How Neutrinos and Anti-neutrinos could differ

Stephen Parke

Fermilab

arXiv:1009.0014 with Joachim Kopp and Pedro Machado

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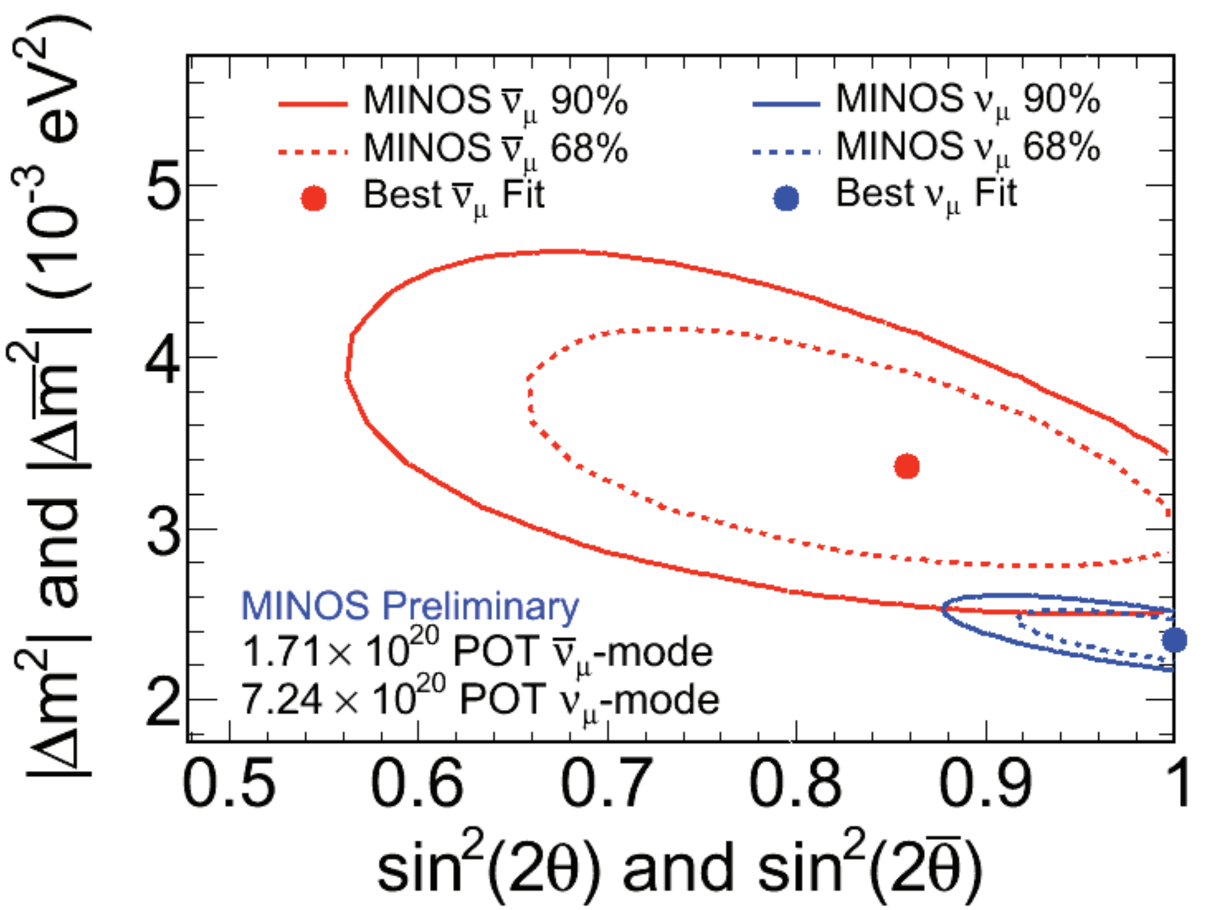
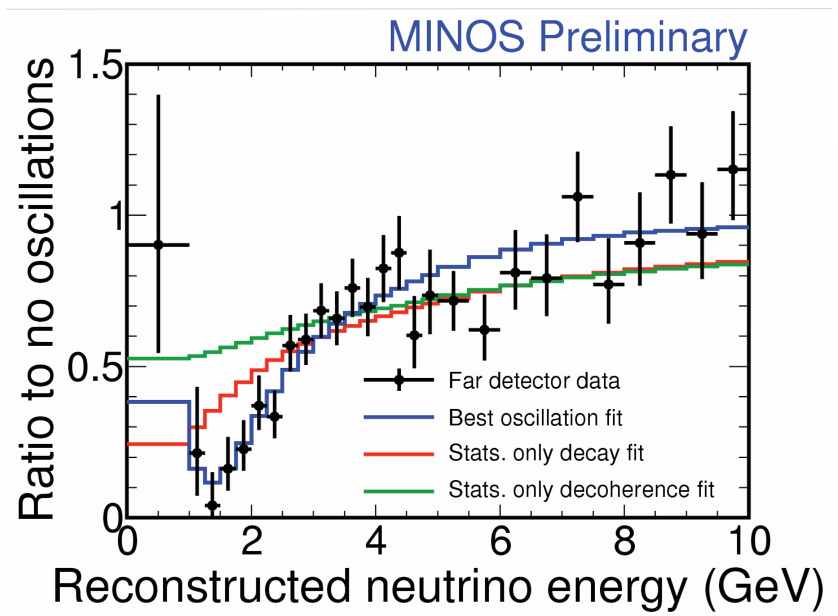
MINOS Results

