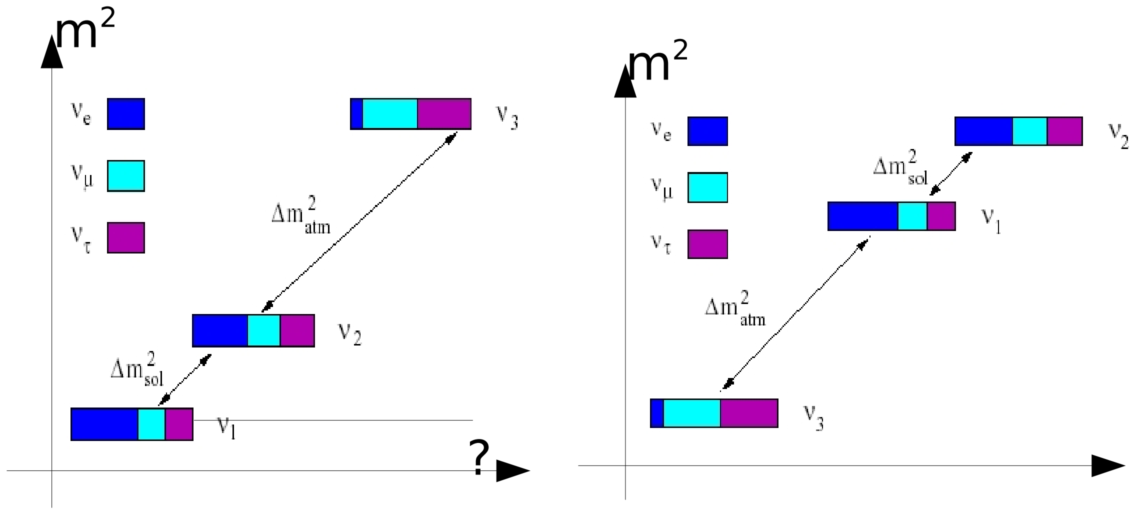
To Infinity and Beyond!

The Quest

$$\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

Value of δ

Normal or inverted?



- Better estimates of the oscillation parameters using accelerators
- Is θ_{23} maximal?
- Is $\nu = \bar{\nu}$?
- What is the absolute mass?

$$U_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & -0.15 \\ -0.4 & 0.7 & 0.6 \\ 0.4 & -0.5 & 0.7 \end{pmatrix}$$

?

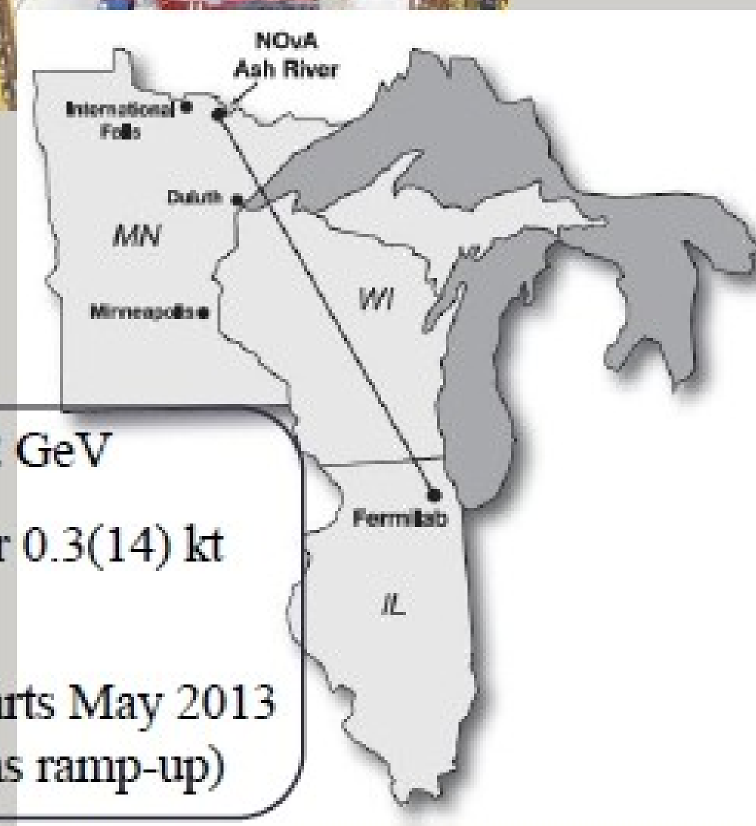
$$U_{CKM} = \begin{pmatrix} 0.975 & 0.222 & 0.004 \\ 0.221 & 0.97 & 0.04 \\ 0.01 & 0.04 & 0.999 \end{pmatrix}$$

The next 20 years

Measurement	Method	Experiments	Why?	When
~~θ_{23}~~	~~ν_μ Disapp.~~	~~T2K, NovA~~	~~Is it maximal?~~	~~2009~~
~~θ_{13}~~	~~ν_e Appear.~~	~~T2K, NovA~~	~~Equal to 0? Can't~~ measure δ_{CP} if it is	~~2012~~
	~~Anti-ν_e~~ Disapp.	~~Reactor~~		~~2012~~
Sgn(Δm_{23}^2)	ν_e / anti-ν_e	Next Gen	Unification, GUT	2020
δ_{CP}		Neutrino Factory	Lepton asymmetry	2035?

Current Experiments

- L=295km, <E>=0.7GeV
- ND280 Near Detector, SuperK (22.5 kt) as Far Detector
- JPARC beam: currently 200kW ramping up to 700kW (<2019)

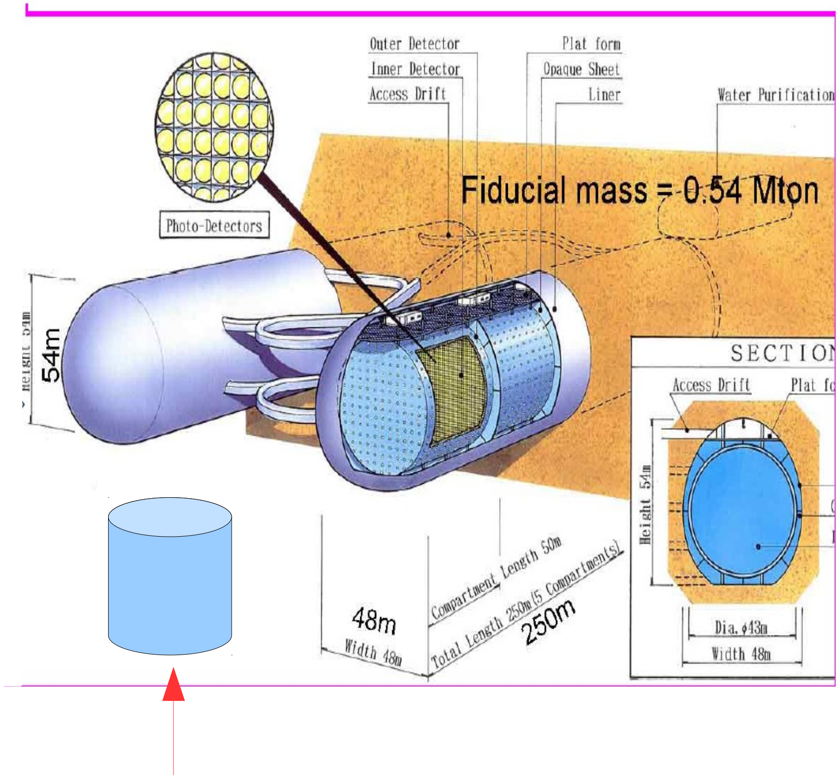


- L=810 km, <E>=2 GeV
- Near(Far) Detector 0.3(14) kt liquid scintillator
- NUMI beam re-starts May 2013 @ 700 kW (6 months ramp-up)

Next generation of experiments

DUSEL Underground Neutrino Experiment (DUNE)

Hyper-Kamiokande



SK (to scale'ish)

- MW beams
- multi-kton far detectors

Dune / HK Comparison

	DUNE	Hyper-K	T2K
Beam Energy	3 GeV	0.7 GeV	0.7 GeV
Baseline (L)	800 km	295 km	295 km
Beam Power	1.2 MW	0.75 MW	0.3 MW
Mass of far detector	70 kton	560 kton	22.5 kton
Technology	Liquid Ar TPC	Water Cerenkov	Water Cerenkov
Running from	2025	2025(30)	

The Future – CP violation and Mass Hierarchy

CP violation?

WARWICK
THE UNIVERSITY OF WARWICK

Measuring δ_{CP} is the ultimate goal of neutrino oscillation experiments. How?

$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E})$$

$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E})$$

$= 0$ if $\alpha = \beta$

CP violation can only take place in *appearance* experiments

Want a channel which is sensitive to δ_{CP} but with an accessible Δm^2.

