Accelerator-based neutrinos
Lecture 1

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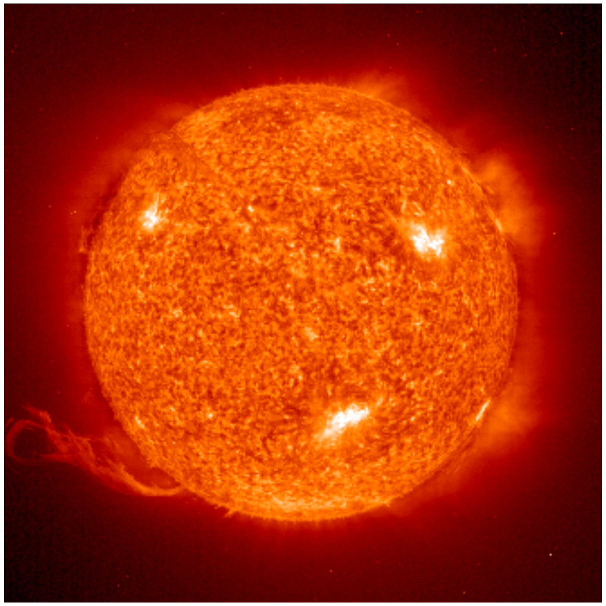
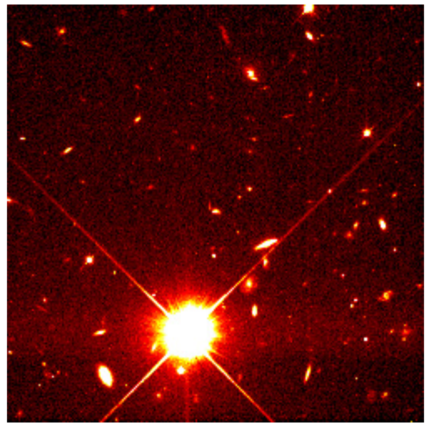
Neutrino sources

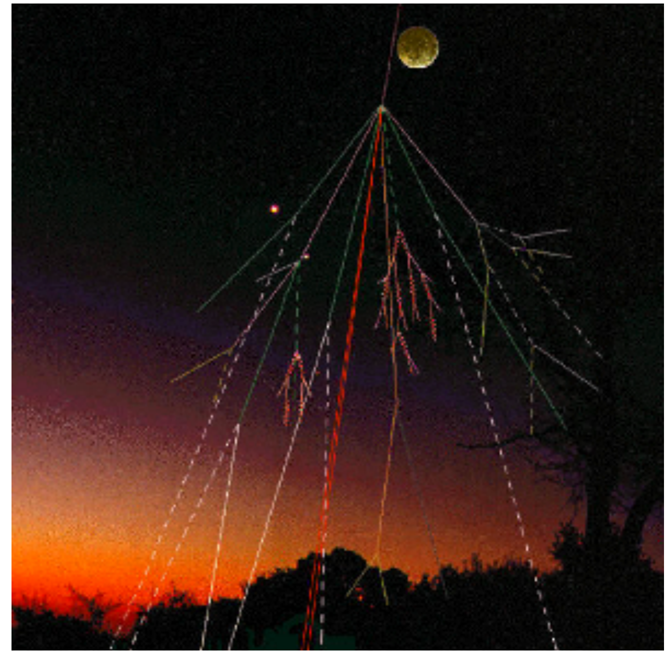
The Sun (fusion)



Galactic and extra-galactic sources (e.g SN)

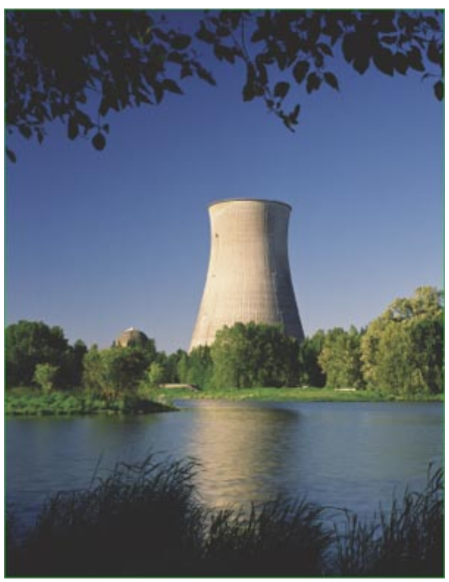


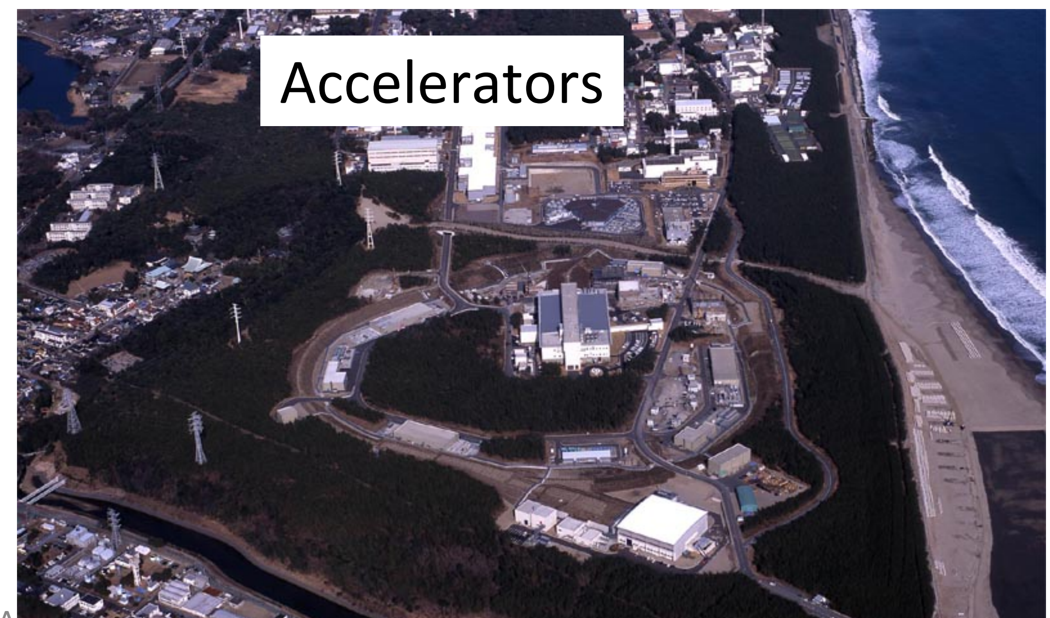
Our atmosphere



Radioactive decays

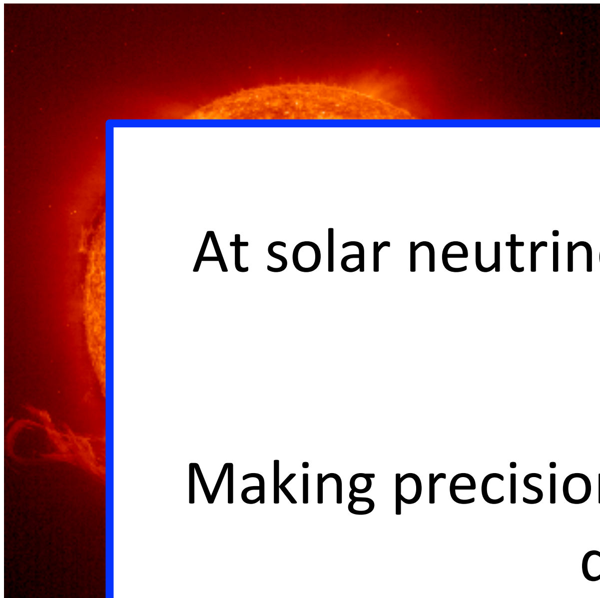
Reactors





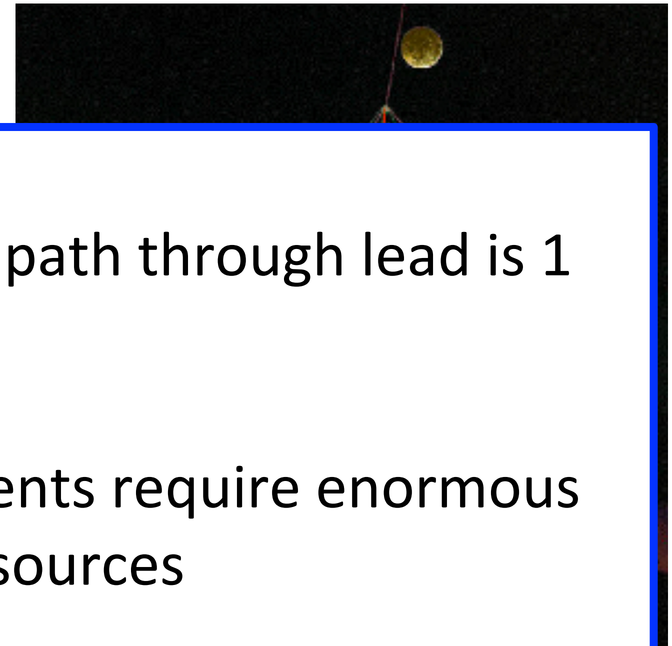
Neutrino sources

The Sun (fusion)



Galactic and extra-galactic sources (e.g. SN)

Our atmosphere



At solar neutrino energies, mean free path through lead is 1 light year

Making precision neutrino measurements require enormous detectors and intense sources

Accelerator-driven neutrino beams are one such method

Radio decay

Reactors

Physics of accelerator based ν experiments

Neutrino oscillation

- Measurements of neutrino mixing parameters
- Nonstandard neutrino mixing

Electroweak tests

- Lorentz violation
- Measurement of $\sin^2\theta_W$
- Discovery of ν_μ, ν_τ

Neutrino interactions

- Charged current interactions
- Neutral current interactions
- Deep inelastic scattering
- Structure functions

Detector R&D

Physics of accelerator based ν experiments

Neutrino oscillation

- Measurements of neutrino mixing parameters
- Nonstandard neutrino mixing

K2K, MINOS, T2K, NOvA
OPERA (& ICARUS)

LSND, Karmen,
MiniBooNE, MicroBooNE
CHORUS, NOMAD

Electroweak tests

- Lorentz violation
- Measurement of $\sin^2\theta_W$
- Discovery of ν_μ, ν_τ

CCFR, CDHS, NuTeV
Gargamelle, DONUT
CHARM

Neutrino interactions

- Charged current interactions
- Neutral current interactions
- Deep inelastic scattering
- Structure functions

ANL, BNL bubble chamber experiments
SciBooNE, MINERvA
COHERENT, CONNIE

Detector R&D

ArgoNeuT
PEANUT

Incomplete list of experiments; later lectures will cover future and proposed experiments
Most experiments cover multiple physics topics

Physics of accelerator based ν experiments

Neutrino oscillation
- Measurements of neutrino mixing parameters
- Nonstandard neutrino mixing

K2K, MINOS, T2K, NOvA
OPERA (& ICARUS)

LSND, Karmen,
MiniBooNE, MicroBooNE
CHORUS, NOMAD

Focus for this set of talks

Electroweak tests
- Lorentz violation
- Measurement of $\sin^2\theta_W$
- Discovery of ν_μ, ν_τ

CCFR, CDHS, NuTeV
Gargamelle, DONUT
CHARM

Neutrino interactions
- Charged current interactions
- Neutral current interactions
- Deep inelastic scattering
- Structure functions

Neutrino cross sections covered by K. McFarland

ANL, BNL bubble chamber experiments
SciBooNE, MINERvA
COHERENT, CONNIE

Detector R&D

Neutrino detection techniques covered by K. Scholberg

ArgoNeuT
PEANUT

Open questions in neutrino mixing

Flavor eigenstates (coupling to the W)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates (definite mass)

Unitary PMNS mixing matrix

Three observed flavors of neutrinos (ν_e, ν_μ , ν_τ) means U is represented by three independent mixing angles (θ_{12}, θ_{23}, θ_{13}) and a CP-violating phase δ

Parameter	best-fit ($\pm 1\sigma$)	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.43 ± 0.06 (2.38 ± 0.06)	$2.23 - 2.61$ $(2.19 - 2.56)$
$\sin^2\theta_{12}$	0.308 ± 0.017	$0.259 - 0.359$
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$	$0.374 - 0.628$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,	$0.380 - 0.641$
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$	$0.0176 - 0.0295$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$	$0.0178 - 0.0298$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ $(1.31^{+0.29}_{-0.33})$	$(0.00 - 0.16) \oplus (0.86 - 2.00)$
		$((0.00 - 0.02) \oplus (0.70 - 2.00))$

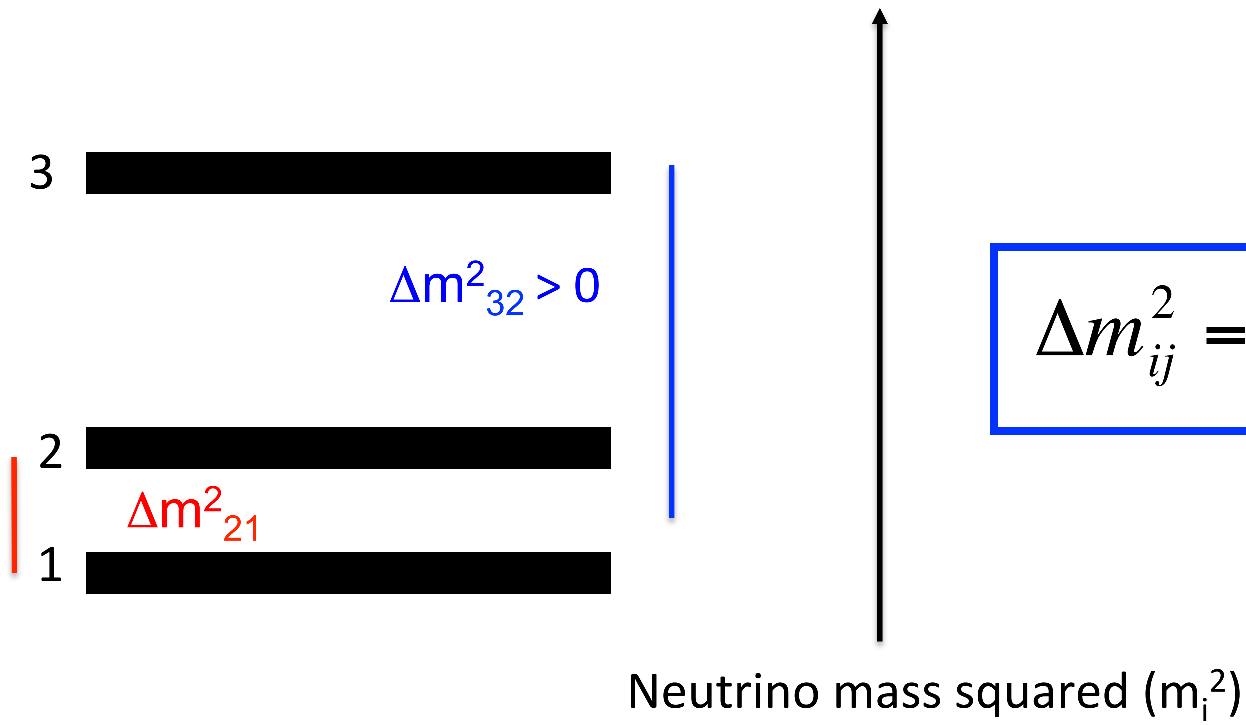
PDG2014

Measurements by accelerator-based experiments

Is θ_{23} mixing maximal (θ_{23}=46°±3°)

Is there CP violation (non-zero δ?)

Open questions in neutrino mixing



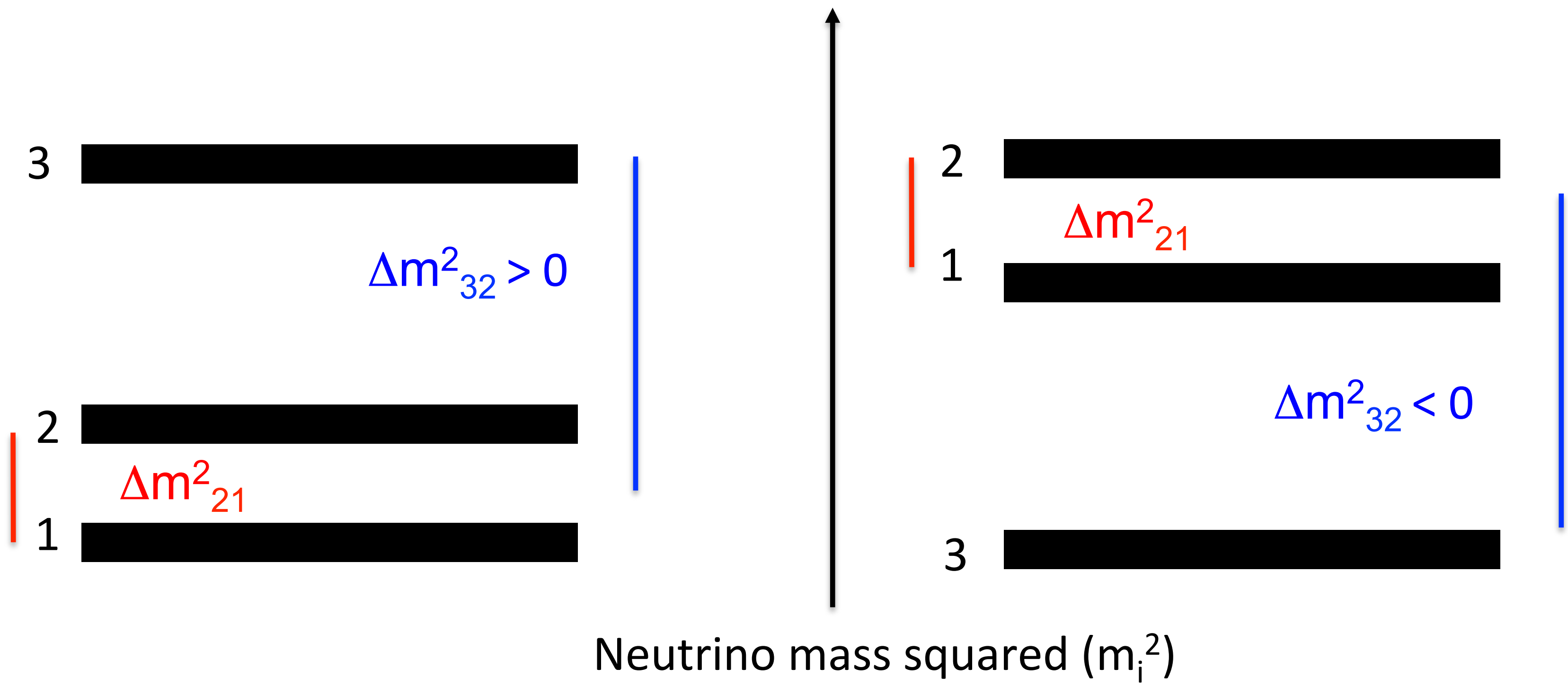
$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Neutrino oscillation measurements are sensitive to the interference of the mass eigenstates (Δm^2)

Two observed mass "splittings", determined from atmospheric/accelerator and solar/reactor neutrino experiments, respectively

- Δm^2(atmospheric) = $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}$ eV^2
- Δm^2(solar) = $\Delta m^2_{21} \sim 7.6 \times 10^{-5}$ eV^2

Open questions in neutrino mixing



The sign of Δm^2_{32}, or the "mass hierarchy" is still unknown

- Normal "hierarchy" is like quarks (m_1 is lightest, $\Delta m^2_{32} > 0$)
- Inverted hierarchy has m_3 lightest ($\Delta m^2_{32} < 0$)

What is the mass hierarchy?

Oscillation probabilities

$|\Delta m^2_{32}| >> \Delta m^2_{21}$, producing high frequency and low frequency oscillation terms

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) + 2\sum_{i>j}\mathrm{Im}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin\left(\frac{2.54\Delta m^2_{ij}L}{E}\right)$$

If choose L, E, such that $\sin^2(\Delta m^2_{32}L/E)$ is of order 1, then Δm^2_{21} terms will be small. Then...

ν_μ "disappear" into ν_e, ν_τ

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

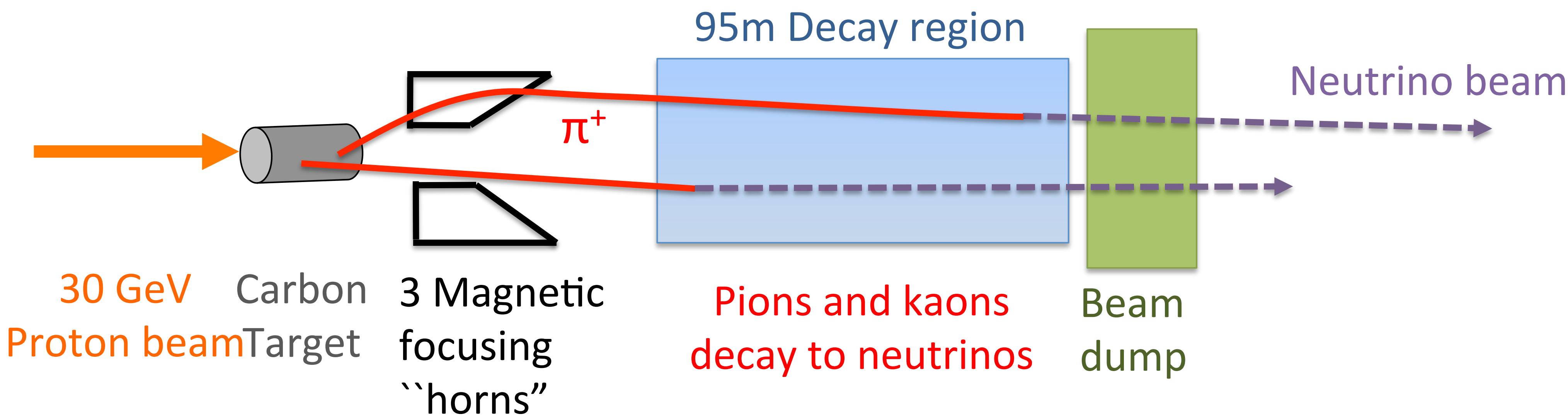
A small amount of ν_e will "appear"

$\Delta m^2_{31} \sim \Delta m^2_{32}$

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{31}L}{E}\right)$$

Only leading order terms shown

Accelerator based neutrino sources



To measure ν_μ disappearance, and ν_e appearance requires a ν_μ source*

- Atmospheric neutrinos include both ν_e and ν_μ from production
- Accelerator based beams are pure ν_μ from a proton -> meson -> decay chain:
  - Typically >99.9% ν_μ
  - Production of neutrinos is “known”, scalable with accelerator improvements
  - Also possible to create antineutrino source

**There are other ways to probe oscillation physics with intense sources, more later*

Oscillation probabilities

ν_μ to ν_e appearance probability expansion:

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{32}} << 1,$$

$$\Delta = \frac{\Delta m^2_{32} L}{4E_\nu}$$

$$A = 2\sqrt{2} G_F N_e \frac{E_\nu}{\Delta m^2_{32}}$$

$$\begin{aligned} P_{\nu_\mu \to \nu_e} = & \frac{1}{(A-1)^2} \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2[(A-1)\Delta] \\ & -(+) \frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times \\ & \sin\delta_{CP} \sin\Delta \sin A\Delta \sin[(1-A)\Delta] \\ & + \frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times \\ & \cos\delta_{CP} \cos\Delta \sin A\Delta \sin[(1-A)\Delta] \\ & + \frac{\alpha^2}{A^2} \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2 A\Delta \end{aligned}$$

Key players:

- $|\Delta m^2_{32}|$ ~ 2.4 x 10^{-3} eV^2 (atmospheric mass splitting)
- Mixing angles: θ_{12}, θ_{23}, θ_{13}
- CP-violating phase δ_{CP}

Approximation from M. Freund, PRD 64, 053003

Neutrinos vs. antineutrinos probability depends on δ_{CP}, mass hierarchy (sign of Δm^2_{32})

- Mass hierarchy is determined through energy dependence of ν_e, ν_μ interactions in matter (matter effects, A terms)

Oscillation probabilities

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Key players:

- $|\Delta m^2_{32}|$ ~ 2.4 x 10^{-3} eV^2 (atmospheric mass splitting)

Subleading terms of ν_μ to ν_e appearance depend on δ_{CP}, mass hierarchy, but interpretation requires precision measurements of:
Δm^2_{32}, θ_{23} (disappearance) and Δm^2_{21}, θ_{12} and θ_{13}

Measurements of ν_μ to ν_e (and $\bar{\nu}_\mu$ to $\bar{\nu}_e$) appearance are sensitive to currently unknown physics

Oscillation probabilities

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

Measure: Δm^2_{32} and $\sin^2 2\theta_{23}$

Experimental controls:

- Fix beam energy (E)
- Place a detector at L, the (first) oscillation maximum

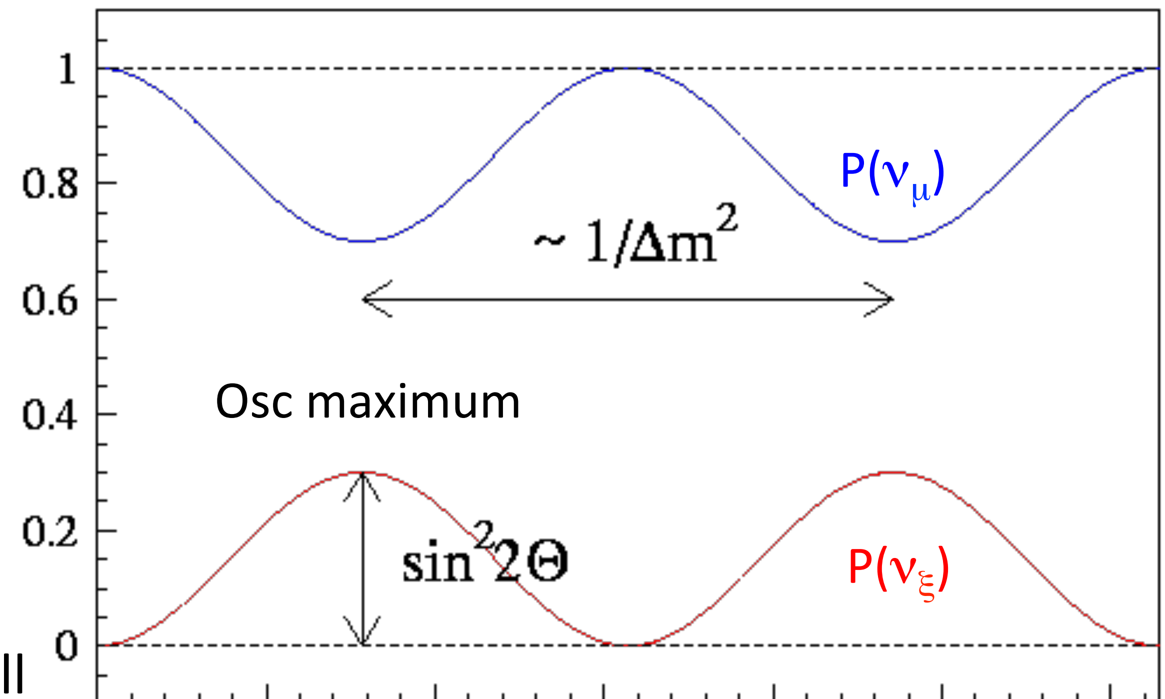
Why not place two detectors, one at L and one at 2L?

