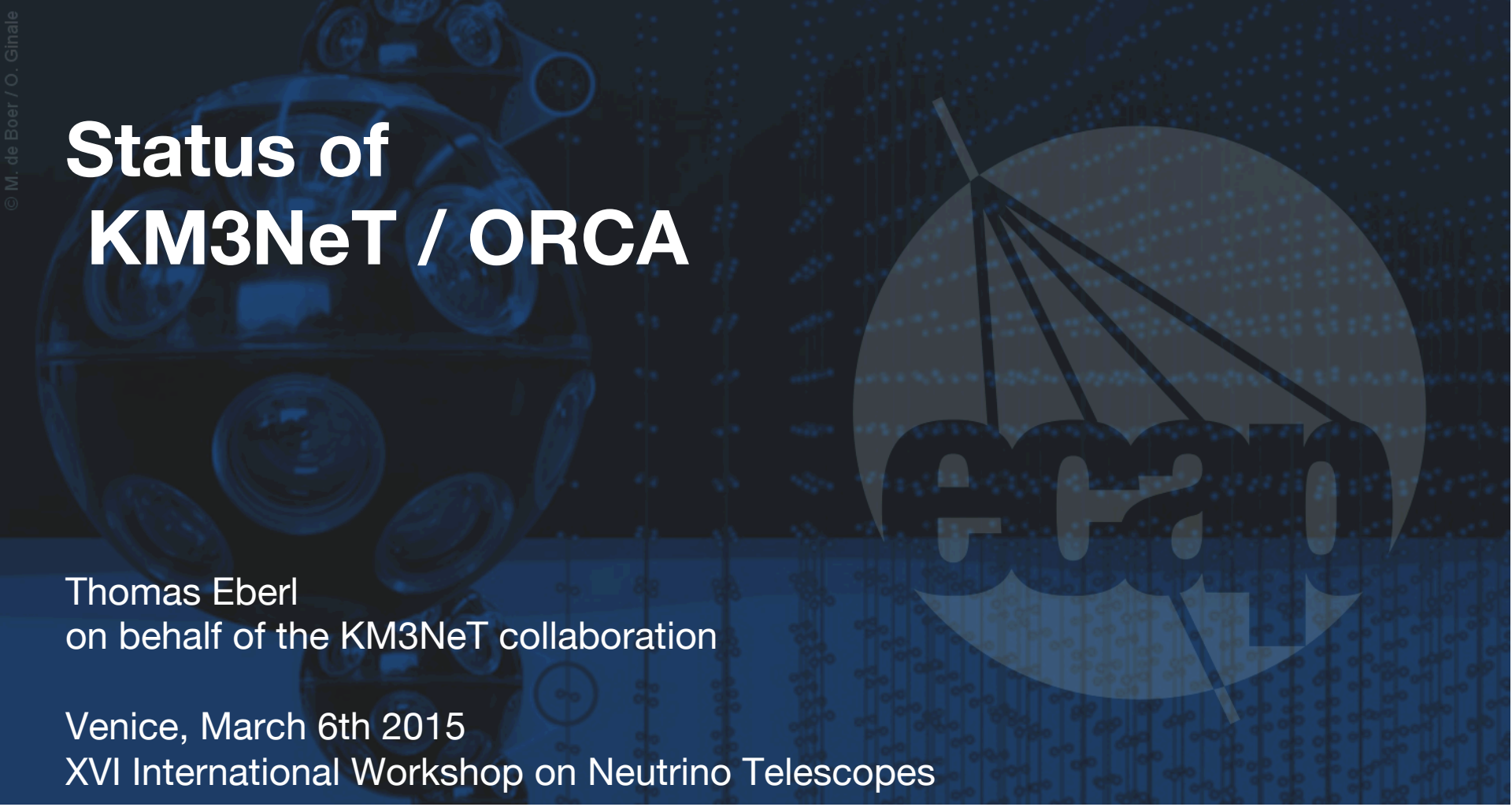


Status of KM3NeT / ORCA

Thomas Eberl
on behalf of the KM3NeT collaboration

Venice, March 6th 2015
XVI International Workshop on Neutrino Telescopes

HELMHOLTZ ASSOCIATION
Alliance for Astroparticle Physics

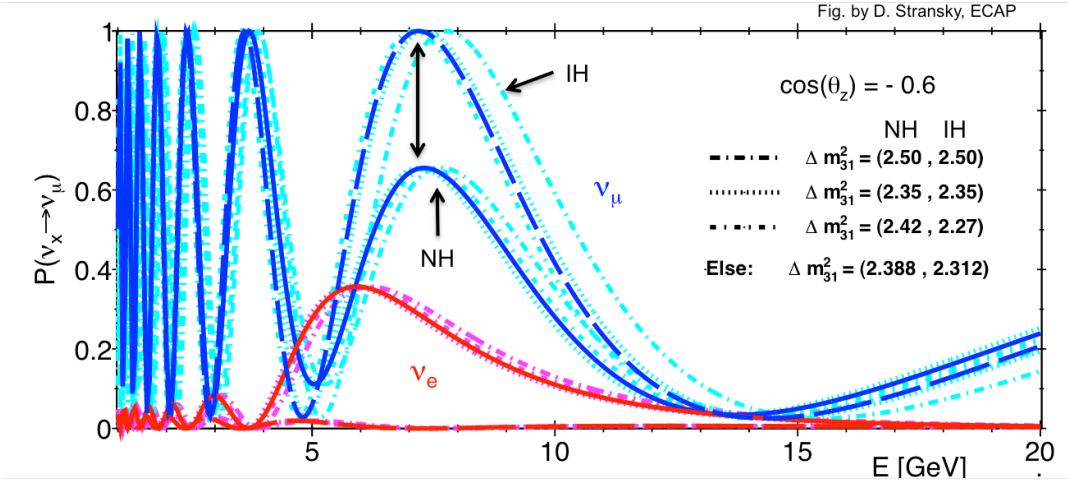
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
NATURWISSENSCHAFTLICHE FAKULTÄT

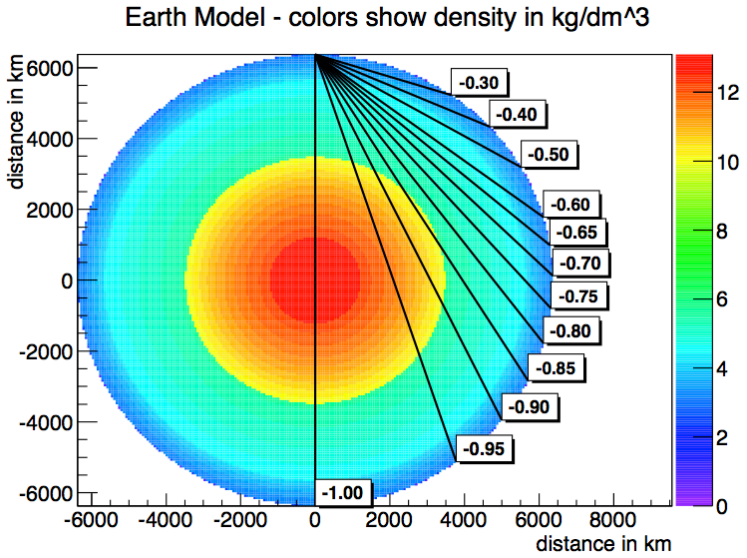
Neutrino mass hierarchy determination

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- 3-flavour oscillation resonance in Earth for E_ν ~ 3 – 10 GeV usable to determine sign of ΔM^2.



- Unequal fluxes and cross-sections of atmospheric neutrinos and anti-neutrinos result in percent-level differences in count rates.

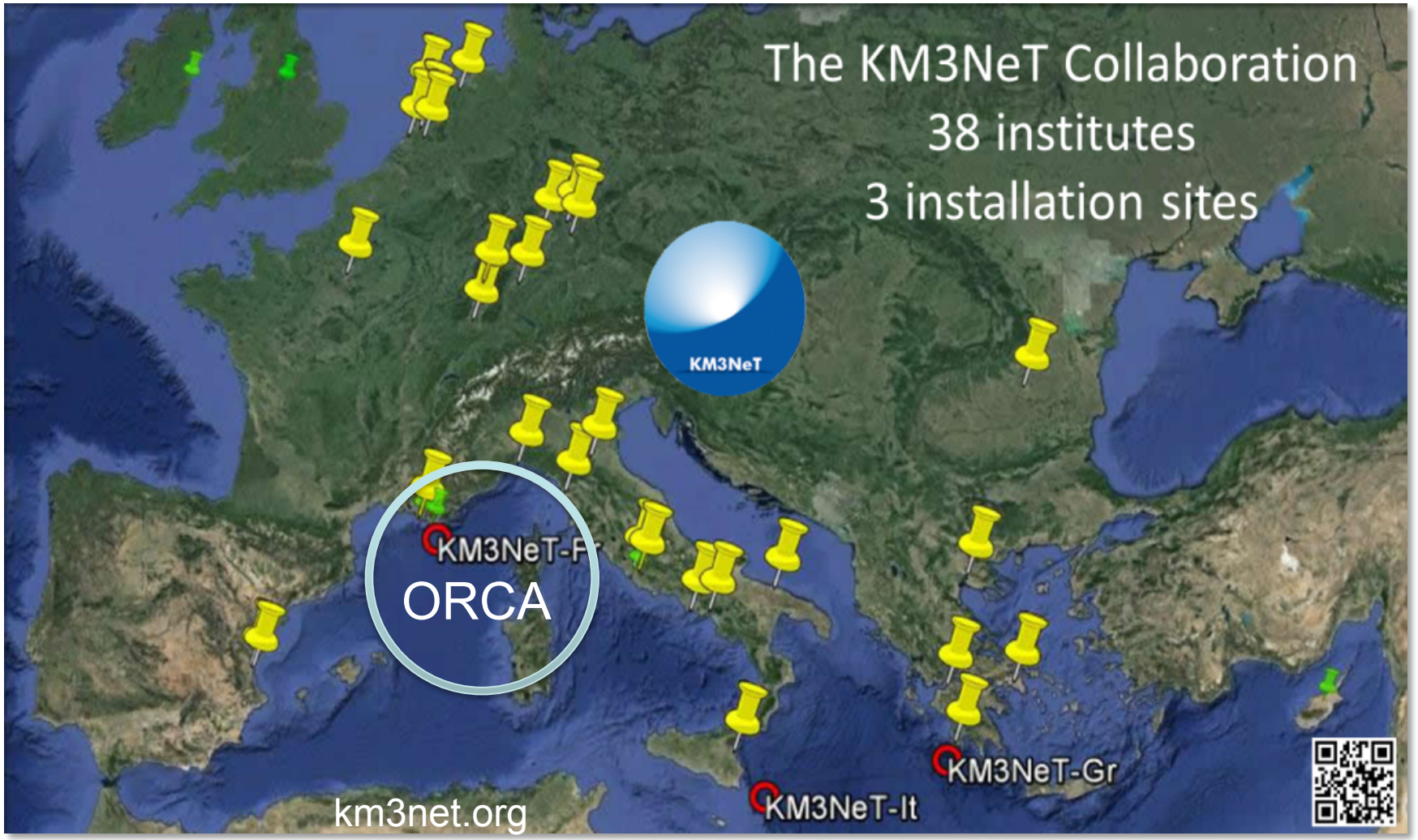


- Measure zenith angle and energy of upgoing atmospheric GeV-scale neutrinos precisely, identify and count muon and electron channel events.

- Improve precision on measurement of ΔM^2 and θ_{atm} .

KM3NeT-Fr: ORCA site

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



KM3NeT / ORCA location

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Phase-1 milestones reached in 12 / 2014

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

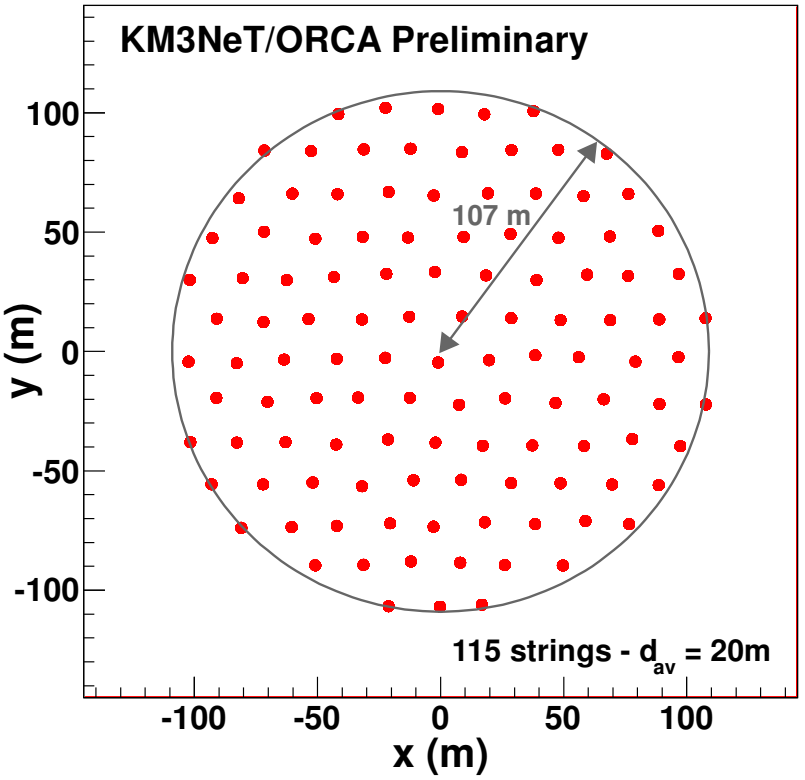
- Cable deployed ✔

- First ARCA-style string integrated at Nikhef in Amsterdam ✔
- Moved to Marseille and validated at CPPM ✔
- Ready for deployment in spring 2015!

Detector design

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

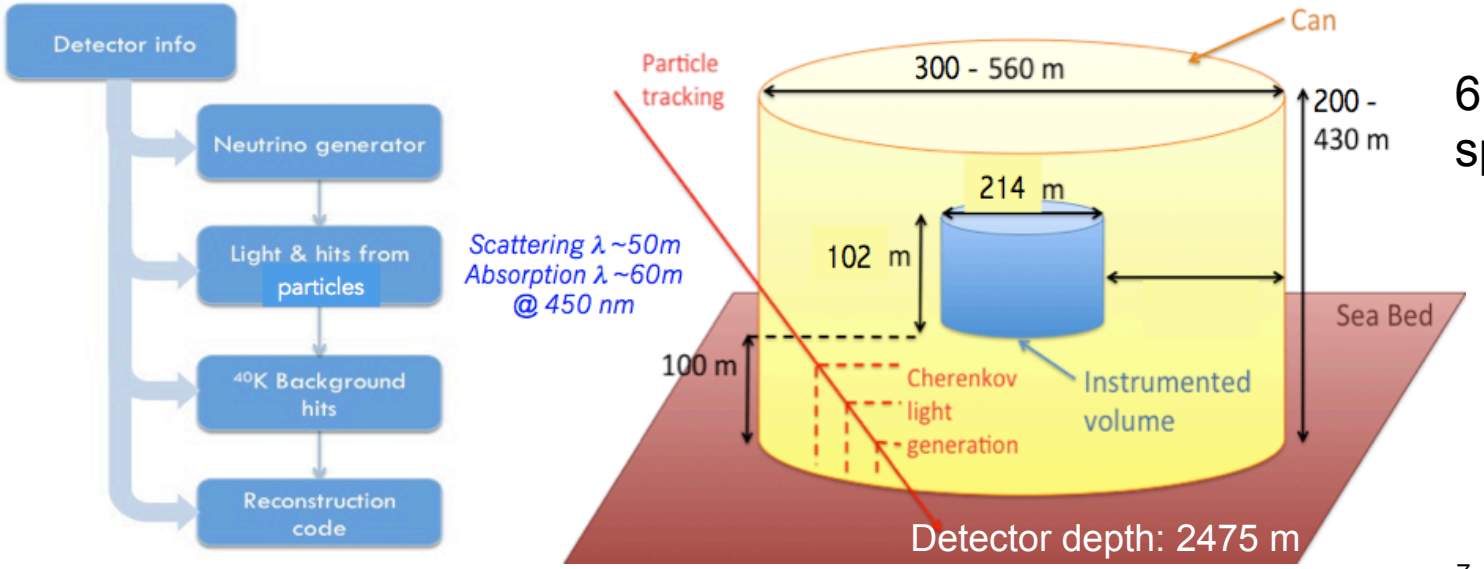
- Resonance signature below 20 GeV requires dense detector
- Use technology identical to KM3NeT/ARCA
- ORCA = 1 KM3NeT building block
  - 115 strings
  - 2070 DOMs, 18 per string
  - Cost estimate: 40 M€
- Optimization parameters under study:
  - String distance: ~20 m
  - DOM vertical spacing: 6 - 12 m
  - 100 m radius, 100 - 200 m height, i.e. ~ 1 - 2% volume of KM3NeT/ARCA building block with same overall photocathode area!



Monte-Carlo simulations

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Based on GENIE and GEANT4
- „Bartol“ atmospheric neutrino flux model, energy range: 1 – 30 GeV
- MUPAGE atmospheric muon generator
  Comp. Phys. Comm. 179 (2008) 12:915
- Optical background: 5 – 10 kHz per PMT, 500 Hz 2-fold coincidence rate
  7-8kHz from PPM-DOM, Eur. Phys. J. C (2014) 74:3056

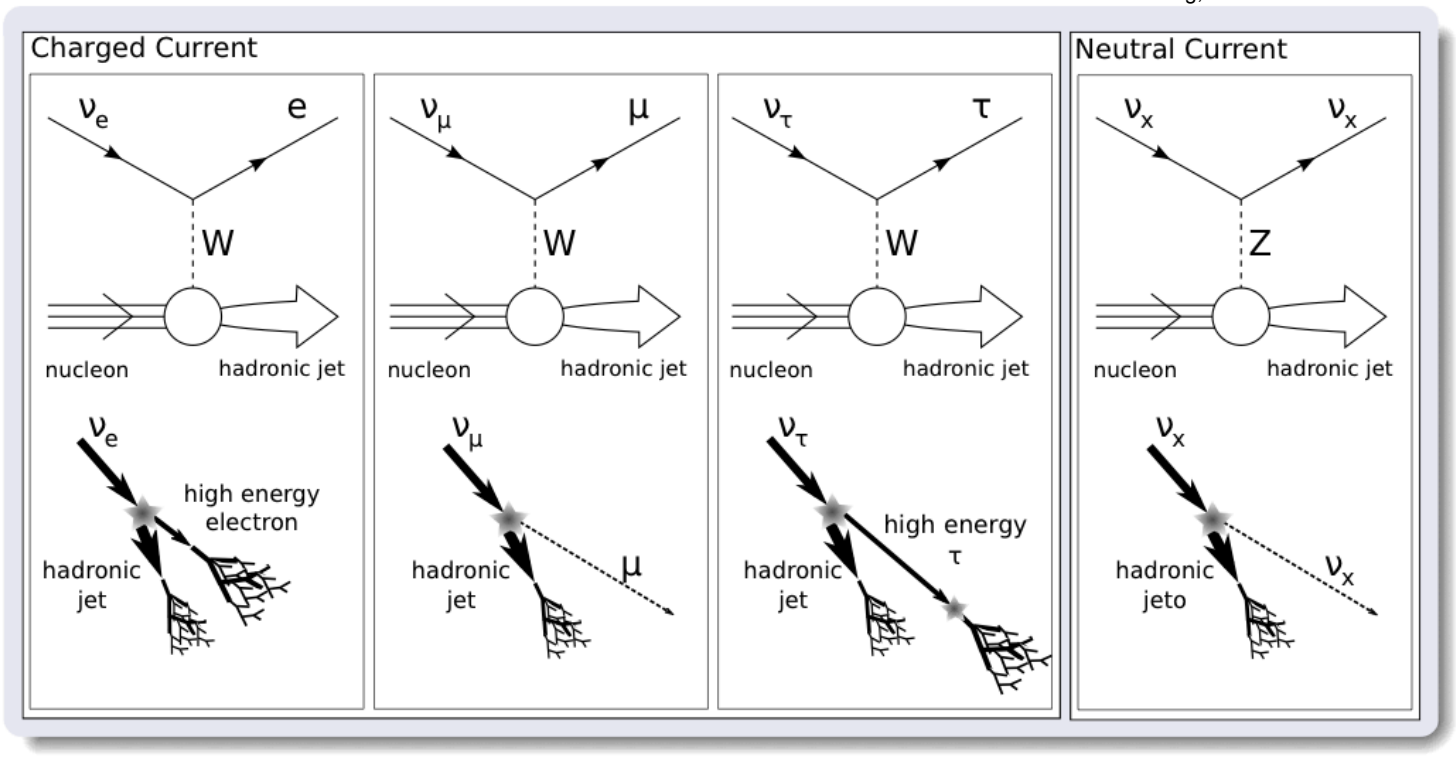


6 m spacing!

