Rencontres de Moriond EW 2012

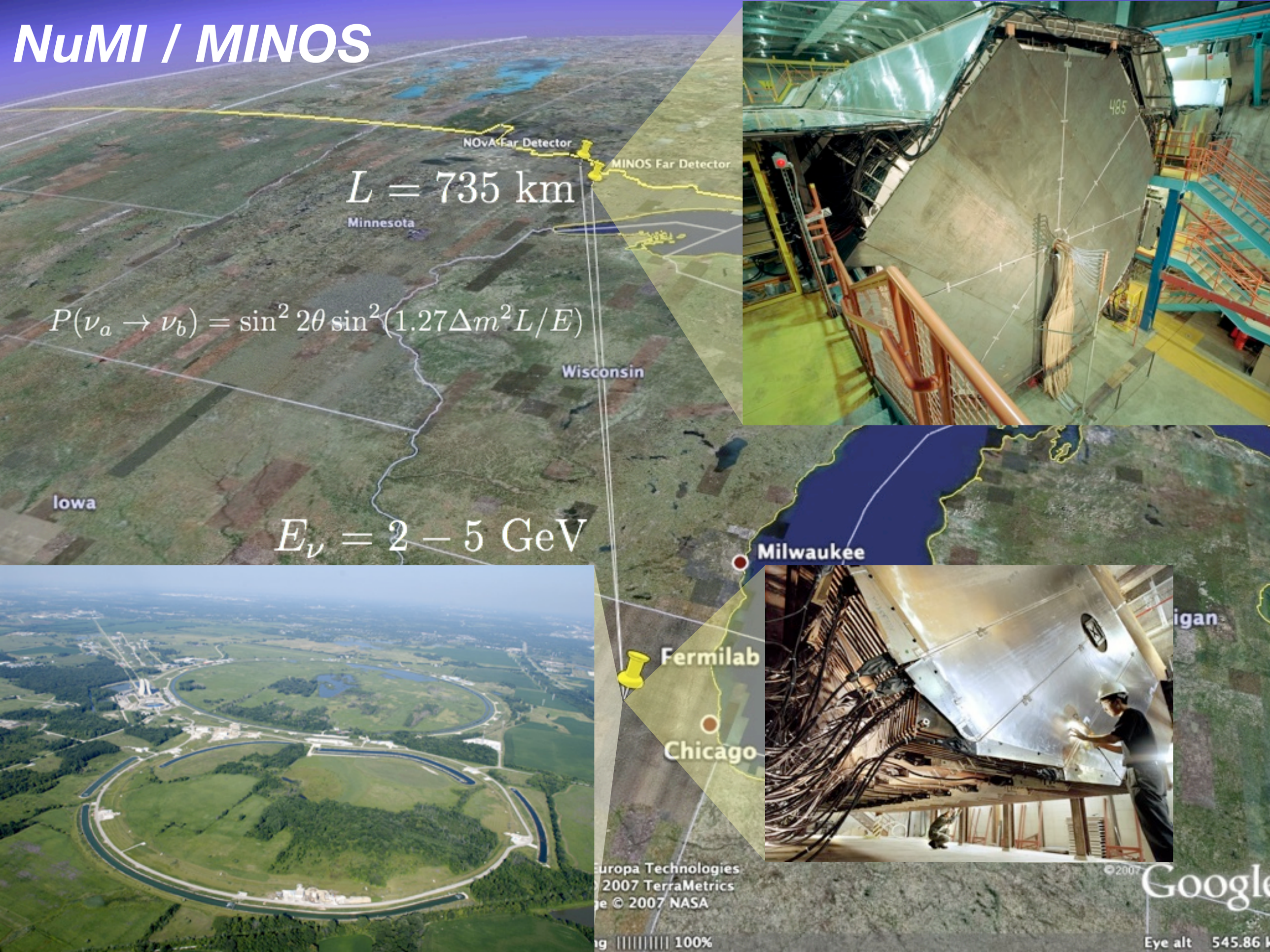
4-10 March 2012
Europe/Paris timezone

MINOS, NOvA, Fermilab perspective

Mark Messier
Indiana University

March 9, 2012

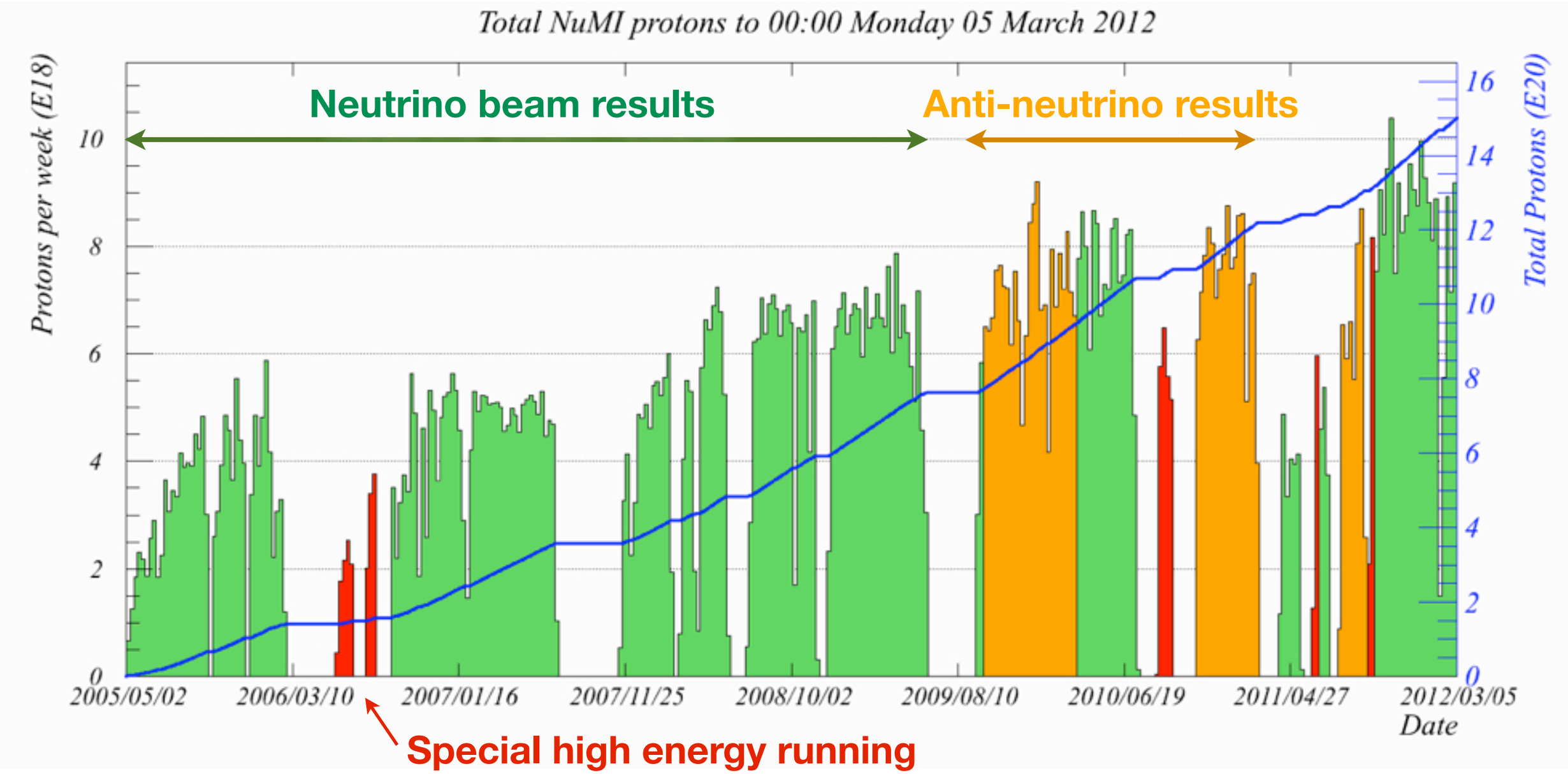
NuMI / MINOS



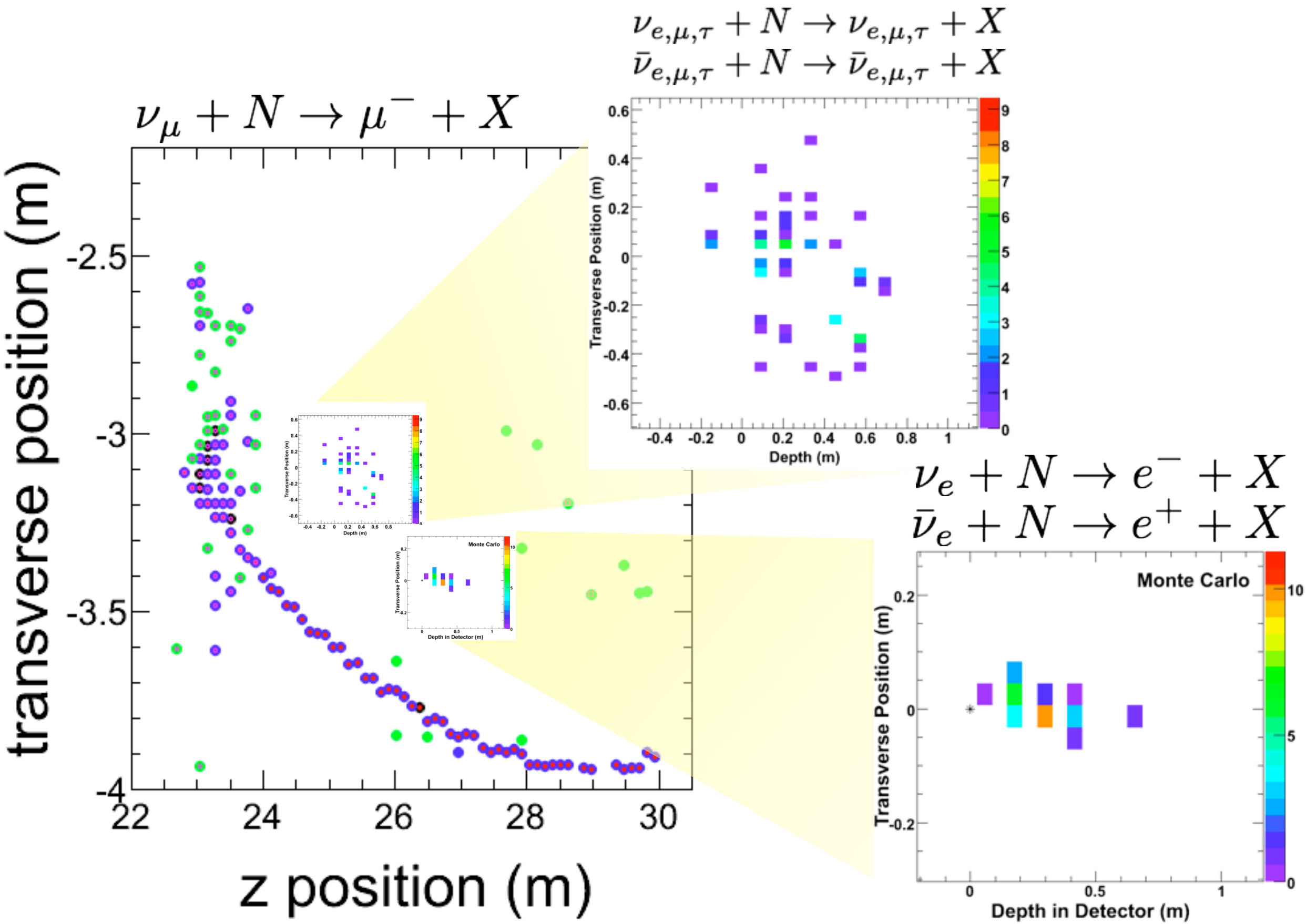
$$L = 735 \text{ km}$$

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$$

$$E_\nu = 2 - 5 \text{ GeV}$$



- NuMI has delivered 15×10^{20} protons to the experiment (250 coulombs)
- 12 in neutrino beam focus
- 3 in anti-neutrino beam focus

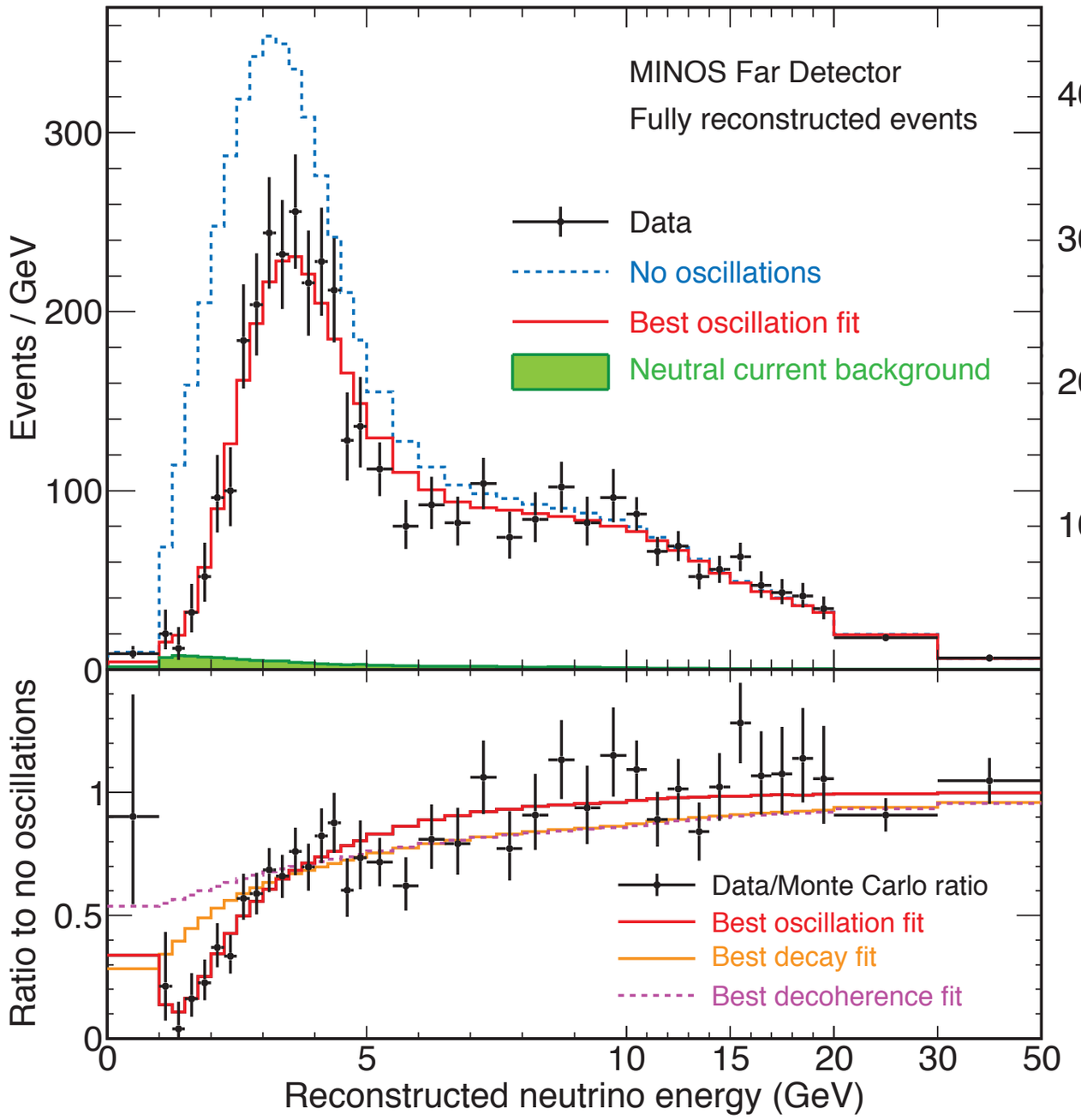

$\nu_{e,\mu,\tau} + N \rightarrow \nu_{e,\mu,\tau} + X$
$\bar{\nu}_{e,\mu,\tau} + N \rightarrow \bar{\nu}_{e,\mu,\tau} + X$
$\nu_\mu + N \rightarrow \mu^- + X$
$\nu_e + N \rightarrow e^- + X$
$\bar{\nu}_e + N \rightarrow e^+ + X$
transverse position (m)
z position (m)
Transverse Position (m)
Depth (m)
Monte Carlo
Depth in Detector (m)

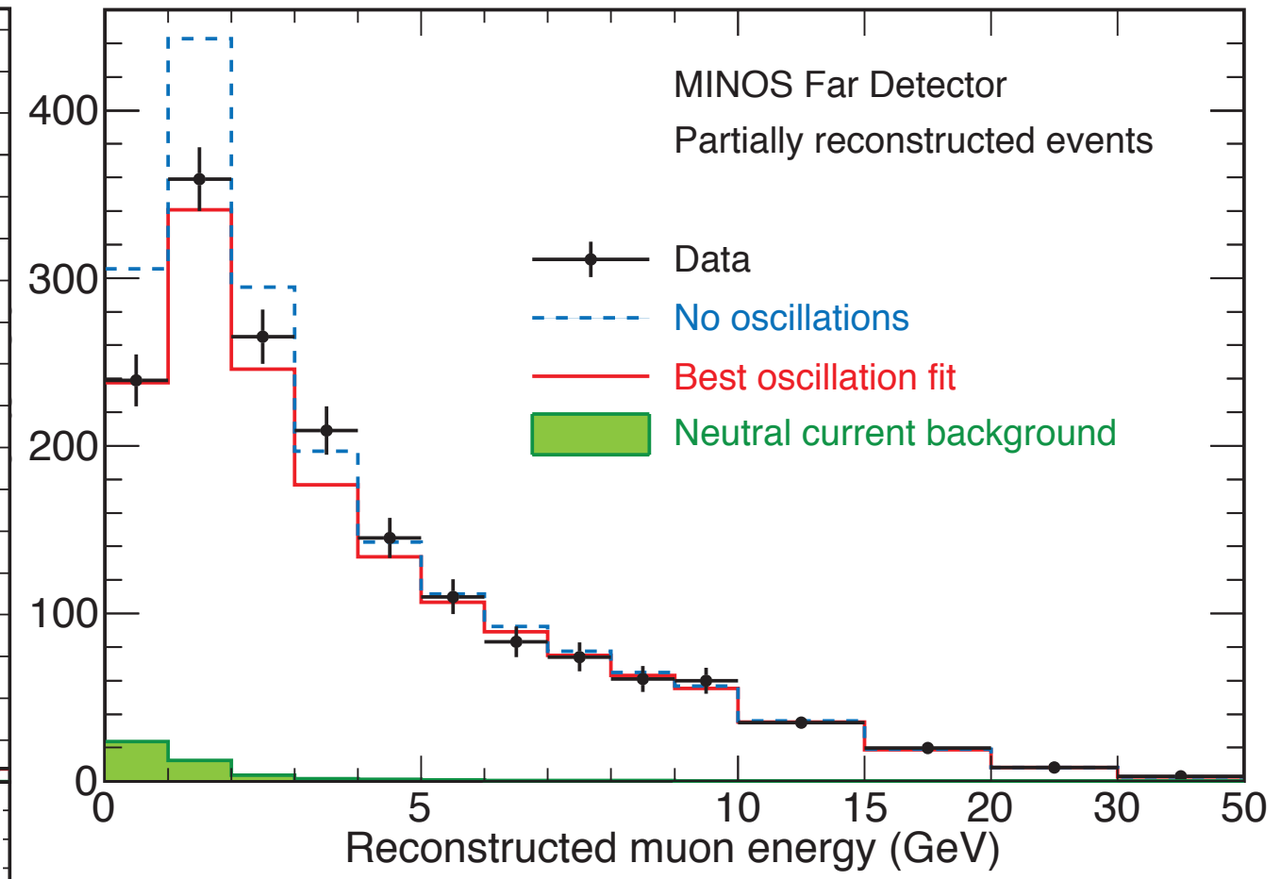
A snapshot of MINOS neutrino physics

ν_μ disappearance	$\lvert\Delta m^2\rvert = 2.33^{+0.12}_{-0.08}\ \mathrm{meV}^2$ $\sin^2(2\theta) > 0.90$	**Phys.Rev.Lett. 106 (2011) 181801** **arXiv:1103.0340 [hep-ex]**
$\bar{\nu}_\mu$ disappearance	$\lvert\Delta \bar{m}^2\rvert = 2.62^{+0.32}_{-0.29}\ \mathrm{meV}^2$ $\sin^2(2\bar{\theta}) > 0.75$	**Submitted to PRL** **arXiv:1202.2772v1 [hep-ex]**
$\bar{\nu}_\mu$ appearance	< few percent	**Phys.Rev.Lett. 107 (2011) 181802** **arXiv:1108.0015 [hep-ex]**
ν_e appearance	$2\sin^2(\theta_{23})\sin^2(2\theta_{13}) = 0.041^{+0.047}_{-0.031}$ $2\sin^2(\theta_{23})\sin^2(2\theta_{13}) = 0.079^{+0.071}_{-0.053}$	**Phys.Rev.Lett. 107 (2011) 181802** **arXiv:1108.0015 [hep-ex]**
Time of flight	$\frac{v-c}{c} = (5.1 \pm 2.9) \times 10^{-5}$	**Phys.Rev. D76 (2007) 072005** **arXiv:0706.0437 [hep-ex]**
Active-sterile mixing	$f_s < 22\%, \theta_{34} < 26^\circ, \theta_{24} < 7^\circ$	**Phys.Rev.Lett. 107 (2011) 011802** **arXiv:1104.3922 [hep-ex]**
CPT violation	$\text{Using neutrinos}: \ a < 1 \times 10^{-23}\ \mathrm{GeV}$ $c < 1 \times 10^{-23}$	**Phys.Rev.Lett. 105 (2010) 151601** **arXiv:1007.2791 [hep-ex]**
	$\text{Using anti}-\text{neutrinos}: \ a < 1 \times 10^{-20}\ \mathrm{GeV}$ $c < 1 \times 10^{-21}$	**Phys.Rev. D85 (2012) 031101** **arXiv:1201.2631 [hep-ex]**
Non-standard, flavor-changing interactions	$\epsilon_{\mu\tau} = -0.068^{+0.083}_{-0.080}$	**Preliminary**

