

Long Baseline Neutrino Oscillations - 2

Mark Messier
Indiana University

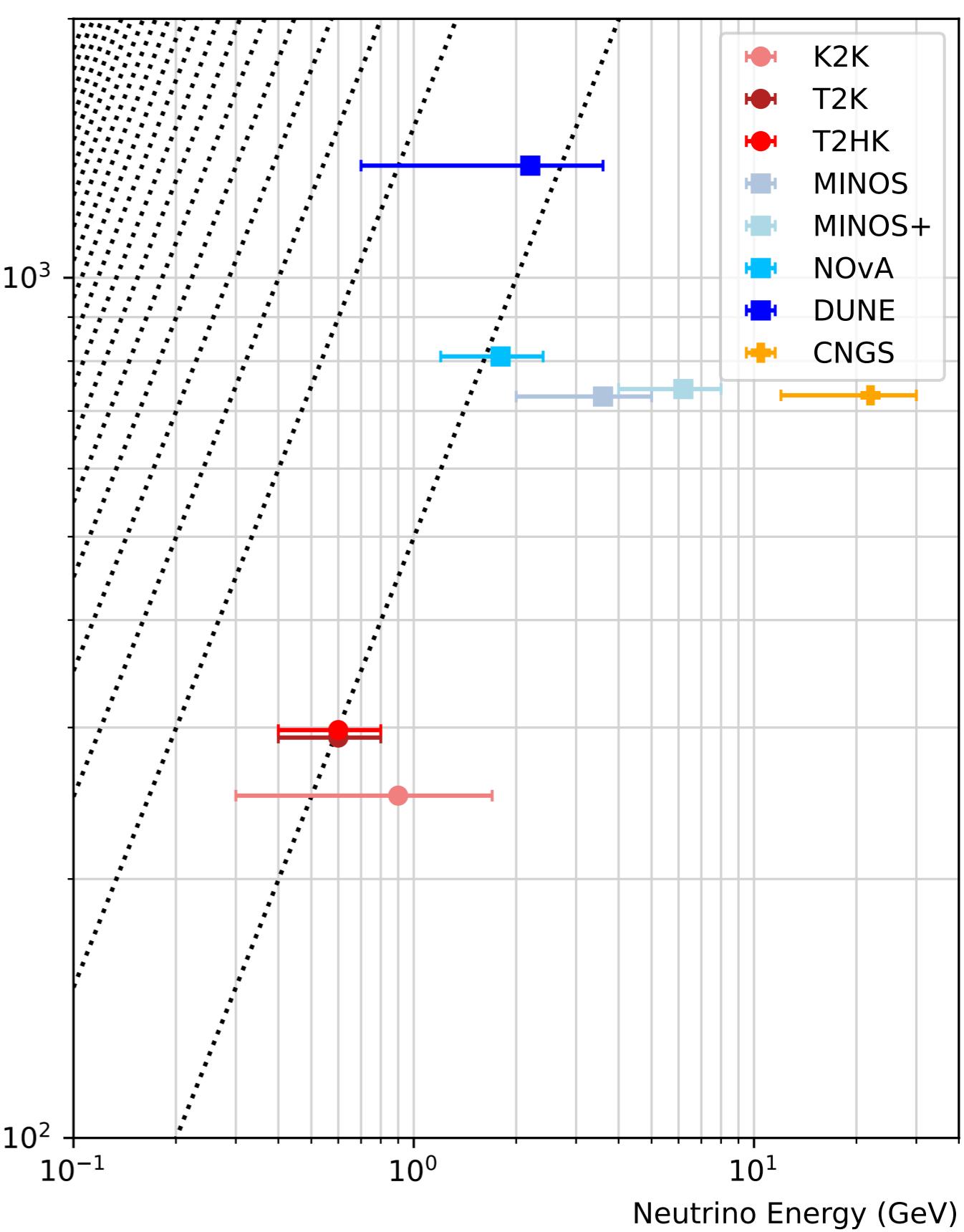
INSS 2023
Fermilab
August 9 and 10

Questions? Comments?

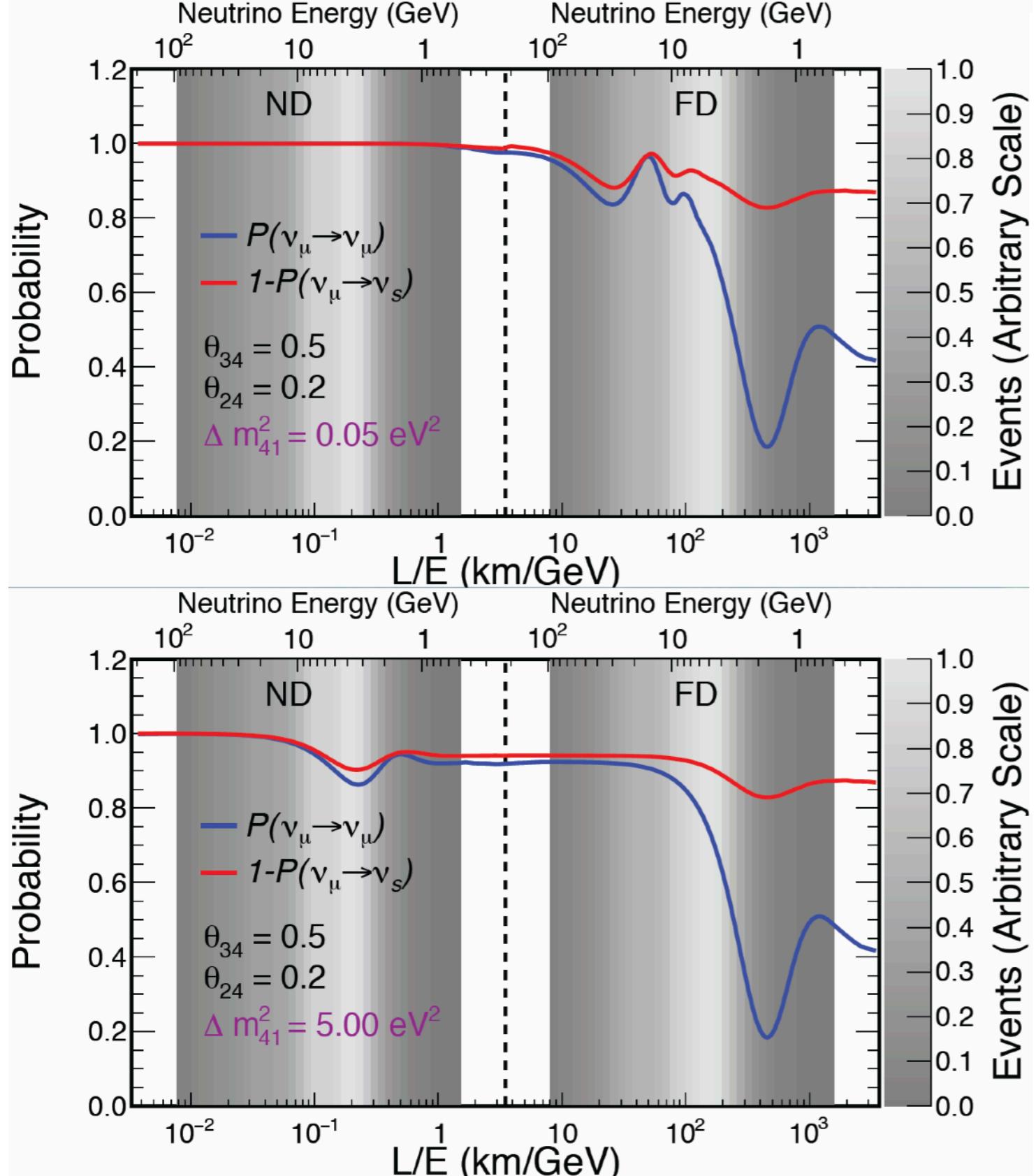
- To submit questions:
 - [https://forms.gle/
E1DNm3LvayA2Jqiq6](https://forms.gle/E1DNm3LvayA2Jqiq6)
- Some code to help with
the homework questions:
 - [https://colab.research.google.com/drive/
1UnJ9_8AuH0uxX-QsE2Pb16niykqjmY8s?usp=sharing](https://colab.research.google.com/drive/1UnJ9_8AuH0uxX-QsE2Pb16niykqjmY8s?usp=sharing)



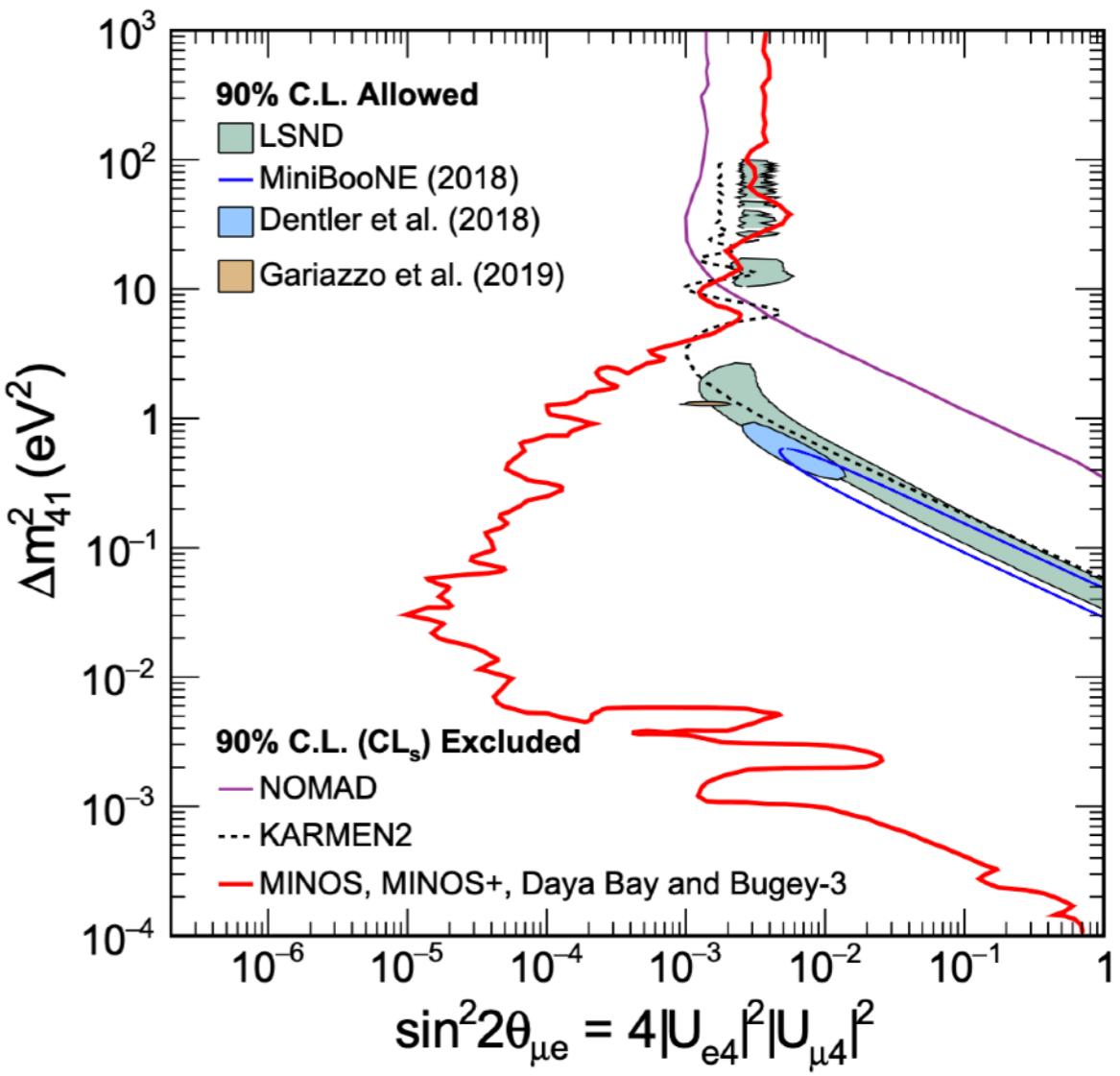
	Dates	Source	Primary Energy (GeV)	P [kW]	M [kt]	L [km]	E [GeV]
K2K	1999 - 2004	KEK PS	12	5.2	22.5	250	0.9
T2K	2010 - present	JPARC	30	515	22.5	295	0.6
T2HK	2027	JPARC	30	[500, 300]	188	295	0.6
MINOS	2005 - 2012	Fermilab Main Injector	120	240	5.4	735	3.6
MINOS+	2013 - 2016	Fermilab Main Injector	120	700	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



