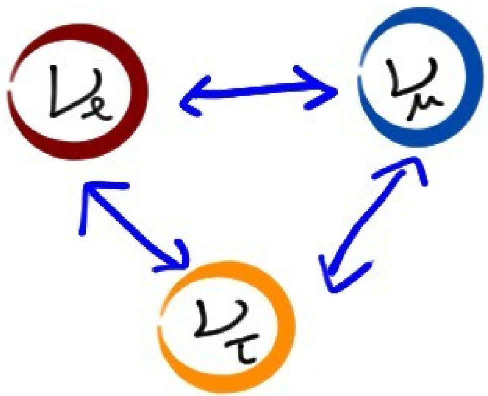
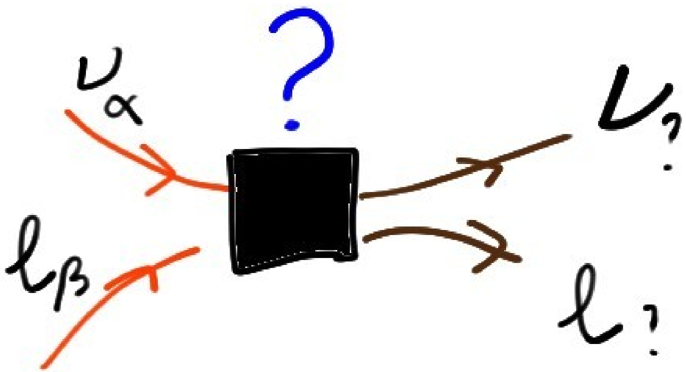
On the sources of CP violation in the Lepton Sector





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EPS-HEP2021

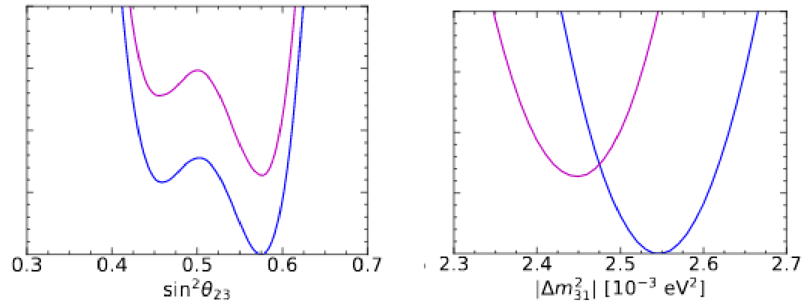
26-30 July 2021

Current experimental situation

de Salas et a.
JHEP02 (2021),071

Capozzi et al.,
arXiv:2107.00532

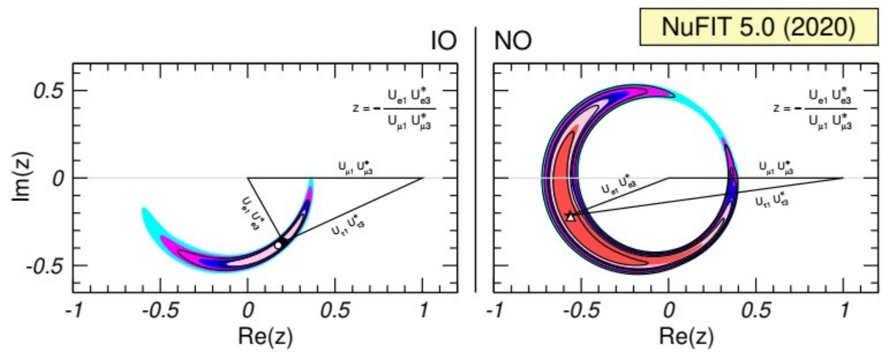
atmospheric sector



problem of the θ_{23} octant

problem of the mass ordering

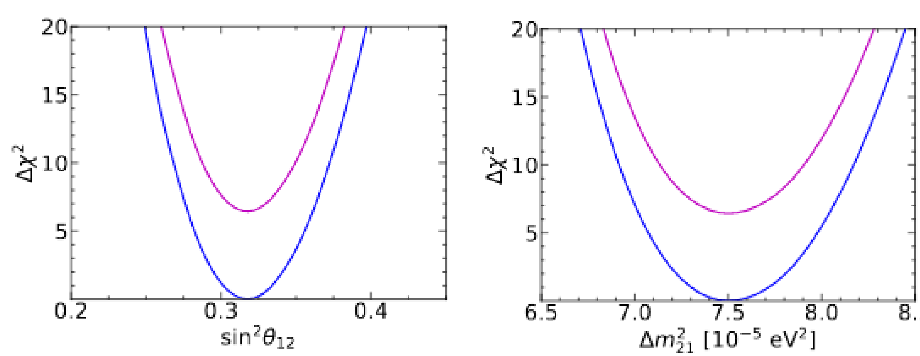
reactor sector



Existence of CP violation in the lepton sector (?)

