Introduction to GLoBES

(General Long Baseline Experiment Simulator)

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7th Vietnam School on Neutrinos, July 26, 2023

Outline

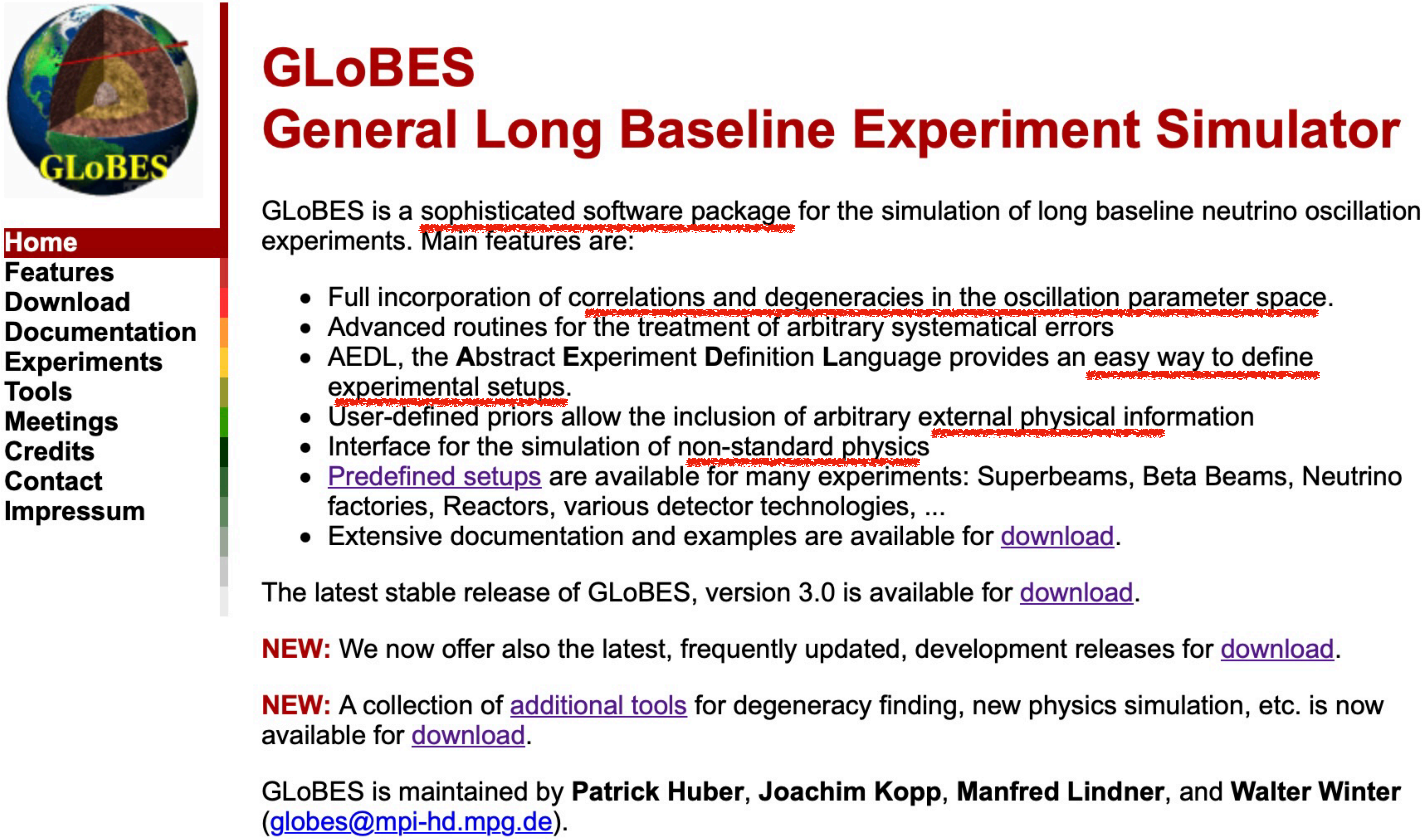
- Preamble
  - Impression
  - The NEED of sensitivity estimation
  - The NEED of joint analysis in neutrino oscillation
- Input and output of the GLoBES
- Understand the framework
  - Retrieve the oscillation probabilities
  - Look at the experimental setup
  - Obtain the event rate
  - Calculate the statistical significance with $\chi^2/\Delta\chi^2$

Source code: https://github.com/cvson/nushortcourse/tree/master/globes

I will go slowly for demonstration, but maybe you can follow offline later if you can't catch up.

GLoBES webpage

https://www.mpi-hd.mpg.de/personalhomes/globes/index.html



GLoBES
General Long Baseline Experiment Simulator

GLoBES is a sophisticated software package for the simulation of long baseline neutrino oscillation experiments. Main features are:

- Full incorporation of correlations and degeneracies in the oscillation parameter space.
- Advanced routines for the treatment of arbitrary systematical errors
- AEDL, the **A**bstract **E**xperiment **D**efinition **L**anguage provides an easy way to define experimental setups.
- User-defined priors allow the inclusion of arbitrary external physical information
- Interface for the simulation of non-standard physics
- Predefined setups are available for many experiments: Superbeams, Beta Beams, Neutrino factories, Reactors, various detector technologies, ...
- Extensive documentation and examples are available for download.

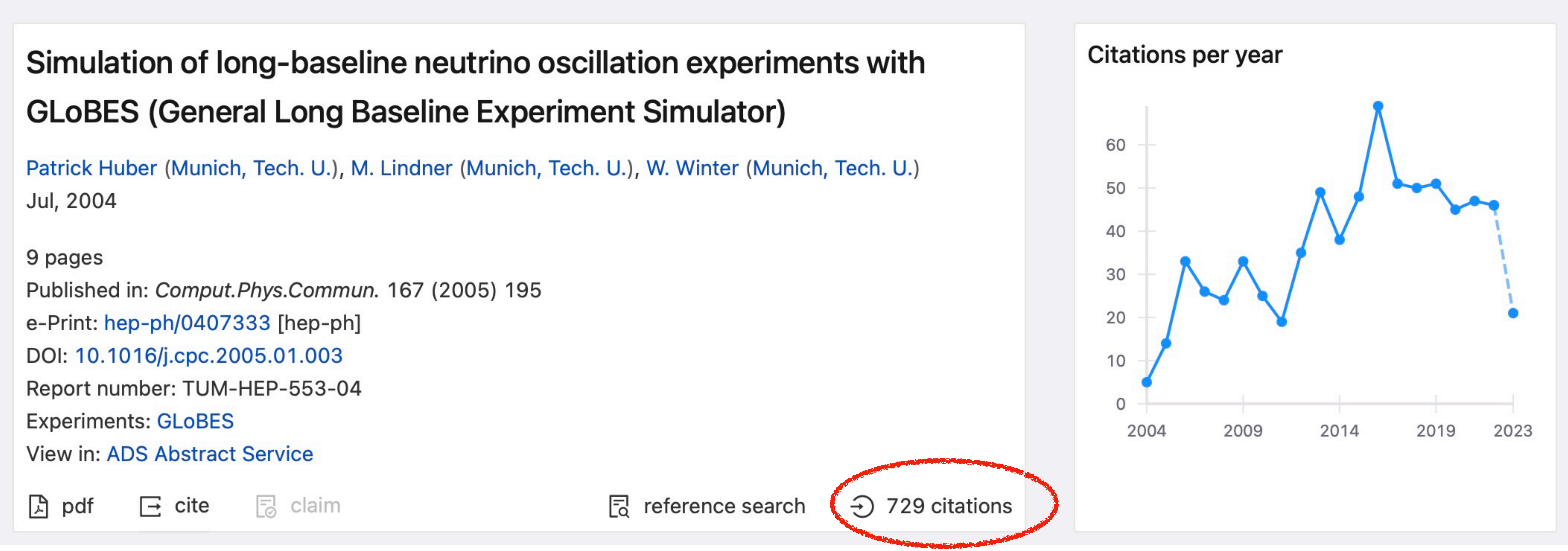
The latest stable release of GLoBES, version 3.0 is available for download.

NEW: We now offer also the latest, frequently updated, development releases for download.

NEW: A collection of additional tools for degeneracy finding, new physics simulation, etc. is now available for download.

GLoBES is maintained by **Patrick Huber**, **Joachim Kopp**, **Manfred Lindner**, and **Walter Winter** (globes@mpi-hd.mpg.de).

GLoBES citations



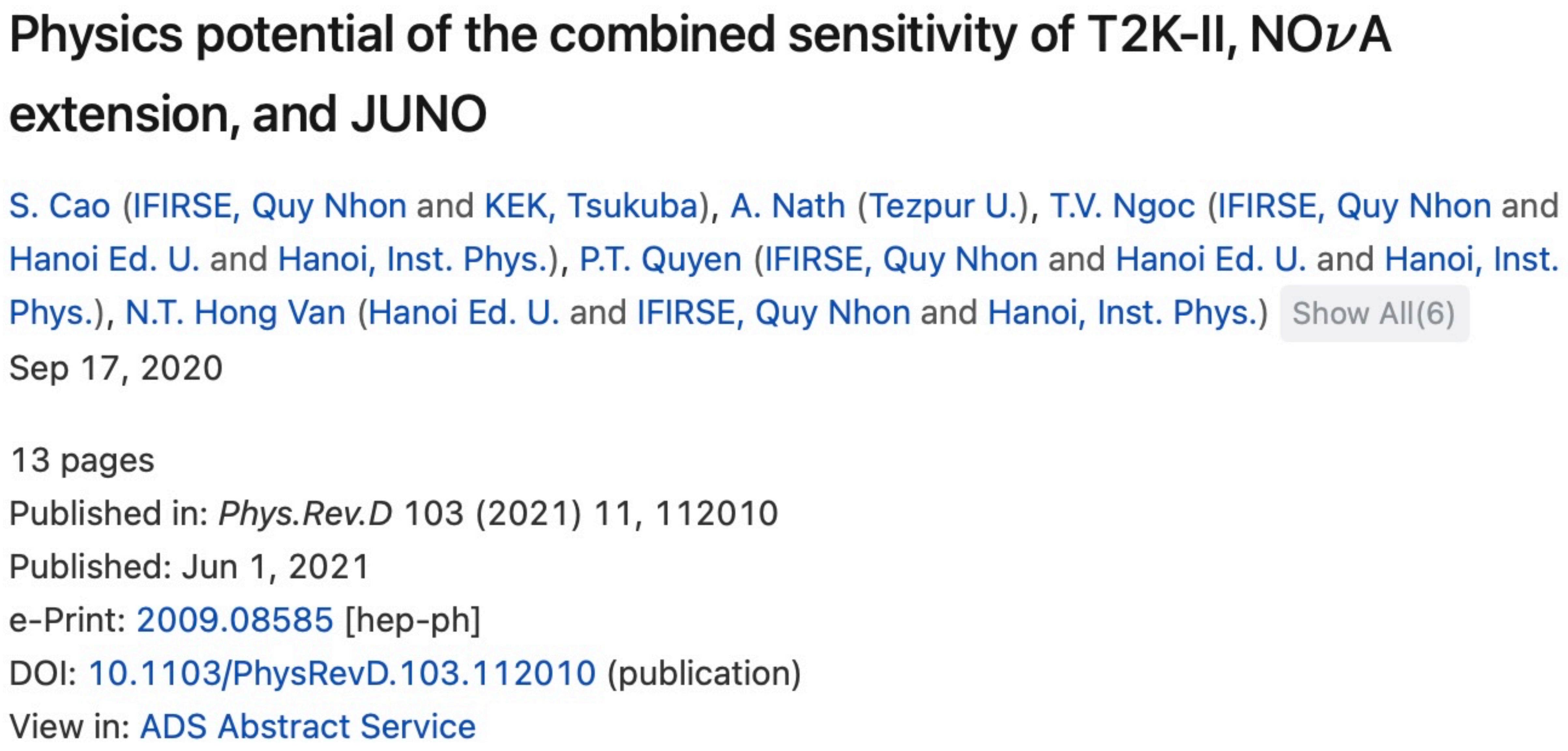
Simulation of long-baseline neutrino oscillation experiments with GLoBES (General Long Baseline Experiment Simulator)

Patrick Huber (Munich, Tech. U.), M. Lindner (Munich, Tech. U.), W. Winter (Munich, Tech. U.)
Jul, 2004

9 pages
Published in: *Comput.Phys.Commun.* 167 (2005) 195
e-Print: hep-ph/0407333 [hep-ph]
DOI: 10.1016/j.cpc.2005.01.003
Report number: TUM-HEP-553-04
Experiments: GLoBES
View in: ADS Abstract Service

The framework is well utilized by both theorists and experimentalists

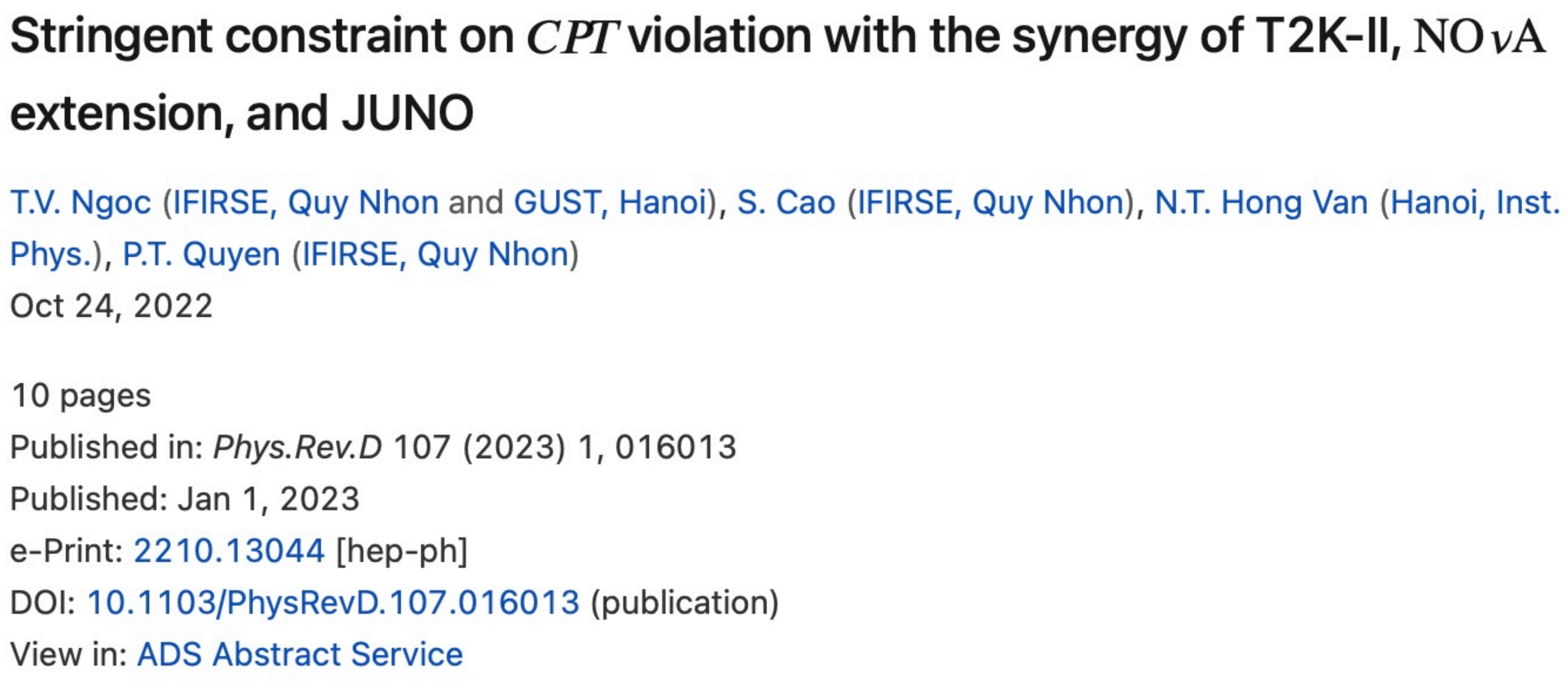
Our recent publication with GloBES



Physics potential of the combined sensitivity of T2K-II, NOνA extension, and JUNO

S. Cao (IFIRSE, Quy Nhon and KEK, Tsukuba), A. Nath (Tezpur U.), T.V. Ngoc (IFIRSE, Quy Nhon and Hanoi Ed. U. and Hanoi, Inst. Phys.), P.T. Quyen (IFIRSE, Quy Nhon and Hanoi Ed. U. and Hanoi, Inst. Phys.), N.T. Hong Van (Hanoi Ed. U. and IFIRSE, Quy Nhon and Hanoi, Inst. Phys.) Show All(6)
Sep 17, 2020

13 pages
Published in: *Phys.Rev.D* 103 (2021) 11, 112010
Published: Jun 1, 2021
e-Print: 2009.08585 [hep-ph]
DOI: 10.1103/PhysRevD.103.112010 (publication)
View in: ADS Abstract Service



Stringent constraint on CPT violation with the synergy of T2K-II, NOνA extension, and JUNO

T.V. Ngoc (IFIRSE, Quy Nhon and GUST, Hanoi), S. Cao (IFIRSE, Quy Nhon), N.T. Hong Van (Hanoi, Inst. Phys.), P.T. Quyen (IFIRSE, Quy Nhon)
Oct 24, 2022

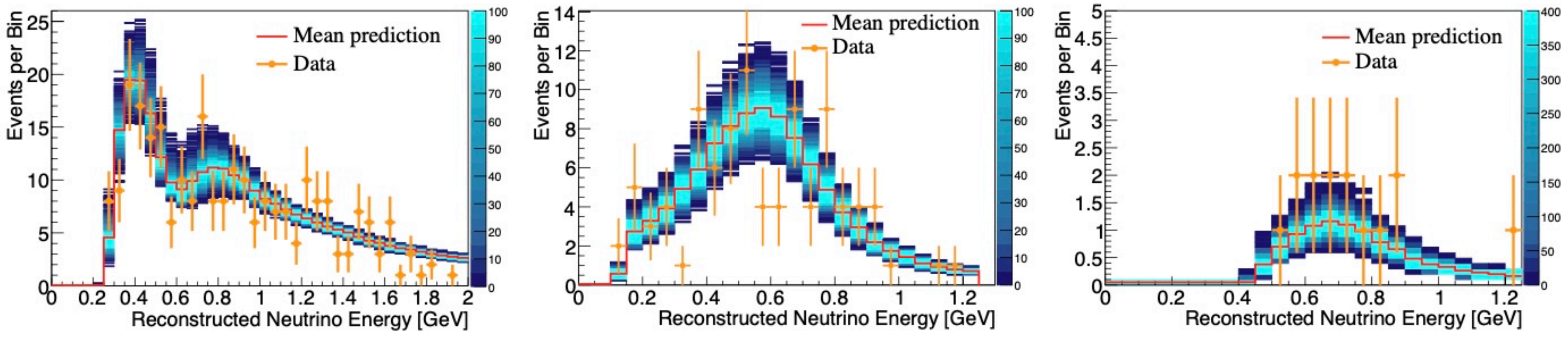
10 pages
Published in: *Phys.Rev.D* 107 (2023) 1, 016013
Published: Jan 1, 2023
e-Print: 2210.13044 [hep-ph]
DOI: 10.1103/PhysRevD.107.016013 (publication)
View in: ADS Abstract Service

We published 2 articles on PRD using GloBES and other works are under preparation for publication

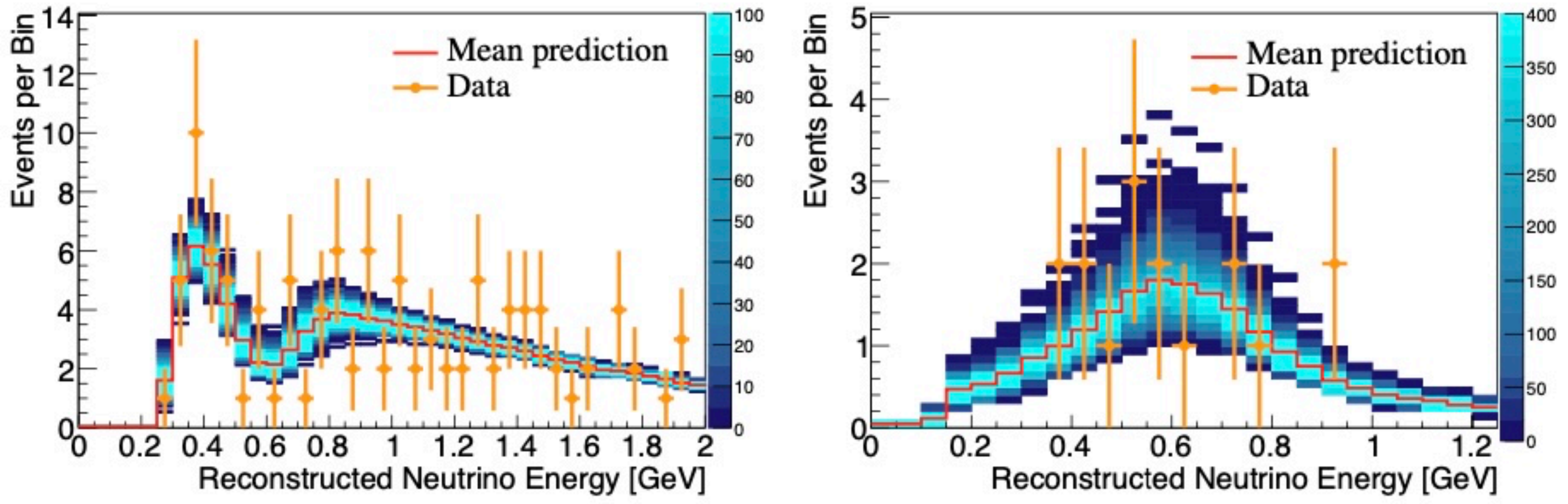
Difference btw/ Data fit and sensitivity study?

