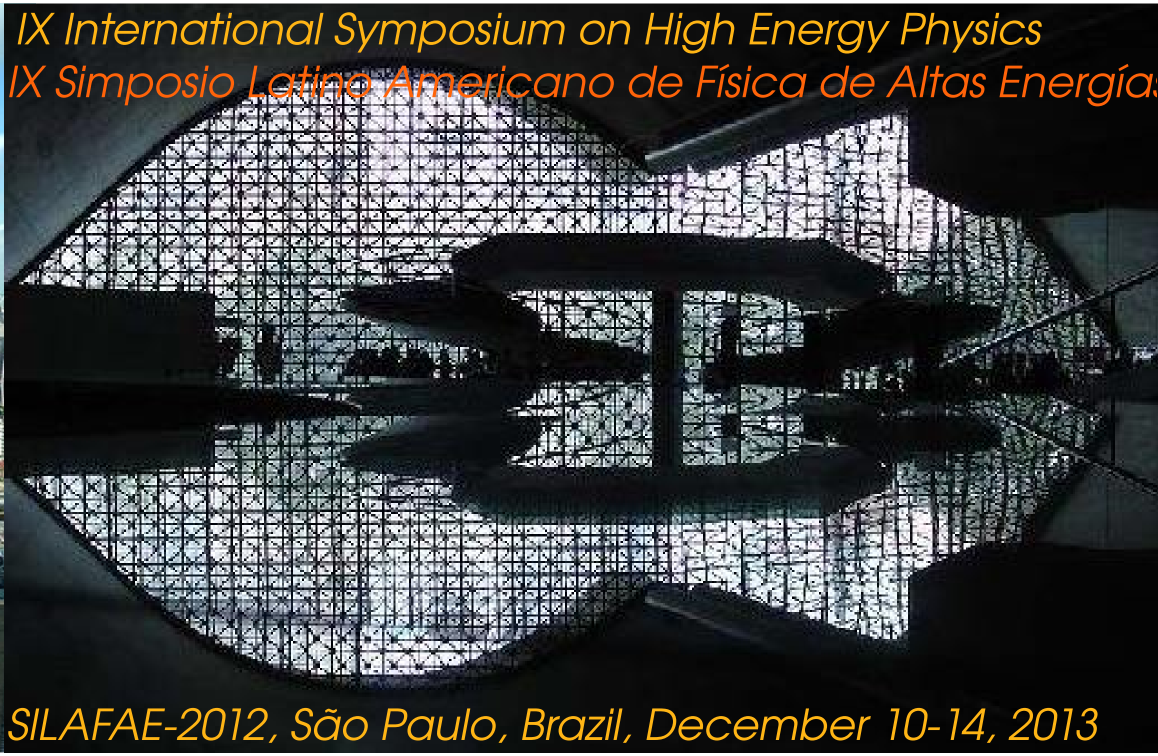
Recent results from MiniBooNE on neutrino oscillations

Alexis A. Aguilar-Arévalo (ICN-UNAM)
(for the MiniBooNE collaboration)



IX International Symposium on High Energy Physics
IX Simposio Latino Americano de Física de Altas Energías

SILAFAE-2012, São Paulo, Brazil, December 10-14, 2013

Outline

LSND and MiniBooNE

Experiment description

Oscillations results (ν_e, $\bar{\nu}_e$ appearance)

Future plans

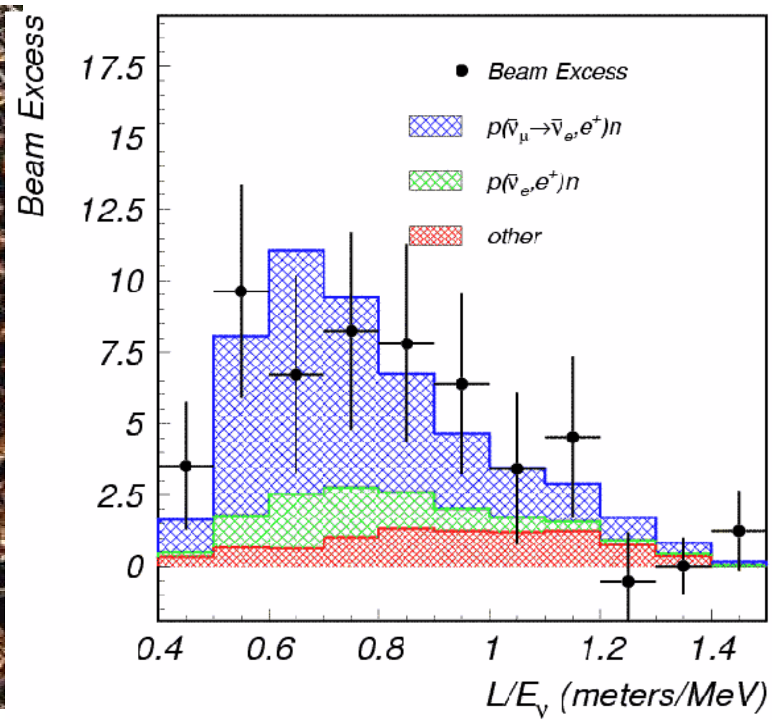
Conclusions

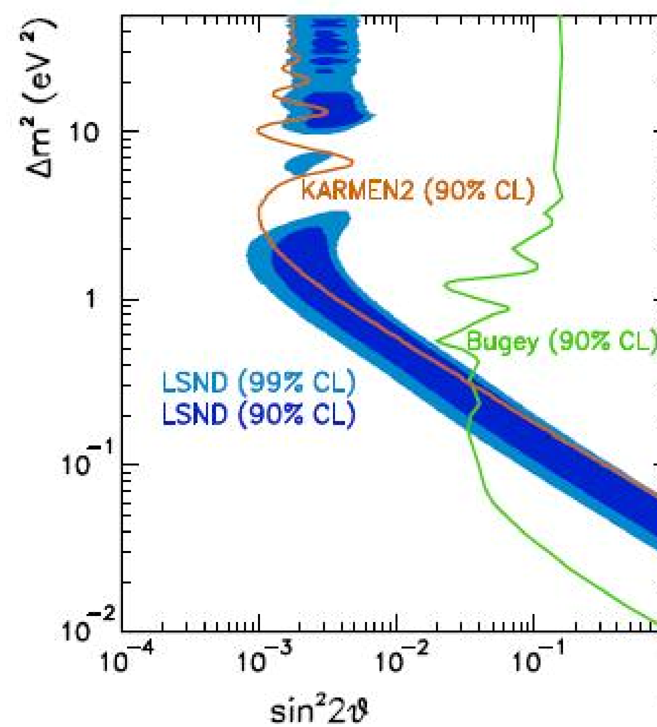
MiniBooNE motivation: LSND

- LSND Experiment (Los Alamos, 1993-1998)
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam: Excess= 87.9 ± 22.4 ± 6 (3.8σ)
- Source is Pion decay at rest: $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

  ν_e signal: Cherenkov light from e^+ with delayed n *capture* (2.2 MeV γ)
- Interpreted as 2ν oscillations: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$

  = (0.245± 0.067± 0.045)%

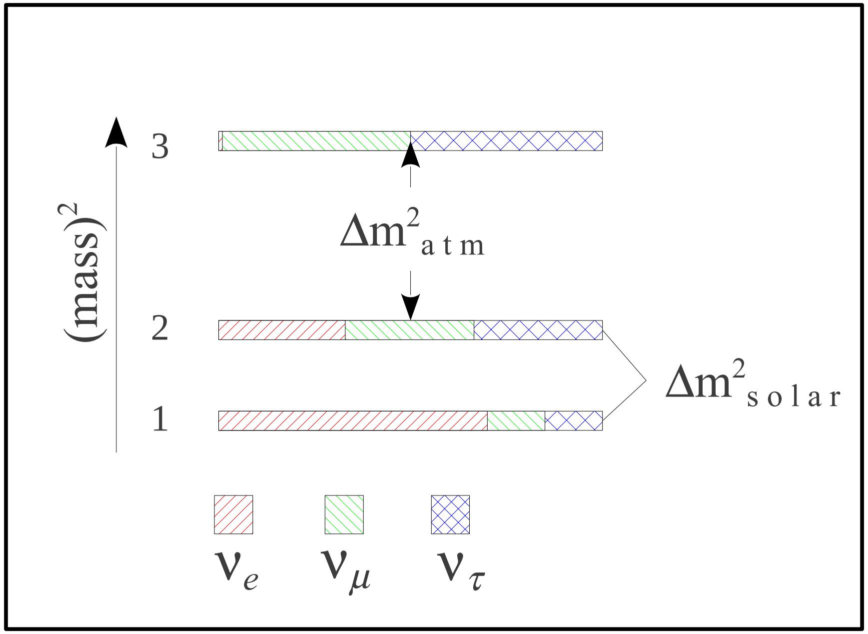


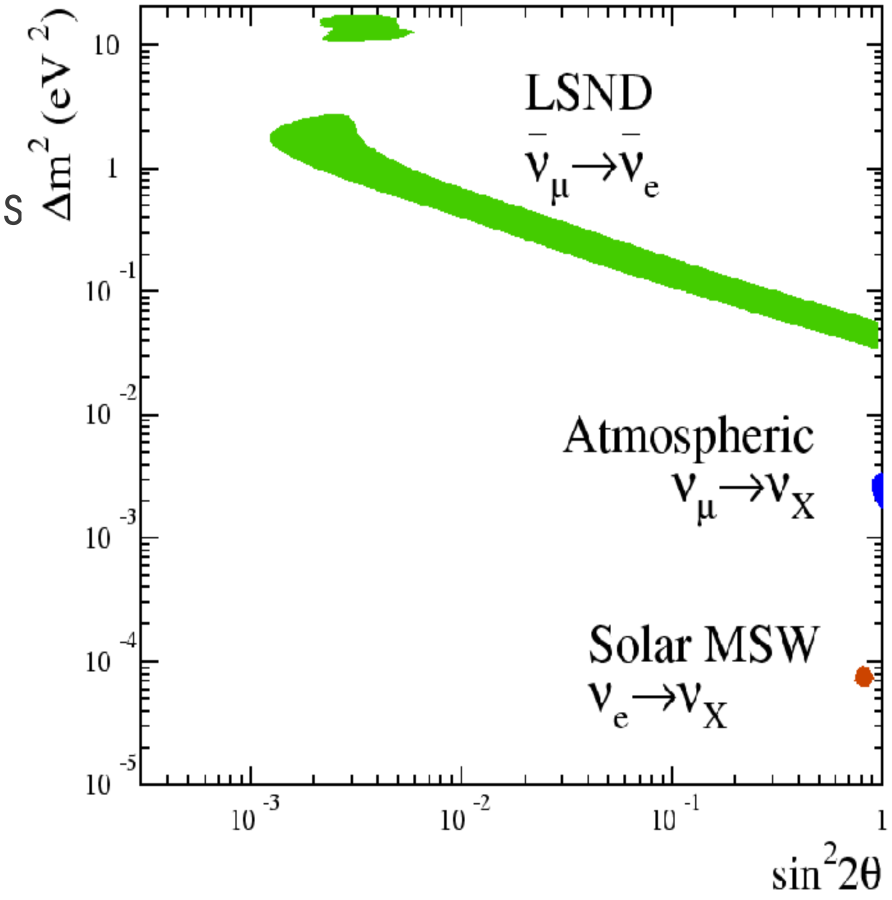


Implication of a high Δm^2 signal

In conflict with results from solar, reactor accel. & atmospheric neutrinos if only 3 ν's

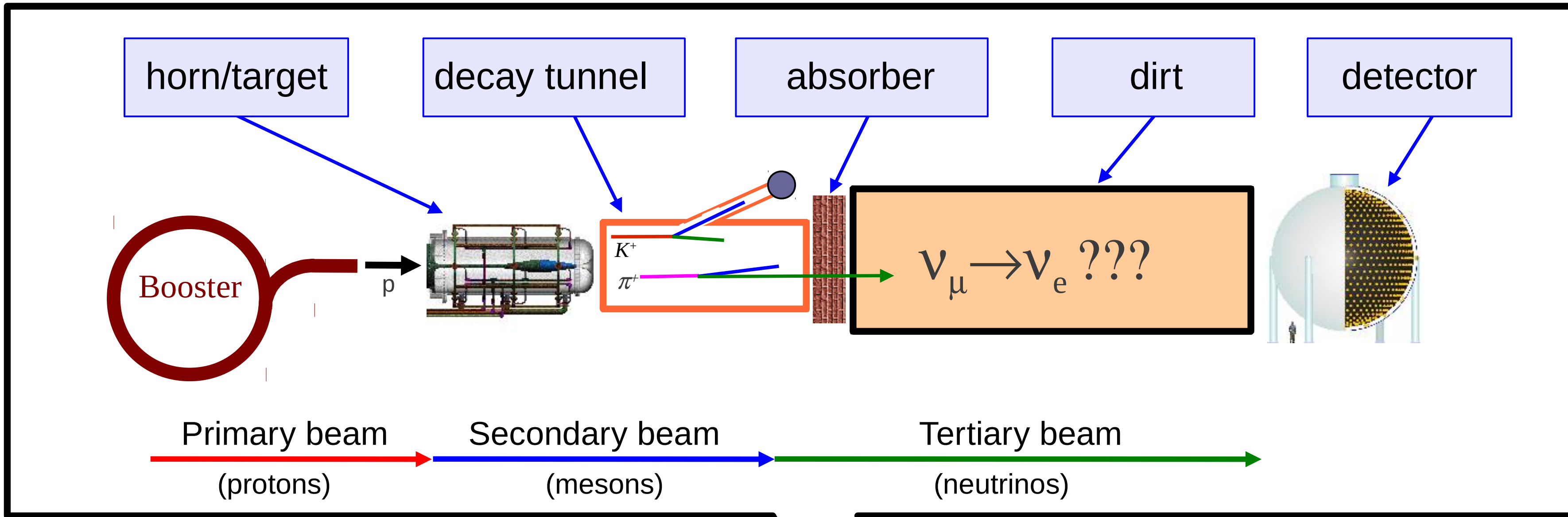
3 neutrinos ⇒ 2 distinct Δm^2 's

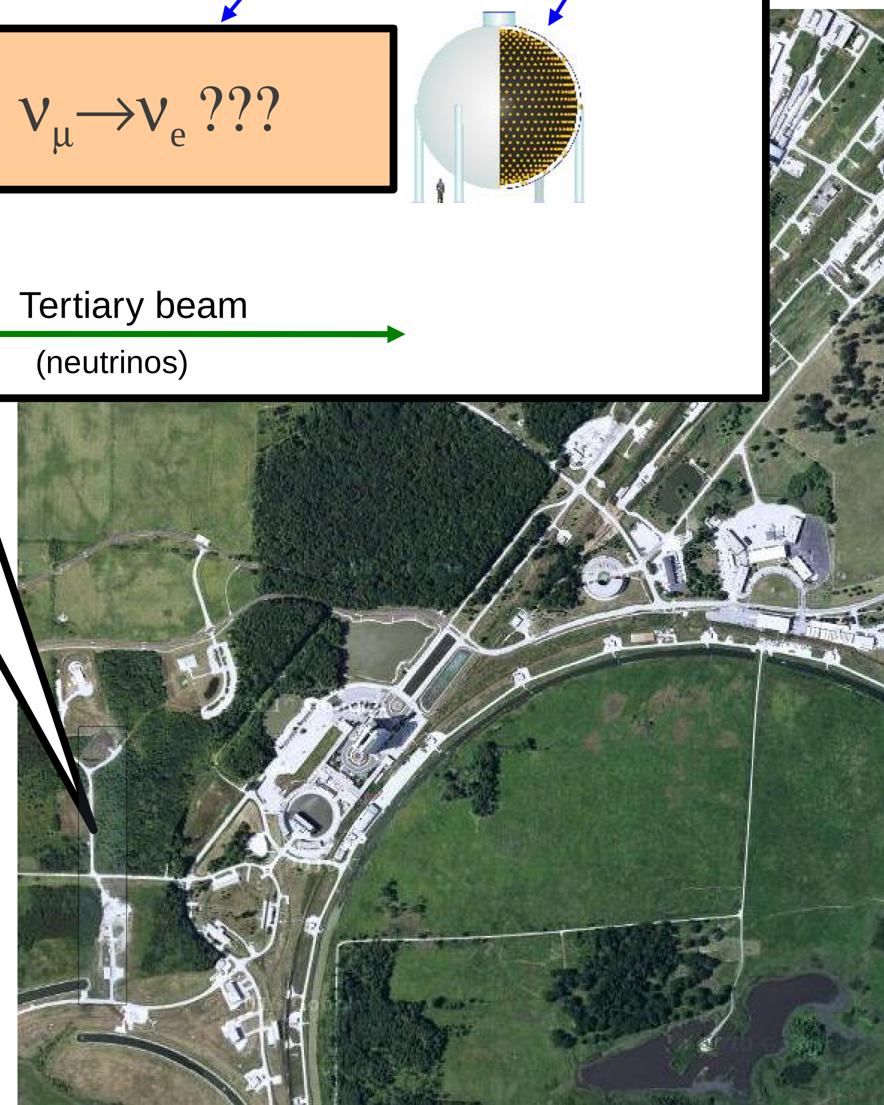




$$\Delta m^2_{LSND} \neq \Delta m^2_{atm} + \Delta m^2_{solar}$$

Mini-BooSter Neutrino Experiment





- *L/E* similar to LSND

  MiniBooNE ~500 m /~500 MeV

  LSND ~30m / 30 MeV

- Horn focused neutrino beam (p+Be)

  Polarity → neutrinos or anti-neutrinos

- Cherenkov Detector

  800 ton mineral oil

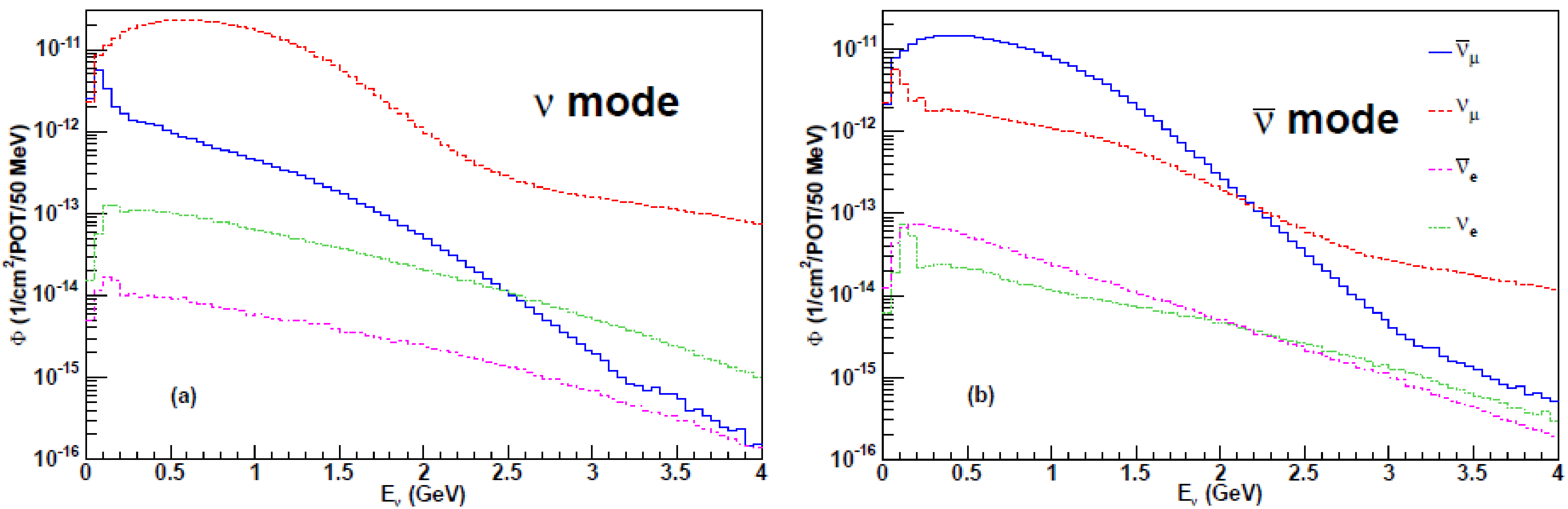
Predicted neutrino flux (MC)

Neutrino mode:

ν_μ	93.6 %	
$\bar{\nu}_\mu$	5.86 %	(WS)
$\nu_e + \bar{\nu}_e$	0.57 %	

Anti-neutrino mode:

ν_μ	15.7 %	(WS)
$\bar{\nu}_\mu$	83.7 %	
$\nu_e + \bar{\nu}_e$	0.6 %	



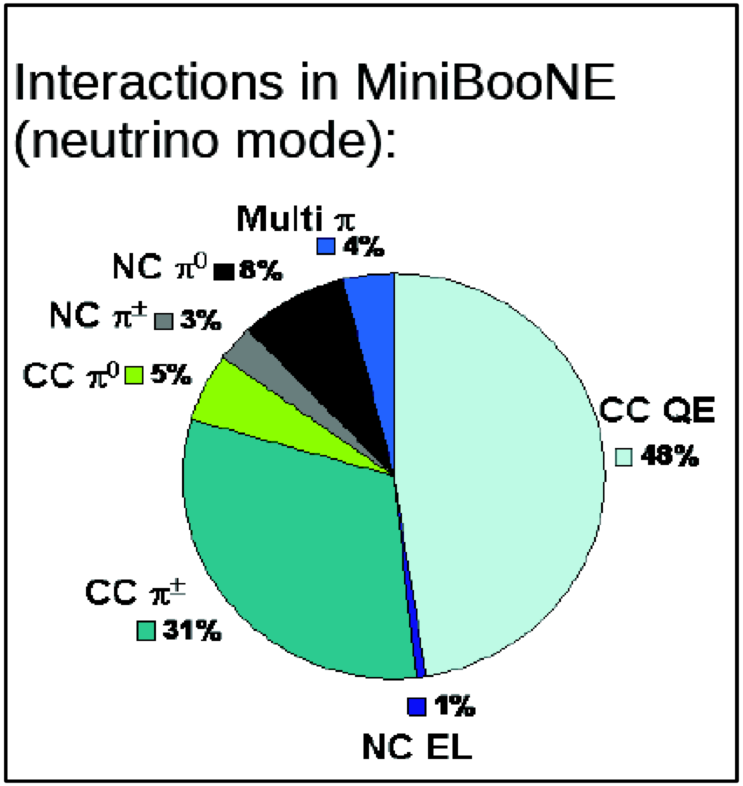
Phys.Rev. D79, 072002 (2009)

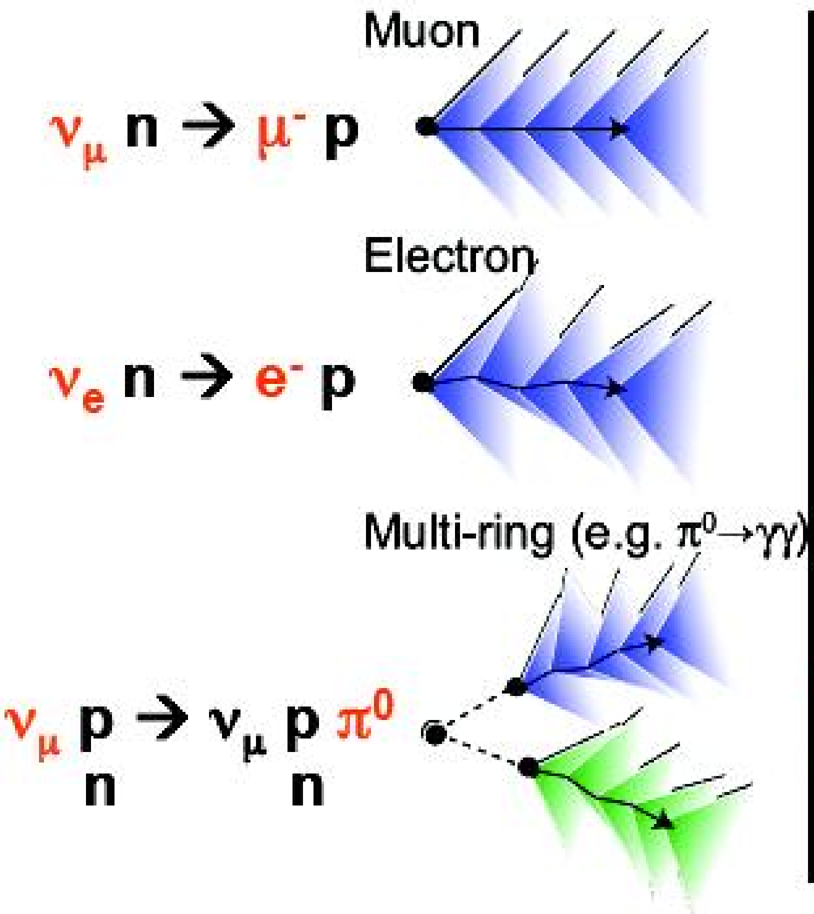
WS: "*wrong sign*"

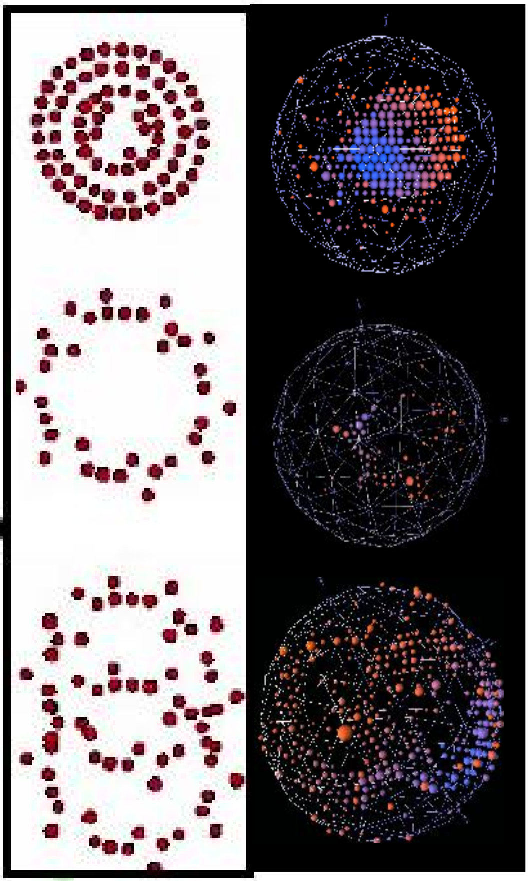
Uses $\pi^{\pm}$ production data from HARP experiment (CERN)

Events in MiniBooNE

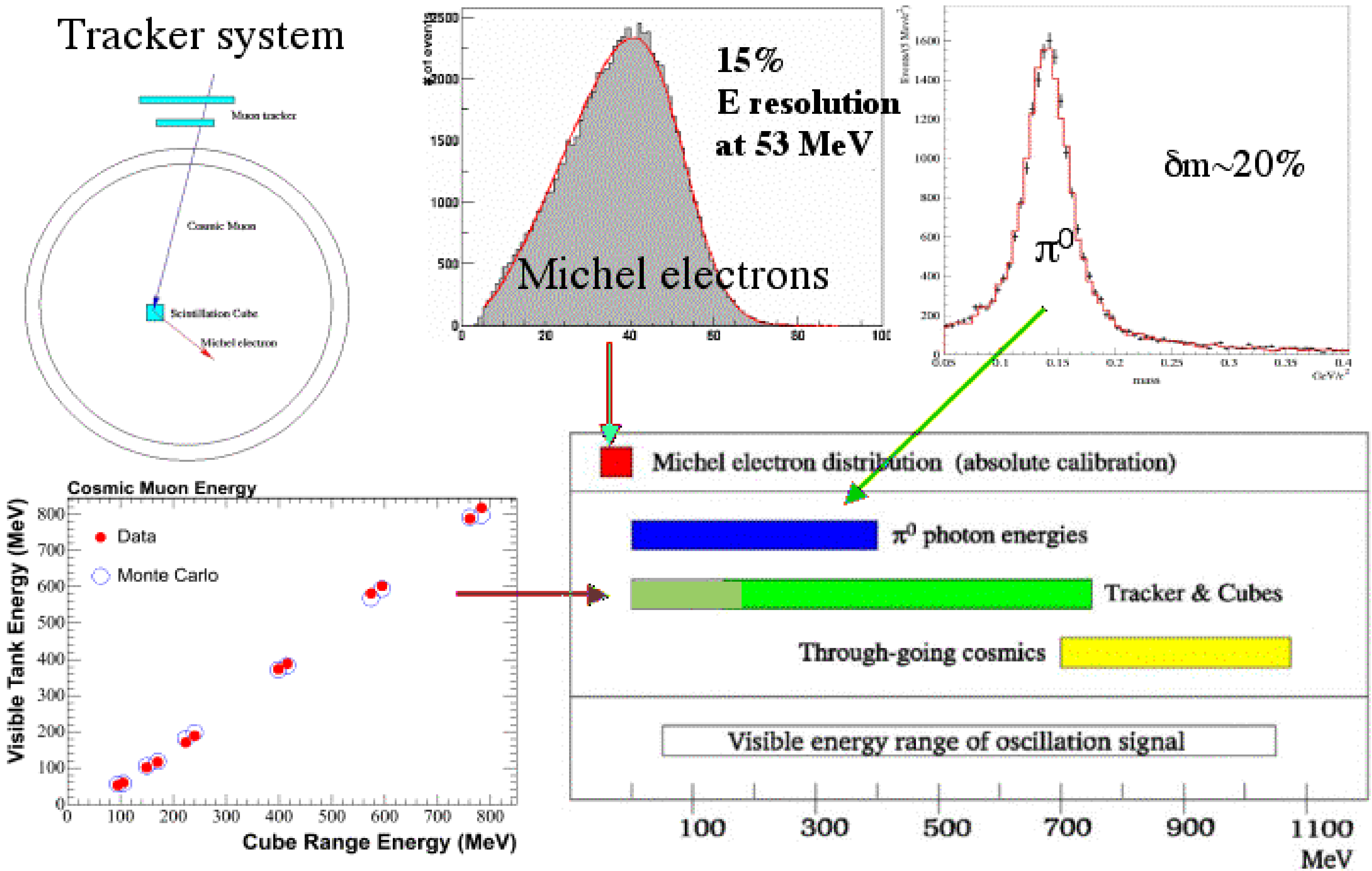
- Identification based on timing and event *topology.*
- Uses primarily Cherenkov light, but also scintillation light



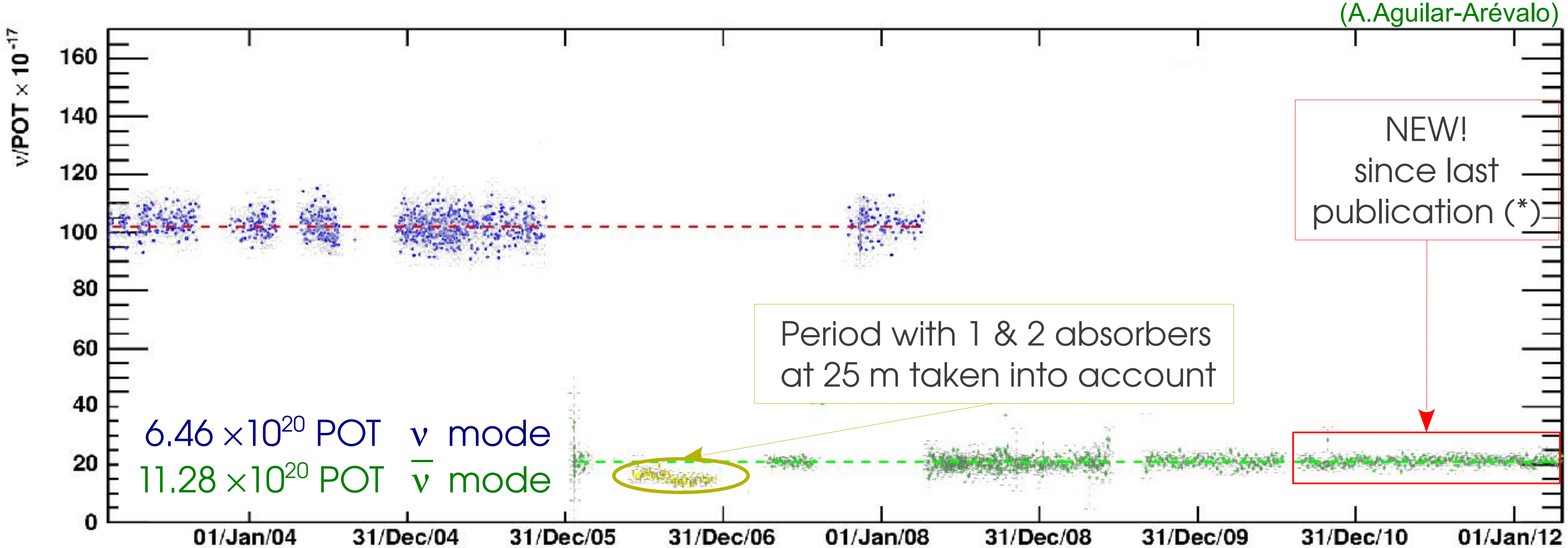


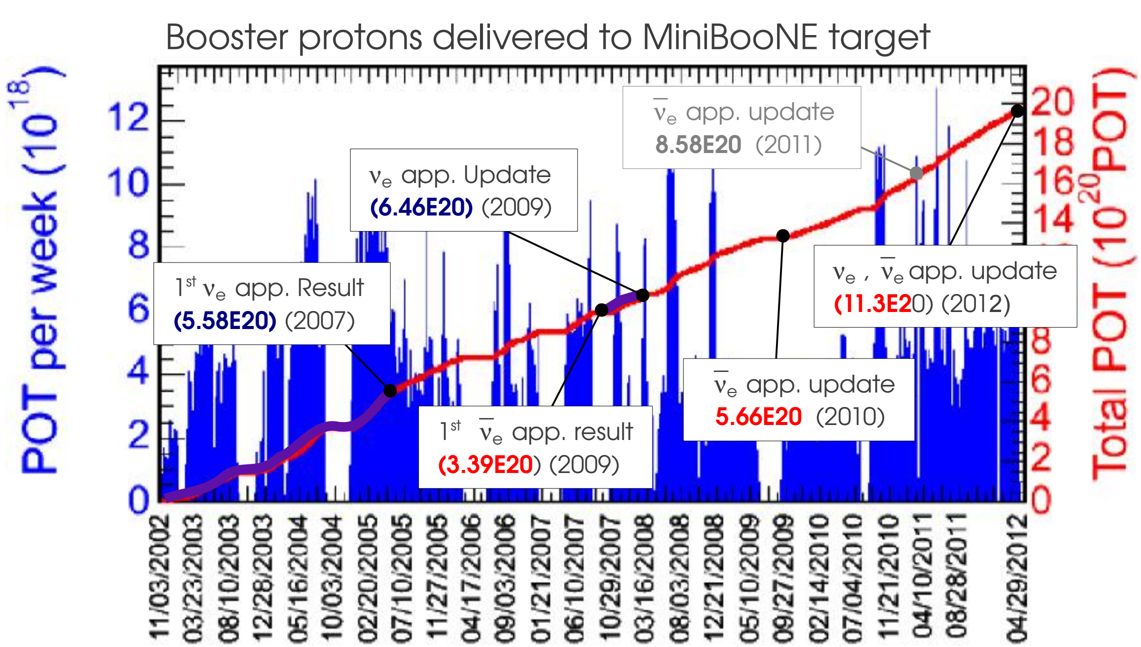


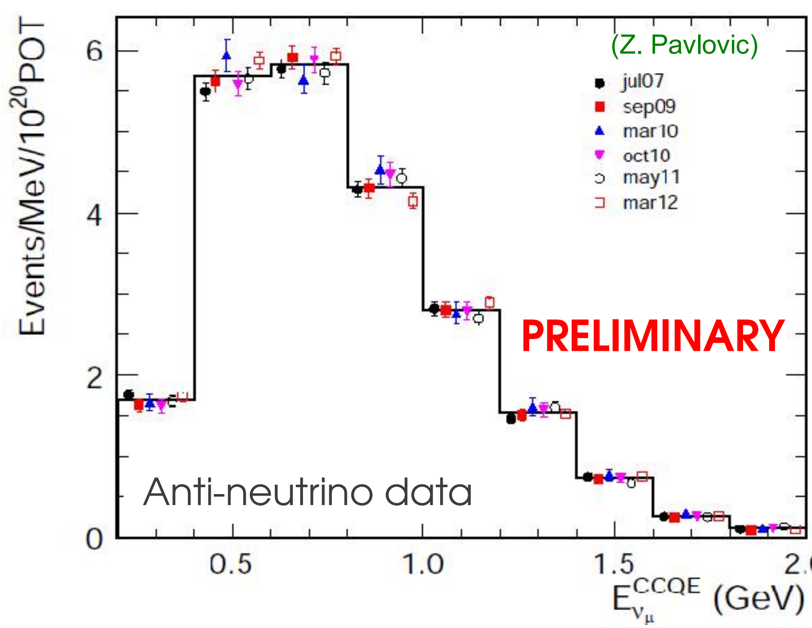
Detector calibration



Experiment progress (10 yr running)

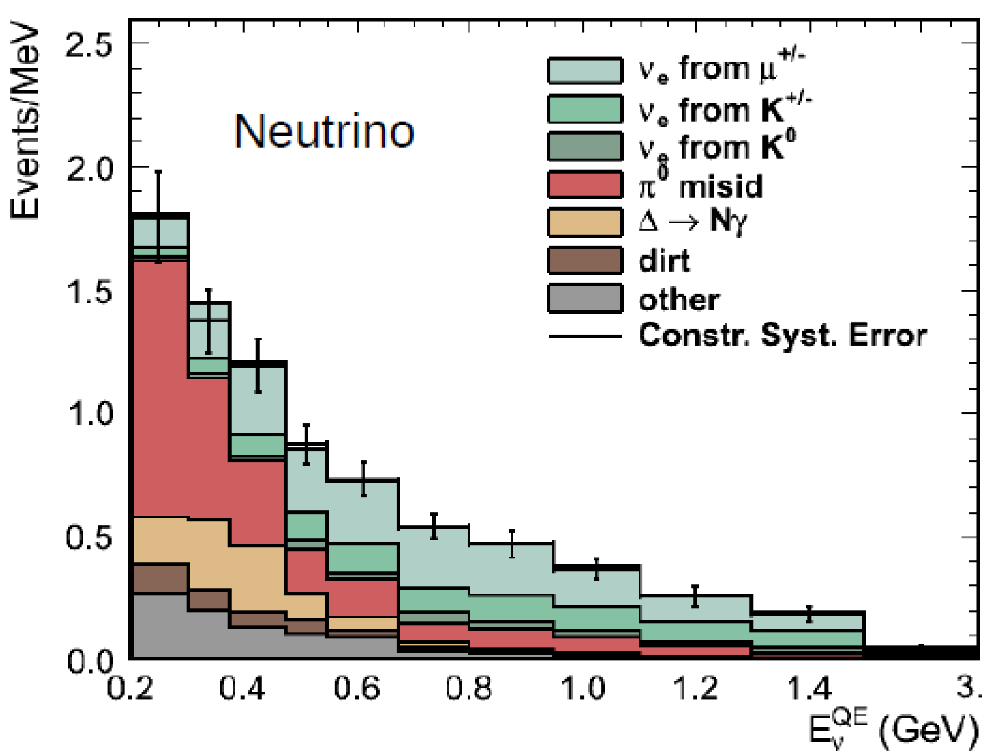


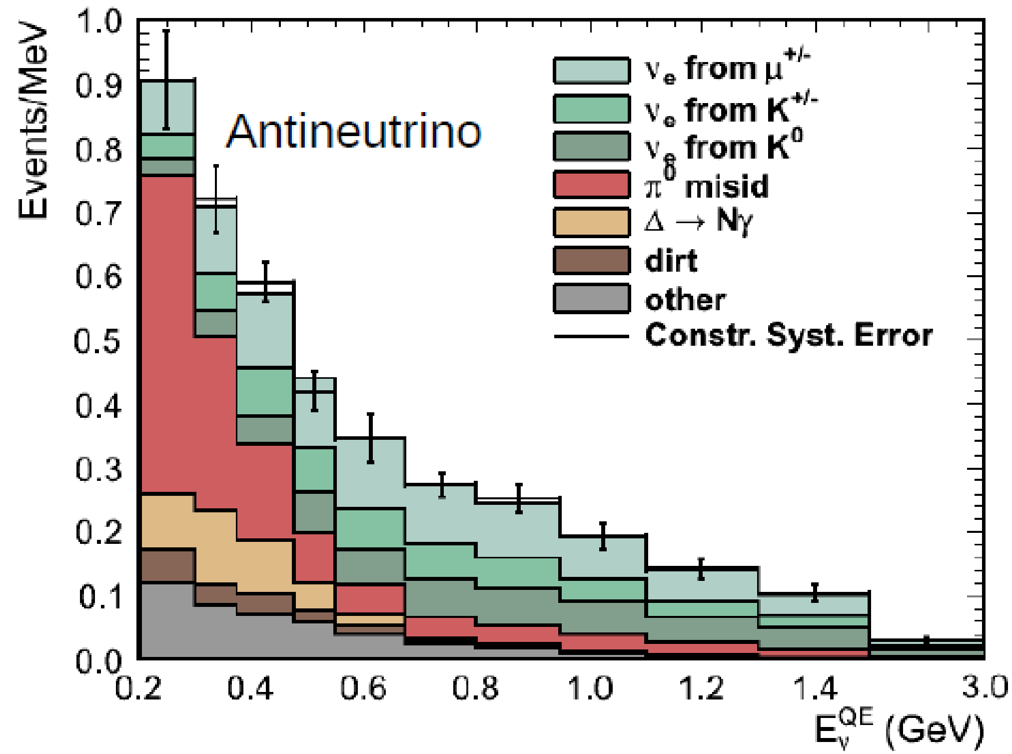




Background predictions (ν & $\bar{\nu}$)