Esteban et al.,
JHEP 09 (2020), 178

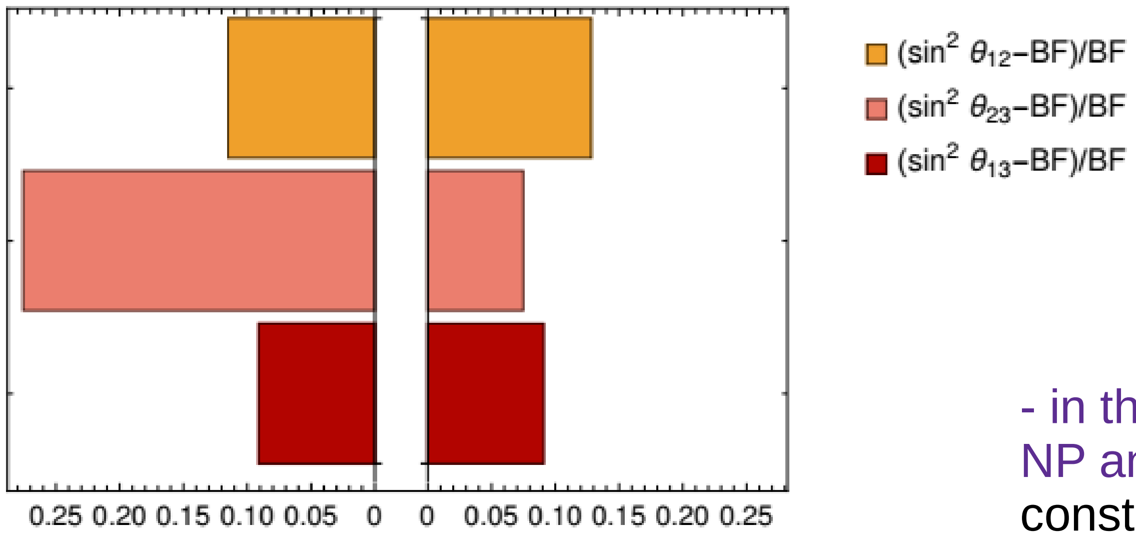
solar sector



Where is New Physics (in neutrino oscillations) ?

$$P \sim \left| A^{SM} + \epsilon A^{NP} \right|^2 \sim P^{SM} + 2\epsilon \Re \left(A^{SM} A^{NP} \right)$$

in the standard 3-ν paradigm



- in the absence of correlation between NP and standard parameters, strong constraints

- if correlation is strong, thus bounds can be (partially) relaxed

New Physics in Neutrino Oscillations

Neutrino mass models

- scenarios where neutrinos new interactions:

modified interactions with detector atoms

modified interactions with matter

- scenarios where the number of neutrino species is larger than 3

imprint on "*astrophysical*" neutrinos

sterile neutrino models – loss of unitarity

- imprint on short-baseline experiments
- imprint on cosmological observables such as the cosmic microwave background and the distribution of matter at large scale

- ….

complementary studies compared to sterile and NSI searches at NT

Future Experimental Alternatives
(some of them)

Accelerator-based long-baseline experiments
- Hyper-Kamiokande, DUNE

Accelerator-based short-baseline experiments
- MINERvA, MicroBooNE, SHiP
- COHERENT

Reactor neutrino experiments
- JUNO
- PROSPECT, SoLid, Watchman
- SOX

Astrophysical neutrino measurements
- PINGU, ORCA
- Hyper-Kamiokande, Jinping
- Super-Kamiokande-Gd
- IceCube-Gen2, KM3NeT, ARA
- PTOLEMY

Goals

- measure of δ_{CP}
- determination of mass hierarchy

Δm^2_{12}	~3%	~0.6%
Δm^2_{23}	~5%	~0.6%
$\sin^2\theta_{12}$	~6%	~0.7%
$\sin^2\theta_{23}$	~20%	N/A
$\sin^2\theta_{13}$	~14% → ~4%	~ 15%

- New Physics

CP violation

Our concern here: study the existence of new sources of CP violation

Let us set our strategy: look for leptonic CP asymmetries

$$A_{\alpha\beta} = \frac{P_{\alpha\beta} - P_{\bar{\alpha}\bar{\beta}}}{P_{\alpha\beta} + P_{\bar{\alpha}\bar{\beta}}}$$

- we DO NOT want to study the sensitivity to some New Physics phase
- we want to assess whether all asymmetries are described in terms of the single leptonic Jarlskog invariant as predicted in the absence of New Physics effects
- to achieve this task:
  * compute the leptonic asymmetries in the Standard Model
  * evaluate the experimental uncertainty on them
  * re-compute the asymmetries including the effects of New Physics
  * check whether the new results are sufficiently away from the Standard model predictions

A. Giarnetti and DM
New Sources of Leptonic CP Violation at the DUNE Neutrino Experiment
Universe 2021, 7(7), 240

CP Asymmetries in the Standard Model: vacuum

$$A_{\alpha\beta} = \frac{P_{\alpha\beta} - P_{\bar{\alpha}\bar{\beta}}}{P_{\alpha\beta} + P_{\bar{\alpha}\bar{\beta}}}$$

Use perturbation theory to evaluate them (given here the vacuum case):

$$\Delta_{21} = \Delta m^2_{21} L/4E_\nu \ll 1. \qquad s_{13} = \frac{r}{\sqrt{2}}, \quad s_{12} = \frac{1}{\sqrt{3}}(1+s), \quad s_{23} = \frac{1}{\sqrt{2}}(1+a)$$

r, s, a = λ~ O(10%)

$$A_{\mu e} = \frac{-12\, r\, \Delta_{21} \sin\delta \ \sin^2\Delta_{31}}{4\Delta_{21}^2 + 9 r^2 \sin^2\Delta_{31} + 6 r\, \Delta_{21} \cos\delta \ \sin 2\Delta_{31}} \sim O(1)$$

$$A_{\mu\tau} = \frac{4}{3} r\, \Delta_{21} \sin\delta \sim O(\lambda^2)$$

$$(A_{\mu\mu} = 0)$$

- $A_{\mu e}$ and $A_{\mu\tau}$ asymmetries in vacuum are suppressed by the small quantities Δ_{21} and θ_{13}
- since the denominators $A_{\mu e}$ is also suppressed, a partial cancellation is at work and, in particular, one generically expects $A_{\mu e} > A_{\mu\tau}$

