Joint fit of long-baseline accelerator neutrino experiments in GNA software

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October, 26, 2022

Neutrino oscillations in matter

Neutrino mixing:

$$\nu_\alpha = \sum_{i=1}^{3} \mathrm{U_{PMNS}} \cdot \nu_i, \quad \alpha = e,\ \mu,\ \tau$$

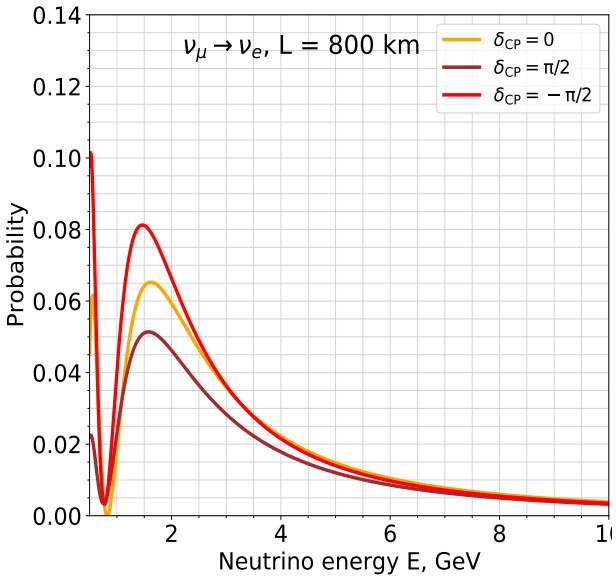
- ν_α – a mass eigenstate
- ν_i – a flavor eigenstate

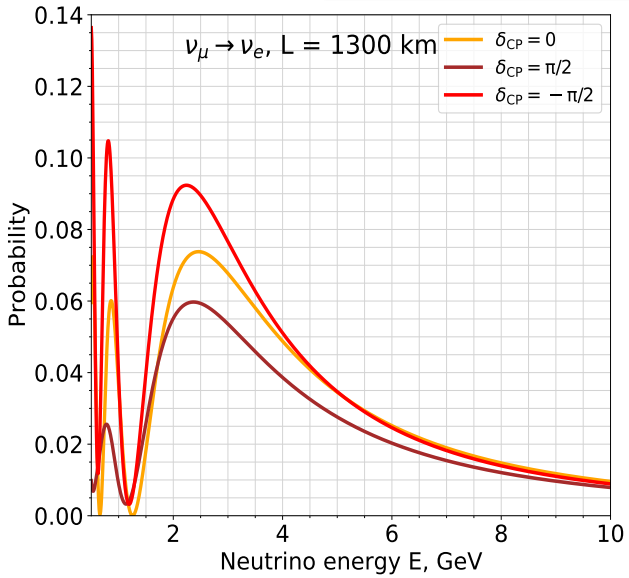
Mixing matrix:

$$\mathrm{U_{PMNS}} \sim \theta_{12},\ \theta_{13},\ \boldsymbol{\theta_{23}},\ \boldsymbol{\delta_{CP}}$$

Oscillation probability depends on:

- parameters of $\mathrm{U_{PMNS}}$
- mass squared differencies: $\Delta m^2_{12},\ \Delta m^2_{13}$ / $\boldsymbol{\Delta m^2_{23}}$
- neutrino mass ordering: **sign $\boldsymbol{\Delta m^2_{23}}$**
- the matter density ρ
- a ratio of an experiment baseline and the neutrino energy $\frac{L}{E}$

