Will MINOS see new physics?

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Ref: N. Kitazawa, HS, and O. Yasuda, hep-ph/0606013

Introduction

Future long-baseline oscillation experiments
search for tiny effects of $\theta_{13},\ \delta,\ \mathrm{sign}(\Delta m^2_{31}),\ \mathrm{etc.}$

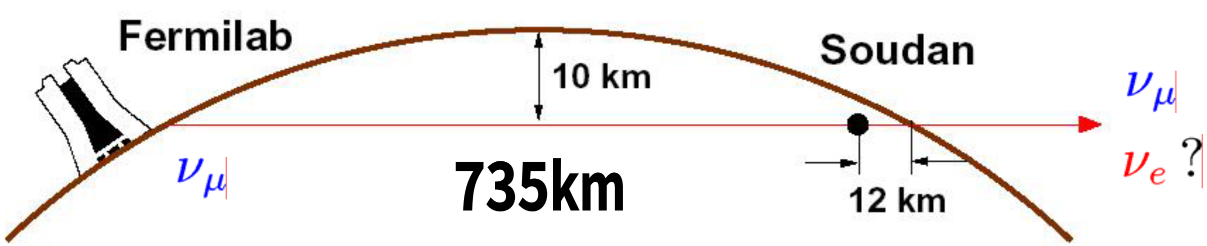
$\longrightarrow$ **high-precision measurements**

Can they see effects of new physics?

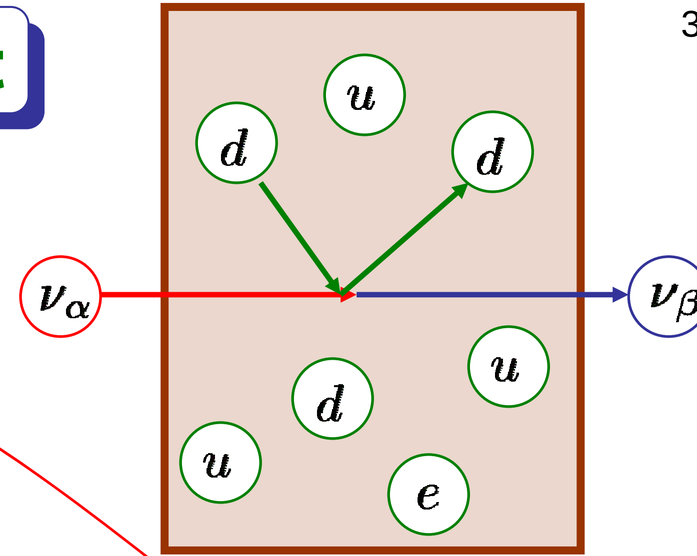
- **non-standard** ν **interaction with source, matter, detector**

We consider non-standard matter effect only.

How is the possibility for ongoing MINOS?



Non-standard matter effect



$$\mathcal{L}_{\text{eff}}^{\text{NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{fP}\,(\overline{\nu}_\alpha\gamma_\rho P_L\nu_\beta)\,(\overline{f}\gamma^\rho P f)$$

$$f = e, u, d \qquad P = P_L, P_R$$

Hamiltonian in flavor basis

$$\mathcal{H} = \frac{1}{2E}U_{\text{MNS}}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix}U_{\text{MNS}}^\dagger + A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

$$\epsilon_{\alpha\beta} \equiv \sum_{f,P}\frac{n_f}{n_e}\epsilon_{\alpha\beta}^{fP} \simeq \sum_P\left(\epsilon_{\alpha\beta}^{eP} + 3\epsilon_{\alpha\beta}^{uP} + 3\epsilon_{\alpha\beta}^{dP}\right)$$

$$A \equiv \sqrt{2}G_F n_e \simeq 1.0\times 10^{-13}\text{eV}\left(\frac{\rho}{2.7\text{g}\cdot\text{cm}^{-3}}\right)$$

ρ **: matter density**

$$\mathcal{H} = \frac{1}{2E} U_{\mathrm{MNS}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U_{\mathrm{MNS}}^{\dagger} + A \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

Low energy
$E \sim 1\mathrm{MeV}$
(ex. reactor)
$\Downarrow$
vacuum osc.
$\Downarrow$
pure measurement of oscillation parameters

Mid energy
$E \sim 1\mathrm{GeV}$
(ex. MINOS)
$\Downarrow$
some effects?
in near future

High energy
$E \sim 10\mathrm{GeV}$
(ex. neutrino factory in far future)
$\Downarrow$
suppression of vacuum osc.
$\Downarrow$
large non-standard effect

Current constraint on $\epsilon_{\alpha\beta}$

no phases for simplicity

constrained stringently by experiments with **charged leptons**??

