Neutrino GDR meeting
Paris, France
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Scientific potential of a neutrino beam from Protvino to ORCA (P2O)

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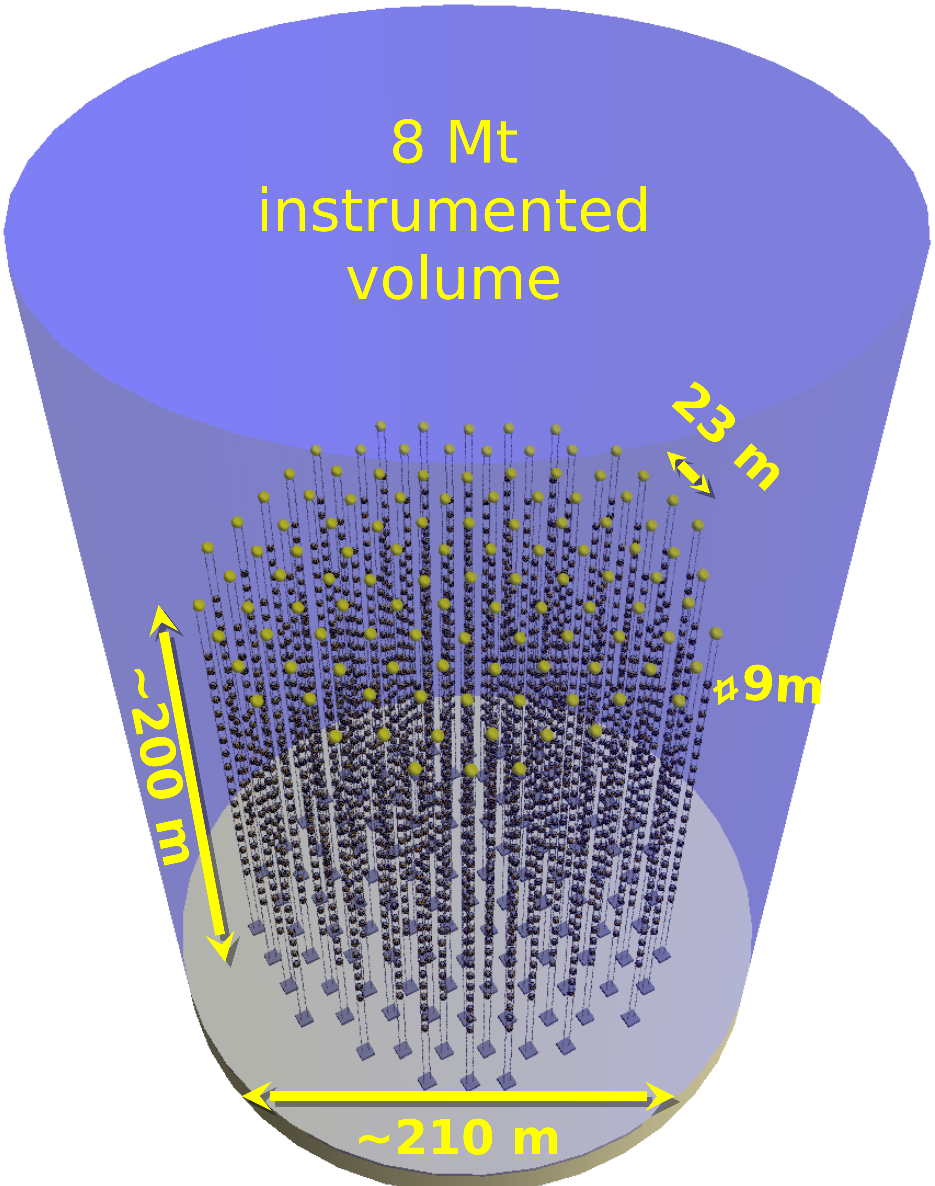
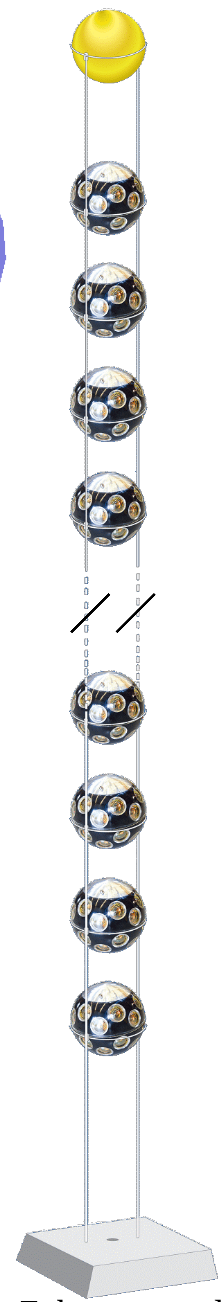
In cooperation with
A. Sokolov, V. Garkusha & A. Zaitsev (IHEP – Protvino)
and the KM3NeT collaboration

- Unique opportunity for a very long baseline experiment (2600 km)
- Sensitivity to neutrino mass hierarchy and CP violation

The far detector : KM3NeT / ORCA



Depth=2475m



Digital Optical Module (DOM)

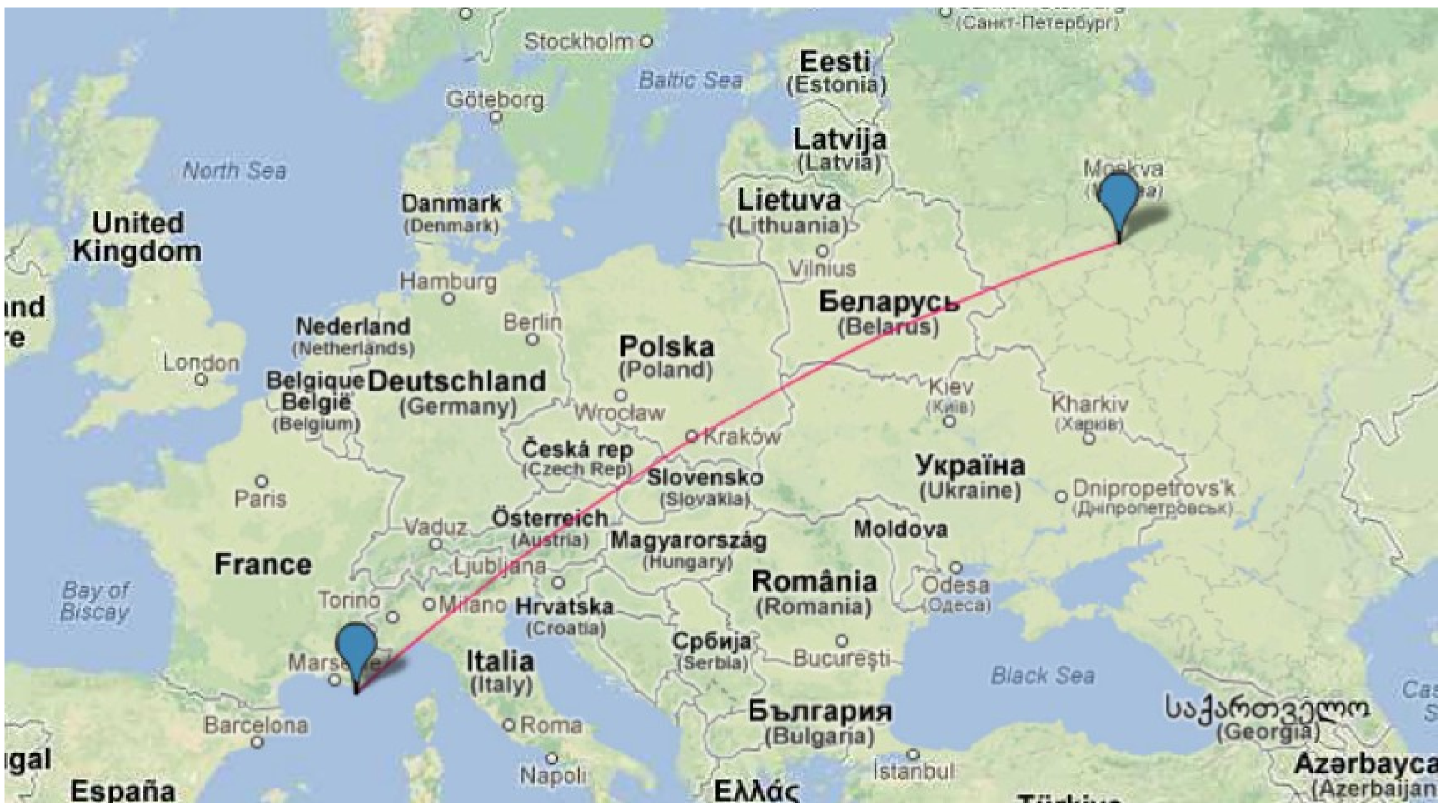
31
3-inch
PMTs
in
17-inch
glass
sphere

115 strings
18 DOMs / string
31 PMTs / DOM
Total: **64 000 PMTs (3”)**

See talk by Liam Quinn

P2O : Protvino to ORCA

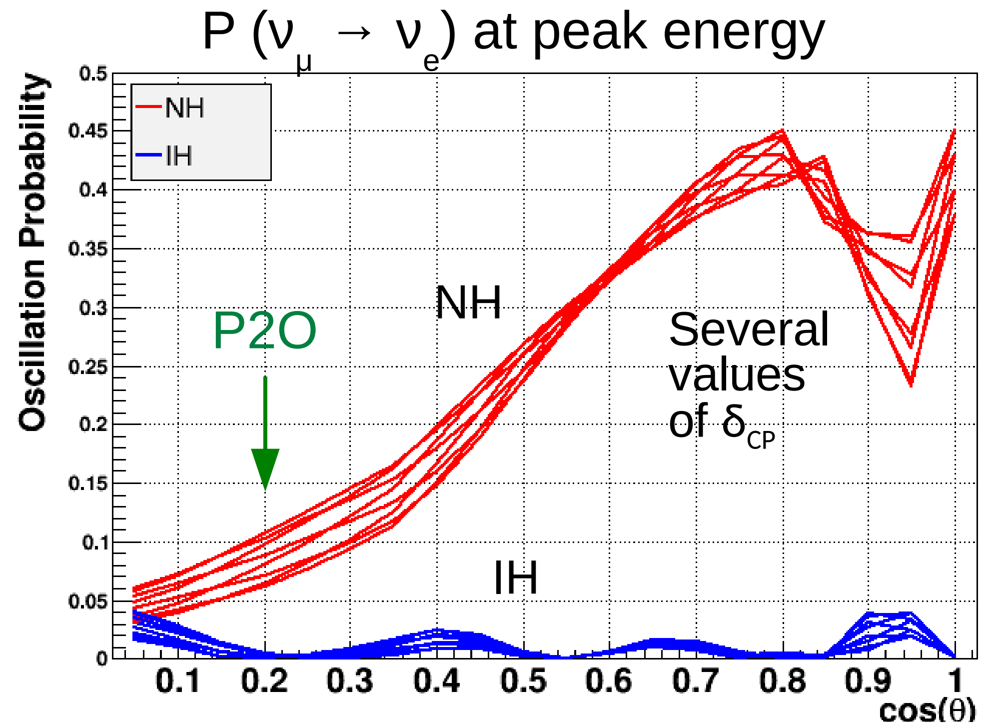
- Baseline 2588 km ; beam inclination : 11.7˚ (cos θ = 0.2)
- Deepest point 134 km : 3.3 g/cm^3
- First oscillation maximum 5.1 GeV
- Sensitivity to mass hierarchy and CP violation