Flux decreases as $1/L^2$:

Event rate scales with flux:

N = Φ x σ x ε

Event rate is (currently) too small



KARMEN website graphic

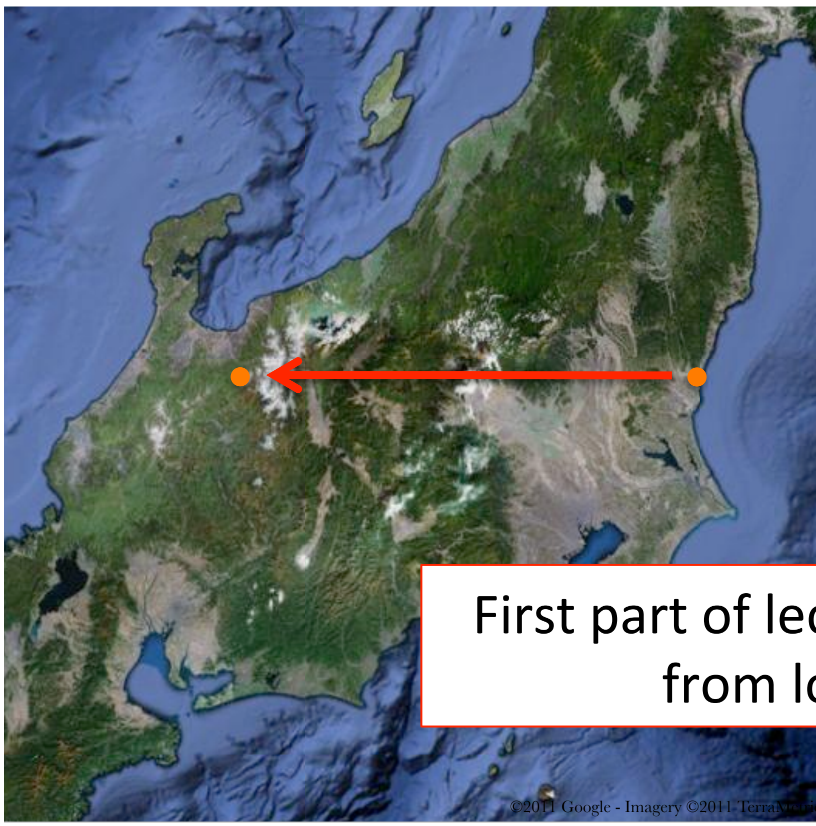
Long baseline experiments

$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right) + \ldots$$

Δm^2_{32}~3×10^{-3} eV^2, want $\sin^2(\Delta m^2 L/E)$ to be of order 1

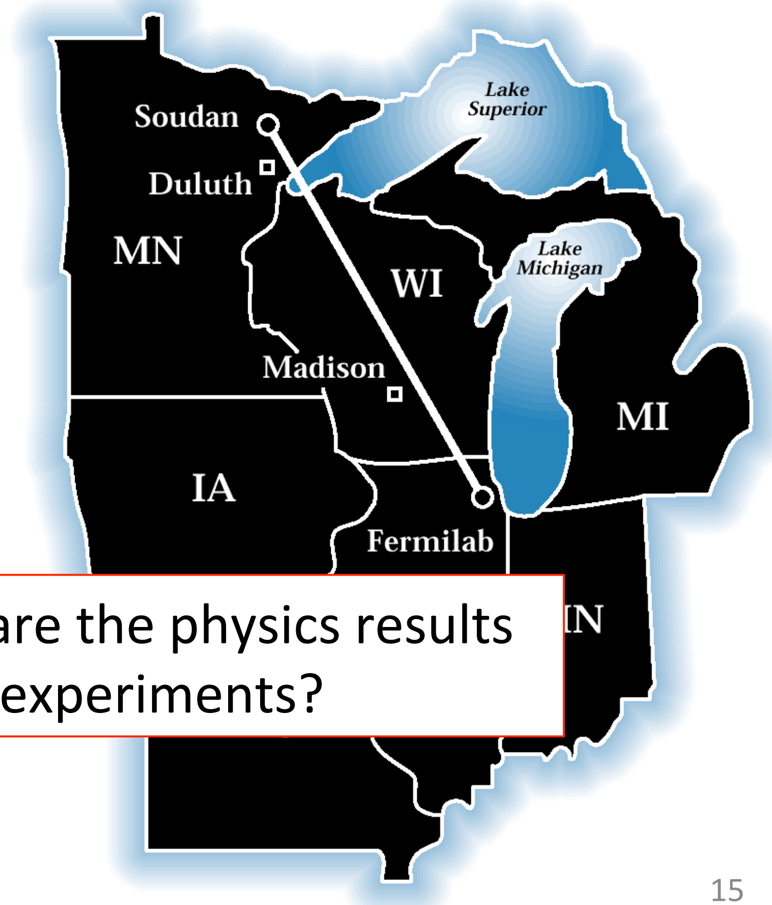
Tokai To Kamioka (T2K) experiment:

Ev(peak) ~0. 6GeV, L=295km



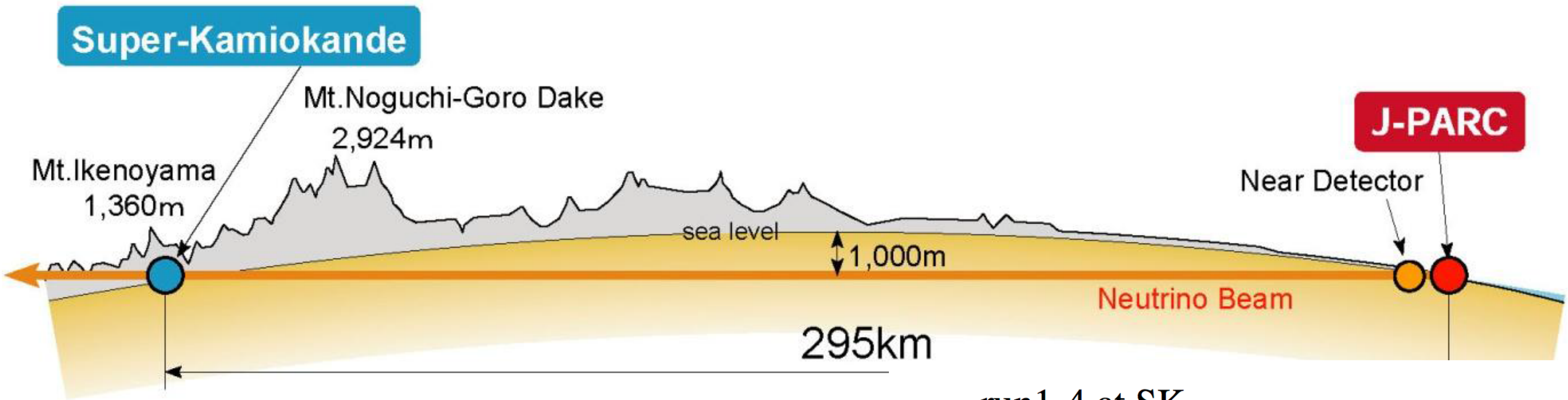
MINOS experiment:

Ev(peak) ~3 GeV, L=735km



First part of lecture: What are the physics results from long baseline experiments?

Accelerator-based experiment example: T2K



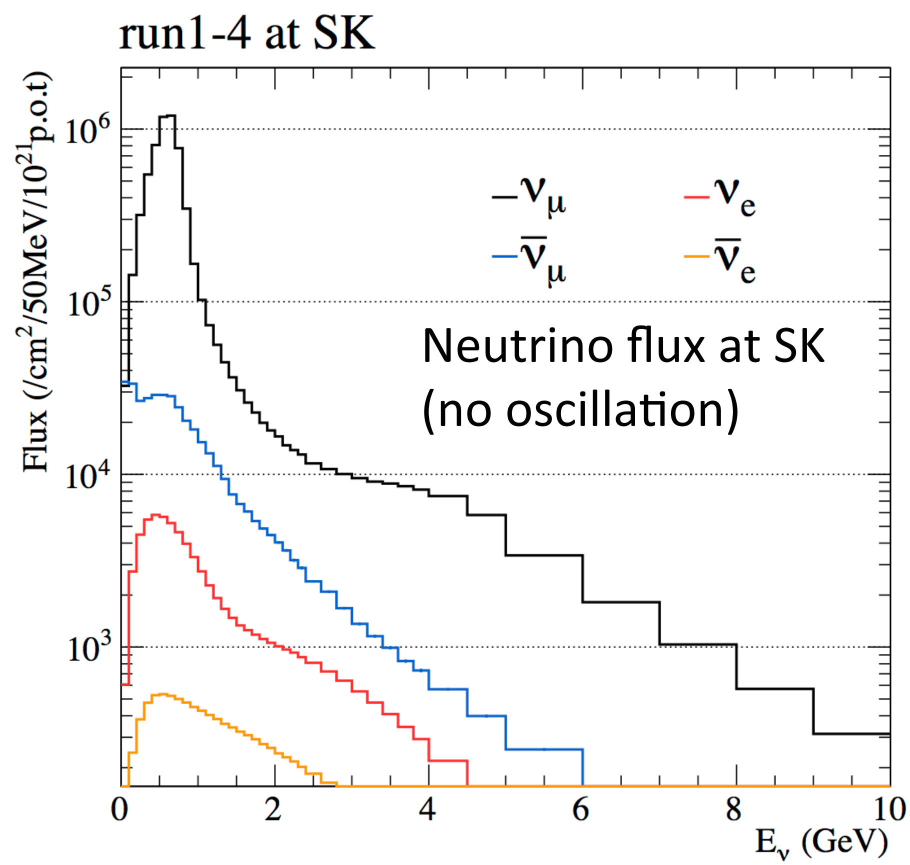
The physics so far:

ν_μ to ν_e (and $\overline{\nu}_\mu$ to $\overline{\nu}_e$) appearance:

- Discovery of ν_e appearance (2013)
- Search for presence of appearance with antineutrinos; necessary step toward future CPV searches

ν_μ, $\overline{\nu}_\mu$ disappearance:

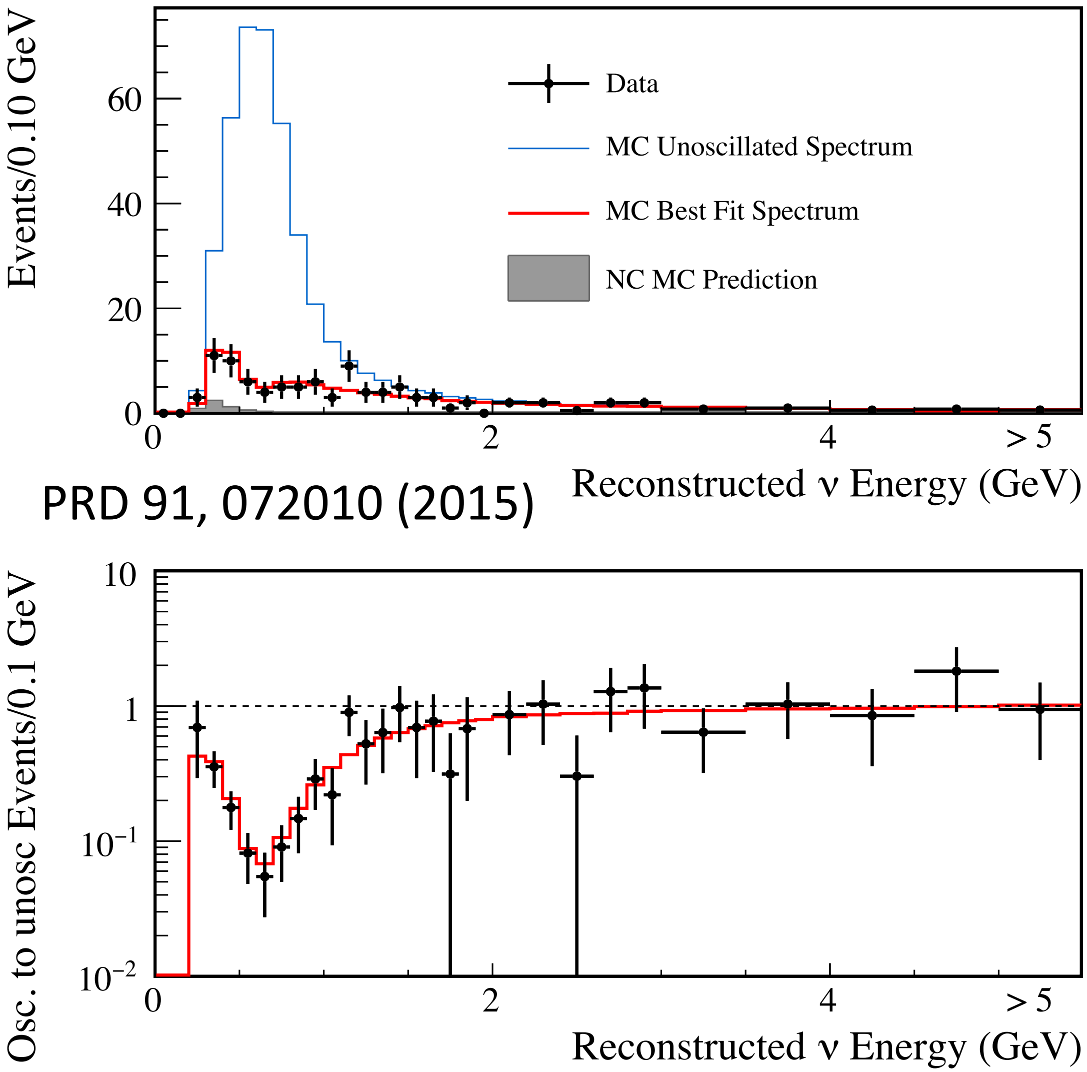
- World's best measurement of θ_{23}
- With antineutrinos: test of NSI or CPT theorem



ν_μ disappearance at T2K

For a fixed baseline (L=295km) oscillation probabilities depend on the neutrino energy E_ν

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right) + \ldots$$



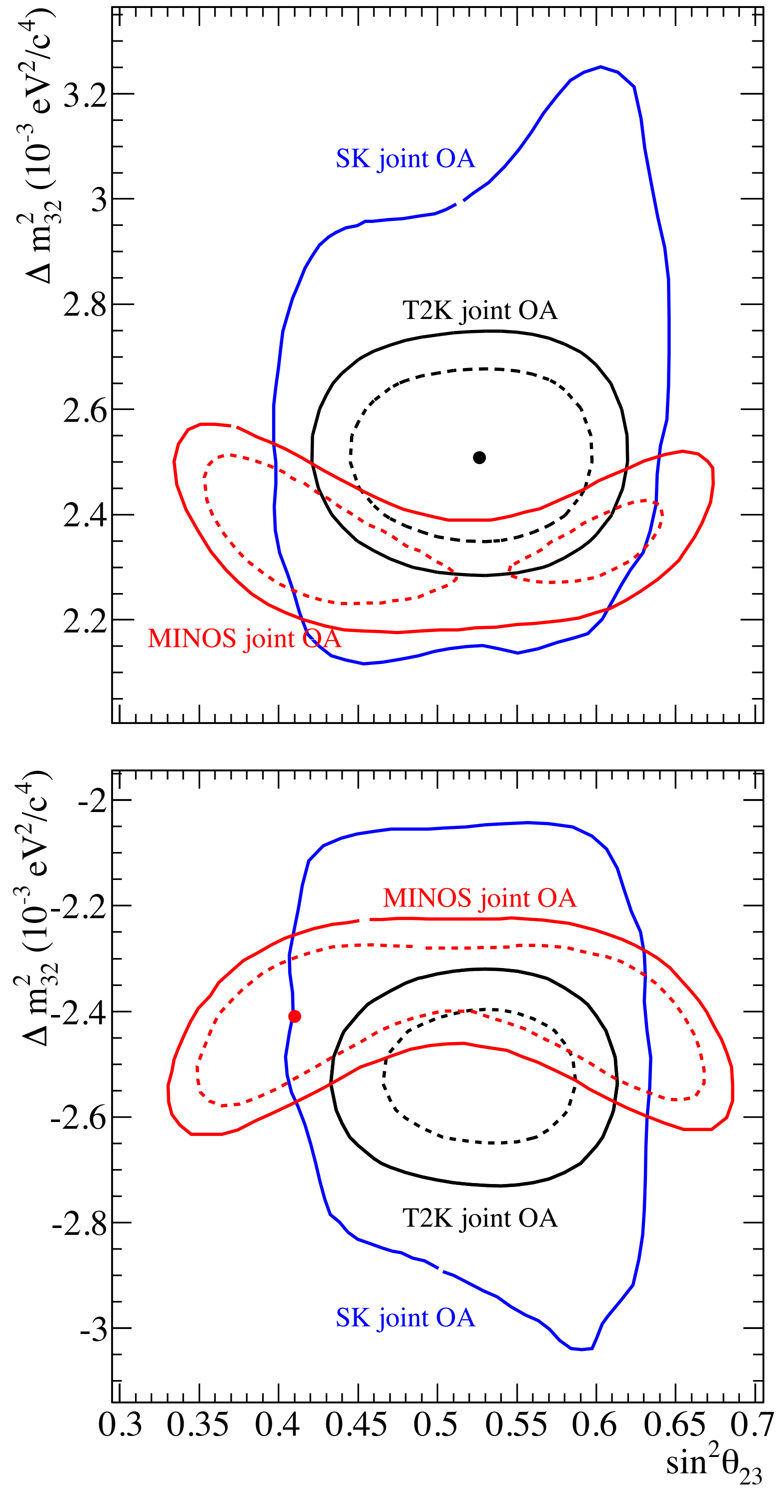
PRD 91, 072010 (2015)

Extract Δm^2, $\sin^2\theta_{23}$ from observed change in overall rate and spectrum

- Energy estimated using lepton momentum, angle and assumed CCQE kinematcs

T2K data favors maximal disappearance

- Provides best constraint on θ_{23} to date, consistent with maximal (45°) mixing



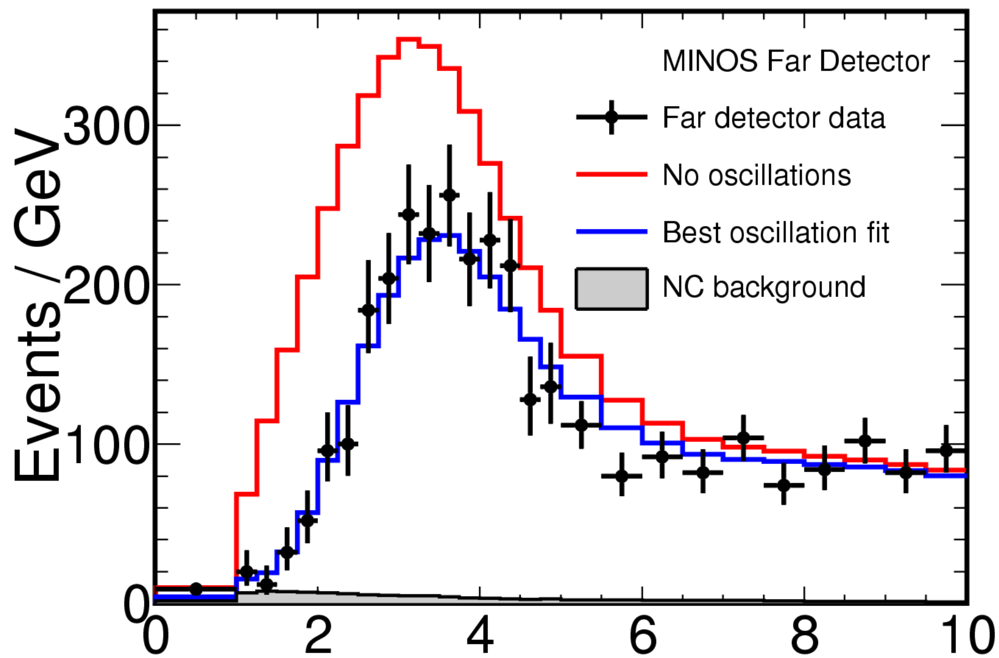
PRD 91, 072010 (2015)

T2K data favors maximal disappearance

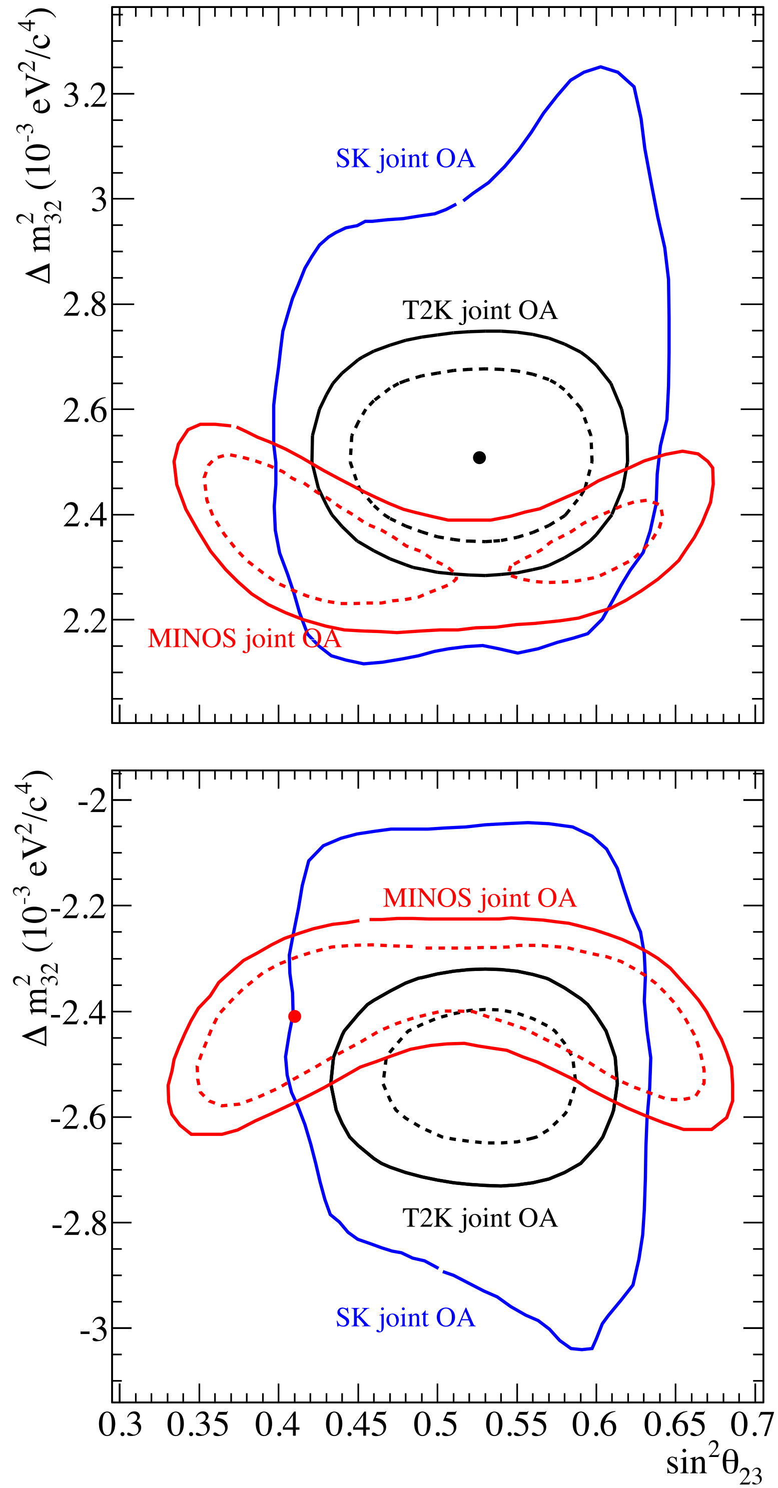
- Provides best constraint on θ_{23} to date, consistent with maximal (45°) mixing
- Atmospheric measurements also important (SK, IceCube)

Best constraint on mass splitting from MINOS experiment

- Energy uses lepton and hadronic state



Phys. Rev. D 85, 031103(R) (2012)
Phys. Rev. Lett. 101, 131802 (2008)
Phys.Rev.D71:112005 (2005)