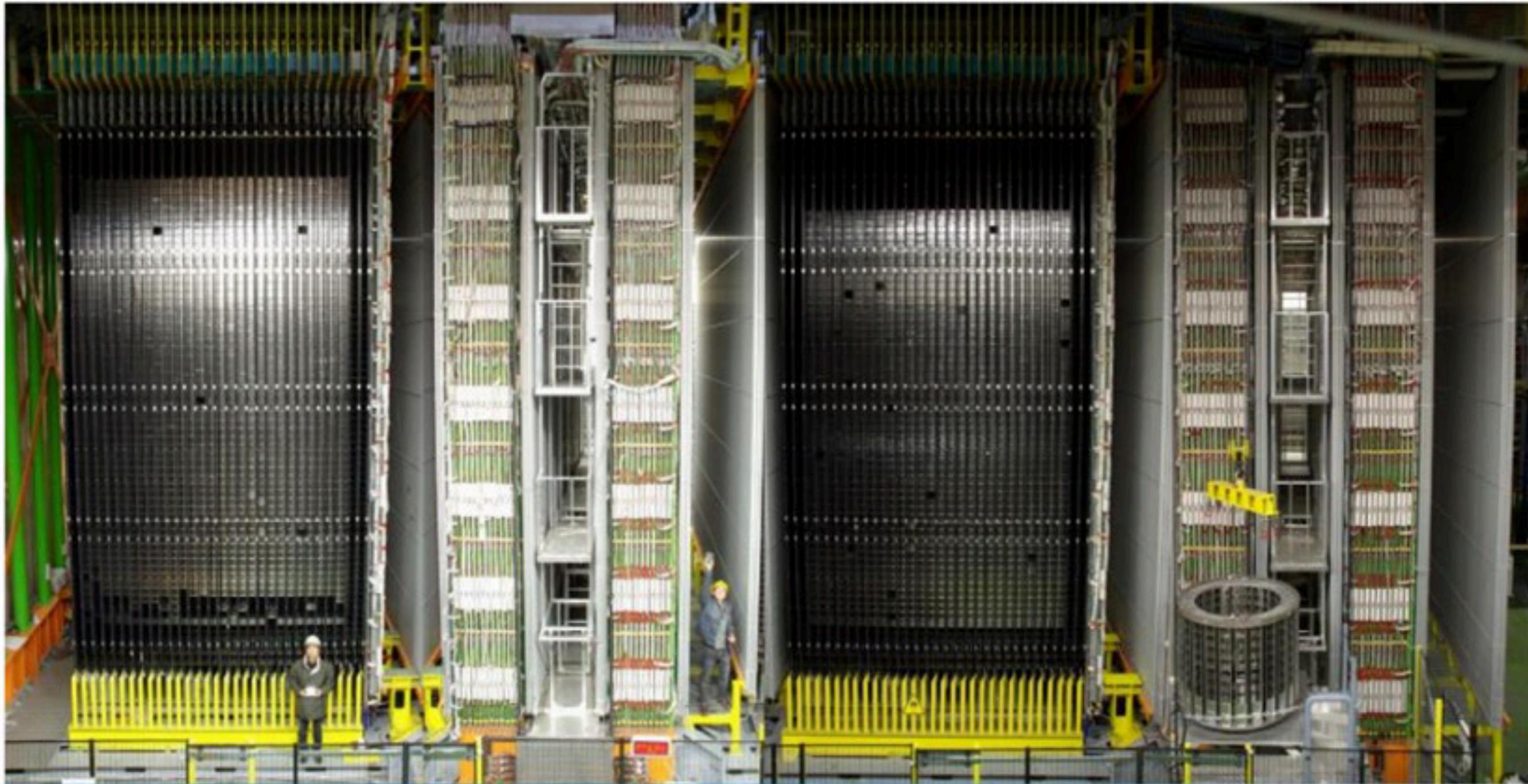
Long baseline experiments



MINOS+



Searches for effects beyond
three-flavor oscillations



OPERA Experiment

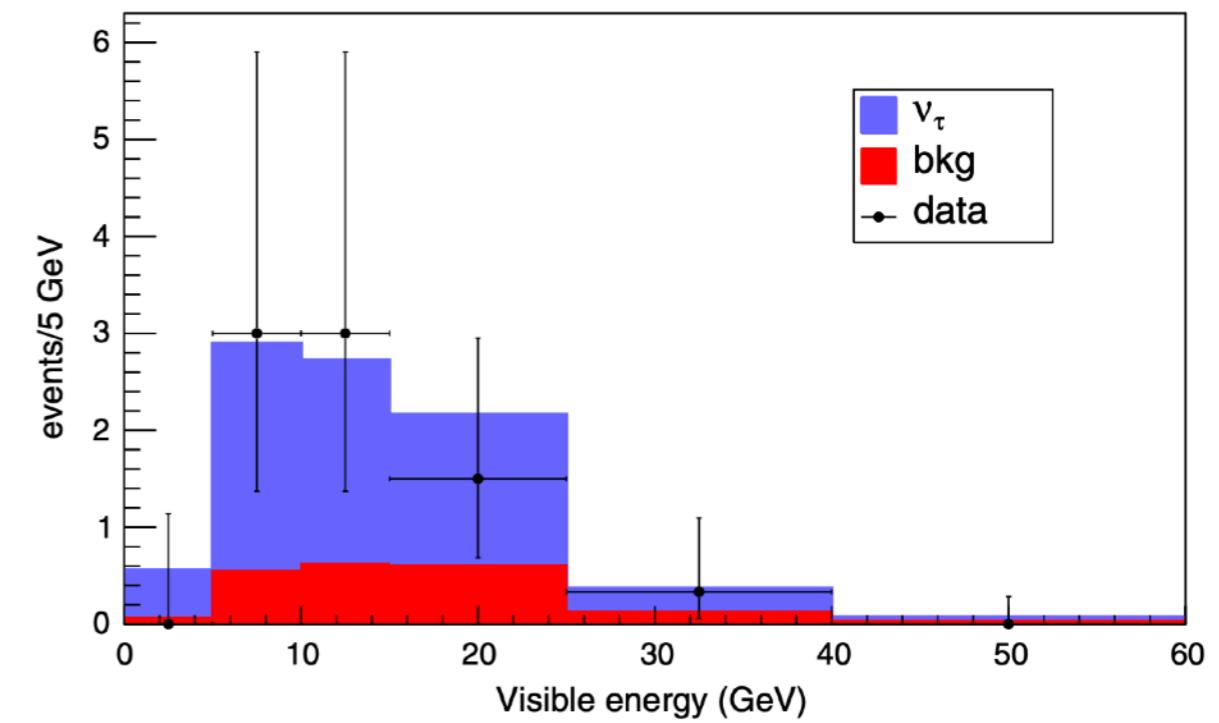
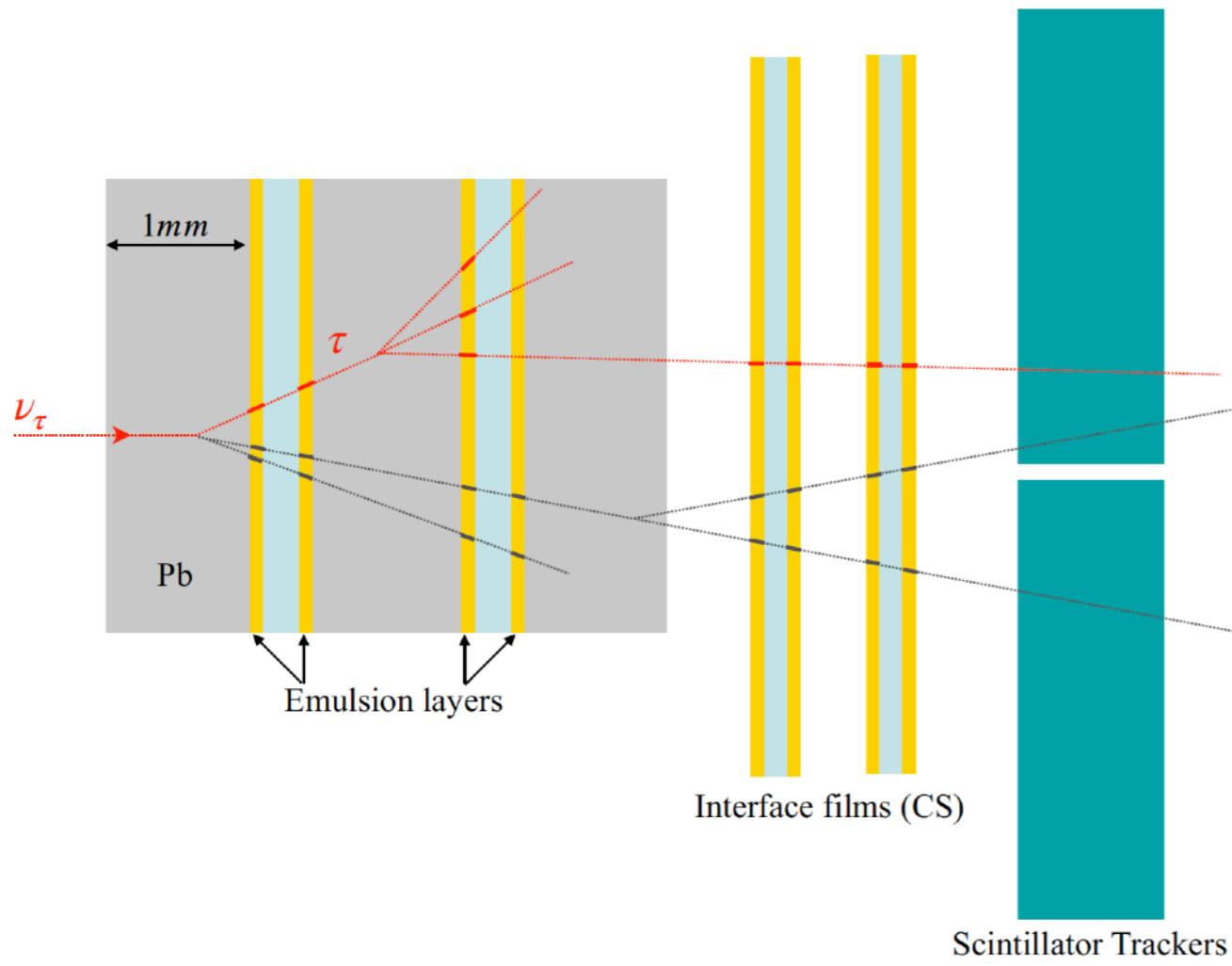
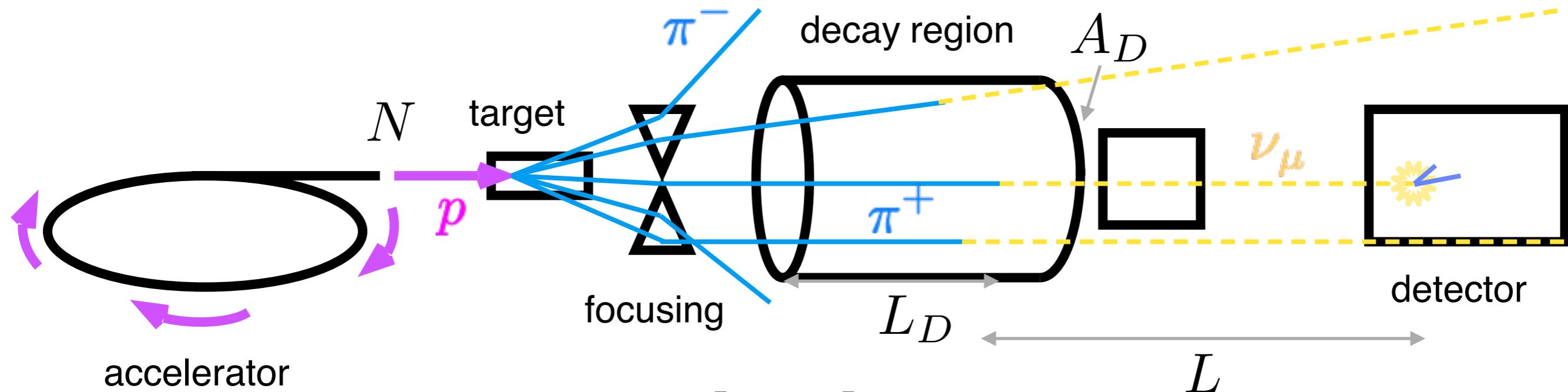


FIG. 1. Stacked plot of visible energy: data are compared with the expectation. Monte Carlo simulation is normalized to the expected number of events reported in Table III.

OPERA Experiment

tau neutrinos appear at >6 sigma



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

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

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

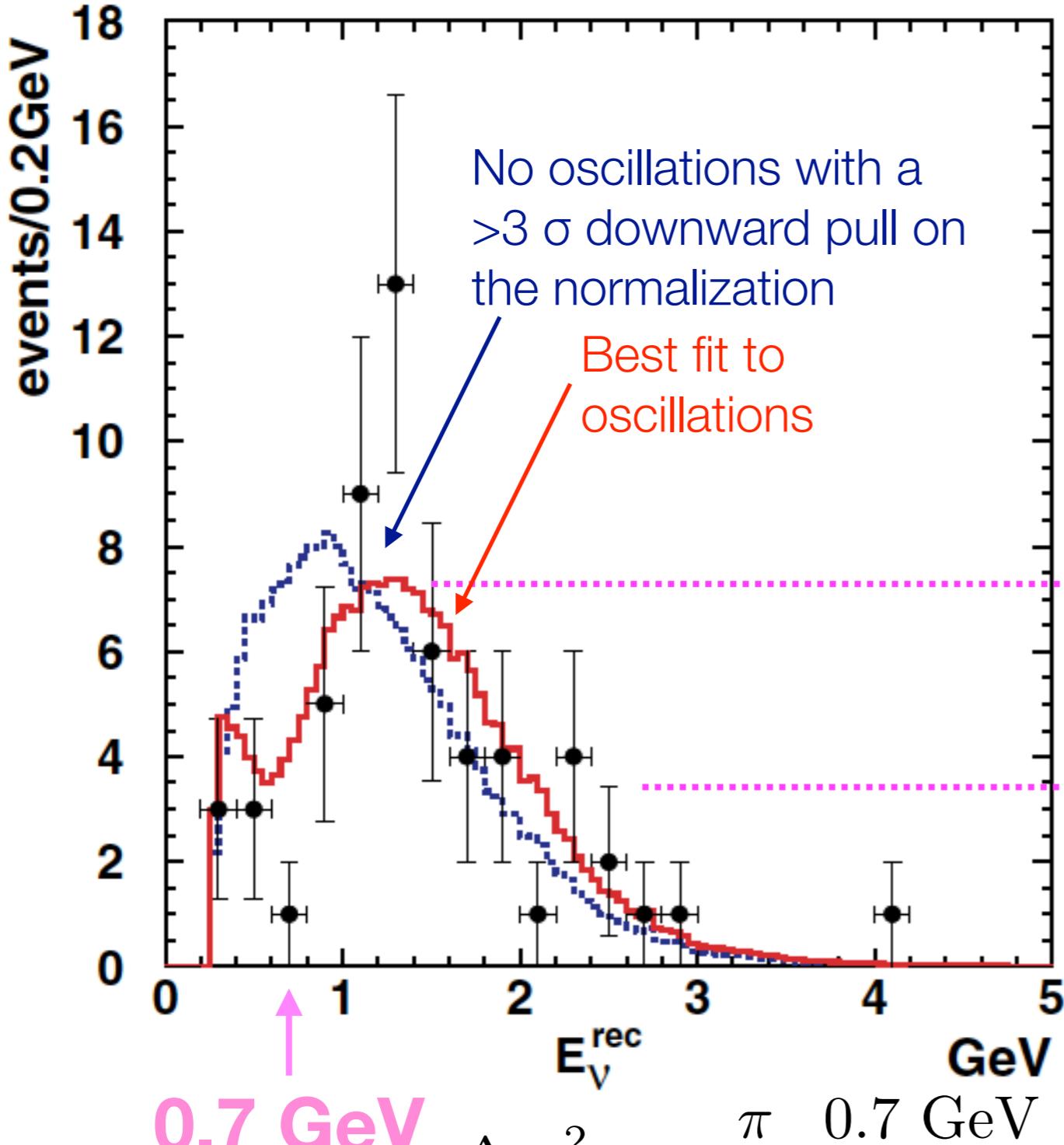
$$\frac{N_{\text{events}}}{[\text{GeV}]} \simeq P [\text{kW}] \cdot M [\text{kt}] \cdot T [\text{years}] \cdot \left(\frac{250}{L [\text{km}]} \right)^2 \cdot \epsilon \cdot E_\nu [\text{GeV}]$$

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?**

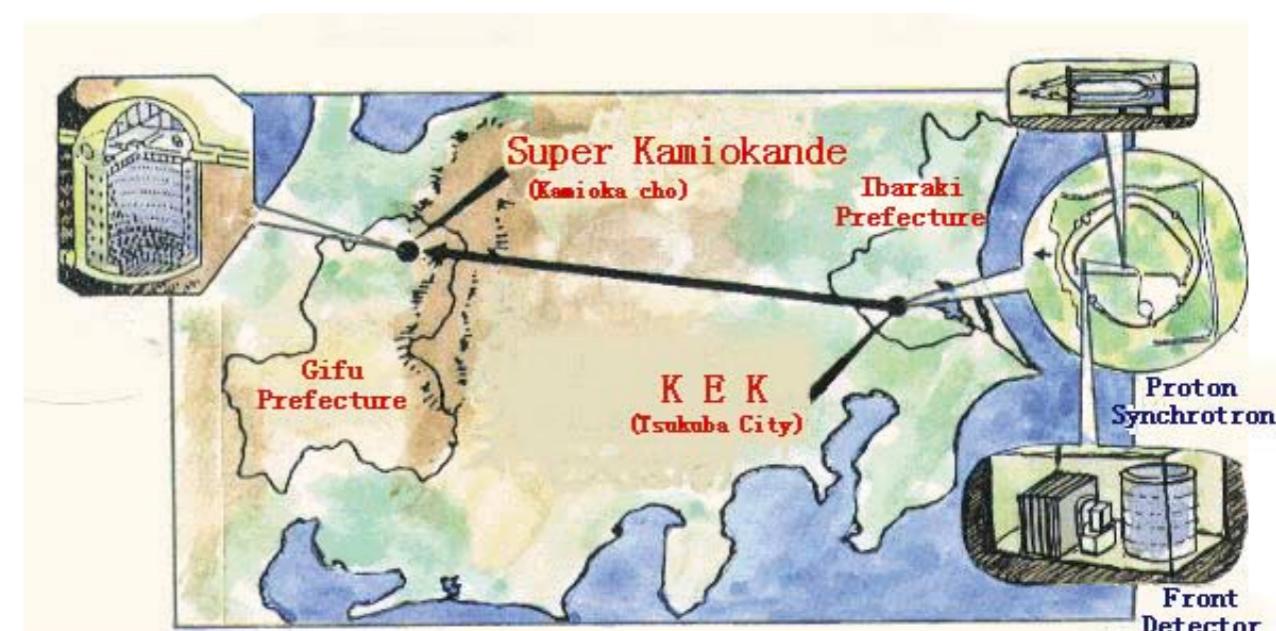
$\frac{N_{\text{events}}}{\text{GeV}} \simeq 10^2 \dots 10^4 \text{ per year}$
(YES, AND MAYBE MUCH BETTER!)