CP Asymmetries in the Standard Model: the case of small matter effects

$$A_{\alpha\beta} = A_{\alpha\beta}^{SM_0} + V_{CC} A_{\alpha\beta}^{SM_1}$$

$\alpha = \frac{\Delta_{21}}{\Delta_{31}}$ $\quad V_{CC} \sim O(\lambda)$ $\quad f_1 \sim O(r^2)$

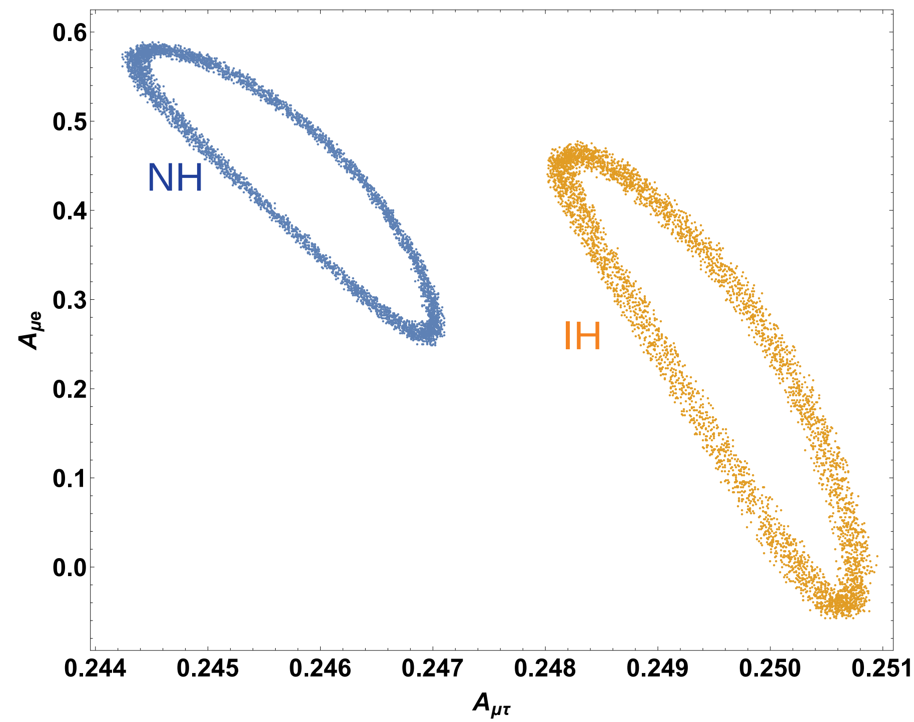
$$\begin{aligned} A_{\mu e}^{SM_1} &= -\frac{6}{f_1} r(\Delta_{31}\cos\Delta_{31} - \sin\Delta_{31})[2\alpha\Delta_{31}\cos\delta\cos\Delta_{31} + 3r\sin\Delta_{31} + \\ &- \frac{24}{f_1} r\alpha^2 \sin^2\delta\, \Delta_{31}^2 \sin^3\Delta_{31}\Big], \longrightarrow O(\lambda) \\ A_{\mu\tau}^{SM_1} &= -2r^2(1 - \Delta_{31}\cot\Delta_{31}) + \frac{8}{27}\alpha^2\Delta_{31}^3\cot\Delta_{31}, \longrightarrow O(\lambda^2) \end{aligned}$$

$$A_{\mu\mu}^{SM_1} = \underbrace{\frac{4}{3} r\alpha\Delta_{31}\cos\delta(\Delta_{31} - \tan\Delta_{31}) - \frac{8}{27}\alpha^2\Delta_{31}^3}_{O(\lambda^2)} \tan\Delta_{31}$$

$A_{\mu e} \approx 1 + \lambda$

$A_{\mu\tau} \approx \lambda^2 + \lambda^2$

$A_{\mu\mu} \approx 0 + \lambda^2$



NSI Oscillation Probabilities

- Oscillations with Neutral Current NSI:

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon_{\alpha\beta}^s |\nu_\beta\rangle$$

$$\langle\nu_\beta^d| = \langle\nu_\beta| + \sum_{\alpha=e,\mu,\tau} \varepsilon_{\alpha\beta}^d \langle\nu_\alpha|.$$

$$P(\nu_\alpha^s \rightarrow \nu_\beta^d) = \left|\langle \nu_\beta^d | e^{-i(H+V_{NSI})L} | \nu_\alpha^s \rangle\right|^2$$

$$V_{\text{NSI}} = \sqrt{2} G_F N_e \begin{pmatrix} \varepsilon_{ee}^m & \varepsilon_{e\mu}^m & \varepsilon_{e\tau}^m \\ \varepsilon_{e\mu}^{m*} & \varepsilon_{\mu\mu}^m & \varepsilon_{\mu\tau}^m \\ \varepsilon_{e\tau}^{m*} & \varepsilon_{\mu\tau}^{m*} & \varepsilon_{\tau\tau}^m \end{pmatrix}$$

$$P(\nu_\alpha^s \rightarrow \nu_\beta^d) = \left|\left[(1+\epsilon^d)^T e^{-i(H+V_{NSI})L} (1+\epsilon^s)^T\right]_{\beta\alpha}\right|^2$$

three more possible sources of CP violation: $\delta_{e\mu}$, $\delta_{e\tau}$, $\delta_{\mu\tau}$

