Recent Results from Long Baseline Neutrino Experiments

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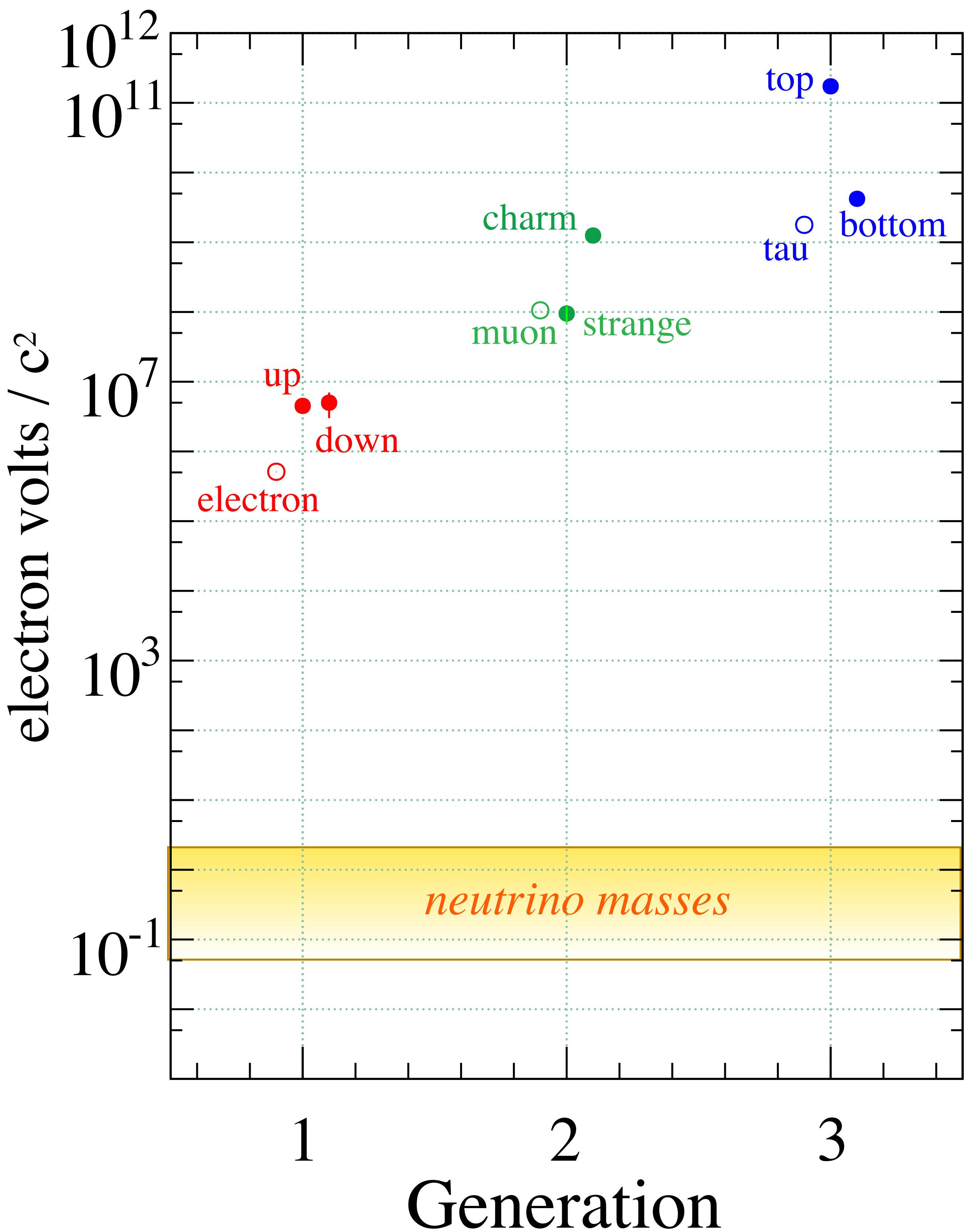
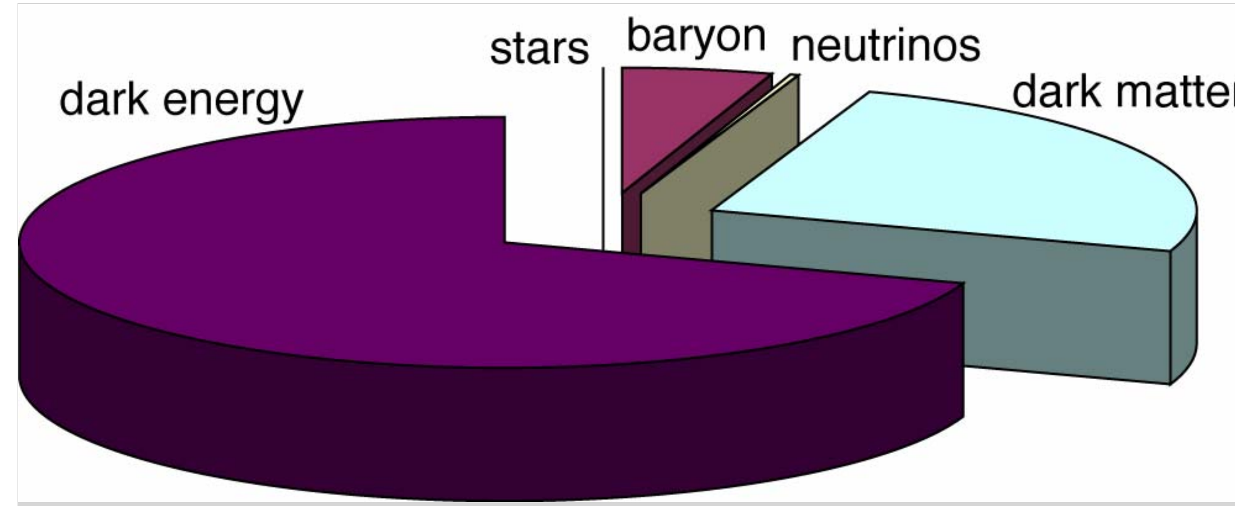
Indiana University / Fermilab / Caltech
Heavy Quarks and Leptons 2010
INFN - Laboratori Nazionali di Frascati
14 October 2010





Stars and galaxies:	~0.5%
Rest of ordinary matter:	~5%
Neutrinos:	~0.3–10%
Dark Matter:	~25%
Dark Energy:	~70%

See-saw mechanism

$$\mathcal{L}_{\text{mass}} = \begin{bmatrix} \nu_L & \nu_R \end{bmatrix} \begin{bmatrix} 0 & m \\ m & M \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix}$$

$$\lambda \simeq \frac{m^2}{M} \simeq \frac{(100\ \text{GeV})^2}{10^{16}\ \text{GeV}} = 10^{-3}\ \text{eV}$$

Neutrino masses and mixing are a window on physics at the GUT scale

Neutrino Mass

Neutrino oscillations

Neutrino masses are too small to have been measured directly, hence we rely on interference measurements.

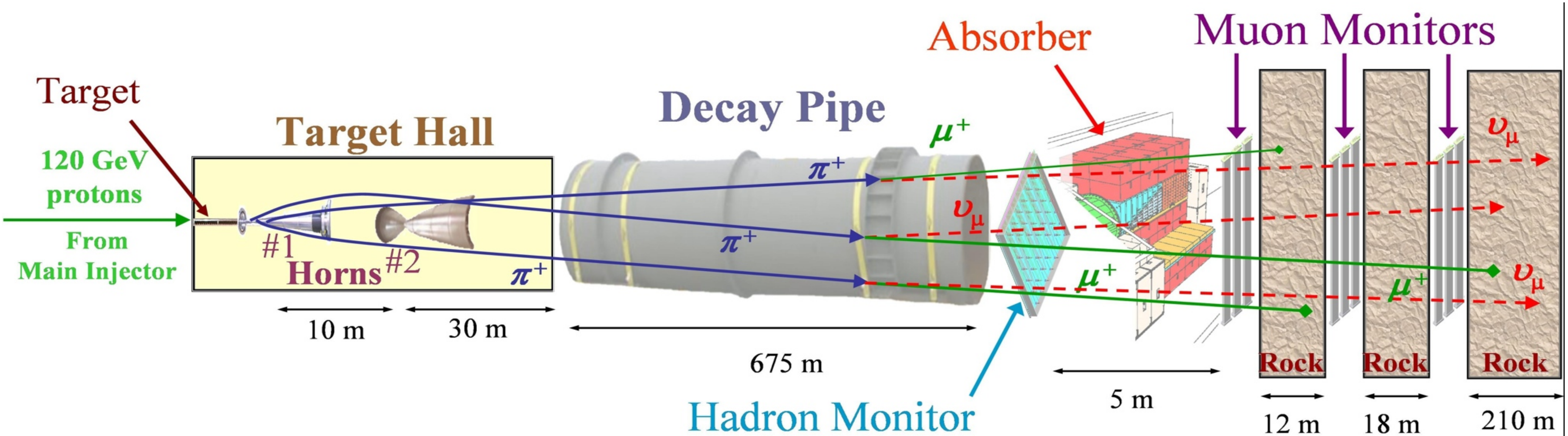
$$\left| \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12}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

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

$\lvert\Delta m^2_{32}\rvert \equiv \lvert m^2_3 - m^2_2\rvert \simeq 2\times 10^{-3}\ \mathrm{eV}^2$	$\Delta m^2_{31} \simeq \Delta m^2_{32}$	$\Delta m^2_{21} \simeq 8\times 10^{-5}\ \mathrm{eV}^2$
$\nu_\mu \longrightarrow \nu_\mu$ $\nu_\mu \longrightarrow \nu_\tau$	$\nu_e \longrightarrow \nu_e$ $\nu_\mu \longrightarrow \nu_e$	$\nu_e \longrightarrow \nu_e$ $\nu_e \longrightarrow \nu_\mu + \nu_\tau$
atmospheric and long baseline	reactor and long baseline	solar and reactor
$\theta_{23} \simeq 45^\circ$	$\theta_{13} < 15^\circ$	$\theta_{12} \simeq 35^\circ$

$$\delta = ?\ \mathrm{sgn}(\Delta m^2_{31})?$$

Neutrino beams from hadron accelerators



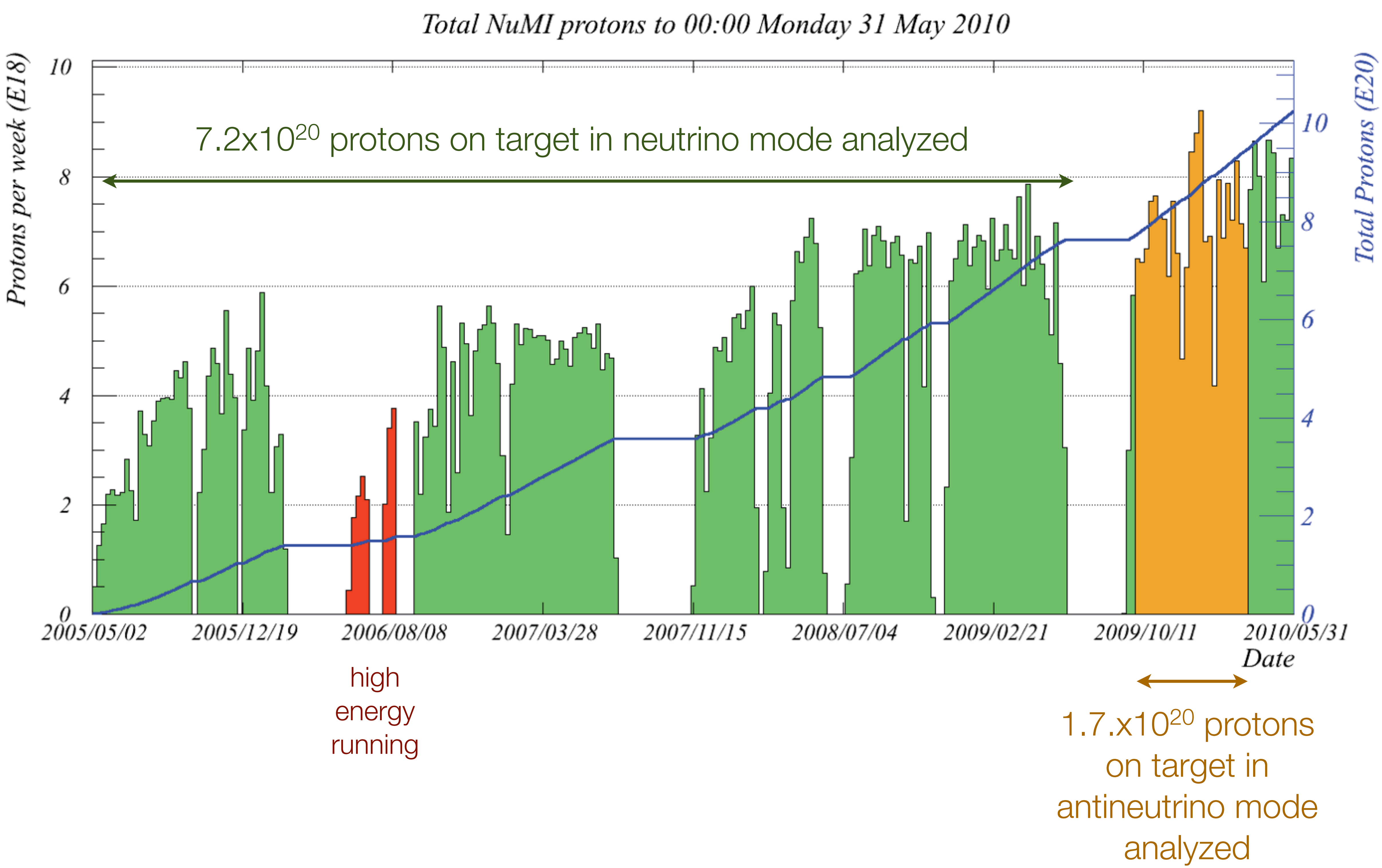
- KEK / NuMI / BooNE / CERN / JPARC neutrino beams use same basic principles
- Typically fluxes are composed of:
  - ~90+% ν_μ from focused π^+ and K^+ decays
  - ~5% $\bar{\nu}_\mu$ from incompletely defocused π^- and K^- decays and "scraping"
  - ~1% $\nu_e+\bar{\nu}_e$ from μ and K decays

MINOS

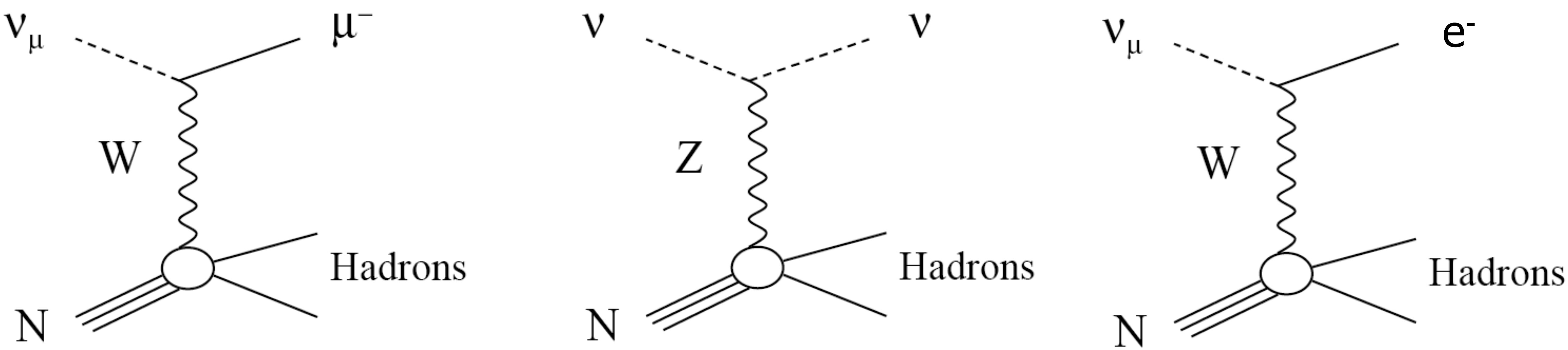
What are the parameters of muon neutrino oscillation?

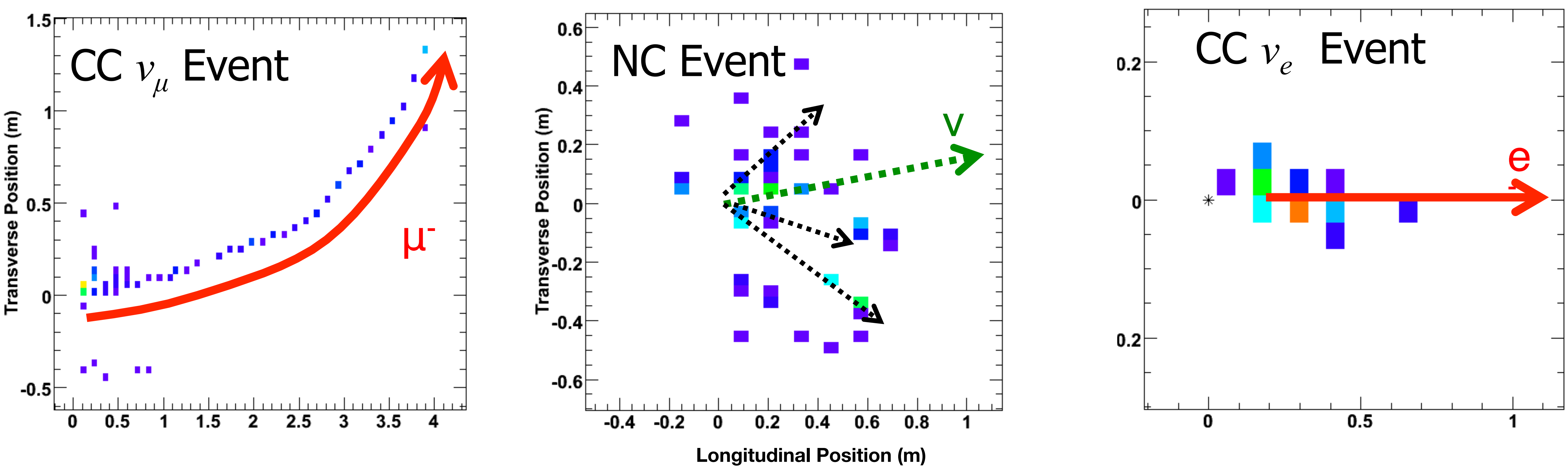
MINOS

Performance of the Fermilab NuMI Beam

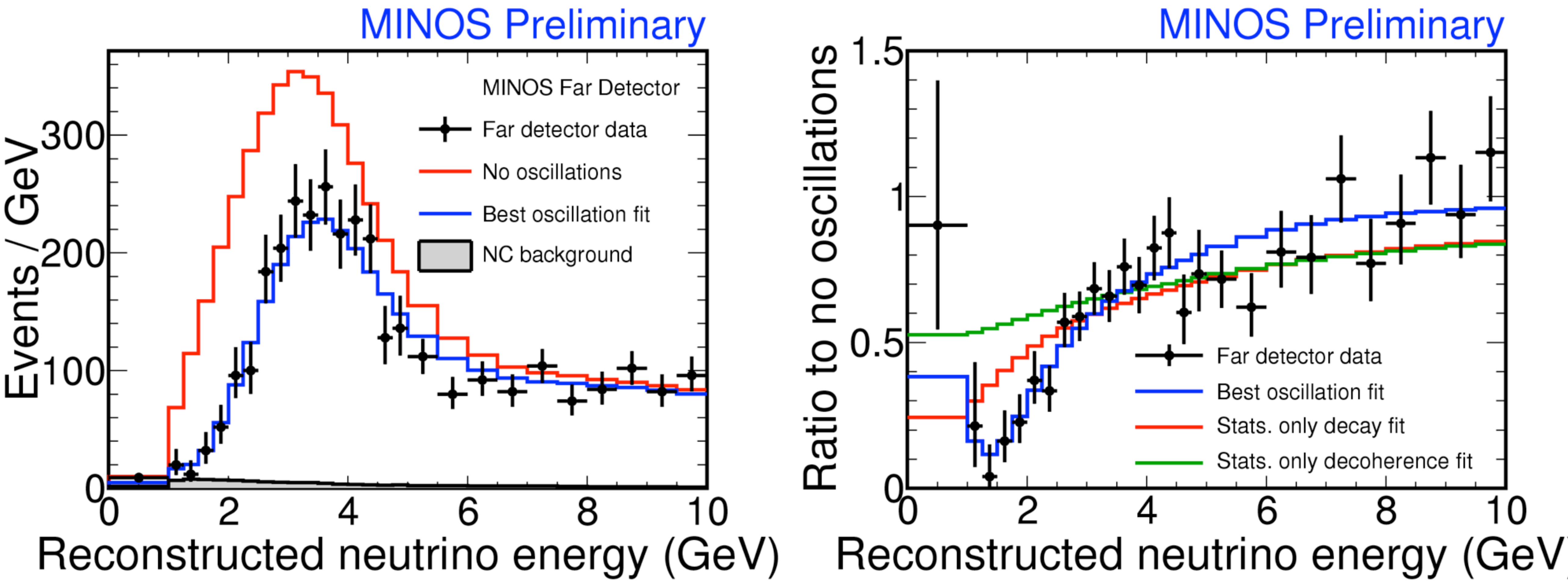


MINOS
Event Topologies

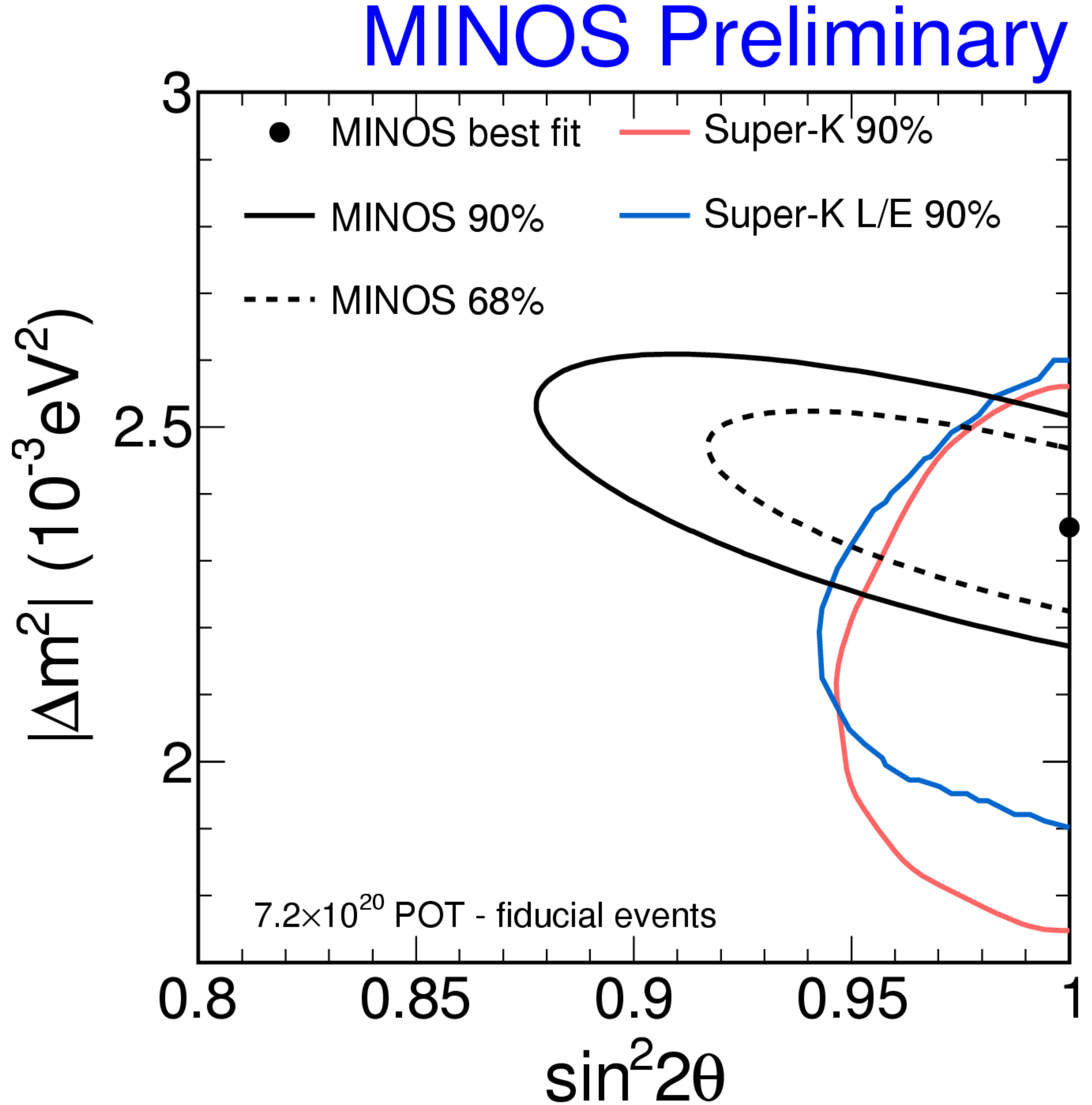




MINOS
Muon neutrino disappearance



- **2451 events expected (no oscillations)**
- **1986 observed**
- Good fit to oscillations (p = 66%)
- Disappearance due to decay disfavored at >6σ
- Disappearance due to decoherence disfavored at >8σ