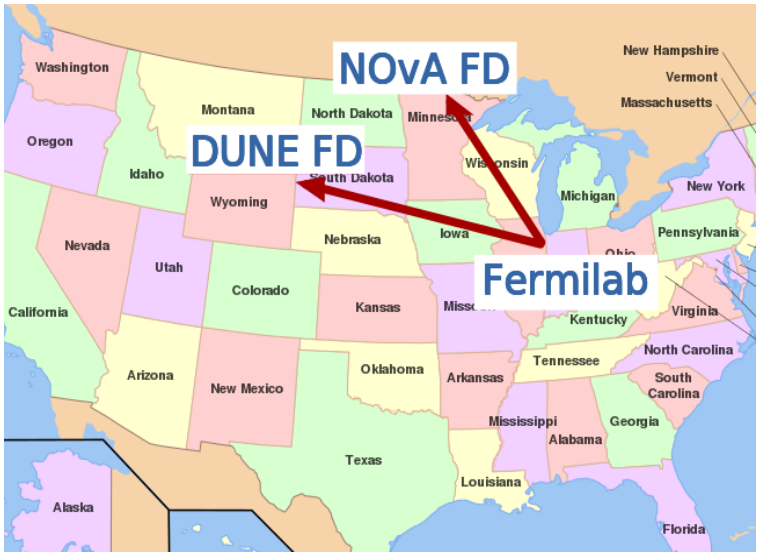




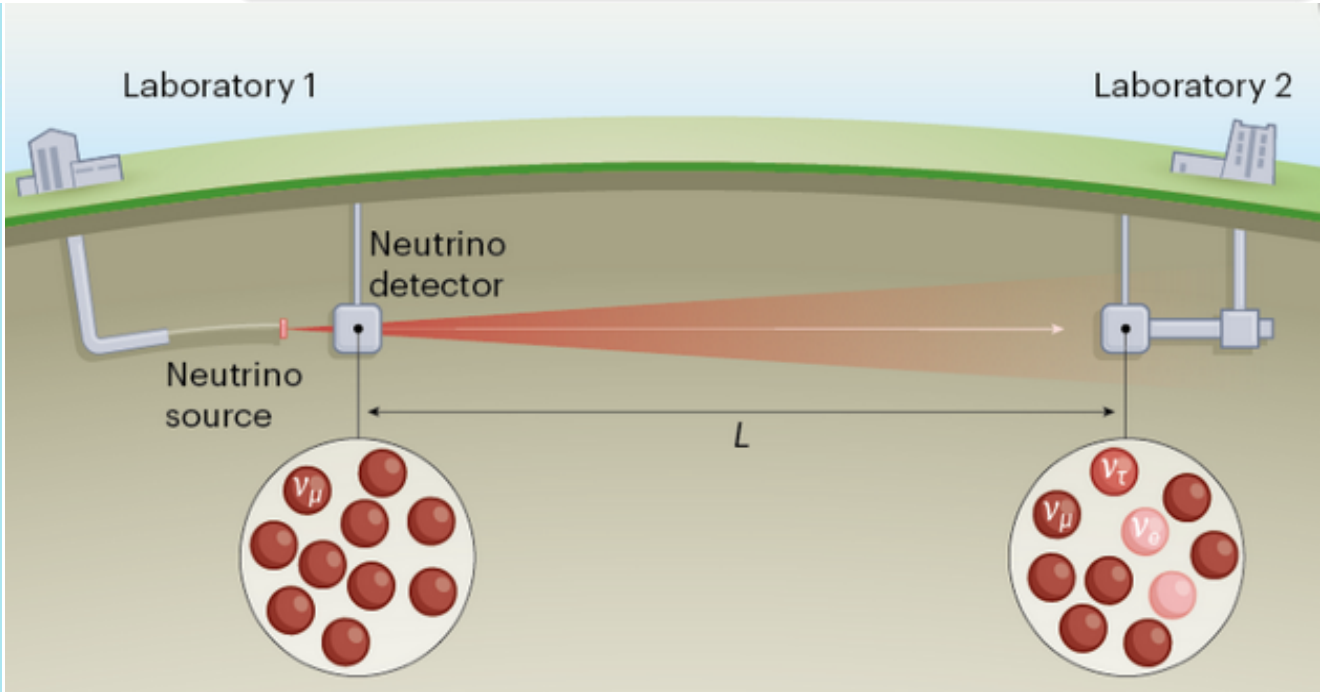
Neurtino types
(for studying neutrino oscillations):

- atmospheric
- **accelerator**
- reactor
- solar

Long-baseline accelerator neutrino experiments



Exp.	NOvA	T2K	DUNE
Start	2014	2010	2026
p source	Fermilab		J-PARC
FD	PVC	Cherenkov	LArTPC
L, km	810	295	1285
M_{FD}^{fid}, kt	14	22.5	40
E, GeV	0.5 – 5	0.5 – 3	0.5 – 8



Global Neutrino Analysis. Developed in DLNP, JINR

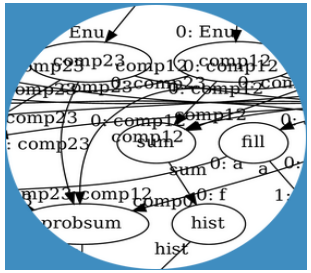
Each experiment has some advantages

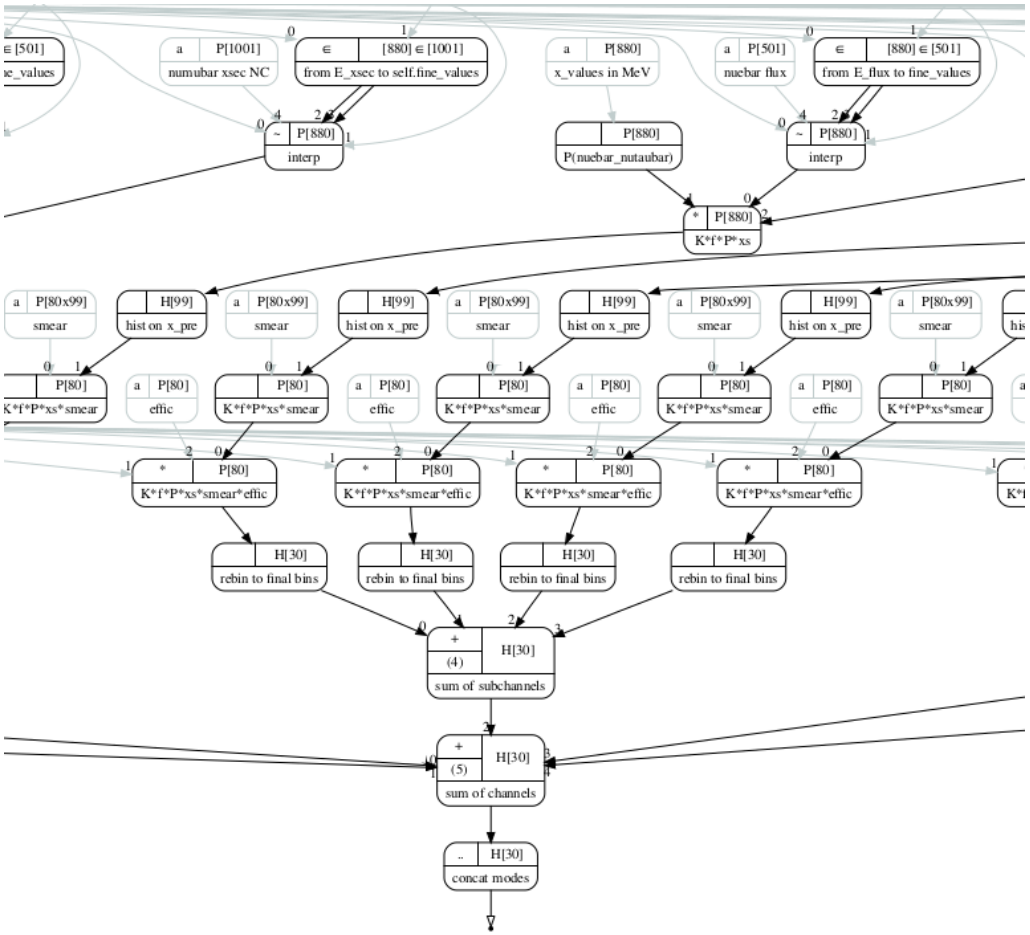
⇓

The goal is to use them together

⇒

GNA is for carrying out a neutrino oscillation analysis with neutrinos of different types.





