Neutrinos:
General Overview of the Experimental Situation

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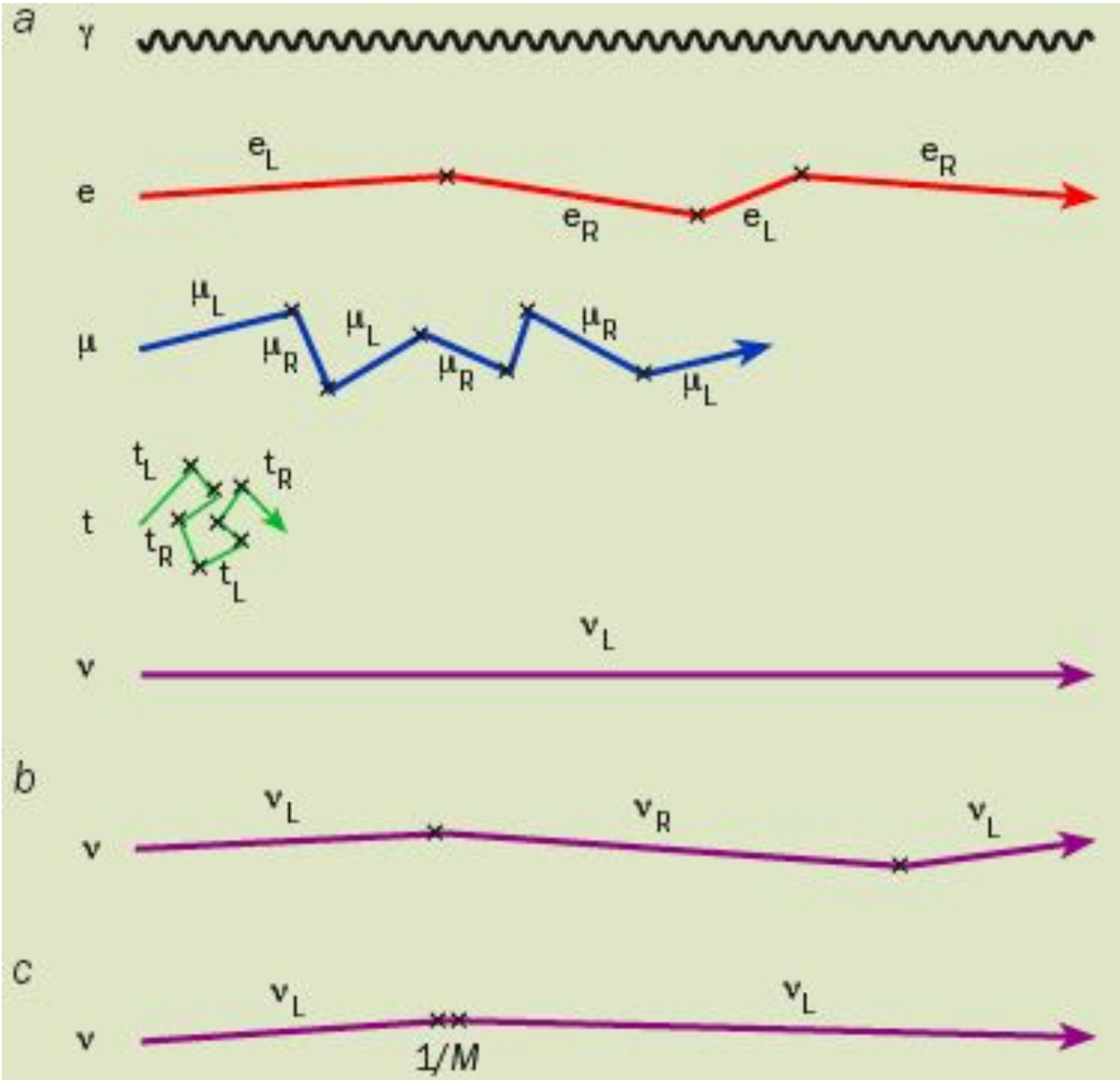
The experimental situation

- Absolute mass / nature of the neutrino
- Neutrino oscillations
- Sterile neutrinos?

Neutrino masses



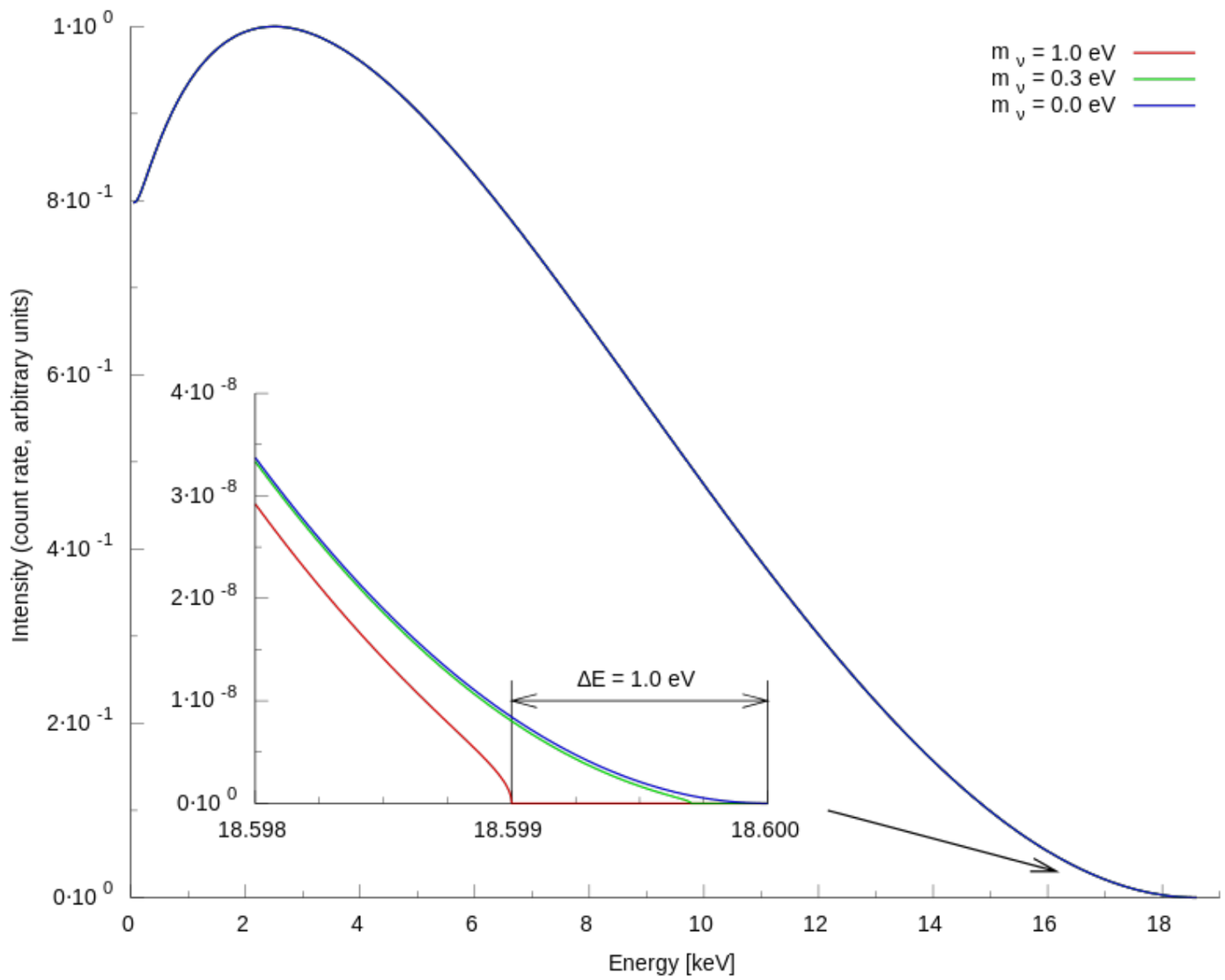
The standard model

Dirac mass

Majorana mass

Absolute neutrino mass scale

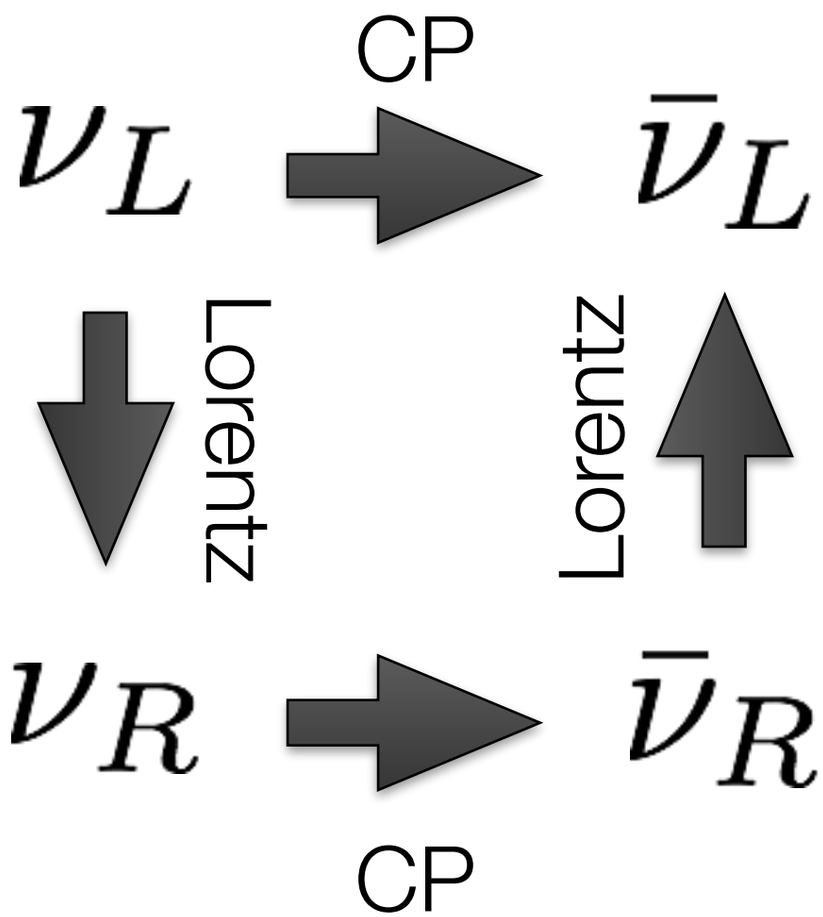
$$^{3}_{1}\mathrm{T} \rightarrow ^{3}_{2}\mathrm{He}^{1+} + e^{-} + \bar{\nu}_e$$



$$m(\nu_e) < 2 \text{ eV } (95\%\text{C.L.})$$

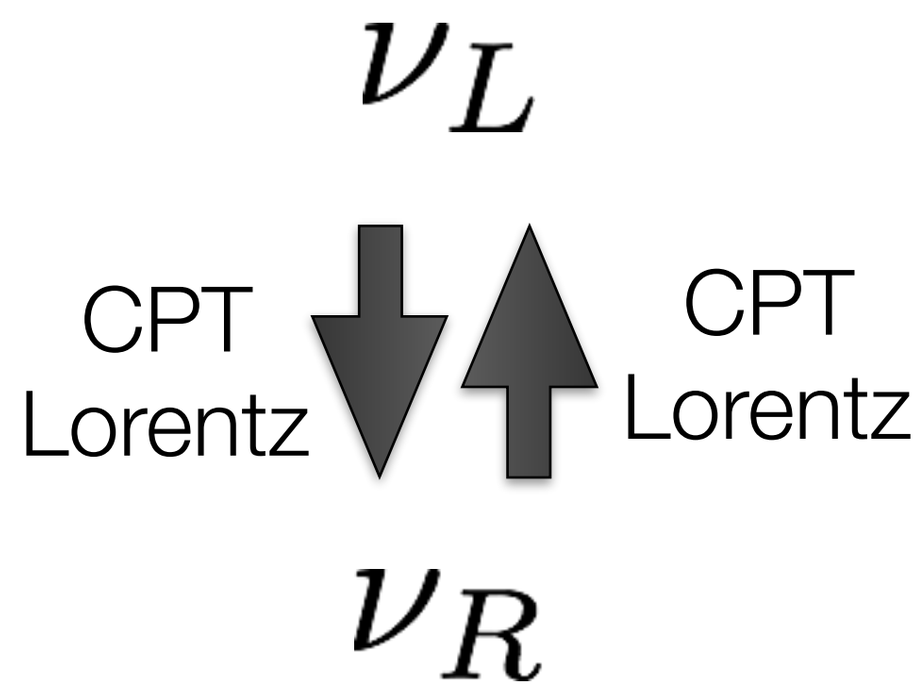
Neutrino-less double-beta decay: Are neutrinos Dirac or Majorana?