Event classes

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

credit: J. Tiffenberg, NUSKY11



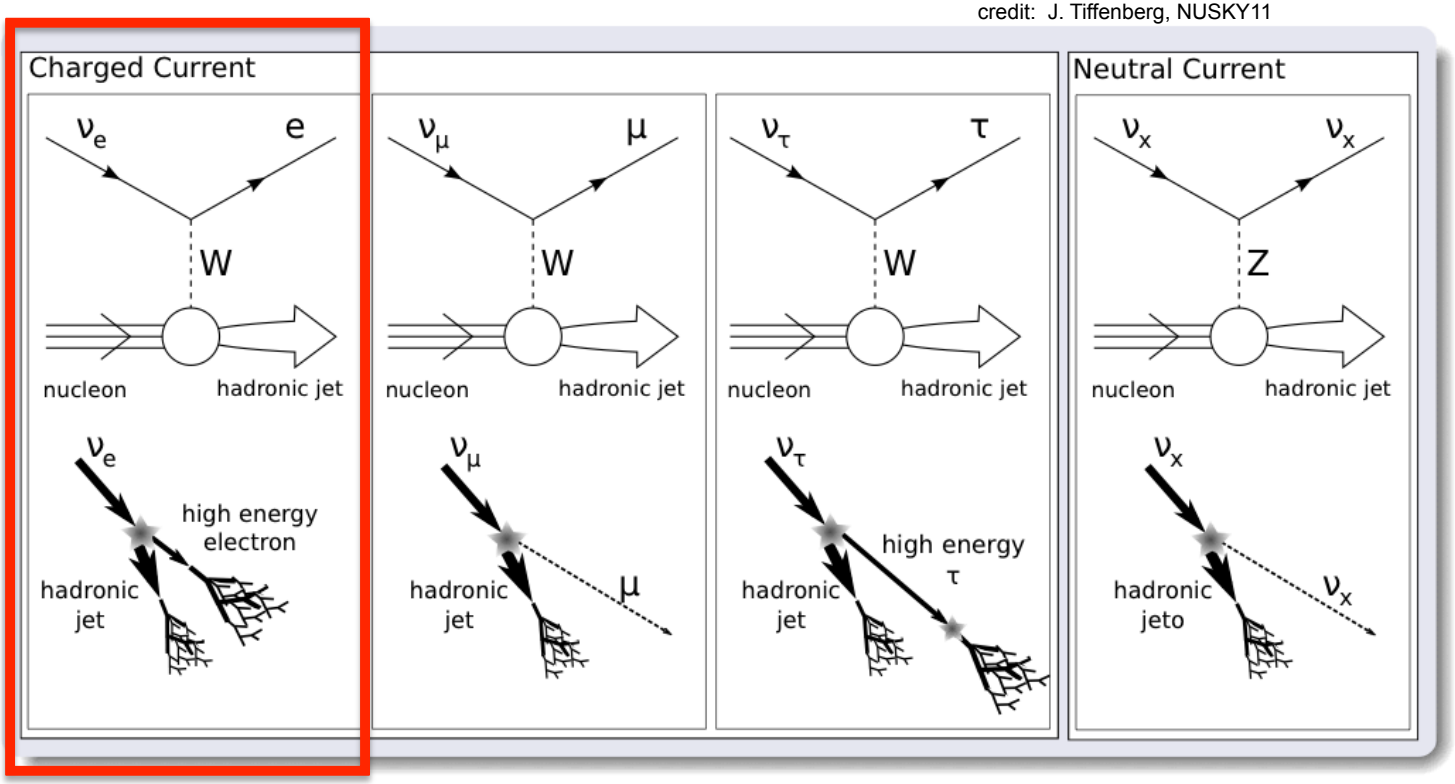
shower-like track-like shower-like shower-like

(17% track-like, τ → μ)

Event classes

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

credit: J. Tiffenberg, NUSKY11

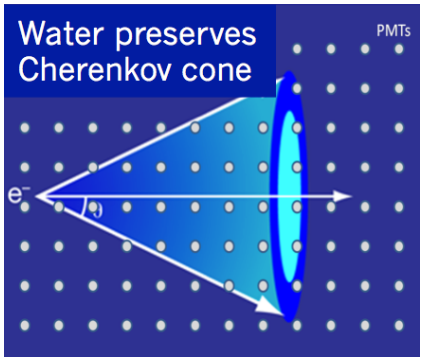


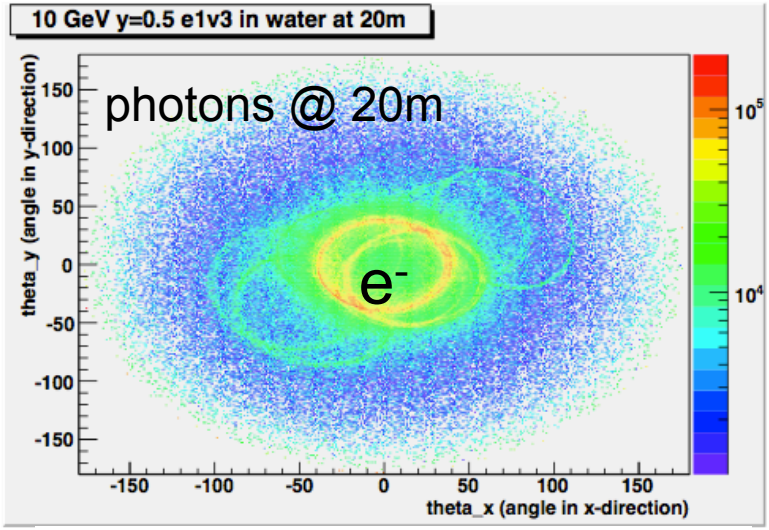
shower-like track-like shower-like shower-like

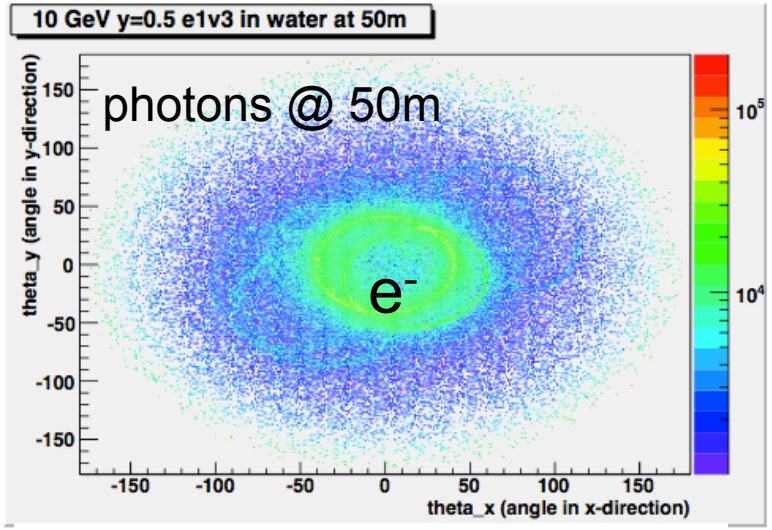
(17% track-like, τ → μ)

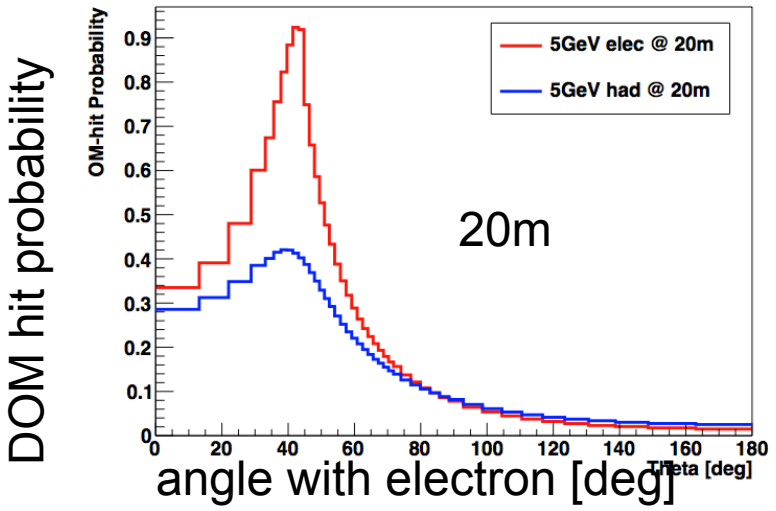
Electron neutrino charged-current event

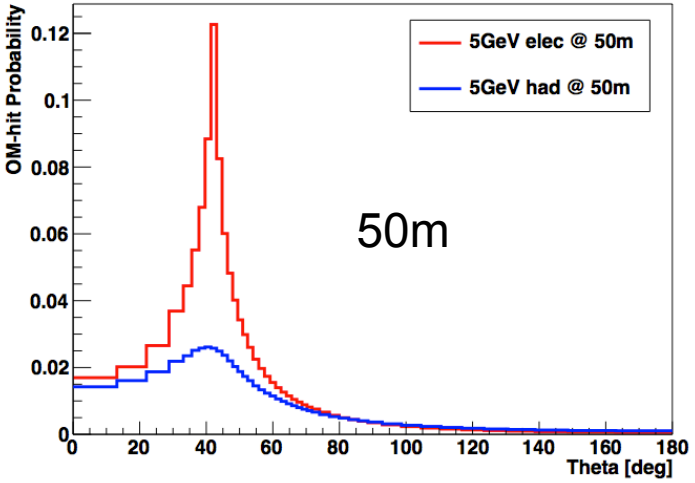
Simulated ν_e^{CC} event with E_ν = 10 GeV and y=0.5











Shower reconstruction algorithm

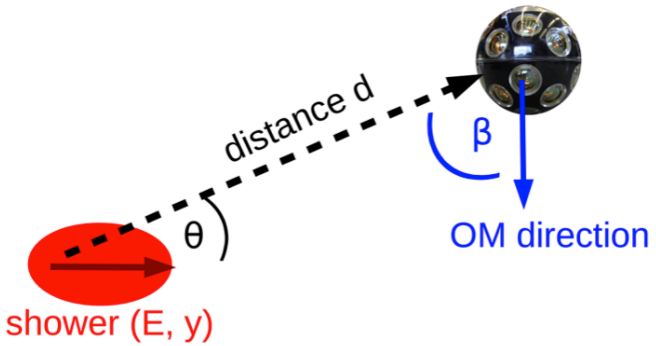
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

1. Vertex reconstruction

    - Iterative maximum likelihood fit using time residuals

2. Energy and direction reconstruction

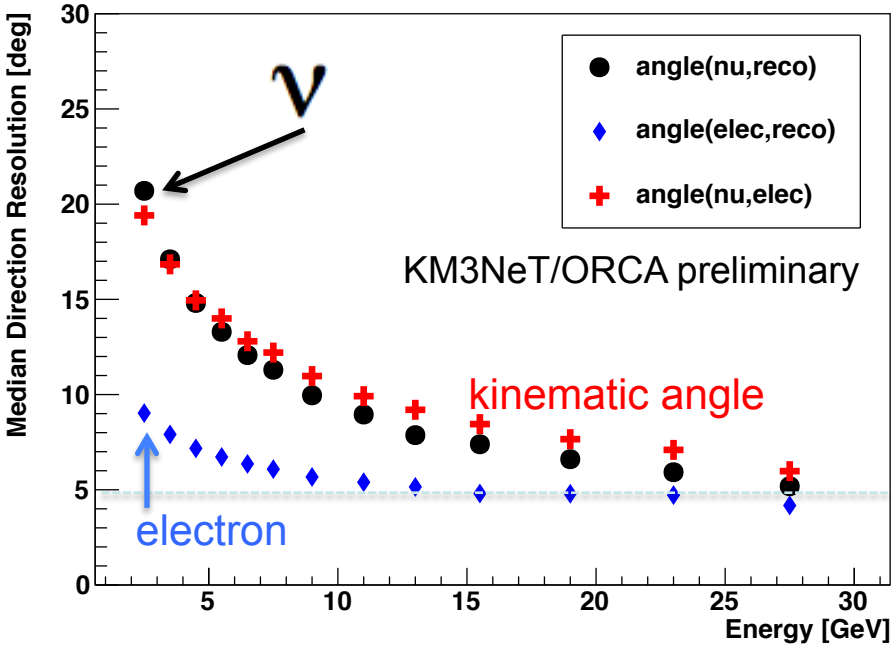
    - Maximum likelihood fit using probability tables from MC for neutrino energy, reaction inelasticity, emission angle, DOM orientation and distance from vertex

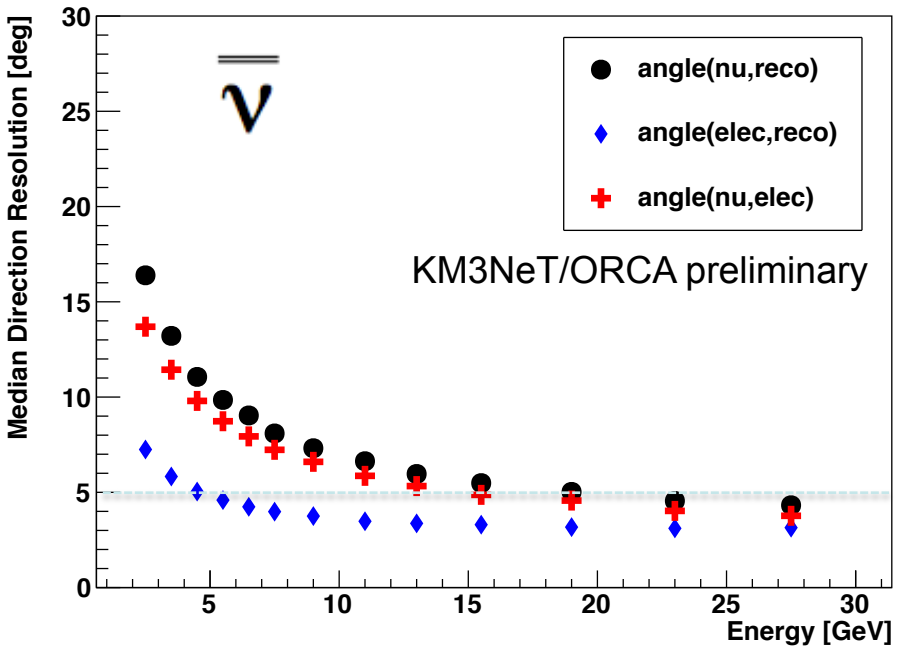


ν_e^{CC} : direction resolution

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

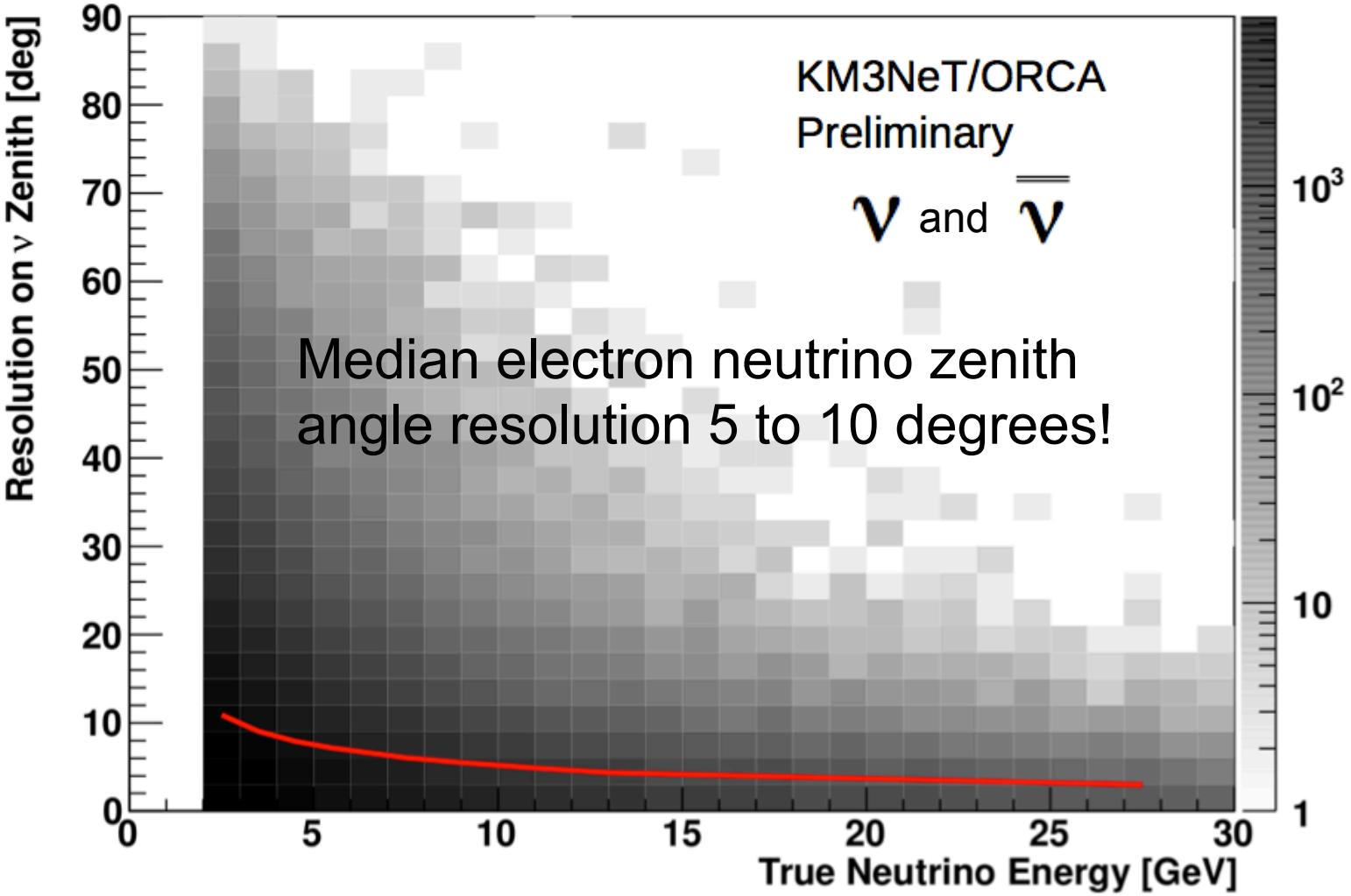
- Reconstruction finds the electron direction in electron (anti-)neutrino charged-current events
- Anti-neutrino events have lower average inelasticity → better angular resolution





ν_e^{CC} : zenith angle resolution

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

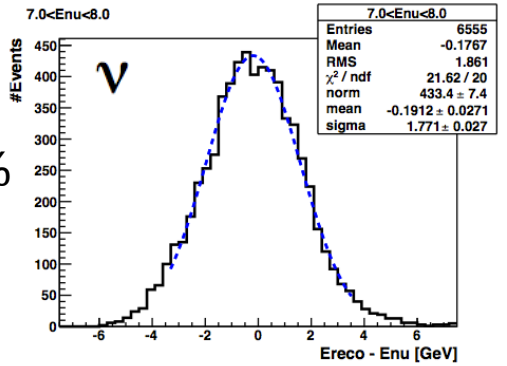


ν_e^{CC} : energy resolution

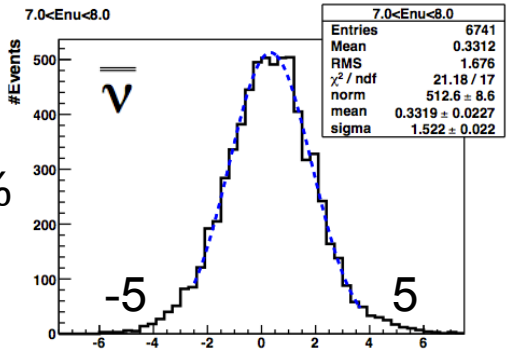
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

$7 < E_{nu} < 8$ GeV

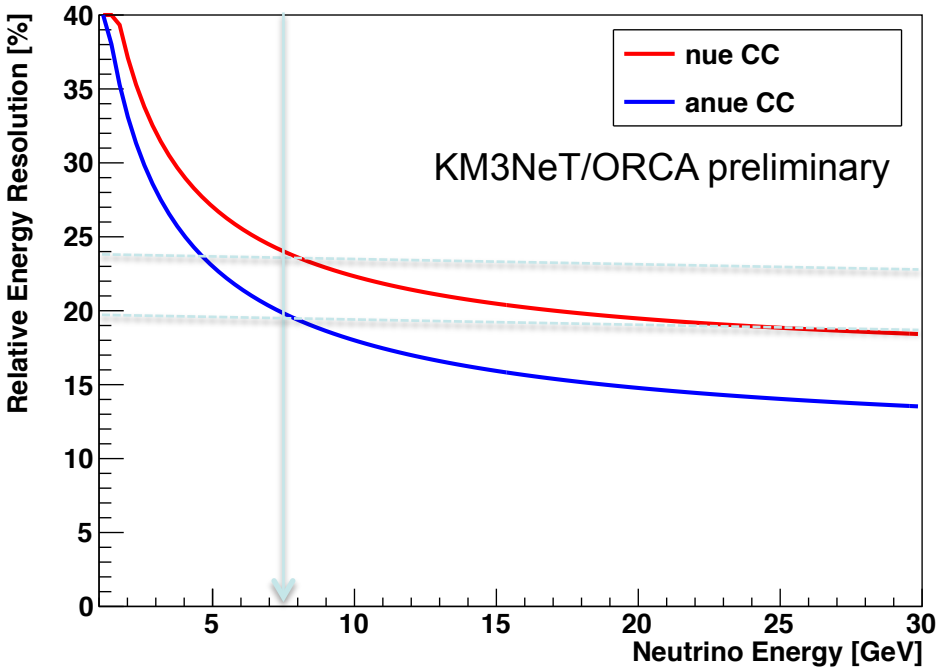
$\sigma/E \sim 24\%$



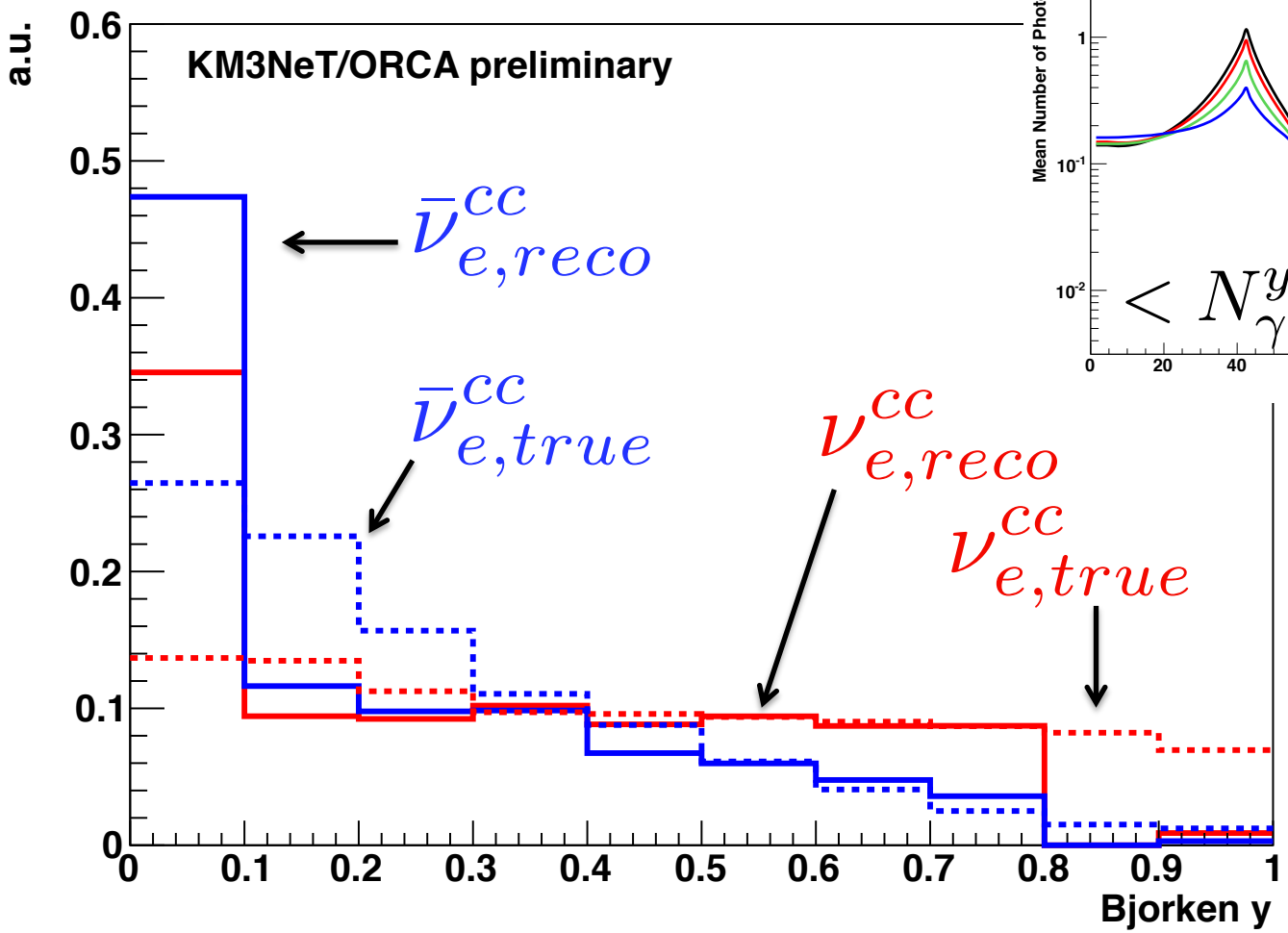
$\sigma/E \sim 20\%$

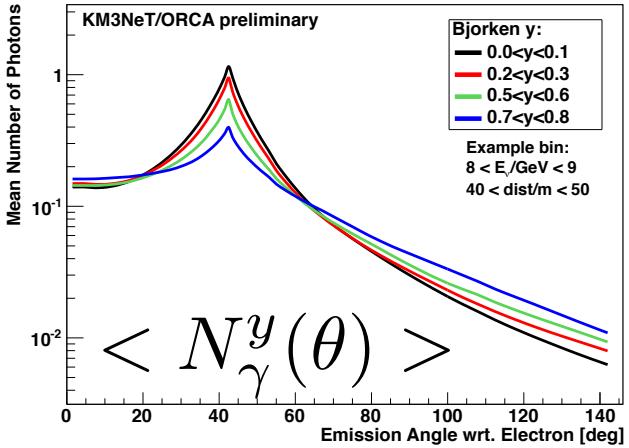


$E_{reco} - E_{nu}$ [GeV]