from P. Vahle, Neutrino 2010

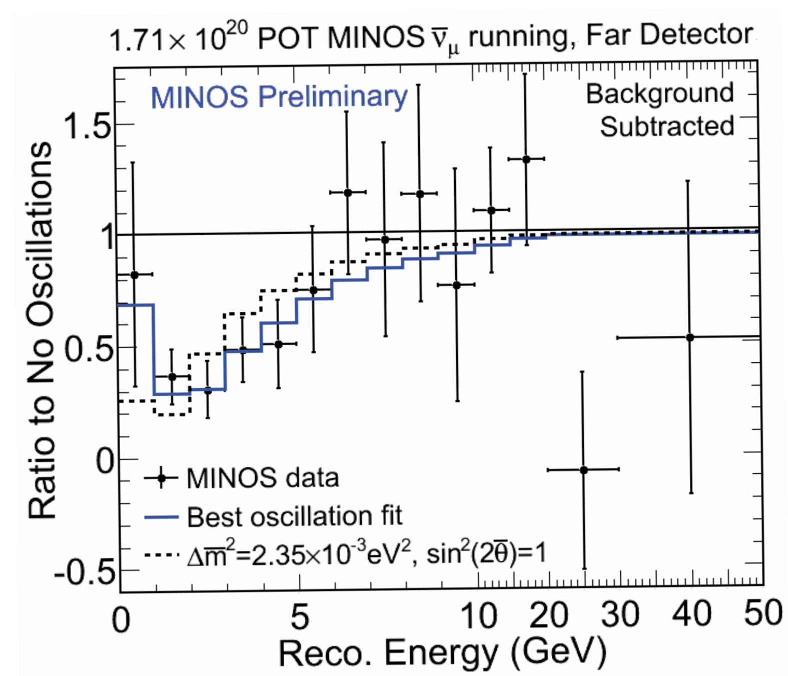


P. Vahle, Neutrino 2010

~2000 events



~100 events



Neutral Current Non-Standard Interactions:

$$H = \frac{1}{2E}\left[U\begin{pmatrix}0 & \\ & \Delta m_{32}^2\end{pmatrix}U^\dagger + A\begin{pmatrix}\epsilon_{\mu\mu}^m & \epsilon_{\mu\tau}^m \\ \epsilon_{\mu\tau}^{m*} & \epsilon_{\tau\tau}^m\end{pmatrix}\right],$$

$$\epsilon_{\tau\tau}^m - \epsilon_{\mu\mu}^m.$$

$$U = \begin{pmatrix}\cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}$$

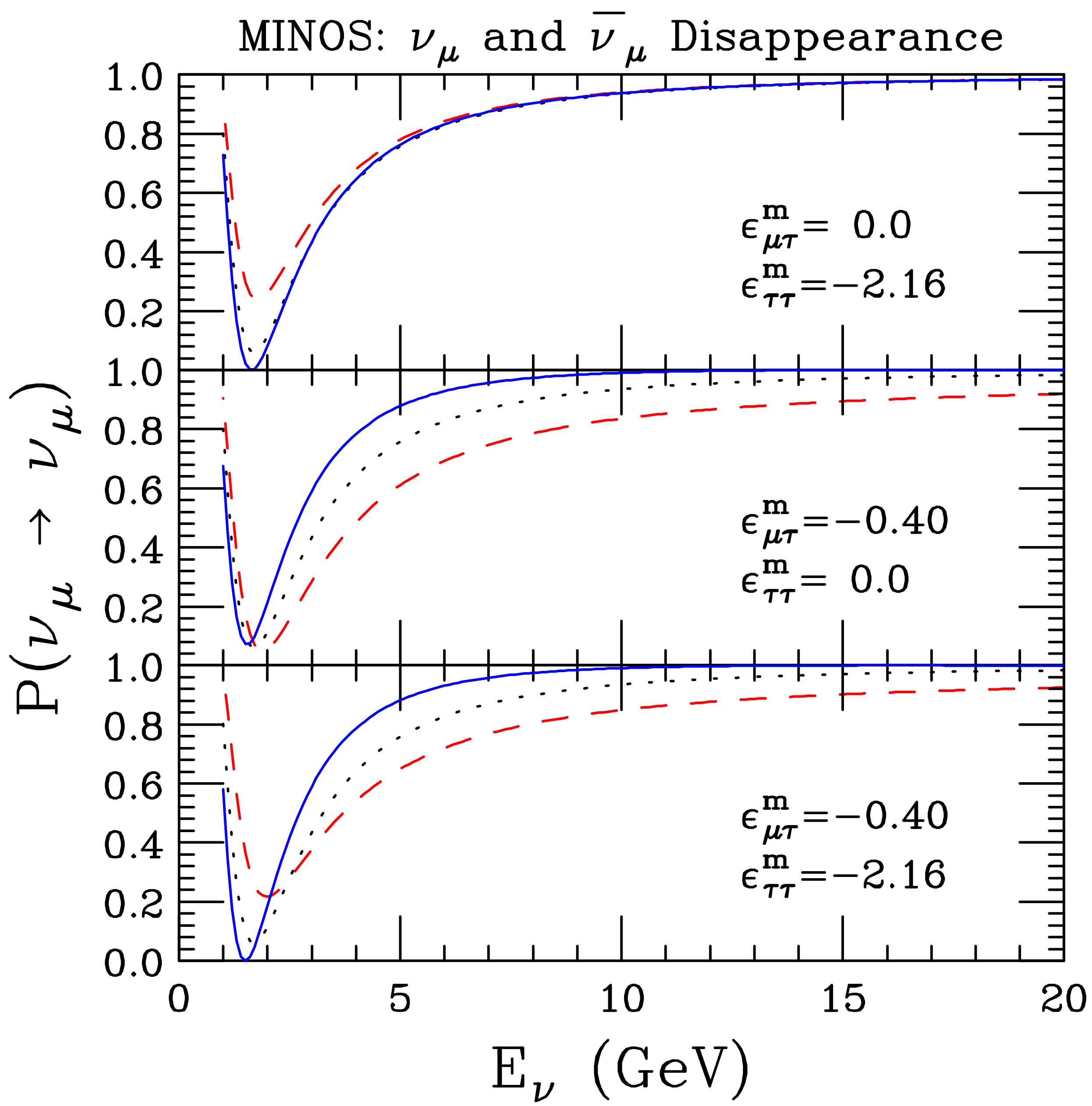
$$P(\nu_\mu \to \nu_\mu) \;=\; 1 - \frac{|\Delta m_{32}^2 \sin 2\theta_{23} + 2\epsilon_{\mu\tau}^m A|^2}{\Delta m_N^4}\sin^2\left(\frac{\Delta m_N^2 L}{4E}\right)$$