The GNA structure is:

- transformations for computational calculations implemented via C++ and ROOT CERN
- Python modules for experiment modeling
- a block structure integrated in a graph
- functions for the statistical analysis

GNA shell of long-baseline accelerator neutrino experiments

A config. file includes:

- flux, xsec, eff input files
- dependence between E_{true} and $E_{\text{recon.}}$
- modes with channels
- the energy range
- oscillation parameters
- detector parameters and etc.

It is a unified shell in GNA that gets a config. file and is able to calculate:

- event rates $\boldsymbol{N}$ in channels and modes
- χ^2 values based on the calculated $\boldsymbol{N}$ and data
- single sensitivities of a given experiment model
- joint sensitivities of a given set of models

```
MODES:
 fhc_app_nue:
  Signal: nue
  FhcRhc: fhc
  AppDis: app
  CH:
   bkg_beam:
     - channel_type: beam
       initial_flavor: nue
       final_flavor: nue
       xsec_type: CC
```

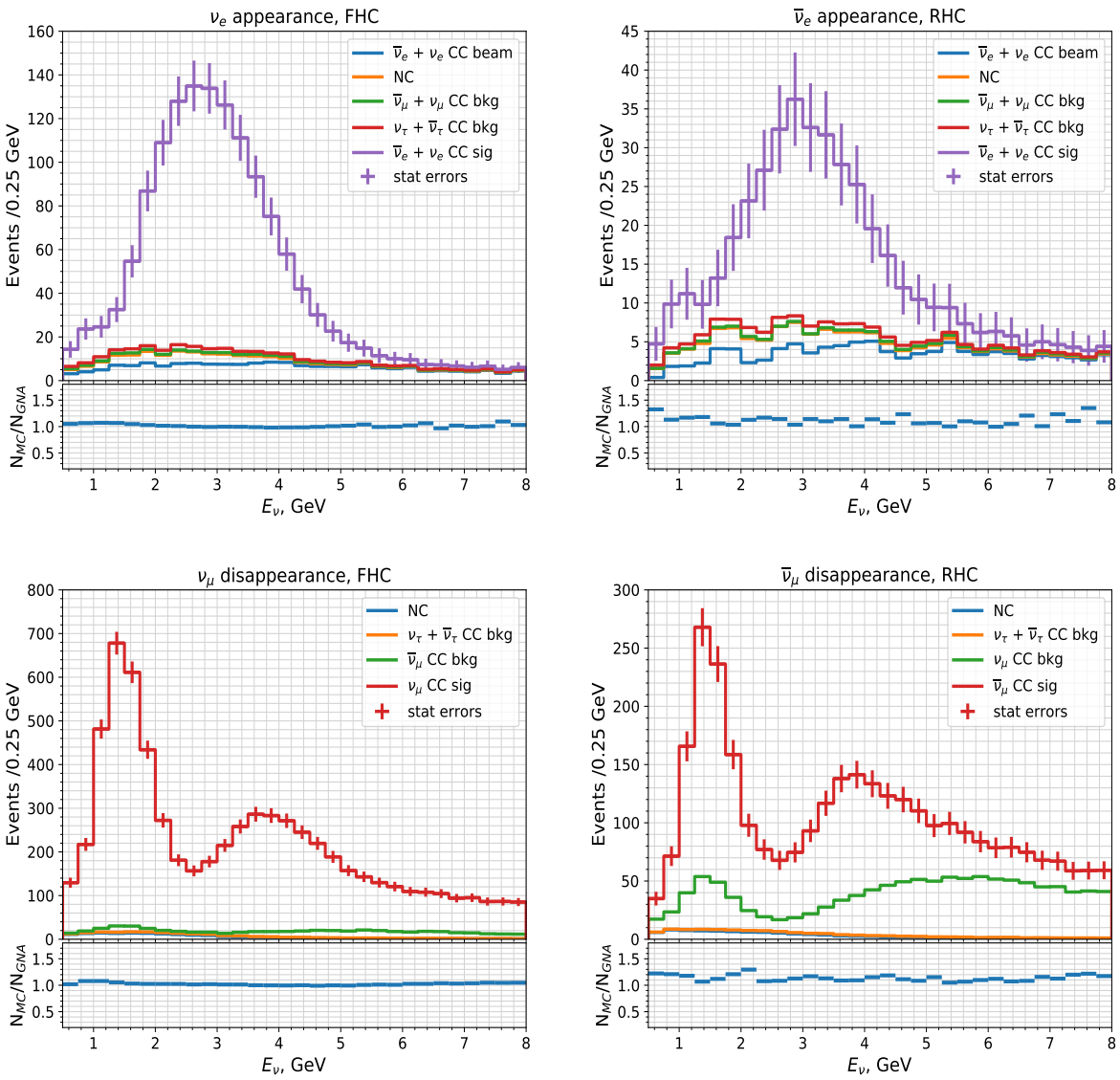
$$\boldsymbol{N}^j_{\text{m}} = \sum_{i=0}^{\text{D}} N^i_{j,m},\ N^i_j = \text{K}\cdot f(E_{\text{true}})_j \cdot P(E_{\text{true}})(\nu_\alpha \to \nu_\beta)_j \cdot$$