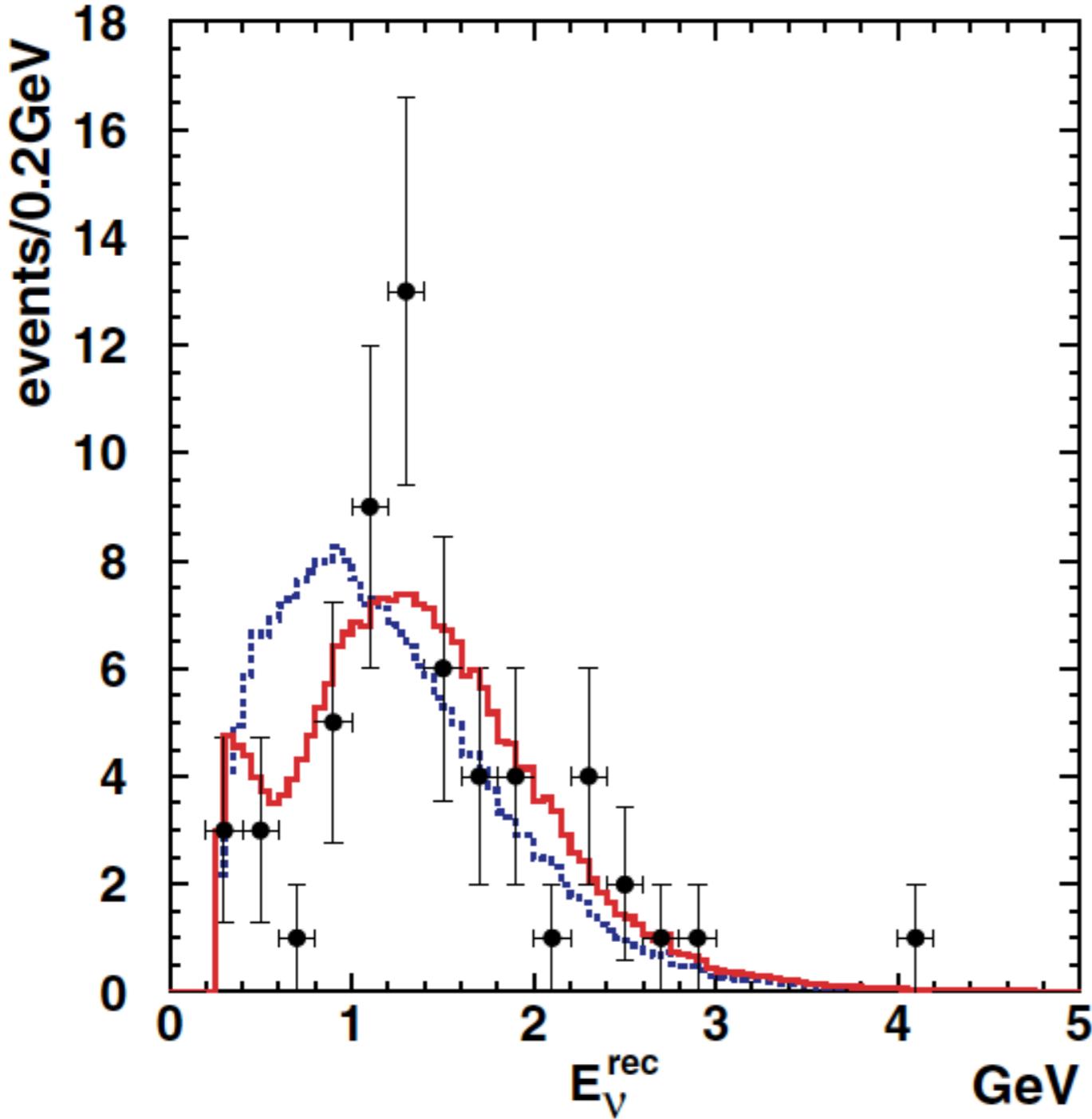
0.7 GeV

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

K2K Experiment

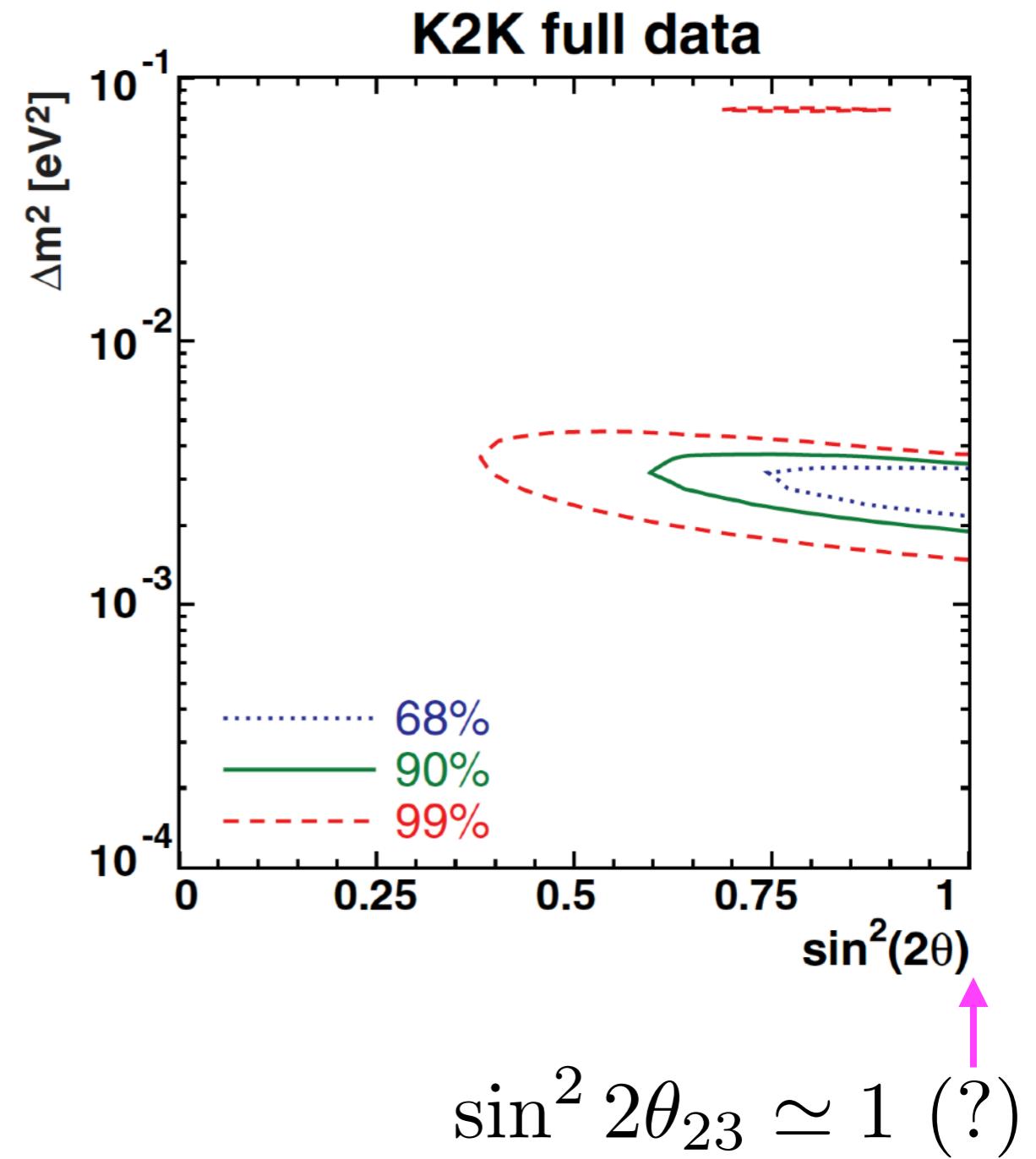


PHYSICAL REVIEW D 74, 072003 (2006)

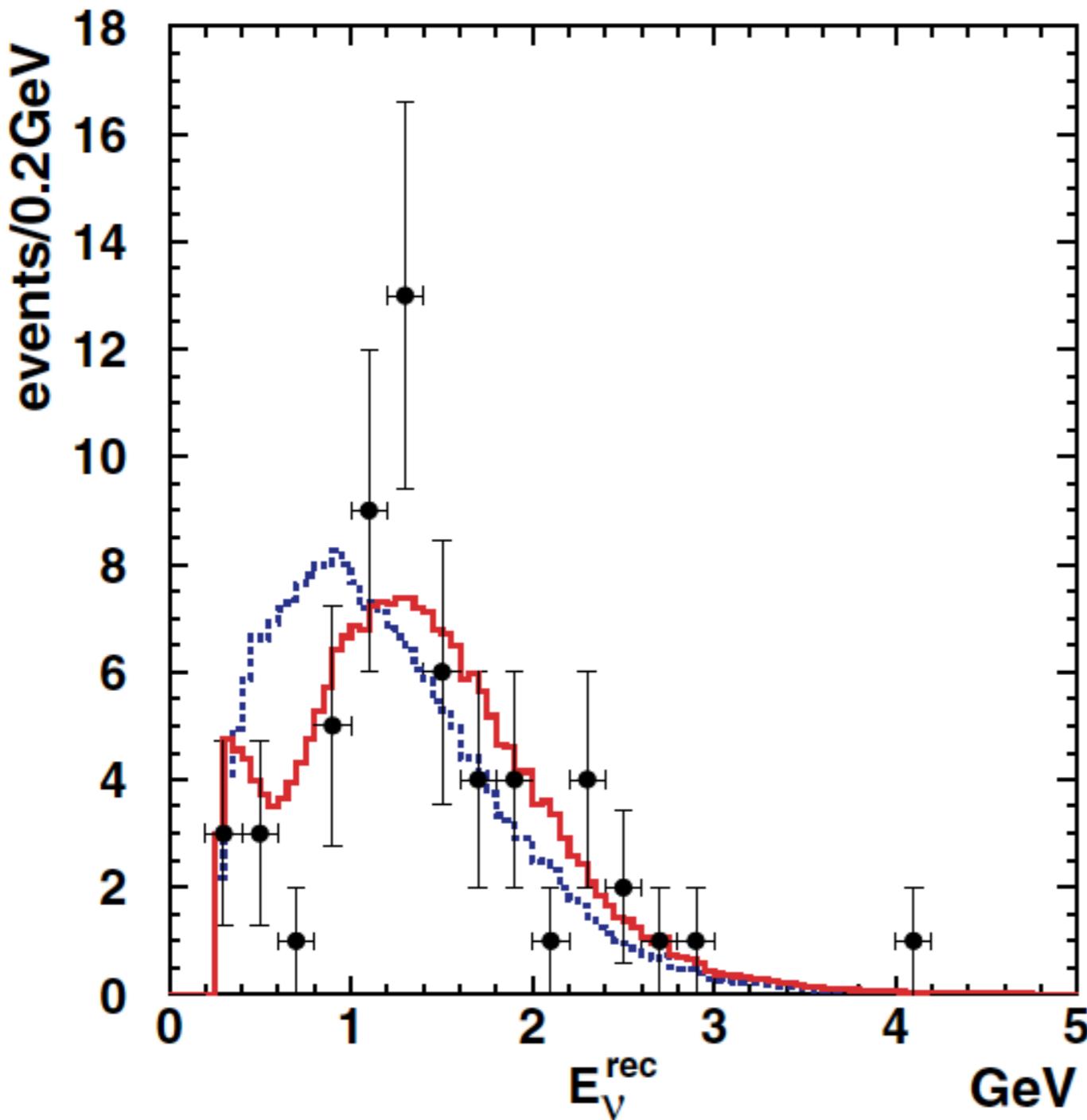


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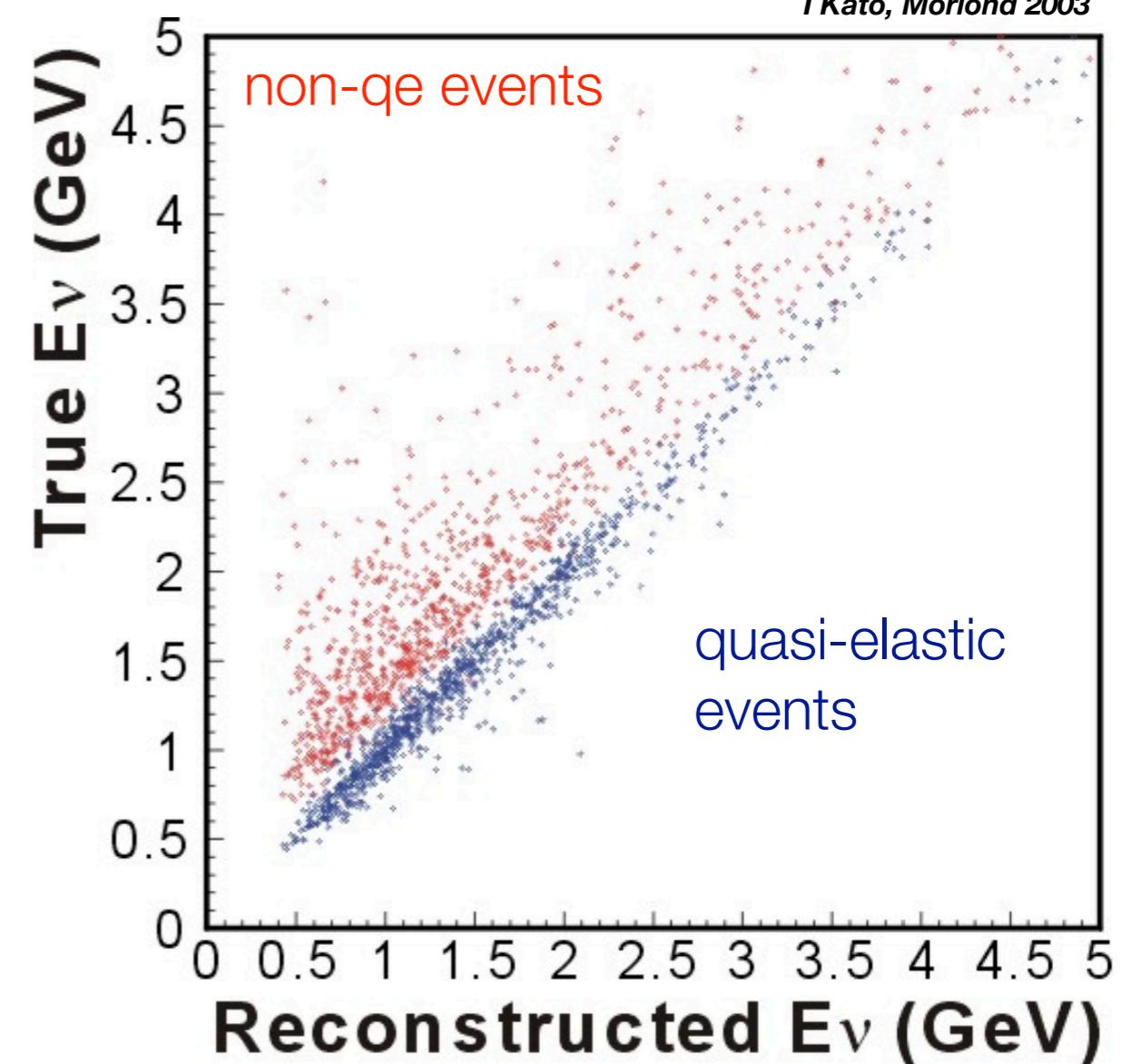


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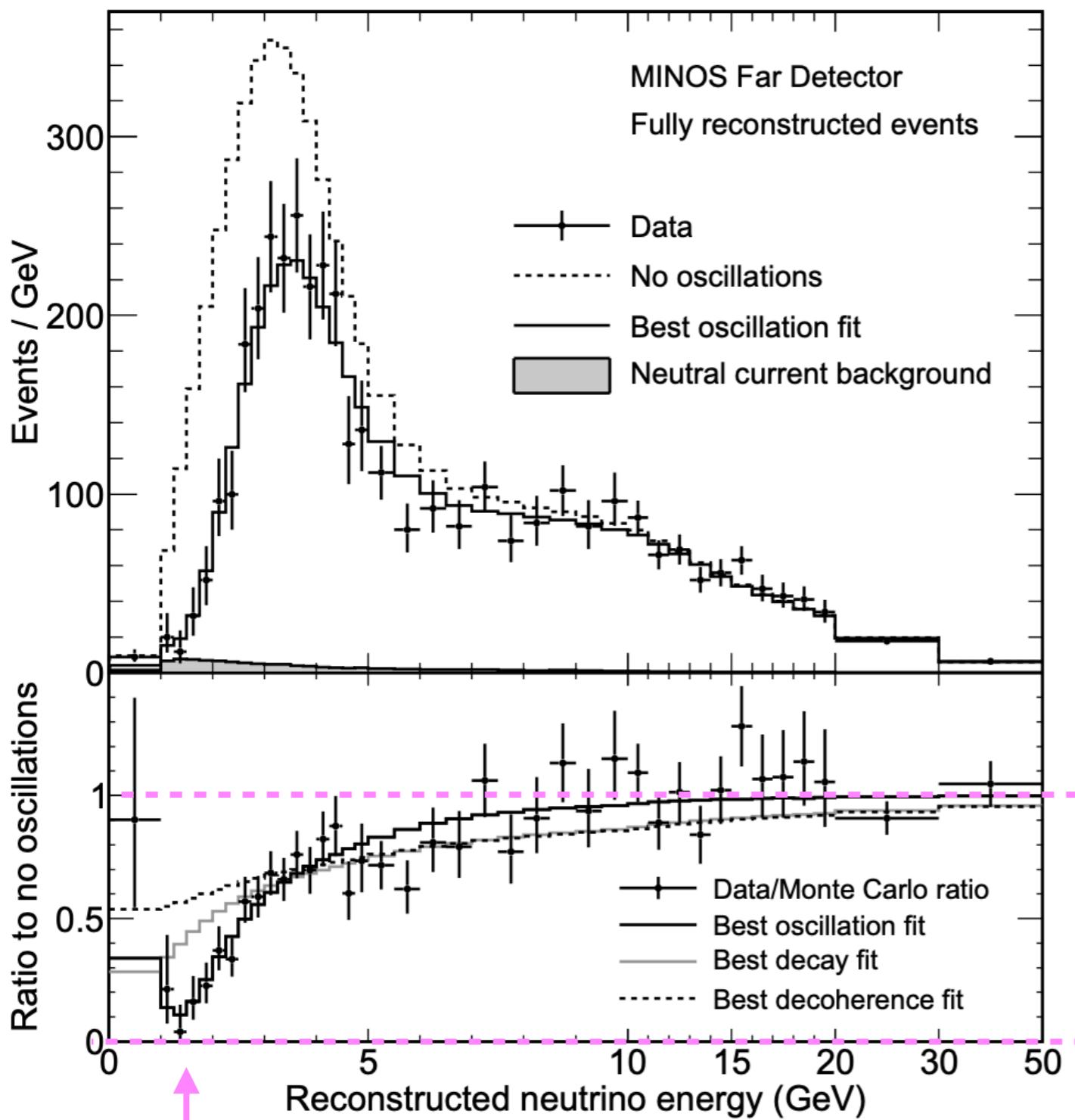