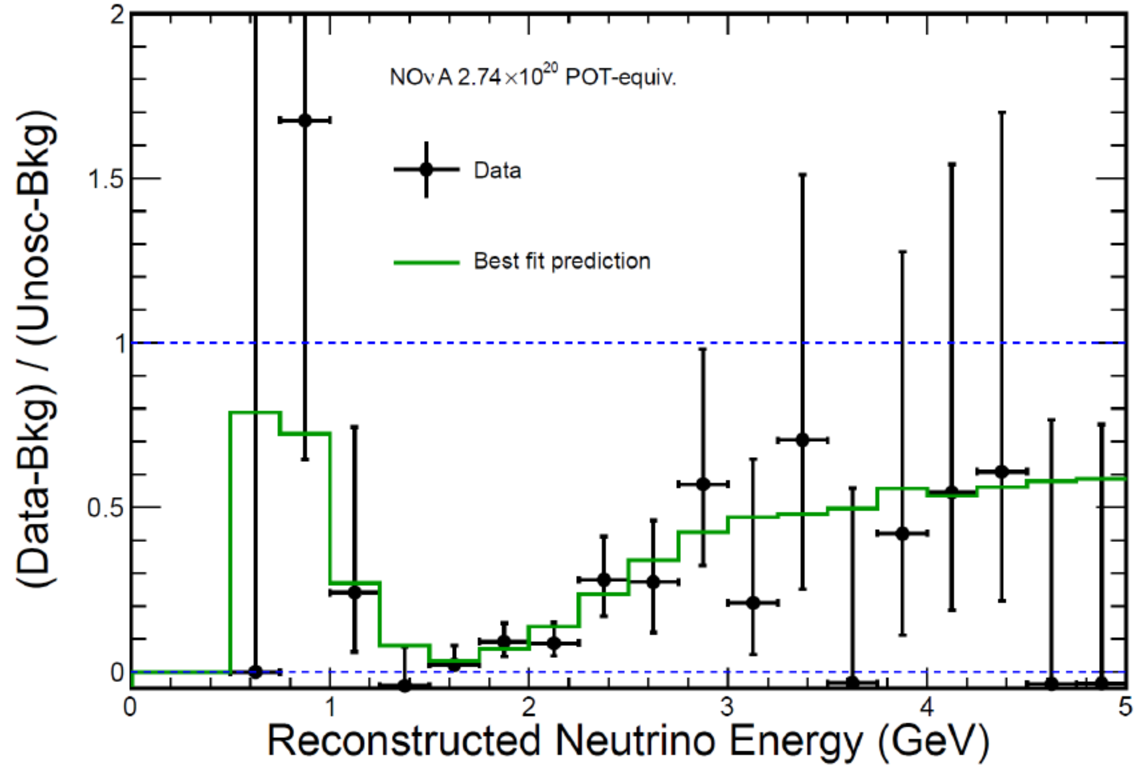
PRD 91, 072010 (2015)

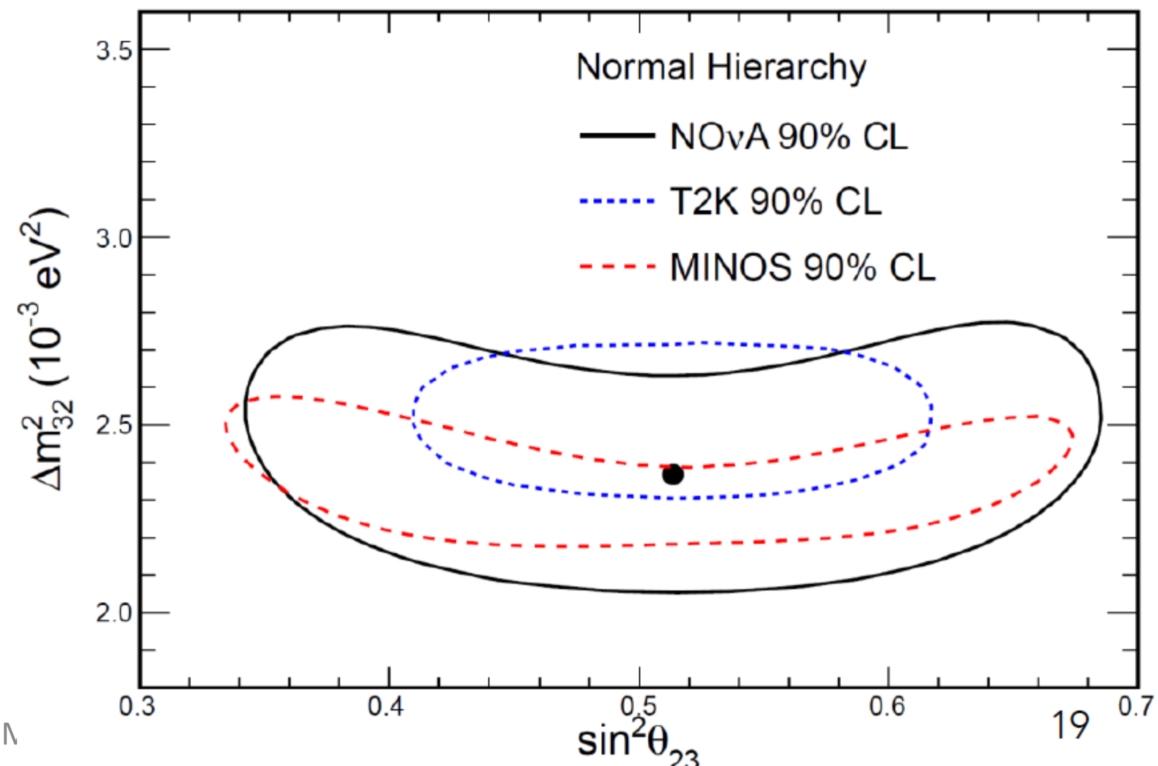
New! NOvA first results

- Compelling measurement with only 7.6% of total data expected
- Consistent with T2K and MINOS + atmospheric measurements

M. Sanchez, NuFact2015

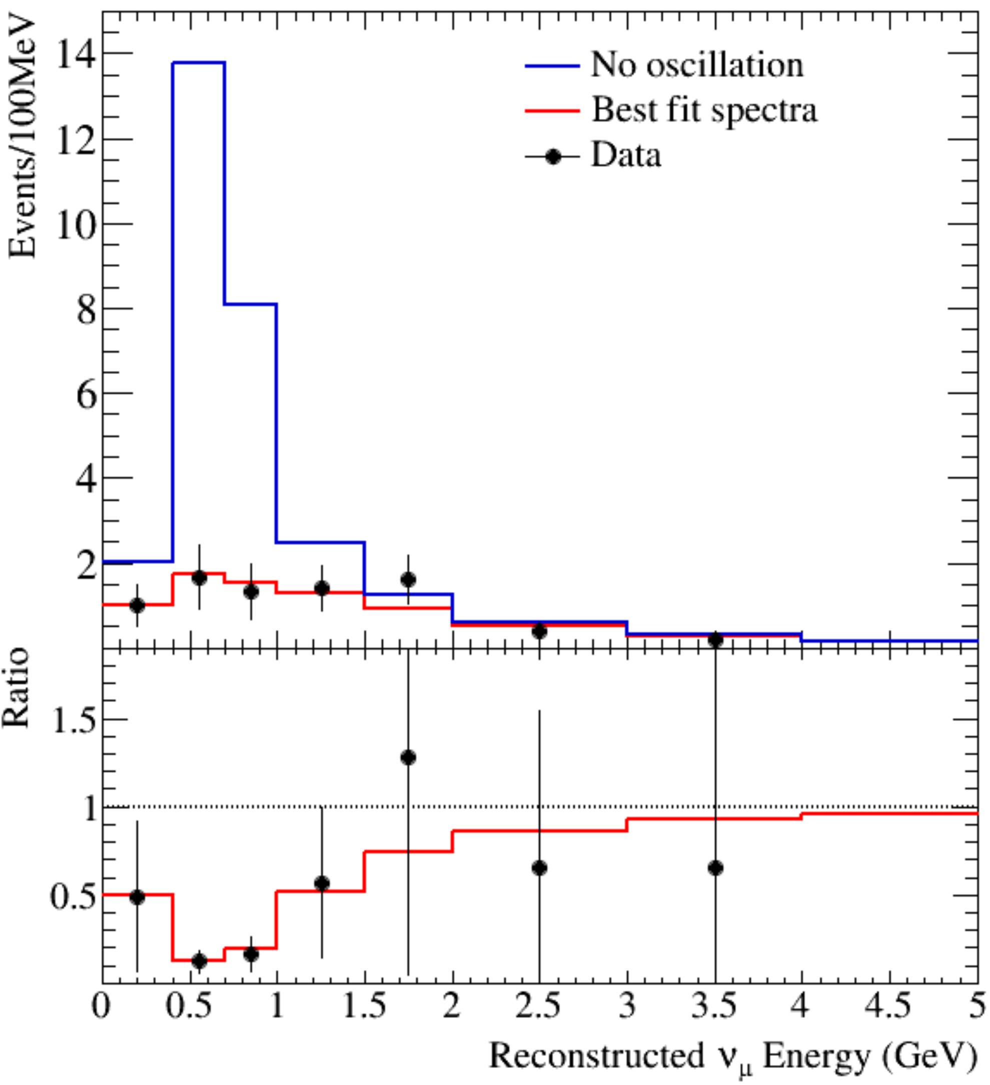
NOνA Preliminary

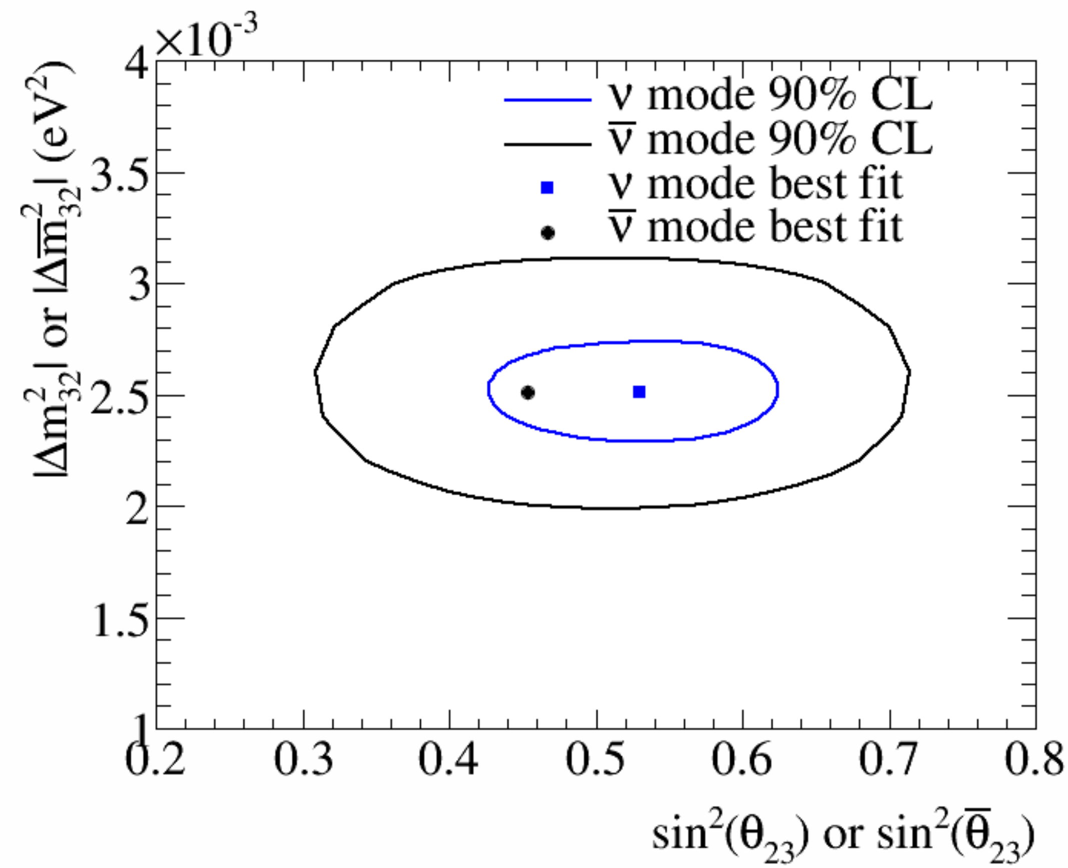




New! T2K first antineutrino disappearance results

- Probe of NSI; consistent with neutrino measurement

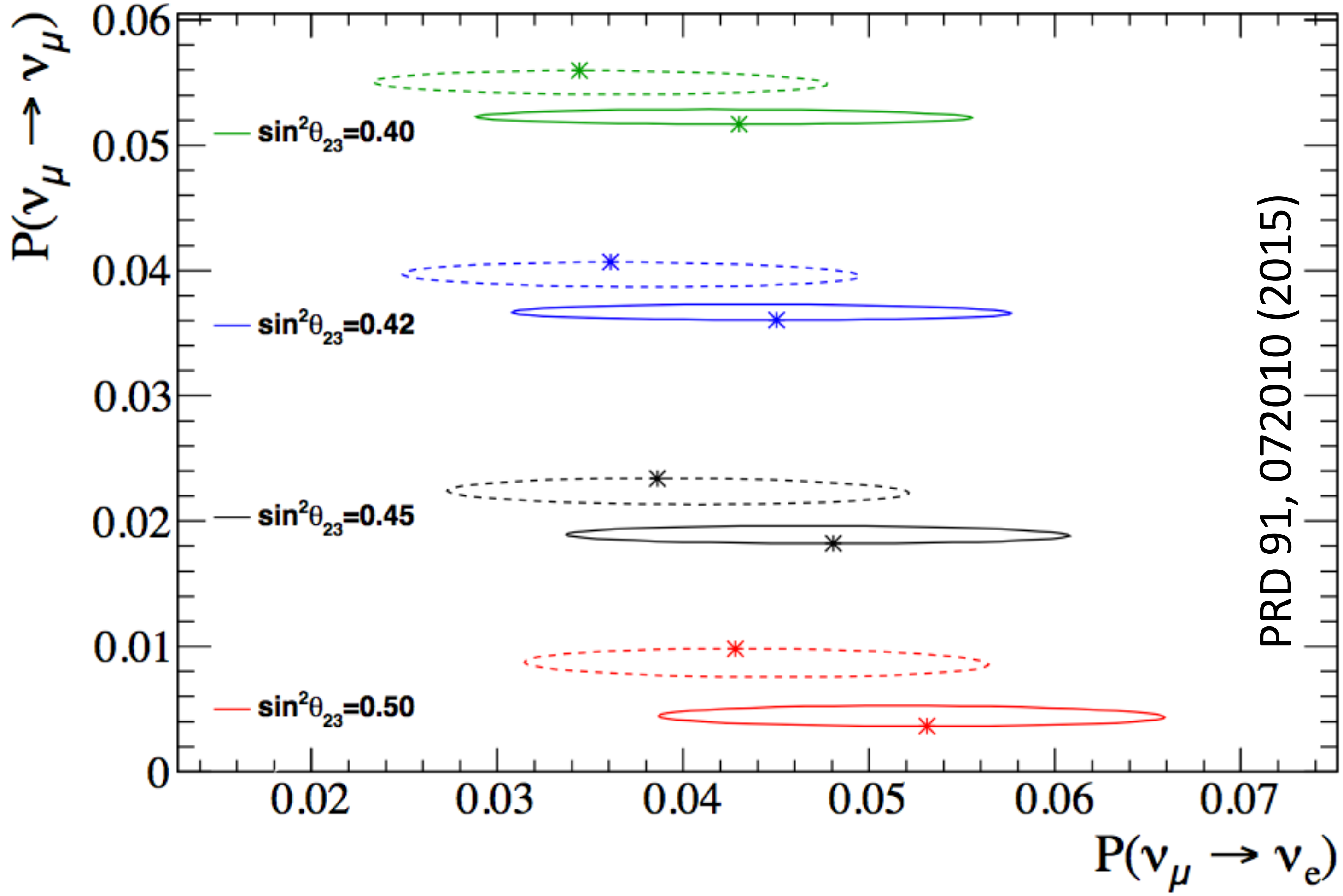




34 events seen, 34 expected

ν_e appearance

ν_μ to ν_e appearance probability depends on all other mixing parameters



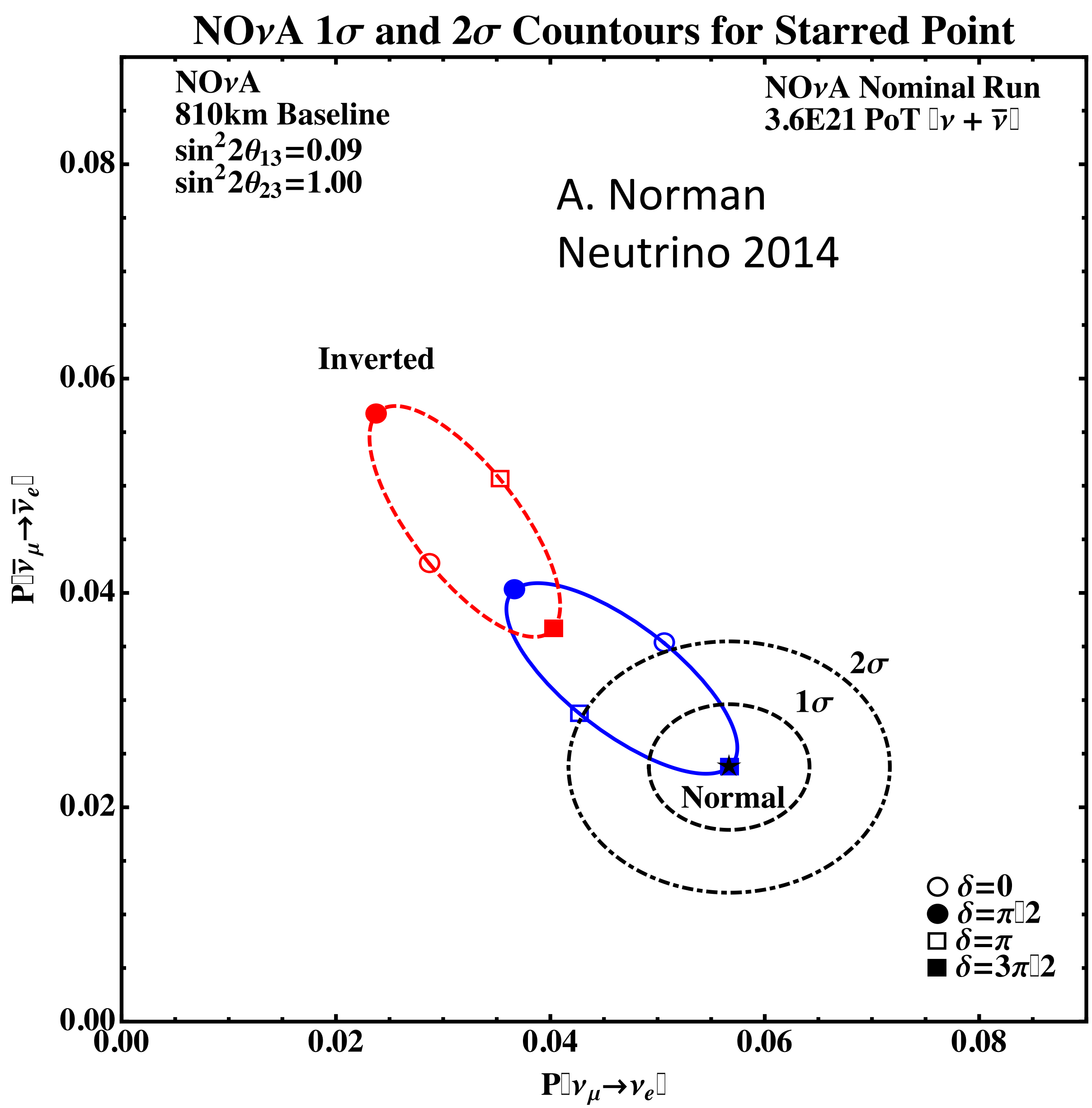
Understanding δ_{CP} currently requires information about θ_{23} (and mass hierarchy)

Critical input from reactor measurements of θ_{13}

ν_e appearance

ν_μ to ν_e appearance probability depends on all other mixing parameters

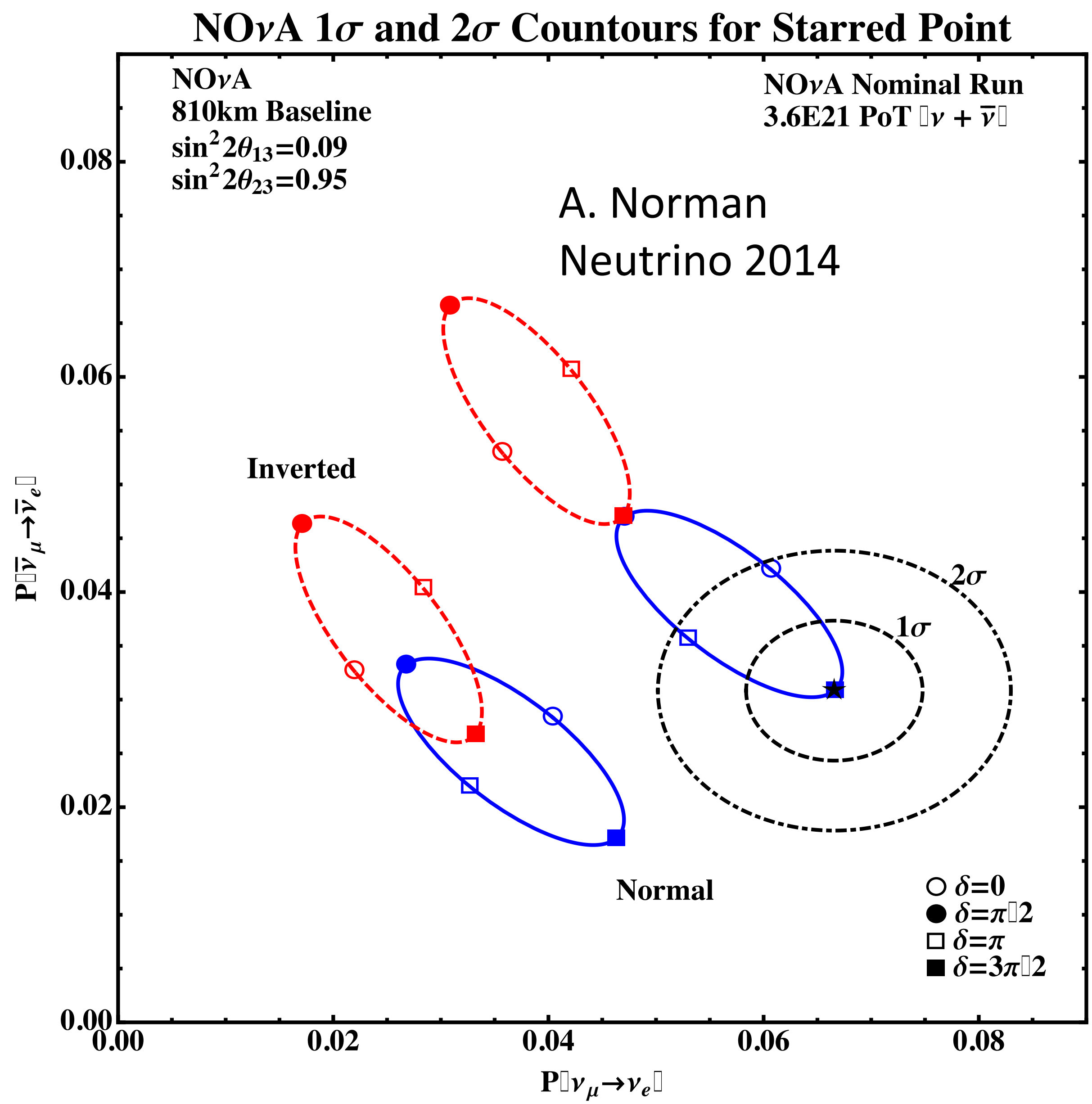
- **Ellipse maps out** how δ_{CP} changes the oscillation probability
- Comparisons between neutrino/antineutrino appearance oscillation probabilities will be used to **infer δ_{CP}, mass hierarchy**



ν_e appearance

ν_μ to ν_e appearance probability depends on all other mixing parameters

- **Ellipse maps out** how δ_{CP} changes the oscillation probability
- Comparisons between neutrino/antineutrino appearance oscillation probabilities will be used to **infer θ_{23} octant**



T2K ν_e appearance

Fit to ν_e candidates' rate and kinematic distributions to determine oscillation parameters

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{1.27\,\Delta m_{31}^2 L}{E}\right)$$

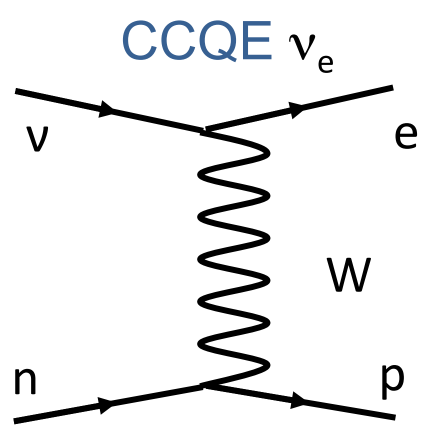
Signal	**# events**
@$\sin^2 2\theta_{13}$=0.1,δcp=0	21.06

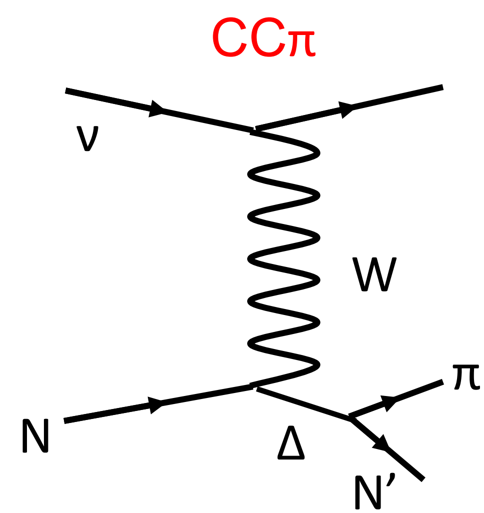
ν_ε signal@Δm^2_{32} =2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1.0
For T2K neutrino data set

