Charged NSI in short baseline experiments

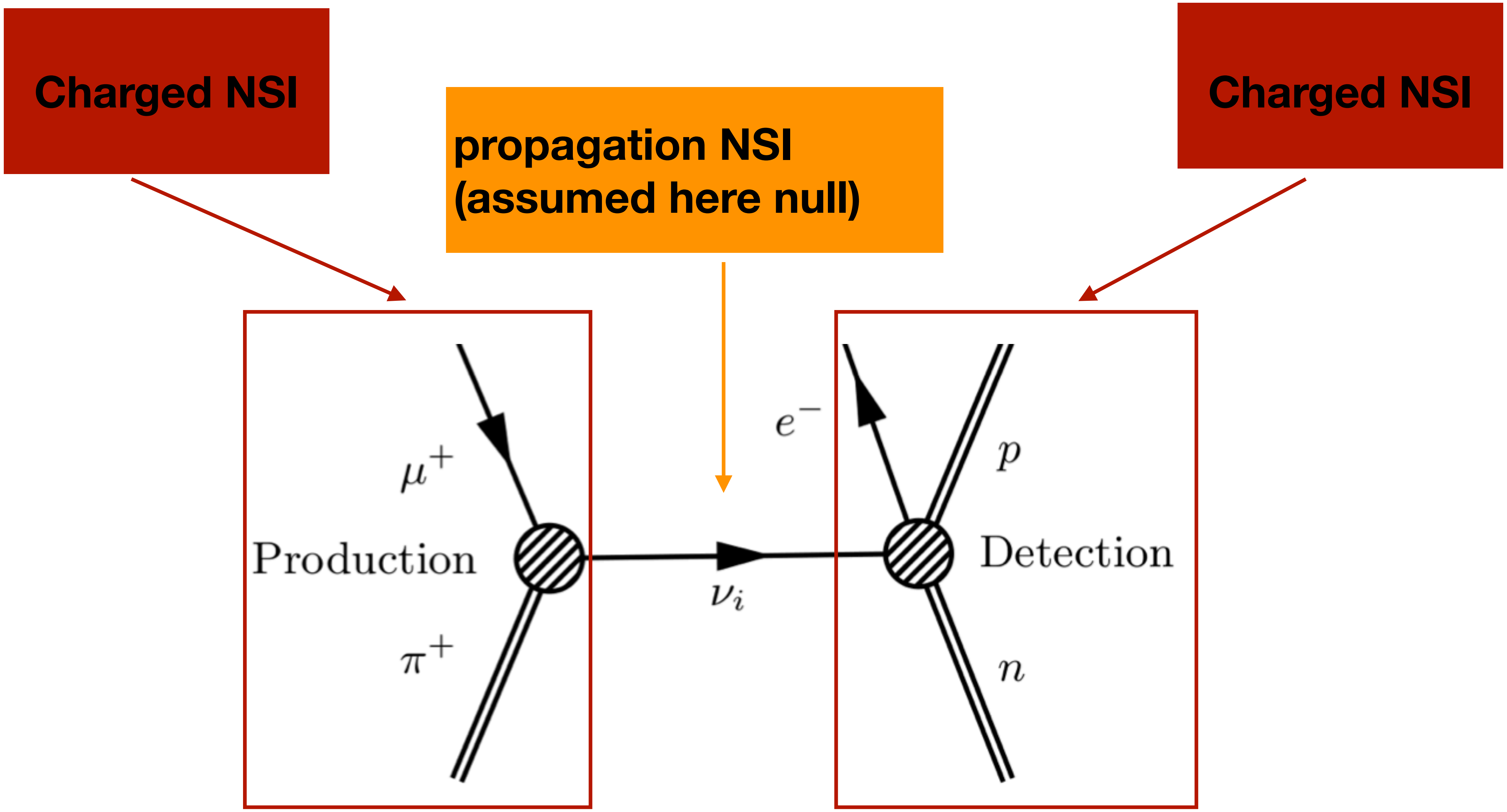
Orlando L. G. Peres
University of Campinas

2nd Short-Baseline Experiment-Theory Workshop April 2-5/24

Cherchiglia, Pasquini, OLGP, Rodrigues, Rossi arxiv:2310.18401

Non-Standard Neutrino Interactions

1991 Guzzo and Masiero
1991 Roulet



Charged NSI

propagation NSI (assumed here null)

