Joint Search for $\bar{\nu}_\mu$ Disappearance at $\Delta m^2 \sim 1$ eV^2

Searching for sterile antineutrinos with SciBooNE & MiniBooNE

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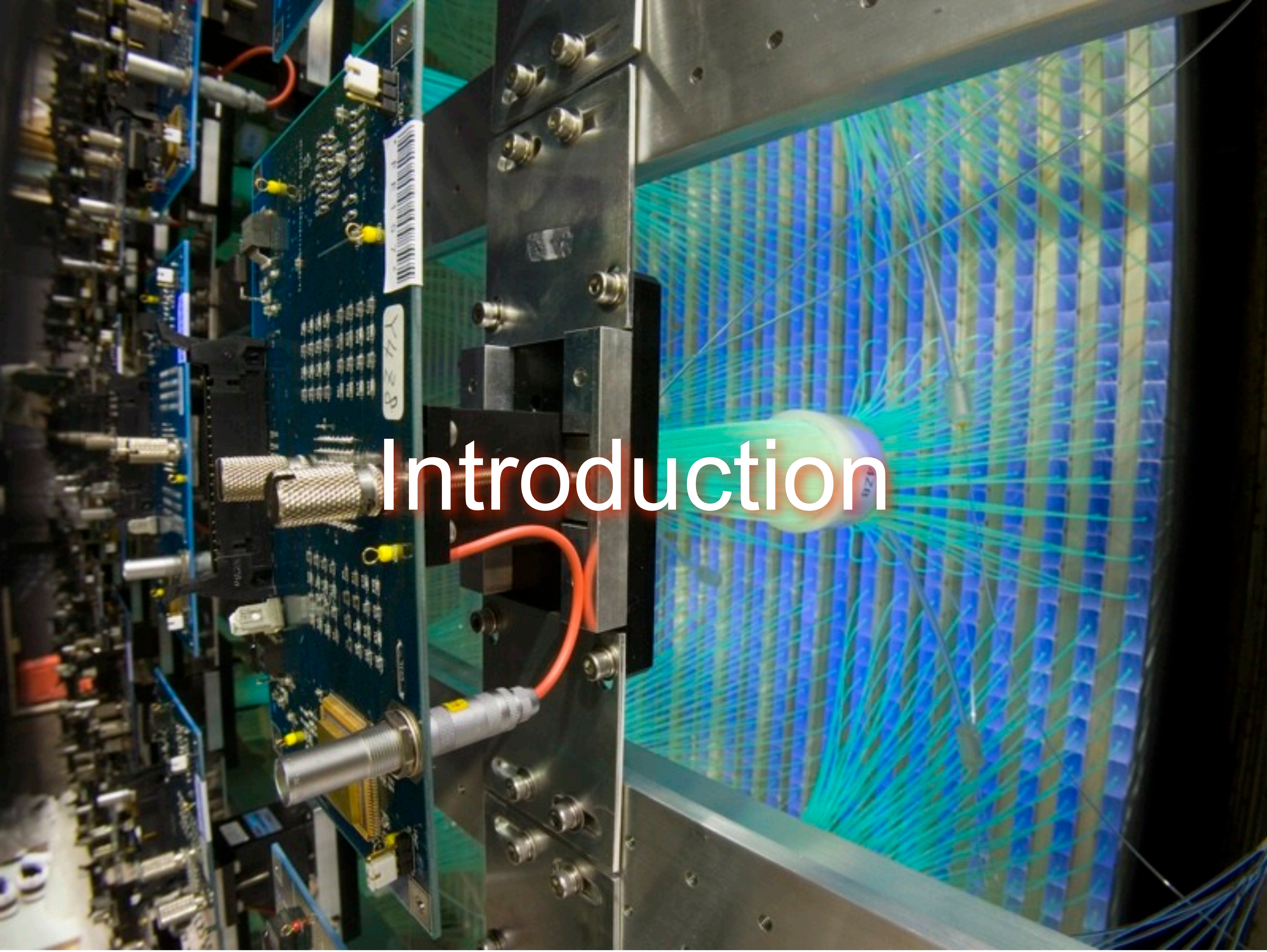
2013 01 16

Outline

- Introduction
  - Neutrino oscillation
  - The LSND signal and sterile neutrinos
- Experiments: SciBooNE and MiniBooNE
- SciBooNE-MiniBooNE joint $\bar{\nu}_\mu$ disappearance analysis
- Results

Introduction

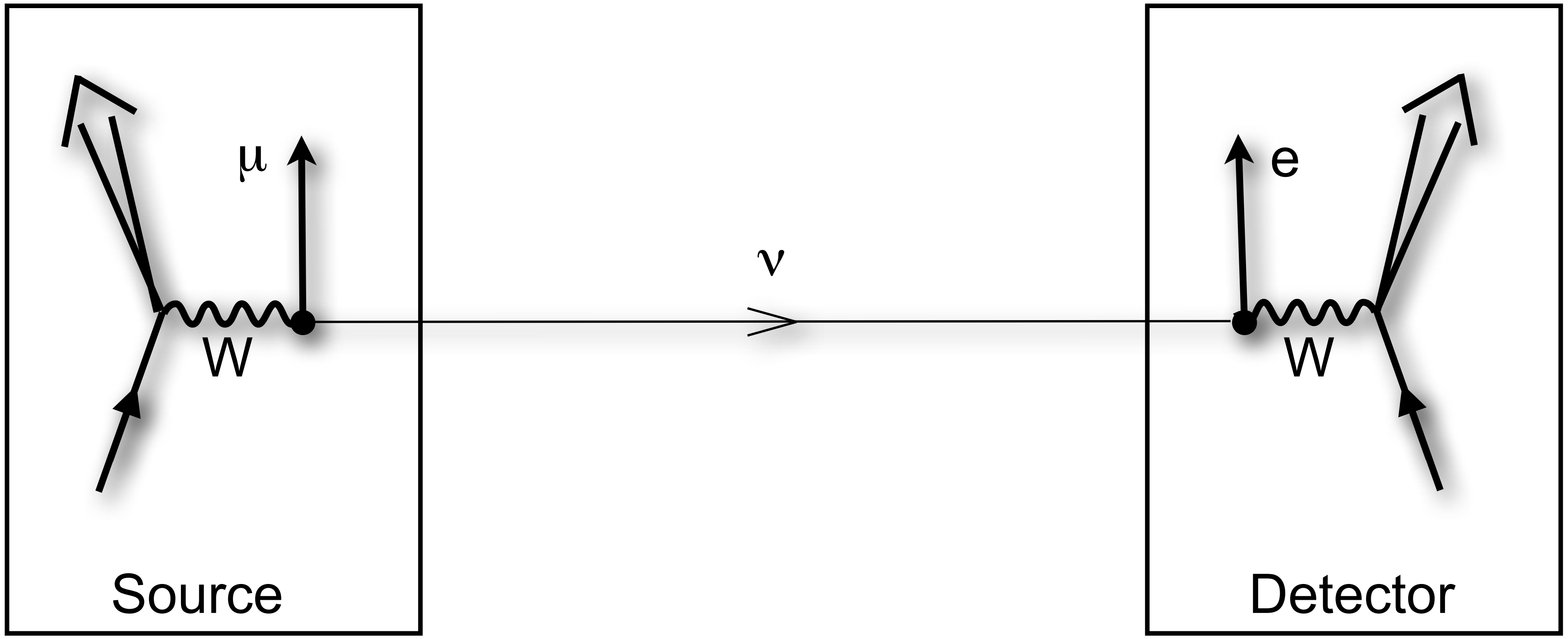


Neutrino oscillation

Pontecorvo

Sov.Phys.JETP 6:429,1957

Sov.Phys.JETP 26:984-988,1968



Maki, Nakagawa, Sakata

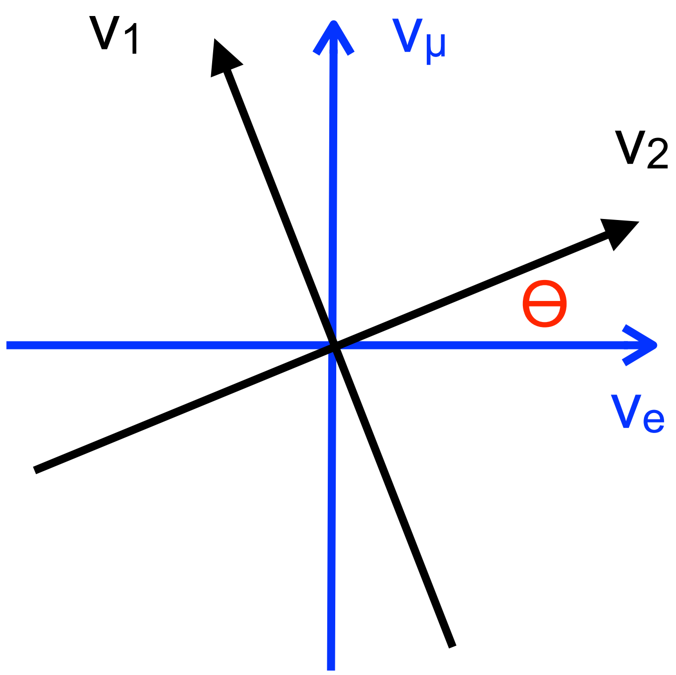
Prog.Theor.Phys. 28, 870 (1962)

- if neutrinos have mass...
  - a neutrino that is produced as a $\bar{\nu}_\mu$
    - (e.g. $\pi^- \to \mu^- \ \bar{\nu}_\mu$)
  - might some time later be observed as a $\bar{\nu}_e$
    - (e.g. $\bar{\nu}_e \, n \to e^+ \, p$)

Neutrino oscillation

In a world with 2 neutrinos,
if the weak eigenstates (ν_e, ν_μ)
are different from the mass eigenstates (ν_1, ν_2):

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}cos\theta & sin\theta\\ -sin\theta & cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$



The weak states are mixtures of the mass states:

$$|\nu_\mu> = -sin\theta|\nu_1> + cos\theta|\nu_2>$$

$$|\nu_\mu(t)> = -sin\theta\,(|\nu_1> e^{-iE_1t}) + cos\theta\,(|\nu_2> e^{-iE_2t})$$

The probability to find a ν_e when you started with a ν_μ is:

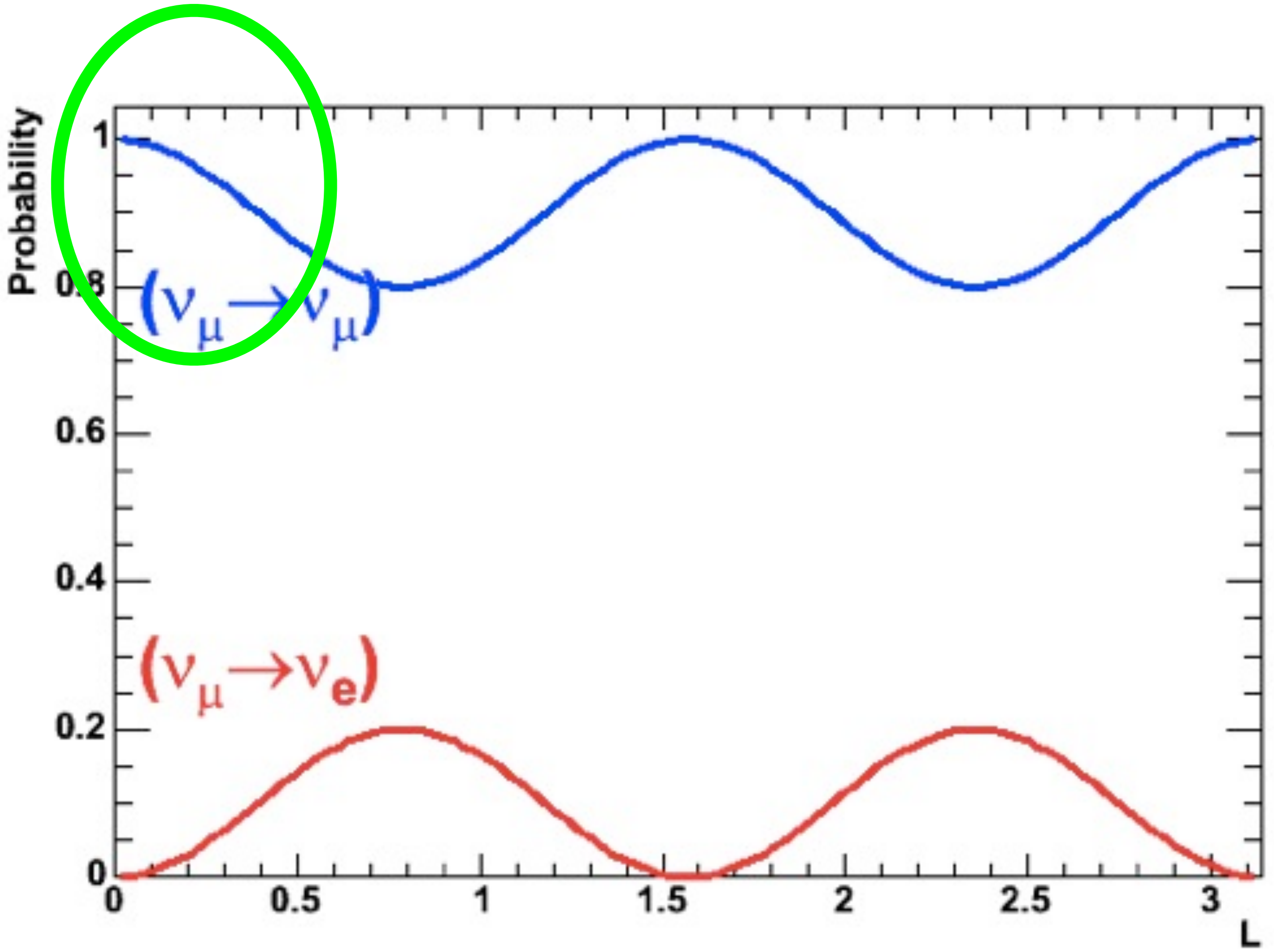
$$P_{oscillation}(\nu_\mu \rightarrow \nu_e) = |<\nu_e|\nu_\mu(t)>|^2$$

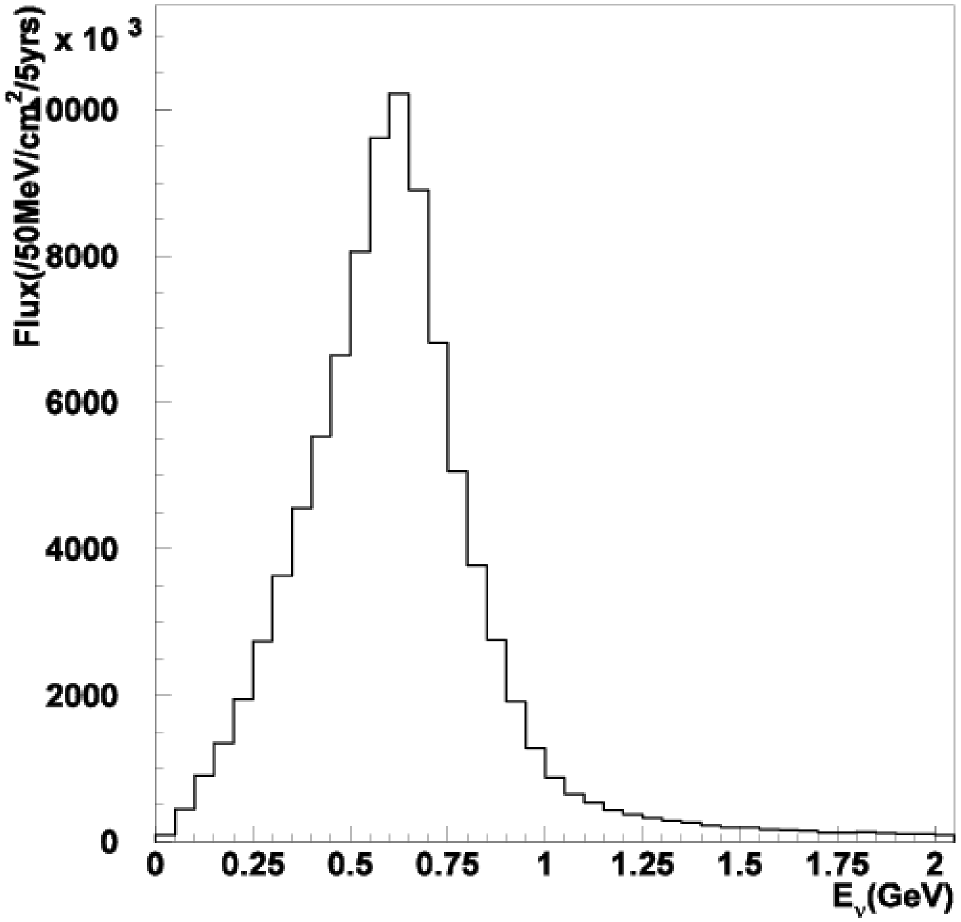
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} \frac{L}{E})$$

- 2 fundamental parameters
  - Δm^2 ↔ period
  - θ_{12} ↔ magnitude

- 2 experimental parameters
  - L = distance travelled
  - E = neutrino energy

- Choose L&E to target ranges of Δm^2 and θ
- Neutrinos disappear and appear





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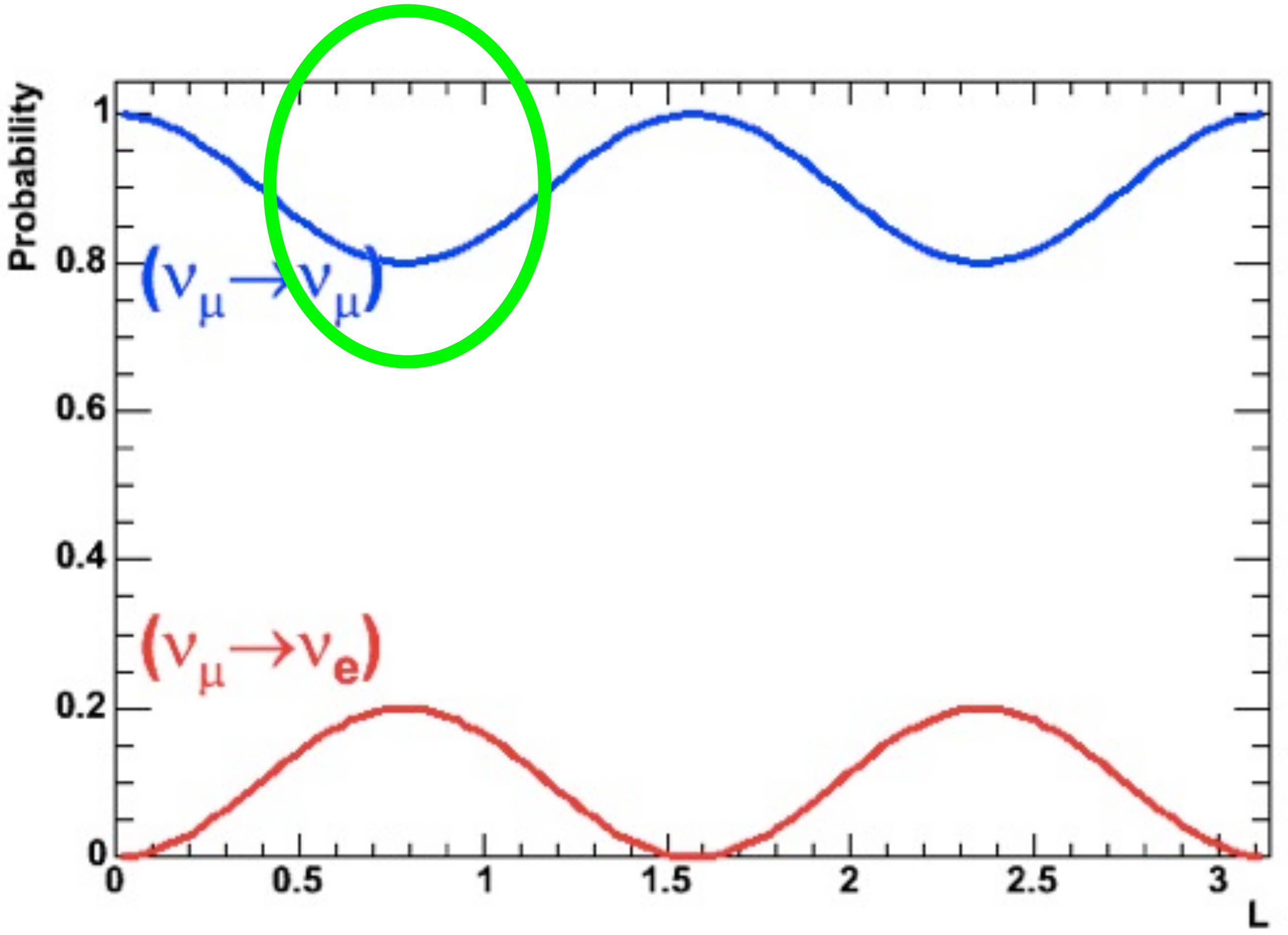

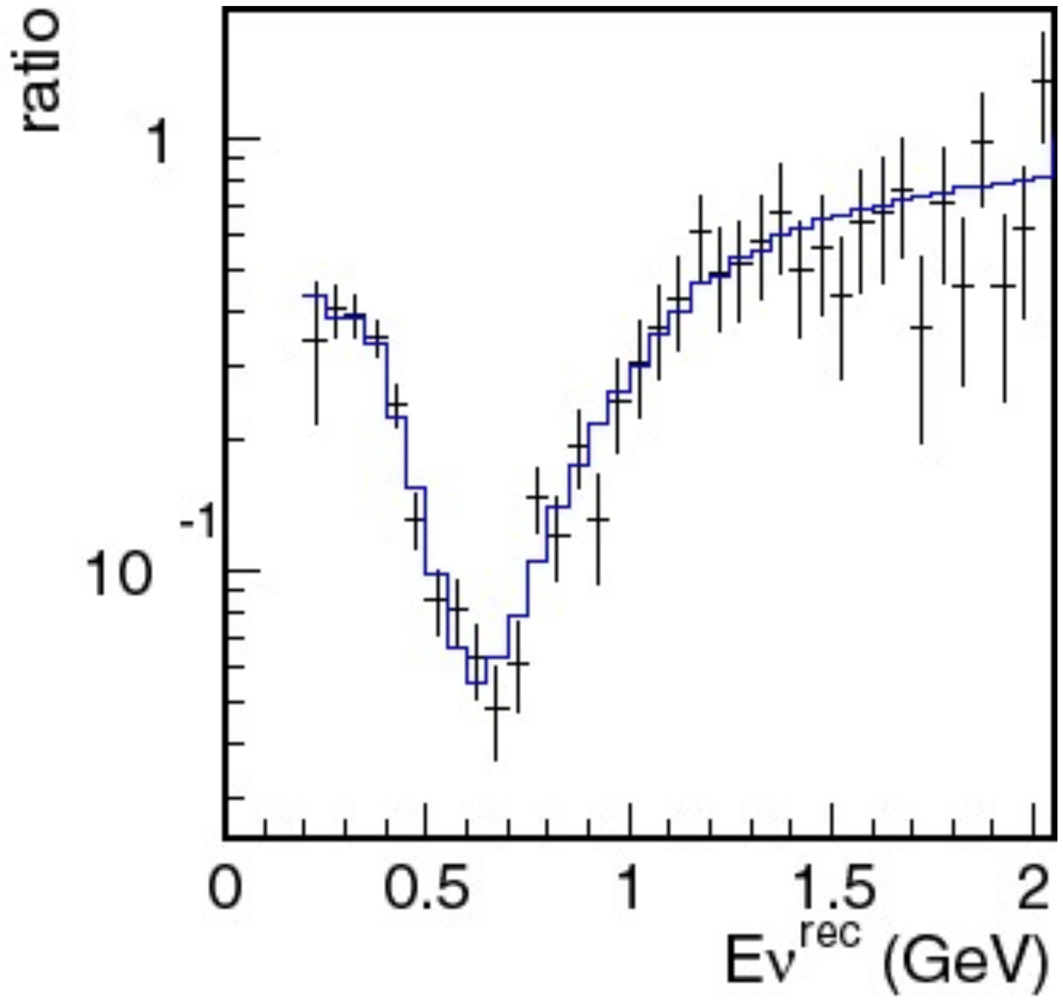

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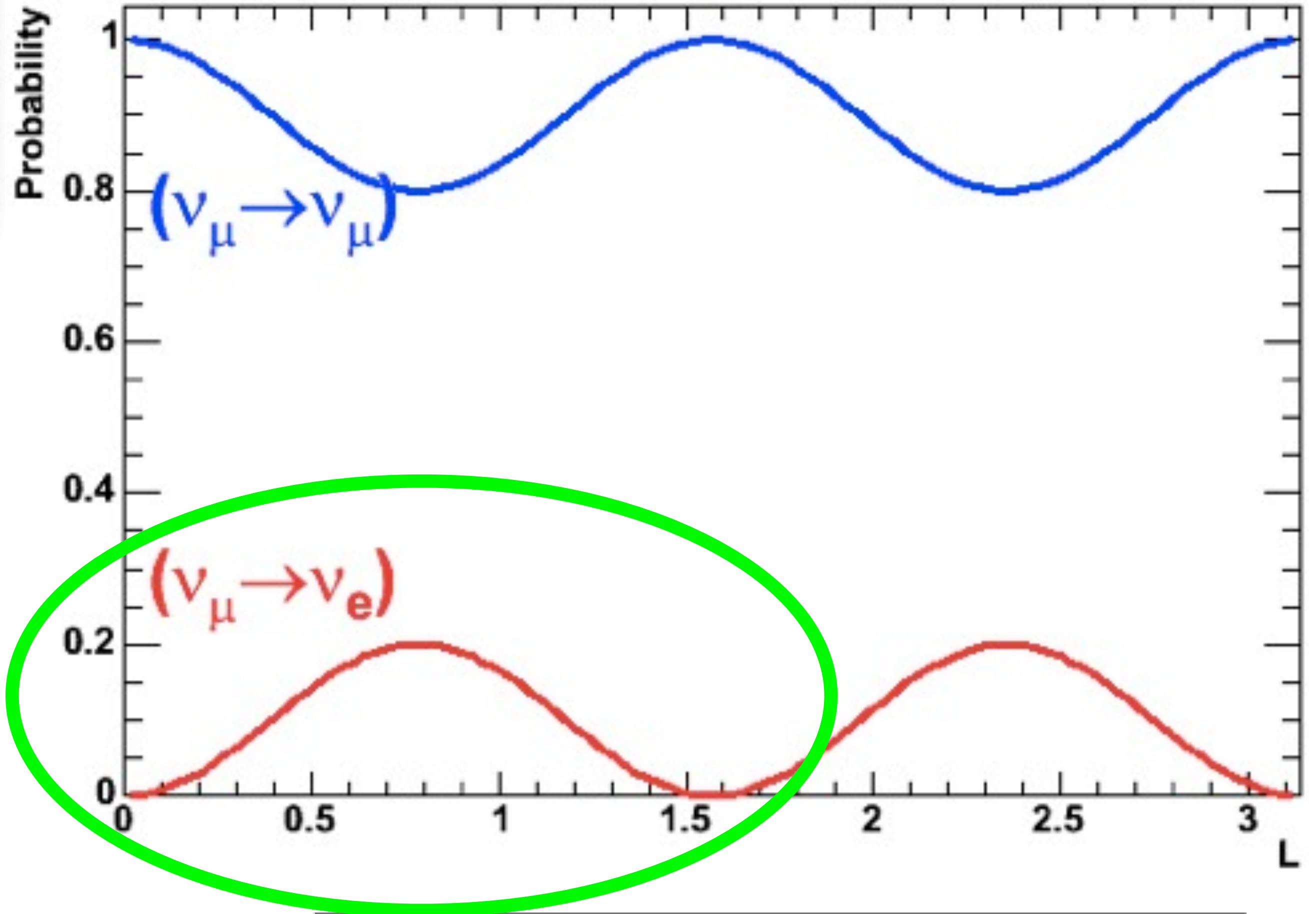
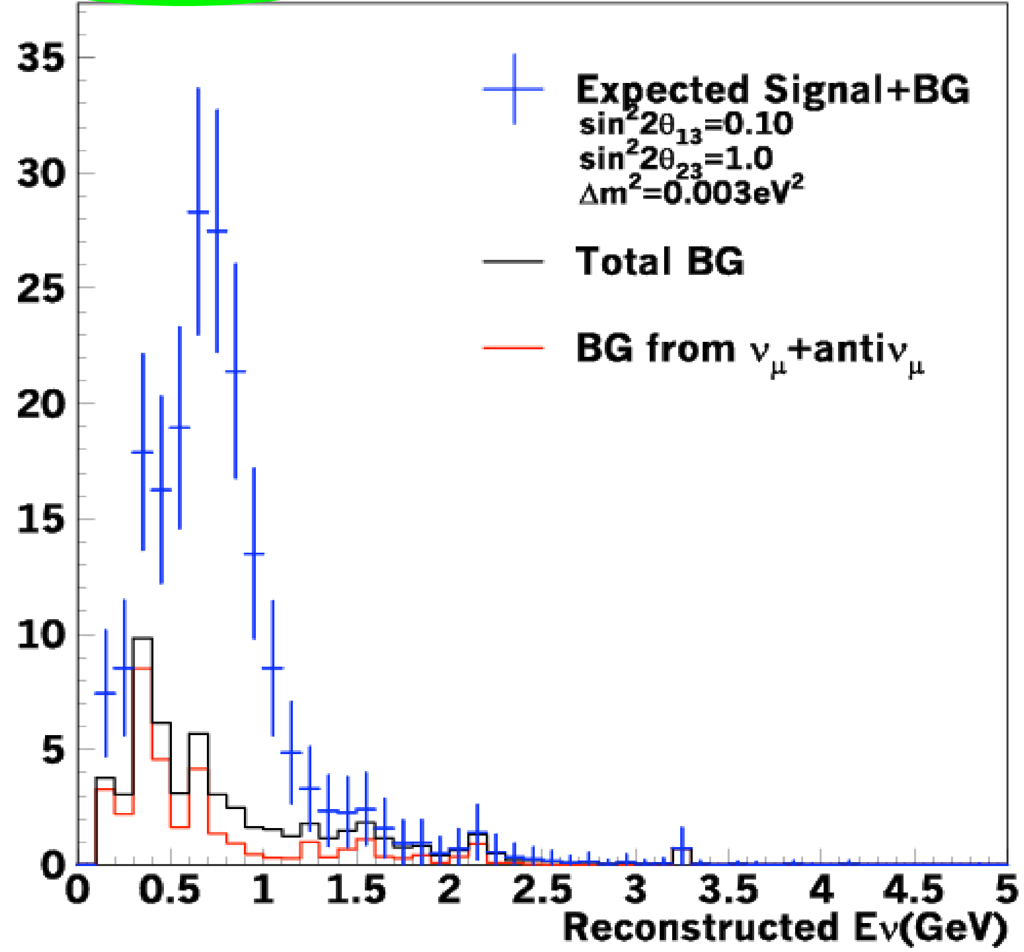
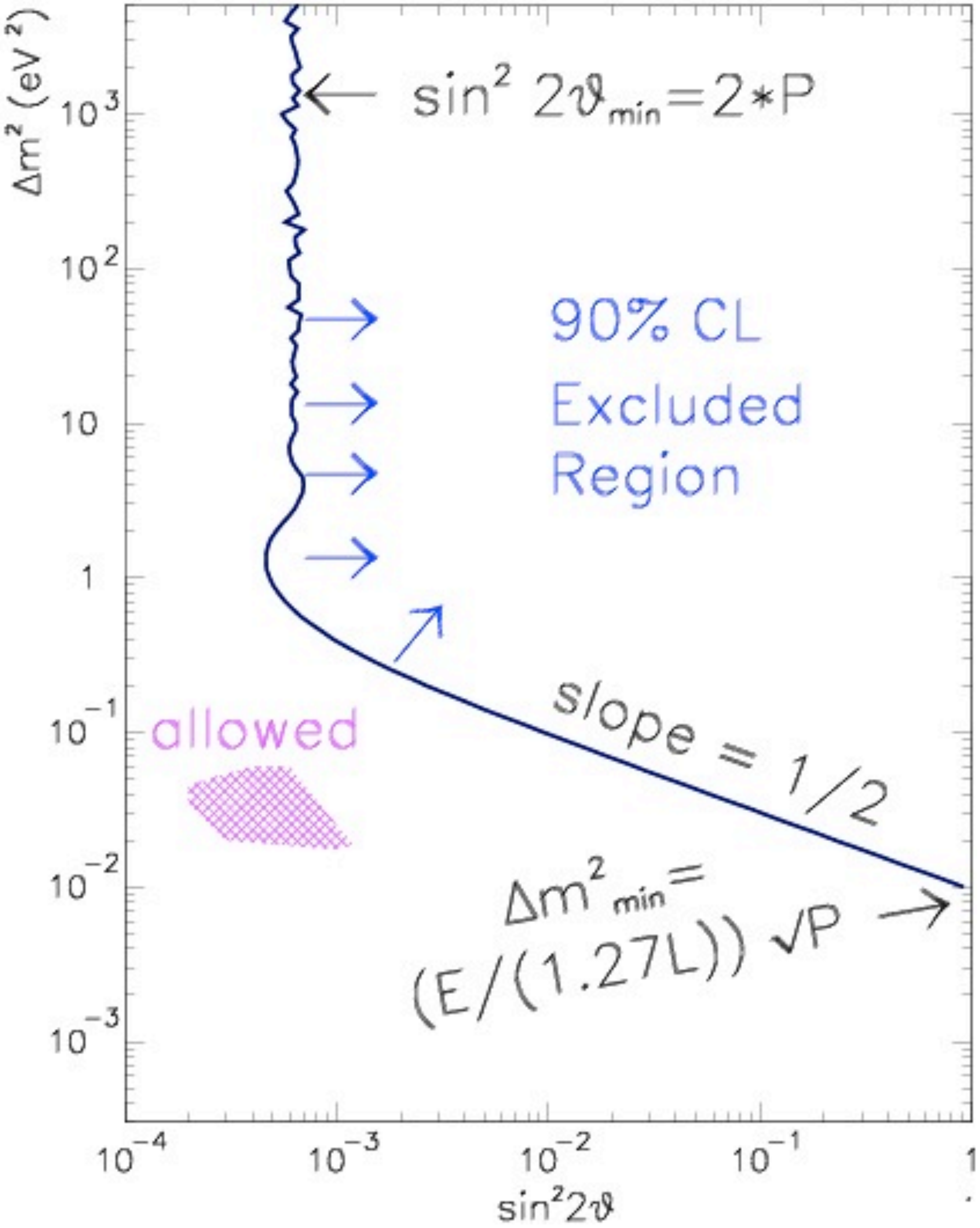


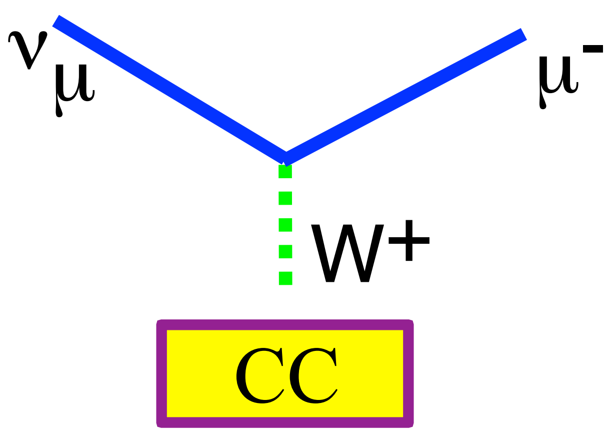


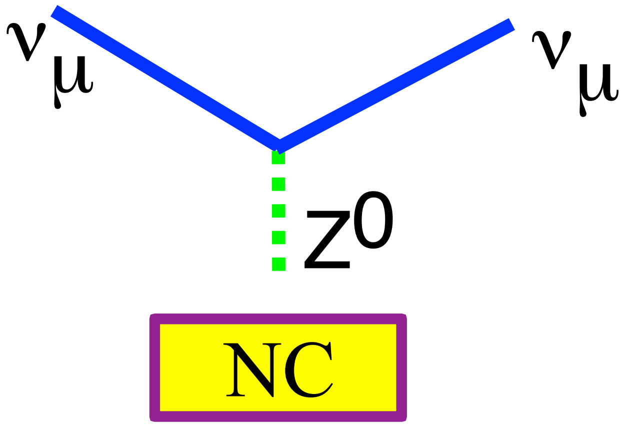
$$P(\nu_\mu \to \nu_e) = sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} \frac{L}{E})$$

- L and E determine Δm^2 sensitivity
- θ_{12} sensitivity determined by statistics, backgrounds, and uncertainties
- No signal: exclusion curve
- Signal: allowed region



Neutrino Interactions





CC interactions preserve neutrino flavour, but require enough energy to produce rest mass of charged lepton!

NC interactions can happen equally for all flavours because there is no energy requirement

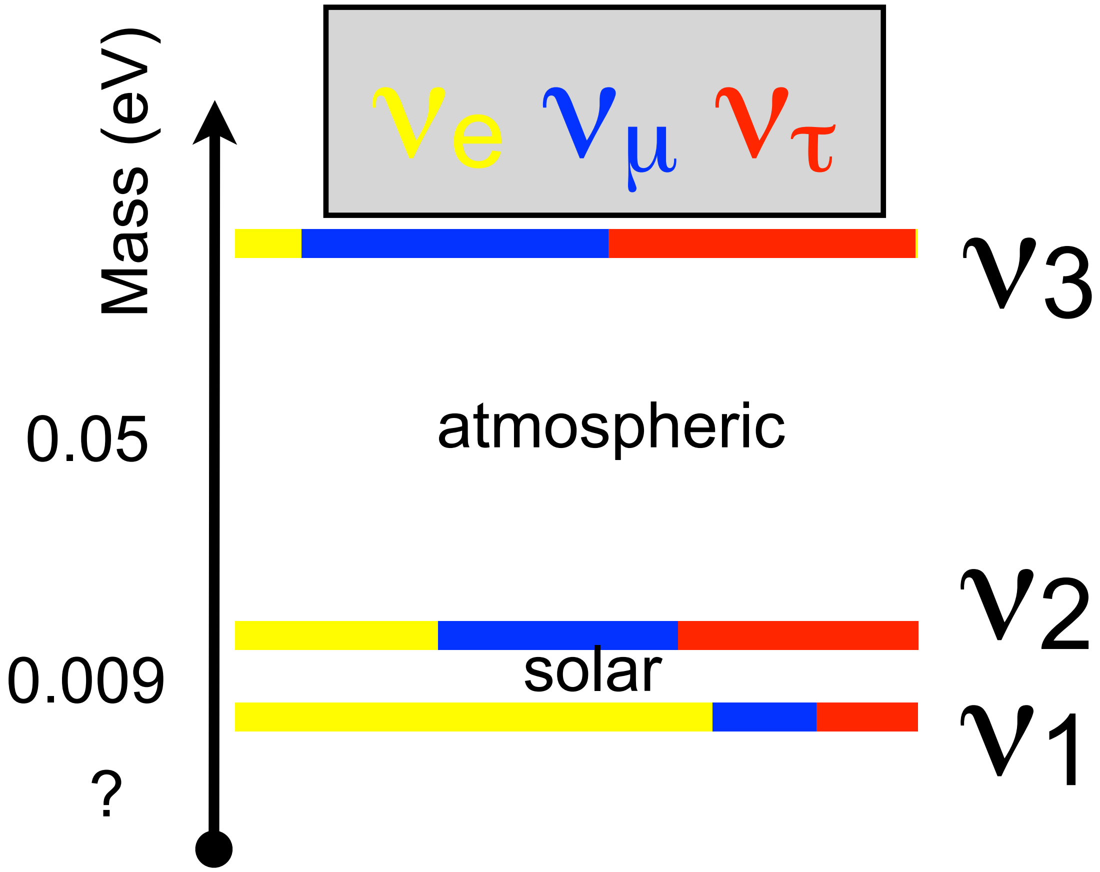
Both interaction modes are useful for neutrino oscillation experiments

Three flavours

flavour atmospheric cross-mixing solar mass

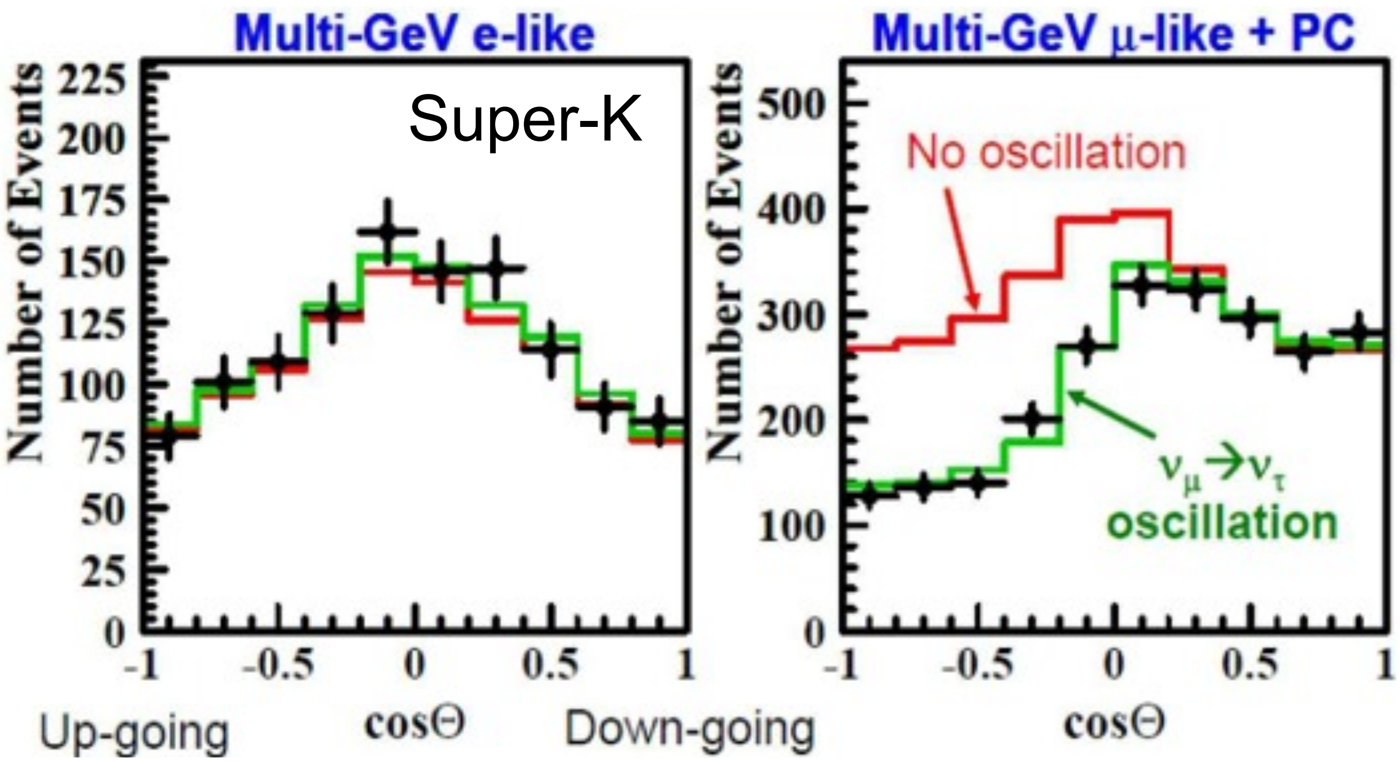
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

where $c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$

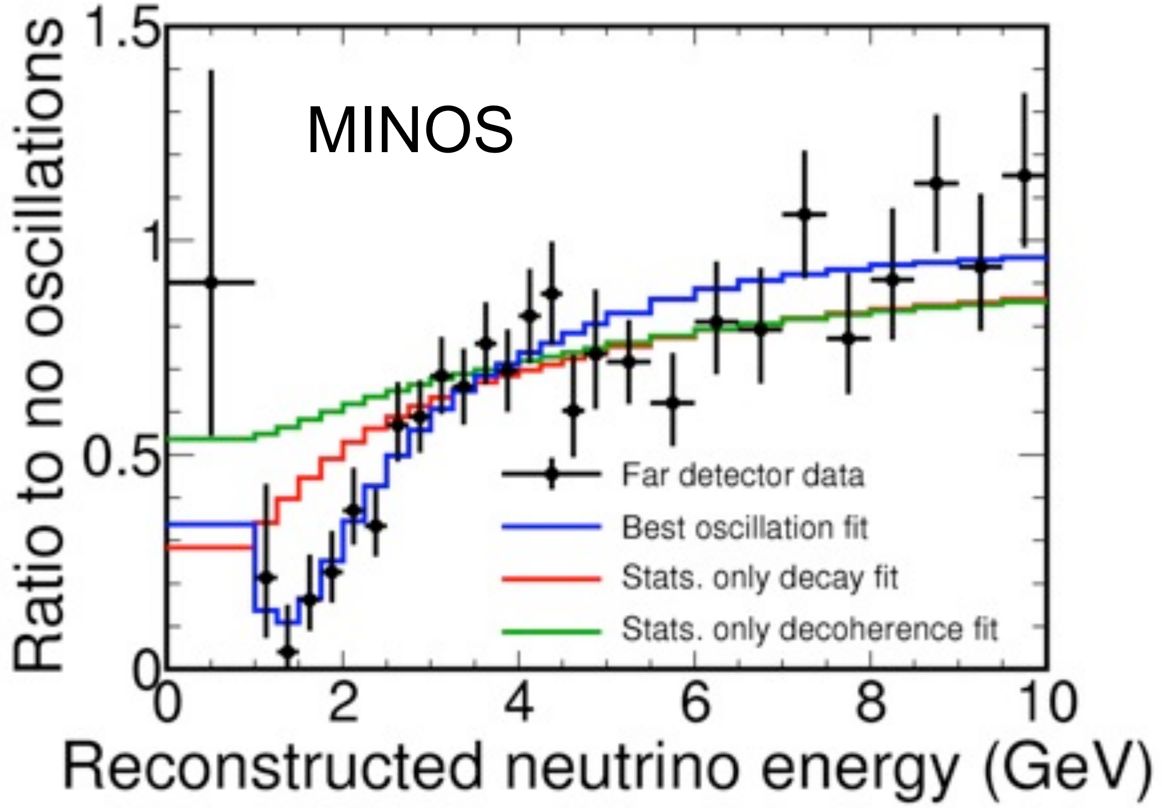


Atmospheric Oscillation

$$\begin{array}{ccccc} \text{flavour} & \text{atmospheric} & \text{cross-mixing} & \text{solar} & \text{mass} \\ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = & \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} & \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} & \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} & \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \end{array}$$