Background	**# events**
beam $\nu_e + \overline{\nu}_e$	3.54
$\nu_\mu + \overline{\nu}_\mu$ (mainly NC) background	1.43
total:	4.97

Signal: CC ν_e candidates from ν_μ to ν_e oscillation

Tag ν_e by selecting electron-like rings (proton below threshold)





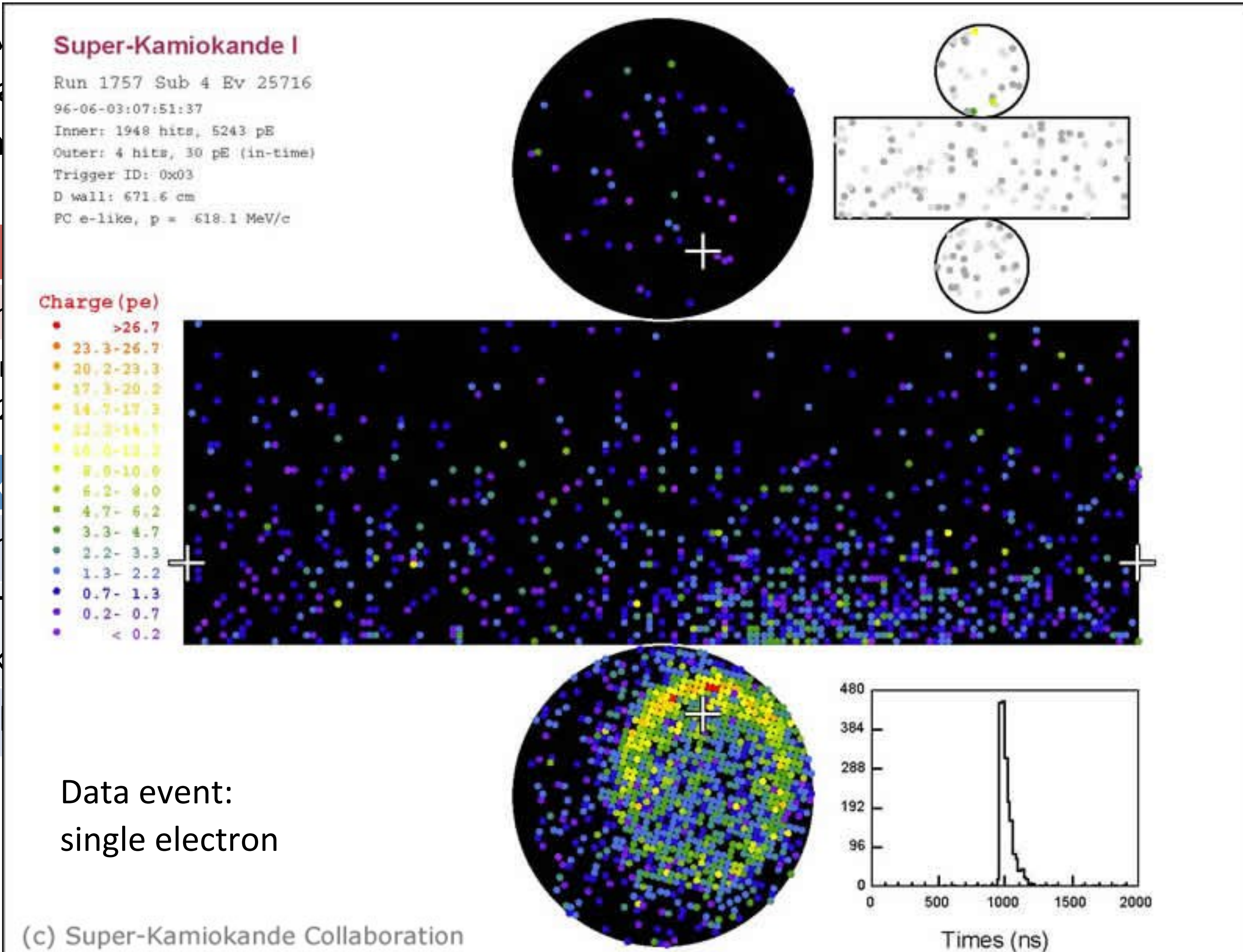
T2K ν_e appearance

Fit to ν
kinema
determ

Sign
@sin
ν_ε sig
For T2

Back
bear
ν_μ +
back
tota

π



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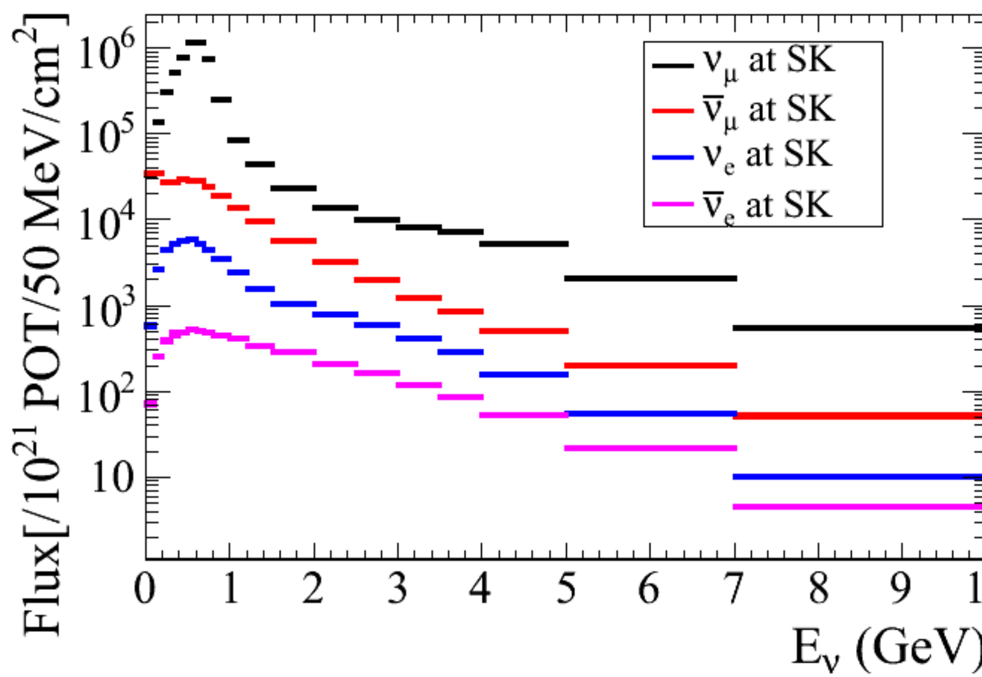
total:	4.97

Background: CC ν_e candidates
Irreducible ν_e produced in beam

Identical to signal except for E_ν dependence



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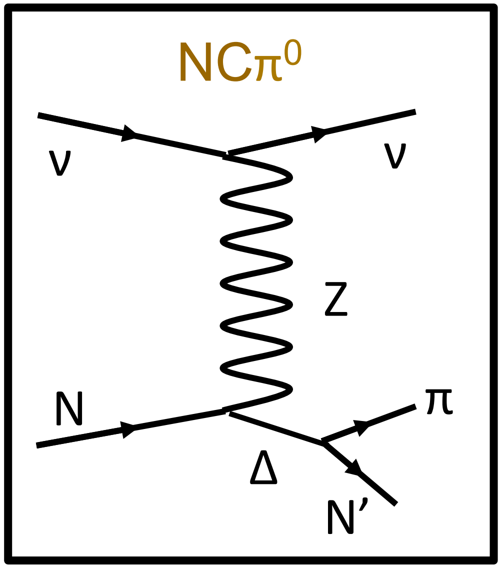
Background	# events
beam $\nu_e + \overline{\nu}_e$	3.54
$\nu_\mu + \overline{\nu}_\mu$ (mainly NC) background	1.43
total:	4.97

Background: NC with a π^0
π^0 decay to two photons; single photon mimics CC ν_e (electromagnetic shower) in Cherenkov detector



T2K ν_e appearance

Fit to ν_e can
kinematic d
determine c

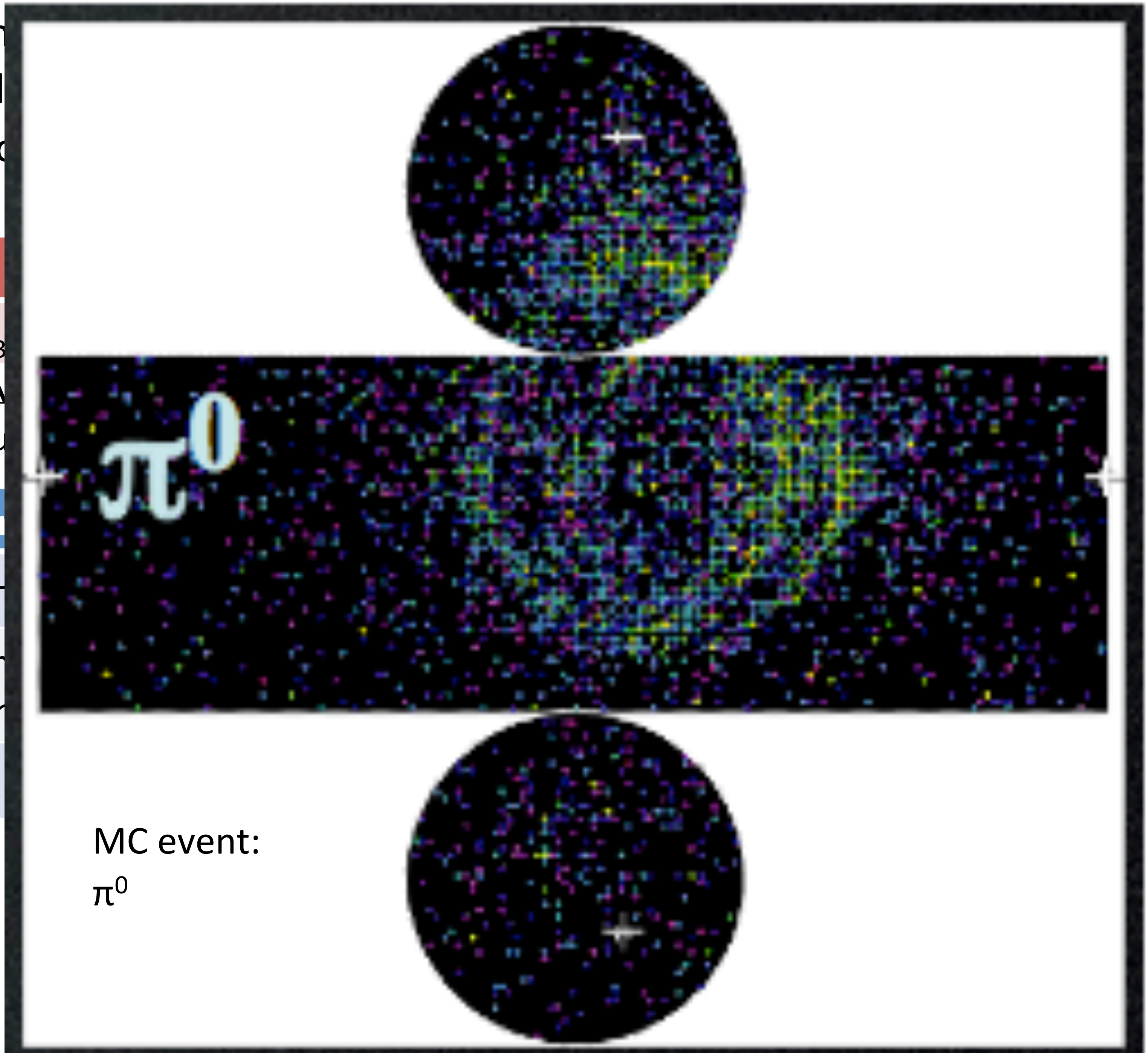
$$27\,\Delta m^2_{31} L \over E$$

Signal
@$\sin^2 2\theta_{13}$

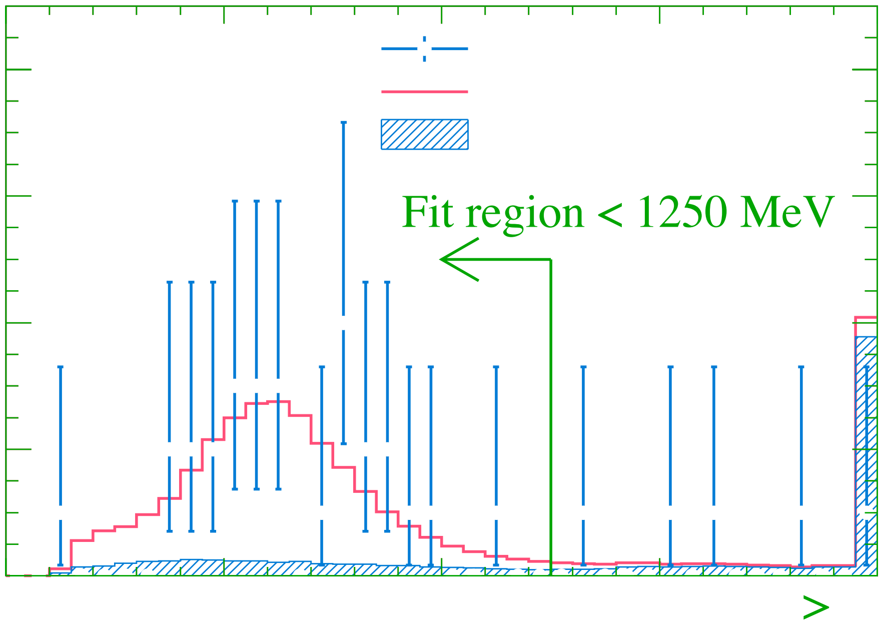
ν_ε signal@Δ
For T2K neu

Backgrou
beam ν_e +
$\nu_\mu + \overline{\nu}_\mu$ (m background
total:

photon
ower) in



T2K ν_e appearance results



28 candidate ν_e events observed

- First observation of CC ν_e appearance!
  - Phys. Rev. Lett. 112, 061802 (2014)

Signal	# events
@$\sin^2 2\theta_{13}$=0.1,δcp=0	21.06

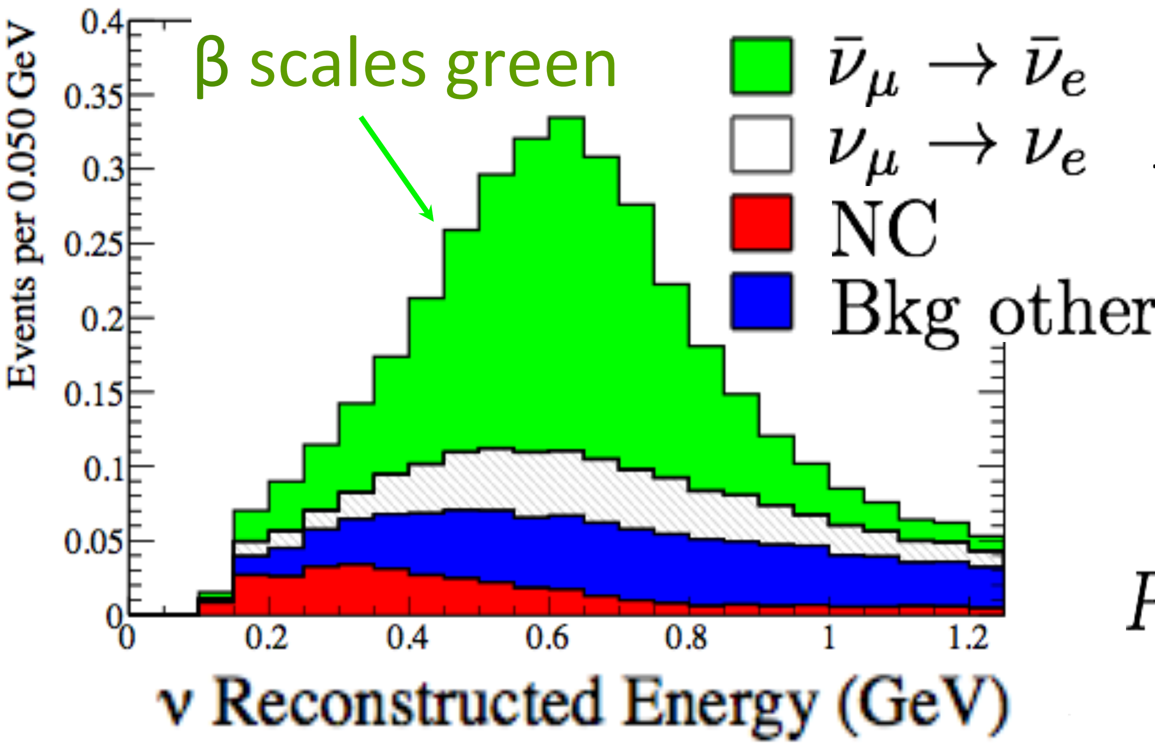
Background	# events
beam $\nu_e + \overline{\nu}_e$	3.54
$\nu_\mu + \overline{\nu}_\mu$ (mainly NC) background	1.43
total:	4.97

T2K antineutrino appearance results

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Sig $\bar{\nu}_\mu \to \bar{\nu}_e$	2.481	3.254	3.939
Bkg $\nu_\mu \to \nu_e$	0.531	0.423	0.341
Bkg NC	0.349	0.349	0.349
Bkg other	0.821	0.821	0.821
Total	4.181	4.848	5.450

Normal hierarchy

Inverted hierarchy



Expect 3.73 (4.18) events based on normal (inverted) hierarchy

Test of no $\bar{\nu}_e$ appearance hypothesis:

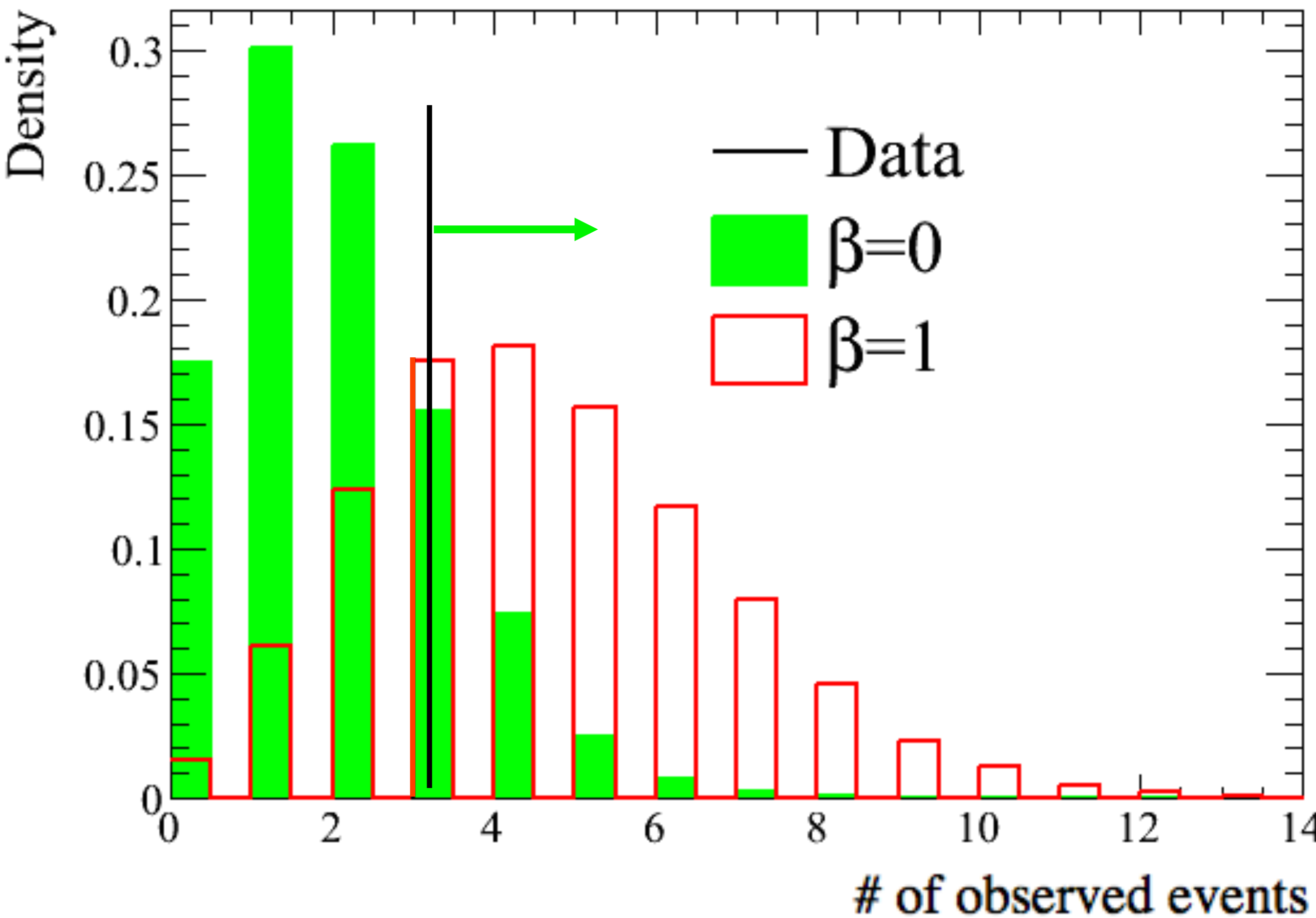
- Significant expected contribution from ν_e appearance
- β=0: no $\bar{\nu}_e$ appearance
- β=1: $\bar{\nu}_e$ appearance

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \beta \times P_{\mathrm{PMNS}}(\bar{\nu}_\mu \to \bar{\nu}_e)$$

T2K antineutrino appearance results

Generate an ensemble of test experiments with β=0 (no $\overline{\nu}_e$ appearance)

- p-value: fraction of test experiments that have as many or more candidate events as T2K data
- Sensitivity: mean p-value for an ensemble of fake data experiments with β=1



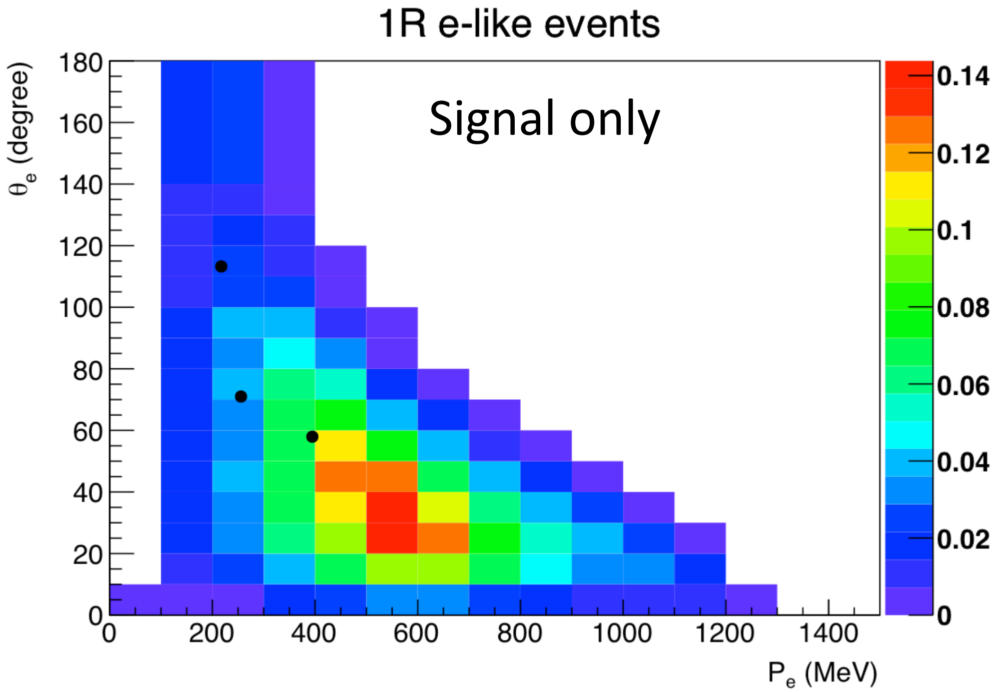
Rate only	p-value	Likelihood ratio
Data: 3 events	0.26	0.9

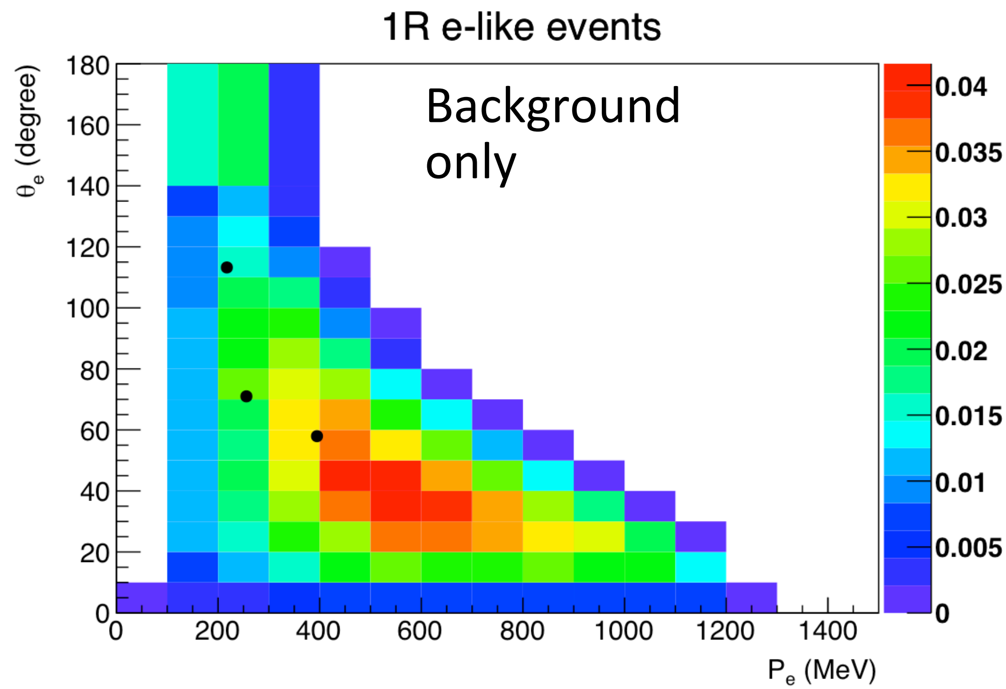
Likelihood ratio:

