Measuring neutrino oscillations in ORCA

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KM3NeT junior group meeting

2020-01-30

Preliminary

- Topical lectures December on neutrino physics: https://indico.nikhef.nl/event/1828/
- Plots on Wikipedia are good

General case of ν oscillations

Lepton Mixing Matrix

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}|\nu_i\rangle; \qquad \alpha = e, \mu, \tau$$

Where U elements from the Lepton Mixing Matrix

$$U = \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \end{array}$$

CP-violating phase δ

$$s_{12} = \sin\theta_{12}$$
$$s_{23} = \sin\theta_{23}$$
$$s_{13} = \sin\theta_{13}$$

All mixing angles have now been measured!

$\theta_{12} \approx 34°$
$\theta_{23} \approx 45°$
$\theta_{13} \approx 8.6°$

→ We may be able to measure CP angle δ

Source: Topical lectures 12-2019, Decowski

Neutrino case: 2 flavors

"Disappearance probability"

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

oscillation amplitude

oscillating factor

e → x: "Appearance probability"

Source: Topical lectures 12-2019, Lisi

Vacuum oscillations

$$P(\nu_e \to \nu_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$P(\nu_\mu \to \nu_e) \simeq s_{23}^2 \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4c_{13}^2 s_{23}^2 (1 - c_{13}^2 s_{23}^2) \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$P(\nu_\mu \to \nu_\tau) \simeq c_{13}^4 \sin^2 2\theta_{23} \left(\frac{\Delta m^2 L}{4E} \right)$$

Source: Topical lectures 12-2019, Lisi

Three ν generations

Octant: $\theta_{23} > 45°$?

$$P_{\nu_\mu \to \nu_e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 \Delta_{31}(1-A)}{(1-A)^2} + \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2(A\Delta_{31})}{A^2} + \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(A\Delta_{31})}{A} \frac{\sin[\Delta_{31}(1-A)]}{1-A} \cos(\Delta_{31} \pm \delta_{CP})$$

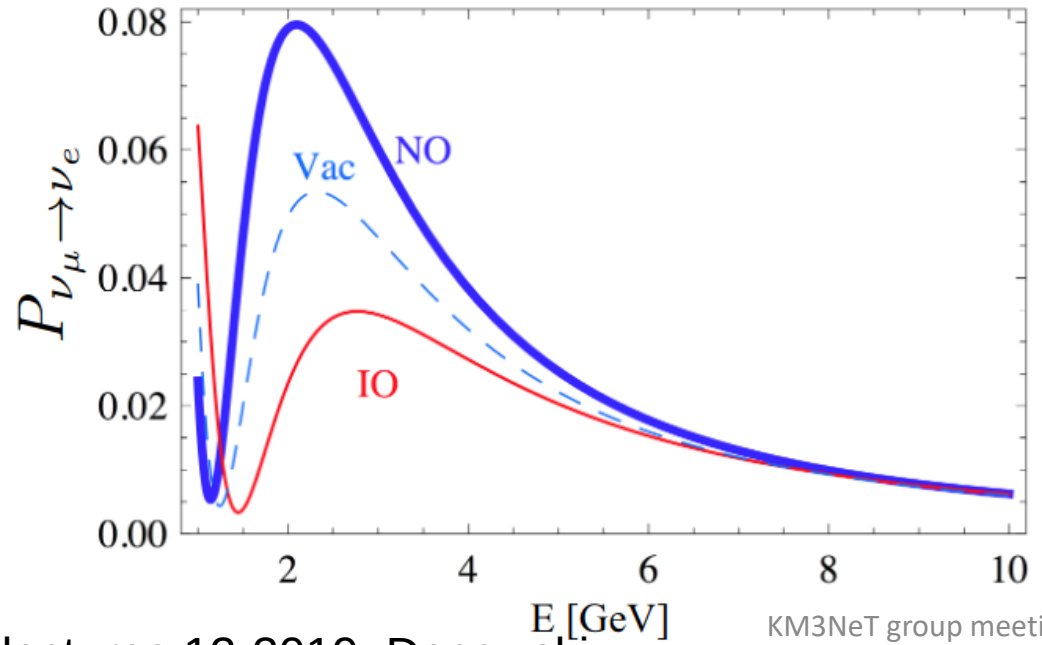
Matter-induced enhancement

CP-term

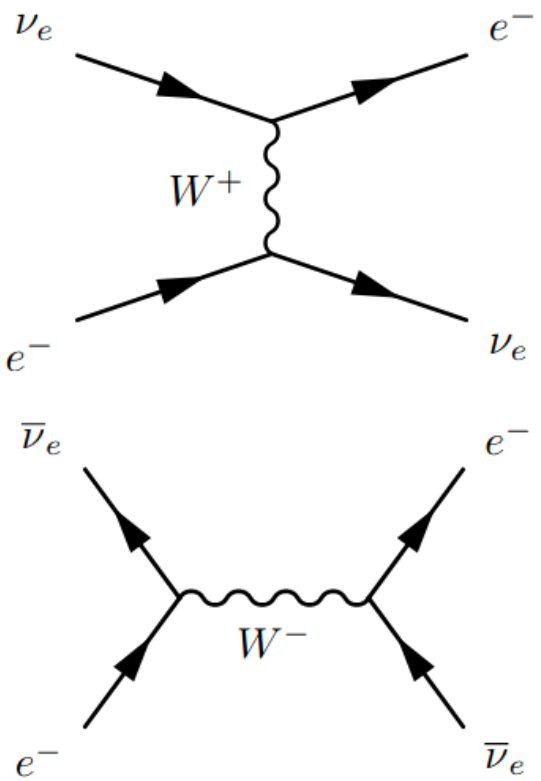
$$\Delta_{31} \equiv \frac{\Delta m^2_{31} L}{4E}$$