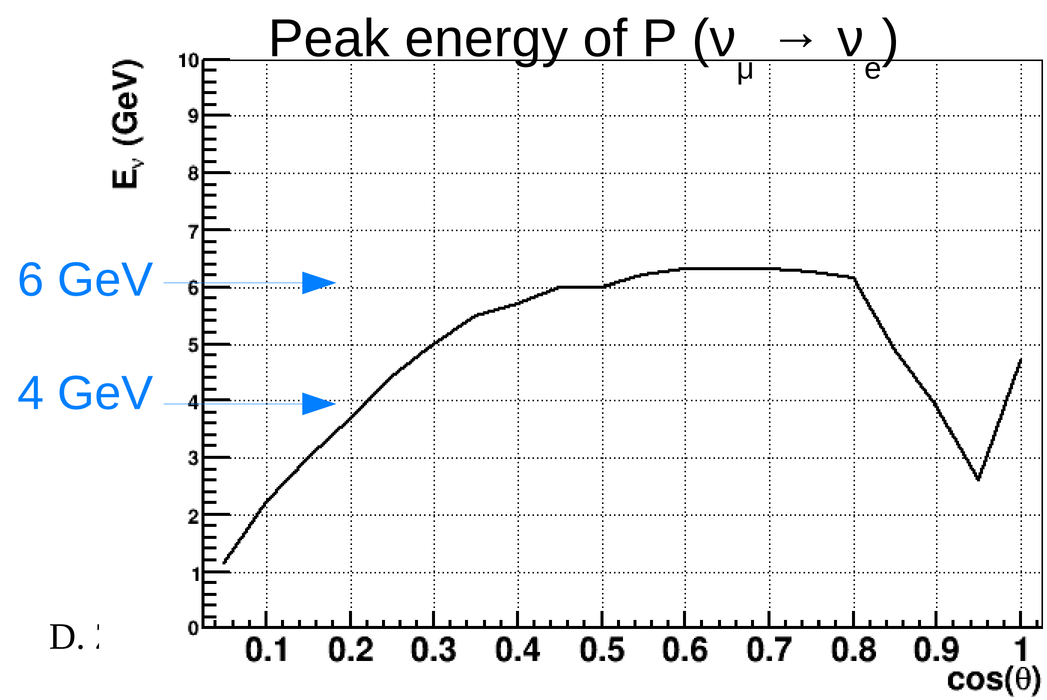


J. Brunner, arXiv:1304.6230; Adv. High En. Phys., 2013, Art. 782538, http://dx.doi.org/10.1155/2013/782538,
D. Zaborov et al., Lomonosov conference, Moscow, August 2017

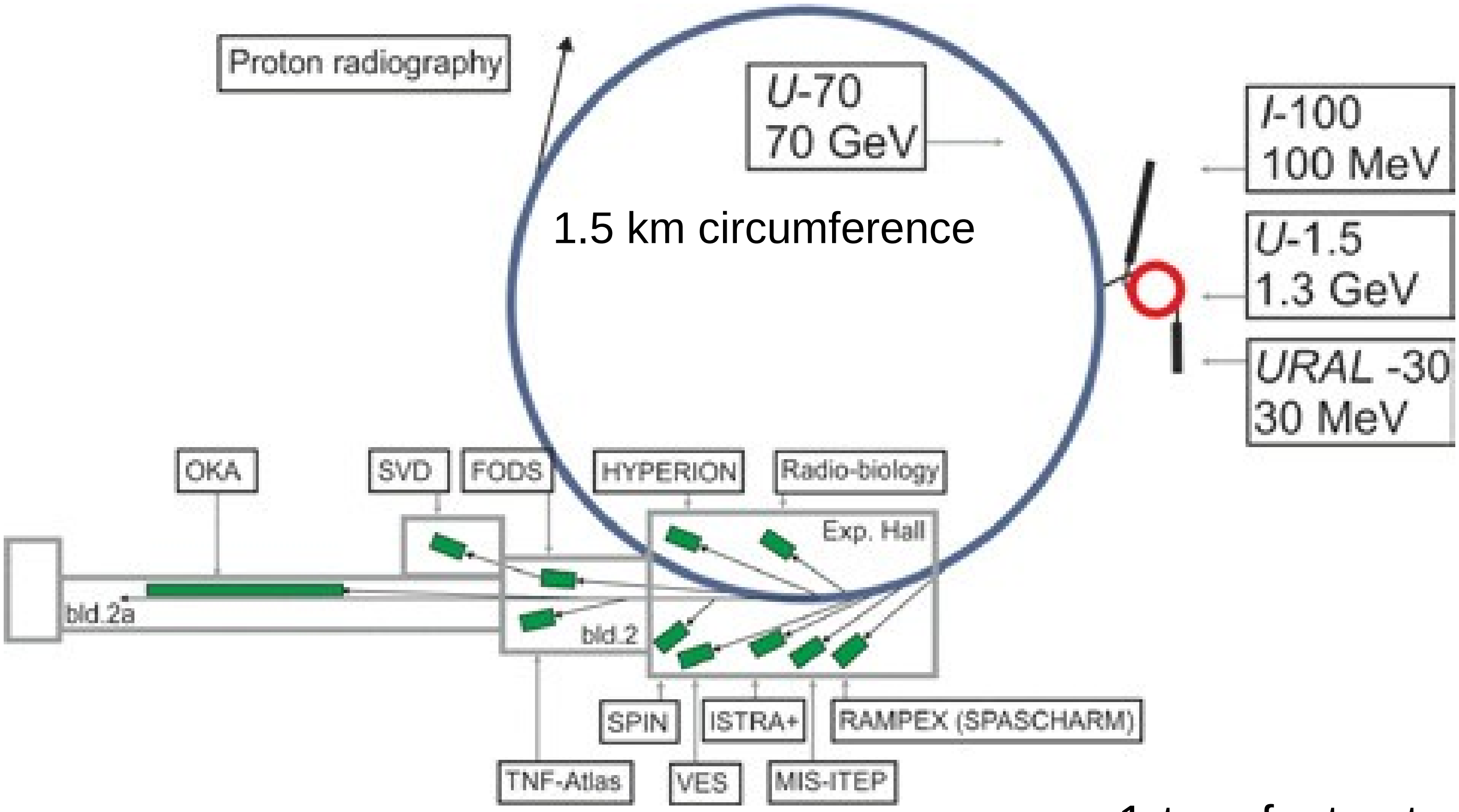
What baseline is best

- Optimal baseline to measure mass hierarchy with beam neutrinos is between 2000 km and 4000 km
- Degeneracy between MH and δ_{CP} for $L < 1000$ km
- Peak energy follows initially first oscillation maximum at $E = 25$ GeV * $\cos\theta$
- levels off at mantle resonance energy (~ 6 GeV)





Protvino accelerator complex
(100 km South of Moscow)



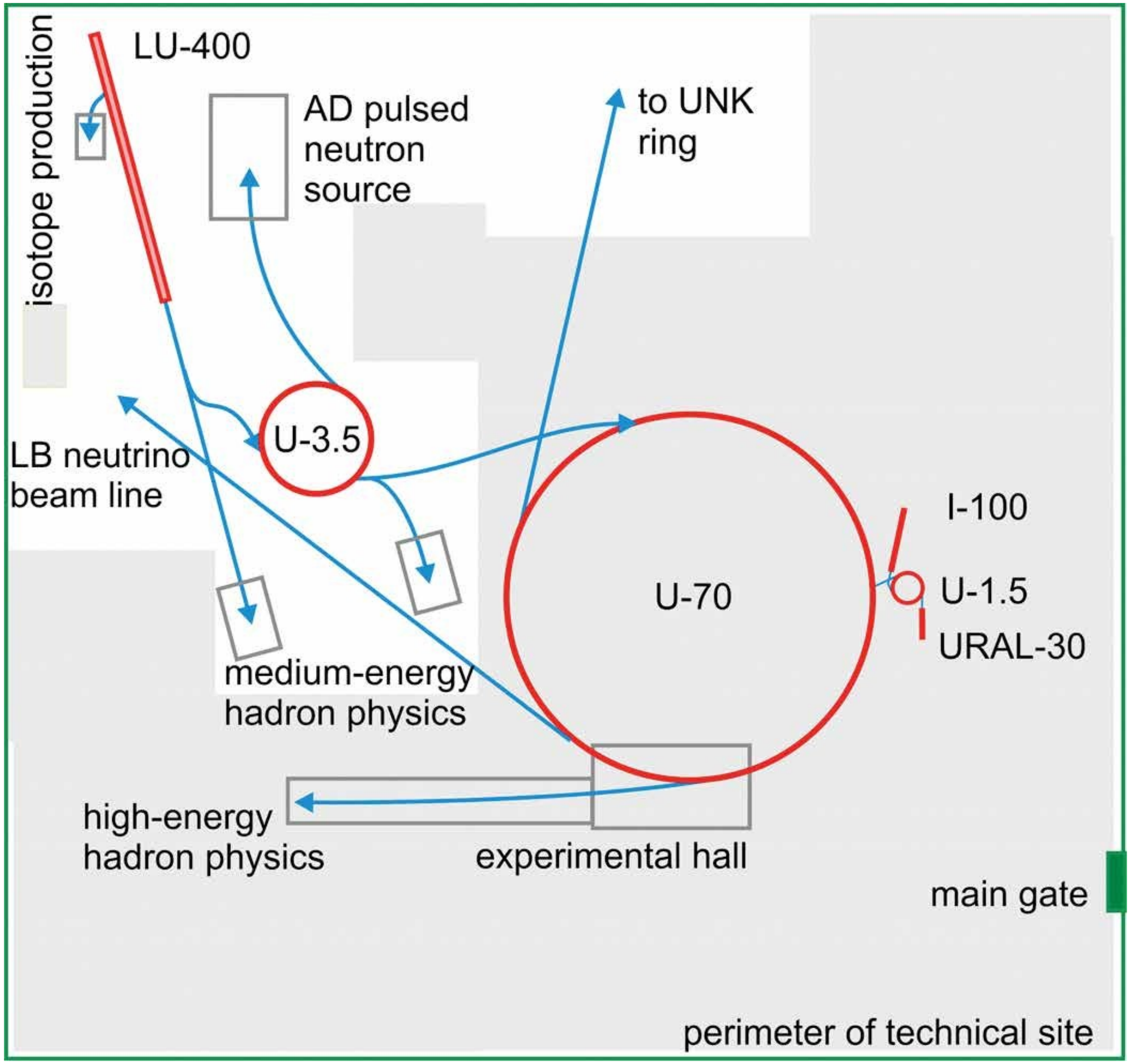
1-turn fast extraction:
5 μs spill every 9 s

U-70 accelerator constructed in 1967
Now operates at 8 - 15 kW for ~ 60 days / yr

Operated by NRC «Kurchatov Institute» – Institute for High Energy Physics (IHEP), Protvino

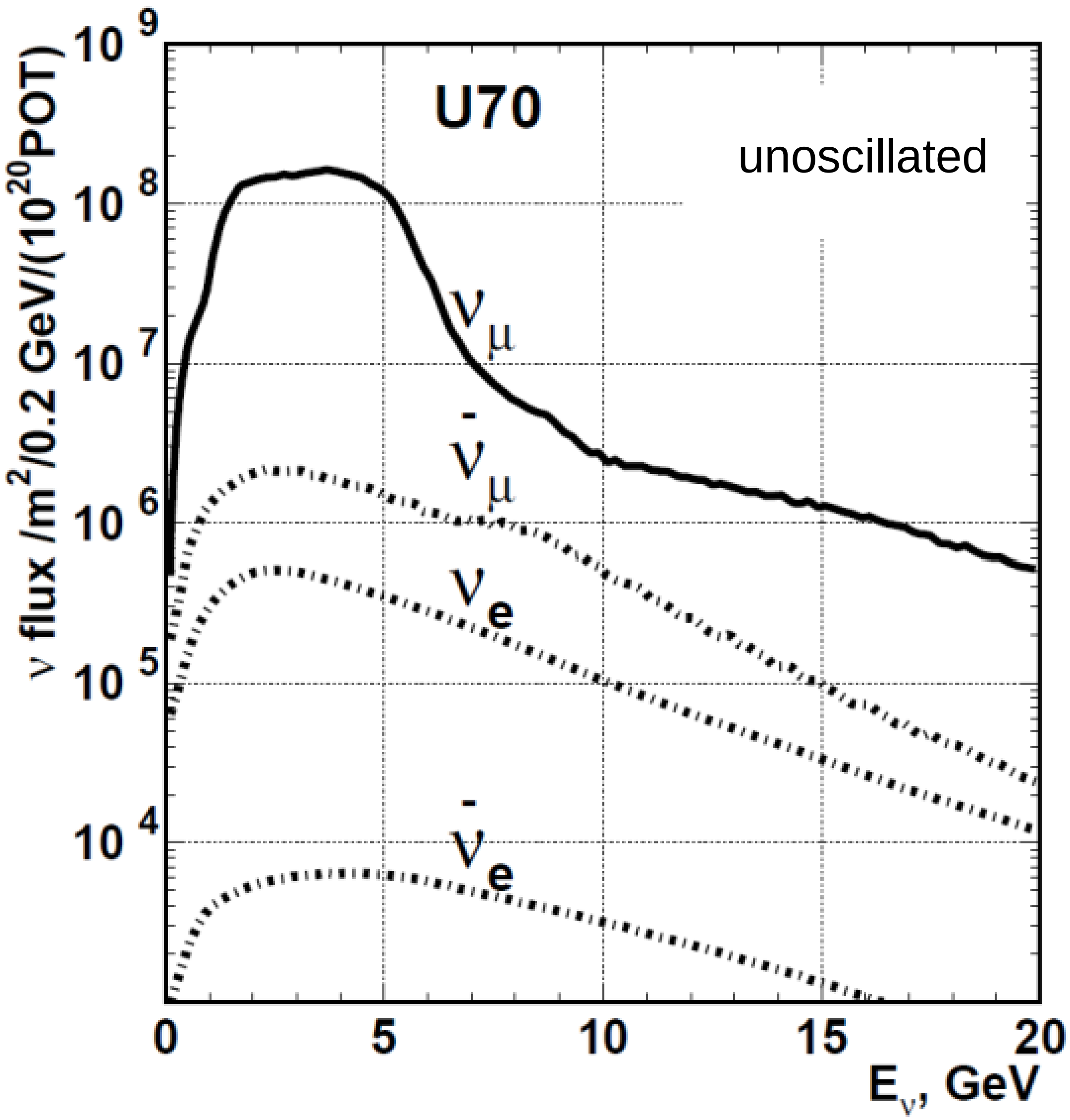
The OMEGA project proposal

- New high intensity linac and booster synchrotron (3.5 GeV)
- 1.1 MW proton beam
- High-intensity spallation neutron source (similar to J-PARC in Japan and SNS in USA)
- 450 kW power at 70 GeV using existing U-70 synchrotron
- A long baseline neutrino beam



