My Thoughts on MiniBooNE

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A Review of the MiniBooNE Excess

1. Short history of MiniBooNE.
2. Excess is EM-like, probably not a background
3. A look at key elements of the excess in neutrino, anti-neutrino, and beam dump mode – energy, angle, radius, timing, etc.
4. Is it neutrino or meson flux related?
5. What does the beam off target run tell us.
6. Anomaly within the anomaly – beam direction hot spot?!
7. My thoughts….

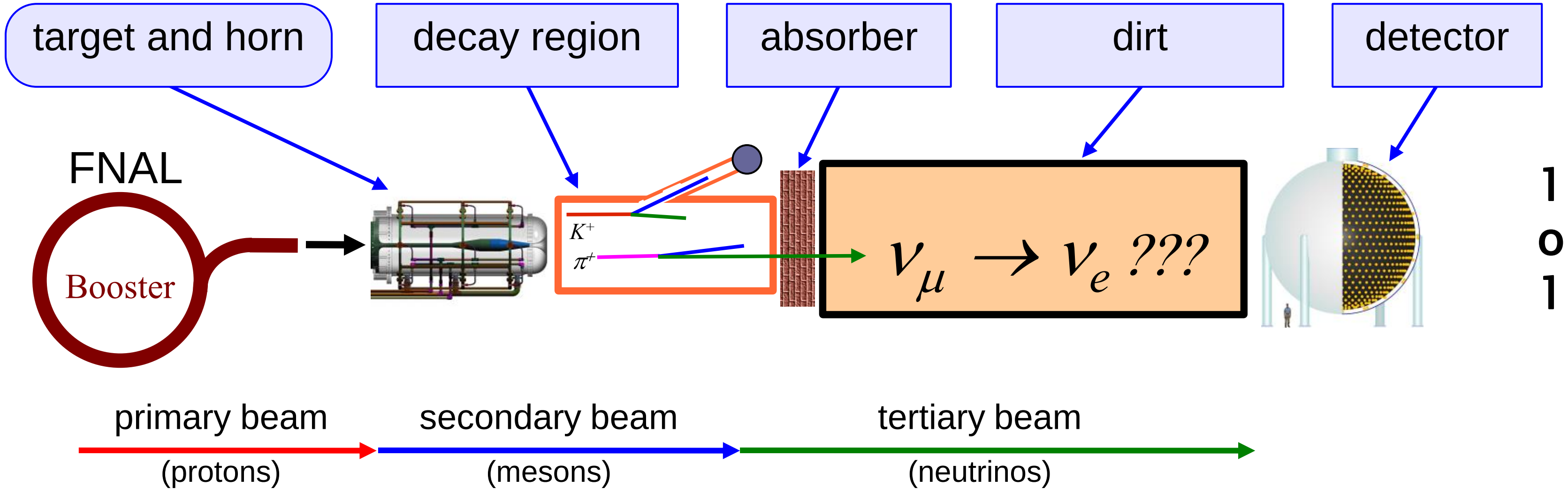
Los Alamos

MiniBooNE (2003-2018) was designed to test the LSND signal

Keep L/E same as LSND
while changing systematics, energy & event signature

$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27\Delta m^2 L/E)$ ➔ Two neutrino fits

LSND: E ~30 MeV L ~30 m L/E ~1
MiniBooNE: E ~500 MeV L ~500 m L/E ~1



1-kton mineral oil detector, 1500 PMT's

Neutrino mode: search for $\nu_\mu \rightarrow \nu_e$ appearance with 18.75E20 POT ➔ assumes CP/CPT conservation
Antineutrino mode: search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance with 11.27E20 POT ➔ direct test of LSND
Beam dump mode: exotic production from proton/neutral-pions: 1.8E20 POT ➔ dark matter search, other.

FNAL has done a great job delivering beam over 15 years!

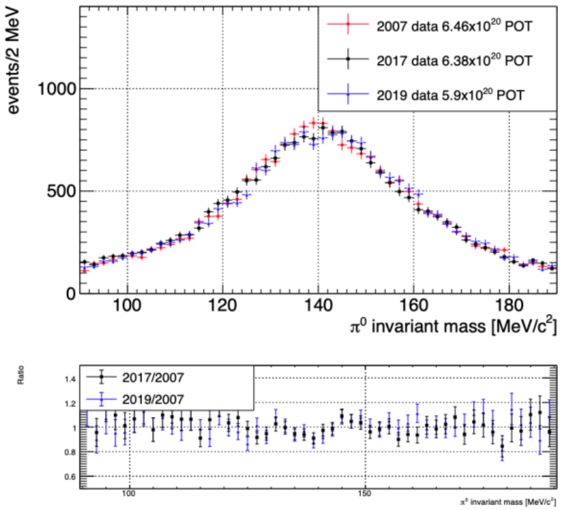
2. Neutrino beam

Stable over 15-year run!

MiniBooNE extracts beam from the 8 GeV Booster

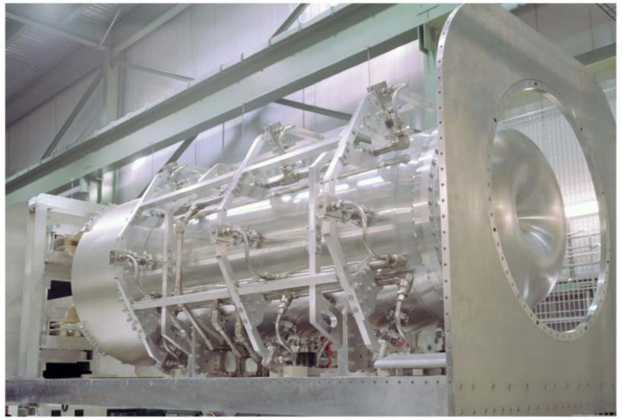
FNAL Booster

NC π^0 mass over time



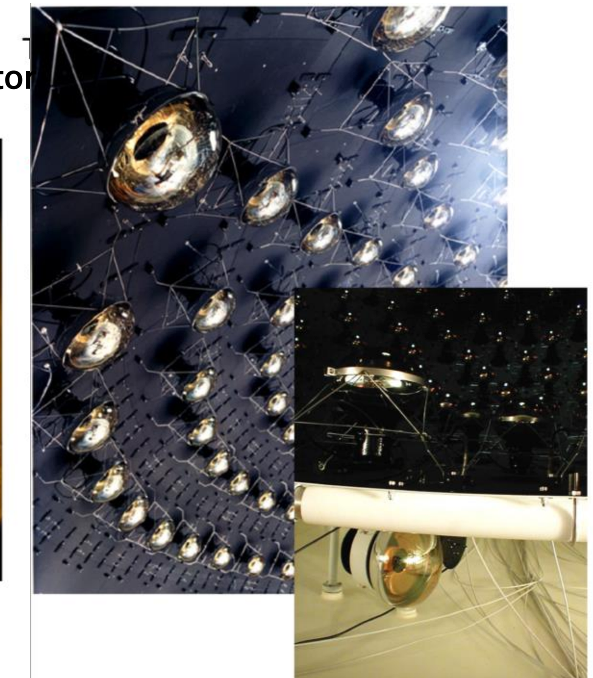
3. Events in the Detector

Magnetic focusing horn



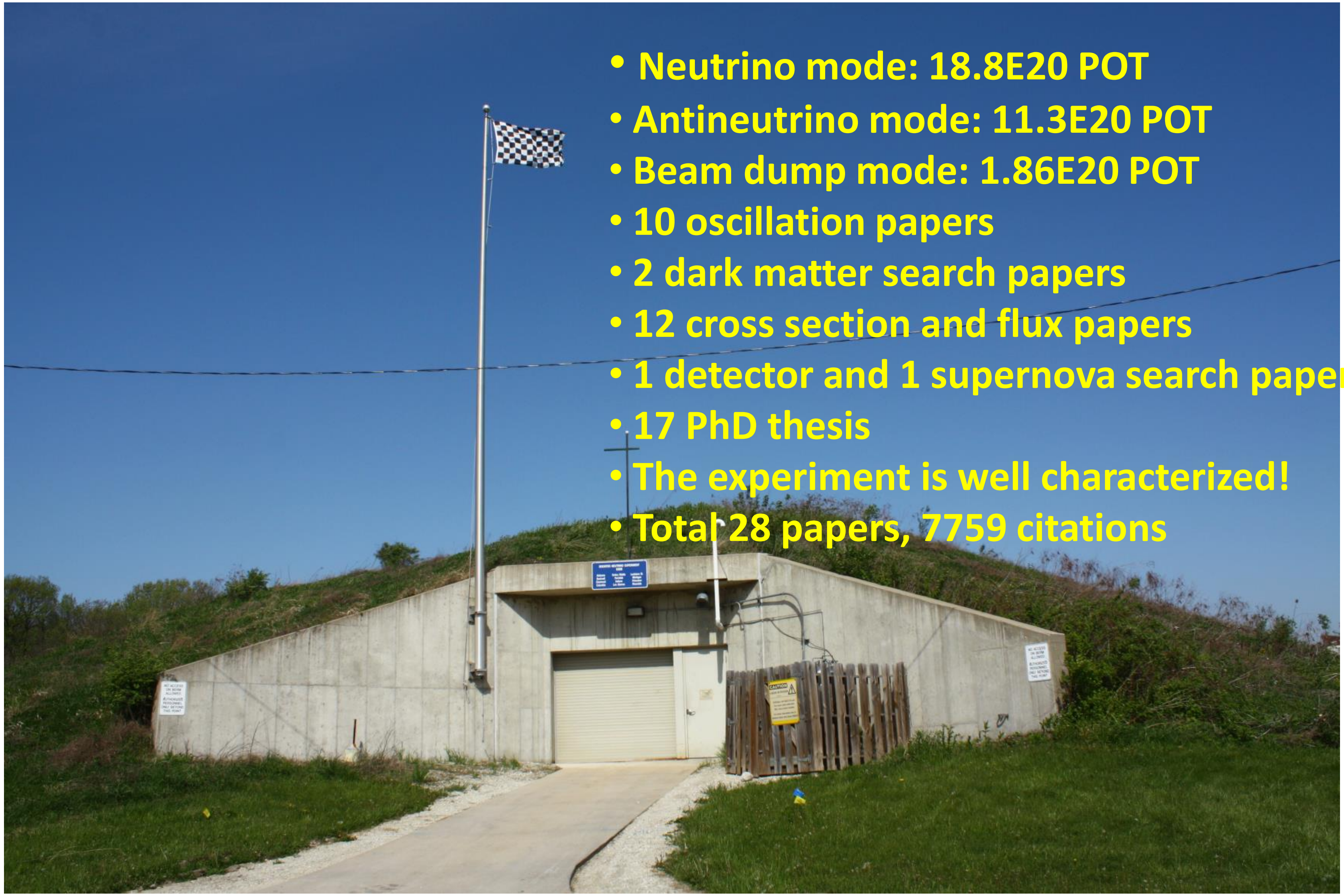
800-ton mineral oil Cerenkov detector
541 m downstream from horn

1520 8” PhotoMultipler Tubes (PMT)



MB detector is still there, could be turned on again…

~20 Years of Successful MiniBooNE Running and Results!

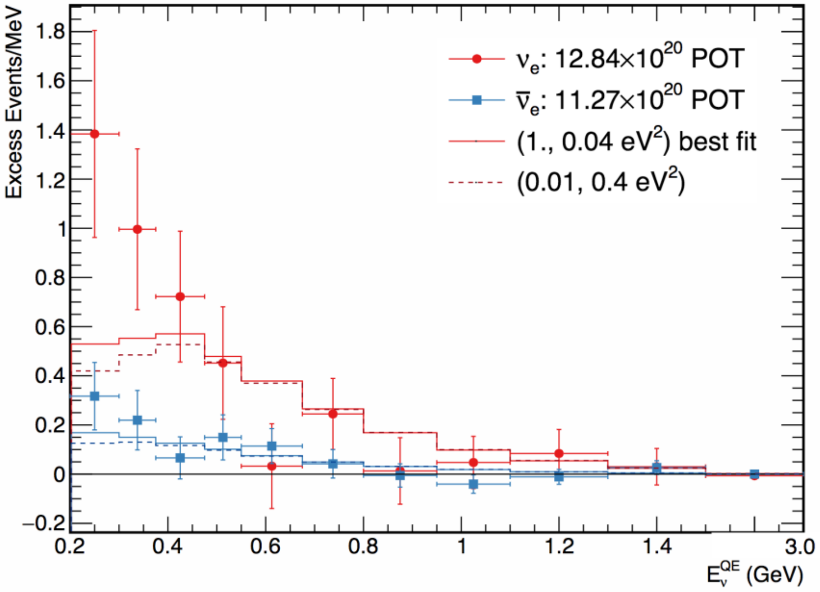


- Neutrino mode: 18.8E20 POT
- Antineutrino mode: 11.3E20 POT
- Beam dump mode: 1.86E20 POT
- 10 oscillation papers
- 2 dark matter search papers
- 12 cross section and flux papers
- 1 detector and 1 supernova search paper
- 17 PhD thesis
- The experiment is well characterized!
- Total 28 papers, 7759 citations

Robust Excess!

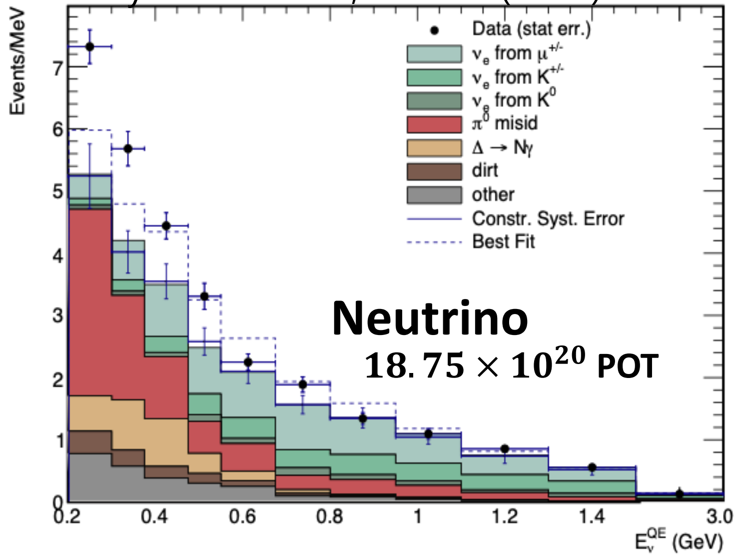
	ν mode	$\bar{\nu}$ mode	Combined
Data	2870	478	3348
Unconstr. Background	2322	398.2	2720.0
Constr.	2309	398.7	2707.7
Excess	560.6 ± 119.6 4.8σ	79.3 ± 28.6 2.8σ	639.9 ± 123.0 **5.2σ**
0.26% (LSND) $\nu_\mu \to \nu_e$	676.3	100.0	776.3

Statistical error is over 12σ!!!