$$A \equiv \frac{2EV}{\Delta m^2_{31}}$$

$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$



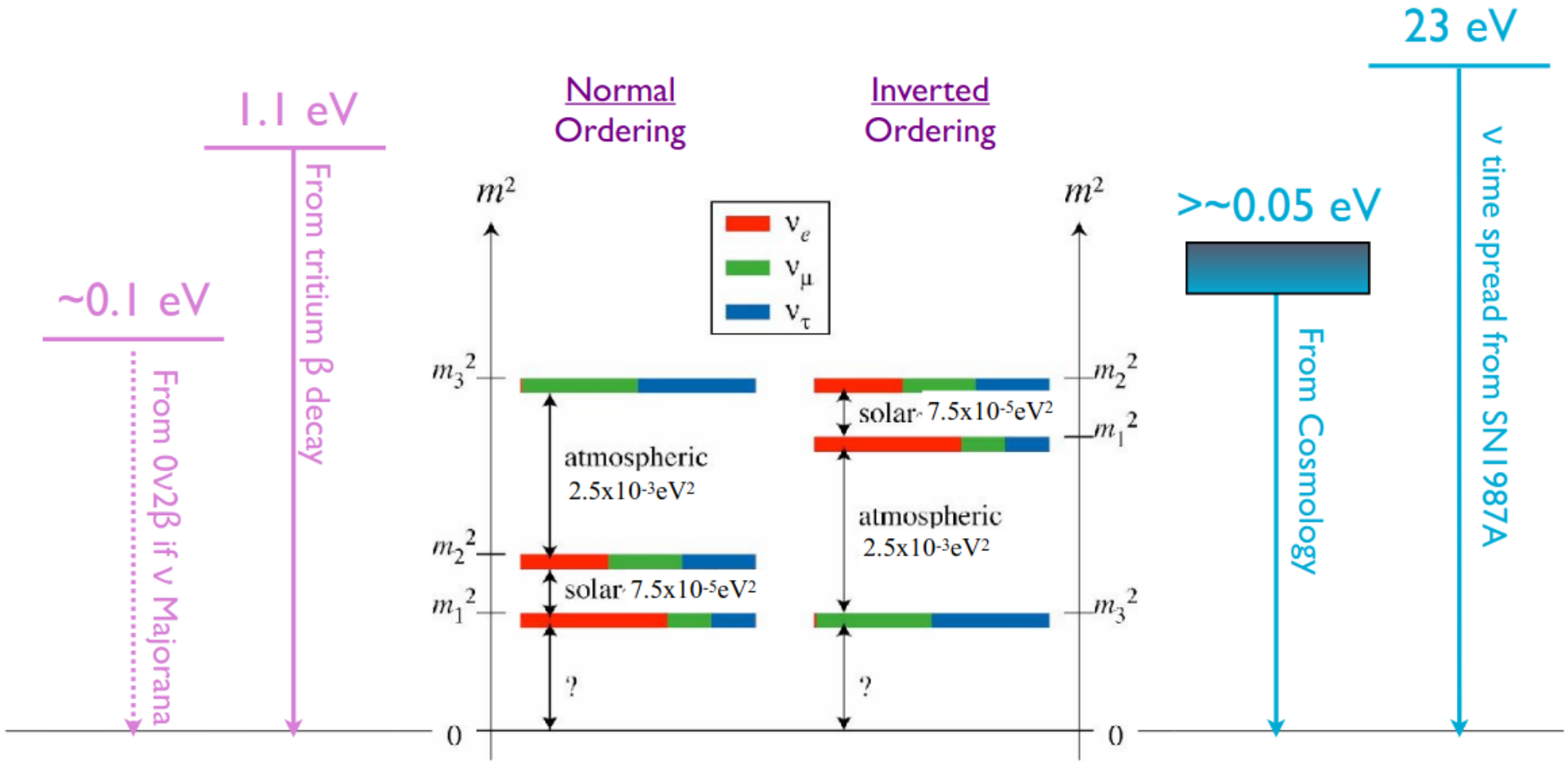
Matter contains e, but no μ, τ



Source: Topical lectures 12-2019, Decowski

Neutrino Masses

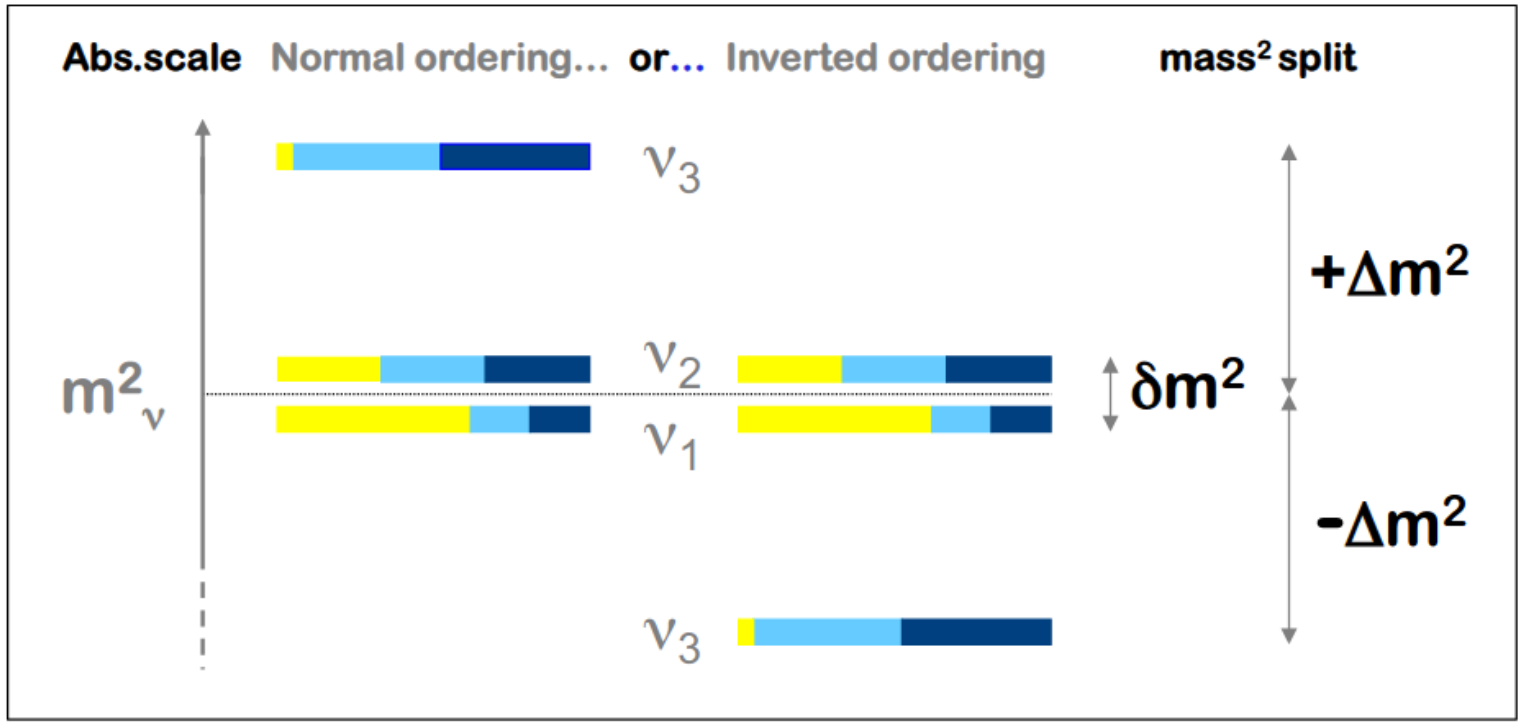
What is the ordering and absolute neutrino mass scale?



Source: Topical lectures 12-2019, Decowski

Present 3ν knowledge in one slide (with 1-digit accuracy)

e μ τ



We have seen:

δm^2 ~ 7×10^{-5} eV²
Δm^2 ~ 2×10^{-3} eV²
$\sin^2\theta_{12}$ ~ 0.3
$\sin^2\theta_{23}$ ~ 0.5
$\sin^2\theta_{13}$ ~ 0.02

We would like to see:

δ (CP)
sign(Δm^2) = ordering
octant(θ_{23})
absolute mass scale
Dirac/Majorana nature

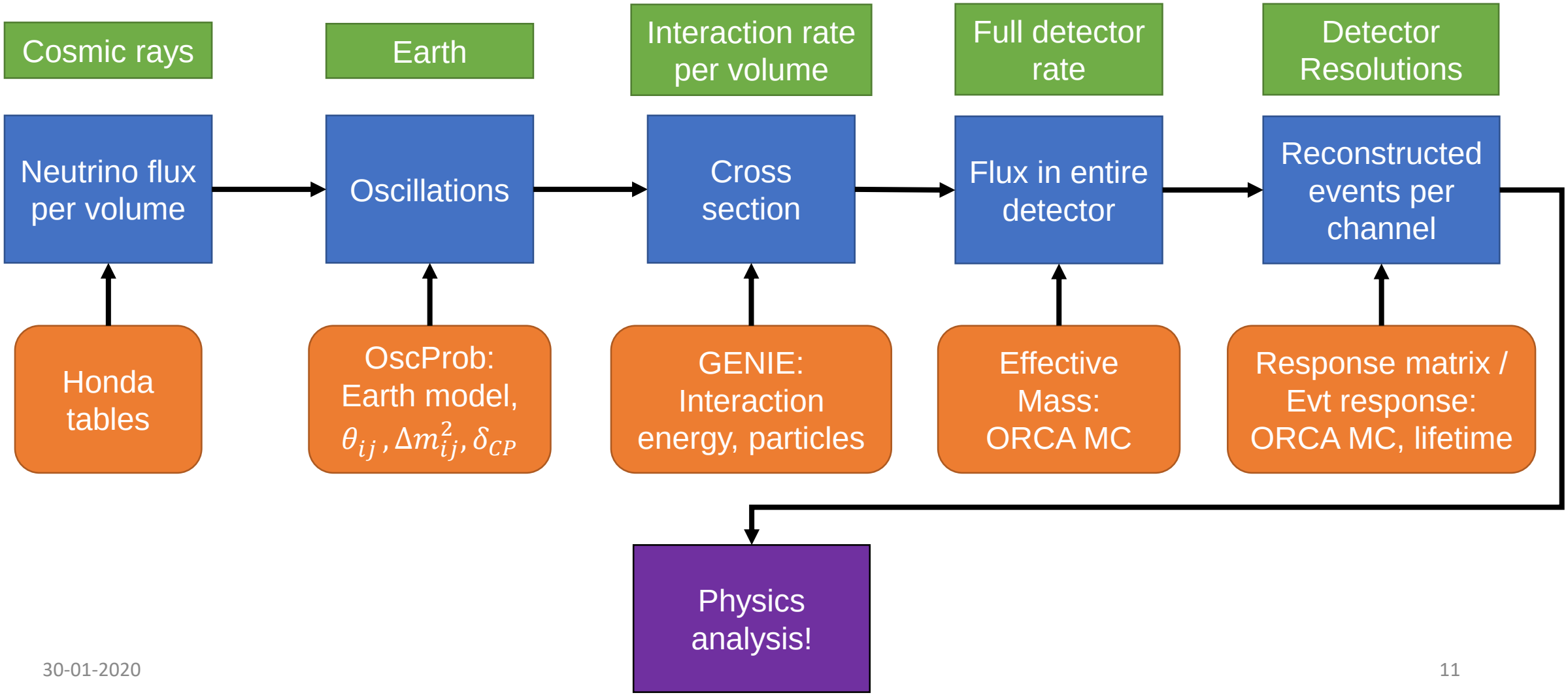
+ Physics beyond 3ν?

(anomalies, new states or interactions)

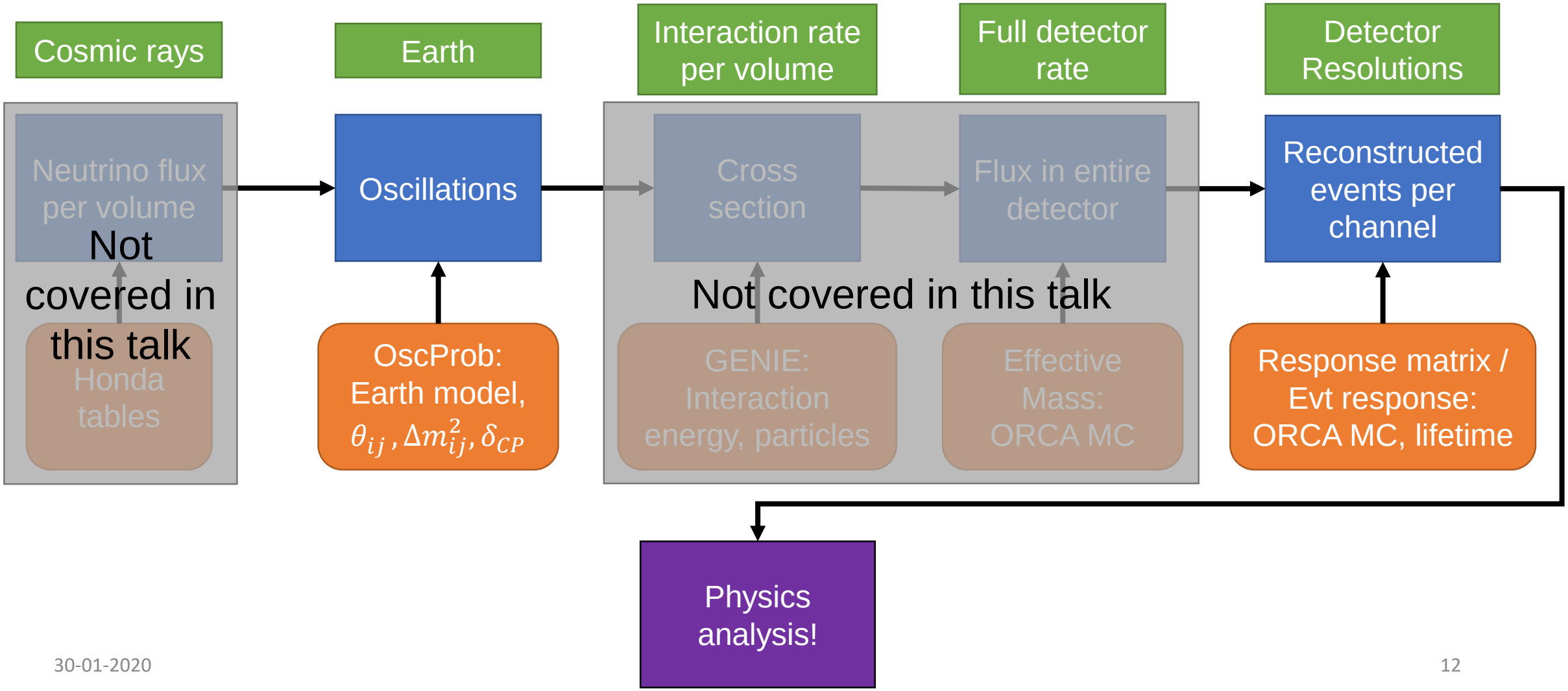
Source: Topical lectures 12-2019, Lisi

The ORCA detector

Overview of MC chain: Making a numeric model



Overview of MC chain: Making a numeric model

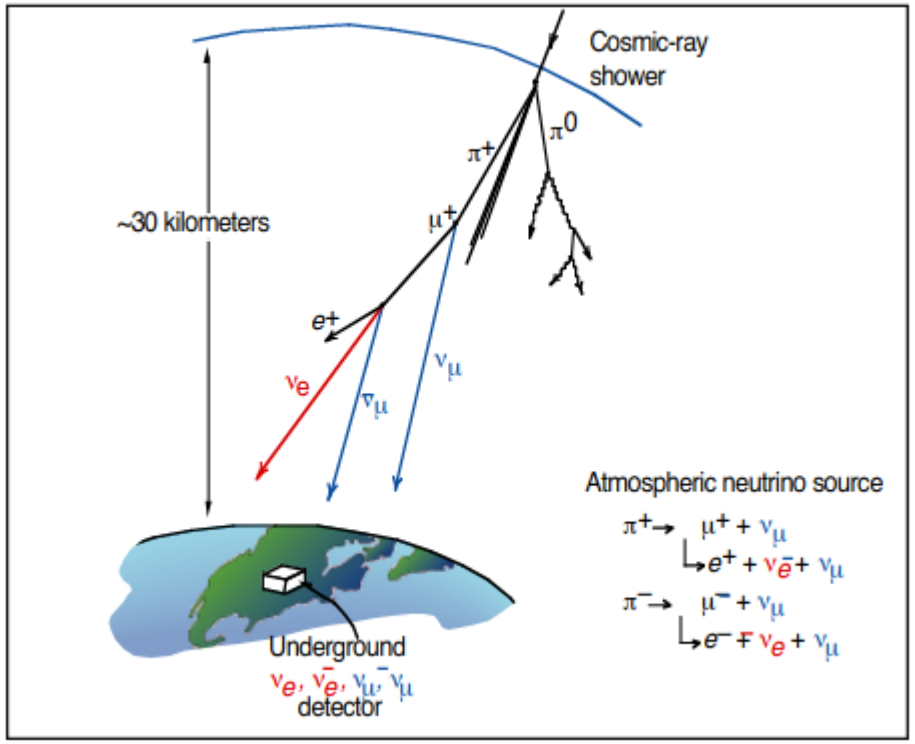


Production channels

ORCA measures atmospheric neutrinos:

Atmospheric neutrinos come from cosmic rays interacting in the atmosphere and the reaction products decaying into neutrinos

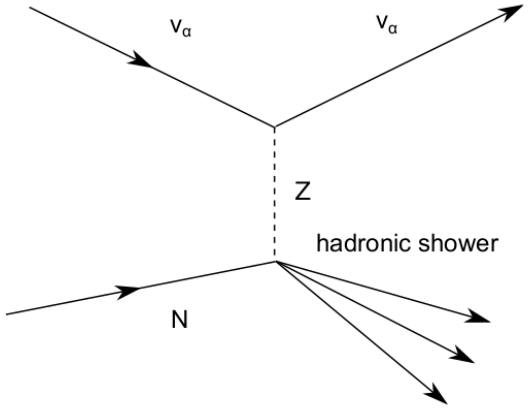
Typical energies are O(GeV)



Source: Topical lectures 12-2019, Lisi

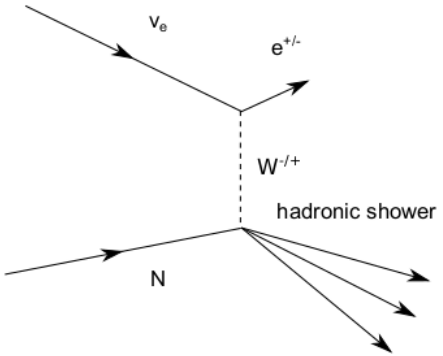
Feynman diagrams

Neutral Current

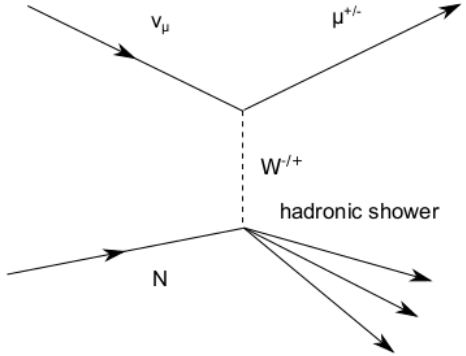


(a) Neutral current interaction for all three neutrino flavors

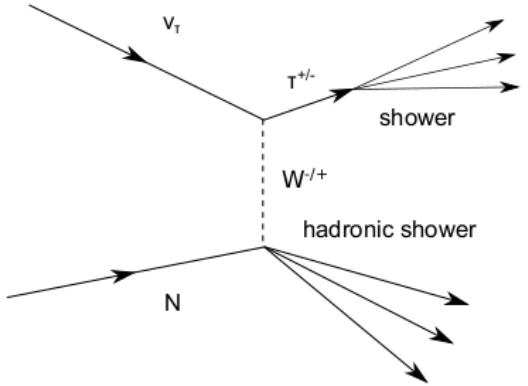
Charged Current



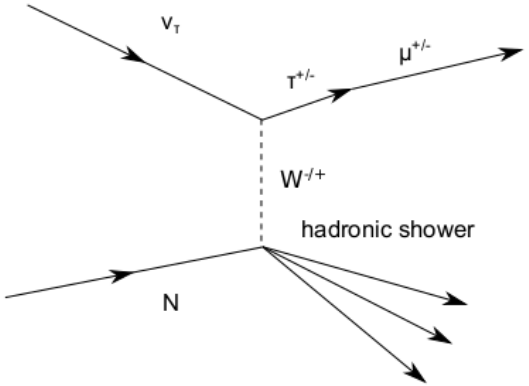
(b) Charged current interaction for electron neutrinos causing a electromagnetic shower



(c) Charged current interaction for muon neutrinos lead to a muon track



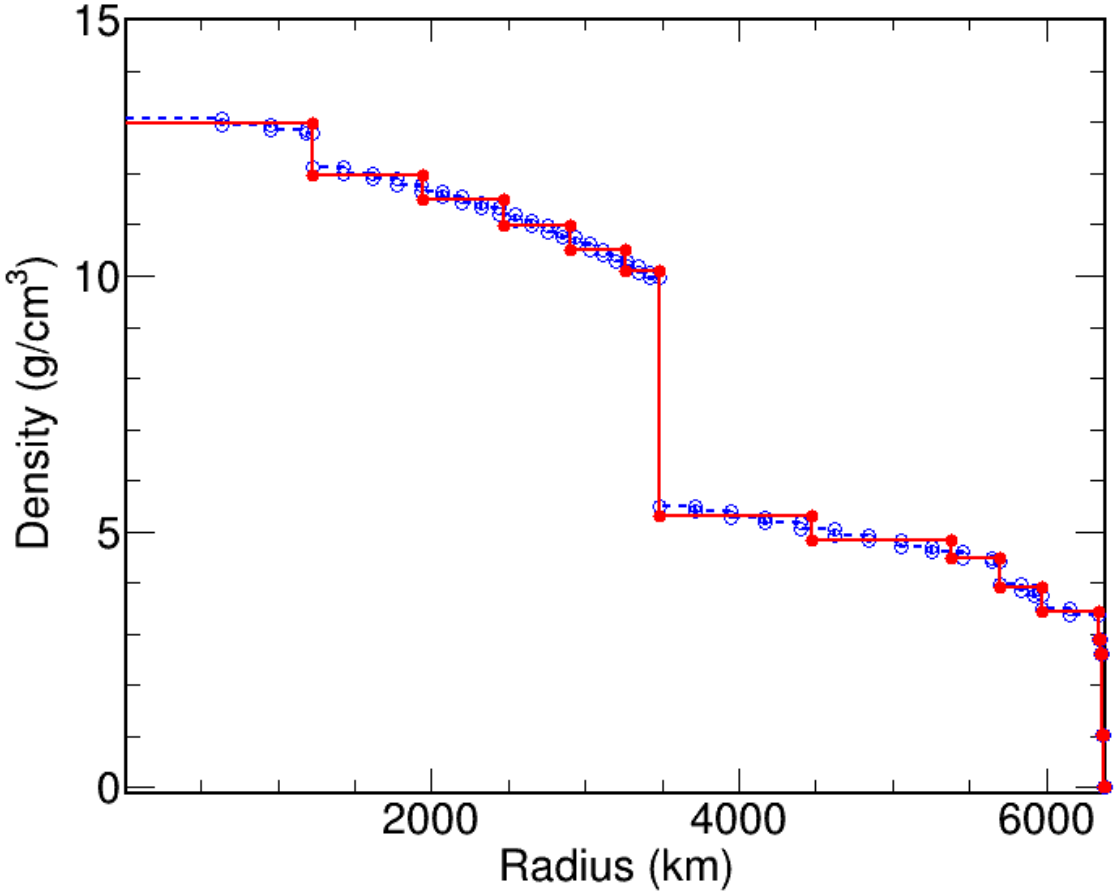
(d) Charged current interaction for tau neutrinos with the tau decaying to an electron or hadrons leading to a second shower

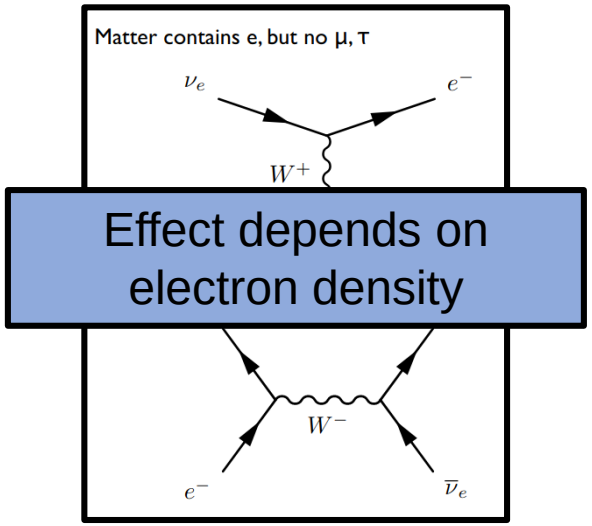


(e) Charged current interaction for tau neutrinos with the tau decaying to a muon (neutrinos neglected)

