MiniBooNE Oscillation Results with Complete Dataset

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on behalf of the MiniBooNE Collaboration
2020/07/02

Massachusetts Institute of Technology

preprint available at arxiv:2006.16883

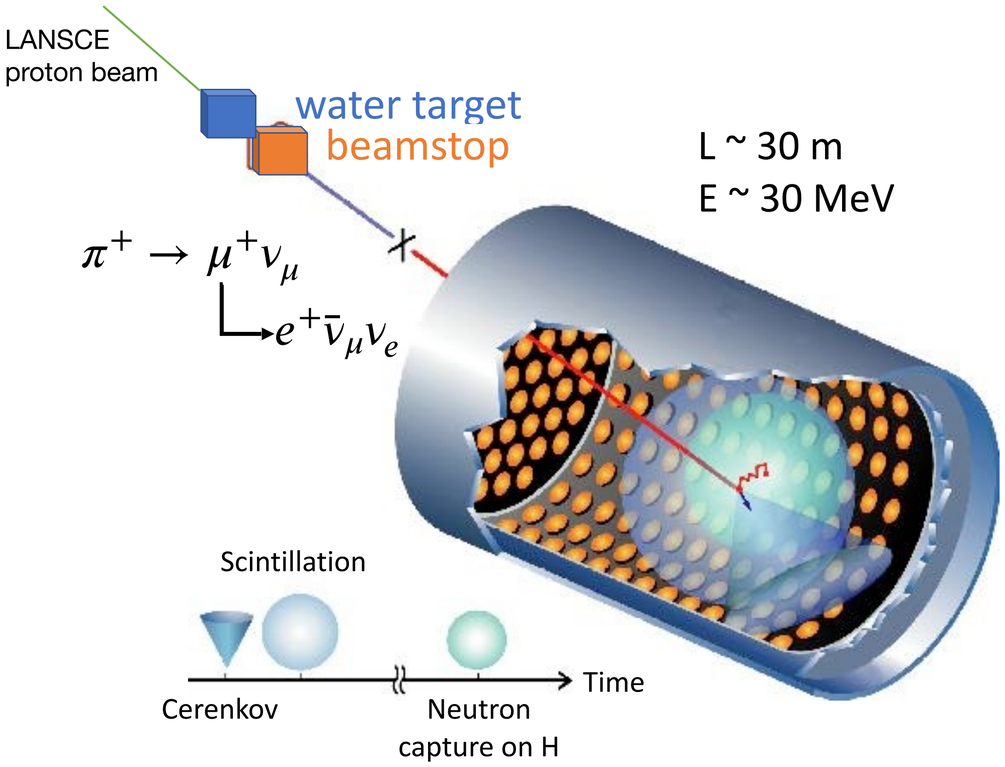
NEUTRINO 2020

Comparing MiniBooNE and LSND

LSND (1993-1998)

0.8 GeV proton beam

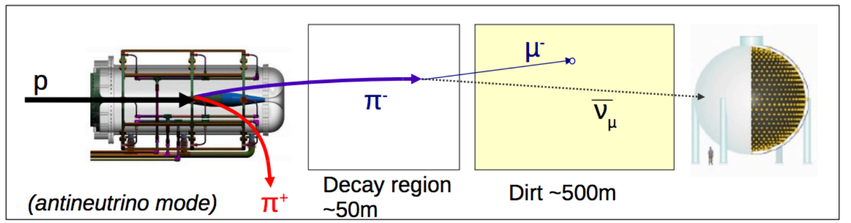
Decay At Rest neutrino flux

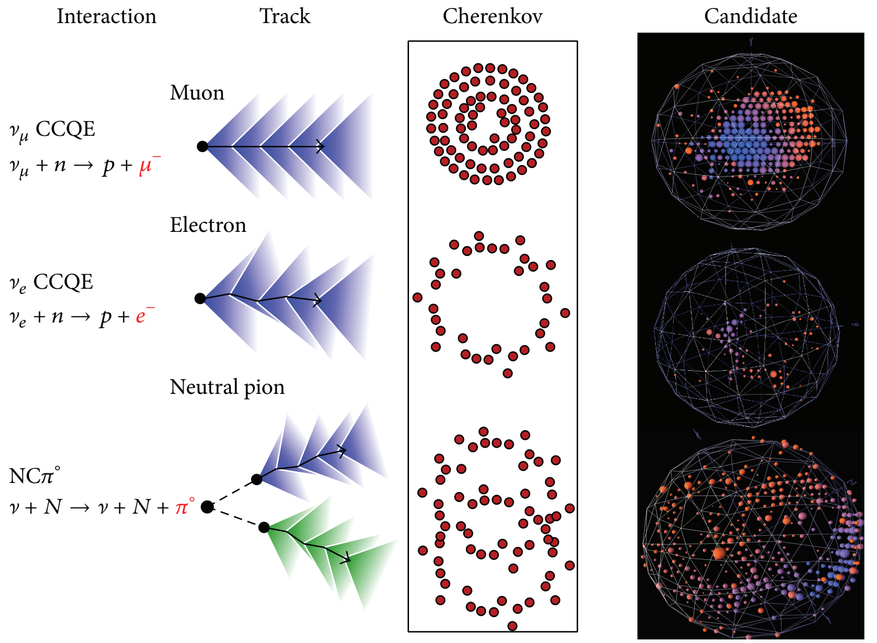


MiniBooNE (2002-2019)

8 GeV proton beam

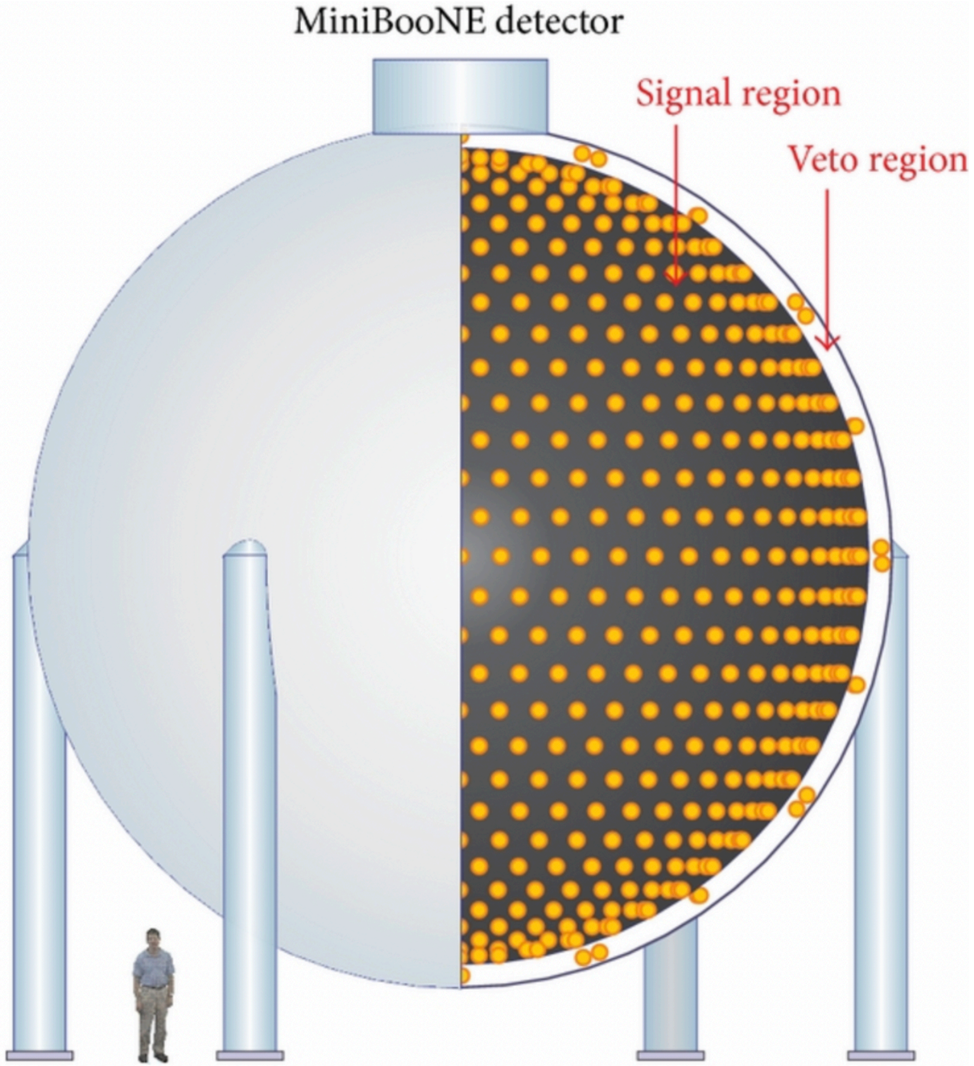
Decay In Flight beam



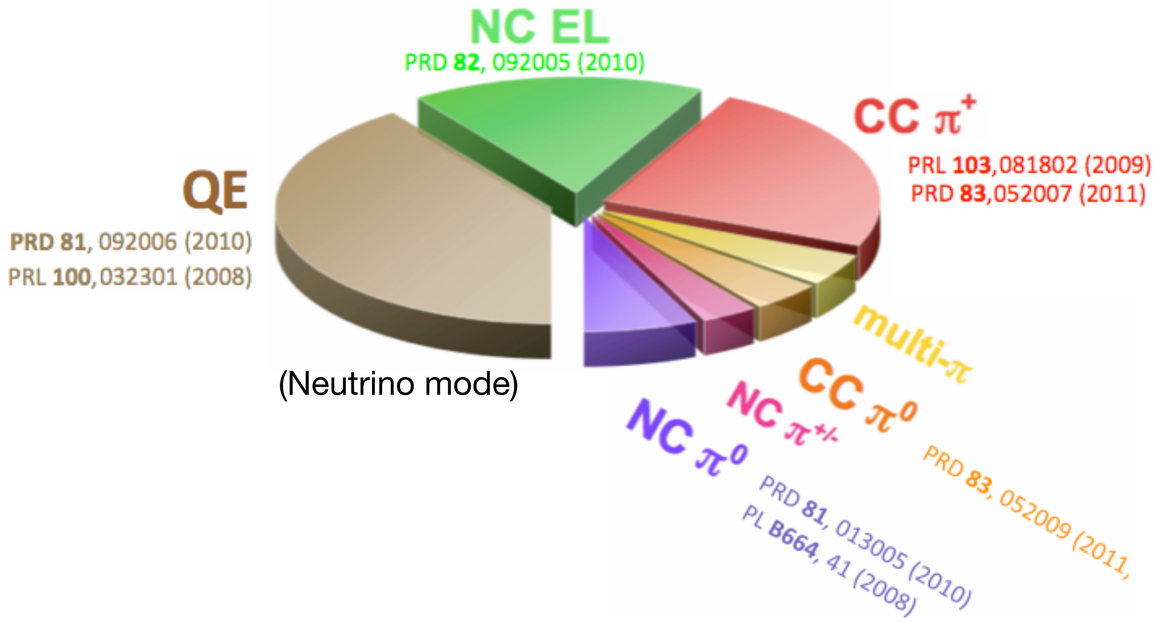


Different systematics. Same L/E baseline.

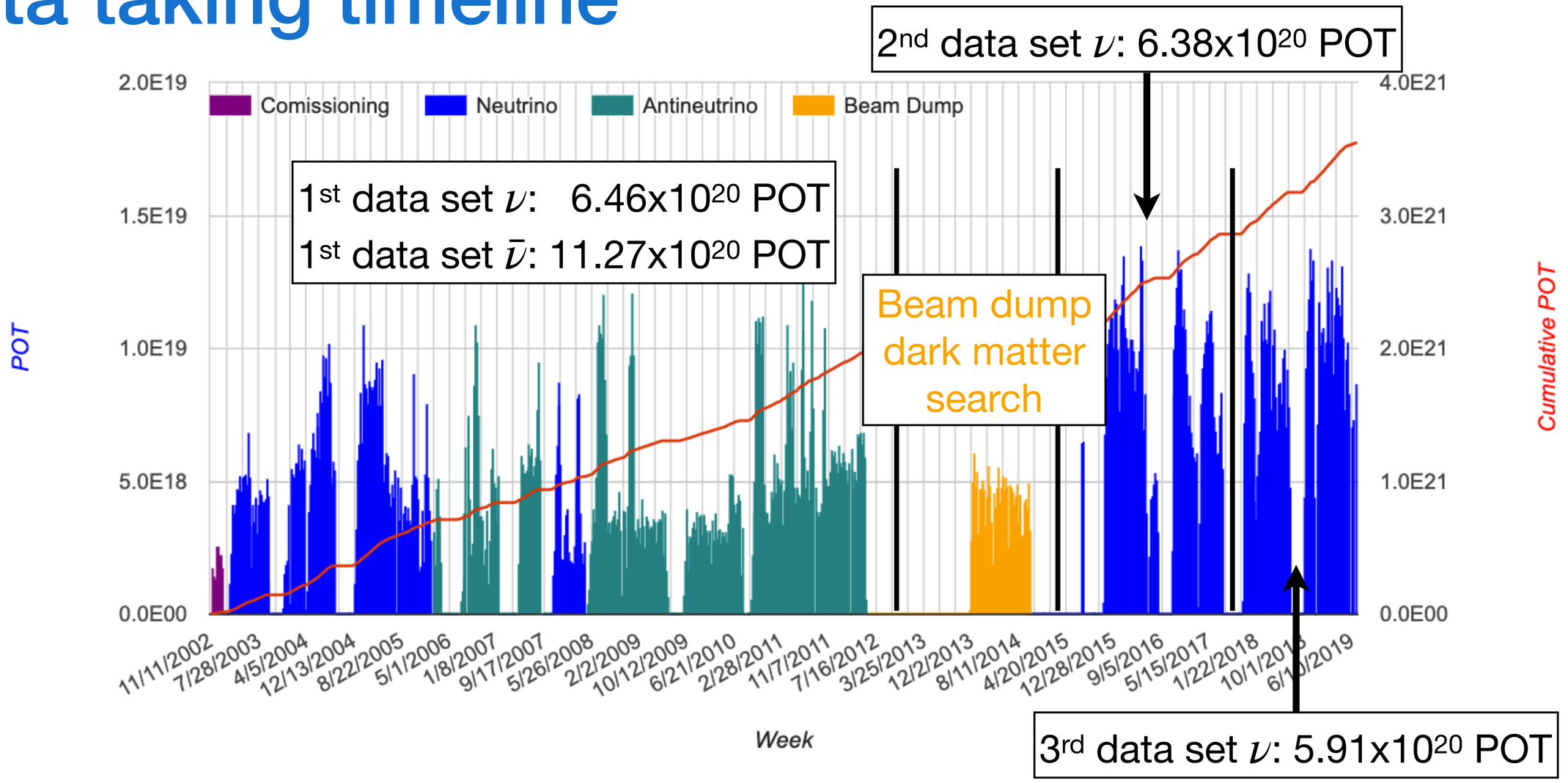
The MiniBooNE Detector



- ⌀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



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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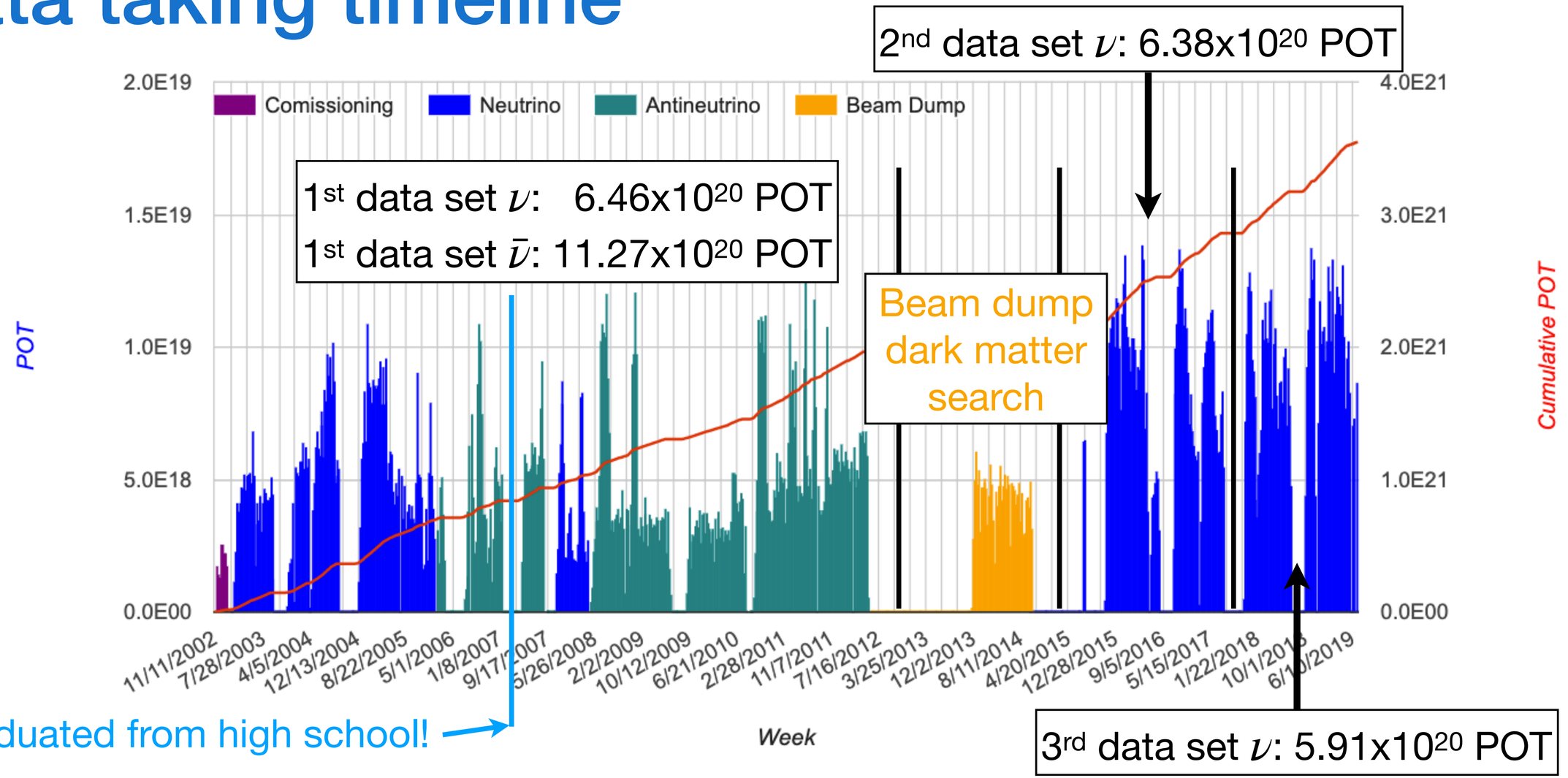