$$\Delta m_N^2 \;=\; \sqrt{(\Delta m_{32}^2\cos 2\theta_{23} + \epsilon_{\tau\tau}^m A)^2 + |\Delta m_{32}^2 \sin 2\theta_{23} + 2\epsilon_{\mu\tau}^m A|^2}$$

For anti-neutrinos, $\epsilon_{\mu\tau}^m \to \epsilon_{\mu\tau}^{m*}$ and $A \to -A$, so that in matter

$P(\nu_\mu \to \nu_\mu) \neq P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ without CPT violation.

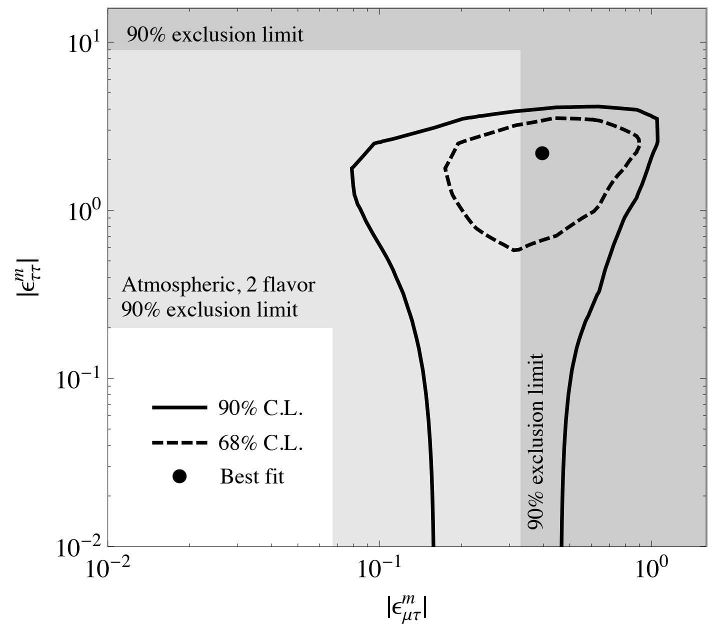
NC-NSI (conti)

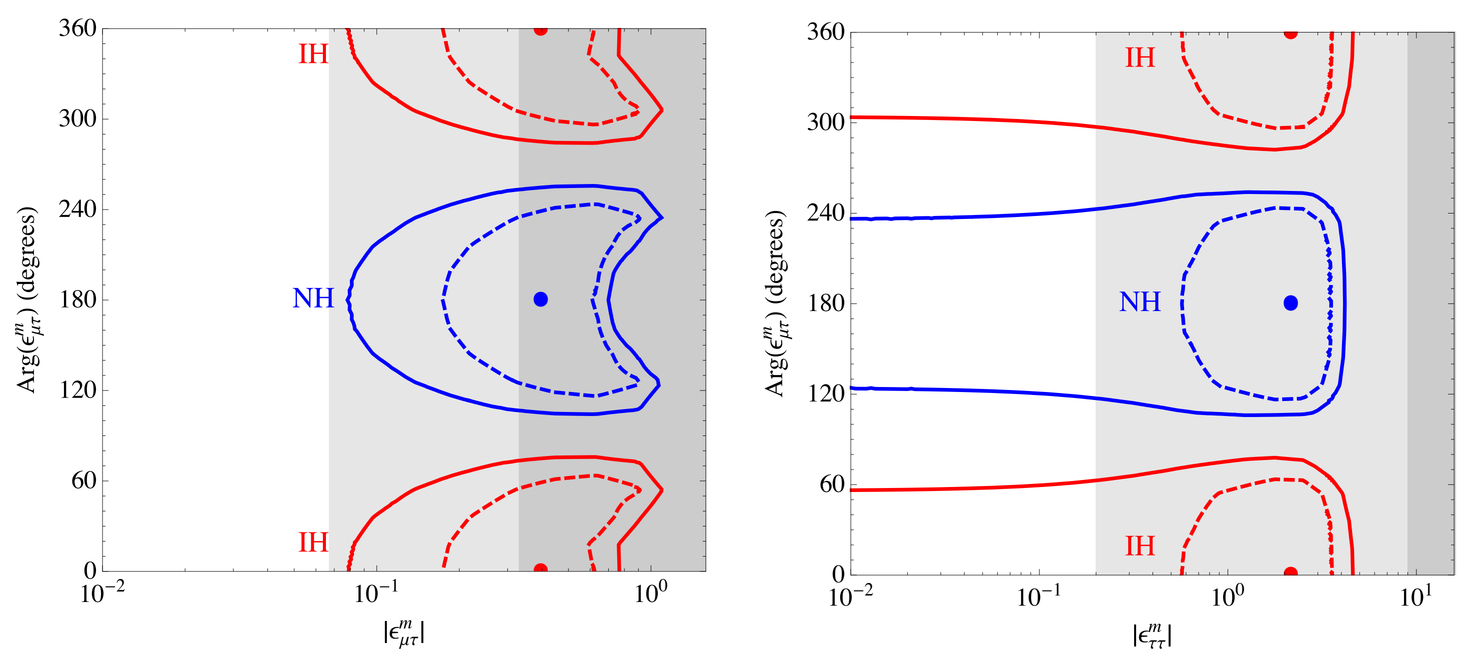


MINOS: ν_μ and $\overline{\nu}_\mu$ Disappearance
$P(\nu_\mu \to \nu_\mu)$
E_ν (GeV)
$\epsilon^m_{\mu\tau}$= 0.0
$\epsilon^m_{\tau\tau}$=−2.16
$\epsilon^m_{\mu\tau}$=−0.40
$\epsilon^m_{\tau\tau}$= 0.0
$\epsilon^m_{\mu\tau}$=−0.40
$\epsilon^m_{\tau\tau}$=−2.16
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20