$$\cdot \sigma(E_{\text{true}})_j \cdot \sum_{k=0}^{n} R(E_{\text{true}}, E_{\text{recon.}})_{jk} \cdot \varepsilon(E_{\text{recon.}})_k$$

$$\chi^2 = -2 \sum_{m=1}^{M} \ln L(N^{\text{mod.}} | N^{\text{data}}) + \frac{(x-\mu)^2}{\sigma^2} =$$

$$= 2 \sum_{m=1}^{M} \sum_{j=1}^{n} (N^{\text{mod.}}_{j,m} \ln N^{\text{data}}_{j,m} - N^{\text{data}}_{j,m} - N^{\text{mod.}}_{j,m} \ln N^{\text{mod.,}}_{j,m}) + \frac{(x-\mu)^2}{\sigma^2}$$

Predicted DUNE FD event rates produced within GNA



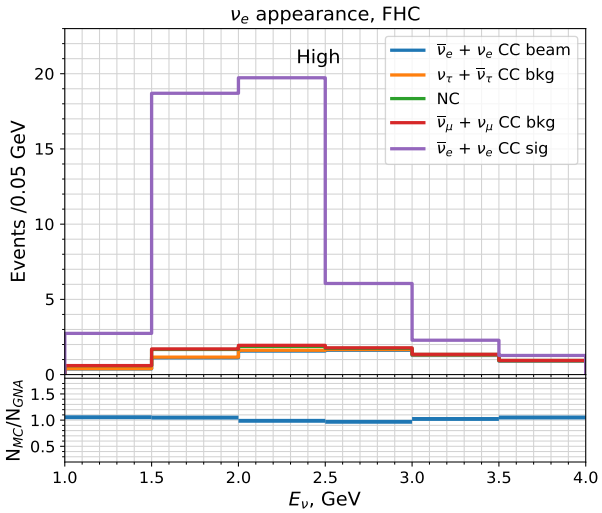
- FHC (forward horn current) / RHC (reverse horn current) with equal running time
- 7 years according to the staged plan:

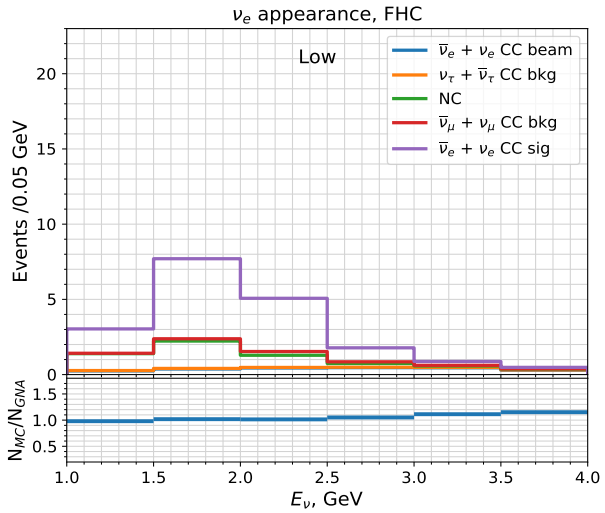
plan	kt	MW
1 year	20	1.2
2 years	30	1.2
3 years	30	1.2
4 years	30	1.2
6 years	40	2.4
10 years	40	2.4

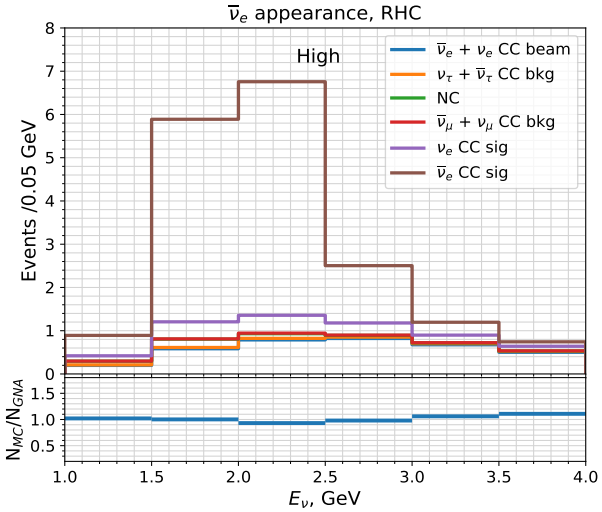
- 4 modes:
  - $\nu_e/\bar{\nu}_e$ appearance
  - $\nu_\mu/\bar{\nu}_\mu$ disappearance
- MC data from: TDR DUNE

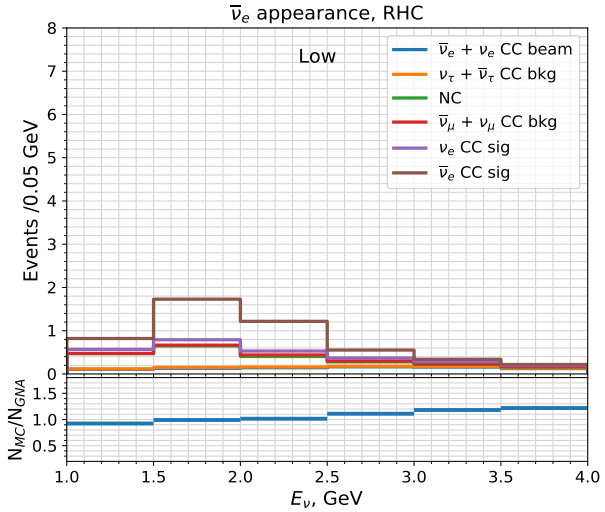
Predicted NOvA FD event rates produced within GNA