$SU(2)$

NO! (from phenomenological viewpoint)

ex.: dim-8 op. with higgs

$$(\overline{L}_\alpha P_R H^c)\,\gamma_\rho\,((H^c)^\dagger P_L L_\beta)\,(\overline{f}\gamma^\rho P f) \longrightarrow (\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)\,(\overline{f}\gamma^\rho P f)$$

$$\not\longrightarrow (\overline{l}_\alpha \gamma_\rho P_L l_\beta)\,(\overline{f}\gamma^\rho P f)$$

indep.

constraint by experiments with neutrinos

$$\epsilon_{\alpha\beta} = \begin{pmatrix} -4 < \epsilon_{ee} < 2.6 & |\epsilon_{e\mu}| < 3.8 \times 10^{-4} & |\epsilon_{e\tau}| < 1.9 \\ & -0.05 < \epsilon_{\mu\mu} < 0.08 & |\epsilon_{\mu\tau}| < 0.25 \\ & & |\epsilon_{\tau\tau}| < 1.9 \end{pmatrix}$$

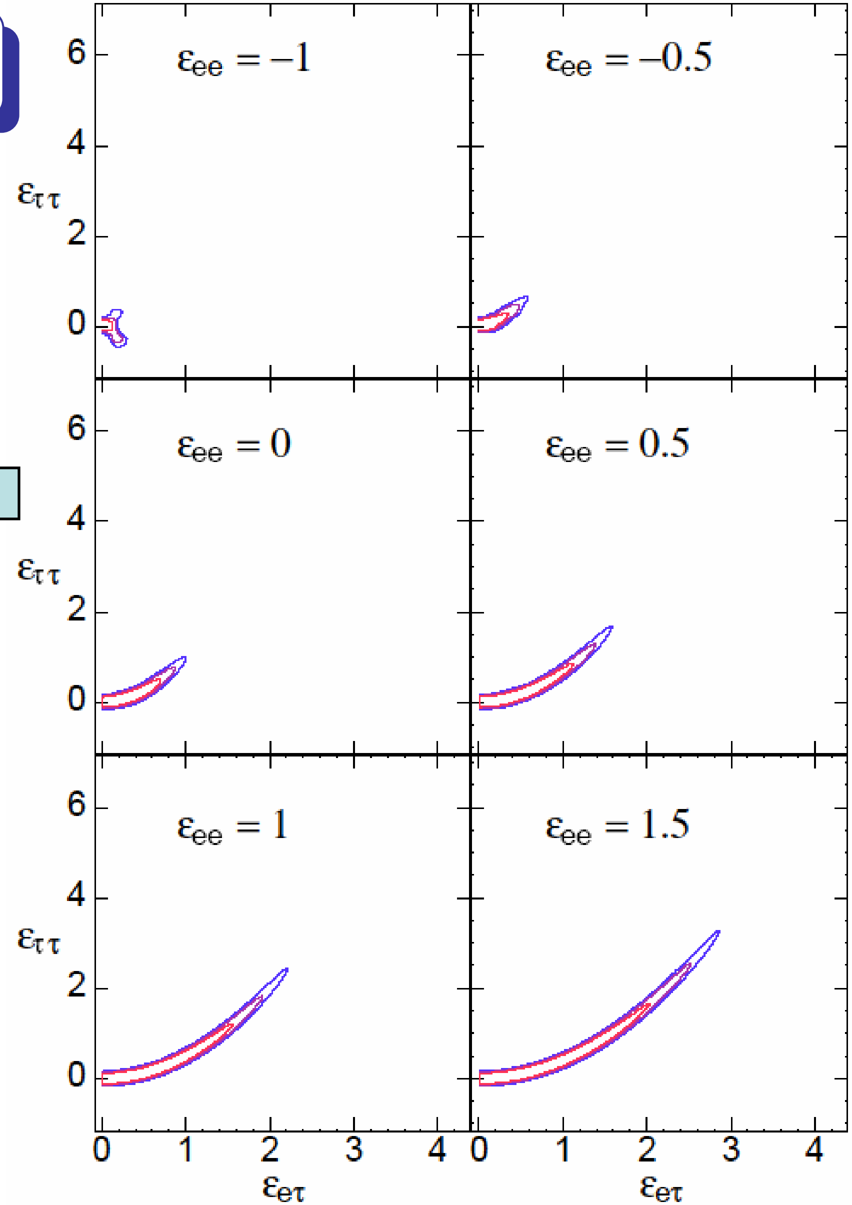
S. Davidson et al., JHEP 0303, 011 (2003)

