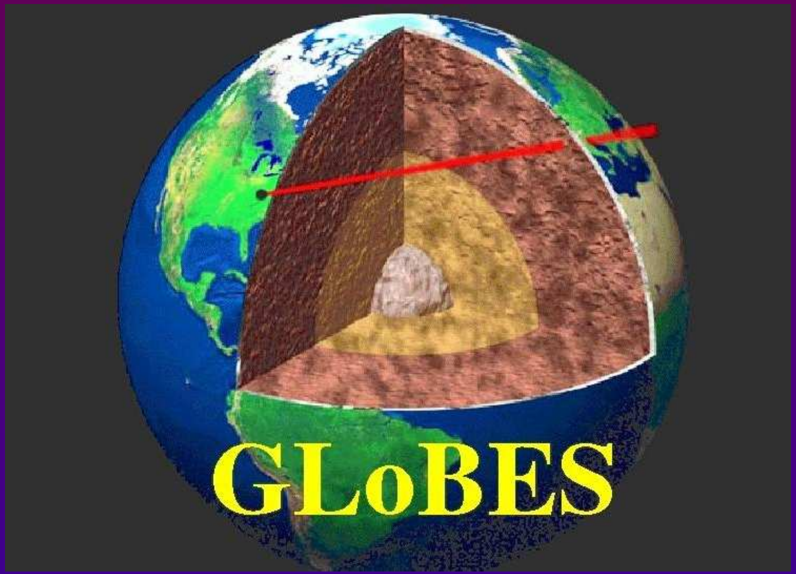
# GLoBES

## and its application to neutrino physics




Mark Rolinec on behalf of the GLoBES Team

Technische Universität München

Cracow Epiphany Conference on Neutrinos and Dark Matter

5-8 January 2006

# Outline

Part I - GLoBES - General Features

- Features
- Basic Structure

Part II - Experiment description in AEDL

- Features
- AEDL-File Example

Part III - Basics and Applications

- Simulation of event rates
- Calculation of $\chi^2$
- $\chi^2$-Projections
- Examples of a variety of applications

# Part I

## GLoBES - General Features

# GLoBES - Purpose

The **G**eneral **Lo**ng **B**aseline **E**xperiment **S**imulator

GLoBES is a software package designed for

- Simulation
- Analysis
- Comparison

of neutrino oscillation long baseline experiments

# GLoBES - Availability

GLoBES can be downloaded as tar-ball together with a detailed manual from

`http://www.ph.tum.de/~globes/`

since August 2004.

The software is developed, documented, maintained and supported by the GLoBES-Team:

- Patrick Huber (UW)
- Joachim Kopp (TUM)
- Manfred Lindner (TUM)
- MR (TUM)
- Walter Winter (IAS)

# GLoBES - Features

- Accurate treatment of systematical errors
- Arbitrary matter density profile & uncertainties
- Arbitrary energy resolution function
- Single and multiple experiment simulation
- Output of oscillation probabilities
- Output of event rates
- Simple $\chi^2$ calculation
- Inclusion of external input
- Projection of $\chi^2$ (minimization)

# GLoBES - Experiments

GLoBES has been used for simulating:

- MINOS, ICARUS and OPERA
- Reactor experiments, Double-CHOOZ, R2D2
- T2K
- NO$\nu$A
- SPL CERN-Fréjus
- JHF-HK (T2K upgrade)
- Neutrino factories
- $\beta$-beams
- BNL neutrino beam

