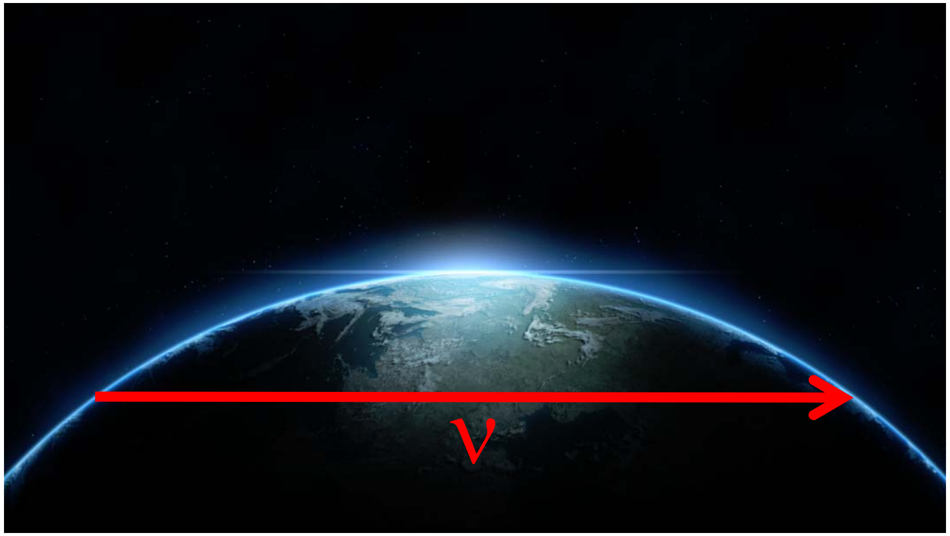
NEUTRINO TELESCOPES AS TARGETS FOR LONG-BASELINE NEUTRINO BEAMS

J. Brunner

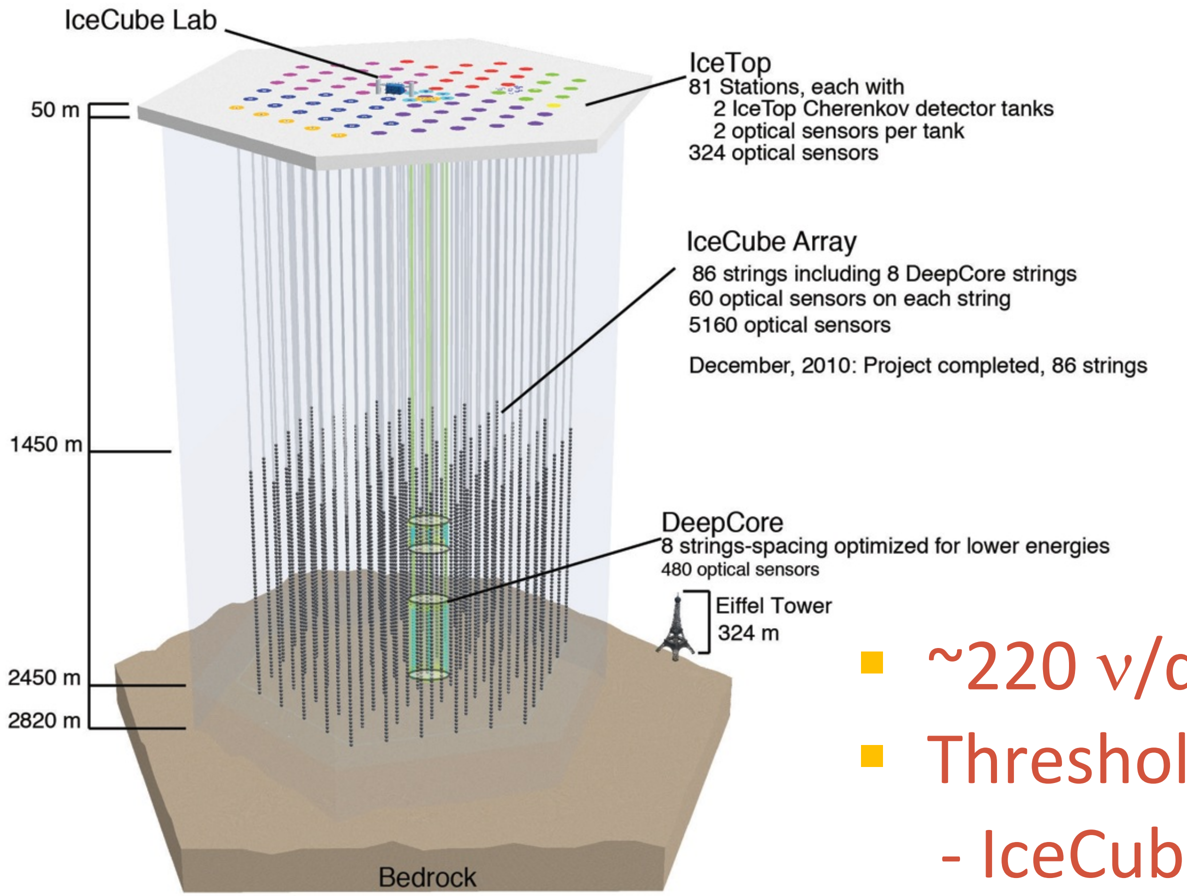
CPPM (Marseille)



Layout

- **Neutrino Telescopes**
  - **(→talk Ch.Spiering, Saturday)**
  - Antares, IceCube/DeepCore
- **Neutrino Oscillations**
  - Results from Antares
  - Results from IceCube/Deep-Core
- **Matter effects & Neutrino Mass hierarchy**
  - PINGU : Low energy extension of IceCube
  - ORCA : Low energy option of KM3Net
- **Neutrino Beams**
  - Muon Event Counting
  - Electron Event Counting

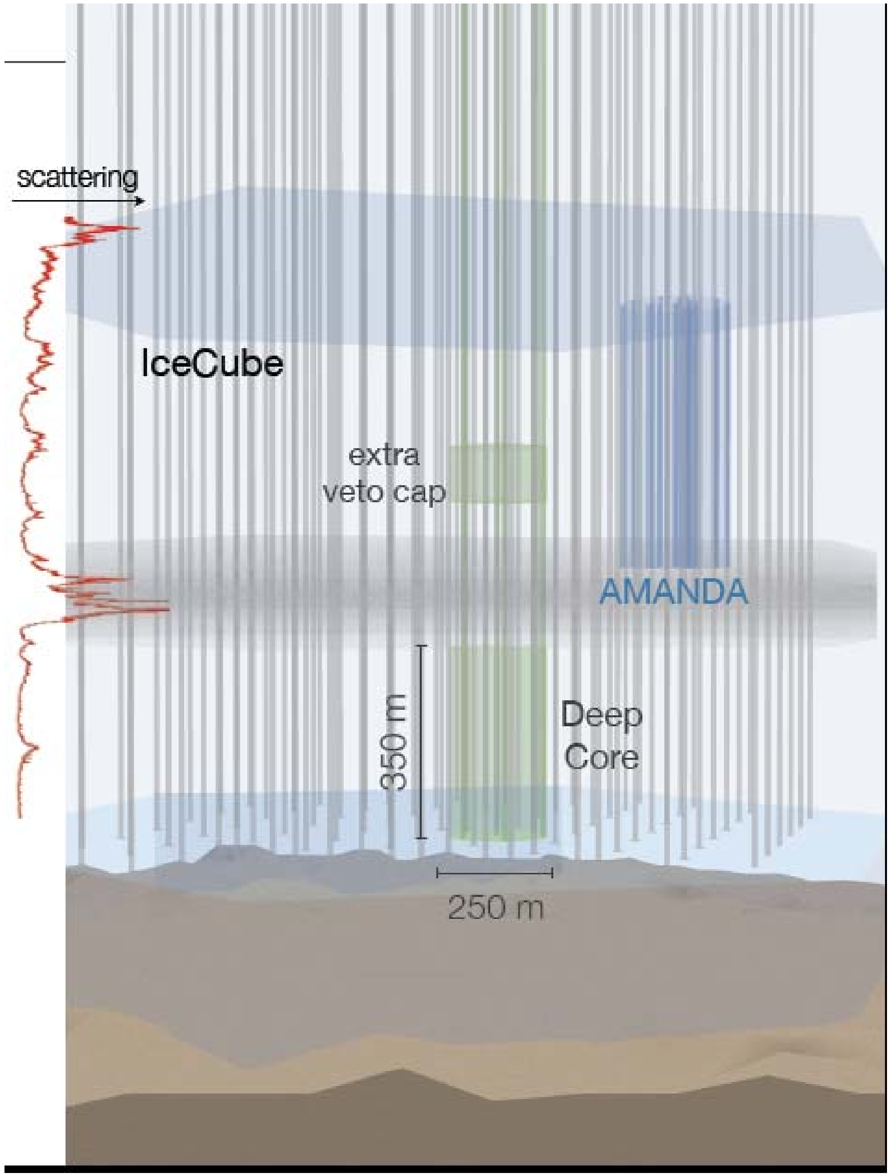
IceCube



- ~220 ν/day
- Threshold
  - IceCube ~ 100 GeV
  - Deep-Core ~10 GeV

Deep-Core

- More densily instrumented than IceCube
  - 8 special strings + 7 nearest standard strings
  - Spacing 45 -72 m
    - (IceCube 125 m)
  - Vertical Spacing 7m
    - (IceCube 20m)
  - Clearest ice (λ_{eff} ~ 45-50 m)
  - High QE PMT (35%)



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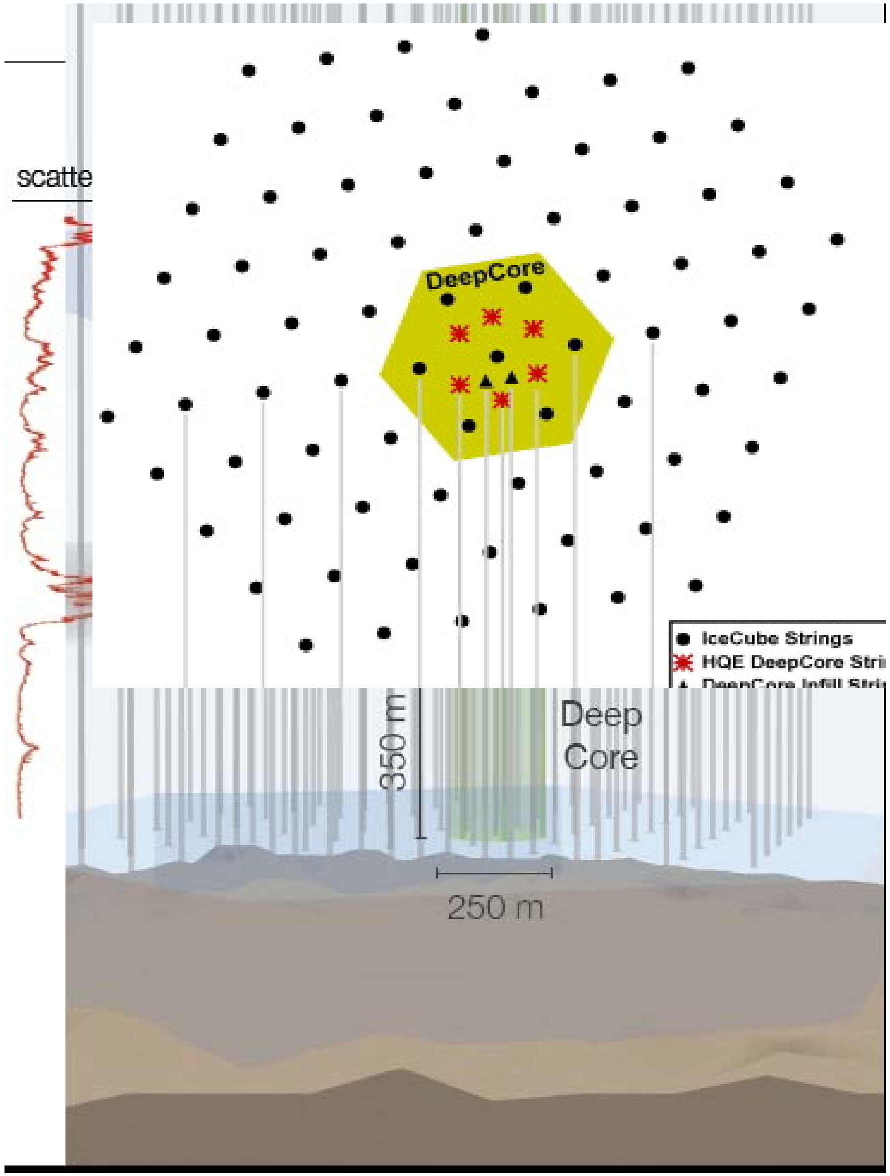
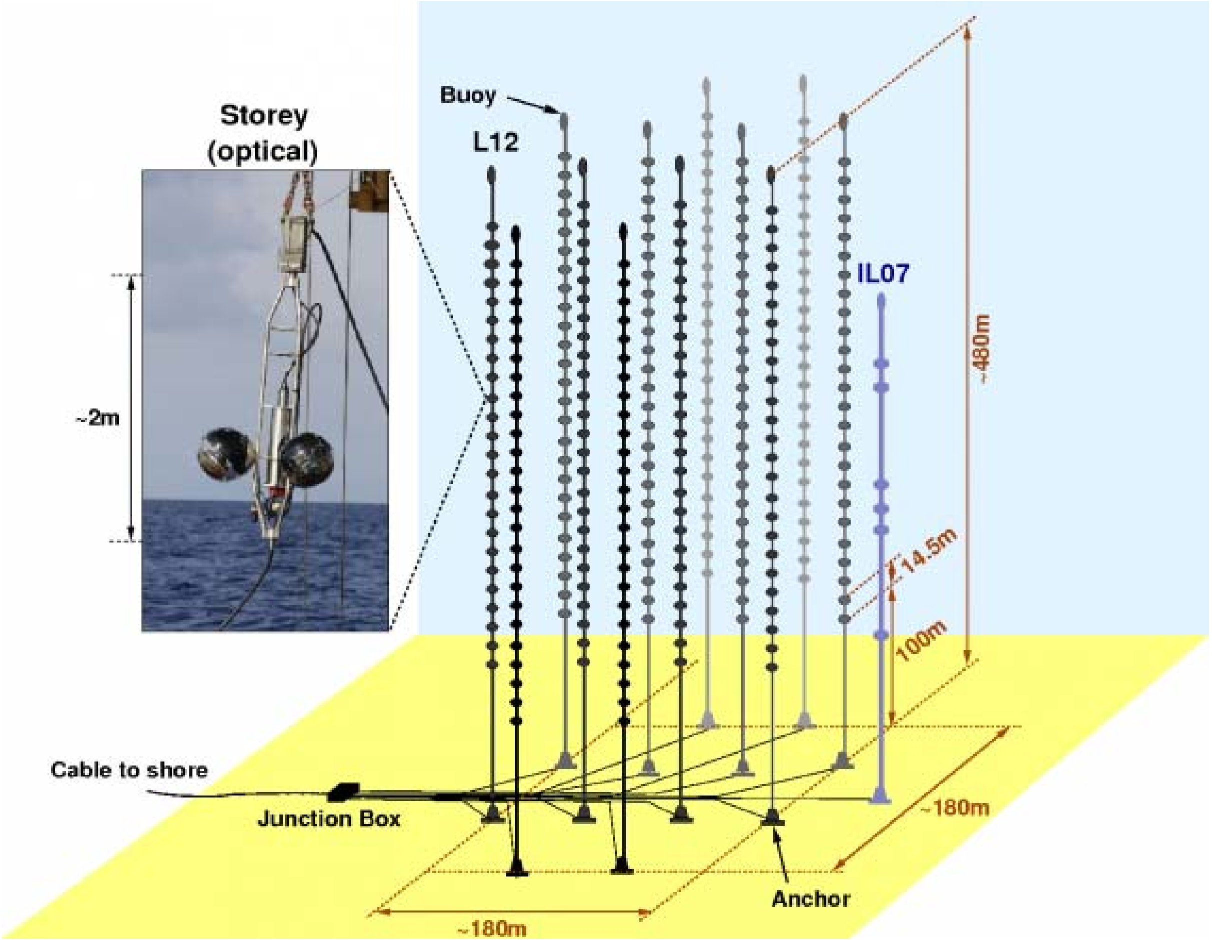


Antares

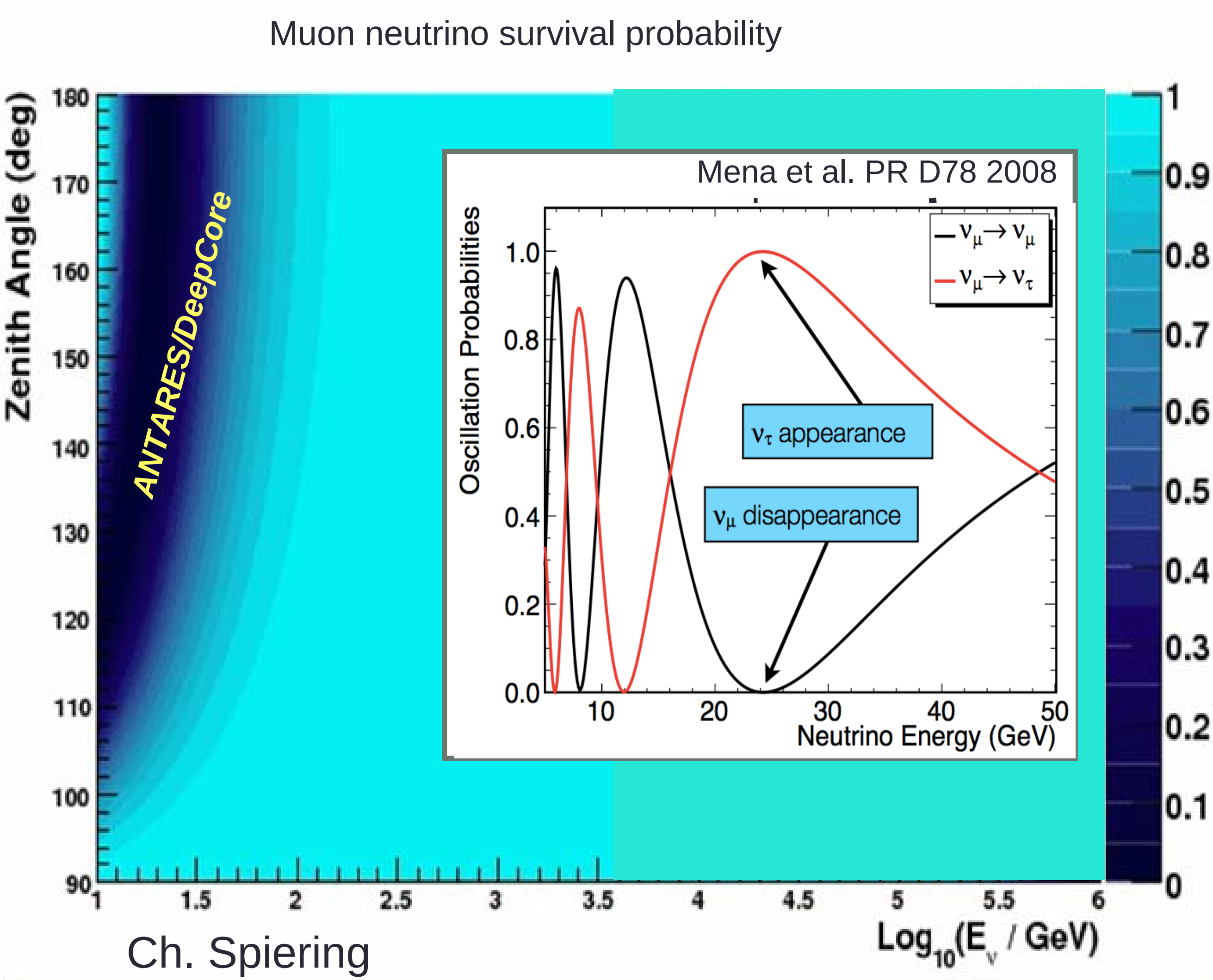
- Mediterranean Sea close to Toulon
- Depth ~2475 km
- Volume ~0.01 km³
- 12 strings,
- each with 25 PMT triplets
- Operating in final configuration since 2008



Oscillations of atmospheric neutrinos

Vertically upward

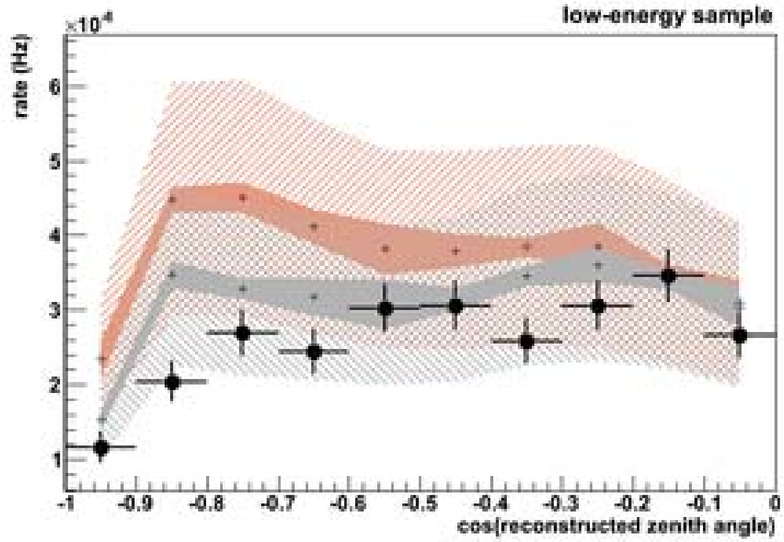
Horizontal



IceCube/Deep-Core results

IC79 :May 2010-April 2011
319 days lifetime
Neutrino events:
    719 DeepCore
    38000 high energy
Zenith angle only analysis

arXiv:1305.3909



IC86 :May 2011-April 2012
343 days lifetime
1487 neutrino events
Strict selection : “direct light”

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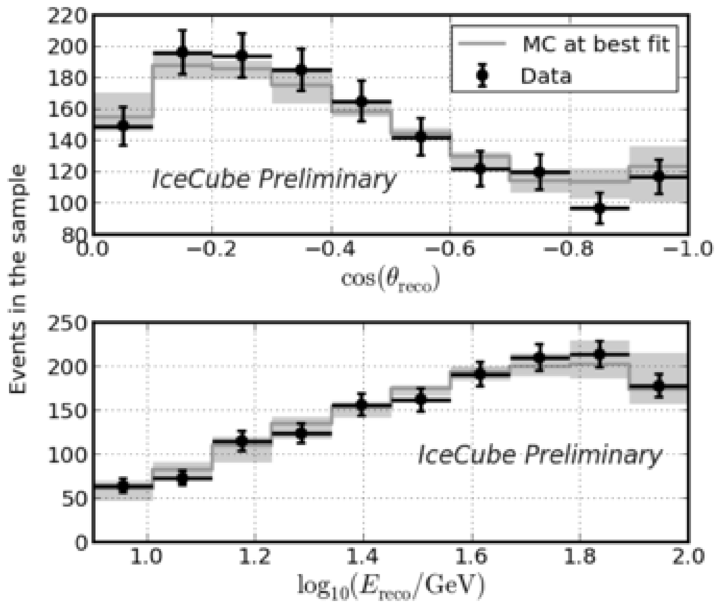