Similar backgrounds in neutrino and anti-neutrino modes

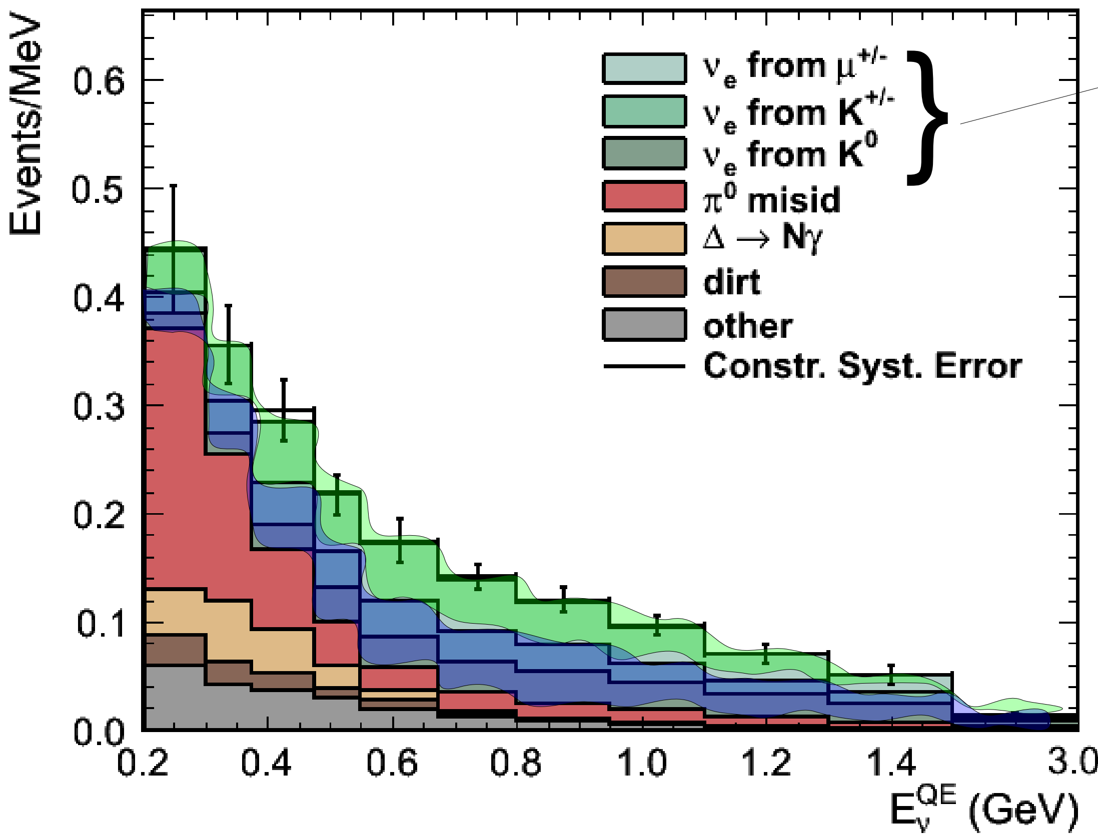




Strategy:

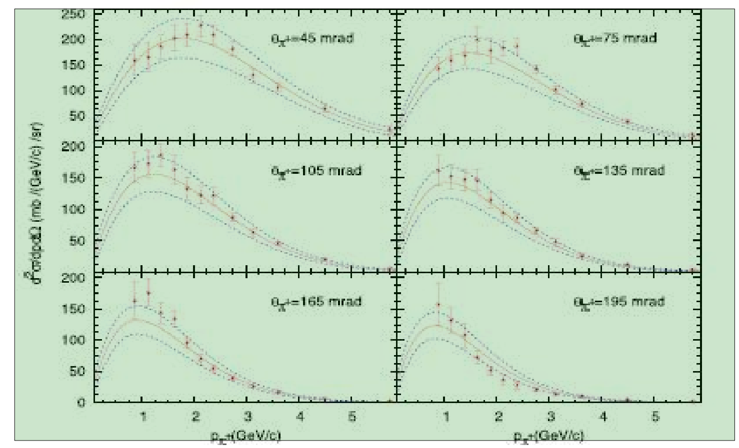
- Start with a beam composed primarily by ν_μ ($\bar{\nu}_\mu$).
- Measure the ν_e ($\bar{\nu}_e$) present in the beam.
- Interpret a ν_e ($\bar{\nu}_e$) excess as oscillations $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$).

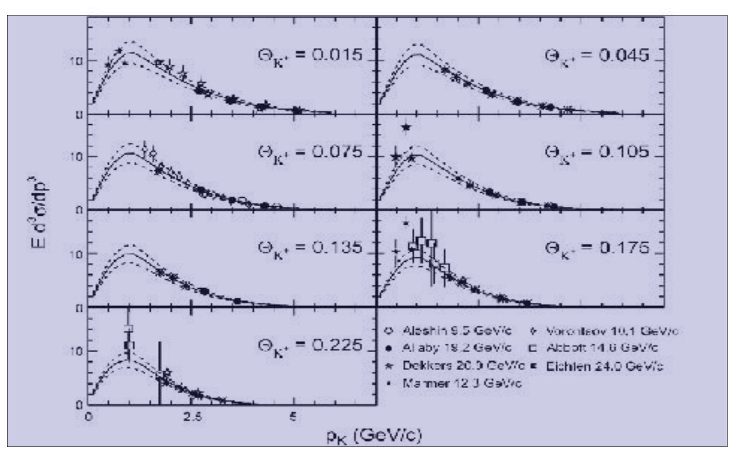
Backgrounds ($\bar{\nu}$ mode)



- Intrinsic ν_e

External measurements
Harp p+Be for $\pi^{\pm}$.



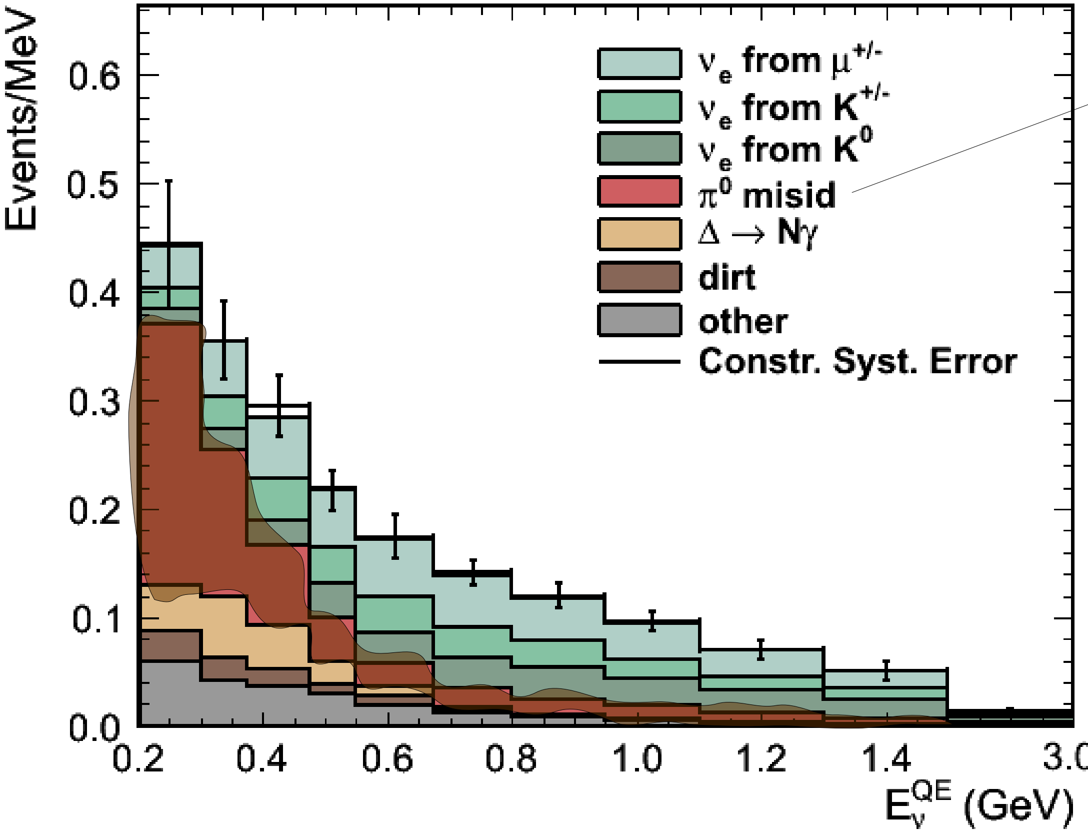


Fits to world's $K^{\pm}/K^0$ data and SciBooNE K+ constraint

Phys. Rev. D79, 072002 (2009)
Phys. Rev. D84, 012009 (2011)

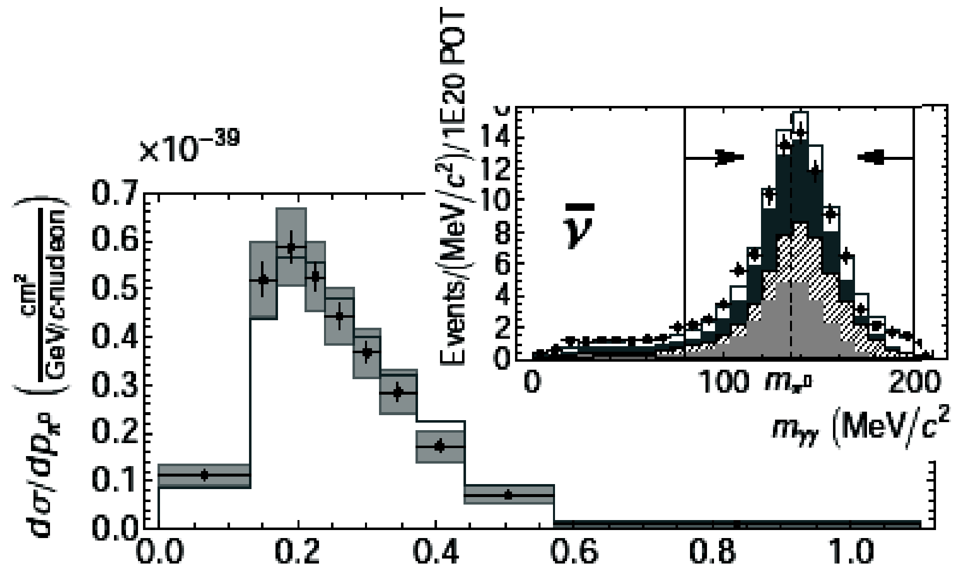
Constrained with MB data

Backgrounds ($\bar{\nu}$ mode)



- NC π^0

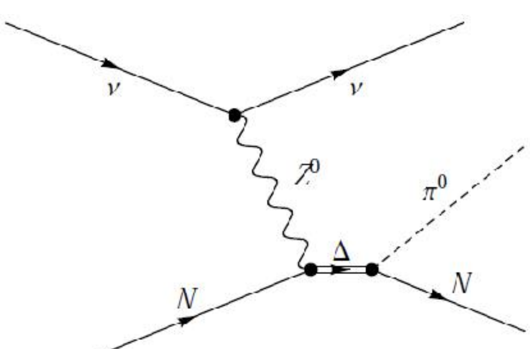
Measured *in situ* by MiniBooNE

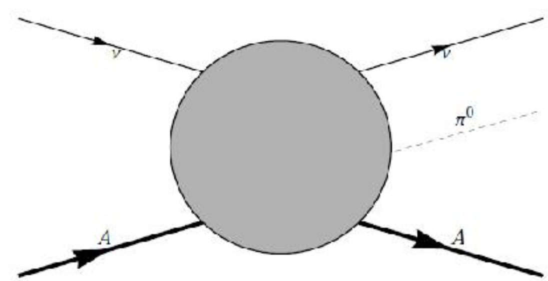


Phys. Rev D81, 013005 (2010)

p_{π^0} (Gev/c)

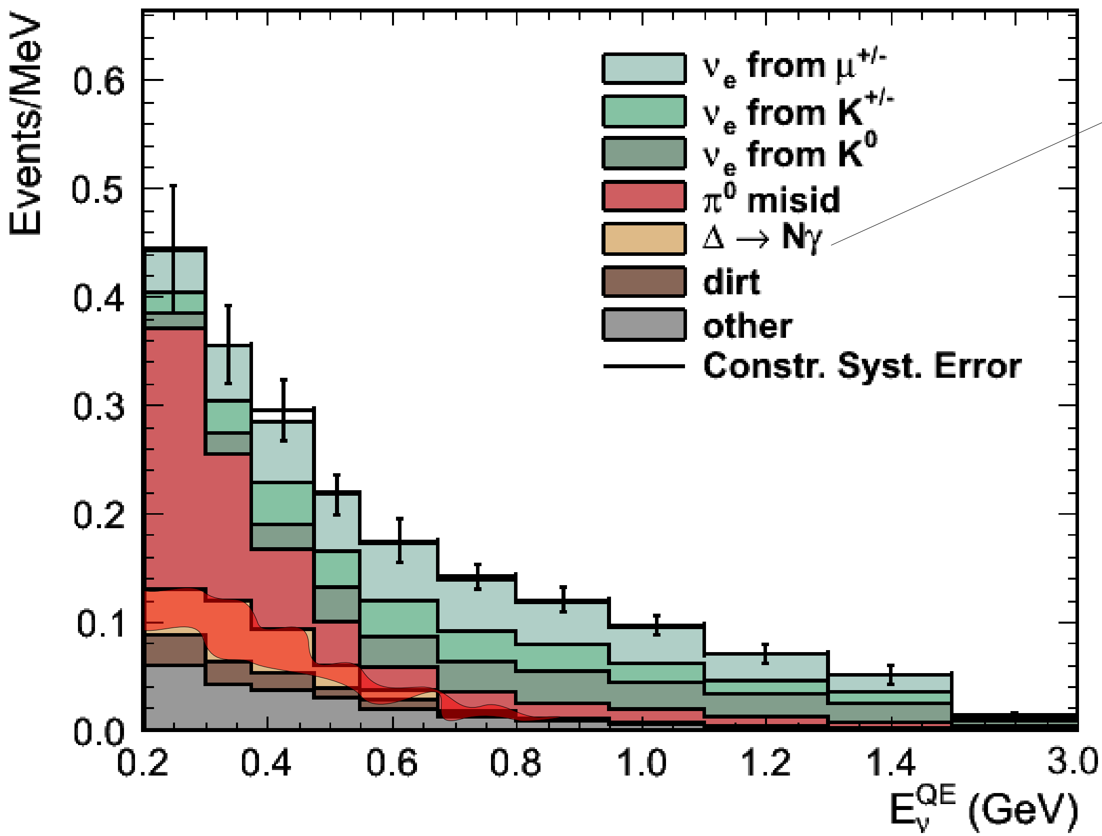
Contributions from resonant (~80%) ...



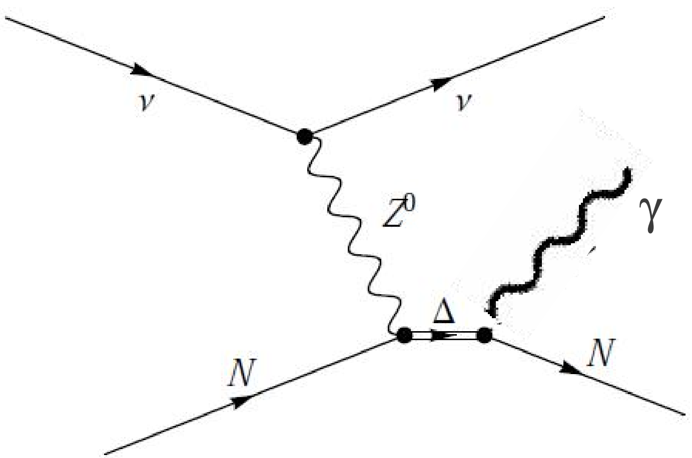


... and coherent (~20%) scattering.

Backgrounds ($\bar{\nu}$ mode)

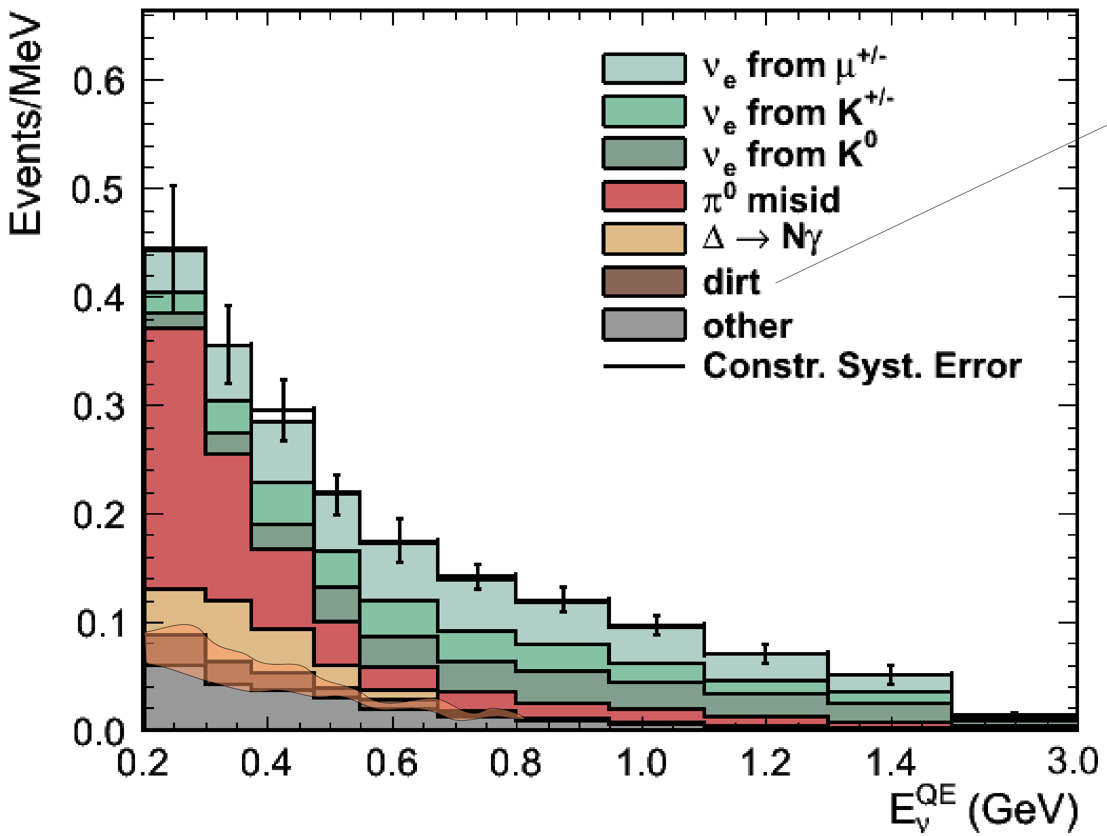


- $\Delta \rightarrow N\gamma$

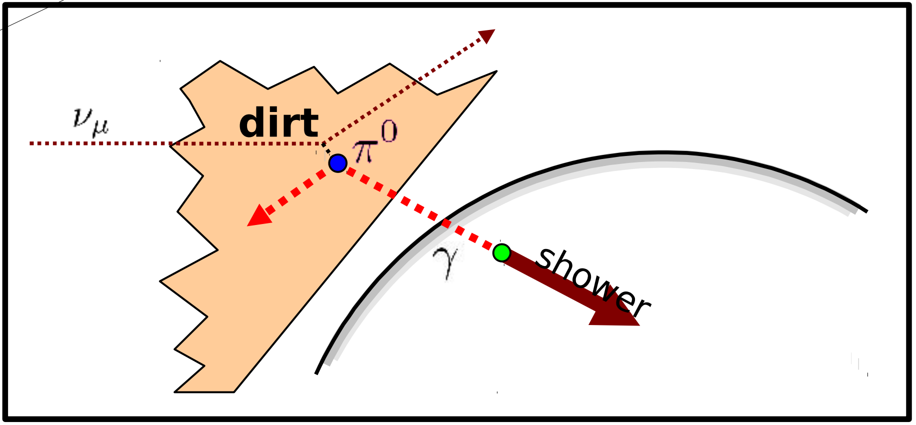


$\Delta \rightarrow N\gamma$ is constrained by the measured resonant NC π^0 rate.

