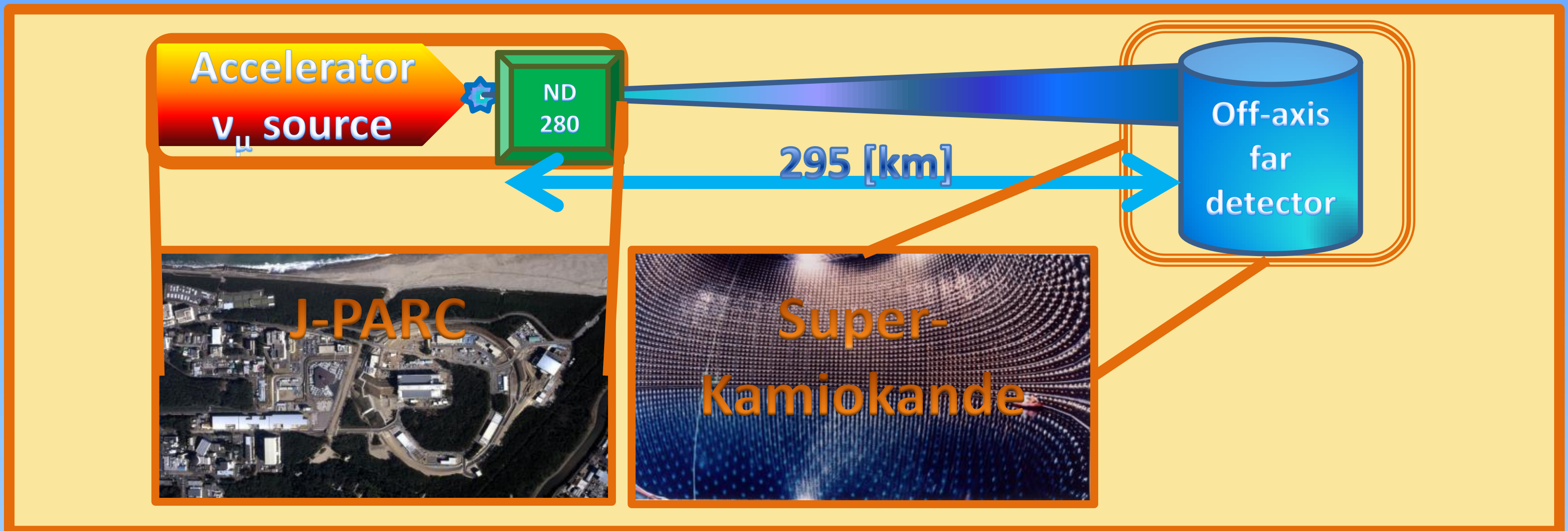
On extraction of neutrino oscillation parameters

Jakub Żmuda

Institute of Theoretical Physics, University of Wroclaw

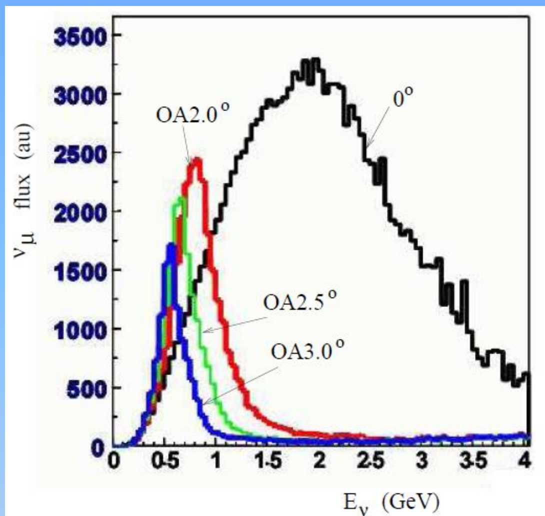
The T2K experiment



Long baseline accelerator neutrino oscillation experiment in Japan

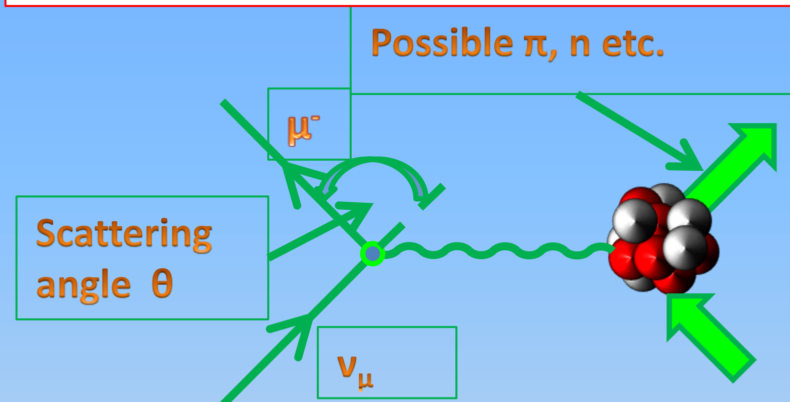
- Precise measurement of the ν_μ disappearance→ determination of Δm^2_{23} and Θ_{23}.
- Search for the ν_e appearance→ measurement of Θ_{13}.
- High statistics, over 10000 neutrino events in 5 years of operation→ small measurement uncertainties!
  $\delta(\Delta m^2_{23}) \approx 4\%$, $\delta(\sin^2(2\Theta_{23})) \approx 1\%$

What do we observe in SK?

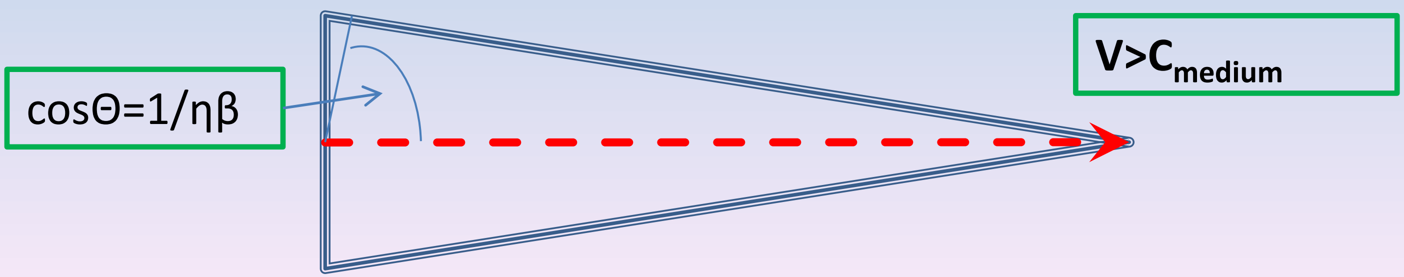


Predicted T2K beam profile for different off-axis angles (Yuri Kudenko, arXiv:0805.0411v1)

In this energy regime neutrinos are mostly scattered off atomic nuclei



- SK -> water Cherenkov detector
- What we really „see" in the detector is the Cherenkov radiation from charged leptons and (sometimes) pions: $\pi^{\pm}$ above the Cherenkov threshold. We see also the radiation from $\pi^0 \rightarrow \gamma\,\gamma$.



