Lecture 4

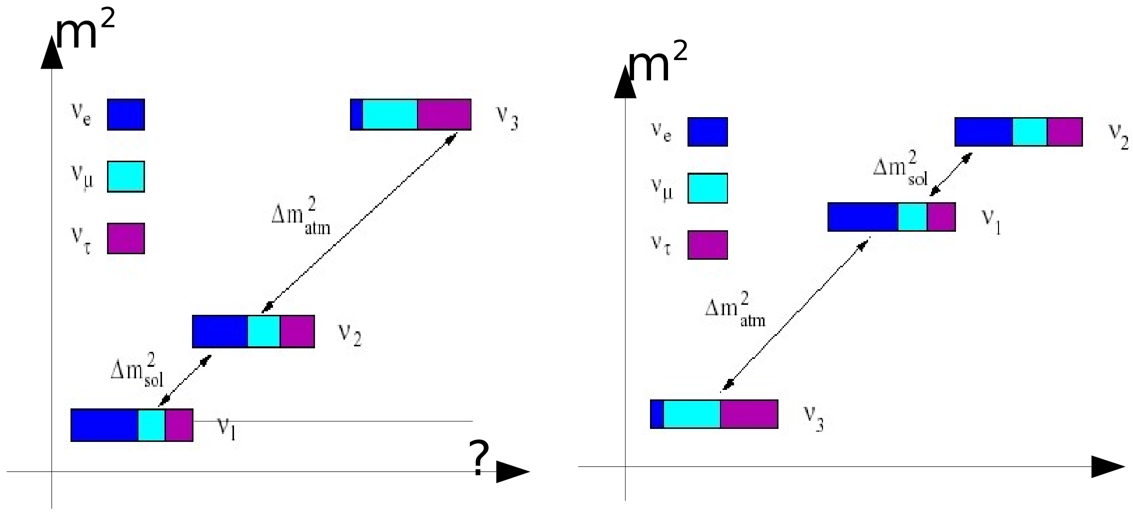
The Future

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 mass heirarchy?



- Better estimates of the oscillation parameters using accelerators
- Is θ_{23} maximal?
- Is the neutrino Majorana?
- What is the absolute mass?

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

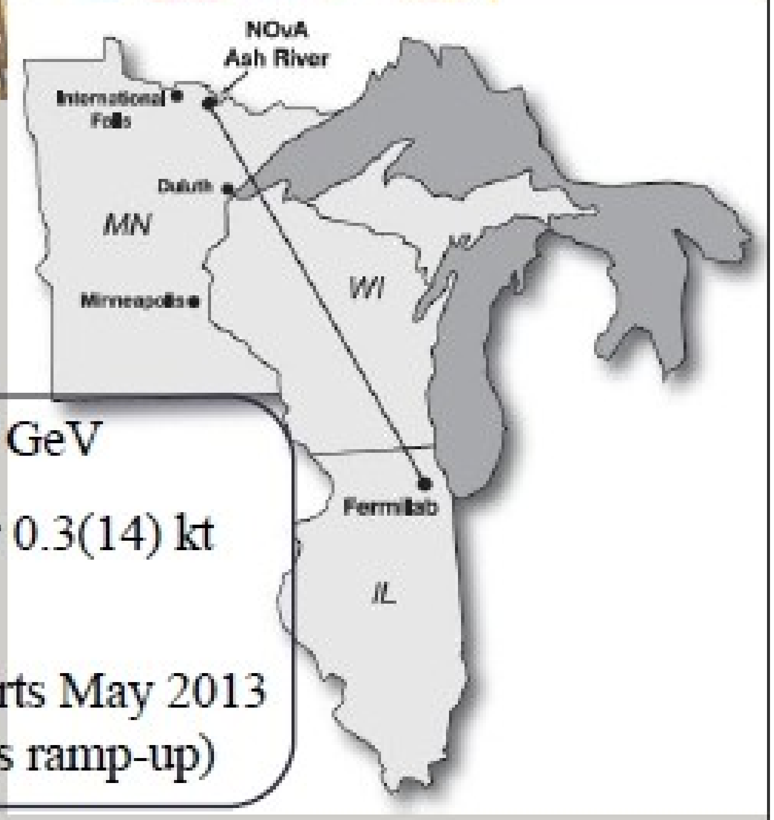
?

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

To The Future and Beyond!

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)

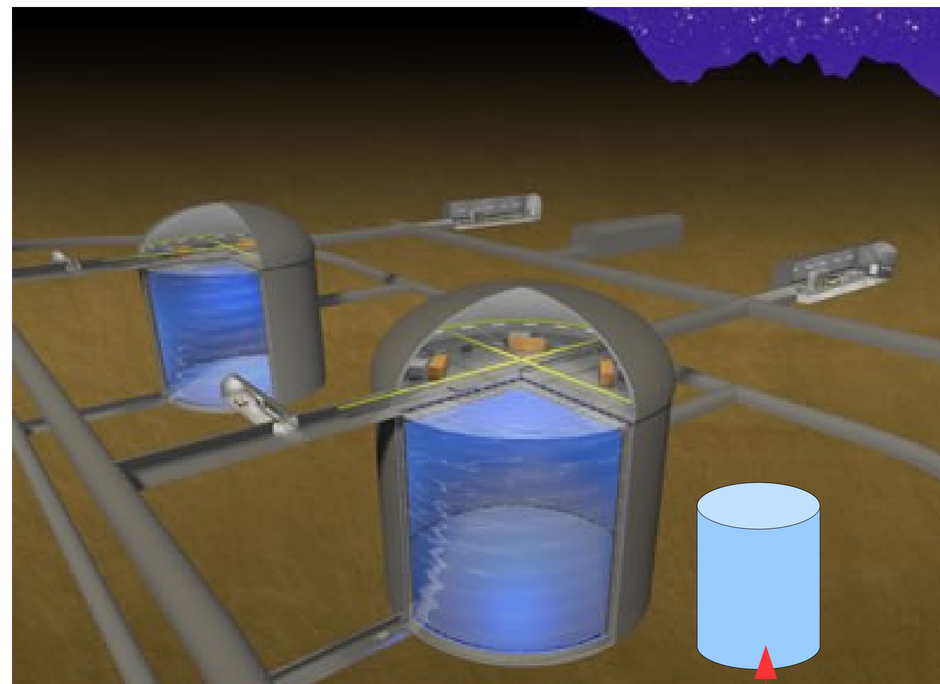


- L=810 km, <E>=2 GeV
- Near(Far) Detector 0.3(14) kt liquid scintillator
- NUMI beam re-starts May 2013 @ 700 kW (6 months ramp-up)

Next generation

DUSEL Underground
Neutrino Experiment (DUNE)

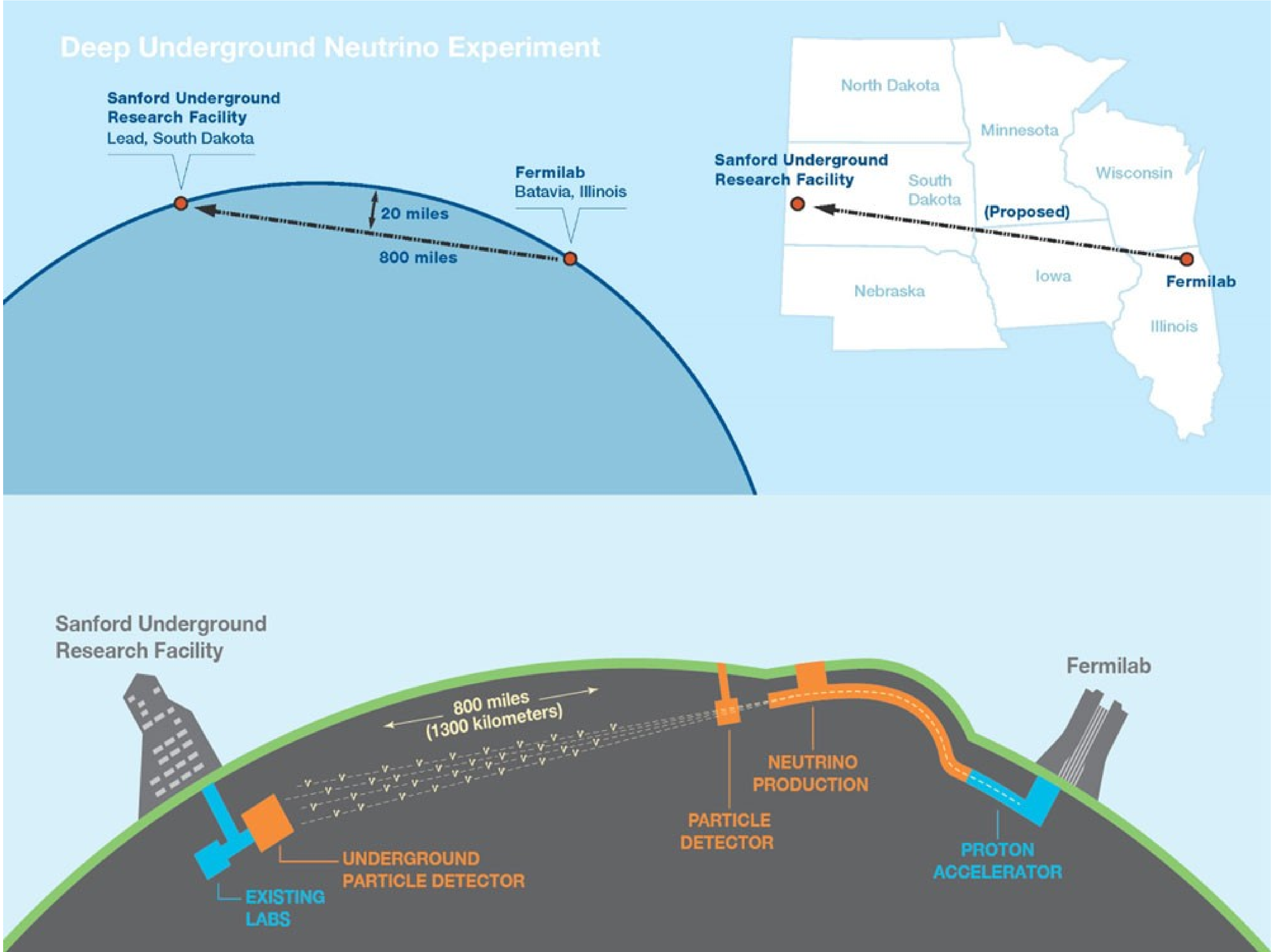
Hyper-Kamiokande



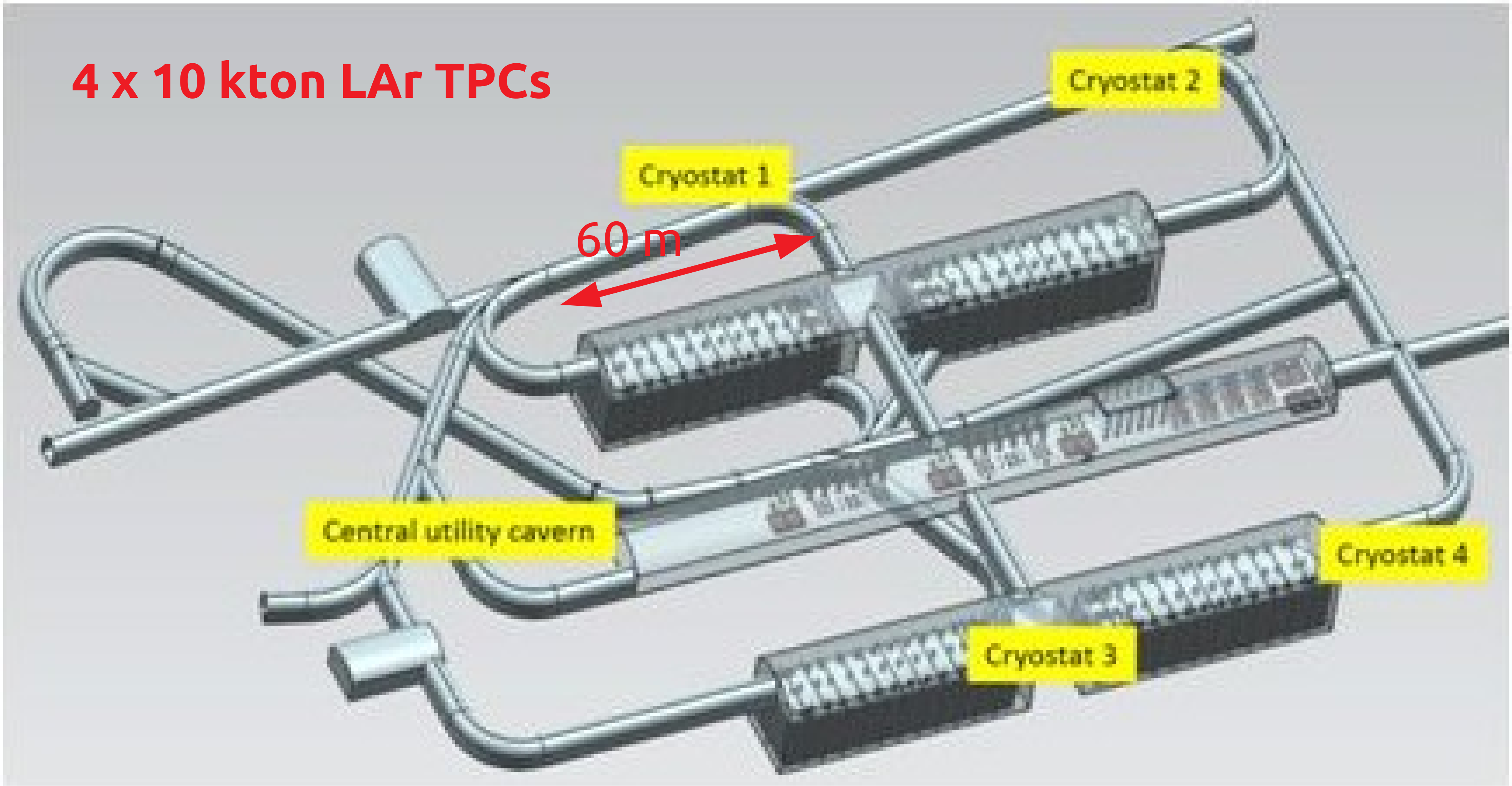
SK (to scale'ish)

- MW beams
- multi-kton far detectors

DUNE in the USA



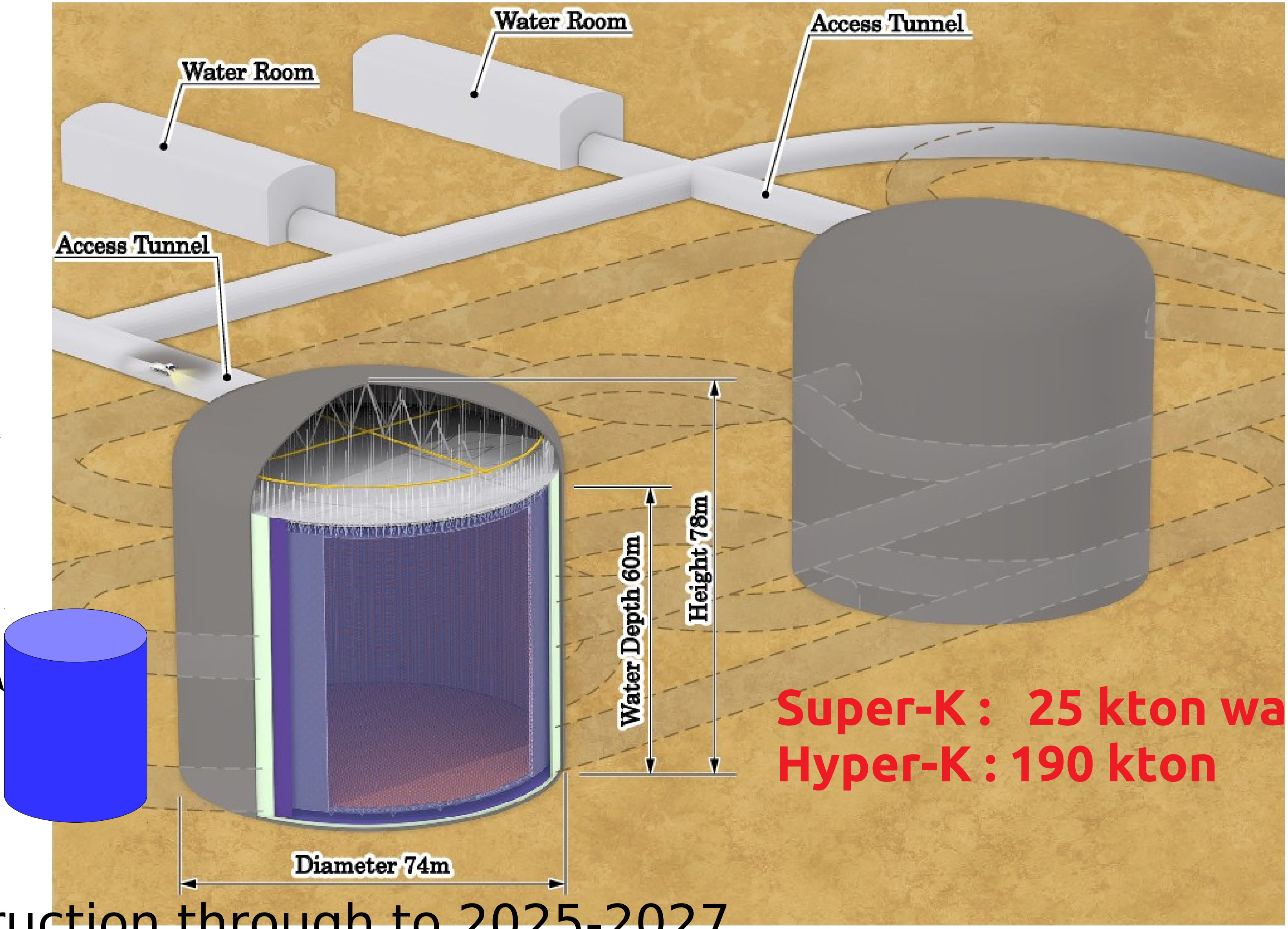
DUNE Far Detector



Construction through to 2025-2028

Hyper-Kamiokande

SuperK
Drawn
To
scale



Super-K : 25 kton water
Hyper-K : 190 kton

Construction through to 2025-2027

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	0.5 MW
Type of Beam	Wideband	Off-axis	Off-axis
Mass of far detector	70 kton	190 kton	22.5 kton
Technology	Liquid Ar TPC	Water Cerenkov	Water Cerenkov
Running from	2028'ish	2028'ish	Now

CP violation and the Mass Hierarchy

CP violation and Mass Hierarchy

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 α = β

CP violation can only take place in *appearance* experiments

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

In all it's naked glory

WARWICK
THE UNIVERSITY OF WARWICK

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

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

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

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

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

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

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

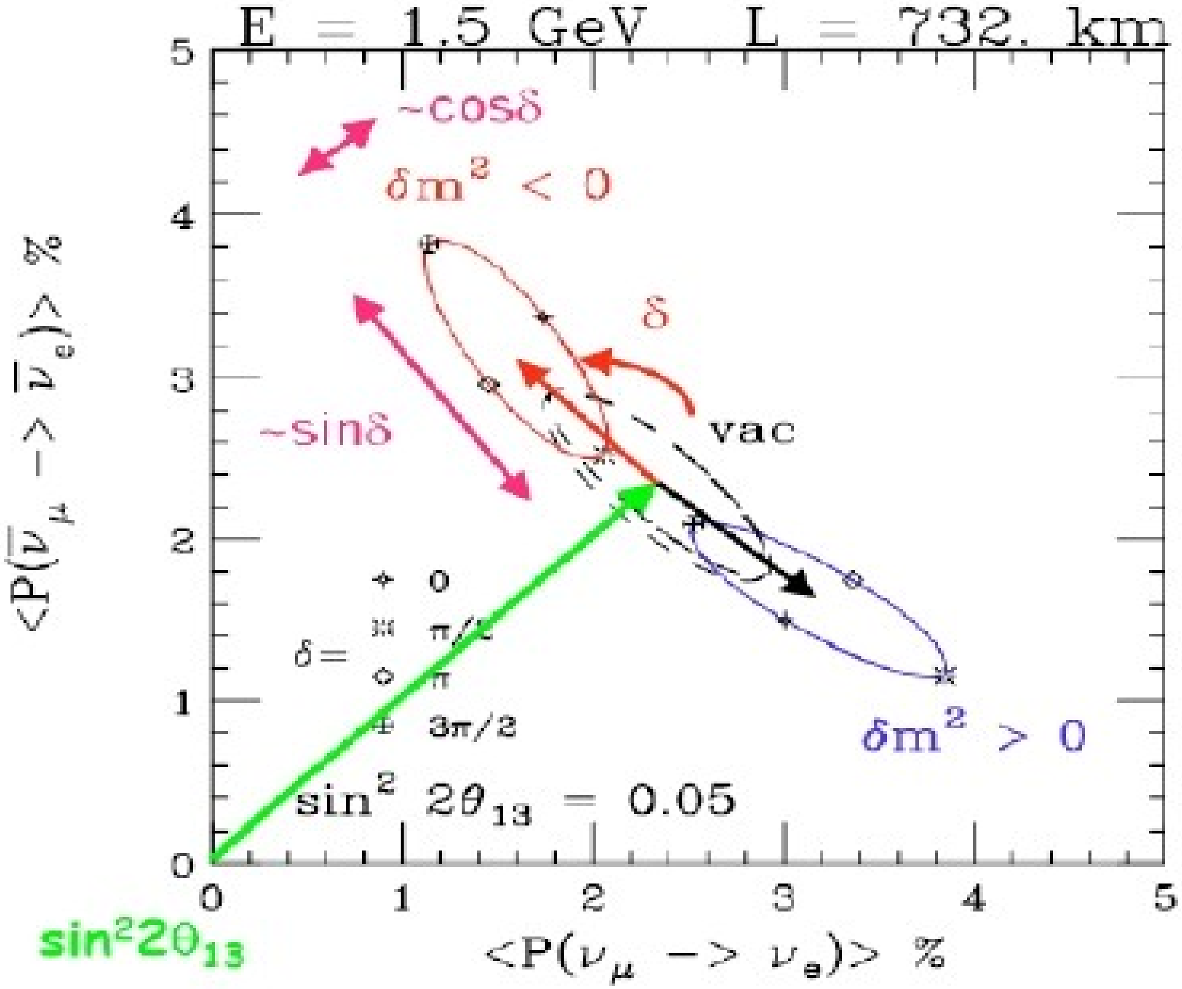
$$B_{-+}=|\Delta_{13}\mp A|$$

$$J=\cos\theta_{13}\,sin2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$$

- θ_{13}
- $\theta_{23}>45$ or $\theta_{23}<45$
- $\mathrm{Sign}(\Delta m_{23}^2)$
- δ_{CP}

Degeneracies

Experiments only measure at most two numbers; but probability has three unknowns and parameters with errors.



