The GNA software for performing neutrino oscillation analysis

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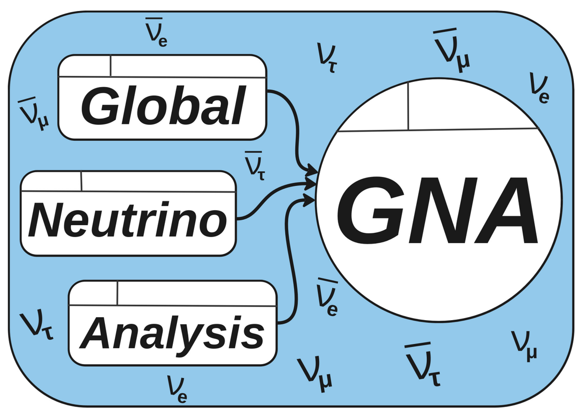
Global Neutrino Analysis (GNA)

- A software for carrying out a data analysis of neutrino events. It includes:
  - ▷ transformation-functions for calculations based on C++, ROOT CERN and Python;
  - ▷ blocks composed in a graph;
  - ▷ functions for a statistical data analysis.



- GNA is developed in the Dzhelepov Laboratory of Nuclear Problems (JINR).

A unified shell for modeling long-baseline experiments in GNA

```
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
```

- The configuration file includes:
  - ▷ paths for flux, xsec, efficiencies files;
  - ▷ the difference between E_{true} and E_{recon} or Gaussian energy resolution;
  - ▷ modes with channels;
  - ▷ an energy scale;
  - ▷ oscillation parameters;
  - ▷ parameters of an experiment.

- The configuration file is an input of the unified shell, then it is possible to calculate:
  - ▷ N event rates in i energy bins for j channels of m modes:

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

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

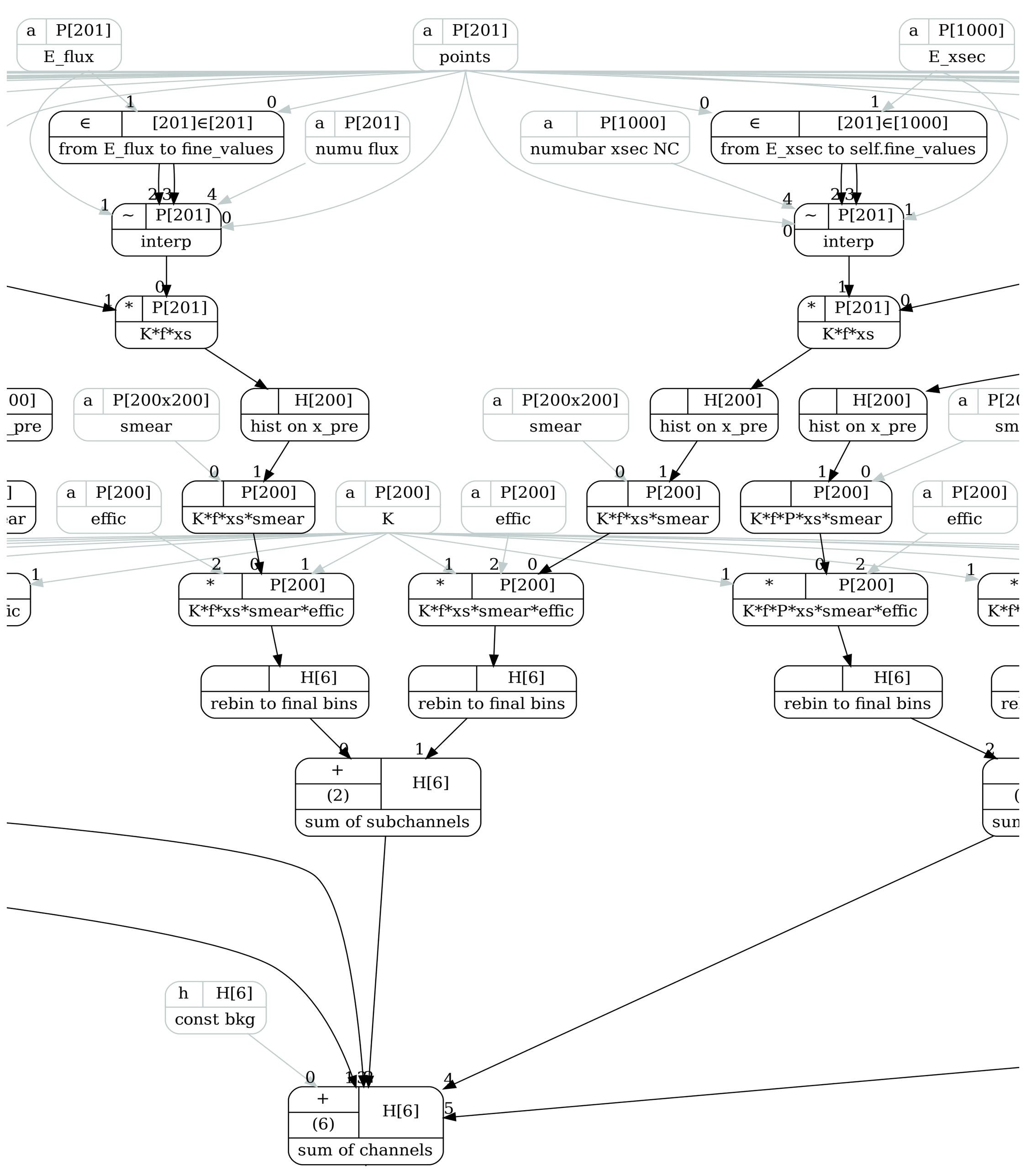
  - ▷ χ^2 values with nuisance terms using calculated event rates and data;