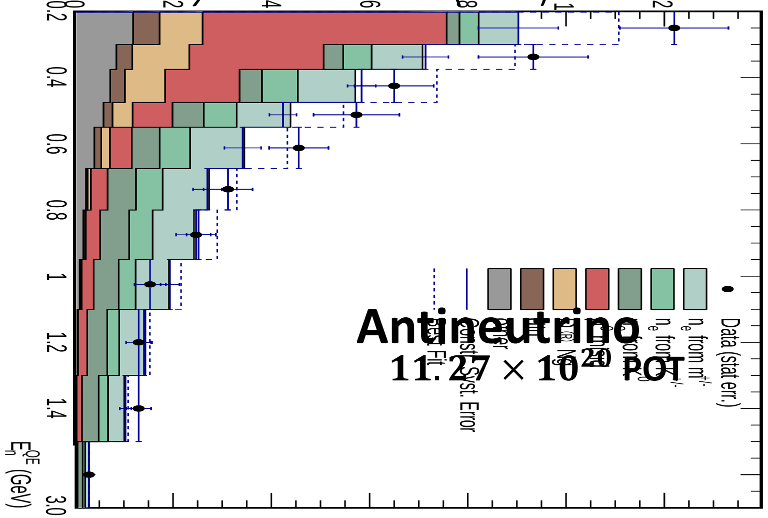


- Combined with LSND (3.8σ), total significance over 6σ

Phys. Rev. D 103, 052002 (2021)



Phys. Rev. Lett. 110 (2013) 161801



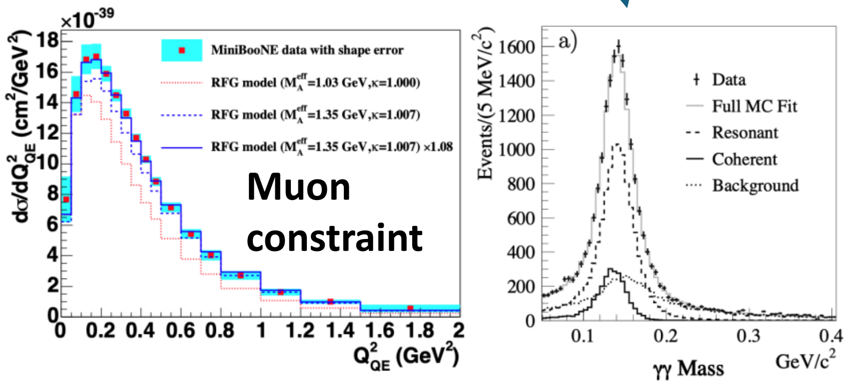
Neutrino/Antineutrino Excesses

most backgrounds constrained by high stats ν_μ rate (poor mans near detector)

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	107.6 ± 28.2	12.9 ± 4.3
NC π^0	732.3 ± 95.5	112.3 ± 11.5
NC $\Delta \rightarrow N\gamma$	251.9 ± 35.2	34.7 ± 5.4
External Events	109.8 ± 15.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	130.8 ± 33.4	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	621.1 ± 146.3	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	280.7 ± 61.2	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K^0_L Decay	79.6 ± 29.9	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	8.8 ± 4.7	6.7 ± 6.0
Unconstrained Bkgd.	2322.6 ± 258.3	398.2 ± 49.7
Constrained Bkgd.	2309.4 ± 119.6	400.6 ± 28.5
Total Data	2870	478
Excess	560.6 ± 119.6	77.4 ± 28.5
0.26% (LSND) $\nu_\mu \rightarrow \nu_e$	676.3	100.0

Constrained from high stats NC π^0 decay

Not constrained



muon constraint did not change central value, but reduced errors.

Got the LSND excess rate right, interesting…

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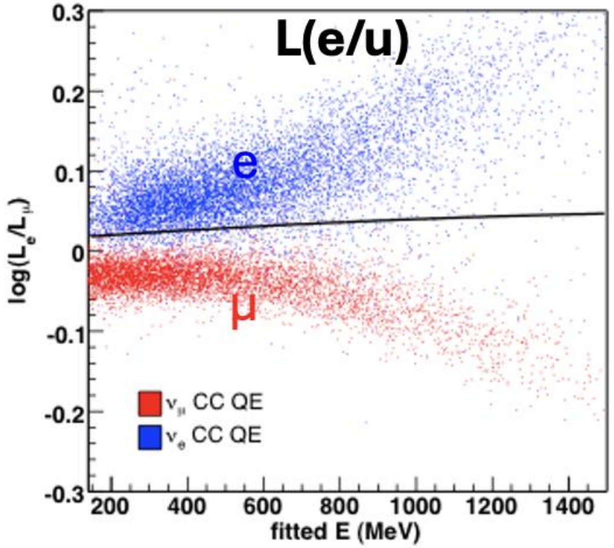
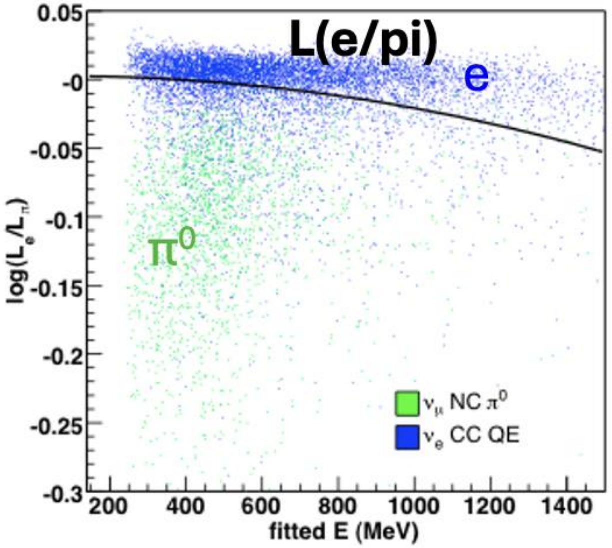
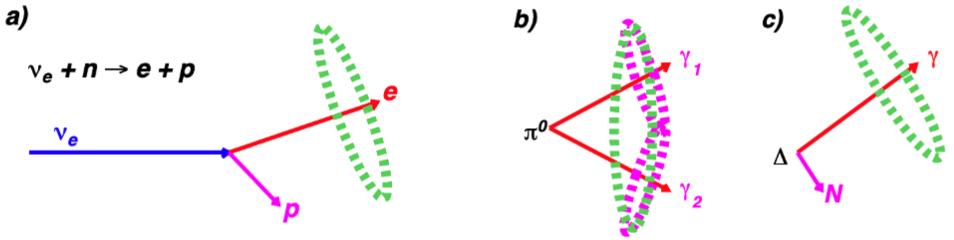
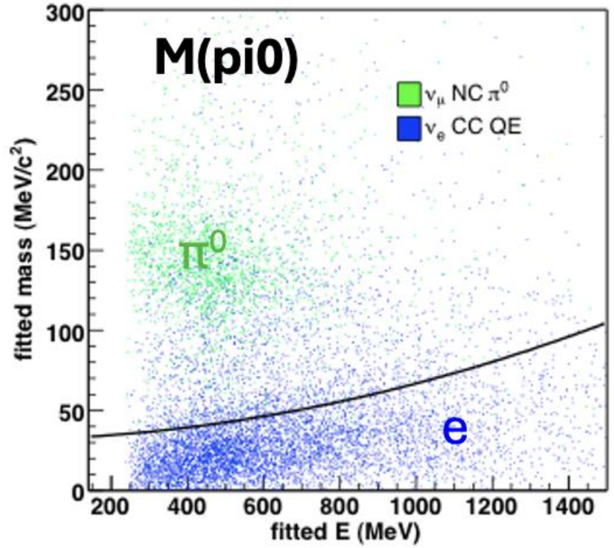
Excess EM-like γ/electron, or co-linear $\gamma\gamma$/e+e-. No information on hadronic final states



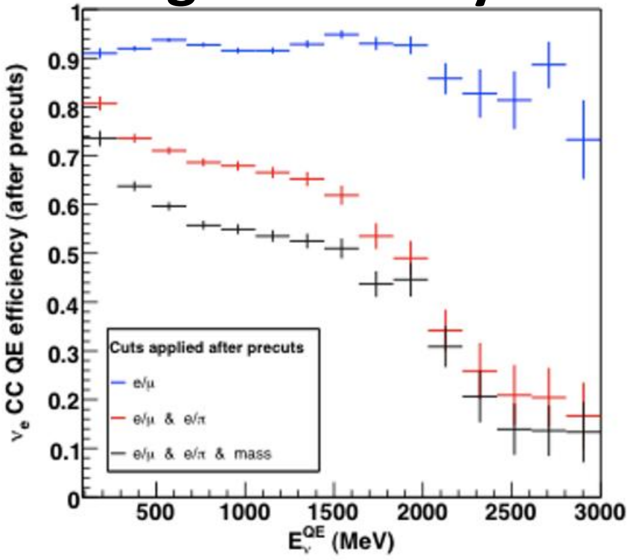


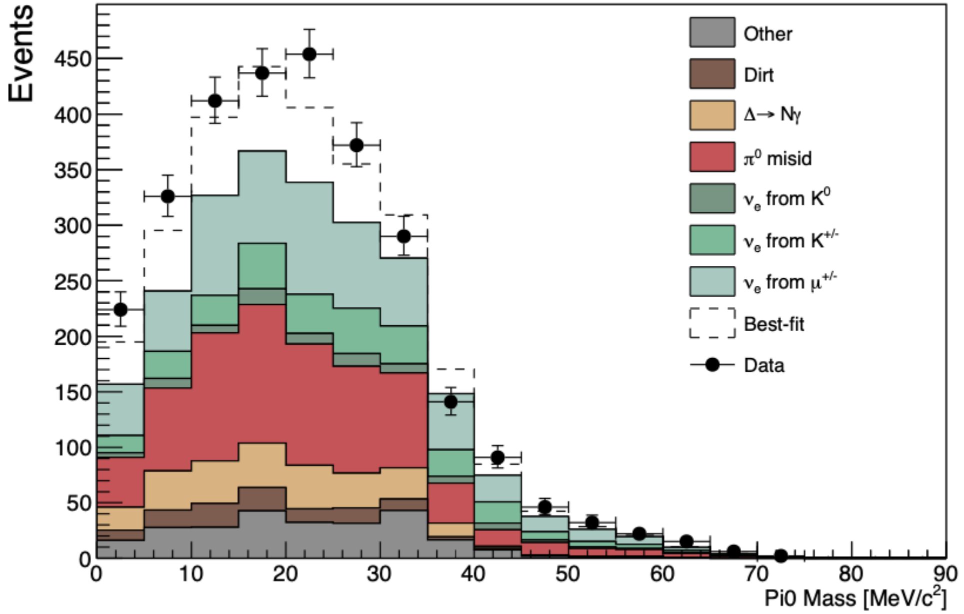


Oscillation cuts select low mass π^0 candidates
small opening angle $\boldsymbol{\gamma\gamma}$
=>Mass equation: $M^2 = 2E_1E_2(1\text{-}\cos\theta)$



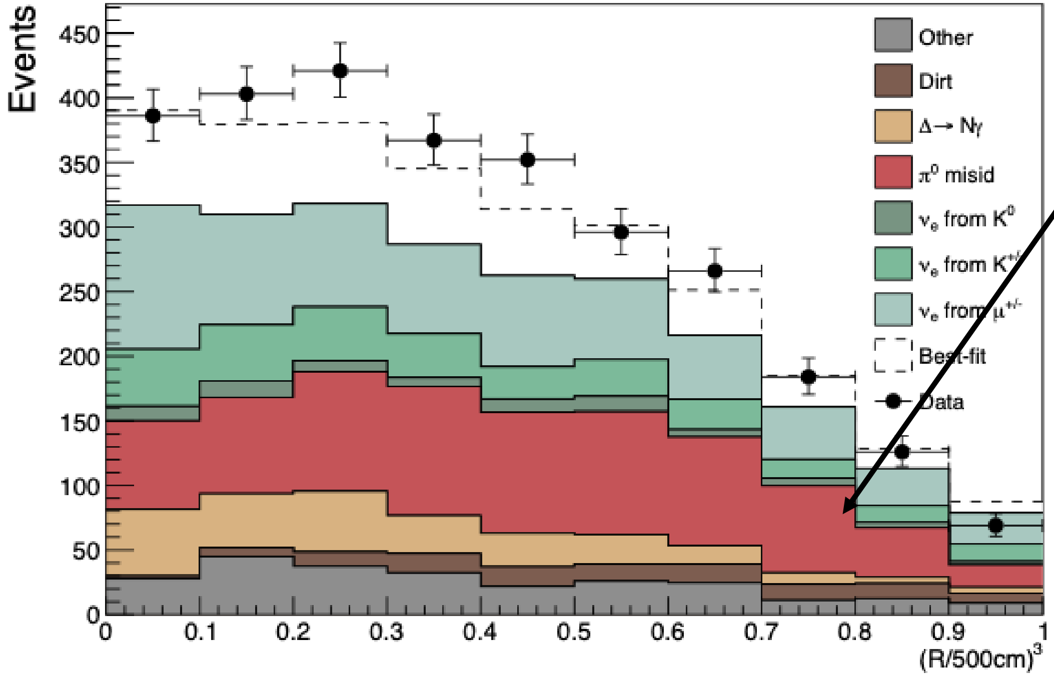
High Efficiency!





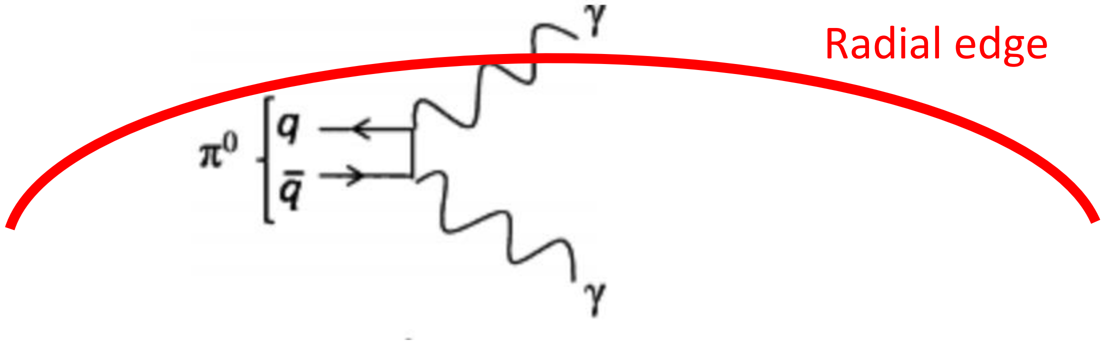
MiniBooNE Background Radial Distributions: π^0 misID disfavored

Neutrino oscillation-cut sample
Volume normalize radius



γ/electron (excess) efficiency decreases near wall due to ~meter extended track length

π^0 decay lose one gamma-ray at detector edge creating mis-ID electron-like event.