Dirac



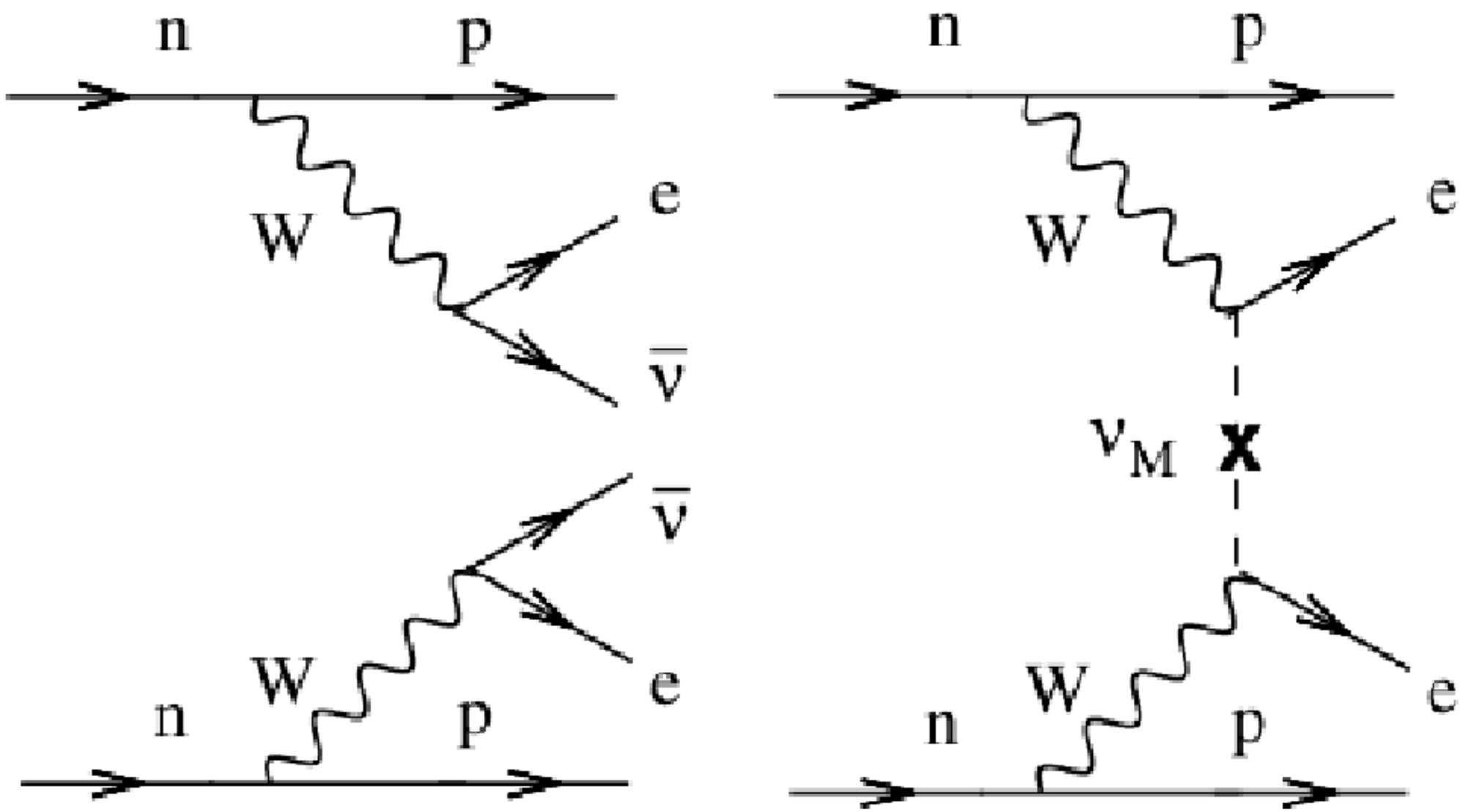
4 states with same mass

Majorana



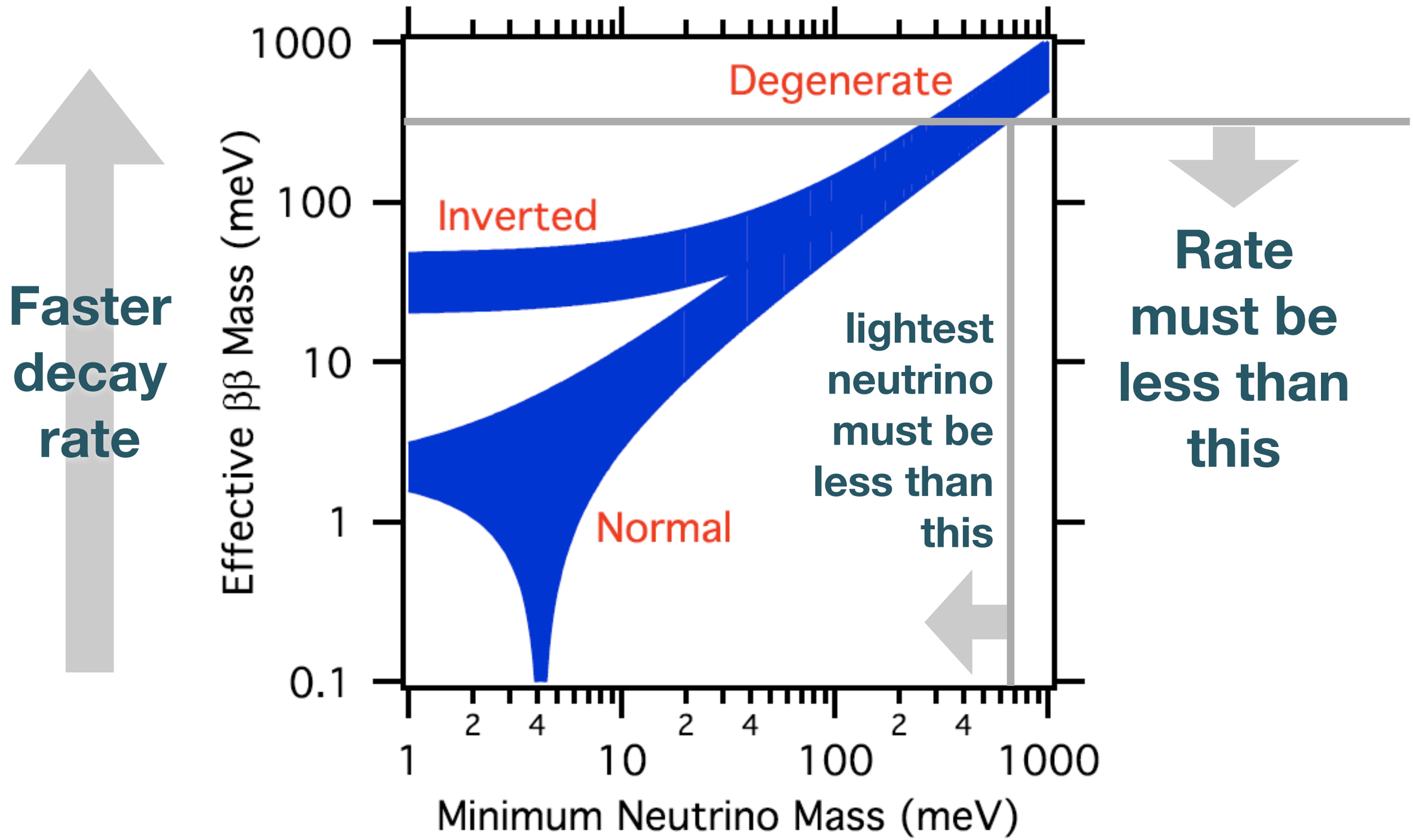
2 states with same mass

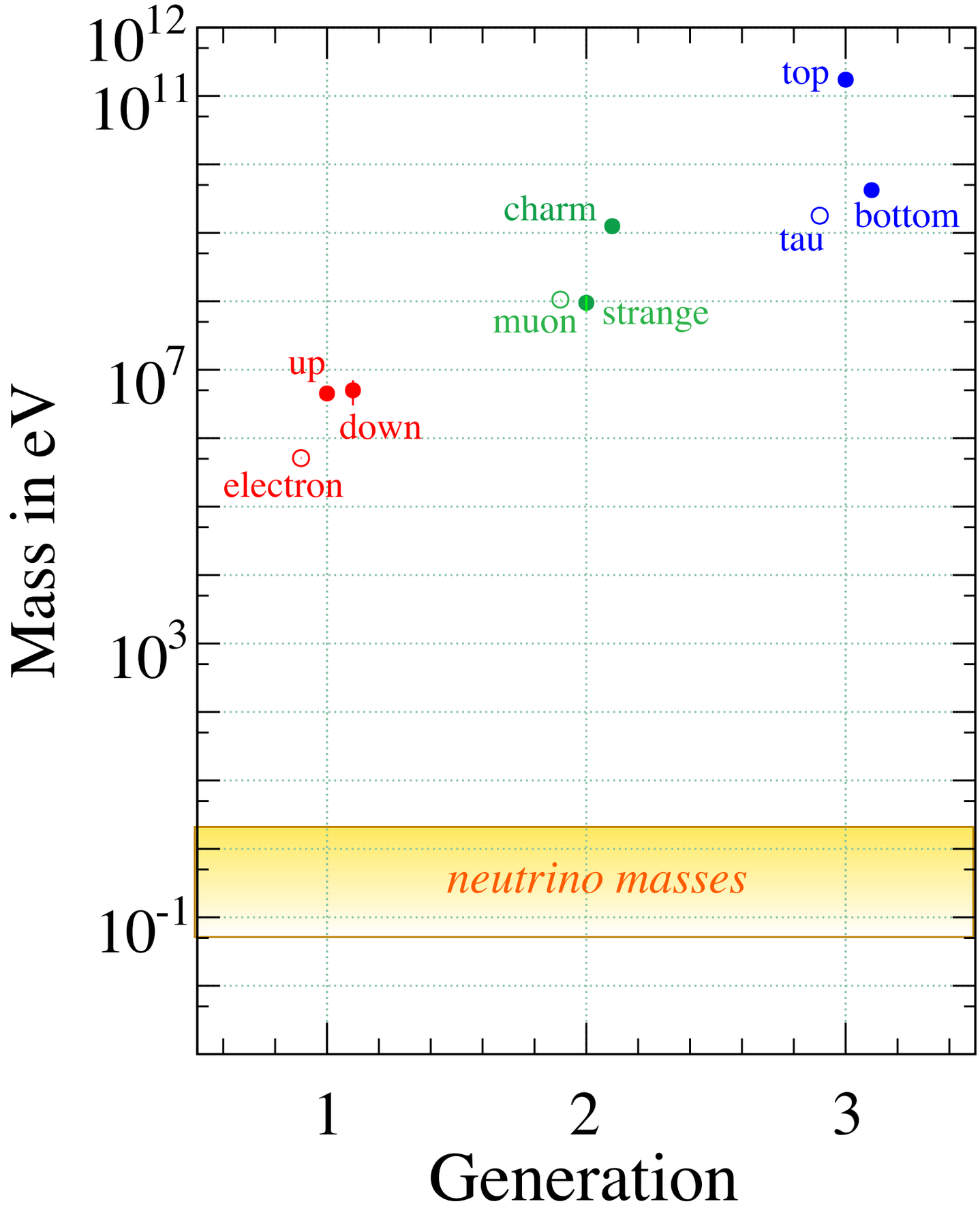
Neutrino-less double-beta decay: Are neutrinos Dirac or Majorana?



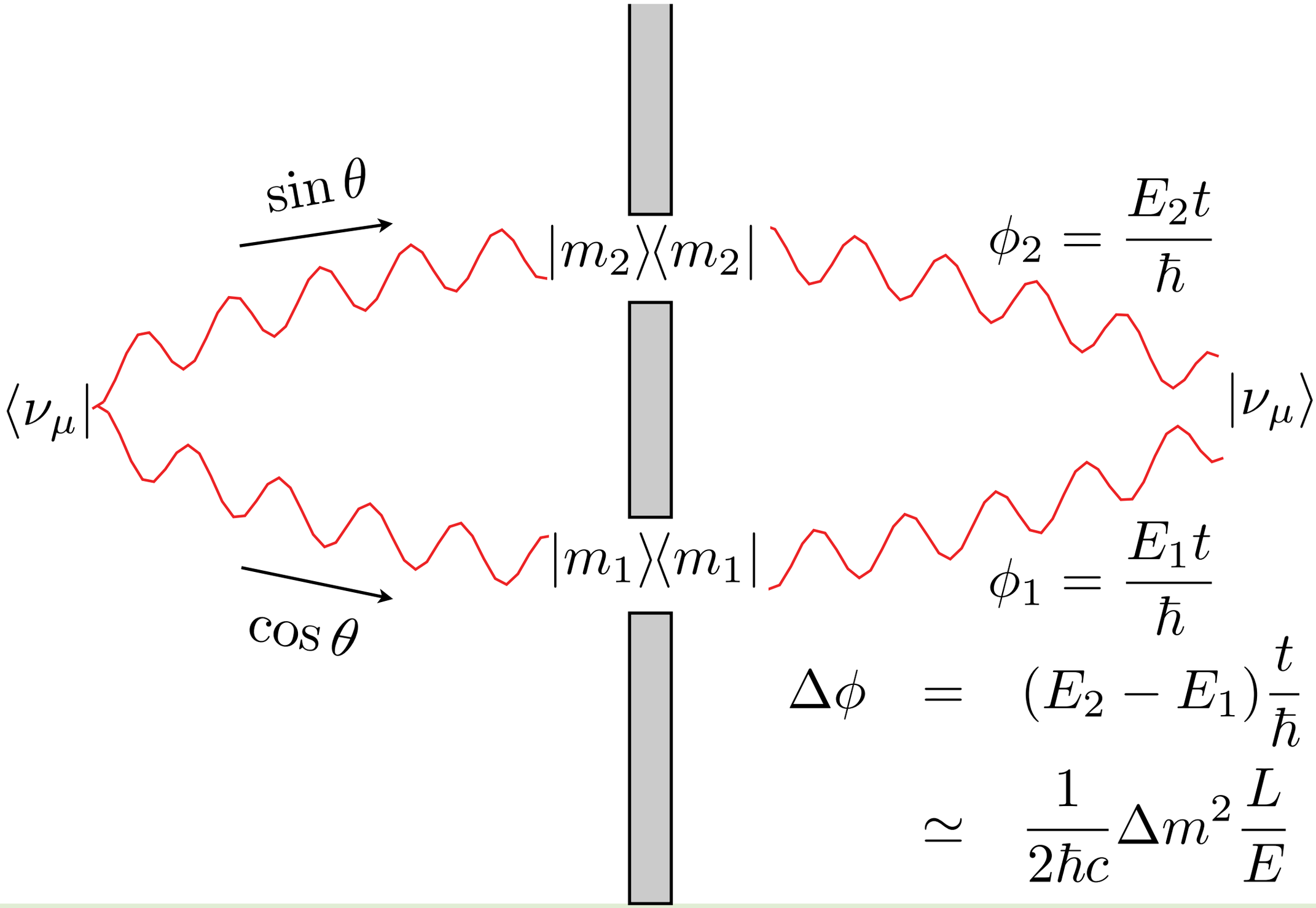
$T_{1/2} = 2.165 \pm 0.016 \pm 0.059 \times 10^{21}$ years $\quad T_{1/2} > 1.1 \times 10^{25}$ years

Neutrino-less double-beta decay: Absolute neutrino mass scale?




