Joint Search for ν_μ Disappearance at $\Delta m^2 \sim 1\ eV^2$

Searching for sterile neutrinos with SciBooNE & MiniBooNE

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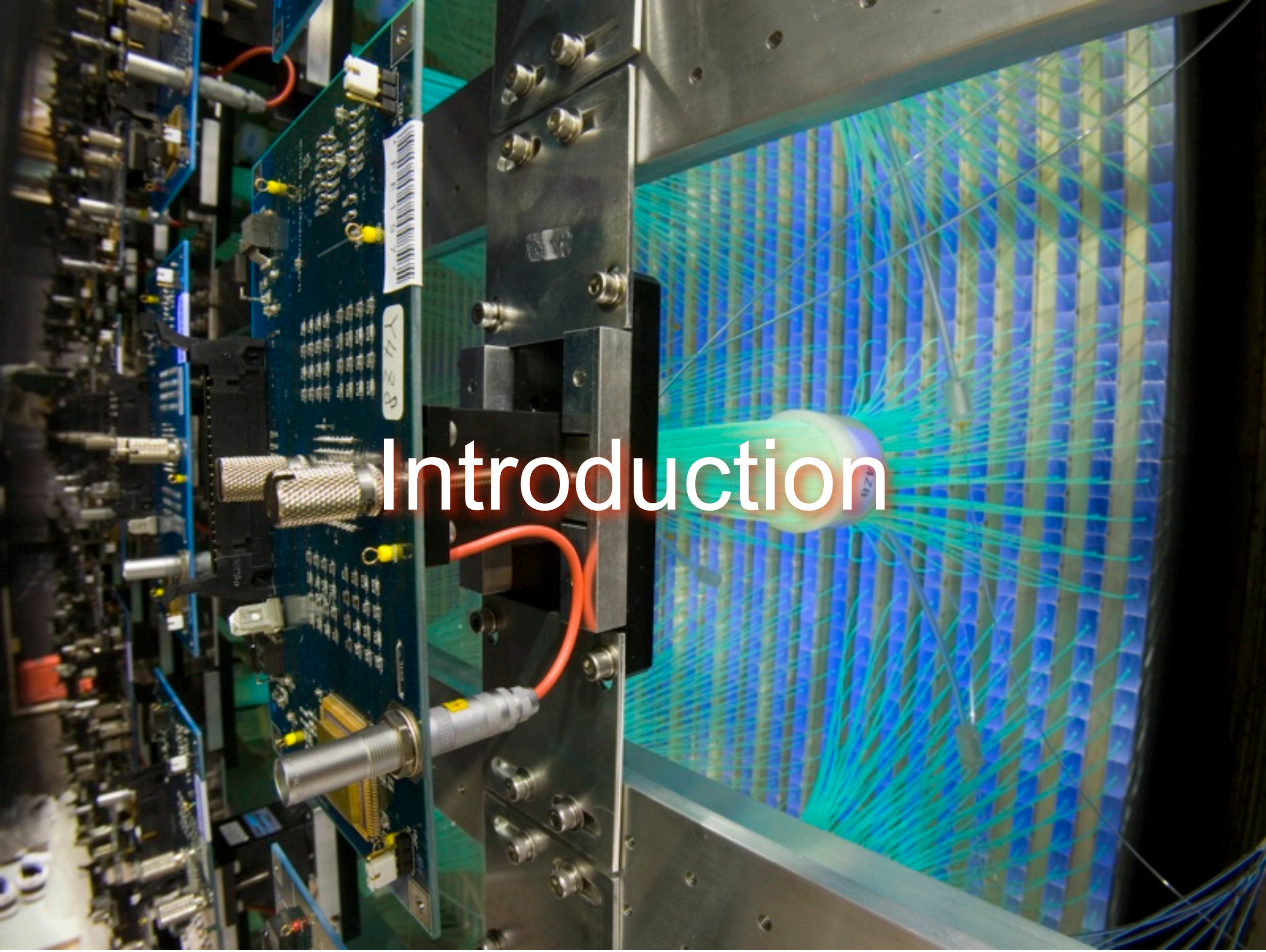
2011 10 12

Outline

- Introduction
  - Neutrino oscillation
  - The LSND signal and sterile neutrinos
- Experiments: SciBooNE and MiniBooNE
- SciBooNE-MiniBooNE joint ν_μ disappearance analysis
- Results



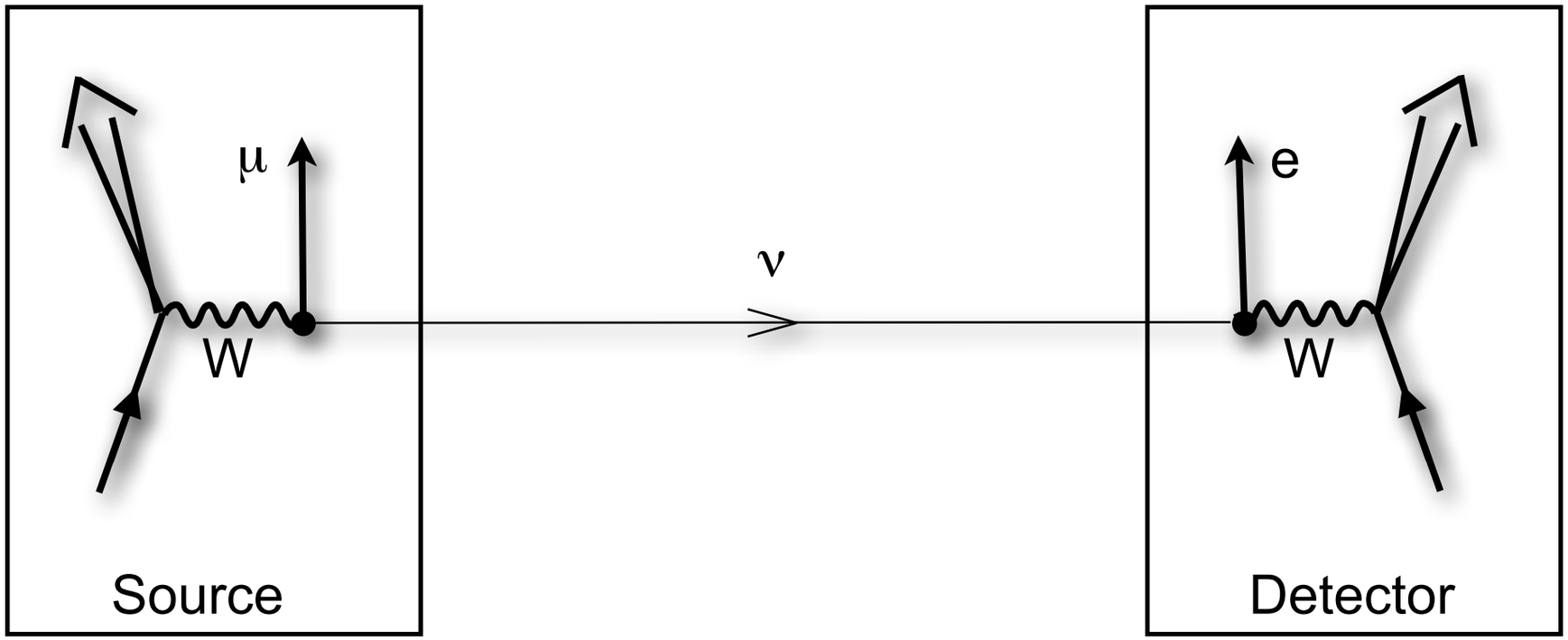
Introduction

Neutrino oscillation

Pontecorvo

Sov.Phys.JETP 6:429,1957

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



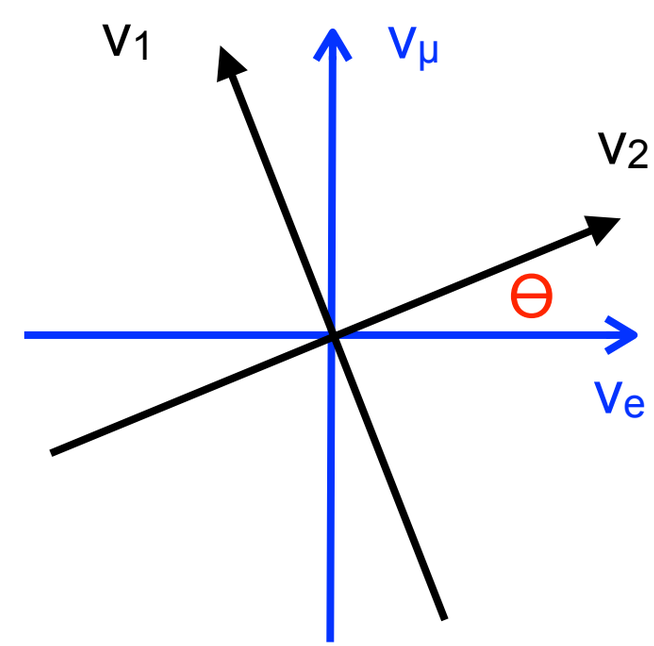
Maki, Nakagawa, Sakata

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

- if neutrinos have mass...
  - a neutrino that is produced as a ν_μ
    - (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$)
  - might some time later be observed as a ν_e
    - (e.g. $\nu_e\, n \rightarrow e^-\, p$)

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:

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

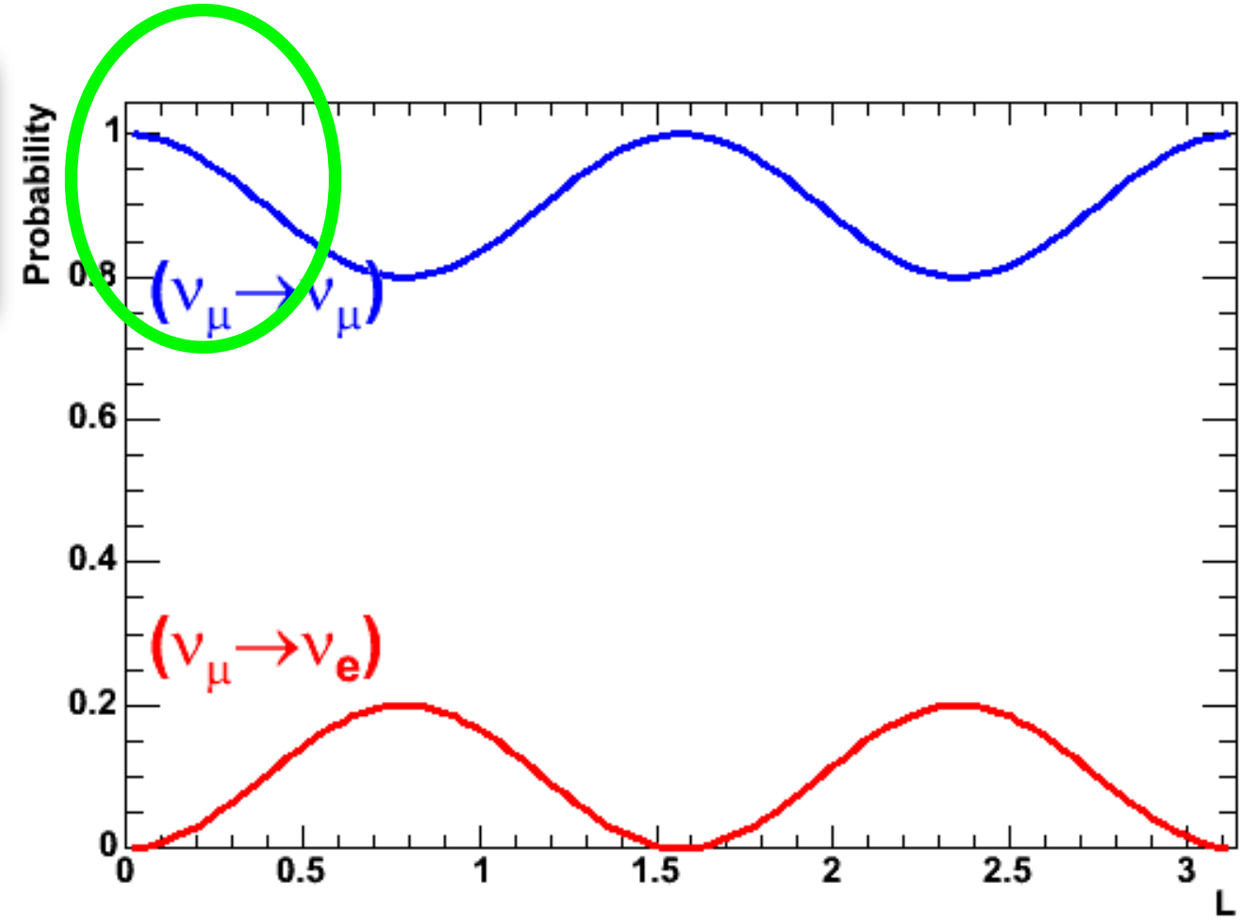
$$|\nu_\mu(t) > = -sin\theta\ (|\nu_1 > e^{-iE_1 t}) + cos\theta\ (|\nu_2 > e^{-iE_2 t})$$

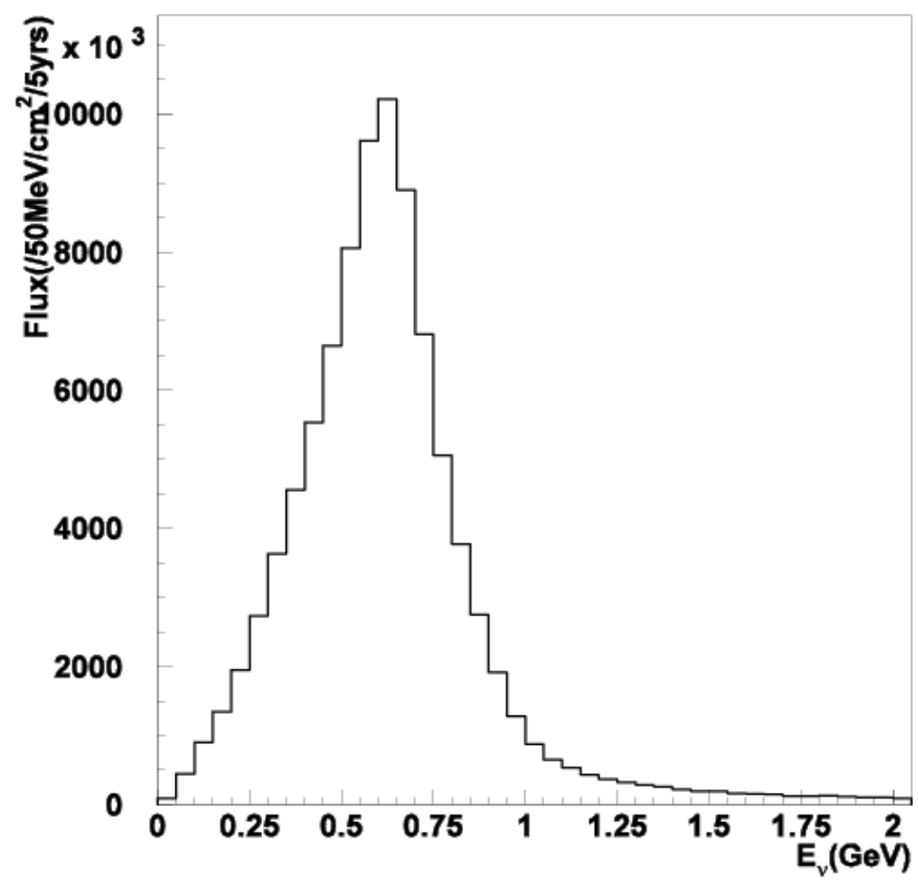
The probability to find a ν_e when you started with a ν_μ is:

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

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

- 2 fundamental parameters
  - $\Delta m^2 \leftrightarrow$ period
  - $\theta_{12} \leftrightarrow$ 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





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

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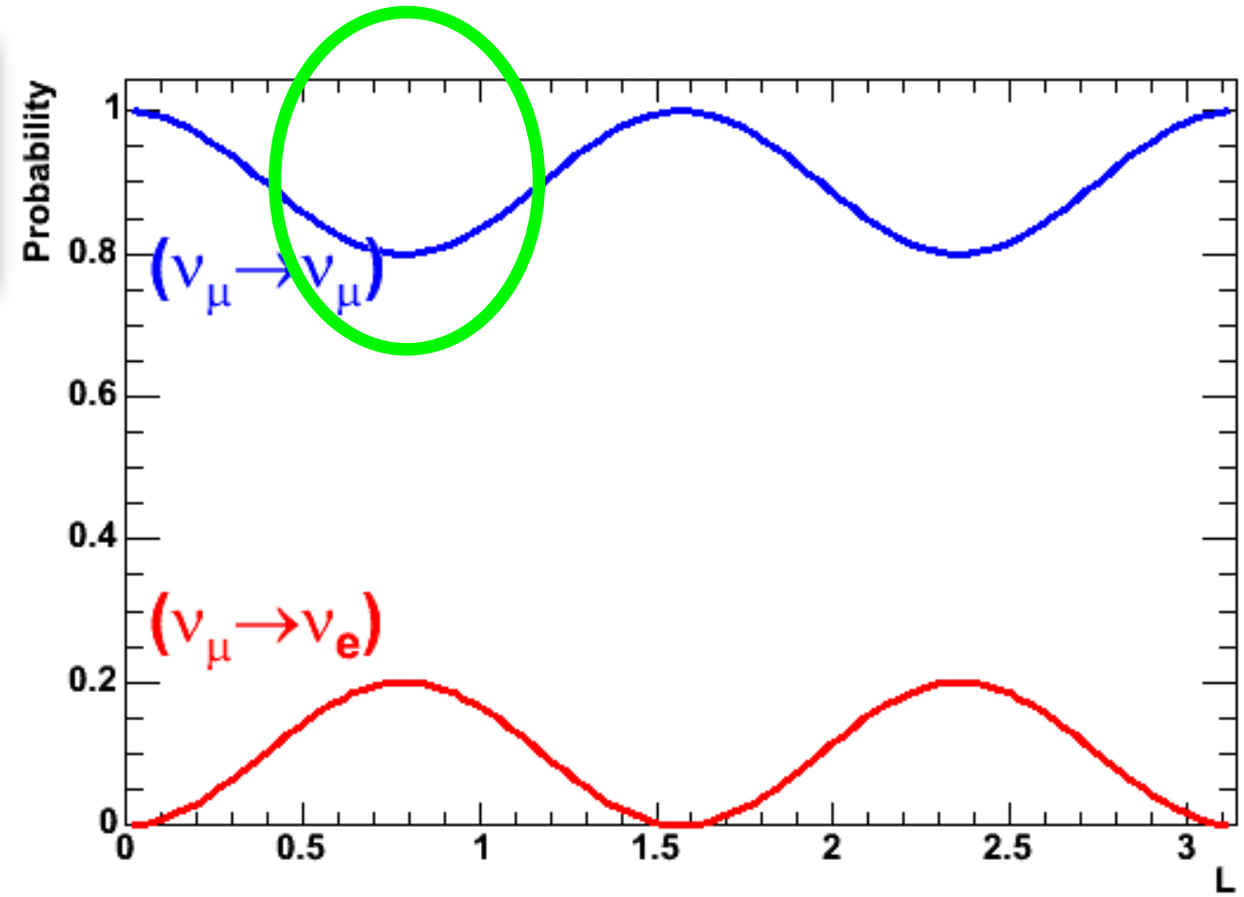

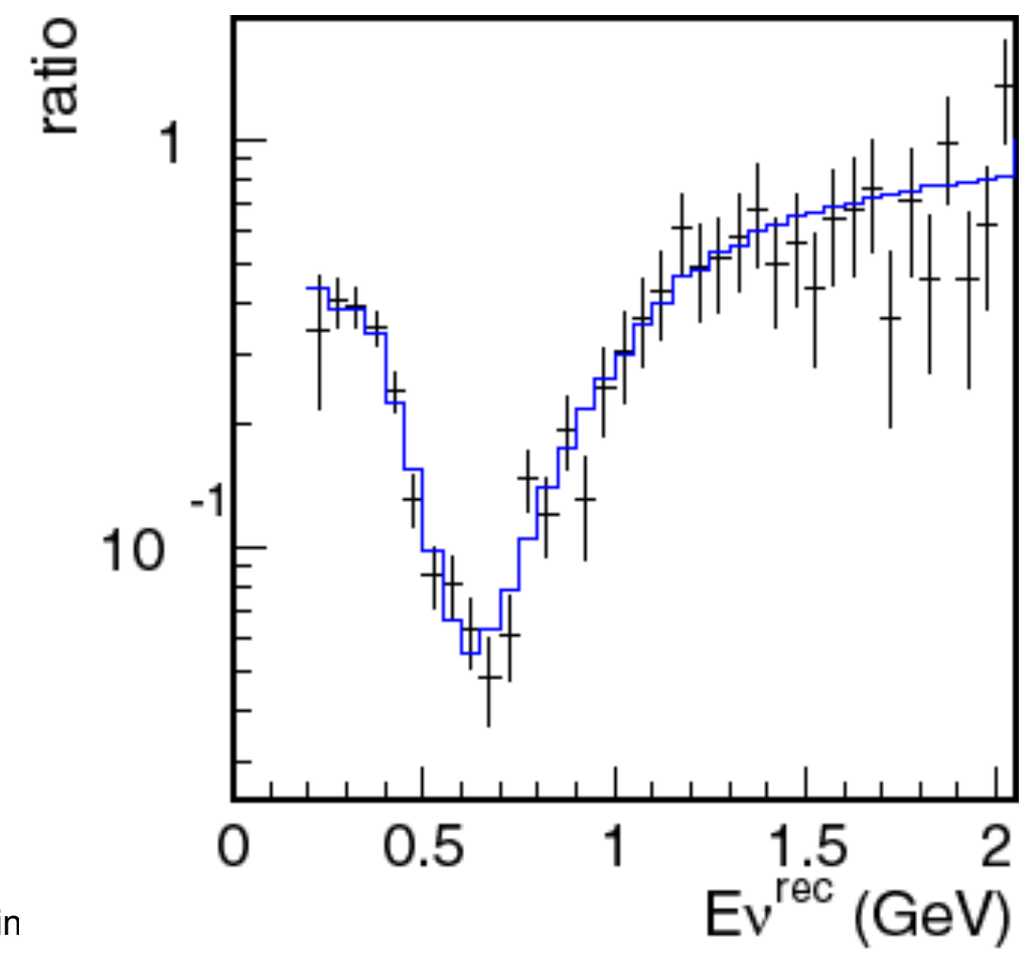

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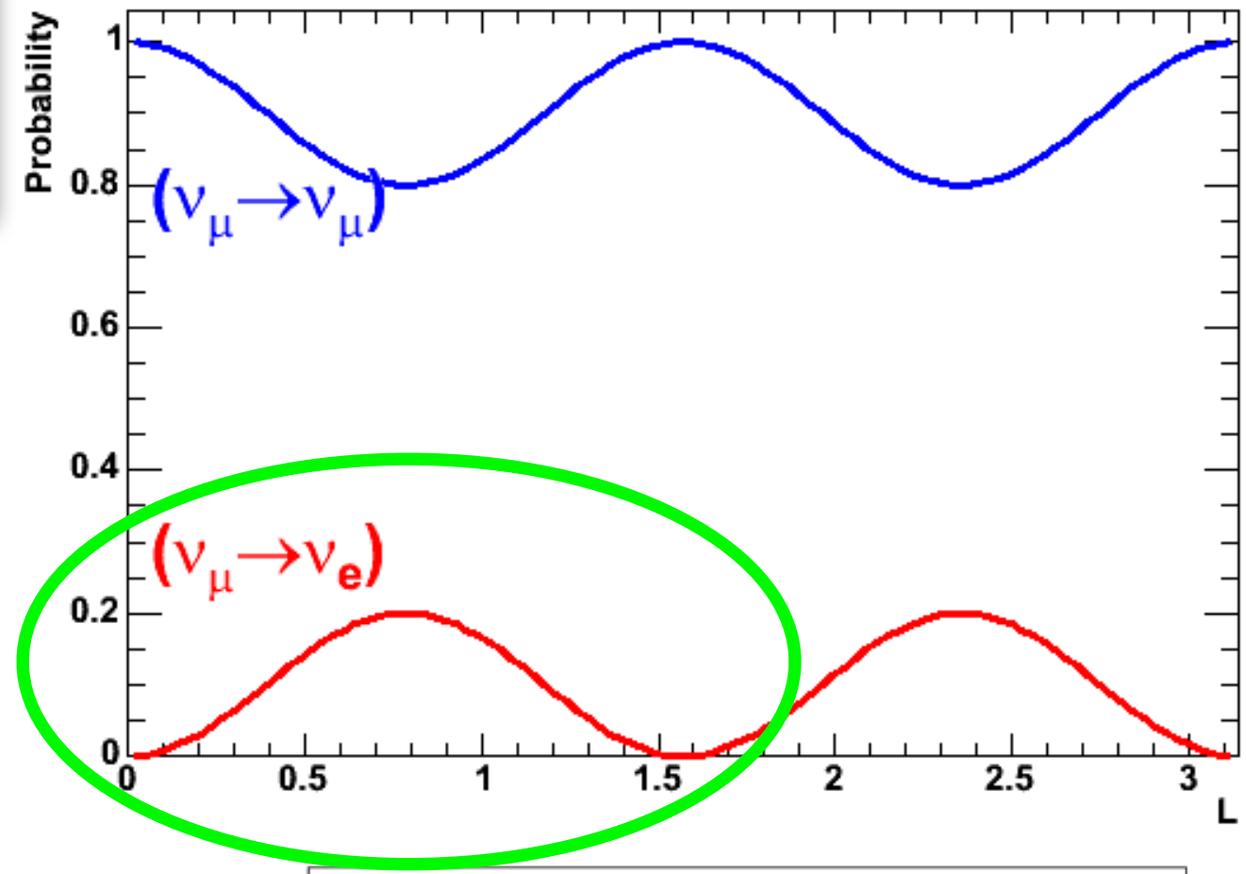
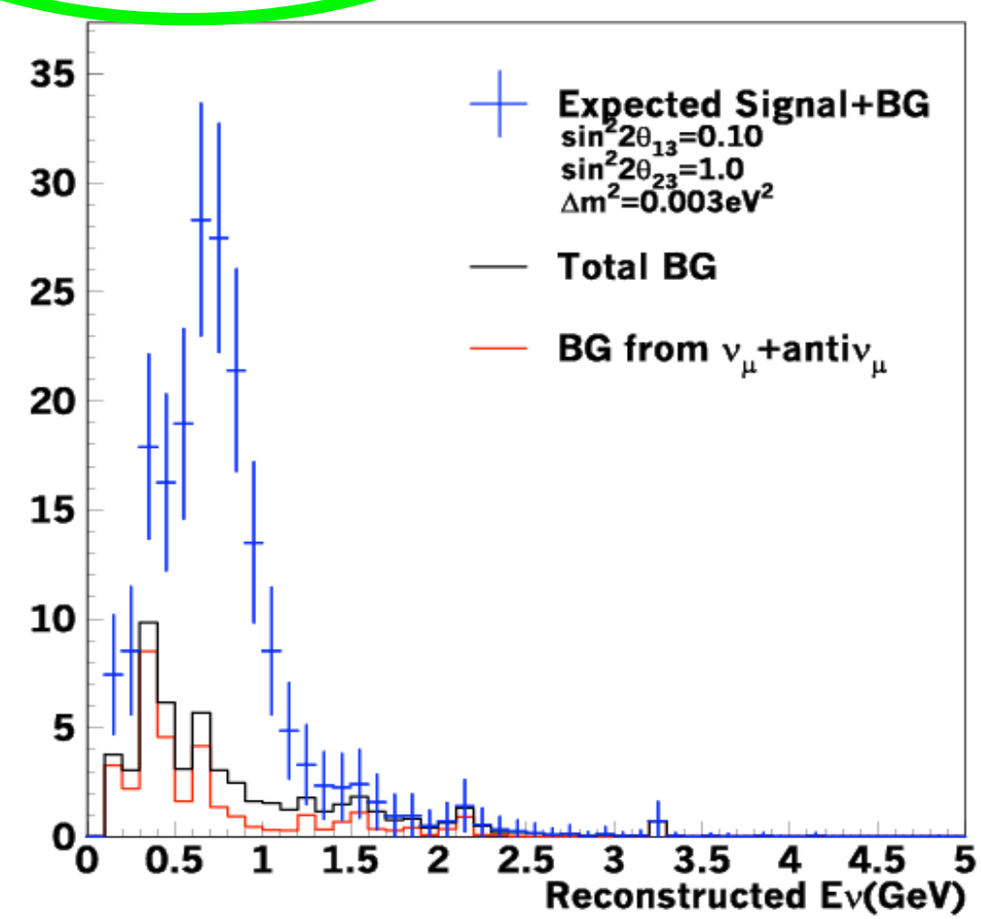
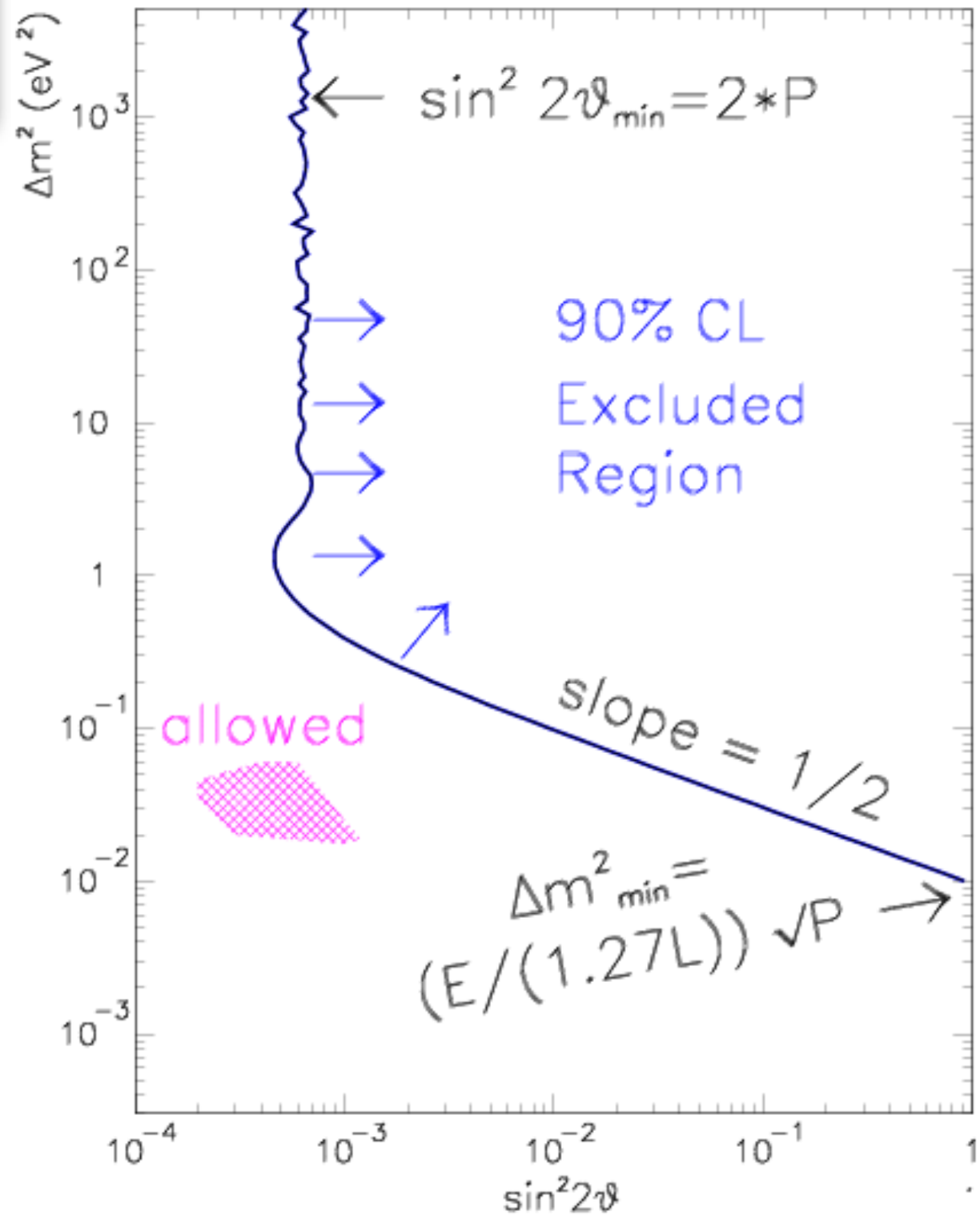


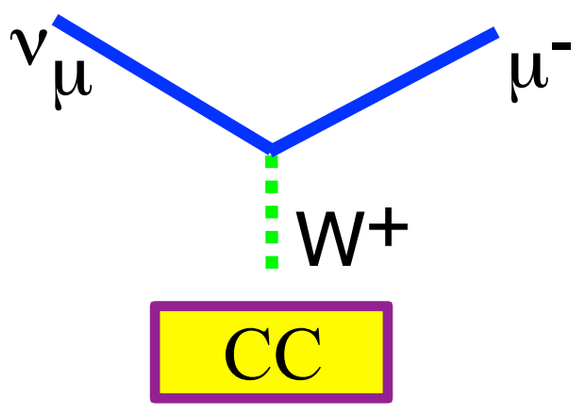


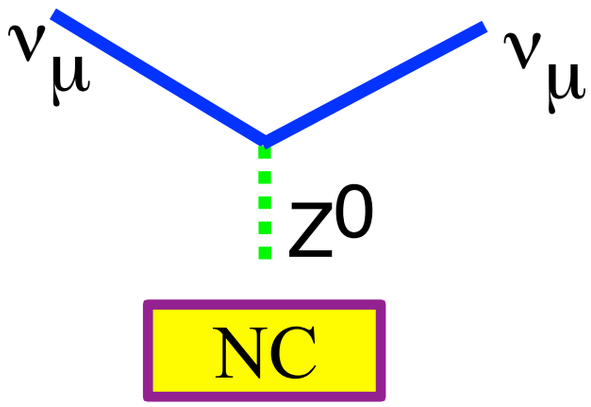
$$P(\nu_\mu \to \nu_e) = sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$

- 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 flavor, but require enough energy to produce rest mass of charged lepton!

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

Both interaction modes are useful for neutrino oscillation experiments!