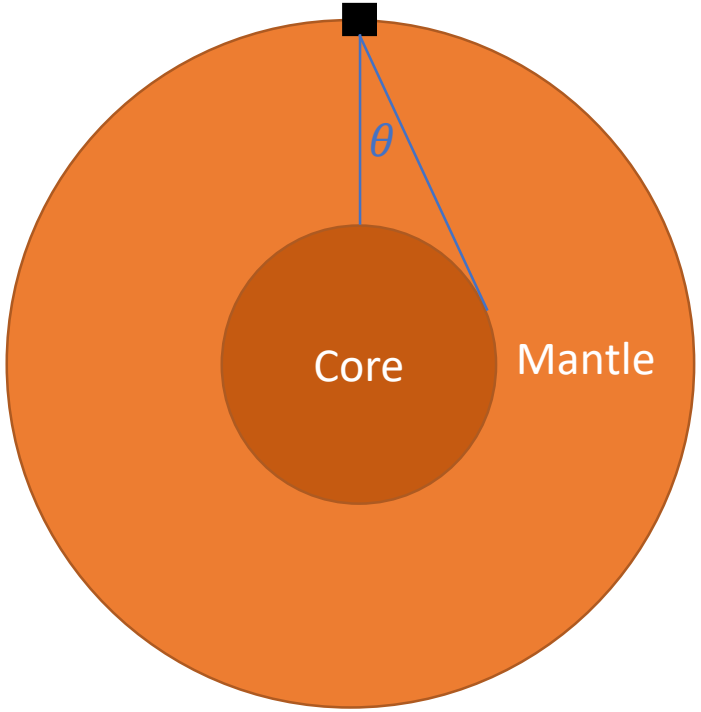
Source: thesis R. Bormuth

Mass effects
Preliminary Earth Model

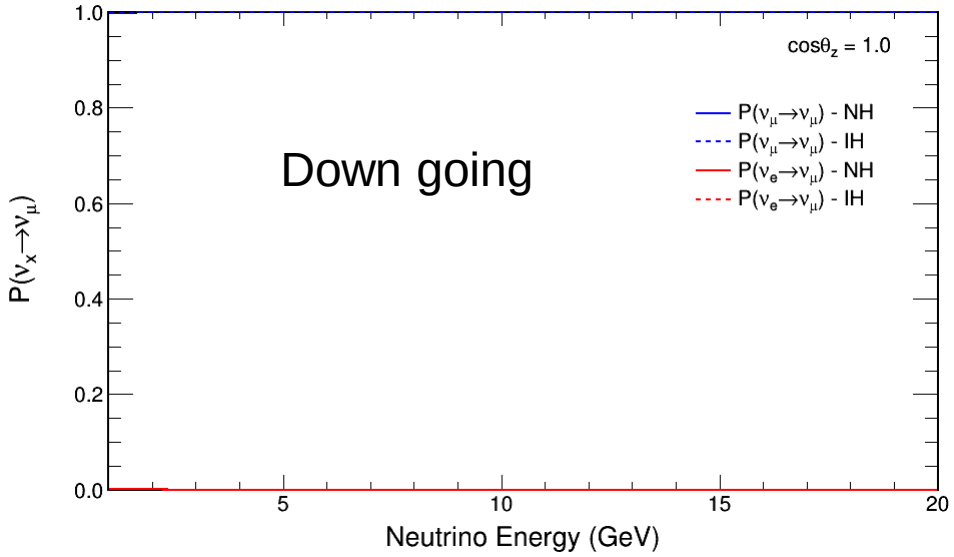


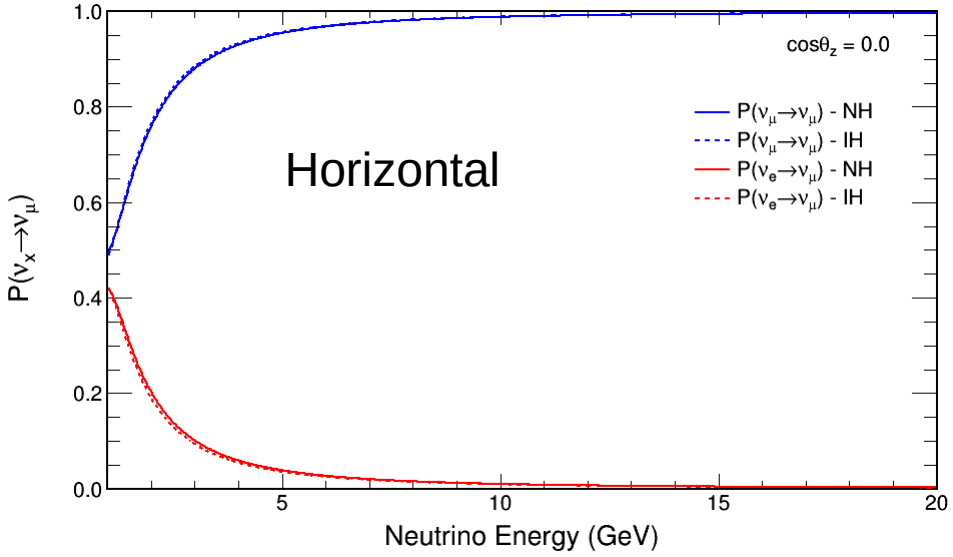


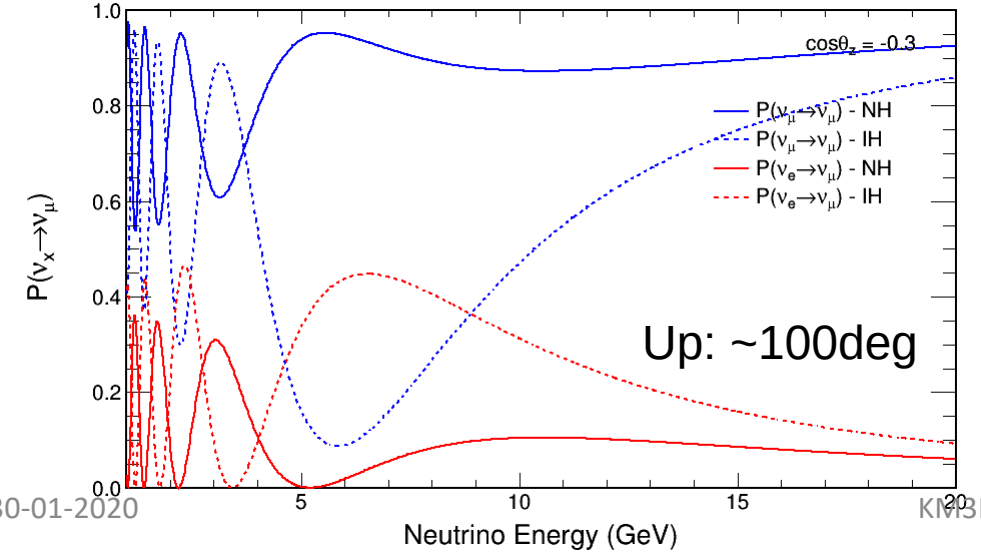
For the core $\cos\theta = 0.86$

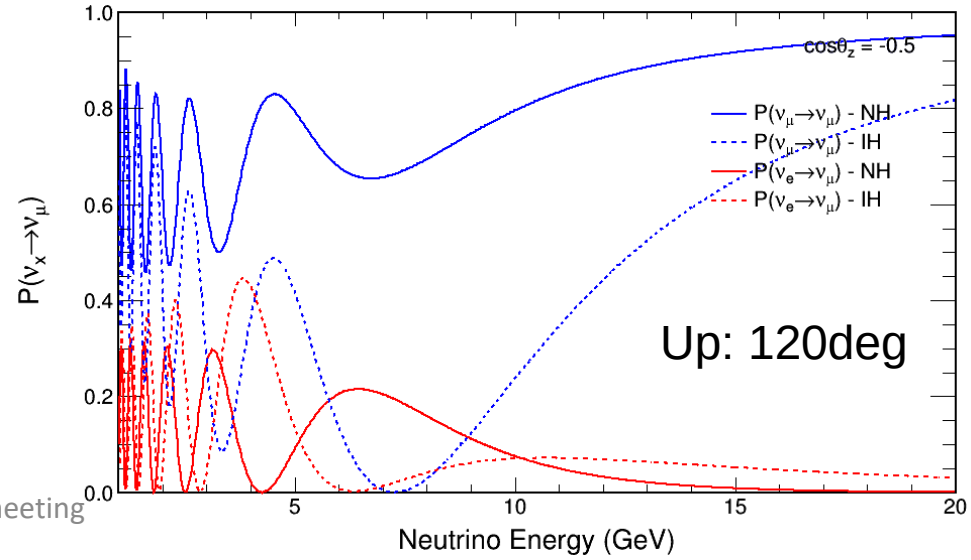