N.E. Tyurin et al, Facility for intense hadron beams (letter of intent), News and Problems of Fundamental Physics 2 (9), 2010, http://exwww.ihep.su/ihep/journal/IHEP-2-2010.pdf

Simulated Neutrino Beam



Beam spectra from *V. Garkusha, F. Novoskoltsev & A. Sokolov, Study of Neutrino Oscillations with the U-70 Accelerator Complex, IHEP Preprint 2015-5* – beam optimized for Protvino-Gran Sasso (on-axis)

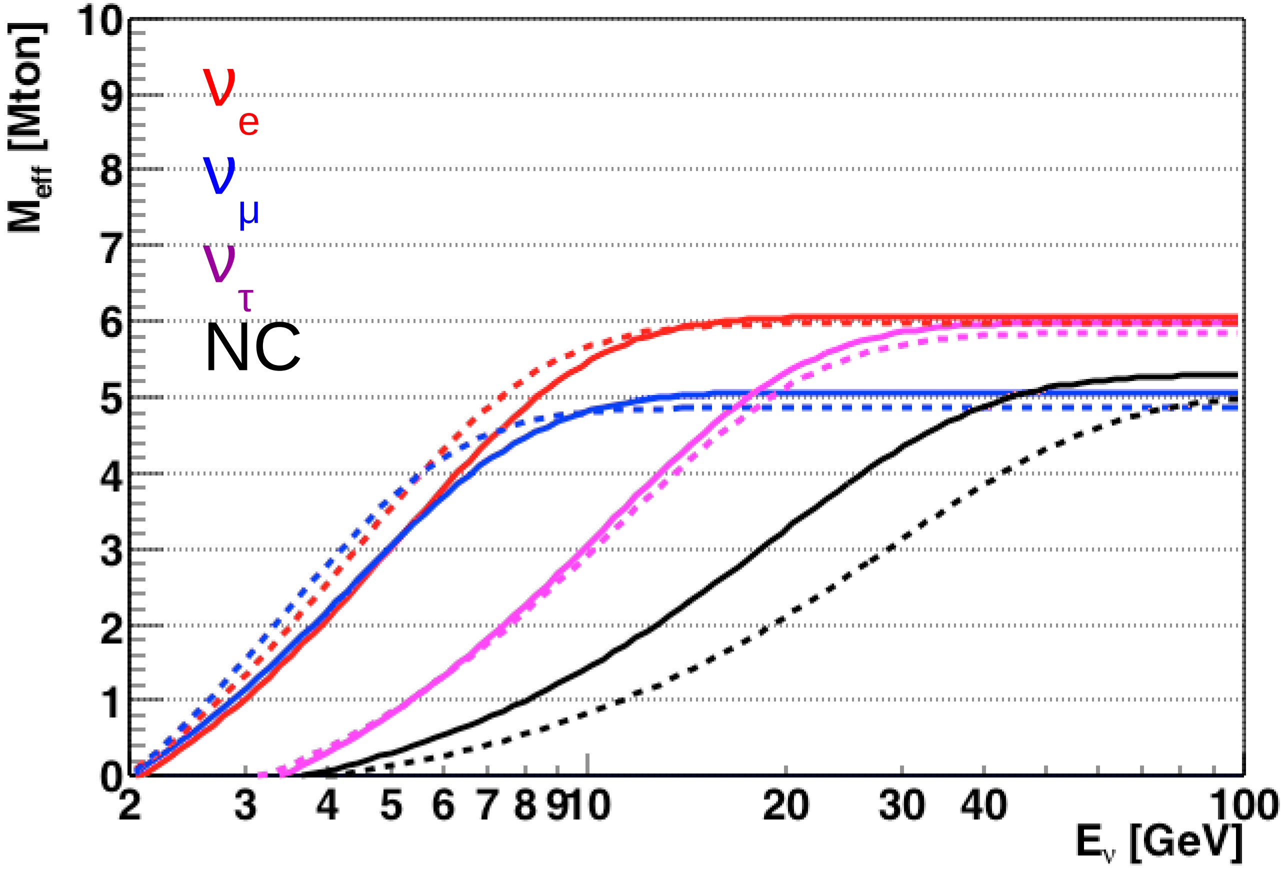
Focus π+ (Neutrino beam)

Beam power : 450 kW,
4 * 10^{20} p.o.t. per year

(for reference:
Fermilab-Nova beam is 700 kW)

ORCA effective mass

After triggering, atmospheric muon rejection and containment cuts



For reference, atmospheric neutrino events/yr:

ν_e CC: 17,300

ν_μ CC: 24,800

ν_τ CC: 3,100

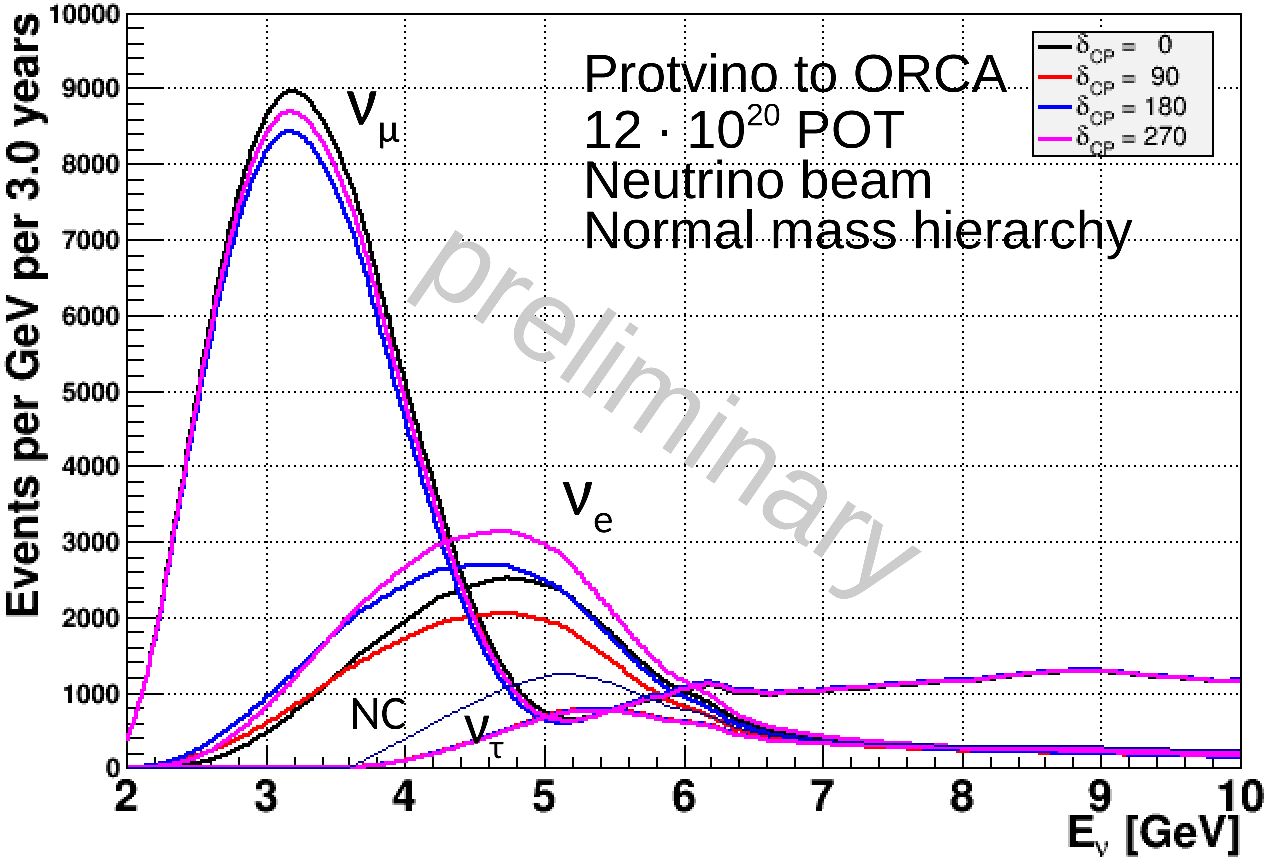
NC:5,300

- Energy threshold determined by DOM spacing
- 1 Mton @ 3 GeV
- 6 Mton @ 10 GeV

Analysis has not been optimized for beam neutrinos (yet)

Expected neutrino rates in ORCA
normal mass hierarchy

Raw event numbers in ORCA



Calculations with GloBES

After 3 years of 450 kW beam:

ν_μ CC: ~ 30000 events

ν_e CC: ~ 8000 events

ν_τ CC: ~ 3500 events

NC: ~ 6000 events

For comparison:
DUNE: ~ 900 ν_e events / yr

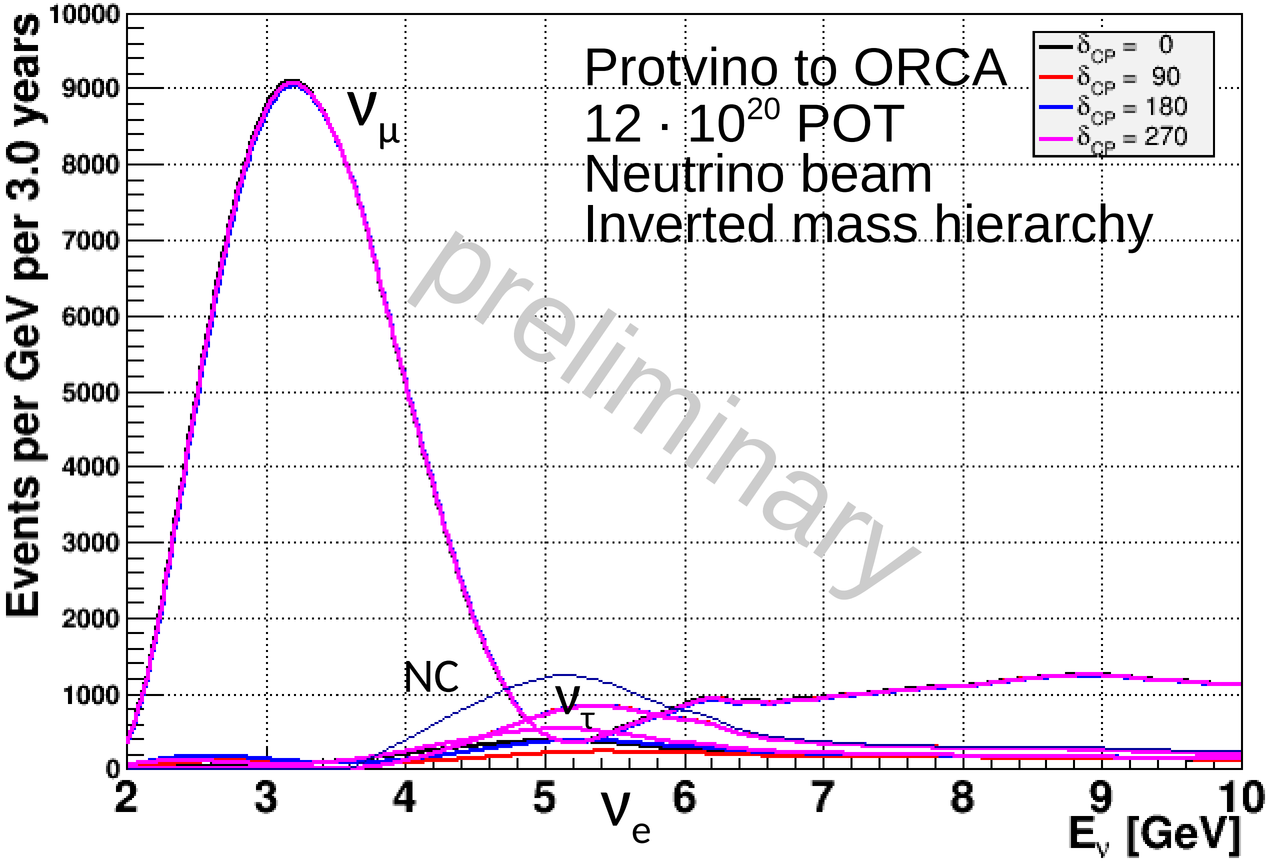
Vacuum oscillation maximum at E = 5.1 GeV