Main difference btw/ Data fit and sensitivity study

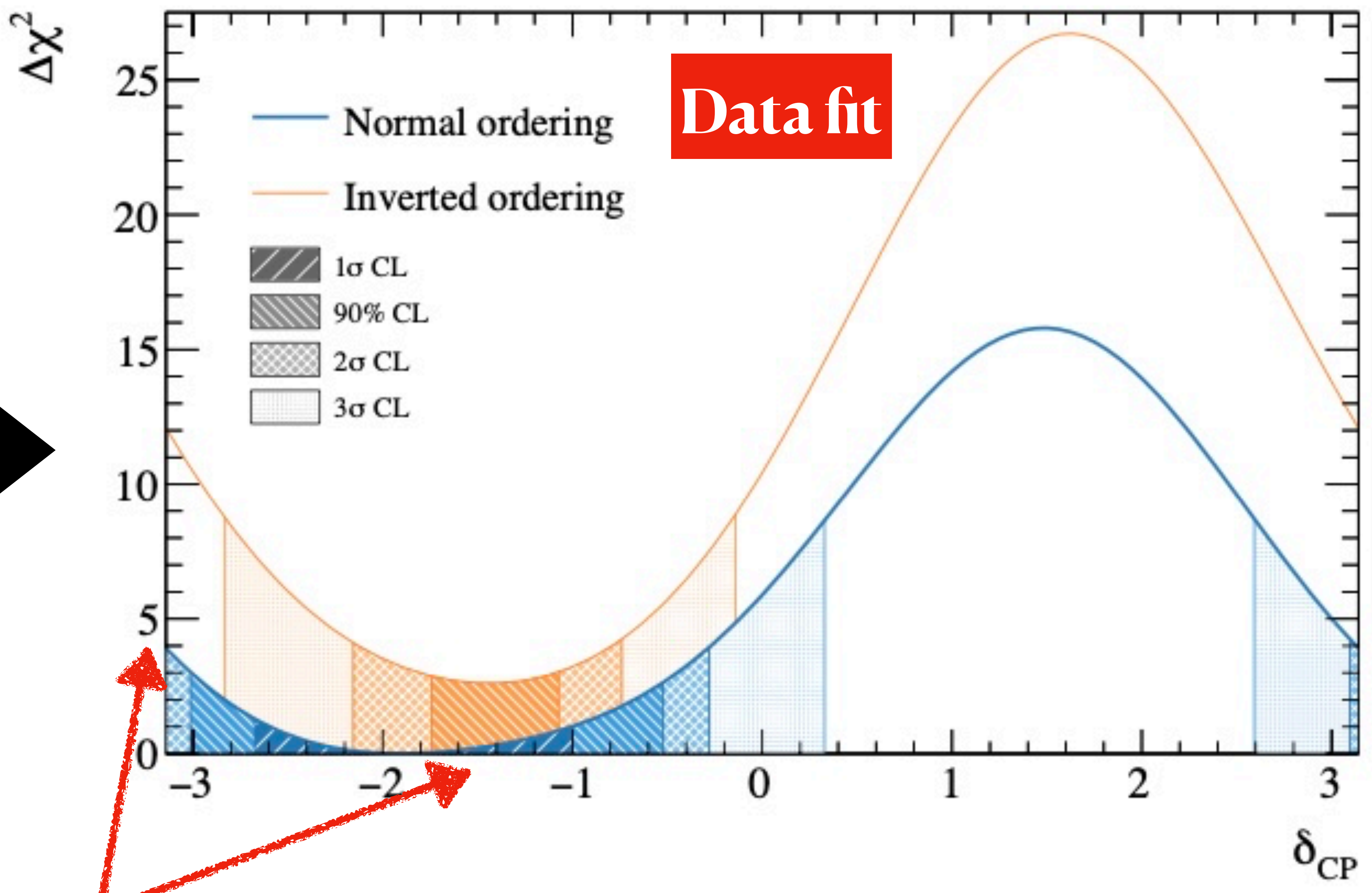
arXiv: 2303.03222 [hep-ex]



(a) ν-mode 1Rμ (b) ν-mode 1Re (c) ν-mode 1Re1de



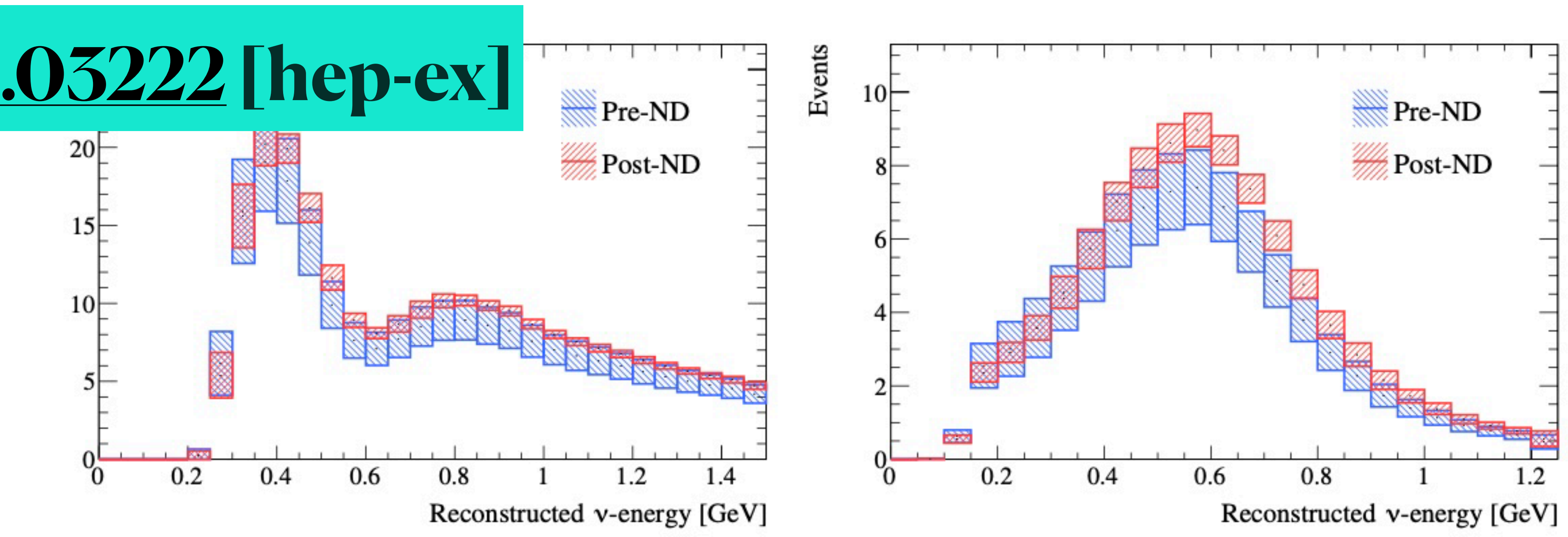
(d) $\overline{\nu}$-mode 1Rμ (e) $\overline{\nu}$-mode 1Re



Data fit is to find the best parameter set to describe the data and estimate the significance to exclude some hypothesis

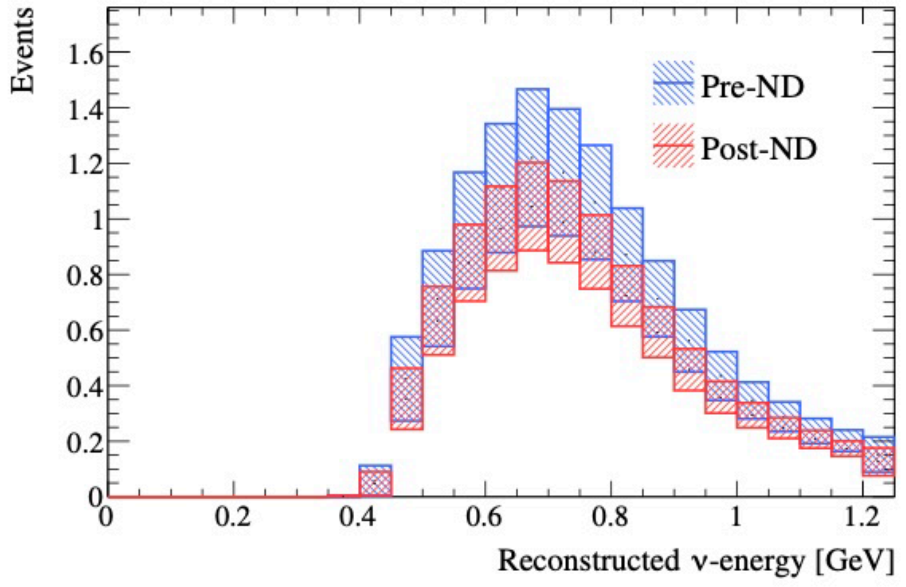
Main difference btw/ Data fit and sensitivity study (cont'd)

arXiv: 2303.03222 [hep-ex]

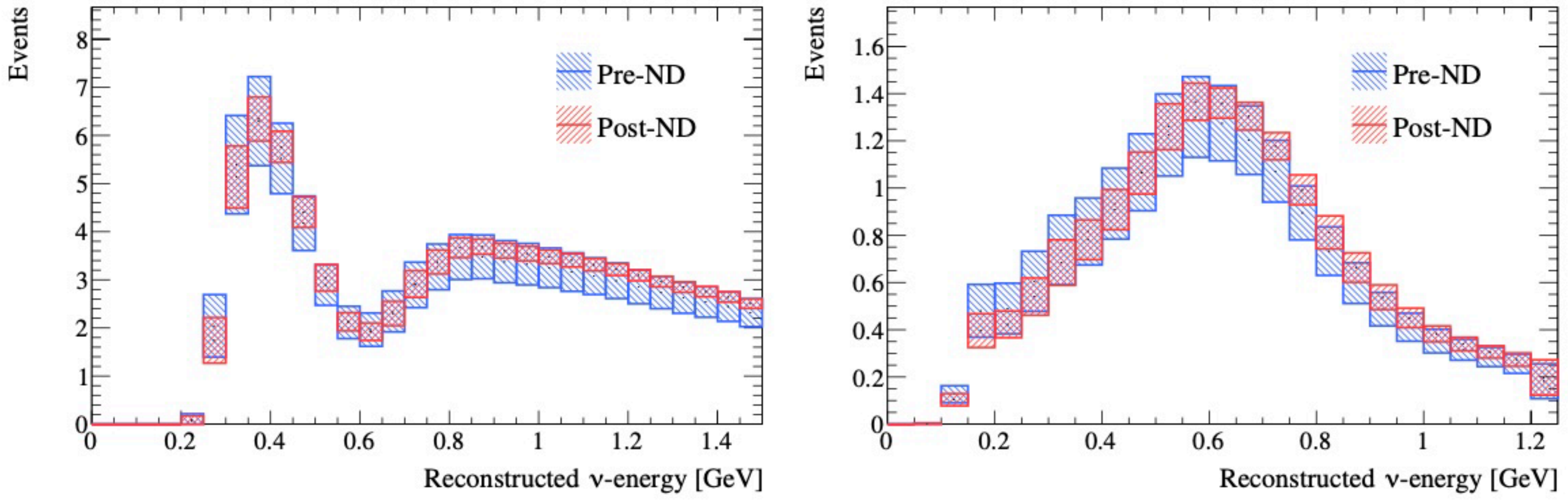


(a) ν-mode 1Rμ

(b) ν-mode 1R*e*

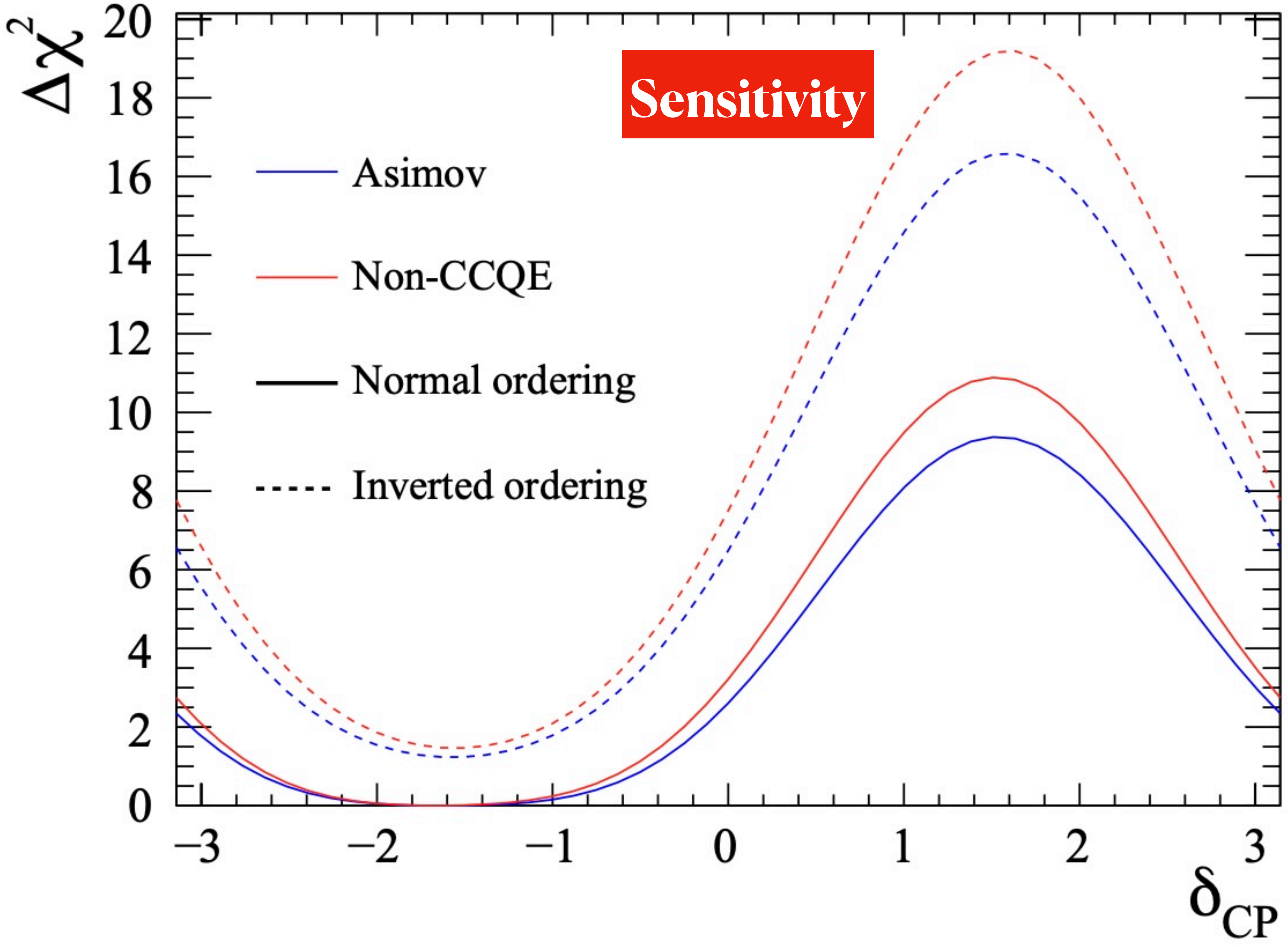


(c) ν-mode 1R*e*1d*e*



(d) $\bar{\nu}$-mode 1Rμ

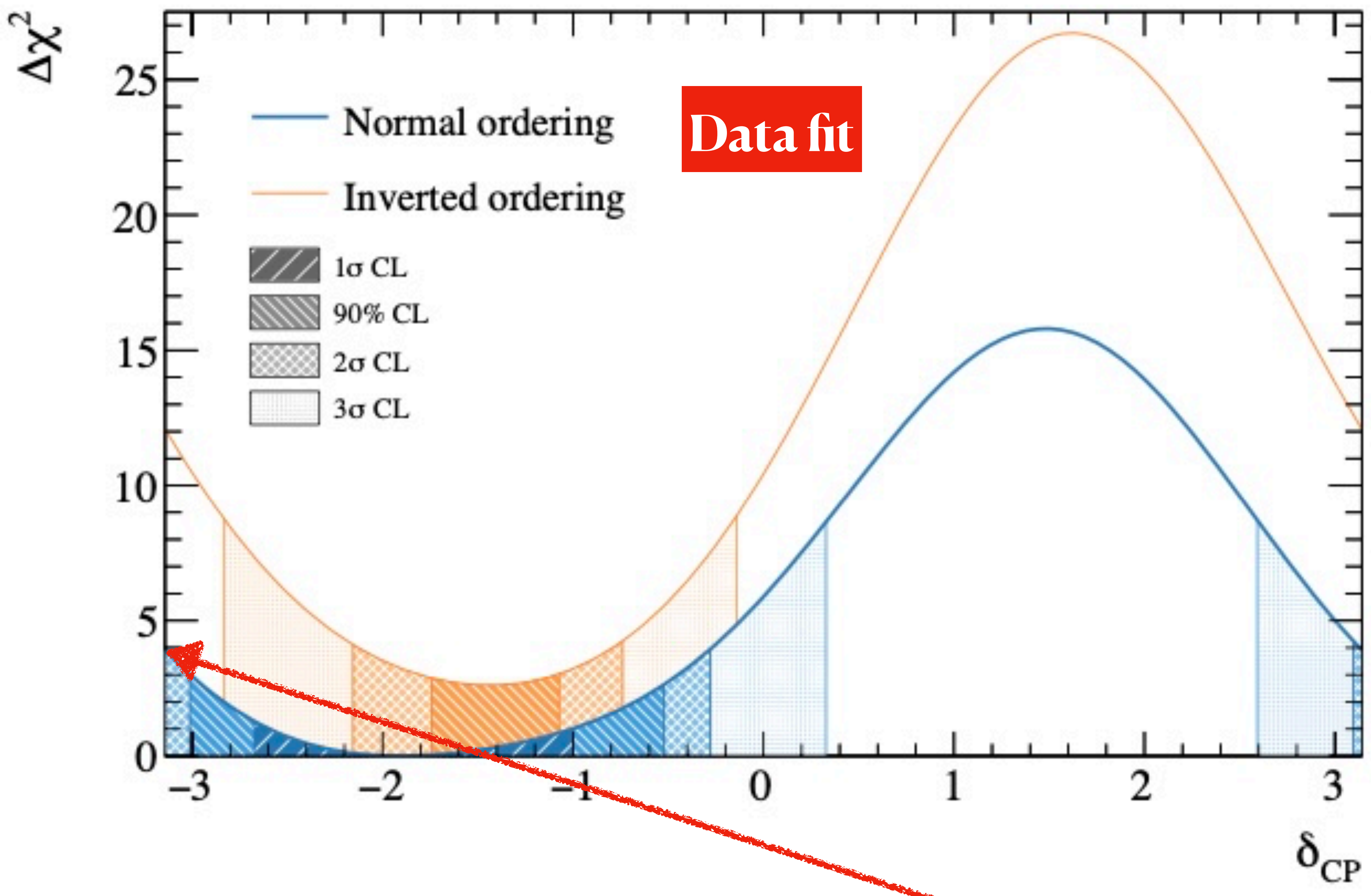
(e) $\bar{\nu}$-mode 1R*e*

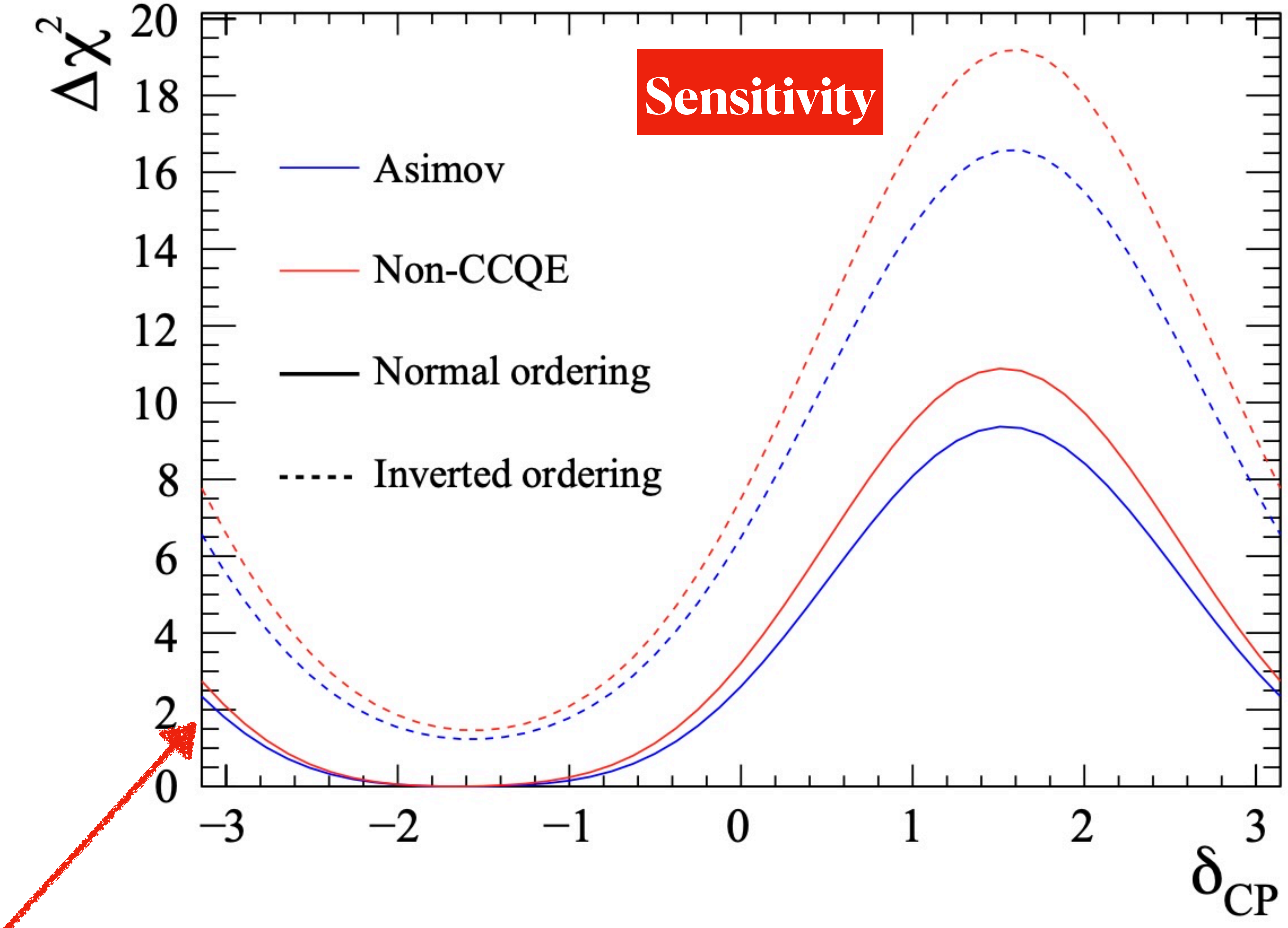


Sensitivity is based on the simulation only (sometimes w/ external data) and need assumption of the true parameters to create "fake" data sets and estimate the statistical significance in various scenario