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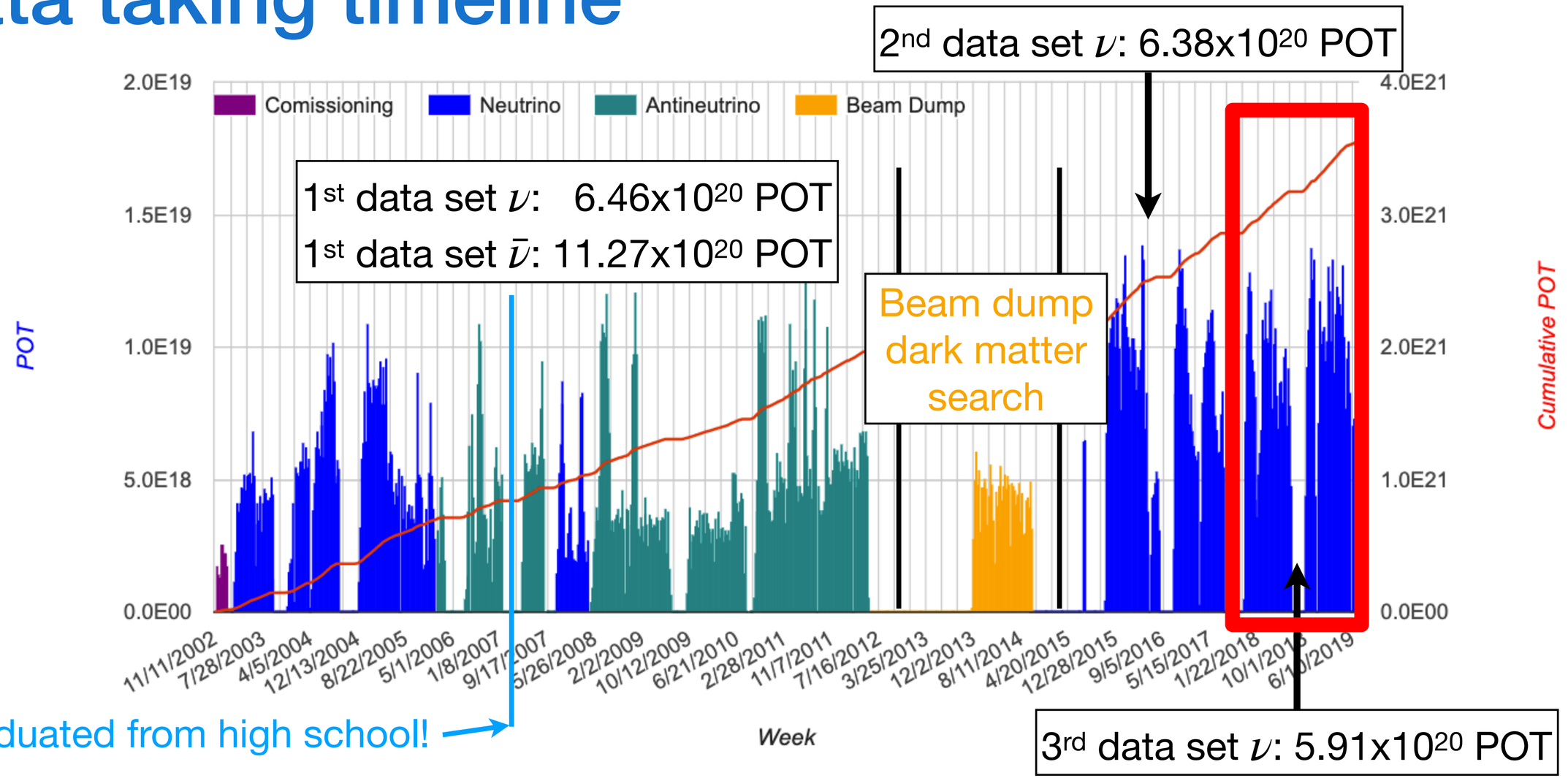

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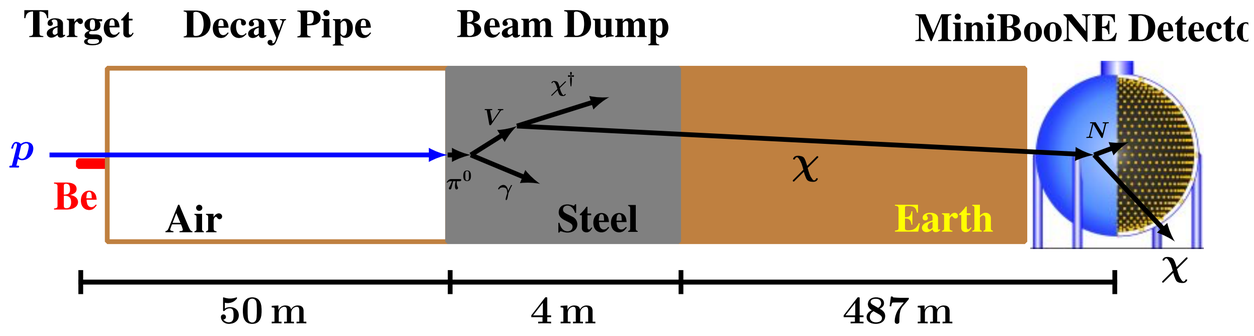
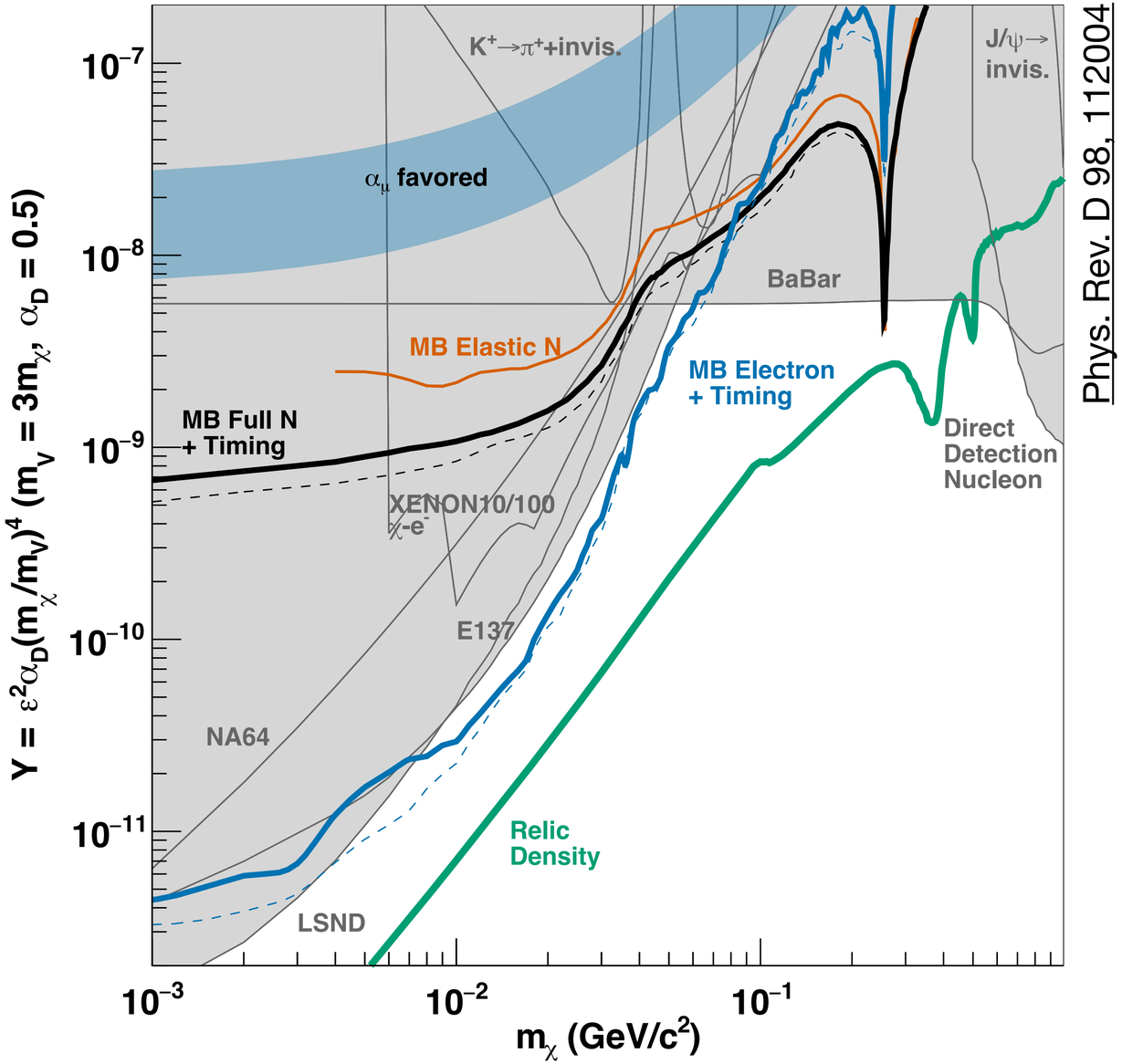
Dark matter run

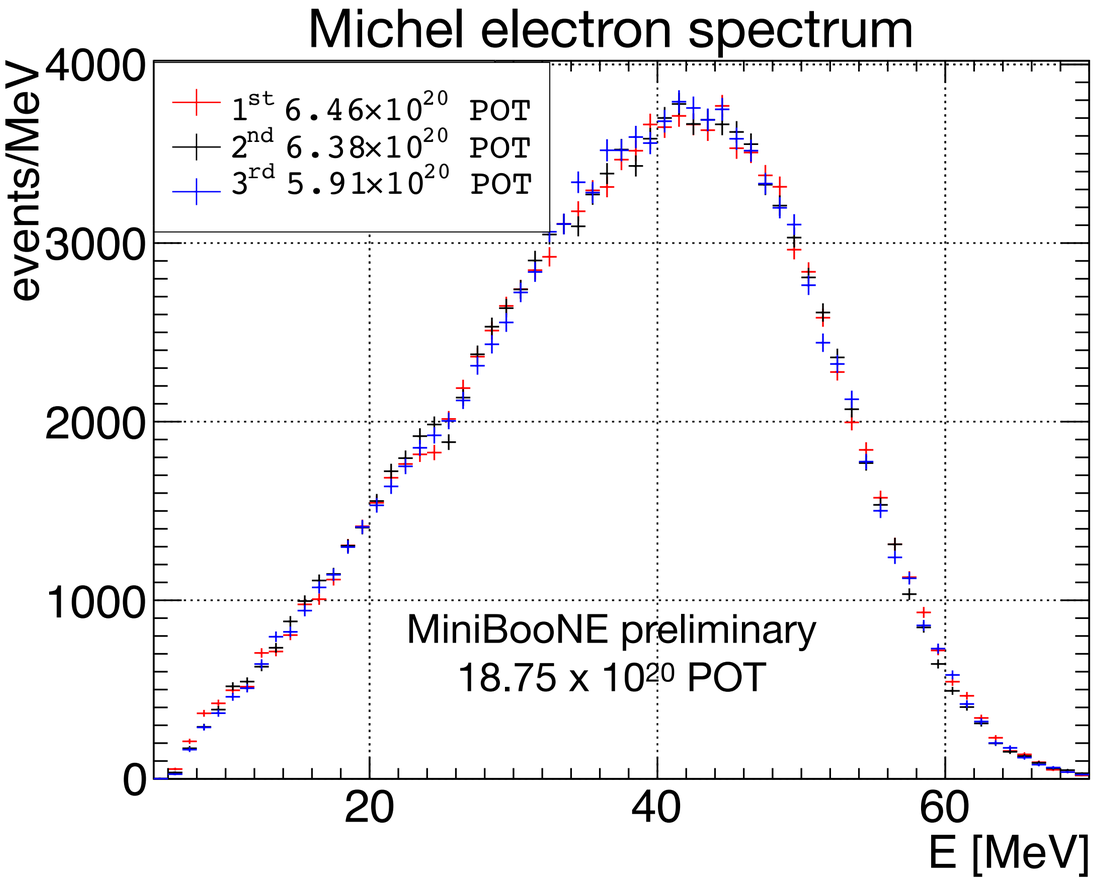
- First dedicated search for direct detection of accelerator-produced dark matter in a proton beamline
- Beam aimed off of the target
- ν flux reduced by ~50
- Demonstrated the power of neutrino detectors in searching for accelerator-produced dark matter

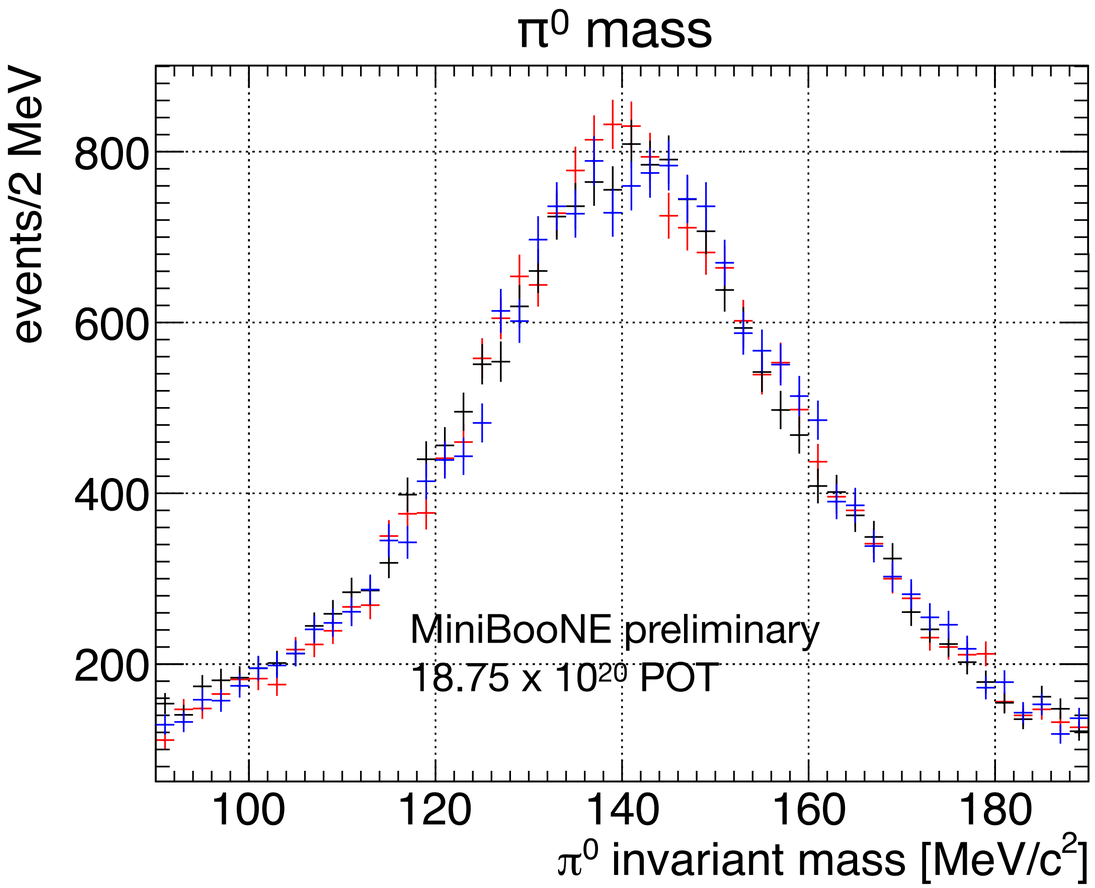




Phys. Rev. D 98, 112004

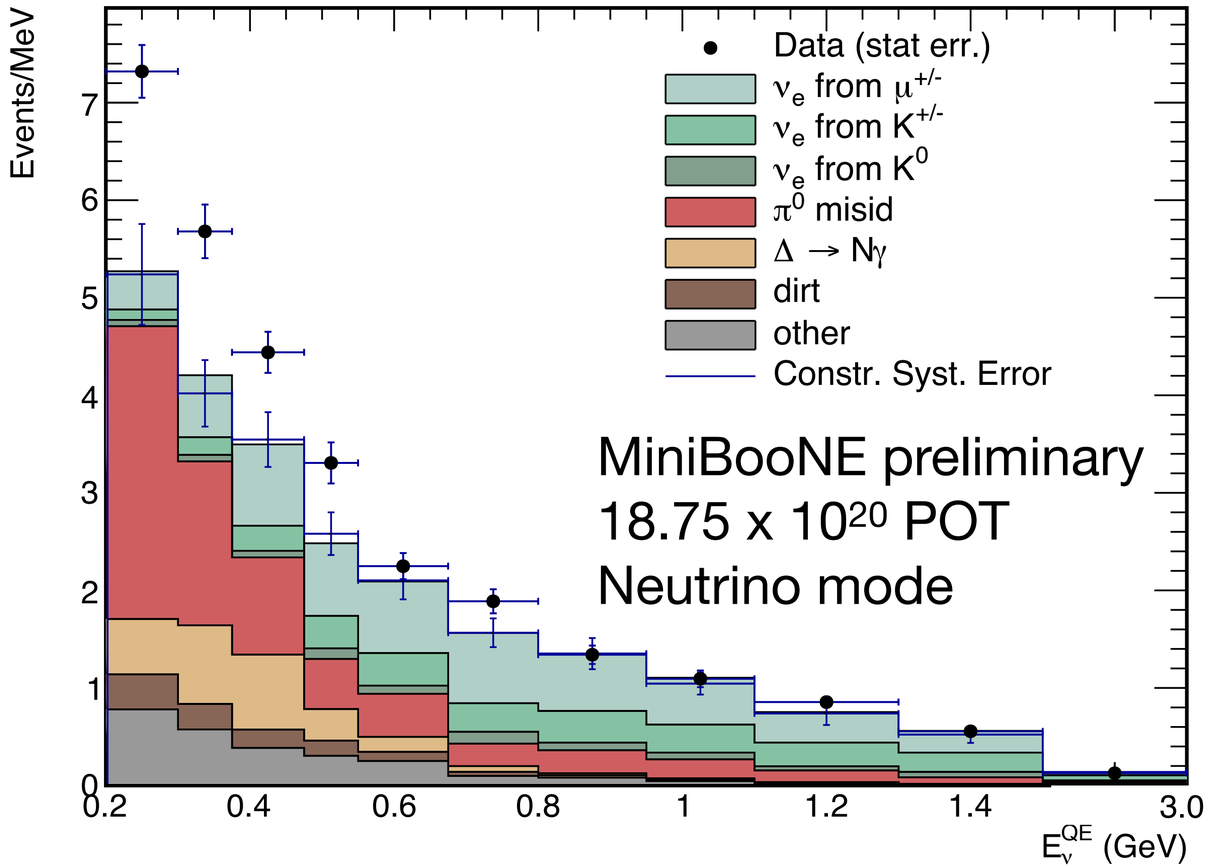
Excellent long term detector stability over 3 run periods