NC-NSI (conti)

3 flavor simulation:

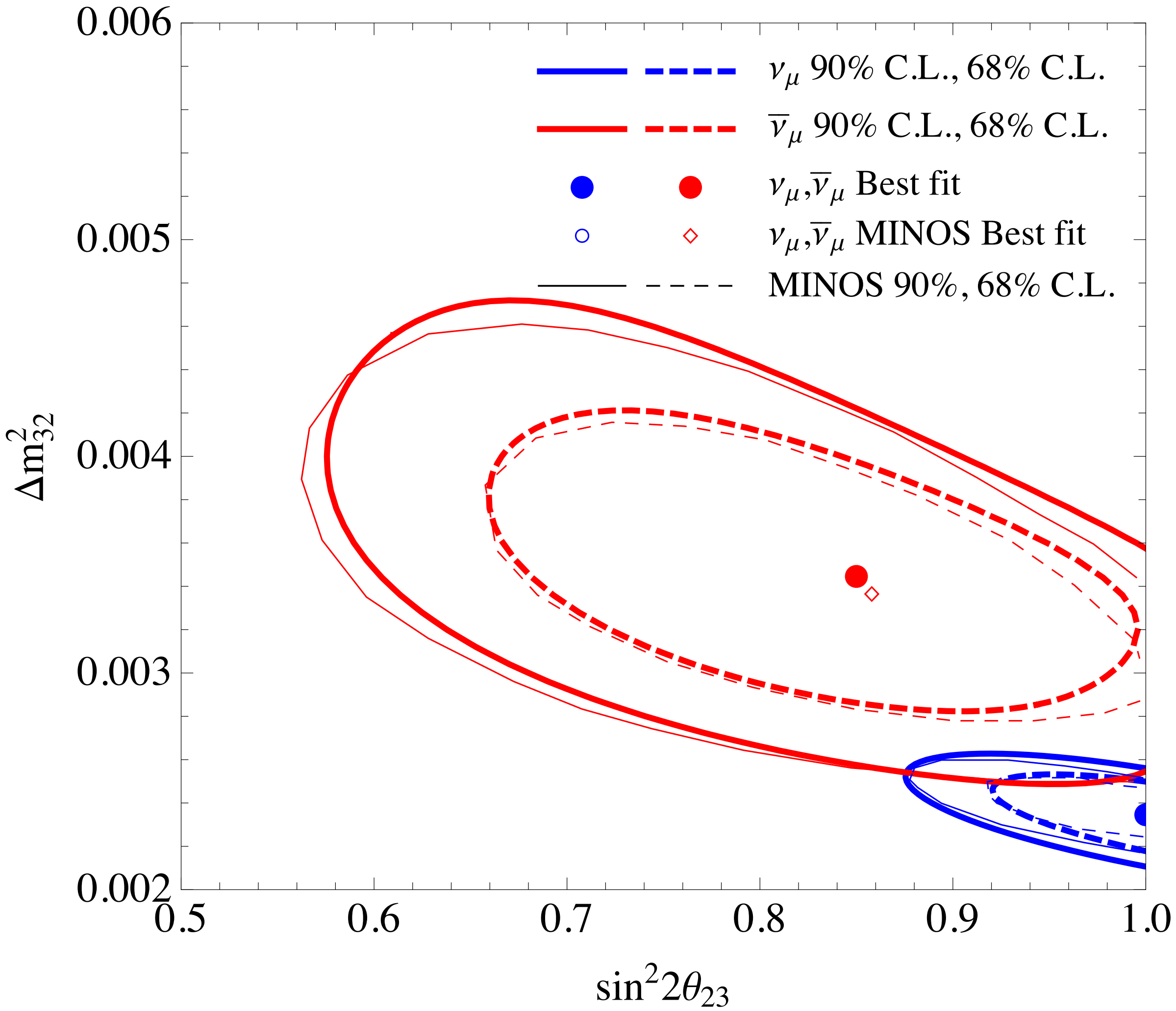




3 times larger than given in

Mann-Cherdack-Musial-Kafka, arXiv:1006.5720 [hep-ph]

NC-NSI (conti)



ν_μ 90% C.L., 68% C.L.
$\overline{\nu}_\mu$ 90% C.L., 68% C.L.
$\nu_\mu, \overline{\nu}_\mu$ Best fit
$\nu_\mu, \overline{\nu}_\mu$ MINOS Best fit
MINOS 90%, 68% C.L.
0.006
0.005
0.004
0.003
0.002
Δm^2_{32}
0.5
0.6
0.7
0.8
0.9
1.0
$\sin^2 2\theta_{23}$

Charge Current NSI

$$\nu_\tau + N \to X + \mu\,,\qquad \mathcal{L}_{\rm NSI} \supset -2\sqrt{2}G_F\epsilon^d_{\tau\mu}V_{ud}\,[\bar{u}\gamma^\rho d]\,[\bar{\mu}\gamma_\rho P_L\nu_\tau] + h.c.\,,$$

Vector only; not axial vector!

