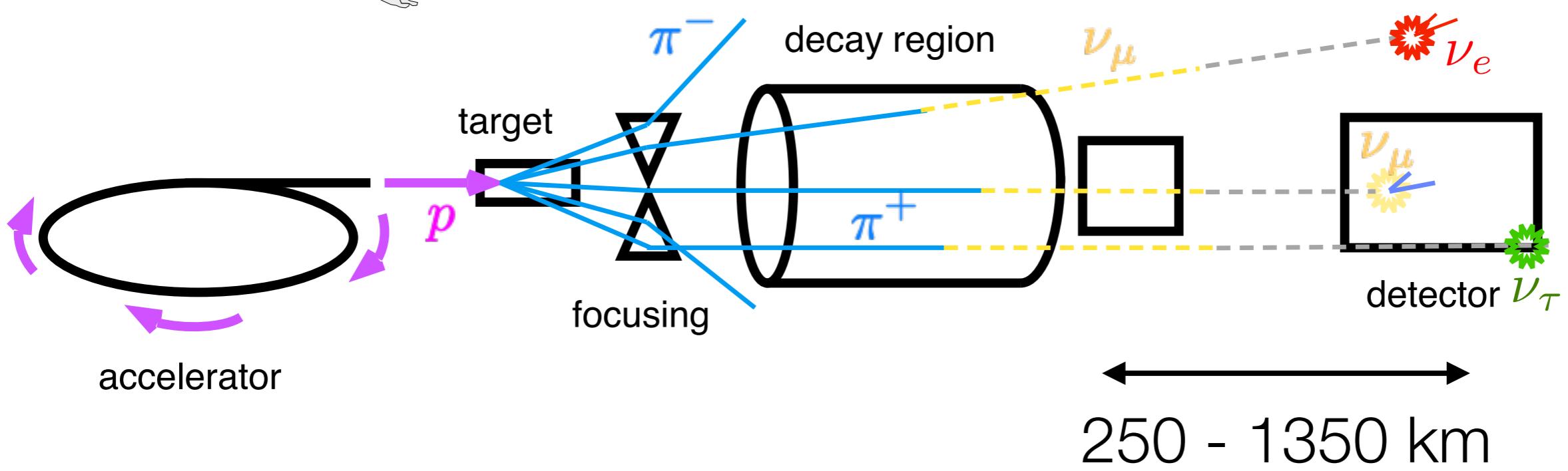
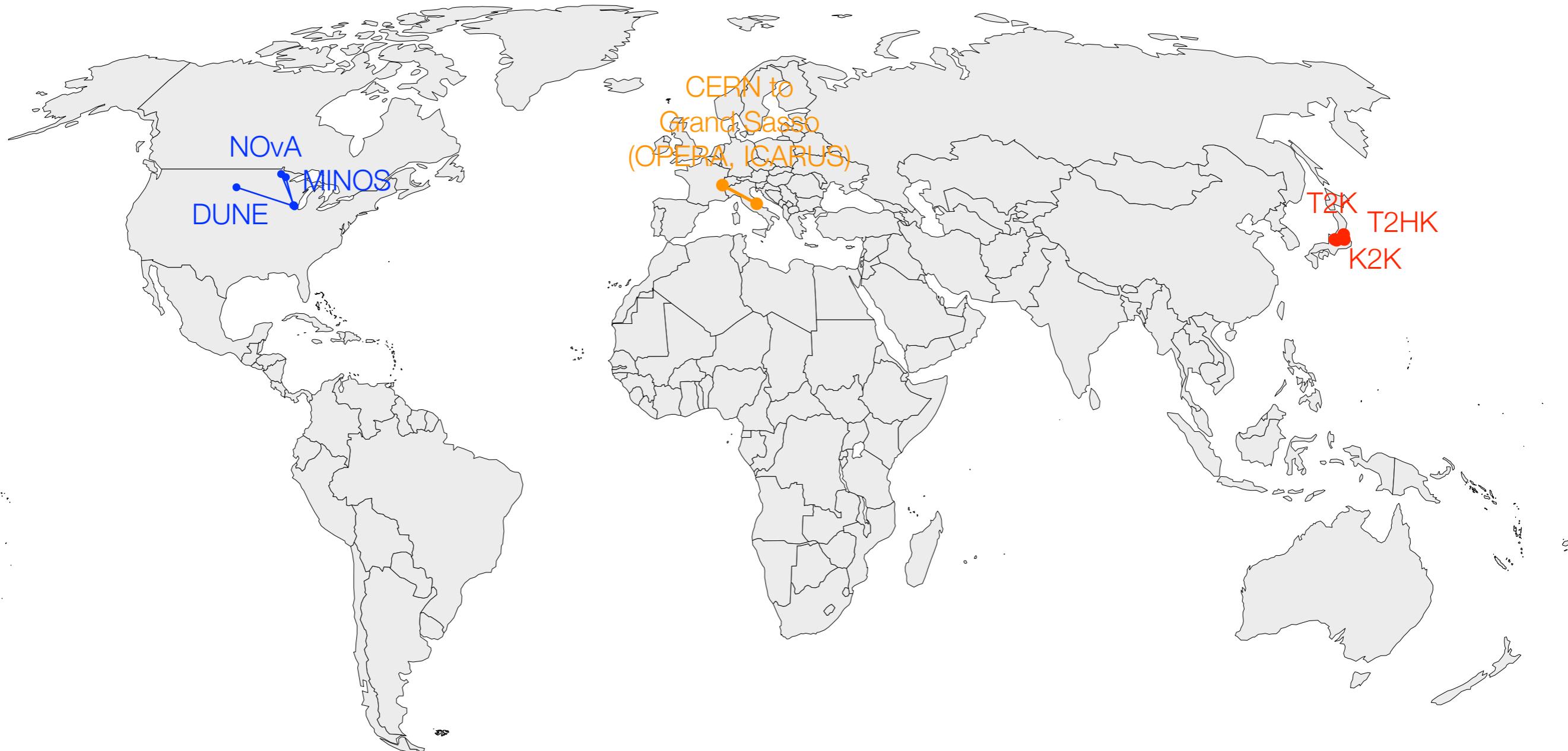


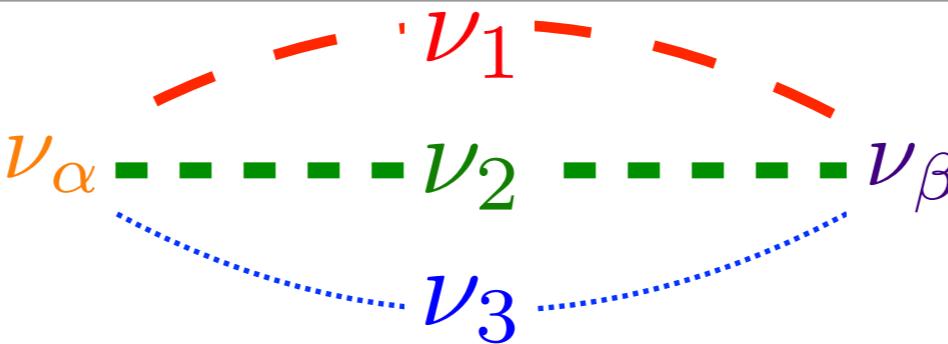
Long Baseline Neutrino Oscillations - 1

Mark Messier
Indiana University

INSS 2023
Fermilab
August 9 and 10



Neutrino oscillations



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

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

$$\begin{aligned} |\Delta m_{32}^2| &\equiv |m_3^2 - m_2^2| \\ &\simeq 2 \times 10^{-3} \text{ eV}^2 \end{aligned}$$

$$\Delta m_{31}^2 \simeq \Delta m_{32}^2$$

$$\Delta m_{21}^2 \simeq 8 \times 10^{-5} \text{ eV}^2$$

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

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

atmospheric and
long baseline

$$\nu_e \rightarrow \nu_e$$

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

reactor and
long baseline

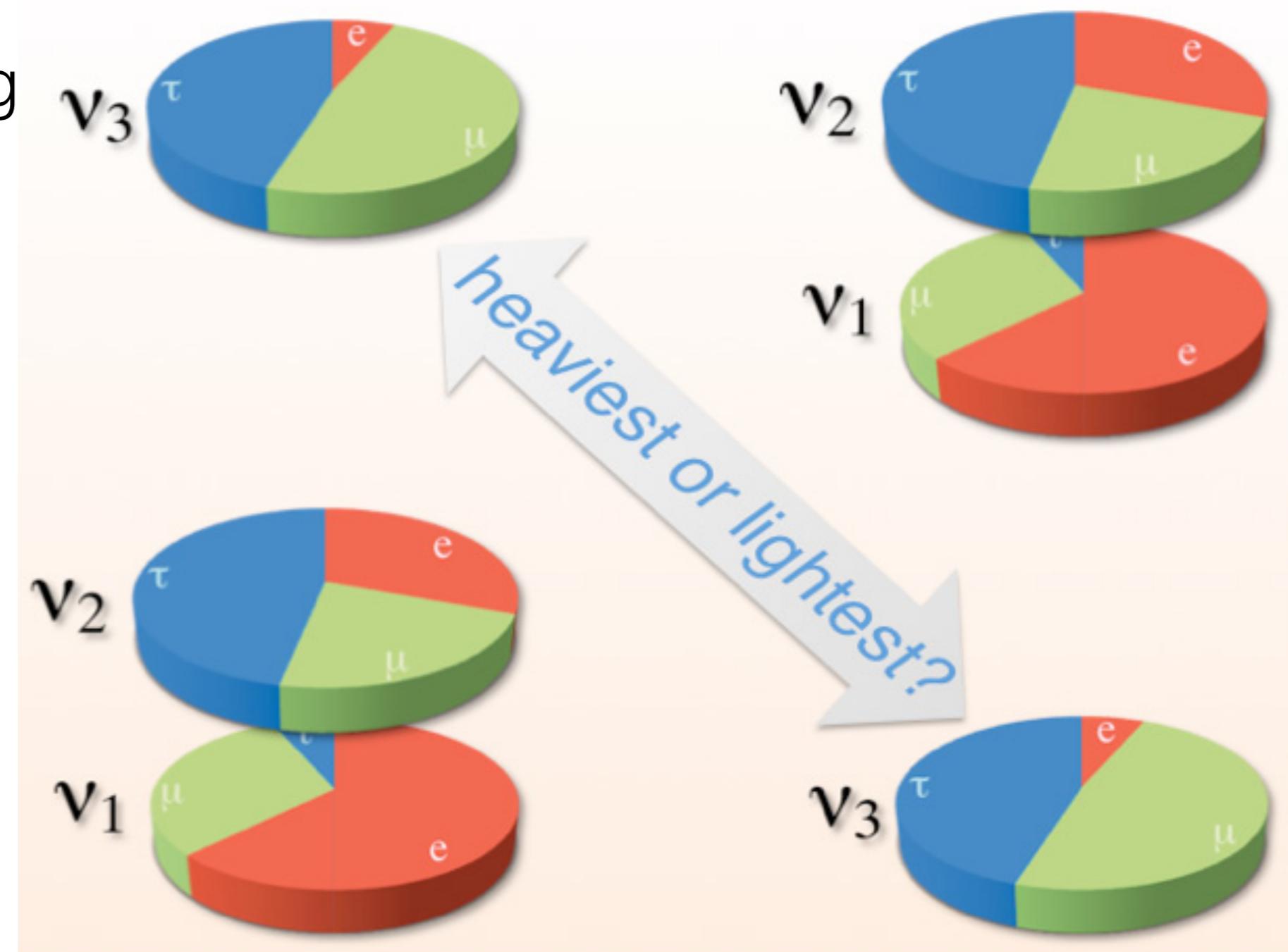
$$\nu_e \rightarrow \nu_e$$

$$\nu_e \rightarrow \nu_\mu + \nu_\tau$$

solar and
reactor

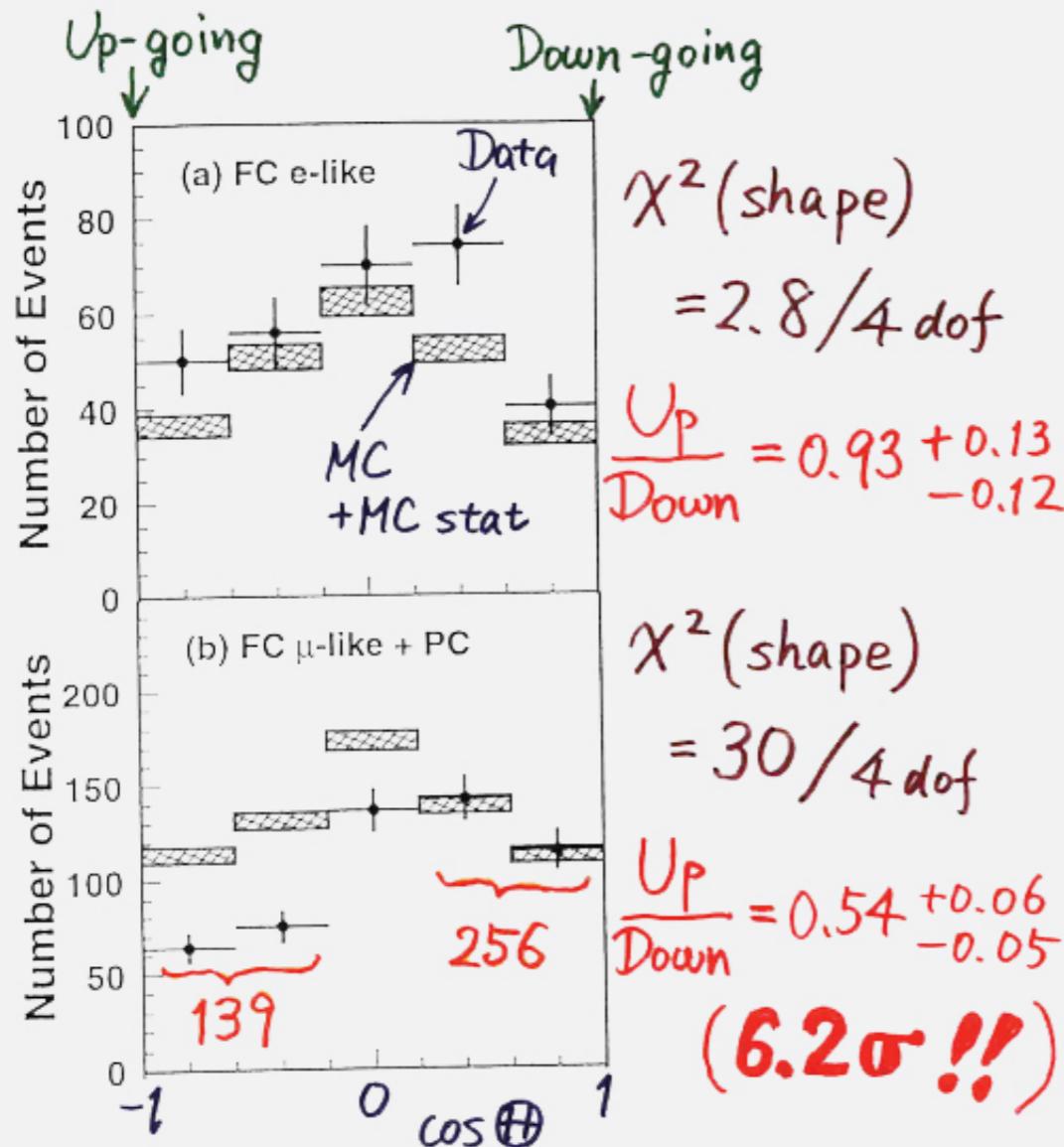
Next Questions In Neutrino Physics

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



Zenith angle dependence (Multi-GeV)