Need more than one measurement at different L/E to disentangle the parameter space

Degeneracies

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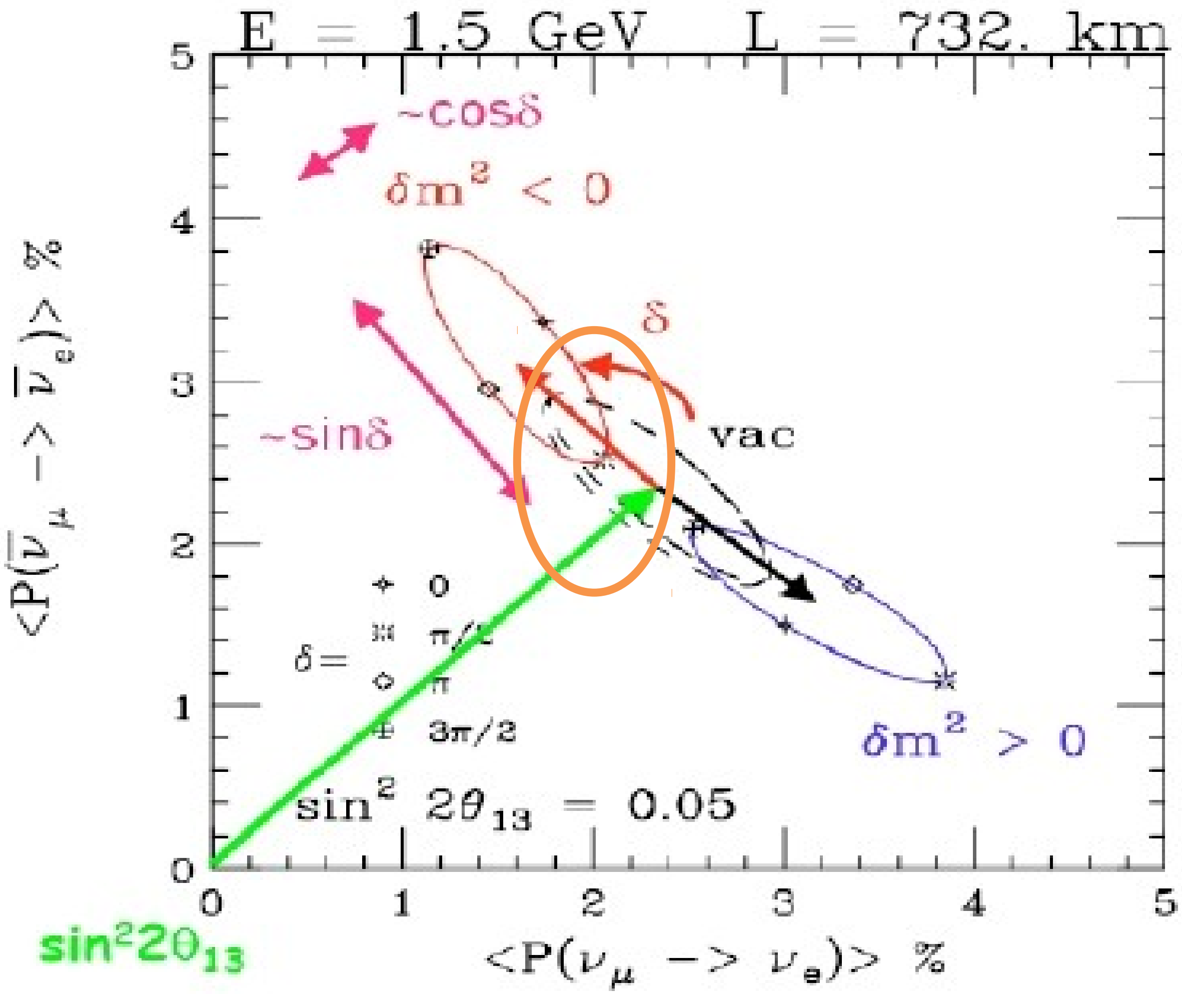


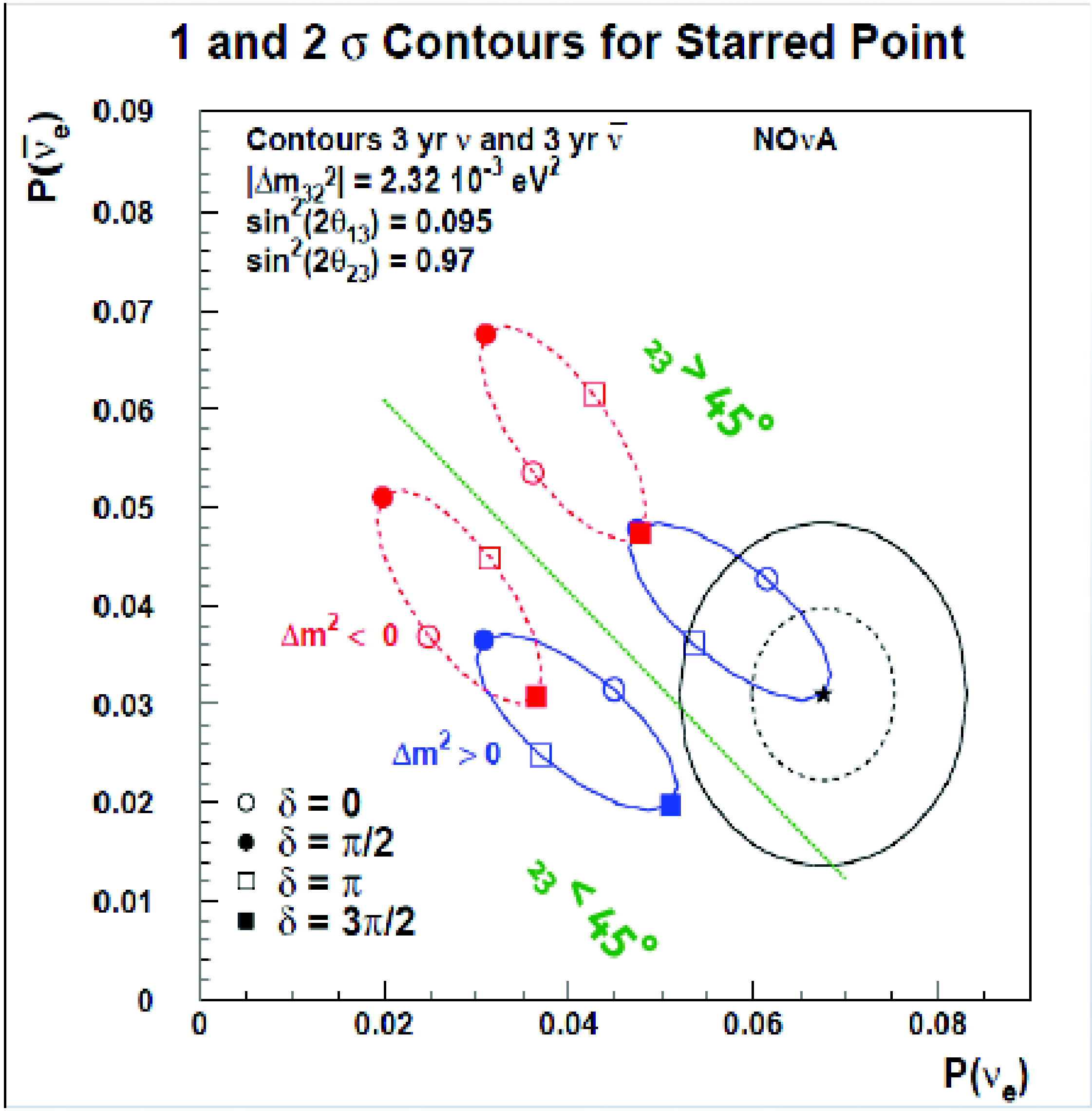
Need more than one measurement at different L/E to disentangle the parameter space

Mass Hierarchy measurements

As baseline grows, matter effects increase

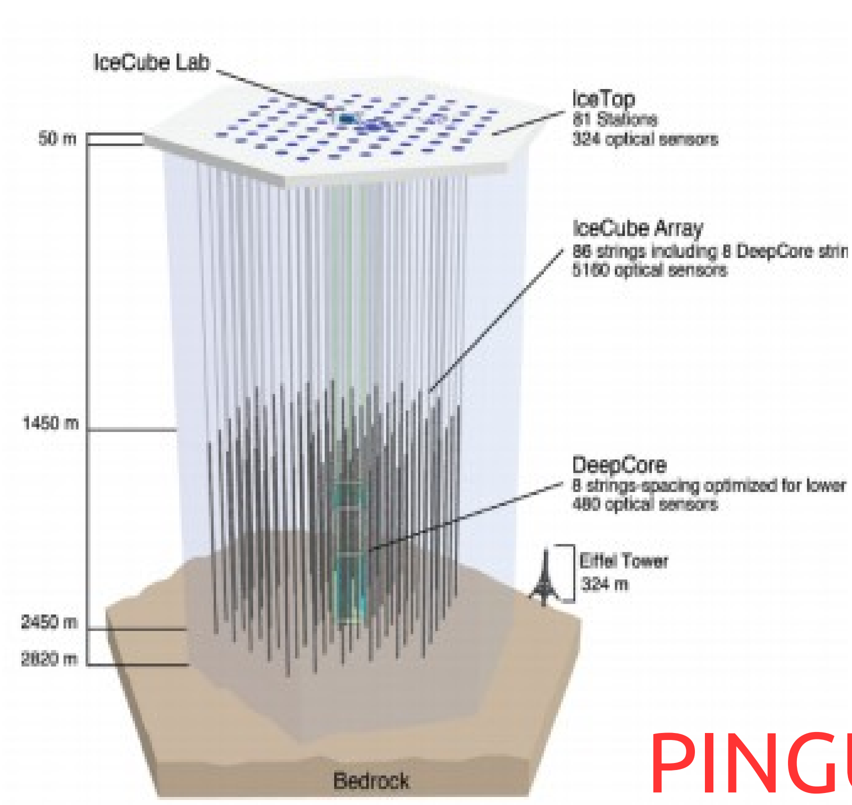
At distances of around 1000 km we can unambiguously identify the mass hierarchy

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

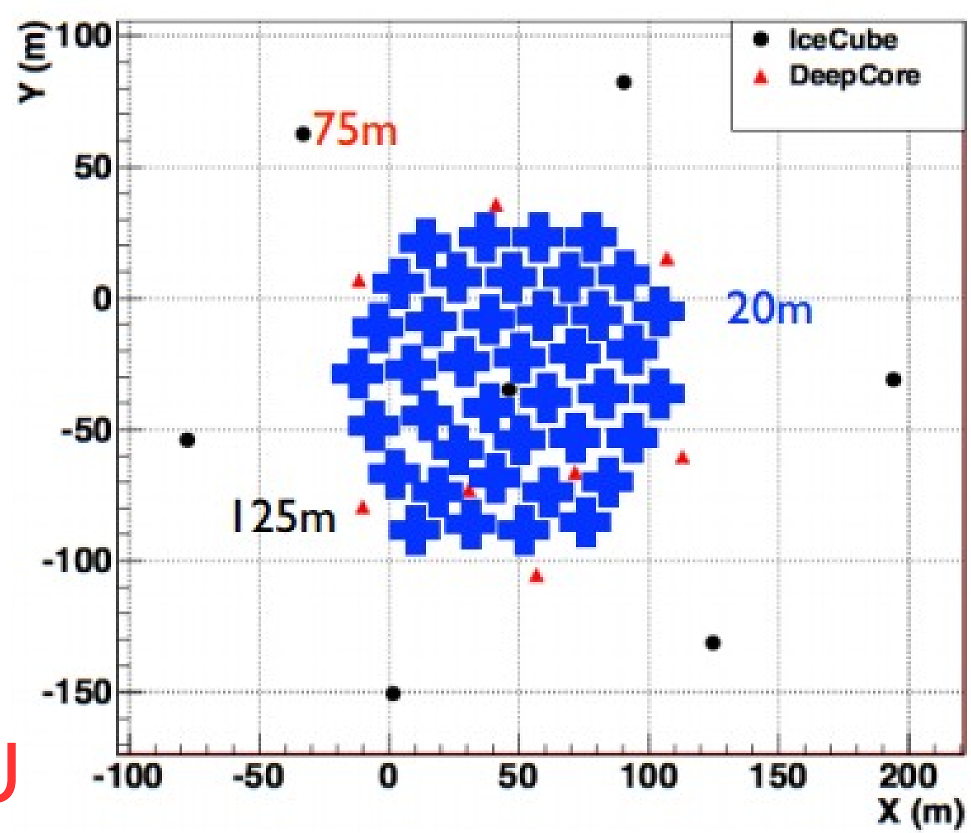


Other approaches

- a number of experiments have been proposed to try to determine the mass hierarchy, including very long baseline reactor experiments (JUNO, RENO)

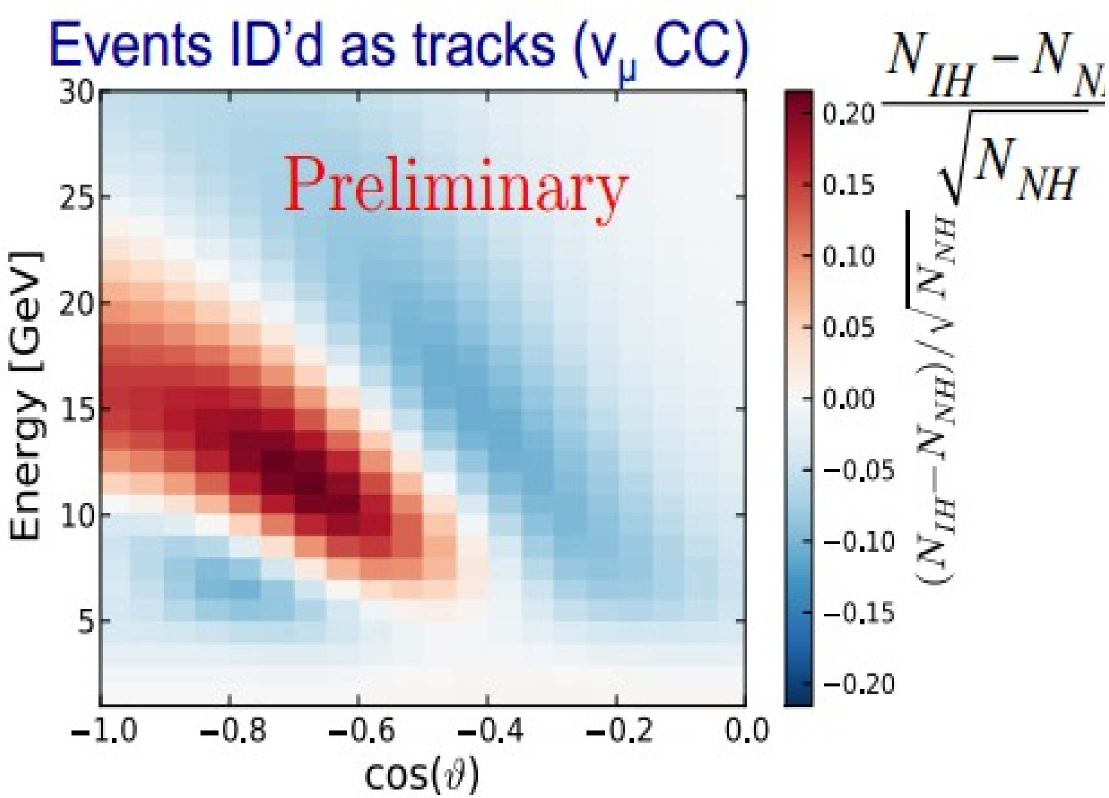


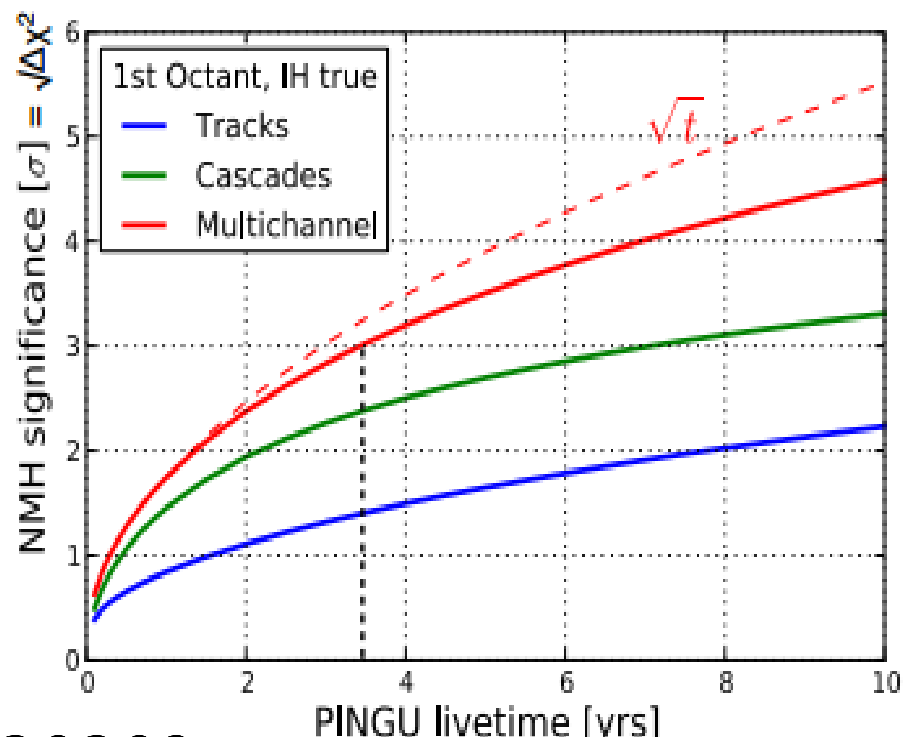
PINGU



PINGU

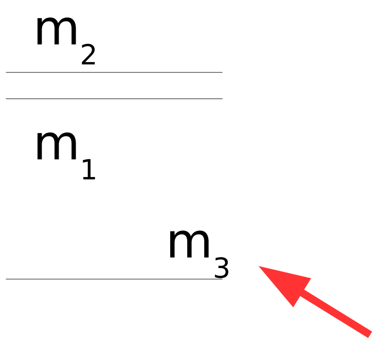
- Study atmospheric neutrinos coming up through the earth at different zenith angles
- Matter effects in the earth are different depending on heirarchy





2020?

Mass hierarchy in $0\nu\beta\beta$ decay



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

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

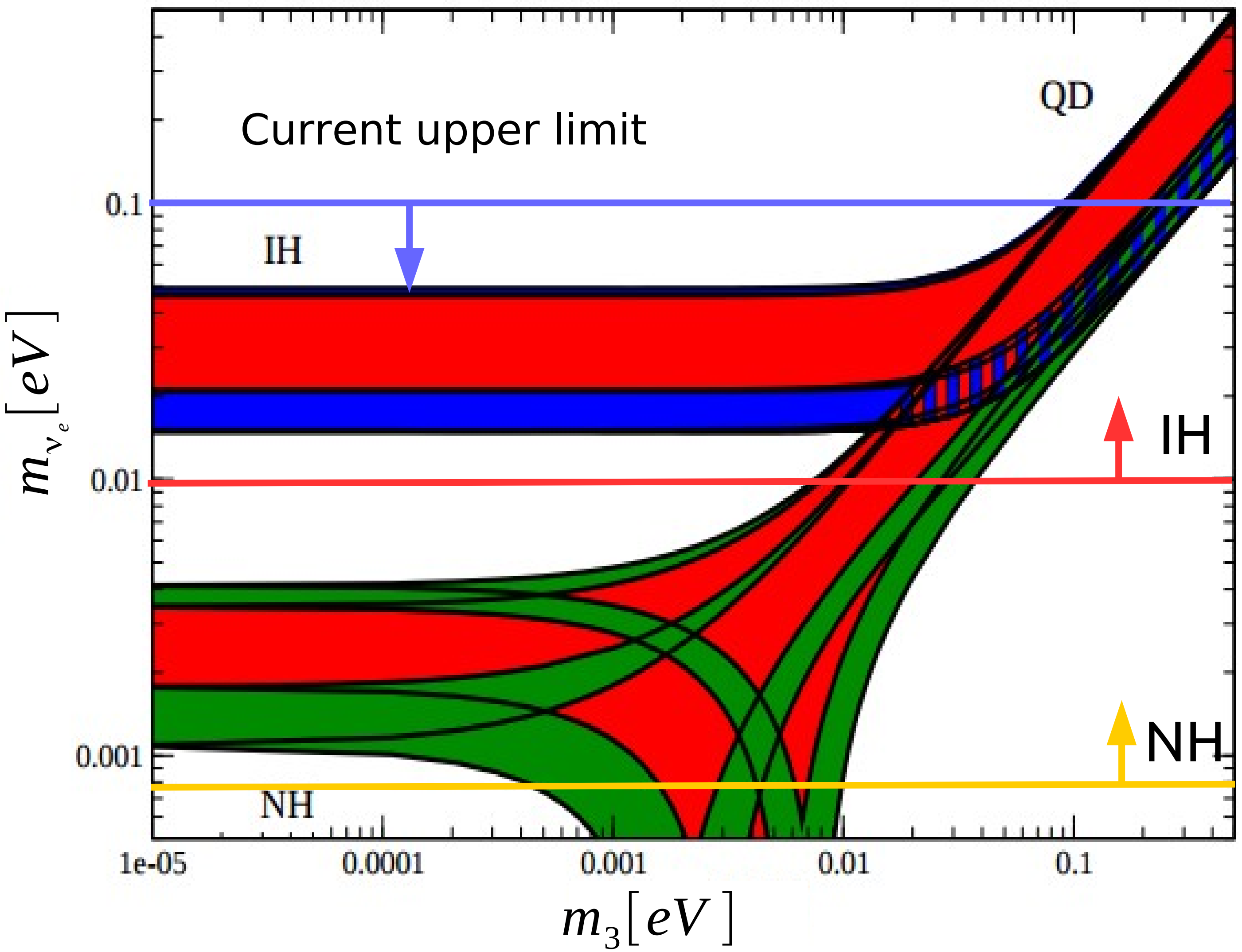
$$m_{\nu_e} = \left|U_{e1}\right|^2 \sqrt{m_3^2 + \Delta m_{23}^2} + \left|U_{e2}\right|^2 \sqrt{m_3^2 + \Delta m_{23}^2} + \left|U_{e3}\right|^2 m_3^2$$

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

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

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 and run 10 times longer
- These are being built now.