ν_e^{CC} : sensitivity to reaction inelasticity

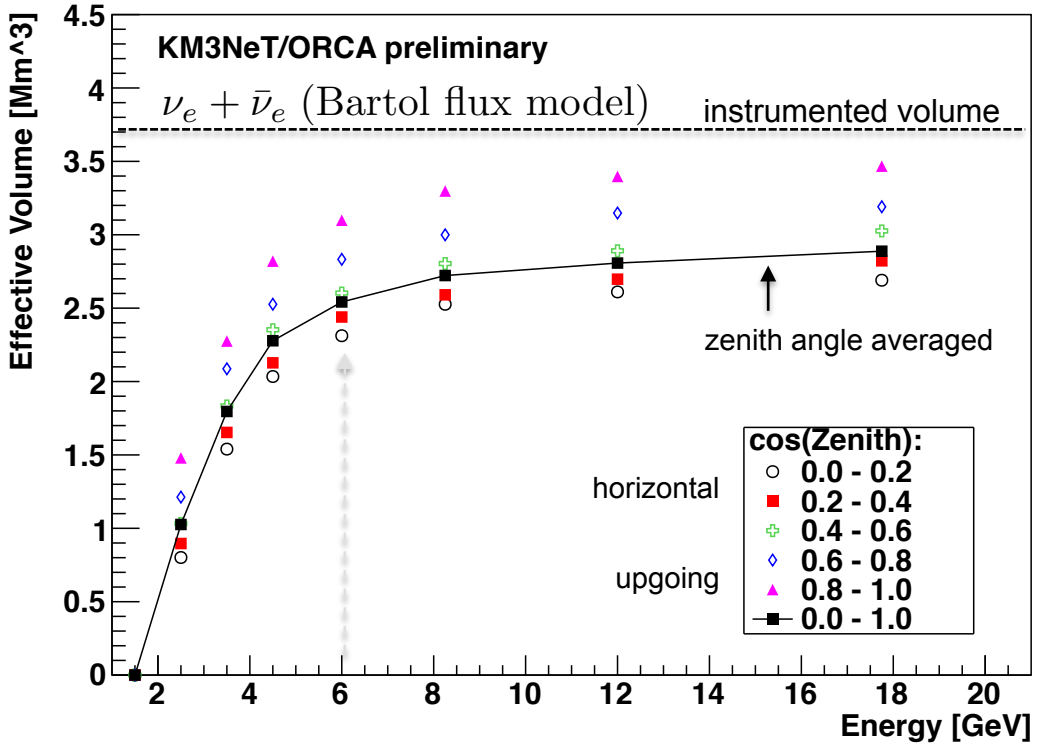




Not yet used in sensitivity study.

ν_e^{CC} : effective volume

- instrumented volume: ~3.7M m^3
- plateau for Bartol flux: ~2.8M m^3
- 90% of plateau reached at E = 6 GeV

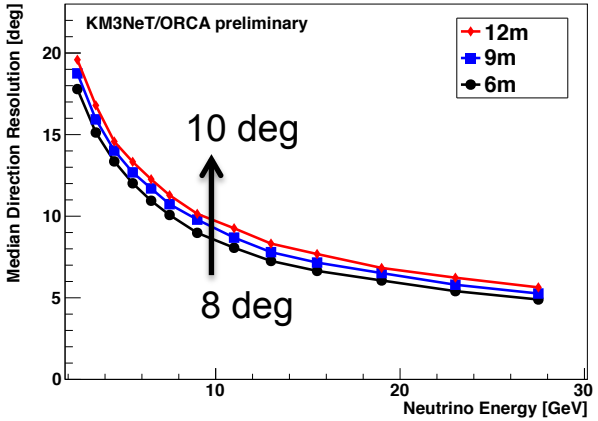


ν_e^{CC} : towards detector layout optimization

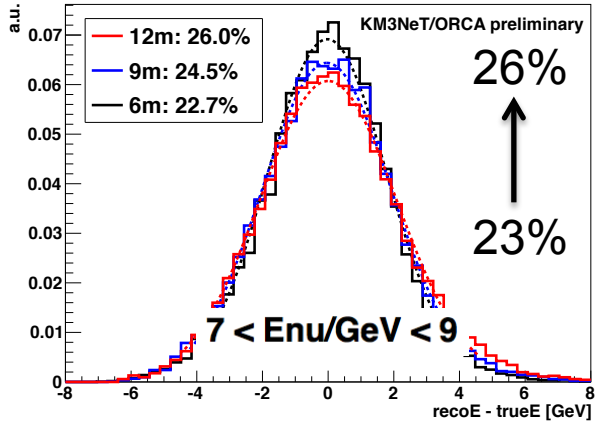
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Vertical DOM spacings: 6m, 9m, 12m
- Average inter-line distance unchanged: 20m

Direction resolution

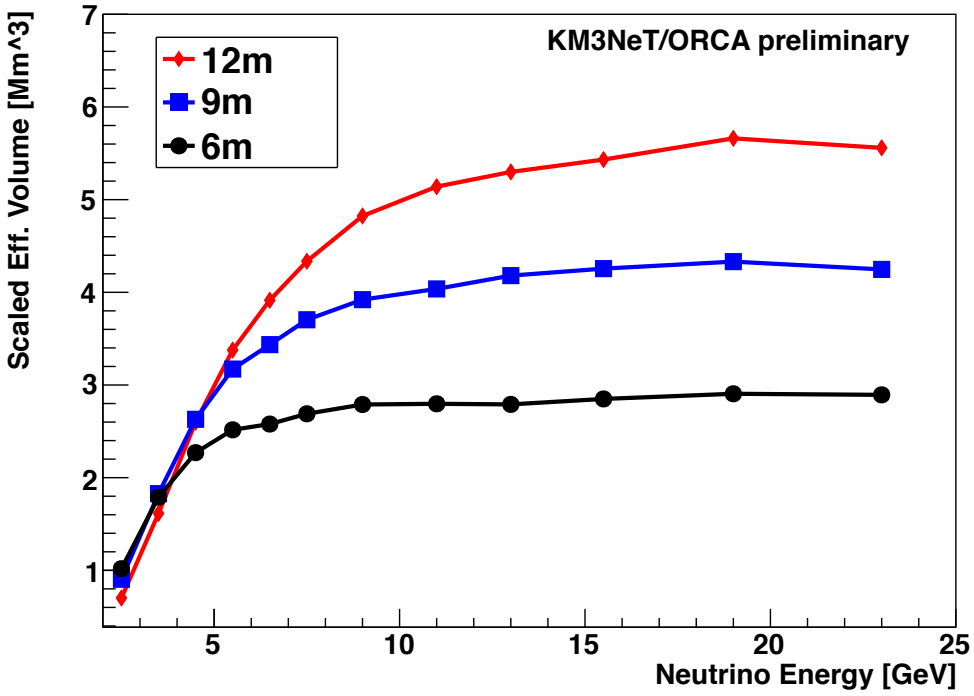


Energy resolution



Scaled effective volume

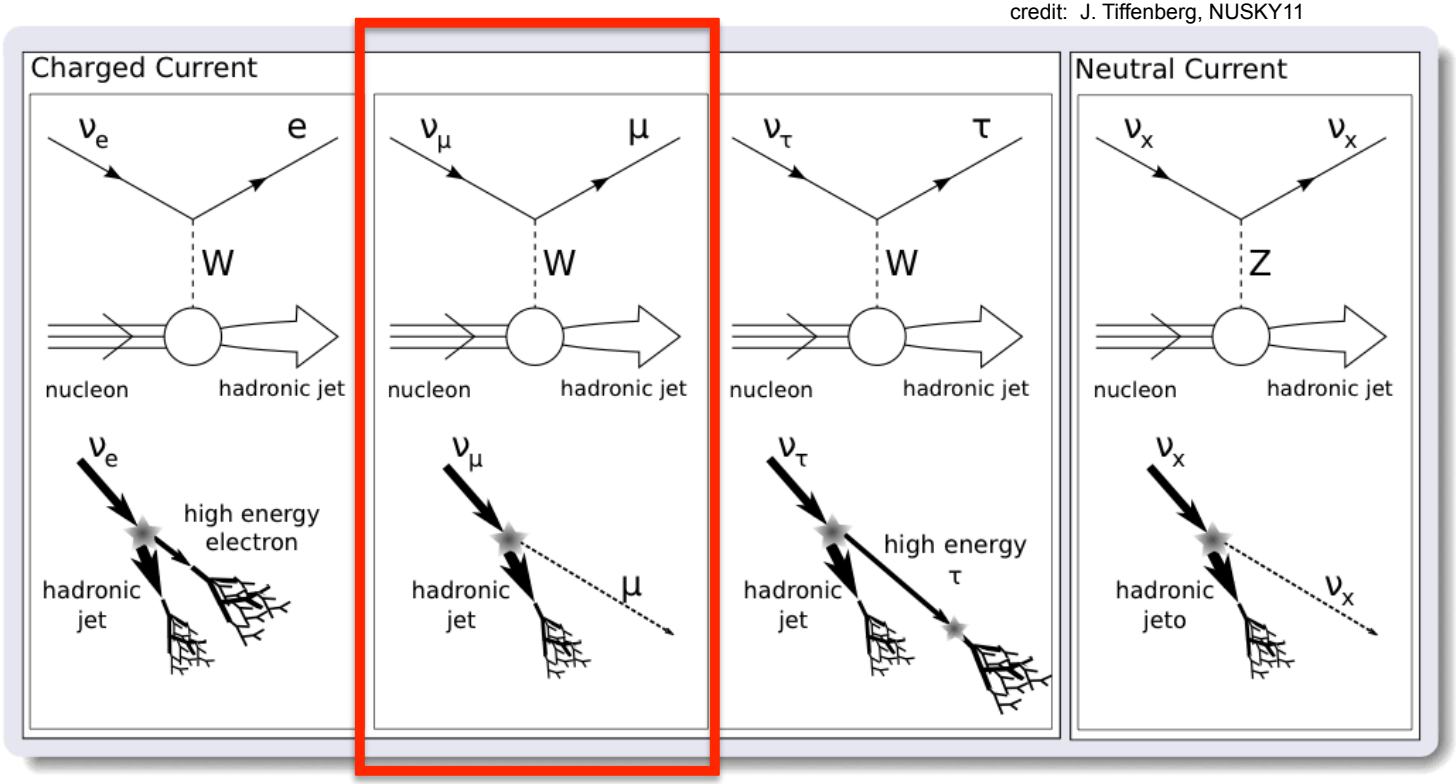
(using 6m simulations and masking, scaling up to same number of DOMs)



Event classes

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

credit: J. Tiffenberg, NUSKY11

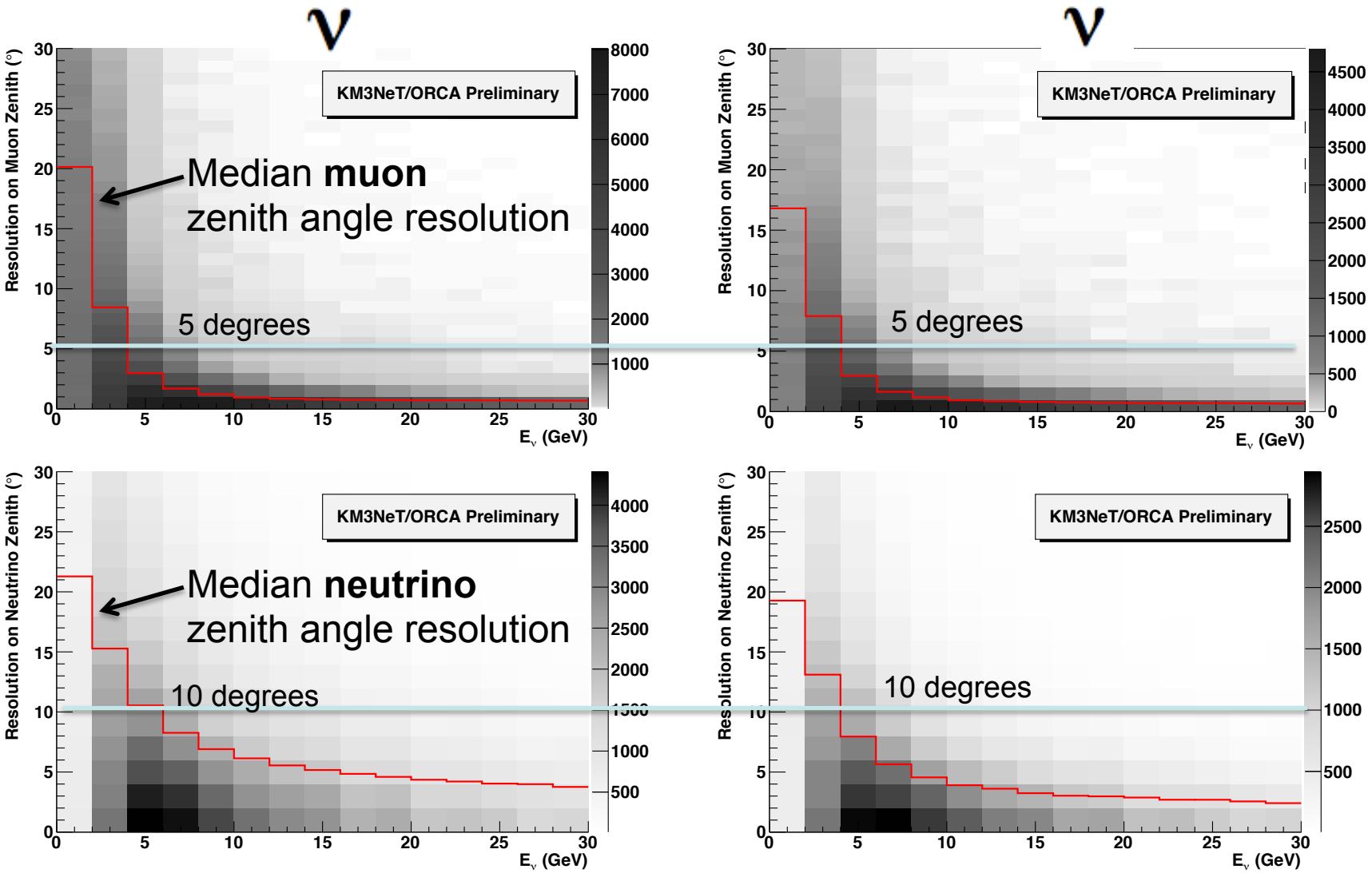


shower-like track-like shower-like shower-like

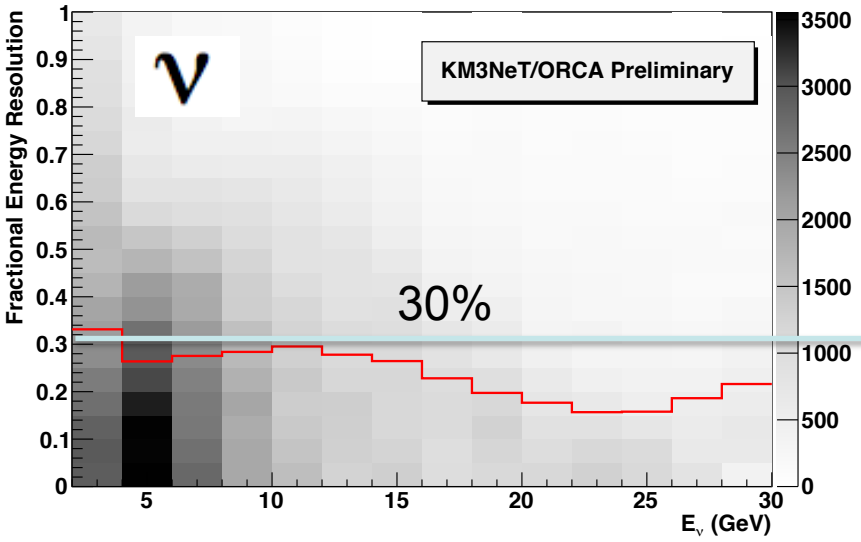
(17% track-like, τ → μ)

