Mass hierarchy discrimination with atmospheric neutrinos in large volume ice/water Cherenkov detectors

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Overview

- development of the new statistical approach
  - 2 unbinned likelihood for hierarchies
  - 2 figures of merit of the experiment:
    - p-value
    - false positive fraction
- Minimal exposure for the discovery calculation
- Testing impact of the model uncertainties
  - neutrino fluxes
  - oscillation parameters
  - …
- Testing impact of the detector performance
- *We were concentrated on muons only (no shower reconstruction was assumed).*

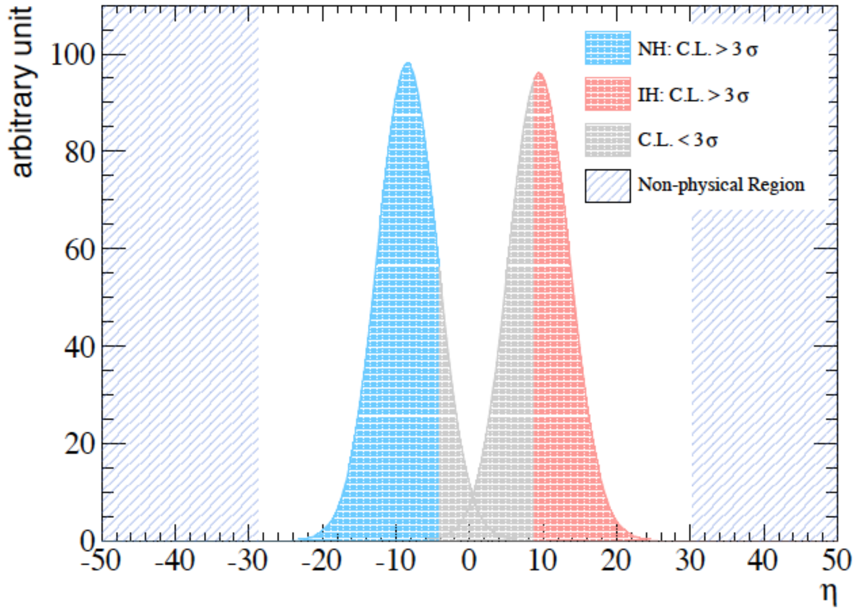
Method

- True hypothesis. Simulations for a given set of parameters -> test experiments.
- Model hypothesis to calculate unbinned likelihood:

$$L_j = \frac{(e^{-\mu_j} \mu_j^n)}{n!} \times \prod_{i=1}^{n} \mathrm{pdf}_j(E_i, \theta_i)$$

- Two likelihoods – for IH model and NH model
- Test statistic $\eta = \log(L_{\mathrm{IH}}/L_{\mathrm{NH}})$

Test statistic distributions



- The Gaussianity was demonstrated with dedicated high statistic tests.
- Choose sigma for C.L. (3σ, 5σ).
- p-value at given C.L. is a fraction of experiments corresponding to

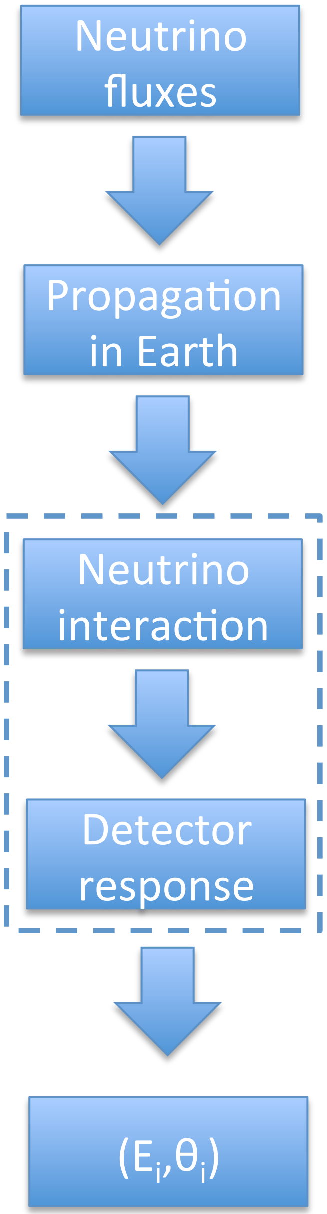
$$\frac{N_t(\eta)}{N_{\mathrm{NH}}(\eta) + N_{\mathrm{IH}}(\eta)} > \alpha$$

t=NH,IH
α(σ)

Toy MC

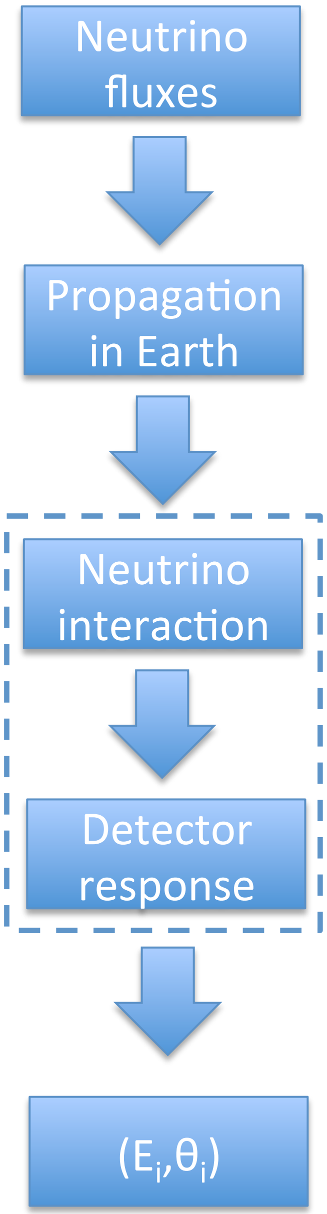
- fast MC tool for mass simulations of the detected events (E_i,θ_i)

- events (E_i,θ_i) are used
  - to create pdf(E,θ) for the two model hypothesis (IH,NH)
  - to calculate test statistics for the test experiments
  - 1000 test experiments to plot distributions and calculate p-value



Toy MC scheme

- Simulations is just a fishing from some pre-generated matrixes.
- Basic ingredients
  - flux model
  - propagator: neutrino oscillation parameters, Earth profile, neutrino cross-sections
  - detector performance
    The performance should be parameterized (energy resolution, angular resolution, effective mass)



1. Baseline atmospheric neutrino flux: HONDA et al.(PRD 2005).
   2D matrix (E,cosθ)

2. PREM. 1000 steps for each baseline(θ). Oscillation probabilities calculated for fixed values of cos(θ) ranging from 0 to 1 with 0.02 step (1D matrix).