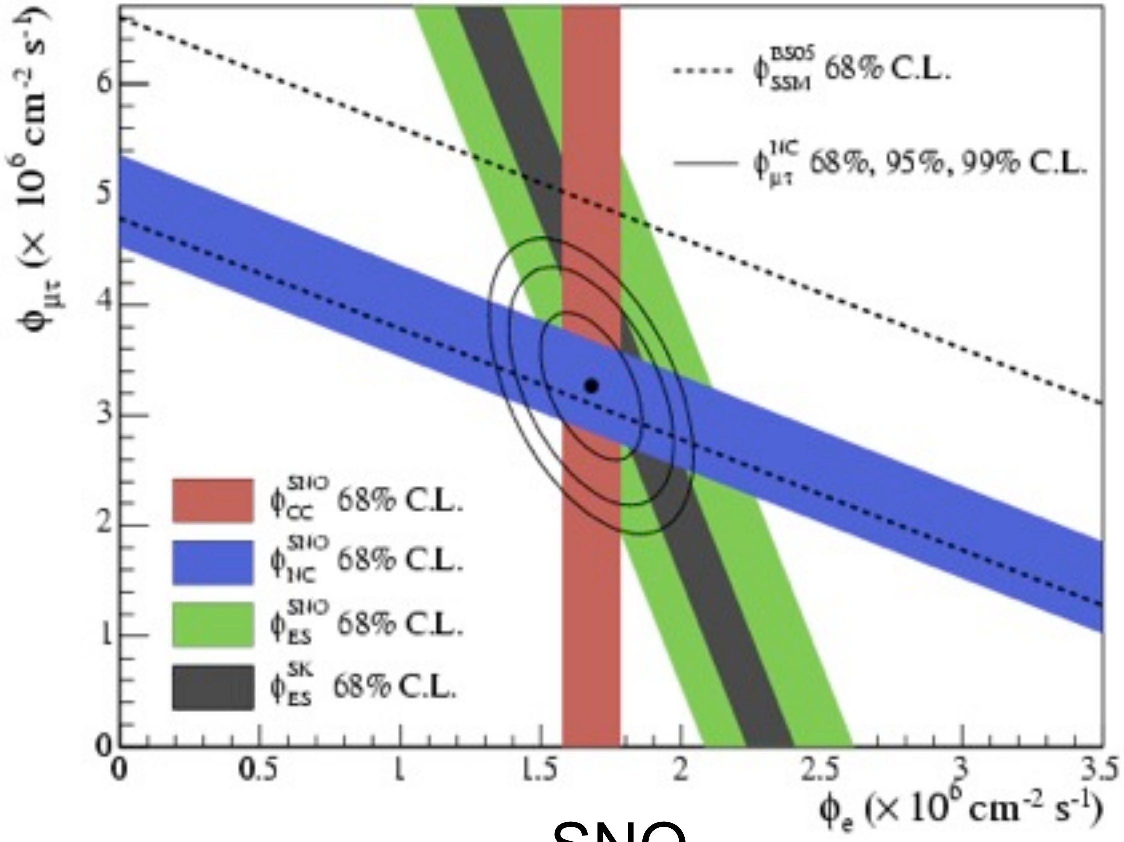
Phys.Rev.Lett.81.1562(1998)



PhysRevLett.101.131802

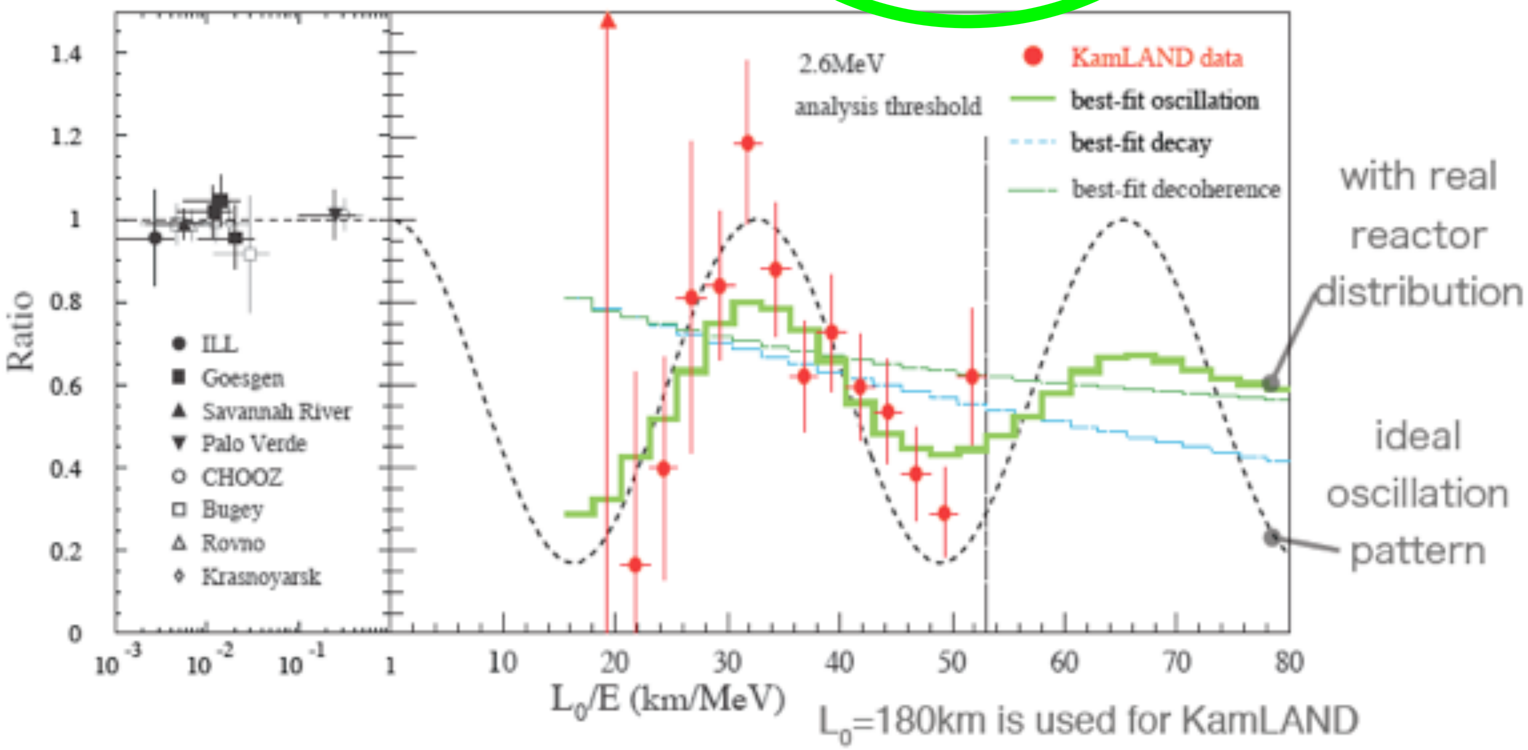
Solar Oscillation

$$\begin{array}{ccccc} \text{flavour} & \text{atmospheric} & \text{cross-mixing} & \text{solar} & \text{mass} \\ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = & \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} & \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} & \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} & \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \end{array}$$



SNO

Phys.Rev.Lett.89.011301 (2002)



with real reactor distribution

ideal oscillation pattern

L_0=180km is used for KamLAND

KamLAND

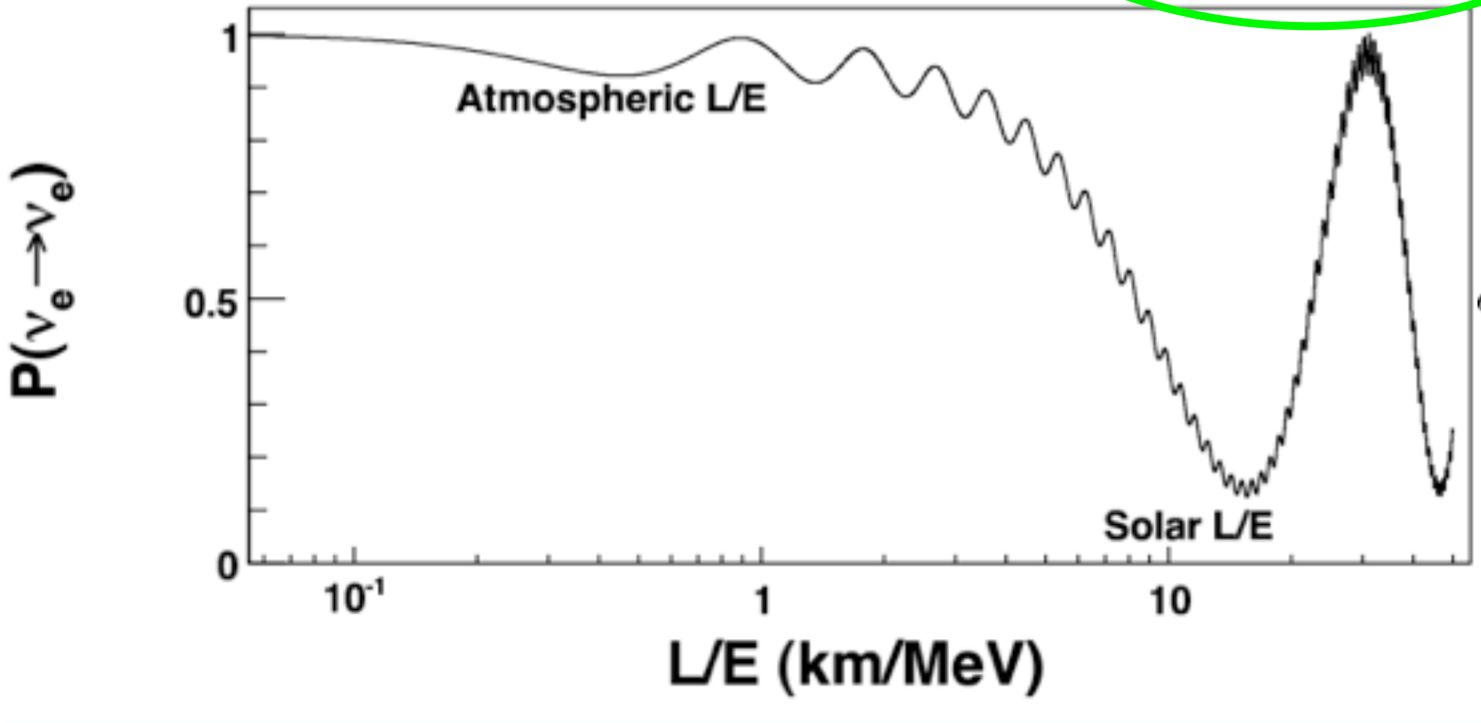
Phys.Rev.Lett.100.221803 (2008)

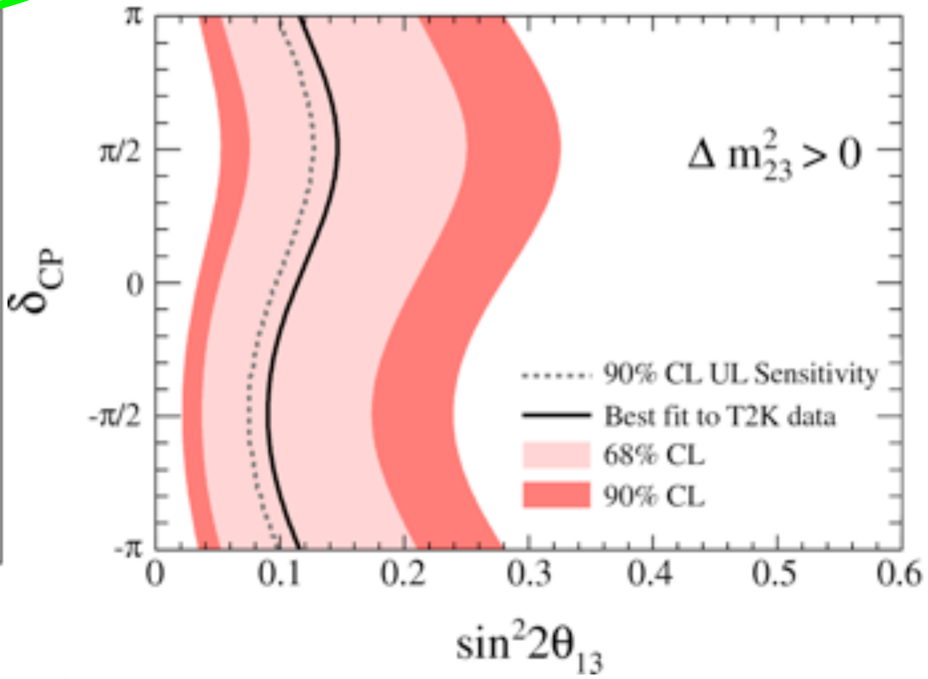
Cross Mixing

flavour atmospheric cross-mixing solar mass

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

10-2





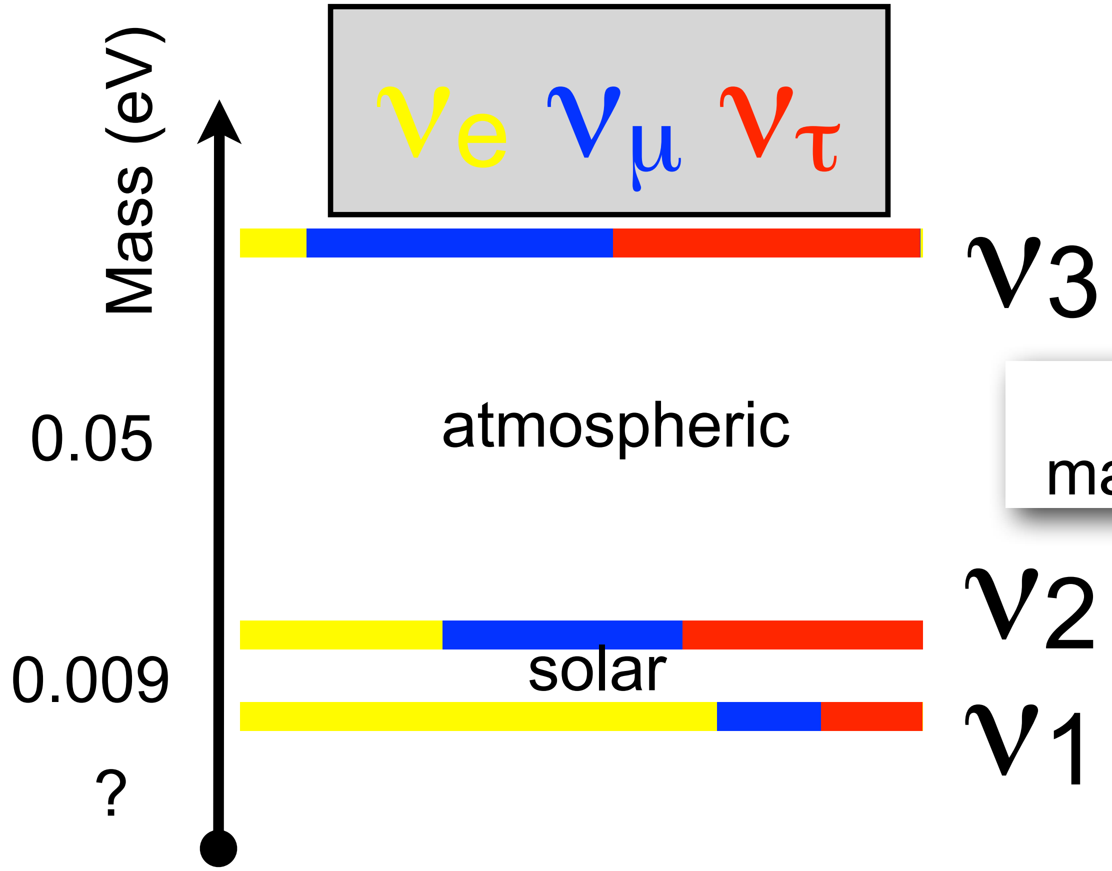
Phys.Rev.Lett.107.041801 (2011)

Causes $\bar{\nu}_e$ disappearance in reactors and ν_e appearance in accelerator experiments

Current picture

$$\overset{\text{flavour}}{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}} = \overset{\text{atmospheric}}{\begin{pmatrix}1&0&0\\ 0&c_{23}&s_{23}\\ 0&-s_{23}&c_{23}\end{pmatrix}} \overset{\text{cross-mixing}}{\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\ 0&1&0\\ -s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}} \overset{\text{solar}}{\begin{pmatrix}c_{12}&s_{12}&0\\ -s_{12}&c_{12}&0\\ 0&0&1\end{pmatrix}} \overset{\text{mass}}{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}$$

where cij=cosθij, sij=sinθij

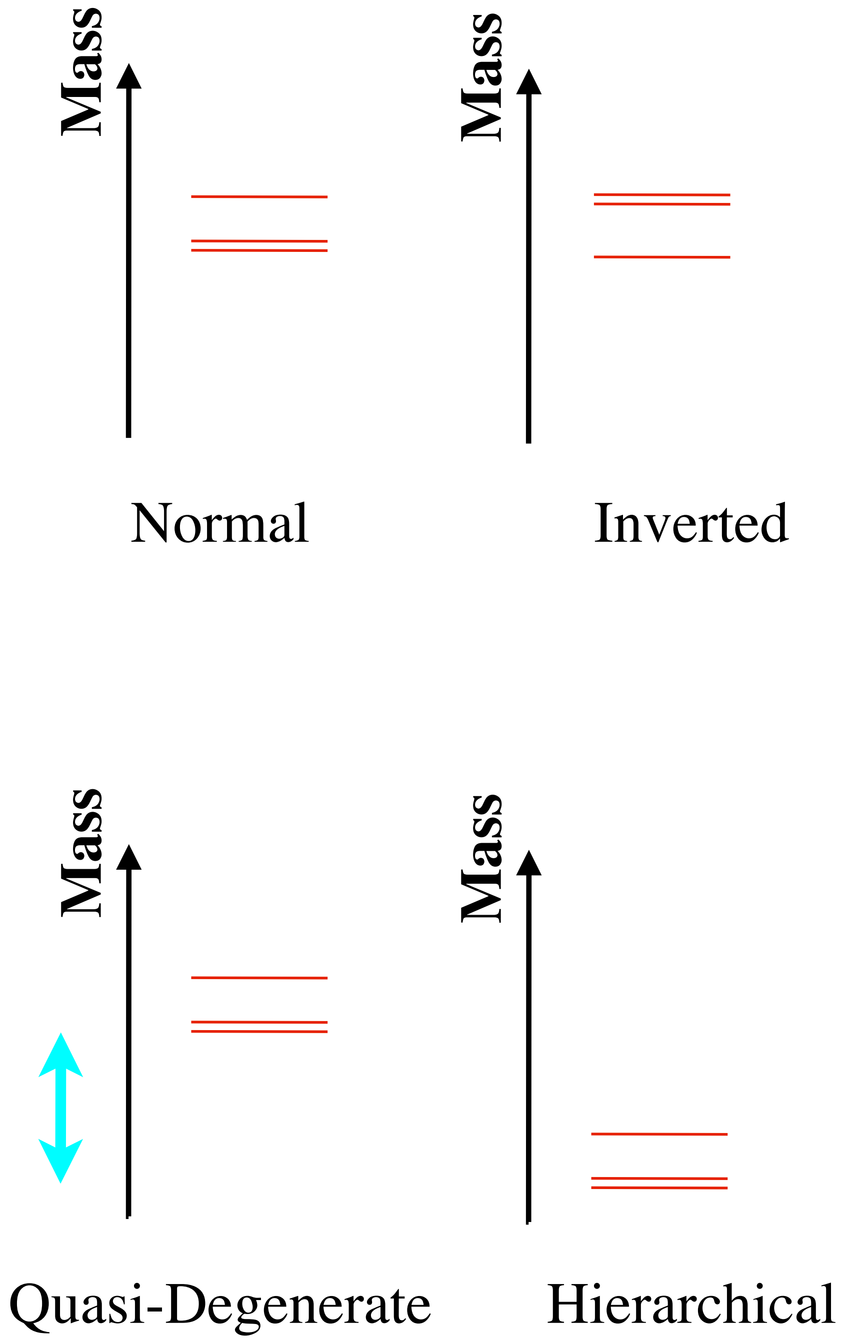


Non-zero δ:
matter vs antimatter

	VALUE
Δm^2_{23}	2.35E-03 (eV^2)
Δm^2_{12}	7.58E-05 (eV^2)
$\sin^2\theta_{12}$	0.306
$\sin^2\theta_{23}$	0.42
$\sin^2\theta_{13}$	0.02
δ	?

arXiv:1106.6028 [hep-ph]

Open Questions



- What is the value of θ_{13}? δ_{CP}??
- What is the mass hierarchy?
- What is the absolute mass scale?
- What is the nature of neutrino mass?
  - Dirac or Majorana?

- Answers important for theories about origins of neutrino mass
  - Relations to flavour? GUTs?
- Cosmological and astrophysical implications

The LSND Signal

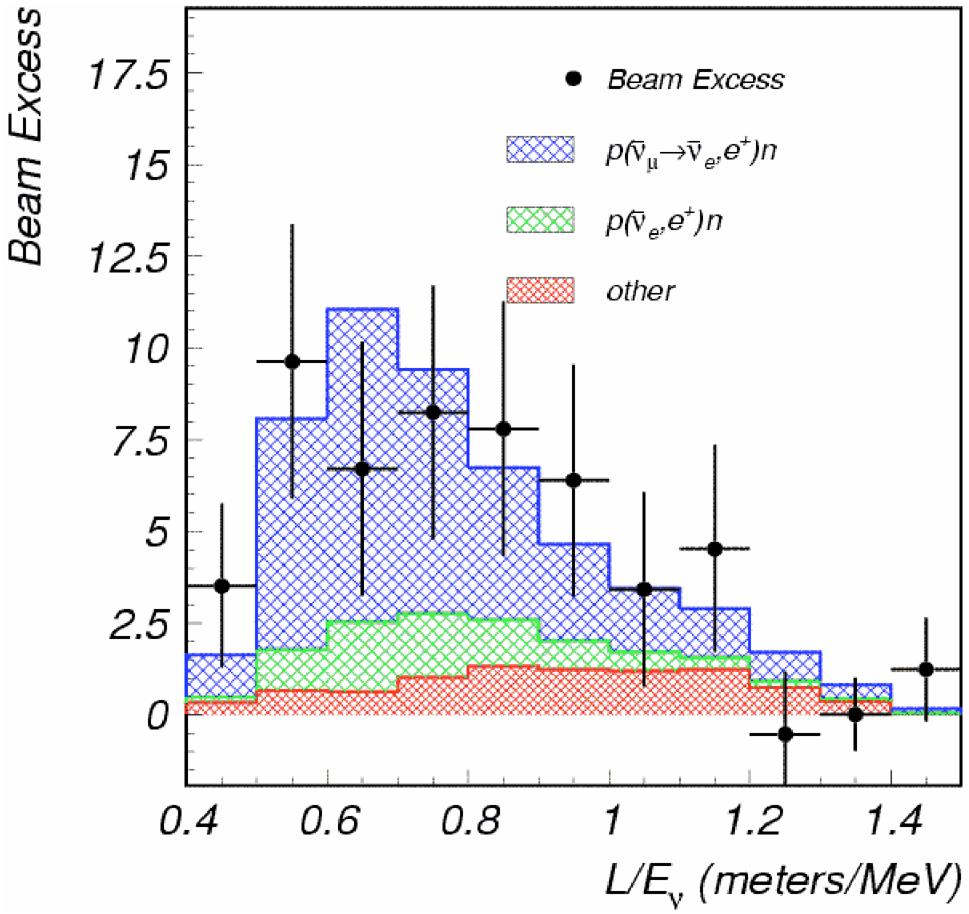
The LSND Signal

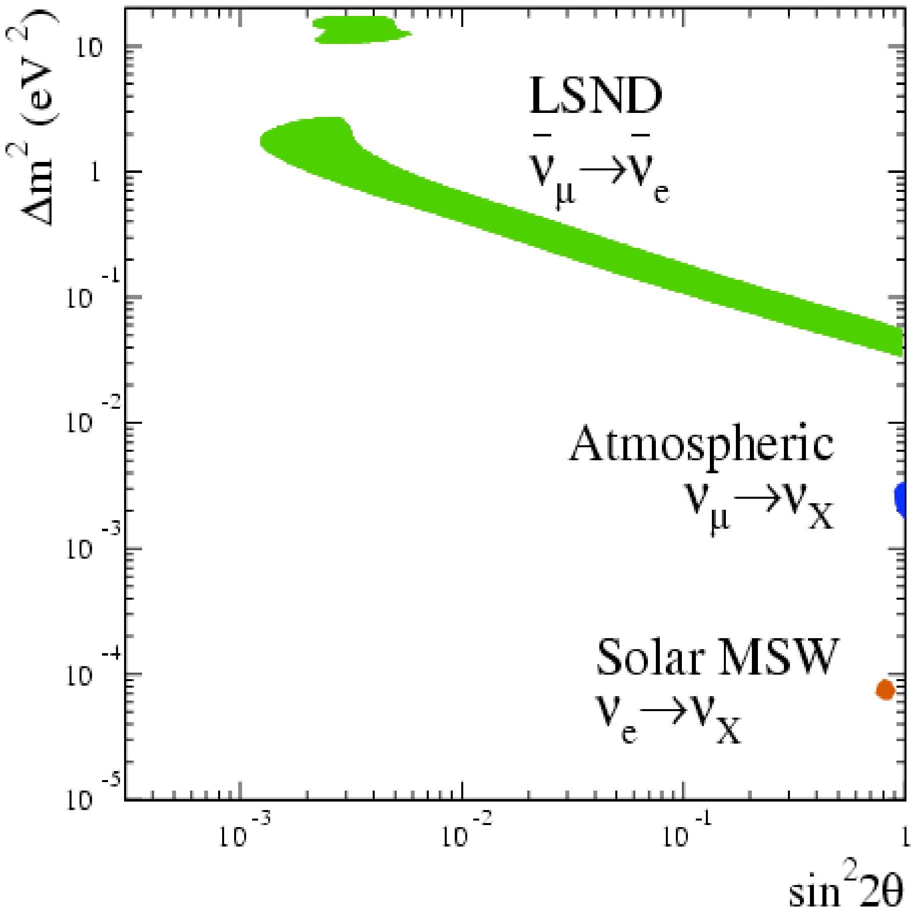
- The LSND experiment observed a small excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam.

Data excess: 87.9 ± 22.4 ± 6.0 (3.8 σ)

Best fit: $\Delta m^2 \sim 1\ \mathrm{eV}^2$, $\sin^2 2\theta \sim 0.003$

Phys.Rev.D 64, 112007 (2001)

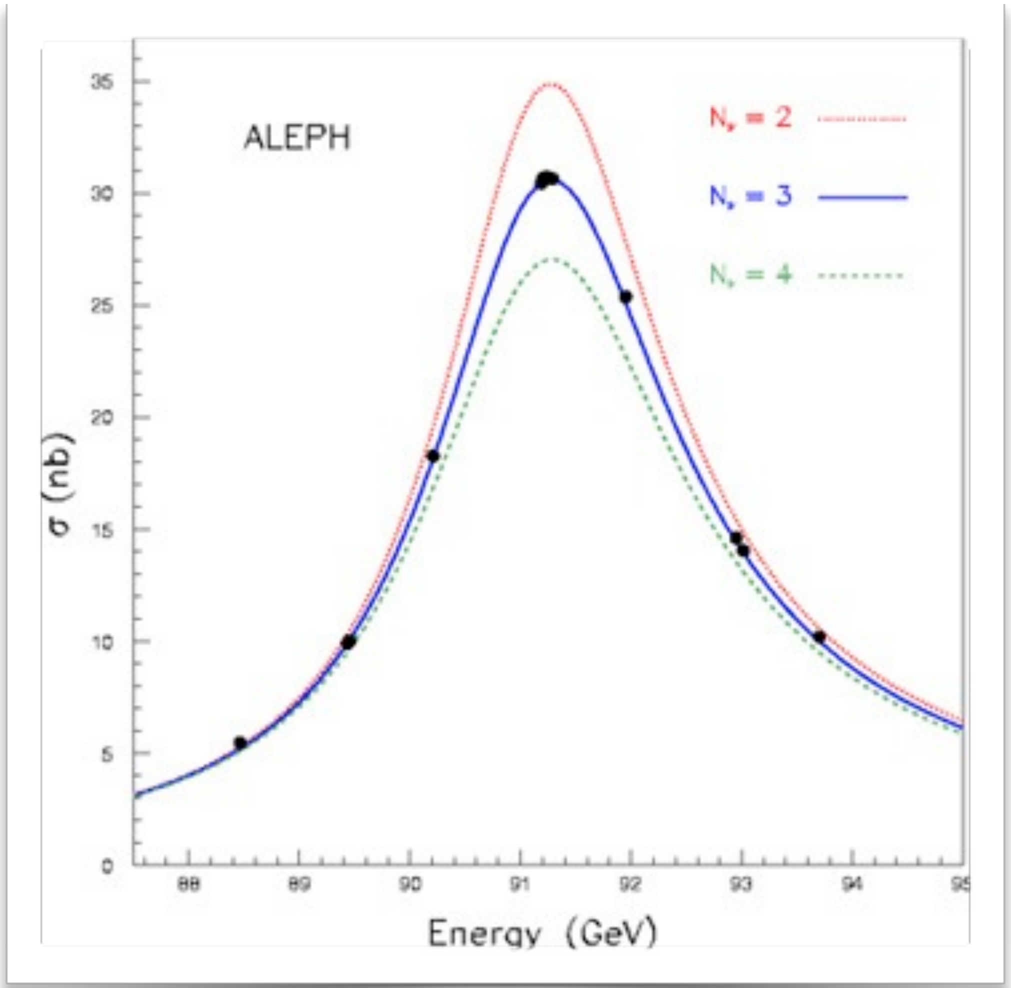




Sterile Neutrinos

- LEP experiments measured the number of light neutrinos: 3
- Only two independent Δm^2 values for 3 neutrinos
  - $2.5 \times 10^{-3} + 7.6 \times 10^{-5} \neq 1$
- LSND signal involves *sterile neutrinos*, if it is due to neutrino oscillation

  ➡They do not interact via the weak force



Phys.Lett.B 313 520 (1993)

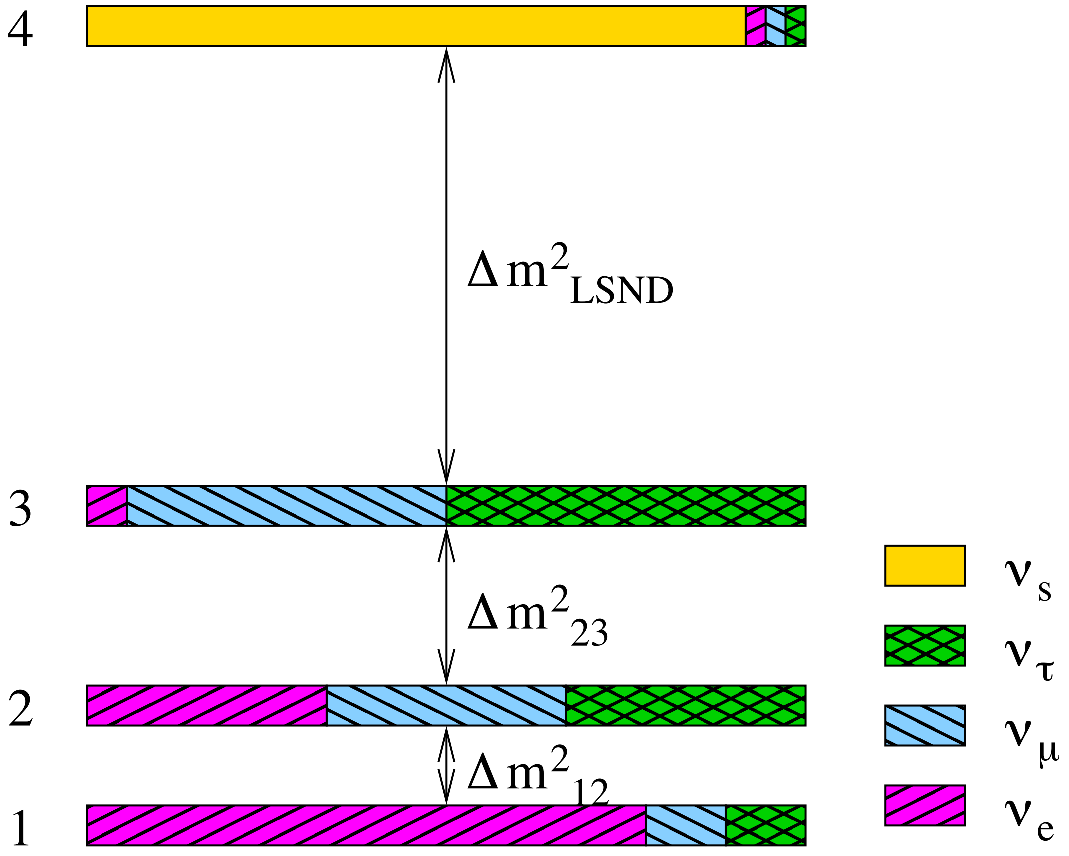
Active-sterile Neutrino Oscillation?

- Sterile neutrinos could still mix with active neutrinos!

A simple realisation of the sterile neutrino is a right-handed neutrino ν_R , which can be mixed with active ν_L.

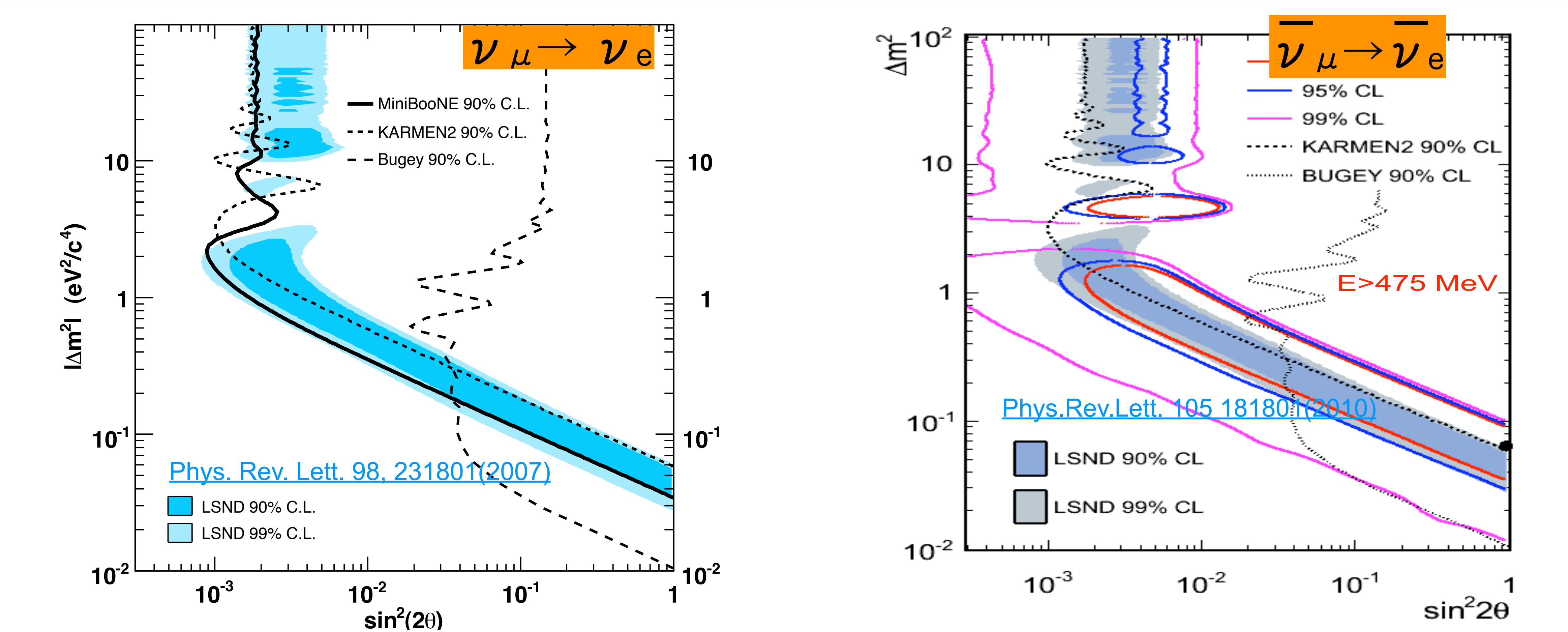
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \cdots \end{pmatrix}$$

3+1 sterile neutrino scheme



MiniBooNE ν_e Results

- MiniBooNE recently tested the LSND signal.
- Ruled out most of LSND region in $\nu_\mu \rightarrow \nu_e$ search.
- However, observed (small) $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess.
  - Consistent with LSND???
- We want to test this with disappearance measurements!



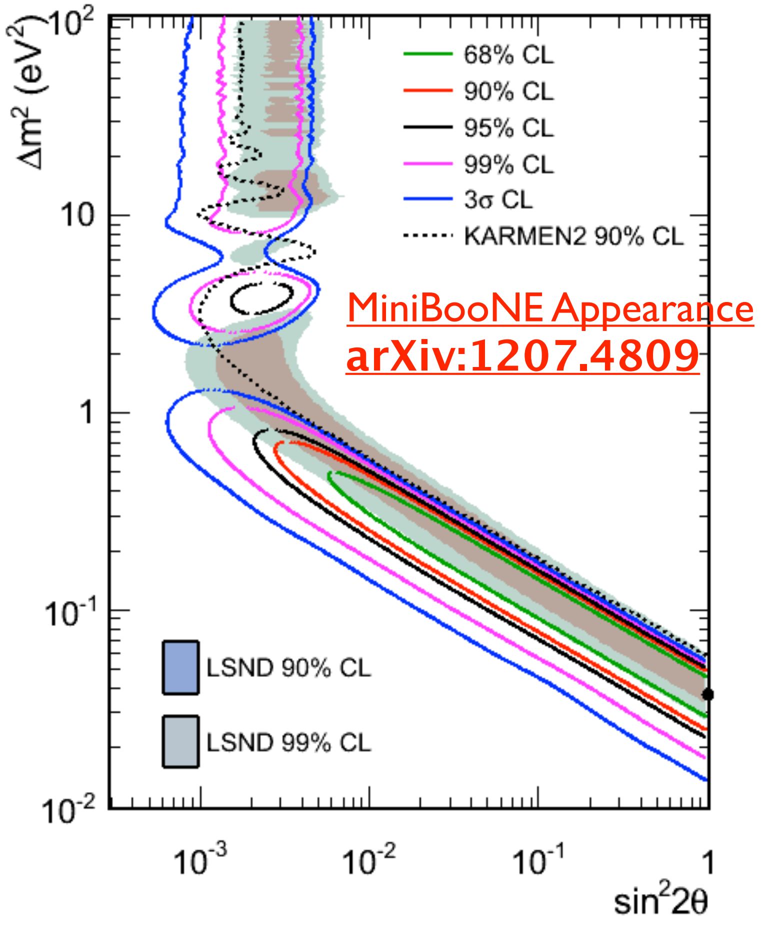
Phys. Rev. Lett. 98, 231801(2007)

Phys.Rev.Lett. 105 181801(2010)

Indications of Sterile Neutrinos?

Gallium Anomaly: ν_e Disappearance?

- SAGE and GALLEX gallium solar neutrino experiments used MCi ^{51}Cr and ^{37}Ar sources to calibrate their detectors
  - A recent analysis claims a significant (3σ) deficit (Giunti and Laveder, 1006.3244v3 [hep-ph])
    - Ratio (observation/prediction) = 0.76 ± 0.09
    - An oscillation interpretations gives $\sin^2 2\theta > 0.07, \Delta m^2 > 0.35 \mathrm{eV}^2$



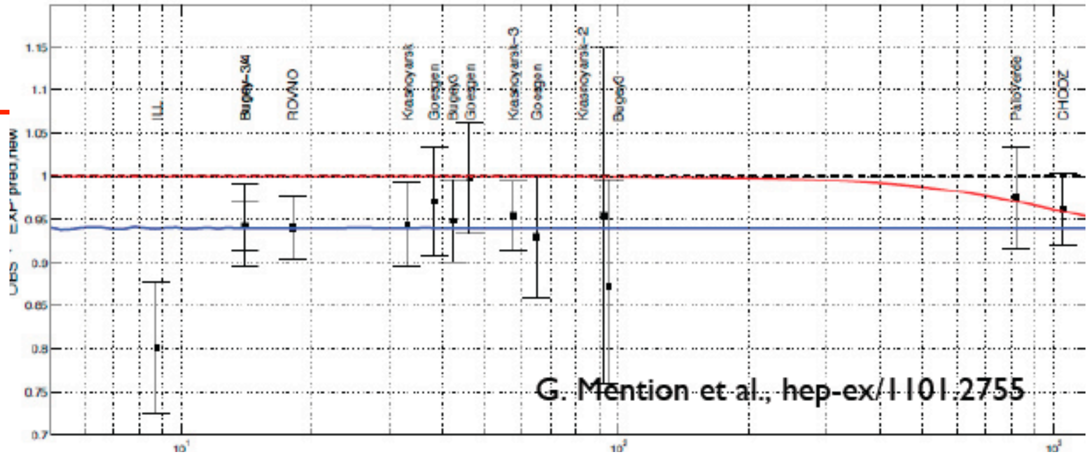
MiniBooNE Appearance
arXiv:1207.4809

Reactor Antineutrino Anomaly

Re-analysis of predicted reactor fluxes based on a new approach for the conversion of the measured electron spectra to anti-neutrino spectra.

- Reactor flux prediction increases by 3%.
- Re-analysis of reactor experiments show a deficit of electron anti-neutrinos compared to this prediction – at the 2.14σ level
- Could be oscillations to sterile with $\Delta m^2 \sim 1 \mathrm{eV}^2$ and $\sin^2 2\theta \sim 0.1$

Red: Oscillations assuming 3 neutrino mixing
Blue: Using a 3+1 (sterile neutrino) model



G. Mention et al., hep-ex/1101.2755

N.B.: several 2-3 σ results don't constitute compelling evidence...

Appearance vs. Disappearance

Testing appearance signals with disappearance measurements

$\nu_\mu \rightarrow \nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) = 4\boxed{|U_{e4}|^2}\boxed{|U_{\mu 4}|^2}\sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

ν_e disappearance

$$P(\nu_e \rightarrow \nu_x) = 1 - 4\boxed{|U_{e4}|^2(1-|U_{e4}|^2)}\sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

ν_μ disappearance

$$P(\nu_\mu \rightarrow \nu_x) = 1 - 4\boxed{|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)}\sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

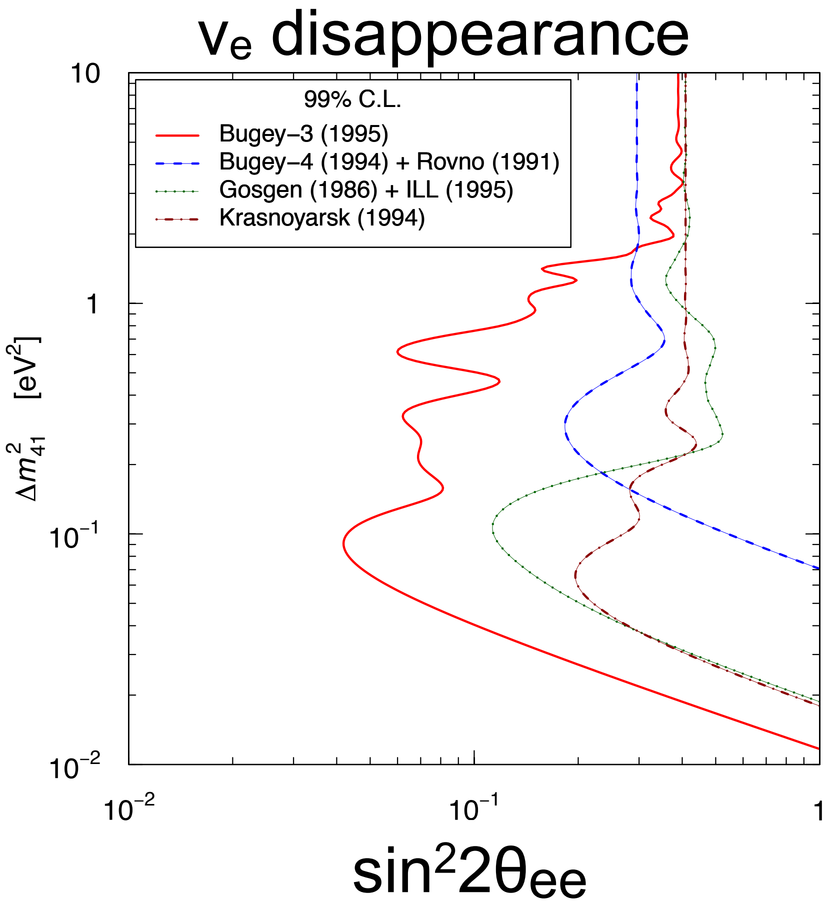
$\nu_\mu \rightarrow \nu_e$ appearance probability can be constrained by ν_e and ν_μ disappearance measurements!