Selected oscillation probabilities









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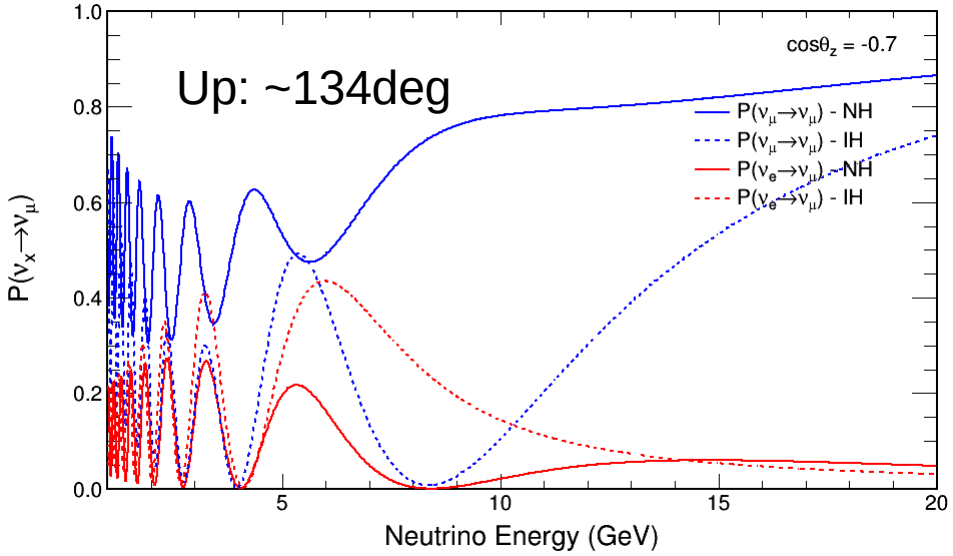
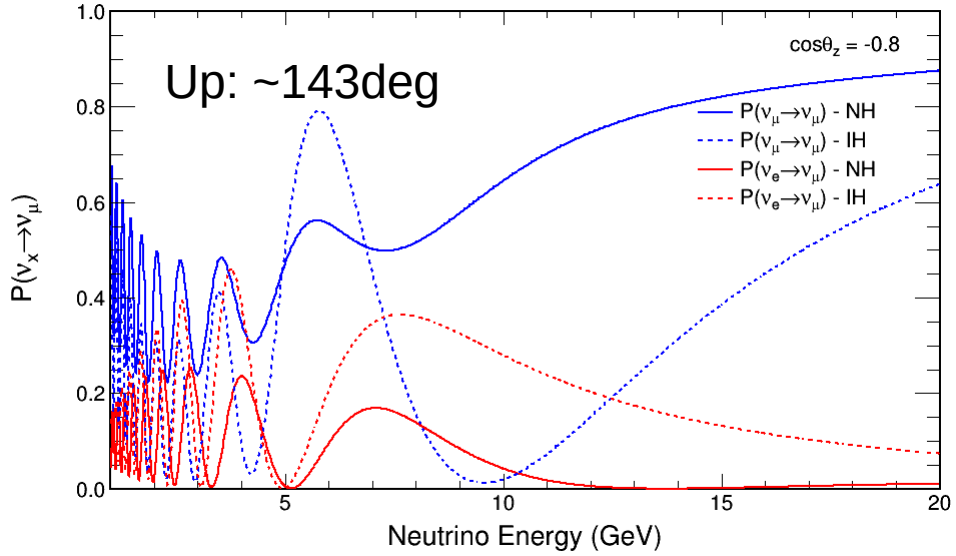
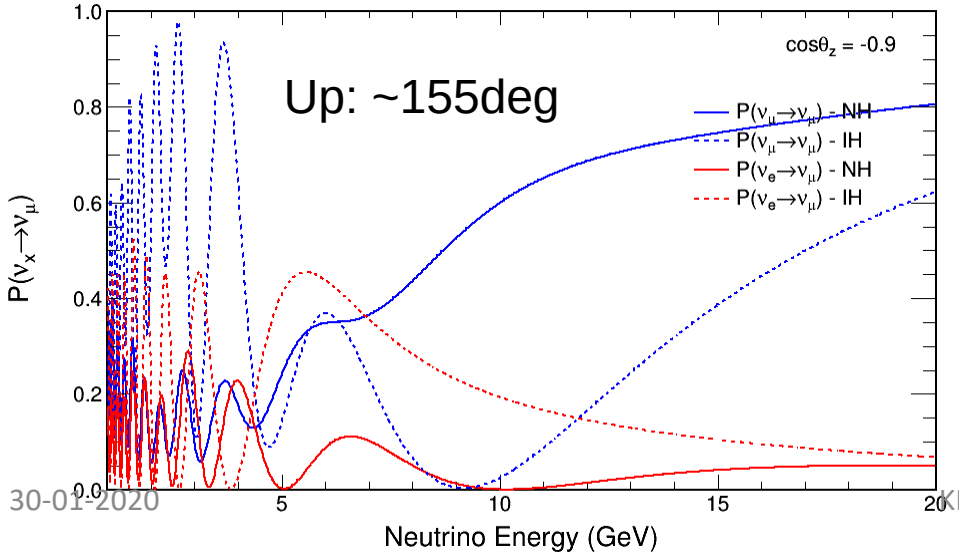
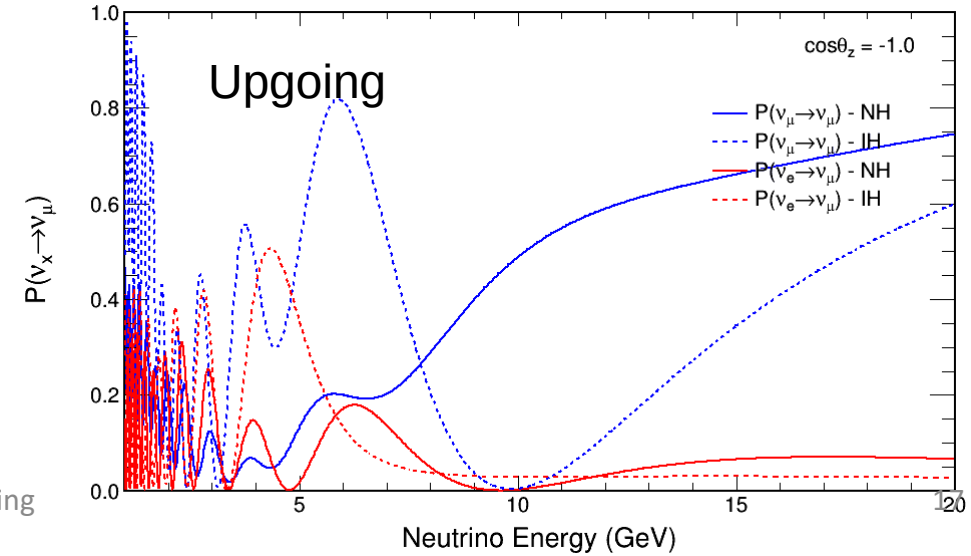
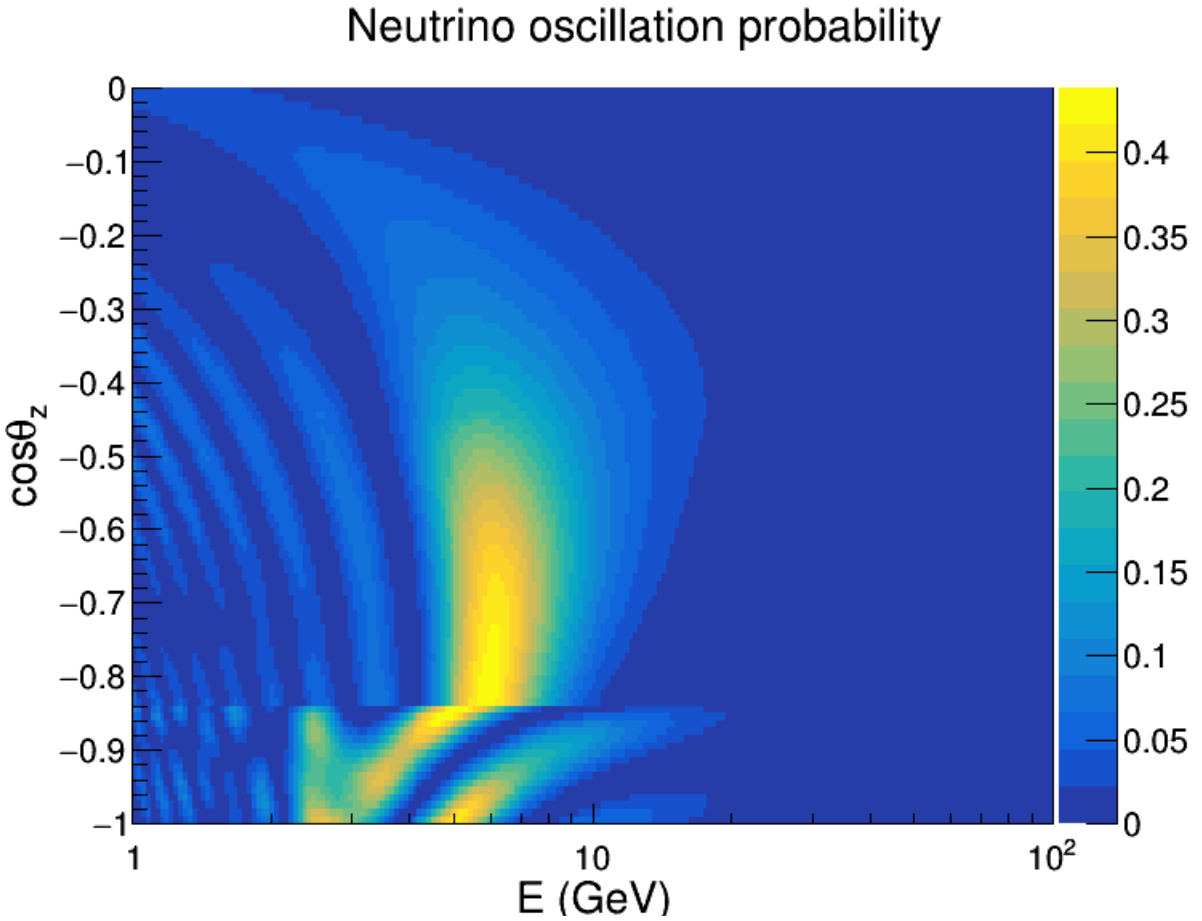