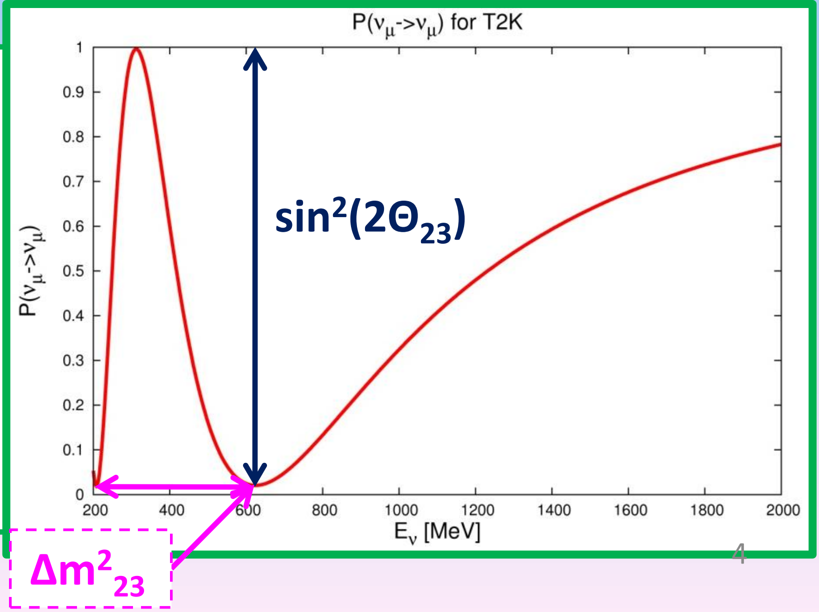
Motivation

Standard (simplified) approach in the muon neutrino disappearance experiment:

- Do a Monte Carlo simulation for your beam and detector to calibrate your experiment. Calculate expecte event rates etc.
- Neutrino energy reconstruction for each event: look for disappearance maximum position and depth → Δm^2_{23} and Θ_{23}

$$\mathbf{P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \cos^4(\Theta_{13}) \sin^2(2\Theta_{23}) \sin^2(1.26 \Delta m^2_{23} L/E[km/GeV])}$$

Neutrino oscillation probability for T2K and ($\Delta m^2_{23} = 2.6 \times 10^{-3}$ [eV^2], $\sin^2(2\Theta_{23}) = 0.98$) . Position of the probability minimum in (L/E) ↔ Δm^2_{23}, depth ↔ $\sin^2(2\Theta_{23})$ ($\cos^4(\Theta_{13}) \approx 1$).



Motivation

Problems with the **neutrino energy reconstruction**:

- The standard formula:

$$\varepsilon_{rec} = \frac{\varepsilon_f(m-\varepsilon_b) - (\varepsilon_b^2 - 2m\varepsilon_b + m_\mu^2)/2}{(m-\varepsilon_b) - \varepsilon_f + k_f \cos(\theta)}$$

Assumption: **pure QEL cc process, nucleon at rest**. Beam direction+ lepton kinematics.

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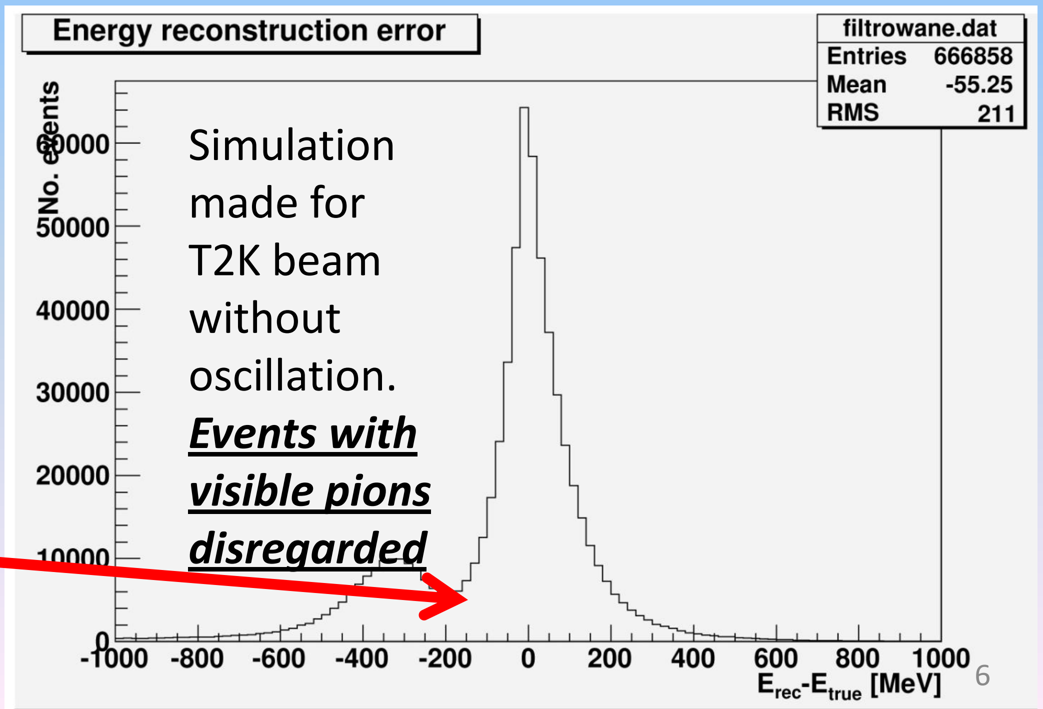
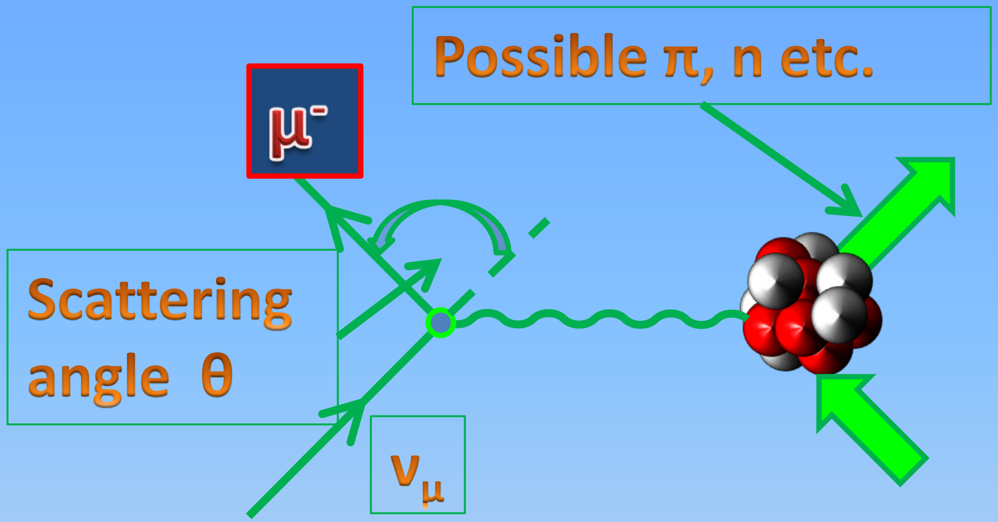
$m_\Delta > m_{pn}$ & disregarded degrees of freedom & dynamics → **source of error!**