Summary of Results

- Clear signal of atmospheric neutrino oscillations seen in IceCube and Antares

- IceCube/DeepCore :
  - One year of data analysed
  - Strong potential for future studies

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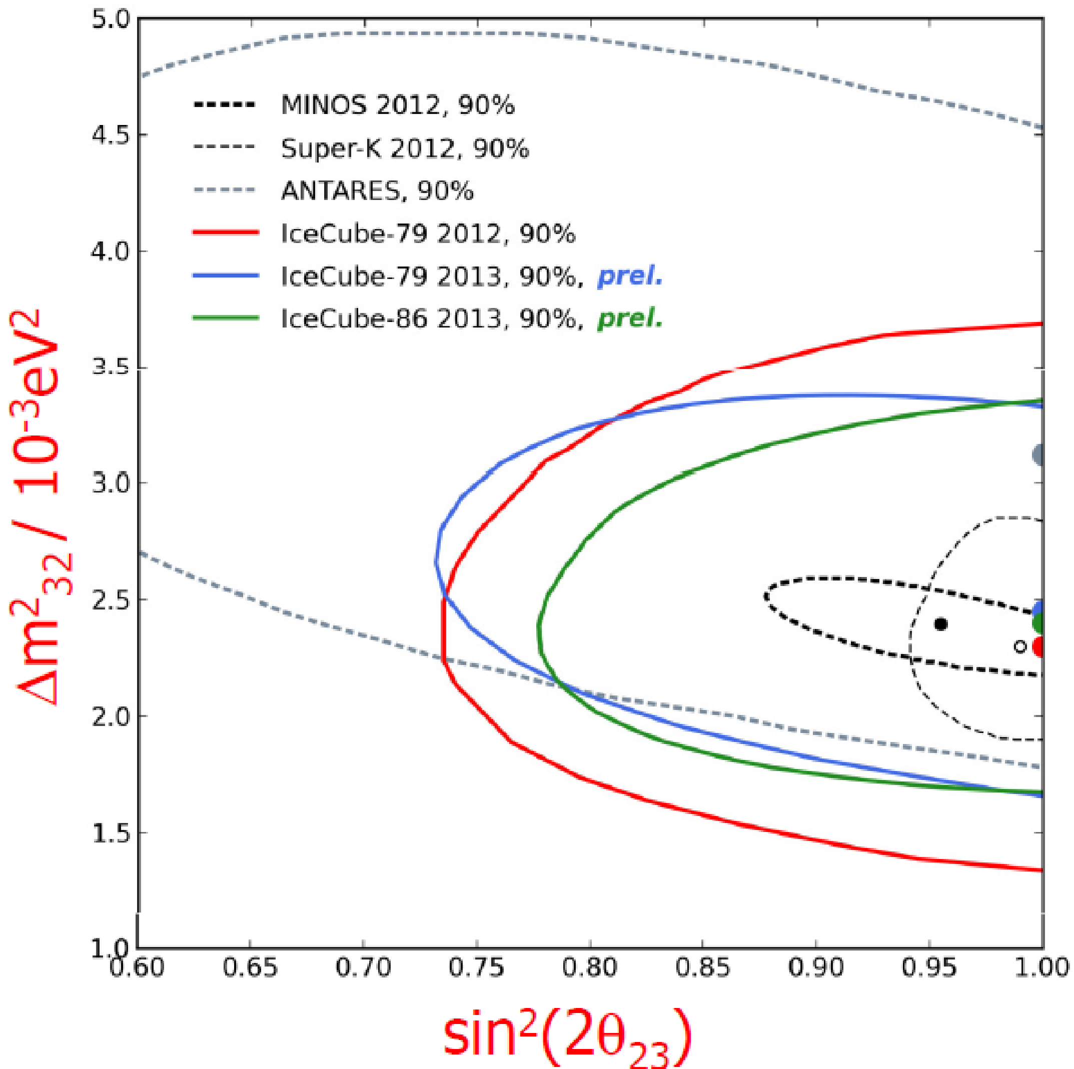

Deep-Core 6 years (2017)

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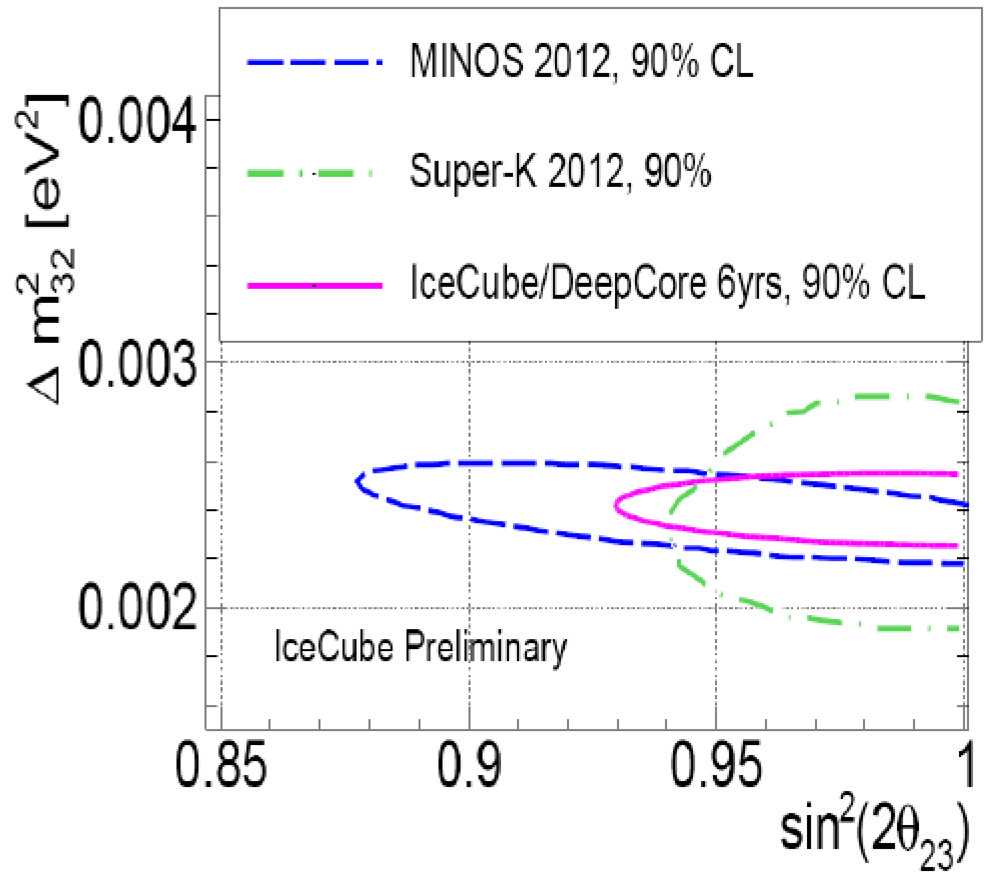
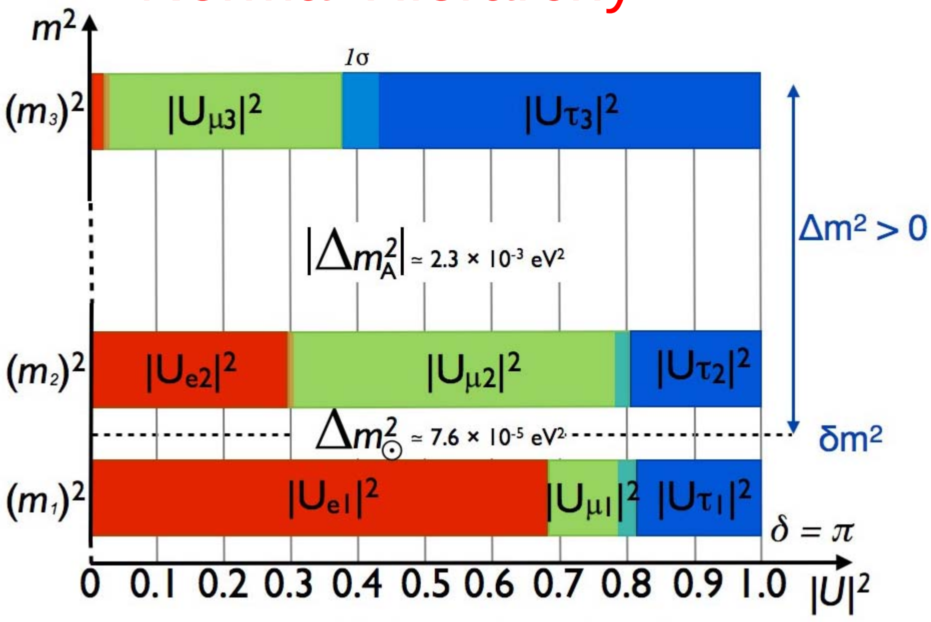
- Current results statistics limited
- Shown extrapolation assumes additional improvements

1) Higher efficiency
2) Better resolutions
3) Smaller systematics uncertainties

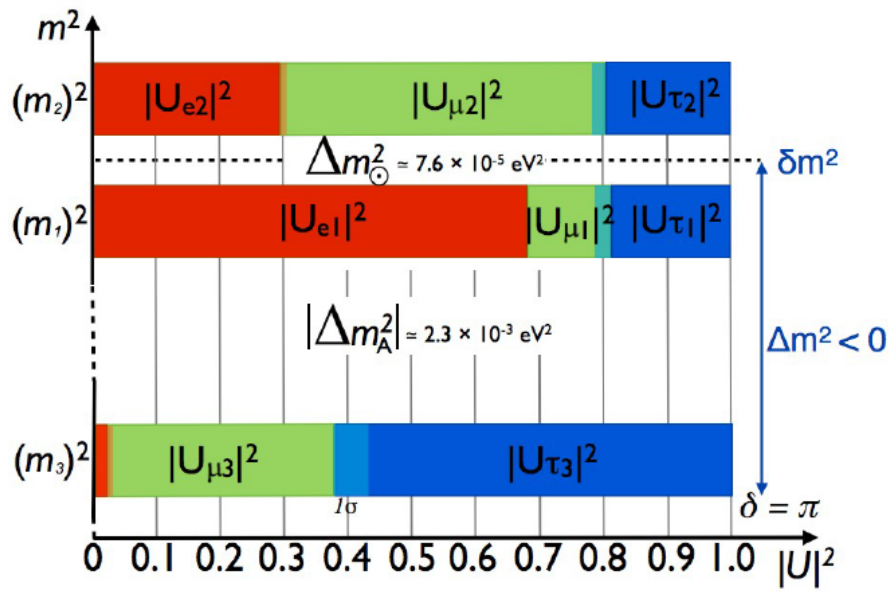


Matter effects & Mass Hierarchy

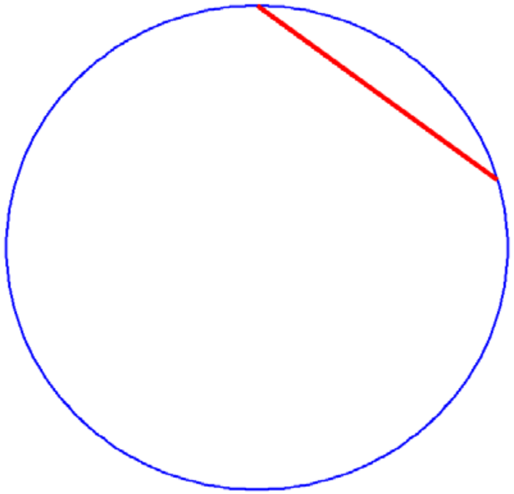
- Solar Neutrinos : Matter effects inside sun
  - → $m_2 > m_1$
- Matter effects in Earth (not yet measured !)
  - → $m_3 >< m_1, m_2$
- Normal Hierarchy



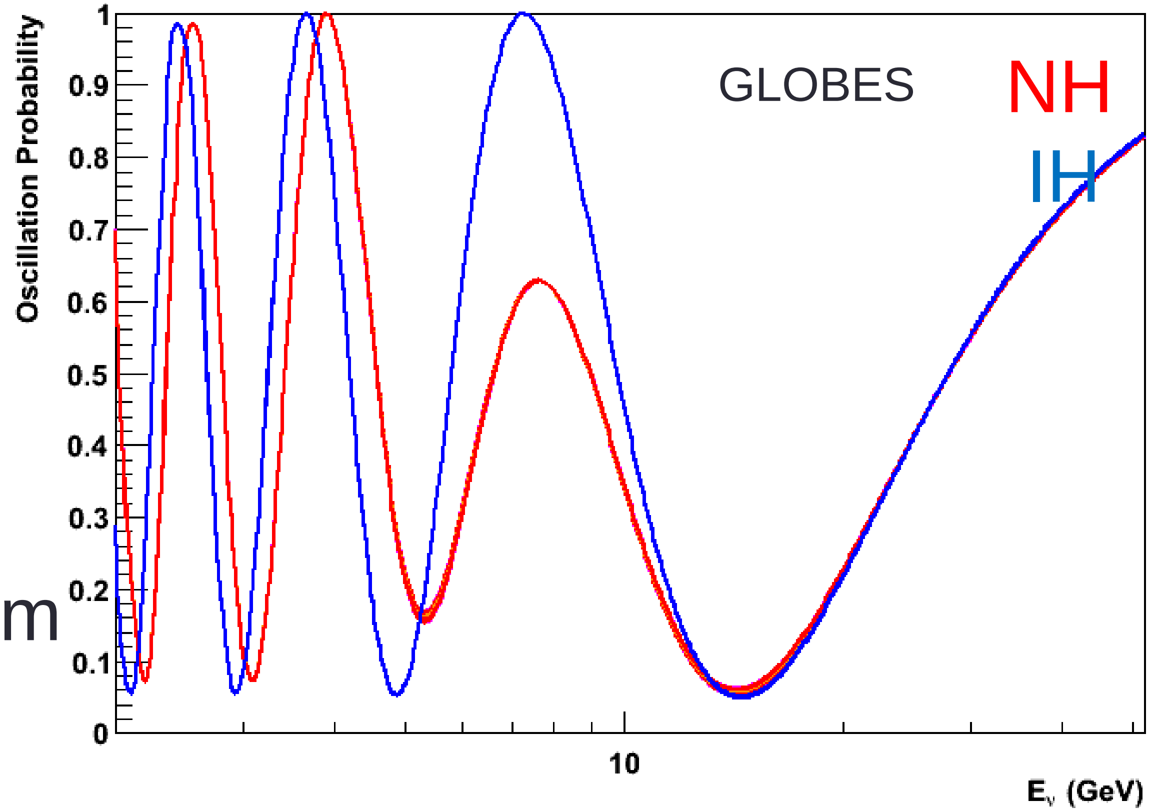
Inverted Hierarchy



Example Earth Matter Effect : $P(\nu_\mu \rightarrow \nu_\mu)$



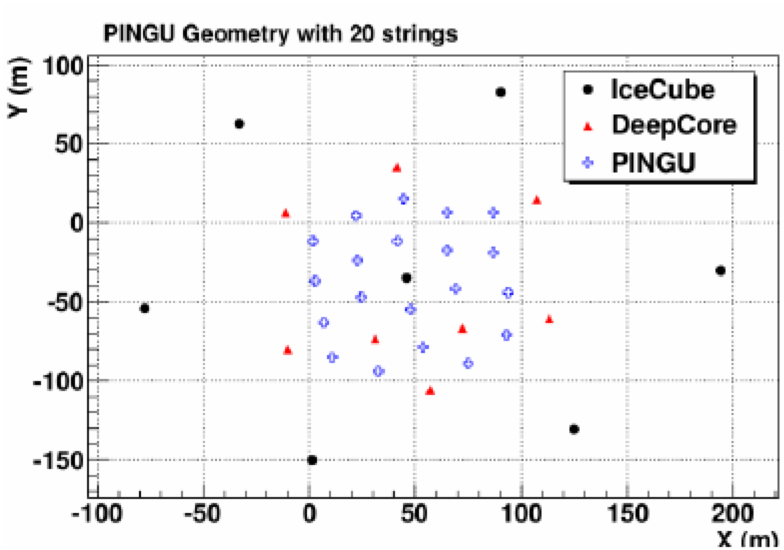
Resonance energy Earth mantle : 6-7 GeV

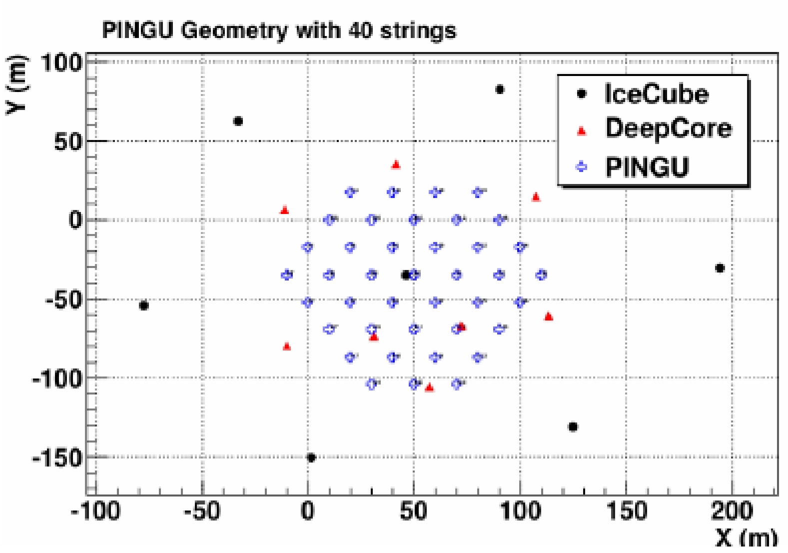


$\cos\theta = 0.6$
Baseline = 7645 km
Inclination = 36.9°

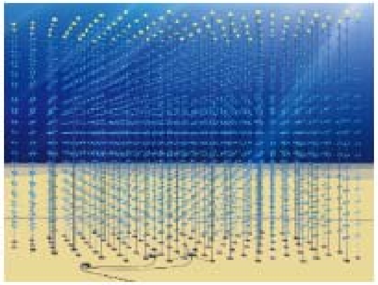
PINGU Design

- Precision IceCube Next Generation Upgrade
- 20-40 Additional Strings inside Deep-Core Volume
- Strings ~300m high, 60-120 Optical Modules
- Instrumented Volume 3-4 Mtons
- Energy threshold ~2 GeV

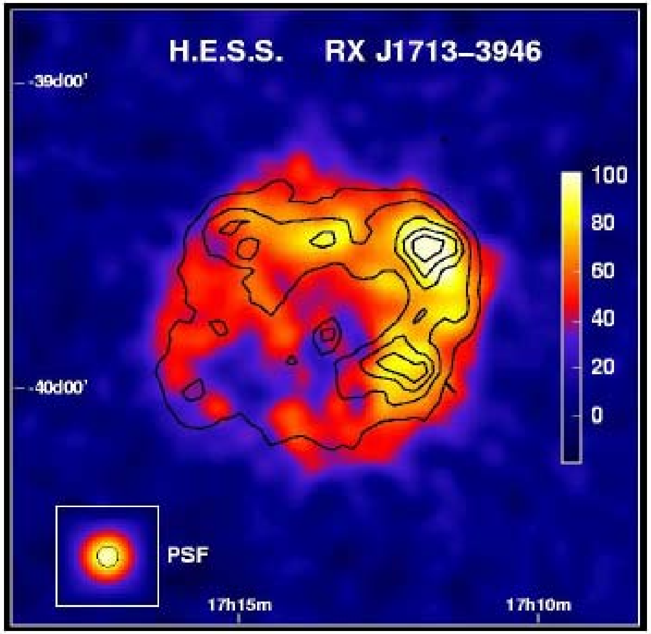




KM3Net project



- Next generation (multi-km^3) neutrino telescope in Mediterranean
- Main goal: detection of ν from galactic sources (SNR)
- recent milestones
  - multi-pmt Optical Module design agreed & prototyped
  - string configuration
  - partial funding obtained
    - ~1/5 of total wishes (~50 strings)
    - must be spent soon → 'phase 1'



KM3Net project

Mutliple small pmt's (helps in photon-counting and background rejection)

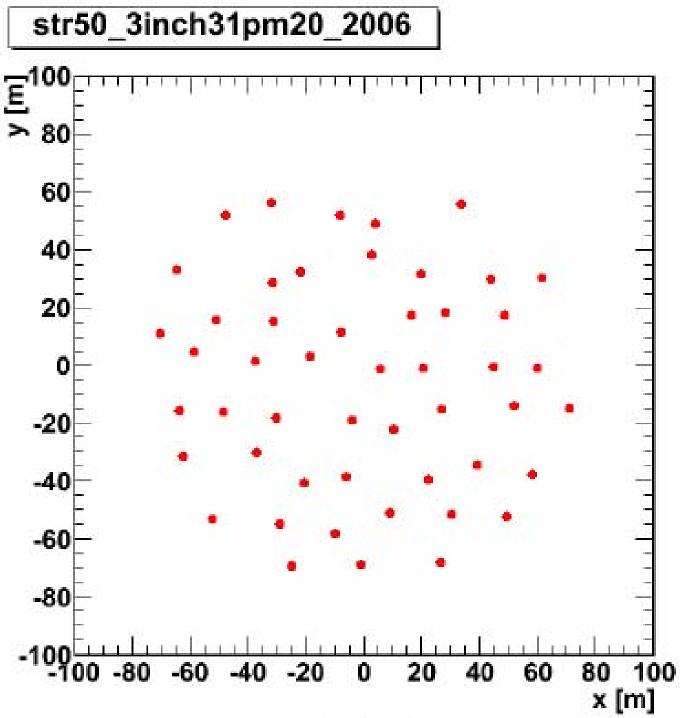
KM3NeT Optical Module integrated in Antares instrumentation line. →

KM3Net – ORCA Layout

Oscillation Research with Cosmics in the Abyss

Instrumented volume = 1.75 Mt

- ✓ 50 Strings
- ✓ OM=31 3"PMTs
- ✓ 20 OM in each string
- ✓ 6 m vertical distance between OM
- ✓ 20 m average distance between strings

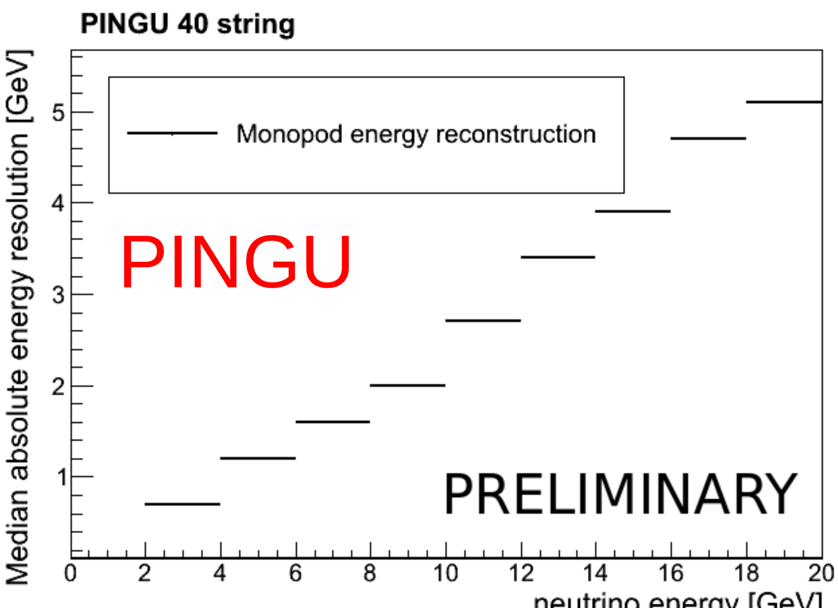


String number can be scaled according to financial situation
Other parameters determined by deployment constaints