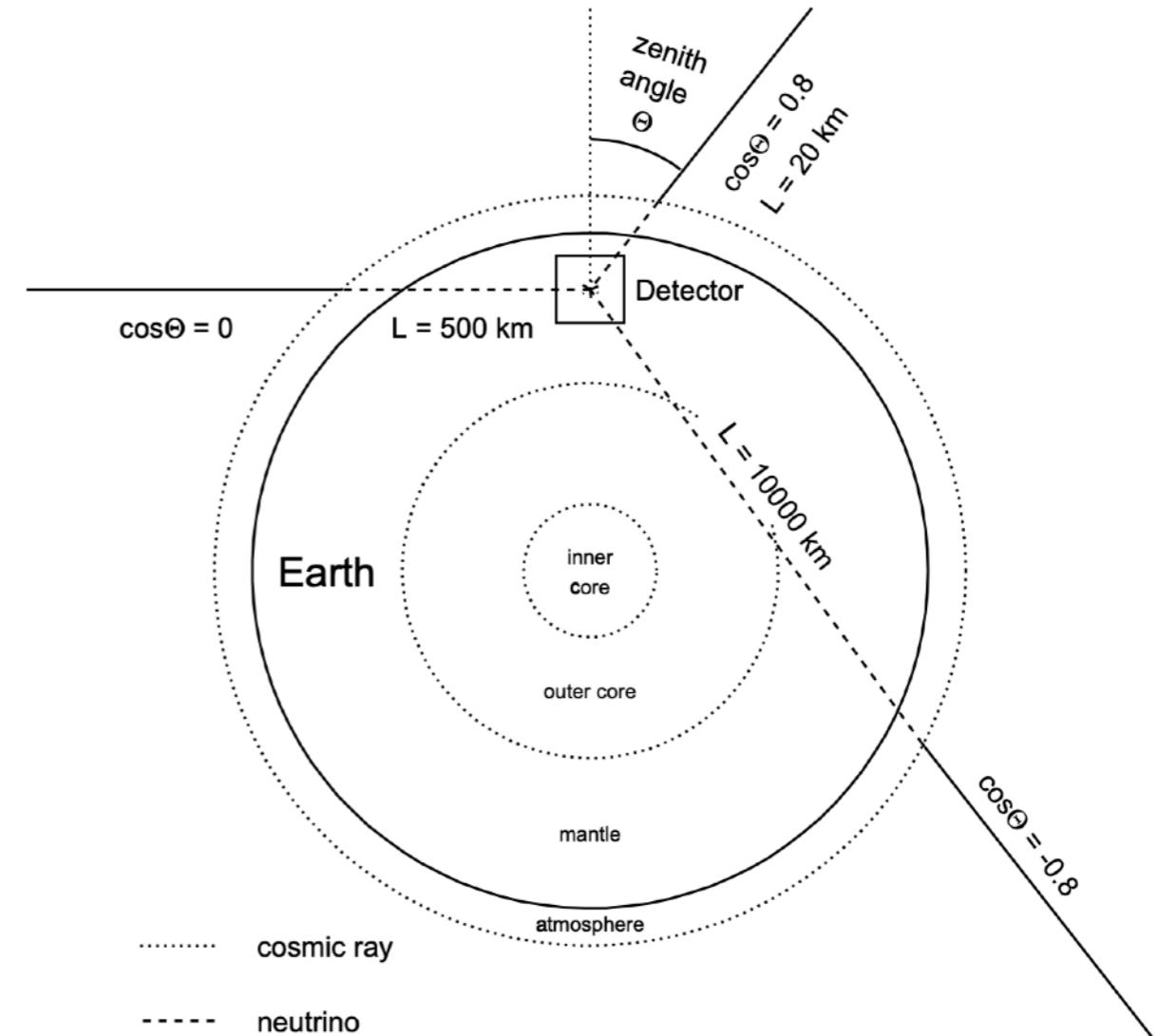
e



* Up/Down syst. error for μ -like

Prediction (flux calculation ... $\lesssim 1\%$
1km rock above SK ... 1.5%) 1.8%

Data (Energy calib. for $\uparrow \downarrow$... 0.7%
Non ν Background ... $< 2\%$) 2.1%



$$\langle E \rangle \simeq 1 \text{ GeV}$$

$$L \simeq 500 \text{ km}$$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 \frac{L}{E} \right)$$

$$\Delta m^2 \simeq \frac{\pi}{2.54} \frac{E}{L} \simeq 2.5 \times 10^{-3} \text{ eV}^2$$

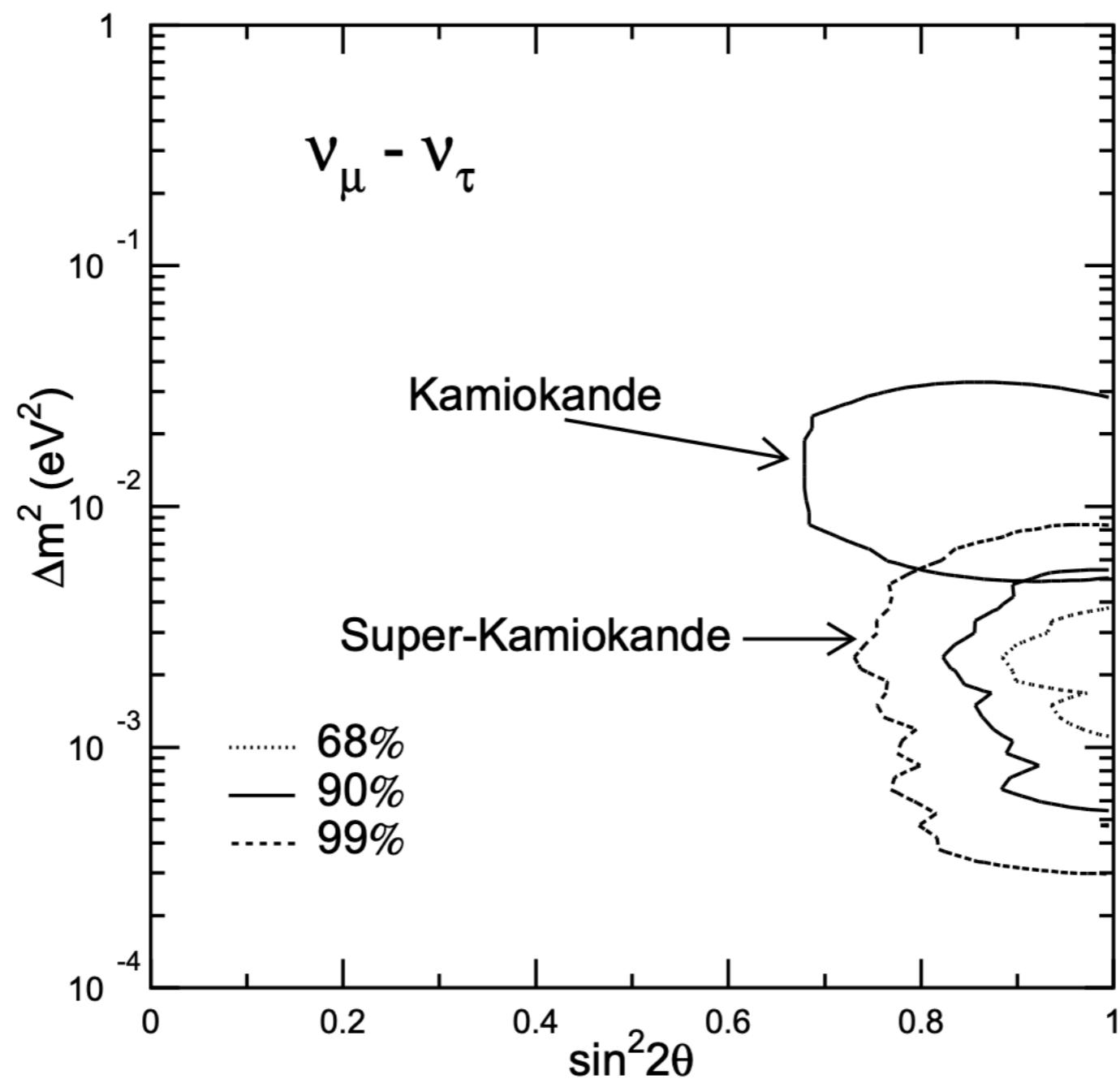
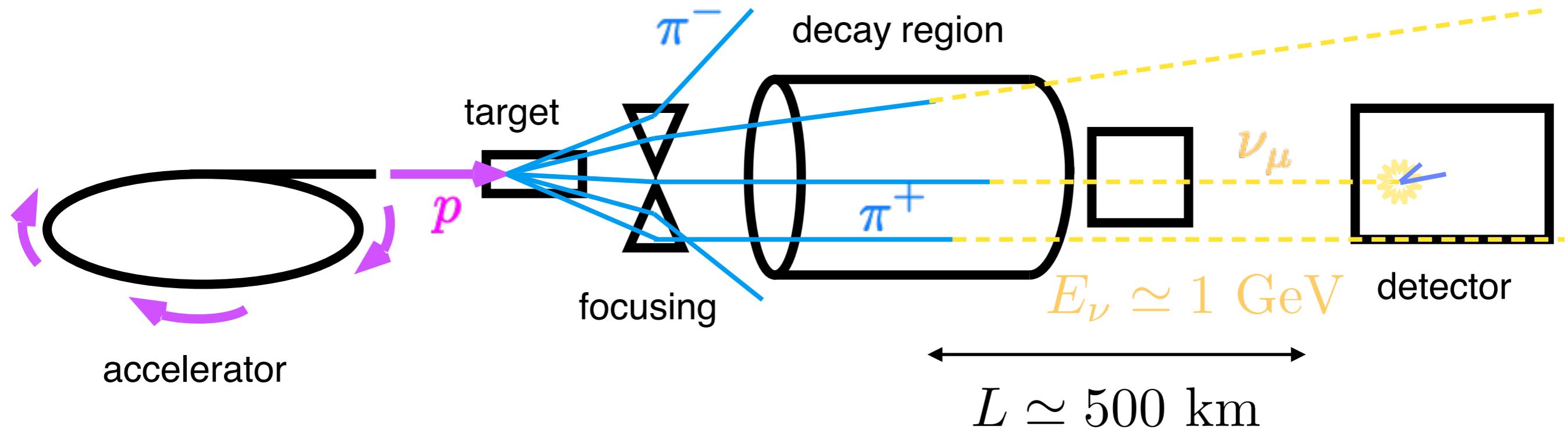


FIG. 2. The 68%, 90% and 99% confidence intervals are shown for $\sin^2 2\theta$ and Δm^2 for $\nu_\mu \leftrightarrow \nu_\tau$ two-neutrino oscillations based on 33.0 kiloton-years of Super-Kamiokande data. The 90% confidence interval obtained by the Kamiokande experiment is also shown.

Let's imagine we are at a “SNOWMASS 1998” and you want to know if its possible to measure the oscillations reported by SK using an accelerator.

Let's see what we can get on the back of an envelope...

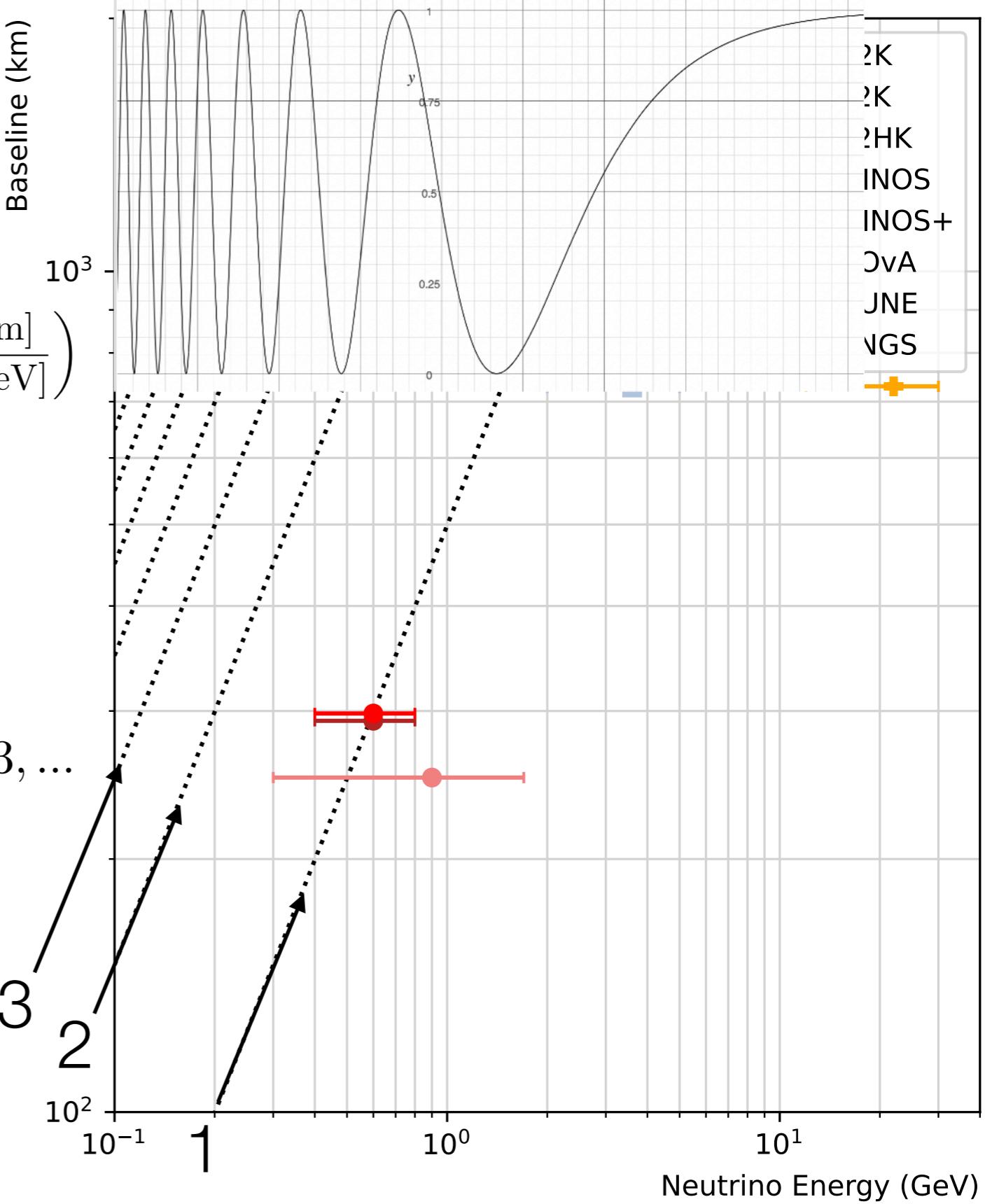


$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 \left(1.27 \Delta m_{32}^2 [\text{eV}^2] \frac{L [\text{km}]}{E [\text{GeV}]} \right)$$

Can we reproduce these conditions using accelerators?