Charged NSI

Non-Standard Neutrino Interactions

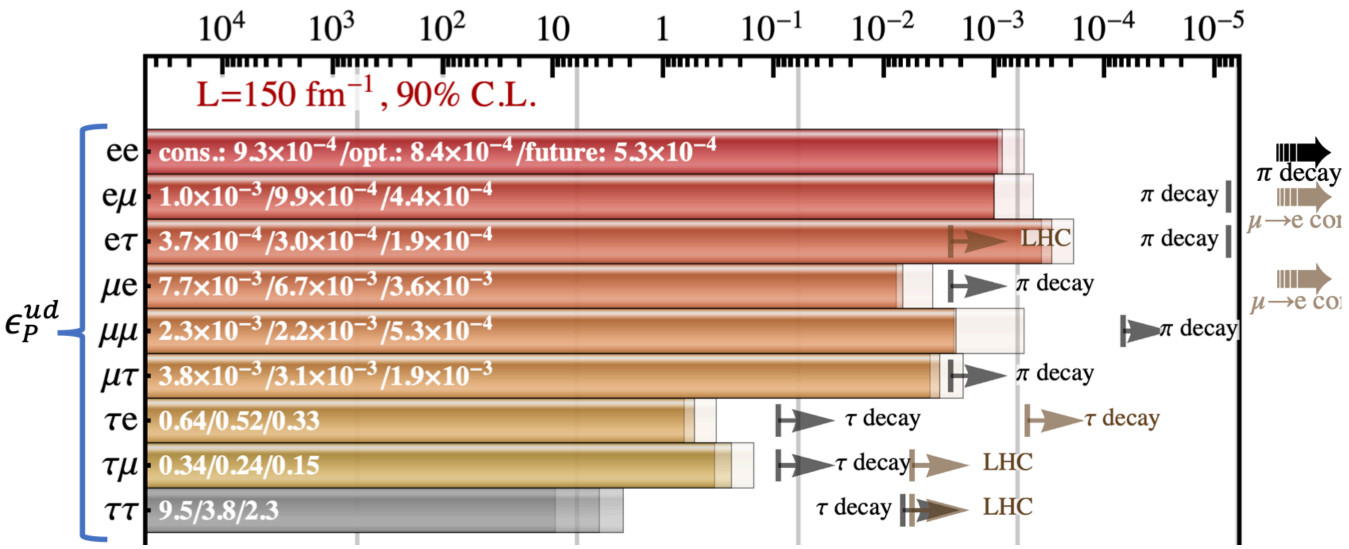
1991 Guzzo and Masiero
1991 Roulet

Charged NSI

A. Falkowski, M. Gonzalez-Alonso, and Z. Tabrizi, JHEP 05, 173, arXiv:1901.04553 316 [hep-ph]

A. Falkowski, M. Gonzalez-Alonso, and Z. Tabrizi, JHEP 11, 048, arXiv:1910.02971 [hep-ph]

Falkowski, Gonzalez-Alonso, Kopp, Soreq and Tabrizi, arxiv:2105.12136

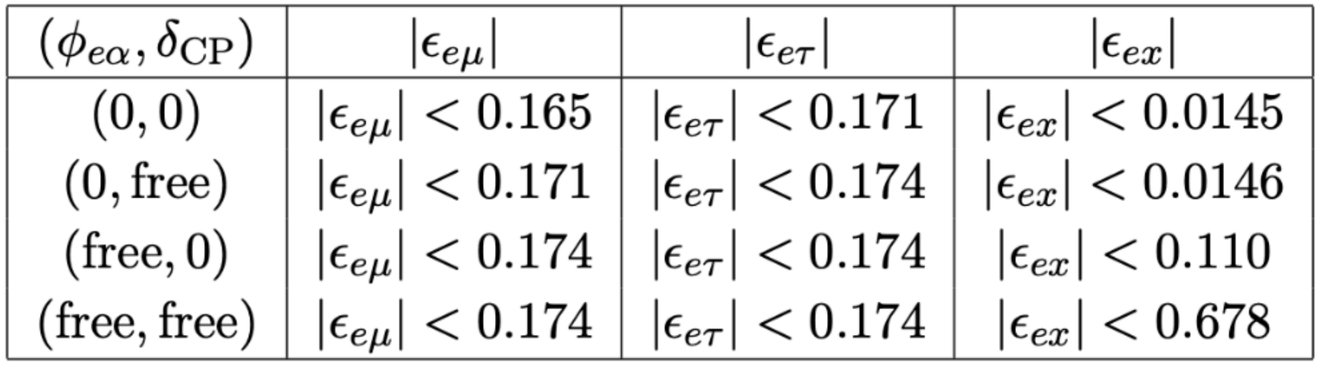


Kopp, Rocco and Z. Tabrizi arxiv:07902 **Zahra Tabrizi** Talk at this conference

Du, Li, Tang, Vihonen and Yu arxiv:2401.02901

Cherchiglia, Pasquini, OLGP, Rodrigues, Rossi arxiv:2310.18401

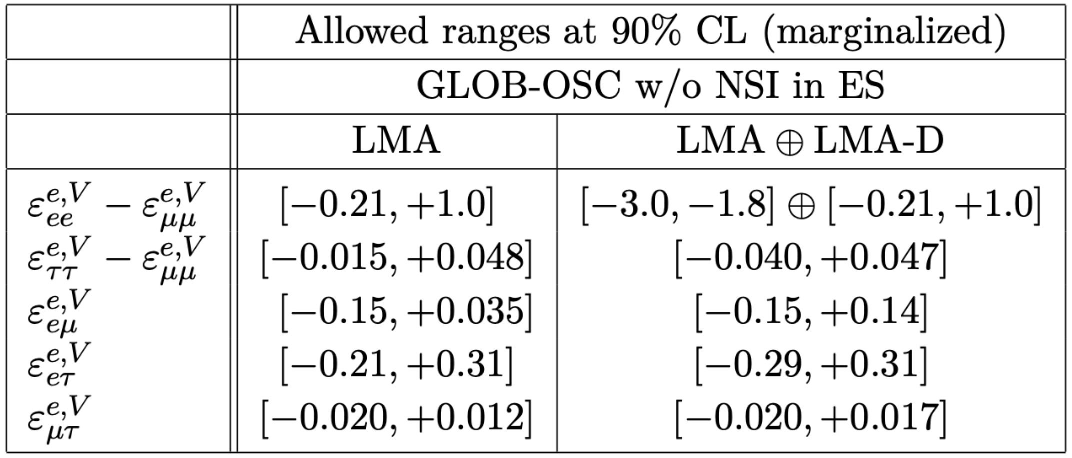
Daya Bay experiment, arxiv:2401.02901



$(\phi_{e\alpha}, \delta_{CP})$	$\lvert\epsilon_{e\mu}\rvert$	$\lvert\epsilon_{e\tau}\rvert$	$\lvert\epsilon_{ex}\rvert$
$(0, 0)$	$\lvert\epsilon_{e\mu}\rvert < 0.165$	$\lvert\epsilon_{e\tau}\rvert < 0.171$	$\lvert\epsilon_{ex}\rvert < 0.0145$
$(0, \text{free})$	$\lvert\epsilon_{e\mu}\rvert < 0.171$	$\lvert\epsilon_{e\tau}\rvert < 0.174$	$\lvert\epsilon_{ex}\rvert < 0.0146$
$(\text{free}, 0)$	$\lvert\epsilon_{e\mu}\rvert < 0.174$	$\lvert\epsilon_{e\tau}\rvert < 0.174$	$\lvert\epsilon_{ex}\rvert < 0.110$
$(\text{free}, \text{free})$	$\lvert\epsilon_{e\mu}\rvert < 0.174$	$\lvert\epsilon_{e\tau}\rvert < 0.174$	$\lvert\epsilon_{ex}\rvert < 0.678$

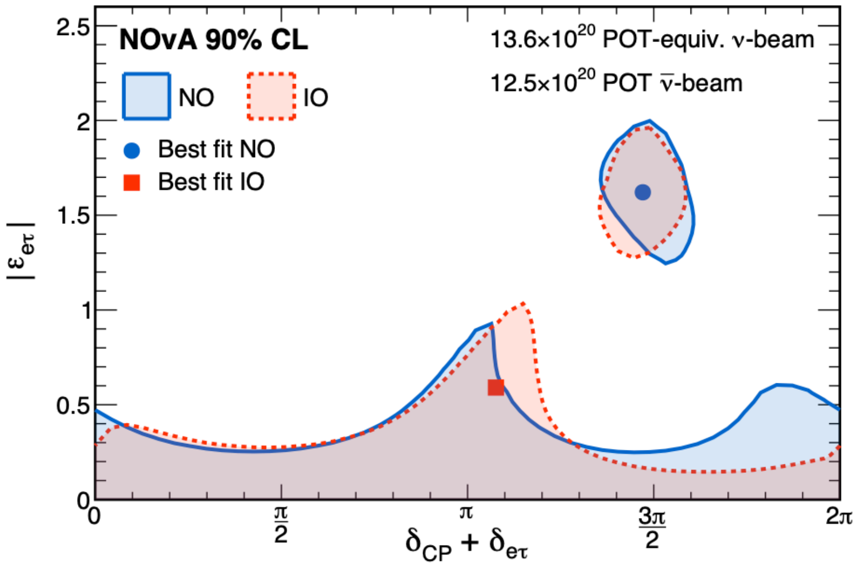
Neutral NSI

Coloma, Gonzalez-Garcia, Maltoni, Pinheiro and Urrea arxiv:2305.07698



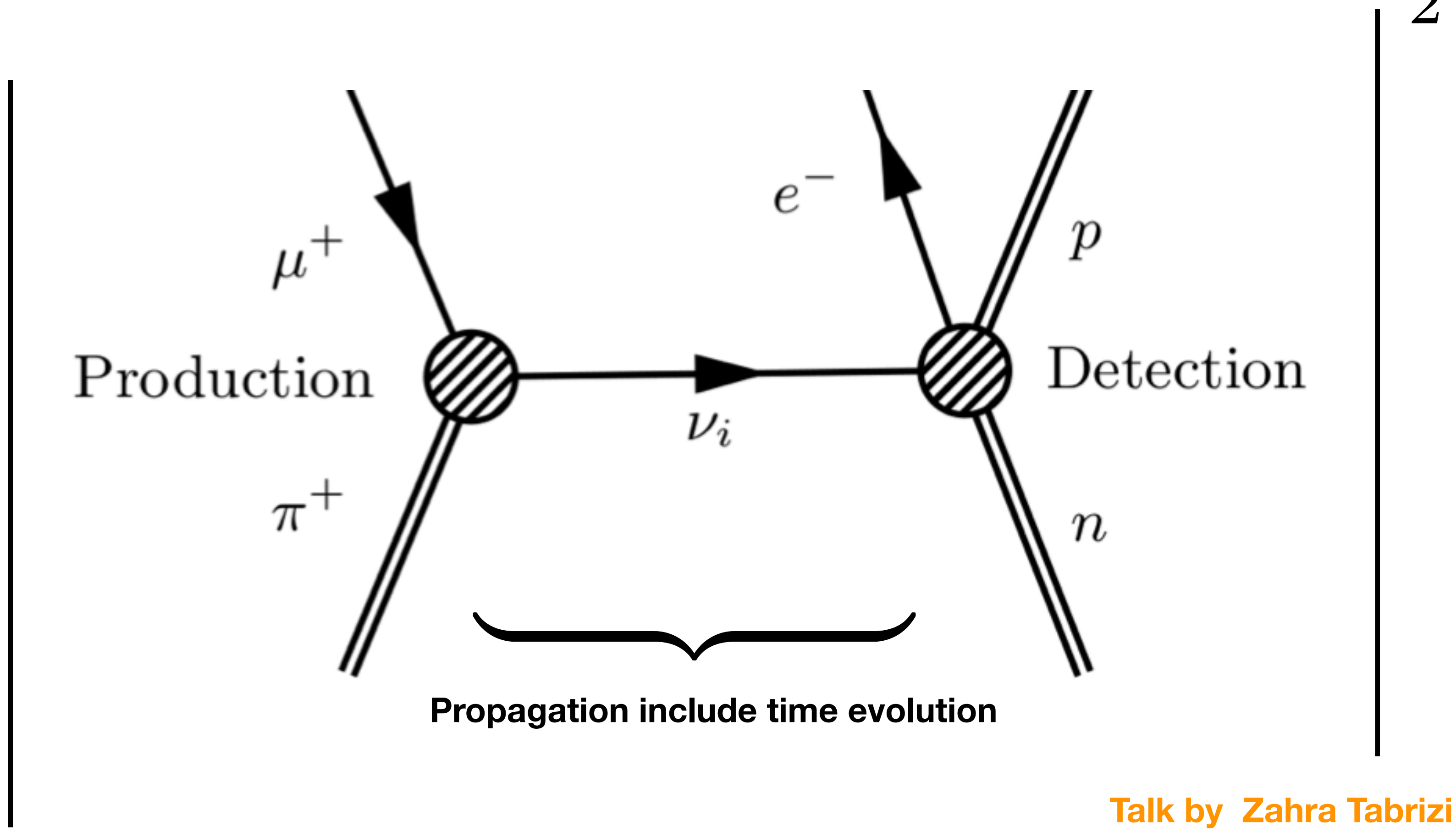
	Allowed ranges at 90% CL (marginalized)	
	GLOB-OSC w/o NSI in ES	
	LMA	LMA ⊕ LMA-D
$\varepsilon_{ee}^{e,V} - \varepsilon_{\mu\mu}^{e,V}$	$[-0.21, +1.0]$	$[-3.0, -1.8] \oplus [-0.21, +1.0]$
$\varepsilon_{\tau\tau}^{e,V} - \varepsilon_{\mu\mu}^{e,V}$	$[-0.015, +0.048]$	$[-0.040, +0.047]$
$\varepsilon_{e\mu}^{e,V}$	$[-0.15, +0.035]$	$[-0.15, +0.14]$
$\varepsilon_{e\tau}^{e,V}$	$[-0.21, +0.31]$	$[-0.29, +0.31]$
$\varepsilon_{\mu\tau}^{e,V}$	$[-0.020, +0.012]$	$[-0.020, +0.017]$

NOVA Acero et al. arxiv:2403.07266



Quantum Field Theory computation of flavor transformation

$$\frac{R^{\mathrm{NSI}}_{\alpha\beta}}{R^{\mathrm{SM}}_{\alpha\beta}} \propto$$



Talk by Zahra Tabrizi on the basics of this procedure

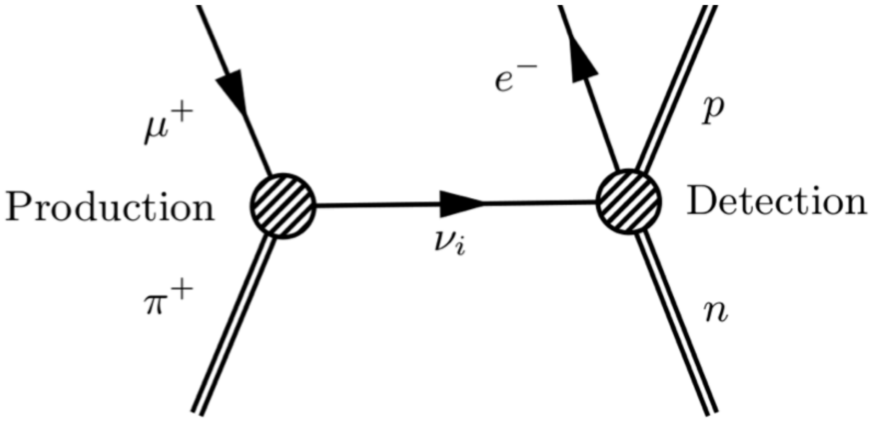
As a proof of concept we will assume a pseudo-scalar interaction

$$\mathcal{L}_{\mathrm{P}} \supset \sqrt{2}\, G_F V^{\mathrm{CKM}}_{ud} \epsilon_{\alpha\beta} \left(\bar{u}\gamma^5 d\right)\left(\bar{\ell}_\alpha P_L \nu_\beta\right) + \mathrm{h.c.}$$

$\epsilon_{\alpha\beta} = |\epsilon_{\alpha\beta}| e^{i\phi_{\mu e}}$ is a complex parameter.