Backgrounds ($\bar{\nu}$ mode)



- Dirt

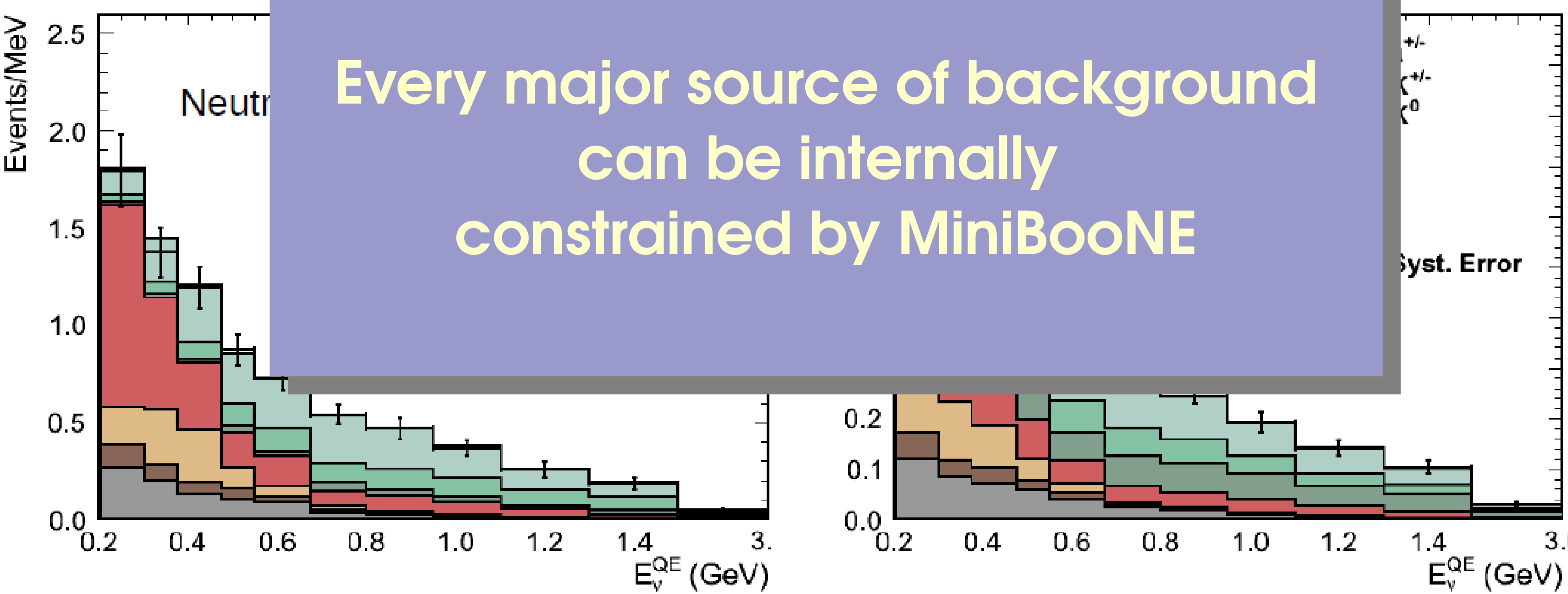


- Events from ν interactions with surrounding dirt
- Events at high R pointing towards the center of the detector

Fit dirt-enhanced sample to extract dirt event rate with ~18% uncertainty.

Background predictions (ν & $\bar{\nu}$)

Similar backgrounds in neutrino and anti-neutrino modes



Every major source of background can be internally constrained by MiniBooNE

Oscillation analysis method

Combined fit to ν_e & ν_μ data

- For each bin i:

$$\Delta_i = N_i^{DATA} - N_i^{MC}$$

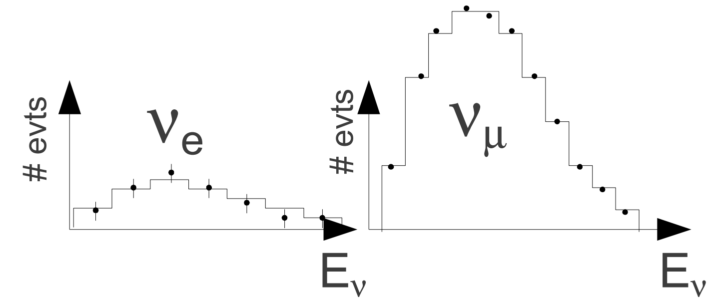
- Scan in Δm^2 & $\sin^2 2\theta$ to calculate $-2\ln(\mathcal{L})$ **over ν_e & ν_μ bins**

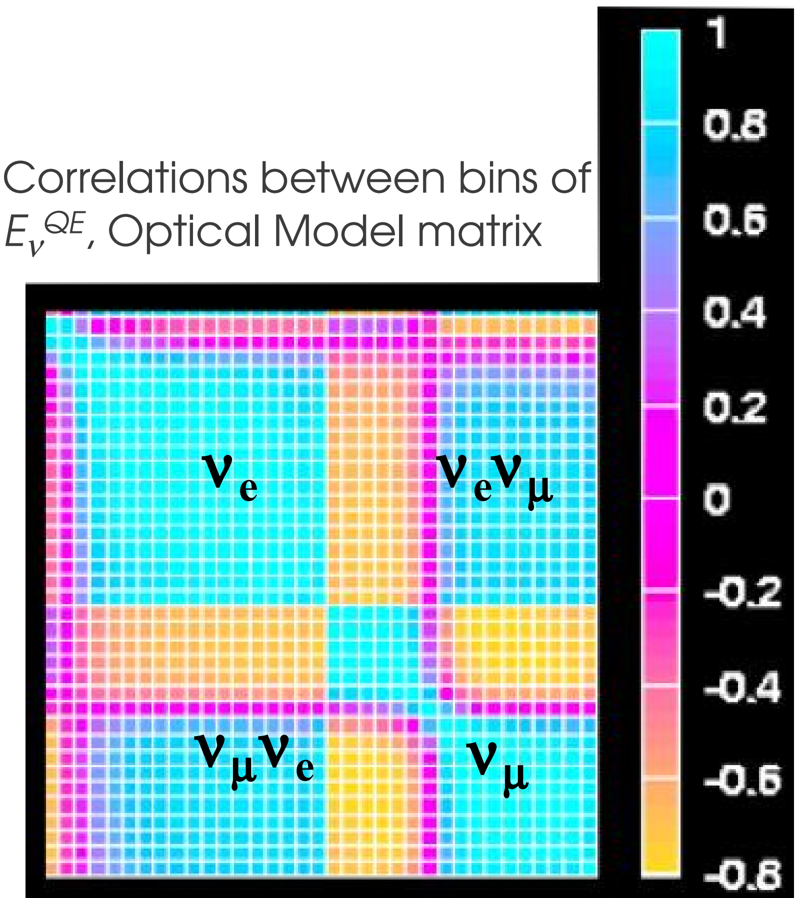
$$-2\ln(\mathcal{L}) = \mathbf{\Delta}\, M^{-1} \mathbf{\Delta}^T + \ln(|M|)$$

- Error matrix M includes systematic errors for ν_e & ν_μ and correlations.
  $M = M_{om} + M_{Xsec} + M_{flux} + M_{\pi 0} + M_{dirt} + M_{K0} + M_{beam} + \ldots$

- Large ν_μ sample constrains many of the uncertainties.

The ν_μ sample works as a near detector.





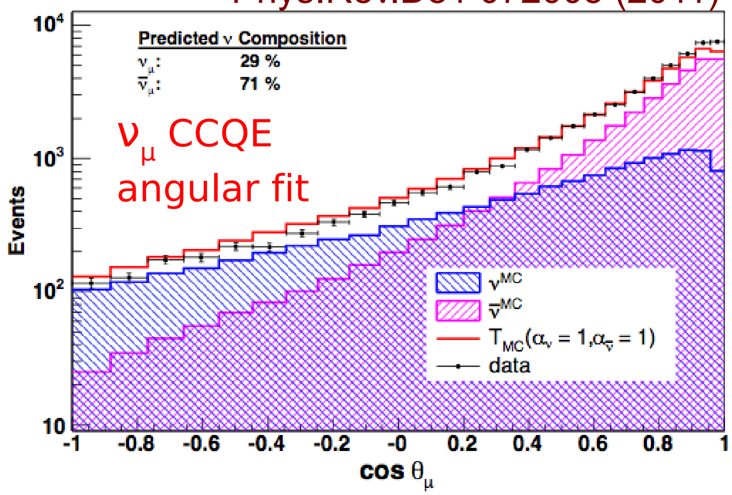
Correlations between bins of E_ν^{QE}, Optical Model matrix

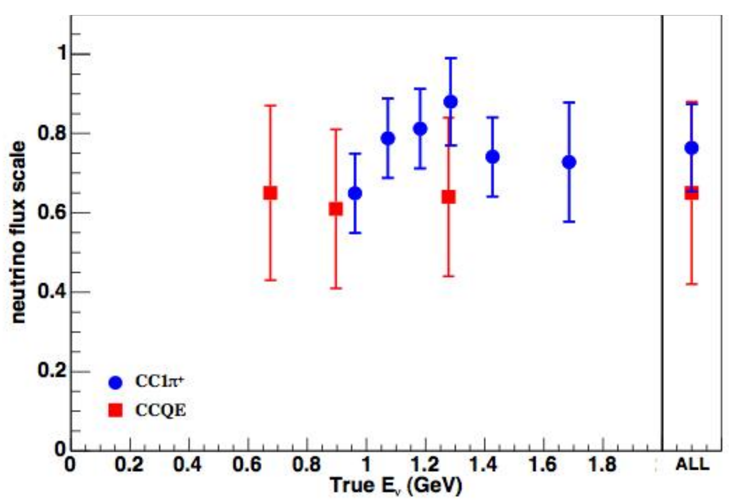
Improvements since 2010 publication

In situ measurement of WS contamination in anti-ν beam.

- ν_μ-CCQE angular fit and new constraint from CCπ+ rate … agree w/expectation

Phys.Rev.D81 072005 (2011)

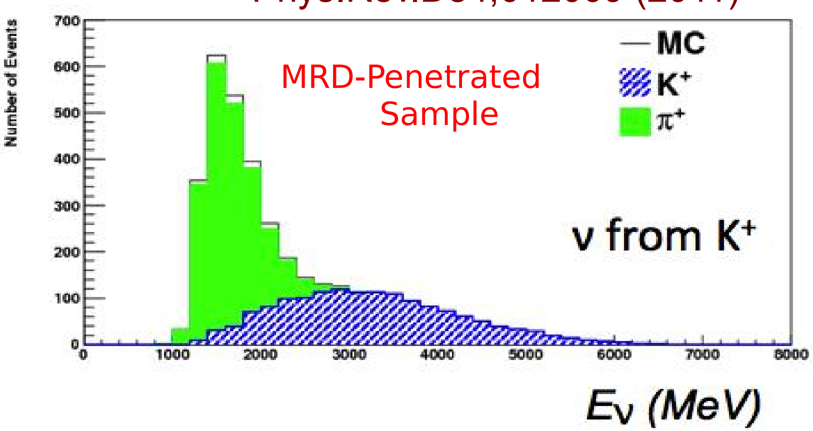


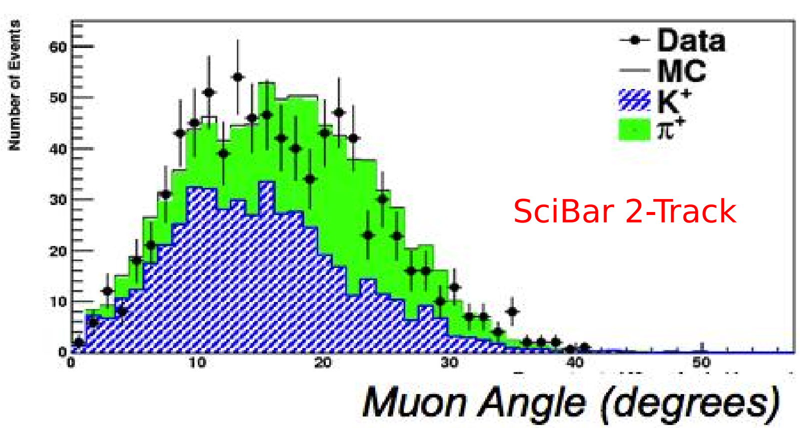


New SciBooNE constraint on intrinsic ν_e from K+.

- Found production to be 0.85+-0.12 relative to prediction, consistent with prior MiniBooNE assessment of 1.00 +-0.30.
- Leading error on K+ bkgd becomes ~20% error from cross section.

Phys.Rev.D84,012009 (2011)

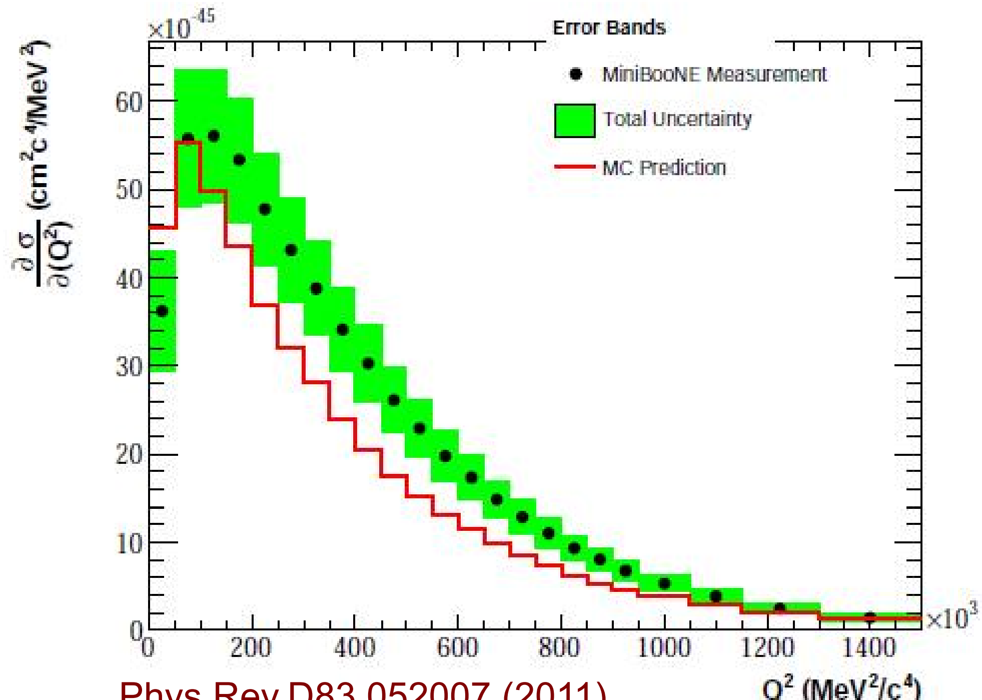




Improvements since 2010 publication

Few other minor updates:

- Higher statistics for all MC samples → reduces fluctuations in error matrices
- Added new error matrix for intrinsic ν_e from K-.
- Improved smoothing algorithm that was being used to assess systematics due to discriminator thresholds and PMT response.
- Applied Q^2 reweighing to CCπ+ events based on internal MB measurement.



Phys.Rev.D83,052007 (2011)

Main improvement:

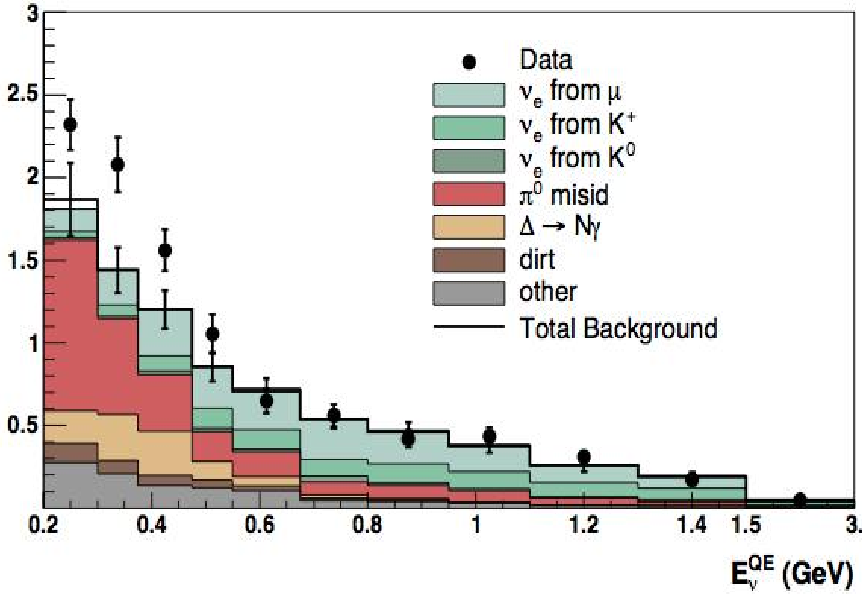
Doubling of anti-ν mode statistics

5.66E20 POT → 11.3E20 POT

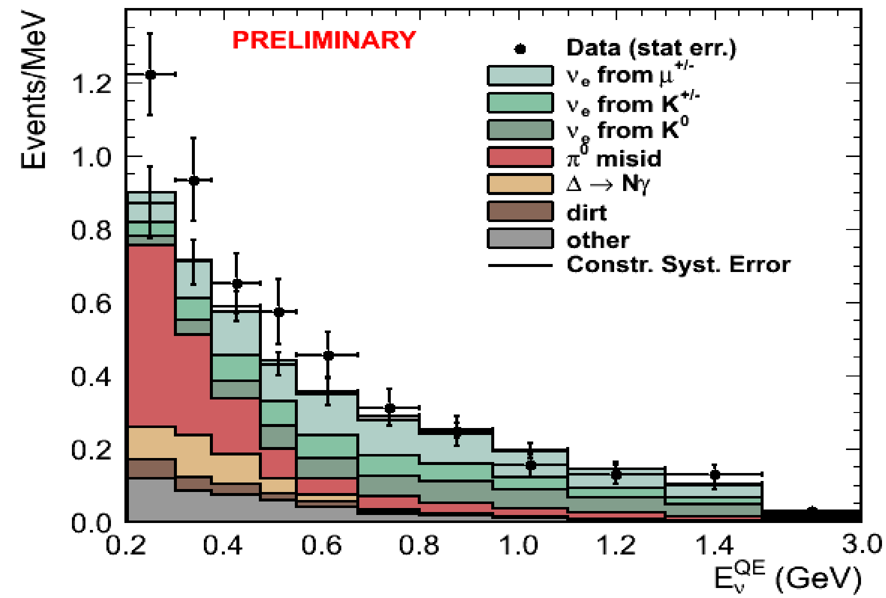
- higher stats. for anti-ν_e appearance
- … and samples used for constraints

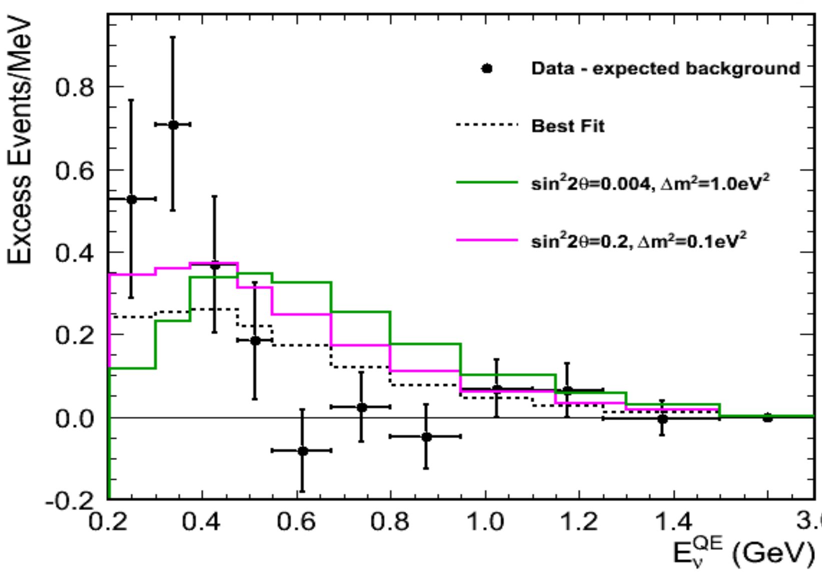
neutrino and anti-neutrino modes, full data sets (2012)