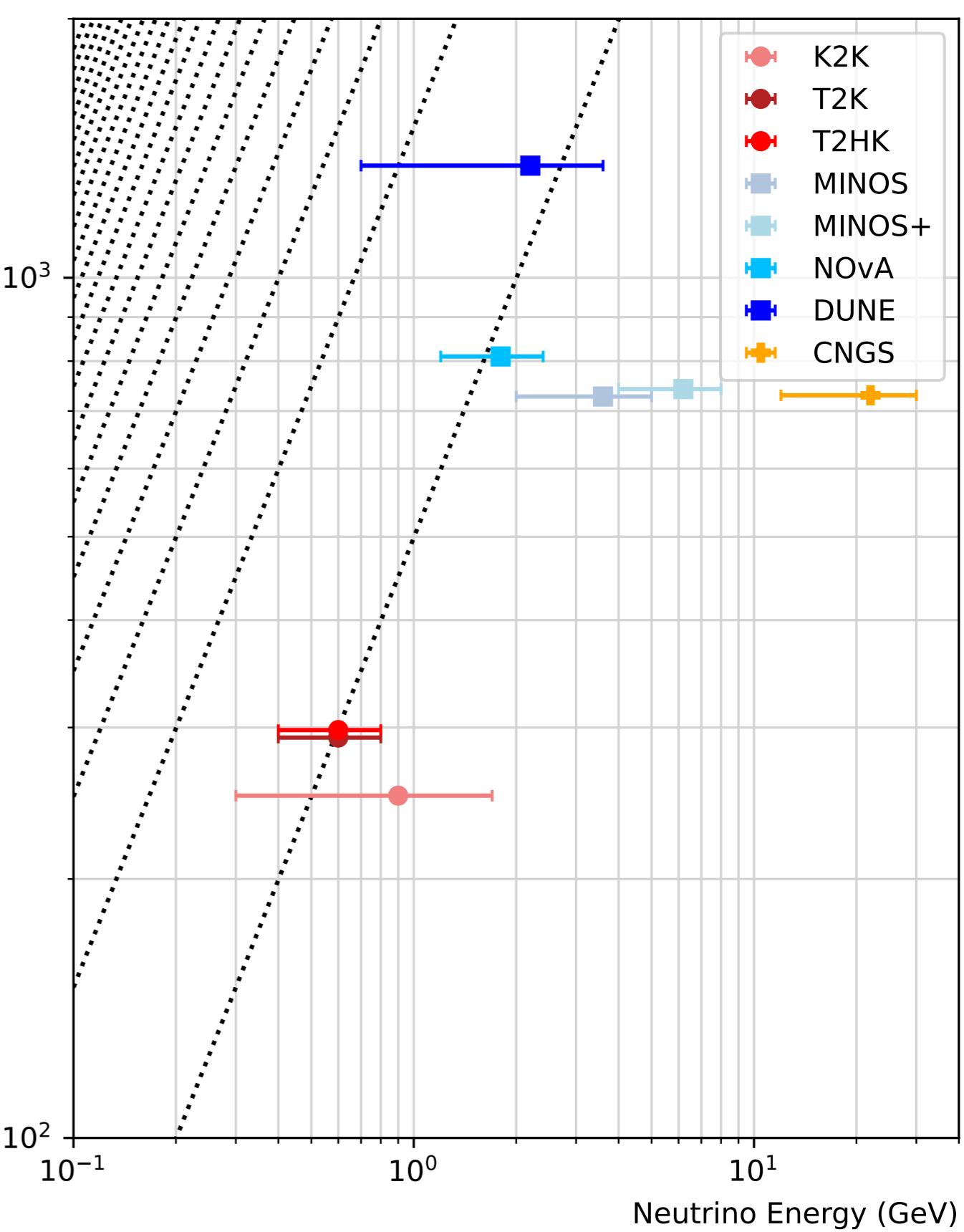
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 \left(1.27 \Delta m_{32}^2 [\text{eV}^2] \frac{L [\text{km}]}{E [\text{GeV}]} \right)$$

$$1.27 \Delta m_{32}^2 \frac{L}{E} = \frac{(2n-1)}{2} \pi \quad \text{for } n = 1, 2, 3, \dots$$

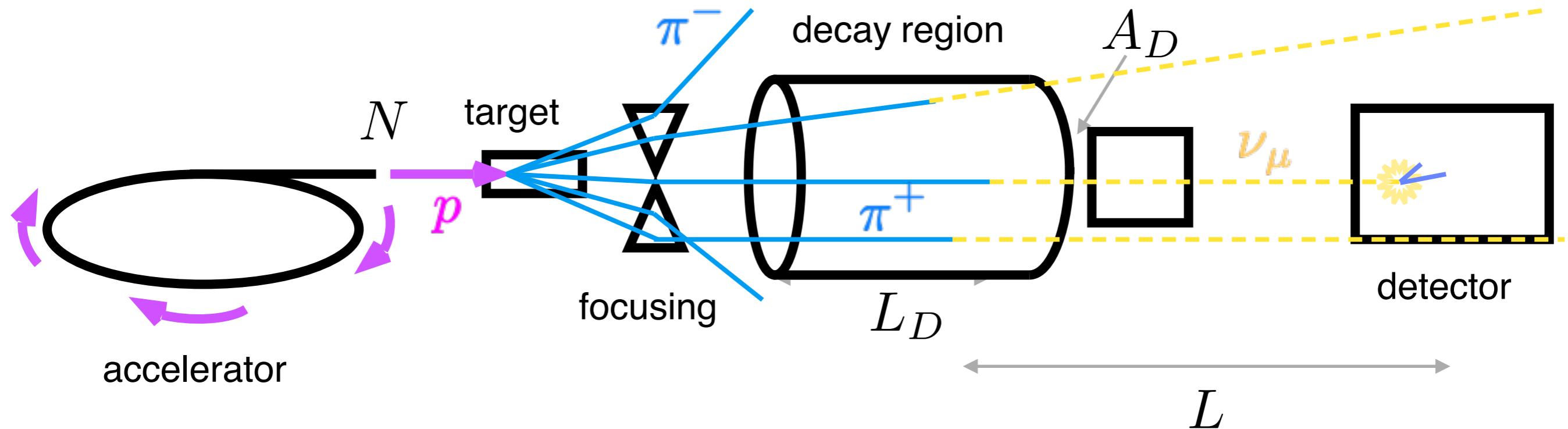


Can we reproduce these conditions using accelerators?

	Dates	Source	Primary Energy (GeV)	P [kW]	M [kt]	L [km]	E [GeV]
K2K	1999 - 2004	KEK PS	12	5.2	22.5	250	0.9
T2K	2010 - present	JPARC	30	515	22.5	295	0.6
T2HK	2027	JPARC	30	[500, 300]	188	295	0.6
MINOS	2005 - 2012	Fermilab Main Injector	120	240	5.4	735	3.6
MINOS+	2013 - 2016	Fermilab Main Injector	120	700	5.4	735	6.2
NOvA	2014- present	Fermilab Main Injector	120	400 - 960	14	810	1.8
DUNE	>2030	Fermilab Main Injector	120	1000 - 2400	40	1350	2.2
CNGS / OPERA	2008 - 2012	CERN PS	400	512	1.25	730	1.25



Long baseline experiments



$$N_{\text{events}} = \left[\int \mathcal{F}(E_\nu, \dots) \cdot \sigma(E_\nu, \dots) \cdot \epsilon(E_\nu, \dots) dE_\nu d\dots \right] \frac{M}{m_N} \cdot T$$

$$\frac{N_{\text{events}}}{\text{GeV}} \simeq \mathcal{F} \cdot \sigma \cdot \epsilon \cdot \frac{M}{m_N} \cdot T$$

neutrino flux

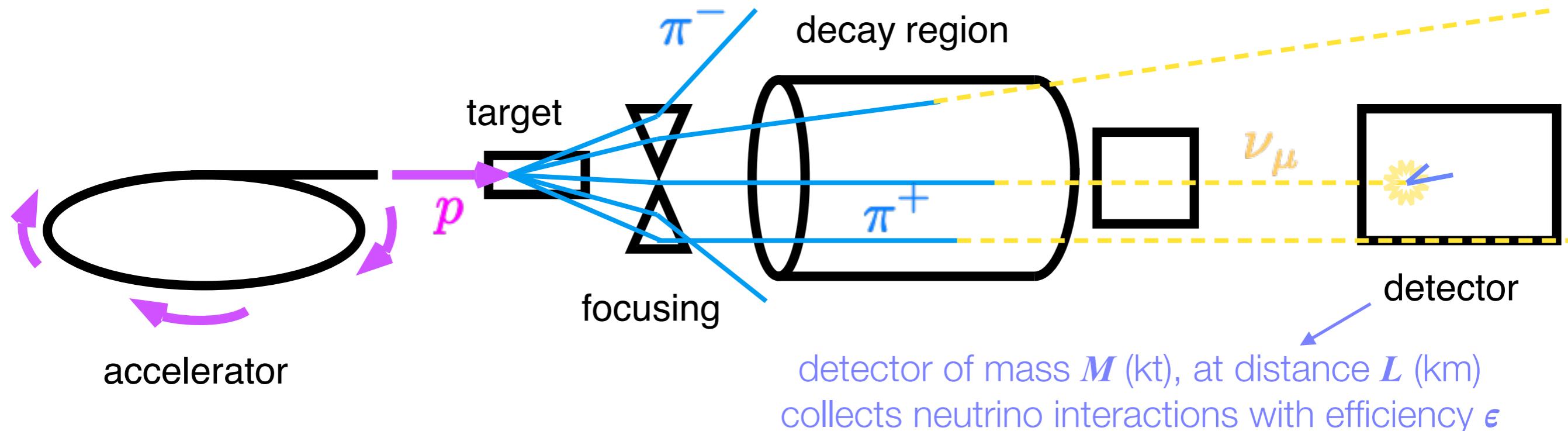
detection and reconstruction efficiency

number of target nucleons: detector mass / nucleon mass

running time

neutrino - nucleon cross-section

Can we reproduce these conditions using accelerators?



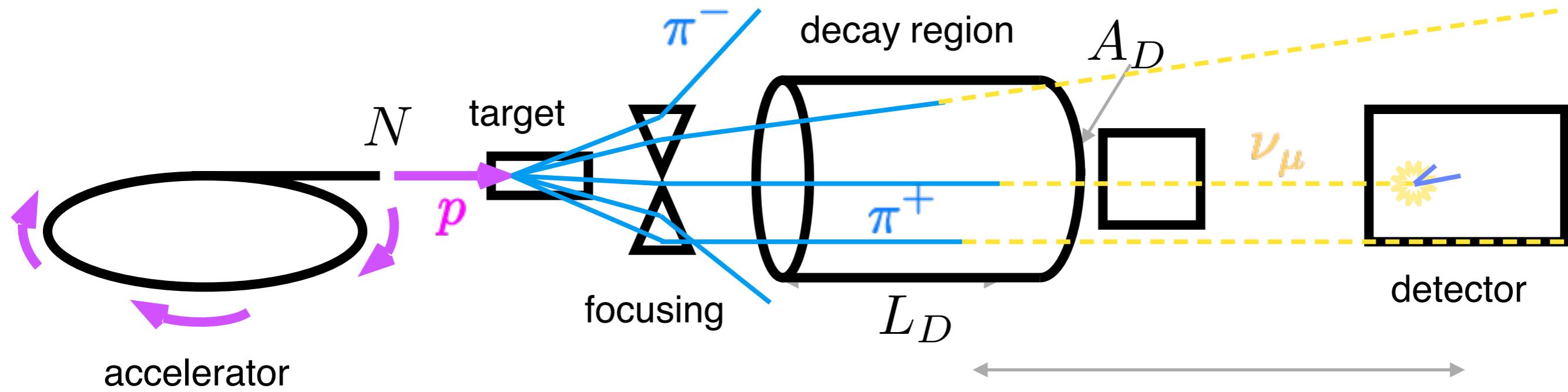
$$\frac{N_{\text{events}}}{\text{GeV}} \simeq \mathcal{F} \cdot \sigma \cdot \epsilon \cdot \frac{M}{m_N} \cdot T$$

$[0.7E_\nu \times 10^{-38} \text{ cm}^2] \cdot \epsilon \cdot \left[\frac{M \times 10^6 \text{ kg}}{1.67 \times 10^{-27} \text{ kg}} \right] \cdot [T \times 3.15 \times 10^7 \text{ s}]$

$$\frac{N_{\text{events}}}{\text{GeV}} = \mathcal{F} \cdot (130E_\nu (MT) [\text{cm}^2 \text{s}])$$

Can we reproduce these conditions using accelerators?