Question

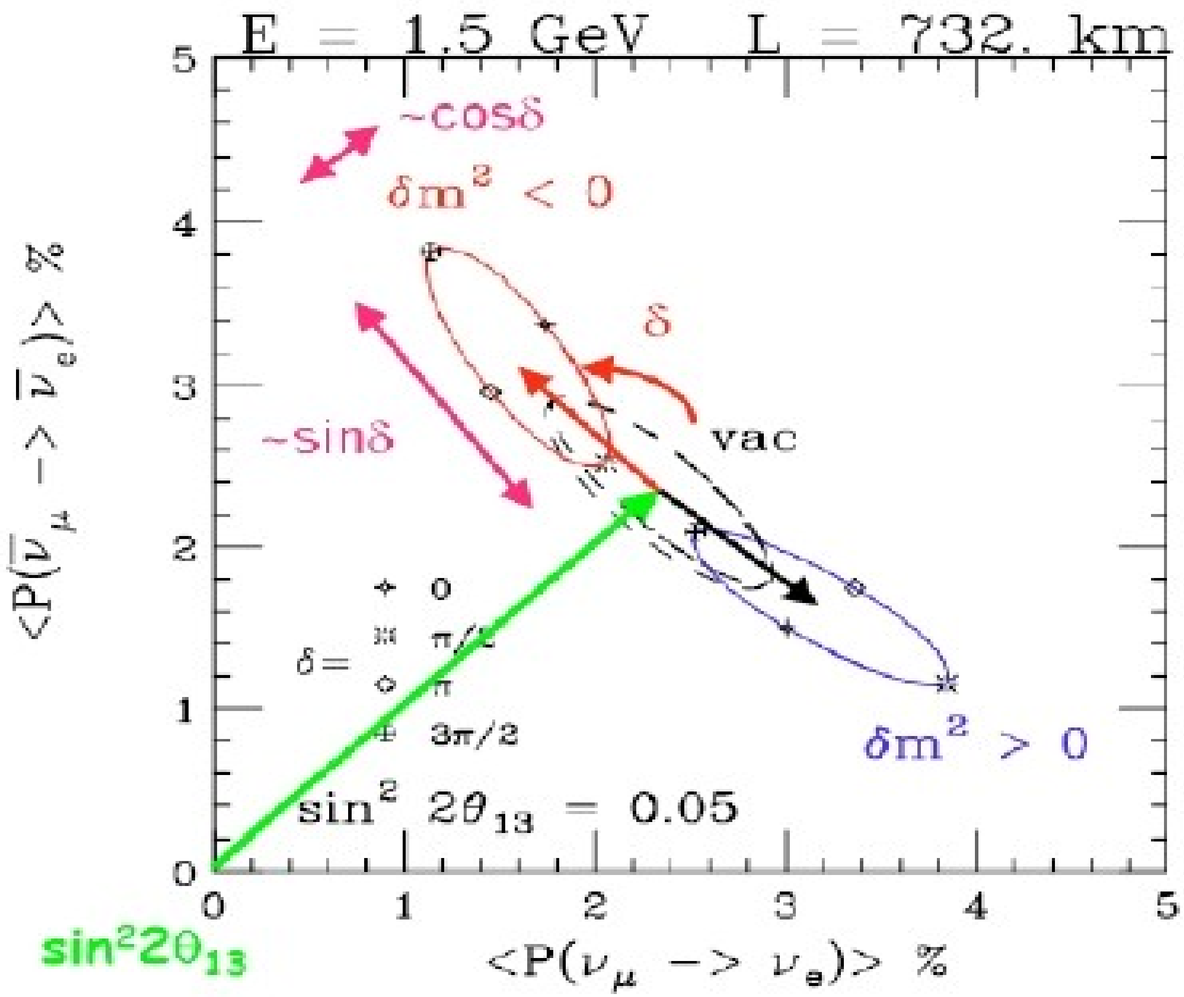
Is there an experimental way of directly showing that the neutrino is a Dirac particle? What about an indirect approach?

Direct measurement : no known accessible observable (radiative decays of non-relativistic massive neutrinos may show differences)

Indirect measurement :

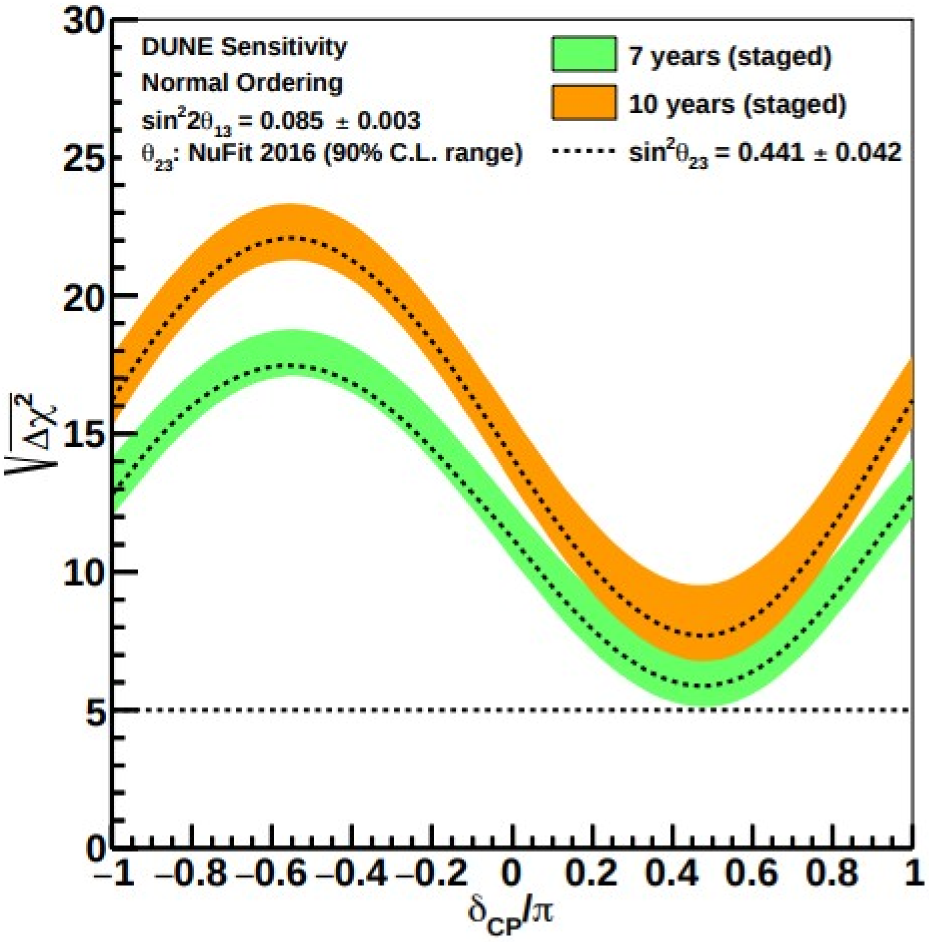
IF : the long-baseline experiments favour inverted hierarchy
AND : KATRIN measures $m(\nu_e)$ in the IH band region
AND : $0\nu\beta\beta$ experiments see nothing
THEN : neutrino can't be Majorana

CP violation

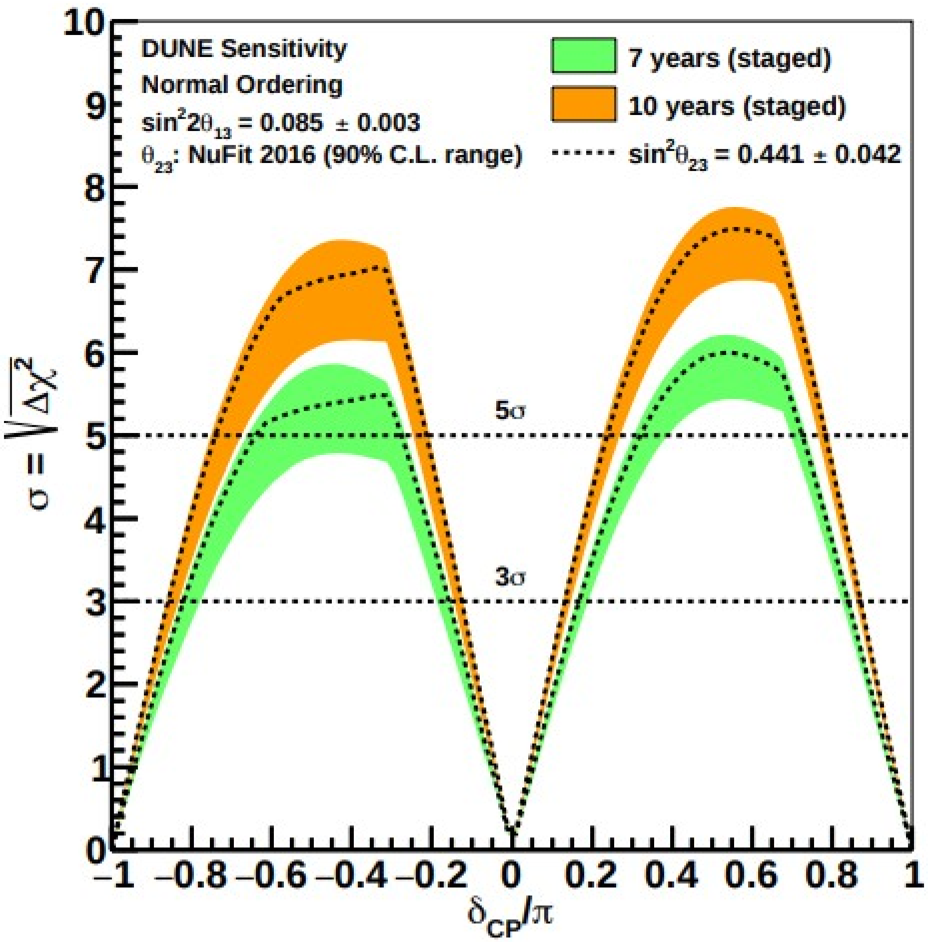


- If mass heirarchy is known then "all" we need to do is precisely measure the ν_e appearance probability for neutrino and anti-neutrino beams and that will give us δ_{CP}
- Do this at at least two independent L/E

δ_{CP} : DUNE Sensitivity

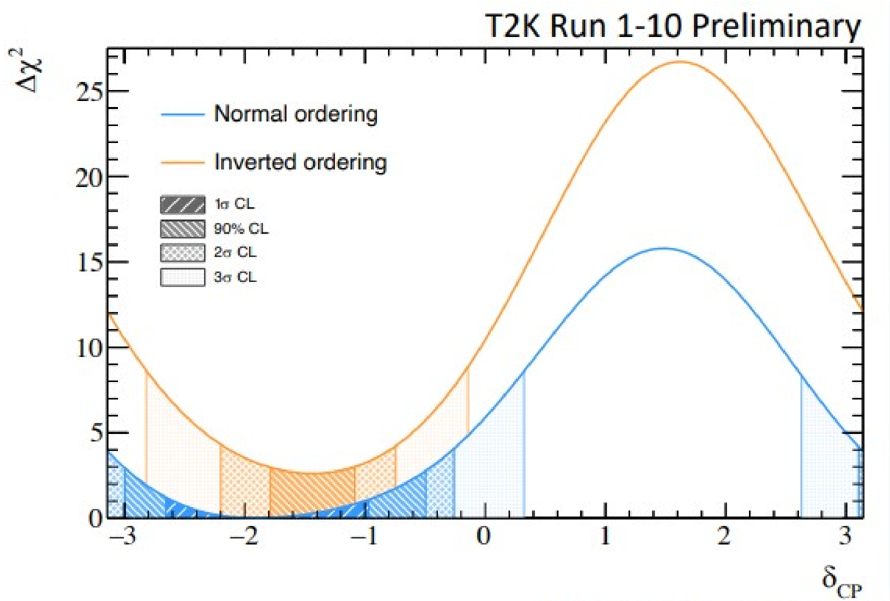


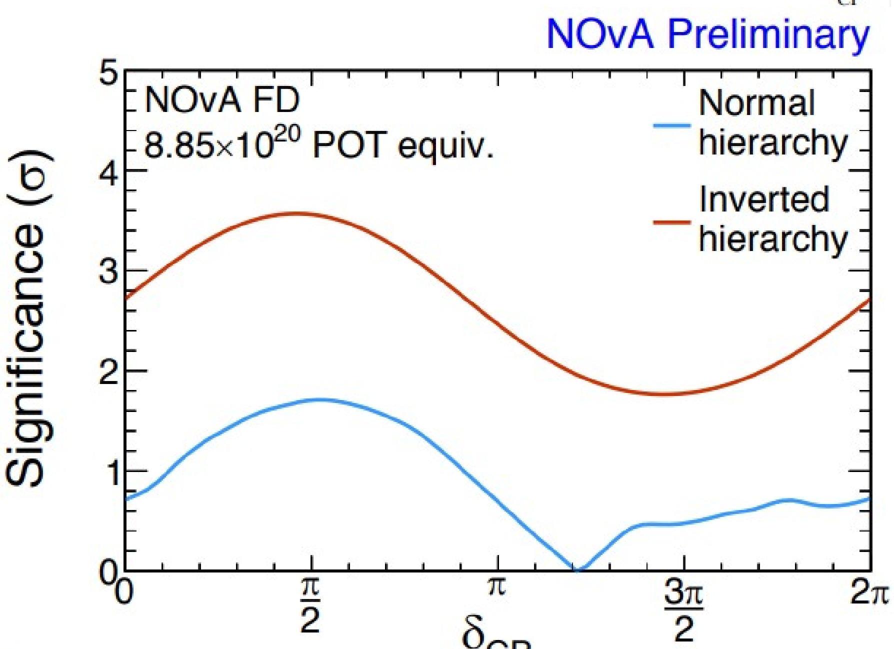
> 5 σ reach after 7 years of running over entire δ_{CP} range



> 5 σ reach after 10 years if δ_{CP} exists in ±[0.2-0.8]π

Hints : T2K & NOvA





- Normal ordering weakly favoured
- 90% CL δ_{CP} : [-2.8,-0.8]
- δ_{CP} = 0 disfavoured at 3σ

- Best fit: Normal hierarchy favoured at 1.8 σ
- δ_{CP} = 1.21 π
- Excludes δ_{CP} = π / 2 in the inverted hierarchy at > 3 σ

Mass Hierarchy Determination

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

Timescale : 2-4 years from now for good indication.
7-10 for 5 σ measurement.

Measurement of δ_{CP}

Next generation of experiments are being planned to measure this

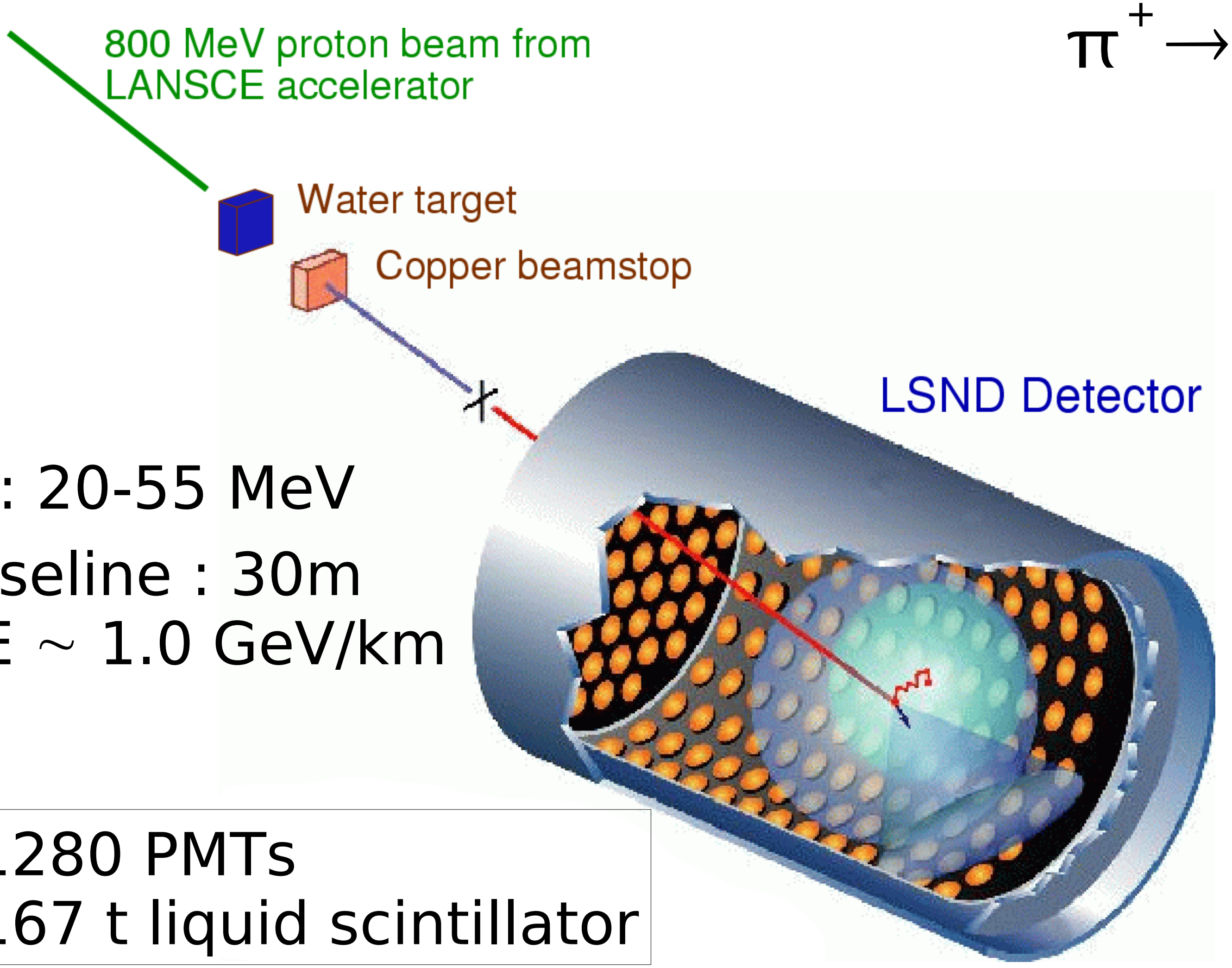
Timescale : 8-10 years from now (including 6 for construction) for 3σ sensitivity to distinguish from no CP-violation scenario (if true δ_{CP} is π/2).

15-20 years for a measurement of δ_{CP} to a precision of 20^o (if true δ_{CP} is π/2).


