The sensitivity of long-baseline accelerator neutrino experiments to the unknown oscillation parameters

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INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS,
60th Course: NEWS FROM THE FOUR INTERACTIONS, Erice

14 – 23 June 2024

Neutrino oscillations in matter

Neutrino mixing:

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

- ν_α – flavor eigenstate
- ν_i – mass eigenstate

Mixing matrix:

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

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The oscillation probability depends on:

- parameters of the U_{PMNS} matrix
- mass squared splittings: Δm^2_{21}, $\boldsymbol{\Delta m^2_{32}}$ / $\boldsymbol{\Delta m^2_{31}}$ (NO/IO)
- the neutrino mass ordering: **sign** $\boldsymbol{\Delta m^2_{32}}$
- the matter density ρ
- a ratio of a baseline and neutrino energy $\frac{L}{E}$

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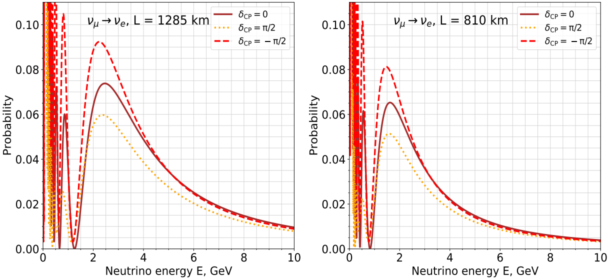

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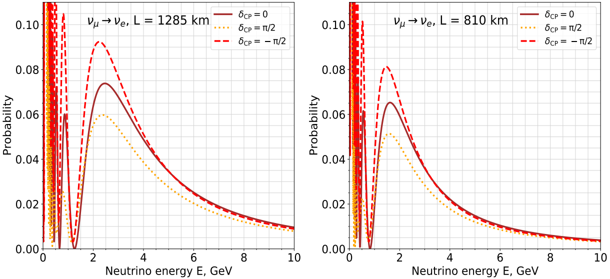
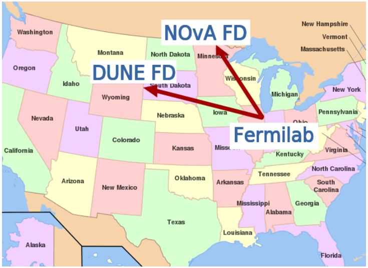


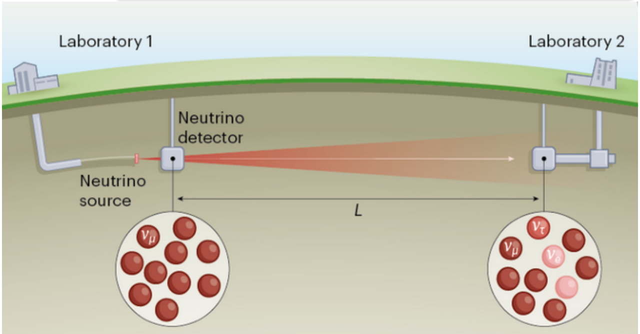
Neutrino sources
(for oscillation study):

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

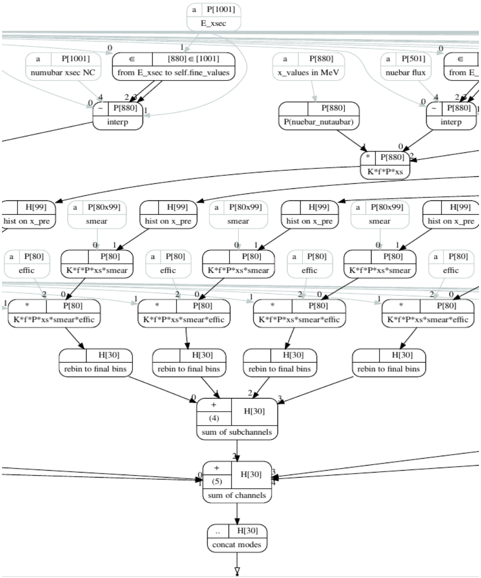
Long-baseline accelerator neutrino experiments (LBL)



Exp.	T2K	NOvA	DUNE
start	2010	2014	≈2030
p source	J-PARC	Fermilab	
FD	WC	liq. scint.	LArTPC
L, km	295	810	1285
M^{fid}_{FD}, kt	22.5	14	40
E, GeV	0 – 3	0.5 – 5	0.5 – 8



Modelling within GNA (developed in JINR)



Tasks:

- to create experiment's models: T2K, NOvA, DUNE;
- to calculate their sensitivities to the unknown oscillation parameters;
- to estimate joint sensitivities.

