Counting Electrons to Measure the Neutrino Mass Hierarchy

J. Brunner

17/04/2013

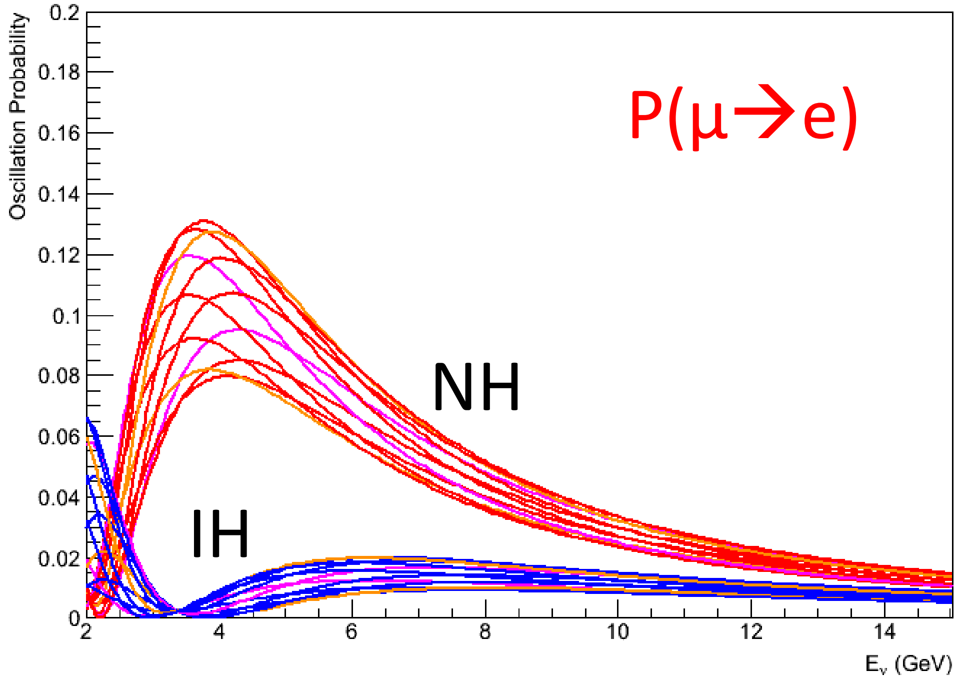
APC

Outline

- Oscillation Probabilities
- Neutrino Cross Sections
- The Proton Accelerator
- The Neutrino Beam
- Detector Performance
- Event Rates / Result

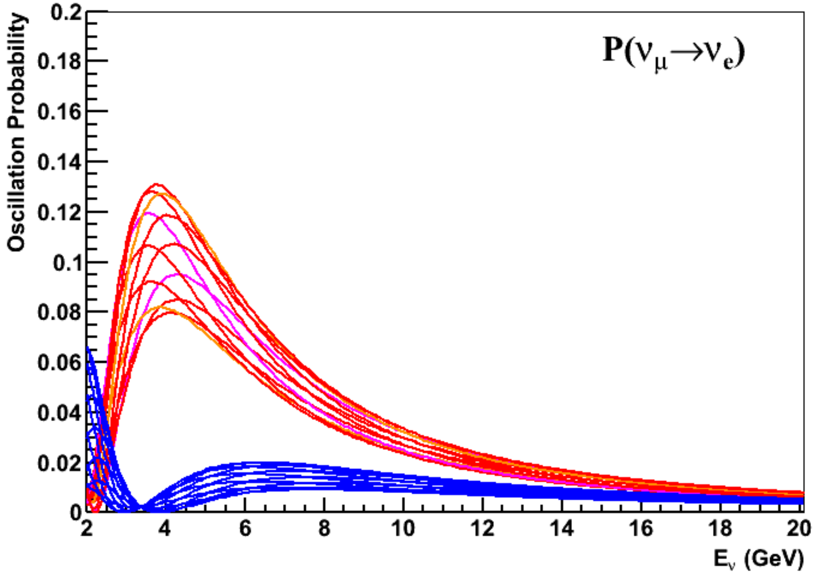
Oscillation Probabilities

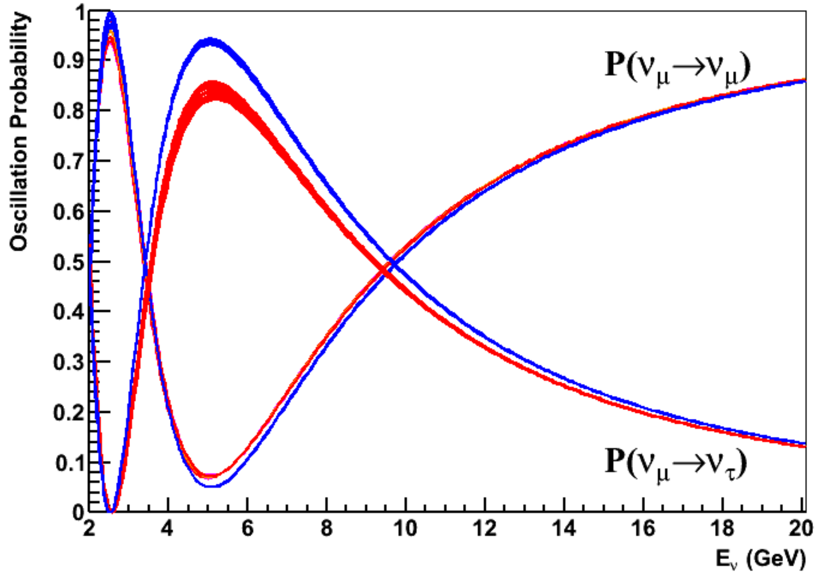
- GLOBES for Baseline of 2600km (neutrinos)
- CP phase in steps of 30 degree
- 0,180 : magenta
- 90,270 : orange
- Width of CP-band
  - About 30%
- NH/IH ≈ 5



Thanks to A. Meregaglia for help with GLOBES

Oscillation Probabilities





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

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

Neutrino Cross sections

Simple parton scaling assumed (QE, Res. ignored)