A. Friedland et al., Phys. Rev. D72, 053009 (2005)

$\boxed{|\epsilon_{\alpha\beta}| \sim 1 \text{ is allowed!!}}$ $\Longrightarrow$ large effect in MINOS?

Constraint with atm. ν and K2K

A. Friedland et al.,
Phys. Rev. D72, 053009 (2005)



We can read off

$$|\epsilon_{e\tau}| < |1 + \epsilon_{ee}|$$

$$\epsilon_{e\tau}^2 \simeq \epsilon_{\tau\tau}(1 + \epsilon_{ee})$$

measured values

$$\sin^2 2\theta_m = 1 \qquad \Delta m_m^2$$

$$\Downarrow$$

true values

$$\sin 2\theta_{23} \simeq \frac{2\cos^2\beta}{1+\cos^2\beta}$$

$$\Delta m_{32}^2 \simeq \frac{1}{2}\left(1 + \frac{1}{\cos^2\beta}\right)\Delta m_m^2 \qquad \tan 2\beta \equiv \frac{2|\epsilon_{e\tau}|}{1 + \epsilon_{ee} - \epsilon_{\tau\tau}}$$

Setup

- three epsilons $\epsilon_{ee},\ \epsilon_{e\tau},\ \epsilon_{\tau\tau}$

$$\epsilon_{e\tau}^2 \simeq \epsilon_{\tau\tau}(1+\epsilon_{ee}) \qquad |\epsilon_{e\tau}| < |1+\epsilon_{ee}|$$