Global **N**eutrino **A**nalysis – a software for carrying out a data analysis of neutrino events. It has:

- transformation-functions for calculations based on C++, ROOT CERN и Python;
- blocks composed in a graph;
- functions for a statistical data analysis.

A unified shell for LBL experiments in GNA

The configuration file:

- flux, xsec, efficiencies;
- the difference between E_{true} and $E_{recon.}$;
- modes with channels;
- energy scale;
- oscillation parameters;
- parameters of exp.

```
MODES:
 fhc_app_nue:
  Signal: nue
  FhcRhc: fhc
  AppDis: app
  CH:
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     - channel_type: beam
       initial_flavor: nue
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The configuration file is an input of the unified shell, then it is possible to calculate:

- N event rates in channels and modes;
- χ^2 values using calculated N and data;
- an individual sensitivity of each experiment;
- a joint sensitivity of all experiments.

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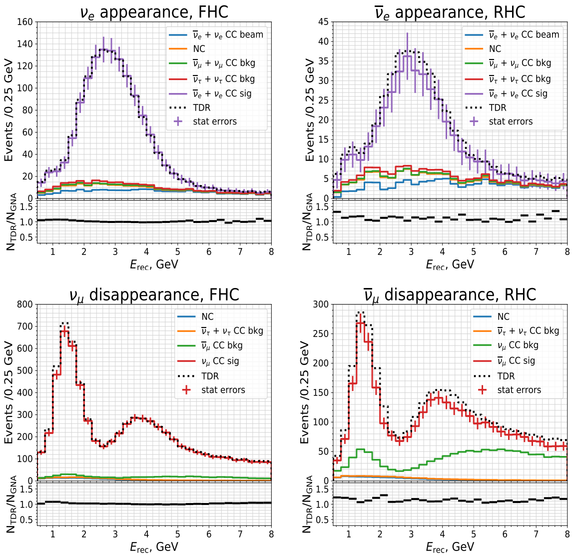
$$N_j^m = \sum_{i=0}^{D} N_{j,m}^i, \quad N_j^i = \mathrm{K} \cdot f(E_{\text{true}})_j \cdot P(E_{\text{true}})(\nu_\alpha \to \nu_\beta)_j \cdot$$

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

$$\chi^2 == -2 \sum_{m=0}^{\mathrm{M}} \sum_{j=0}^{\mathrm{B}} (N_{j,m}^{\text{data}} \ln N_{j,m}^{\text{mod.}} - N_{j,m}^{\text{mod.}} - N_{j,m}^{\text{data}} \ln N_{j,m}^{\text{data}} + N_{j,m}^{\text{data}}) + \frac{(x-\mu)^2}{\sigma^2}$$

DUNE FD energy spectra (event rates vs $E_{recon.}$) in the GNA

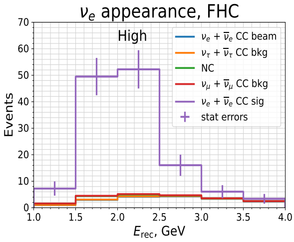


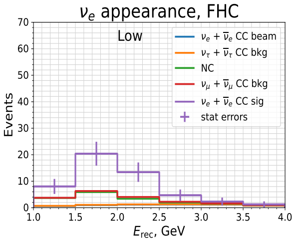
- FHC (forward horn current) / RHC (reverse horn current), equal running time