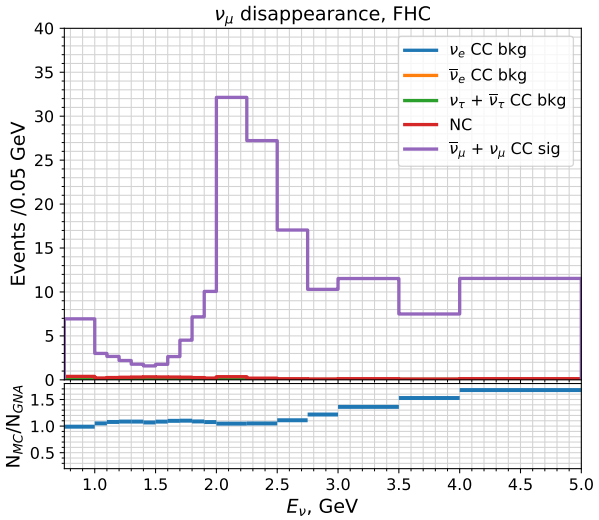
- High / Low PID

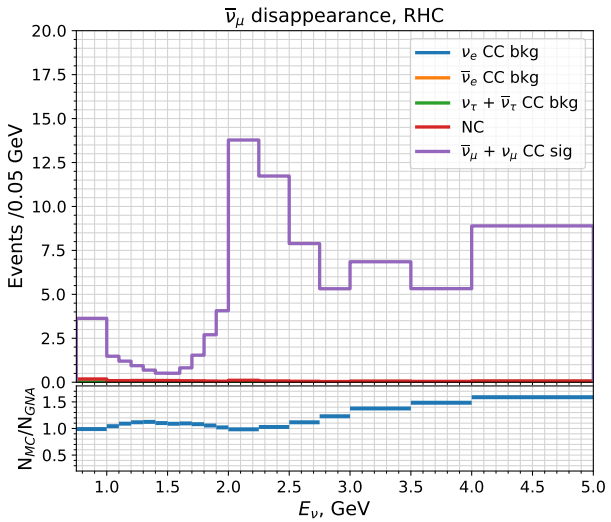






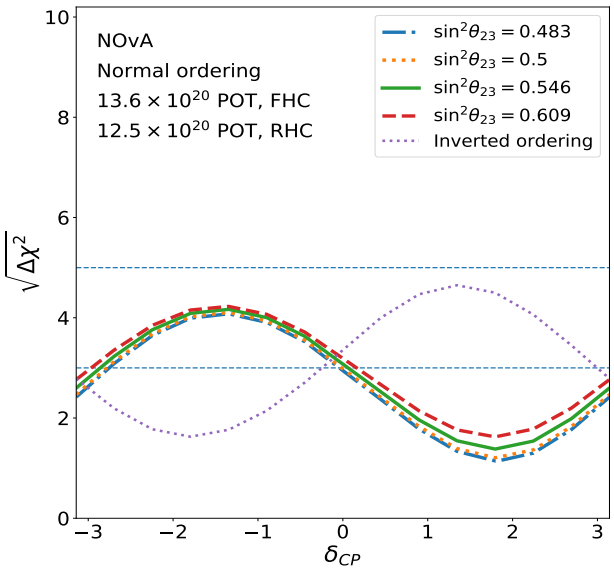


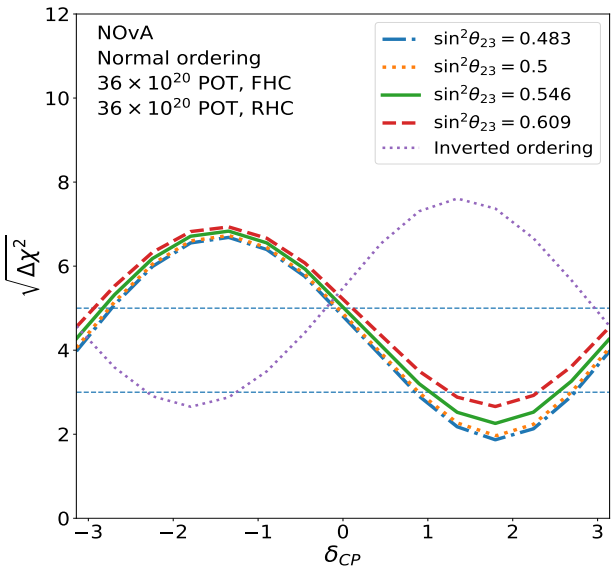




- $13.6\ (12.5) \times 10^{20}$ POT (protons on target), FHC (RHC)

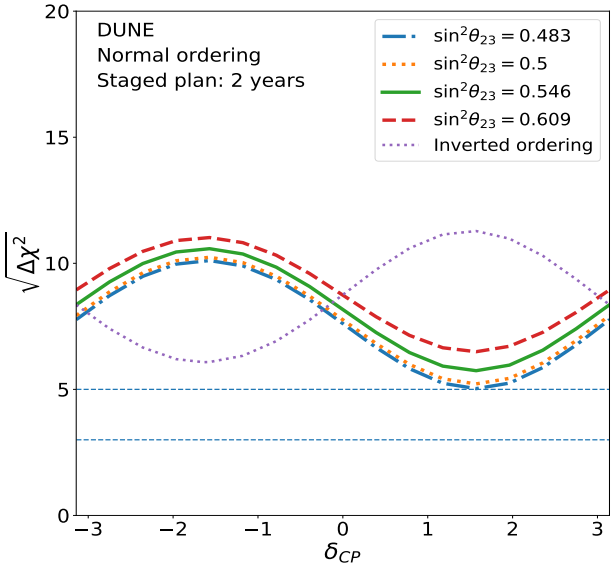
Single neutrino mass ordering sensitivities