Impact of Disappearance Experiments

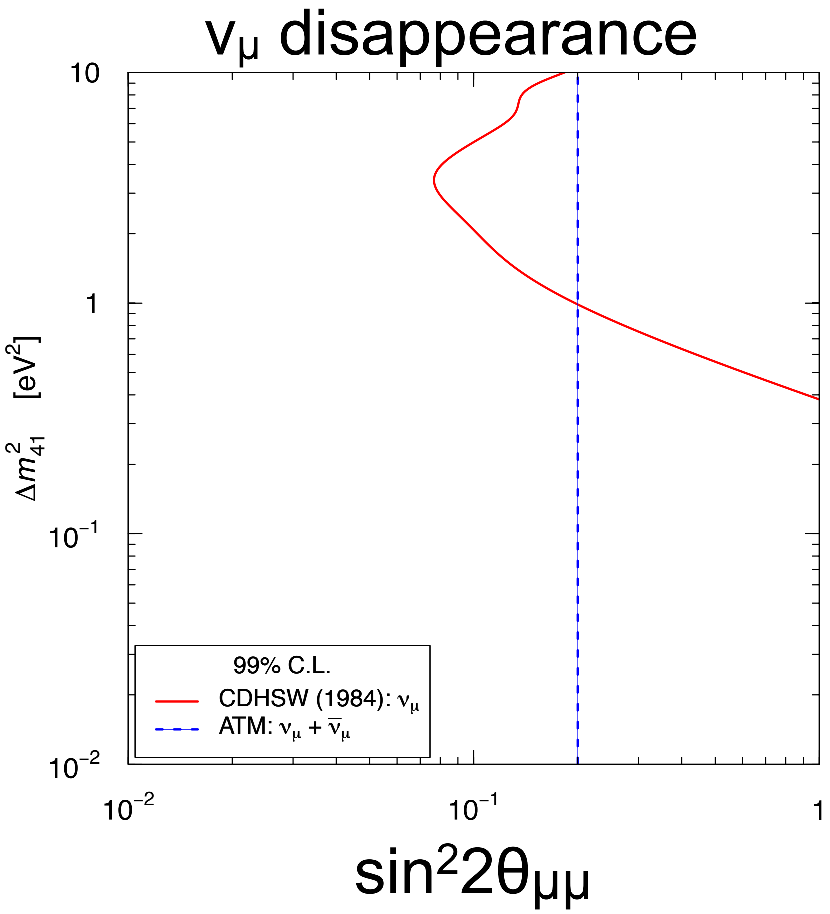
Compatibility of the existing measurements in (3+1) model

[C. Giunti, arXiv:1110.3914](https://arxiv.org/abs/1110.3914)

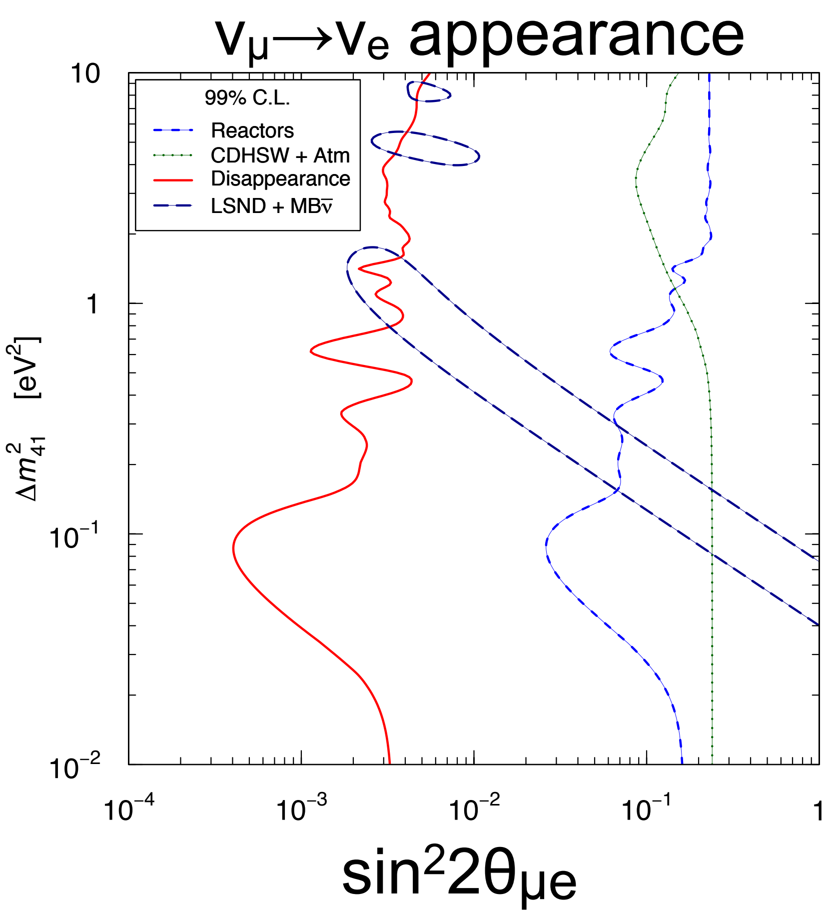
(see also J. Kopp, M. Maltoni, T. Schwetz, arXiv:1103.4570)



ν_e disappearance



ν_μ disappearance



$\nu_\mu \to \nu_e$ appearance

- Most of LSND region not compatible with disappearance results.
- Disappearance measurement is a powerful tool!

Other Scenarios

- 3+2 sterile neutrino mixing

  PRD 76, 093005 (2007)
  PRD 80, 073001 (2009)
  arXiv:1103.4570

- Sterile neutrinos in extra dimensions

  PRD 72, 095017 (2005)

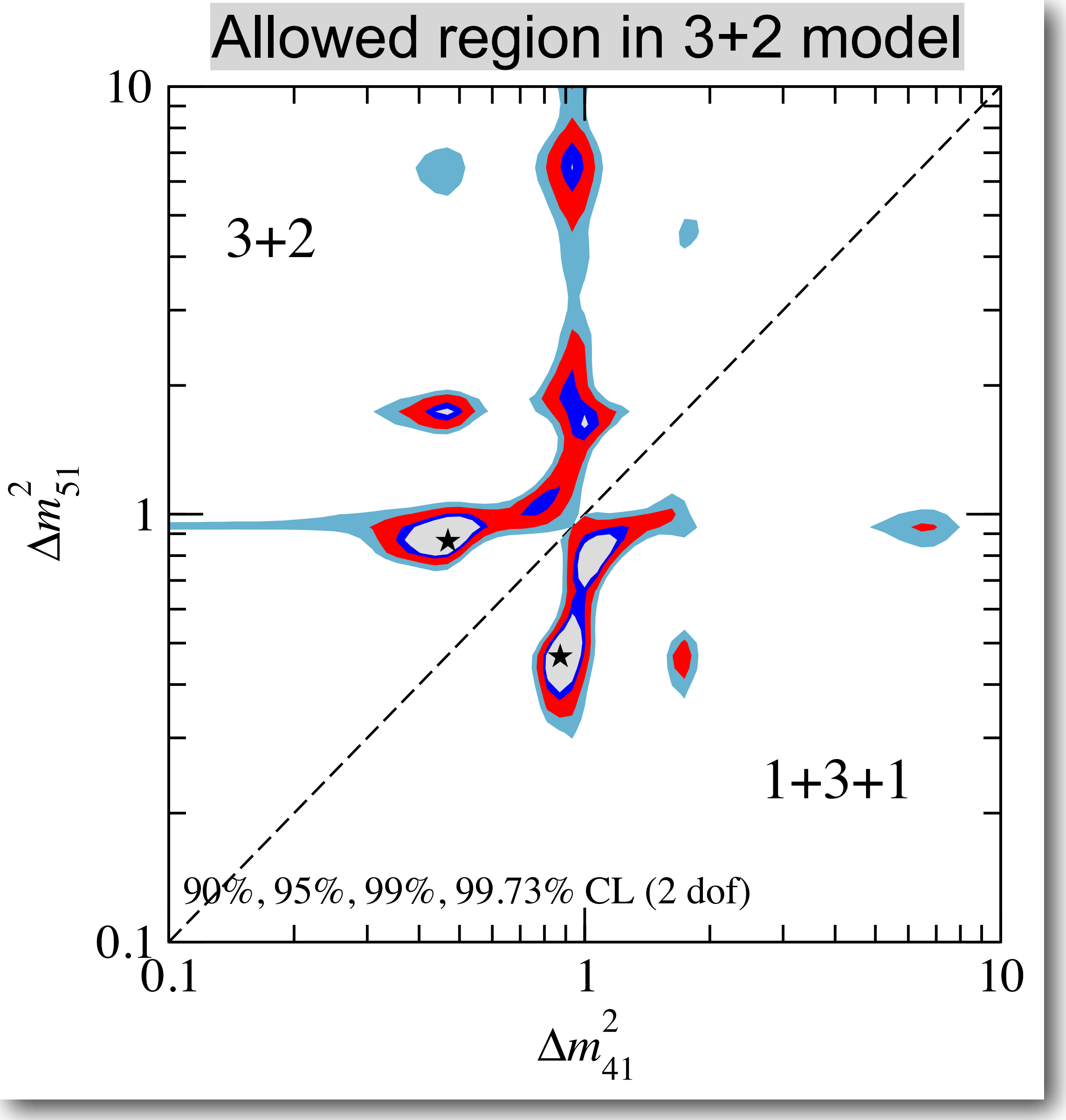
- Decaying sterile neutrino

  JHEP 09, 048 (2005)

- CPT violation

  PRD 77, 033001 (2008)

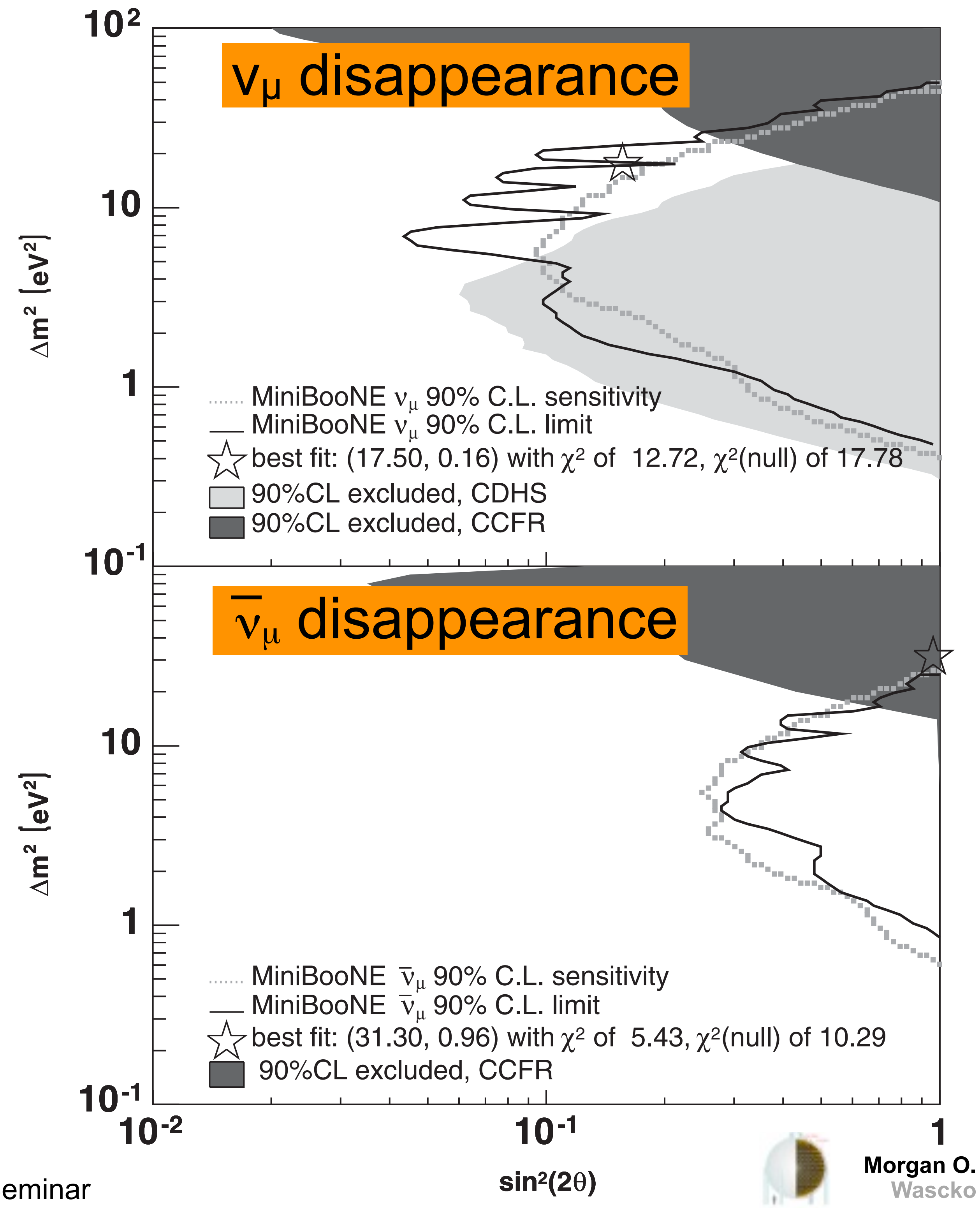
J. Kopp, M. Maltoni, T. Schwetz, arXiv:1103.4570



Disappearance measurements can constrain these models.

ν_μ Disappearance Measurements

- Important to independently test ν_μ and $\bar{\nu}_\mu$ disappearance.
  - Testing CPT-invariance.
- Recently, MiniBooNE searched for ν_μ and $\bar{\nu}_\mu$ disappearance with MiniBooNE data only (PRL 103, 0611802)
- That analysis used the flux shape only, and suffered from large flux and cross section uncertainties.
- Improve with near detector constraints!

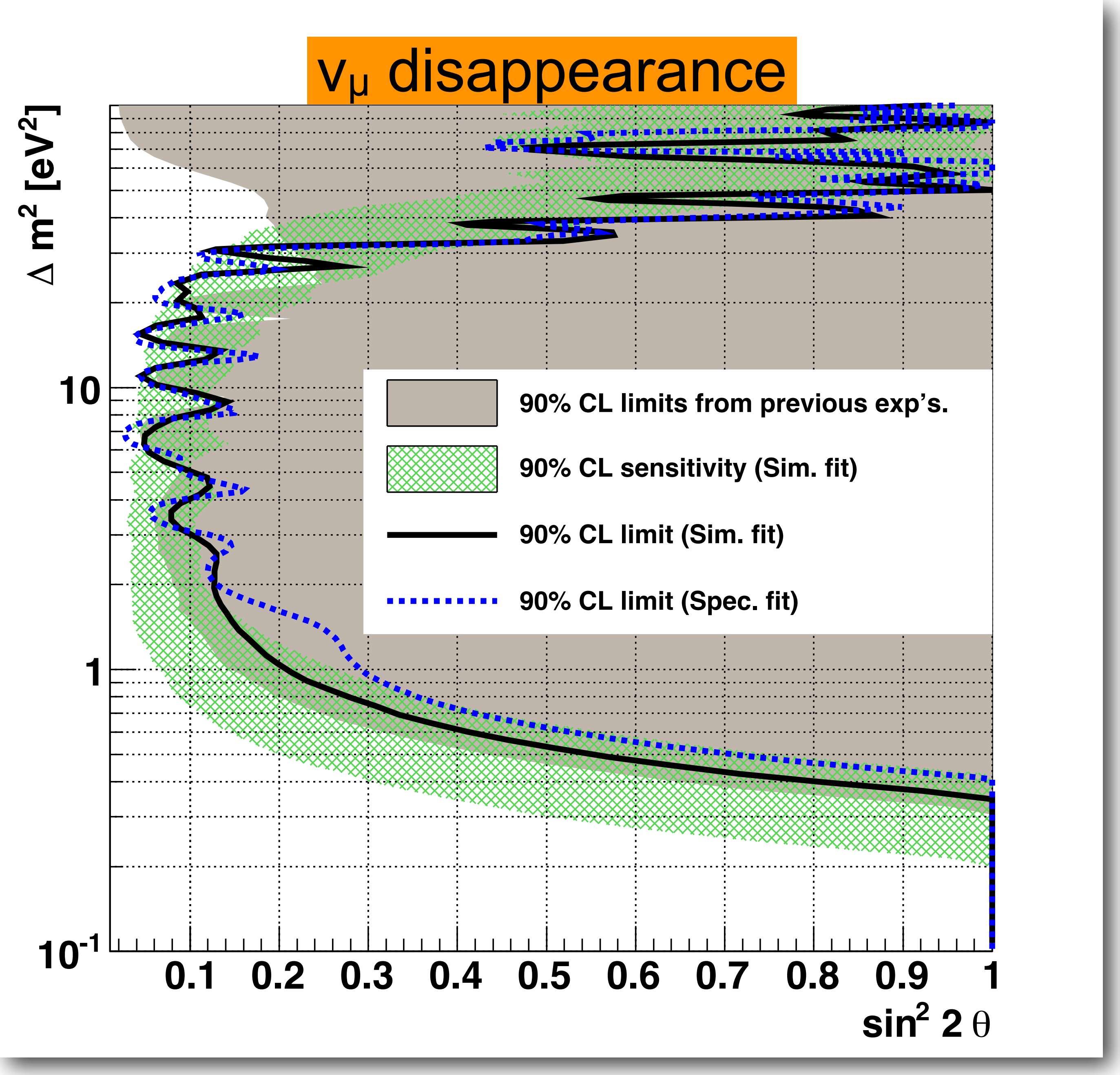


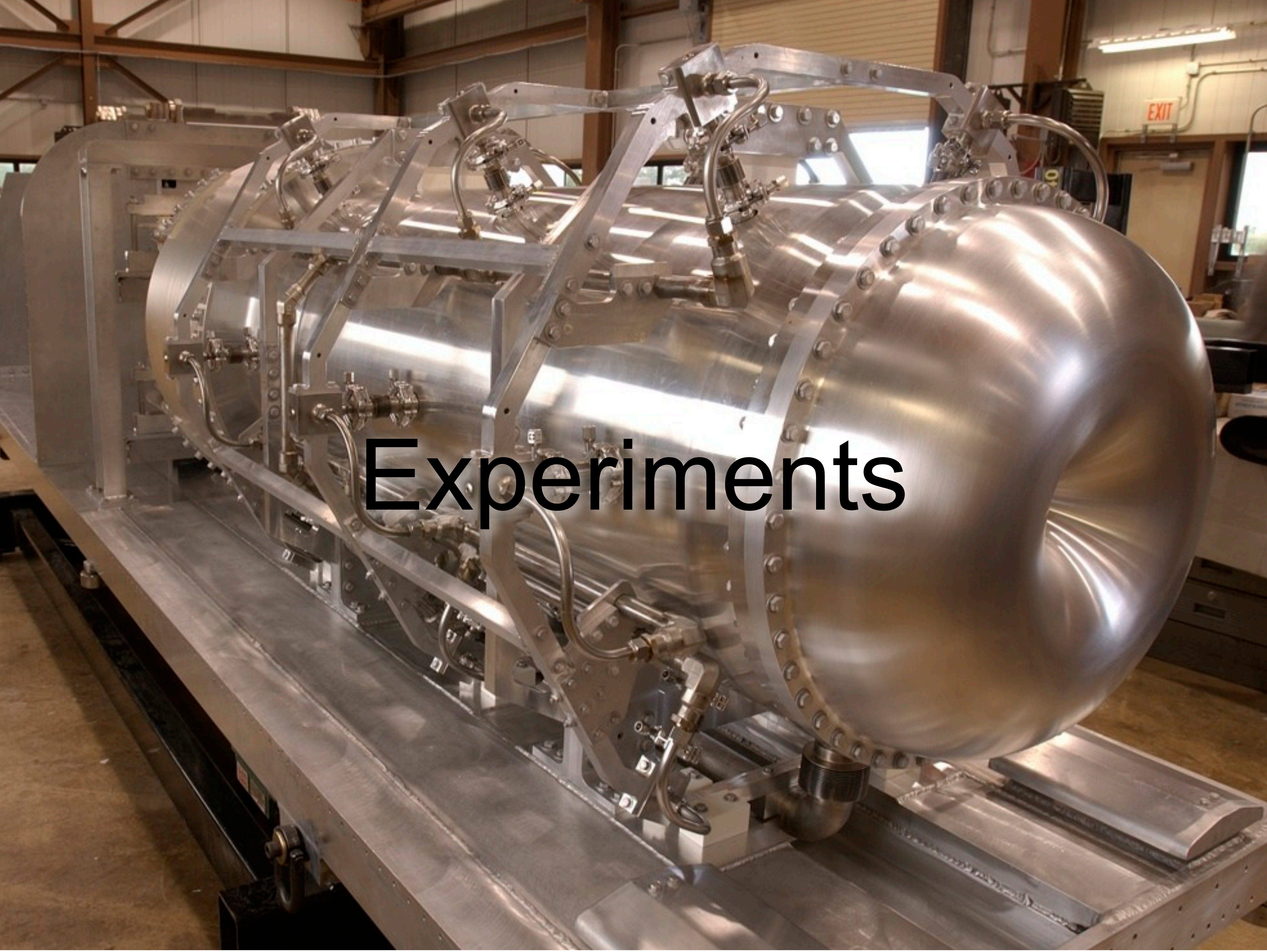
ν_μ Disappearance Measurements

- Important to independently test ν_μ and $\bar{\nu}_\mu$ disappearance.
    - Testing CPT-invariance.
- SciBooNE and MiniBooNE have already produced a joint ν_μ disappearance result
- World's strongest limit at $10 < \Delta m^2 < 30$ eV^2

arXiv:1106.5685[hep-ex]

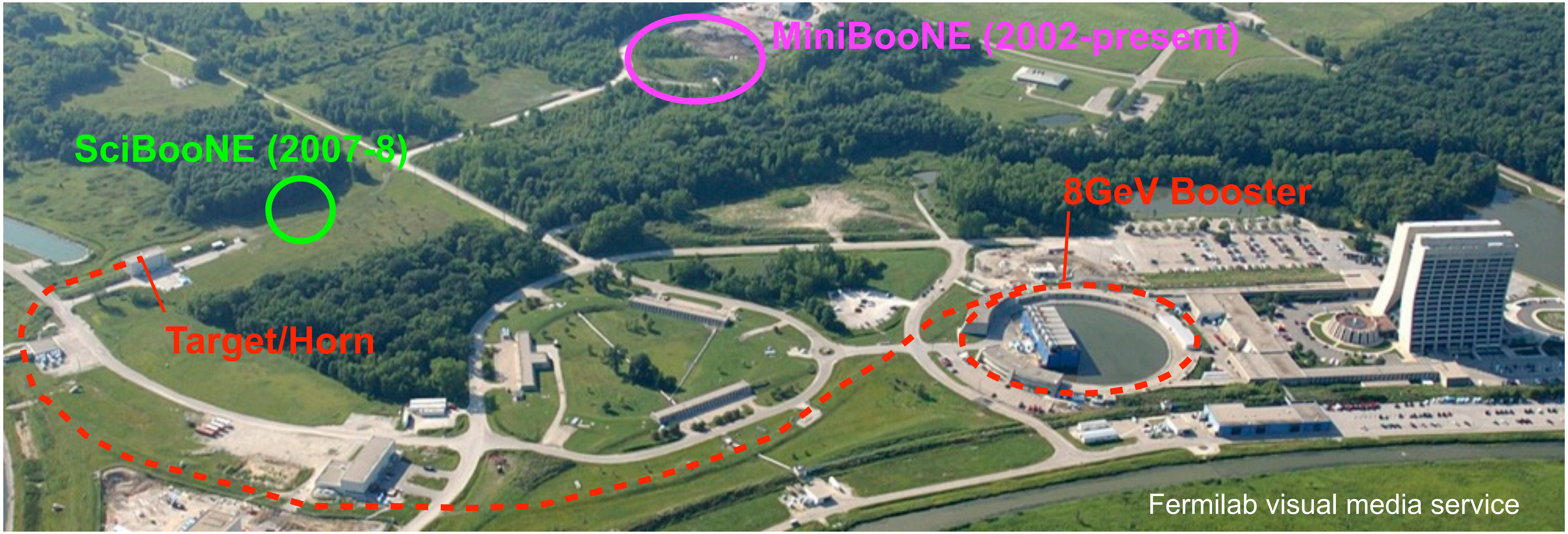
*Phys. Rev. D **85** 032007 (2012)*



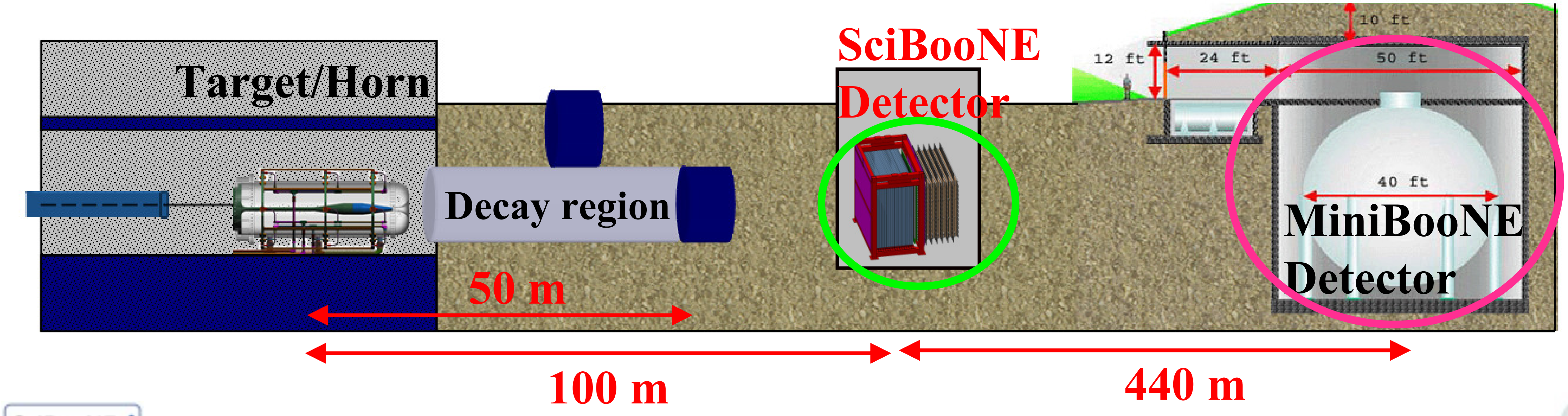


Experiments

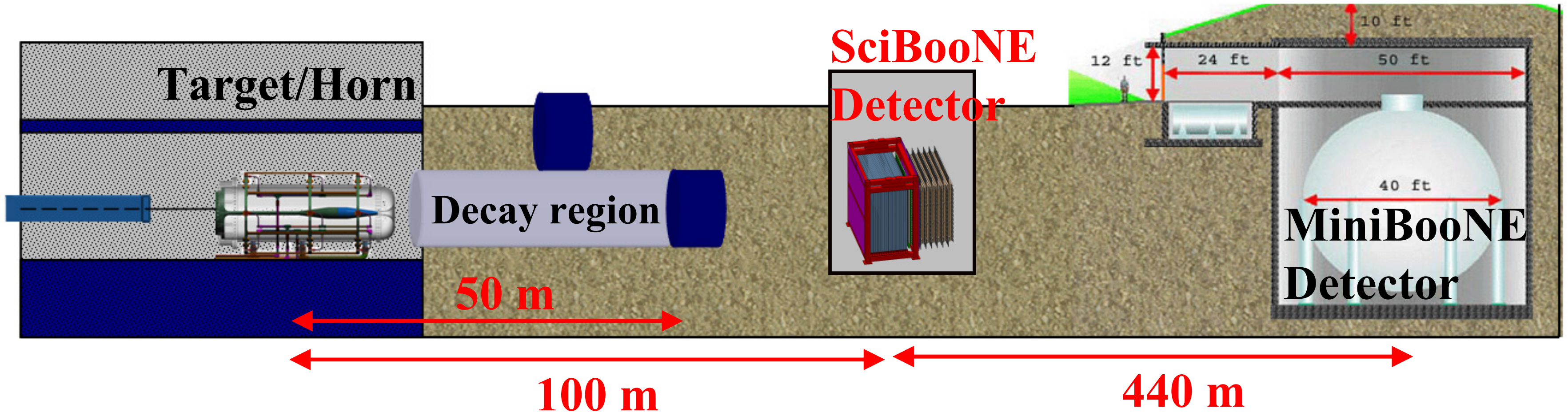
Overview



Fermilab visual media service



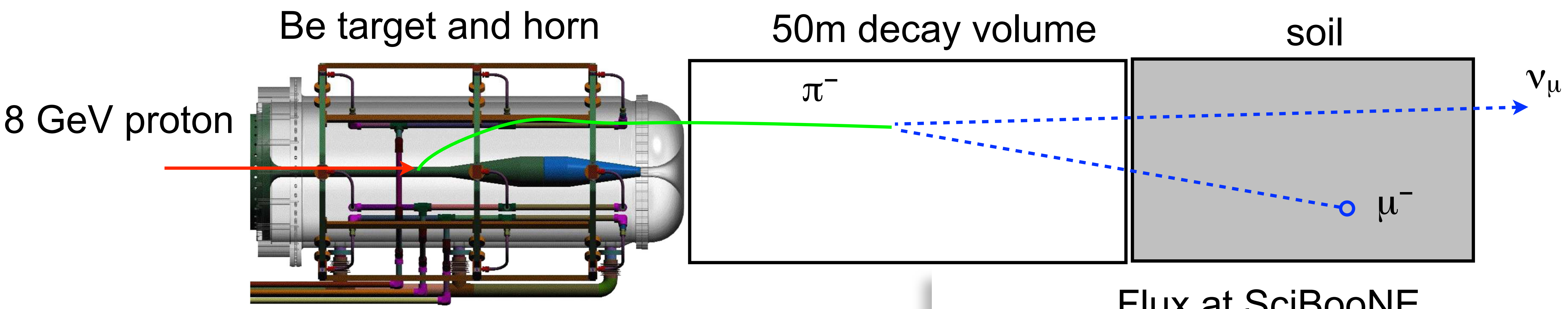
Overview



- MiniBooNE is designed to test the LSND signal
  - LSND L/E: 20m/30MeV ~ 0.7 meter/MeV
  - MiniBooNE L/E: 540m / 0.8 GeV ~ 0.7 m/MeV
- SciBooNE (2007-2008) has two purposes
  - Precise measurement of neutrino cross section for future oscillation experiments (T2K, etc)
  - MiniBooNE near detector

Common beamline + Common neutrino target (both carbon) → Significant reduction of systematic errors

Fermilab Booster ν Beam



Be target and horn

50m decay volume

soil

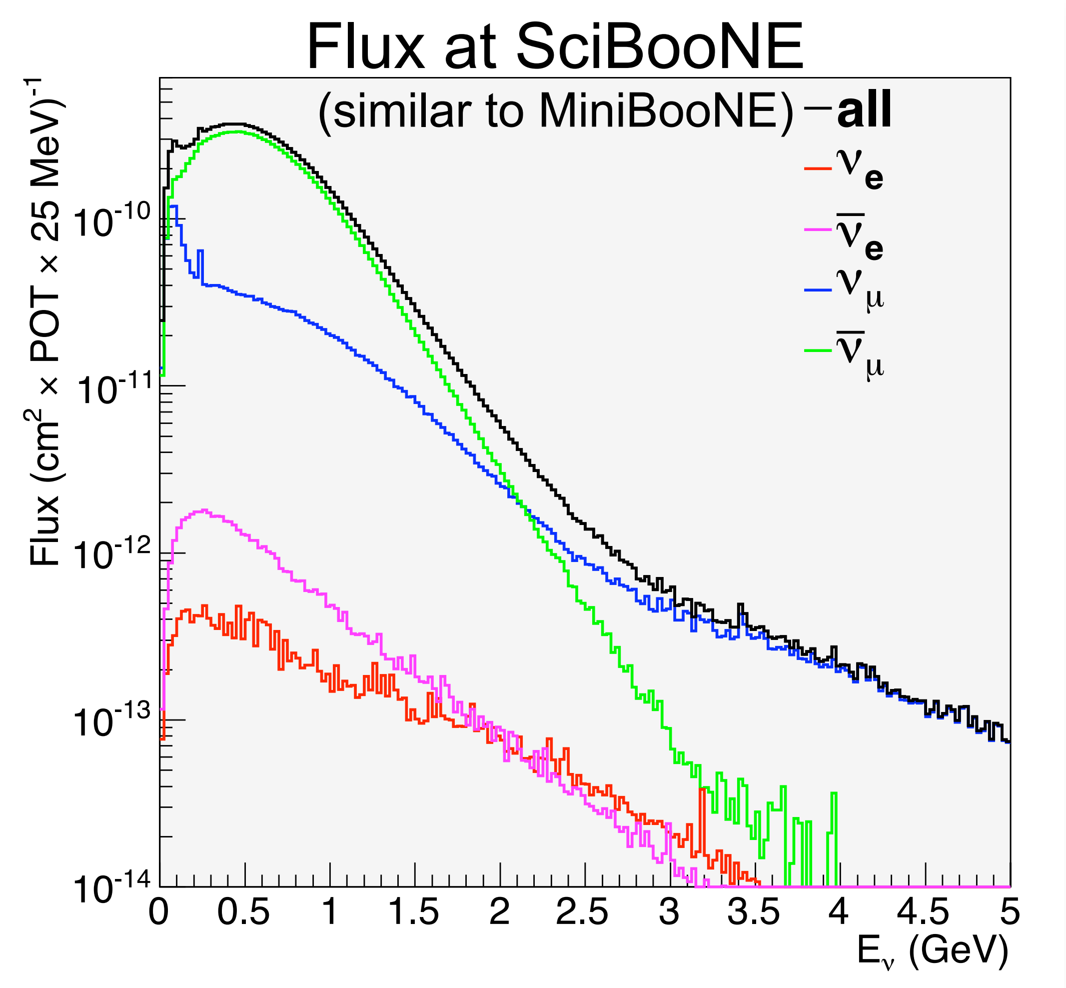
8 GeV proton

π^-

μ^-

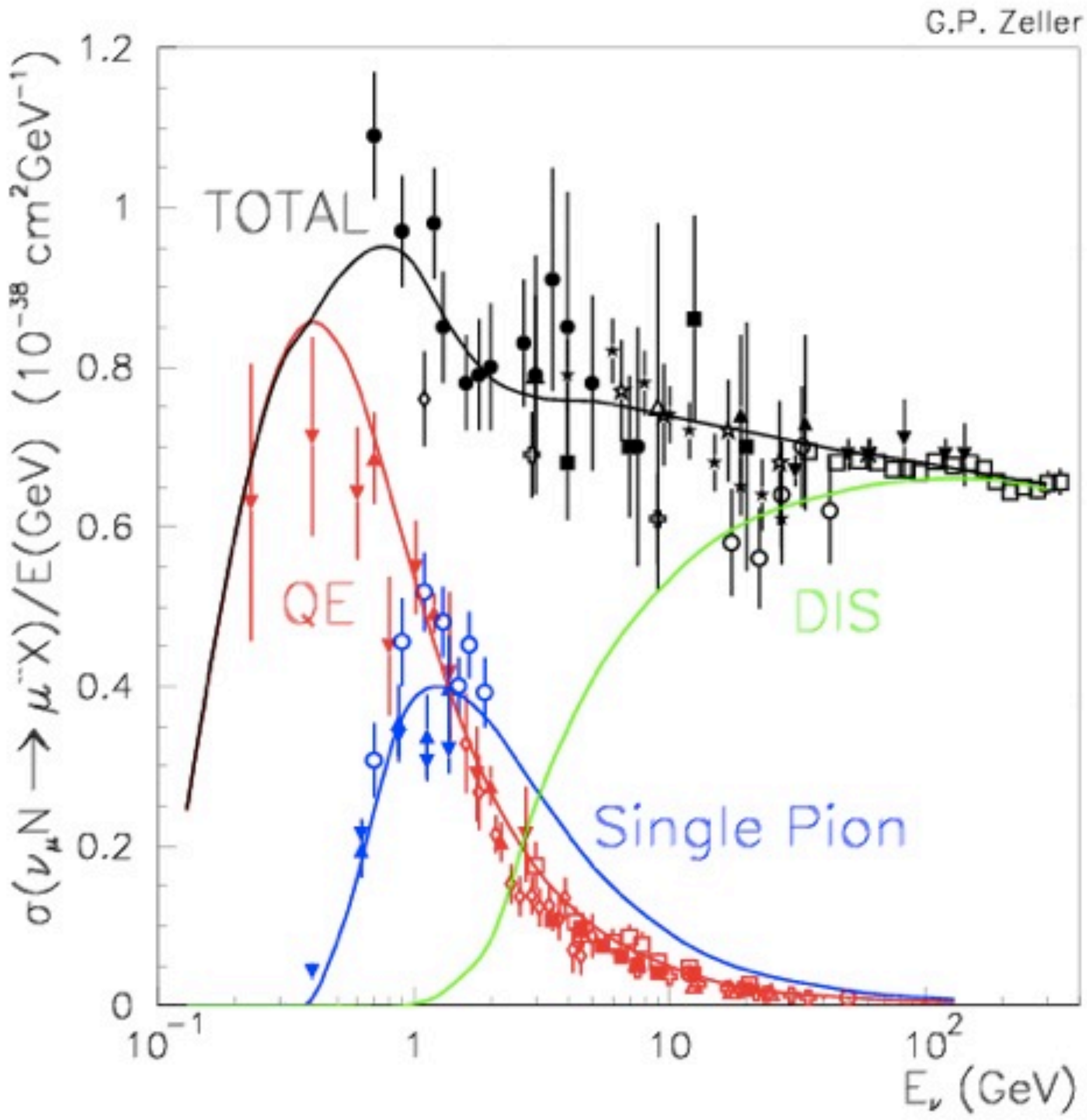
ν_μ

- Intense $\bar{\nu}_\mu$ beam with the mean energy of ~0.6 GeV
  - 93% pure muon flavour beam.
    - WS BGs need to be constrained
  - ν_μ beam is also produced by inverting horn polarity.



Phys.Rev.D79,072002(2009)

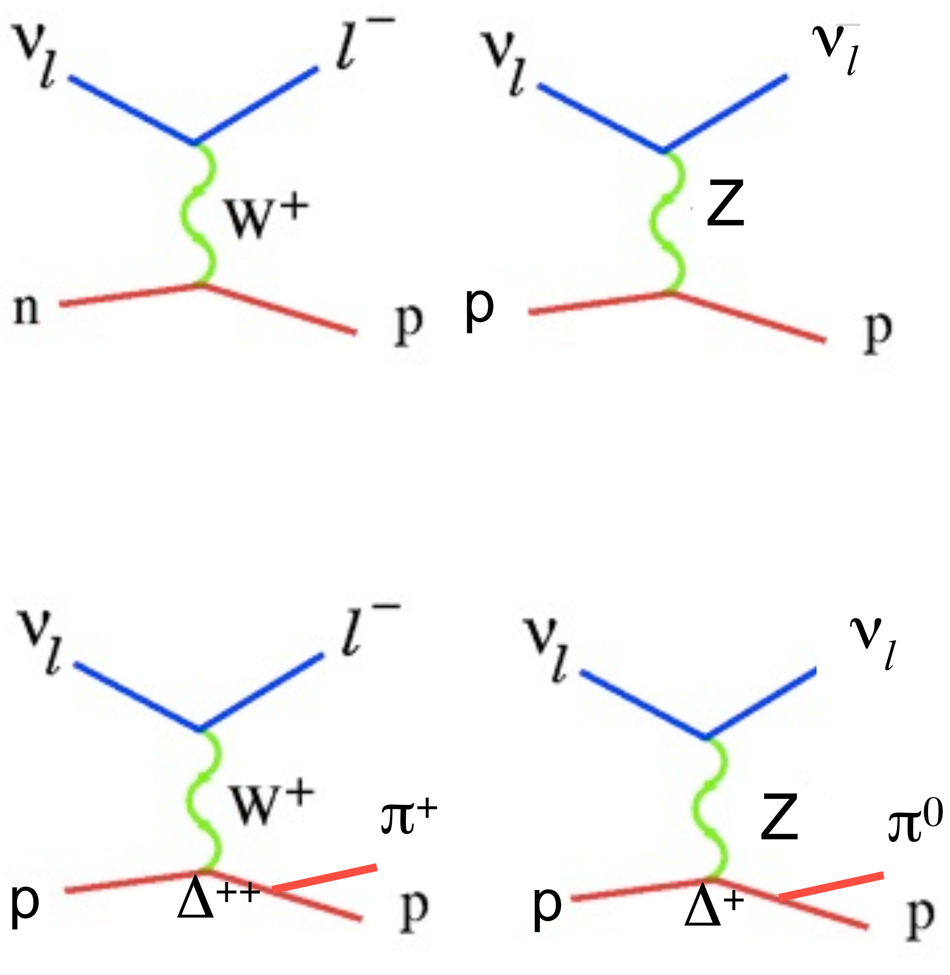
Neutrino Interactions



Neutrino interaction data before oscillation era

CC / NC
quasi-elastic
scattering
(QE)
42% / 16%

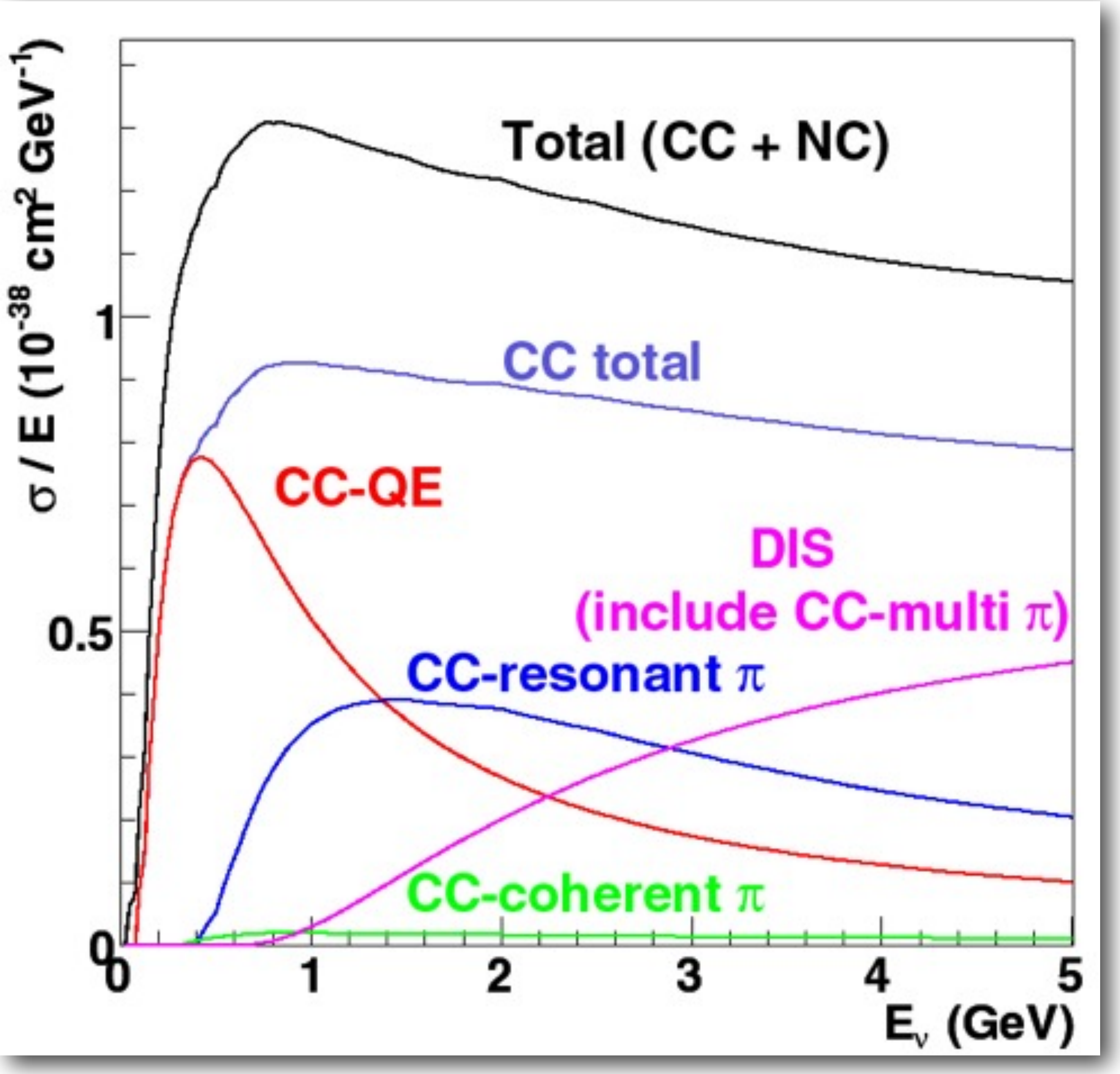
CC / NC
resonance
production (1π)
25% / 7%



Pseudo-Feynman diagrams of neutrino interactions

Neutrino Event Generation

Use two event generators:
NEUT and NUANCE



- Quasi-Elastic
  - Llewellyn Smith, Smith-Moniz
  - M_A=1.2GeV/c2
  - P_F=217MeV/c, E_B=27MeV (for Carbon)
- Resonant π
  - Rein-Sehgal (2007)
  - M_A=1.2 GeV/c2
- Coherent π
  - Rein-Sehgal (2006)
  - M_A=1.0 GeV/c2
- Deep Inelastic Scattering
- GRV98 PDF
- Bodek-Yang correction

CC/NC-1π

- Intra-nucleus interactions

SciBooNE Collaboration

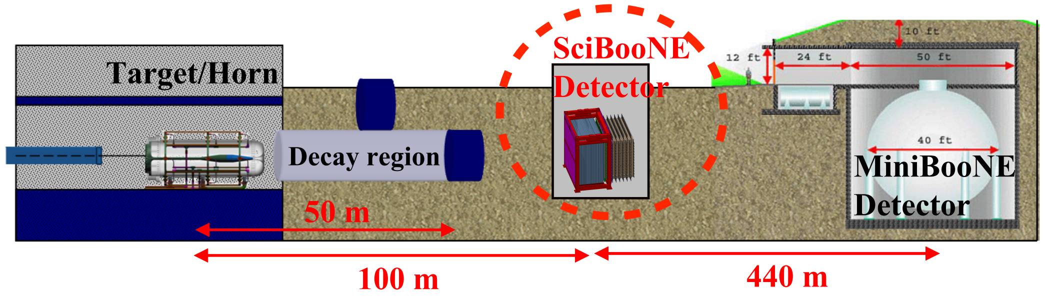

SciBooNE, 2008

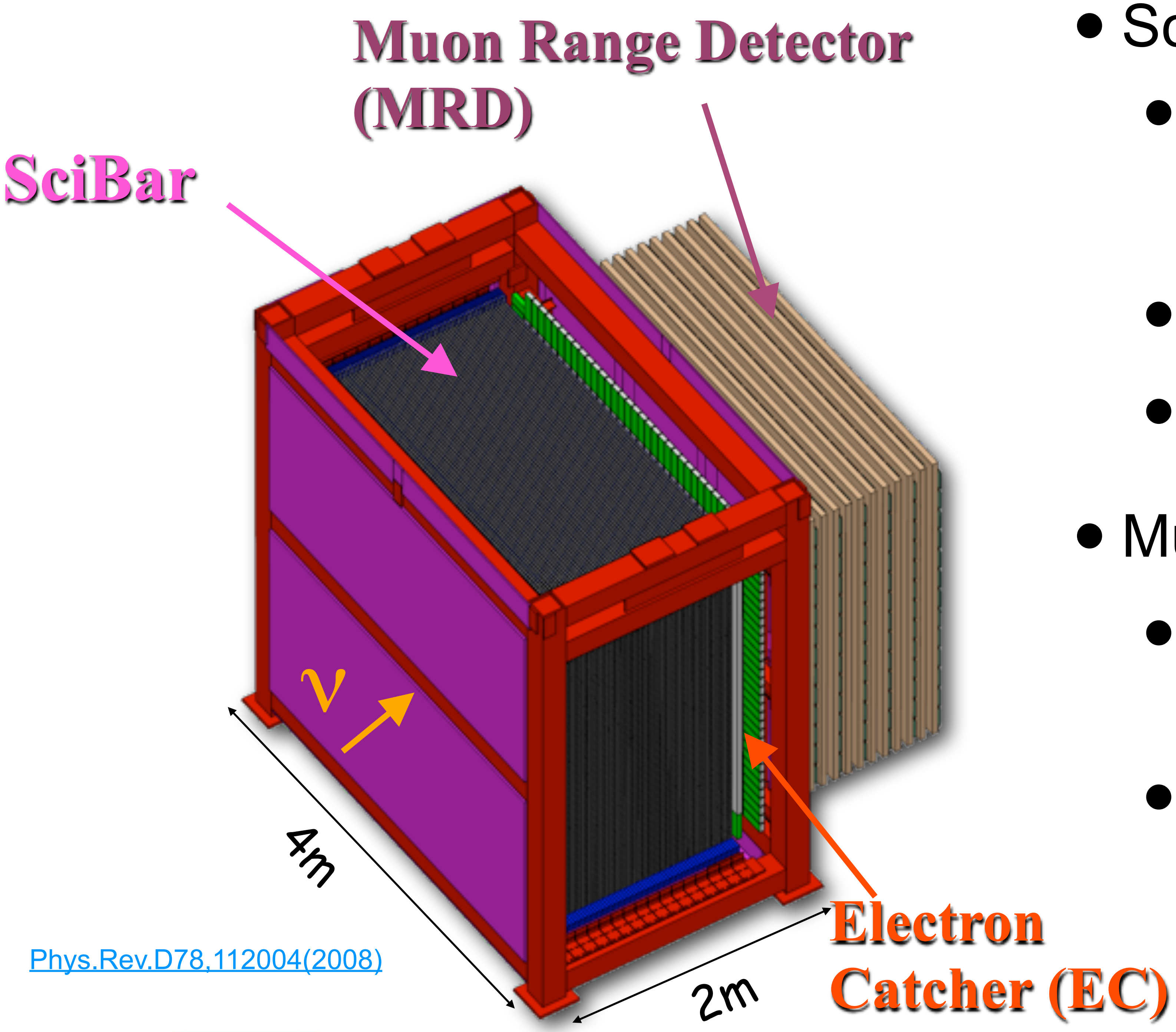
63 physicists
5 countries 18 institutions