- 7 years according to the staged plan:

plan	kt	MWt
1 year	20	1.2
2 years	30	1.2
3 years	30	1.2
4 years	40	1.2
7 years	40	2.4
10 years	40	2.4

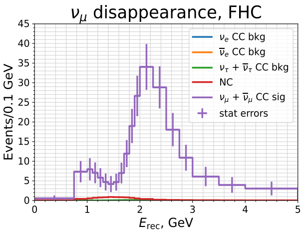
- 4 modes:
  – $\nu_e/\bar{\nu}_e$ appearance
  – $\nu_\mu/\bar{\nu}_\mu$ disappearance
- MC data from: TDR DUNE

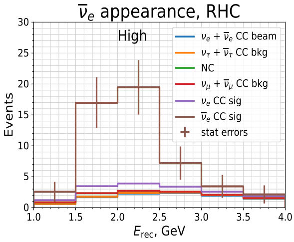
NOvA FD energy spectra (event rates vs $E_{recon.}$) in the GNA

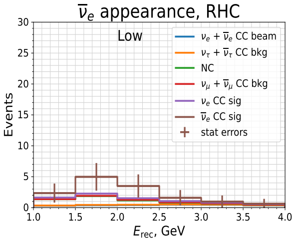


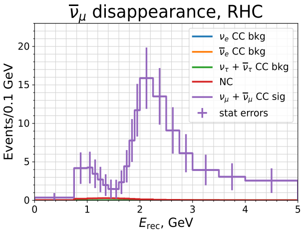


High / Low PID



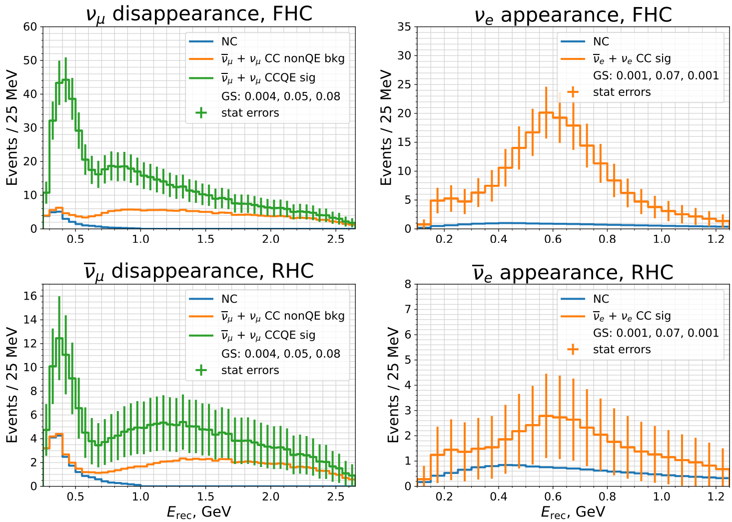






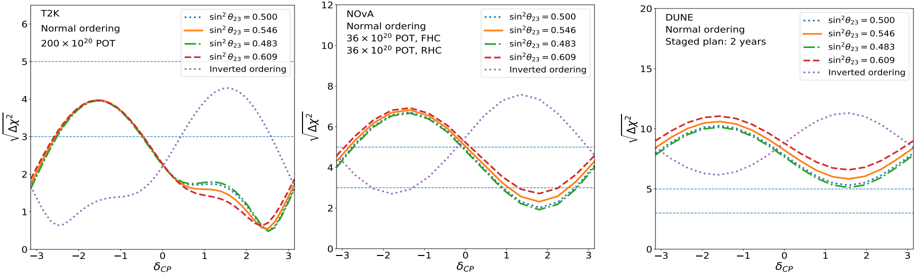
36×10^{20} POT (protons on target) in each regime

T2K FD energy spectra (event rates vs $E_{recon.}$) in the GNA



200 × 10^{20} POT (FHC+RHC): $\nu_\mu/\overline{\nu_\mu}$ disappearance / $\nu_e/\overline{\nu_e}$ appearance

T2K, NOvA, DUNE sensitivities to the neutrino mass ordering

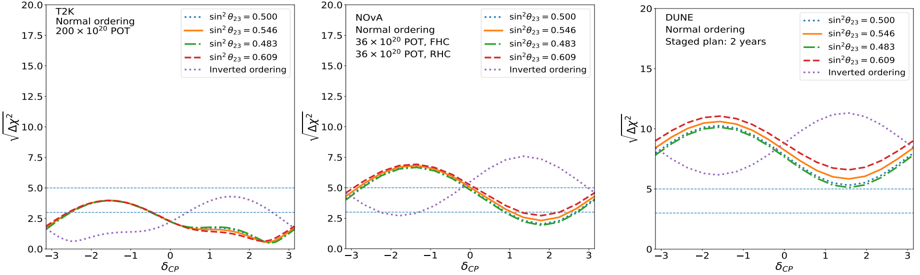


$$\sqrt{\Delta\chi^2} = \sqrt{\chi^2_{\text{IO}} - \chi^2_{\text{NO}}}\ (\text{NO}) \quad \text{or} \quad \sqrt{\Delta\chi^2} = \sqrt{\chi^2_{\text{NO}} - \chi^2_{\text{IO}}}\ (\text{IO})$$

- different $\sin^2\theta_{23}$ values around the best fit from NuFIT 4.0;
- both orderings;
- δ_{CP} in the whole $[-\pi, \pi]$ range.

- DUNE vs (NOvA, T2K): DUNE will be able to resolve the neutrino mass ordering problem at 5σ significant level in 2 years.
- NOvA vs T2K: due to the longer baseline (810 km vs 295 km) NOvA is more sensitive to the neutrino mass ordering than T2K.

T2K, NOvA, DUNE sensitivities to the neutrino mass ordering



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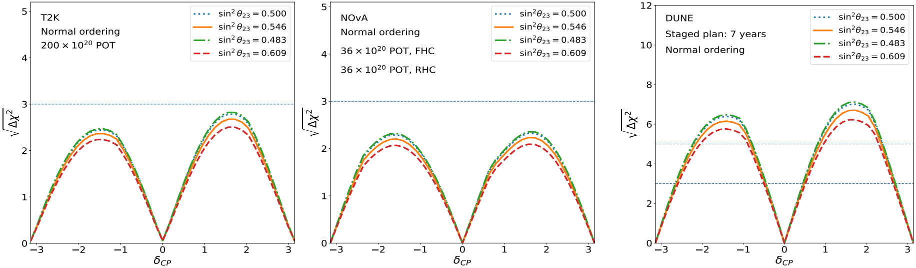
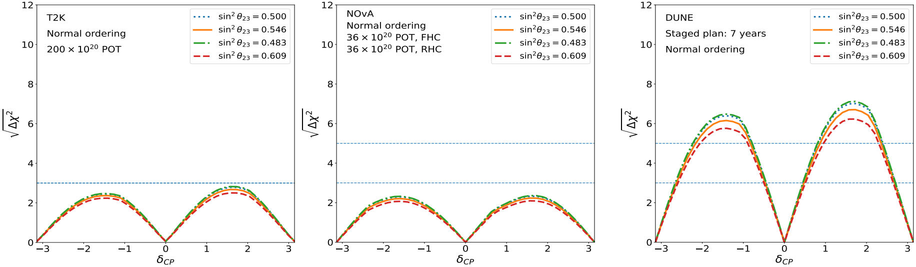
T2K, NOvA, DUNE sensitivities to the δ_{CP} phase