$\nu_\mu \rightarrow \nu_\mu$

Phys.Rev.Lett. 106 (2011) 181801
arXiv:1103.0340v1 [hep-ex] 2 Mar 2011

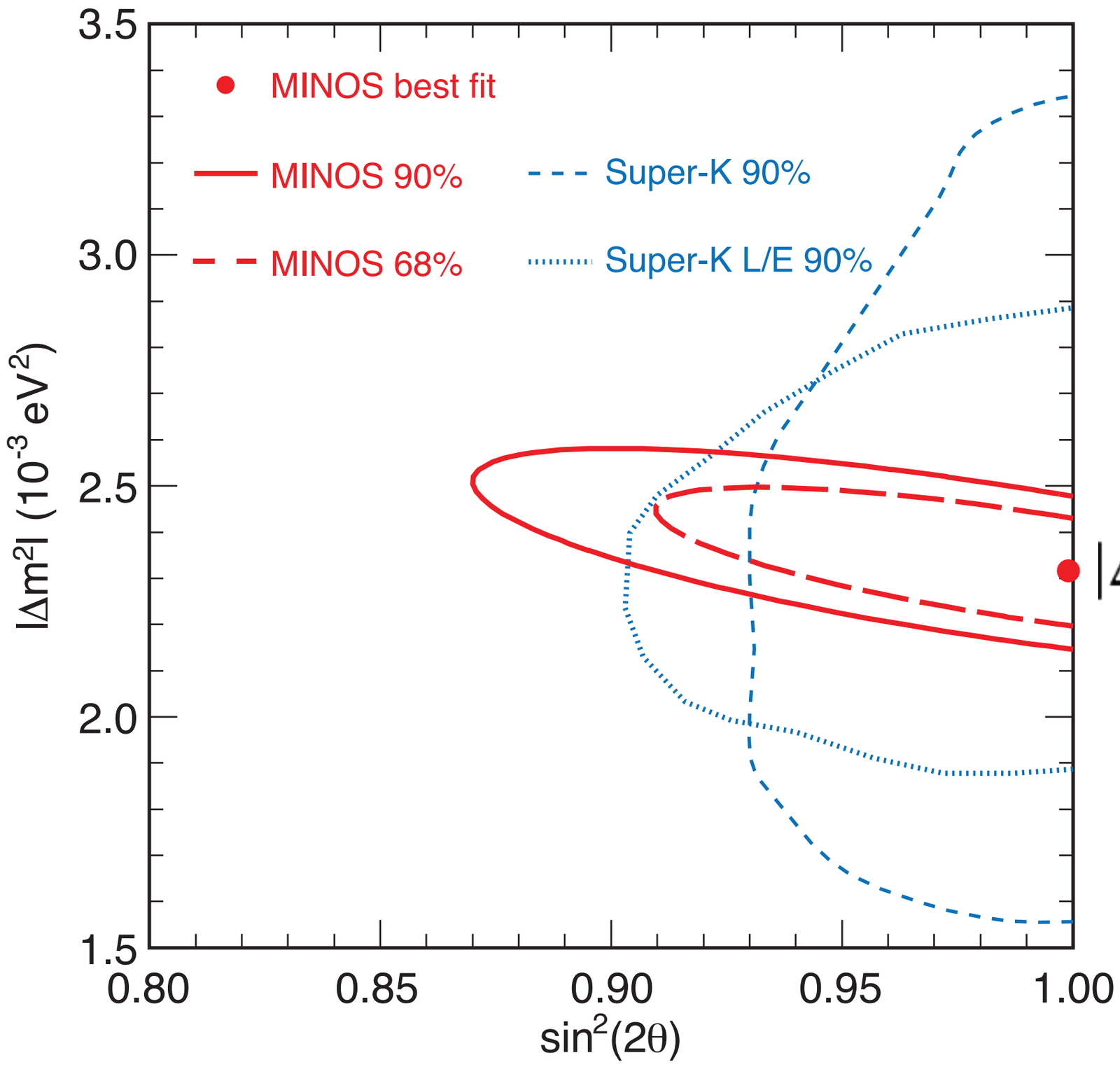




Run Period	POT (10^{20})	Predicted (No oscillations) Fully	Predicted (No oscillations) Partially	Observed (Far Detector) Fully	Observed (Far Detector) Partially
I	1.269	426	375	318	357
II	1.943	639	565	511	555
III	3.881	1,252	1,130	1,037	977
HE	0.153	134	136	120	128
Total	7.246	2,451	2,206	1,986	2,017

$\nu_\mu \to \nu_\mu$

Phys.Rev.Lett. 106 (2011) 181801
arXiv:1103.0340v1 [hep-ex] 2 Mar 2011



$$|\Delta m^2| = 2.32^{+0.12}_{-0.08}\ \mathrm{meV}^2$$

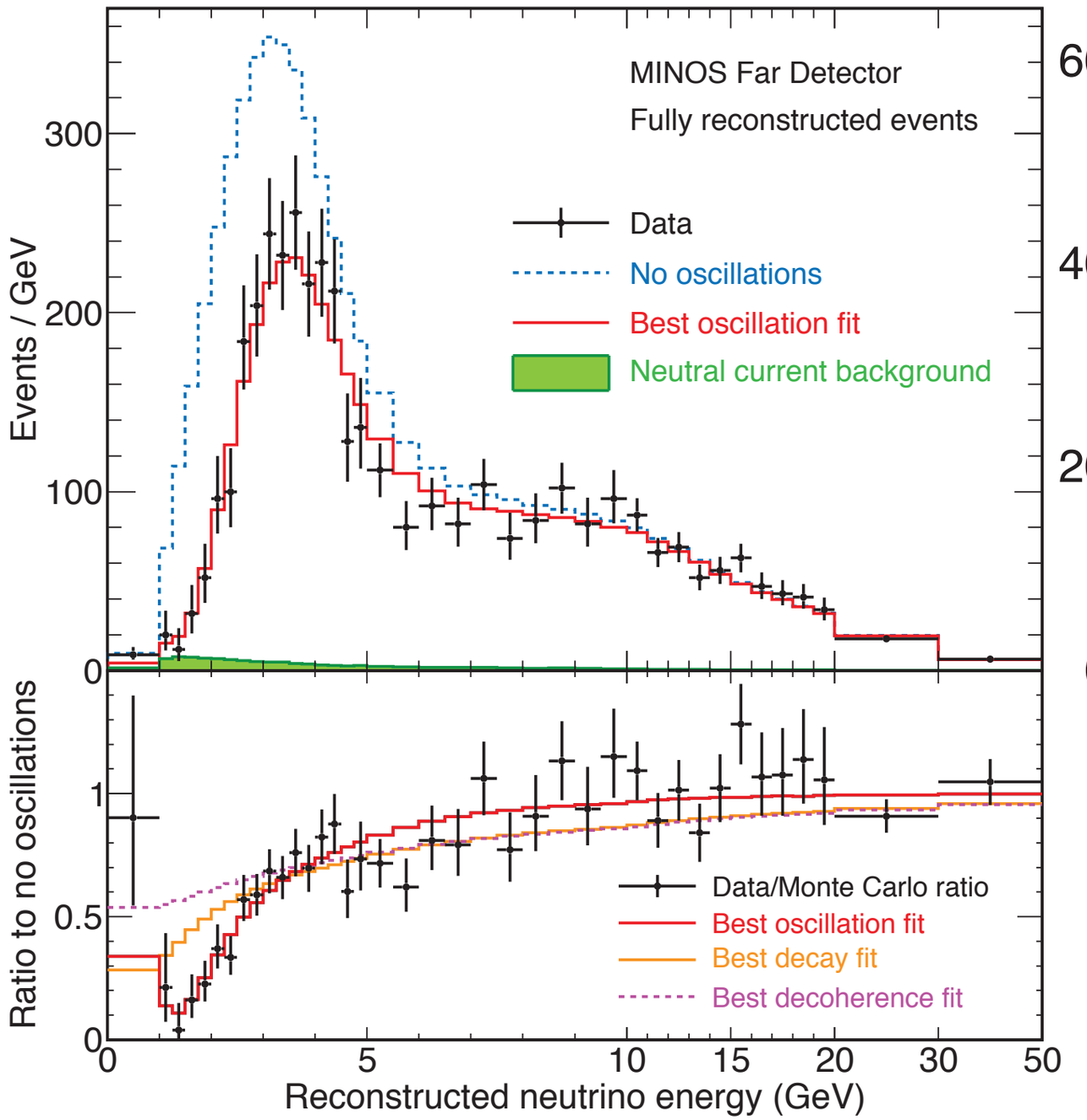
$$\sin^2 2\theta > 0.9\ (90\%\ \mathrm{C.L.})$$

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

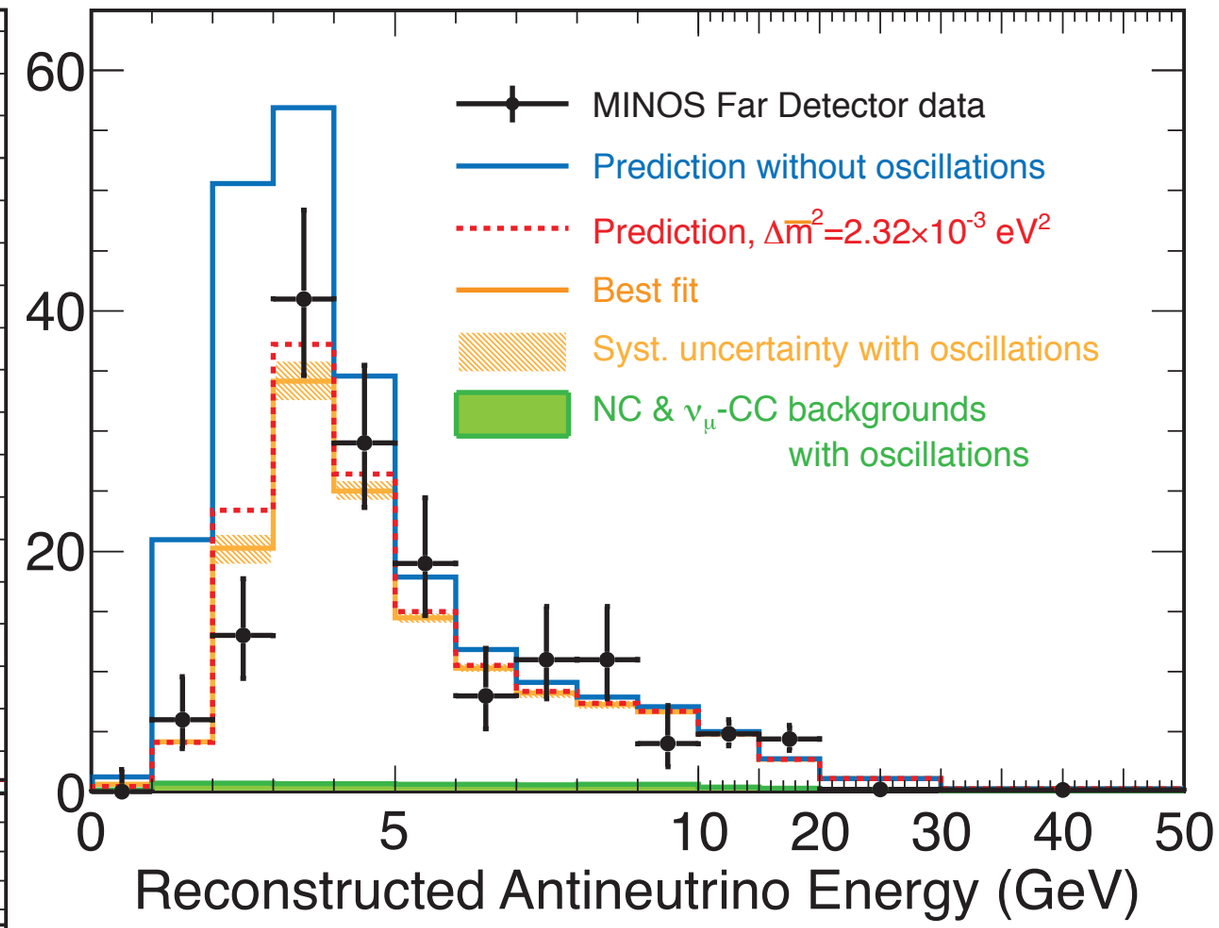
Submitted to PRL
arXiv:1202.2772 [hep-ex]

Do neutrinos and anti-neutrinos oscillate the same way?

ν_μ charged current events



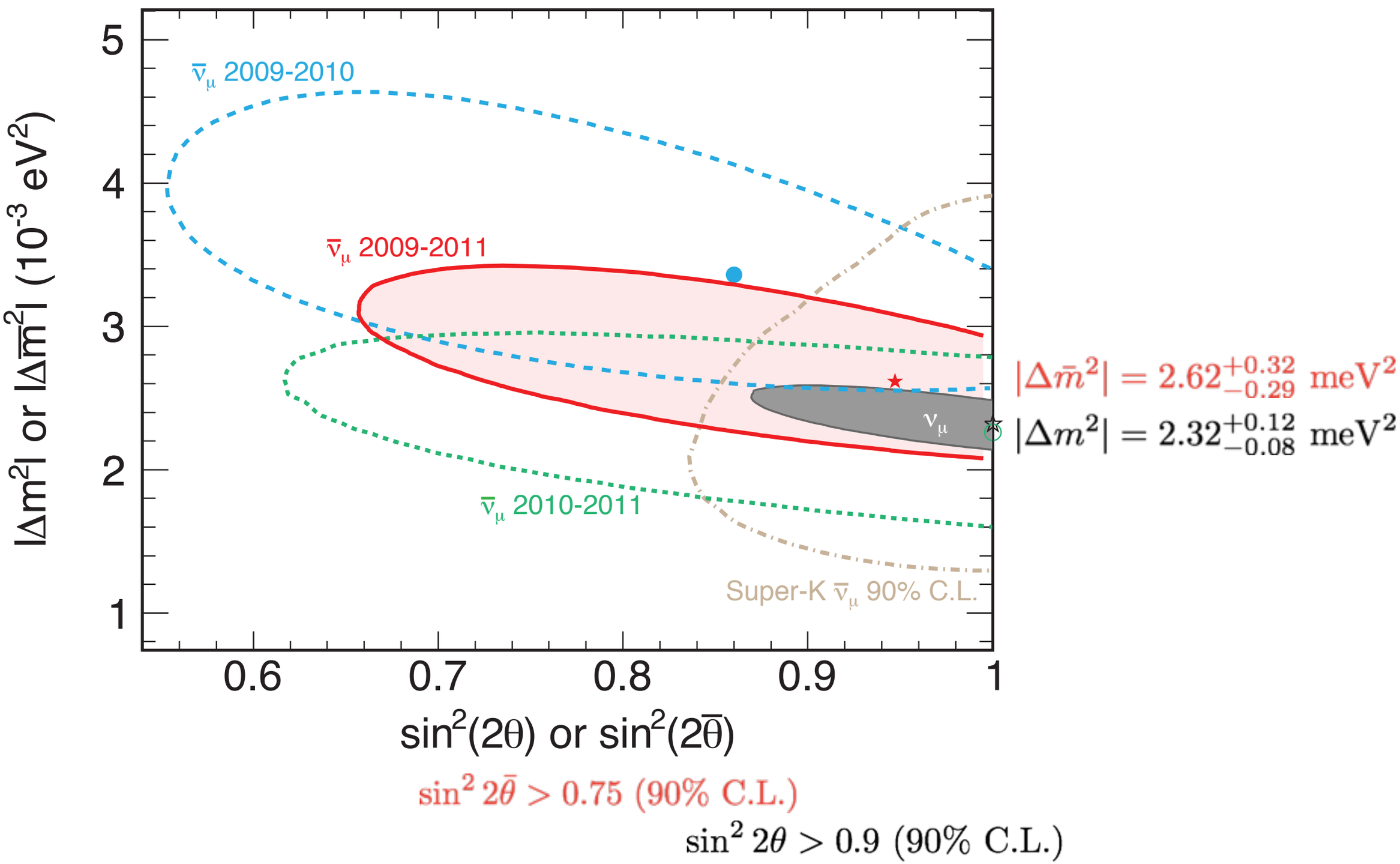
$\bar{\nu}_\mu$ charged current events



$\bar{\nu}_\mu \to \bar{\nu}_\mu$

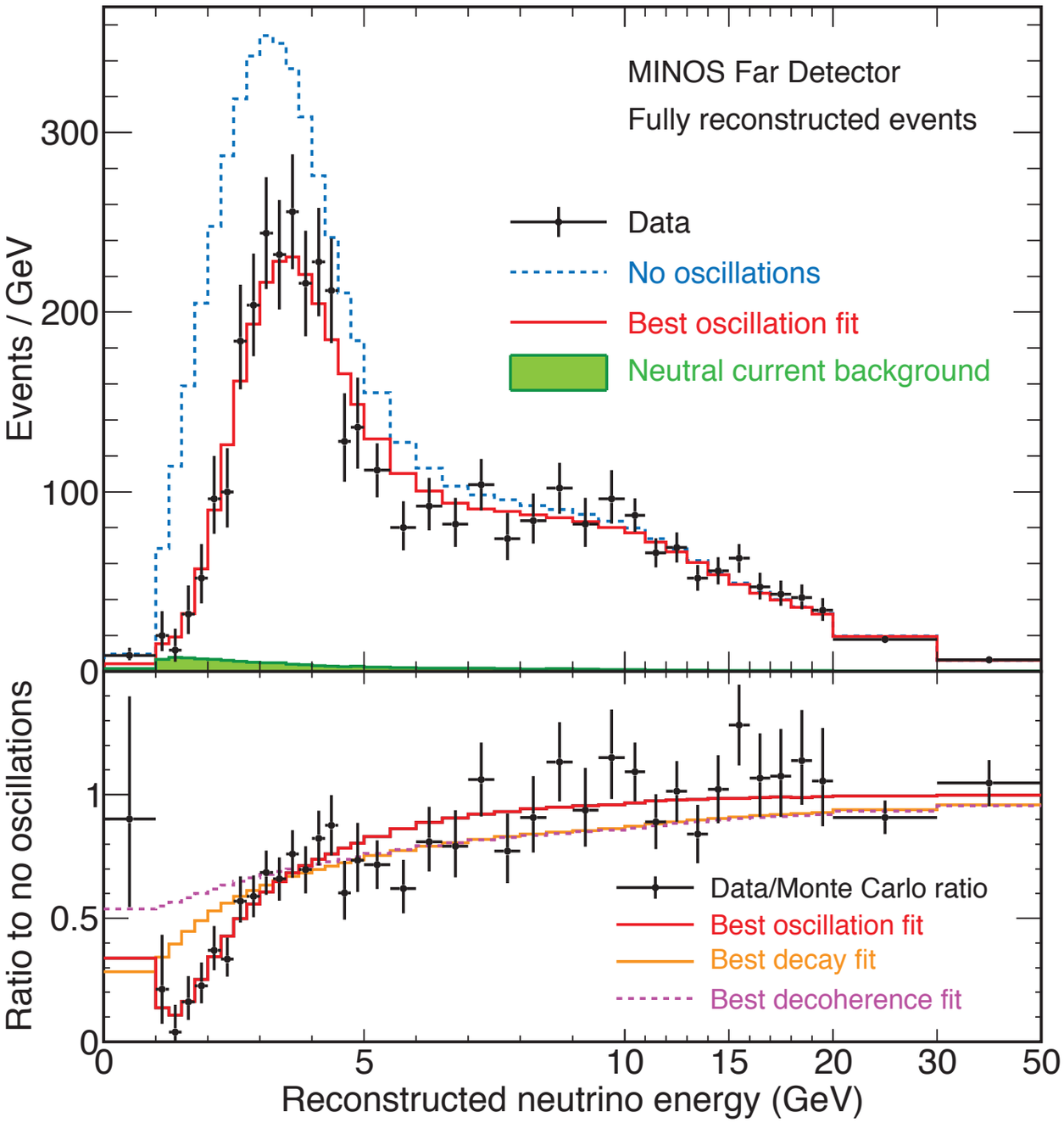
Submitted to PRL
arXiv:1202.2772 [hep-ex]

Do neutrinos and anti-neutrinos oscillate the same way?