Most ν_μ convert to ν_τ which remains largely invisible (CC reaction suppressed by τ mass)

$\nu_\mu \rightarrow \nu_e$ transitions are enhanced by the MSW effect, resonance energy 3.8 GeV

Expected neutrino rates in ORCA
inverted mass hierarchy

Raw event numbers in ORCA



Calculations with GloBES

ν_μ CC: ~ 30000 events

ν_e CC: ~ 2000 events

ν_τ CC: ~ 3700 events

NC: ~ 6000 events

$\nu_\mu \rightarrow \nu_e$ transitions suppressed by the MSW effect

If inverted mass hierarchy is true, switch to anti-neutrino beam (for CPV studies)

Multi-Parameter fit of simulated data

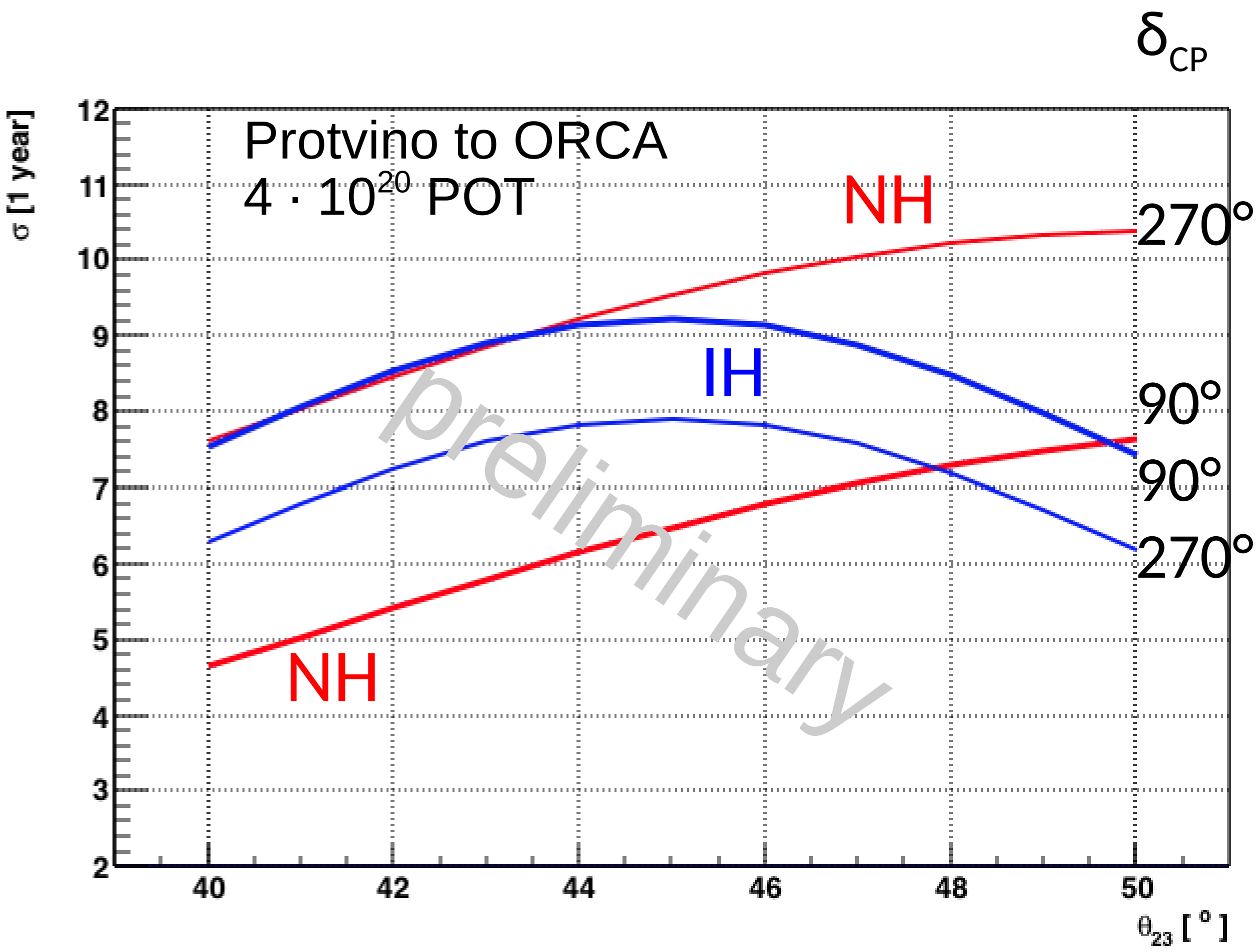
- Combined fit of nuisance and oscillation parameters
- No neutrino/anti-neutrino skew
- No spectral index skew
- No energy scale shift

Parameter	True value	Prior	Start value
θ_{12}	33.4°	fix	fix
Δm^2 [eV^2]	7.53 10^{-5}	fix	fix
θ_{13}	8.42°	0.15°	8.42°
θ_{23}	41.5°	1.3°	41.5°
ΔM^2 [eV^2]	2.44 10^{-3}	0.06	2.44 10^{-3}
δ_{CP}	many	no	many

* Only used for CP fits, not for NMH

Parameter	True value	Prior	Start value
Norm ν_e CC	from ν_μ CC	fix	fix
Norm ν_μ CC	1	0.05	1
Norm ν_τ CC	1	0.10	1
Norm NC	1	0.05	1
PID	1	0.10	1
ν / $\bar{\nu}$	1	fix	fix