6.46e20 POT neutrino mode



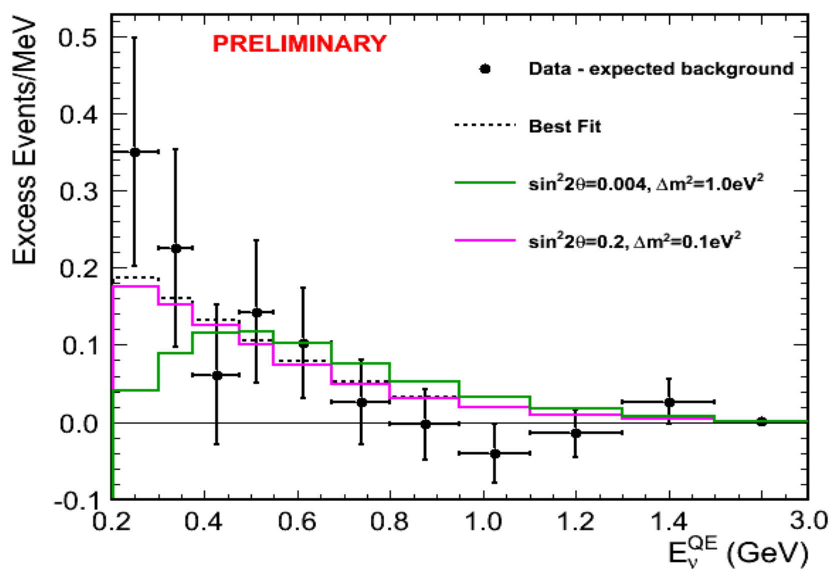
11.3e20 POT anti-neutrino mode





Excess: 146.3 ± 28.4 ± 40.2

(200 MeV $<E_\nu^{QE}<$ 1250 MeV)



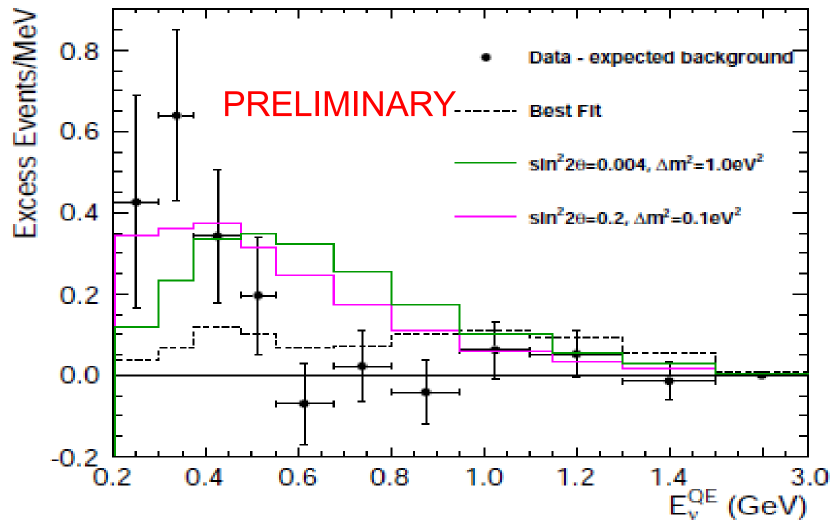
Excess: 77.8 ± 20.0 ± 23.4

(200 MeV $<E_\nu^{QE}<$ 1250 MeV)

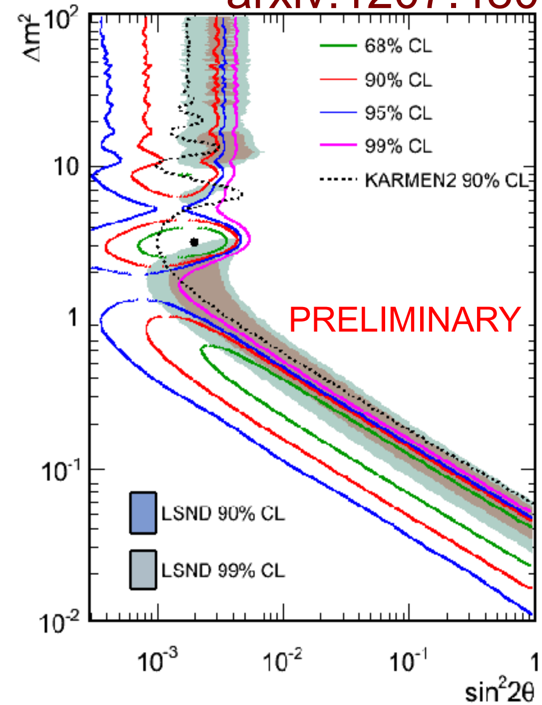
Updated result with neutrinos

arxiv:1207.4809

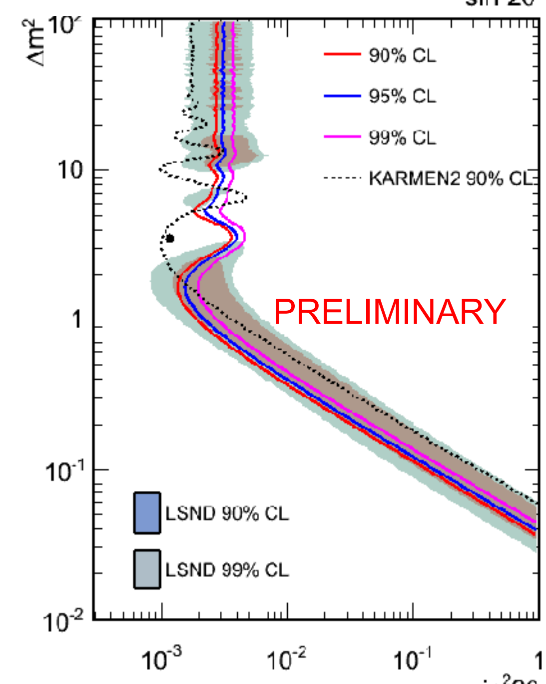
6.46E20 POT neutrino mode



E>200 MeV



E>475 MeV



- Excess (200-1250 MeV): 146.3 ± 28.4 ± 40.2
- Tension between fits in the two regions.
  → May be reduced by taking into account multi-nucleon knock-outs **M. Martini et al. arXiv:1211.1523**)

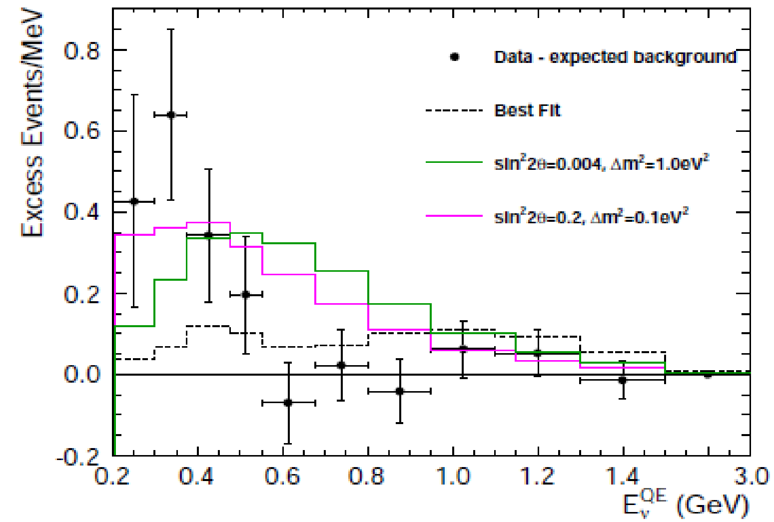
ν mode	E > 200 MeV	E > 475 MeV
χ^2(null)	22.81	6.35
Prob(null)	0.5%	36.6%
χ^2(bf)	13.24 ⟷	3.73
Prob(bf)	6.12%	42.0%

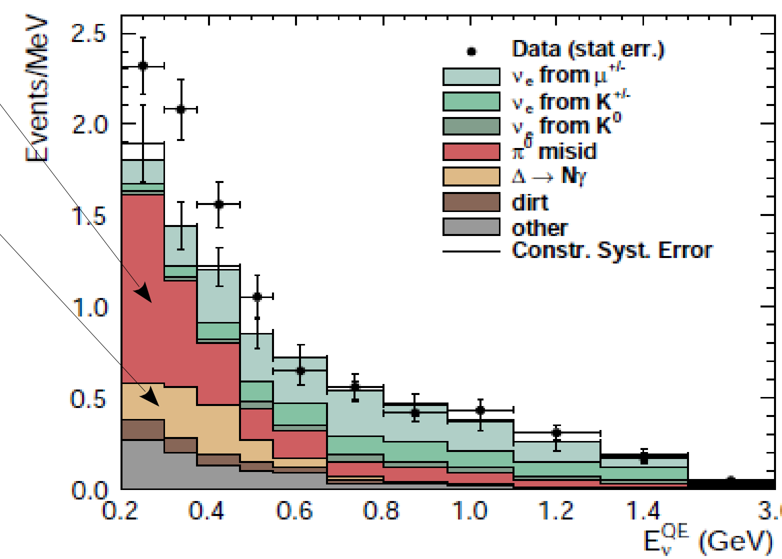
What we know about the low-E excess

- Not a stat fluctuation, statistically 6σ
- Unlikely to be intrinsic ν_e, small bkg at low E
- NC π^0 background dominates
  - ➔ Reduces significance to 3σ
  - ➔ Heavily constrained by NC π^0 *in situ* measurement
- Region where single γ can contribute
- MB ties $\Delta \rightarrow N\gamma$ expected rate to be 1% of measured NC π^0 rate
  - ➔ Number of theory calculations for various single γ processes
  - ➔ All find total cross section within 20% of MB ~5×10^{-42} cm^2/N
  - ➔ Would need nearly 300% change

R. Hill, arxiv:0905.0291
Jenkins & Goldman, arxiv:0906.0984
Serot & Zhang, arxiv:1011.5913

Neutrino mode

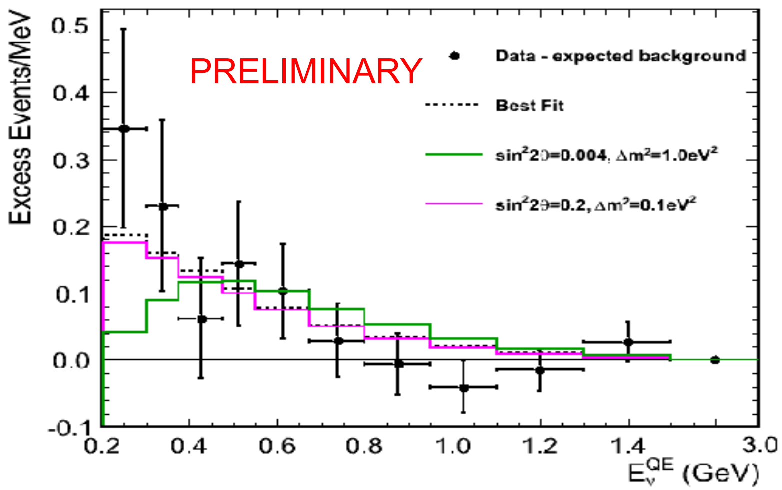




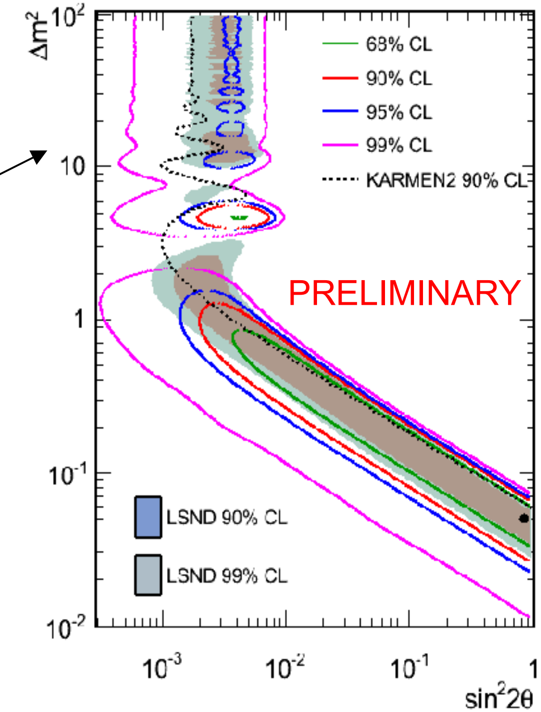
MicroBooNE experiment will study this excess

Updated result with anti-neutrinos

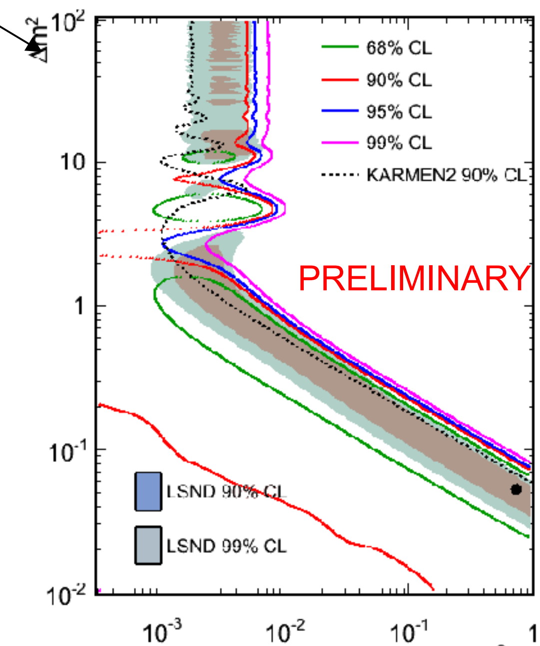
11.27E20 POT anti-neutrino mode



E>200 MeV



E>475 MeV



Excess (200-1250 MeV):78.2±20.0±23.4

No tension between fits in two energy regions

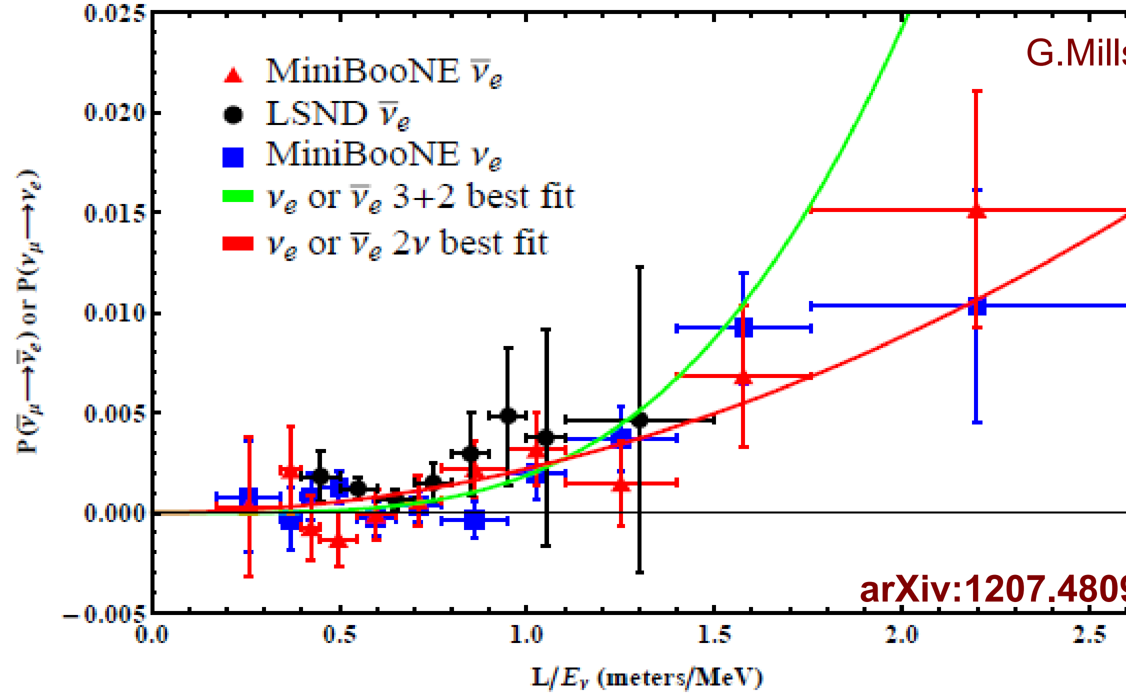
Caveat: WS ν_μ assumed not to oscillate

anti-ν mode	E > 200 MeV	E > 475 MeV
χ^2(null)	16.6	7.8
Prob(null)	5.4%	24.6%
χ^2(bf)	4.8	3.3
Prob(bf)	67.1%	49.2%

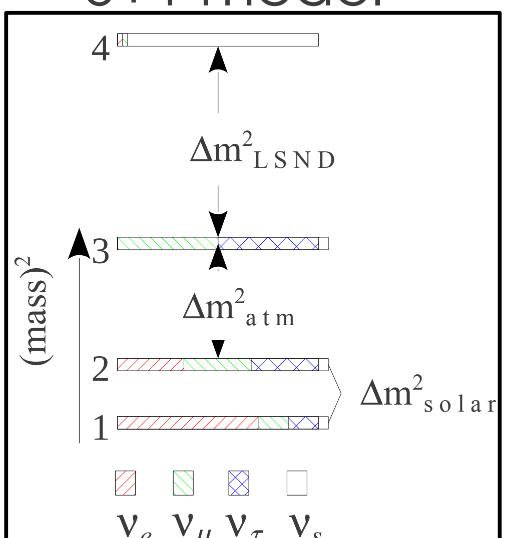
sin²2θ

L/E dependence

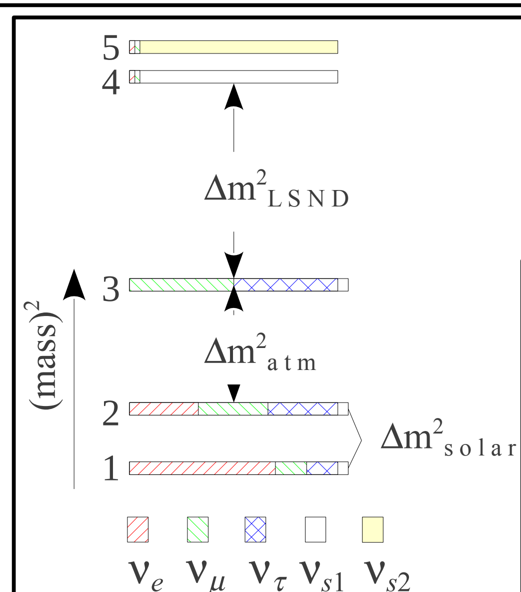
- A model independent way to look at the data
- Excess dependence on L/E consistent in the 3 data sets: (MB-ν, MB-$\bar{\nu}$, LSND)
- 3+1 and 3+2 models with sterile nu's can fit the data.