Look for $P(\nu_\mu \rightarrow \nu_e) \neq P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$

In all it's naked glory

$$P(\nu_\mu(\overline{\nu_\mu}) \rightarrow \nu_e(\overline{\nu_e})) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_{-+}}\right)^2 \sin^2\left(\frac{B_{+-}}{2}L\right)$$

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A}{2}L\right)$$

$$P_3 = J\cos\delta\cos\left(\frac{\Delta_{23}}{2}L\right)\left(\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_{-+}}\right)\sin\left(\frac{A}{2}L\right)\sin\left(\frac{B_{-+}}{2}L\right)$$

$$P_4 = \pm J\sin\delta\sin\left(\frac{\Delta_{23}}{2}L\right)\left(\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_{-+}}\right)\sin\left(\frac{A}{2}L\right)\sin\left(\frac{B_{-+}}{2}L\right)$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E}$$

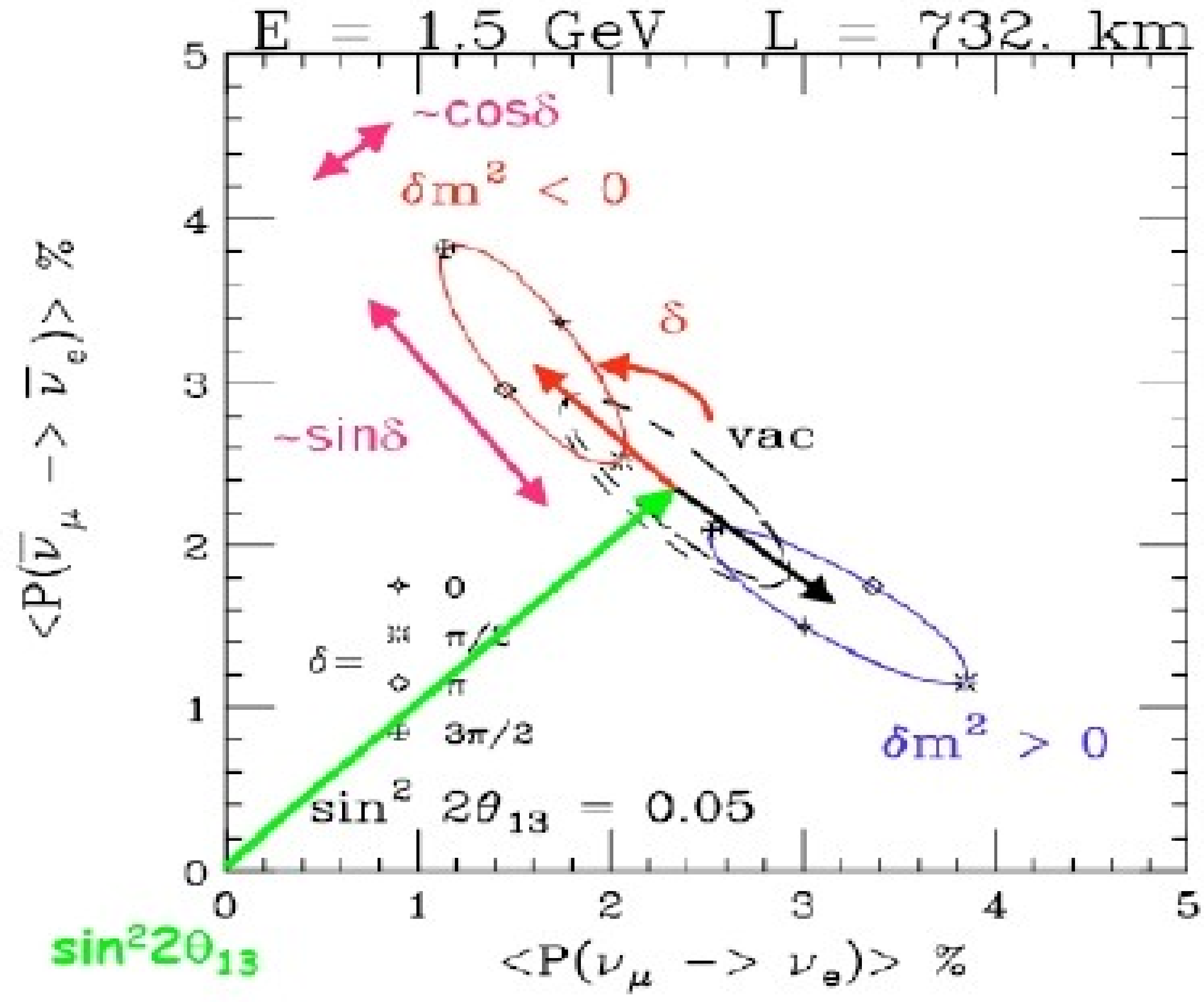
$$A = \sqrt{2}G_F N_e$$

$$B_{-+} = |\Delta_{13} \mp A|$$

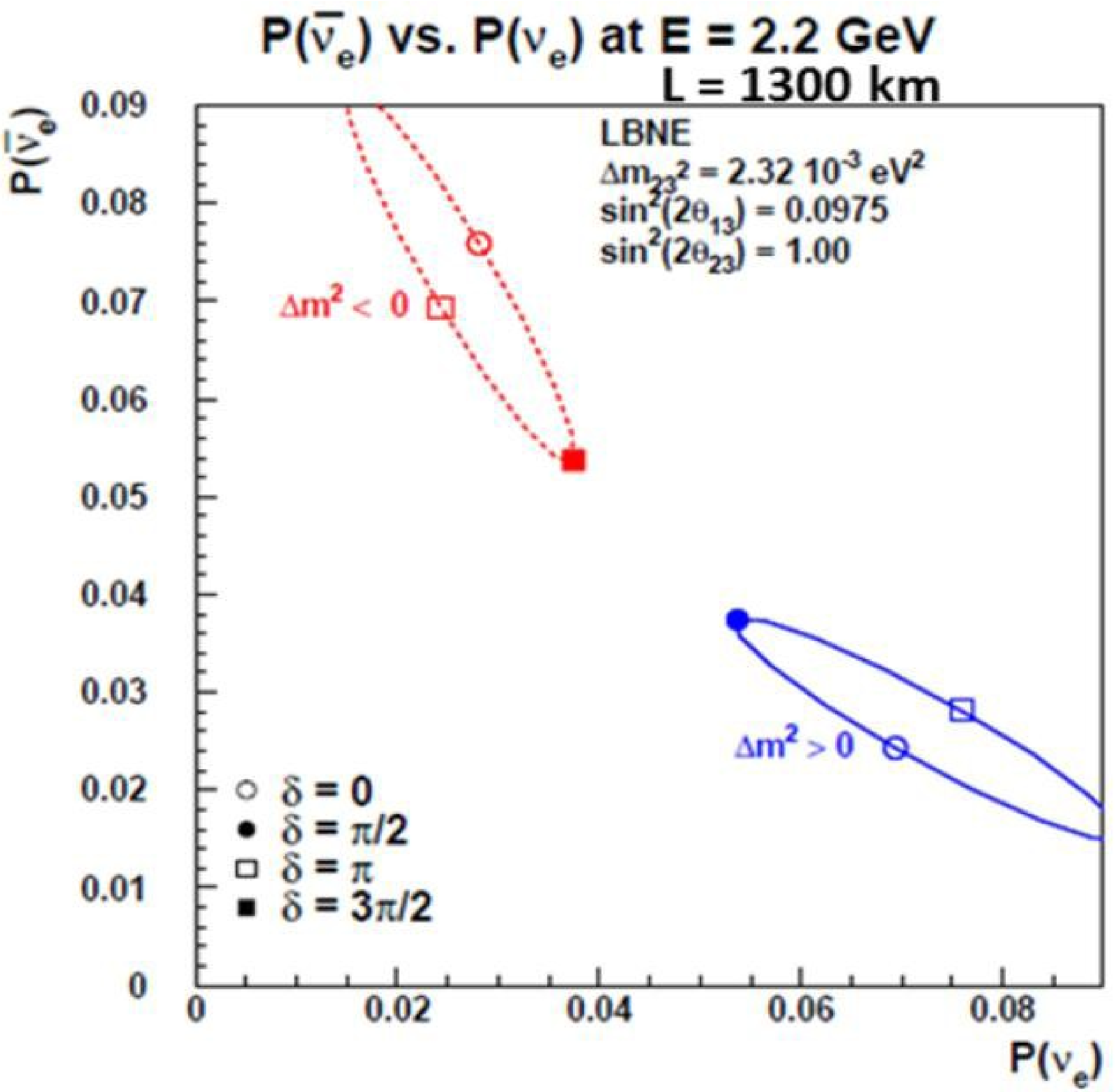
$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$$

- Θ_{13}
- $\Theta_{23} > 45$ or $\Theta_{23} < 45$
- $\mathrm{Sign}(\Delta m_{23}^2)$
- δ