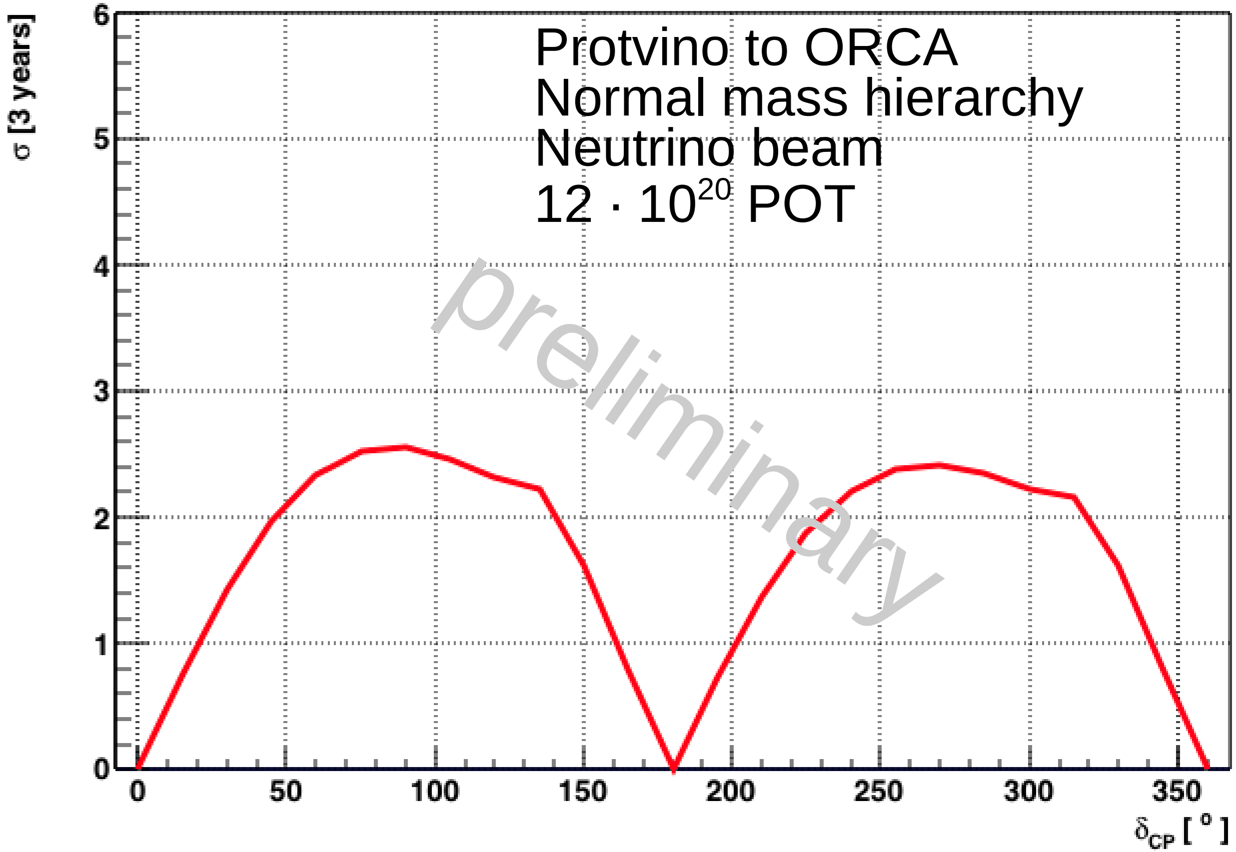
P2O sensitivity to mass hierarchy



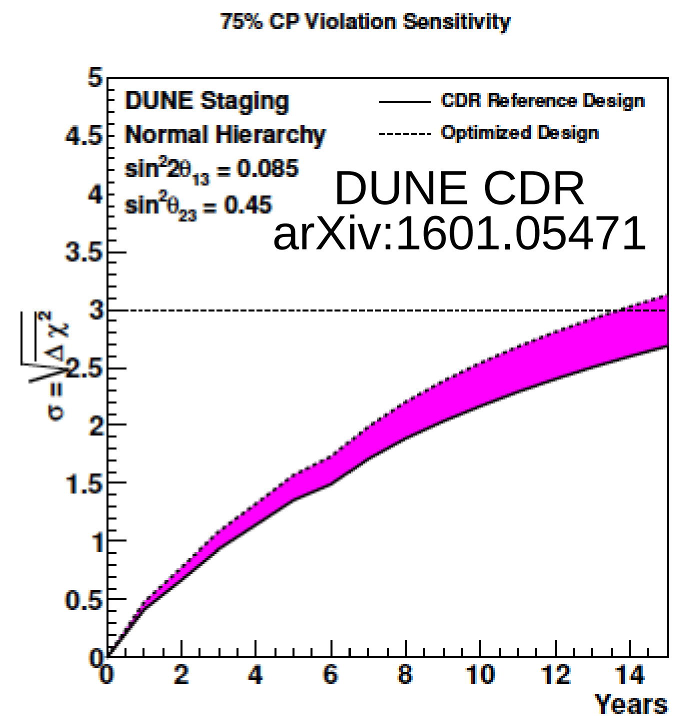
> 5 sigma after 1 year of 450 kW beam

Sensitivity to CP violation

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

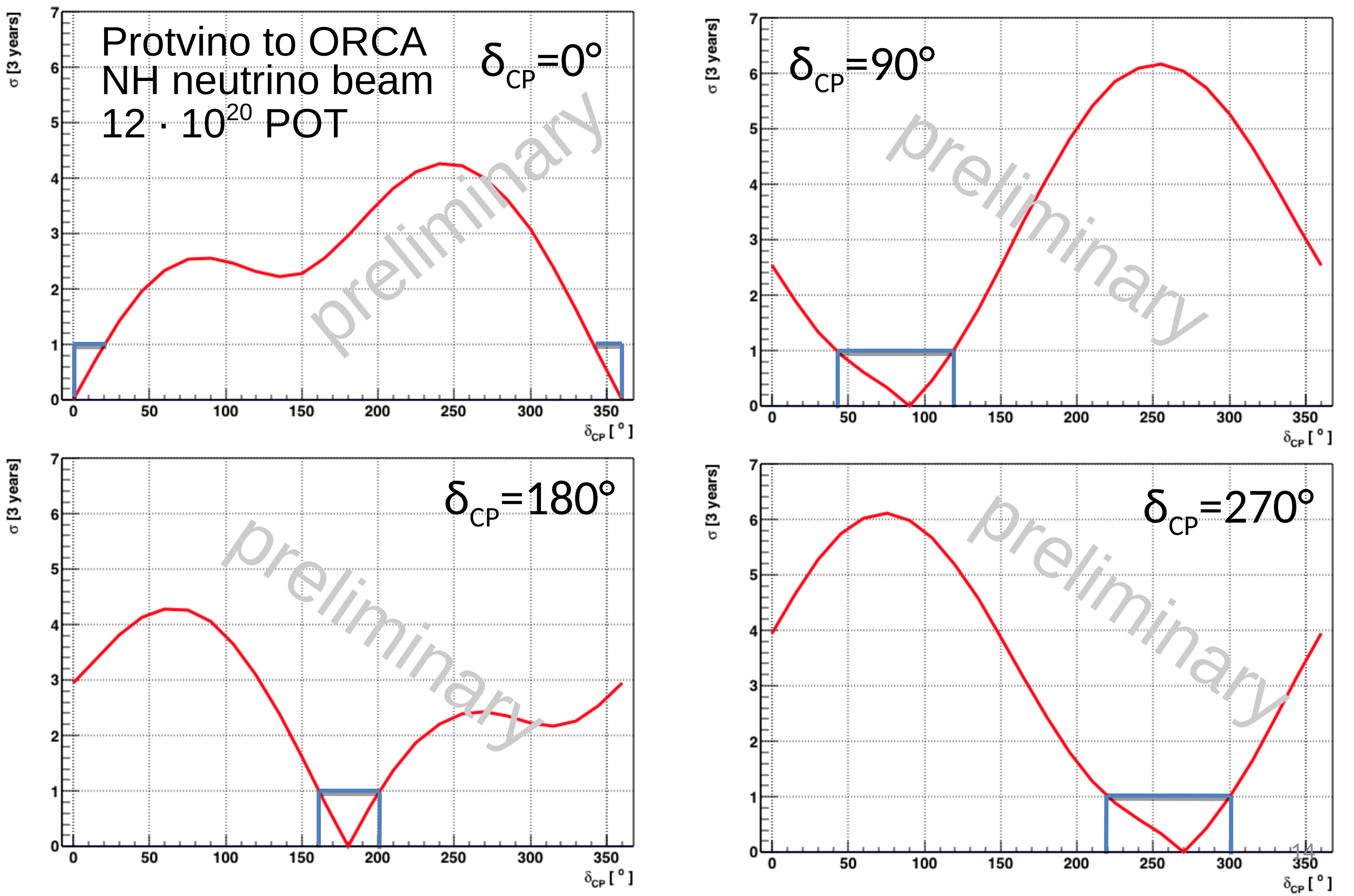


Competitive with DUNE!

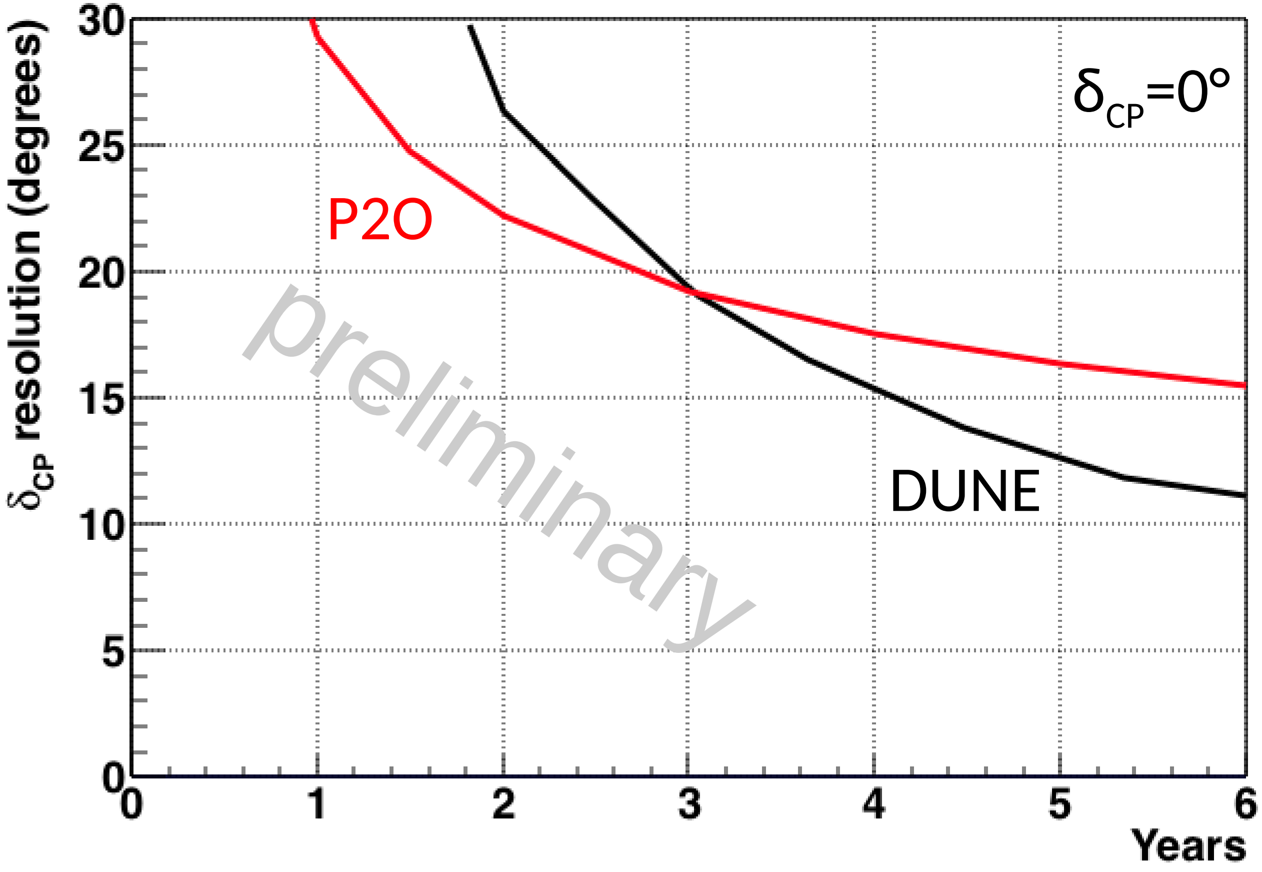


~ 2 sigma after 3 years of 450 kW beam

Simulated measurement of δ_{CP}

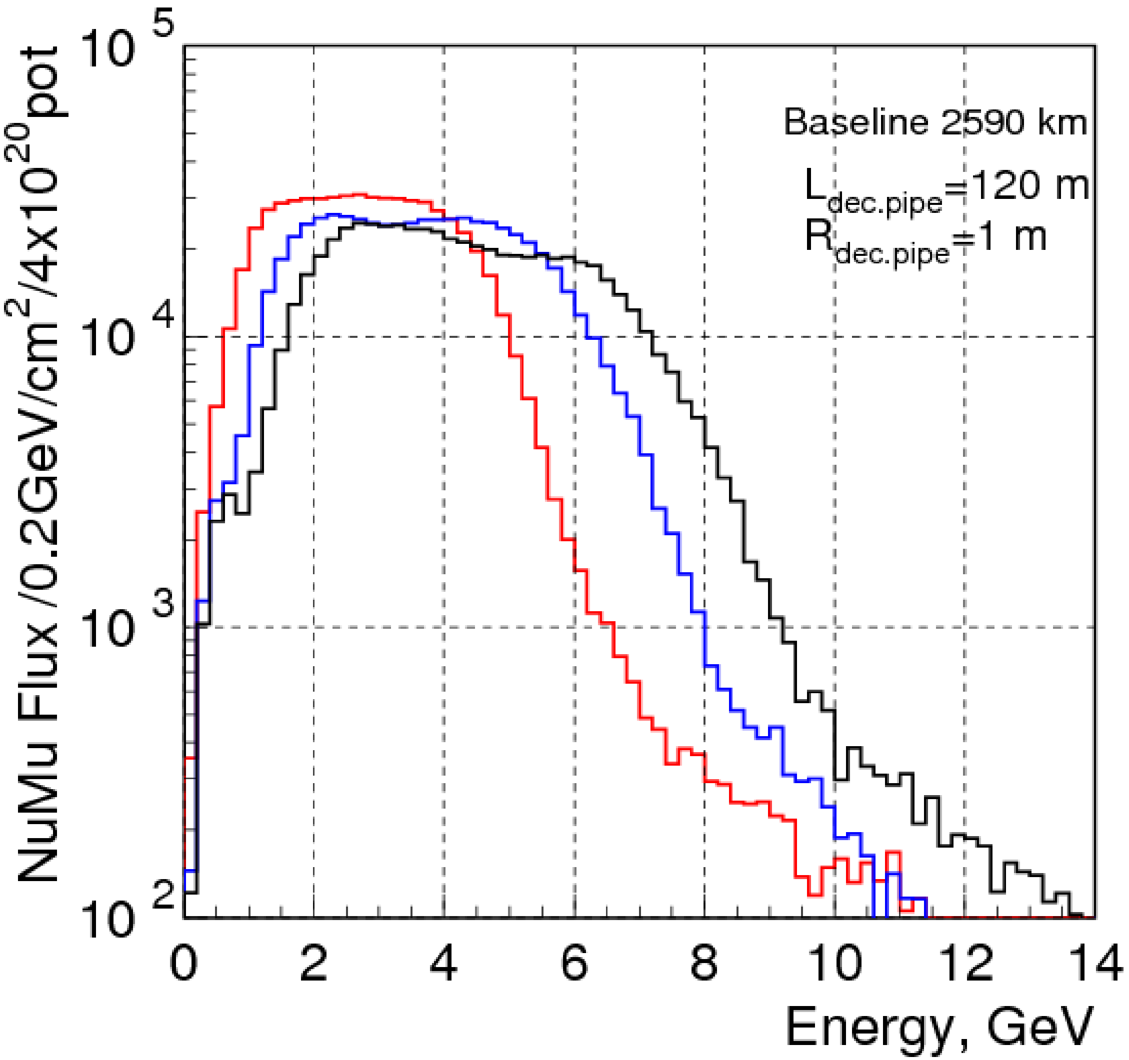


Measurement accuracy for δ_{CP}



NB: this study uses preliminary estimates of systematic uncertainties

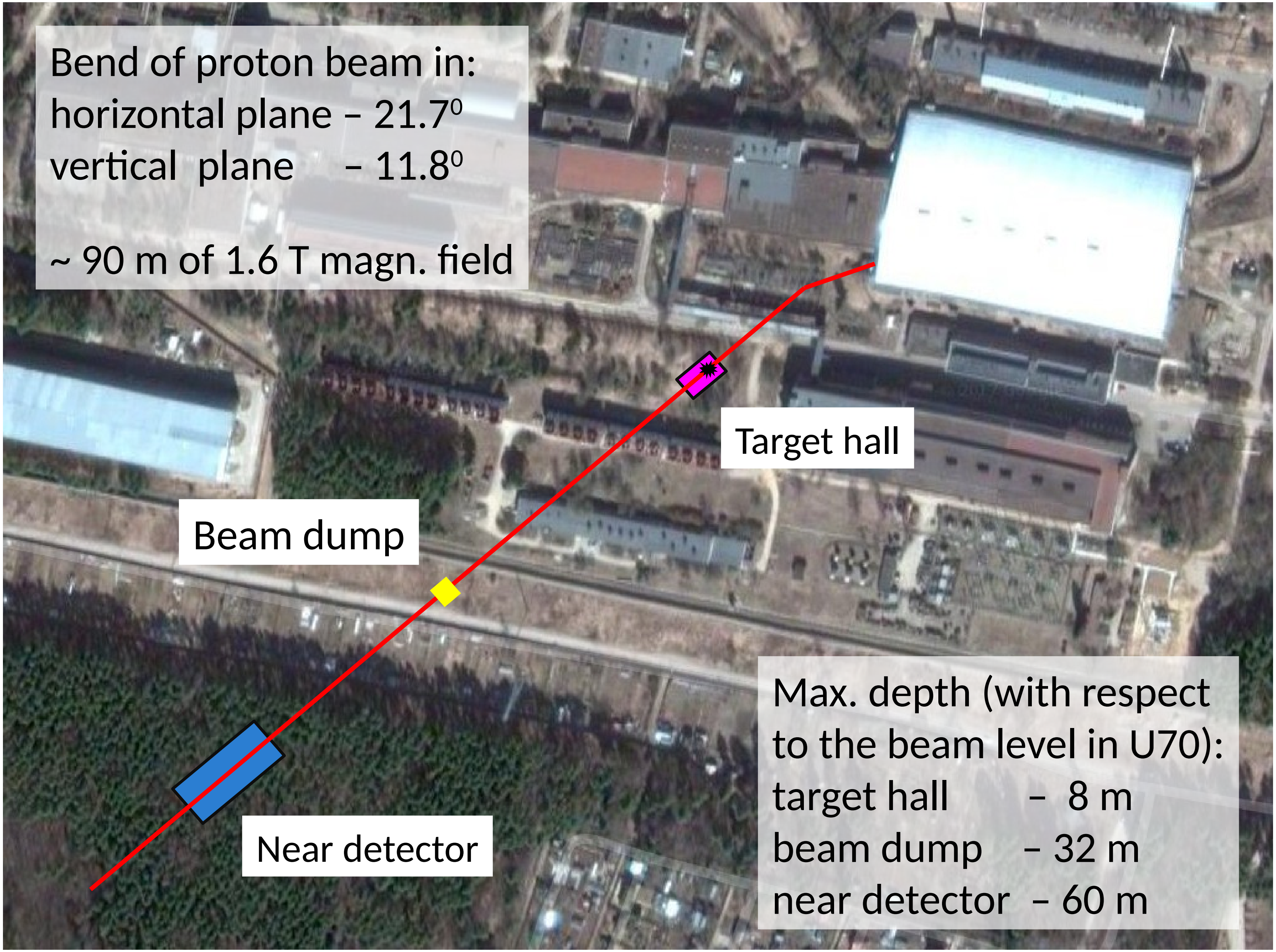
Beam optimization (work in progress)