- Existing bounds

Blennow, Choubey, Ohlsson, Pramanik and Raut, JHEP08 (2016), 090
Biggio, Blennow, and Fernandez-Martinez, JHEP08, 090 (2009), 0907.0097

from G_F, pion decay, unitarity of CKM, oscillation experiments

$$|\varepsilon_{\alpha\beta}^{s/d}| < \begin{bmatrix} 0.041 & 0.025 & 0.041 \\ 0.026 & 0.078 & 0.013 \\ 0.12 & 0.018 & 0.13 \end{bmatrix}$$

mainly from neutrino-electron scattering and neutrino oscillations

$$|\varepsilon_{\alpha\beta}^m| < \begin{bmatrix} 4.2 & 0.3 & 3.0 \\ 0.3 & - & 0.04 \\ 3.0 & 0.04 & 0.15 \end{bmatrix}$$

CP asymmetries – Adding the NSI contributions

by construction, the new terms are all proportional to V_{CC}

$$A_{\alpha\beta} = A_{\alpha\beta}^{SM_0} + V_{CC} A_{\alpha\beta}^{SM_1} + V_{CC} A_{\alpha\beta}^{NSI}$$

$$A_{\mu e}^{NSI} = F[\epsilon_{e\mu}, \epsilon_{e\tau}]$$ $\longrightarrow$ first order dependence on NSI parameters but suppressed by matter effects → globally is an O(λ) correction

$$A_{\mu\tau}^{NSI} = 8\,\epsilon_{\mu\tau} \cos\delta_{\mu\tau} \Delta_{31} \cot\Delta_{31} + G[\epsilon_{e\mu}, \epsilon_{e\tau}, \epsilon_{\mu\tau}, \epsilon_{\tau\tau}]$$

$$A_{\mu\mu}^{NSI} = -8\,\epsilon_{\mu\tau} \cos\delta_{\mu\tau} \Delta_{31} \tan\Delta_{31} + H[\epsilon_{e\mu}, \epsilon_{e\tau}, \epsilon_{\mu\tau}, \epsilon_{\tau\tau}]$$

first order correction on NSI parameters

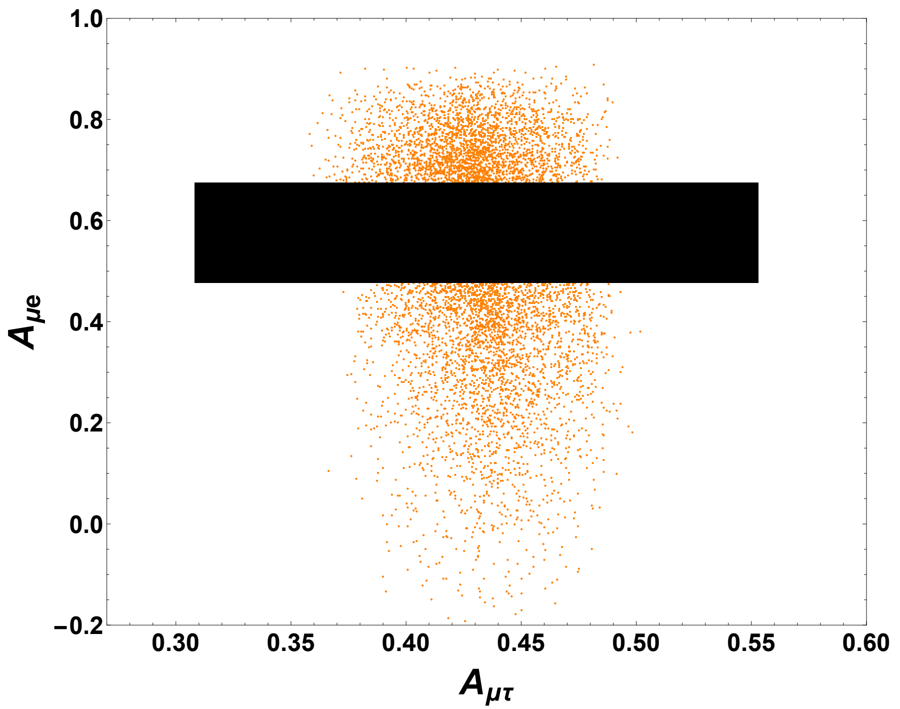
SM		SM + NSI
$A_{\mu e} \approx 1 + \lambda$	→	$A_{\mu e} \approx 1 + \lambda + \lambda$
$A_{\mu\tau} \approx \lambda^2 + \lambda^2$		$A_{\mu\tau} \approx \lambda^2 + \lambda^2 + \lambda^2$
$A_{\mu\mu} \approx 0 + \lambda^2$		$A_{\mu\mu} \approx 0 + \lambda^2 + \lambda^2$