Main difference btw/ Data fit and sensitivity study (cont'd)

arXiv: 2303.03222 [hep-ex]



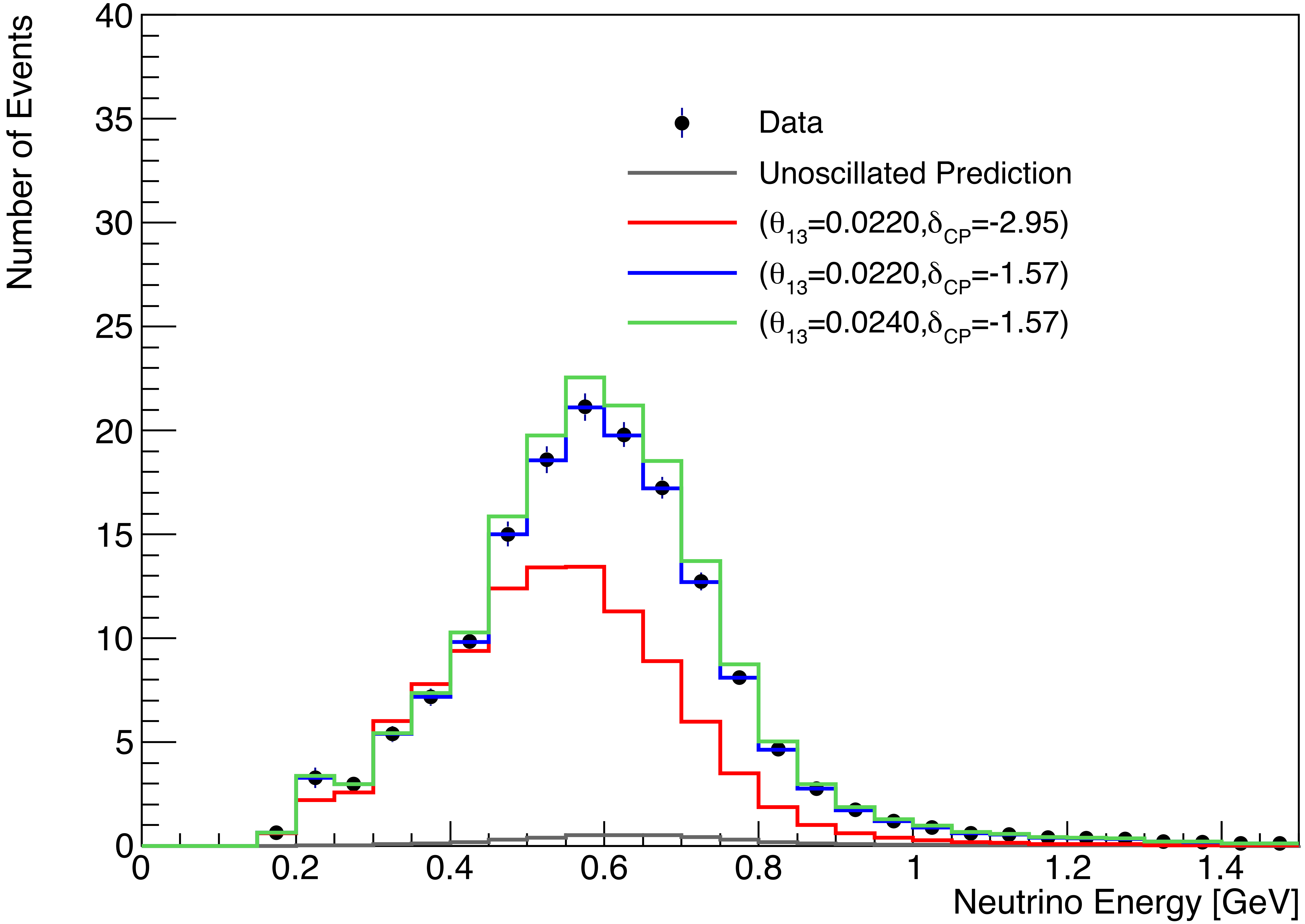


The statistical significance (eg. to exclude CP violation) can be difference between data fit and sensitivity estimation

In “Neutrino Exp. in Nutshell” lecture, I showed some demonstration with sensitivity estimation

Example with electron neutrino appearance search

https://github.com/cvson/nushortcourse/tree/master/sensitivity



An illustration for CP violation sensitivity

https://github.com/cvson/nushortcourse/tree/master/sensitivity

.gif file https://imgur.com/a/cQfNjTO

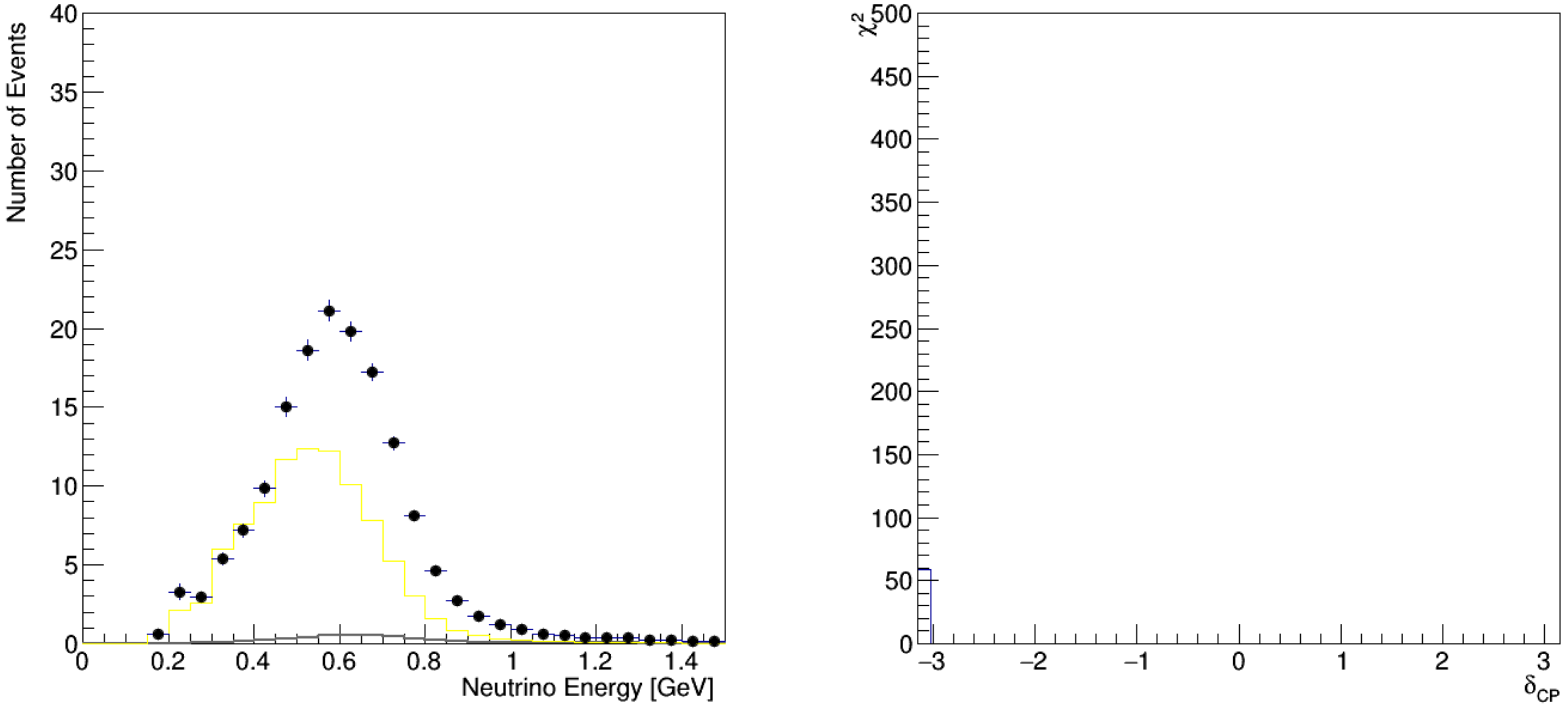


Illustration for comparing data with various prediction on the left with χ^2 calculated corresponding on the right.

Why is this simple simulation not enough for sensitivity study?

- Only consider signal, free from background
- Assume that neutrino energy reconstruction is perfect
- Do not take into account the systematic uncertainties
- ...

These assumptions are too unrealistic and we need something close to describe the experiments with all uncertainties are taken into account. This is main motivation for GLoBES development.

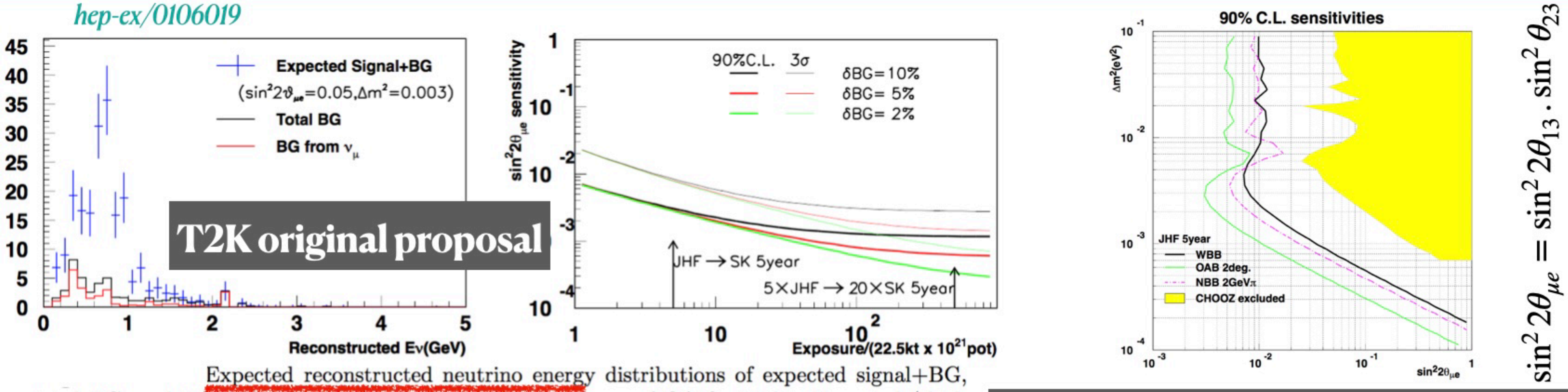
It’s important to investigate the sensitivity study when designing the experiment and analyzing the data.

The NEED of sensitivity estimation

Ref: Neutrino Exp. in nutshell

Design experiments: evaluate the sensitivity (cont'd)

hep-ex/0106019



T2K original proposal

$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23}$$

Expected reconstructed neutrino energy distributions of expected signal+BG, total BG, and BG from ν_μ interactions for 5 years exposure of OA2°. Right: Expected (thick lines:) 90%CL sensitivity and (thin lines:) 3σ discovery contours as the functions of exposure time of OA2°. In left figure, expected oscillation signals are calculated with the oscillation parameters: $\Delta m^2 = 3 \times 10^{-3}$ eV^2,$\sin^2 2\theta_{\mu e} = 0.05$. In right figures, Three different contours correspond to 10%, 5%, and 2% uncertainty in the background estimation.

"NO" answer is also valuable. Both discovery and exclusion advance the human knowledge.

Normally, **physic potentials** (*how good/"sensitive"*) of designed detector much be computed for various scenario of underlying parameters:

- **Range of parameter(s)** in which detector can **explore**
- At what **values** of parameter(s), detector can make **observation/discovery**
- Evaluation at this stage may **simplify detector performance** (e.g. *systematic errors*)

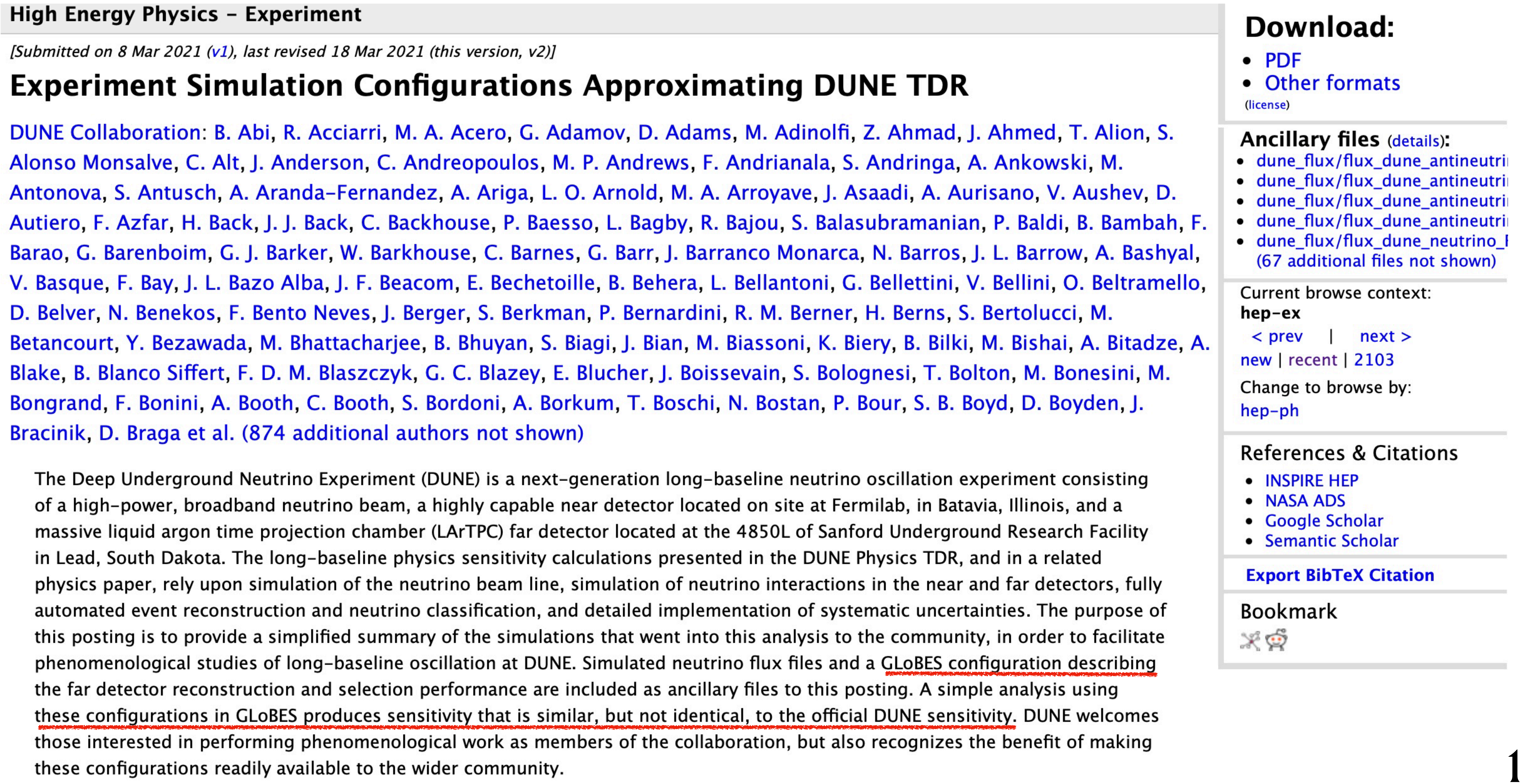
Design Exp.

T2K, NOvA, etc

Do muon neutrino transform into electron neutrinos at given distance of travel?

DUNE exp.

https://arxiv.org/abs/2103.04797



High Energy Physics – Experiment

[Submitted on 8 Mar 2021 (v1), last revised 18 Mar 2021 (this version, v2)]

Experiment Simulation Configurations Approximating DUNE TDR

DUNE Collaboration: B. Abi, R. Acciarri, M. A. Acero, G. Adamov, D. Adams, M. Adinolfi, Z. Ahmad, J. Ahmed, T. Alion, S. Alonso Monsalve, C. Alt, J. Anderson, C. Andreopoulos, M. P. Andrews, F. Andrianala, S. Andringa, A. Ankowski, M. Antonova, S. Antusch, A. Aranda-Fernandez, A. Ariga, L. O. Arnold, M. A. Arroyave, J. Asaadi, A. Aurisano, V. Aushev, D. Autiero, F. Azfar, H. Back, J. J. Back, C. Backhouse, P. Baesso, L. Bagby, R. Bajou, S. Balasubramanian, P. Baldi, B. Bambah, F. Barao, G. Barenboim, G. J. Barker, W. Barkhouse, C. Barnes, G. Barr, J. Barranco Monarca, N. Barros, J. L. Barrow, A. Bashyal, V. Basque, F. Bay, J. L. Bazo Alba, J. F. Beacom, E. Bechetoille, B. Behera, L. Bellantoni, G. Bellettini, V. Bellini, O. Beltramello, D. Belver, N. Benekos, F. Bento Neves, J. Berger, S. Berkman, P. Bernardini, R. M. Berner, H. Berns, S. Bertolucci, M. Betancourt, Y. Bezawada, M. Bhattacharjee, B. Bhuyan, S. Biagi, J. Bian, M. Biassoni, K. Biery, B. Bilki, M. Bishai, A. Bitadze, A. Blake, B. Blanco Siffert, F. D. M. Blaszczyk, G. C. Blazey, E. Blucher, J. Boissevain, S. Bolognesi, T. Bolton, M. Bonesini, M. Bongrand, F. Bonini, A. Booth, C. Booth, S. Bordoni, A. Borkum, T. Boschi, N. Bostan, P. Bour, S. B. Boyd, D. Boyden, J. Bracinik, D. Braga et al. (874 additional authors not shown)

The Deep Underground Neutrino Experiment (DUNE) is a next-generation long-baseline neutrino oscillation experiment consisting of a high-power, broadband neutrino beam, a highly capable near detector located on site at Fermilab, in Batavia, Illinois, and a massive liquid argon time projection chamber (LArTPC) far detector located at the 4850L of Sanford Underground Research Facility in Lead, South Dakota. The long-baseline physics sensitivity calculations presented in the DUNE Physics TDR, and in a related physics paper, rely upon simulation of the neutrino beam line, simulation of neutrino interactions in the near and far detectors, fully automated event reconstruction and neutrino classification, and detailed implementation of systematic uncertainties. The purpose of this posting is to provide a simplified summary of the simulations that went into this analysis to the community, in order to facilitate phenomenological studies of long-baseline oscillation at DUNE. Simulated neutrino flux files and a GLoBES configuration describing the far detector reconstruction and selection performance are included as ancillary files to this posting. A simple analysis using these configurations in GLoBES produces sensitivity that is similar, but not identical, to the official DUNE sensitivity. DUNE welcomes those interested in performing phenomenological work as members of the collaboration, but also recognizes the benefit of making these configurations readily available to the wider community.