by atmospheric ν and K2K

- no phases

- values of input parameters

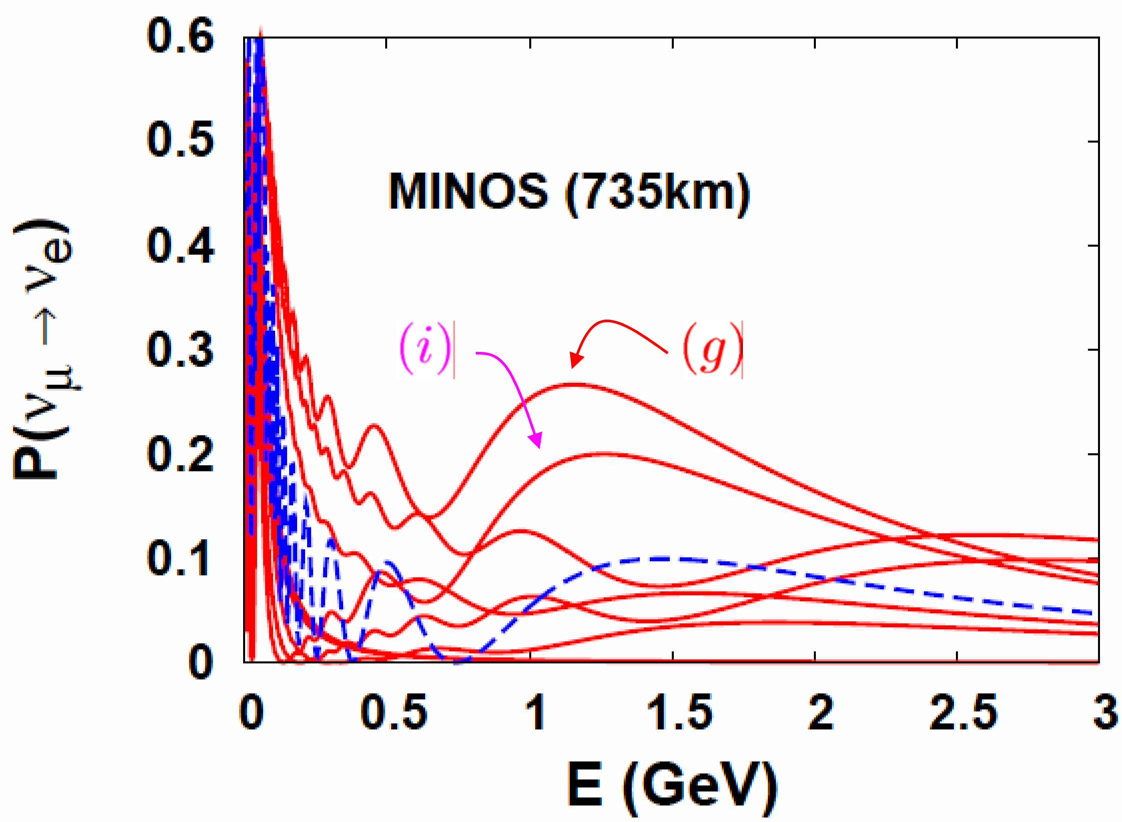
$$\rho = 2.7\mathrm{g}\cdot\mathrm{cm}^{-3},\quad 0 < \Delta m_{31}^2 = 2.5\times10^{-3}\mathrm{eV}^2,\quad \Delta m_{21}^2 = 8\times10^{-5}\mathrm{eV}^2,$$
$$\sin^2 2\theta_{23} = 1,\quad \sin^2 2\theta_{12} = 0.8,\quad 0 \le \sin^2 2\theta_{13} \le 0.16,\quad \delta = 0$$

- ν_e appearance ($\nu_\mu \to \nu_e$ oscillation)