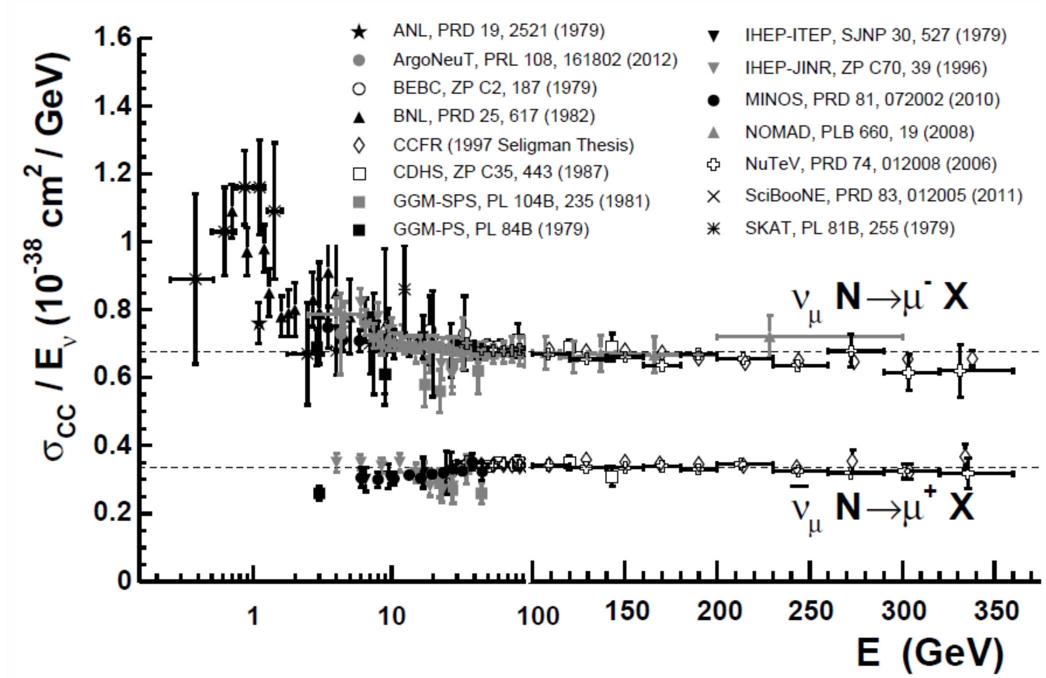
Flavour universality

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

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

m_τ threshold

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



NC approximation

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

Neutrino Cross sections

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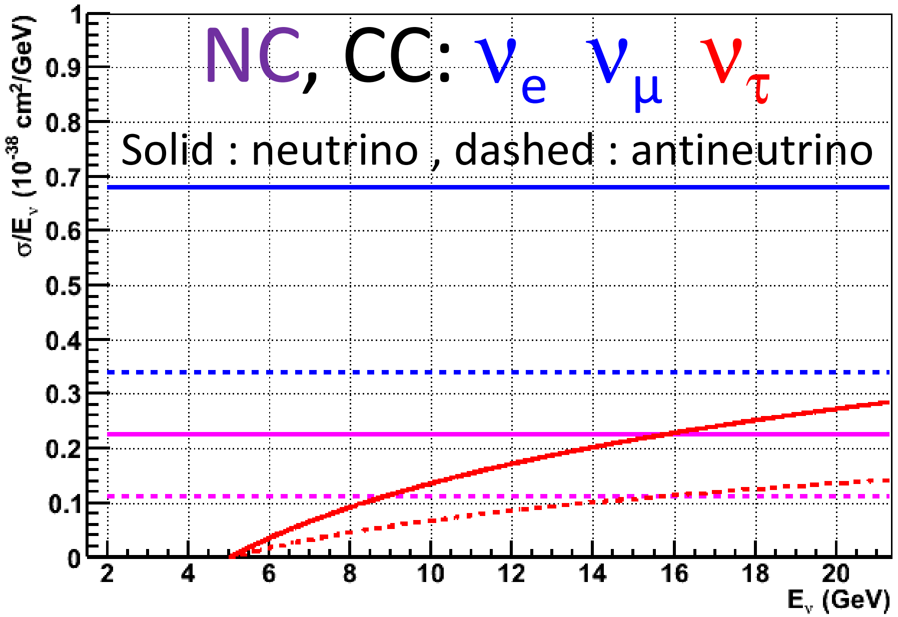
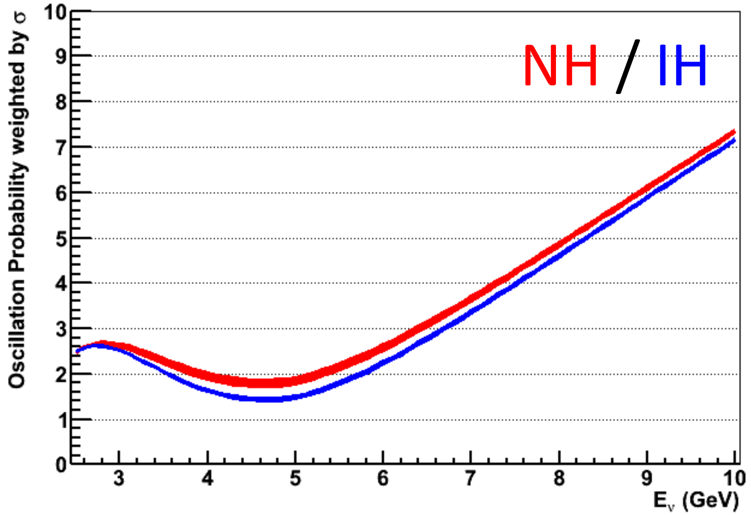
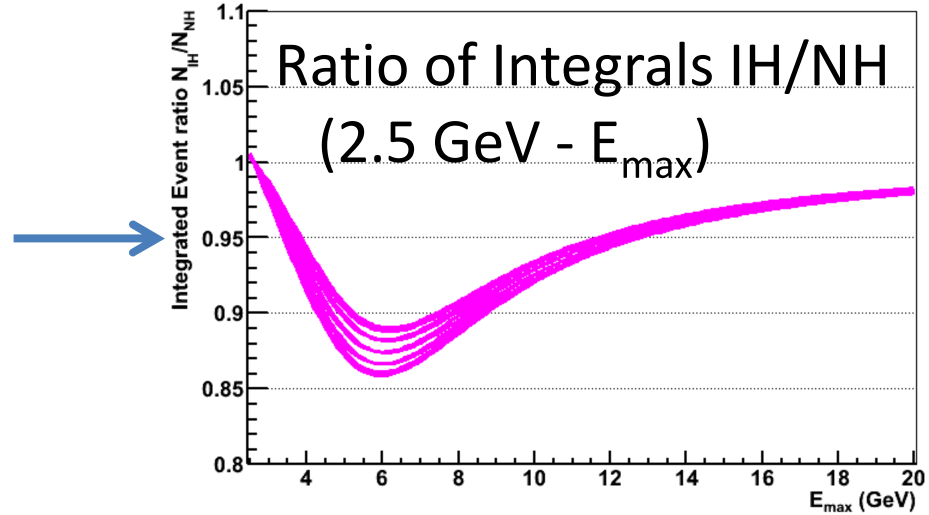


Cross Section Weighted P_{osc}

- Allows to find optimal energy range for MH determination
- No flavour tagging or CC/NC separation used
- Kinematical suppression of ν_τ exploited