10^{12}
10^{11}
10^{7}
10^{3}
10^{-1}
Mass in eV
top
bottom
tau
charm
muon
strange
up
down
electron
neutrino masses
1
2
3
Generation

Neutrino Oscillations



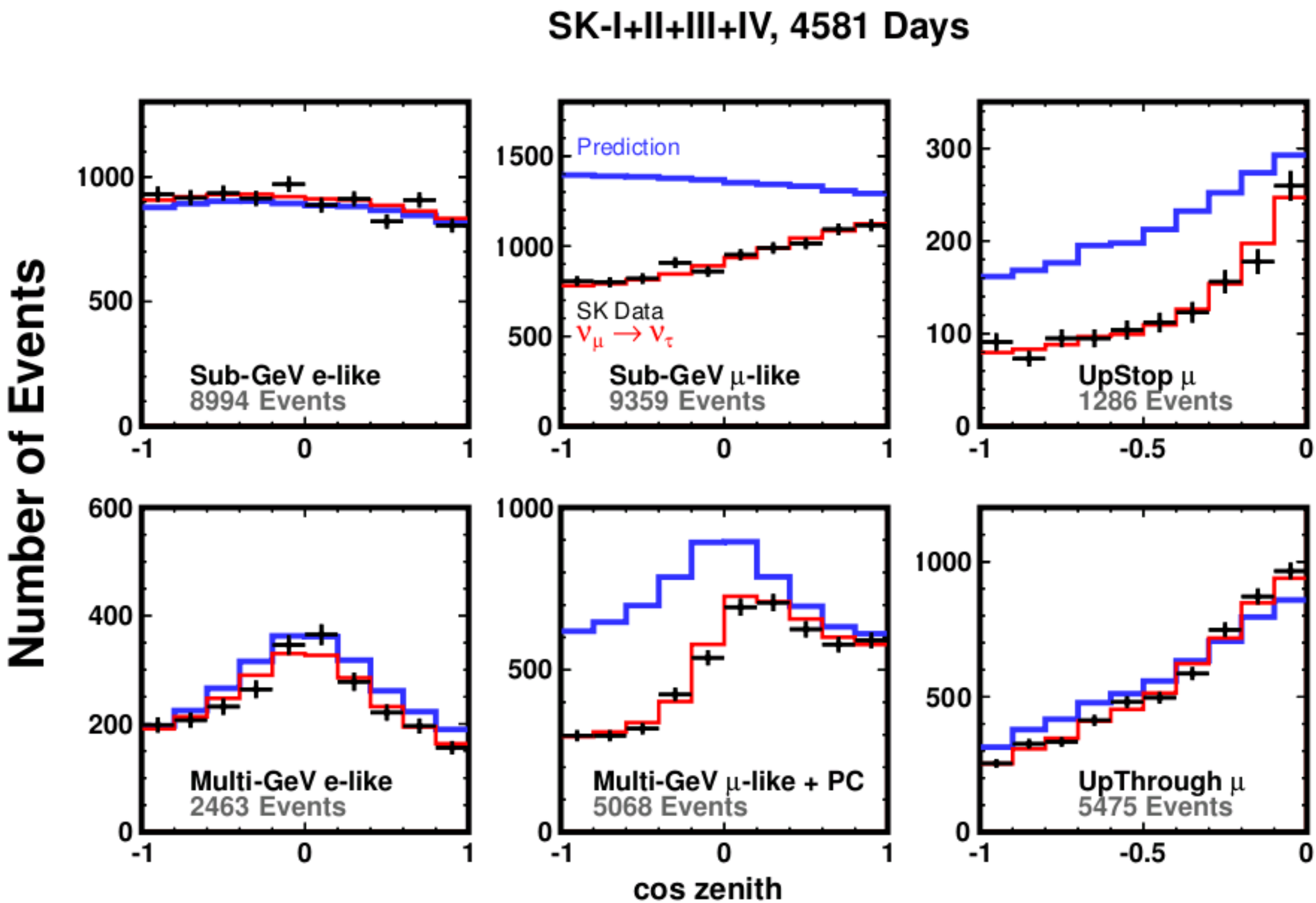
$$\begin{aligned}\Delta\phi &= (E_2 - E_1)\frac{t}{\hbar} \\ &\simeq \frac{1}{2\hbar c}\Delta m^2 \frac{L}{E}\end{aligned}$$

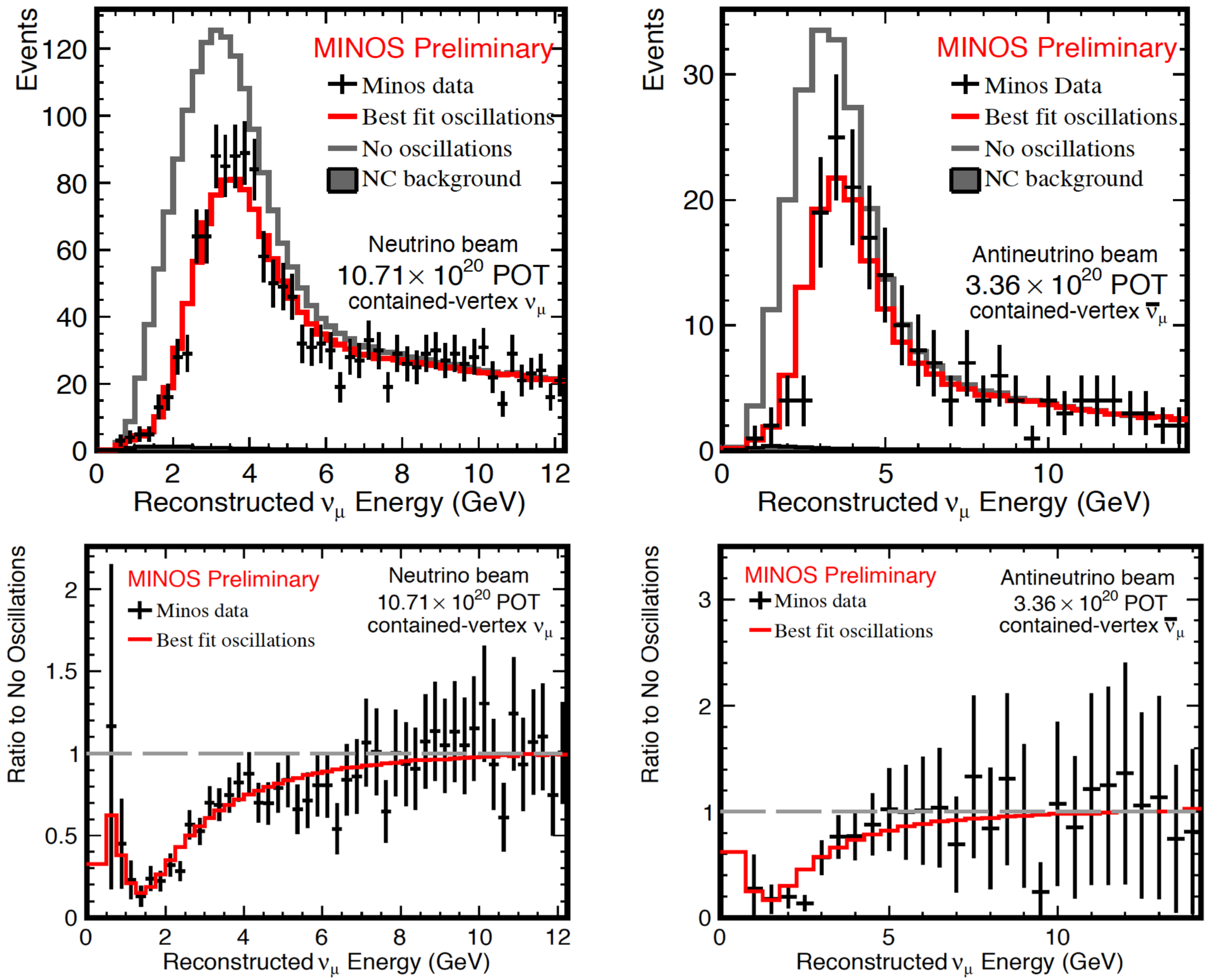
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2[\mathrm{eV}^2]\frac{L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