Three flavors

flavor atmospheric cross-mixing solar mass

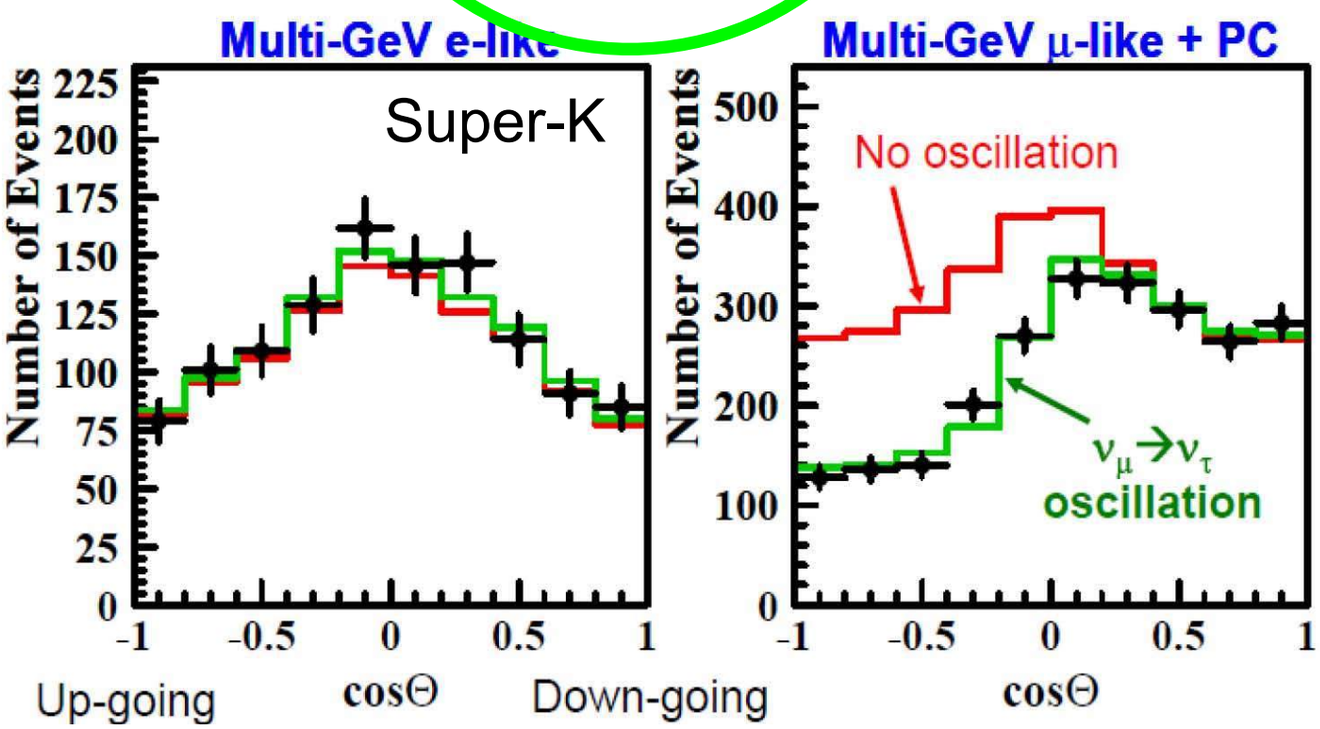
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}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

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

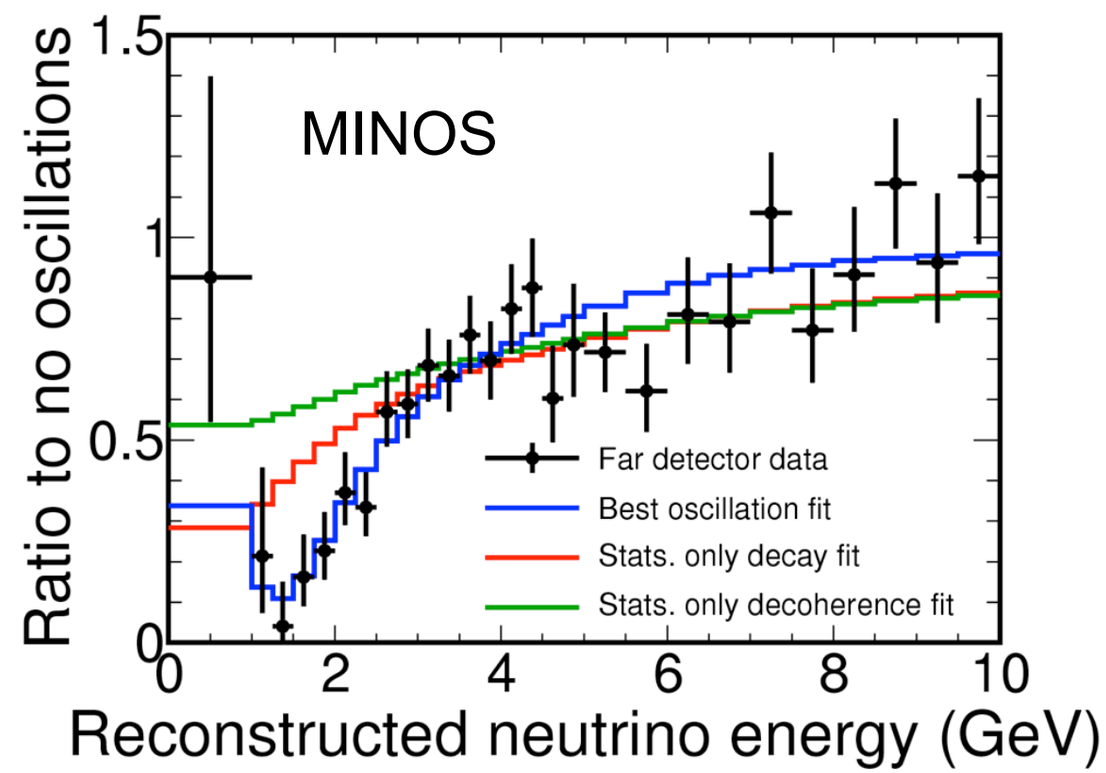
Atmospheric Oscillation

flavor atmospheric cross-mixing solar mass

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



Phys.Rev.Lett.81.1562(1998)

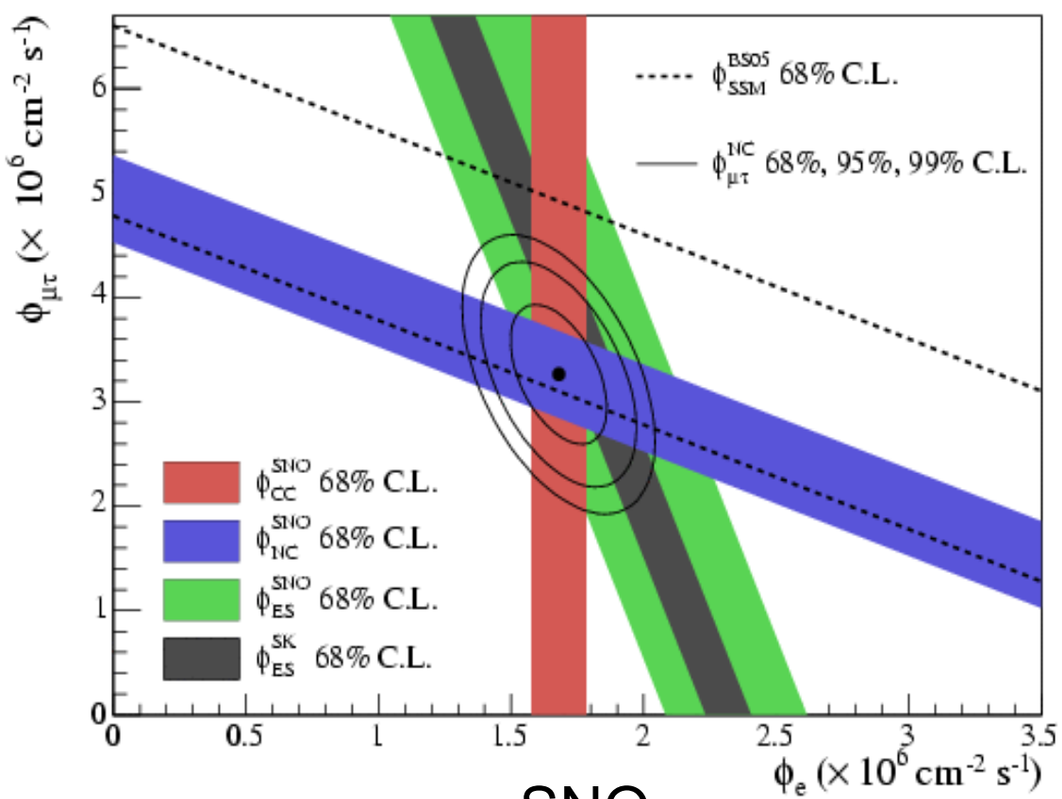


PhysRevLett.101.131802

Solar Oscillation

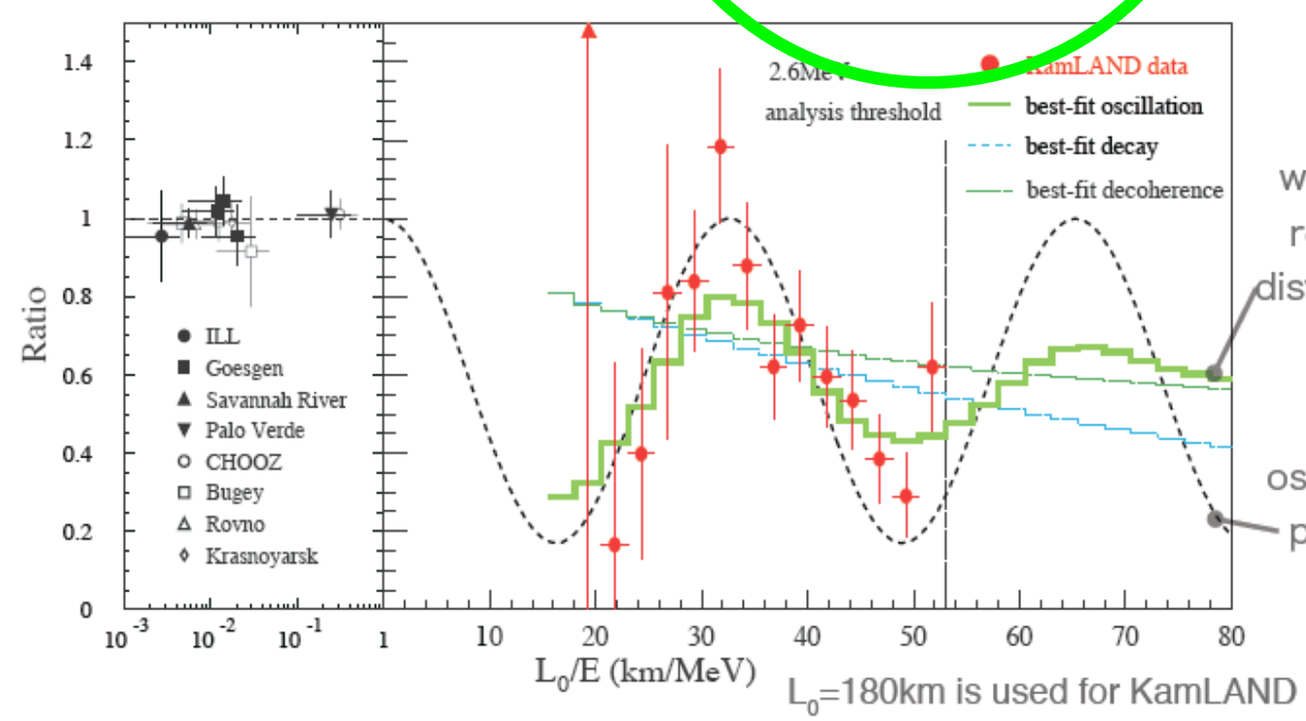
flavor atmospheric cross-mixing solar mass

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



SNO

Phys.Rev.Lett.89.011301 (2002)



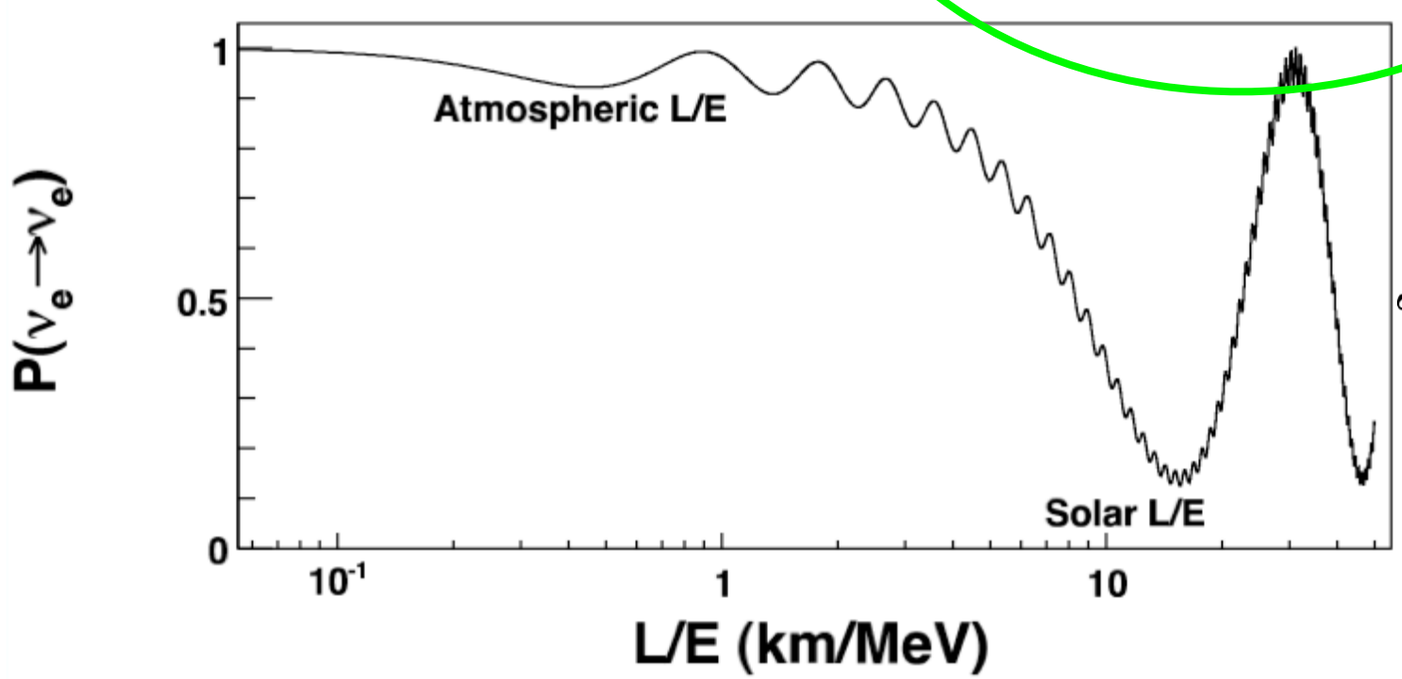
KamLAND

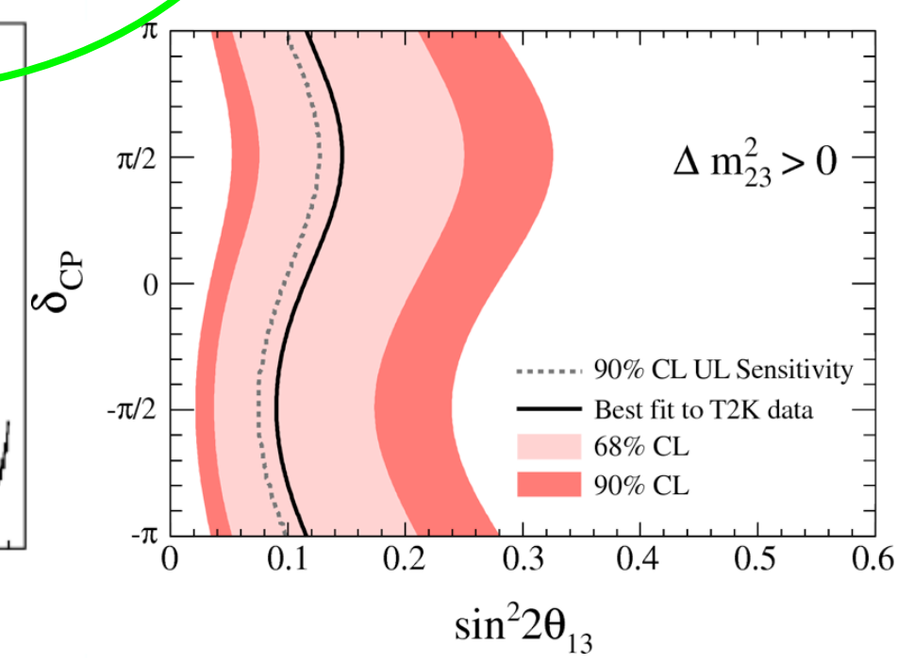
Phys.Rev.Lett.100.221803 (2008)

Cross Mixing

flavor atmospheric cross-mixing solar mass

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





Phys.Rev.Lett.107.041801 (2011)

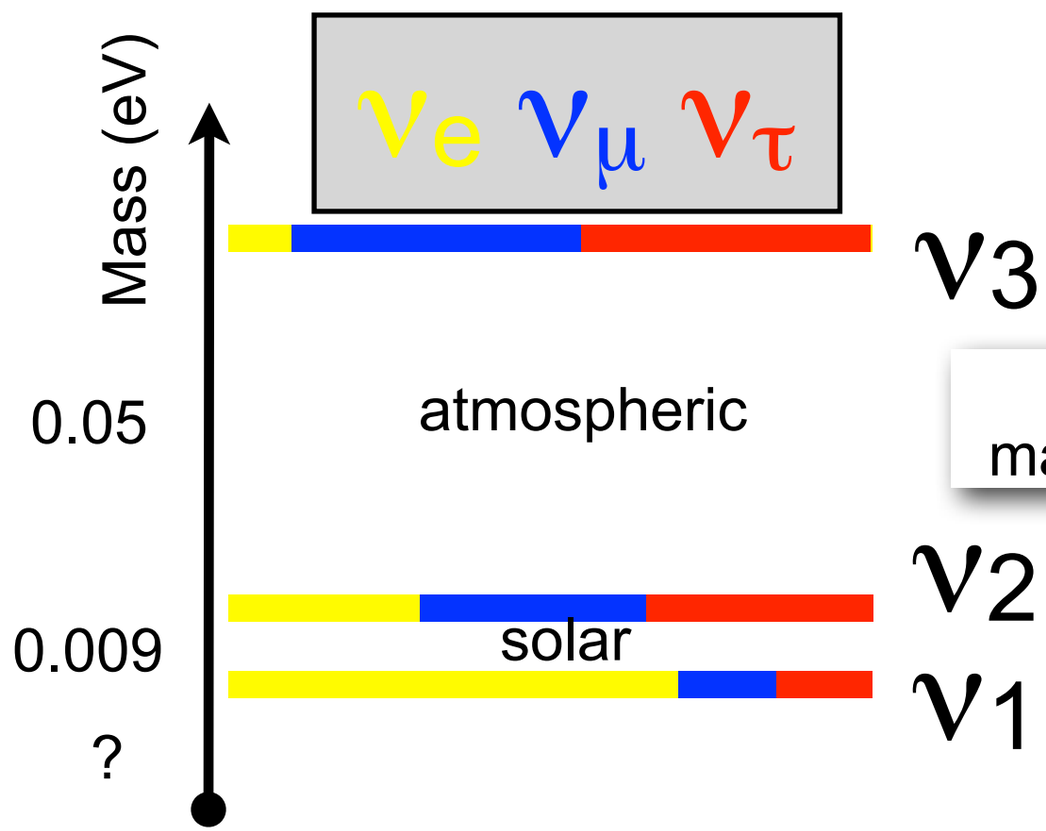
Causes $\bar{\nu}_e$ disappearance in reactors and ν_e appearance in accelerator experiments

Current picture

flavor 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 cij=cosθij, sij=sinθij

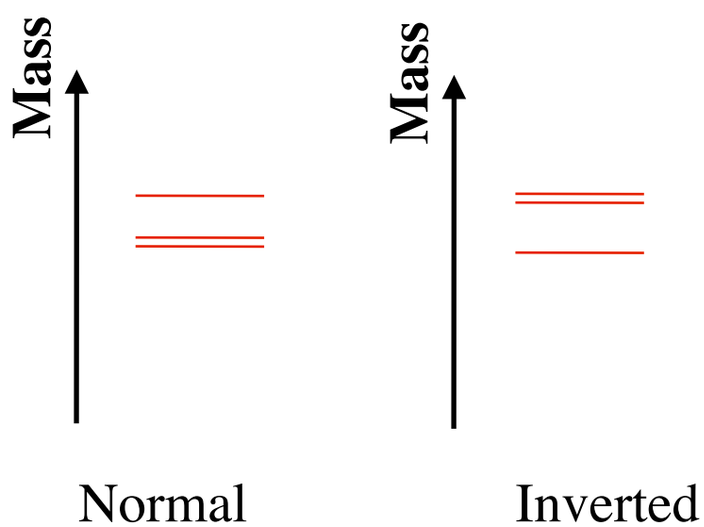


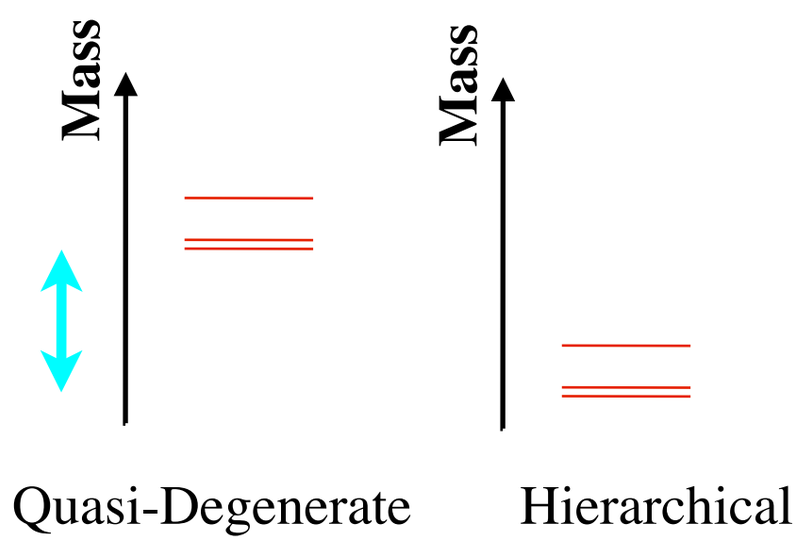
Non-zero δ:
matter vs antimatter

	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 flavor? GUTs?
- Cosmological and astrophysical implications

The LSND Signal

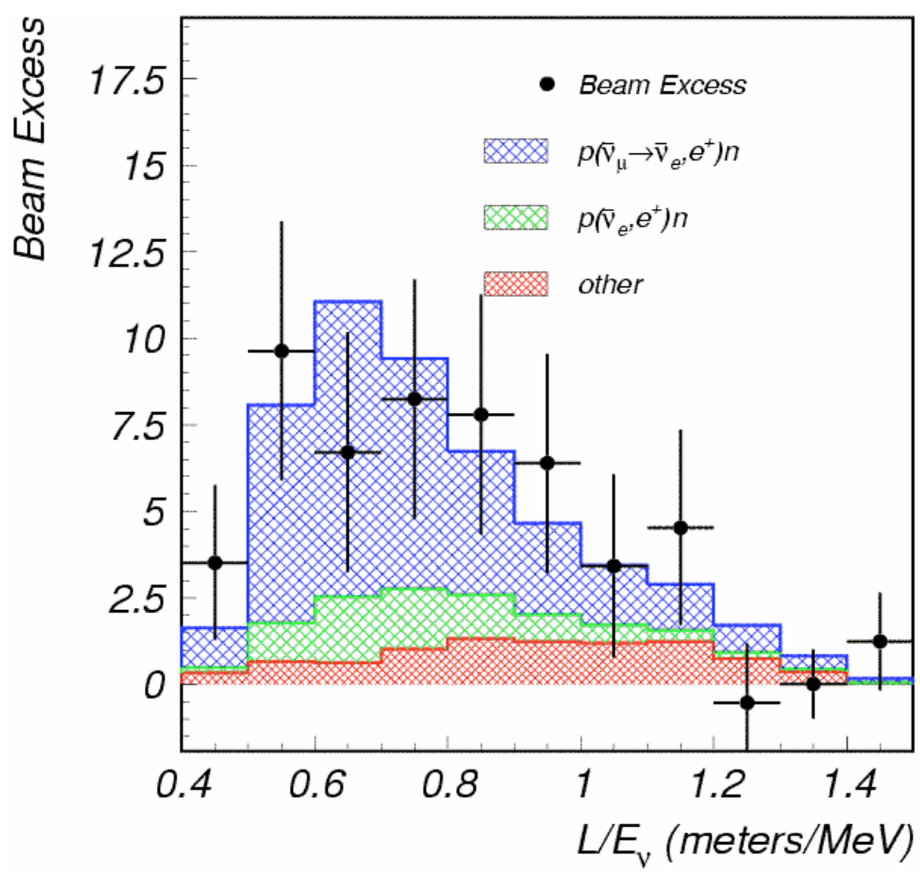
The LSND Signal

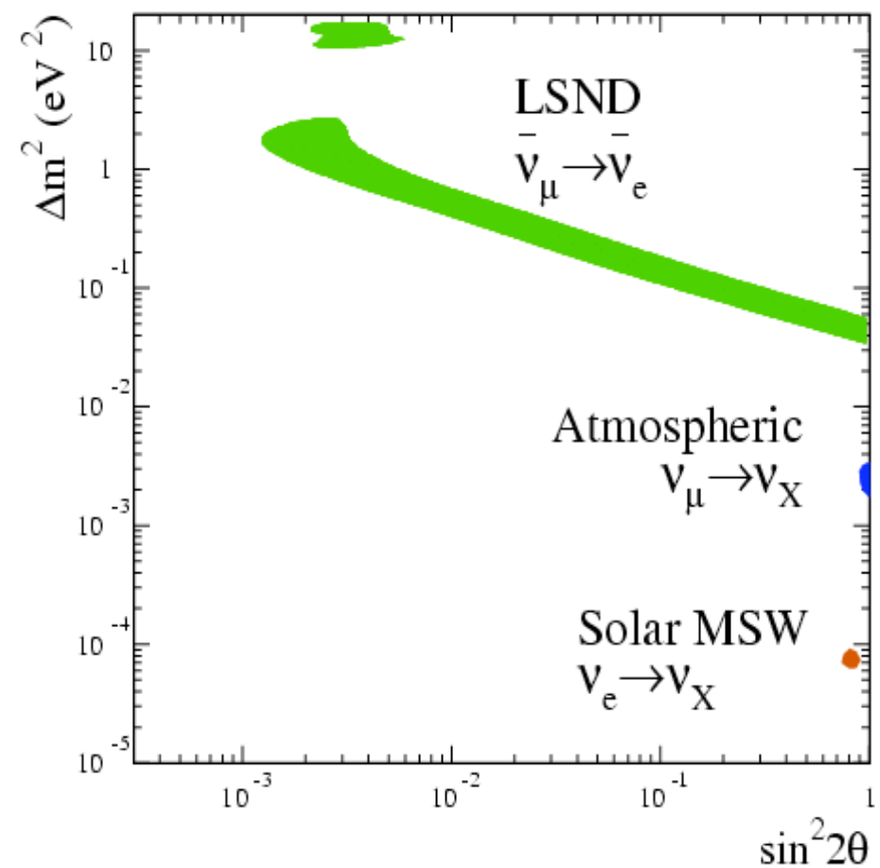
- The LSND experiment observed a small excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam.

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

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

Phys.Rev.D 64, 112007 (2001)

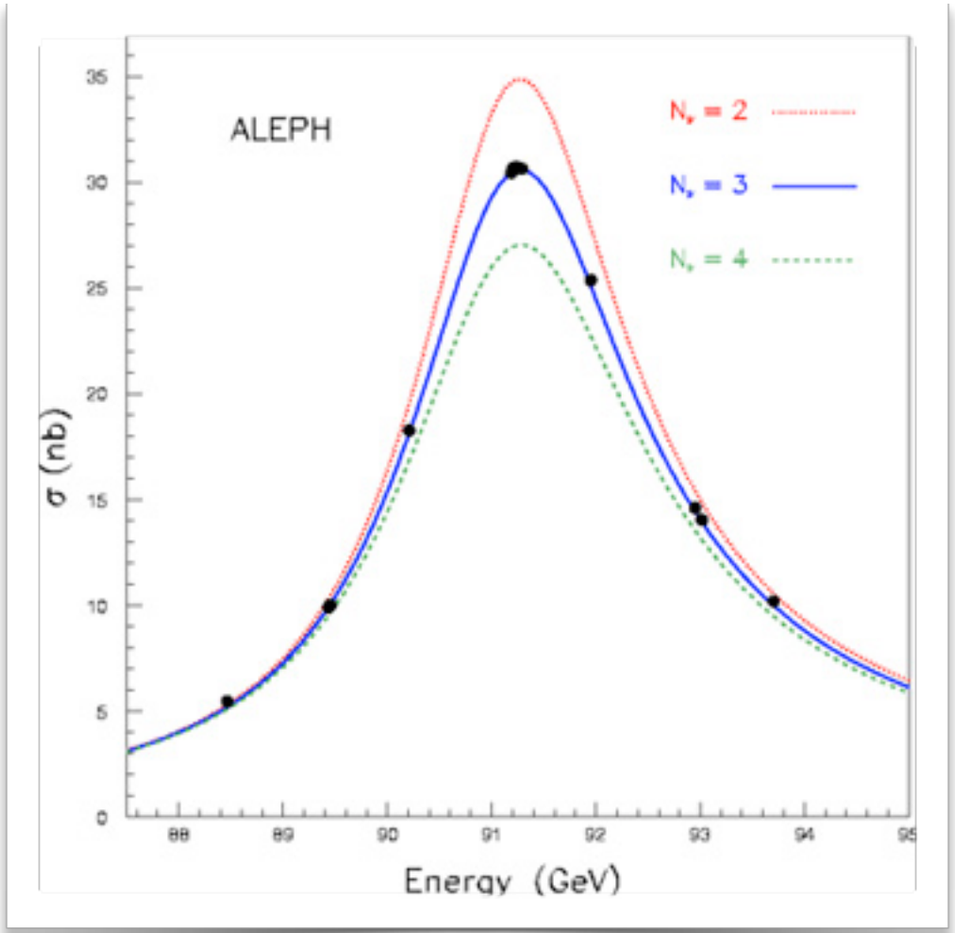




Sterile Neutrinos

- LEP experiments measured the number of light neutrinos: 3
- Only two independent Δm^2 values for 3 neutrinos
  - $2.5\times10^{-3} + 7.6\times10^{-5} \neq 1$
- 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)

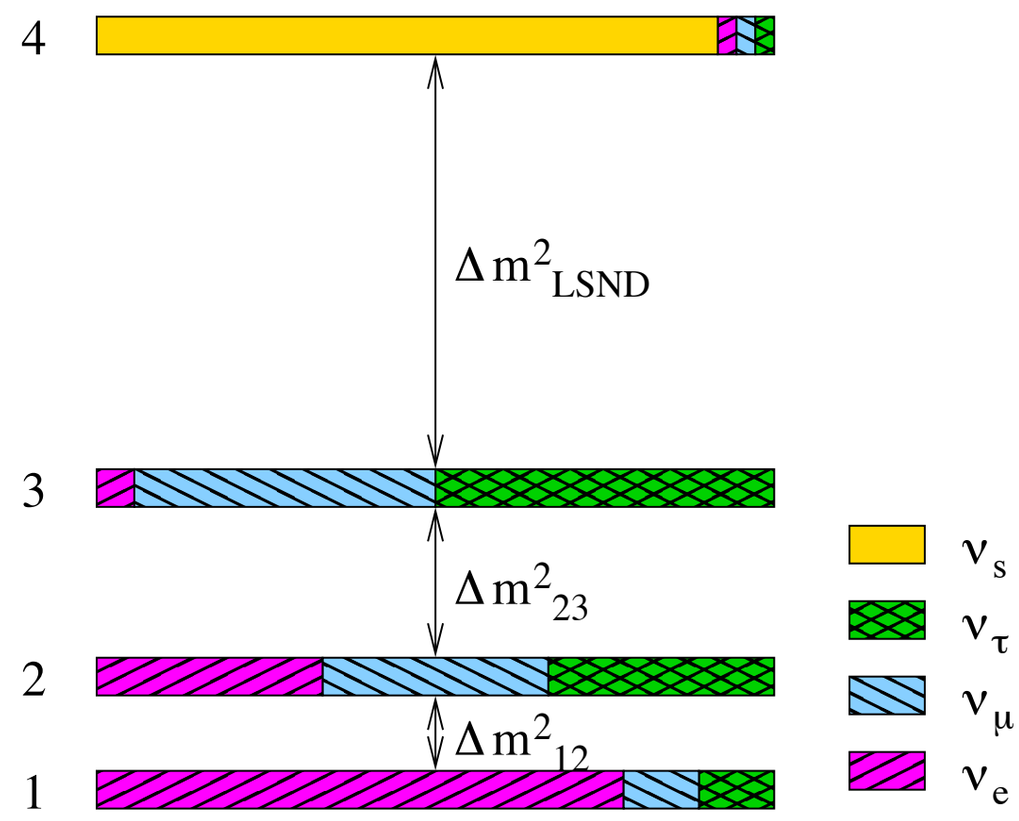
Active-sterile Neutrino Oscillation?

- 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.

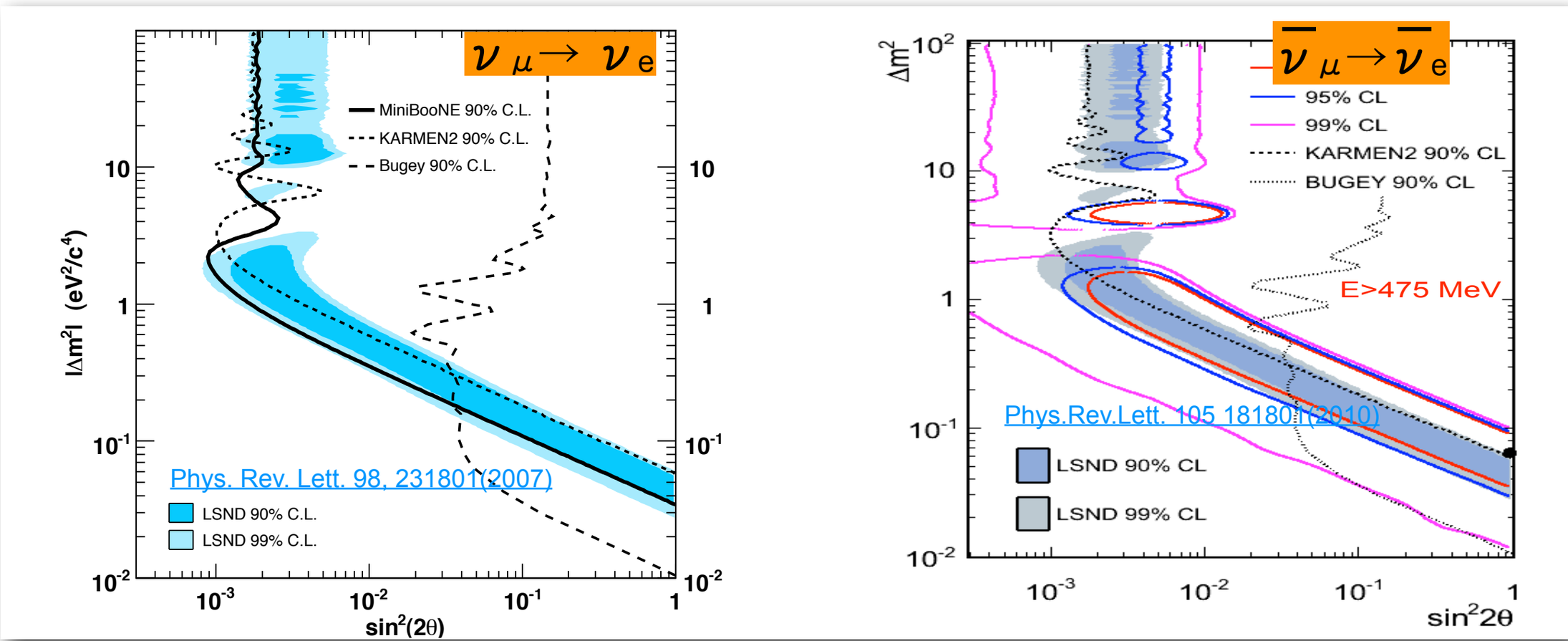
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix}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

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!



Appearance vs. Disappearance

Testing appearance signals with disappearance measurements

$\nu_\mu \rightarrow \nu_e$ appearance

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

ν_e disappearance

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

ν_μ disappearance

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

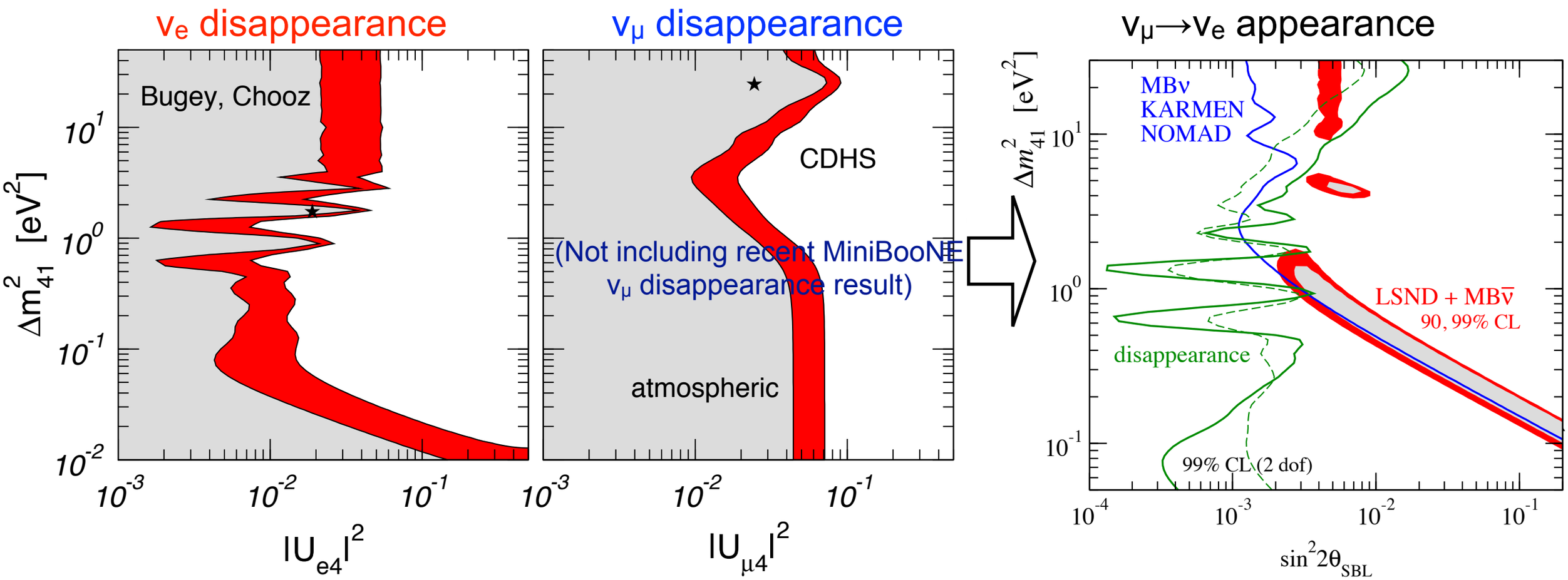
$\nu_\mu \rightarrow \nu_e$ appearance probability can be constrained by ν_e and ν_μ disappearance measurements!