gauge invariance? later

$$\nu_\mu + N \to X + \mu$$

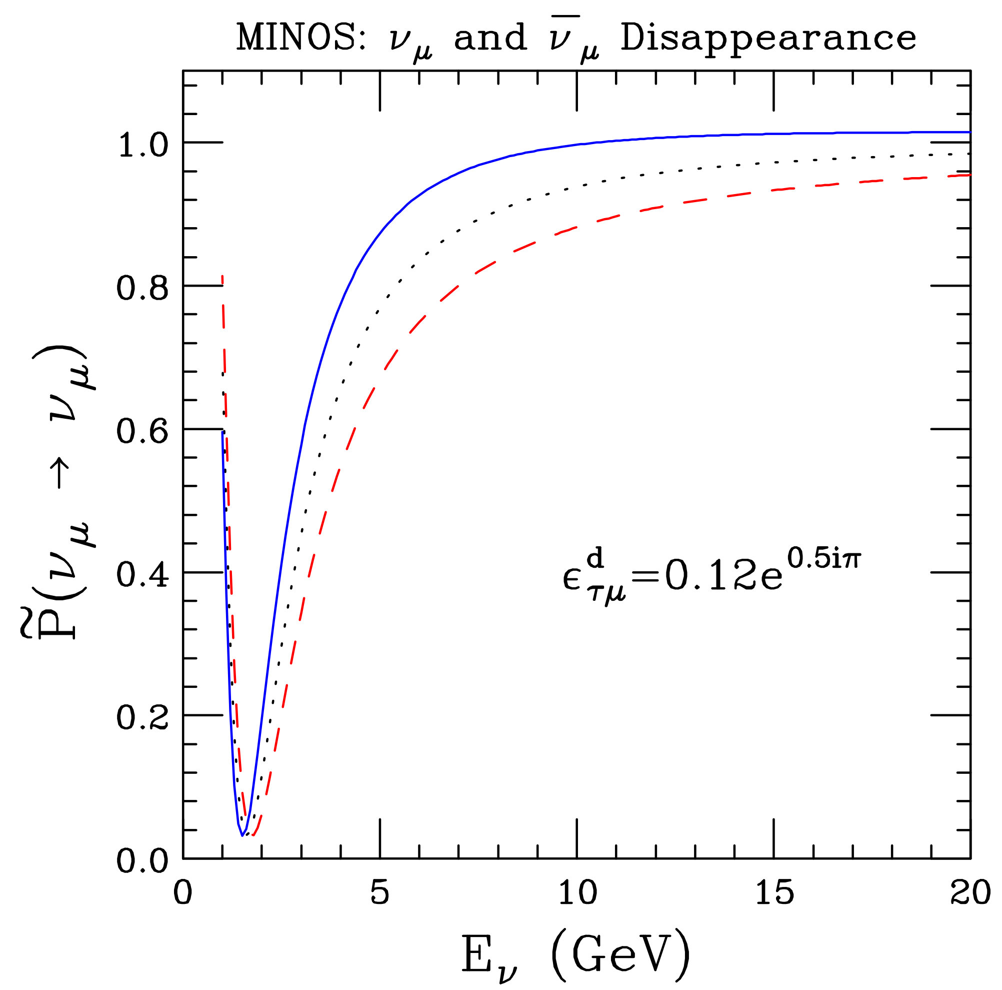
$$\nu_\mu \xrightarrow{\rm osc.} \nu_\tau + N \to X + \mu$$

$$\tilde{P}(\nu_\mu \to \nu_\mu) = 1 - \left[1 + 2\,|\epsilon^d_{\tau\mu}|\cot 2\theta_{23}\cos\left[\arg(\epsilon^d_{\tau\mu})\right] - |\epsilon^d_{\tau\mu}|^2\right]\sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$$
$$+ 2\,|\epsilon^d_{\tau\mu}|\sin 2\theta_{23}\sin\left[\arg(\epsilon^d_{\tau\mu})\right]\sin\left(\frac{\Delta m^2_{32}L}{4E}\right)\cos\left(\frac{\Delta m^2_{32}L}{4E}\right)\,.$$

For anti-neutrinos, the sign of $\arg(\epsilon^d_{\tau\mu})$ has to be reversed, and thus