Universitat Autonoma de Barcelona
University of Cincinnati
University of Colorado, Boulder
Columbia University
Fermi National Accelerator Laboratory
High Energy Accelerator Research Organization (KEK)
Imperial College London
Indiana University
Institute for Cosmic Ray Research (ICRR)
Kyoto University
Los Alamos National Laboratory
Louisiana State University
Massachusetts Institute of Technology
Purdue University Calumet
Universita degli Studi di Roma "La Sapienza“ and INFN
Saint Mary's University of Minnesota
Tokyo Institute of Technology
Unversidad de Valencia

Spokespersons:
M.O. Wascko (Imperial), T. Nakaya (Kyoto)

SciBooNE detector





Phys.Rev.D78,112004(2008)

- Located 100 m from target.
- SciBar:
  - Fully active scintillator tracker (~14000 strips)
  - Neutrino target (~10 ton)
  - Main component： CH
- Muon Range Detector (MRD)
  - Sandwich type detector of steel + plastic scintillator.
  - Reconstruct muon energy from path-length

MiniBooNE Collaboration

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J. M. Conrad[5], D. C. Cox[8], A. Curioni[16], Z. Djurcic[5], D. A. Finley[7], B. T. Fleming[16], R. Ford[7], F. G. Garcia[7],
G. T. Garvey[9], J. A. Green[8,9], C. Green[7,9] , T. L. Hart[4], E. Hawker[15], R. Imlay[10], R. A. Johnson[3], P. Kasper[7],
T. Katori[8], T. Kobilarcik[7], I. Kourbanis[7], S. Koutsoliotas[2], E. M. Laird[12], J. M. Link[14], Y. Liu[11], Y. Liu[1],
W. C. Louis[9], K. B. M. Mahn[5], W. Marsh[7], P. S. Martin[7], G. McGregor[9], W. Metcalf[10], P. D. Meyers[12], F. Mills[7],
G. B. Mills[9], J. Monroe[5], C. D. Moore[7], R. H. Nelson[4], P. Nienaber[13], S. Ouedraogo[10], R. B. Patterson[12],
D. Perevalov[1], C. C. Polly[8], E. Prebys[7], J. L. Raaf[3], H. Ray[9], B. P. Roe[11], A. D. Russell[7], V. Sandberg[9],
R. Schirato[9], D. Schmitz[5], M. H. Shaevitz[5], F. C. Shoemaker[12], D. Smith[6], M. Sorel[5], P. Spentzouris[7],
I. Stancu[1], R. J. Stefanski[7], M. Sung[10], H. A. Tanaka[12], R. Tayloe[8], M. Tzanov[4], M. O. Wascko[10],
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[3] *University of Cincinnati, Cincinnati, OH 45221*
[4] *University of Colorado, Boulder, CO 80309*
[5] *Columbia University, New York, NY 10027*
[6] *Embry Riddle Aeronautical University, Prescott, AZ 86301*
[7] *Fermi National Accelerator Laboratory, Batavia, IL 60510*
[8] *Indiana University, Bloomington, IN 47405*
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[10] *Louisiana State University, Baton Rouge, LA 70803*
[11] *University of Michigan, Ann Arbor, MI 48109*
[12] *Princeton University, Princeton, NJ 08544*
[13] *Saint Mary's University of Minnesota, Winona, MN 55987*
[14] *Virginia Polytechnic Institute & State University, Blacksburg, VA 24061*
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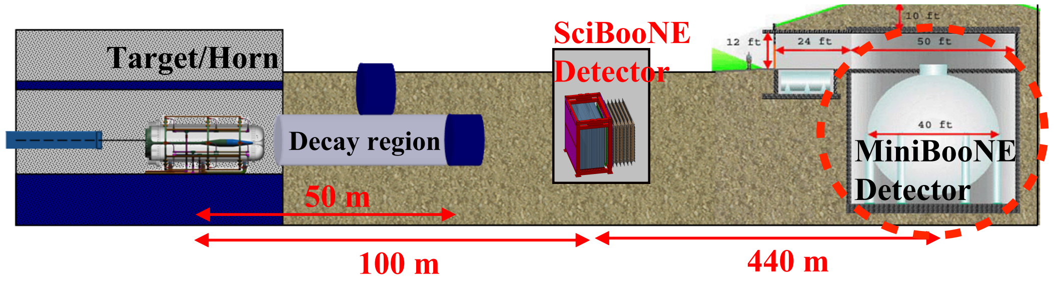
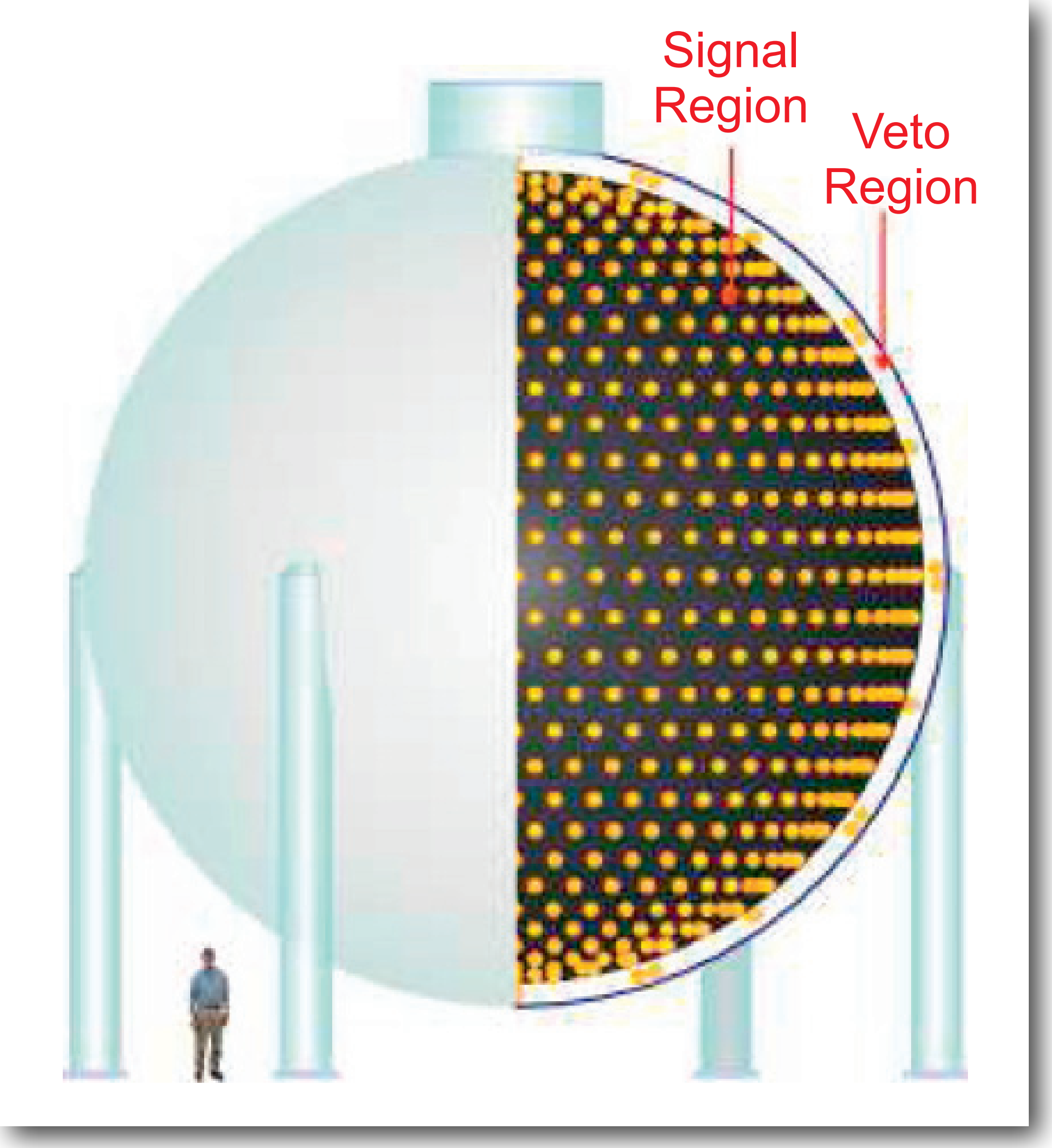
[16] *Yale University, New Haven, CT 06520*

MiniBooNE detector





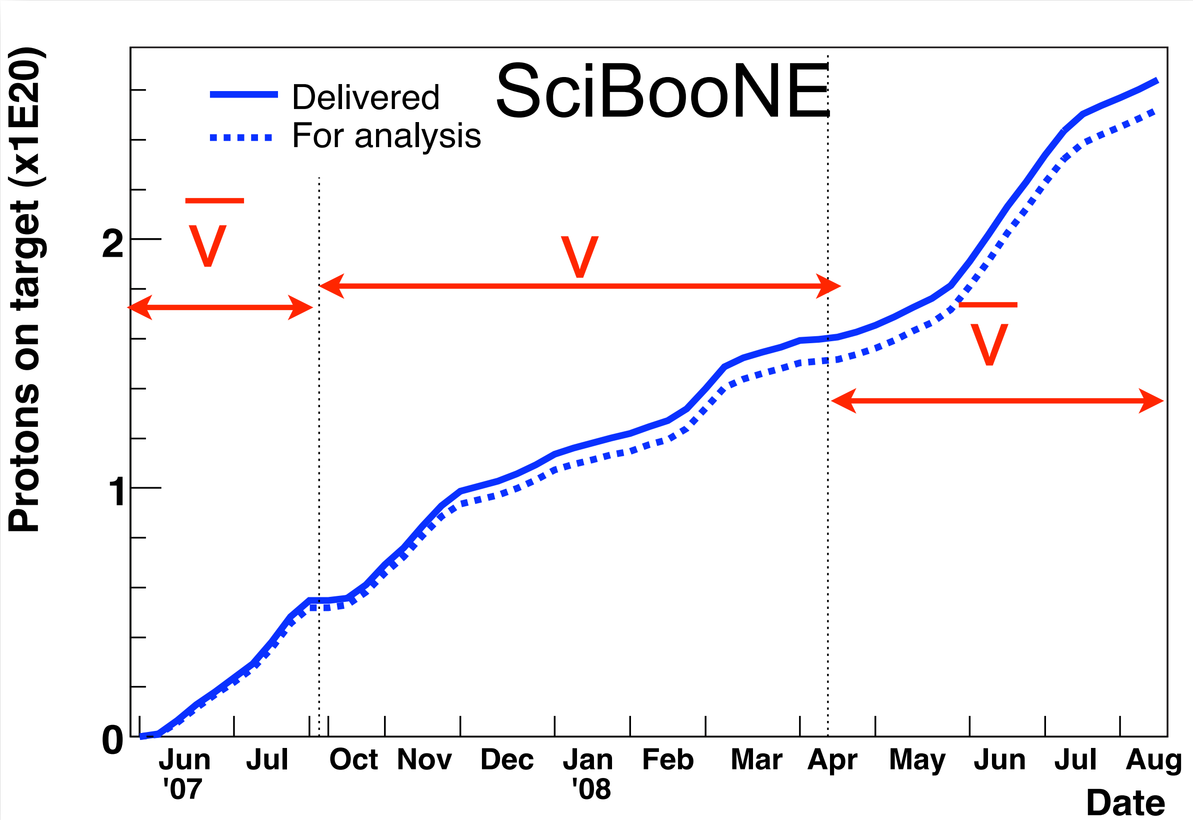
- Located 540 m from target
- Mineral oil Cherenkov detector
  - n = 1.47
  - Select $\bar{\nu}_\mu$ with single muon and decay electron signal.
  - Total mass: 800 ton
  - Main component: CH_2
- Taking beam data since 2002

Nucl.Instrum.Meth.A599:28-46,2009

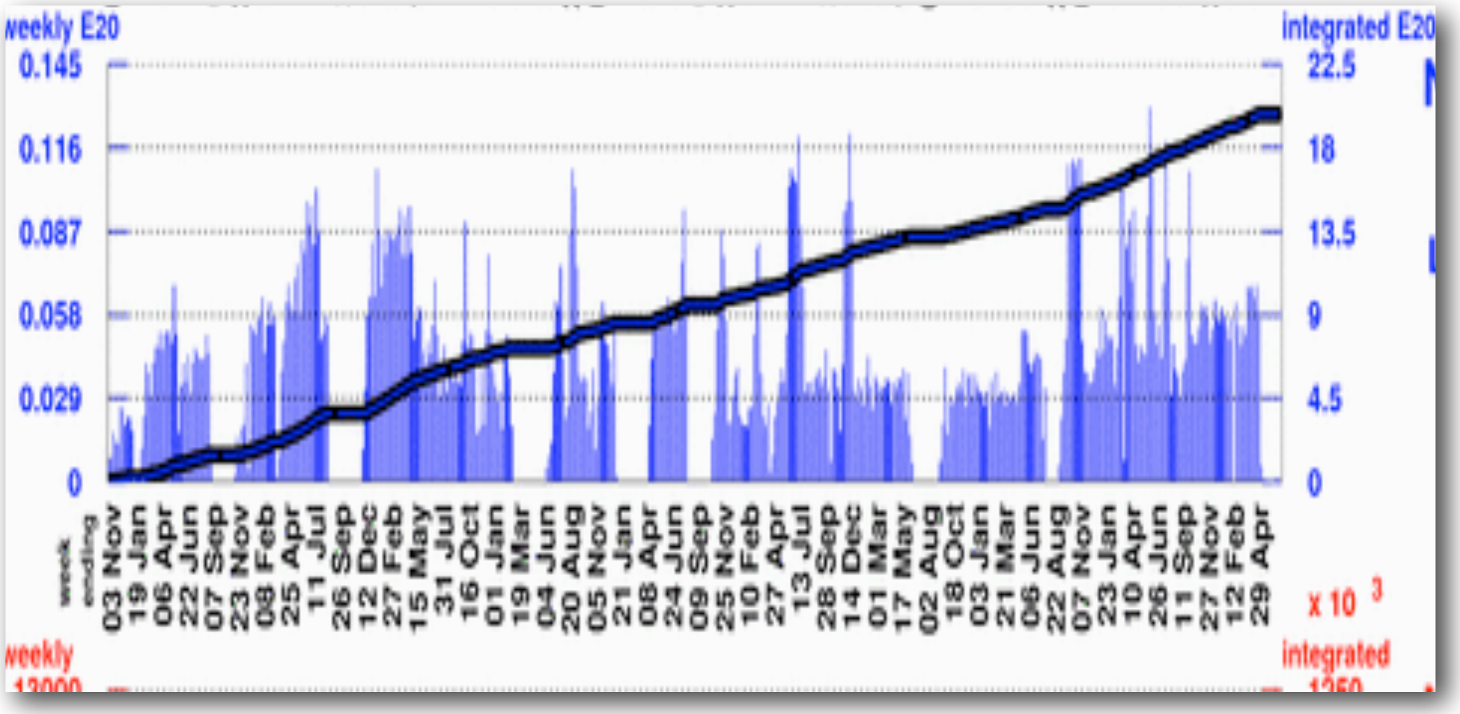
2 detectors share the beam and the target material (both carbon)

Data sets

Period	BNB Mode	SciBooNE POT	MiniBooNE POT
Sep. 2002 - Dec. 2005	Neutrino	–	5.58×10^{20}
Jan. 2006 - Aug. 2007	Antineutrino	0.52×10^{20} (from Jun. 2007)	1.71×10^{20}
Oct. 2007 - Apr. 2008	Neutrino	0.99×10^{20}	0.83×10^{20}
Apr. 2008 - present	Antineutrino	1.01×10^{20} (until Aug. 2008)	8.4×10^{20}

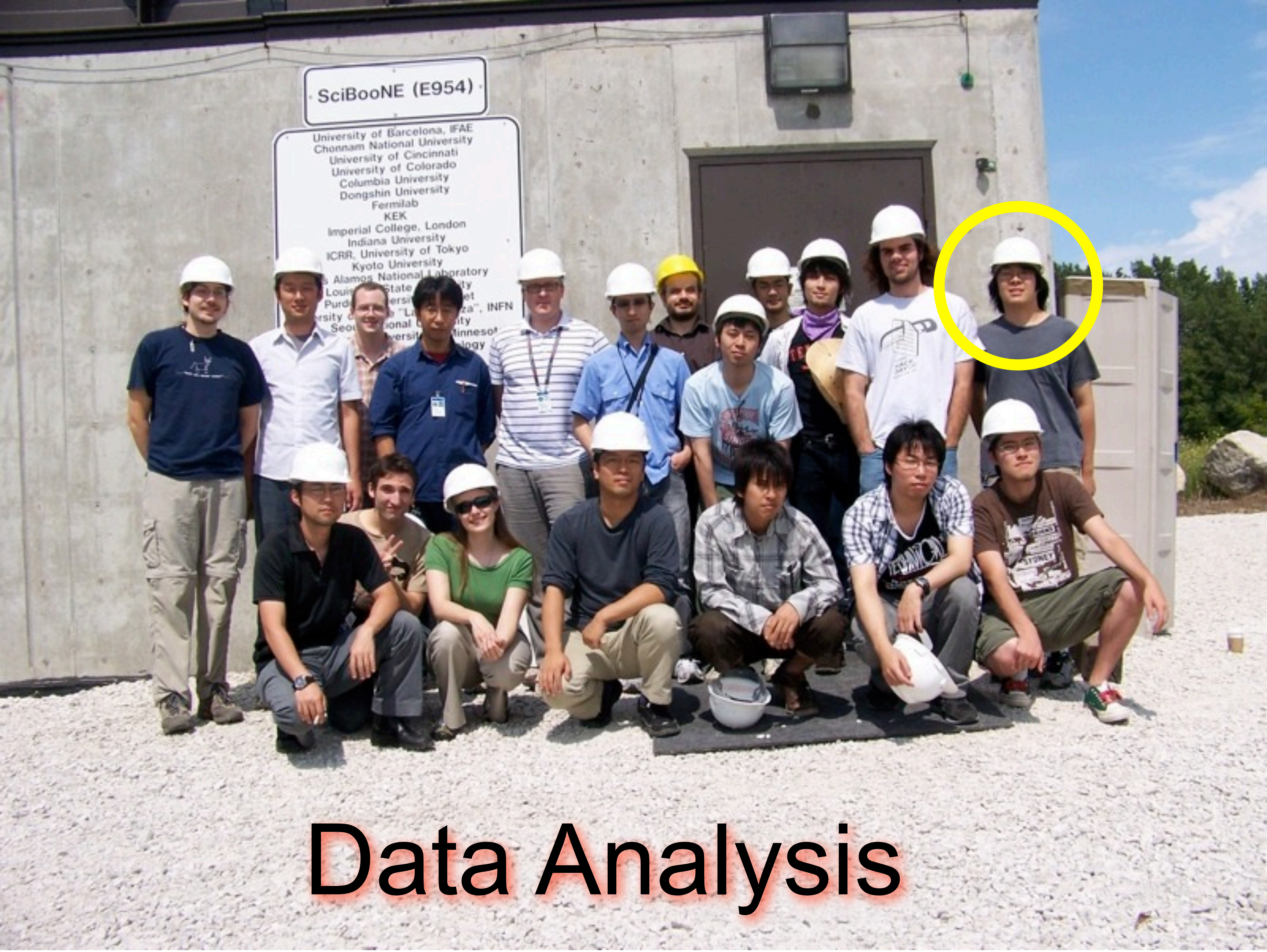


MiniBooNE



Analysis of the full antineutrino data sets presented today

- SciBooNE: $(0.5 + 1.0) \times 10^{20}$ POT
- MiniBooNE: $(1.7 + 8.4) \times 10^{20}$ POT



Data Analysis

Analysis Overview

Simultaneous fit to data from both detectors

SB + MB Rec. E$_\nu$ Prediction ⟷ **SB + MB Rec. E$_\nu$ Data**

Oscillation Fit

$$\chi^2 = \sum_{i,j=1}^{\boxed{42}} (D_i - N_i) \left(M^{-1}\right)_{ij} (D_j - N_j),$$

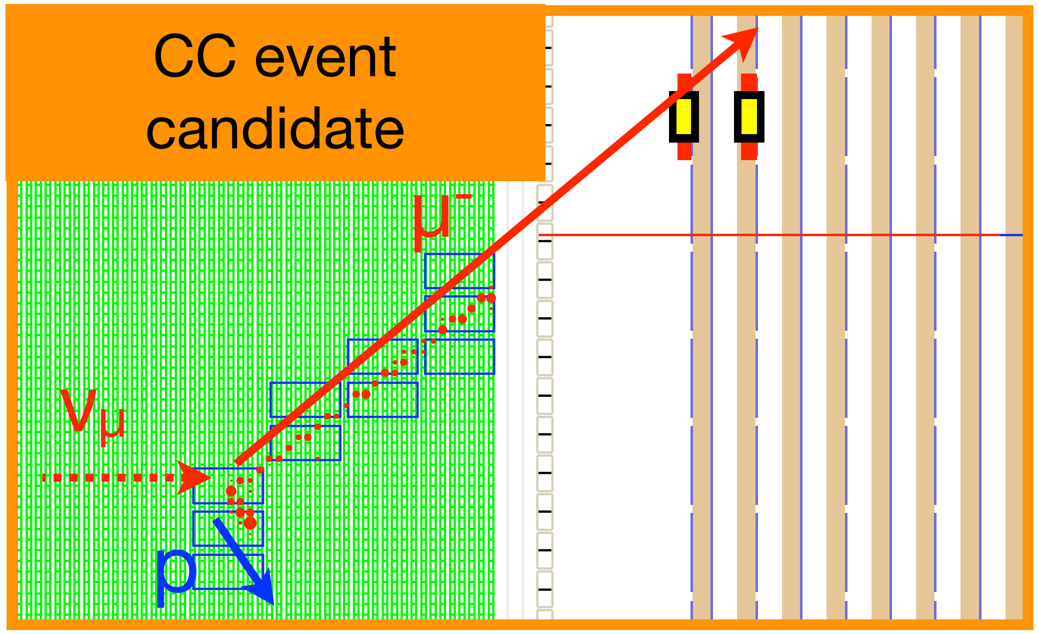
Advantages:

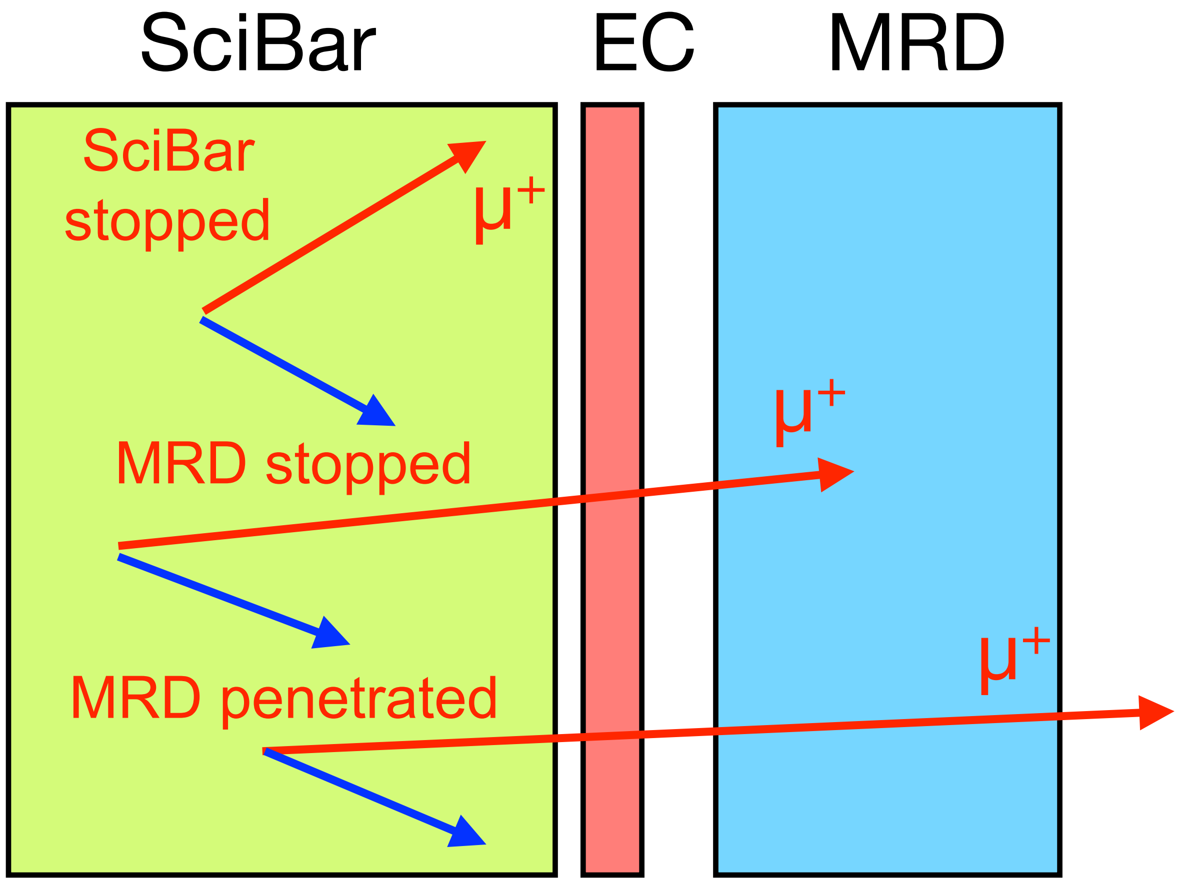
Direct fit for disappearance in SciBooNE and MiniBooNE.

Accounts for oscillation in both detectors.

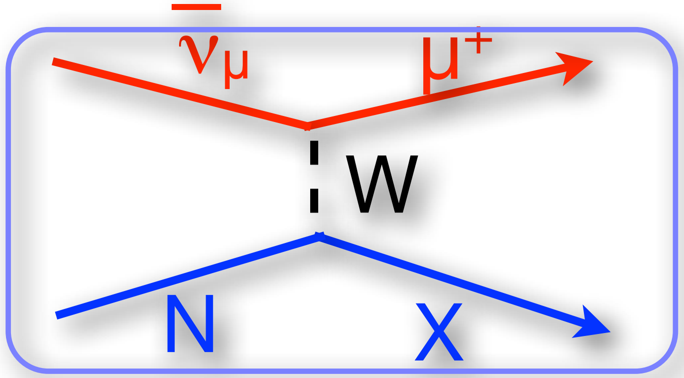
Correlation between the two constrains systematic error.

SciBooNE event selection



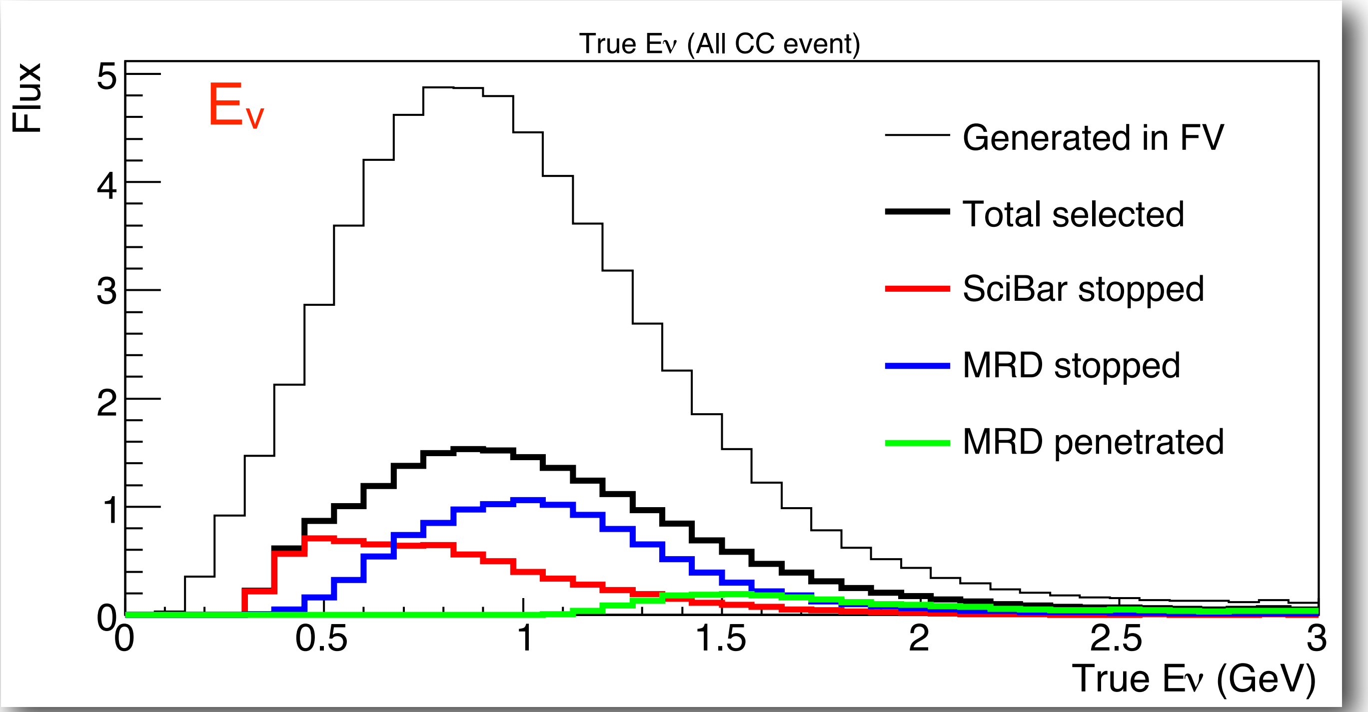


Use charged current inclusive sample



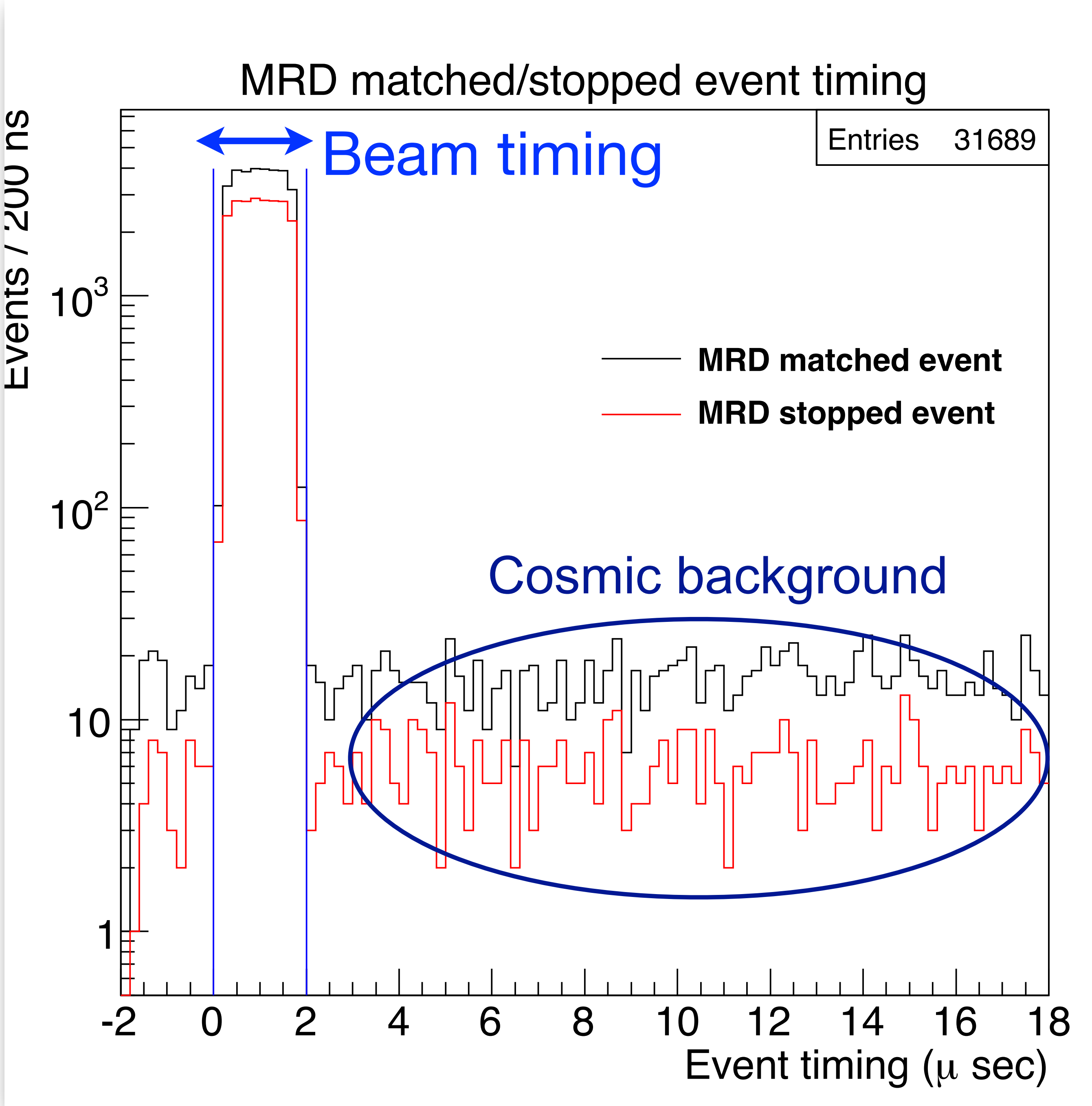
- Select MIP-like energetic tracks (P_μ>0.25GeV)
- Reject side-escaping muons.
- 3 samples:
  - SciBar-stopped (P_μ,θ_μ)
  - MRD-stopped (P_μ,θ_μ)
  - MRD-penetrated (θ_μ)

P_μ: Muon momentum reconstructed by its path-length
θ_μ: Muon angle w.r.t. beam axis

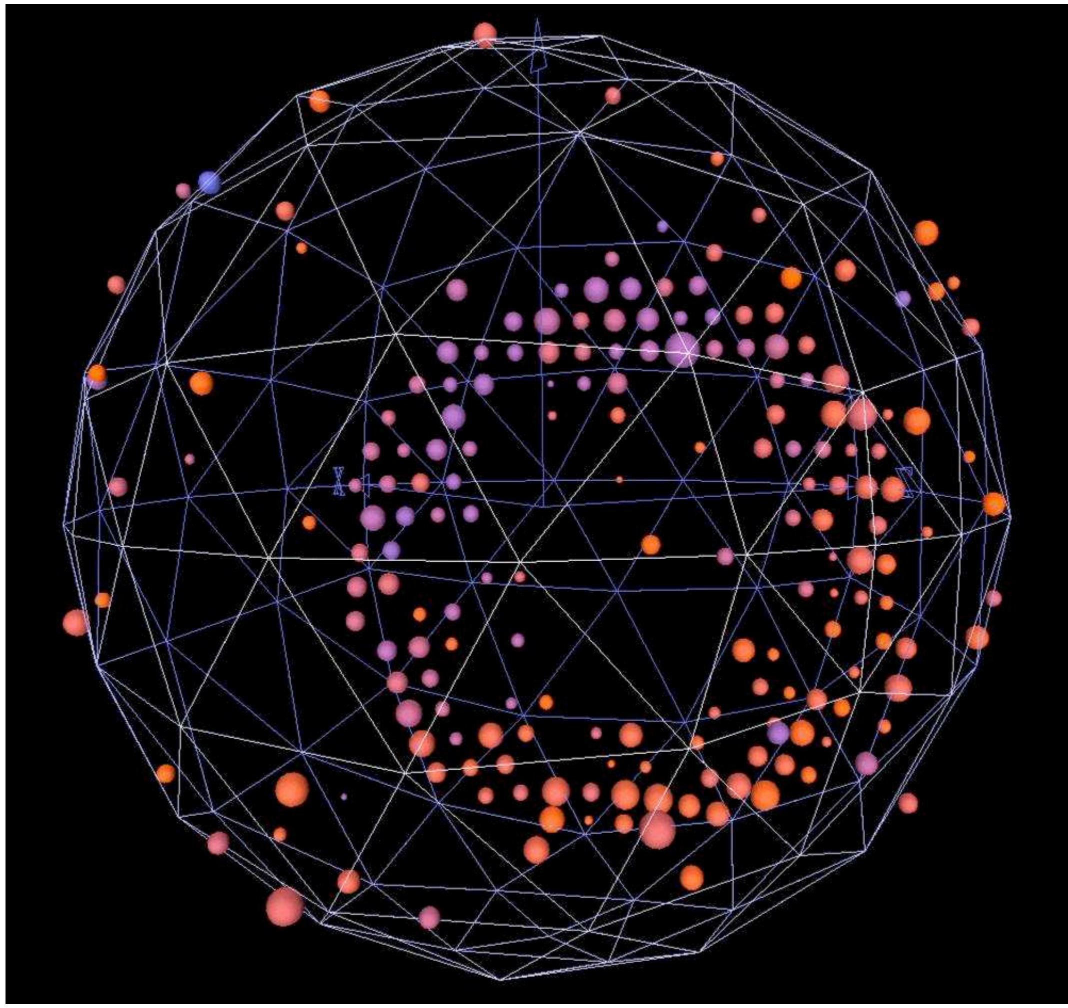


Neutrino event selection

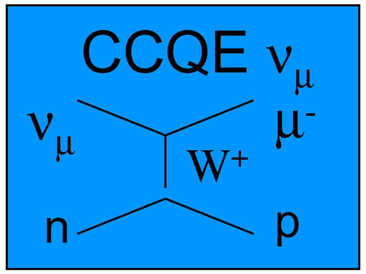
- Booster provides pulsed beam with 1.6 μsec width.
- Require the event time to be within the 2 μsec beam window.
  - Less than 0.5% cosmic ray contamination.
- ~10 k events total.

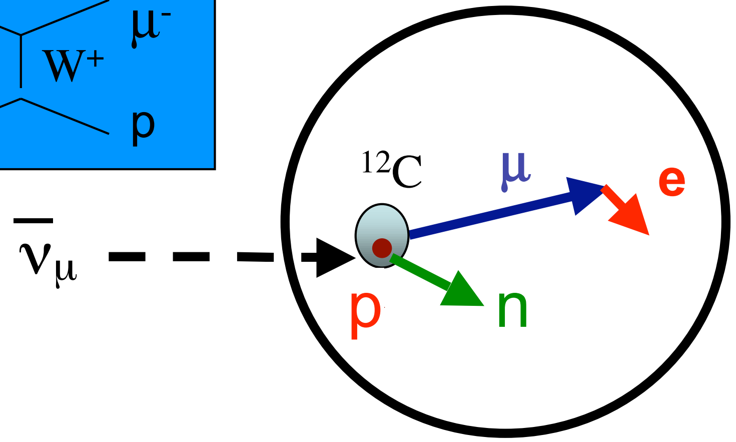


MiniBooNE reconstruction



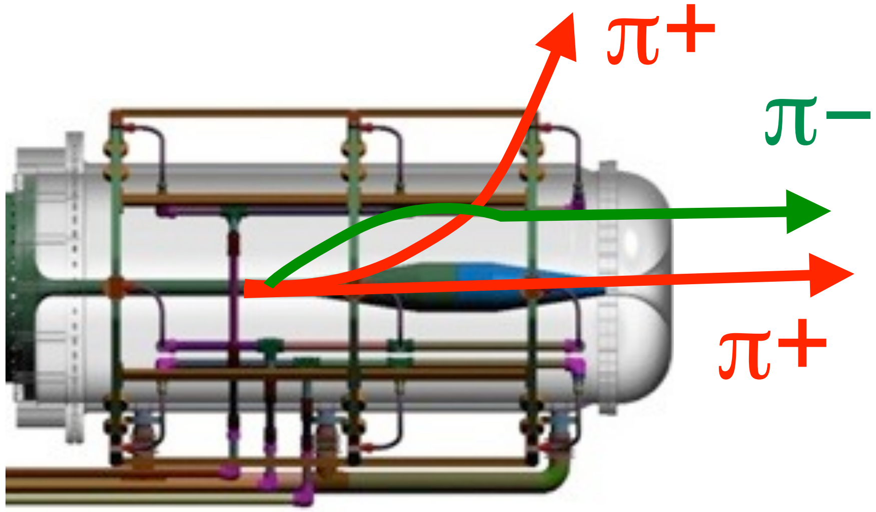
- Employ same selection/reconstruction as used in previous MiniBooNE-only analysis ([PRL 103, 061802 (2009)](PRL 103, 061802 (2009)))
- Select CC quasi-elastic (QE) ($\bar{\nu}_\mu p \rightarrow \mu^+ n$) like events by requiring hits from muon and its decay electron.
  - Reconstruct muon kinematics from the Cherenkov light yield.
  - Reconstruct neutrino energy from muon kinematics.
  - >68 k events!