A toolbag full of spanners

LSND

The LSND experiment was the first accelerator experiment to report a positive appearance signal



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$$

$$\overline{\nu}_\mu \Leftrightarrow \overline{\nu}_e$$

E_ν : 20-55 MeV

baseline : 30m

L/E ~ 1.0 GeV/km

1280 PMTs

167 t liquid scintillator

$$\overline{\nu}_e \, p \rightarrow e^+ n$$

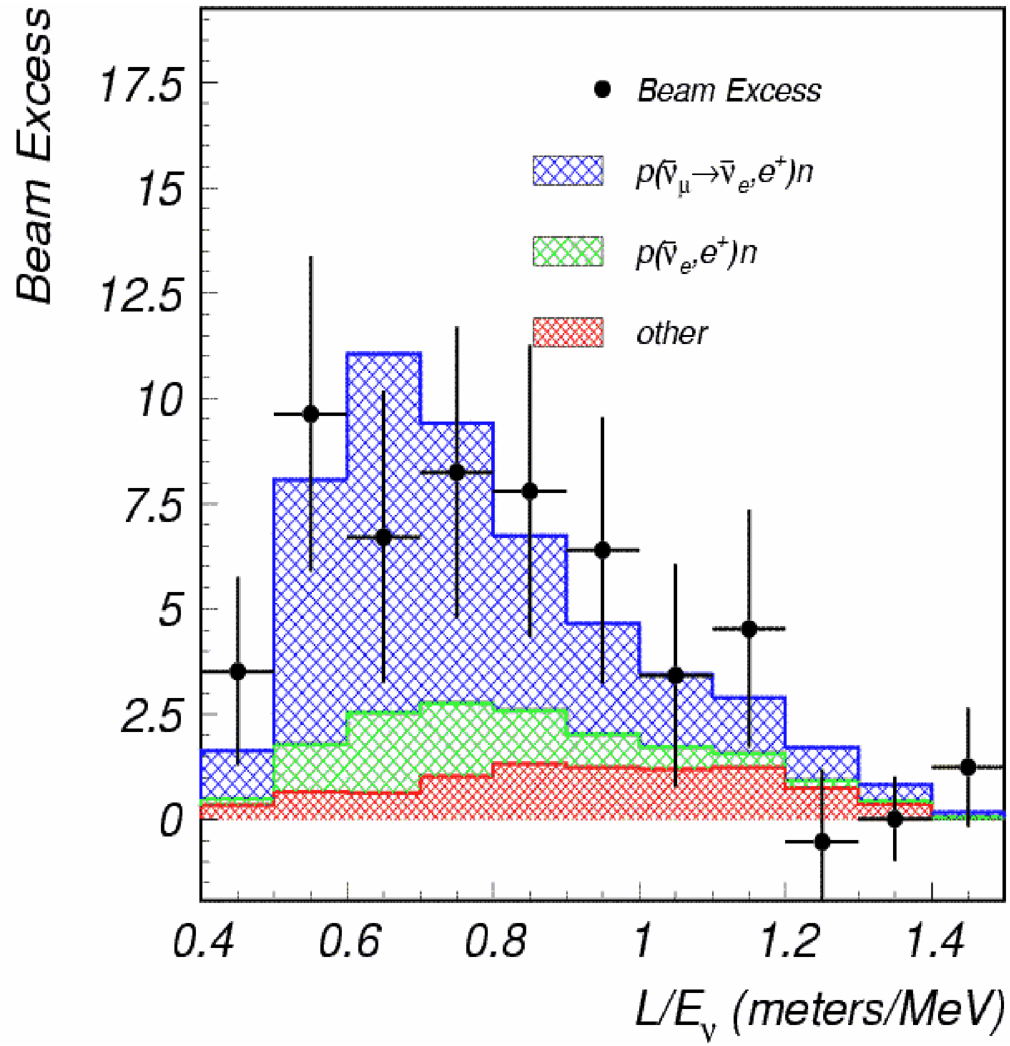
(e^+:) 20-60 MeV

$$n \, p \rightarrow \gamma \, d$$

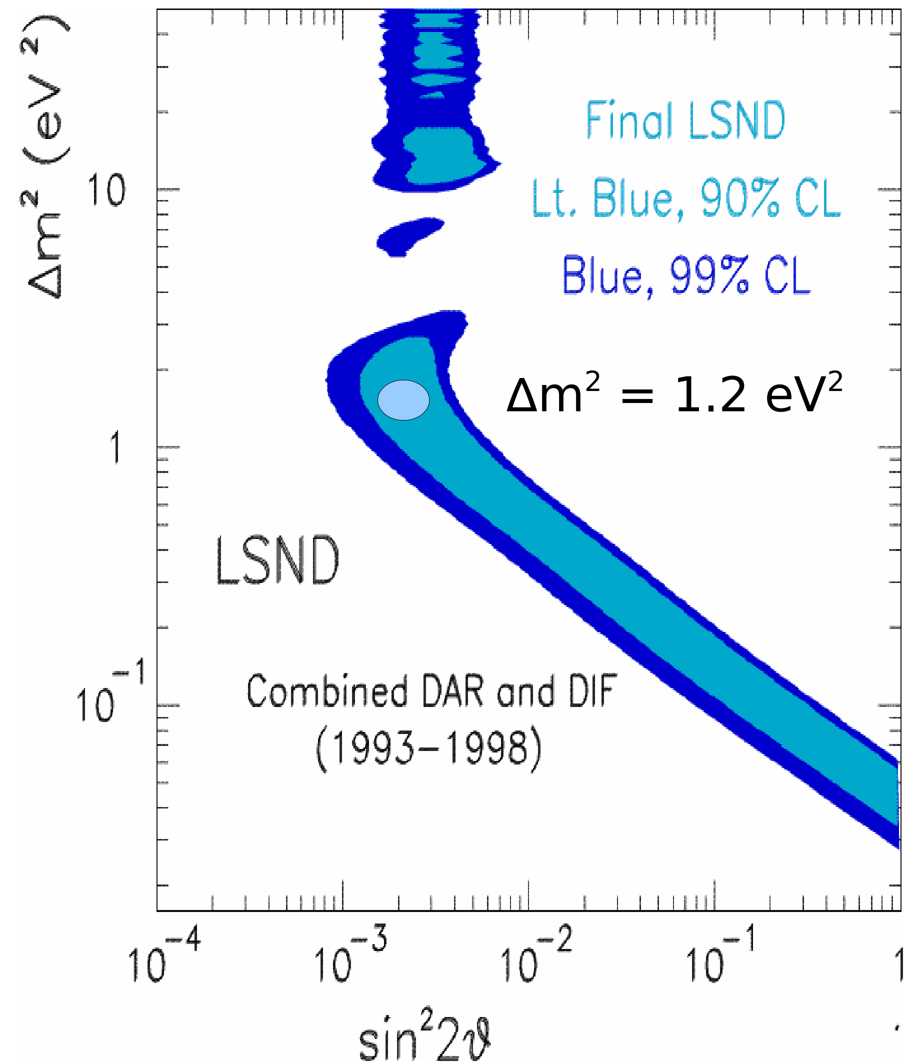
(γ:) 2.2 MeV

LSND Result (1997)

87.9 ± 22.4 ± 6 excess events from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



3.3 σ evidence for oscillations



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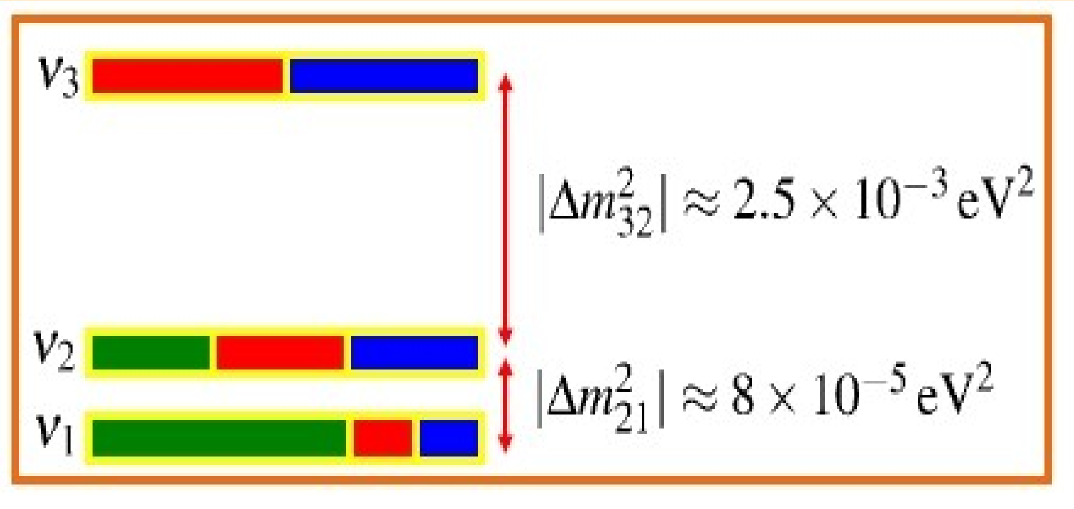
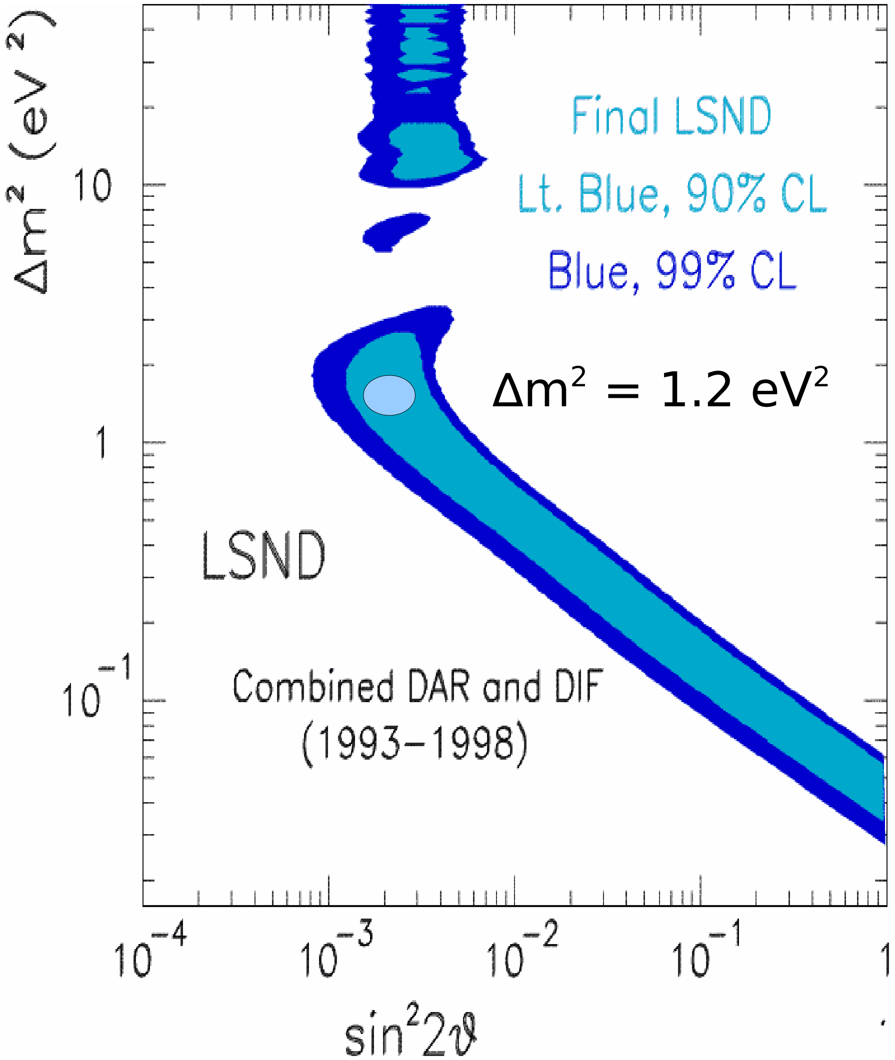
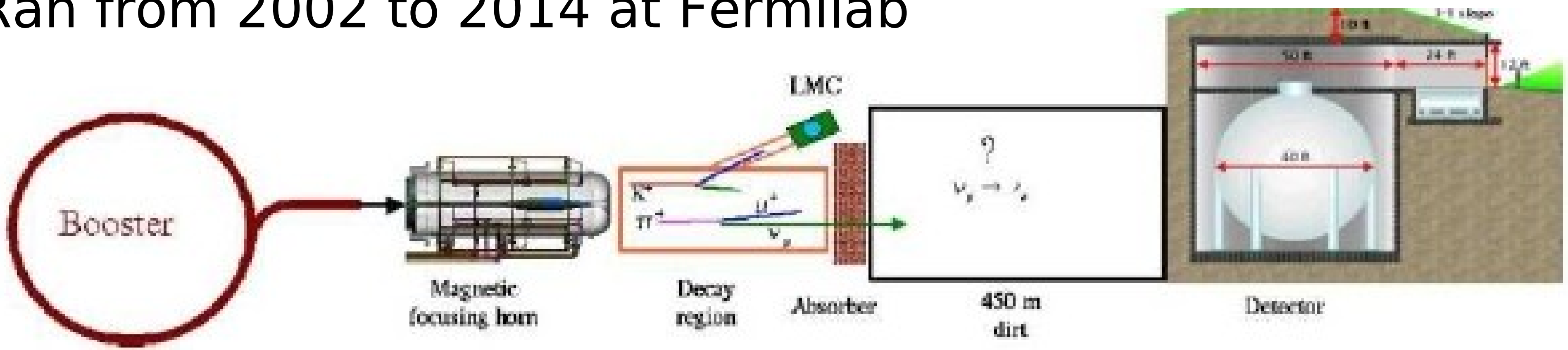


- Already know 2 mass splittings
- LSND implies : $\Delta m^2 \approx 1$ eV^2
- 3 independent Δm^2 implies
- <u>**4 neutrino mass states!?!?**</u>



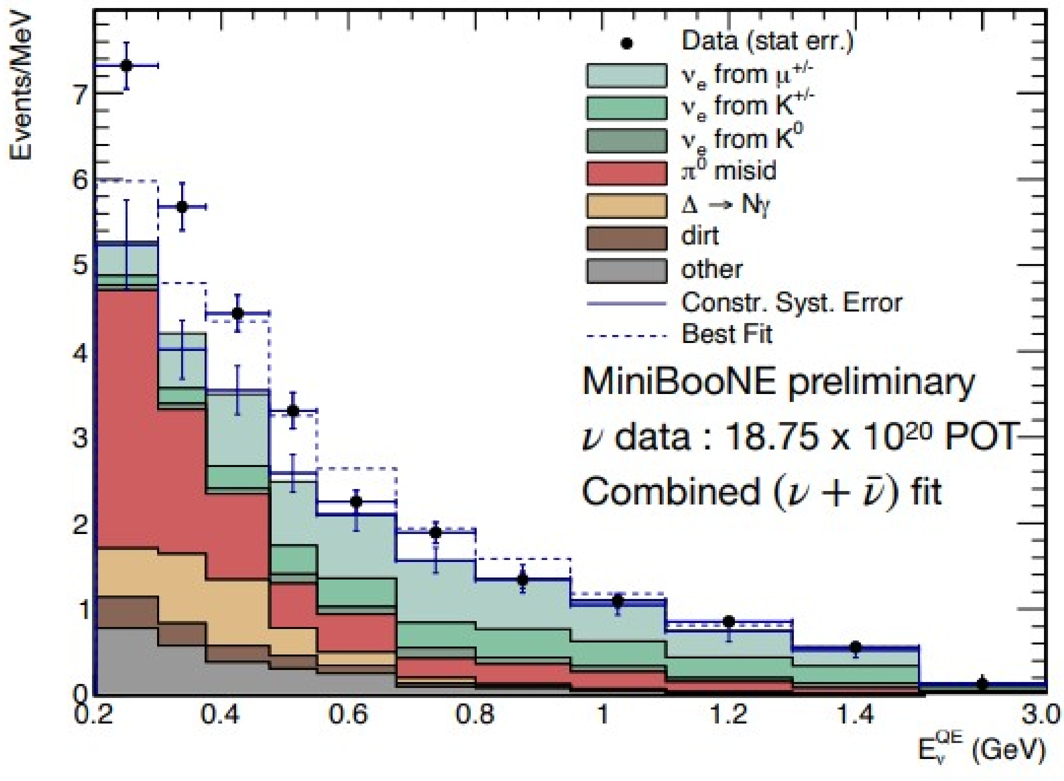
MiniBooNE

Ran from 2002 to 2014 at Fermilab

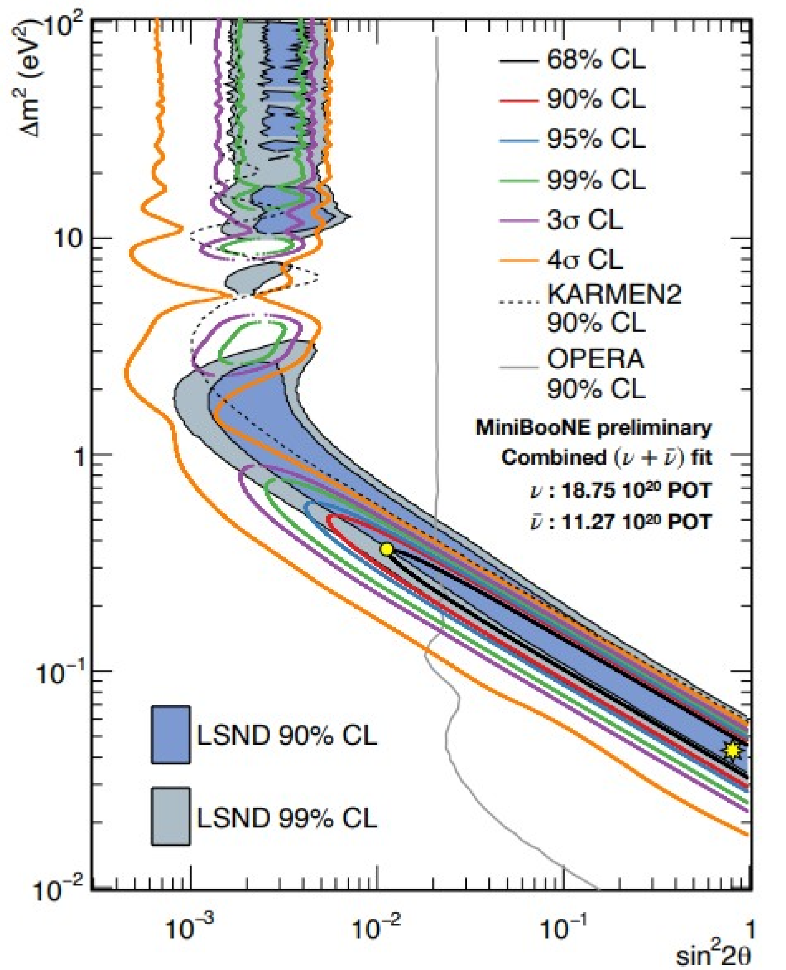


- Average neutrino energy ≈ 1 GeV
- L/E the same as LSND
- Same technology as LSND
- Different energy = different event types = different systematics

miniBooNE Results



Excess at the level of 4.8 σ



Neutrino + Anti-Neutrino Mode

$(\Delta m^2, \sin^2 2\theta) = (0.043\ \text{eV}^2,\ 0.807)$

$\chi^2/ndf = 21.7/15.5$ (prob = 12.3%)

The Gallium Anomaly

We've discussed the Homestake experiment which studied the reaction

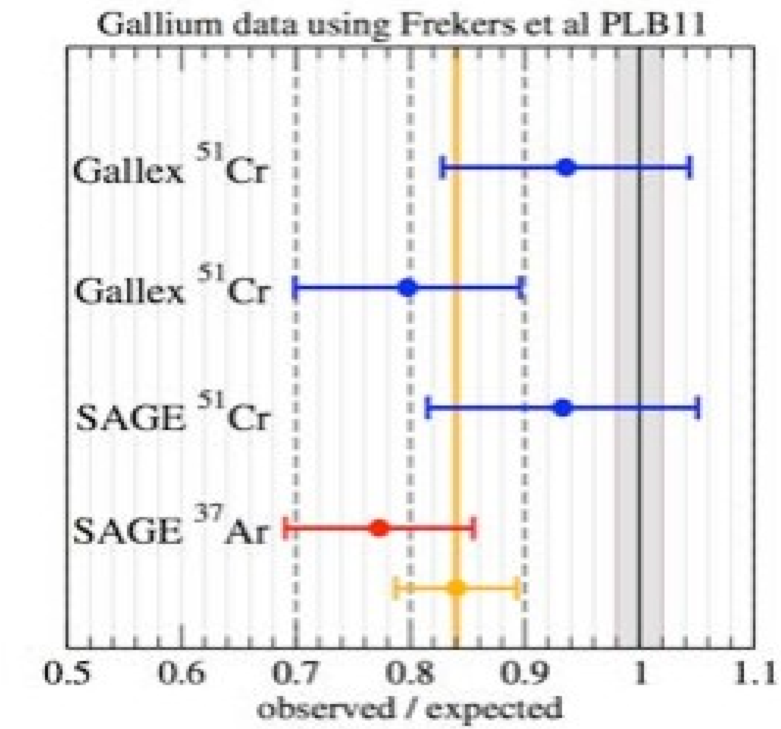
$$\nu_e + Cl^{37} \rightarrow Ar^{37} + e^-$$

A couple of experiments (SAGE and GALLEX) also studied

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}\mathrm{Ge} + e^-$$

In early 2000's the response of GALLEX was being tested using MCi radioactive sources.

Sources emitted ν_e which were then observed using the standard Ge signature



$$L/E \approx 0.1\,m/0.1\,MeV \rightarrow \Delta m^2 \approx 1\,eV^2$$

(or is it our understanding of the low energy ν-Ga cross section, or is it just bad luck?)

The reactor anomalies

- pre-2011 : measurement of the total neutrino flux from reactors agreed with expectation.