PINGU – ORCA : Energy

- Energy reconstruction from total light yield
- Ice is a better calorimeter due to scattering

- Energy reconstruction from fitted track length



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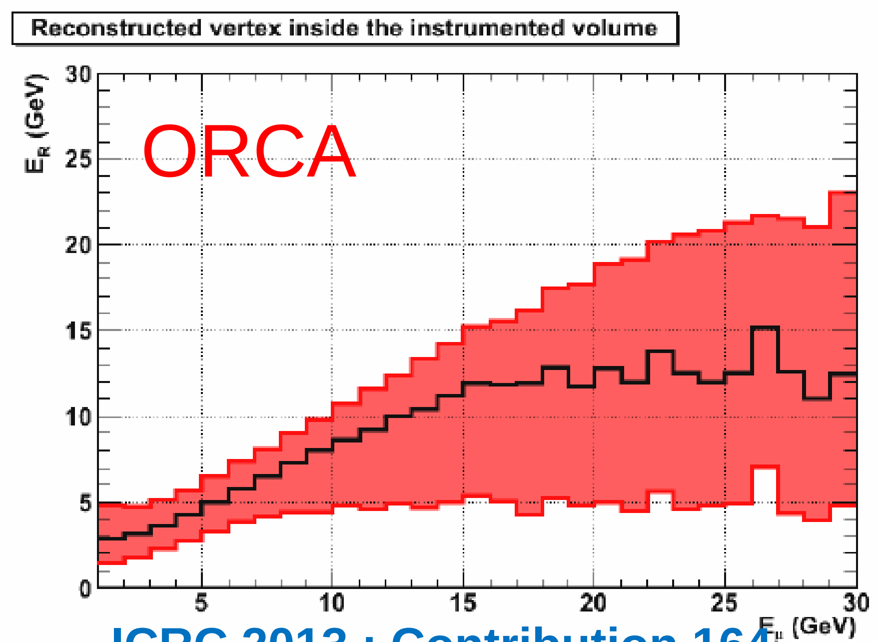

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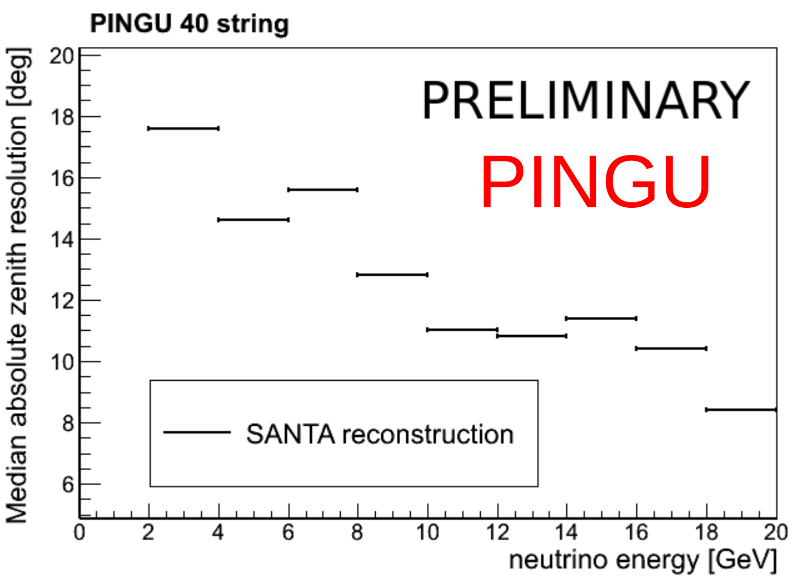
PINGU – ORCA : Zenith angle

- Resolution close to kinematical limit
- Water is a better tracker due to absence of scattering



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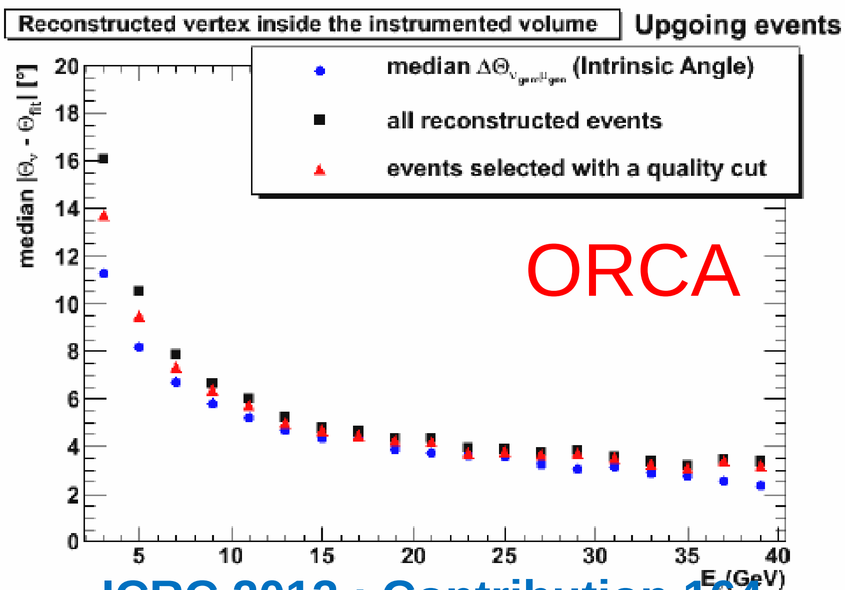

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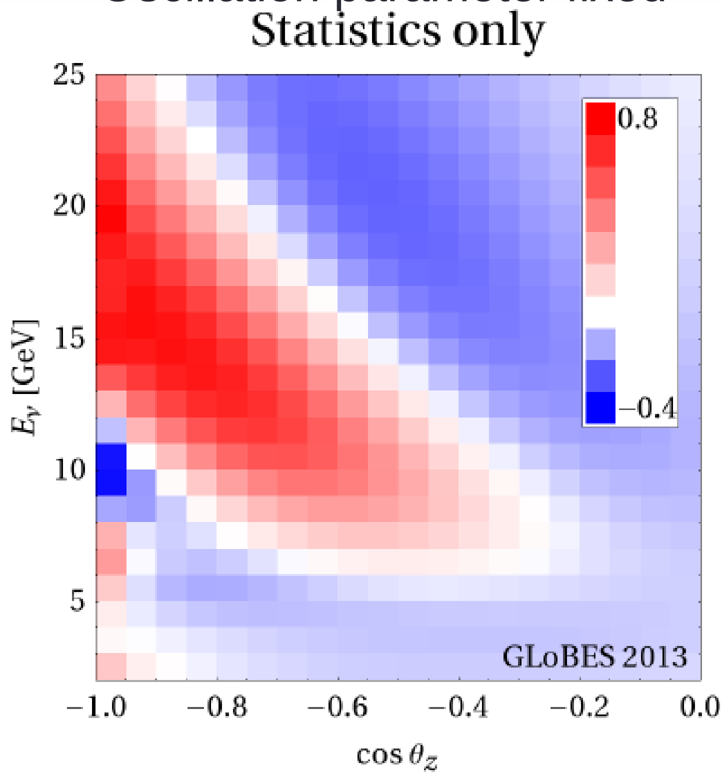
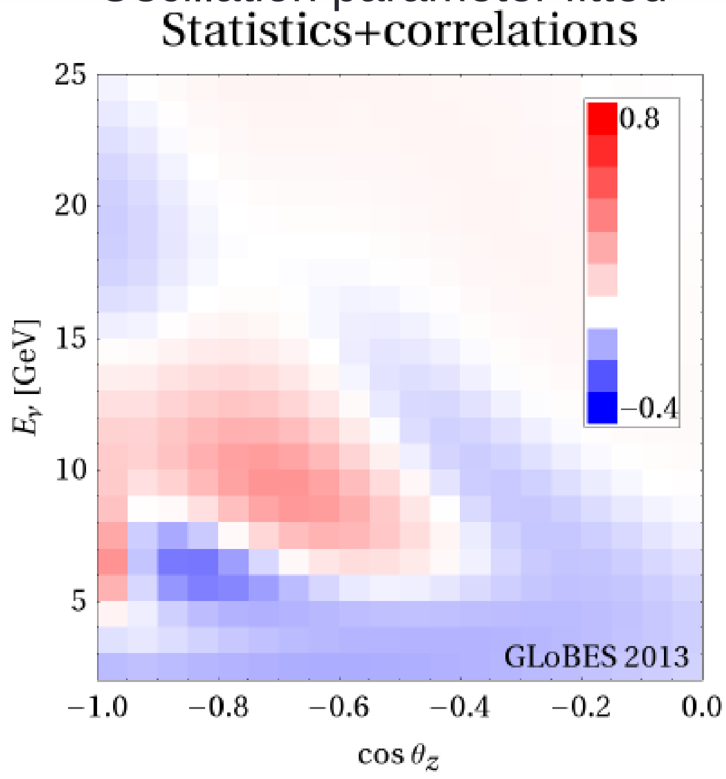
Sensitivity Calculation

- Fit of event count in Energy-Zenith space
- Color code : bin-by-bin significance of hierarchy difference

Oscillation parameter fixed



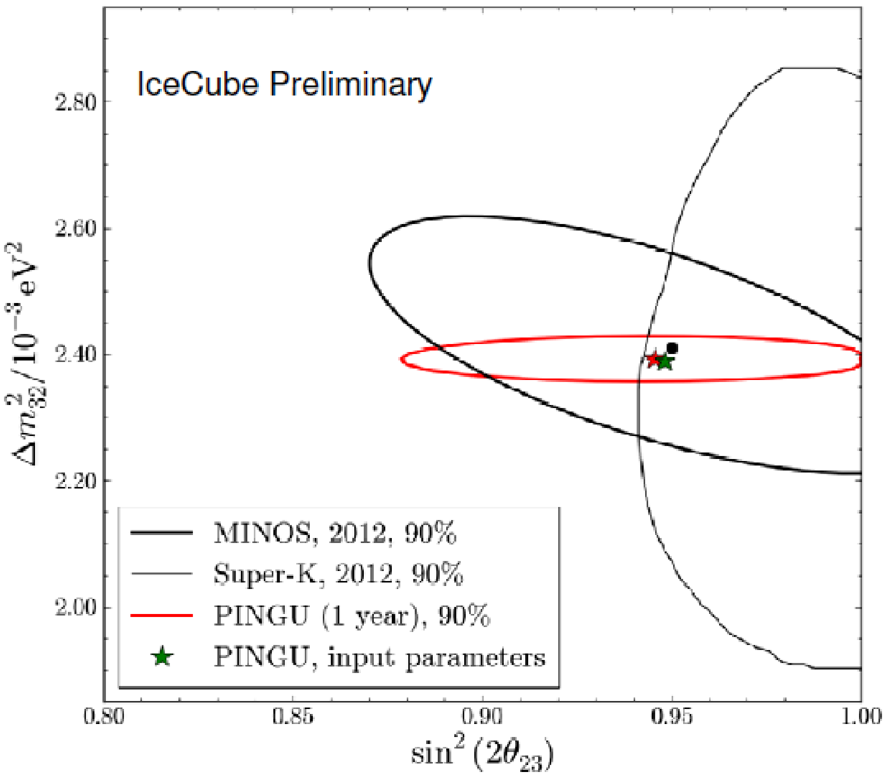
Oscillation parameter fitted



W. Winter : arXiv:1305.5539

PINGU Oscillation parameters

- Side effect of correlation between mass hierarchy and oscillation parameters
- After one year of data taking with PINGU competitive measurement of dm^2_{32}



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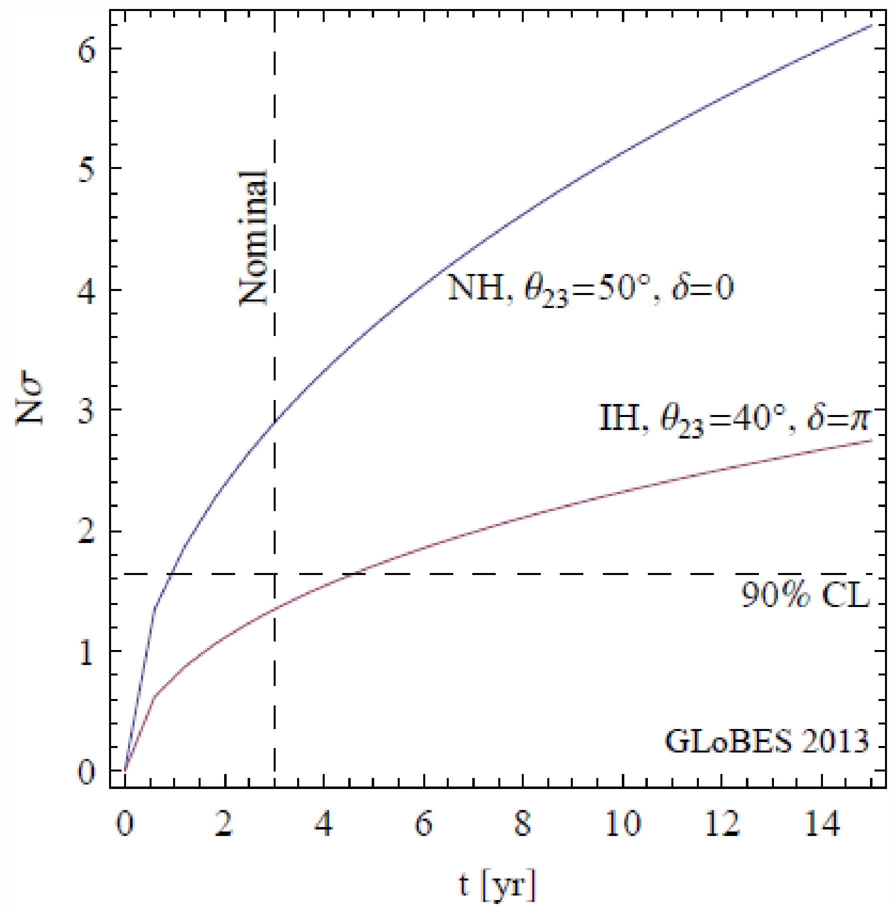
Sensitivity Calculation

- 3 years PINGU (20 lines)
- 1.3-2.9 sigma separation of mass hierarchy hypothesis

- Challenges of measurements with atmospheric neutrinos:
- Cancellations !
  - neutrinos / antineutrinos
  - muons / electrons (flavour ID)
  - Energy resolution
  - Oscillation parameters



W. Winter : arXiv:1305.5539

Neutrinos from Beams

- Eliminate ambiguities
- Improve mass hierarchy sensitivity

COUNTING MUONS TO PROBE THE NEUTRINO MASS SPECTRUM

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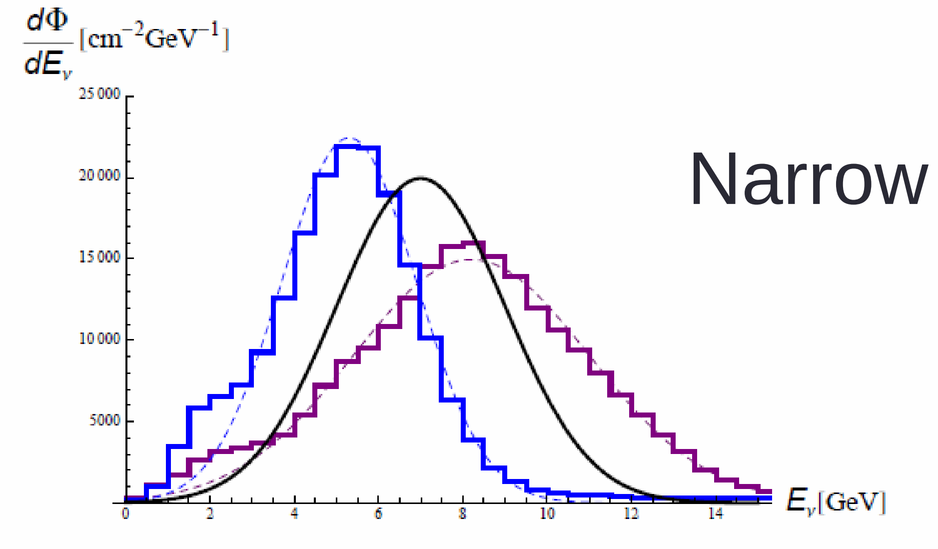
[2] DEPARTAMENTO DE FISICA, DCEI, UNIVERSIDAD DE GUANAJUATO, LEÓN, GUANAJUATO, MÉXICO
[3] GRAN SASSO SCIENCE INSTITUTE (INFN), L'AQUILA, ITALY

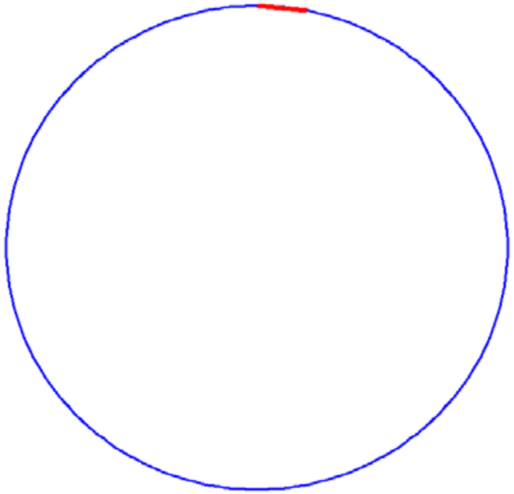
arXiv:1301.4577

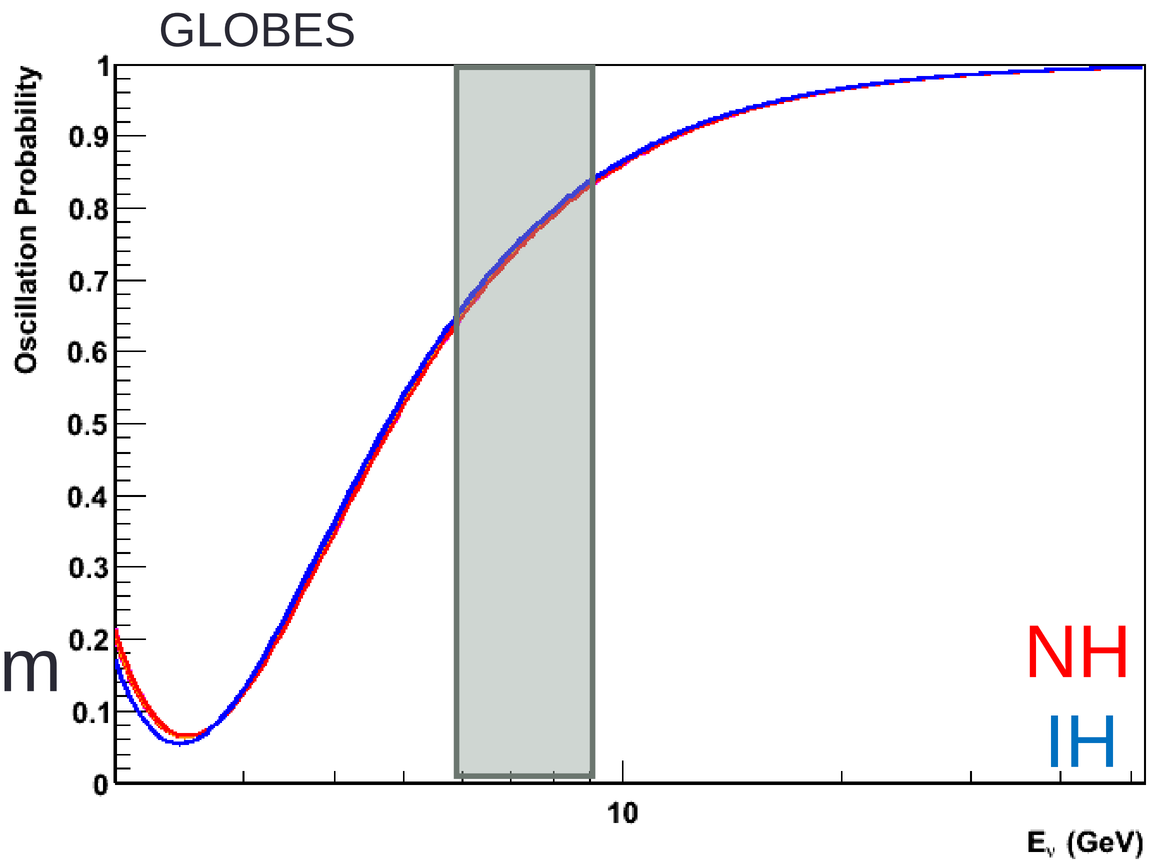


Narrow band beam 6-9 GeV

10^{20} p.o.t.