# GLoBES - Basic Structure

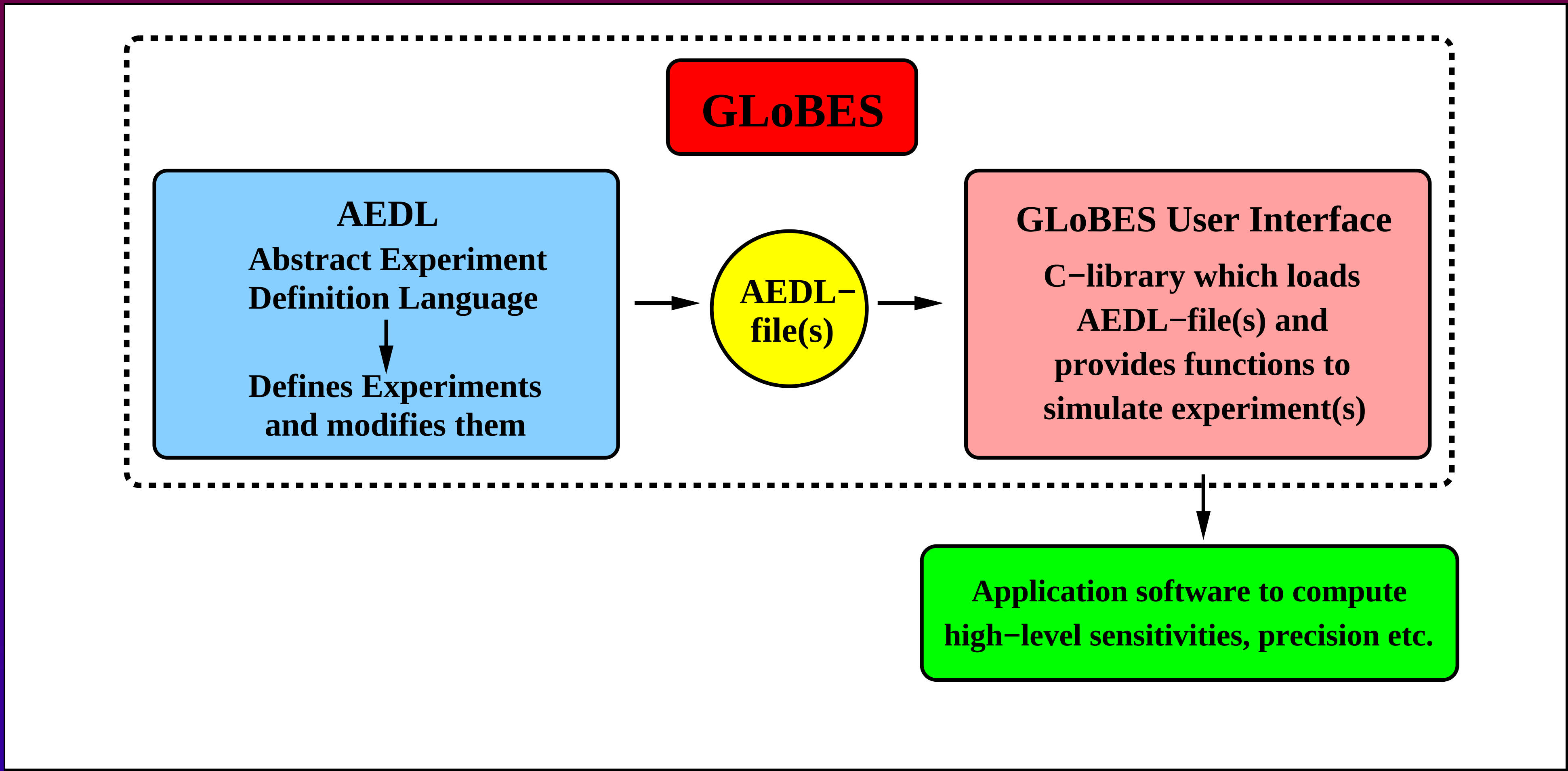


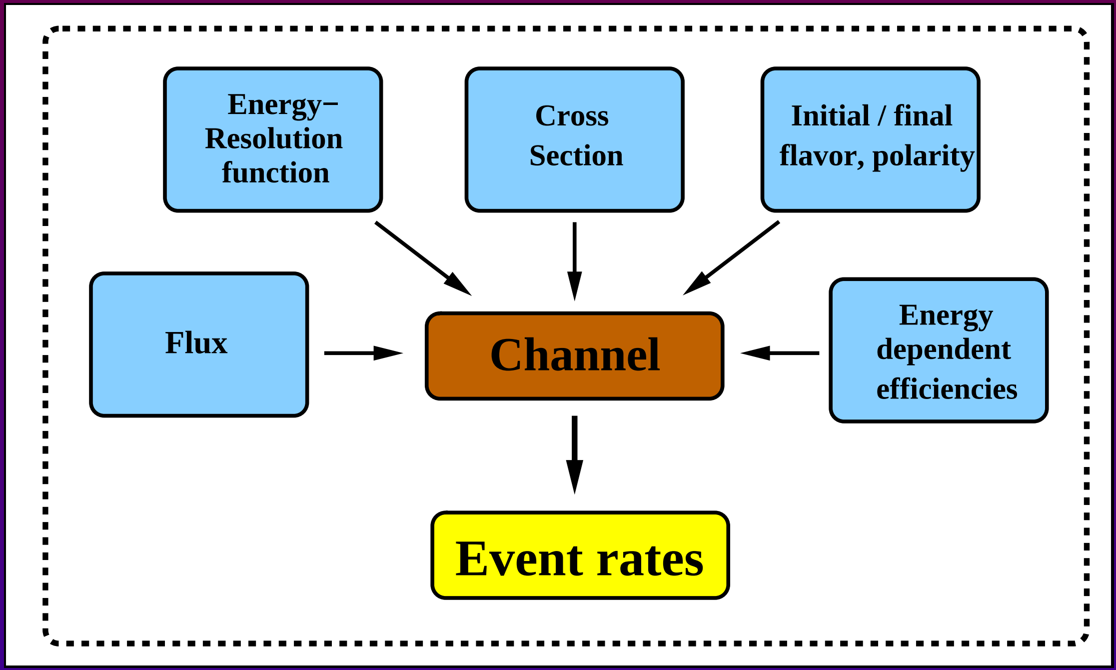

Figure taken from P. Huber, M. Lindner and W. Winter, Comput. Phys. Commun. **167** (2005) 195

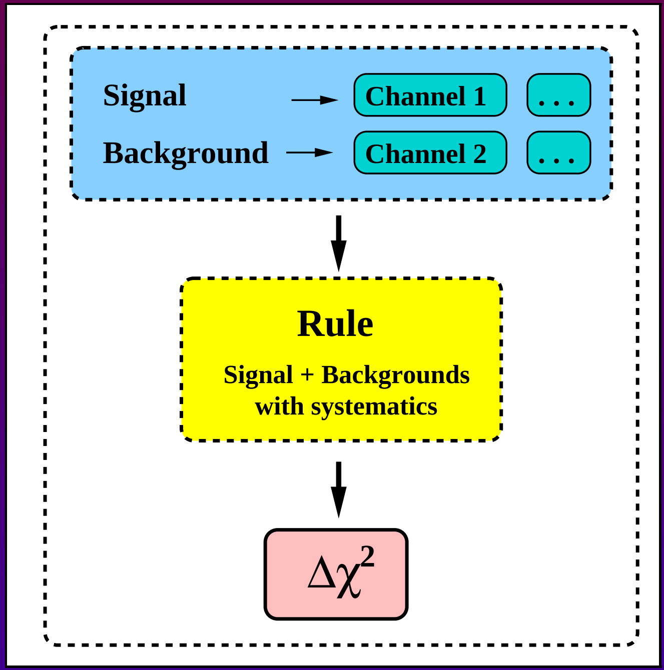
# Part II

## Experiment Description in AEDL

# AEDL - Features

The experiment is described within one file: `Name.glb`




Figures taken from P. Huber, M. Lindner and W. Winter, Comput. Phys. Commun. **167** (2005) 195

- Experiments can contain an arbitrary number of rules
- GLoBES can handle any number of experiments

# AEDL-File - Example

Flux and cross sections can be loaded from external files:

```
flux(#user_flux)<
@flux_file = "user_flux_file.dat"
@time = 5.0 /* years */
@power = 4.0 /* MW */
@norm = 1.0
>
```

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

For the case of a neutrino factory GLoBES provides a builtin flux:

```
flux(#nf_flux_mu_plus)<
@builtin = 1
@parent_energy = 50.0 /* GeV */
@stored_muons = 5.33e+20
@time = 8.0 /* years */
>
```