Quantum Field Theory computation of flavor transformation

$$\frac{R^{\text{NSI}}_{\alpha\beta}}{R^{\text{SM}}_{\alpha\beta}} \propto \left| \qquad \right|^2$$



$$= \left| \frac{\mathcal{M}^{\text{osc}}_{\alpha\beta} + \mathcal{M}^{\text{NSI}}_{\alpha\beta}}{\mathcal{M}^{\text{SM}}_{\alpha\beta}} \right|^2 = P^{\text{NSI}}_{\alpha\beta}$$

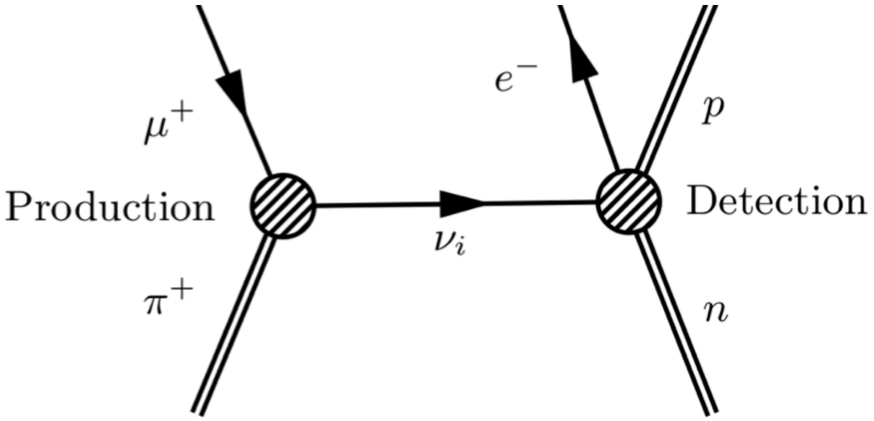
As a proof of concept we will assume a pseudo-scalar interaction

$$\mathcal{L}_{\text{P}} \supset \sqrt{2}\, G_F V^{\text{CKM}}_{ud} \epsilon_{\alpha\beta} \left(\bar{u}\gamma^5 d\right) \left(\bar{\ell}_\alpha P_L \nu_\beta\right) + \text{h.c.}$$

Let's assume a non-zero parameter $\epsilon_{\mu e} = |\epsilon_{\mu e}| e^{i\phi_{\mu e}}$

Quantum Field Theory computation of flavor transformation

$$\frac{R^{\mathrm{NSI}}_{\alpha\beta}}{R^{\mathrm{SM}}_{\alpha\beta}} \propto \Bigg| \quad \Bigg|^2 = P^{\mathrm{NSI}}_{\alpha\beta}$$



How to get the full matter probability? We can solve numerically but we will take advantage to have an analytical computation of this probability.

From Asano and Minakata, JHEP 06, 022 (2011), arXiv:1103.4387 [hep-ph]. We have analytical formulae for usual oscillations,

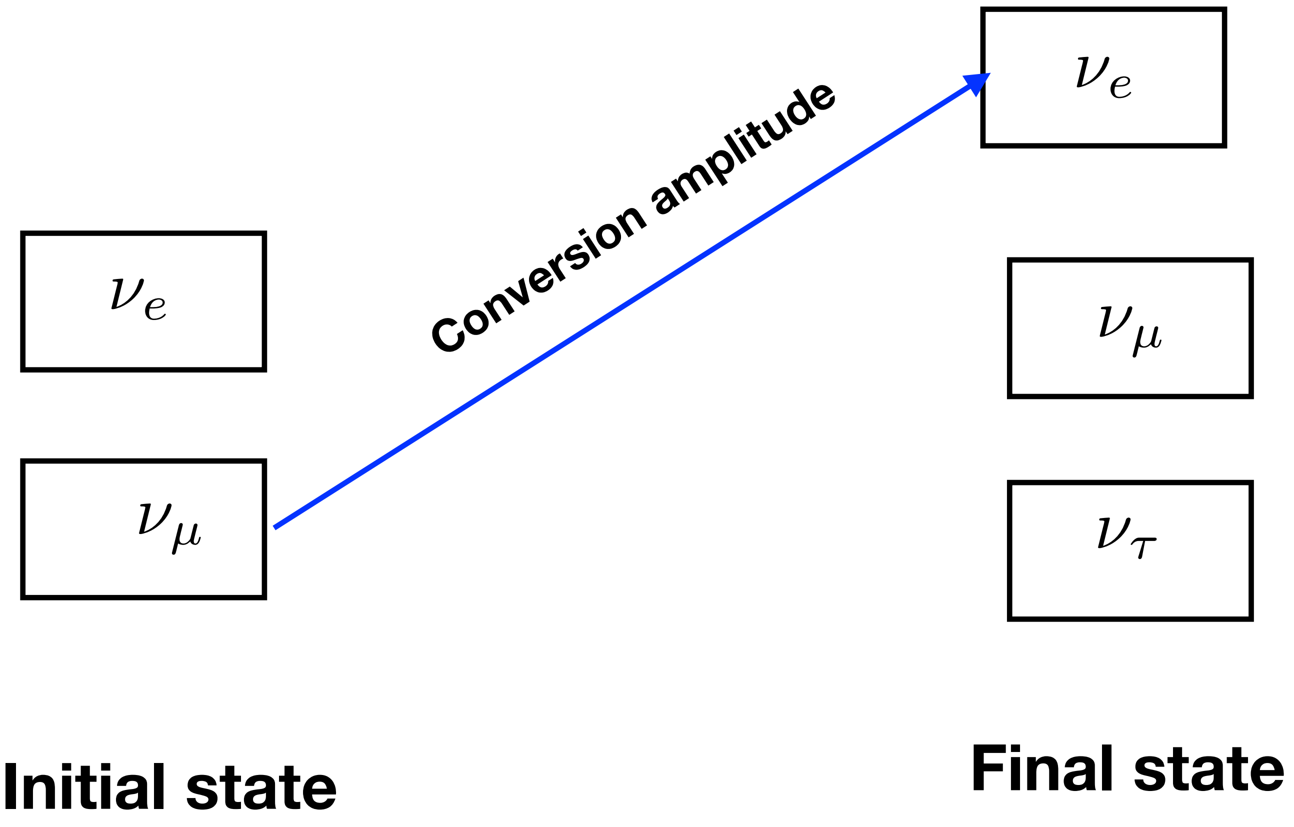
$$P^{\mathrm{OSC}}_{\mu\beta} = \left| S^{\mathrm{OSC}}_{\beta\mu} \right|^2 ,$$

Series solution $\sin\theta_{13}$ $r_\Delta = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$

The Asano-Minakata work with amplitudes, most of other analytical formulae work with probabilities.