Impact of Disappearance Experiments

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

M. Maltoni, J. Conf. Ser. 110, 082011 (2008)

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



- LSND region is incompatible 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)

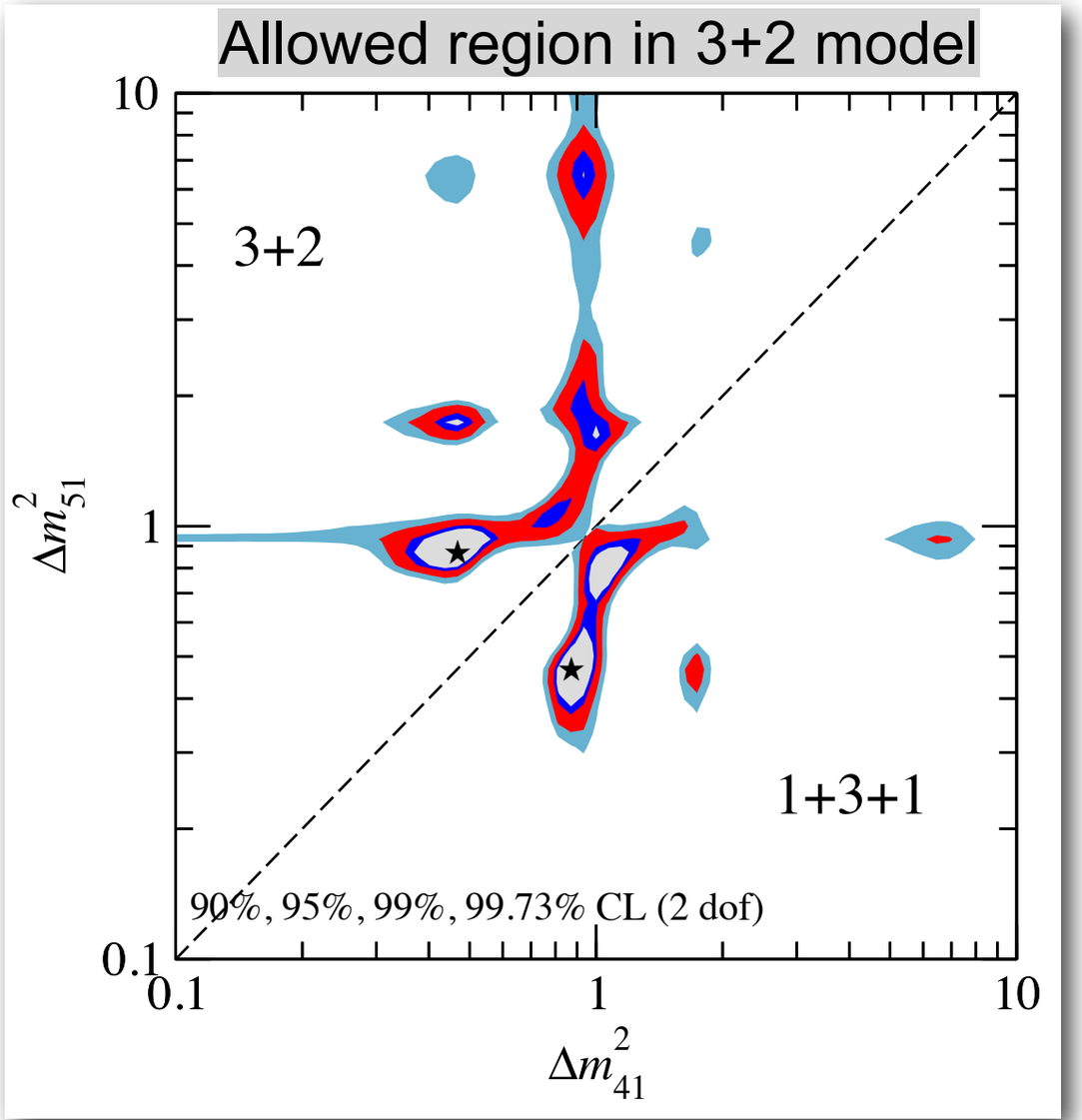
- Decaying sterile neutrino

  JHEP 09, 048 (2005)

- CPT violation

  PRD 77, 033001 (2008)

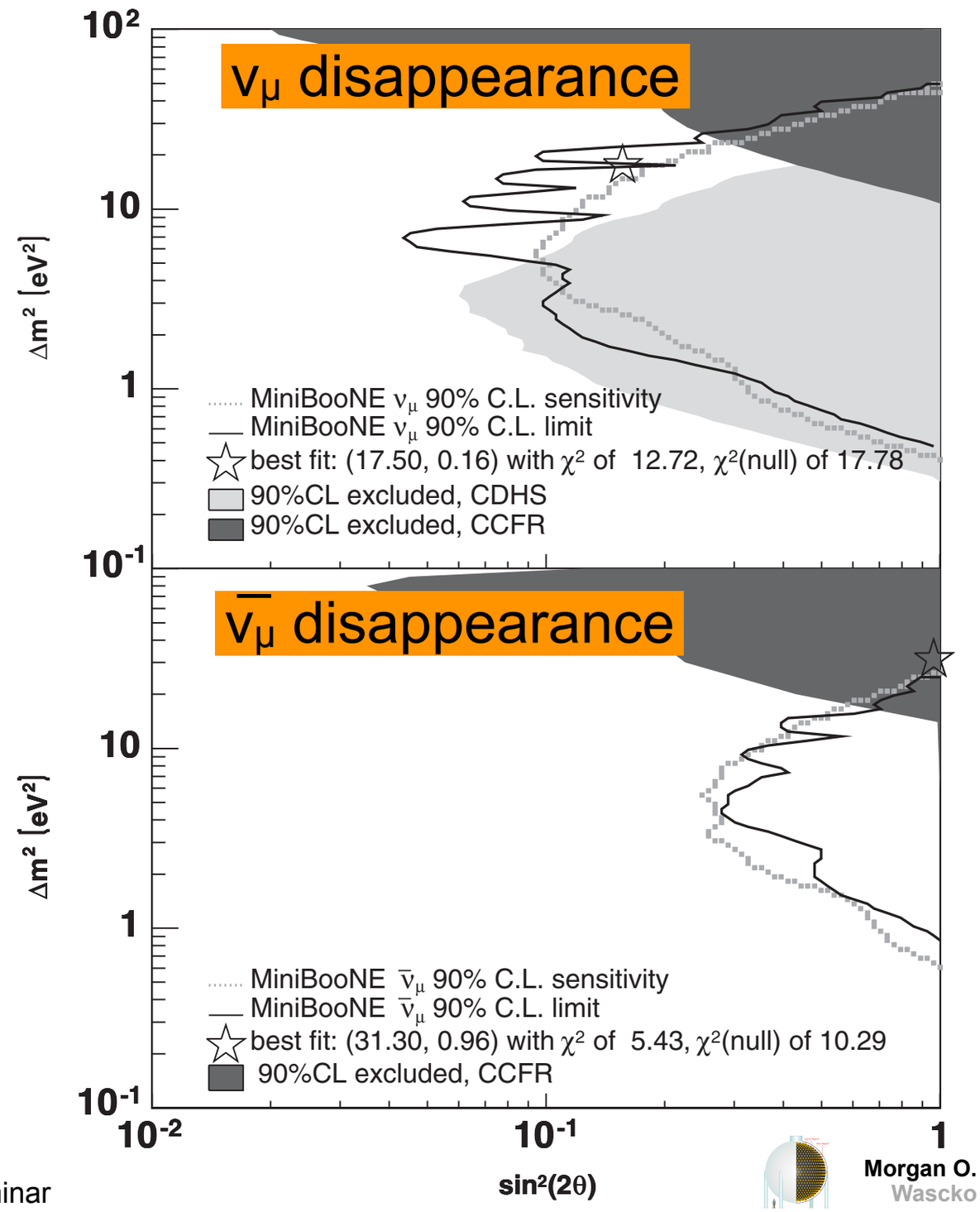
J. Kopp, M. Maltoni, T. Schwetz, arXiv:1103.4570

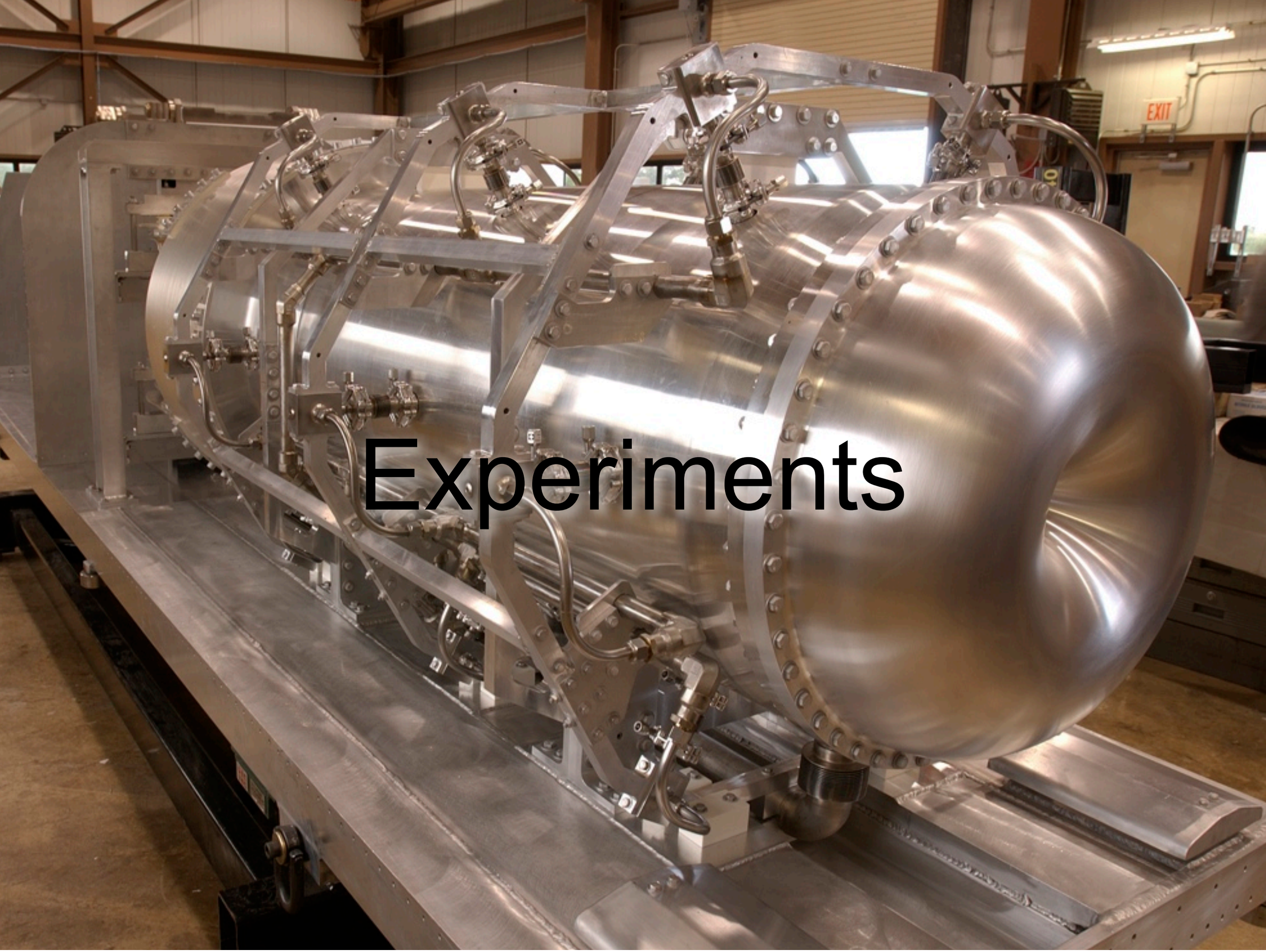


Disappearance measurements can constrain these models.

ν_μ Disappearance Measurements

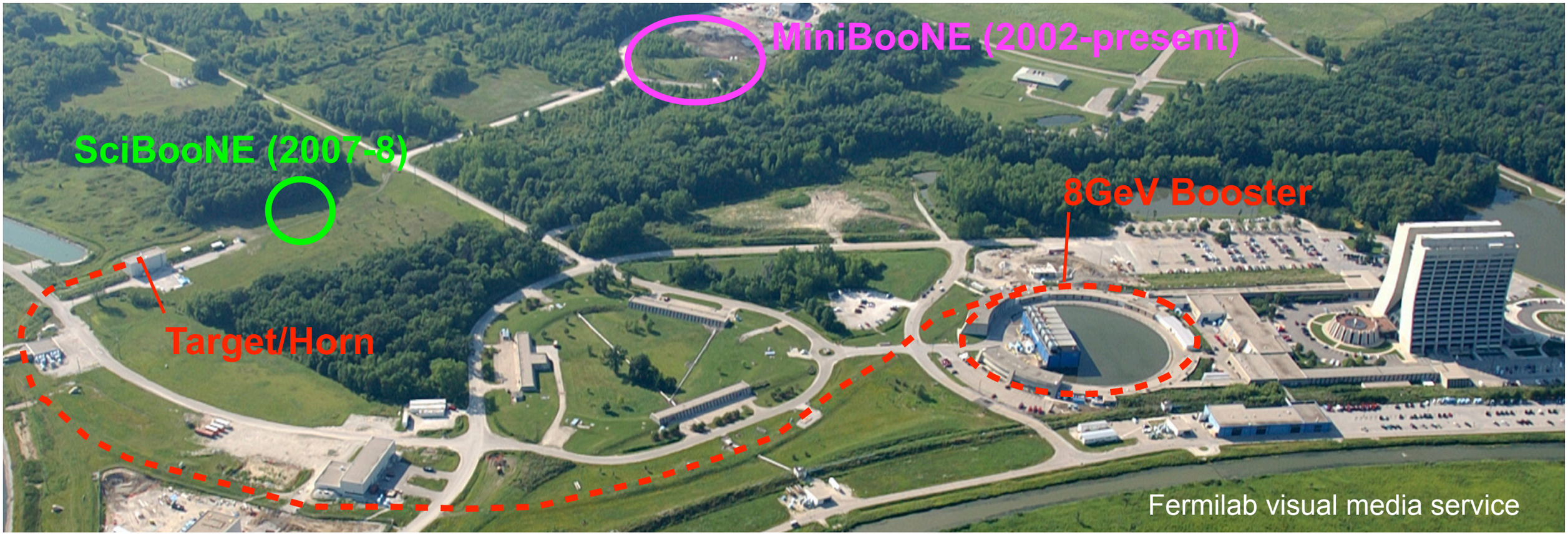
- Important to independently test ν_μ and $\bar{\nu}_\mu$ disappearance.
  - Testing CPT-invariance.
- Recently, MiniBooNE searched for ν_μ and $\bar{\nu}_\mu$ disappearance with MiniBooNE data only (PRL 103, 0611802)
- That analysis used the flux shape only, and suffered from large flux and cross section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

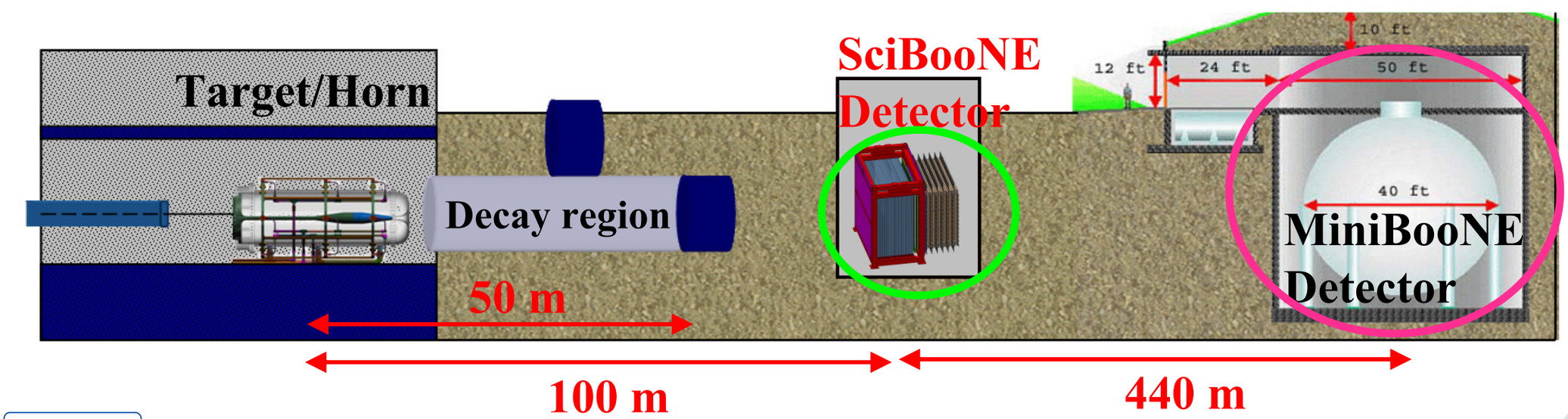




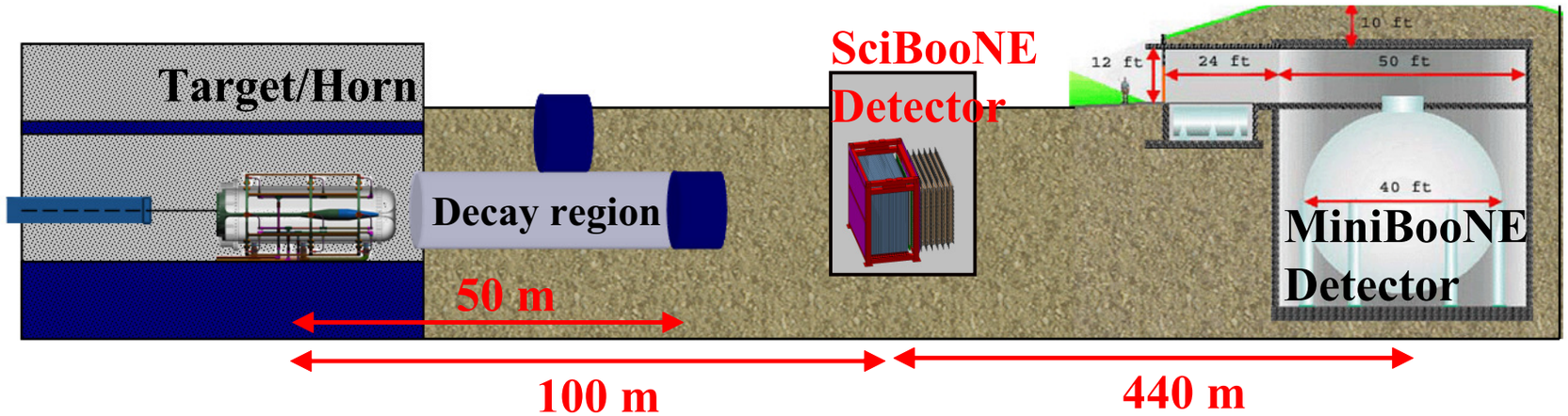
Experiments

Overview


MiniBooNE (2002-present)
SciBooNE (2007-8)
8GeV Booster
Target/Horn
Fermilab visual media service


Target/Horn
Decay region
SciBooNE
Detector
10 ft
12 ft
24 ft
50 ft
40 ft
MiniBooNE
Detector
50 m
100 m
440 m

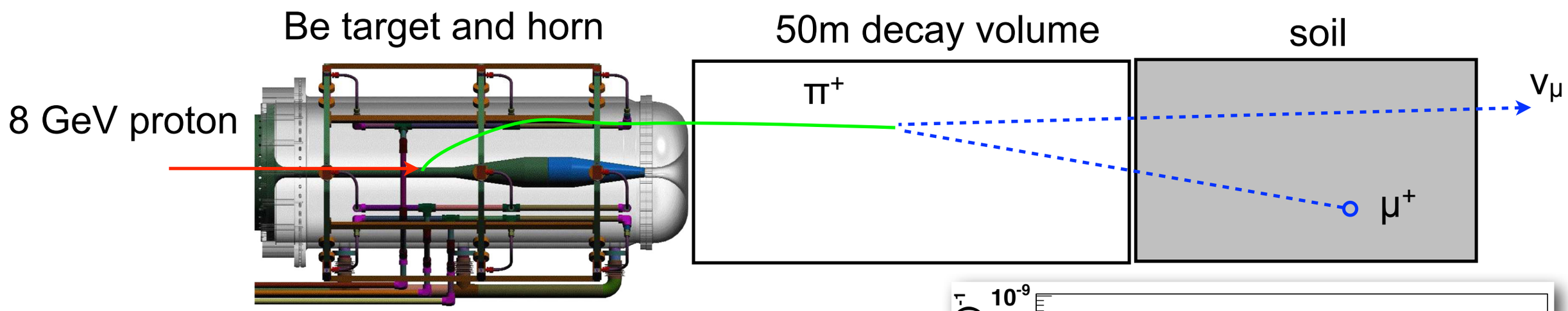
Overview



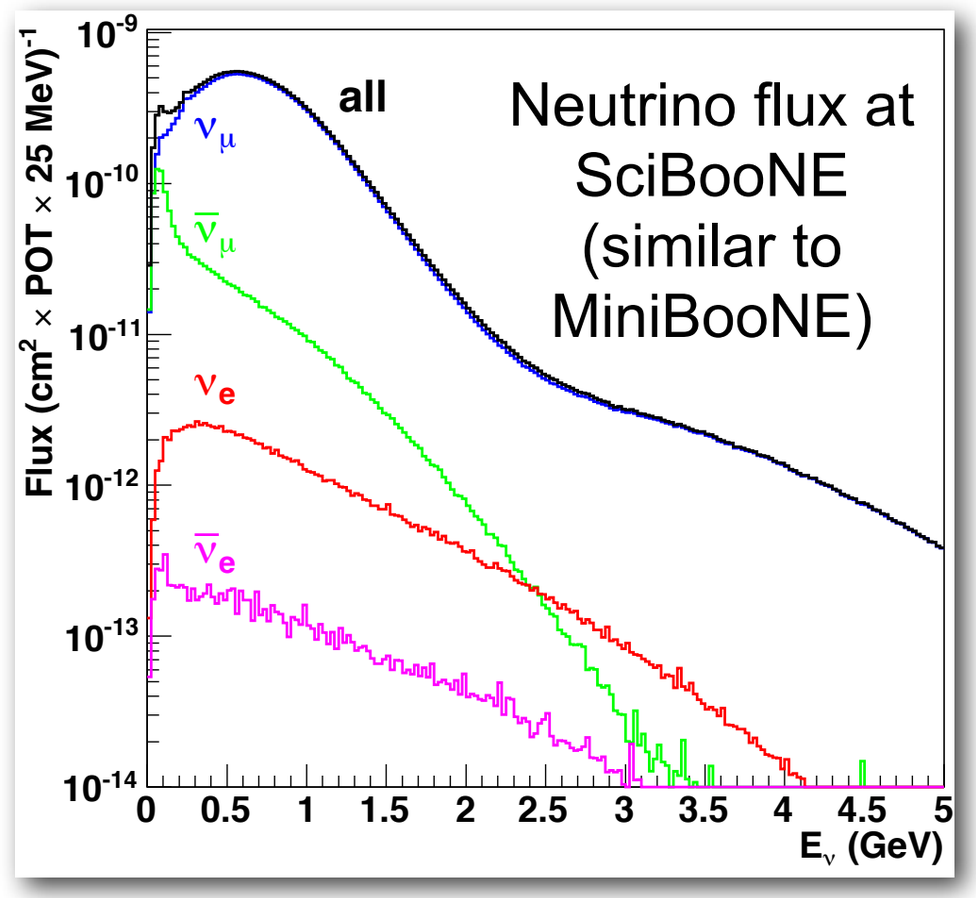
- MiniBooNE is designed to test the LSND signal
  - LSND L/E: 20m/30MeV ~ 0.7 meter/MeV
  - MiniBooNE L/E: 540m / 0.8 GeV ~ 0.7 m/MeV
- SciBooNE (2007-2008) has two purposes
  - Precise measurement of neutrino cross section for future oscillation experiments (T2K, etc)
  - MiniBooNE near detector

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

Fermilab Booster ν Beam

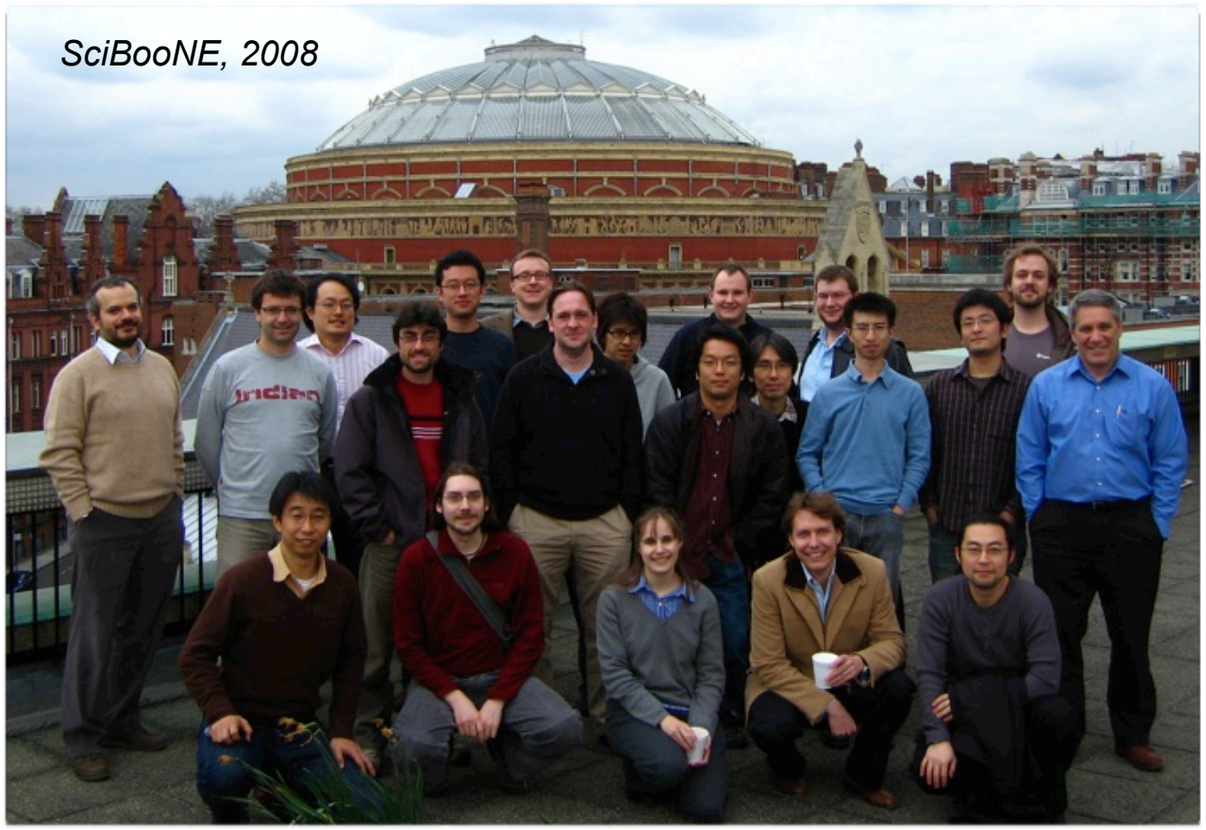


- Intense ν_μ beam with the mean energy of ~0.8 GeV
  - 93% pure ν_μ beam.
- $\bar{\nu}_\mu$ beam is also produced by inverting horn polarity.



Phys.Rev.D79,072002(2009)

SciBooNE Collaboration

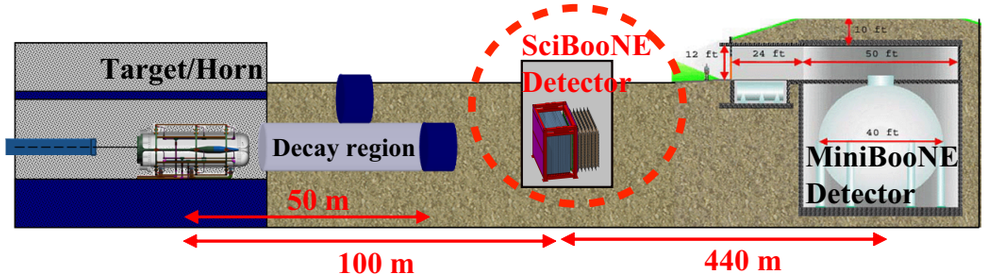


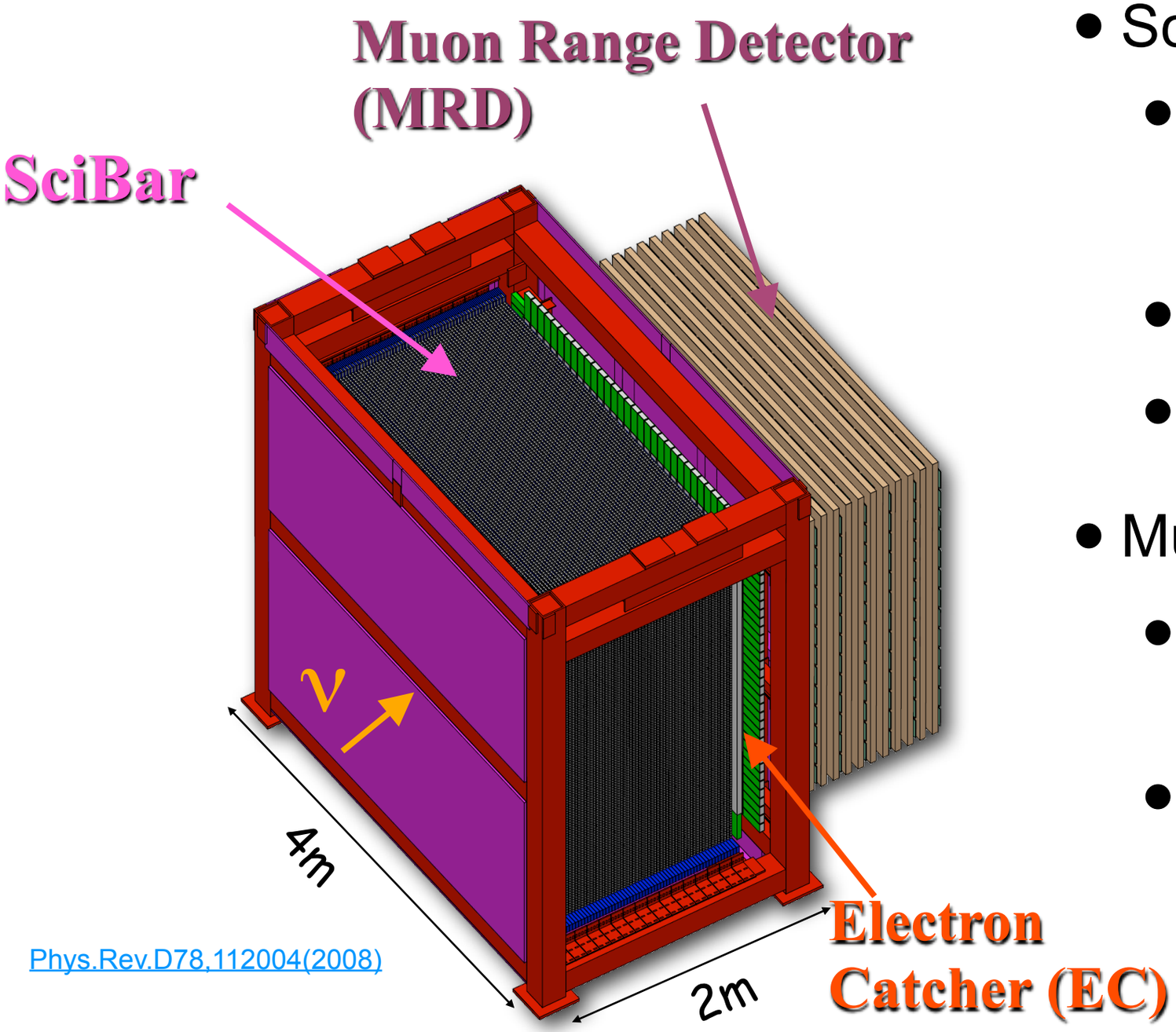
Universitat Autonoma de Barcelona
University of Cincinnati
University of Colorado, Boulder
Columbia University
Fermi National Accelerator Laboratory
High Energy Accelerator Research Organization (KEK)
Imperial College London
Indiana University
Institute for Cosmic Ray Research (ICRR)
Kyoto University
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

63 physicists
5 countries 18 institutions

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

A. A. Aguilar-Arevalo[5], A. O. Bazarko[12], S. J. Brice[7], B. C. Brown[7], L. Bugel[5], J. Cao[11], L. Coney[5], 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], R. Van de Water[9], D. H. White[9], M. J. Wilking[4], H. J. Yang[11], G. P. Zeller[5], E. D. Zimmerman[4]

