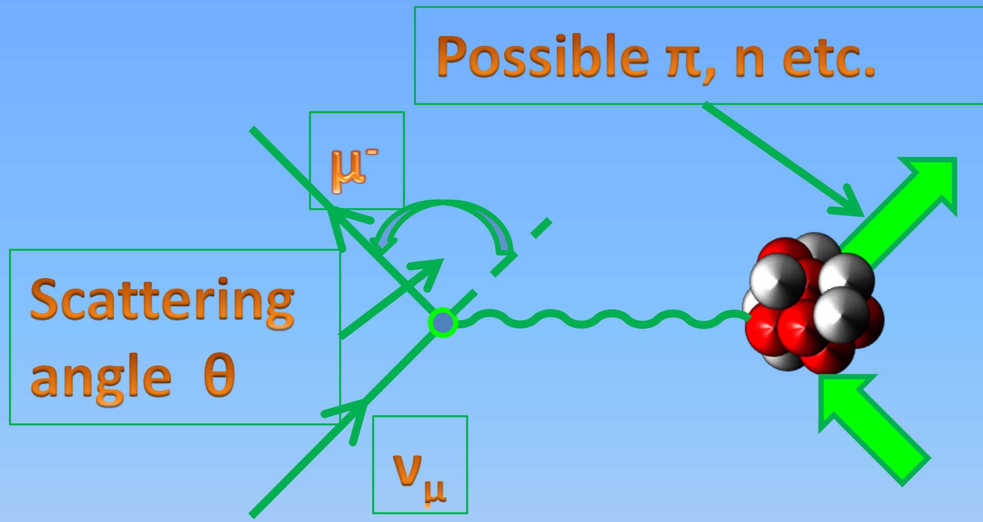
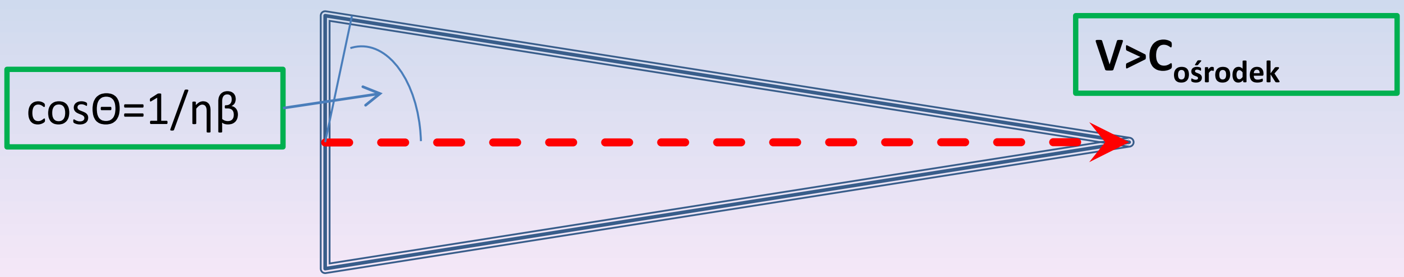
An alternative approach to extraction of oscillation parameters