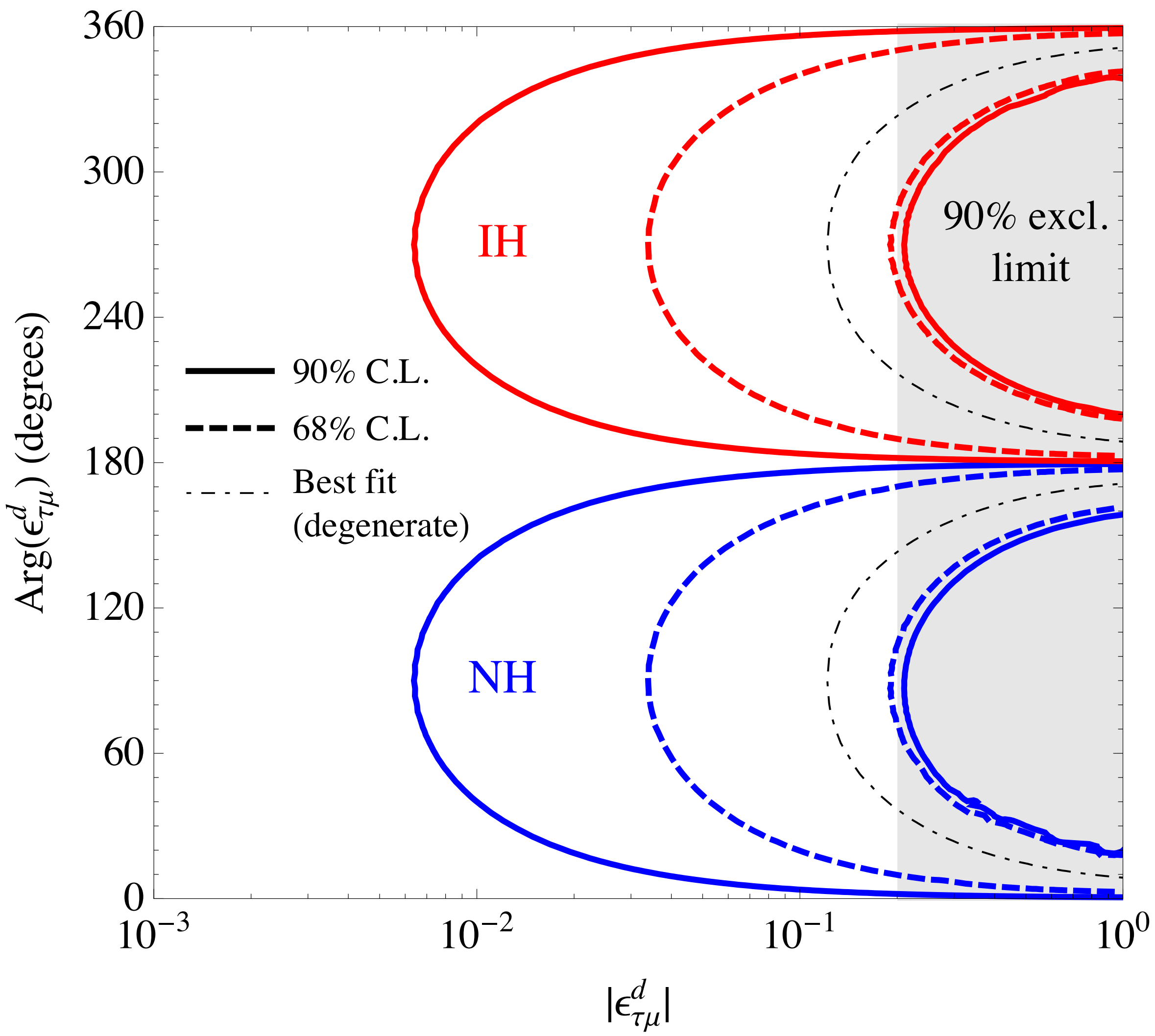
$$\tilde{P}(\nu_\mu \to \nu_\mu) \neq \tilde{P}(\bar{\nu}_\mu \to \bar{\nu}_\mu)\,.$$

CC-NSI (conti)


MINOS: ν_μ and $\bar{\nu}_\mu$ Disappearance
$\tilde{P}(\nu_\mu \to \nu_\mu)$
E_ν (GeV)
$\epsilon^d_{\tau\mu}=0.12e^{0.5i\pi}$
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20

CC-NSI (conti)

3 flavor simulation:



New Bound on CC-NSI

$$\tau^\pm \to \mu^\pm \pi^0$$

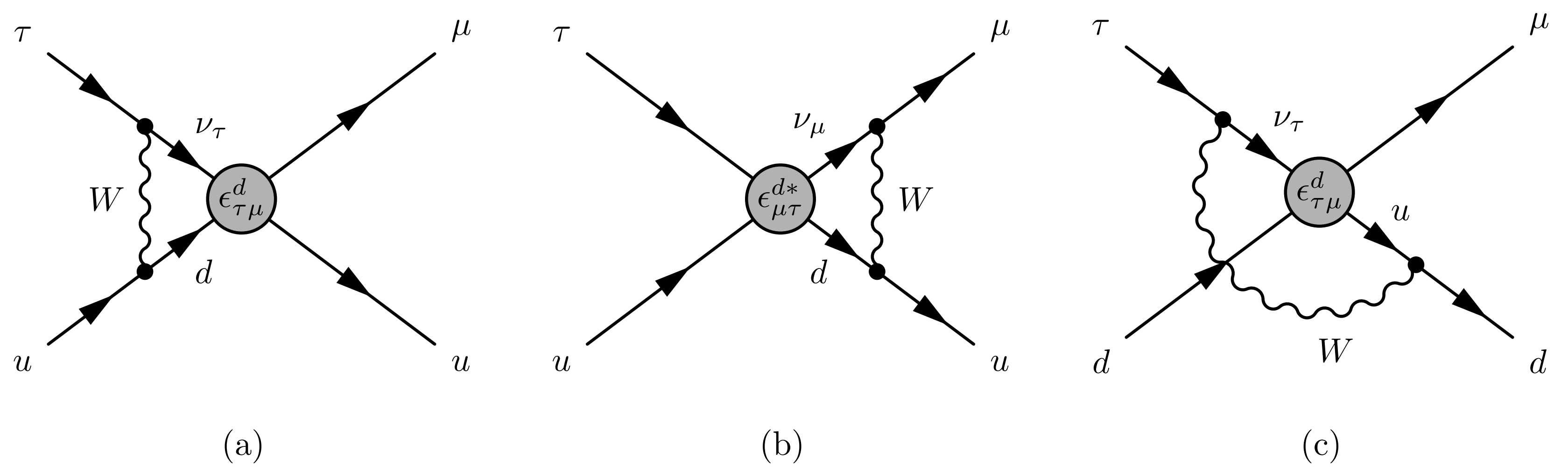


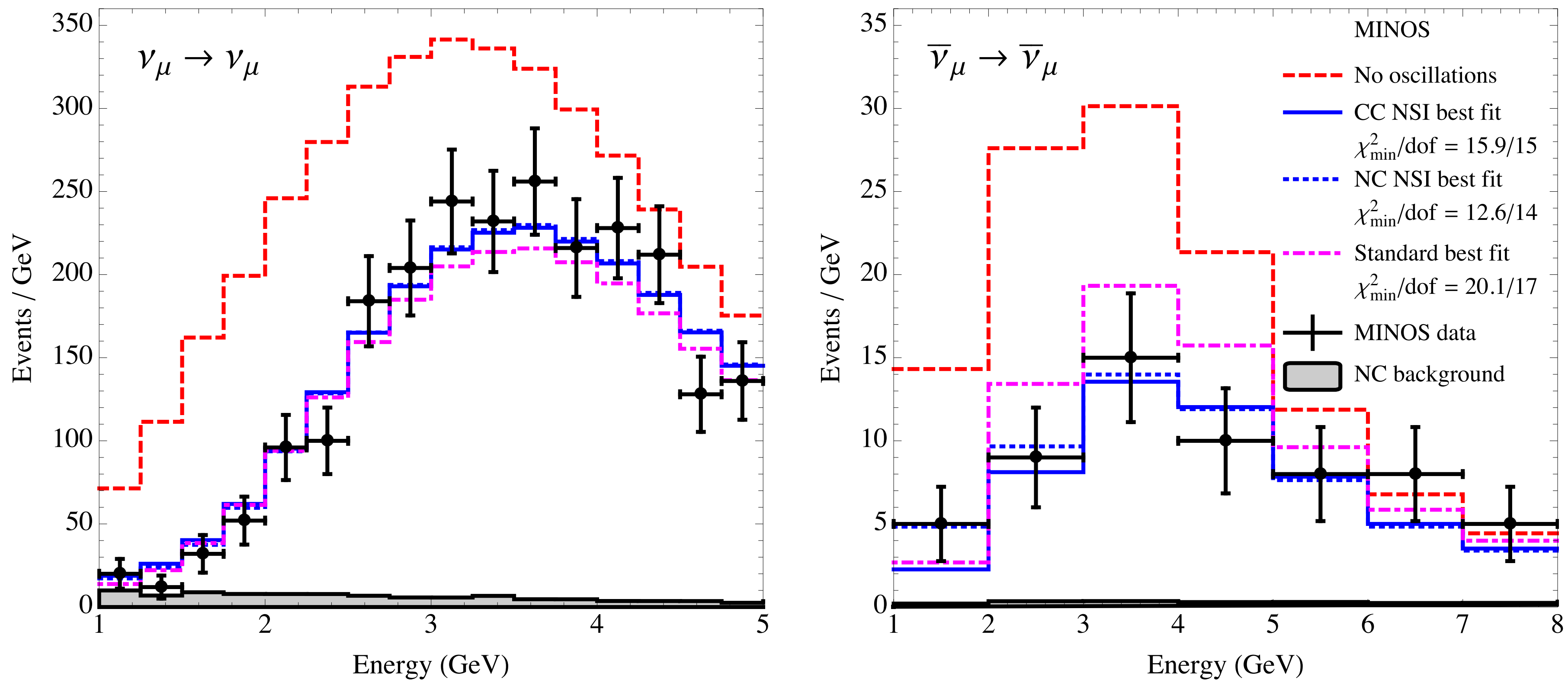
Figure 9: (a) and (b) The loop diagrams used to constrain $\epsilon^d_{\tau\mu}$ and $\epsilon^d_{\mu\tau}$, respectively. (c) A similar diagram that does not have a logarithmic divergence.

$$|\epsilon^d_{\tau\mu}| \simeq \sqrt{\frac{2\,\mathrm{BR}(\tau^\pm \to \mu^\pm\pi^0)}{\mathrm{BR}(\tau^\pm \to \pi^\pm\nu_\tau)}\,\frac{4\pi s_w^2}{3\alpha}}\,.$$

$$\mathrm{BR}(\tau^\pm \to \mu^\pm\pi^0) < 1.1\times 10^{-7}$$

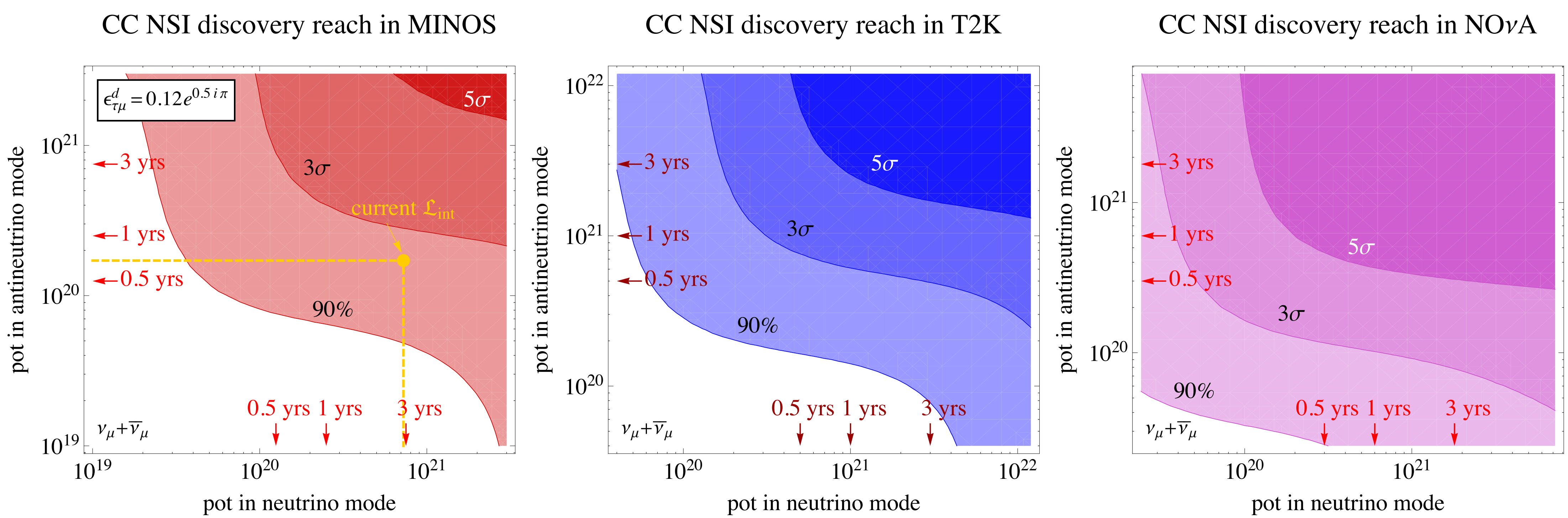
$$|\epsilon^d_{\tau\mu}| \lesssim 0.20\,.$$