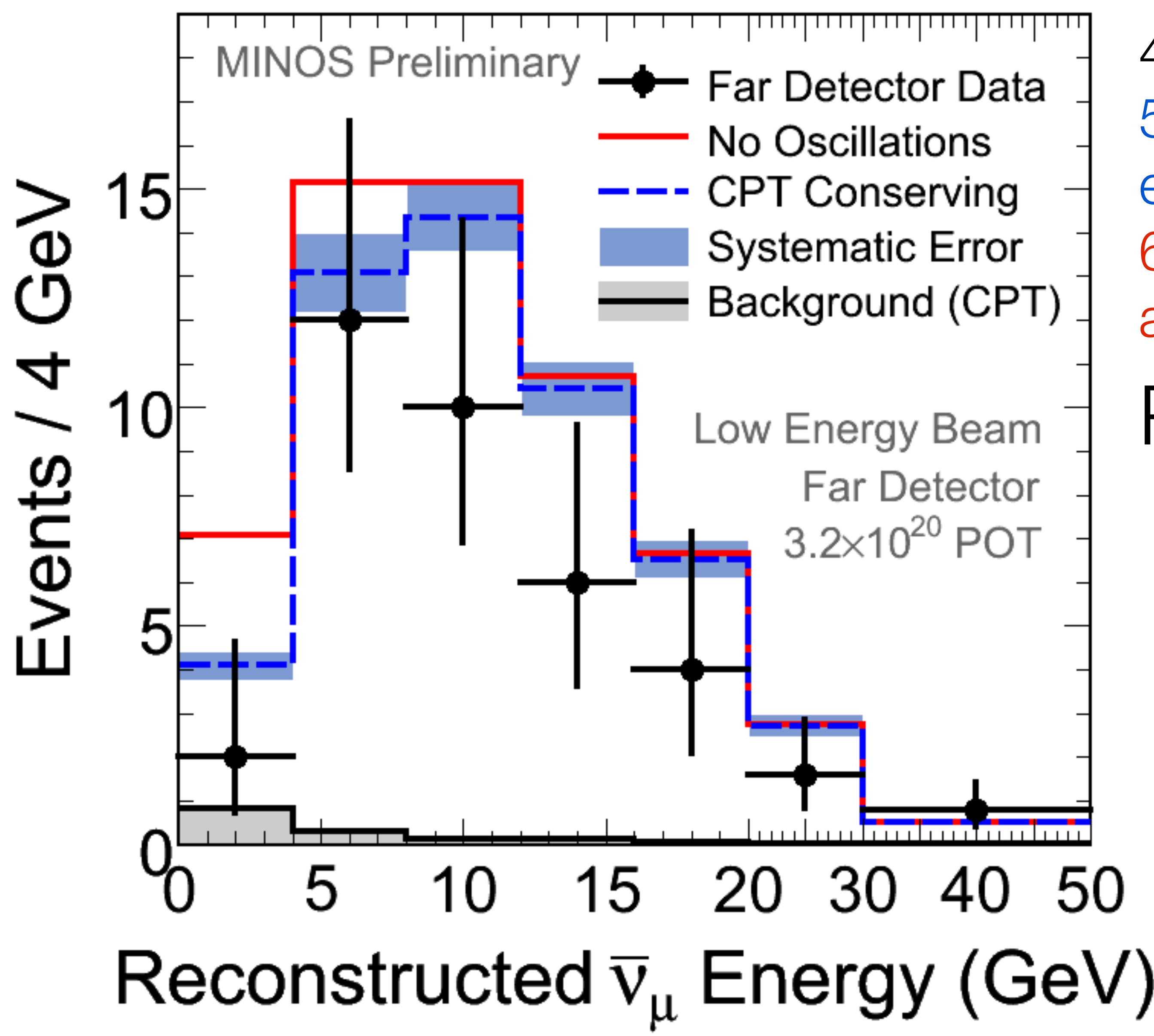
$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \mathrm{eV}^2$$
$$\sin^2(2\theta) > 0.91 \ (90\%\mathrm{C.L.})$$

MINOS

Muon neutrino disappearance

MINOS

Do $\nu_\mu \rightarrow \bar{\nu}_\mu$ transitions occur?



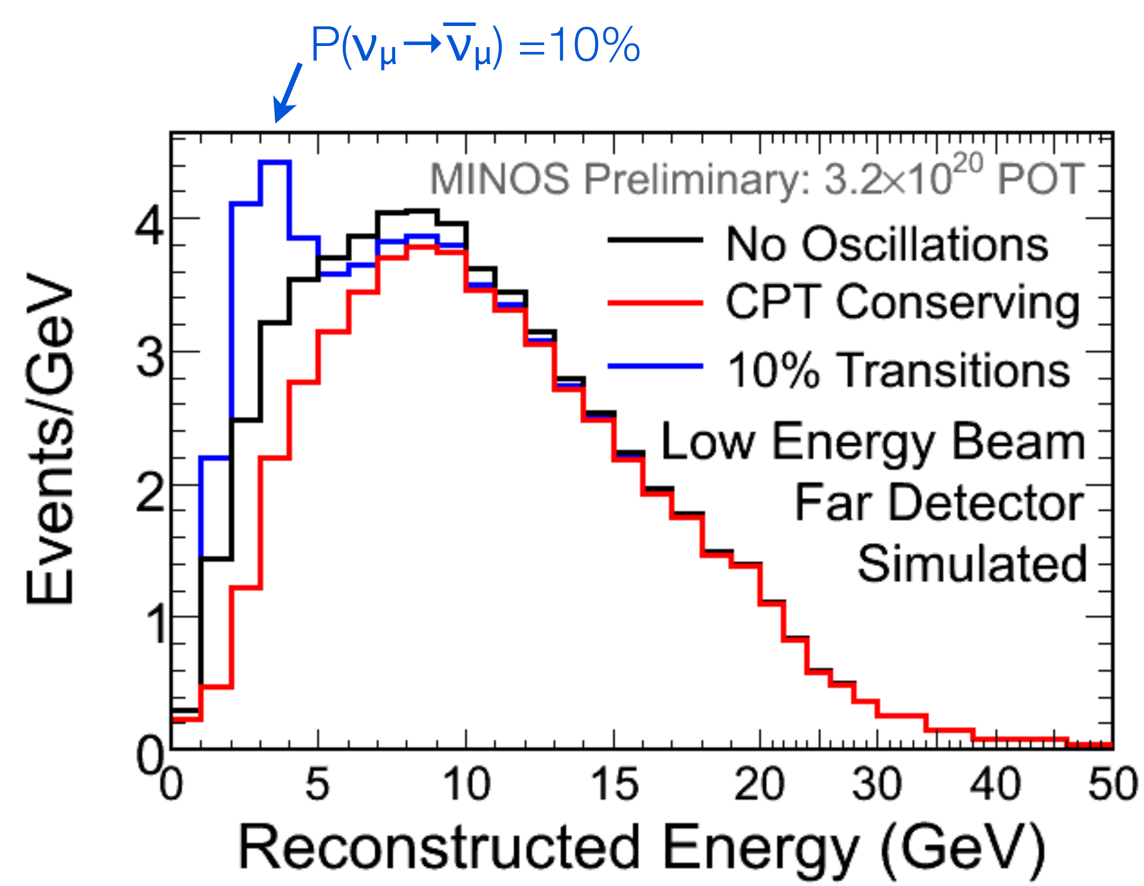
Energy spectrum of antineutrino events at MINOS far detector when recorded during neutrino beam operation

42 events observed

58.3 ± 7.6 (stat.) ± 3.6 (syst.) expected using neutrino oscillation parameters

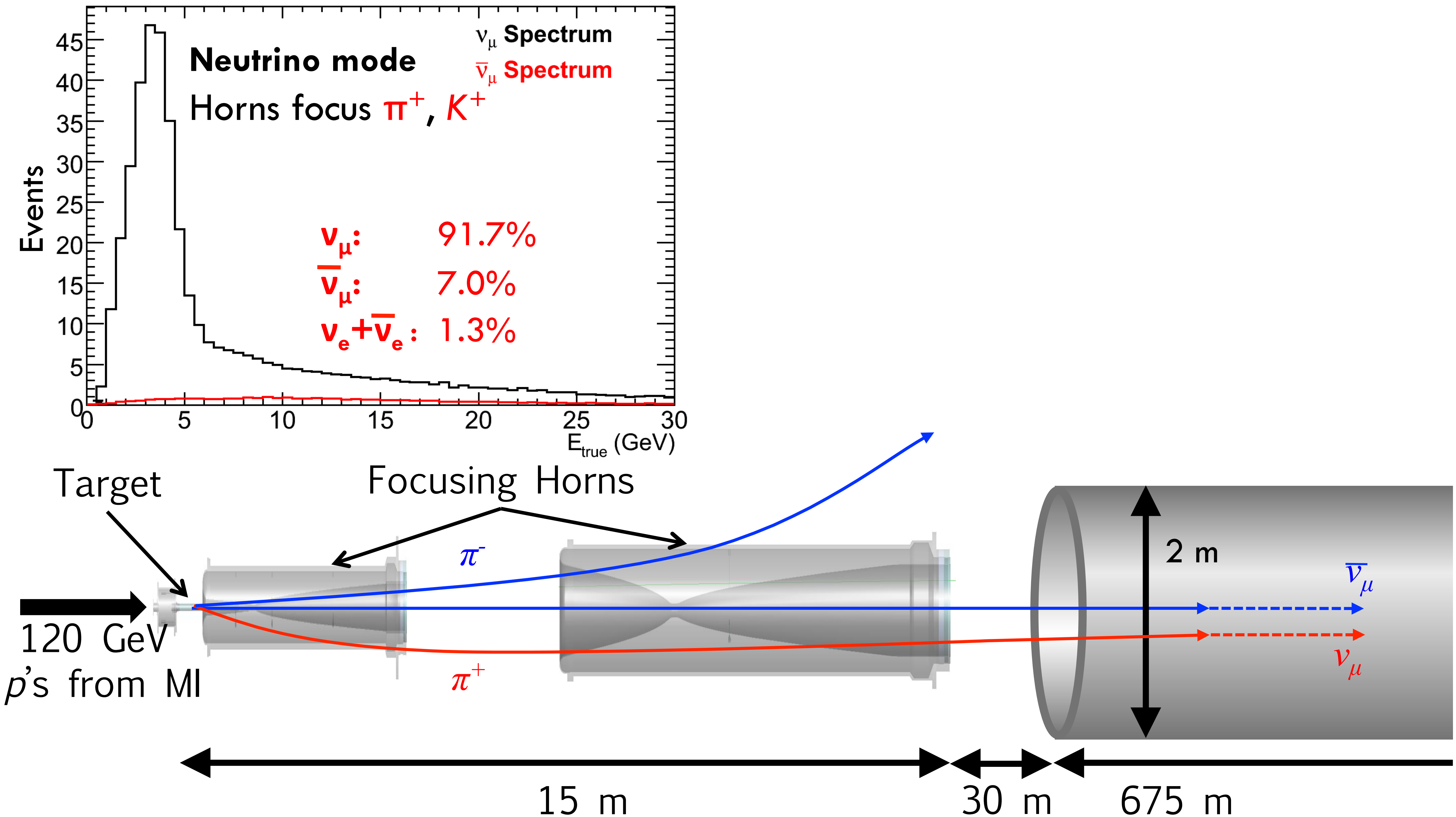
64.6 ± 8.0 (stat.) ± 3.9 (syst.) expected assuming no oscillations

$P(\nu_\mu \rightarrow \bar{\nu}_\mu) < 2.6\%$ @ 90% C.L.



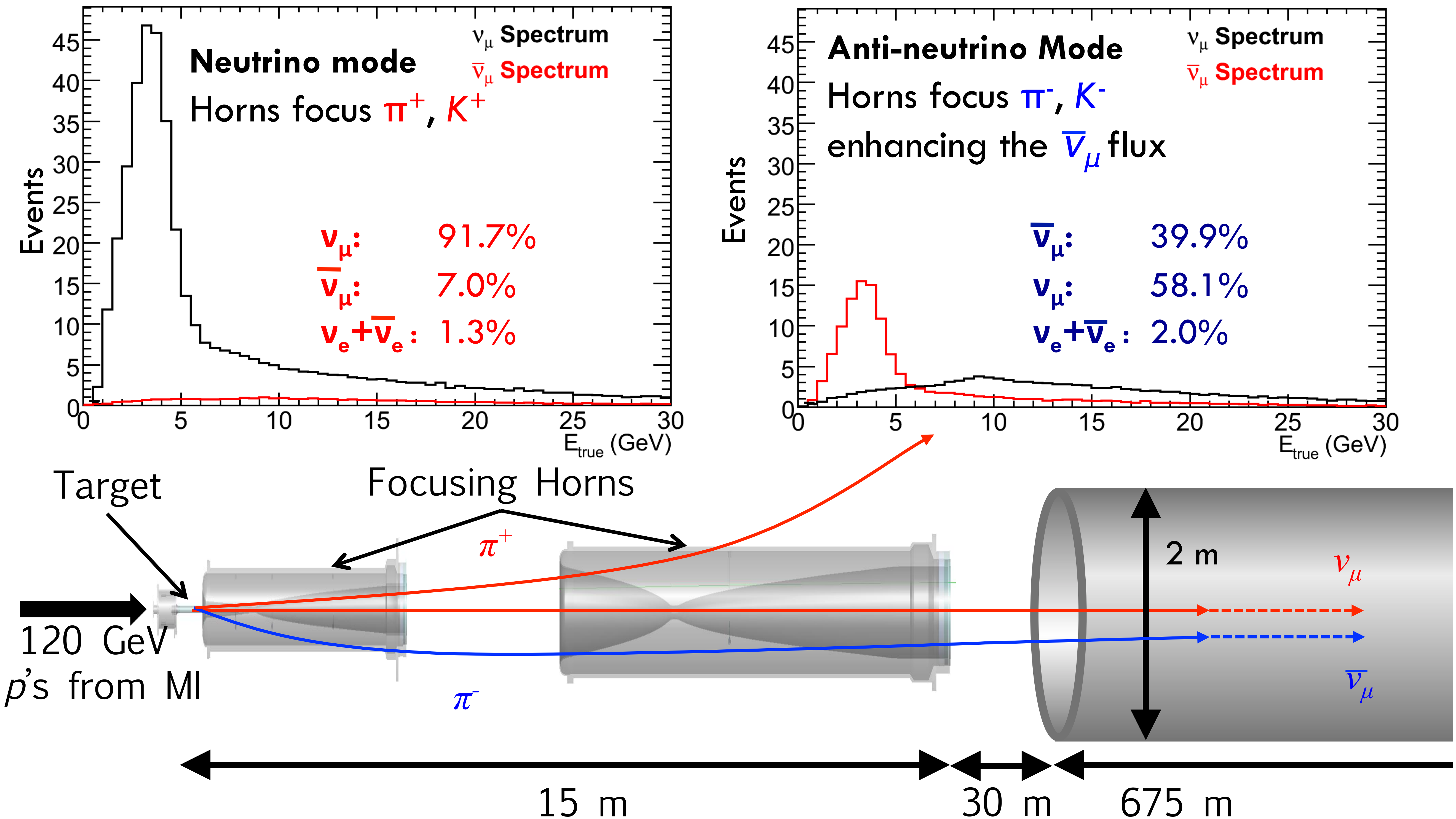
MINOS

Neutrino and Antineutrino beams



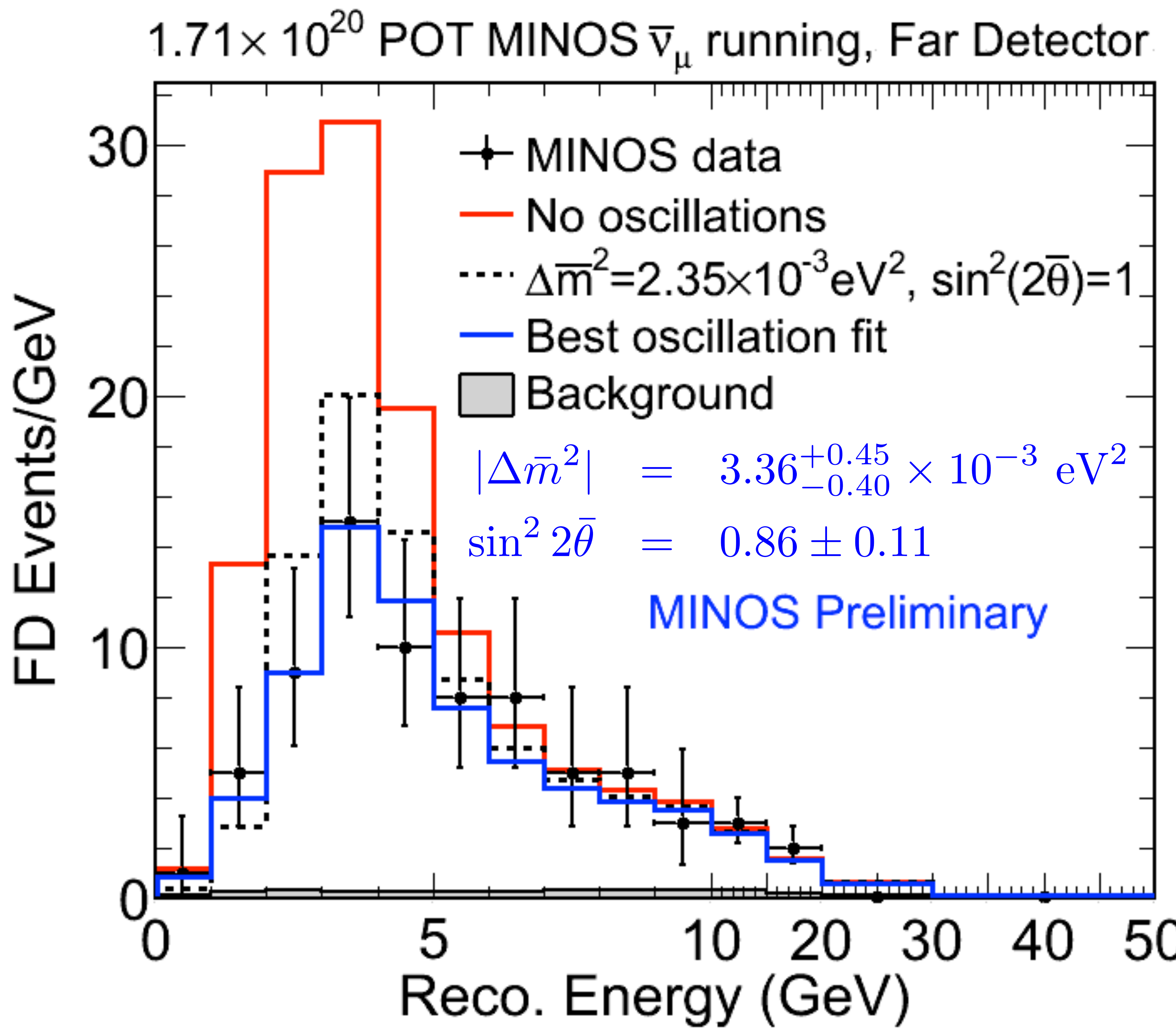
MINOS

Neutrino and Antineutrino beams



MINOS

Does $P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$?