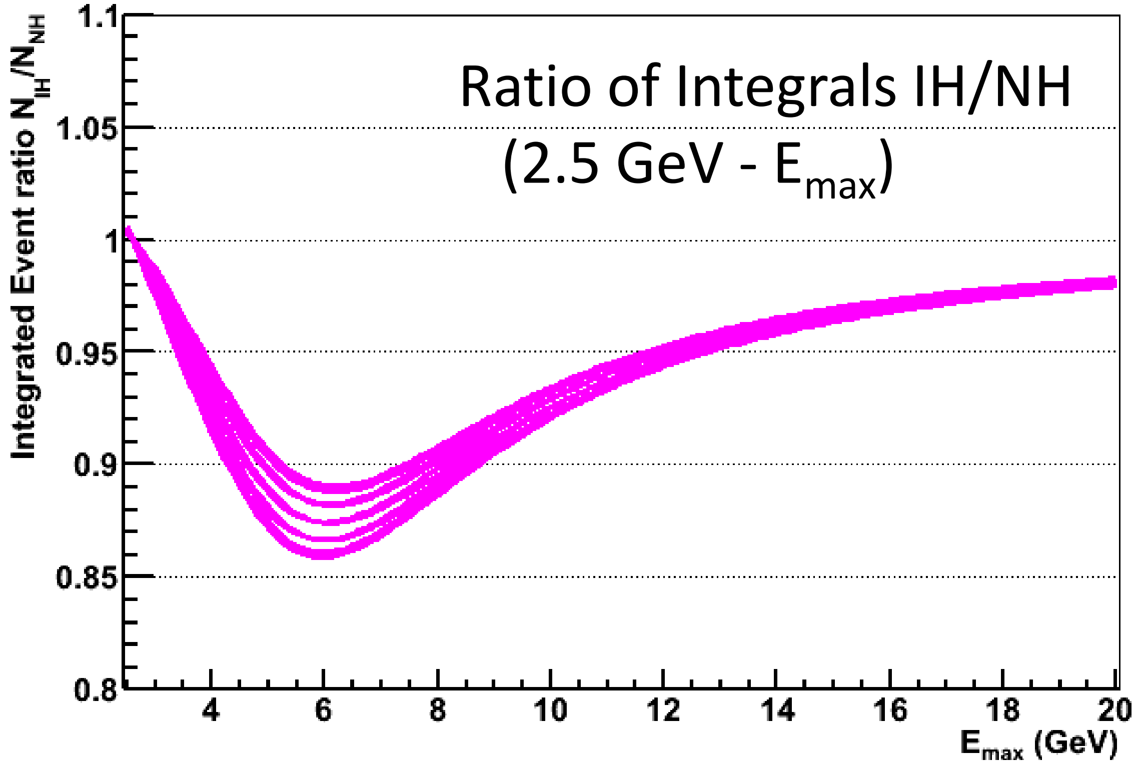
$$P^{\sigma}_{\mu}(E_\nu) = \frac{1}{\left[\sigma^{CC}_{\nu_\mu} + \sigma^{NC}_{\nu}\right](E_0)} \sum_{\alpha} \left[P(\mu \rightarrow \alpha)\sigma^{CC}_{\nu_\alpha} + \sigma^{NC}_{\nu}\right](E_\nu)$$



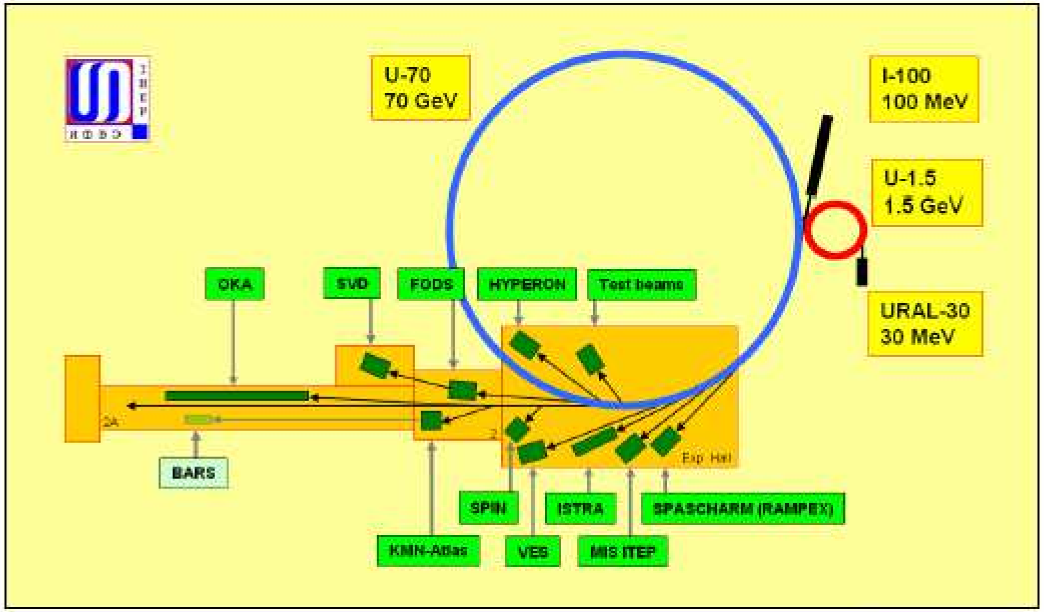


Cross Section Weighted P_{osc}

- Optimal energy range for "event counting" 2-6 GeV
- 11-14% suppression of IH w.r.t. NH



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

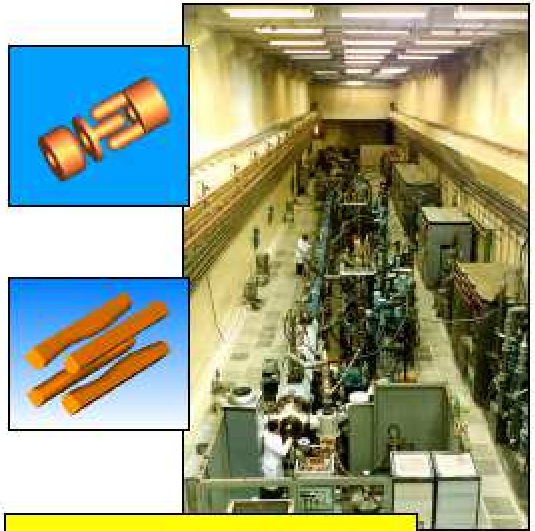
to note: OKA (#21), FODS (#22), stretcher (#25)

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

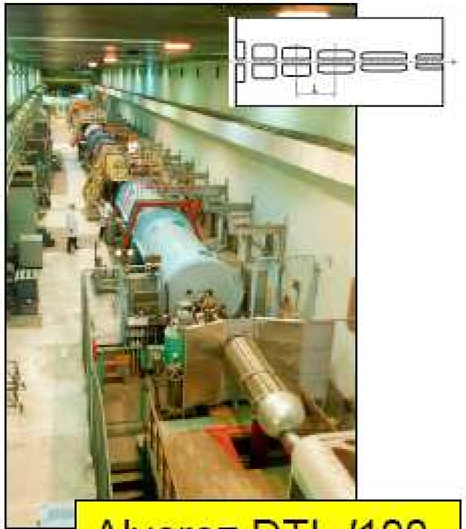
In a SIS-18, SIS-100 name convention:
- LIS-233 [T·m]
- LIS-6.9 [T·m]