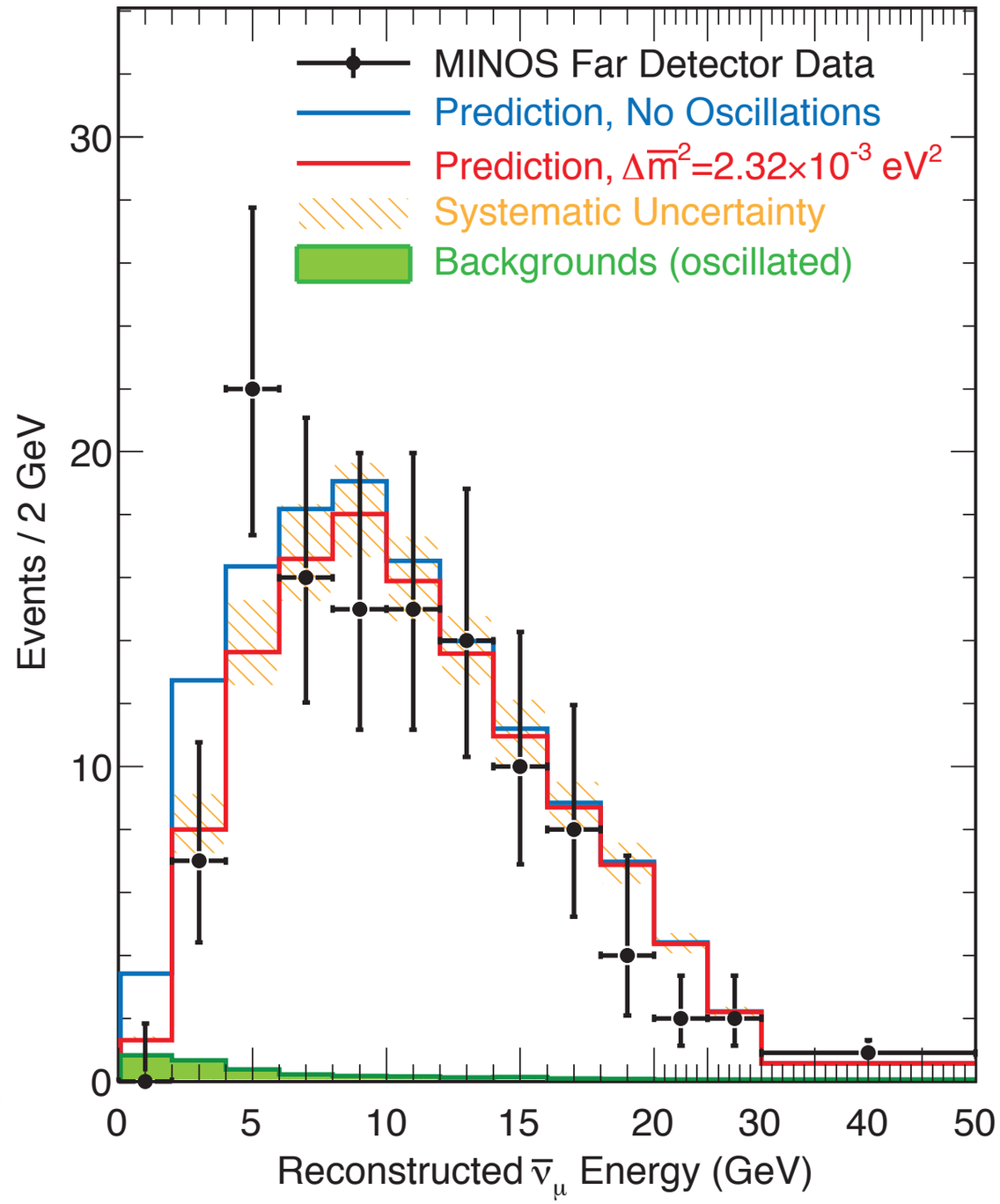


$\bar{\nu}_\mu \to \bar{\nu}_\mu$ & $\nu_\mu \to \bar{\nu}_\mu$

Phys.Rev. D84 (2011) 071103
arXiv:1108.1509 [hep-ex]



$\nu_\mu \to \nu_\mu$

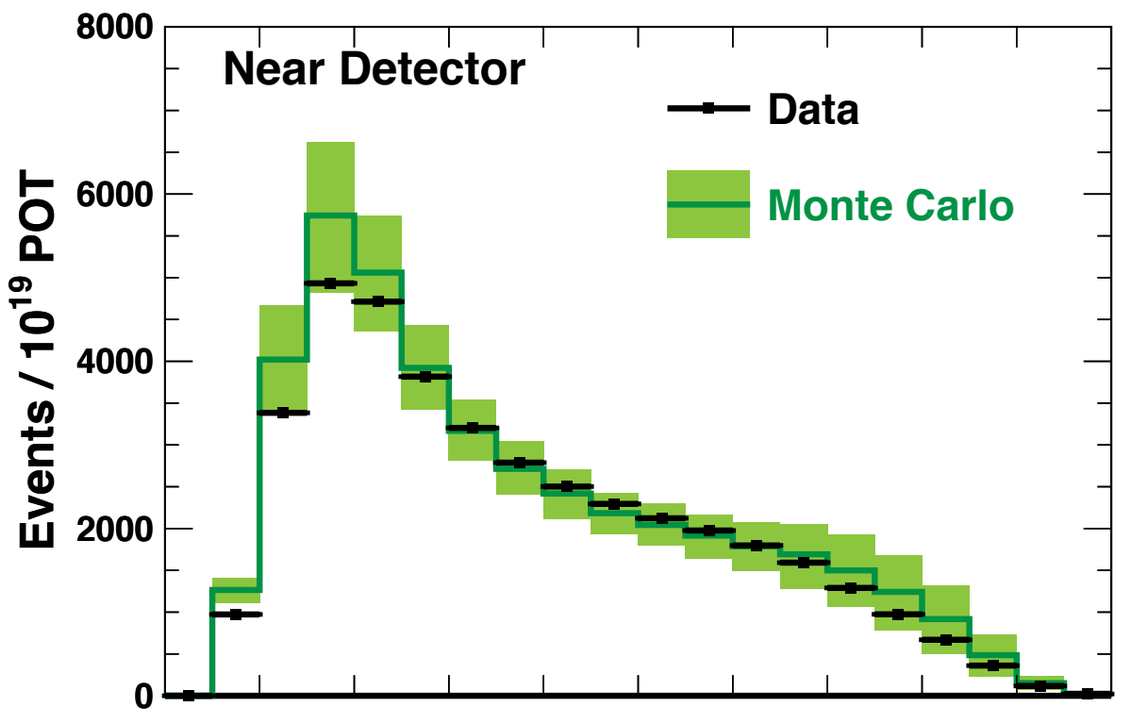


$\bar{\nu}_\mu \to \bar{\nu}_\mu \; + \; \nu_\mu \to \bar{\nu}_\mu$

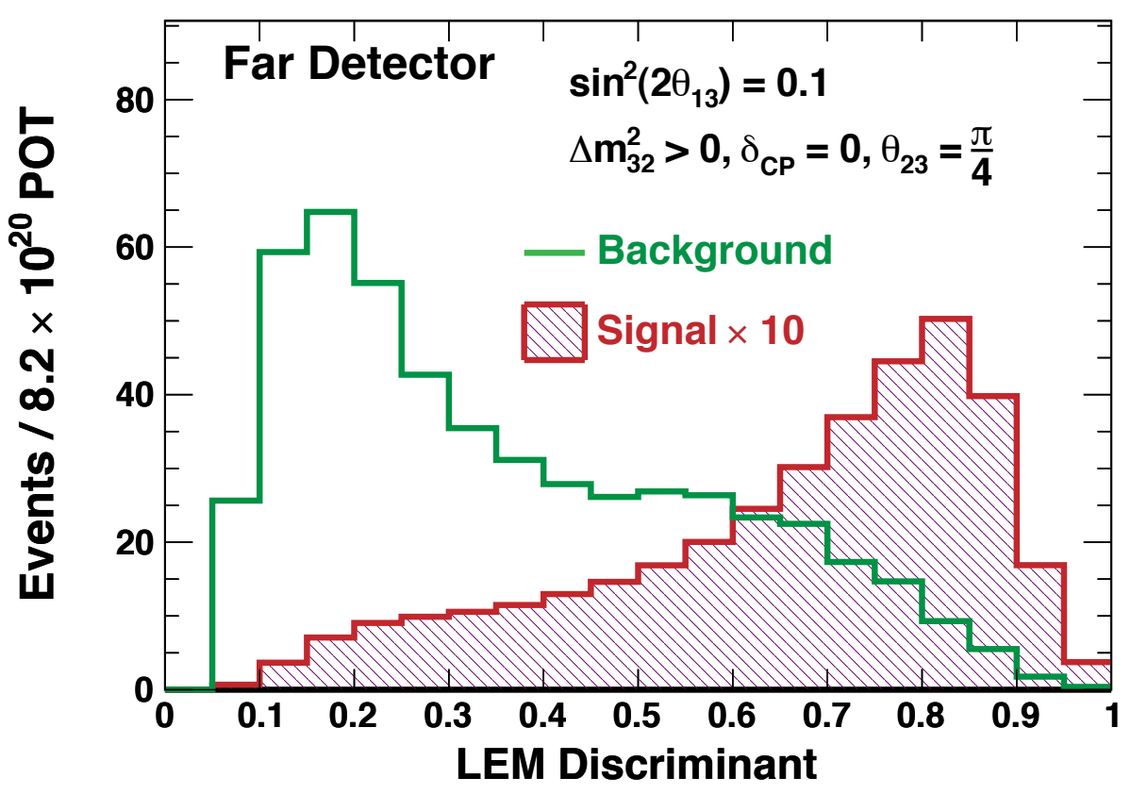
$\nu_\mu \to \nu_e$

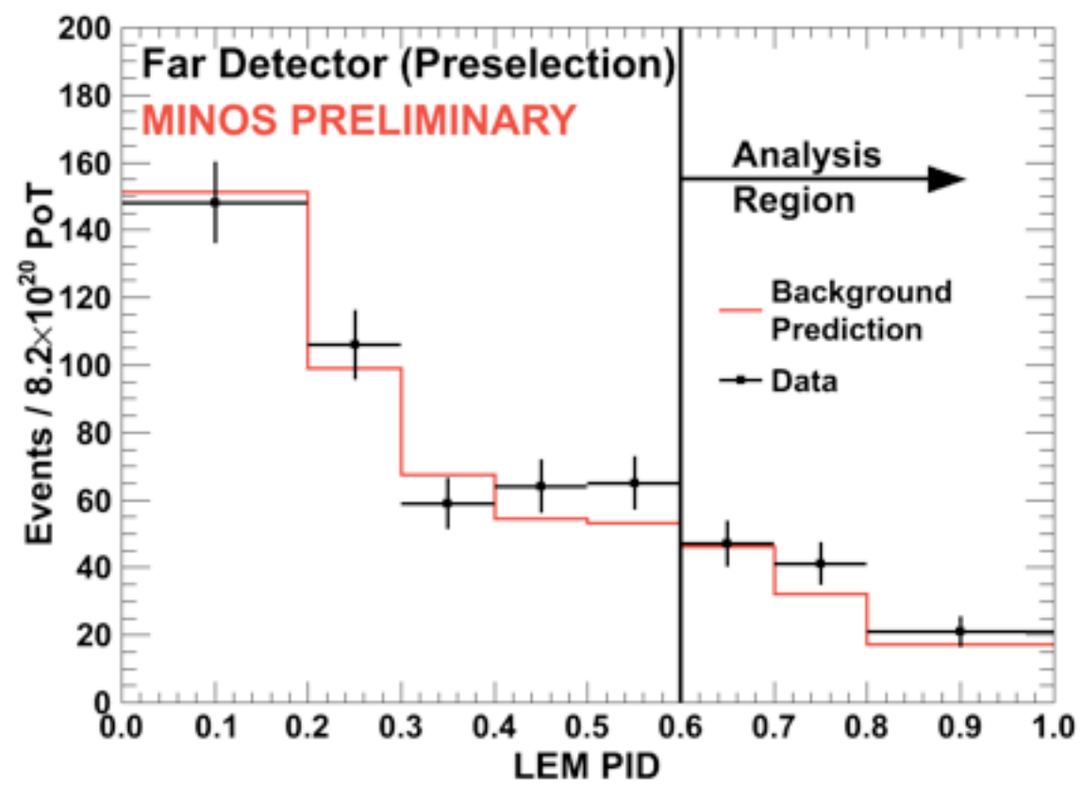
Phys.Rev.Lett. 107 (2011) 181802
arXiv:1108.0015 [hep-ex]

Do muon neutrinos oscillate to electron neutrinos?



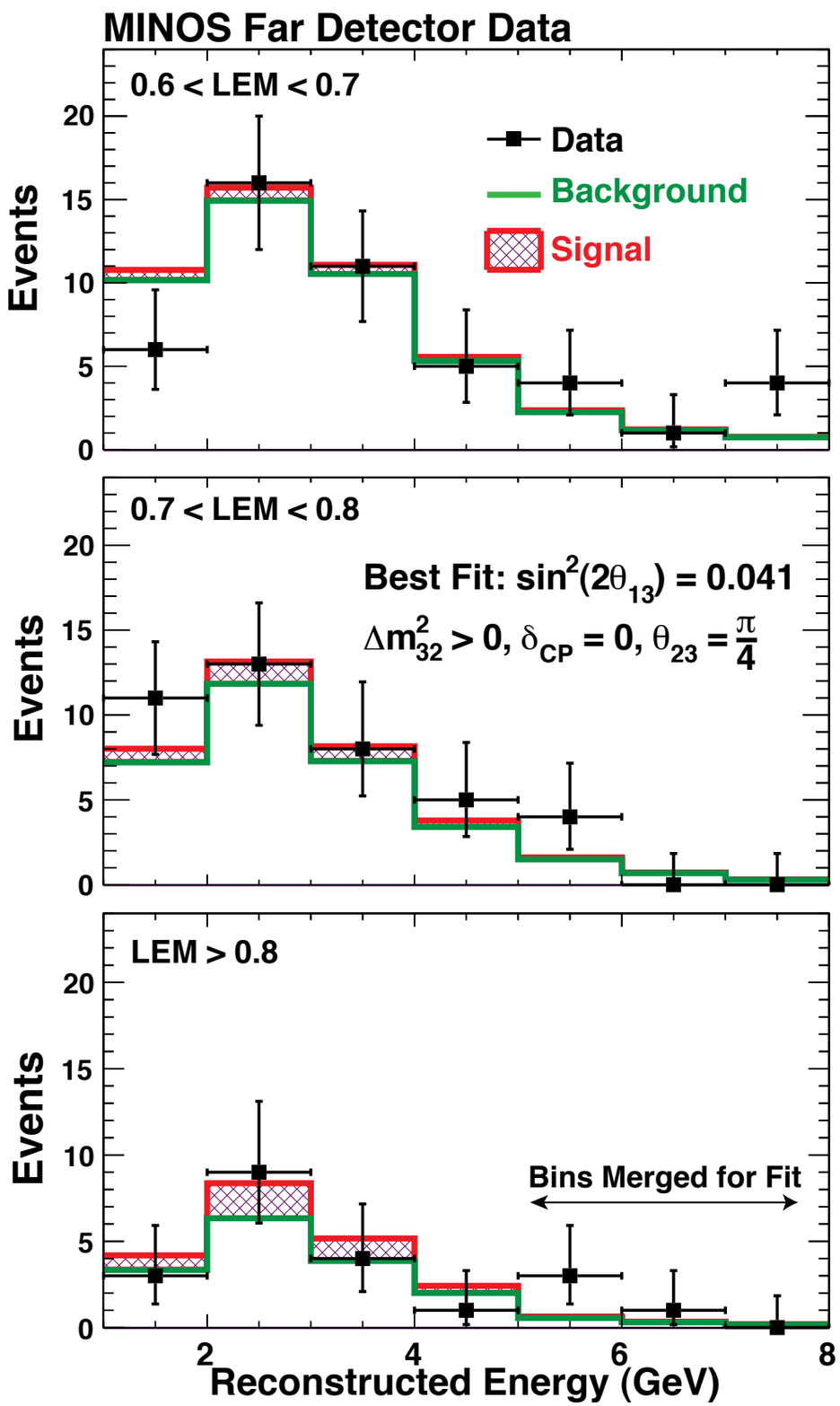
Backgrounds : 49.6 ± 2.7 (syst.) ± 7.0 (stat.)
Observed : 62 ($+1.65\sigma$ over background)