Degeneracies



Matter Effects

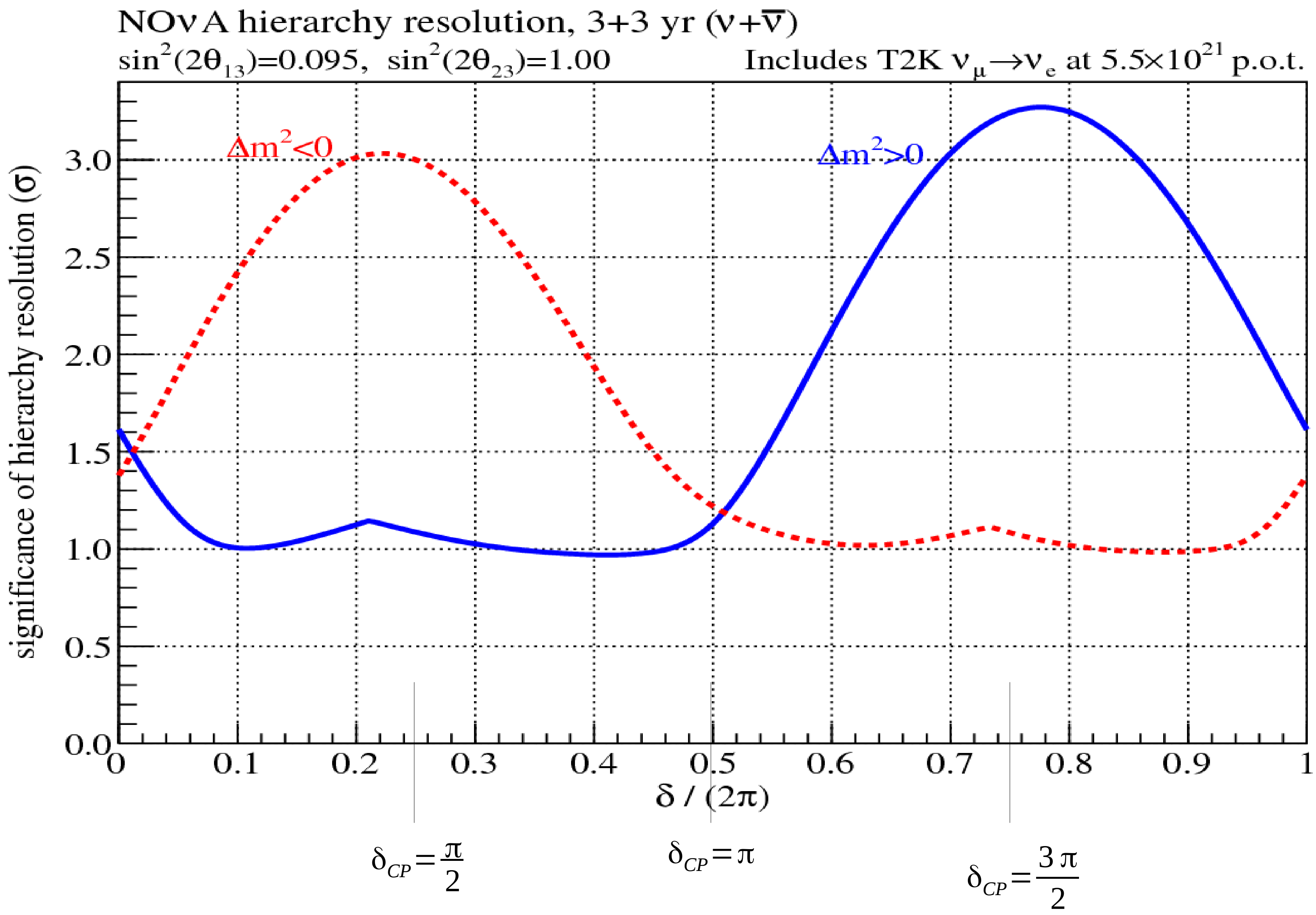


As baseline grows, matter effects increase

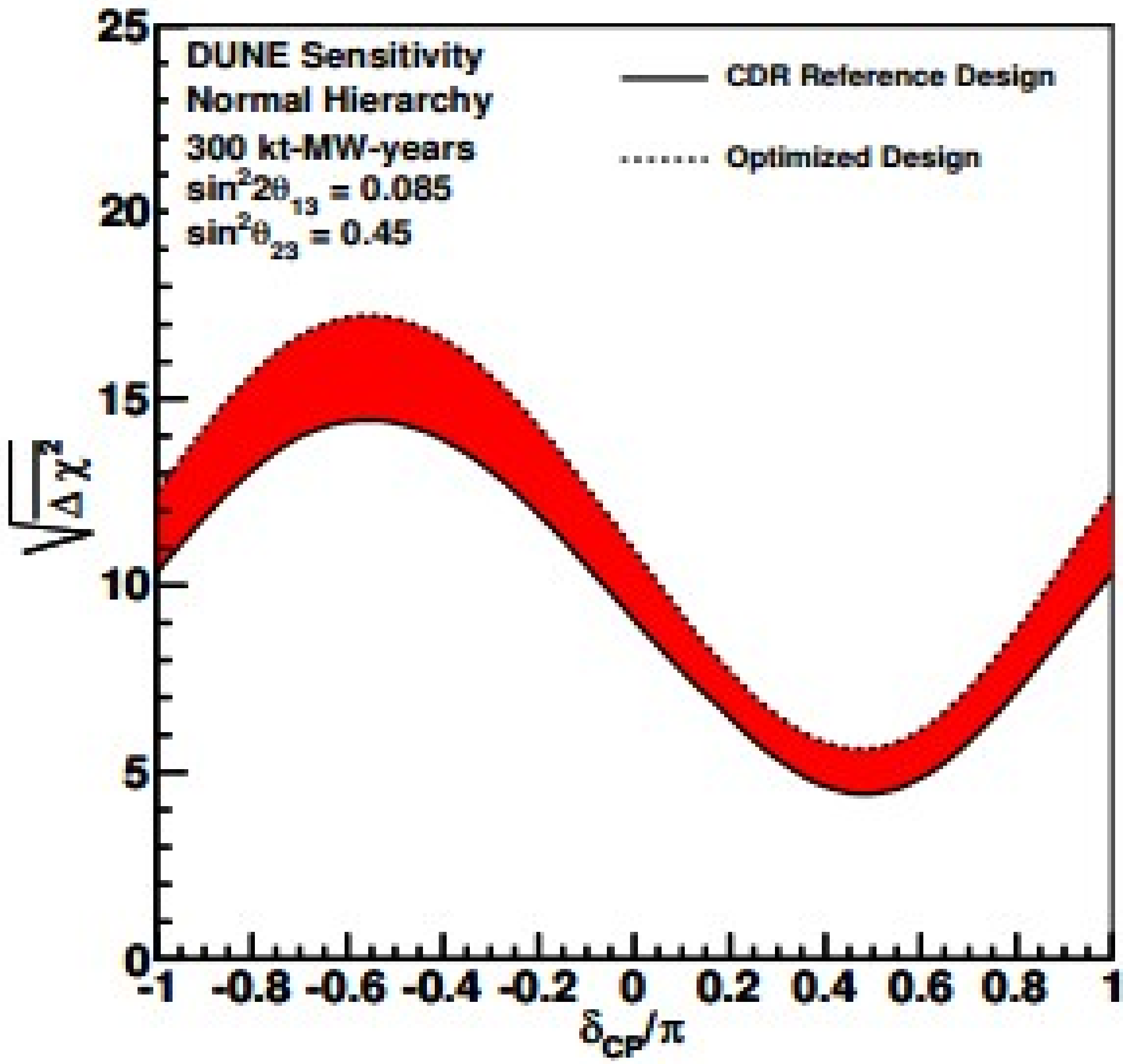
At distances of around 1000 km we can unambiguously identify the mass heirarchy

Once we've done that we need to determine CP phase

T2K + NOVA Reach



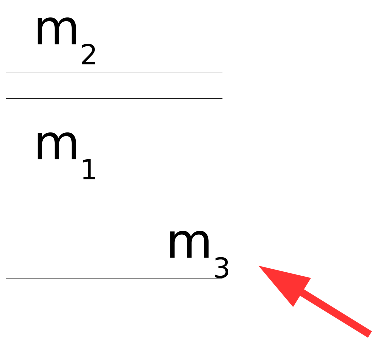
Mass Hierarchy Determination - DUNE



- 70 kton far detectors
- 1 MW beam power
- 4 years of running

- 5 σ sensitivity at all δ_{CP}

Mass hierarchy in 0νββ decay



$$\Gamma_{0\nu} \propto m_{\nu_e} = m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 + m_3 |U_{e3}|^2$$

In the inverted hierarchy : $m_3 << m_1 \approx m_2$, $\Delta m_{13}^2 \approx \Delta m_{23}^2$
and m_3 is the lightest mass state, so we can write