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- PDF
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(license)

Ancillary files (details):

- dune_flux/flux_dune_antineutri
- dune_flux/flux_dune_antineutri
- dune_flux/flux_dune_antineutri
- dune_flux/flux_dune_antineutri
- dune_flux/flux_dune_neutrino_
- (67 additional files not shown)

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Other important motivation to use GloBES: to perform the joint analysis

$$\overrightarrow{osc.para.} = (\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP})$$

- No single experiment can be sensitive to all parameters
- One need to combine multiple dataset from multiple experiment to understand the full picture of neutrino oscillation
- GLoBES also allows us to examine the global neutrino data from multiple experiments.

https://www.globesfit.org/software.html

GLoBES installation

GLoBES installation

https://ifirse.icise.vn/nugroup/vson/2023/wiki/doku.php?id=globes#installation

Software requirement

- gcc and make
- GNU scientific library
- [optional] ROOT

Get latest source code at
https://www.mpi-hd.mpg.de/personalhomes/globes/download.html

On Ubuntu

```
wget https://www.mpi-hd.mpg.de/personalhomes/globes/download/globes-3.2.18.tar.gz
tar -xvf globes-3.2.18.tar.gz
mkdir buildglobes3218
./configure --prefix=/home/ifirseqn04/offline/globes/buildglobes3218
make install
//add to PATH
export PATH=/home/ifirseqn04/offline/globes/buildglobes3218/bin:$PATH
```

On MacOS

```
 ./configure --prefix=/Users/cvson/meOffline/globes/rebuiltglobes3218 --disable-binary
make install
export PATH=/Users/cvson/meOffline/globes/rebuiltglobes3218/bin:$PATH
```

Input and output of the GLoBES

Concept of the neutrino oscillation measurement

- Ref: Neutrino Exp. in nutshell

1. Need source of ν_μ
2. Put detector at some distance from ν_μ source
3. Look for ν_e appeared from ν_μ source in detector

Far detector measurement

$$N_i^{far\ det.}(\overrightarrow{o}) = \boxed{\Phi_{flux} \times \sigma_{xsec.}} \times M_{\det.} \times \epsilon_{det.} \times P(\overrightarrow{o})$$

Constrained by Near Det. **Det. Mass** **det. efficiency** **osc. prob.**

where $$\overrightarrow{o} = (\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}; \rho_{mat.}, L)$$

When consider neutrino energy reconstruction and flavor

$$N^{\nu_\beta}(E_\nu^{reco.}, \overrightarrow{o}) = \Phi_{flux}^{\nu_\alpha}(E_\nu^{true}) \times \sigma_{int.}^{\nu_\beta}(E_\nu^{true}) \times M_{det.} \times \epsilon_{det.}^{\nu_\beta}(E_\nu^{true}) \times M(E_\nu^{true.}, E_\nu^{reco.})$$
$$\times P(\nu_\alpha \to \nu_\beta | E_\nu^{true}, \overrightarrow{o})$$

Energy reconstruction

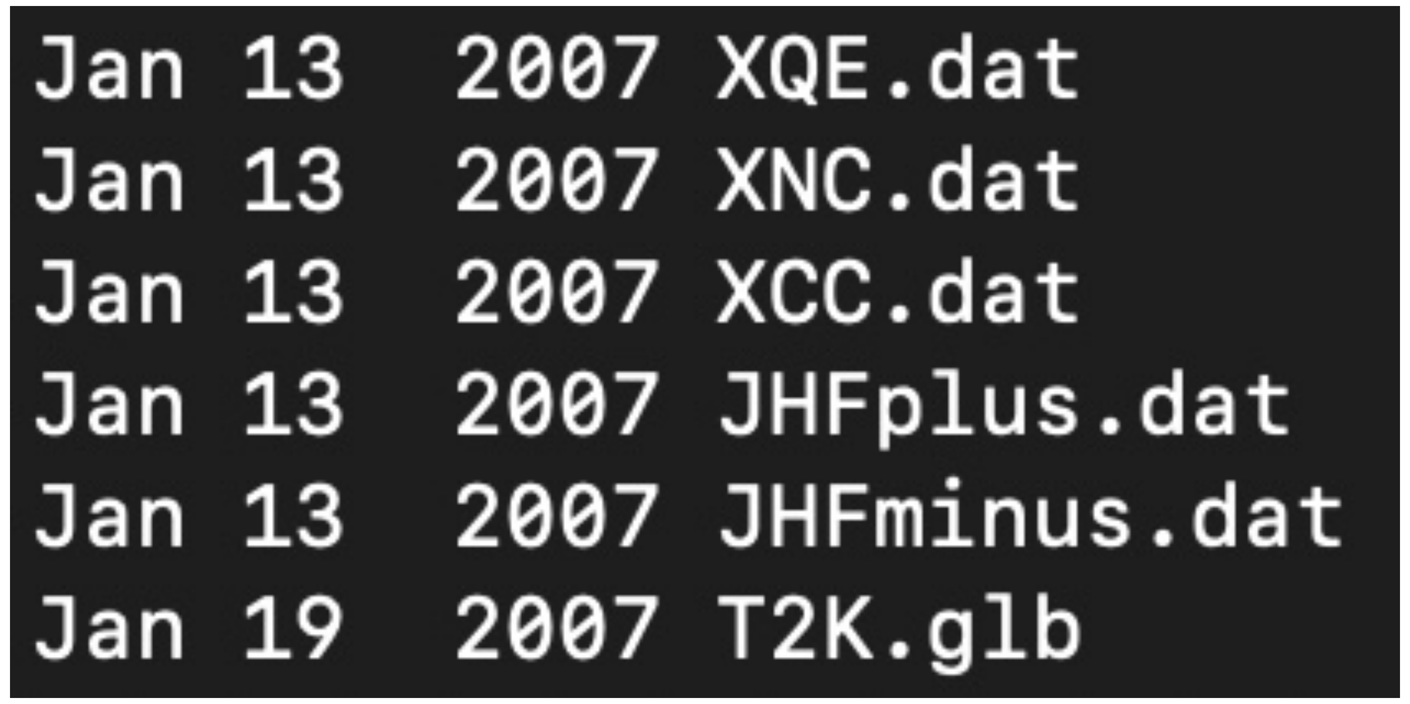
We need all these inputs to define an experiment!

But quite often that you don't have all experimental inputs from the published materials. In that case you need some approximation.

Let's look at one pre-defined experiment

you get file here:

https://www.mpi-hd.mpg.de/personalhomes/globes/glb/T2K.html



```
Jan 13  2007 XQE.dat
Jan 13  2007 XNC.dat
Jan 13  2007 XCC.dat
Jan 13  2007 JHFplus.dat
Jan 13  2007 JHFminus.dat
Jan 19  2007 T2K.glb
```

JHFplus.dat
JHFminus.dat

XQE.dat
XNC.dat
XCC.dat

$$N^{\nu_\beta}(E_\nu^{reco.}, \overrightarrow{o}) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true}) \times \boxed{M_{det.} \times \epsilon^{\nu_\beta}_{det.}(E_\nu^{true}) \times M(E_\nu^{true.}, E_\nu^{reco.})}$$

$$\times P(\nu_\alpha \rightarrow \nu_\beta | E_\nu^{true}, \overrightarrow{o})$$

T2K.glb

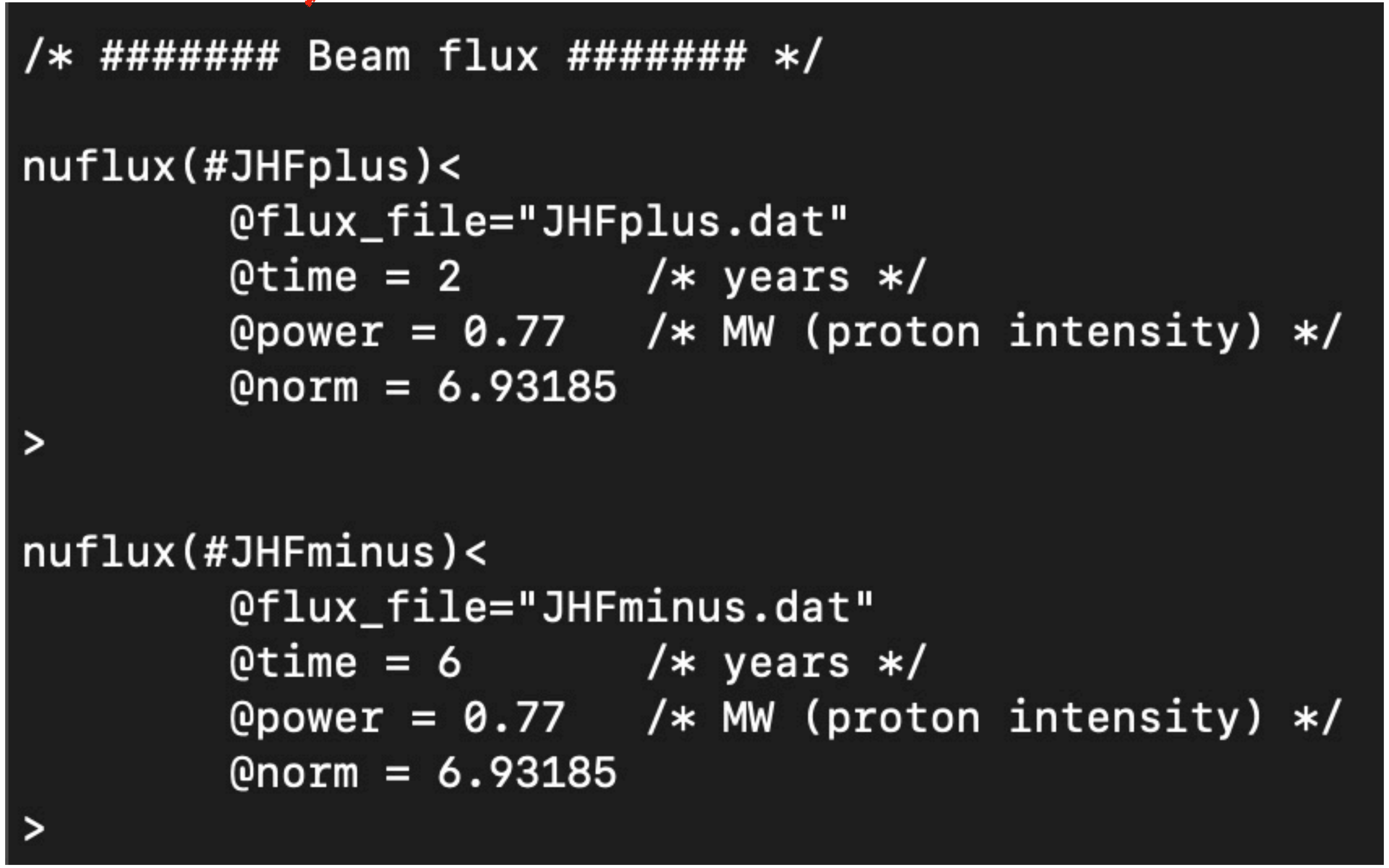
Built-in framework

Let's look at one pre-defined experiment

https://www.mpi-hd.mpg.de/personalhomes/globes/glb/T2K.html

$$N^{\nu_\beta}(E_\nu^{reco.}, \vec{o}) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true}) \times M_{det.} \times \epsilon^{\nu_\beta}_{det.}(E_\nu^{true}) \times M(E_\nu^{true.}, E_\nu^{reco.})$$

$$\times P(\nu_\alpha \to \nu_\beta | E_\nu^{true}, \vec{o})$$



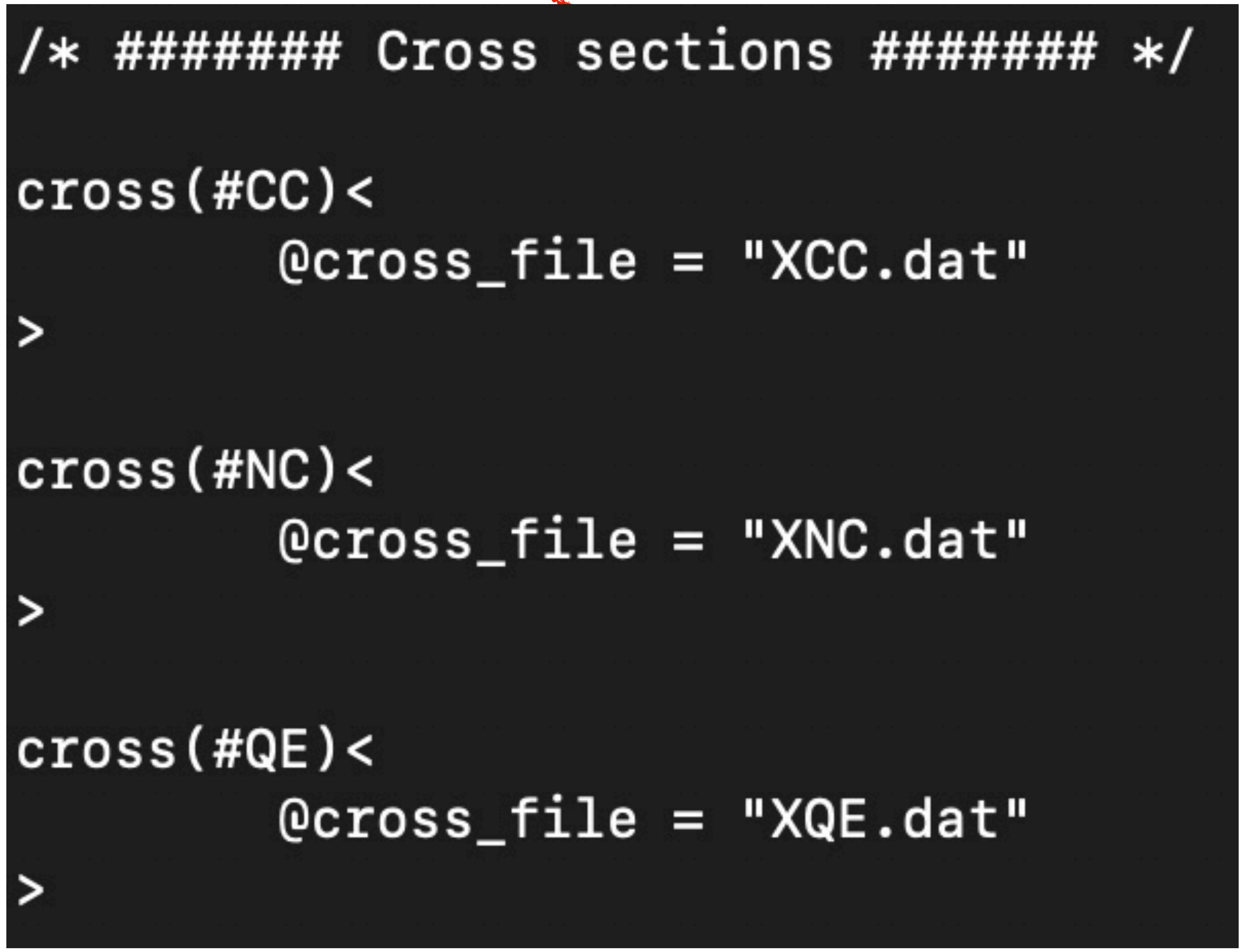
```
/* ####### Beam flux ####### */

nuflux(#JHFplus)<
        @flux_file="JHFplus.dat"
        @time = 2        /* years */
        @power = 0.77    /* MW (proton intensity) */
        @norm = 6.93185
>

nuflux(#JHFminus)<
        @flux_file="JHFminus.dat"
        @time = 6        /* years */
        @power = 0.77    /* MW (proton intensity) */
        @norm = 6.93185
>
```

Let's look at one pre-defined experiment

https://www.mpi-hd.mpg.de/personalhomes/globes/glb/T2K.html

$$N^{\nu_\beta}(E_\nu^{reco.}, \vec{o}) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true}) \times M_{det.} \times \epsilon^{\nu_\beta}_{det.}(E_\nu^{true}) \times M(E_\nu^{true.}, E_\nu^{reco.})$$

$$\times P(\nu_\alpha \to \nu_\beta | E_\nu^{true}, \vec{o})$$



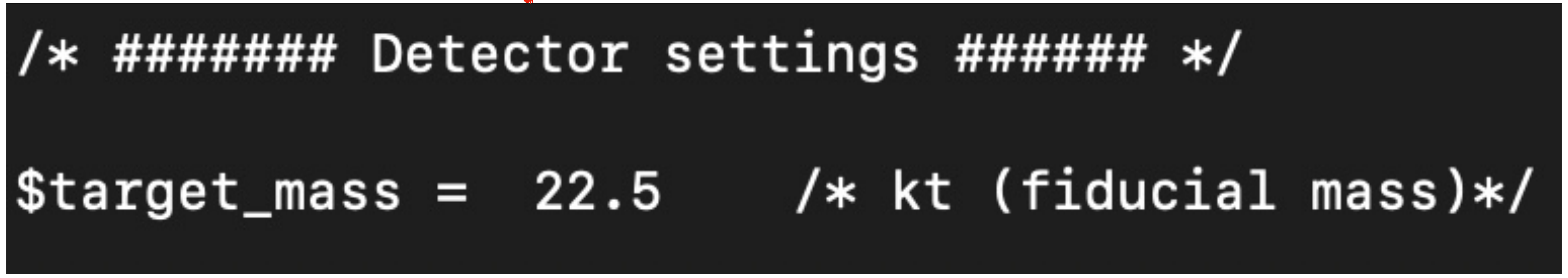
```
/* ####### Cross sections ####### */

cross(#CC)<
        @cross_file = "XCC.dat"
>

cross(#NC)<
        @cross_file = "XNC.dat"
>

cross(#QE)<
        @cross_file = "XQE.dat"
>
```

Let's look at one pre-defined experiment

https://www.mpi-hd.mpg.de/personalhomes/globes/glb/T2K.html

$$N^{\nu_\beta}(E_\nu^{reco.}, \overrightarrow{o}) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true}) \times M_{det.} \times \epsilon^{\nu_\beta}_{det.}(E_\nu^{true}) \times M(E_\nu^{true.}, E_\nu^{reco.})$$

$$\times P(\nu_\alpha \to \nu_\beta | E_\nu^{true}, \overrightarrow{o})$$



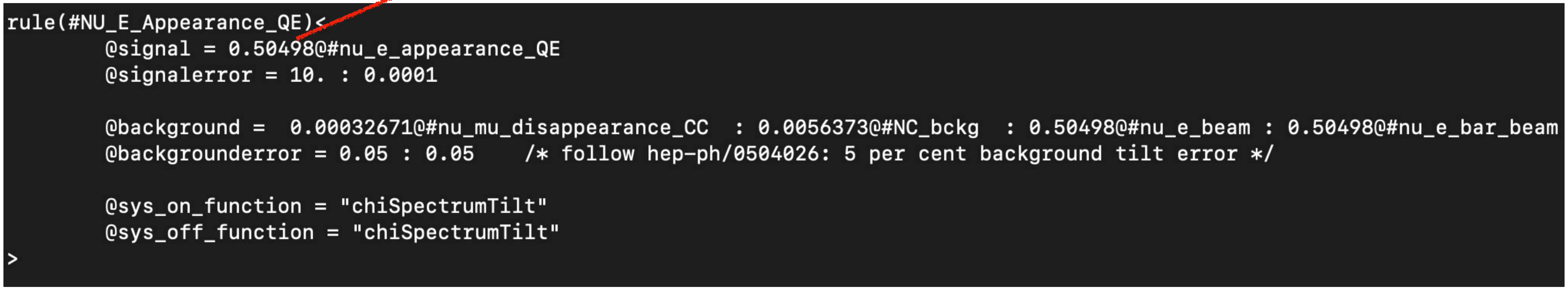
```
/* ####### Detector settings ###### */

$target_mass =  22.5    /* kt (fiducial mass)*/
```

Let's look at one pre-defined experiment

https://www.mpi-hd.mpg.de/personalhomes/globes/glb/T2K.html

$$N^{\nu_\beta}(E_\nu^{reco.}, \vec{o}) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true}) \times M_{det.} \times \epsilon^{\nu_\beta}_{det.}(E_\nu^{true}) \times M(E_\nu^{true.}, E_\nu^{reco.})$$

$$\times P(\nu_\alpha \to \nu_\beta \,|\, E_\nu^{true}, \vec{o})$$



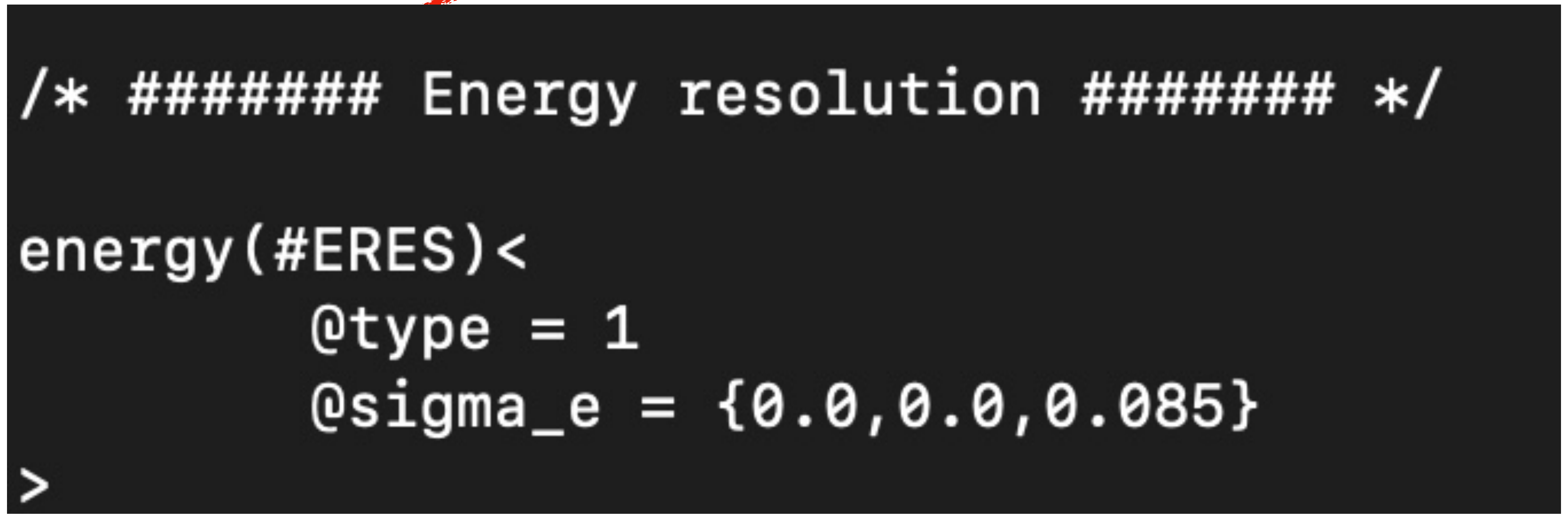
```
rule(#NU_E_Appearance_QE)<
        @signal = 0.50498@#nu_e_appearance_QE
        @signalerror = 10. : 0.0001

        @background =  0.00032671@#nu_mu_disappearance_CC  : 0.0056373@#NC_bckg  : 0.50498@#nu_e_beam : 0.50498@#nu_e_bar_beam
        @backgrounderror = 0.05 : 0.05    /* follow hep-ph/0504026: 5 per cent background tilt error */

        @sys_on_function = "chiSpectrumTilt"
        @sys_off_function = "chiSpectrumTilt"
>
```

Ref. To GLoBES manual

Let’s look at one pre-defined experiment

https://www.mpi-hd.mpg.de/personalhomes/globes/glb/T2K.html

$$N^{\nu_\beta}(E_\nu^{reco.}, \overrightarrow{o}) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true}) \times M_{det.} \times \epsilon^{\nu_\beta}_{det.}(E_\nu^{true}) \times M(E_\nu^{true.}, E_\nu^{reco.})$$
$$\times P(\nu_\alpha \to \nu_\beta | E_\nu^{true}, \overrightarrow{o})$$