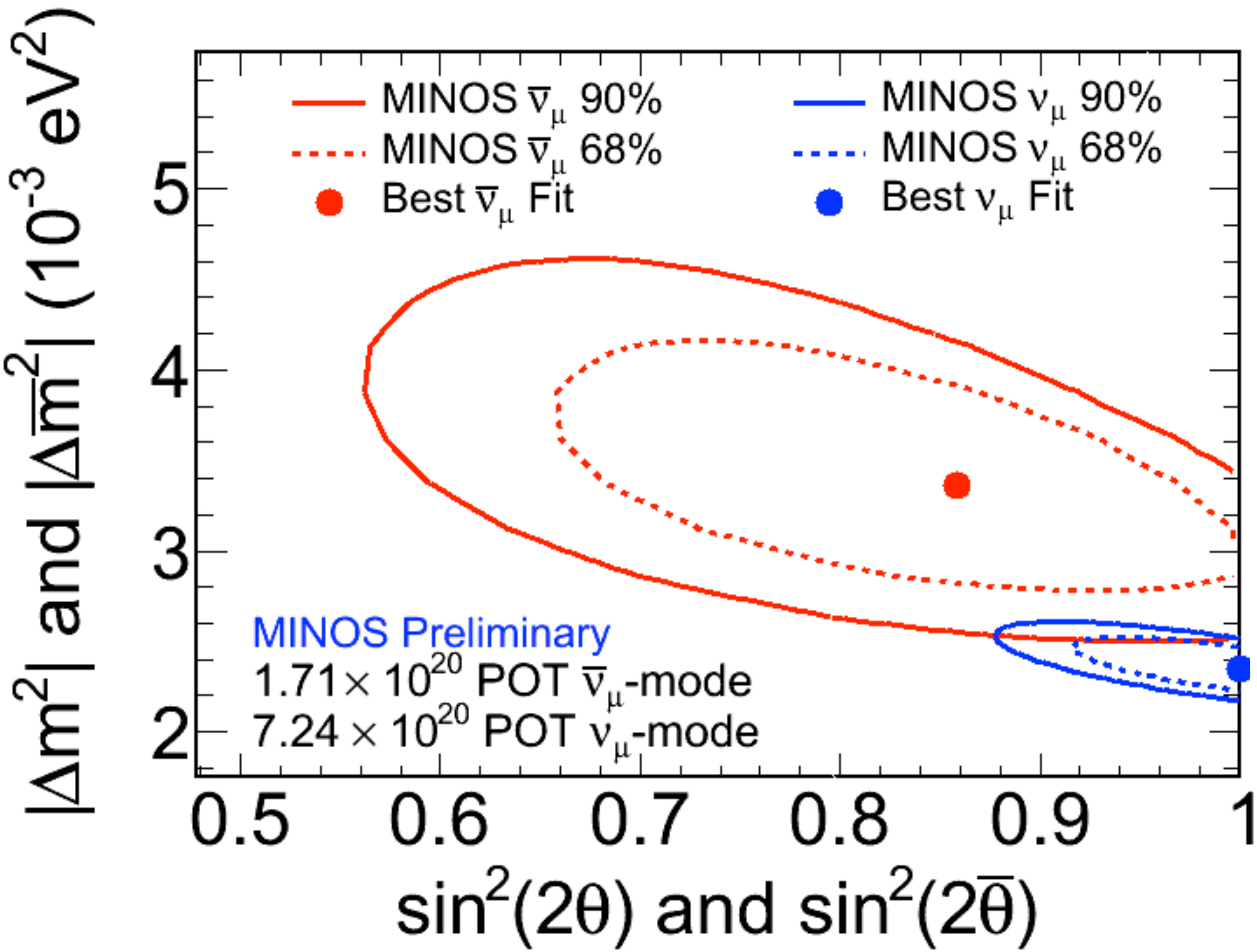


155 events predicted w/o oscillations

97 events observed

MINOS

Does $P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$?



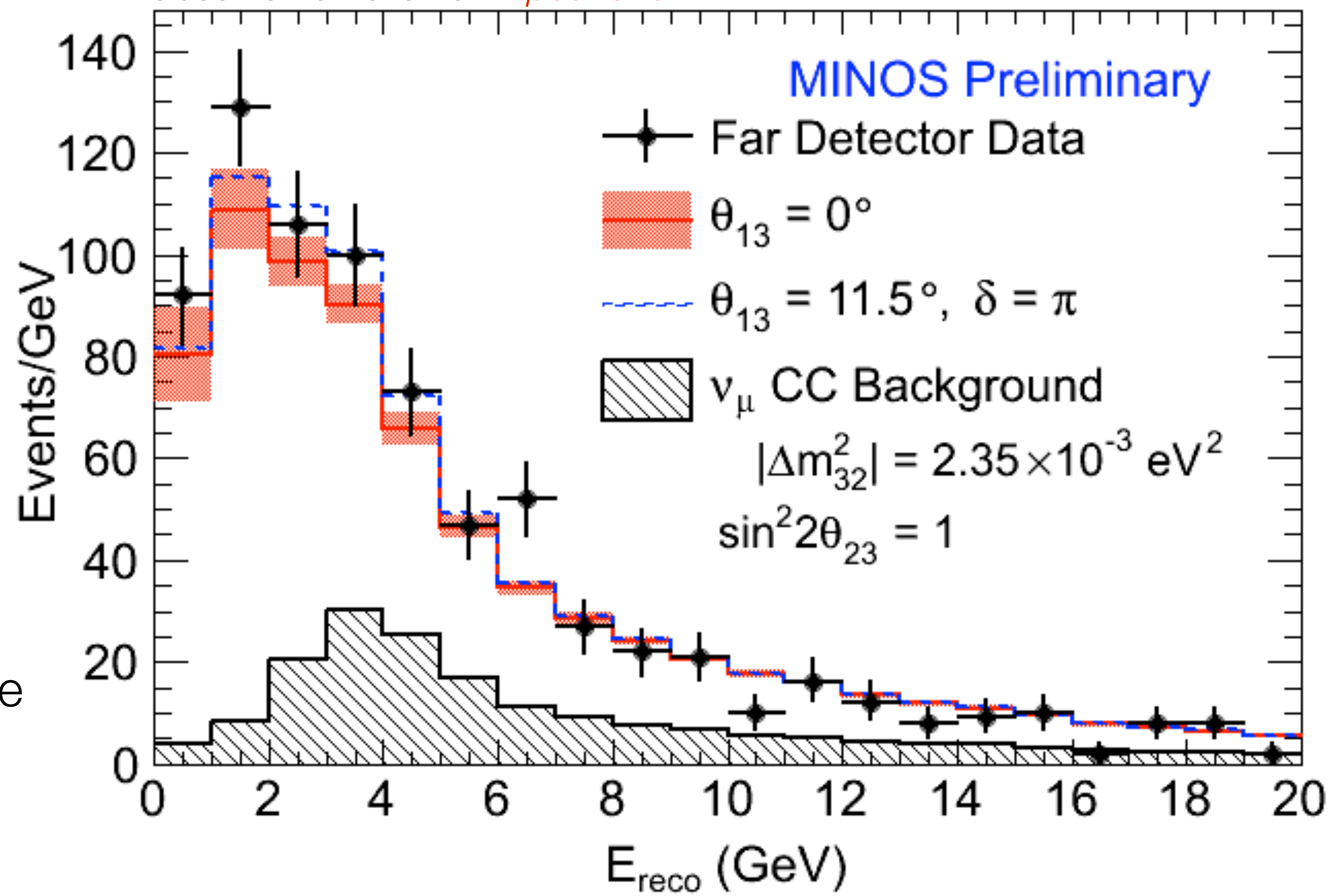
Additional antineutrino running during the next year will roughly double the data set

MINOS

Is the total neutrino flux conserved? Are there sterile neutrinos?

- Use neutral-current event rate at far detector to measure total neutrino flux.
- Oscillations involving active flavors changes flavor content of beam, but leaves total flux unchanged.
- Oscillations involving sterile neutrino or non-oscillations disappearance mechanisms (eg. decay) would change the total rate.

Observe 757 events. Expect 820.

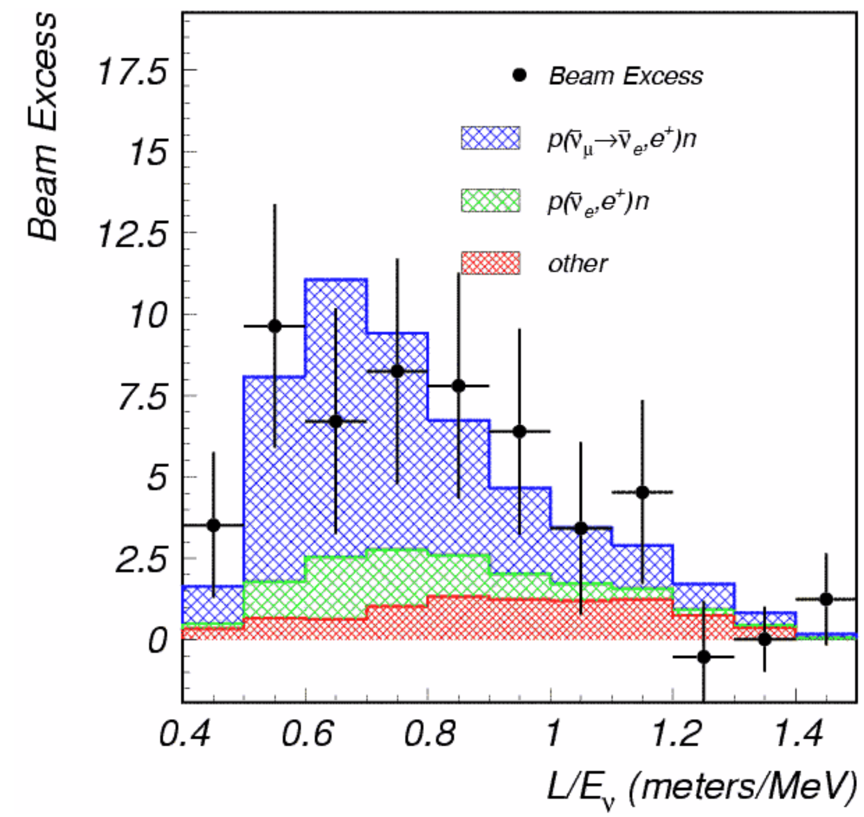


Limit sterile content of beam to below 22% (90% C.L.)

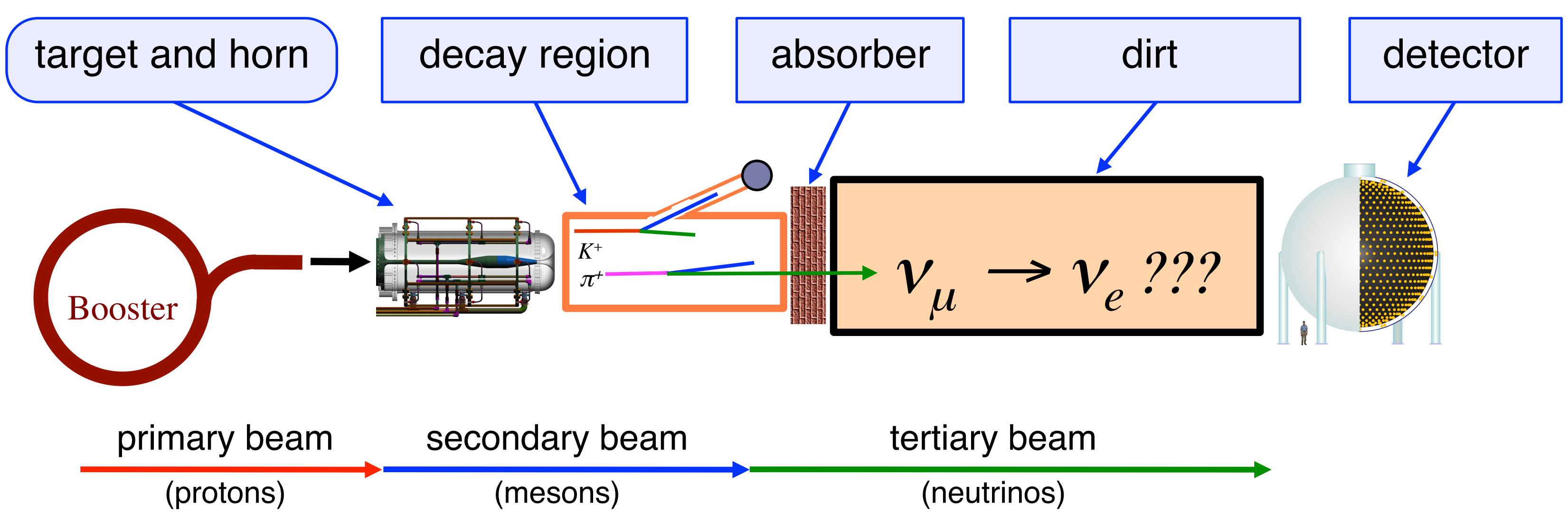
40% if $\nu\mu \rightarrow \nu e$ oscillations included at CHOOZ 90% C.L. limit.

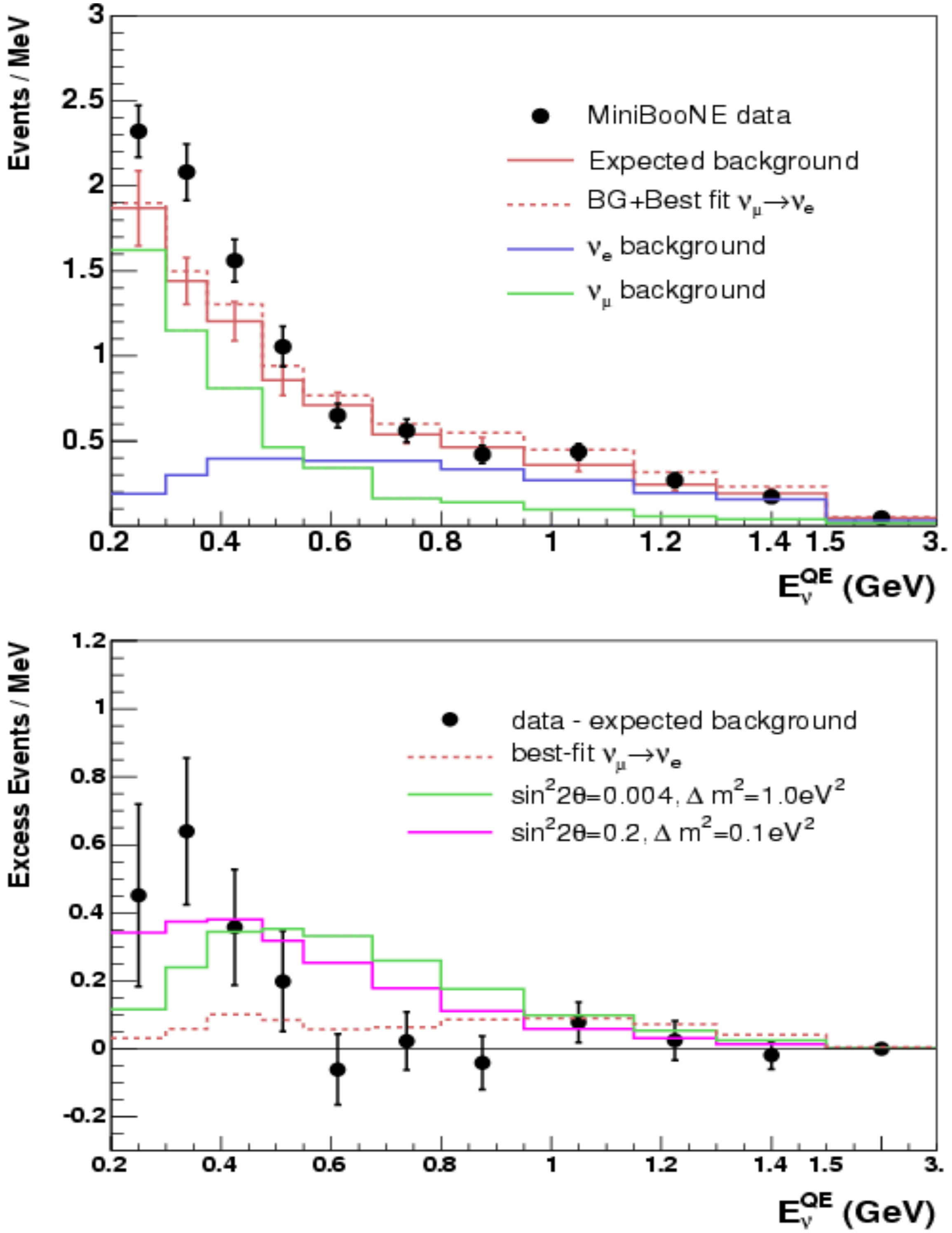
Short baseline oscillations

- If the neutrino had a mass of 1 eV or more it would be a good cold dark matter candidate. This fact motivated a large number of neutrino oscillations experiments in the 1970's, 80's,and 90's.
- All but one of these experiments reported null results
- The one positive result was reported by the LSND experiment which saw $\bar{\nu}_e$ appearance from $\bar{\nu}_\mu$'s produced from a stopped pion source. They reported a 3.8σ excess of 87.9 ± 23.2 $\bar{\nu}_e$ events with $L/E \approx 30$ m / 30 MeV ~ 1 km/GeV.

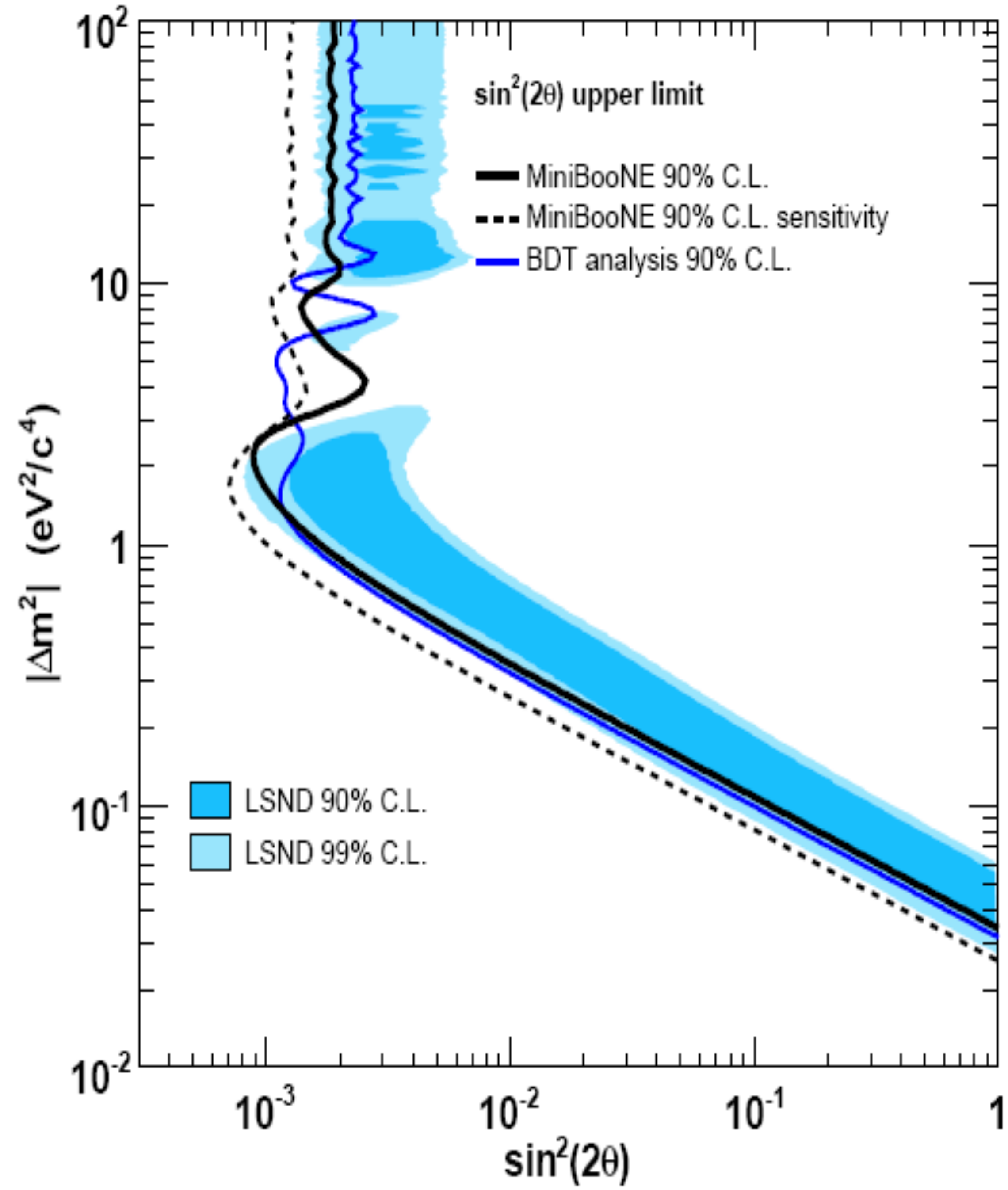


- The MiniBooNE experiment was built to test this report using $L/E \approx 300$ MeV/300 m ~ 1 km/GeV