exposure in kiloton years



accelerator intensity, protons on target (POT) per second

$$\mathcal{F} \simeq N \left[\frac{\text{protons}}{\text{s}} \right] \cdot \gamma \left[\frac{\nu}{\text{proton}} \right] \cdot \frac{1}{A_D} \left(\frac{L_D}{L} \right)^2$$

accelerator power

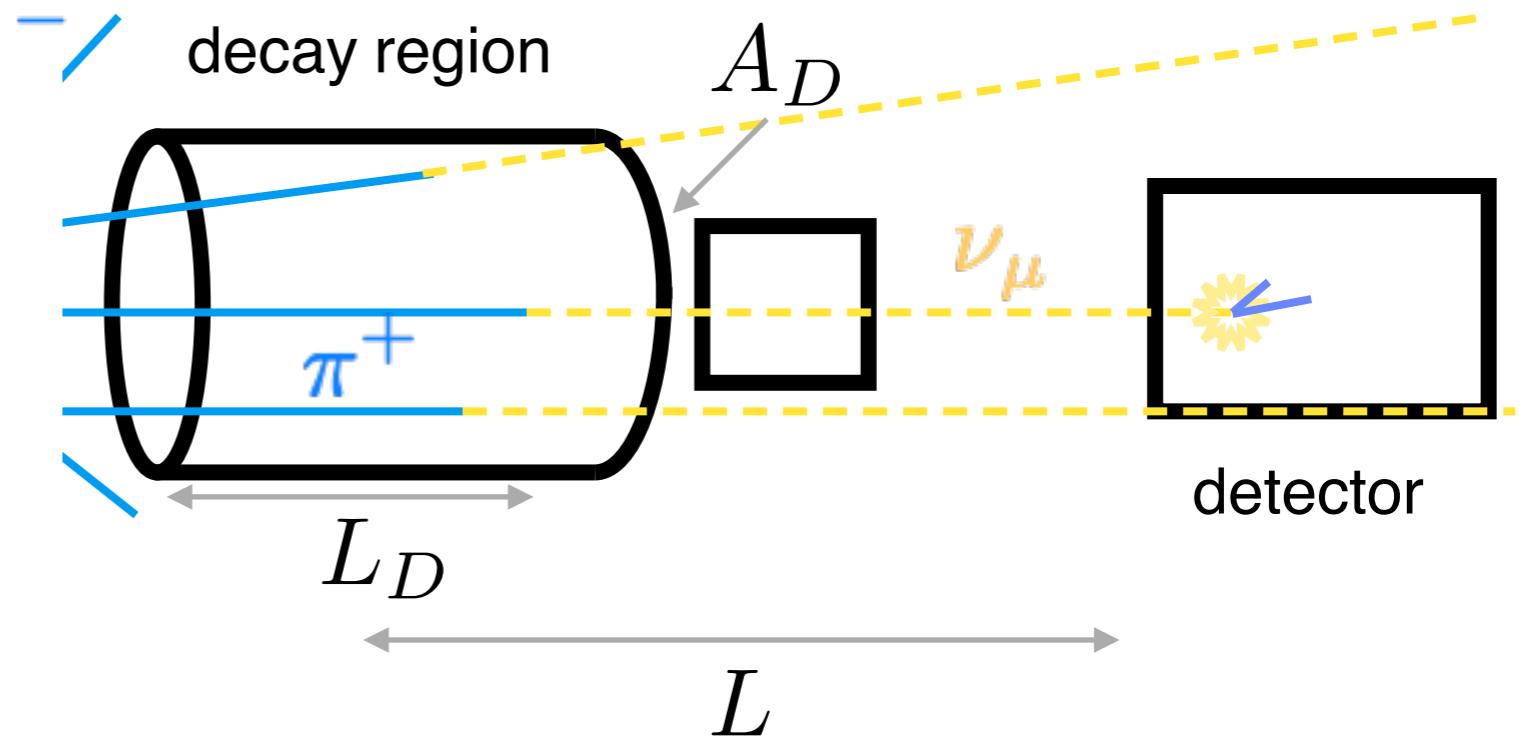
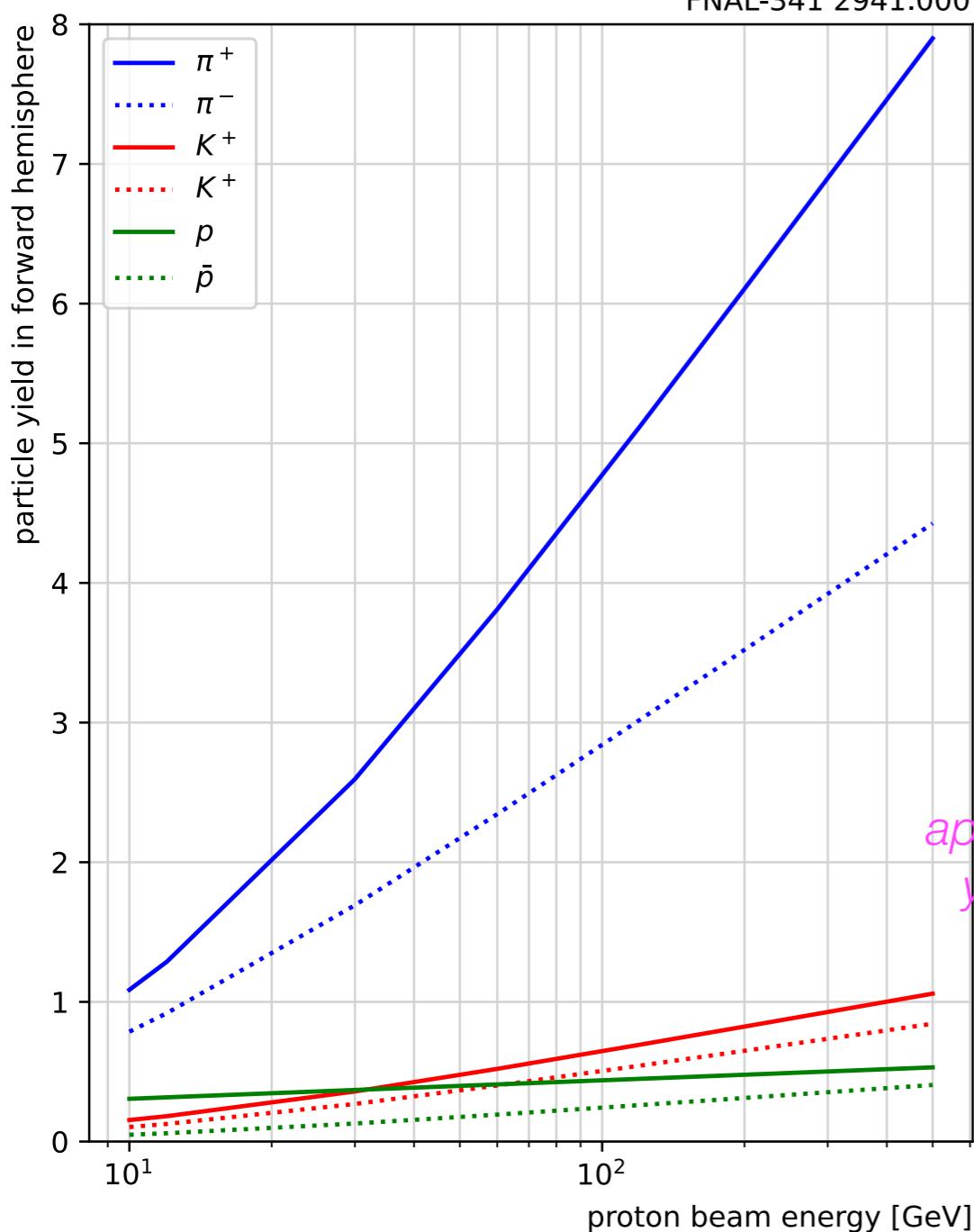
$$N \simeq \frac{P \text{ [kW]}}{E_0 \text{ [GeV]}} \cdot \frac{1 \text{ GeV}}{1.6 \times 10^{-13} \text{ kJ}} = 6.3 \times 10^{12} \frac{P}{E_0}$$

proton energy

Can we reproduce these conditions using accelerators?

NOvA, for example

$$N = 6.3 \times 10^{12} \frac{700 \text{ kW}}{120 \text{ GeV}} = 3.7 \times 10^{13} \text{ protons/s} \\ = (4.9 \times 10^{13} \text{ protons/pulse}) / (1.3 \text{ s/pulse})$$



$$\gamma \simeq \frac{E_0[\text{GeV}]}{20} \cdot \epsilon_{\text{focusing}}$$

approximate pion
yield per proton
on target

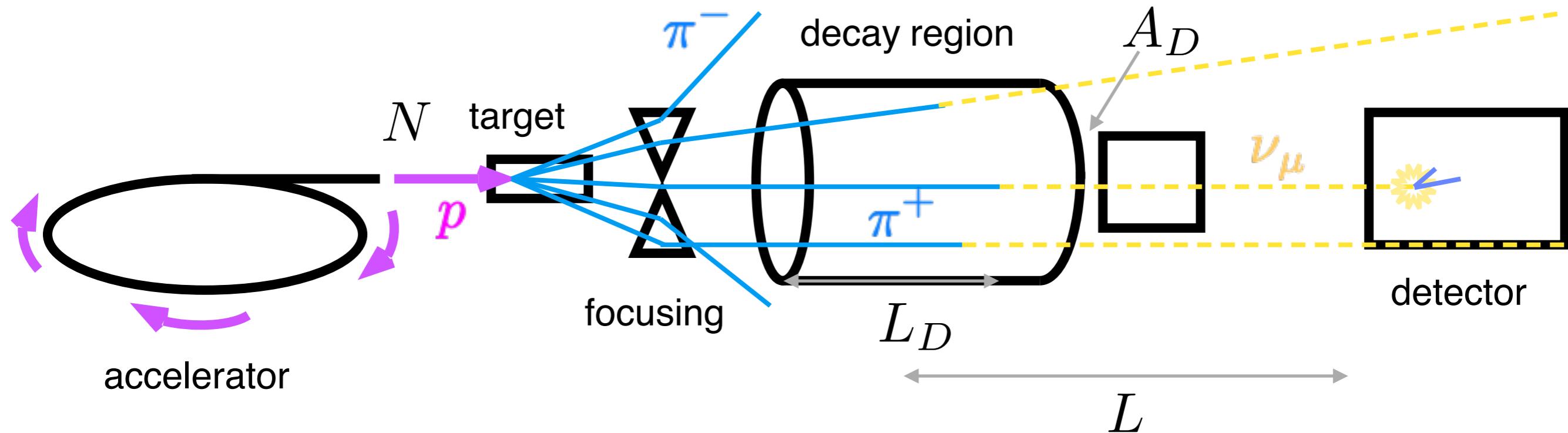
$$\epsilon_{\text{focusing}} = \frac{\Omega_D}{2\pi} F \simeq \frac{\pi A_D}{2\pi L_D^2} F$$

$$(\simeq 2 \times 10^{-6}) (100(?))$$

$$\simeq 2 \times 10^{-4}$$

$$\gamma \simeq \frac{E_0}{1 \times 10^5} \text{ neutrinos/proton}$$

**Can we reproduce these
conditions using accelerators?**



$$\mathcal{F} \simeq N \left[\frac{\text{protons}}{\text{s}} \right] \cdot \mathcal{Y} \left[\frac{\nu}{\text{proton}} \right] \cdot \frac{1}{A_D} \left(\frac{L_D}{L} \right)^2$$

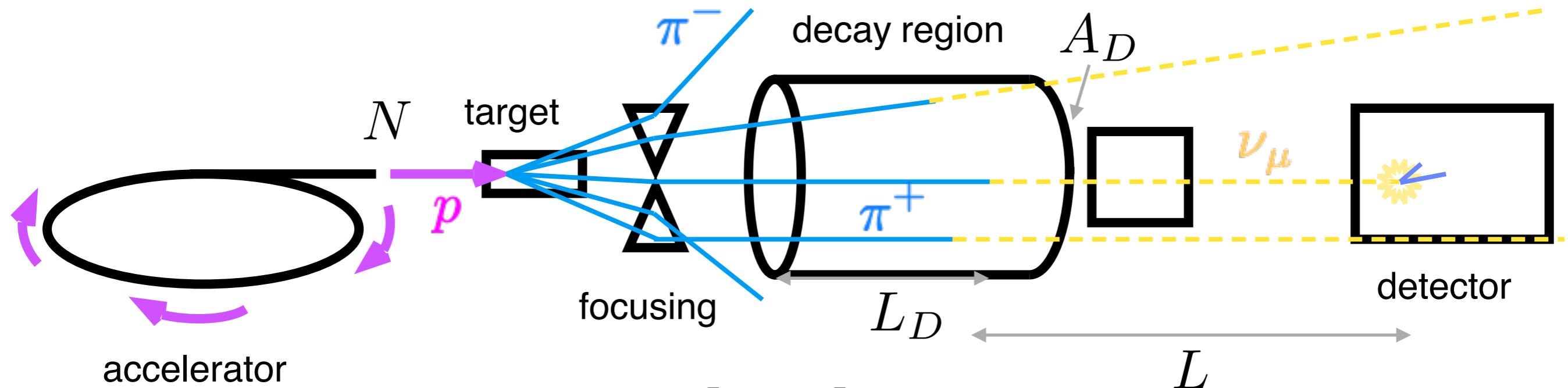
$L_D \simeq 0.5 \text{ km}$

$A_D \simeq \pi(100 \text{ cm})^2$

$$\mathcal{F} \simeq 6.3 \times 10^{12} \frac{P}{E_0} \cdot \frac{E_0}{10^5} \cdot \frac{1}{1.3 \times 10^5 L^2} \left[\frac{1}{\text{cm}^2 \text{ s}} \right]$$

$$\mathcal{F} \simeq 500 \frac{P}{L^2} \left[\frac{1}{\text{cm}^2 \text{ s}} \right]$$

Can we reproduce these conditions using accelerators?



$$\mathcal{F} \simeq 500 \frac{P}{L^2} \left[\frac{1}{\text{cm}^2 \text{ s}} \right]$$

$$L_D \simeq 0.5 \text{ km}$$

$$\frac{N_{\text{events}}}{\text{GeV}} = \mathcal{F} \cdot (130 E_\nu (MT) [\text{cm}^2 \text{s}])$$

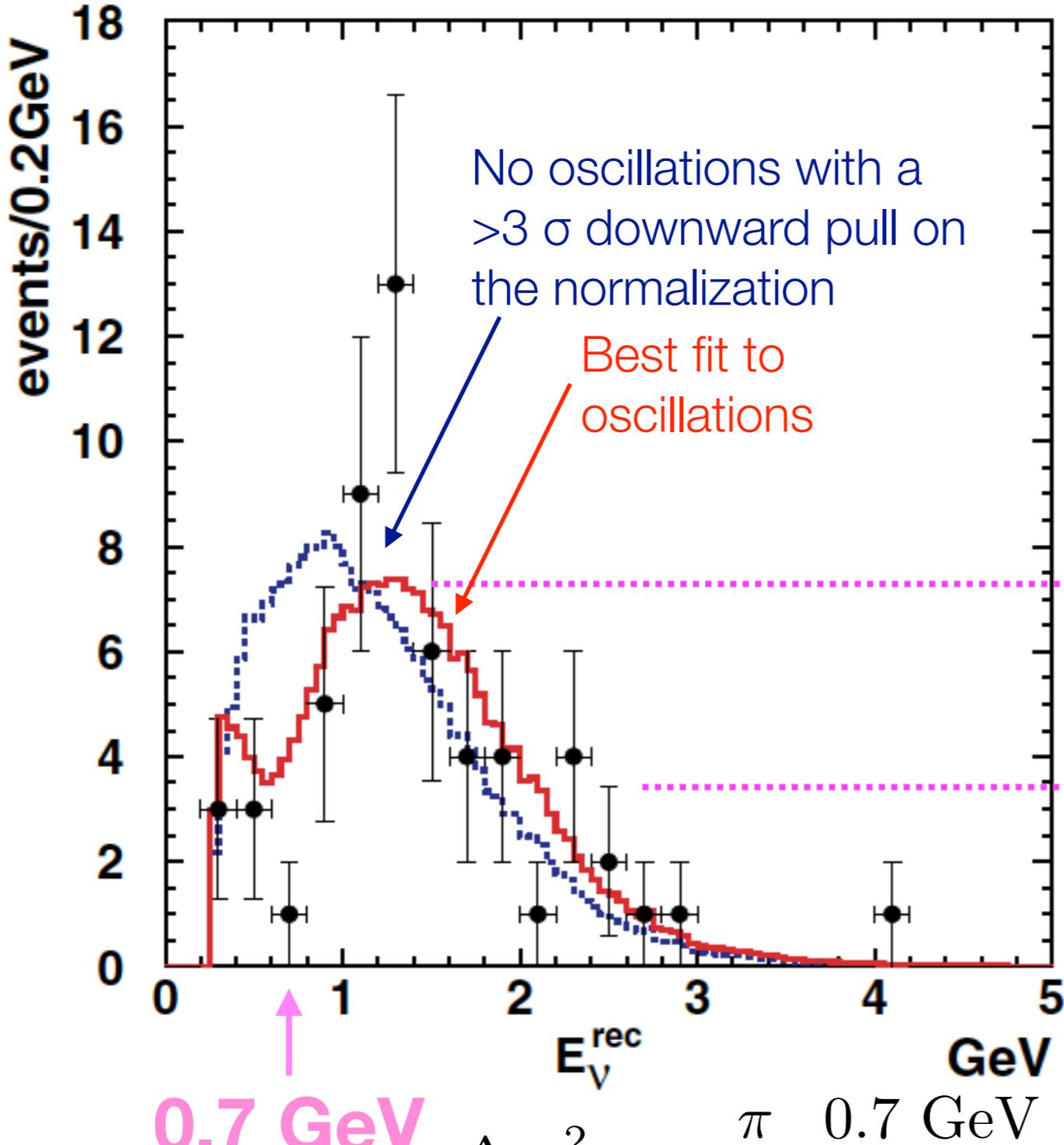
$$\frac{N_{\text{events}}}{\text{GeV}} \simeq P [\text{kW}] \cdot M [\text{kt}] \cdot T [\text{years}] \cdot \left(\frac{250}{L} \right)^2 \cdot \epsilon \cdot E_\nu [\text{GeV}]$$