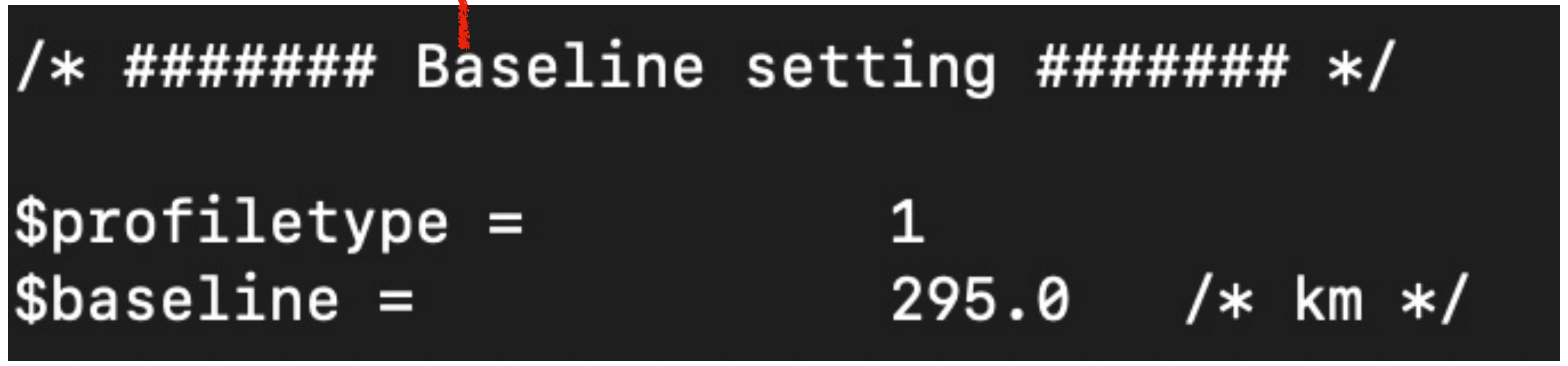
```
/* ####### Energy resolution ####### */

energy(#ERES)<
        @type = 1
        @sigma_e = {0.0,0.0,0.085}
>
```

Let's look at one pre-defined experiment

https://www.mpi-hd.mpg.de/personalhomes/globes/glb/T2K.html

$$N^{\nu_\beta}(E_\nu^{reco.}, \overrightarrow{o}) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true}) \times M_{det.} \times \epsilon^{\nu_\beta}_{det.}(E_\nu^{true}) \times M(E_\nu^{true.}, E_\nu^{reco.})$$

$$\times P(\nu_\alpha \to \nu_\beta | E_\nu^{true}, \overrightarrow{o})$$



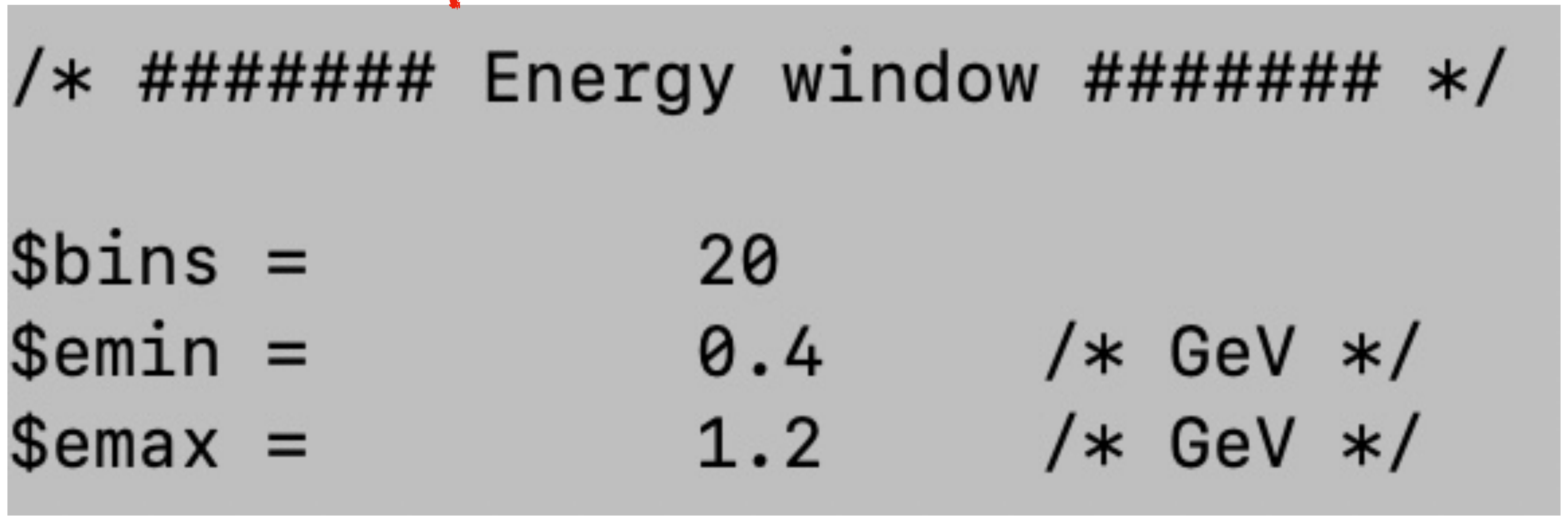
```
/* ####### Baseline setting ####### */

$profiletype =          1
$baseline =             295.0    /* km */
```

$$\overrightarrow{o} = (\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}; \rho_{mat.}, L)$$

Let's look at one pre-defined experiment

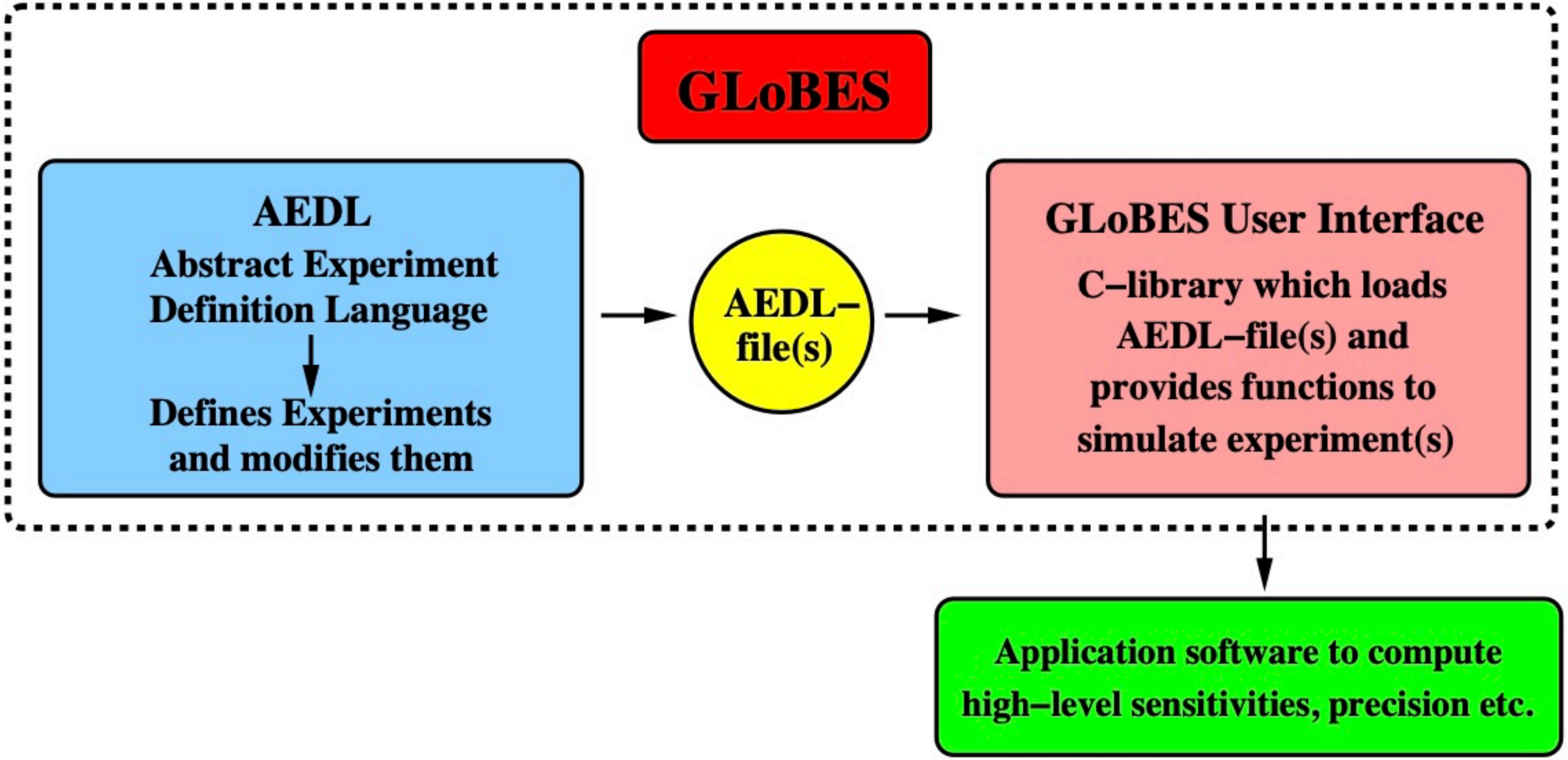
https://www.mpi-hd.mpg.de/personalhomes/globes/glb/T2K.html

$$N^{\nu_\beta}(E_\nu^{reco.}, \vec{o}) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true}) \times M_{det.} \times \epsilon^{\nu_\beta}_{det.}(E_\nu^{true}) \times M(E_\nu^{true.}, E_\nu^{reco.}) \times P(\nu_\alpha \to \nu_\beta | E_\nu^{true}, \vec{o})$$



```
/* ####### Energy window ####### */

$bins =          20
$emin =          0.4       /* GeV */
$emax =          1.2       /* GeV */
```

All inputs are presented as Abstract description of experiment



GLoBES

AEDL

Abstract Experiment Definition Language

Defines Experiments and modifies them

AEDL–file(s)

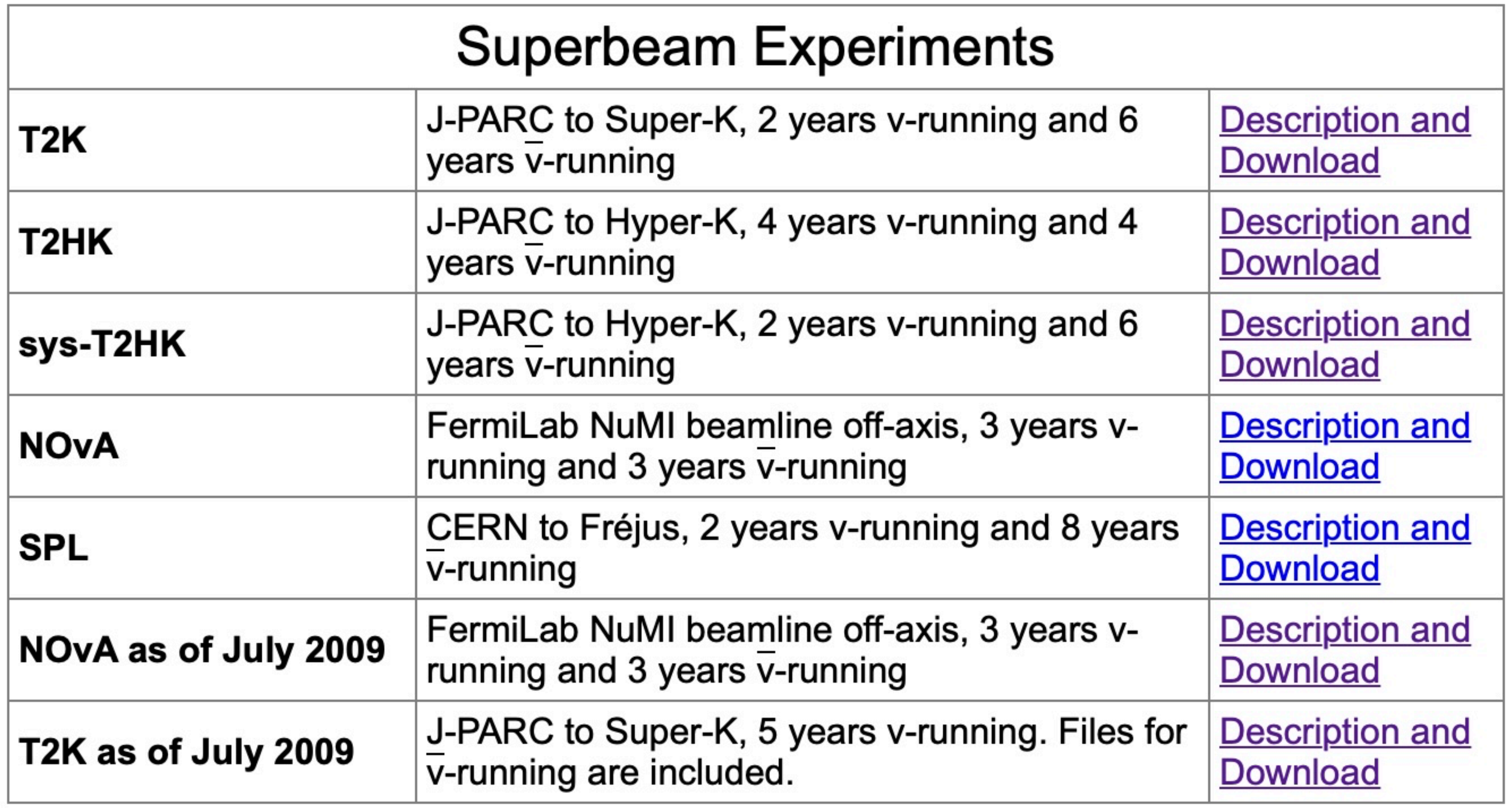
GLoBES User Interface

C–library which loads AEDL–file(s) and provides functions to simulate experiment(s)

Application software to compute high–level sensitivities, precision etc.

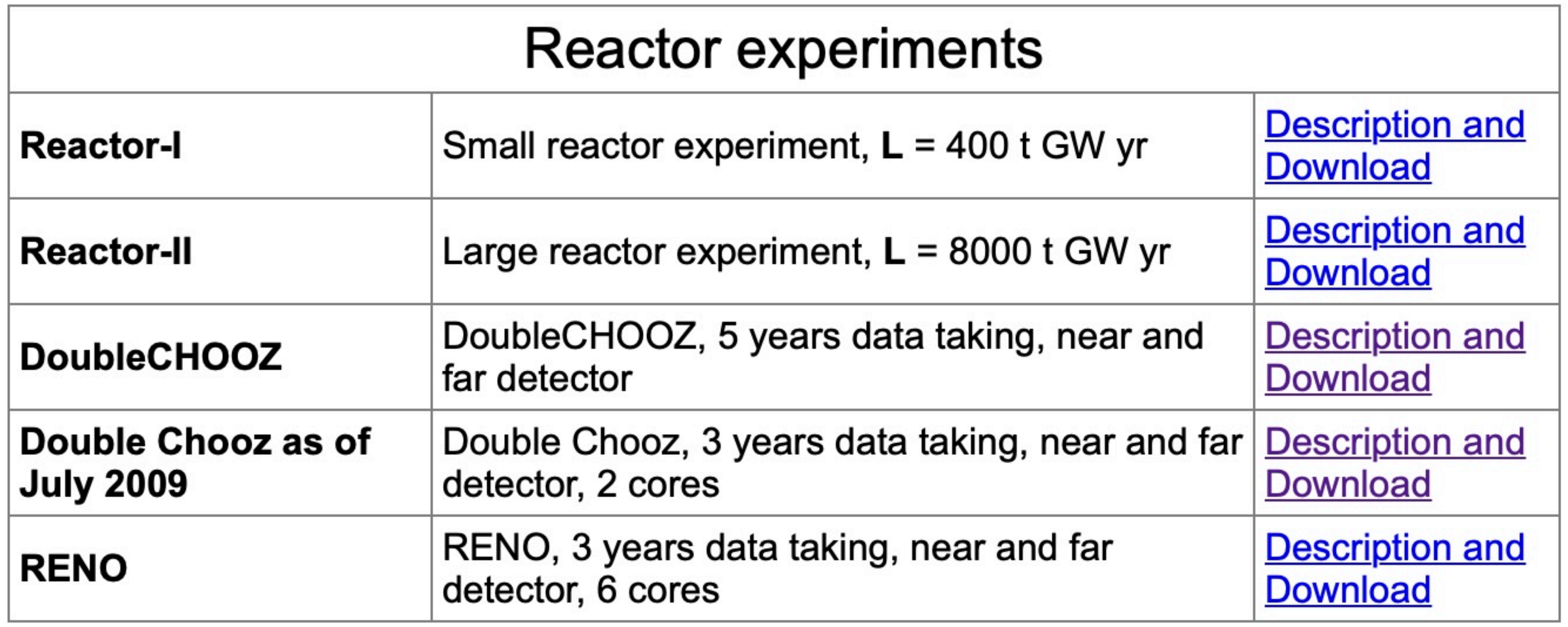
Some pre-define experiments

https://www.mpi-hd.mpg.de/personalhomes/globes/experiments.html



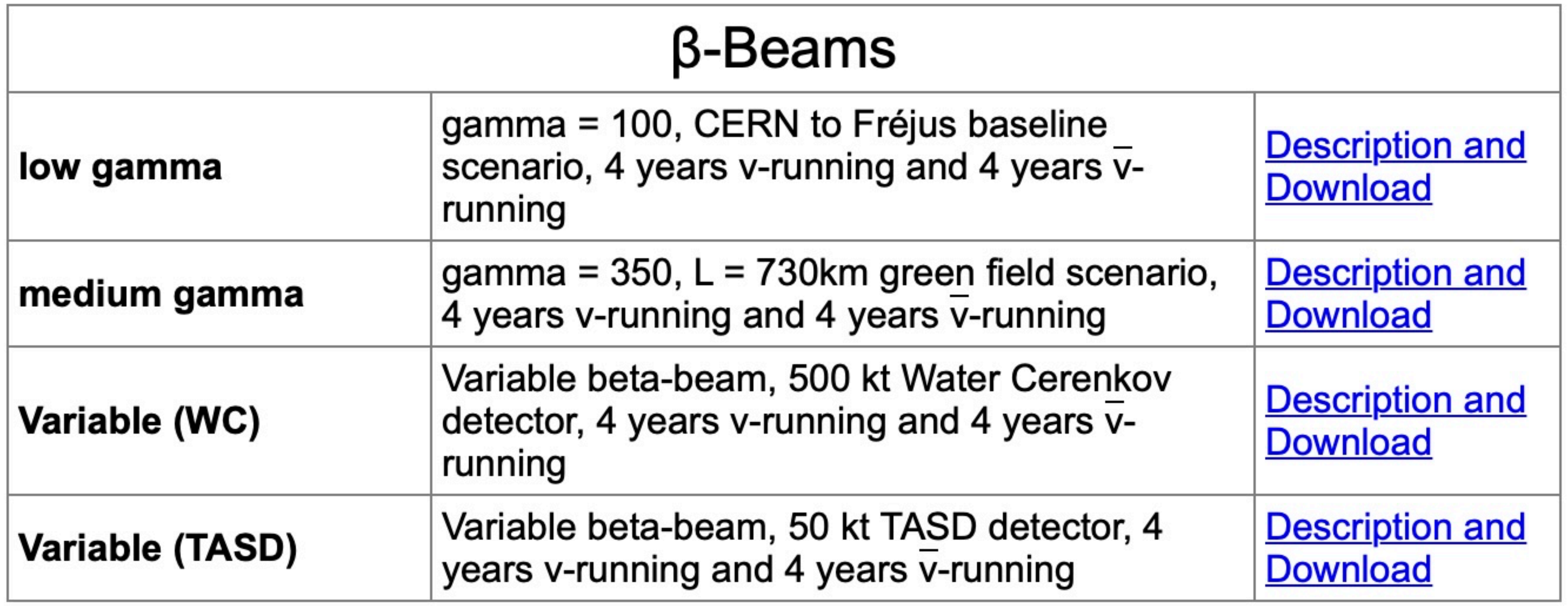
Superbeam Experiments

T2K	J-PARC to Super-K, 2 years ν-running and 6 years ν̄-running	Description and Download
T2HK	J-PARC to Hyper-K, 4 years ν-running and 4 years ν̄-running	Description and Download
sys-T2HK	J-PARC to Hyper-K, 2 years ν-running and 6 years ν̄-running	Description and Download
NOνA	FermiLab NuMI beamline off-axis, 3 years ν-running and 3 years ν̄-running	Description and Download
SPL	CERN to Fréjus, 2 years ν-running and 8 years ν̄-running	Description and Download
NOνA as of July 2009	FermiLab NuMI beamline off-axis, 3 years ν-running and 3 years ν̄-running	Description and Download
T2K as of July 2009	J-PARC to Super-K, 5 years ν-running. Files for ν̄-running are included.	Description and Download



