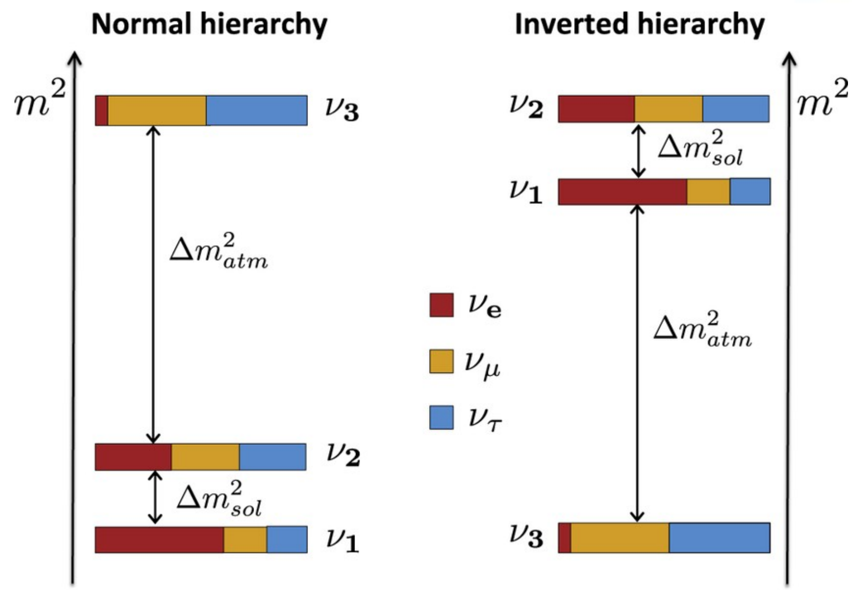
The Future of Neutrino Oscillation Measurements

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?



Mass Ordering?

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

$$U_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & -0.15 \\ -0.4 & 0.7 & 0.6 \\ 0.4 & -0.5 & 0.7 \end{pmatrix} \quad U_{CKM} = \begin{pmatrix} 0.975 & 0.222 & 0.004 \\ 0.221 & 0.97 & 0.04 \\ 0.01 & 0.04 & 0.999 \end{pmatrix}$$

?