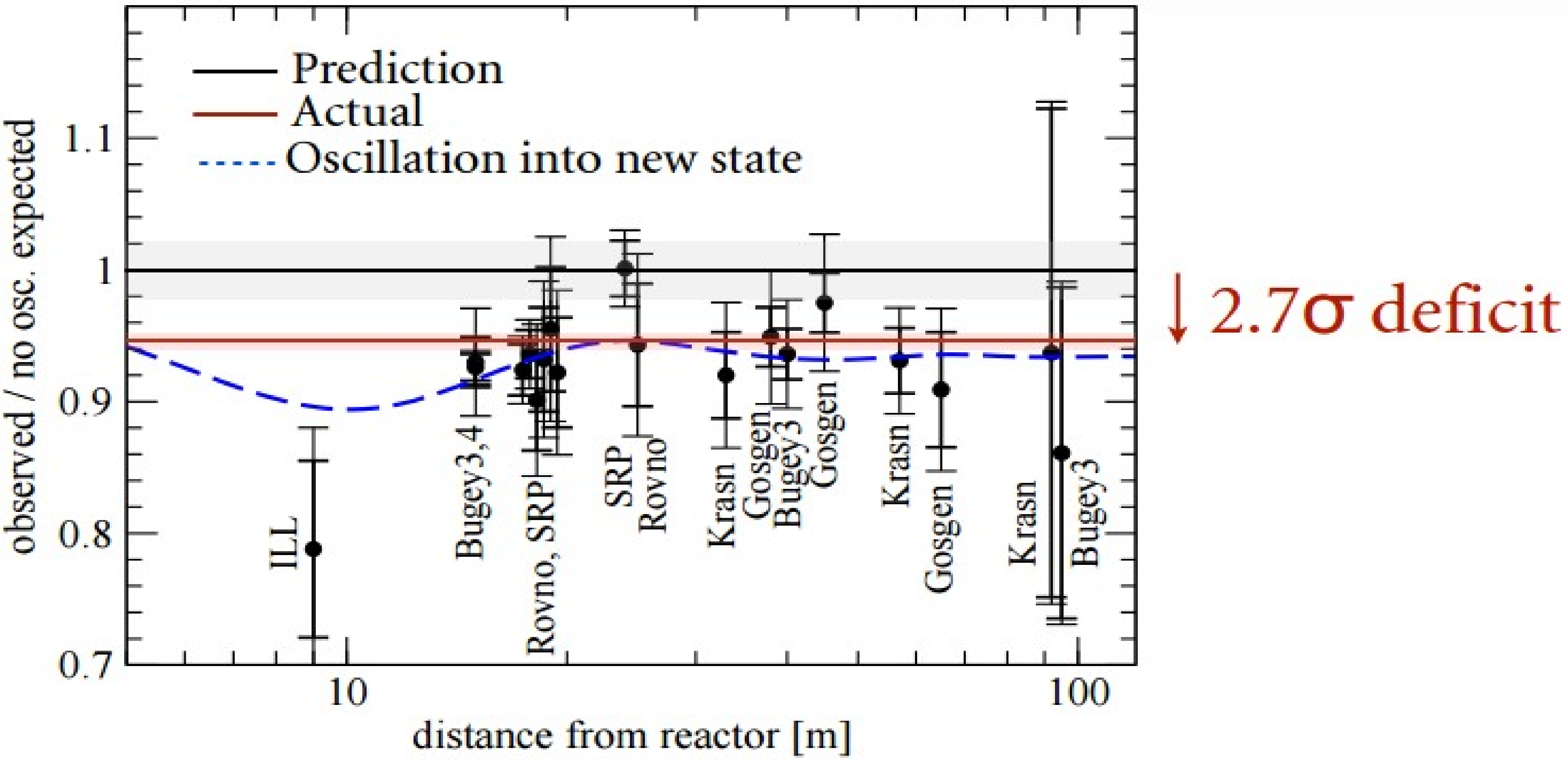
- In 2011, new techniques in modelling nuclear reactions led to a re-evaluation of the expected electron antineutrino flux. The new estimate was about 6% **higher** than the old.

- Suddenly all the experiments now observed a general **deficit** of electron antineutrinos being detected at the detector

$$N(\bar{\nu}_e) = \Phi^{old}(\bar{\nu}_e)\sigma \longrightarrow \Phi^{new}(\bar{\nu}_e)\sigma \times P(\bar{\nu}_e \rightarrow \nu_s)$$

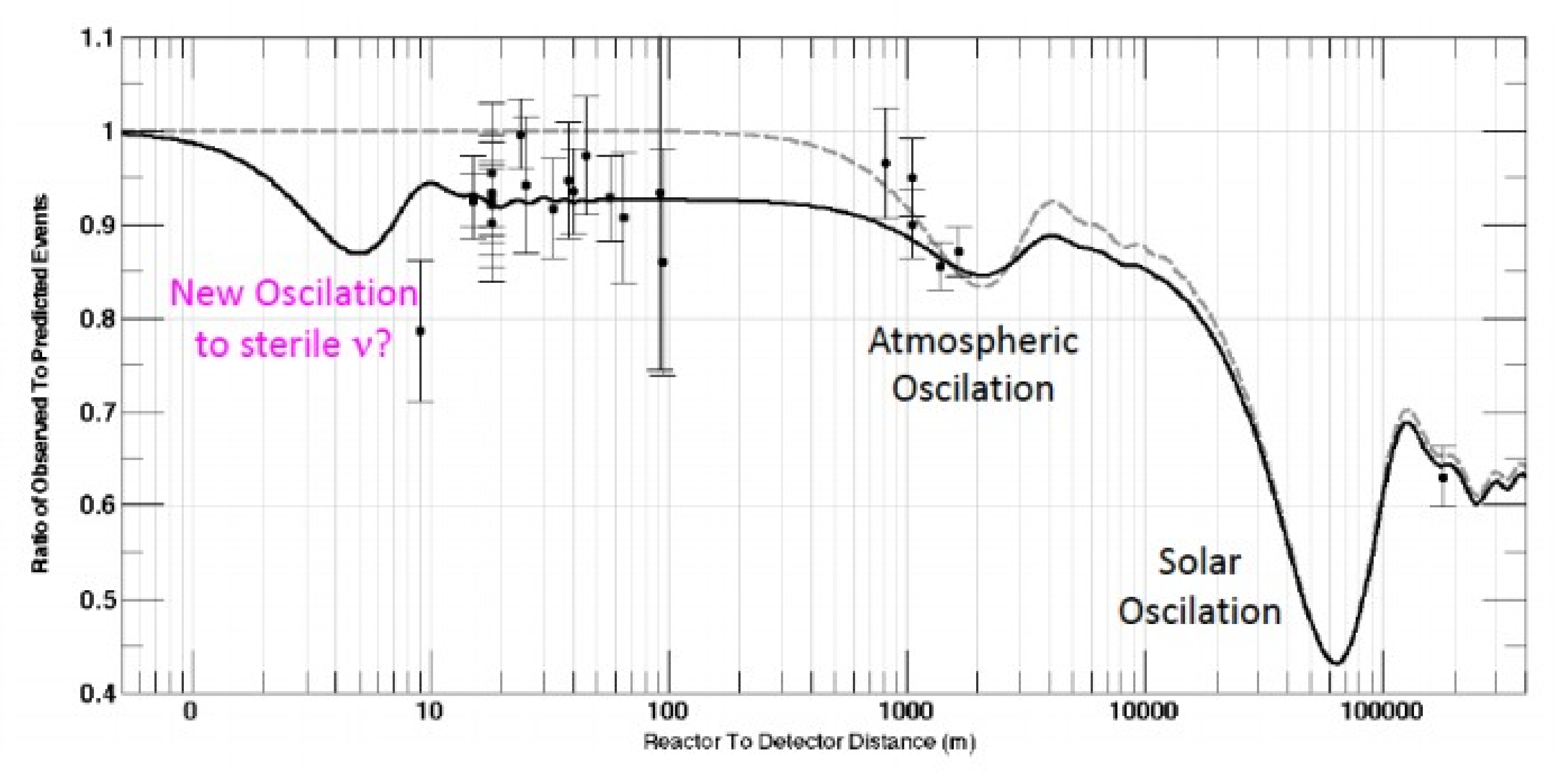
- Could this be (i) the new flux estimate is just a bit dodgy or (ii) we have short baseline neutrino oscillations to a sterile state?

Reactor Anomaly

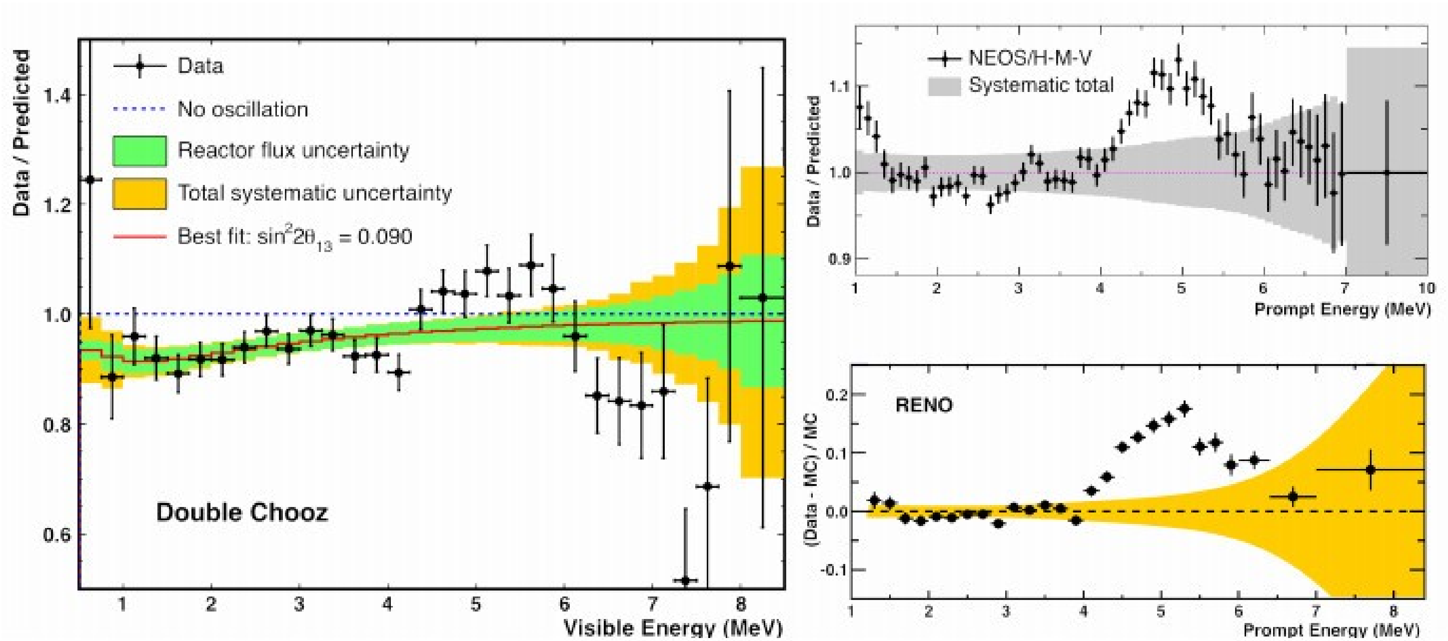


Deficit consistent with a sterile state with $\Delta m^2 \sim 1.5\ eV^2$
Reactor antineutrino flux calculations are VERY hard to do

Global Oscillation Fit

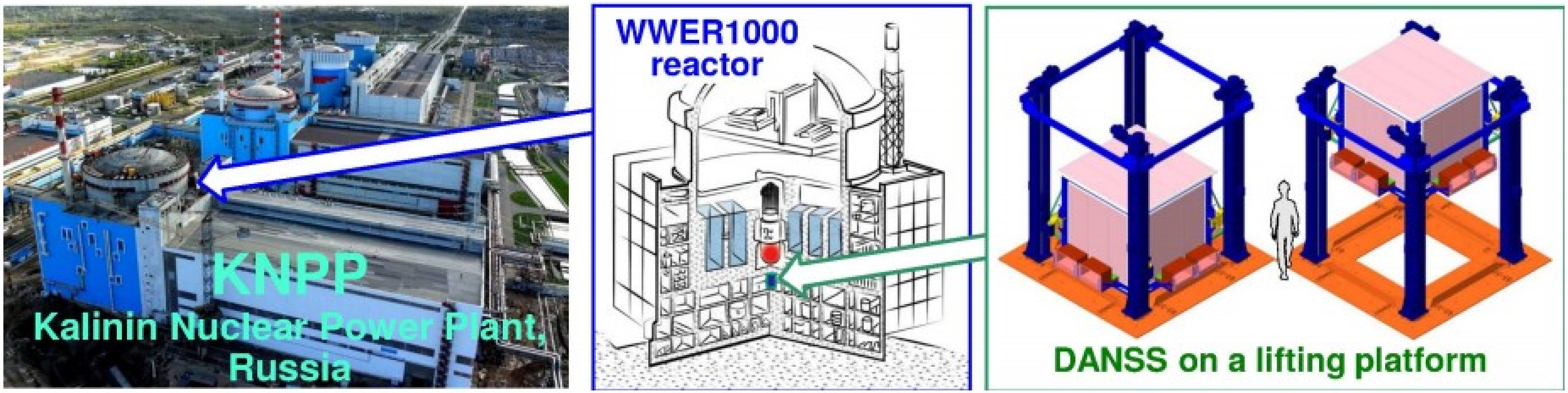


The Bump

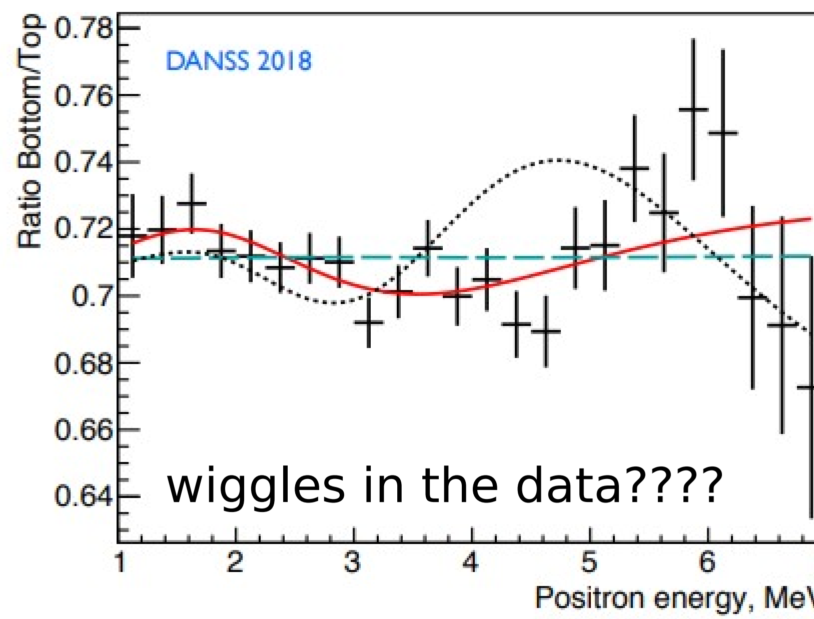


- Overall there is a deficit of events with the new reactor flux estimates
- Between 4-6 GeV there seems to be an *excess* beyond the flux errors
- Seen in all reactor experiments
- This is quite hard to explain away using sterile neutrinos!
- Prejudice is that this is due to modelling nuclear physics

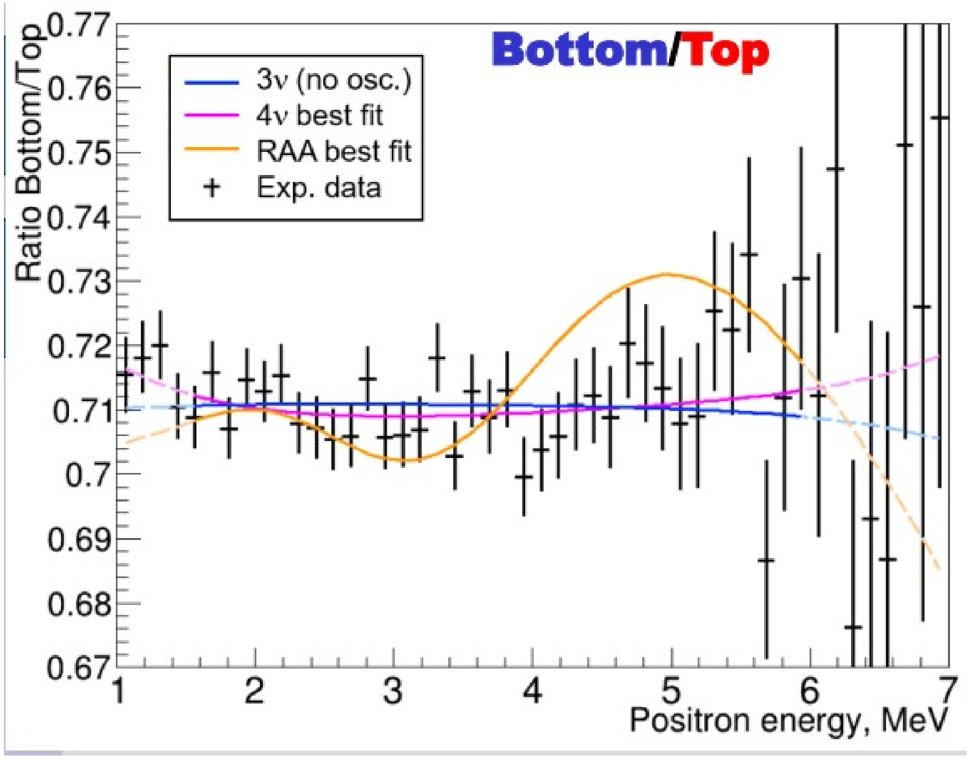
Reactor Experiments



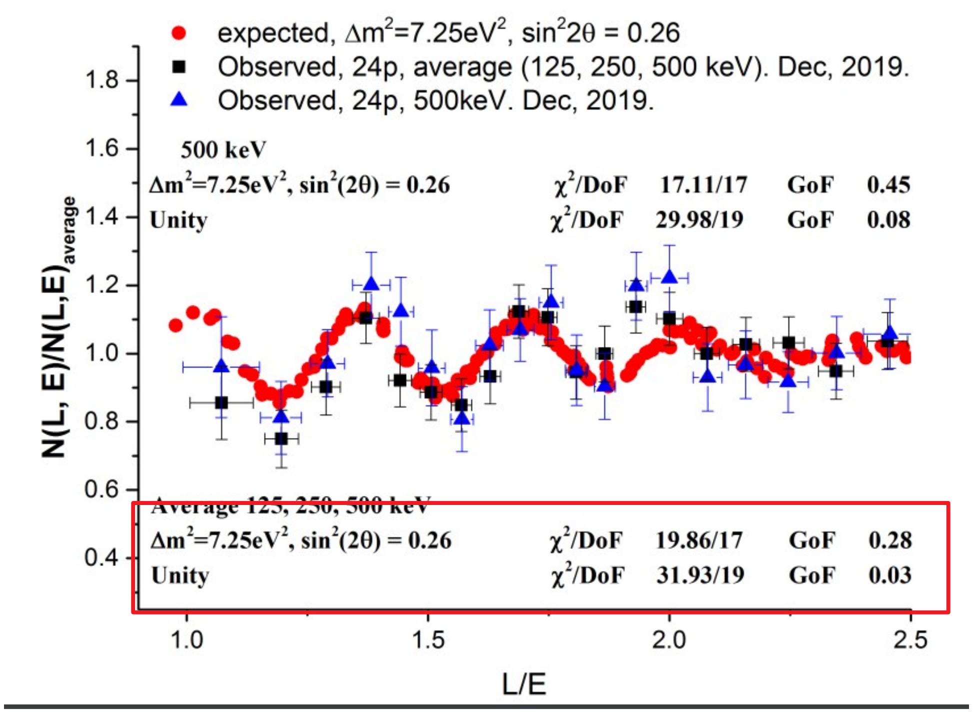
- Installed on a moveable platform under a 3 GW reactor
- Large neutrino flux
- Variable source-distance distance using the same detector
- Down : 12.7 m from reactor
- Up : 10.7 m from reactor



Reactor Experiments



DANSS (2020)
No visible effect



Neutrino4 (2020)
Claimed signal

Situation unclear : other experiments (Stereo, SoLiD, Prospect) may clarify

Decaying sterile neutrinos?

Lorentz violation?

CPT Violation?

Extra dimensions?

3+1 sterile?
3+2 ?
3+n ?

Experimental problems?

No bleedin' idea

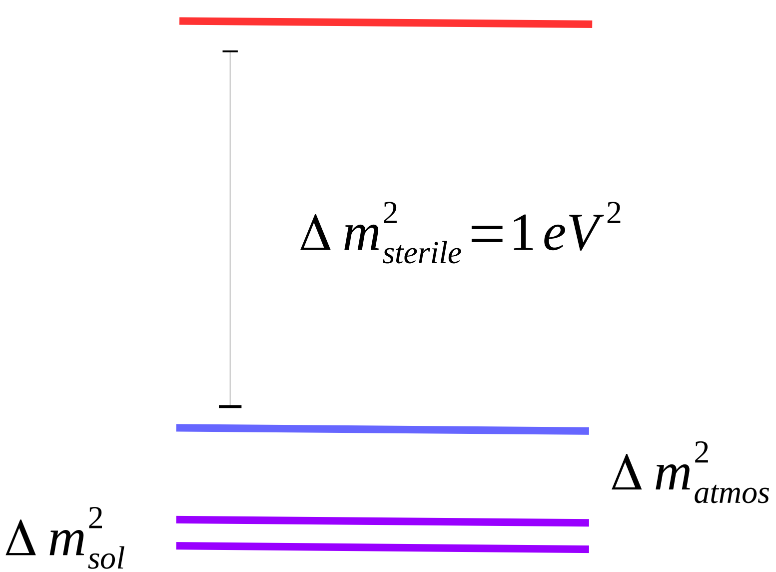
Wait for more data

Summary of sterile hints

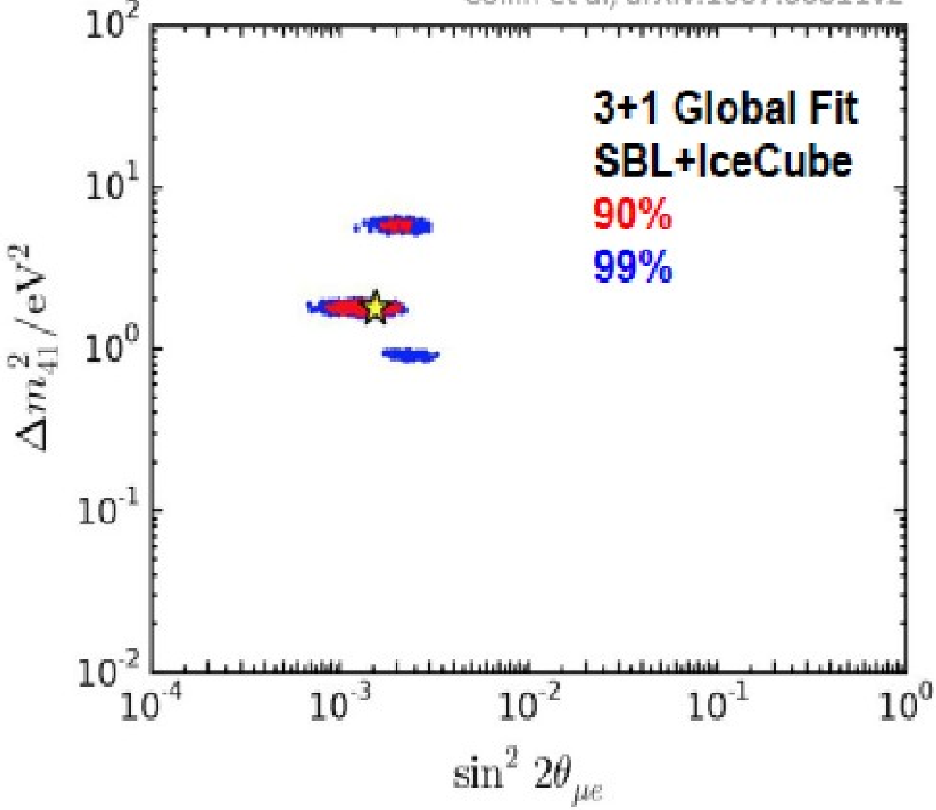
There are odd hints, each at the level of 2-3 σ, that they may be at least one other light sterile state floating around with $\Delta m^2 \sim 1\ eV^2$. This is not very easy to fit into the standard model.