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

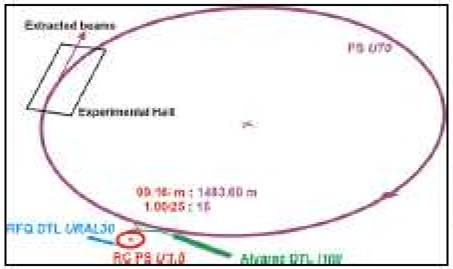
Proton Accelerator Complex Protvino



RFQ DTL *URAL*30



Alvarez DTL *I*100



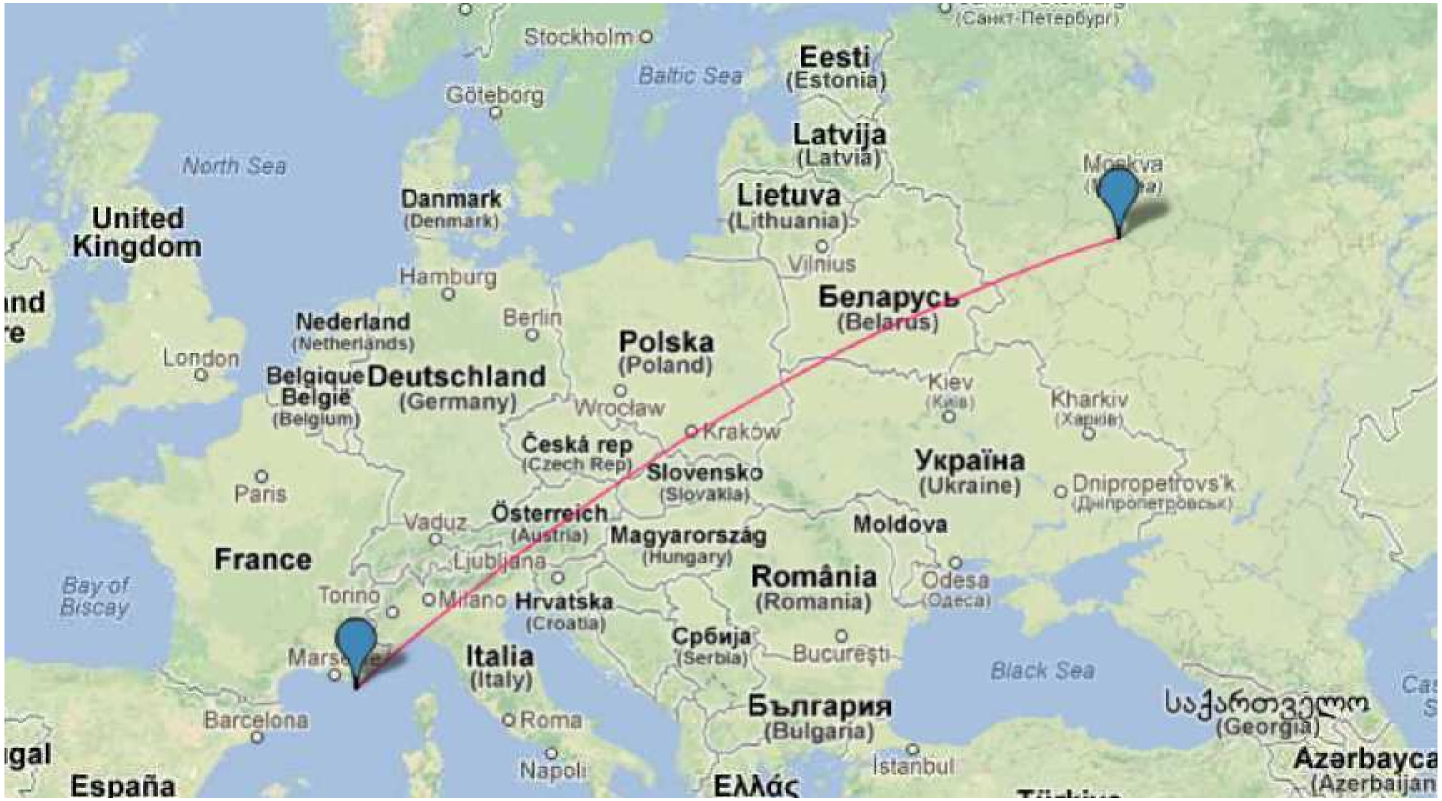
RC PS *U*1.5

Main PS *U*70

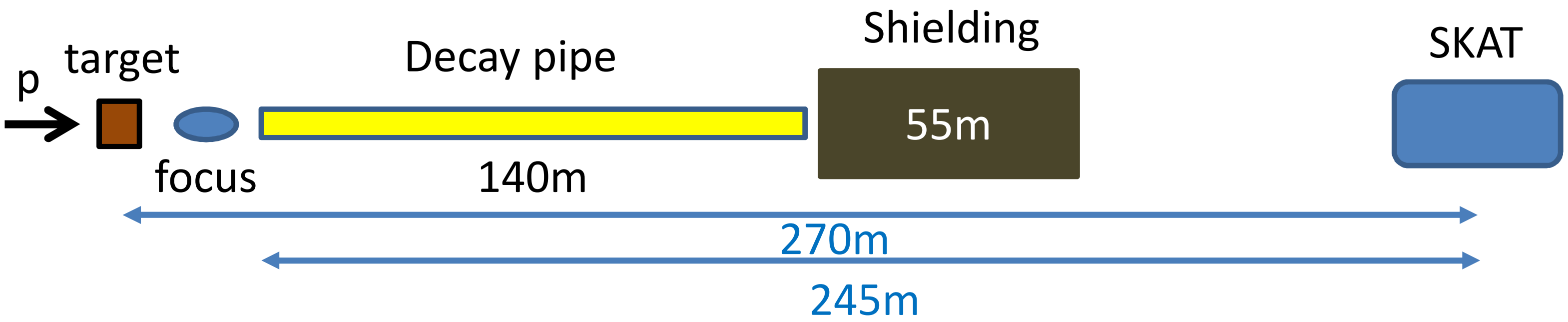
Presentation S. Ivanov (IHEP) on 22/11/2012 @ CERN

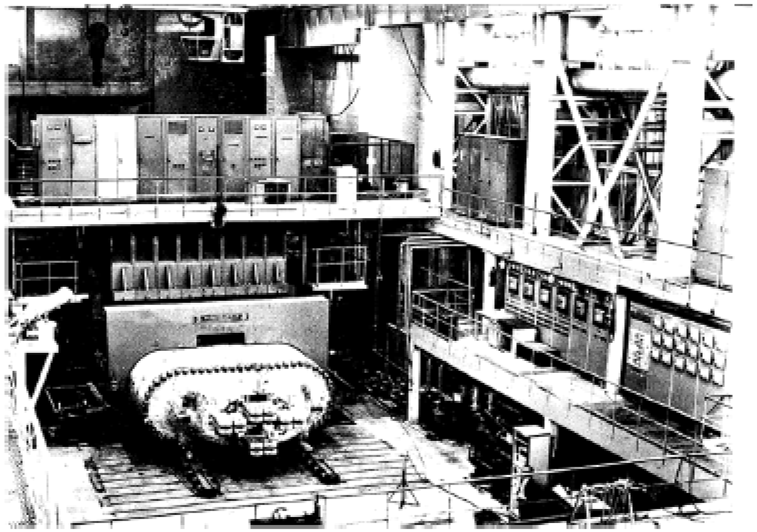
Where is Protvino ?