Simulation made for T2K beam without oscillation. ***Events with visible pions disregarded***

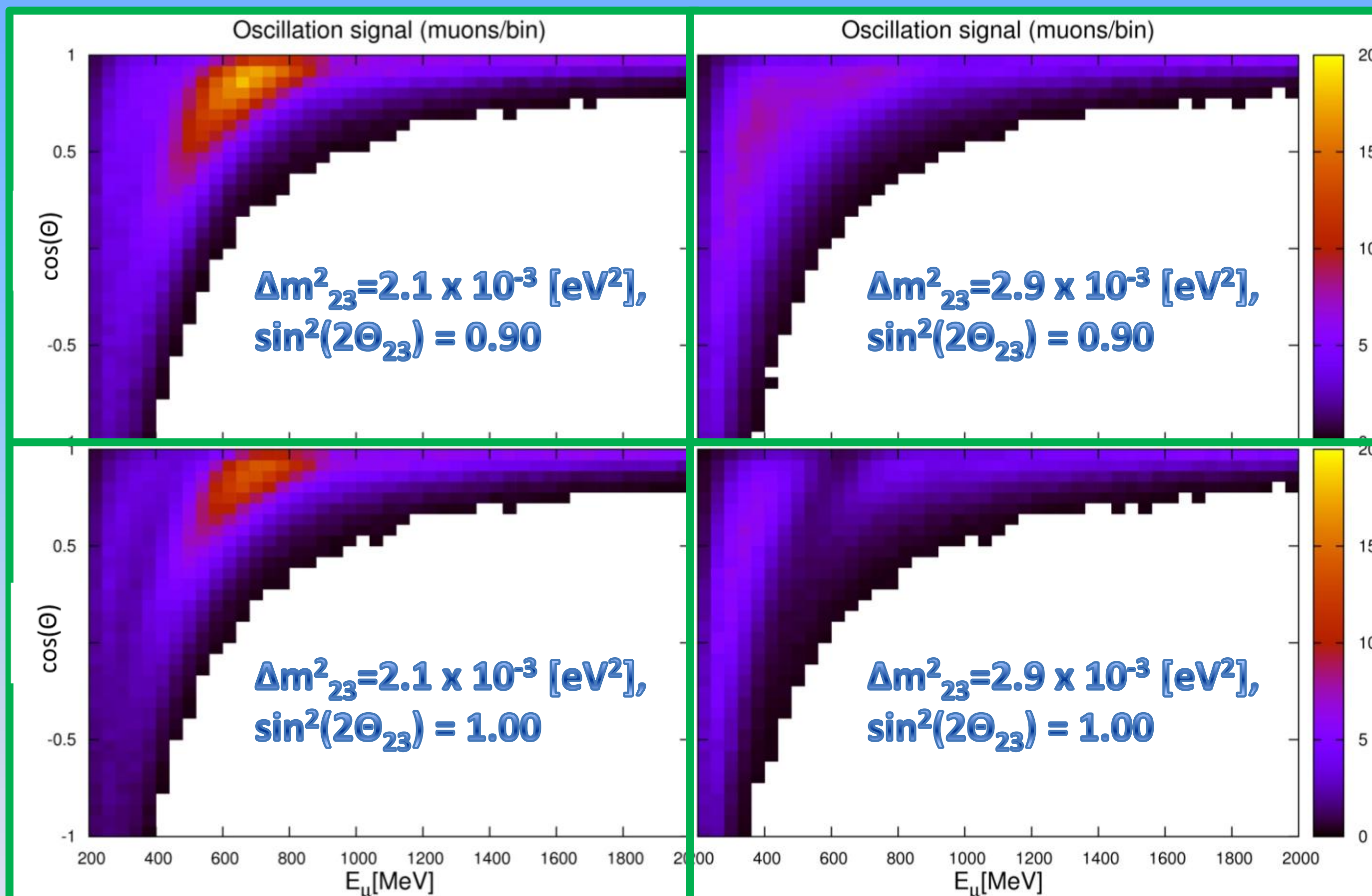
What do we observe in SK?



- What we really „see" in the detector are the charged lepton scattering angles and energies and (sometimes) pions: $\pi^{\pm}$ above the Cherenkov threshold and $\pi^0 \rightarrow \gamma\ \gamma$.
- T2K prediction: approx. **<u>1600 ν_μ cc events/year</u> <u>without oscillation.</u>**
- **What can we get by skiping the energy reconstruction and using only what we observe directly?**

Oscillation signal, as observed in the muon distribution (events generated by NuWro)

Depth and position of the oscillation signal is visibly modulated by the Δm^2_{23} and Θ_{23}, despite of the nuclear dynamics influence. As expected.



Events with visible pions have been discarded.

- **Muon distribution is a very good observable for neutrino oscillation measurement!**

The algorithm

NuWro: 2x1000000 events. T2K beam, target: water, dynamics: FG (one can also use the spectral function) + intranuclear cascade

↓

Rejection of events with visible pions (π^0-all, π^+&π^- - above the Cherenkov threshold)

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Sampling of events from $P(\nu_\mu \rightarrow \nu_\mu)(E_\nu)$
Very high statistics
$\Delta m^2_{23} \in [21,29] \times 10^{-4}$ [eV^2], step 5×10^{-4}[eV^2]
$\sin^2(2\Theta_{23}) \in [0.88,1.00]$, step 0.005

Muon distribution histograms (reference):
Scaled down to predicted T2K statistics

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Sampling of events from $P(\nu_\mu \rightarrow \nu_\mu)$ (E_ν)
Statistics: tuned to about 10000 events without the oscillation (approx. 6 years for T2K).

Muon distribution histograms
(„data <u>samples”</u>)

The algorithm

NuWro: 2x1000000 events. T2K beam, target: water, dynamics: FG (one can also use the spectral function) + intranuclear cascade

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Statistics: tuned to about 10000 events without the oscillation (approx. 6 years for T2K).