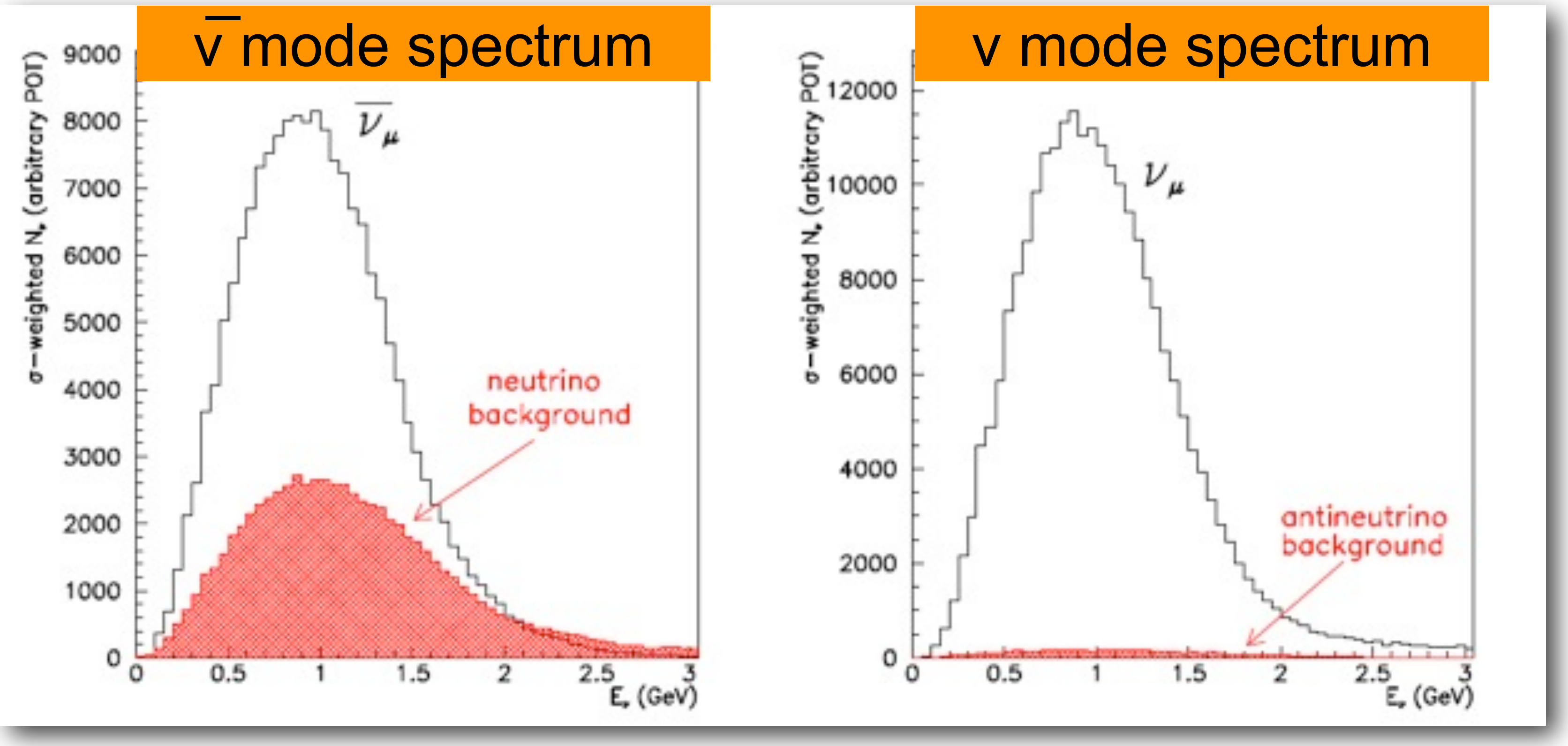




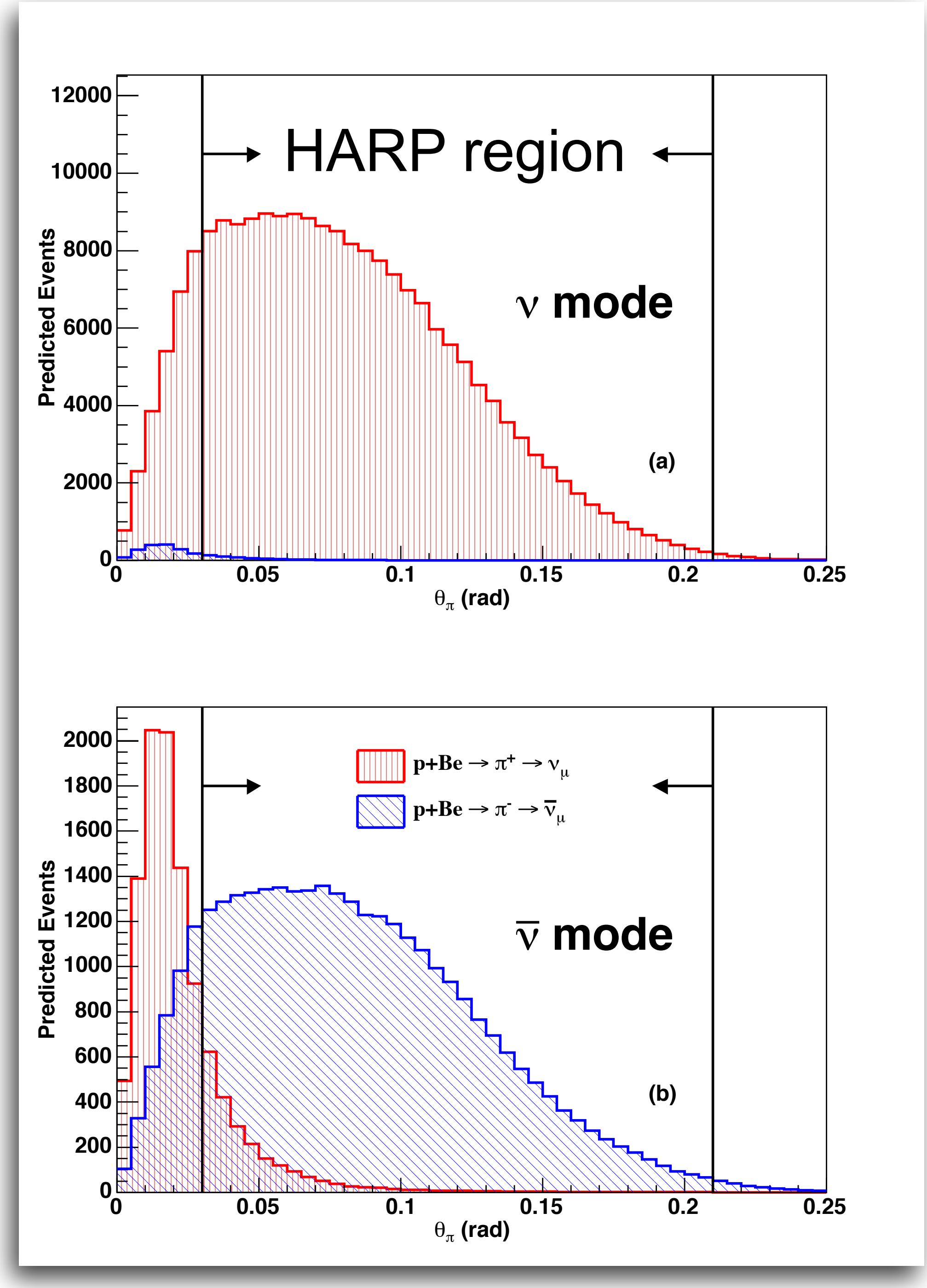
$$E_\nu^{rec} = \frac{m_p^2 - (m_n - E_B)^2 - m_\mu^2 + 2(m_n - E_B)\boxed{E_\mu}}{2(m_n - E_B - \boxed{E_\mu} + \boxed{p_\mu}\cos\boxed{\theta_\mu})}$$

Wrong Sign Backgrounds




ν̄ mode spectrum

ν mode spectrum



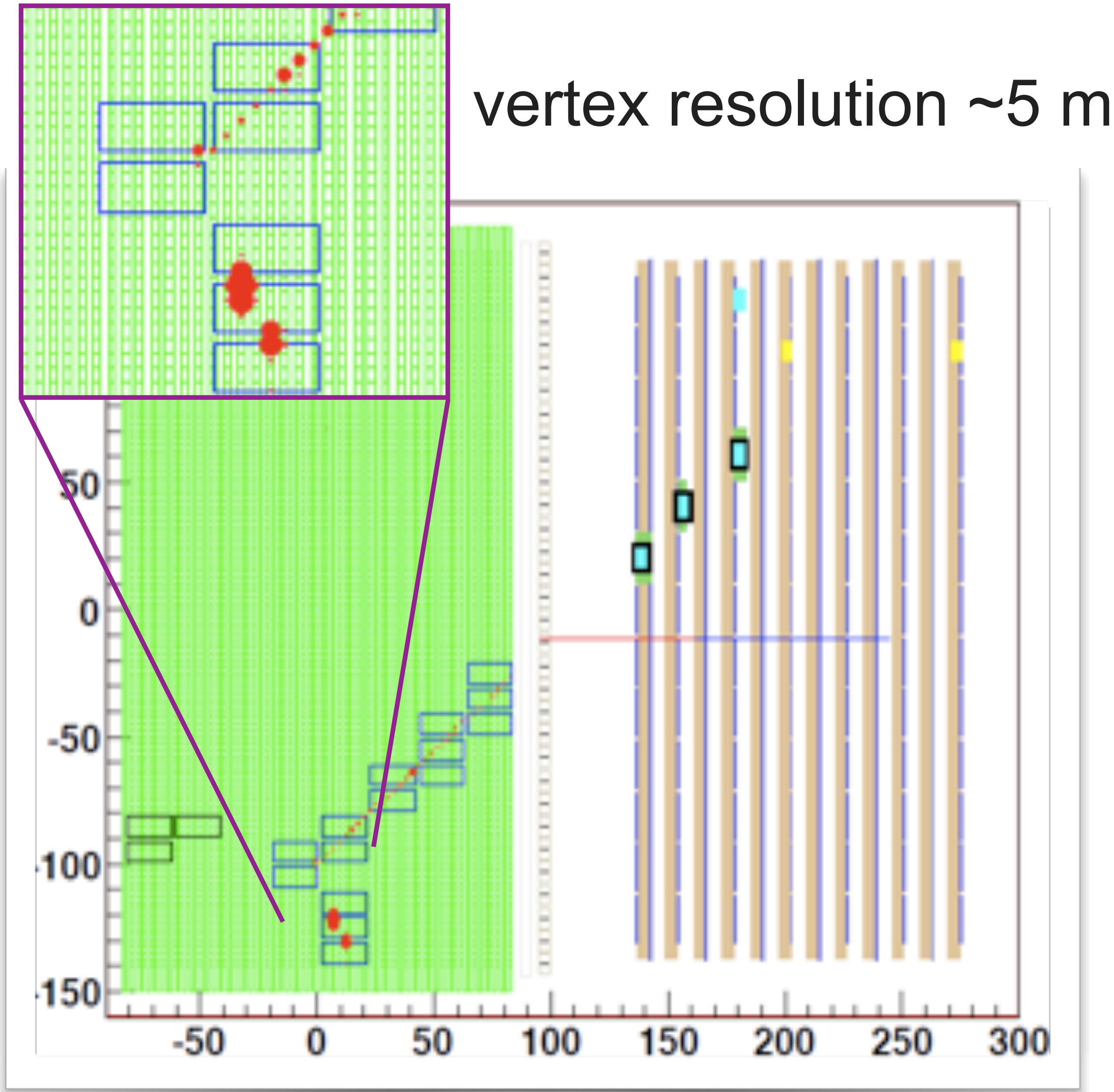
MiniBooNE Phase II Letter of Intent

Nucl.Phys.Proc.Suppl.159:79-84,2006

arXiv:1102.1964 [hep-ex]

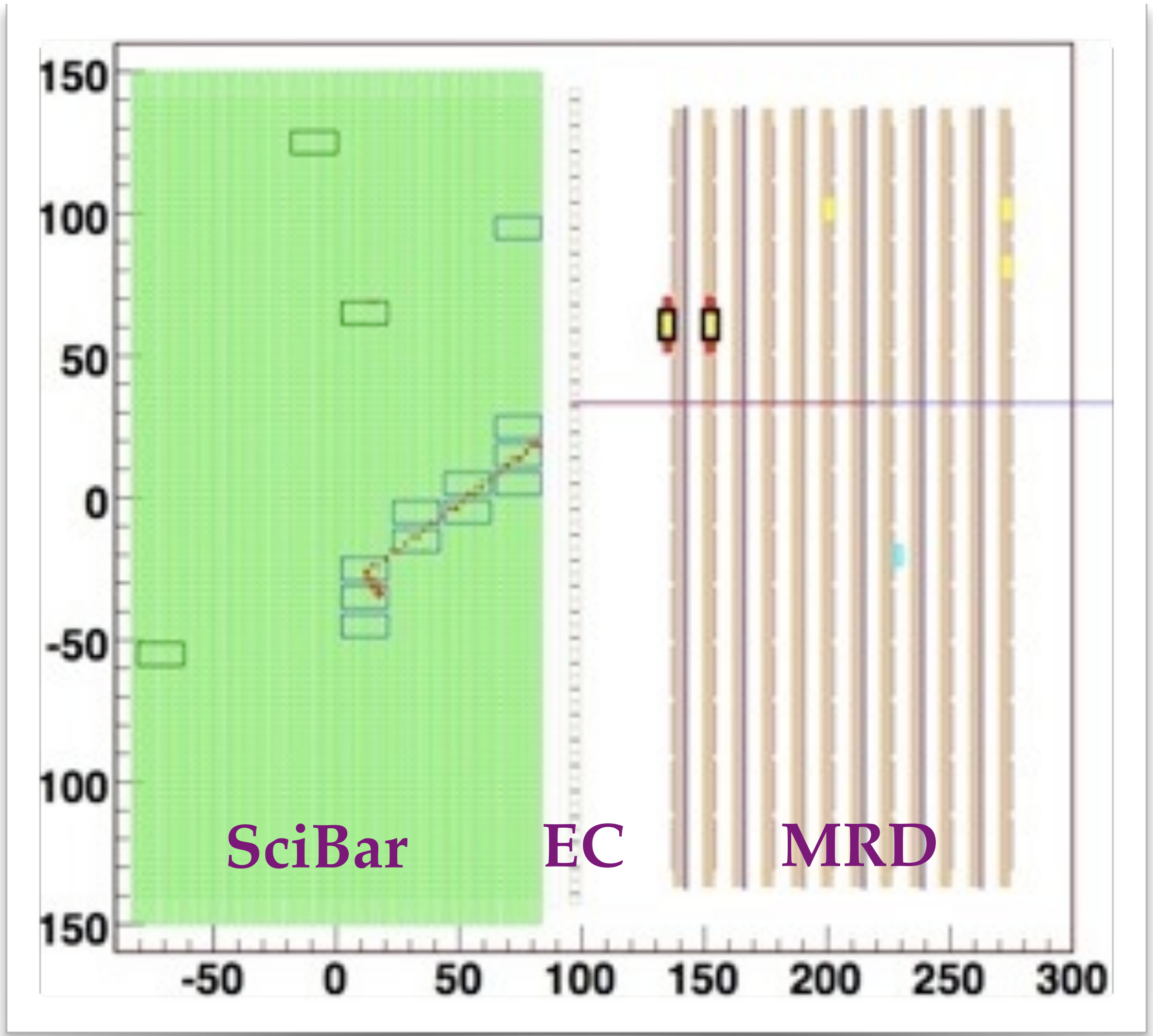
SciBooNE WS Constraint

- ● ADC hits (area ∝ charge)
- ☐ TDC hits (32ch OR)


vertex resolution ~5 mm

$\bar{\nu}_\mu$ CC-QE candidate

($\bar{\nu}_\mu + p \rightarrow \mu + n$)

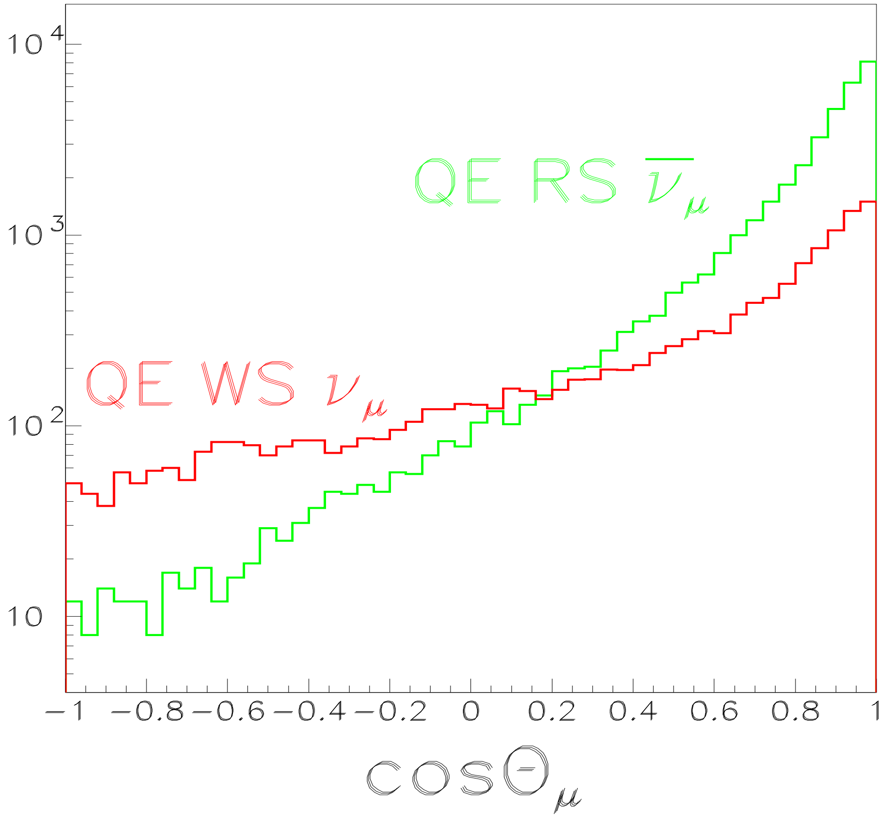


ν_μ CC-QE candidate

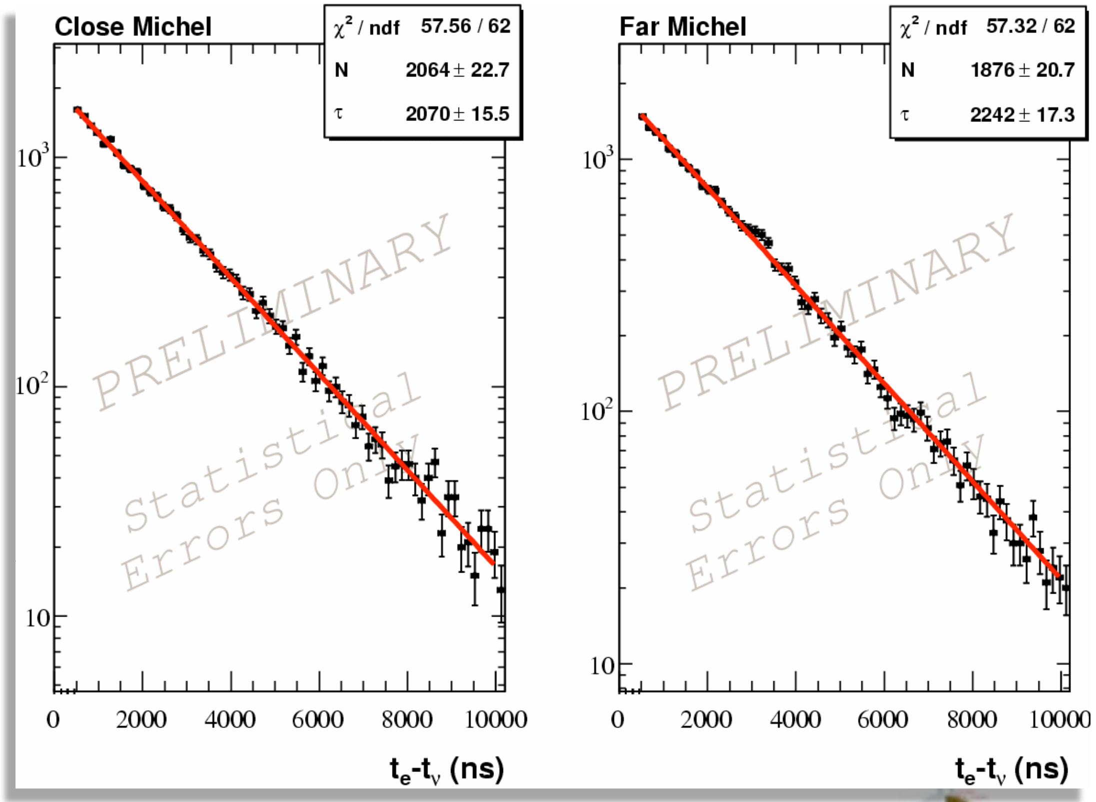
($\nu_\mu + n \rightarrow \mu + p$)

MiniBooNE WS Constraints

1. CCQE muons have different angular distributions
   - Excellent angular resolution due to cosmic muon calibration



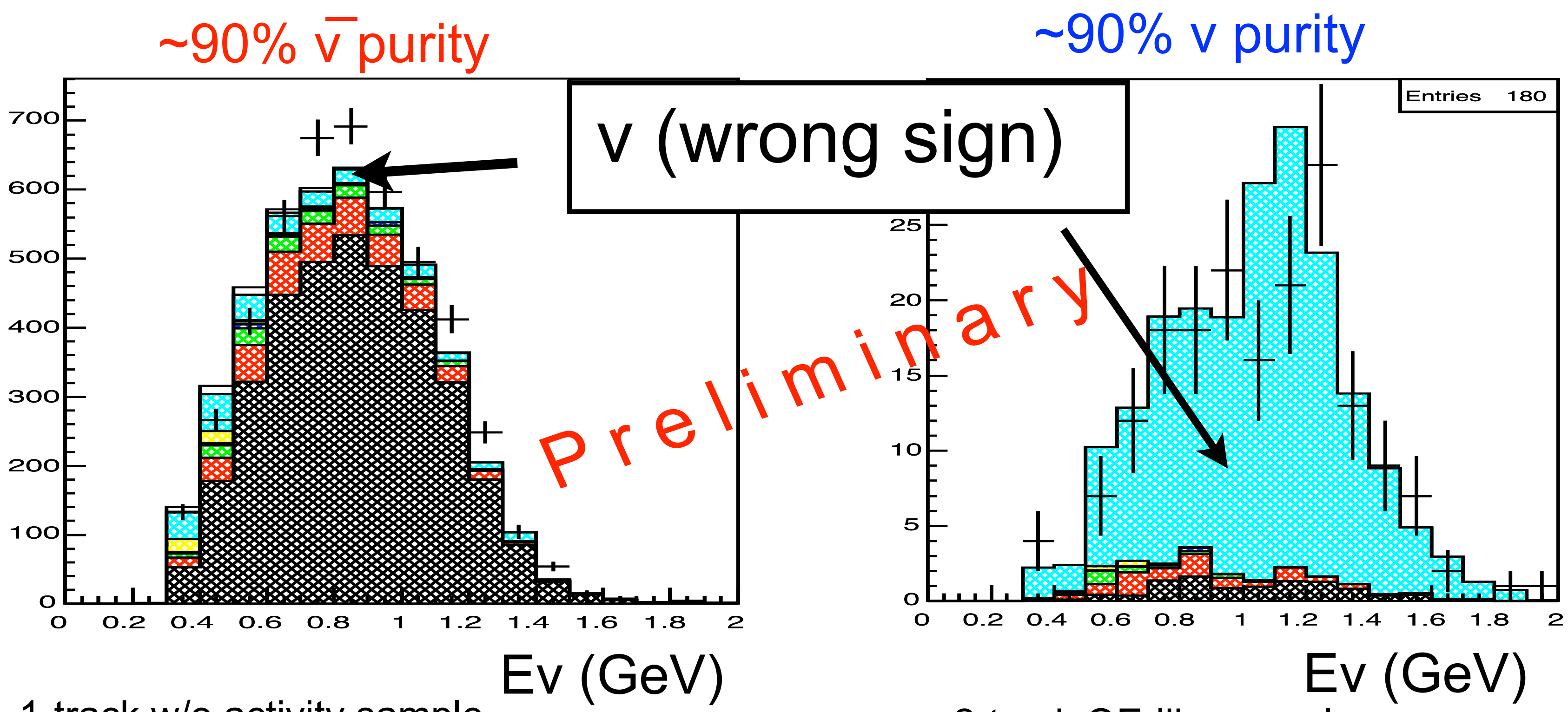
2. CCπ+ event selection:
   - Tag $\nu_\mu N \rightarrow \mu^- \pi^+ N$ events with two Michel electrons
   - π- captured by C, do not decay
     - Cannot tag $\overline{\nu}_\mu N \rightarrow \mu^+ \pi^- N$ events: only 1 Michel
   - Two Michel sample is 85% pure WS
     - Check with muon lifetimes



WS Constraints

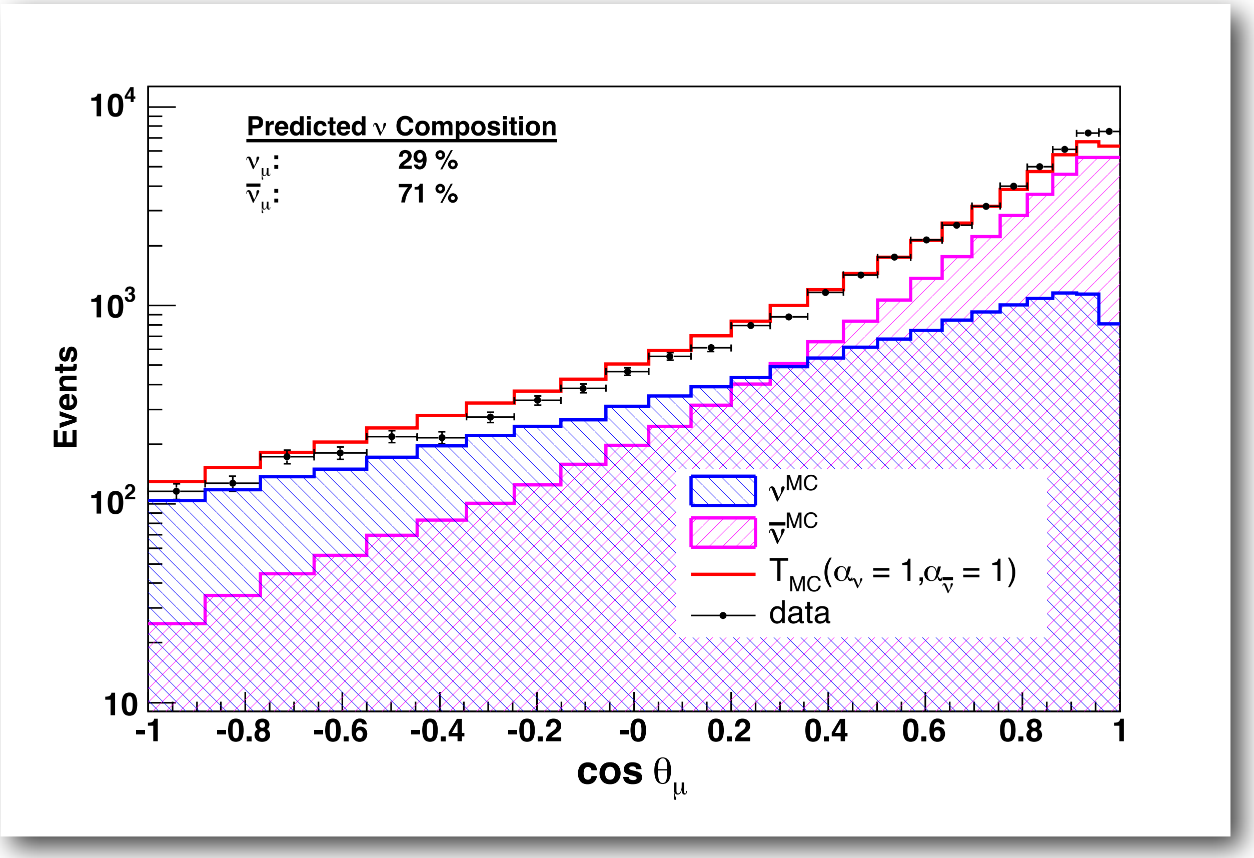
SciBooNE &
MiniBooNE
WS constraints adjust
prediction by ~20% and reduce
errors to ~15%

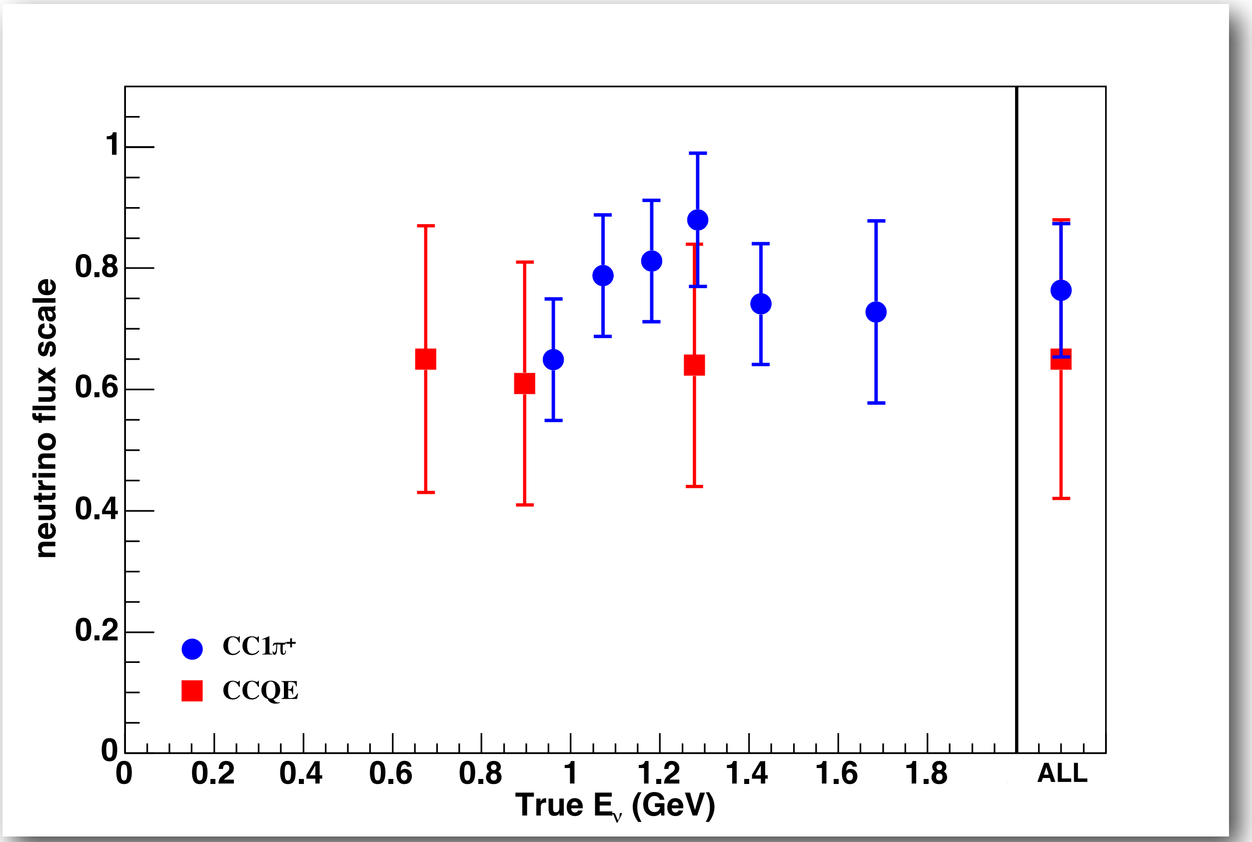
Phys.Rev.D ***84*** *072005 (2011)*



1-track w/o activity sample

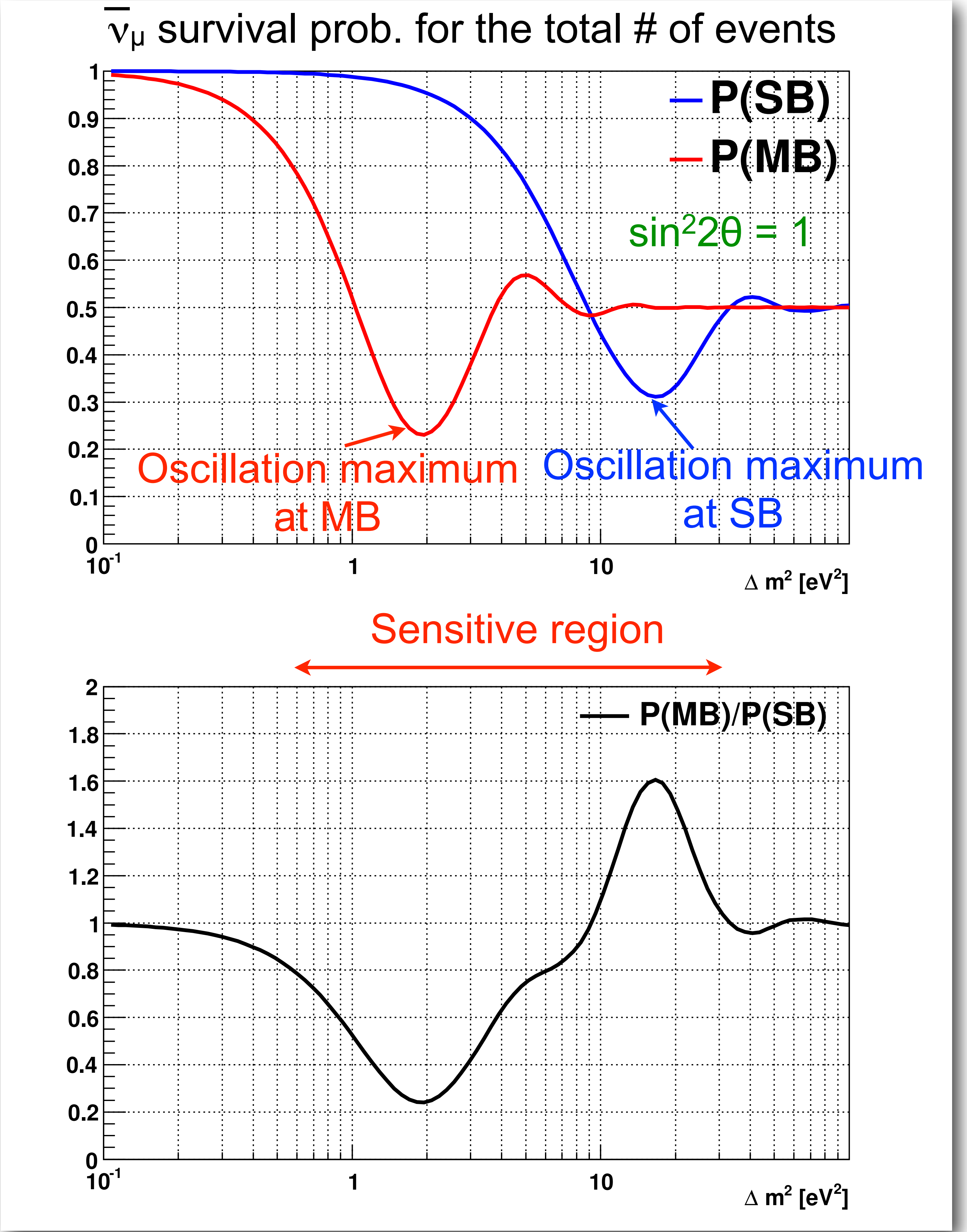
2-track QE-like sample



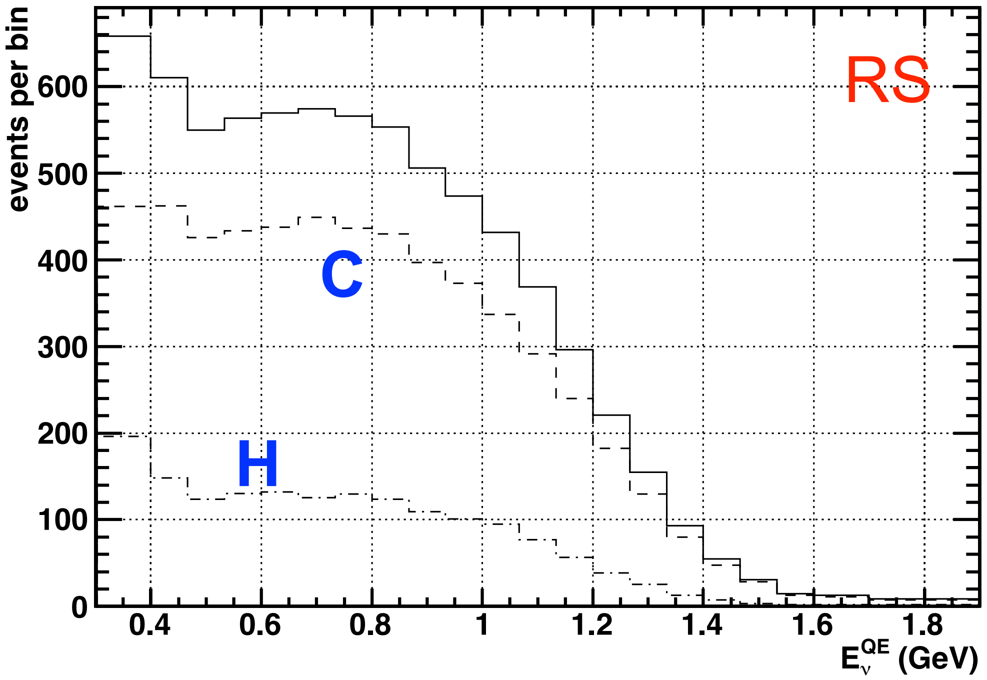


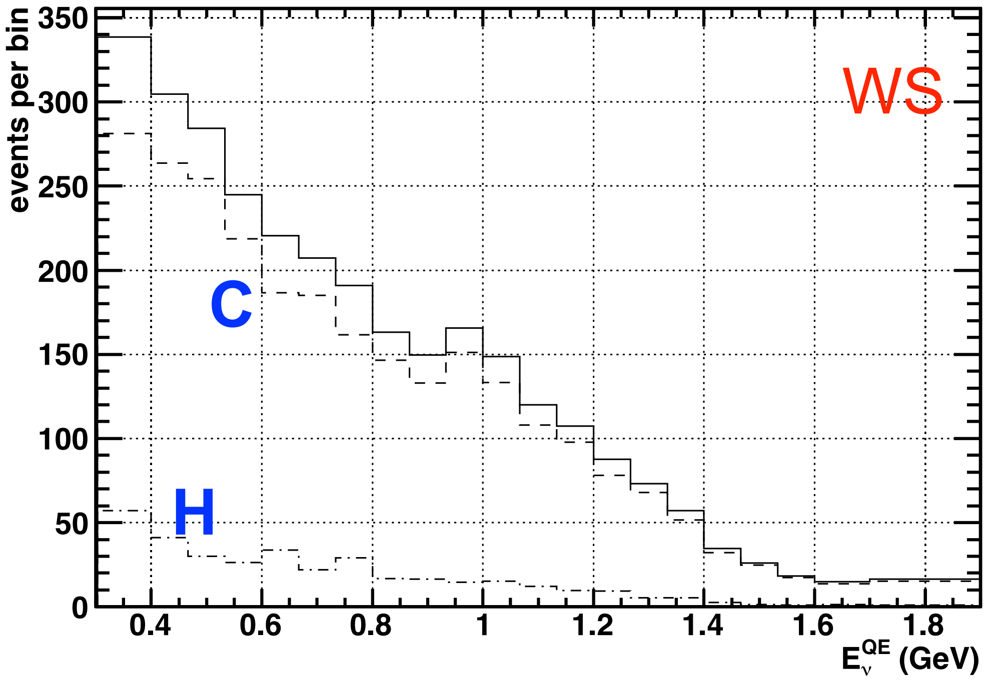
Oscillations at both detectors

- Oscillation reaches maximum at the first oscillation peak,
  - then washes out at high Δm^2 by integrating over neutrino energy.
- Since we compare the MB flux with SB, P(MB)/P(SB) is the expected signal.
- Ratio can go up or down depending on Δm^2.



SciBooNE event predictions

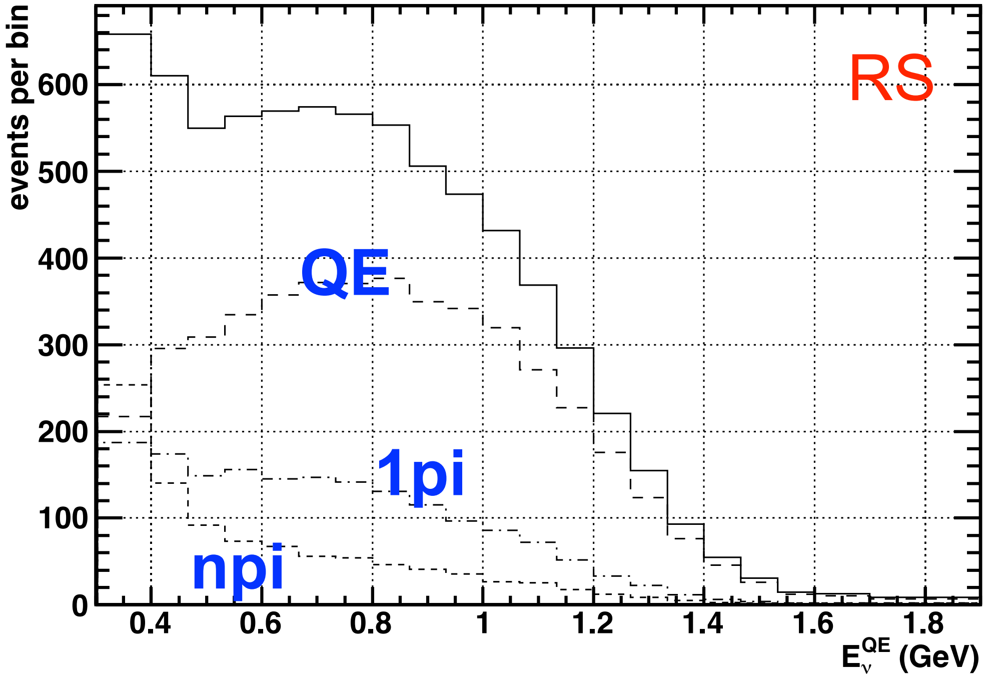


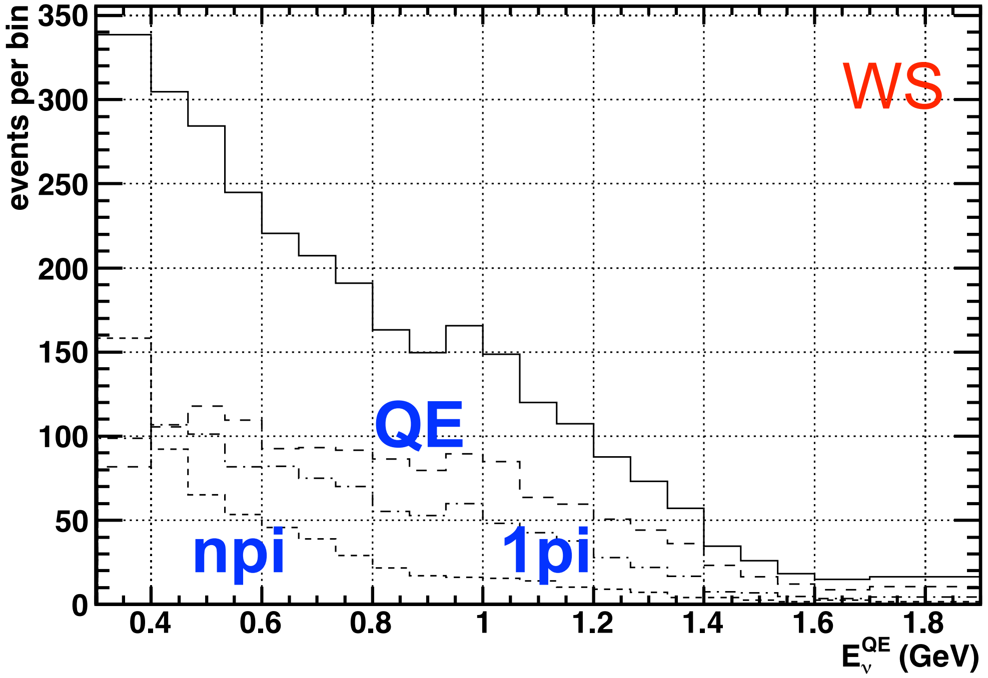


$$E_\nu^{rec} = \frac{m_p^2 - (m_n - E_B)^2 - m_\mu^2 + 2(m_n - E_B)E_\mu}{2(m_n - E_B - E_\mu + p_\mu \cos\theta_\mu)}$$

- Fit in bins of reconstructed neutrino energy
- Need to understand contributions from
  - Targets, C and H
  - Process, QE, 1pi, npi

SciBooNE event predictions

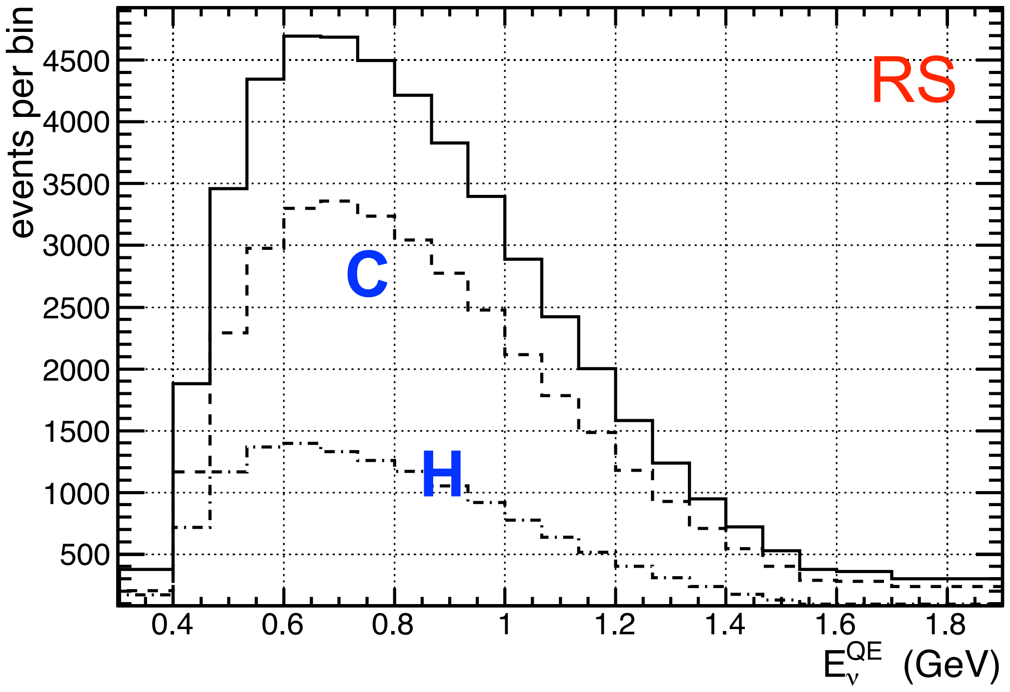


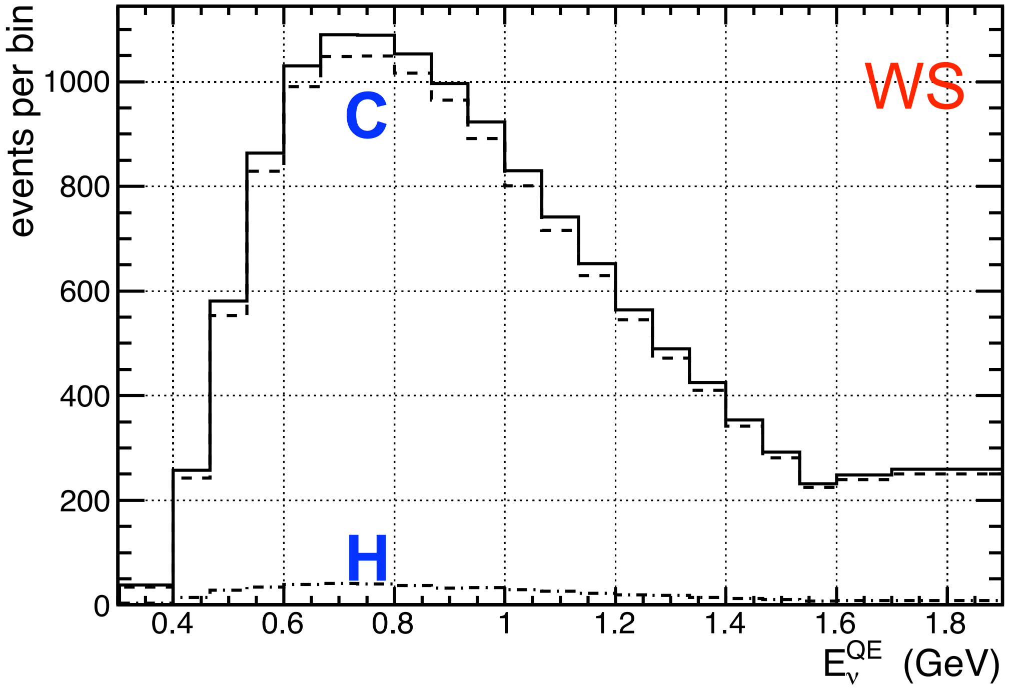


$$E_\nu^{rec} = \frac{m_p^2 - (m_n - E_B)^2 - m_\mu^2 + 2(m_n - E_B)E_\mu}{2(m_n - E_B - E_\mu + p_\mu \cos\theta_\mu)}$$

- Fit in bins of reconstructed neutrino energy
- Need to understand contributions from
  - Targets, C and H
  - Process, QE, 1pi, npi