Standard oscillation

$\pi^+ \to \mu^+ + \nu_\mu$


ν_e

ν_μ

Conversion amplitude

ν_e

ν_μ

ν_τ

Initial state

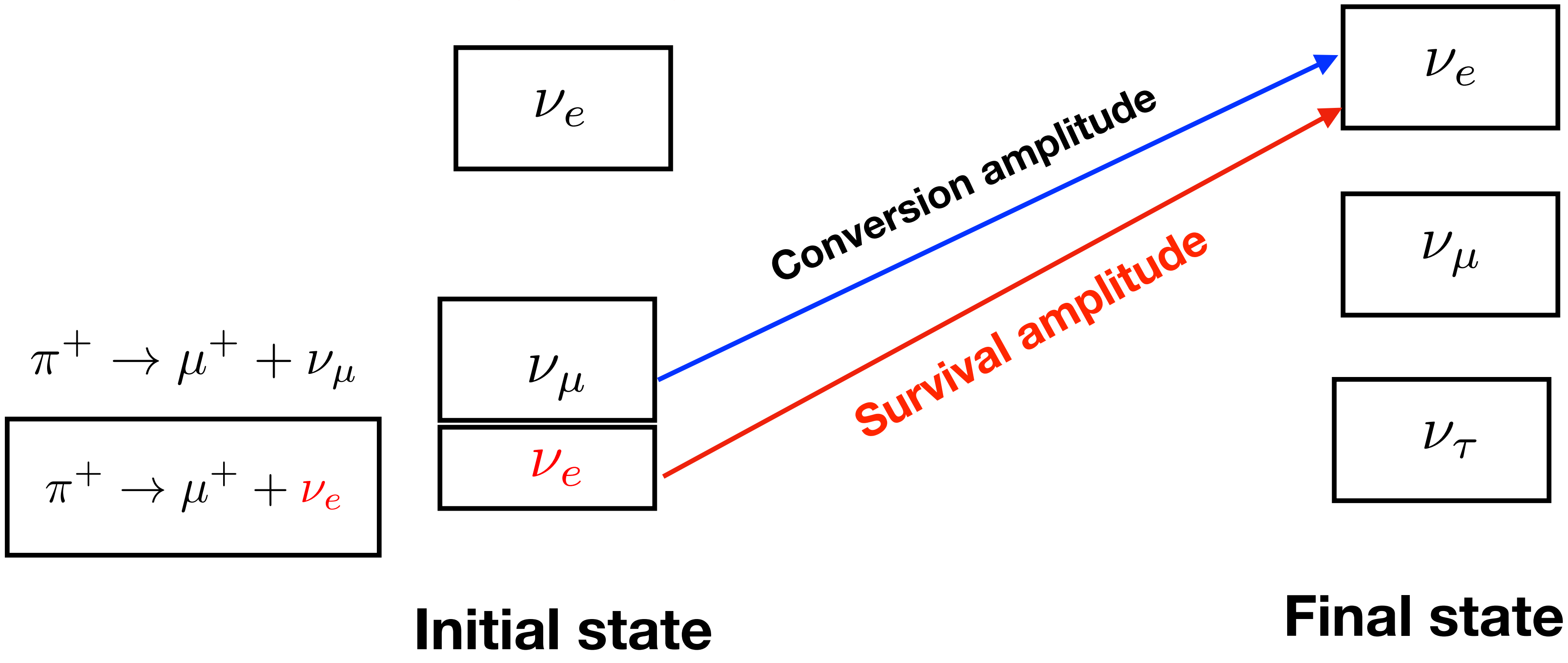
Final state

The full probability with matter effect for three neutrinos

$$P_{\mu\beta}^{\mathrm{OSC}} = \left|S_{\beta\mu}^{\mathrm{OSC}}\right|^2,$$

Series solution $\sin\theta_{13}$ $r_\Delta = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$

Charged NSI $\epsilon_{\mu e} = |\epsilon_{\mu e}| e^{i\phi_{\mu e}}$



$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\pi^+ \rightarrow \mu^+ + \nu_e$

ν_e

ν_μ

ν_e

Conversion amplitude

Survival amplitude

ν_e

ν_μ

ν_τ

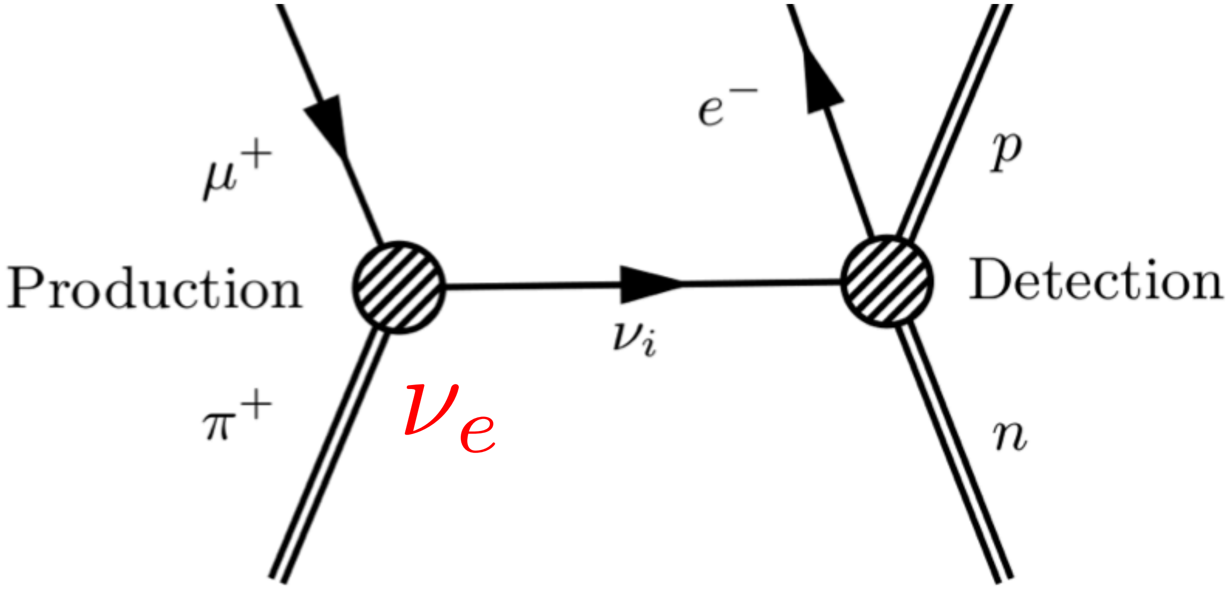
Initial state

Final state

$$P_{\mu e}^{\mathrm{NSI}} = \left| S_{e\mu}^{\mathrm{OSC}} - p_\mu \epsilon_{\mu e}^* S_{ee}^{\mathrm{OSC}} \right|^2 ,$$

Series solution $\sin\theta_{13}$ $r_\Delta = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$

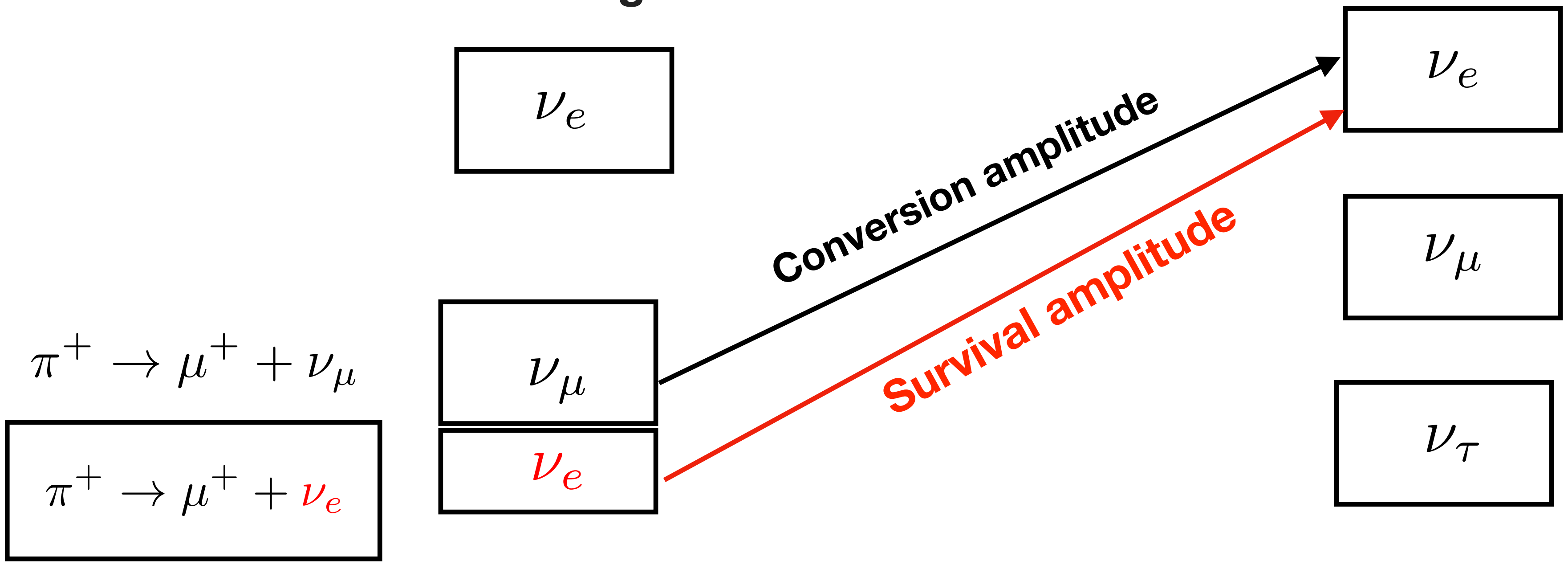
Charged NSI $\epsilon_{\mu e} = |\epsilon_{\mu e}| e^{i\phi_{\mu e}}$



The time evolution for Charged NSI is similar to the time evolution in usual oscillation scenario.

$$P_{\mu e}^{\rm NSI} = \left| S_{e\mu}^{\rm OSC} - p_{\mu} \epsilon_{\mu e}^{*} S_{ee}^{\rm OSC} \right|^2 ,$$

Charged NSI



ν_e

Conversion amplitude

Survival amplitude

$\pi^+ \to \mu^+ + \nu_\mu$

$\pi^+ \to \mu^+ + \nu_e$

ν_μ

ν_e

ν_e

ν_μ

ν_τ

Initial state

Final state

\

$$P^{\mathrm{OSC}}_{\mu\beta} = \left|S^{\mathrm{OSC}}_{\beta\mu}\right|^2 ,$$

CP violation from PMNS mixing matrix

$$P^{\mathrm{NSI}}_{\mu e} = \left|S^{\mathrm{OSC}}_{e\mu} - p_\mu \epsilon^*_{\mu e} S^{\mathrm{OSC}}_{ee}\right|^2 ,$$