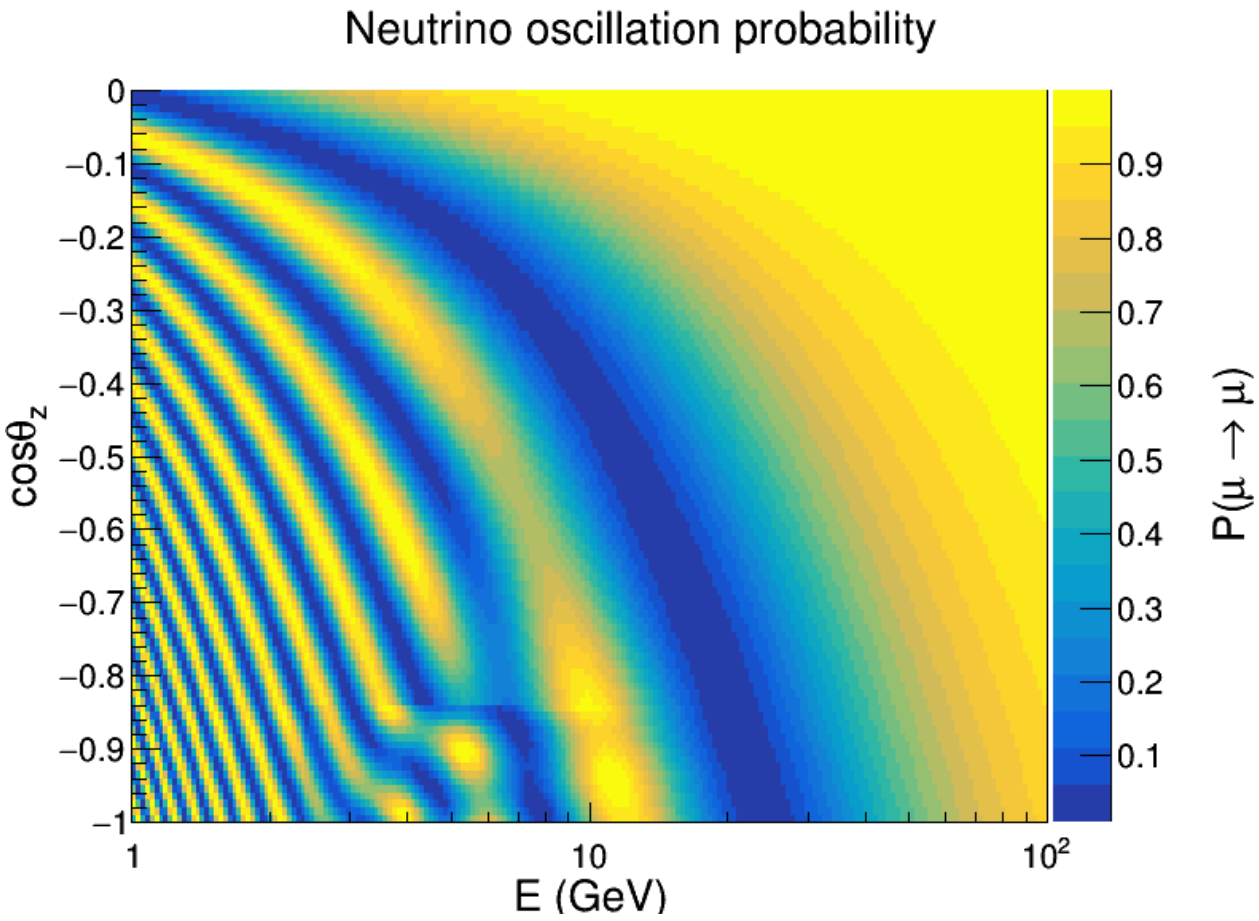




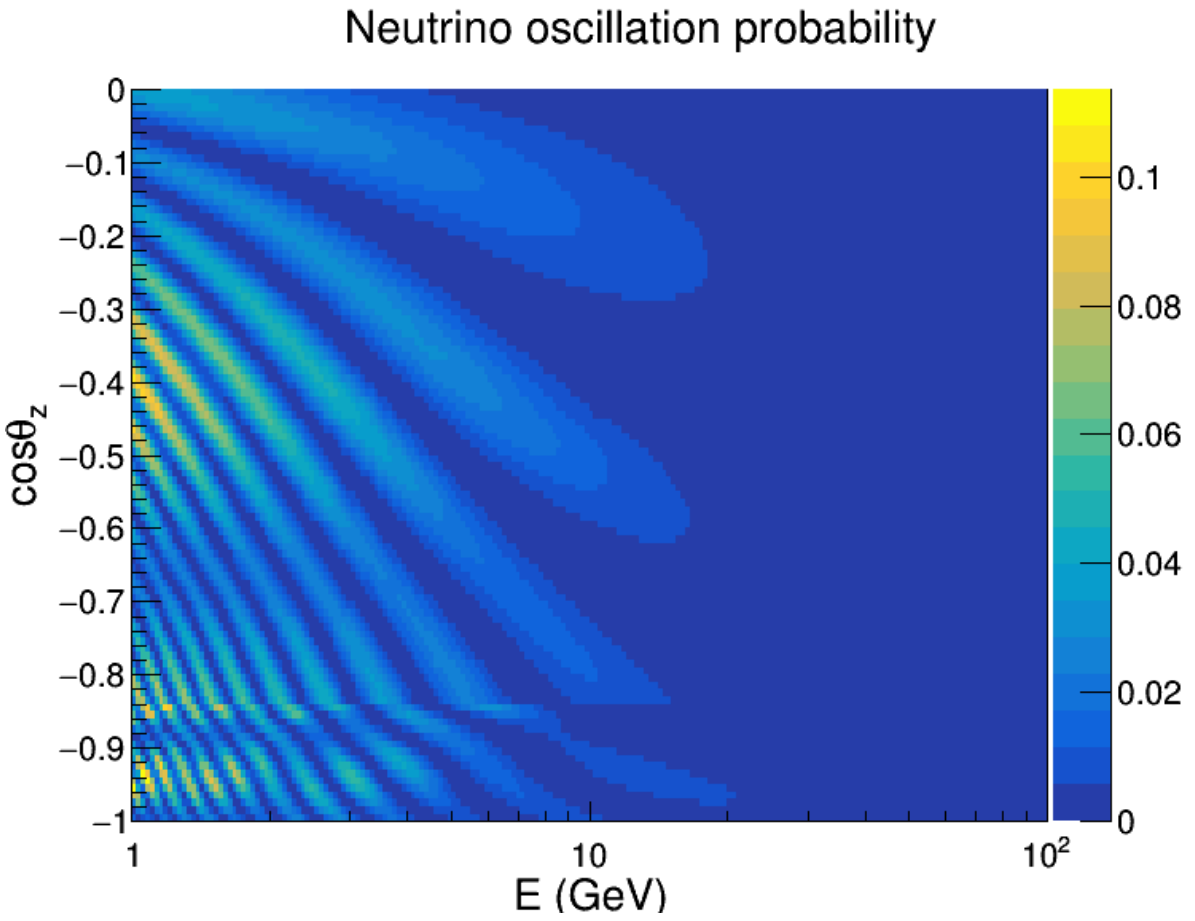


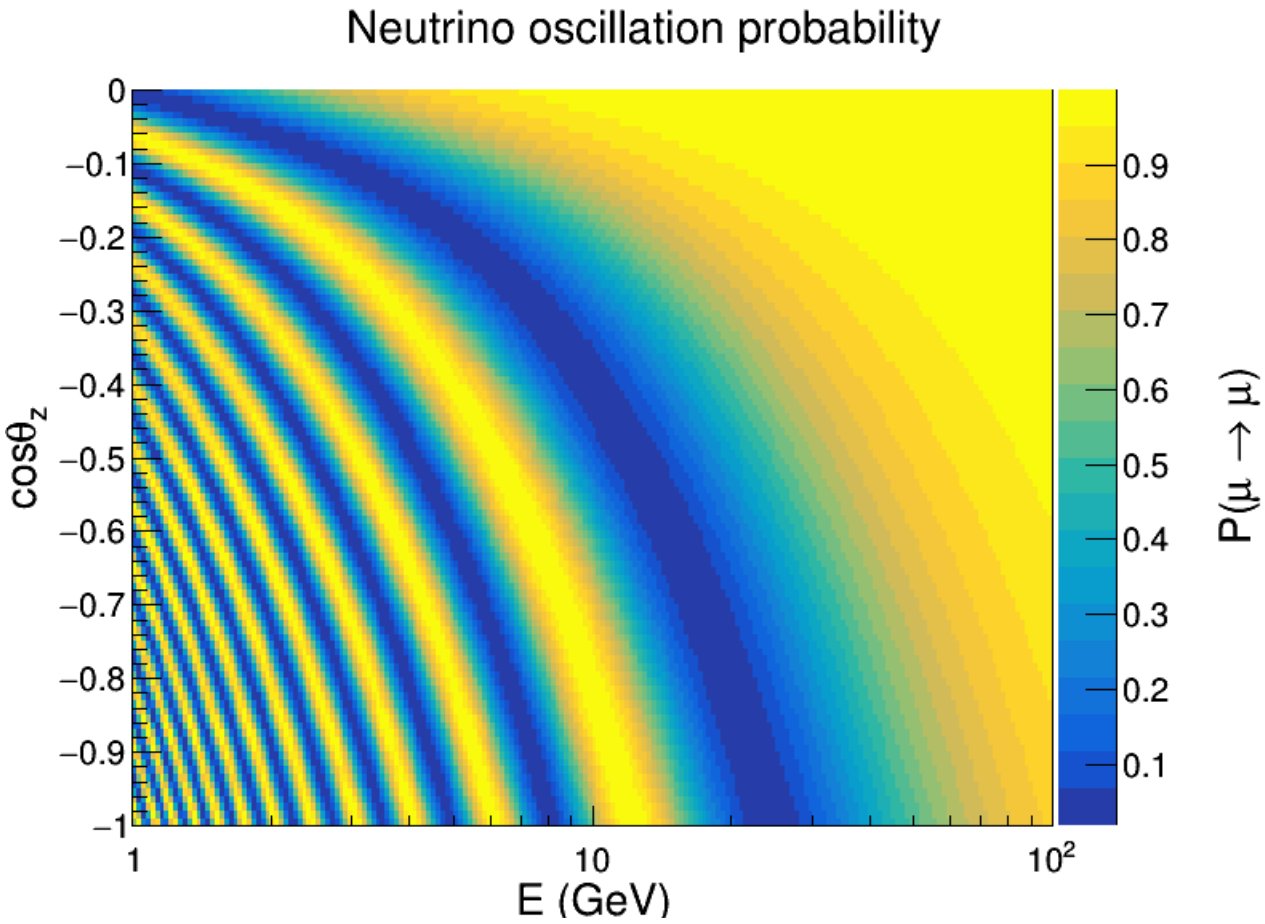
Oscillogram
Normal ordering





Oscillogram
Inverted ordering





From theory to measurement

- Oscillations depend on energy and length traveled

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

oscillation amplitude — oscillating factor

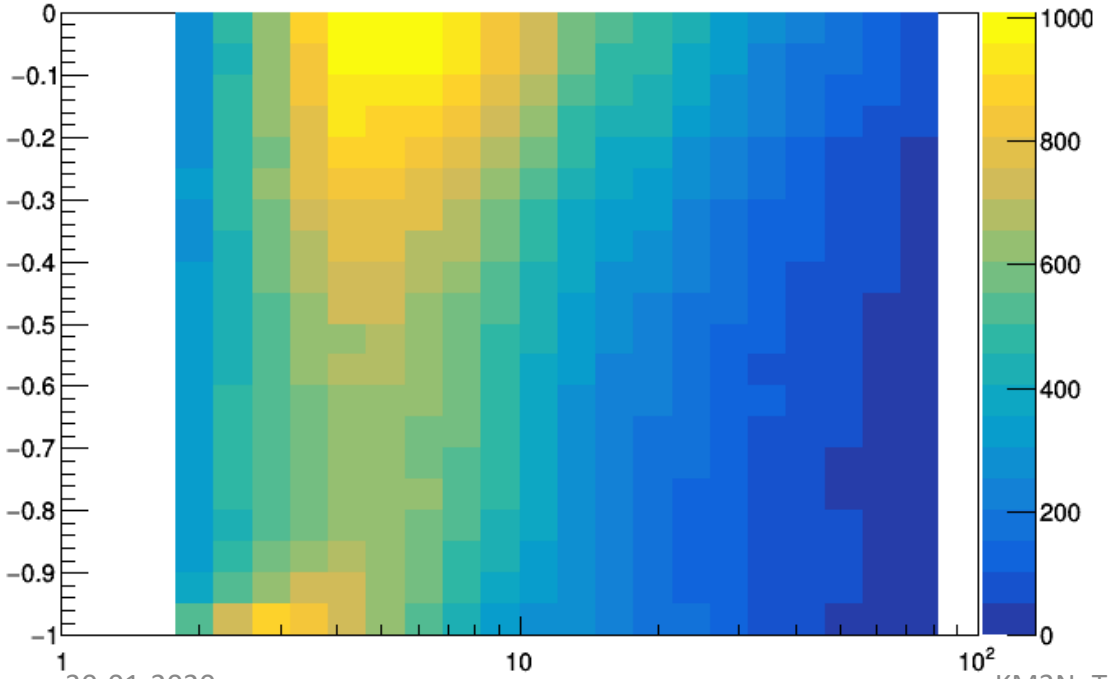
- $L = L_0 \cos\theta$

ORCA115 detector output 1/3

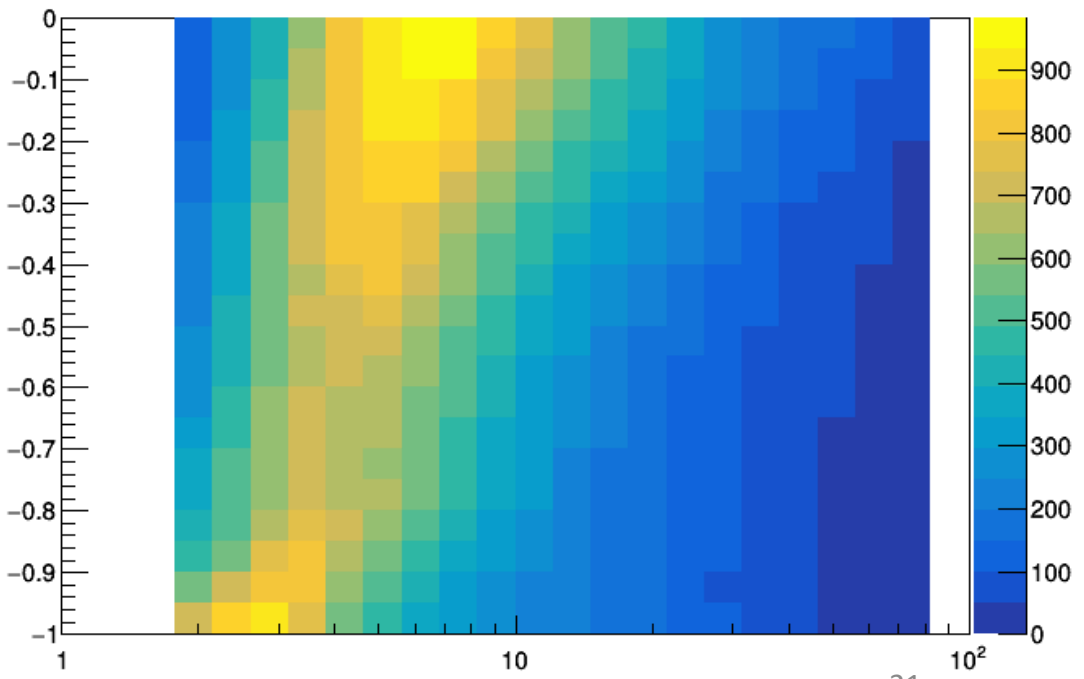
We apply cuts on muons and noise
NB: this is only neutrino events in MC, no atm muons