[1] *University of Alabama, Tuscaloosa, AL 35487*
[2] *Bucknell University, Lewisburg, PA 17837*
[3] *University of Cincinnati, Cincinnati, OH 45221*
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[5] *Columbia University, New York, NY 10027*
[6] *Embry Riddle Aeronautical University, Prescott, AZ 86301*
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[8] *Indiana University, Bloomington, IN 47405*
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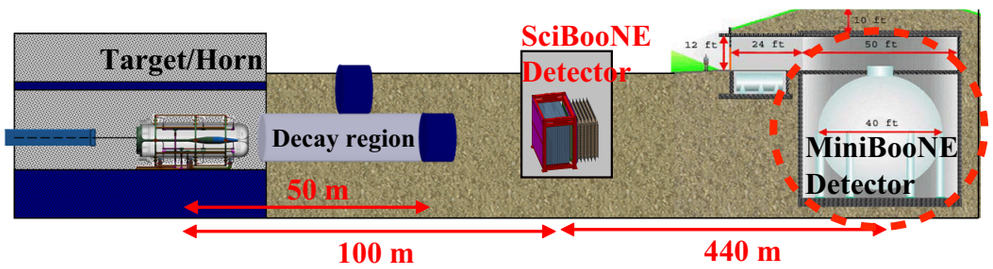
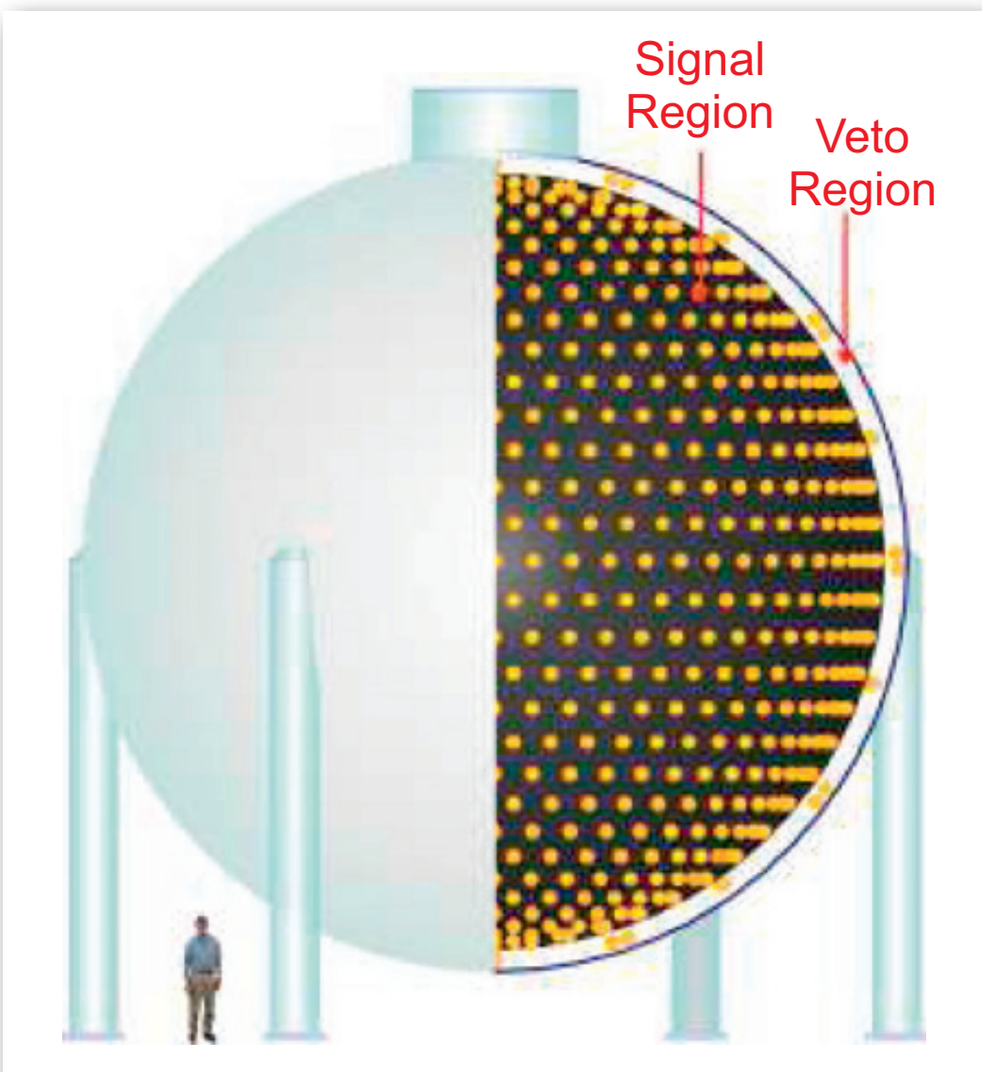
[10] *Louisiana State University, Baton Rouge, LA 70803*
[11] *University of Michigan, Ann Arbor, MI 48109*
[12] *Princeton University, Princeton, NJ 08544*
[13] *Saint Mary's University of Minnesota, Winona, MN 55987*
[14] *Virginia Polytechnic Institute & State University, Blacksburg, VA 24061*
[15] *Western Illinois University, Macomb, IL 61455*
[16] *Yale University, New Haven, CT 06520*

MiniBooNE detector





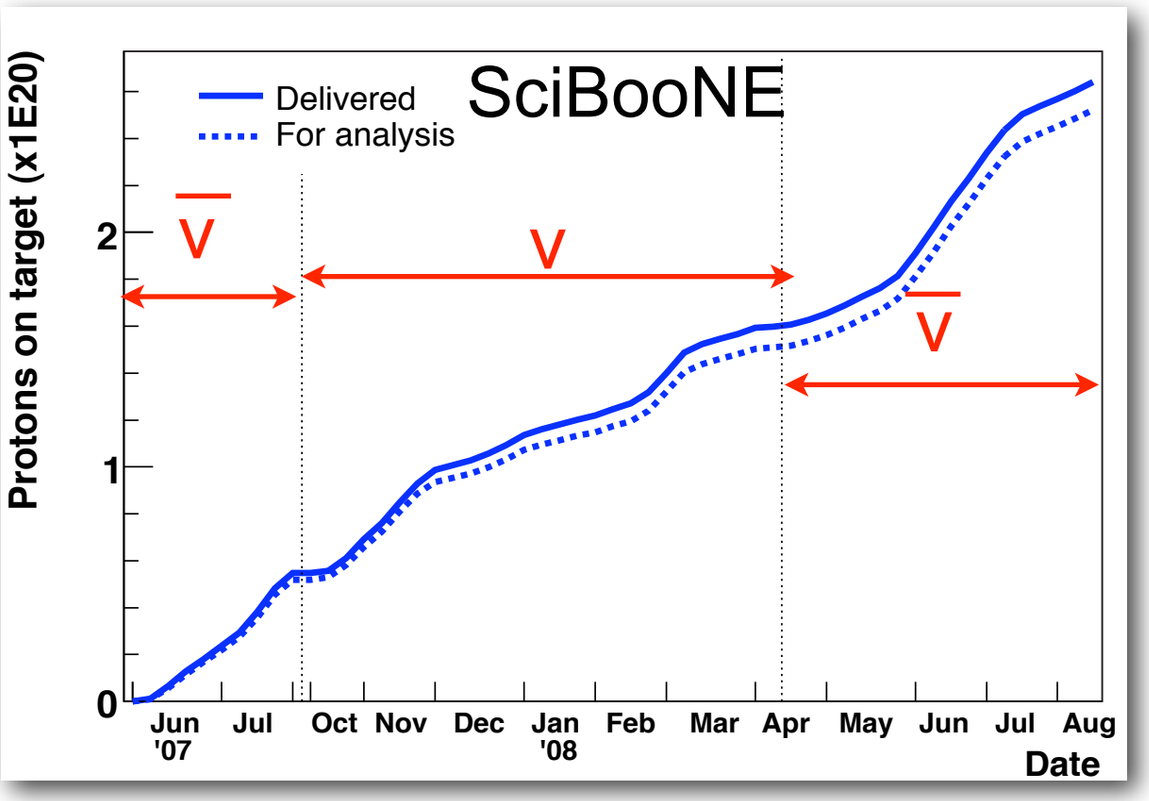
- Located 540 m from target
- Mineral oil Cherenkov detector
  - n = 1.47
  - Select ν_μ with single muon and decay electron signal.
  - Total mass: 800 ton
  - Main component: CH_2
- Taking beam data since 2002

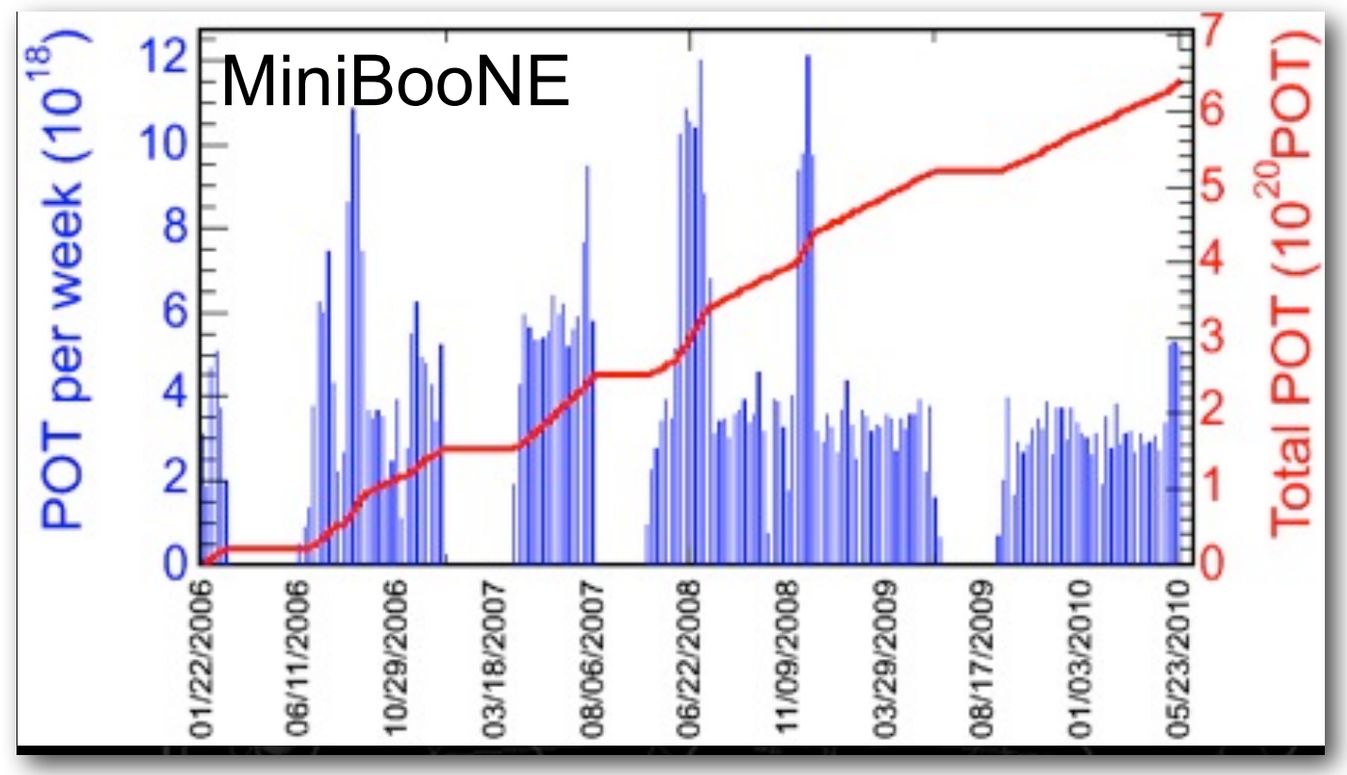
Nucl.Instrum.Meth.A599:28-46,2009

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

Data sets

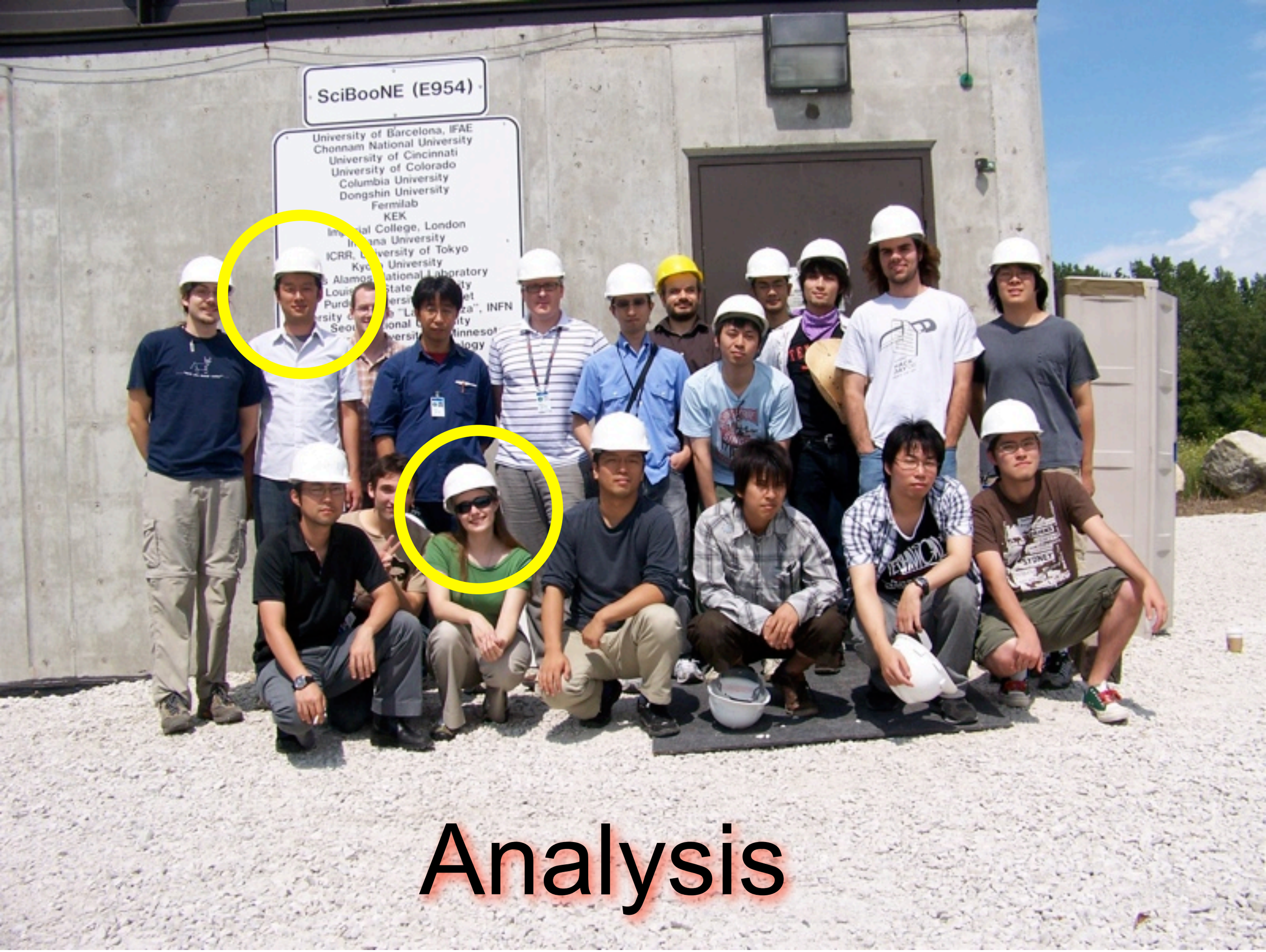
Period	BNB Mode	SciBooNE POT	MiniBooNE POT
Sep. 2002 - Dec. 2005	Neutrino	–	5.58×10^{20}
Jan. 2006 - Aug. 2007	Antineutrino	0.52×10^{20} (from Jun. 2007)	1.71×10^{20}
Oct. 2007 - Apr. 2008	Neutrino	0.99×10^{20}	0.83×10^{20}
Apr. 2008 - present	Antineutrino	1.01×10^{20} (until Aug. 2008)	ongoing





Analysis of the full neutrino data sets is presented today

- SciBooNE: 0.99 x 10^{20} POT
- MiniBooNE: (5.58 + 0.83) x 10^{20} POT


SciBooNE (E954)
University of Barcelona, IFAE
Chonnam National University
University of Cincinnati
University of Colorado
Columbia University
Dongshin University
Fermilab
KEK
Indiana University
Kyoto University
Purdue
Seoul
Minnesota

Analysis

Analysis Overview

Two independent analyses

Spectrum fit

SciBooNE data

↓ Spectrum fit

CC interaction rate measurement

↓

MiniBooNE rec. E_ν prediction

↕ Oscillation Fit

MiniBooNE rec. E_ν data

Advantage:
Decouple oscillation fit from constraint.
Observe the effects of the constraint.

Simultaneous fit

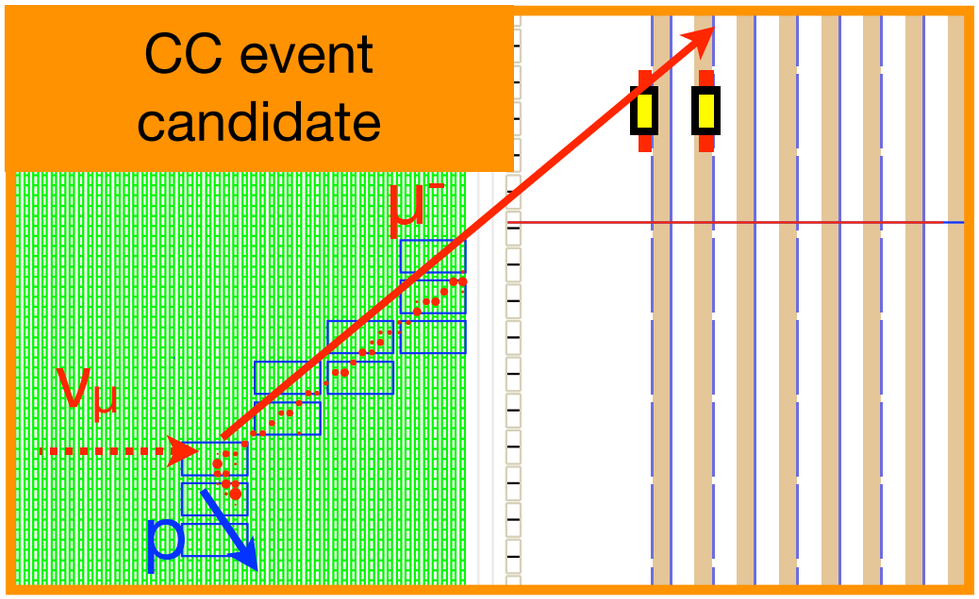
SB + MB Rec. E_ν Data

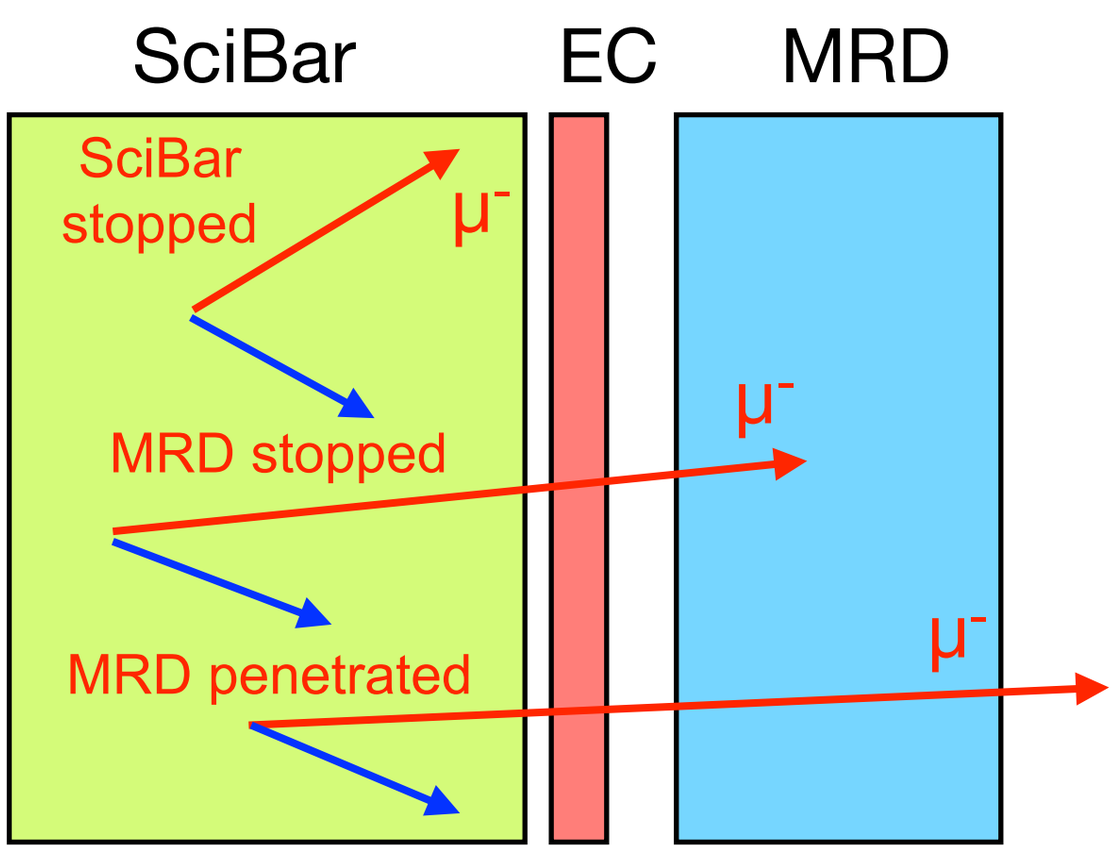
↕ Oscillation Fit

SB + MB Rec. E_ν Prediction

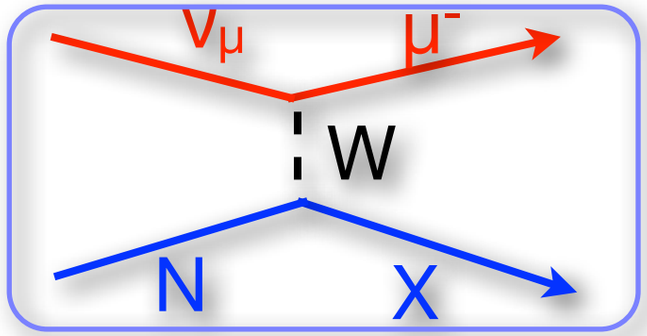
Advantage:
Direct fit for disappearance in SciBooNE and MiniBooNE.
Correlation between the two constrain systematic error.

SciBooNE event selection



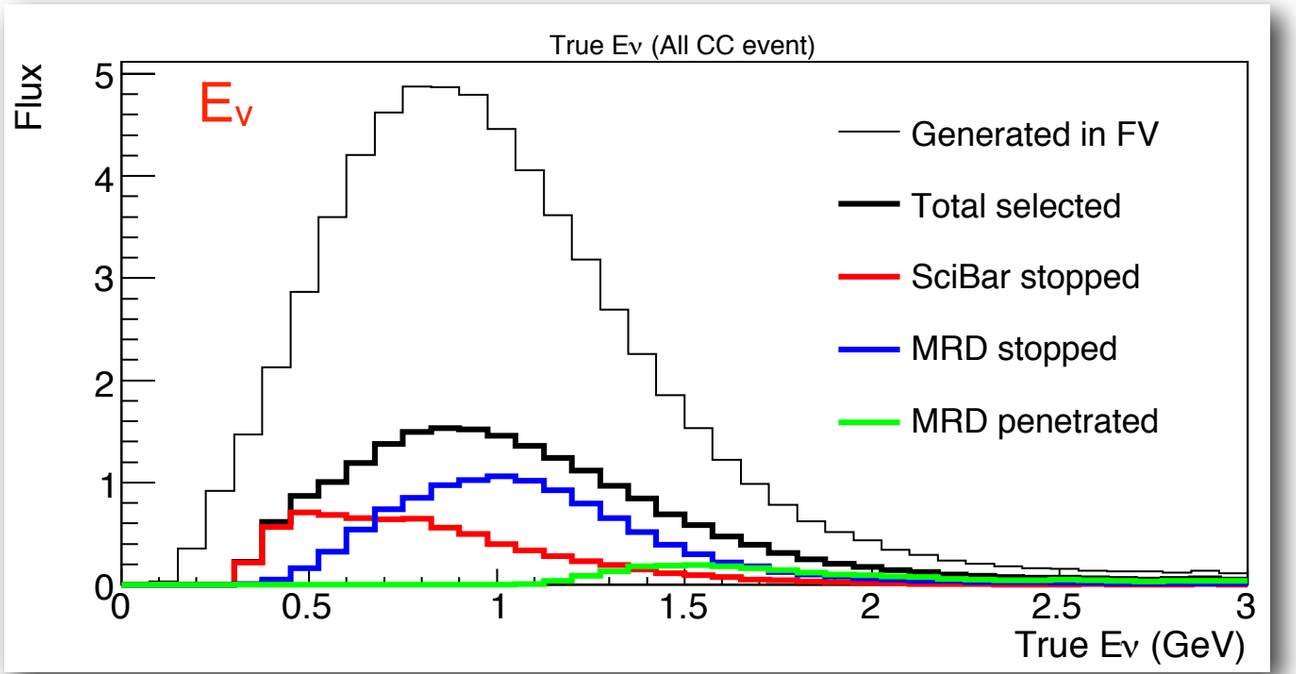


Use charged current inclusive sample



- 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)

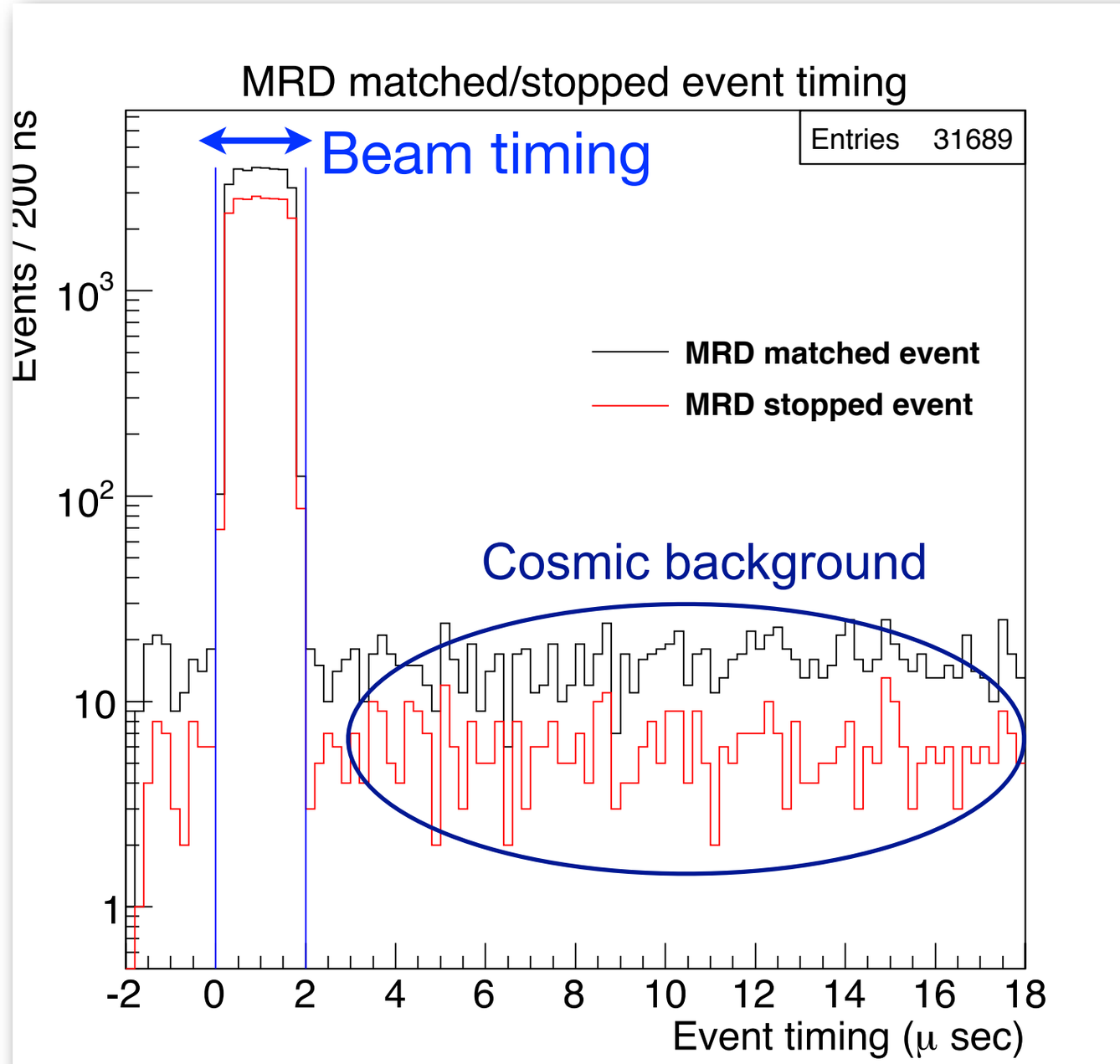
P_μ: Muon momentum reconstructed by its path-length
θ_μ: Muon angle w.r.t. beam axis



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.

- ~14K SciBar-stopped events.
- ~20K MRD-stopped events.
- ~4K MRD-penetrated events.



Muon distributions

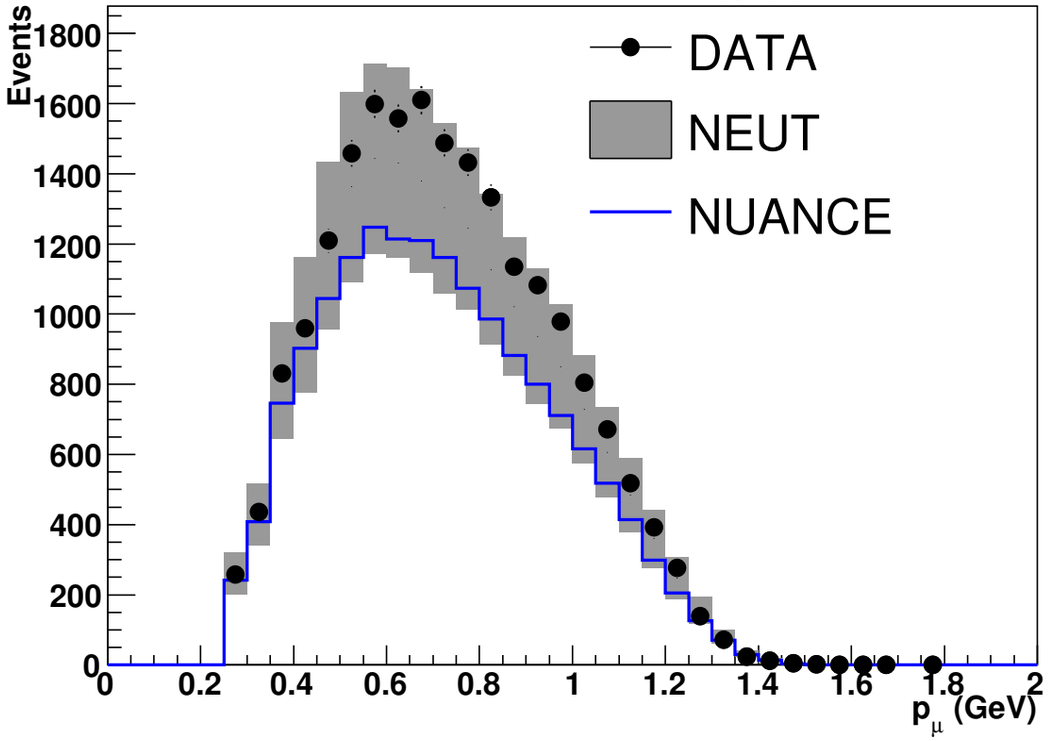
- We use two neutrino interaction generators

NEUT: SK, K2K, T2K, etc (+ all other cross section measurements in SciBooNE)
NUANCE: MiniBooNE, etc (Use NUANCE for this joint oscillation analysis)

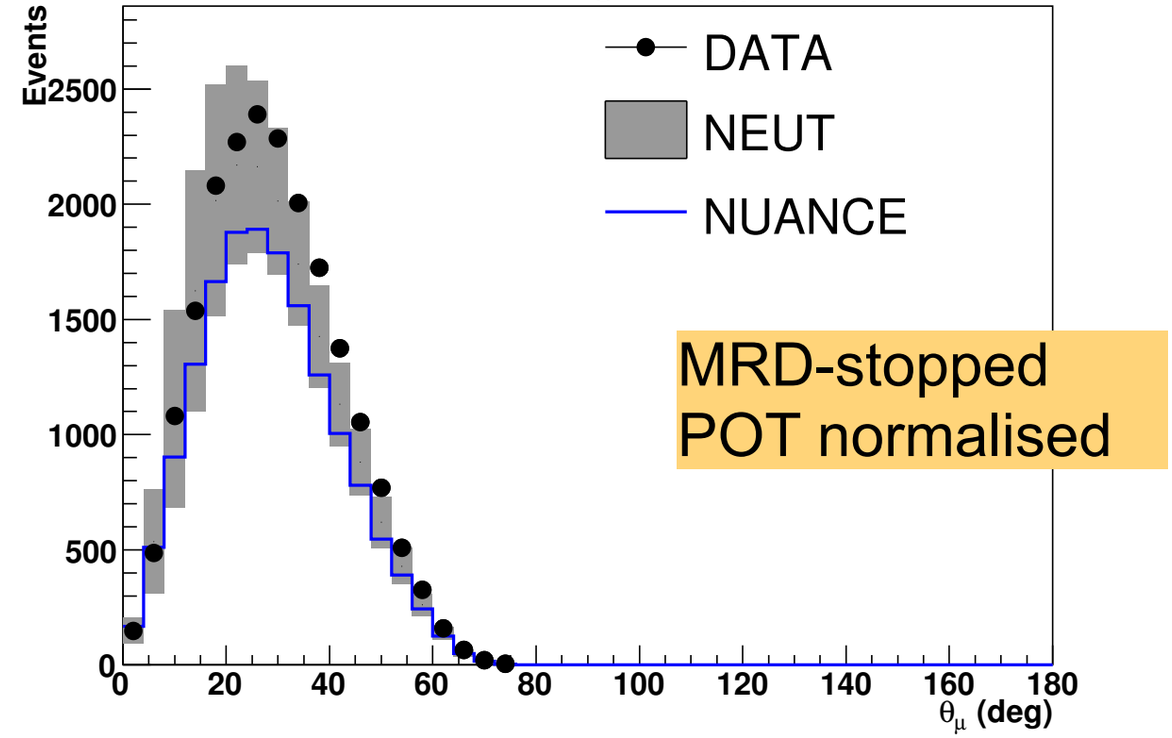
Both tuned to explain data, but predict different cross sections.