3. Cross sections from GloBES. (E, cosθ) matrixes with expected number of nu+anu events using (1)&(2) and assuming 1Mt effective mass.
   Neutrino muon kinematics simulated with GENIE. 2 distributions
   $E_\mu(E_\nu)$ and $\theta(E_\nu)$. Random fishing from them.

4. So far track/energy reconstruction of the muons only. Final matrixes for the muons 5 GeV – 40 GeV (reasonable energy and track reconstruction, well known cross-sections).

Reference oscillation parameters.

$$\text{NH: } m_1 < m_2 < m_3, \text{ with } \Delta m^2_{21} \equiv \delta m^2 \text{ and } \Delta m^2_{32} \simeq \Delta m^2_{31} \equiv \Delta m^2$$

$$\text{IH: } m_3 < m_1 < m_2, \text{ with } \Delta m^2_{21} \equiv \delta m^2 \text{ and } \Delta m^2_{23} \simeq \Delta m^2_{13} \equiv \Delta m^2$$

assuming this formalism, the values of Δm^2_{31} are different for IH, NH both from theoretical and experimental view shift is not constrained (CP is not known)

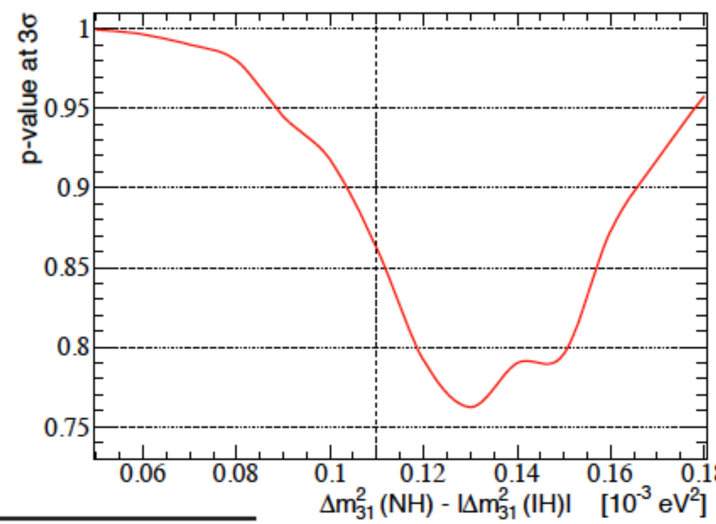
$$\delta m^2_{31} = \Delta m^2_{31}(\text{NH}) - |\Delta m^2_{31}(\text{IH})|$$
$$= 2\Delta m^2_{21}(\cos^2\theta_{12} - \cos\delta_{CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23})$$

- No fit is done. The "worst case discrimination scenario" was chosen for

$$\Delta m^2_{31}(\text{NH}) - |\Delta m^2_{31}(\text{IH})|$$

low exposure for this plot (34 Mt x year)

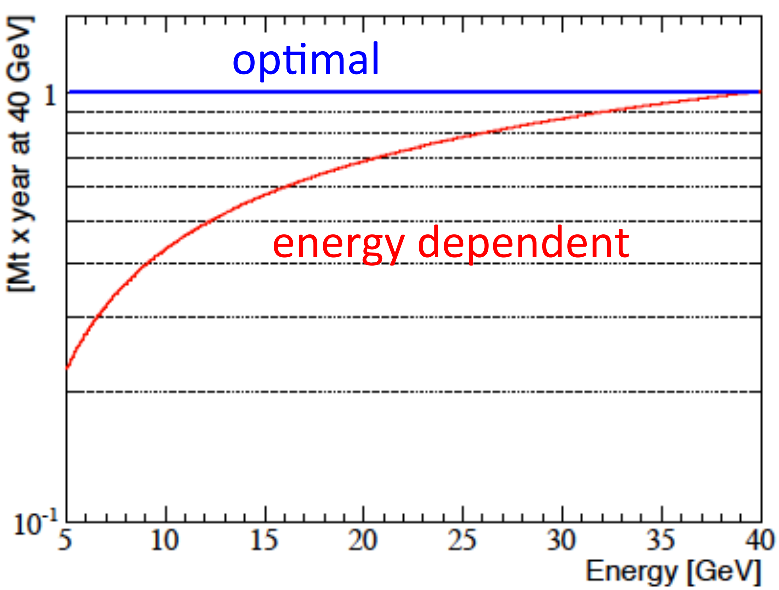
- for bigger exposure shift has minor impact

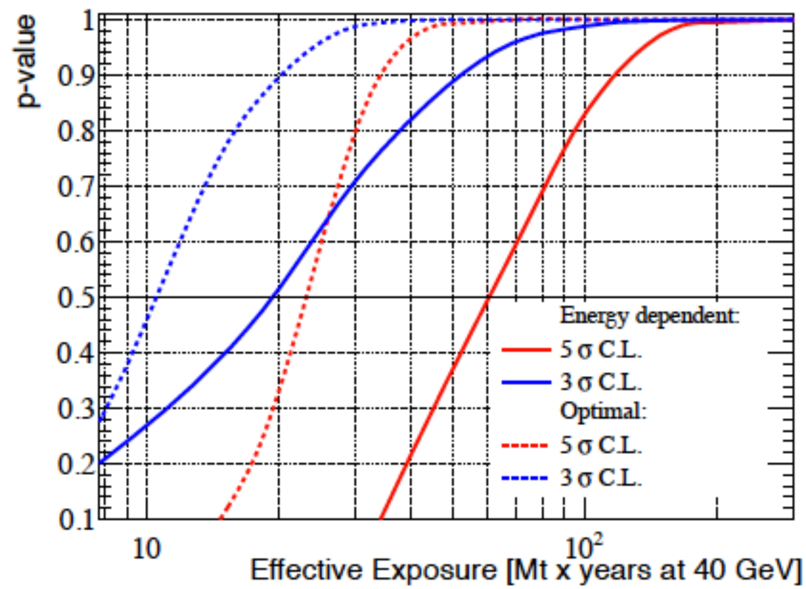


Parameter	Value
Δm^2_{21} [1]	$(7.58^{+0.22}_{-0.26})\times10^{-5}$ eV^2
Δm^2_{31}(NH) [46]	$(2.45 \pm 0.09)\times10^{-3}$ eV^2
Δm^2_{31}(IH)	0.13×10^{-3} eV^2 - Δm^2_{31}(NH)
$\sin^2(2\theta_{12})$ [1]	$0.849^{+0.071}_{-0.059}$
$\sin^2(2\theta_{13})$ [47]	0.096 ± 0.013
$\sin^2(2\theta_{23})$ [1]	$0.974^{+0.028}_{-0.032}$

Ideal detector exposure.