Muon distribution histograms
(„data <u>samples”</u>)

Chi² test: identify samples with the reference histogram.
MC statistical error estimation: how many of the 200 samples will be identified with the right reference histogram??

As an input this method requires the <u>*knowledge of beam shape*</u>, <u>*expected event rate*</u> and good <u>*nuclear dynamics*</u>. No direct energy reconstruction is needed. Systematic errors (cross sections, pion cascade, beam characteristics etc.) not included!

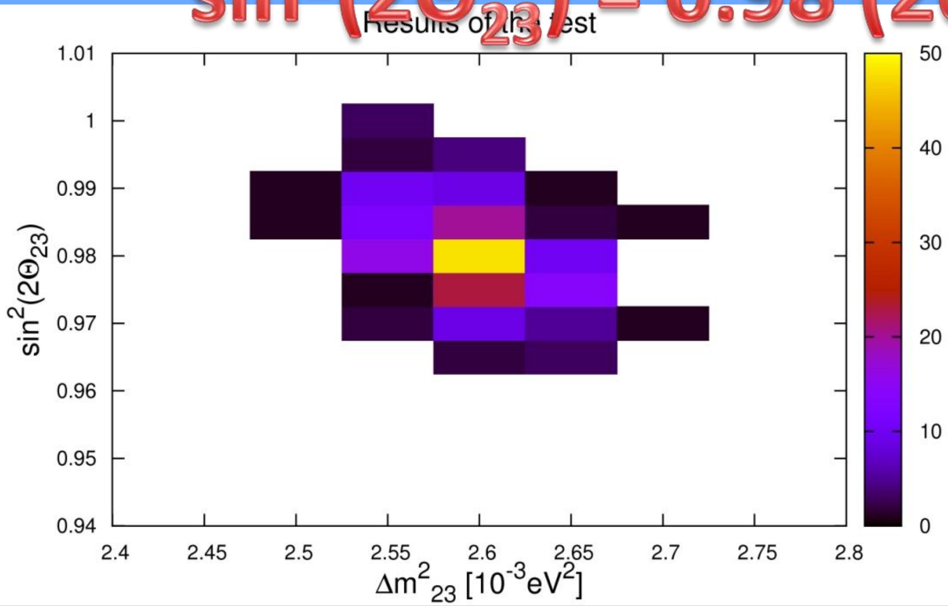
Statistical tests

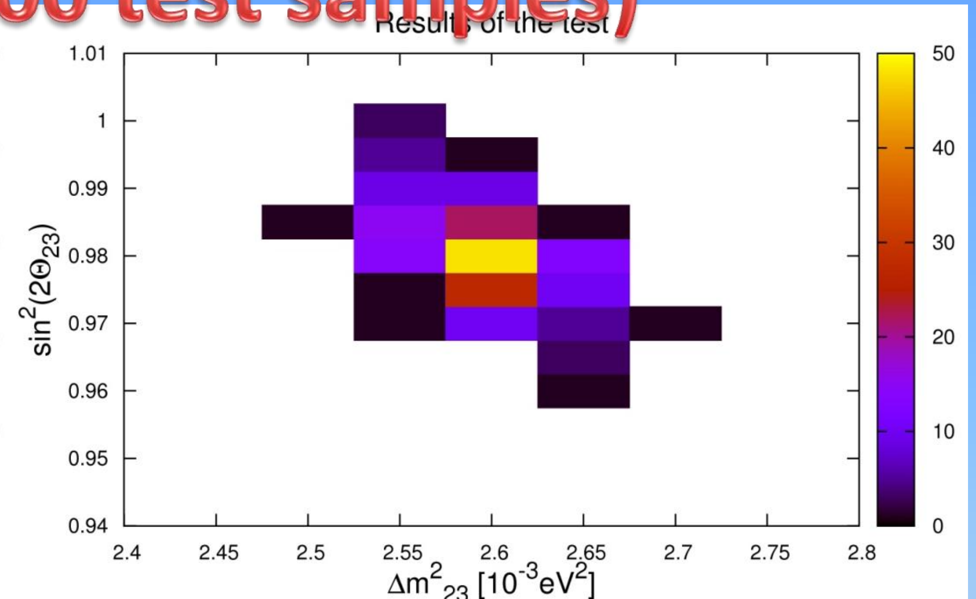
- Many tests for various binnings and statistical cuts have been performed.
- Both Chi^2 and Poisson statistics have been used.
- Muon energy region from the Cherenkov threshold to 1200 [MeV] has been taken into account.
- Optimal results have been obtained from the **Poisson** statistical test:

$$F = 2\sum_{i=1}^{N_b}\left(n_i - N_i + N_i ln\frac{N_i}{n_i}\right)$$

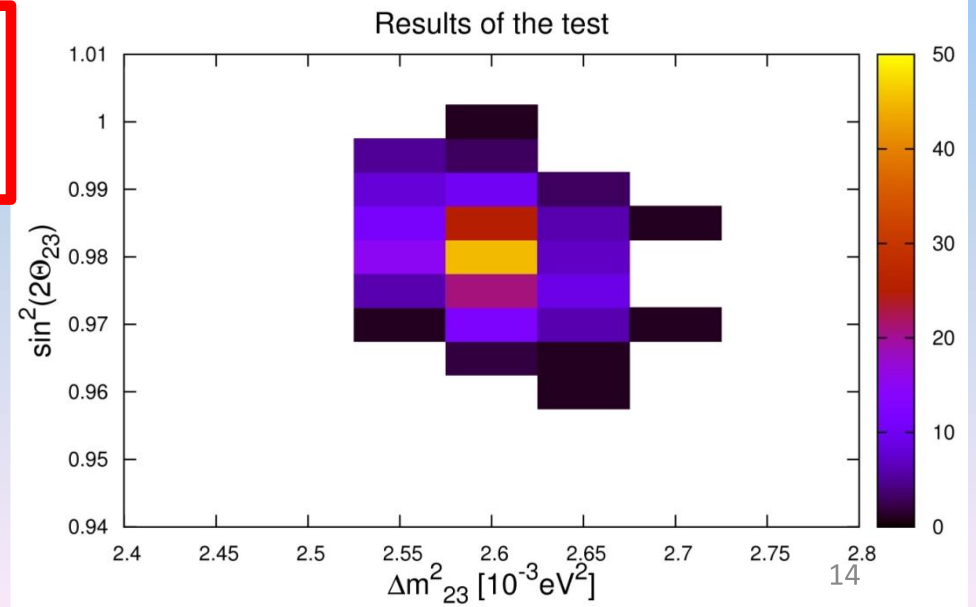
- N_b → number of „active" bins (with large enough statistics), N_i → number of muon events in the bin, n_i → expected number of muons from the reference histogram
- Statistical cut has been set to 3 events in a bin.