CC-NSI (conti)

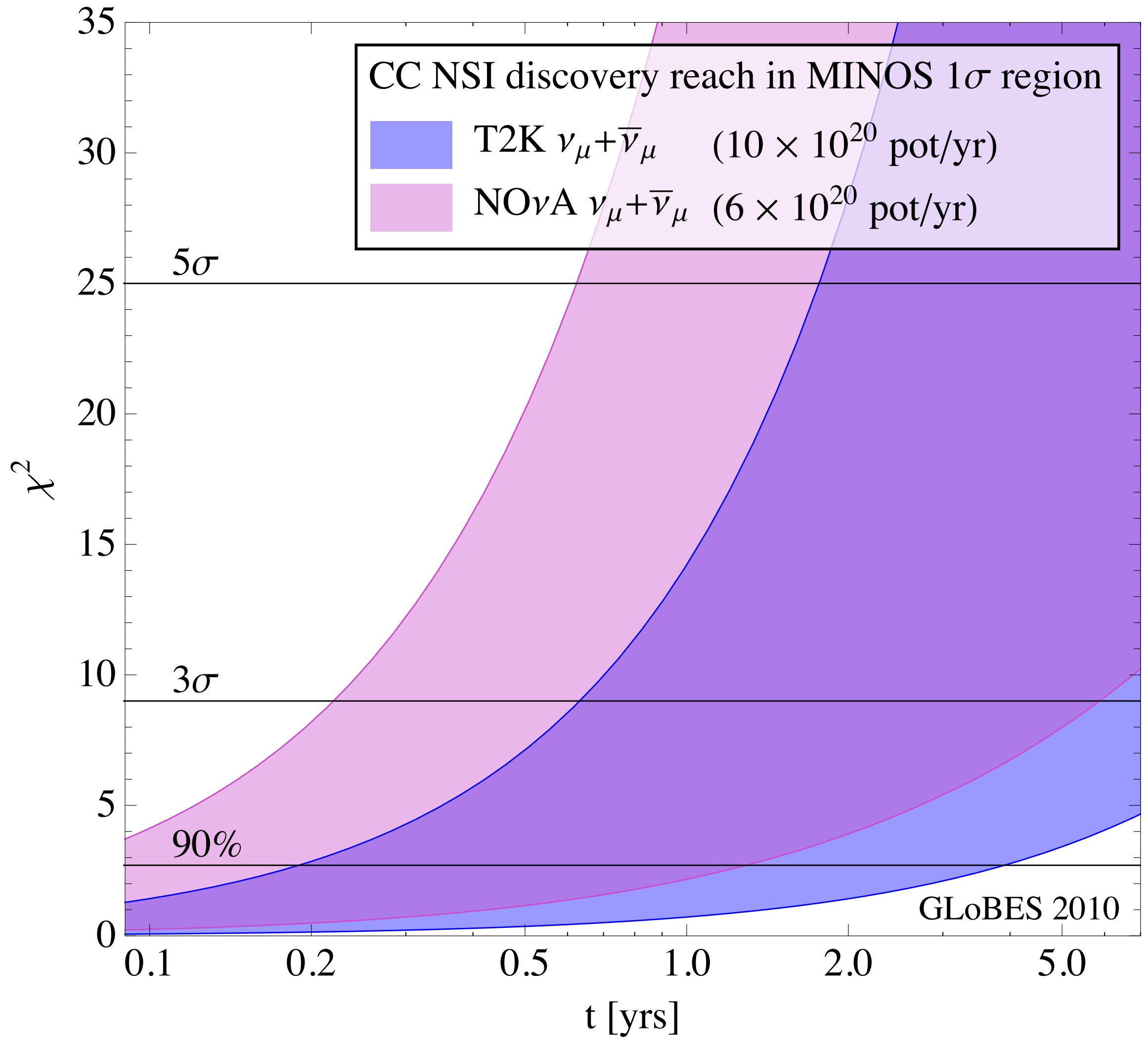


$\nu_\mu \to \nu_\mu$
Events / GeV
Energy (GeV)
$\bar{\nu}_\mu \to \bar{\nu}_\mu$
MINOS
No oscillations
CC NSI best fit
χ^2_{min}/dof = 15.9/15
NC NSI best fit
χ^2_{min}/dof = 12.6/14
Standard best fit
χ^2_{min}/dof = 20.1/17
MINOS data
NC background

CC-NSI in future exp.



CC-NSI in future exp.



Gauge Invariance:

If one imposes SU(2)×U(1) gauge invariance then

$$\epsilon^{d}_{\tau\mu} < \mathcal{O}(10^{-4})$$

see arXiv:1005.0756

The only escape is if our operator is mediated by light particles ($< M_W$)!!!

"Neutrino NSI mediated by light (<< MW), weakly coupled particles—is less well explored in the literature, so a scenario of this type could be responsible for the effects seen by MINOS. This is particularly interesting as models containing light new particles have recently received a lot of attention in the context of Dark Matter searches."

What's interesting MINOS/T2K/NOvA ....

can constrain such operators explicitly!

Conclusions

MINOS anomaly:

- Neutral Current NSI excluded by Atmospheric ν's
- Charge Current NSI can explain the anomaly provide one can evade SU(2)$\times$U(1) gauge invariance. Explicit model needed!
- MINOS/T2K/NOvA... can directly constrain such CC NSI's.