- Perfect muon energy/track reconstruction
- No biases on parameters
- Exposure normalized to 1 Mt x year at 40 GeV

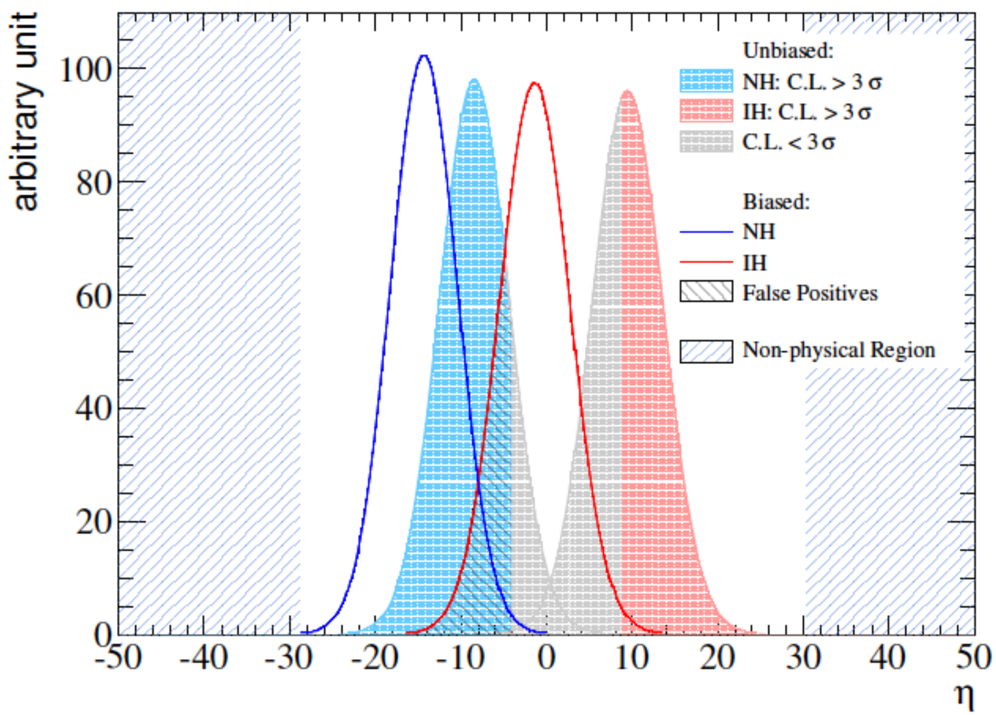




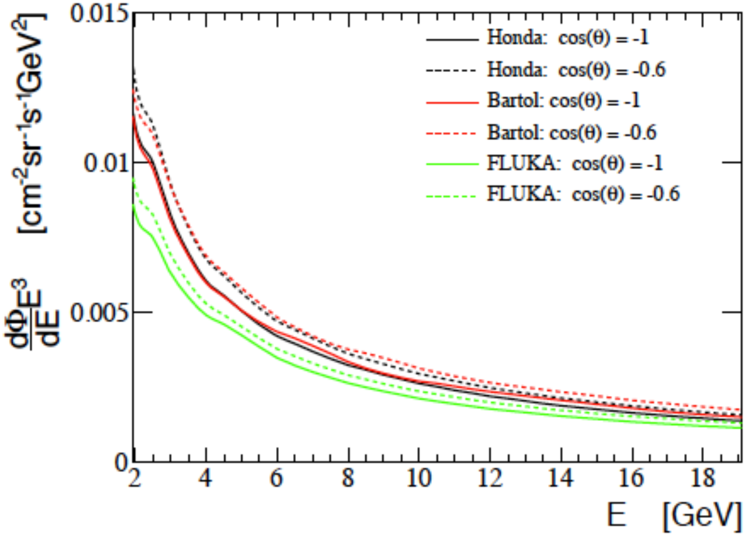
- the minimal required effective exposure is 60 Mt × year (p–value threshold at 0.5 at 5 C.L.)
- 170 Mt × year was chosen for the analysis

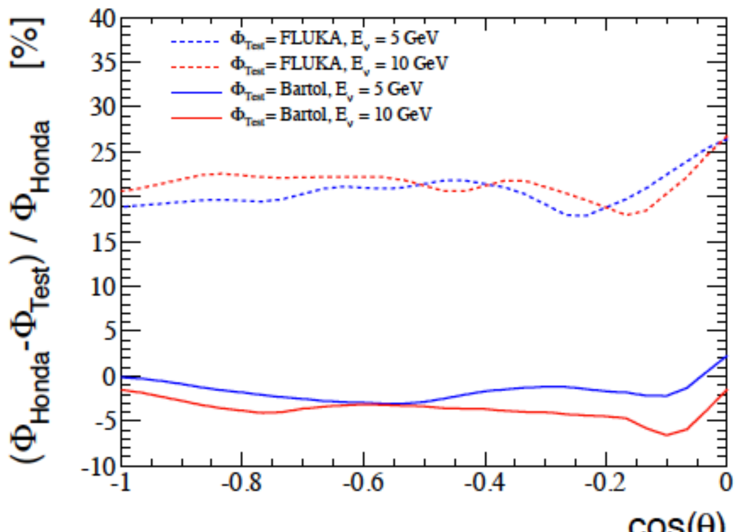
Systematic effects study.

- If the true hypothesis is different from the model hypothesis (there is a bias) the η distributions changes (basically shifts).
  - p-value decreases
  - an area of false positives appears.



Atmospheric flux uncertainty.