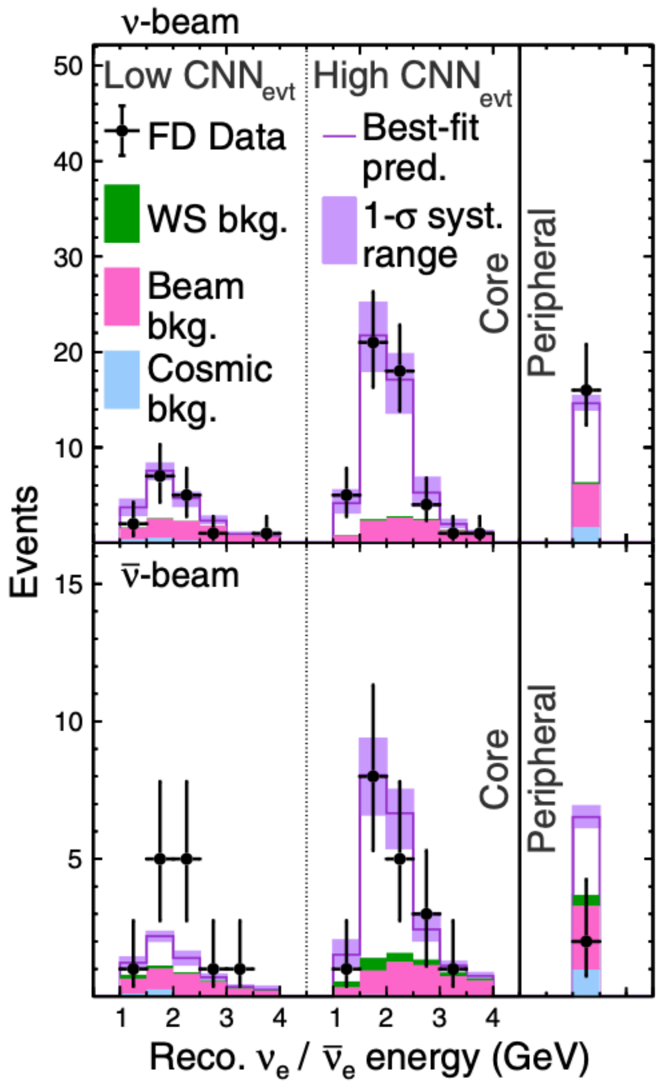
CP violation from $\epsilon_{\mu e}$ phase (“Wolfenstein like”)

As an example of charged NSI application for real data

ν_e **appearance data (NOVA and T2K)**

$$P_{\mu e}^{\mathrm{NSI}} = \left| S_{e\mu}^{\mathrm{OSC}} - p_\mu \epsilon_{\mu e}^{*} S_{ee}^{\mathrm{OSC}} \right|^2 ,$$

NOνA

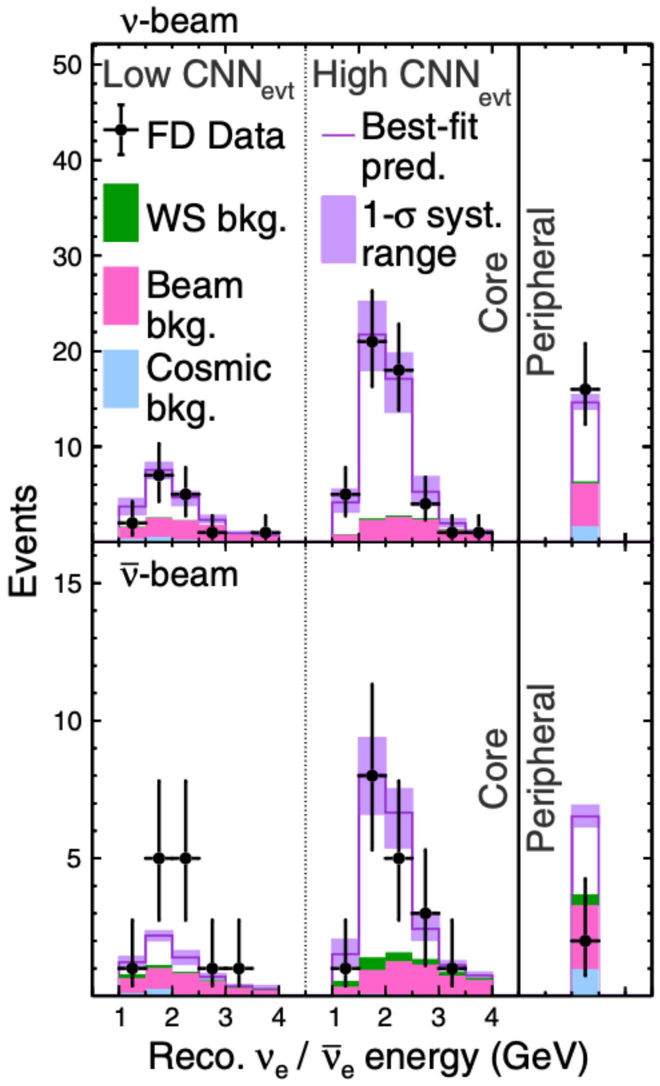


As an example of charged NSI application for real data

ν_e **appearance data**

NOνA

Experiment	
NOVA	
Particle	POT
Neutrinos	13.6×10^{20}
Anti-neutrinos	12.5×10^{20}
T2K	
Particle	POT
Neutrinos	14.7×10^{20}
Anti-neutrinos	16.4×10^{20}

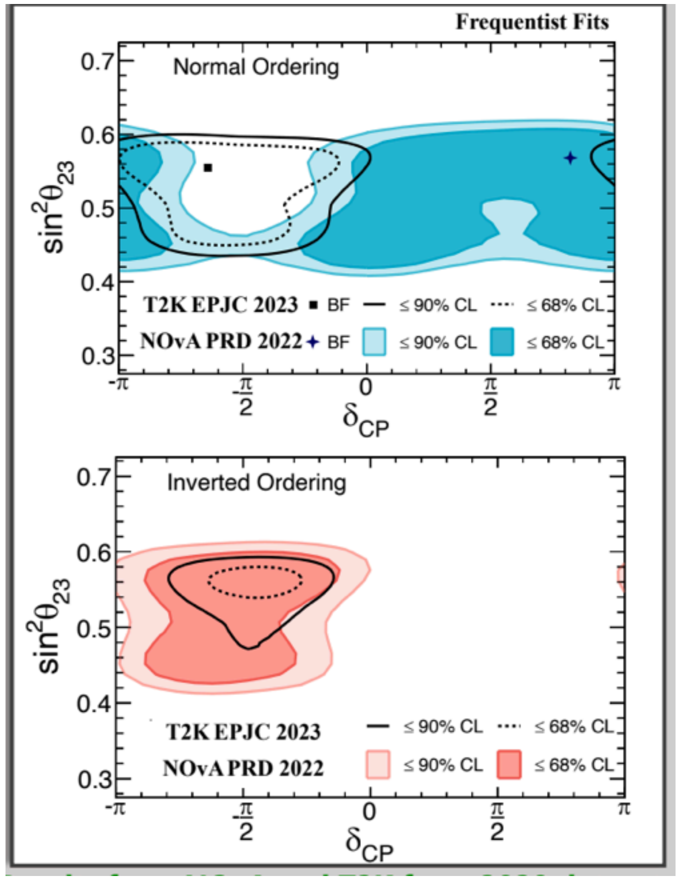


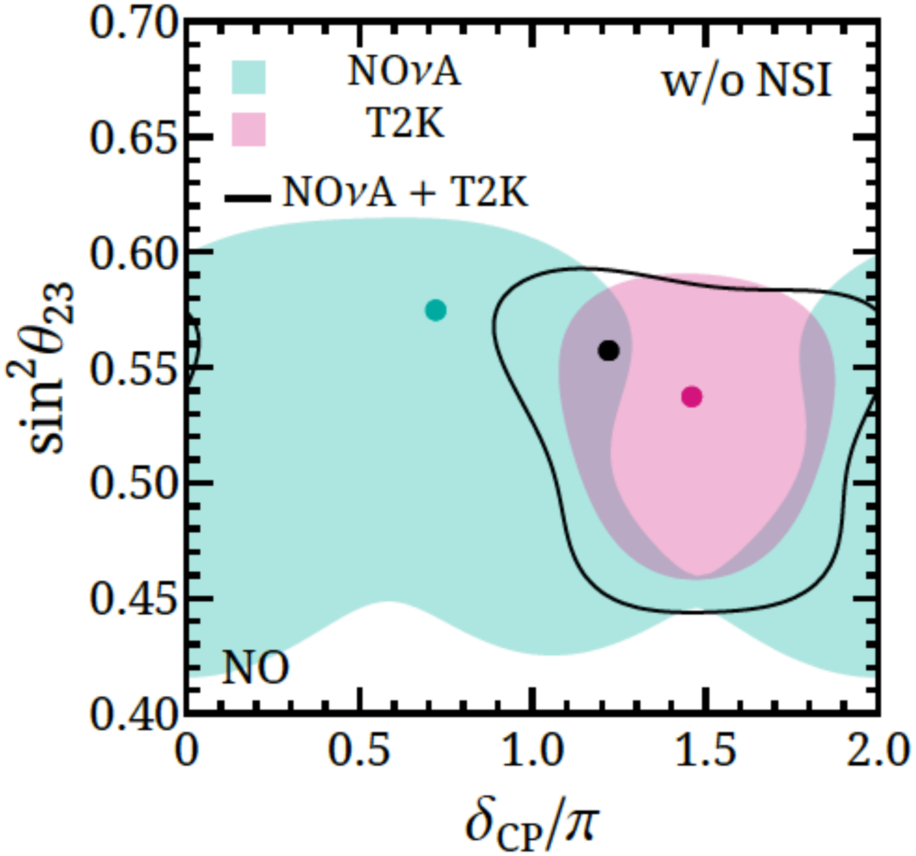
GLOBES to simulate the electron/muon neutrino (anti-neutrino).

Priors: $\sin^2 2\theta_{13} = 0.083 \pm 0.0031$

We fixed $\Delta m^2_{21} = 7.53 \times 10^{-3} \mathrm{eV}^2$ $\quad \sin^2\theta_{12} = 0.307$

Tension between T2K and NOVA (?!)