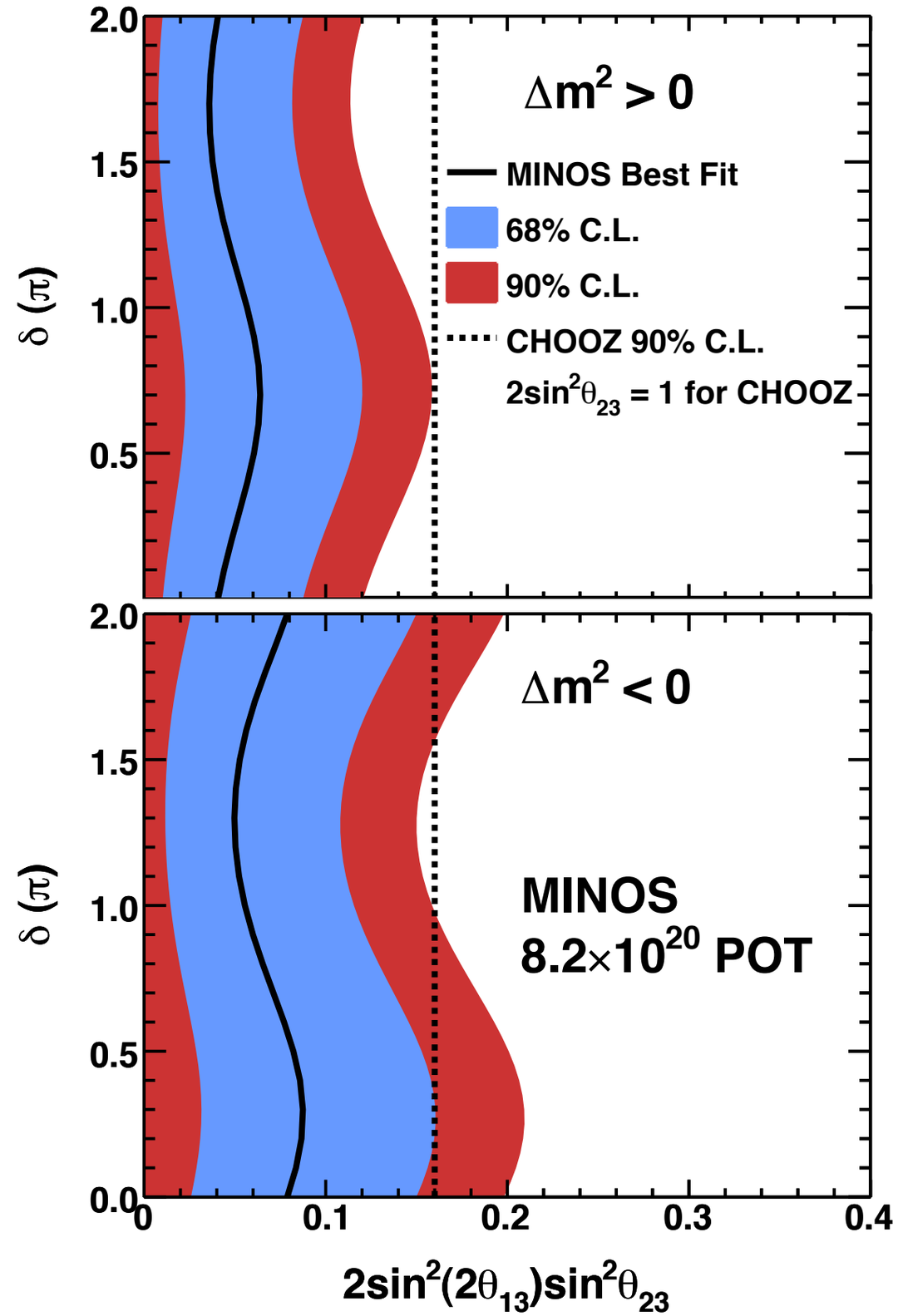


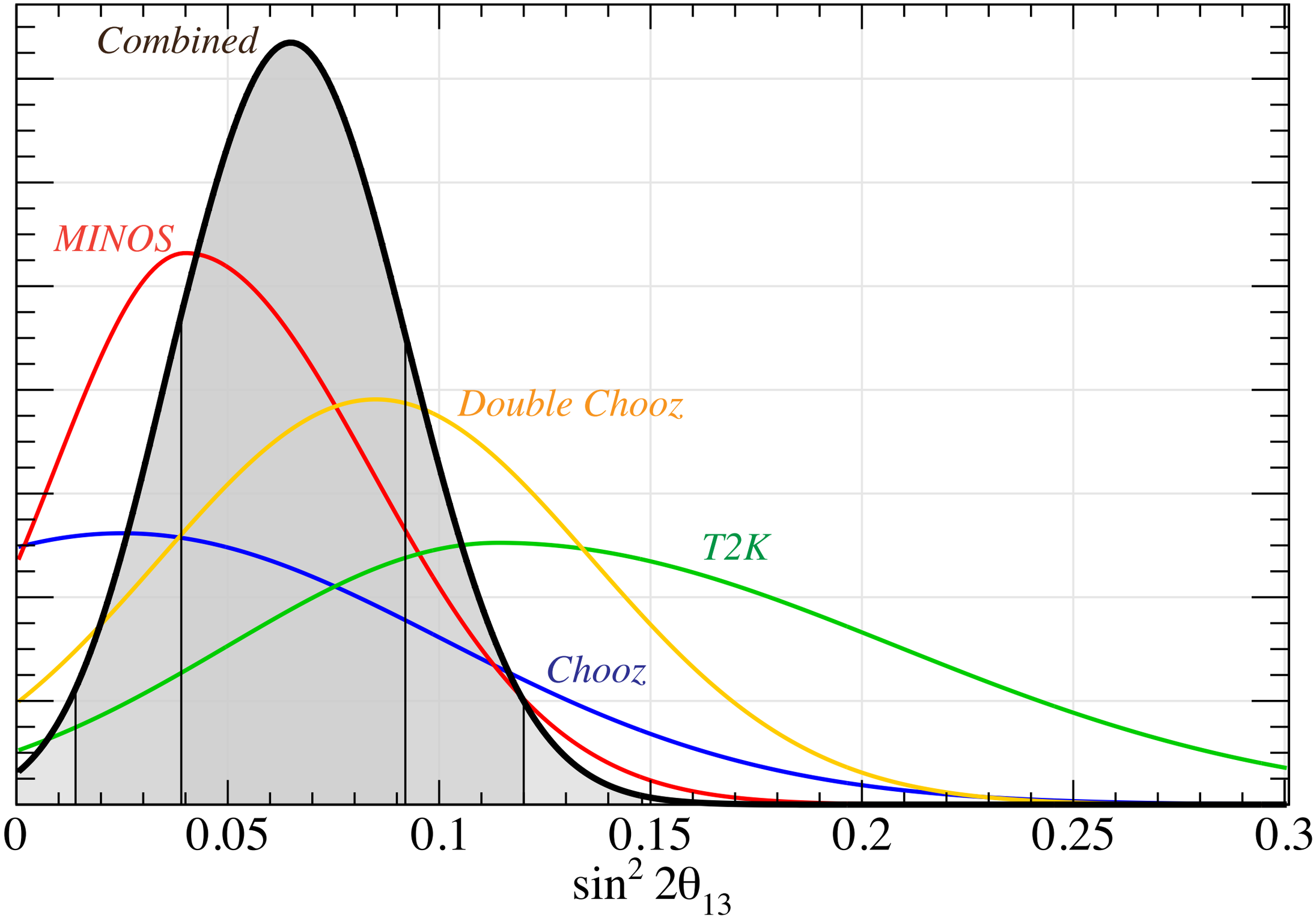


$\nu_\mu \rightarrow \nu_e$

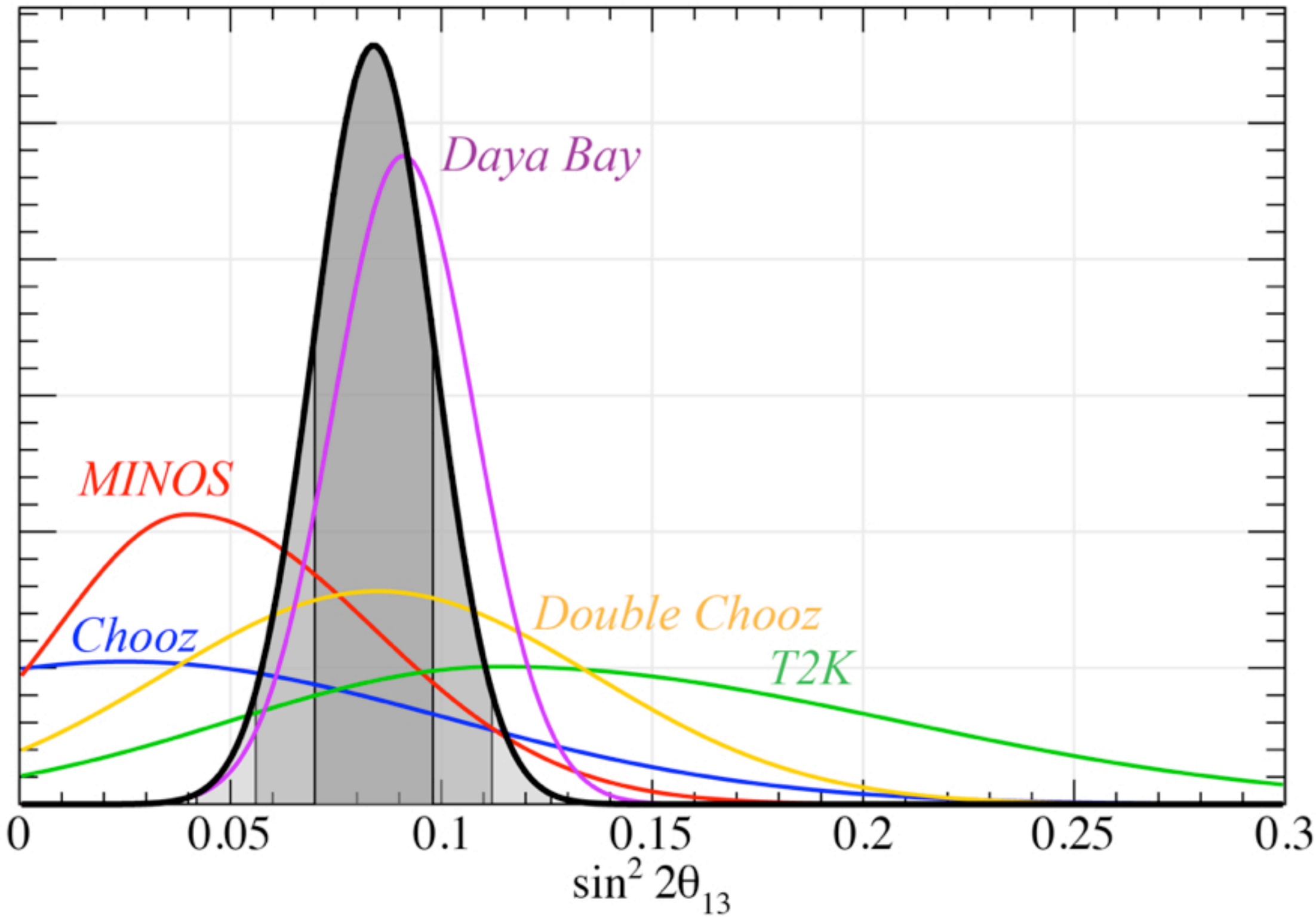
Phys.Rev.Lett. 107 (2011) 181802
arXiv:1108.0015 [hep-ex]



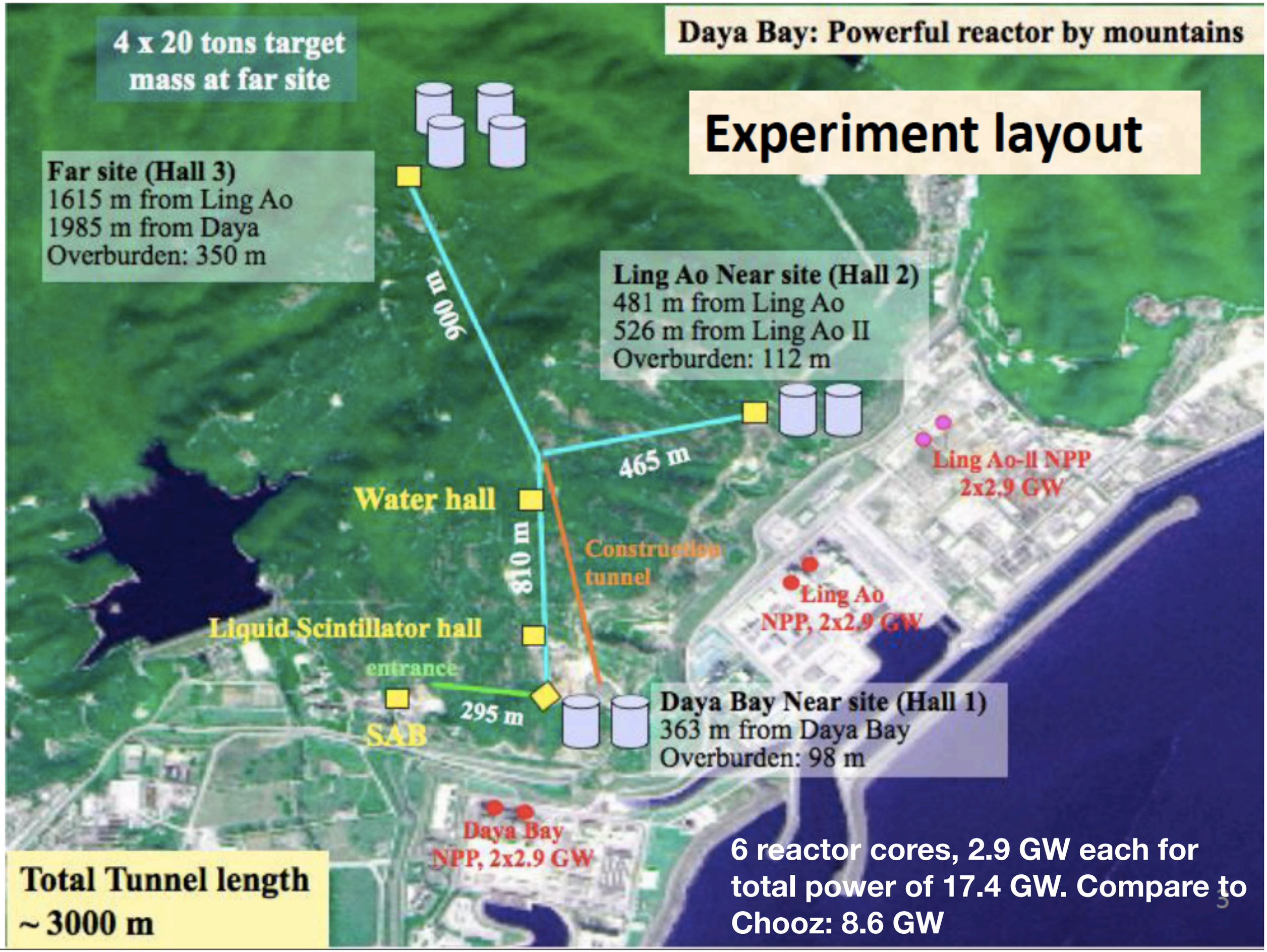




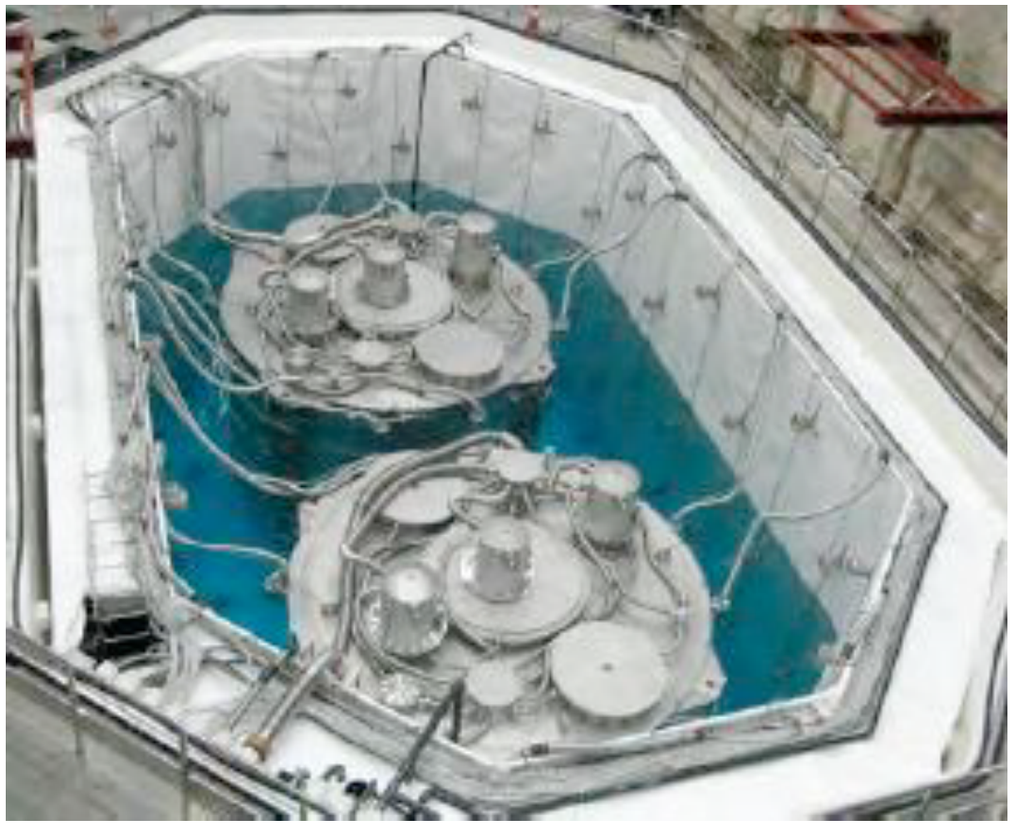
Ideogram of recent θ_{13} results for normal hierarchy, $\delta_{CP}=0$, and maximal θ_{23}

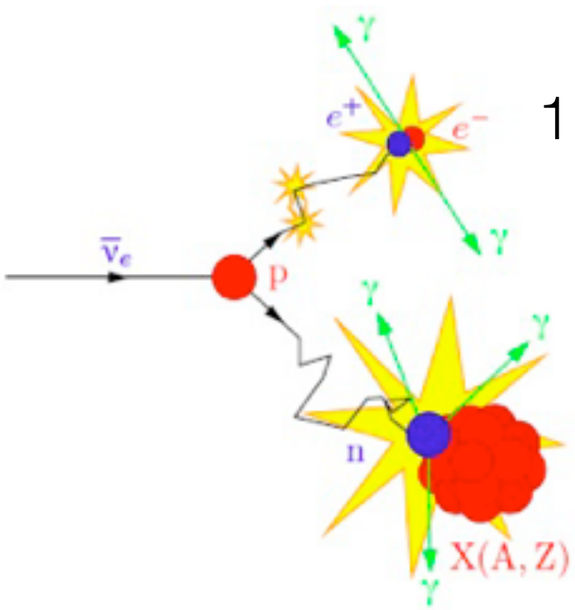


Ideogram of recent θ_{13} results for normal hierarchy, $\delta_{CP}=0$, and maximal θ_{23}


Daya Bay: Powerful reactor by mountains
4 x 20 tons target mass at far site
Experiment layout
Far site (Hall 3)
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m
900 m
Ling Ao Near site (Hall 2)
481 m from Ling Ao
526 m from Ling Ao II
Overburden: 112 m
465 m
Ling Ao-II NPP
2x2.9 GW
Water hall
810 m
Construction tunnel
Ling Ao
NPP, 2x2.9 GW
Liquid Scintillator hall
entrance
295 m
SAB
Daya Bay Near site (Hall 1)
363 m from Daya Bay
Overburden: 98 m
Daya Bay
NPP, 2x2.9 GW
Total Tunnel length
~ 3000 m
6 reactor cores, 2.9 GW each for total power of 17.4 GW. Compare to Chooz: 8.6 GW