- 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

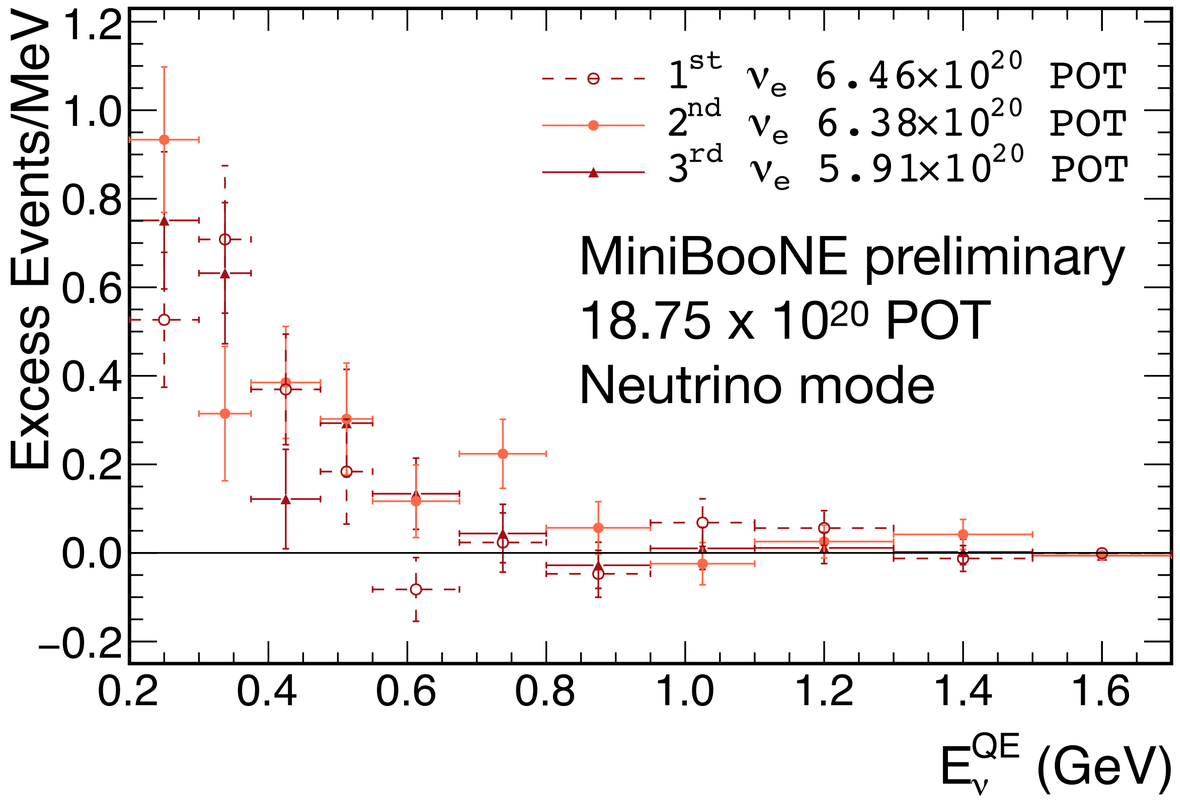
Neutrino energy and 3ν prediction



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

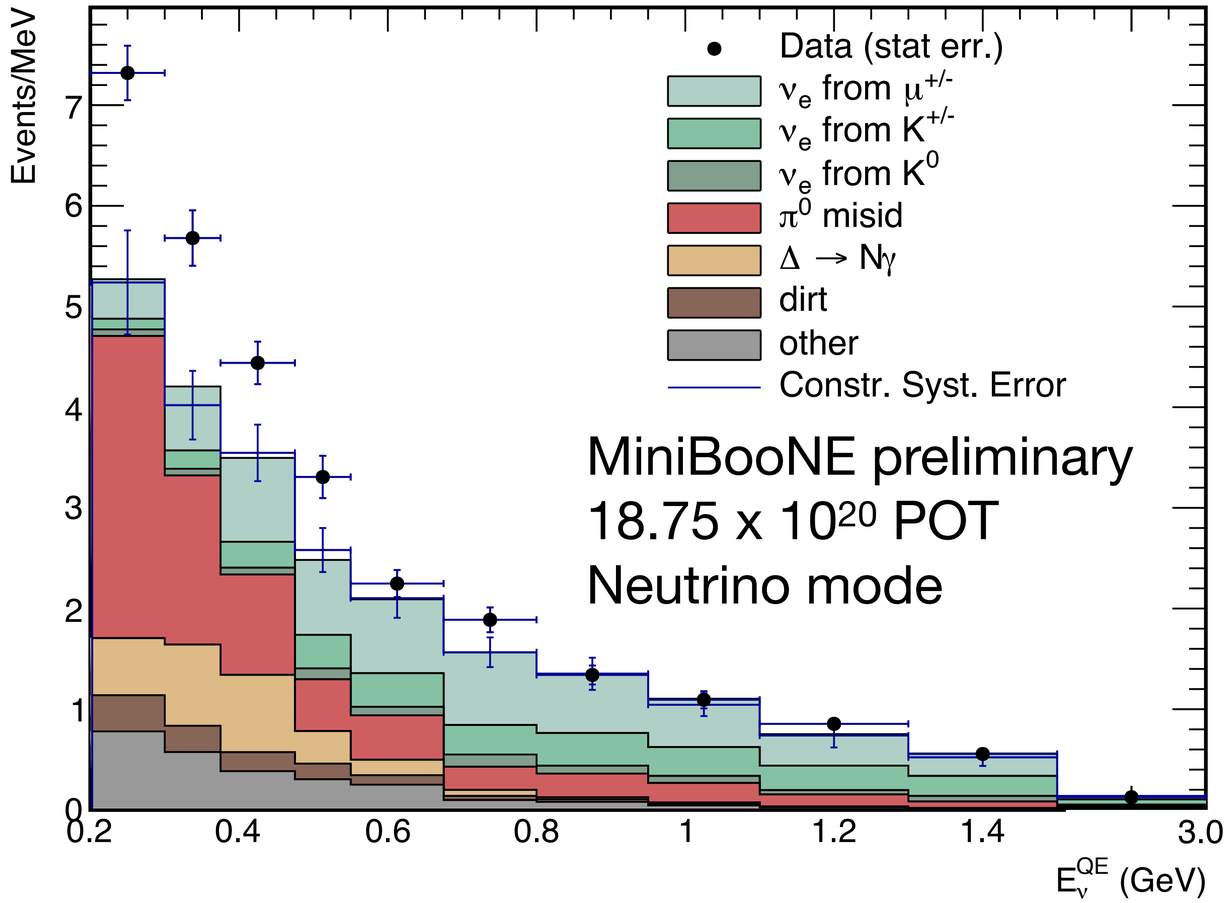
- **Significance : 4.7 σ in neutrino mode only**

ν_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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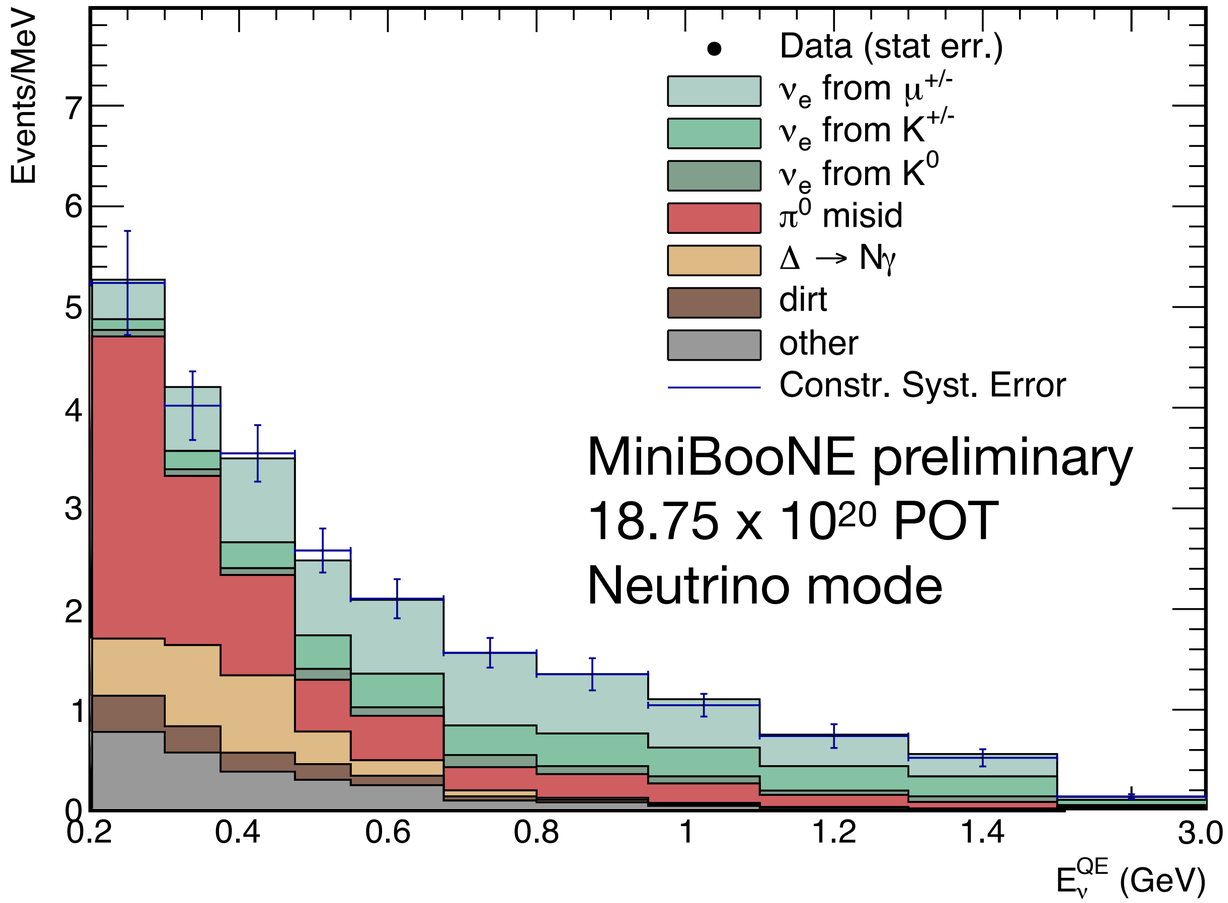
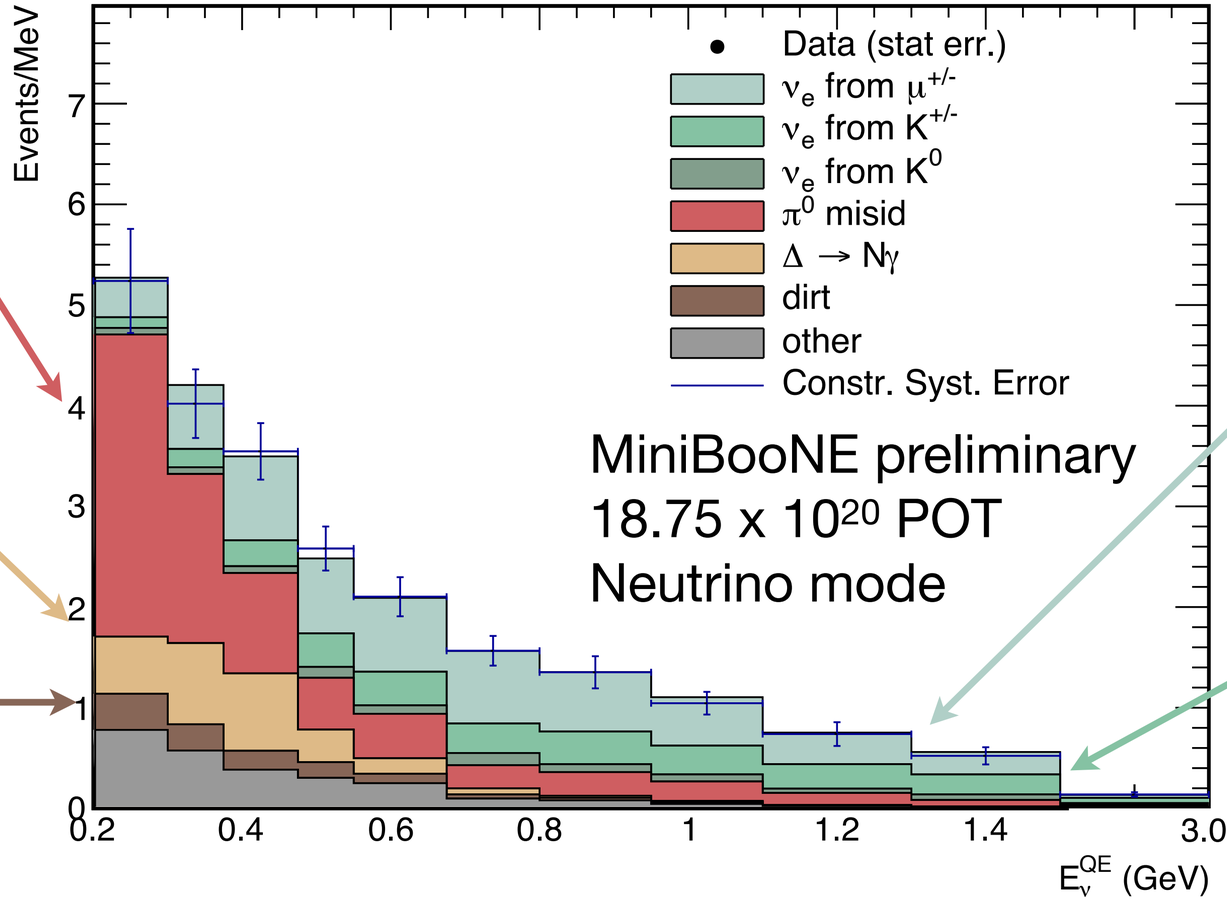


Constraining the backgrounds

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

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

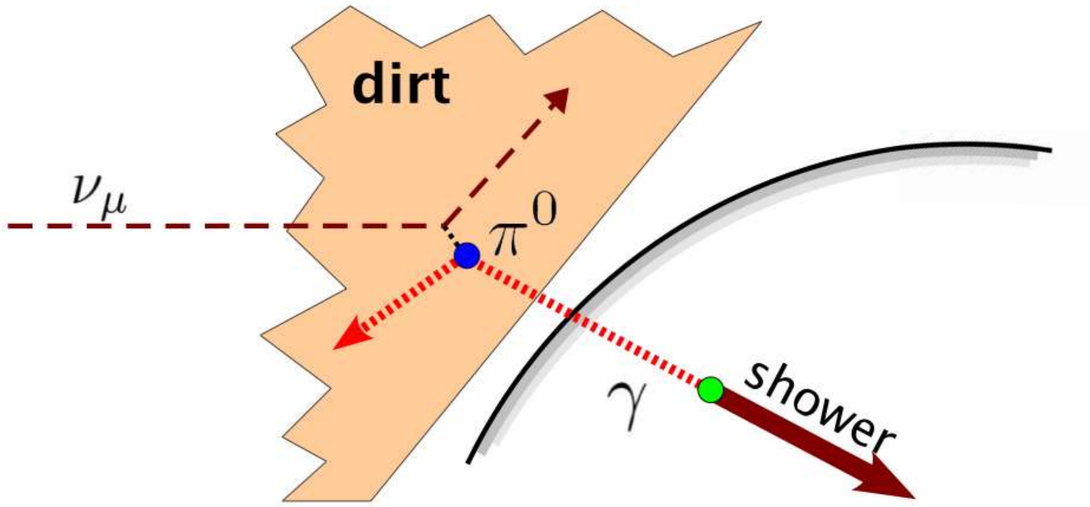
Dirt
constrained from *in situ* dirt data sample



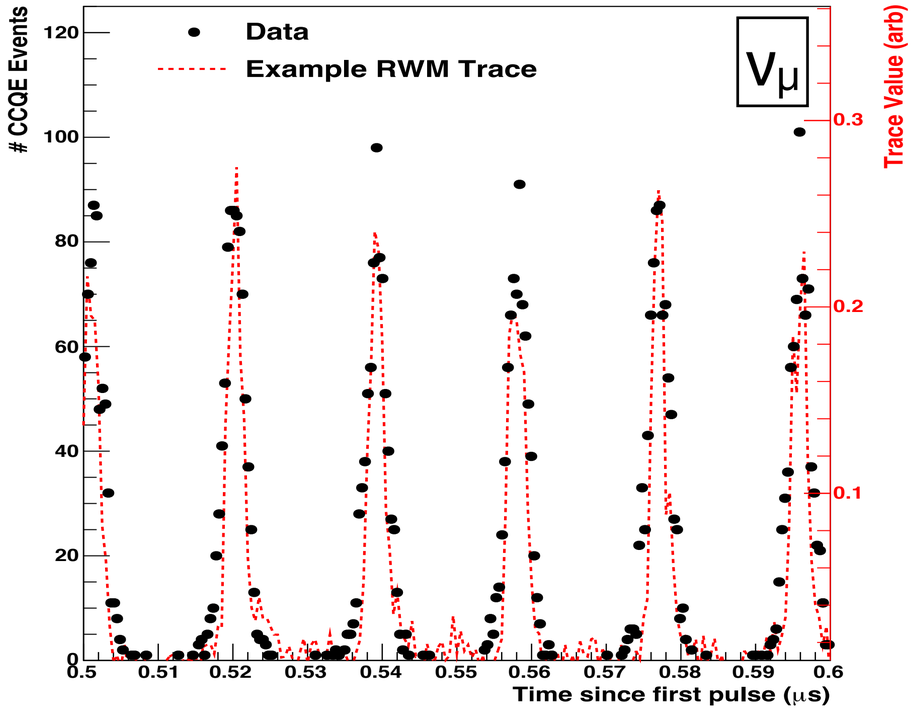
ν_e from μ decay
is constrained by *in situ* ν_μ CCQE measurement

ν_e from K decay
constrained from *in situ* high energy events + SciBooNE high energy ν_μ event rate

New : Dirt constraint with timing



Phys. Rev. D 98, 112004



- 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**

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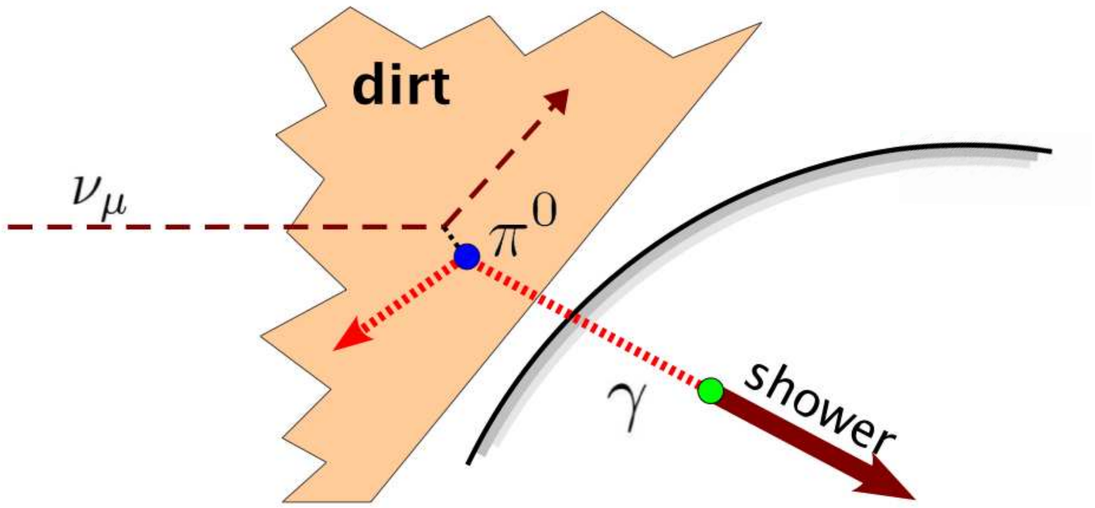

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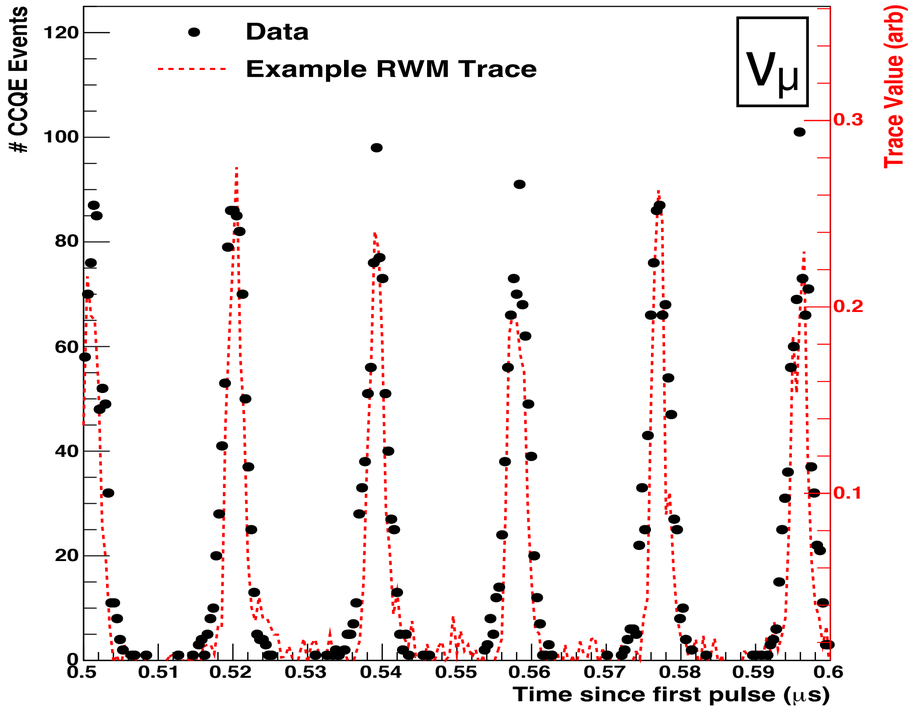

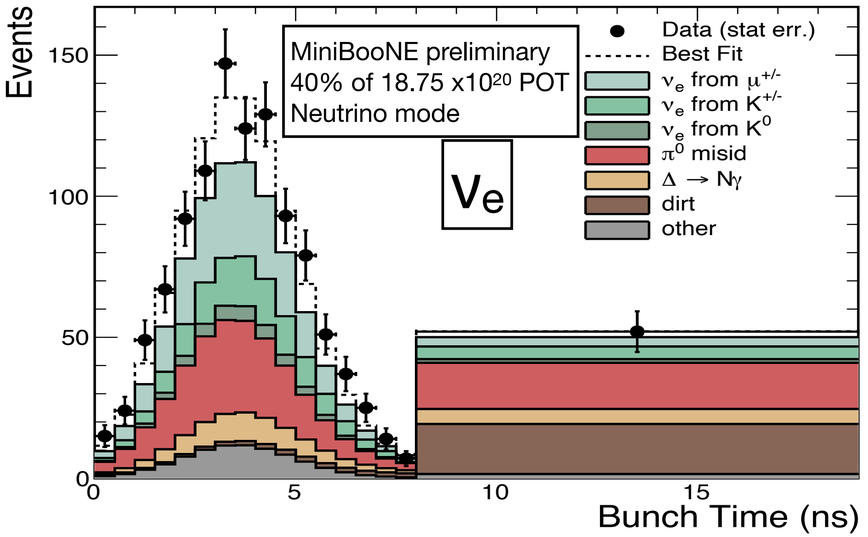

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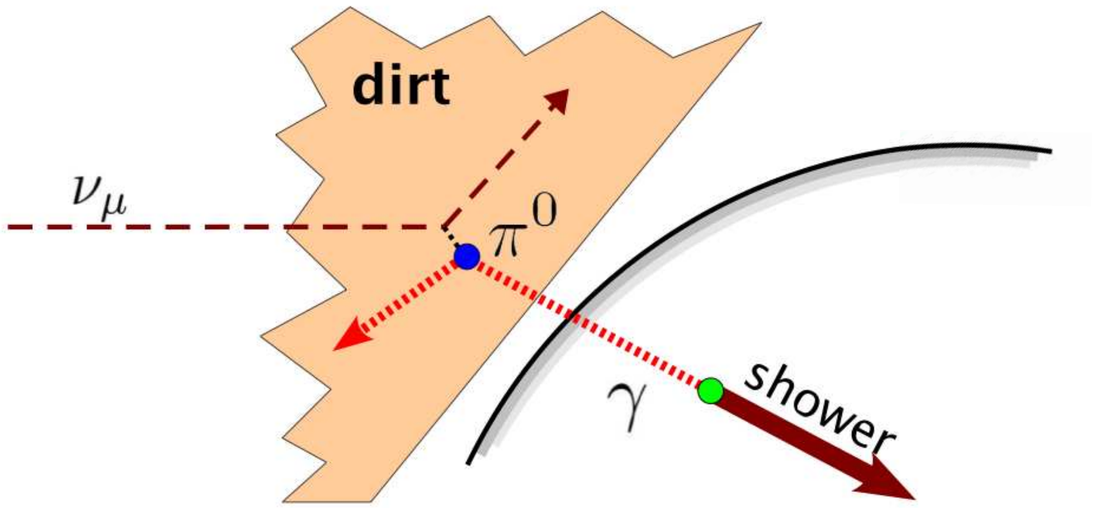