$$\chi^2 = -2 \sum_{m=0}^{M} \sum_{j=0}^{B} \left(N_{j,m}^{\text{data}} \ln N_{j,m}^{\text{mod.}} - \right.$$

$$\left. - N_{j,m}^{\text{mod.}} - N_{j,m}^{\text{data}} \ln N_{j,m}^{\text{data}} + N_{j,m}^{\text{data}} \right) + \frac{(x-\mu)^2}{\sigma^2}$$

- Finally, the whole point of these calculations is to estimate individual and joint sensitivities of experiments to oscillation parameters.

A model graph fragment in the GNA



- Creating a graph allows us to control the correctness of model.
- It is unnecessary to recalculate the full model during the fit → the lazy evaluation.
- There is an opportunity to add some blocks during the fit → the extensibility.
- This approach makes a process of simulation faster and more efficient.

References

- GNA page: http://gna.pages.jinr.ru/gna/
- Git repository: https://git.jinr.ru/gna/gna

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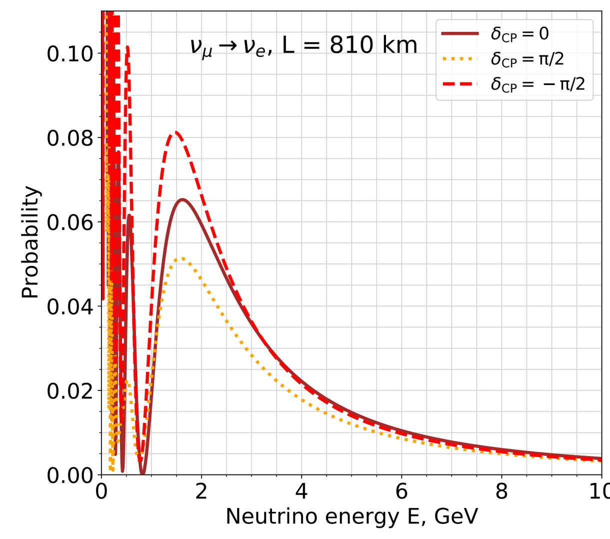
Neutrino oscillations in matter

- Neutrino mixing: $\nu_\alpha = \sum_{i=1}^{3} U_{\alpha,i}^* \cdot \nu_i, \quad \alpha = e,\ \mu,\ \tau,$

  ν_α – flavour eigenstates, ν_i – mass eigenstates.
- Pontecorvo-Maki-Nakagawa-Sakata matrix $\mathbf{U}$ is a lepton mixing matrix: $\mathbf{U} \sim \theta_{12},\ \theta_{13},\ \theta_{23},\ \delta_{\text{CP}}$.
- The oscillation probability depends on:
  - ▷ parameters of $\mathbf{U}$ matrix;
  - ▷ mass squared differences: Δm_{21}^2, Δm_{32}^2;
  - ▷ the neutrino mass ordering: sign Δm_{32}^2;
  - ▷ the matter density ρ;
  - ▷ a ratio of a baseline and neutrino energy $\frac{L}{E}$.