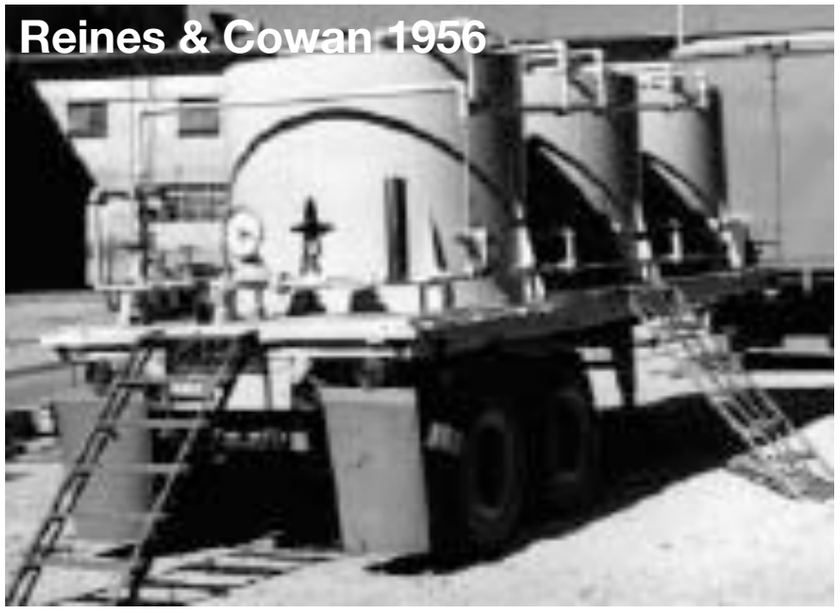
The Daya Bay Detectors



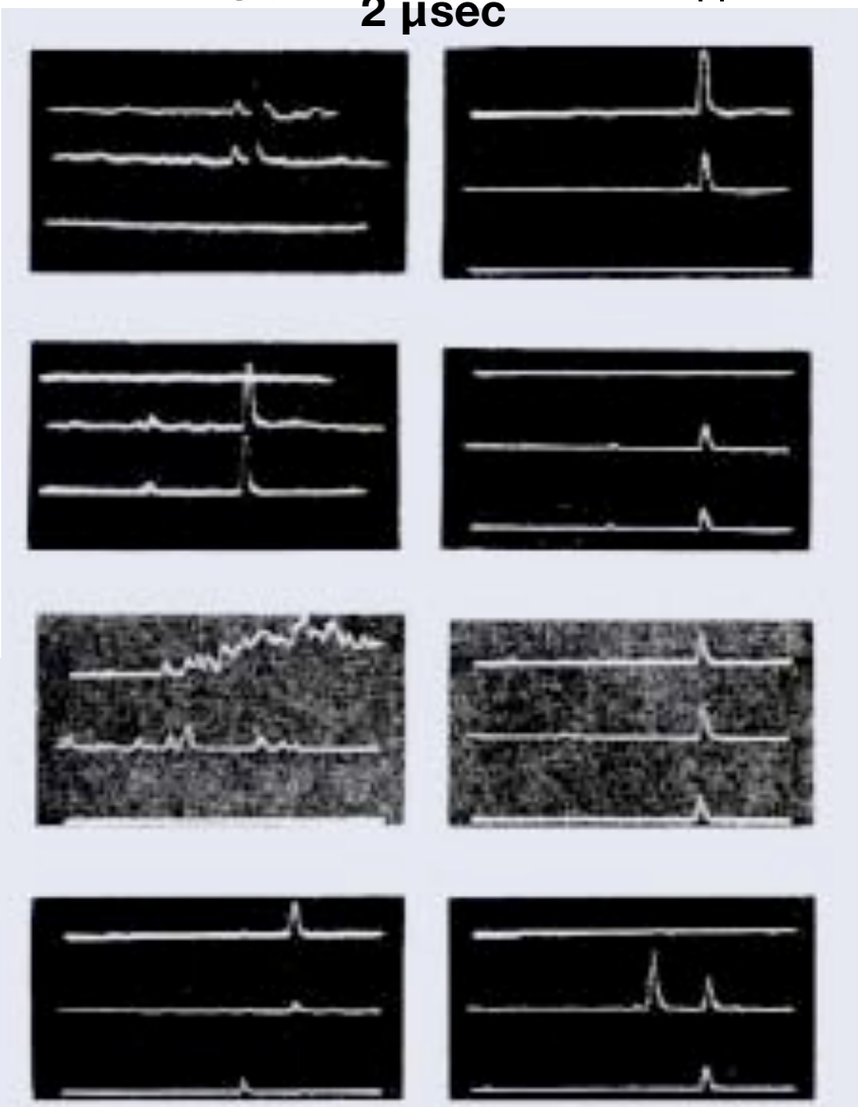


1.8 - 8 MeV prompt

8 MeV delayed

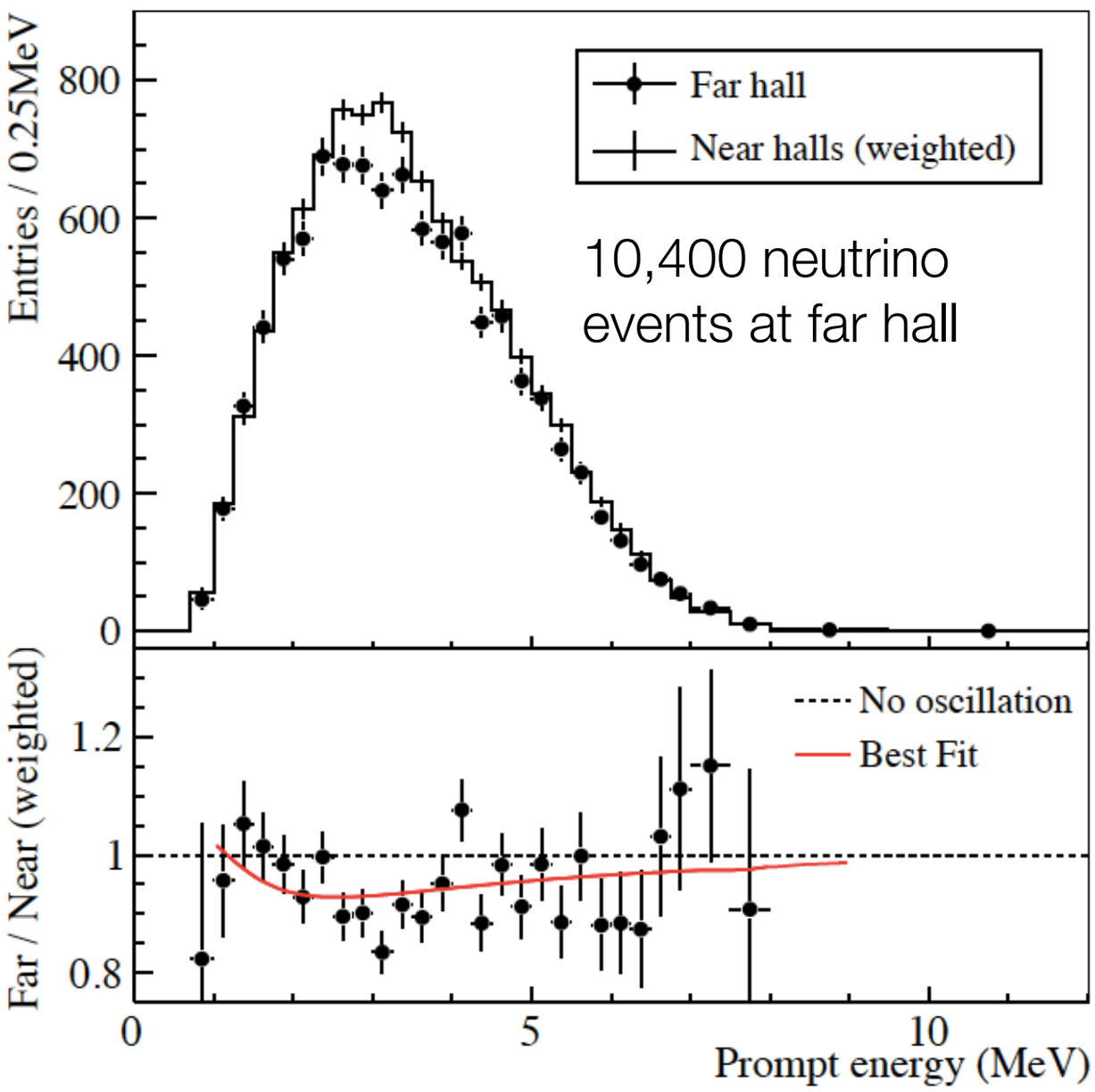


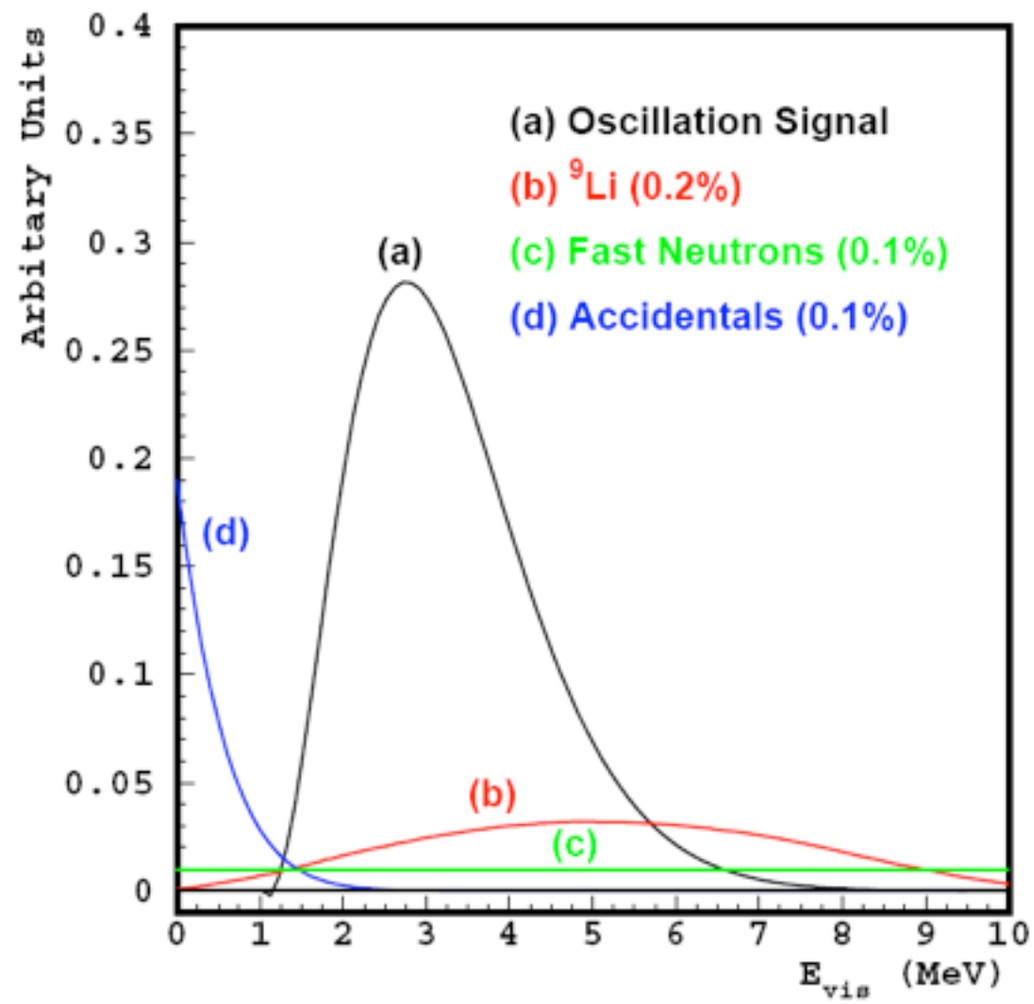
e+ ⟵ 2 μsec ⟶ n



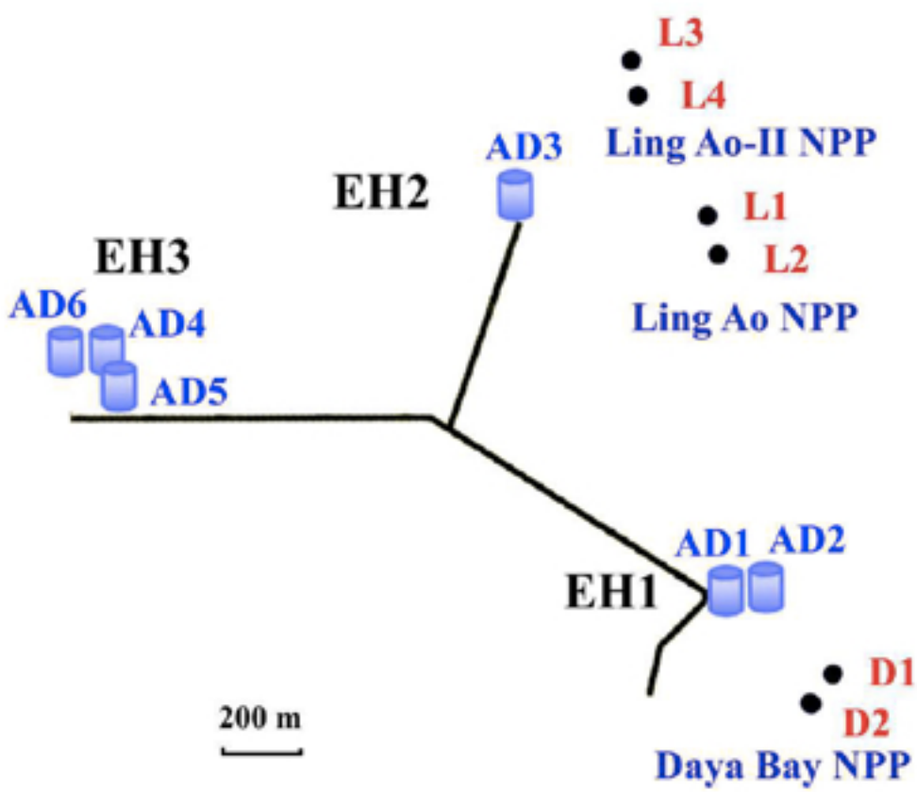
Los Alamos Science, Number

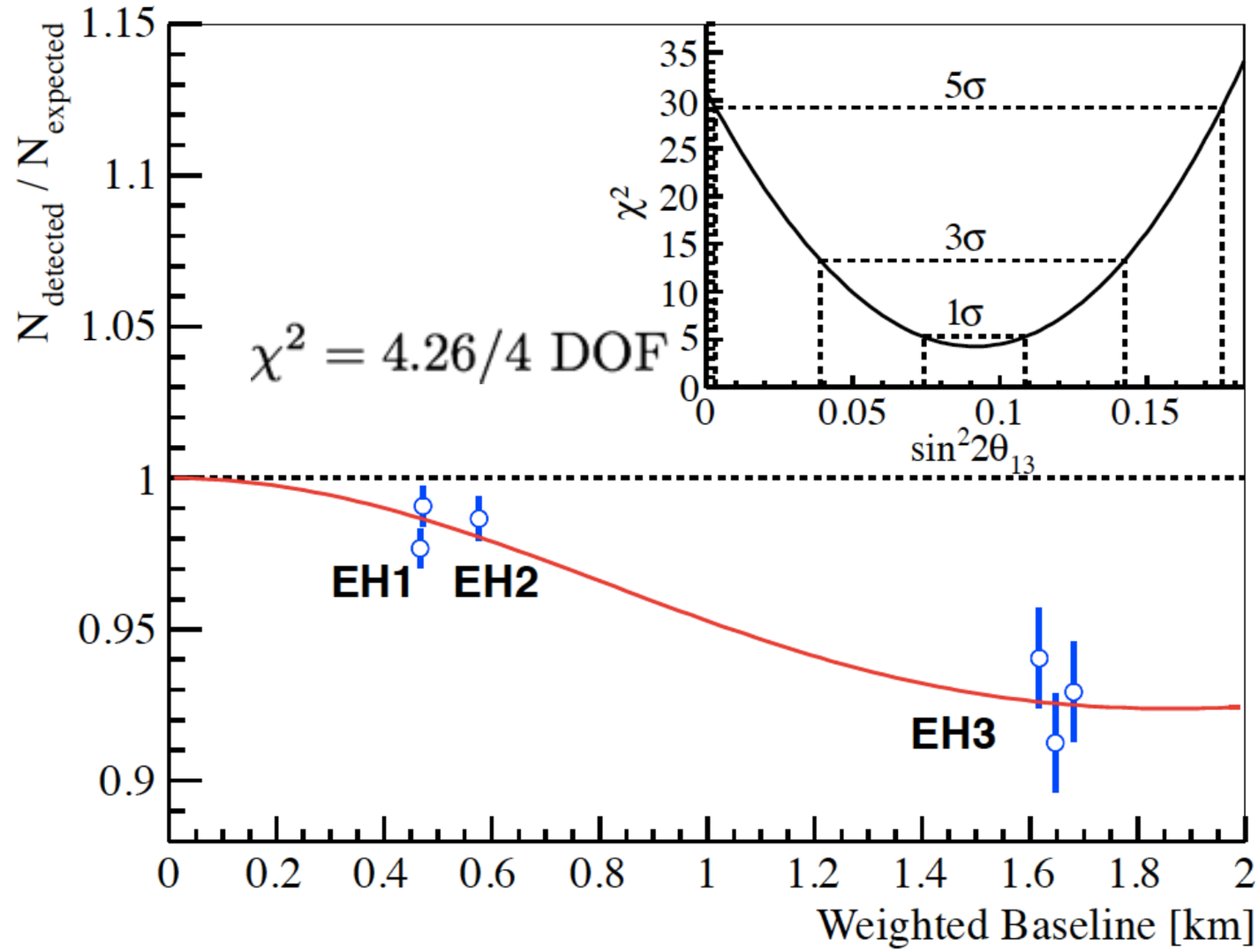
Neutrino candidates





Daya Bay Rate Measurements

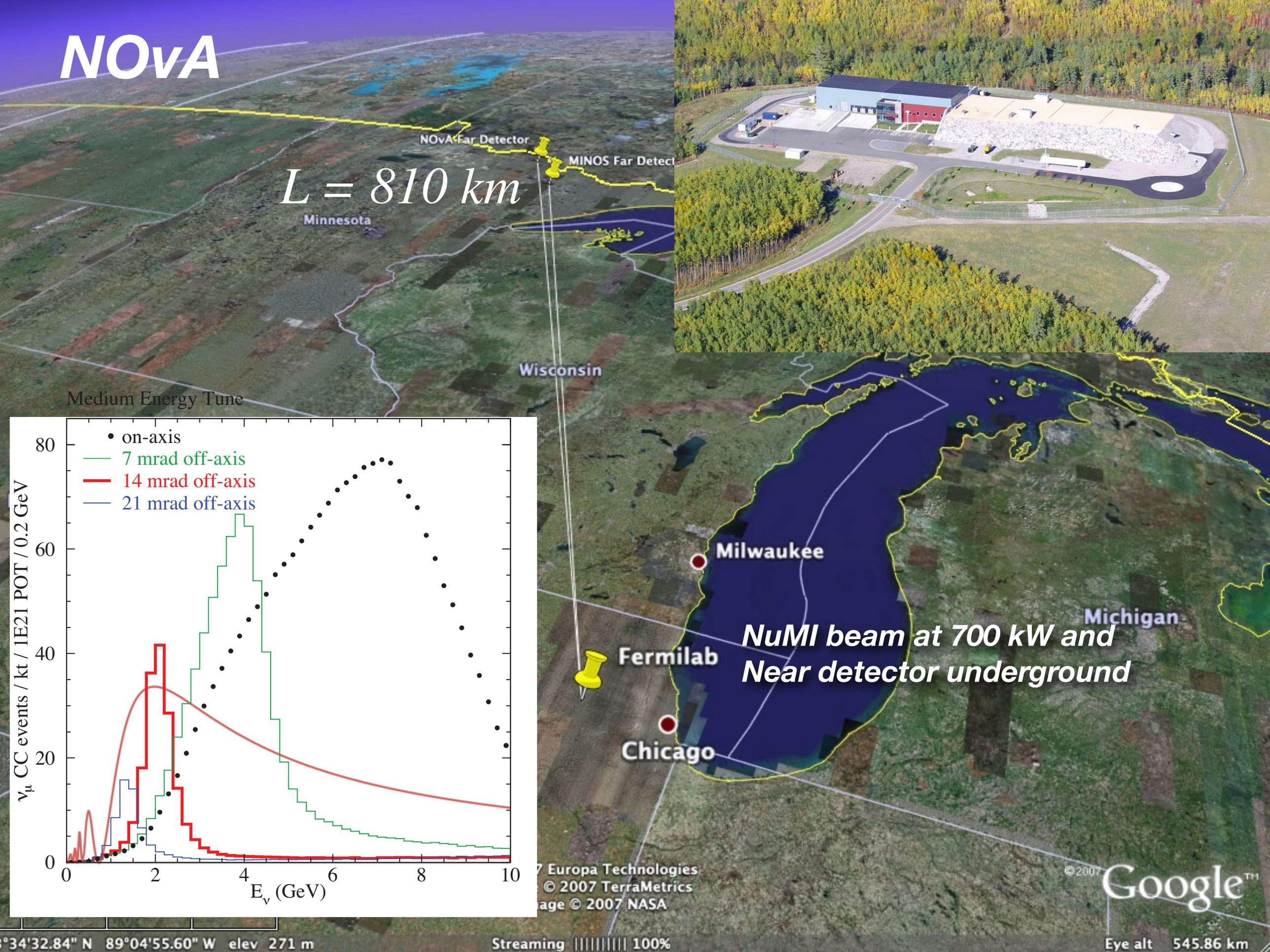


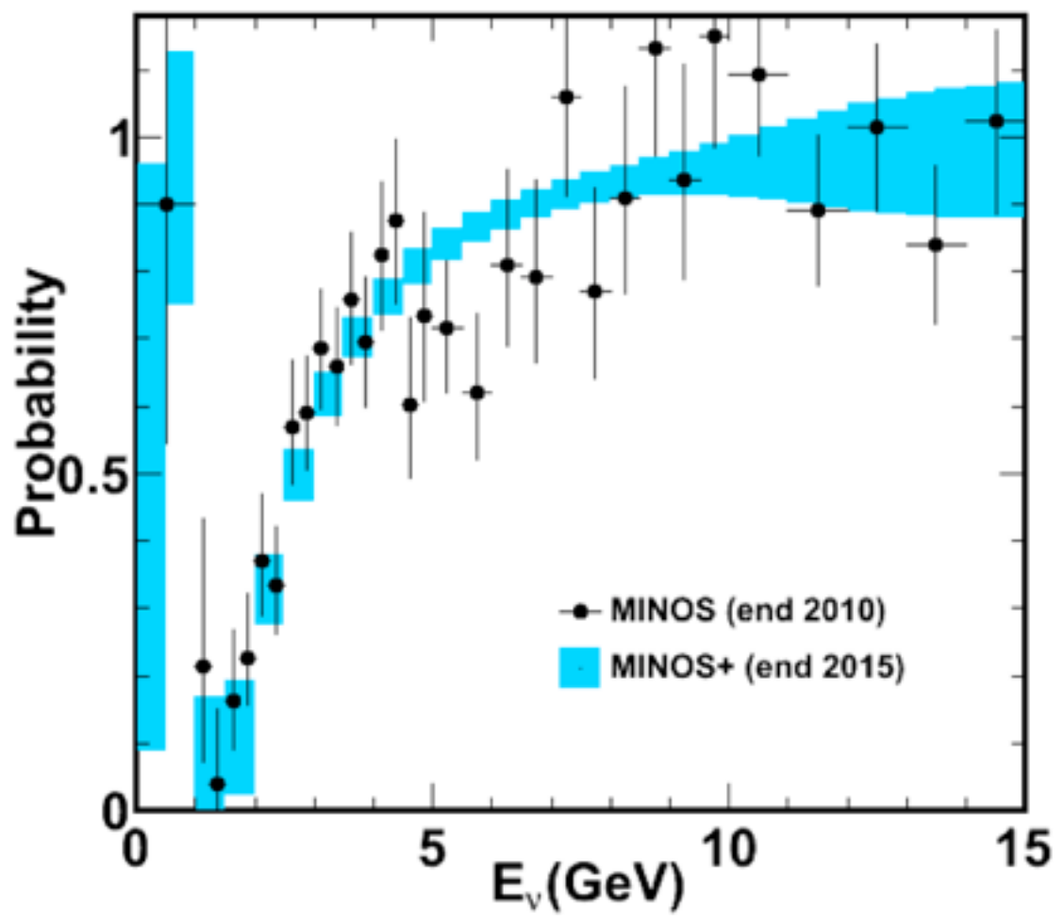


$$P(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2(2\theta_{13}) \sin^2\left(1.27\Delta m^2_{32}[\mathrm{eV}^2]\frac{L\ [\mathrm{m}]}{E\ [\mathrm{MeV}]}\right) + \sin^2(2\theta_{23})\cos^4(\theta_{13})\sin^2\left(1.27\Delta m^2_{21}\ [\mathrm{eV}^2]\frac{L\ [\mathrm{m}]}{E\ [\mathrm{MeV}]}\right)$$

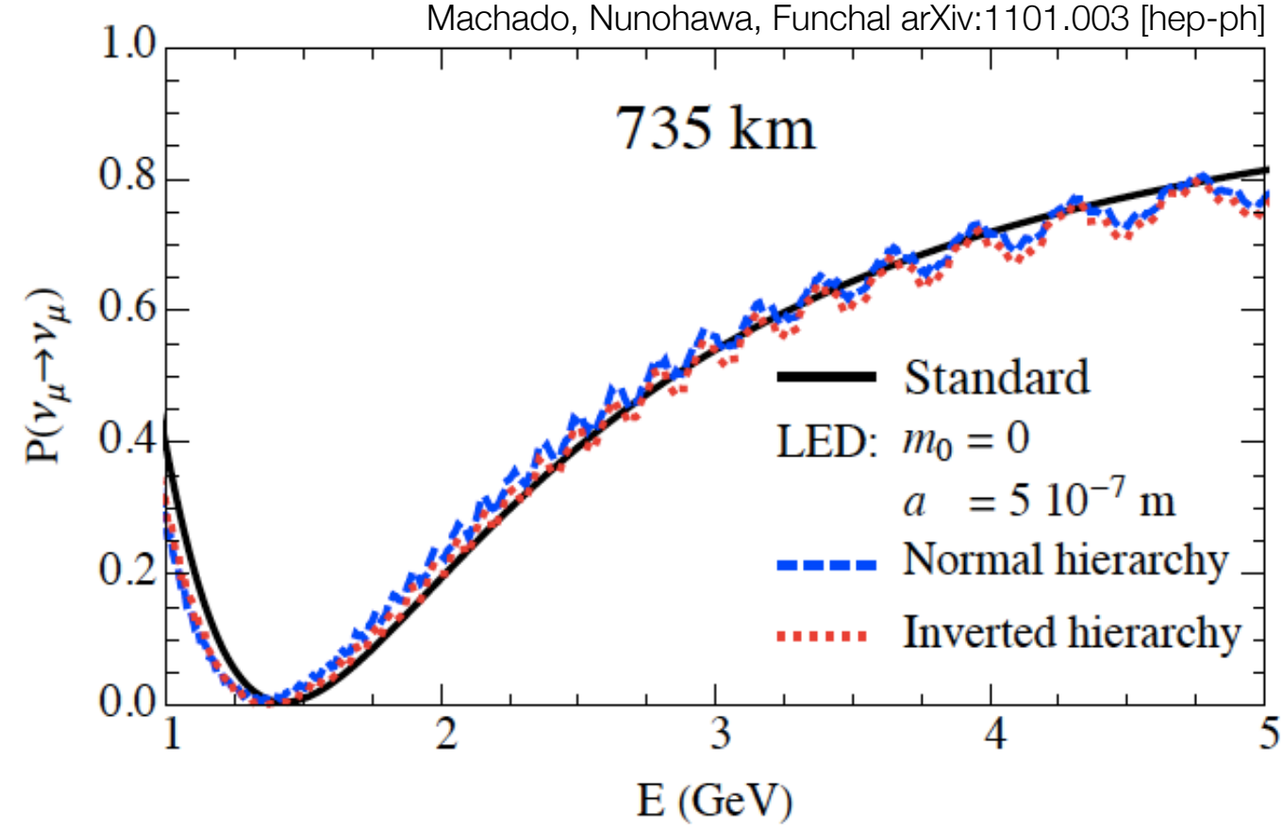
$$\sin^2 2\theta_{13} = 0.092 \pm 0.016\ (\mathrm{stat.}) \pm 0.005\ (\mathrm{syst.})$$

NOvA


NOvA Far Detector
MINOS Far Detect
L = 810 km
Minnesota
Wisconsin
Milwaukee
Michigan
Fermilab
Chicago
NuMI beam at 700 kW and
Near detector underground
Medium Energy Tune
on-axis
7 mrad off-axis
14 mrad off-axis
21 mrad off-axis
ν_μ CC events / kt / 1E21 POT / 0.2 GeV
E_ν (GeV)
0
20
40
60
80
0
2
4
6
8
10
© 2007 TerraMetrics
© 2007 NASA
Google
Streaming 100%
Eye alt 545.86 km