Jakub Żmuda

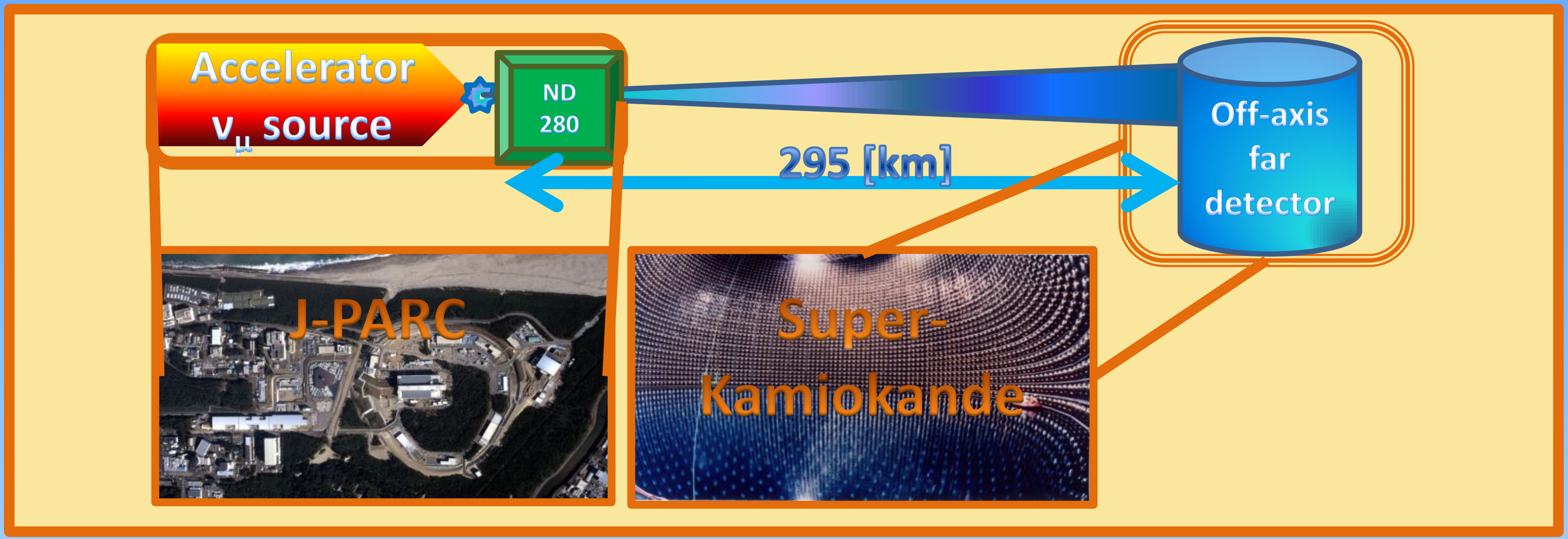
What do we observe in SK?



- 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 $\pi^0 \rightarrow \gamma\,\gamma$.



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!
  $\delta(\Delta m^2_{23}) \approx 4\%$, $\delta(\sin^2(2\Theta_{23})) \approx 1\%$

Motivation

Standard approach in the muon neutrino disappearance experiment:

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

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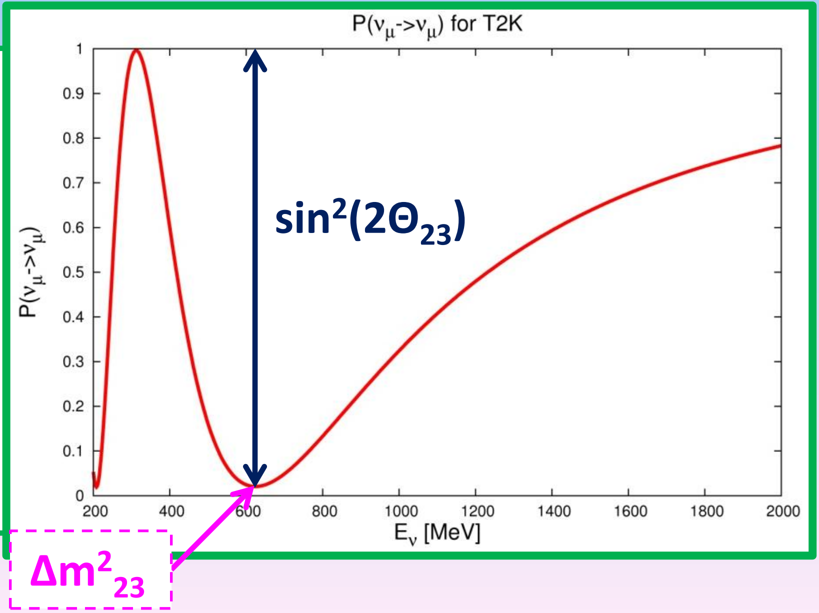
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \cos^4(\Theta_{13})\sin^2(2\Theta_{23})\sin^2(1.26\Delta m^2_{23} L/E[km/GeV])$$

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 brobability minimum in (L/E) ↔ Δm^2_{23}, depth ↔ $\sin^2(2\Theta_{23})$ ($\cos^4(\Theta_{13}) \approx 1$).