Excess falls off at wall more rapidly due to lower efficiency.
Tighter radial cuts increases excess significance

Selection	Data	Background	Excess	Significance
$200 < E_\nu^{QE} < 1250$ MeV & $R < 5m$	2870	2309.4 ± 119.6	560.6 ± 119.6	4.7σ
$150 < E_\nu^{QE} < 1250$ MeV & $R < 5m$	3172	2560.4 ± 131.5	611.6 ± 131.5	4.7σ
$200 < E_\nu^{QE} < 1250$ MeV & $R < 4m$	1978	1519.4 ± 81.9	458.6 ± 81.9	5.6σ
$200 < E_\nu^{QE} < 1250$ MeV & $R < 3m$	864	673.9 ± 41.2	190.1 ± 41.2	4.6σ

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MiniBooNE Background Radial Distributions: Dirt and pi0 disfavored

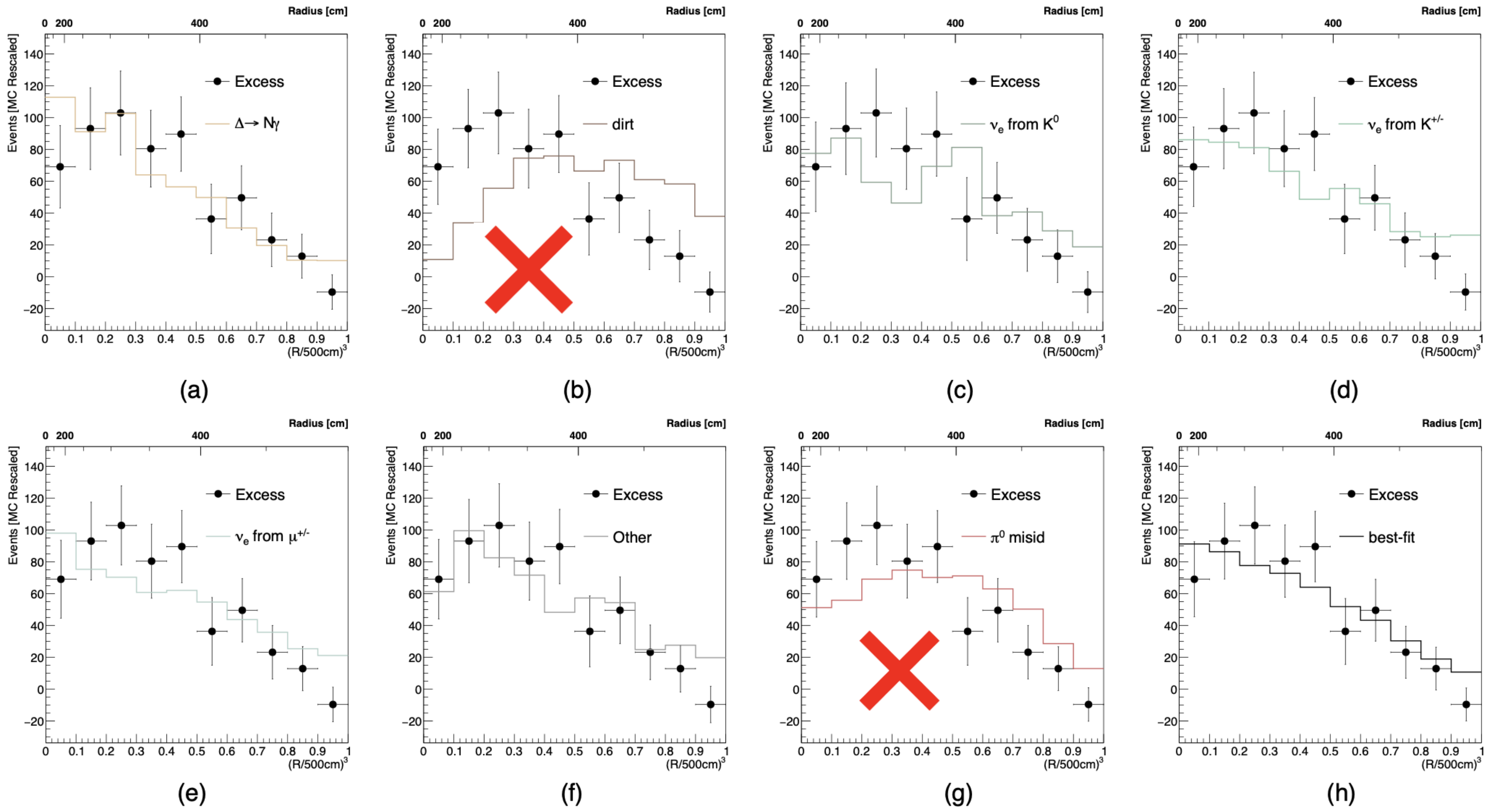

TABLE IV: *The result of log-likelihood shape-only fits to the radial distribution in neutrino mode, assuming only statistical errors, where different processes are normalized to explain the observed event excess. The two-neutrino hypothesis fits the radial distribution best with a $\chi^2 = 8.4/9ndf$, while the NC π^0 hypothesis has a worse fit with a $\chi^2 = 17.2/9ndf$. Also shown is the multiplicative factor that is required for each hypothesis to explain the observed event excess.*

Hypothesis	Multiplicative factor	$\chi^2/9ndf$
NC $\Delta \to N\gamma$ 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

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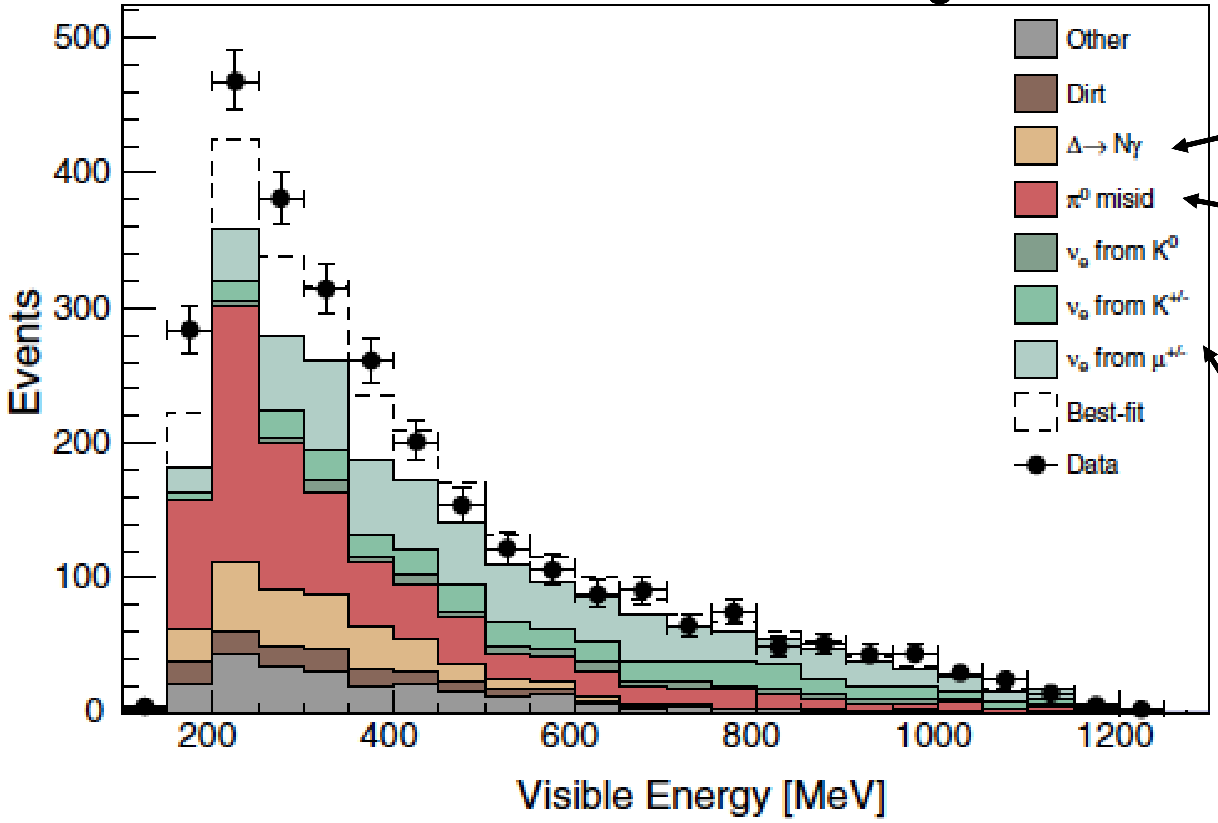
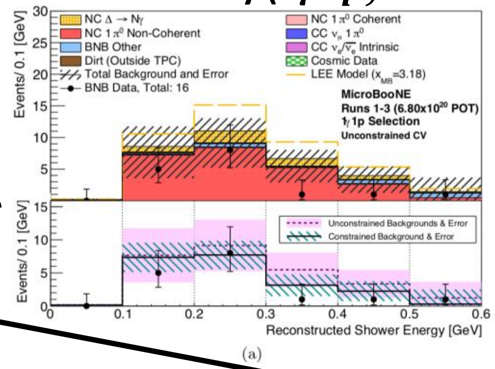
Recent MicroBooNE Results (arXiv 2110.00409 + 2110.14054 + other uB papers) confirms MiniBooNE backgrounds

New MicroBooNE results demonstrates MB excess is robust – confirmed Delta radiative, π^0, and intrinsic υ_e backgrounds estimates.

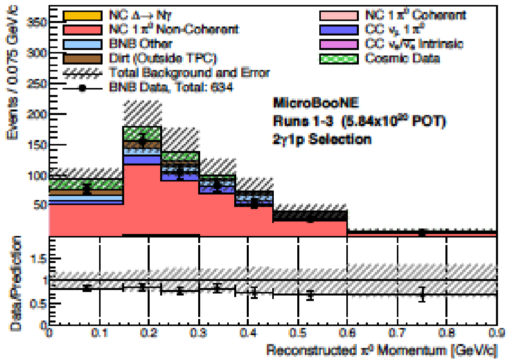
uB confirms MB standard model backgrounds



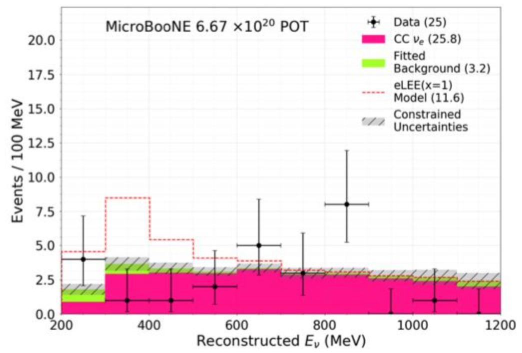
Delta Decay ($1\gamma 1p$)



π^0 ($2\gamma 1p$)

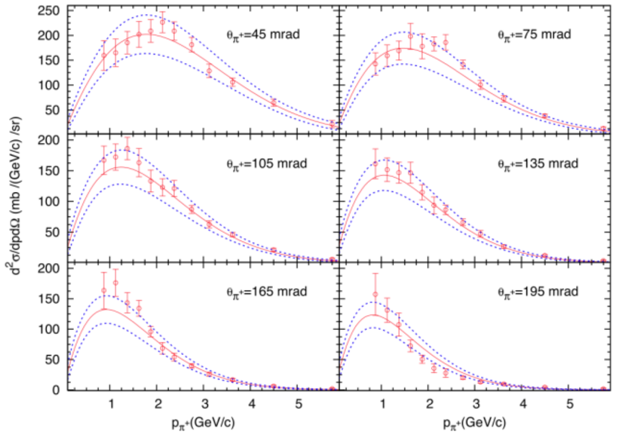


Intrinsic υ_e (1e1p)



Low Energy Roll Over: Not run-away backgrounds!

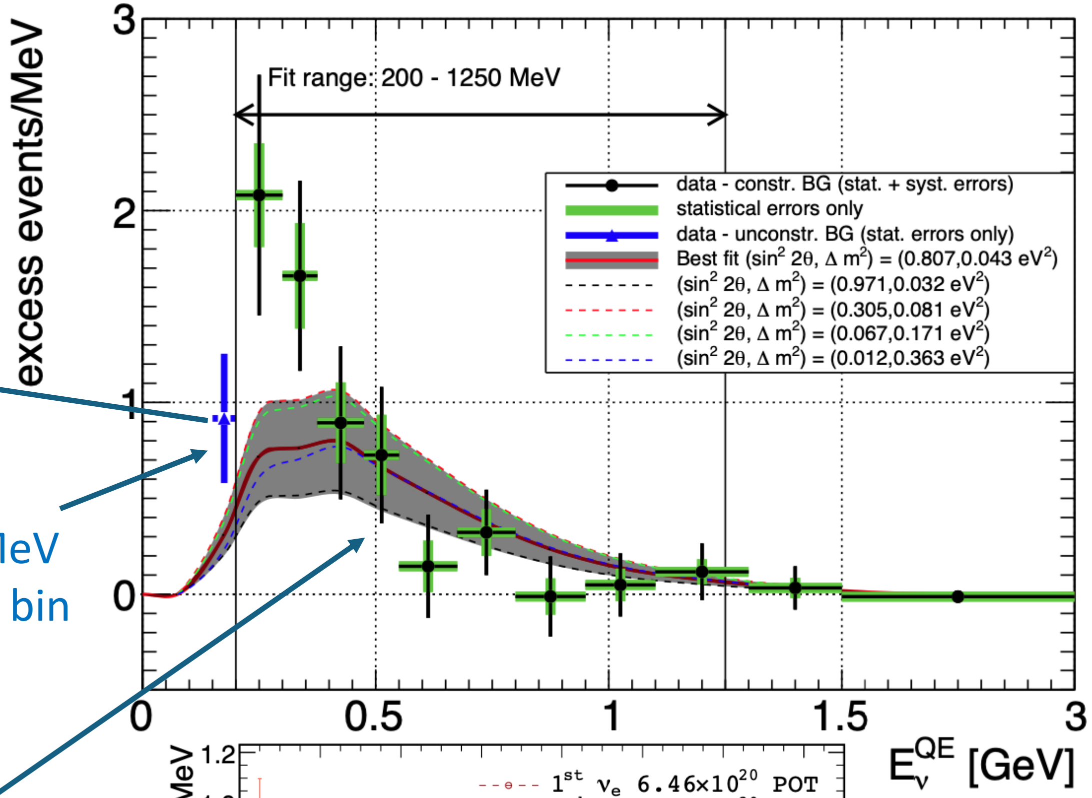
Expect event turn over as beam produced pion flux turns off at low E