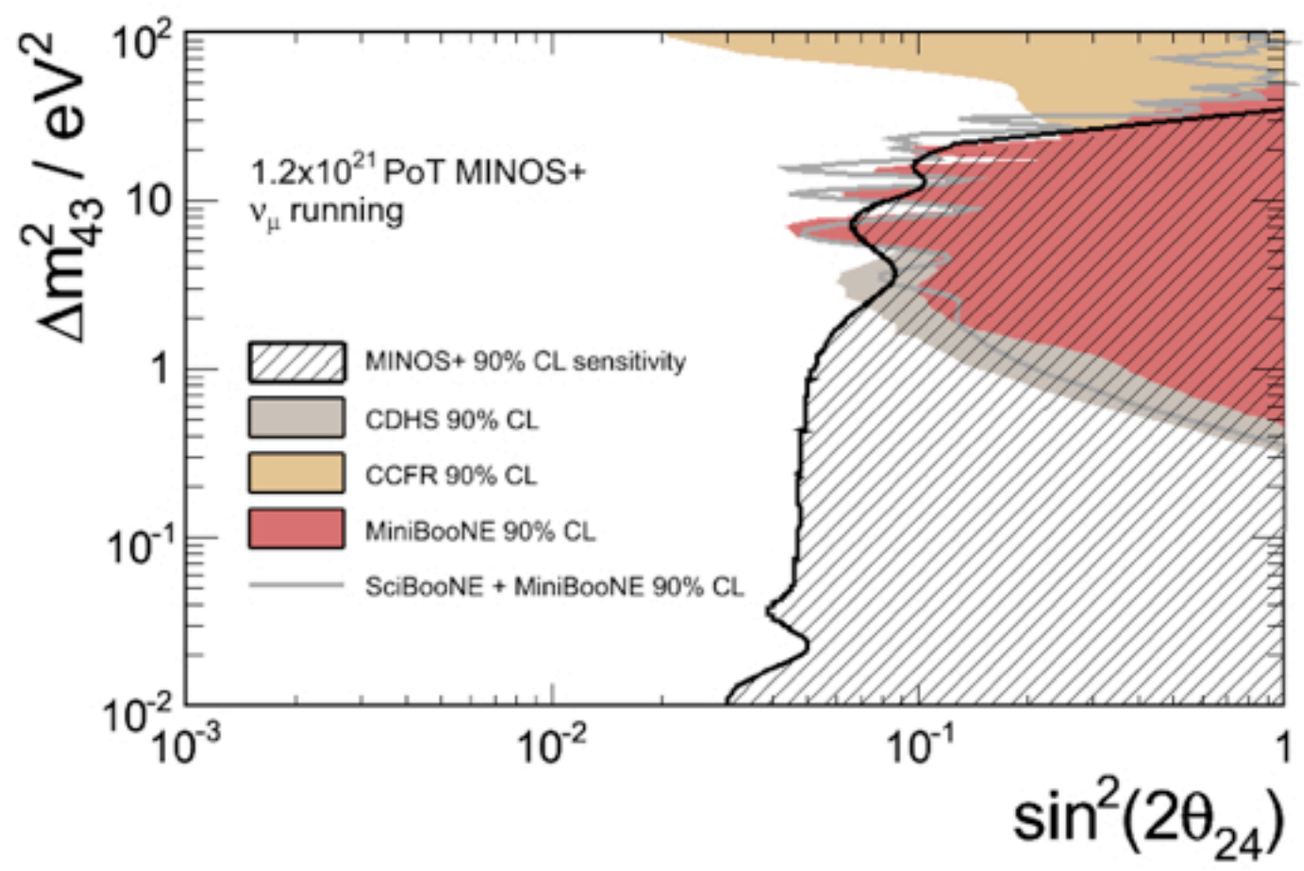
Machado, Nunohawa, Funchal arXiv:1101.003 [hep-ph]

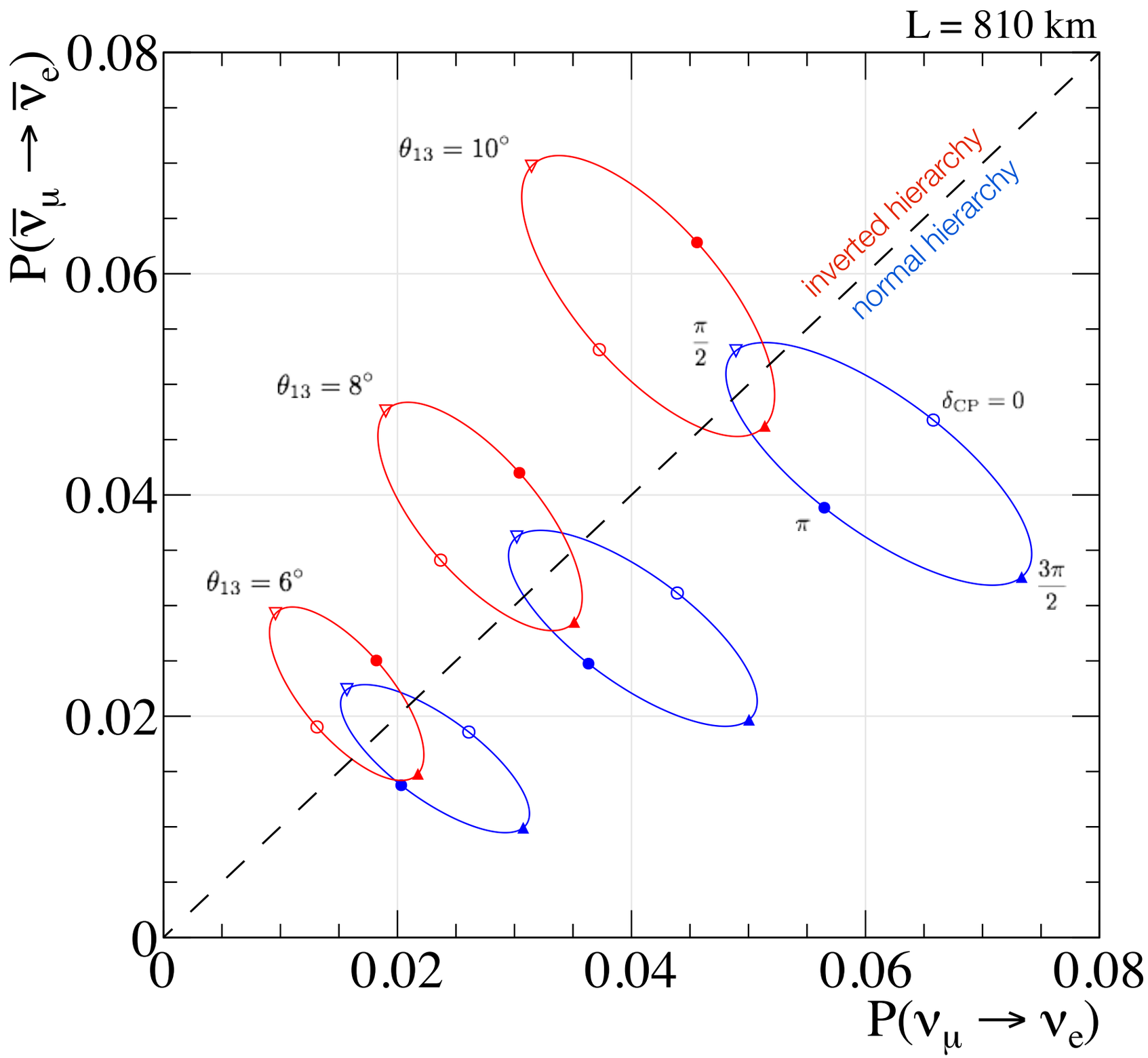


MINOS+

Running MINOS in the NOvA Era

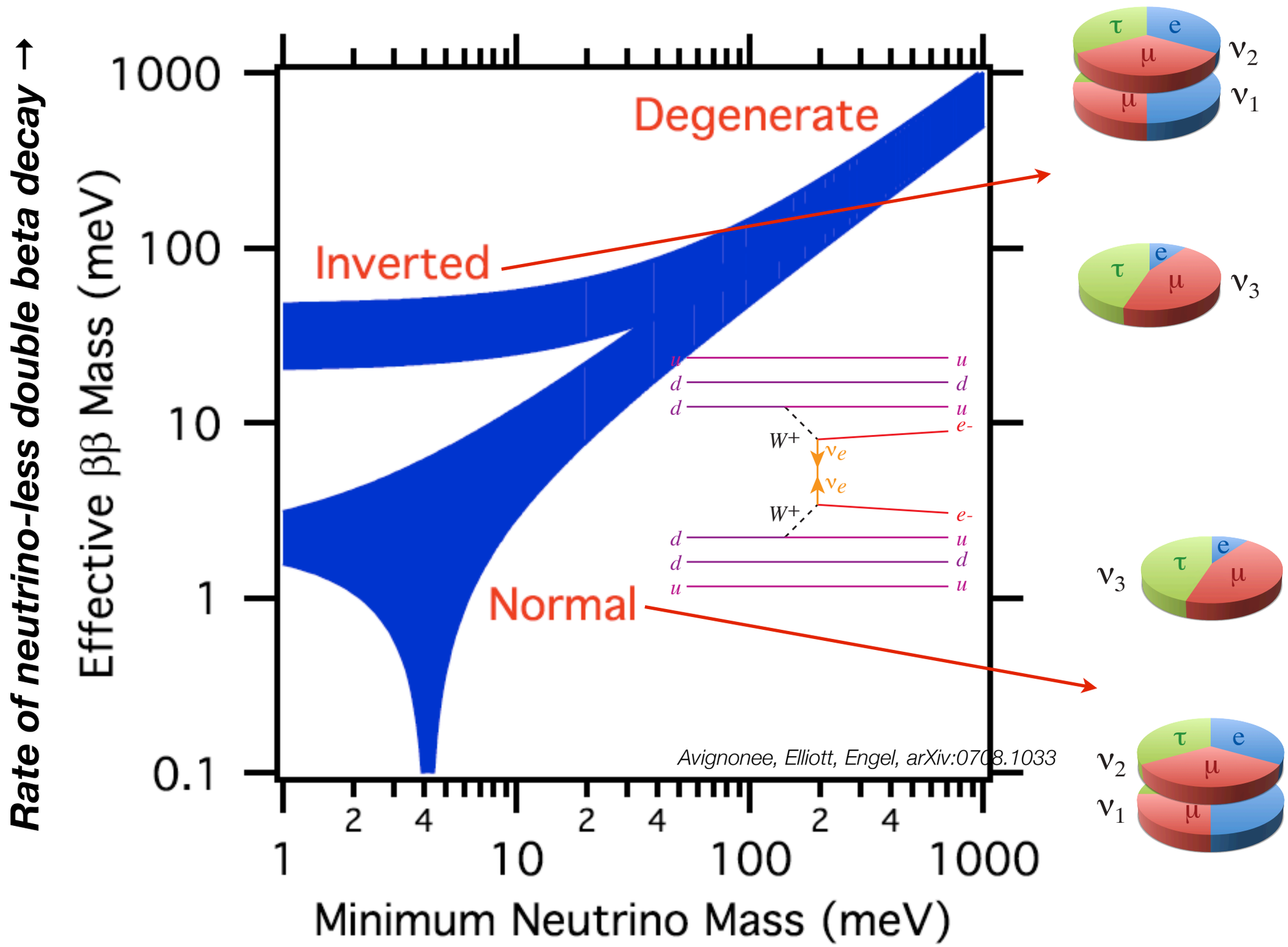
MINOS+ will use the high statistics of the NuMI mediun energy beam to explore oscillations at high energy.

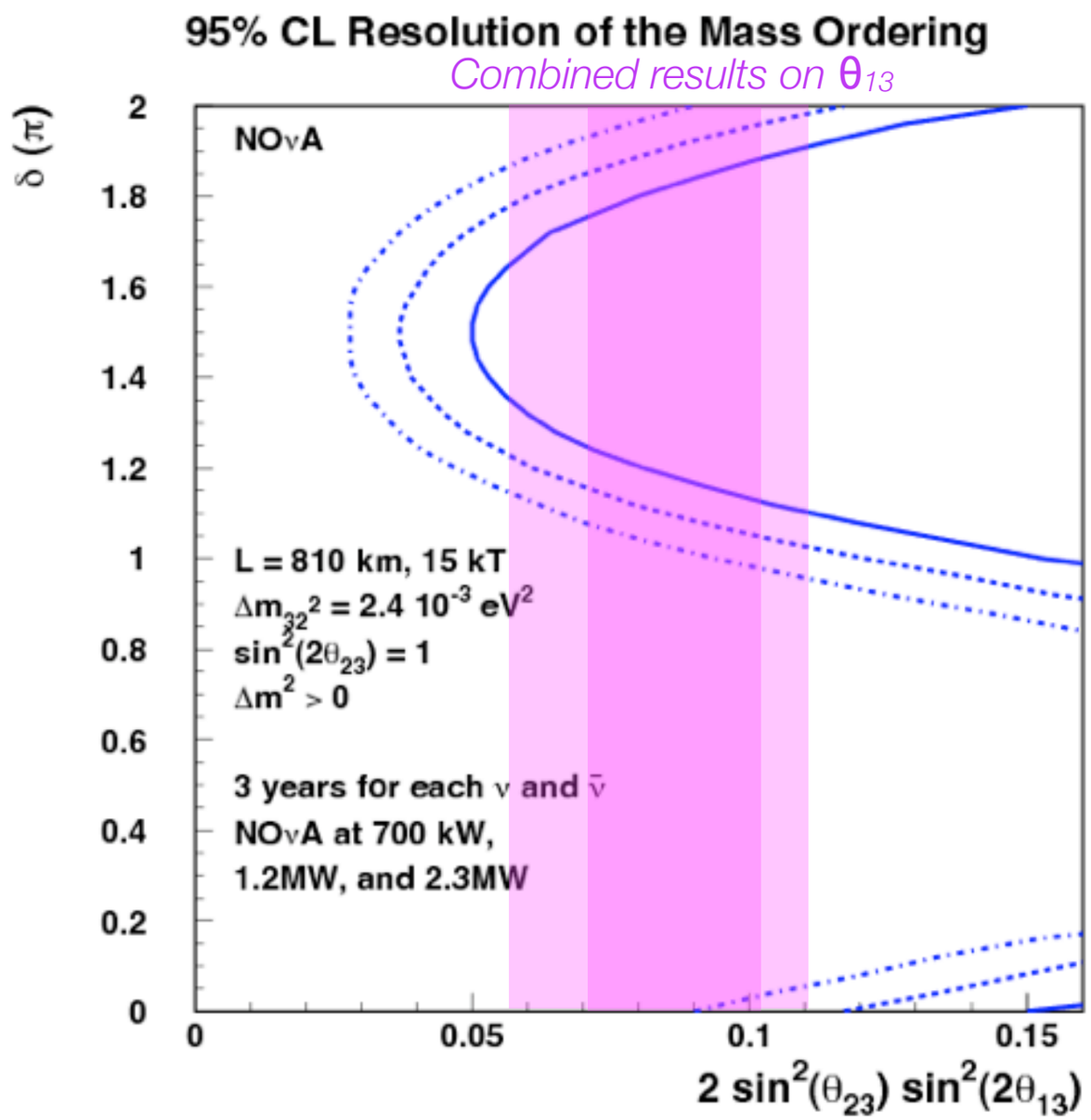


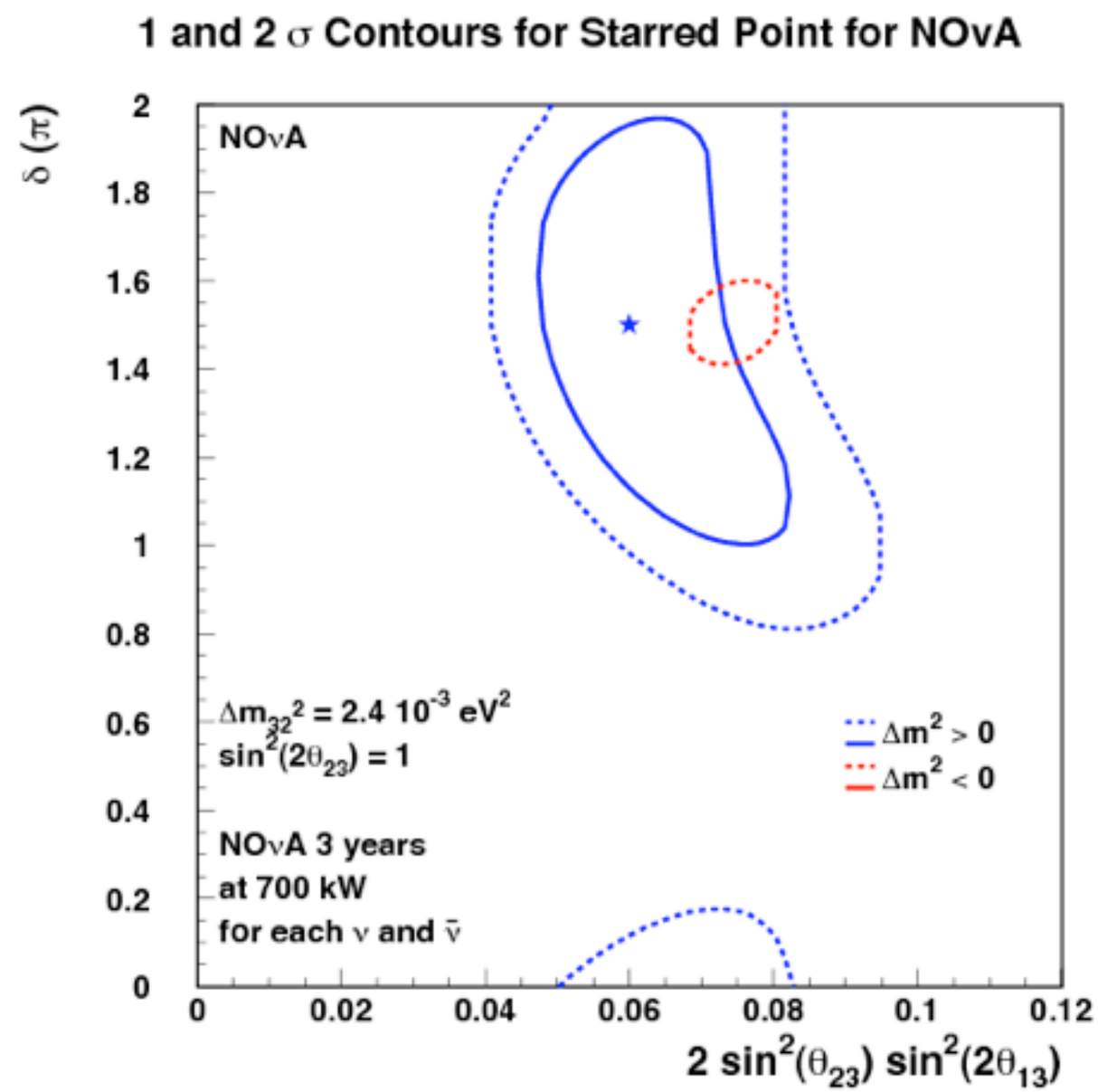


Neutrino oscillations at long baseline

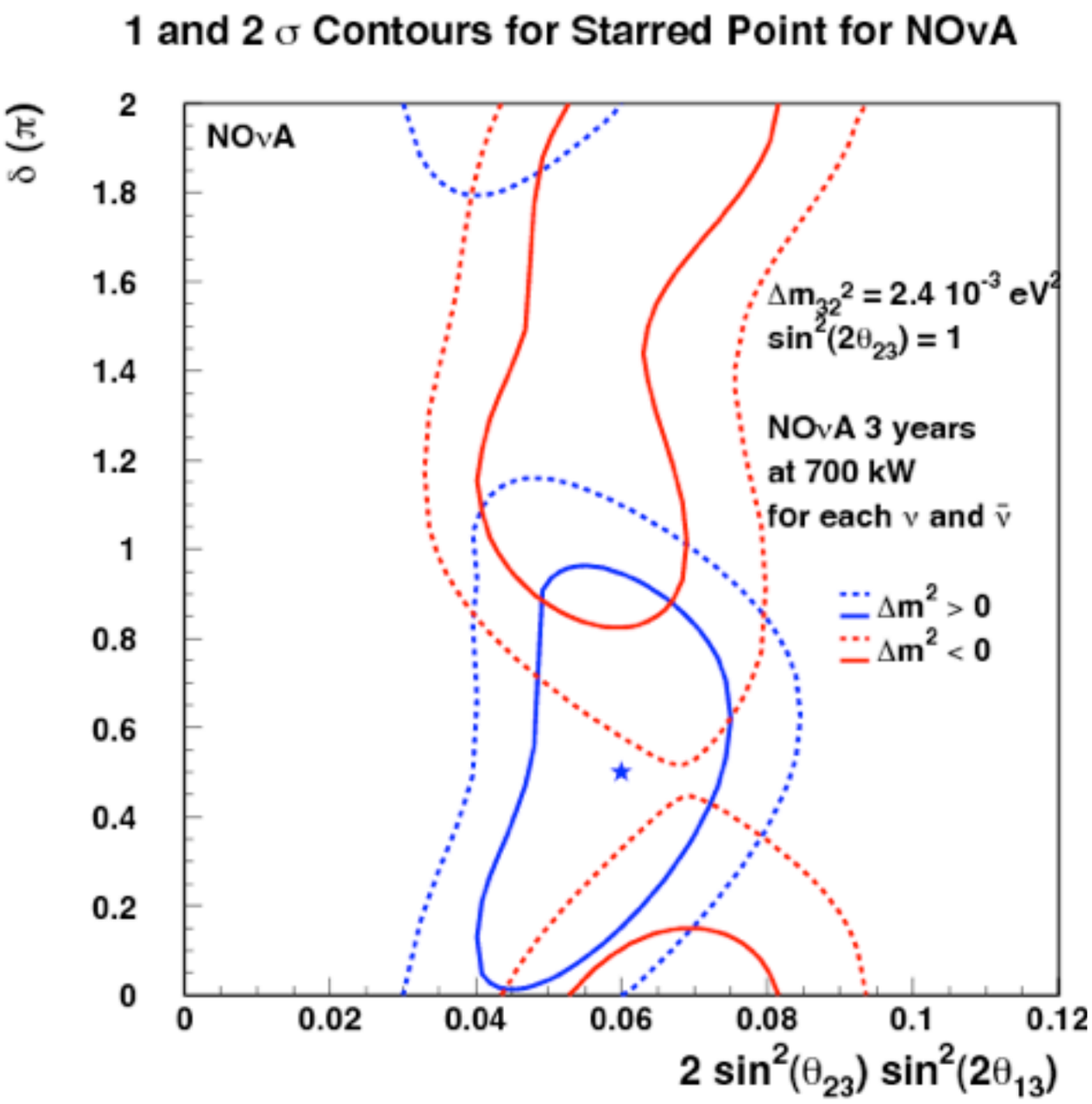
Mass hierarchy and the nature of the neutrino