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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**. FG+ beam direction+ lepton kinematics.

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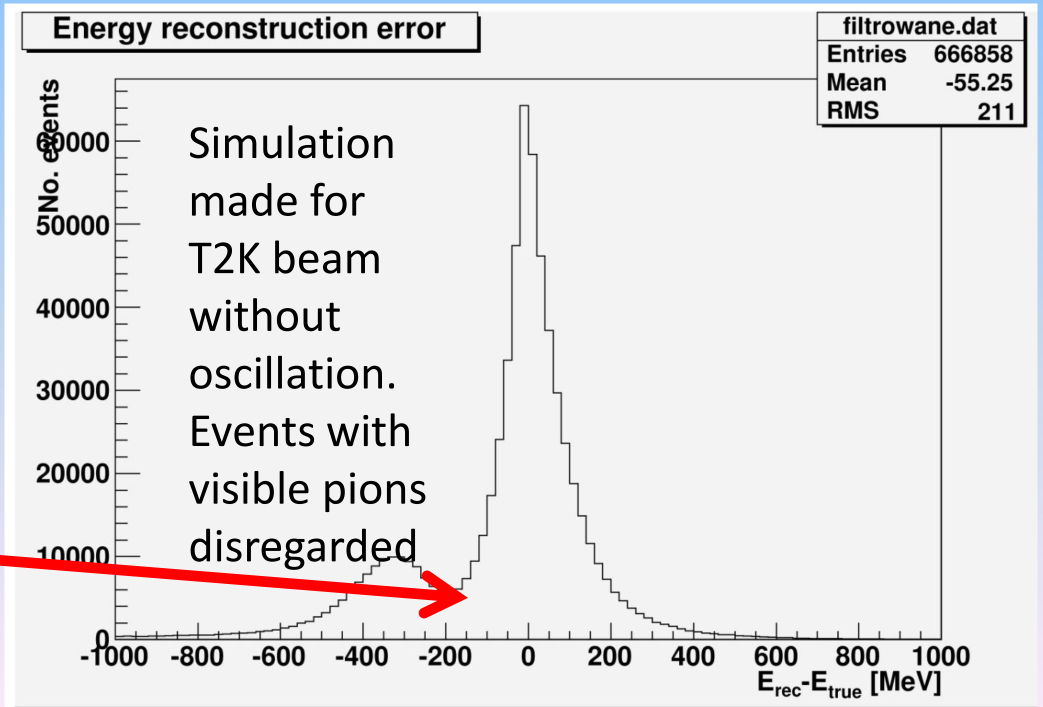

$m_\Delta > m_{pn}$ & disregarded degrees of freedom & dynamics → **systematic error!**