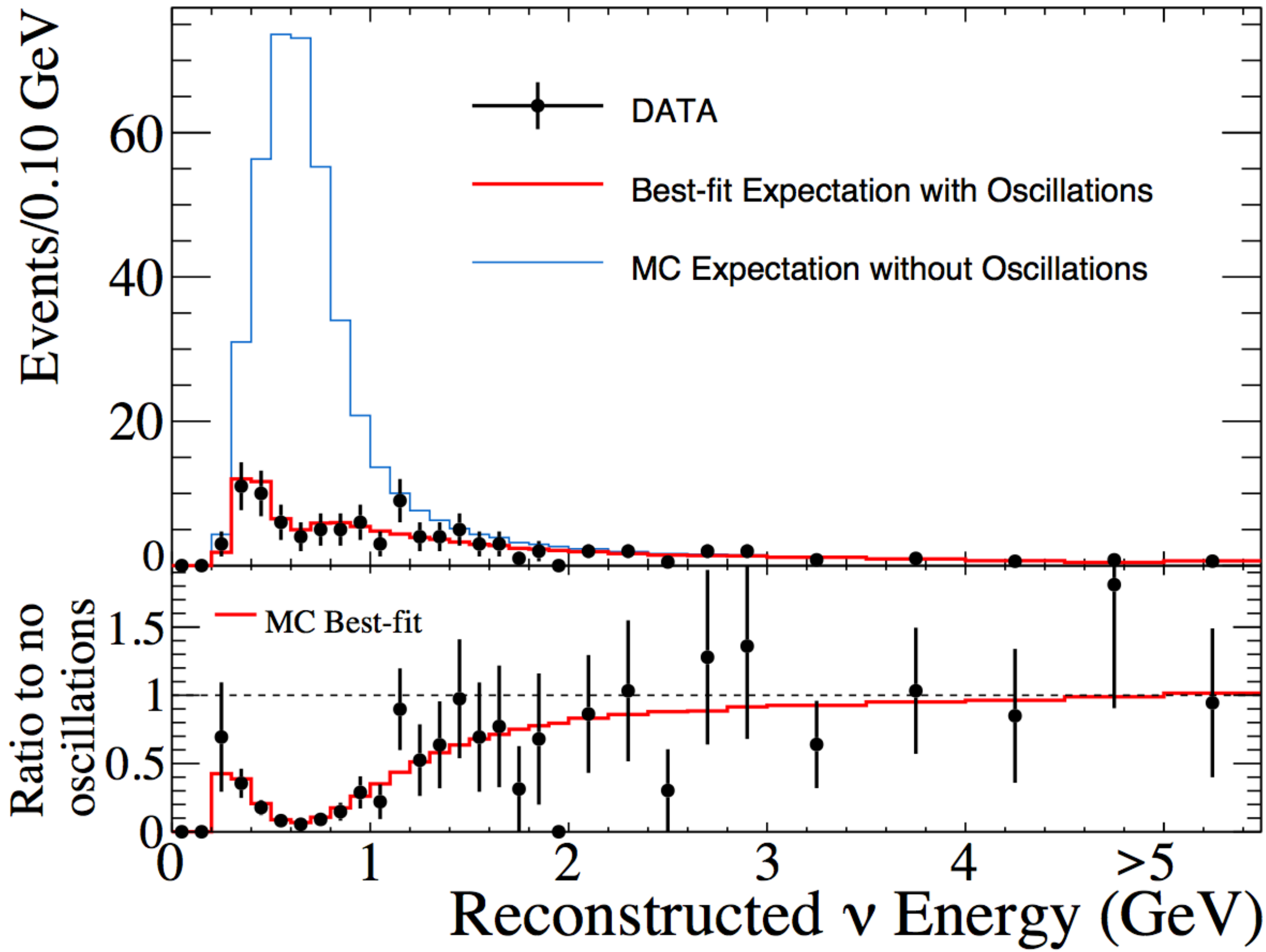
Neutrino oscillations

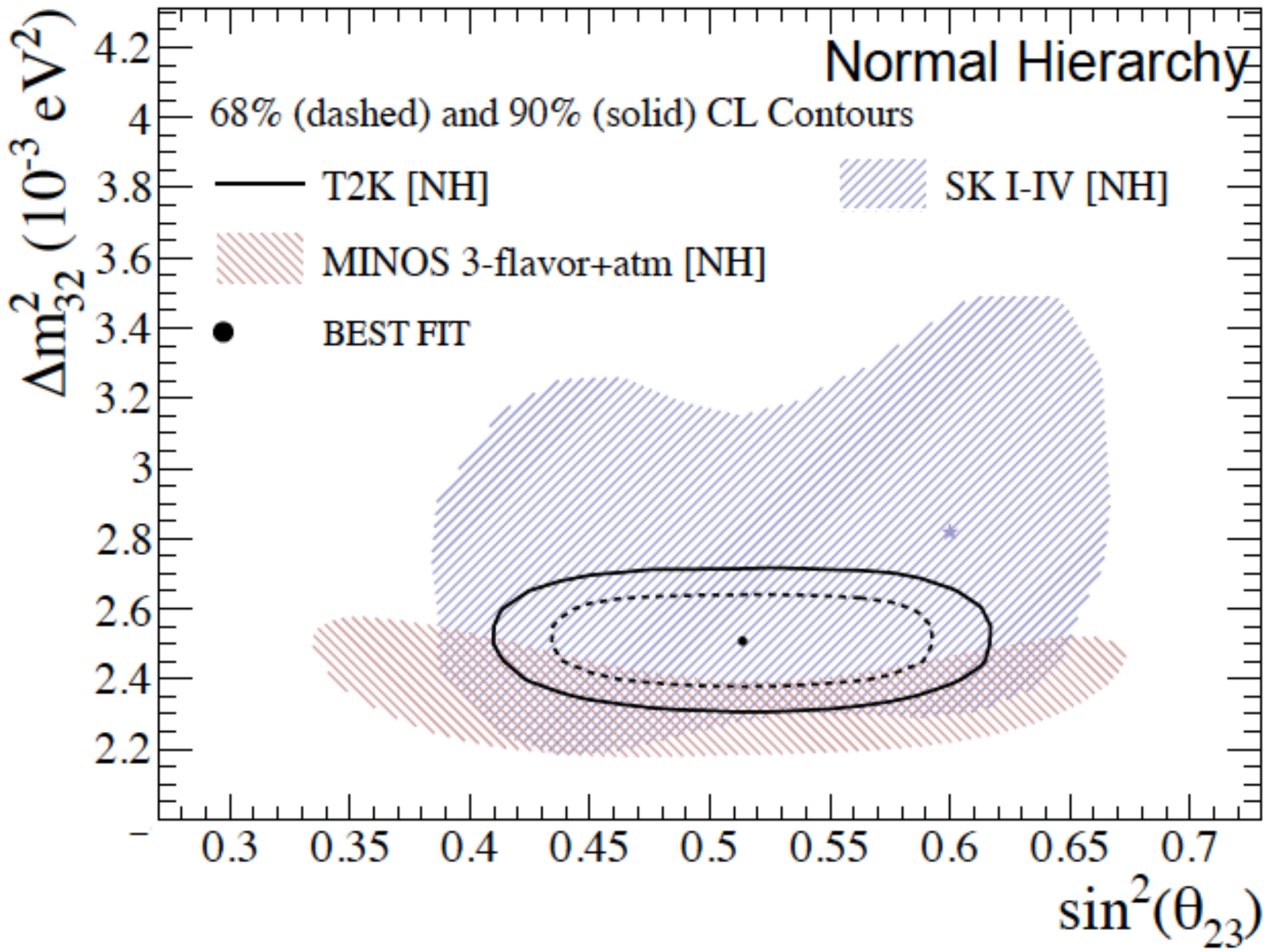
$$\left| \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\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

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

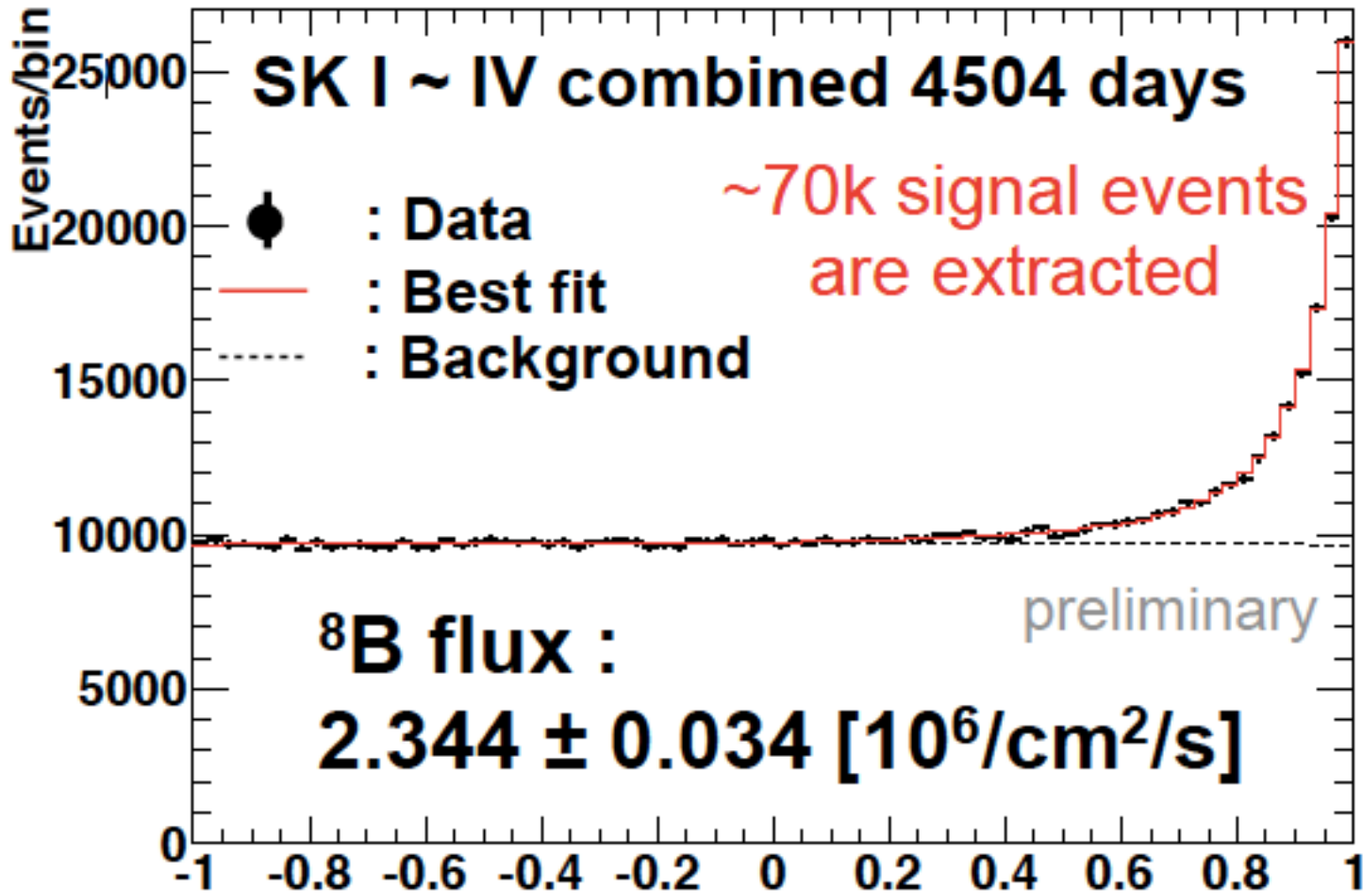

SK-I+II+III+IV, 4581 Days
Number of Events
Prediction
SK Data
$\nu_\mu \rightarrow \nu_\tau$
Sub-GeV e-like
8994 Events
Sub-GeV μ-like
9359 Events
UpStop μ
1286 Events
Multi-GeV e-like
2463 Events
Multi-GeV μ-like + PC
5068 Events
UpThrough μ
5475 Events
cos zenith


MINOS Preliminary
Minos data
Best fit oscillations
No oscillations
NC background
Neutrino beam
10.71× 10^20 POT
contained-vertex ν_μ
Events
Reconstructed ν_μ Energy (GeV)
MINOS Preliminary
Minos Data
Best fit oscillations
No oscillations
NC background
Antineutrino beam
3.36 × 10^20 POT
contained-vertex ν̄_μ
Events
Reconstructed ν_μ Energy (GeV)
MINOS Preliminary
Minos data
Best fit oscillations
Neutrino beam
10.71× 10^20 POT
contained-vertex ν_μ
Ratio to No Oscillations
Reconstructed ν_μ Energy (GeV)
MINOS Preliminary
Minos data
Best fit oscillations
Antineutrino beam
3.36 × 10^20 POT
contained-vertex ν̄_μ
Ratio to No Oscillations
Reconstructed ν_μ Energy (GeV)

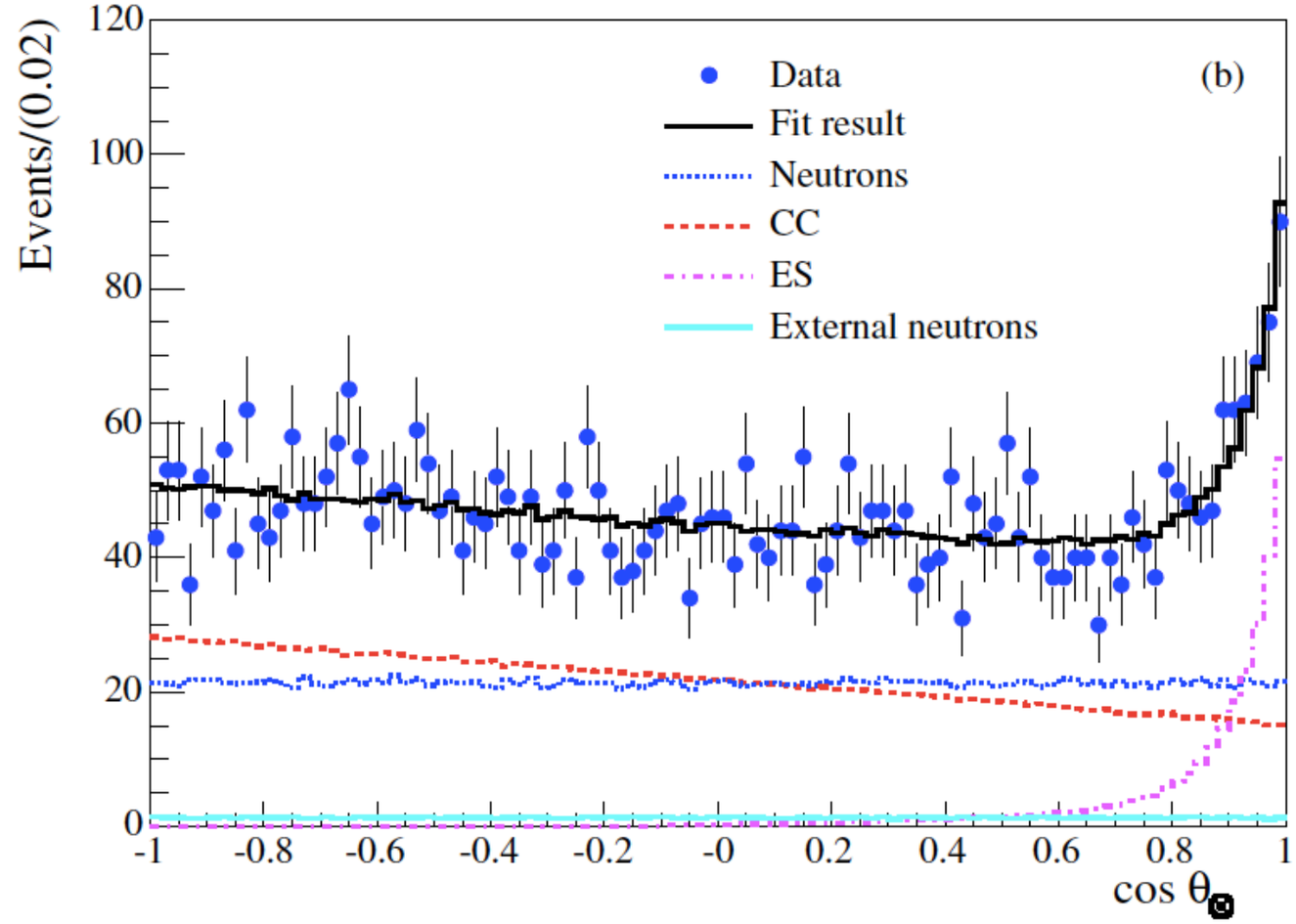

Events/0.10 GeV
60
40
20
0
DATA
Best-fit Expectation with Oscillations
MC Expectation without Oscillations
Ratio to no oscillations
1.5
1
0.5
0
MC Best-fit
0
1
2
3
4
>5
Reconstructed ν Energy (GeV)

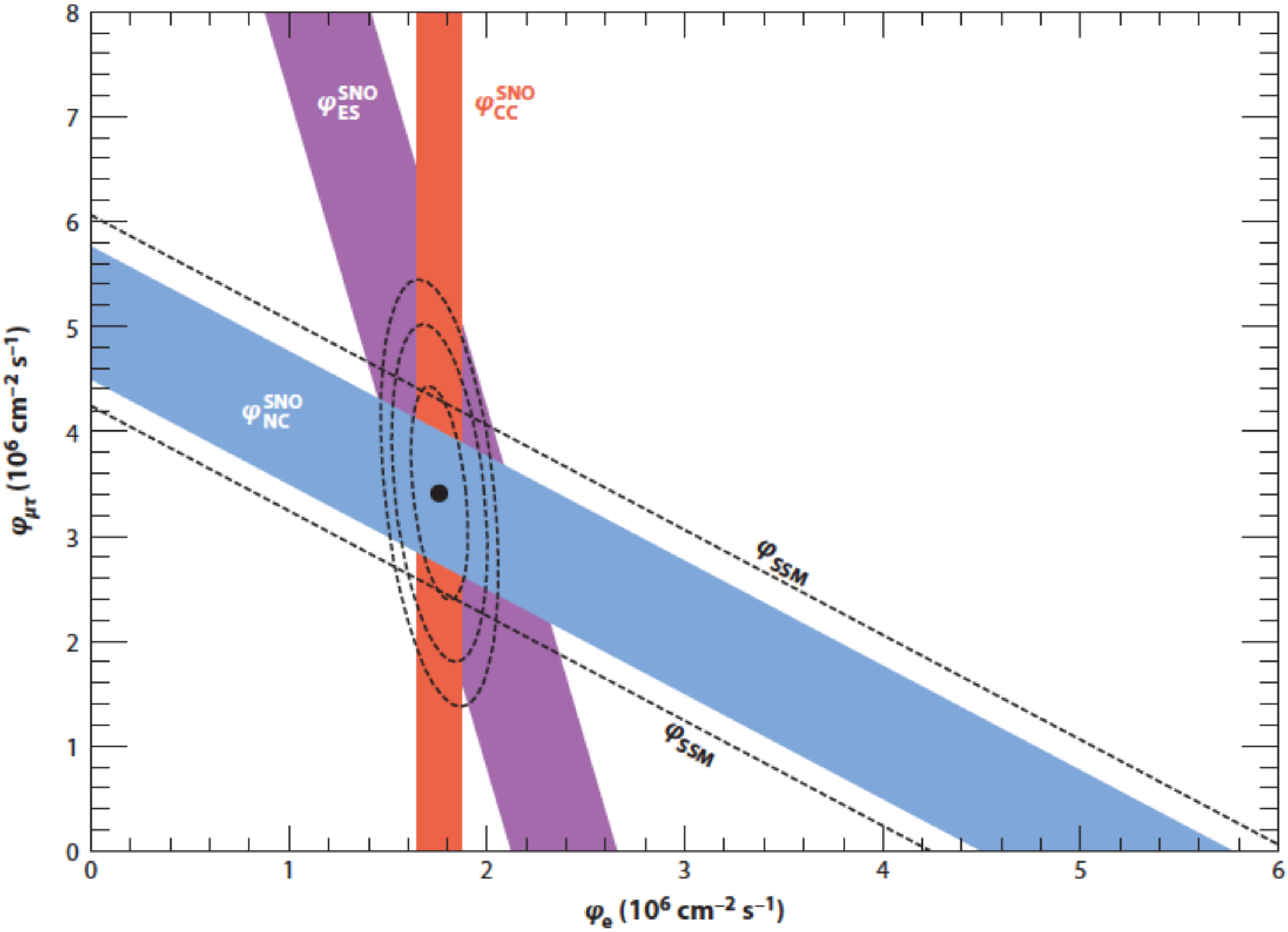

Normal Hierarchy
68% (dashed) and 90% (solid) CL Contours
T2K [NH]
SK I-IV [NH]
MINOS 3-flavor+atm [NH]
BEST FIT
Δm^2_{32} (10^{-3} eV^2)
4.2
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
$\sin^2(\theta_{23})$