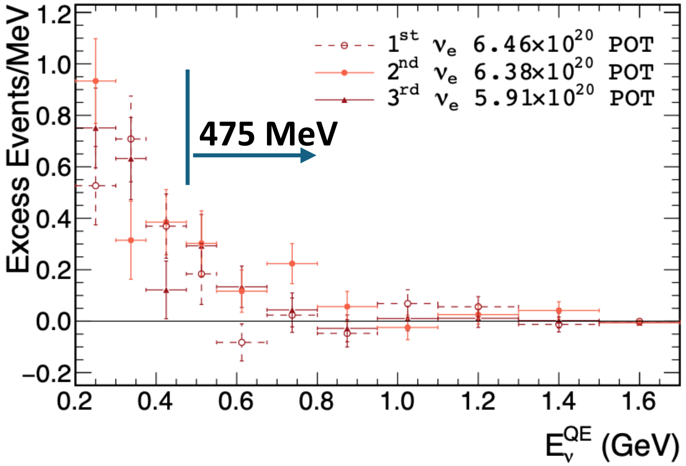
Phys. Rev. D 79 (2009) 072002

HARP pion flux measurement on Be with 8.9GeV protons

Neutrino mode 18.75E20POT, Phys Rev D 103 (2021) 5, 052002



New 150 MeV low energy bin



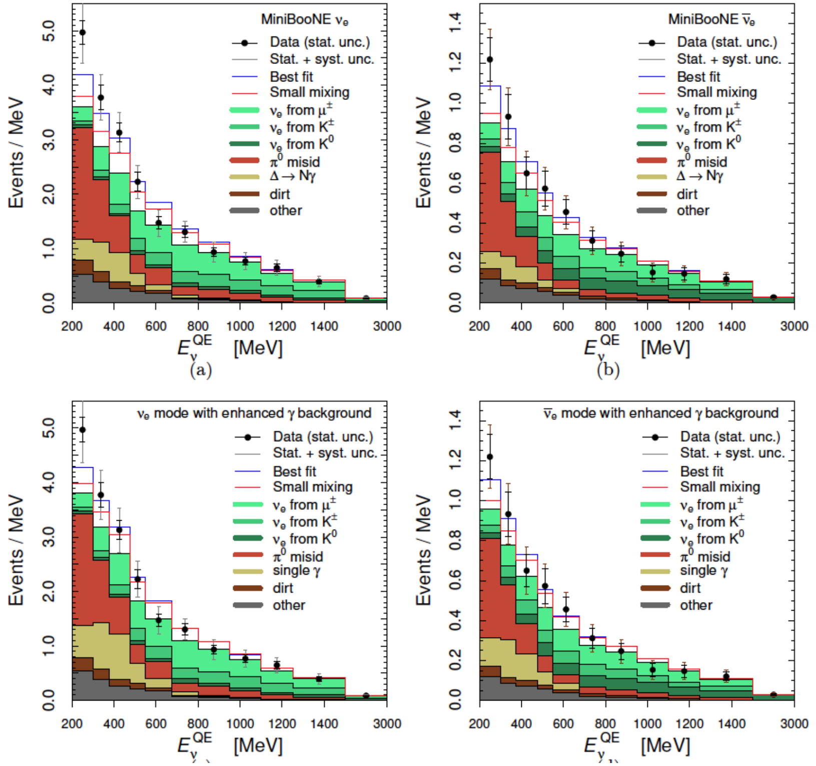
More data increased excess > 475MeV
No longer just a LEE!

Significant low energy peak not consistent with oscillations, but higher energy excess more consistent with oscillations.
=> two processes at work?

Other Background Tests/Studies

Increase Delta decay rate (single γ)

C. Giunti, A. Ioannisian. G. Ranucci
arXiv: 1912.01524



	MB	$\widetilde{\text{MB}}$	LSND+MB	LSND+$\widetilde{\text{MB}}$	App+MB	App+$\widetilde{\text{MB}}$
χ^2_{min}	22.8	20.9	29.5	21.8	81.1	72.3
NDF	20	20	25	31	69	75
GoF	30%	40%	24%	89%	15%	57%
$\Delta m^{2(\text{bf})}_{41}$	0.0417	0.0372	0.046	0.0398	0.58	0.692
$\sin^2 2\vartheta^{(\text{bf})}_{e\mu}$	0.98	0.98	1.00	1.00	0.0065	0.004

Table 2. Minimum χ^2, number of degrees of freedom (NDF) and Goodness of Fit (GoF) of the analyses of the data of short-baseline $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ experiments discussed in the text without (MB) and with ($\widetilde{\text{MB}}$) our enhanced single-γ background in MiniBooNE. $\Delta m^{2(\text{bf})}_{41}$ and $\sin^2 2\vartheta^{(\text{bf})}_{e\mu}$ are the best-fit values of the corresponding oscillation parameters.

Different Pi0 generators

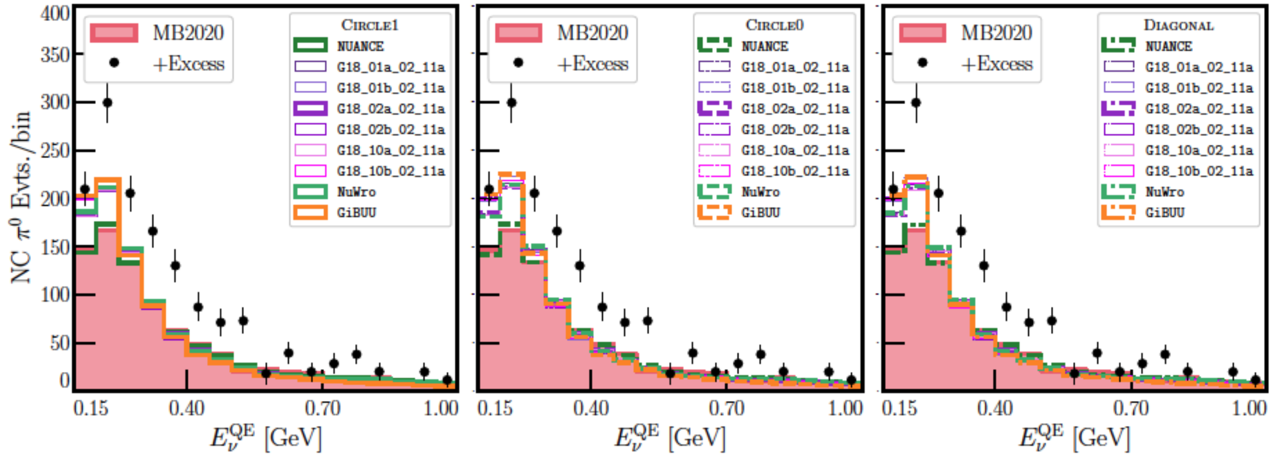
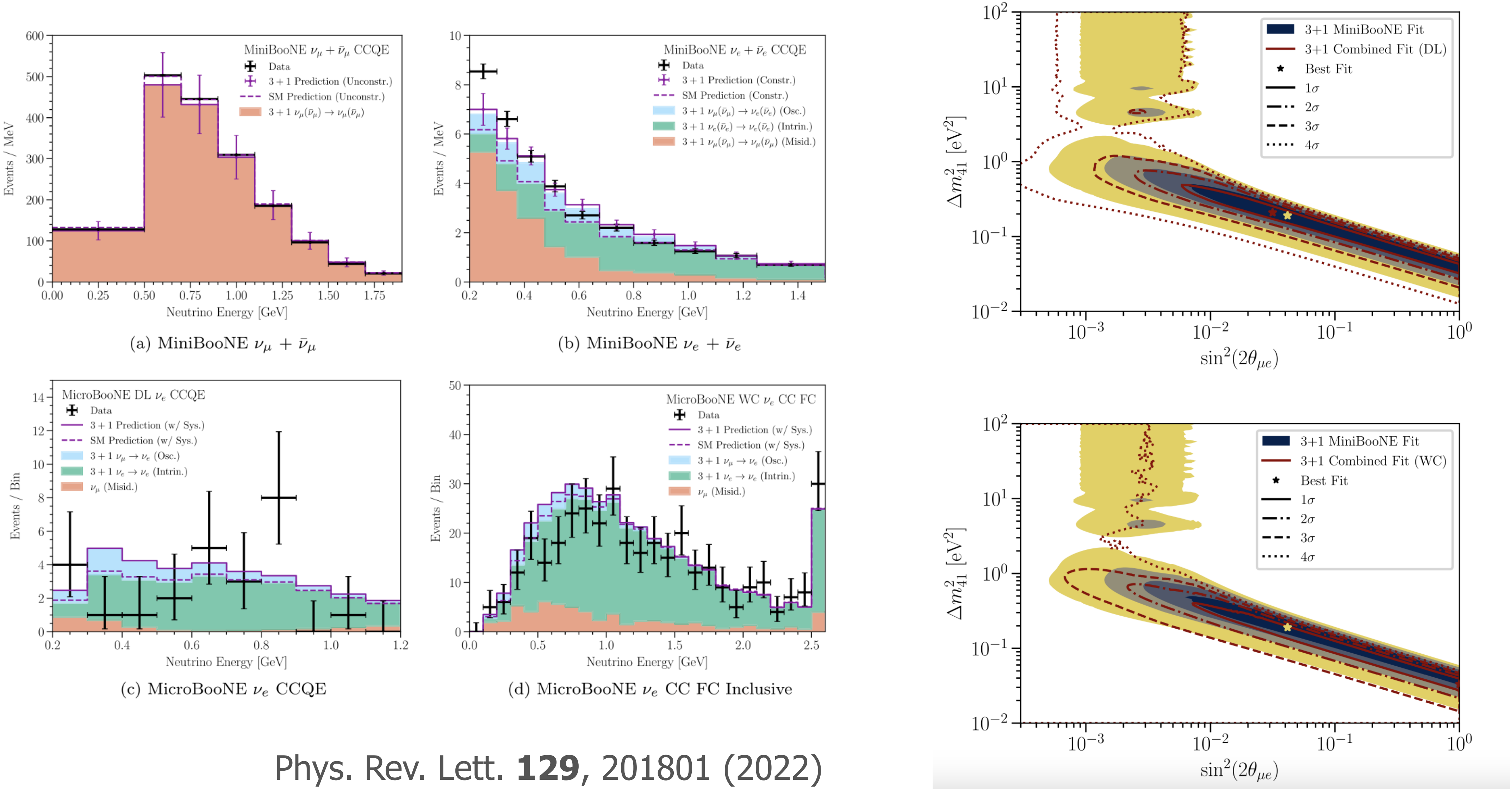


Figure 12. Predicted distributions of NCπ^0 background events in MiniBooNE (neutrino mode) as a function of the reconstructed neutrino energy, E_ν^{QE}, from different Monte Carlo generators. In each case, we derive the π^0/e^- separation cut using our NUANCE (the generator used by MiniBooNE) MC samples and apply them to the various generators. The three panels correspond to the three different cut shapes introduced in section 3.1. The official MiniBooNE background prediction [2] is shown in red.

arXiv: 2210.08021, Kelly&Kopp

MicroBooNE and MiniBooNE 3+1 combined fit: MiniBooNE excess dominates



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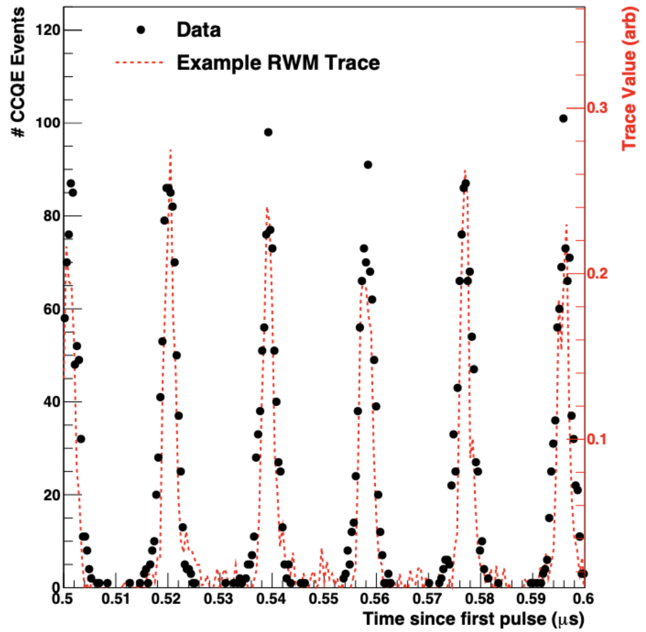
~nsec timing wrt beam: Excess events travel at/near speed of light

High stats muon neutrino data matches 53MHz RF beam structure



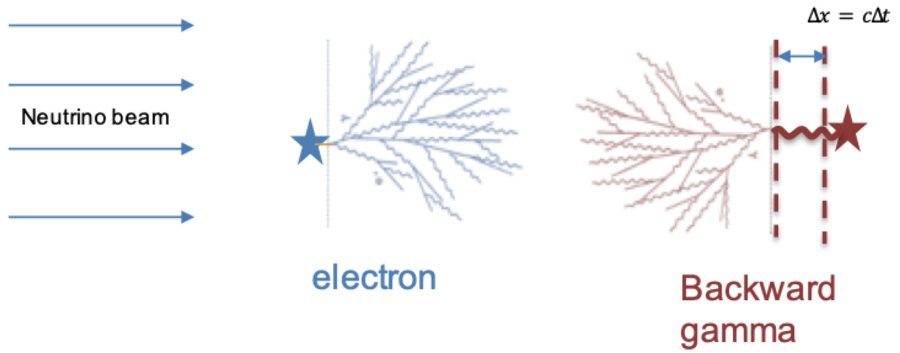
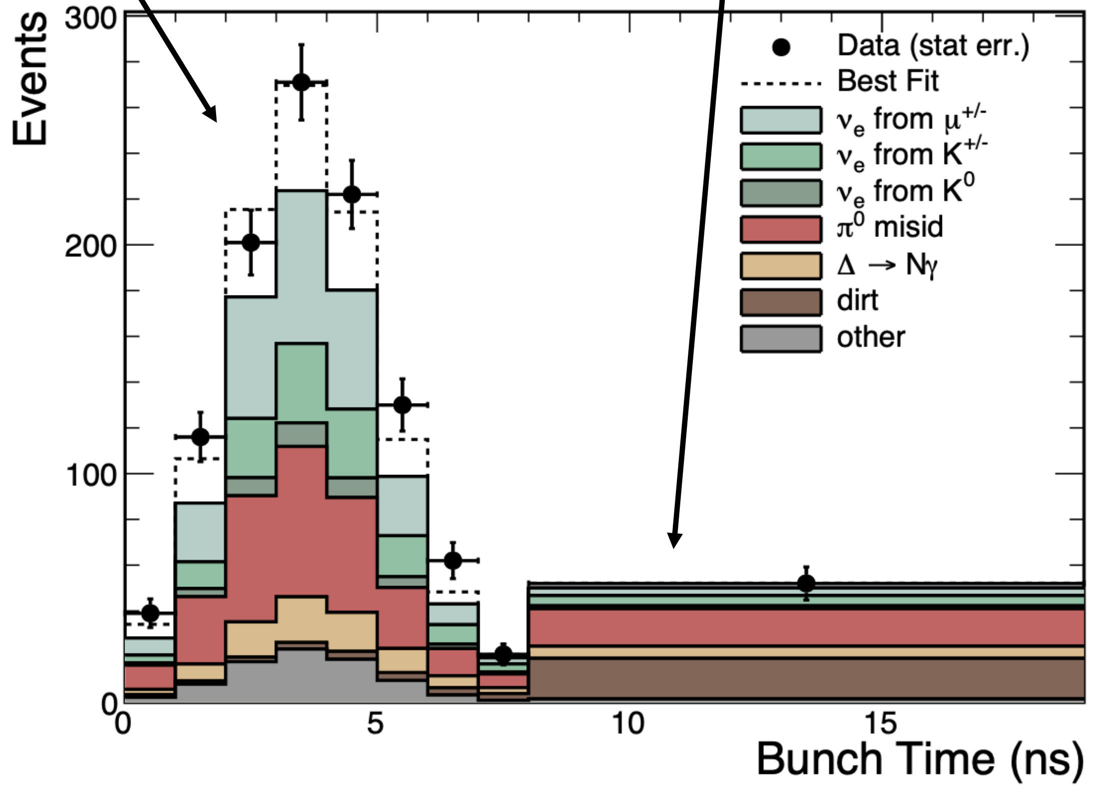


FIG. 14. Illustration of the timing difference between an electron event and a backward-going photon.