$\longrightarrow$ small "BG" by the standard oscillation

No result for the appearance has been released in MINOS

Oscillation probabilities with $\epsilon_{\alpha\beta} \sim 1$



$\epsilon_{ee}, \epsilon_{e\tau}, \epsilon_{\tau\tau}$

$\sin^2 2\theta_{13} = 0.16, \quad \epsilon = 0$

$\sin^2 2\theta_{13} = 0, \quad \epsilon \neq 0$

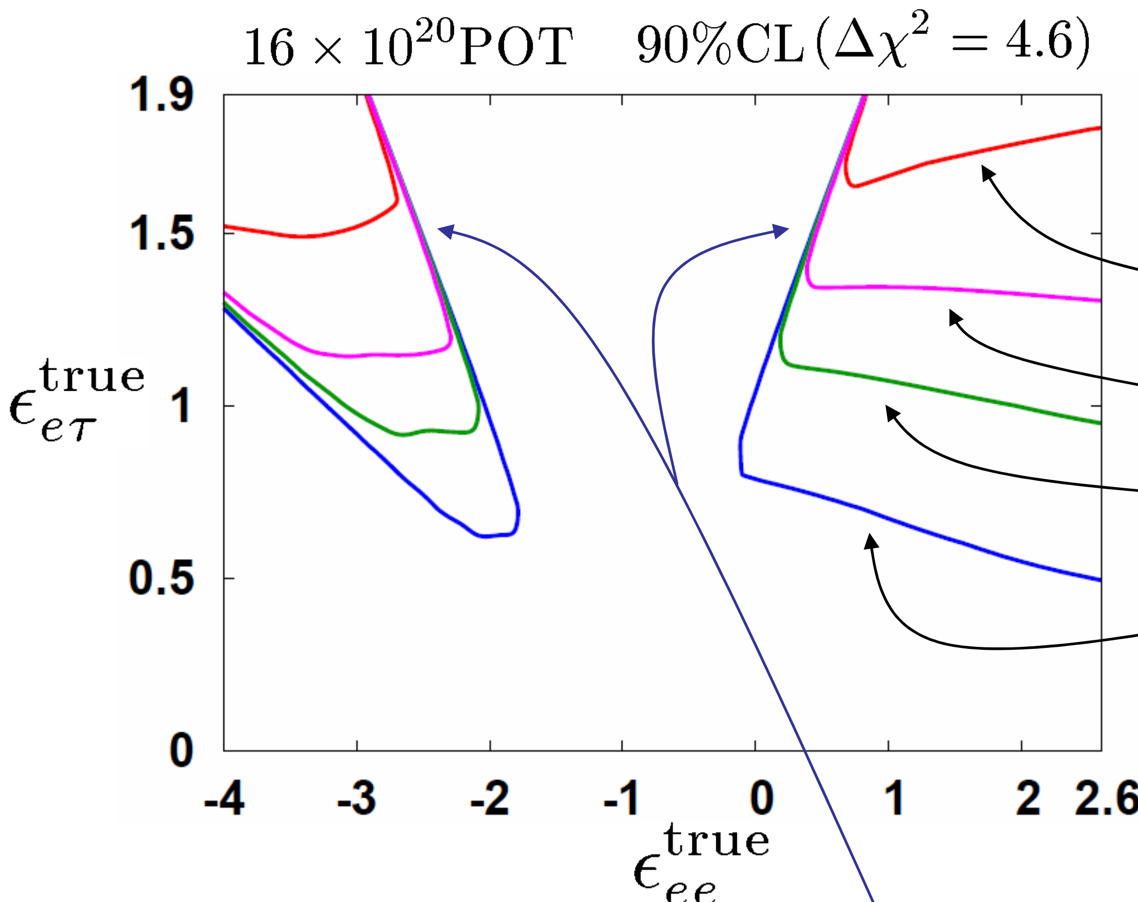
Prob. with $|\epsilon| \sim 1$ can be much larger than standard prob.

significant statistically?

set	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
ϵ_{ee}	-4	-4	-4	0	0	0	2.6	2.6	2.6
$\epsilon_{e\tau}$	-1.9	0	1.9	-1	0	1	-1.9	0	1.9
$\epsilon_{\tau\tau}$	-1.2	0	-1.2	1	0	1	1	0	1

$\epsilon_{e\tau}^2 = \epsilon_{\tau\tau}(1 + \epsilon_{ee})$

Can we exclude $\epsilon_{ee} = \epsilon_{e\tau} = 0$ in MINOS?



cuts of the region in $\epsilon_{ee}^{\mathrm{true}}$-$\epsilon_{e\tau}^{\mathrm{true}}$-$\theta_{13}^{\mathrm{true}}$ space at