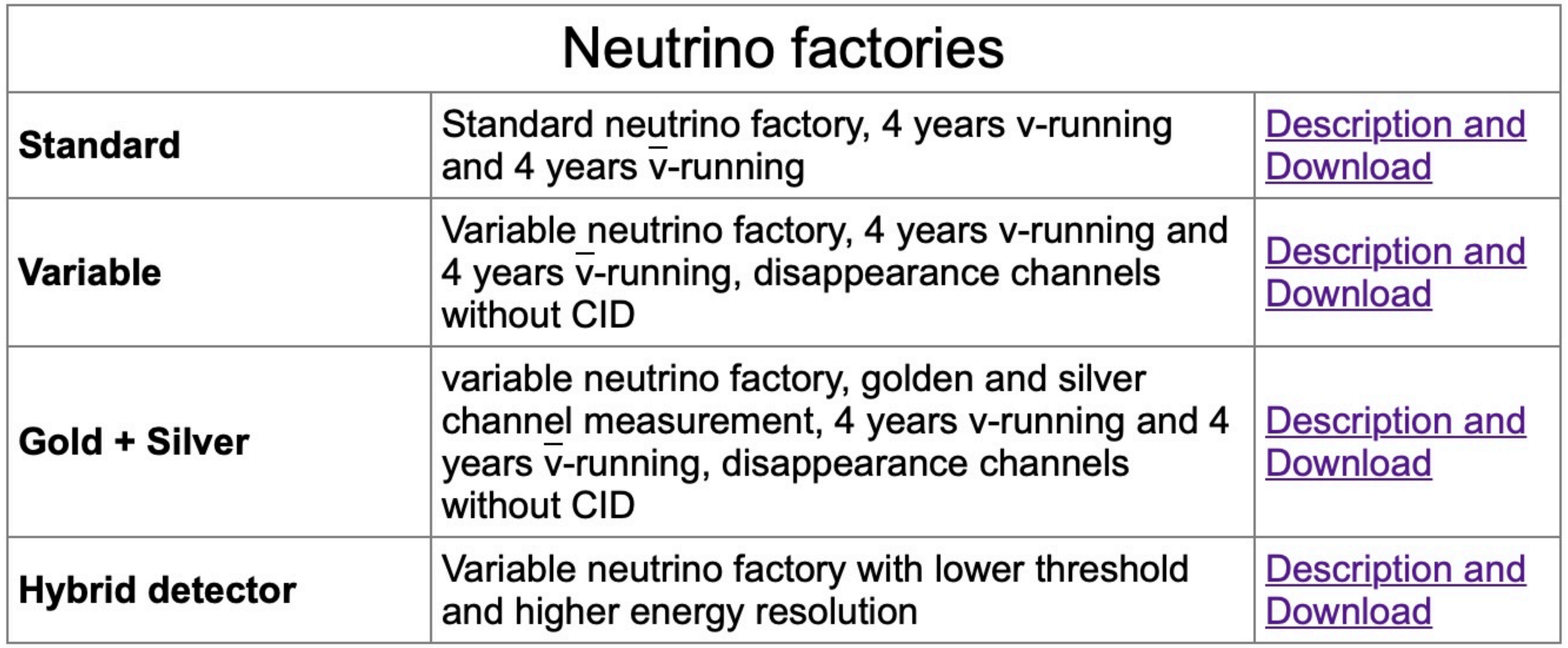
Reactor experiments

Reactor-I	Small reactor experiment, **L** = 400 t GW yr	Description and Download
Reactor-II	Large reactor experiment, **L** = 8000 t GW yr	Description and Download
DoubleCHOOZ	DoubleCHOOZ, 5 years data taking, near and far detector	Description and Download
Double Chooz as of July 2009	Double Chooz, 3 years data taking, near and far detector, 2 cores	Description and Download
RENO	RENO, 3 years data taking, near and far detector, 6 cores	Description and Download



β-Beams

low gamma	gamma = 100, CERN to Fréjus baseline scenario, 4 years ν-running and 4 years ν̄-running	Description and Download
medium gamma	gamma = 350, L = 730km green field scenario, 4 years ν-running and 4 years ν̄-running	Description and Download
Variable (WC)	Variable beta-beam, 500 kt Water Cerenkov detector, 4 years ν-running and 4 years ν̄-running	Description and Download
Variable (TASD)	Variable beta-beam, 50 kt TASD detector, 4 years ν-running and 4 years ν̄-running	Description and Download



Neutrino factories

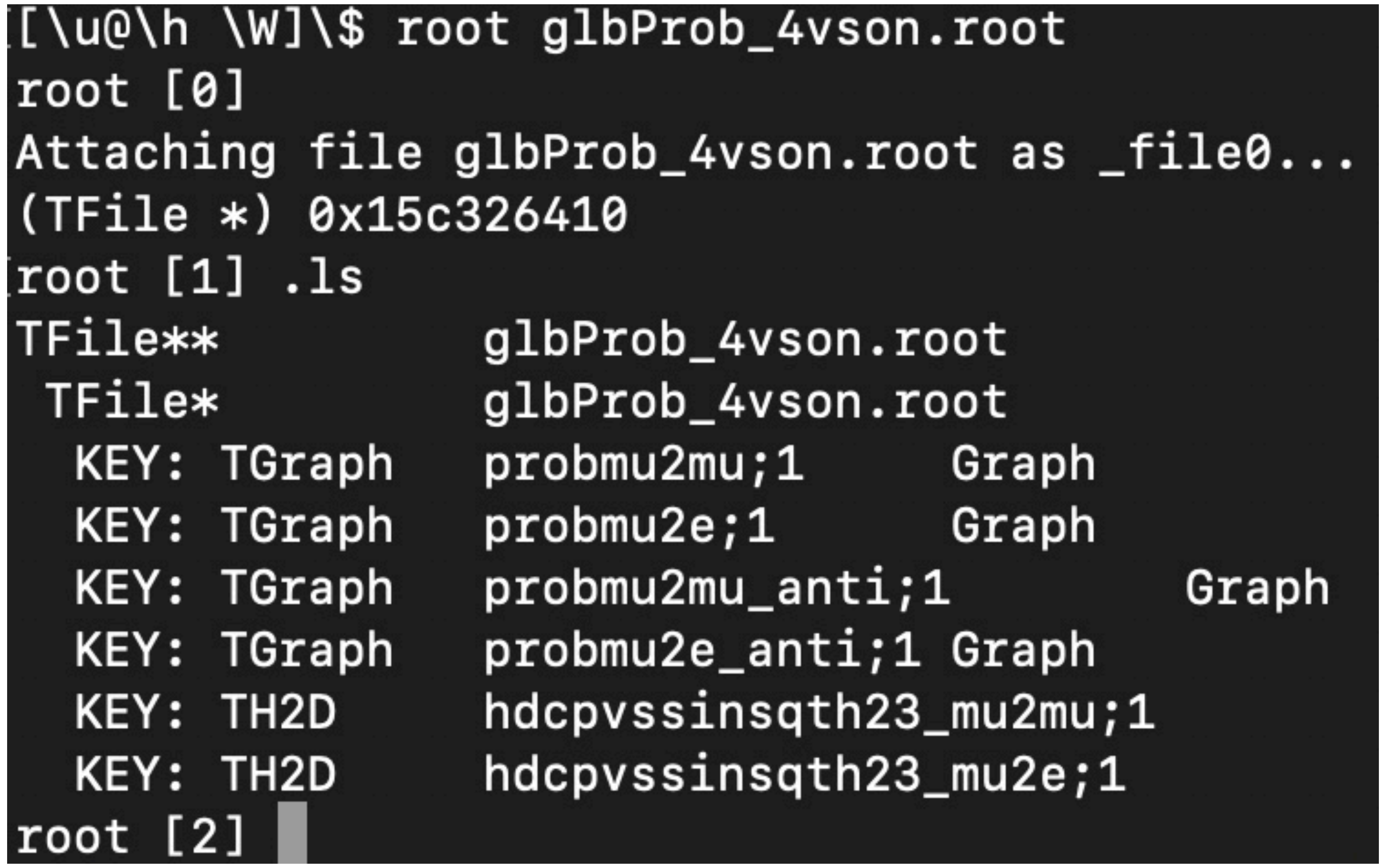
Standard	Standard neutrino factory, 4 years ν-running and 4 years ν̄-running	Description and Download
Variable	Variable neutrino factory, 4 years ν-running and 4 years ν̄-running, disappearance channels without CID	Description and Download
Gold + Silver	variable neutrino factory, golden and silver channel measurement, 4 years ν-running and 4 years ν̄-running, disappearance channels without CID	Description and Download
Hybrid detector	Variable neutrino factory with lower threshold and higher energy resolution	Description and Download

Warning: Some are out-of-date. One must consider these setup as starter then modify to get a better description of experiment in reality

3-flavor oscillation probability framework implemented in GLoBES

Check oscillation probability

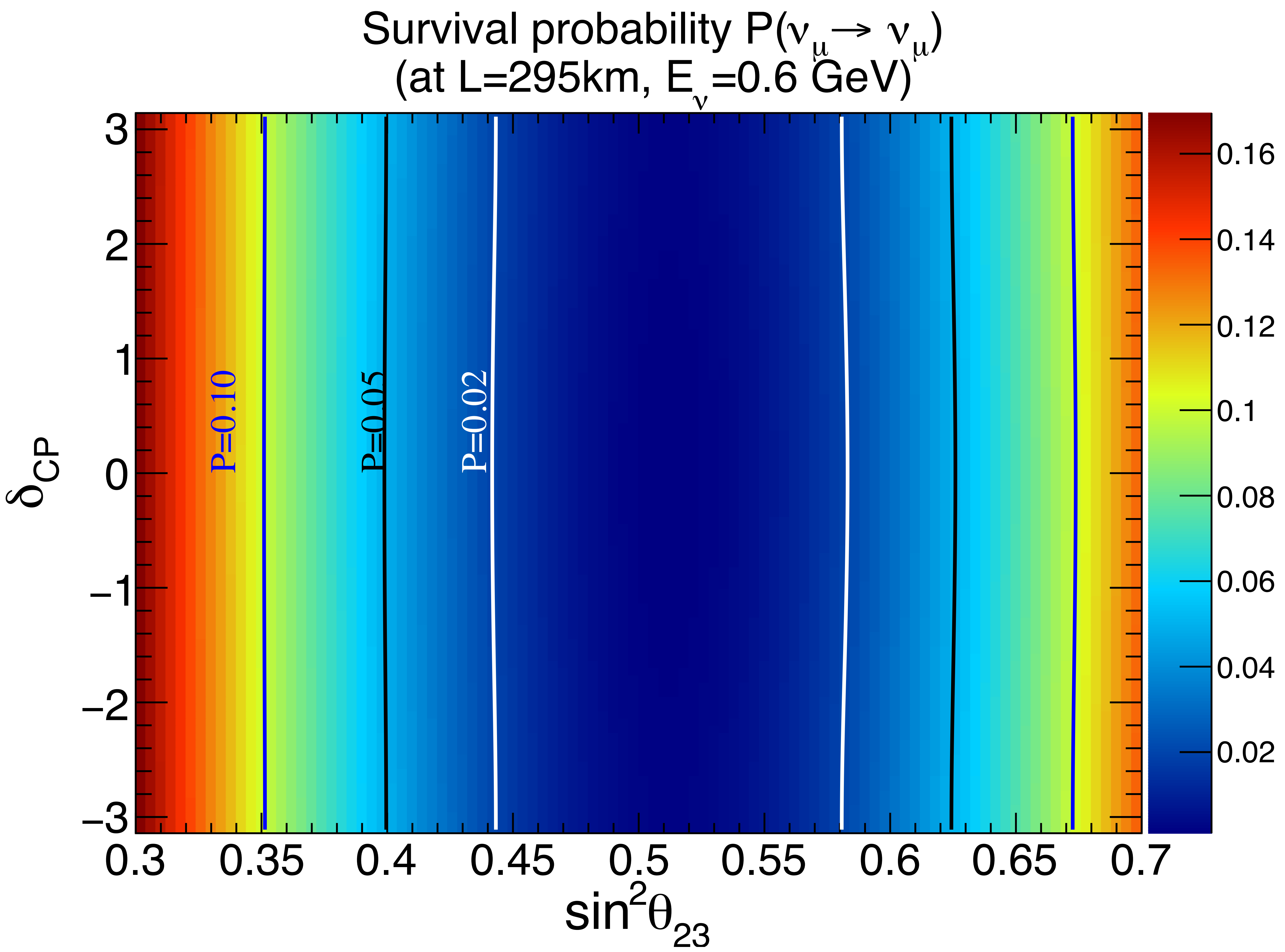
- You need to modify Makefile
- Source code: glbProb.c
- Compile: make glbProb
- Run: ./glbProb
    - Produce glbProb_4vson.root



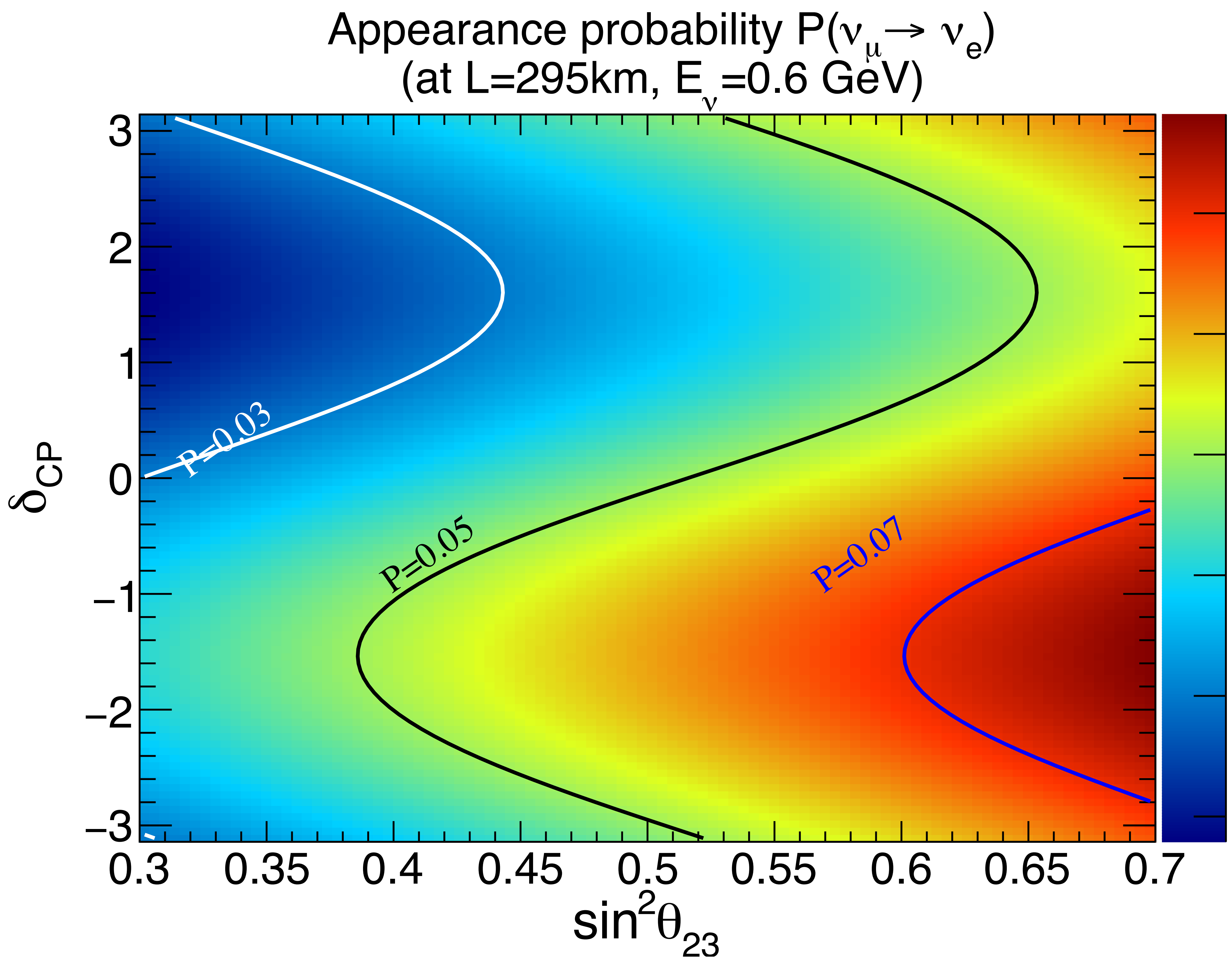
```
[\u@\h \W]\$ root glbProb_4vson.root
root [0]
Attaching file glbProb_4vson.root as _file0...
(TFile *) 0x15c326410
root [1] .ls
TFile**         glbProb_4vson.root
 TFile*         glbProb_4vson.root
  KEY: TGraph   probmu2mu;1     Graph
  KEY: TGraph   probmu2e;1      Graph
  KEY: TGraph   probmu2mu_anti;1        Graph
  KEY: TGraph   probmu2e_anti;1 Graph
  KEY: TH2D     hdcpvssinsqth23_mu2mu;1
  KEY: TH2D     hdcpvssinsqth23_mu2e;1
root [2]
```

Check oscillation probability: more fancy thing

Use plot_dcpth23_prob.C to make plot



Survival probability $P(\nu_\mu \rightarrow \nu_\mu)$
(at L=295km, E_ν=0.6 GeV)

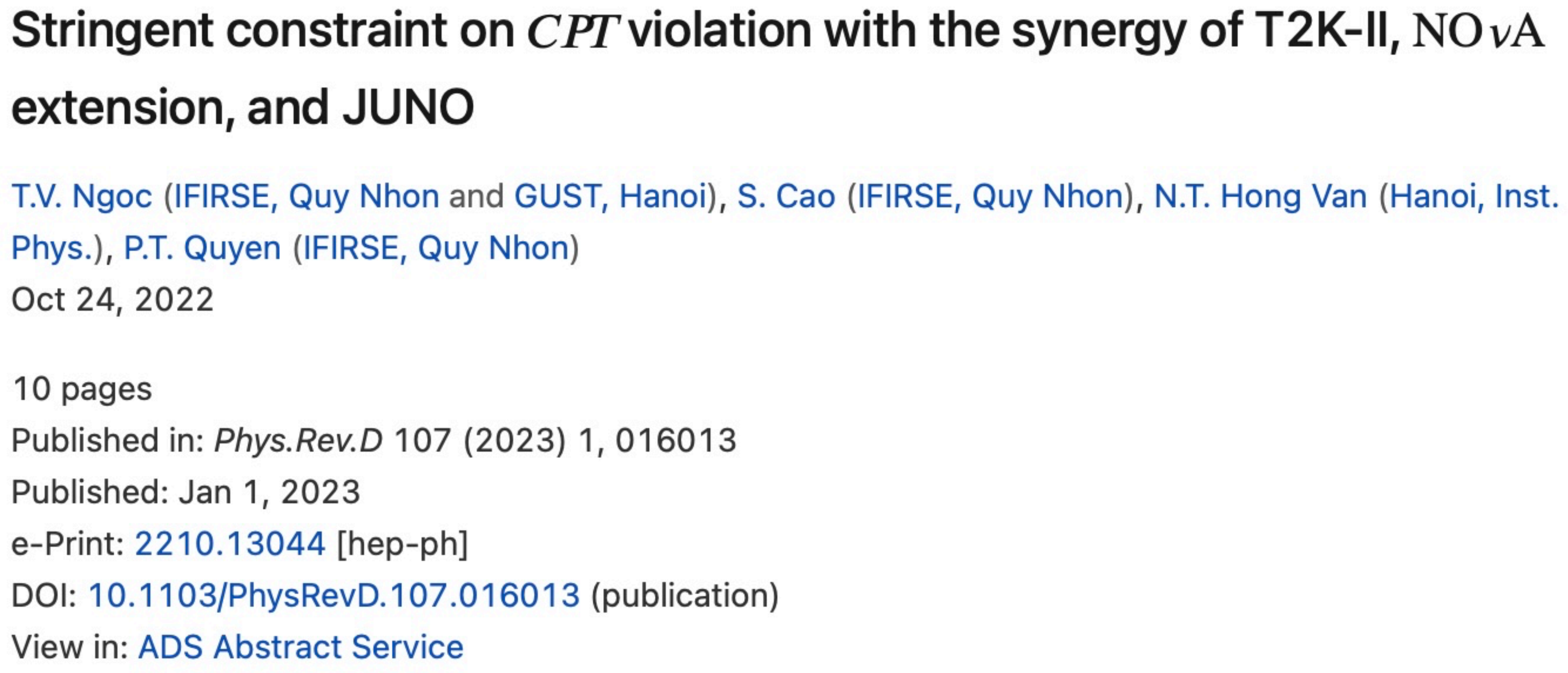


Appearance probability $P(\nu_\mu \rightarrow \nu_e)$
(at L=295km, E_ν=0.6 GeV)

These plots illustrate the parameter degeneracy in the neutrino oscillation measurements with T2K (also other long-baseline neutrino exp.)