It is very hard to find an oscillation model, including steriles, which is consistent with *all* of the data

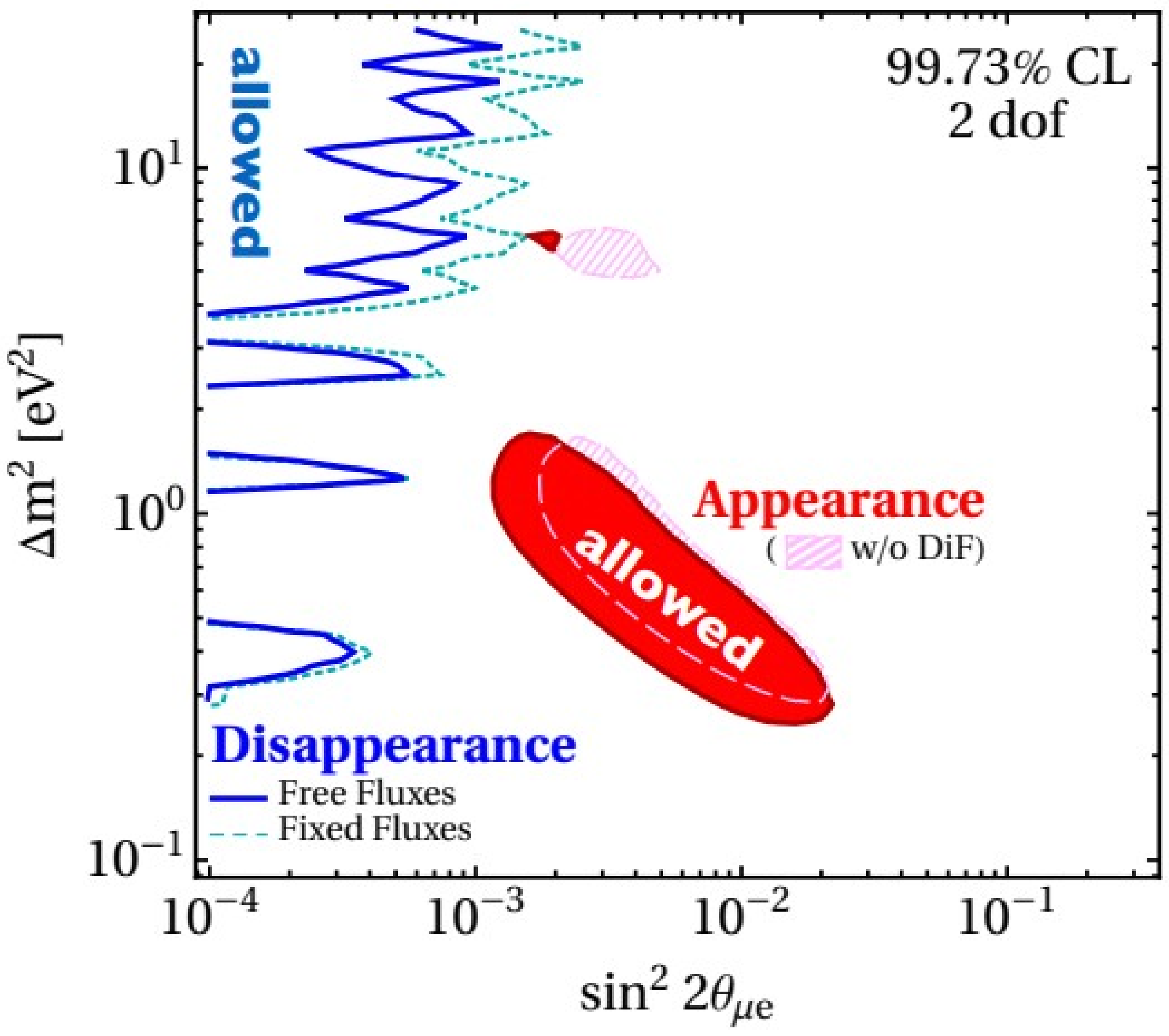
Current "best model" is a 3+1 model but it doesn't fit very well



Collin et al, arXiv:1607.00011v2



Sterile Global Fit



4σ discrepancy between appearance and disappearance experimental results

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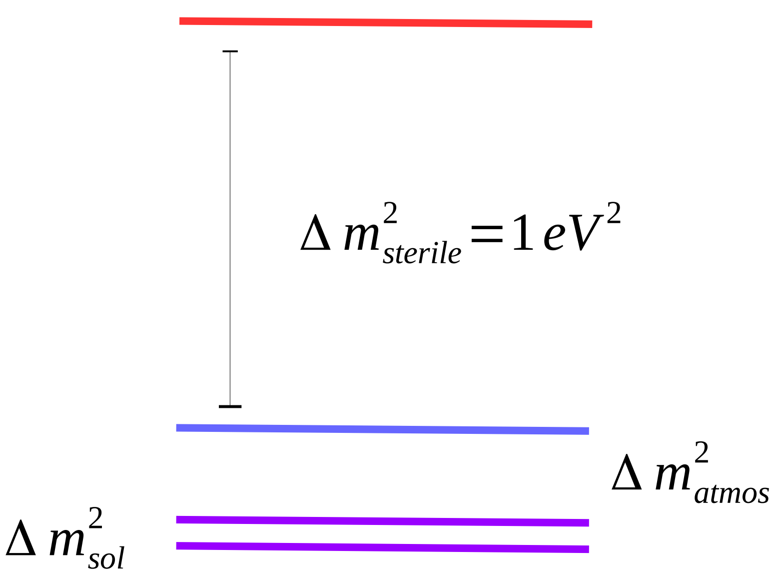


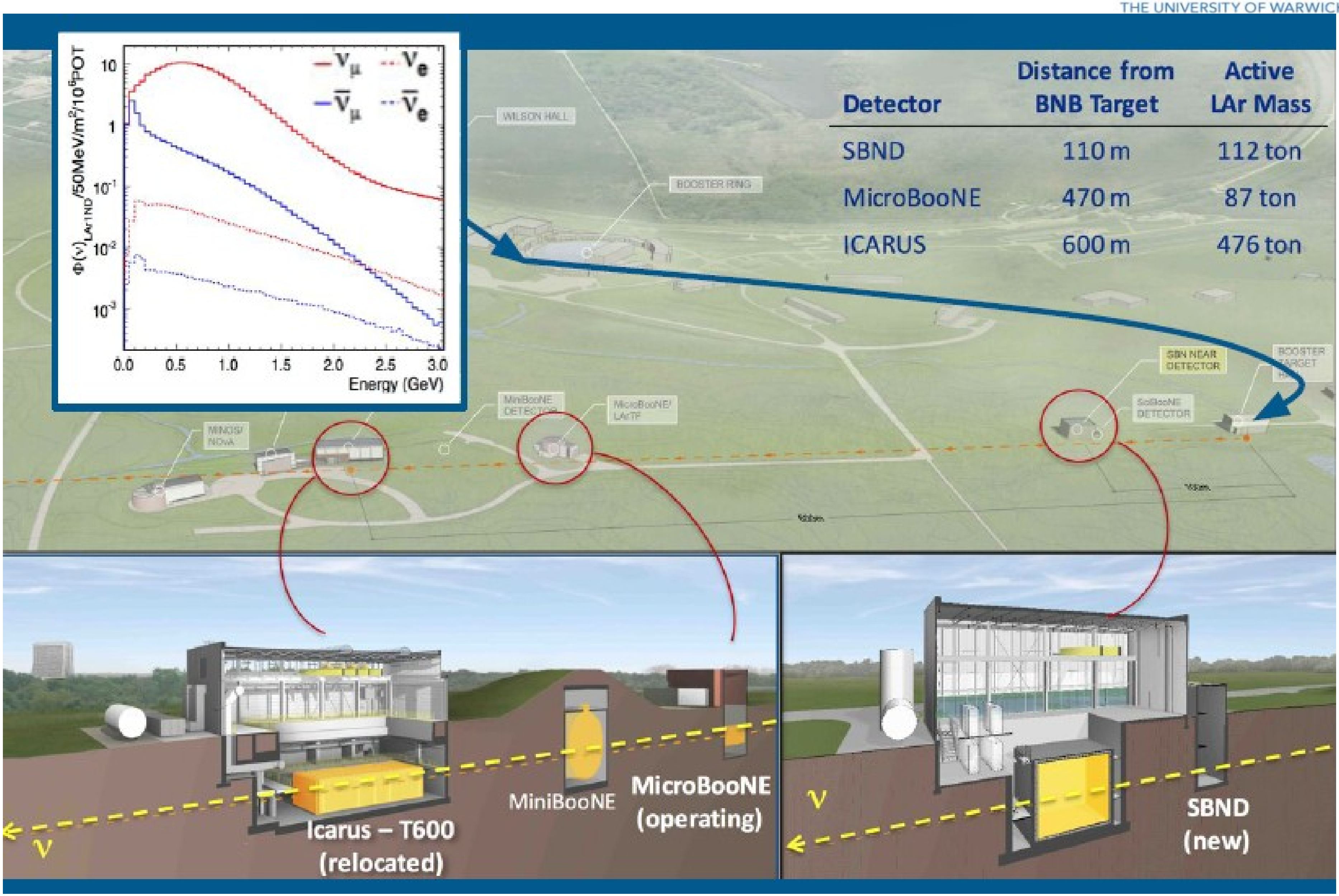
It could all be a conspiracy of systematics

New experiments are being built now to search for signs of steriles in neutrino oscillations at high Δm^2

Experimental Summary

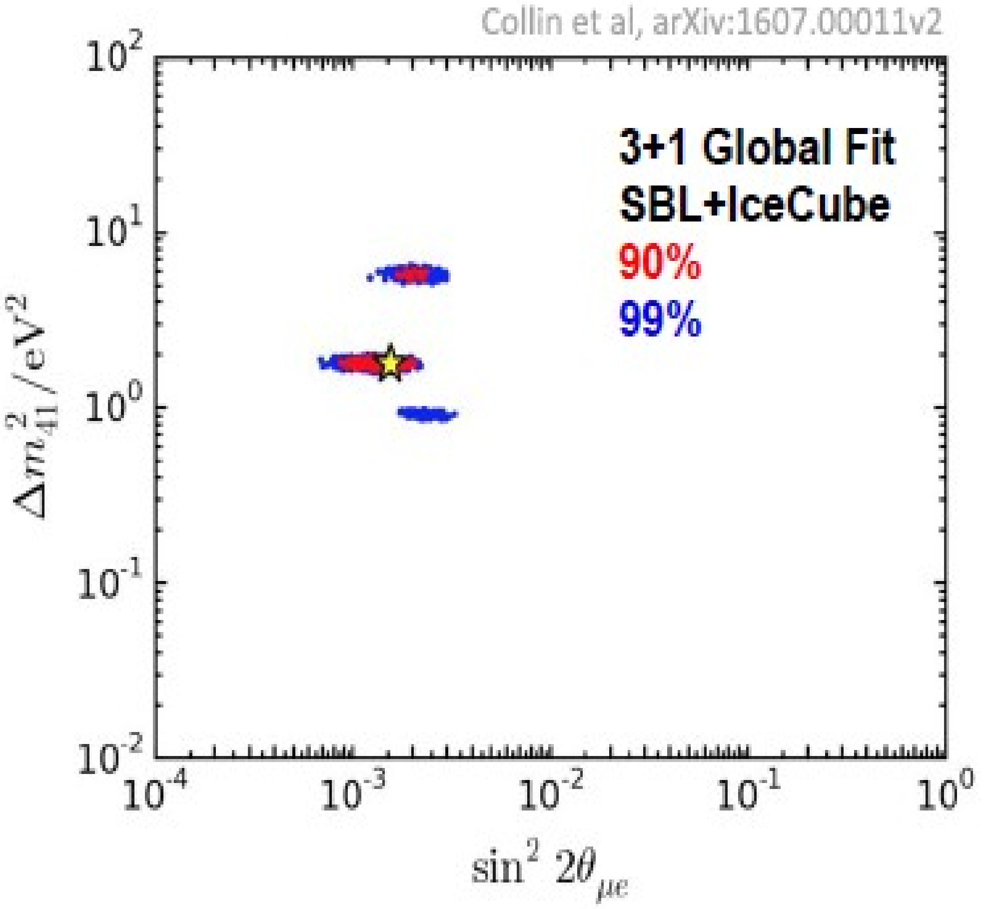
Reactor Experiments					
Name	**Location**	**Power (MW)**	**Distance (m)**	**Target mass (t)**	**Technology**
NEOS	China	2700	25	1	Gd – Liq. Scint.
DANSS	Russia	3000	9-12	0.9	Gd – Plastic. Scint.
Neutrino4	Russia	90	6-12	1.5	Gd – Liq. Scint.
Stereo	France	58	9-11	1.7	Gd – Liq. Scint.
Prospect	USA	85	7-12	3	Li6 – Liq. Scint.
SOLID	Belgium	100	6-11	1.6	Li6F – Plastic Scint.
Accelerator Experiments					
SBND	USA		110-600		LAr TPC
IsoDAR	Japan		16		Li8 Decay at rest to KamLAND
SHIP	CERN		80-90		Multiple

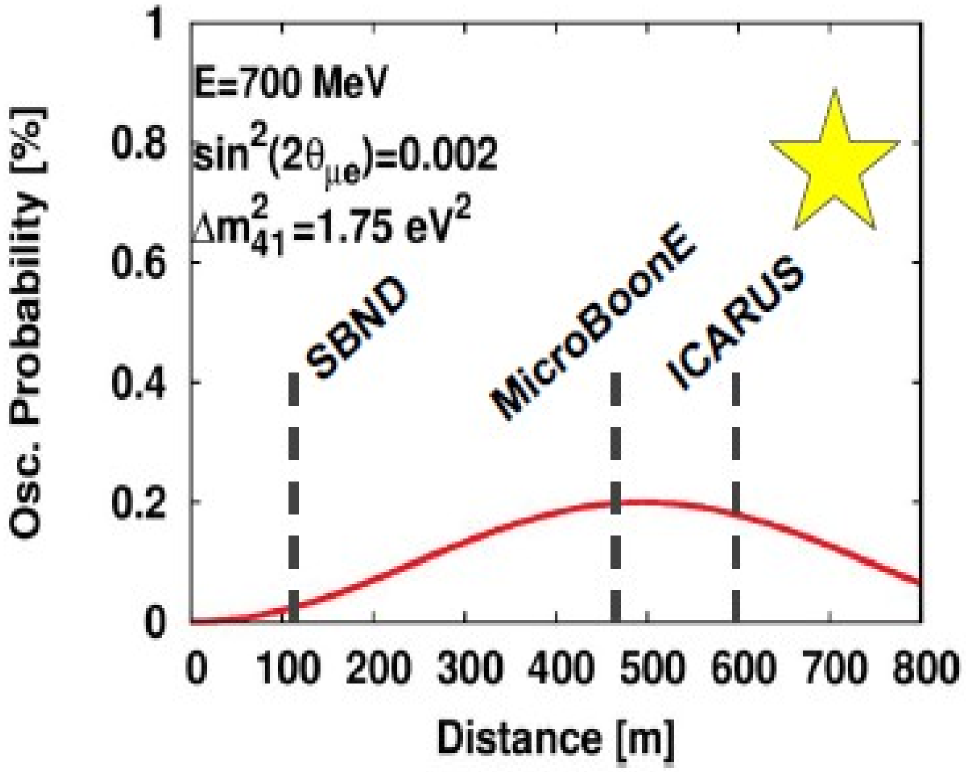
SBND



Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

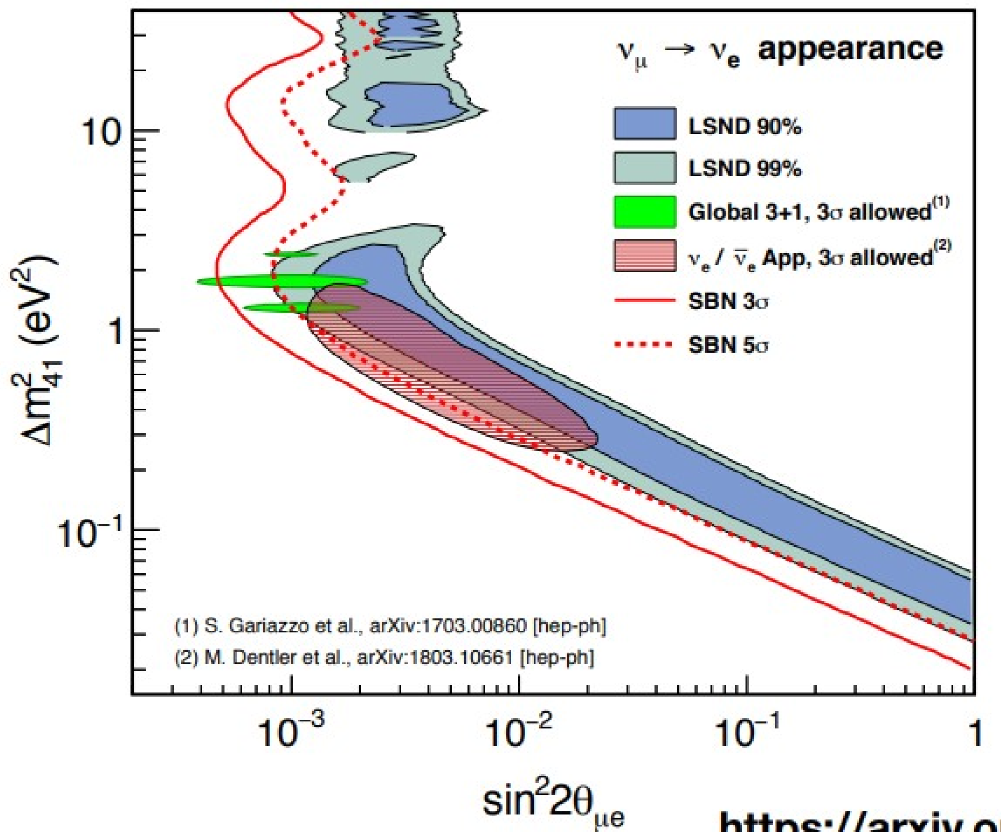
SBND


Collin et al, arXiv:1607.00011v2
3+1 Global Fit
SBL+IceCube
90%
99%
$\Delta m^2_{41}/\mathrm{eV}^2$
$\sin^2 2\theta_{\mu e}$

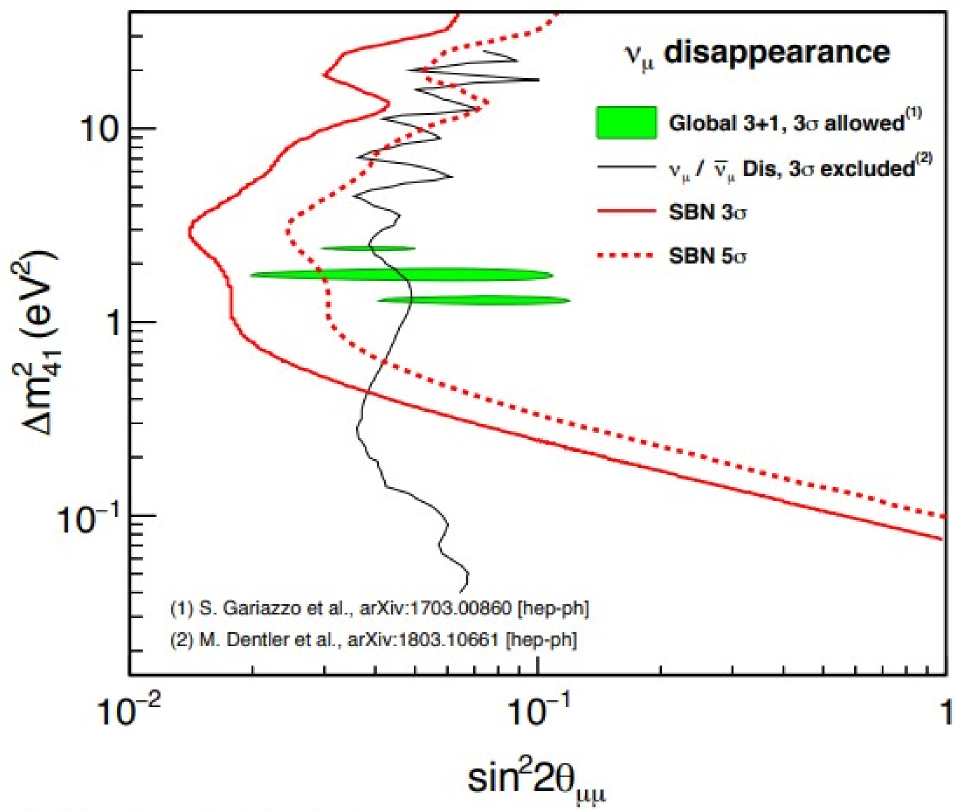

E=700 MeV
$\sin^2(2\theta_{\mu e})$=0.002
Δm^2_{41}=1.75 eV^2
SBND
MicroBooneE
ICARUS
Osc. Probability [%]
Distance [m]