Excess events at or near the speed of light < 50MeV particle

Disfavors pi0 and dirt



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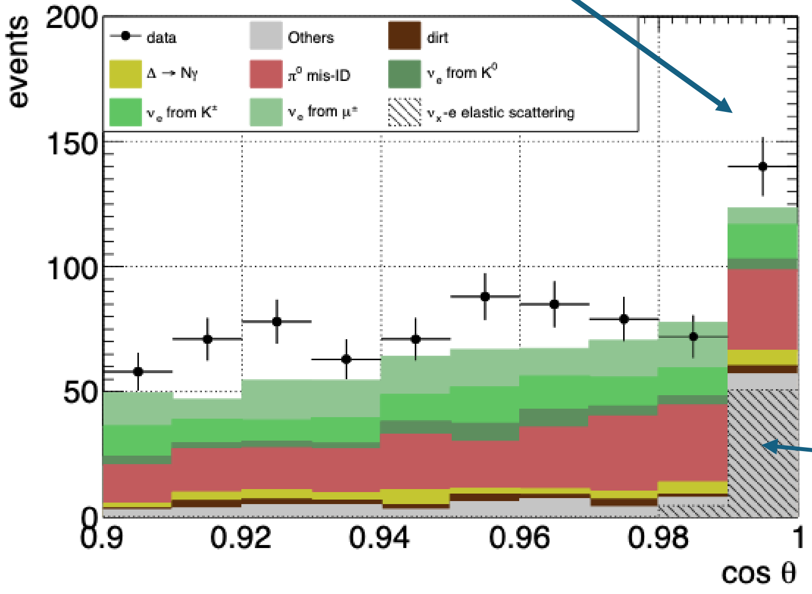
Very forward pointing angle wrt beam: Elastic Scattering

No funny business from muon neutrino magnetic moment, NC dark matter scattering, etc



Expected ν-e ES scattering

FIG. 16: The MiniBooNE neutrino mode $\cos\theta$ distribution for $\cos\theta > 0.9$, corresponding to the total 18.75×10^{20} POT neutrino data in the visible energy range from 150 to 1250 MeV, for ν_e CCQE data (points with statistical errors) and predicted backgrounds (colored histograms). Neutrino-electron elastic scattering events are shown as the hatched region in the "Others" category.

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Neutrino Angular (wrt beam) distributions

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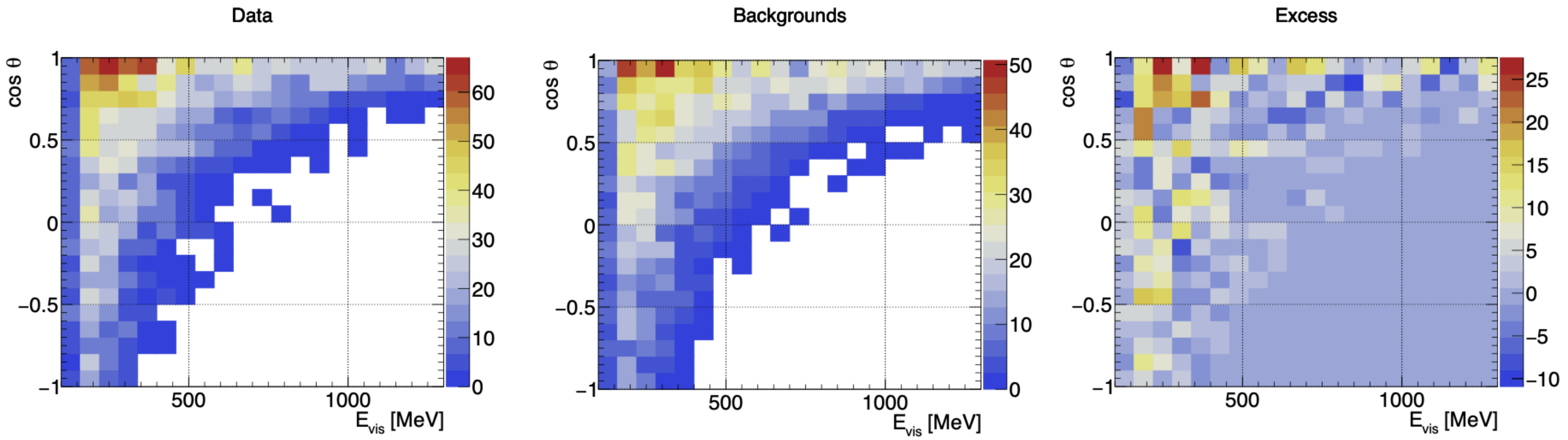
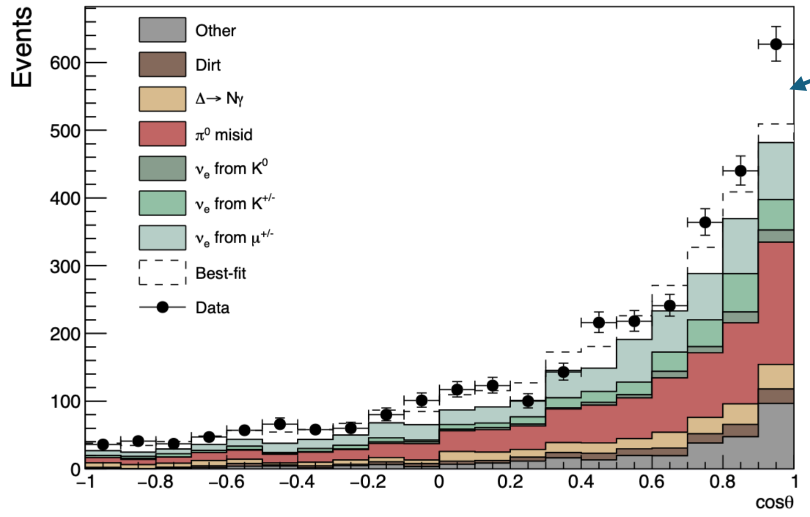
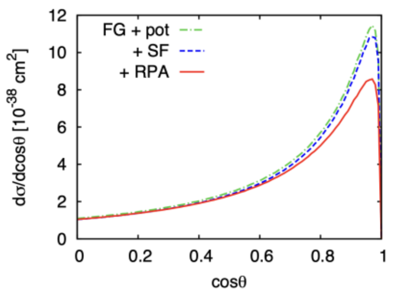
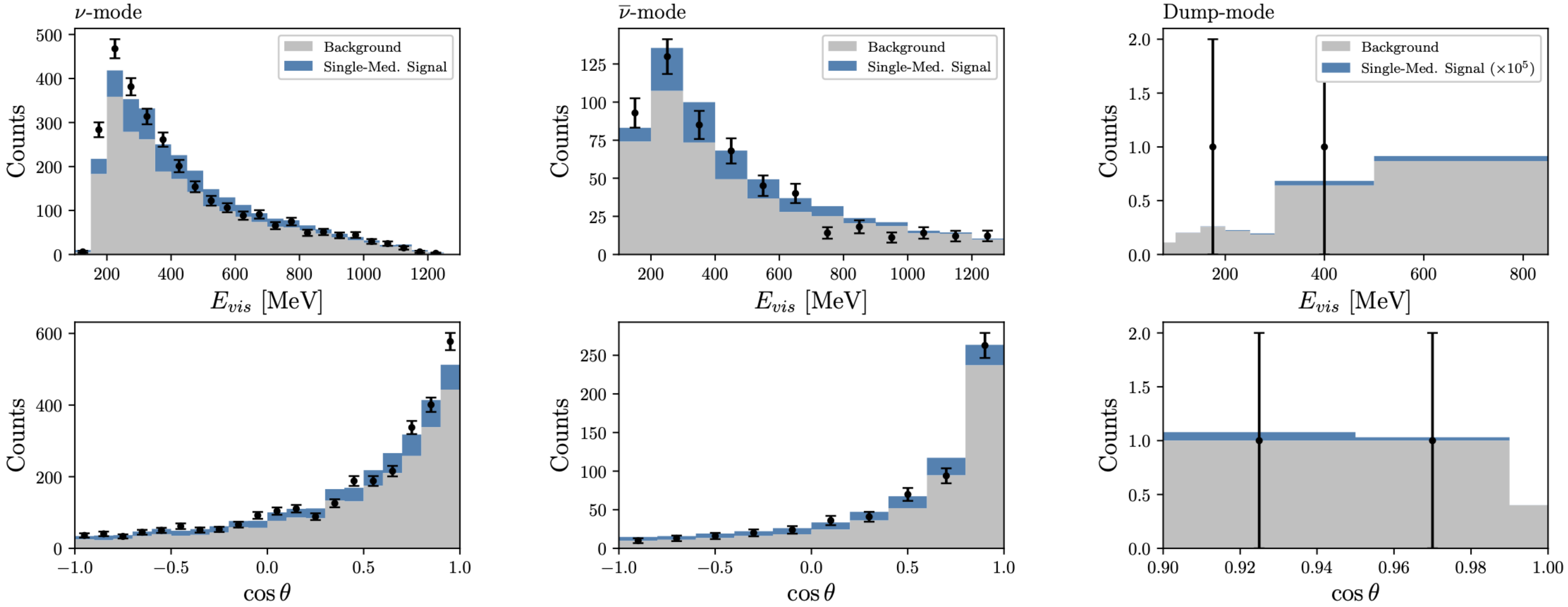


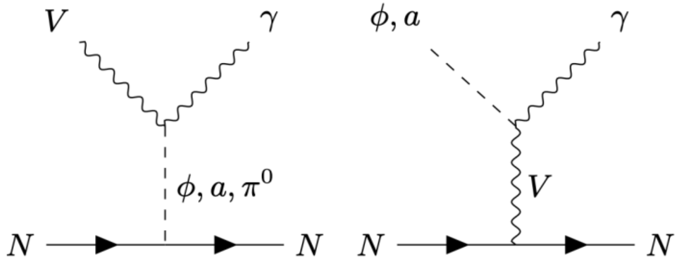


3+1 osc hypothesis tension at small angle: CC ν_e has significant backward distribution



Off forward e/γ scattering via >MeV Mediator





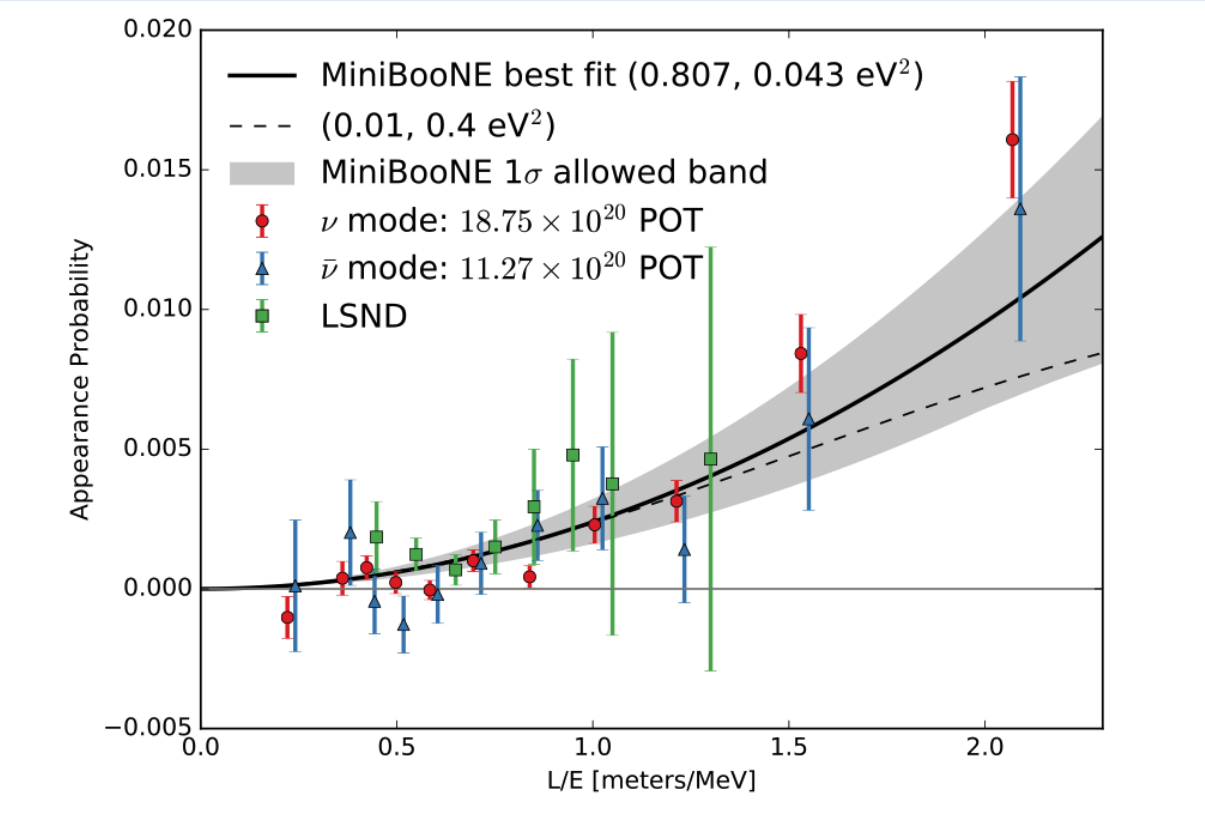
One example process – photo-conversion: **See Adrian Thompsons talk (arXiv:2309.02599)**

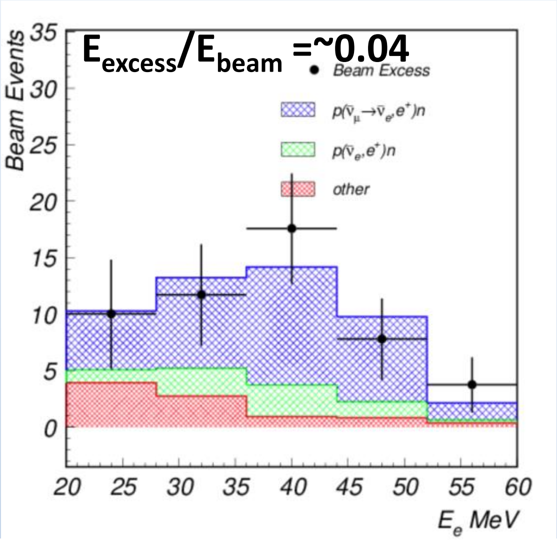
Many other examples will be presented at this work-shop.