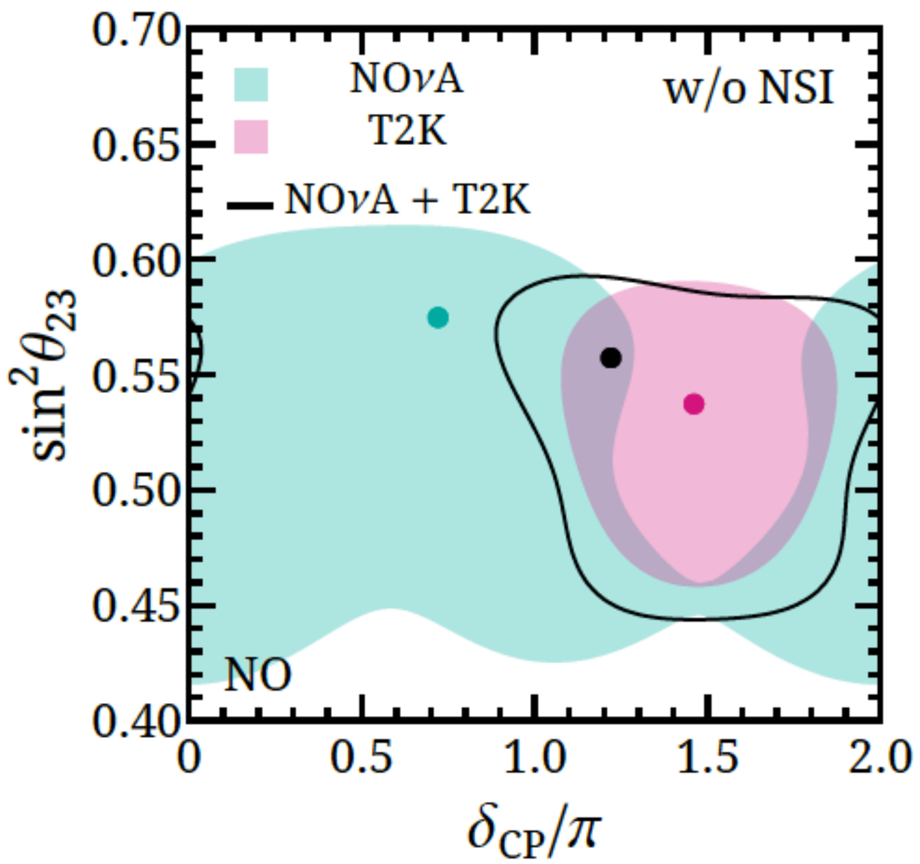


T2K and NOVA results

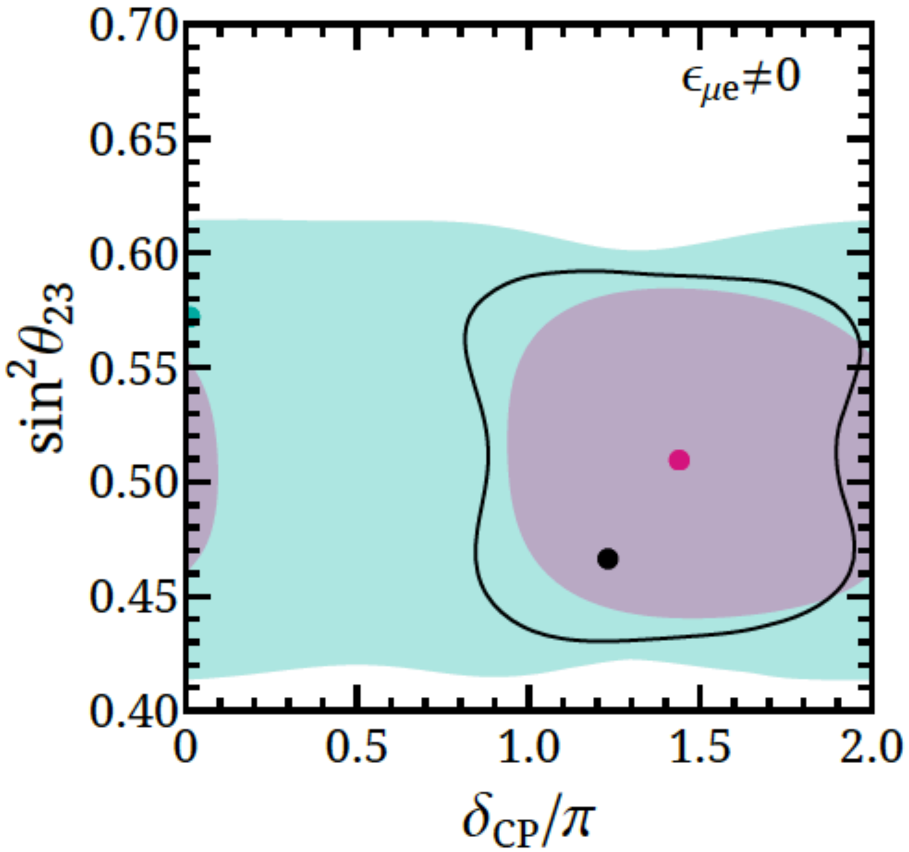
Our results for T2K and NOVA data

What happen when we switch on the charged NSI?

Charged NSI X Standard oscillation



Standard Oscillation



Charged NSI

First terms of the probability,

Standard oscillation CP violating factor

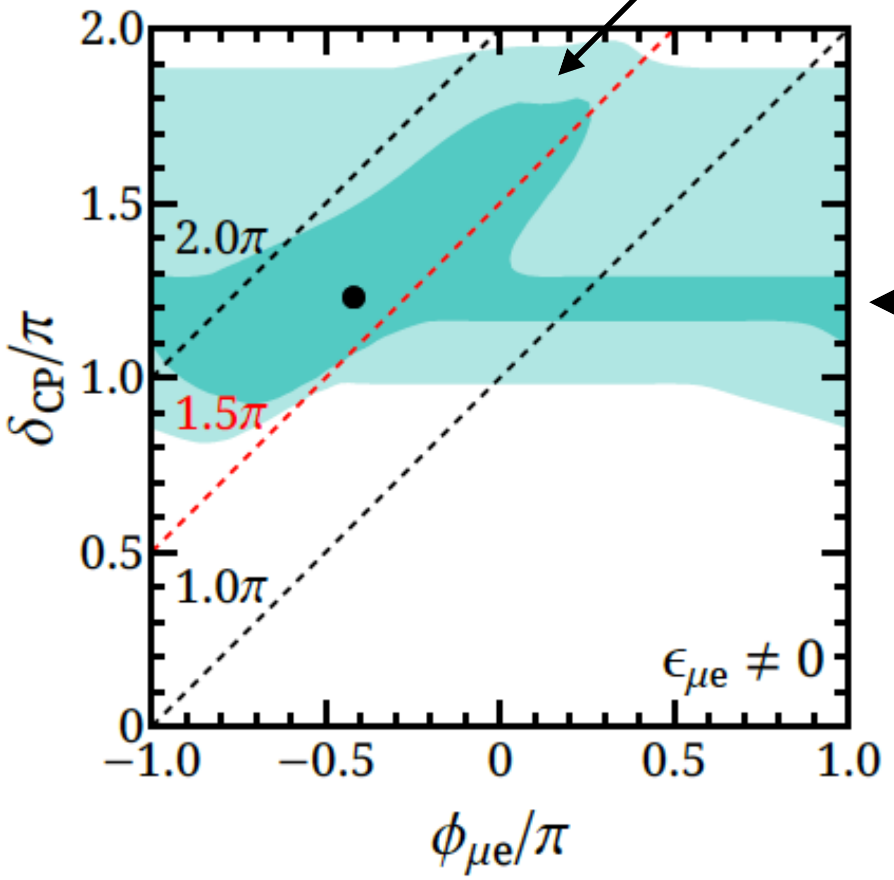
$$\frac{\Delta L}{2} \equiv \frac{\Delta m_{31}^2 L}{4E_\nu}$$

$$P_{\mu e}^{\rm NSI} = 4\frac{s_{13}^2 s_{23}^2}{(1-r_a)^2}\sin^2\frac{(1-r_a)\Delta L}{2} + \frac{8J_r r_\Delta}{r_a(1-r_a)}\boxed{\cos\left(\delta_{\rm CP}+\frac{\Delta L}{2}\right)}\sin\frac{r_a\Delta L}{2}\sin\frac{(1-r_a)\Delta L}{2}$$
$$+ p_\mu^2|\epsilon_{\mu e}|^2 + 4p_\mu|\epsilon_{\mu e}|\frac{s_{13}s_{23}}{1-r_a}\sin\left(\frac{(1-r_a)\Delta L}{2}\right)\boxed{\sin\left(\delta_{\rm CP}-\phi_{\mu e}+\frac{(1-r_a)\Delta L}{2}\right)} + \mathcal{O}(r_\Delta, s_{13}^2)\,.$$

Charged NSI oscillation CP violating factor

Charged NSI CP violation

What happened to the CP phases?