SBND

ν_e appearance



ν_μ disappearance

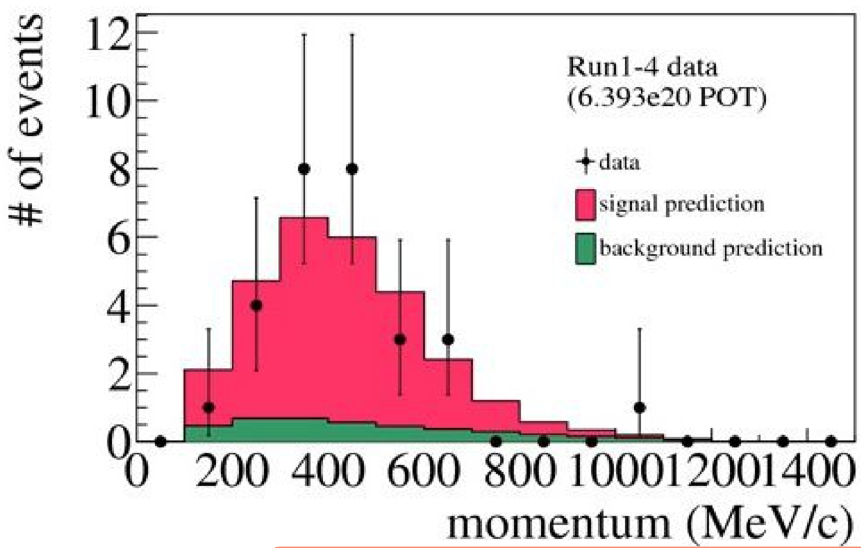


https://arxiv.org/pdf/1903.04608.pdf

- SBN cover much of the parameters allowed by past anomalies at >5σ significance
  - Starts taking data in 2022 (currently)

Neutrino Cross-sections

Systematic Uncertainties



To do these sort of measurements

Measure number of events at Far Detector

Compare with expected number of events

$$Expected\ Number\ of\ events = \sigma \Phi T \epsilon$$

Cross Section

10-100%

Neutrino Flux

5-10%

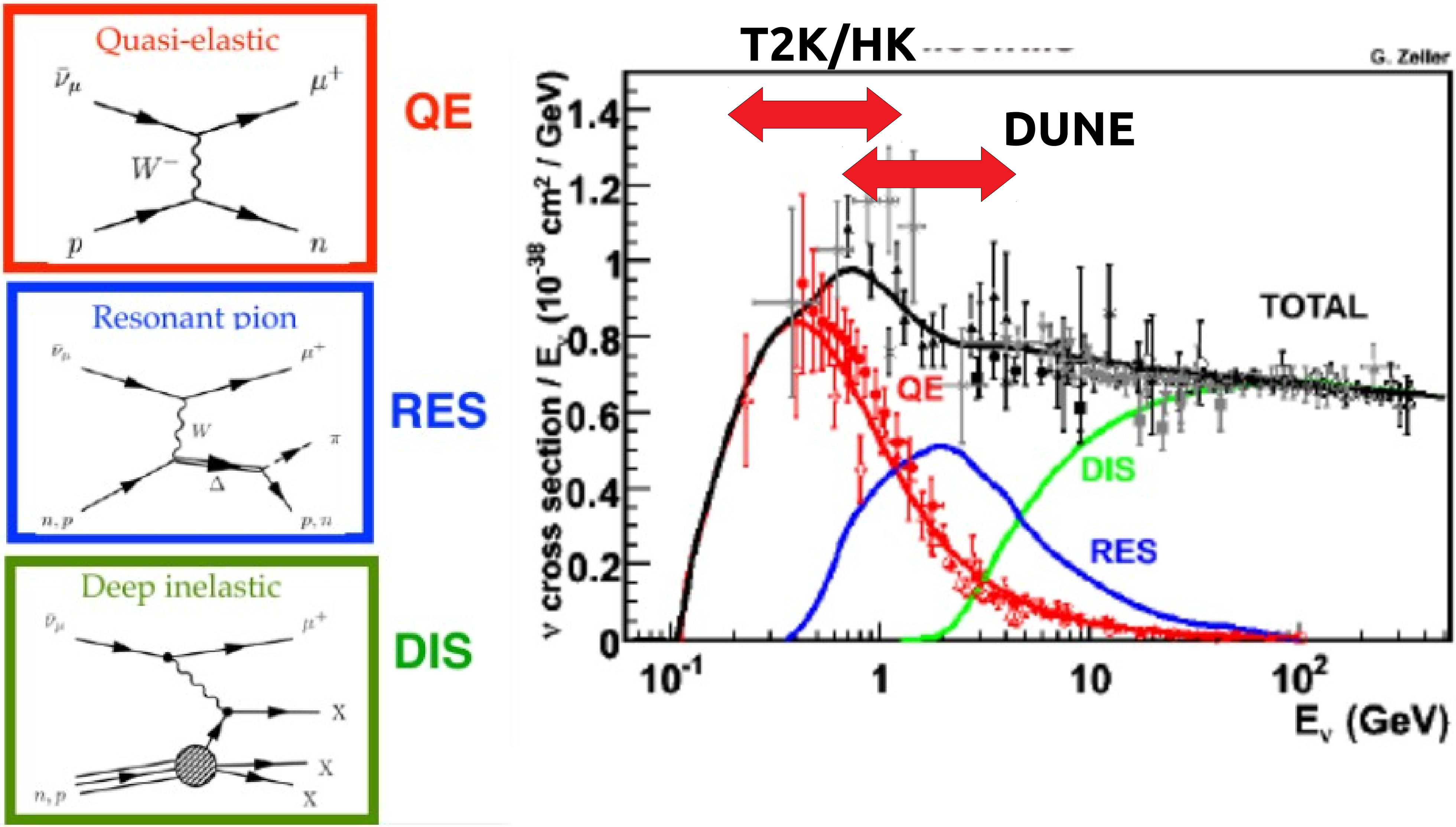
Number of Targets

1-2%

Selection Efficiency

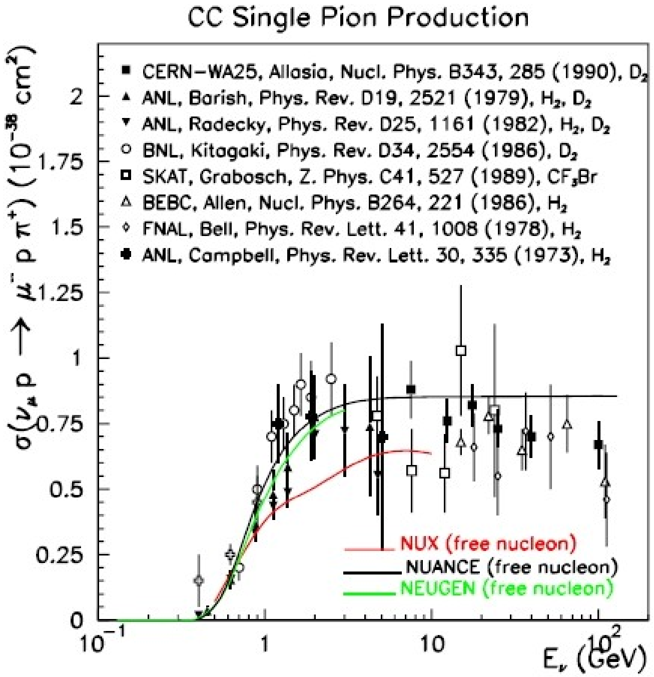
10%

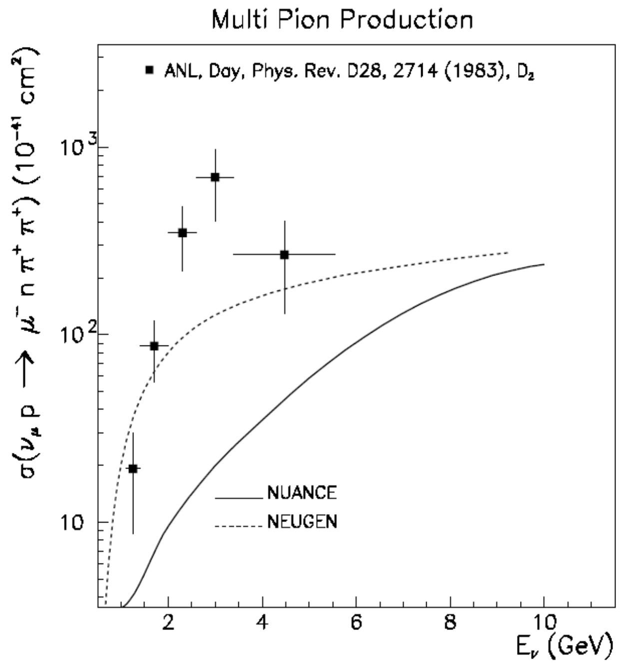
Neutrino Interactions

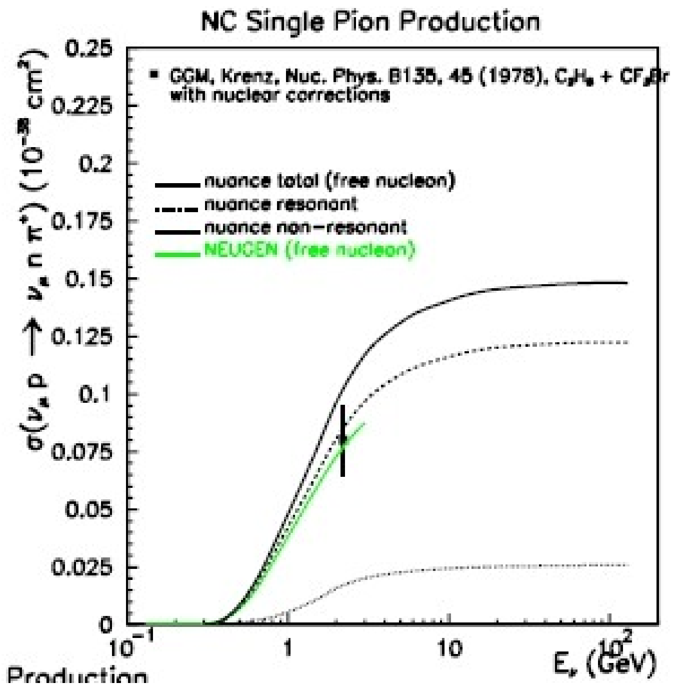


Xsec data pre 2007

The data was impressively imprecise





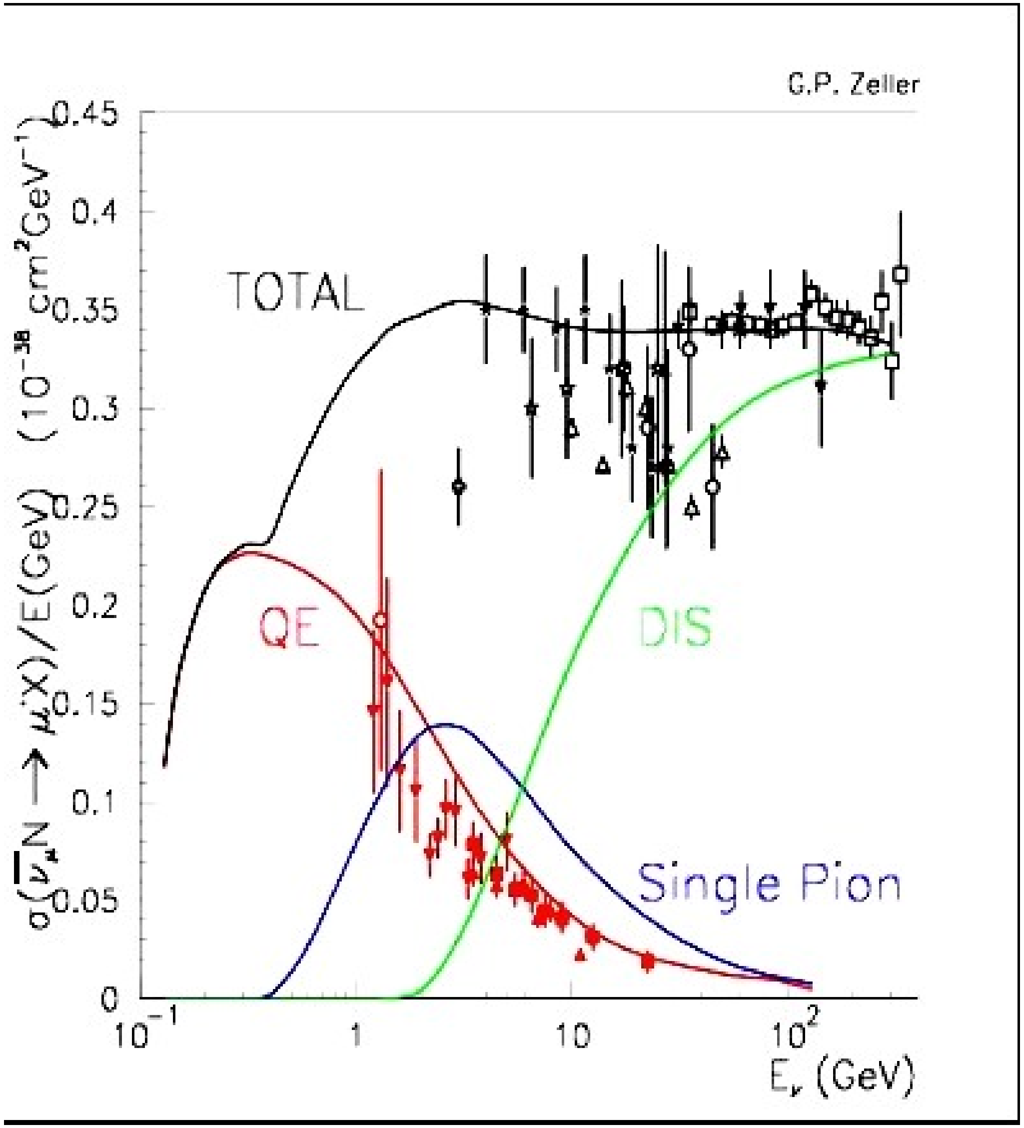


$\nu_\mu p \rightarrow \mu^- p \pi^+$

$\nu_\mu p \rightarrow \mu^- n \pi^+ \pi^+$

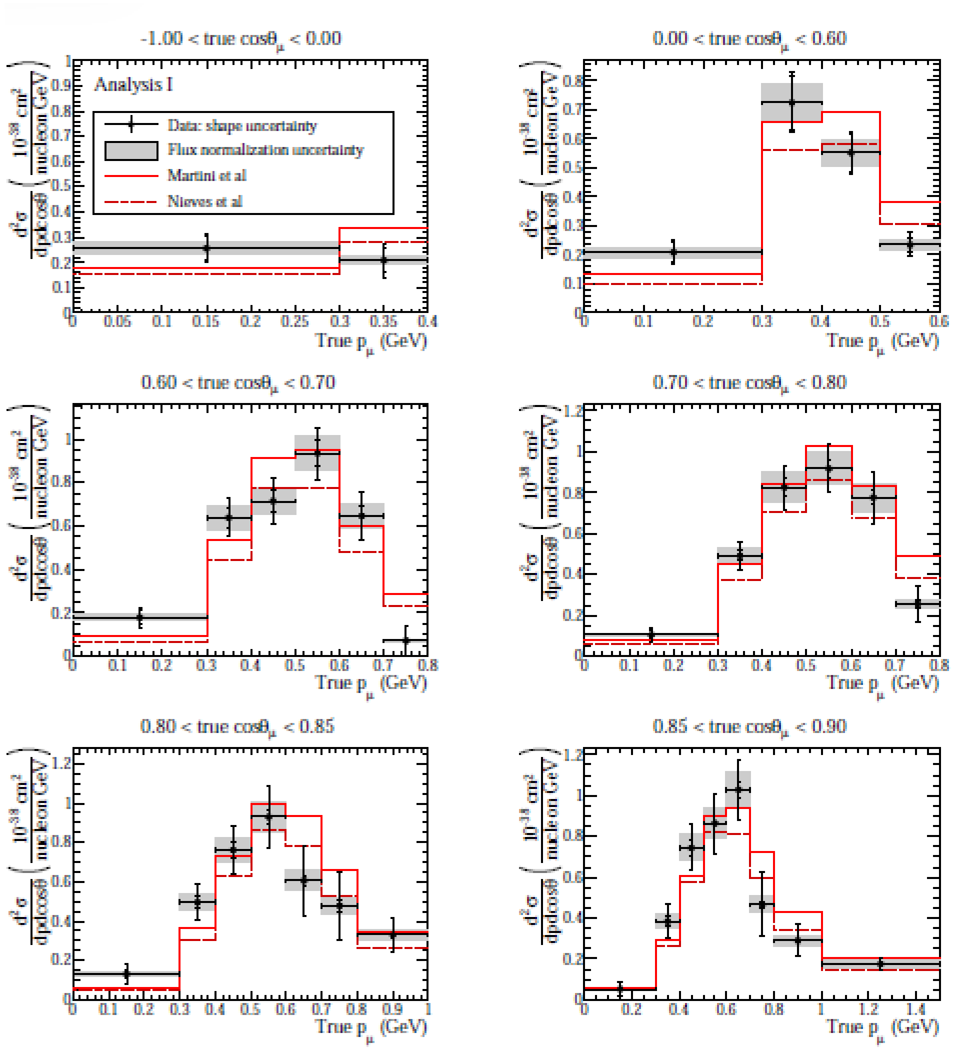
$\nu_\mu p \rightarrow \nu_\mu n \pi^+$

World Data for Antineutrinos

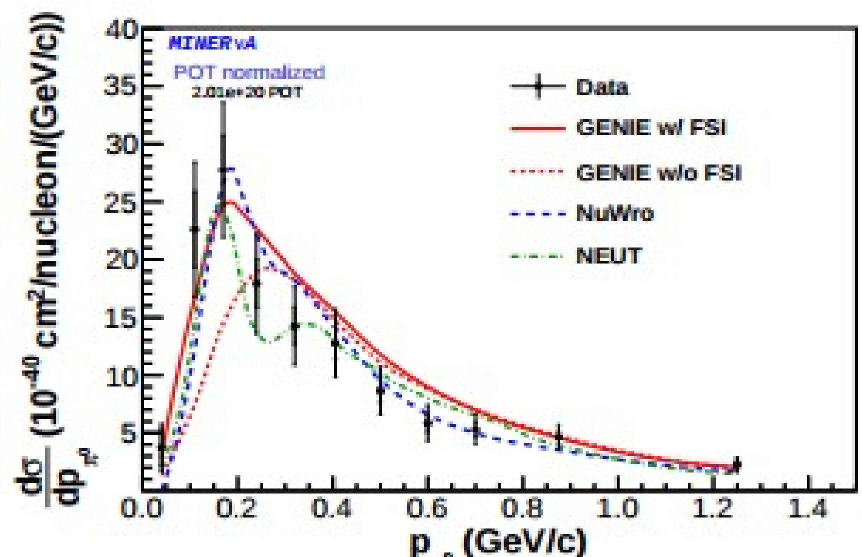


It’s slowly getting better

WARWICK
THE UNIVERSITY OF WARWICK



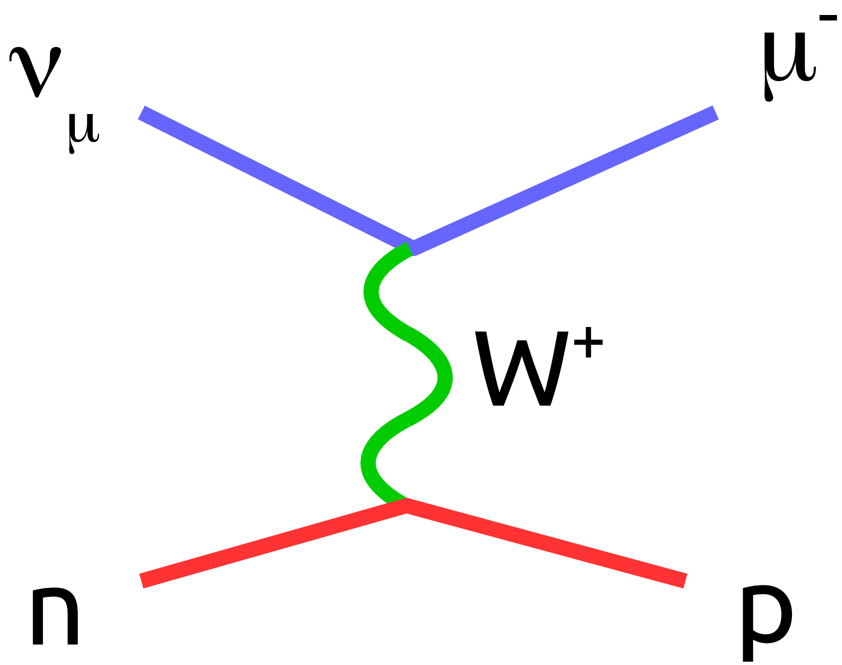
CC 0π differential Xsec from T2K
arXiv:1602.03652



CC π^0 differential xsec from MINERvA
Phys.Lett. B749 (2015) 130-136

Lot's of effort going into trying to understand neutrino interaction cross sections