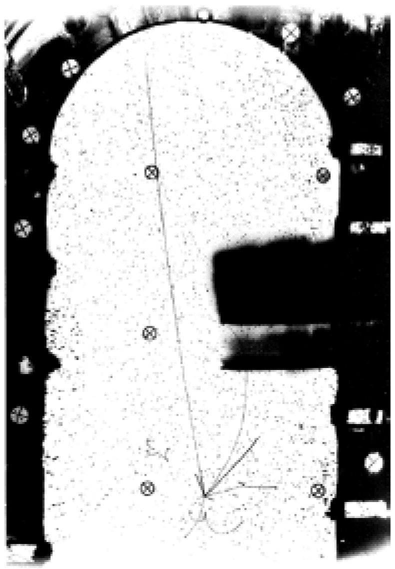
- Baseline 2588km ; beam inclination : 11.7˚ ($\cos\theta = 0.2$)
- Similar distance to Frejus : 2400km
- Deepest point 134km : 3.3 g/cm^3
- With upgrade 10^{21} p.o.t. in 3 years might be feasible

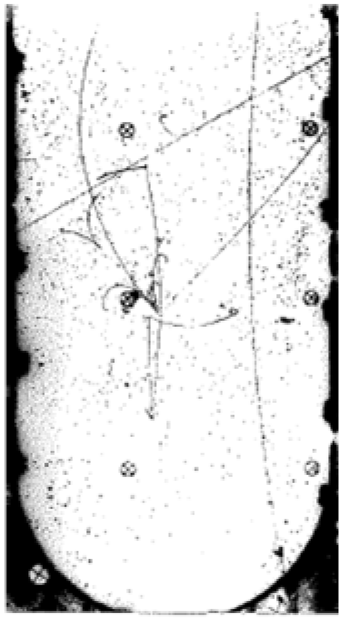


SKAT bubble chamber





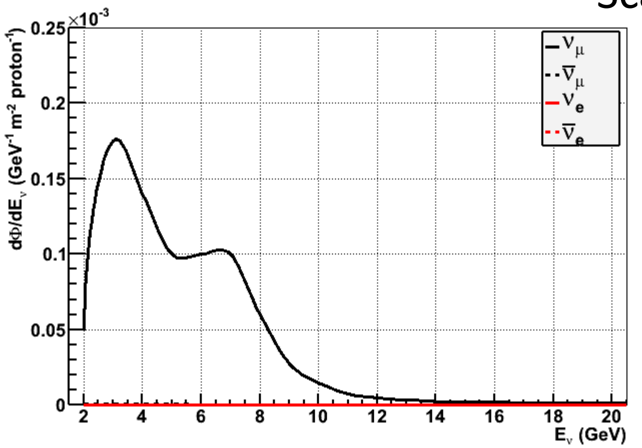




Courtesy: R. Nahnhauer

Beam parametrisation (1988)