MiniBooNE and LSND consistent with oscillation or beam dump interpretation

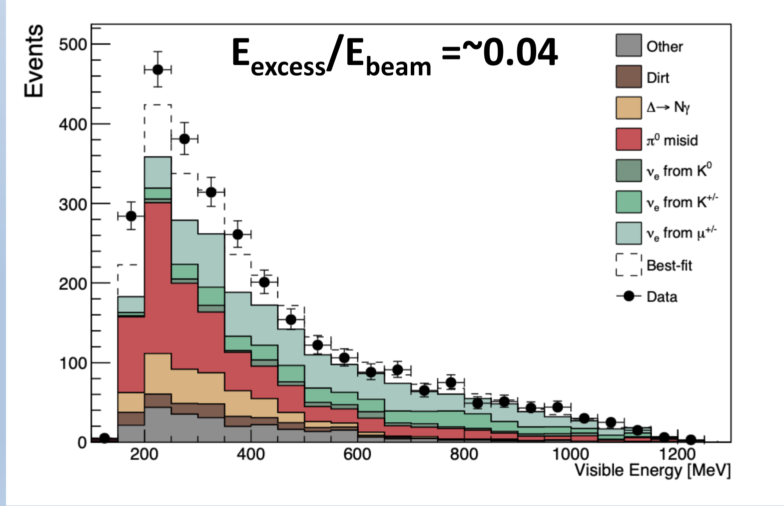
or E_{excess}/E_{beam} (long lived particle production)

Similar L/E oscillations,





e+ and neutron

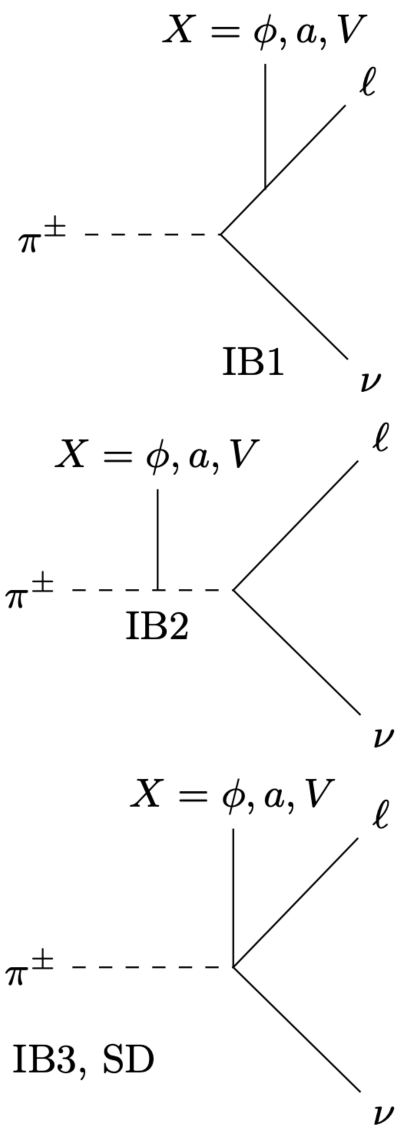


e or photon

- MiniBooNE L/E consistent with LSND excess => oscillations?
- MiniBooNE E_{excess}/E_{beam} same as LSND => beam dump particle production?

Rare Meson Decay Solutions (Meson Portal)

Excess rates between nu/antinu and beam-dump scale with neutrino flux **OR** charged meson rates.



Neutrino experiments have large meson flux and sensitive detectors. Competitive/better than current limits from traditional rare meson decay searches.

Vector-portal dark matter			
Scenario	$(m_{V_1}, m_{V_2}, m_\chi, m_{\chi'})$	$\epsilon_1\epsilon_2 g_2'^2/(4\pi)$	χ^2/dof
Single	$(17, -, 8, 40)$ MeV	3.6×10^{-9}	2.5 (2.9)
Double	$(17, 200, 8, 50)$ MeV	1.3×10^{-7}	2.2 (2.6)
Long-lived (pseudo)scalar			
Scenario	$(m_{Z'}, m_{\phi/a})$	$g_\mu g_n \lambda$ [MeV^{-1}]	χ^2/dof
Scalar	$(49, 1)$ MeV	2.2×10^{-8}	2.0 (2.1)
Pseudoscalar	$(85, 1)$ MeV	5.9×10^{-7}	2.0 (2.1)

TABLE I. Summary of example fits. In the single-mediator scenario, m_{V_2} is irrelevant, and $\epsilon_2 = \epsilon_1$ and $g_2' \to g_1'$. Due to the mass values of the mediators appearing in the scattering process, we fit the data in the limit of nucleon (nucleus) scattering for the double-mediator scenario (the others). The χ^2 in the parentheses are the values with statistics only.

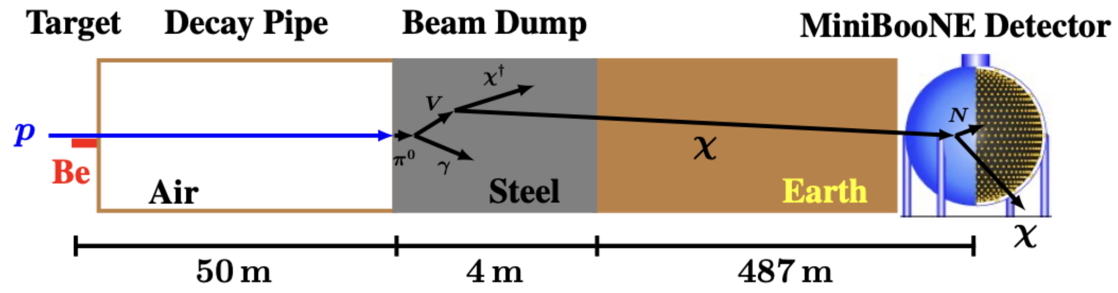
Channel (BR)	limit ($\times 10^{-8}$)	Model i) ($\times 10^{-12}$) Single	Model i) Double	Model ii) ($\times 10^{-8}$) ϕ	Model ii) a
$K \to \mu\nu_\mu V(\phi)$ [78]	2000 (300)	500	680	230	100
$K \to e\nu_e\nu\nu$ [53]	6000	530	720	–	–
$K \to \mu(e)\nu_{\mu(e)}ee$ [53]	7.4(2.7)	500(530)	680(720)	–	–
$\pi \to \mu(e)\nu_{\mu(e)}X$ [79]	600(50)	0.12(25)	0.17(34)	120(–)	1.1(–)
$\pi \to \mu(e)\nu_{\mu(e)}ee$ [53]	– (0.37)	0.12(25)	0.17(34)	–	–

TABLE II. Relevant exotic decays of $\pi^\pm/K^\pm$ and existing upper limits at 90% CL. X stands for invisibly decaying (massive) bosons. The predicted BRs (third though last columns) are based on the following parameter choices: $(\epsilon_1, \frac{g_1'^2}{4\pi}) \simeq (6.0 \times 10^{-5}, 1)$ for the single-mediator scenario, $(\epsilon_1, \epsilon_2, \frac{g_2'^2}{4\pi}) \simeq (7.0 \times 10^{-5}, 1.0 \times 10^{-4}, 0.5)$ for the double-mediator scenario, $(g_\mu, g_n, \lambda) \simeq (5 \times 10^{-3}, 10^{-2}, 4.4 \times 10^{-4}$ MeV$^{-1})$ for the scalar scenario, and $(g_\mu, g_n, \lambda) \simeq (10^{-2}, 10^{-2}, 6.5 \cdot 10^{-3}$ MeV$^{-1})$ for the pseudo-scalar scenario.

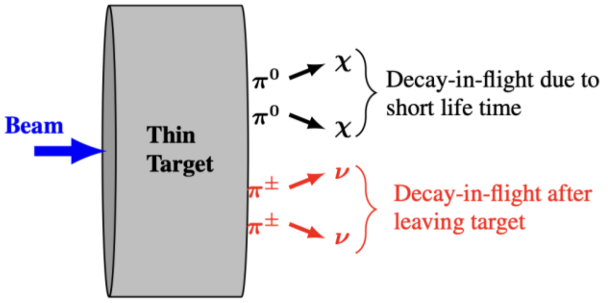
Phys. Rev. Lett. 129 (2022) 11, 111803 and arXiv:2309.02599

MiniBooNE Beam Dump: First dedicated proton accelerator Dark Matter search

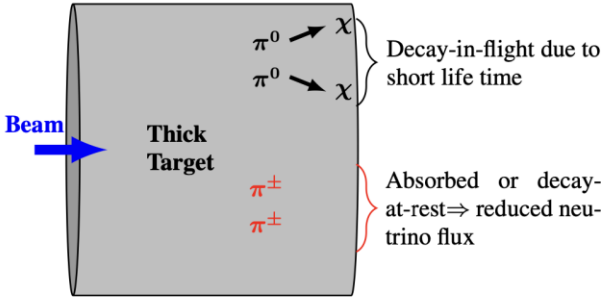
Phys. Rev. Lett. **118**, 221803 (2017), and Phys. Rev. D 98, 112004 (2018)



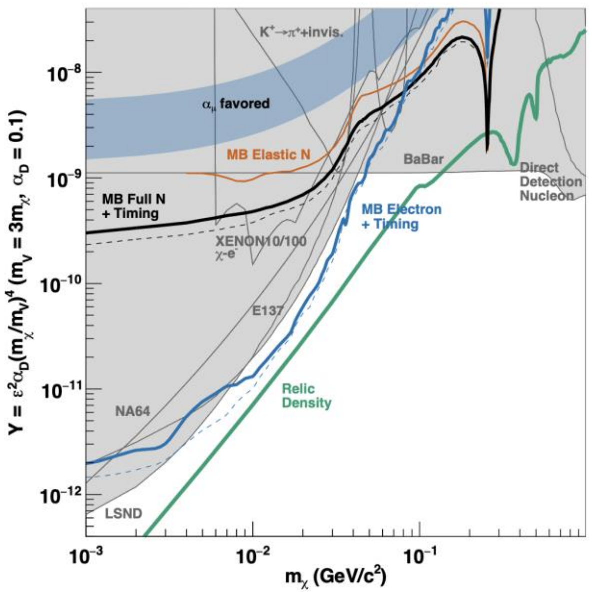
Neutrino flux and backgrounds reduced by a factor of x27
Expect ~2 excess events assuming neutrino scaling



Beam π^0 enhancement

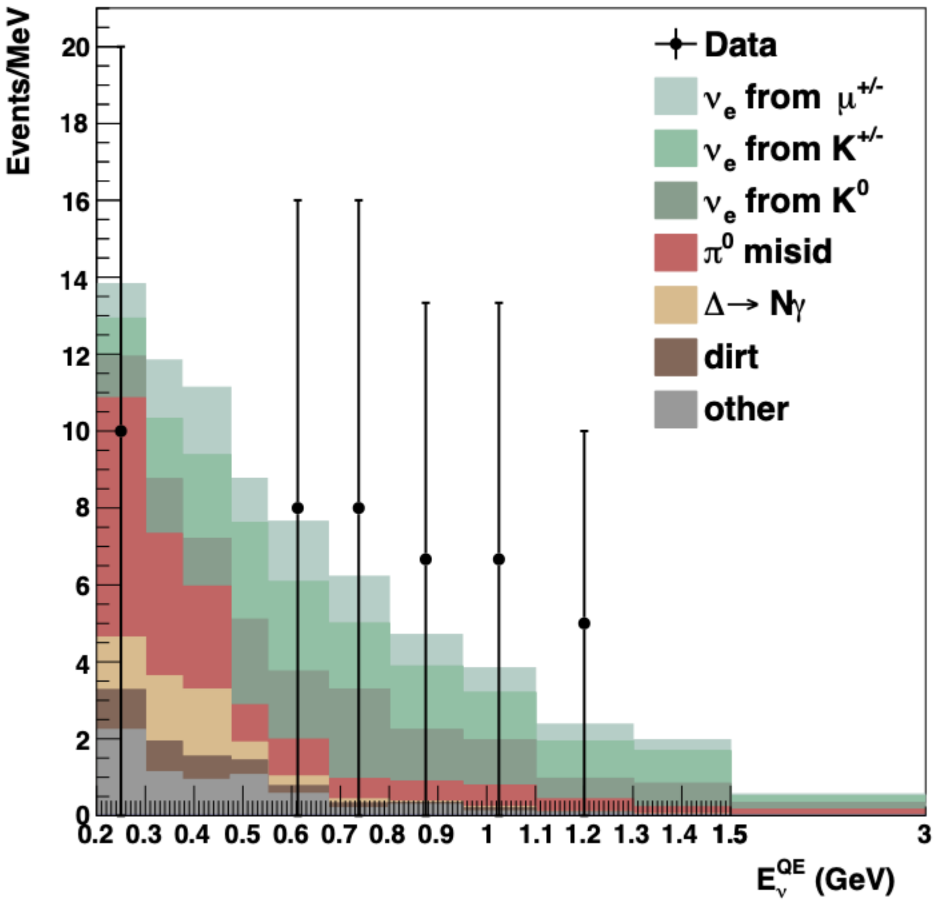


DM limits



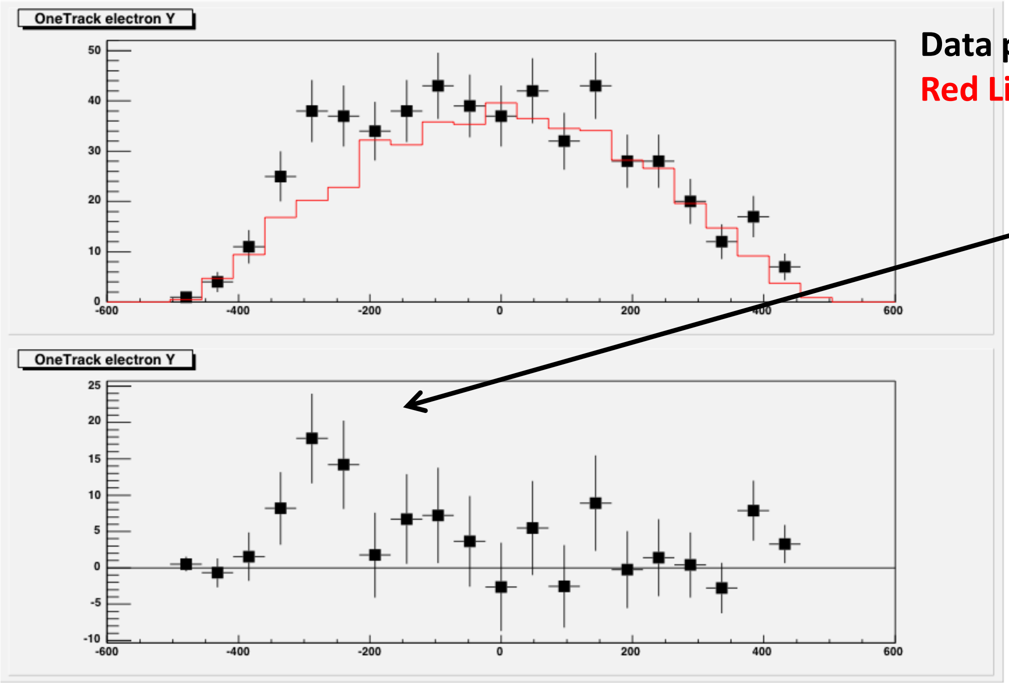
(a) vector portal ($\alpha_D = 0.1, m_V = 3m_\chi$)

Oscillation cuts: Expect 8 events, observe 6: If excess scaled with POT, or neutral pion production/decay, then expect ~35 events



Anomaly in the Anomaly: Spatial Hot Spot along beam direction
Oh no, not more weirdness!!