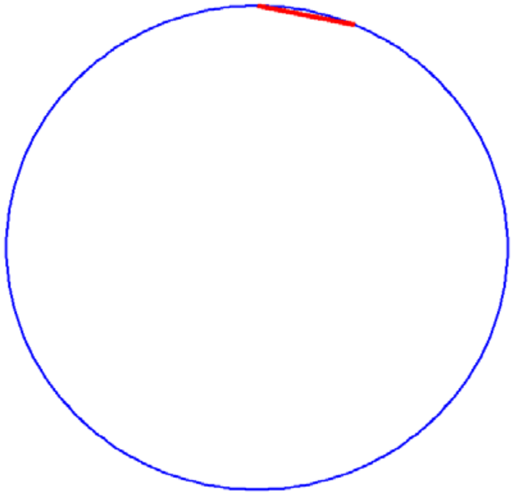
$P(\nu_\mu \rightarrow \nu_\mu)$

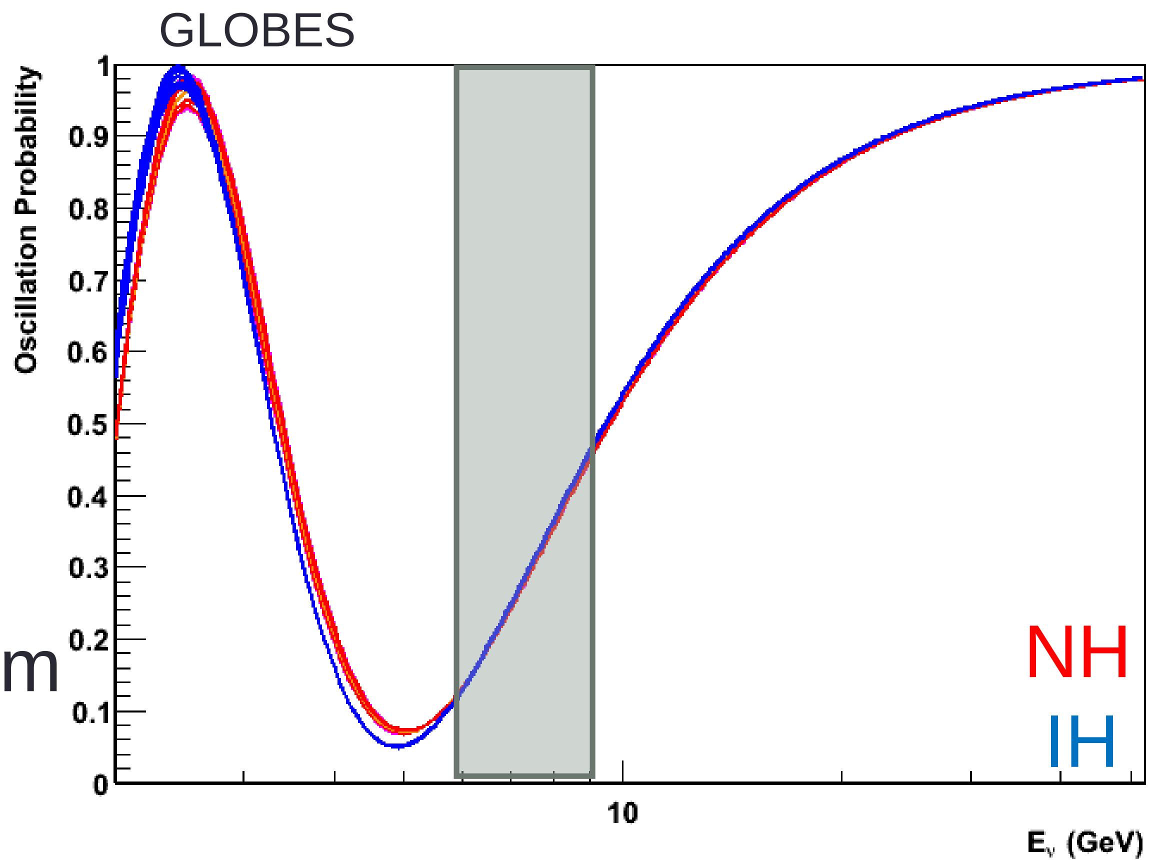




$\cos\theta = 0.1$
Baseline = 1274 km
Inclination = 5.7°

$P(\nu_\mu \rightarrow \nu_\mu)$



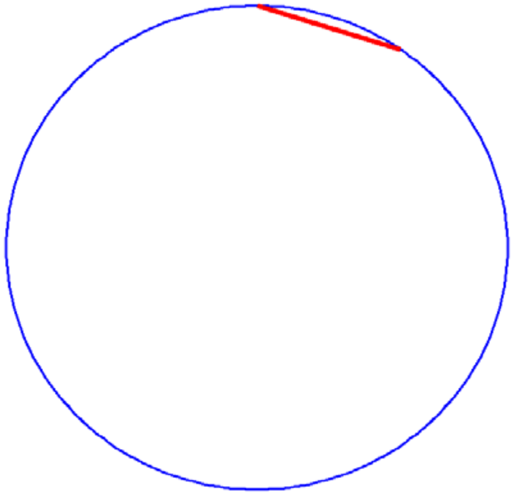


cosθ = 0.2

Baseline = 2548 km

Inclination = 11.5°

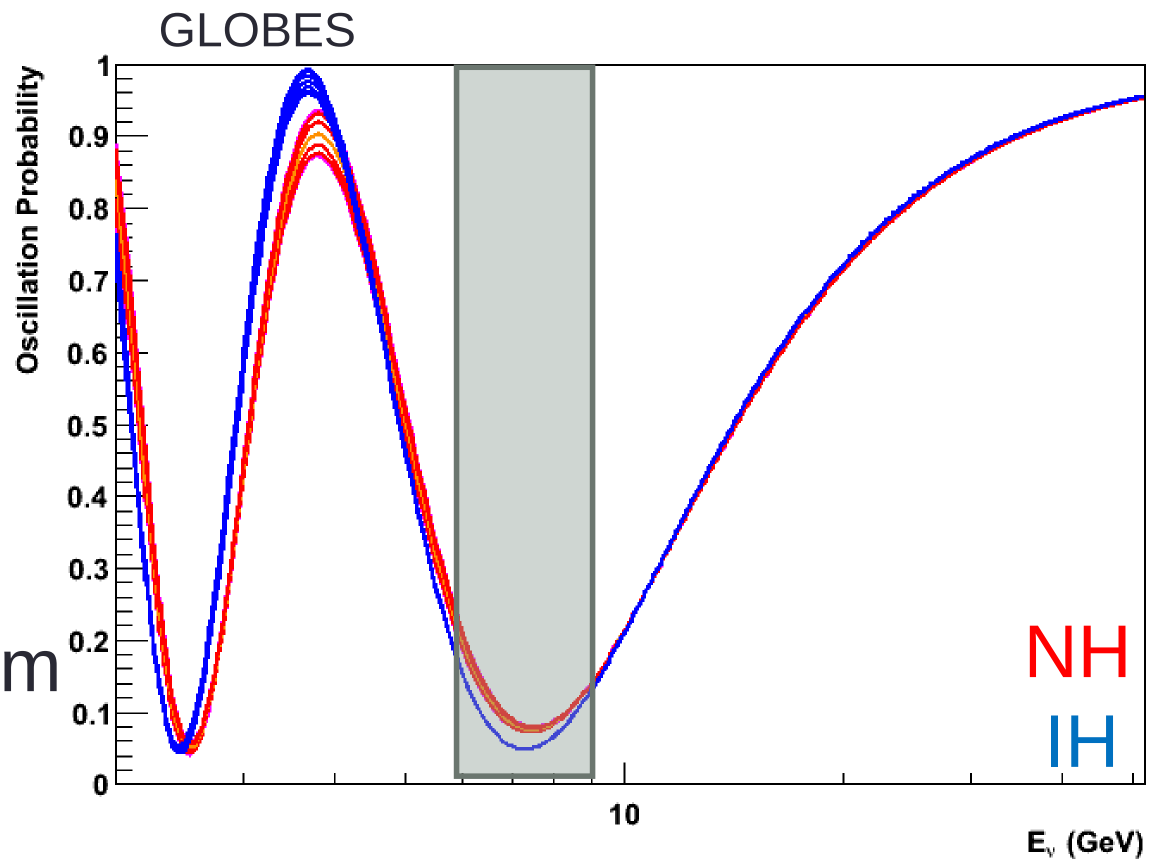
$P(\nu_\mu \rightarrow \nu_\mu)$



$\cos\theta = 0.3$

Baseline = 3823 km

Inclination = 17.4°



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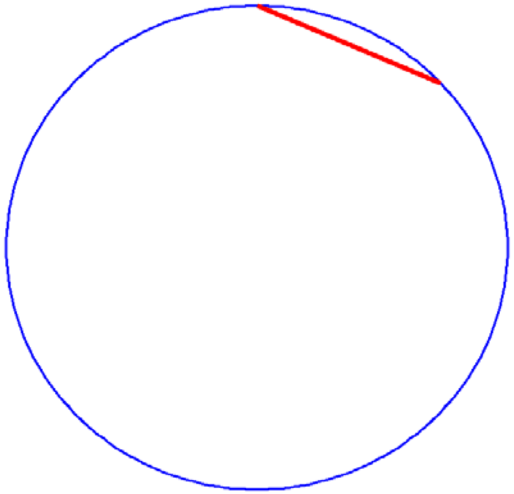
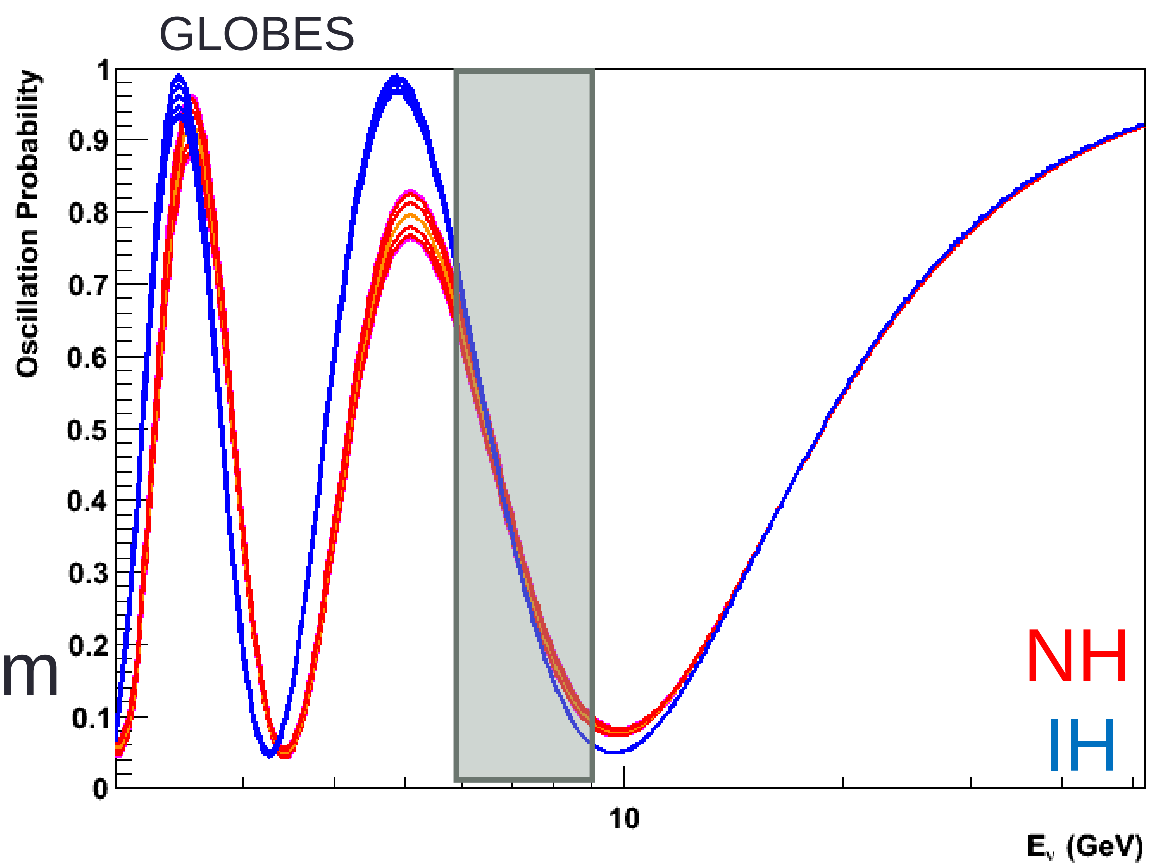
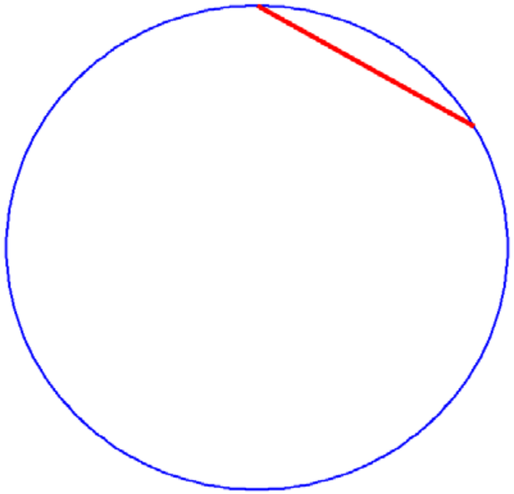


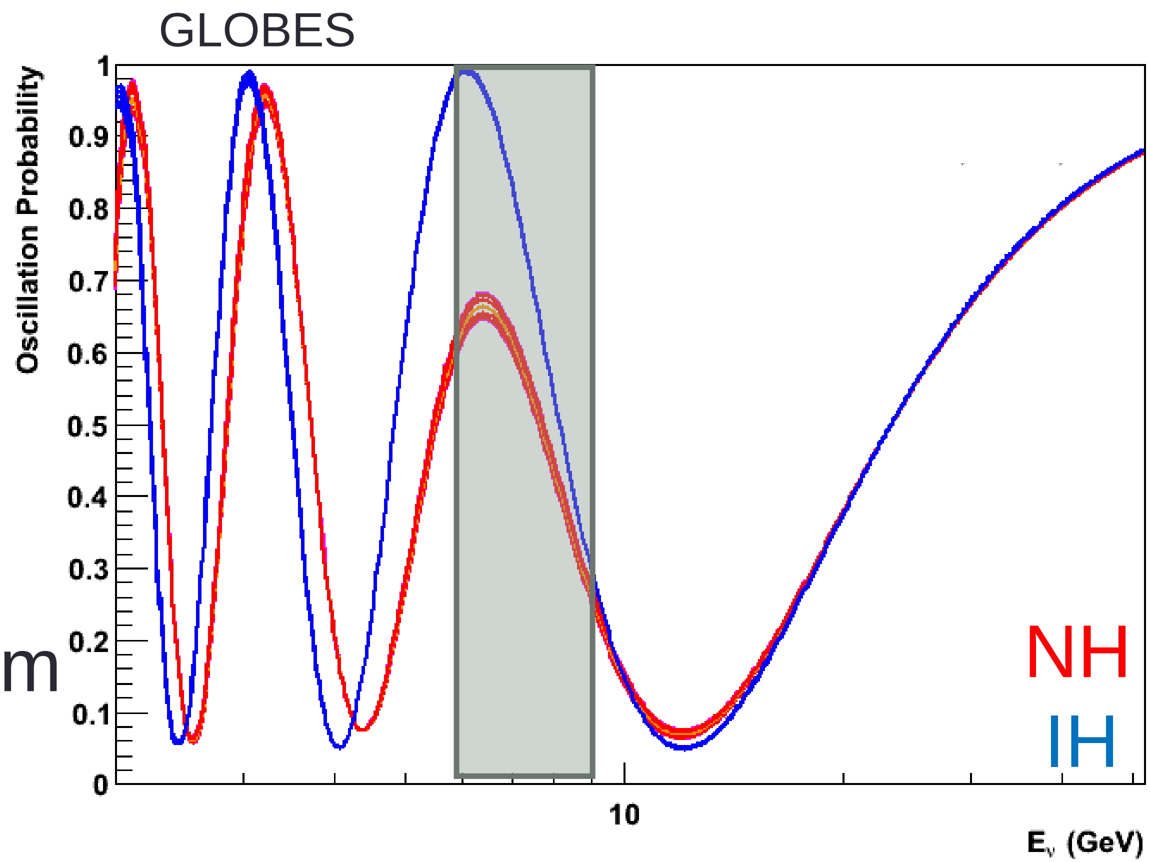
cosθ = 0.4
Baseline = 5097 km
Inclination = 23.6°



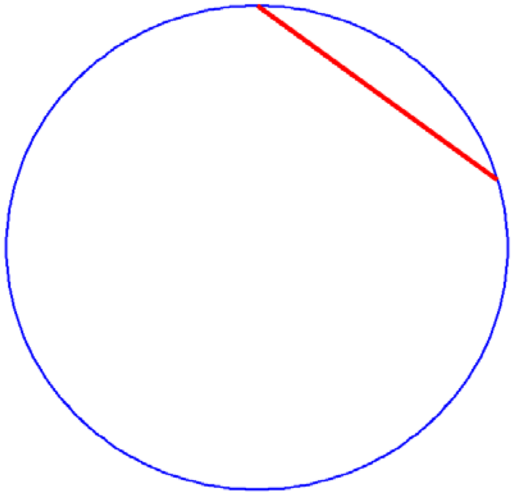
$P(\nu_\mu \rightarrow \nu_\mu)$



$\cos\theta = 0.5$
Baseline = 6371 km
Inclination = 30.0°



$P(\nu_\mu \rightarrow \nu_\mu)$



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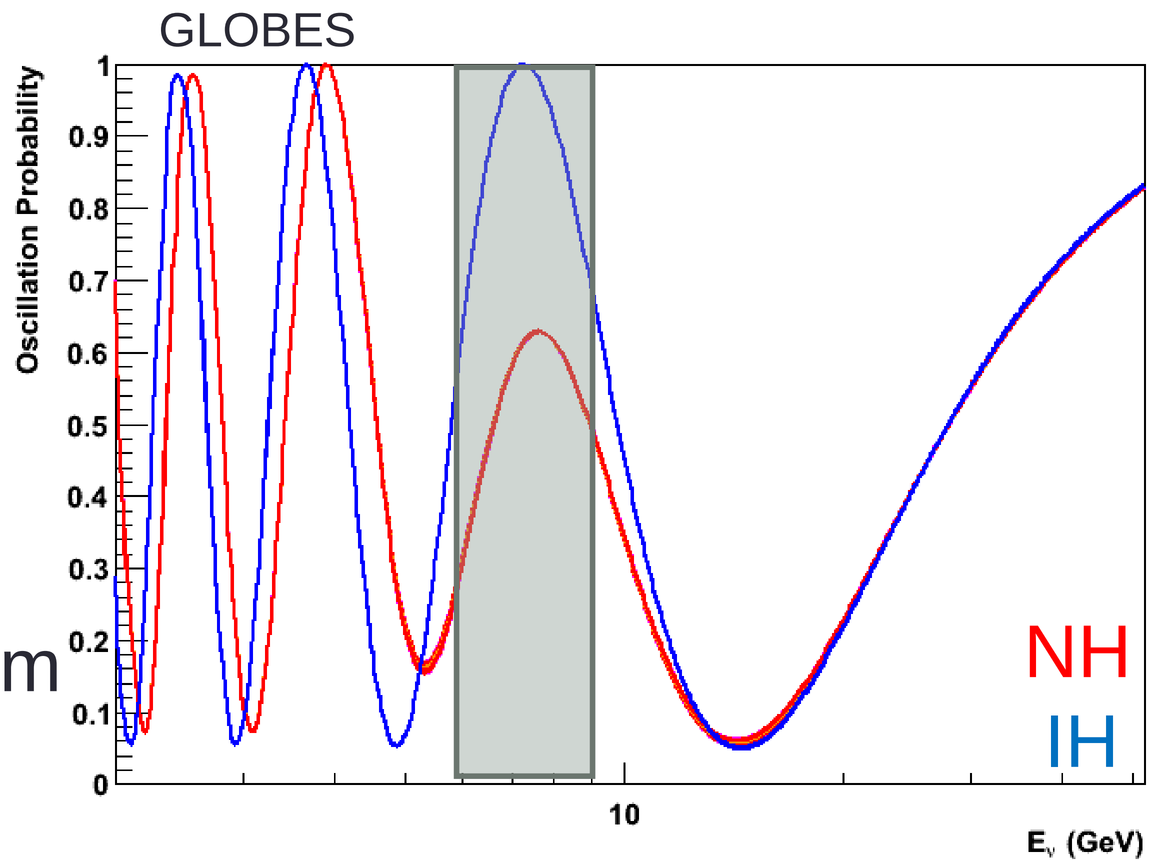
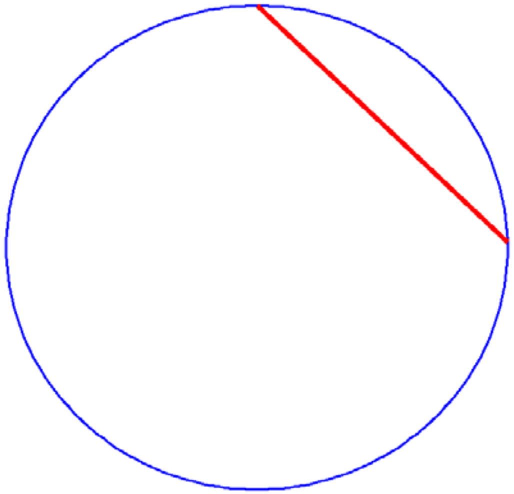
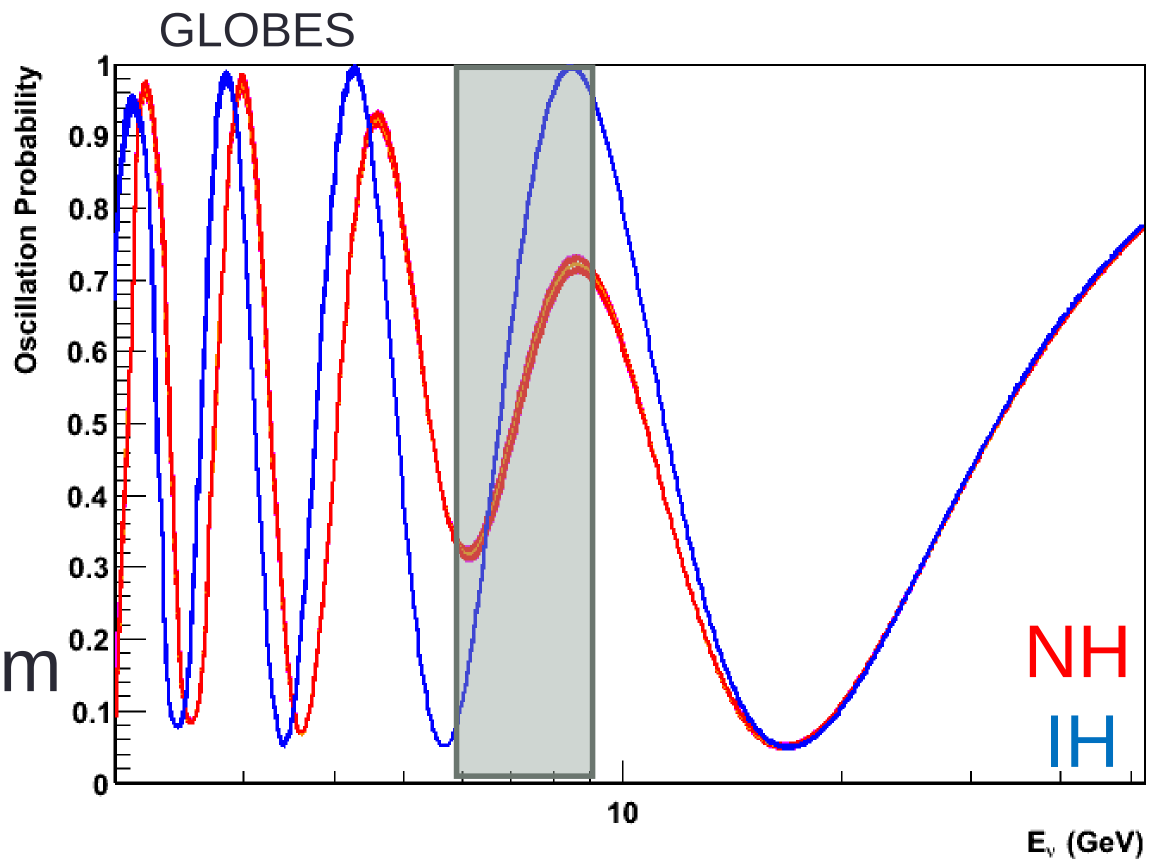