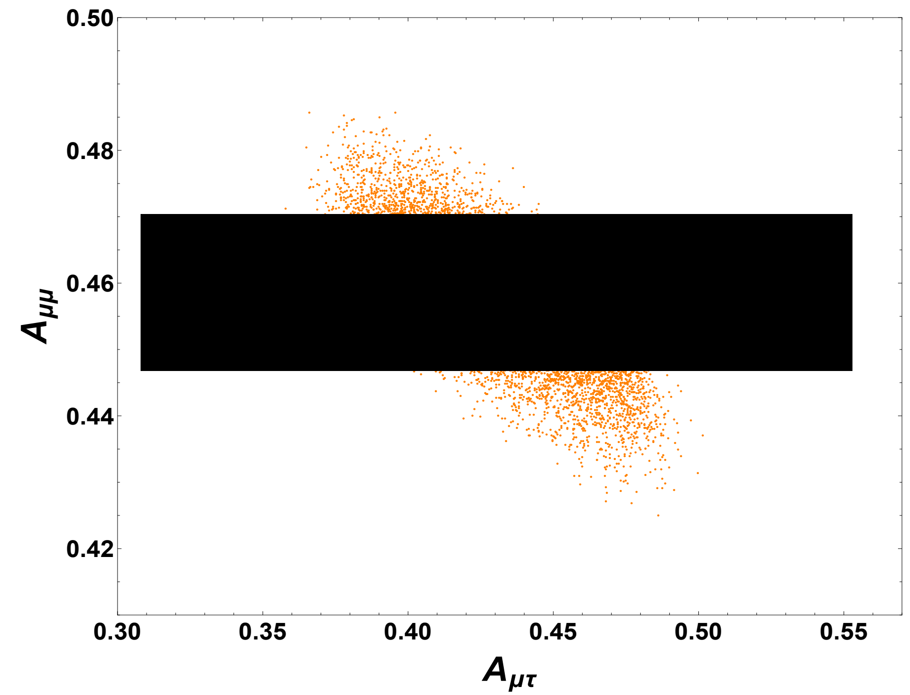
CP asymmetries – Adding the NSI contributions

Integrated asymmetries: working with number of events in DUNE

$$A_{\alpha\beta} = \frac{N_\beta - \bar{N}_\beta}{N_\beta + \bar{N}_\beta}$$

- scatter plot: asymmetries obtained varying NSI parameters
- square = error bars from statistics + systematic errors





Due to the small statistics, $A_{\mu\tau}$ does not seem to perform well

$A_{\mu e}$ (and $A_{\mu\mu}$) show the best sensitivity to new sources of CP violation in the NSI model

3+1 sterile neutrino model

- Three more rotation in the definition of the PMNS mixing matrix

$$U = R(\theta_{34})R(\theta_{24})R(\theta_{23}, \delta_2)R(\theta_{14})R(\theta_{13}, \delta_3)R(\theta_{12}, \delta_1)$$

two more possible sources of CP violation: δ_1 and δ_2

three small new mixing angles: θ_{14}, θ_{24}, θ_{34}

- Hamiltonian

matter potential from NC interactions

$$\left[\frac{1}{2E_\nu}U\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 & 0 \\ 0 & 0 & \Delta m^2_{31} & 0 \\ 0 & 0 & 0 & \Delta m^2_{41} \end{pmatrix}U^\dagger + \begin{pmatrix} A_{CC}+A_{NC} & 0 & 0 & 0 \\ 0 & A_{NC} & 0 & 0 \\ 0 & 0 & A_{NC} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}\right]$$

CP asymmetries in the 3+1 neutrino model

$$A_{\alpha\beta} = A_{\alpha\beta}^{SM} + A_{\alpha\beta}^{3+1}$$

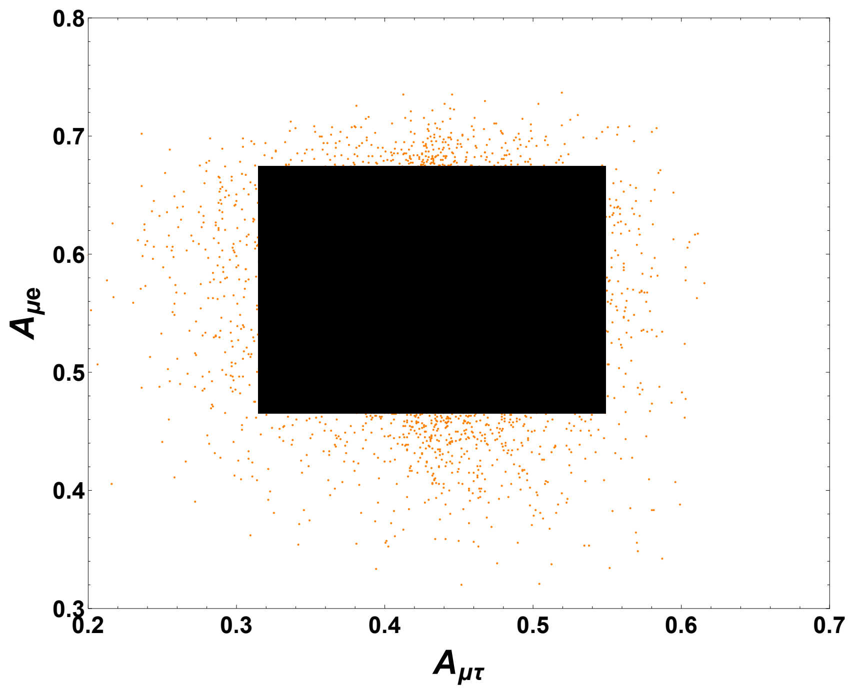
$$A_{\mu e}^{3+1} = O(\lambda) = f\left(s_{14}\, s_{24}/r\right)$$

No dependence on the 34 rotation

$$A_{\mu\mu}^{3+1} = O(\lambda^2) = 4\, s_{24}\, s_{34}\, V_{NC} \tan\Delta_{31}\, \Delta_{31} \cos\delta_3$$

significantly large contributions from sterile mixing 34, barely constrained

$$A_{\mu\tau}^{3+1} = O(\lambda^2) = 2\, s_{24}\, s_{34} \cot\Delta_{31} \left(\sin\delta_3 - 2\, V_{NC}\, \Delta_{31} \cos\delta_3\right)$$