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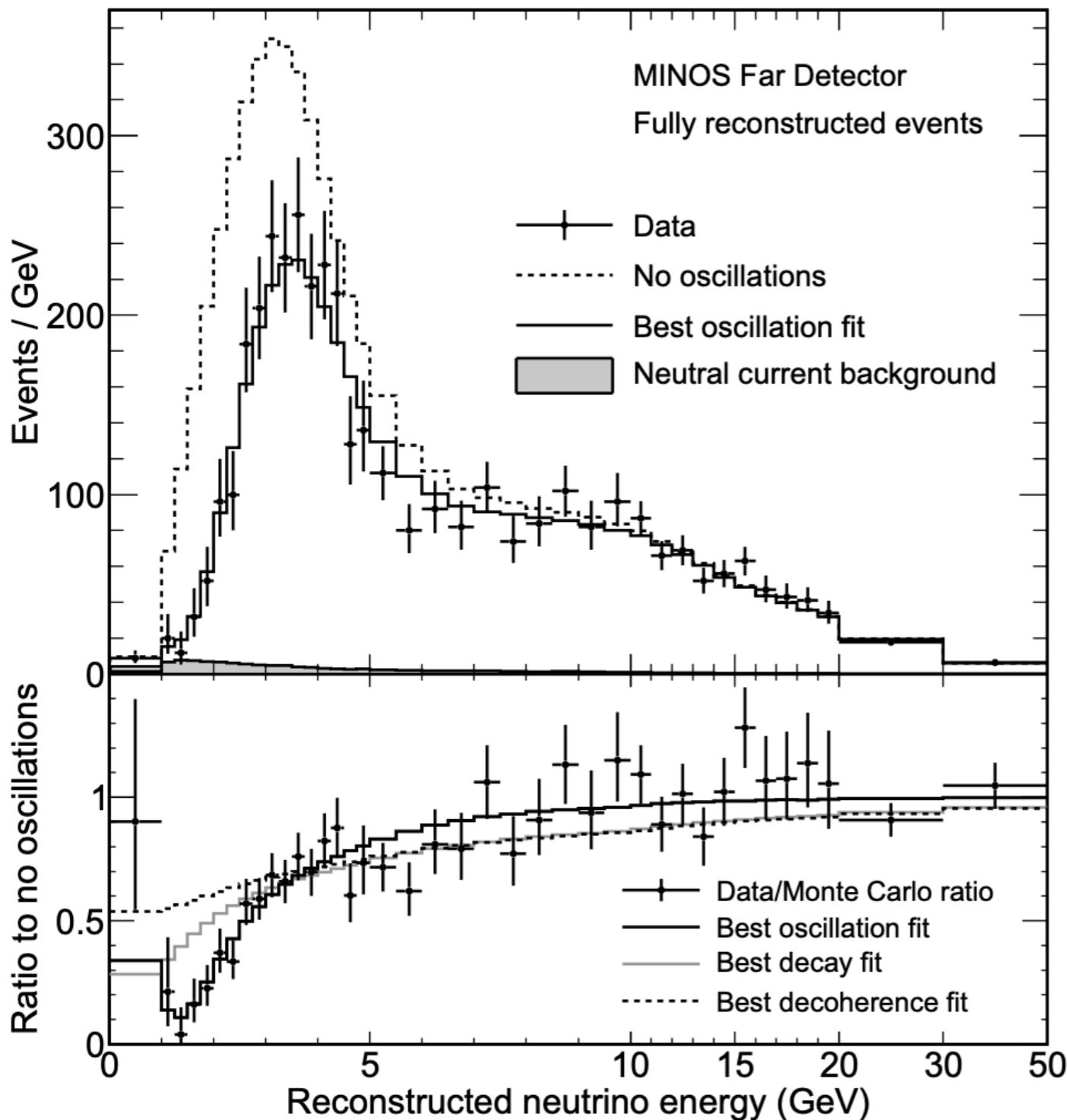
$$E_\nu^{\text{rec}} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + P_\mu \cos\theta_\mu}$$



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

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

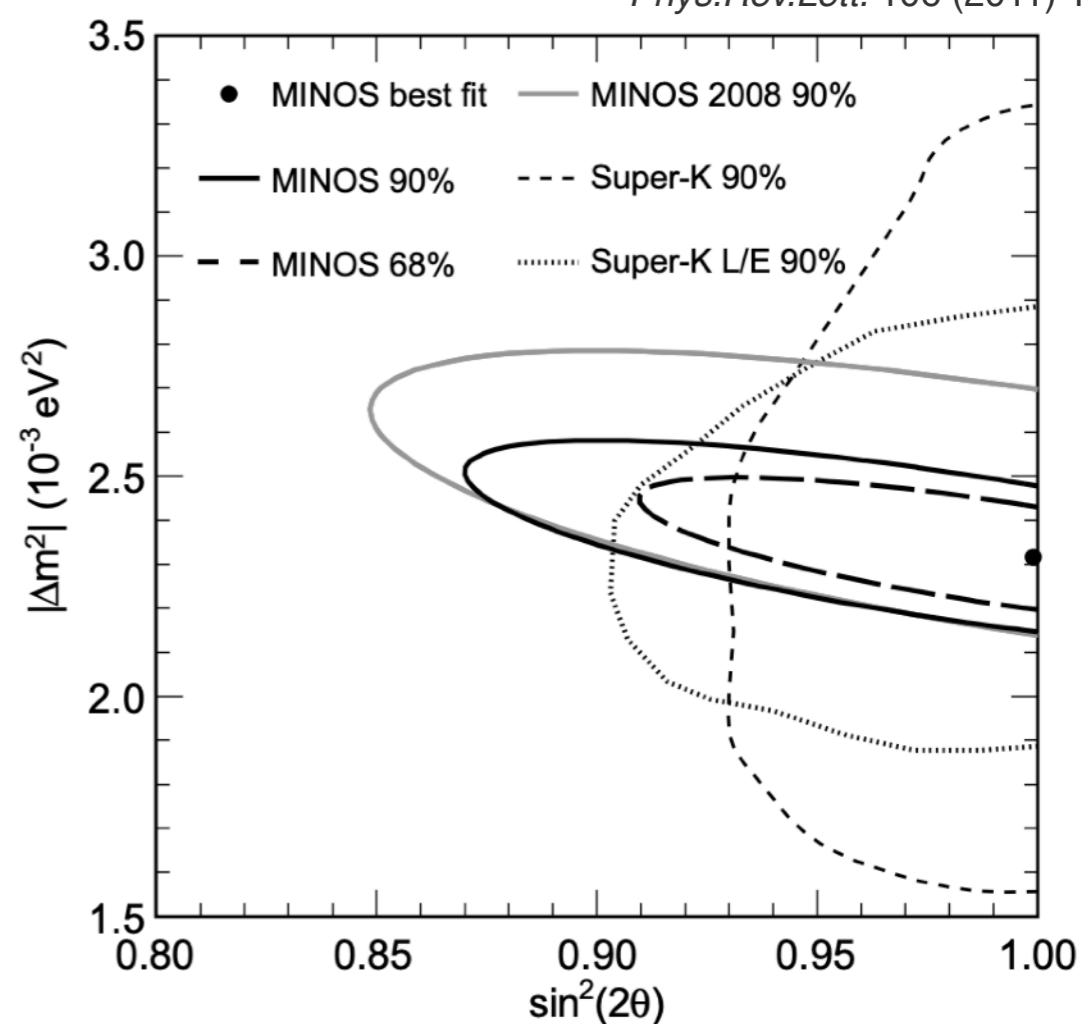


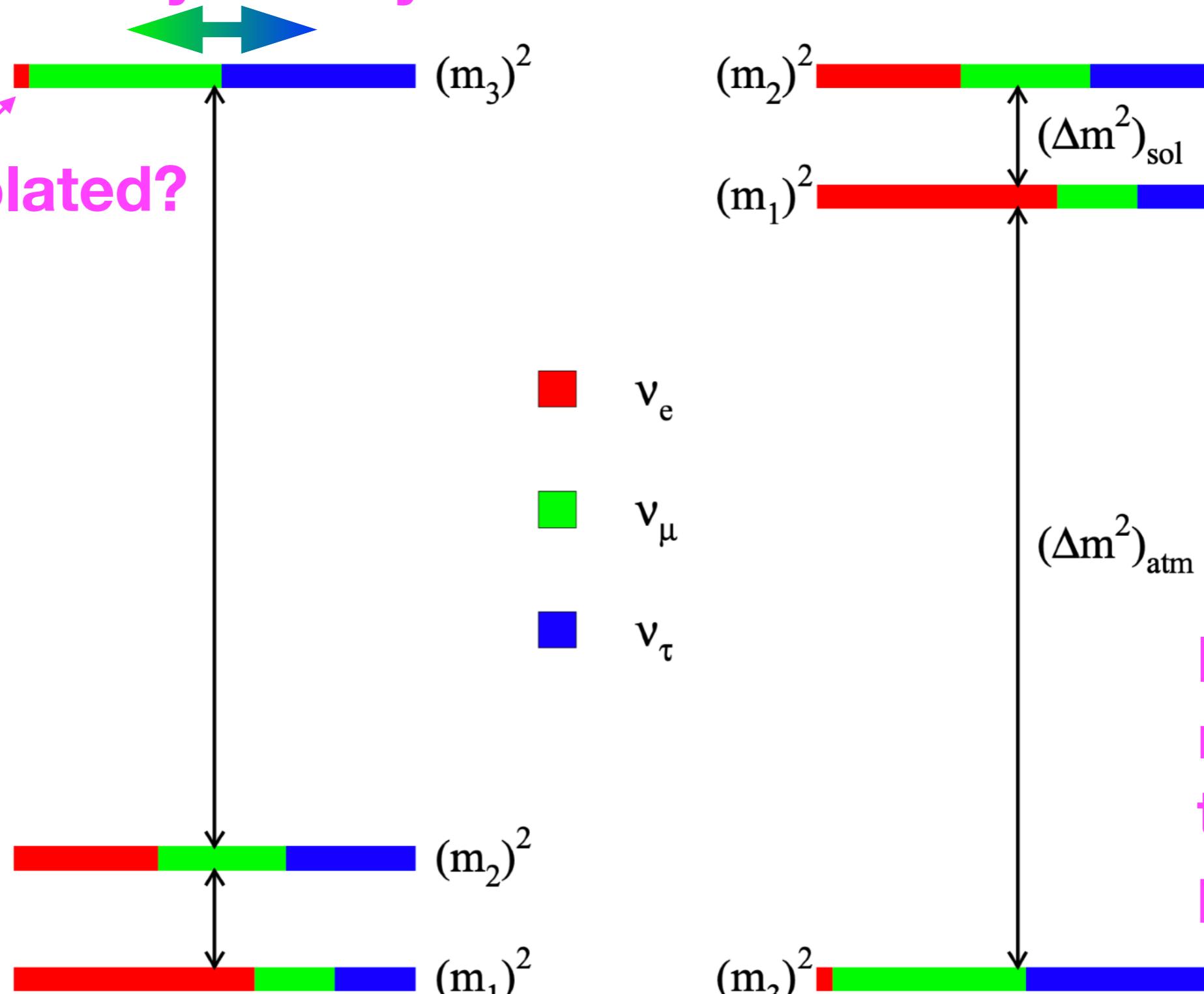
FIG. 4: Likelihood contours of 68% and 90% C.L. around the best fit values for the mass splitting and mixing angle. Also shown are contours from previous measurements [3, 4].

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

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

Is this symmetry real?

Is CP violated?



Is there
more to
this
picture?

normal hierarchy \longleftrightarrow inverted hierarchy

Which ordering is the correct one?

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]

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

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

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

$aL = 0.08$ 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. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

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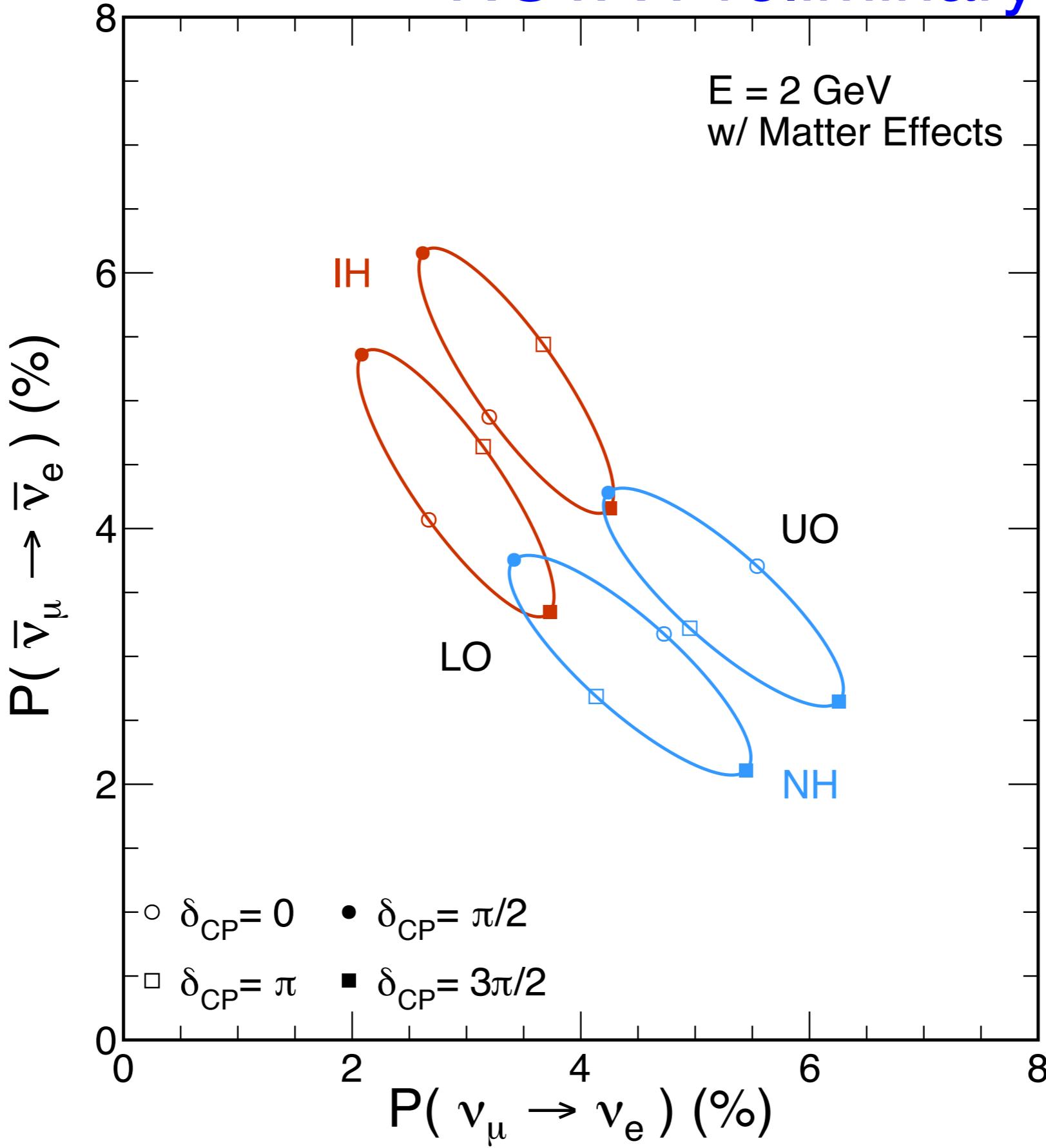
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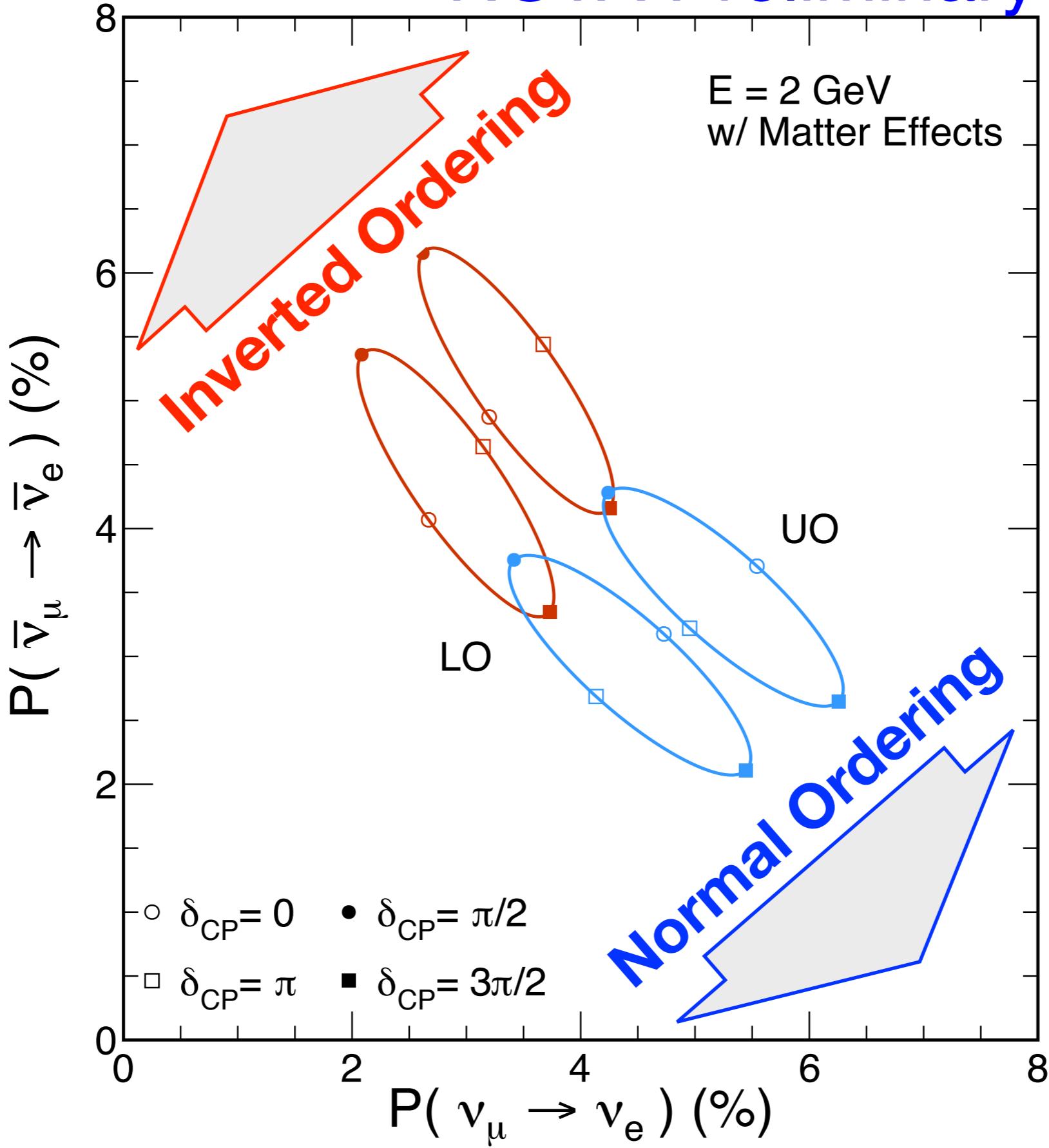
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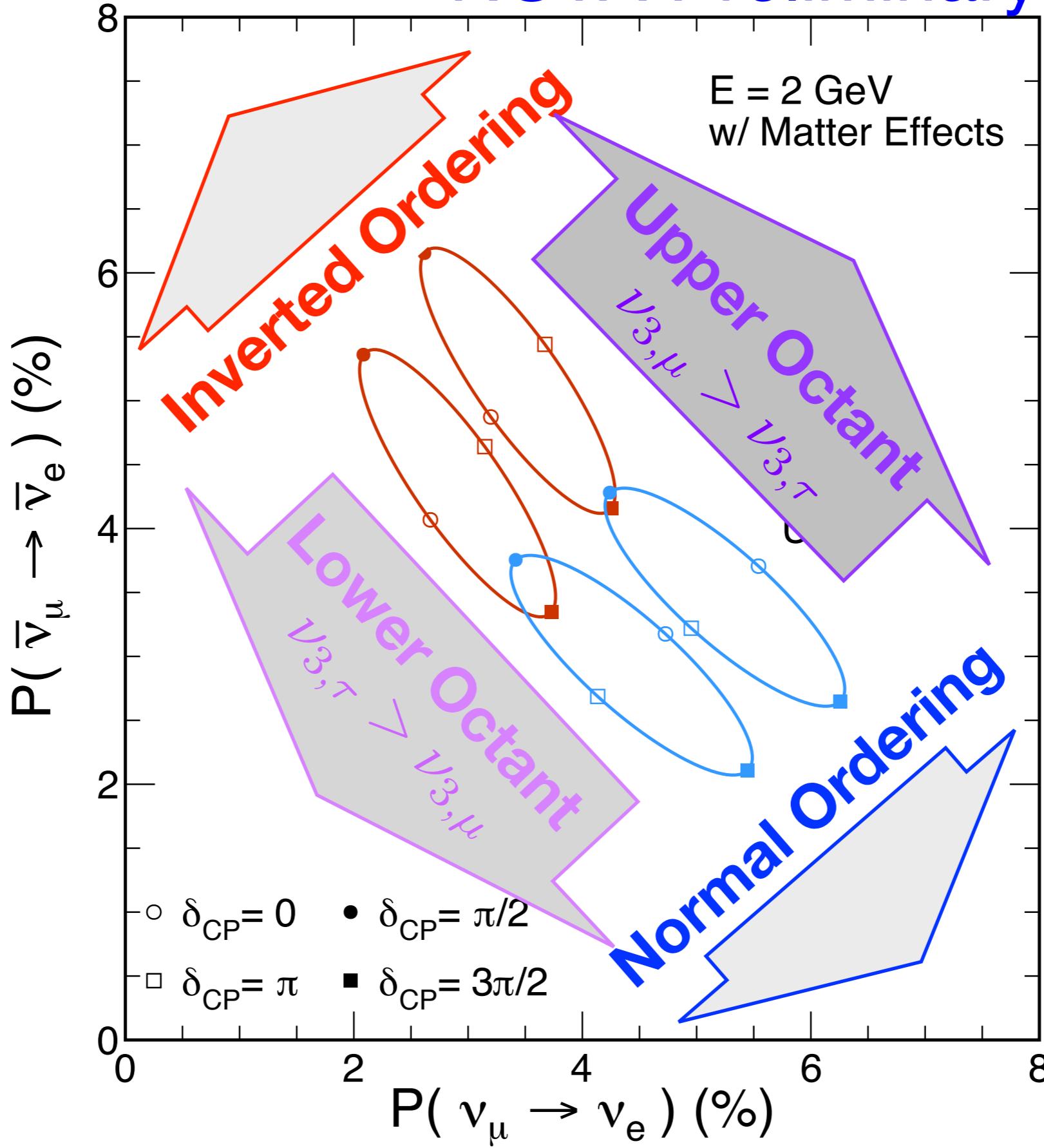
NOvA Preliminary