MiniBooNE event predictions





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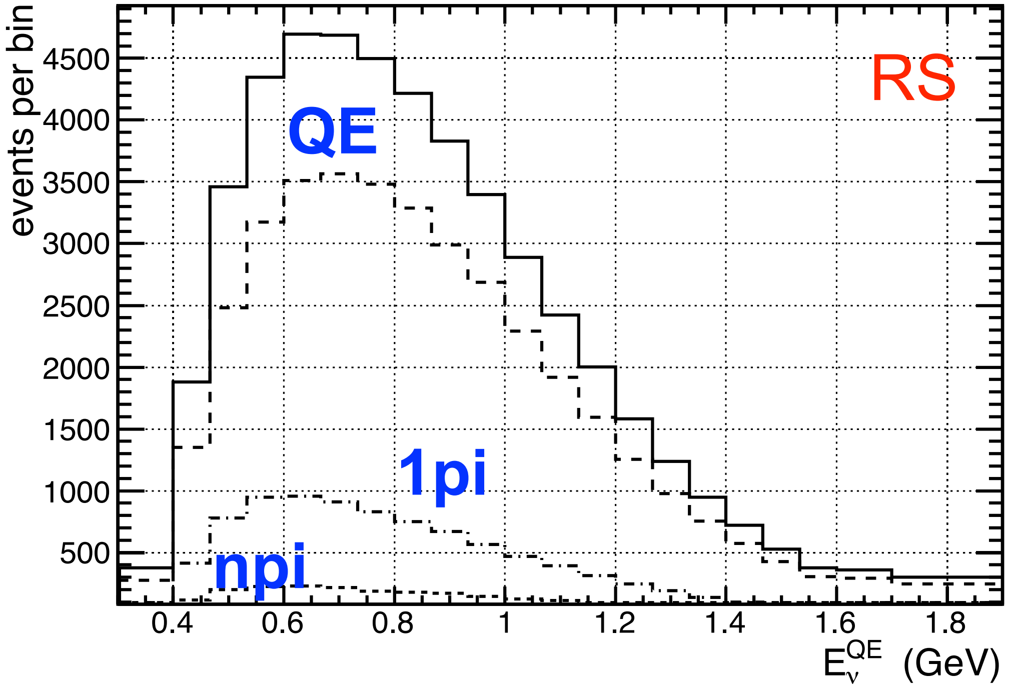
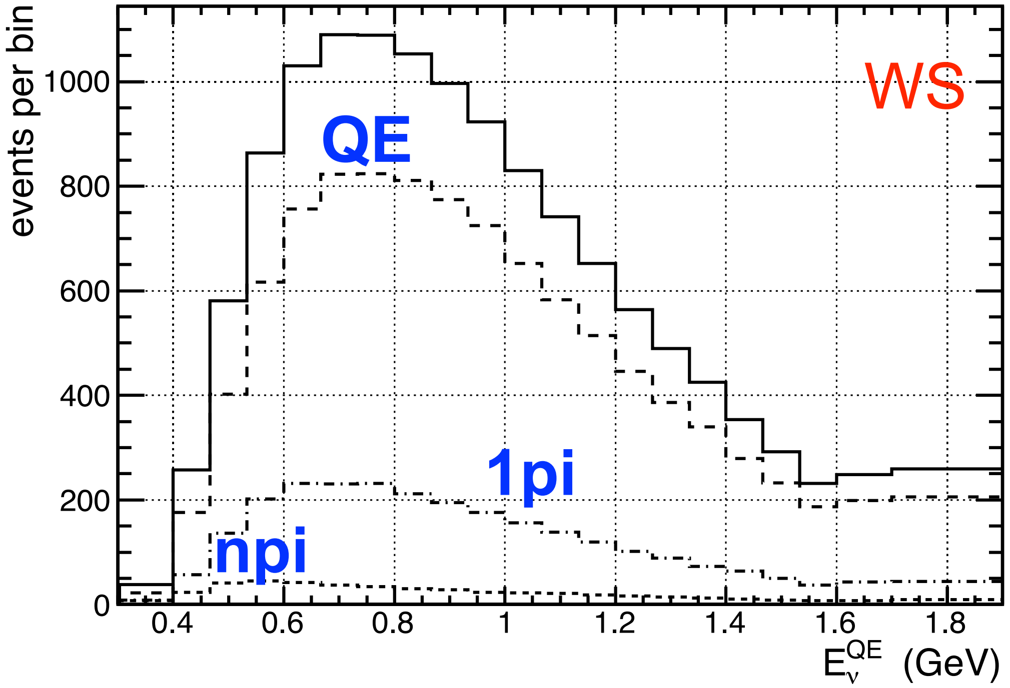
- Fit in bins of reconstructed neutrino energy
- Need to understand contributions from
  - Targets, C and H
  - Process, QE, 1pi, npi

MiniBooNE event predictions





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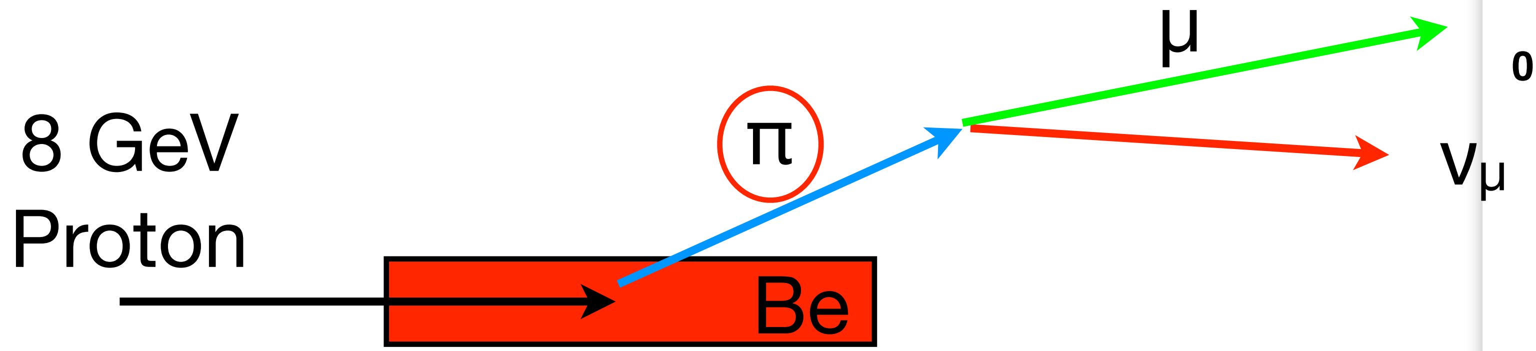
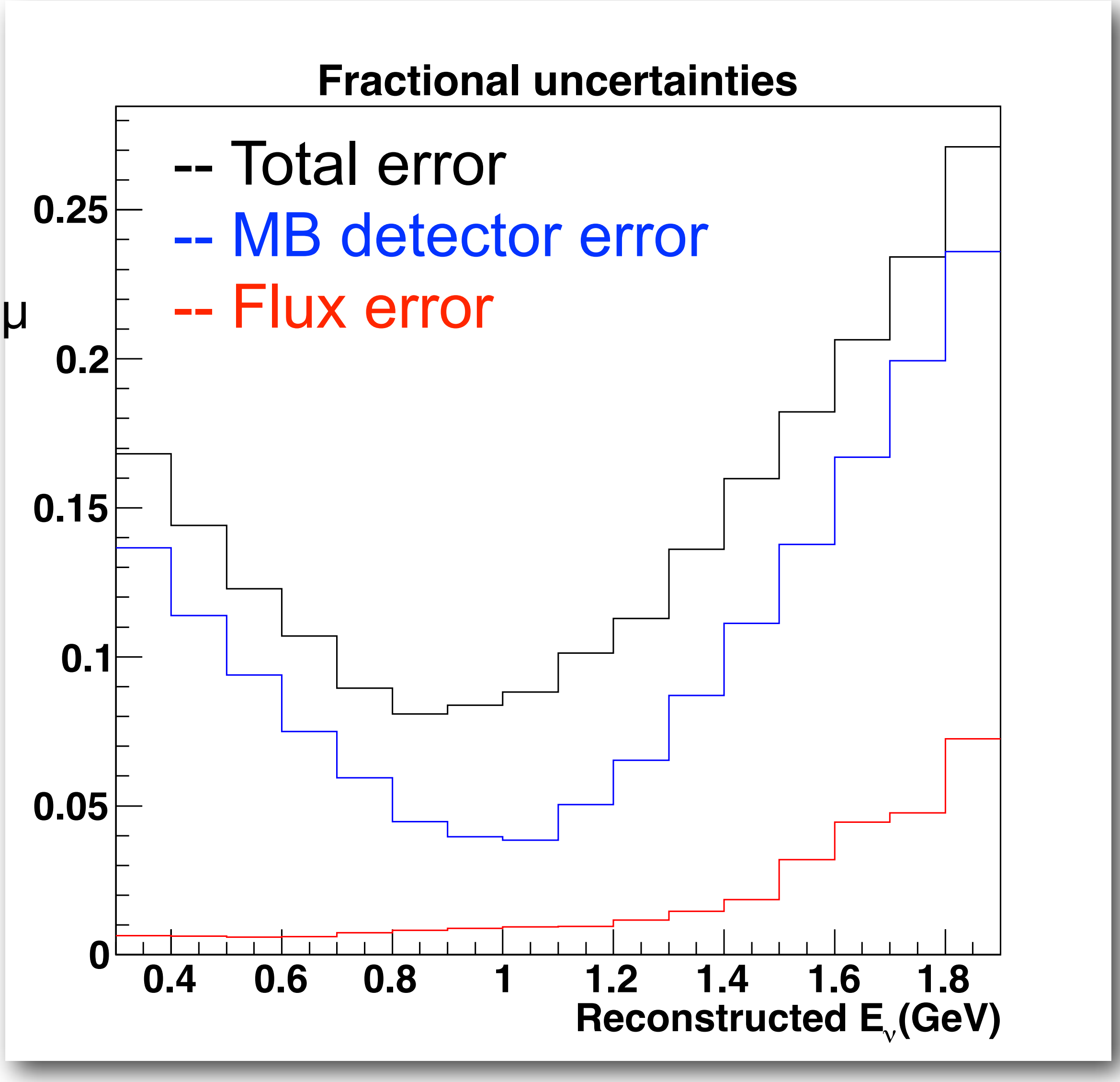
- Fit in bins of reconstructed neutrino energy
- Need to understand contributions from
  - Targets, C and H
  - Process, QE, 1pi, npi

Systematic uncertainties(1)

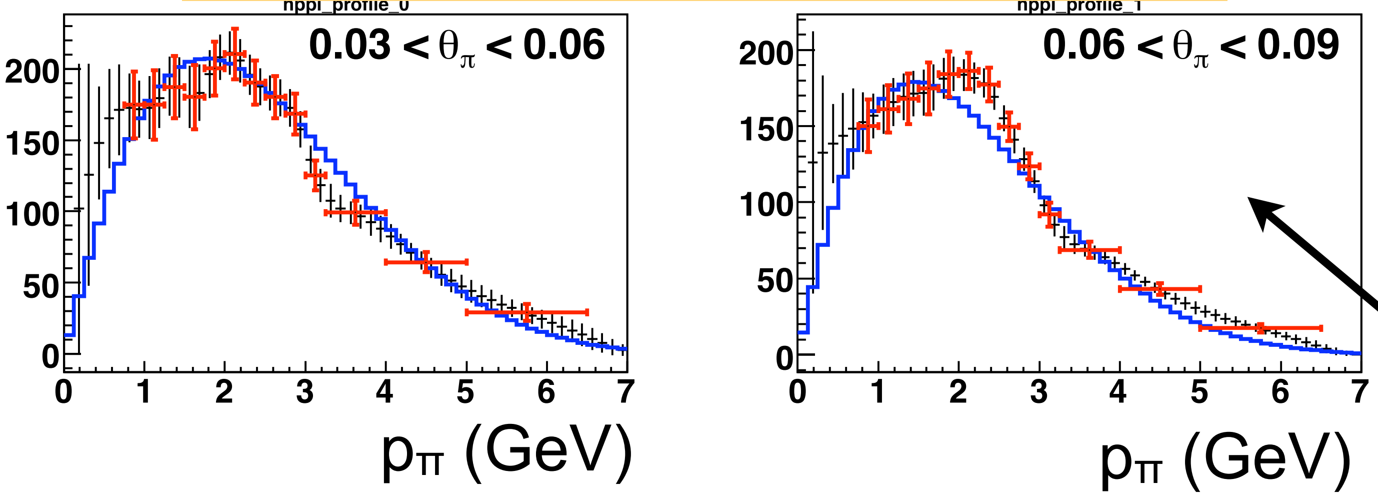
Flux uncertainties





- Use HARP p-Be interaction measurement uncertainty for the error analysis.
- Becomes negligible after taking ratio between SciBooNE and MiniBooNE

π^+ production cross section

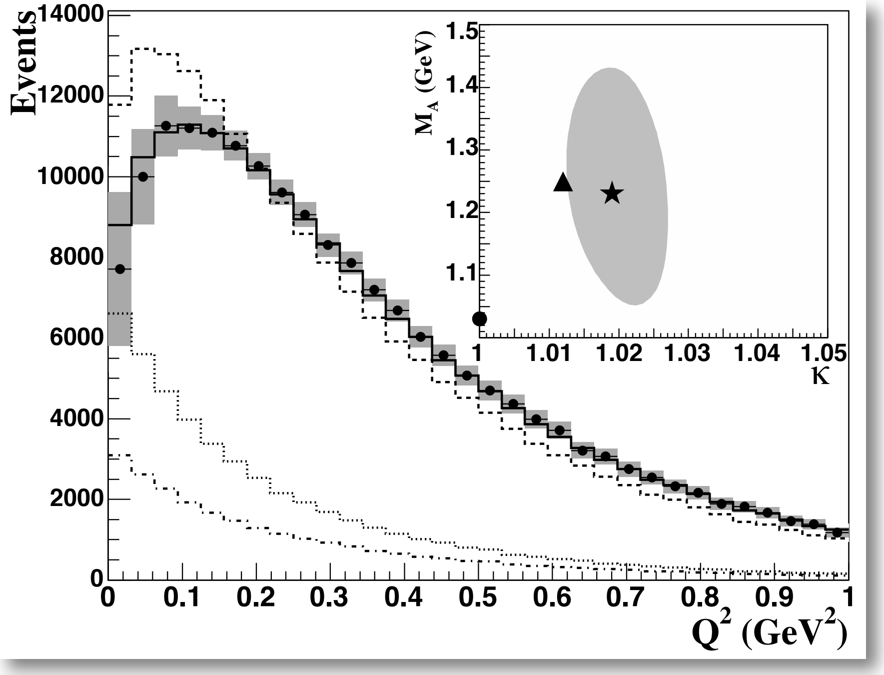


-- Cross section used for MC production
-- HARP data
-- Spline interpolation of HARP data

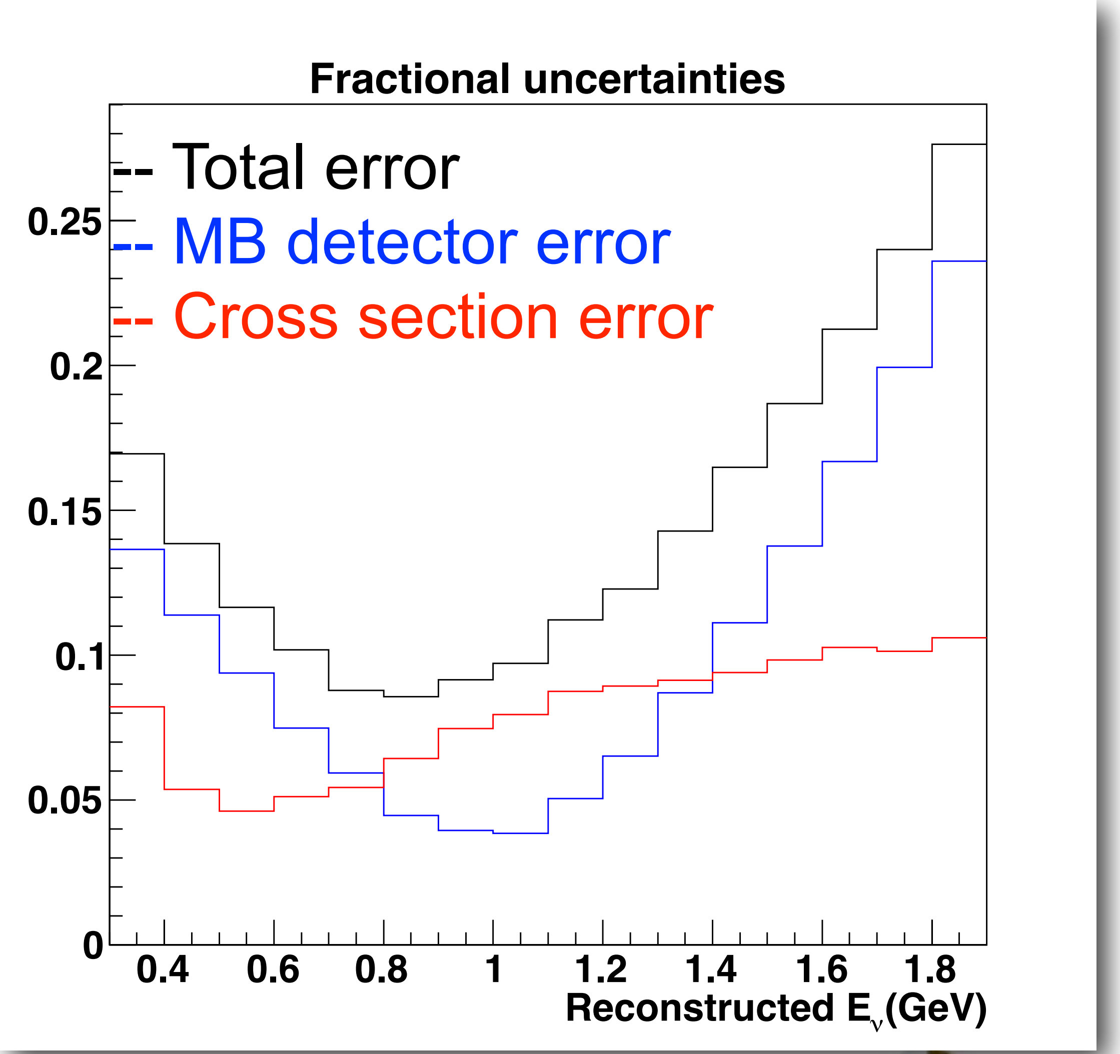
Systematic uncertainties (2)

Cross section uncertainties

MiniBooNE CCQE sample
Q^2 distribution



- Variations of Q^2 (muon angle) distribution can change relative acceptance.
  - SciBooNE: (mostly) forward muons
  - MiniBooNE: isotropic acceptance.
- The major source of the systematic error, together with the MB detector response error.

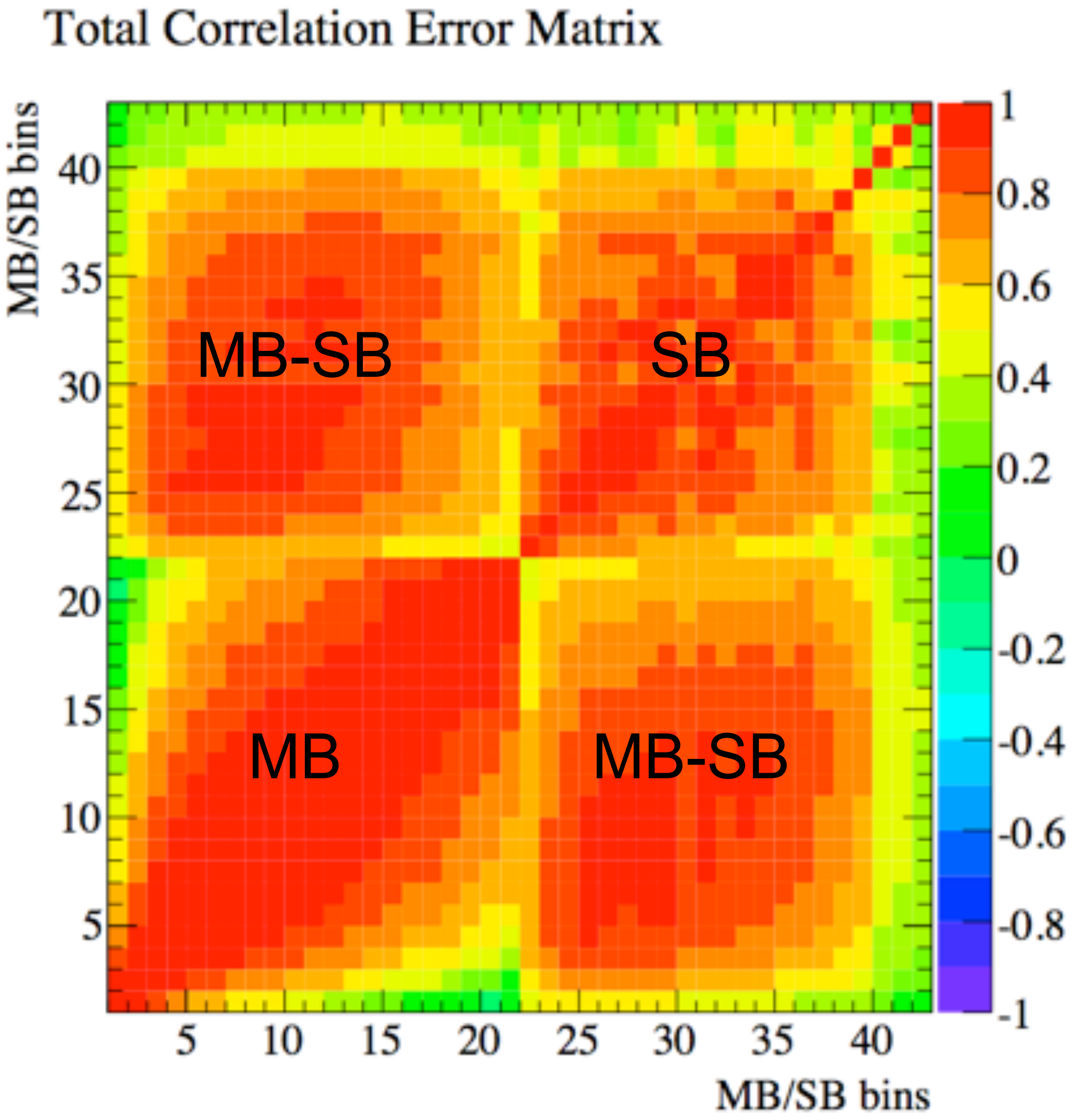


Oscillation fit

- The χ^2 ranges over bins in reconstructed energy for both SciBooNE and MiniBooNE.
- Use $\Delta\chi^2$ test statistic and Feldman-Cousins method for analysis
- Construct one large error matrix for both detectors simultaneous
  - Strong correlations between detectors constrain errors powerfully

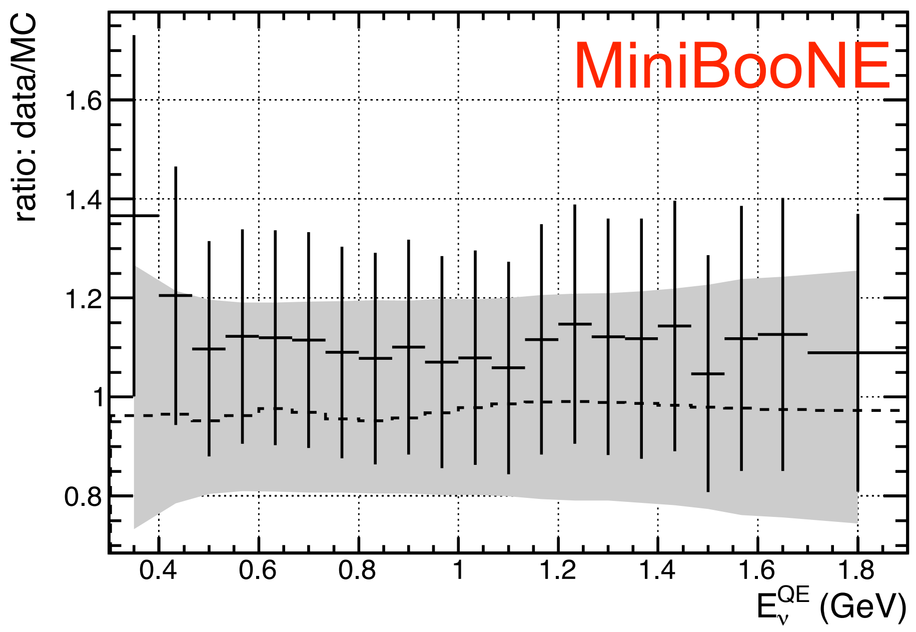
$$\chi^2 = \sum_{i,j=1}^{42} (D_i - N_i) \left(M^{-1}\right)_{ij} (D_j - N_j),$$

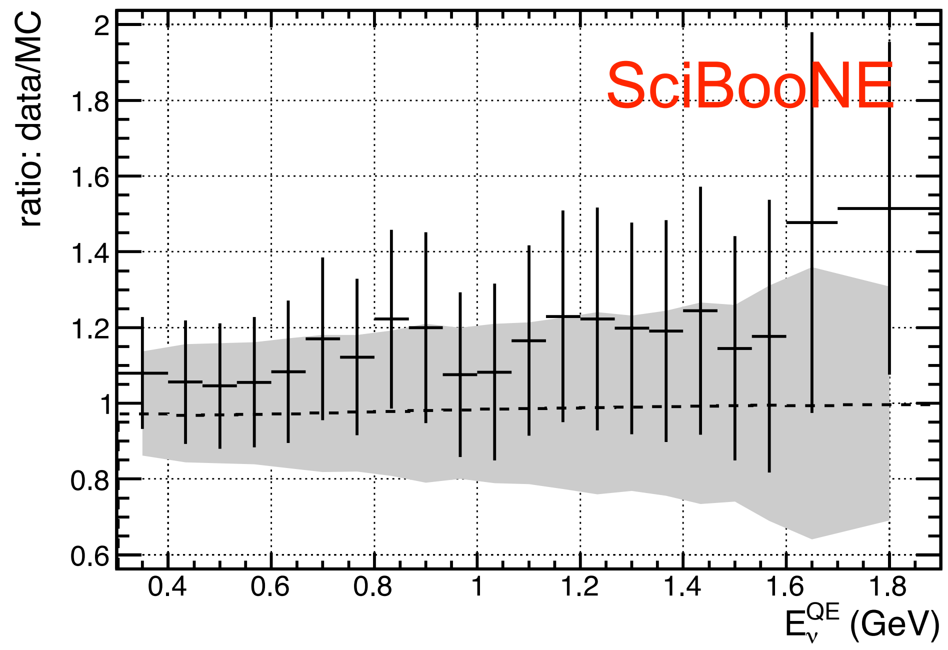
$$\Delta\chi^2 = \chi^2 \left(X(\theta_{\text{phys}}), M(\theta_{\text{phys}})\right) - \chi^2 \left(X(\theta_{\text{BF}}), M(\theta_{\text{BF}})\right)$$



Results

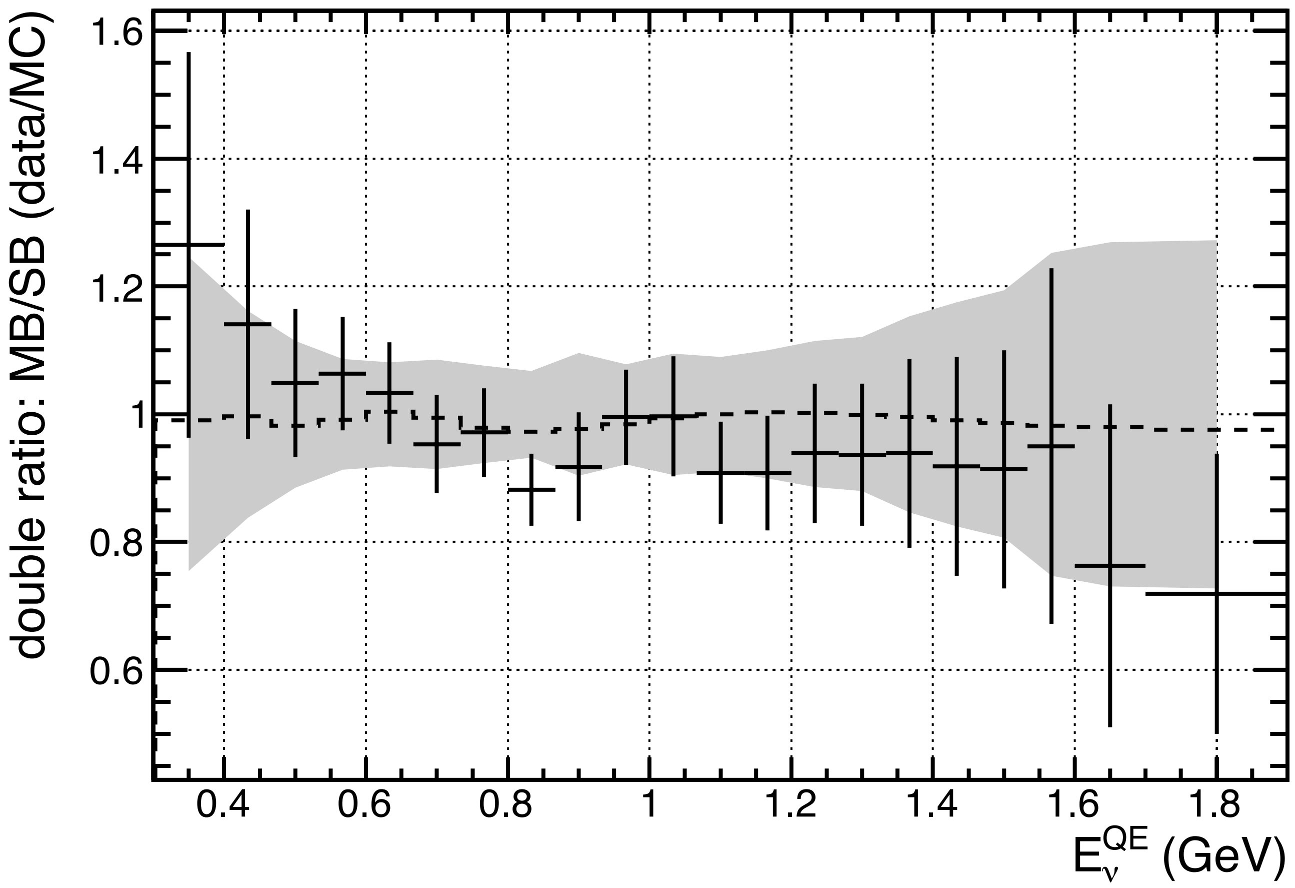
Uncertainty reduction





Data/MC ratios with errors show reduction of systematic uncertainties

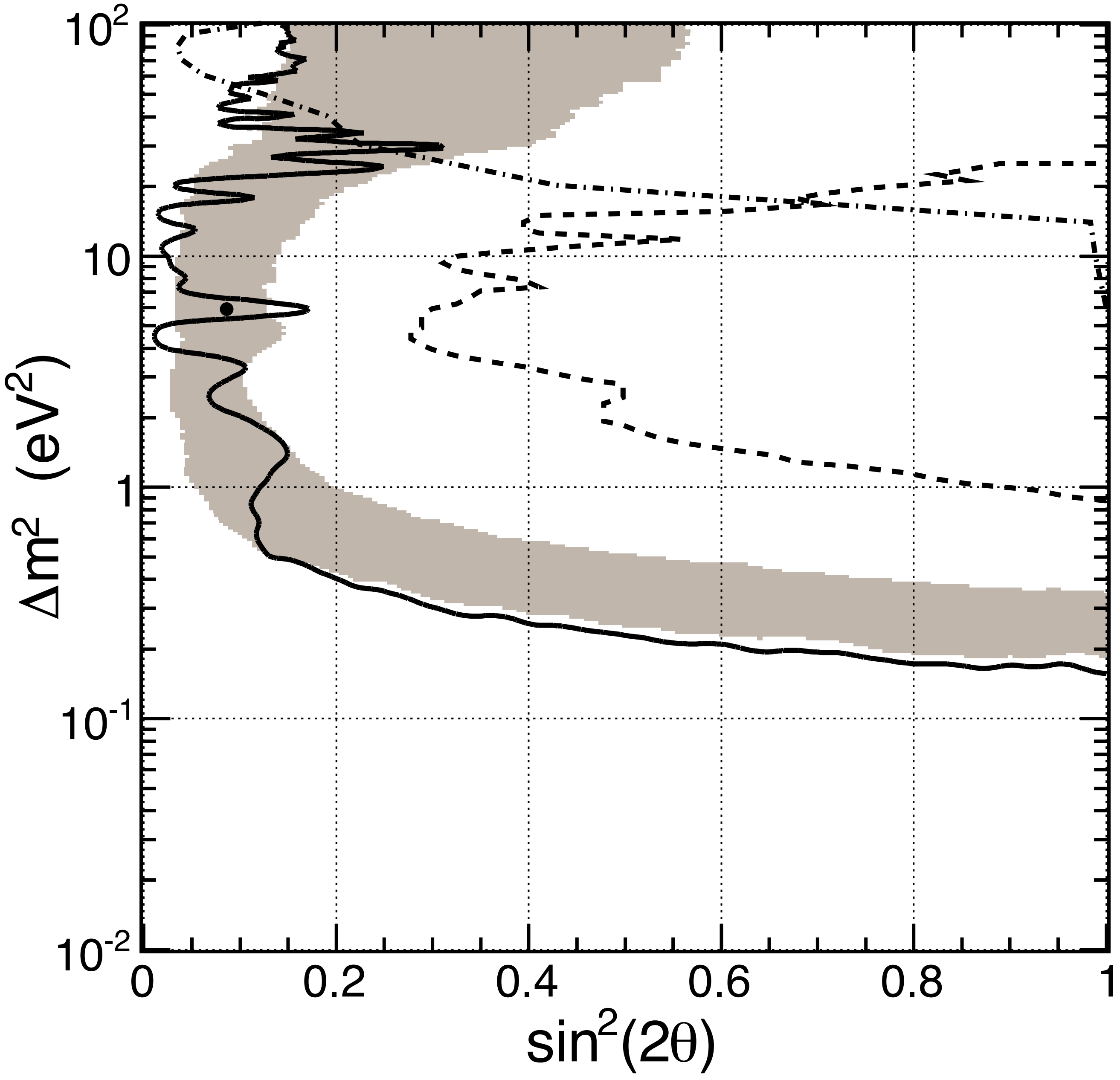
Both SciBooNE and MiniBooNE show slight data excesses



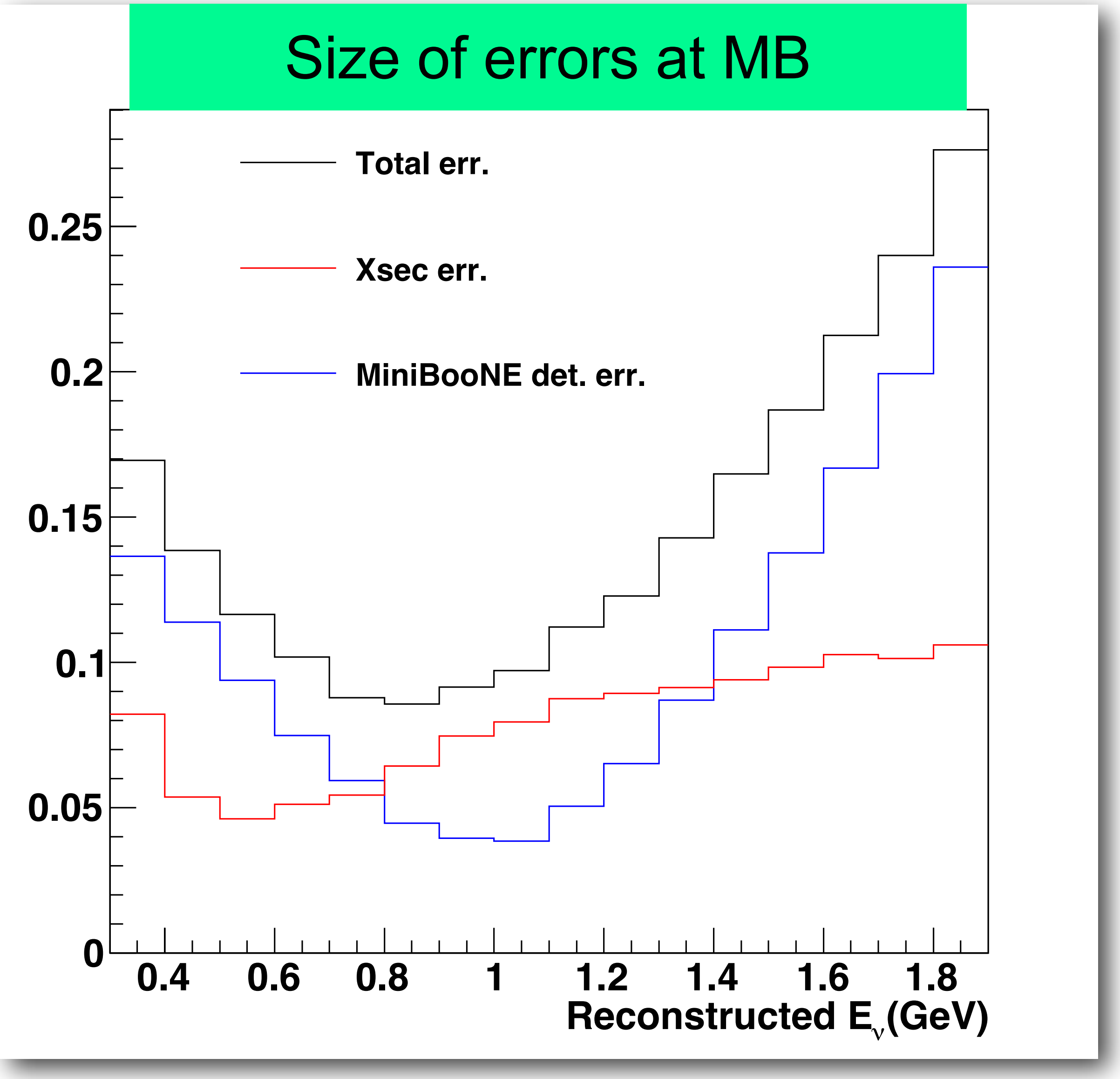
90% CL limit

- No disappearance signal observed
  - Data consistent with null oscillation hypothesis.
  - The observed limit shows slight deviations from the ±1σ band.
- World's strongest limit at $0.2 < \Delta m^2 < 60$ eV^2

Phys. Rev. D ***86****, 052009 (2012).*



Discussion



- Possible Improvements:
  - Dominant uncertainties: neutrino x-section and MiniBooNE detector response.
  - To reduce detector error, need identical detectors or $10^{\sim 2}$MeV e^- calibration.
  - Further analysis of SciBooNE (and MiniBooNE) data could reduce the cross section errors *if we had newer/better cross section models*.

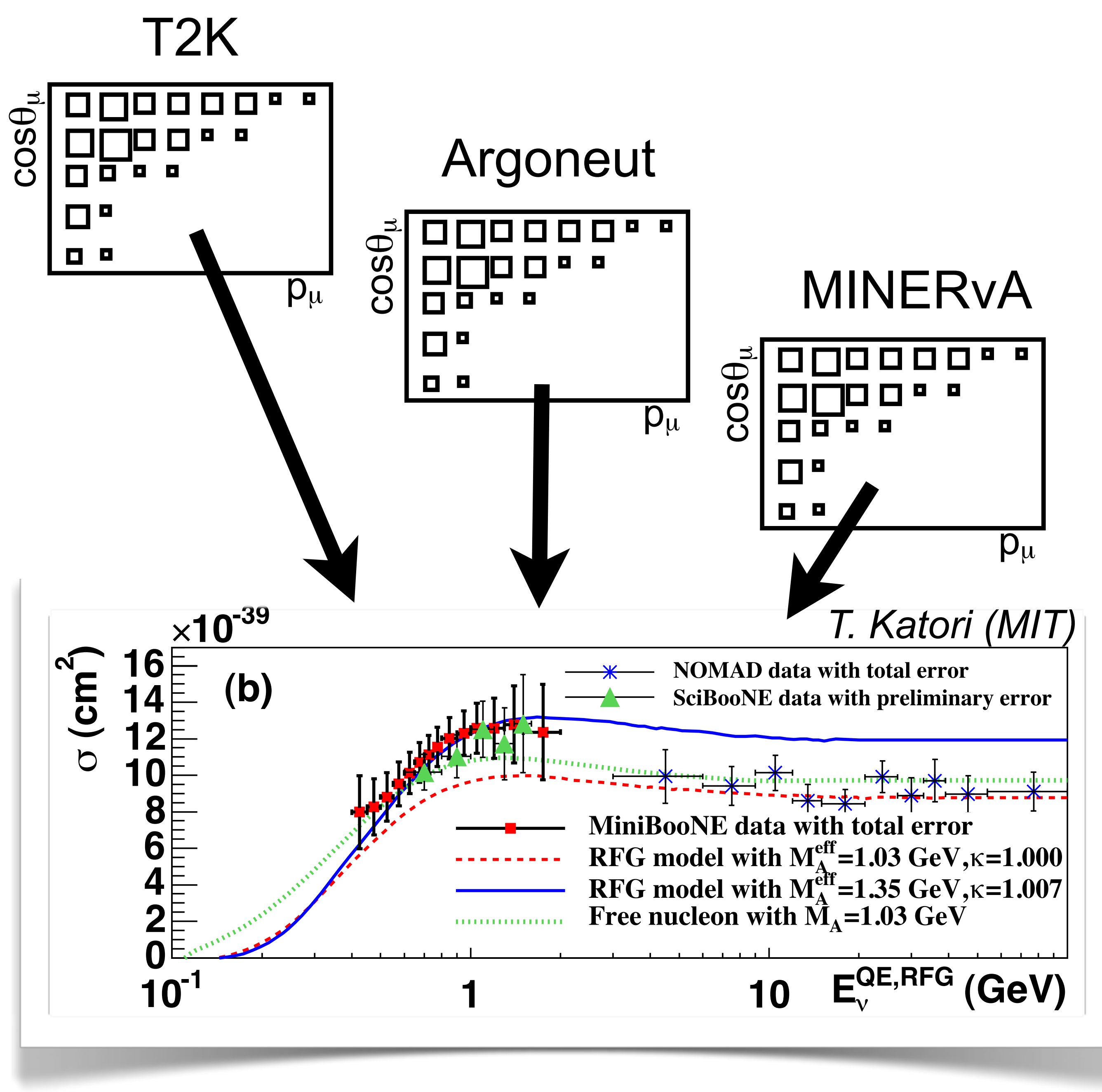
Growing Consensus

- We need broad coverage of neutrino interactions

  ➡Model independent measurements at many energies, nuclei

- Move away from process cross-sections
  - σ(QE), σ(res π), σ(coh π)
- Instead measure final state particle cross-sections
  - σ(CC), $\sigma(\mu)$, $\sigma(\mu+p)$, $\sigma(\mu+\pi)$

➡*Since θ_{13} is large, we need to understand these systematics in order to measure CP violation!*

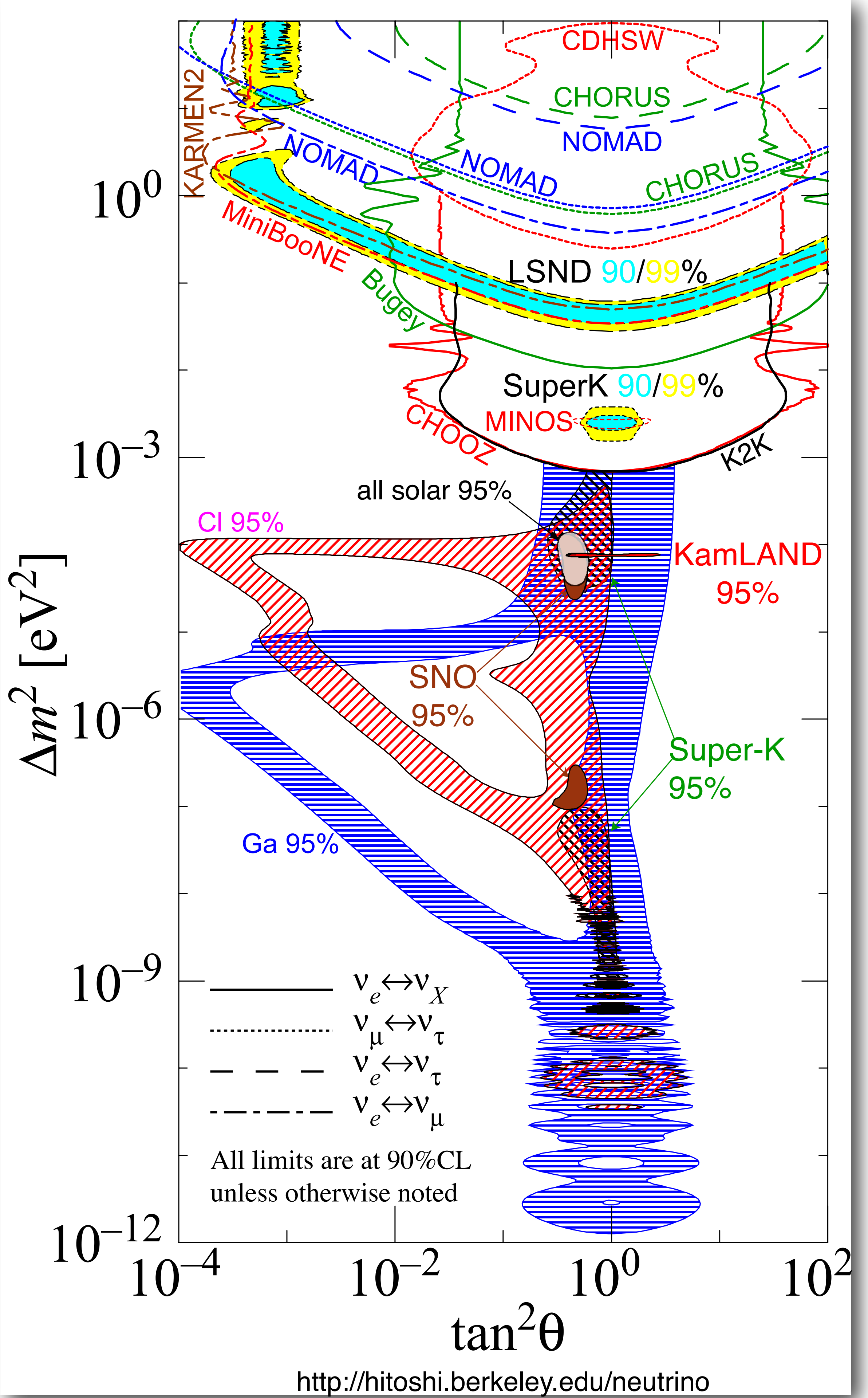


Conclusions

- We have performed a joint search for muon antineutrino disappearance at $\Delta m^2 \sim 1\text{eV}^2$ with SciBooNE and MiniBooNE.
- No evidence for numubar disappearance.
  - Set world's best 90%CL limit at $0.2 < \Delta m^2 < 60\ \text{eV}^2$.
- Pushed limits into interesting regions for global fits.
  - (Still waiting for new global fits...)
- *Phys. Rev. D* ***86****, 052009 (2012).*

Thanks!