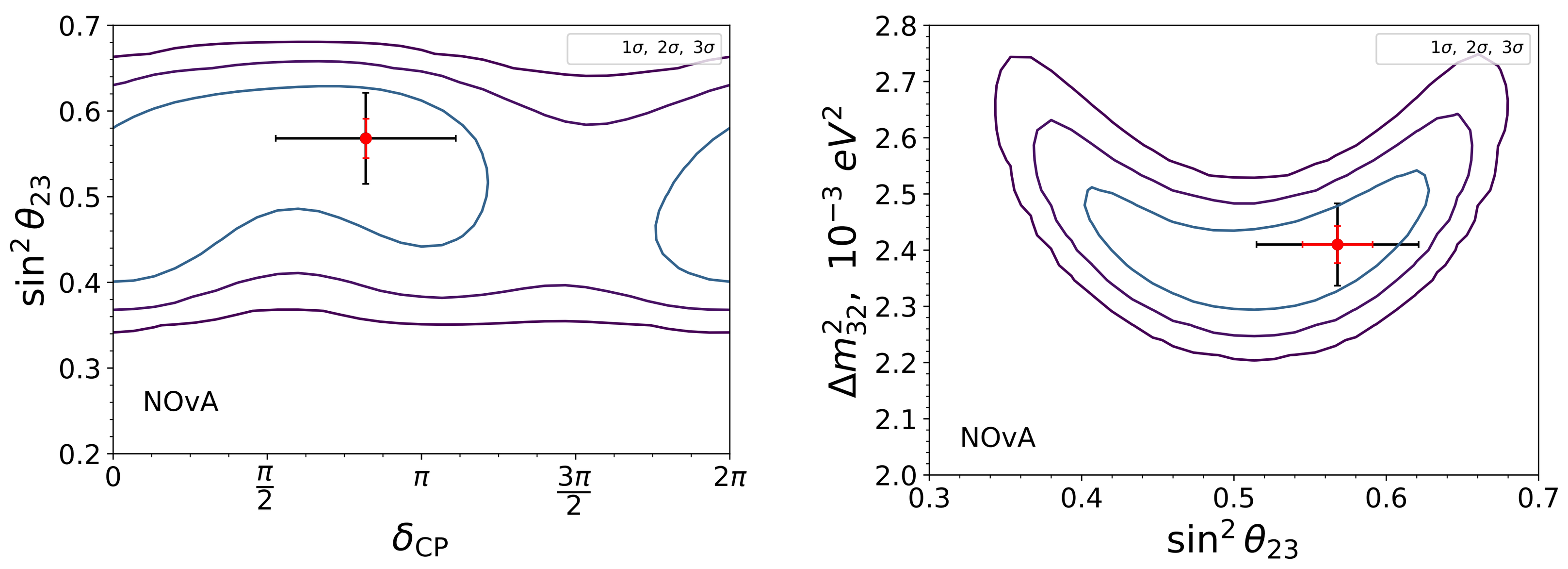


- There are unknown parameters: the sign of Δm_{32}^2, the octant of θ_{23}, and δ_{CP}.