L(β=0)/L(β=1) is close to 1

Data does not favor or disfavor $\overline{\nu}_e$ appearance

T2K antineutrino appearance results





Data does not favor or disfavor $\bar{\nu}_e$ appearance

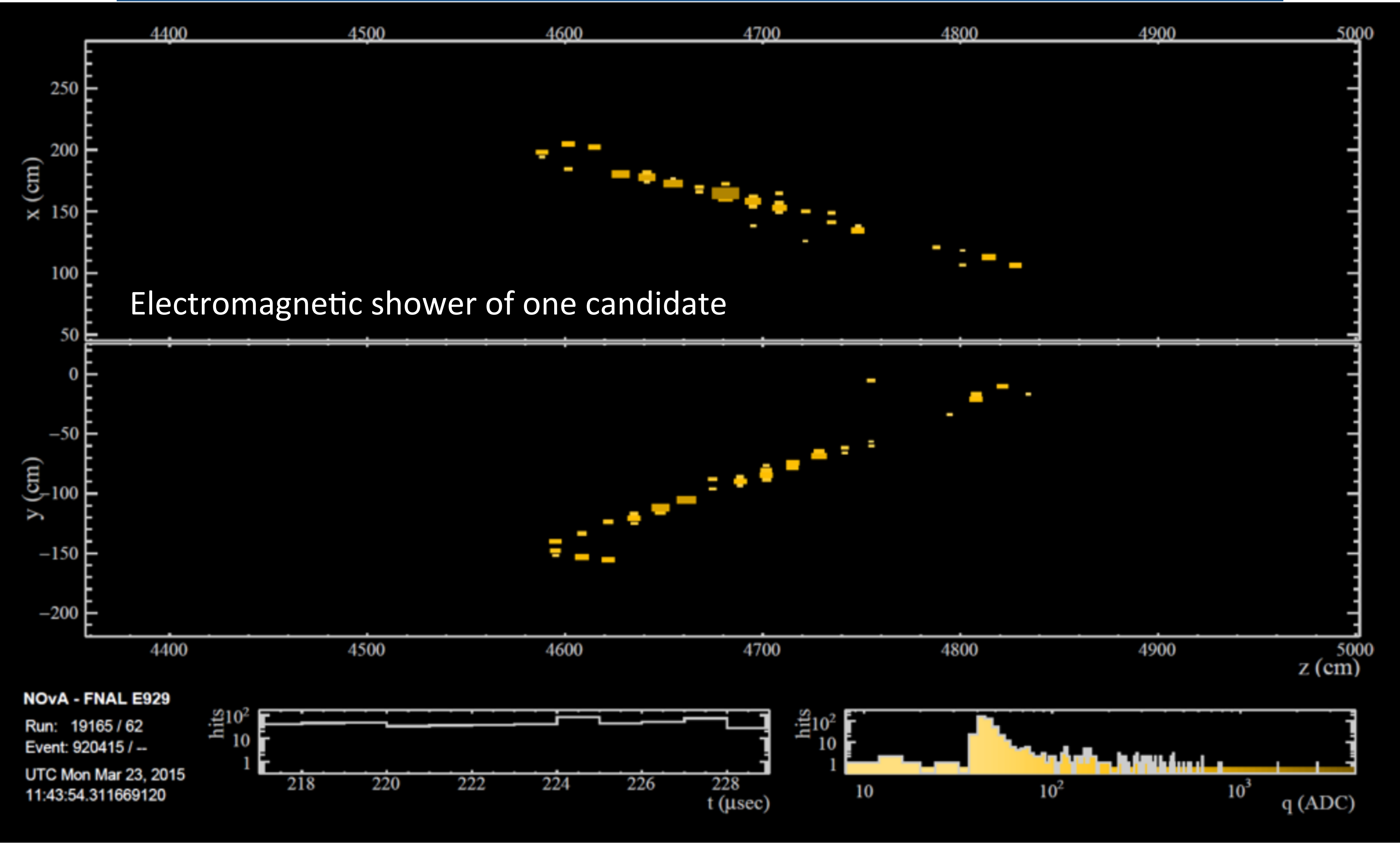
NOvA ν_e appearance results

M. Sanchez, NuFact2015

6, 11 candidate ν_e events observed with two selections in tracking detector

- Also signal dominated (~1 event background)
- 3.3σ/5.5σ evidence for CC ν_e appearance
- Consistent with T2K

NOvA ν_e appearance results



Aside 1: blind analyses

In a blind analysis, the analysers:

- Perform all checks and cross checks required prior to looking at the data; prevents tuning away or enhancing signals
- Report any changes post-unblinding
- Example: Expect nue appearance. Hide the expected nue appearance signal in a 'box' until the entire analysis chain is prepared and reviewed. Then, count the number of nue candidates
- Possible bias:
  - Revisiting event selection after seeing the data
  - Could try to reject events (because you want no signal events) or add events to the sample (because you want a signal, this one's close enough!)

Blindness is to avoid bias, additional resources in backups

NOvA used this for their first results

Aside 2: trials factor

NOvA sees 6 events with one selection, and 11 events with another selection

- ``Beware of trials factor for choosing 11 events after the fact''

Trials factor: With large data sets, expect some number of anomalies (statistically)

- Example: 200 medical researchers test 200 drugs. One researcher finds a statistically significant effect at the 99.9% C.L., and publishes. The other 199 find nothing, and publish nothing.
- But, chance of one drug giving a false signal: 0.1%.
- Chance that at least one of 199 drugs will give a significant result at this level: 18%

NOvA chose the primary analysis in advance of seeing the event rate, so avoided the risk of choosing the more exciting answer after the fact

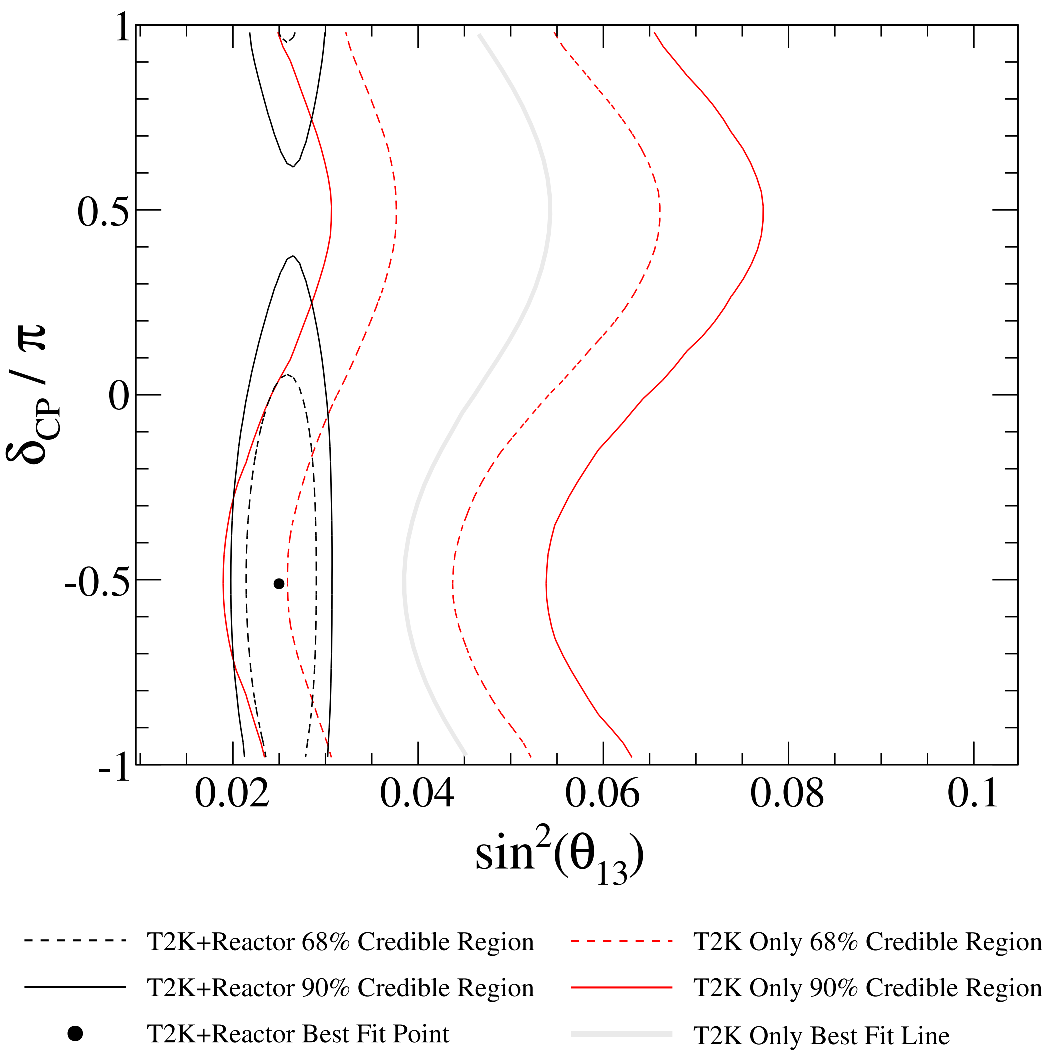
Report what you measure!

Global picture of ν_e appearance

Long baseline experiments depend on δ_{CP} + θ_{13} + …

Reactor experiments are pure measurements of θ_{13}

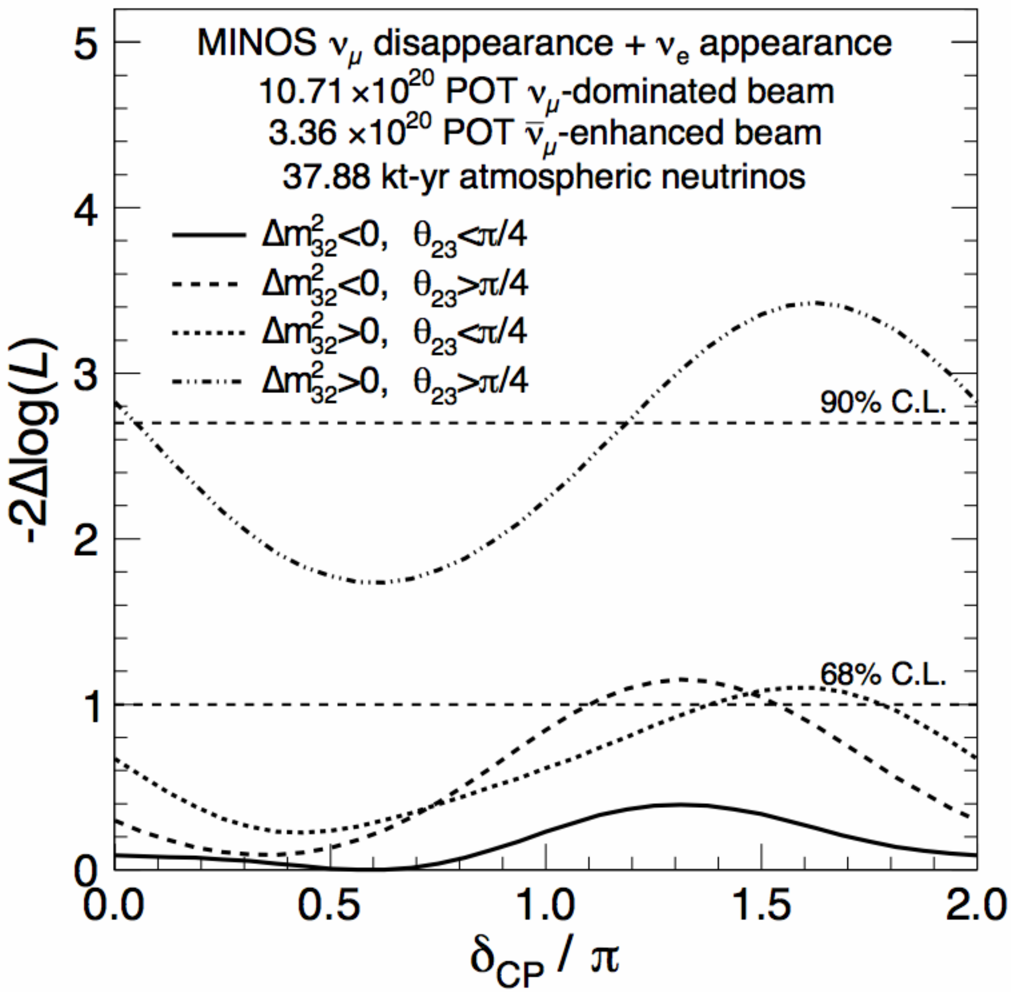
Large number of events observed by T2K, NOvA restrict allowed hierarchy + δ_{CP}



PRD 91, 072010 (2015)

Global picture of ν_e appearance

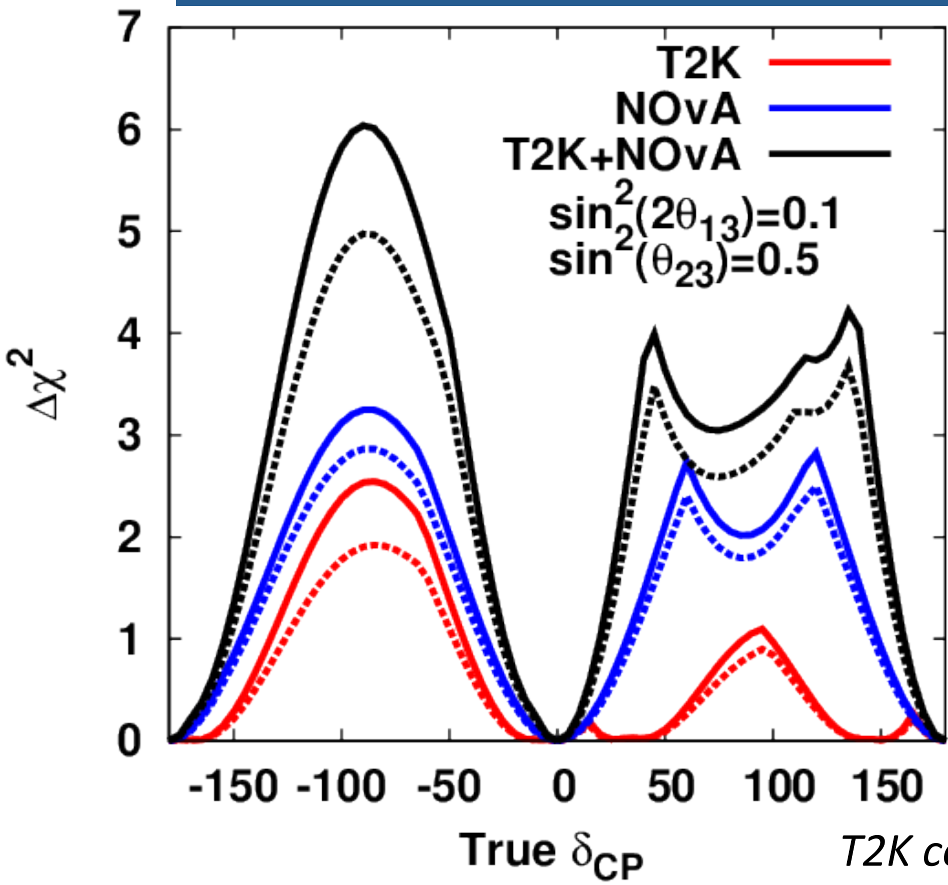
- T2K, NOvA favors δ_{CP} around 3π/2 at 90%CL, disfavored by MINOS?
- But hierarchy is not determined due to entanglement with δ_{CP} and octant
  - Not strong statements yet!

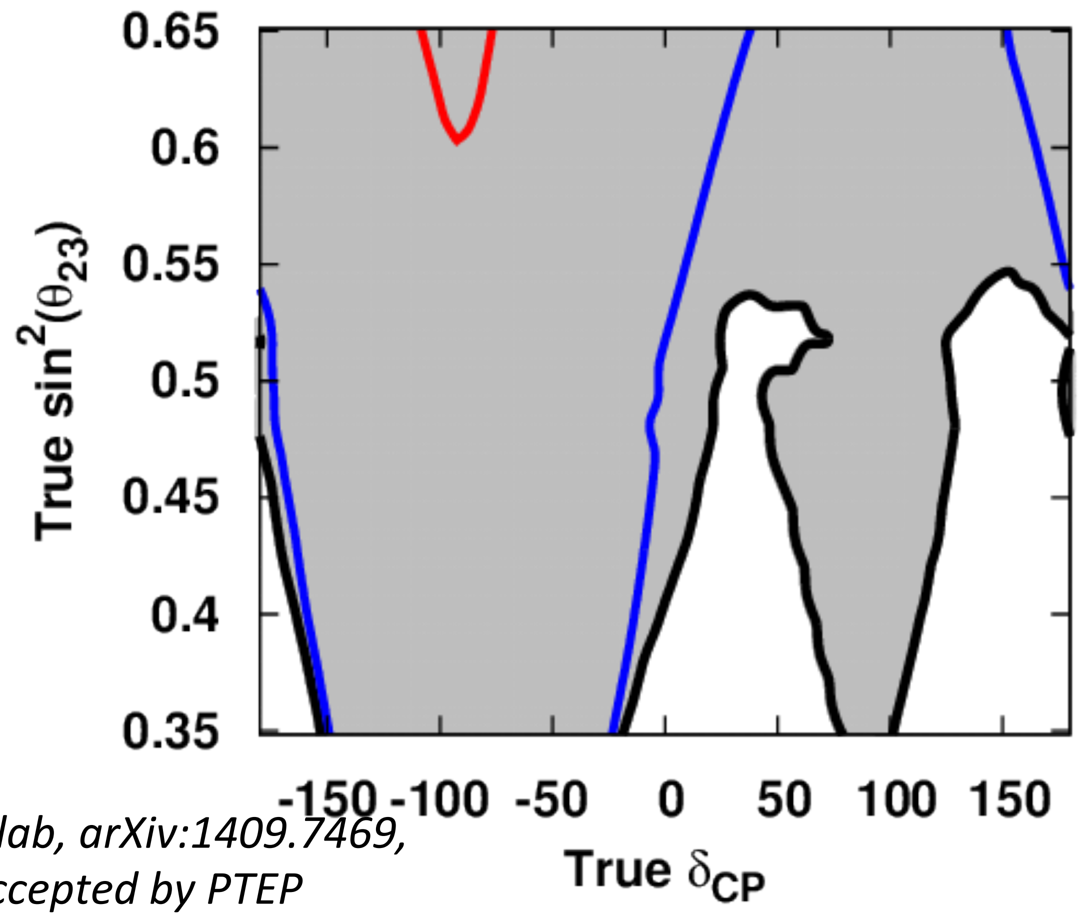


PRD 91, 072010 (2015)

Probability	$\Delta m^2_{32}>0$	$\Delta m^2_{32}<0$	Sum
$\sin^2\theta_{23} \leq 0.5$	16.5%	20.0%	36.5%
$\sin^2\theta_{23} > 0.5$	28.8%	34.7%	63.5%
Sum	45.3%	54.7%	

Future ν_e appearance results





T2K collab, arXiv:1409.7469, accepted by PTEP

NOvA's higher energy (peak E_ν~2 GeV) and longer baseline (L~810km) has a different dependence on mass hierarchy through the matter effect than T2K's

- Gray regions are where the mass hierarchy can be determined to 90% CL for T2K(red), NOvA (blue), and T2K+NOvA (black) for full run of both experiments
  - **95%CL determination for 1/3rd of δ_{CP} space for maximal θ_{23}**

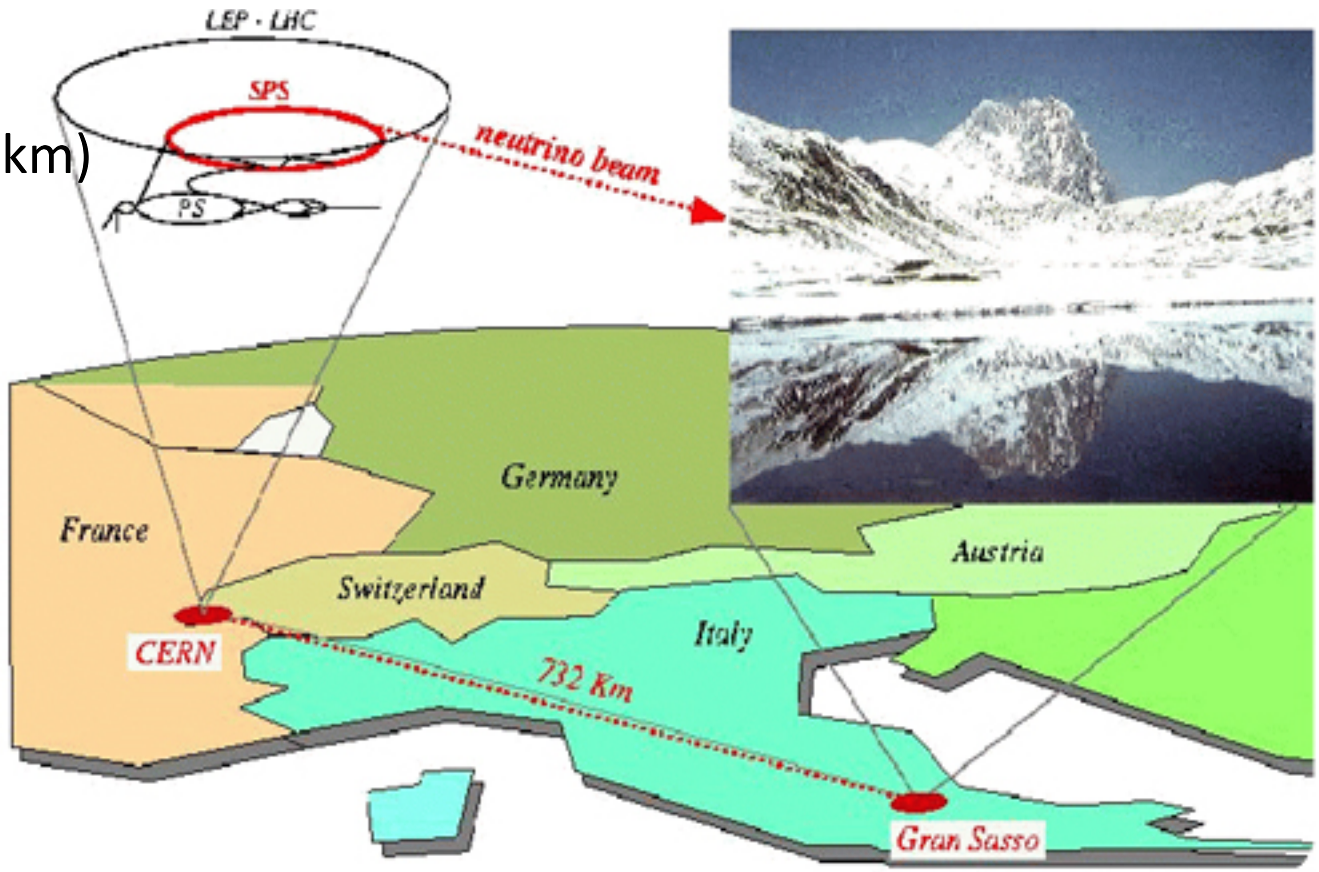
*Unknown complications of θ_{23} and δ_{CP} in this equation mean multiple experiments are **complementary***

The OPERA experiment

On-axis beam ($E_\nu \approx 17$ GeV)
CERN to Gran Sasso, Italy (730km)