Mass Ordering and CP violation

CP violation and Mass Hierarchy

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

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

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

= 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

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

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

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

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

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

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

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

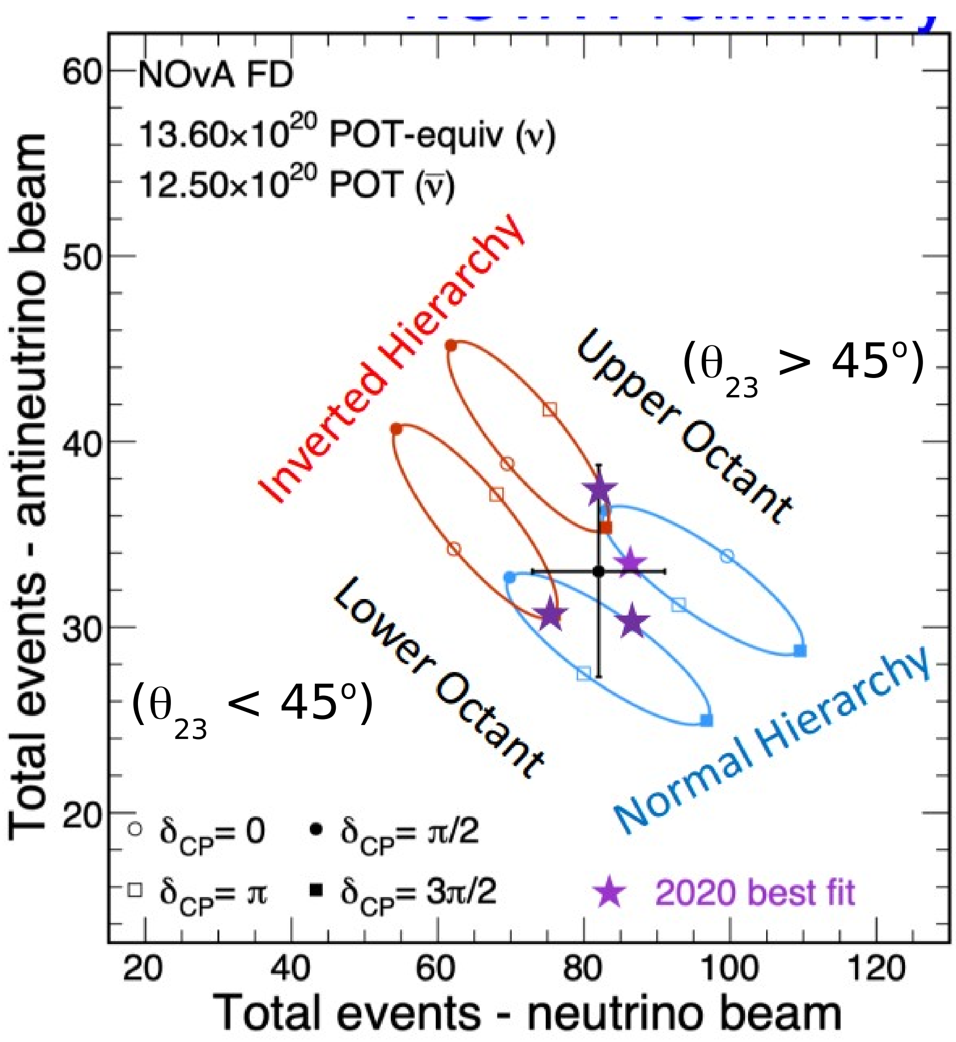
$$B_{-+}=|\Delta_{13}\mp A|$$

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

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

Degeneracies

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



As baseline increases ellipses move further apart – need lots of distance to unravel the mass hierarchy

In practice multiple measurements at different L/E are needed

Mass hierarchy in 0νββ decay

m_2

m_1

m_3

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

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

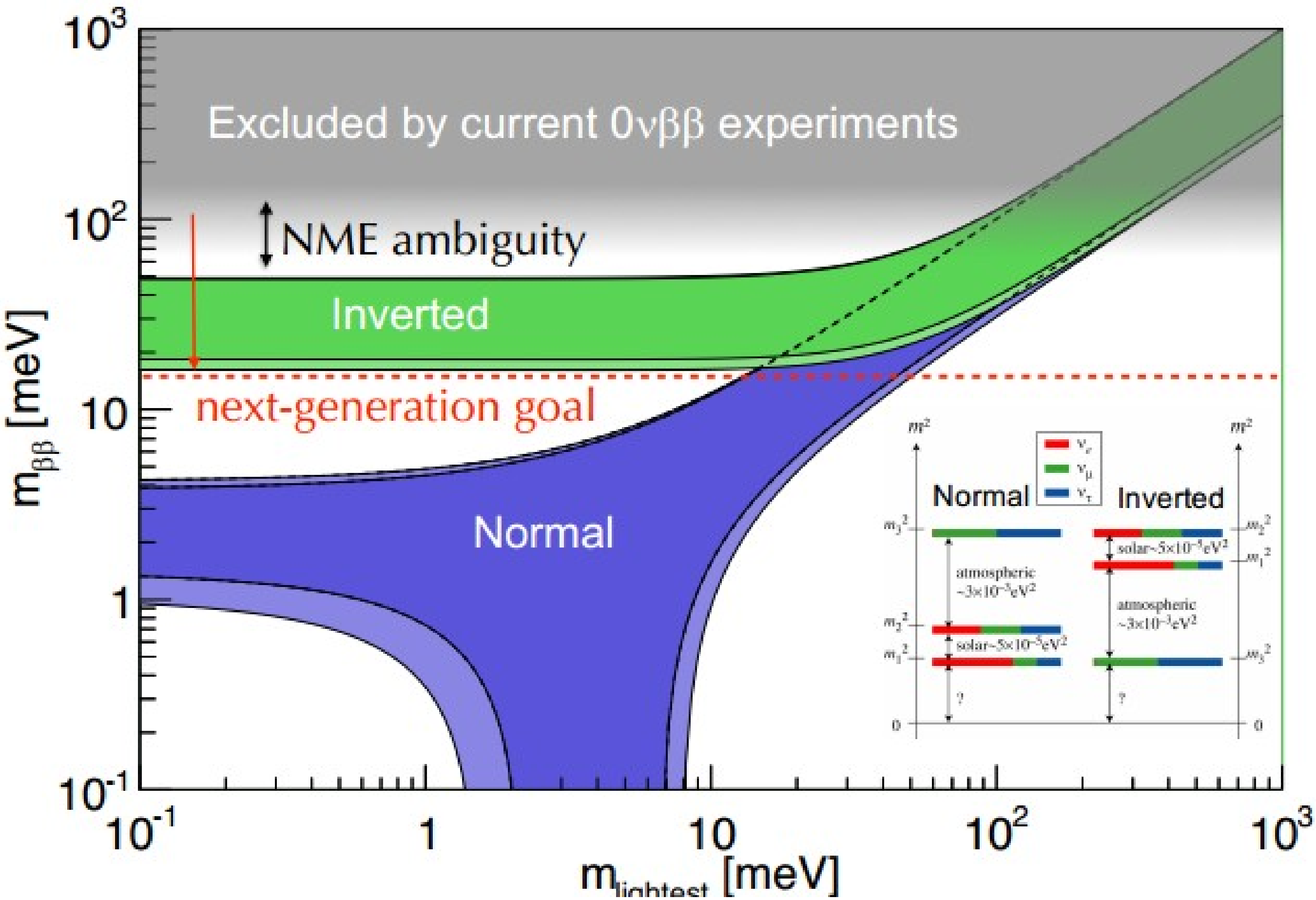
$$m_{\nu_e} = |U_{e1}|^2 \sqrt{m_3^2 + \Delta m_{23}^2} + |U_{e2}|^2 \sqrt{m_3^2 + \Delta m_{23}^2} + |U_{e3}|^2 m_3^2$$