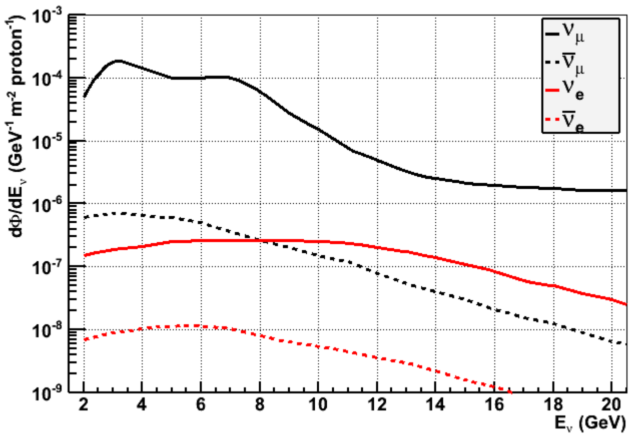
- Neutrino Focus
- Anti-Neutrino Focus

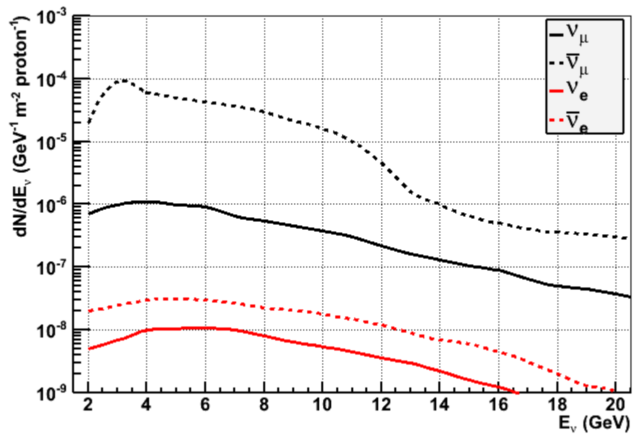


Scaling to ANTARES site

$(0.245/2600)^2$

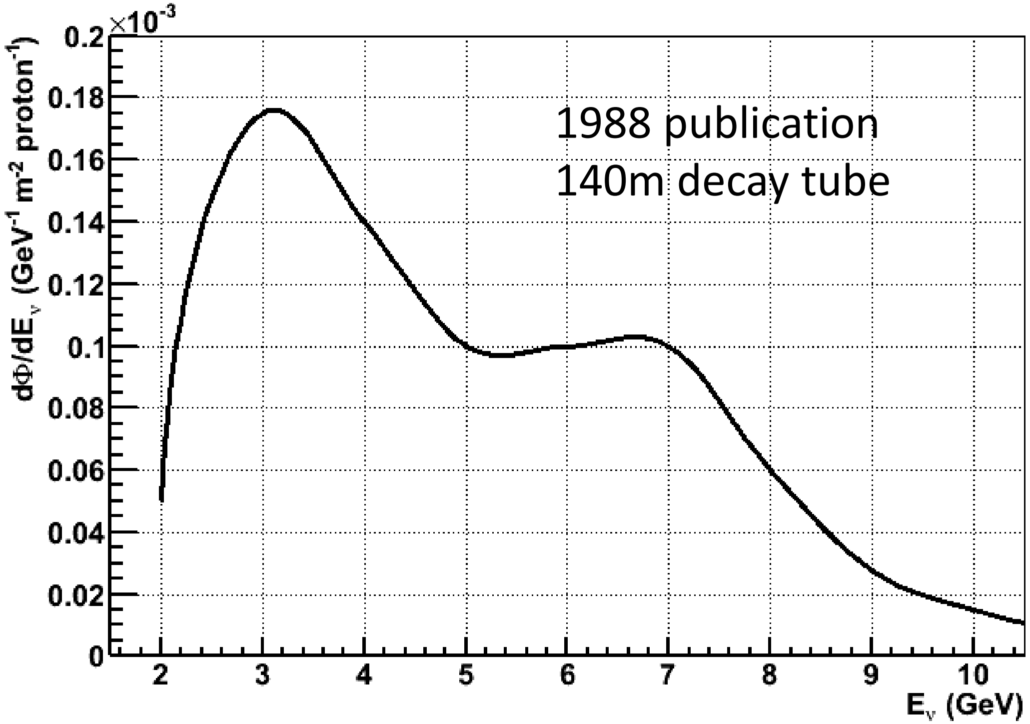
Z. Phys. C 40 (1988) 487





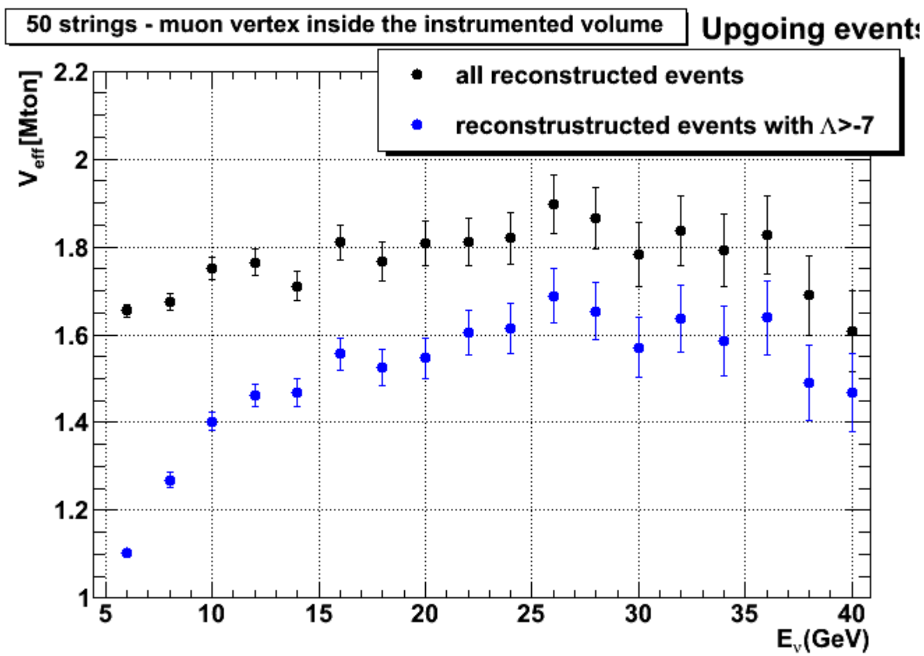
Beam parametrisation (1988)

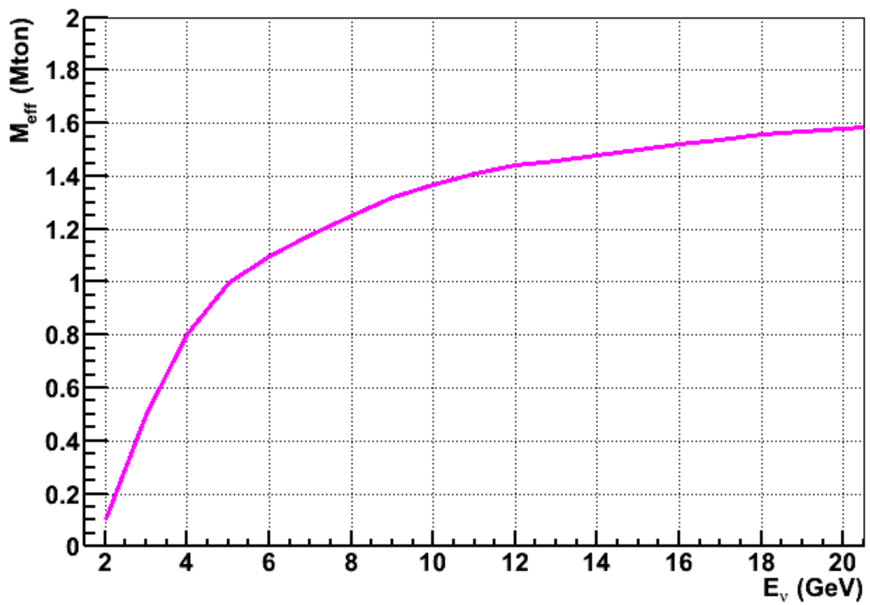
- Very clean ν_μ beam
- Less than 1% contaminations from other flavours
- Most neutrinos between 1-8 GeV



Effective Mass

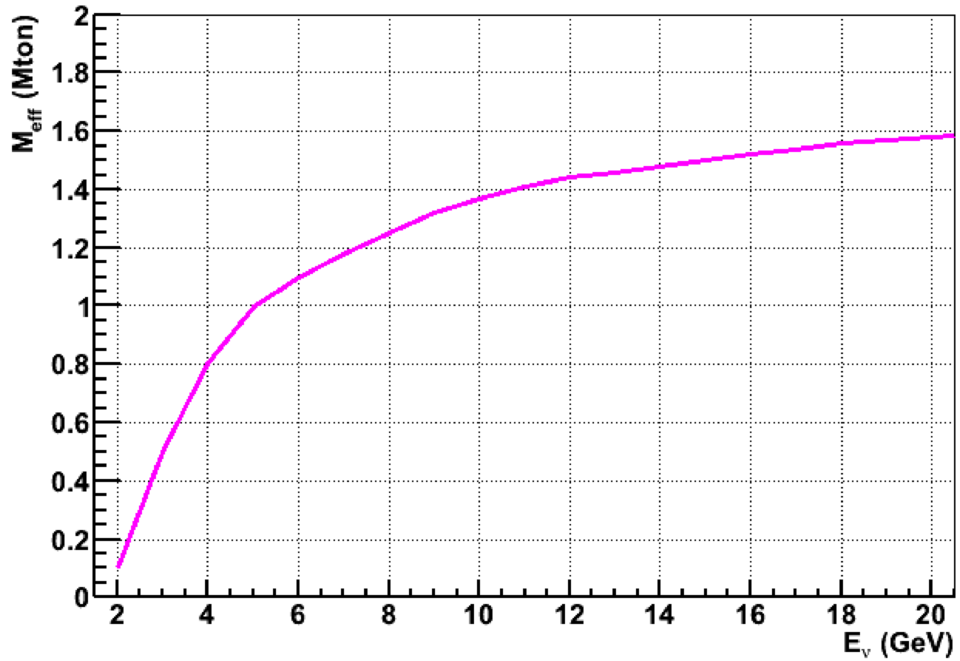
- From study of A. Trovato for “default” ORCA detector
- Vertex in instrumented volume
- Reco Quality cut (track)
- Conservative here
  - beam direction known, no background from atmospherics





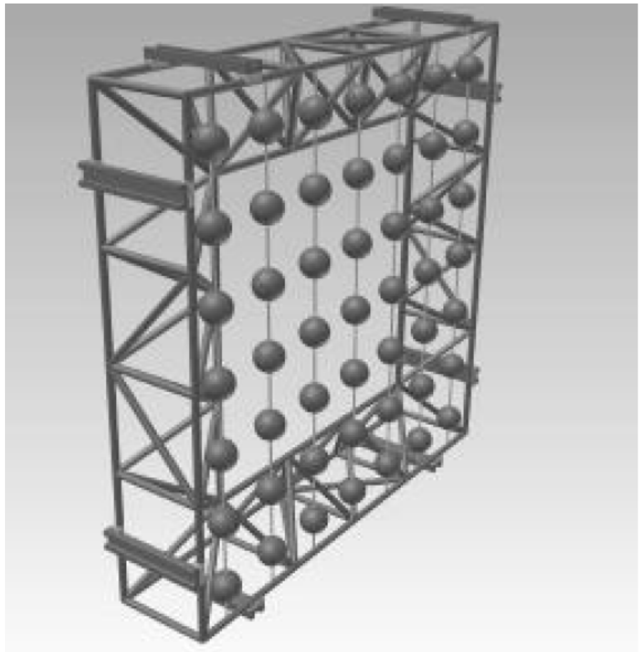
Effective Mass

- Same function used for all CC interaction
  - Same light output for ν_μ and ν_e → ok
  - Conservative for ν_τ due to escaping neutrinos
- NC evaluated at E/2



Flavour identification

- Need to separate "tracks" from "cascades"
- 2004 @ Villars : C2GT project (F. Dydak)
  - CERN to Gulf of Taranto