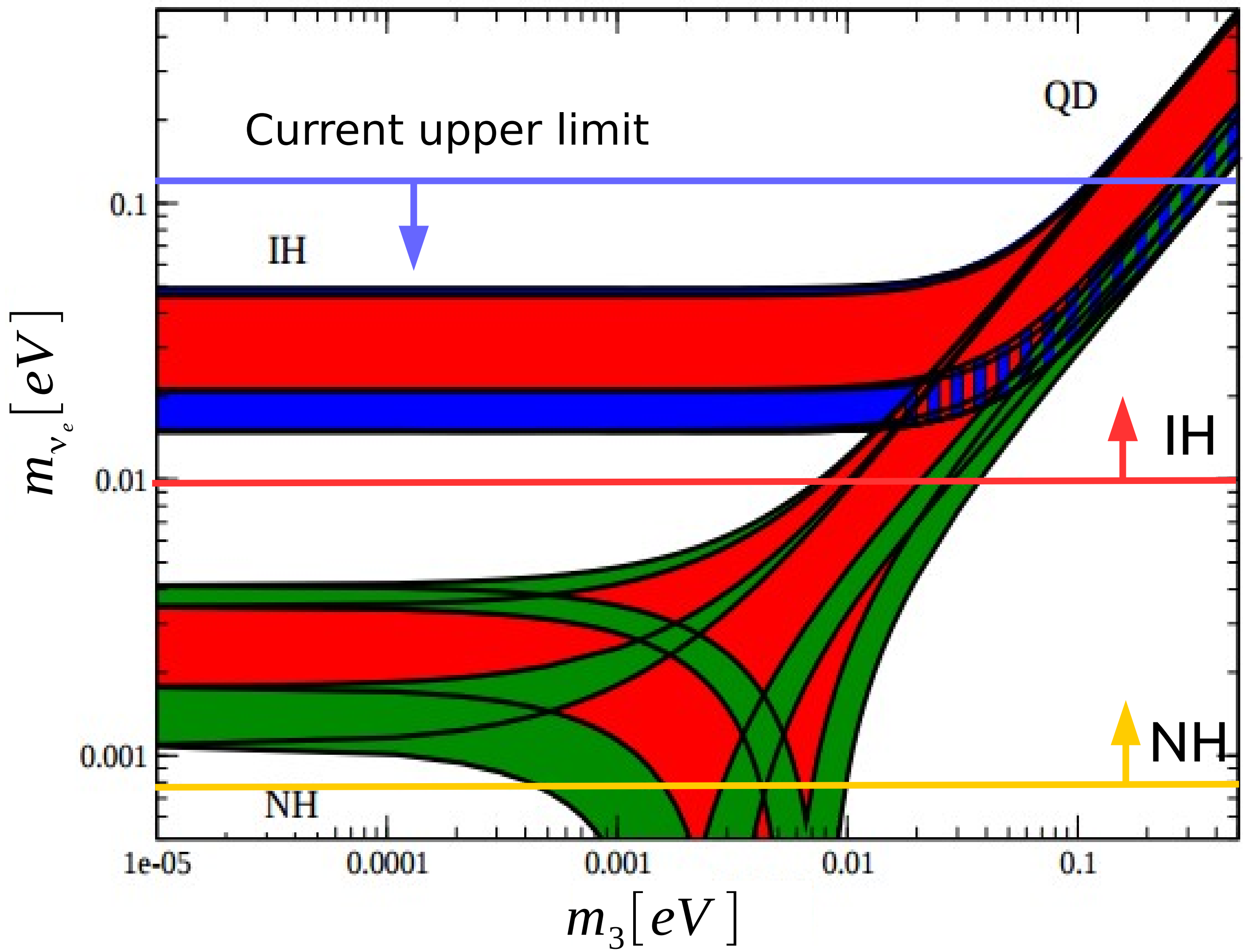
$$m_{2\beta} = |U_{e1}|^2 \sqrt{m_3^2 + \Delta m_{23}^2} + |U_{e2}|^2 \sqrt{m_3^2 + \Delta m_{23}^2} + |U_{e3}|^2 m_3^2$$

Setting m_3 to zero (not a bad approximation) one can show that

$$m_{2\beta} > \sqrt{\Delta m_{23}^2} \cos^2 \theta_{13}$$

i.e for the inverted hierarchy, the decay rate, $\Gamma_{0\nu}$, would have a *lower limit.*

Mass hierarchy & 0νββ decay



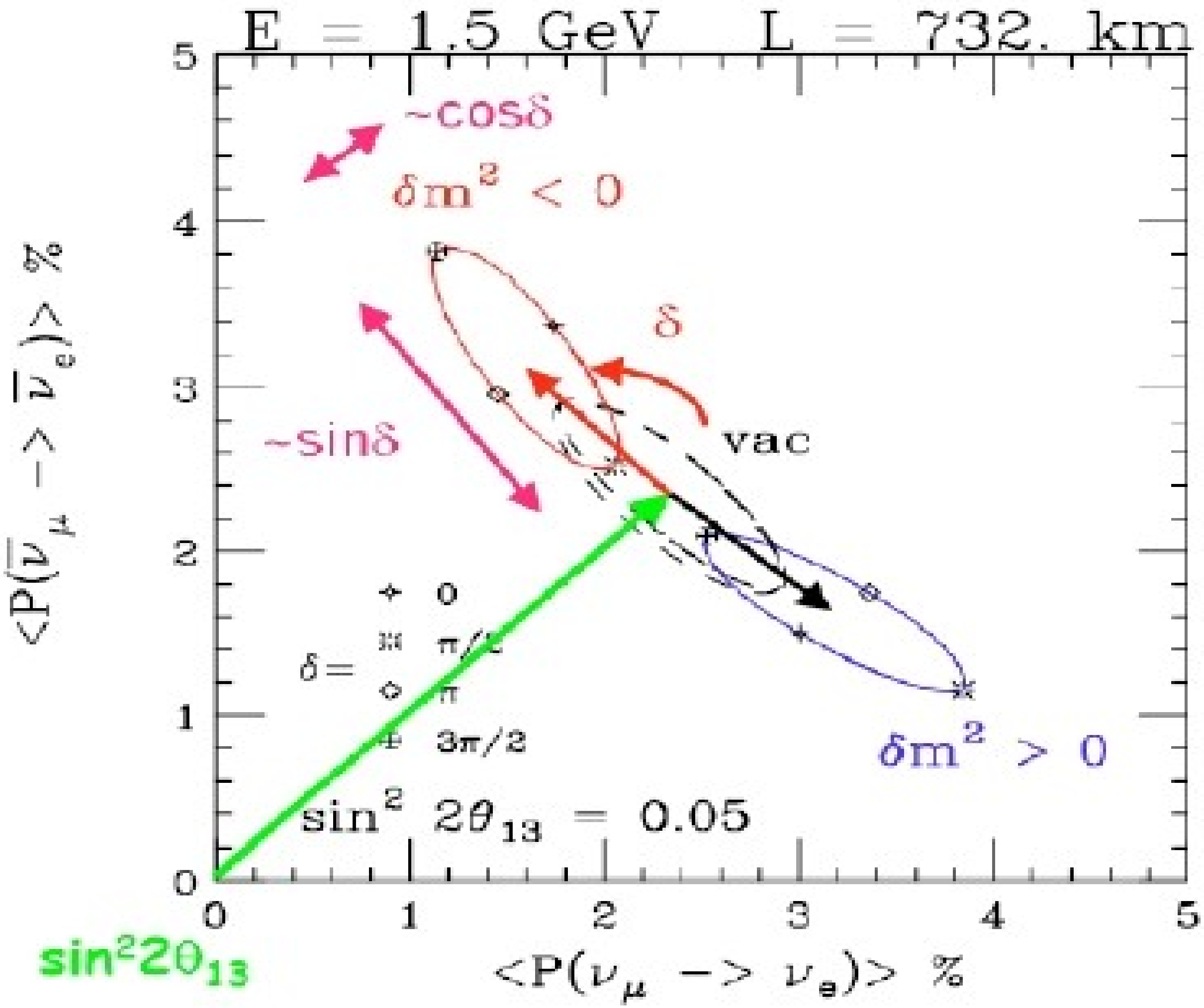
- Experimental limit needs to decrease by a factor of 10
- Limit scales with mass and run time
- Experiments need to be 10 times bigger
- These are being built now.

Mass Hierarchy Determination

A number of different experiments, both accelerator and $0\nu\beta\beta$ decay focused, are now trying to determine the mass hierarchy.