# AEDL-File - Example continued

## Basic characteristics of Experiment:

```
$target_mass = 50.0 /* kt */

$profiletype = 1
$baseline = 3000.0 /* km */
$density = 2.7 /* g cm ^ -3 */

$bins = 20
$emin = 4.0 /* GeV */
$emax = 50.0 /* GeV */

$sampling_points = 20
$sampling_min = 4.0
$sampling_max = 50.0
```

Mass of Detector (fiducial volume)

Baseline and
Density Profile
(average density, PREM or manually defined)

Energy window:
Reconstructed neutrino energy
Analysis level (after energy smearing)

Energy window:
True neutrino energy
Integral Evaluation (before energy smearing)

# AEDL-File - Example continued

Descripion of energy resolution:

```
energy(#ERES)<
@type = 1
@sigma_e = (alpha,beta,gamma)
>
```

Gaussian energy resolution function

with width $\sigma$:

$\sigma(E) = \alpha \times E + \beta \times \sqrt{E} + \gamma$

```
energy(#manual_smearing_matrix)<
@energy =
{0,2,0.863,0.182,0.00267}:
{0,3,0.151,0.697,0.151,0.00101}:
...
{16,19,0.00936,0.278,0.483,0.136};
>
```

Manual energy smearing:

energy smearing matrix $M_{ij}$

- number of rows: `$bins`
- number of columns: `$sampling_points`

# AEDL-File - Example

Defining different channels:

```
channel(#nu_mu_dissappearance)<
@channel = #user_flux :  +:  m:  m:  #CC: #ERES
@pre_smearing_efficiencies = {0.333,0.666,0.999,1.,1., ...  ,1.,1.}
>
```

```
channel(#nu_mu_NC_bckg)<
@channel = #user_flux :  +:  NOSC_m:  NOSC_m:  #NC:
#manual_smearing_matrix
>
```

Additional features:

- @post_smearing_efficiencies
- @pre_smearing_background
- @post_smearing_background

# AEDL-File - Example continued

Defining the Rules:

```
>rule(#Nu_Mu_DIS)<
@signal = 0.86@#nu_mu_dissappearance
@signalerror = 0.04 :  0.0001

@background = 0.11@#nu_mu_NC_bckg :  0.11@#nu_e_NC_bckg :  0.05@#BCKG_3
@backgrounderror = 0.05 :  0.0001

@errordim_sys_on = 2
@errordim_sys_off = 0

@energy_window = 4.0 :  50.0
>
```

# Part III

# GLoBES - Basics and Applications

# GLoBES - **Basics**

Alays to be done:

```
glbInit(argv[0]);
```

Initialize the GLoBES Library

```
glbClearExperimentList();
```

Delete earlier loaded AEDL-Files

```
glbDefineAEDLVariable("Variable",
  double value);
```

Define Variables within the AEDL-File

(has to be set in `Name.glb`)

```
glbInitExperiment("Name.glb",
  &glb_experiment_list[0],
  &glb_num_of_exps);
```

Load the experiment described in `Name.glb` to the experiment list (arbitrary number possible)

# GLoBES - Reference Rates

Set the simulated "Data" - Event Rates:

```
glb_params true_values = glbAllocParams();

glbDefineParams(true_values,th12,th13,
  th23,delta,sdm,ldm);

glbSetOscillationParameters(true_values);

glbSetRates();

  ...
glbFreeParams(true_values);
```

Initialize a parameter vector

Assign parameter values for the parameter vector true_values $(\theta_{12}, \theta_{13}, \theta_{23}, \delta, \Delta m^2_{21}, \Delta m^2_{31})$

Set true_values to be the "True Values"

Let GLoBES calculate the reference event rate vector

Free the parameter vector true_values at the end

# GLoBES - $\chi^2$ Calculation

## Simple $\chi^2$ including systematics

```
glb_params fit_values = glbAllocParams();
```

Initialize another parameter vector

```
glbDefineParams(fit_values,th12',th13',
  th23',delta',sdm',ldm');
```

Assign parameter values for the parameter vector fit_values $(\theta_{12}`, \theta_{13}`, \theta_{23}`, \delta`, \Delta m^2_{21}`, \Delta m^2_{31}`)$

```
glbSwitchSystematics(GLB_ALL,
  GLB_ALL,GLB_ON);
```

Switch on systematical errors

```
double chi =
  glbChiSys(fit_values,GLB_ALL,GLB_ALL);
```

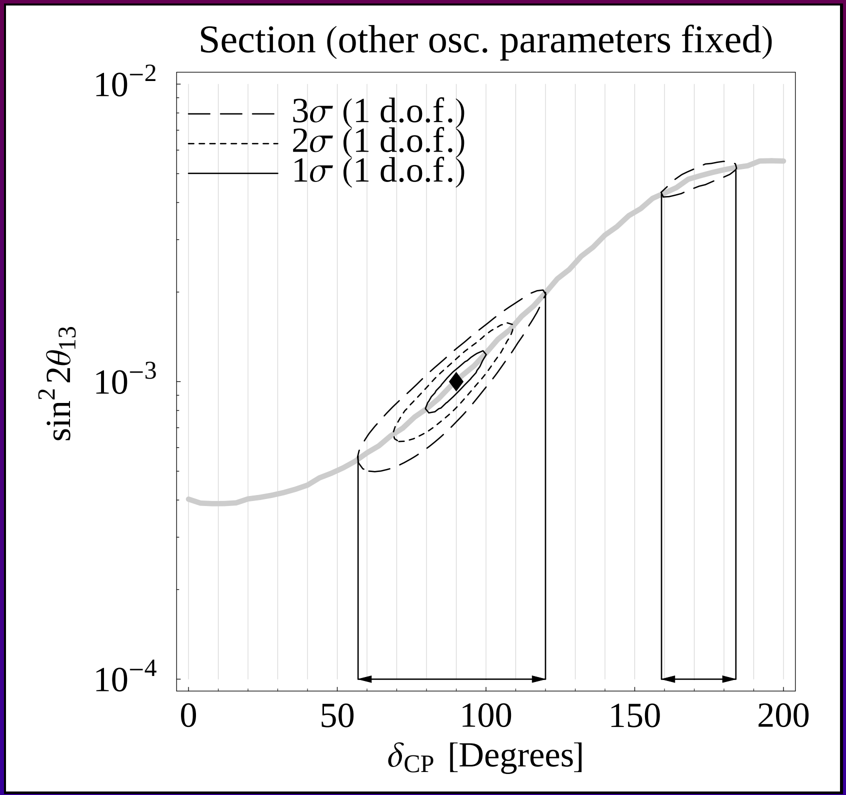
Calculate the $\chi^2$ at the parameter vector fit_values

```
glbFreeParams(fit_values);
```