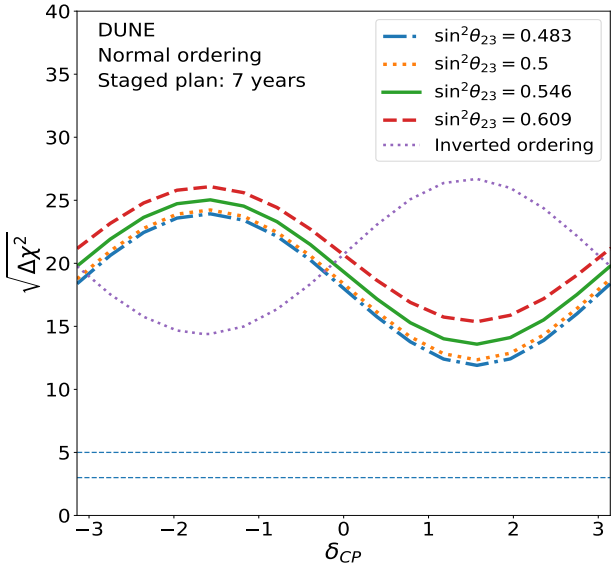




- different values of $\sin^2\theta_{23}$ around the NuFIT 4.0 best-fit value
- both mass orderings
- δ_{CP} along the whole $[-\pi, \pi]$ range

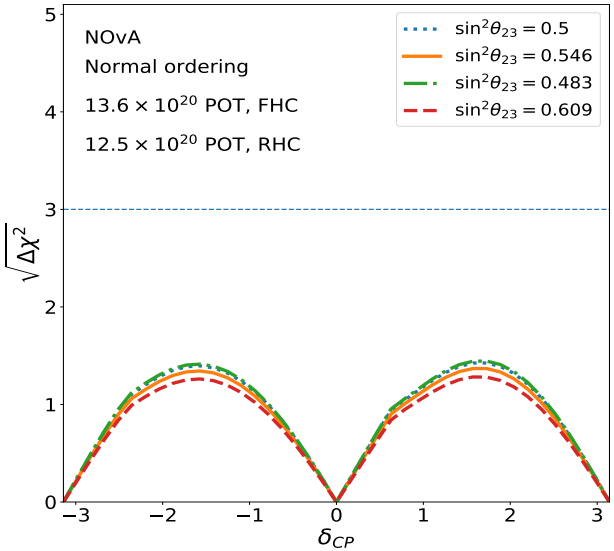
$$\sqrt{\Delta\chi^2} = \sqrt{\chi^2_{IO} - \chi^2_{NO}}\ (\text{NO}) \quad / \quad \sqrt{\Delta\chi^2} = \sqrt{\chi^2_{NO} - \chi^2_{IO}}\ (\text{IO})$$

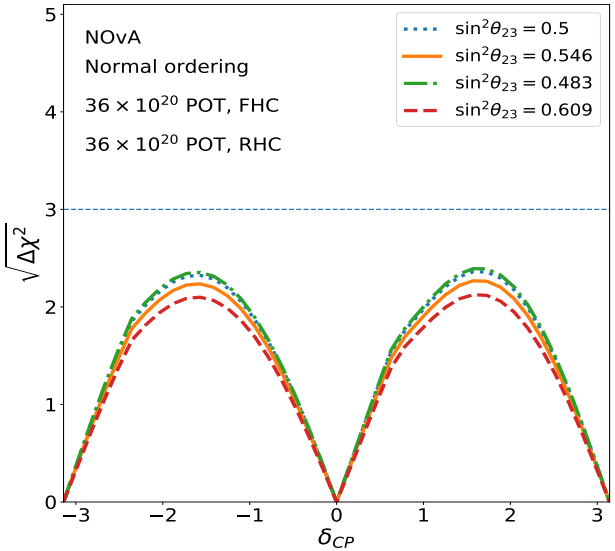




- NOvA:
  - POT in 2020
  - POT in 2026
- DUNE:
  - 2 years of exposure
  - 7 years of exposure