Poisson results for Δm^2_{23}=2.6 x 10^{-3} [eV^2], $\sin^2(2\Theta_{23})$ = 0.98 (200 test samples)





From top left (clockwise): Energy bins 75 [MeV], 50 [MeV], 50 [MeV]
Angular bins: 0.1, 0.4, 0.1 in cos(Θ)



- These plots show, how many of the 200 test samples have been identified with each reference histogram corresponding to a point in the (Δm^2_{23}, $\sin^2(2\Theta_{23})$) lattice.

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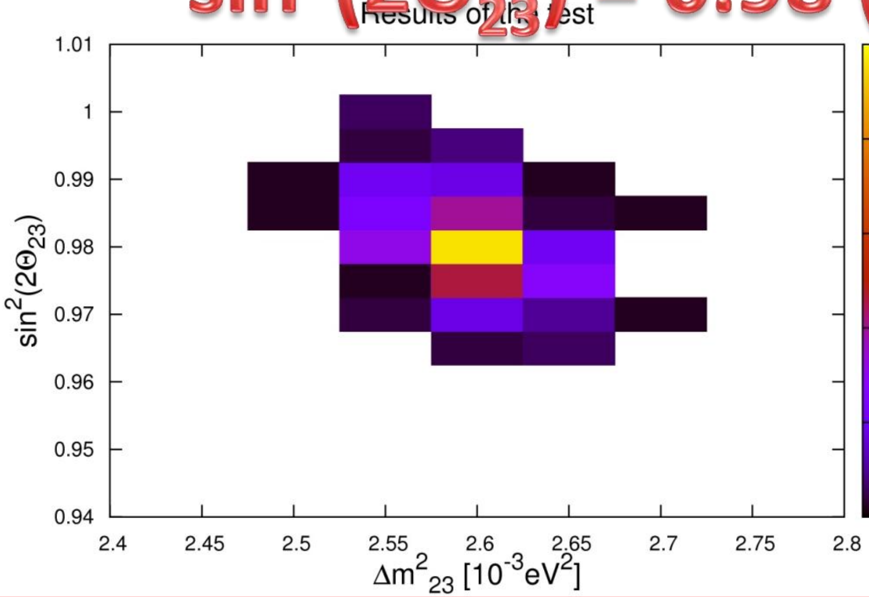