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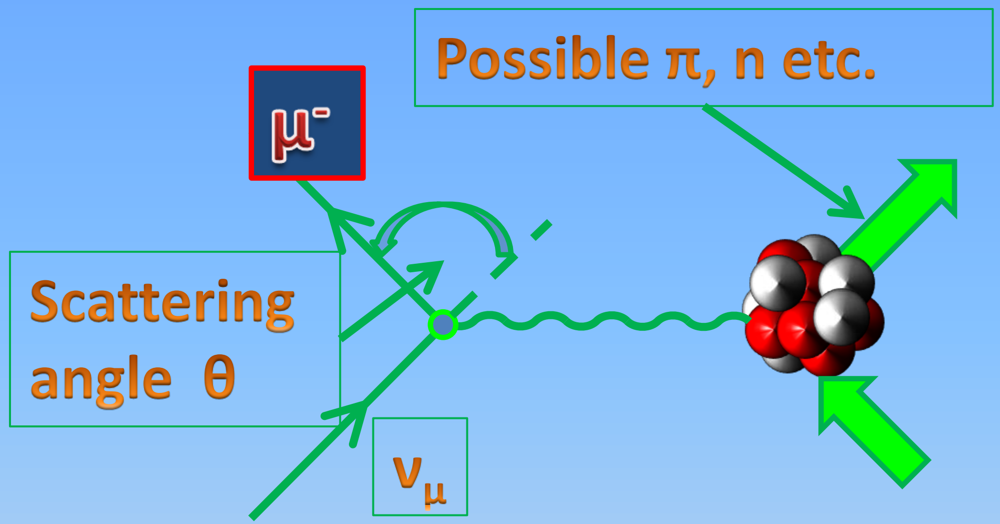

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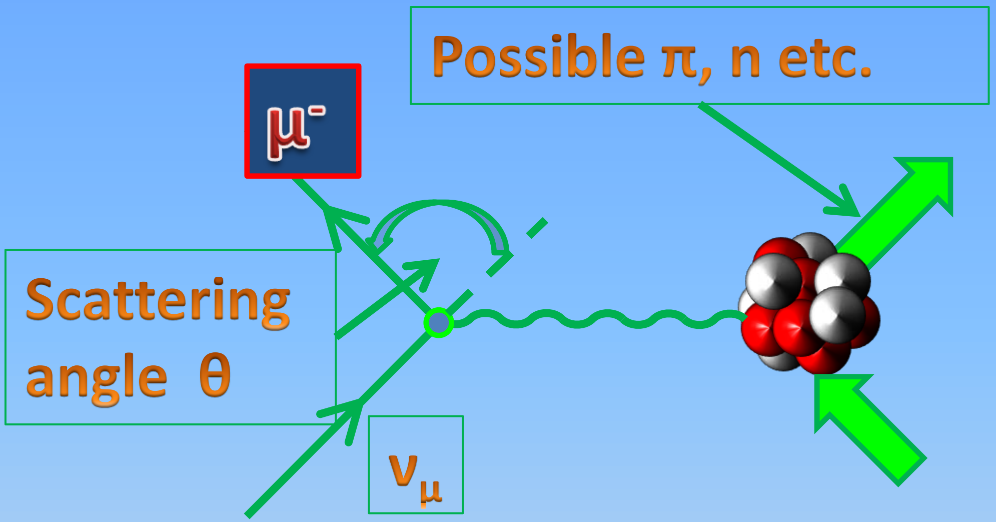