NOvA Preliminary



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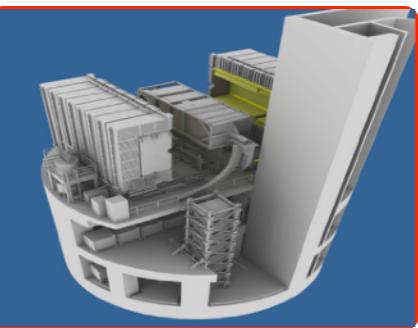
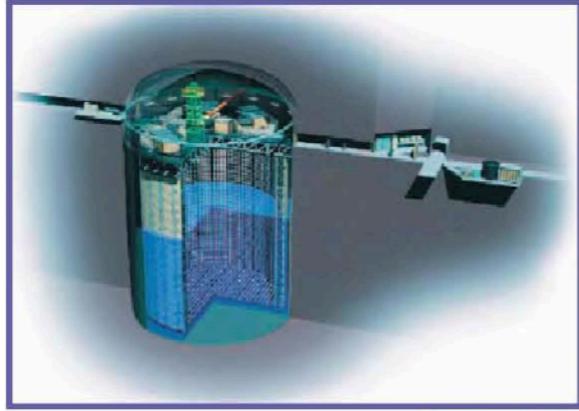


T2K

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

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

Super-Kamiokande
(ICRR, Univ. Tokyo)



INGRID + ND280

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

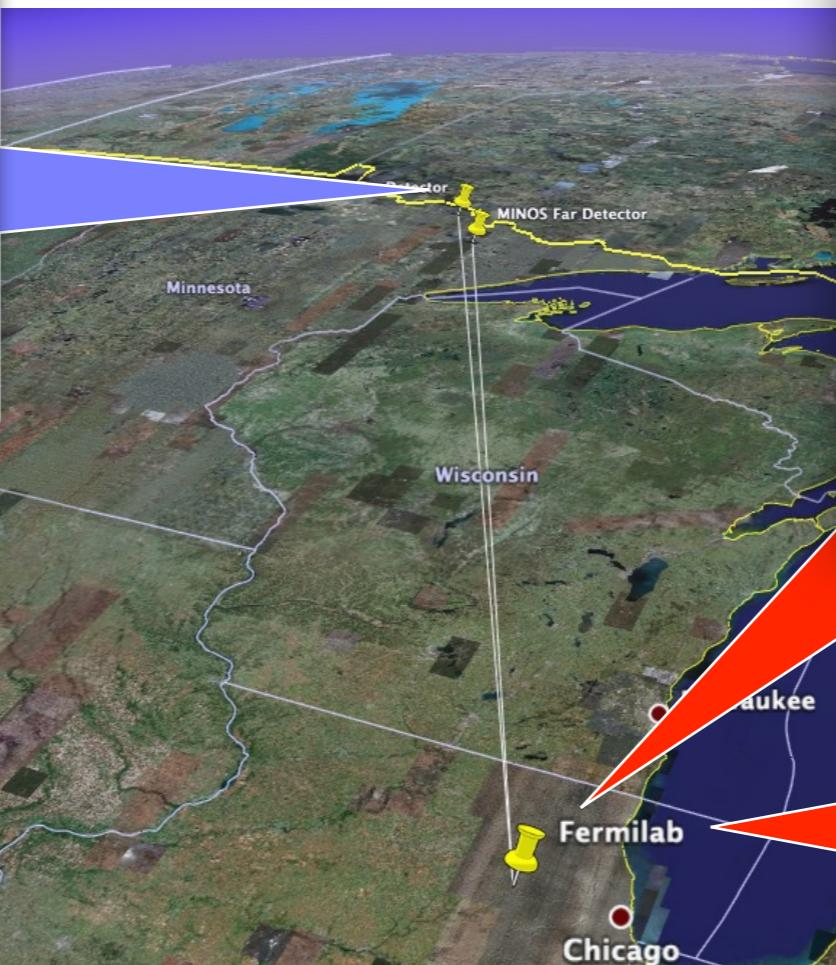


NOvA

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

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

NOvA Far Detector



NOvA
Near
Detector

Fermilab Main Injector



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

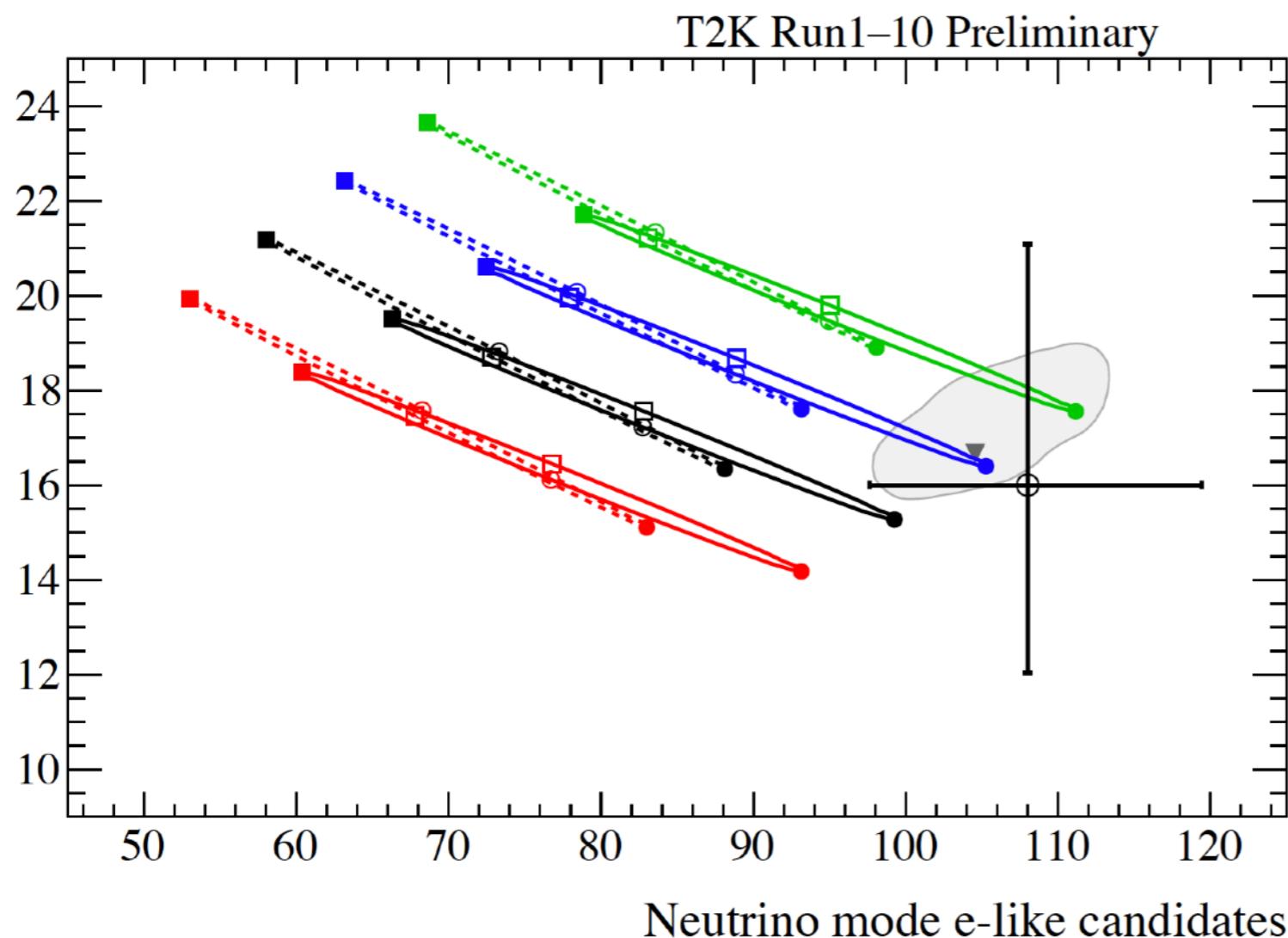
Factor	Type	Inverts for $\bar{\nu}$?	NOvA	T2K
Matter effect (mass ordering)	Binary	Yes	$\pm 19\%$	$\pm 10\%$
CP violation	Bounded, continuous	Yes	$[-22...+22]\%$	$[-29...+29]\%$
θ_{23} octant	Unbounded, continuous	No	$[-22...+22]\%$	$[-22...+22]\%$

Nota bene:

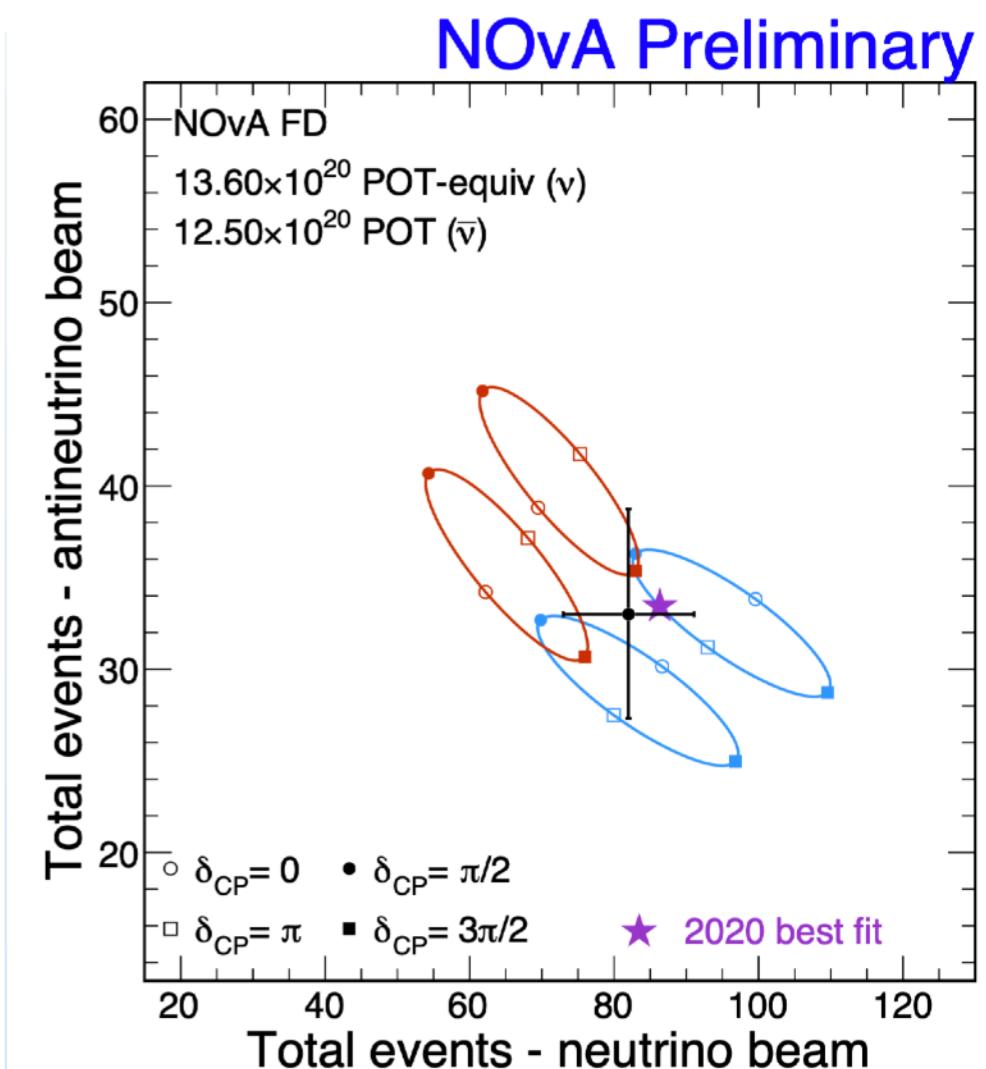
- Calculations are for rate only; there is some additional information in the energy spectrum
- These estimates neglect non-linearities in combining different effects
- In the calculation of the matter effect and CP violation effects the calculated values account for the fact that T2K runs at an energy 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 sees a large difference between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



NOvA does not. CPV and mass ordering remain to be resolved.