beam power P ranges from
100 to 1000 kW

detector mass M ranges
from 5 to 200 kt

**Can we reproduce these
conditions using accelerators?**

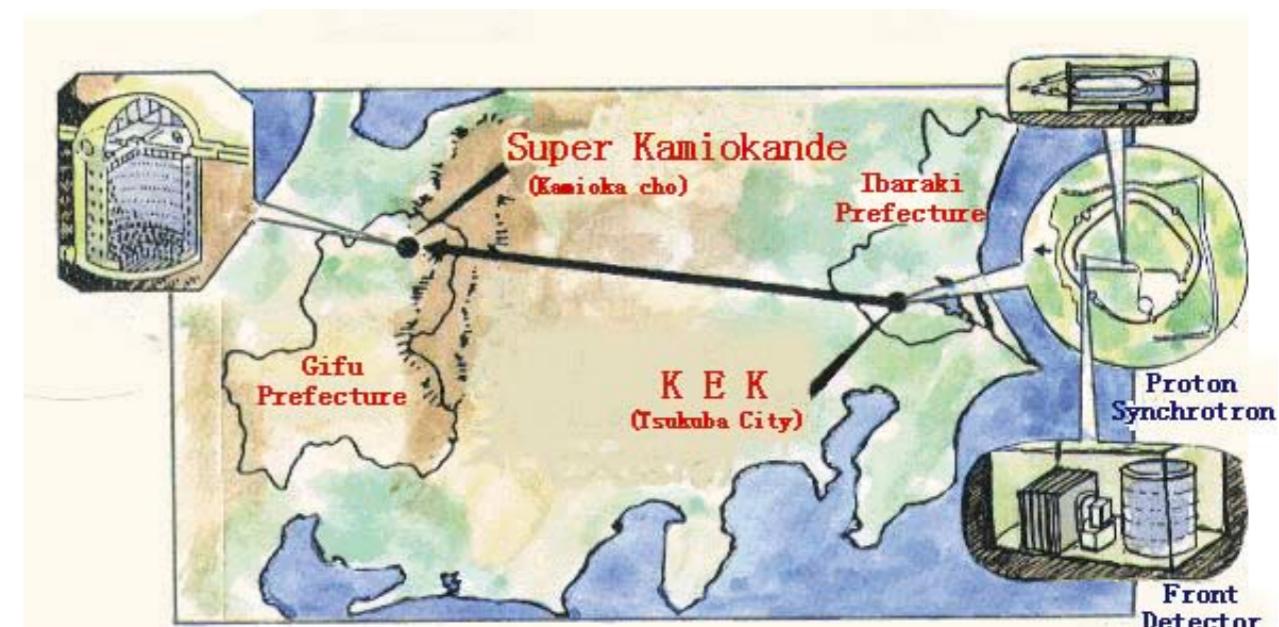
$\frac{N_{\text{events}}}{\text{GeV}} \simeq 10^2 \dots 10^4 \text{ per year}$
 (YES, AND MAYBE MUCH BETTER!)



0.7 GeV

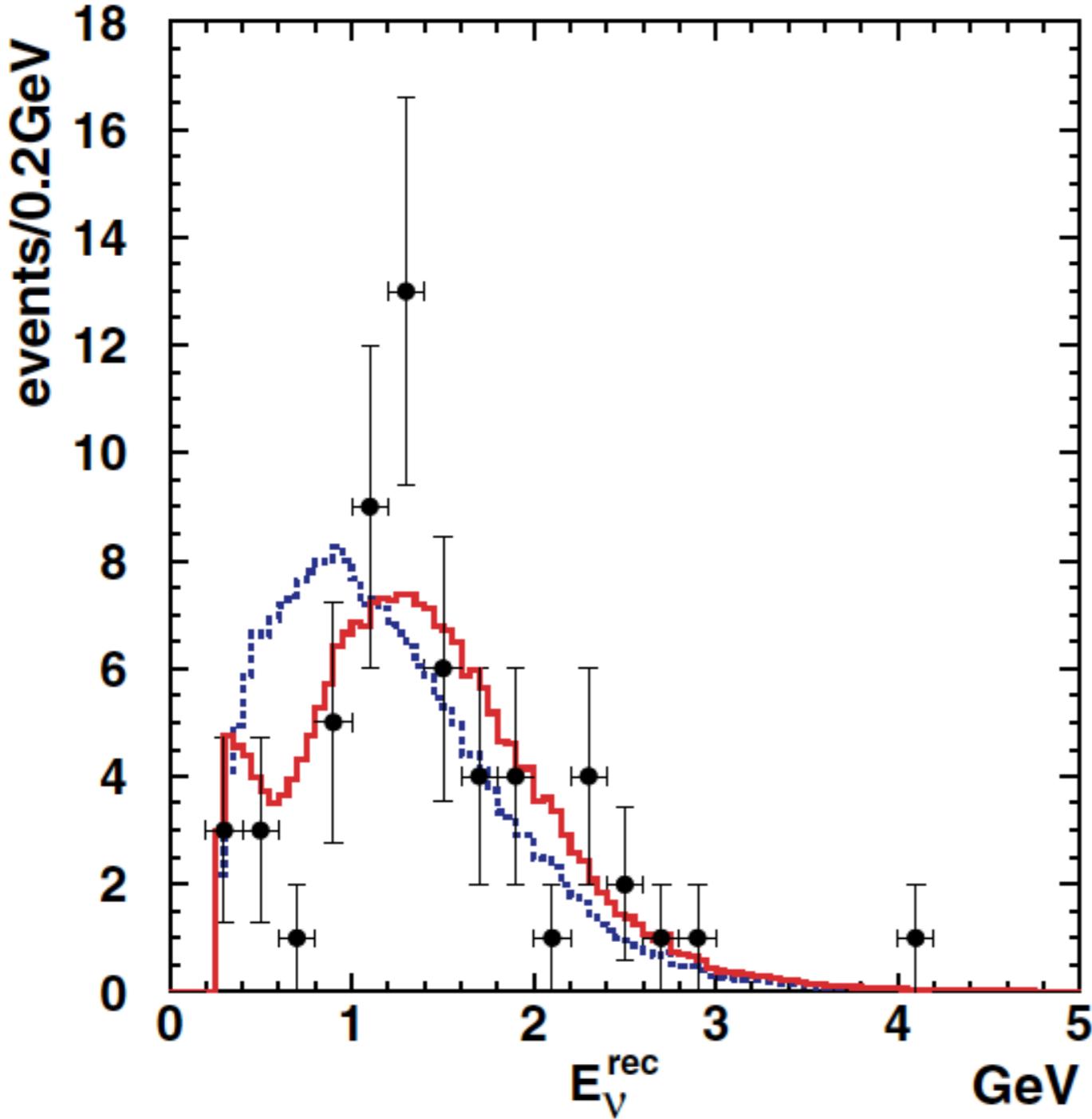
$$\Delta m_{32}^2 \simeq \frac{\pi}{2.54} \frac{0.7 \text{ GeV}}{250 \text{ km}} = 3 \times 10^{-3} \text{ eV}^2$$

K2K Experiment



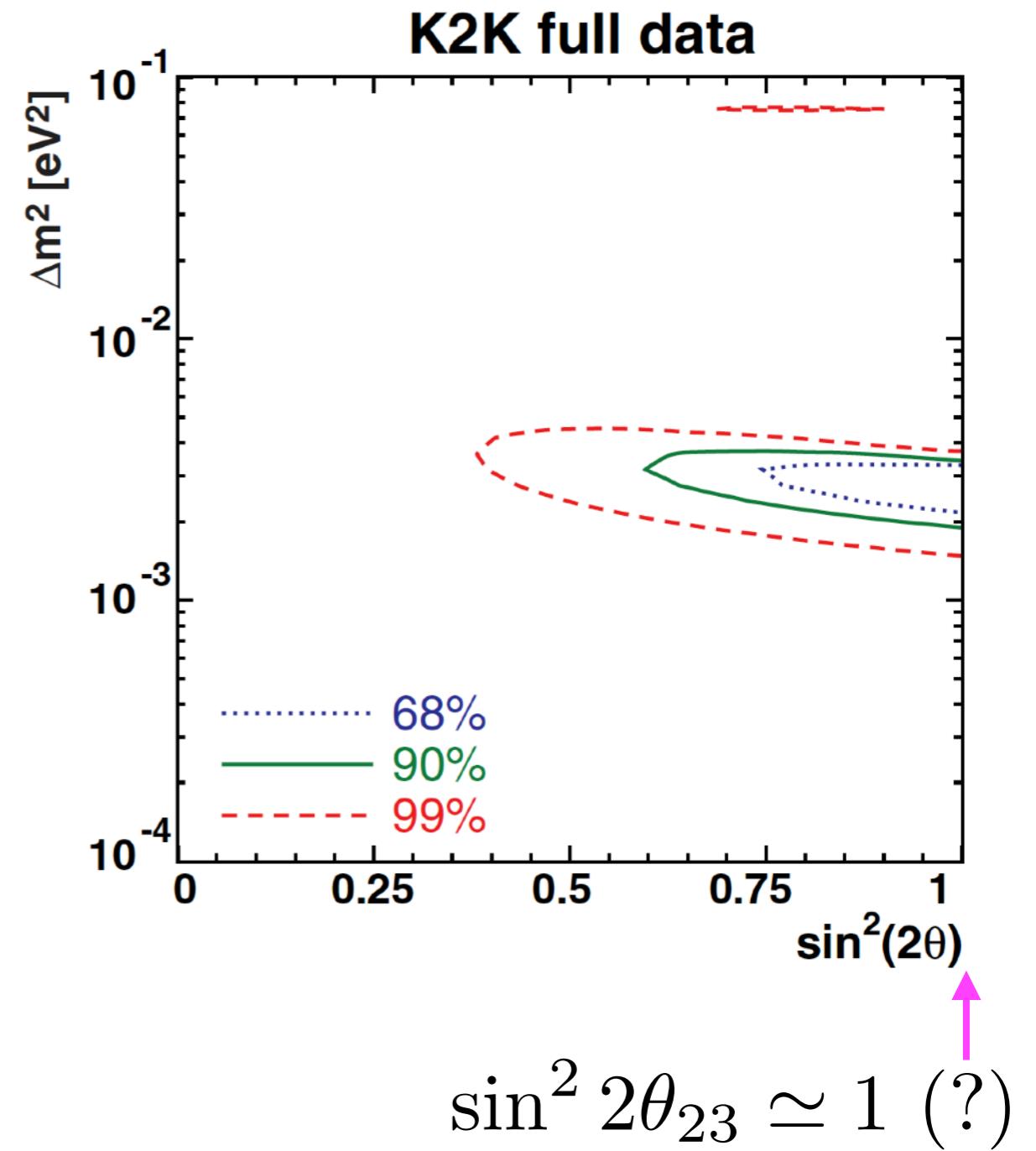
$$\sin^2 2\theta_{23} \simeq ?$$

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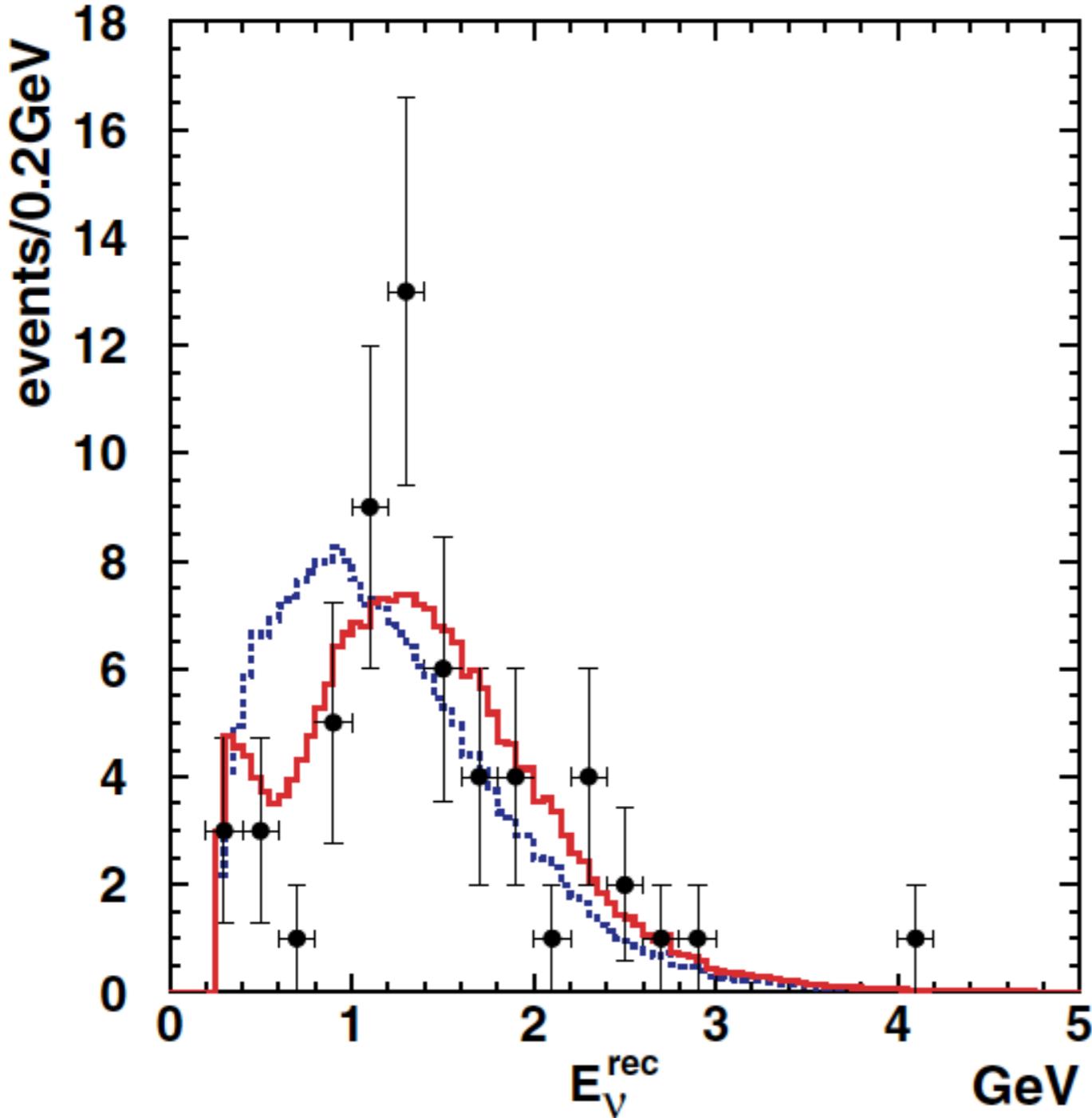