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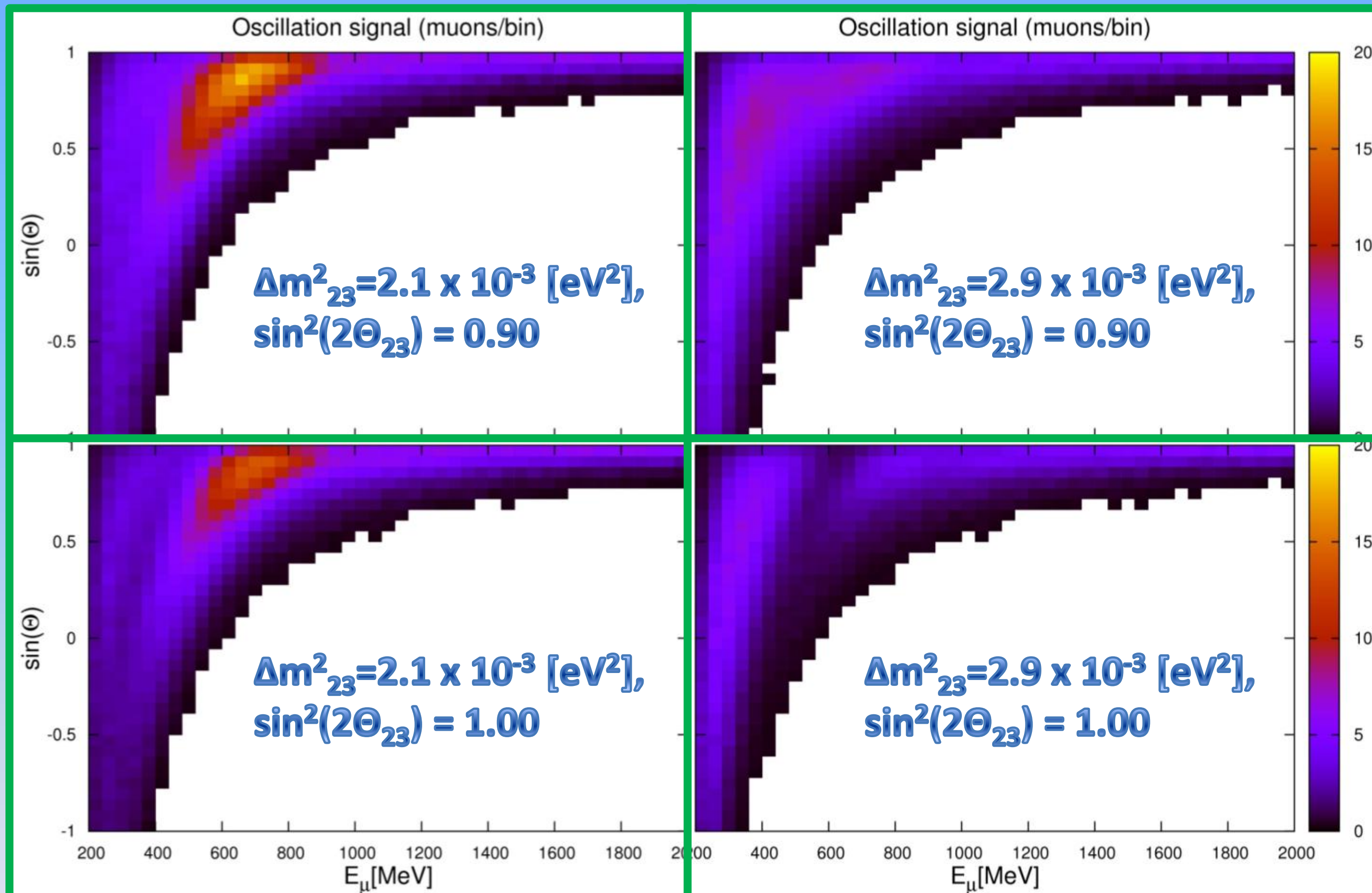
- **Try to use the direct observables!**

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}, despise of the nuclear dynamics influence. As expected!