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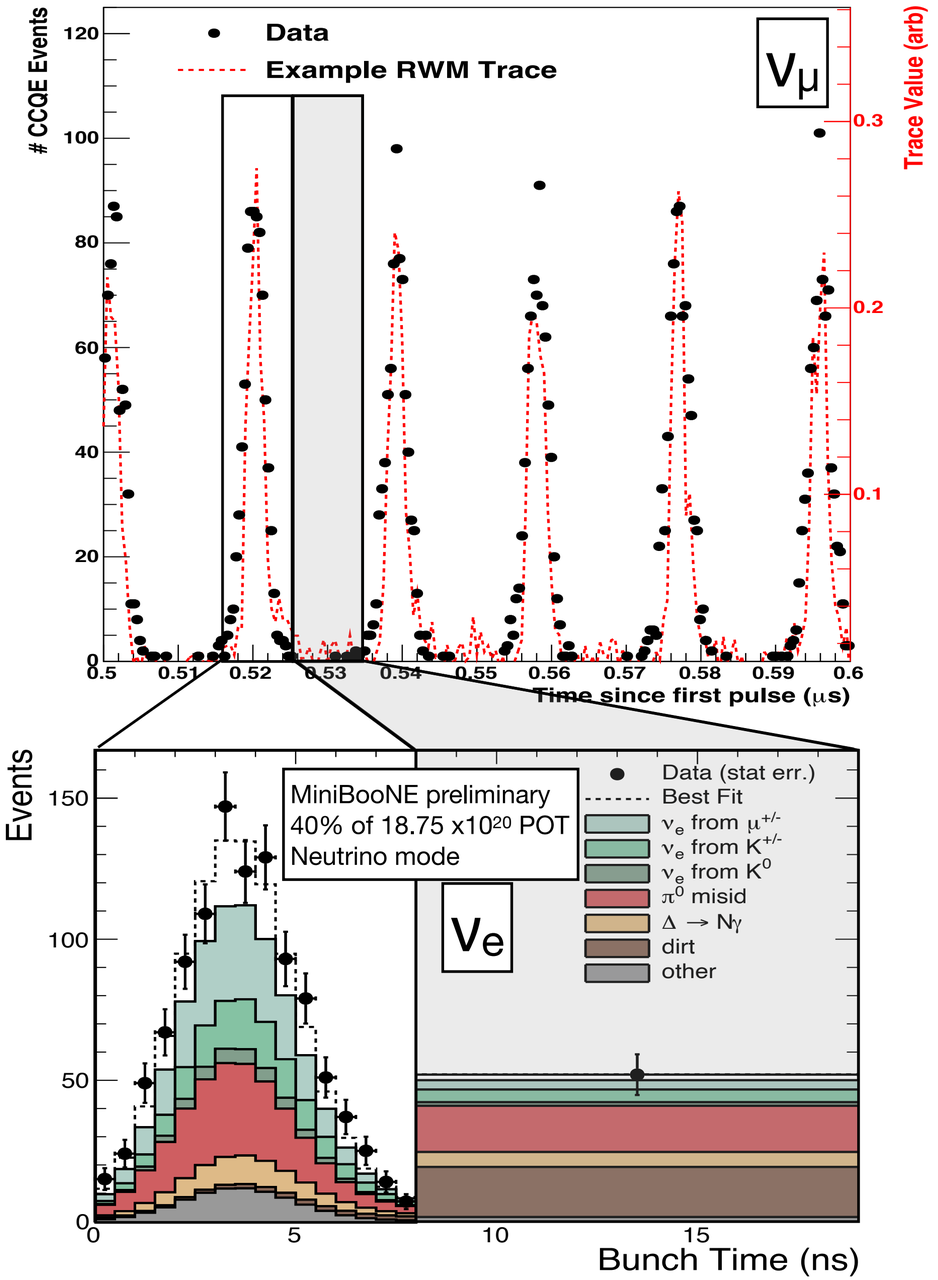
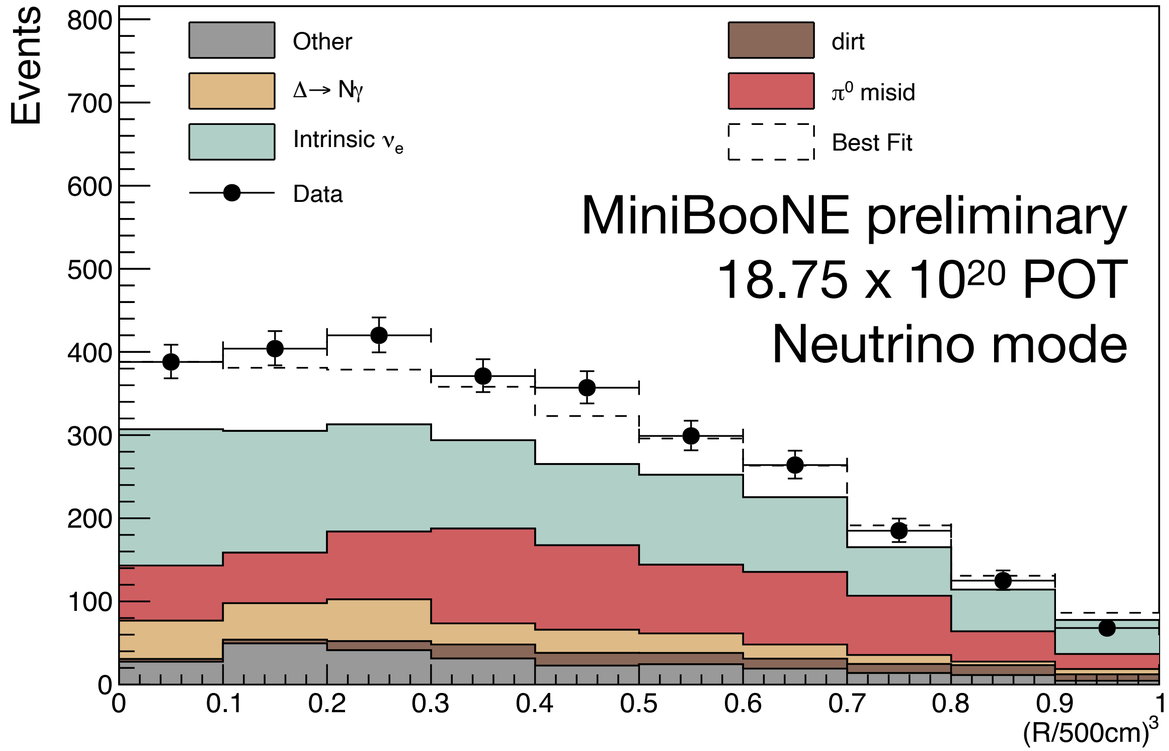
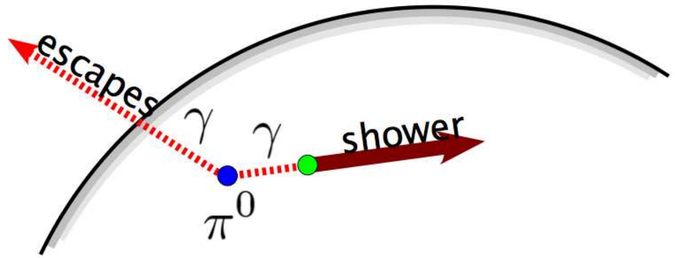


New : Radial distribution disfavors dirt and π^0 background





Example of a π^0 mis-ID

- 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 π^0 background would have peaked near the edge
  (higher probability of missing one of the γ)
- Similar approach to SNO's CC/NC constraint
- Second best candidate : NCγ background

Excess shape tests

Hypothesis	$\chi^2/9ndf$	$\Delta\chi^2$ to Best Fit
2ν Oscillations	6.6	0
NC π^0 Background	20.8	14.2
NC γ Background	7.4	0.8
Intrinsic ν_e Background	16.1	9.5
External Background	57.5	50.9
Other Background	8.6	2.0

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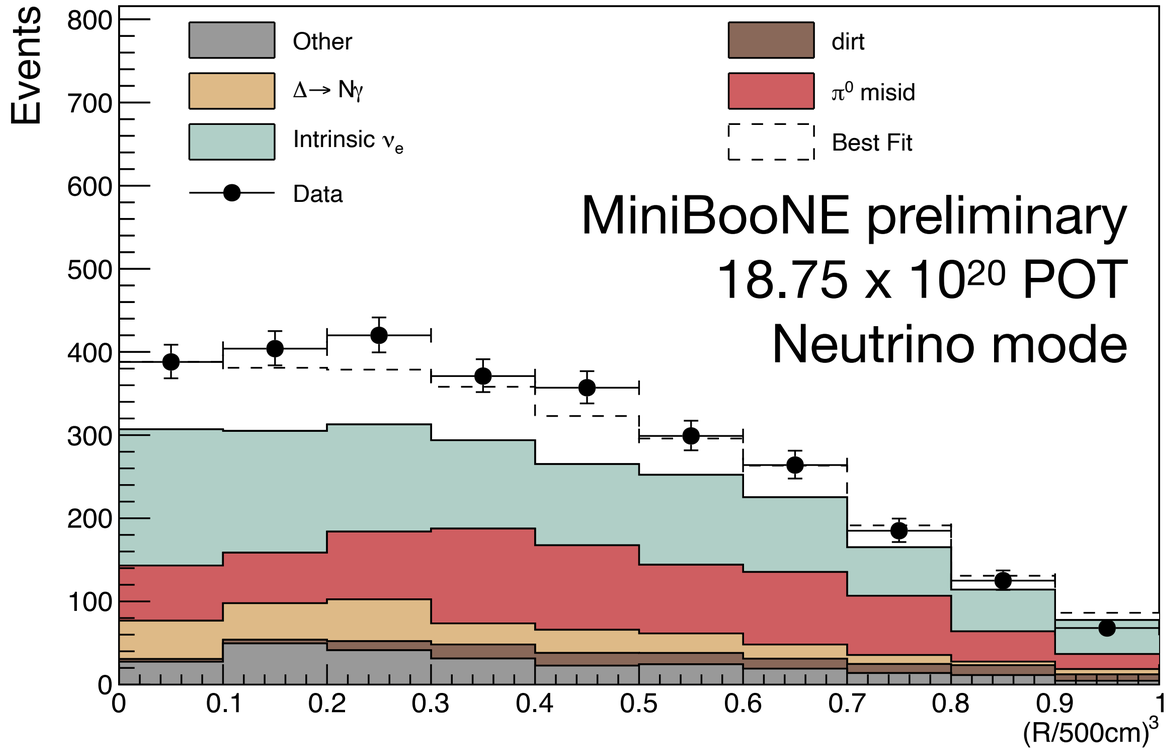

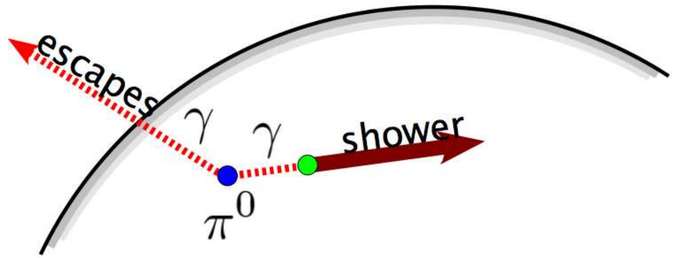

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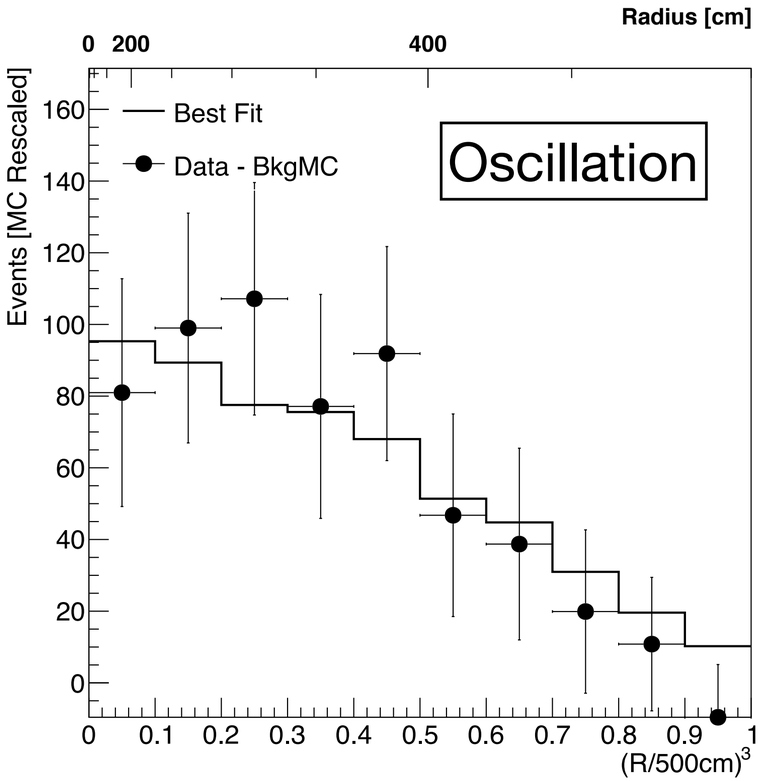
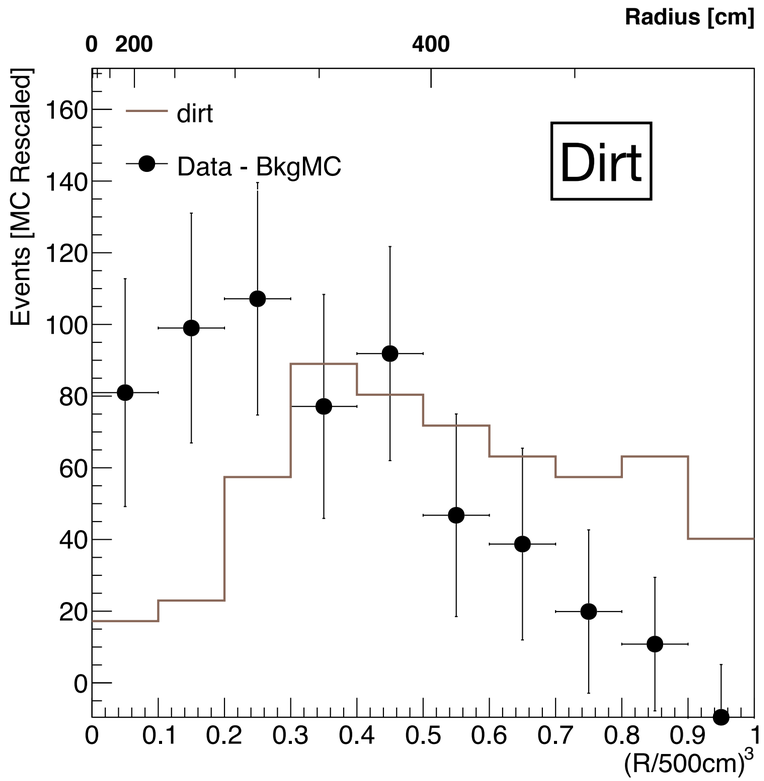
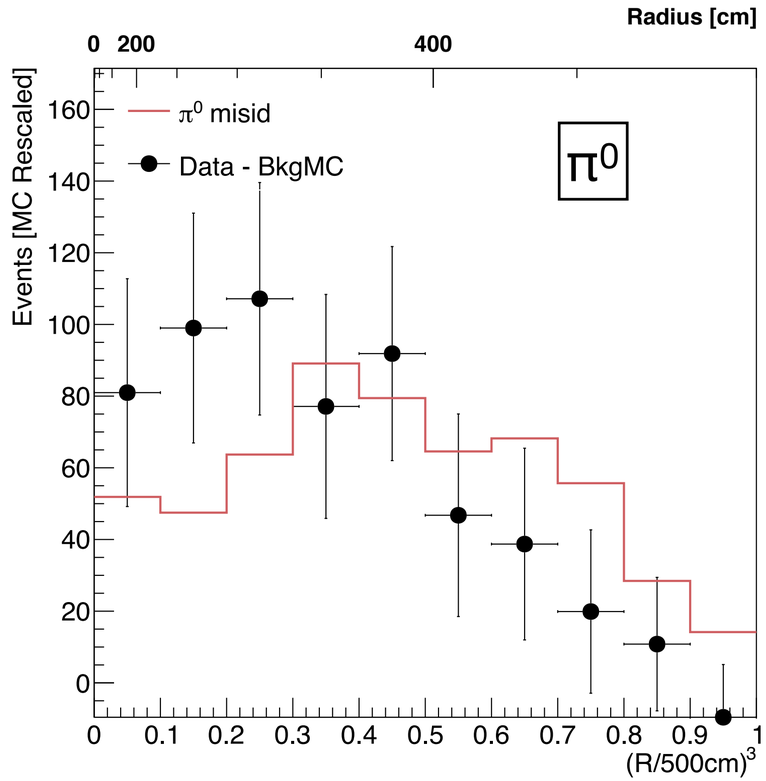
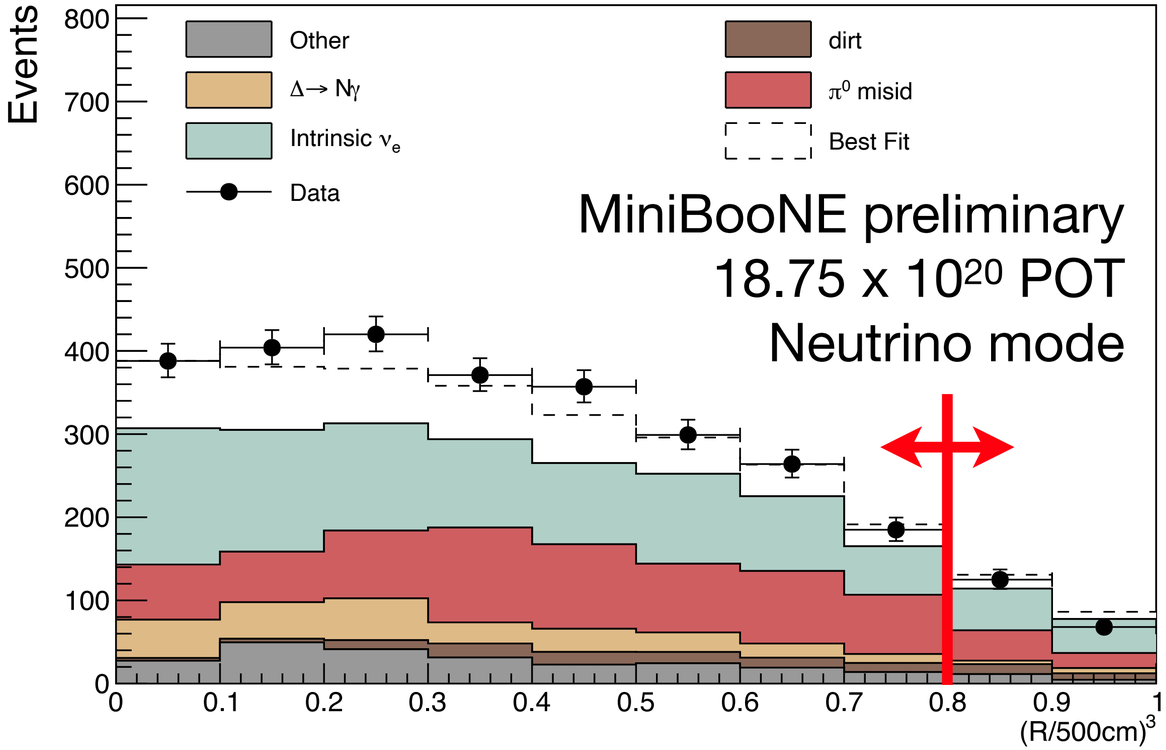