Oscillation Observations



http://hitoshi.berkeley.edu/neutrino

- Atmospheric region: $\Delta m^2 \sim 10^{-3}$ eV^2
  - Super-K, K2K, MINOS, etc
- Solar region: $\Delta m^2 \sim 10^{-5}$ eV^2
  - SNO, Super-K, KamLAND, etc

Only 2 Δm^2 regions are allowed in the current SM with 3 neutrino generations

However, there is one more region claimed by the LSND experiment at $\Delta m^2 \sim 1$ eV^2

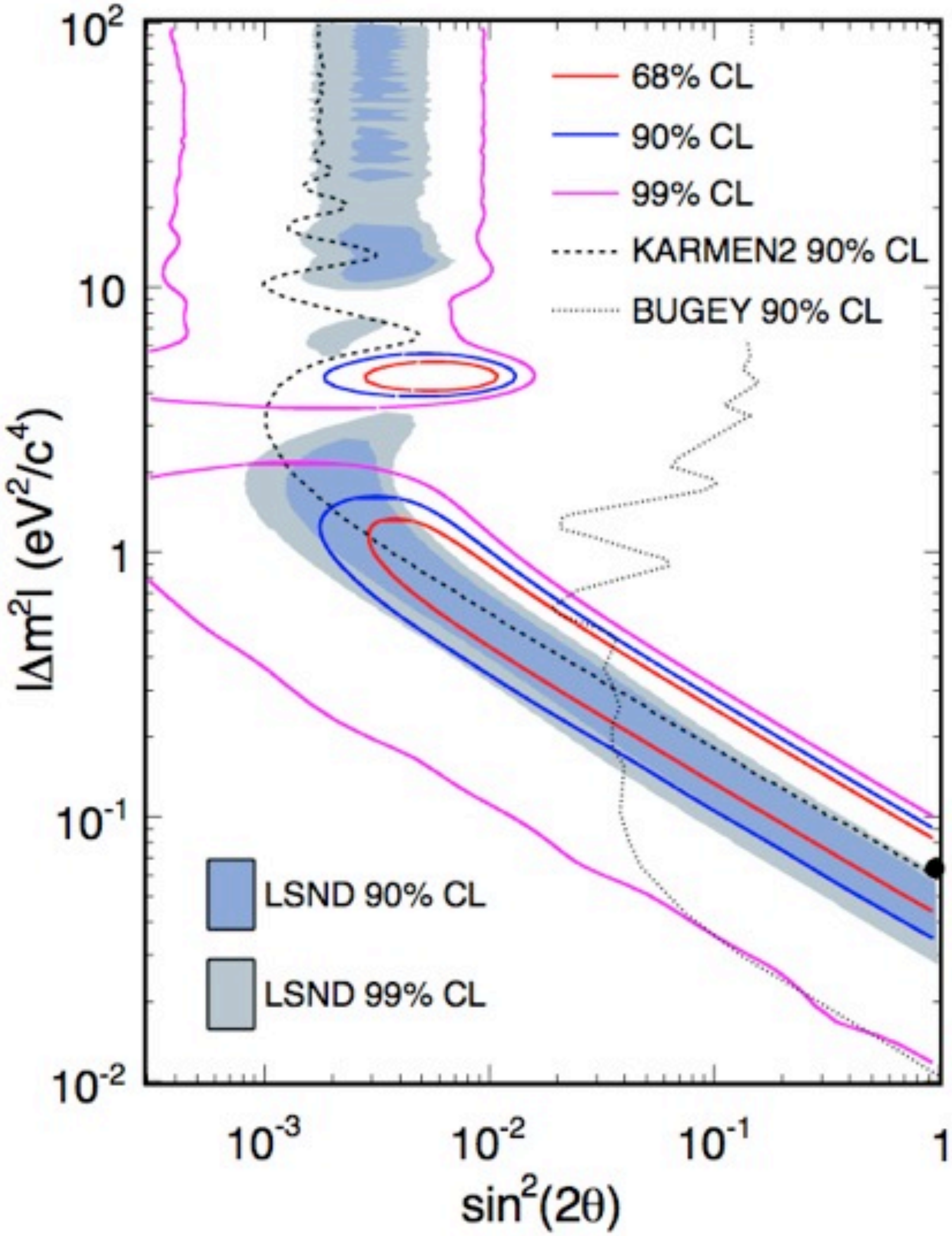
What does MiniBooNE claim?

1. **No ν_e excess in ν_μ beam above 475 MeV.**
   - ➡ Maximal oscillation sensitivity if LSND is L/E and CPT invariant.
2. **3σ excess (128 ± 43) of ν_e candidates in ν_μ beam below 475 MeV.**
   - ➡ Does not fit well to a 2ν mixing hypothesis
3. **Small excess (18±14) below 475 MeV in $\bar{\nu}_\mu$ beam.**
   - ➡ Rules out some ν_μ beam low-E excess explanations.
4. **Small excess (20.9 ± 14) in $\bar{\nu}_\mu$ beam above 475 MeV.**
   - ➡ Null hypothesis in 475-1250 MeV region has p-value 0.005
   - ➡ 2ν fit prefers LSND-like signal at 99.4% CL.

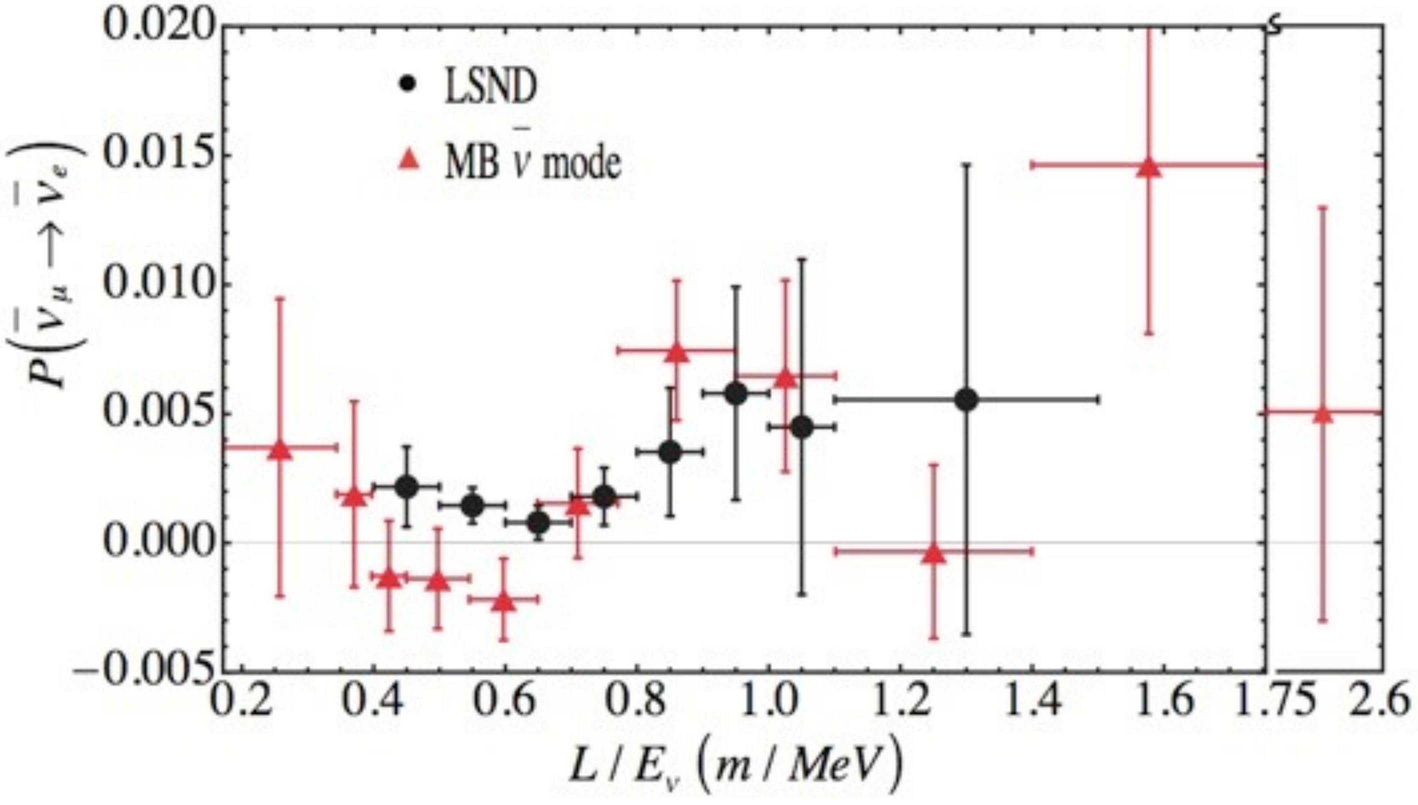
Comparing MB to LSND

Fit to 2ν mixing model

Phys.Rev.Lett.105:181801,2010

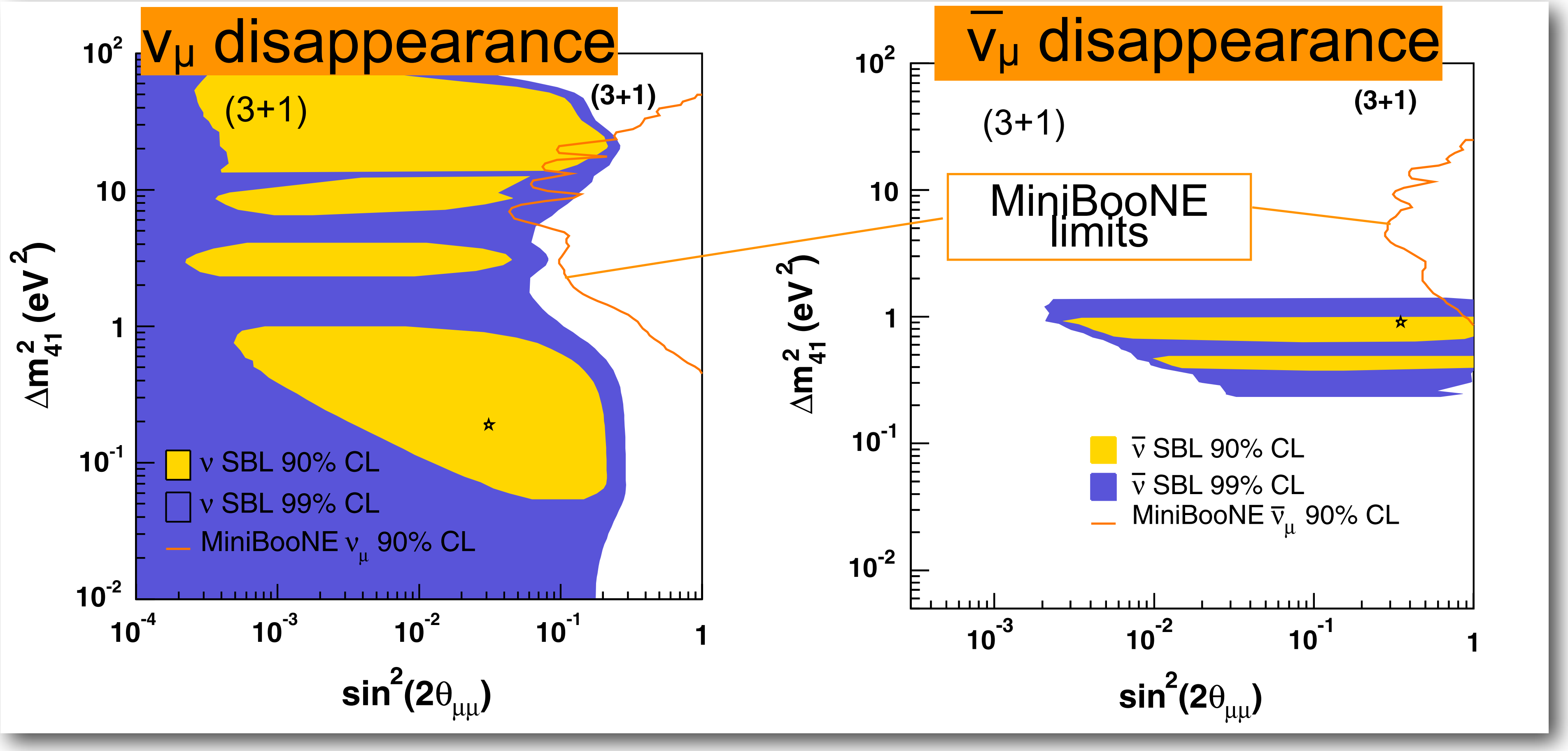


Model-independent plot of inferred oscillation probability



ν_μ Disappearance (cont'd)

- Large allowed region from global fit to world data with (3+1) model, if ν_μ and $\bar{\nu}_\mu$ fit independently.

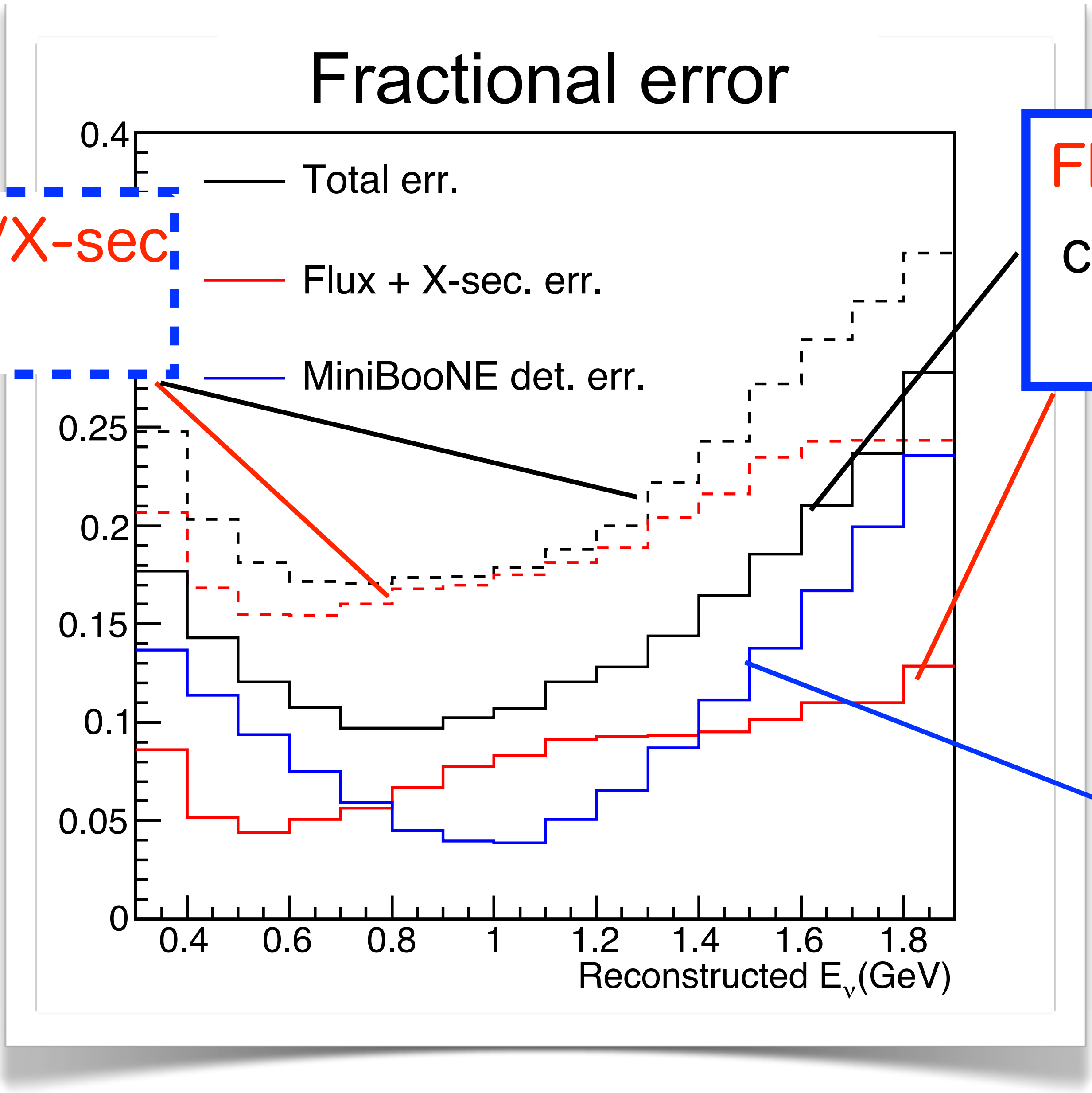


Allowed regions from (3+1) global fits

G. Karagiorgi, et al. Phys. Rev. D **80**, 073001 (2009)

- Try to improve MiniBooNE results **with a near detector (SciBooNE).**
  - **Flux+shape analysis with reduced systematic error.**

MiniBooNE prediction



MiniBooNE-only Flux/X-sec and total error

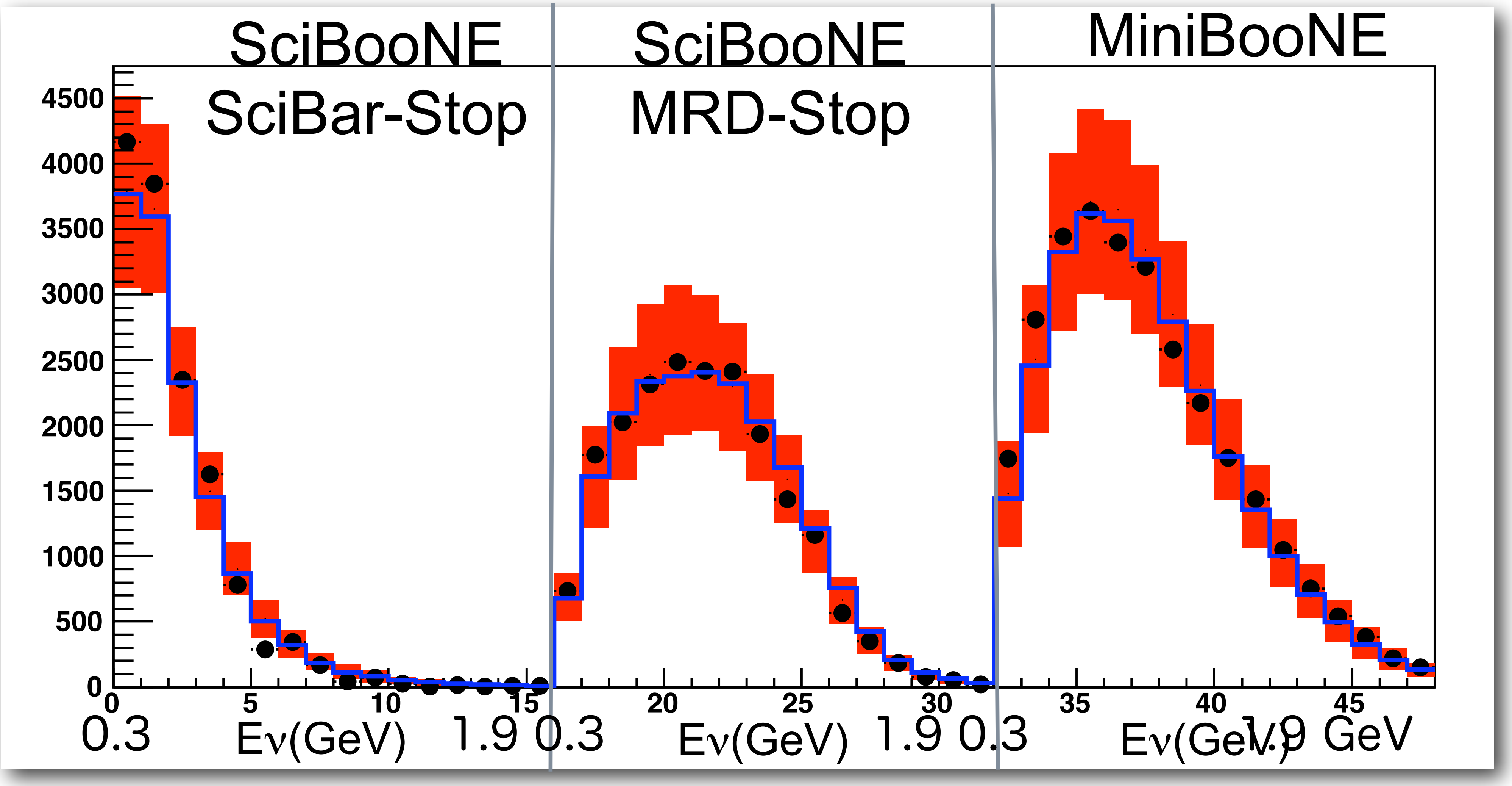
Flux/X-sec and total error constrained by SciBooNE data

MiniBooNE detector response error

Successfully reduced flux and cross section errors to the same level as the MiniBooNE detector response errors.

Simultaneous Fit

- Fit reconstructed E_ν distributions from SciBar-stopped, MRD-stopped and MiniBooNE samples simultaneously.
  - 16 bins/sample x 3 sample = 48 bins
- All bin-to-bin correlation is included into the fit.
  - Off-diagonal elements are strongly correlated.



● Fake Data

🟥 MC with error (Diagonal part)

* MiniBooNE distribution is scaled by ~1/7

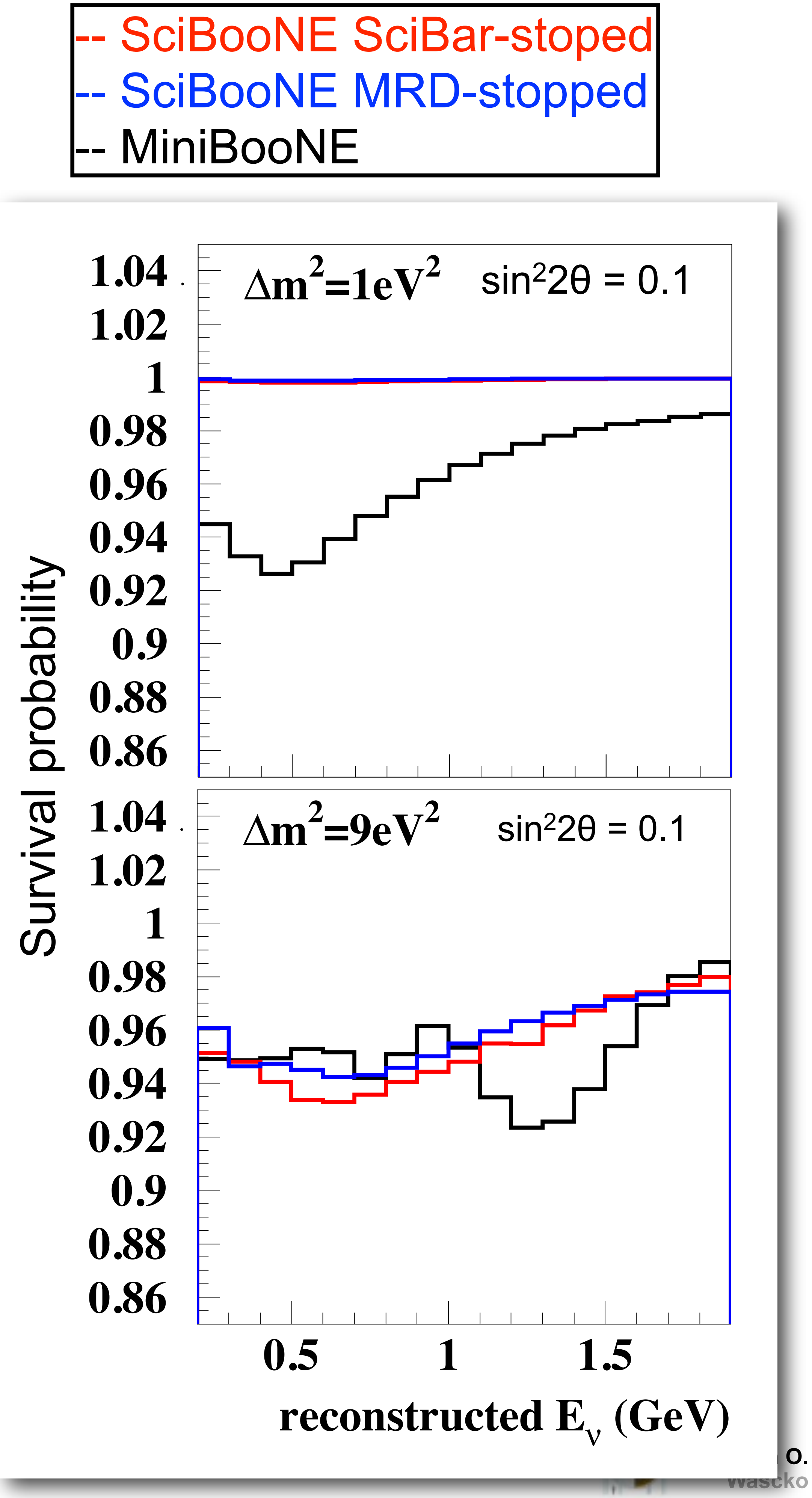
Simultaneous Fit

- MC prediction is renormalised by the number of events in SciBooNE.
- Evaluate $\Delta\chi^2$ = χ^2(each point) -χ^2(best)

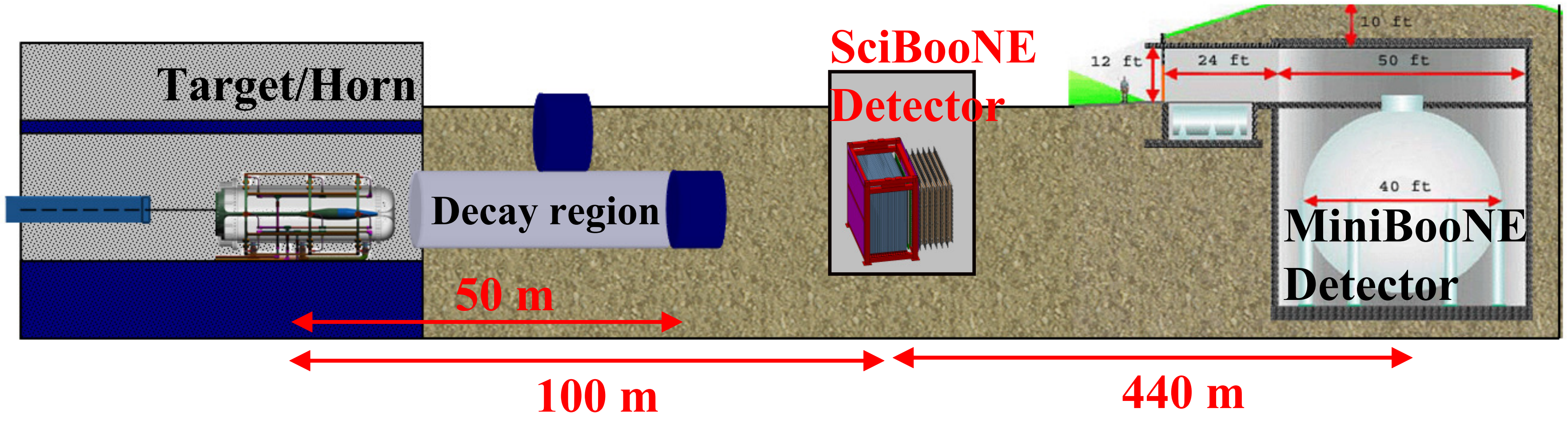
$$\chi^2 = \sum_{i,j}^{BINS} (d_i - Np_i) {M_{ij}}^{-1} (d_j - Np_j)$$

d_i: Data
p_i: Prediction (function of osc. parameter)
M_{ij}: 48x48 covariance matrix
N: Renormalization factor

- Again, Feldman-Cousins's method is used to determine the CLs.

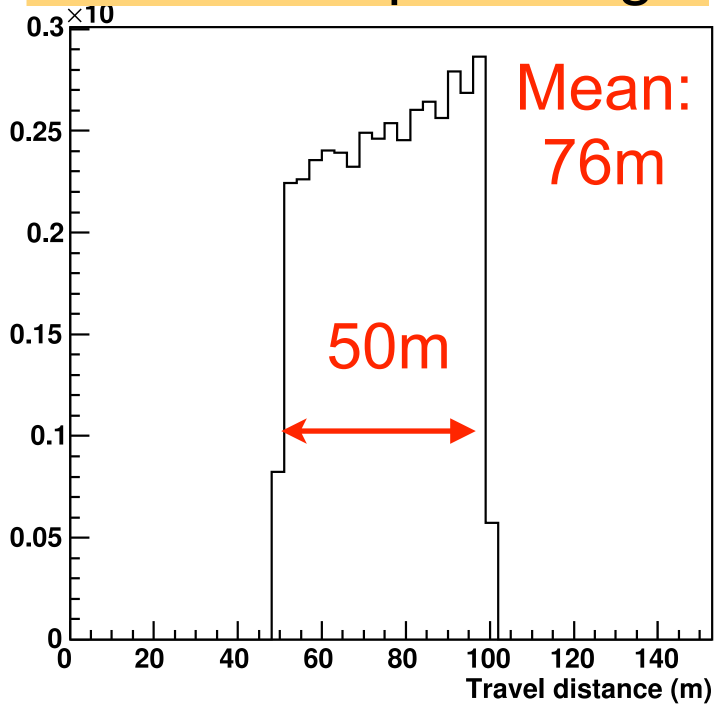


Predicting oscillation signal

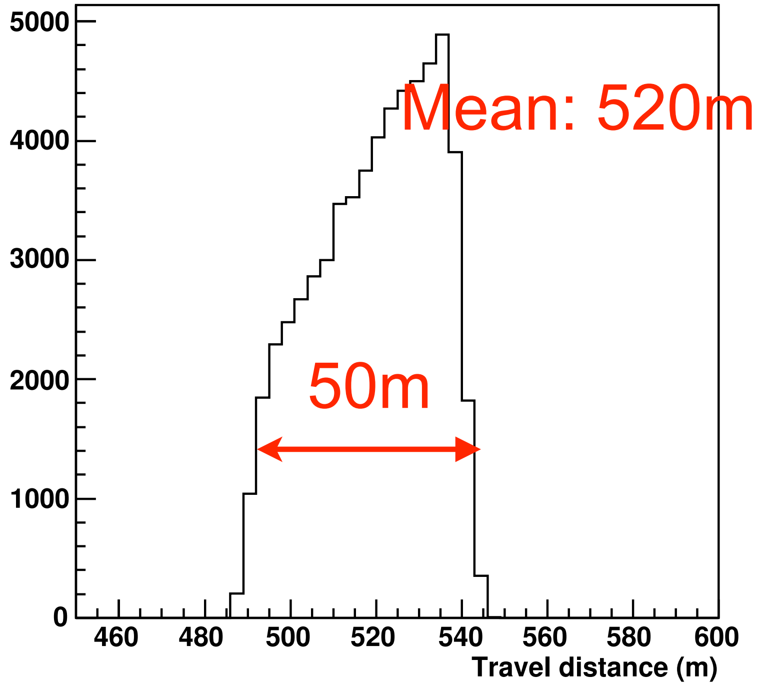


- Mean v path-length for SciBooNE events: ~76m
- Mean v path-length for MiniBooNE events: ~520m
- Each has 50m spread due to the finite length of the decay volume
- We consider three effects:
    - Oscillation at SciBooNE
    - Oscillation at MiniBooNE
    - Smearing effect due to 50m spread

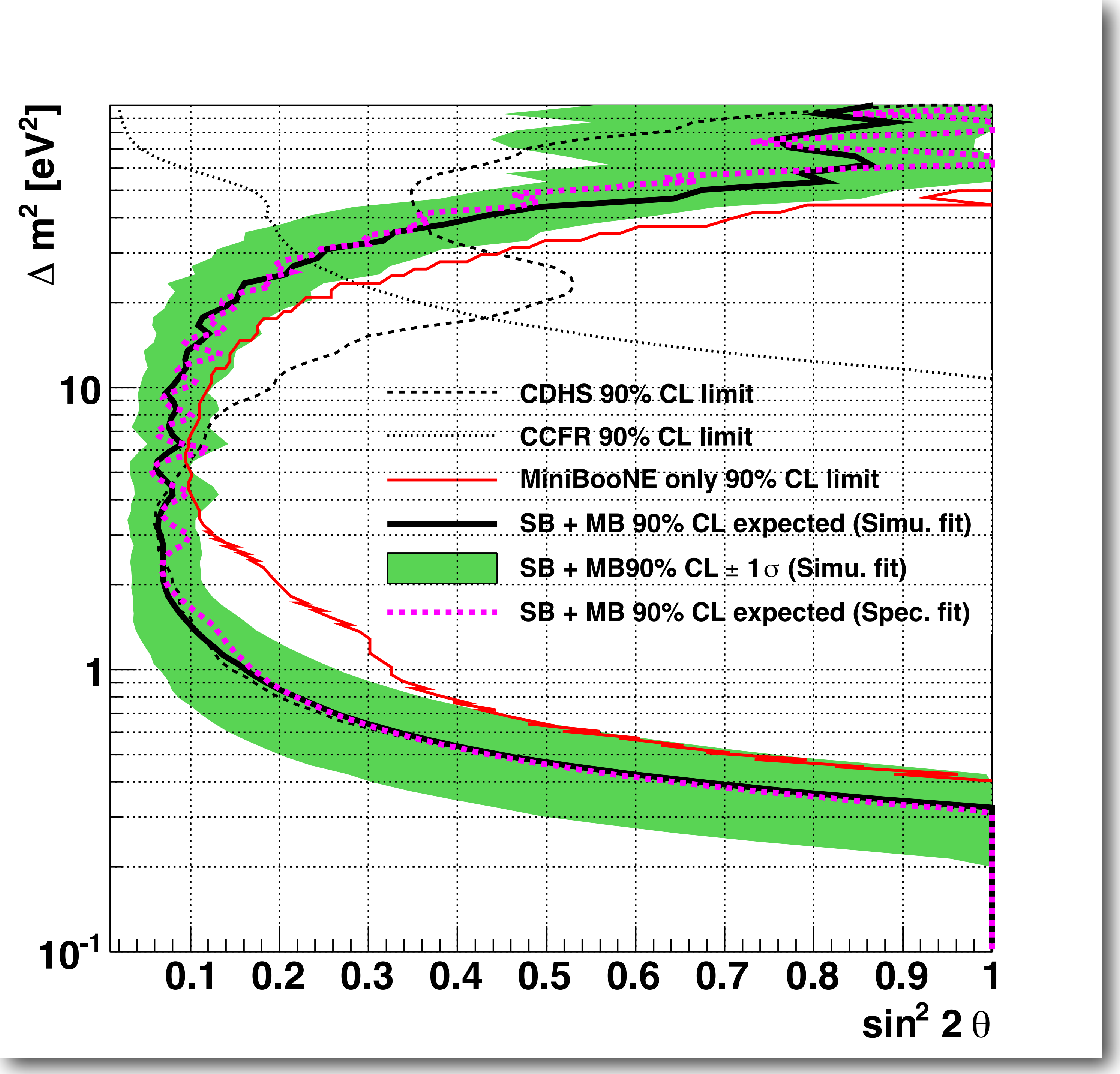
SciBooNE v path-length



MiniBooNE v path-length



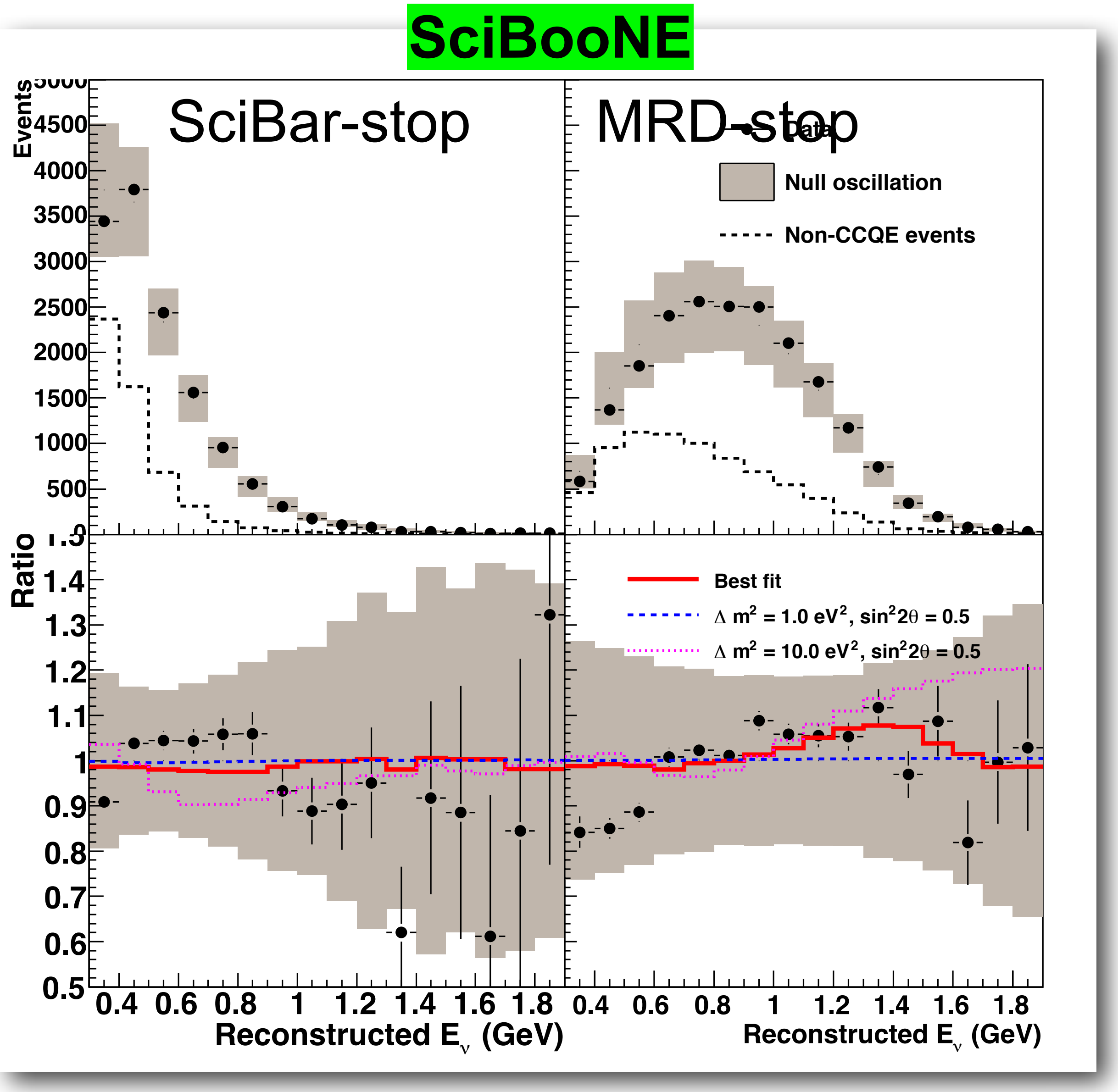
Simultaneous fit sensitivity



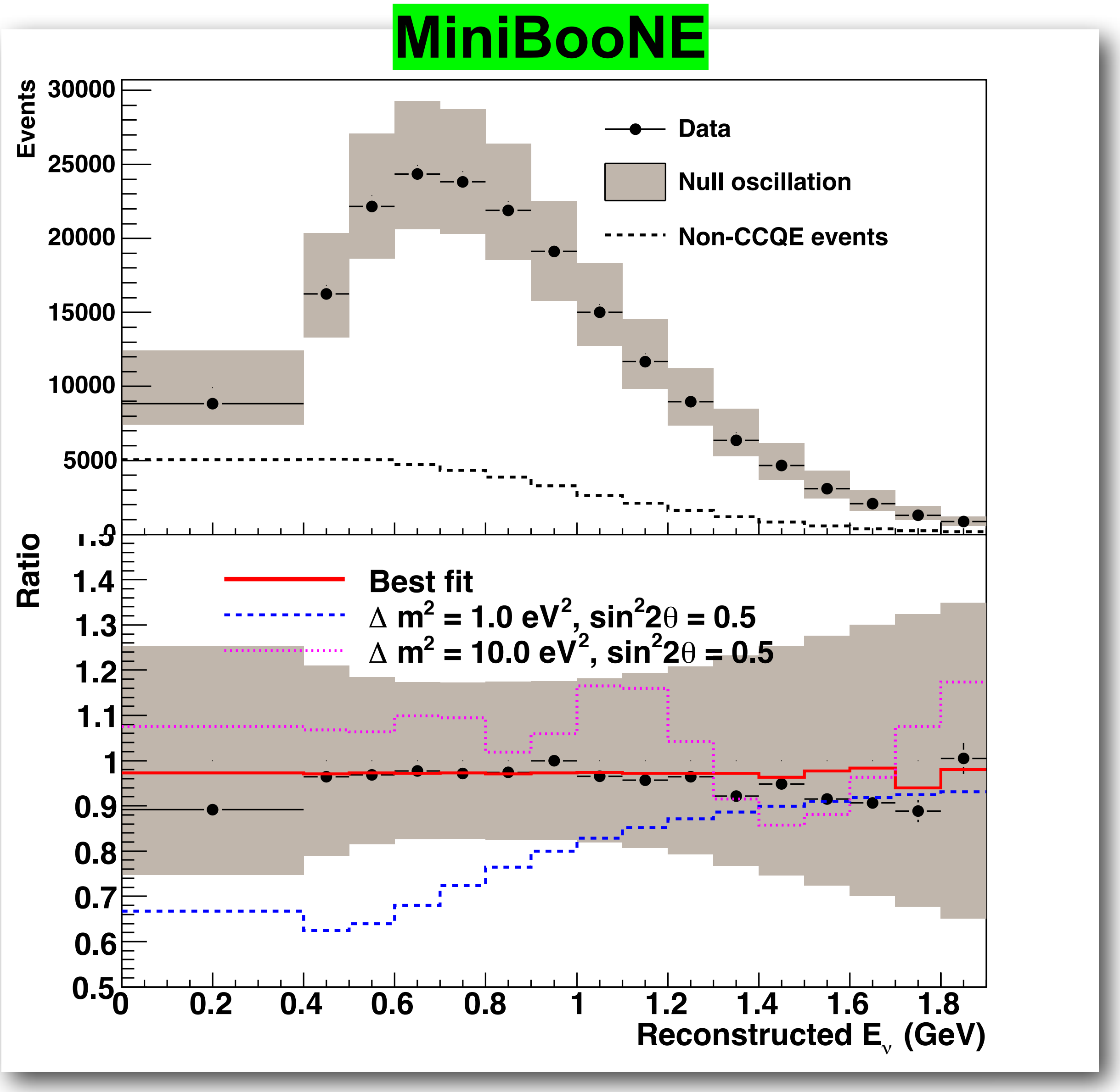
- **Sensitivities of the two analysis method are (roughly) the same.**
- Simultaneous fit sensitivity curve is smoother because of smaller binning effects than the spectrum fit analysis.

Simultaneous fit result

SciBooNE



MiniBooNE



Best: $\Delta m^2 = 43.7$ eV^2, $\sin^2 2\theta = 0.60$

χ^2(null) = 45.1/48(DOF)

χ^2(best) = 39.5/46(DOF)

$\Delta\chi^2 = \chi^2$(null) - χ^2(best) = 5.6

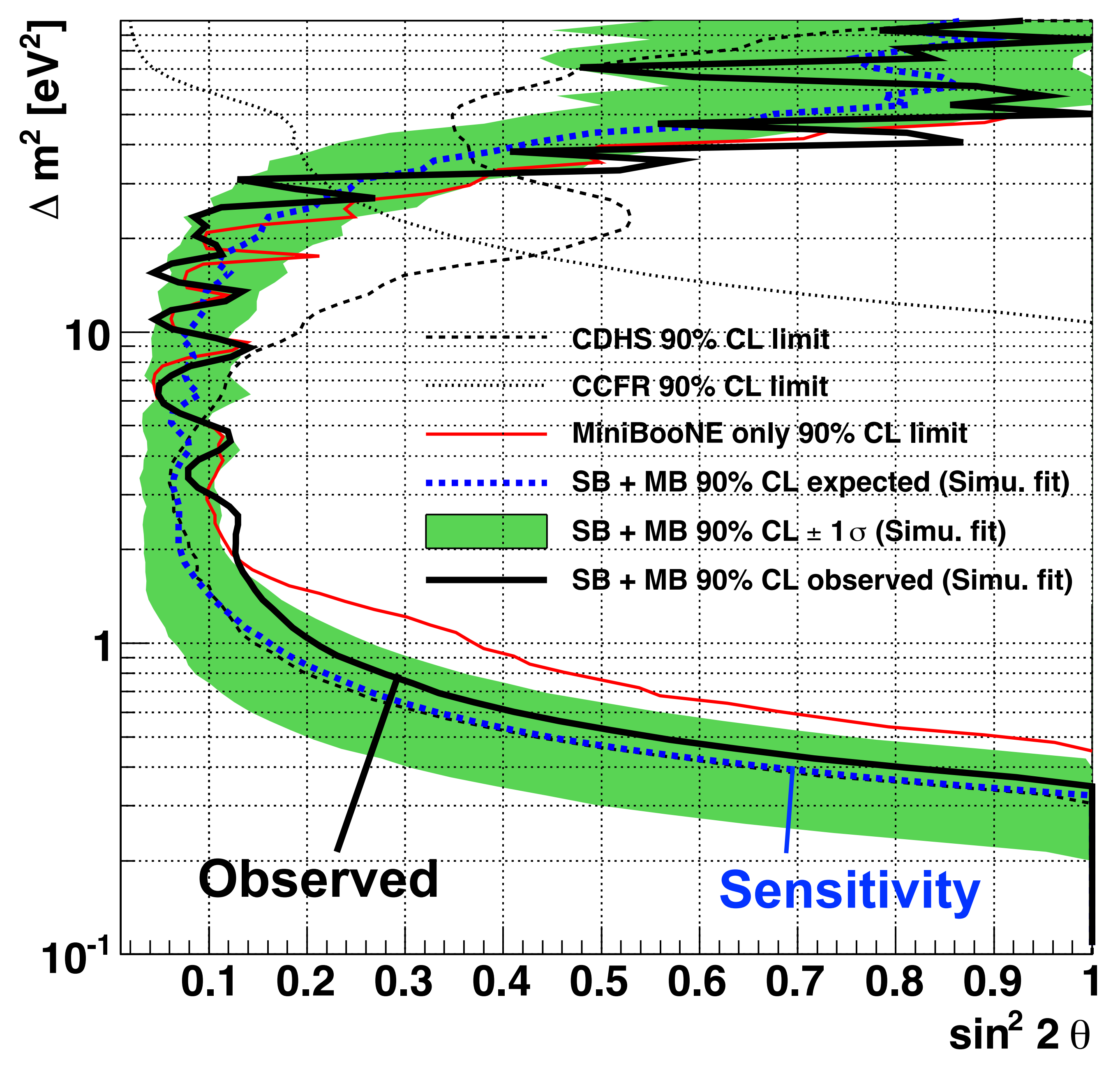
$\Delta\chi^2$ (90%CL, null) = 9.3

(estimated by simulation)

No significant oscillation signal observed.