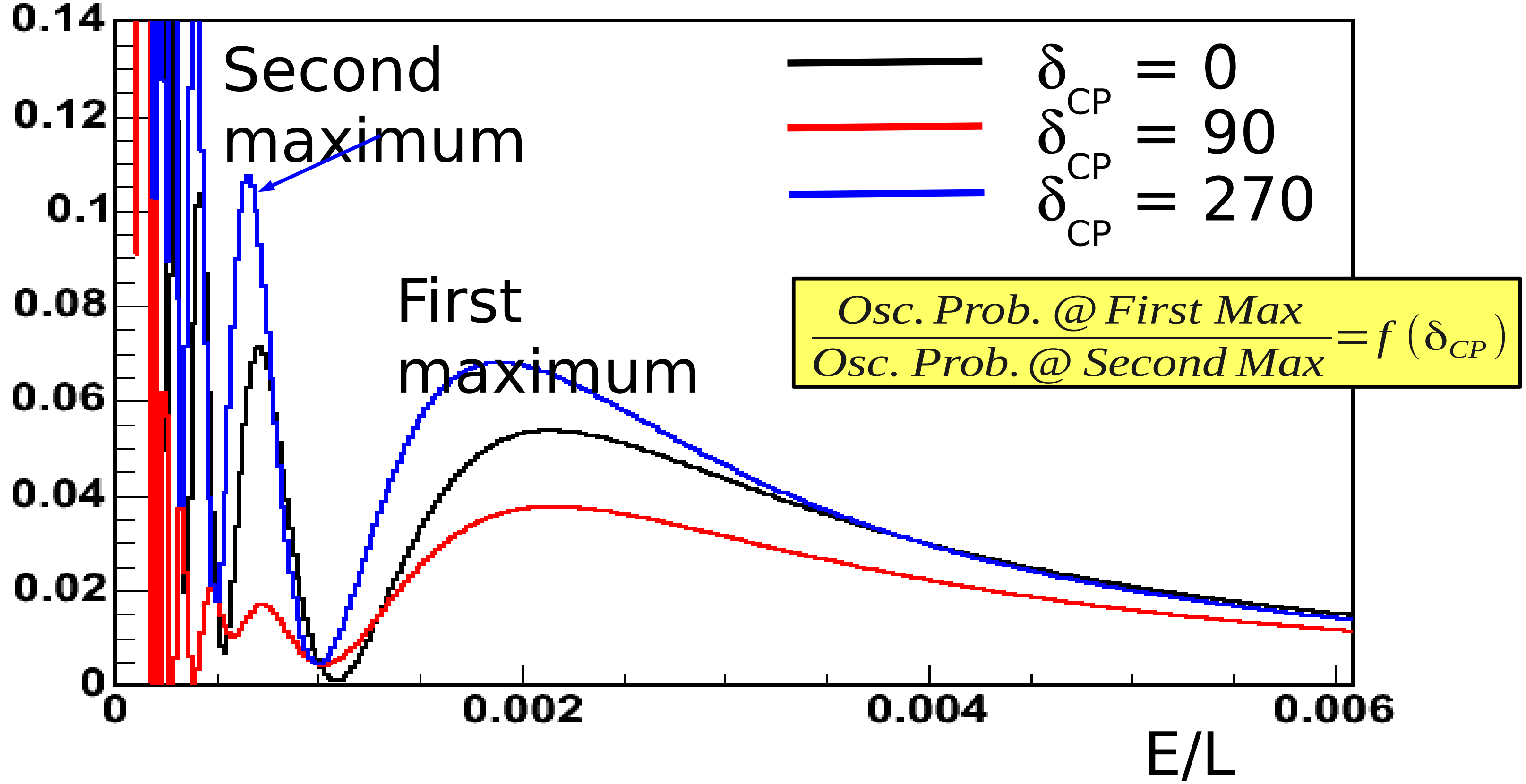
Timescale : 10-15 years from now (although good indications before hand – mass hierarchy is a binary measurement, after all)

Degeneracies



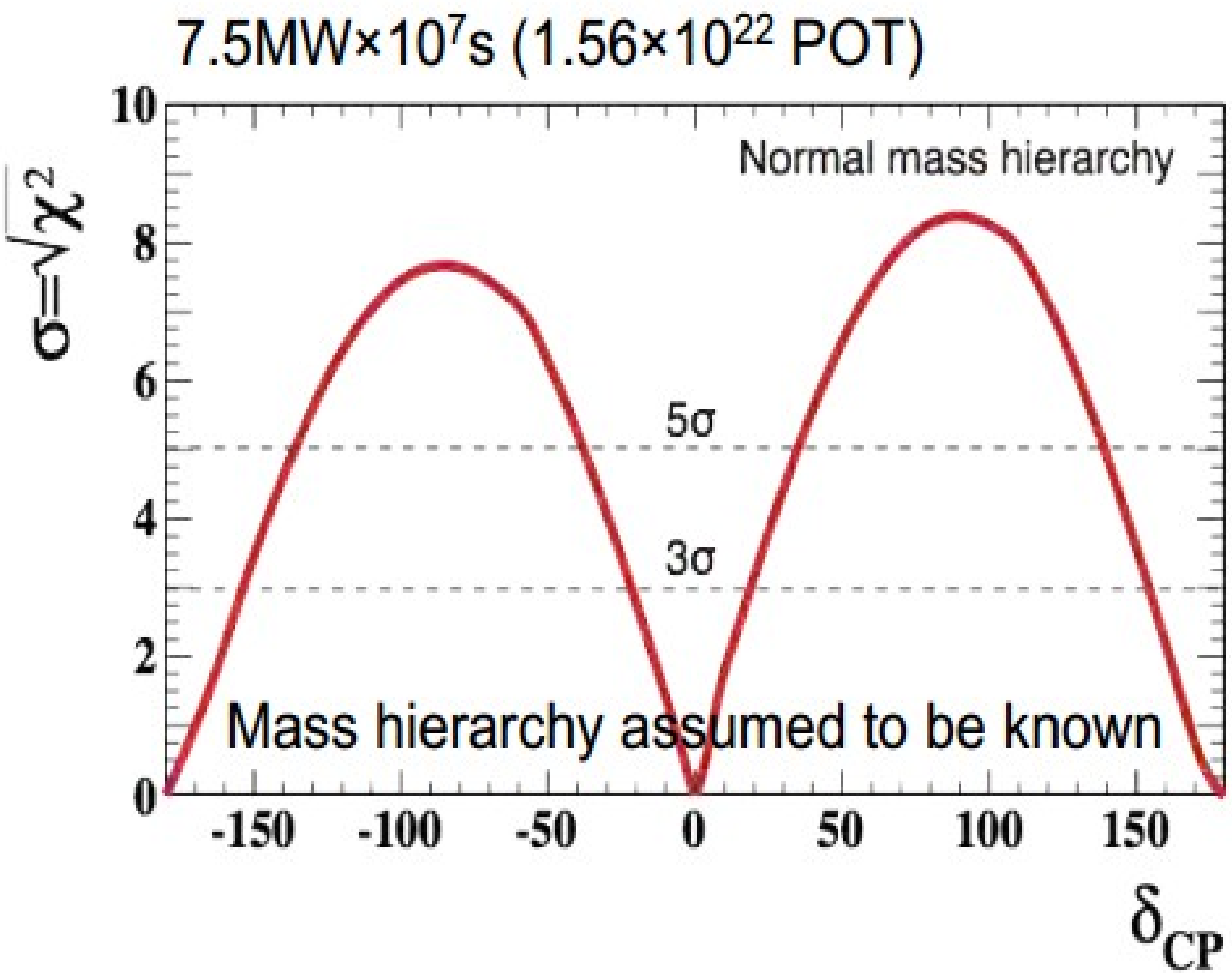
A way around the degeneracies

$\nu_\mu \rightarrow \nu_e$ oscillation probability



Could study CPV using an experiment sensitive to both maxima using only a neutrino beam.