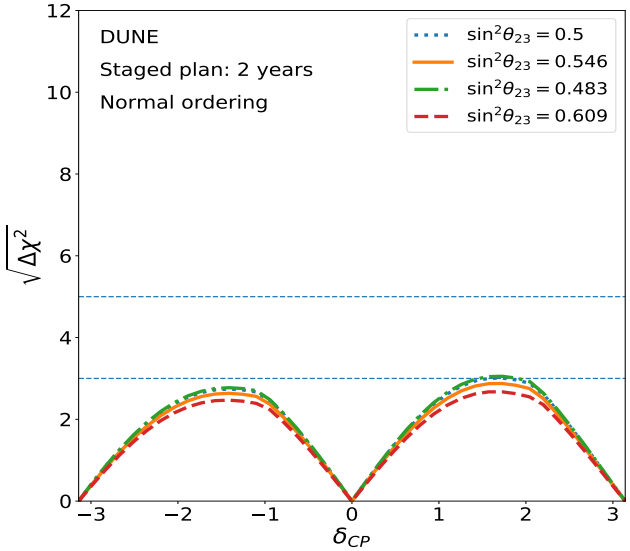
Single δ_{CP} sensitivities

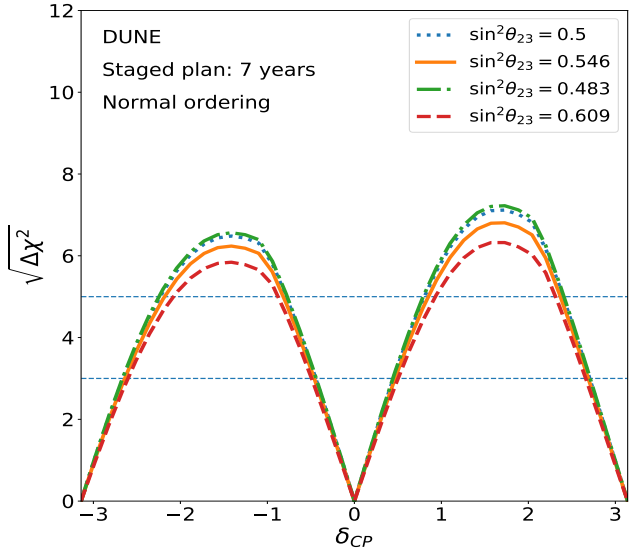




- different values of $\sin^2\theta_{23}$ around the NuFIT 4.0 best-fit value
- normal ordering
- δ_{CP} along the whole $[-\pi, \pi]$ range

$$\sqrt{\Delta\chi^2} = \sqrt{\chi^2_{\delta_{CP}} - \chi^2_{\delta_{CP}=0,\pm\pi}} \text{ (NO)} \quad \Rightarrow \quad \sqrt{\Delta\chi^2} = 0 \text{ in } \delta_{CP} = 0, \pm\pi$$





- NOvA:
  - POT in 2020
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- DUNE:
  - 2 years of exposure
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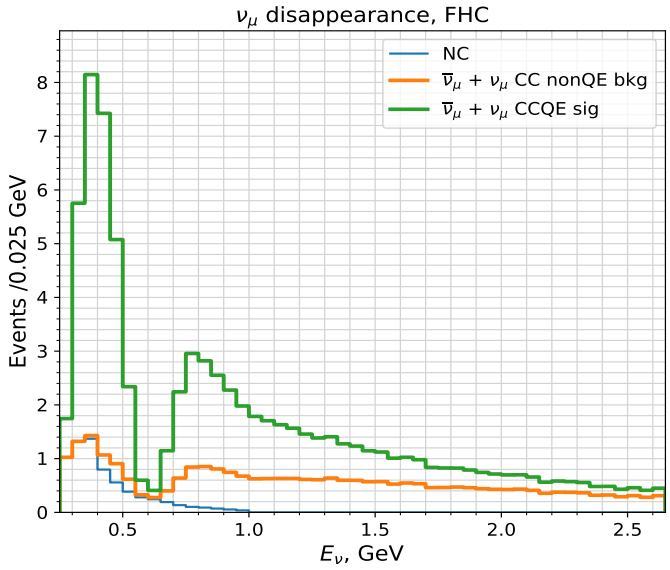
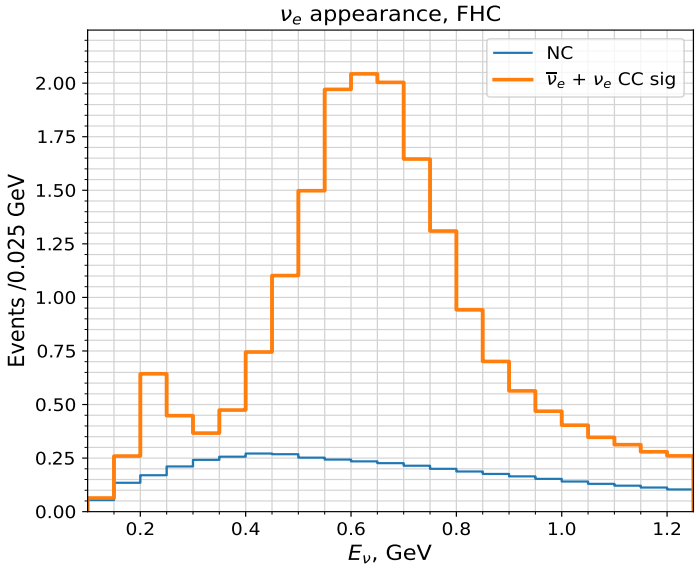
Predicted T2K FD event rates produced within GNA