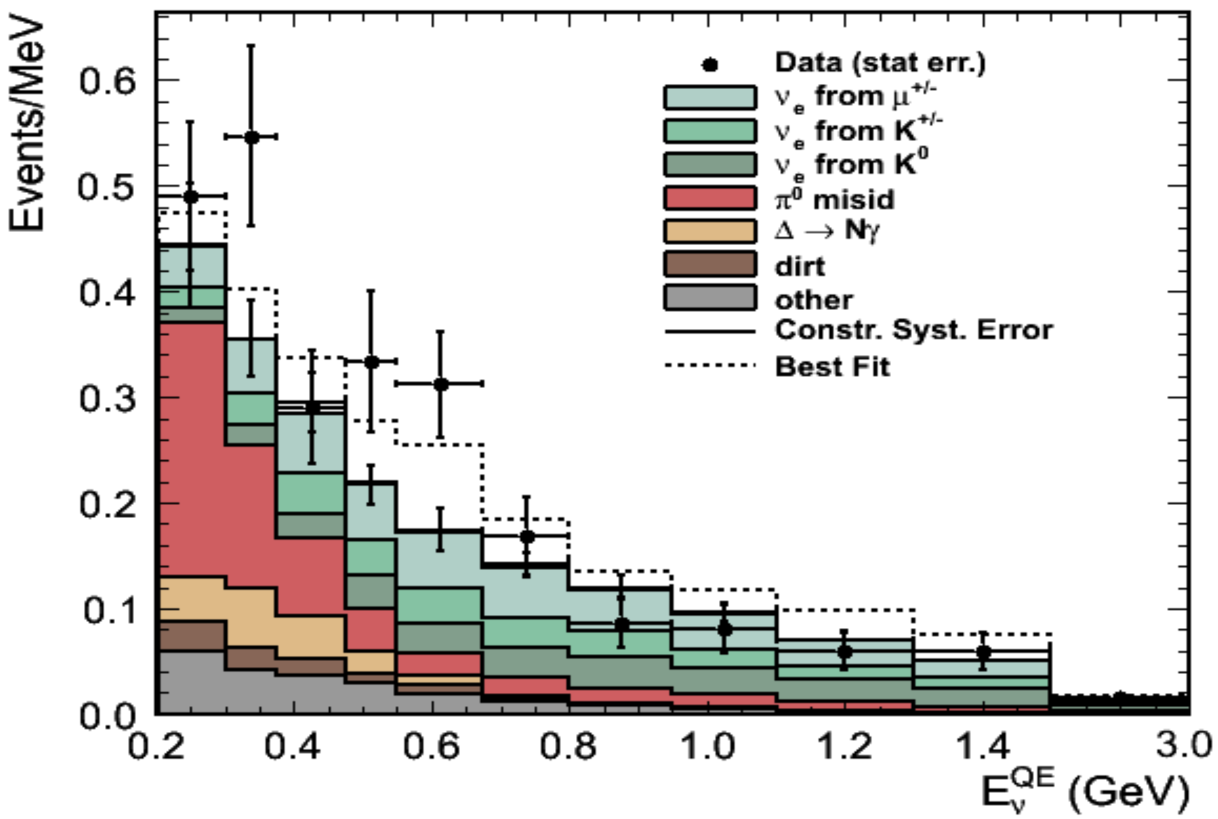


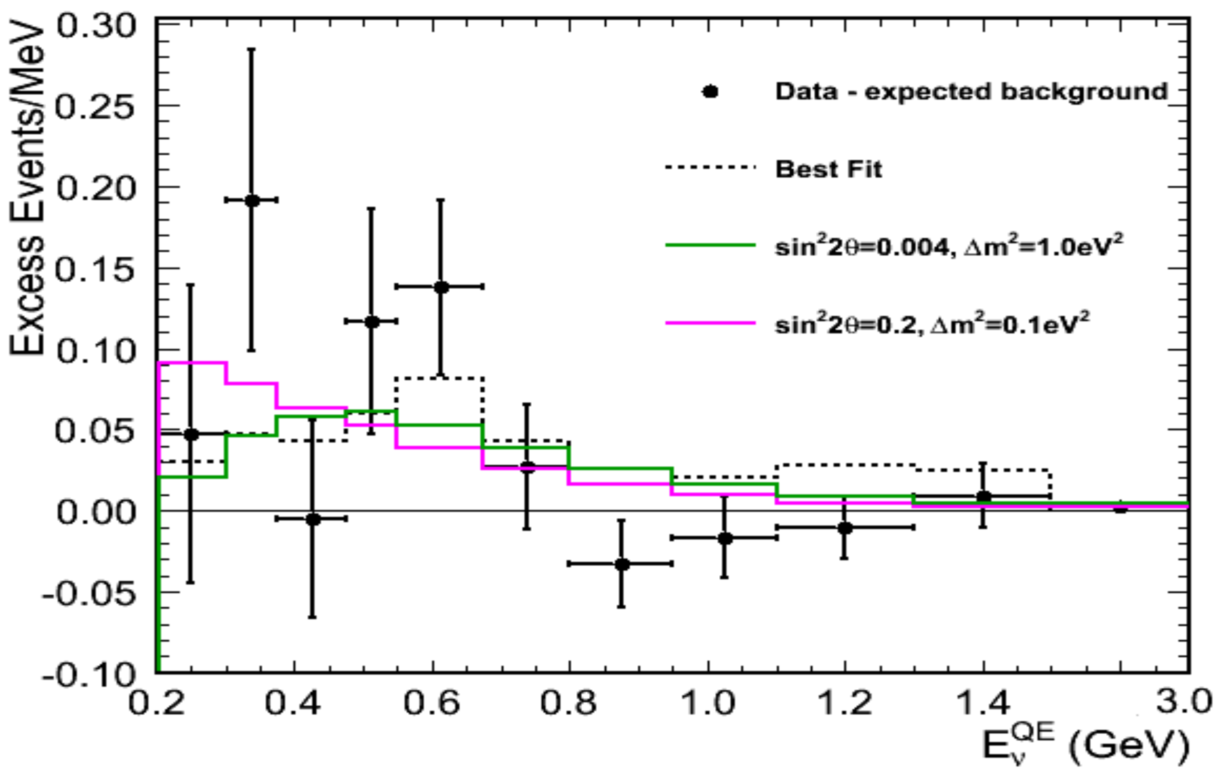
Top: Raw event rates, Bottom, background subtracted event rates.



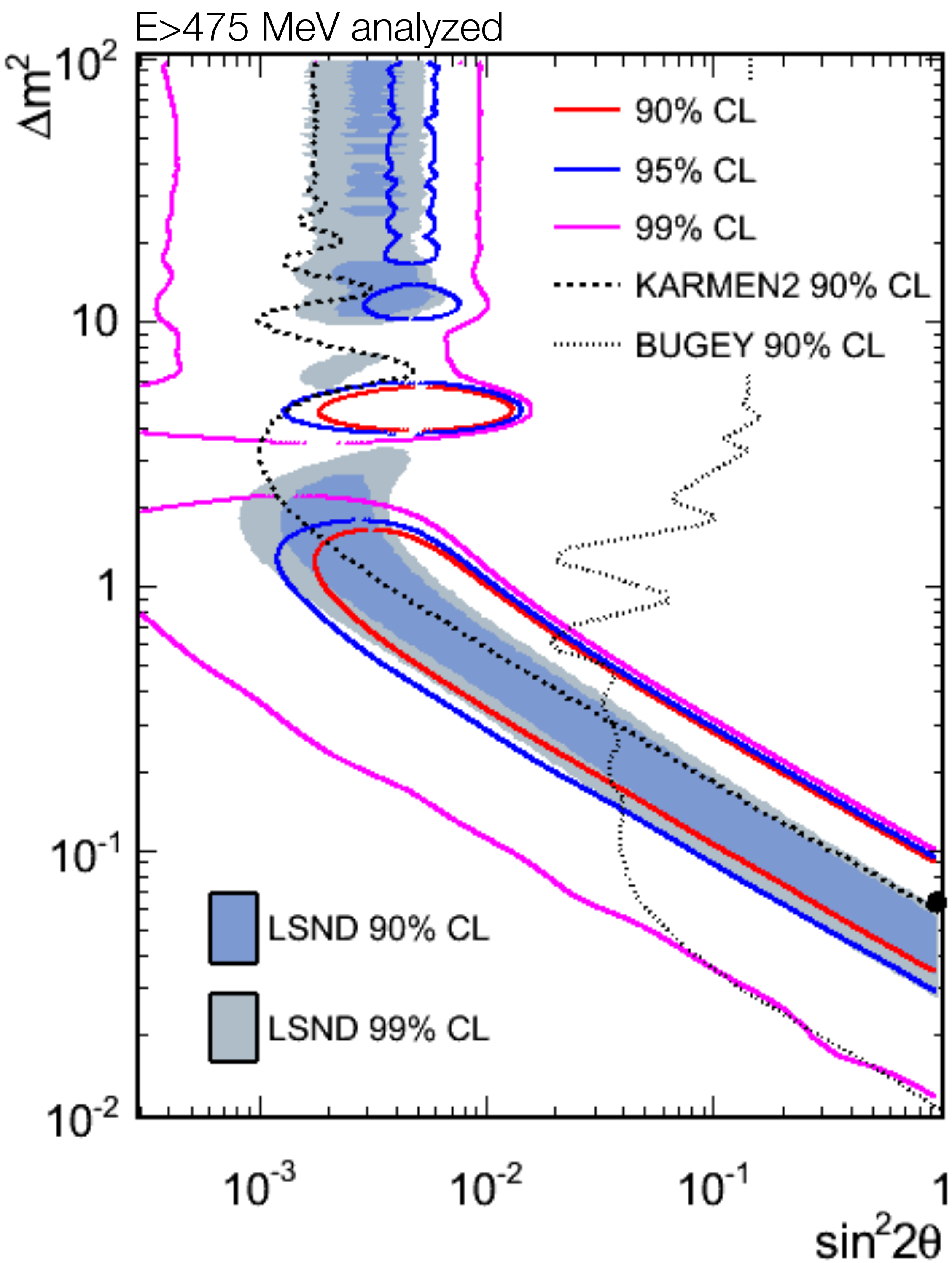
MiniBooNE has collected 6.5E20 POT in neutrino mode. This data shows a curious excess at low energies but is inconsistent with LSND oscillations parameters (green and pink lines at left).

MiniBooNE Neutrino Results





Top: Raw event rates, Bottom, background subtracted event rates.

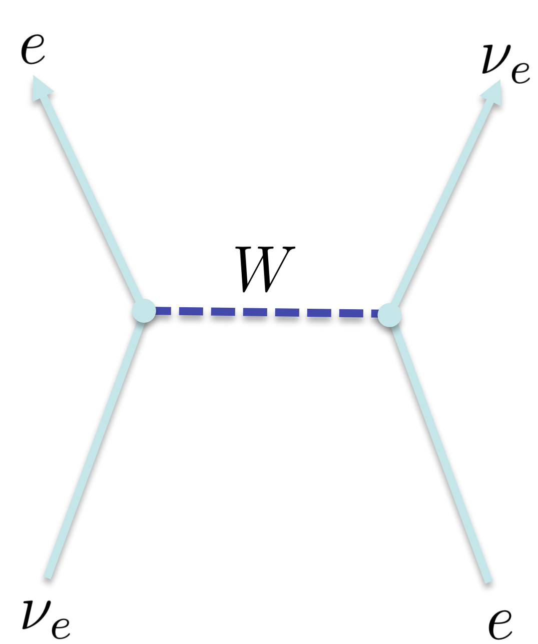


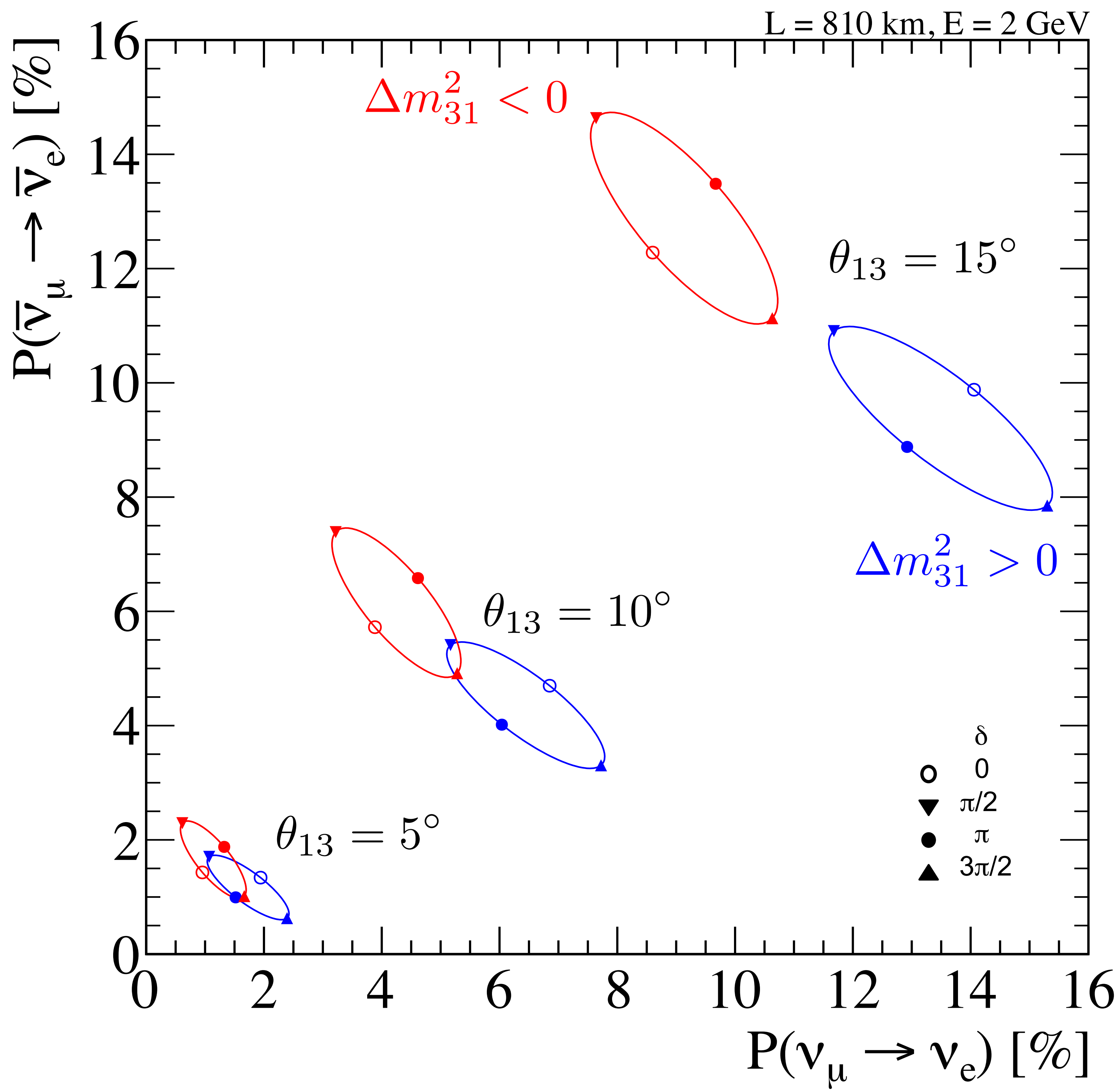
MiniBooNE has collected 5.7E20 POT in antineutrino mode. This data has an excess between 500 and 700 MeV which is consistent with oscillations using the LSND parameters (pink and green curves at left).

MiniBooNE Antineutrino Results

Electron neutrino appearance in long baseline experiments

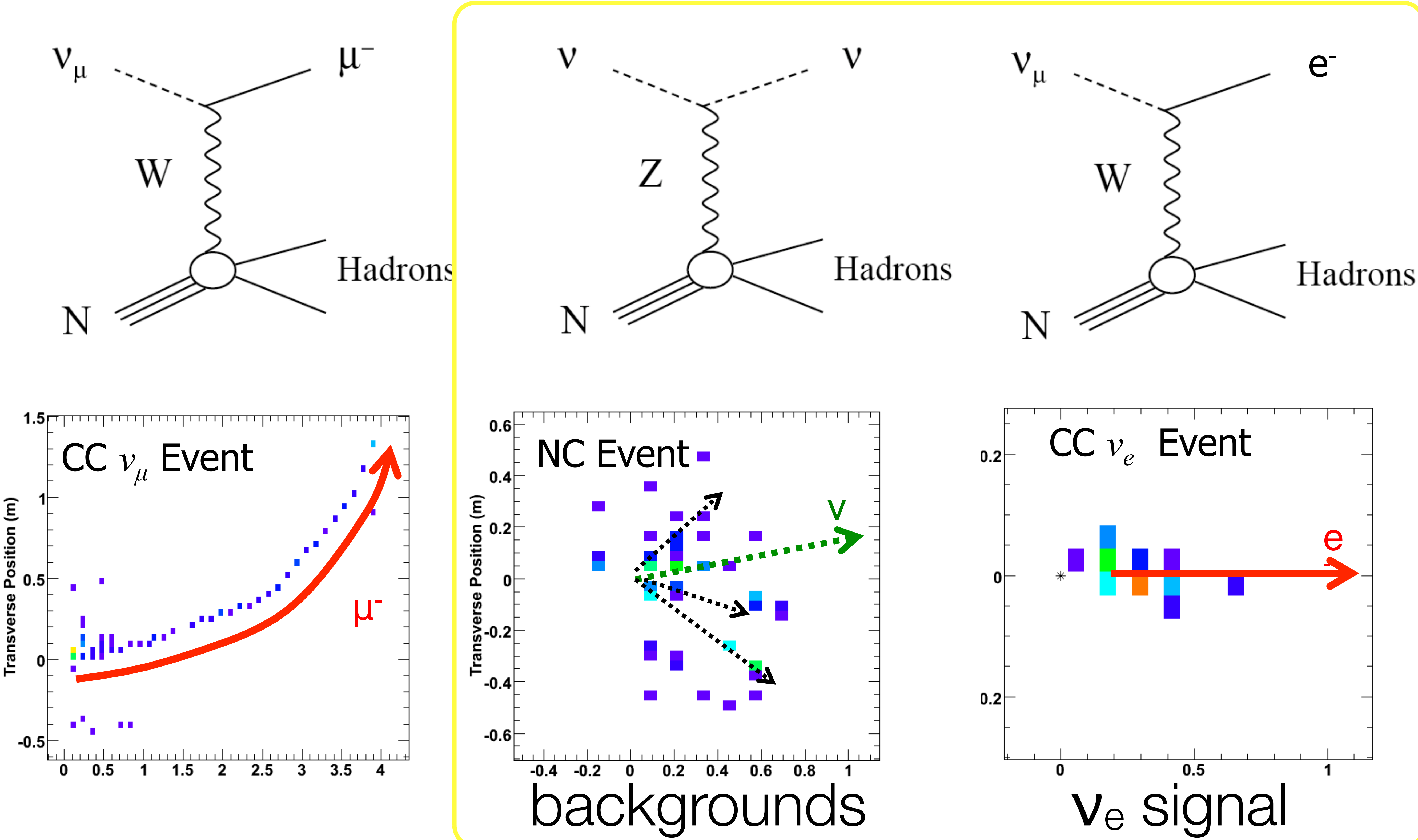
- For $\nu_\mu \rightarrow \nu_e$ oscillations interference introduces a dependence on the CP-violating phase δ
- Matter effect introduces a dependence on the sign of Δm^2_{31}