Charged NSI case

Standard oscillation limit

Standard Oscillation

Charged NSI

First terms of the probability,

Standard oscillation CP violating factor

$$\frac{\Delta L}{2} \equiv \frac{\Delta m_{31}^2 L}{4E_\nu}$$

$$P_{\mu e}^{\rm NSI} = 4\frac{s_{13}^2 s_{23}^2}{(1-r_a)^2}\sin^2\frac{(1-r_a)\Delta L}{2} + \frac{8J_r r_\Delta}{r_a(1-r_a)}\boxed{\cos\left(\delta_{\rm CP}+\frac{\Delta L}{2}\right)}\sin\frac{r_a\Delta L}{2}\sin\frac{(1-r_a)\Delta L}{2}$$
$$+ p_\mu^2|\epsilon_{\mu e}|^2 + 4p_\mu|\epsilon_{\mu e}|\frac{s_{13}s_{23}}{1-r_a}\sin\left(\frac{(1-r_a)\Delta L}{2}\right)\boxed{\sin\left(\delta_{\rm CP}-\phi_{\mu e}+\frac{(1-r_a)\Delta L}{2}\right)} + \mathcal{O}(r_\Delta, s_{13}^2)\,.$$

Charged NSI oscillation CP violating factor

ν_τ appearance

There are different scenarios where ν_τ appearance can be a signal for BSM

Standard Oscillation

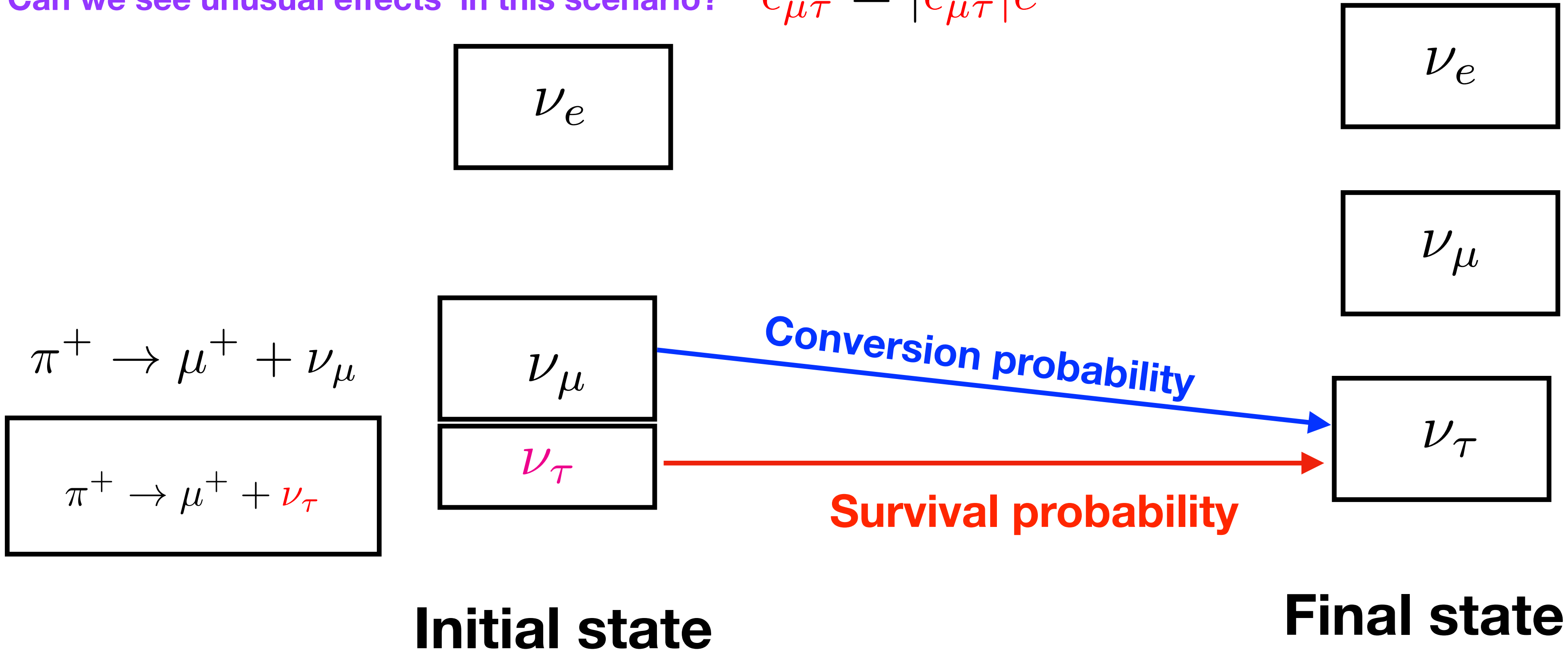
	ν_τ appearance
far detector	yes
near detector	no

BSM scenario

3+1 sterile scenario
non-unitarity
neutral NSI scenario (propagation)
light boson

	ν_τ appearance
far detector	yes
near detector	yes

Can we see unusual effects in this scenario? $\epsilon_{\mu\tau} = |\epsilon_{\mu\tau}| e^{i\phi_{\mu\tau}}$



ν_e

$\pi^+ \to \mu^+ + \nu_\mu$

ν_μ

Conversion probability

$\pi^+ \to \mu^+ + \nu_\tau$

ν_τ

Survival probability

Initial state

ν_e

ν_μ

ν_τ

Final state

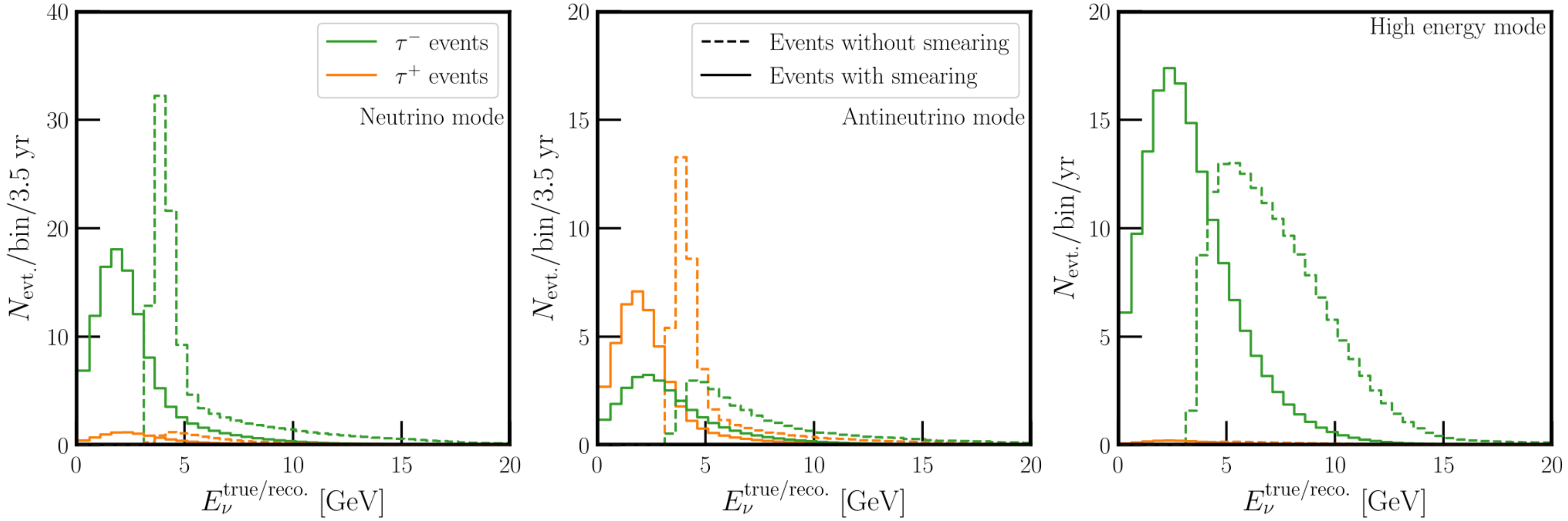
ν_τ **appearance**

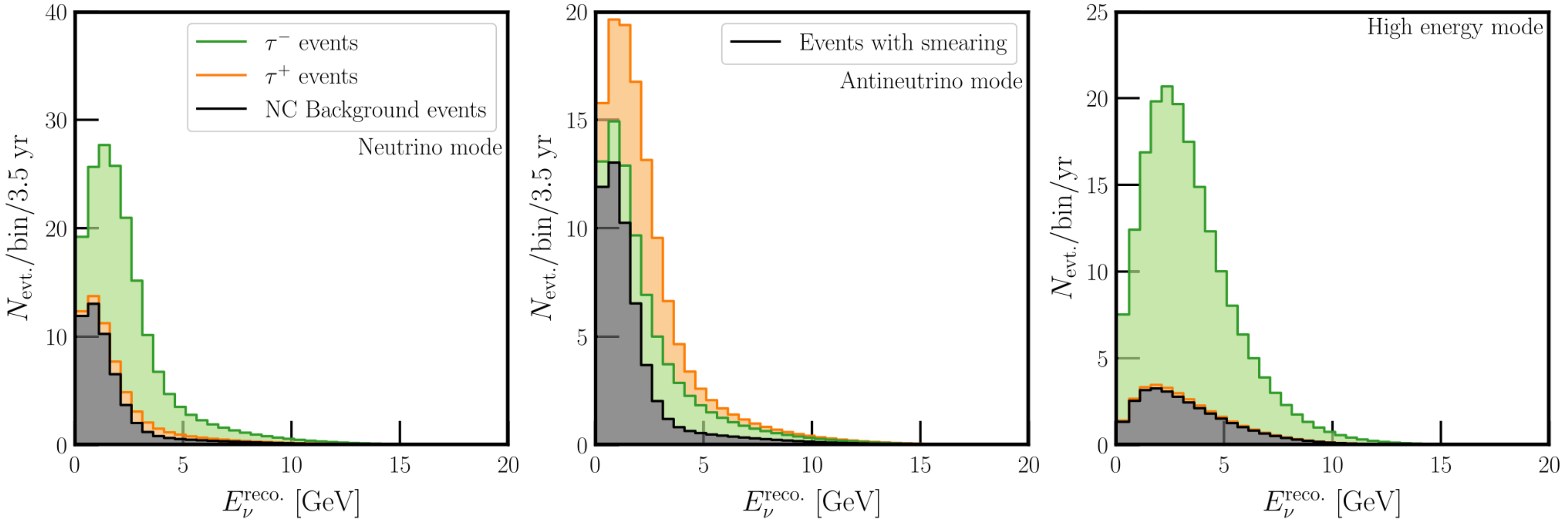
$$P_{\mu\tau}^{\mathrm{NSI}} = \left| S_{\tau\mu}^{\mathrm{OSC}} - p_\mu \epsilon_{\mu\tau}^* S_{\tau\tau}^{\mathrm{OSC}} \right|^2 ,$$