Super-Kamiokande

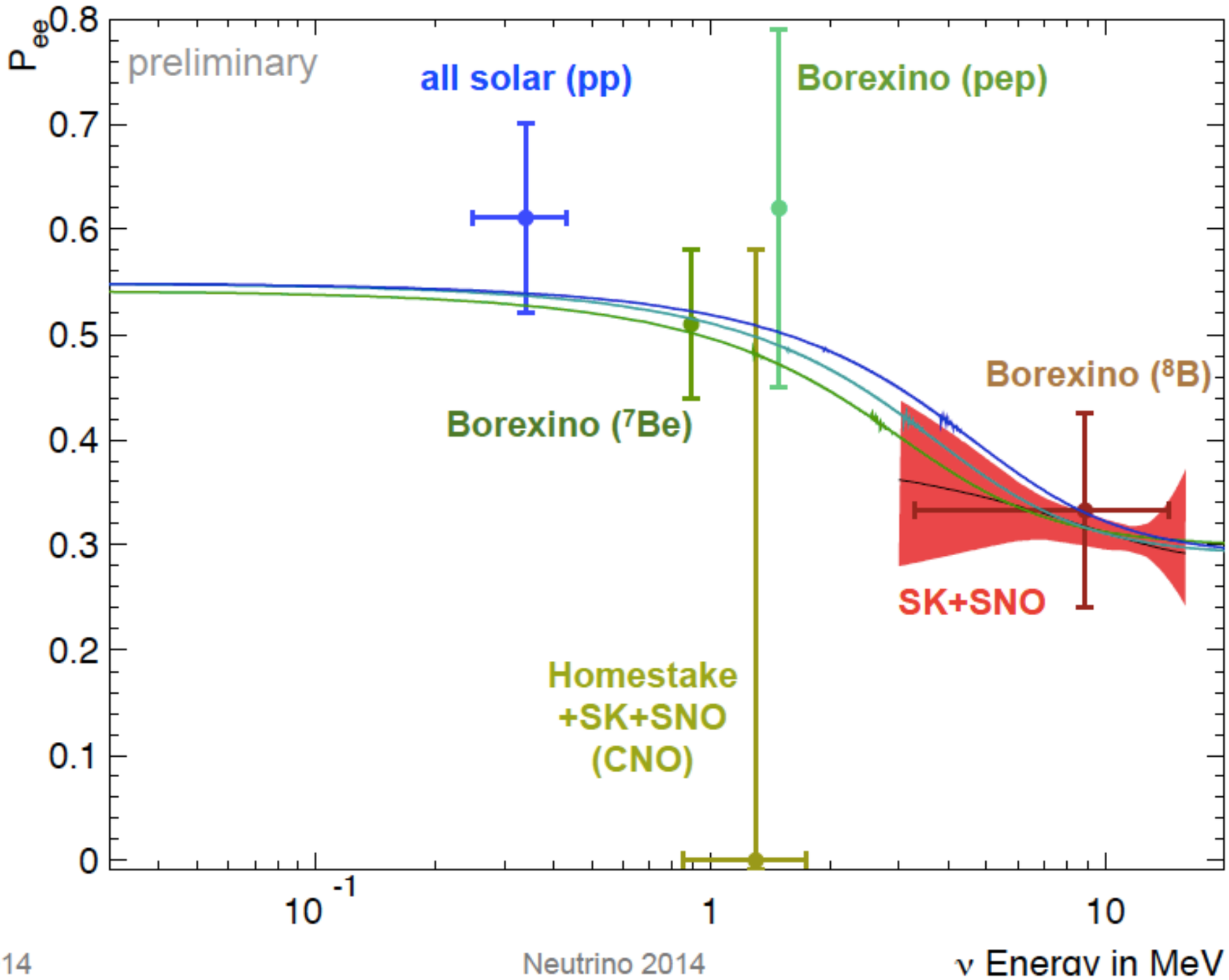


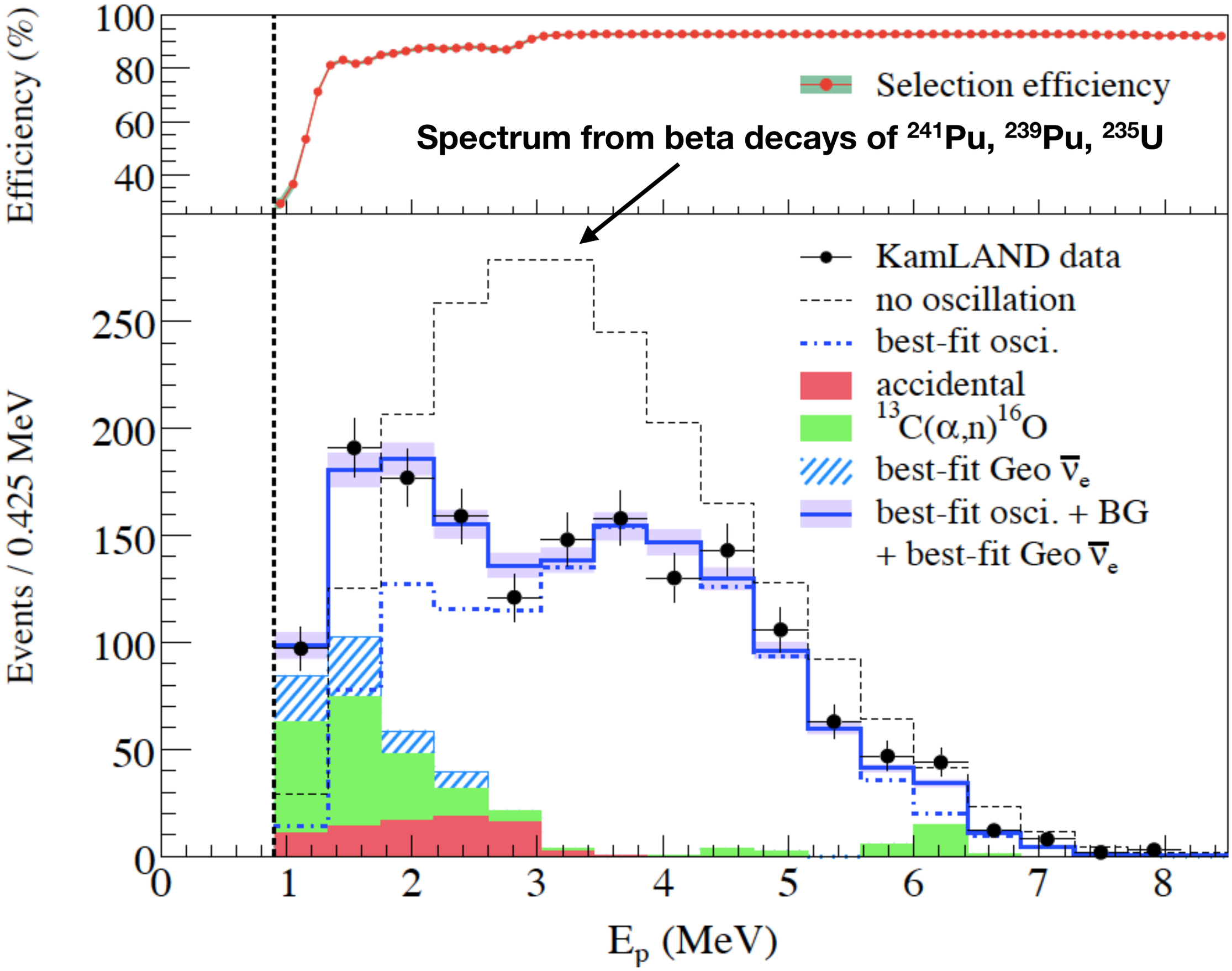
SNO



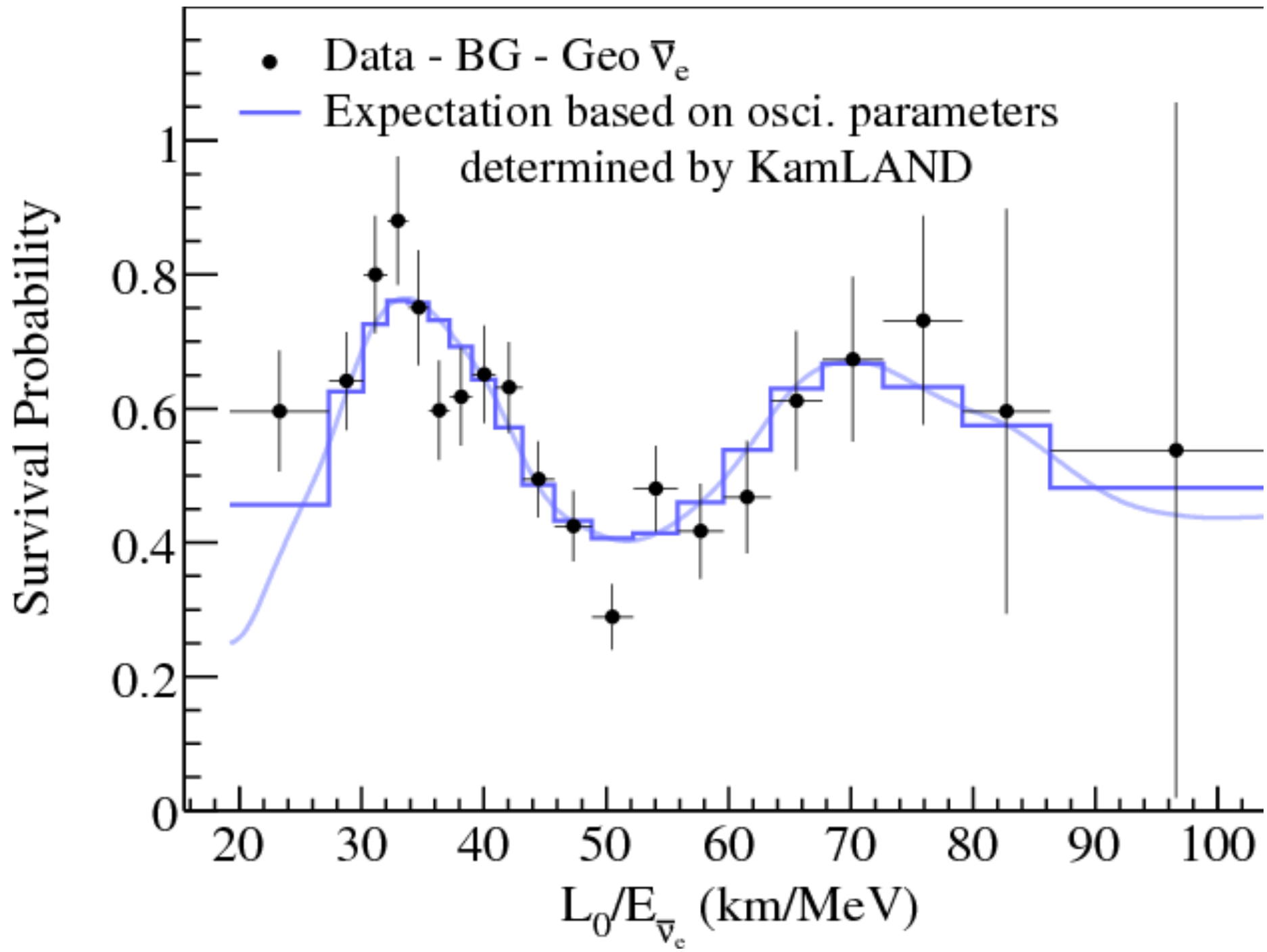

φ_{ES}^{SNO}
φ_{CC}^{SNO}
φ_{NC}^{SNO}
φ_{SSM}
φ_{SSM}
$\varphi_{\mu\tau}$ (10^6 cm^{-2} s^{-1})
φ_e (10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
7
8