⇨ Testing these in a single experiment (SciBooNE) is an important topic!

muon momentum (p_μ)



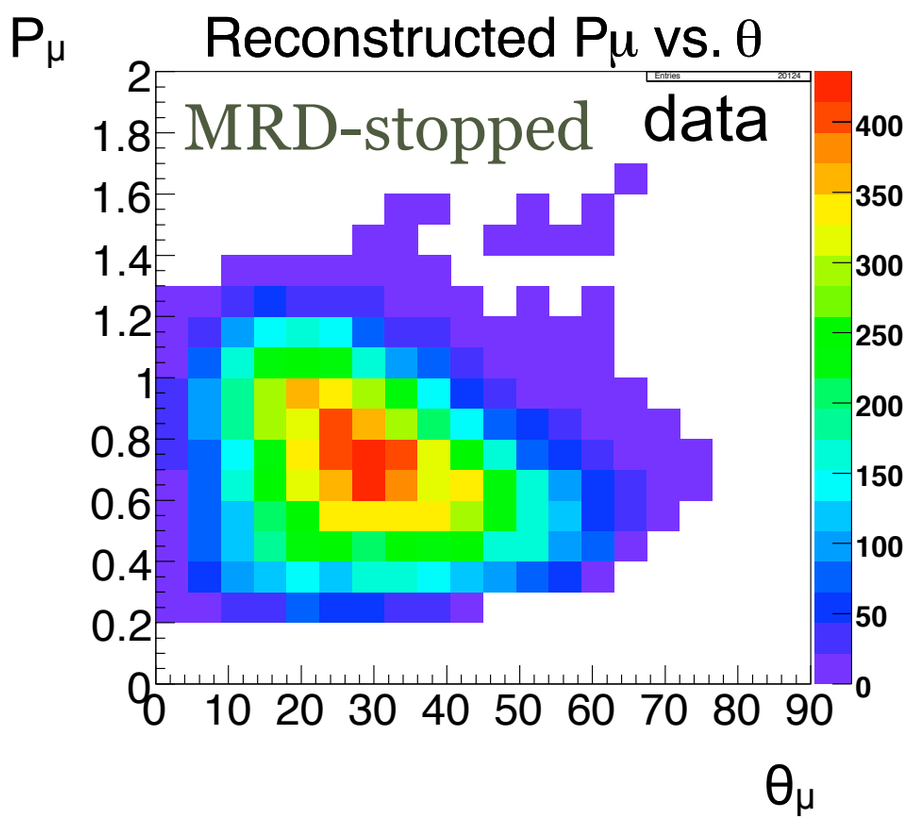
muon angle (θ_μ)



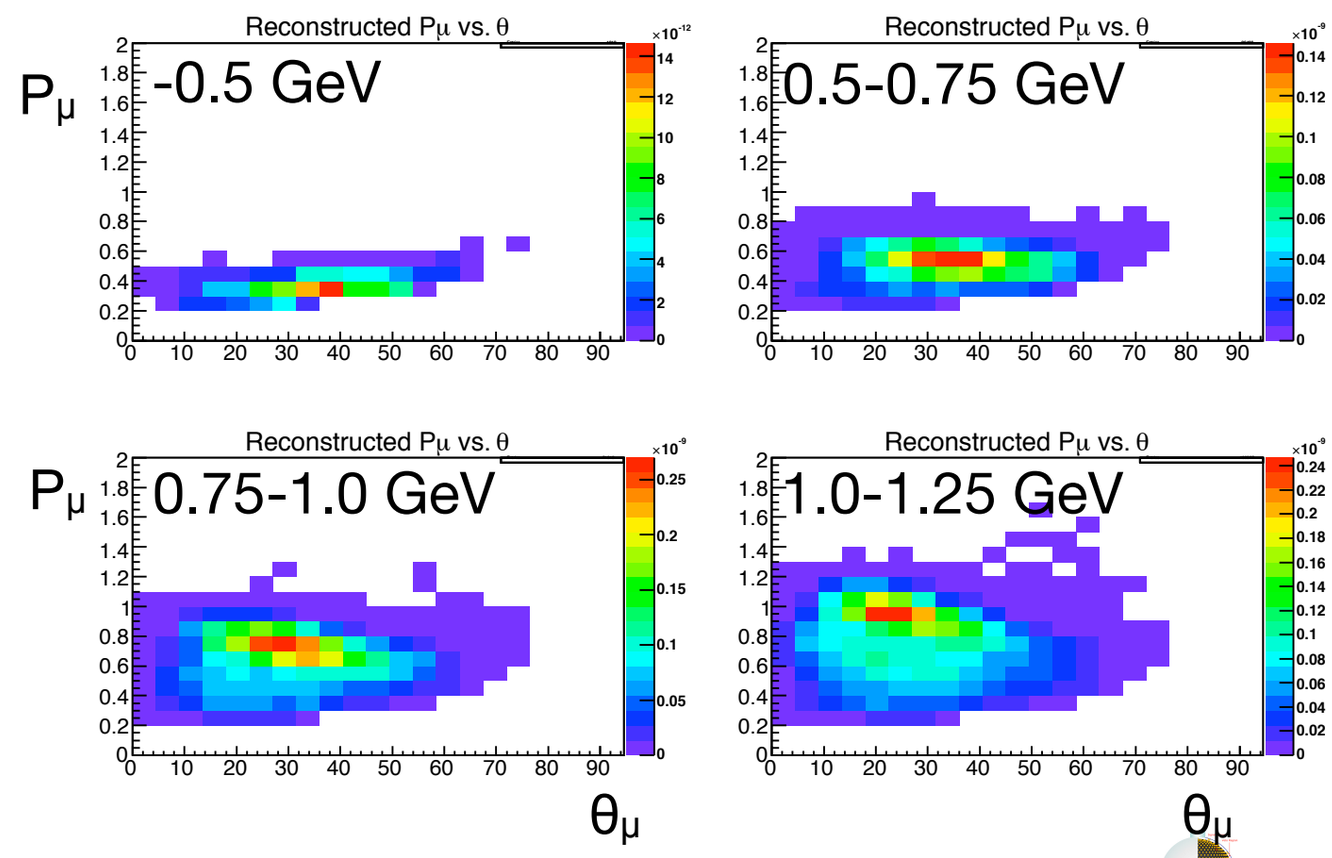
MC reproduces data within the (large) systematic error

Spectrum fit

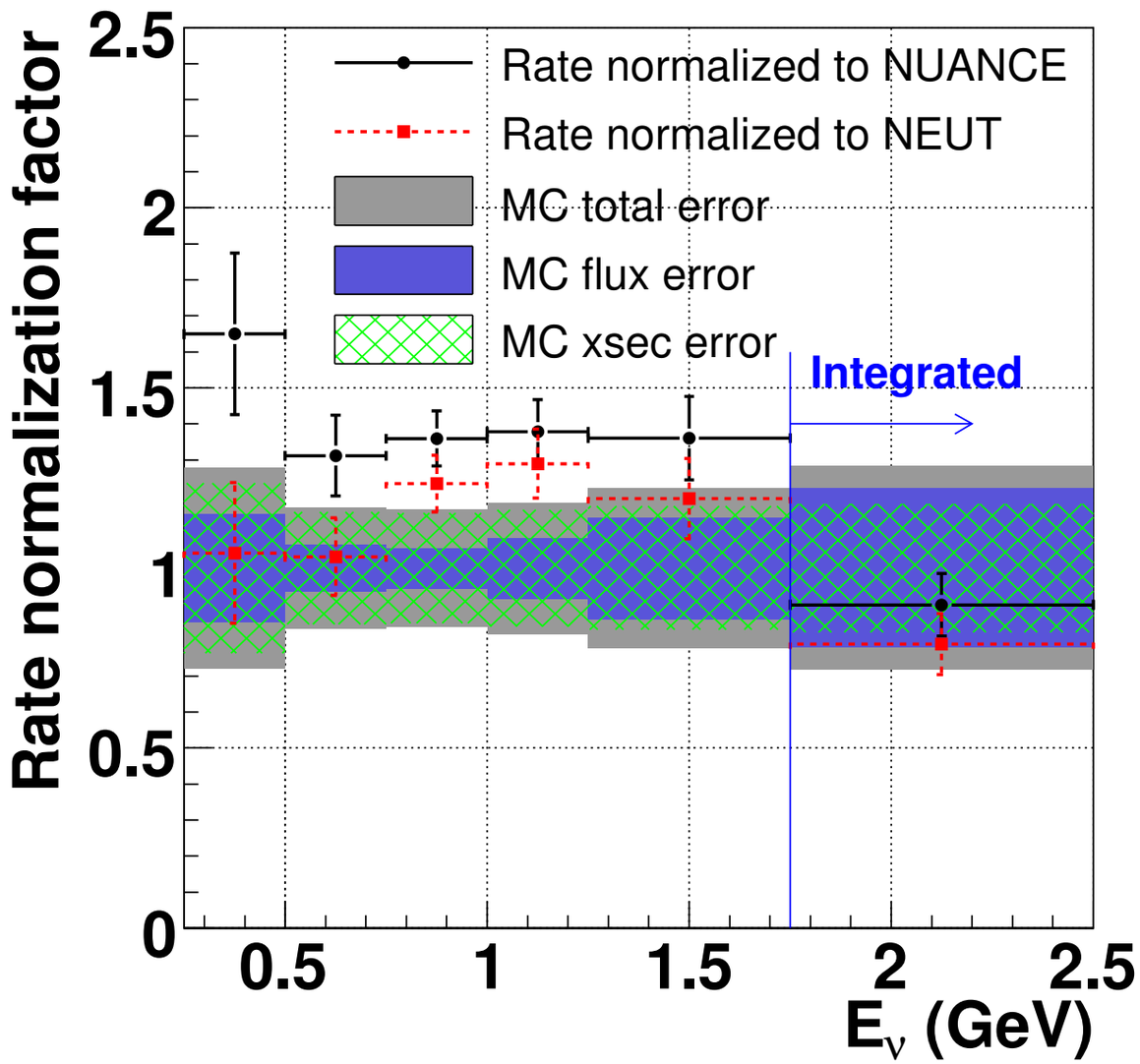
- Tune MC prediction by re-weighting as a function of true neutrino energy.
- Determine the rate normalisation factor which best fits the p_μ vs. θ_μ 2D distributions.
  - All three samples (SciBar-stop, MRD-stop and MRD-penetrated samples) are used simultaneously.



MC template (MRD-stop)



CC interaction rate



- Extract CC interaction rate

$$\mathcal{R}_i = \frac{f_i \cdot \mathcal{N}_i^{pred} \cdot P_i}{\epsilon_i}$$

normalisation factor

predicted # of events

Purity

Efficiency

- This is the product of (flux) x (cross-section)

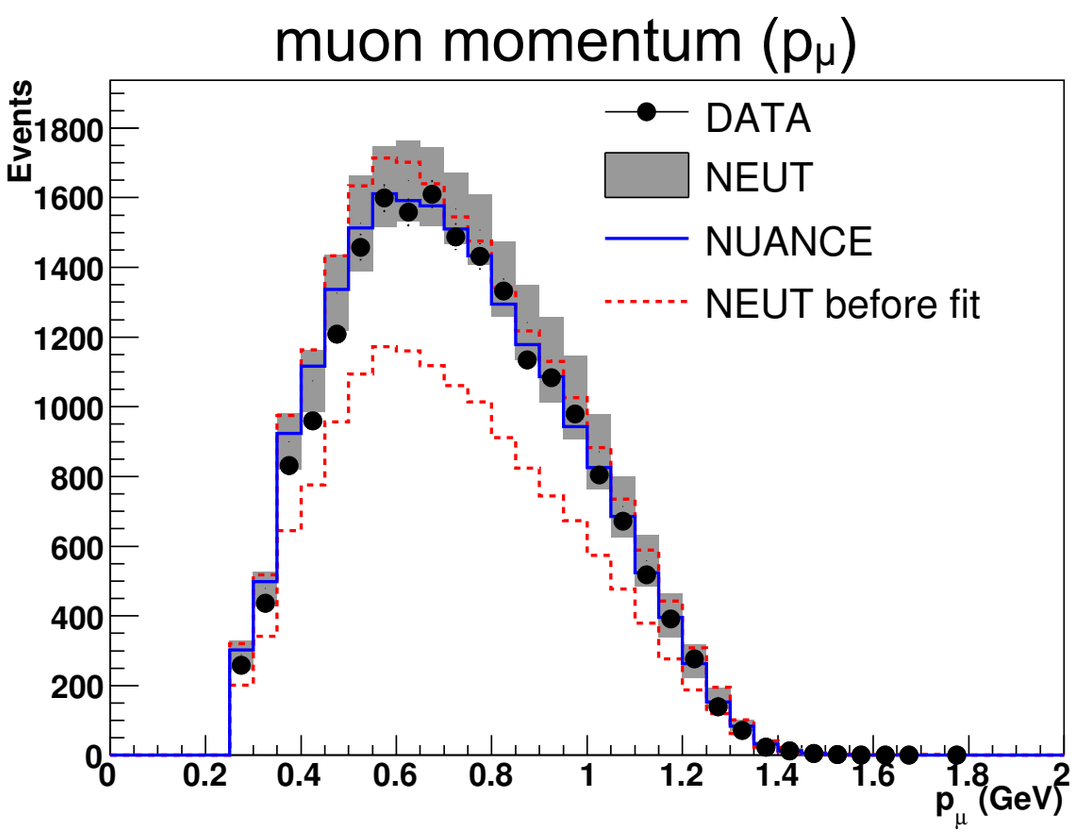
⇨ Direct input for this joint ν_μ disappearance analysis

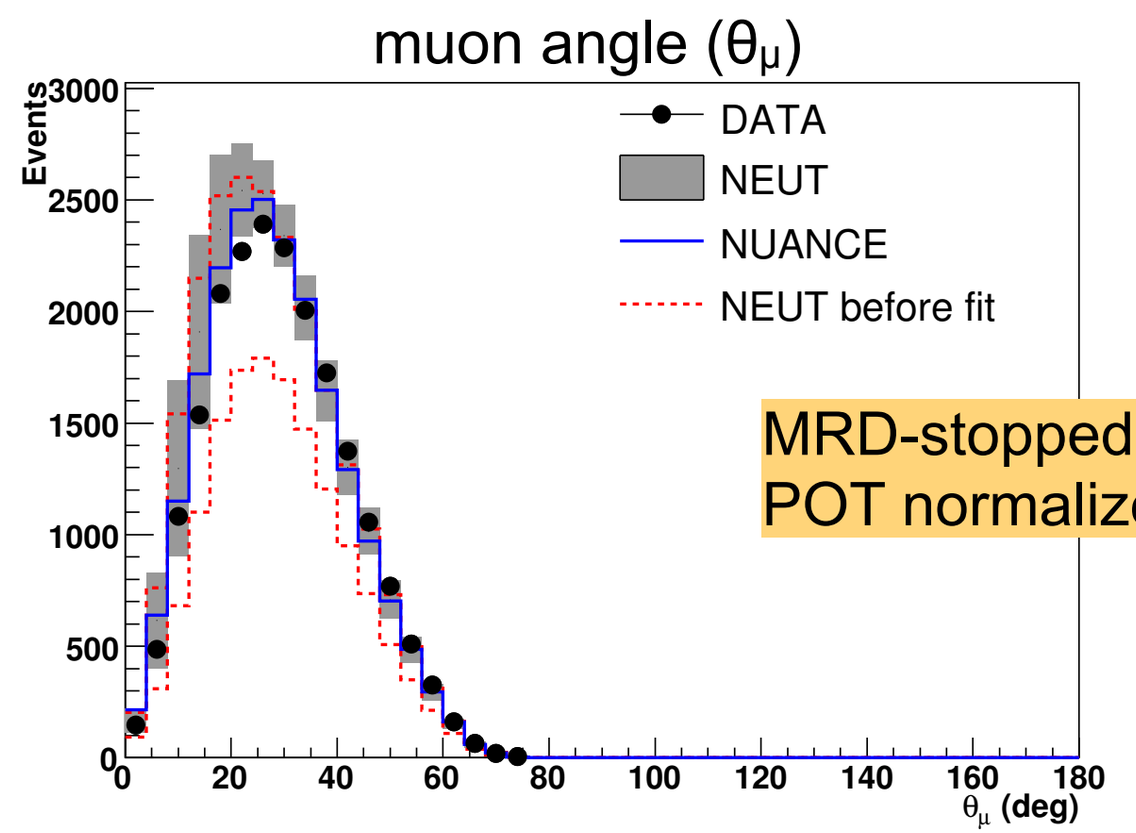
Phys. Rev. D **83**, 012005 (2011)

Parameter	f_0	f_1	f_2	f_3	f_4	f_5
E_ν range (GeV)	0.25 - 0.5	0.5 - 0.75	0.75 - 1.0	1.0 - 1.25	1.25 - 1.75	1.75+

Distributions after fit

- Apply obtained rate normalisation factors.
- Confirmed that the MC distributions reproduce the data, and the errors are much smaller after fit.





MRD-stopped
POT normalized

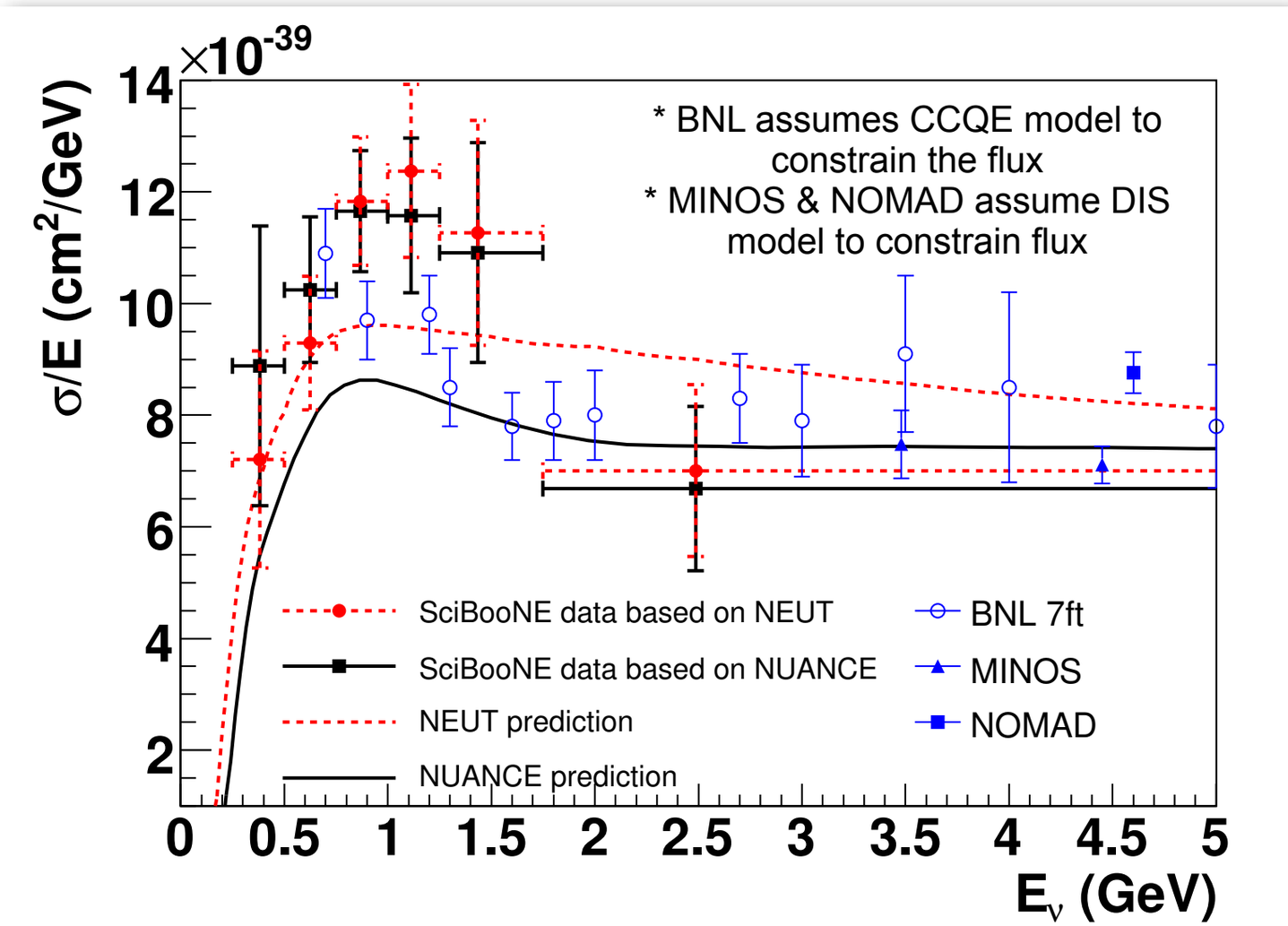
CC inclusive cross section

Extract CC inclusive cross section:

$$\sigma_i = f_i \cdot < \sigma_{CC}^{pred} >_i = \frac{f_i \cdot \mathcal{N}_i^{pred} \cdot P_i}{\epsilon_i \cdot T \cdot \Phi_i},$$

T: number of target nucleons
Φ: total flux

Phys. Rev. D **83**, 012005 (2011)



- First measurement of CC-inclusive cross section on carbon in the 1 GeV region
- NEUT & NUANCE based measured xsecs consistent.
- ~Consistent with MINOS, NOMAD and old BNL bubble chamber (deuterium) measurements
- Used to tune MC for T2K.

Analysis Overview

Two independent analyses

Spectrum fit

SciBooNE data

↓ Spectrum fit

CC interaction rate measurement

↓

MiniBooNE rec. E_ν prediction

↕ Oscillation Fit

MiniBooNE rec. E_ν data

Advantage:
Decouple oscillation fit from constraint.
Observe the amount of constraint.

Simultaneous fit

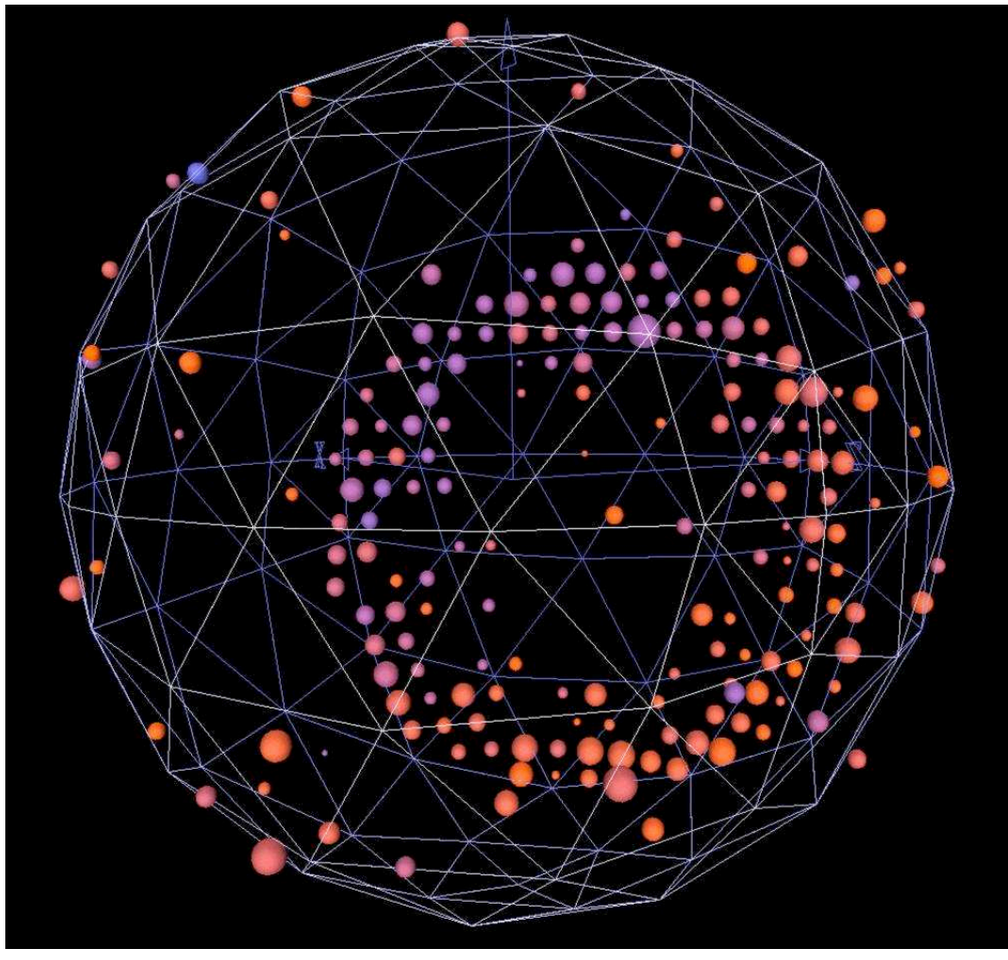
SB + MB Rec. E_ν Data

↕ Oscillation Fit

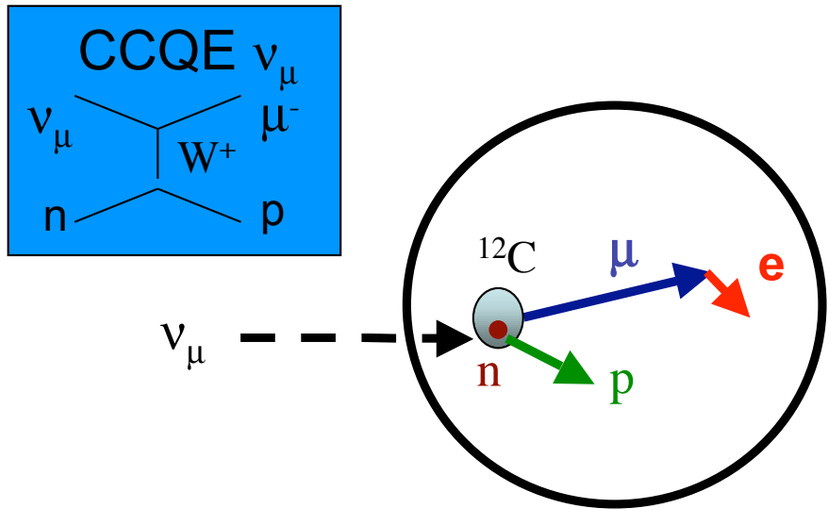
SB + MB Rec. E_ν Prediction

Advantage:
Direct fit for disappearance in SciBooNE and MiniBooNE.
Correlation between the two constrain systematic error.

MiniBooNE reconstruction



- Employ same selection/reconstruction as used in previous MiniBooNE-only analysis (PRL 103, 061802 (2009))
- Select CC quasi-elastic (QE) ($\nu n \rightarrow \mu p$) 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.
  - >150k events!



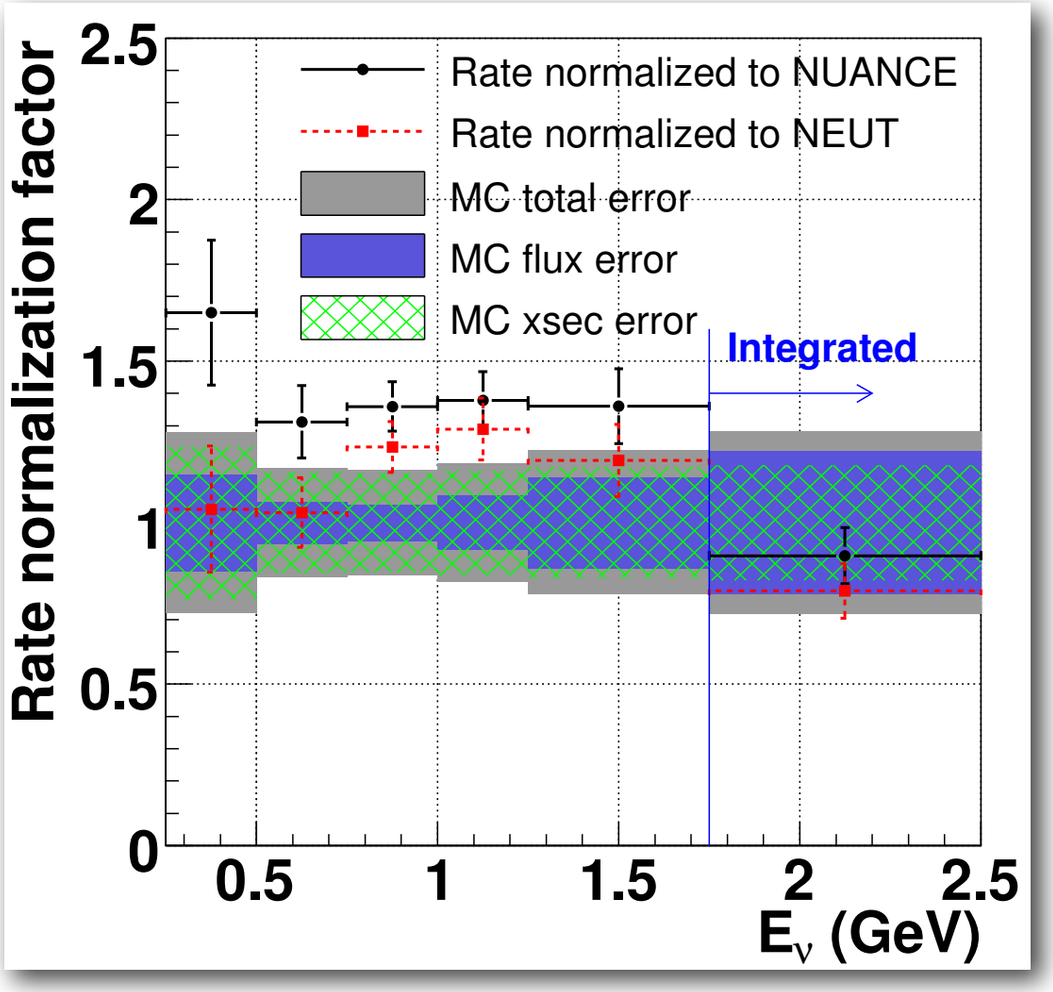
$$E_\nu^{rec} = \frac{m_p^2 - (m_n - E_B)^2 - m_\mu^2 + 2(m_n - E_B)E_\mu}{2(m_n - E_B - E_\mu + p_\mu \cos\theta_\mu)}$$

MiniBooNE prediction

- Apply the rate normalisation factor obtained by SciBooNE analysis to MiniBooNE.

Systematic errors:

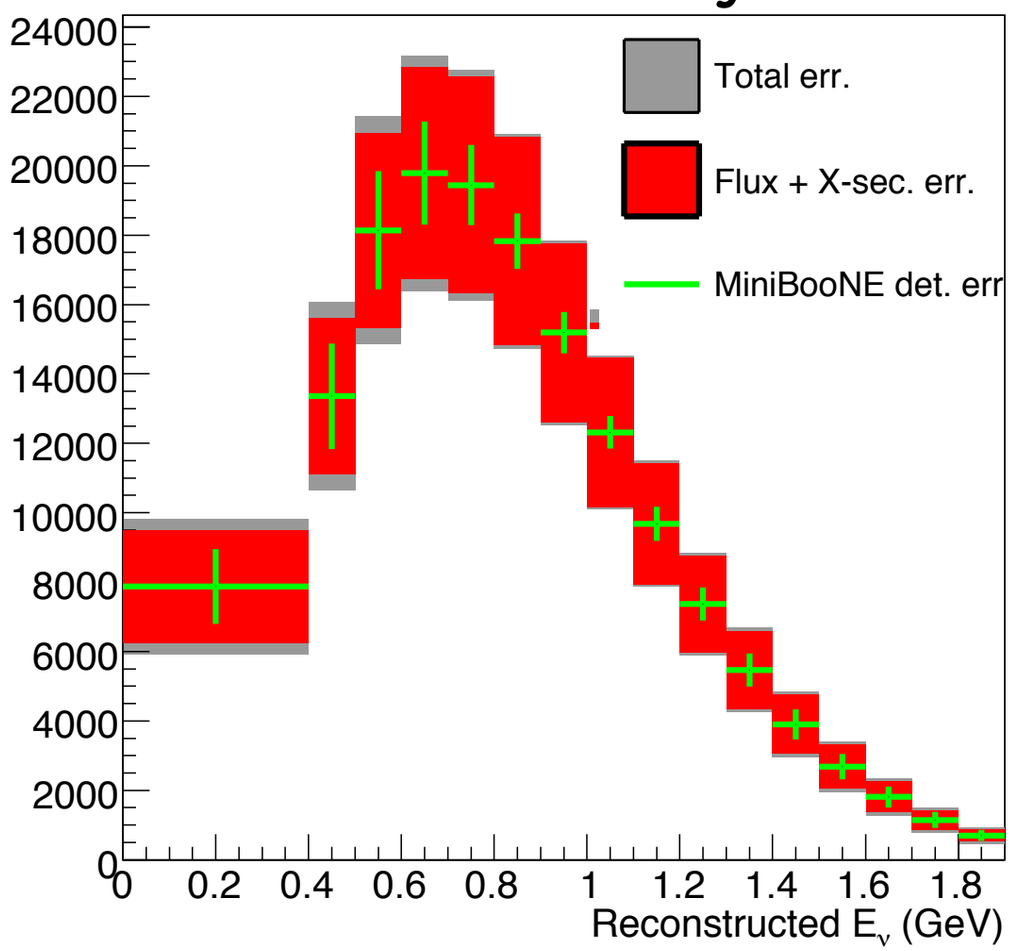
- Most flux and cross section errors cancel between SciBooNE and MiniBooNE.
- Remaining errors:
  - Relative flux difference
  - Efficiency variation due to cross section model uncertainties.
  - MiniBooNE detector response errors.



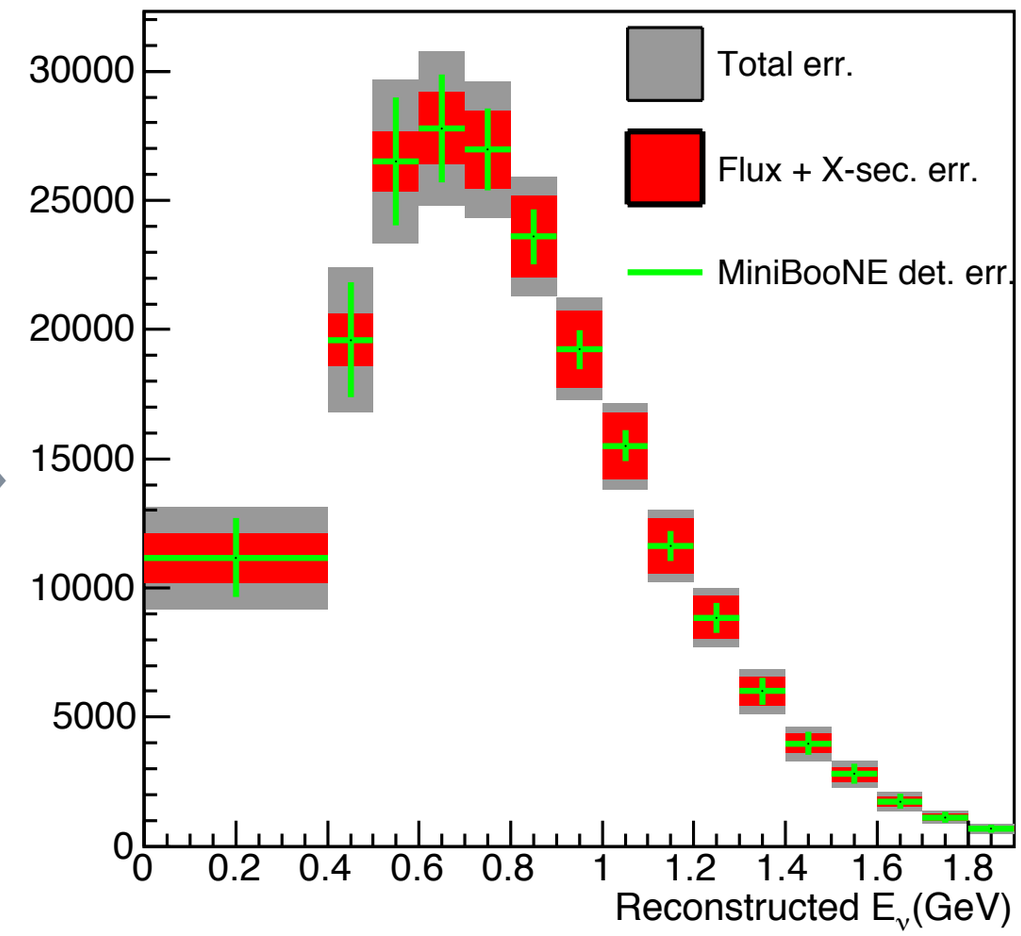
Carefully estimate these errors!