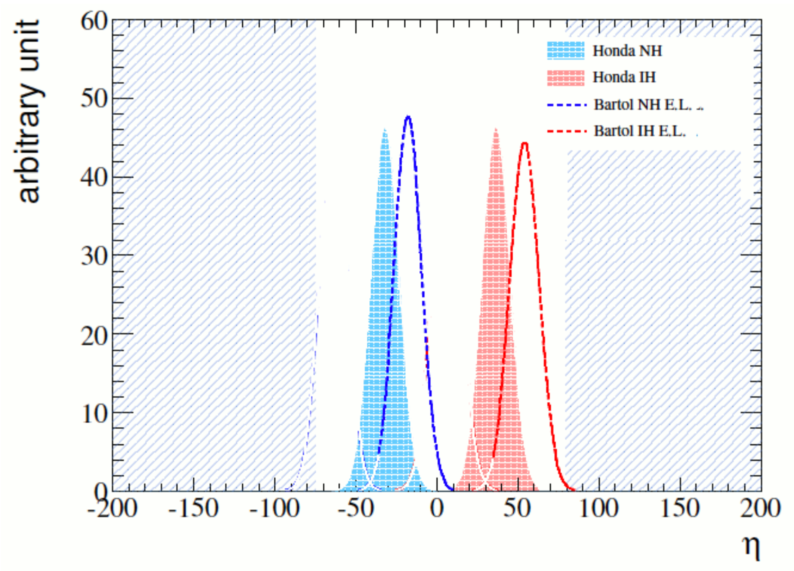
Fluxes from atmflux_new studied:

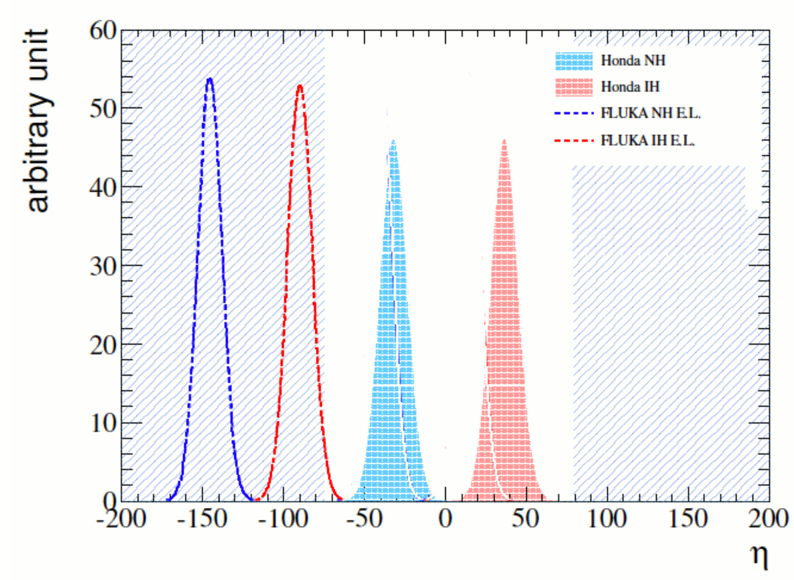
- Honda 1995
- FLUKA 2002
- Bartol 1995

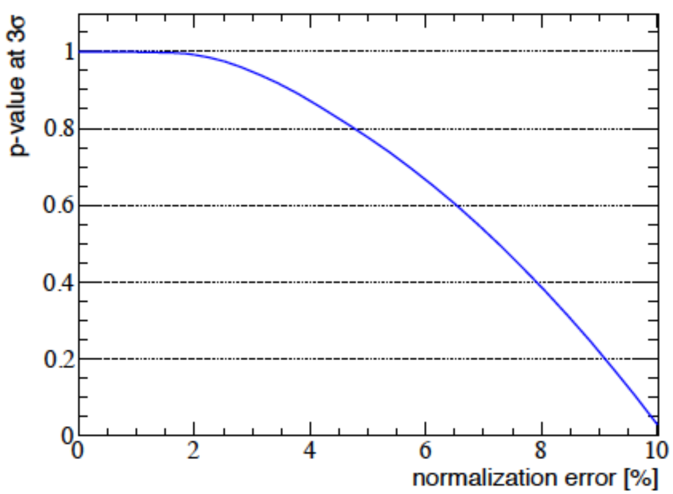
- New fluxes exist (3D calculations, etc.). But the main uncertainties: interaction of CR with light nuclei and CR flux measurements remains unchanged introducing ~20% uncertainty.

- FLUKA and Honda are ~20% different in the normalization.
- The shape differences ~5%

Atmospheric flux models.







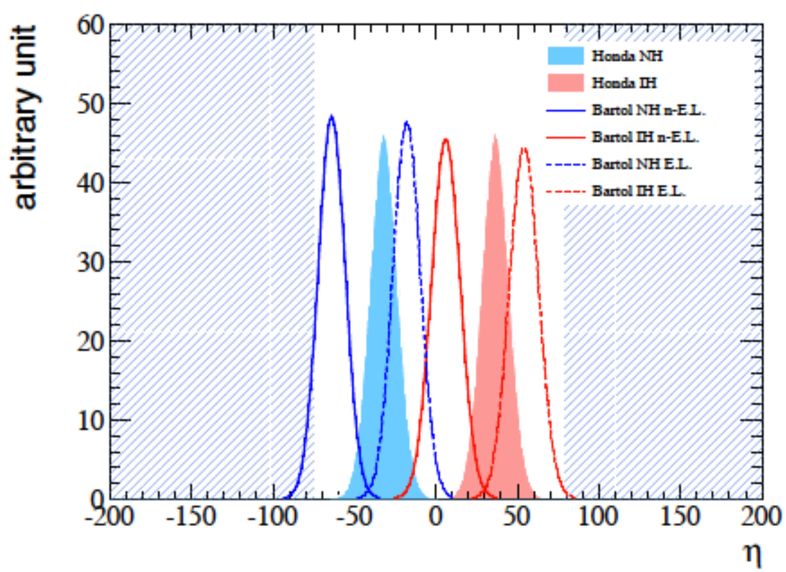
- Bartol-Honda p=0.851 at 5 σ
  FLUKA-Honda p=0 at 5 σ
- *Normalize the flux to the area where there are no oscillations*?