Sensitivities to the unknown oscillation parameters

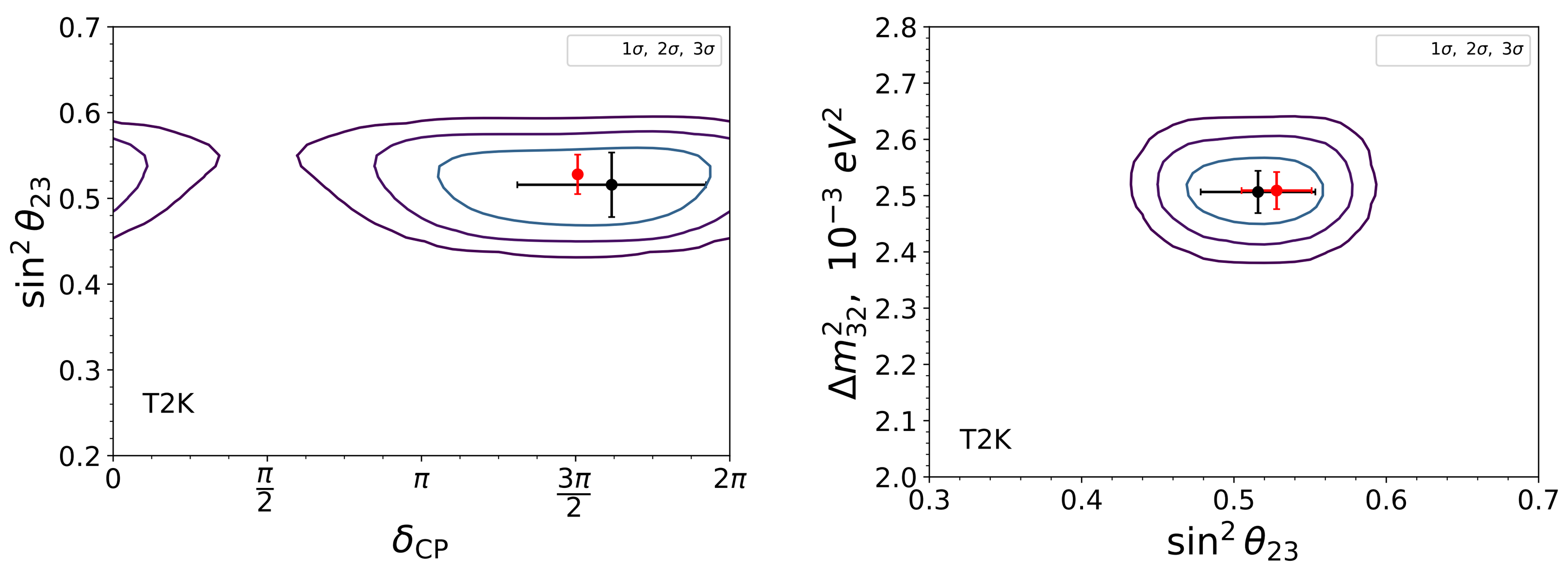
- There are 2 operating long-baseline neutrino oscillation experiments: NOvA (NuMI Off-axis ν_e Appearance) and T2K (Tokai to Kamioka).
- 2 dimensional contours with Asimov dataset (MC) within GNA:
  - ▷ assuming the normal neutrino mass ordering;
  - ▷ 12 modes in NOvA:

    - 4 $\nu_e/\overline{\nu}_e$ appearance (high, low PID), 8 $\nu_\mu/\overline{\nu}_\mu$ disappearance (quartiles with the different hadron energy fraction):



  - ▷ 5 modes in T2K:

    - 2 $\nu_e/\overline{\nu}_e$ + 1 ν_e CC1π appearance, 2 $\nu_\mu/\overline{\nu}_\mu$ disappearance in both regimes (forward horn current, reverse horn current):



• – expected MC best fit points, • – calculated best fit points (after analysis).

The future global fit

- previous and current oscillation experiments:

Type	Experiments	Parameters	Energy
Solar + KamLAND	Homestake, GALLEX/GNO, SAGE, Borexino, SNO, SuperK + KamLAND	$\Delta m_{21}^2,\ \theta_{21}$	0.1 — 20 MeV
SBL reactor	RENO, Double Chooz, Daya Bay	$\Delta m_{31}^2(\Delta m_{ee}^2),\ \theta_{31}$	1 — 8 MeV
Accelerator	MINOS, K2K, T2K, NOvA	$\Delta m_{32}^2,\ \theta_{23},\ \delta_{CP}$	1 — 10 GeV
Atmosphere	IceCube DeepCore, SuperK	$\Delta m_{31}^2,\ \theta_{23}$	0.1 — 100 GeV

- future neutrino oscillation experiments: JUNO, DUNE, T2HK, KM3NeT ORCA, ESSνSB and others.

The **goal** is to combine experiments and estimate their global sensitivities to unknown oscillation parameters within the GNA software.