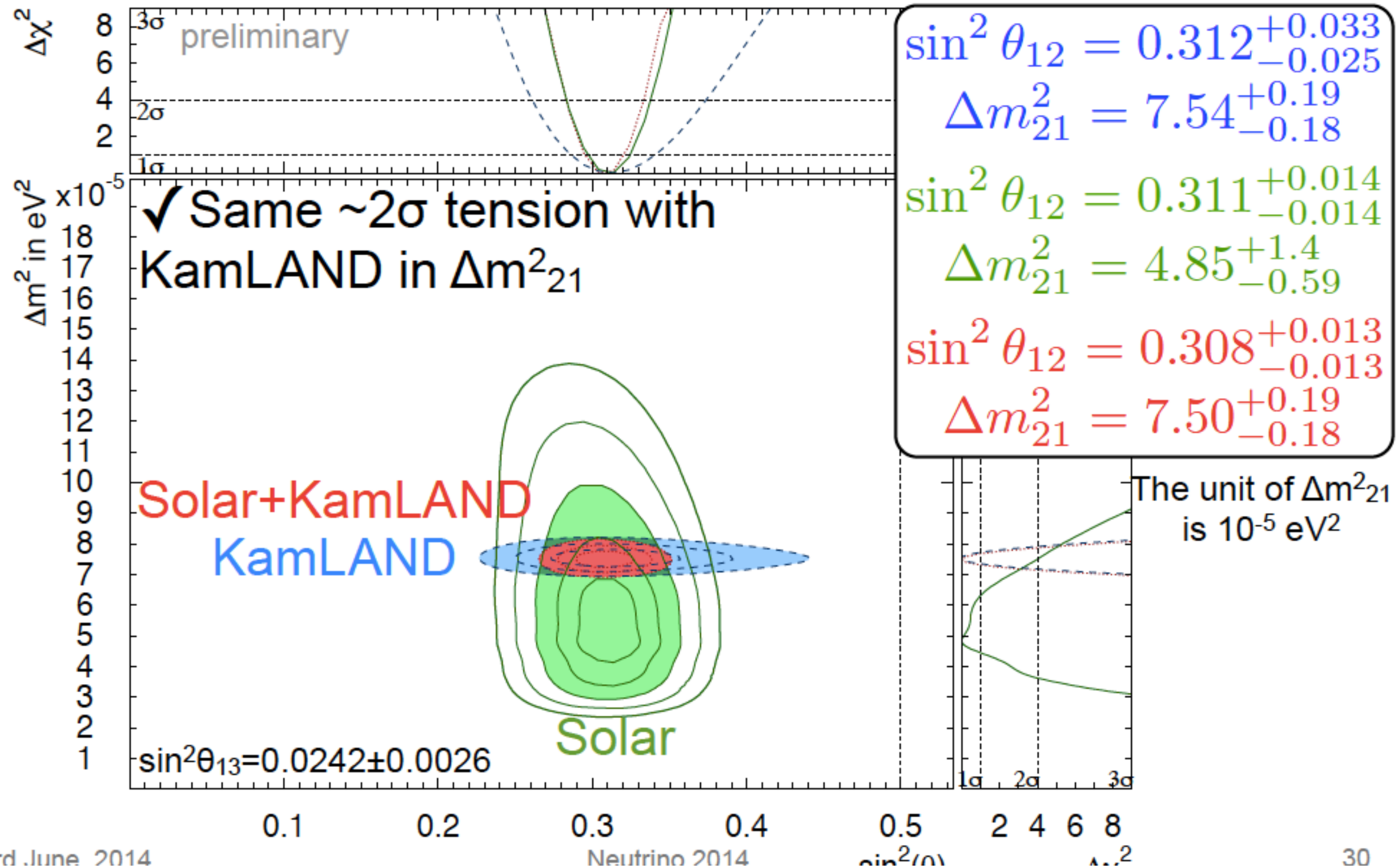
Solar neutrinos

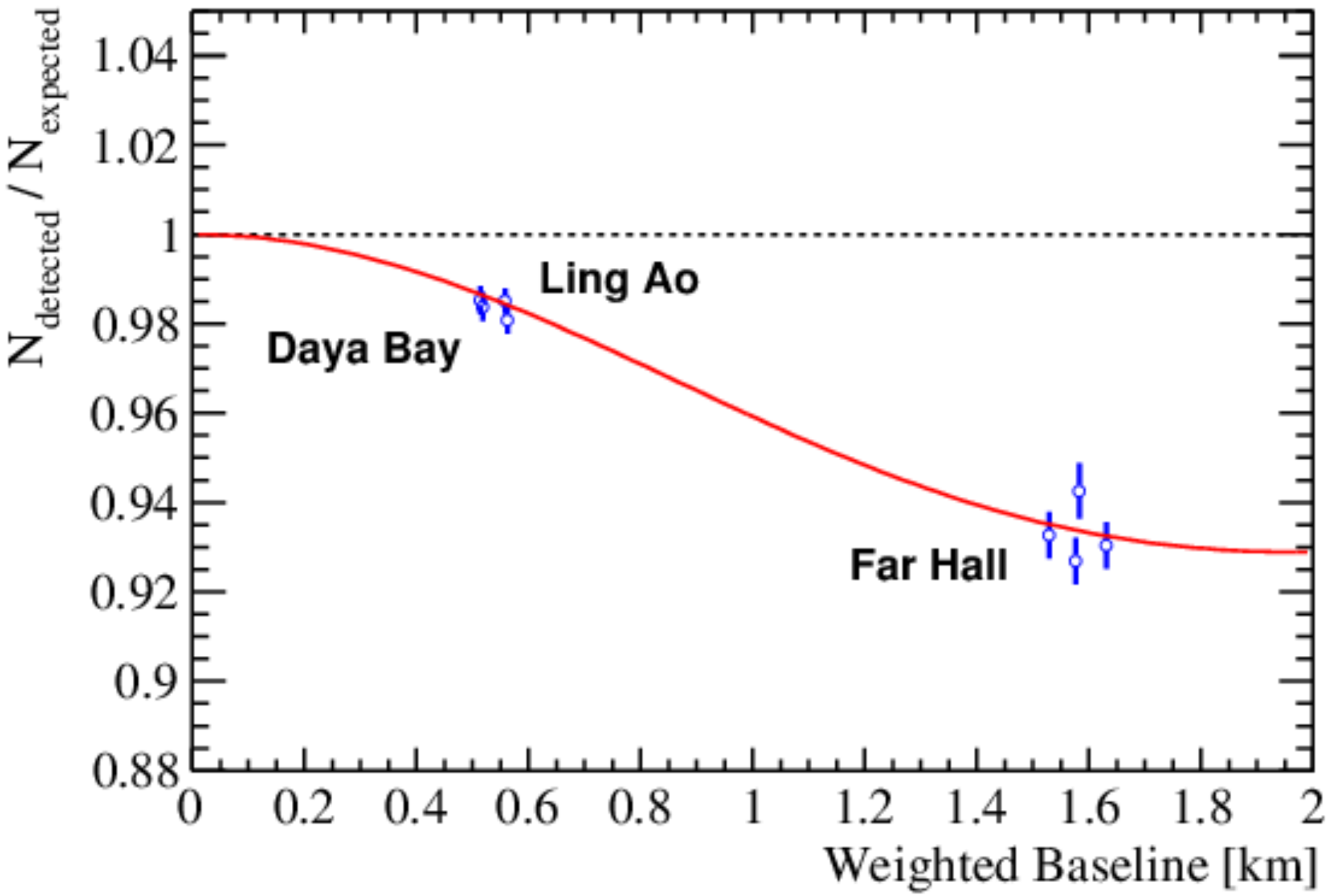


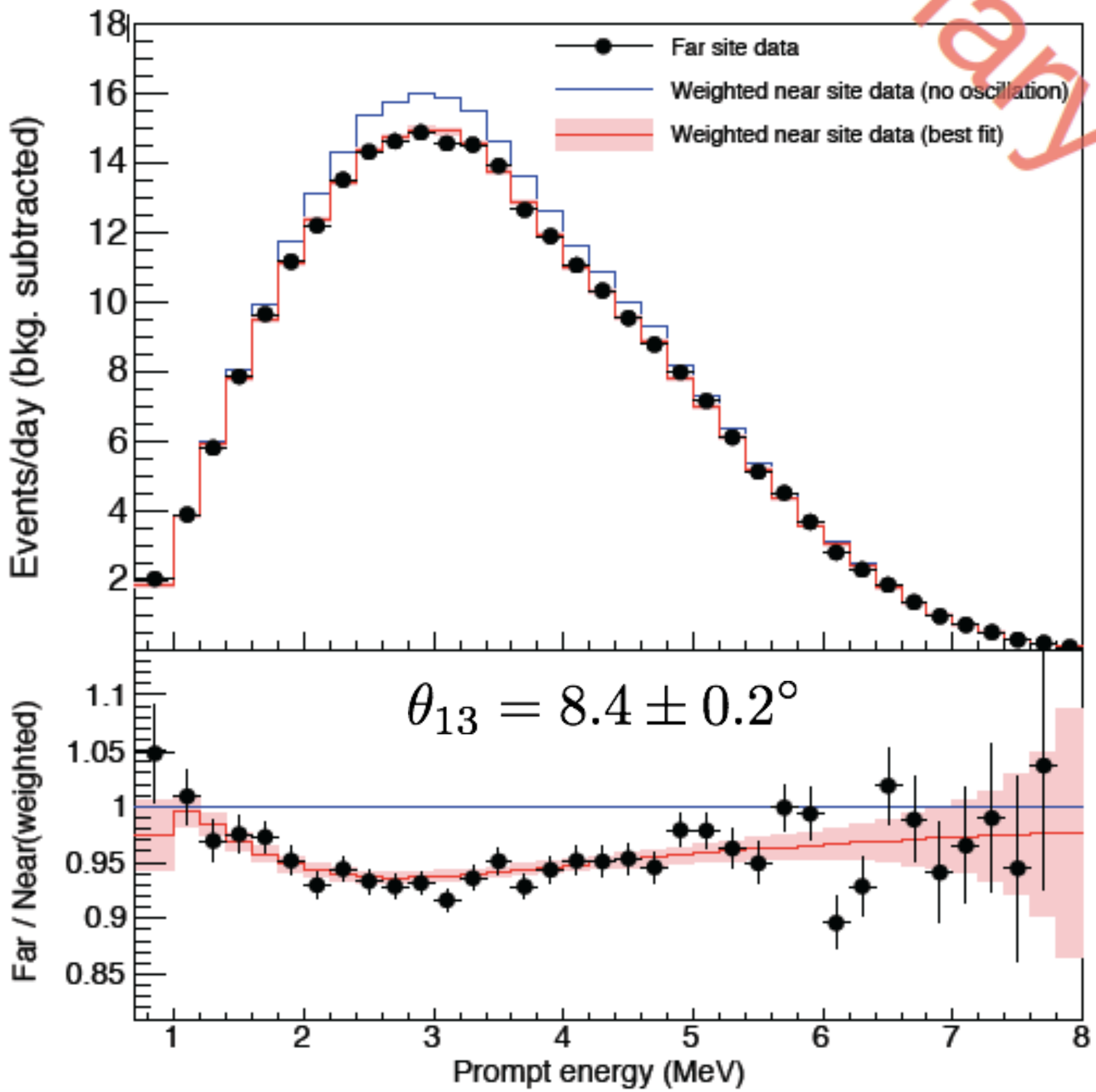

Efficiency (%)
100
80
60
40
Selection efficiency
Spectrum from beta decays of ^{241}Pu, ^{239}Pu, ^{235}U
Events / 0.425 MeV
250
200
150
100
50
0
KamLAND data
no oscillation
best-fit osci.
accidental
$^{13}C(\alpha,n)^{16}O$
best-fit Geo $\bar{\nu}_e$
best-fit osci. + BG
+ best-fit Geo $\bar{\nu}_e$
0
1
2
3
4
5
6
7
8
E_p (MeV)

KamLAND


Data - BG - Geo $\bar{\nu}_e$
Expectation based on osci. parameters determined by KamLAND
Survival Probability
0
0.2
0.4
0.6
0.8
1
20
30
40
50
60
70
80
90
100
$L_0/E_{\bar{\nu}_e}$ (km/MeV)