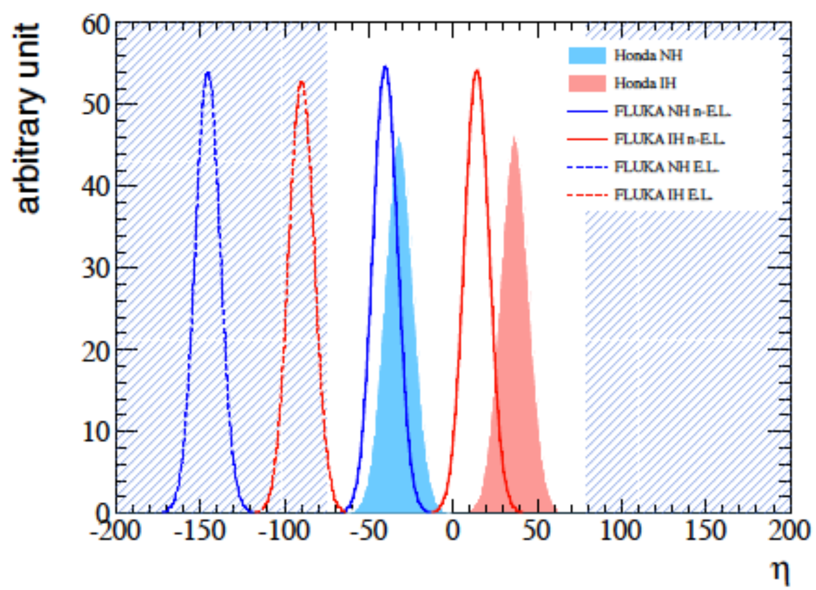
- if normalization still has uncertainty > 2%

$$L_j = \frac{(e^{-\mu_j}\mu_j^n)}{n!} \times \prod_{i=1}^{n} \mathrm{pdf}_j(E_i, \theta_i)$$

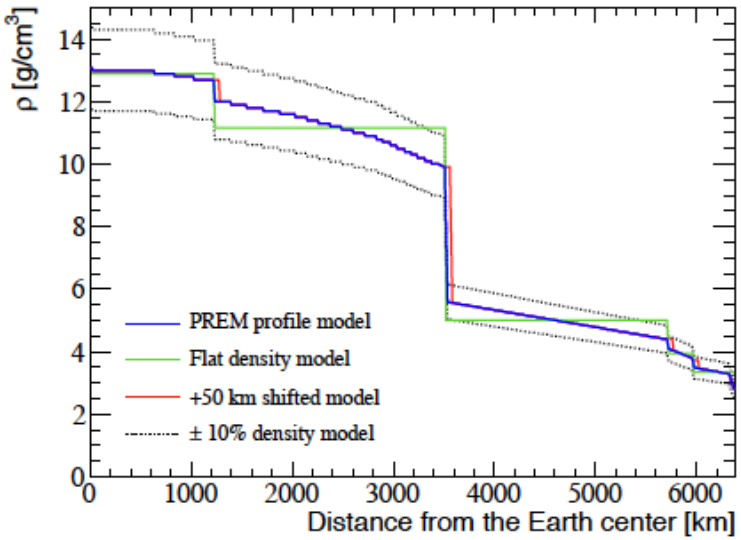
non-extended likelihood
Bartol-Honda p=0.502
FLUKA-Honda p=0.655

extended likelihood
Bartol-Honda p=0.851
FLUKA-Honda p=0





Earth density profile.



- 50 km limit shift – no impact
- assumption of the flat density profile – no impact ($p=0.999$ at 3 σ)
- reducing the overall density by 10% - $p=0.996$
- density is increased by 10% - $p=0.872$
- varying the overall density factor by 1% - no effect

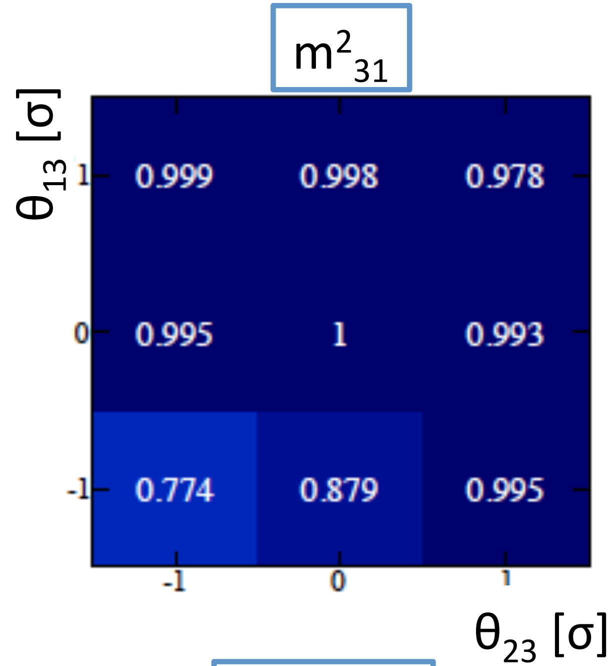
- introduced biases are larger than the known uncertainties or even unphysical