Important: GLoBES allows the flexibility to modify the oscillation prob. framework

In this work, for example, we use additional parameters to model the CPT effect where neutrinos and anti-neutrinos can be driven by different set of parameters



Stringent constraint on CPT violation with the synergy of T2K-II, NOνA extension, and JUNO

T.V. Ngoc (IFIRSE, Quy Nhon and GUST, Hanoi), S. Cao (IFIRSE, Quy Nhon), N.T. Hong Van (Hanoi, Inst. Phys.), P.T. Quyen (IFIRSE, Quy Nhon)
Oct 24, 2022

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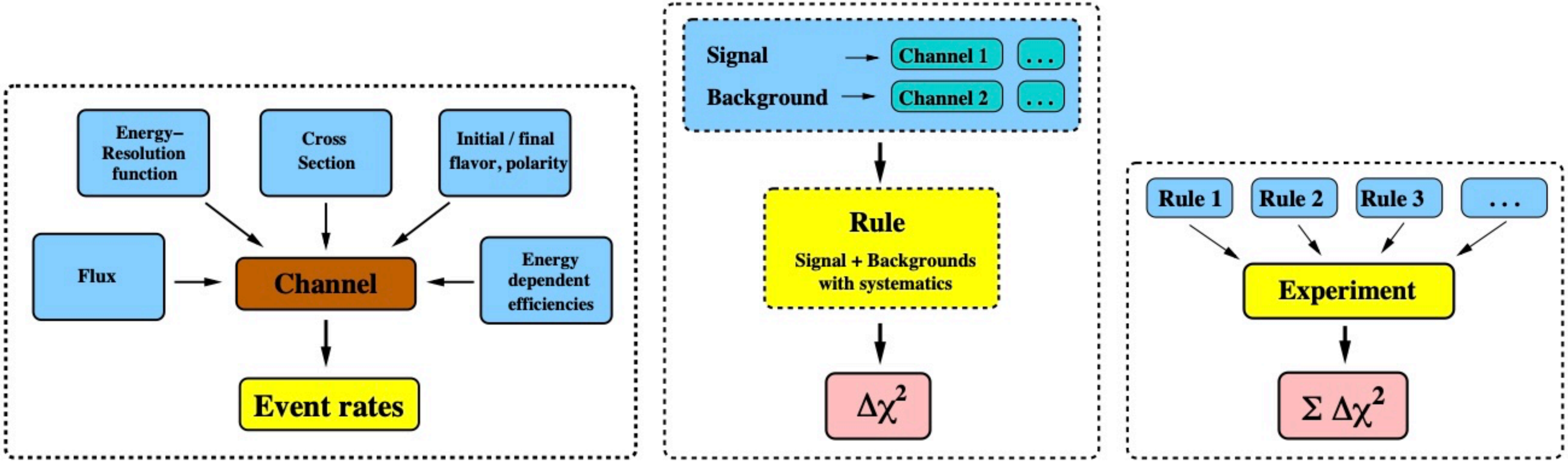
DOI: 10.1103/PhysRevD.107.016013 (publication)
View in: ADS Abstract Service

General concept of experiment



Event rate

Event rate: can obtain directly from command line

For example you get file here:

https://www.mpi-hd.mpg.de/personalhomes/globes/glb/T2K.html

$$\overrightarrow{o}_{glob.} = (\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}, \Delta m^2_{21}, \Delta m^2_{31})$$

```
globes -p ‘0.583, 0.149, 0.857, +1.57, 0.0000741, 0.002511' -t T2K.glb
```

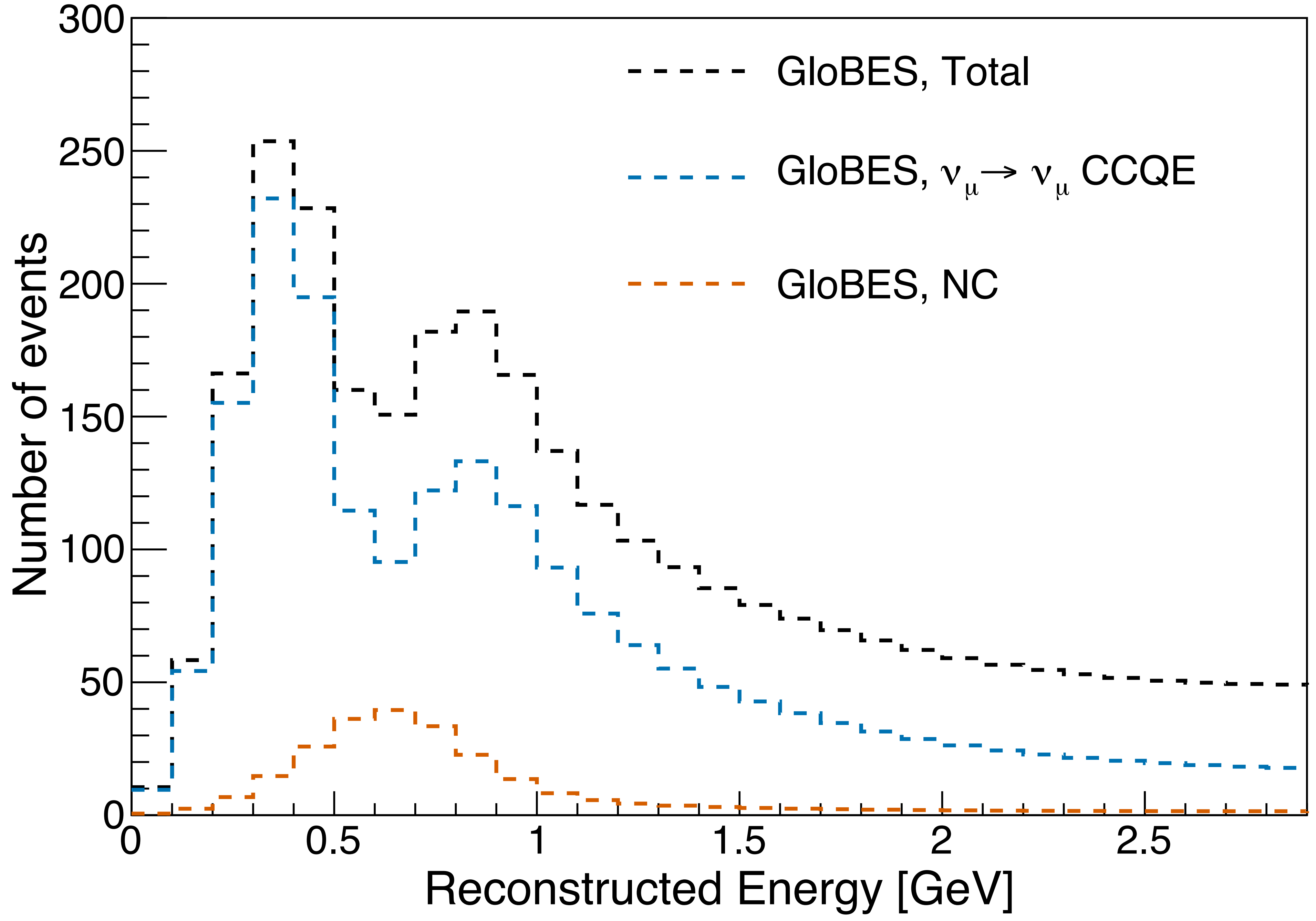
This specific value can be obtained from the global neutrino fit data at http://www.nu-fit.org/?q=node/256

Obtain the event rate and other info.

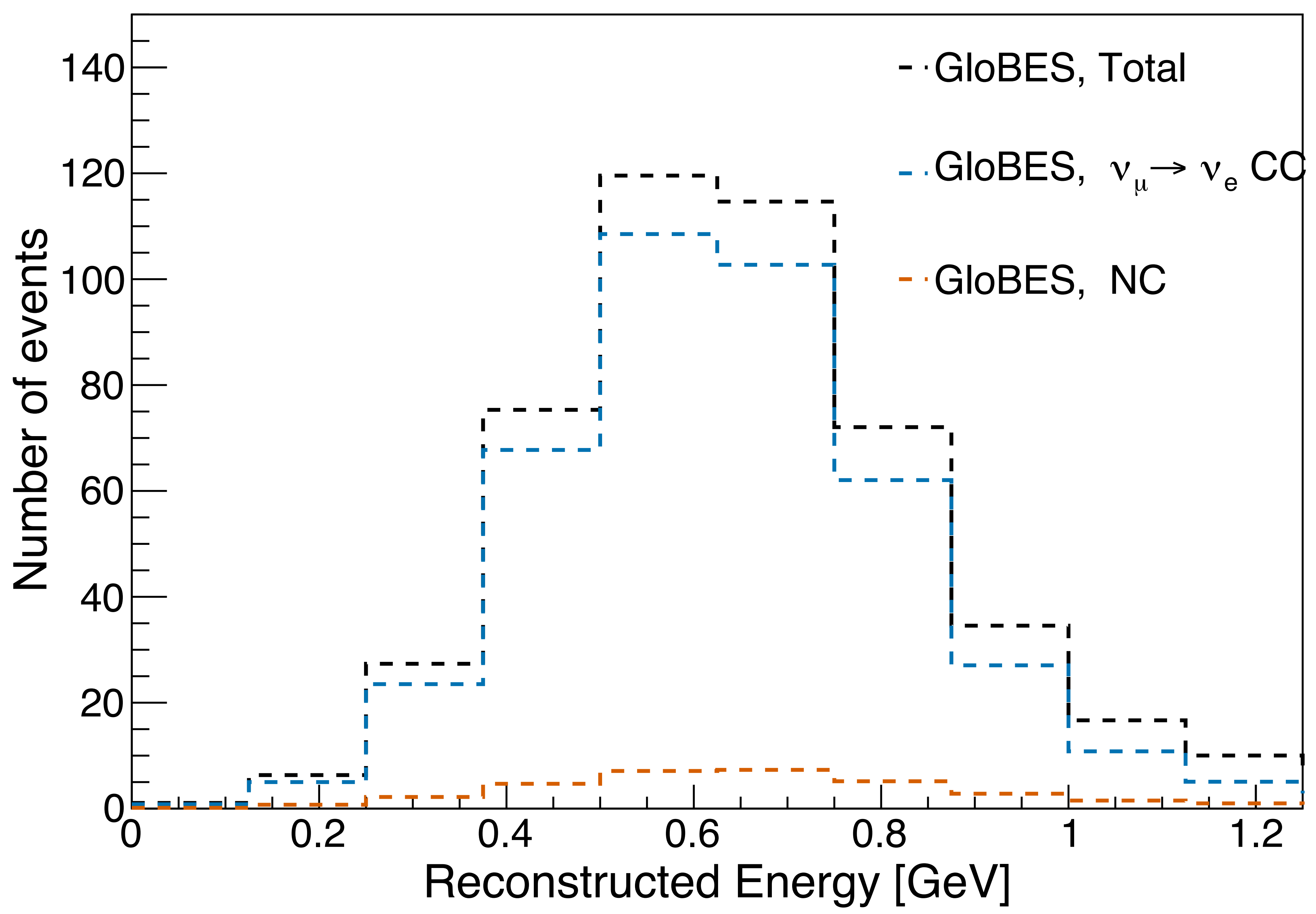
- You need to modify Makefile
- Source code: eventrateall.c
- Compile: make eventrateall
- Run: ./eventrateall
  - If use t2k2_final_nosmear.glb -> eventrate_all_t2k2_final_nosmear.root

Event rate: Output from the GLoBES

muon neutrino disappearance



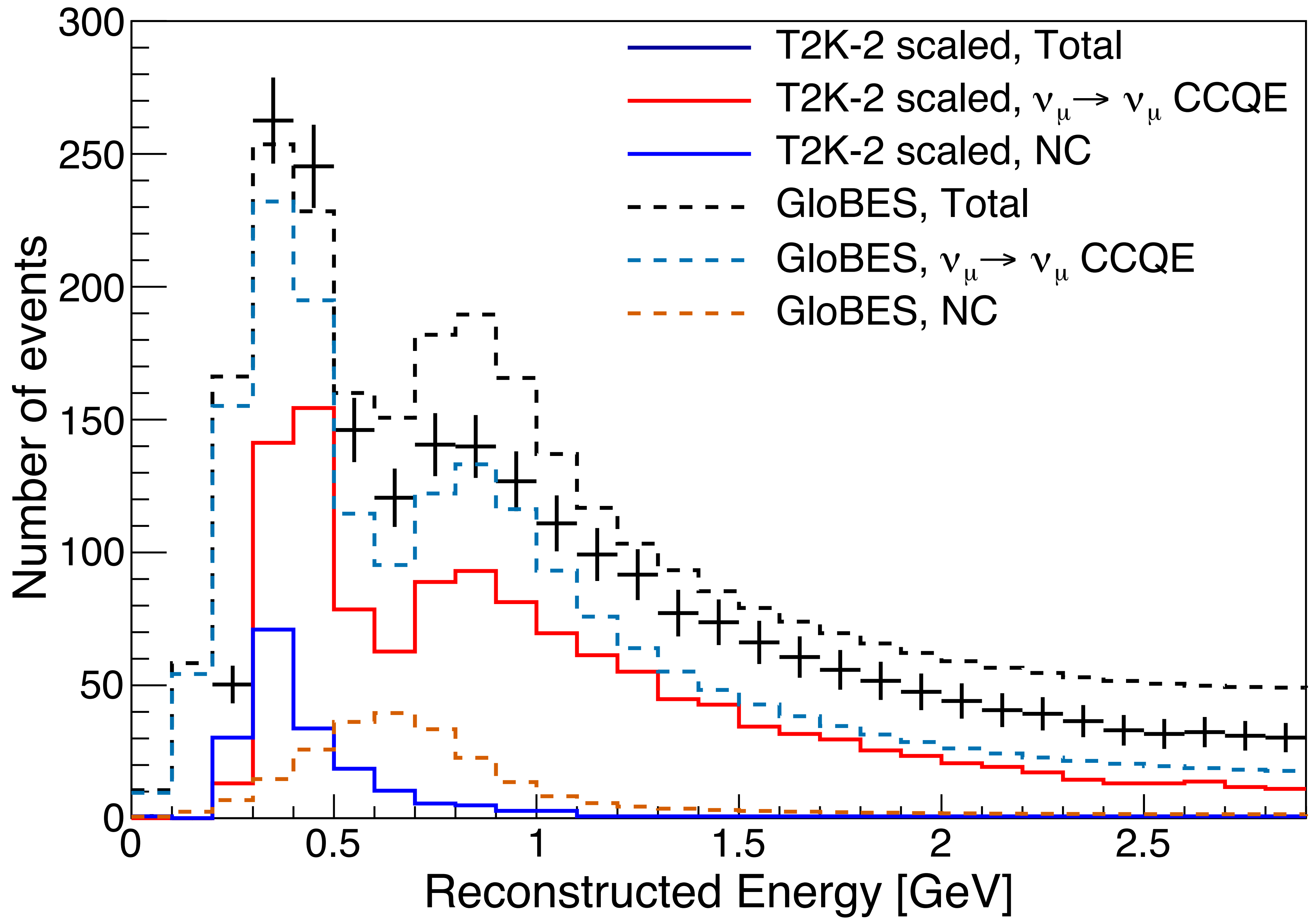
Electron neutrino disappearance

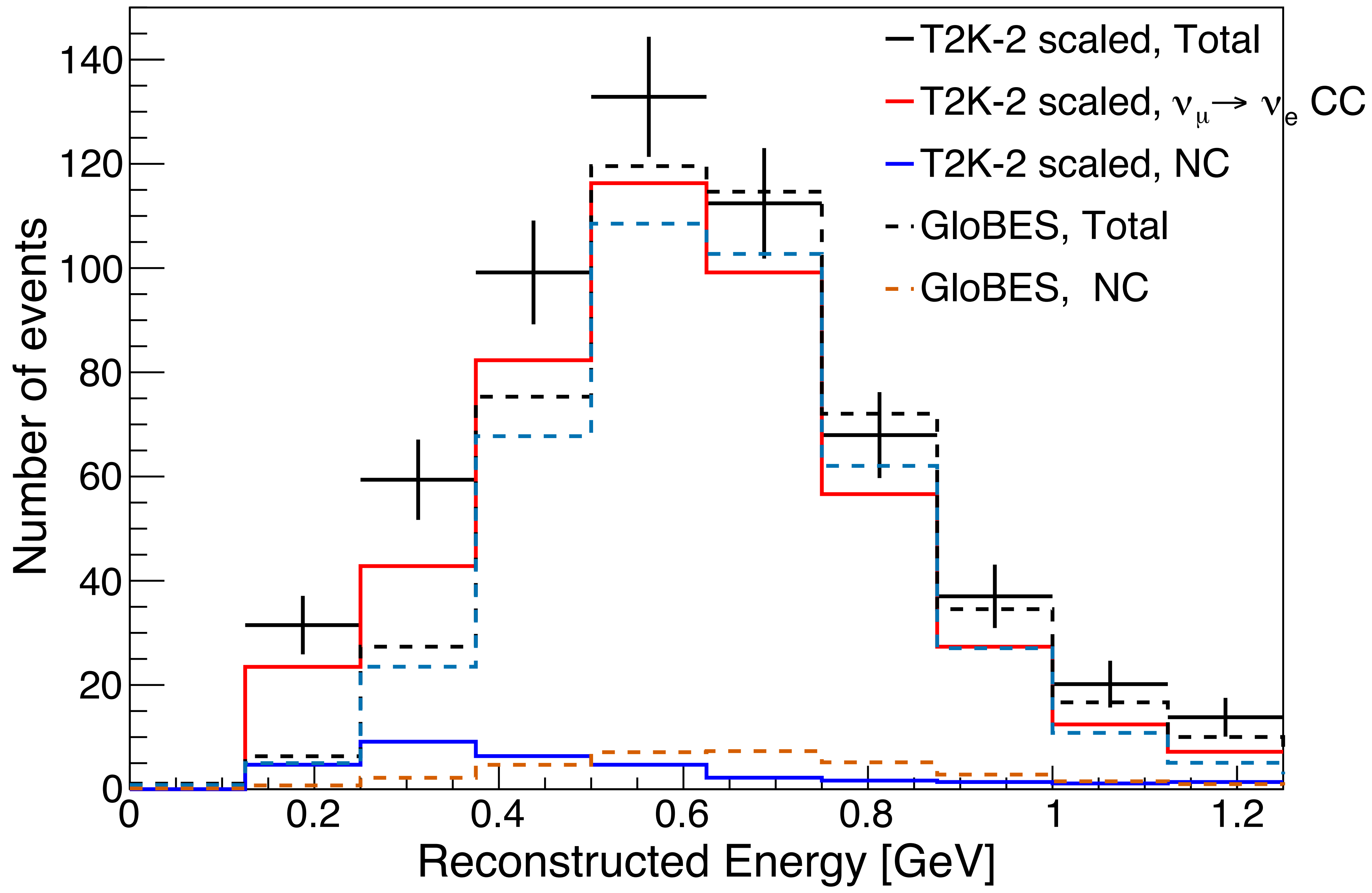


Use checkNoSmearing_all_final.C to plot

Event rate: Output from the GLoBES

Use checkNoSmearing_all_final.C to plot



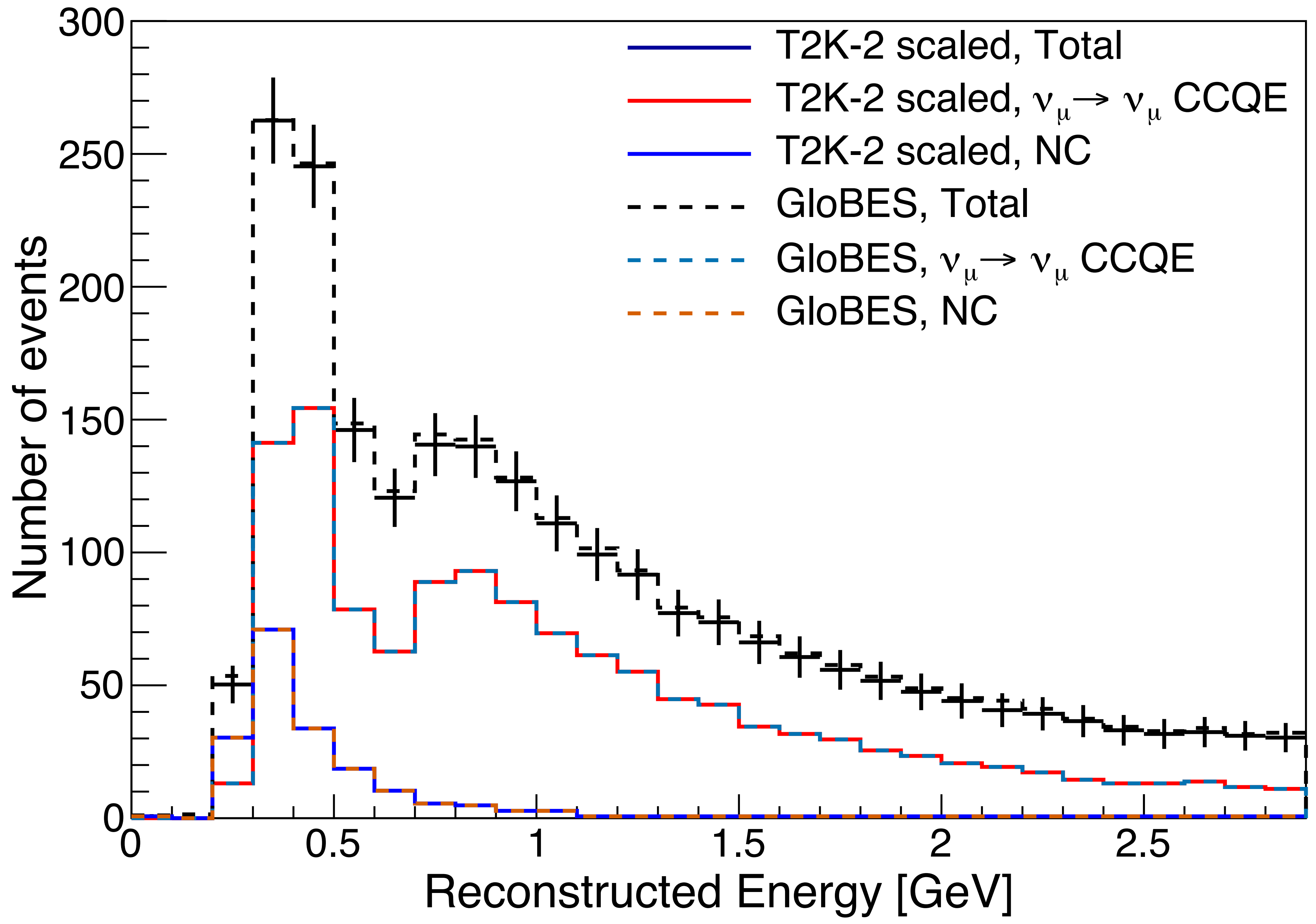


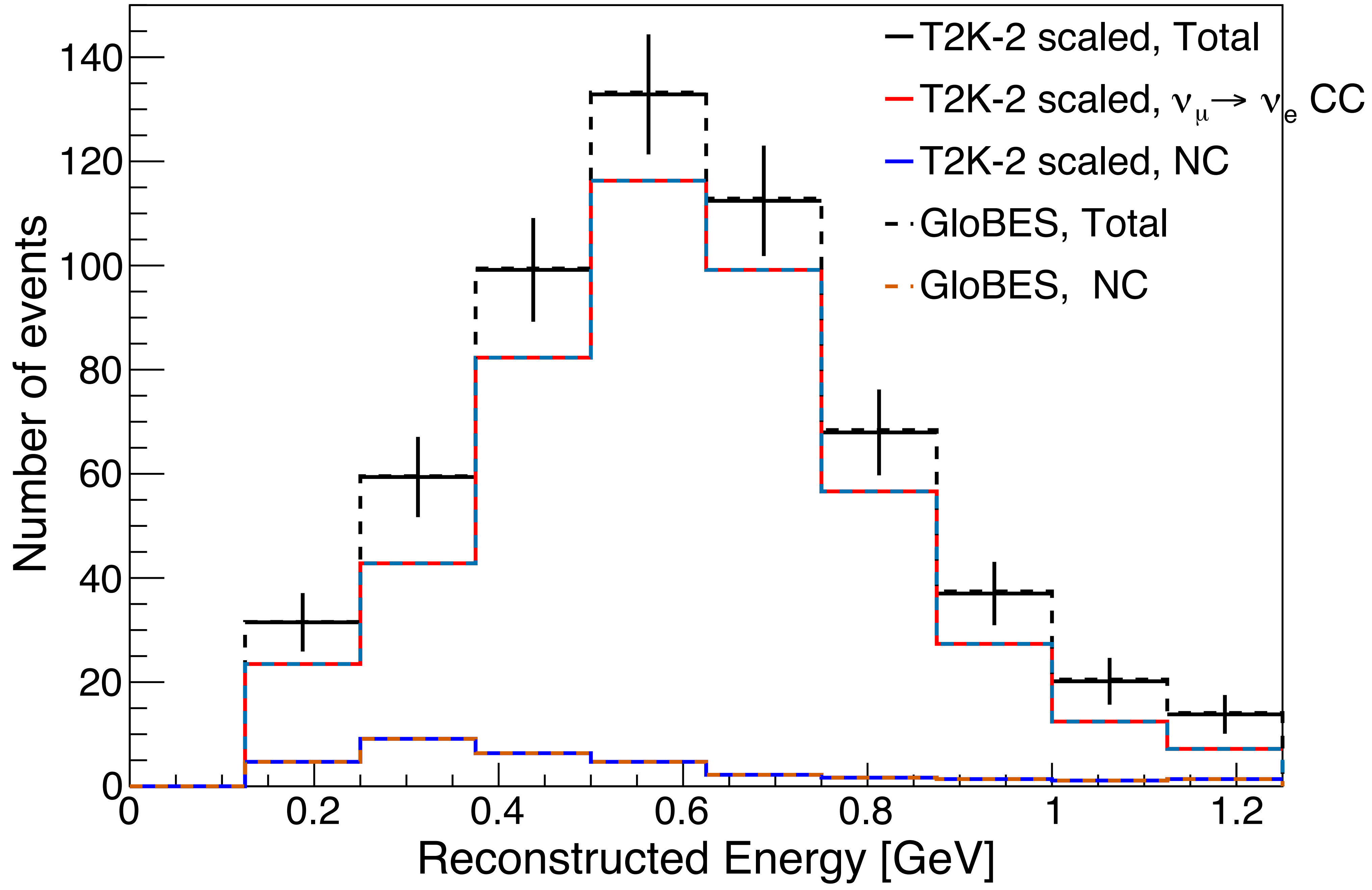
You try to compare with the simulation from real exp.