Flavour identification

- 2004 @ Villars : C2GT project (F. Dydak)
- Clean separation of ν_μ CC and ν_e CC at 0.8 GeV
- OM spacing 3m

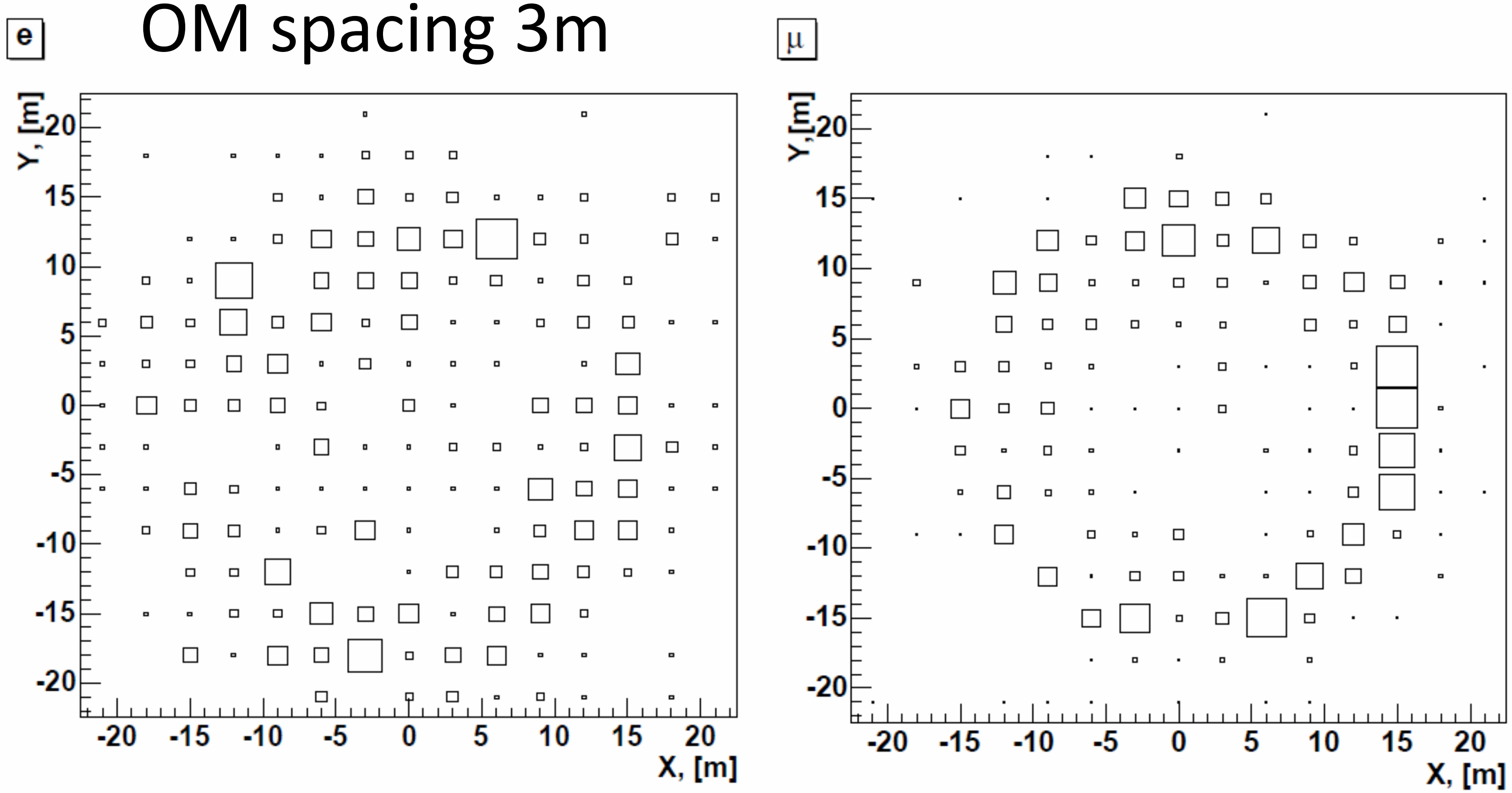
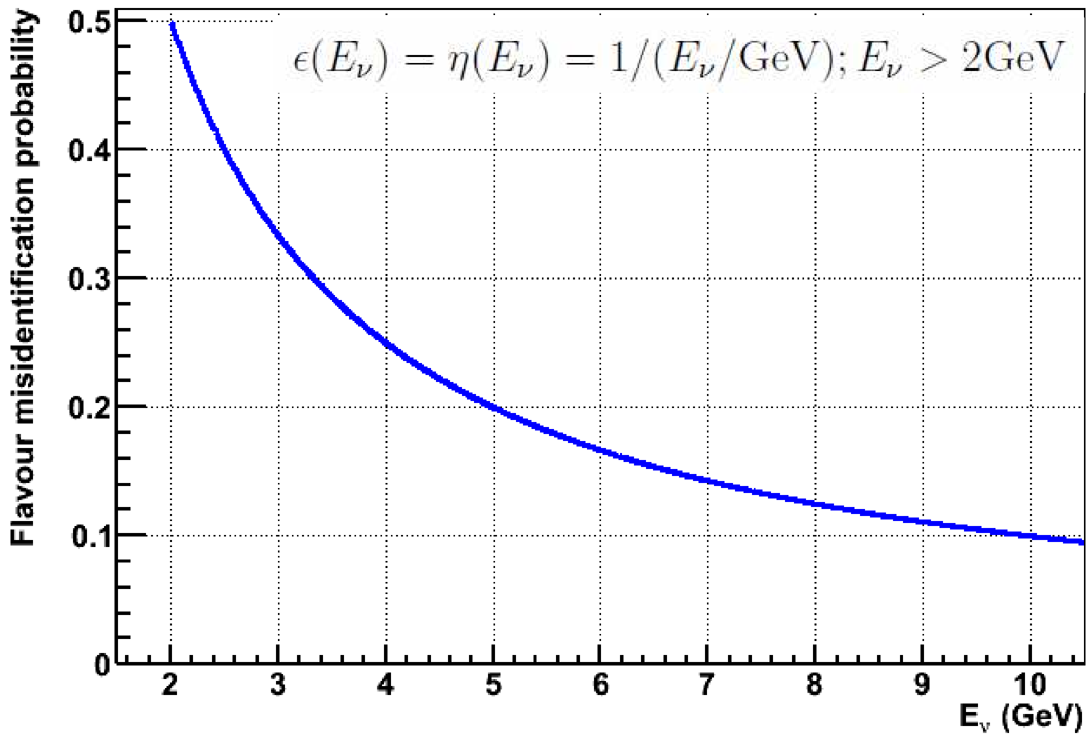


Figure 8: Cherenkov rings of a typical electron (top) and muon (bottom) event with 800 MeV total energy; the vertex is located 20 m upstream of the detector plane