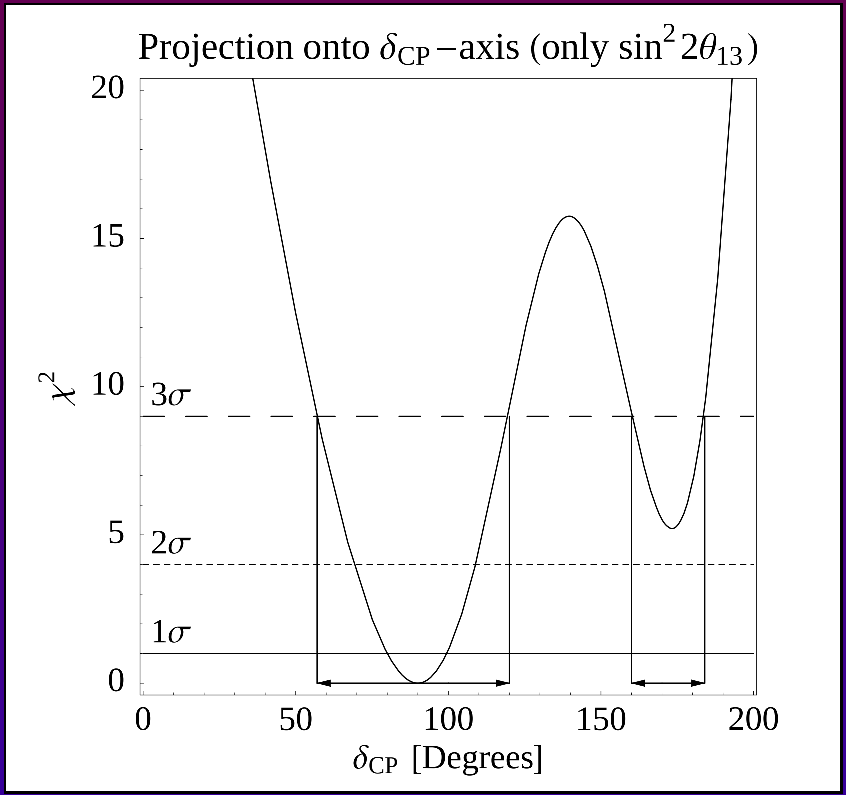
Free the parameter vector fit_values at the end

# GLoBES - **Projection of $\chi^2$**

Projection of two-parameter correlations (Here $\delta$ - $\sin^2 2\theta_{13}$)




`glbChiSys`




`glbChiDelta`

Figures taken from P. Huber, M. Lindner and W. Winter, Comput. Phys. Commun. **167** (2005) 195

# GLoBES - **Projection of $\chi^2$**

Including parameter correlations by projection of $\chi^2$

```
glbDefineParams(in_error,d_th12,d_th13,
  d_th23,d_delta,d_sdm,d_ldm);
```

Define the errors on oscillation parameters (external input)

```
glbSetDensityParams(in_error,
  d_rho,GLB_ALL);
```

Give the error on the matter density $\rho$

```
glbSetStartingValues(start);
```

Set center values for defined errors

```
glbSetInputErrors(in_error);
```

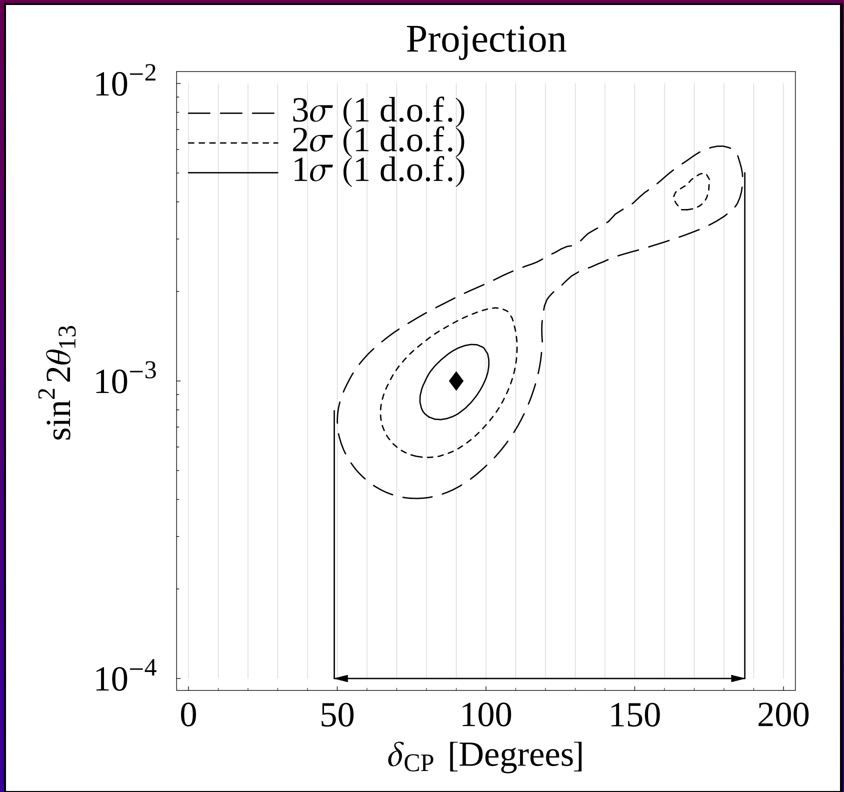
Set all errors as defined before

```
double chiProj = glbChiTheta(fit_values,
  minimum,GLB_ALL);
```