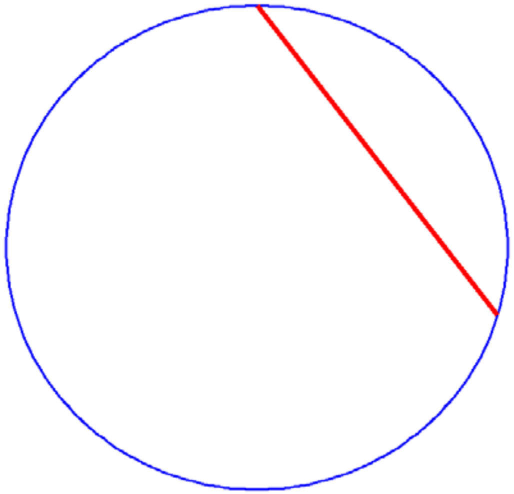
$P(\nu_\mu \rightarrow \nu_\mu)$



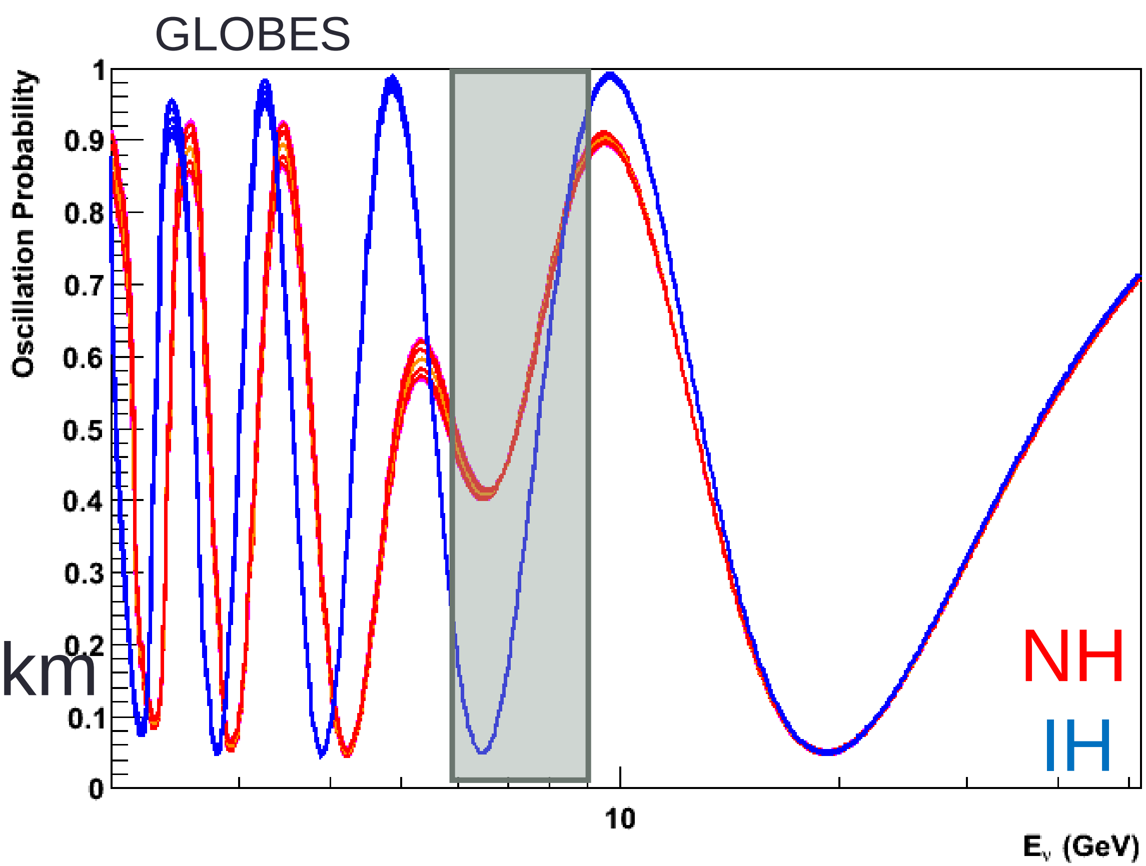
$\cos\theta = 0.7$
Baseline = 8919 km
Inclination = 44.4°



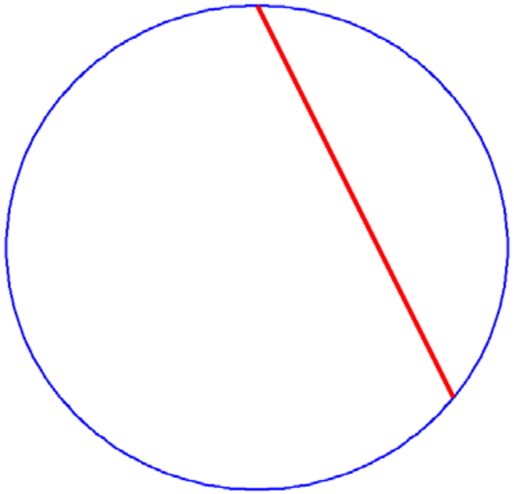
$P(\nu_\mu \rightarrow \nu_\mu)$



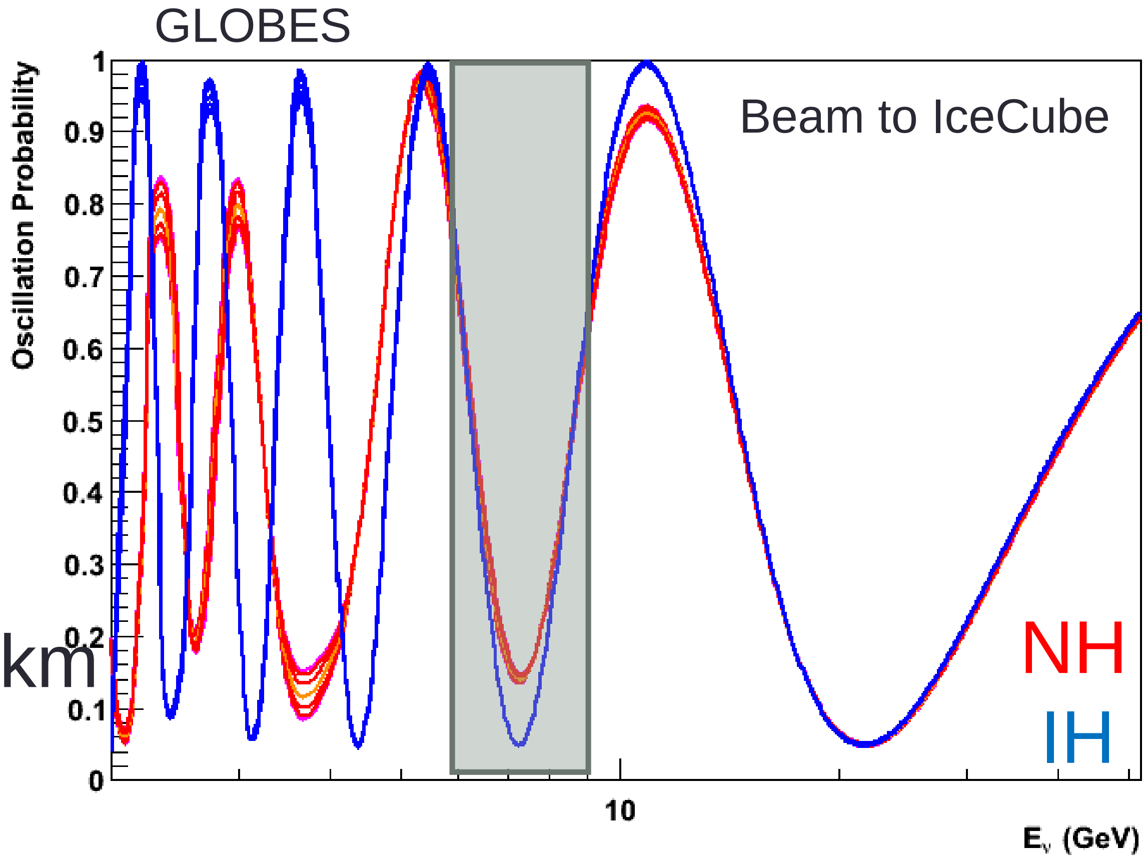
$\cos\theta = 0.8$
Baseline = 10194 km
Inclination = 53.1°



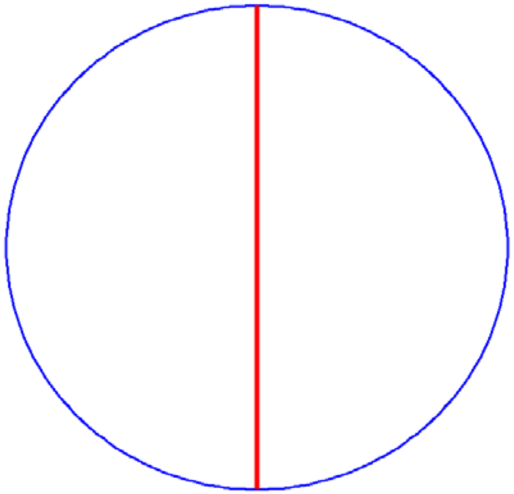
$P(\nu_\mu \rightarrow \nu_\mu)$



cosθ = 0.9
Baseline = 11468 km
Inclination = 64.2°

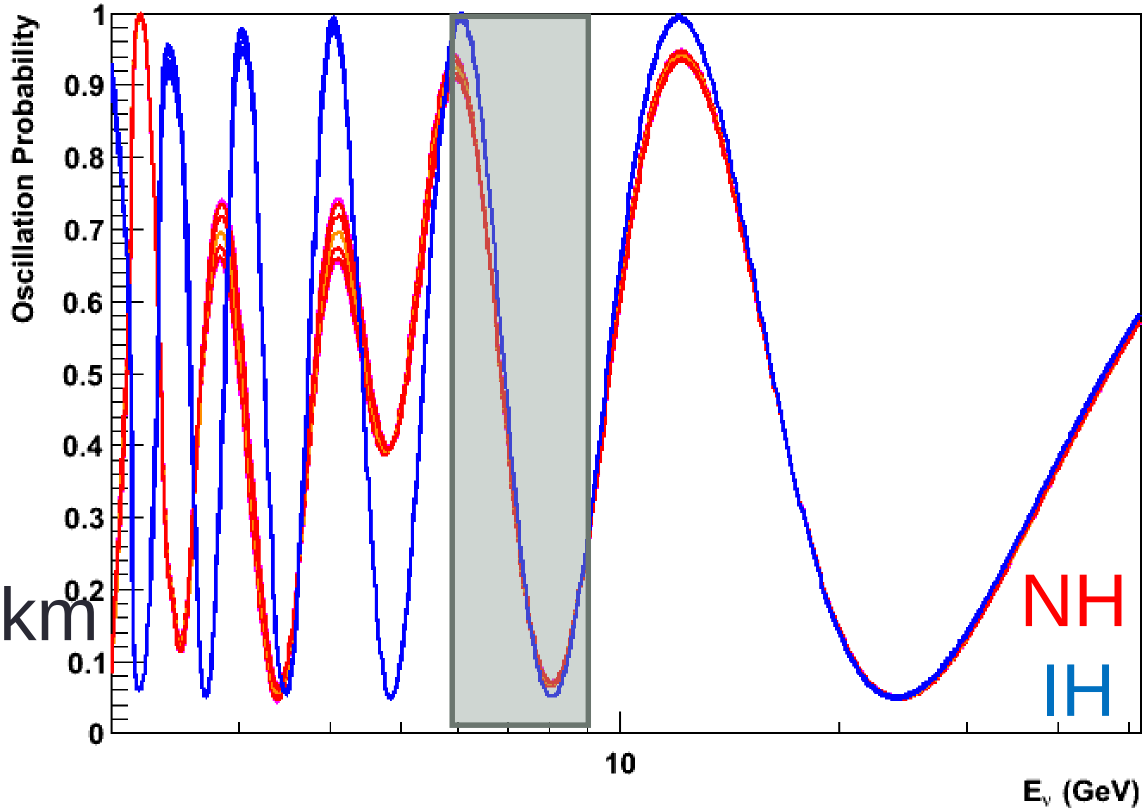


$P(\nu_\mu \rightarrow \nu_\mu)$



cosθ = 1.0
Baseline = 12742 km
Inclination = 90.0°

GLOBES



Counting Muons from Beam Neutrinos

- Optimal Beamline : 7000-8000 km

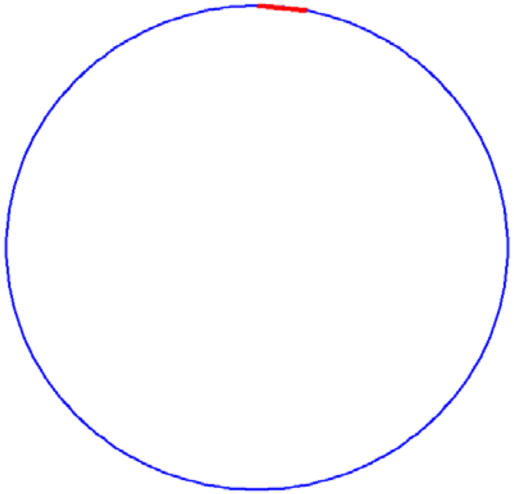
	Fermilab	CERN	J-PARC
South Pole	11600	11800	11400
Sicily	**7800**	1230	9100
Baikal Lake	8700	**6300**	3300

arXiv:1301.4577

- Favoured Option:
  - FermiLab – KM3Net site in Mediterranean Sea
  - 1300 versus 950 events for both mass hierarchy hypotheses in Mton underwater detector (ORCA)

- → Inverse approach : Counting "Electrons"

$P(\nu_\mu \rightarrow \nu_e)$



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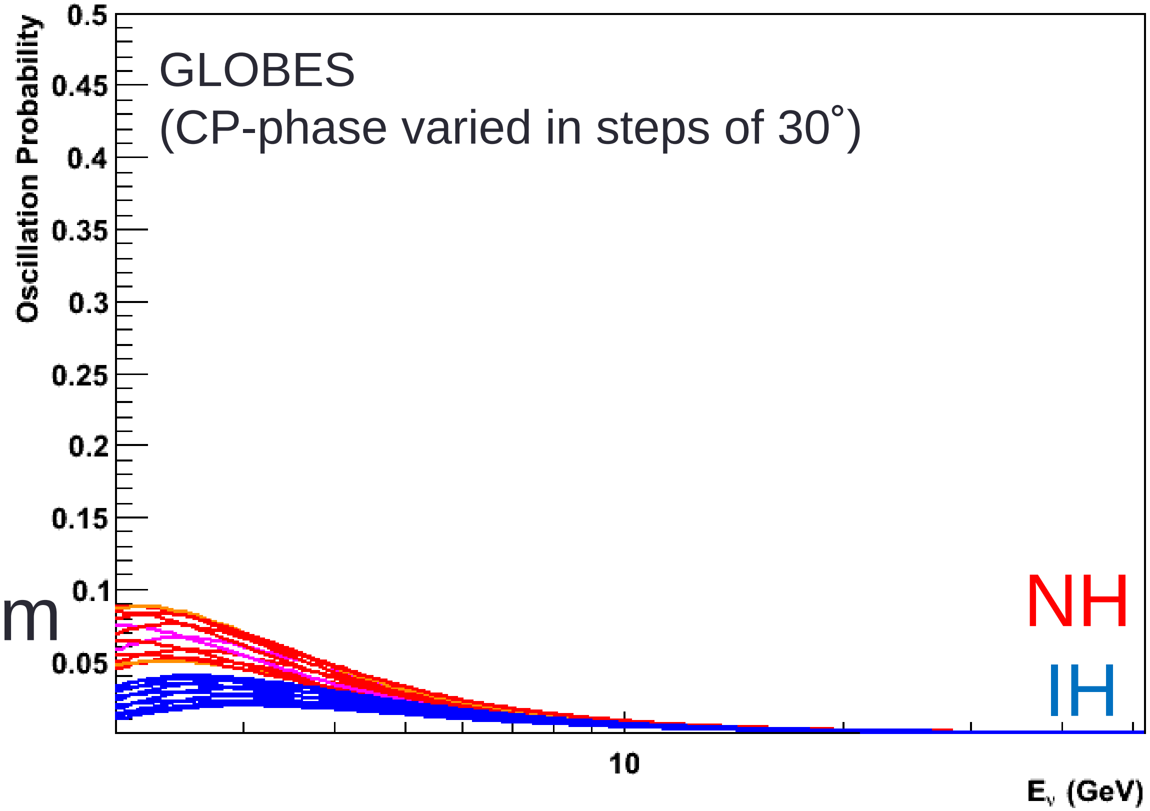
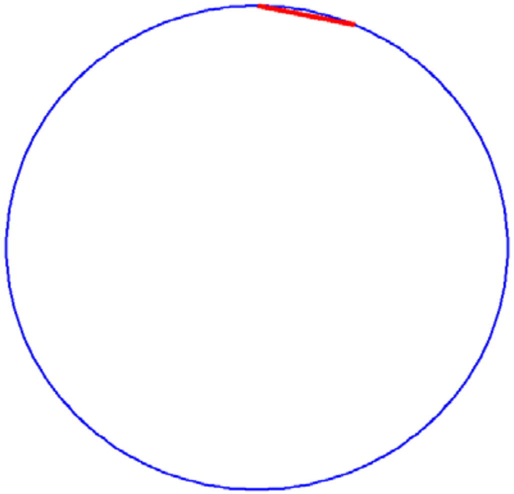
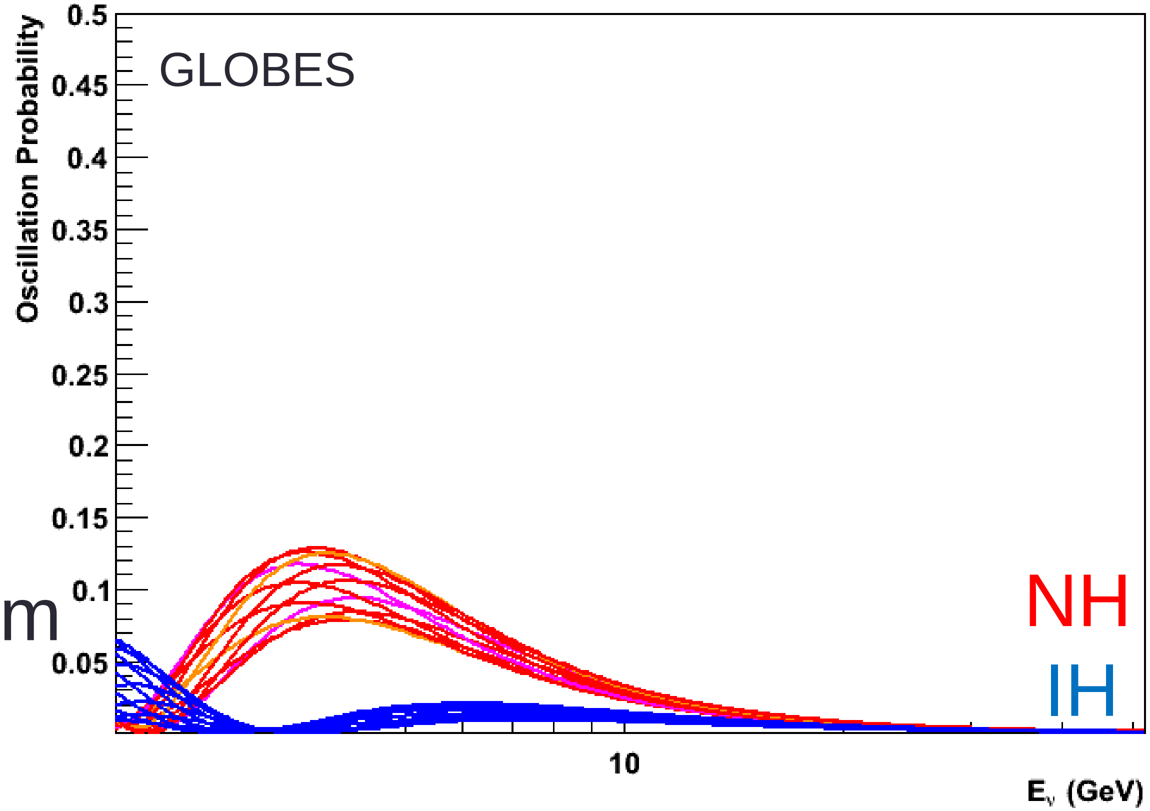