It's not the same! Why?

Event rate: Output from the GLoBES

The AEDL file w/ post-smearing is in t2k2_final_nosmear.glb & use checkWithSmearing_all_final.C to plot





You can implement a post-efficiency smearing to "match" the real experiment's simulation.

This is not a unique method for matching real experiment with GLoBES output

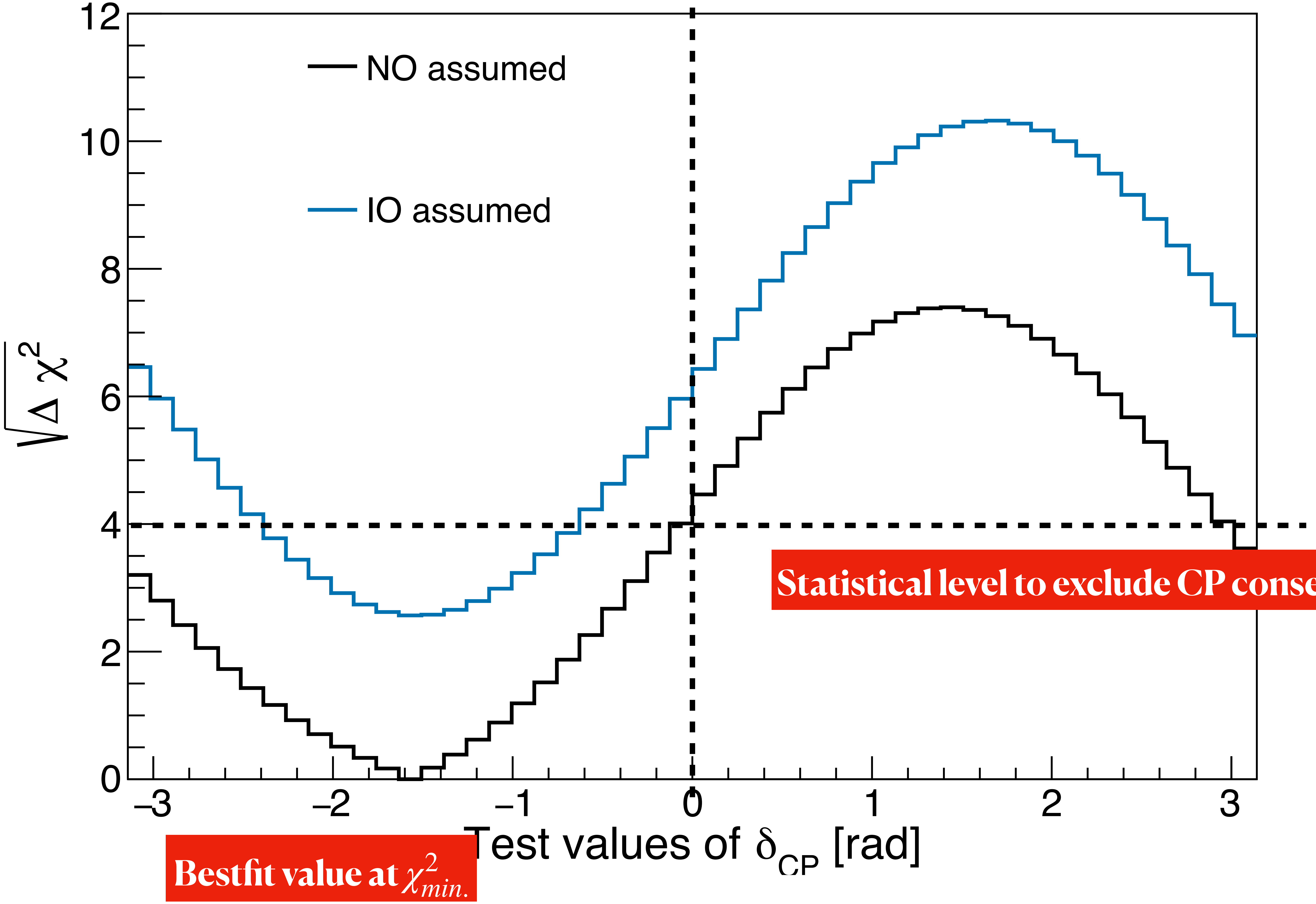
Sensitivity

Obtain the CP violation sensitivity for one true value of δ_{CP}

- You need to modify Makefile
- Source code: test_cp_null_simple.c
- Compile: make test_cp_null_simple
- Run: ./test_cp_null_simple
  - If use t2k2_final_nosmear.glb -> t2k2_final_nosmear_sensi_cp_simple.root
  - If use t2k2_final_wsmear.glb -> t2k2_final_wsmear_sensi_cp_simple.root

Sensitivity at dcp = -pi/2, MO is normal

Use plot_dcp_t2k2_simple.C to make plot



Statistical level to exclude CP conservation

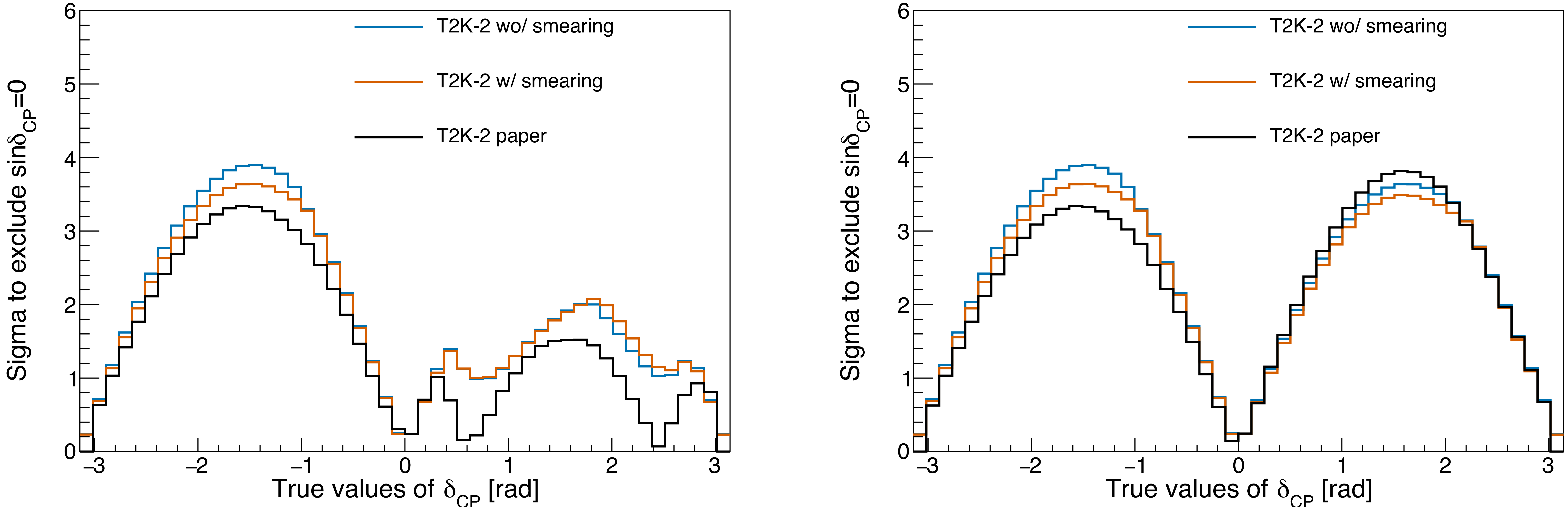
Bestfit value at $\chi^2_{min.}$

Obtain the CP violation sensitivity for whole range of δ_{CP}

- You need to modify Makefile
- Source code: test_cp_null.c
- Compile: make test_cp_null
- Run: ./test_cp_null
  - If use t2k2_final_nosmear.glb -> t2k2_final_nosmear_sensi_cp.root
  - If use t2k2_final_wsmear.glb -> t2k2_final_wsmear_sensi_cp.root

Sensitivity as function of true value of CP phase

Use plot_dcp_t2k2.C to make plot

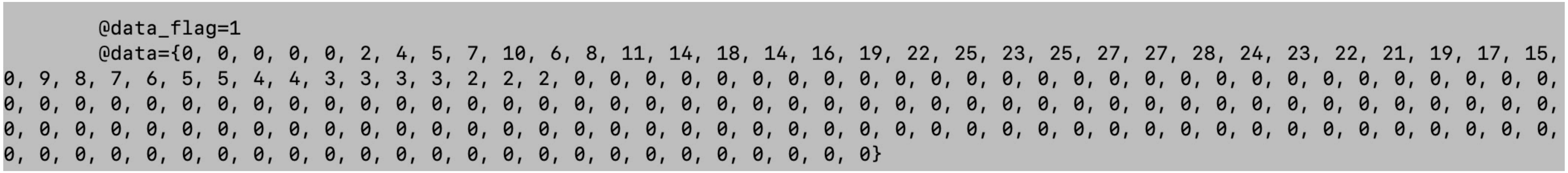


IT's quite complicated. Not so bad consistency with real simulation.

(Fake) data fit

Generate fake data

- Source code: createFakeData_forFit.C
- Run: root -b -q createFakeData_forFit.C with no Poisson fluctuation
- Then copy output to t2k2_final_wsmear_wdata.glb, same as t2k2_final_wsmear.glb but adding fake data



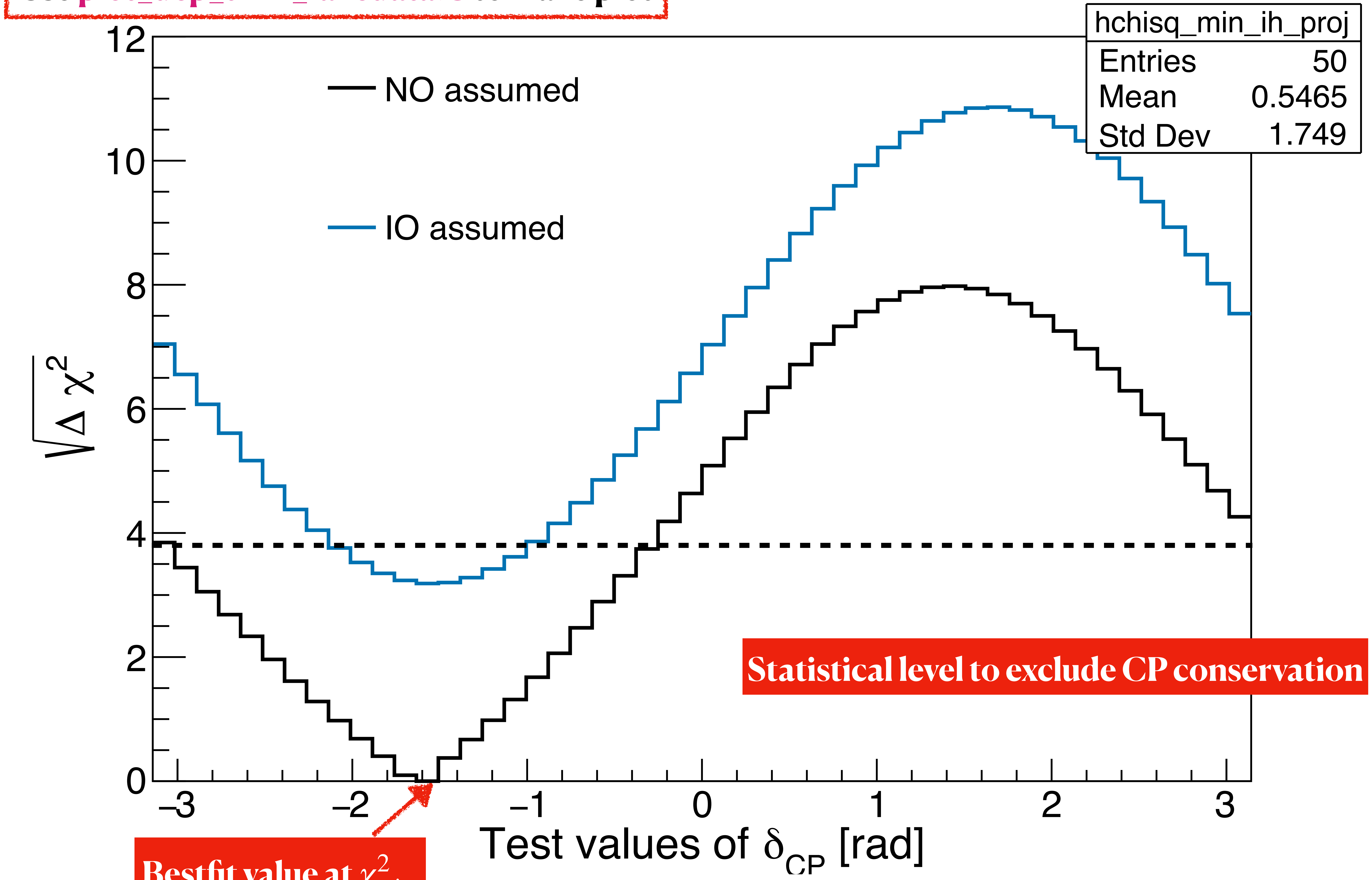
```
        @data_flag=1
        @data={0, 0, 0, 0, 0, 2, 4, 5, 7, 10, 6, 8, 11, 14, 18, 14, 16, 19, 22, 25, 23, 25, 27, 27, 28, 24, 23, 22, 21, 19, 17, 15,
0, 9, 8, 7, 6, 5, 5, 4, 4, 3, 3, 3, 3, 2, 2, 2, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}
```

Run fit to fake data

- You need to modify Makefile
- Source code: test_cp_null_fakedata.c
- Compile: make test_cp_null_fakedata
- Run: ./test_cp_null_fakedata
  - Output t2k2_final_wsmear_fakedata_cp.root

Fitting result of the fake data

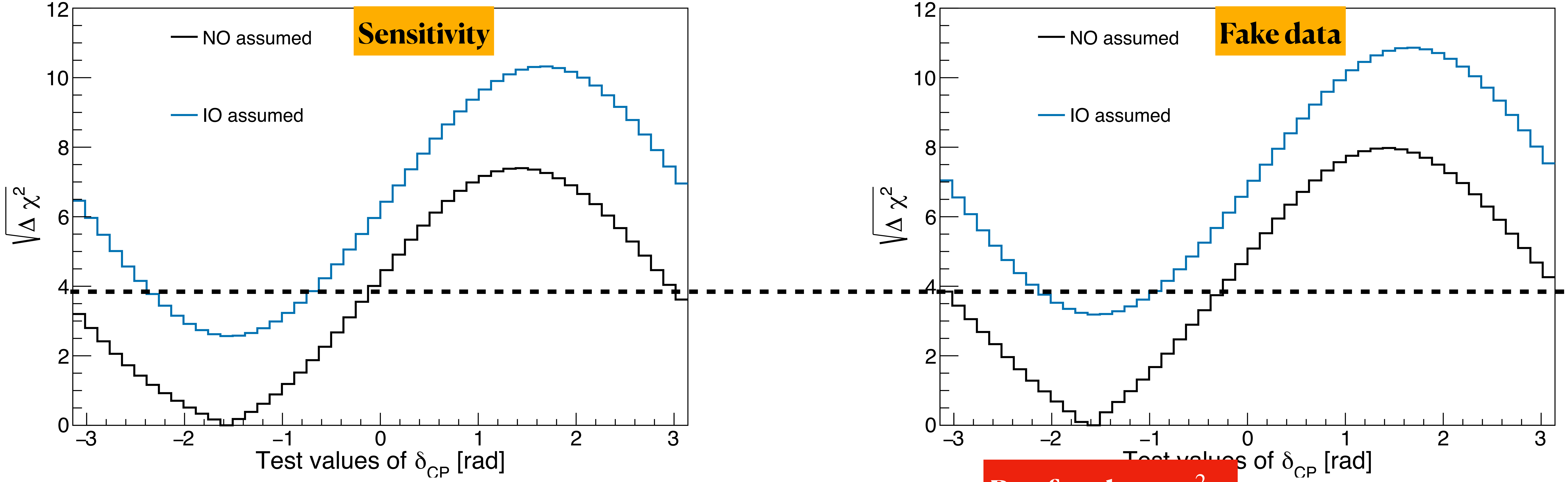
Use plot_dcp_t2k2_fakedata.C to make plot



Statistical level to exclude CP conservation

Bestfit value at $\chi^2_{min.}$

Fitting result of the fake data



Bestfit value at $\chi^2_{min.}$

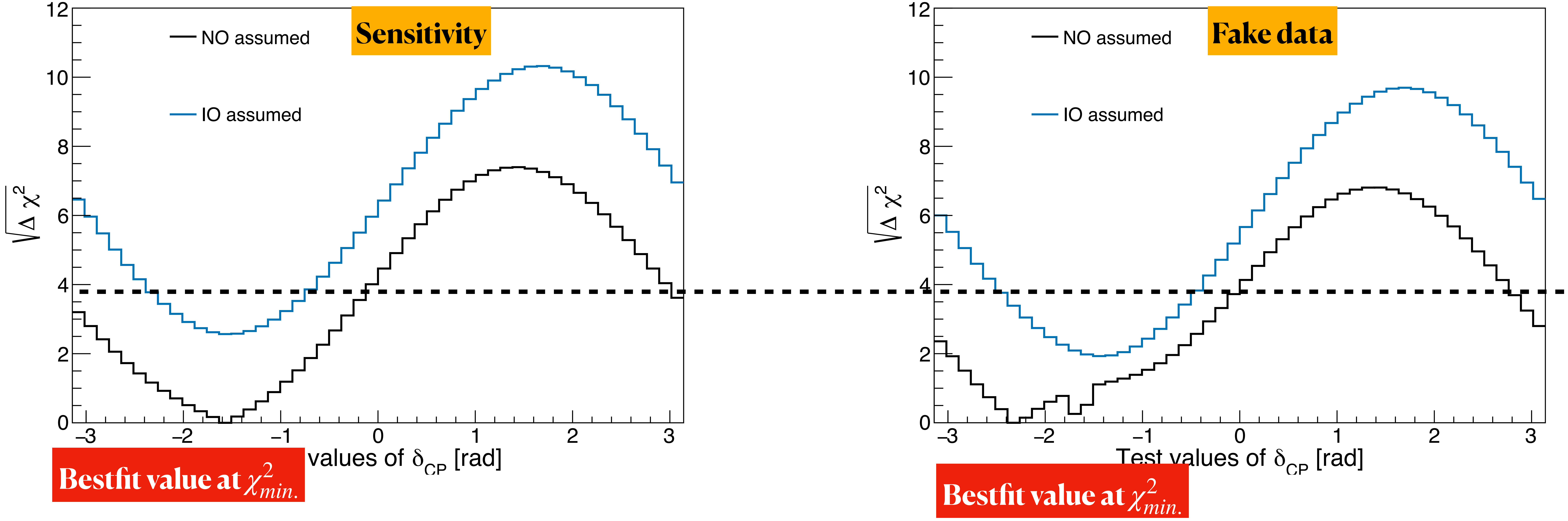
Bestfit value at $\chi^2_{min.}$

The two are almost identical since there is no Poisson fluctuation applied in the fake data

Generate fake data with Poisson fluctuation

- Source code: createFakeData_forFit.C
- Run: root -b -q createFakeData_forFit.C with Poisson fluctuation
- Then copy output to t2k2_final_wsmear_wdata_poissonFluc.glb, same as t2k2_final_wsmear.glb but adding fake data

Fitting result of the fake data with Poisson fluctuation



Sensitivity

Fake data

Bestfit value at $\chi^2_{min.}$

Bestfit value at $\chi^2_{min.}$

They are different when Poisson fluctuation is applied in the fake data

Summary

- You can do many thing with GLoBES: sensitivity testing, design optimization, data fit....
- But of course, it can't replace the real experiment!

We have multiple projects available for students (undergrad/master/Ph.D.) to explore. If you are interested, please join us.

Reference

- GLoBES manual https://www.mpi-hd.mpg.de/lin/events/globes07/
- Workshop on Physics and Applications of the GLoBES software https://www.mpi-hd.mpg.de/lin/events/globes07/