- Red: two 3 m horns as in arXiv:1412.0804
- Blue: target shifted towards the beam
- Black: target shifted towards the beam + horns moved further away from each other

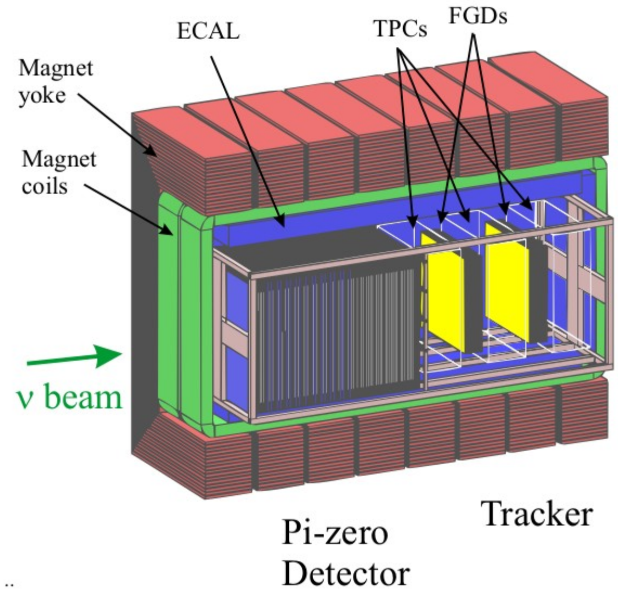
Idea: choose the beam option which gives best sensitivity to CP violation

Possible location of the neutrino beam line



Thinking of Near detector

T2K-like?



Water tank?

?

DUNE-like?

?

High granularity?

… ?

Water-based scintillator?

?

Cross-section measurements?

?

Suggestions are very welcome

The low intensity (& low cost) option

- Use existing accelerator chain upgraded to maximum possible intensity
- Assume we have a 45 kW beam (upgrade to 30 kW currently in progress)
- Assume we gain a factor of 2 by optimizing the beam and the ORCA data analysis

5 sigma on mass hierarchy after 5 yr of 45 kW beam

but marginal sensitivity to CP violation, unless ORCA is also upgraded

Could serve as Phase 1 on the way to full intensity

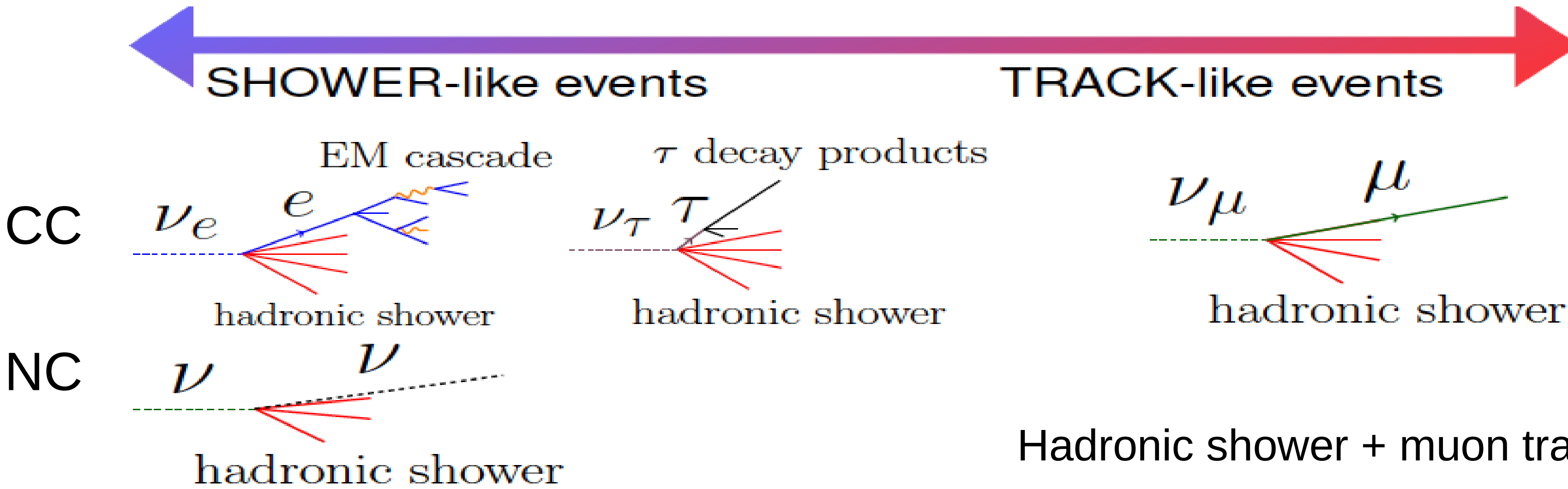
Conclusion

- Directing a neutrino beam from Protvino to ORCA is of high scientific interest
- Determination of the neutrino mass hierarchy with a high statistical significance and well controlled systematic uncertainties
- Measurement of the CP-violating phase δ (competitive with DUNE, T2HK)
- Informal collaboration with IHEP established, initiative supported by IHEP directorate