$A_{\mu e}$ and $A_{\mu\tau}$ show the best sensitivity to sterile neutrinos

Conclusions

- On-going and planned neutrino experiments will probe the PMNS with huge precision
- Good chance to investigate <u>New Physics effects</u> in Neutrino oscillations:

  several "Beyond the Standard Model" scenarios, including sterile neutrinos and Non-Standard Interactions
- the μ-e CP asymmetry shows the best sensitivity to both NP scenarios (with $\mu\ \mu$ also good for NSI and $\mu\ \tau$ for 3+1)

Asymmetry	**SM**	**NSI**	**3+1**
$A_{\mu e}$	1	λ^2	λ
$A_{\mu\mu}$	λ^3	λ^2	λ^2
$A_{\mu\tau}$	λ^2	λ^2	λ^2
$A_{\mu s}$	-	-	1

Backup slides

Non-standard Neutrino Interactions (NSI)

- A matter NSI operator is induced in fermionic seesaw models once the heavy fermions (singletsor triplets) are integrated out leading to a d= 6 operator that modifies the neutrino kinetic energy.
- After a transformation to obtain canonical kinetic terms, modified couplings of the leptons to the gauge bosons, characterized by deviations from unitarity of the leptonic mixing matrix, are induced.
- Upon integrating out the gauge bosons with their modified couplings, NSI operators are therefore obtained.

SU(2) formulation

- Large NSI could be generated by some other new physics at an energy above the electroweak scale. As a consequence, an SU(2) gauge invariant formulation of NSI is mandatory
- However, in that case, strong bounds stemming from four-charged fermion processes would apply
- In order to avoid these constraints, cancellations among different higher-dimensional operators are required

Non-standard Neutrino Interactions (NSI)

- Many new-physics parameters, huge parameter space:

$\varepsilon^{s,f,f}_{\alpha\beta}$ arbitrary complex matrices

$\varepsilon^{m,f}_{\alpha\beta}$ hermitean complex matrices

there exists arguments to reduce the parameter space

- for the non-standard matter effects, only coupling to electrons, up quarks, and down quarks is important
- non-standard couplings involving τ leptons are irrelevant in reactor and beam sources since τ-production is impossible
- for $l_\alpha = e$, all corresponding ε's are vanishing in superbeams because of no-e production
- in Superbeam source and detector: f=u, f′=d .
- ...

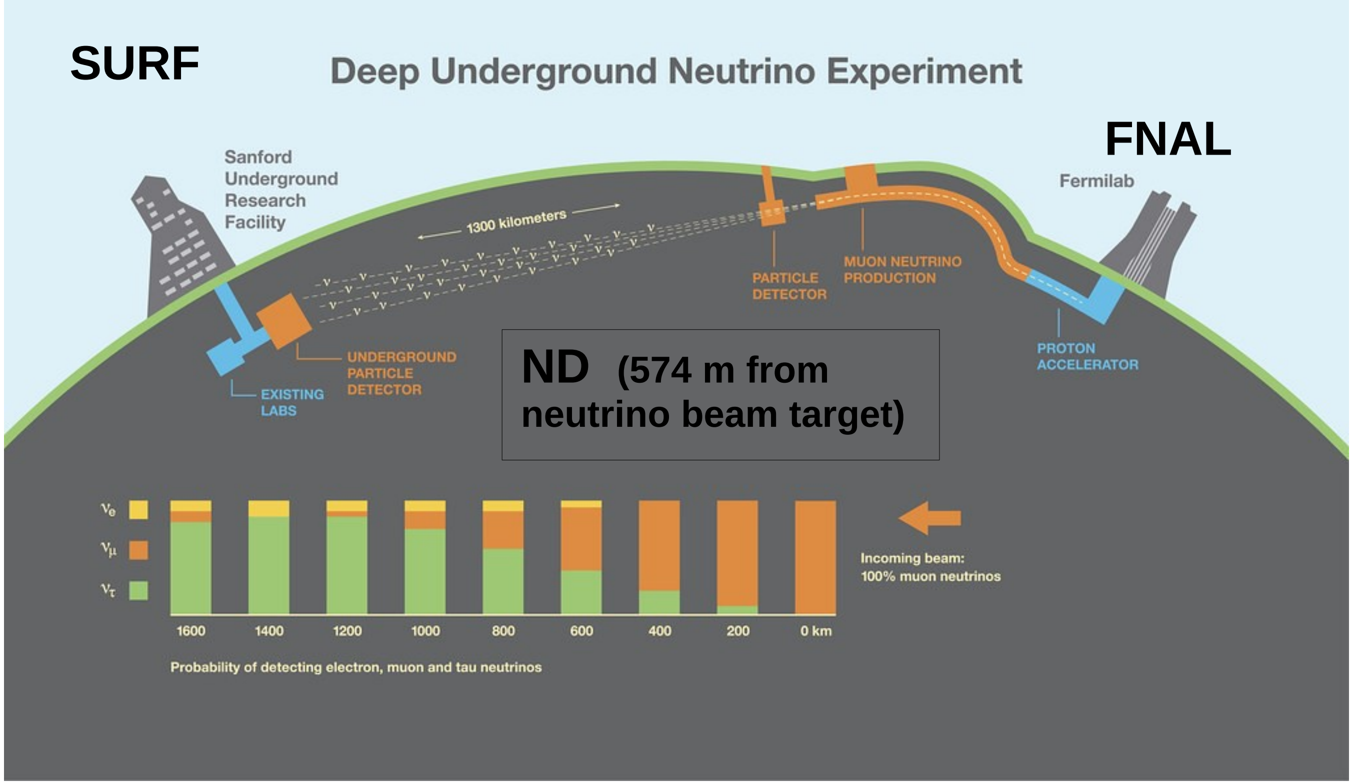
Introducing DUNE

“Deep Underground Neutrino Experiment”