Antinu Oscillation-cut sample: Y-axis (detector up/down)



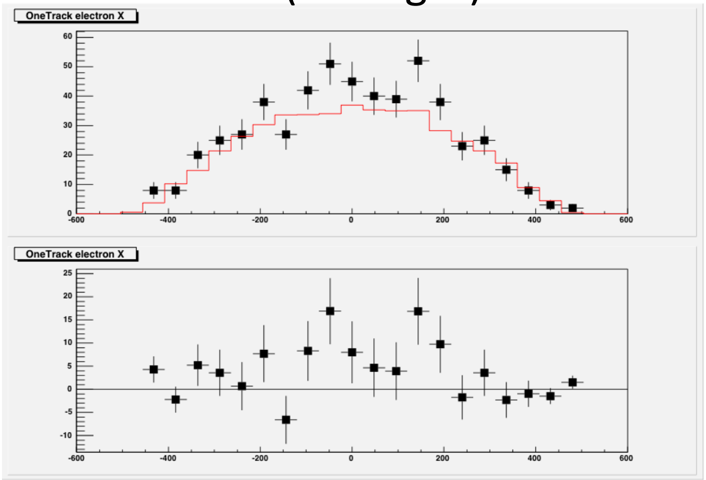
Data points: excess

Red Line: MC

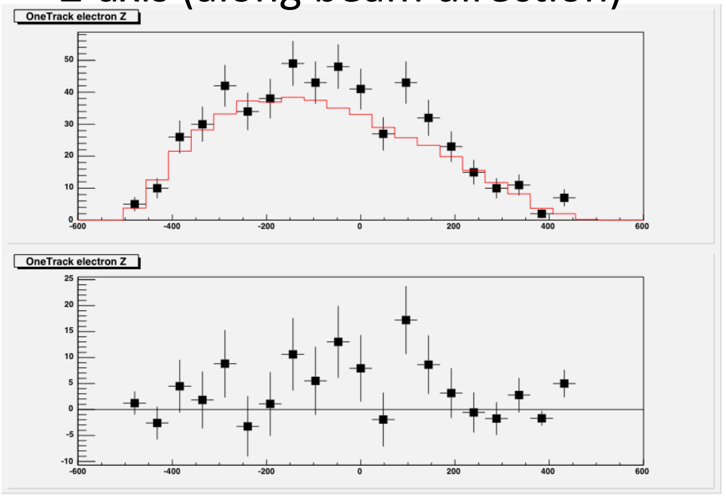
”Hey, isn’t the beam at Y ~ -2m!?” Geoff Mills, Jan 5, 2011.

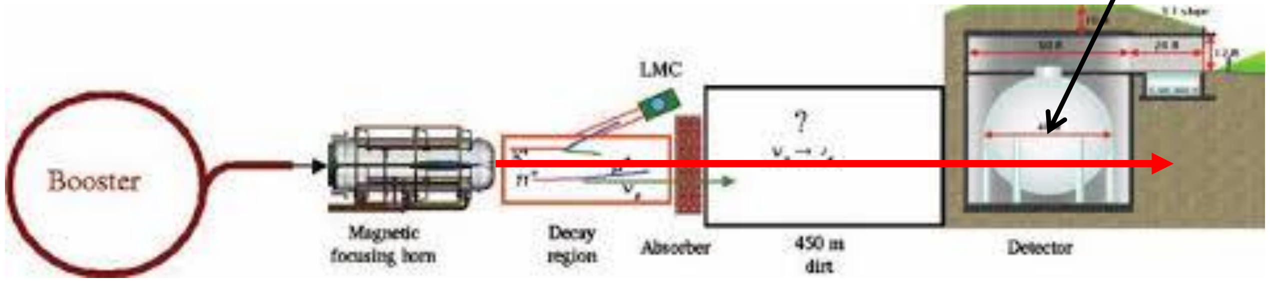
> Due to construction offsets, detector center is 190 cm higher than beam.

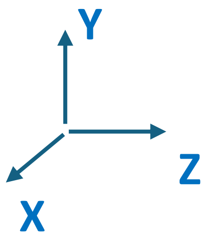
X-axis (left-right)



Z-axis (along beam direction)







Look else-where effect lessens significance, but what about look-here!

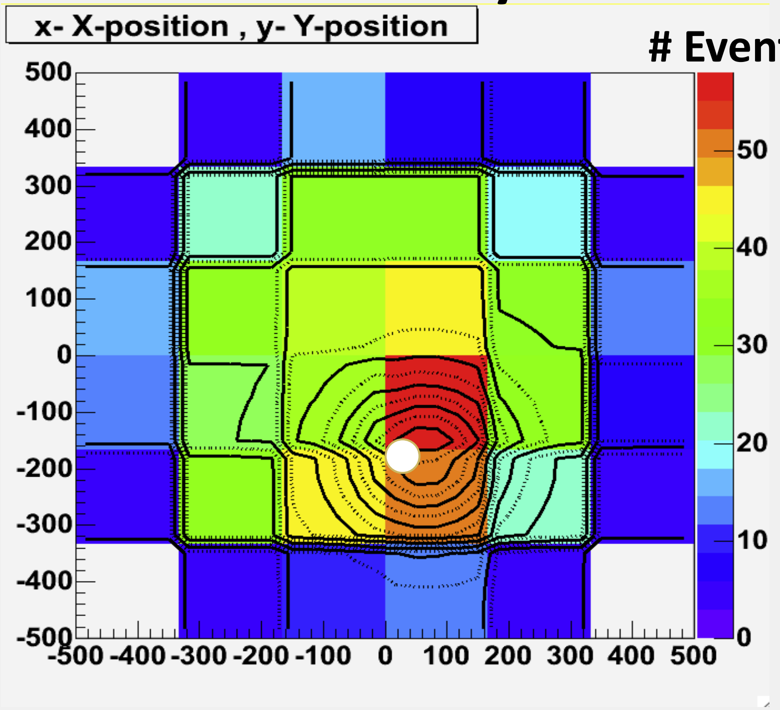
High stats muon/pi0 samples show spatial anomalies.

X-Y plot (perpendicular to the z-axis – beam direction) 11.27E20POT Antineutrino Oscillation-cut Data Set (2006-2012)

Hotspot width over 500m baseline corresponds to ~2 milliRadians wrt beam direction

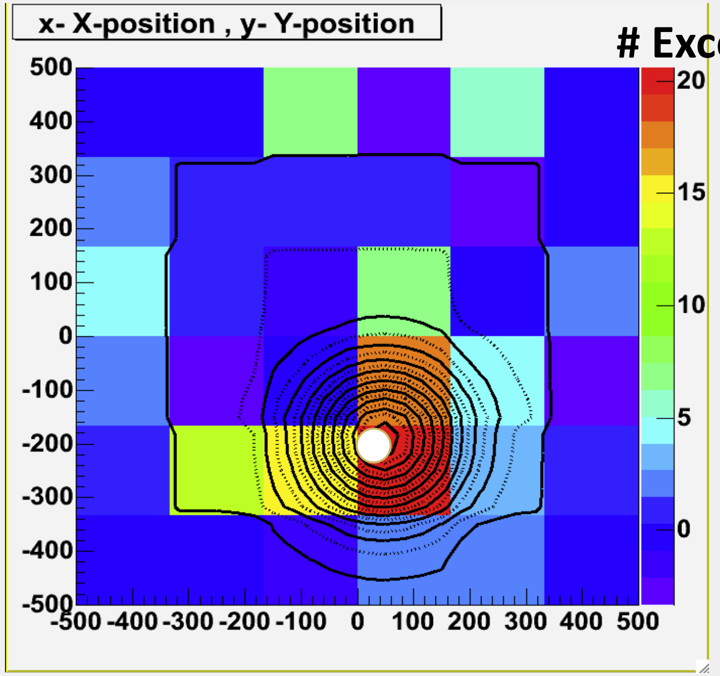
DATA Only

Events



DATA - MC

Excess Events



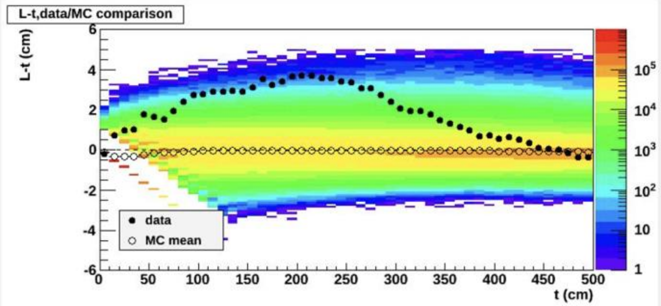
Effect only seen in antinu mode. If signal scales with POT, then neutrino mode swamped with beam backgrounds.

- Efficiency correct background + 2-D Gaussian fit= 55 +/- 22 events,
- Hot spot Gaussian width= ~93 cm (1-sigma) = 2 mRadians
- BPM projection of the Proton Beam direction (the white circle)

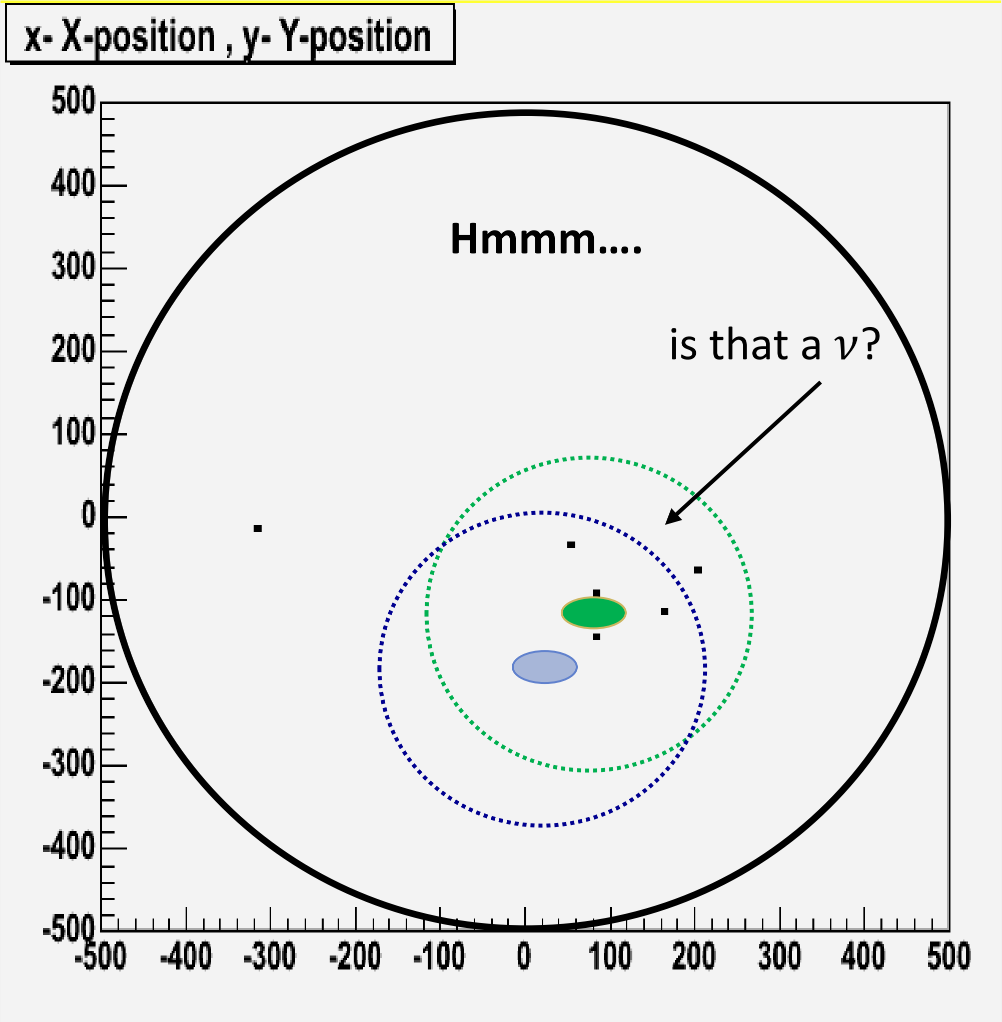
  X= 14.2 +/- 35.0 cm

  Y= -187.8 +/- 35.0 cm ← Detector built 2m higher than beam line

Hot spot spatial test wrt beam: ~3-sigma



The real reason for the beam dump mode run was to check the hot spot:
From POT scaling expect ~7 oscillation-cut events in hot spot



- Green dot/dashed line represents SWIC corrected projected beam position and 2σ HotSpot radius X_{beam}= 75 cm; Y_{beam}= -114cm
- Blue dot and dashed line are antinu best fit hot spot position and 2σ radius: X_{Antinu}= 14cm; Y_{Antinu}= -188cm