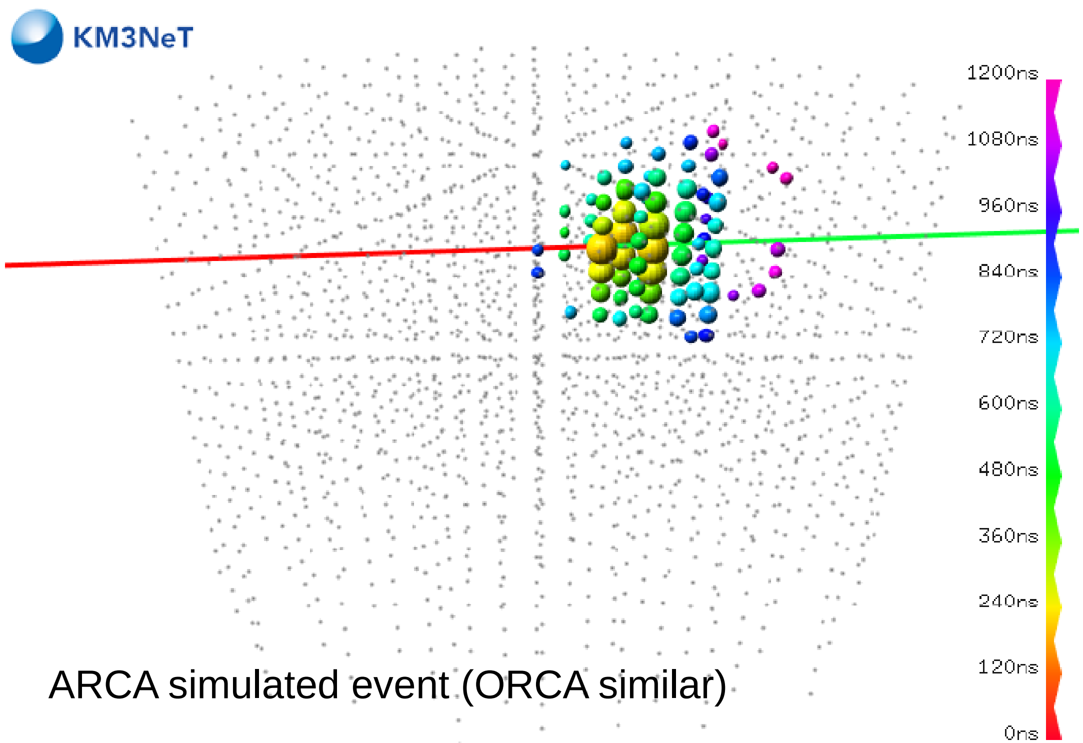
New collaborators are welcome

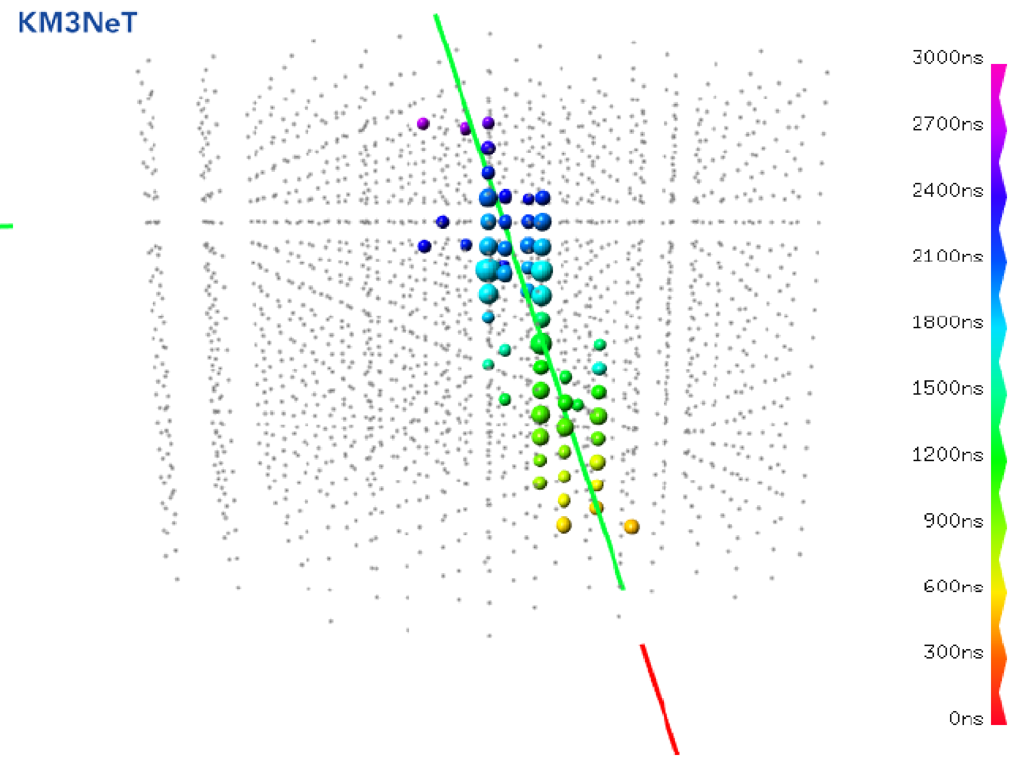
Backup slides

Particle ID



Hadronic shower + muon track

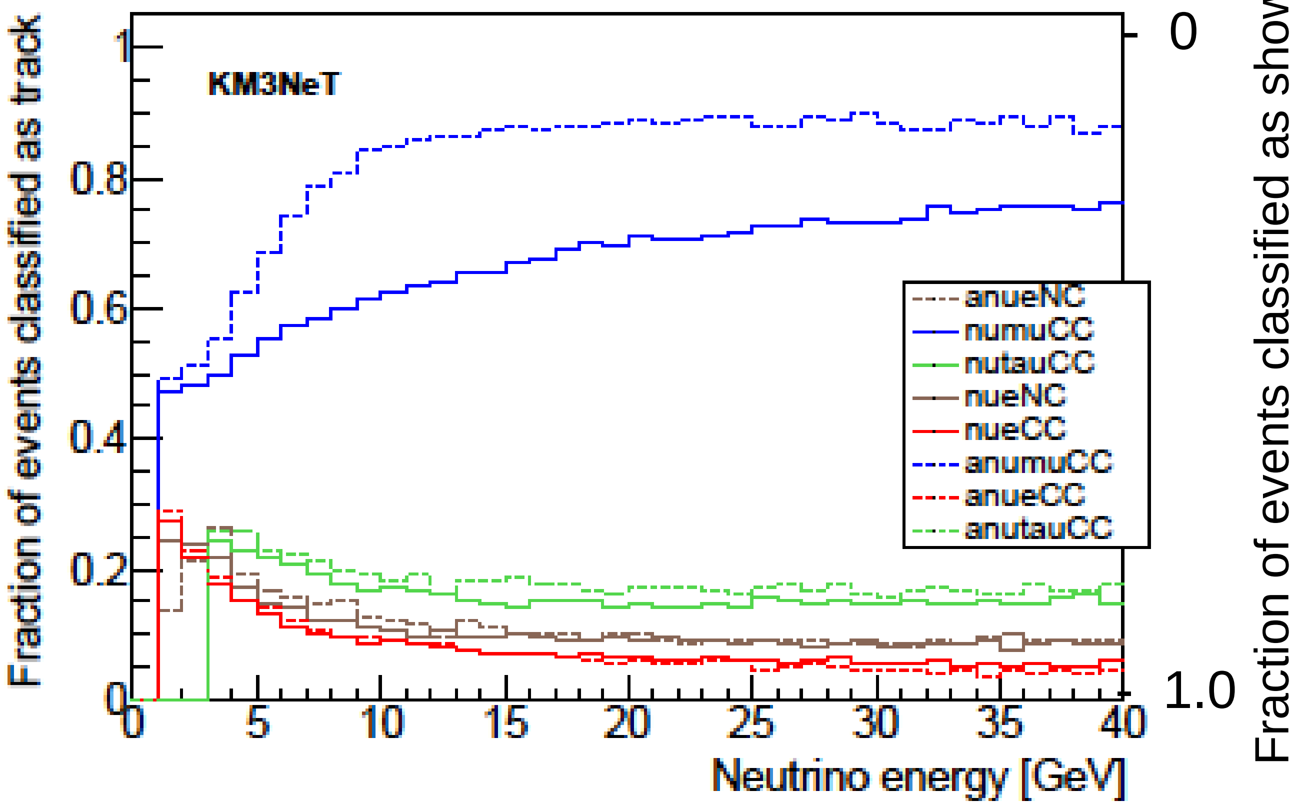




ARCA simulated event (ORCA similar)

Particle ID performance

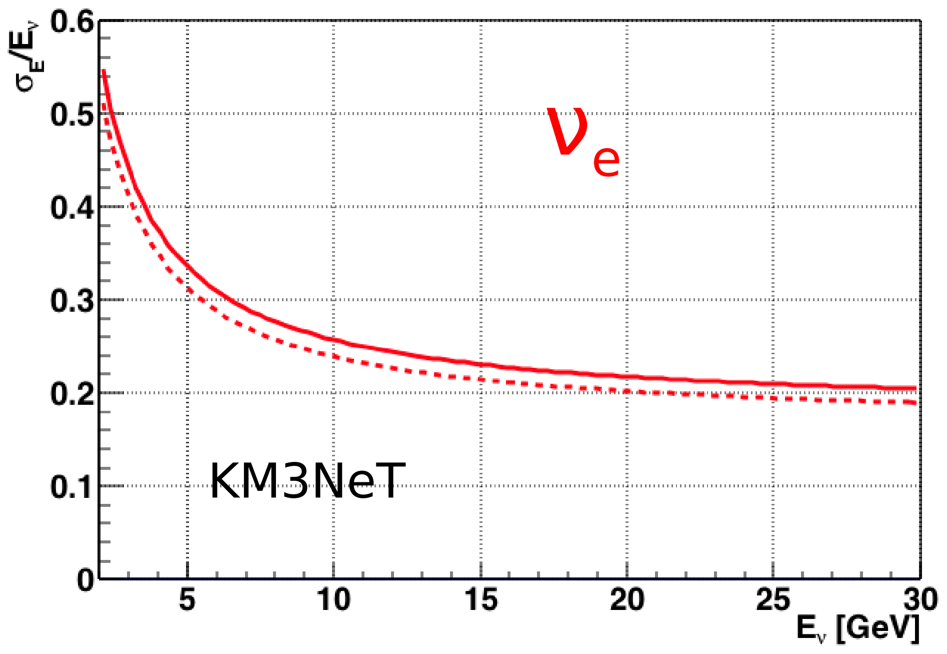
Track / Shower event classification

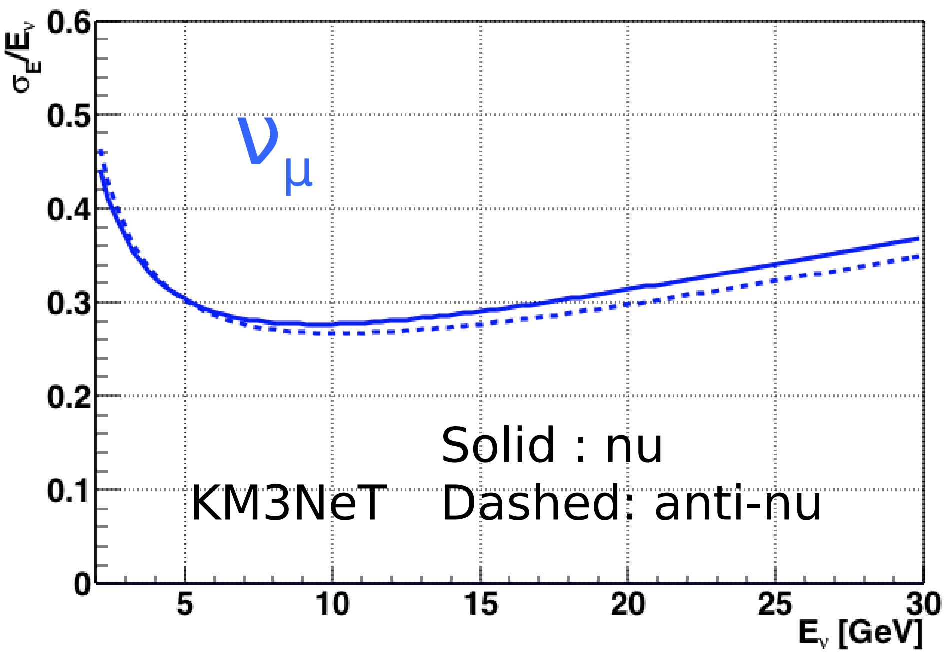


At 10 GeV:

- 90% correct ID of n_e^{CC}
- 70% correct ID of n_m^{CC}

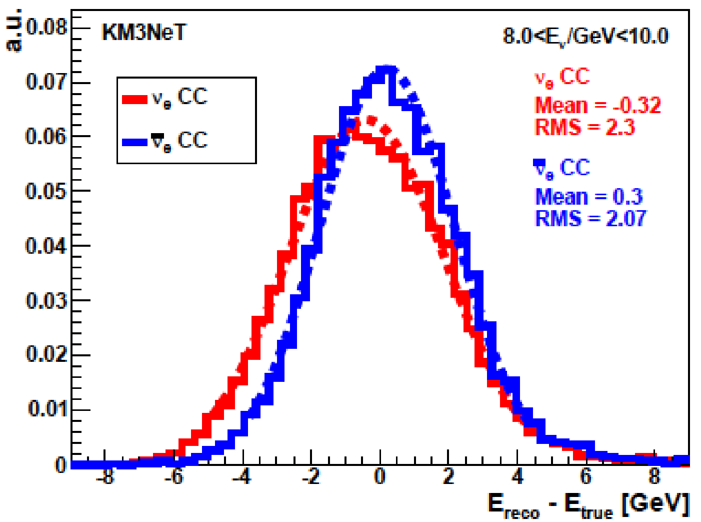
Energy resolution





Energy resolution better than 30% in relevant range

Distribution close to Gaussian

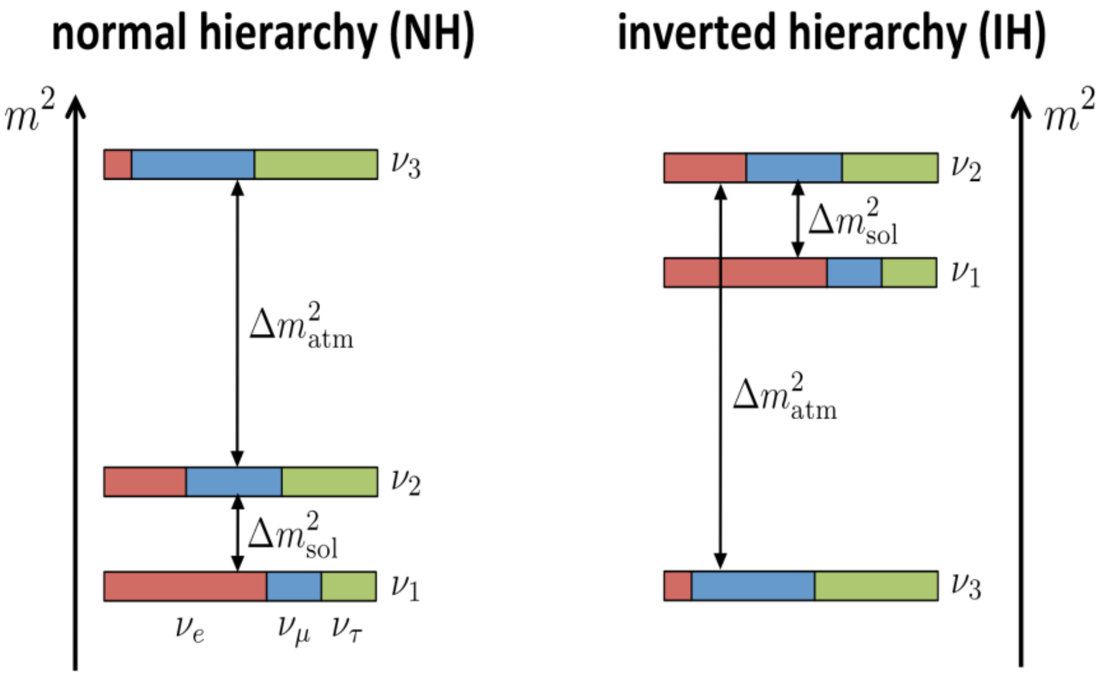


Benefits of beam neutrinos

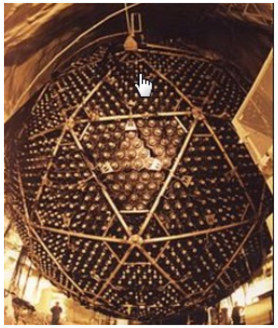
- Clean muon neutrino or anti-neutrino beam (chosen by horn polarity)
  - Flavor oscillations more pronounced (ν_μ / ν_e)
  - Matter effect more pronounced (ν / anti-ν)
- Known baseline
  - No zenith angle uncertainty
- Known direction
  - kinematics constraints

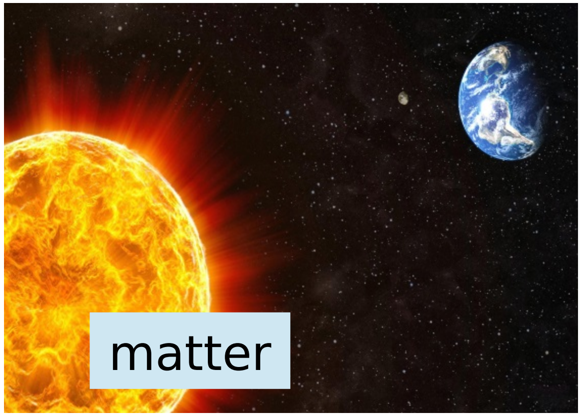
    better event reconstruction / particle ID possible
- Short beam spills
  - Factor 1 000 000 suppression of atmospheric muon and atmospheric neutrino backgrounds
  - Background estimation from “off” data

Neutrino mass hierarchy (ordering)

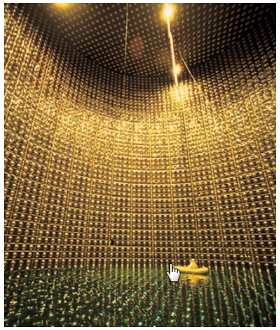


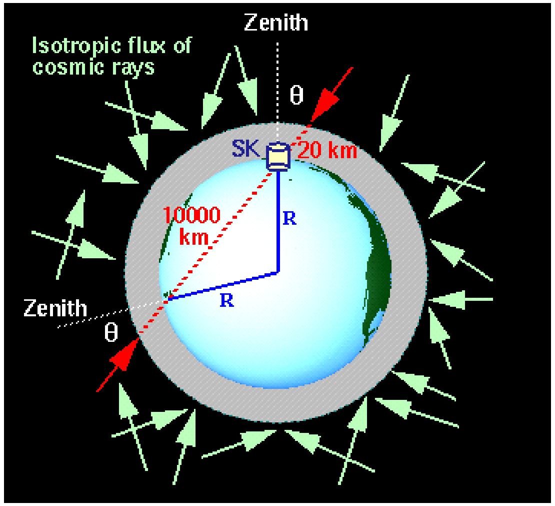
$\Delta m^2_{\rm solar}$: sign known





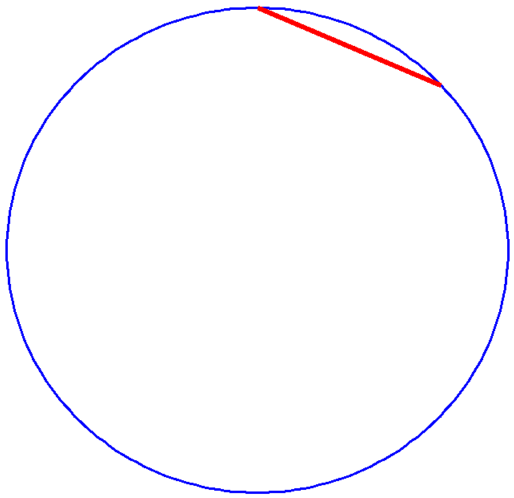
$\Delta m^2_{\rm atmospheric}$: sign unknown





Important for theory, 0νββ, ...