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K2K Experiment

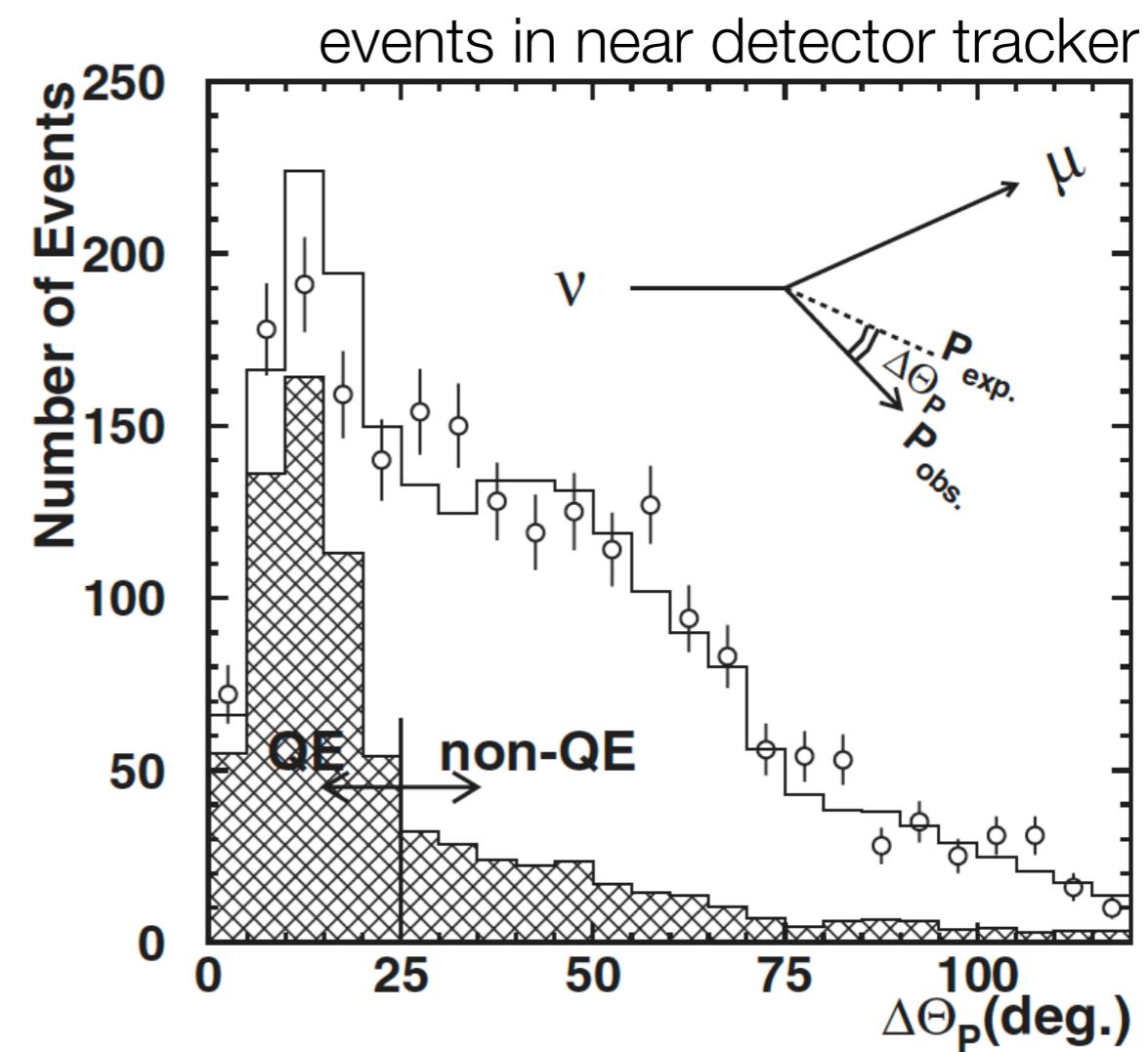


PHYSICAL REVIEW D 74, 072003 (2006)



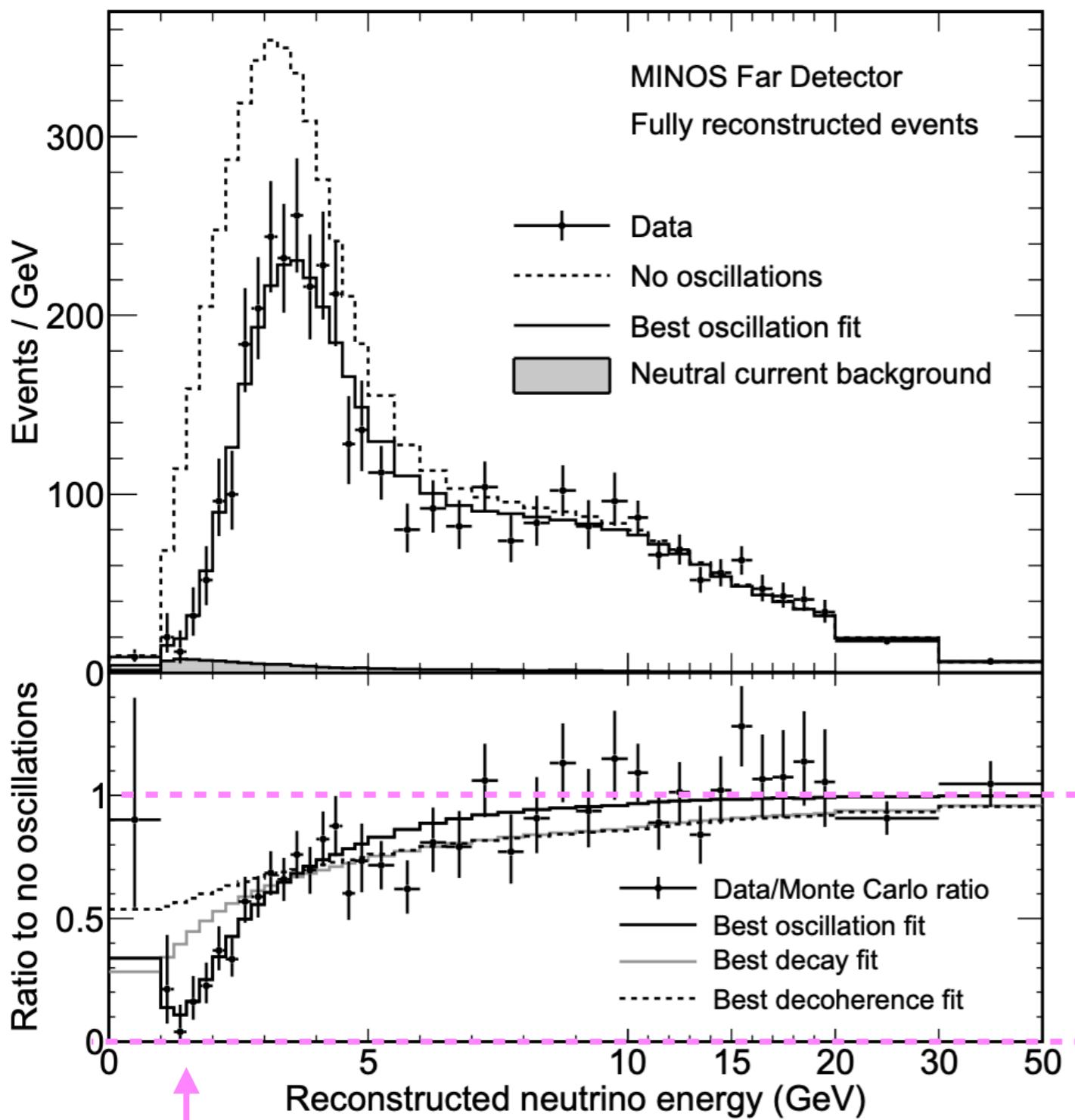
$$\Delta m_{32}^2 \simeq \frac{\pi}{2.54} \frac{0.7 \text{ GeV}}{250 \text{ km}} = 3 \times 10^{-3} \text{ eV}^2$$

K2K Experiment



$$E_{\nu}^{\text{rec}} = \frac{m_N E_{\mu} - m_{\mu}^2/2}{m_N - E_{\mu} + P_{\mu} \cos\theta_{\mu}}$$

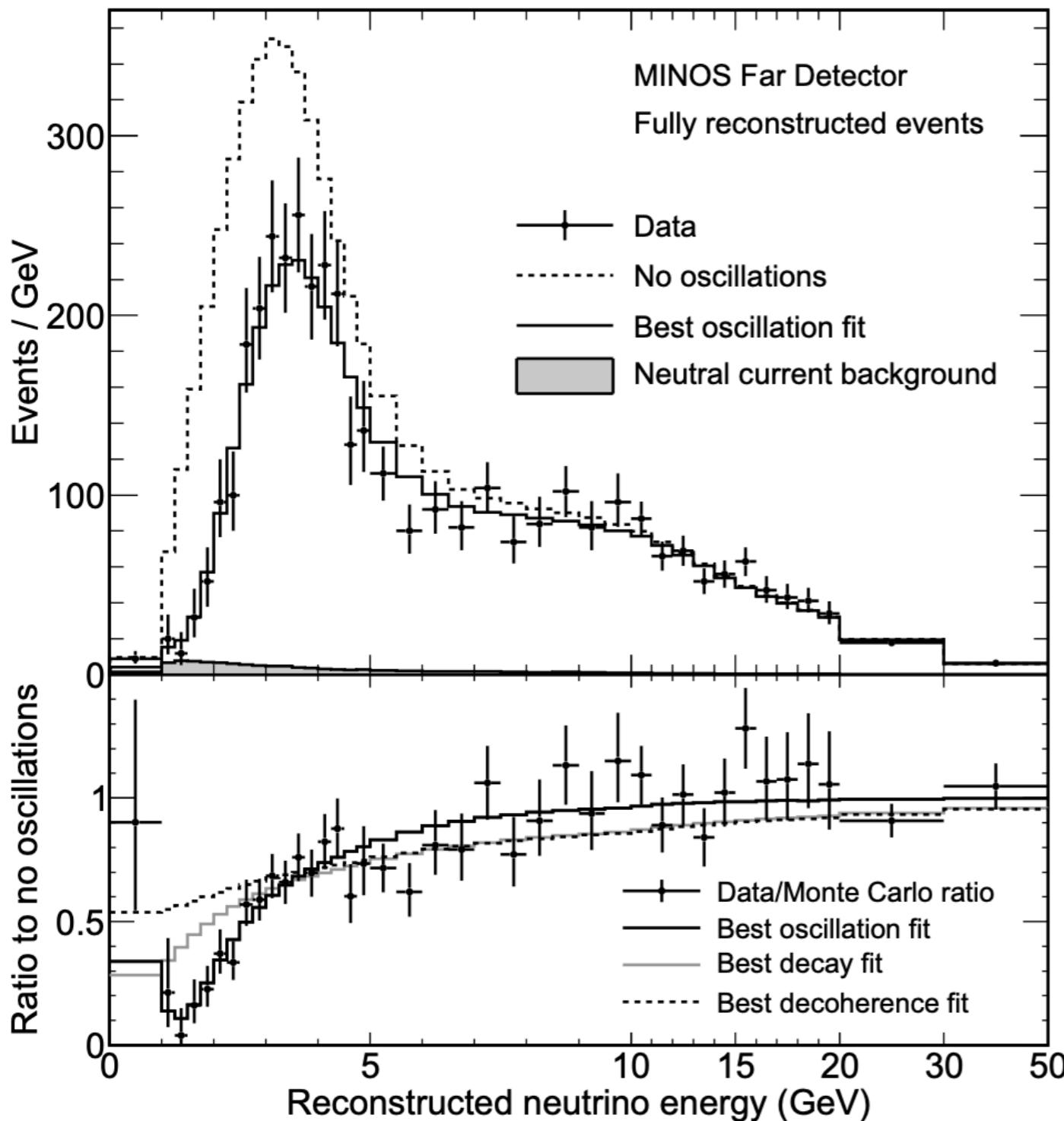
PHYSICAL REVIEW D 74, 072003 (2006)



$$\sin^2 2\theta_{23} \approx 1$$

1.4 GeV $\Delta m_{32}^2 \sim \frac{\pi}{2.54} \frac{1.4 \text{ GeV}}{735 \text{ km}} = 2.3 \times 10^{-3} \text{ eV}^2$

MINOS Experiment



MINOS Experiment

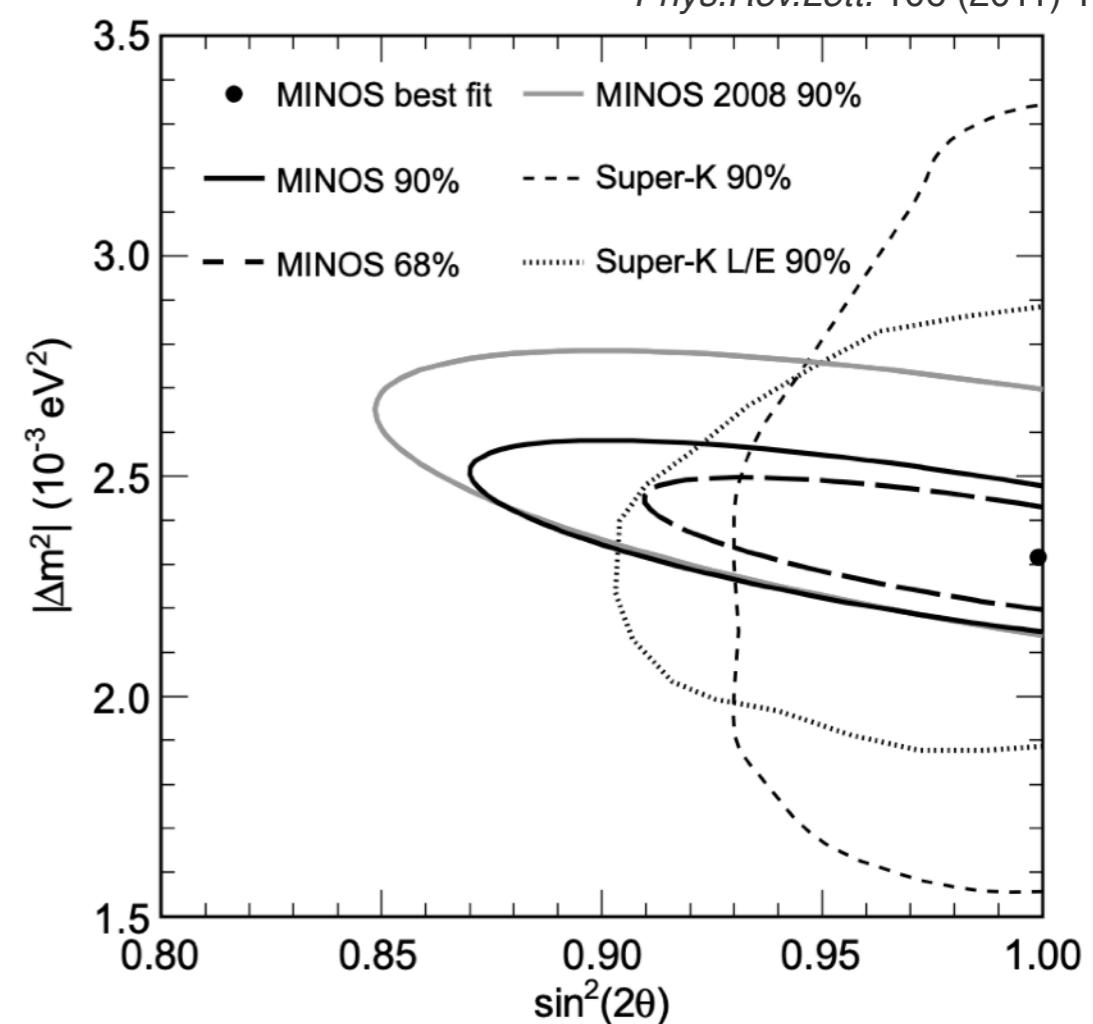


FIG. 4: Likelihood contours of 68% and 90% C.L. around the best fit values for the mass splitting and mixing angle. Also shown are contours from previous measurements [3, 4].