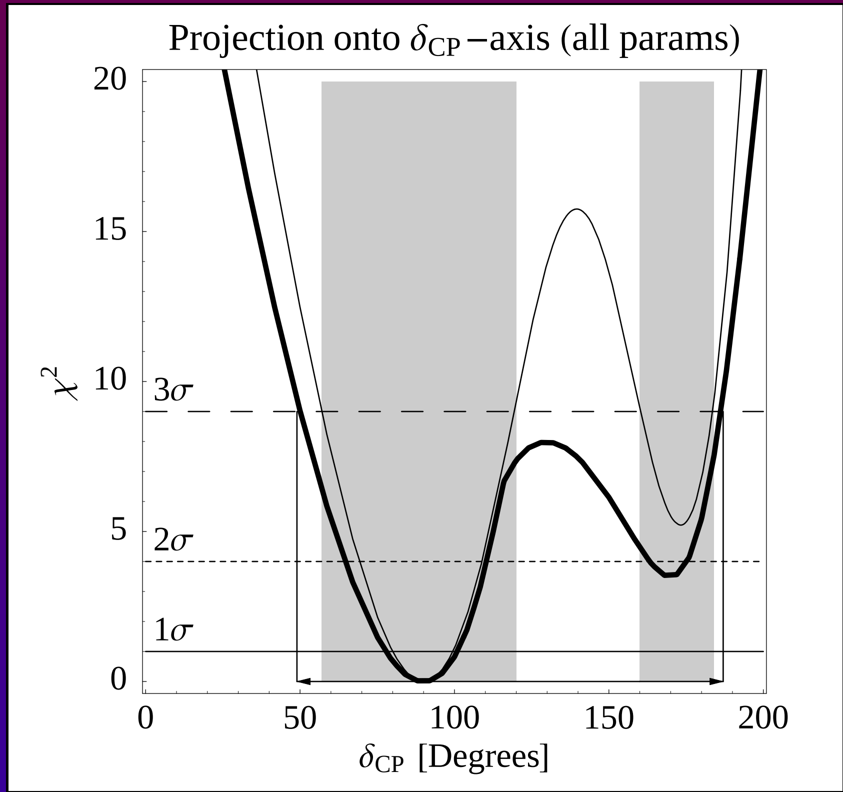
Calculate a projection with respect to $\sin^2 2\theta_{13}$

# GLoBES - **Projection of $\chi^2$**

Projection of six-parameter correlations




`glbChiThetaDelta`




`glbChiDelta`

Figures taken from P. Huber, M. Lindner and W. Winter, Comput. Phys. Commun. **167** (2005) 195

# GLoBES - **Applications I**

Atmospheric oscillation parameters $\Delta m^2_{31}$ and $\sin^2\theta_{23}$

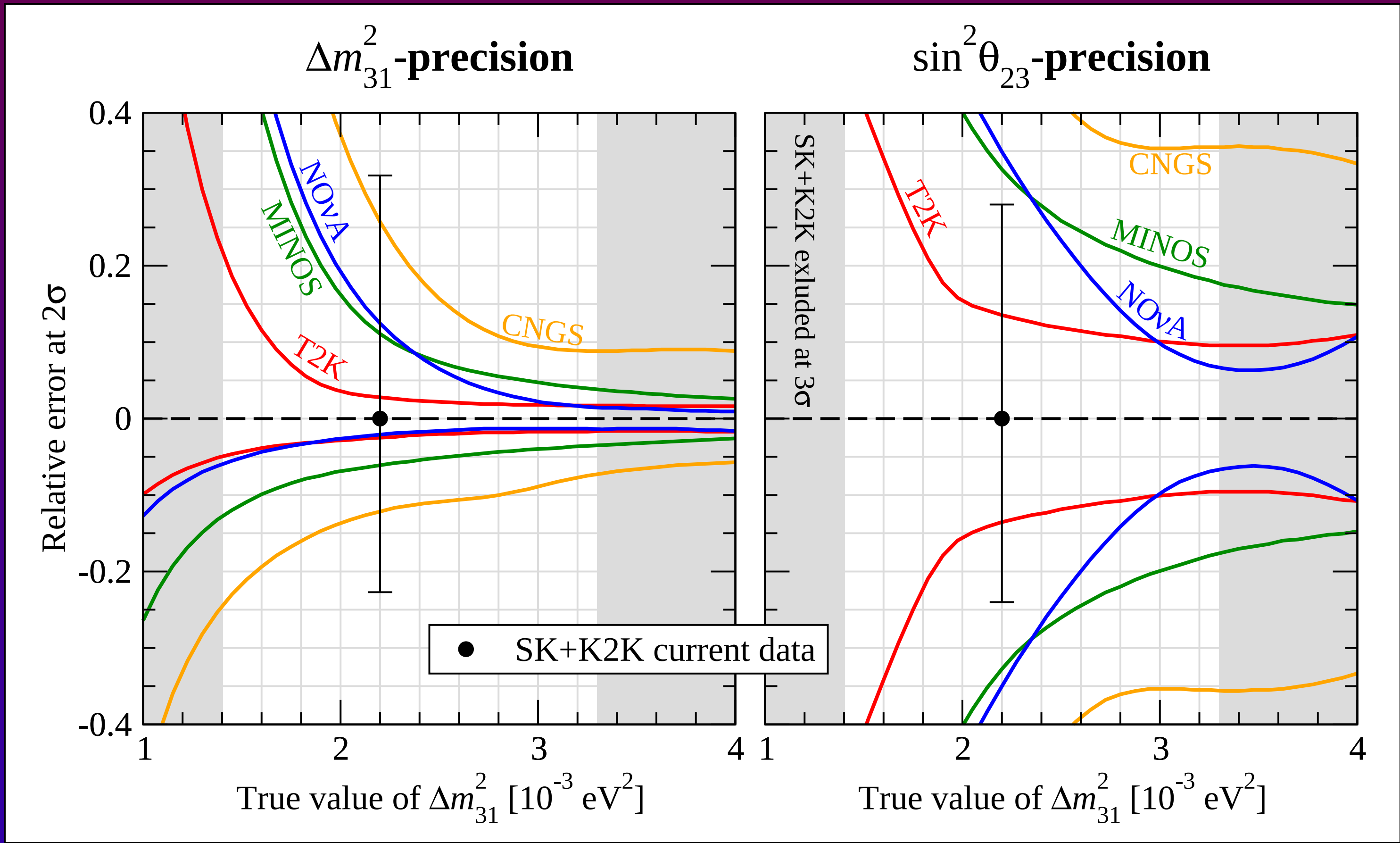



Figure taken from **T. Schwetz**, P. Huber, M. Lindner, MR, W. Winter, hep-ph/0412133