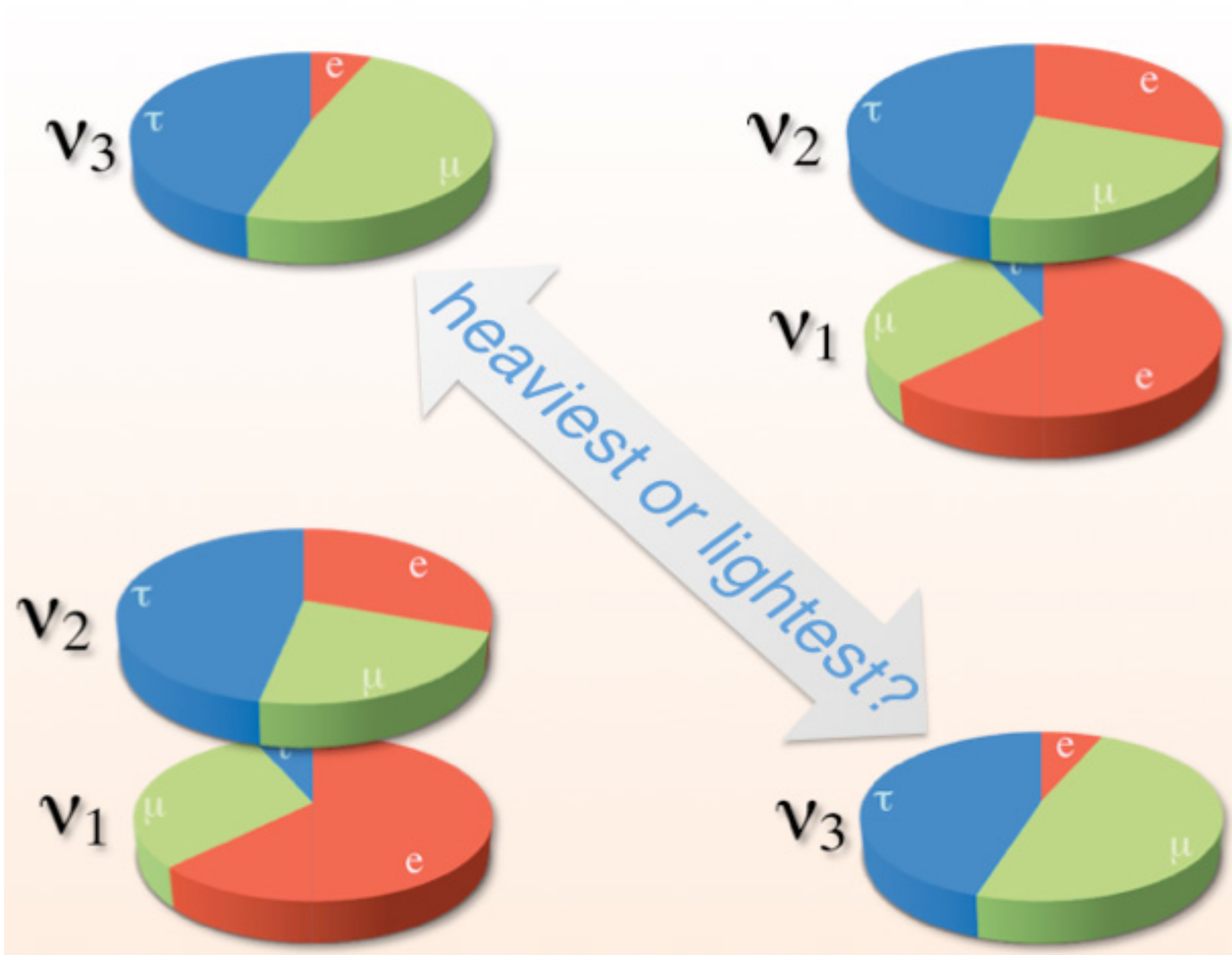

preliminary
$\Delta\chi^2$
3σ
2σ
1σ
✓Same ~2σ tension with KamLAND in Δm^2_{21}
Δm^2 in eV^2 x10^{-5}
Solar+KamLAND
KamLAND
Solar
$\sin^2\theta_{13}$=0.0242±0.0026
$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$
$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$
$\sin^2\theta_{12} = 0.311^{+0.014}_{-0.014}$
$\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$
$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.013}$
$\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$
The unit of Δm^2_{21} is 10^{-5} eV^2

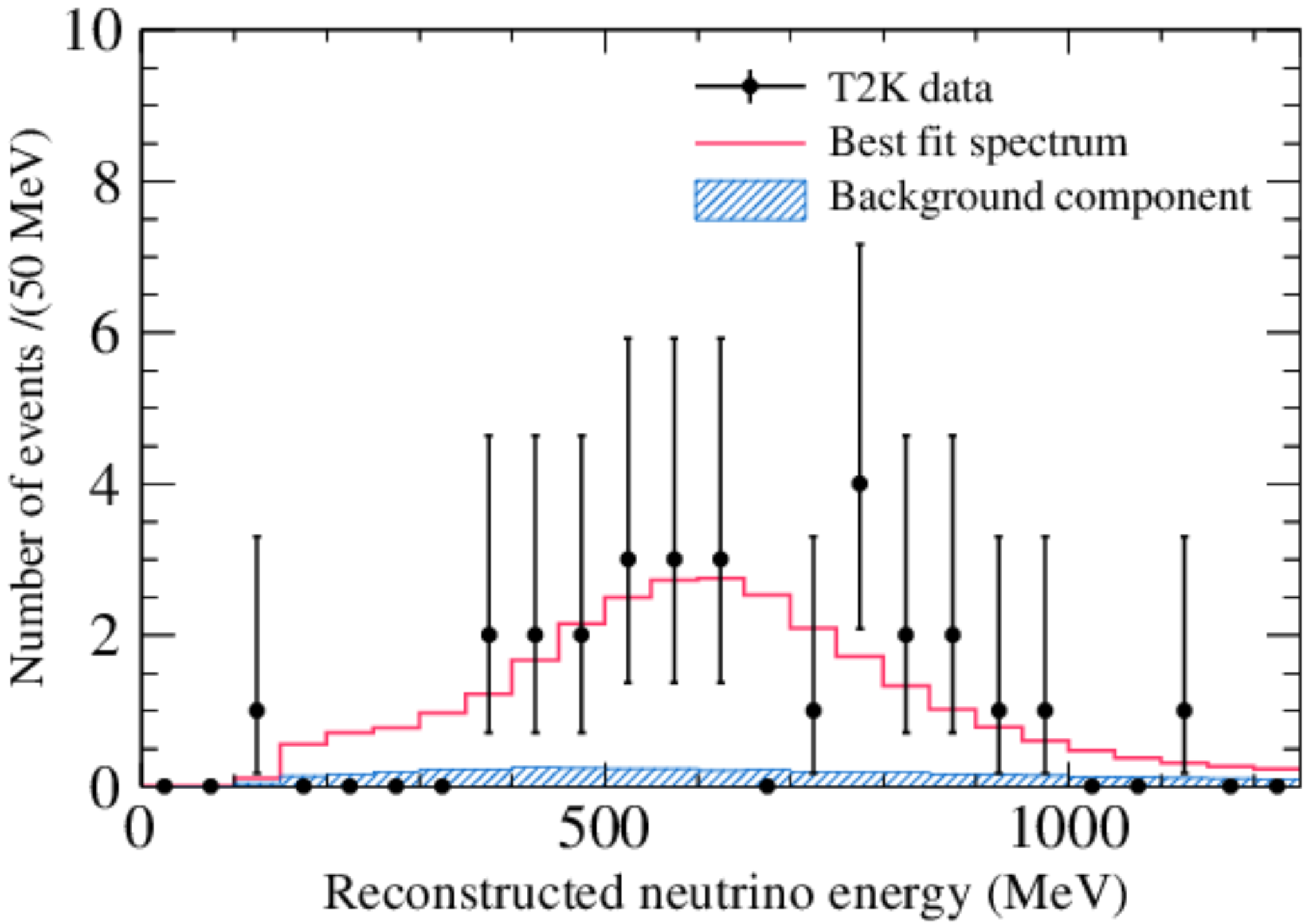

$N_{detected} / N_{expected}$
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
0.88
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Weighted Baseline [km]
Ling Ao
Daya Bay
Far Hall


Far site data
Weighted near site data (no oscillation)
Weighted near site data (best fit)
Events/day (bkg. subtracted)
$\theta_{13} = 8.4 \pm 0.2°$
Far / Near(weighted)
Prompt energy (MeV)

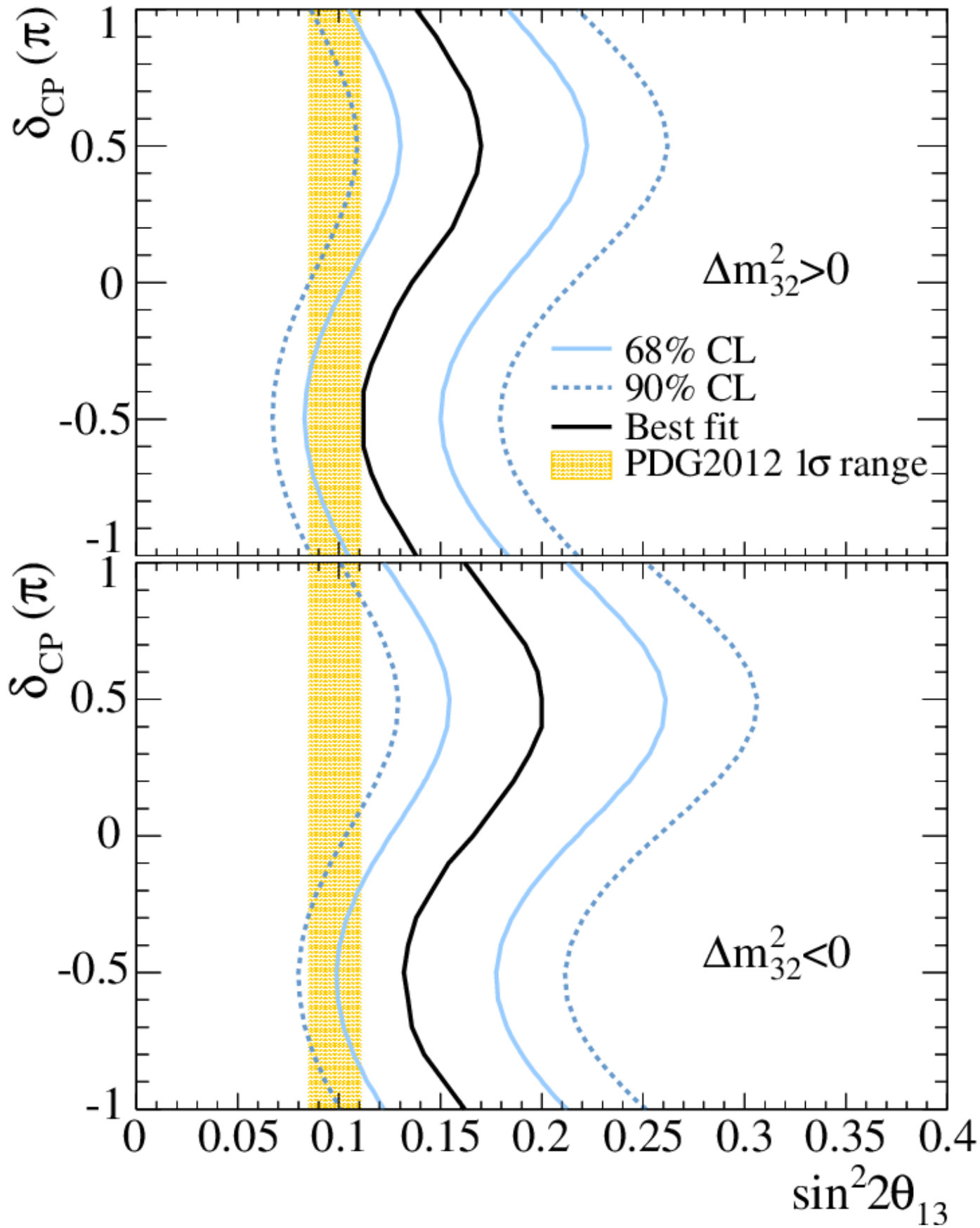
Next Questions In Neutrino Physics

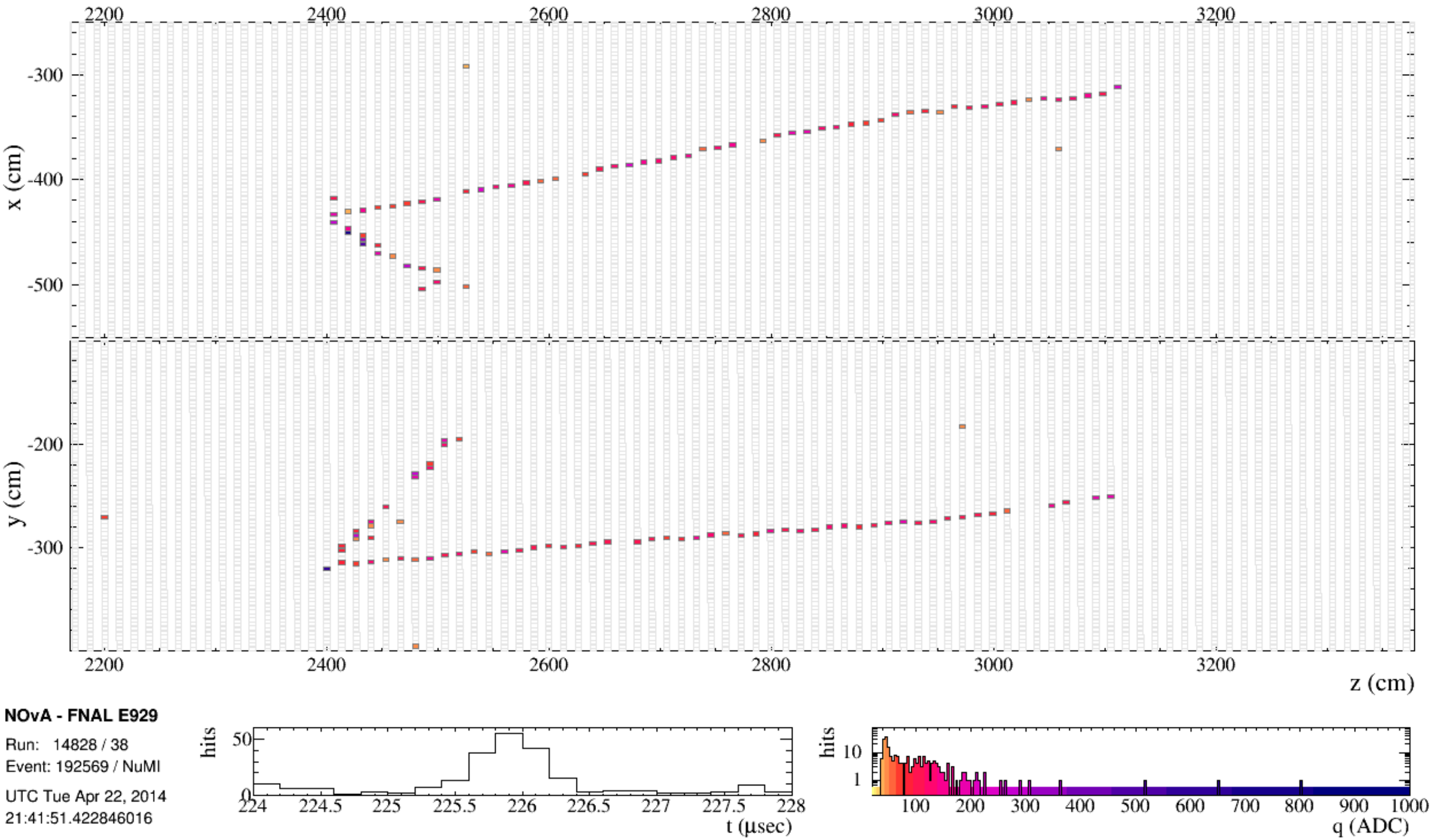
- Mass hierarchy
- Nature of ν_3 - θ_{23} octant
- Is CP violated?
- Is there more to this picture?