$$\sin^2 2\theta_{23} \approx 1$$

$$\Delta m_{32}^2 \approx \frac{\pi}{2.54} \frac{1.4 \text{ GeV}}{735 \text{ km}} = 2.3 \times 10^{-3} \text{ eV}^2$$

Neutrino oscillations at long baseline

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_\mu) &\simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \Delta_{3i} \\ &\simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{3i} \end{aligned}$$

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) &\simeq |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}}|^2 \\ &= P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta) \end{aligned}$$

$$\sqrt{P_{\text{atm}}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} \mp aL)}{\Delta_{31} \mp aL} \Delta_{31}$$

$$\sqrt{P_{\text{sol}}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{aL} \Delta_{21}$$

$aL = 0.08$ for $L = 295$ km

$aL = 0.23$ for $L = 810$ km

$aL = 0.37$ for $L = 1300$ km

Parameter

Channels

Question

$\sin^2 2\theta_{23}$: $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$:

Is θ_{23} maximal?

$\sin^2 \theta_{23} \sin^2 2\theta_{13}$: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Octant of θ_{23}

sign $[\Delta_{31}]$: $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Neutrino mass hierarchy

δ_{CP} : $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Is CP violated?

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$$\simeq 1 - \boxed{\sin^2 2\theta_{23}} \sin^2 \Delta_{3i}$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}}|^2$$

$$= \boxed{P_{\text{atm}}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}}P_{\text{sol}}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)$$

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$$a = G_F N_e / \sqrt{2} \simeq \frac{1}{3500 \text{ km}}$$

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$$P(\nu_\mu \rightarrow \nu_e) \simeq |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}}|^2$$

$$= P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}}P_{\text{sol}}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)$$

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Is CP violated?

Neutrino oscillations at long baseline

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \Delta_{3i}$$

$$\simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{3i}$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}}|^2$$

$$= P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)$$

$$\sqrt{P_{\text{atm}}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} \mp aL)}{\Delta_{31} \mp aL} \Delta_{31}$$

$$\sqrt{P_{\text{sol}}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{aL} \Delta_{21}$$

$$aL = 0.08 \text{ for } L = 295 \text{ km}$$

$$aL = 0.23 \text{ for } L = 810 \text{ km}$$

$$aL = 0.37 \text{ for } L = 1300 \text{ km}$$

Parameter

Channels

Question

$\sin^2 2\theta_{23}$: $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$:

Is θ_{23} maximal?

$\sin^2 \theta_{23} \sin^2 2\theta_{13}$: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Octant of θ_{23}

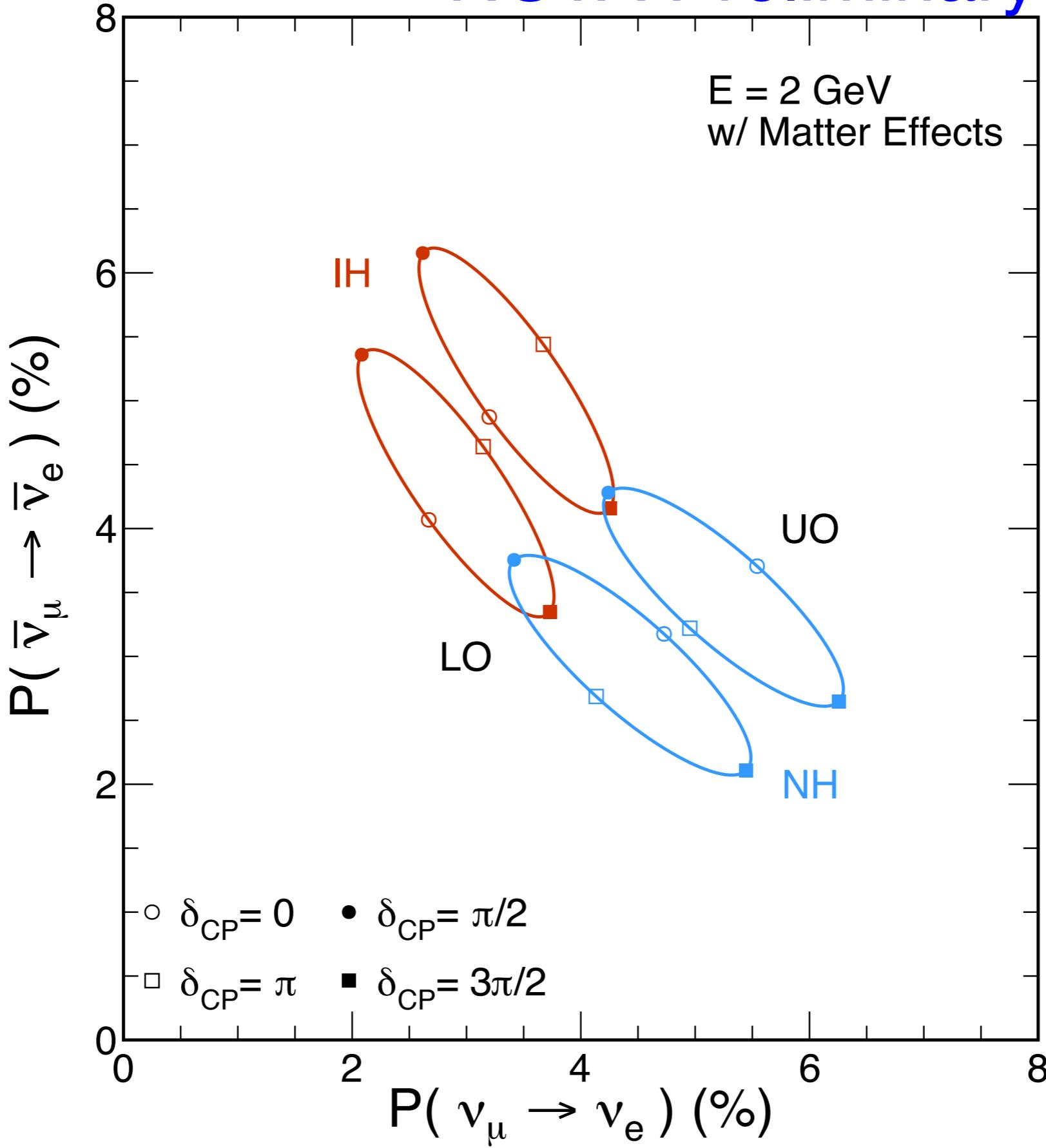
sign $[\Delta_{31}]$: $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Neutrino mass hierarchy

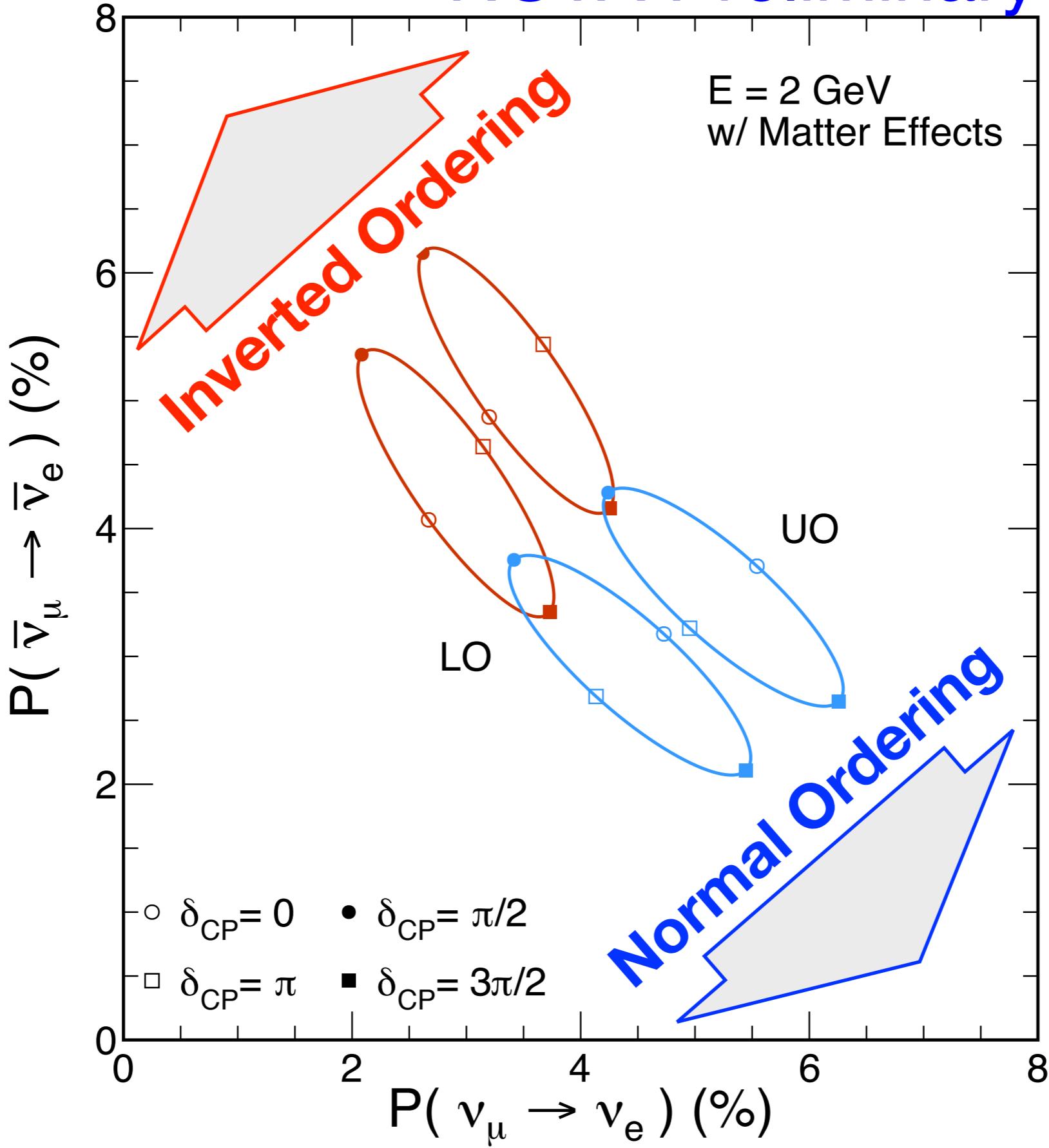
δ_{CP} : $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Is CP violated?

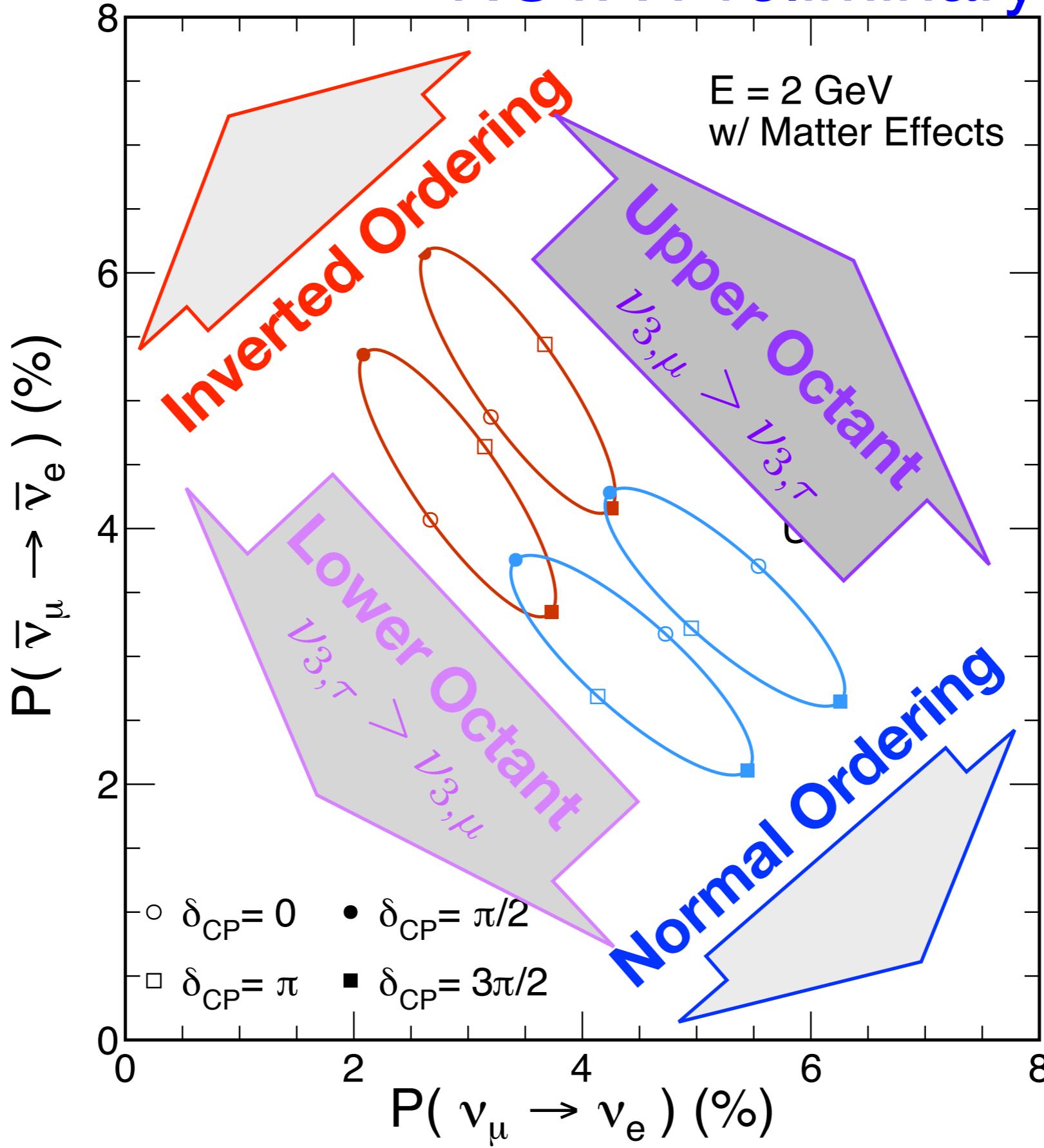
NOvA Preliminary



NOvA Preliminary



NOvA Preliminary

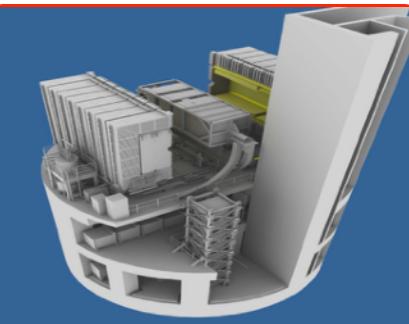
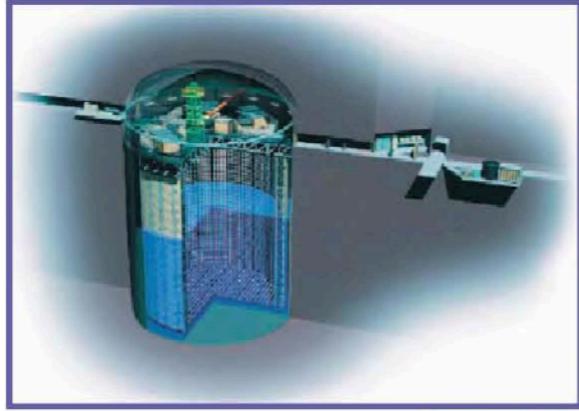