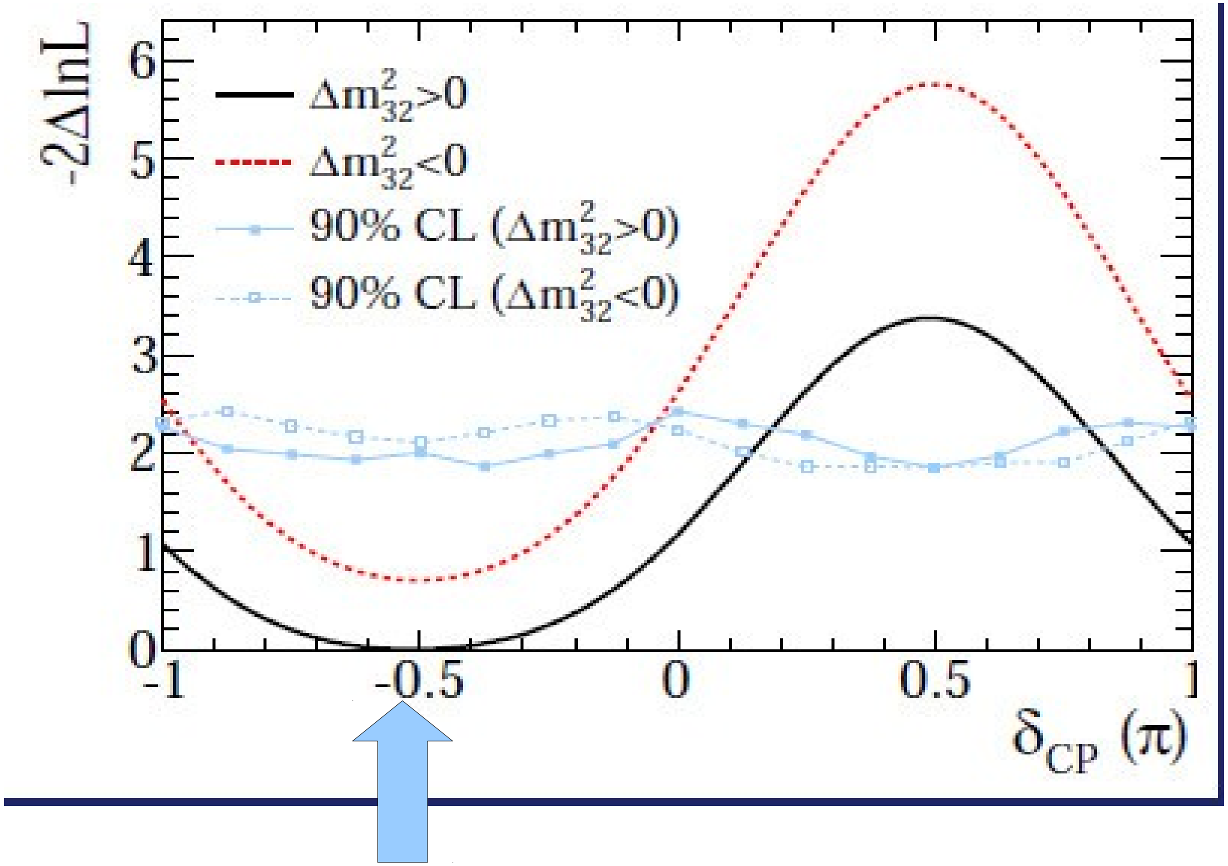
DUNE / HK Reach



5 σ significance for sin $\delta_{CP} \neq 0$ over 56% of δ_{CP} space

20% precision at δ_{CP} = -90 degrees

Hint of δ_{CP}?



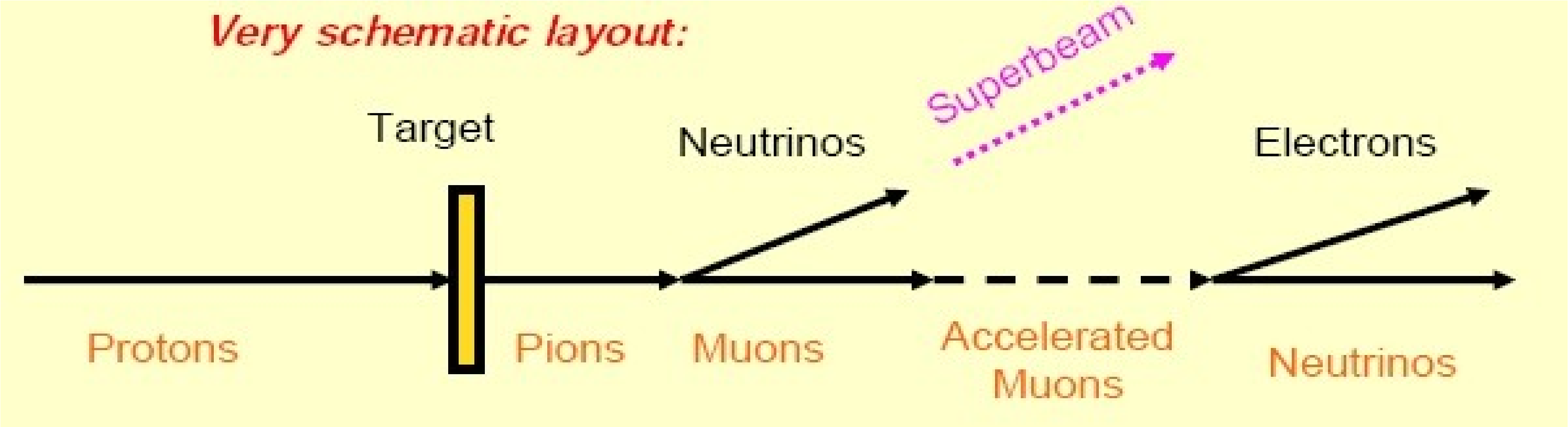
Fitting full 3-flavour model to T2K ν_e appearance data suggests δ_{CP} > 0 disfavoured (mild sensitivity to second oscillation maximum)?

Next Generation Summary

- Future Superbeam facilities (LBNF, Hyper-K) will look for CPV and mass heirarchy measurements using Very Long Baseline experiments
- Being designed now and in operation in 10 years - upgrade of the existing beams (J-PARC, NUMI) and new main detector
- a lot of R&D already done. Detector is on the cutting edge, but could be build soon with more work.
- Cost on the order of £700 million (shared over many countries)
- What we do next

Neutrino Factories

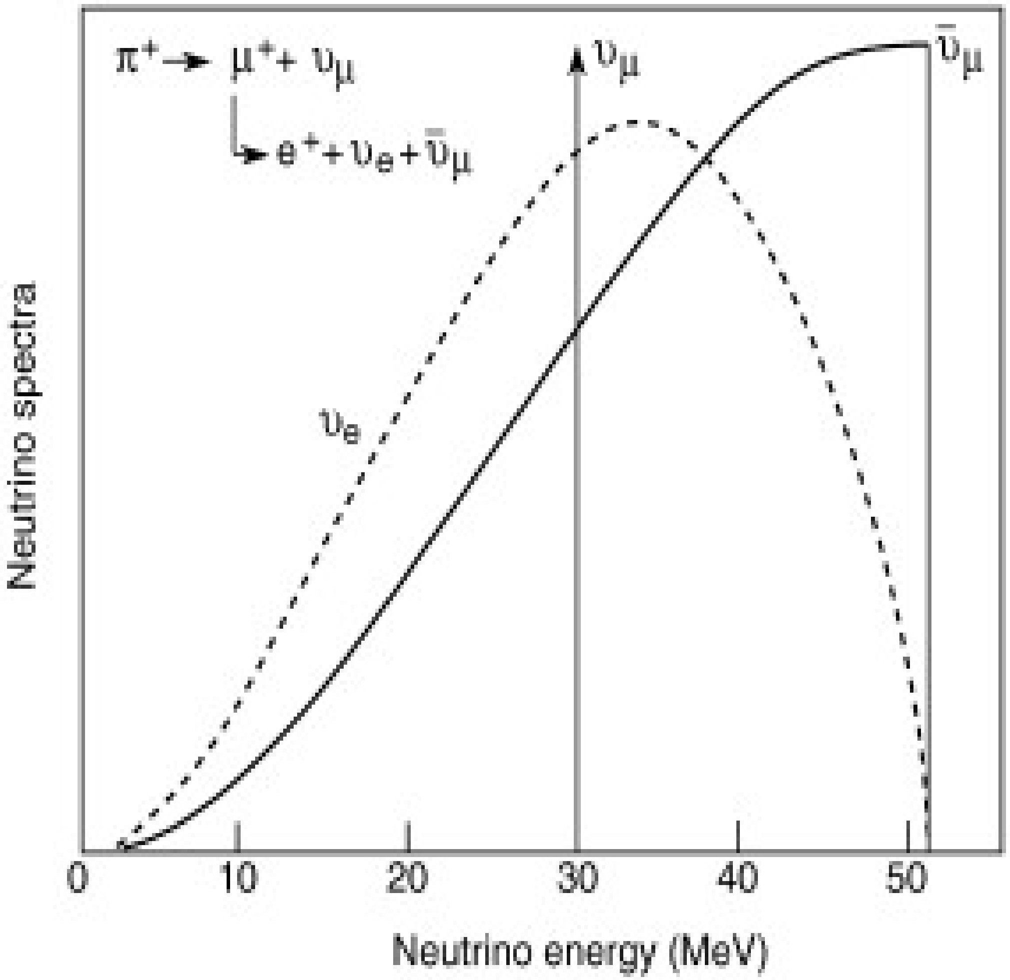
In a conventional beam the neutrinos from pion decay
In a neutrino factory the neutrinos come from muon decay



$$\mu^- \rightarrow \nu_\mu \overline{\nu_e} e^-$$
$$\mu^+ \rightarrow \overline{\nu_\mu} \nu_e e^+$$

Beam is very clean
50% ν_μ, $\overline{\nu}_e$
Extremely high flux
Precise and predictable energy spectrum