3+1 model



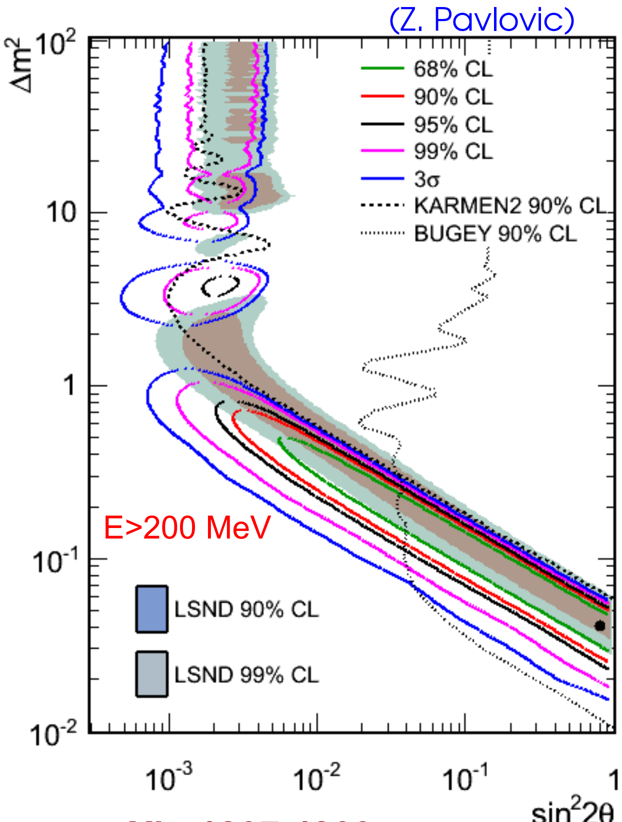
$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) = \underbrace{\sin^2 2\theta}_{4|U_{e4}|^2|U_{\mu4}|^2} \sin^2(1.27 \underbrace{\Delta m^2}_{\Delta m_{41}^2} L/E)$$



3+2 model

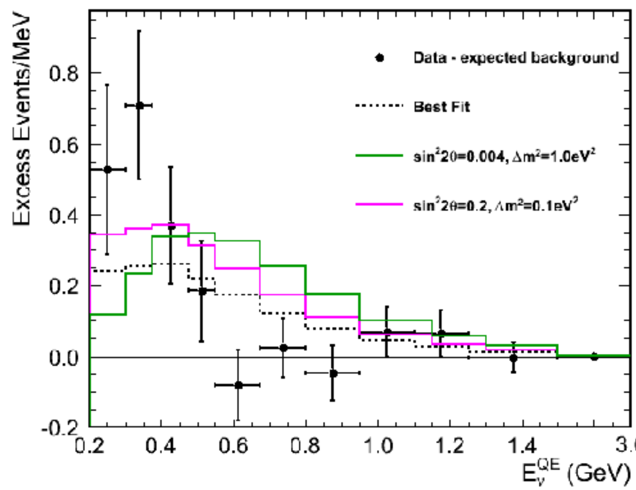
$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) = 4\,|U_{e4}|^2\,|U_{\mu4}|^2 \sin^2(1.27\,\Delta m^2_{41}\,L/E) + 4\,|U_{e5}|^2\,|U_{\mu5}|^2 \sin^2(1.27\,\Delta m^2_{51}\,L/E) + 4\,|U_{e4}|\,|U_{\mu4}|\,|U_{e5}|\,|U_{\mu5}| \sin(1.27\,\Delta m^2_{41}\,L/E \sin(1.27\,\Delta m^2_{51}\,L/E) \cos(1.27\,\Delta m^2_{54}\,L/E \pm \varphi_{45})$$

Simultaneous 3+1 fit to ν and anti-ν data

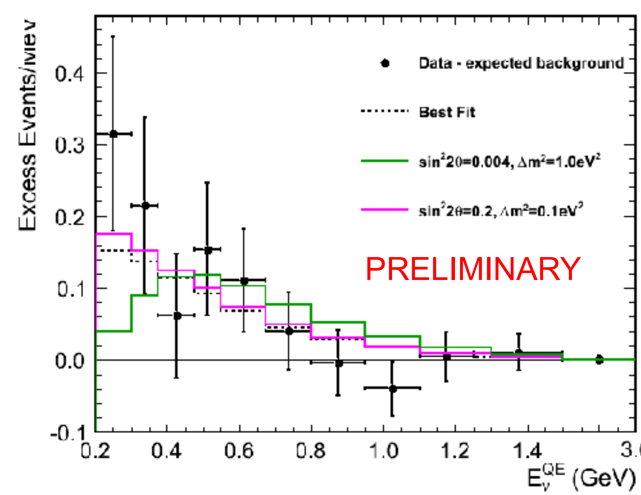


arXiv:1207.4809

- WS accounted for properly
- Construction of correlated systematic error matrix
- E>200 MeV BF preferred at 3.6 σ **over null**.



Simultaneous fit (E>200 MeV) with fully-correlated systematic to entire MB neutrino and anti-neutrino data

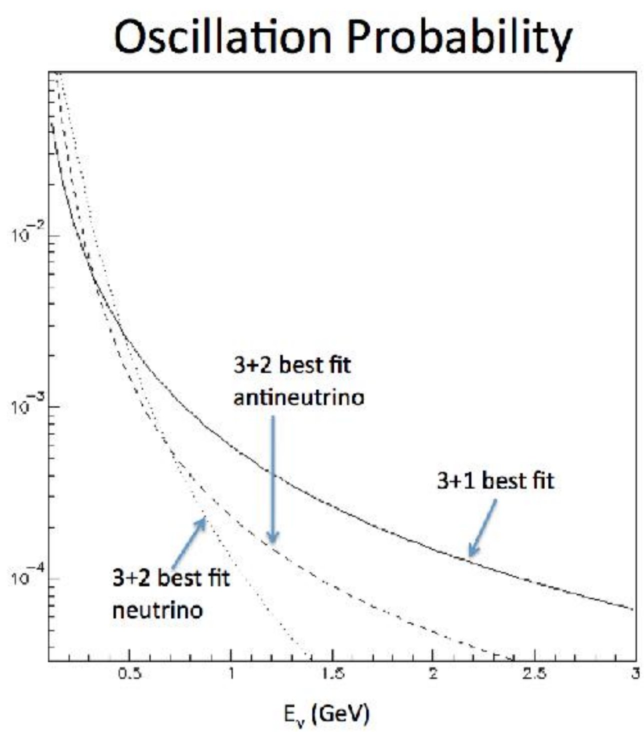


combined	E > 200 MeV	E > 475 MeV
χ^2(null)	42.53	12.87
Prob(null)	0.1%	35.8%
χ^2(bf)	24.72	10.67
Prob(bf)	6.7%	35.8%

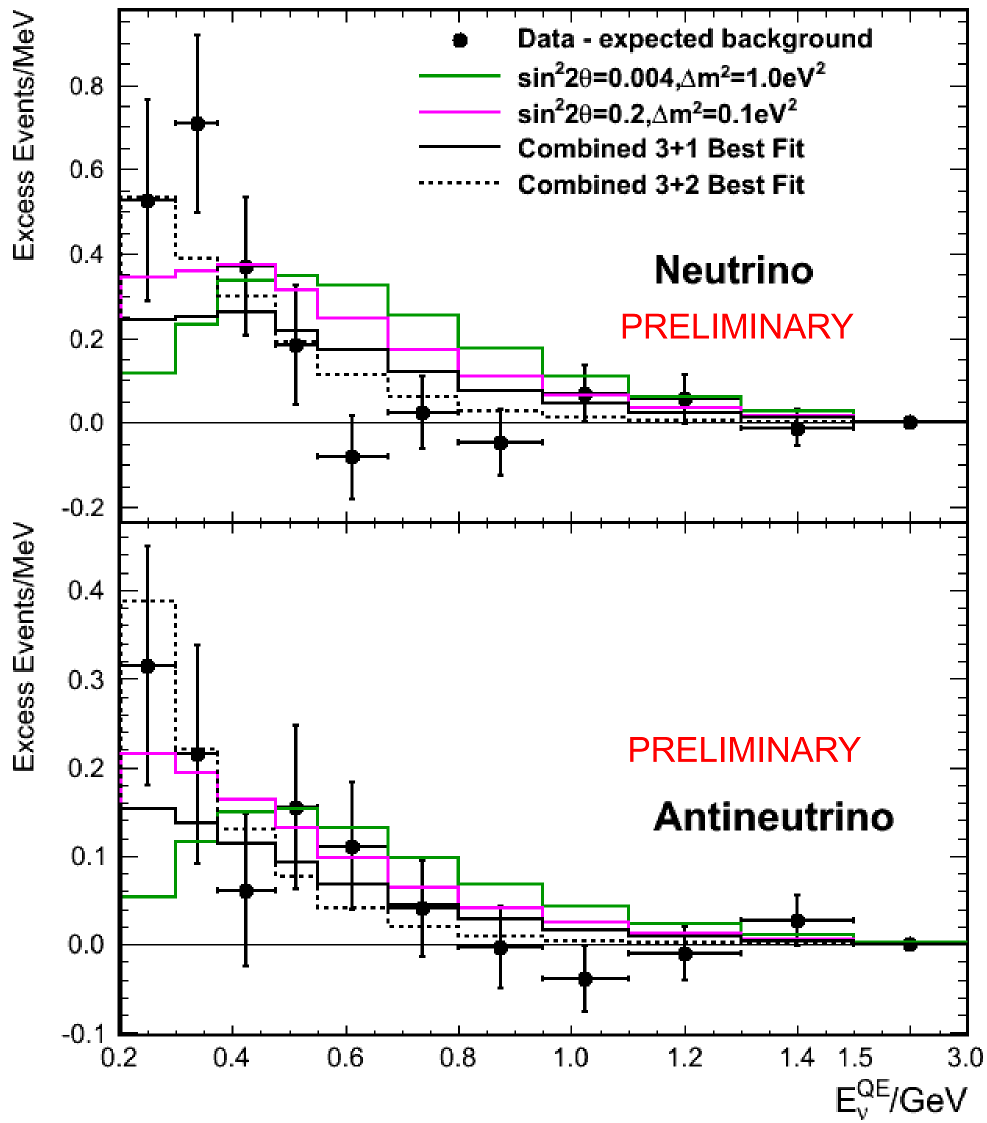
Total Excess: 240.3 +/- 34.5 +/- 52.6

3+2 model

- Allows CP violation effects.
- Fits better the shape of MiniBooNE excess
- Better fit to world data (see e.g. arxiv:1207.4765 for recent global fits)



arXiv:1207.4809



Conclusions

- Current MiniBooNE run ended. Collected $(6.46_{(\nu)}+11.27_{(\bar{\nu})})\times 10^{20}$ POT

- In the energy range 200-1250 MeV, MiniBooNE observes an excess of nue candidates in neutrino mode (3.4 σ) and in anti-neutrino mode (2.8 σ).
  - ➔ The combined excess is **240±34.56±52.6 (3.8σ)**

- Simultaneous ν_e, $\bar{\nu}_e$ fits show some tension in data within a simple 2 neutrino oscillation model.
  - ➔ Some theoretical ideas exist to alleviate the tension (arXiv:1211.1523)
  - ➔ Much better fit achieved with 3+2 model.

- Future plans/ideas include:
  - ➔ Run with beam off-target mode to make light Dark Matter search
  - ➔ Add scintillator to mineral oil to increase sensitivity to oscillations in low energies.


Thank you !

Backup

Mini-Booster Neutrino Experiment

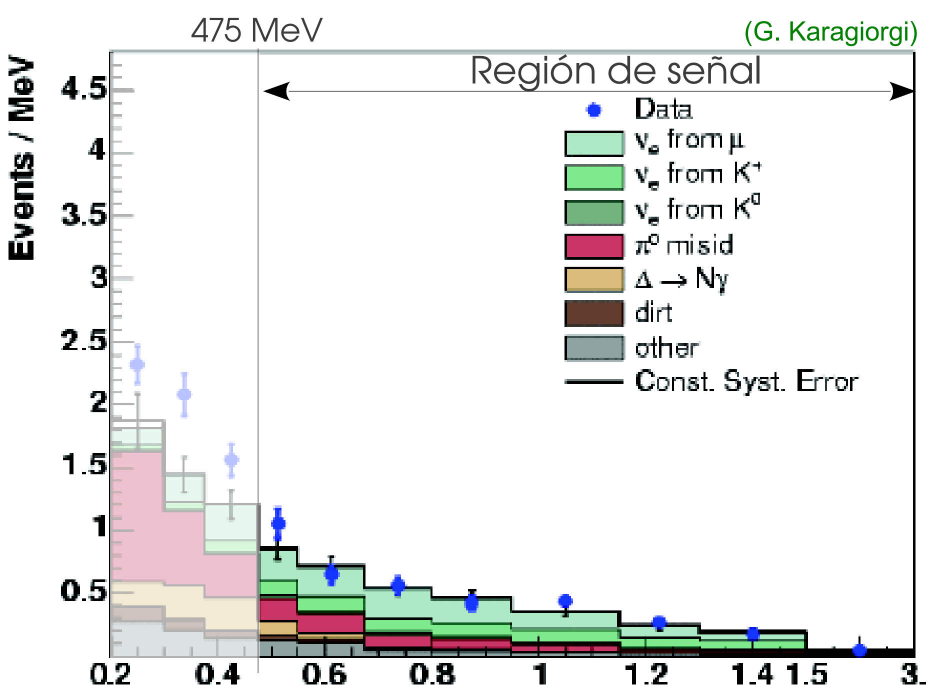
A. A. Aguilar-Arevalo[12], C. E. Anderson[15], S. J. Brice[6], B. C. Brown[6], L. Bugel[11], J. M. Conrad[11], Z. Djurcic[2], B. T. Fleming[15], R. Ford[6], F. G. Garcia[6], G. T. Garvey[9], J. Mirabal[9], J. Grange[7], J. A. Green[8,9], R. Imlay[10], R. A. Johnson[3], G. Karagiorgi[11], T. Katori[8,11], T. Kobilarcik[6], S. K. Linden[15], W. C. Louis[9], K. B. M. Mahn[5], W. Marsh[6], C. Mauger[9], W. Metcalf[10], G. B. Mills[9], C. D. Moore[6], J. Mousseau[7], R. H. Nelson[4], V. Nguyen[11], P. Nienaber[14], J. A. Nowak[10], B. Osmanov[7], Z. Pavlovic[9], D. Perevalov[1], C. C. Polly[6], H. Ray[7], B. P. Roe[13], A. D. Russell[6], M. H. Shaevitz[5], M. Sorel[5*], J. Spitz[15], I. Stancu[1], R. J. Stefanski[6], R. Tayloe[8], M. Tzanov[4], R. G. Van de Water[9], M. O. Wascko[10†], D. H. White[9], M. J. Wilking[4], G. P. Zeller[6], E. D. Zimmerman[4]
(The MiniBooNE Collaboration)

Result with neutrinos (c. 2009)

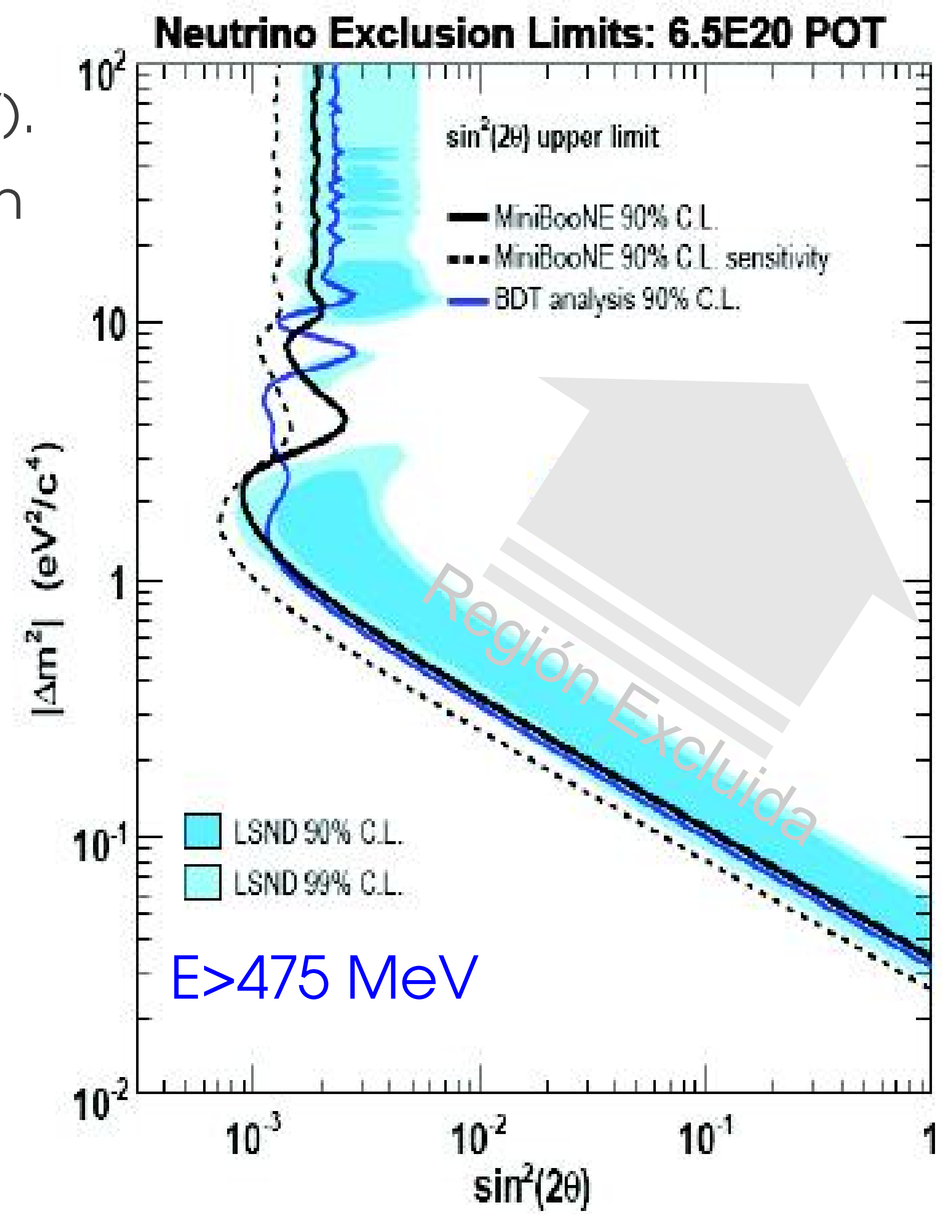
6.46E20 POT in neutrino mode

No excess in signal region (E>475 MeV).

Excludes 2 ν oscillations as explanation of LSND (if no CP violation)



PRL 102, 101802 (2009)

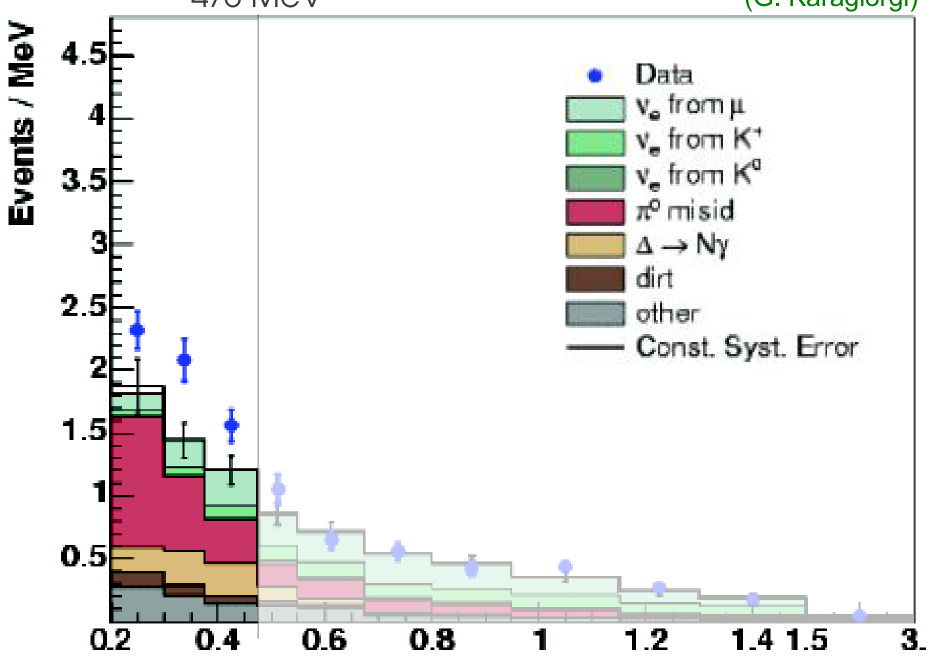


Result with neutrinos (c. 2009)

Region E<475 MeV showed excess of ν_e**-like events:**

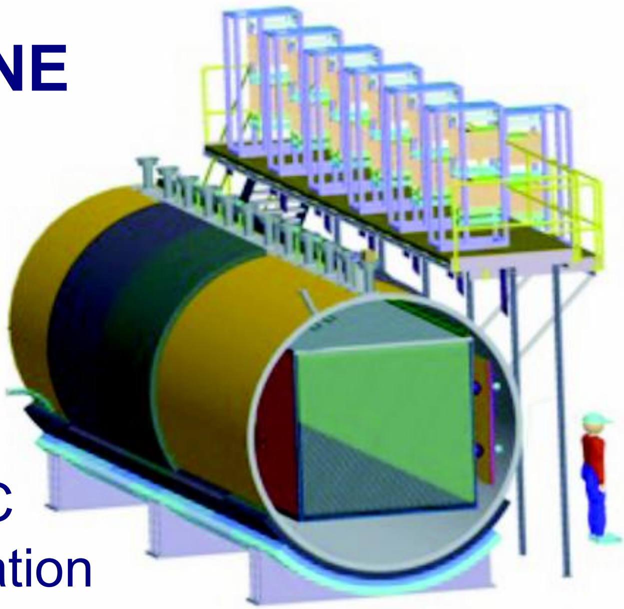
128.8 ± 20.4 ± 38.3 (3σ)