Neutrino oscillations at long baseline

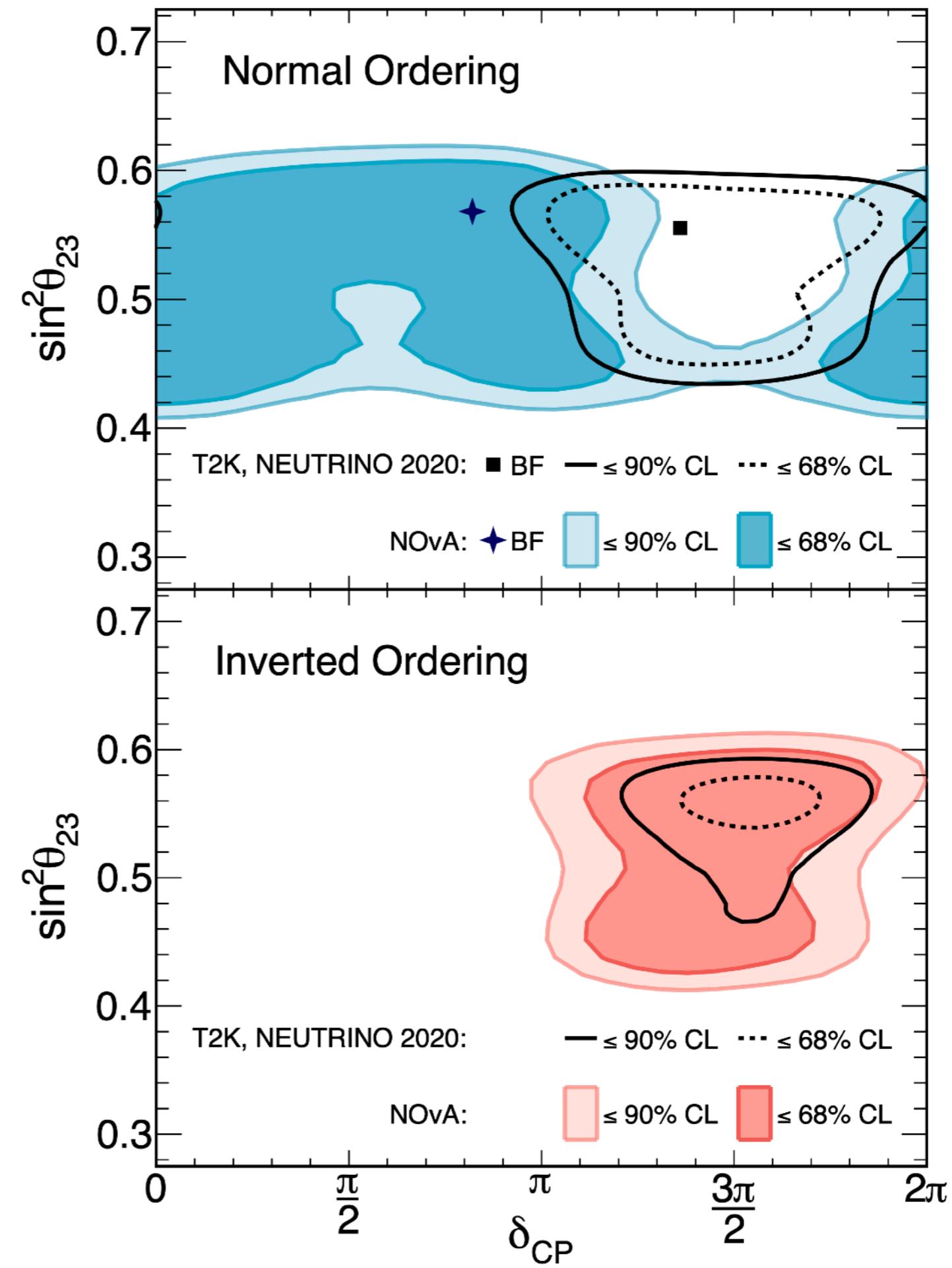
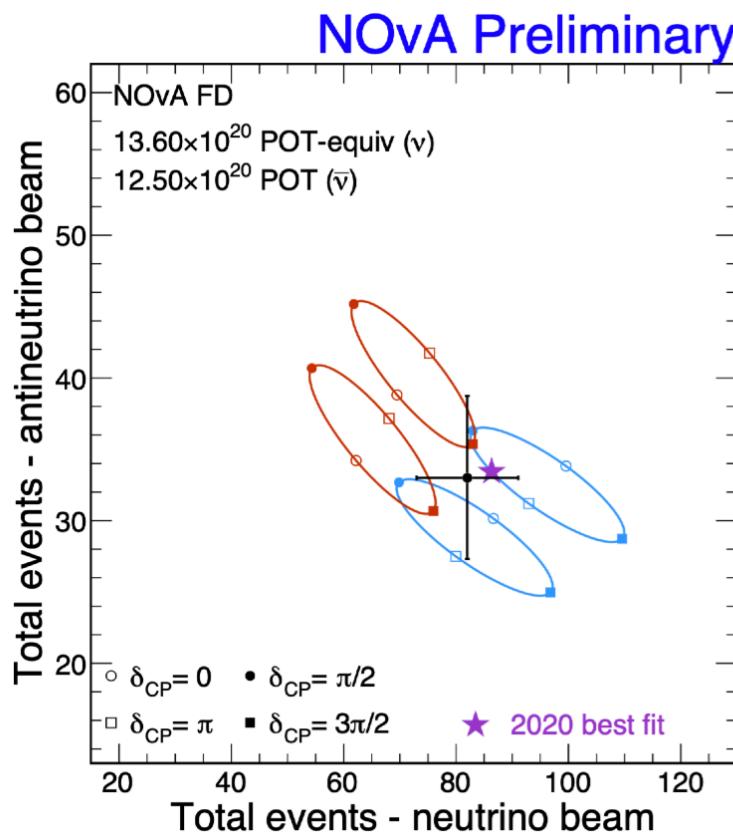
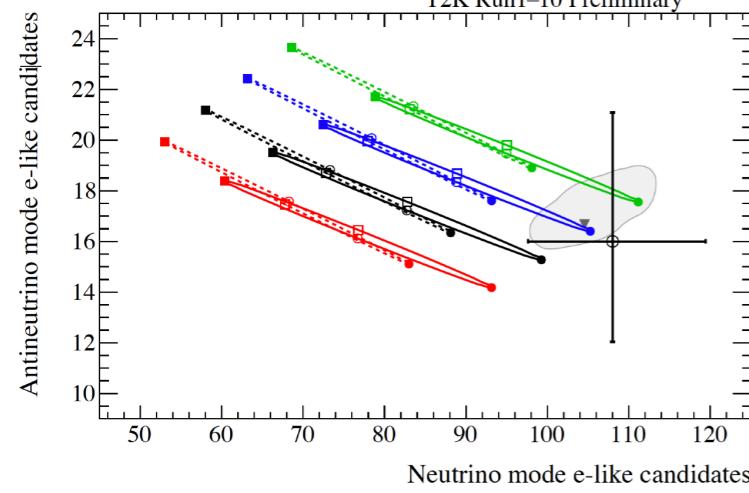
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$$\begin{aligned}
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 &\simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{3i} \\
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 &= P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)
 \end{aligned}$$

~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?

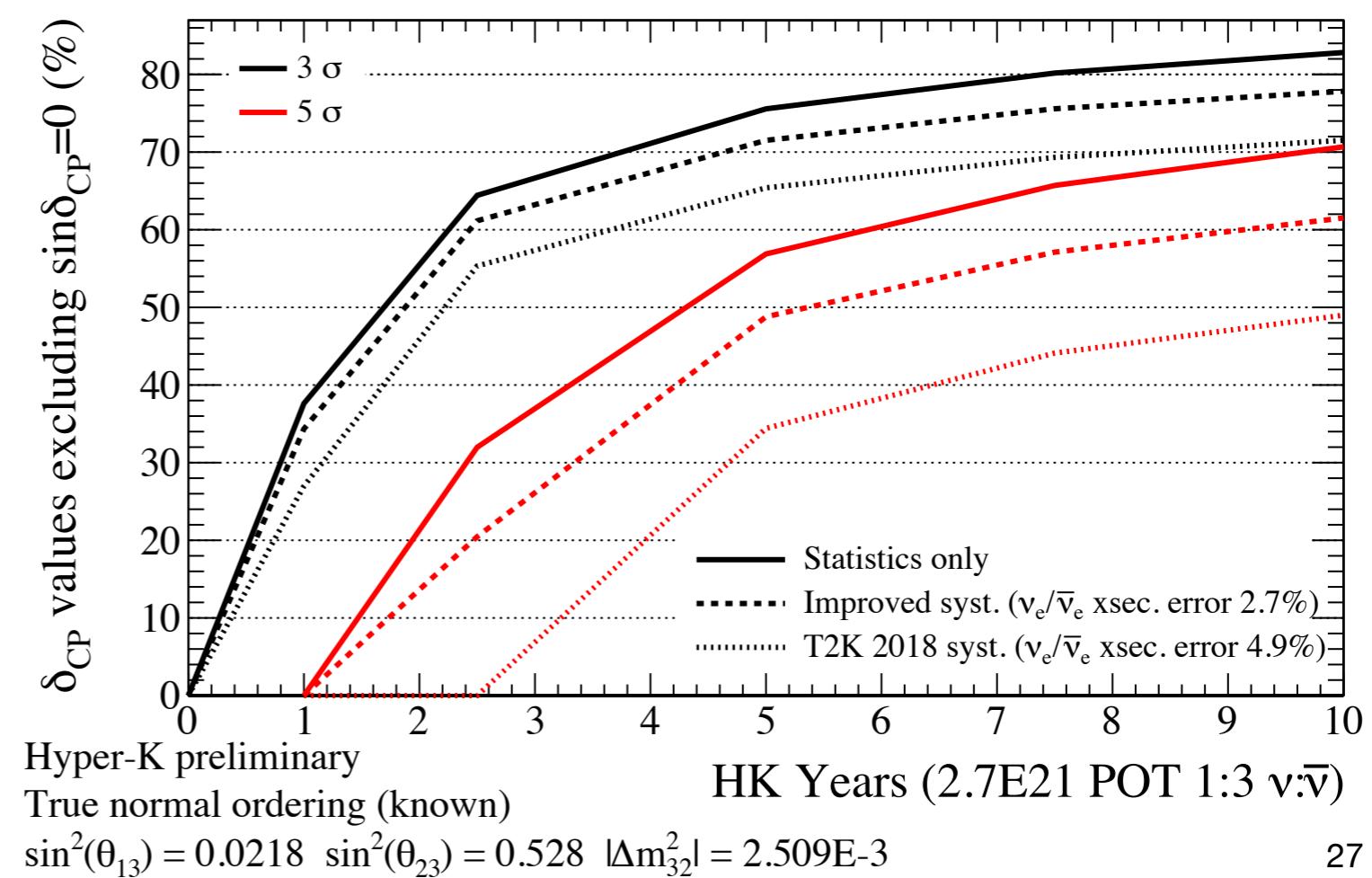
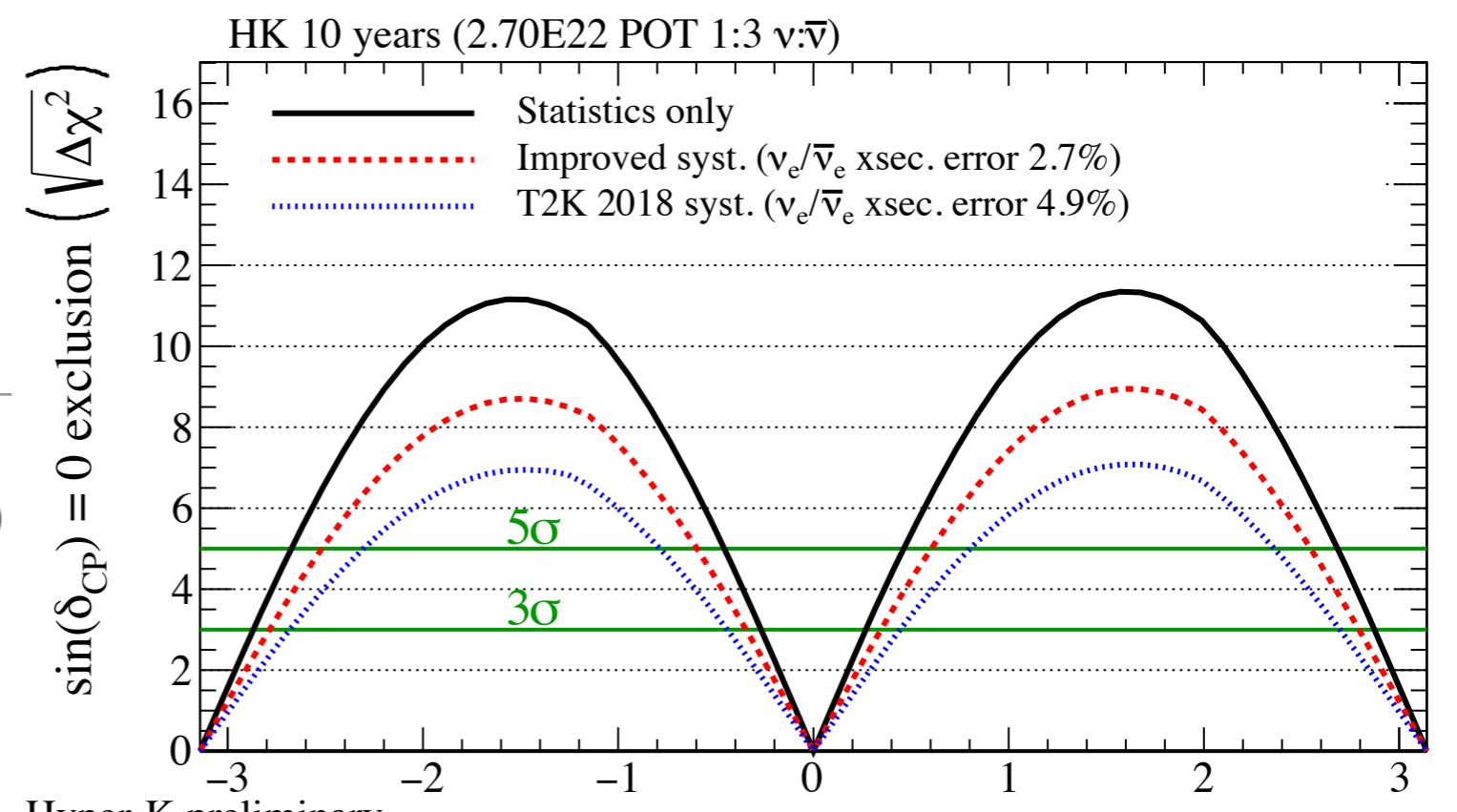


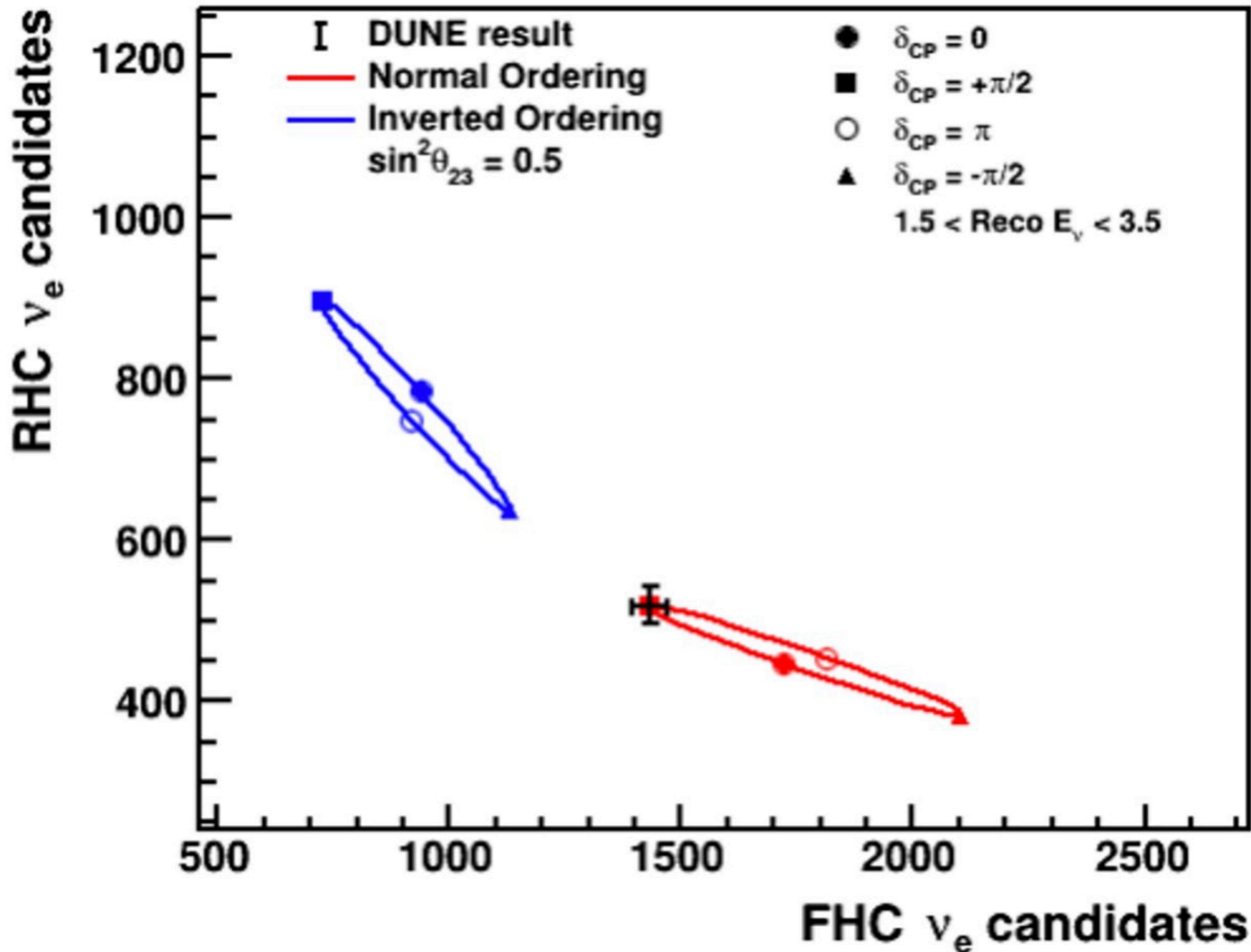
T2HK

Data taking expected to begin in 2027

5 σ discovery of CP violation in 10 years for 60% of δ_{CP} values

The search depends strongly on resolving the mass ordering and controlling systematic uncertainties