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

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

- DUNE vs (NOvA, T2K): DUNE sensitivity will be higher then 3σ level for some values of δ_{CP} in 7 years
- NOvA vs T2K: due to the shorter baseline T2K is more sensitive to the δ_{CP} phase than NOvA



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

- different $\sin^2\theta_{23}$ values around the best fit one NuFIT 4.0
- both orderings
- $\delta_{\rm CP}$ in the whole $[-\pi, \pi]$ range

- DUNE vs (NOvA, T2K): DUNE sensitivity will be higher then 3σ level for some values of $\delta_{\rm CP}$ in 7 years
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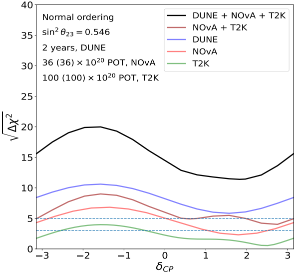
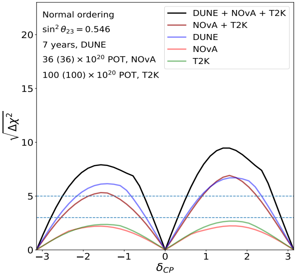
Joint T2K, NOvA и DUNE sensitivities to the unknown oscillation parameters





- It is expected that NOvA+T2K will give the first prediction of the neutrino mass ordering and the $\delta_{\rm CP}$ phase (for some values) at $> 5\sigma$ level

- joint T2K+NOvA+DUNE sensitivities to the neutrino mass ordering and the $\delta_{\rm CP}$ phase:

Sensitivity	min($n\sigma$)	range of $\delta_{\rm CP}$ values $> 5\sigma$
Joint	11.4	[-2.51, -0.63] ∪ [0.63, 2.51] (60%)

Conclusion

During the study of the neutrino oscillation phenomenon:

- There was a comparison of long-baseline accelerator neutrino experiments such as T2K, NOvA (currently working), and the future DUNE experiment.

- The unified shell for FD spectra modeling was developed in the GNA.

- Individual and joint sensitivities of three experiments to the unknown oscillation parameters were calculated. The unknown parameters are the neutrino mass ordering and the CP phase.

Thank you for your attention!