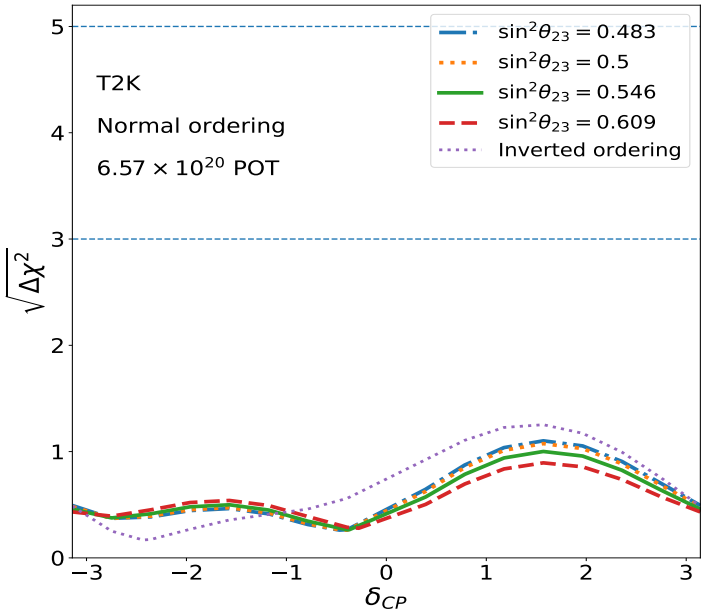




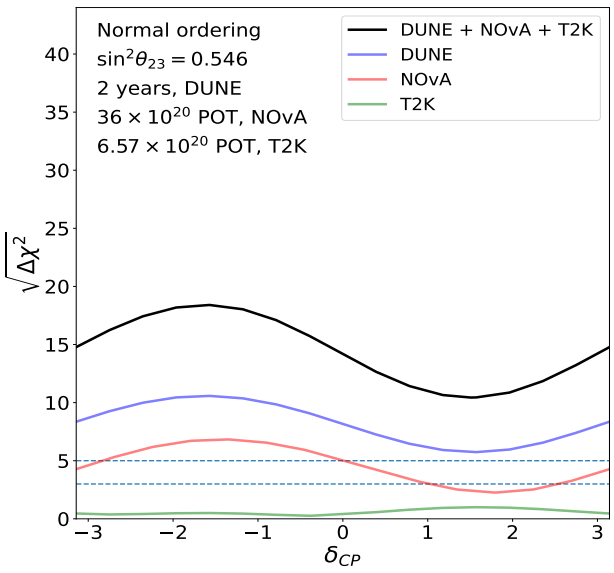
- the total exposure is 6.57×10^{20} POT
- ν_e appearance mode in FHC
- ν_μ disappearance mode in FHC

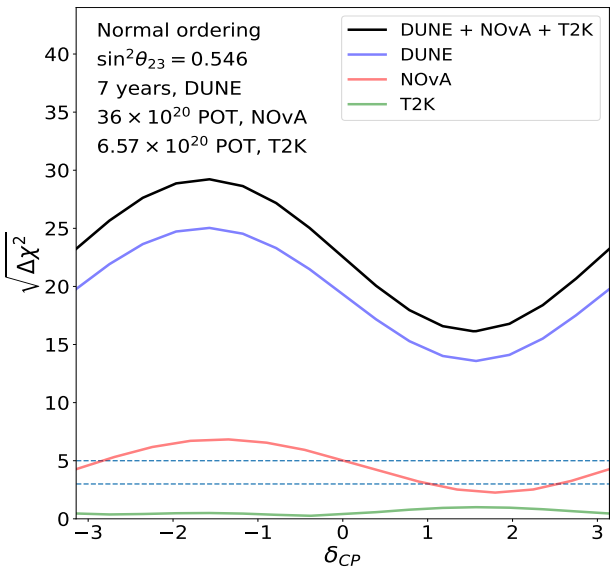
Due to the lack of open T2K RHC inputs the sensitivities were produced:

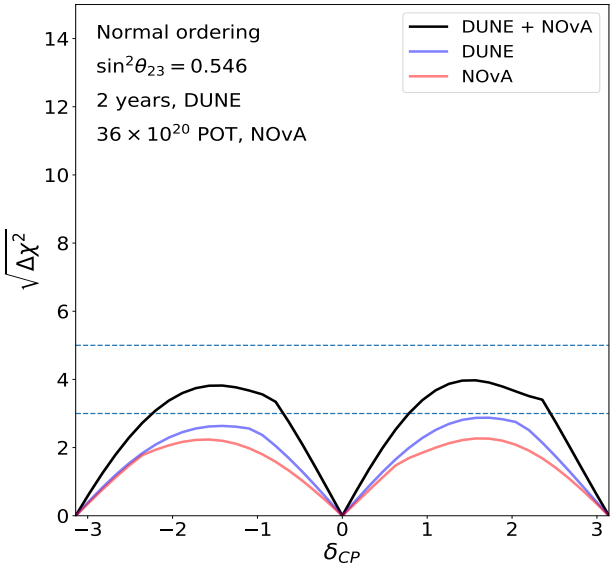
- only to the neutrino mass ordering

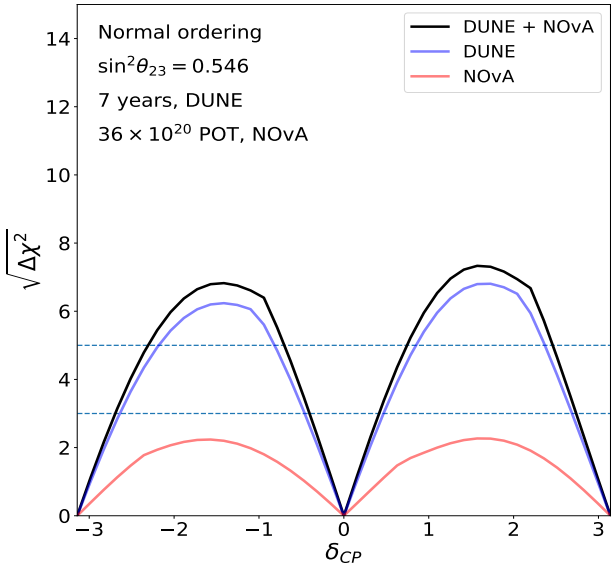


Joint neutrino mass ordering and δ_{CP} sensitivities









- Single sensitivities are also shown.
- the total NOvA exposure for all plots
- 2 / 7 years according to the DUNE plan
- T2K events are into the neutrino mass ordering sensitivities

We are looking forward to the DUNE start and its measurements into the 3 flavor neutrino paradigm of the Standard model of elementary particles.

Thank you for your attention!

Supported by the Russian Science Foundation under grant agreement no. 22-22-00389.