90% CL limit from simultaneous fit

- The observed limits are within the ±1σ band.
  - Another support for null oscillation signal.
- World strongest limit at $10 < \Delta m^2 < 30$ eV^2
  - Constrain sterile neutrino mixing parameters.



systematic uncertainties

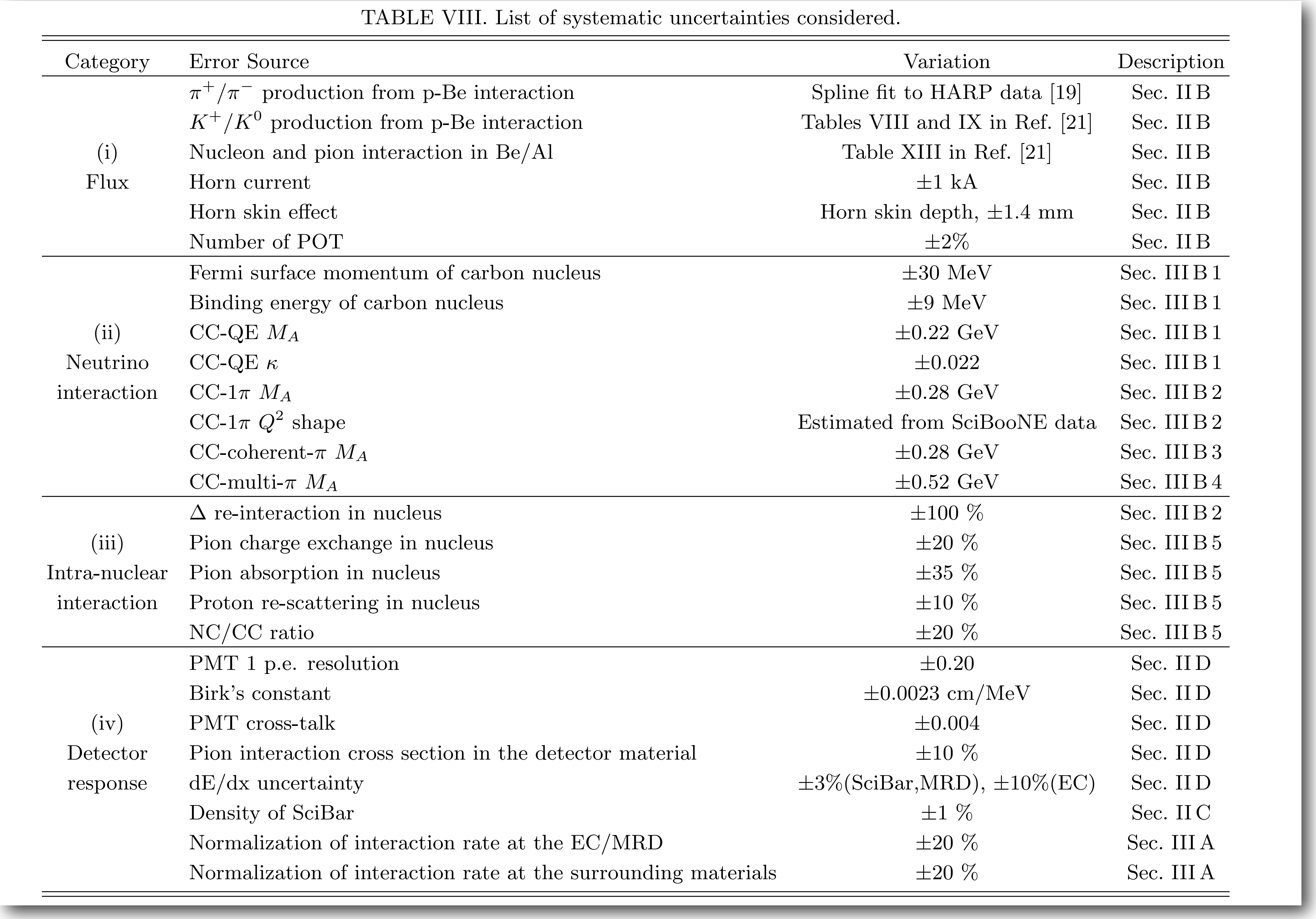


TABLE VIII. List of systematic uncertainties considered.

Category	Error Source	Variation	Description
(i) Flux	π^+/π^- production from p-Be interaction	Spline fit to HARP data [19]	Sec. II B
	K^+/K^0 production from p-Be interaction	Tables VIII and IX in Ref. [21]	Sec. II B
	Nucleon and pion interaction in Be/Al	Table XIII in Ref. [21]	Sec. II B
	Horn current	±1 kA	Sec. II B
	Horn skin effect	Horn skin depth, ±1.4 mm	Sec. II B
	Number of POT	±2%	Sec. II B
(ii) Neutrino interaction	Fermi surface momentum of carbon nucleus	±30 MeV	Sec. III B 1
	Binding energy of carbon nucleus	±9 MeV	Sec. III B 1
	CC-QE M_A	±0.22 GeV	Sec. III B 1
	CC-QE κ	±0.022	Sec. III B 1
	CC-1π M_A	±0.28 GeV	Sec. III B 2
	CC-1π Q^2 shape	Estimated from SciBooNE data	Sec. III B 2
	CC-coherent-π M_A	±0.28 GeV	Sec. III B 3
	CC-multi-π M_A	±0.52 GeV	Sec. III B 4
(iii) Intra-nuclear interaction	Δ re-interaction in nucleus	±100 %	Sec. III B 2
	Pion charge exchange in nucleus	±20 %	Sec. III B 5
	Pion absorption in nucleus	±35 %	Sec. III B 5
	Proton re-scattering in nucleus	±10 %	Sec. III B 5
	NC/CC ratio	±20 %	Sec. III B 5
(iv) Detector response	PMT 1 p.e. resolution	±0.20	Sec. II D
	Birk's constant	±0.0023 cm/MeV	Sec. II D
	PMT cross-talk	±0.004	Sec. II D
	Pion interaction cross section in the detector material	±10 %	Sec. II D
	dE/dx uncertainty	±3%(SciBar,MRD), ±10%(EC)	Sec. II D
	Density of SciBar	±1 %	Sec. II C
	Normalization of interaction rate at the EC/MRD	±20 %	Sec. III A
	Normalization of interaction rate at the surrounding materials	±20 %	Sec. III A

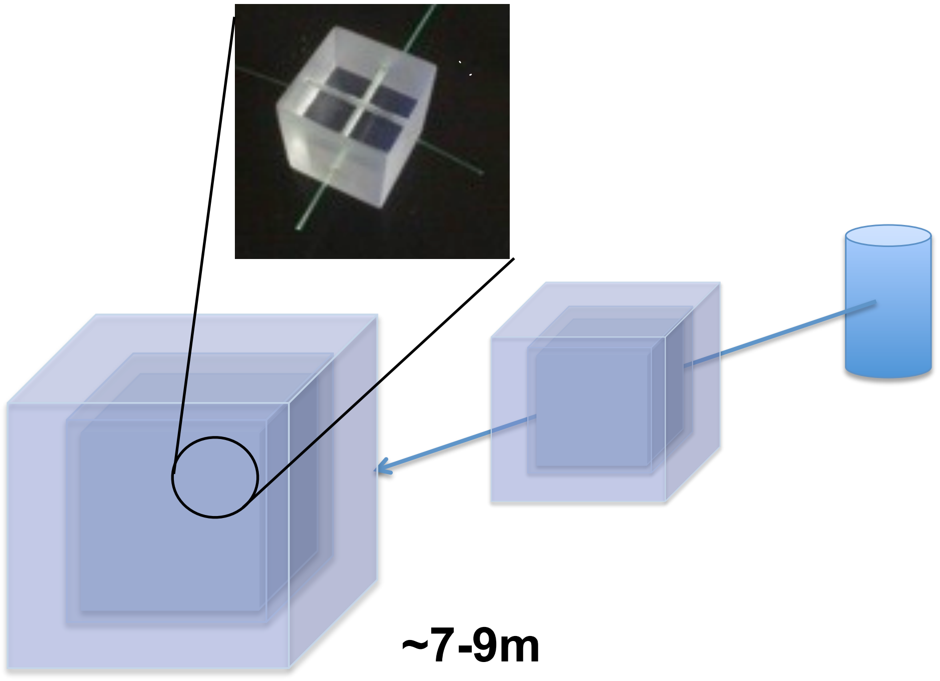
To test reactor flux and Ga anomalies

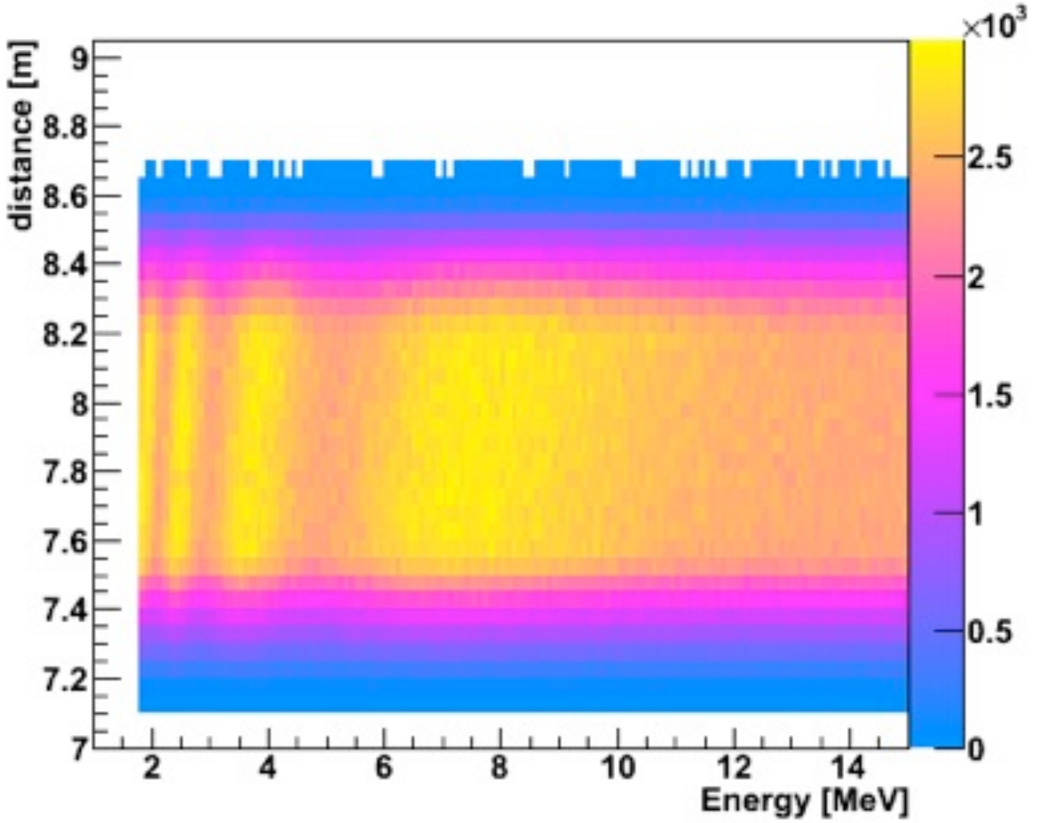
Antonin Vacheret <Antonin.Vacheret@physics.ox.ac.uk>

SOLiD

solid segmented plastic scintillator detectors

- Novel approach to detect antineutrinos at reactors
  - composite scintillator cells with Li^6
  - compact system with minimal shielding (1.5m footprint for 1T Fiducial mass)
  - very low sensitivity to gamma background
  - can achieve better signal to background ratio than traditional liquid scintillator system
- Originally developed for reactor monitoring purposes





Δm^2=2.35, $\sin^2 2\theta_{ee}$ = 0.165

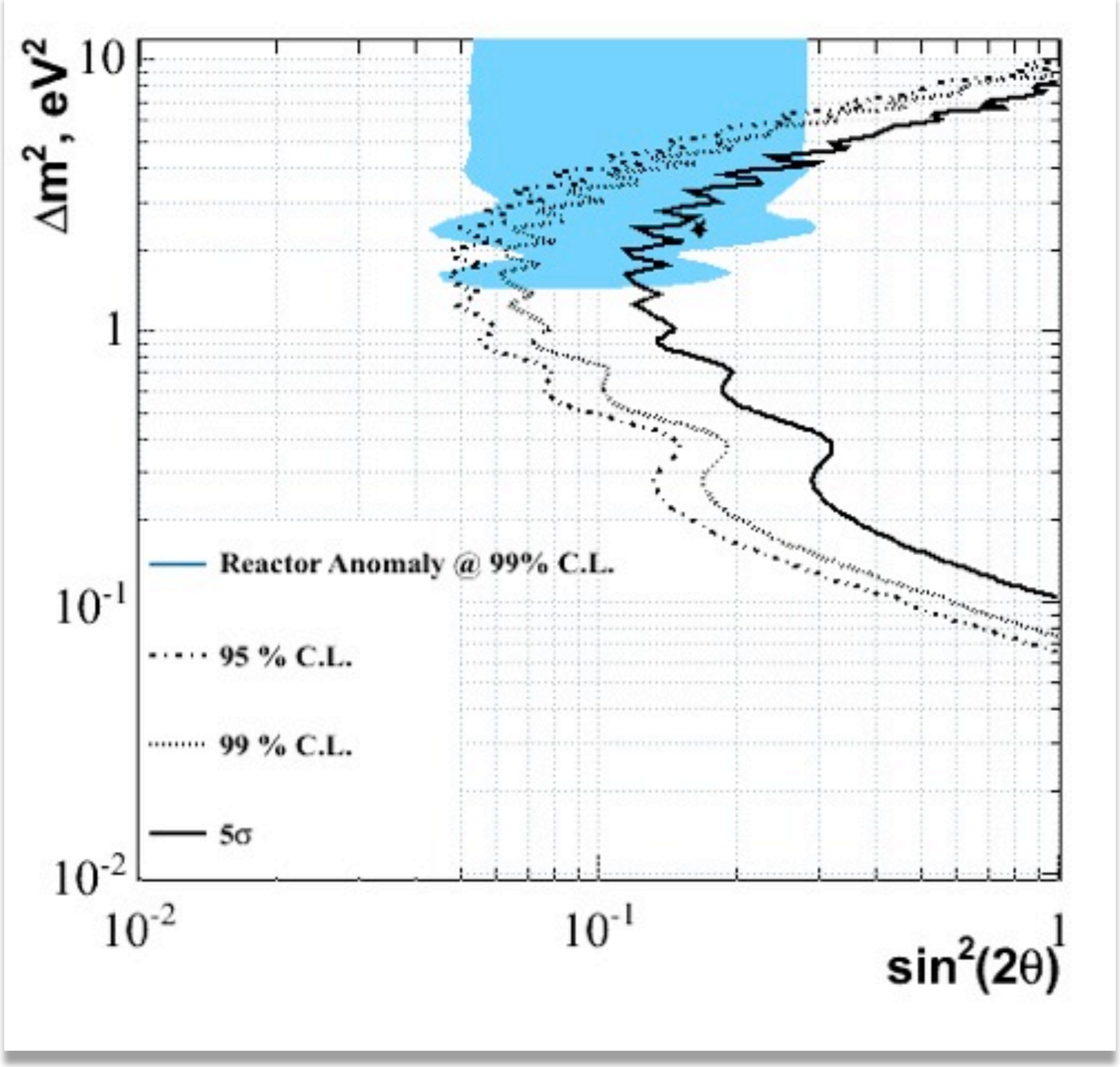
To test reactor flux and Ga anomalies

Antonin Vacheret <Antonin.Vacheret@physics.ox.ac.uk>

SOLiD

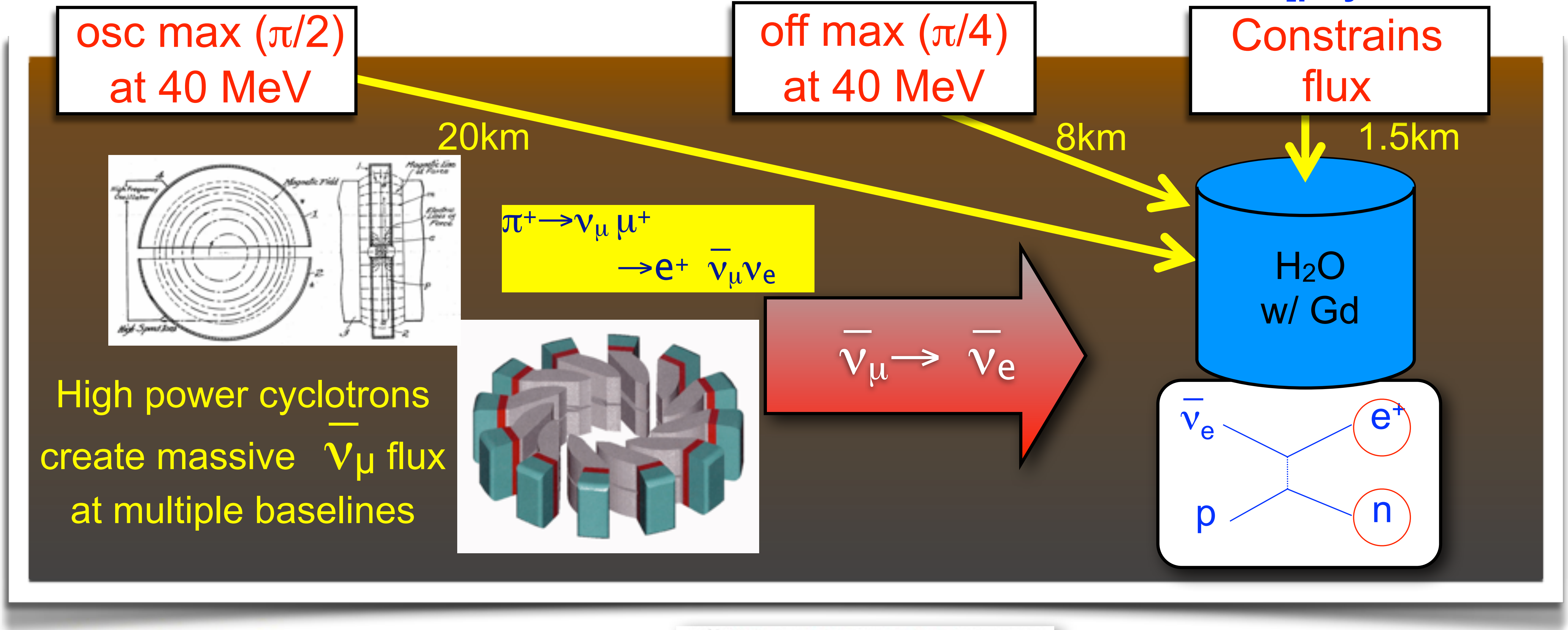
solid segmented plastic scintillator detectors

- Measurement at ILL (2 years) (~50k events)
  - Baselines assumed: 7.5 m near and 9 m far (being optimised)
  - (ILL 0.8m x 0.4m core can provide best resolution on SBL oscillations)
- shape analysis using two detector baseline
  - signal from ratio of spectra
  - 3D vertex reconstruction (< 10 cm resolution)
  - $\sigma_E/E \sim 0.1$ MeV



DAEδALUS

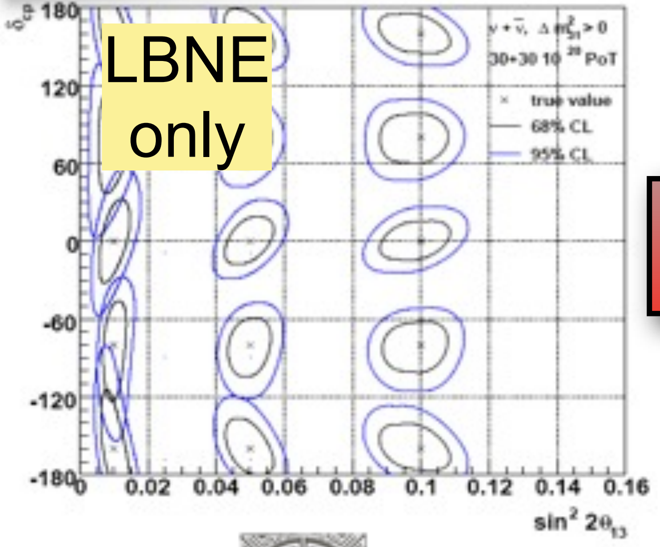
arXiv:1006.0260 [physics.ins-det]



$\pi^+ \rightarrow \nu_\mu \mu^+$
$\rightarrow e^+ \; \bar{\nu}_\mu \nu_e$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

High power cyclotrons create massive $\bar{\nu}_\mu$ flux at multiple baselines



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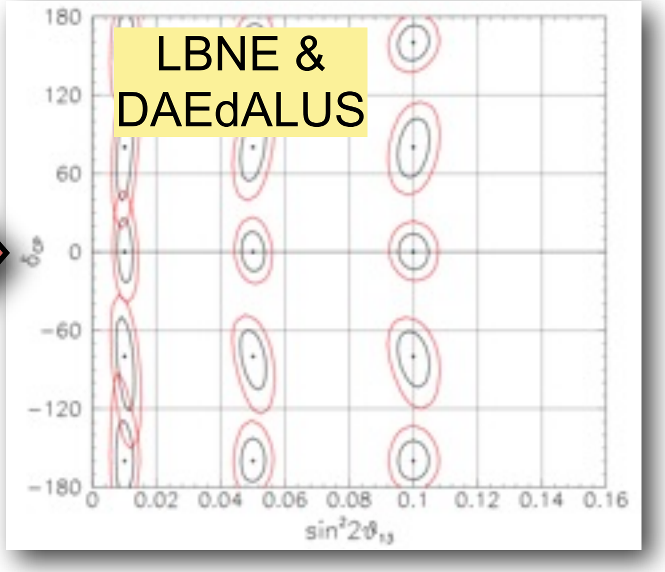


Physics studies done assuming H_2O detector in LBNE, but same performance achievable with Hyper-K or LBNO

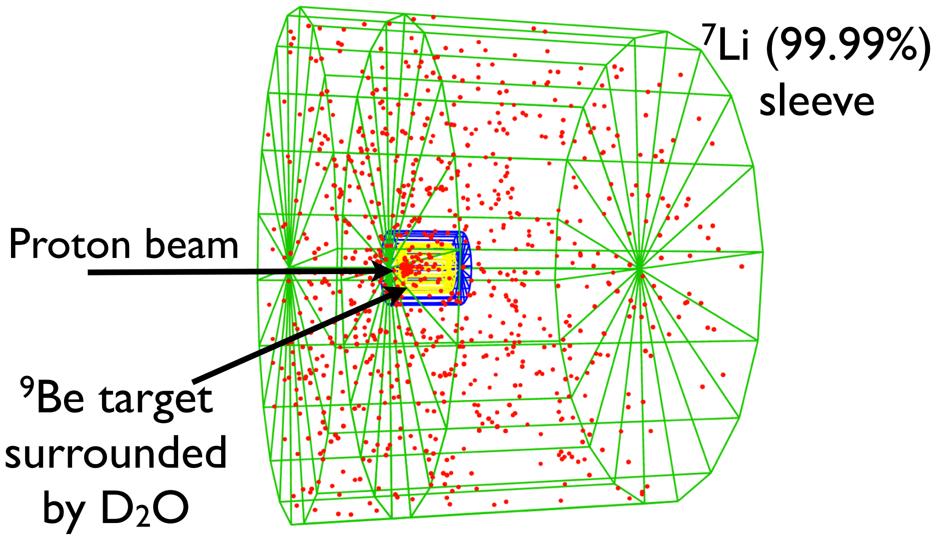
To test reactor flux and Ga anomalies

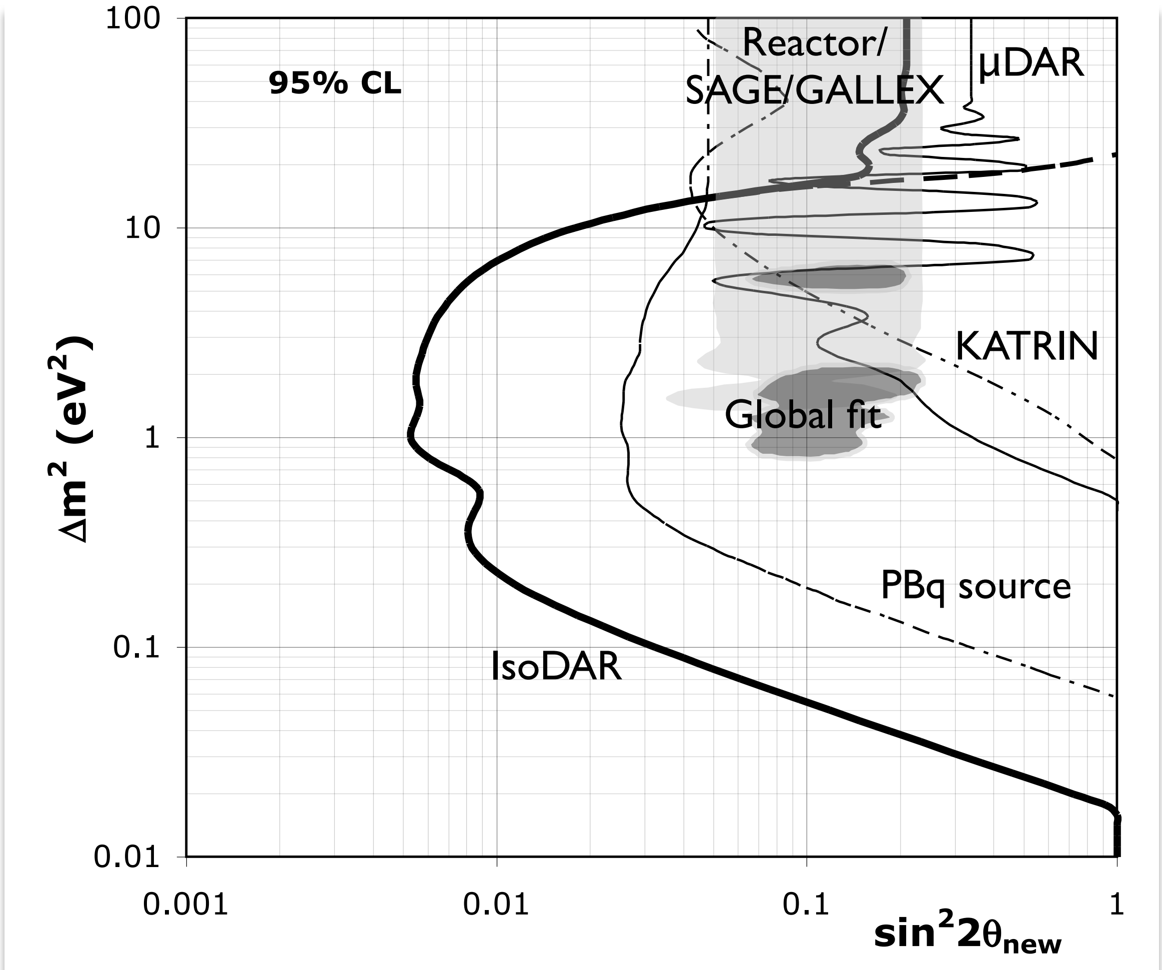
Adriana Bungau <A.Bungau@hud.ac.uk>

DAEδALUS

Medium term: IsoDAR

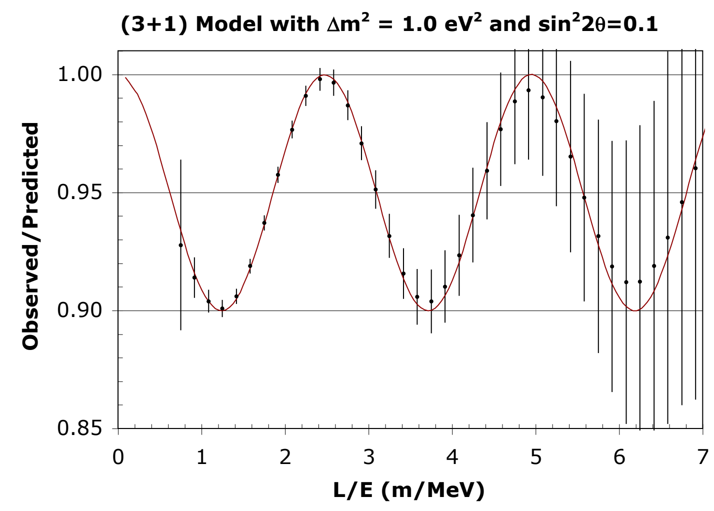
arXiv:1205.4419 [hep-ex]

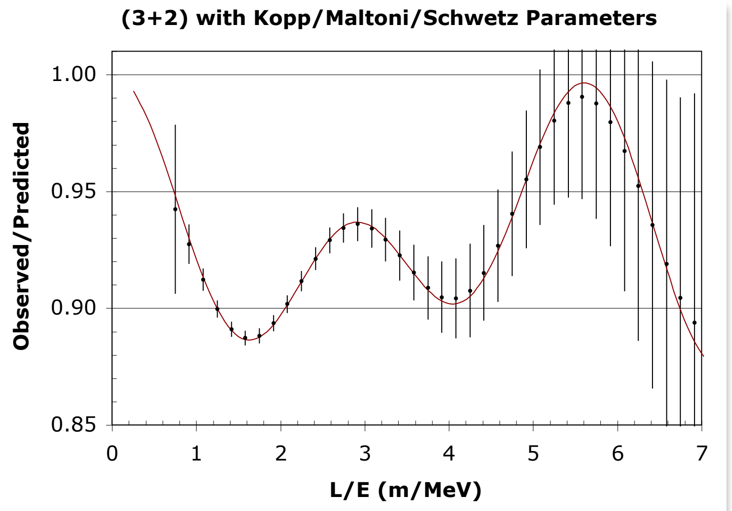




- High power cyclotrons create high $\bar{\nu}_e$ flux
- $n+Li^7 \rightarrow Li^8$

  ↪ $\bar{\nu}_e$, $\langle E_\nu \rangle = 6.4$MeV

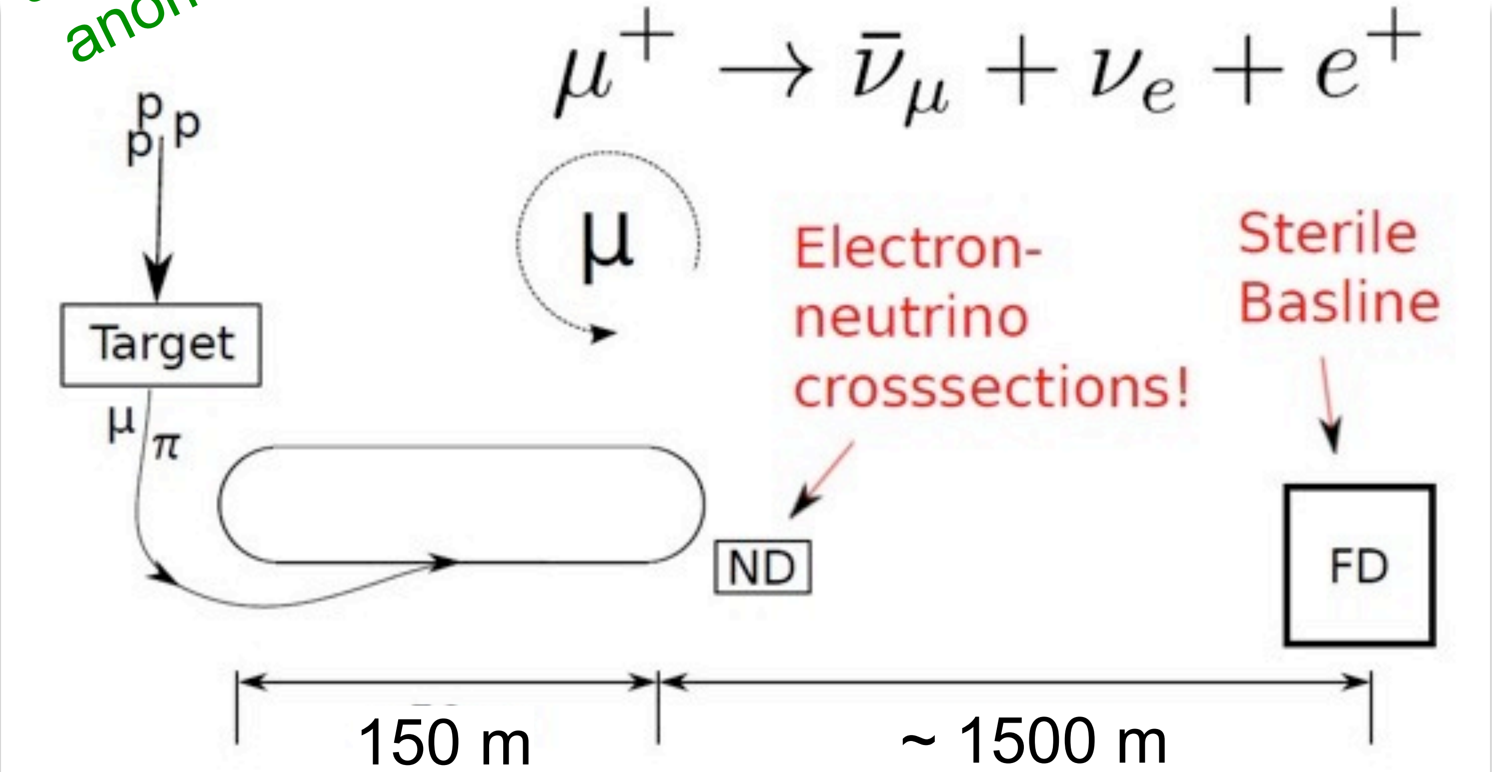




- Placed near a good $\bar{\nu}_e$ detector (e.g. KamLAND) gives excellent sensitivity to sterile oscillation
- UK involved in accelerator and beam dump studies

To test LSND & MiniBooNE, Ga, and reactor anomalies

NuSTORM



[arXiv:1206.0294 [hep-ex]](arXiv:1206.0294)

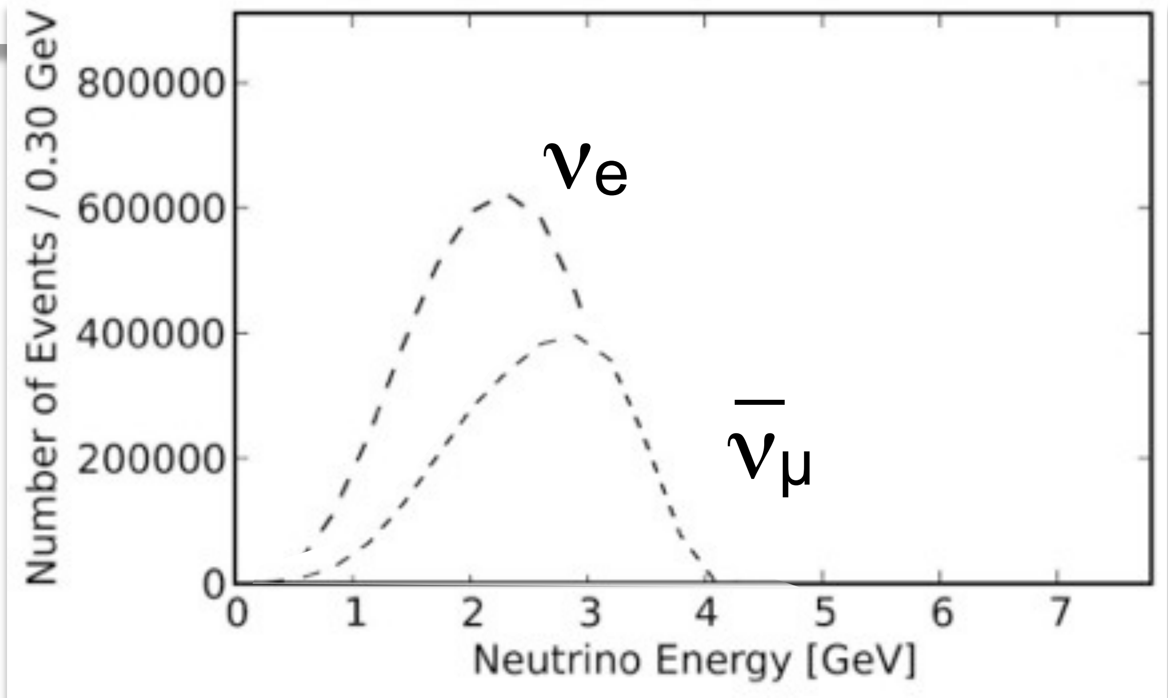
Multiple sterile ν channels

Appearance Channel:

$\nu_e \longrightarrow \nu_\mu$

Must reject the wrong sign μ with **high** efficiency

Event rates/100T at Fe ND 50m from straight with μ^+ stored

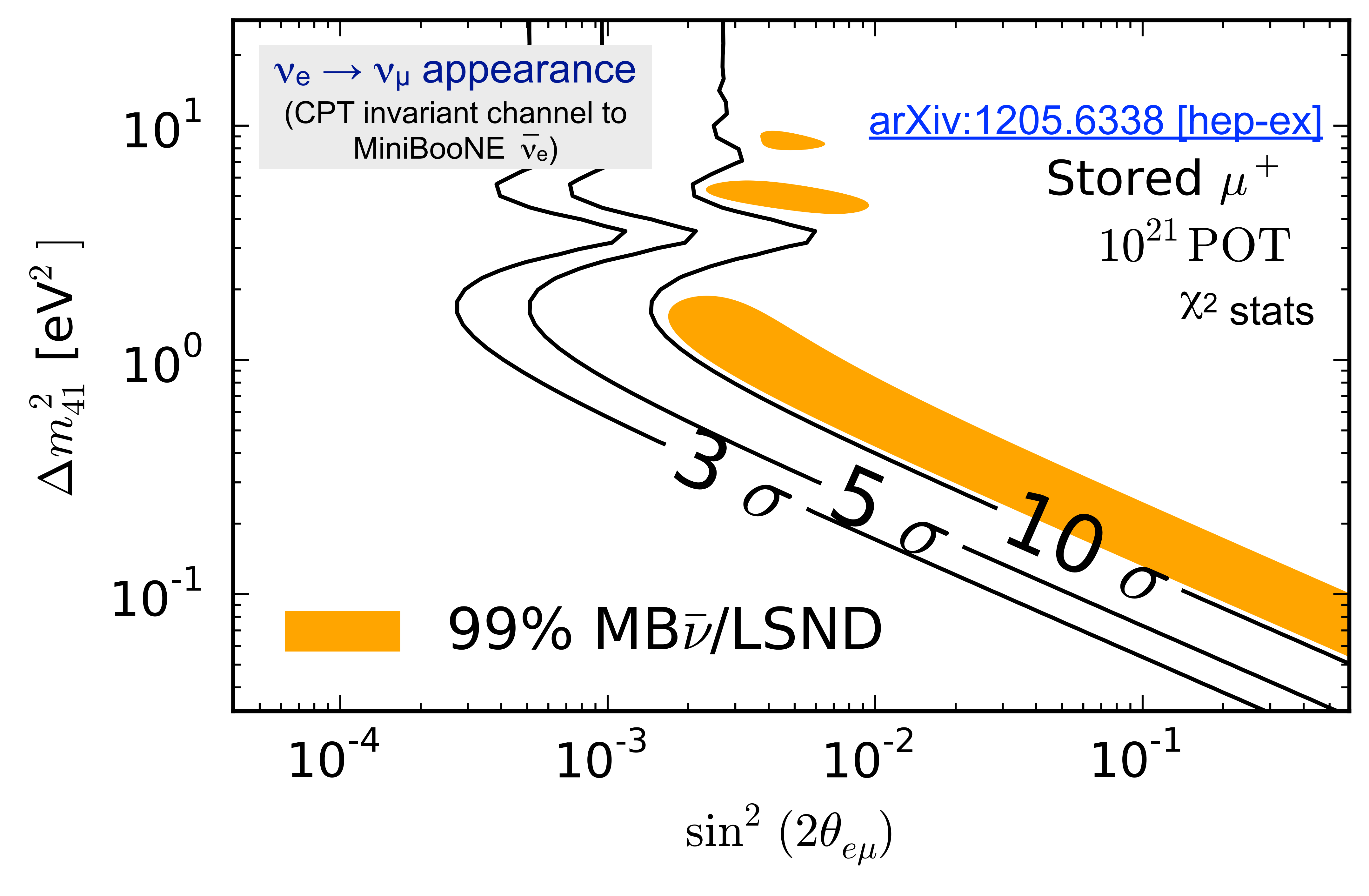


Received positive feedback from Fermilab PAC
http://www.fnal.gov/directorate/program_planning/phys_adv_com/PAC%20Comments%20and%20Recommendations.pdf

http://www.fnal.gov/directorate/program_planning/June2012Public/P-1028_LOI_Final.pdf

Christopher Tunnell <c.tunnell1@physics.ox.ac.uk>

NuSTORM: oscillations



3+1
Assumption

NuSTORM physics programme

- As an experiment, NuSTORM can:
  - ✓ Perform direct tests of the LSND and MiniBooNE anomalies.
  - ✓ Perform direct tests of the Gallium and reactor anomalies.
  - ✓ Test the CP- and T-conjugated channels, constrain with disappearance.
  - ✓ Make precise and **unique** measurements of ν_μ and ν_e cross-sections

Valuable physics input for δ_{CP} searches

- As a facility, NuSTORM:
  - ✓ Provides an accelerator technology test bed
  - ✓ Provides a powerful ν detector test facility
- As a programme, NuSTORM:
  - ✓ Provides an important step on the path toward discovery in neutrinos and collider physics

Excellent synergy with superbeams!

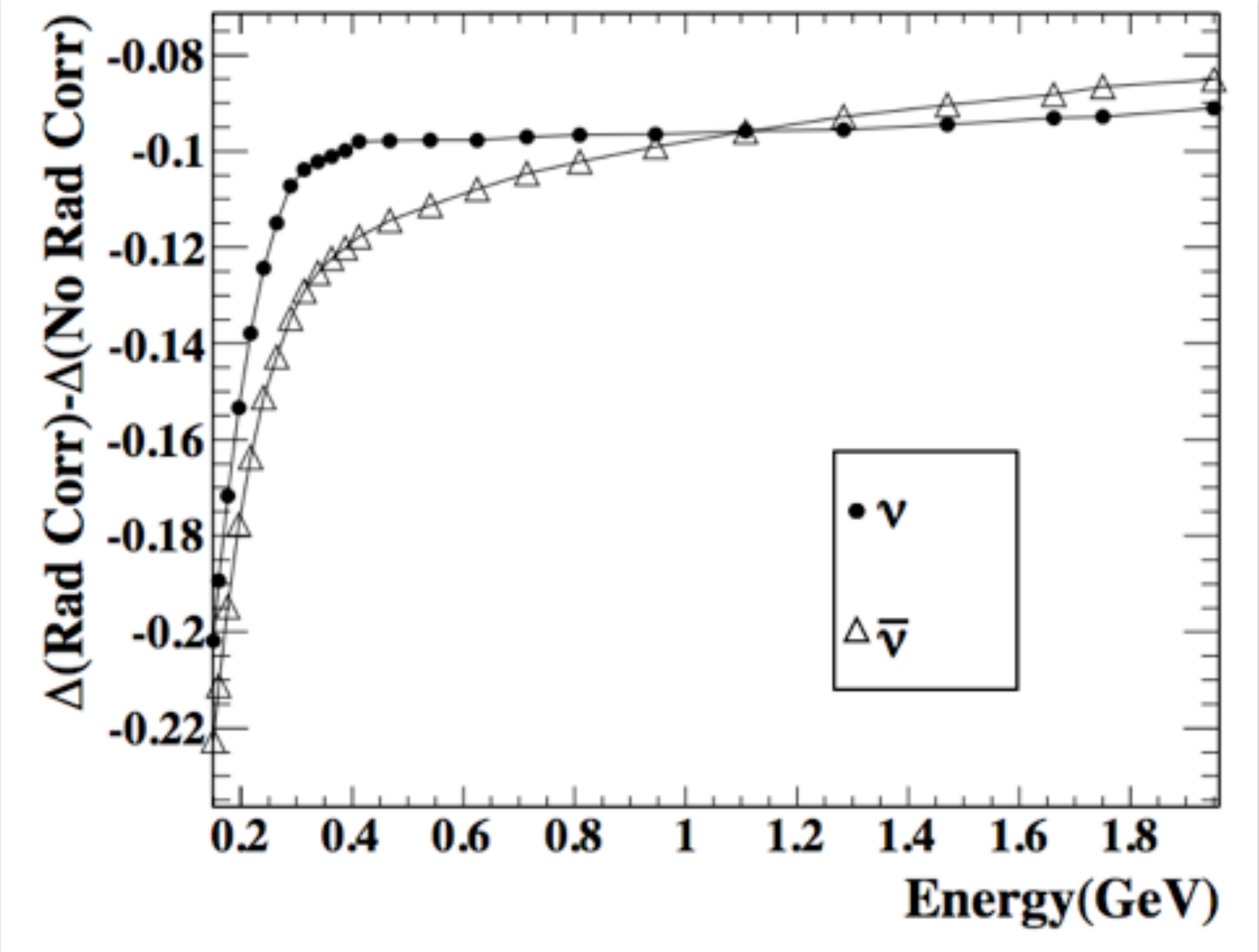
NuSTORM ν Cross-sections

- NuSTORM presents only way to measure ν_e, $\bar{\nu}_\mu$ (& $\bar{\nu}_e$,ν_μ) cross-sections in the same detector(s)
  - Supports future long-baseline experiments!
  - E_ν matched well to needs of these experiments

Recent calculations showing expectations for differences between ν_e and ν_μ cross-sections

We need data!

NuSTORM members have submitted a statement to the PPAP and the CERN Strategy Committee



arXiv:1206.6745 [hep-ph]