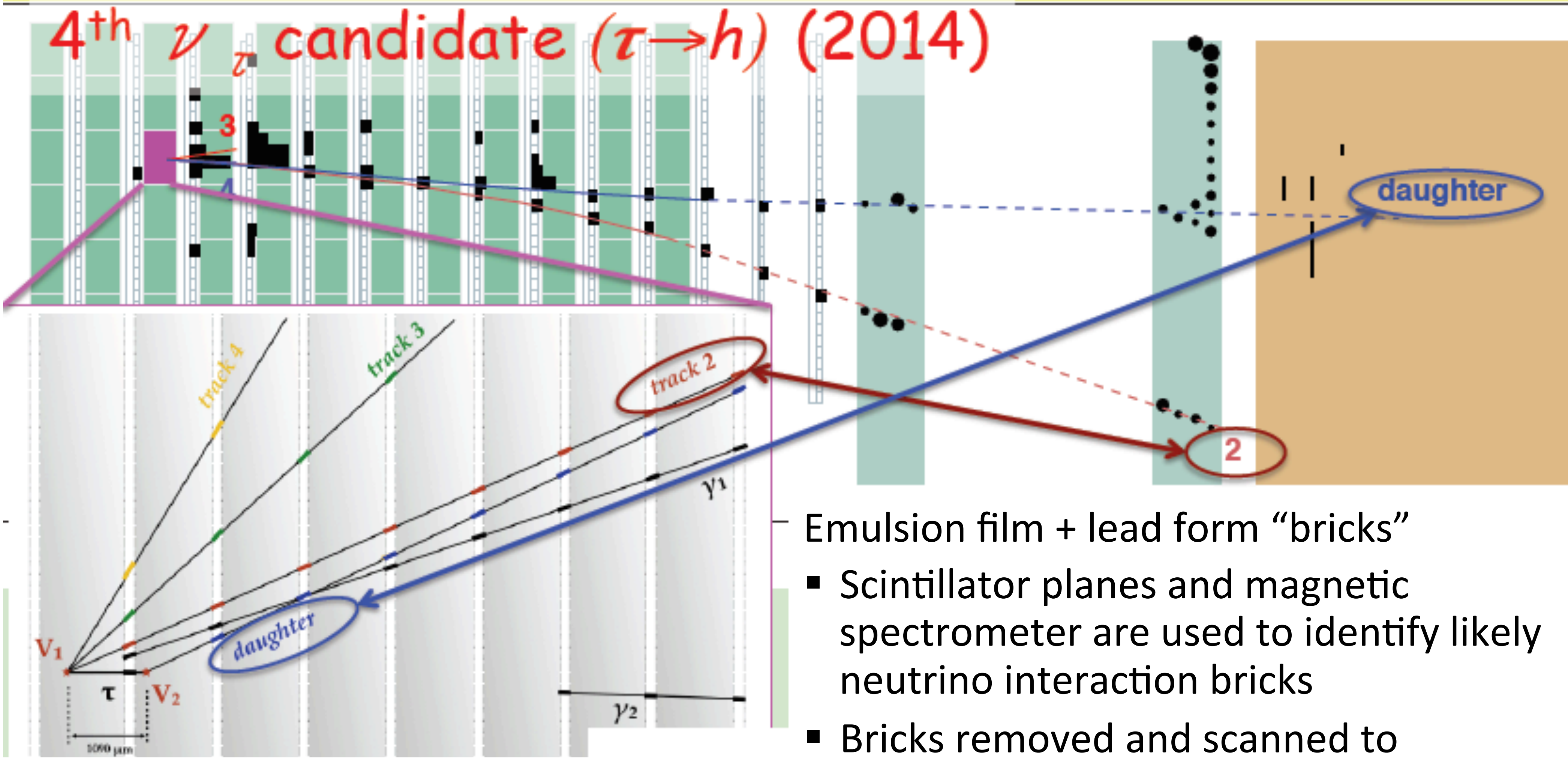
<u>OPERA physics run:</u>
Operated from 2008-2012
Neutrinos: 1.8×10^{20} POT

<u>Measurements of</u>:
ν_τ appearance



OPERA plots from S. Dusini, Neutrino2014

OPERA ν_τ appearance results



Emulsion film + lead form "bricks"

- Scintillator planes and magnetic spectrometer are used to identify likely neutrino interaction bricks
- Bricks removed and scanned to determine τ decay candidate interactions

ν_τ appearance expected signal 2.10±0.4, background 0.23±0.04

Observed 4 candidate events (no oscillation excluded at 4.2σ)

A third appearance experiment

LSND Experiment: observation of 3.8σ excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam

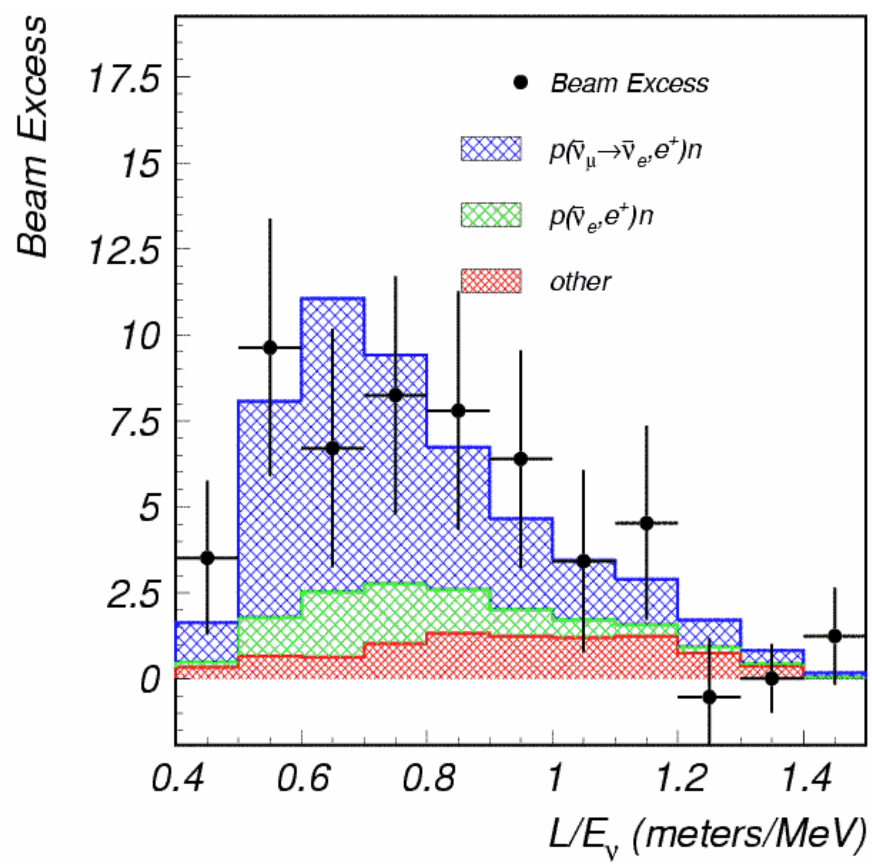
"Short baseline": E_ν ~30 MeV, L~30m

$\bar{\nu}_e$ detected with inverse beta decay and delayed n capture

There are two independent Δm^2, as $\Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$

LSND observed $\Delta m^2 \sim 1 eV^2 >> \Delta m_{21}^2$ (10^{-5} eV^2) + Δm^2_{32} (10^{-3} eV^2)

Inconsistent with just three mass eigenstates, is it new physics?



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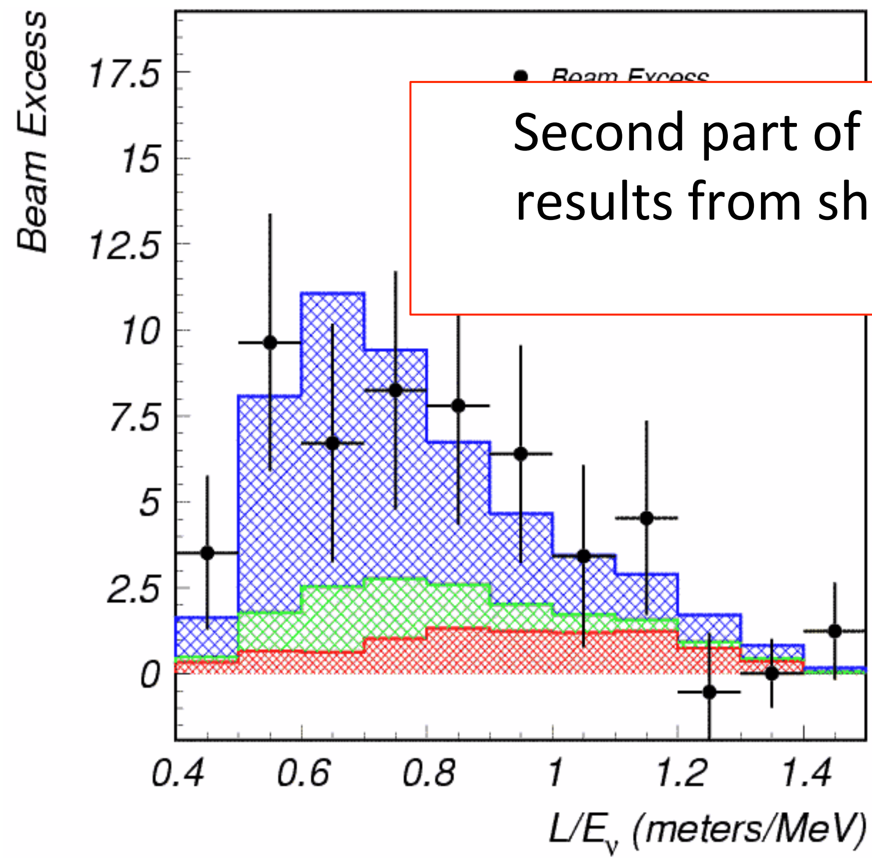


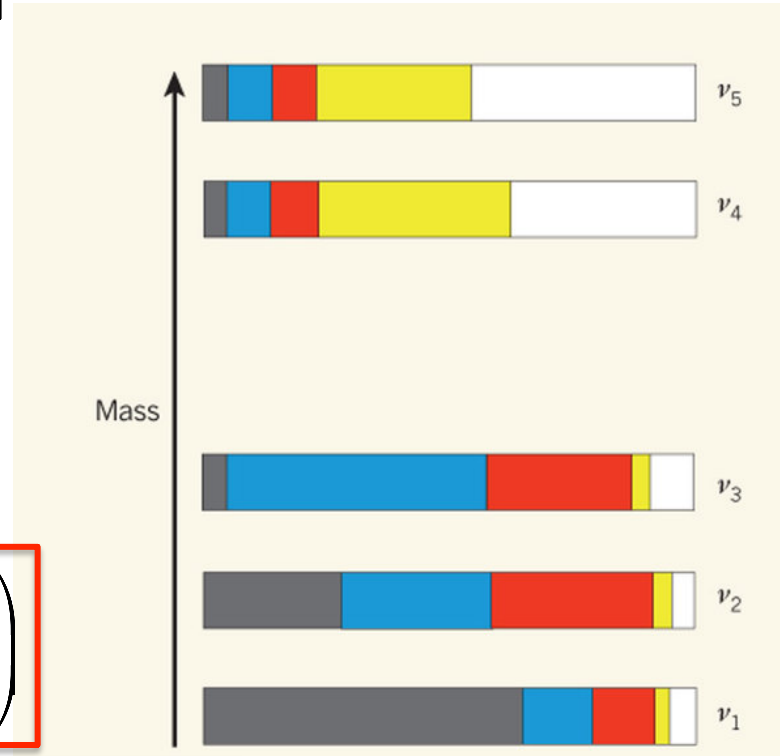
Second part of lecture: What are the physics results from short baseline (sterile neutrino) experiments?

Sterile neutrinos

One explanation for the LSND oscillation signal is to add another "sterile" flavor of neutrino (or 2 or N) to the mixing matrix:

Adding 1 sterile neutrino is 3+1, adding N is 3+N

$$U_{\alpha i} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \nu_s \end{pmatrix} \begin{pmatrix} U_{e1} & U_{e2} & \cdots & U_{eN} \\ U_{\mu 1} & U_{\mu 2} & \cdots & U_{\mu N} \\ U_{\tau 1} & U_{\tau 1} & \cdots & U_{\mu N} \\ \vdots & \vdots & \ddots & \vdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_N \end{pmatrix}$$



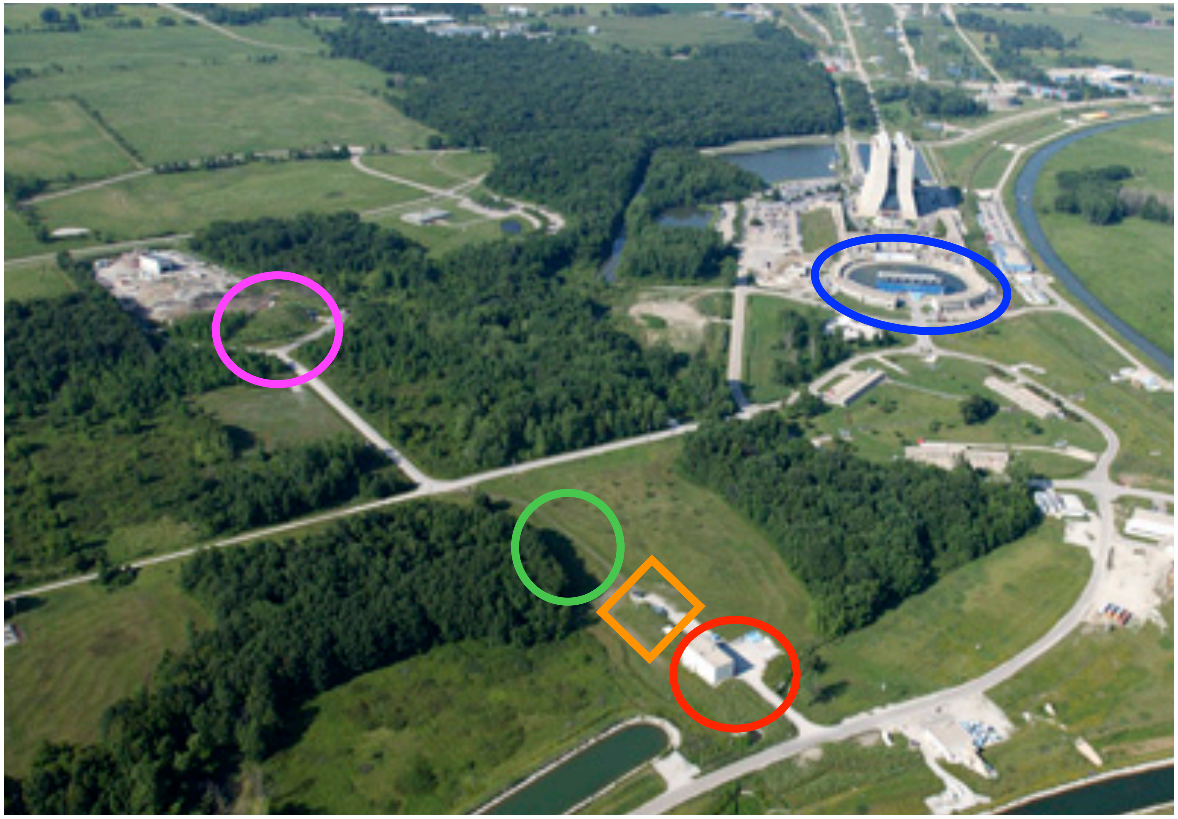
3+1 oscillation probability:

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

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

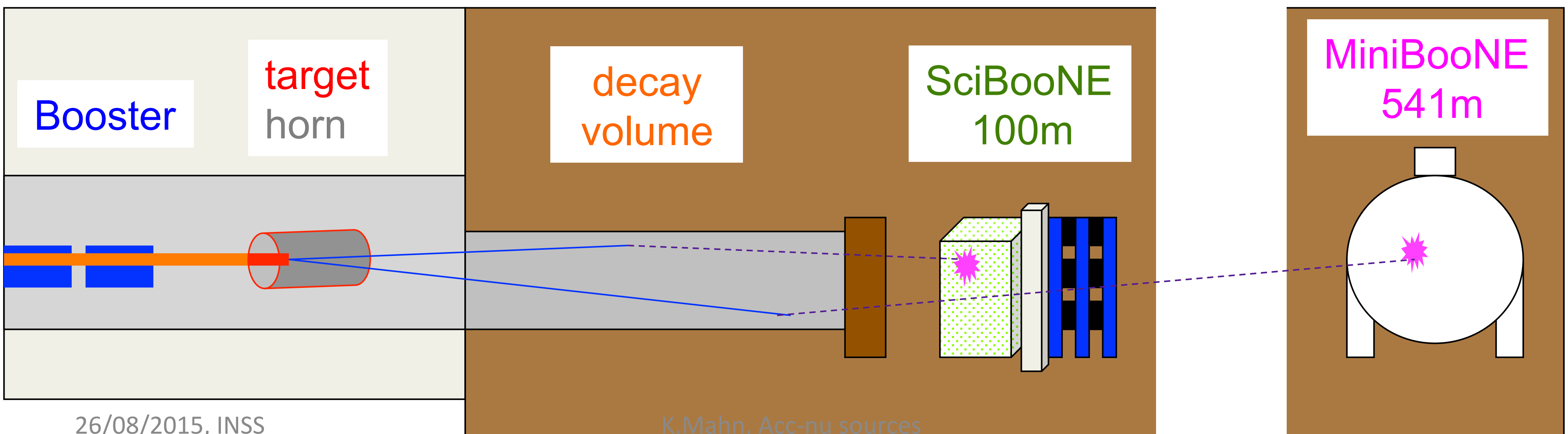
W.C. Louis, Nature, Volume: 478, Pages: 328–329

The Booster Neutrino Experiments (BooNEs)

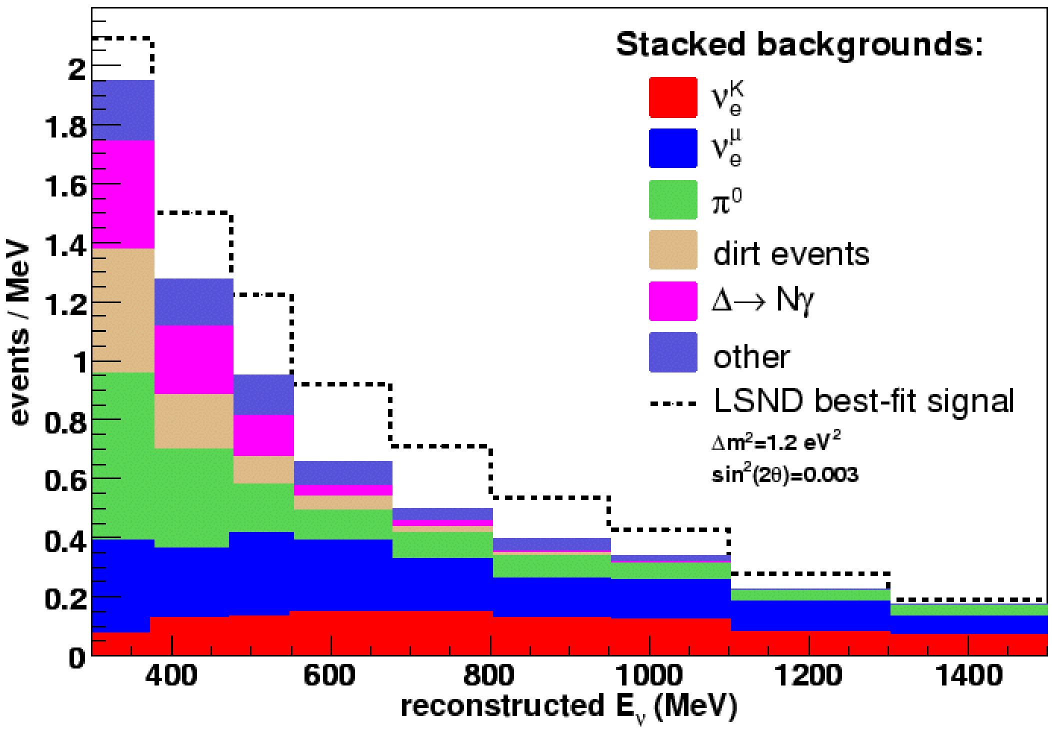


- MiniBooNE placed for maximal LSND oscillation (541 m at 1 GeV; $\Delta m^2 \sim 1 eV^2$)
- Different signal identification, systematics
- SciBooNE reused from earlier experiments

Beamline now to be used for short baseline neutrino program (SBN)



MiniBooNE ν_e appearance analysis



Signal

(Dm^2=1eV^2, sin^{2}2q=0.004)

Background

- misidentified ν_μ (mainly π^0s)
- ν_e from μ^+ decay
- ν_e from K^+, K^0 decay
- $\Delta \Rightarrow N\gamma$
- External backgrounds

Similar to T2K appearance analysis:

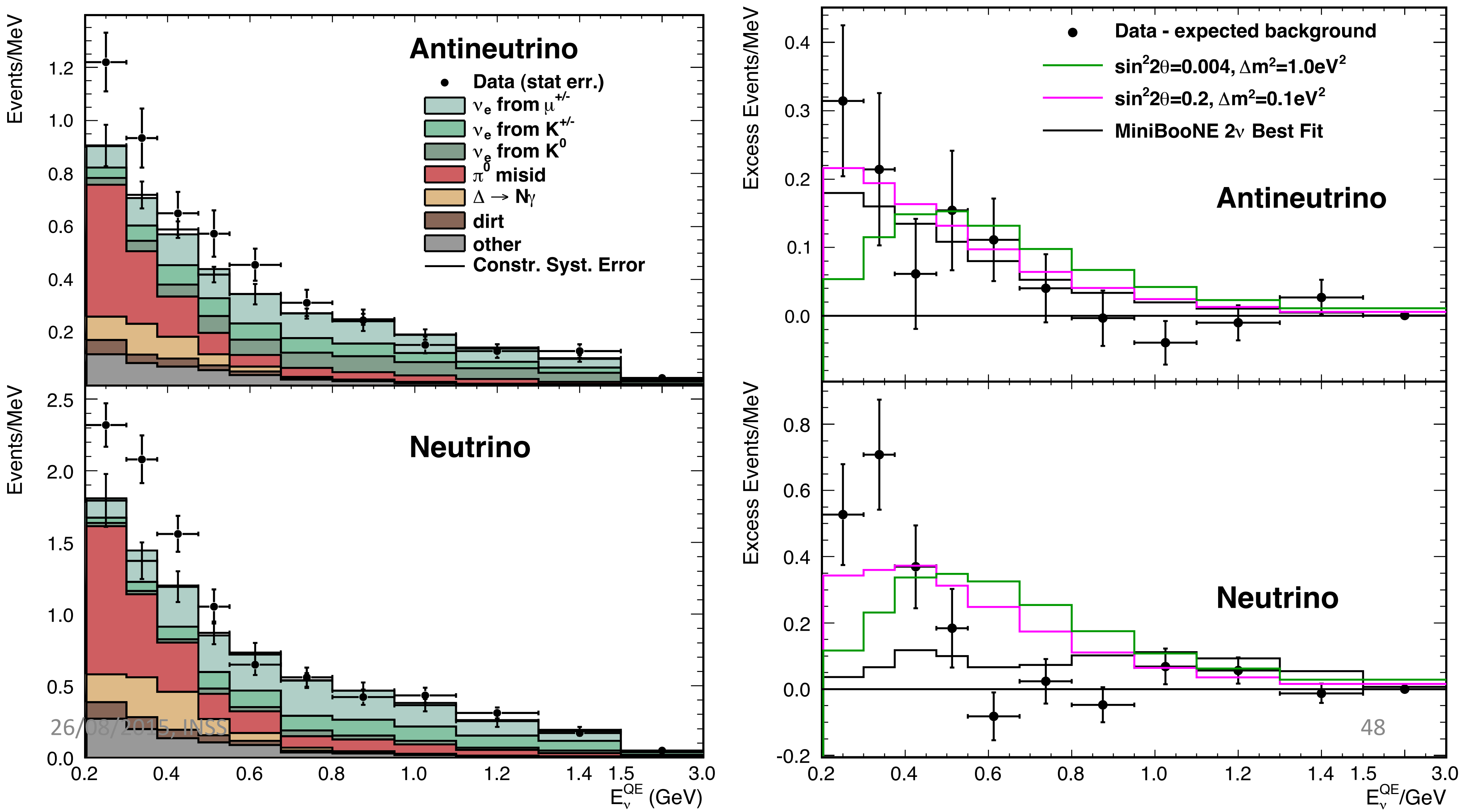
- Backgrounds from NC, intrinsic ν_e

Main difference: much smaller oscillation probability (0.25%), background dominated

MiniBooNE ν_e appearance results

Lack of $\nu_\mu \rightarrow \nu_e$ appearance but observation of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance

- Low energy excess drives tension in neutrinos, not well mapped to 3+1 signal
- Photon background? MicroBooNE to test

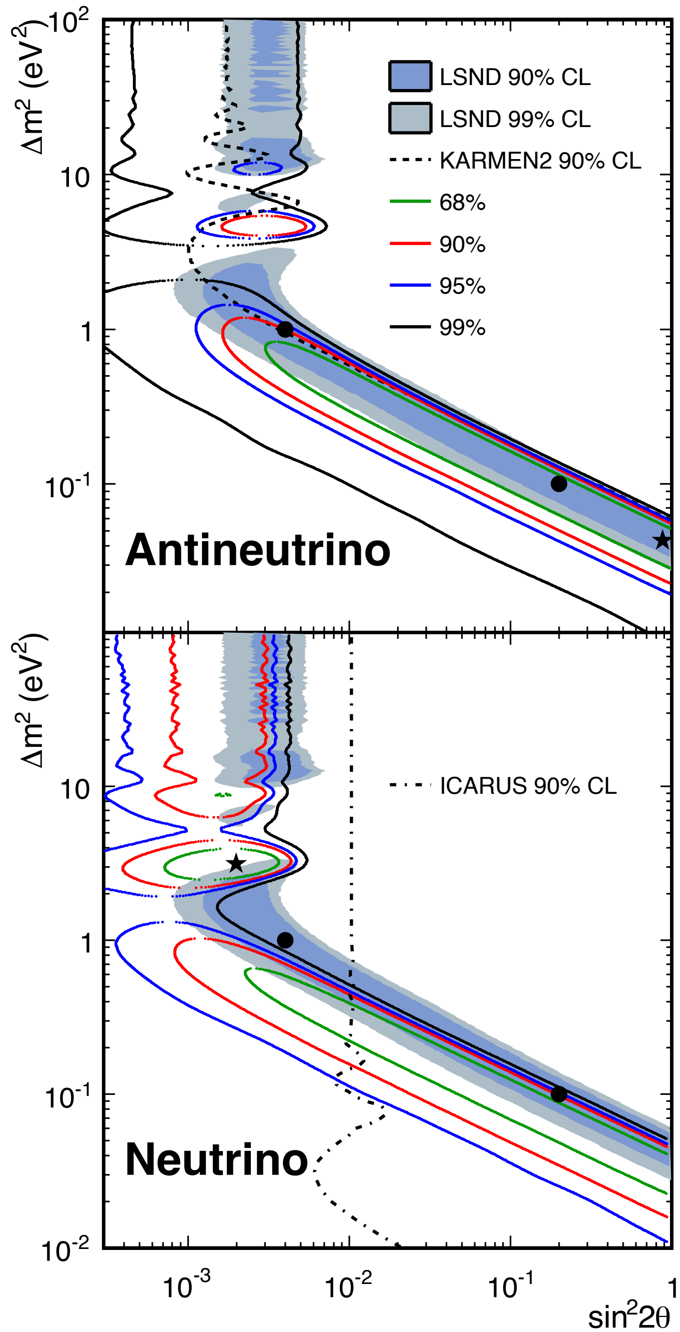


Global ν_e appearance results

- Neutrino data fit: PRL 98:231801,2007
- Antineutrino data fit: PRL 105:181801,2010
- Combined fit of neutrino and antineutrino data have 3.8σ signal for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
  - PRL 110, 161801 (2013)