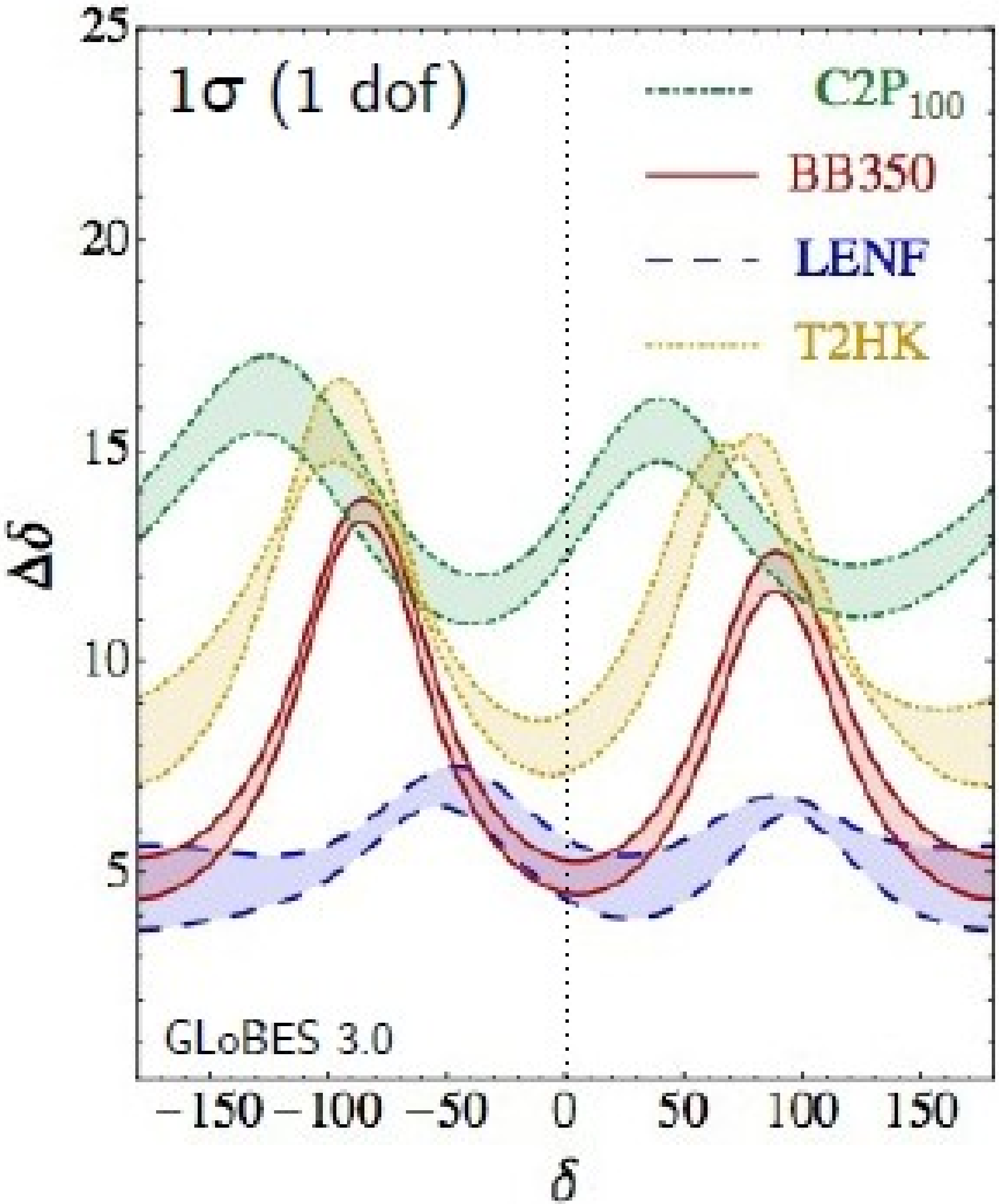
Neutrino Spectra & Event rates



Event rate : 20 million events per 100 g per cm^2 of material per year

T2K Equivalent : 120 per 100g per cm^2 per year

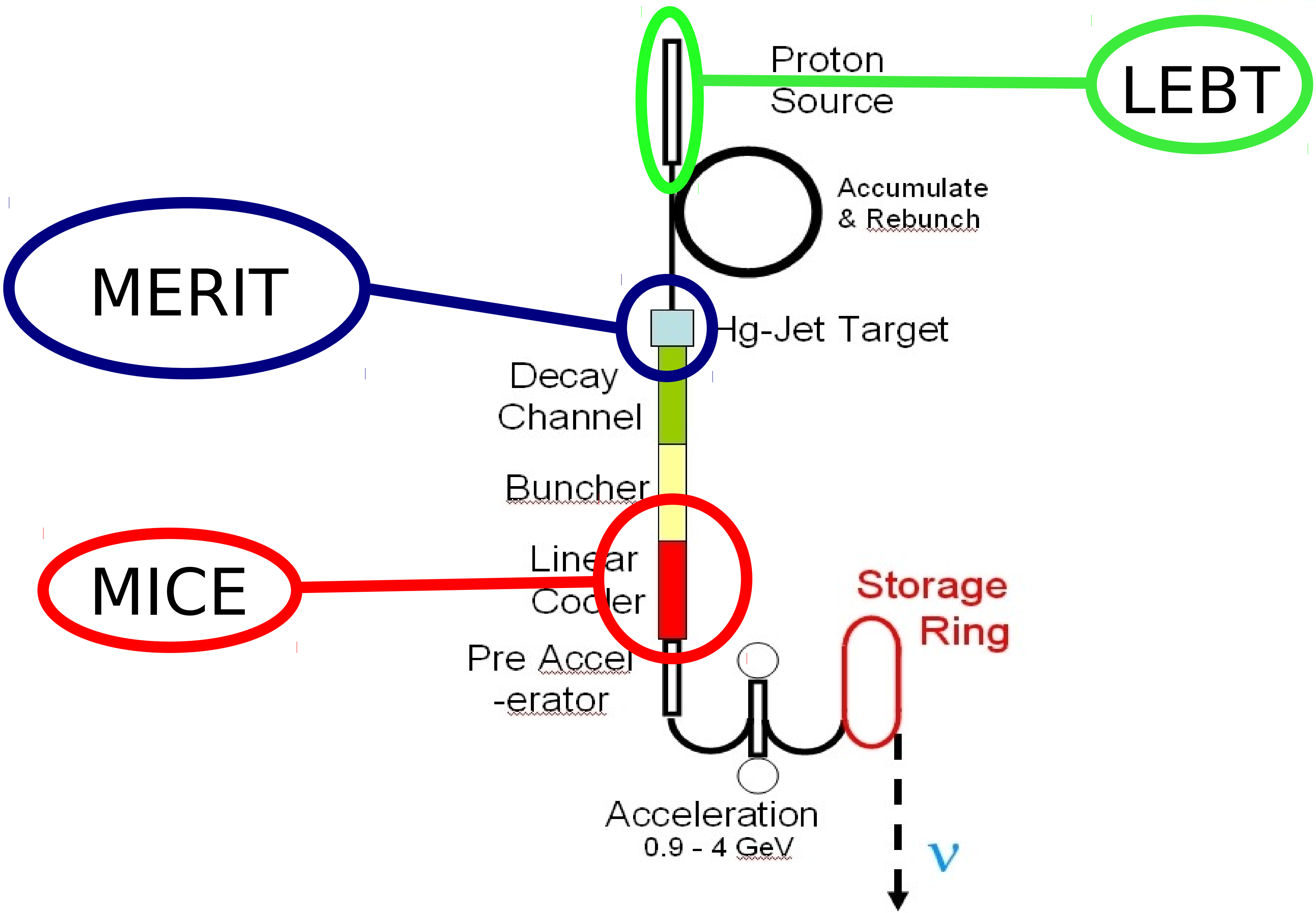
Fantastic for neutrino interaction studies



CP Precision

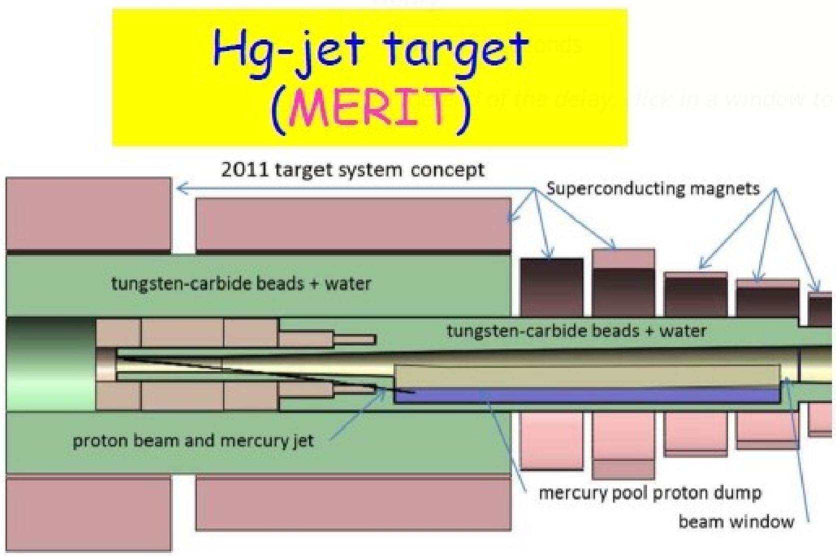
Neutrino Factory beats all other facilities