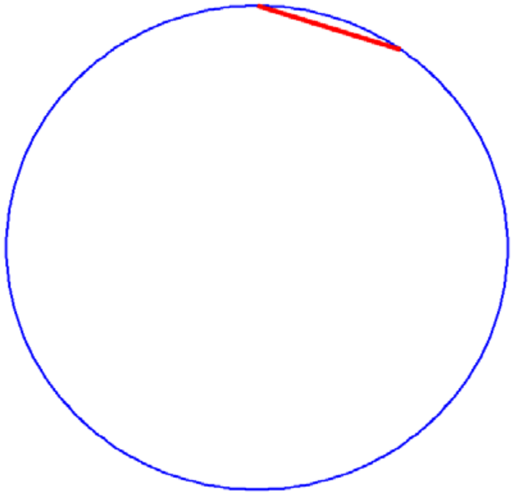
$P(\nu_\mu \rightarrow \nu_e)$

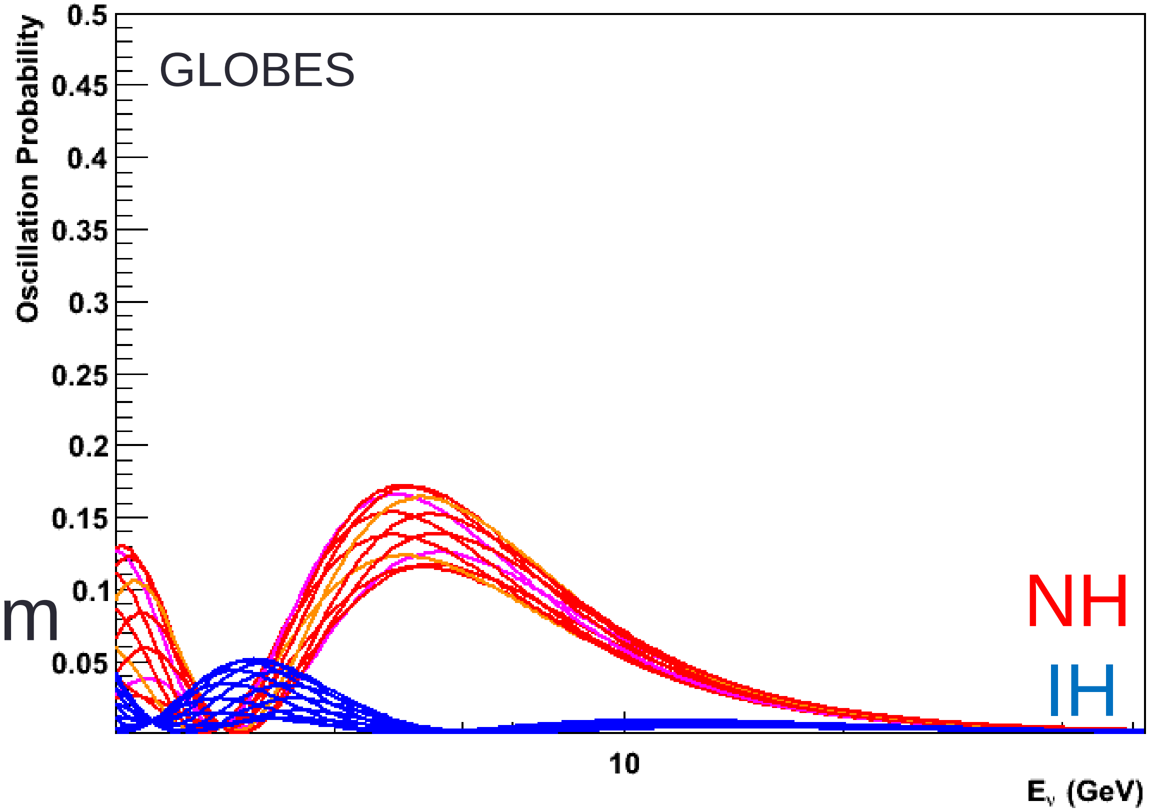




cosθ = 0.2
Baseline = 2548 km
Inclination = 11.5°

$P(\nu_\mu \rightarrow \nu_e)$





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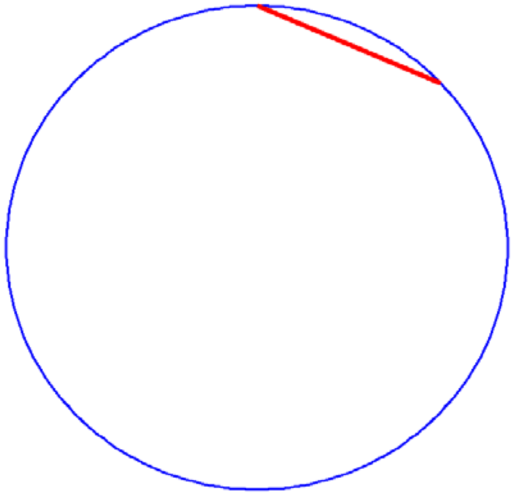
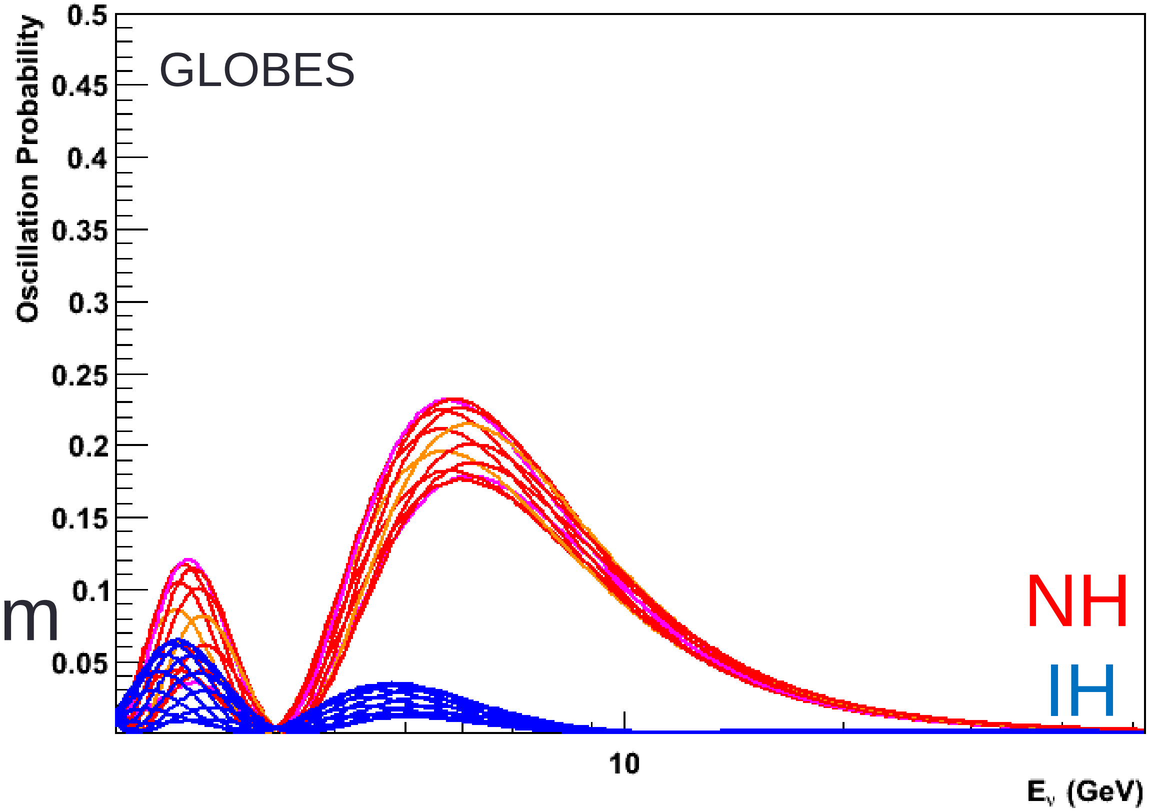
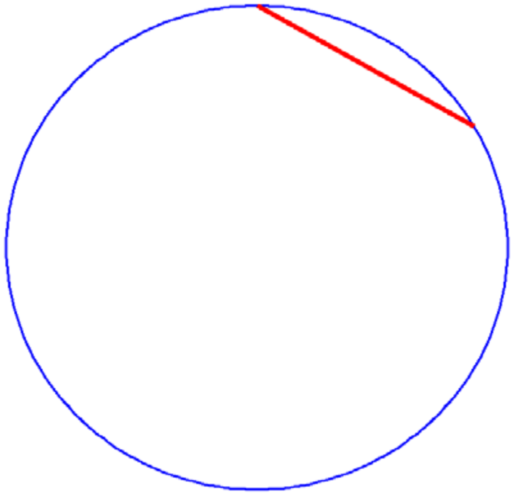
$P(\nu_\mu \rightarrow \nu_e)$