ICARUS experiment (~730km flight distance, 20 GeV neutrinos) sees no evidence for appearance

- Eur. Phys. J. C (2013) 73:2345
- Will move to beamline at FNAL for additional tests



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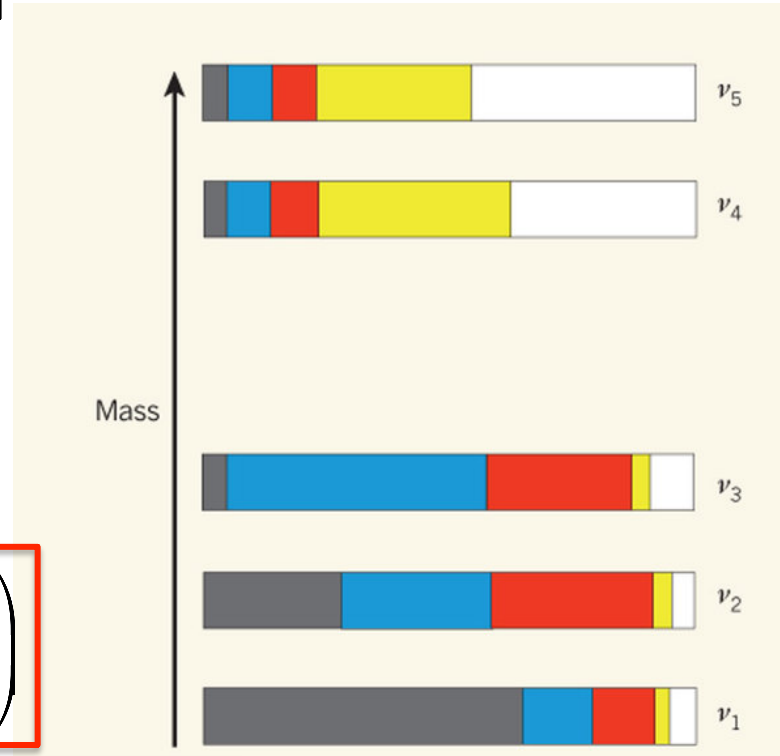

3+1 oscillation probability:

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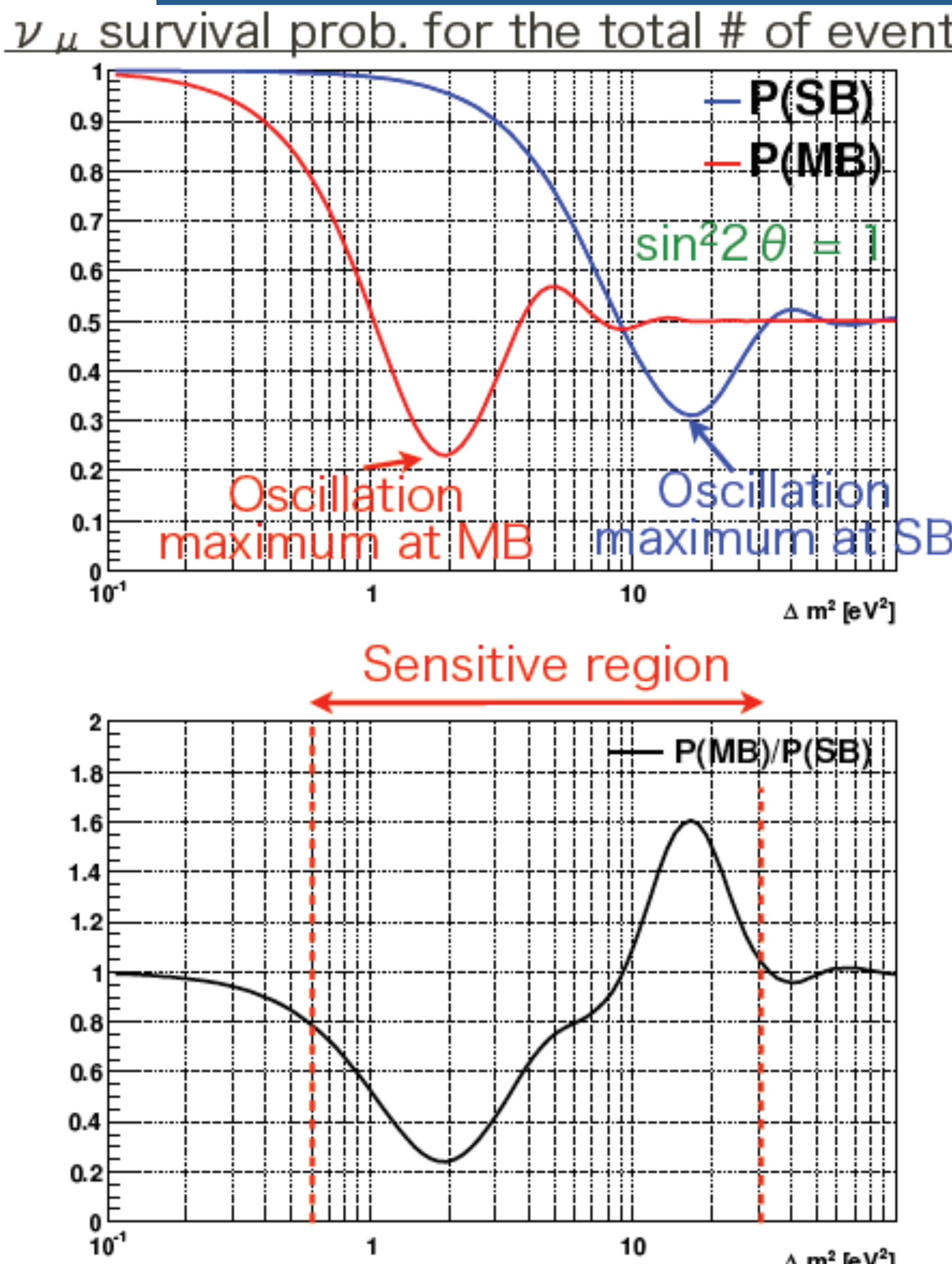
W.C. Louis, Nature, Volume: 478, Pages: 328–329

Disappearance at SciBooNE and MiniBooNE



Consider a 3+1 oscillation model:

$$P(\nu_\mu \rightarrow \nu_{x\neq\mu}) \cong \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Below Δm^2~0.5 eV^2, ν_μ have not oscillated yet

At 0.5 < Δm^2 < 2 eV^2, events at MiniBooNE undergo oscillation

At 2 < Δm^2 < 30 eV^2, events at SciBooNE also undergo oscillation

Above Δm^2~30 eV^2, oscillation is an overall normalization change, where MiniBooNE/SciBooNE are insensitive

Oscillation probability vs neutrino energy

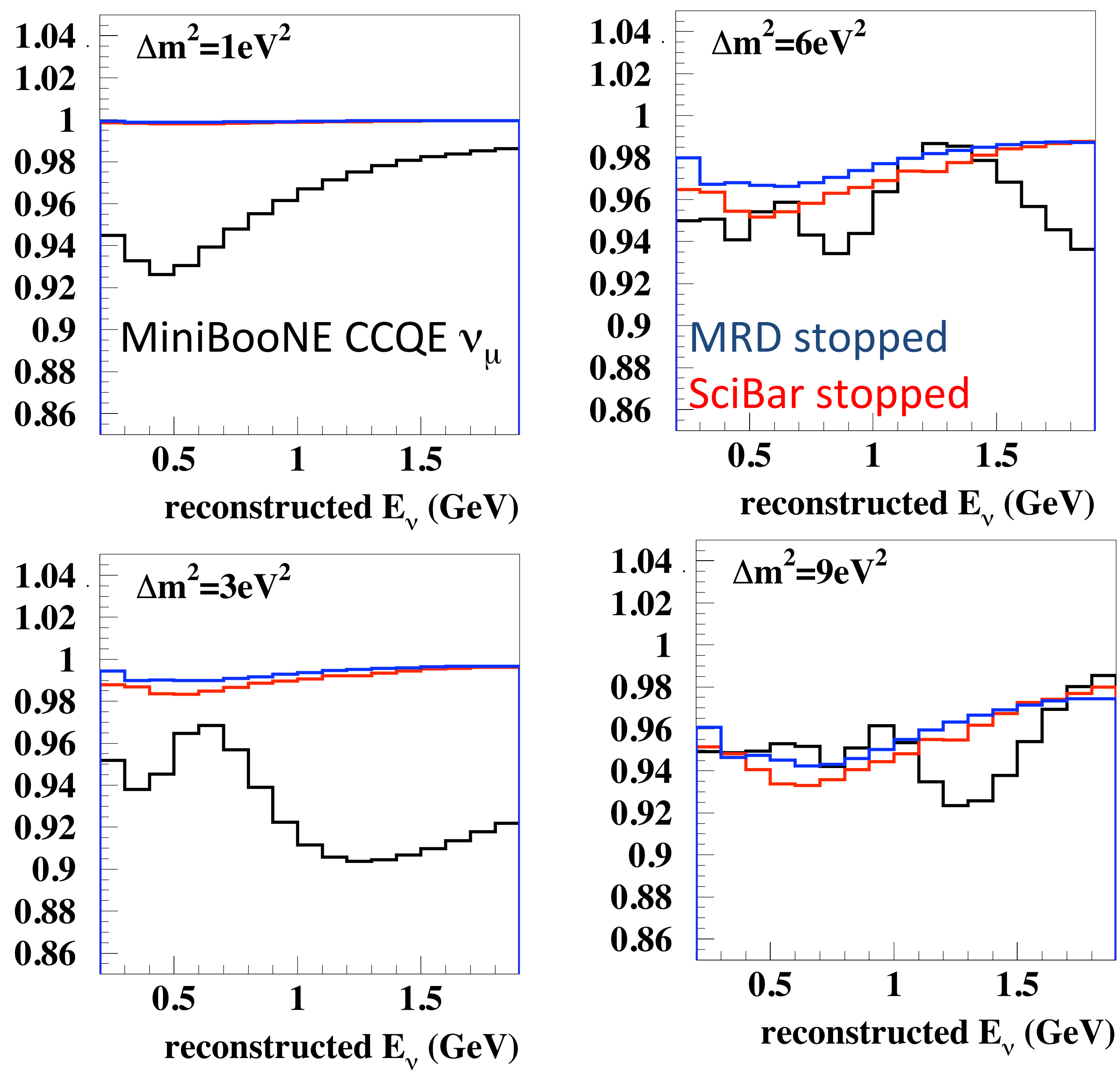
Disappearance observable as a deficit and distortion to neutrino energy spectrum

Includes:
- Oscillation of all CC ν_μ interactions at SciBooNE and MiniBooNE
- Distribution of distance travelled by neutrinos (L)

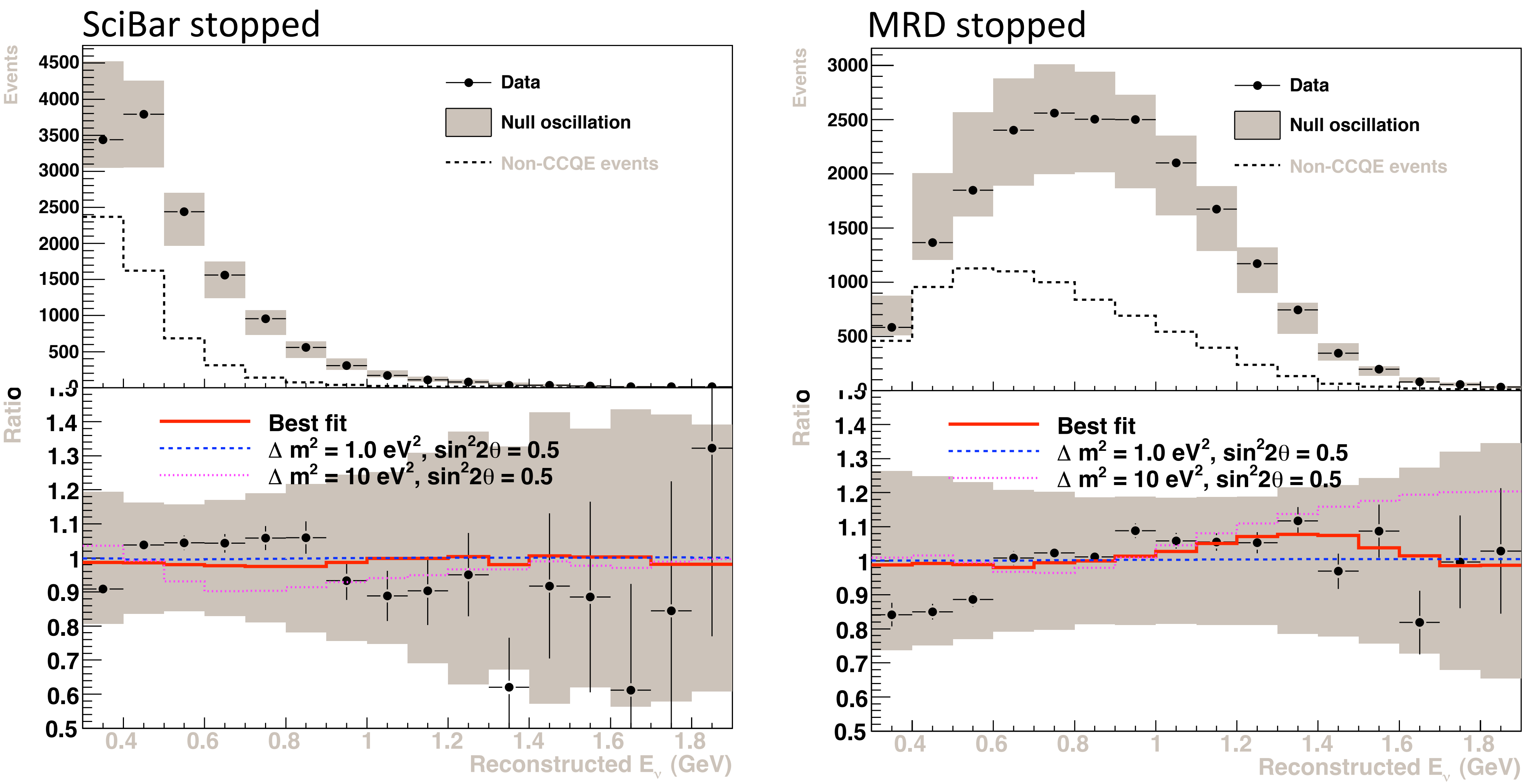
	Mean L
SciBooNE	~76m
MiniBooNE	~520m

~50m spread in L due to finite decay volume

Ratio of oscillated spectrum to unoscillated ($\sin^2 2\theta = 0.10$)



SciBooNE CC ν_μ data set



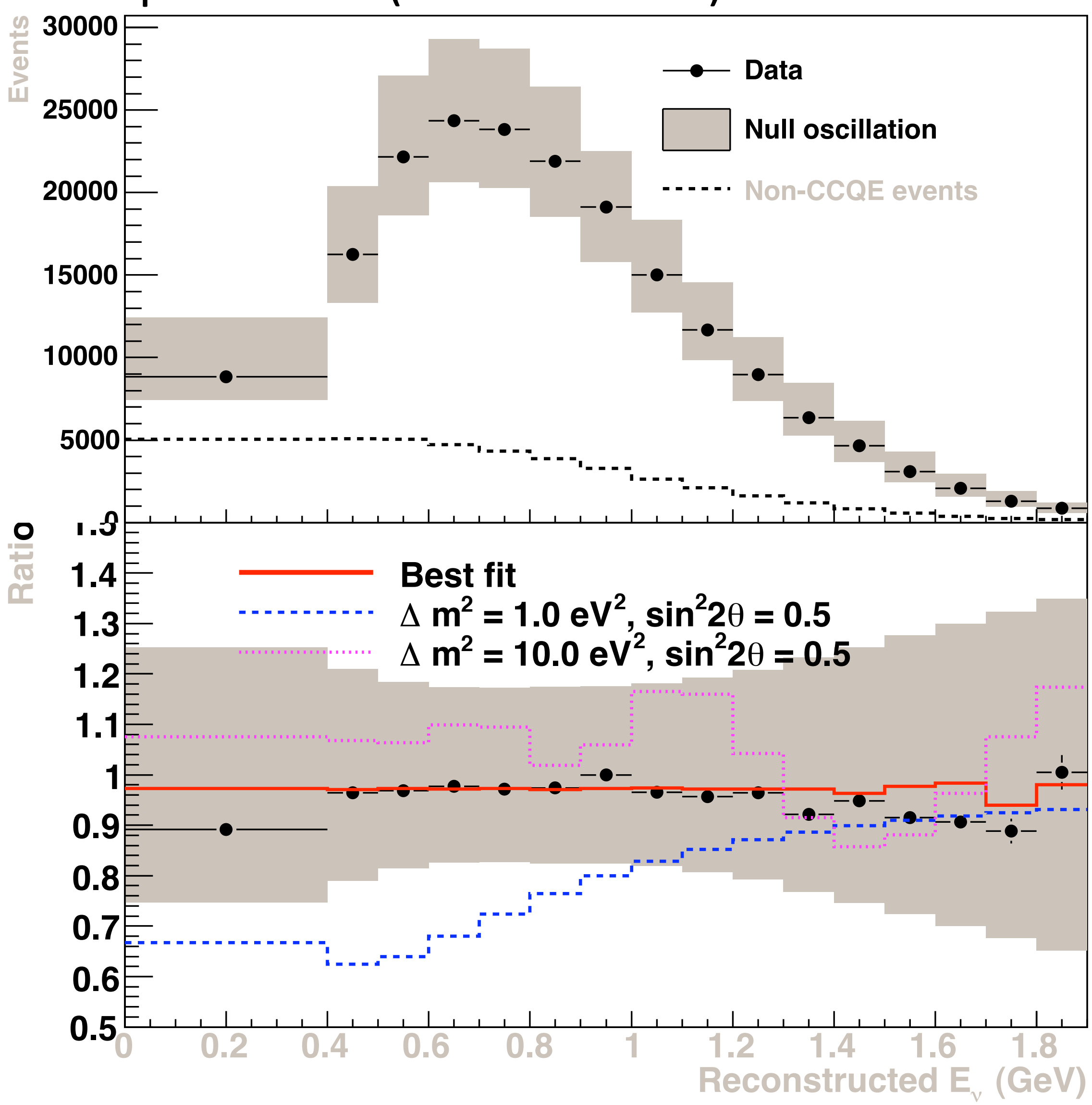
First, test agreement of SciBooNE datasets:

- No evidence for oscillation at SciBooNE

Error bands include neutrino flux, cross section and detector uncertainties

MiniBooNE CCQE ν_μ data set

MiniBooNE CCQE ν_μ data set
+ prediction (no oscillation)



Fit 16+16+16 bins in total = 48

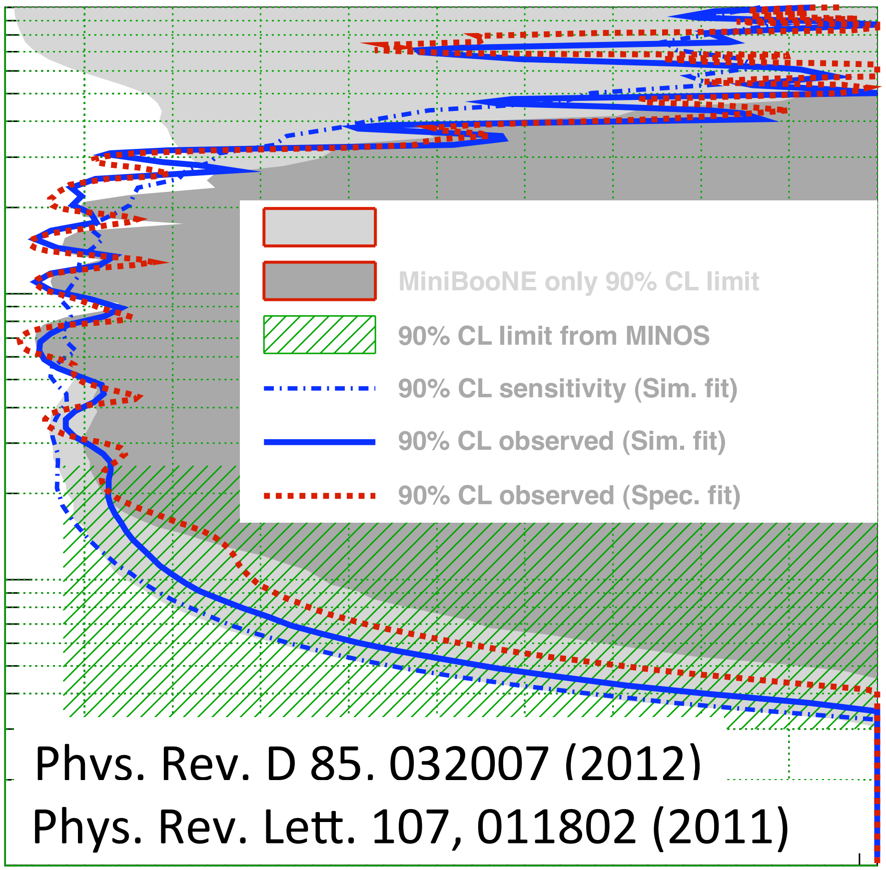
χ^2 (null) = 45.1/ 48 (DOF)
χ^2 (best) = 39.5/ 46 (DOF)
At Δm^2 = 43.7 eV^2, $\sin^2 2\theta$ = 0.60

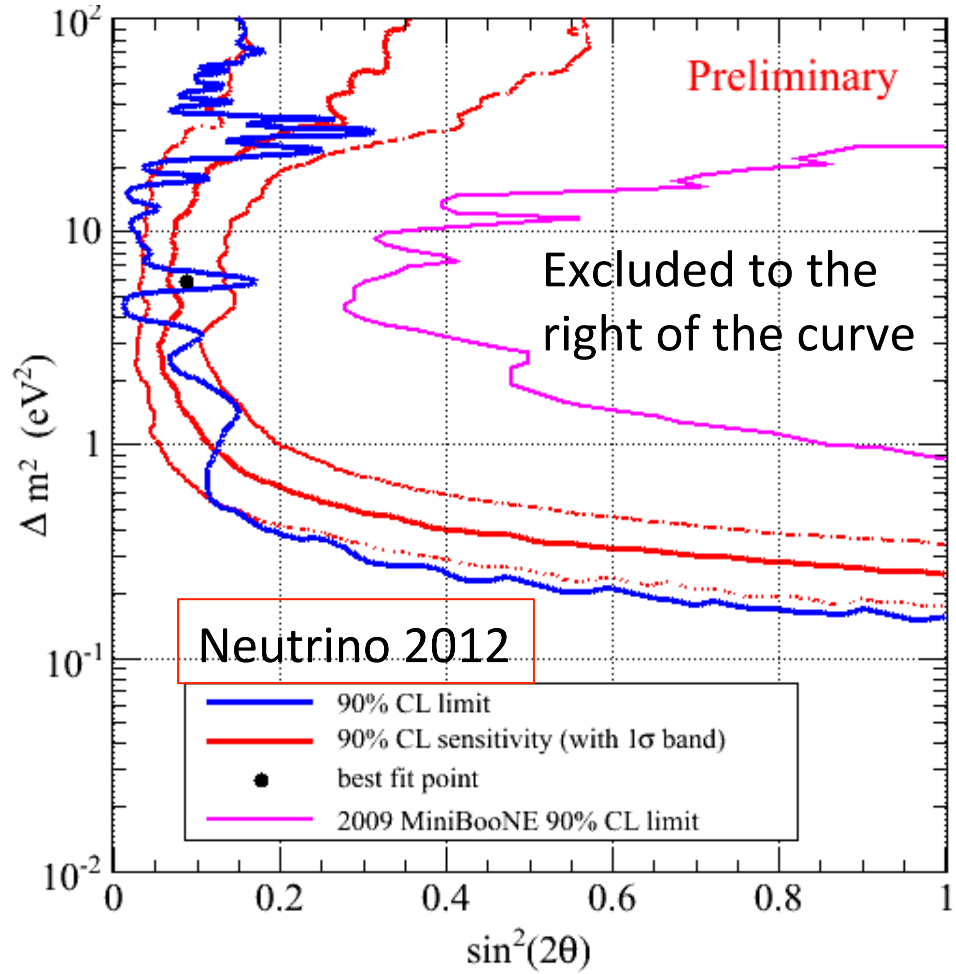
$\Delta\chi^2 = \chi^2(\text{null}) - \chi^2(\text{best}) = 5.6$

$\Delta\chi^2$ (90% CL, null) = 9.3
(estimated from frequentist techniques)