Shape inconsistent with 2ν osc.
MicroBooNE will study its origin →

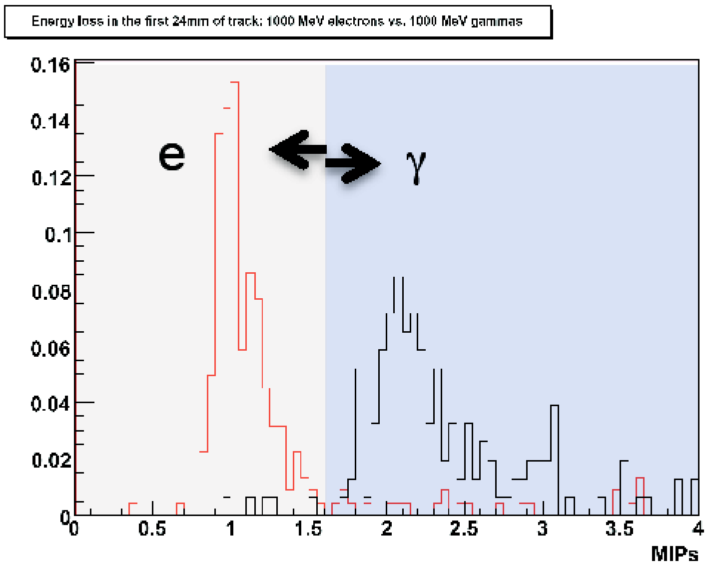


PRL 102, 101802 (2009)

MicroBooNE



Liquid Ar TPC
e/γ discrimination

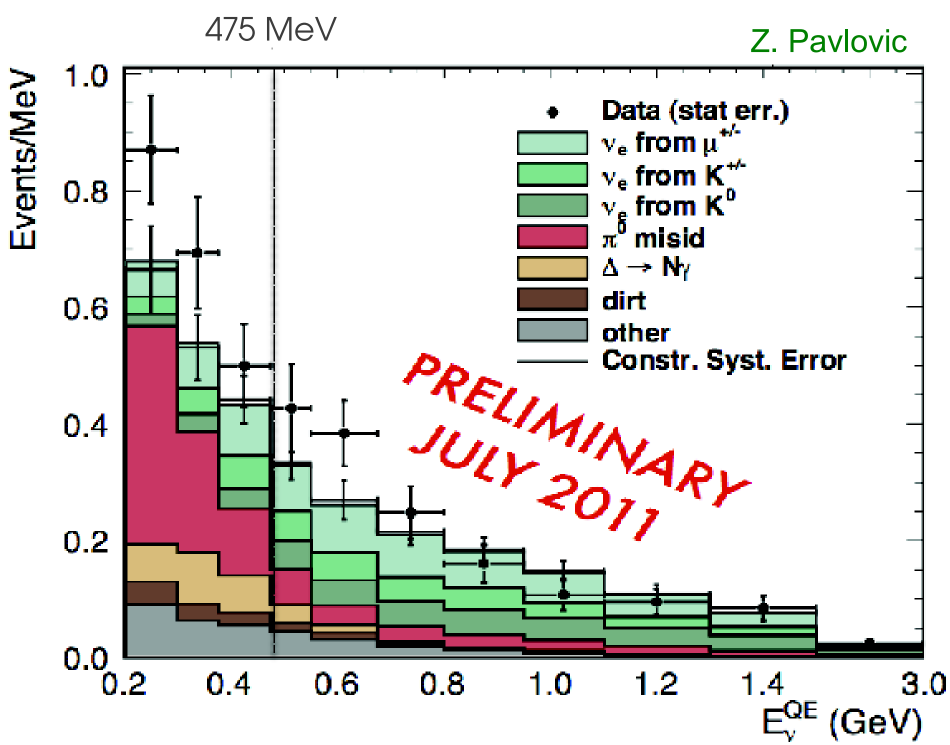


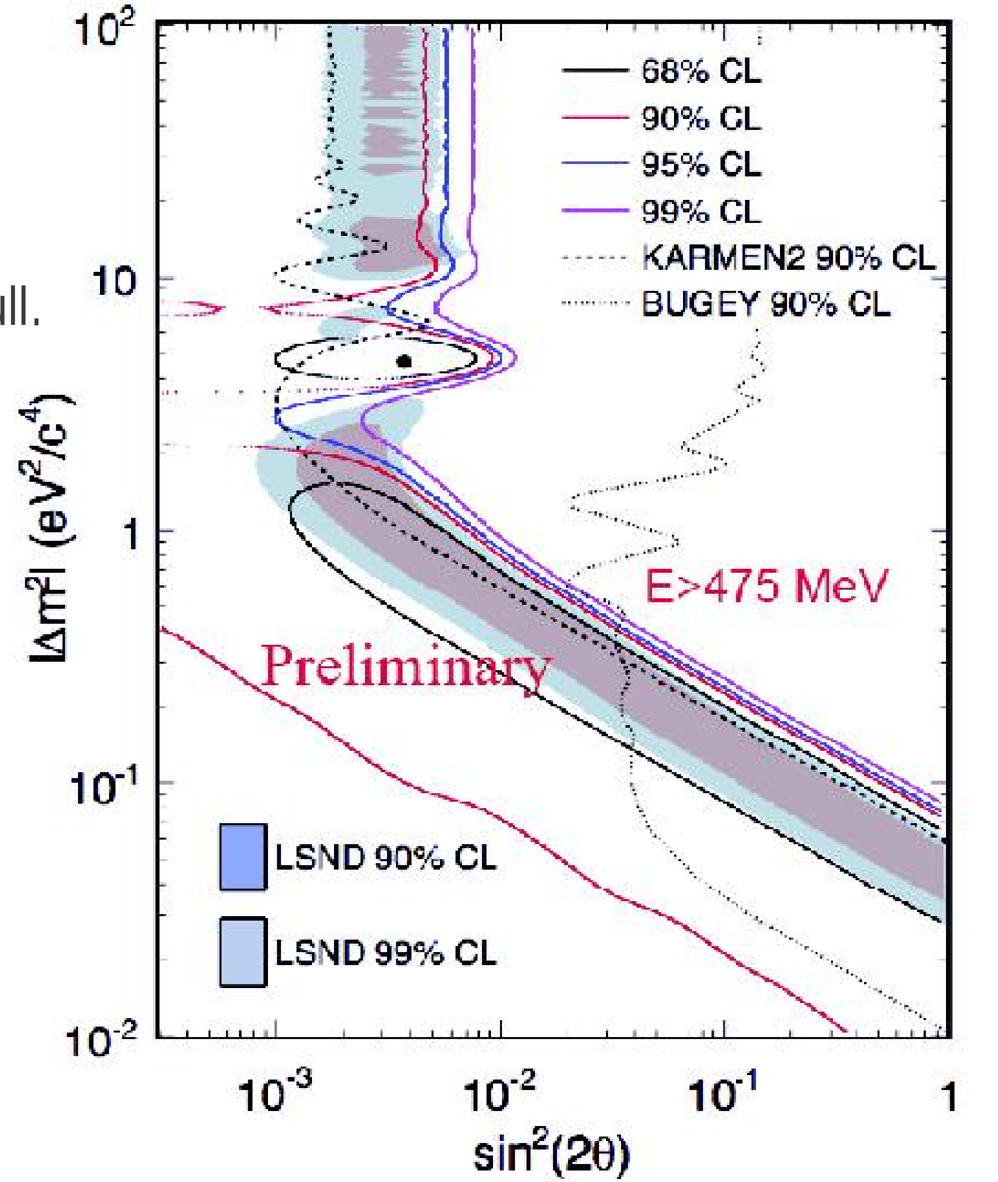
Result with anti-neutrinos (c. 2011)

8.58E20 POT anti-neutrino mode

E>475 MeV: Excess = 38.6 ± 18.6
E>200 MeV: Excess = 57.7 ± 28.5

Fit favors 2ν osc. at 91.1% C.L. over null.
Consistent with LSND result.

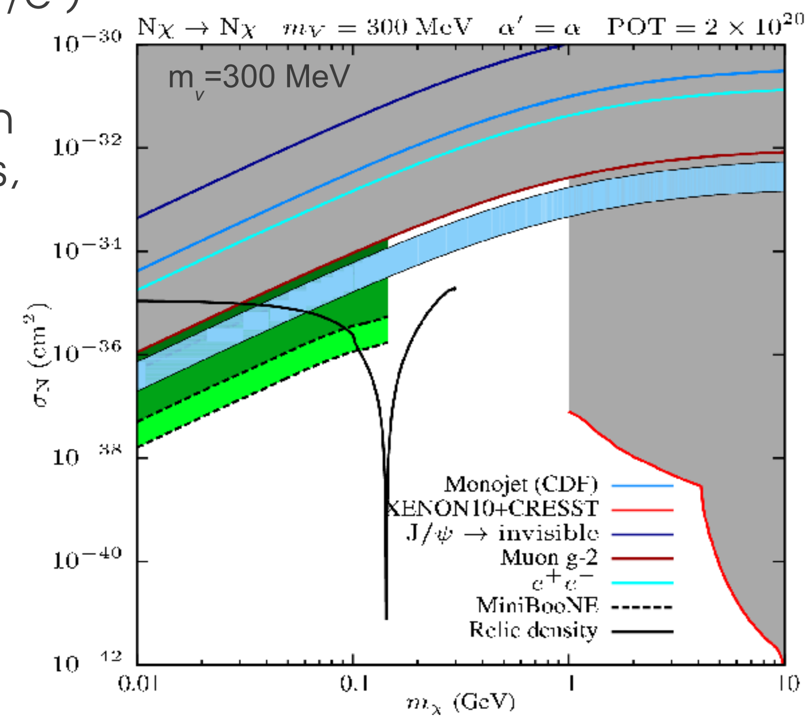


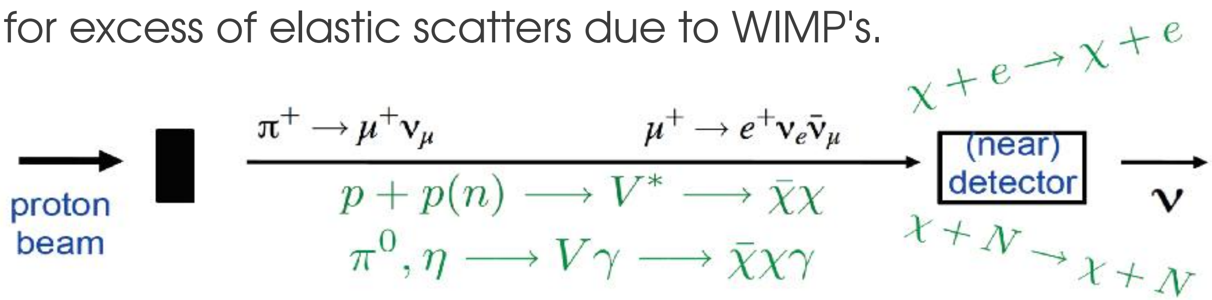


Future plans of MiniBooNE

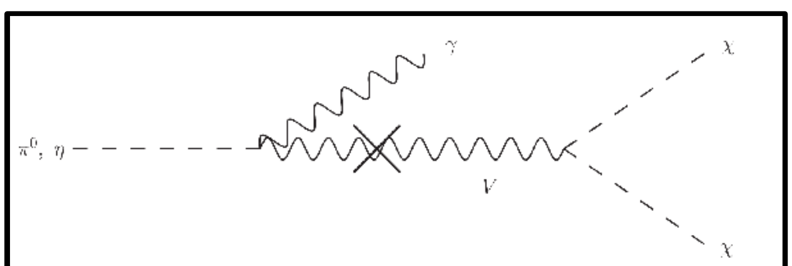
Proposal: Beam off-target running → light Dark Matter (DM) search.

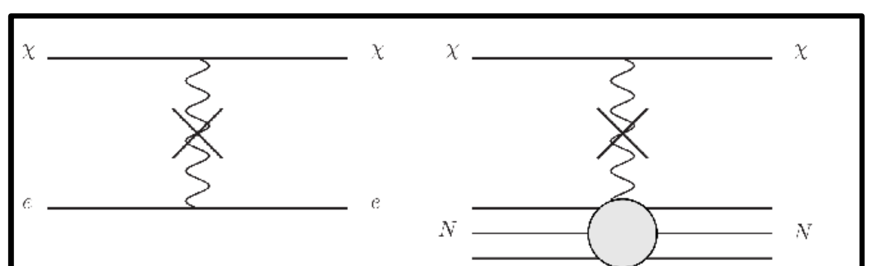
- Recent theoretical work highlights light WIMP's (m_χ<200 MeV/c^2) as good DM candidates.
- Sub-GeV WIMP's could couple to the SM via a mediator with renormalizable interactions. Constraints from particle physics, astrophysics, and cosmology select a U(1) vector V^μ as the most viable mediator candidate.
- MiniBooNE has unique opportunity to search for light mass WIMP's/mediators (10-200 MeV/c^2) in region consistent with g-2 anomaly.
- How? Run beam off-target to impact protons against 25 m absorber (neutrino production severely reduced), and look for excess of elastic scatters due to WIMP's.





P. deNiverville, D. McKeen and A. Ritz, Phys. Rev. D 86, 035022 (2012)





Future plans of MiniBooNE

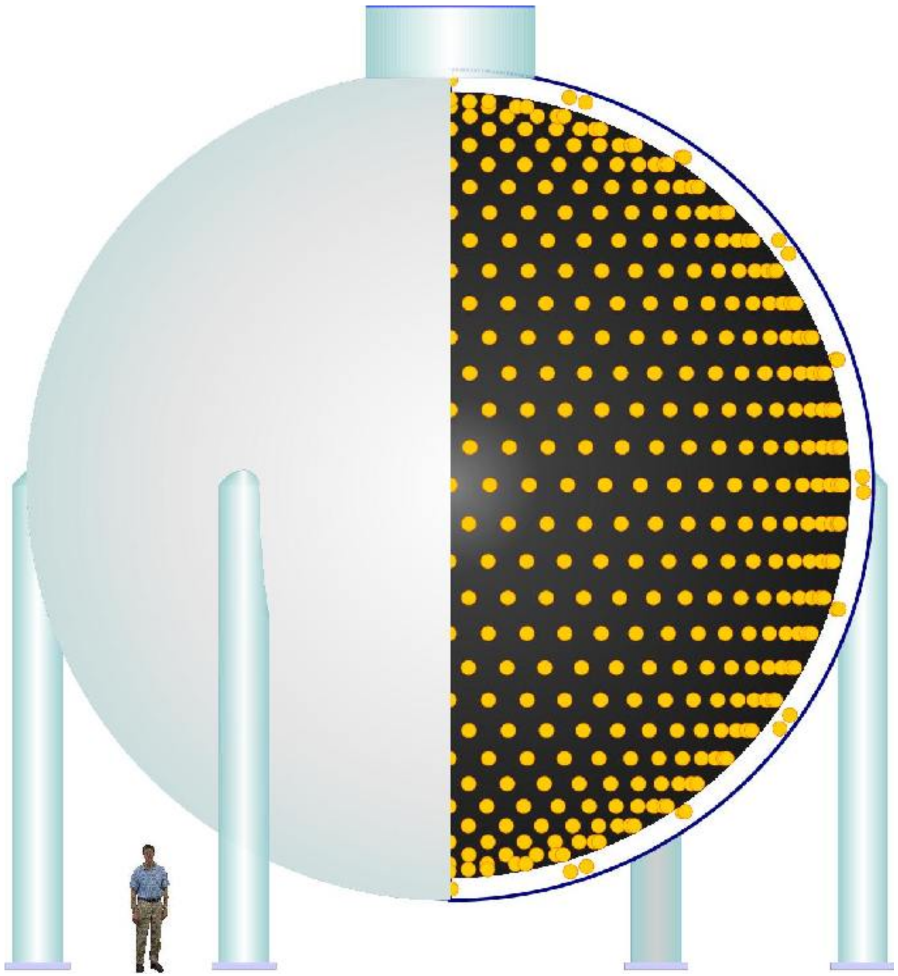
LOI: Add scintillator to MB detector oil → enhance low E detection

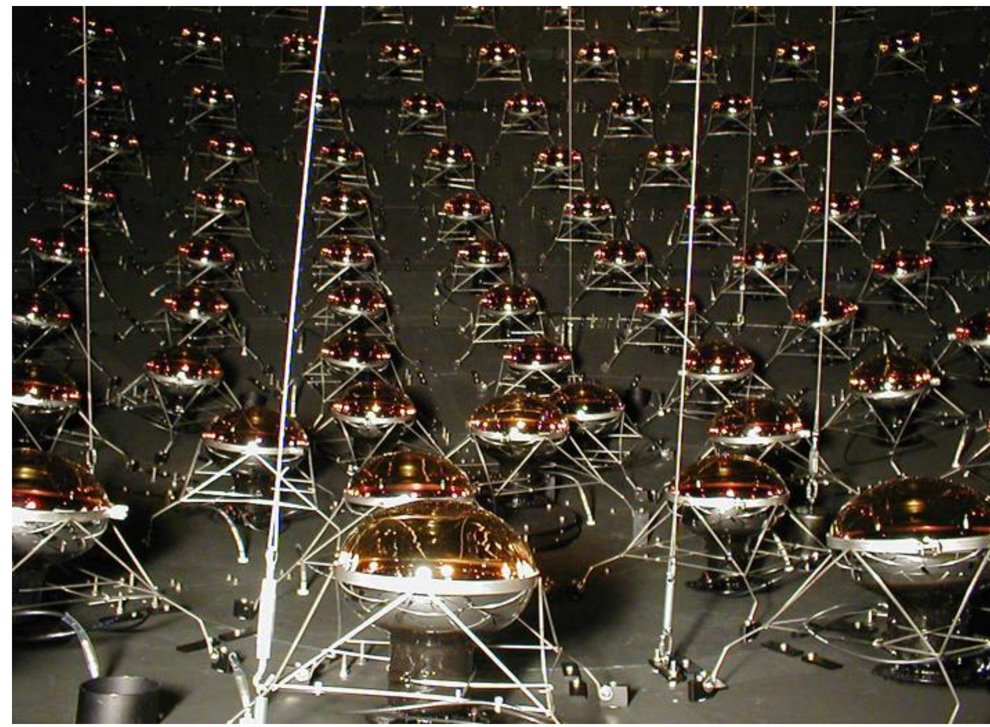
- Add scintillator to the MB oil to allow a test of the NC/CC nature of thelow-E excess. Run for 3 yr to get ~6.5E20 POT. Complementary to MicroBooNE.
- NC neutrino interactions have a higher probability to have associated neutrons than CC interactions. Detection of 2.2 MeV γ from n capture will allow measuring the neutron fraction in low-E events.
- A ν_e appearance search with neutron-fraction measurement, would increase the excess significance beyond 5σ.
- Will allow a study of the strange-quark contribution to nucleon spin, measurement of $\nu_\mu {}^{12}C \rightarrow \mu^- {}^{12}N$ reaction, test of CCQE assumption in ν energy reconstruction.