# GLoBES - **Applications II**

Deviation from maximal mixing $\sin^2\theta_{23} = 0.5$

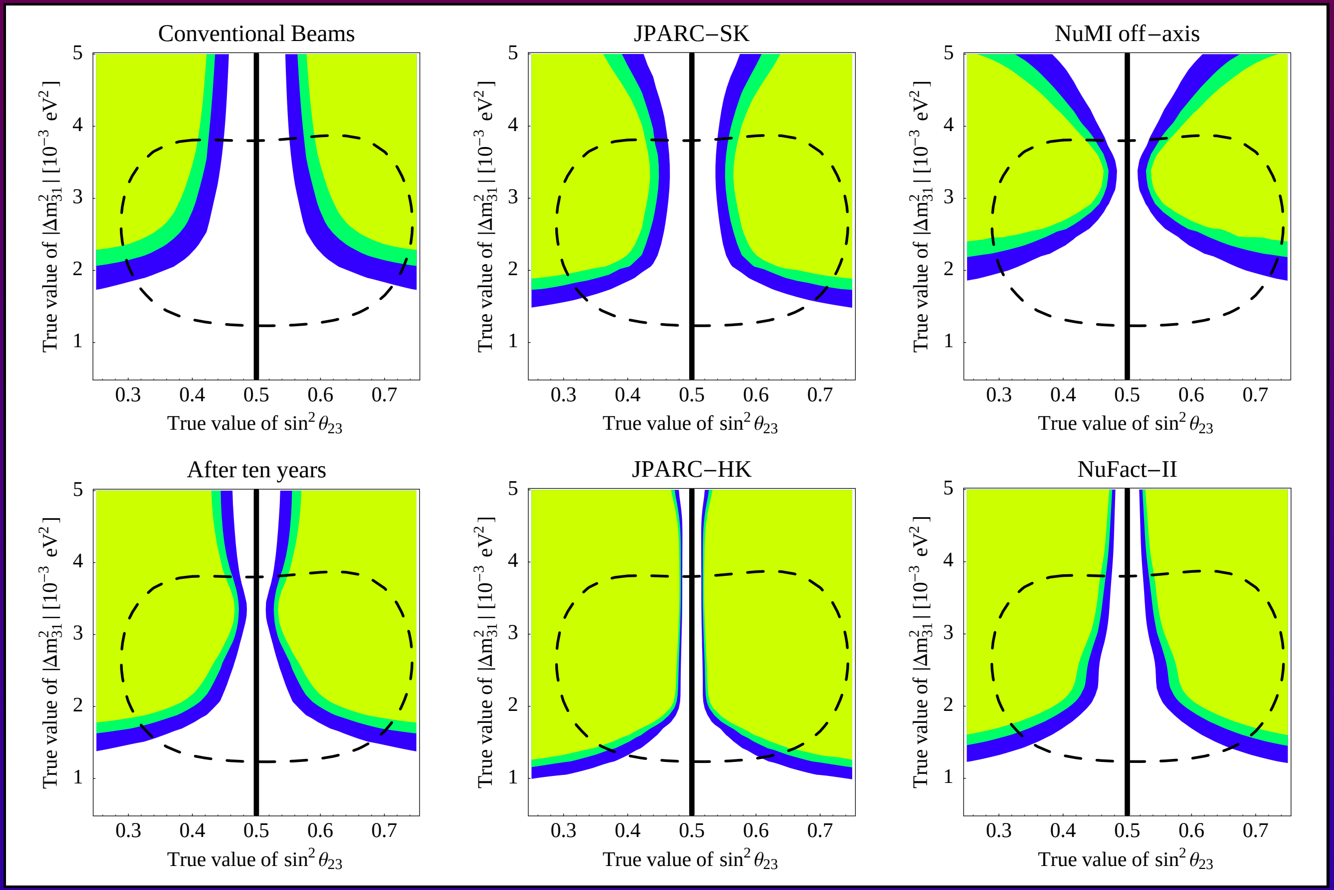
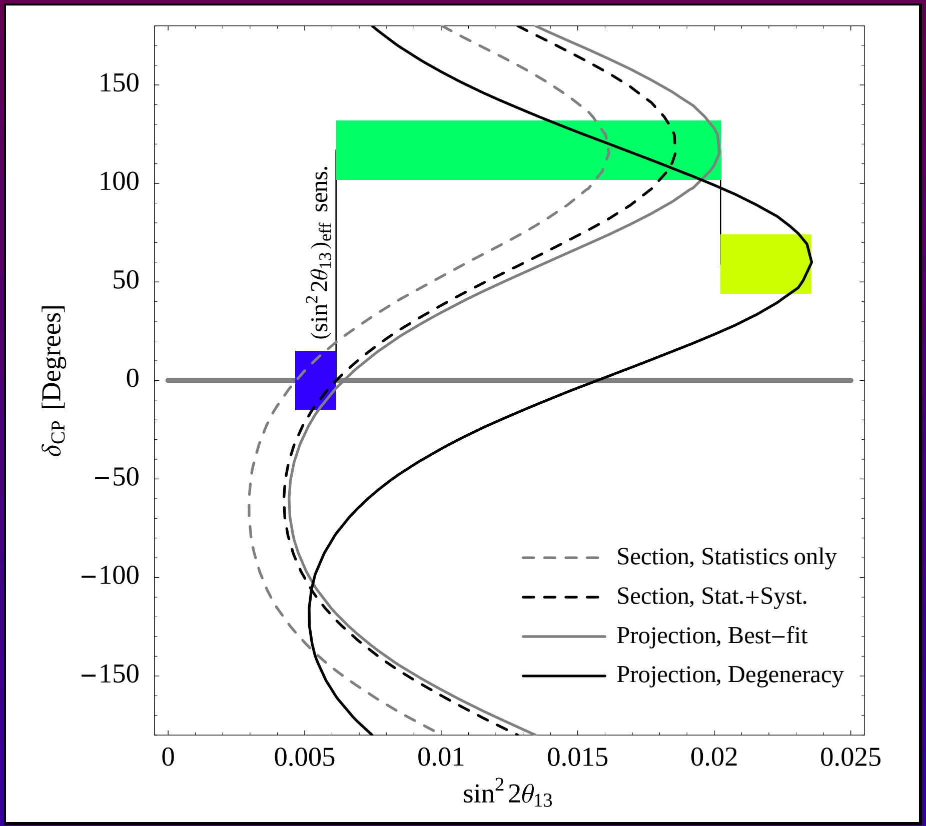