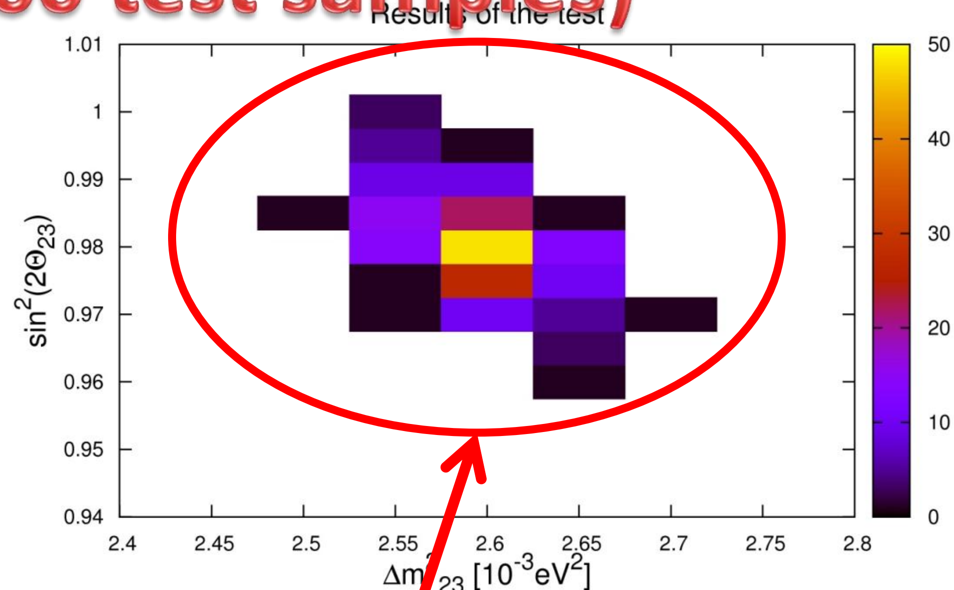

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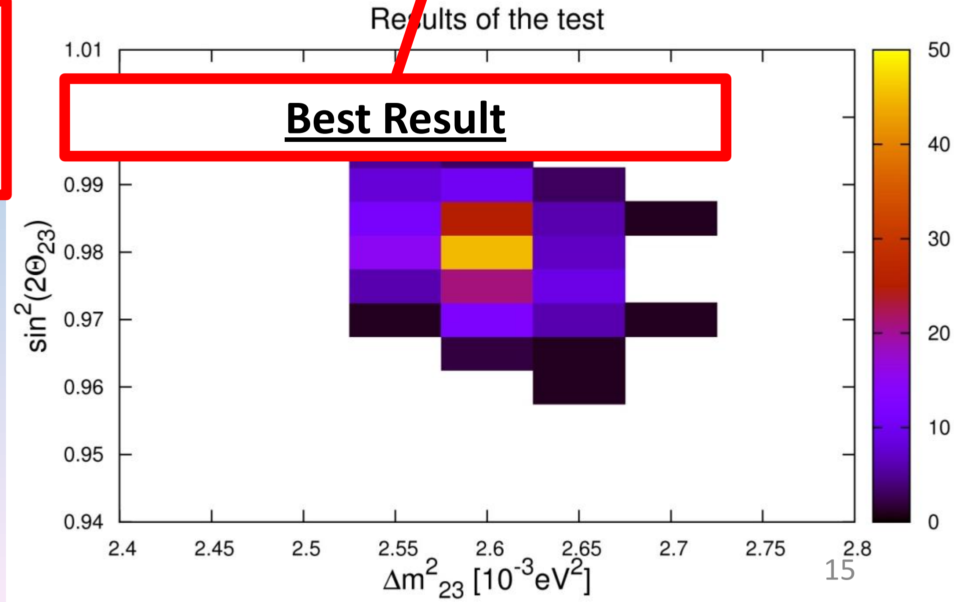
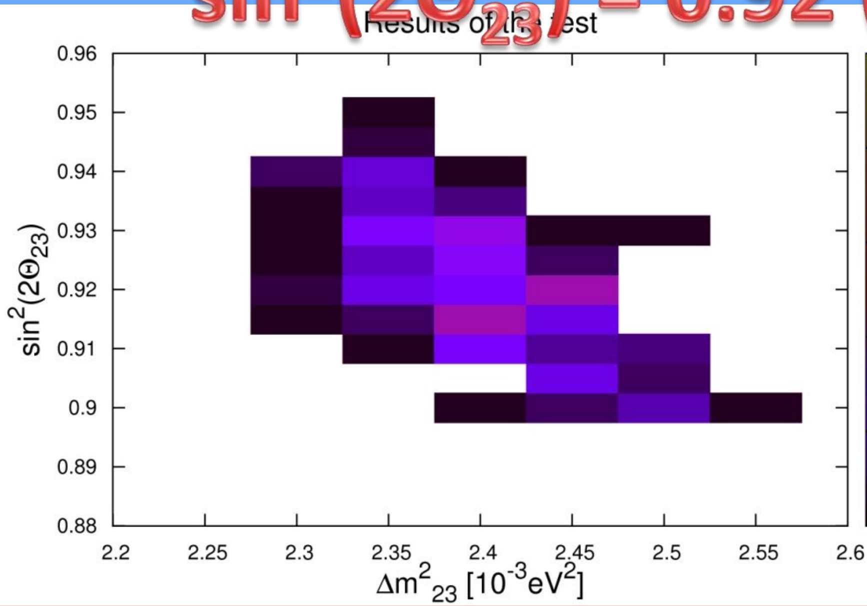
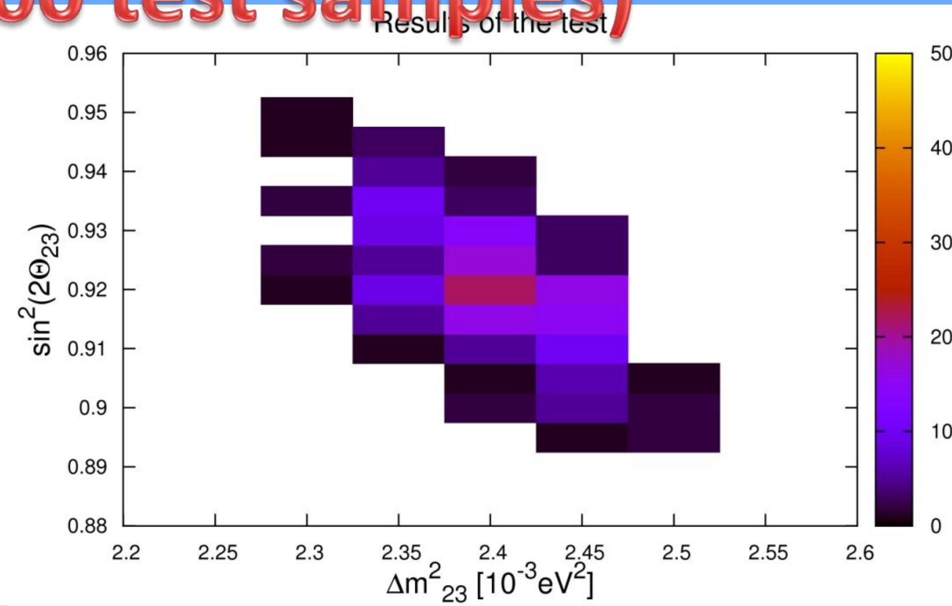


Best Result

- These plots show, how many of the test samples have been identified with each reference histogram corresponding to a point in the (Δm^2_{23}, $\sin^2(2\Theta_{23})$) lattice

Poisson results for $\Delta m^2_{23}=2.4 \times 10^{-3}$ [eV^2], $\sin^2(2\Theta_{23}) = 0.92$ (200 test samples)