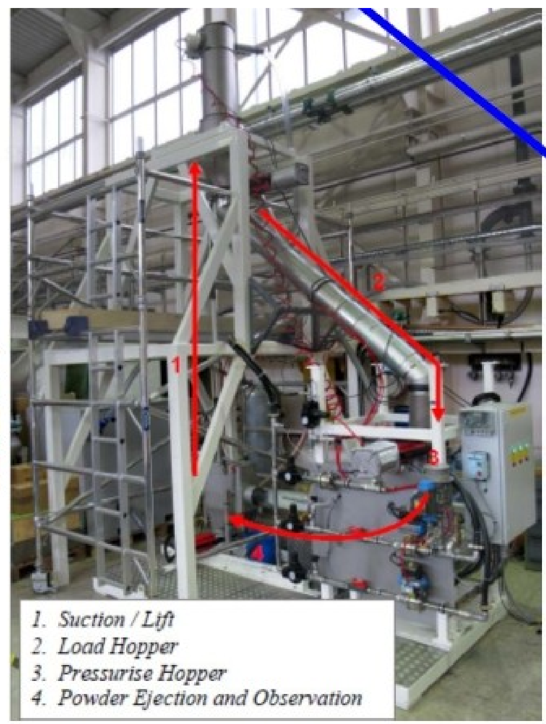
Neutrino Factory Design

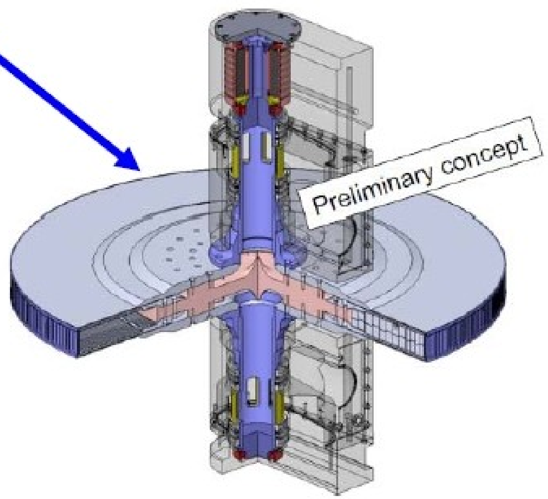


Targetry

Energy per pulse on target is on the order of 2 MJ, delivered in an area of 0.1 cm^2 in less than 2 ns every 20 ms or so.
This leads to a temperature rise and fall of more than 1000 degrees per hit. Huge damage to target and surrounding material.





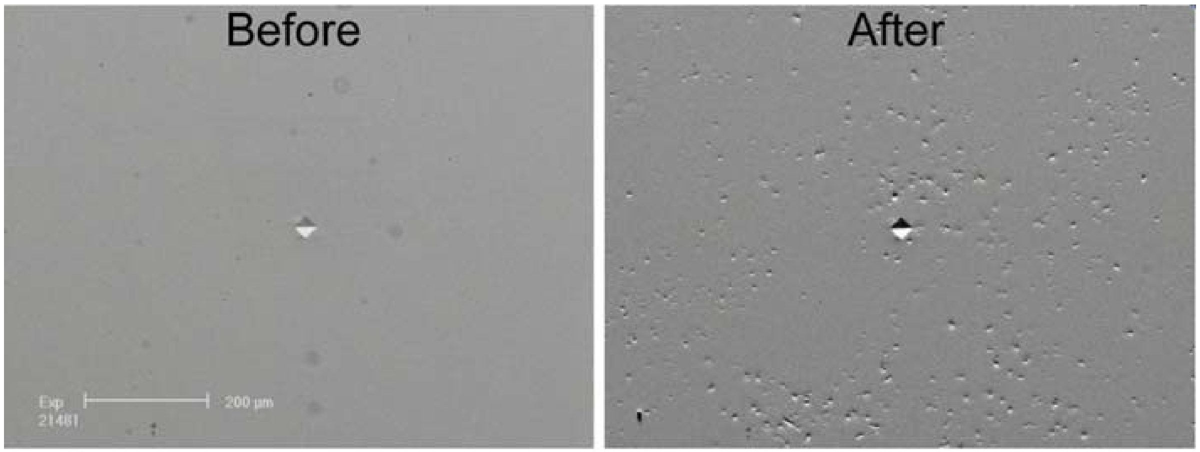


Mercury Jet

Powder Jet

Rotating Disc

Issues



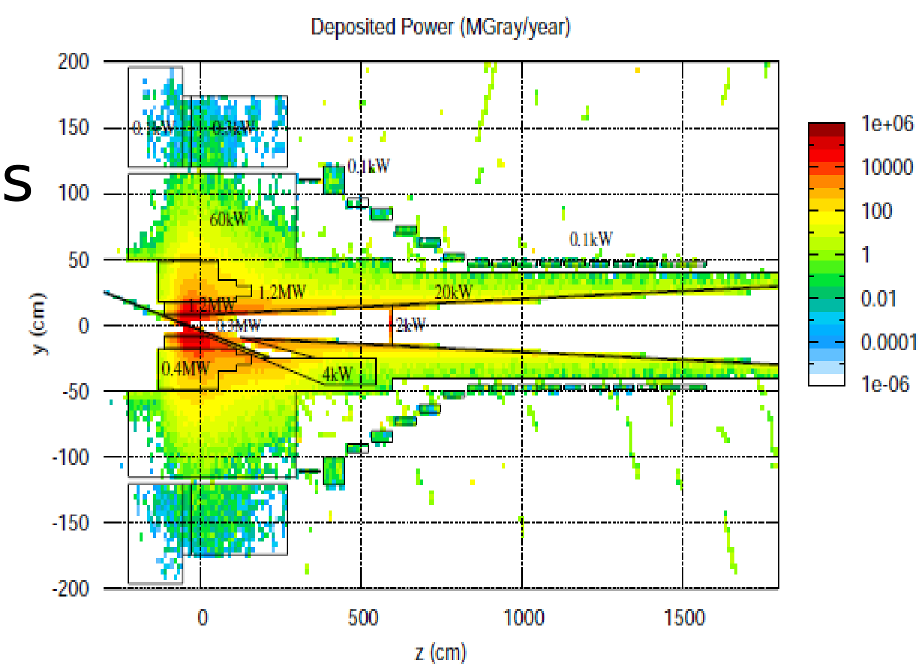
TL - High Power Target
Specimen # 29754
Equivalent SNS Power Level = 2.5

Cavitation of Target wall by flying mercury droplets.

This could erode the entire thing over period of use

Radiation damage of surrounding shielding due to neutrons could make the superconducting magnets that surround the target region quench - i.e. become normally conducting.

Same thing happened to LHC magnets after first switch-on



Engineering Challenges

WARWICK
THE UNIVERSITY OF WARWICK

- 4 MW Proton beam hits a target. Proton beam is being designed now at Fermilab - called “Project X”
- Target survives and generates a spray of π/K
    - (Can we make a target which does survive?)
- π/K decay to muons
- Muons must be directed into the accelerator system
- Muons must be stored until they decay. The accelerator is fighting the decay time of the muon.
- Neutrinos must be directed in the right direction

Neutrino Factory Summary

- Best discovery potential and sensitivity from all options.
- Couldn't be built now. If we decided to build one it, and its detectors, wouldn't be ready until 2040 or so. Design study underway and the problems are being addressed by demonstrator experiments.
- Cost on the order of £2 billion (LHC cost £3 billion; the Shard cost 0.5 billion; the trains for HS-2 will cost 7 billion).
- Can we do this now? No.
- Should we do this now? It's the best, but is it worth it? Much discussion in the field now about what to do after LBNF/HK.

CP Violation Measurement

WARWICK
THE UNIVERSITY OF WARWICK

Timescale : Determination of non-zero δ_{CP} at 5 σ by 2030, although indications well-before hand
Precision measurement depends on the value of δ_{CP}, what machines are available, and what other data we need to combine but possibly not before 2035 (?)

General Summary

- Neutrino Physics is one of the most active fields in modern-day particle physics
- Establishment of the existence of neutrino mass has opened up fields of study in particle physics, astrophysics and cosmology and has led to an international research effort planned on the timescale of decades.
- We have learned a bit of what is going on
- We have a lot more to learn
- Neutrinos have always been the joker in the deck. Just when you think you understand them, they do something unexpected. Expect more surprises.

Final Comments

All lectures have either been uploaded (for slides) or scanned in (for paper) lectures to the Moodle PX435 site.

There are some interesting papers on the site – look especially at the last one by Boris Kayser which talks about Majorana neutrinos in a coherent way

Over Easter I will release the formal write-ups for this lecture series. I'm revising at the moment.

Good luck in whatever you do next !


END