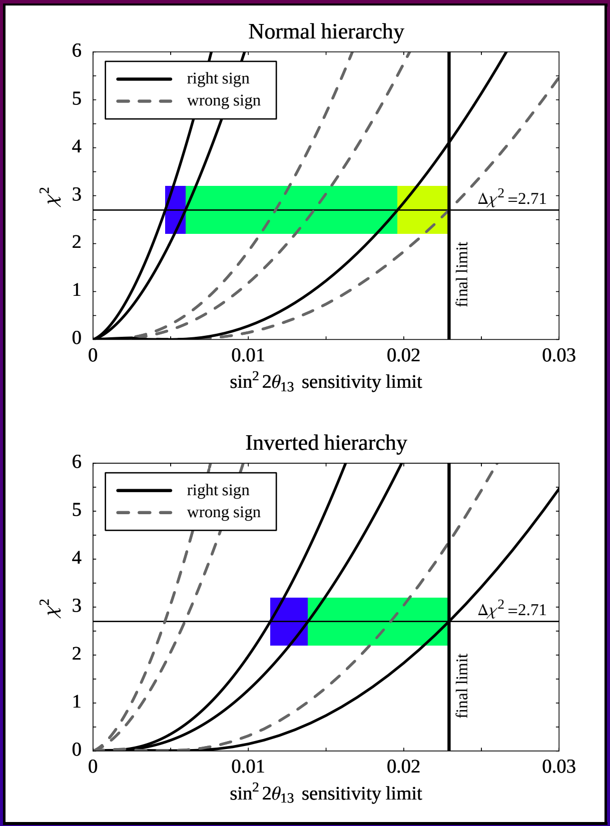

Figure taken from S. Antusch, P. Huber, J. Kersten, T. Schwetz, W. Winter, Phys. Rev. D70 (2004) 097302

# GLoBES - **Applications III**

Sensitivity to $\sin^2 2\theta_{13}$ (true value $\sin^2 2\theta_{13} = 0$)




`glbChiSys`

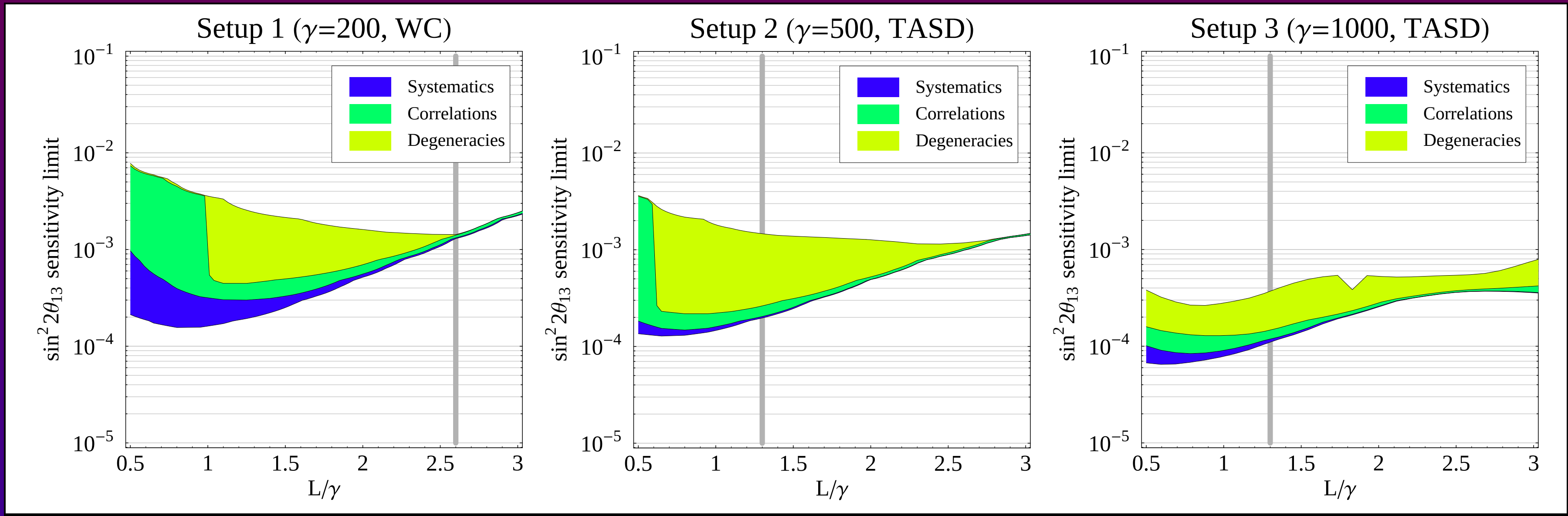



`glbChiTheta`

Figures taken from P. Huber, M. Lindner, MR, T. Schwetz and W. Winter, Phys. Rev. D 70 (2004) 073014