- Scaling dirt and π^0 backgrounds to fit the excess
- The "best fit" corresponds to a 2v oscillation with a sterile neutrino, and fit the observed excess better than a single background

New : Radial distribution disfavors dirt and π^0 background

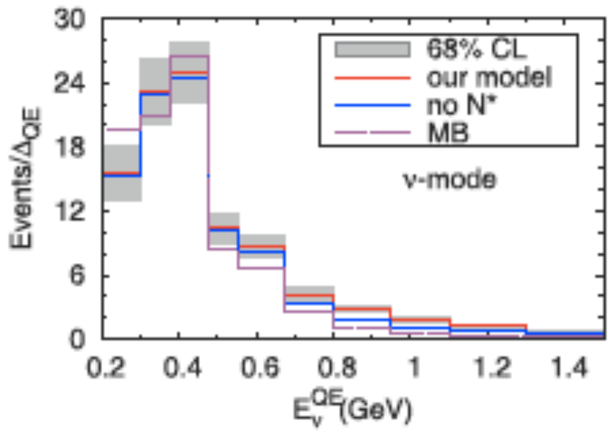


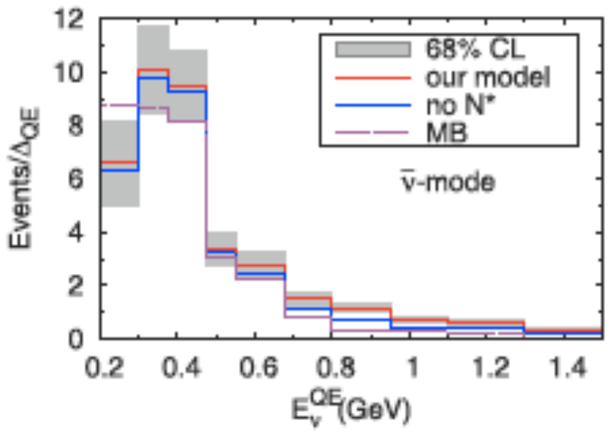
- Investigate if the excess is caused by events spilling in or spilling out of the fiducial volume by varying the fiducial cut
- Excess remains significant when rejecting outer layers of the detector : excess within the detector volume

Fiducial cut	Excess	significance
$R < 500$ cm	560.6 ± 119.6	$4.7\ \sigma$
$R < 400$ cm	472.6 ± 81.7	$5.8\ \sigma$
$R < 300$ cm	208.8 ± 40.3	$5.2\ \sigma$

$NC\ \Delta \rightarrow N\gamma$ 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 γ/π⁰ 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

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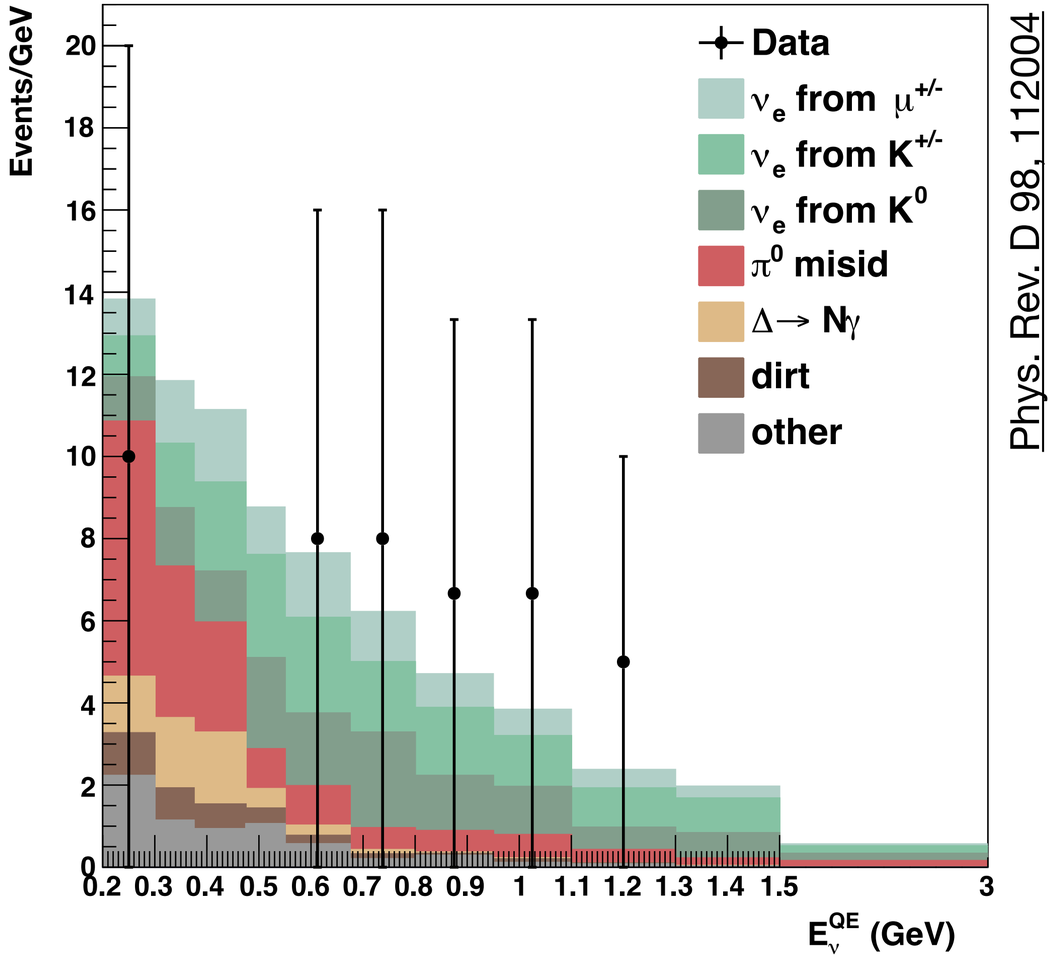
Phys. Lett. B 740 (2015) 16-22

New : Constraints from the beam dump run

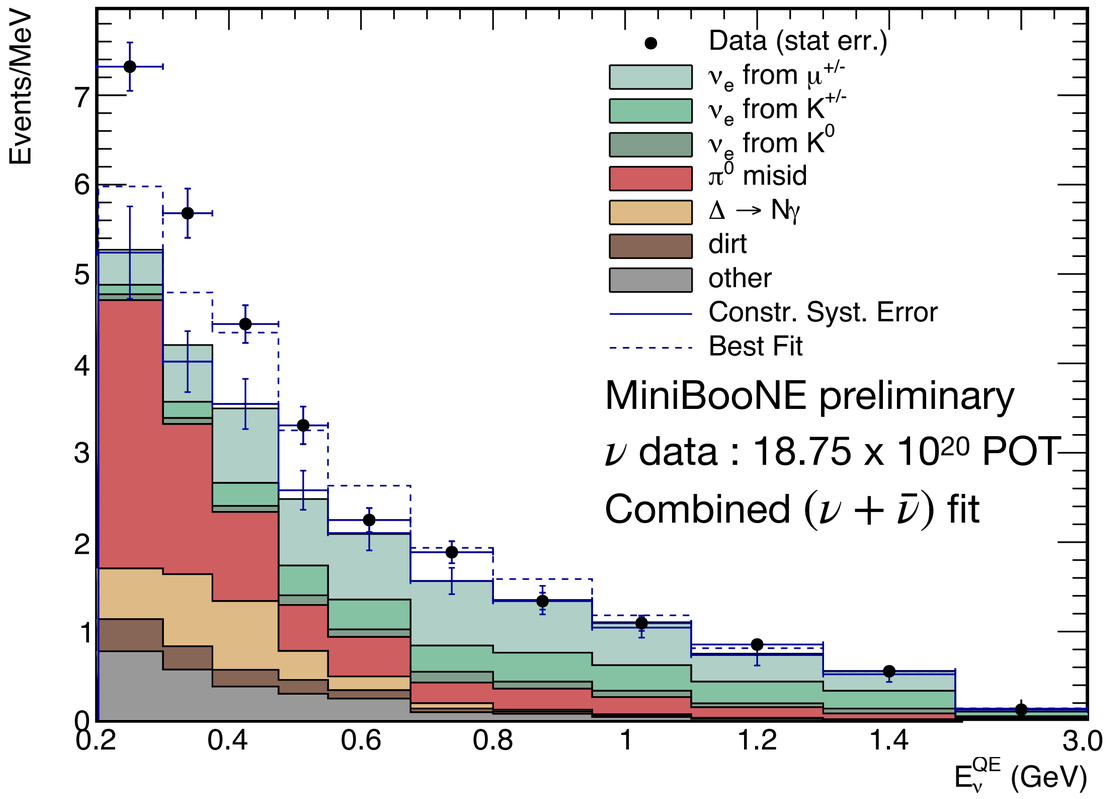
- Reduction in neutrino production
- No change to neutral meson production and proton bremsstrahlung to first order
  - ➡ Can directly test models that predict the oscillation excess does not scale as neutrino scales (e.g. vector portal, inelastic dark matter, …)

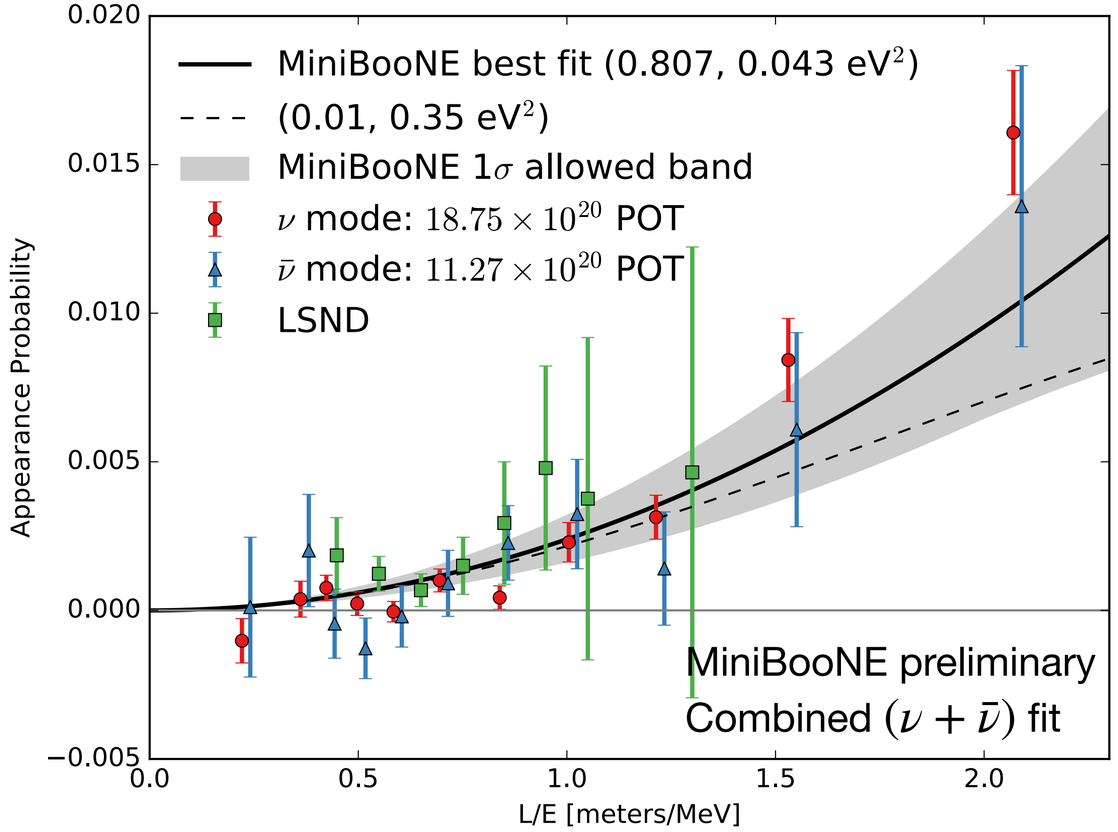
- **Expected :** 35.5±7.4 excess events in [200,1250] MeV for a POT-scaling excess
- **Measured :** 6 events, 8.8 backgrounds expected
  - ➡ -2.8 excess events
  - ➡ Explanation that scale only by POT instead of neutrino production are **ruled out at 4.6σ**

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



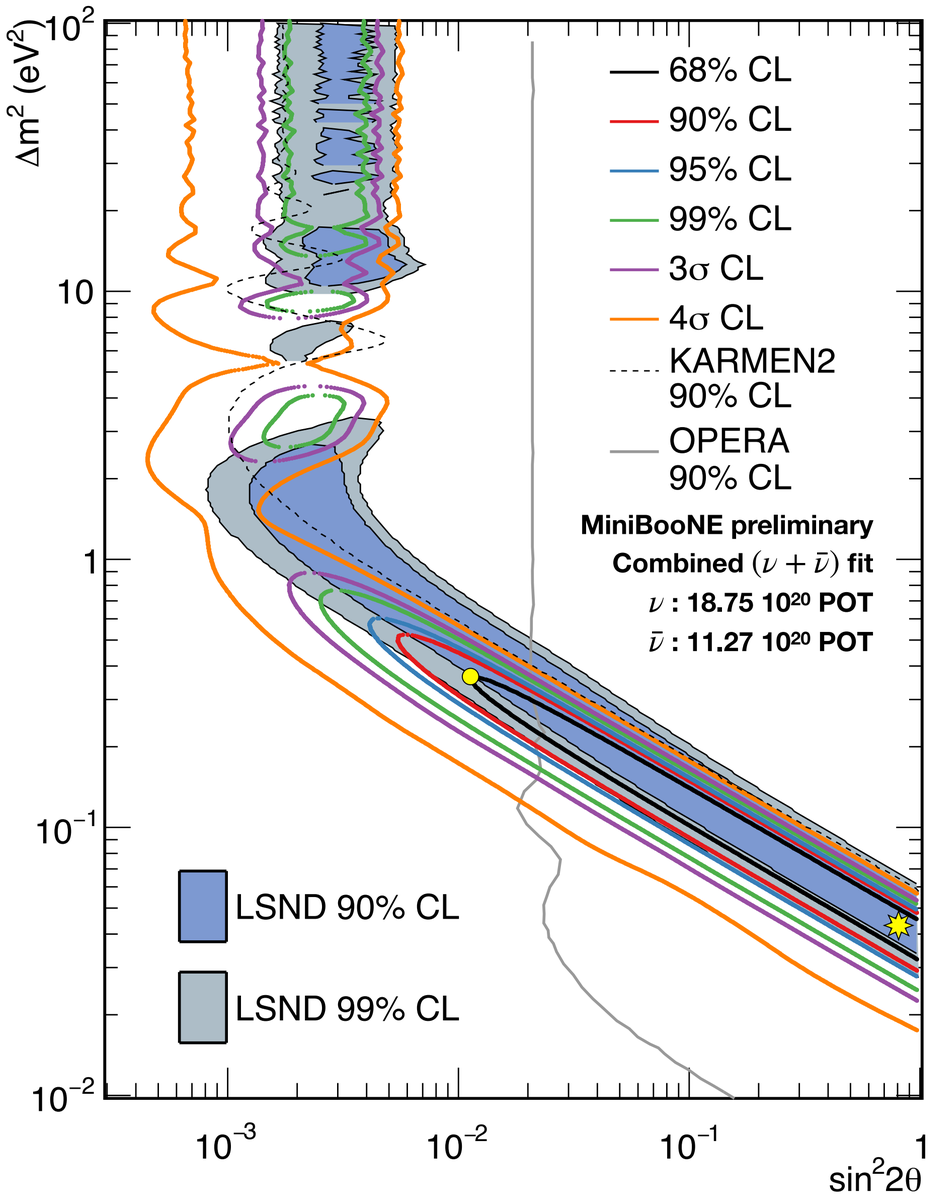
Excess interpretation in a sterile neutrino hypothesis



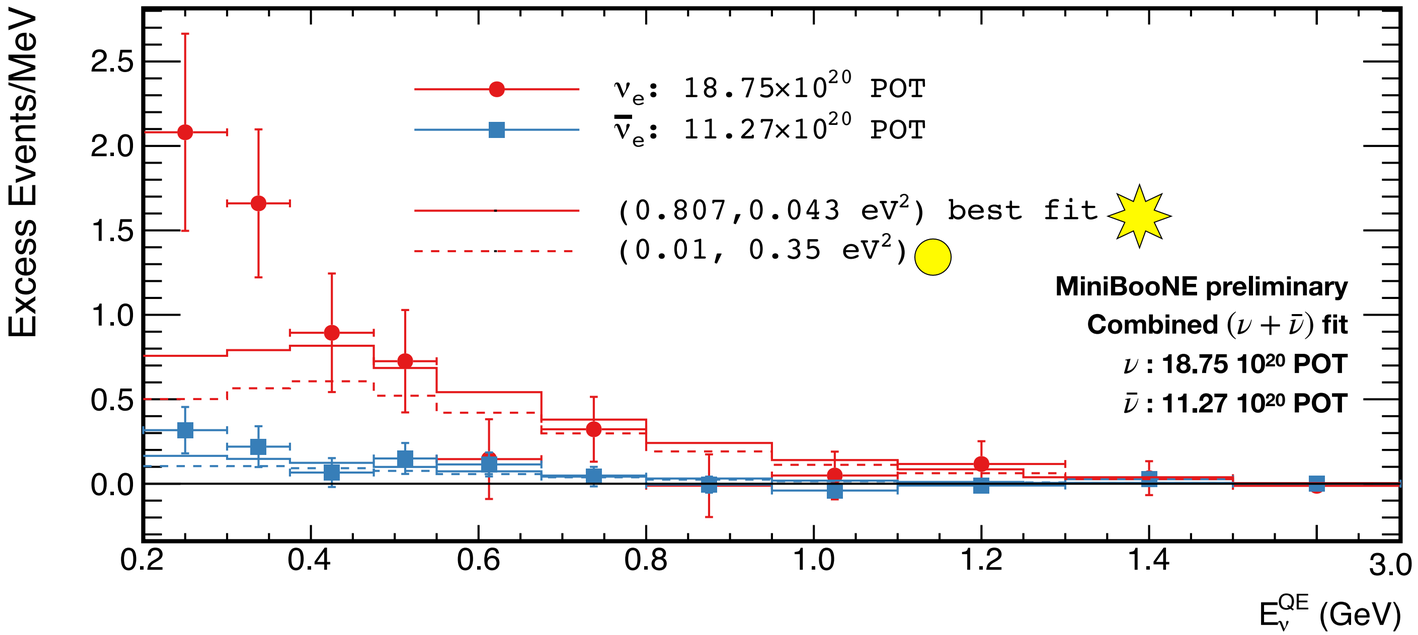


- Combined $(\nu + \bar{\nu})$ fit
- LSND and MiniBooNE points follow the same best fit 2v oscillation interpretation