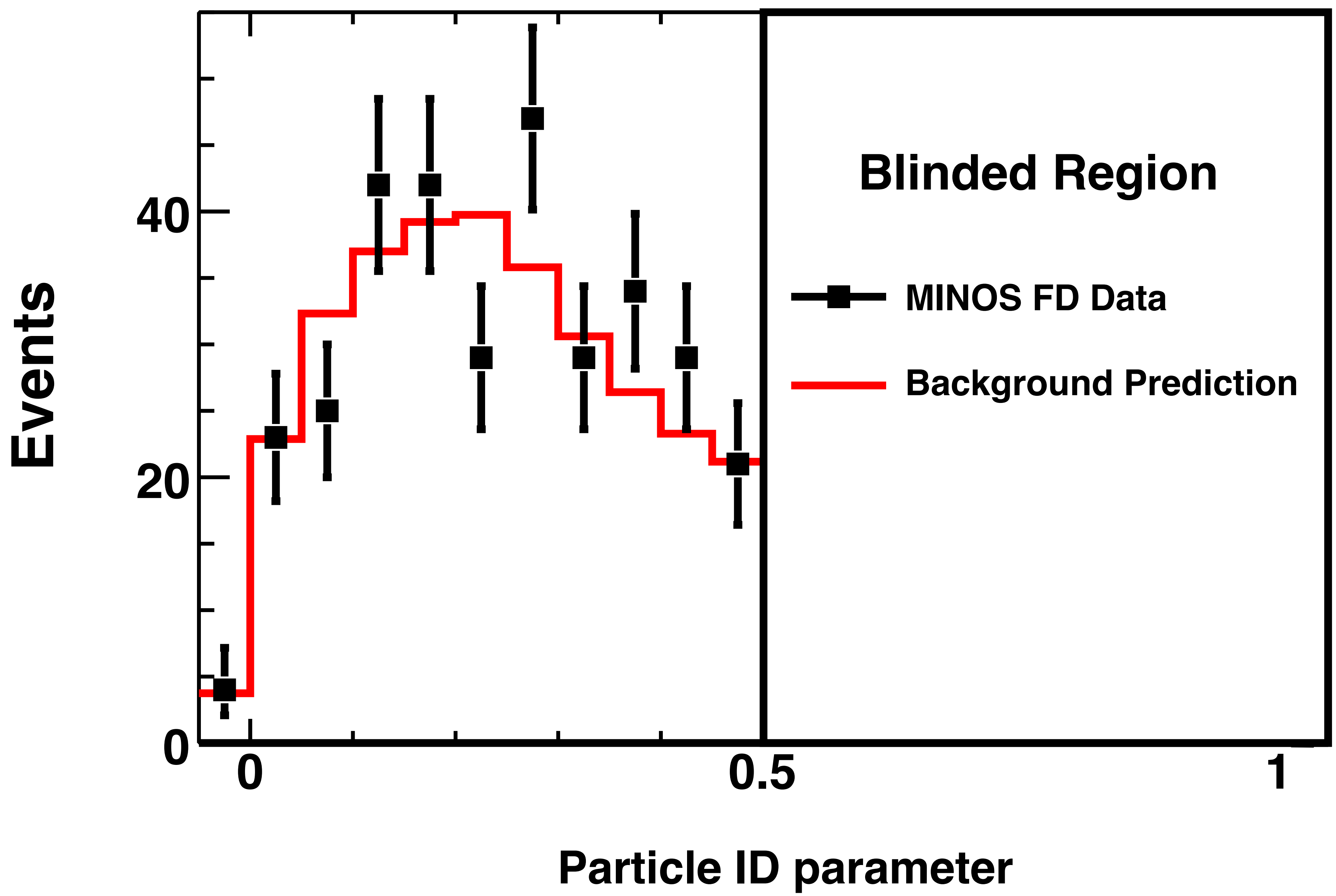


MINOS

Event Topologies

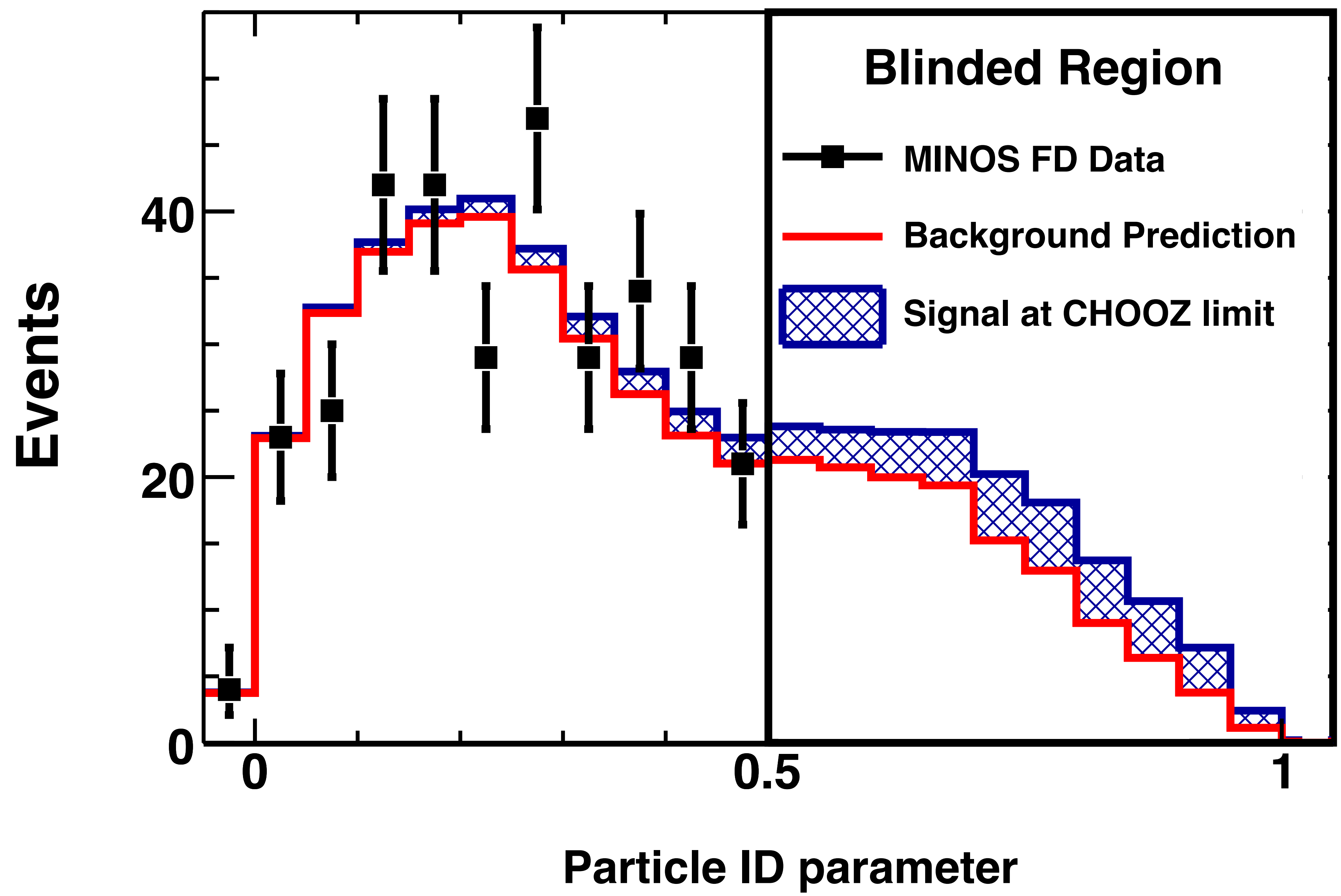


MINOS $\nu_\mu \rightarrow \nu_e$
What is θ_{13}?



⇐ backgrounds ν_e signal ⇒

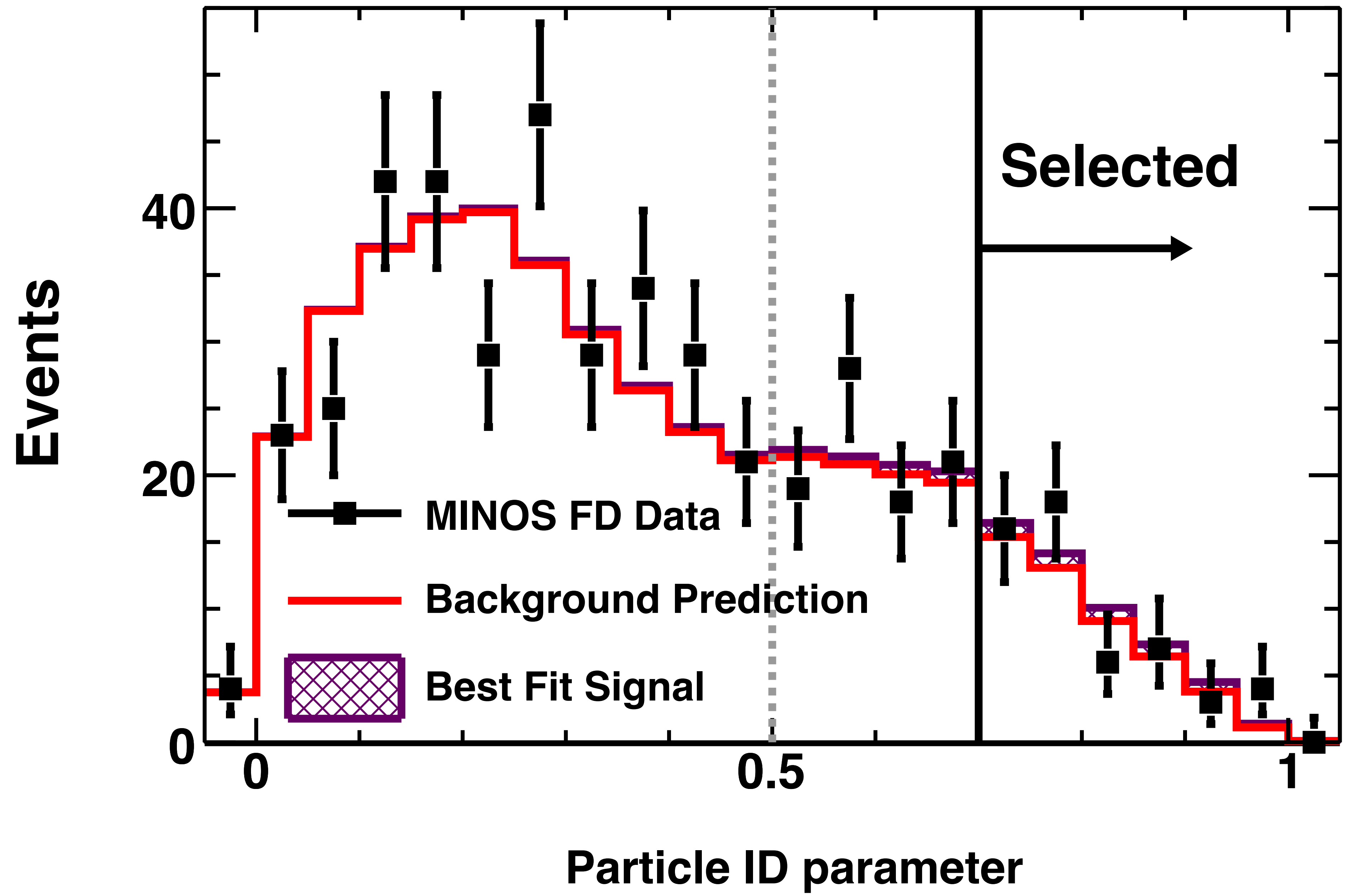
MINOS $\nu_\mu \rightarrow \nu_e$
What is θ_{13}?



⇐ backgrounds ν_e signal ⇒

MINOS $\nu_\mu \rightarrow \nu_e$

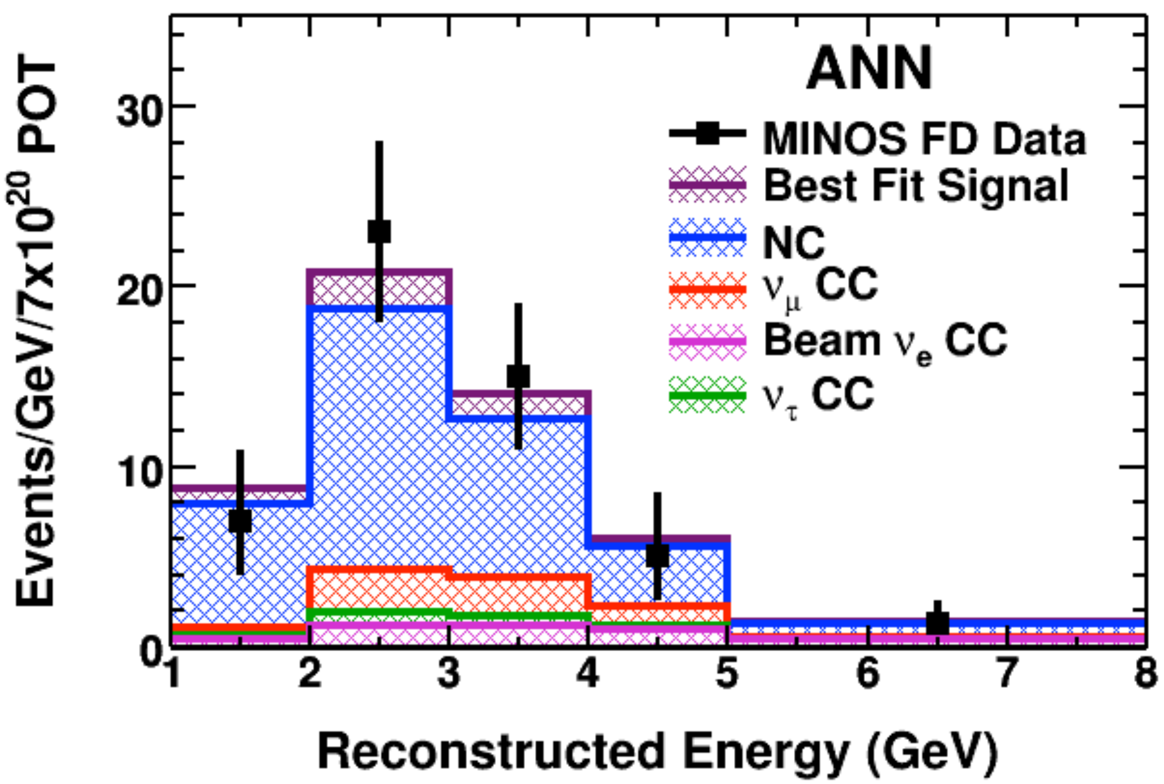
What is θ_{13}?



⇐ backgrounds ν_e signal ⇒

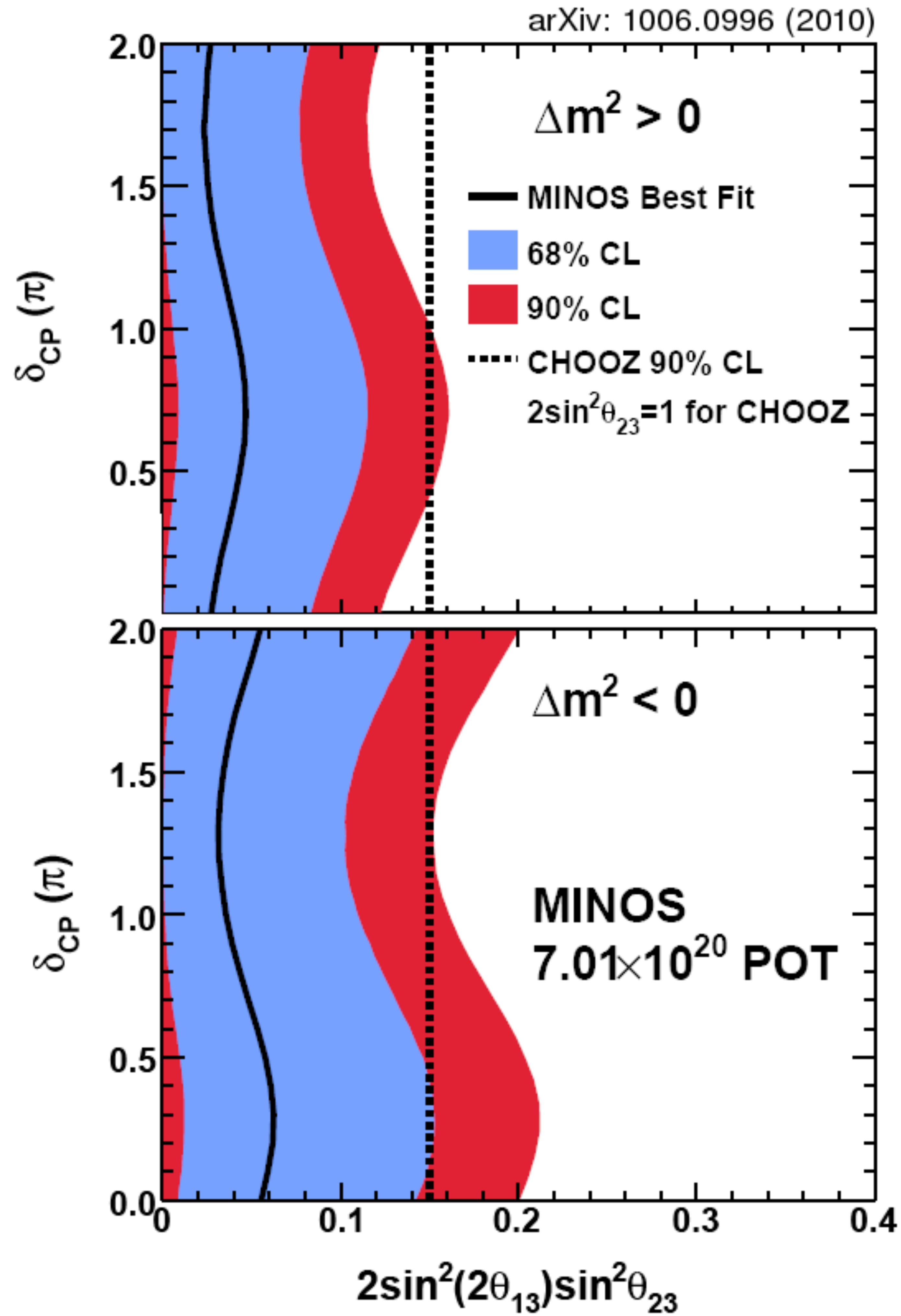
MINOS $\nu_\mu \rightarrow \nu_e$

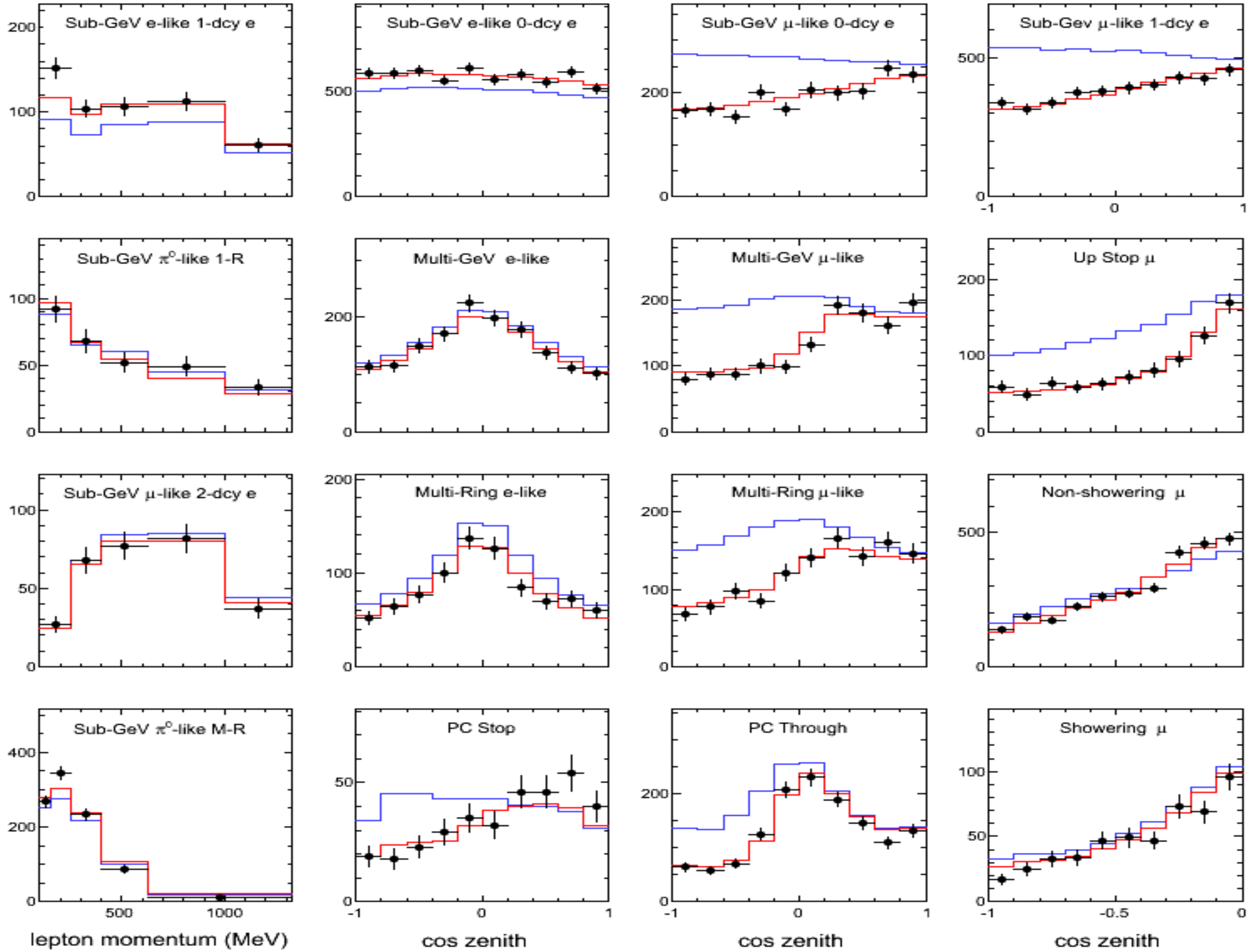
What is θ_{13}?



- 49.1 ± 7.0 (stat.) ± 2.7 (syst.) expected
- 54 Observed (0.7σ excess)

- $\sin^2(2\theta_{13})$<0.12 (NH 90% C.L.)
- $\sin^2(2\theta_{13})$<0.20 (IH 90% C.L.)





Super-Kamiokande
Atmospheric Neutrinos

~3000 days of exposure
no oscillations / best fit $\nu_\mu \rightarrow \nu_\tau$

Normal Hierarchy X^2=469.9/416 DOF

Parameter	Best point	90% C.L. allowed	68% C.L. allowed
Δm^2_{23} (x10^3)	2.11 eV^2	1.88 - 2.75 eV^2	1.99 - 2.54 eV^2
$\sin^2\theta_{23}$	0.525	0.406 - 0.629	0.441 - 0.597
$\sin^2\theta_{13}$	0.006	< 0.066	< 0.036
CP-δ	220º	-	140.8 - 297.3º

Inverted Hierarchy X^2=468.3/416 DOF

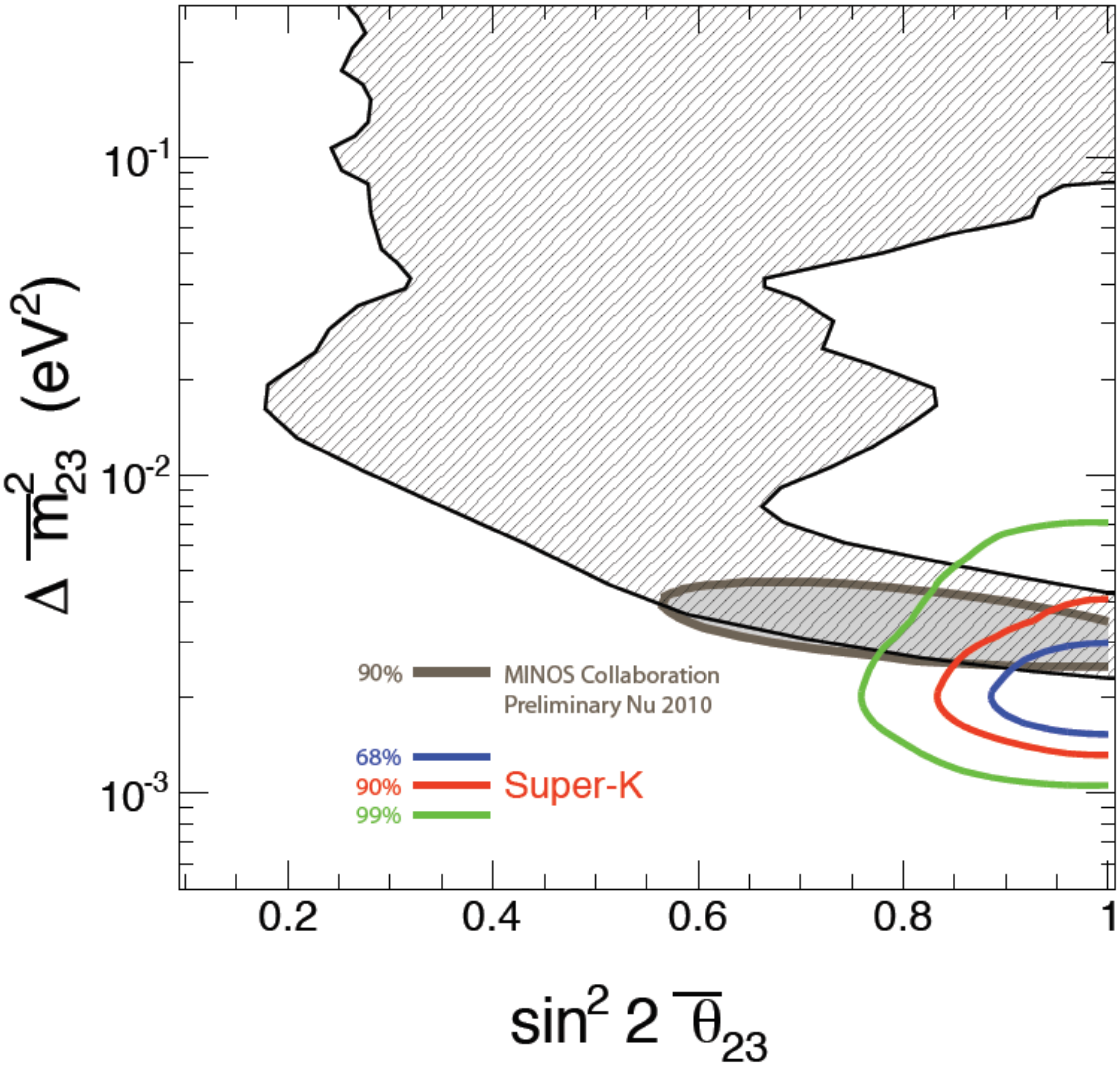
Parameter	Best point	90% C.L. allowed	68% C.L. allowed
Δm^2_{23} (x10^3)	2.51 eV^2	1.98 - 2.81 eV^2	2.09 - 2.64 eV^2
$\sin^2\theta_{23}$	0.575	0.426 - 0.644	0.501 - 0.623
$\sin^2\theta_{13}$	0.044	< 0.122	0.0122 - 0.0850
CP-δ	220º	121.4 - 319.1º	165.6 - 280.4º