T2K

$E_\nu \simeq 0.7 \text{ GeV}$,

$$\Delta \equiv \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 295 \text{ km}}{0.7 \text{ GeV}} \simeq \frac{\pi}{2}$$

Super-Kamiokande
(ICRR, Univ. Tokyo)



INGRID +
ND280

J-PARC Main Ring
(KEK-JAEA, Tokai)

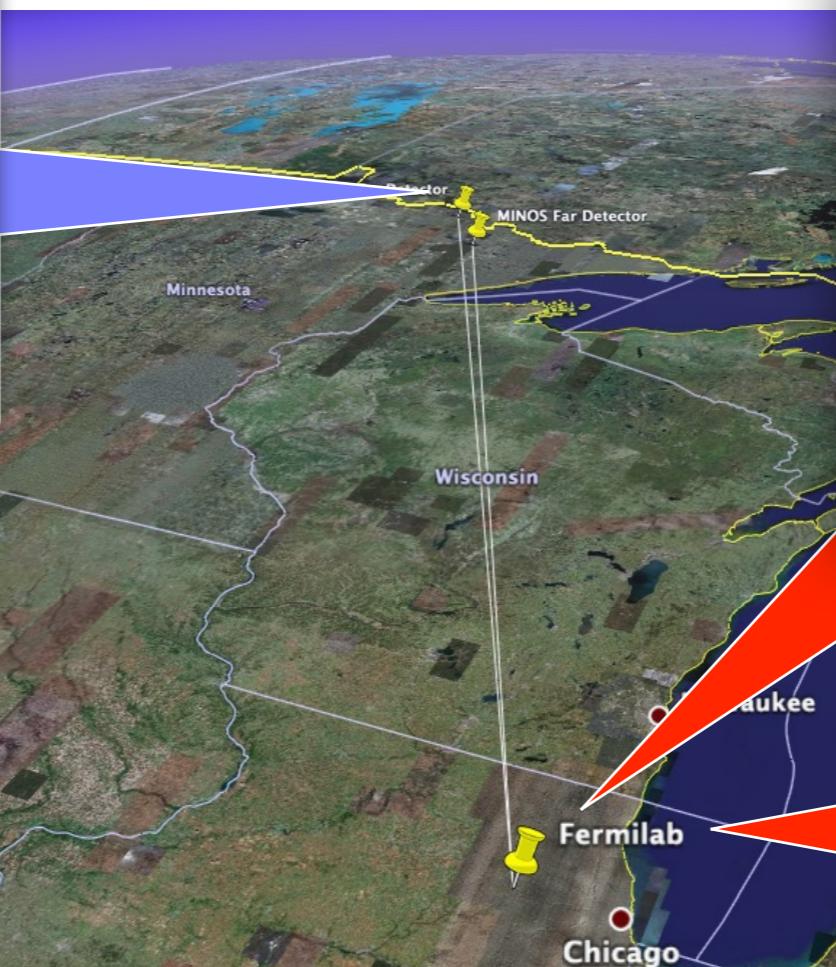


NOvA

$E_\nu \simeq 2 \text{ GeV}$,

$$\Delta \equiv \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 810 \text{ km}}{2 \text{ GeV}} \simeq \frac{\pi}{2}$$

NOvA Far Detector



NOvA
Near
Detector

Fermilab Main Injector



Summary of sensitivity of $\nu_\mu \rightarrow \nu_e$ rates to physics questions

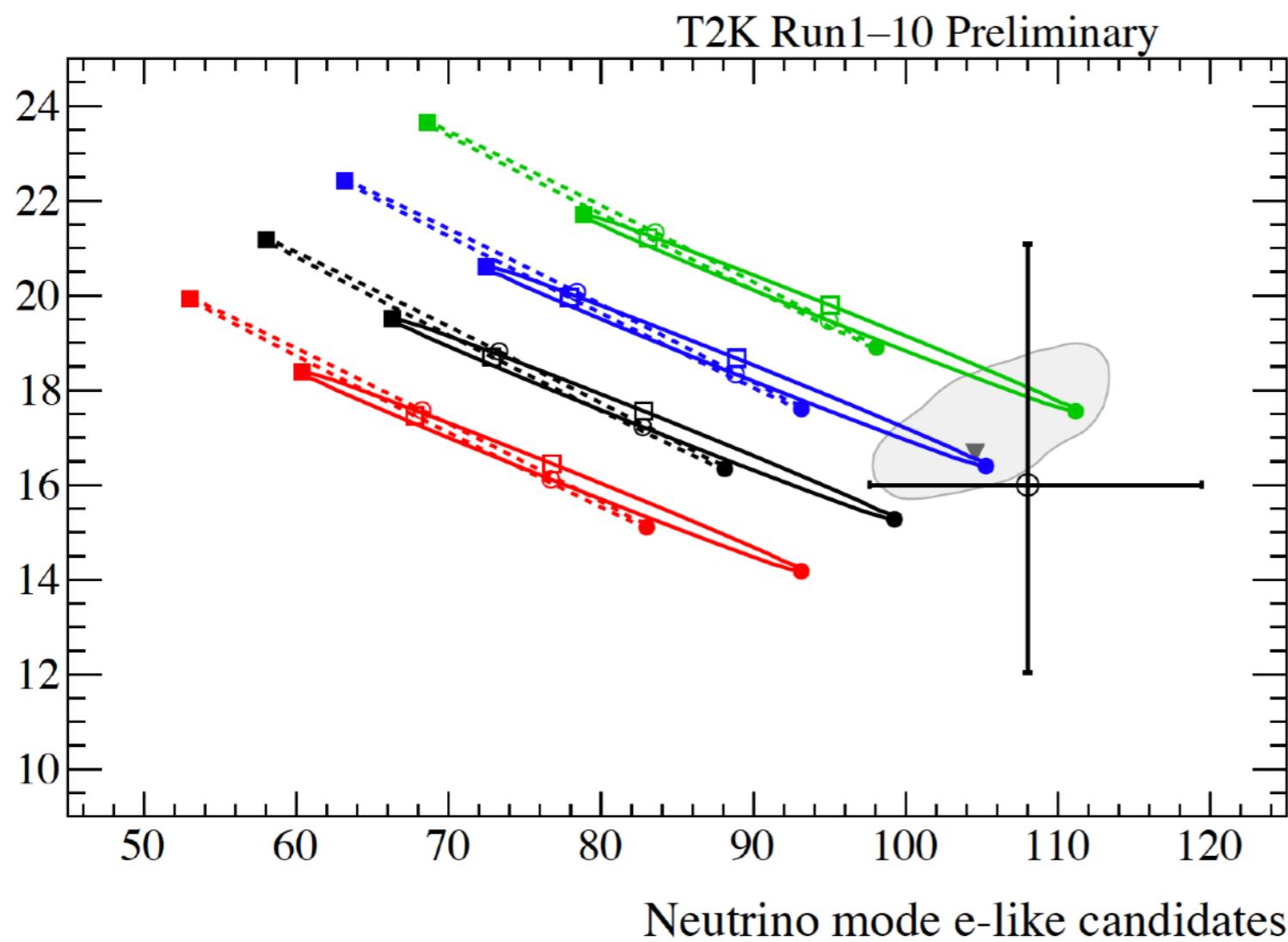
Factor	Type	Inverts for $\bar{\nu}$?	NOvA	T2K
Matter effect (mass ordering)	Binary	Yes	$\pm 19\%$	$\pm 10\%$
CP violation	Bounded, continuous	Yes	$[-22...+22]\%$	$[-29...+29]\%$
θ_{23} octant	Unbounded, continuous	No	$[-22...+22]\%$	$[-22...+22]\%$

Nota bene:

- Calculations are for rate only; there is some additional information in the energy spectrum
- These estimates neglect non-linearities in combining different effects
- In the calculation of the matter effect and CP violation effects the calculated values account for the fact that T2K runs at an energy on the first oscillation maximum while NOvA runs at an energy slightly above the oscillation maximum
- θ_{23} was varied inside the $\pm 2\sigma$ range found by a recent global fit (PRD 90, 093006)

Mass ordering and CP violation

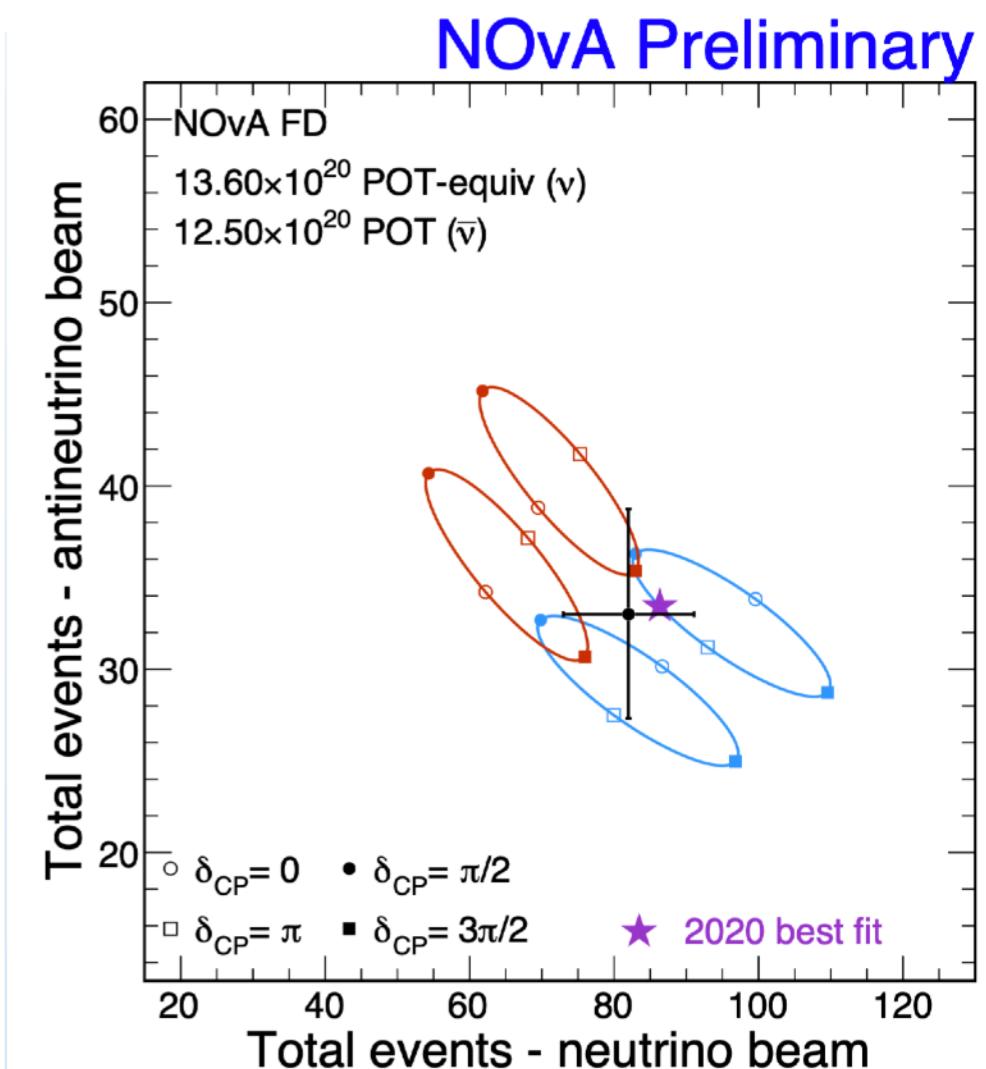
Antineutrino mode e-like candidates



T2K

$$P(\nu_\mu \rightarrow \nu_e)$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$



NOvA

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$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_\mu) &\simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \Delta_{3i} \\
 &\simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{3i} \\
 P(\nu_\mu \rightarrow \nu_e) &\simeq |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}}|^2 \\
 &= P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)
 \end{aligned}$$

~zero at
oscillation
maximum
~1 at
oscillation
maximum

$$\begin{aligned}
 \sqrt{P_{\text{atm}}} &= \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} \mp aL)}{\Delta_{31} \mp aL} \Delta_{31} & aL &= 0.08 \text{ for } L = 295 \text{ km} \\
 \sqrt{P_{\text{sol}}} &= \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{aL} \Delta_{21} & a = G_F N_e / \sqrt{2} &\simeq \frac{1}{3500 \text{ km}} & aL &= 0.23 \text{ for } L = 810 \text{ km} \\
 &&&&& aL &= 0.37 \text{ for } L = 1300 \text{ km}
 \end{aligned}$$

Parameter	Channels	Question
$\sin^2 2\theta_{23}$:	$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$:	Is θ_{23} maximal?
$\sin^2 \theta_{23} \sin^2 2\theta_{13}$:	$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:	Octant of θ_{23}
sign $[\Delta_{31}]$:	$\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:	Neutrino mass hierarchy
δ_{CP} :	$\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:	Is CP violated?

Questions? Comments?

- To submit questions:
 - [https://forms.gle/
E1DNm3LvayA2Jqiq6](https://forms.gle/E1DNm3LvayA2Jqiq6)
- Some code to help with
the homework questions:
 - [https://colab.research.google.com/drive/
1UnJ9_8AuH0uxX-QsE2Pb16niykqjmY8s?usp=sharing](https://colab.research.google.com/drive/1UnJ9_8AuH0uxX-QsE2Pb16niykqjmY8s?usp=sharing)