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

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

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

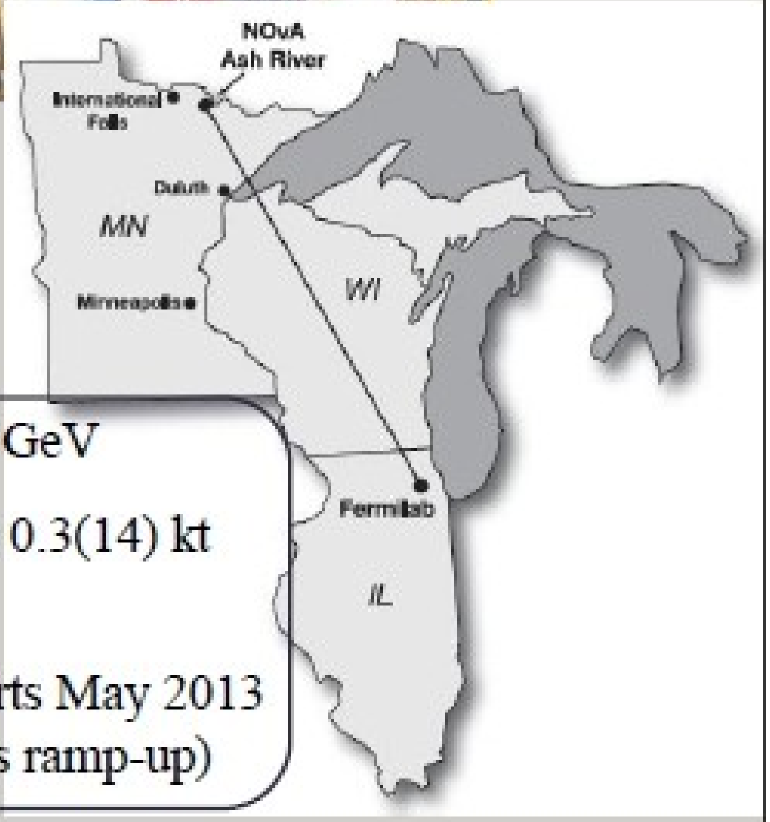
Mass hierarchy & 0νββ decay



- 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.