Super-Kamiokande

Three flavor results

θ_{12} Δm^2_{12} fixed at solar values.

arXiv:1002.3471v2



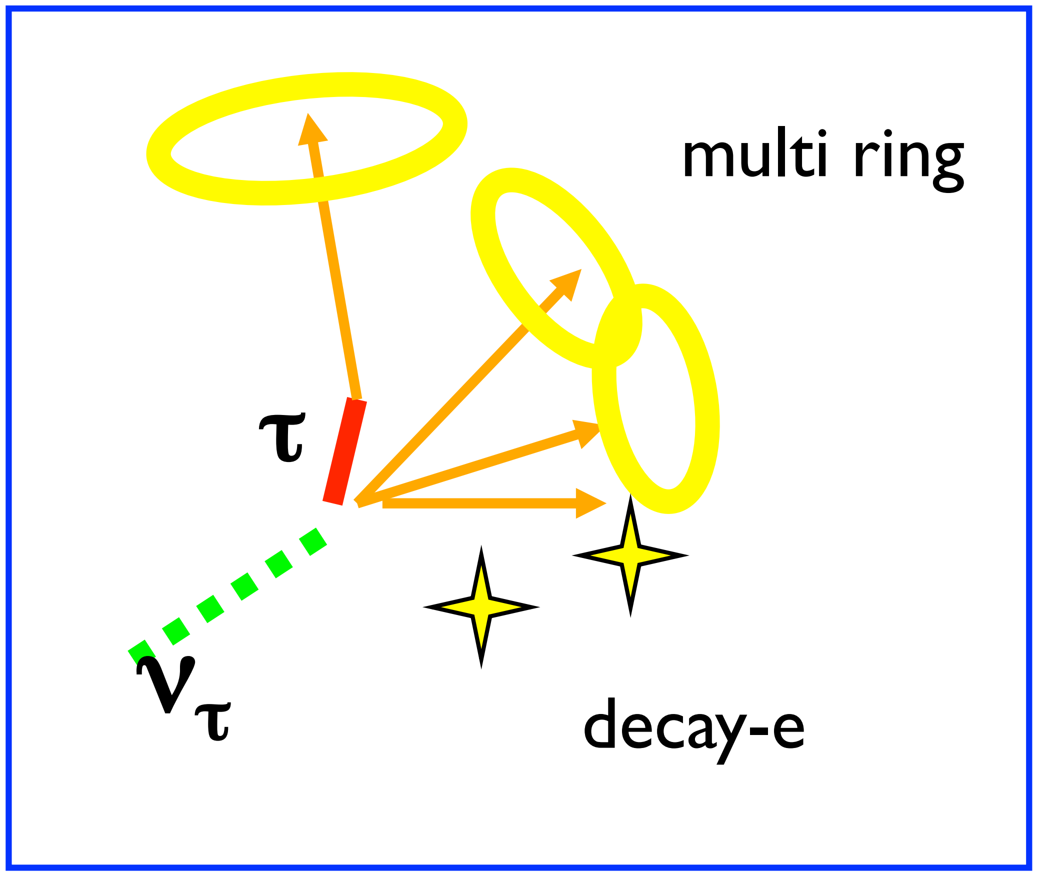
Super-Kamiokande

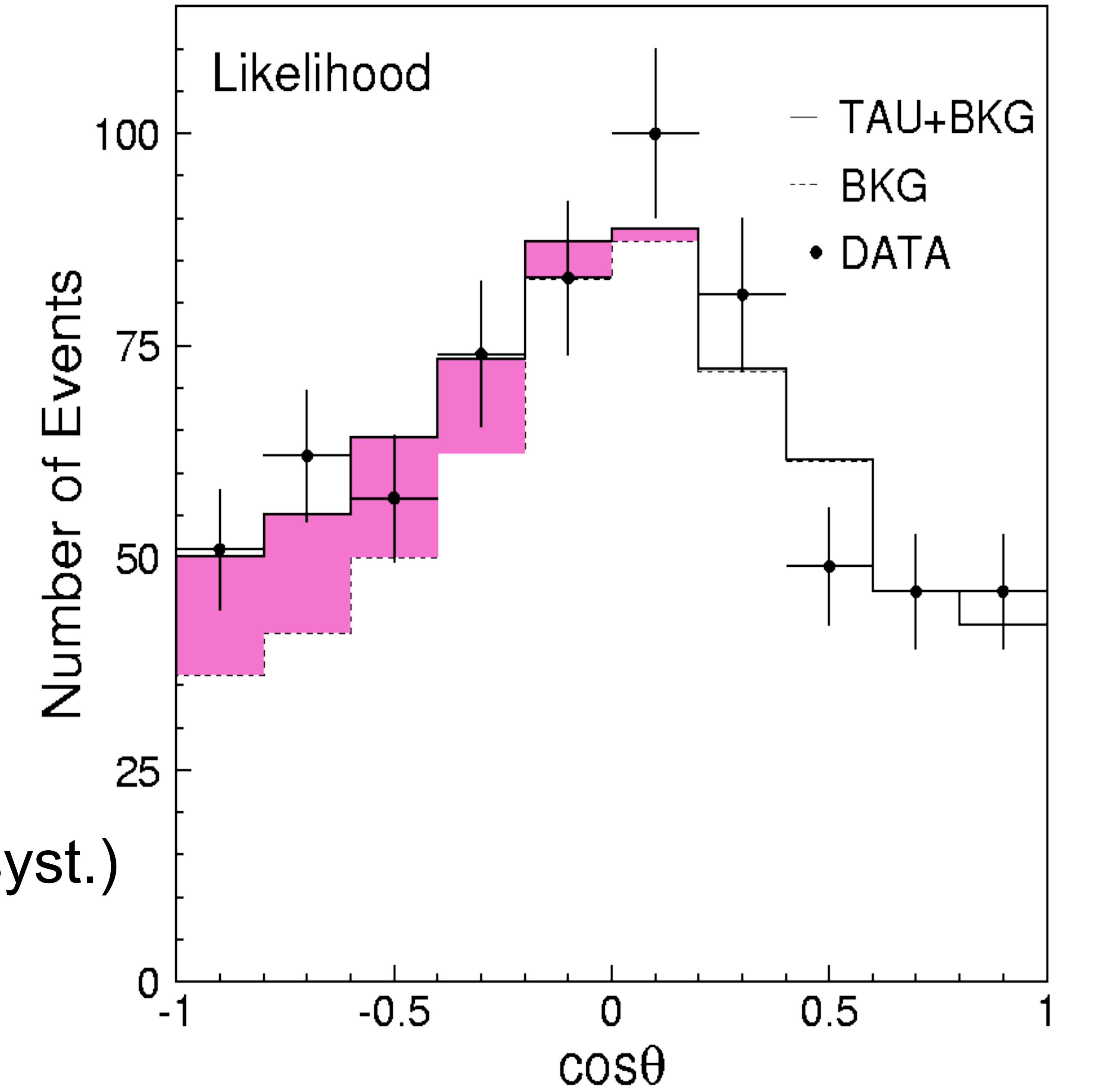
Antineutrino oscillations

$$\begin{aligned} \Delta\bar{m}^2_{23} &= 2.0\times 10^{-3}\ \text{eV}^2 \\ \sin^2(2\bar{\theta}_{23}) &= 1.0 \end{aligned}$$

Super-Kamiokande

Statistical Search for ν_τ Appearance



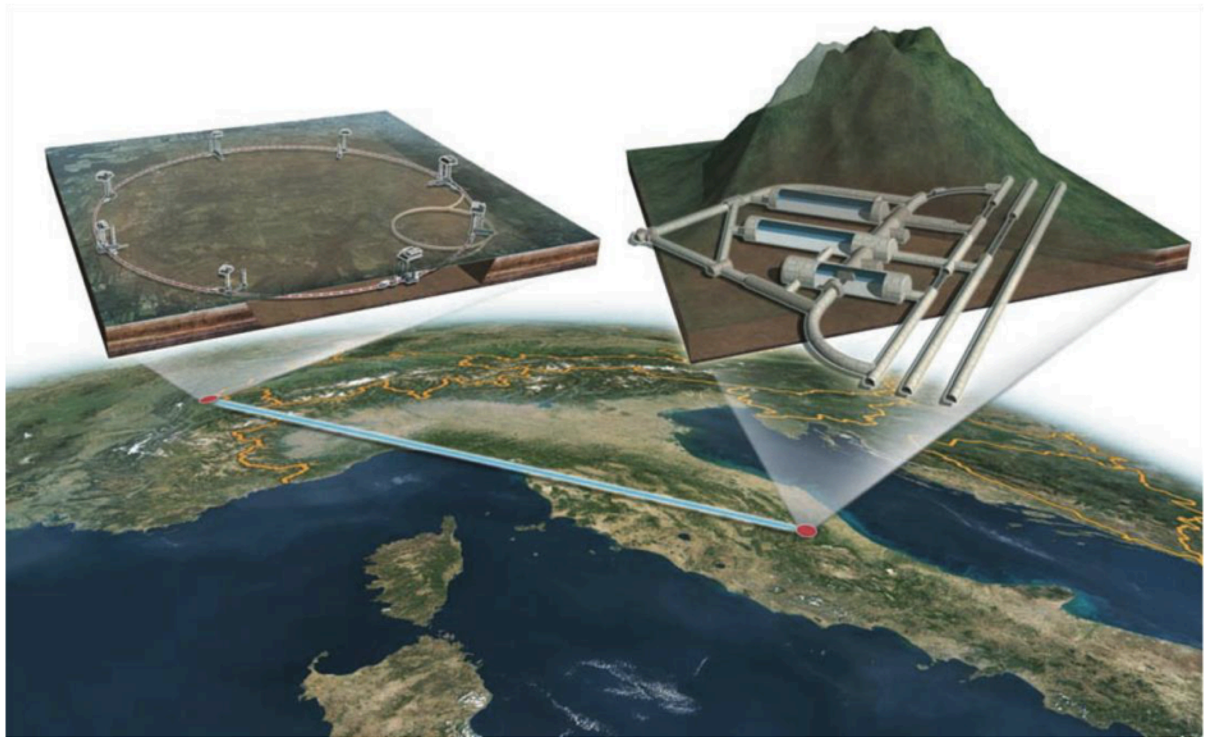


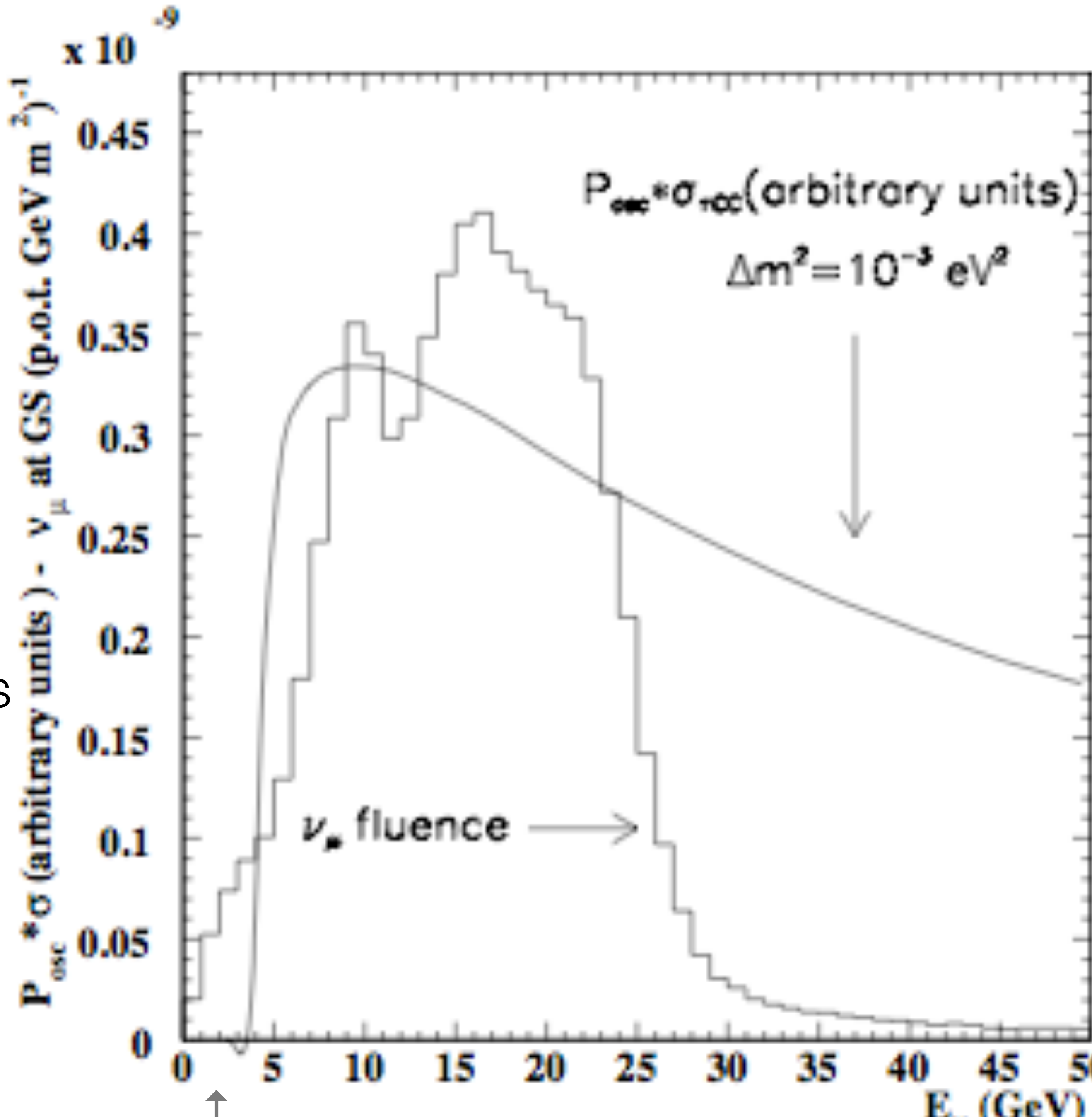
- Best-fit tau excess:
  138+/-48(stat.)+15/-32(syst.)
- Expected: 78+/-26(syst.)

PRL97,171801 (2006)

OPERA

Direct observation of of ν_τ from $\nu_\mu \rightarrow \nu_\tau$ oscillations



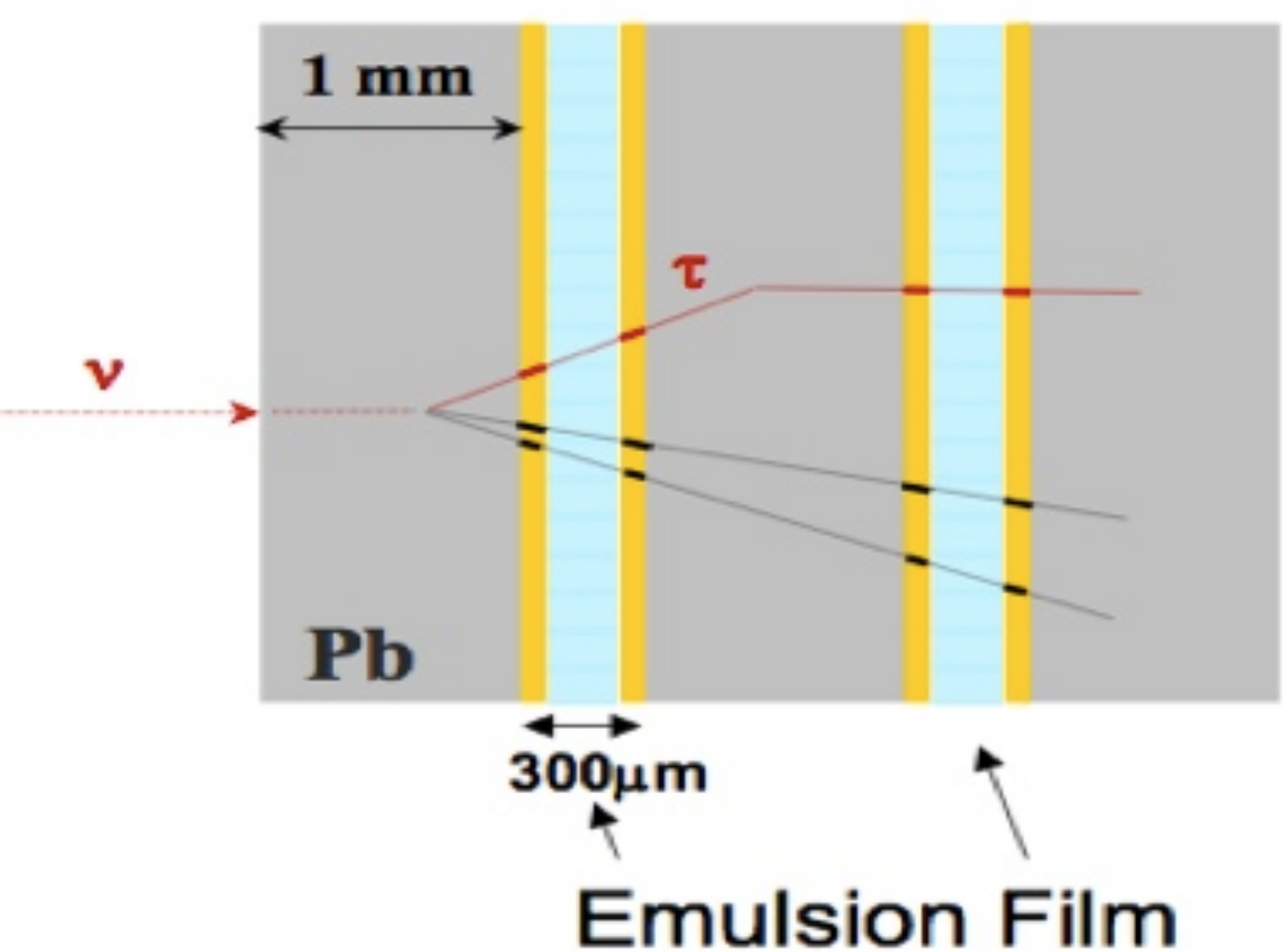


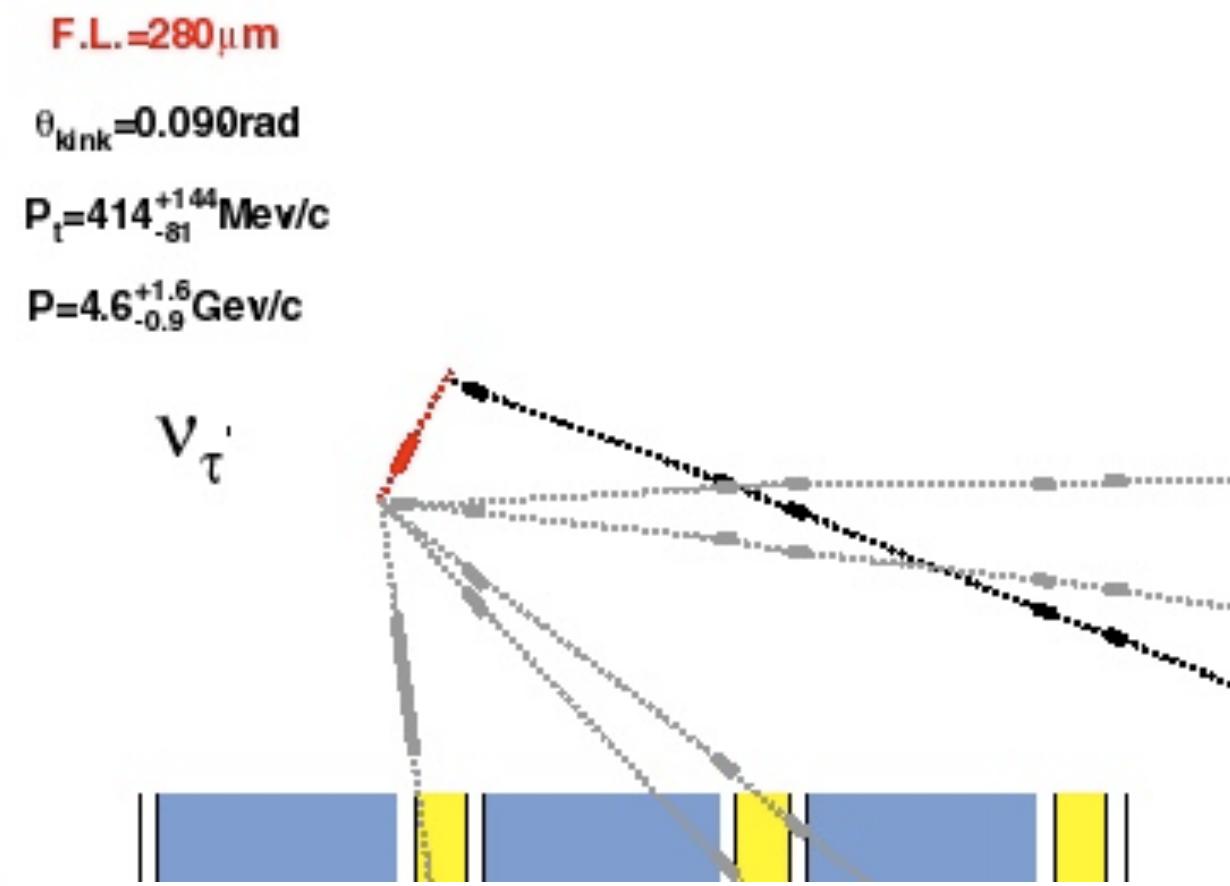
- Beam tuned to maximize ν_τ interactions at 730 km.
- Far from oscillation maximum due to high τ production threshold
- Collected 7.04×10^{19} protons on target through July 2010. Expected rates:
  - 7380 ν_μ CC + NC
  - 50 ν_e CC
  - 36 ν_τ CC (2.5×10^{-3} eV^2)