- 1300 km baseline
- Large (70 kt) LArTPC far detector
- 1.5 km underground
- Near Detector (ND) w/LAr component

“Physics goals”

- ν and $\bar{\nu}$ oscillations (δ_{CP}, θ_{13}, θ_{23}, ordering of nu masses)
- Supernova burst neutrinos
- Beyond Standard Model processes



DUNE events

- neutrino signal channels:

- ν_e appearance and ν_μ disappearance channels
  (2% and 5% systematic normalization errors)

Background	Normalization Uncertainty	Correlations
For $\nu_e/\bar{\nu}_e$ appearance:		
Beam ν_e	5%	Uncorrelated in ν_e and $\bar{\nu}_e$ samples
NC	5%	Correlated in ν_e and $\bar{\nu}_e$ samples
ν_μ CC	5%	Correlated to NC
ν_τ CC	20%	Correlated in ν_e and $\bar{\nu}_e$ samples
For $\nu_\mu/\bar{\nu}_\mu$ disappearance:		
NC	5%	Uncorrelated to $\nu_e/\bar{\nu}_e$ NC background
ν_τ	20%	Correlated to $\nu_e/\bar{\nu}_e$ ν_τ background

T. Alionet al[DUNE Collaboration], arXiv:1606.09550 [physics.ins-det]

- ν_τ appearance channel

electron mode
- 6% overall detection efficiency for the signal
- signal-to-background ratio of 2.45
- signal systematic uncertainty of 20%

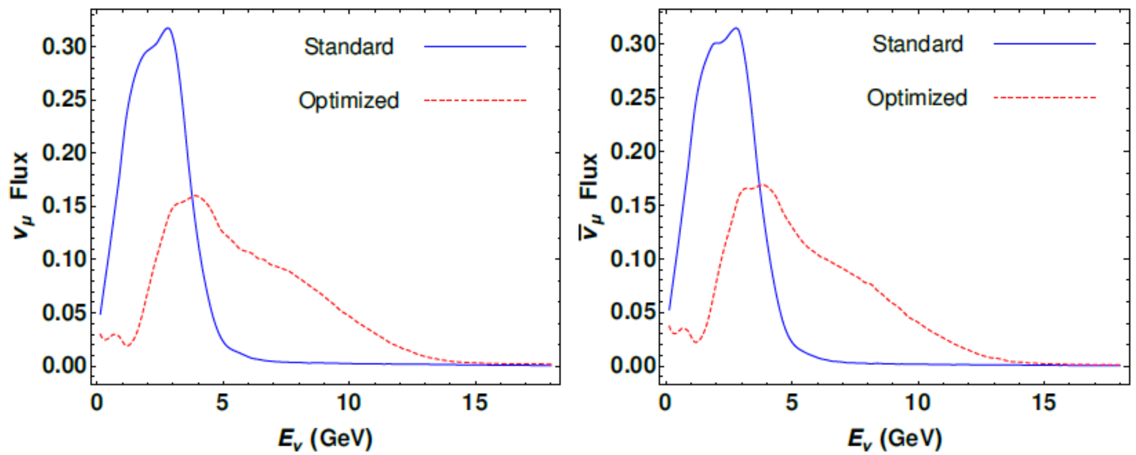
hadronic mode
- we take into account that only 30% of the τ-s are detected
- 0.5% of the NC events as a background

- neutral current events
  (hadronic shower with a certain visible energy)

- overall 90% signal detection efficiency
- systematic uncertainty at 10%
- backgrounds come from the mis-identification of CC events (mainly a conservative 10% of the ν_μ and ν_e^{CC} events)

Flux options in DUNE

M. Bishai and M. Dolce, *Optimization of the LBNF/DUNE beamline for tau neutrinos*, in Document Database (DocDB) for DUNE and LBNF [http://docs.dunescience.org/cgi-bin/RetrieveFile?docid=2013&filename=DOLCE_M_report.pdf&version=1].



standard

ν mode	
ν_τ Signal	277
$\bar{\nu}_\tau$ Signal	26
Total Signal	303
$\nu_e + \bar{\nu}_e$ CC Bkg (beam)	333 + 38
$\nu_e + \bar{\nu}_e$ CC Bkg (oscillation)	1753 + 12

$\bar{\nu}$ mode	
ν_τ Signal	68
$\bar{\nu}_\tau$ Signal	85
Total Signal	153
$\nu_e + \bar{\nu}_e$ CC Bkg (beam)	117 + 104
$\nu_e + \bar{\nu}_e$ CC Bkg (oscillation)	90 + 188