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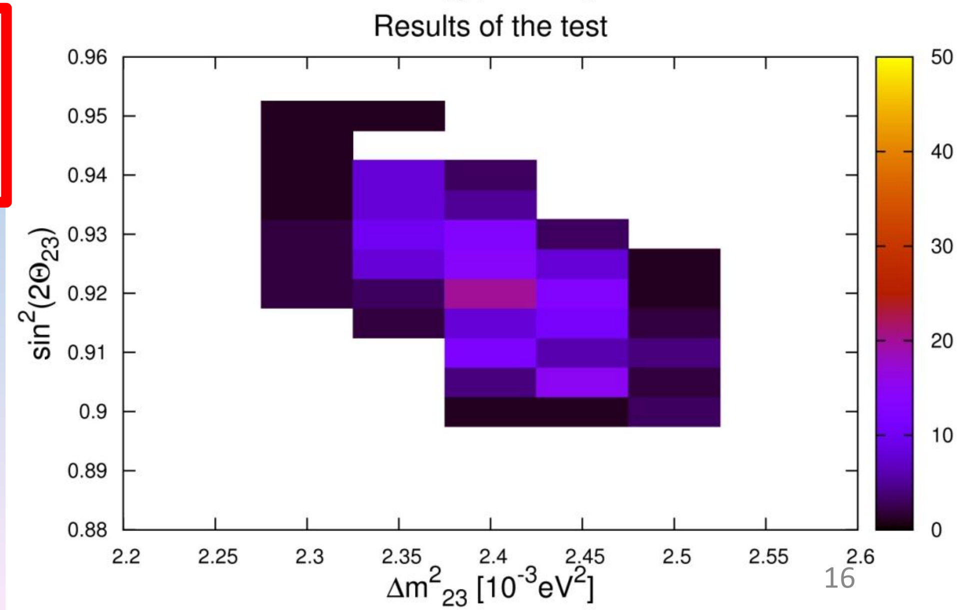
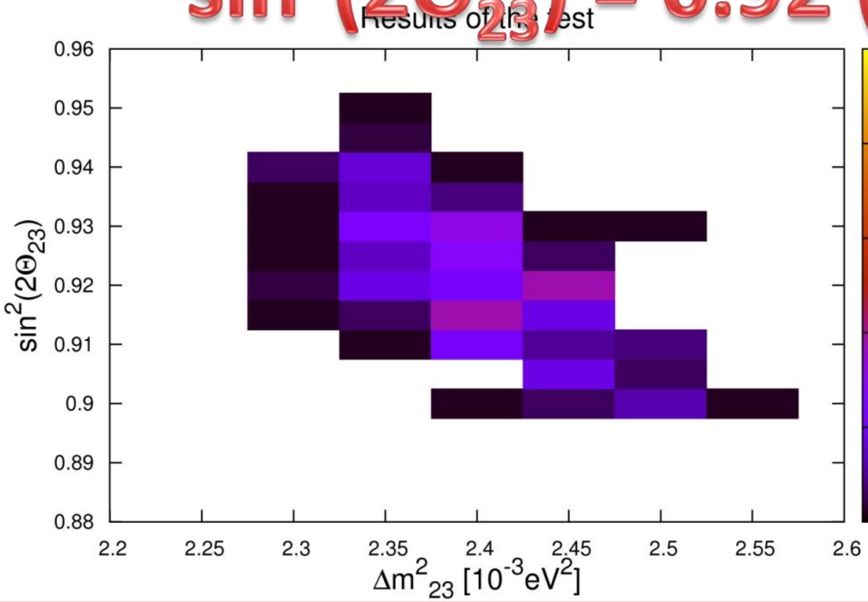
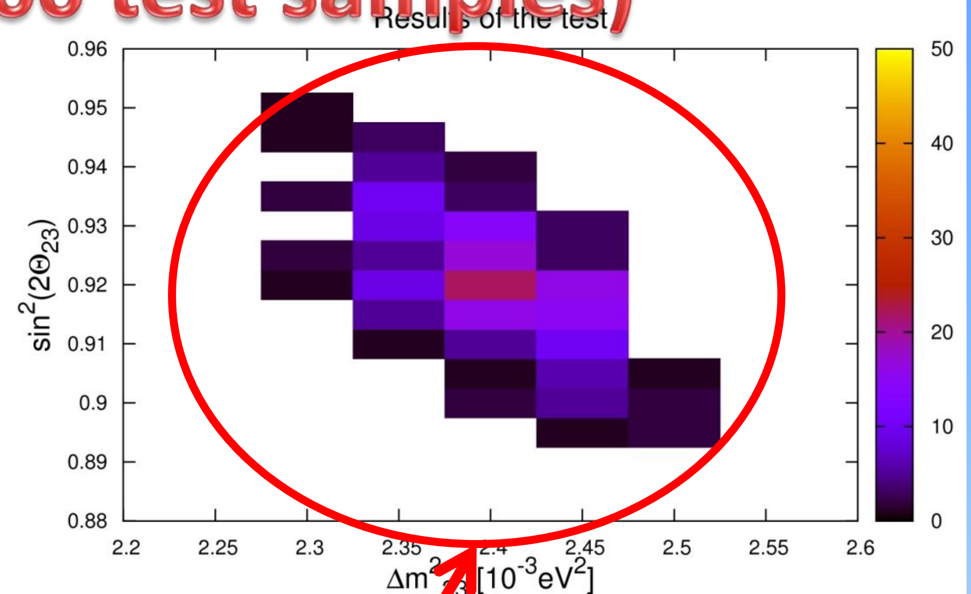
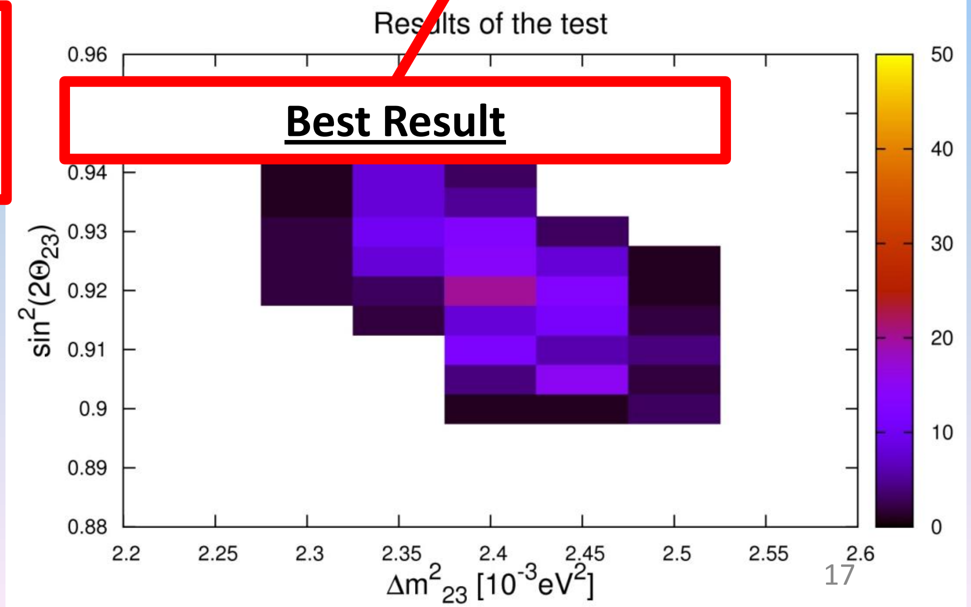


- The accuracy is dependent on the region, in which true values of (Δm^2_{23}, $\sin^2(2\Theta_{23})$) are located.
- Smaller oscillation parameters -> bigger spread of the results.

Poisson results for Δm^2_{23}=2.4 x 10^{-3} [eV^2], $\sin^2(2\Theta_{23})$ = 0.92 (200 test samples)







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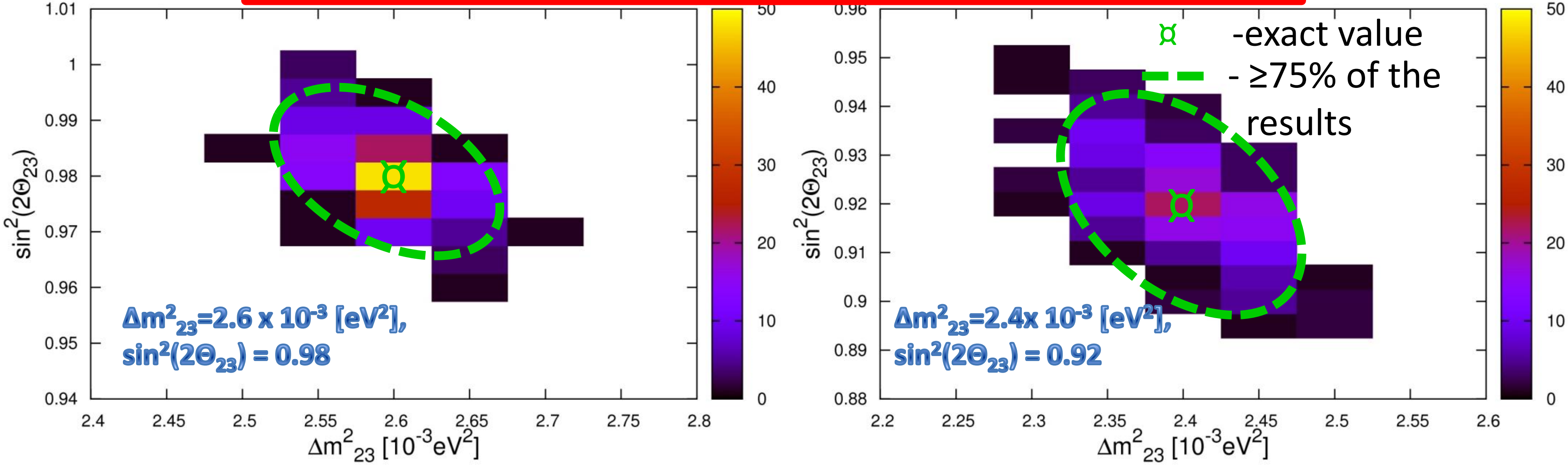
Approximate statistical error estimation

Poisson, 50 [Mev]x 0.4[cos(Θ)], 3 events cut, 200 test samples



Approx. Errors (statistical only!)	Abs. error	Rel. error
Δm^2_{23}	$\pm 0.5 \times 10^{-4}$ [eV^2]	±2-3%
$\sin^2(2\Theta_{23})$	±0.02	±2-3%

Conclusions

- The proposed method may be used in the search for Δm^2_{23} and $\sin^2(2\Theta_{23})$ values.