Drell-Yan production of new particle?
See Doo-Jin Kim's talk…

My Thoughts…

- LSND and MiniBooNE appearance signals are robust and have stood the test of time and scrutiny. Solar neutrino anomaly took ~30 years to solve!
- MB excess EM-like, near speed of light propagation (<50 MeV). LSND and MB excesses have similar L/E (oscillations), and similar E_{excess}/E_{beam} (dump production).
- 3+1 oscillation energy and angle fits not ideal, more complicated oscillations could be at play suggested by global fits or multiple process at work? e.g. sterile neutrinos + meson portals, etc??
- Neutrino SBL experiments provide some of the best rare pion decay measurements (meson portal models) – is there a signal? uB, CCM, SBND and ICARUS will test in detail soon.
- If MiniBooNE hot spot real (yeah, sure!), then SBND could potentially see a dramatic spatial distribution (~cm hot spot along beam direction), but due to high backgrounds best to run in beam dump mode.
  - Kicker magnet installed in BNB allows running neutrino and beam dump mode simultaneously (nu:BD ratio 5:1, for example).
- **Coming years will be interesting and telling, have fun!**

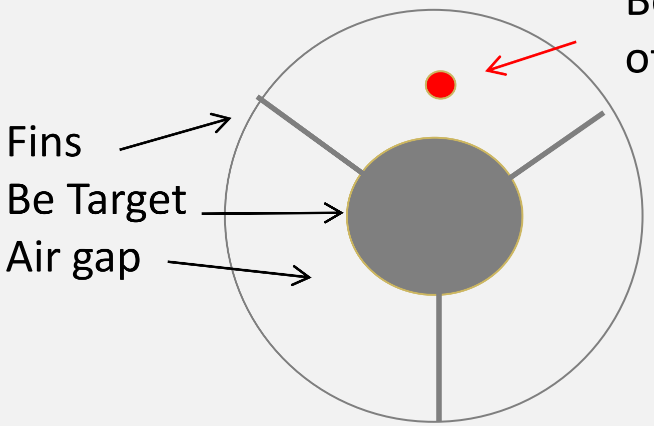
Source of Unconstrained Errors

TABLE III: *The fractional unconstrained systematic uncertainties in the* $200 < E_\nu^{QE} < 1250\ MeV$ *energy range.*

Systematic Uncertainty	Fraction of Event Excess
Cross Section	35%
Optical Model	23%
π^+ Production	14%
Neutrino Flux	7%
K^0 Production	4%
K^+ Production	4%

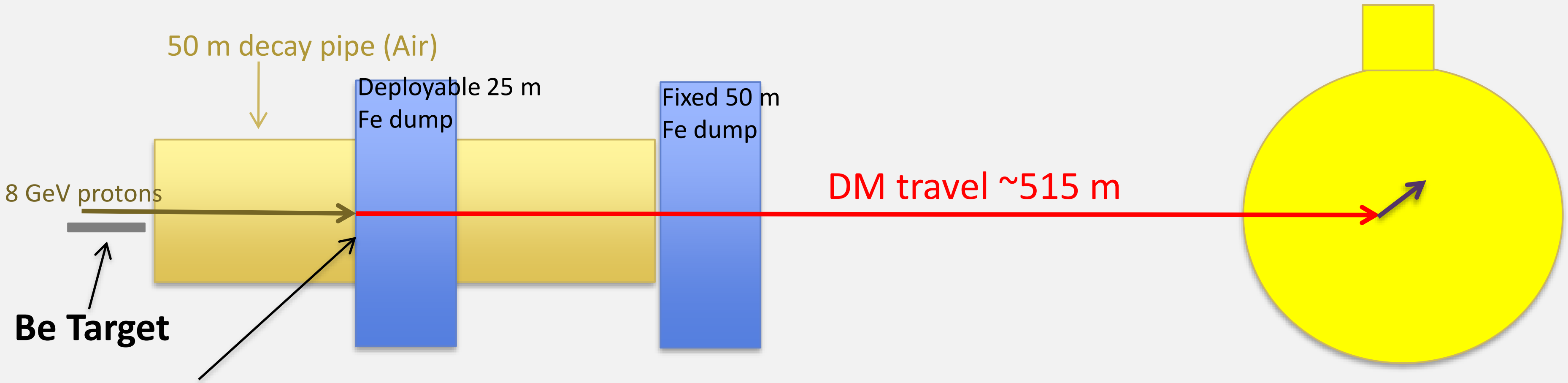
Beam Off Target Running

MB has the capability to steer the protons past the target and onto the 25m or 50m iron dump



Beam spot position in beam off target mode (~1 mm spread)

-Target is 1 cm diameter
-Air gap between target and horn inner conductor is ~1 cm

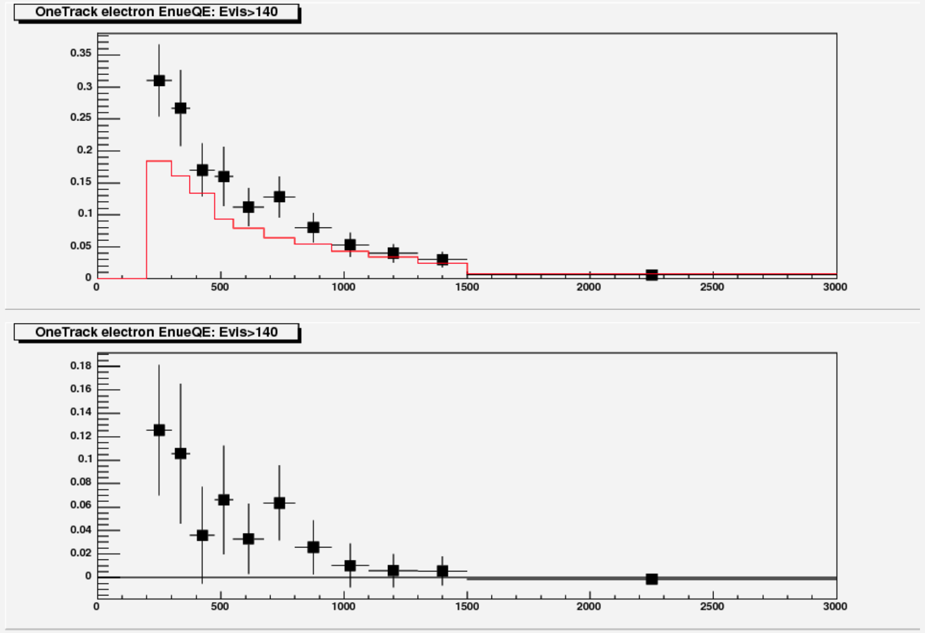


- π^0 and η produced by protons in the iron quickly decay producing WIMPs (χ)
- Charged mesons are absorbed in the iron before decaying, which significantly reduces the neutrino flux (still some production from proton-Air interactions).

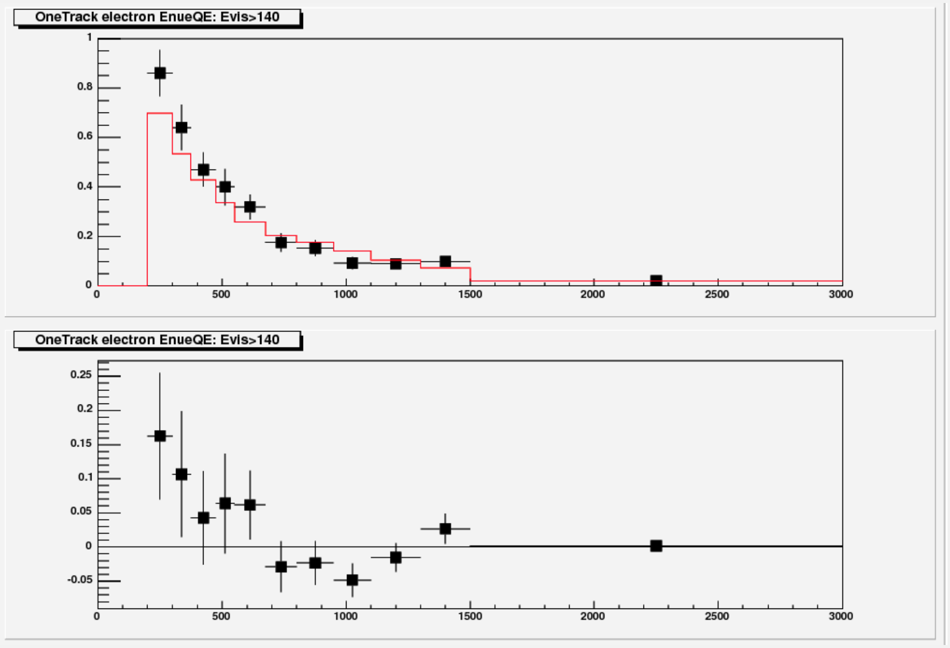
Kinematics of Events inside and outside the fitted hot spot

AntiNeutrino EnuQE: 10.87E20 POT

Rcut < 2.0*Sigma (22% Eff corrected volume)



Rcut > 2.0*Sigma



200 < E < 475   Data-MC= 68-43.9= 24.1

475 < E < 1250 Data-MC= 68-44.9= 23.9

200 < E < 475   Data-MC= 181-152.5= 28.5

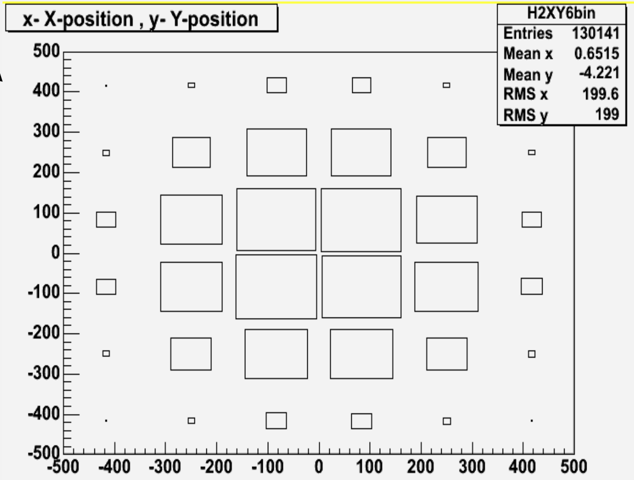
475 < E < 1250 Data-MC= 145-147.6= -2.6

Rcut > 2.0*Sigma region looks like the neutrino low energy excess in magnitude and shape

HotSpot Fit Model

(Same as for Antinu Data Fits)

- Symmetric 2D Gaussian – 4 parameters
  - Gaussian normalization
  - Gaussian width (sometimes fixed)
  - Gaussian X and Y (sometimes fixed).
- Monte Carlo - XY background shape from neutrino EM box (no dirt).
  - 1 parameter for normalization
- Data bin errors are +/-sqrt(N_{ij})
- 6x6 binning (good for low stats)
- LogLiklihood fit



Alignment Offsets: Working Closely with BNB and Alignment Group

X = positive beam right when looking downstream beam line
Y (stationing) = Best fit line as found quads Q873-Q874-Q875 and positive downstream beam line
Z = positive upward when looking downstream beam line (and orthogonal to the beam)

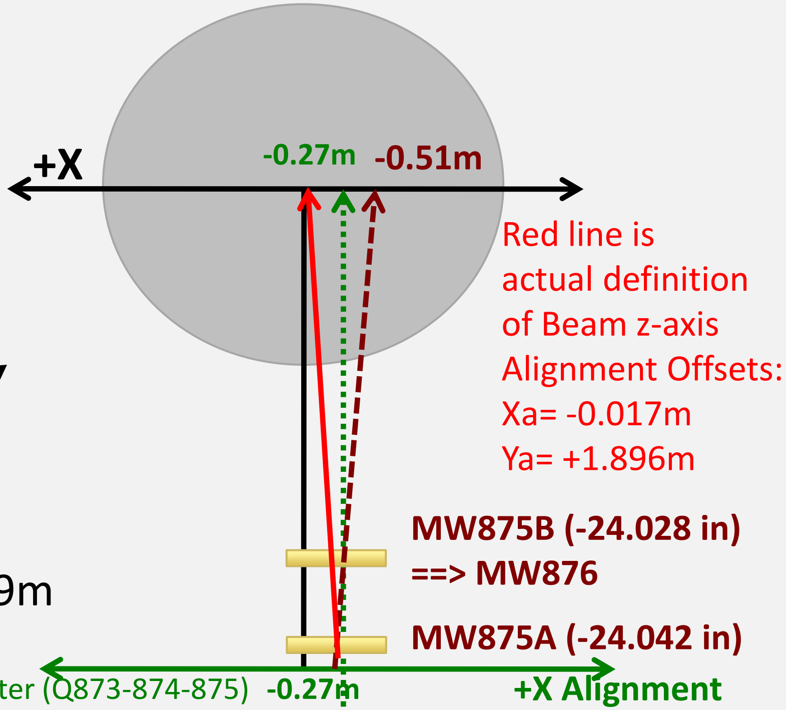
NAME	X [in]	Y [in]	Z [in]	
MW875A_CT	-0.023	38.849	0.036	
MW875B_CT	-0.002	85.082	0.091	
CTR_MB_Det_as_found	-10.618	21552.968	85.047	
CTR_MB_Det_as_found	**-0.2697**	**547.4465**	**2.1602**	m

- Distance between Multiwires: dMW= 1174.32mm
- Distance between MW875 and detector center: dDect= 545.28 m

Independent check: Heights from levels		
	H [in]	dH [in]
Upst Wire Chamber MW875A_CT	8676.031	
Dnst Wire Chamber MW875B_CT	8676.093	0.063
Heights from Laser Tracker coordinates as set:		
	H [in]	dH [in]
Upst Wire Chamber MW875A_CT	8676.043	
Dnst Wire Chamber MW875B_CT	8676.084	0.041
Horizontal Chechs		
Independent check: Offsets from random control points line		
(True North Azimuth of line confirmed by Independent Gyro to 18 arcsec = 0.086mrad)		
	dx [in]	ddx [in]
Upst Wire Chamber MW875A_CT	-24.042	
Dnst Wire Chamber MW875B_CT	-24.028	0.014
Offsets computed from coordinates		
	dx [in]	ddx [in]
Upst Wire Chamber MW875A_CT	-24.076	
Dnst Wire Chamber MW875B_CT	-24.048	0.027
Detector Center position from the multiwires line		

Gravity Method: 1.896 – ((1.6mm/dMW) x dDect)= 1.153 m

Beam offset in detector coordinates: Y= -1.15m



- Horizontal Average 0.014 and 0.027 in == 0.521 mm
- Hor Offset= -0.017m – ((0.521/dMW)*dDect)= -0.259m
- **Beam offset in detector coordinates: X= -0.26m**