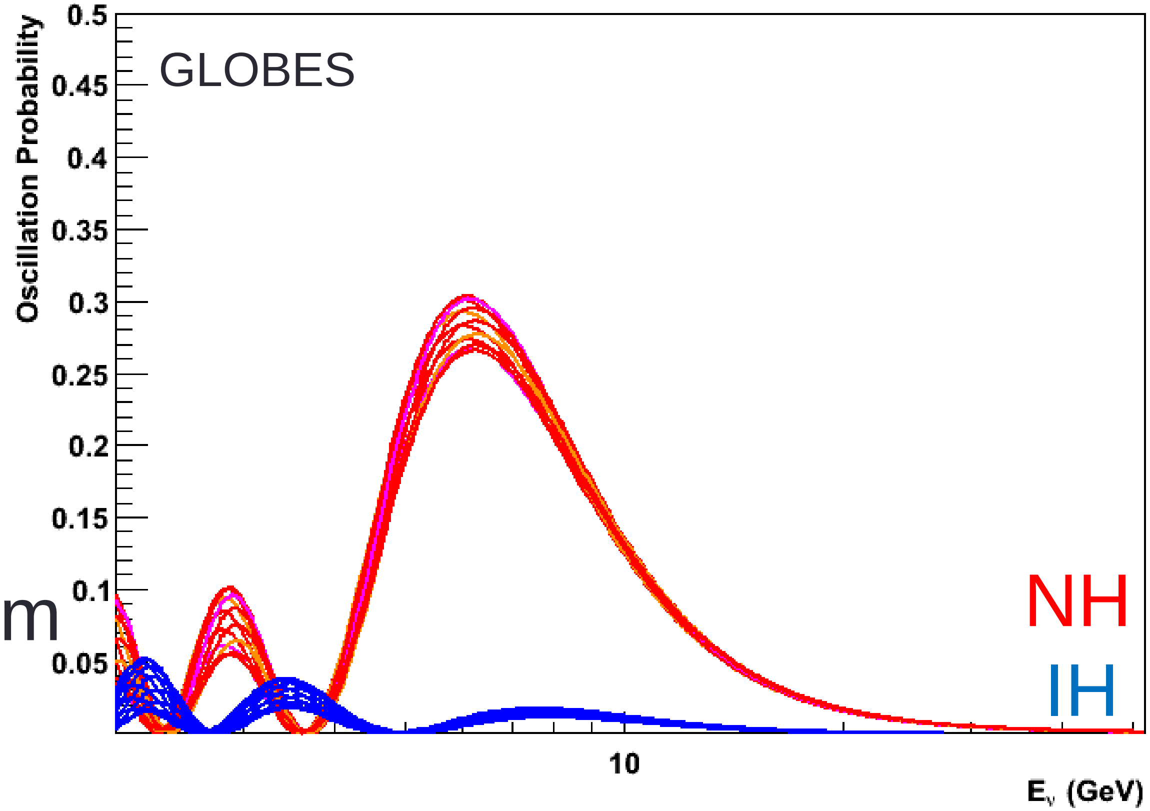


$\cos\theta = 0.4$
Baseline = 5097 km
Inclination = 23.6°

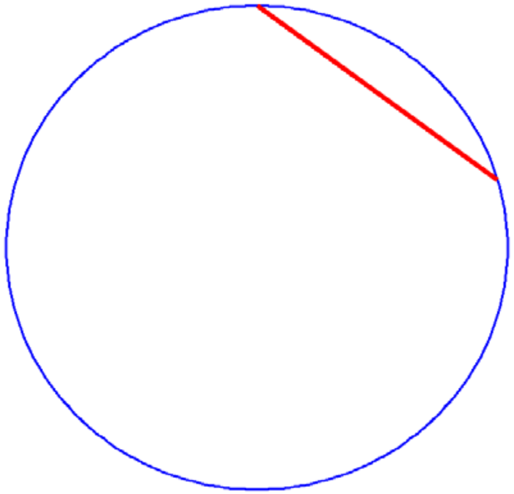
$P(\nu_\mu \rightarrow \nu_e)$



cosθ = 0.5
Baseline = 6371 km
Inclination = 30.0˚



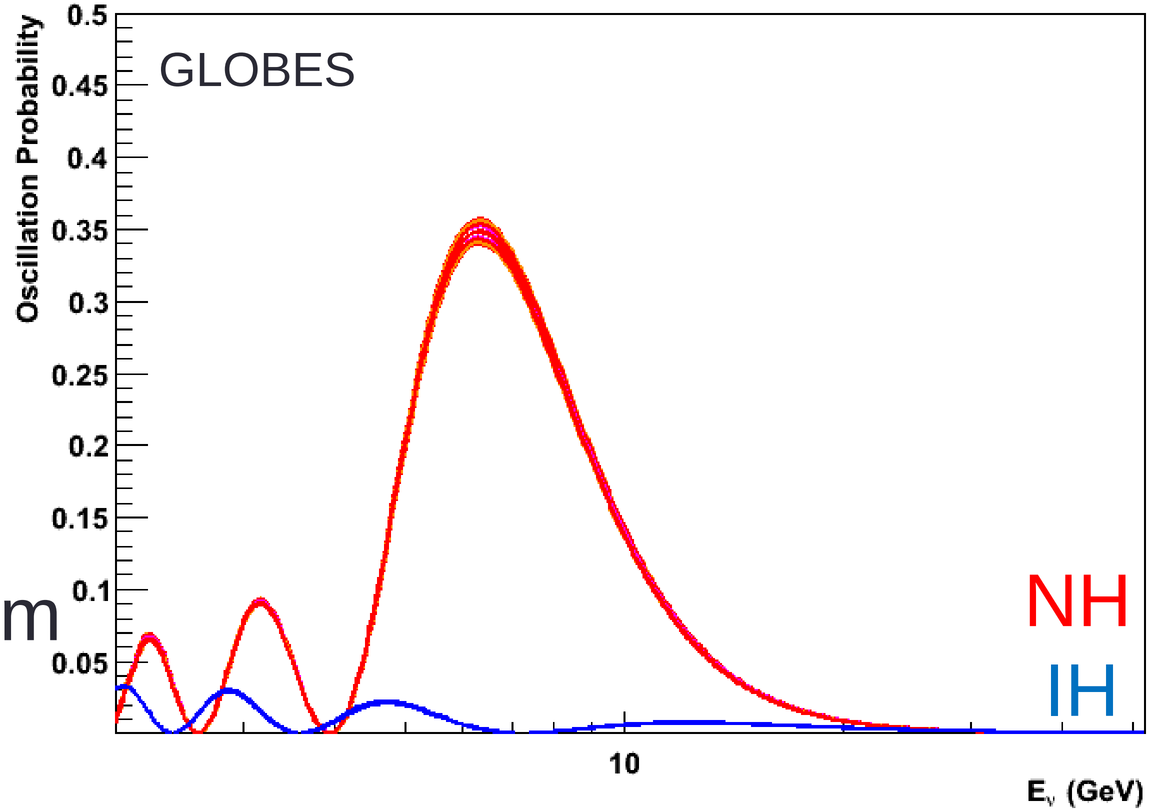
$P(\nu_\mu \rightarrow \nu_e)$



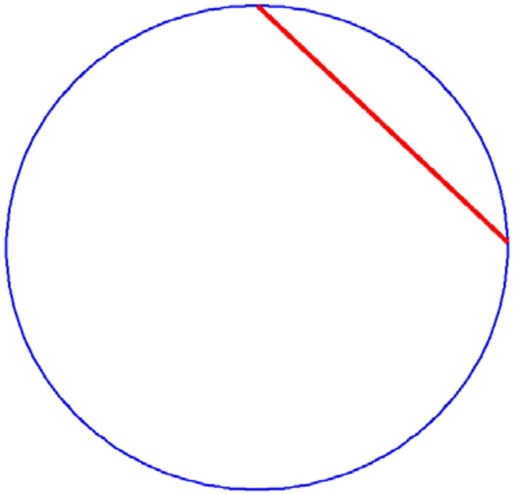
$\cos\theta = 0.6$

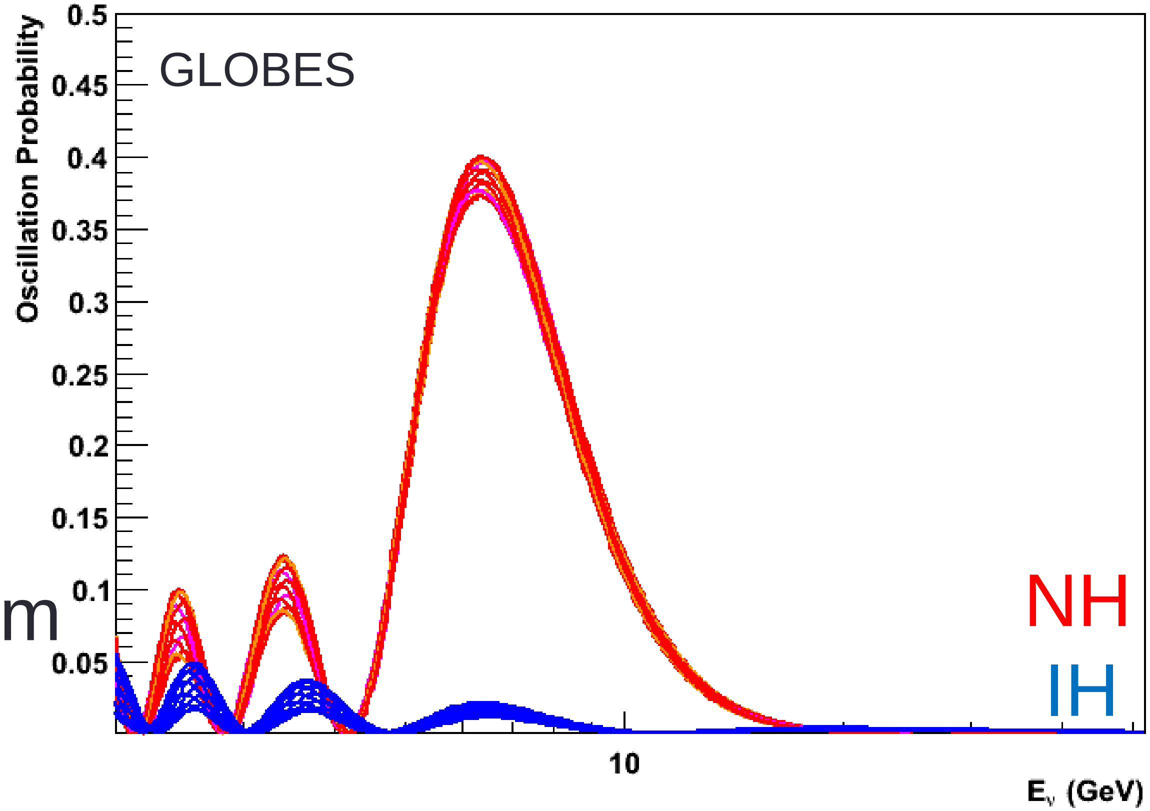
Baseline = 7645 km

Inclination = 36.9°



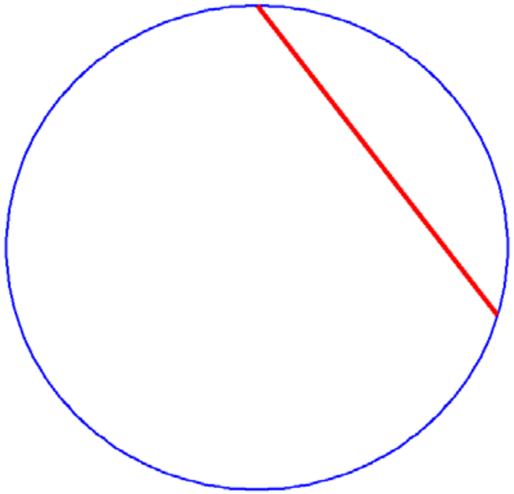
$P(\nu_\mu \rightarrow \nu_e)$

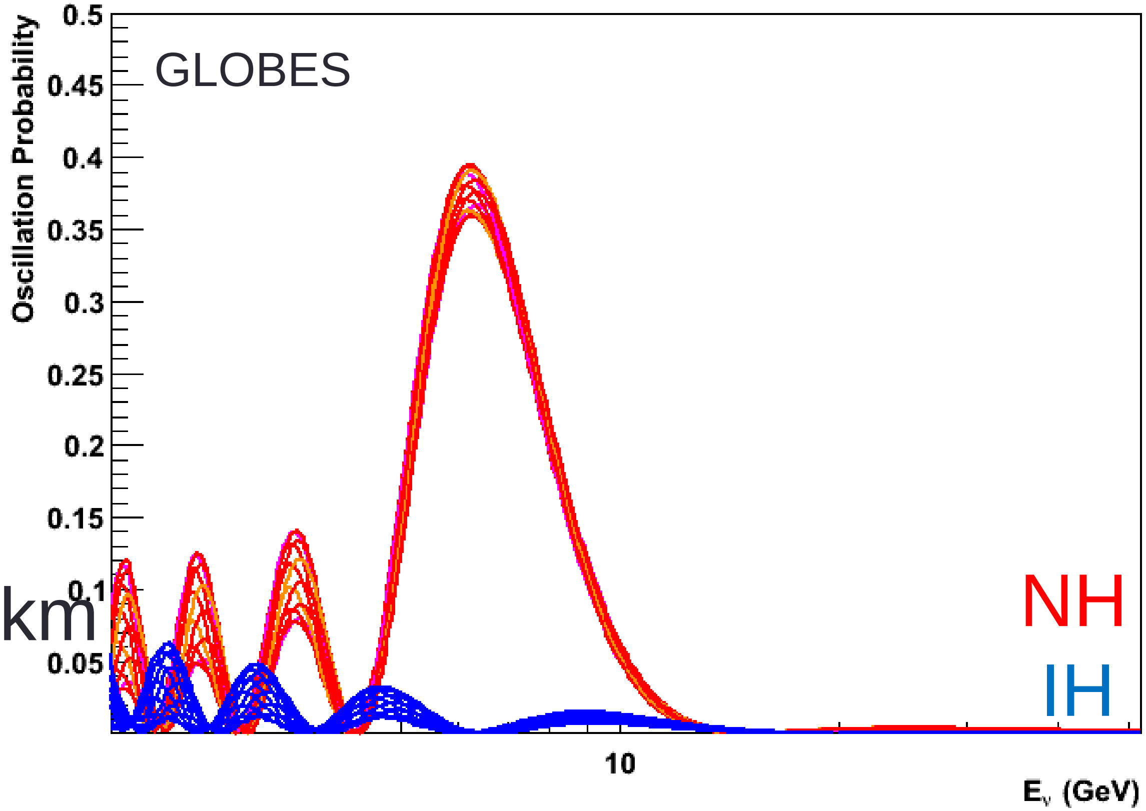




cosθ = 0.7
Baseline = 8919 km
Inclination = 44.4°

$P(\nu_\mu \rightarrow \nu_e)$



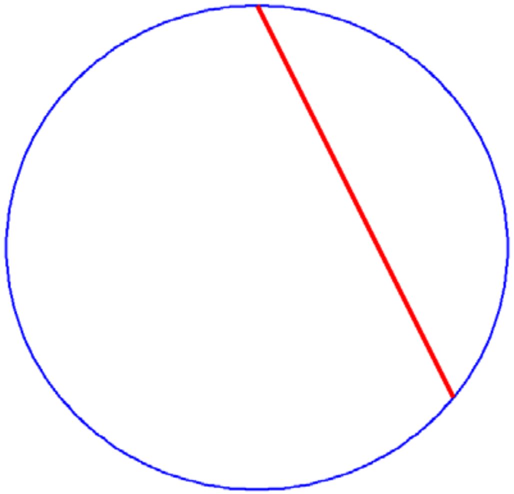


cosθ = 0.8

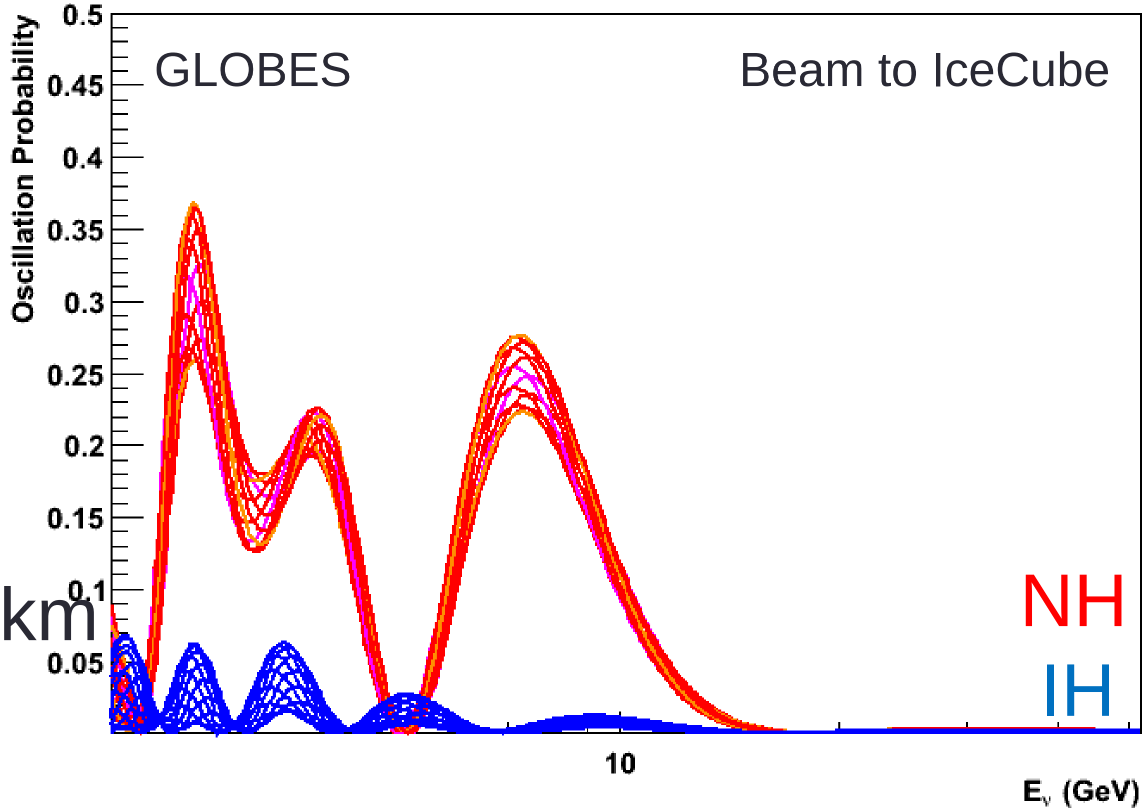
Baseline = 10194 km

Inclination = 53.1°

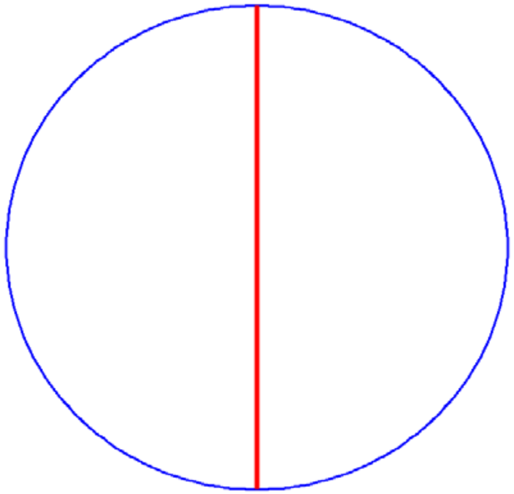
$P(\nu_\mu \rightarrow \nu_e)$

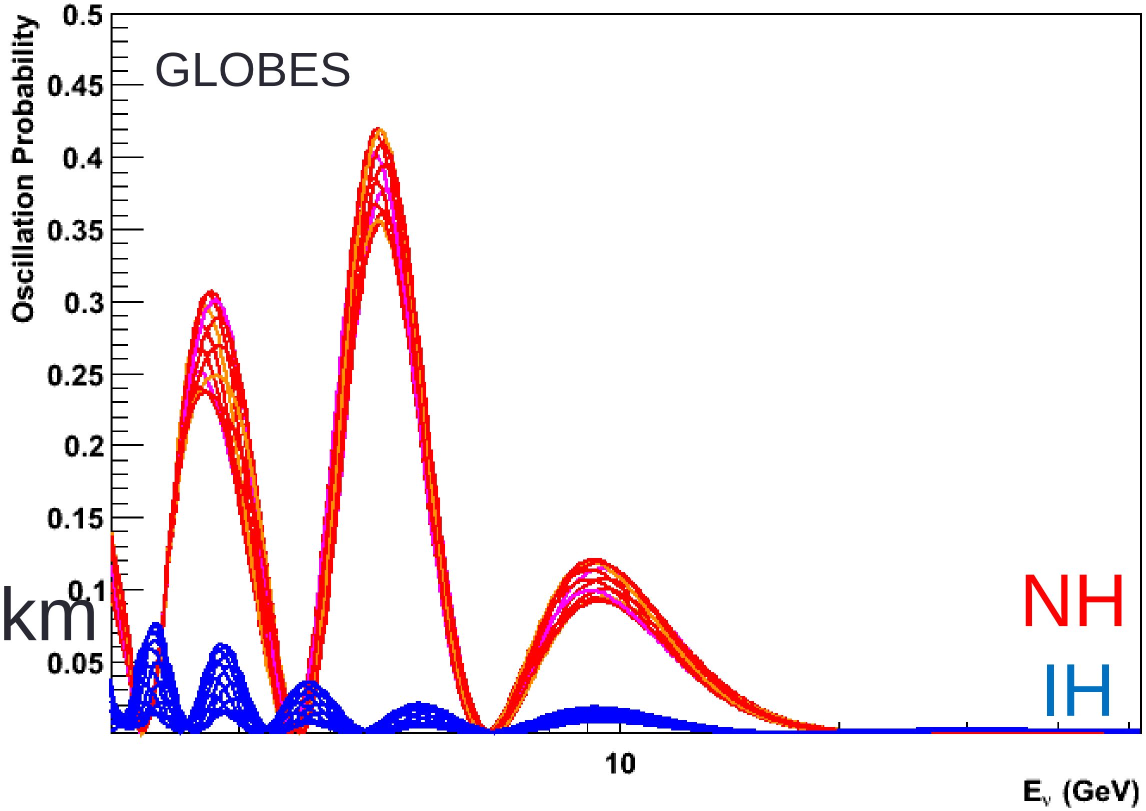


cosθ = 0.9
Baseline = 11468 km
Inclination = 64.2°



$P(\nu_\mu \rightarrow \nu_e)$

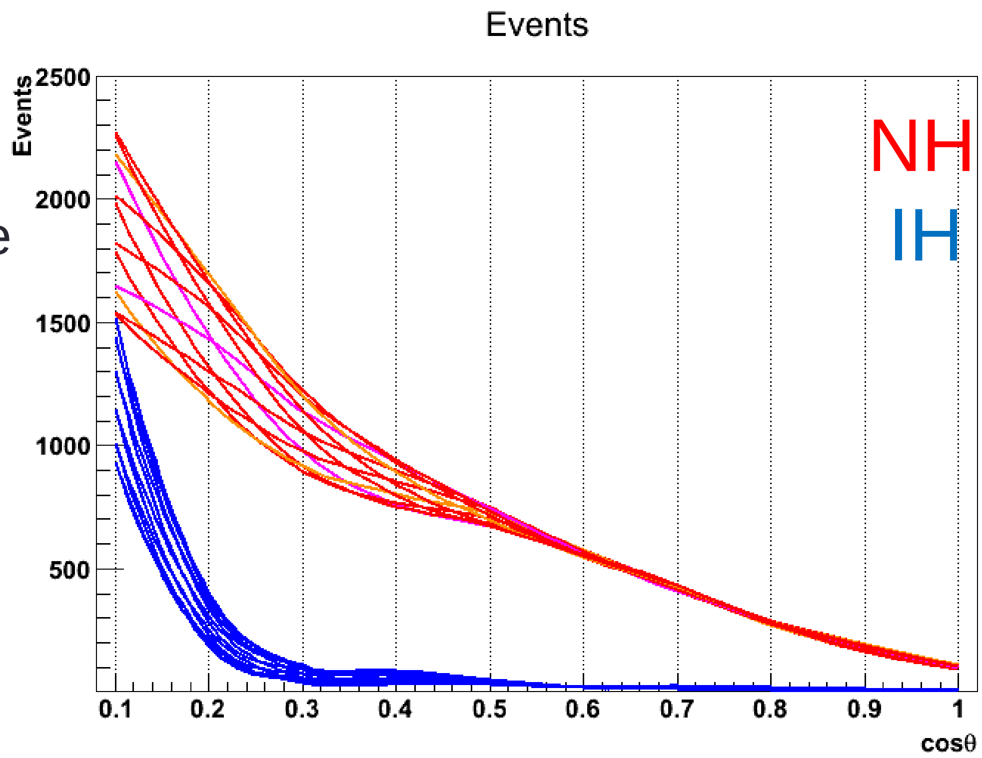




$\cos\theta = 1.0$
Baseline = 12742 km
Inclination = 90.0°

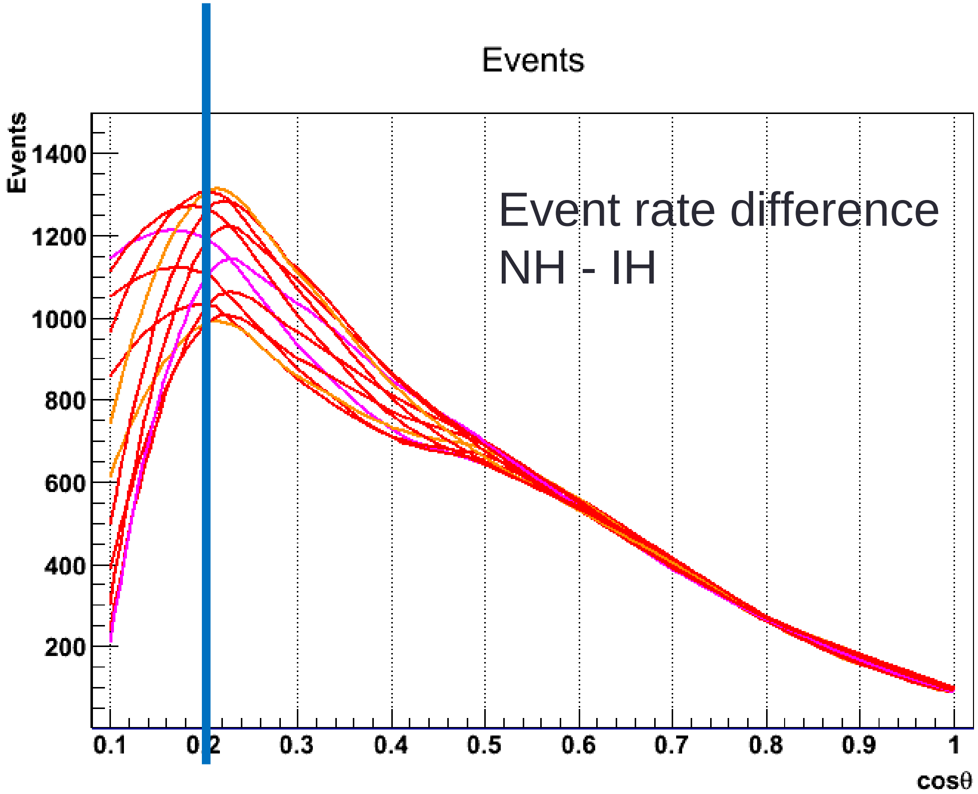
Optimal Baseline ?

- For L>2000km the oscillation probabilities are always well separated for both MH hypotheses
- To find optimal baseline calculate event rates
  - $N \sim 1/L^2$
  - N ~ E (cross section)
  - Fixed beam profile
  - ORCA detector response

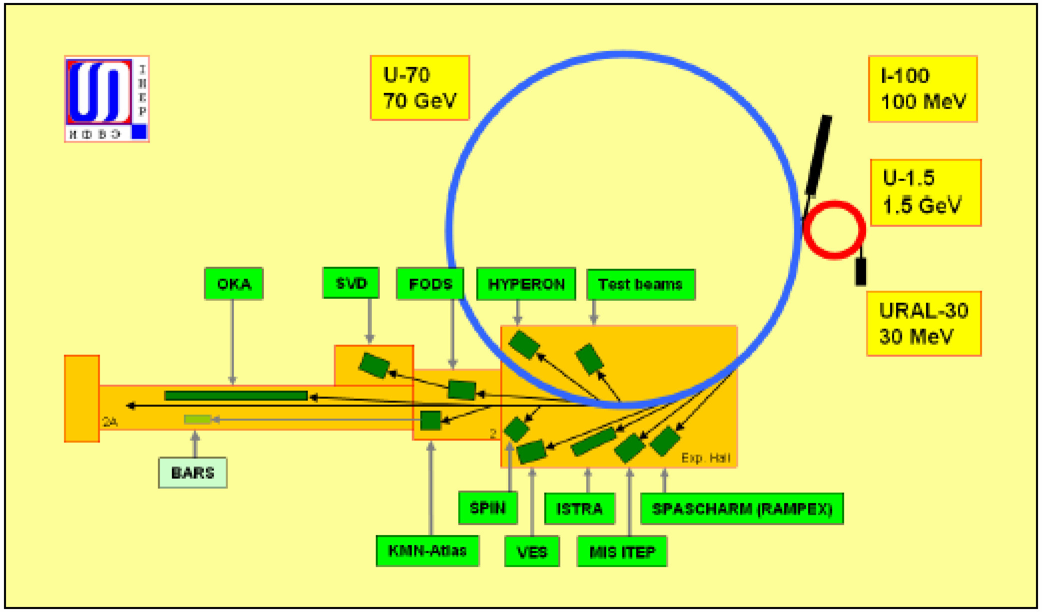


Optimal Baseline

- L=2600km maximizes the difference in event rates between two MH hypotheses



Proton Accelerator Complex Protvino



4 machines (since Oct 2007):
- 2 linacs
- 2 synchrotrons

Modes:
- proton (default) URAL30-U1.5-U70
- light-ion (*d*, C) I100(2 of 3)-U1.5-U70

to note: OKA (#21), FODS (#22), stretcher (#25)

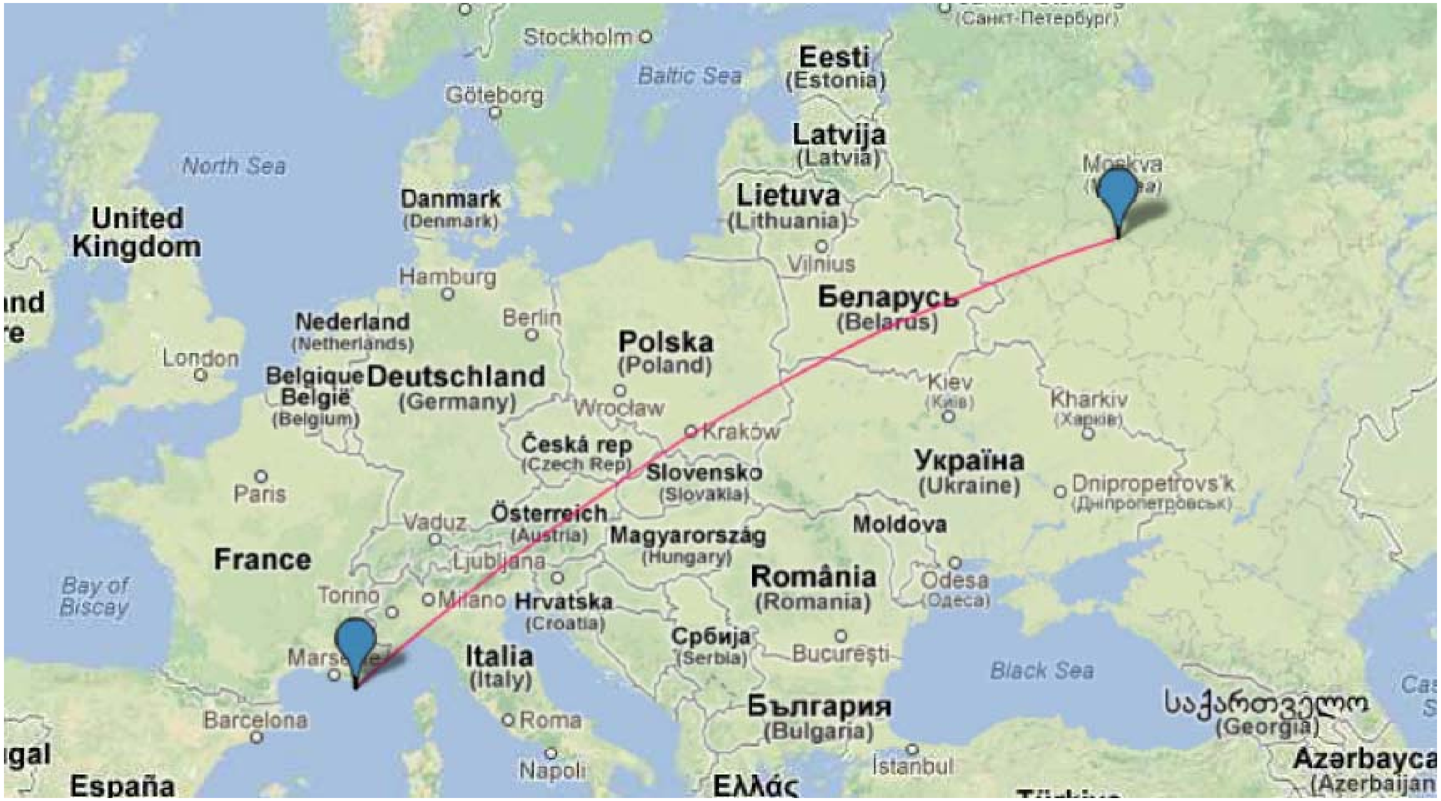
Light-ion:
- high energy 24.1-34.1 GeV/u
- intermediate energy 453-455 MeV/u

In a SIS-18, SIS-100 name convention:
- LIS-233 [T·m]
- LIS-6.9 [T·m]

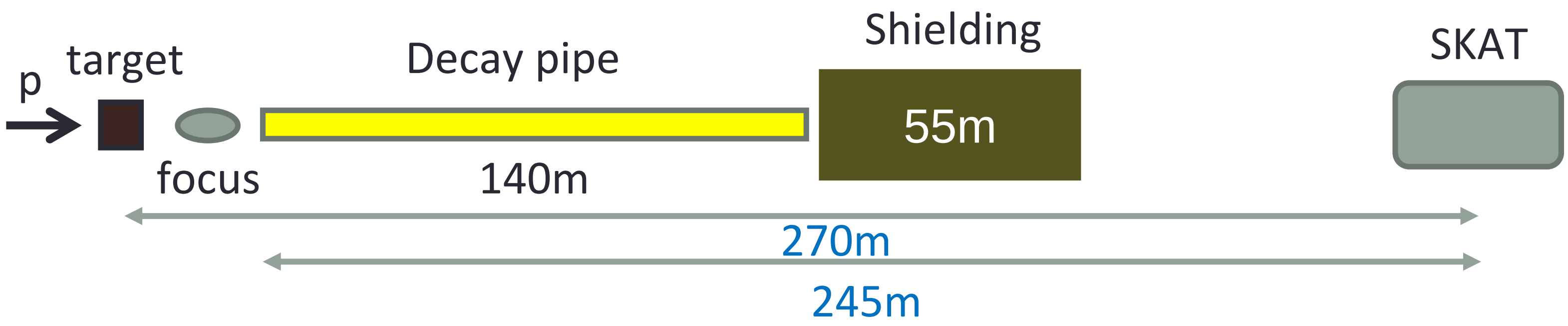
Presentation S. Ivanov (IHEP) on 22/11/2012 @ CERN → Talk Wednesday

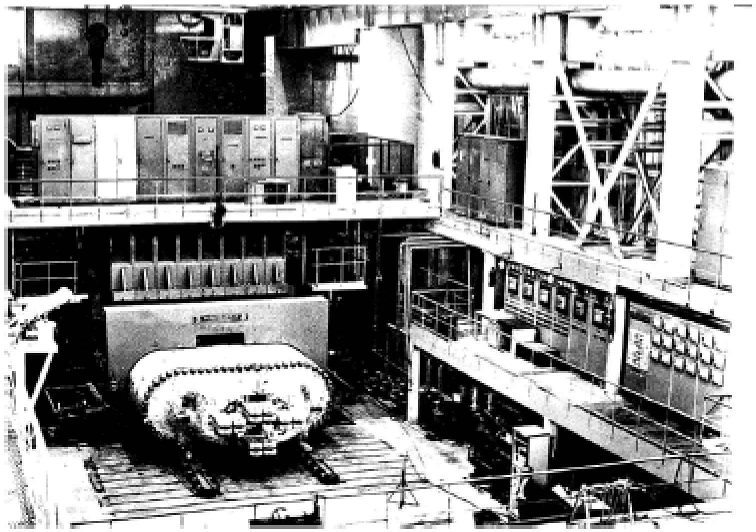
Protvino – ANTARES (ORCA)

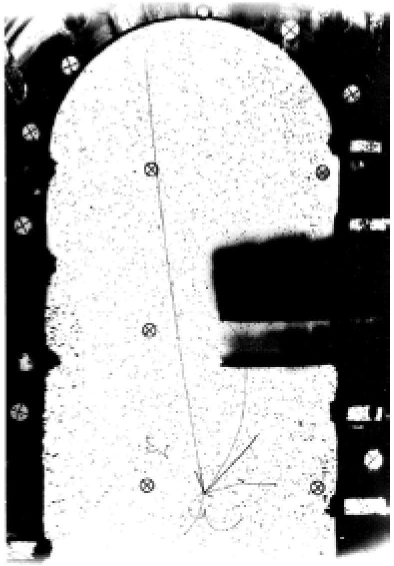
- Baseline 2588km ; beam inclination : 11.7° (cosθ = 0.2)
- Deepest point 134km : 3.3 g/cm^3

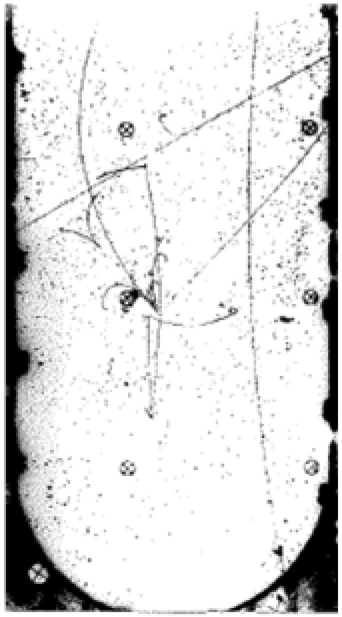


SKAT bubble chamber





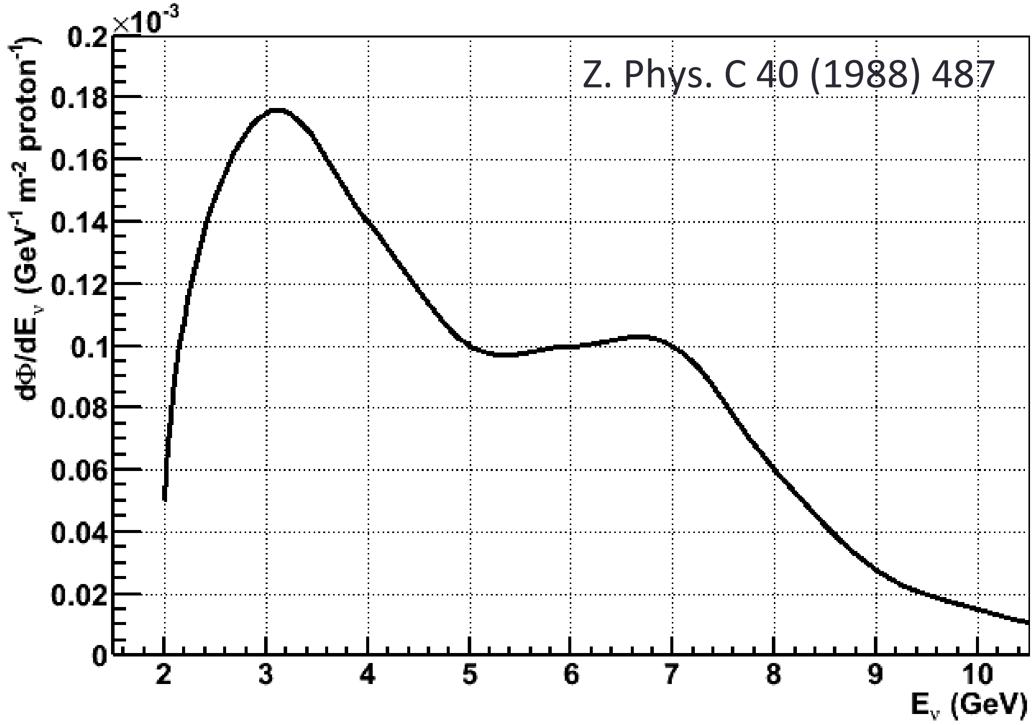




Courtesy: R. Nahnhauer

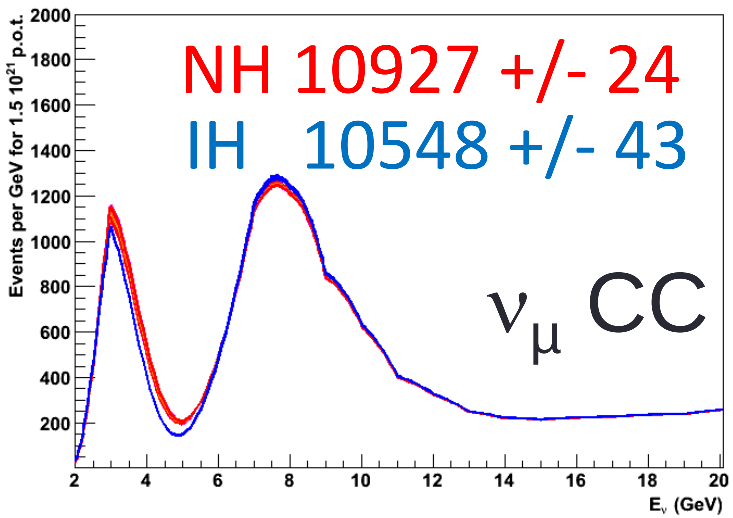
Beam parametrisation (1988)