↑

oscillation maximum @1.4 GeV

OPERA
Lead/Emulsion Target Bricks

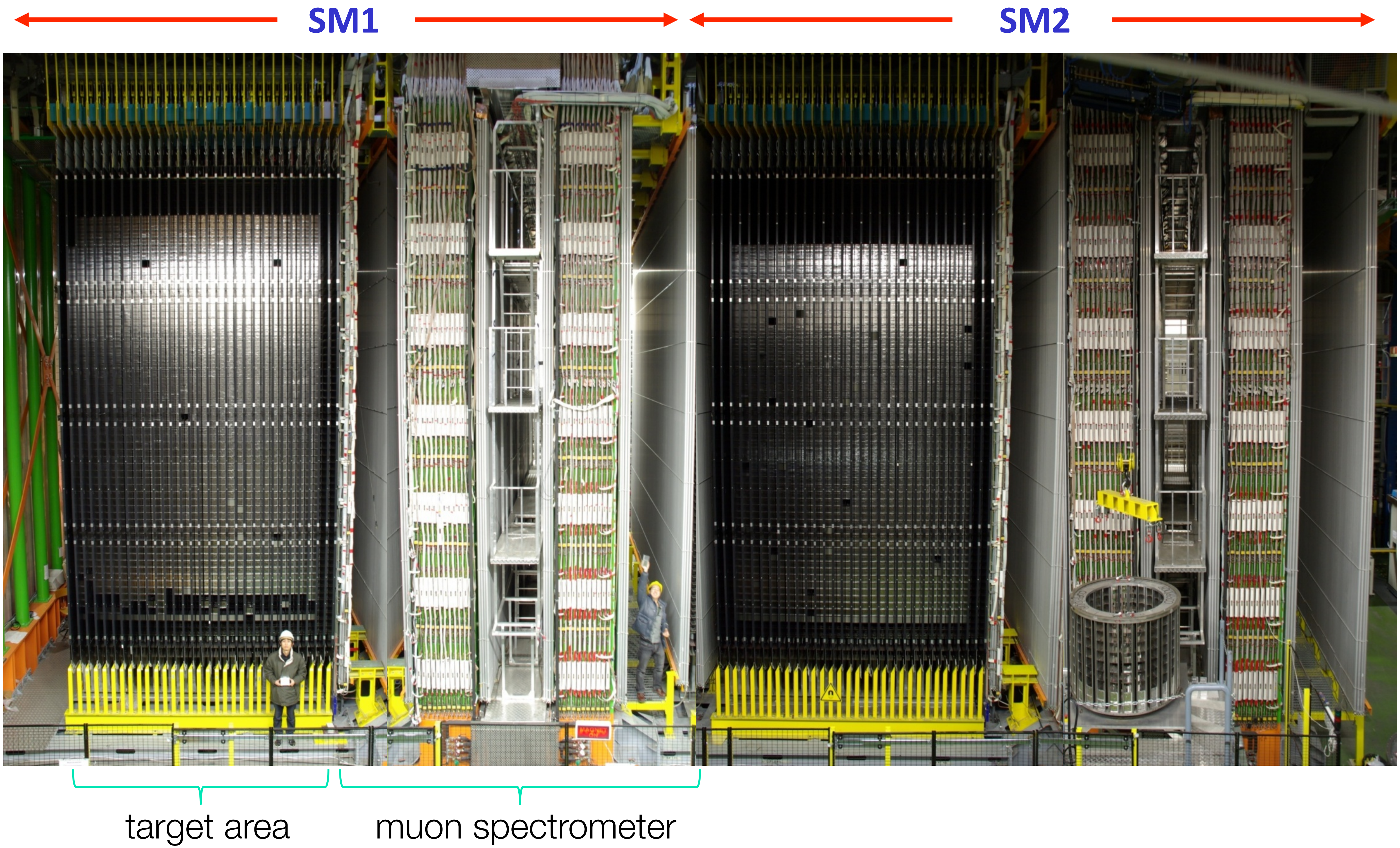




Direct observation of ν_τ by DONUT
9 events / 1.5 BG
Phys. Lett. B 504, 218 (2001)

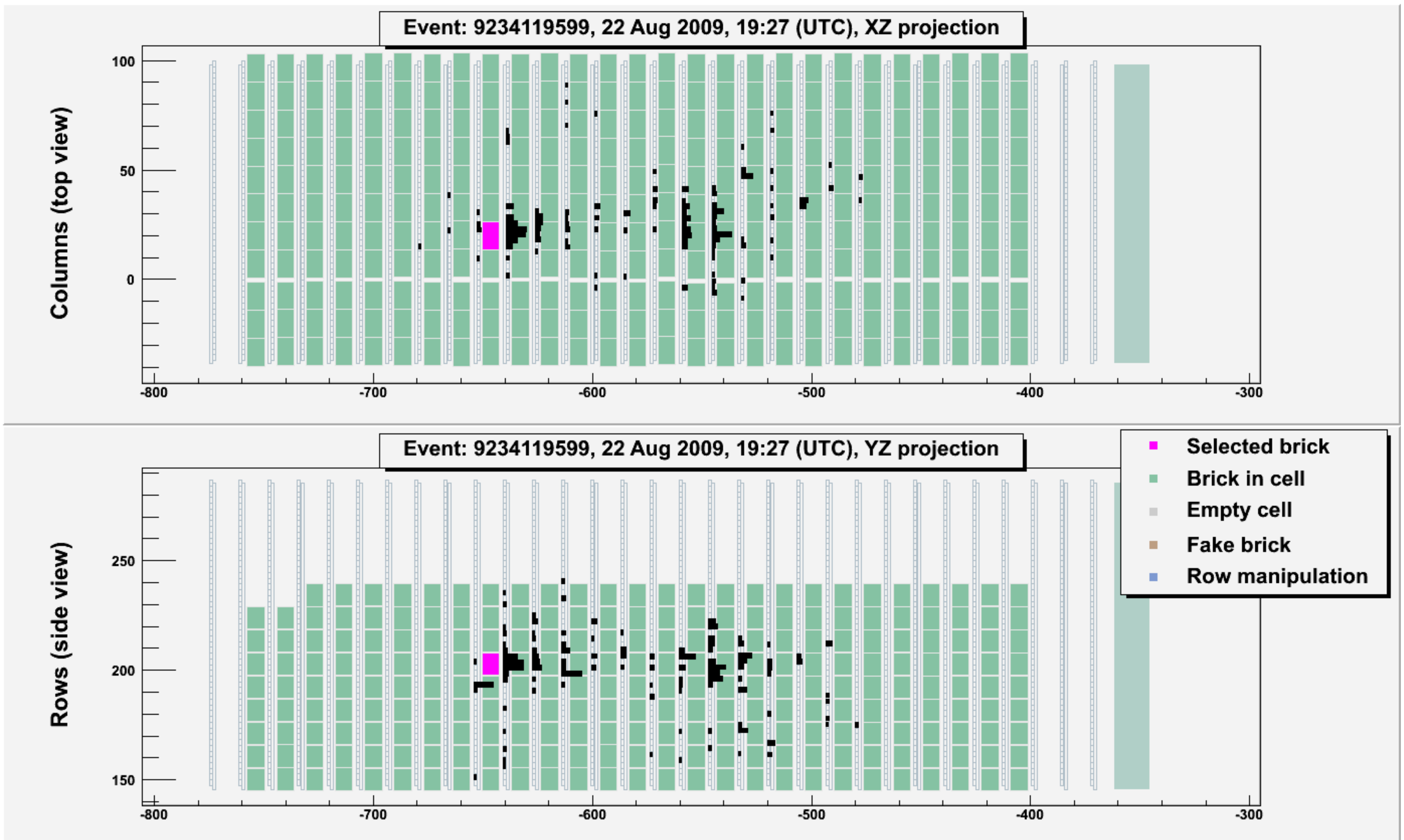
OPERA

Lead-emulsion bricks with muon spectrometer

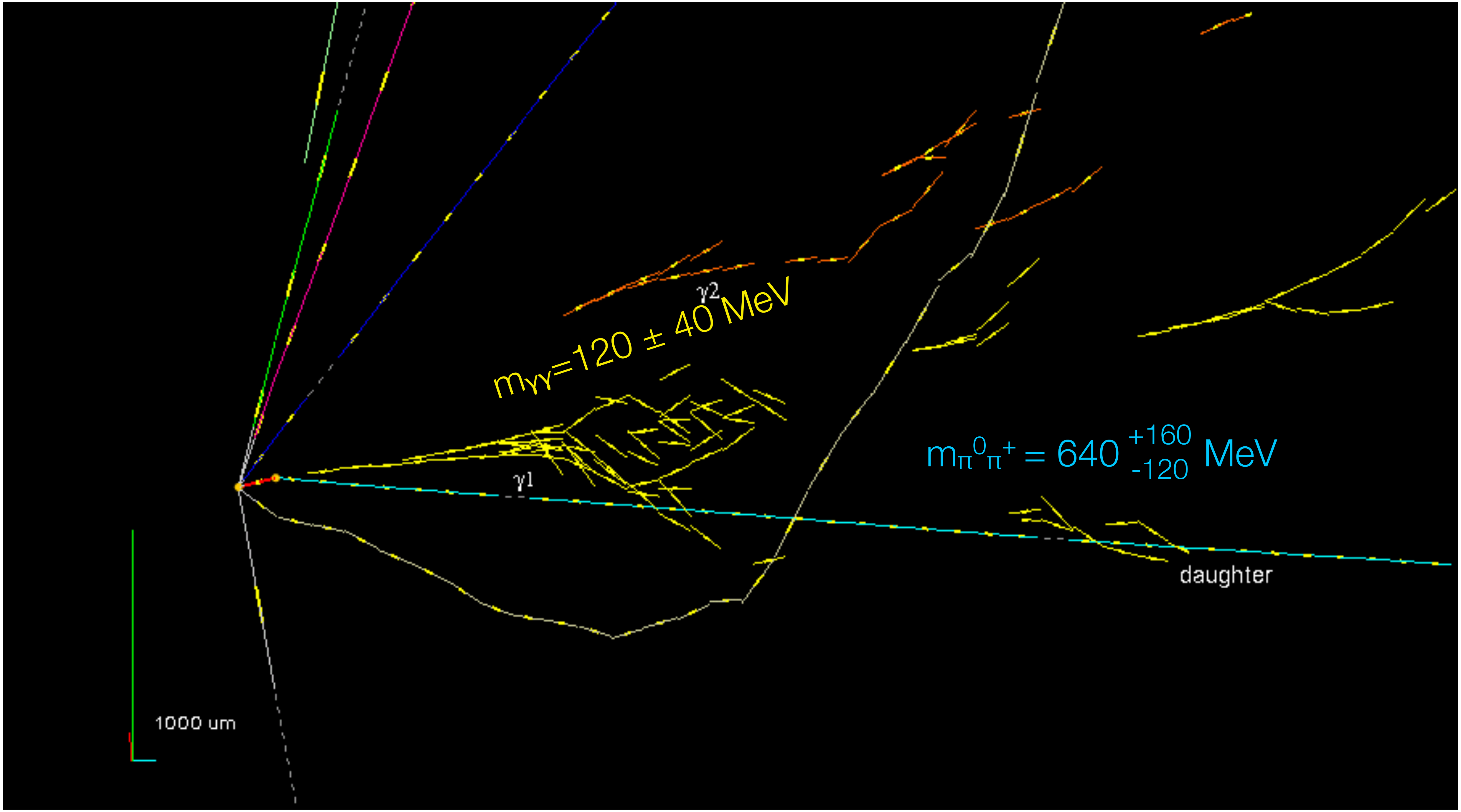


OPERA

Muon-less event UTC 22 August 2009, 19:27

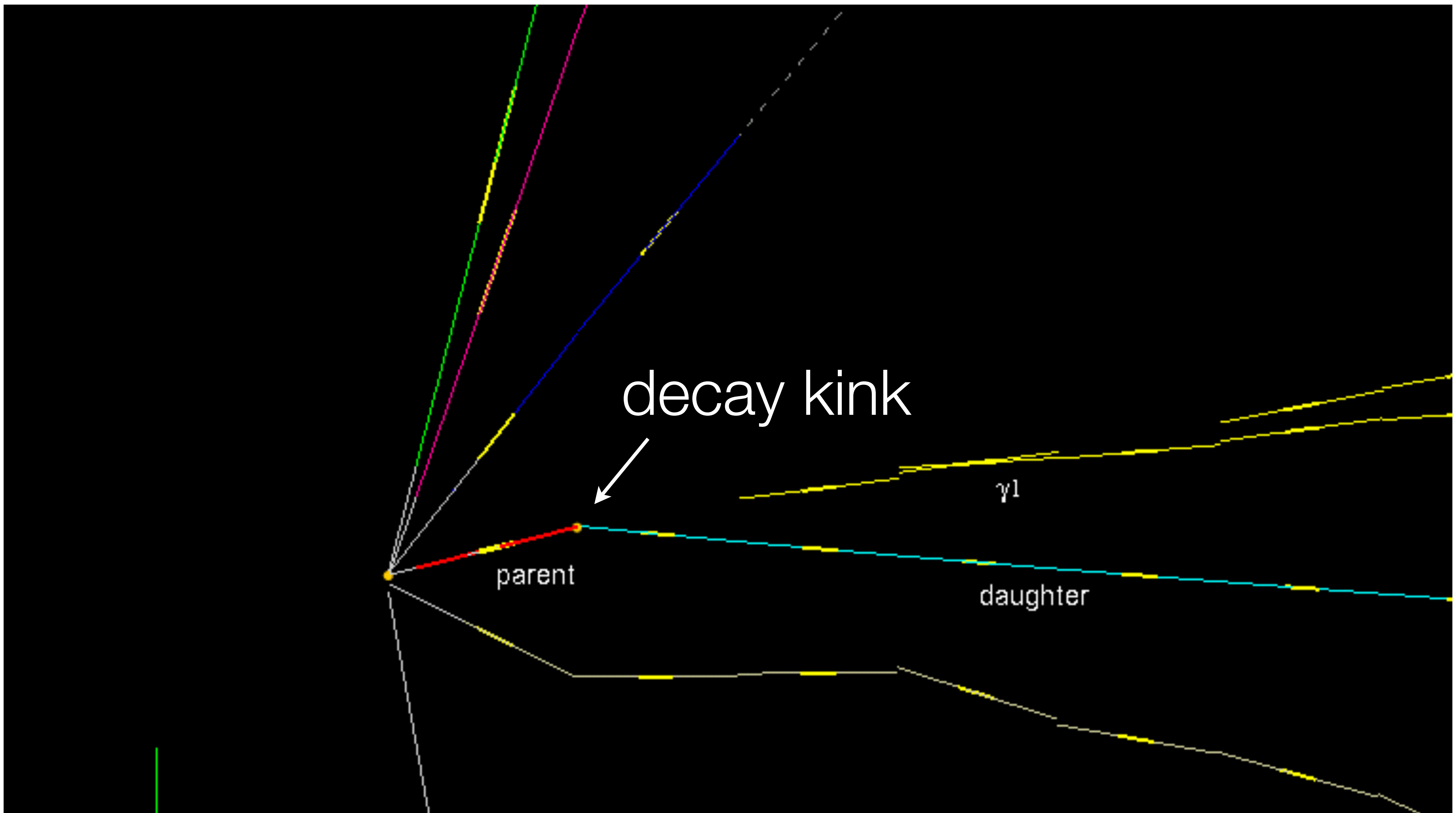


OPERA
Muon-less event



25% of tau's decay via $\tau \rightarrow \rho(770)\ \nu_\tau$

Observation of a first ν_τ candidate event in the **OPERA** experiment in the CNGS beam *Phys. Lett. B 691 (2010)*



1 ν_τ event / 0.045 ± 0.020 background (2σ significance)
Complete scan of all data through 2009 by end of year
Continue running through 2012

Quick look ahead
(More tomorrow in "New Experiments" session)

- Next generation of oscillations experiments soon to be coming online
- Focus is
  - Is $\theta_{13}>0$?
  - What is the neutrino mass hierarchy?
  - Is $\theta_{23}=45^{o}$ a new symmetry?
  - Is CP violated in the lepton sector?

Double CHOOZ / Daya Bay / Reno

Is $\theta_{13}>0$?