$\sin^2 2\theta_{13}^{\mathrm{true}} = 0$

$\sin^2 2\theta_{13}^{\mathrm{true}} = 0.05$

$\sin^2 2\theta_{13}^{\mathrm{true}} = 0.1$

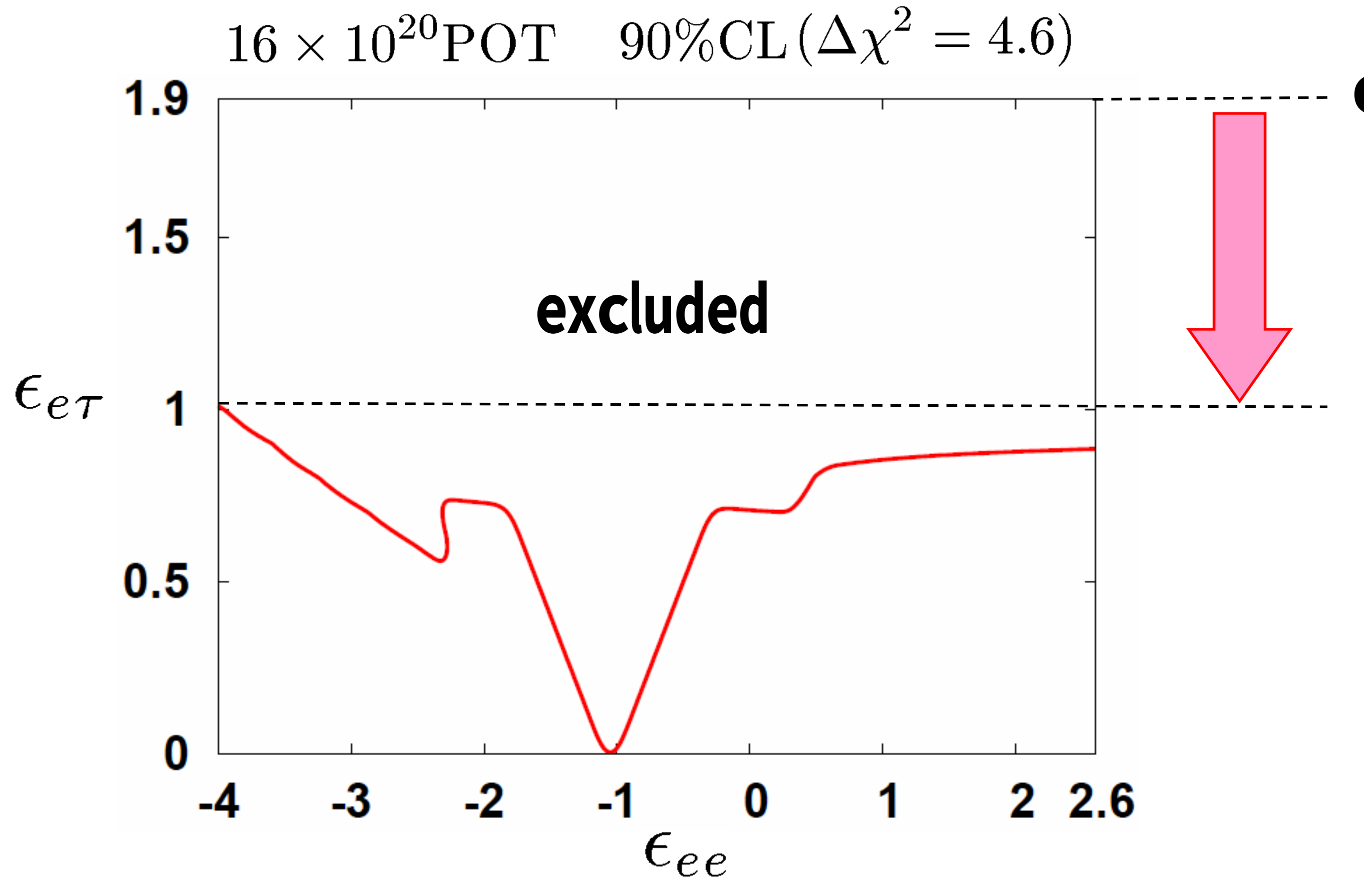
$\sin^2 2\theta_{13}^{\mathrm{true}} = 0.16$

If true values exist within the region,
number of appearance events becomes so large (≥ 70)
that can not be explained by θ_{13} only (≤ 50)

How much can constraint on ϵ be improved?

no ν_e appearance case

$$\epsilon_{ee}^{\rm true} = \epsilon_{e\tau}^{\rm true} = \theta_{13}^{\rm true} = 0$$



If MINOS does not see ν_e appearance,
a constraint is improved form $|\epsilon_{e\tau}| \le 1.9$ to $|\epsilon_{e\tau}| \le 1$

Conclusion

- Even in ongoing MINOS,
  $\epsilon \sim 1$ can give so large number of ν_e appearance
  that can not be explained by θ_{13} only.

  $\Longrightarrow$ We can see that the non-standard effect exists.

- If MINOS does not observe ν_e appearance,
  we can improve a constraint on a non-standard effect.

$$|\epsilon_{e\tau}| \leq 1.9 \xrightarrow[\text{improved}]{} |\epsilon_{e\tau}| \leq 1$$

Let us be looking forward to seeing results of the appearance search in MINOS