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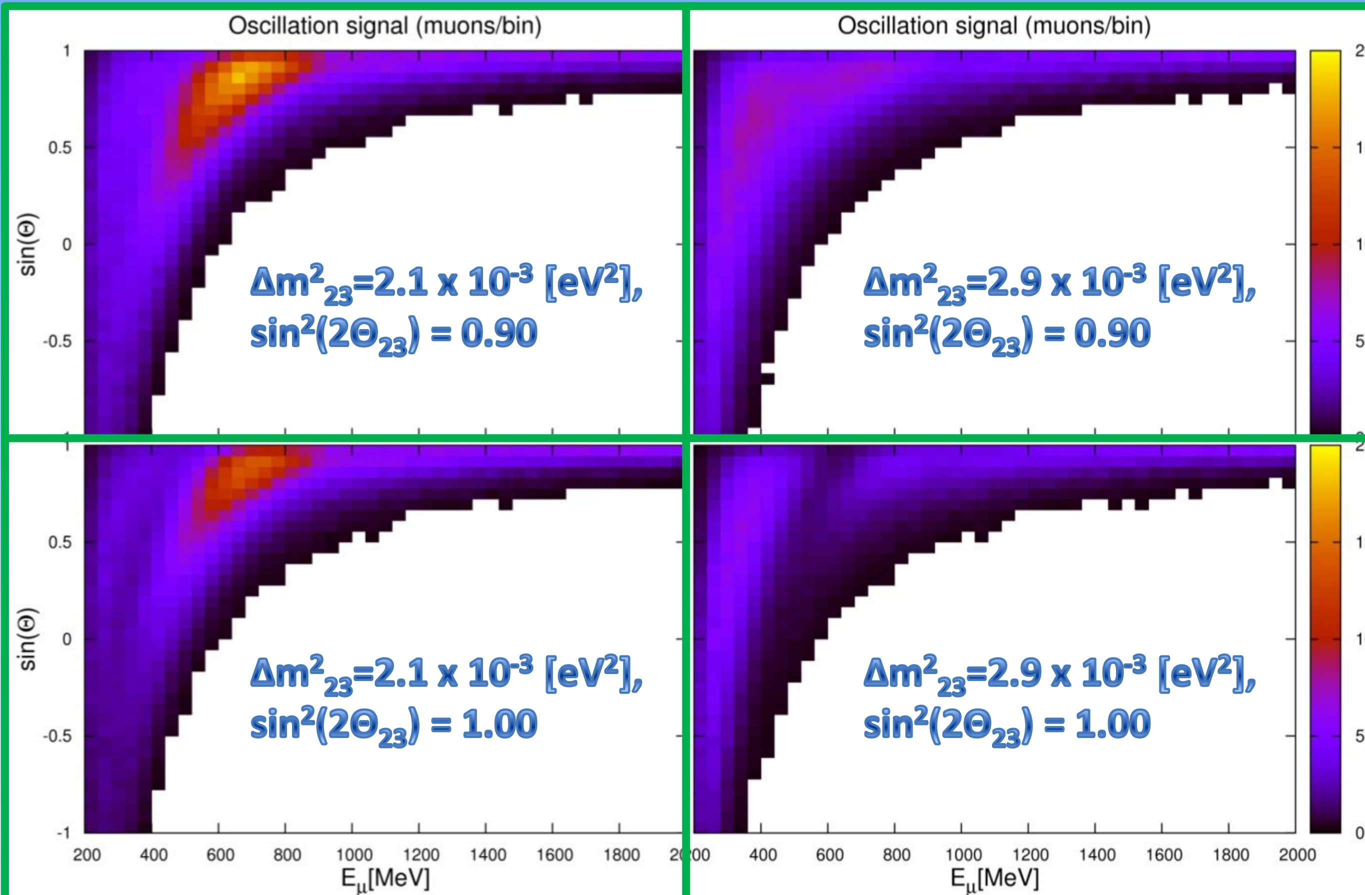

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- **Muon distribution should be a very good observable for neutrino oscillation measurement!**

The algorithm

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Sampling of events from $P(\nu_\mu \rightarrow \nu_\mu)(E_\nu)$

Very high statistics

Δm^2_{23} ∈[21,29] x10^{-4} [eV^2], step 5x10^{-4}[eV^2]