$\bar{\nu}_e \to \bar{\nu}_e$ at nuclear reactors

<u>*Double Chooz*</u>

-Running by the end of the year

-$\sin^2 2\theta_{13}$ = 0.06 (90%CL) by 2011

-$\sin^2 2\theta_{13}$ = 0.03 by 2014

<u>*RENO*</u>

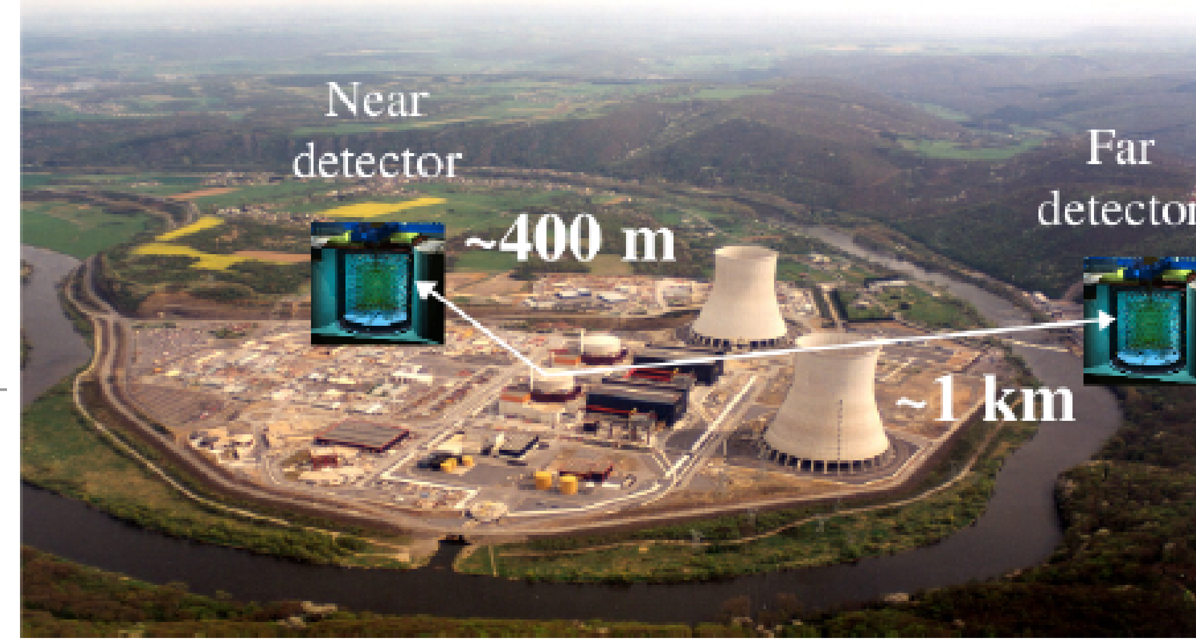
-Running in early 2011

-$\sin^2 2\theta_{13}$ = 0.02 by 2014

<u>*Daya Bay*</u>

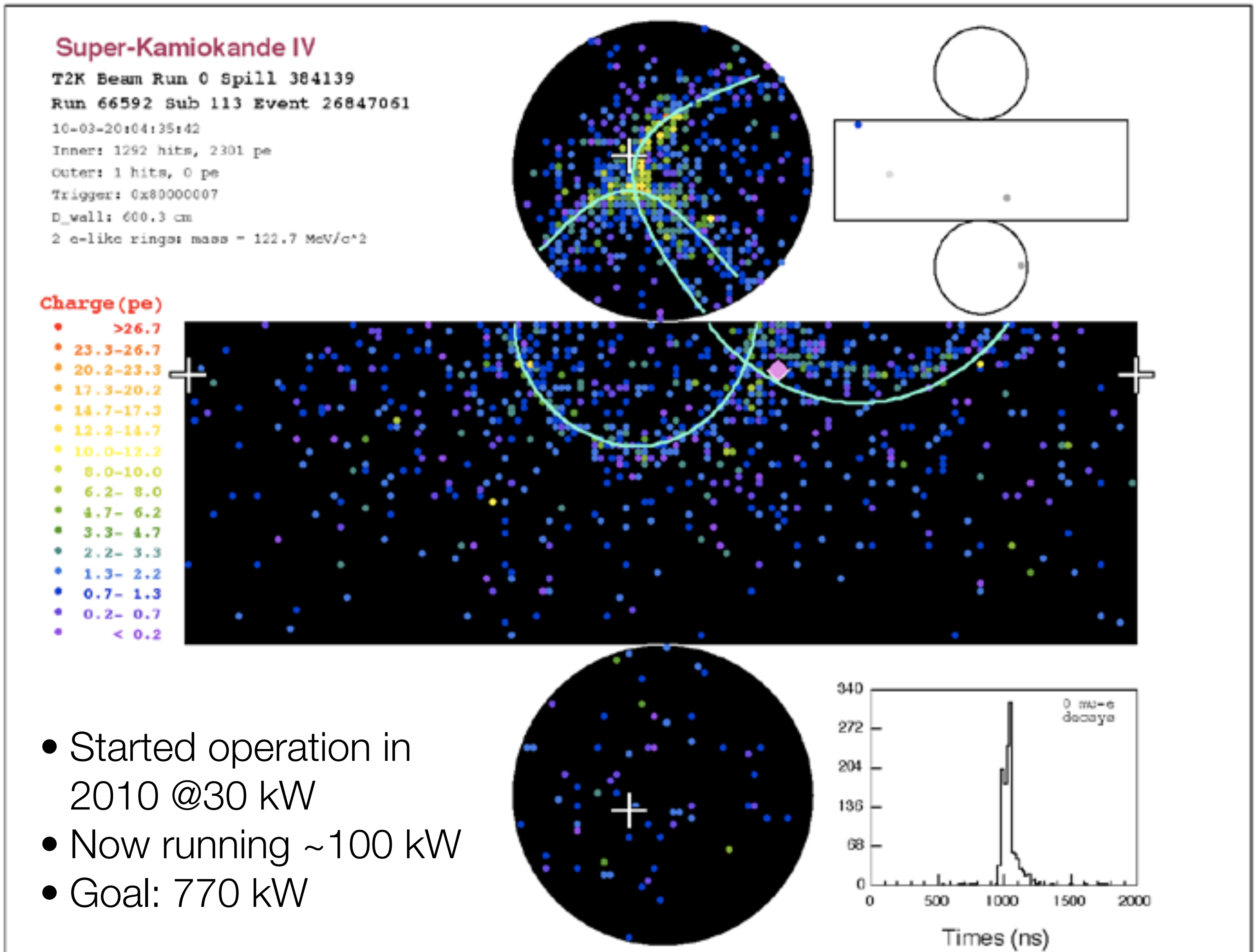
-Data taking in 2012

-$\sin^2 2\theta_{13}$ = 0.01 by 2014



T2K

$\nu_\mu \rightarrow \nu_e$ search and precision $\nu_\mu \rightarrow \nu_\mu$

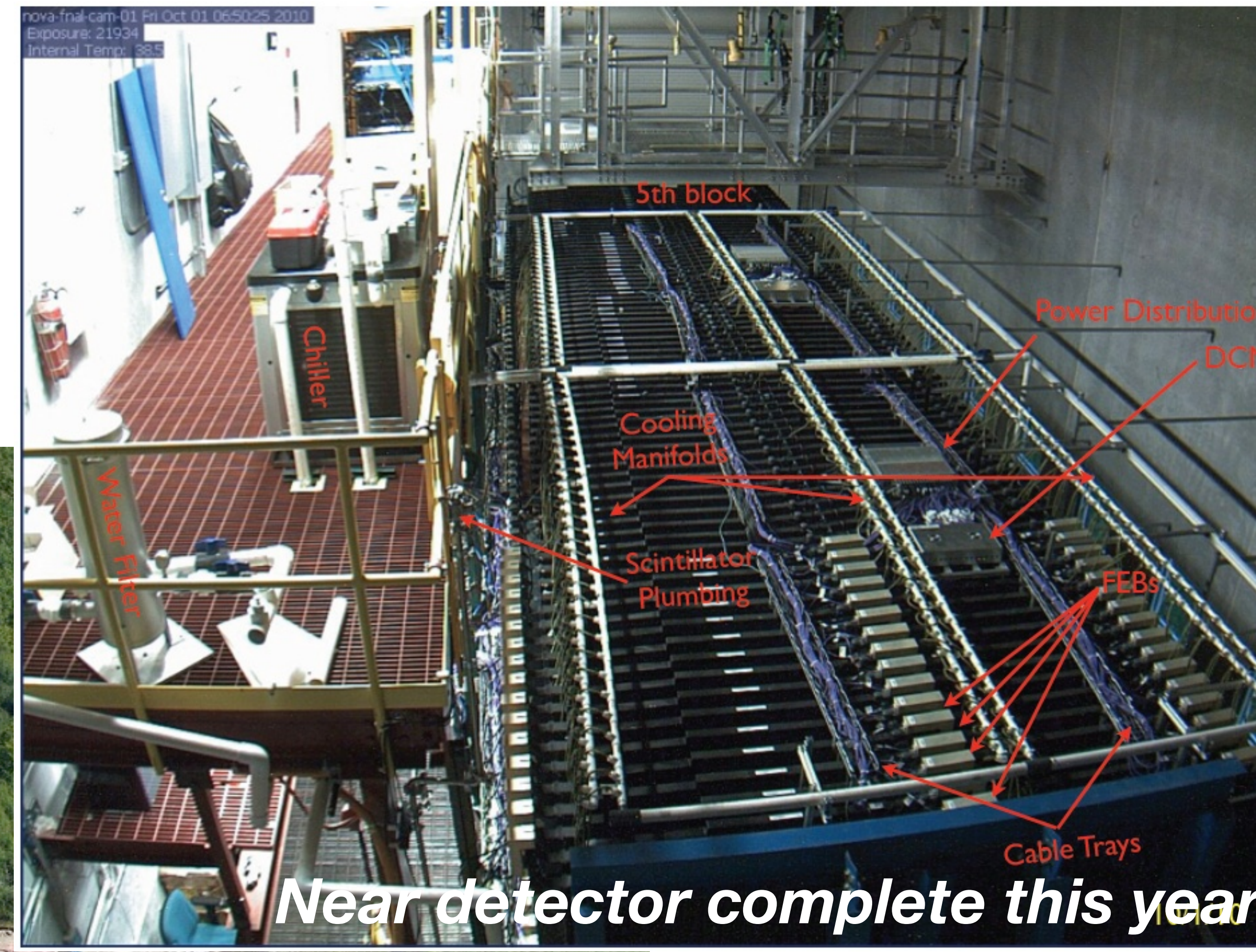


- Started operation in 2010 @30 kW
- Now running ~100 kW
- Goal: 770 kW

NOvA

$\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$ search, precision $\nu_\mu \to \nu_\mu$ & $\bar{\nu}_\mu \to \bar{\nu}_\mu$

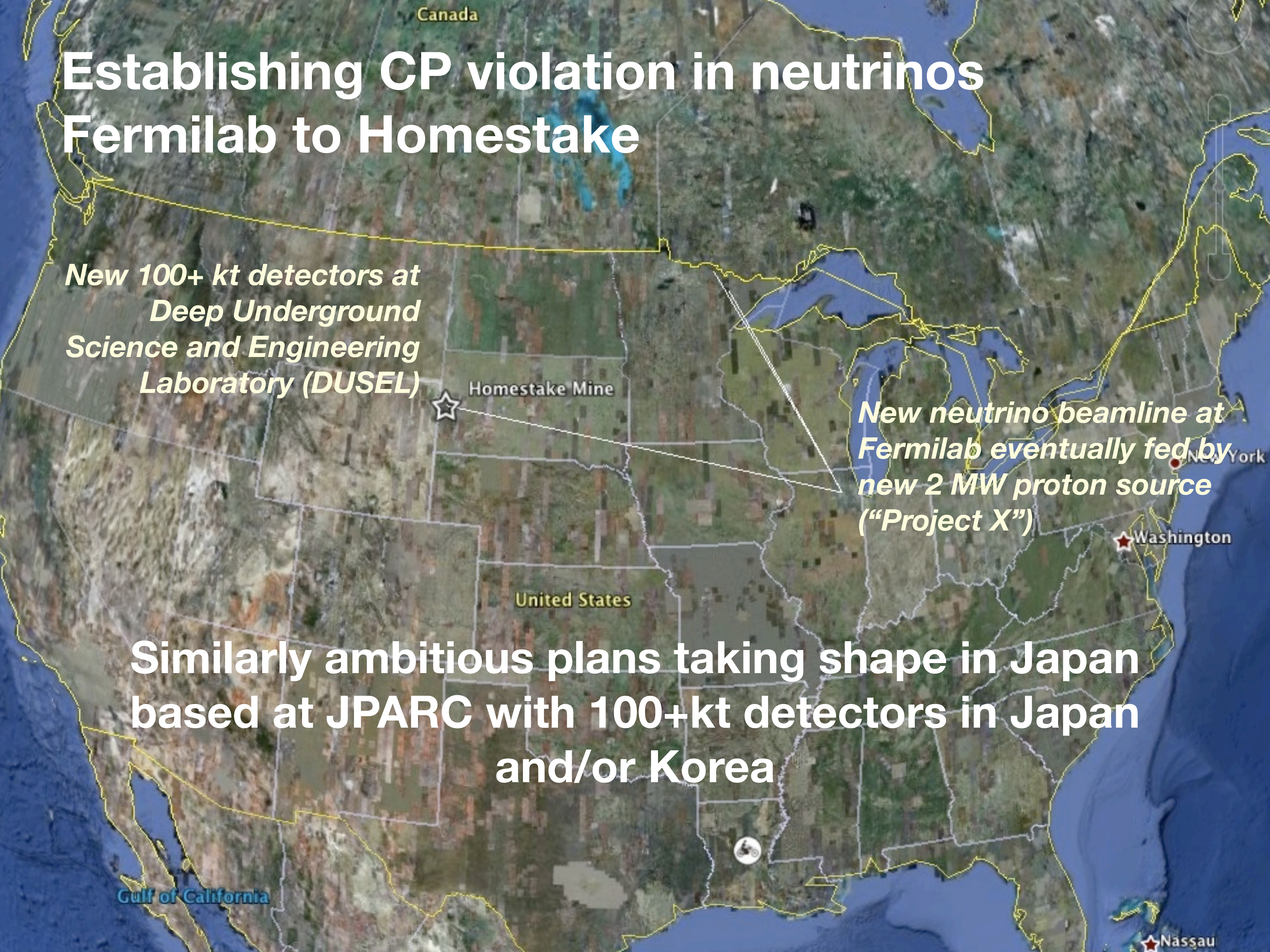
Second generation NuMI oscillation experiment
First data in 2013



Near detector complete this year

Far detector lab complete in 2011

Establishing CP violation in neutrinos Fermilab to Homestake



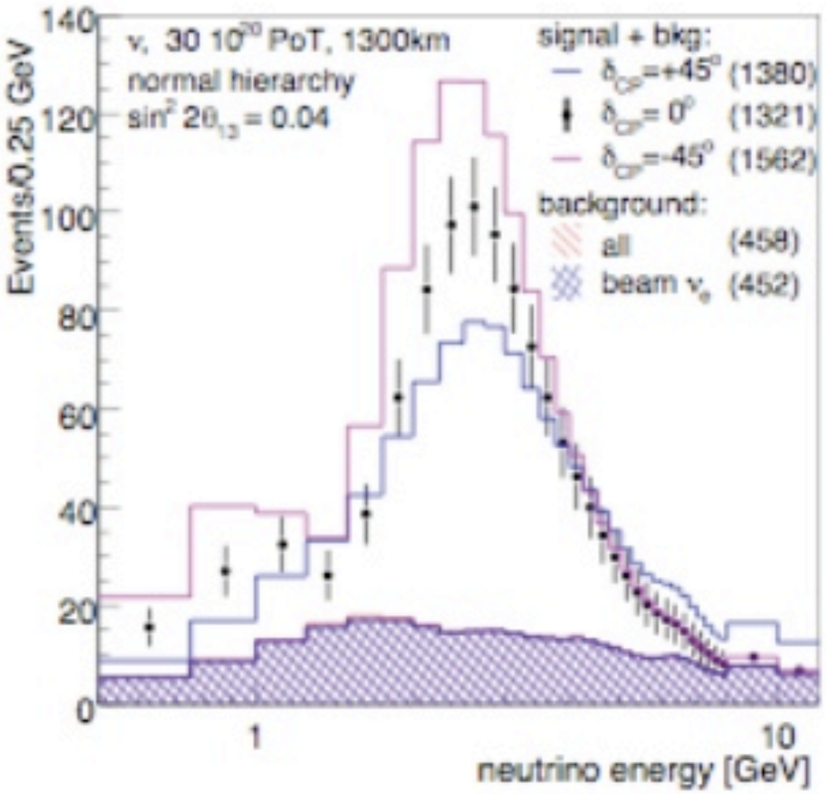
New 100+ kt detectors at Deep Underground Science and Engineering Laboratory (DUSEL)

New neutrino beamline at Fermilab eventually fed by new 2 MW proton source ("Project X")

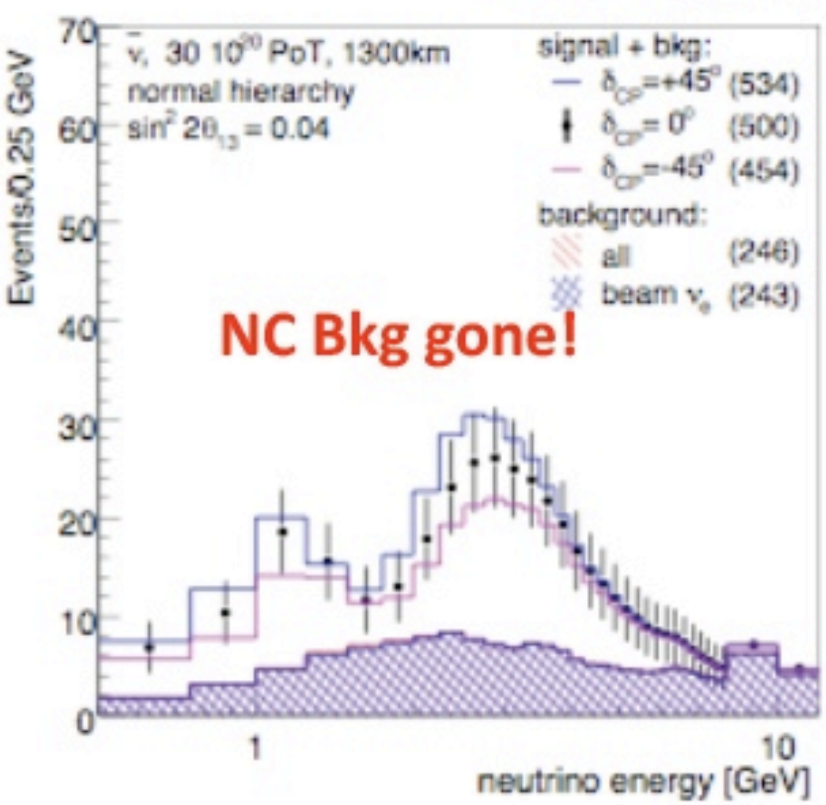
Similarly ambitious plans taking shape in Japan based at JPARC with 100+kt detectors in Japan and/or Korea

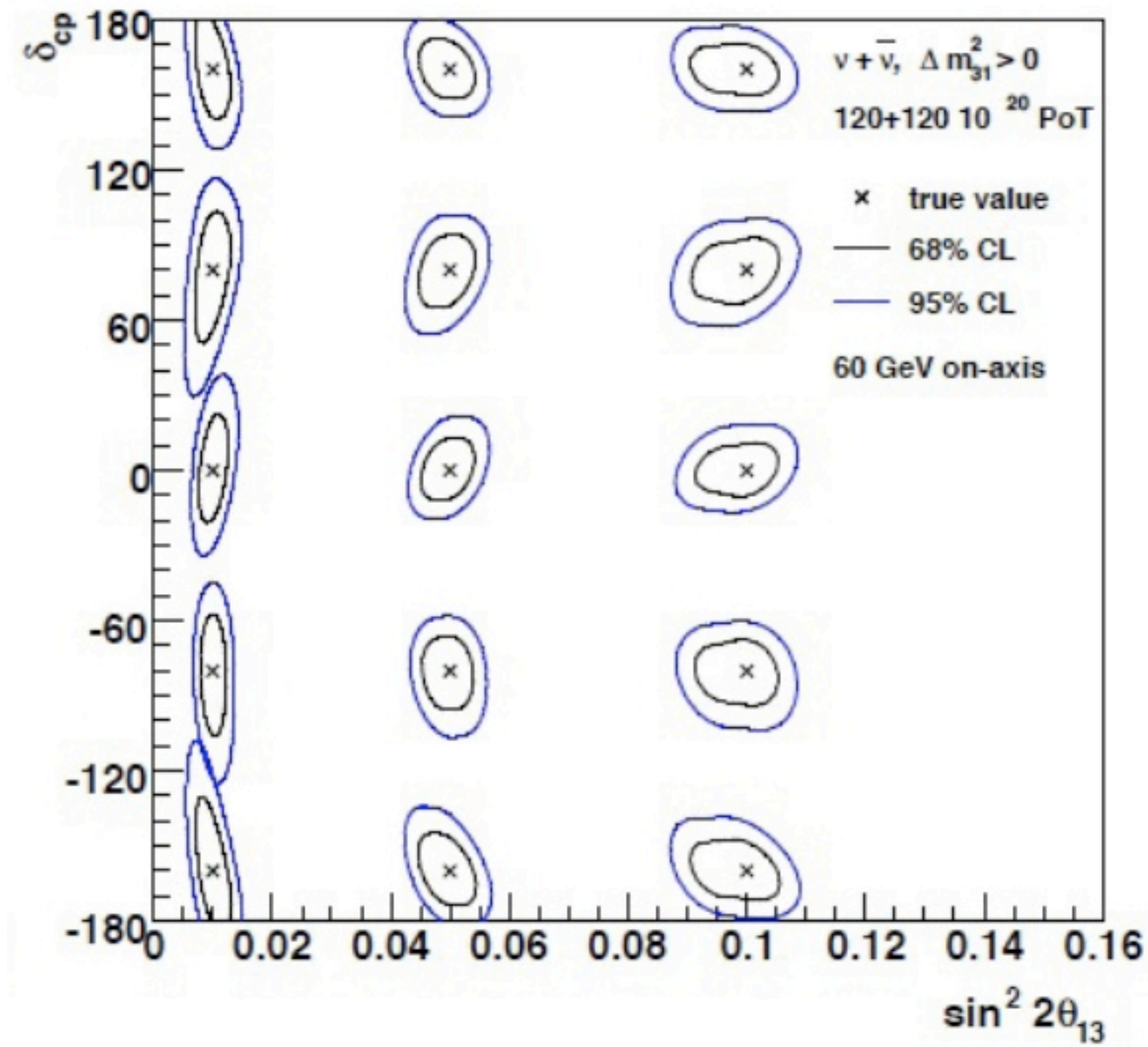
Establishing CP violation in neutrinos

ν



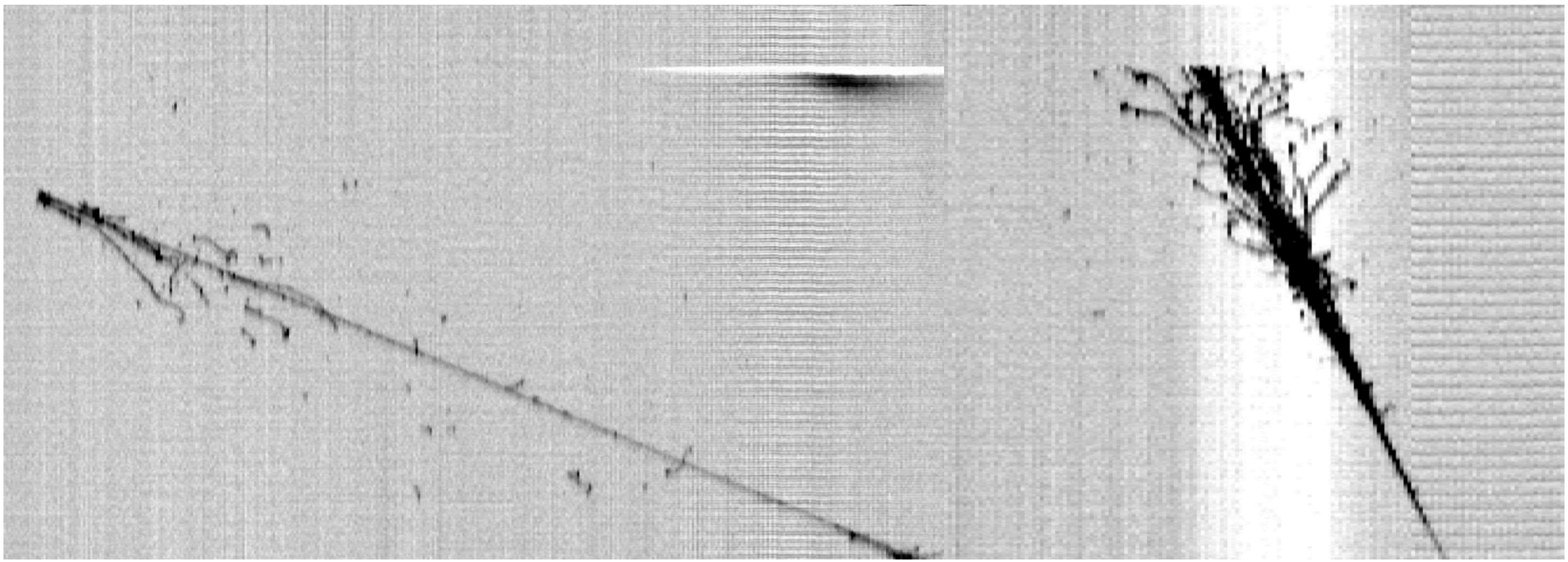
$\bar{\nu}$





ICARUS

Large scale Liquid Argon Time Projection Chamber



ICARUS has been operational since May 2010

0.6 kT Liquid Argon TPC

~1 mm granularity

Summary

- ***MINOS***

$$\nu_\mu \rightarrow \nu_\mu \quad \begin{array}{rcl} |\Delta m^2| & = & 2.35^{+0.11}_{-0.08} \times 10^{-3} \mathrm{eV}^2 \\ \sin^2(2\theta) & > & 0.91 \ (90\%\mathrm{C.L.}) \end{array} \quad \begin{array}{rcl} |\Delta \bar{m}^2| & = & 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \mathrm{eV}^2 \\ \sin^2 2\bar{\theta} & = & 0.86 \pm 0.11 \end{array}$$

$\nu_\mu \rightarrow \nu_e$ $\sin^2(2\theta_{13})<0.12$ (NH 90% C.L.), $\sin^2(2\theta_{13})<0.20$ (IH 90% C.L.)

- ***MiniBooNE*** - LSND-style oscillations not seen in neutrino running. Report confirmation in anti-neutrino running (99.4% C.L.).

- ***OPERA*** - Observation of $\nu_\mu \rightarrow \nu_\tau$ at >2 sigma.

- ***ICARUS*** - now operational. First large scale LqAr TPC.