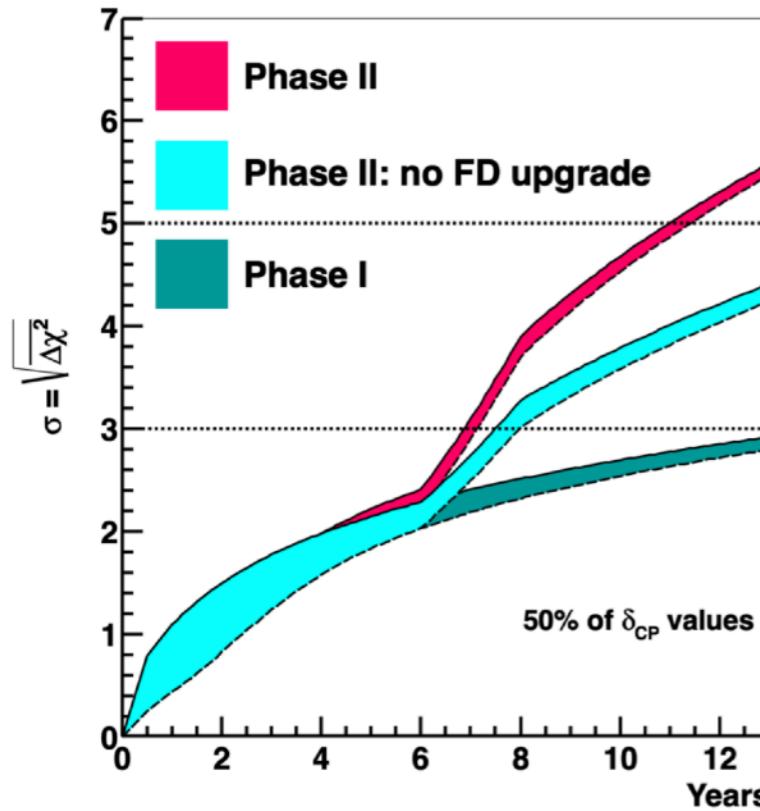




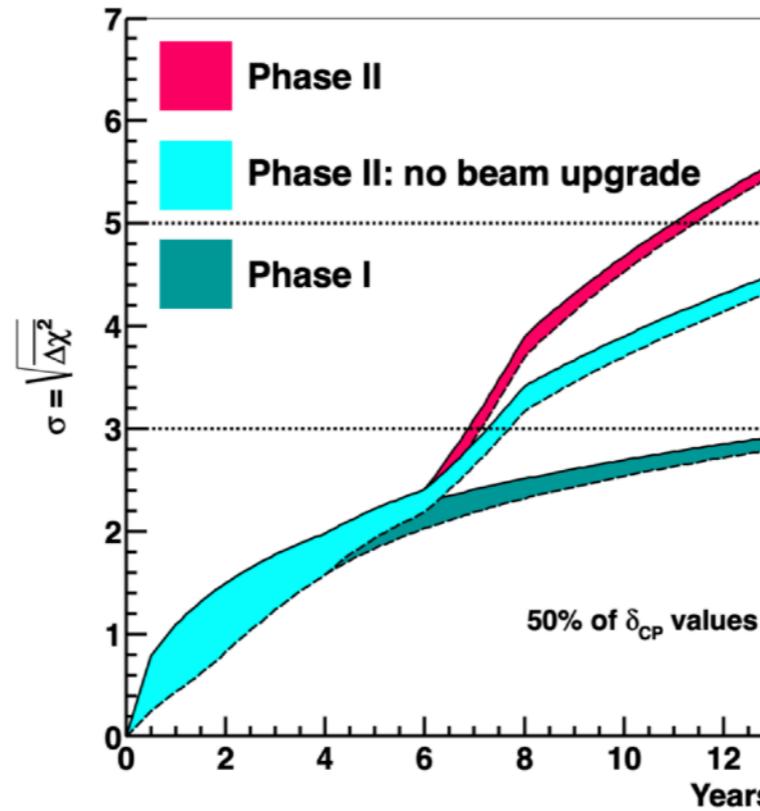
Mass Ordering with DUNE

>5 sigma in 6 years even for
“worst case” parameters

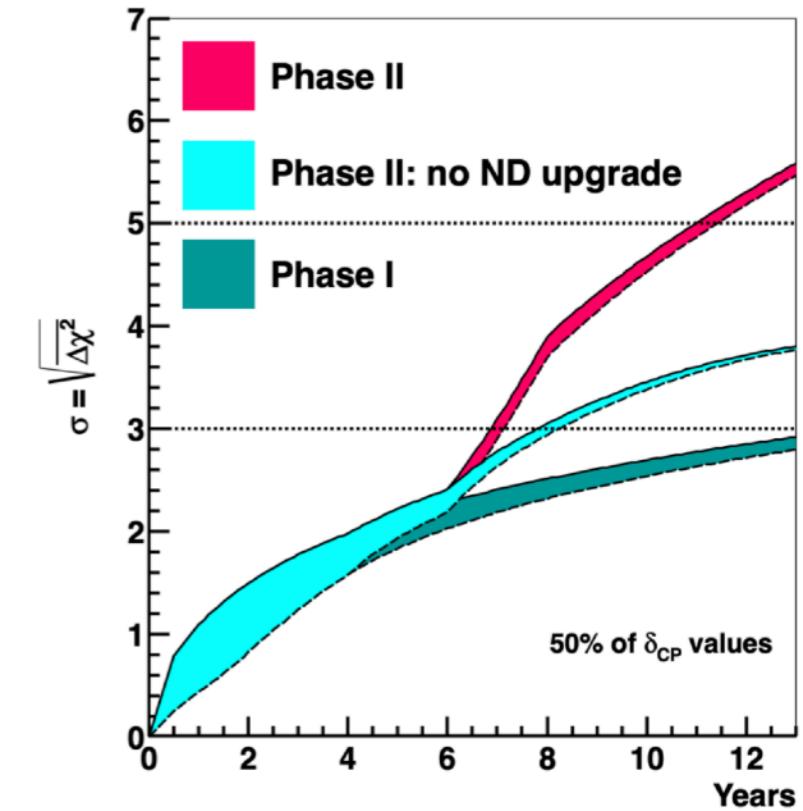
DUNE discovery potential for CP Violation and beyond



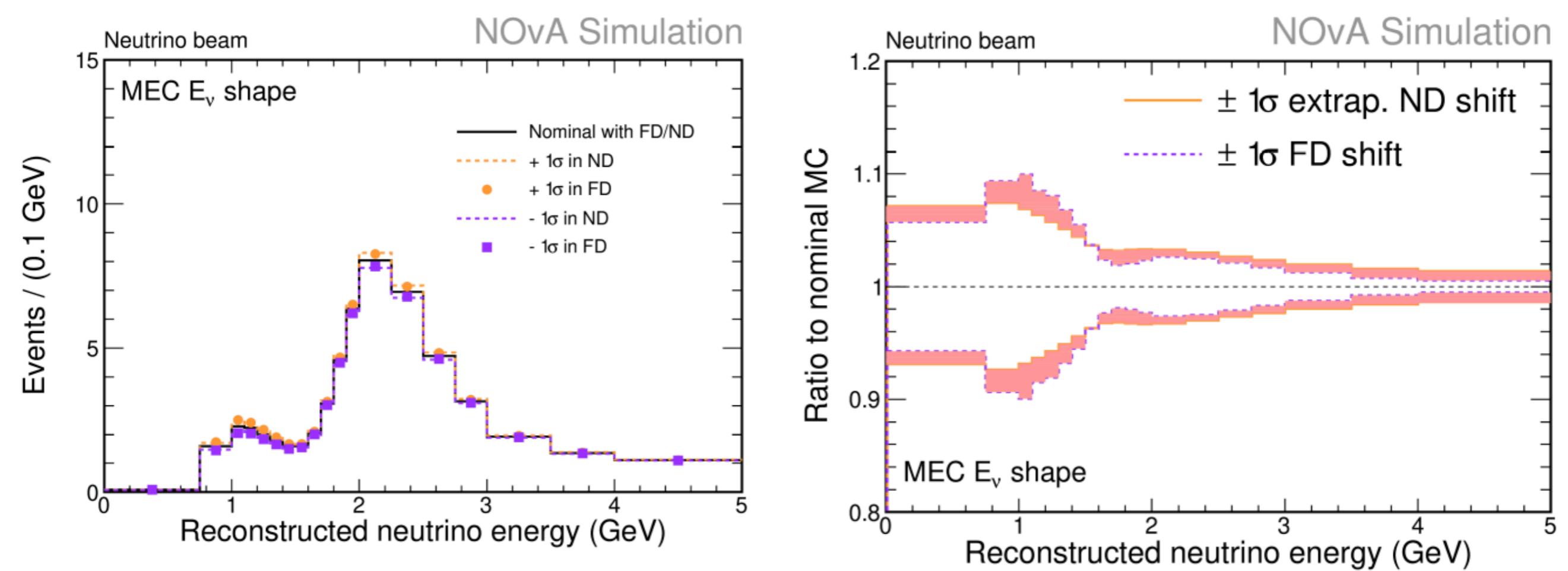
Start data taking
with **2** detector
modules then **4**