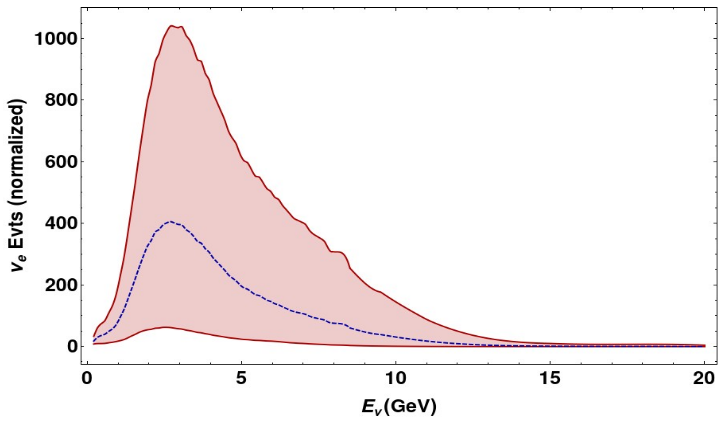
optimized

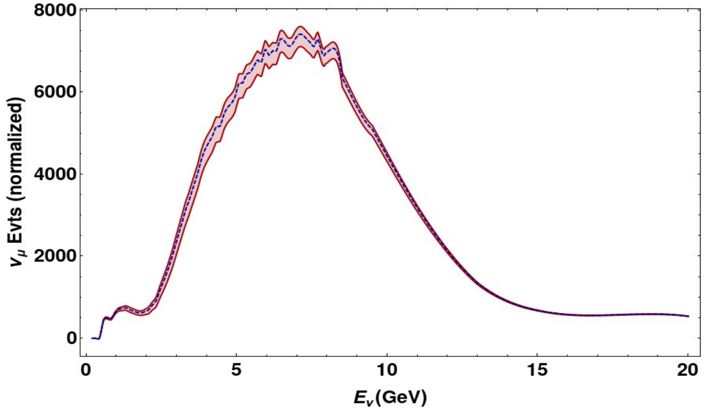
ν mode	
ν_τ Signal	2673
$\bar{\nu}_\tau$ Signal	34
Total Signal	2707
$\nu_e + \bar{\nu}_e$ CC Bkg (beam)	688 + 63
$\nu_e + \bar{\nu}_e$ CC Bkg (oscillation)	1958 + 11

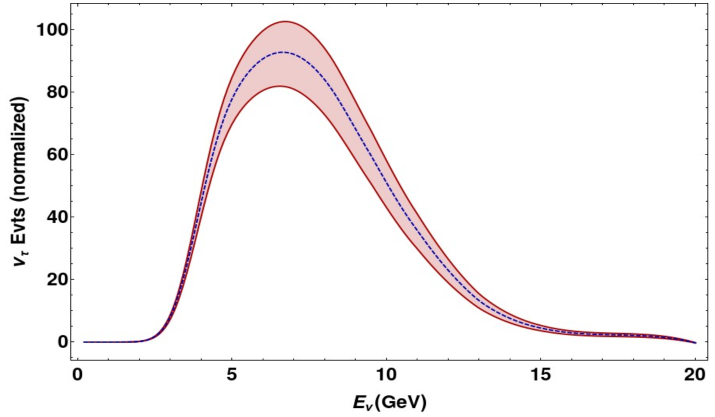
$\bar{\nu}$ mode	
ν_τ Signal	98
$\bar{\nu}_\tau$ Signal	983
Total Signal	1081
$\nu_e + \bar{\nu}_e$ CC Bkg (beam)	176 + 177
ν_e CC Bkg (oscillation)	76 + 324

A factor of ~10 more tau events

Effects of NSI on the event spectra







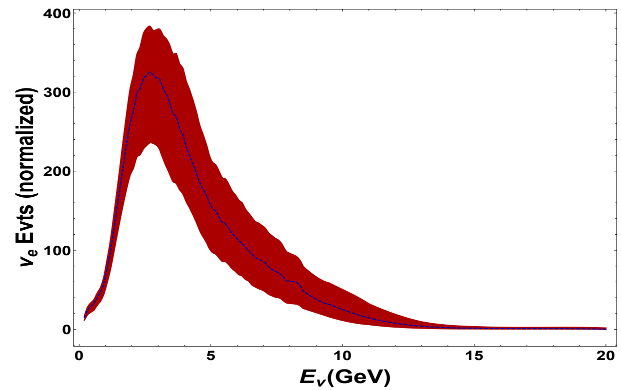
Dotted blue lines: SM events

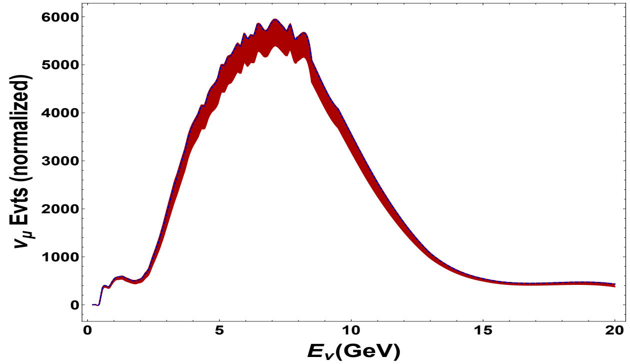
Red bands: range of events while varying matter NSI parameters in their allowed ranges

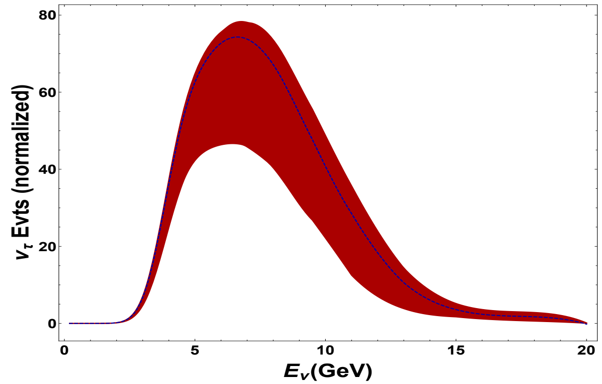
$\nu_\mu \rightarrow \nu_e$ is the most sensitive channel

But how sensitive ?

Effects of a sterile state on the event spectra







Dotted blue lines: SM events

Red bands: range of events while varying 3+1 sterile parameters in their allowed ranges

$\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ are the most sensitive channels

how sensitive ?