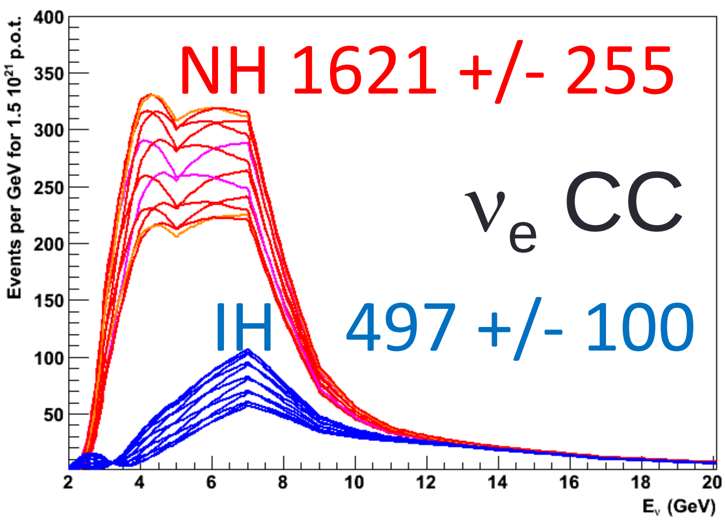
- Very clean ν_μ beam
- Less than 1% contaminations from other flavours
- Most neutrinos between 1-8 GeV



Event rates - Signal

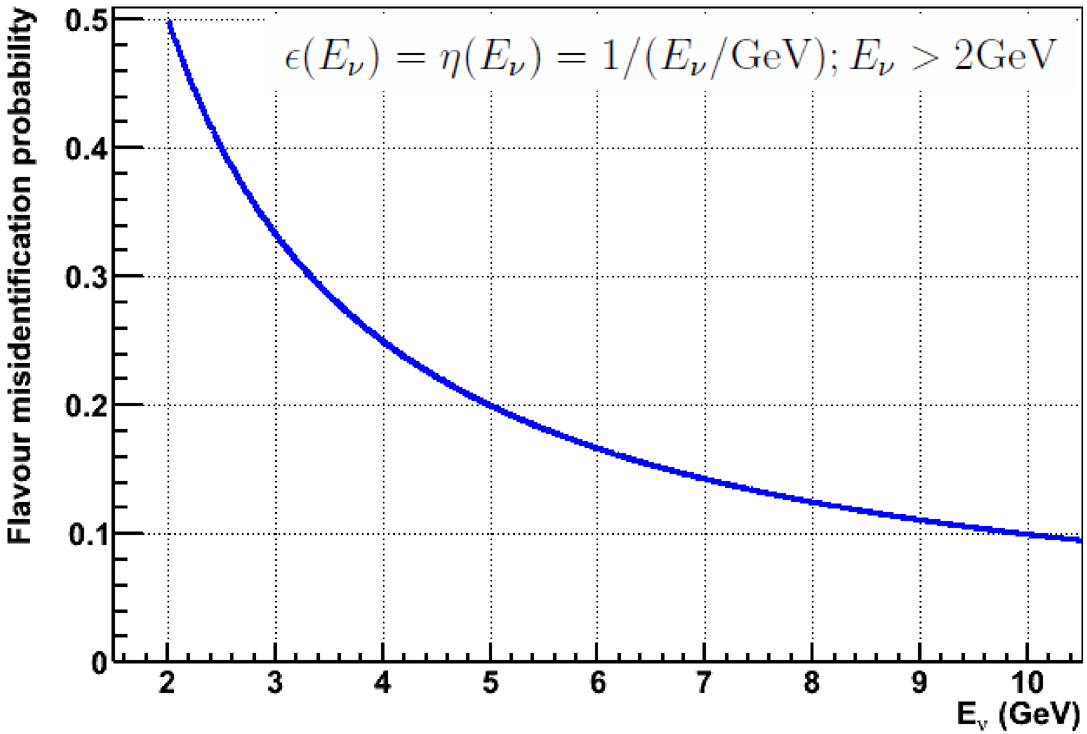
- Event numbers for 1.5 10^{21} p.o.t.s
- 20 σ statistical separation of both Mass Hierarchy hypotheses from signal
- 10000 muon events for beam normalisation
  - 3.5% separation between MH hypotheses
- Other contributions: ν_τ: 1316 +/- 13 ; 1416 +/- 8 ; NC : 4732





Flavour identification

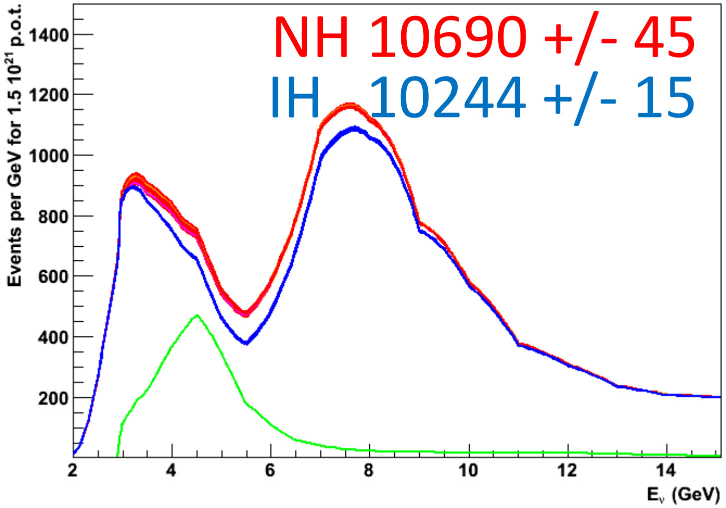
- Misidentification probability :
  - assume same for both directions
  - 50% at 2 GeV → random ; 20% at 5 GeV ; 10% at GeV



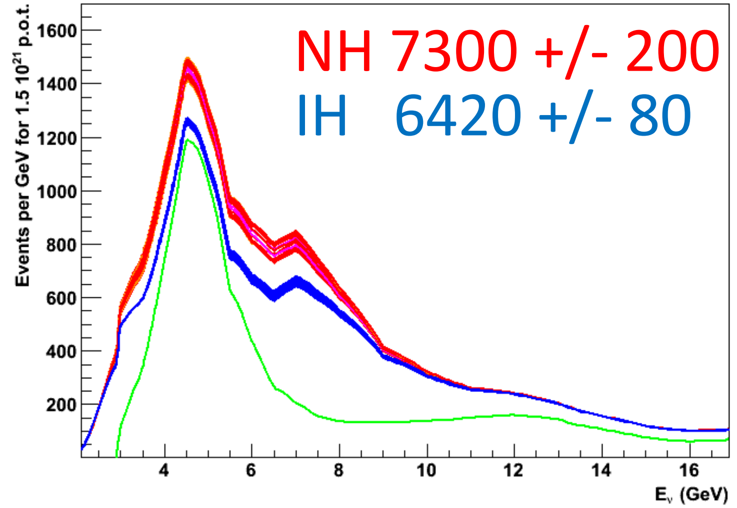
Event rates – All Flavours & Mis-ID

- Event numbers for 1.5 10^{21} pots
- 9-18% difference for NH/IH
- 7 σ statistical separation of MH hypotheses
- Can allow for few % syst. Uncertainty
- No requirement of energy reconstruction

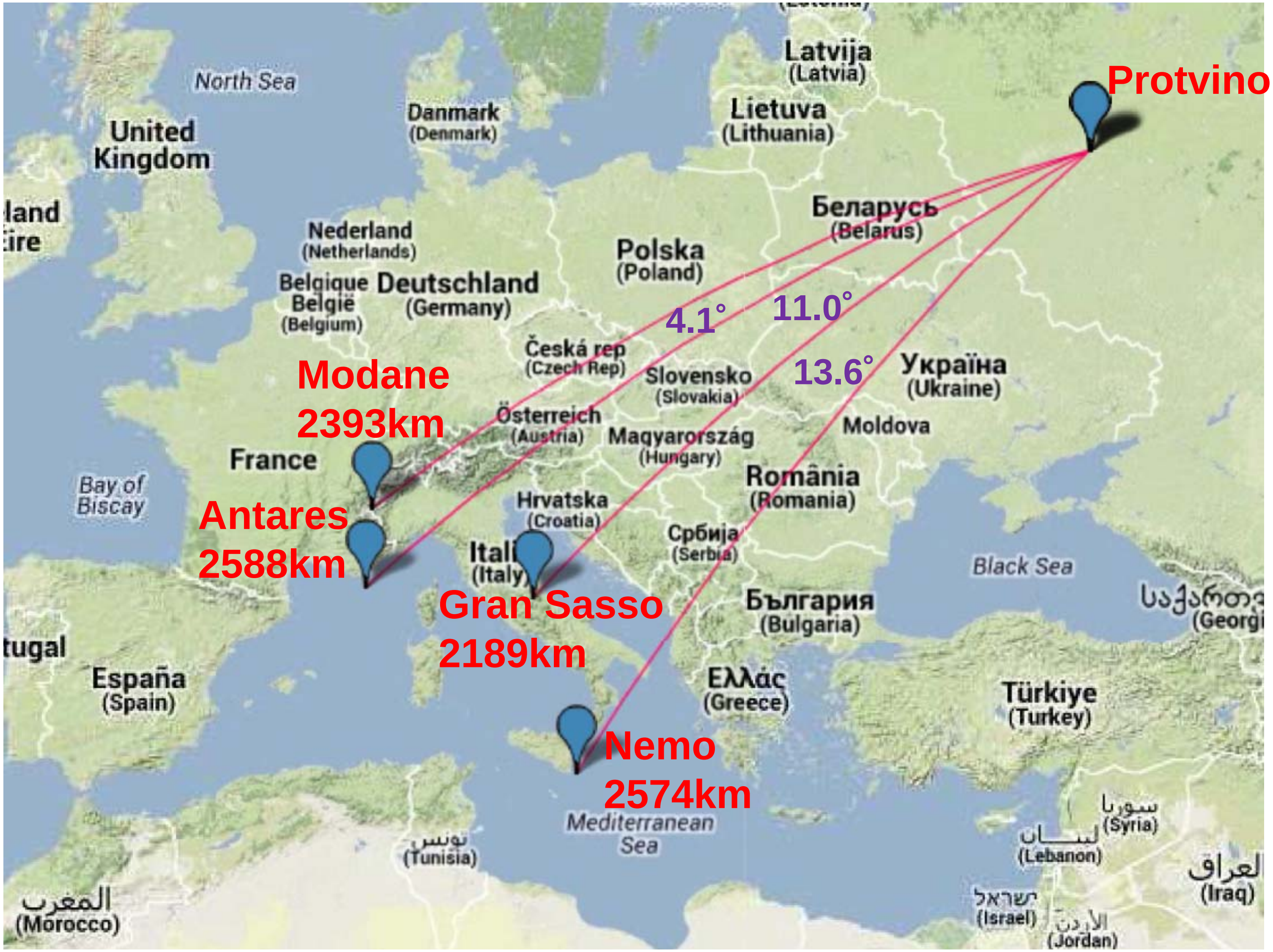
tracks



cascades



Synergies between potential Sites



Conclusion

- Upgraded proton accelerator at Protvino well suited for LBL towards Mediterranean Sea
- Needed : 10^{21} p.o.t. within few years
- Preliminary Performance Figures of ORCA encouraging
- Synergy with Underground Labs in the same beam
- Complementary to measurement with atmospheric ν

- **→High Significance determination of Mass Hierarchy**

Backup

Oscillation parameters

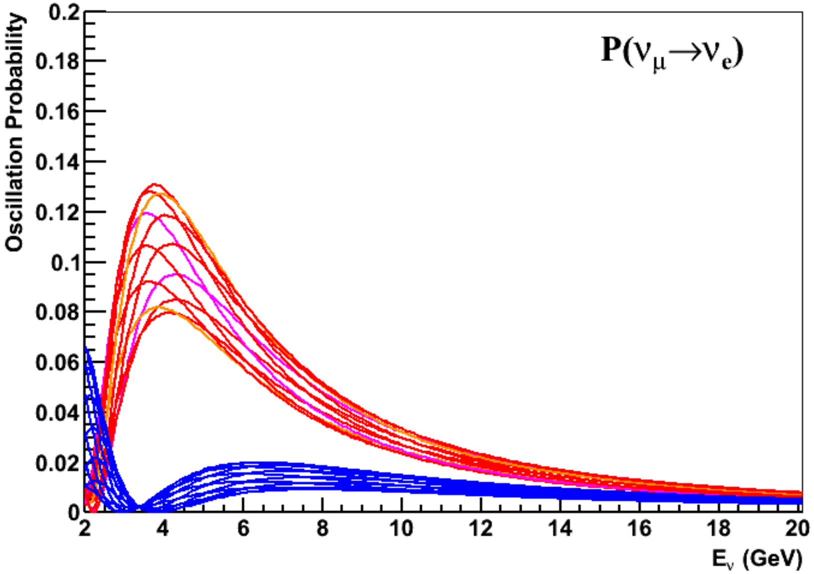
- Taken from Global Fit (Fogli et al.) for both hierarchy options
- CP phase left free

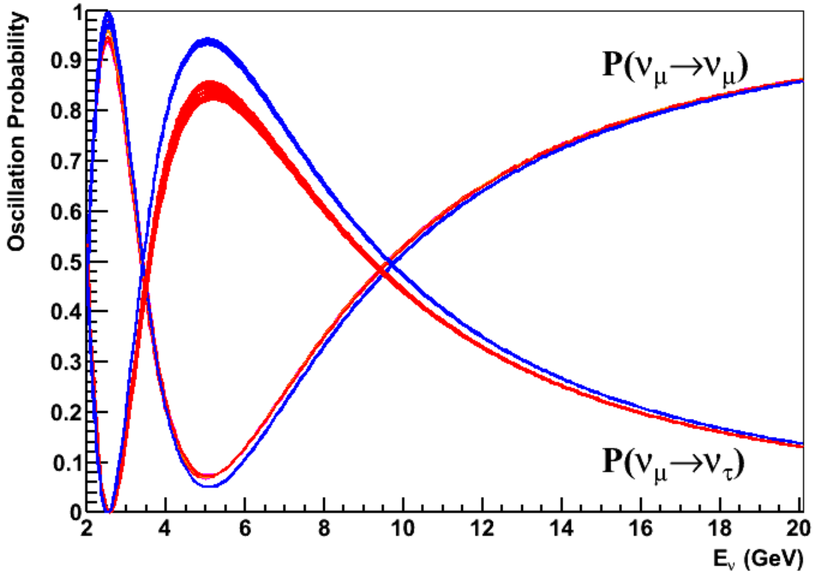
Arxiv:1205.5254

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH.

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49	2.26 – 2.53	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66	1.93 – 2.90	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67	1.94 – 2.91	1.71 – 3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10	3.48 – 4.48	3.31 – 6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31	3.53 – 4.84 $\oplus$ 5.43 – 6.41	3.35 – 6.63

Oscillation Probabilities





- All relevant oscillation probabilities taken into account
- Full 3-flavour treatment
- CP-phase variations included

Neutrino Cross sections

Simple parton scaling assumed (QE, Res. ignored)

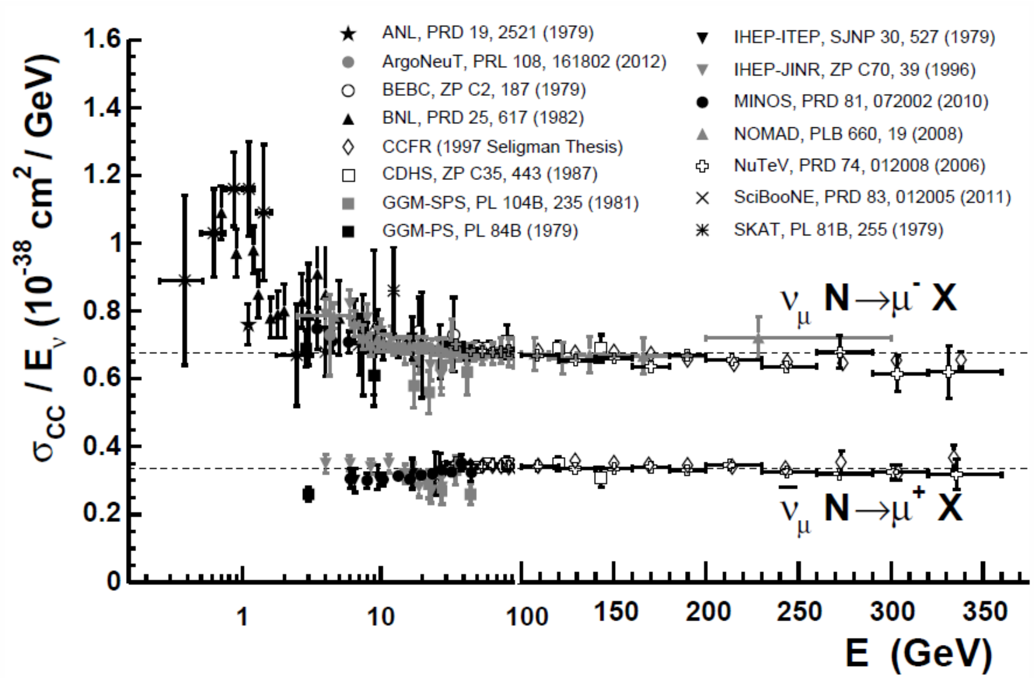
Flavour universality

$$\sigma^{CC}_{\nu_\mu}(E_\nu) = 0.68 \cdot (E_\nu/GeV)10^{-38}\mathrm{cm}^2$$
$$\sigma^{CC}_{\bar\nu_\mu}(E_\nu) = 0.34 \cdot (E_\nu/GeV)10^{-38}\mathrm{cm}^2$$

n$\sigma^{CC}_{\nu_e} = \sigma^{CC}_{\nu_\mu}$ and $\sigma^{CC}_{\bar\nu_e} = \sigma^{CC}_{\bar\nu_\mu}$

$$\sigma^{CC}_{\nu_\tau} = \sigma^{CC}_{\nu_\mu} 0.29 \log\left(\frac{E_\nu}{E_0}\right)$$

$$\sigma^{NC}_{\nu}(E_\nu) = \frac{1}{3}\sigma^{CC}_{\nu_\mu}(E_\nu)$$
$$\sigma^{NC}_{\bar\nu}(E_\nu) = \frac{1}{3}\sigma^{CC}_{\bar\nu_\mu}(E_\nu)$$



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n $\sigma^{CC}_{\nu_e} = \sigma^{CC}_{\nu_\mu}$ and $\sigma^{CC}_{\bar{\nu}_e} = \sigma^{CC}_{\bar{\nu}_\mu}$

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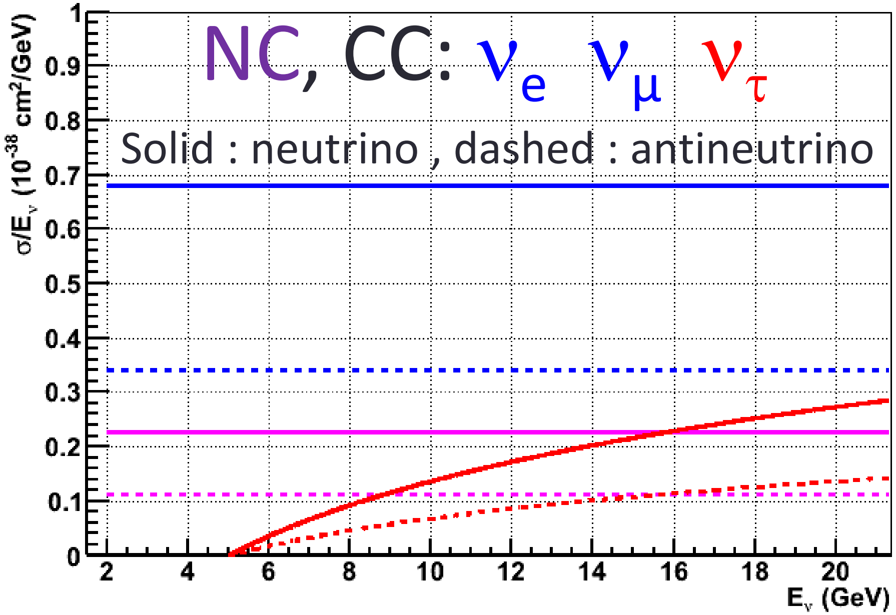

Event rates

- Here : no flavour misidentification
- CC Rates
- $$\frac{dN_\alpha}{dE_\nu} = N_{pot}\left(\frac{l_{SKAT}}{l_{LBL}}\right)^2 \frac{M_{eff}(E_\nu)}{m_p} \left[\sigma^{CC}_{\nu_\alpha}\left(\frac{d\Phi_{\nu_\mu}}{dE_\nu}P_{\mu\alpha} + \frac{d\Phi_{\nu_e}}{dE_\nu}P_{e\alpha}\right) + \sigma^{CC}_{\bar{\nu}_\alpha}\left(\frac{d\Phi_{\bar{\nu}_\mu}}{dE_\nu}P_{\overline{\mu\alpha}} + \frac{d\Phi_{\bar{\nu}_e}}{dE_\nu}P_{\overline{e\alpha}}\right)\right]$$

$$\frac{dN_{NC}}{dE_\nu} = N_{pot}\left(\frac{l_{SKAT}}{l_{LBL}}\right)^2 \frac{M_{eff}(E_\nu/2)}{m_p} \left[\sigma^{NC}_{\nu}\left(\frac{d\Phi_{\nu_\mu}}{dE_\nu} + \frac{d\Phi_{\nu_e}}{dE_\nu}\right) + \sigma^{NC}_{\bar{\nu}}\left(\frac{d\Phi_{\bar{\nu}_\mu}}{dE_\nu} + \frac{d\Phi_{\bar{\nu}_e}}{dE_\nu}\right)\right]$$

Event rates

- Include Background and Flavour tagging
- Total Background :

$$\frac{dN_{bg}^{track}}{dE_\nu} = \epsilon \frac{dN_{sig}^{casc}}{dE_\nu} + \left[\epsilon(1 - BR_{\tau\mu}) + (1-\eta)BR_{\tau\mu}\right] \frac{dN_\tau}{dE_\nu} + \epsilon \frac{dN_{NC}}{dE_\nu}$$

$$\frac{dN_{bg}^{casc}}{dE_\nu} = \eta \frac{dN_{sig}^{track}}{dE_\nu} + \left[(1-\epsilon)(1 - BR_{\tau\mu}) + \eta BR_{\tau\mu}\right] \frac{dN_\tau}{dE_\nu} + (1-\epsilon) \frac{dN_{NC}}{dE_\nu}$$

$$\frac{dN_{tot}^{track}}{dE_\nu} = (1-\eta) \frac{dN_{sig}^{track}}{dE_\nu} + \frac{dN_{bg}^{track}}{dE_\nu}$$

$$\frac{dN_{tot}^{casc}}{dE_\nu} = (1-\epsilon) \frac{dN_{sig}^{casc}}{dE_\nu} + \frac{dN_{bg}^{casc}}{dE_\nu}.$$