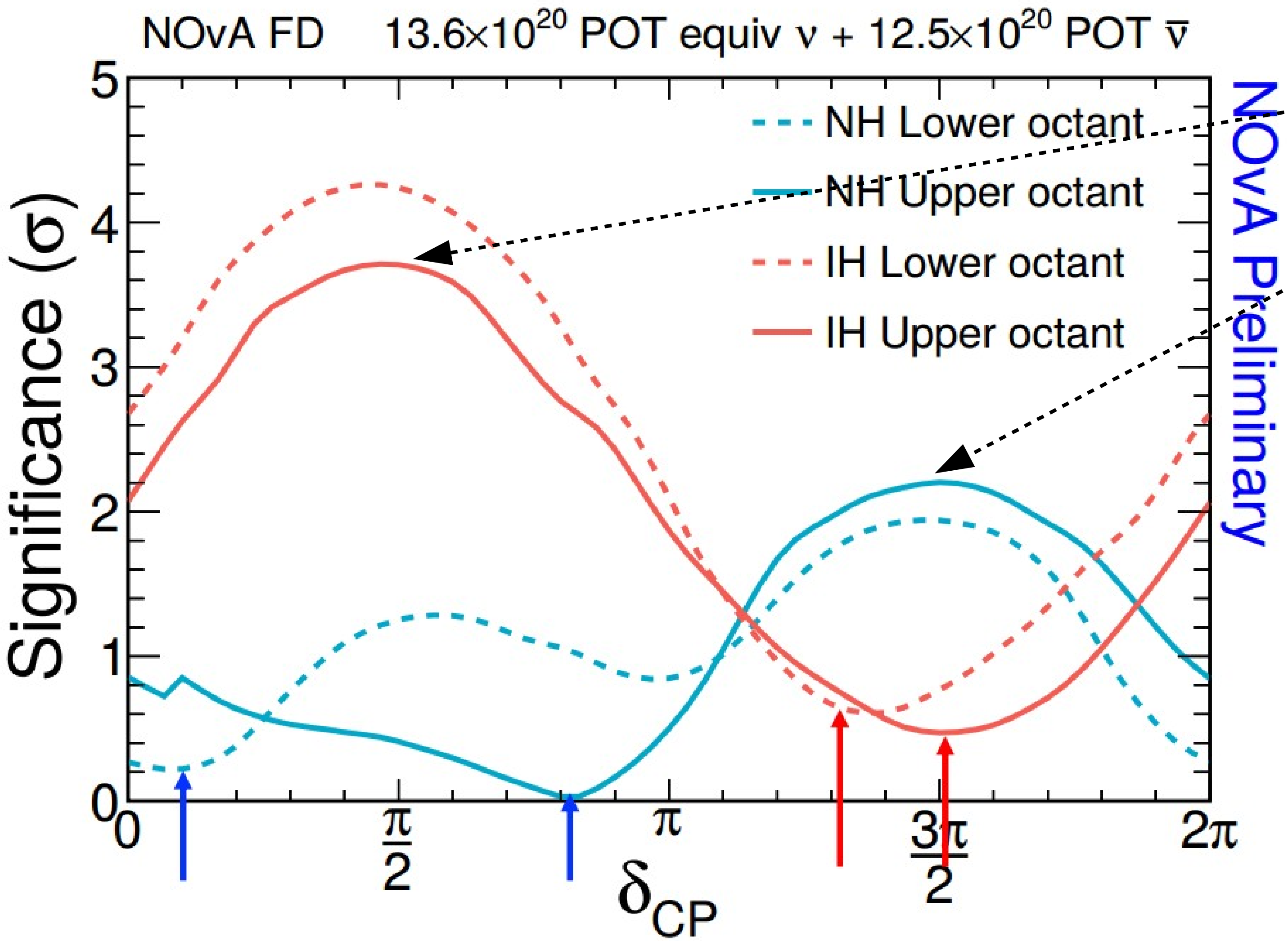
Current Experiments

- 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)

