The data fitter of neutrino oscillation experiments in the GNA software

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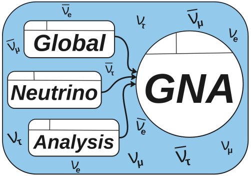
Global Neutrino Analysis (GNA)

GNA is a software for carrying out a data analysis of neutrino events

It includes:

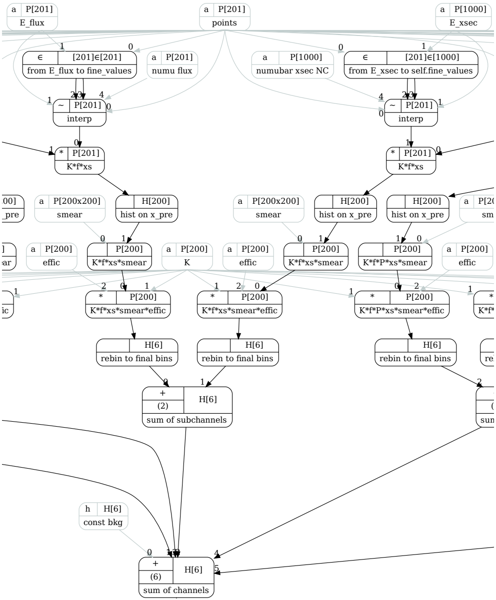
- transformation-functions for calculations based on C++, ROOT CERN and Python;
- blocks composed in a graph;
- functions for a statistical data analysis: minimizers, scan functions, fitting ones...



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

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

A model graph fragment in the GNA



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

```
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 some physical quantities.

- N event rates in i energy bins for j channels of m modes:

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

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

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

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

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

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

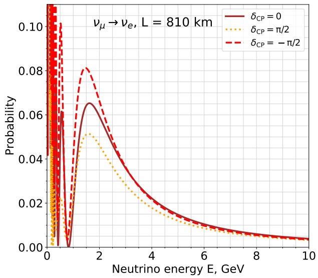
Neutrino oscillations in matter

- Neutrino mixing: $\nu_\alpha = \sum_{i=1}^{3} \mathrm{U}^*_{\alpha,\mathrm{i}} \cdot \nu_i, \qquad \alpha = e,\ \mu,\ \tau,$

  ν_α – flavour eigenstates, ν_i – mass eigenstates.
- Pontecorvo-Maki-Nakagawa-Sakata matrix U is a lepton mixing matrix: $\mathrm{U} \sim \theta_{12},\ \theta_{13},\ \theta_{23},\ \delta_{\mathrm{CP}}$.

The oscillation probability depends on:

- parameters of U matrix;
- mass squared differences: Δm^2_{21}, Δm^2_{32};
- the neutrino mass ordering: sign Δm^2_{32};
- the matter density ρ;
- a ratio of a baseline and neutrino energy $\frac{L}{E}$.



The sign of Δm^2_{32}, the octant of θ_{23}, and δ_{CP} are unknown parameters.

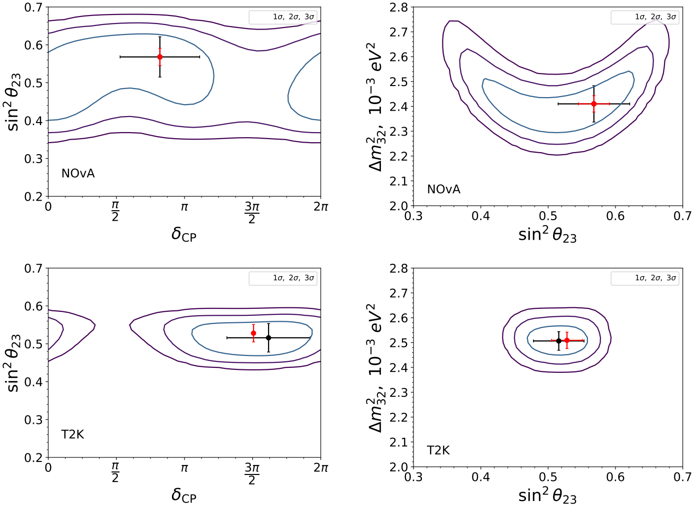
Sensitivities to the unknown oscillation parameters [1/2]

There are 2 operating long-baseline neutrino oscillation experiments:

NOvA (NuMI Off-axis ν_e Appearance) and T2K (Tokai to Kamioka)

- 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)

2 dimensional contours with Asimov dataset (MC) within GNA



• – expected MC best fit points, • – calculated best fit points.

The future global fit

- previous and current oscillation experiments:

Type	Experiments	Parameters	Energy
Solar+KamLAND	Homestake, GALLEX/GNO, SAGE, Borexino, SNO, SuperK + KamLAND	$\Delta m^2_{21},\ \theta_{12}$	0.1–20 MeV
SBL reactor	RENO, Double Chooz, Daya Bay	$\Delta m^2_{31} (\Delta m^2_{ee}),\ \theta_{13}$	1–8 MeV
Accelerator	MINOS, K2K, T2K, NOvA	$\Delta m^2_{32},\ \theta_{23},\ \delta_{CP}$	1–10 GeV
Atmospheric	IceCube DeepCore, SuperK	$\Delta m^2_{31},\ \theta_{23}$	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.

Thank you for attention!

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