Flavour identification

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



Event rates

- Here : no flavour misidentification
- CC Rates

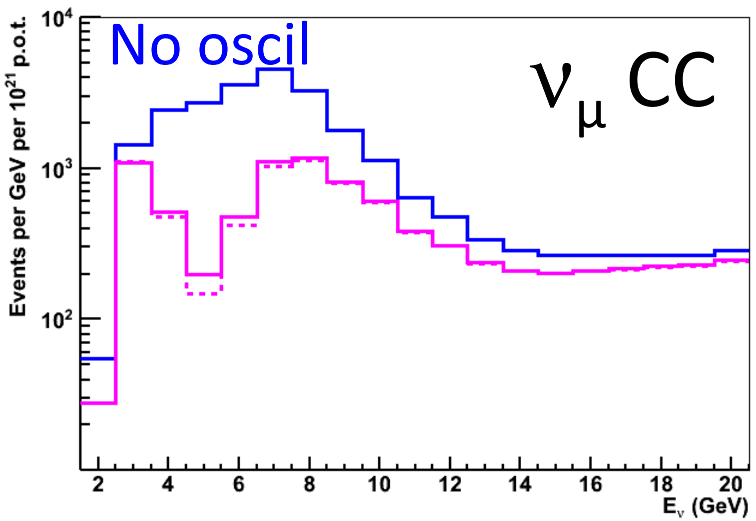
$$\frac{dN_\alpha}{dE_\nu} = N_{pot}\left(\frac{l_{SKAT}}{l_{LBL}}\right)^2 \frac{M_{eff}(E_\nu)}{m_p} \left[\sigma^{CC}_{\nu_\alpha}\left(\frac{d\Phi_{\nu_\mu}}{dE_\nu}P_{\mu\alpha} + \frac{d\Phi_{\nu_e}}{dE_\nu}P_{e\alpha}\right) + \sigma^{CC}_{\bar{\nu}_\alpha}\left(\frac{d\Phi_{\bar{\nu}_\mu}}{dE_\nu}P_{\overline{\mu\alpha}}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

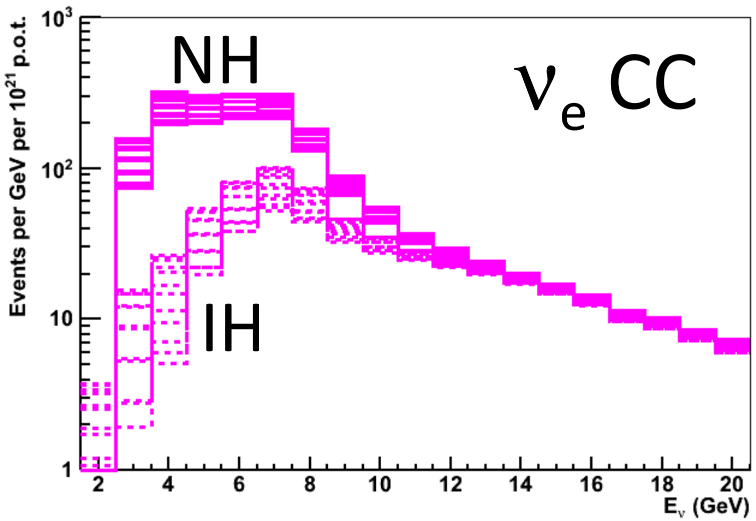
- NC Rates

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

Event rates

- Event numbers for 1.5 10^{21} pots
  - NH : 1621 +/- 255 (CP-phase variations)
  - IH : 497 +/- 100 (CP-phase variations)
- 20 sigma statistical separation of both Mass Hierarchy hypotheses from signal
- 10000 muon events for beam normalisation





Event rates

- Include Background and Flavour tagging
- Total Background :

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

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

- Total Event Rate :

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

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

Event rates

- Event numbers for 1.5 10^{21} pots
- 9-18% difference for NH/IH
- 7 sigma statistical separation of MH hypotheses
- With 3-4% syst uncertainty still 3 sigma for MH test
- No assumption on energy reconstruction !
- Background largely independent from MH (& CP)

Channel	Tracks NH	Tracks IH	Cascades NH	Cascades IH
No oscil	26315		—	
Signal	8990	8735	1134-1547	350-519
Misreco	232-329	47-79	1326	1280
ν_τ	324-332	351-355	978-998	1057-1068
NC	1092	1092	3640	3640
BG Total	1655-1745	1494-1522	5944-5964	5977-5988
Total	10645-10736	10229-10257	7099-7491	6338-6496

Event rates

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- 9-18% difference for NH/IH
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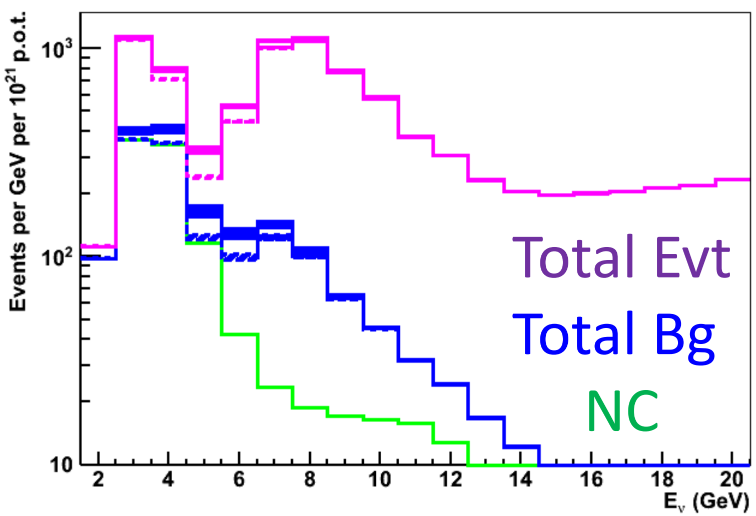
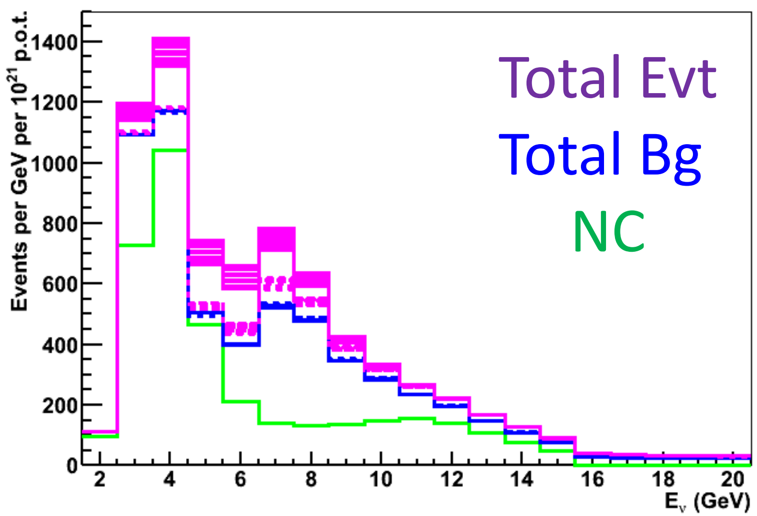
Tracks



Cascades



Systematic Uncertainties

- Detector Response
- Water parameters
  - Extensively studied in ANTARES
- Neutrino flux
  - Can be monitored with muon events
- Neutrino Cross Section
  - Ongoing and planned short baseline Experiments
- Oscillation parameters
  - ORCA with atmospheric neutrinos

Conclusion

- Powerful proton accelerator at Protvino well suited for LBL towards Mediterranean Sea
- Preliminary Performance Figures of ORCA encouraging
- Complementary to measurement with atmospheric neutrinos
- High Significance determination of Mass Hierarchy after few years of data taking