NOvA and T2K

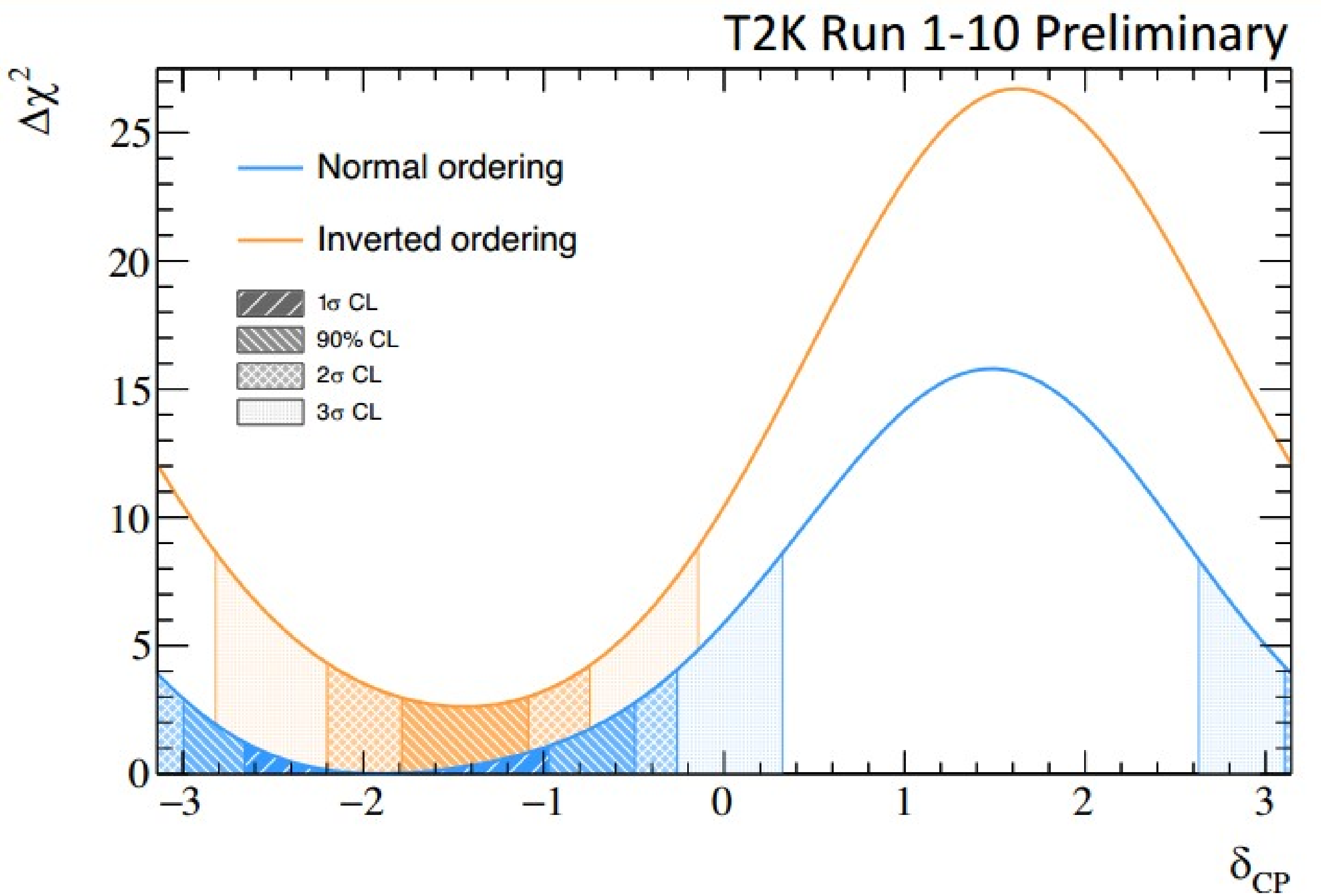


Exclude IH and $\delta_{CP} = \pi/2$ @ > 3 σ

Exclude NH and $\delta_{CP} = 3\pi/2$ @ > 2 σ

A. Himmel, NOvA Oscillation Results, Neutrino 2020

NOvA and T2K

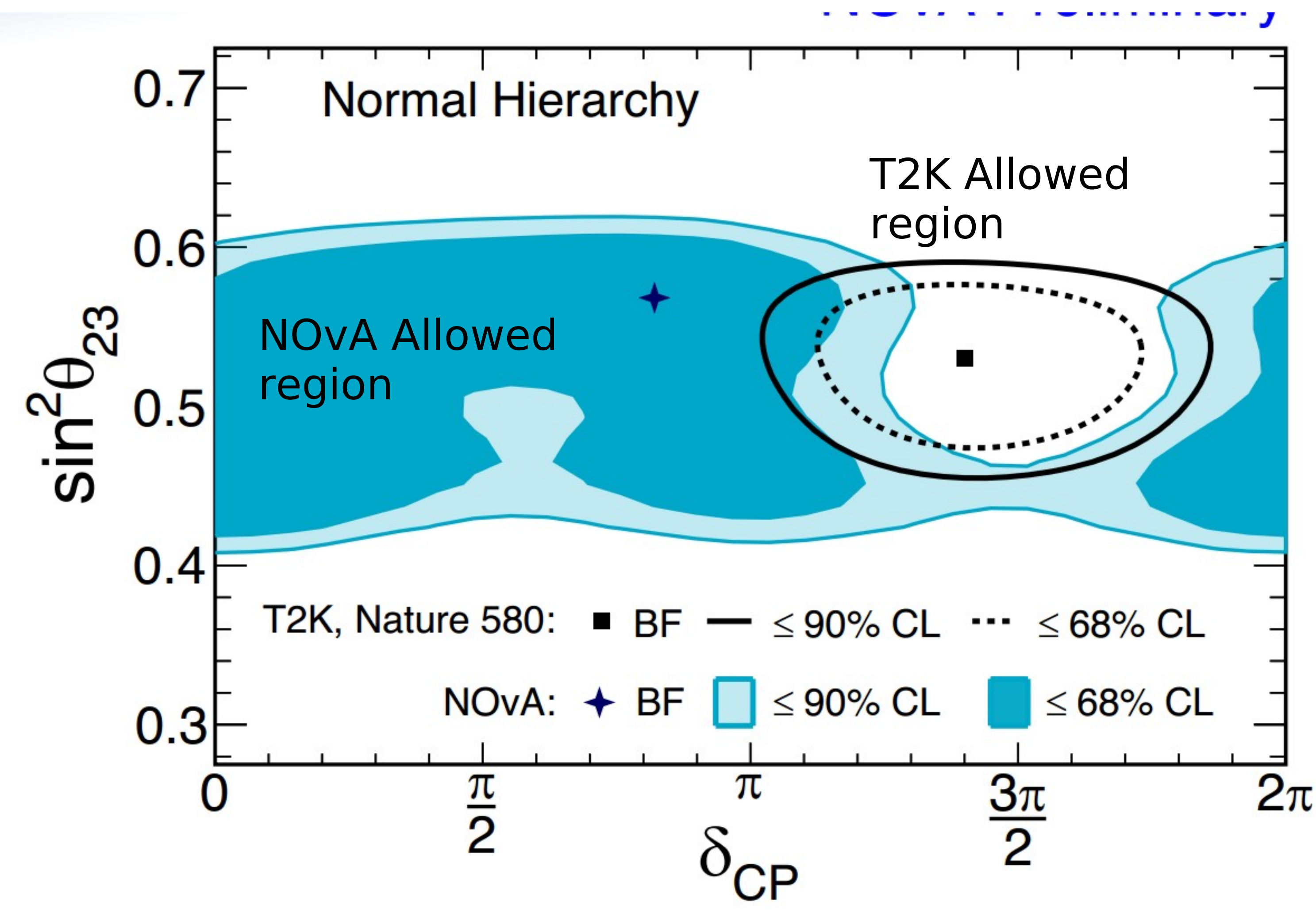


- T2K is not really sensitive to heirarchy as it is too short a baseline, but favours NH