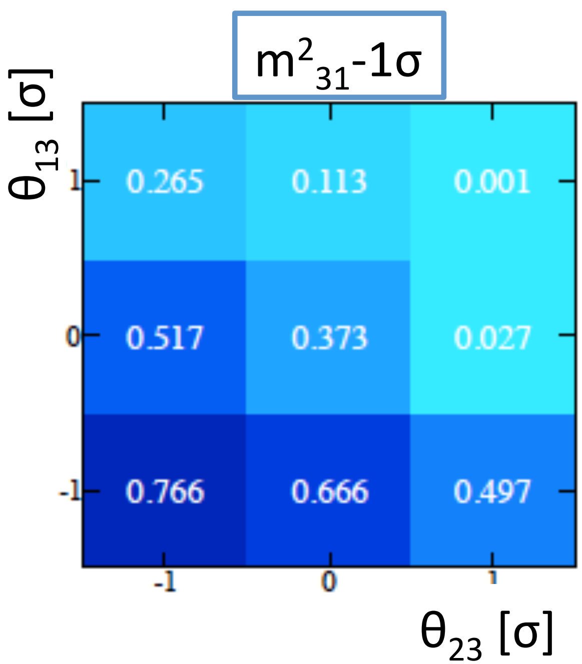
Neutrino oscillation parameters

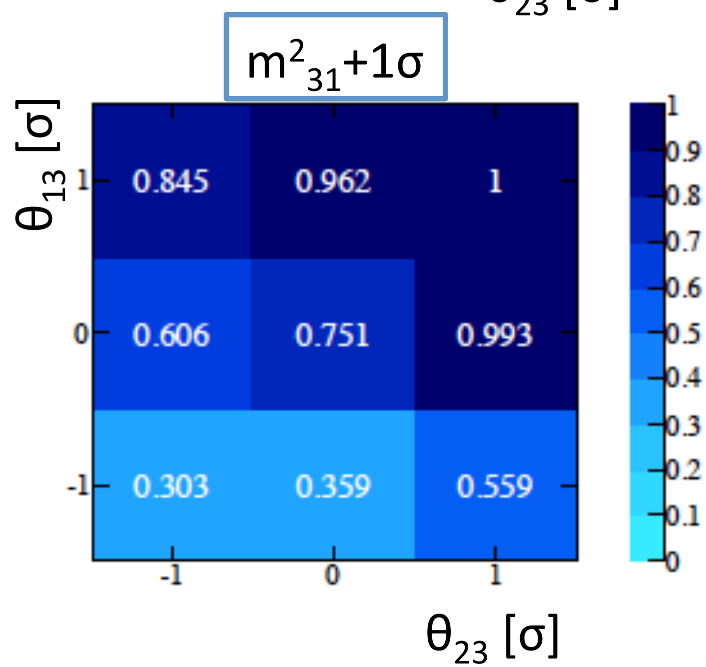
- each oscillation parameter value is biased in the true hypothesis, by ±1 σ from the central value while keeping unaltered the model hypothesis.
- biasing $\Delta m^2_{31}(\mathrm{NH}) - |\Delta m^2_{31}(\mathrm{IH})|$ simultaneously with other parameters have minor impact (maximum variation ±8% for biasing together with Δm^2_{31} for 34 Mt x year)
- almost no impact while biasing solar parameters (bias on θ_{12} and Δm^2_{12} has maximum spread of 0.1% at 3 σ level). No degradation in combination with Δm^2_{31}

Reactor sector.

- p-value at 3 σ C.L.

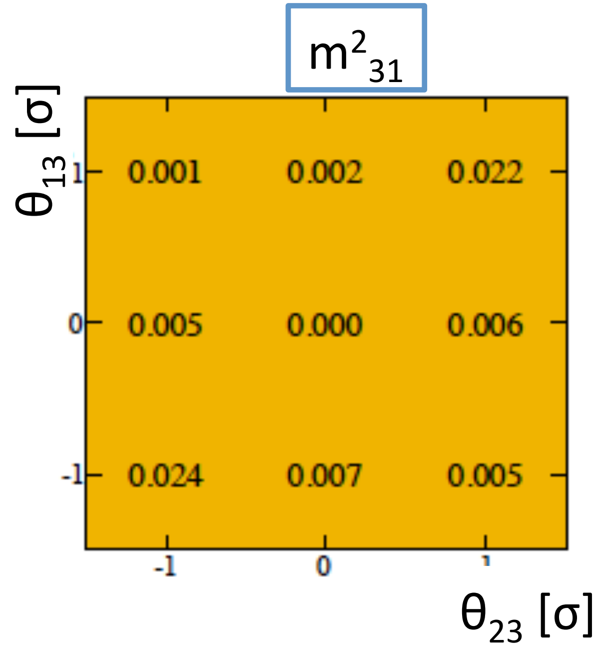


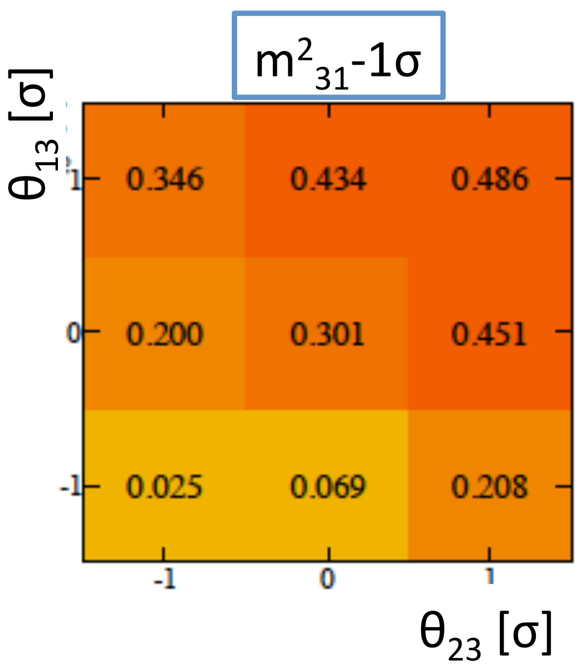


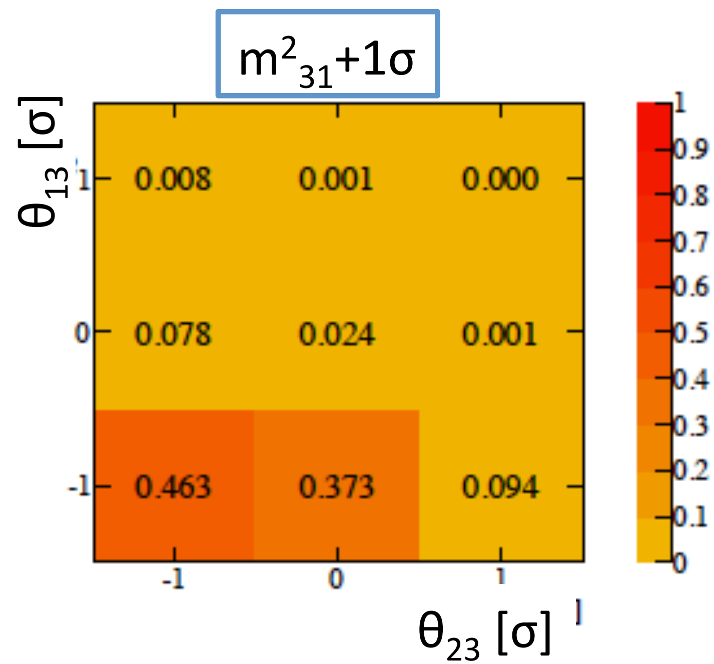


Reactor sector.

- fraction of false positives at 3 σ C.L.