MiniBooNE prediction

MiniBooNE only error

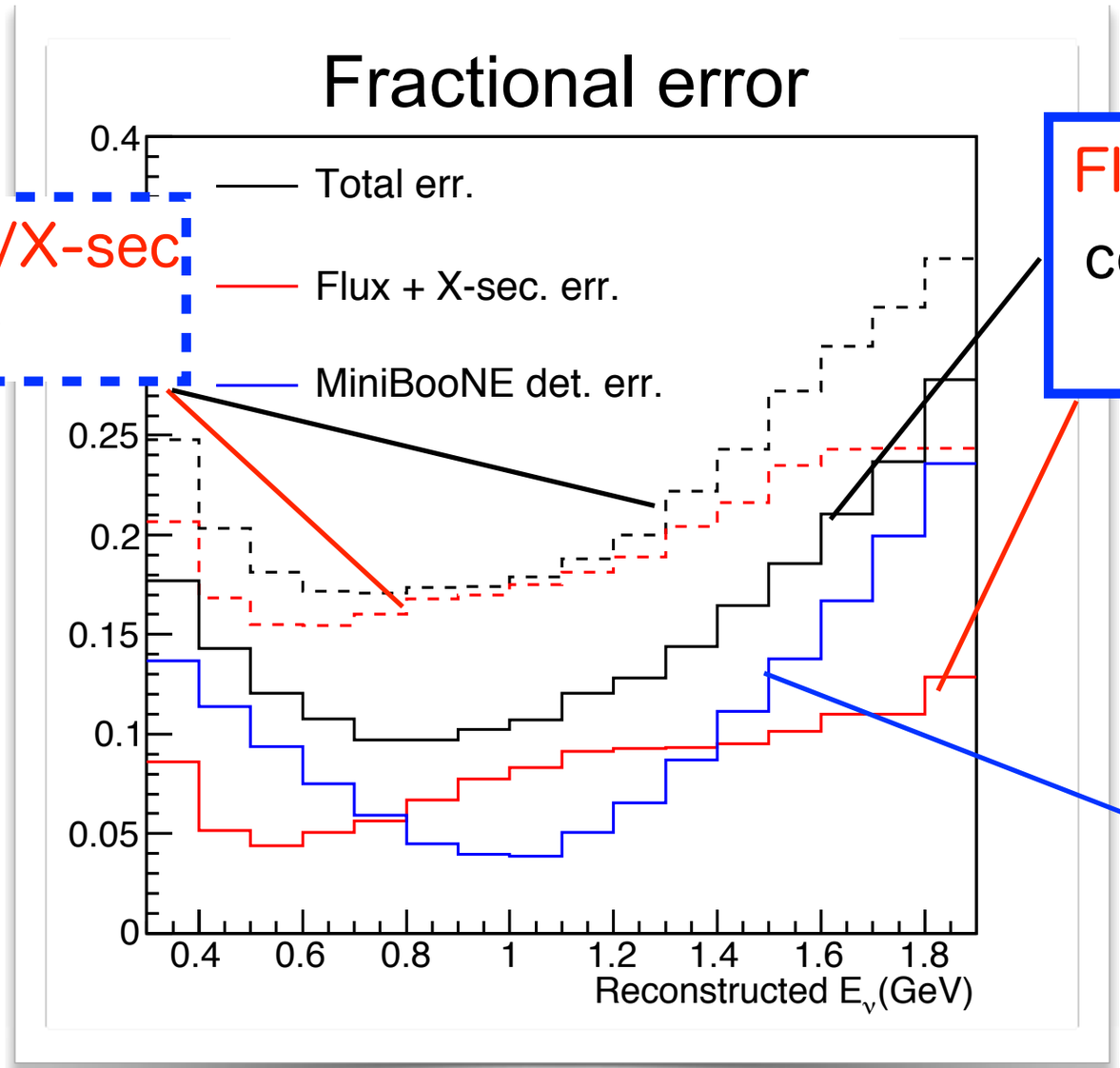


Error for this joint analysis



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

MiniBooNE prediction



MiniBooNE-only Flux/X-sec and total error

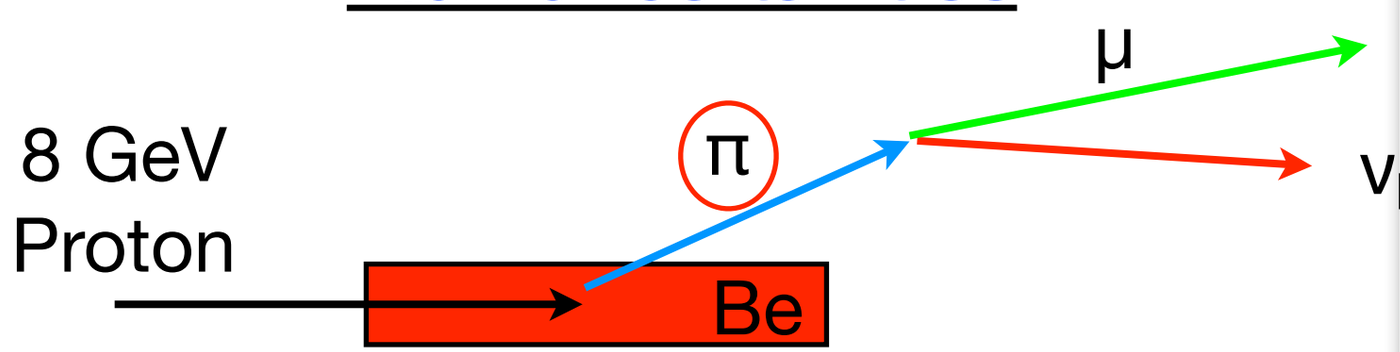
Flux/X-sec and total error constrained by SciBooNE data

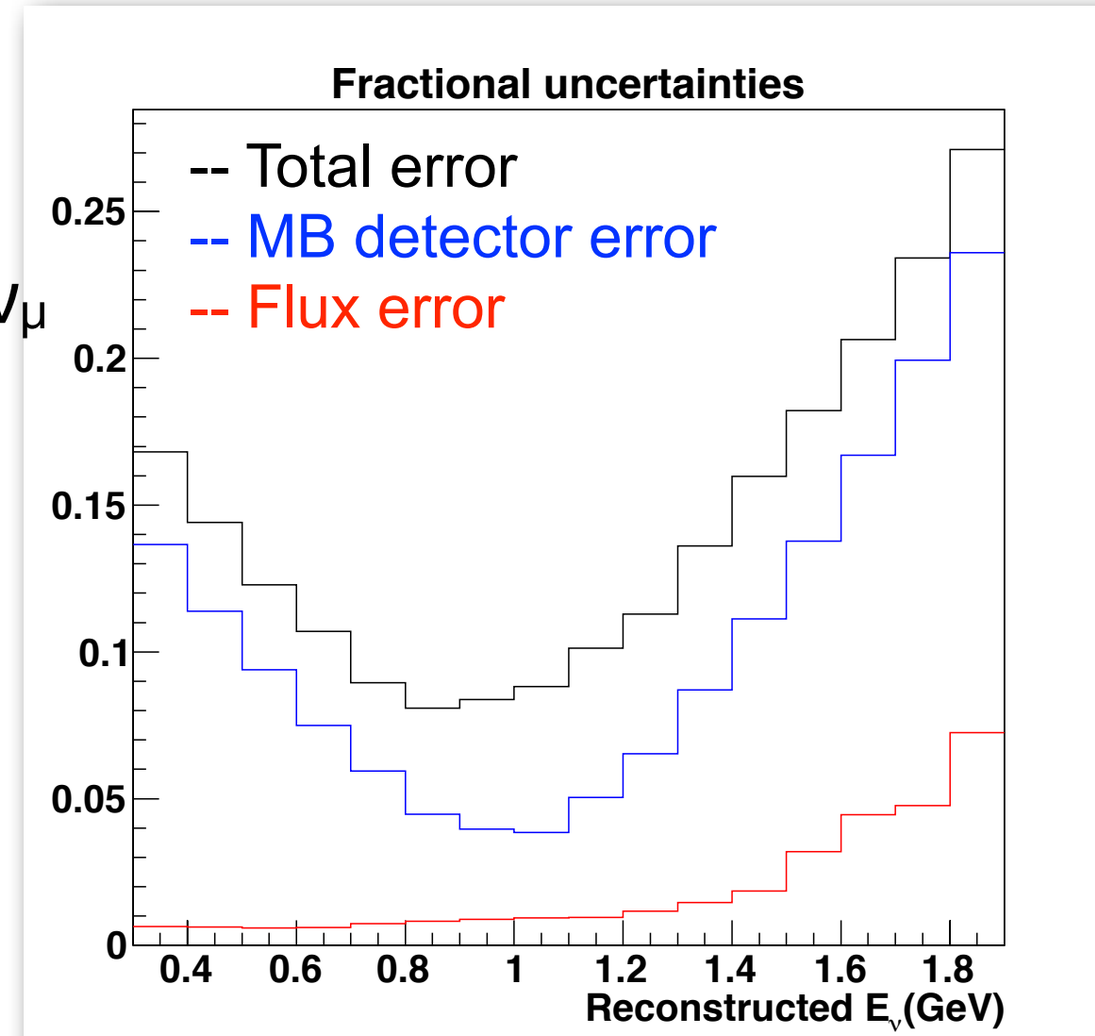
MiniBooNE detector response error

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

Systematic uncertainties(1)

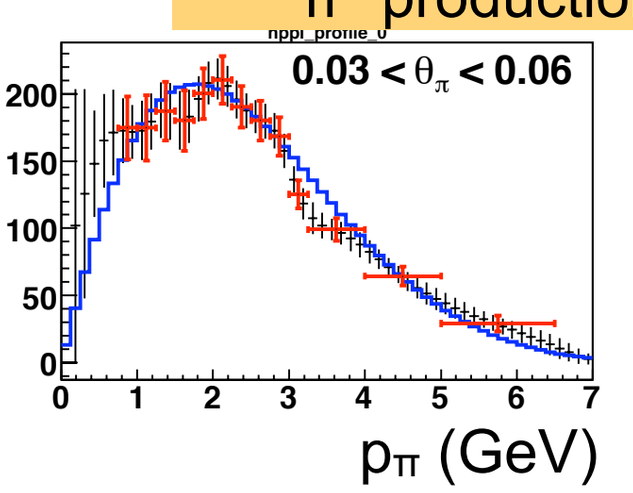
Flux uncertainties

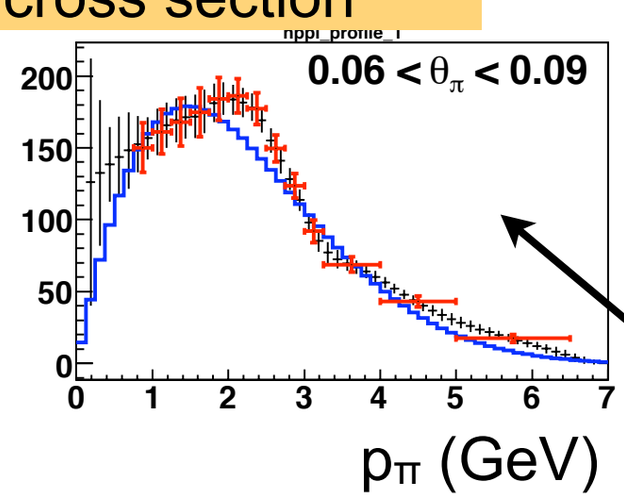




- Use HARP p-Be interaction measurement uncertainty for the error analysis.
- Becomes negligible after taking ratio between SciBooNE and MiniBooNE

π^+ production cross section





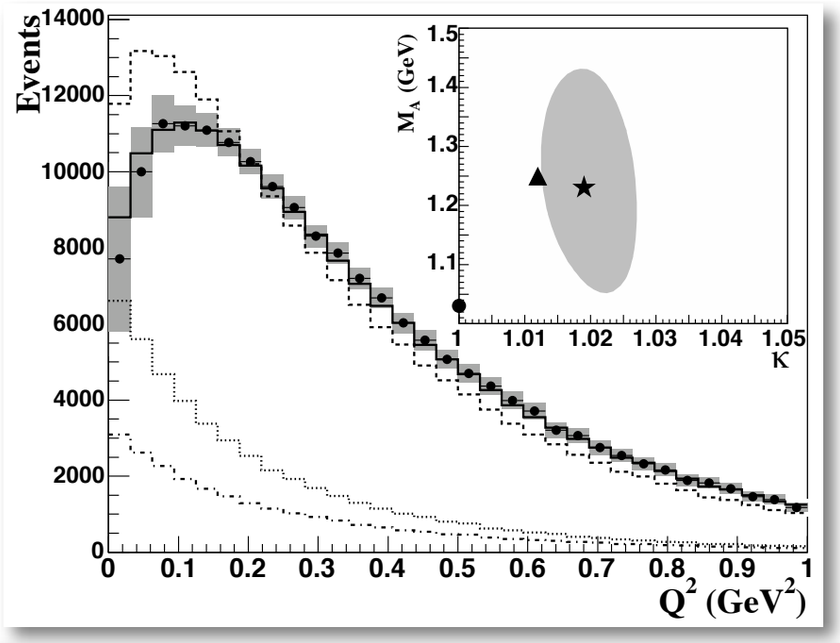
-- Cross section used for MC production
-- HARP data
-- Spline interpolation of HARP data

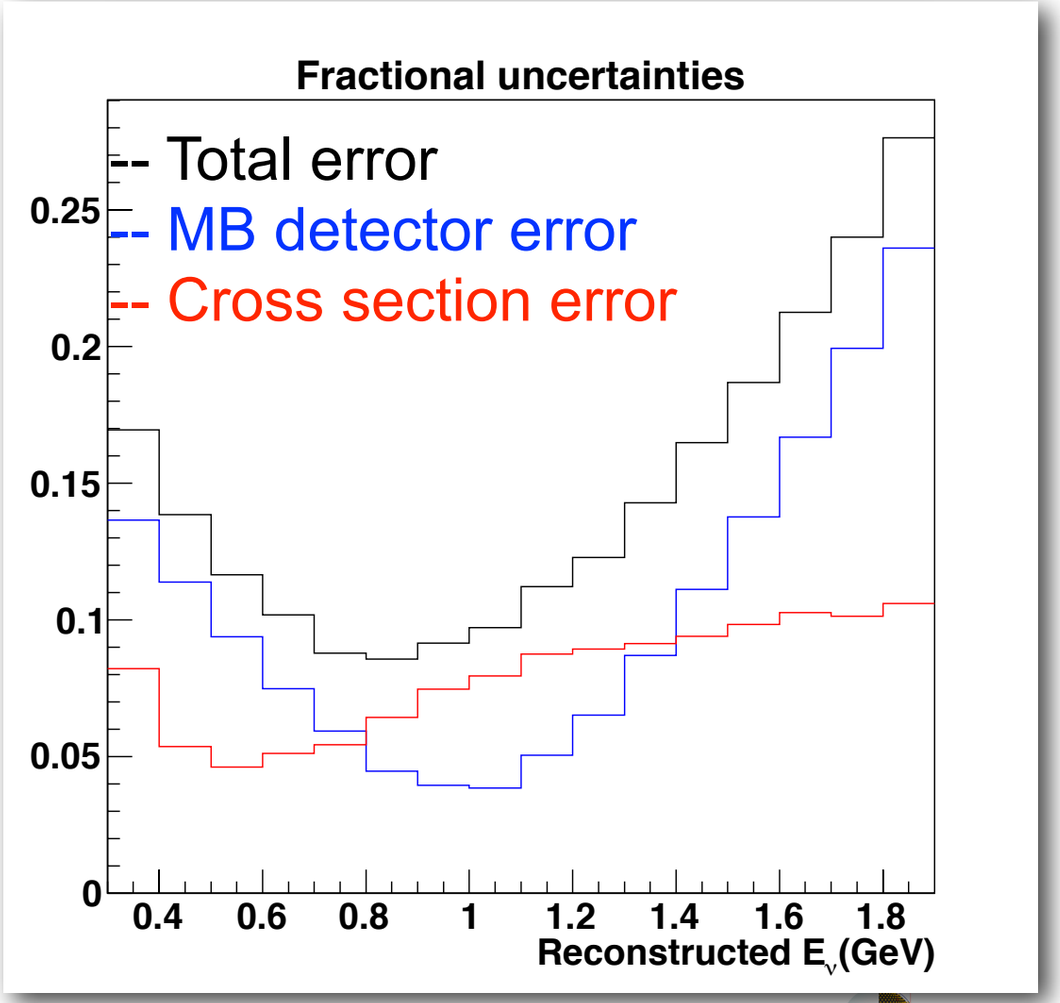
Systematic uncertainties (2)

Cross section uncertainties

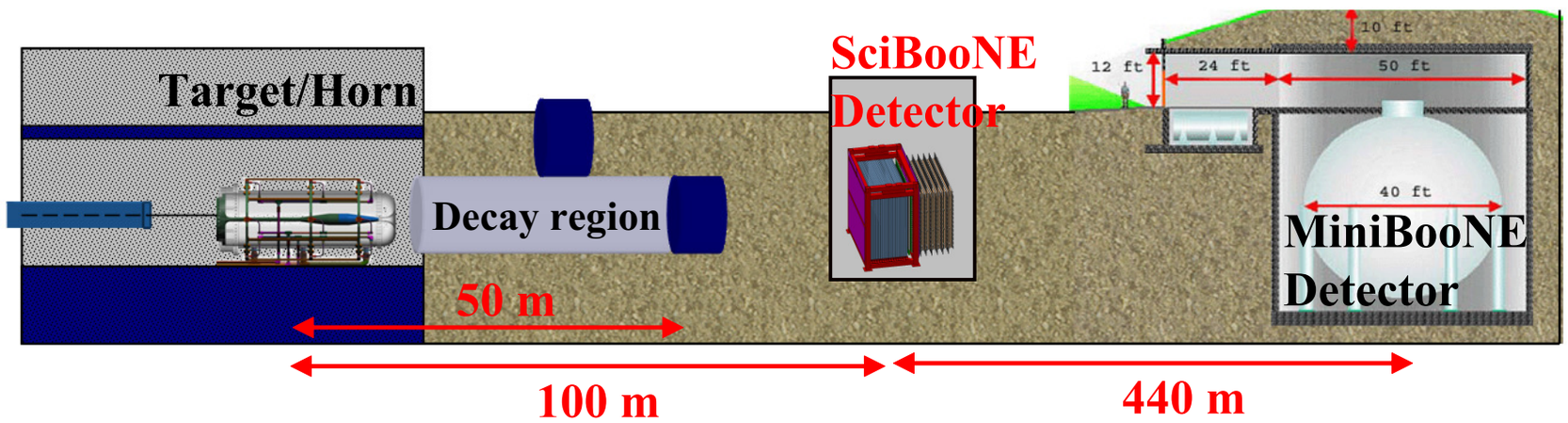
- Variations of Q^2 (muon angle) distribution can change relative acceptance.
  - SciBooNE: (mostly) forward muons
  - MiniBooNE: isotropic acceptance.
- The major source of the systematic error, together with the MB detector response error.

MiniBooNE CCQE sample
Q^2 distribution

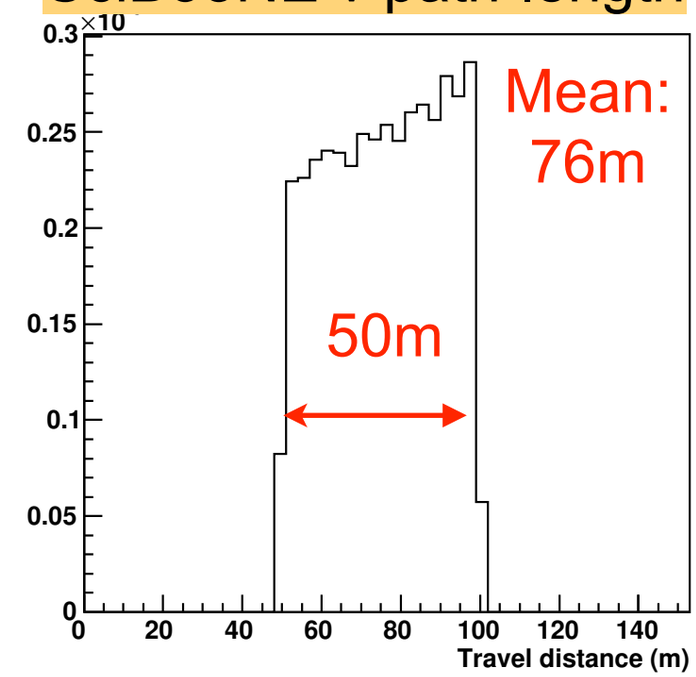




Predicting oscillation signal

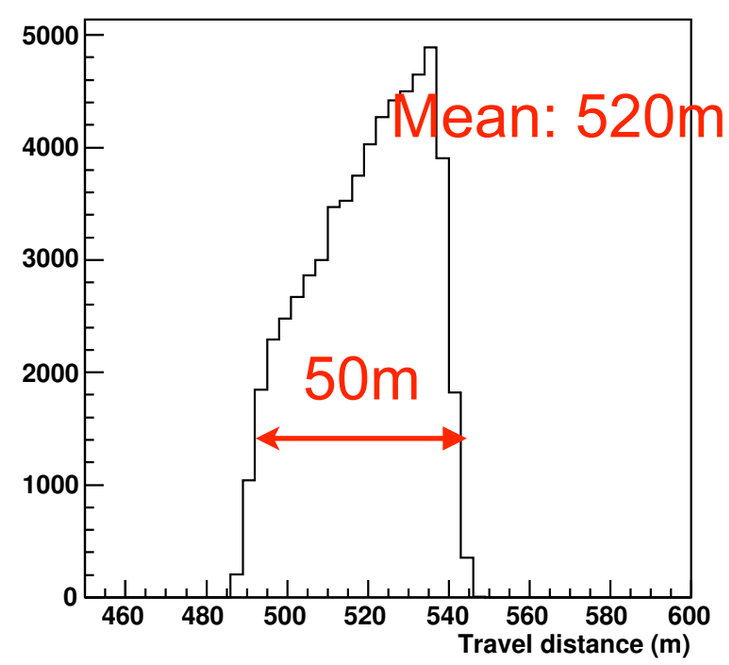


SciBooNE ν path-length



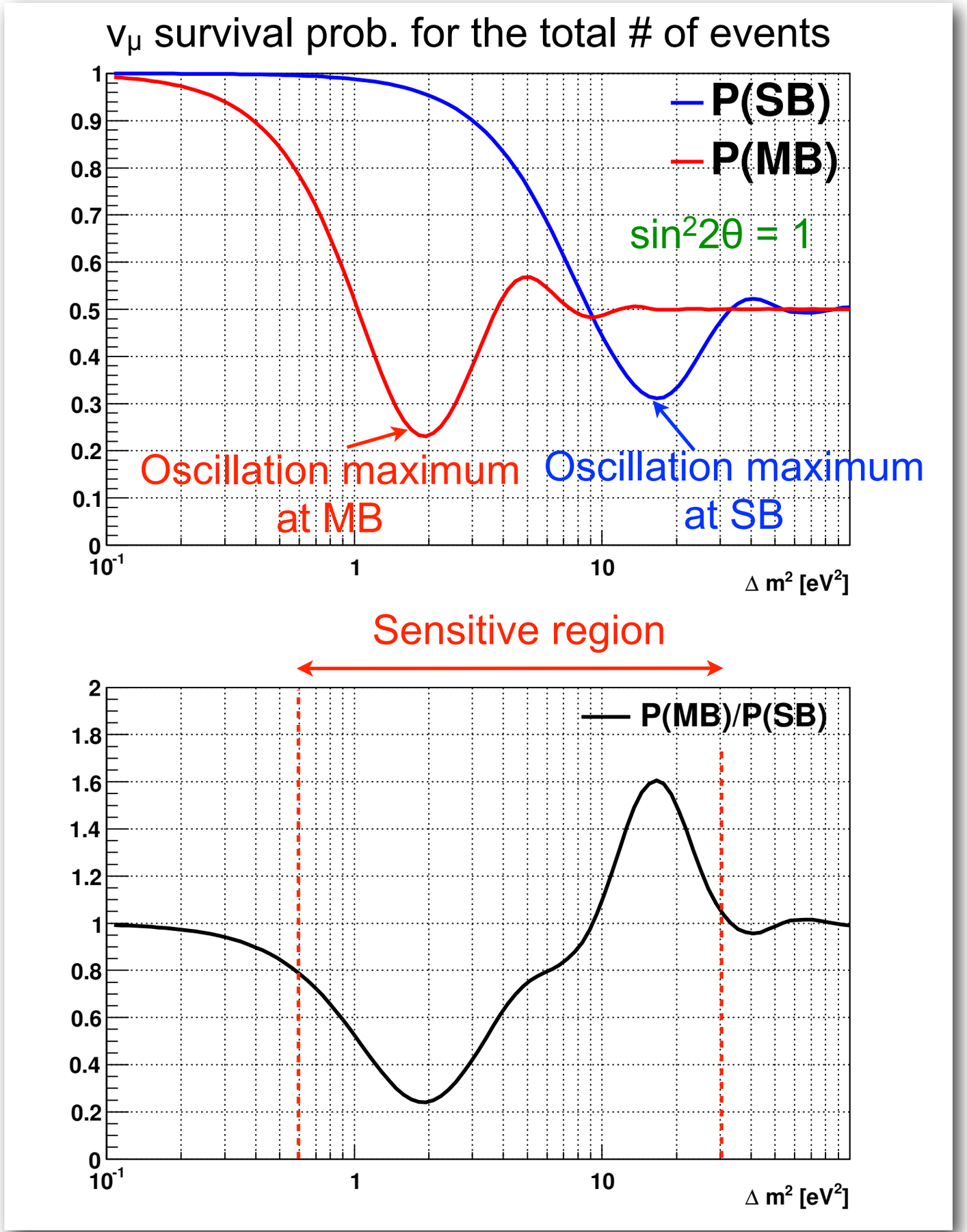
- Mean ν path-length for SciBooNE events: ~76m
- Mean ν path-length for MiniBooNE events: ~520m
- Each has 50m spread due to the finite length of the decay volume
- We consider three effects:
  - Oscillation at SciBooNE
  - Oscillation at MiniBooNE
  - Smearing effect due to 50m spread

MiniBooNE ν path-length



Oscillation probability

- Oscillation reaches maximum at the first oscillation peak,
  - then washes out at high Δm2 by integrating over neutrino energy.
- Since we compare the MB flux with SB, P(MB)/P(SB) is the expected signal.
- Sensitive to oscillations in range $0.5 < \Delta m^2 < 30\ eV^2$.



Spectrum fit

- Test oscillation hypothesis for two flavors, and scan over (Δm^2, $\sin^2 2\theta$) plane.

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

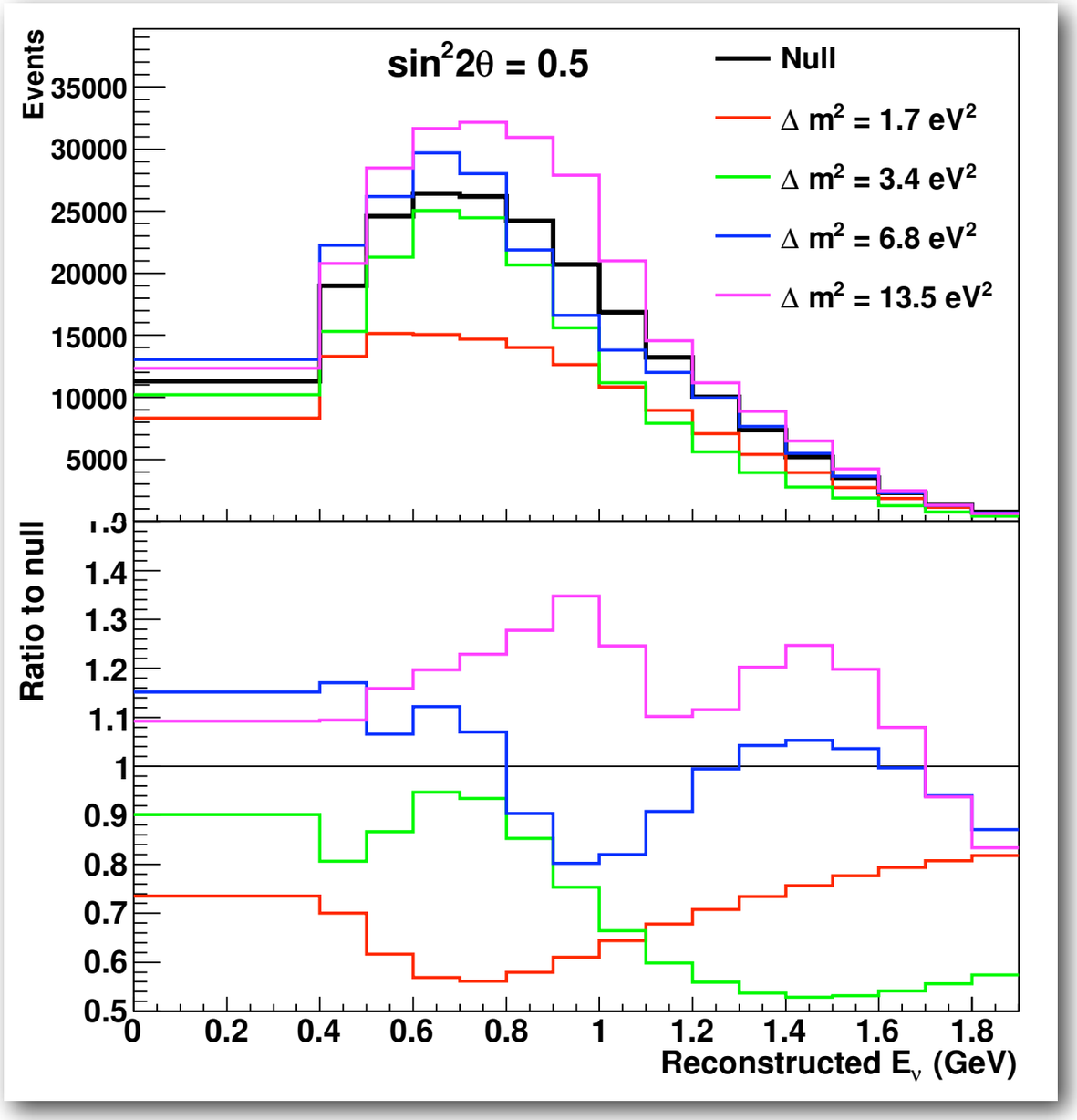
- Evaluate
  $\Delta\chi^2 = \chi^2(\text{each point}) - \chi^2(\text{best})$

$$\chi^2 = \sum_{jk}(M_j^{obs} - M_j^{pred})V_{jk}^{-1}(M_k^{obs} - M_k^{pred})$$

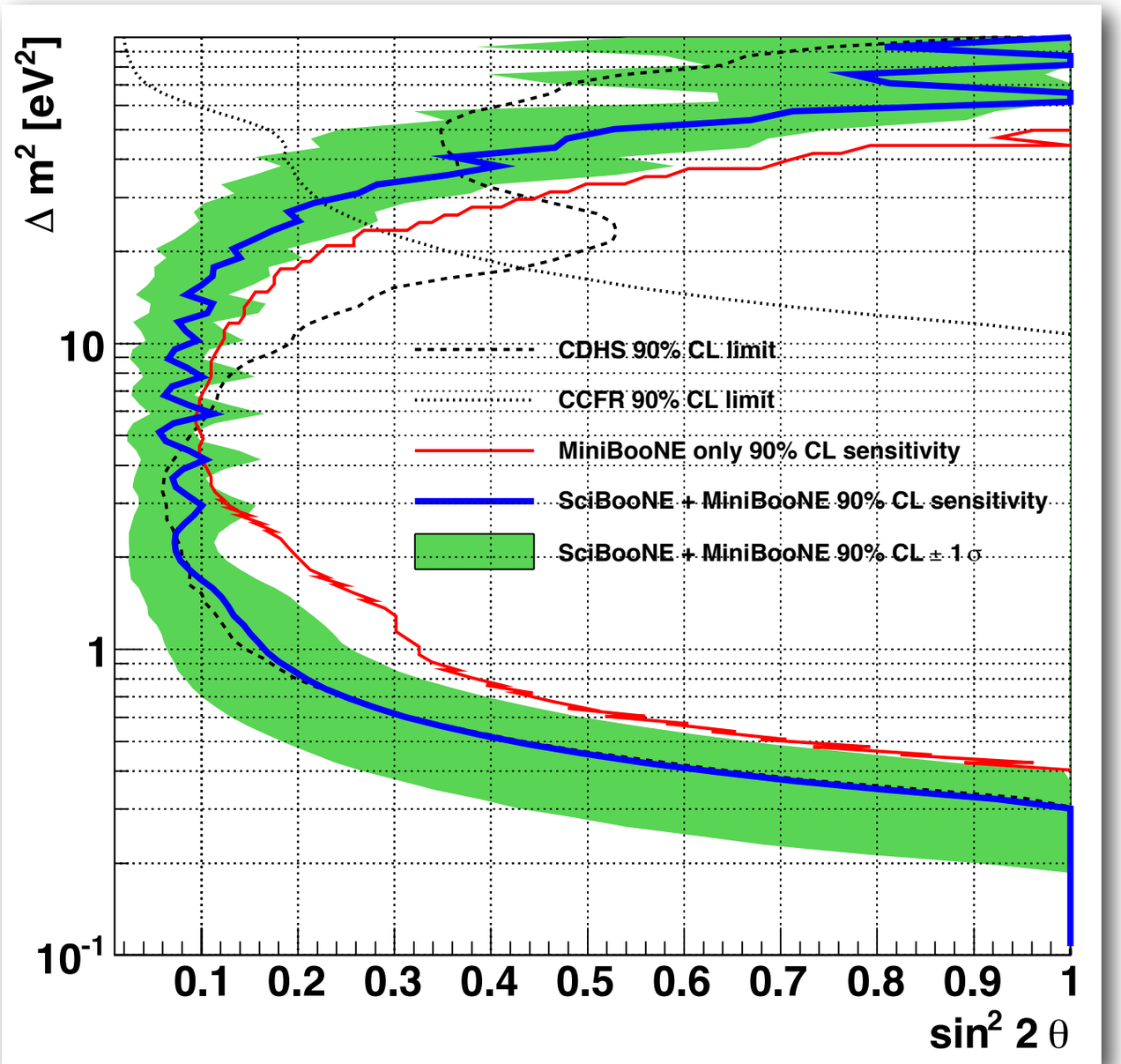
M^{obs}: Data
M^{pred}: Prediction
(function of osc. parameter)
V: Covariance matrix

- Use Feldman-Cousins for confidence level of $\Delta\chi^2$ values.

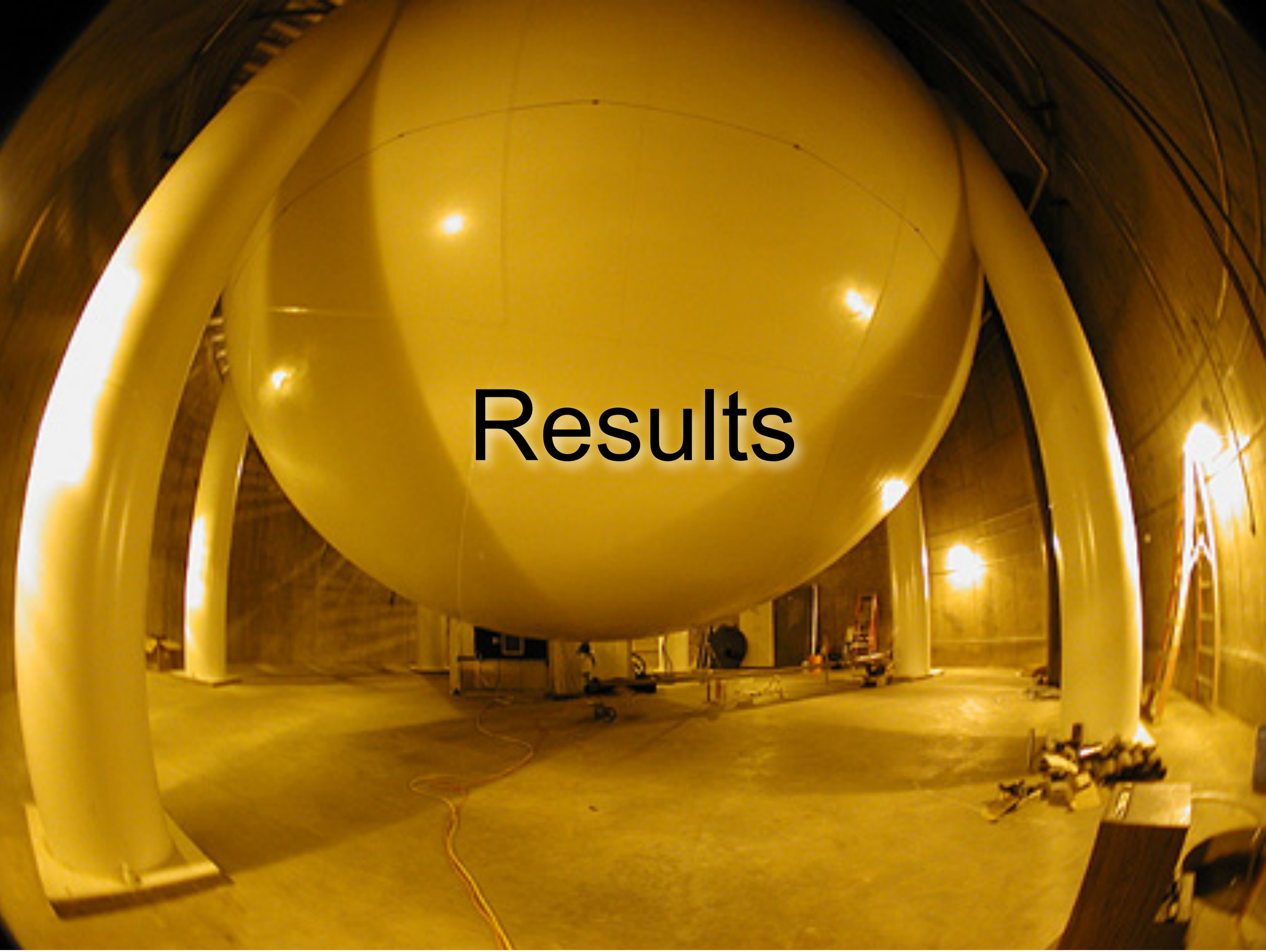
MiniBooNE E_ν(rec) prediction



Spectrum fit sensitivity



- Sensitivity reaches $\sin^2 2\theta \sim 0.1$ in $1 < \Delta m^2 < 20\ eV^2$
- Significantly improved from MiniBooNE-only analysis.
- Achieved world's best sensitivity at $0.5 < \Delta m^2 < 30\ eV^2$



Results

Spectrum fit result

Fit both MiniBooNE new and old data

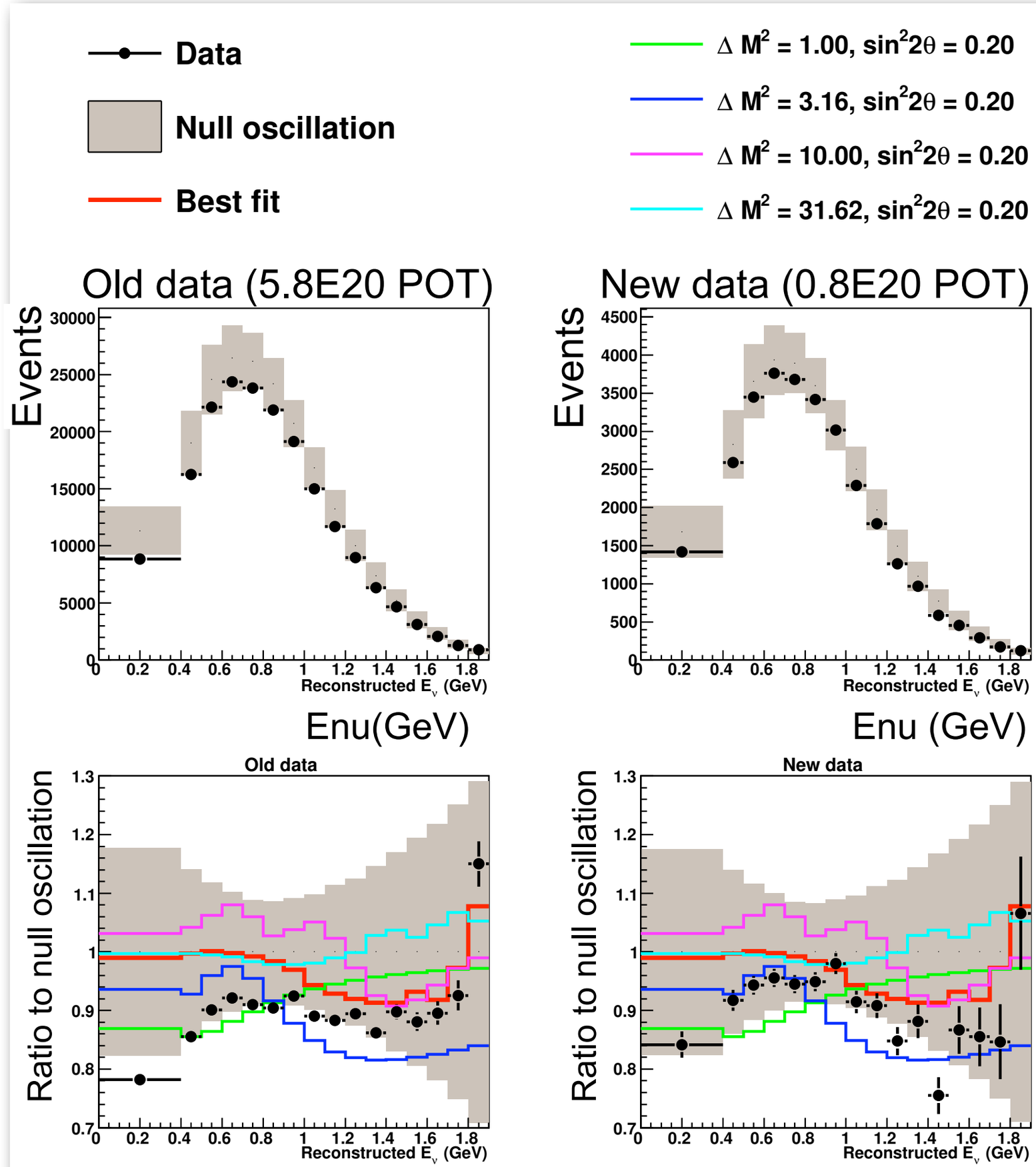
Best: $\Delta m^2 = 41.7\ eV^2$, $\sin^2 2\theta = 0.51$

χ^2(null) = 41.5/32(DOF)
χ^2(best) = 35.6/30(DOF)
$\Delta\chi^2 = \chi^2(null) - \chi^2(best) = 5.9$

$\Delta\chi^2$ (90%CL, null) = 8.4
(estimated by simulation)

No significant oscillation signal observed.