$\sin^2(2\Theta_{23})$ ∈ [0.88,1.00], step 0.005

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Muon distribution histograms (<u>reference</u>):
Energy: 100 [MeV] bins; 0.2 to 1.2 [GeV]
Angle : $\pi/4$ bins
Scaled down by ≈(0.01x0.25)
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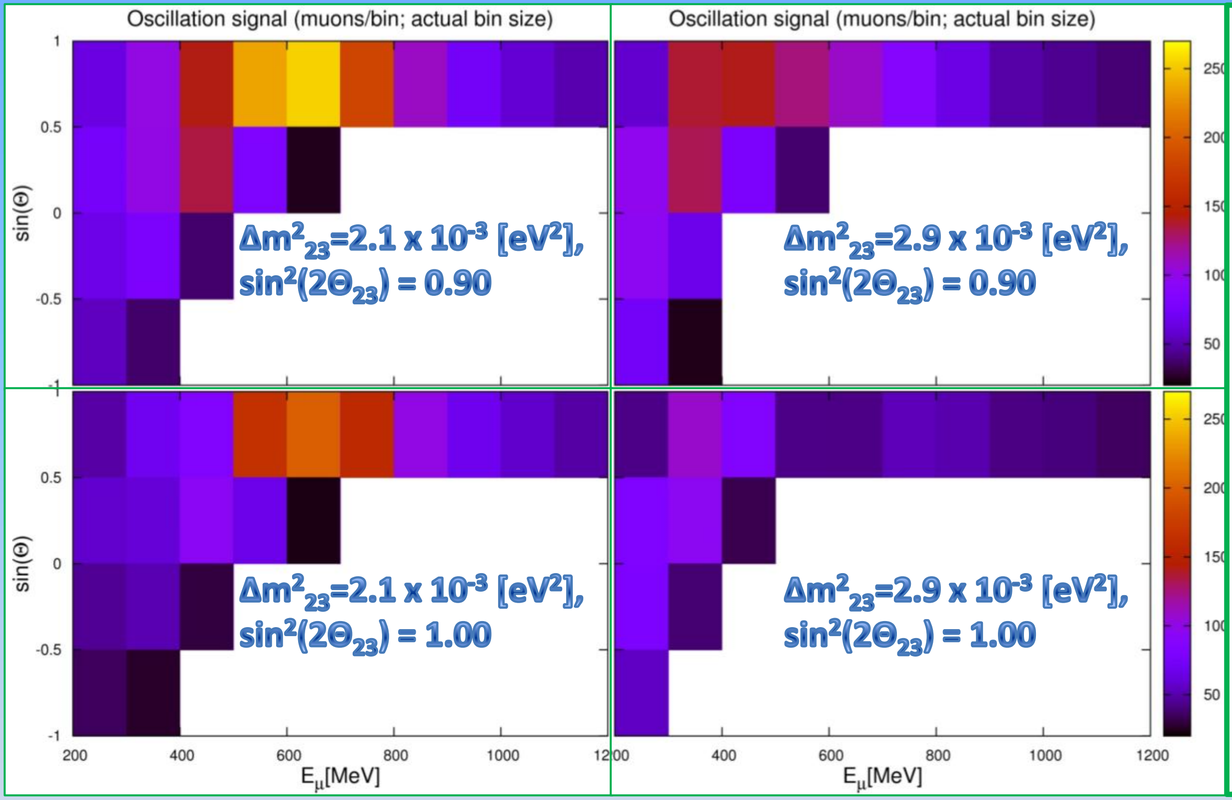
Of course, this is only an estimation of the statistical error for the method. Systematic errors (cross sections, pion kaskade, beam characteristics etc.) not included!