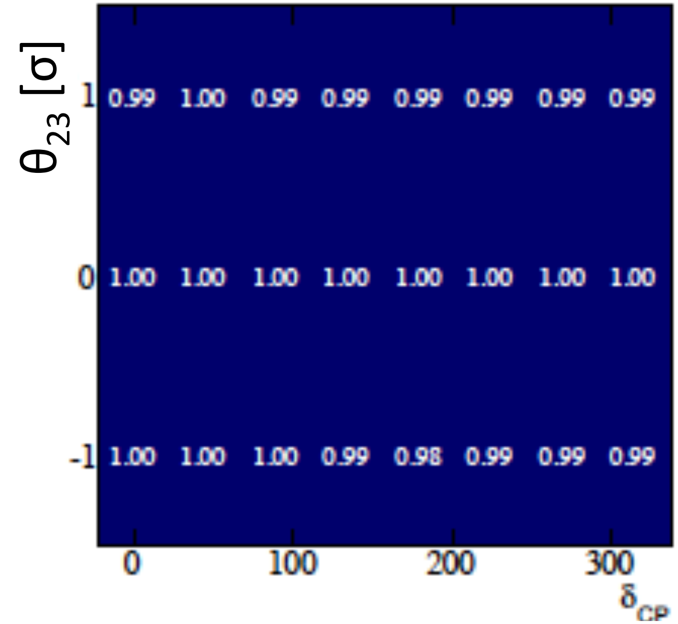


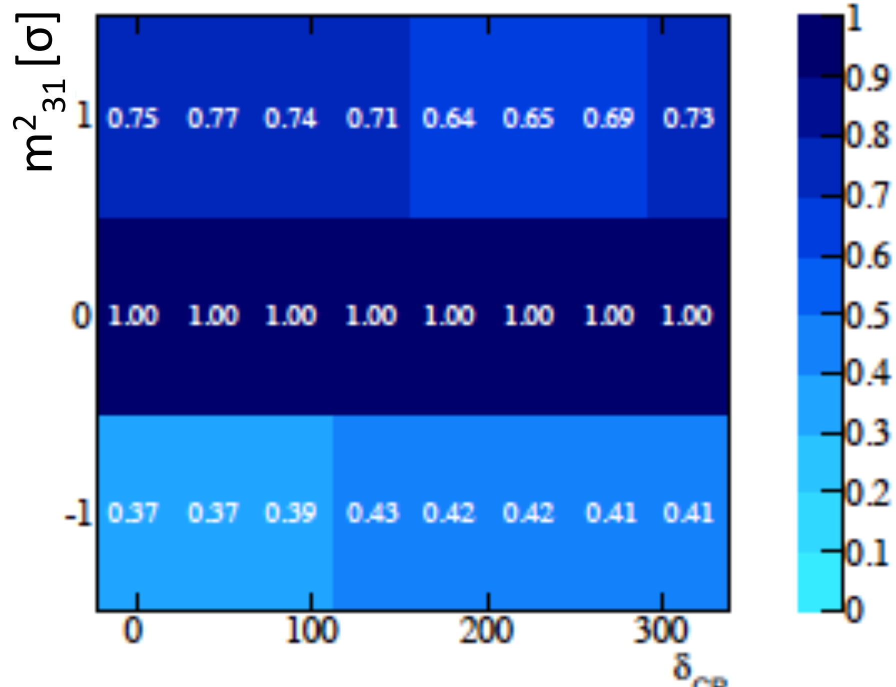


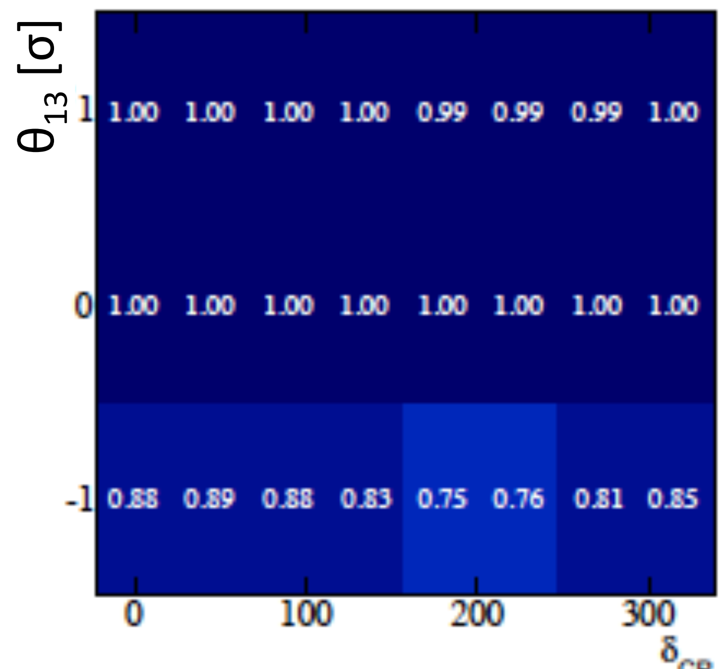


CP phase.

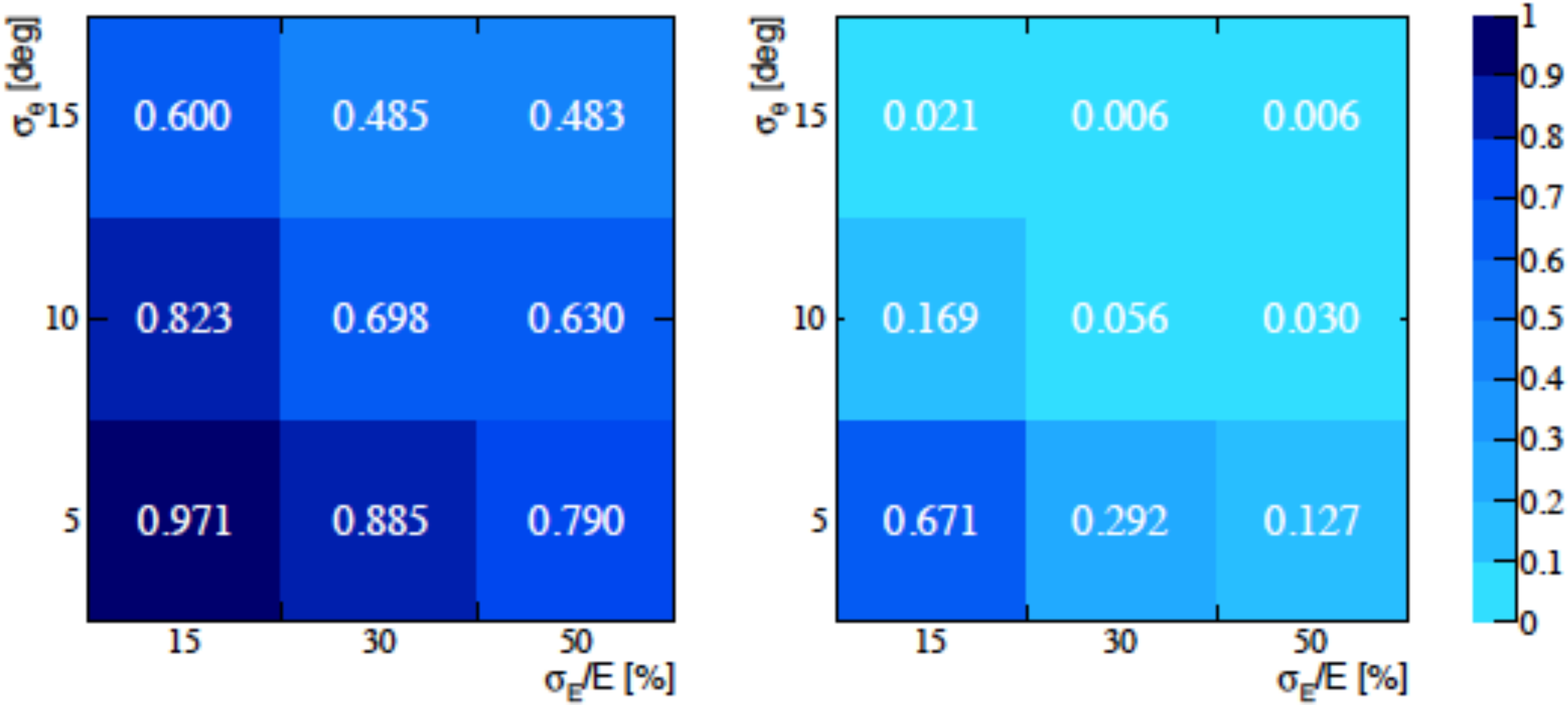
- p-value at 3 σ C.L.