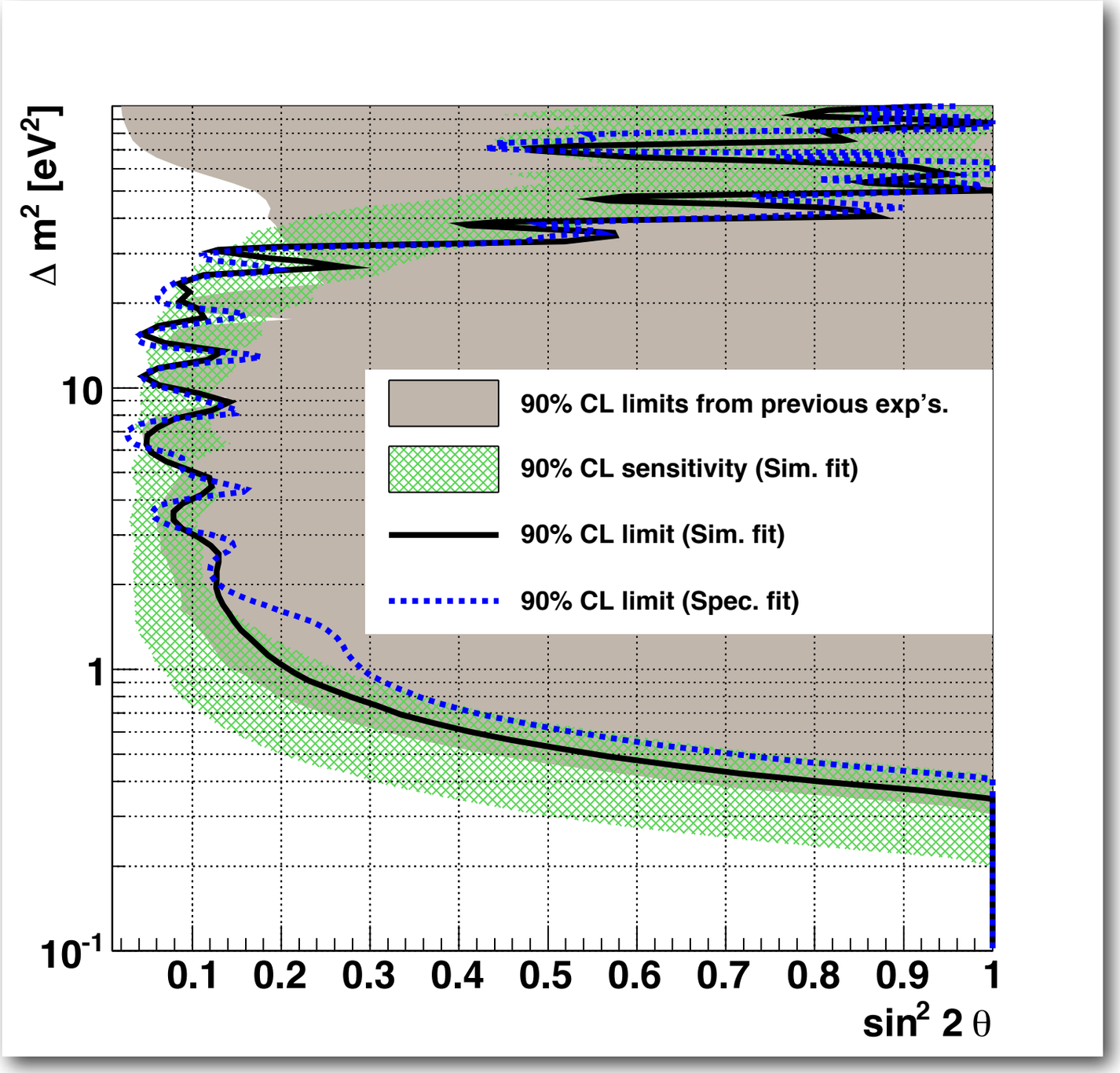
Small data/MC discrepancy found, but doesn't match oscillation signature.



90% CL limit

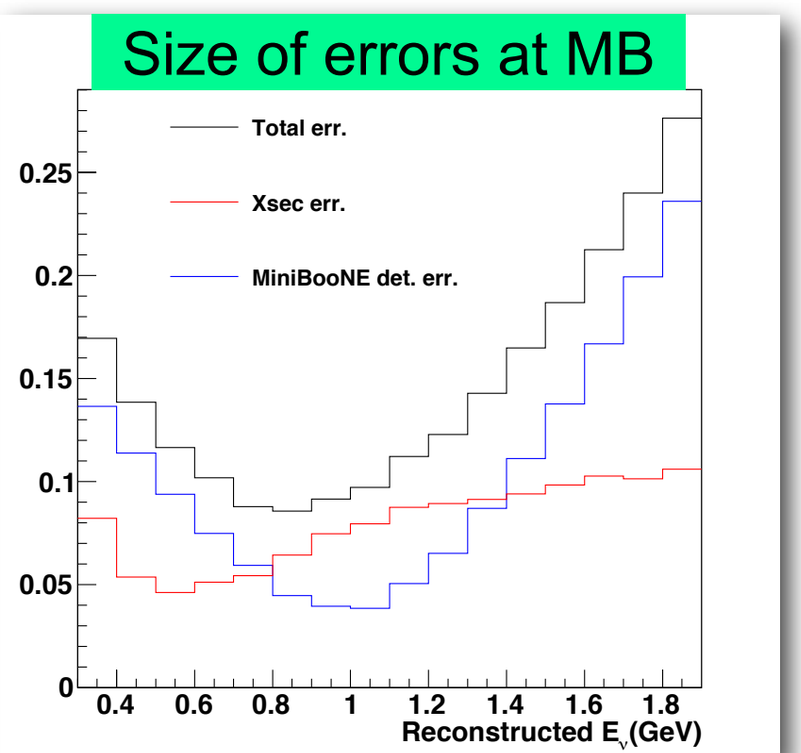
- The observed limits from both analyses are within the ±1σ band.
  - More support for null oscillation hypothesis.
- World's strongest limit at $10 < \Delta m^2 < 30\ eV^2$

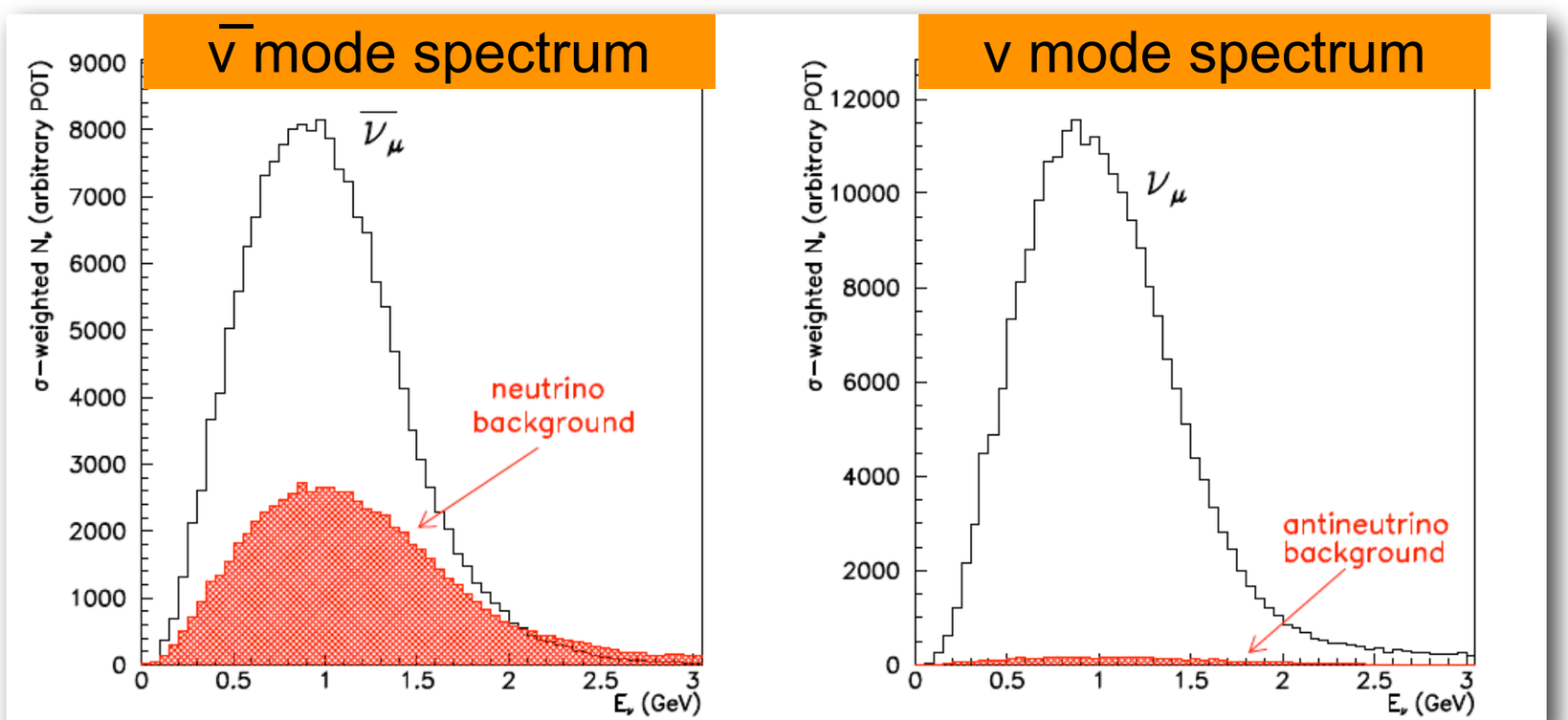
arXiv:1106.5685[hep-ex]



Discuss!

- Possible Improvements:
  - Dominant uncertainties: neutrino x-section and MiniBooNE detector response.
  - Further analysis of SciBooNE (and MiniBooNE) data could reduce the cross section errors if we had newer/better cross section models.
  - To reduce detector error, need identical detectors or $10^{\sim 2}$ MeV e^- calibration.
- Muon antineutrino disappearance analysis ⇐Particularly interesting!
  - These analysis methods are directly applicable to anti-neutrino analysis.
  - ν-mode result constrains ν BG, together with a direct measurement by MiniBooNE (arXiv:1102.1964) and event-by-event separation by SciBooNE



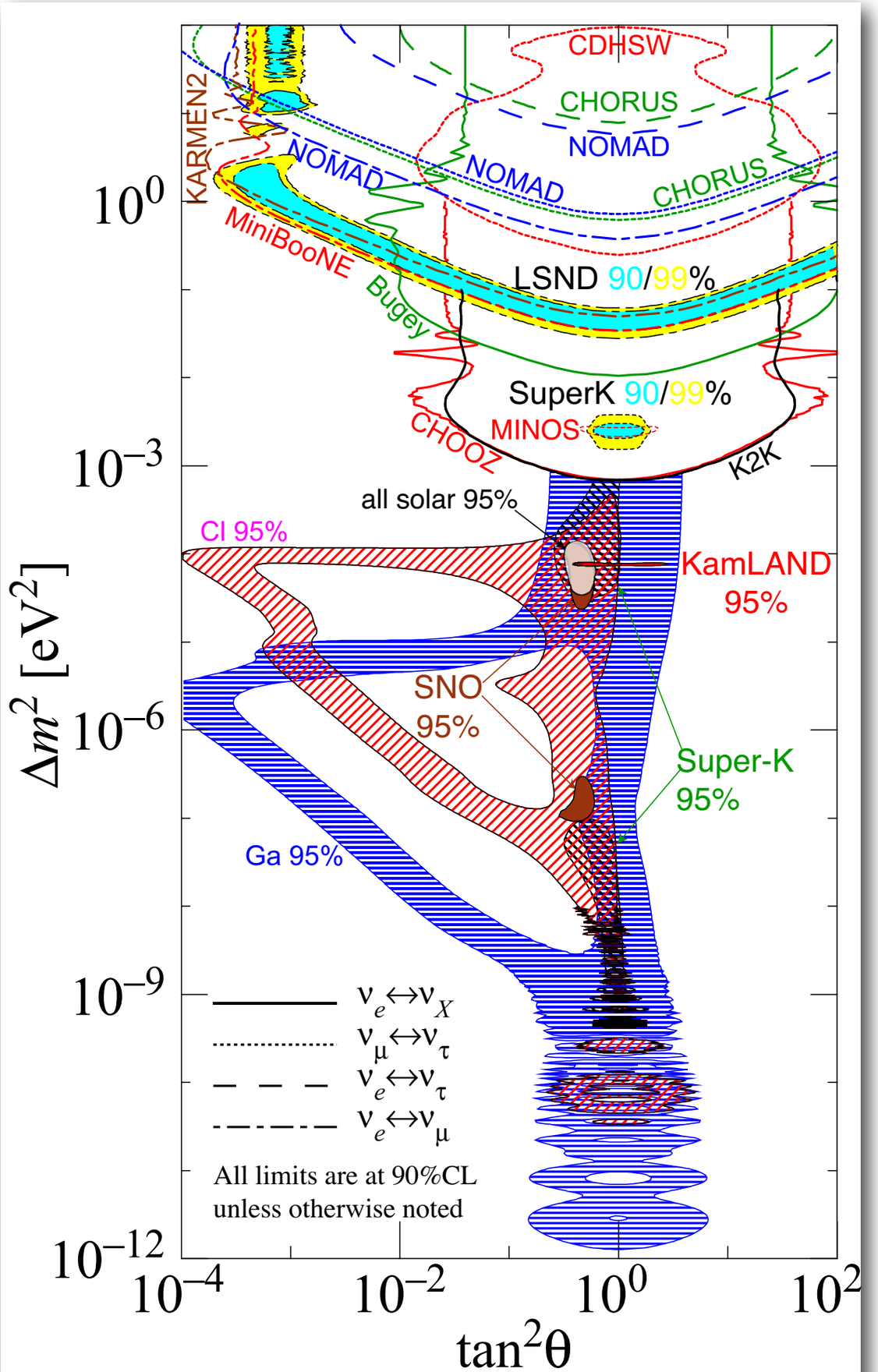


Conclusions

- We have performed a joint search for muon neutrino disappearance at $\Delta m^2 \sim 1 eV^2$ with SciBooNE and MiniBooNE.
- Two independent analyses performed; both showed consistent results.
  - Achieved world's best sensitivity at $0.5 < \Delta m^2 < 30\ eV^2$.
  - No significant signal found.
  - Set the best 90%CL limit at $10 < \Delta m^2 < 30\ eV^2$.
- Paper on archive, submitted to Phys.Rev.D.

  arXiv:1106.5685[hep-ex]
- Stay tuned for a forthcoming joint muon anti-neutrino disappearance analysis!


Thanks!



http://hitoshi.berkeley.edu/neutrino

Oscillation Observations

- 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

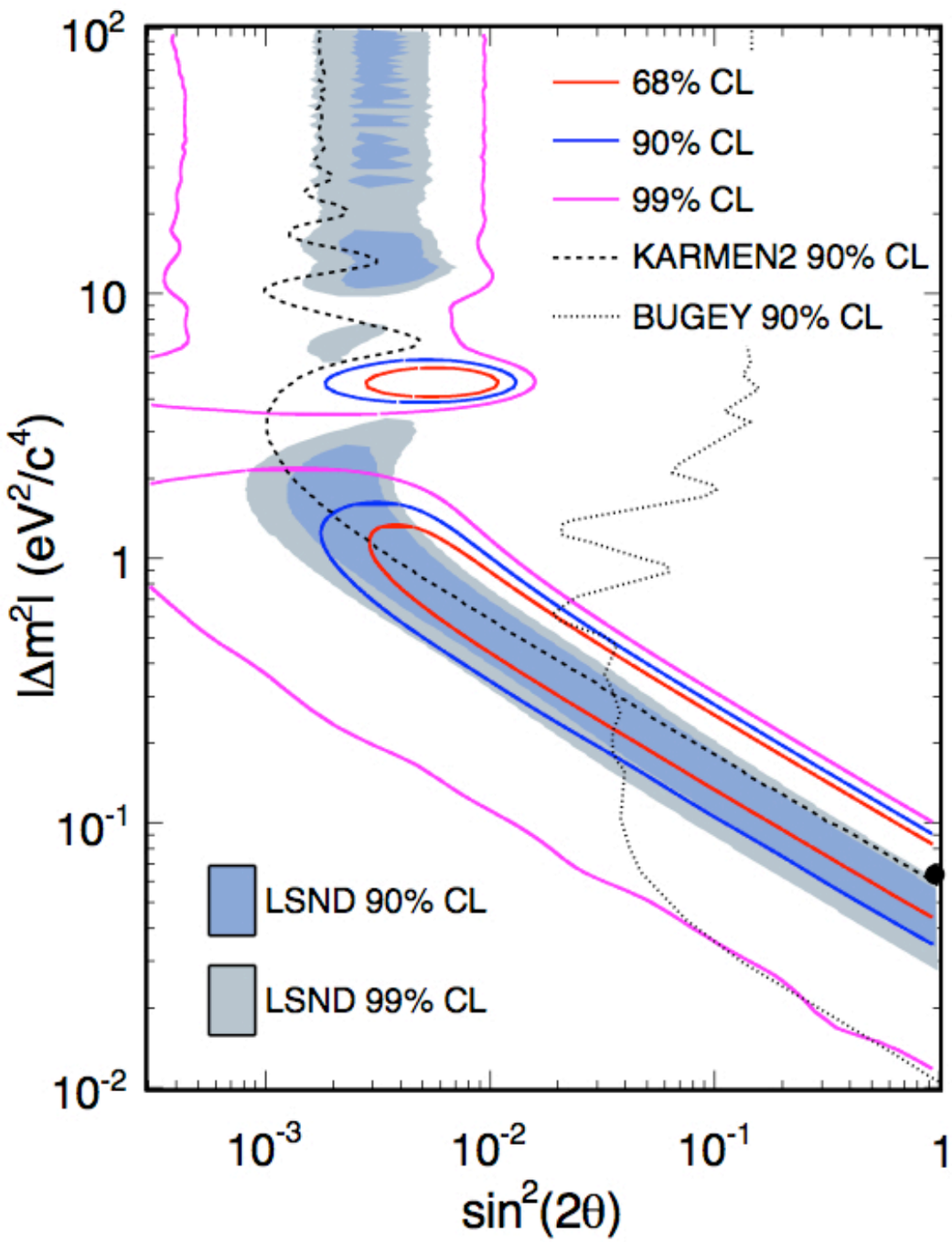
What does MiniBooNE claim?

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.

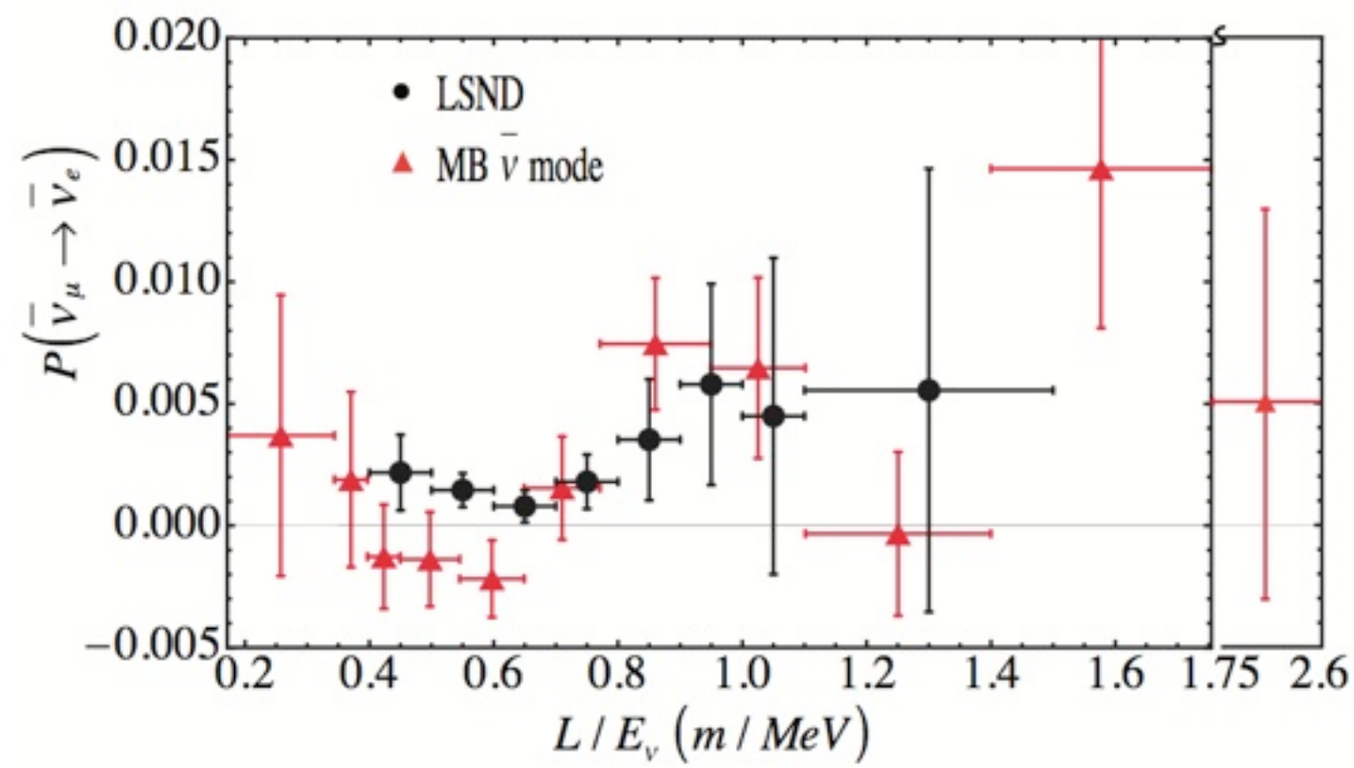
Comparing MB to LSND

Fit to 2ν mixing model

Phys.Rev.Lett.105:181801,2010

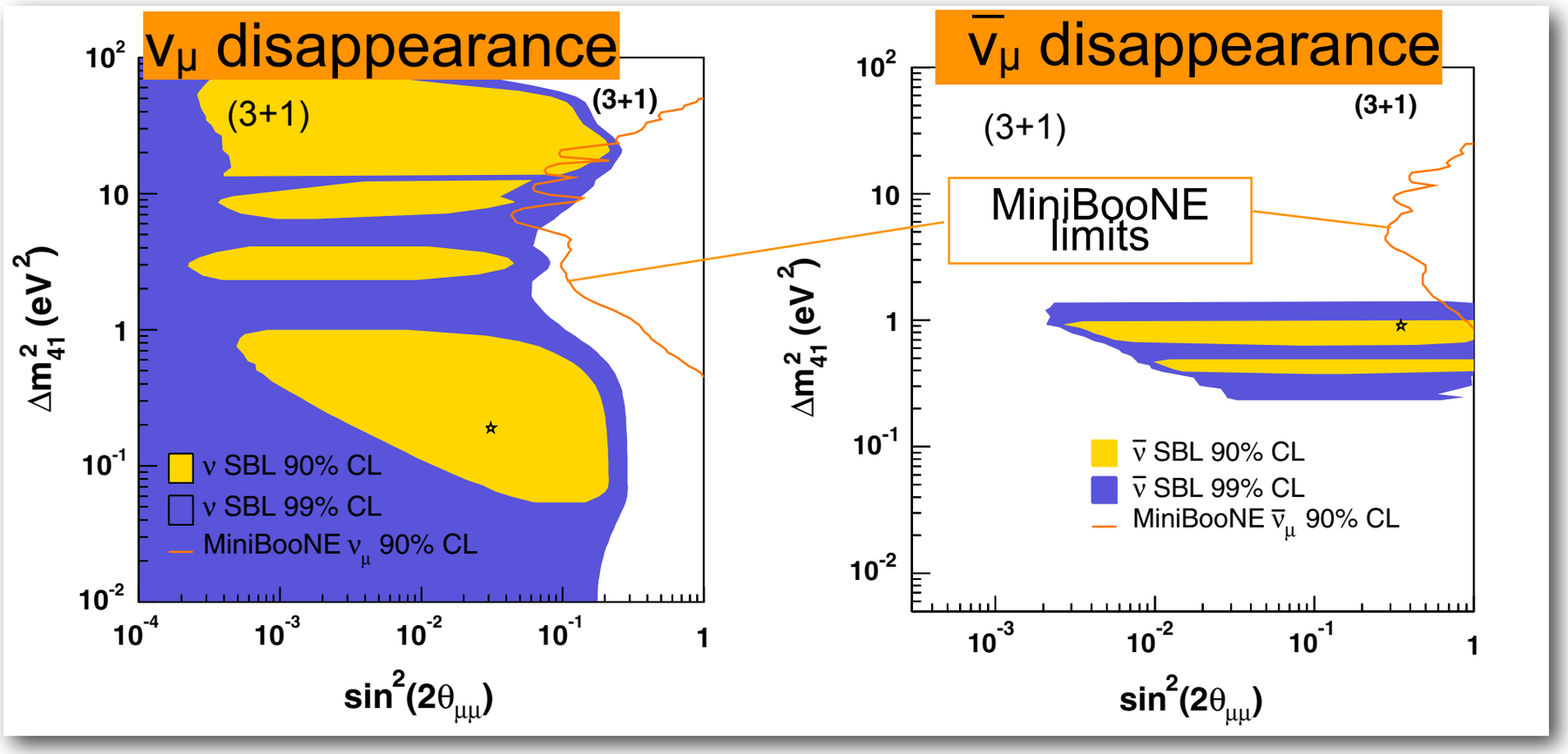


Model-independent plot of inferred oscillation probability



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.**

Analysis Overview

Two independent analyses

Spectrum fit

SciBooNE data

↓ Spectrum fit

CC interaction rate measurement

↓

MiniBooNE rec. E_ν prediction

↕ Oscillation Fit

MiniBooNE rec. E_ν data

Advantage:
Decouple oscillation fit from constraint.
Observe the amount of constraint.

Simultaneous fit

SB + MB Rec. E_ν Data

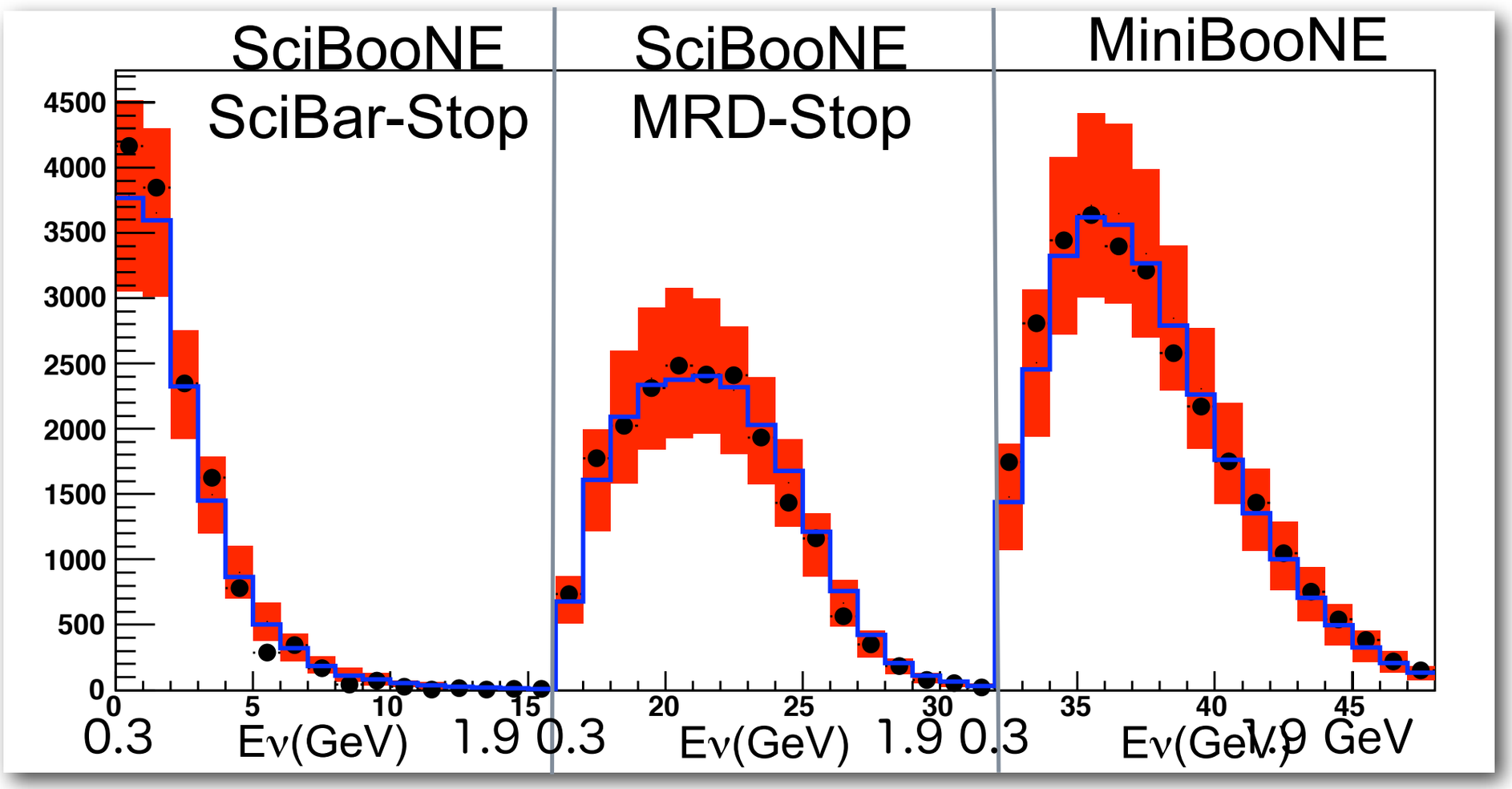
↕ Oscillation Fit

SB + MB Rec. E_ν Prediction

Advantage:
Direct fit for disappearance in SciBooNE and MiniBooNE.
Correlation between the two constrain systematic error.