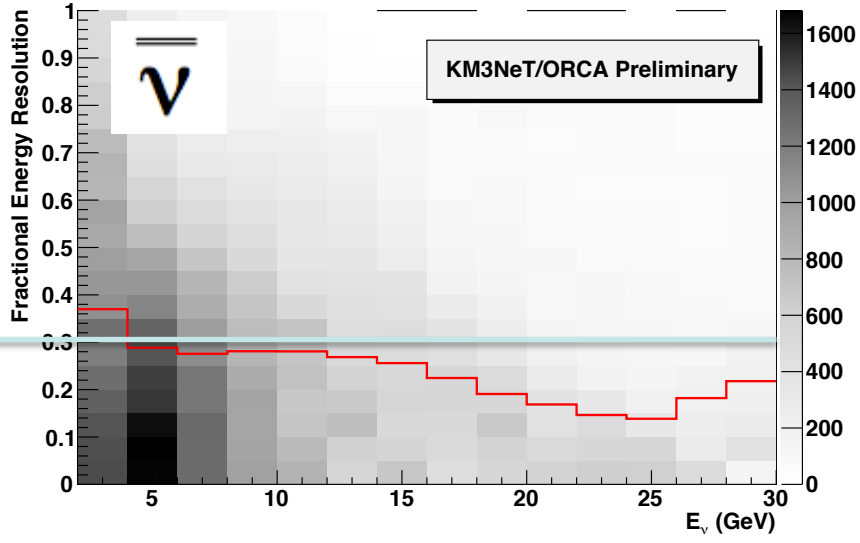
ν_μ^{CC} : zenith angle resolution

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



ν_μ^{CC} : energy resolution



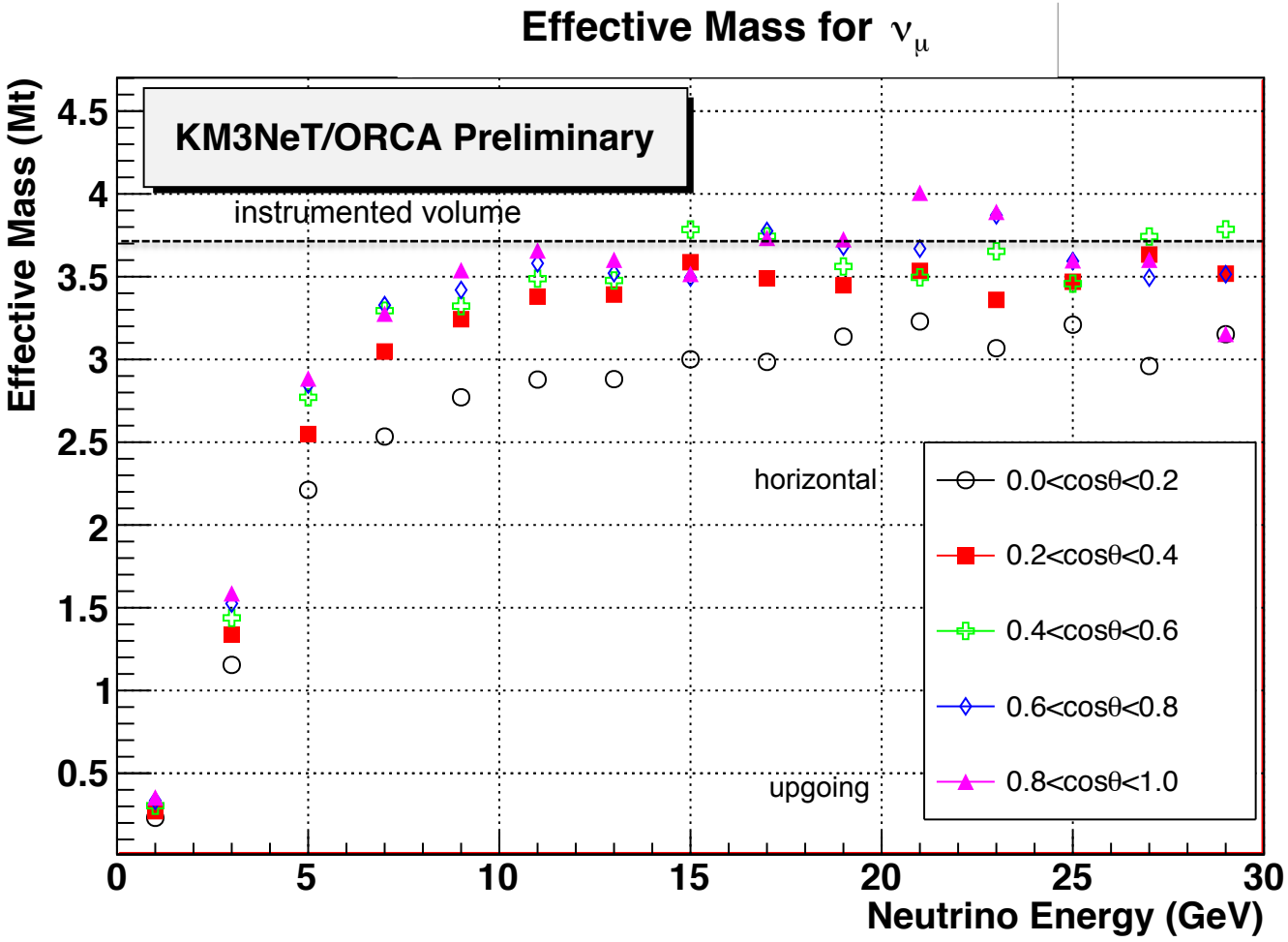


---- Median energy resolution

$$\text{fractional resolution} := \frac{|E_\nu - E_{\text{reco}}|}{E_\nu}$$

ν_μ^{CC}: effective mass

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

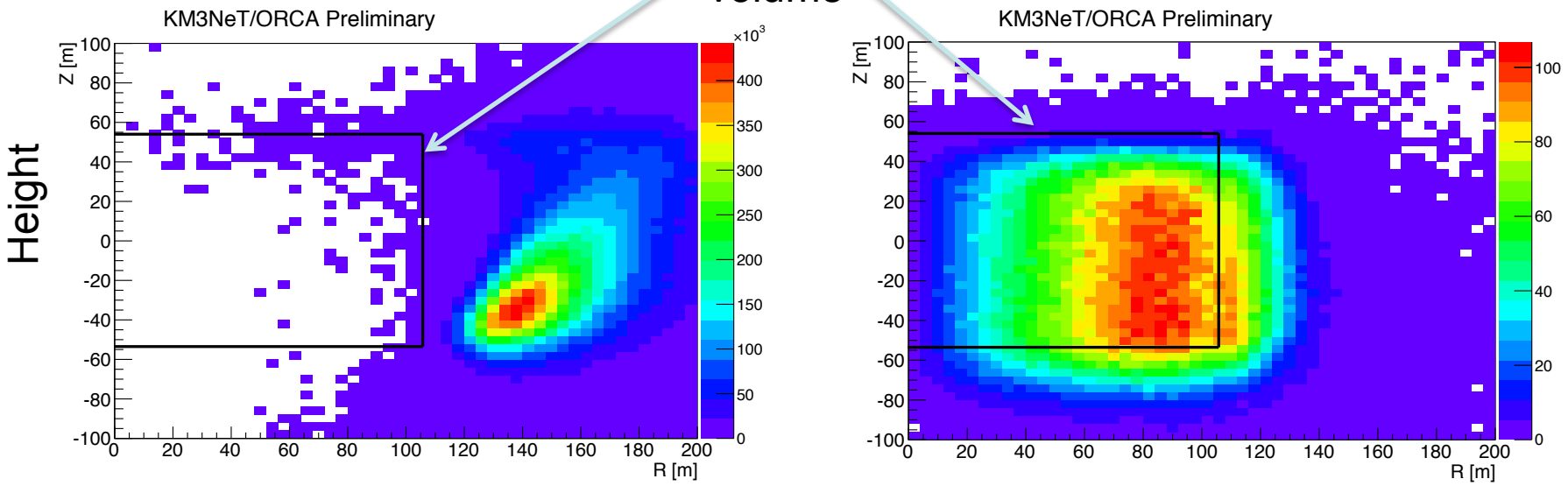


Atmospheric muon rejection

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

... using a cut on the track reconstruction pseudo-vertex of misreconstructed muons

Instrumented volume



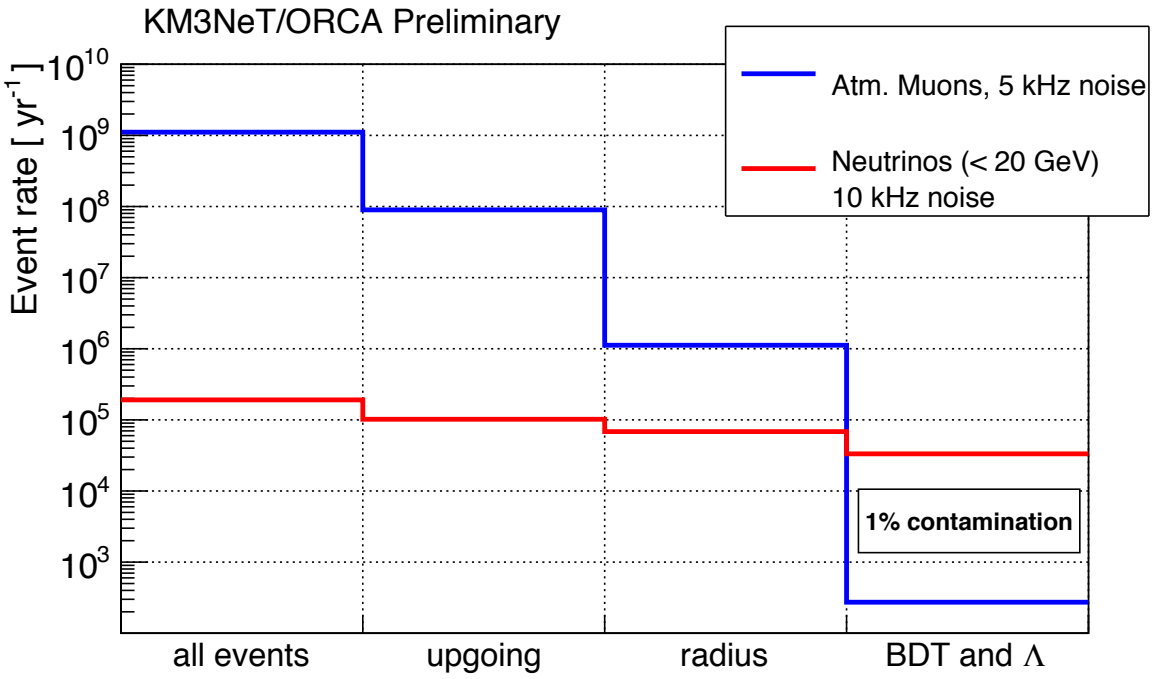
Atmospheric muons misreconstructed as upgoing

Upgoing atmospheric neutrinos $E_\nu < 20$ GeV

Atmospheric muon rejection

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

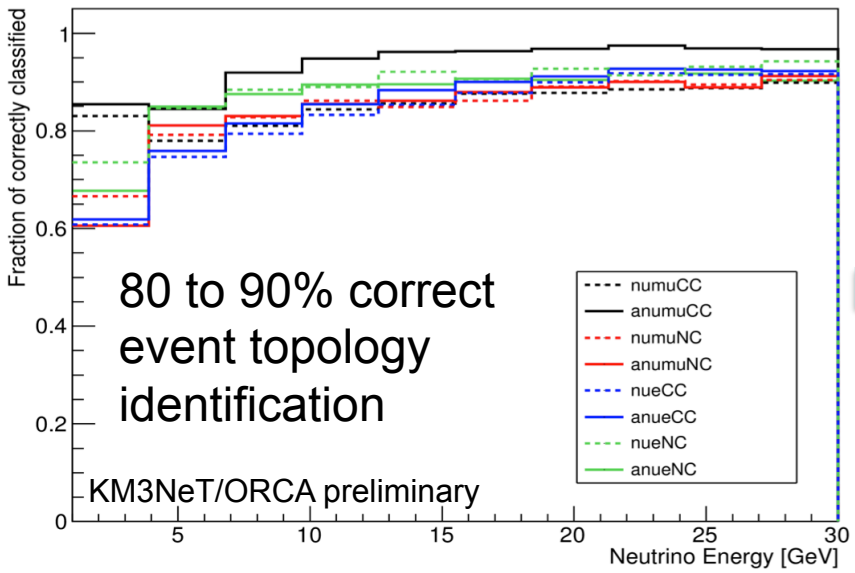
- Boosted Decision Tree (BDT) machine-learning algorithm.
- Trained on pseudovertex position,
  track quality parameters and reconstructed zenith angle.

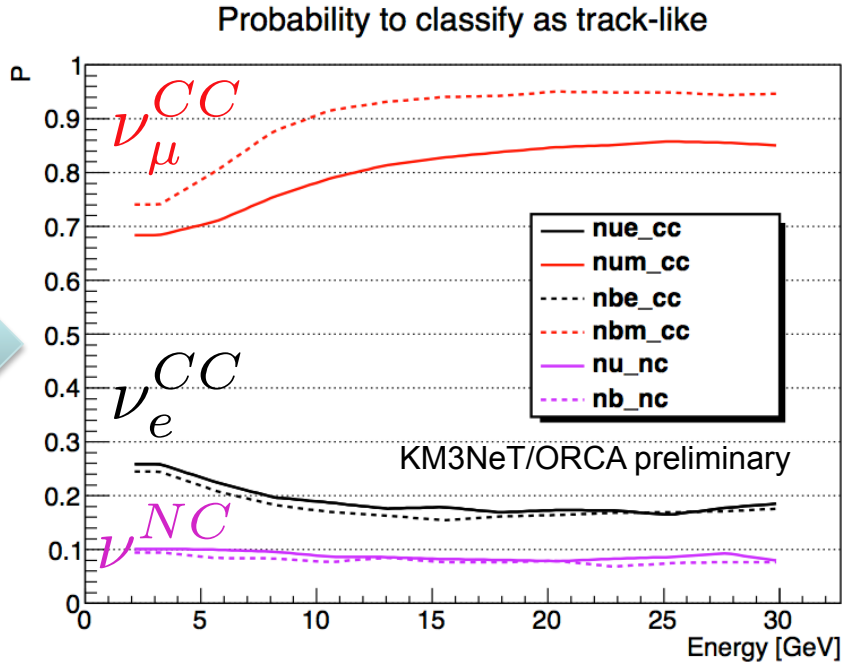


ν_μ^{CC} efficiency: **60%** @ muon contamination: **1%**

Event class identification

- Discrimination between 2 classes of events:
  track-like (ν_μ^{CC}) and shower-like (ν^{NC}, ν_e^{CC})
- Classification using „Random Decision Forest“ machine-learning algorithm.
- Discrimination mainly due to event reconstruction observables.





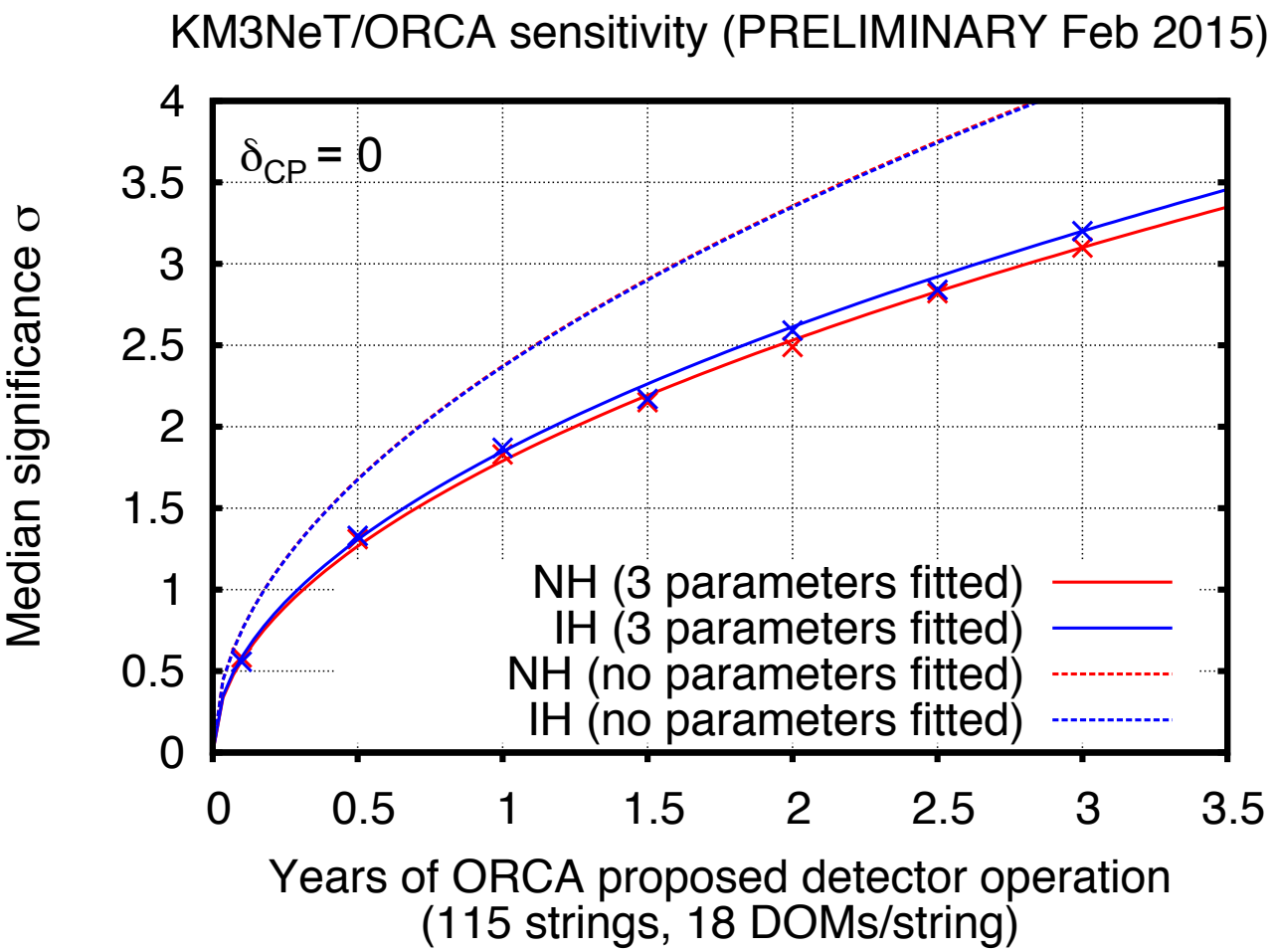
Sensitivity calculation

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

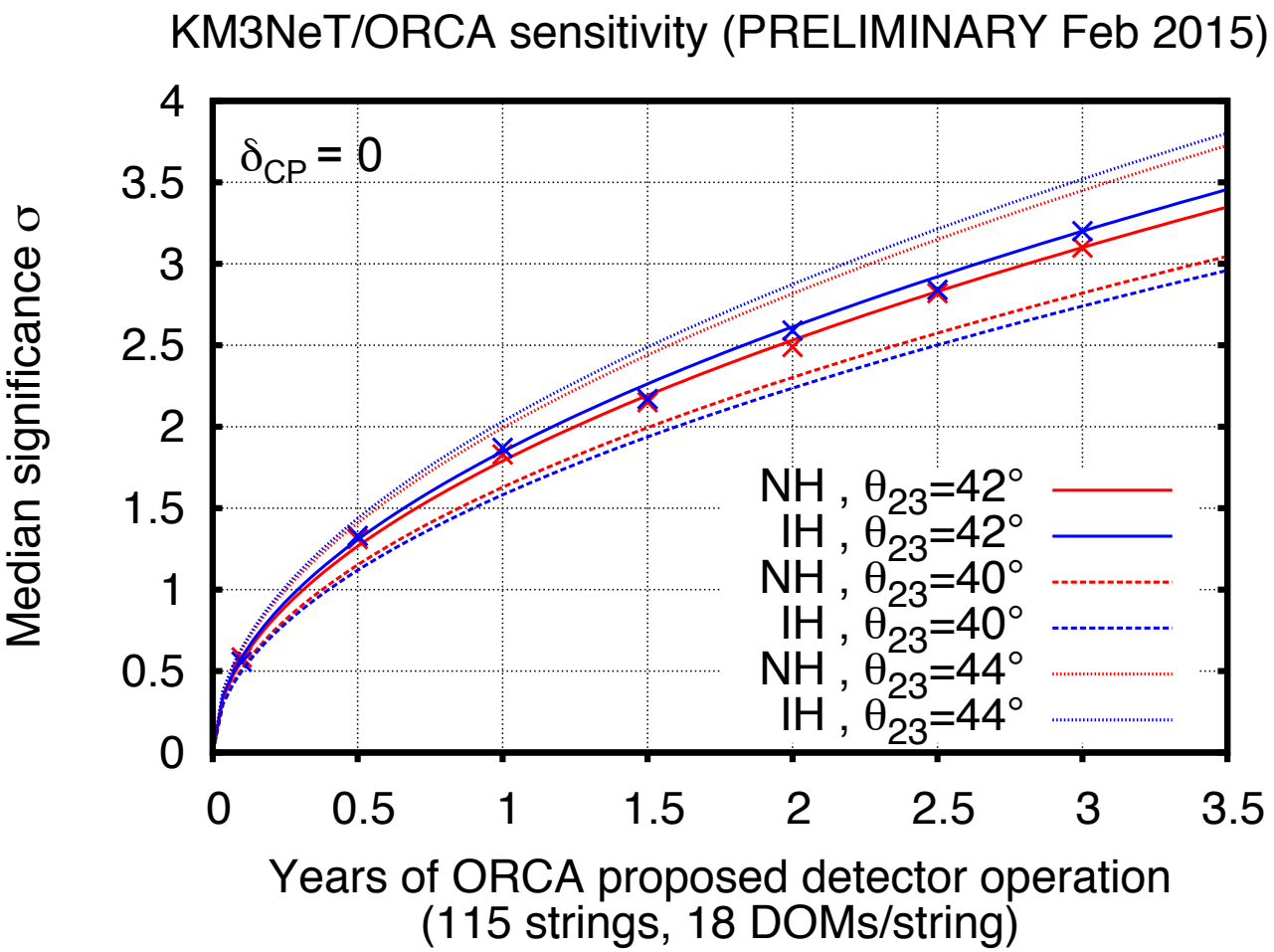
- Mass hierarchy hypothesis test employing likelihood ratio
- Likelihood fitting of ΔM^2, θ_{23} and flux normalization
- Pseudo-experiments use
  - atmospheric neutrino flux (Frejus)
  - neutrino cross sections (GENIE)
  - fixed set of oscillation parameters, $\delta_{CP} = 0$
  - 3-flavour earth matter oscillations (checked against GLOBES)
  - track vs shower event classification
  - full MC detector efficiency / resolution response matrices including misidentified and NC events
  - atmospheric muon contamination in track channel
  - neutral current event contamination