Peak energy example

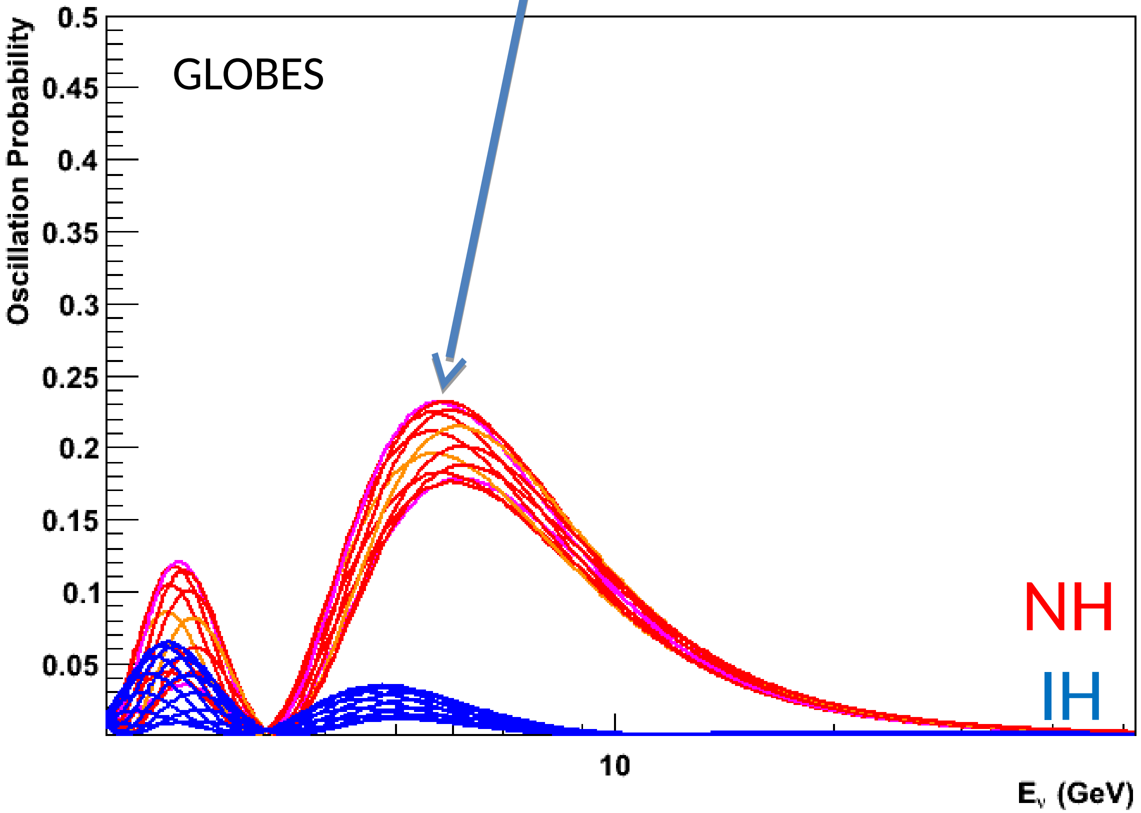


cos θ = 0.4

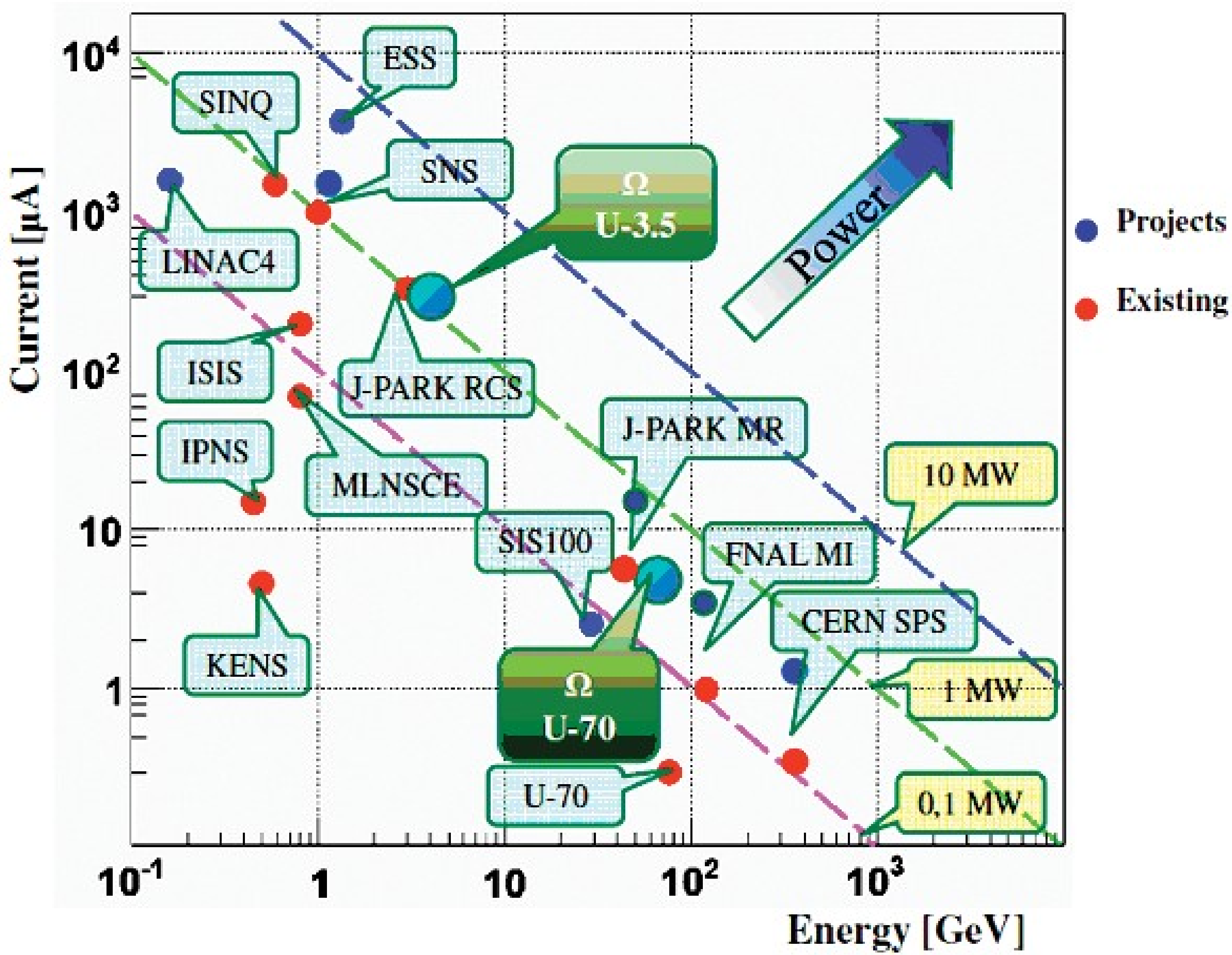
Baseline = 5097 km

Inclination = 23.6˚

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

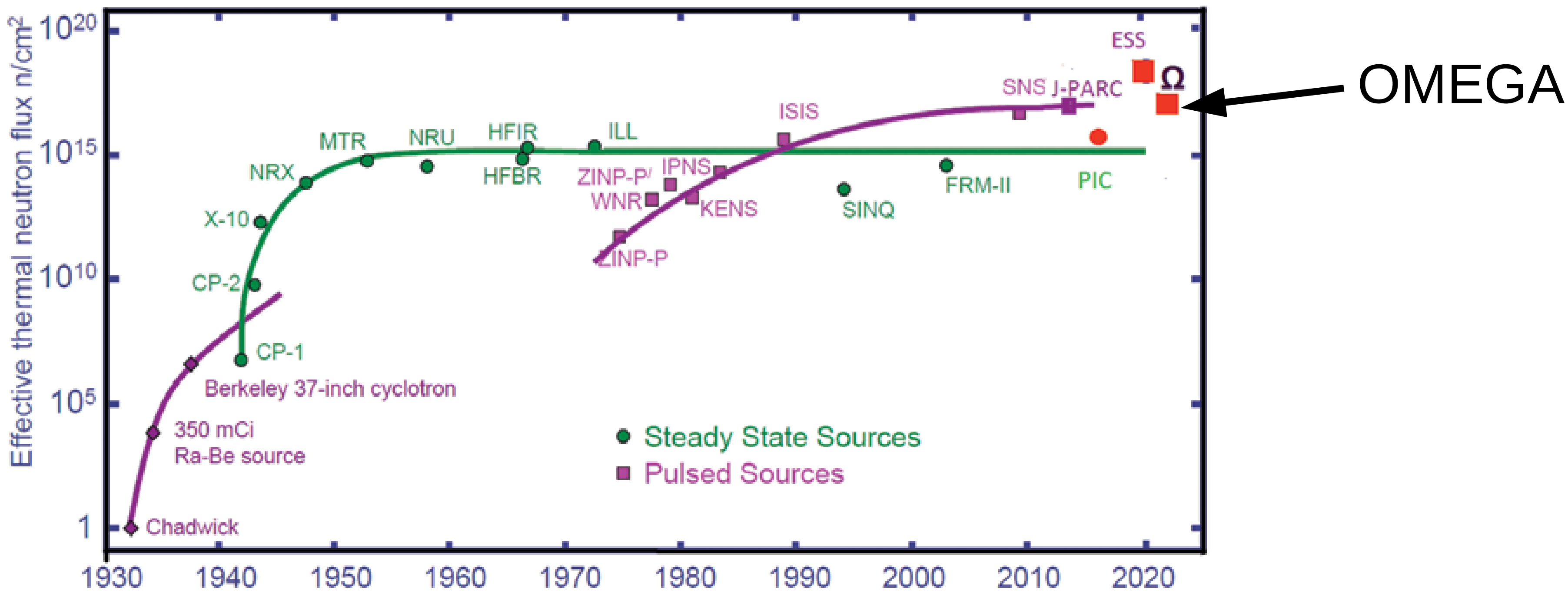


The OMEGA project



The OMEGA project proposal (continued)

- Intended primarily for applied research (material science, protein structure, rapid processes, etc)



ESS: European Spallation Source: 2-5 MW, under construction in Lund, Sweden

PIC: 100 MW nuclear reactor, NRC «Kurchatov Institute» – PNPI, Gatchina (near St. Petersburg), construction 1976-2019

Cost estimates

Table extracted from the OMEGA project LoI

№	Object	Cost (million rubles)	M € (approx)
1	Linac LU-400	7 200	**180**
2	RC PS U-3.5	10 100	**250**
3	Neutrino channel	1 500	**40**
4	Near Neutrino Detector	1 000	25
5	Neutron source (target station T1)	8 400	210
6	Neutron research set-ups	1 500	40
7	Injection from U-3.5 to U-70	800	**20**
8	Target stations T2 and T3	800	20
9	Infrastructure	700	17
10	Total	32 000	**800**

Using 2003 exchange rate 40:1

Costs dominated by accelerator construction and neutron source