Non-standard ν_μ disappearance results

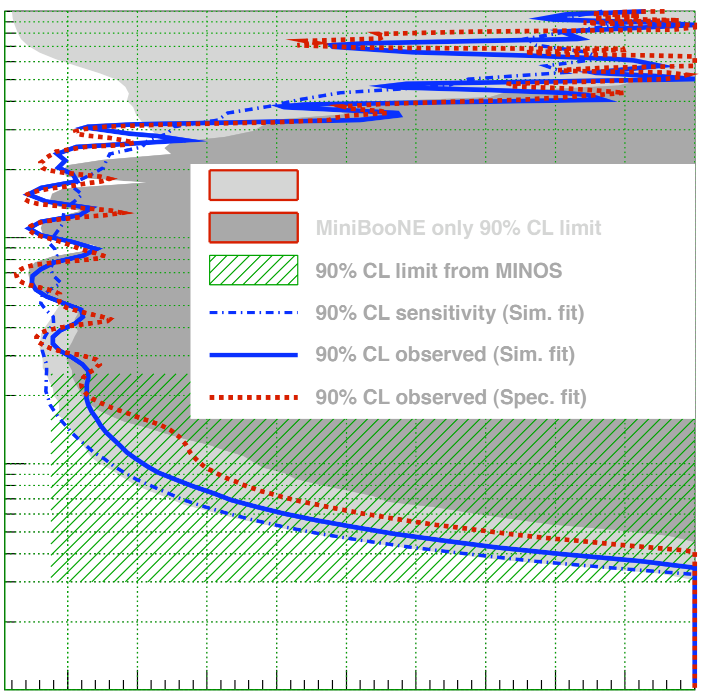
Joint search for non standard disappearance with MiniBooNE and SciBooNE data is consistent with no ν_μ or $\bar{\nu}_\mu$ disappearance at 90%CL

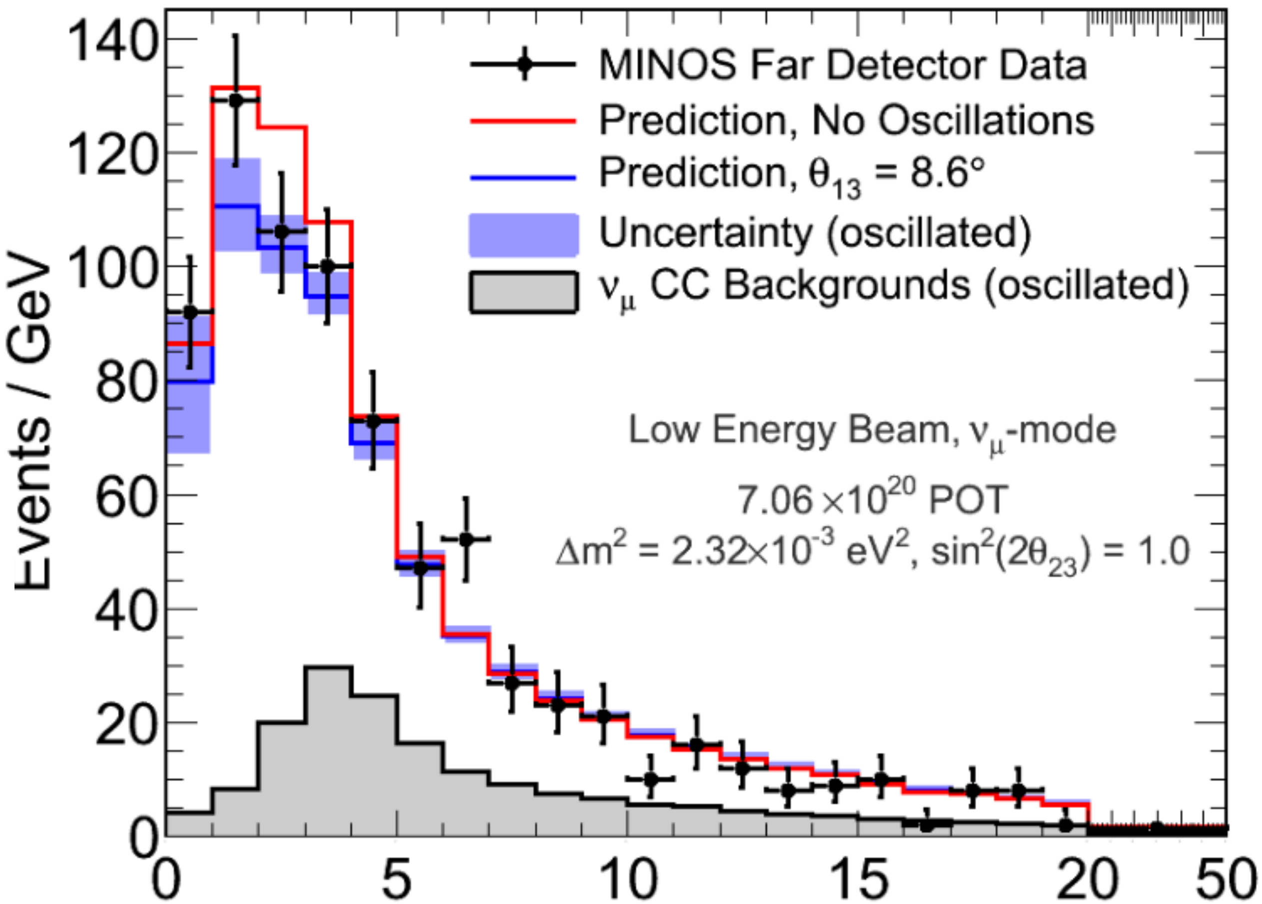




Short baseline physics at long baseline

The presence of a sterile neutrino would produce a deficit of active flavors at the far detector (NC deficit)

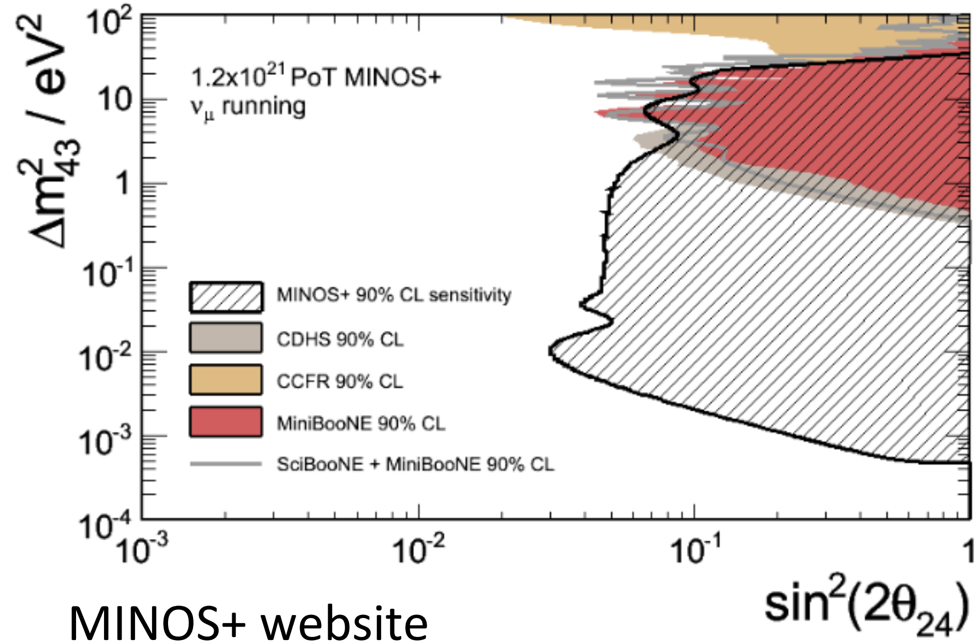




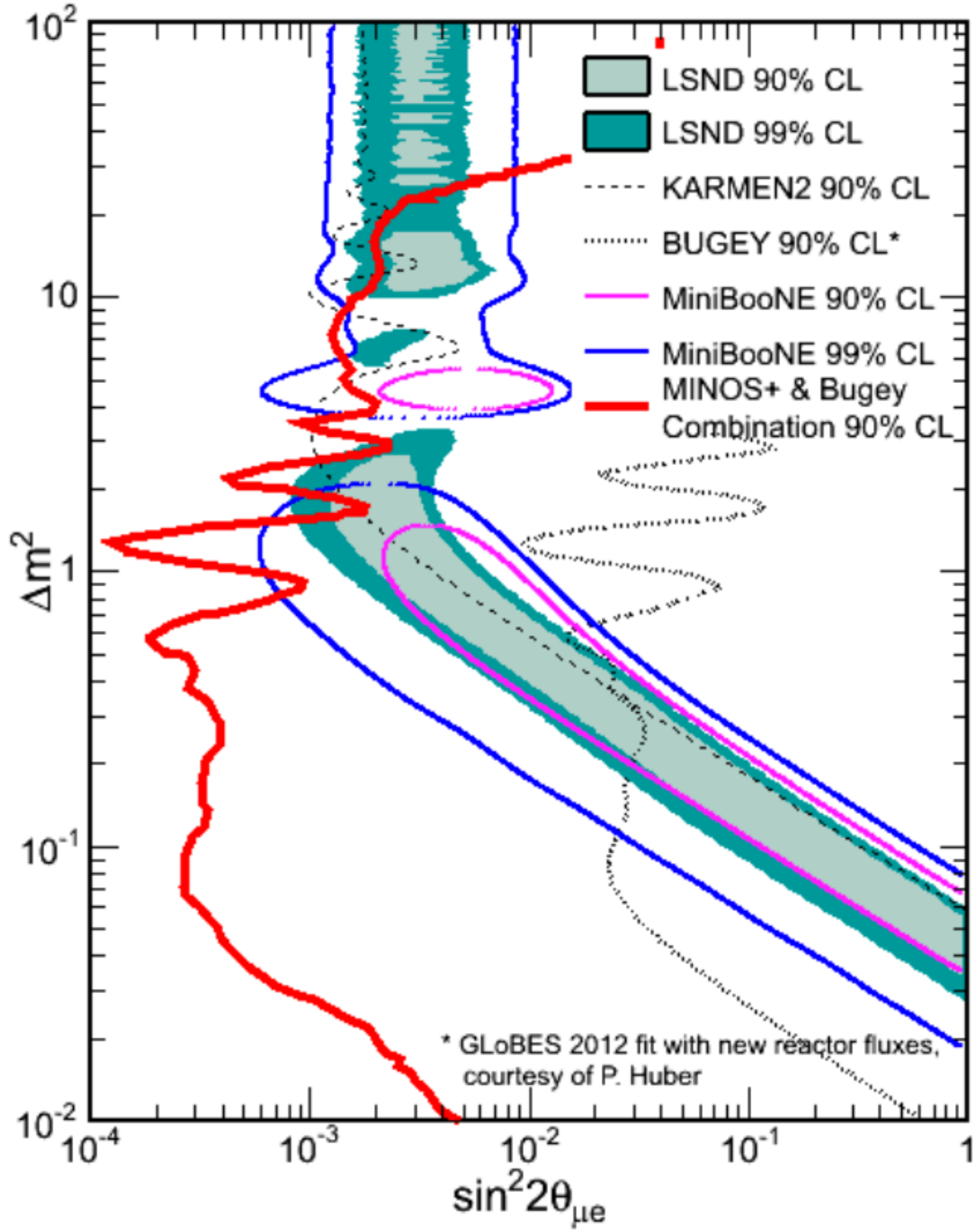
Green limit from MINOS NC far detector events

- Consistent with expected flux, and no sterile mixing

Short baseline physics at long baseline



MINOS+ website



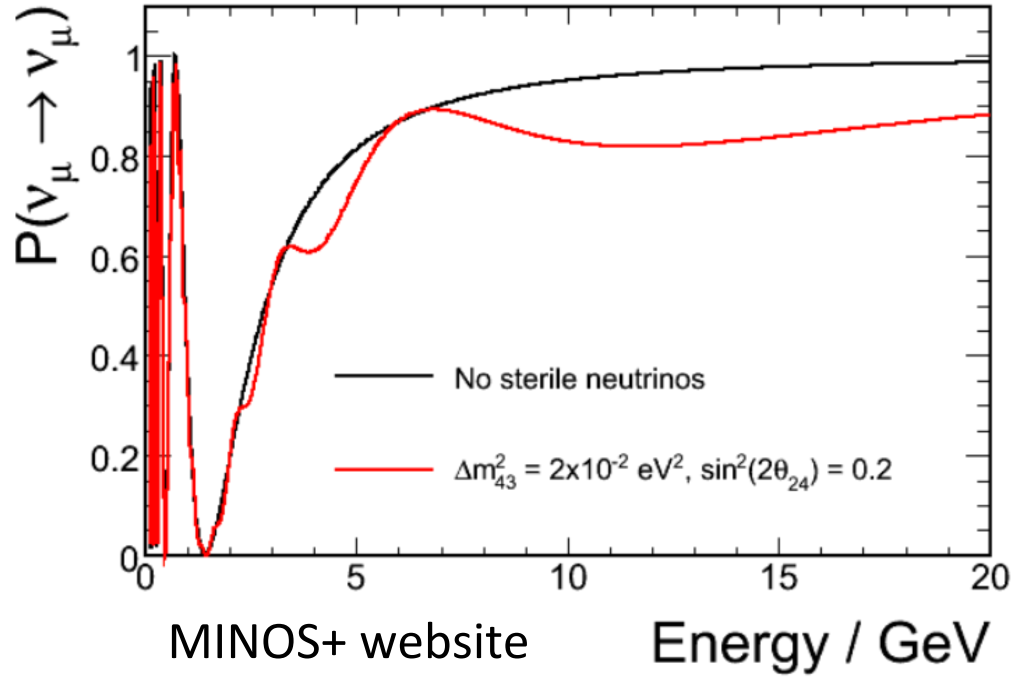
MINOS+ experiment running concurrent with NOvA can expand the sterile search

Tension between SBL CC, LBL NC disappearance results and SBL CC appearance results

NSI long baseline physics

MINOS+ experiment running concurrent with NOvA will also use CC samples to probe steriles, NSI mixing (large extra dimensions)

- MINOS has done tests of NSI coupling as well already



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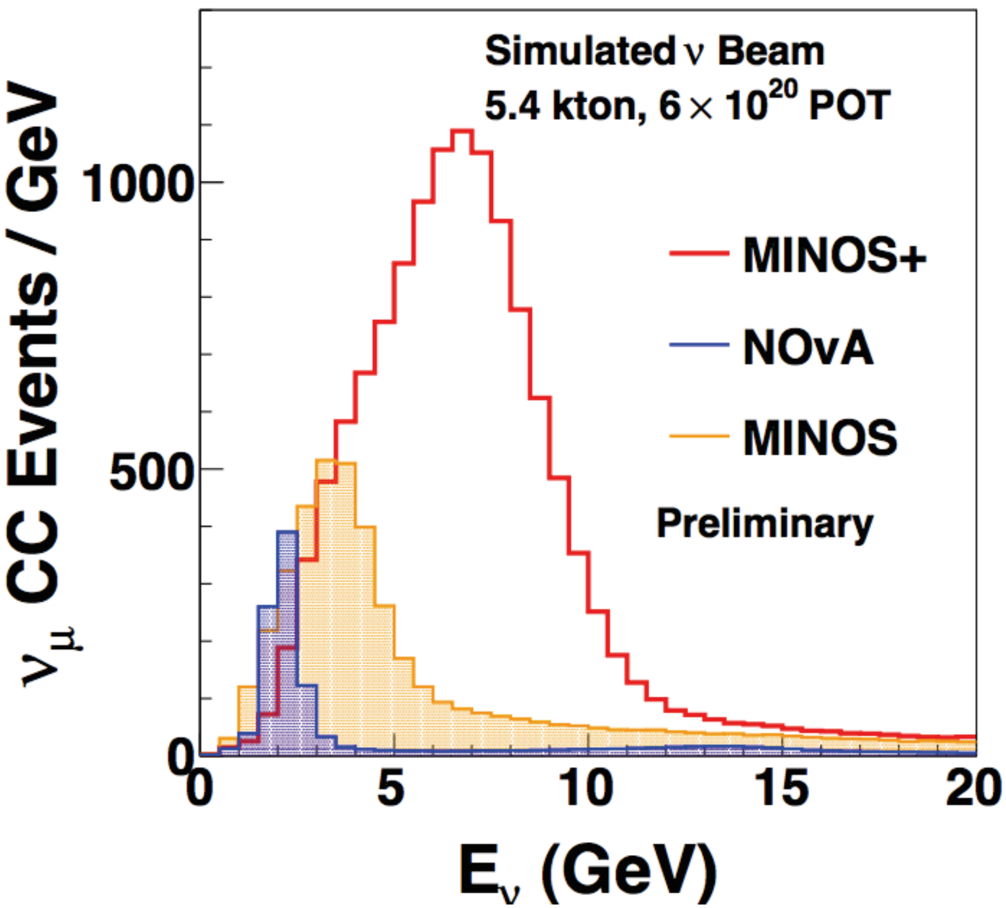
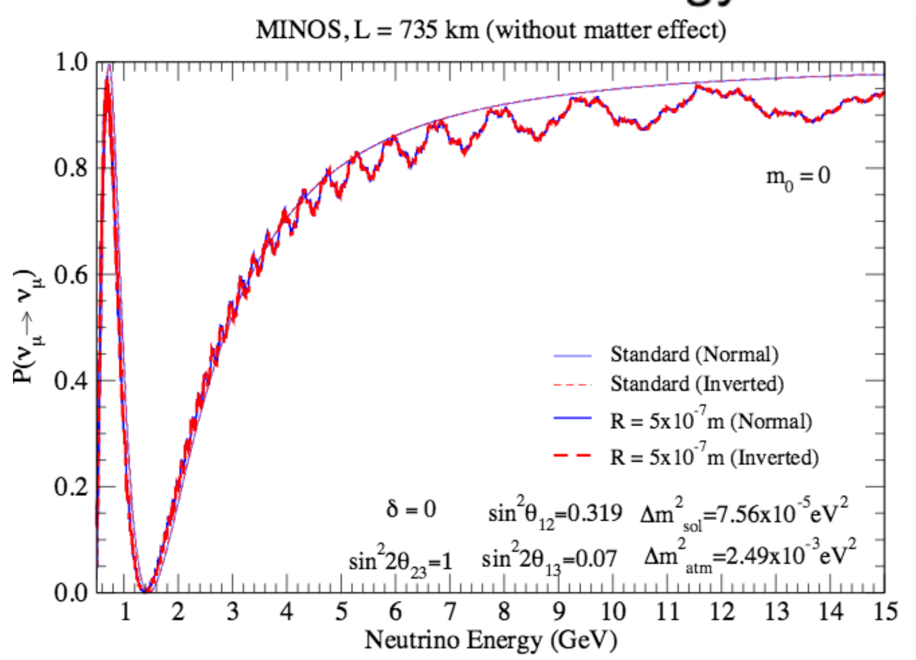




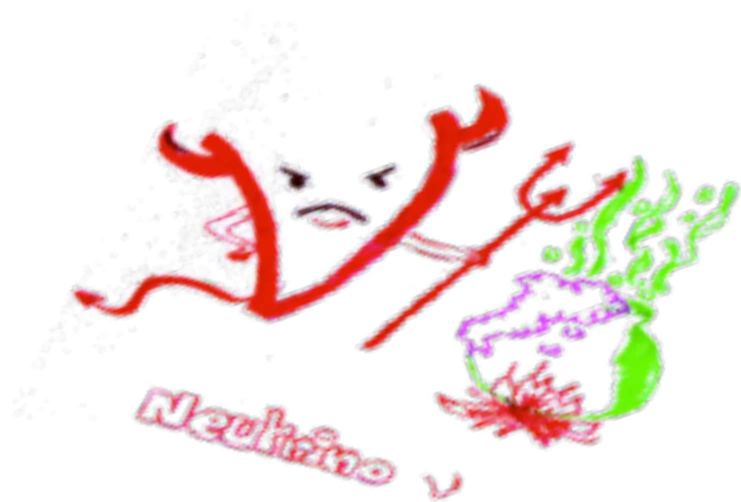
First lecture summary

(Some of) the rich physics which uses neutrino beams

- Consistent picture emerging of three active flavor mixing
- Puzzles remain for non standard ν oscillation such as sterile ν

Next lecture: the devil is in the details

- How do we build neutrino beams?
- What are the challenges of performing experiments?



S. Gilardoni
INSS09

Questions? Want to know more about a particular topic? Let's talk!

Backup slides

Blindness resources

Selectivity and Discord, by Allan Franklin, University of Pittsburgh Press, 2002.

How Experiments End, by Peter Louis Galison, University of Chicago Press, 1987.

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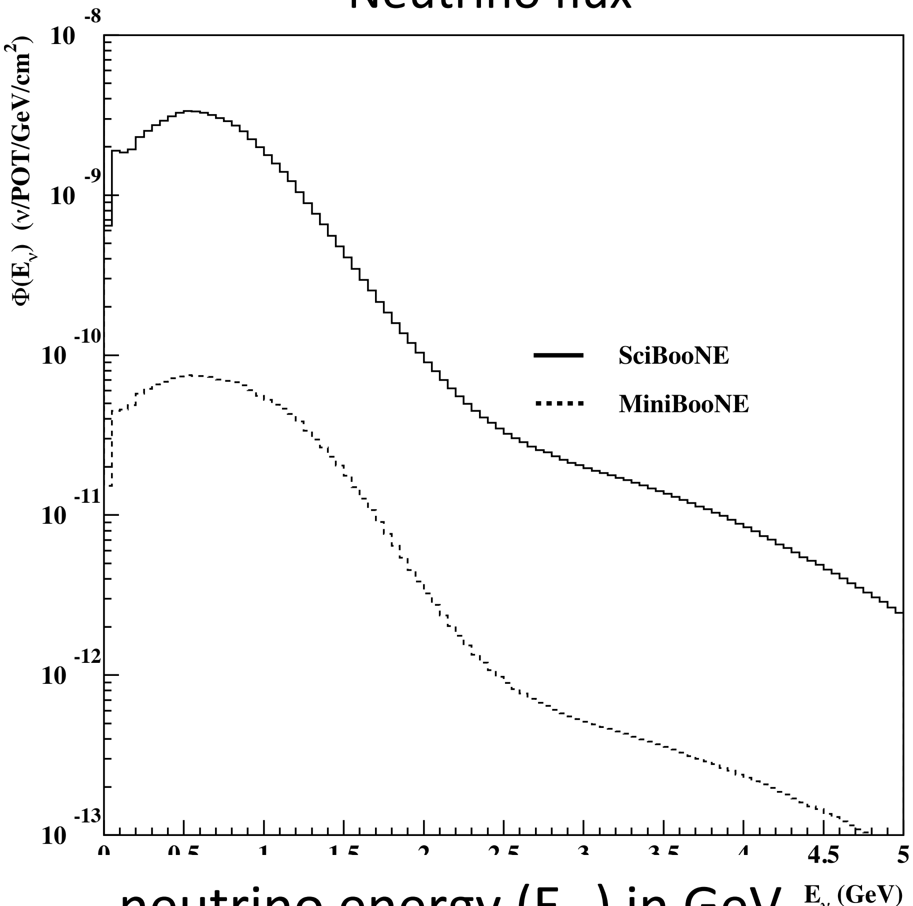
Thanks to S. Oser

MiniBooNE (wide-band) neutrino flux

Neutrino flux



neutrino energy (E_ν) in GeV

Predominantly ν_μ

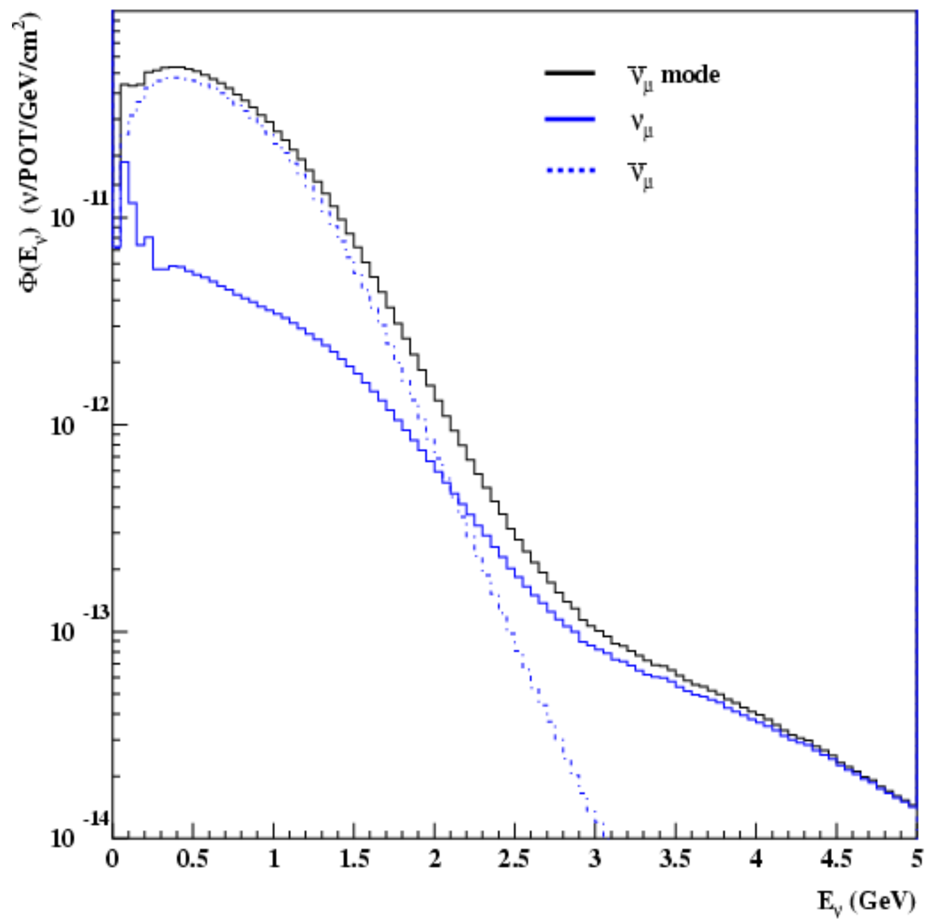
- ~6% $\bar{\nu}_\mu$, ~0.5% $\nu_\varepsilon + \bar{\nu}_\varepsilon$

In MiniBooNE: ~1 ν per 1e15 POT

In SciBooNE: ~0.5 ν per 1e15 POT

~5x closer, ~50x smaller

Antineutrino flux



Significant neutrino component to antineutrino running condition (~16% ν_μ in flux)