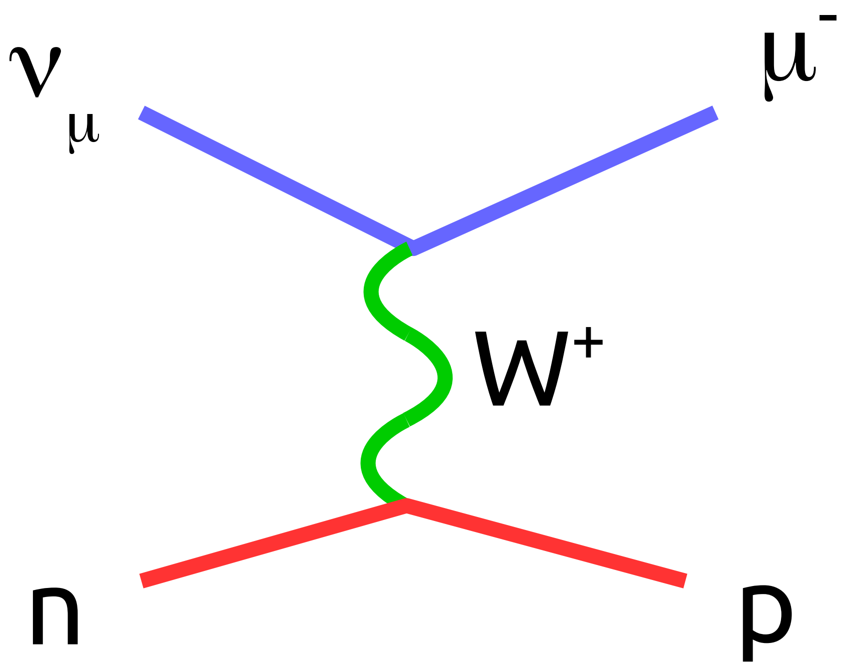
eg : Quasi-Elastic Scattering



- Usually thought of as a single nucleon knock-out process
- In the past has been used as a “standard candle” to normalise other cross sections
- Heavily studied in the 1970's and 1980's and considered to be “understood”

I. Very important for current oscillation experiments as it dominates the total cross section at a few GeV

Quasi-Elastic Scattering



- Usually though of as a single nucleon knock-on process
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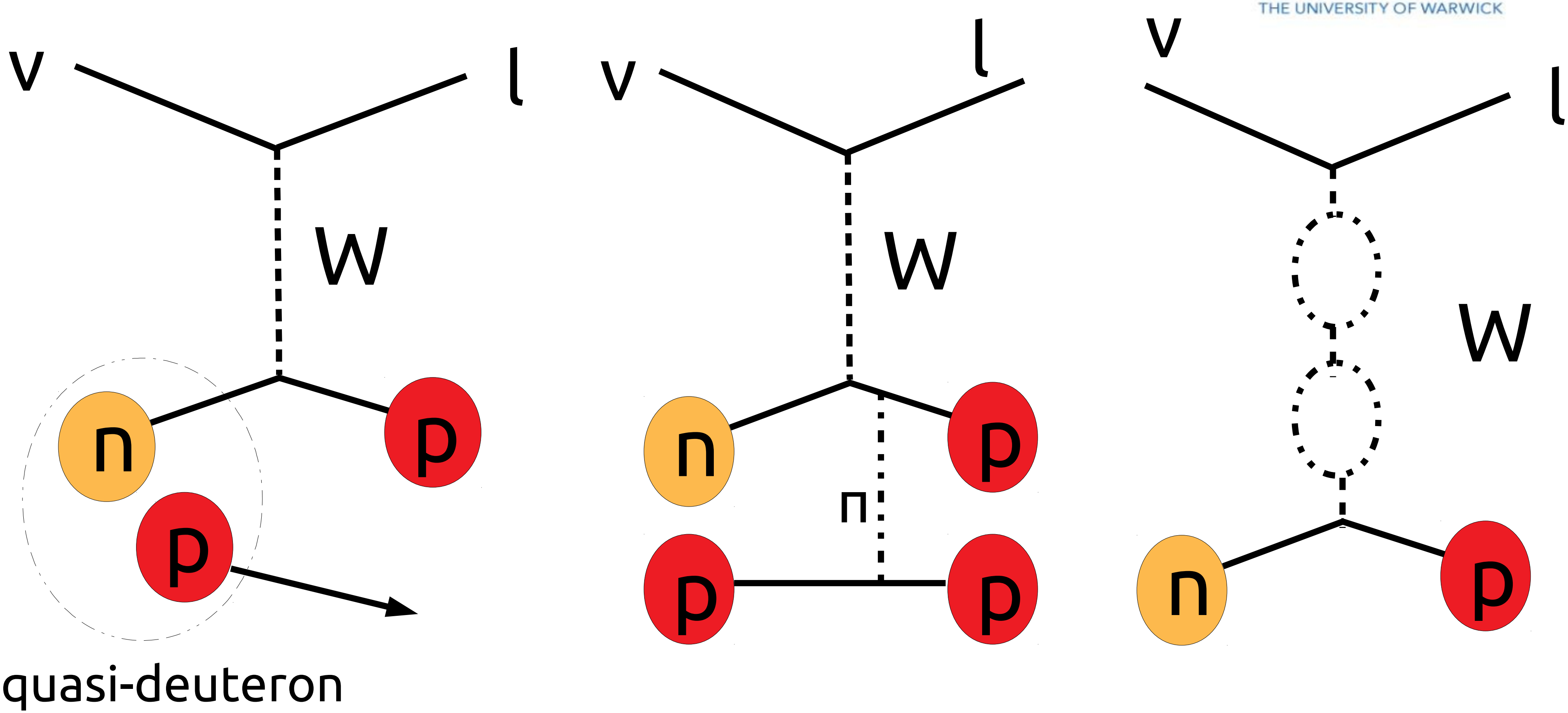
- Heavily studied in the 1970's and 1980's and considered to be "understood"

II. Energy reconstruction is unbiased assuming 2 body kinematics

$$E_{\nu;rec} = \frac{2(m_N - E_B)E_\mu - (E_B^2 - 2m_N E_B + m_\mu^2)}{2(m_N - E_B - E_\mu + |p_\mu|\cos\theta_\mu)}$$

Nuclear Effects



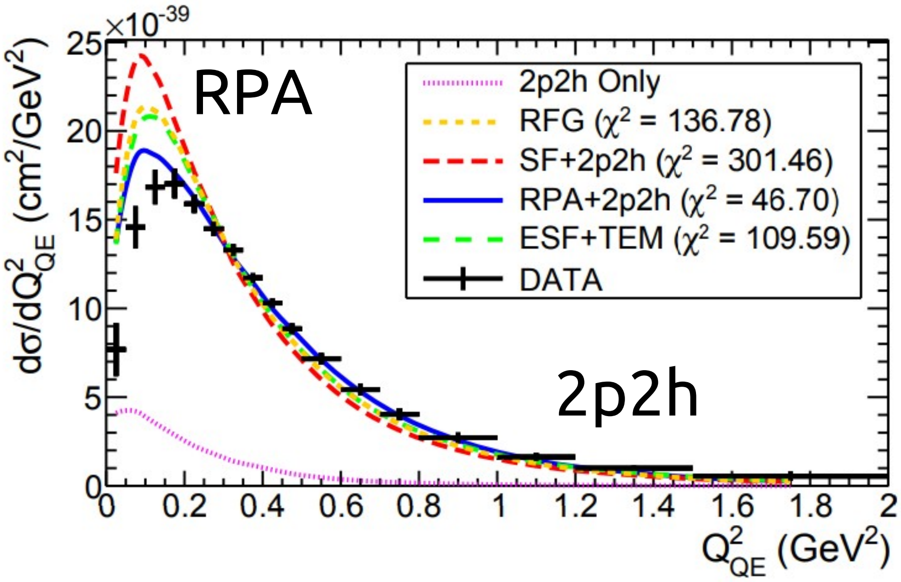
Short-range correlations (SRC)

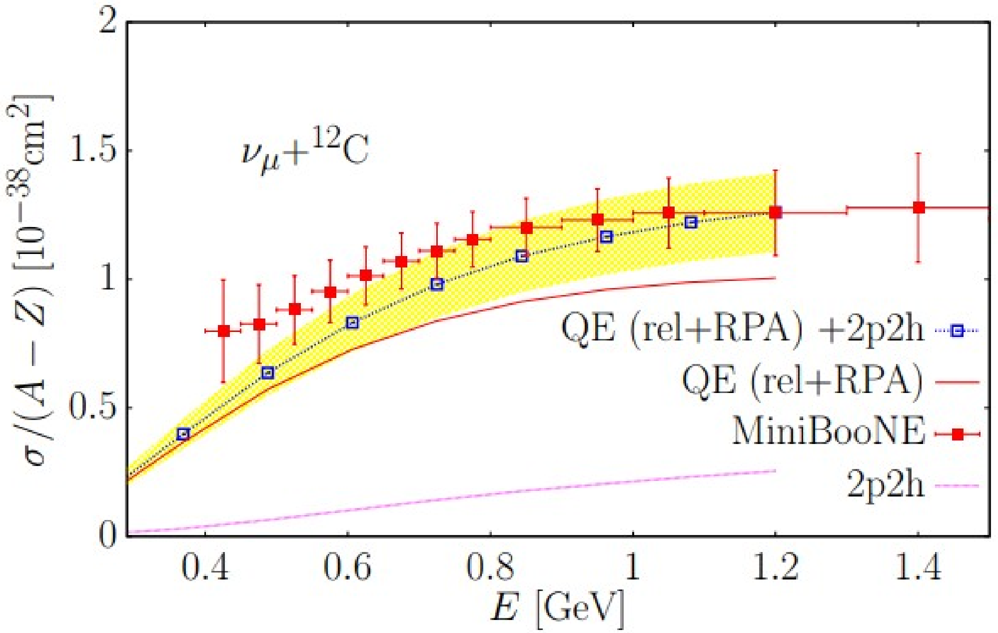
Meson Exchange Currents (MEC)

RPA effects
W polarisation changes strength of weak interaction

2p2h processes - medium to high Q^2

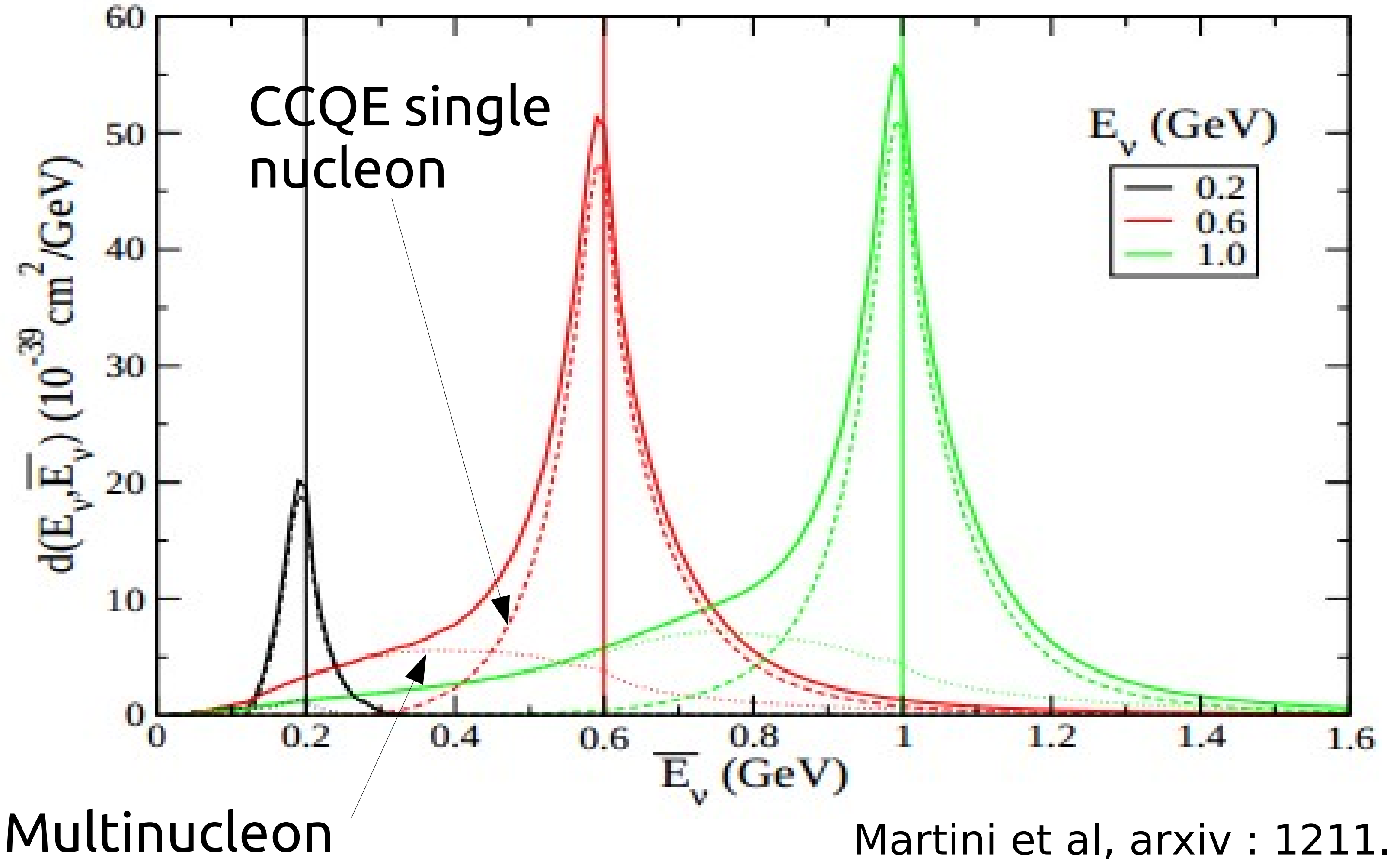
Effect of nuclear corrections





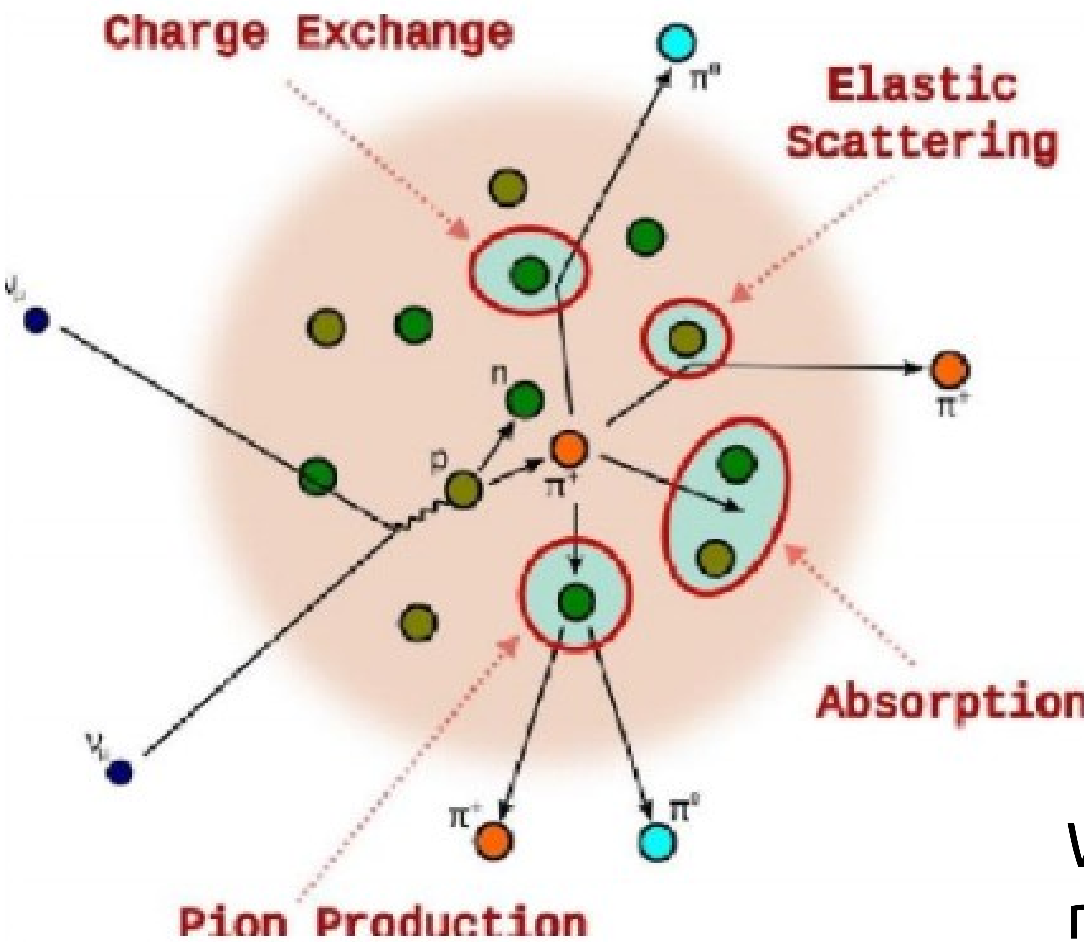
- Models change Q^2 shape in different regions
- Models add a new channel which increases the total cross section

Effect on energy reconstruction



Martini et al, arxiv : 1211.1523

Final State Interactions

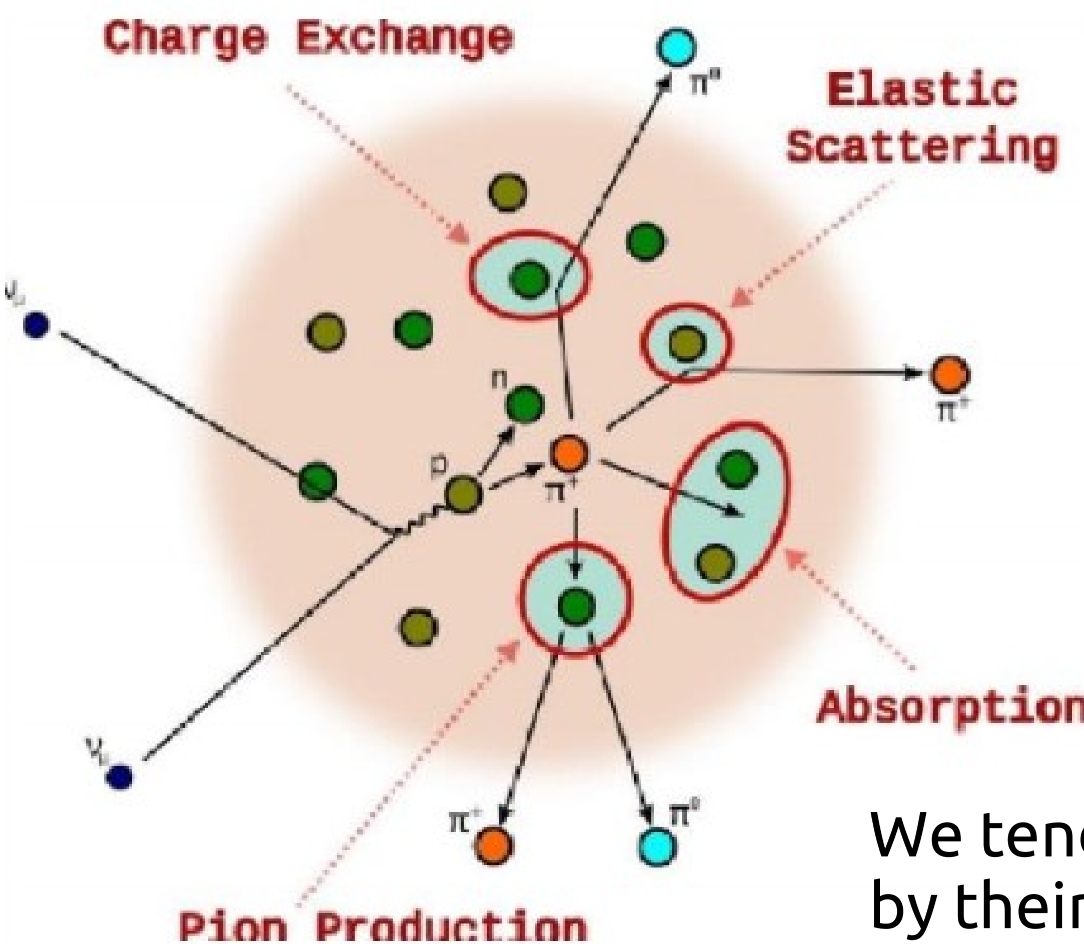


In the nuclear medium

- Outgoing protons can
  - Scatter
  - Lose energy
- Outgoing pions can
  - scatter
  - be absorbed
  - create more pions
  - charge exchange

What you see in the detector may not be what happened at the interaction point

Final State Interactions



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We tend to categorise events by their final state content now rather than their theoretical "label"

Lesson learned….

- It's taken T2K more than 10 years to understand the simplest neutrino interaction – and we still don't really understand the hadronic side of any interaction.
- We have managed to halve the systematic uncertainty from the model.
- Any experiment at different energies or using different types of nuclei as targets will have similar problems.
- I'm looking at you, DUNE
- DUNE operates at 3 GeV – the region of resonance production which hasn't had anywhere near as much theoretical attention as QE at T2K energies has – and uses Argon.
- DUNE does have the advantage that its Far Detector and Near Detector have the same target material (Ar) so the relative effects sort-of cancel.

Summary on xsec

- We measure events = flux*cross section

- We don't generally have a handle on the flux to better than 7% - there is a lot of work trying to deal with this.

- The other side of the coin, cross-sections, are even more poorly known.

- We need new, high-statistics, measurements of these cross sections on multiple target materials and at multiple energies : MINERvA, T2K/HyperK Near detector, DUNE ND, dedicated HP-TPC experiments

Concluding Remarks

The neutrino is : light, neutral, left-handed (chiral) and almost left-handed (helicity). It is generated purely in weak interactions (which is why it is chiral). Their cross sections are tiny and we need big detectors to look at them. They mix and can undergo flavour oscillations.

They may be the reason that we are here at all.

But...what is their mass? Why is it so small? Why are the mixing parameters so odd? What about these hints of a 1 eV sterile state? Is it Majorana? If not – then how do you explain mass without the Higgs? What is the CP violating phase?

Still lots of questions remain – watch this space.....

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