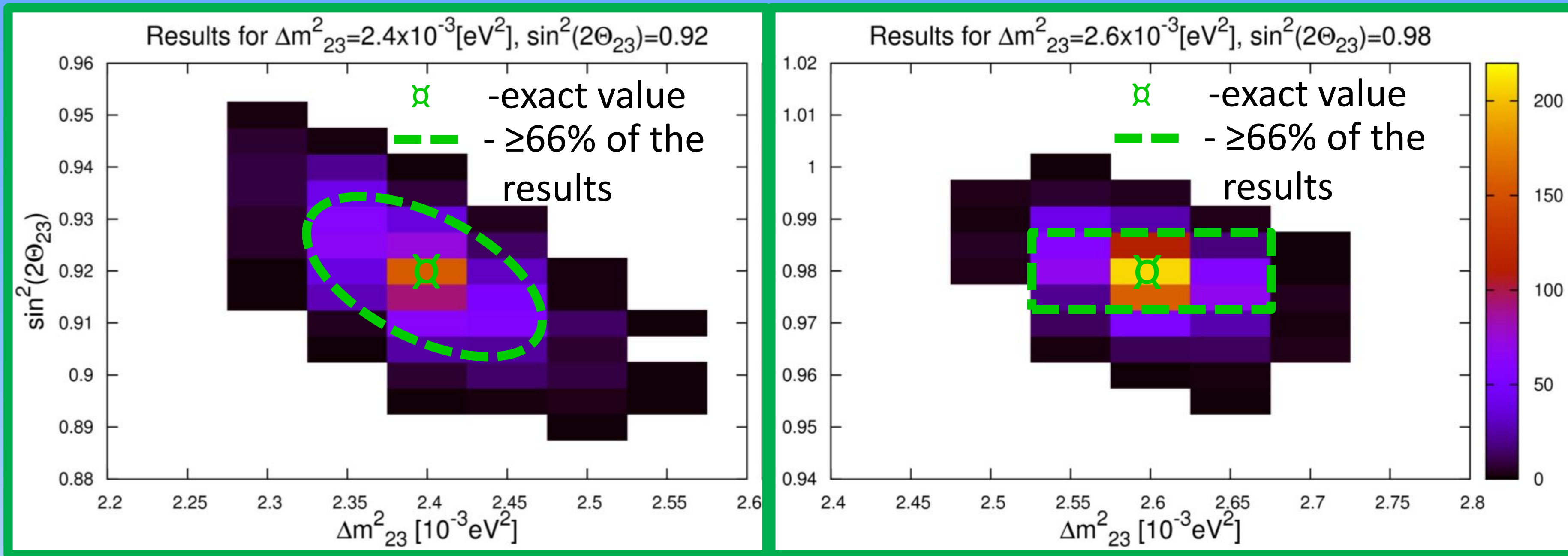
Oscillation signal (actual bin size, as used in the program)



Probably highest resolution possible with uniform bins.

- Oscillation signal clearly visible in lower resolution.
- Higher resolution probably possible for non-uniform bins.

The results



Description:

These plots shows the results of Chi² test made for two different oscillation parameter values:**(Δm^2_{23} = 2.4 x 10^{-3} [eV^2], $\sin^2(2\Theta_{23})$ = 0.92)** and **Δm^2_{23} = 2.6 x 10^{-3} [eV^2], $\sin^2(2\Theta_{23})$ = 1.00)***.

Each bin gives the number of MC muon signal samples, which have been identified with a pair of oscillation parameters (Δm^2_{23}, $\sin^2(2\Theta_{23})$).

*Rest of the parameters used in this test: Δm^2_{12} = 7.6 x 10^{-5} [eV^2] , $\sin^2(2\Theta_{12})$ = 0.87, $\sin^2(2\Theta_{13})$= 0.01.

Conclusions

- The proposed method gives good precision in the search for Δm^2_{23} and $\sin^2(2\Theta_{23})$ values. 1σ areas are not bigger, than 1×10^{-4} [eV^2] (around 4%) in Δm^2_{23} and 0.01-0.02 in $\sin^2(2\Theta_{23})$ (around 2-3%),depending on the area, but without inclusion of the systematic errors.

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- The proposed method gives good precision in the search for Δm^2_{23} and $\sin^2(2\Theta_{23})$ values. 1σ areas are not bigger, than $1\text{x}10^{-4}$ [eV^2] (around 4%) in Δm^2_{23} and 0.01-0.02 in $\sin^2(2\Theta_{23})$ (around 2-3%),depending on the area, but without inclusion of the systematic errors.
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- 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. One can also try to use better dynamical models, like the nuclear spectral function for oxygen or better pion production and kaskade.

References

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[4] F. Sanchez, *Acta Phys. Pol. B* **40**, 2621 (2009).