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Δm^2_{23}	$\pm 0.5 \times 10^{-4}$ [eV^2]	$\pm$2-3%
$\sin^2(2\Theta_{23})$	$\pm$0.02	$\pm$2-3%

- Poisson statistical test seems to be the best method.
- Risk of going too close to the actual experiment resolution (50 [MeV] bins).
- One can make an extra effort to find optimal muon bin distribution. (Maybe a neuron network would work better then plain Chi^2?)
- The systematic errors will clearly add some uncertainty.
- Tests of the stability against nuclear cross-sections, as well as against the beam parameters have to be performed.

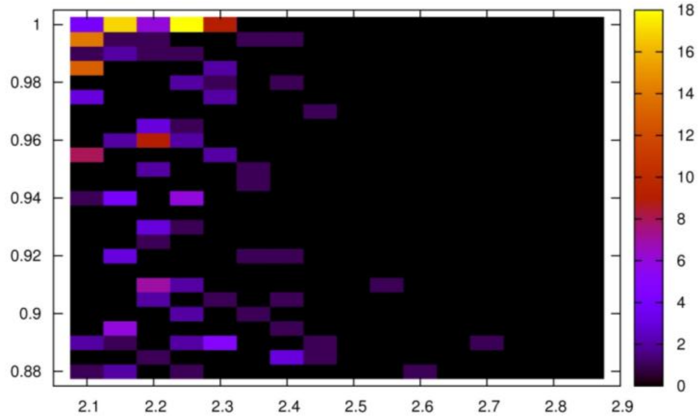
References

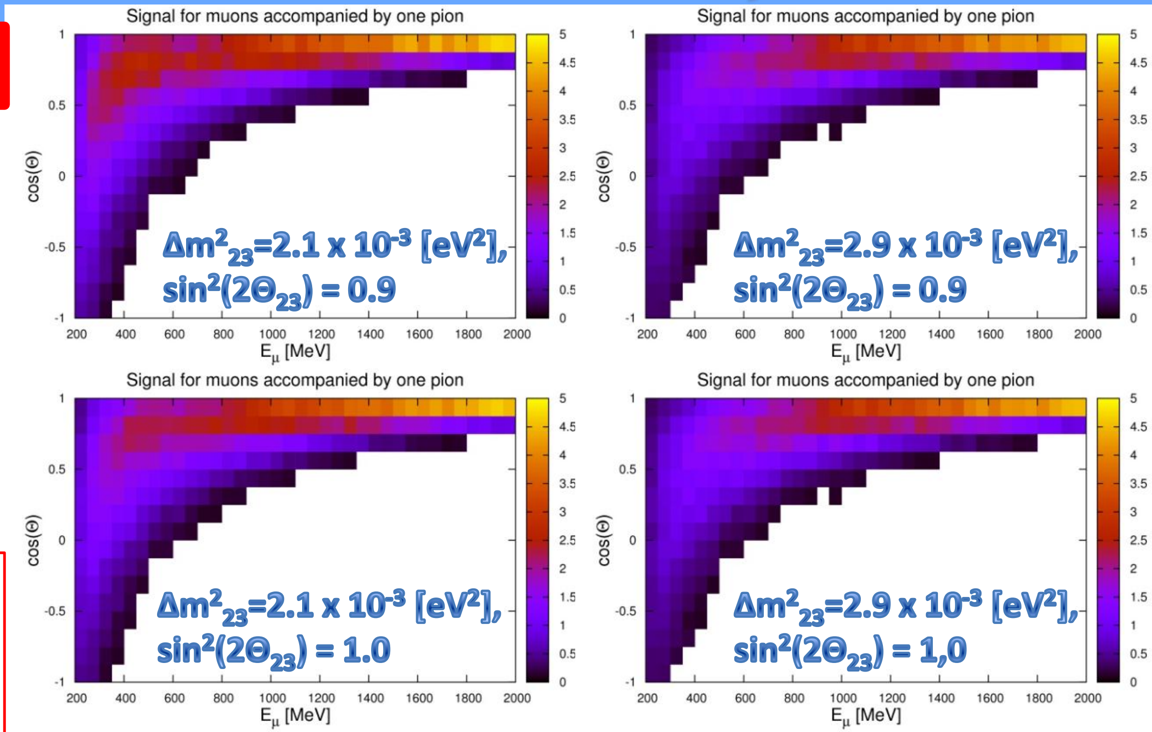
- [1] M. H. Ahn *et al. (K2K Collaboration), Phys. Rev. D74 (2006) 072003.*
- [2] A. V. Butkevich, *Phys. Rev. C78 (2008) 015501.*
- [3] P. F. Loverre (K2K and T2K Collaborations), *J. Phys. Conf. Ser. 39 (2006) 323.*
- [4] Y. Obayashi (T2K Collaboration), *"Reach of Future Accelerator and Reactor Neutrino Efforts",*
- [arXiv:0807.4012 [hep-ex]].
- [5] C. Juszczak, *Acta Phys. Pol. B40 (2009) 2507.*
- [6] Y. Ashie *et al. [Super-Kamiokande Collaboration], Phys. Rev. D71 (2005) 112005.*
- [7] A. Rodriguez *et al. [K2K Collaboration], Phys. Rev. D78 (2008) 032003.*

Supplement slides

Why the pionic events have been rejected?

Results of the test for $1\mu+1\pi$ events





This plot has the same meaning, as the plots shown on the previous slides. The reconstructed parameters should be $\Delta m^2_{23}=2.2 \times 10^{-3}$ [eV^2], $\sin^2(2\Theta_{23}) = 0.92$

- Events with pions never give good results, independent on binning, statistical cuts and statistics (they also fail the tests with Poisson statistics). This may happen due to the smearing and shifting of the oscillation signal coming from additional degrees of freedom (pions). Other reson is low statistic. Maybe one should use full pion dynamics.