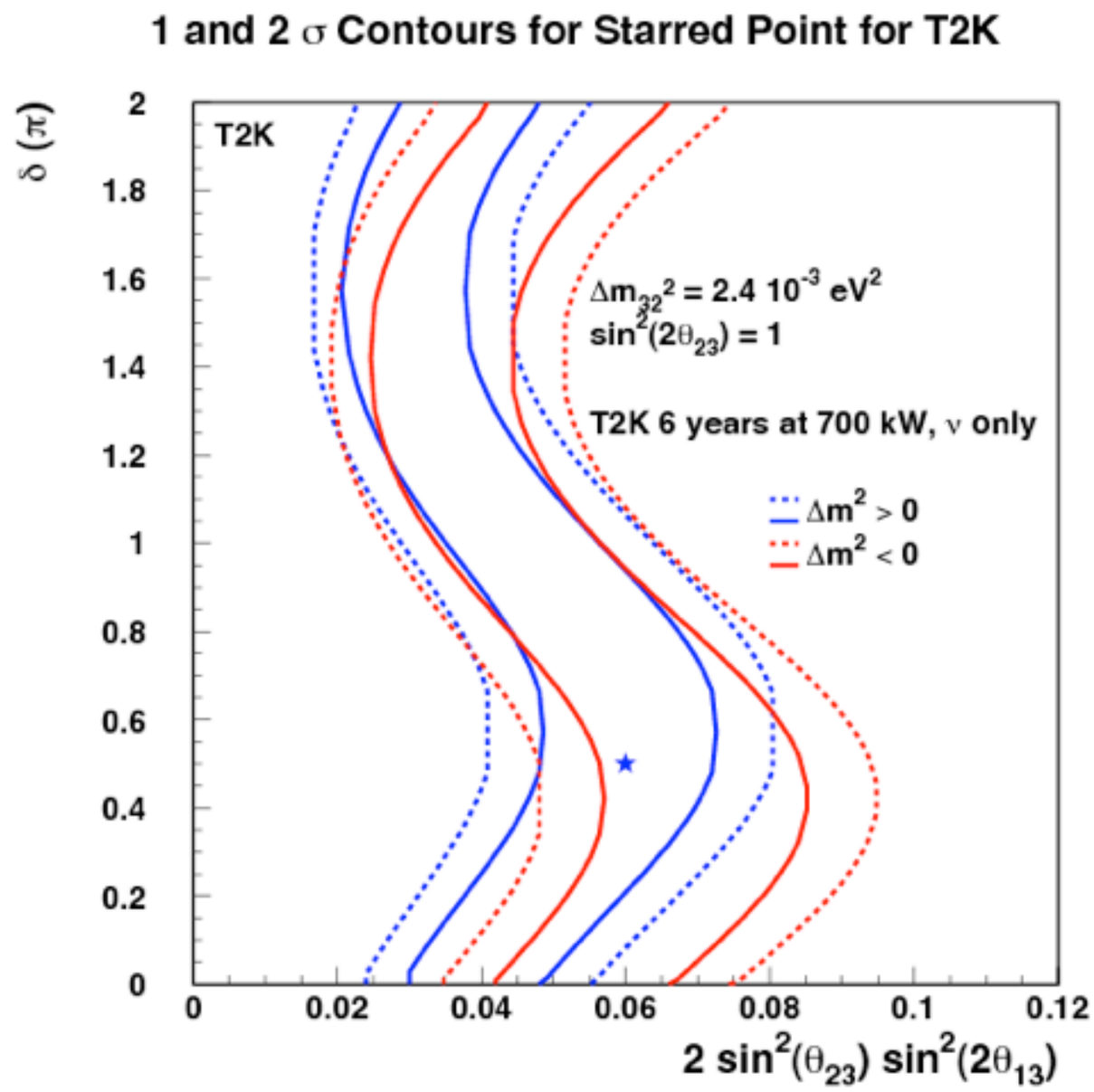






Resolution of the mass hierarchy and measurement of δ_{CP}



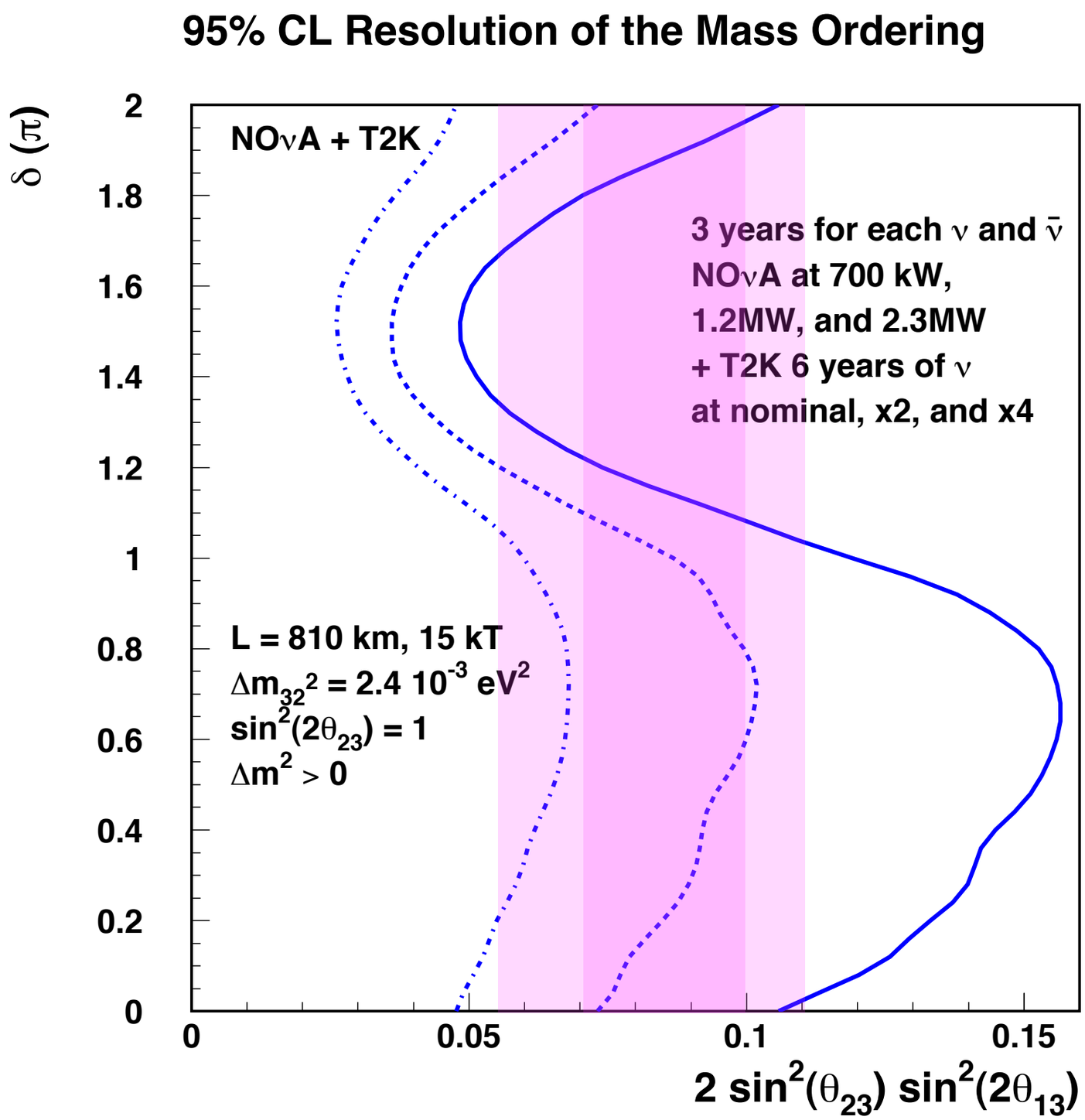


contours assuming normal hierarchy /contours assuming inverted hierarchy

Combining NOvA with T2K in worst case

As NOvA runs both neutrinos and antineutrinos its contours are relatively straight. T2K's contours trace an "S" which intersects NOvA's contours in the lower part of the plot.

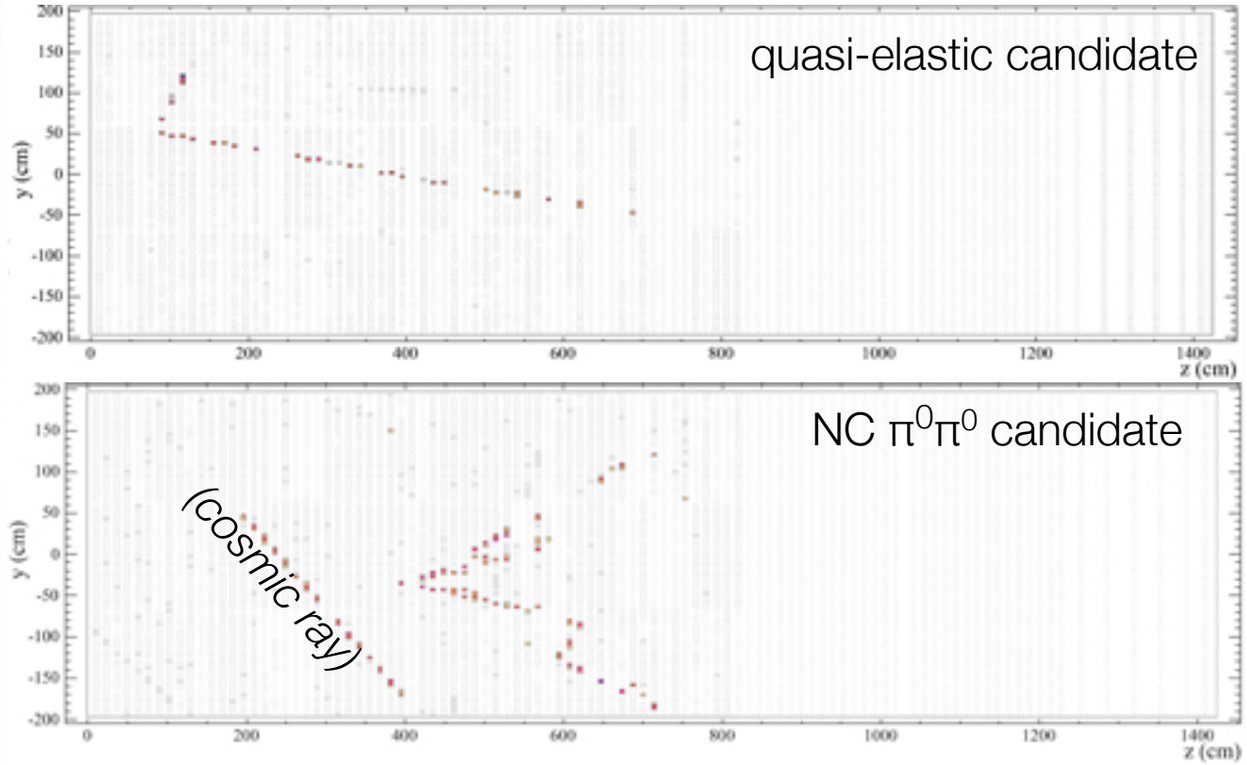
Combining NOvA with T2K



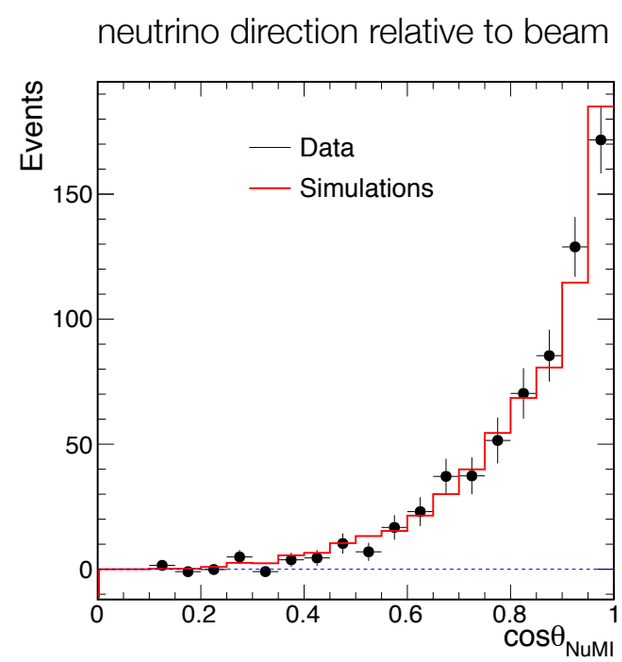
- In worst case hierarchy + δ_{CP} combination, NOvA + T2K taken together can have hierarchy reach down to 0.1 if they can double their planned exposures.

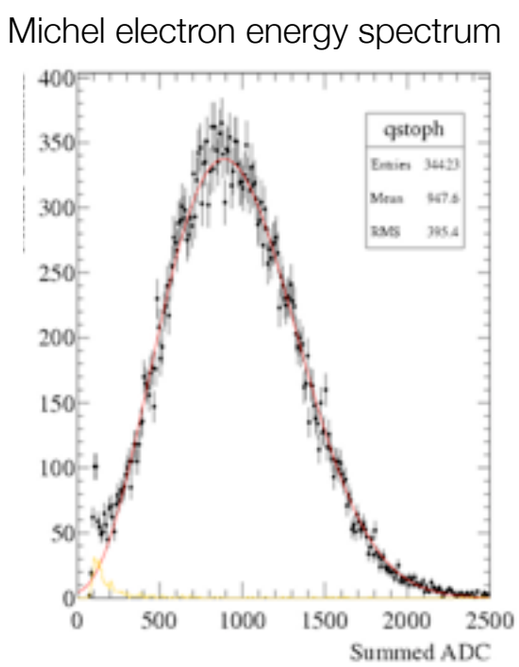
- In case of NOvA this could be achieved with a 5 kt liquid argon detector