# GLoBES - **Applications IV**

Change AEDL variables within calculations




```
glbDefineAEDLVariable("baseline",value);
```

Figure taken from P. Huber, M. Lindner, MR, W. Winter, hep-ph/0506237

# GLoBES - **Applications V**

Assume large true value $\sin^2 2\theta_{13} = 0.1$

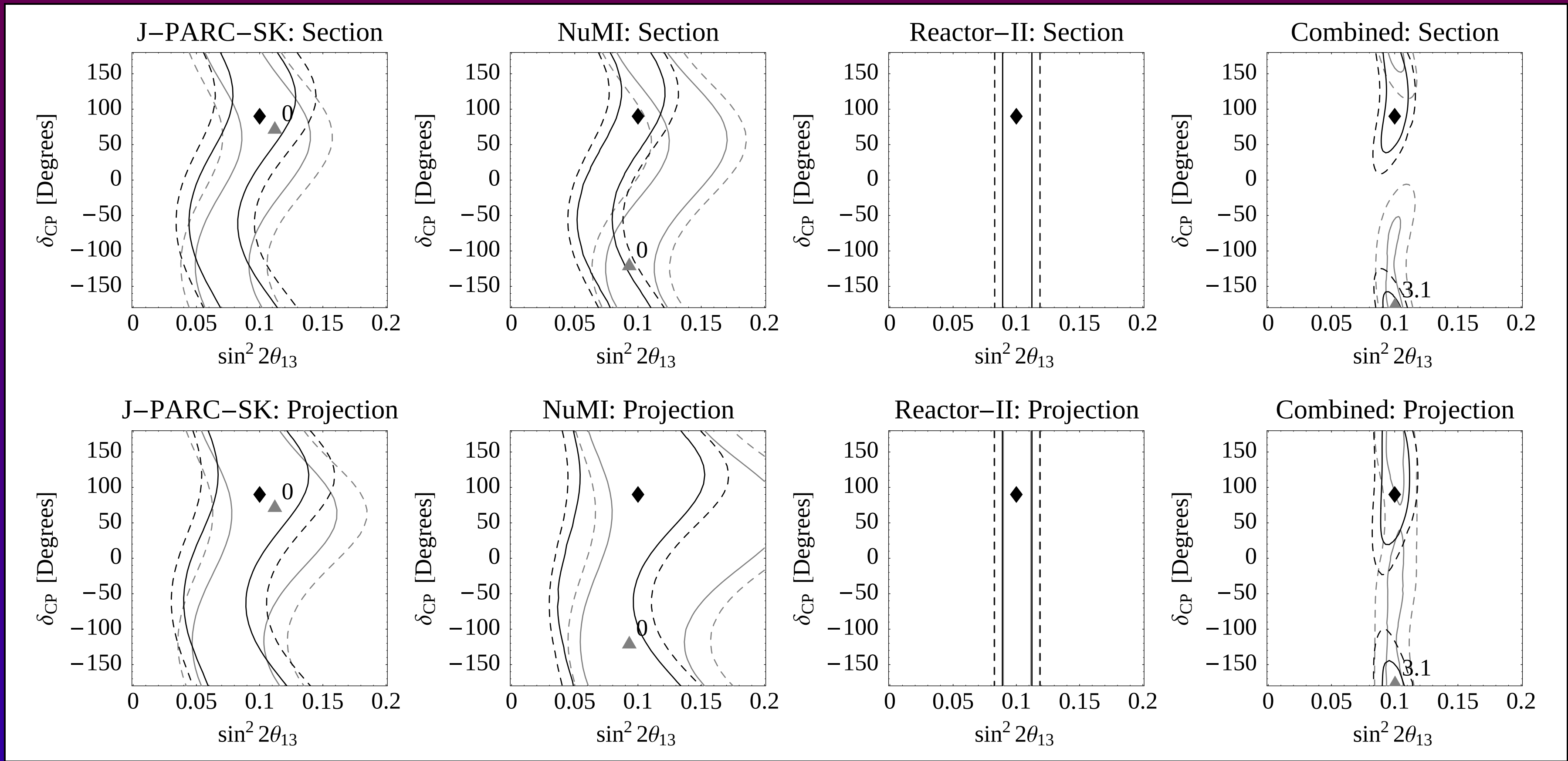



Figure taken from P.Huber, M.Lindner, MR, T.Schwetz, W.Winter, Phys. Rev. D 70 (2004) 073014

# Conclusions

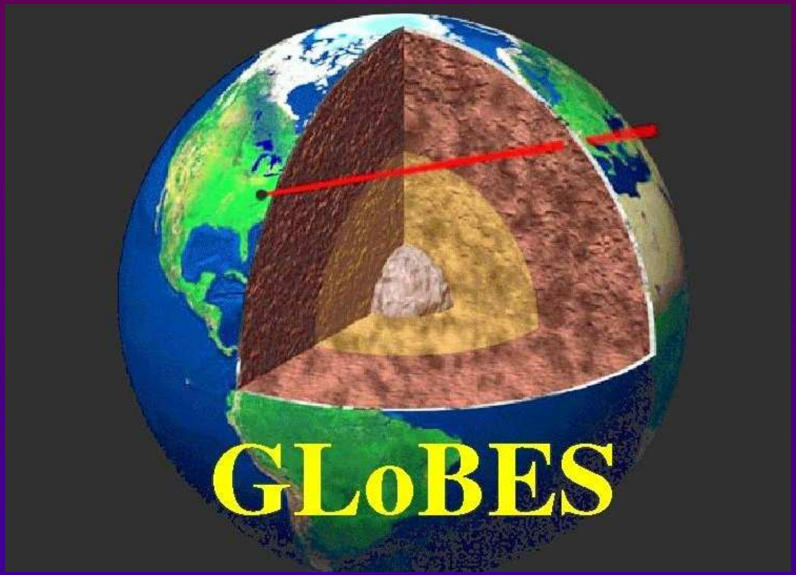
GLoBES is a

- well tested
- powerful
- flexible

software package for the

- Simulation
- Analysis
- Comparison

of neutrino oscillation experiments




So remember: `www.ph.tum.de/~globes/`