Preferred regions in sterile neutrino hypothesis



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

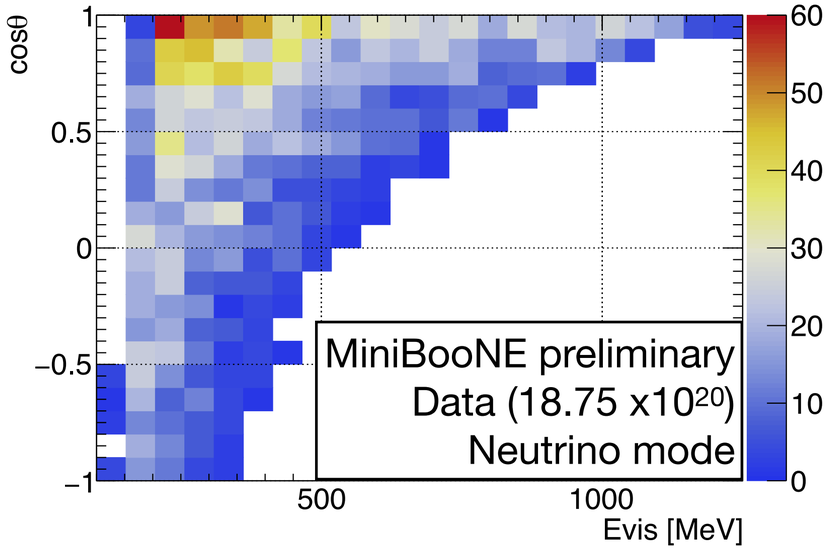


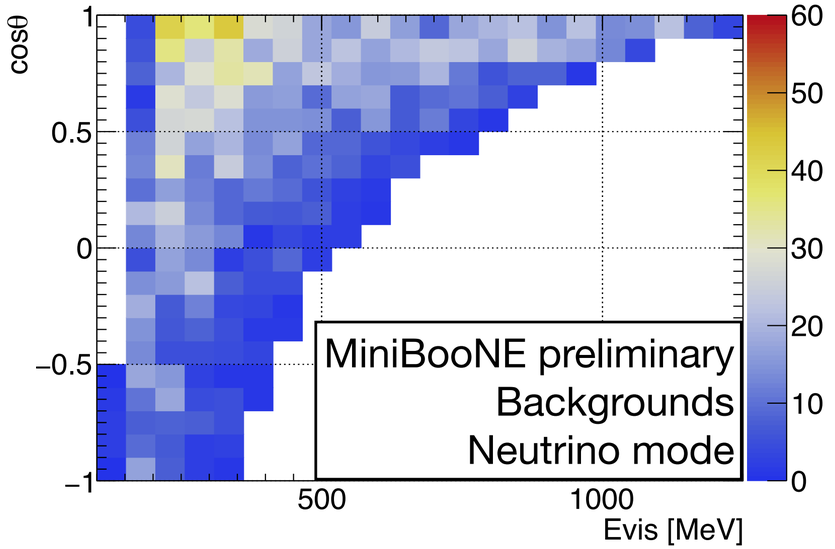
Neutrino + Anti-Neutrino Mode

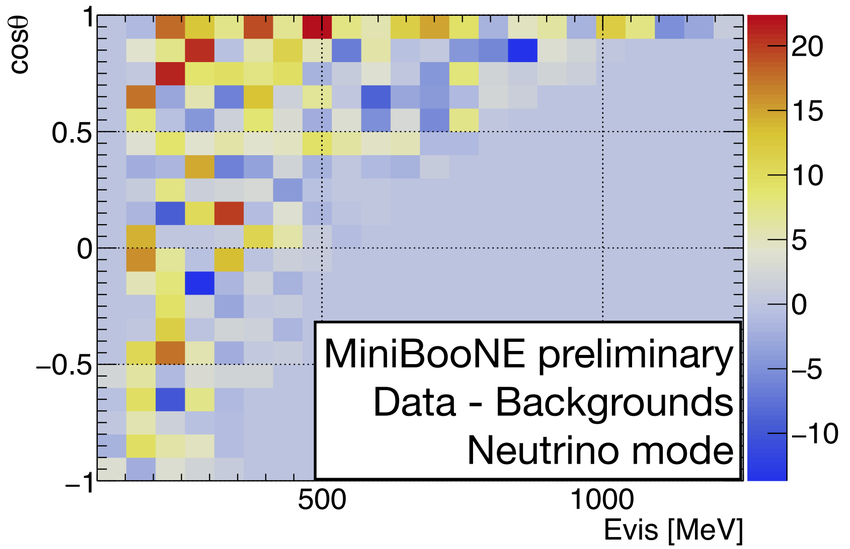
$(\Delta m^2, \sin^2 2\theta) = (0.043\ \text{eV}^2,\ 0.807)$

$\chi^2/ndf = 21.7/15.5\ (\text{prob} = 12.3\%)$

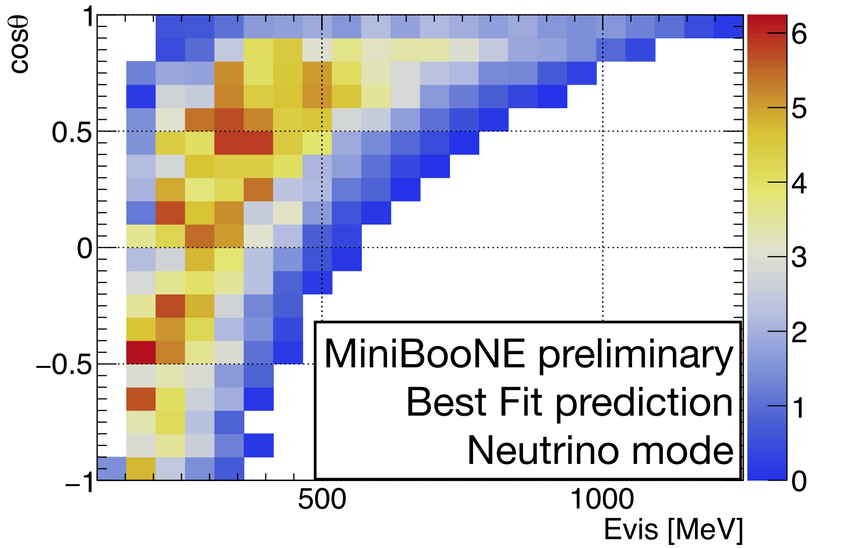
New : cos(θ) VS E_{vis} Distributions for ν_e samples







- 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



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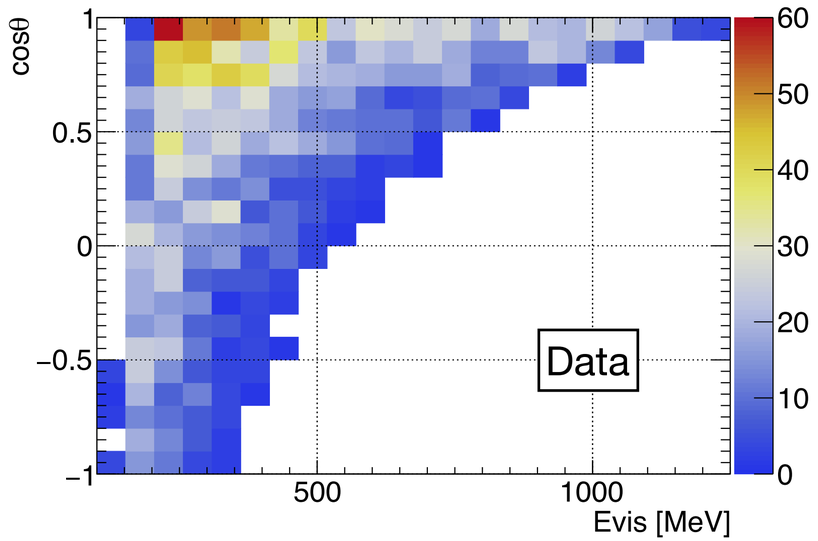
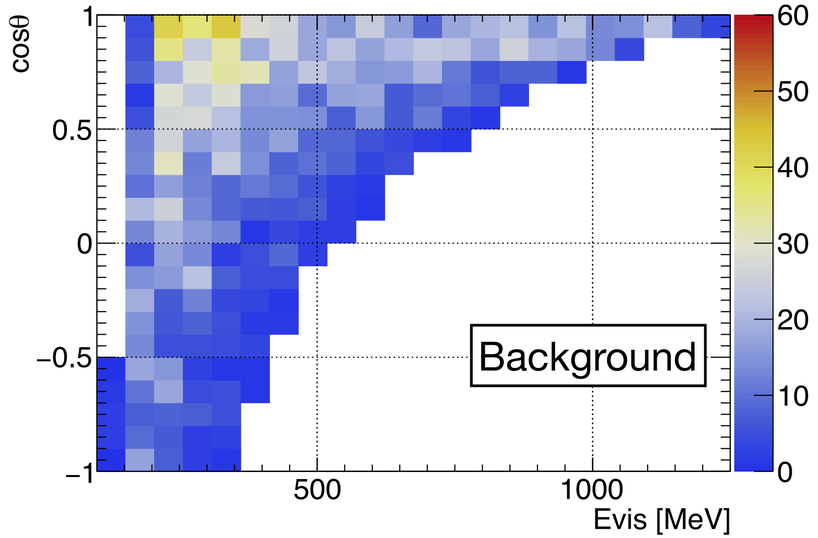
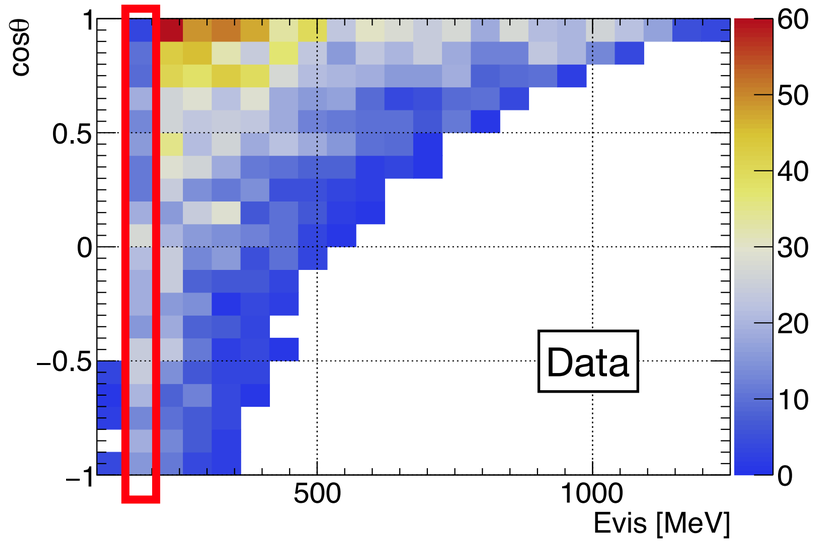
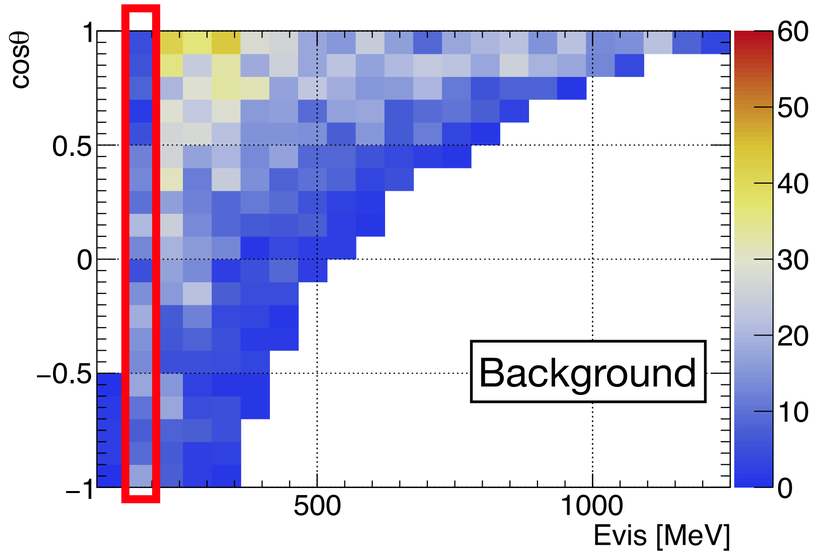




Easier to visualize the excess in 1D plots of cosθ for slices of E_{vis}

New : cos(θ) VS E_{vis} Distributions for ν_e samples





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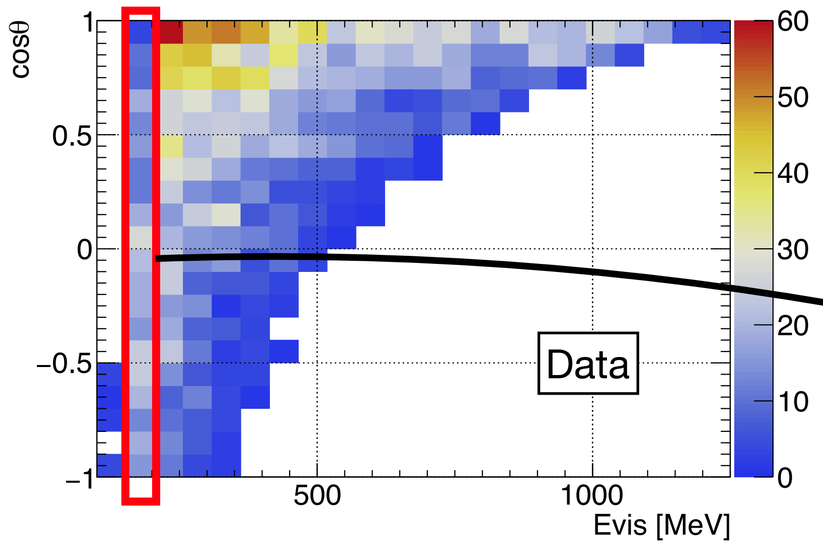
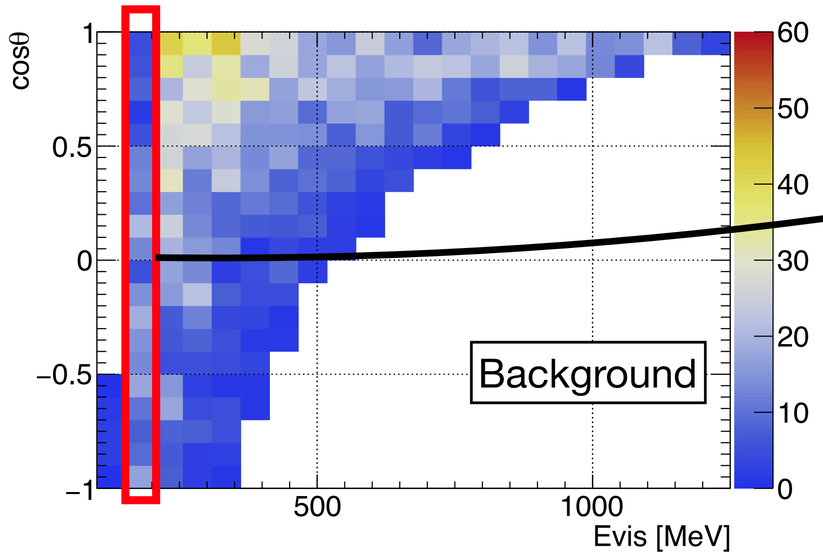
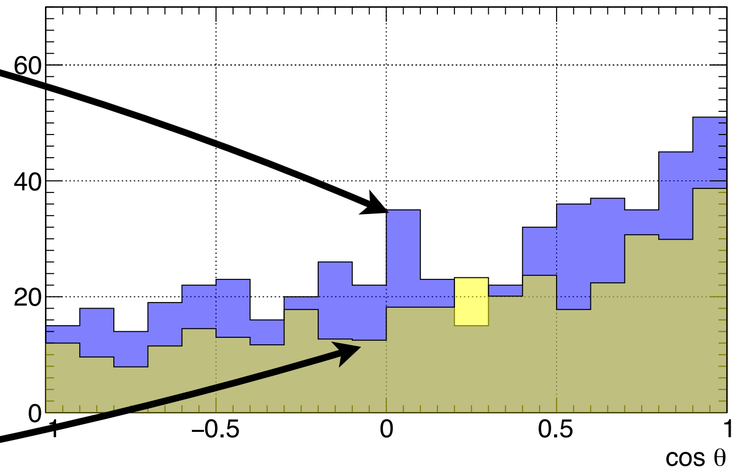




Easier to visualize the excess in 1D plots of cosθ for slices of E_{vis}



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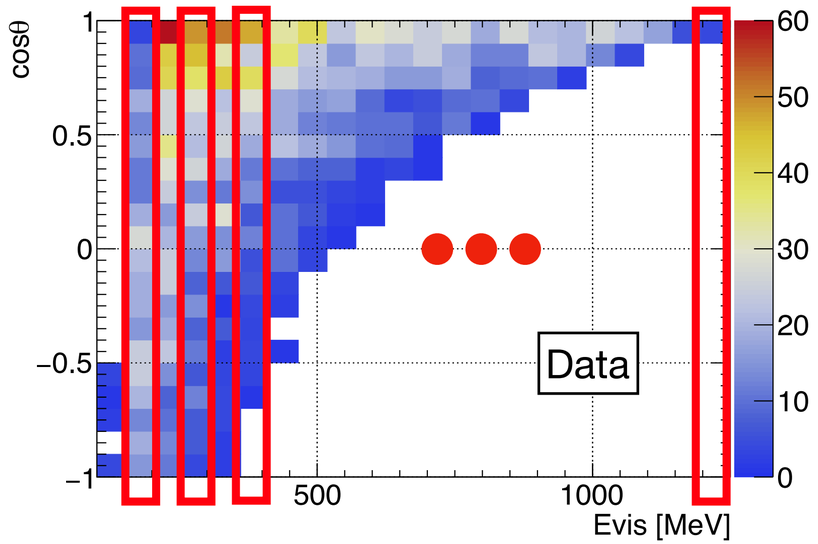

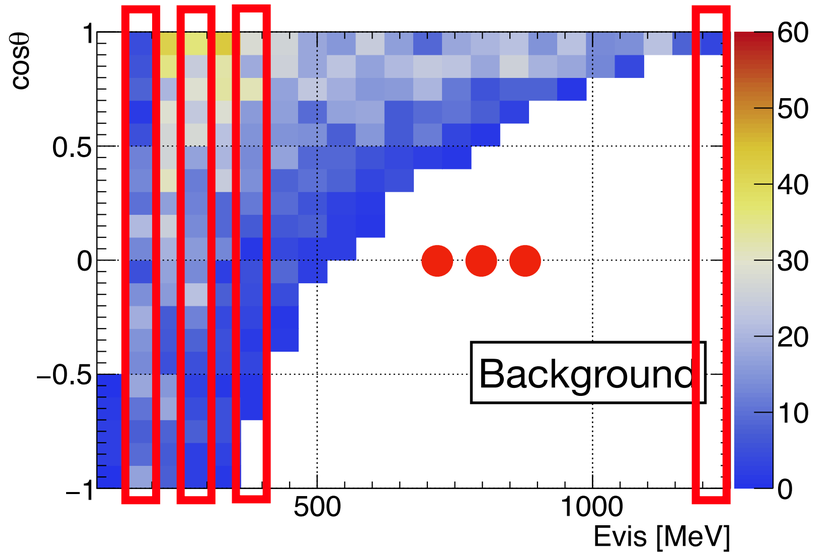

Easier to visualize the excess in 1D plots of cosθ for slices of E_{vis}

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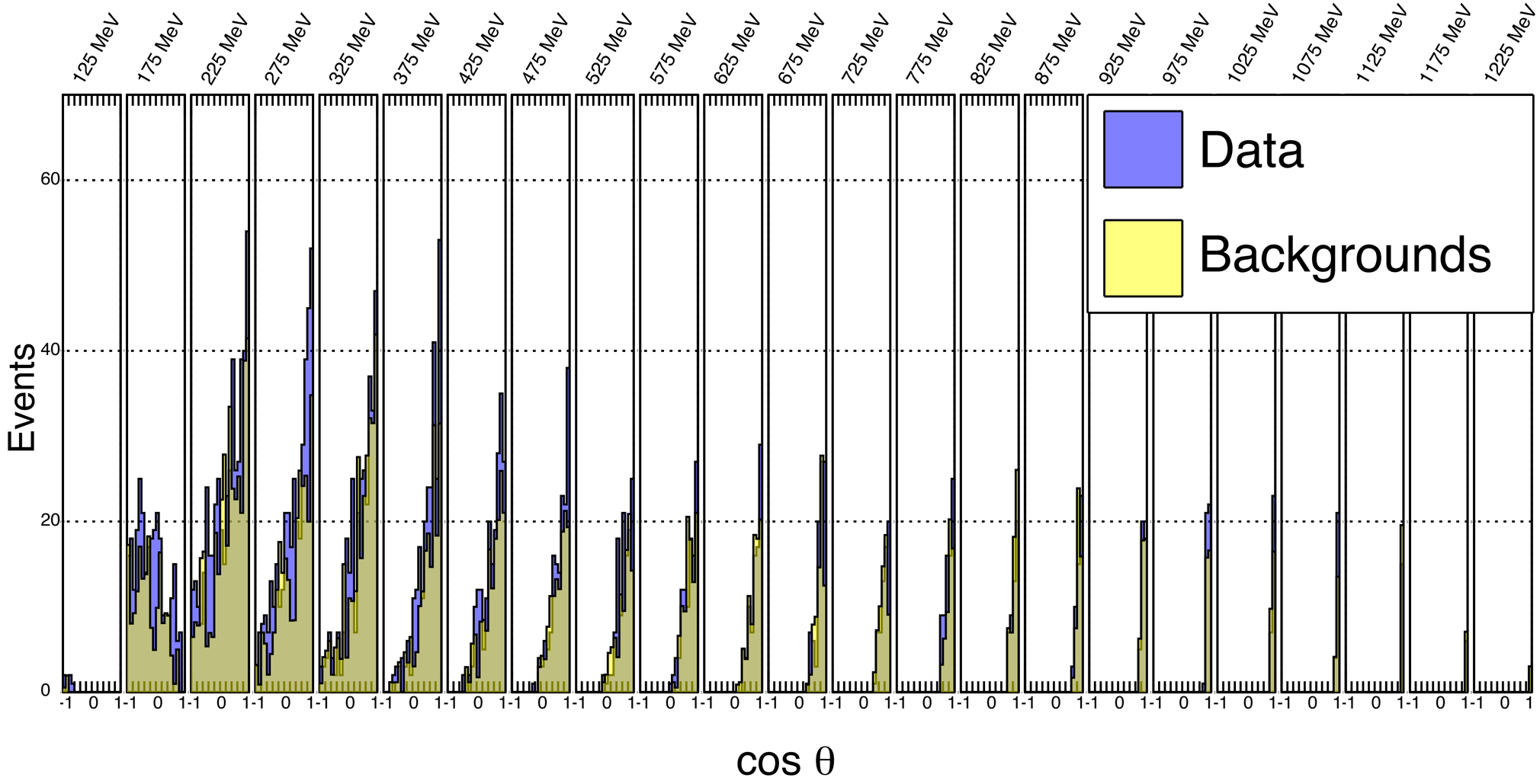

- The excess at low energy occurs across a wide range of cos θ

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 π^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

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Thank you!