NOvA Prototype Detector

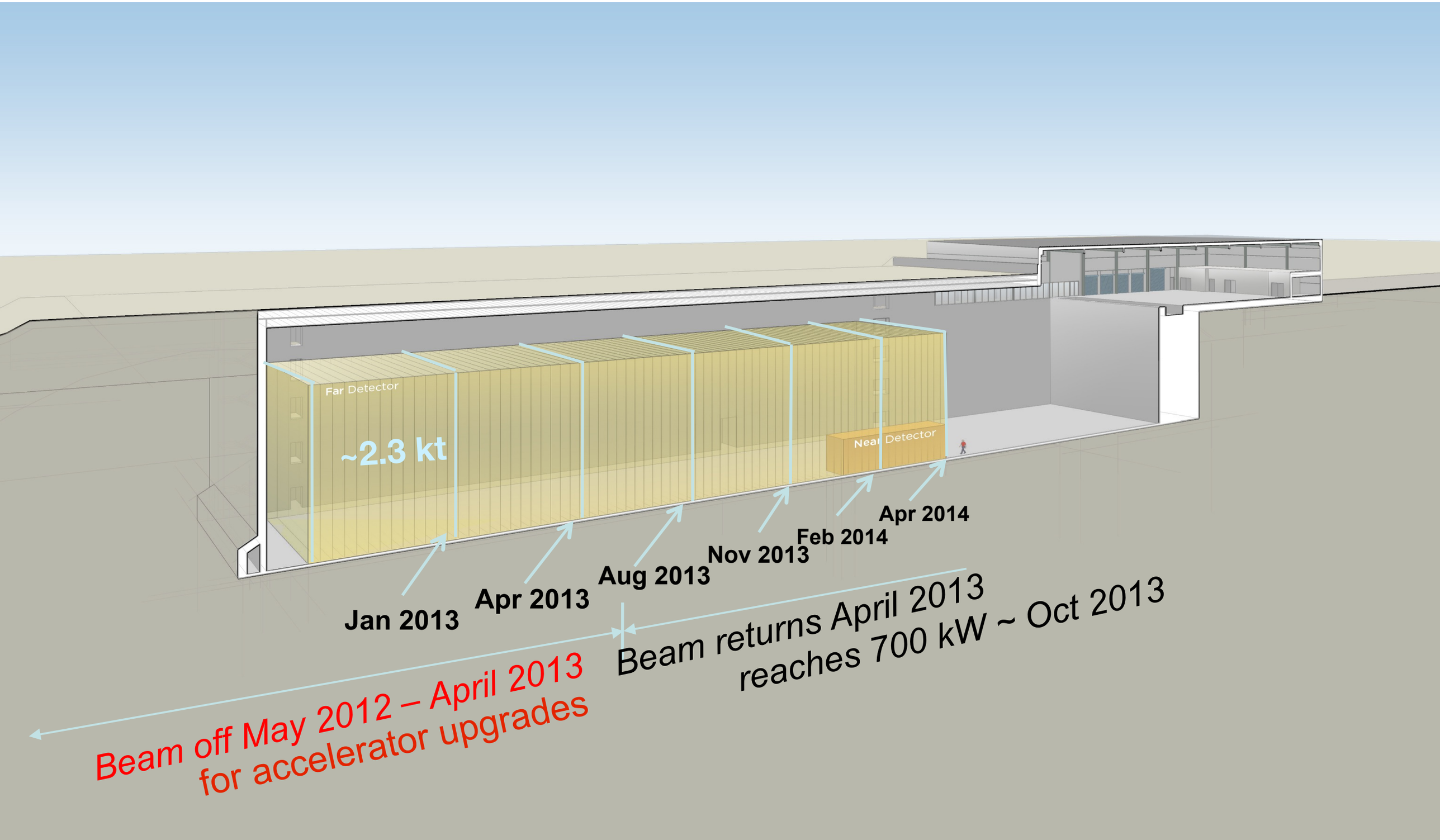


Events from the NuMI beam seen at 110 mrad

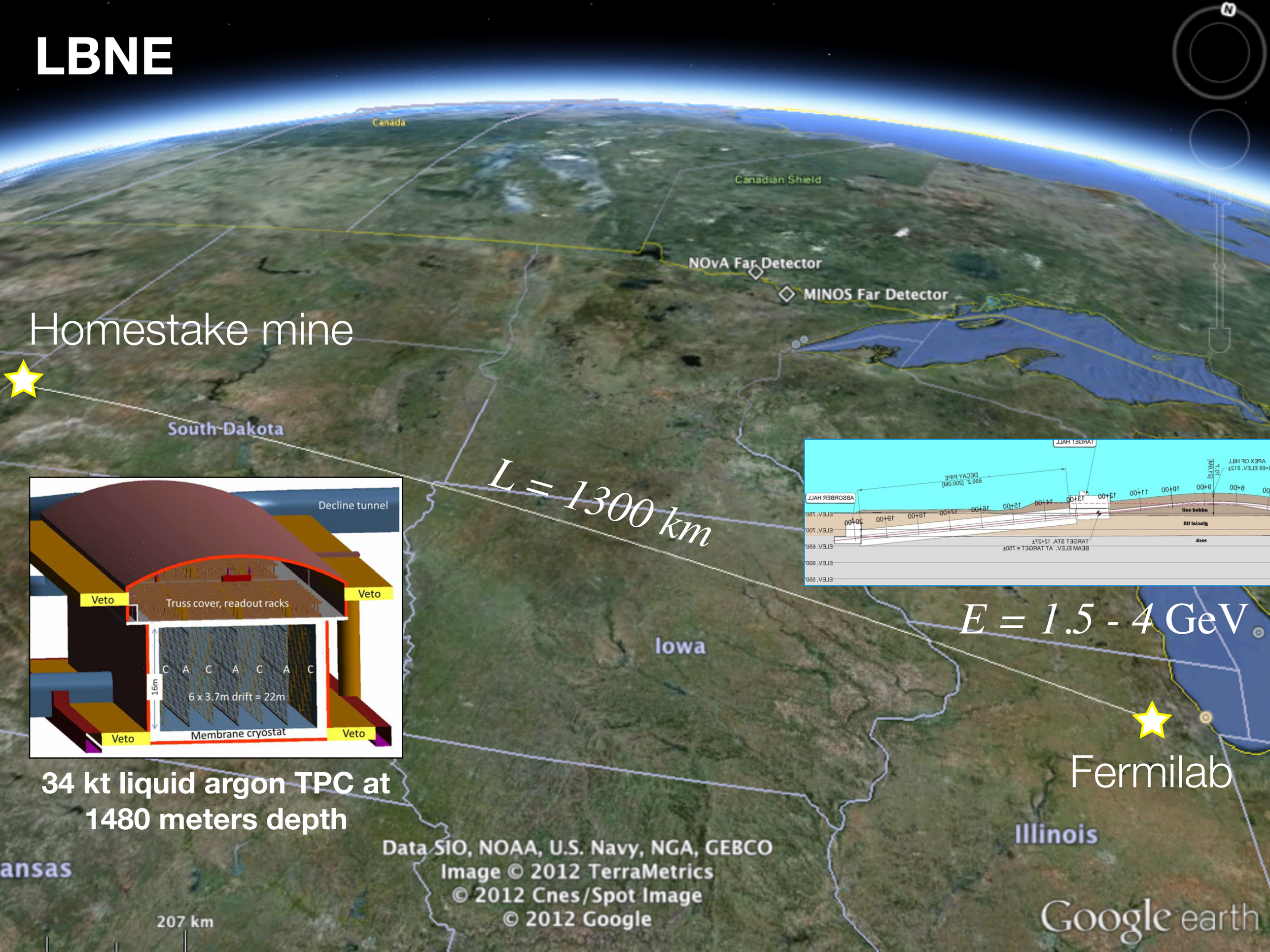




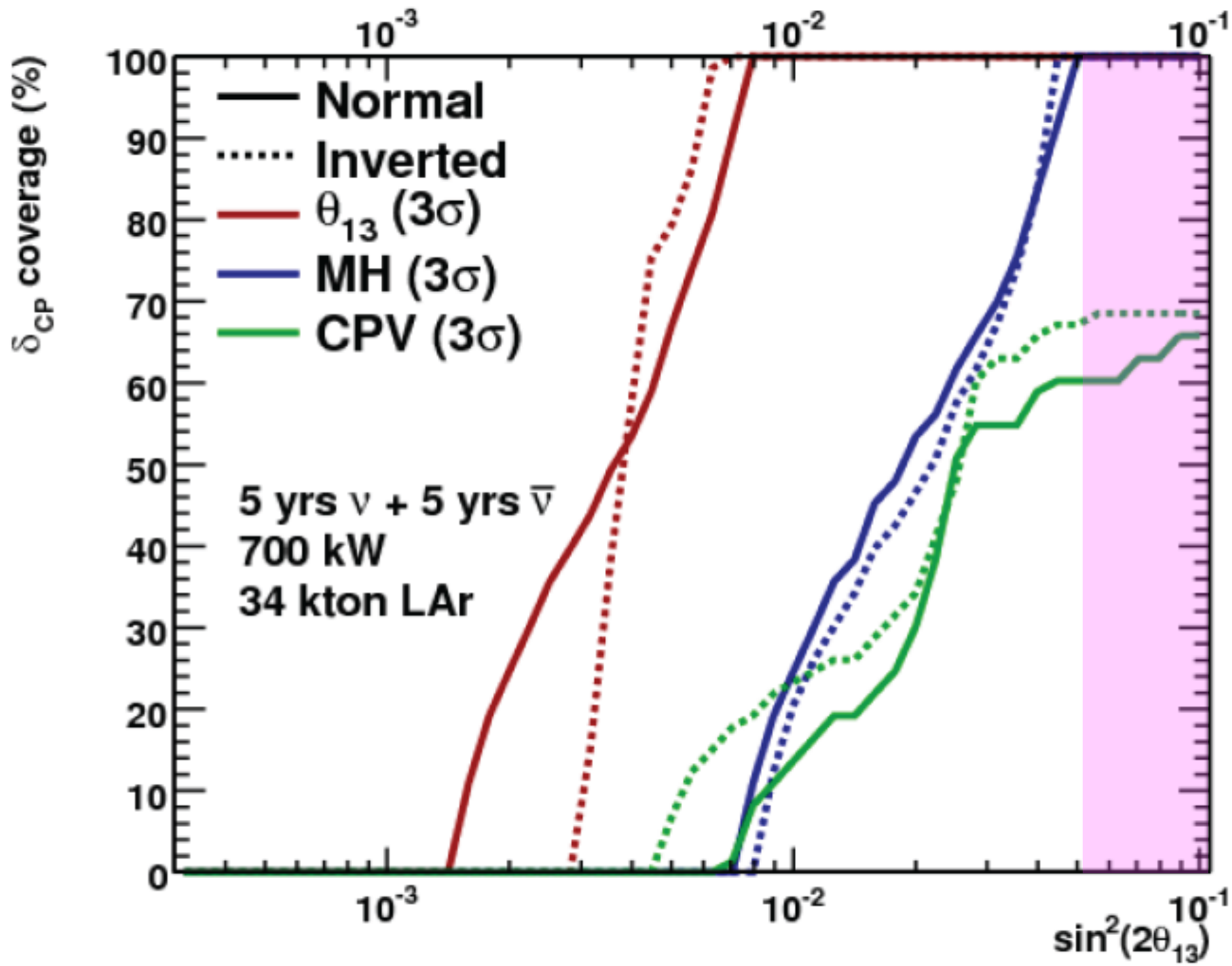
NOvA construction schedule



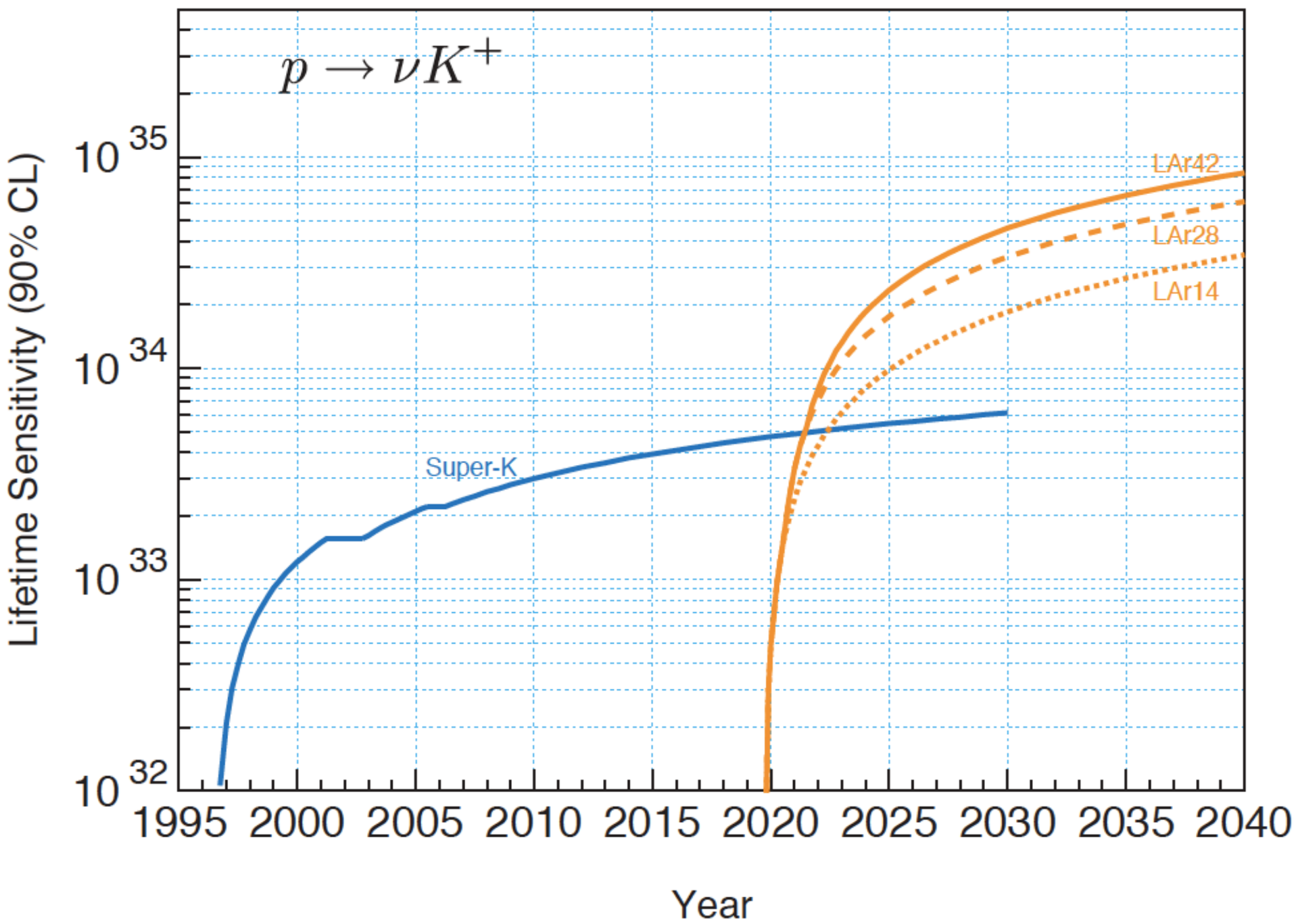
LBNE


Canada
Canadian Shield
NOvA Far Detector
MINOS Far Detector
Homestake mine
South Dakota
L = 1300 km
Decline tunnel
Veto
Truss cover, readout racks
Veto
C A C A C A C
16m
6 x 3.7m drift = 22m
Veto
Membrane cryostat
Veto
34 kt liquid argon TPC at
1480 meters depth
E = 1.5 - 4 GeV
Iowa
Fermilab
Illinois
ansas
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2012 TerraMetrics
© 2012 Cnes/Spot Image
© 2012 Google
207 km
Google earth

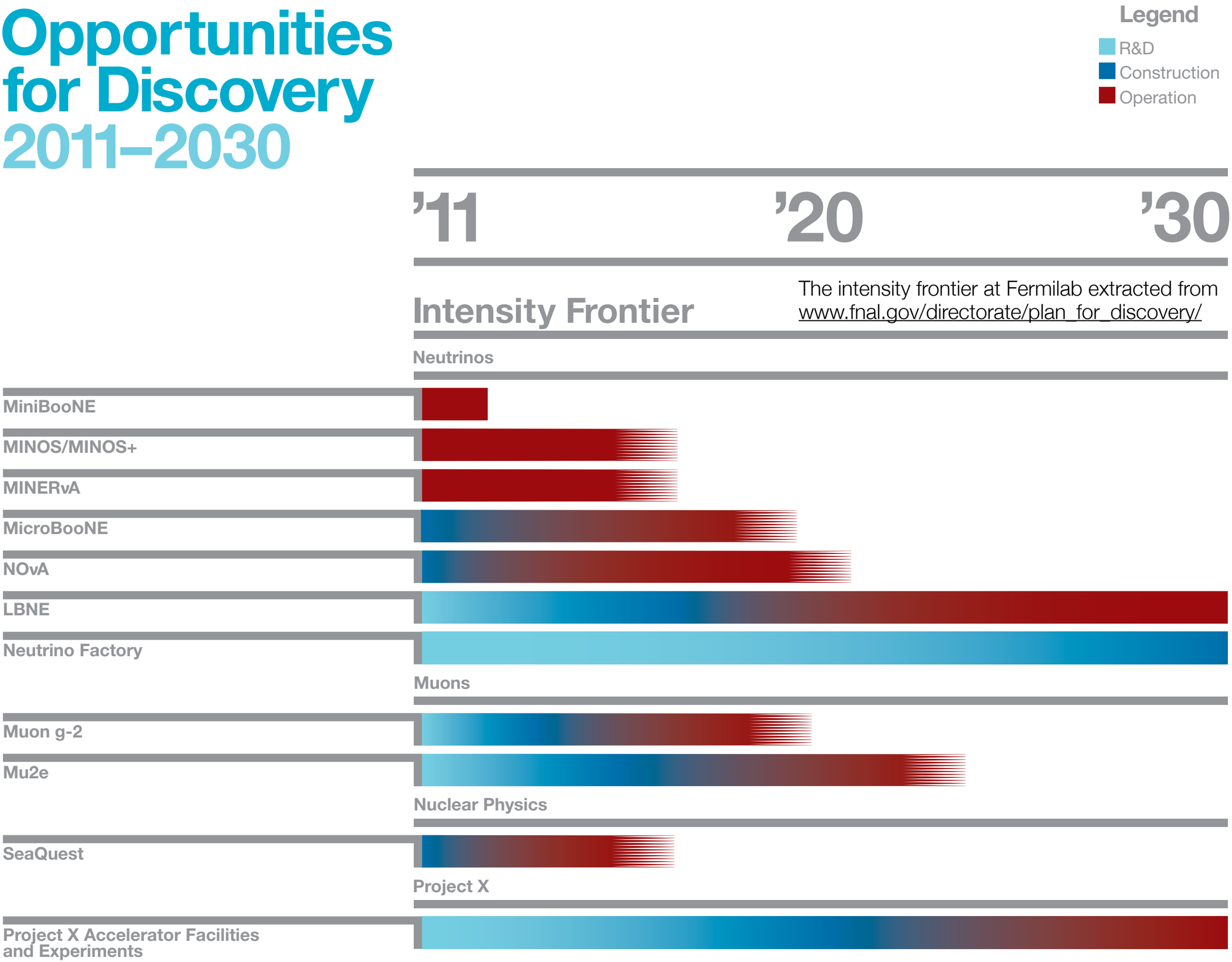
LBNE physics reach: Neutrino physics



LBNE physics reach: Proton decay



Opportunities for Discovery 2011–2030



The intensity frontier at Fermilab extracted from www.fnal.gov/directorate/plan_for_discovery/

Backup Slides

Events in NOvA

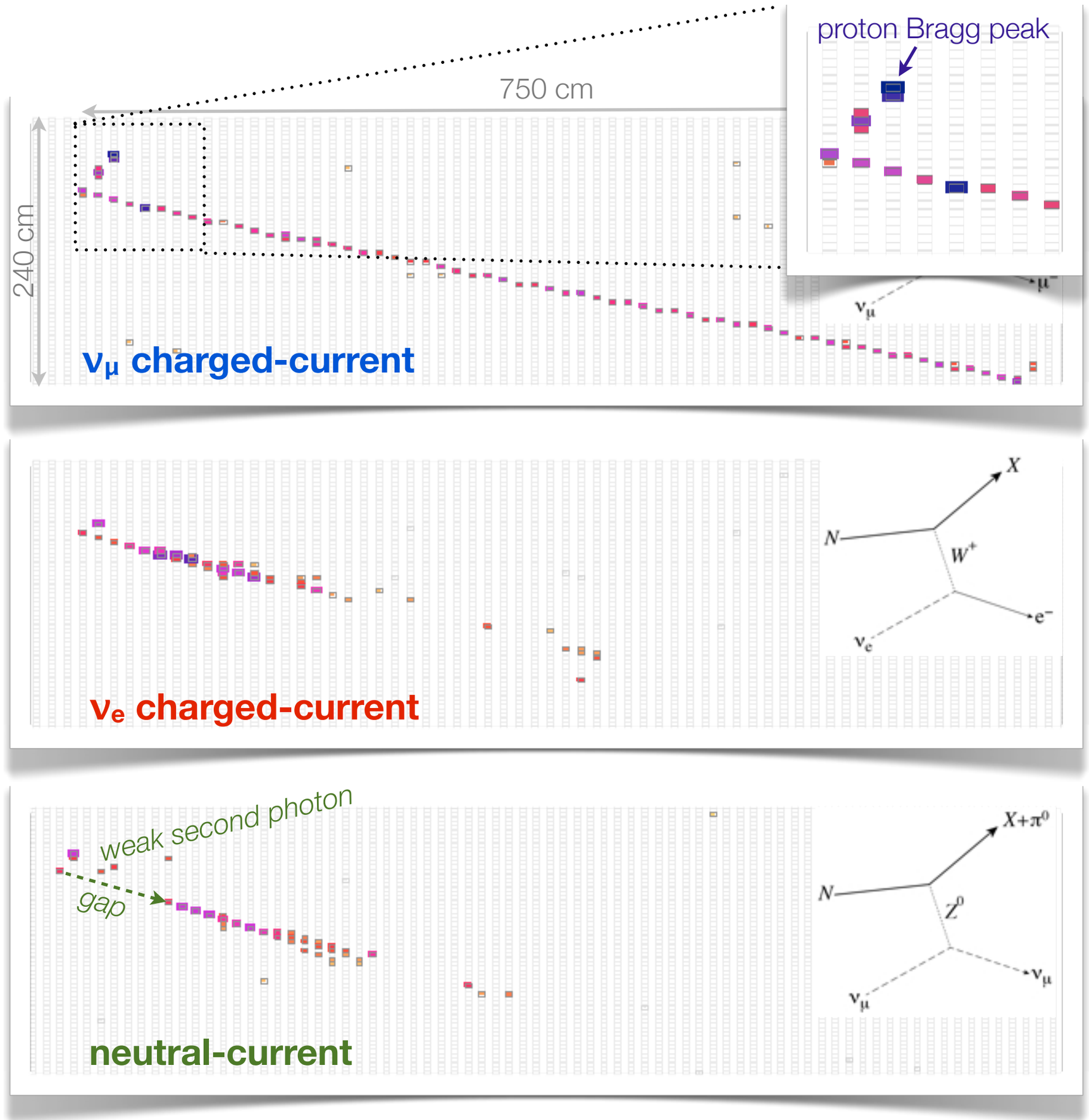
Topologies of basic interaction channels shown at right. Each "pixel" is a single 4 cm x 6 cm x 15 m cell of liquid scintillator

Top: ν_μ *charged-current*
Center: ν_e *charged-current*
Bottom: *neutral-current*

Need >100:1 rejection against background

Detector challenge: Achieve large target mass (10's+ kilotons) while maintaining high granularity to avoid confusing the detection channels

NOvA achieves 35% efficiency for ν_e CC while limiting NC→ν_e CC fake rate to 0.1%



Time of flight improvement plan

Phase 1	Phase 2	Phase 3
6-9 months	12 months	2013 onwards
Re-analyse existing data, reducing dominant uncertainties	Hardware improvements for 2012 data taking	Further hardware improvements Beam energy and intensity upgrades
19-35 ns sys. uncertainty	11-18 ns sys. uncertainty	2-7 ns sys. uncertainty

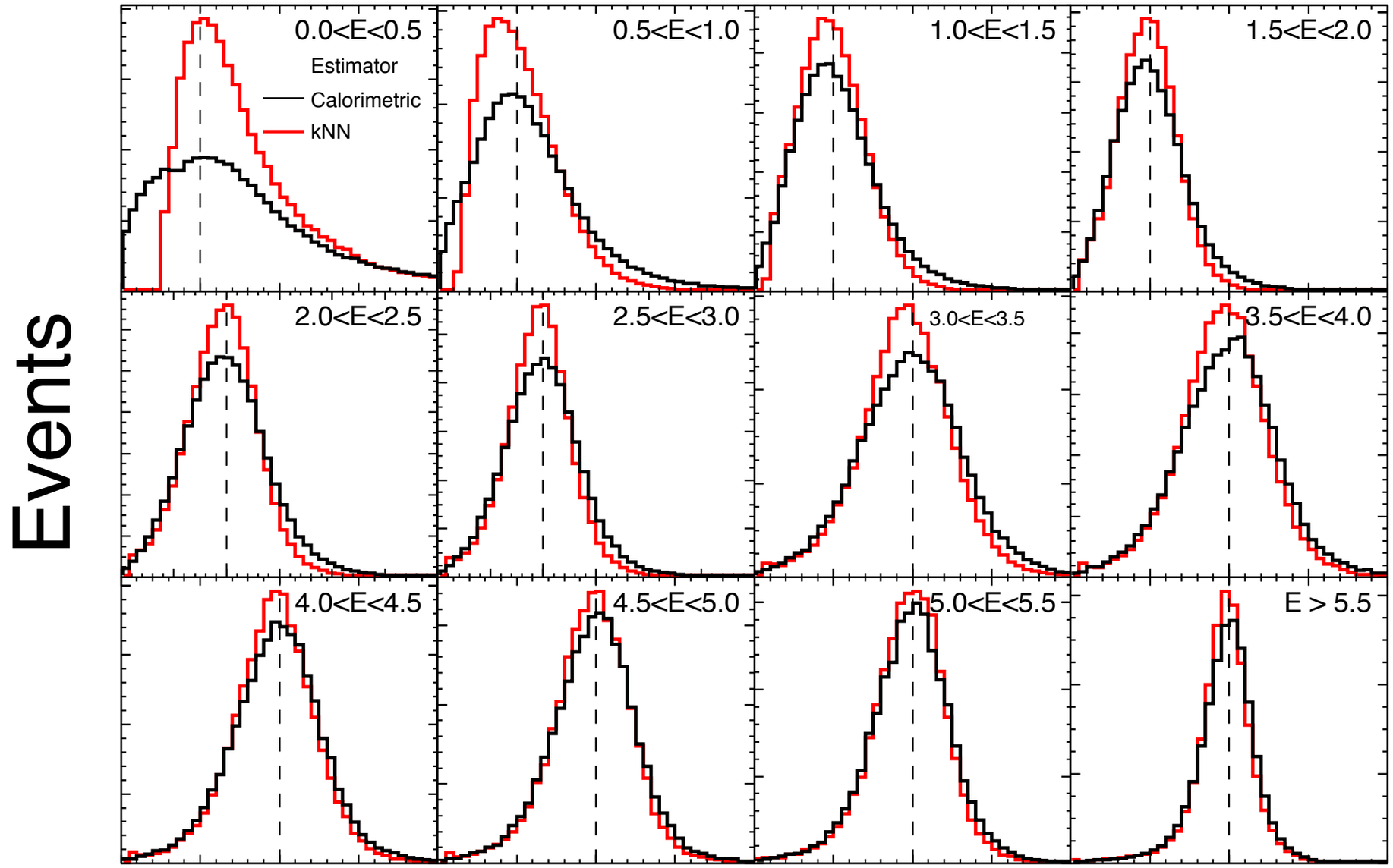
Phys.Rev.Lett. 106 (2011) 181801
arXiv:1103.0340v1 [hep-ex] 2 Mar 2011

Analysis Improvements In Latest Results

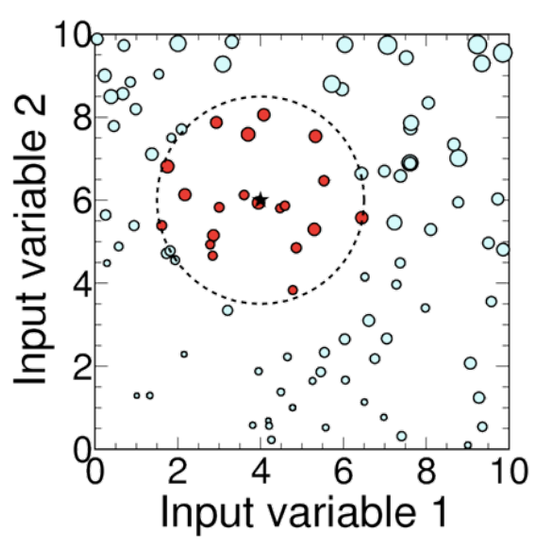
- **Statistics**
  - Data set more than double the size of the previous report
  - Added event samples
    - Fit both positive and negative track charge signs. Important to reclaim events with short tracks in oscillation peak which previously were lost to incorrect charge assignment.
    - Include events with vertices outside the detector fiducial volume (detector + rock) which produce entering muon tracks. So called “partially reconstructed events”.
    - Improved low energy particle identification. 77% efficient below 2 GeV with 6.5% NC background rate.
- **Analysis improvements**
  - Analyze events separated energy resolution
  - Improved hadronic energy estimator using multivariate technique

$\nu_\mu \rightarrow \nu_\mu$

Phys.Rev.Lett. 106 (2011) 181801
arXiv:1103.0340v1 [hep-ex] 2 Mar 2011



Reconstructed/true shower energy



kNN technique uses average properties of simulated events from neighborhood around event to characterize event

Variables:

- Number of hit planes in primary shower
- Energy of first two showers
- Shower energy within 1 m of track vertex