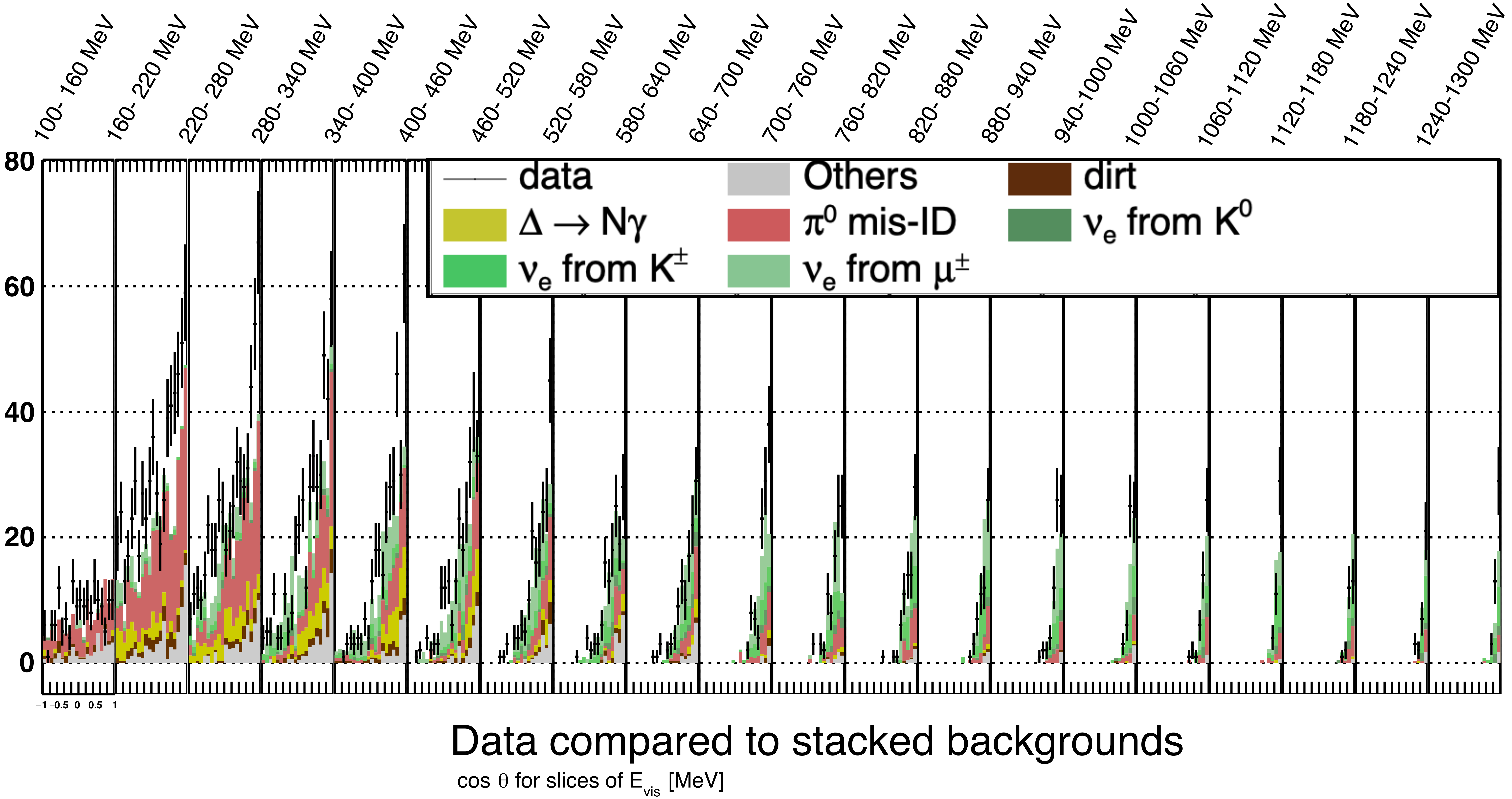




- Compare data to backgrounds in the ($E_{vis}$,cosθ) space
- We believe that these distributions will guide theorists to explain our data
- These data will soon be provided in a data release with systematic errors



# cos(θ) VS $E_{vis}$ Distributions for $\nu_e$ samples




Data compared to stacked backgrounds

- The excess at low energy occurs across a wide range of cos θ

# Summary

- MiniBooNE presented a full analysis of **17 years of data taking**
- The **event excess has remained stable** in shape and magnitude over the different data releases
- We now have a 4.7σ significance in neutrino mode only, and a **4.8 σ significance** in a combined $(\nu + \bar{\nu})$ analysis for our **nominal cut of R<500 cm.**
- Several explanations for the excess are disfavored
  - NC $\pi^0$
  - Dirt event
  - Dark matter run ruled out non-neutrino-related beam backgrounds
- In the spirit of responding to requests for more information, we are now in a position to provide additional information on timing, visible energy VS angle of lepton scatter, and radius.
- Further studies under way to better understand the excess, including investigating Meson Exchange Currents, stay tuned!

**preprint available at arxiv:2006.16883**

# Thank you!