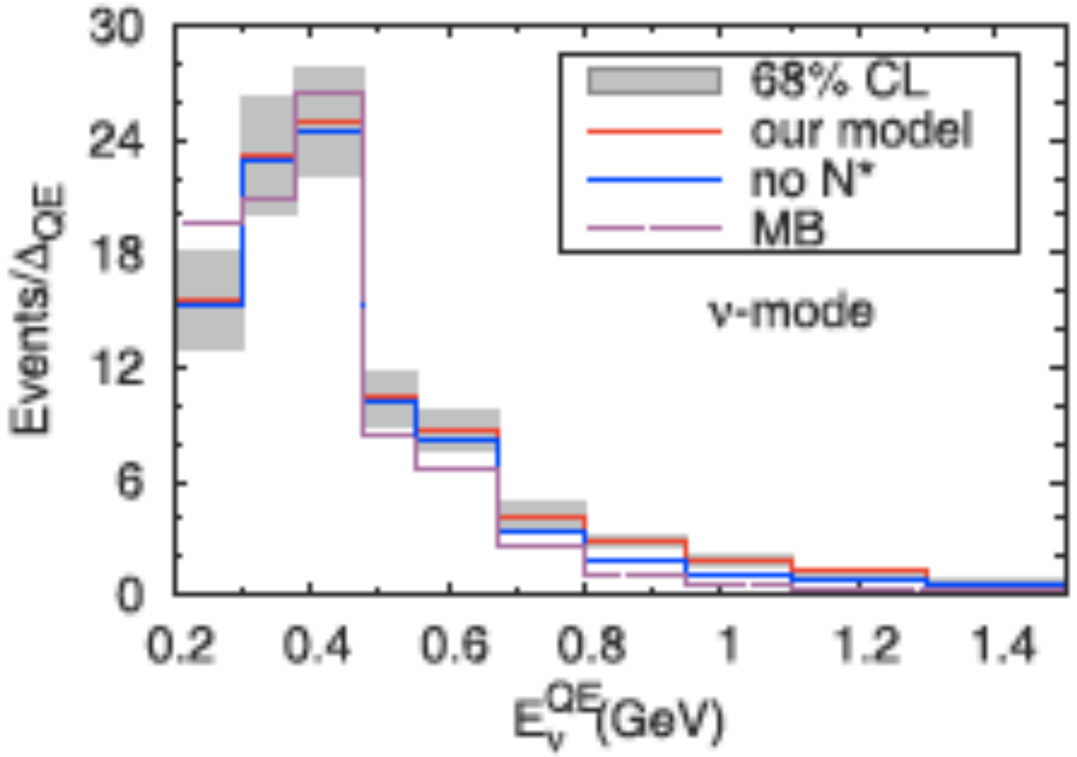
Constraining Δ->Nγ background from NCπ⁰ background

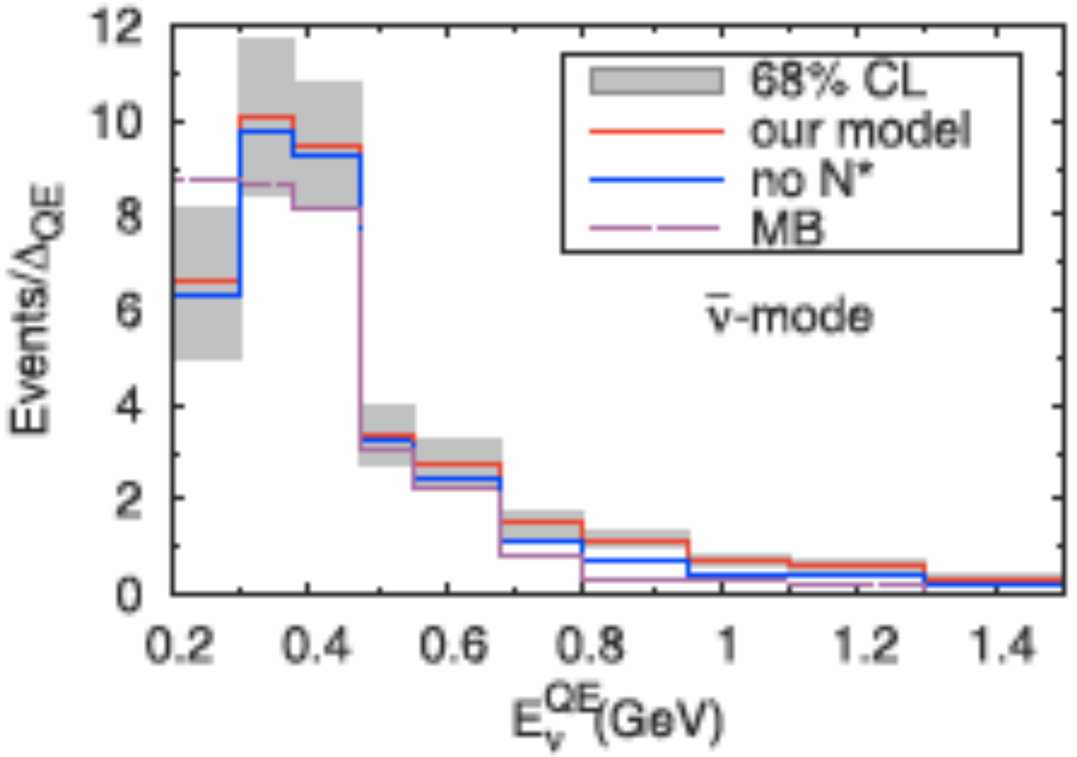
- NC π^0 produced by :
  - Δ production in ^{12}C (52.2%)
  - Δ production in H_2 (15.1%)
  - Coherent scattering on ^{12}C (12.5%)
  - Coherent scattering H_2(3.1%)
  - higher mass resonance (12.9%)
  - non resonant BG (4.2%)

- 2/3 of Δ decay in π^0
- 62.5% π^0 can escape the nucleus
- Δ->Nγ BR = 0.60% for ^{12}C
- Δ->Nγ BR = 0.68% for H_2

$$\frac{N_{\Delta\to N\gamma}}{N_{NC\pi^0}} = \left(0.151 \times 0.0068 \times 1.5\right) + \left(0.522 \times 0.0060 \times 1.5\right)/0.625 = 0.0091$$

Theoretical Estimates for NC-γ production Agree well with MiniBooNE Estimates





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

Theoretical Estimates for NC-γ production Agree well with MiniBooNE Estimates

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

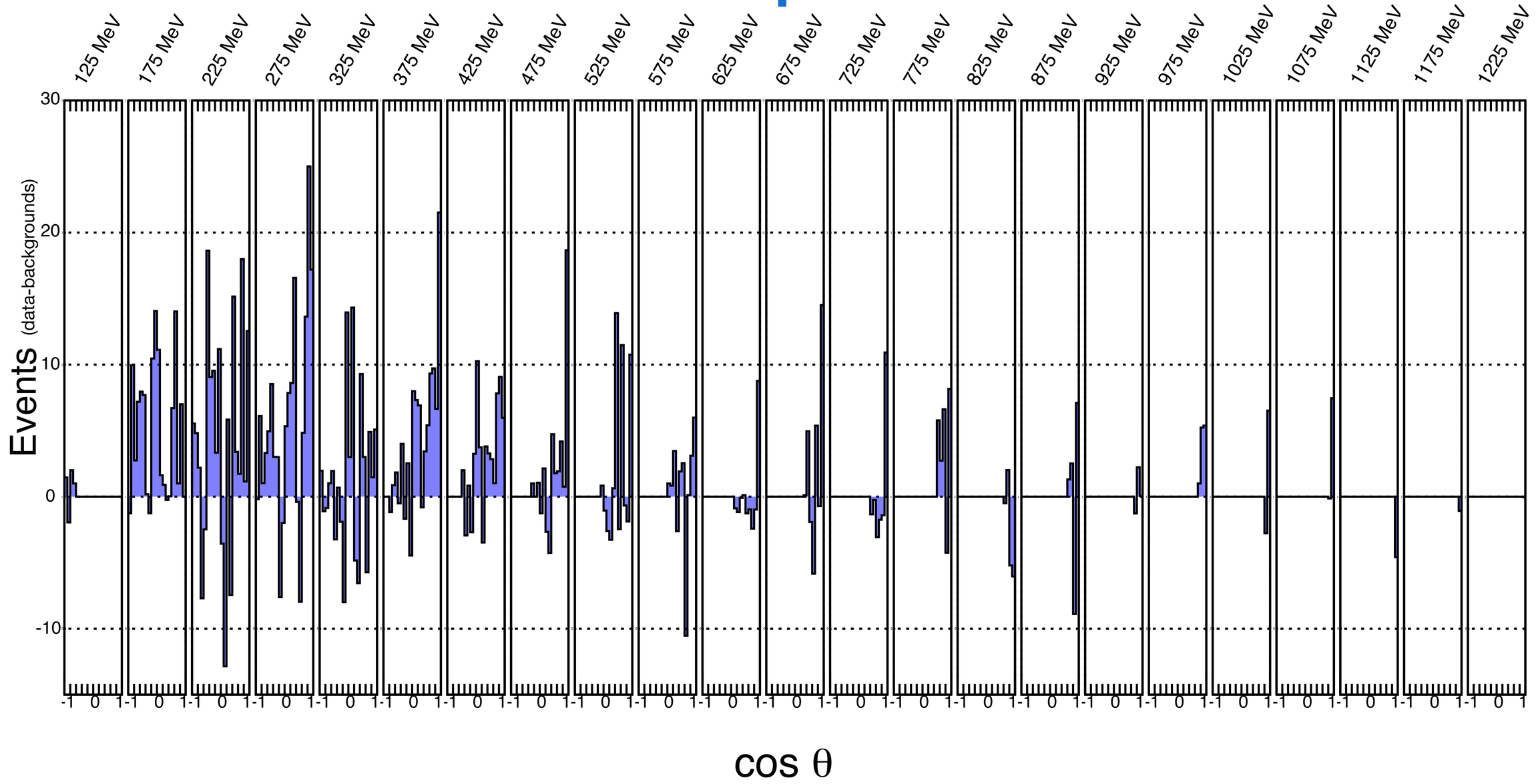
Can neutrino-induced photon production explain the low energy excess in MiniBooNE?

Xilin Zhang [a,b,*], Brian D. Serot [b,1]

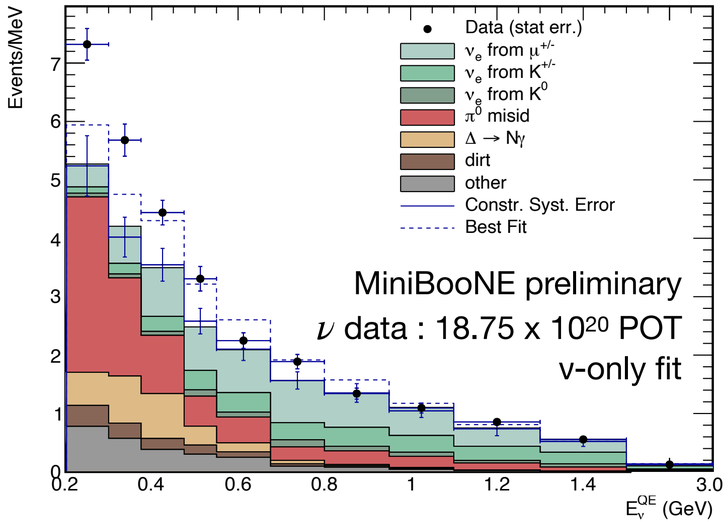
[a] Institute of Nuclear and Particle Physics and Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA
[b] Department of Physics and Center for Exploration of Energy and Matter, Indiana University, Bloomington, IN 47405, USA

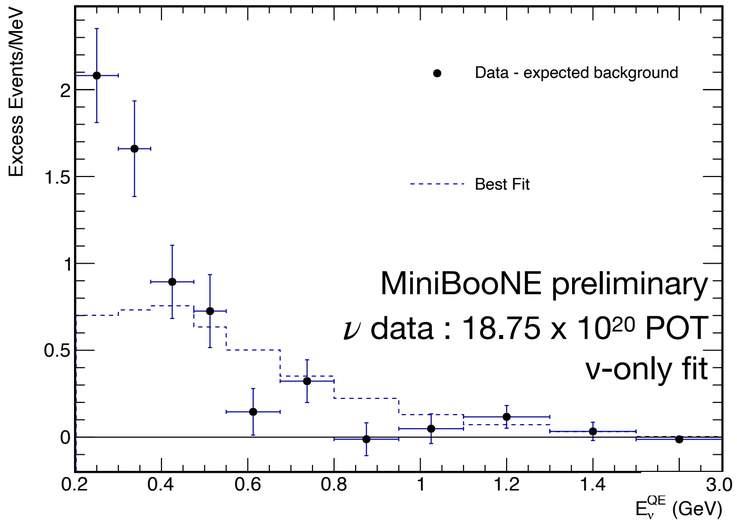
Phys. Lett. B 719(2013) 409-414

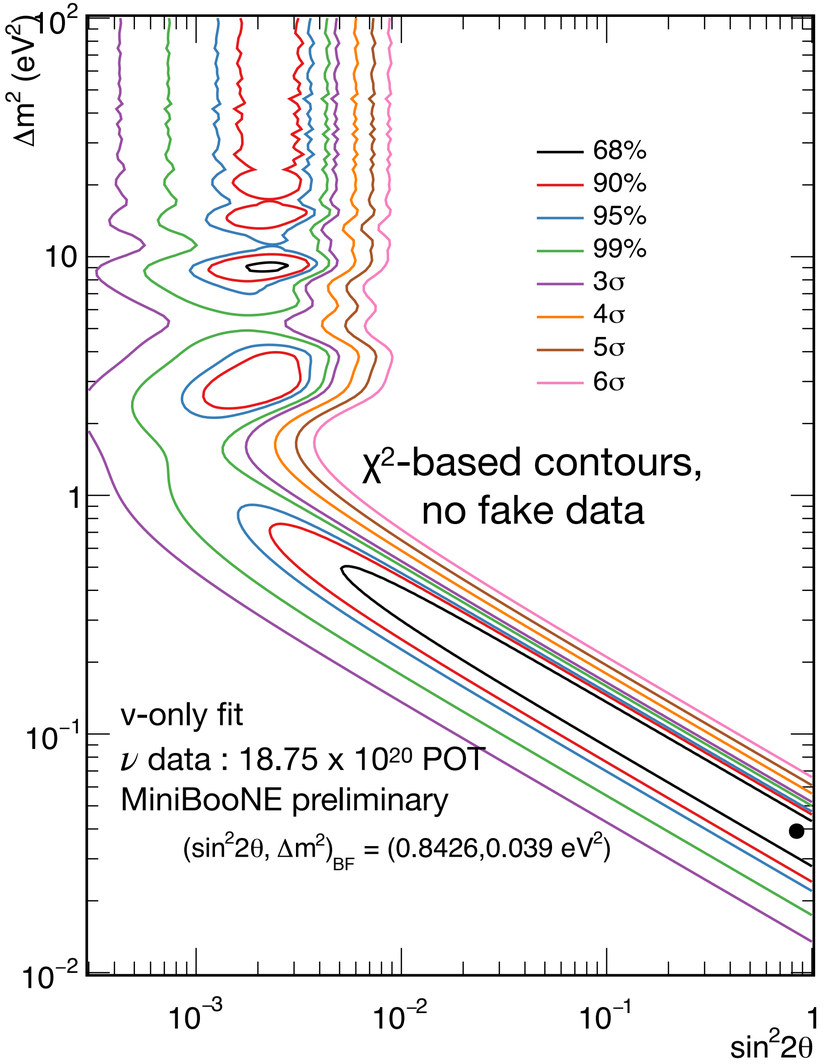
Excess for cosθ VS Evis plot



Neutrino only fit



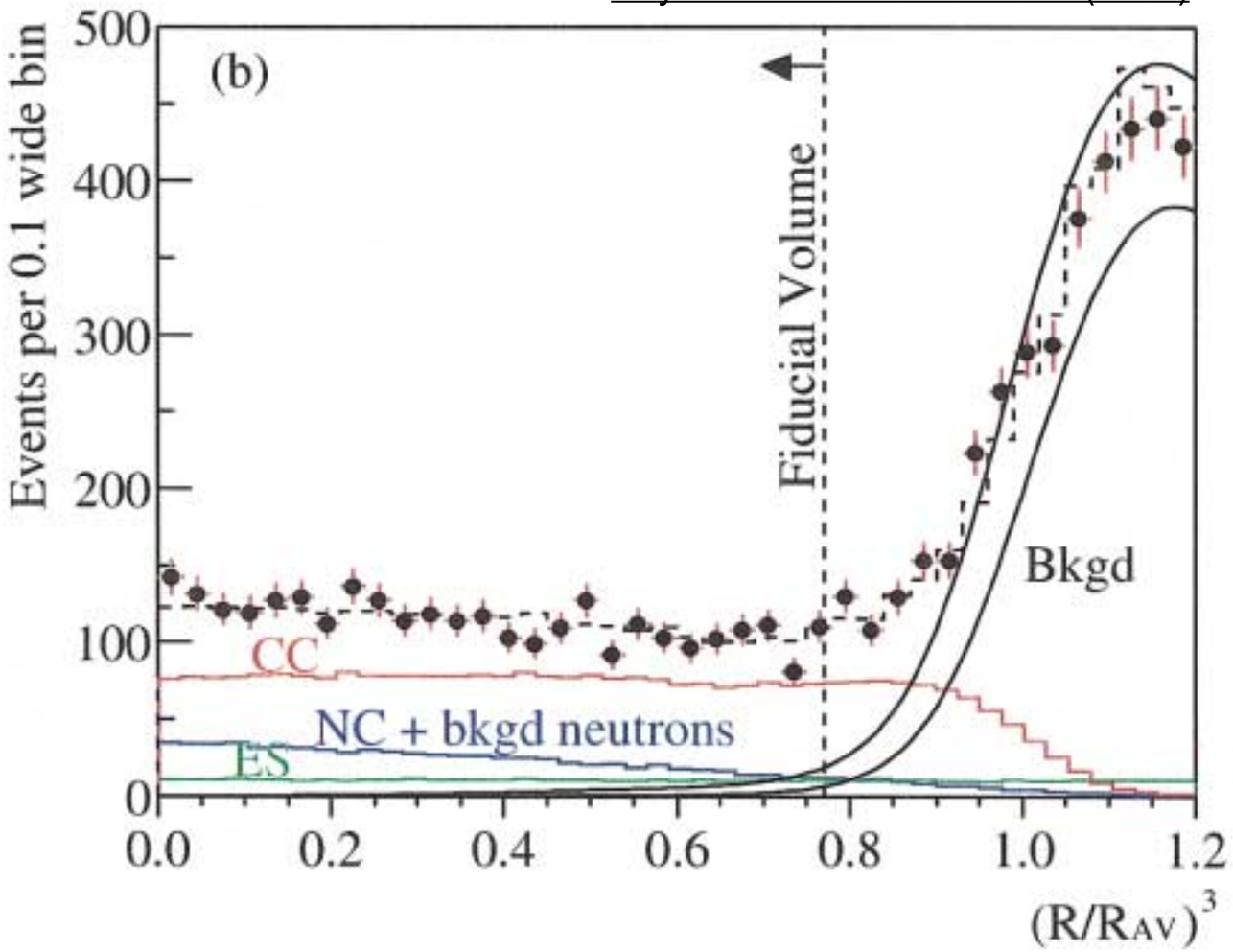




- Only a small difference with respect to the $(\nu + \bar{\nu})$ combined fit
- nu-only : $(\sin^2 2\theta, \Delta m^2) = (0.843,\ 0.039\ \mathrm{eV}^2)$
- $(\nu + \bar{\nu})$: $(\sin^2 2\theta, \Delta m^2) = (0.807,\ 0.043\ \mathrm{eV}^2)$