ν_τ appearance , we follow

- A. De Gouvea, K. Kelly, G. V. Stenico and P. Pasquini, *Phys.Rev.D* 100 (2019) 1, 016004 • e-Print: 1904.07265 [hep-ph]

Tau neutrino appearance in DUNE (from de Gouvea)

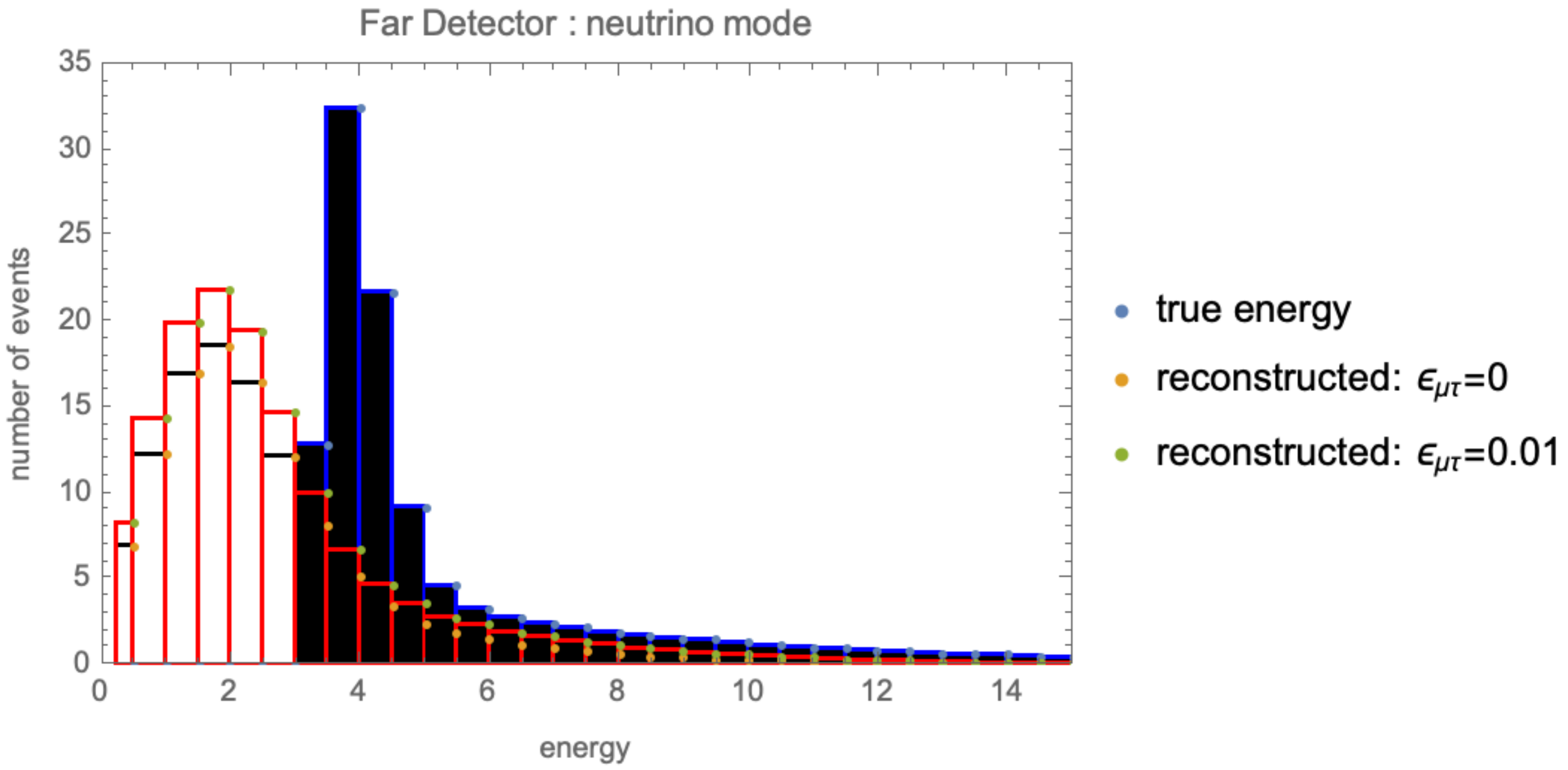




Normalization uncertainty, NC background included

Tau neutrino appearance in far neutrino detector at DUNE with charged NSI

(work in progress, far detector)



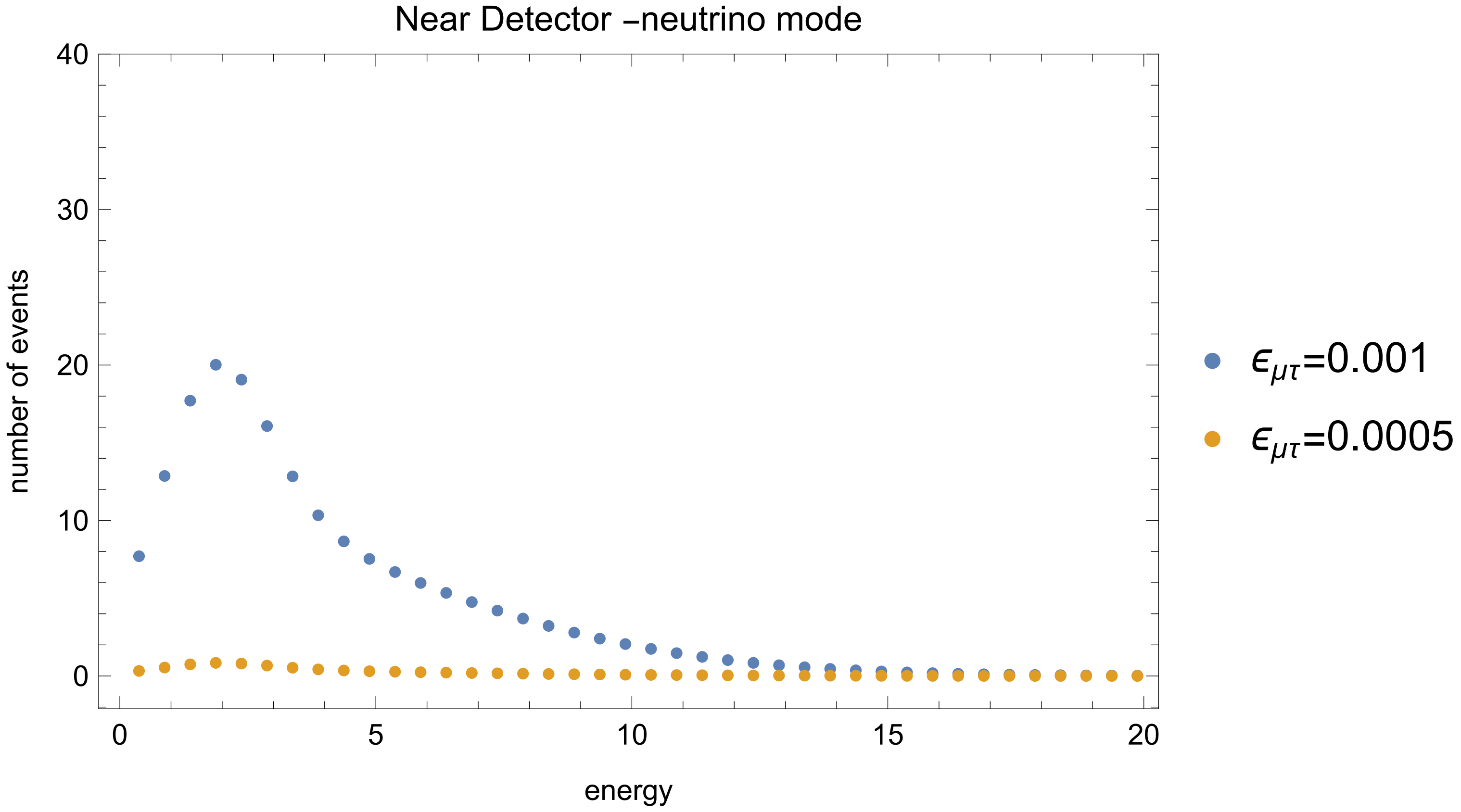
With the same assumptions we can reach $\epsilon_{\mu\tau} < 6.7 \times 10^{-3} \quad 90\% \mathrm{C.L.}$

The projected sensitivity from FASER is $\epsilon_{\mu\tau} < 3.8 \times 10^{-3} \quad 90\% \mathrm{C.L.}$

Still working in progress, effects of charged NSI in muon disappearance not included

Similar for Tau neutrino appearance in near neutrino detector **(work in initial state, near detector)**

Not yet fully polished, different assumptions from far detector



the NC estimation still ongoing.

We can get a conservative value of $\epsilon_{\mu\tau} = 1 \times 10^{-4}$

$$P_{\mu\tau}^{\mathrm{NSI}} = \left| S_{\tau\mu}^{\mathrm{OSC}} - p_\mu \epsilon_{\mu\tau}^* S_{\tau\tau}^{\mathrm{OSC}} \right|^2 ,$$

Conclusions

NSI for neutrinos is a interesting topic of interest in neutrino phenomenology

Charged NSI can have different behavior of propagation NSI

New source of CP violation from charged NSI, can change the results of appearance experiments

Charged NSI with taus can induce tau neutrino appearance in far and near detector

My question: Usually in LBL, electron neutrino came from three-body decay.
In the charged NSI (NSI at source) electron neutrino can came from two-body decay.
this can help discriminate ?