These are many reconstructed events, classified to track or shower

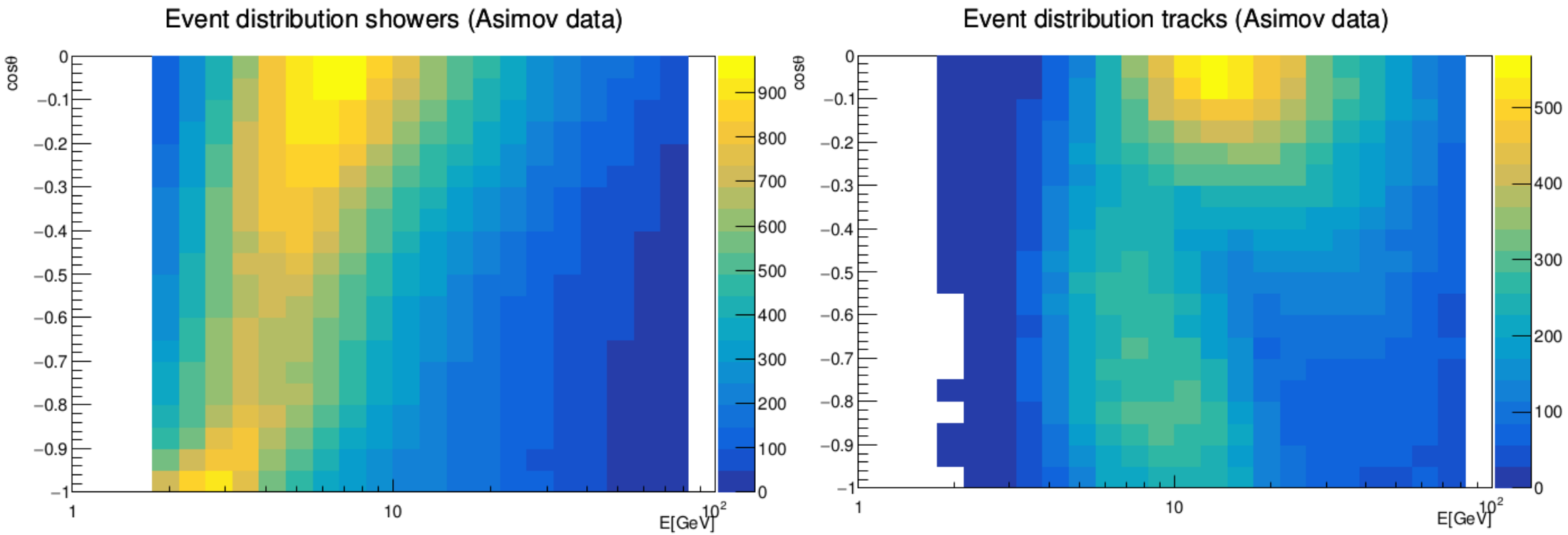
All events: shower channel



Selected events: shower channel



ORCA115 detector output 2/3



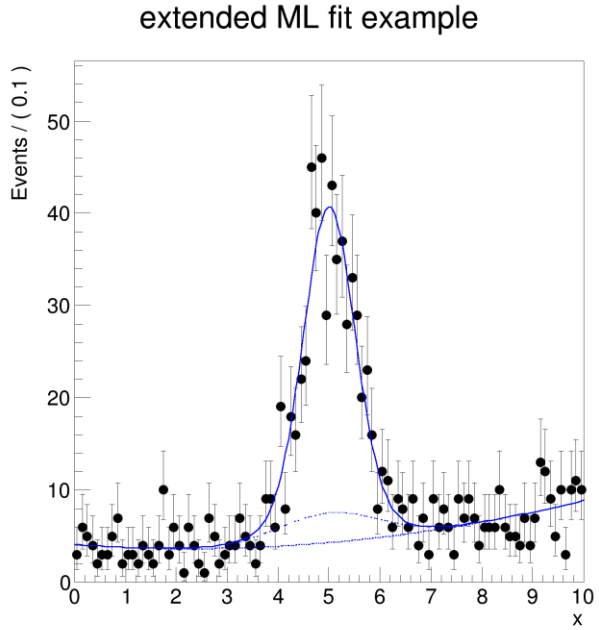
Model fitting

- χ^2-minimization, fitted in both θ_{23} quadrants
- Simultaneous pdf fit for track and shower channels
- Sensitivity: $S = \sqrt{\Delta\chi^2}$

Parameter	Central value NO	Central value IO	Treatment
θ_{12} (°)	0.297	0.297	
θ_{13}(°)	0.215	0.216	
θ_{23}(°)	0.425	0.589	
$\Delta m^2_{21}(\mathrm{eV}^2)$	7.37e-5	7.37e-5	
$\Delta m^2_{31}(\mathrm{eV}^2)$	2.56e-3	-2.54e-3	
δ_{CP}	1.38π	1.31π	

Left empty!

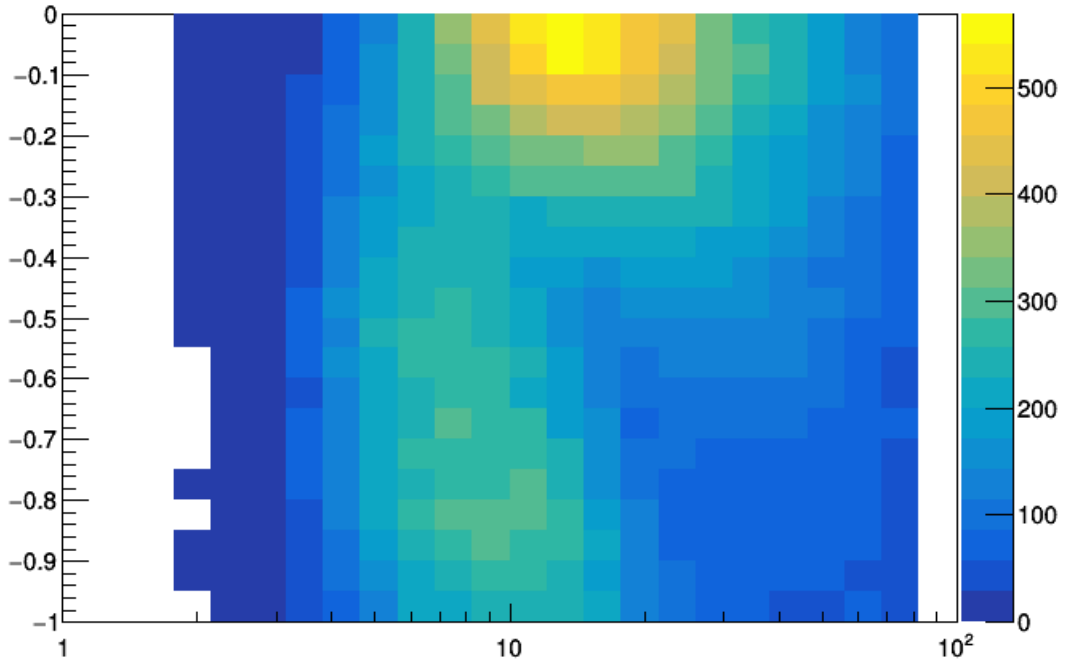
Free to fit, fixed or constrained by priors



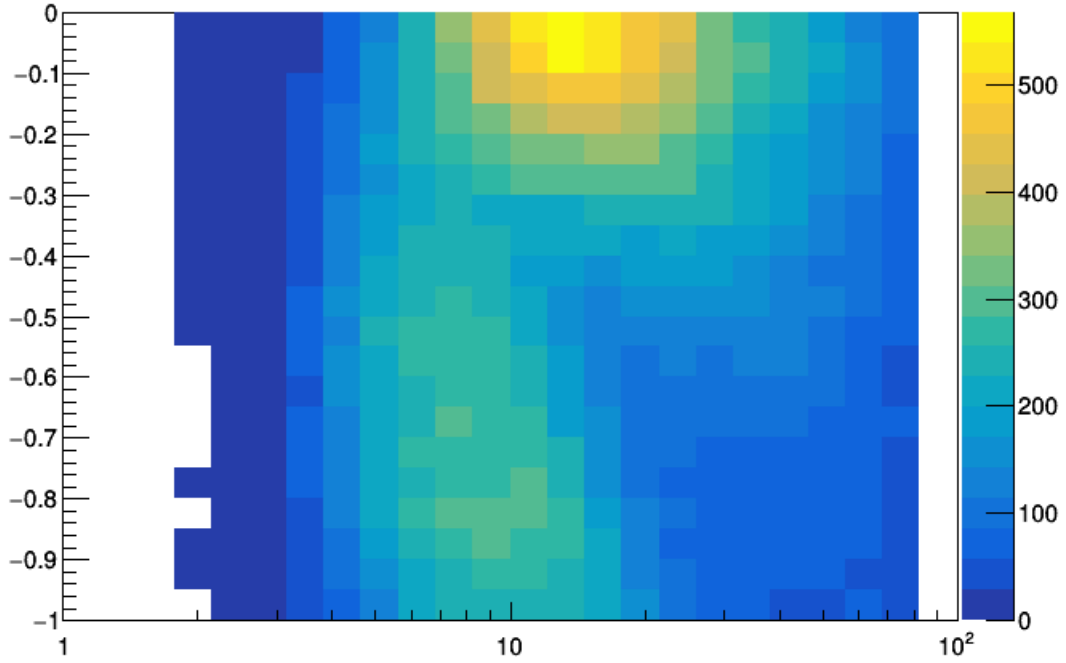
https://root.cern.ch/doc/master/rf202__extendedmlfit_8C.html

ORCA115 detector output 3/3
NO vs. IO

Normal ordering (tracks)



Inverted ordering (tracks)



What is the difference???