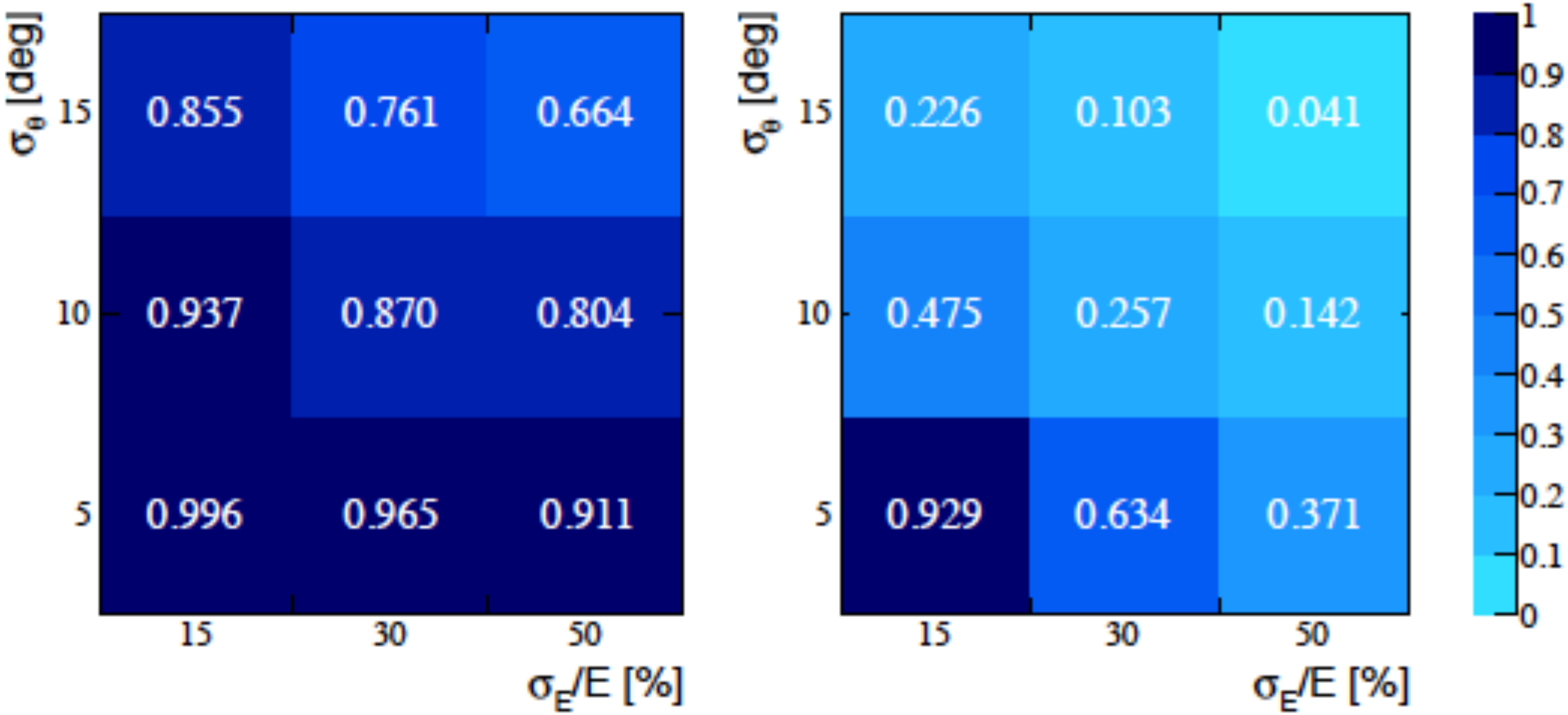


Detector performance.



- p-value at 3 σ and 5 σ C.L.

Detector performance.



- p-value at 3 σ and 5 σ C.L.
  for 1 GeV muon energy thresholds.

Conclusions

- Minimum required exposure was found to be 60 Mt x year at 40 GeV (for a 50% discrimination probability at 5 σ)
- This number can be significantly reduced by
  - improving the detection efficiency in the 5–10 GeV muon energy region
  - going down below 1 GeV has less impact and hard to achieve
- Minor uncertainties impact
  - Earth density
  - Atmospheric fluxes shape
  - CP phase
  - shift between m^2_{31}(NH) and m^2_{31}(IH)
  - θ_{12} and m^2_{12}
- Overall normalization of atmospheric flux is critical
  - anchoring the flux at high energies
  - using non extended liklihood
- An important dependence of the NMH determination on the values of θ_{13}, θ_{23} and m^2_{31} .

More.

- The software written for this work is a great tool for evaluating detector performance.
- It maybe used for:
  - Detector configuration optimization.
    - Realistic energy and track reconstruction
    - Effective mass performance for ORCA
  - Reconstruction software evaluation.
- Modification of software is possible for:
  - including the shower reconstruction
  - fit oscillation parameters

THANK YOU FOR ATTENTION