Sensitivity to neutrino mass hierarchy

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

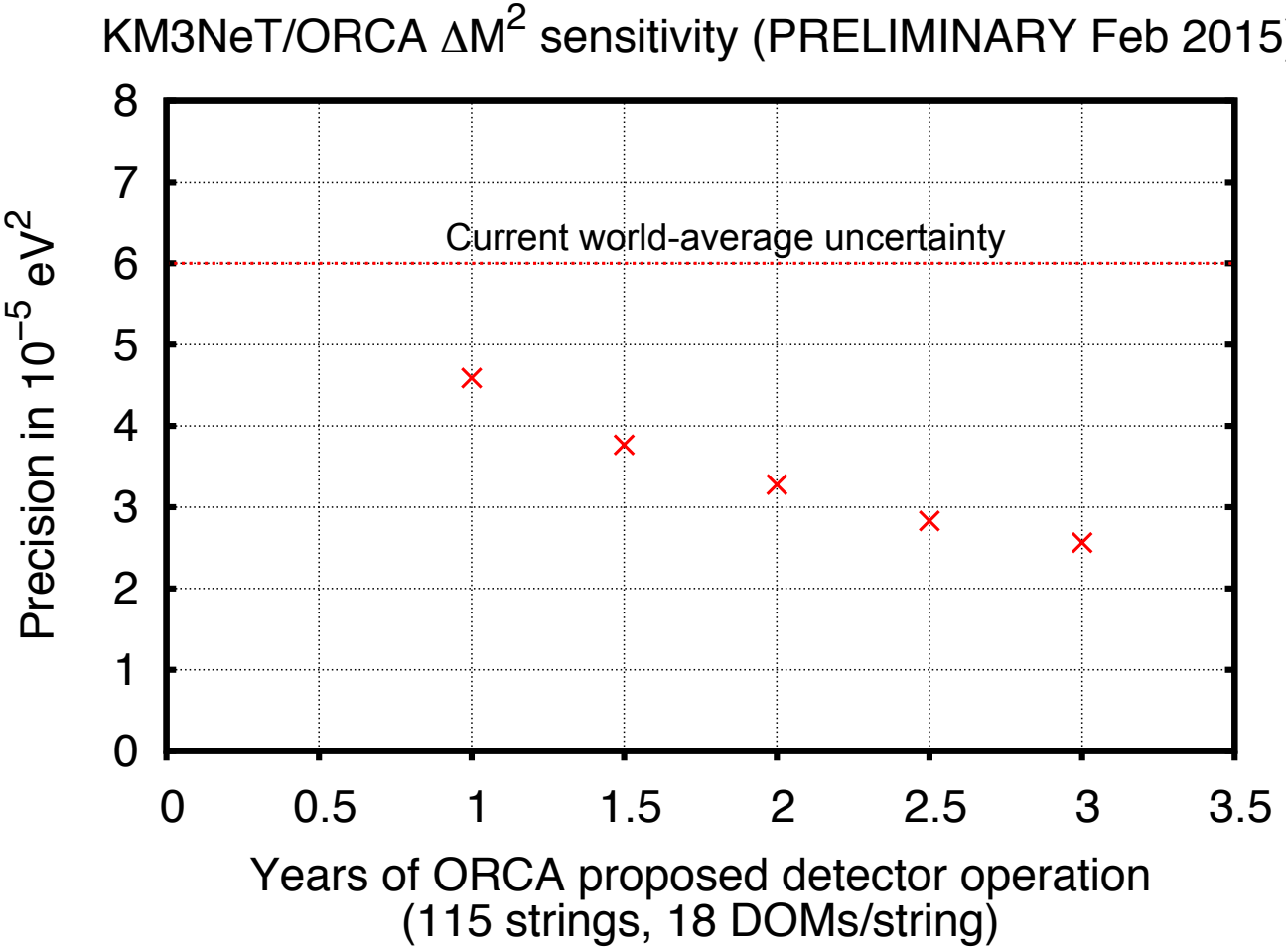


Sensitivity to neutrino mass hierarchy



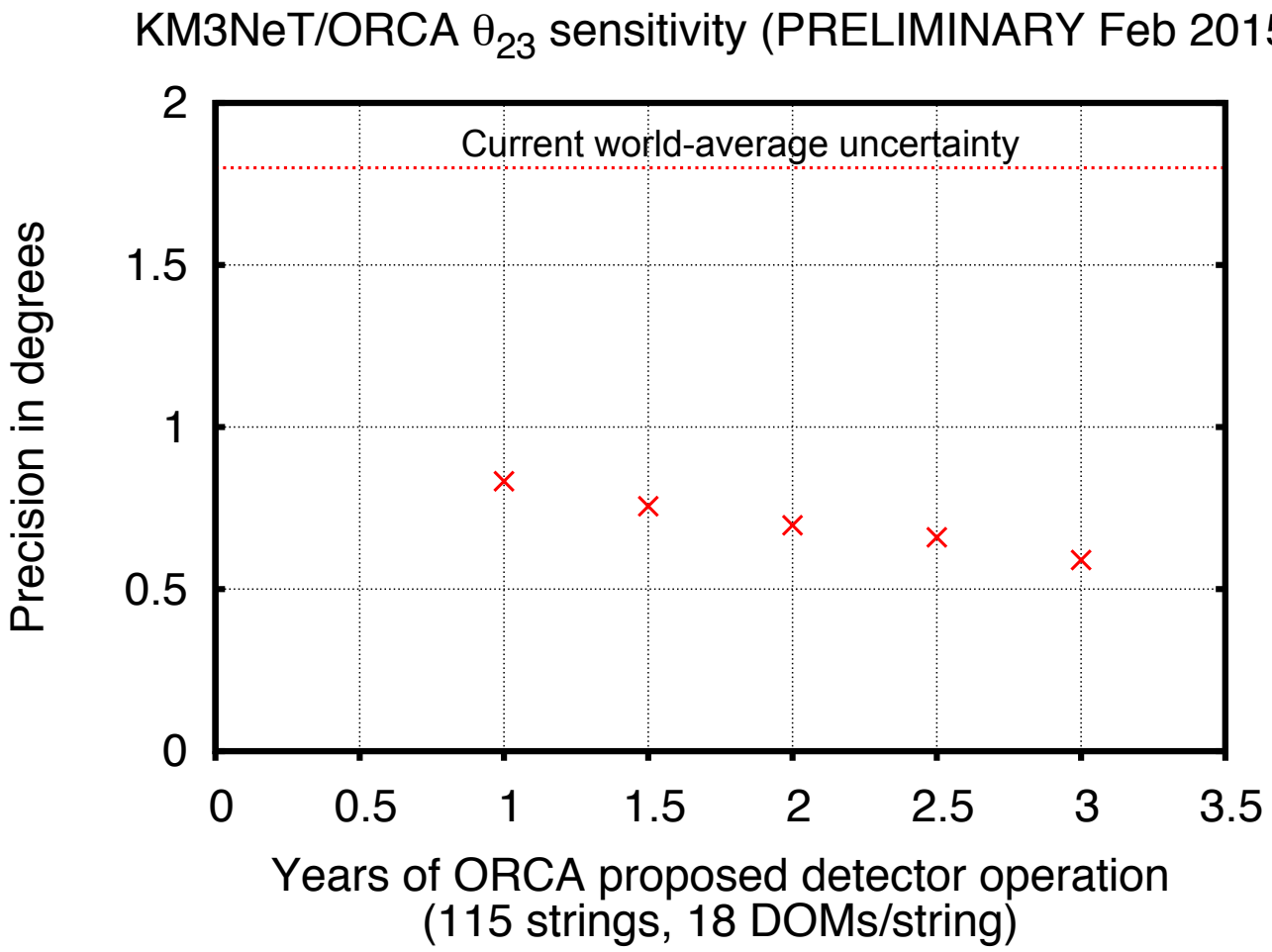
Sensitivity to ΔM^2

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



Sensitivity to θ_{23}

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



KM3NeT / ORCA milestones

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Phase	€	Year	Milestone
1	✔	12 / 2014	Shore cable installation to KM3NeT-Fr site ✔
1	✔	mid 2015	Deployment test with ORCA-style string
1	✔	end 2015	First ORCA string integrated
1	✔	end 2016	6 strings deployed and operational
2.0		2017	Start of construction
2.0		2018	Start of continous operation
2.0		2020	Construction completed

KM3NeT / ORCA summary and outlook

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- ORCA is part of KM3NeT 2.0.
- Event reconstruction performance promising.
  - Some sensitivity to reaction inelasticity in muon and electron channel
- Sensitivity study well advanced and encouraging:
  - **3σ median significance for NMH determination in 3 years seems feasible.**
  - **Relevant improvement on atmospheric oscillation parameter precision in reach.**
- Detector layout optimization and inclusion of additional systematics in sensitivity study ongoing.
- First 6 strings financed and operational end 2016 at KM3NeT-Fr site, completion of ORCA possible until 2020.

Thank you for your attention!

HELMHOLTZ ASSOCIATION
Alliance for Astroparticle Physics

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
NATURWISSENSCHAFTLICHE FAKULTÄT

Backup Slides

HELMHOLTZ ASSOCIATION
Alliance for Astroparticle Physics

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
NATURWISSENSCHAFTLICHE FAKULTÄT

ORCA cost breakdown

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Total additional costs for ORCA are estimated at 40 M€.

Included:

- procurement of components
- transport and deployment
- on-line computing / monitoring
- QA/QC
- contingency

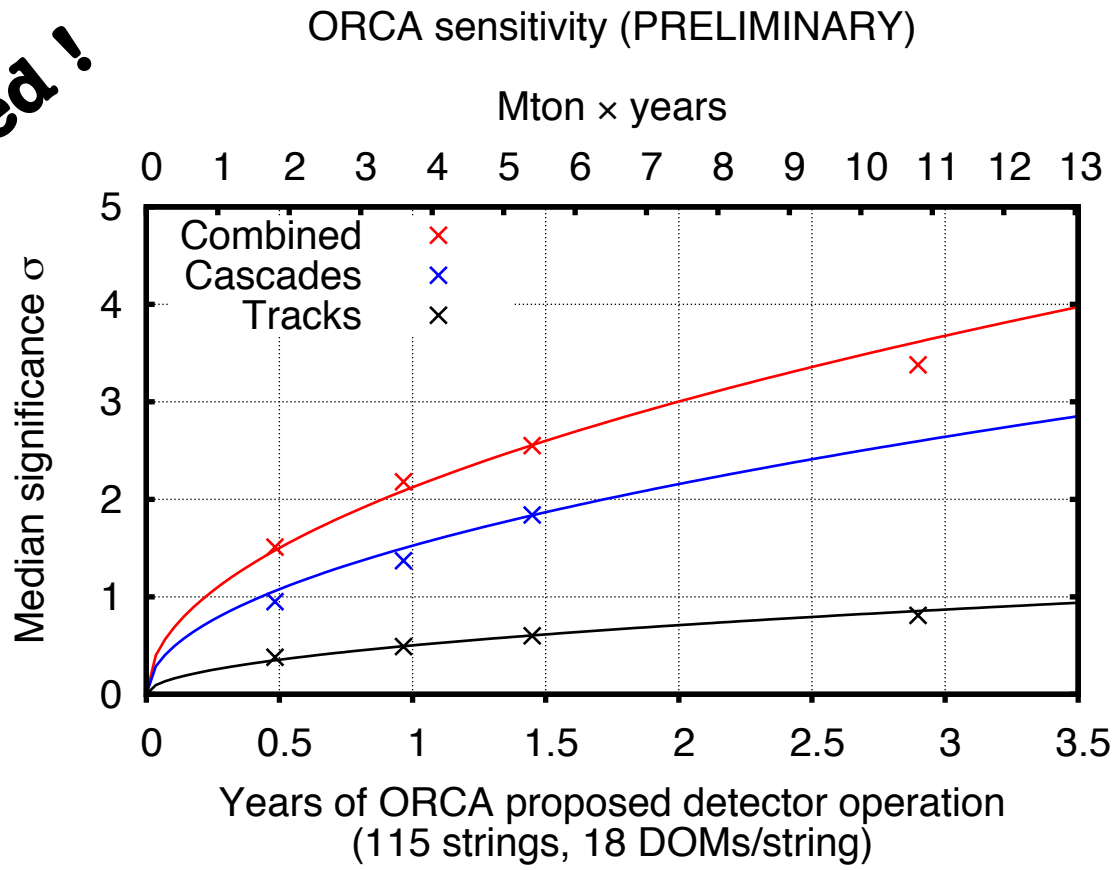
Not included:

- scientists and technicians at member institutes
- meetings
- permanent data storage and offline computing

Sensitivity 2014

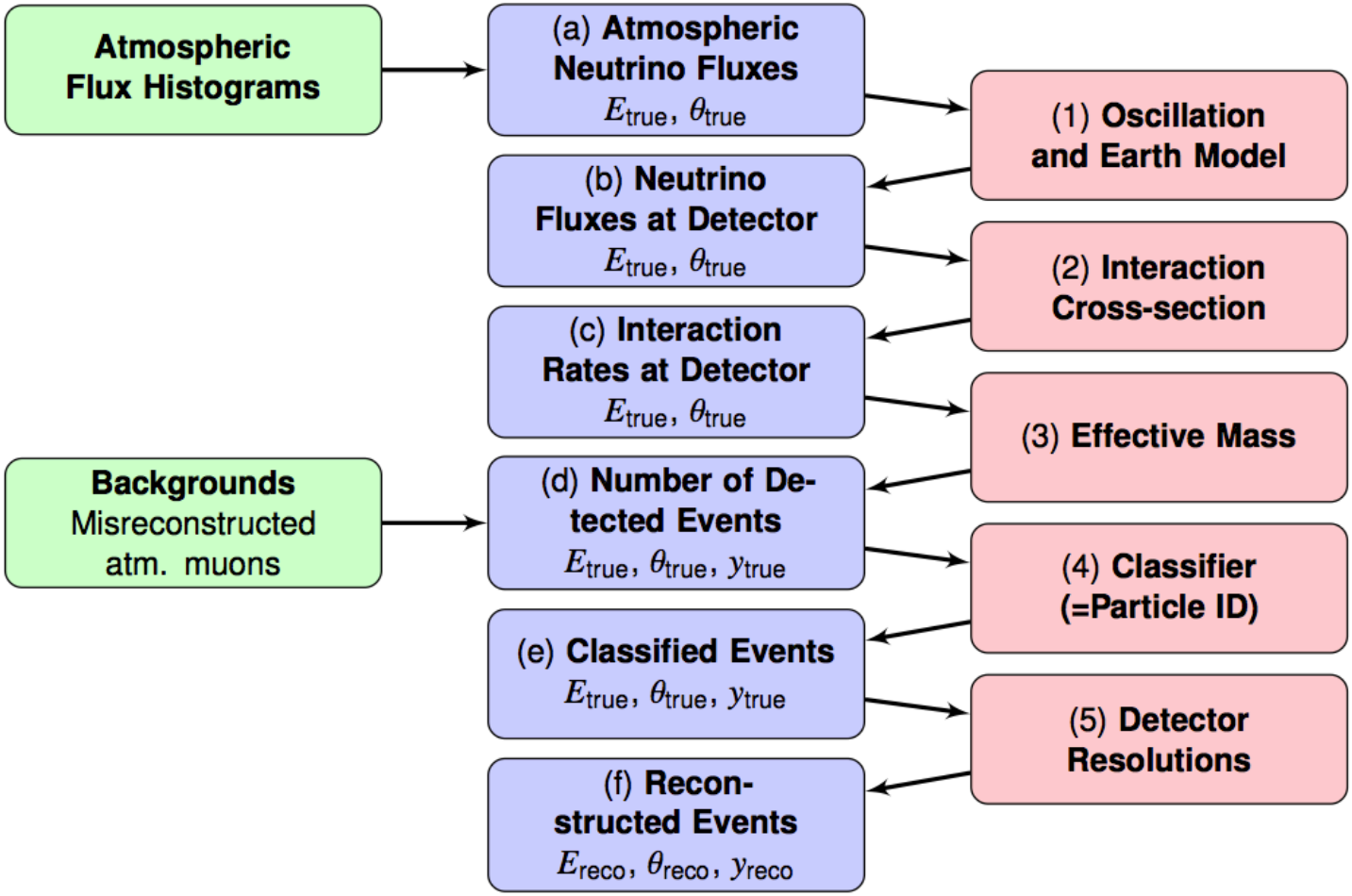
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Outdated !



Sensitivity study

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



Systematics for sensitivity study

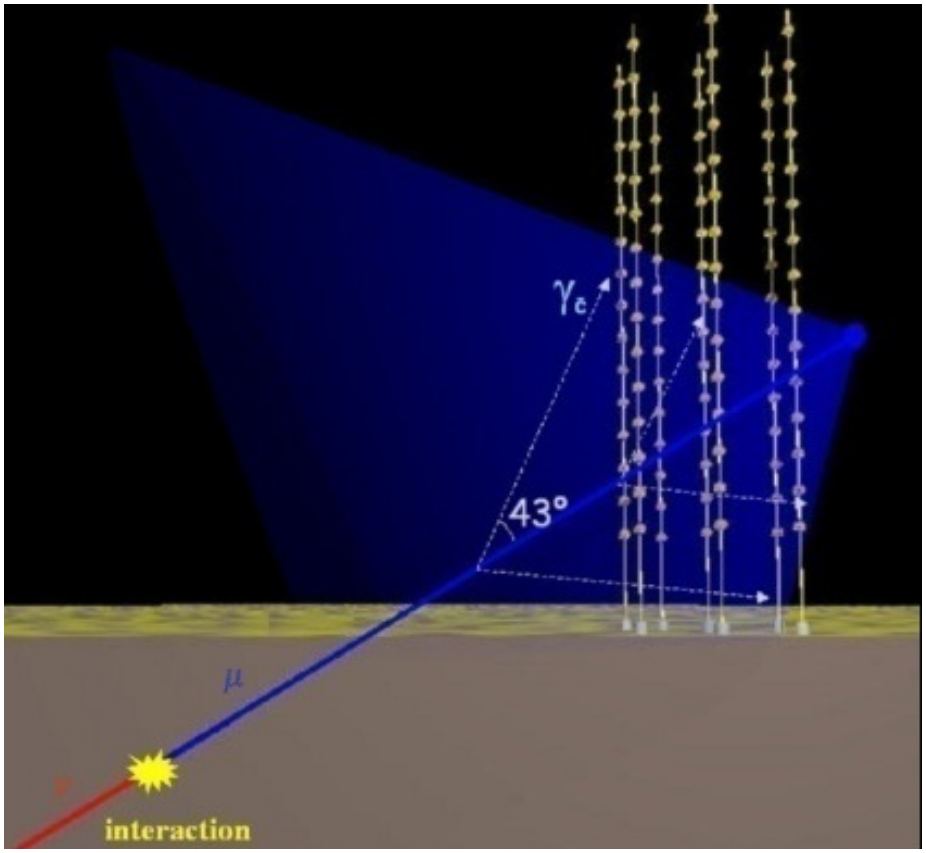
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Effect	Nuisance Parameter	Default	Constraint
Normalisation	R_{Norm}	1	none
Mass difference	ΔM^2	$2.43 \cdot 10^{-3}$ eV	none
Mixing angle	θ_{13}	9°	1°
Mixing angle	θ_{23}	39°	none
CP phase	δ_{CP}	0	none
Energy slope	ϵ_E	0	3%
Energy scale	Δ_E	0	0.3 GeV
Angular slope	$\epsilon_{\cos\vartheta}$	0	1%
Angular scale	$\Delta_{\cos\vartheta}$	0	0.01
Asymmetry $\nu/\bar{\nu}$	$\varepsilon(\nu/\bar{\nu})$	0	0.03
Asymmetry μ/e	$\varepsilon(\mu/e)$	0	0.05
$track/shower$	$\varepsilon(tr/sh)$	0	0.05
NC scale	ε_{NC}	0	0.05
ν_τ scale	ε_{ν_τ}	0	0.05
$\sigma(E)$ scale	$\varepsilon_{\sigma(E)}$	0	0.05
$\sigma(\cos\vartheta)$ scale	$\varepsilon_{\sigma(\cos\vartheta)}$	0	0.05

How does a neutrino telescope work?

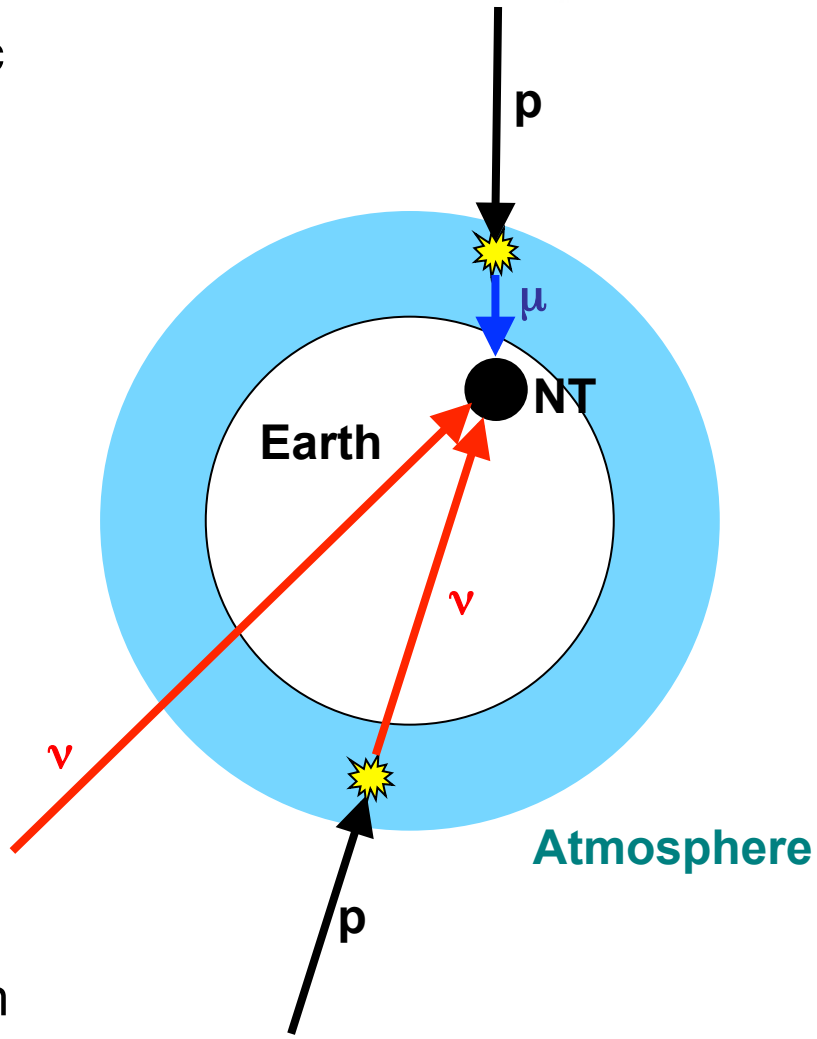
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

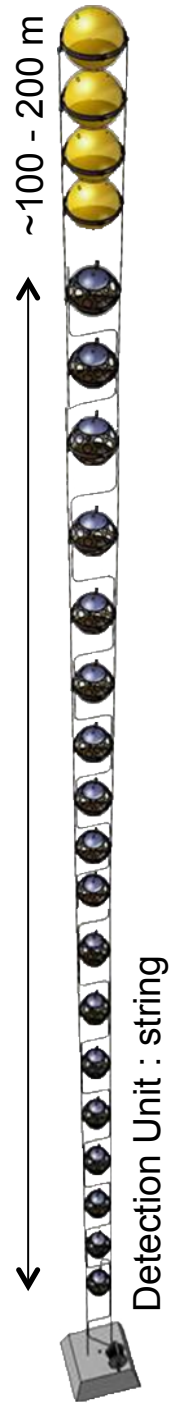
- Neutrino interacts in the (vicinity of the) telescope
- Charged secondaries cross the detector volume and stimulate Cherenkov emission
- Light recorded by a 3D-array of photo-sensors
- Density determines energy threshold and event reconstruction capabilities



Signal and Background

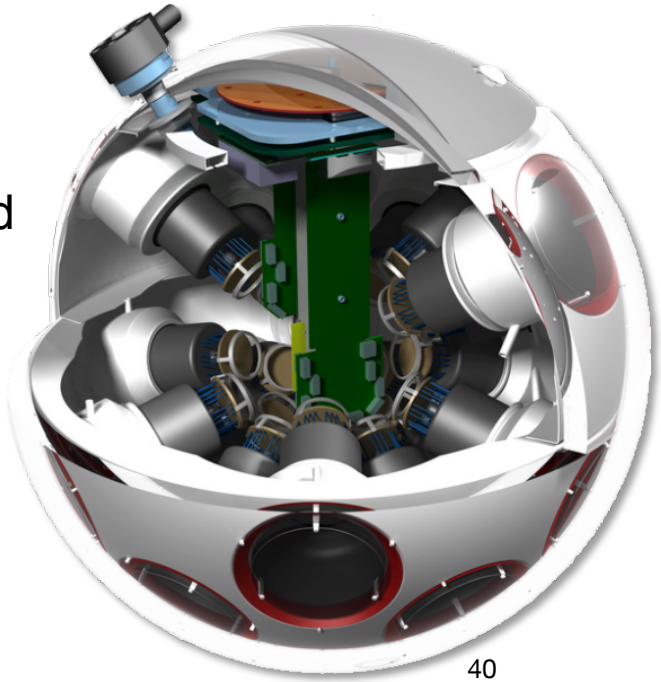
- **Signal:** GeV-scale atmospheric neutrinos from cosmic-ray interactions in the atmosphere
- **Background:** Atmospheric muons from cosmic-ray interactions in atmosphere above neutrino telescope
  - penetrate down to neutrino telescope
  - exceed neutrino event rate by several orders of magnitude
- **Background:** Light from K40 decays and bioluminescence in sea water