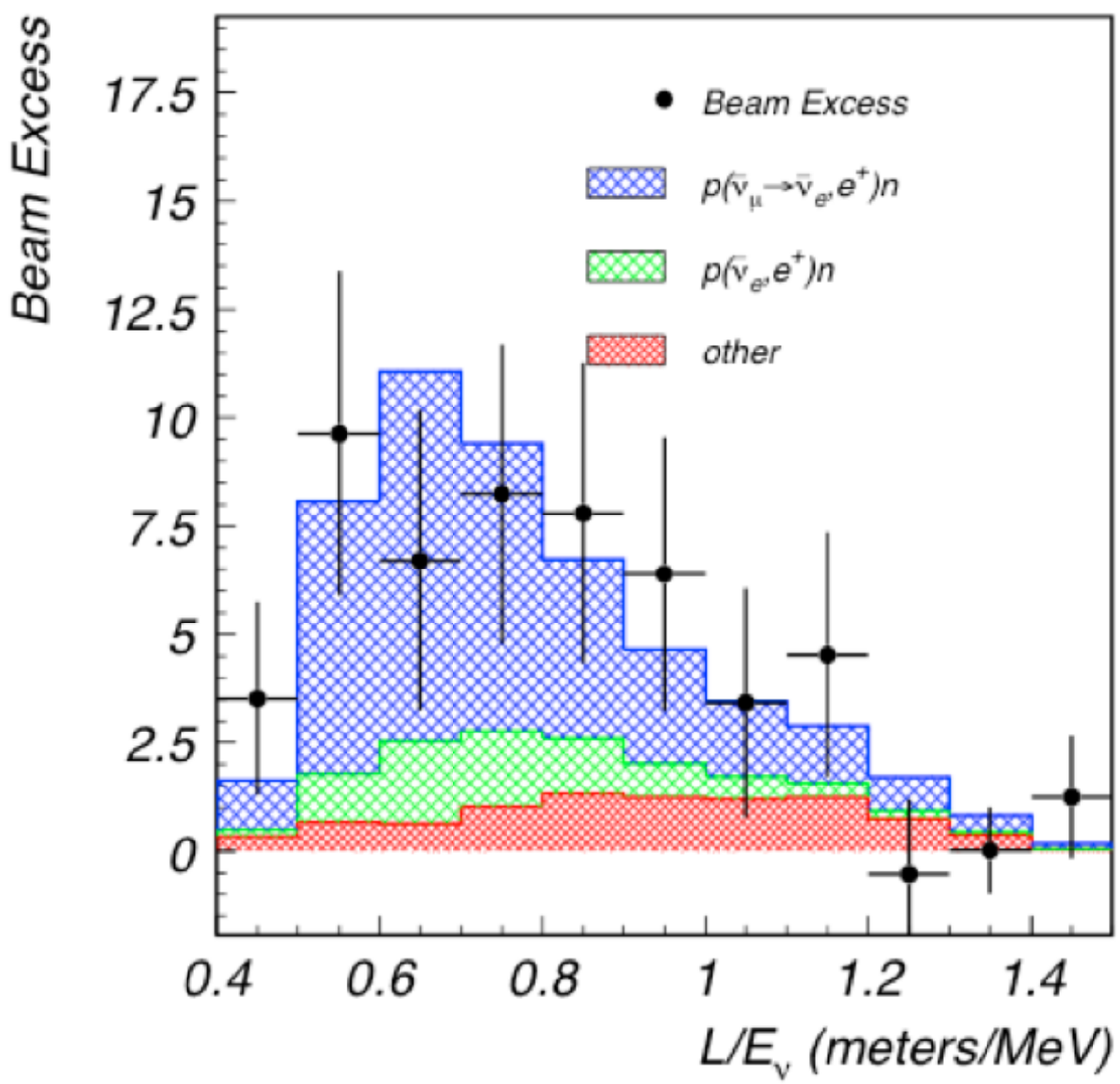


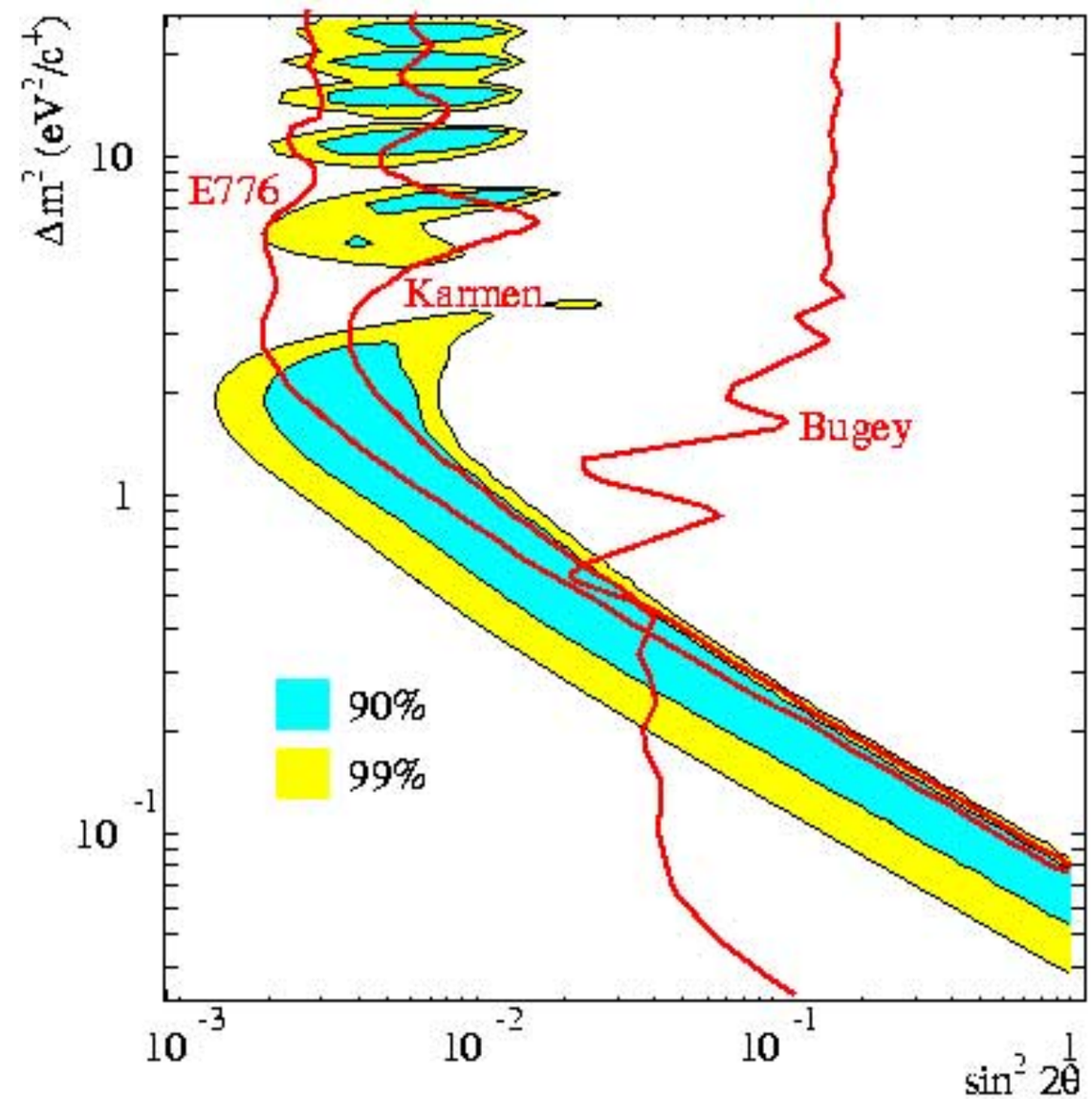
28 events on background of 5

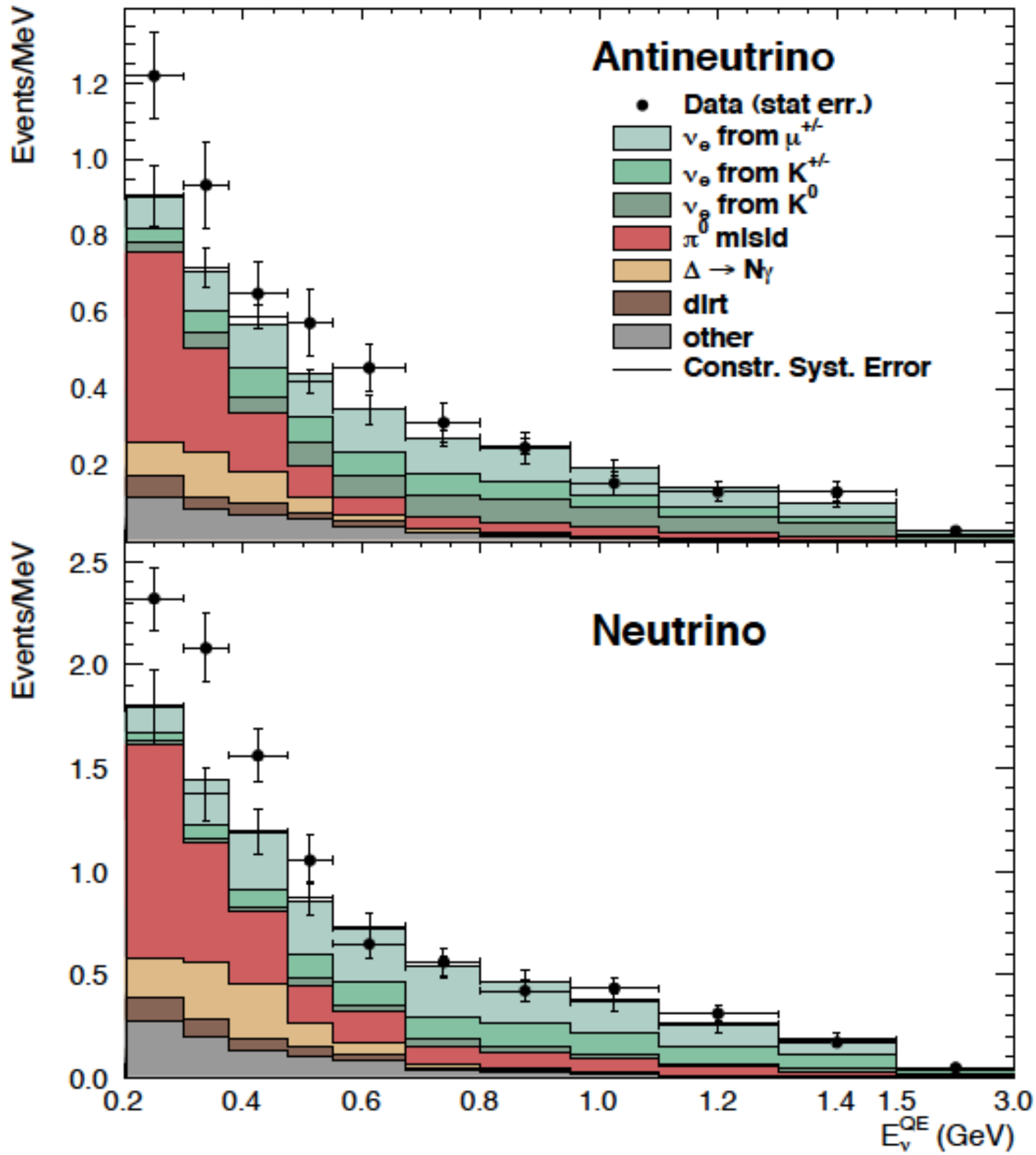

δ_{CP} (π)
1
0.5
0
-0.5
-1
$\Delta m^2_{32}>0$
68% CL
90% CL
Best fit
PDG2012 1σ range
$\Delta m^2_{32}<0$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
$\sin^2 2\theta_{13}$


x (cm)
y (cm)
z (cm)
hits
t (μsec)
hits
q (ADC)
NOvA - FNAL E929
Run: 14828 / 38
Event: 192569 / NuMI
UTC Tue Apr 22, 2014
21:41:51.422846016

Sterile neutrinos?






Antineutrino
Data (stat err.)
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Constr. Syst. Error
Neutrino
Events/MeV
E_ν^{QE} (GeV)

Neutrino oscillations

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

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

$\lvert\Delta m^2_{32}\rvert \equiv \lvert m_3^2 - m_2^2\rvert$ $\simeq 2\times 10^{-3}\ \mathrm{eV}^2$	$\Delta m^2_{31} \simeq \Delta m^2_{32}$	$\Delta m^2_{21} \simeq 8\times 10^{-5}\ \mathrm{eV}^2$
$\nu_\mu \longrightarrow \nu_\mu$	$\nu_e \longrightarrow \nu_e$	$\nu_e \longrightarrow \nu_e$
$\nu_\mu \longrightarrow \nu_\tau$	$\nu_\mu \longrightarrow \nu_e$	$\nu_e \longrightarrow \nu_\mu + \nu_\tau$
atmospheric and long baseline	reactor and long baseline	solar and reactor
$\theta_{23} \simeq 45^\circ$	$\theta_{13} = 9^\circ$	$\theta_{12} \simeq 35^\circ$

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