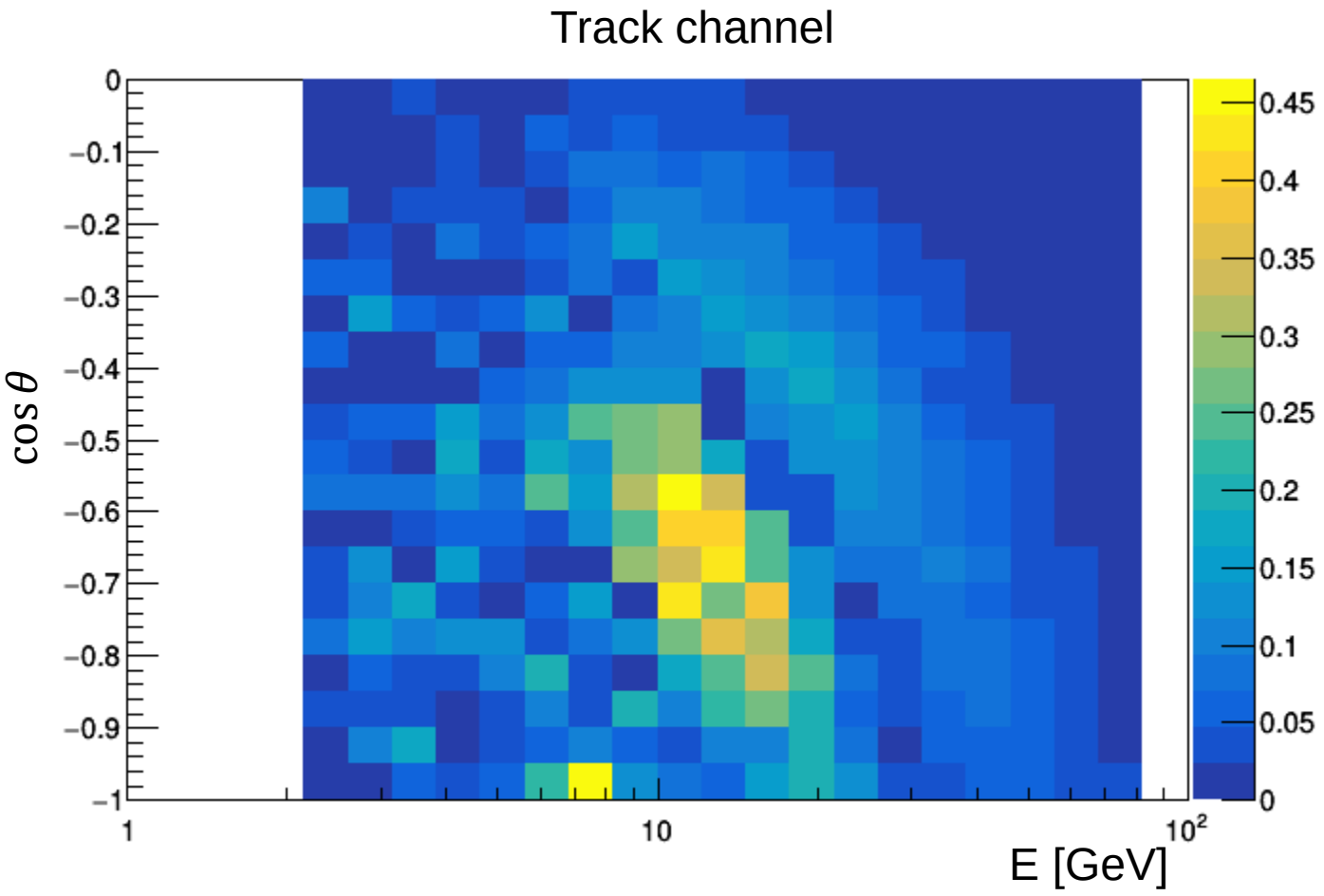
Neutrino Mass Ordering: Asymmetry

- Asymmetry per bin i:

$$A_i = \frac{N_{NO}^i - N_{IO}^i}{\sqrt{N_{NO}^i}}$$

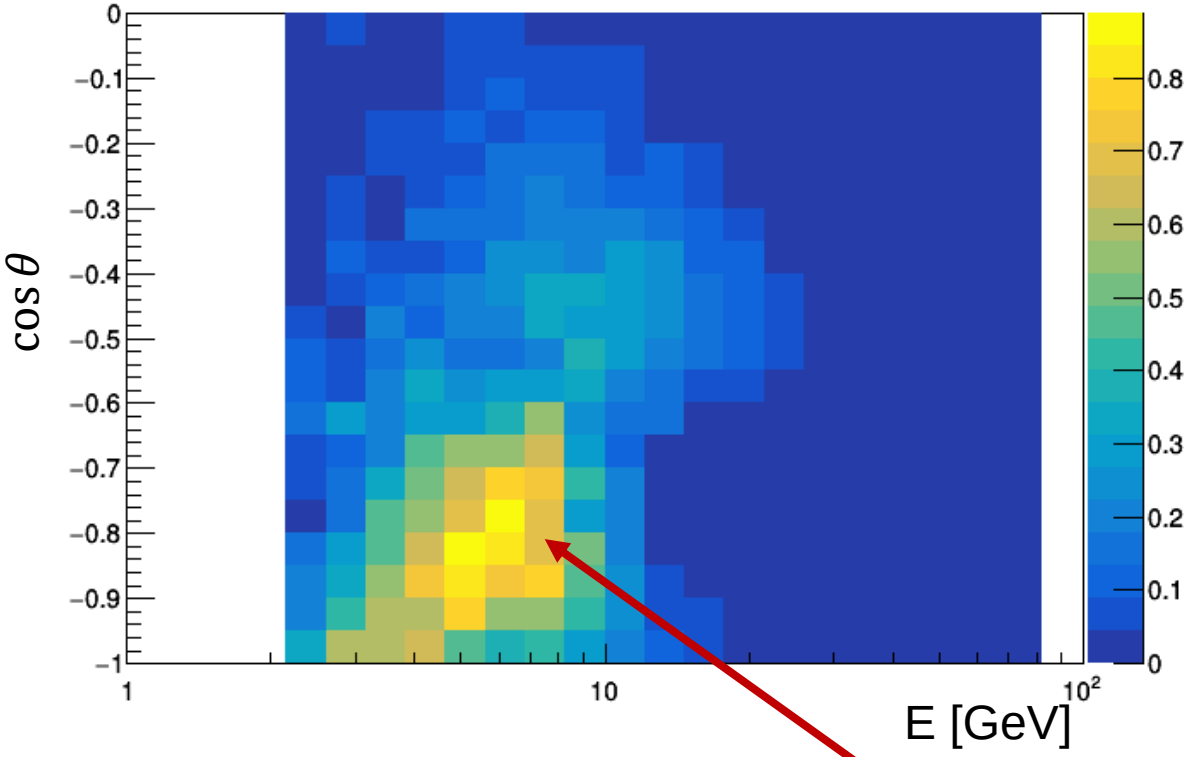
- Proxy for the χ^2 value:

$$\chi_i^2 = \frac{(O_i - M_i)^2}{M_i}$$

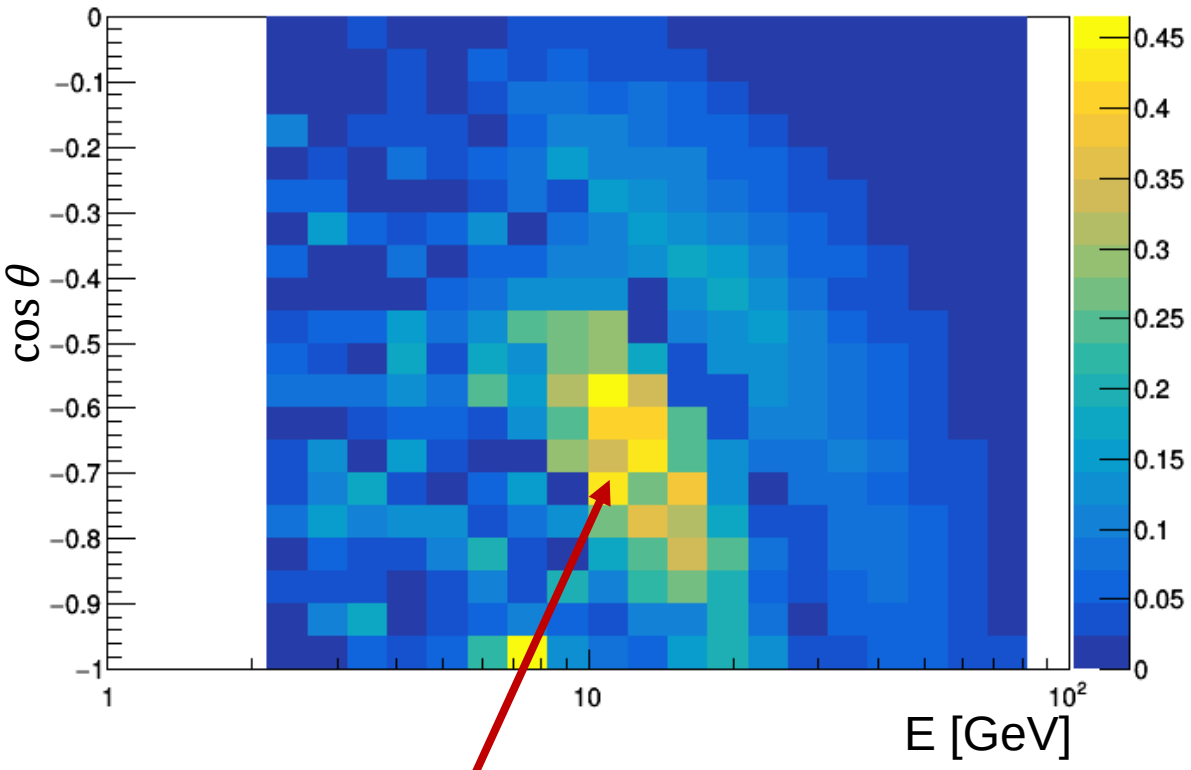


Asymmetry:
track and shower signal regions

Shower channel



Track channel



Most χ^2 comes from this region!
Low energy…

Systematics

- Reconstructed energy (over-/underestimation)
- Reconstructed incoming angle
- Reconstructed particle type (PID)
- Flux (how many ν per flavor) → Flux ratios
- Cross sections
- Earth model uncertainties (effects on oscillations)
- Detector effects (PMTs, etc)

Backup