Fermilab proton power
1.2 MW then **2.4 MW**

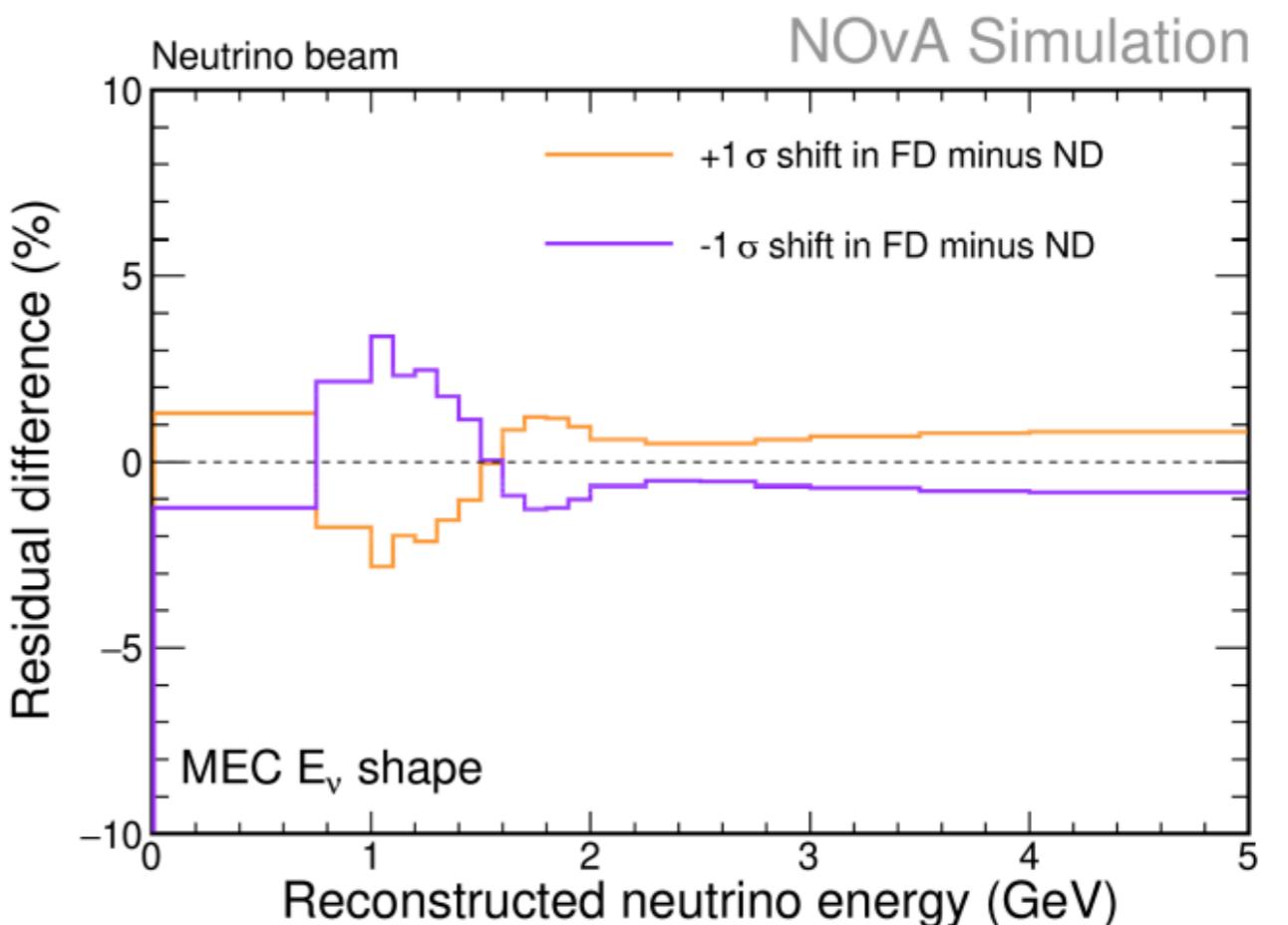


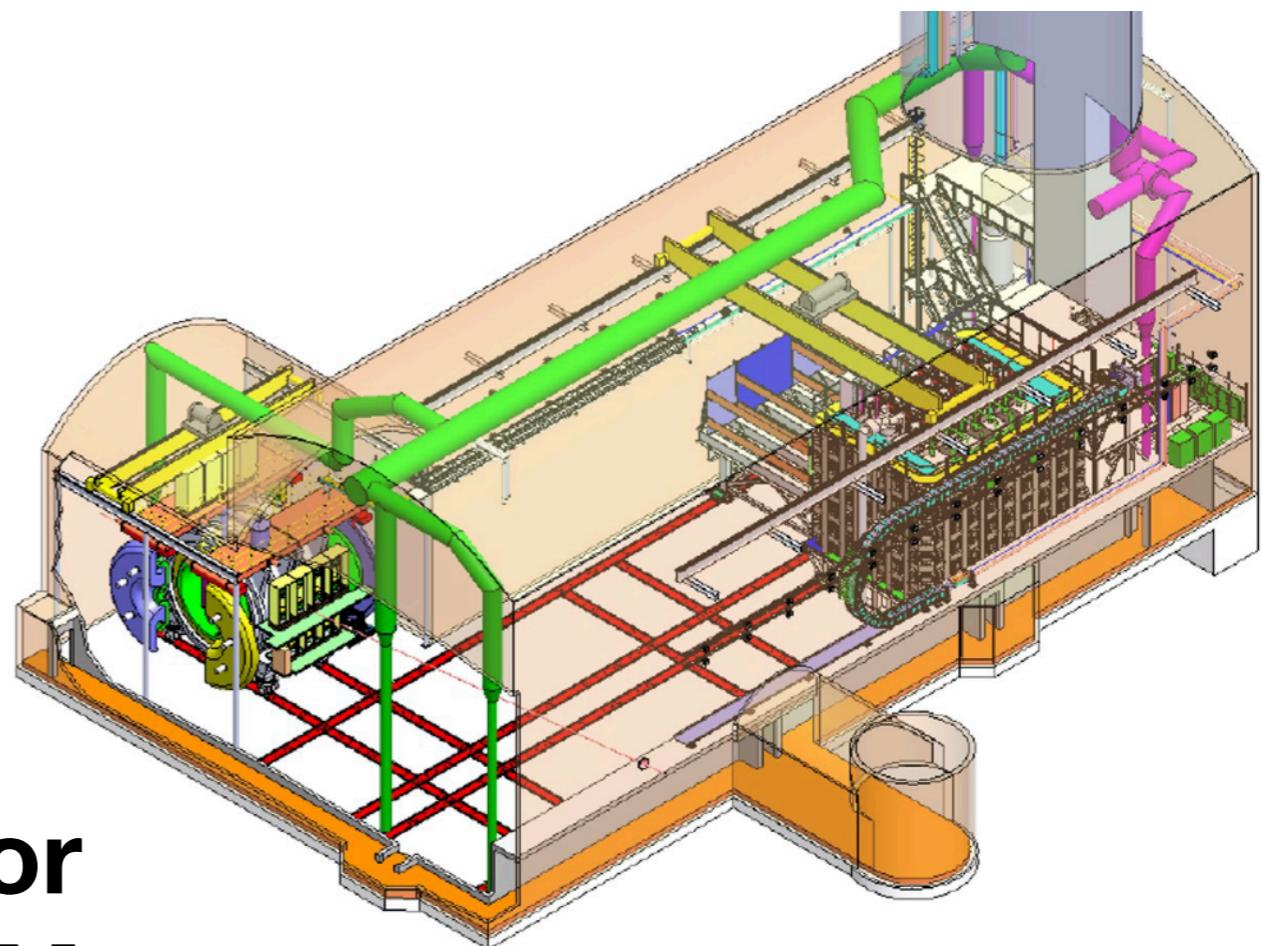
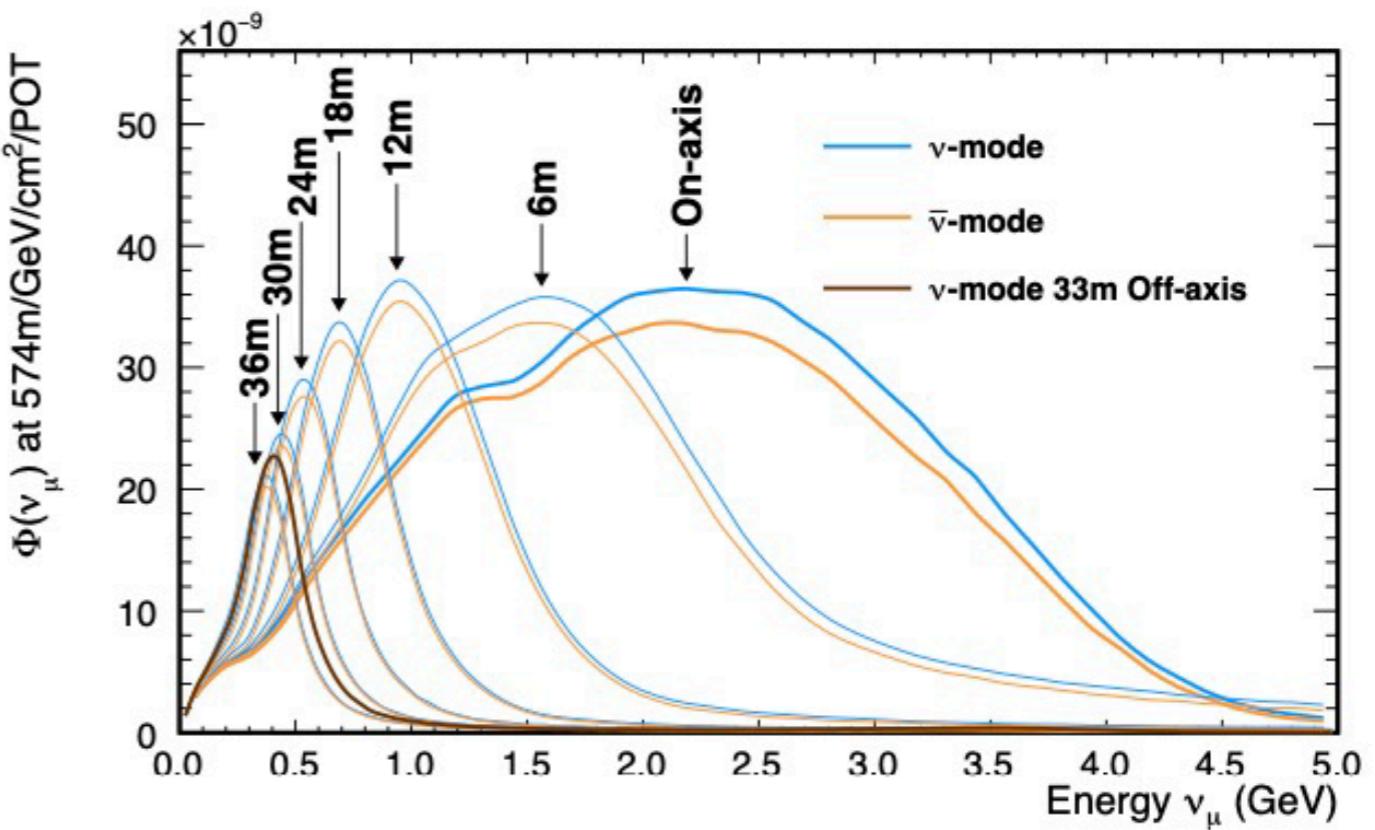
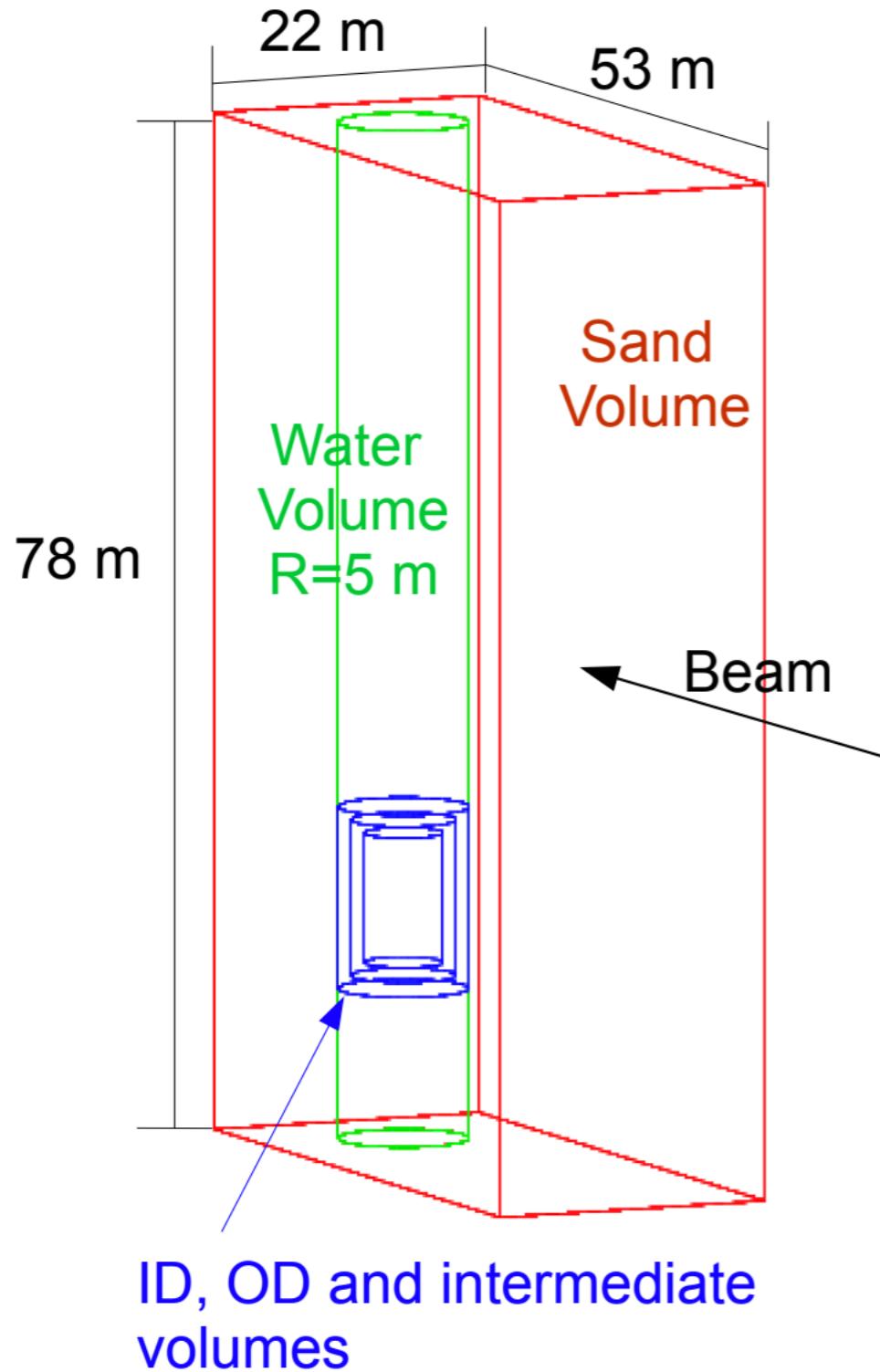
Phase one
near detector
and **Phase**
two near
detector



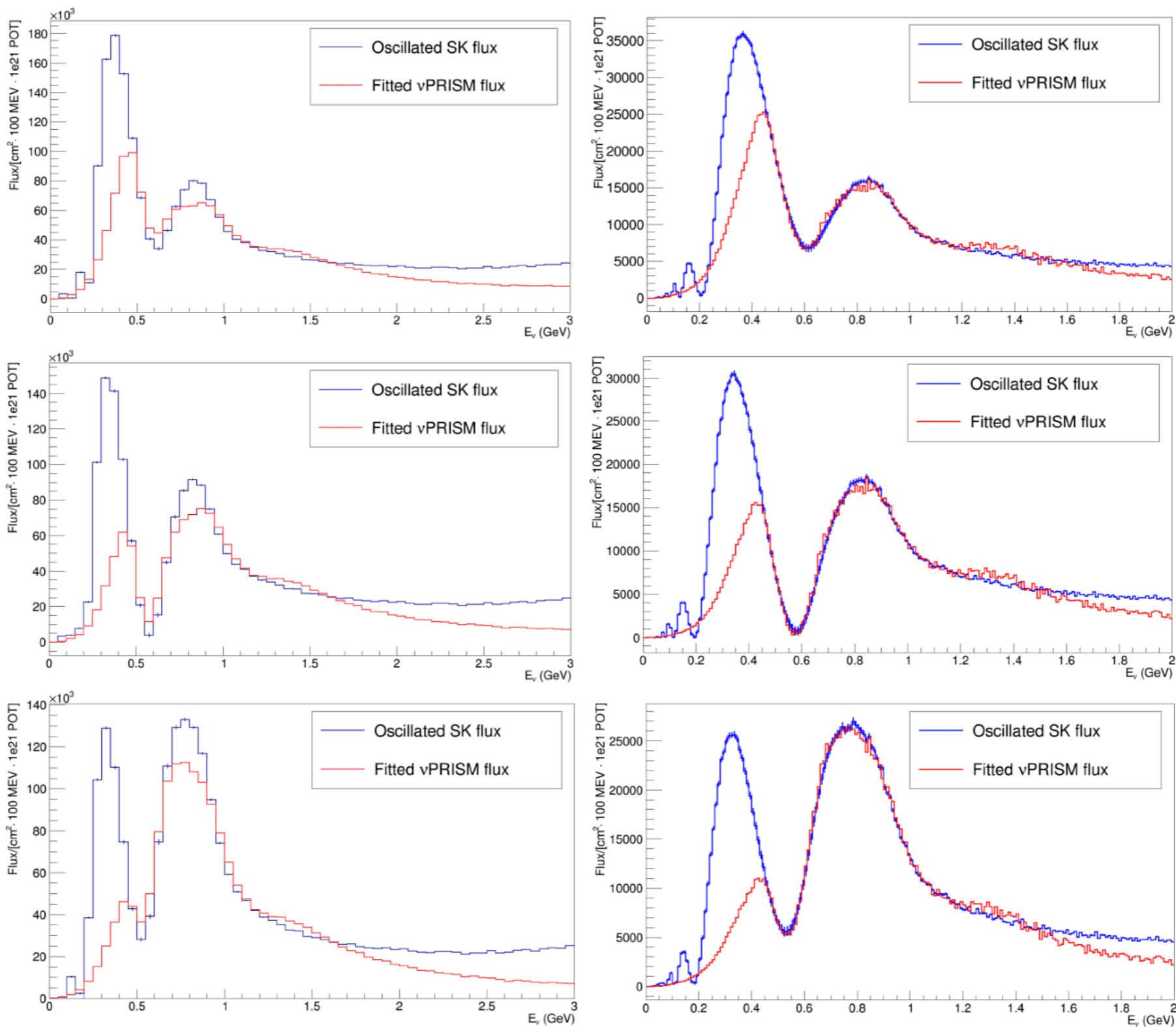
Impact of near detector extrapolation

In this study, we shift the FD to the edge of our MEC event systematic. Then we shift the ND to the edge and extrapolate based on the nominal (unshifted) extrapolation. While MEC is an overall $\sim 10\%$ impact on the rates, after extrapolation it is reduced to 3%.





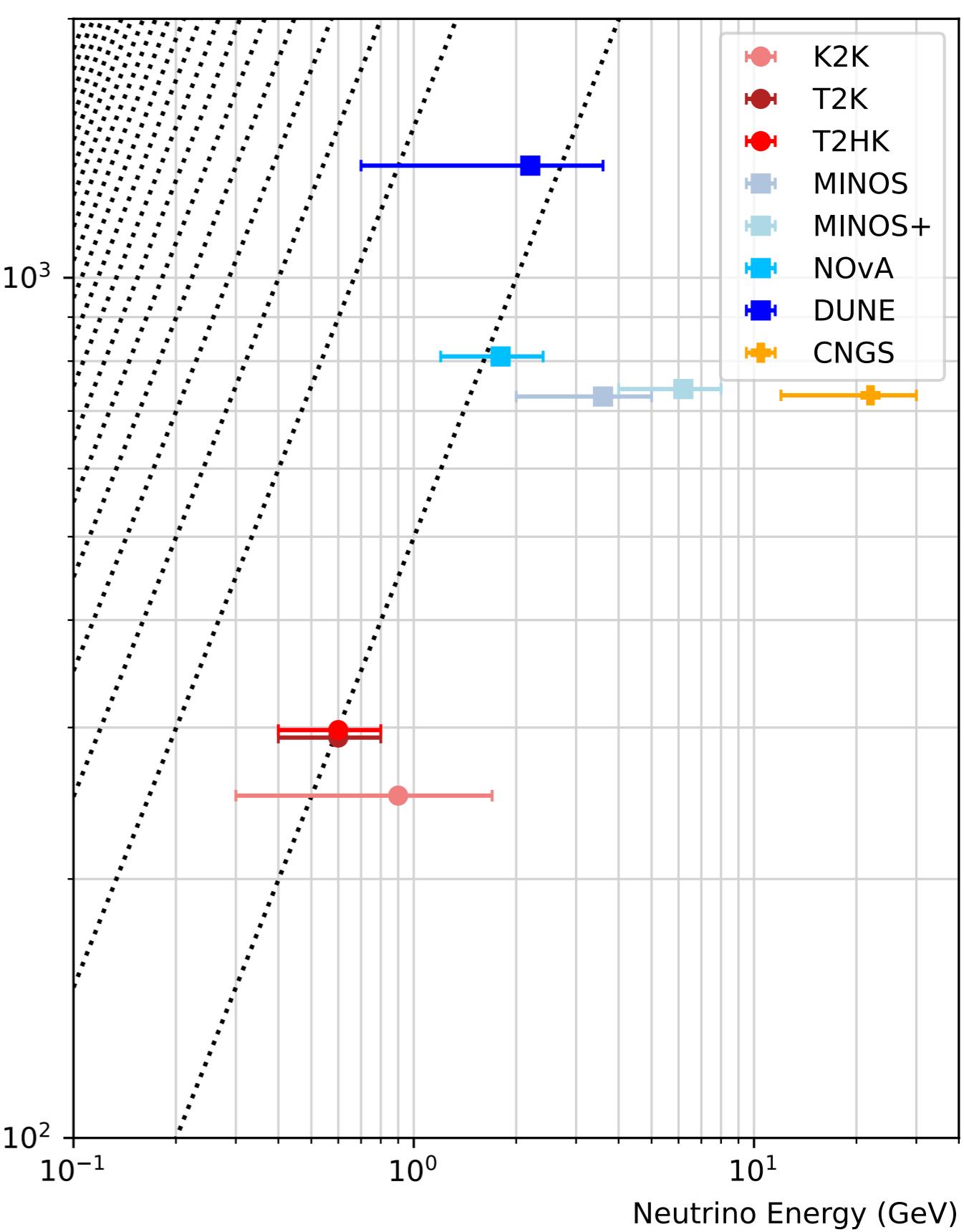
nuPRISM proposal for T2HK and DUNE PRISM



nuPRISM Proposal for T2HK

Using super position combination of ND fluxes can match FD oscillated spectra.

	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

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)