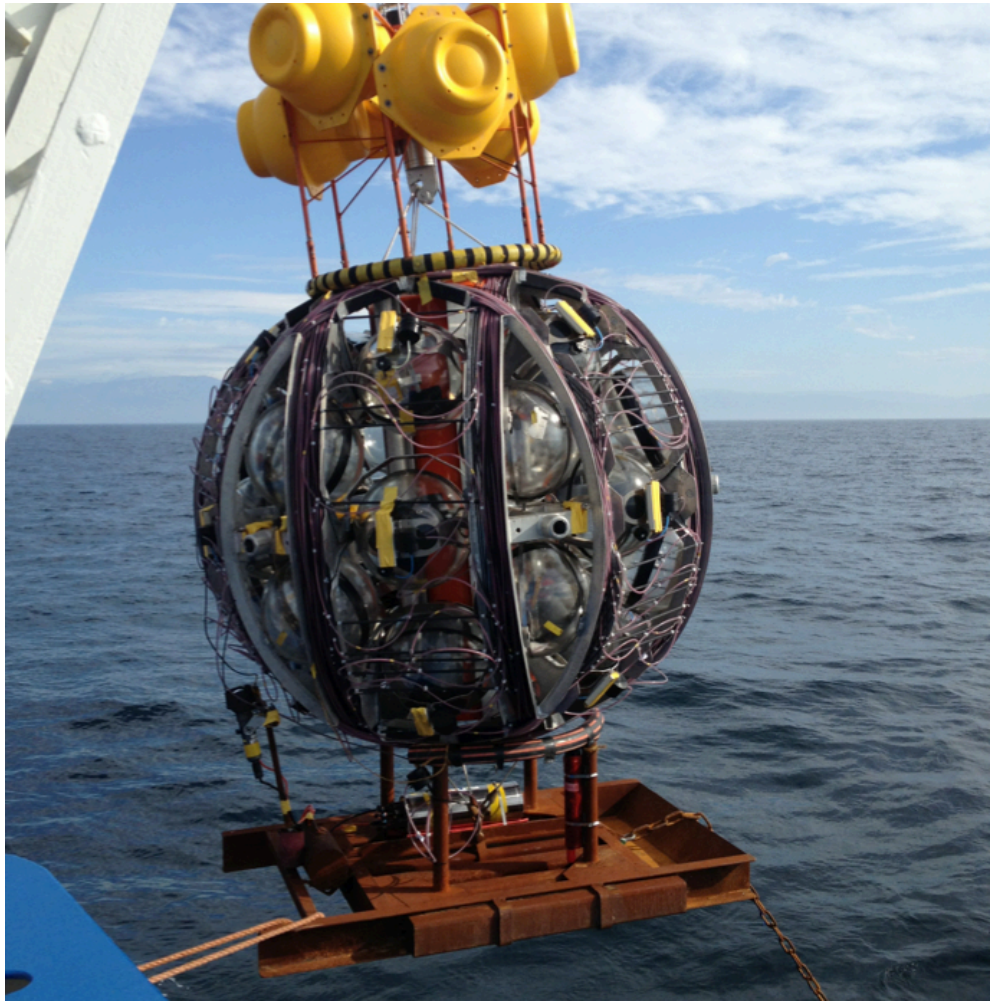
KM3NeT: optical module

- 17-inch glass sphere
- Segmented cathode area with
  31 x 3-inch PMTs, 19 down, 12 up
- Light concentrator ring
- LED and piezo inside sphere for time and position calibration
- Compass and tiltmeter inside sphere for orientation calibration



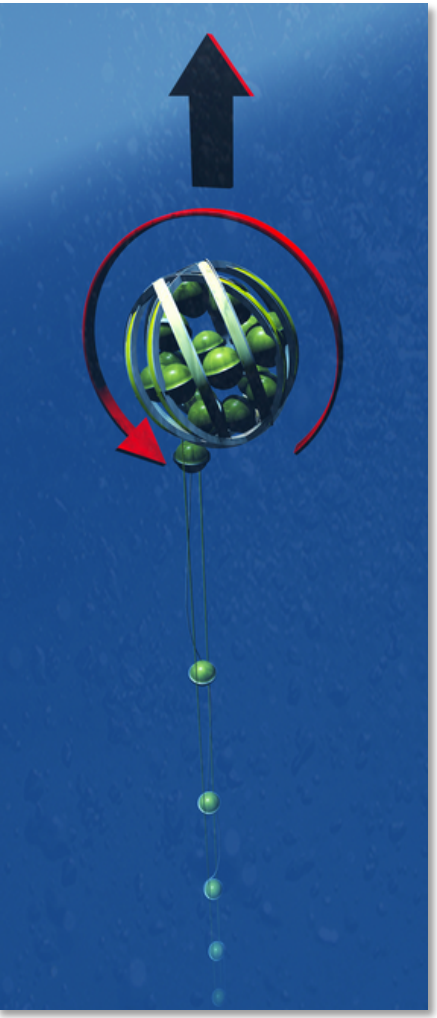
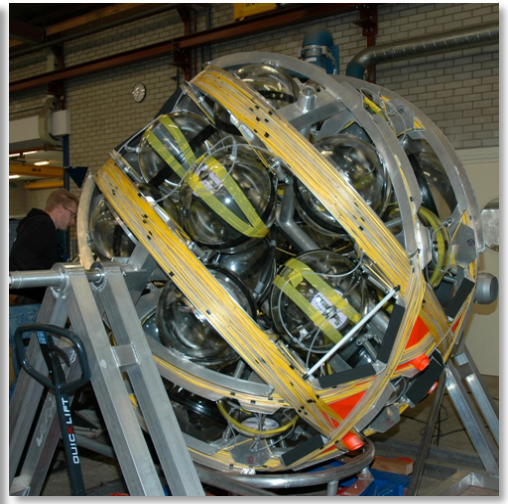
Deployment test

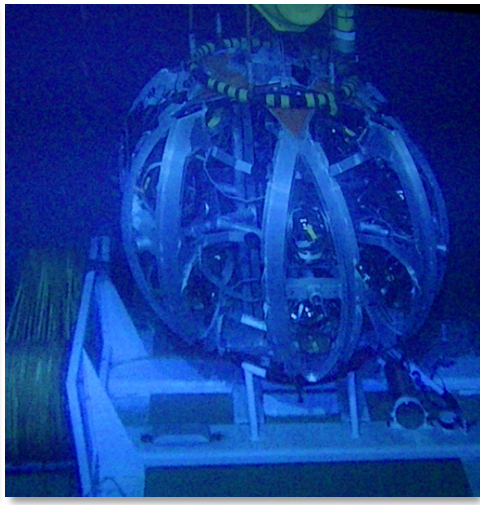
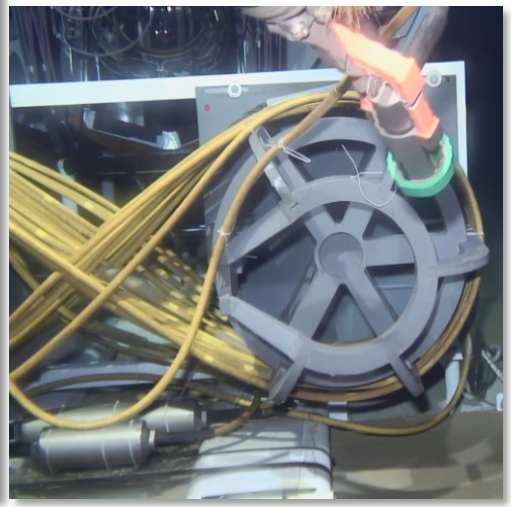
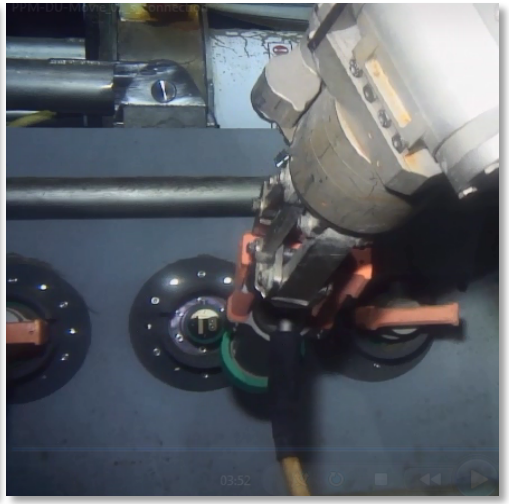
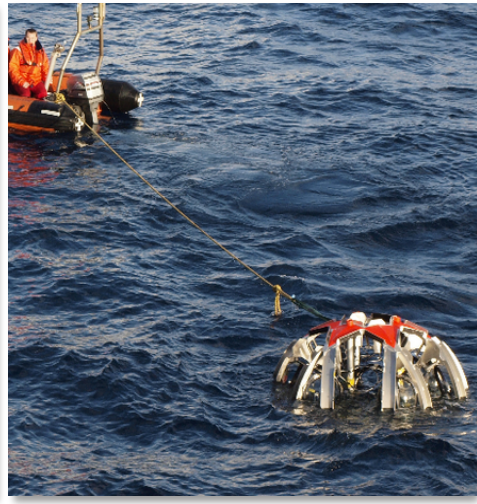
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



Deployment of test string, 100 km off-shore Sicily at -3500 m

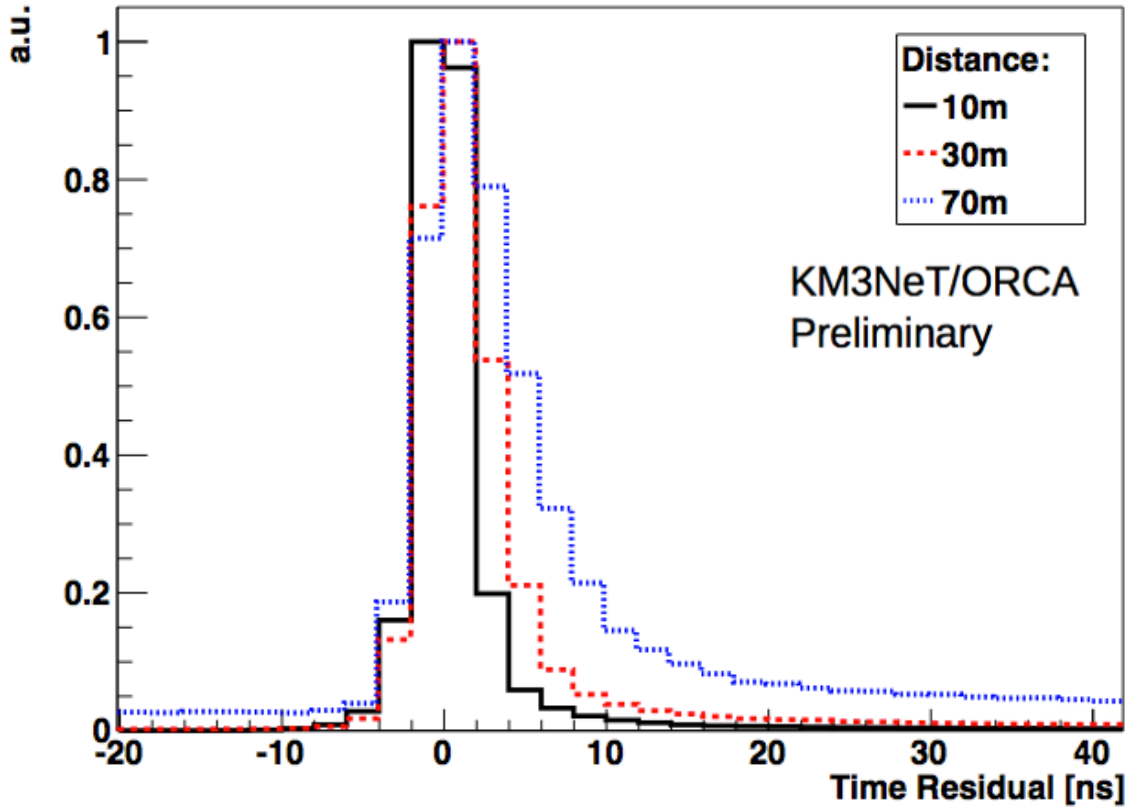
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

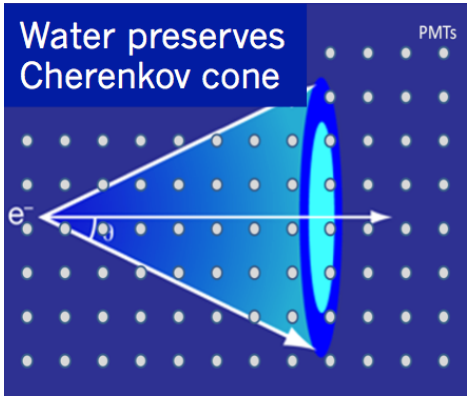



ν_e^{CC} : Time residual distribution

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS





Normalized to 1, fully contained events, 5kHz optical background per PMT, distance PMT to vertex

Electron neutrino charged-current events

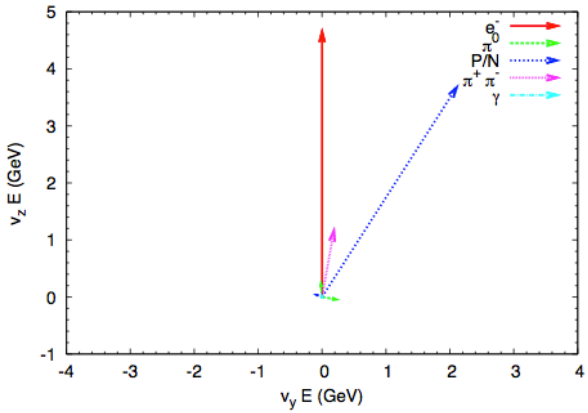
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

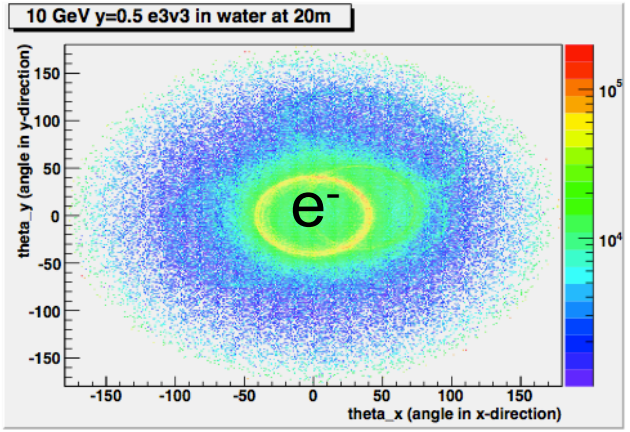
Two different ν_e CC events with $E_\nu \approx 10\,\mathrm{GeV}$ and $y \approx 0.5$ in the upper and lower row.

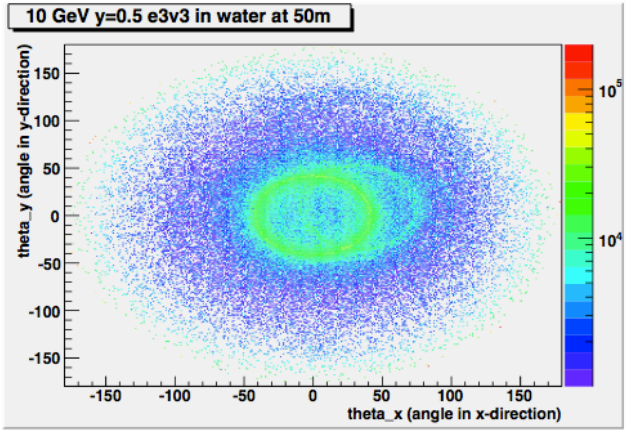
vertex distance:

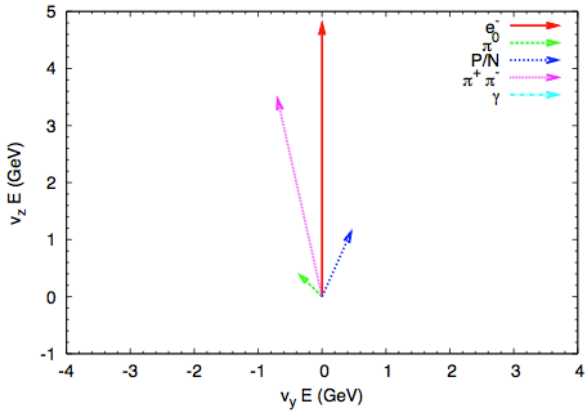
20 m shell

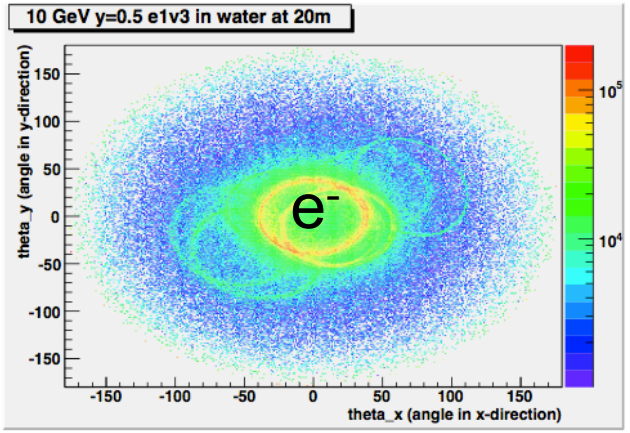
50 m shell

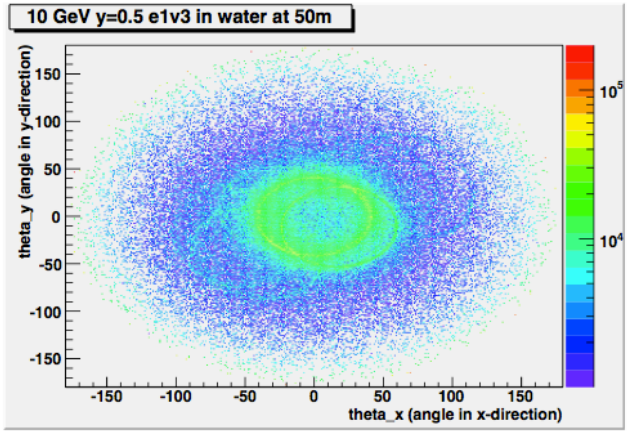






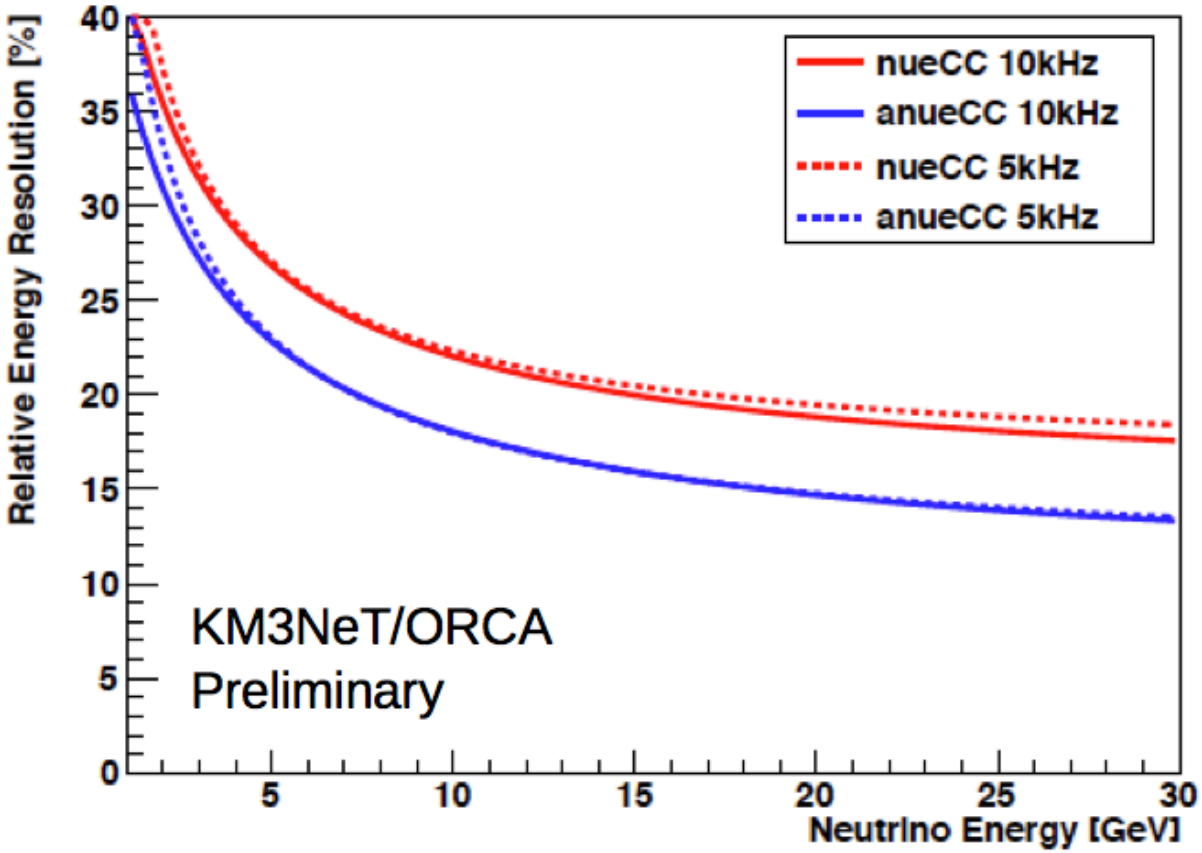






ν_e^{CC} : energy resolution for 5 kHz and 10 kHz optical background rates per PMT