Radial distribution in SNO

Phys. Rev. Lett. 89.011301 (2002)



- NC and CC contributions have difference R-dependencies, one can use the radial distribution to estimate the relative contribution of each process.
- SNO is only one of the many examples of experiment using radial position to constrain components of their data

PID variables : μ/e log likelihood

arxiv:1805.12028[hep-ex]

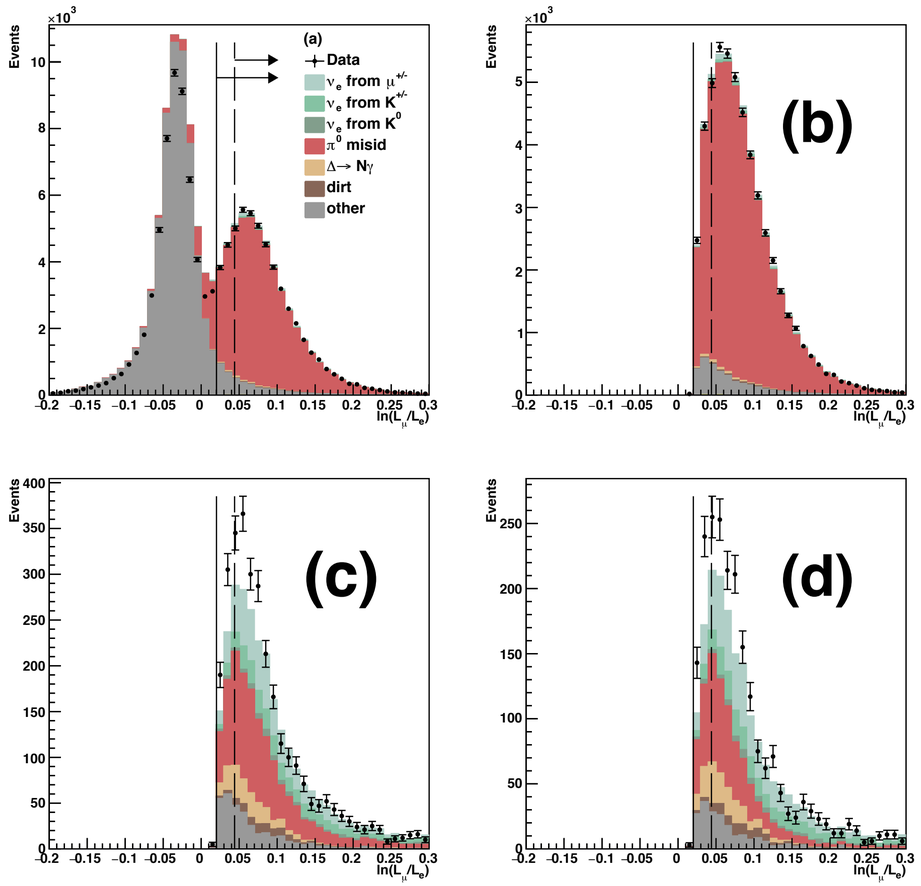
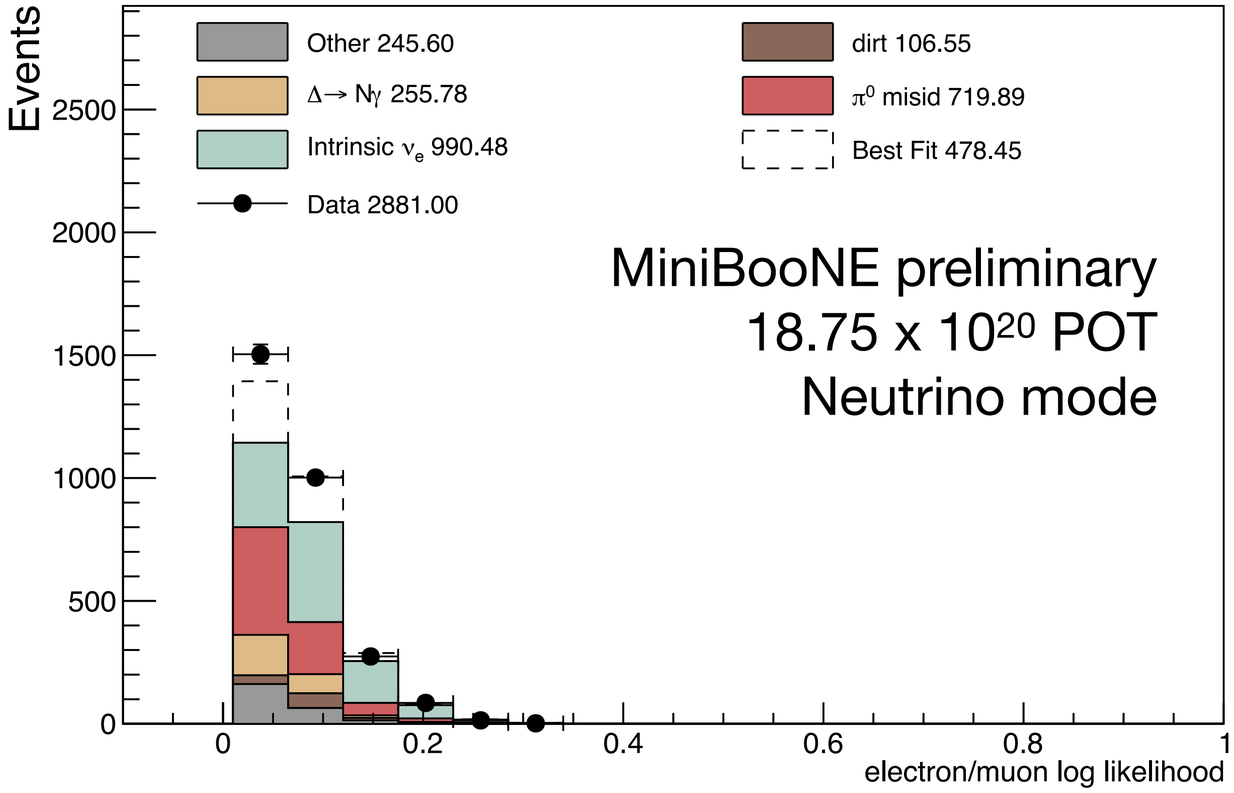


FIG. 9: Comparisons between the data and simulation for the electron-muon likelihood distribution after successive cuts are applied: (a) no PID cut, (b) electron-muon likelihood cut, (c) electron-muon plus electron-pion likelihood cuts, and (d) electron-muon plus electron pion likelihood cuts plus a gamma-gamma mass cut. The vertical lines in the figures show the range of energy-dependent cut values.



PID variables : π/e log likelihood

arxiv:1805.12028[hep-ex]

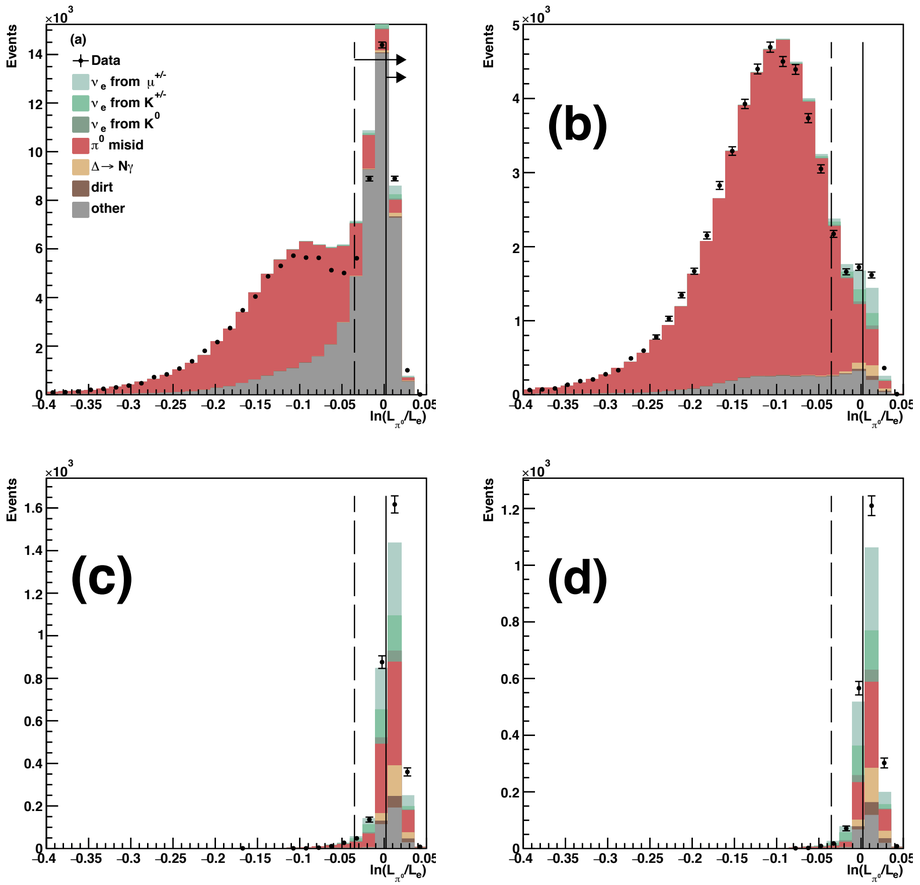
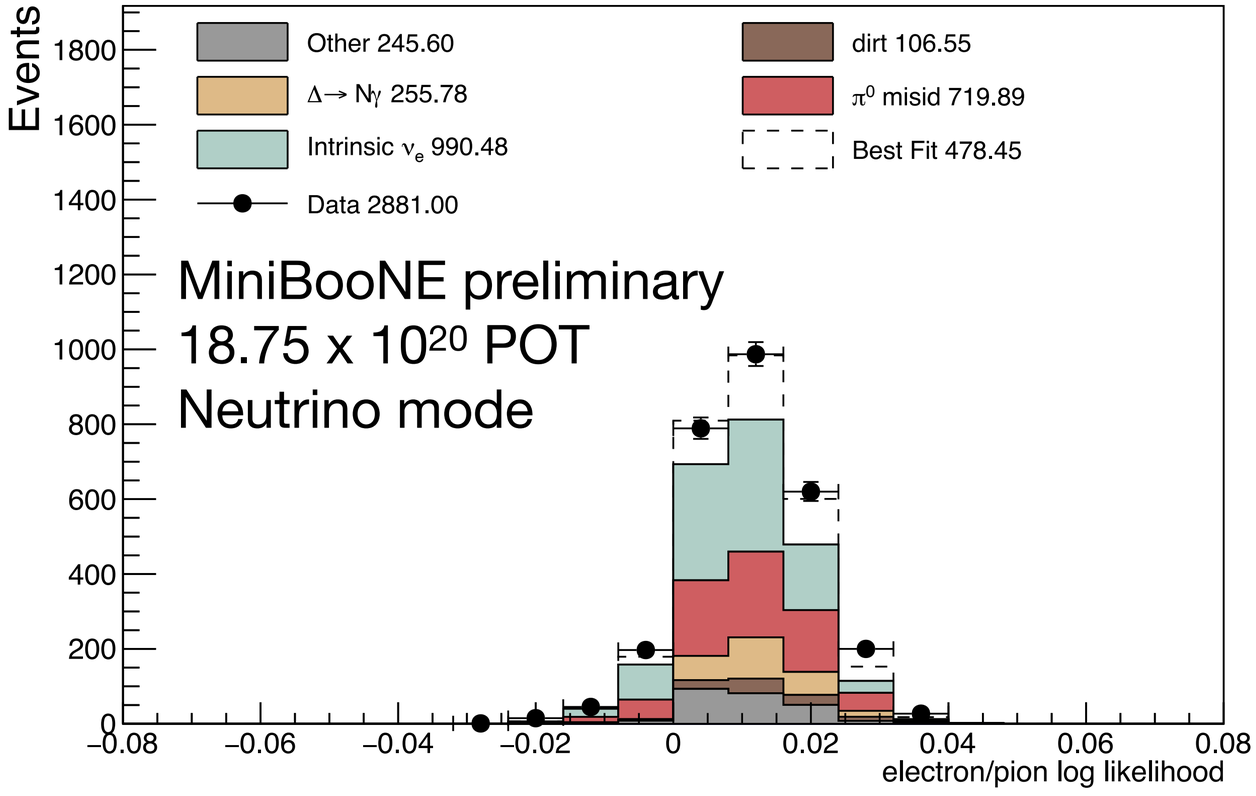


FIG. 10: Comparisons between the data and simulation for the electron-pion likelihood distribution after successive cuts are applied: (a) no PID cut, (b) electron-muon likelihood cut, (c) electron-muon plus electron-pion likelihood cuts, and (d) electron-muon plus electron pion likelihood cuts plus a gamma-gamma mass cut. The vertical lines in the figures show the range of energy-dependent cut values.



PID variables : $m_{\gamma\gamma}$ distribution

arxiv:1805.12028[hep-ex]

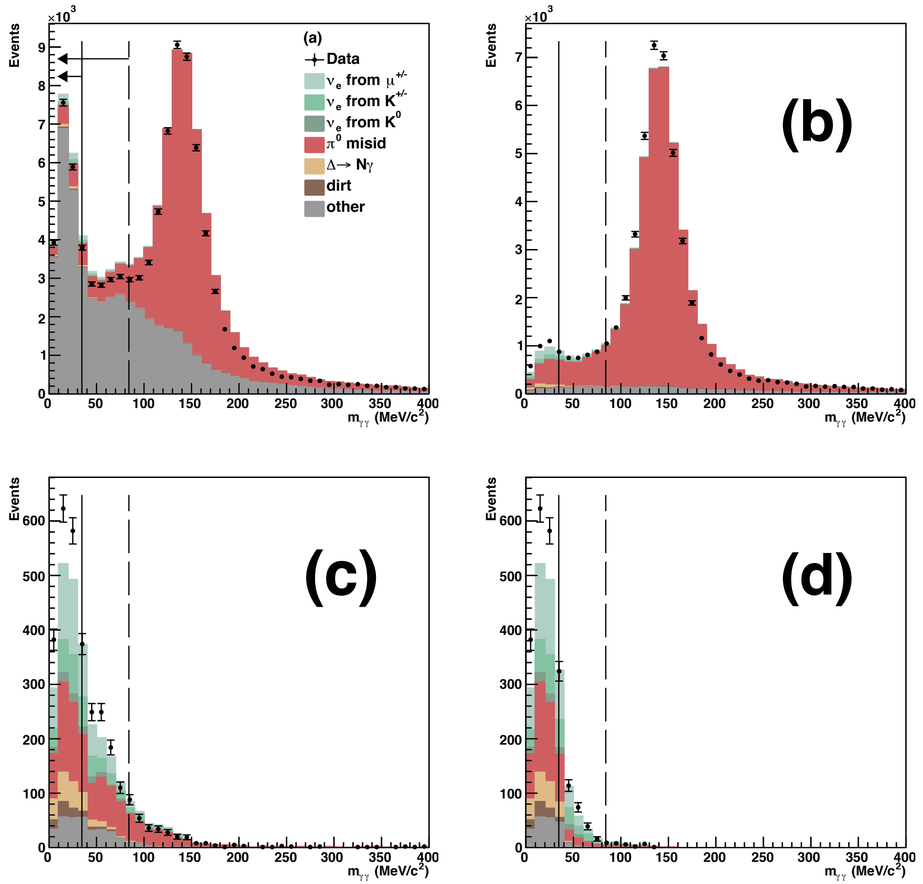
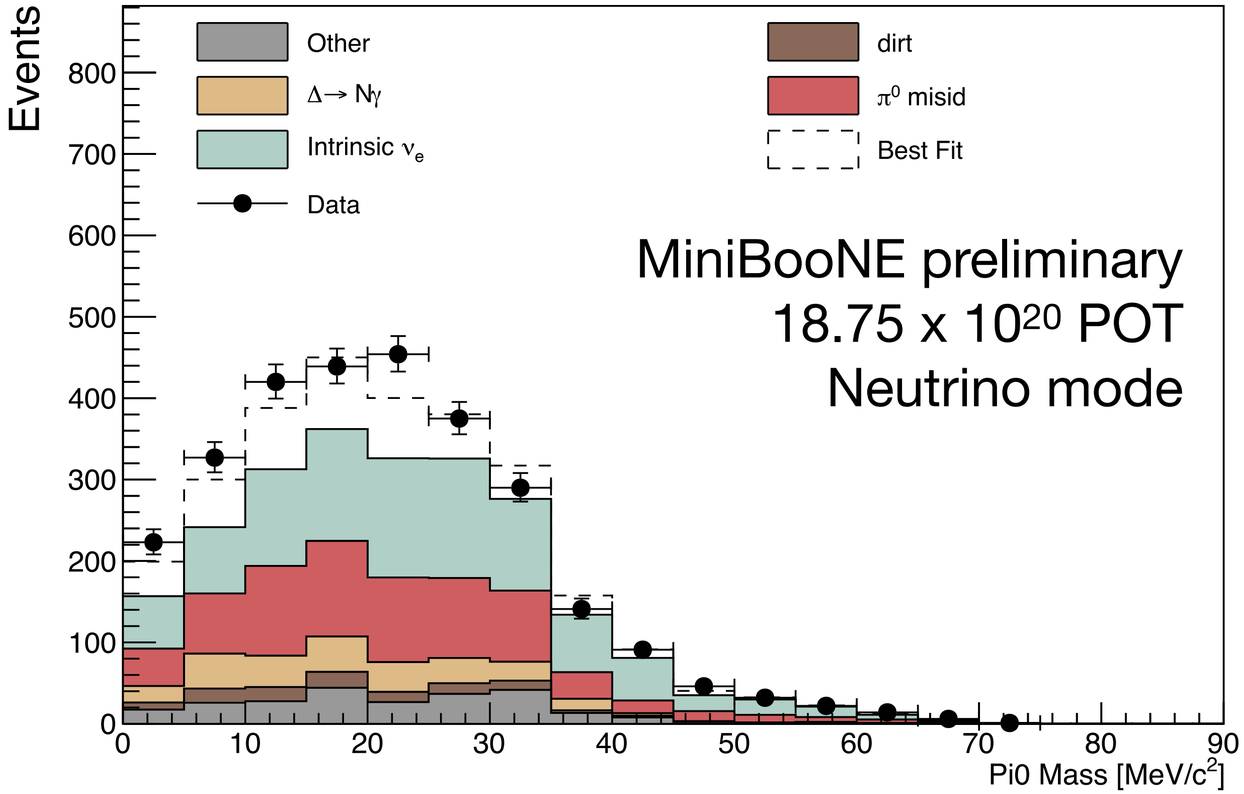



FIG. 11: Comparisons between the data and simulation for the gamma-gamma mass distribution after successive cuts are applied: (a) no PID cut, (b) electron-muon likelihood cut, (c) electron-muon plus electron-pion likelihood cuts, and (d) electron-muon plus electron pion likelihood cuts plus a gamma-gamma mass cut. The vertical lines in the figures show the range of energy-dependent cut values.