Simultaneous Fit

- Fit reconstructed E_ν distributions from SciBar-stopped, MRD-stopped and MiniBooNE samples simultaneously.
  - 16 bins/sample x 3 sample = <u>48 bins</u>
- 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

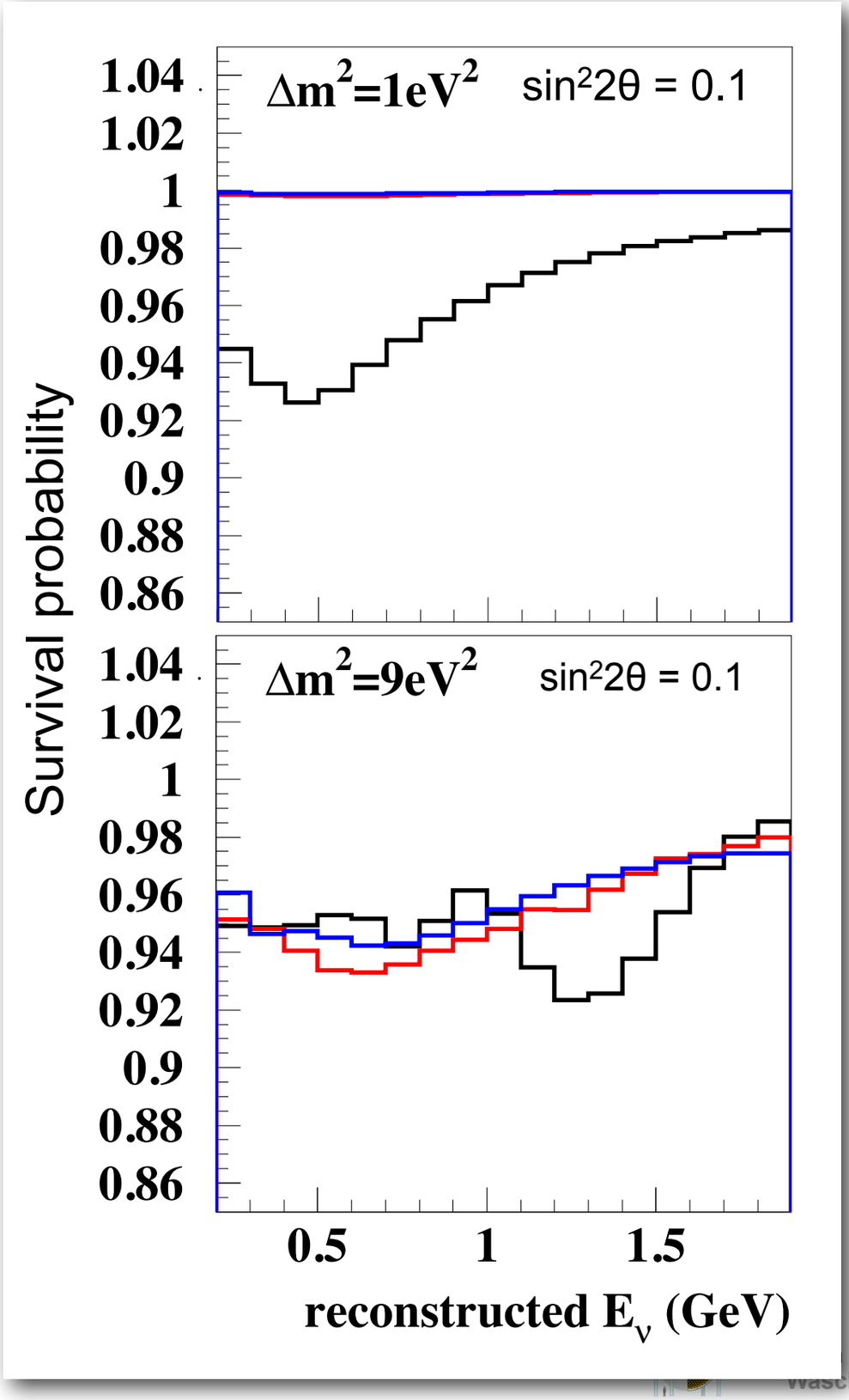
-- SciBooNE SciBar-stoped
-- SciBooNE MRD-stopped
-- MiniBooNE

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

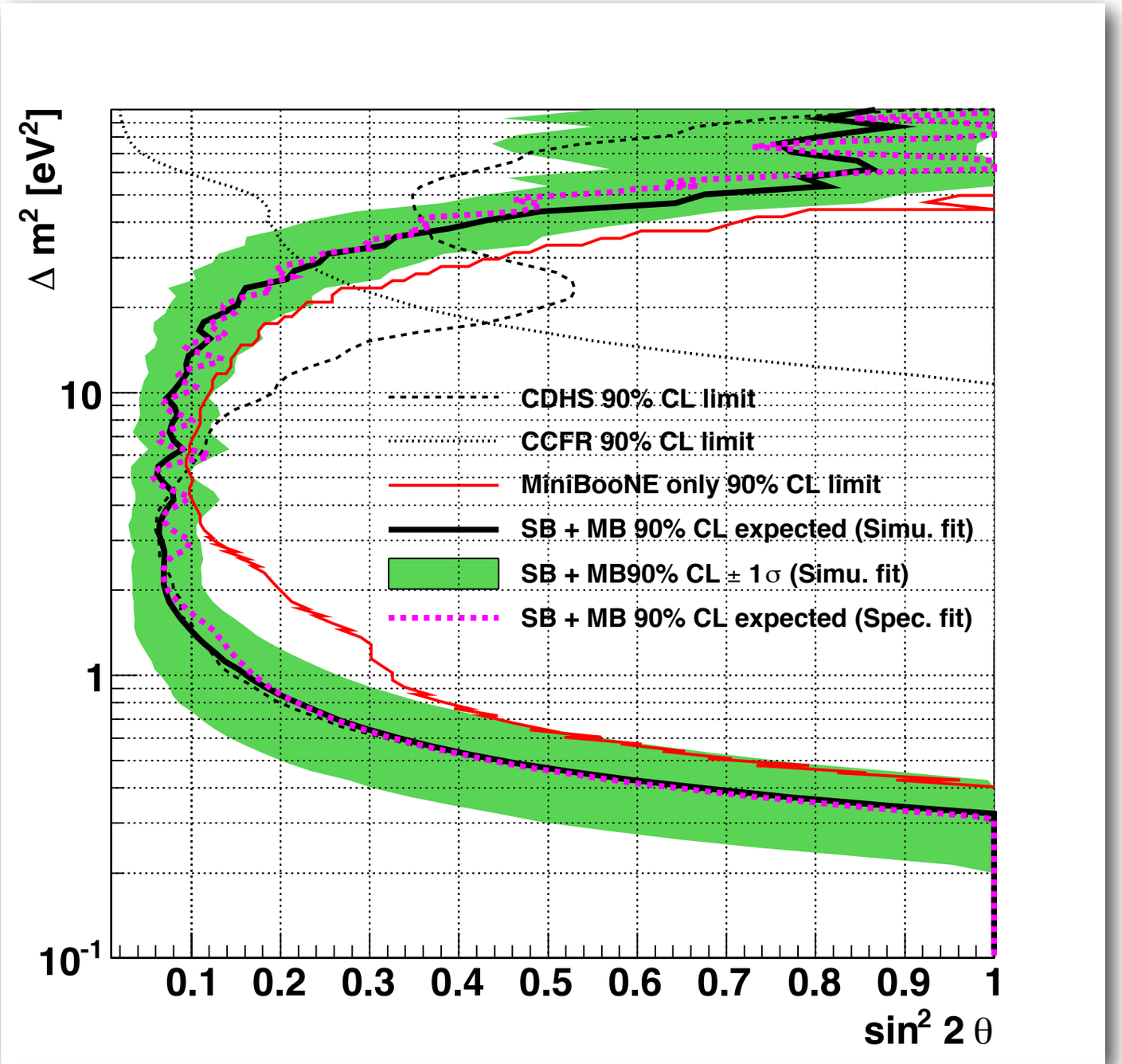
$$\chi^2 = \sum_{i,j}^{BINS} (d_i - Np_i) M_{ij}{}^{-1} (d_j - Np_j)$$

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.



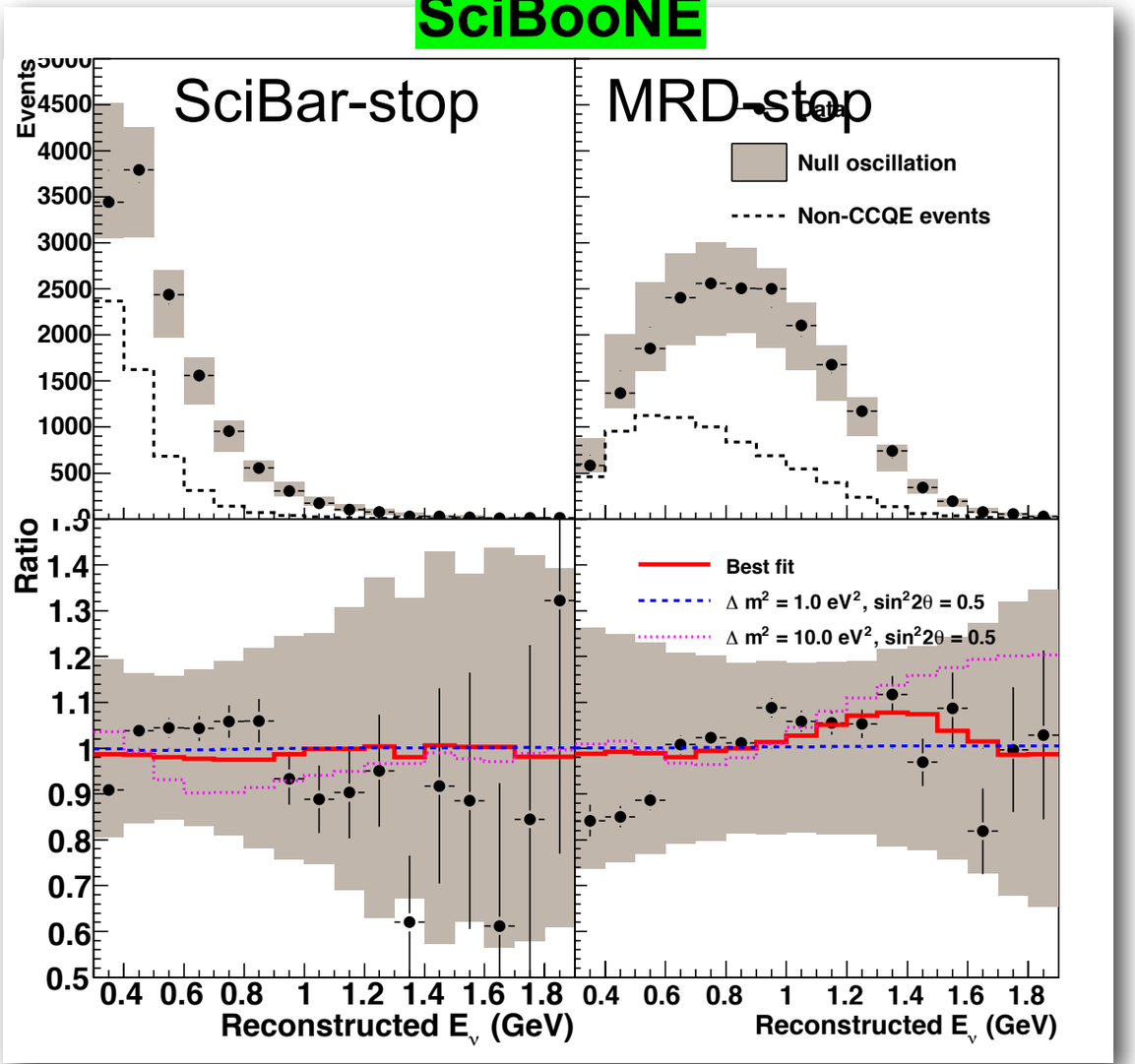
Simultaneous fit sensitivity



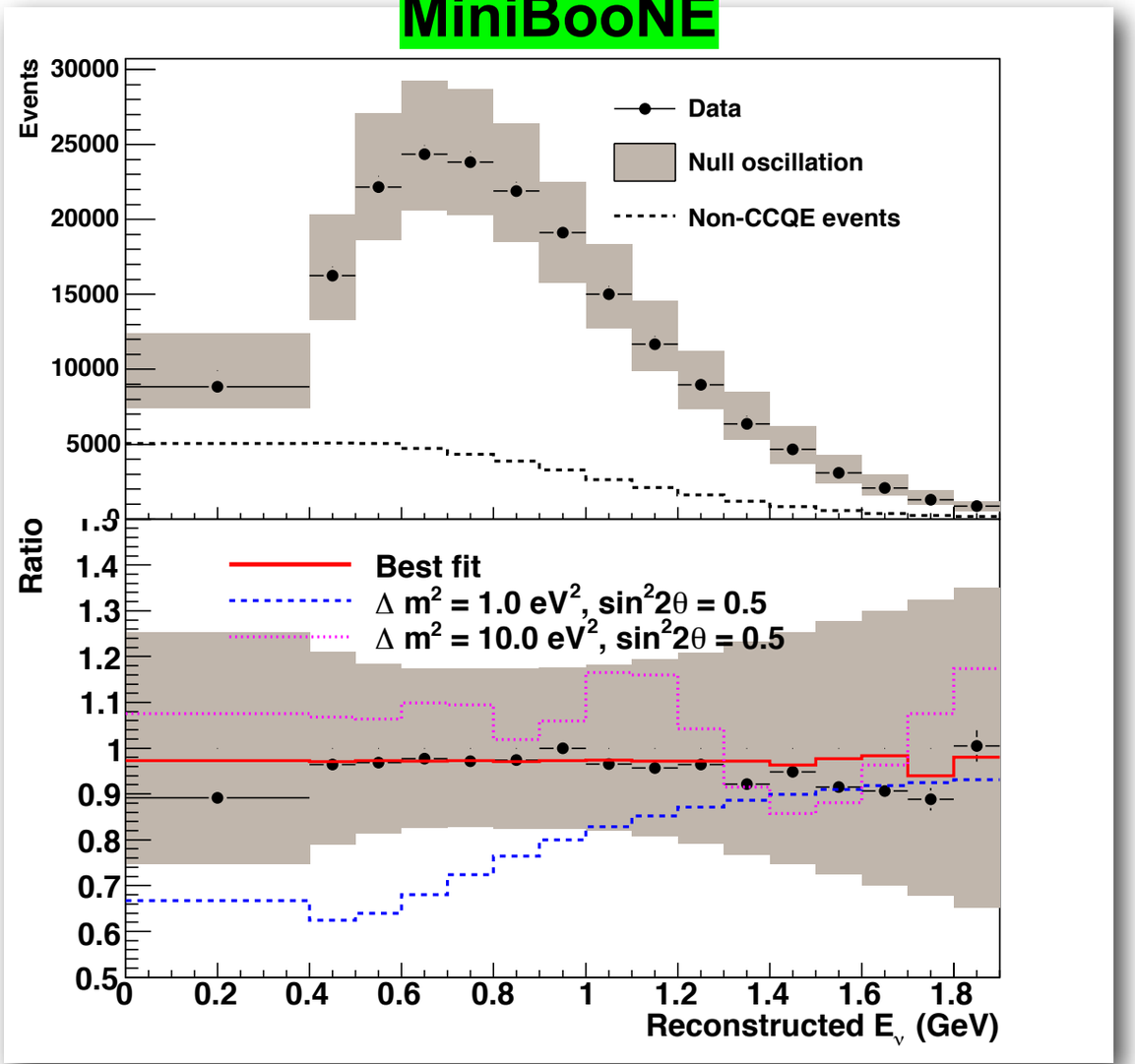
- **Sensitivities of the two analysis method are (roughly) the same.**
- Simultaneous fit sensitivity curve is smoother because of smaller binning effects than the spectrum fit analysis.

Simultaneous fit result

SciBooNE



MiniBooNE



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

$\chi^2(null) = 45.1/48(DOF)$

$\chi^2(best) = 39.5/46(DOF)$

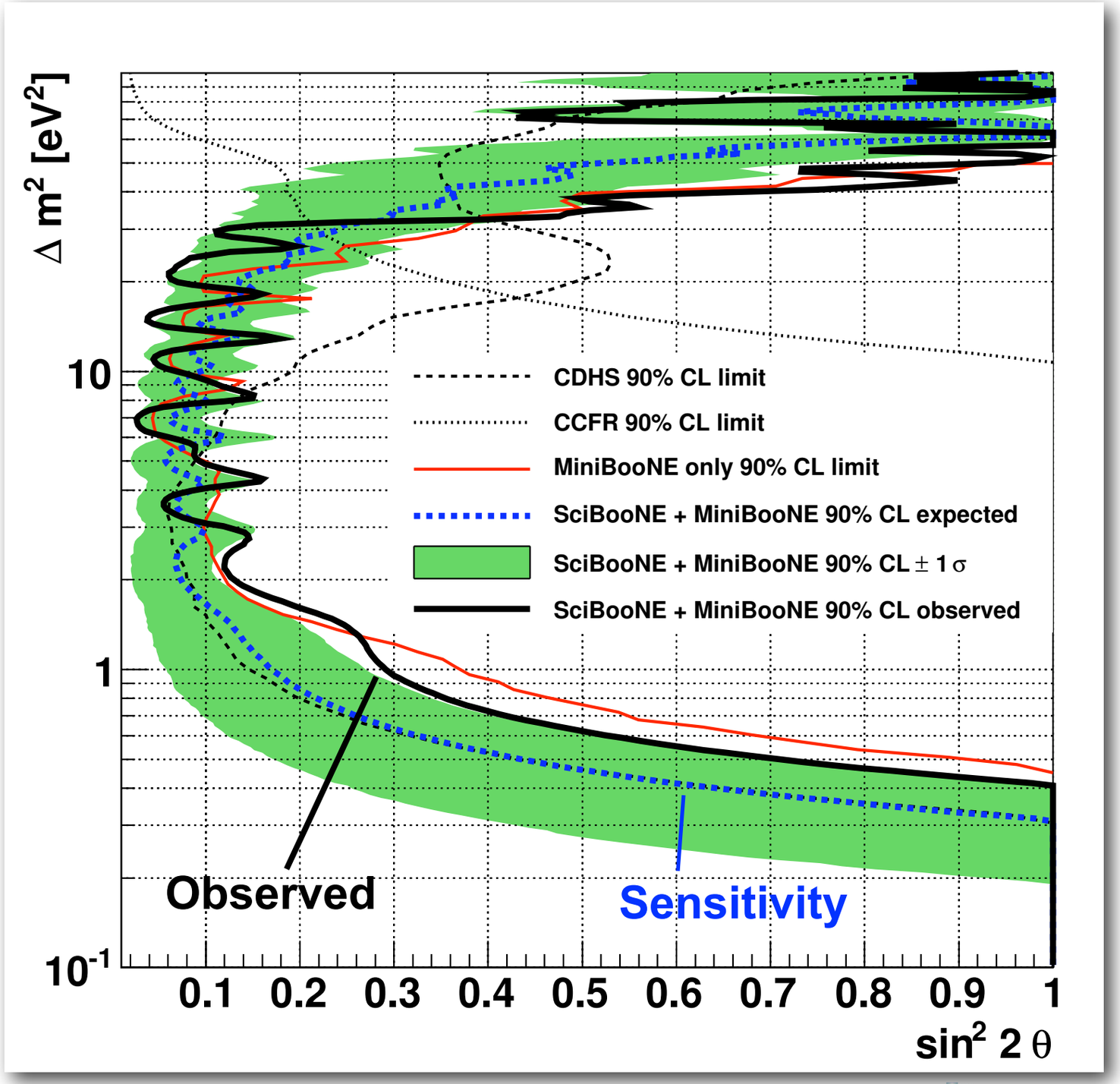
$\Delta\chi^2 = \chi^2(null) - \chi^2(best) = 5.6$

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

No significant oscillation signal observed.

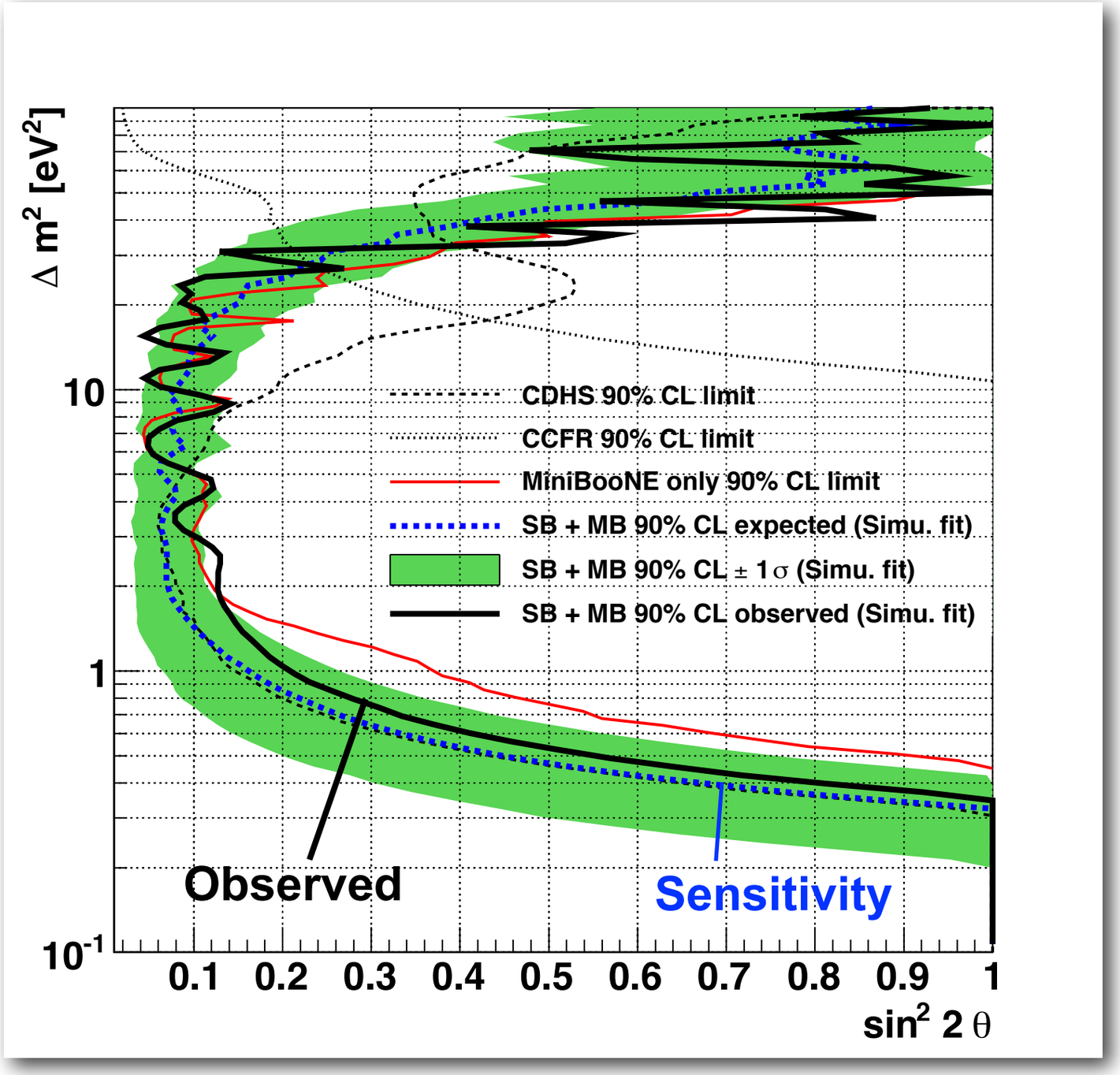
90% CL limit from spectrum fit

- 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.



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

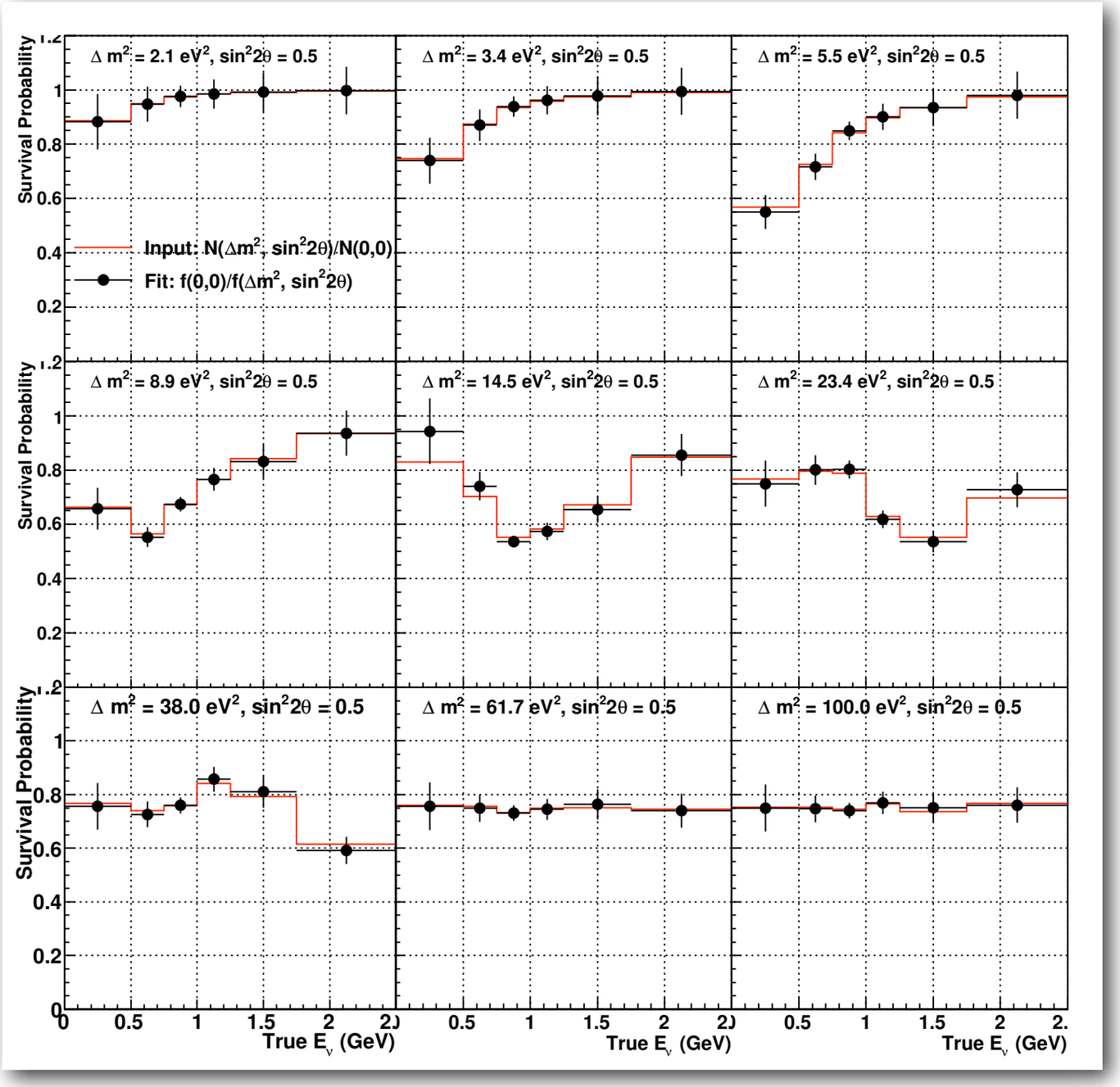
TABLE VIII. List of systematic uncertainties considered.

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

Rate normalisation factors from SciBooNE spectrum fit

Energy region (GeV)	ν_μ CC rate normalization factor NEUT	NUANCE
0.25 - 0.50	1.04 ± 0.20	1.65 ± 0.22
0.50 - 0.75	1.03 ± 0.11	1.31 ± 0.11
0.75 - 1.00	1.23 ± 0.08	1.36 ± 0.08
1.00 - 1.25	1.29 ± 0.10	1.38 ± 0.09
1.25 - 1.75	1.19 ± 0.11	1.36 ± 0.12
1.75 -	0.79 ± 0.08	0.90 ± 0.09

Test of SB spectrum fit with oscillation effects



Black points: fit result

Red lines: input value

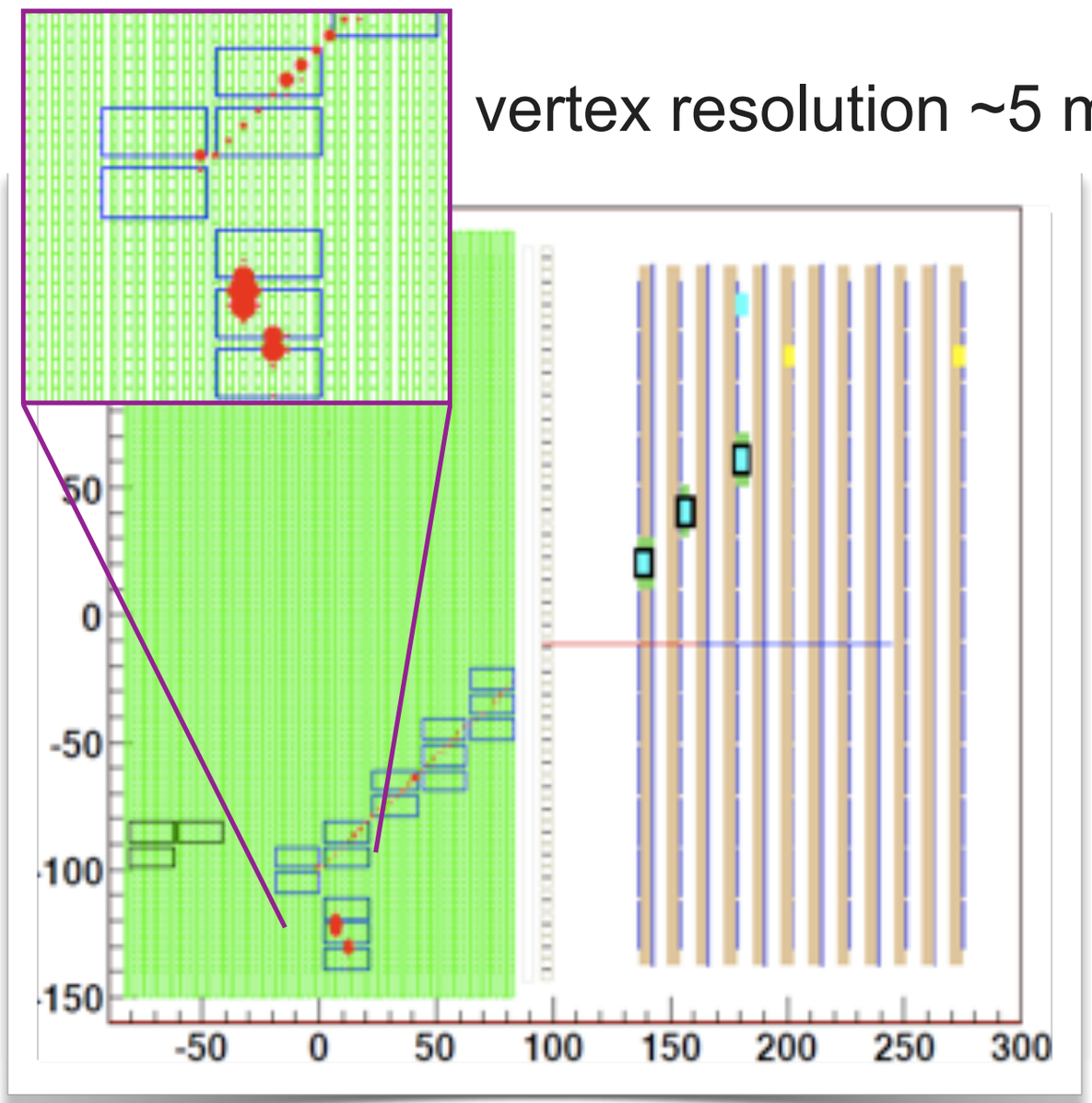
Neutrino event displays

Real SciBooNE Data

ADC hits (area ∝ charge)

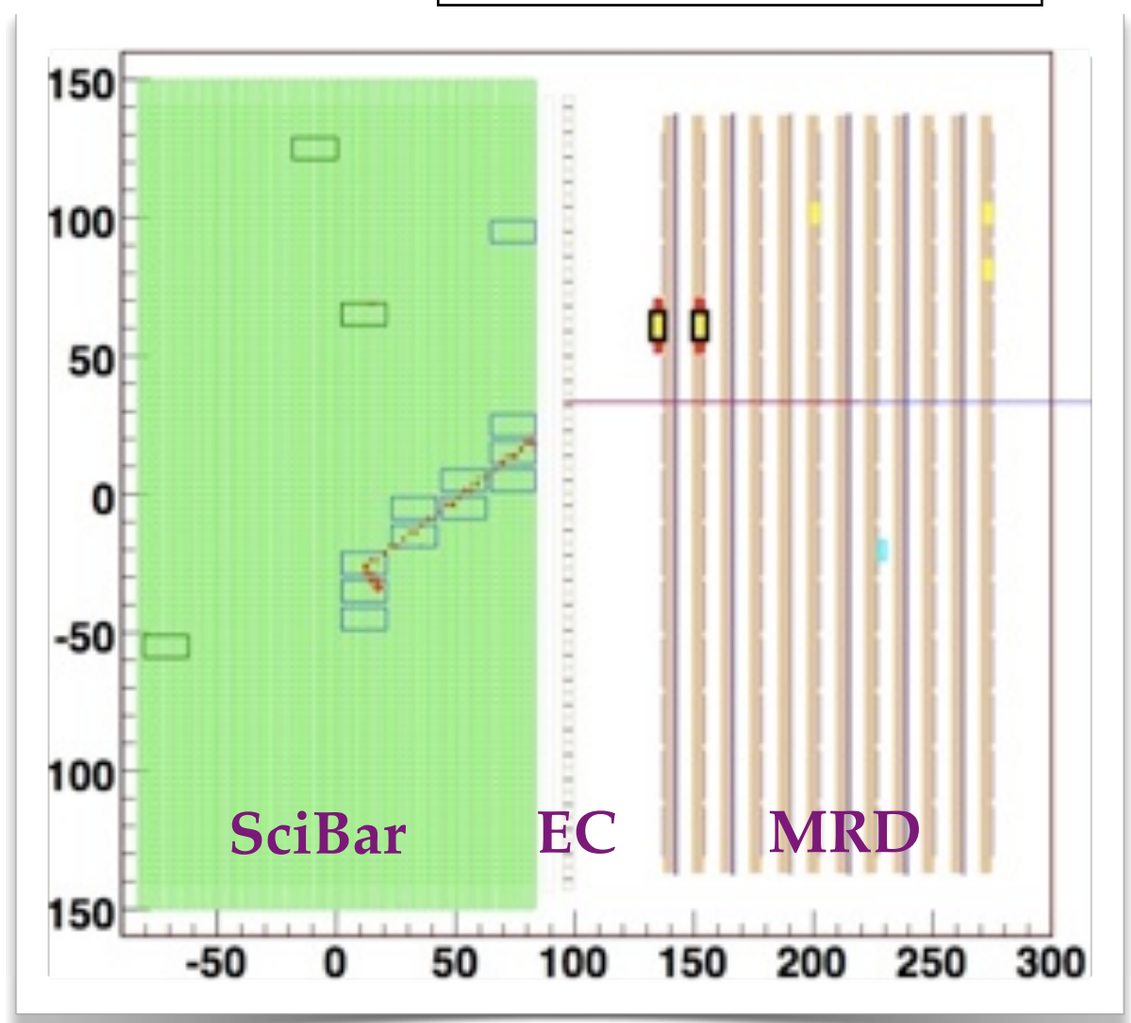
TDC hits (32ch OR)

vertex resolution ~5 mm



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

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



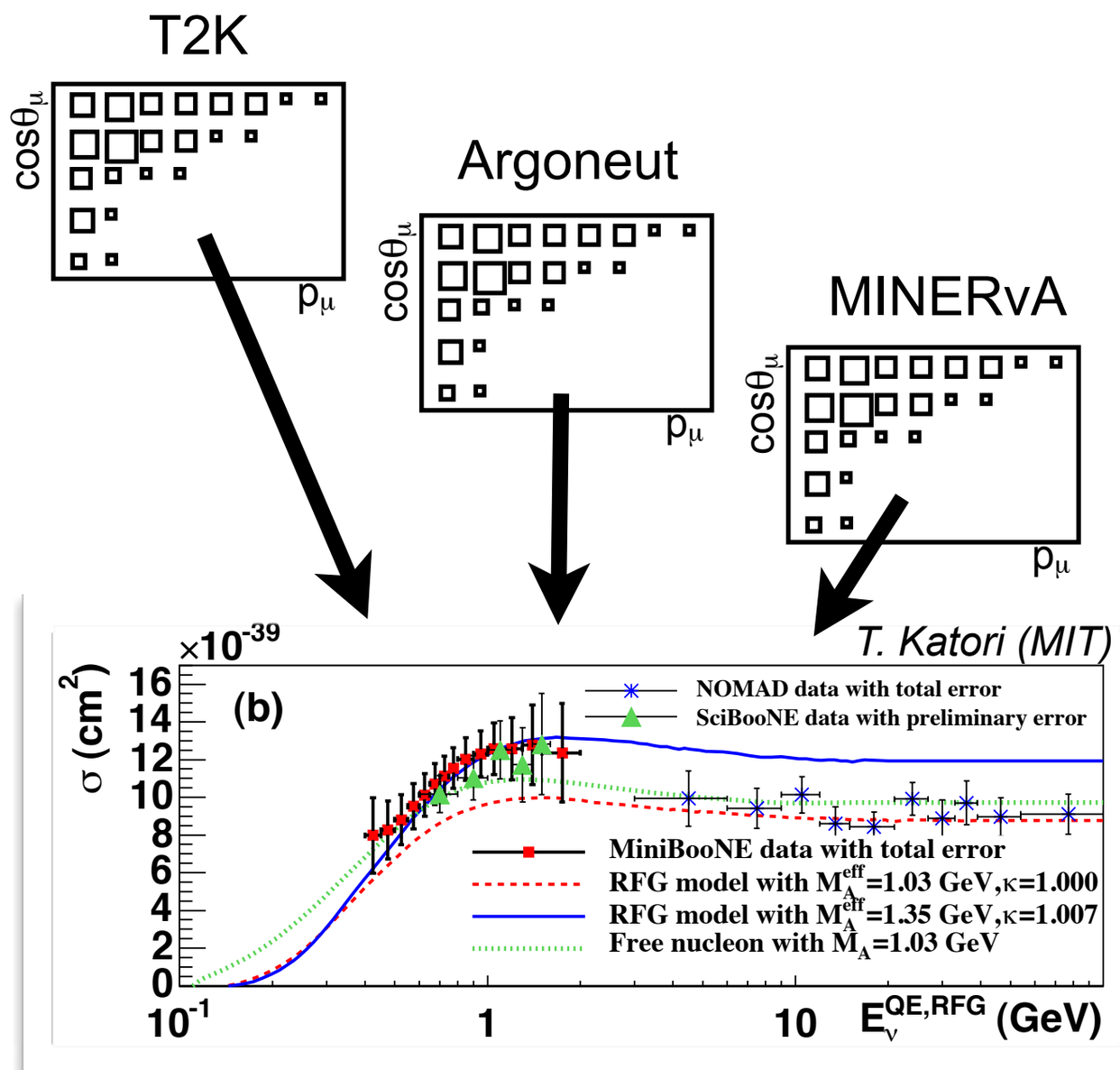
ν_μ CC-QE candidate

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

Growing Consensus

- We need broad coverage
  ➡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), σ(μ), σ(μ+p), σ(μ+π)

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



Same goes for NC...

Discuss!

- Possible Improvements:
  - Dominant uncertainties: neutrino x-section and MiniBooNE detector response.
  - Further analysis of SciBooNE (and MiniBooNE) data could reduce the cross section errors if we had newer/better cross section models.
  - To reduce detector error, need identical detectors or $10^{\sim 2}$ MeV e^- calibration.
- Muon antineutrino disappearance analysis ⇐Particularly interesting!
  - These analysis methods are directly applicable to anti-neutrino analysis.
  - ν-mode result constrains ν BG, together with a direct measurement by MiniBooNE (arXiv:1102.1964) and event-by-event separation by SciBooNE.