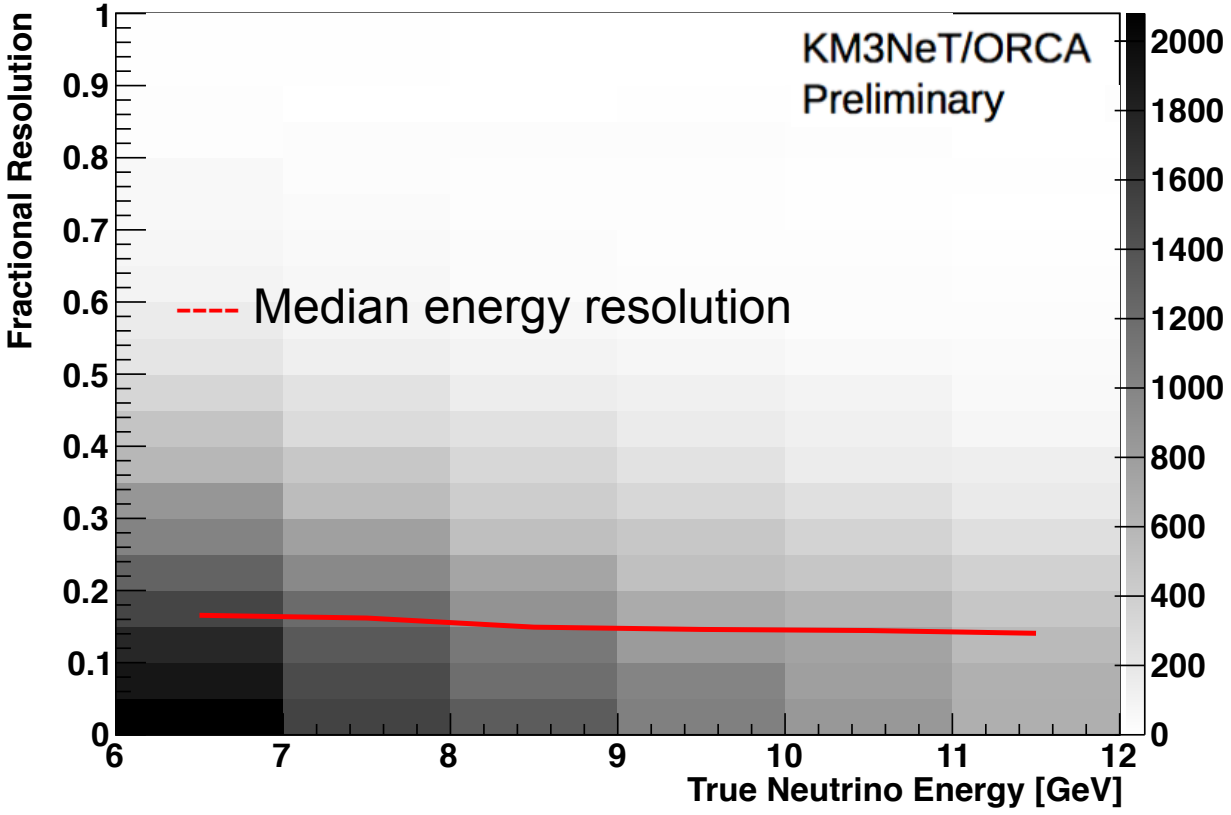
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



ν_e^{CC} : fractional energy resolution

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

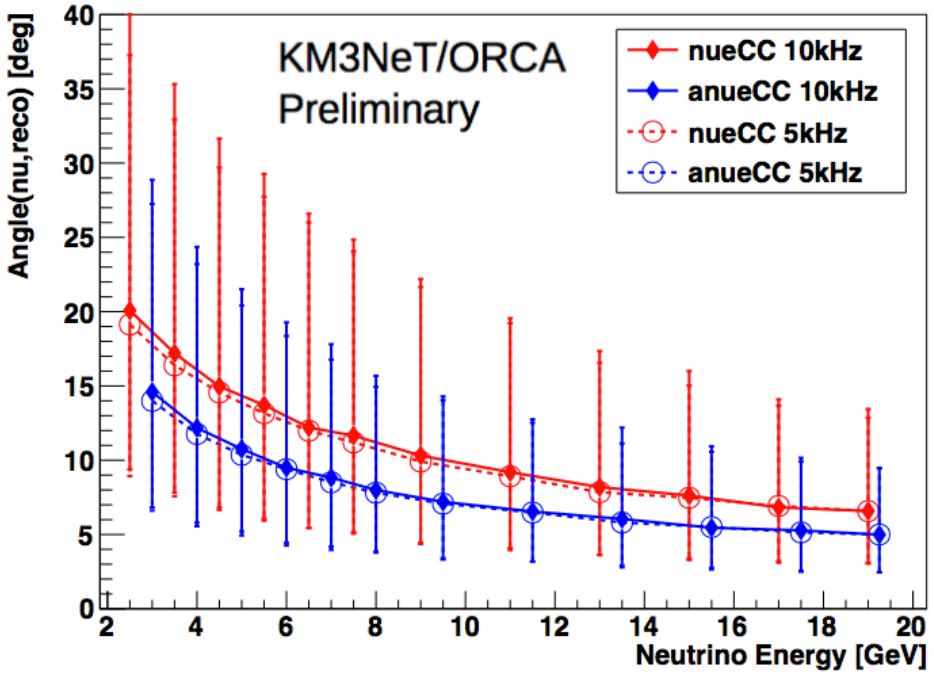
$$\text{fractional resolution} := \frac{|E_\nu - E_{\text{reco}}|}{E_\nu}$$



ν_e^{CC} : median directional resolution

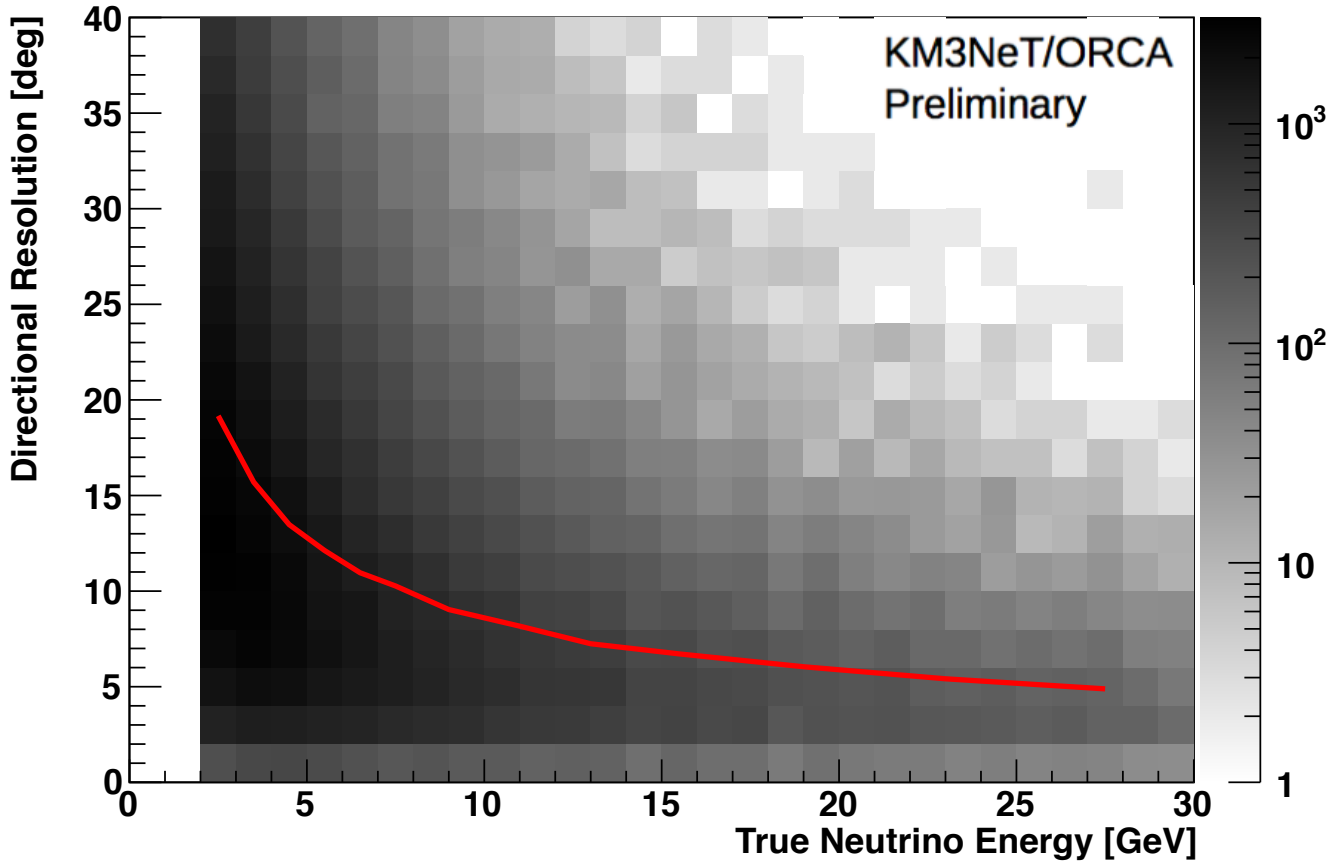
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- error bars: 15% and 85% quantiles
- neutrinos and anti-neutrinos
- negligible differences between 5 and 10 kHz single PMT optical background rates



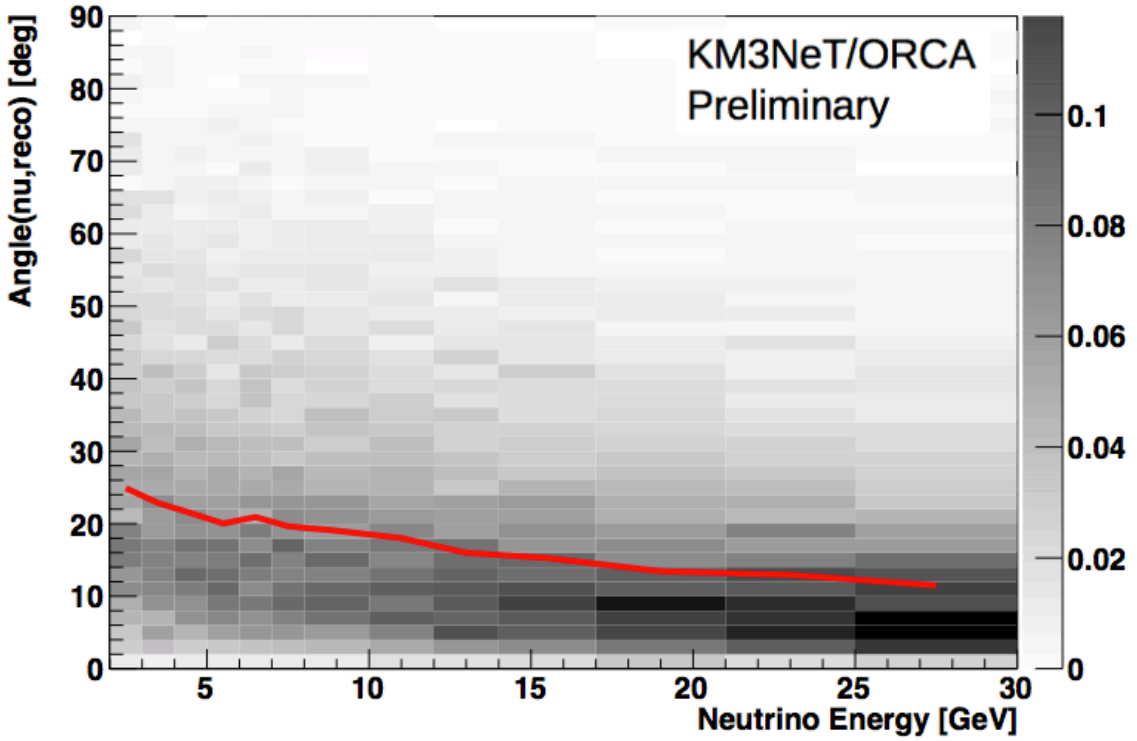
ν_e^{CC} : directional resolution

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



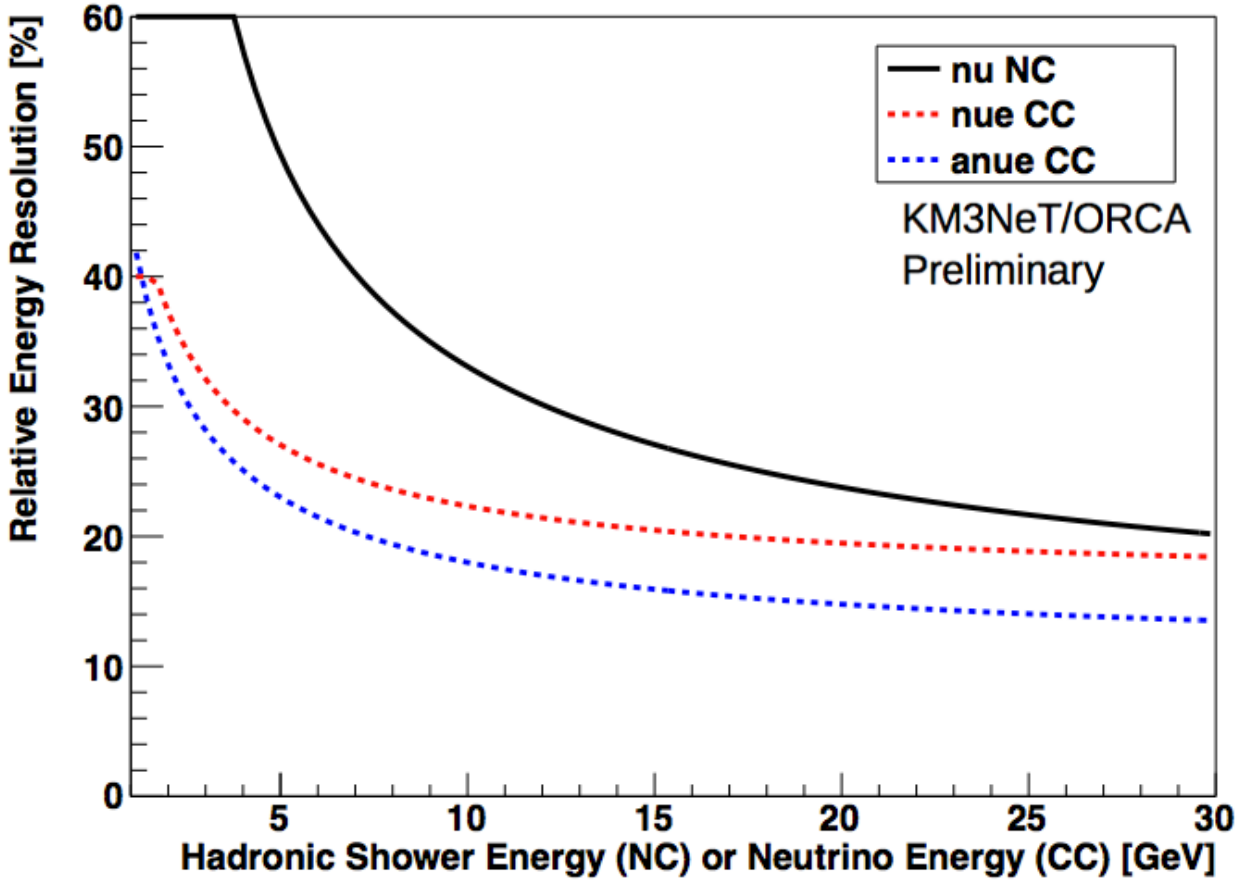
ν^{NC} : direction resolution

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



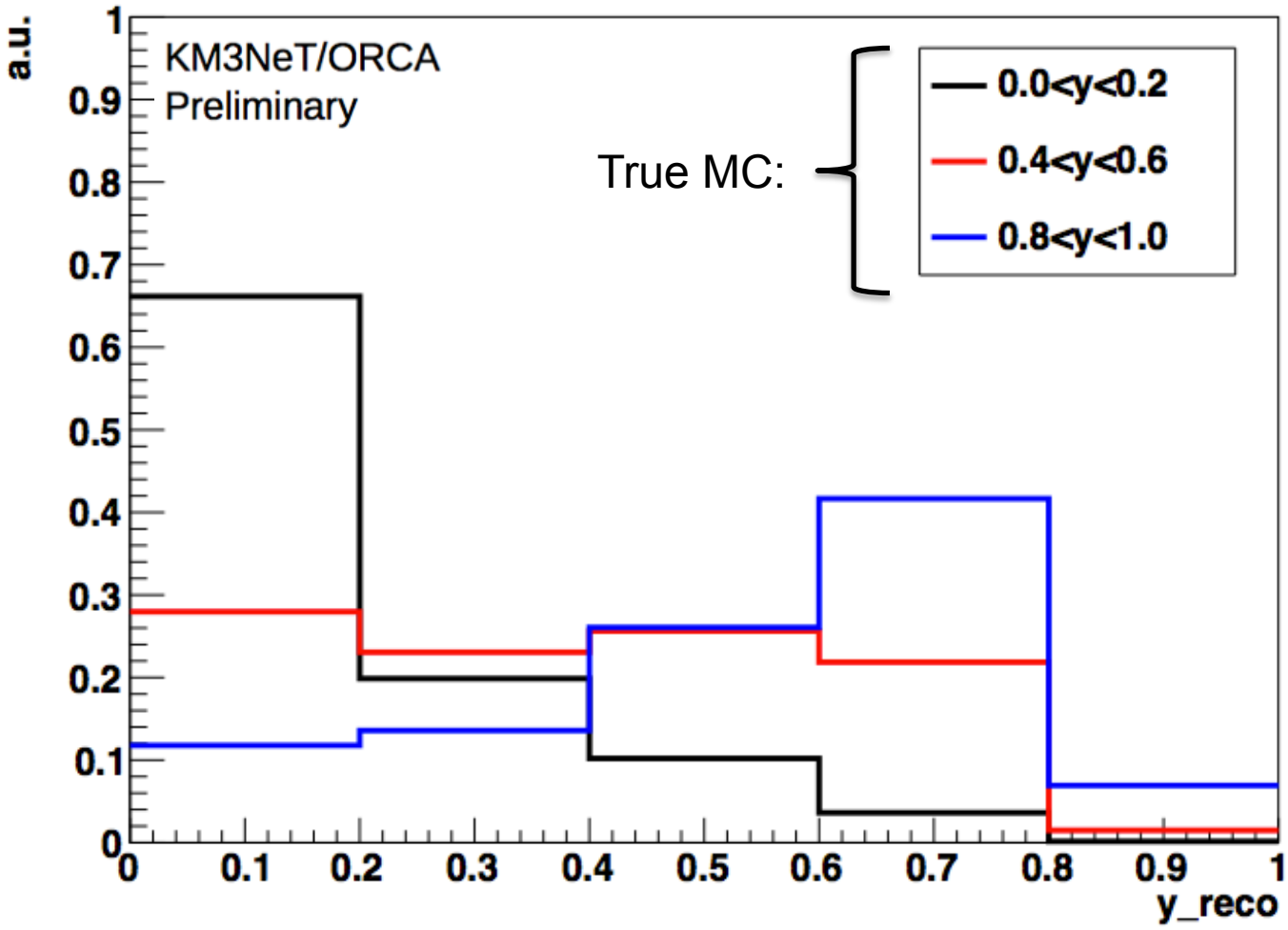
ν_e^{CC} / ν^{NC} : relative energy resolution

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



ν_e^{CC} : reconstructed reaction inelasticity

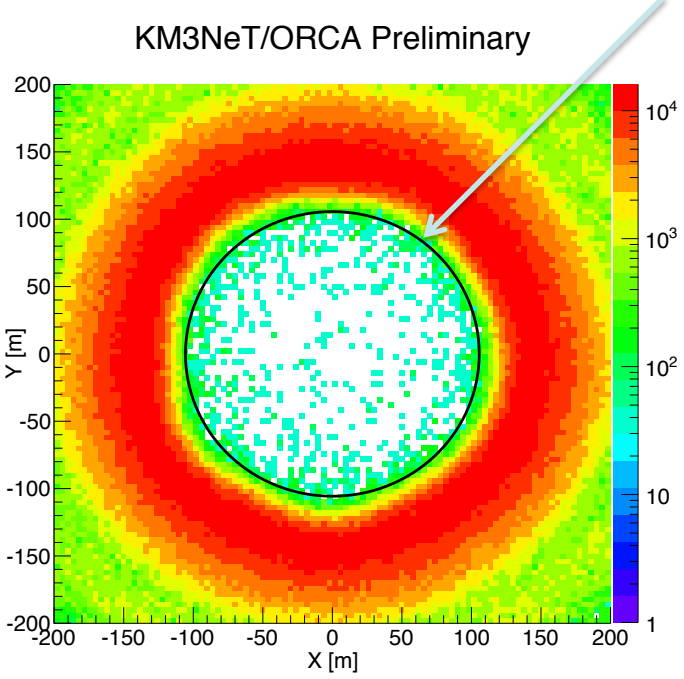
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