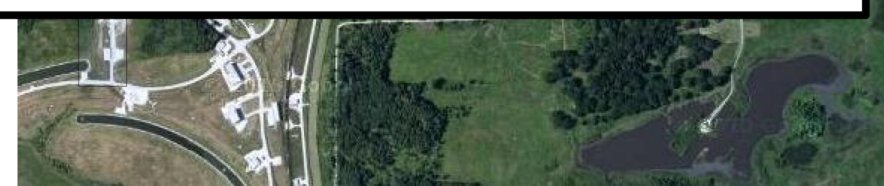
arXiv:1210.2296

Mini-**Boo**ster **N**eutrino **E**xperiment

horn/target | decay tunnel | absorber | dirt | detector





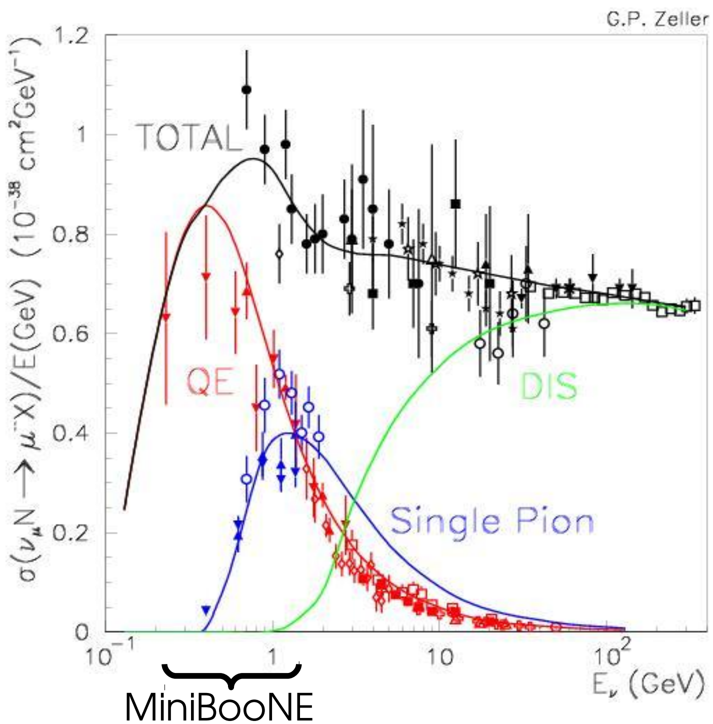


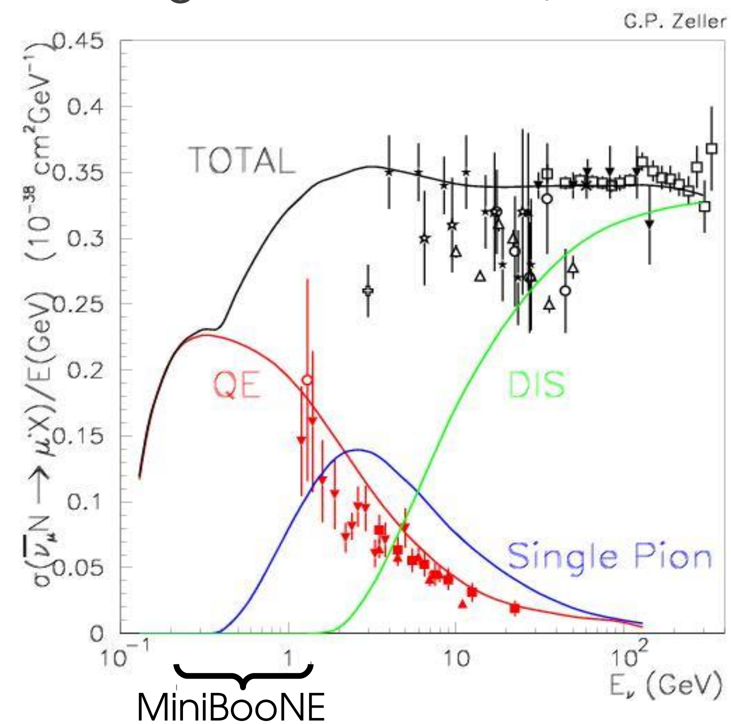
~1 kton mineral oil (CH_2) Cherenkov detector

12 m diameter, 1280 inner PMTs, 240 veto PMTs

Neutrino Interactions (ν & $\bar{\nu}$)

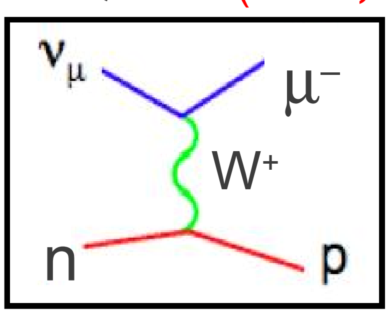
Cross sections modeled with NUANCE event generator (D. Casper, U.C. Irvine)





(T. Katori, J. Grange)

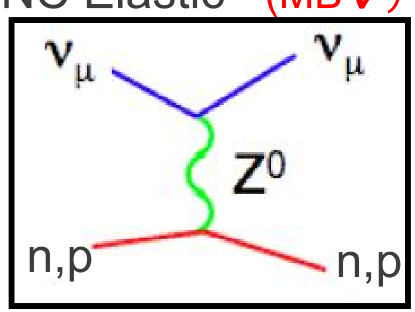
CCQE (MB ✓)



PRL **100**, 032301 (2008)
PRD **81**, 092005 (2010)

(D. Perevalov)

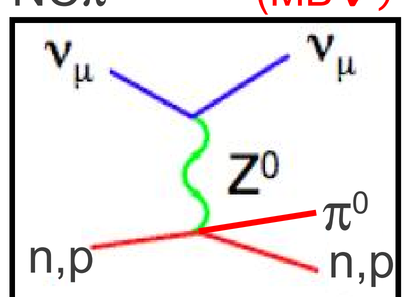
NC Elastic (MB ✓)



PRD **82**, 092005 (2010)

(C. Anderson, J. Link)

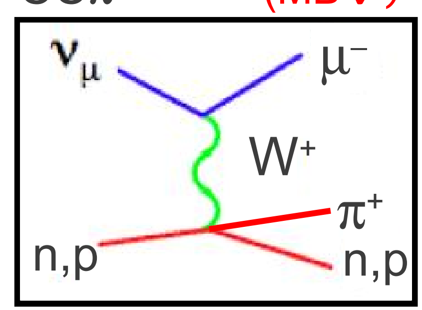
NCπ^0 (MB ✓)



PLB **664**, 41 (2008)
PRD **81**, 013005 (2010)

(S. Linden, M. Wilking)

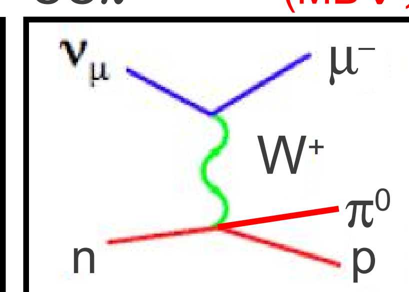
CCπ^+ (MB ✓)



PRL **103**, 081801 (2009)
PRD **83**, 052007 (2011)

(R. Nelson)

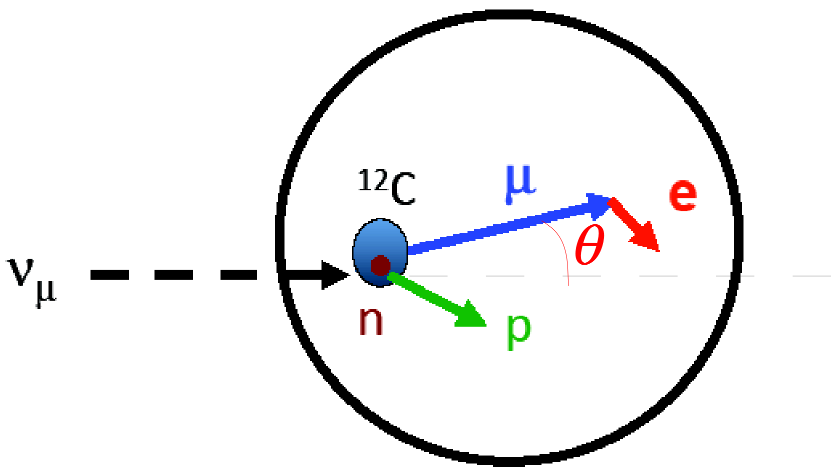
CCπ^0 (MB ✓)



PRD **83**, 052009 (2011)

CCQE events in MiniBooNE

CCQE: Charged-Current Quasi-Elastic
Single μ events + decay *e*

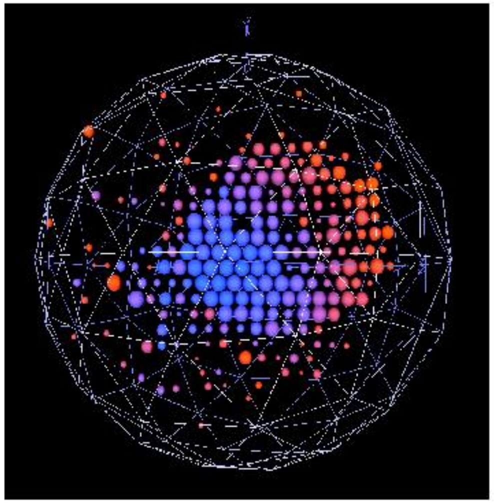


- Events produce Cherenkov light recorded by PMTs (charge, time).
- Two sets of hits separated in time (μ,*e*)
- Minimal hits in the veto.
- Require 1st set of hits above decay electron energy endpoint, 2nd set below
- Endpoint of 1st track consistent of vertex of 2nd track.
- Also require events within fiducial volume beam timing, and data quality selections.

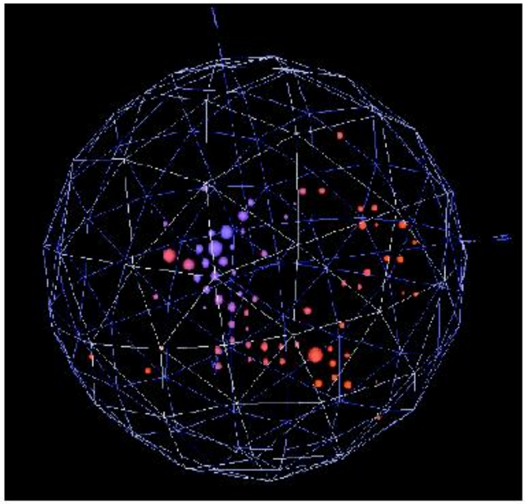
Muon's Energy (E_μ) and angle (θ_μ) give the neutrino energy:

$$E_\nu^{QE} = \frac{2M'_n E_\mu - [M'^2_n + m^2_\mu - M^2_p]}{2[M'_n - E_\mu + p_\mu \cos\theta_\mu]}$$

M_N: Mass of nucleon N



μ candidate

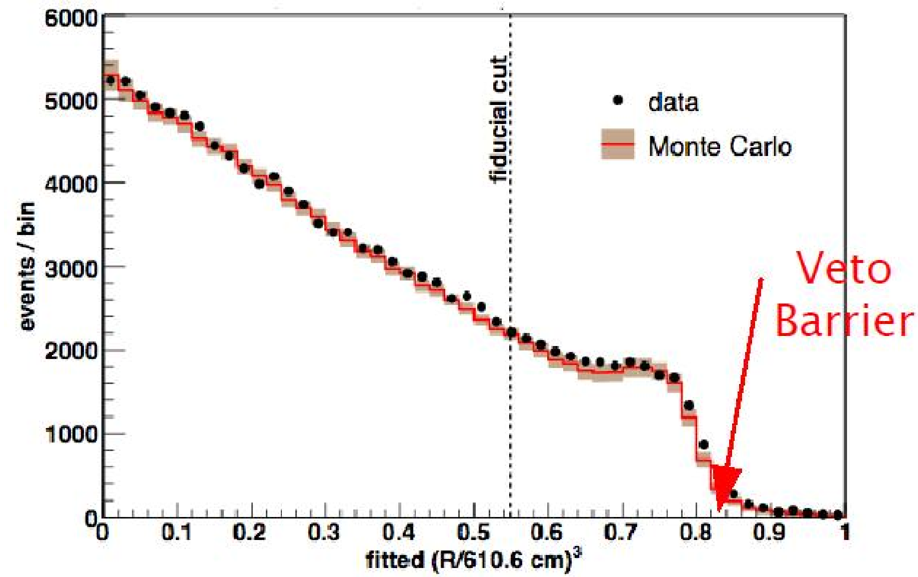


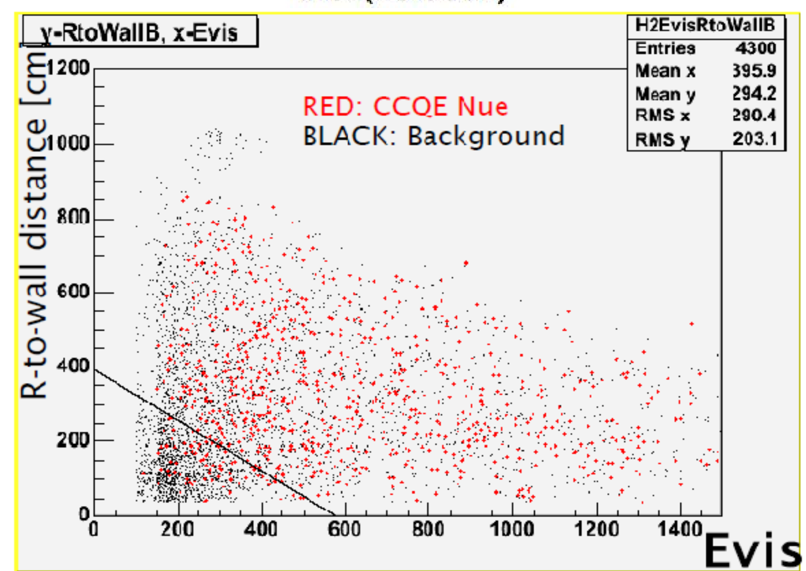
e candidate

Signal selection, $\overset{(-)}{\nu}_e$ appearance

Identical in neutrino and anti-neutrino analyses.

- The Pre-cuts:
  - ➔ No late time activity, *removes μ decay e's, cuts ~80% of ν_μ CCQE events.*
  - ➔ Veto Hits <6, *contained & not cosmic ray.*
  - ➔ Tank Hits >200 & E_{vis} > 140 MeV, *removes NC elastic bkgds. And remaining μ decay e's*
  - ➔ Radius < 500 cm, *far enough from PMT's to avoid hard to model region.*
  - ➔ R-to-Wallbackward cut, *removes bkgds from beam interacting outside of detector.*





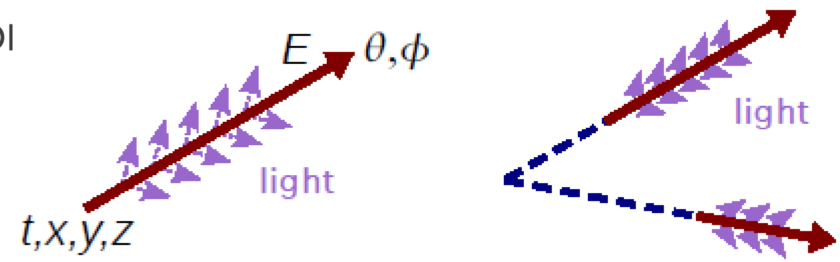
Aimed at selecting $\overset{(-)}{\nu}_e$-CCQE events

$$\nu_e + n \rightarrow e^- + p$$

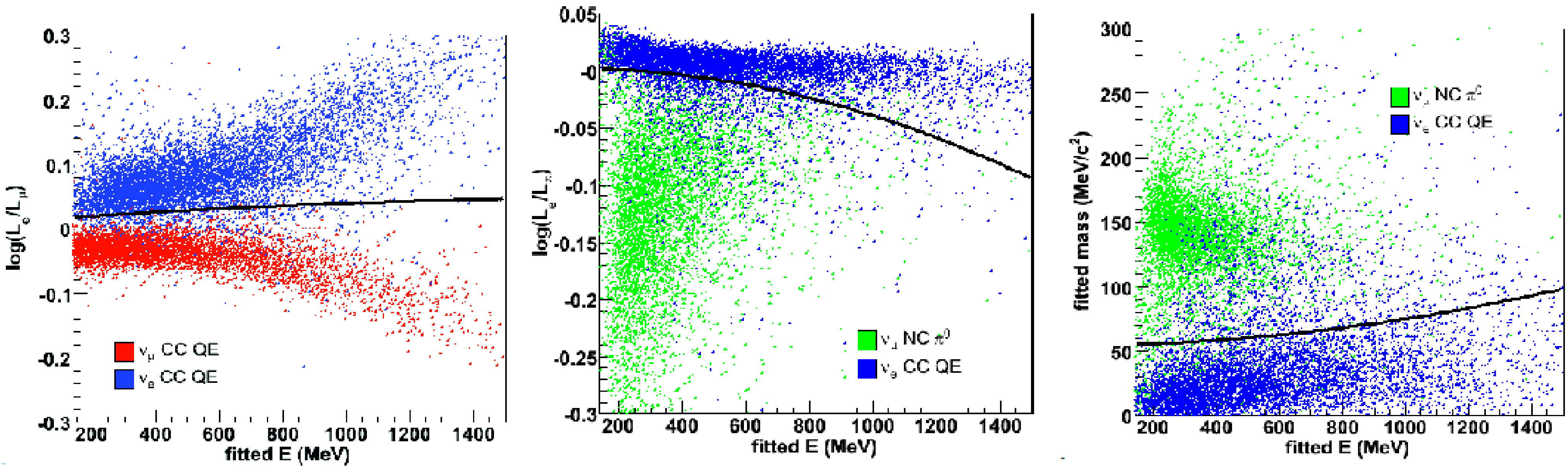
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Signal selection, $\overset{(-)}{\nu}_e$ appearance

- Form charge (Q) and time (T) PDF's, and fit for track parameters under 3 hypotheses:
  1. Track is from electron
  2. Track is from Muon
  3. Two tracks from γ's from π^0 decay

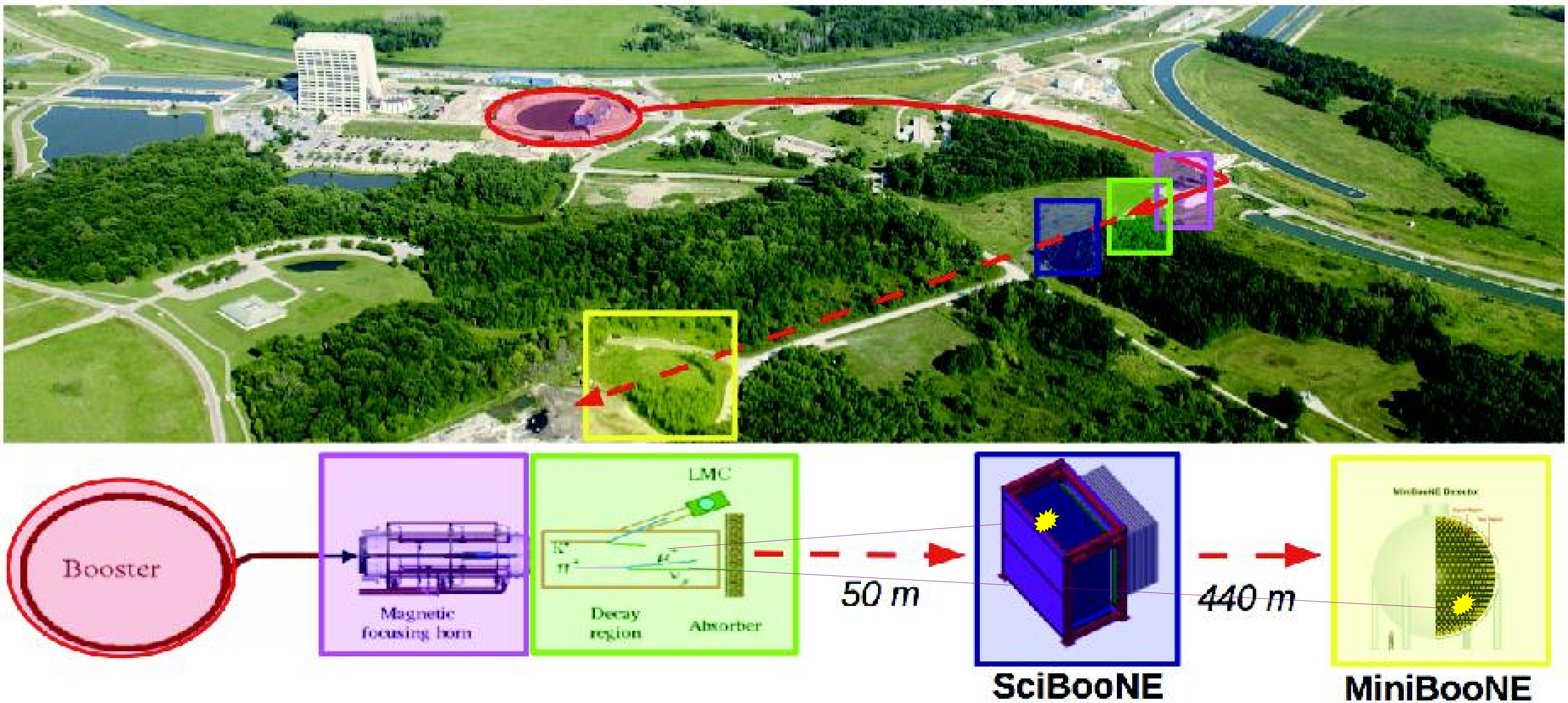


- Apply energy-dependent cuts on **L(e/μ)**, **L(e/π)** and π^0 mass to search for single electron events.
- Plot events passing cuts as a function of reconstructed energy and fit for two neutrino oscillations



SciBooNE

- SciBooNE: a fine-grained tracking detector 50 m Downstream of proton target in same ν beam.



- Provides powerful check of upstream beam content