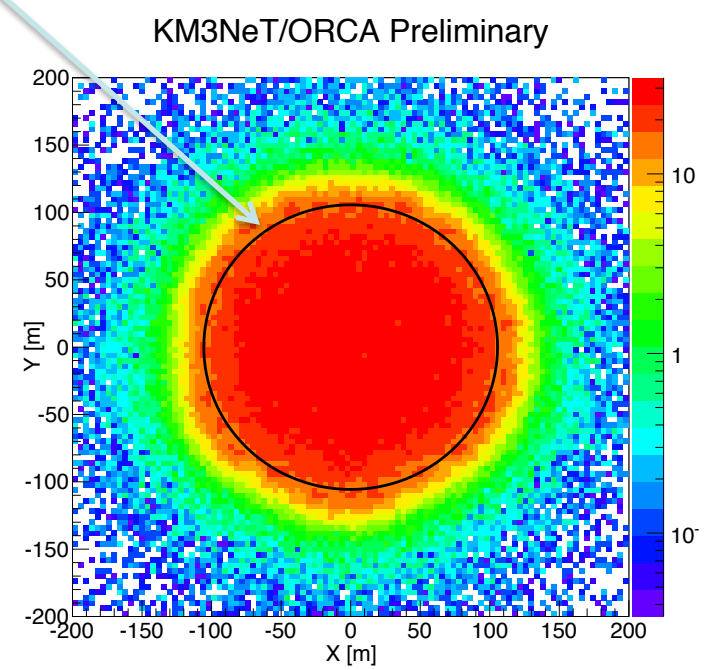
Track reconstruction pseudovertex

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Instrumented volume



Atmospheric muons misreconstructed as upgoing

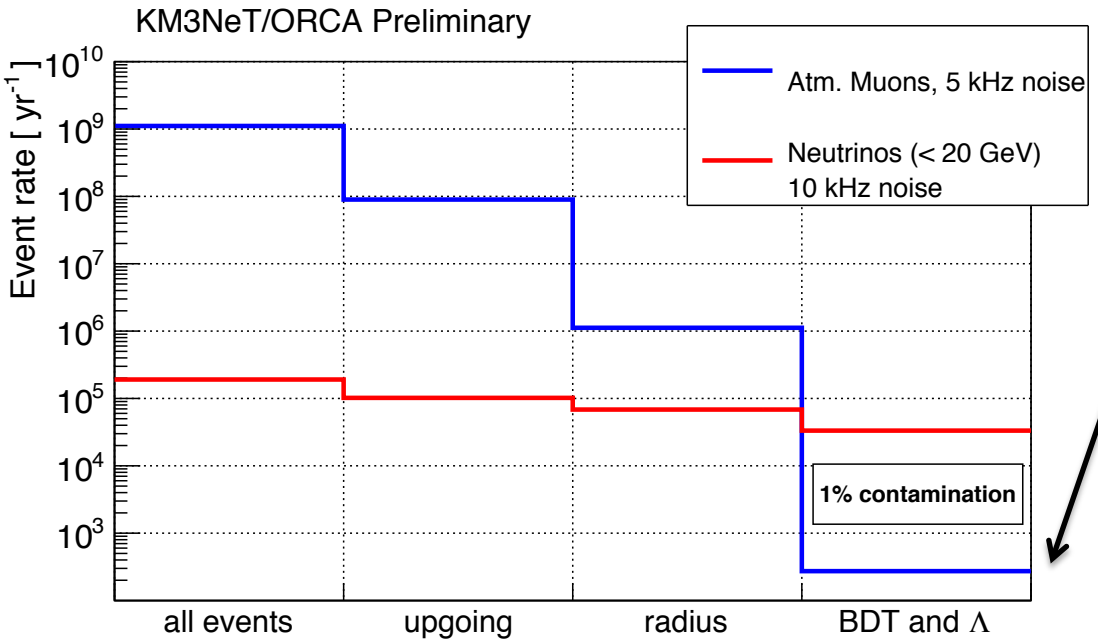


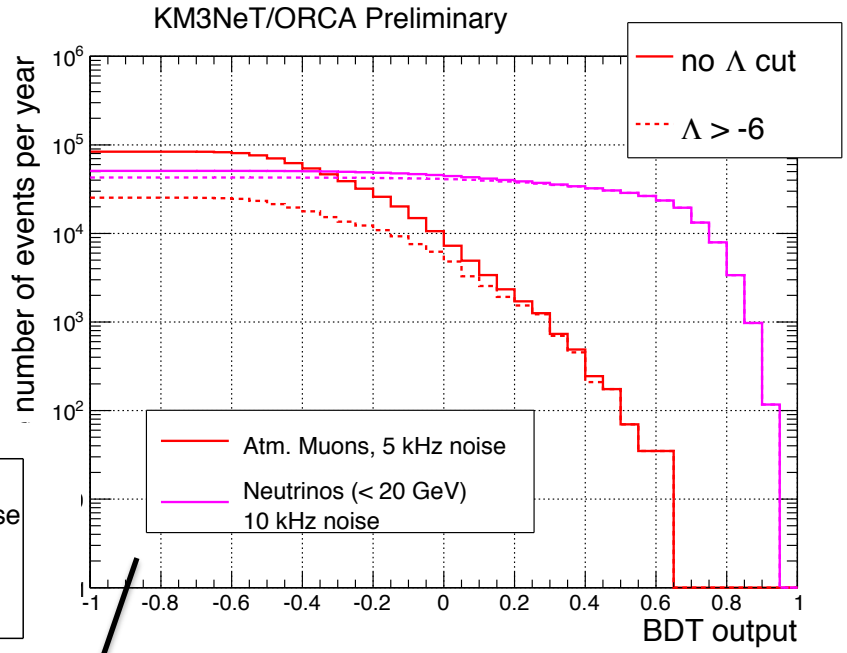
Upgoing atmospheric neutrinos $E_\nu < 20$ GeV

Atmospheric muon rejection

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Boosted Decision Tree machine-learning algorithm.
- Trained on pseudovertex position, track quality parameters and reconstructed zenith angle.

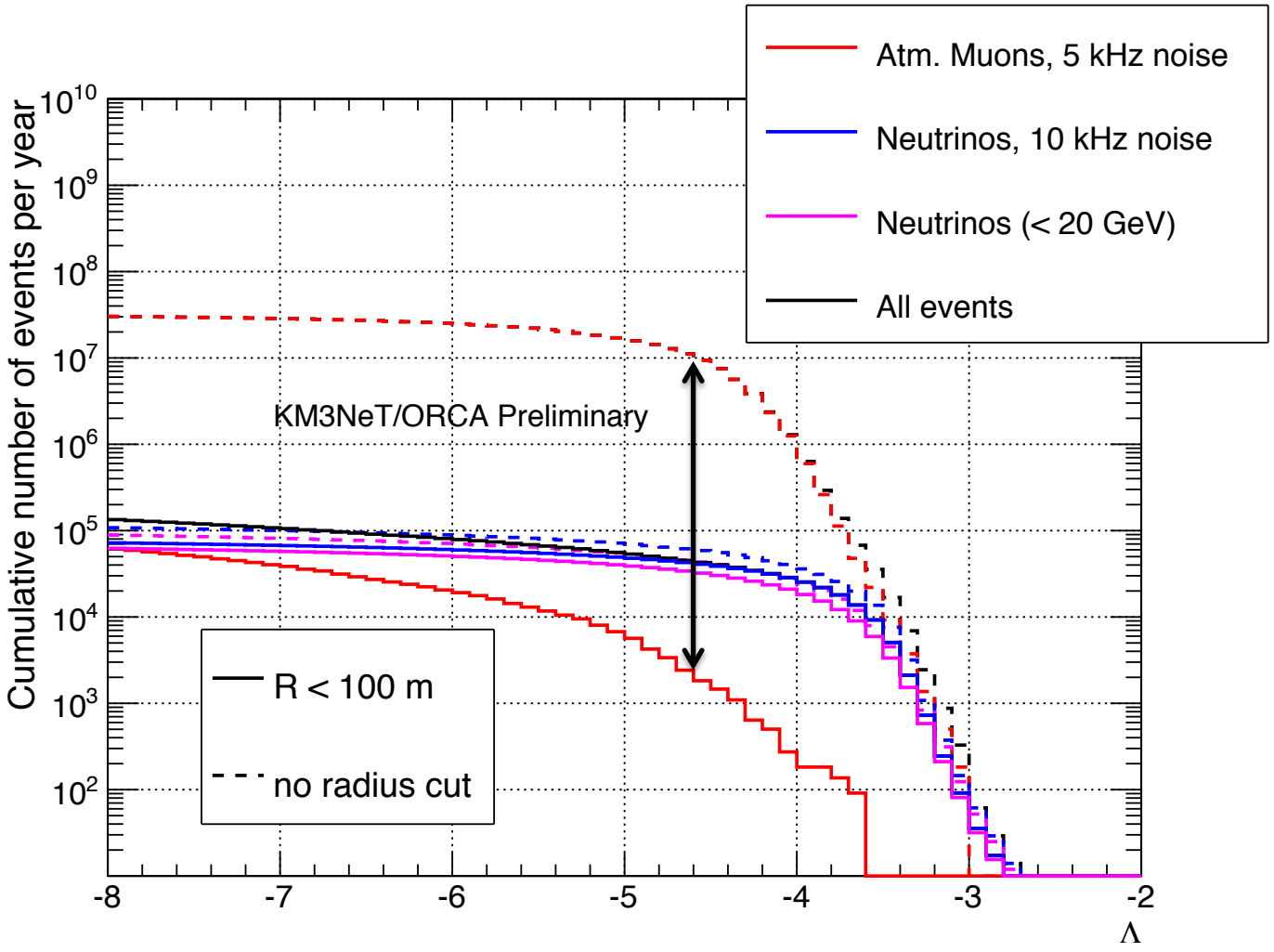




ν_μ^{CC} efficiency: 60%

@ muon contamination: 1%

Atmospheric muon rejection



The 3-flavour neutrino oscillation picture

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Neutrino flavour and mass eigenstates are not the same:

$$\text{[mass]} \rightarrow \quad |\nu_i\rangle = \sum_{\alpha=1}^{3} U_{i\alpha}|\nu_\alpha\rangle \quad \leftarrow \text{[flavour]}$$

- Mixing matrix parameterisation (neglecting Majorana phases):

$$U_{\text{PNMS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \cdot \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \cdot \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$ and CP violating phase δ

The 3-flavour neutrino oscillation picture

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Neutrino oscillation parameters known to fair precision (PDG 2014, best fit for normal hierarchy):

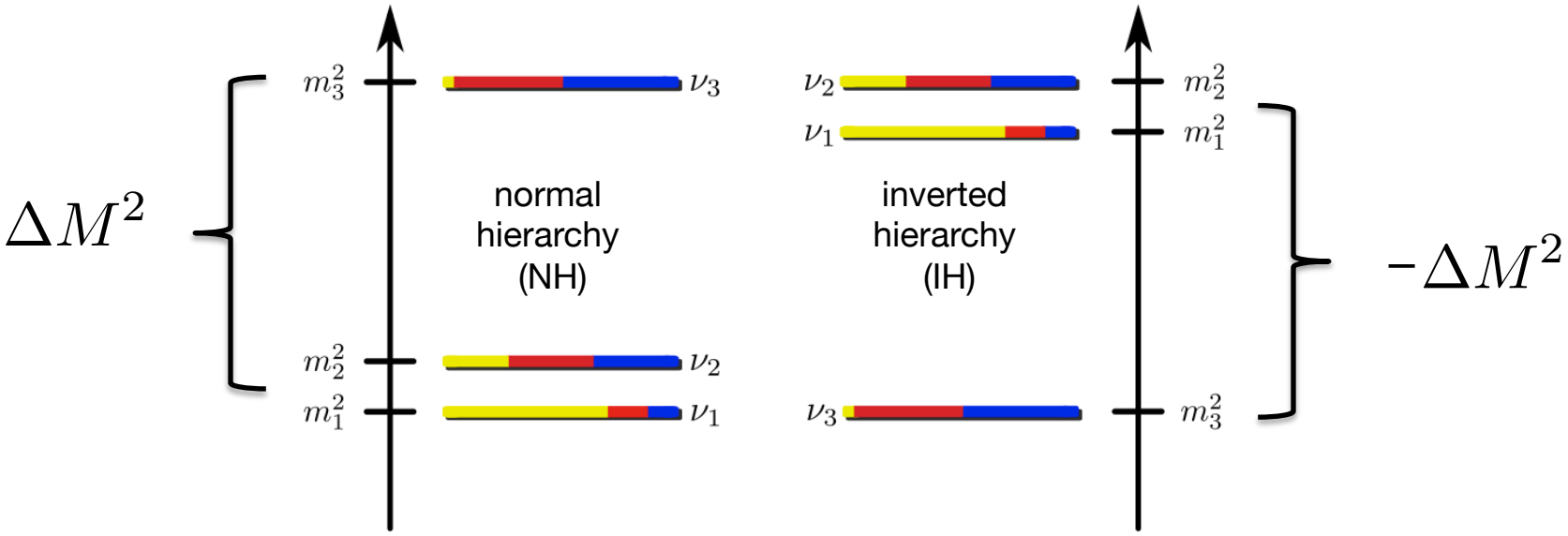
$$\Delta m^2_{21} = 7.54 \times 10^{-5}\ \mathrm{eV}^2\,; \quad |\Delta M^2| = 2.43 \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2\theta_{12} = 0.31\,; \quad \sin^2\theta_{23} = 0.44\,; \quad \sin^2\theta_{13} = 0.02$$

- Unknowns:
  - Absolute neutrino mass
  - CP violating phase δ
  - Sign of ΔM^2, i.e. the neutrino mass hierarchy

The neutrino mass hierarchy

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Mass hierarchy determined by unknown sign of ΔM^2



- Fundamental parameter of particle physics, knowledge crucial e.g ...
  → to reduce uncertainty for measurements of δ_{CP} violation.
  → to define scope for future neutrinoless double beta decay searches.
  → to determine absolute neutrino mass scale from cosmology.
  → to help a detailed understanding of core-collapse supernovae.

Neutrino oscillations and mass hierarchy

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Neutrino propagation in matter different for ν_e and $\nu_{\mu,\tau}$:

  $\nu_e e^- \rightarrow \nu_e e^-$ and $\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$ via W and Z exchange

  $\nu_{\mu,\tau} e^- \rightarrow \nu_{\mu,\tau} e^-$ and $\overline{\nu}_{\mu,\tau} e^- \rightarrow \overline{\nu}_{\mu,\tau} e^-$ via Z exchange only

  Result: Modification of flavour oscillation patterns!

- Mikheyev-Smirnov-Wolfenstein effect (MSW effect)
  dominant cause of solar neutrino oscillations,
  allowed to determine sign of Δm^2_{21}.

Neutrino oscillations and mass hierarchy

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- 3-Flavour transition probability in matter:

$$P_{3\nu}(\nu_e \to \nu_\mu) = \sin^2\theta_{23} \cdot \sin^2 2\theta_{13}^m \cdot \sin^2\left(\frac{\Delta_{31}^m L}{4E_\nu}\right)$$

with $\sin^2 2\theta_{13}^m = \sin^2 2\theta_{13}\left(\frac{\Delta M^2}{\Delta_{31}^m}\right)^2$

and $\Delta_{31}^m = \sqrt{(\Delta M^2 \cos 2\theta_{13} \pm A)^2 + (\Delta M^2 \sin 2\theta_{13})^2}$

$A = -\sqrt{2} G_F N_e$ for ν and $A = \sqrt{2} G_F N_e$ for $\bar{\nu}$

G_F : Fermi constant $\quad$ N_e : electron density

Neutrino oscillations and mass hierarchy

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- 3-Flavour transition probability in matter:

$$P_{3\nu}(\nu_e \to \nu_\mu) = \sin^2\theta_{23} \cdot \sin^2 2\theta_{13}^m \cdot \sin^2\left(\frac{\Delta_{31}^m L}{4E_\nu}\right)$$

$$\Delta_{31}^m = \sqrt{(\Delta M^2 \cos 2\theta_{13} \pm A)^2 + (\Delta M^2 \sin 2\theta_{13})^2}$$

→ resonance if $A = \Delta M^2 \cos 2\theta_{13}$ for neutrinos in normal and for anti-neutrinos in inverted hierarchy

→ use effect to determine the sign of ΔM^2

Mass hierarchy and atmospheric neutrinos

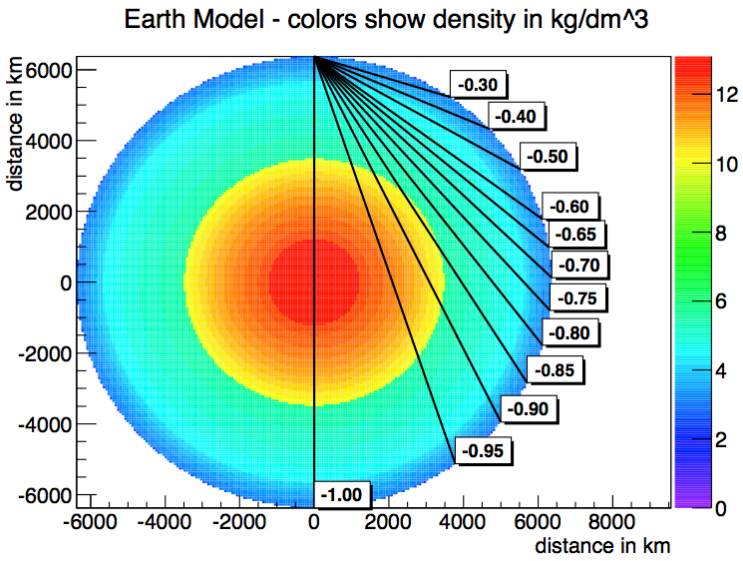
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Resonance energy in Earth matter:

$$E_{\nu,res} = \frac{\Delta m^2_{31} \cos 2\theta_{13}}{2\sqrt{2} G_F N_e} \simeq 7 \text{ GeV} \left(\frac{4.5 \text{ g/cm}^3}{\rho} \right) \left(\frac{\Delta m^2_{31}}{2.4 \times 10^{-3} \text{ eV}^2} \right) \cos 2\theta_{13}$$

or roughly: $E_{\nu,res} \approx \frac{30}{\rho[\text{g/cm}^3]} \text{ GeV}$

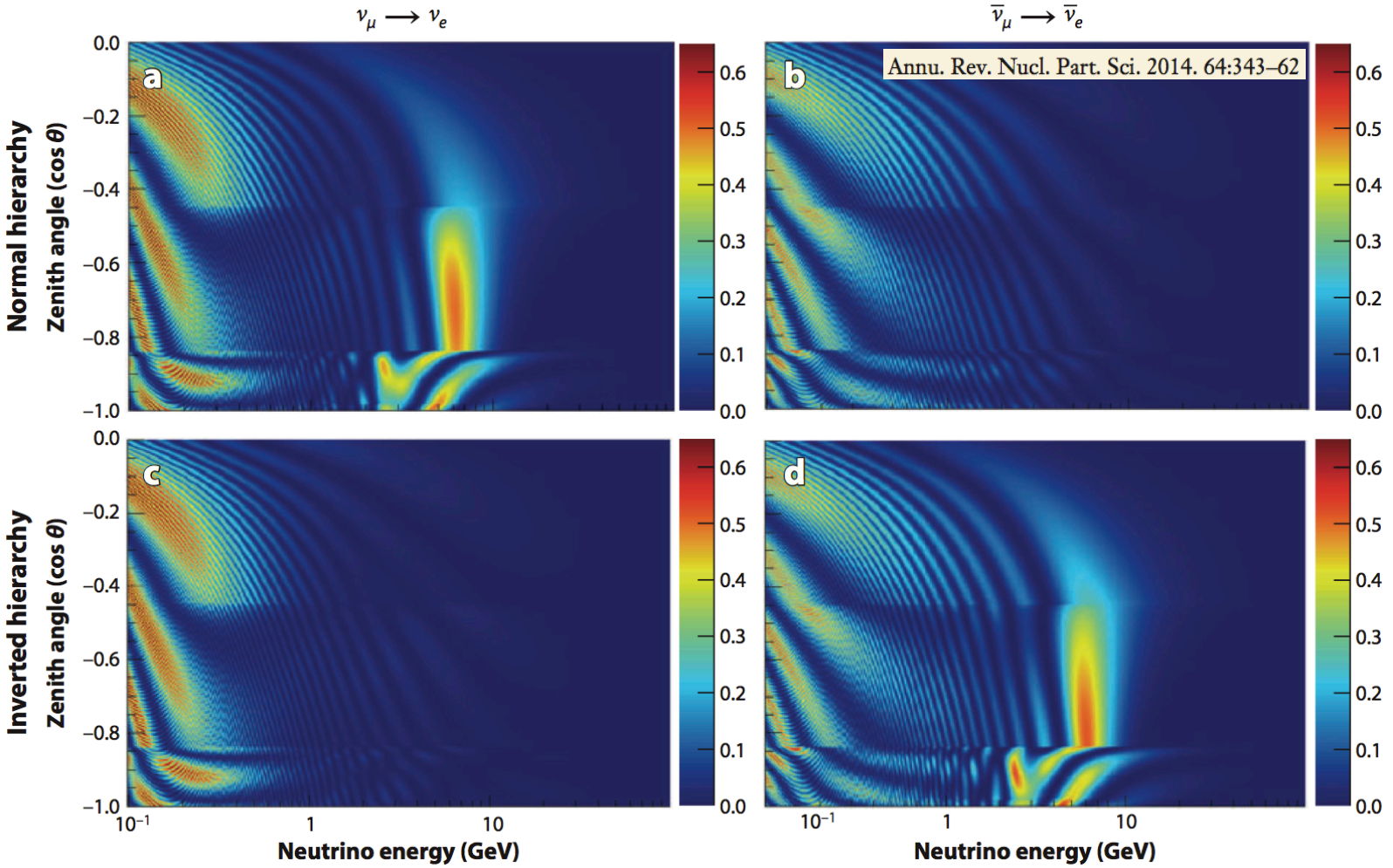
- GeV-scale atmospheric electron and muon neutrinos ideally suited.
- Earth density induces resonance for energies 3 → 10 GeV.



after A.M. Dziewonski, D.L. Anderson, Phys. Earth Planet. Inter., 25 (1981) 297-356

ν_μ to ν_e oscillograms in matter

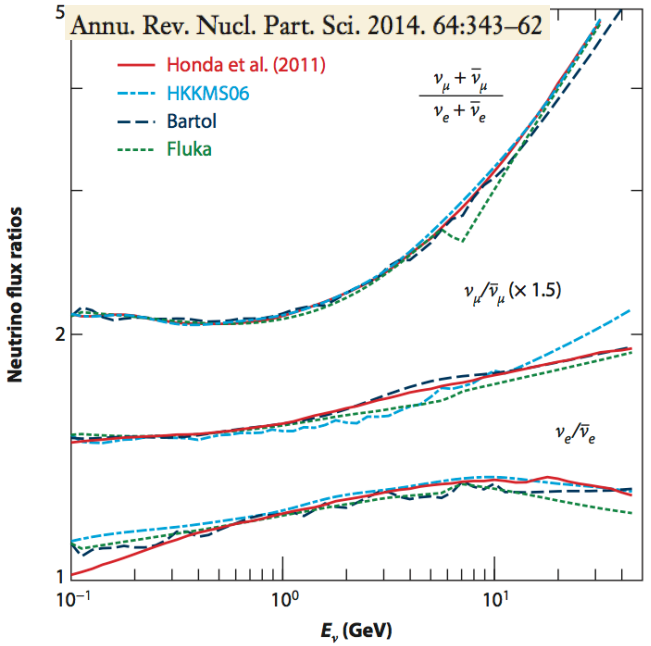
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



Mass hierarchy and atmospheric neutrinos

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

In neutrino telescopes: neutrinos and anti-neutrinos cannot be distinguished, but percent-level net effect remains since:

- neutrino and anti-neutrino cross-sections on the nucleon different at relevant GeV energies: $\sigma(\nu N) \approx 2 \cdot \sigma(\bar{\nu} N)$

- Fluxes of electron / muon neutrinos and anti-neutrinos from the atmosphere are different.