- Disfavours $\delta_{CP}>0$ at 2-3σ

For NovA comparison : shift plot (and scale) leftwards by π and wrap-around

P. Dunne, T2K Oscillation Results, Neutrino 2020

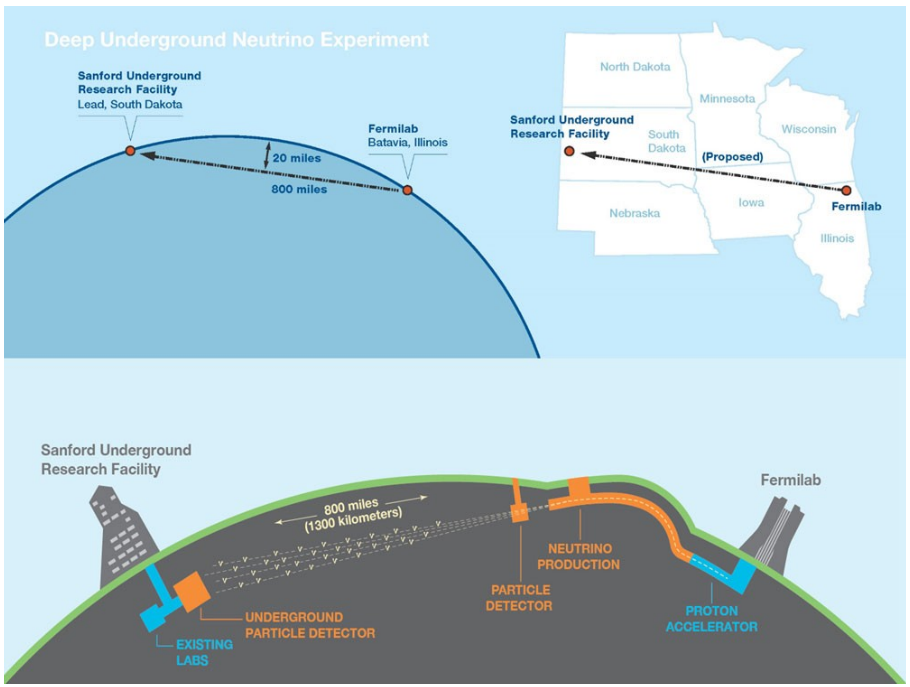
NOvA and T2K



- Tension between NovA and T2K results
- Efforts underway to do a joint T2K/NOVA analysis

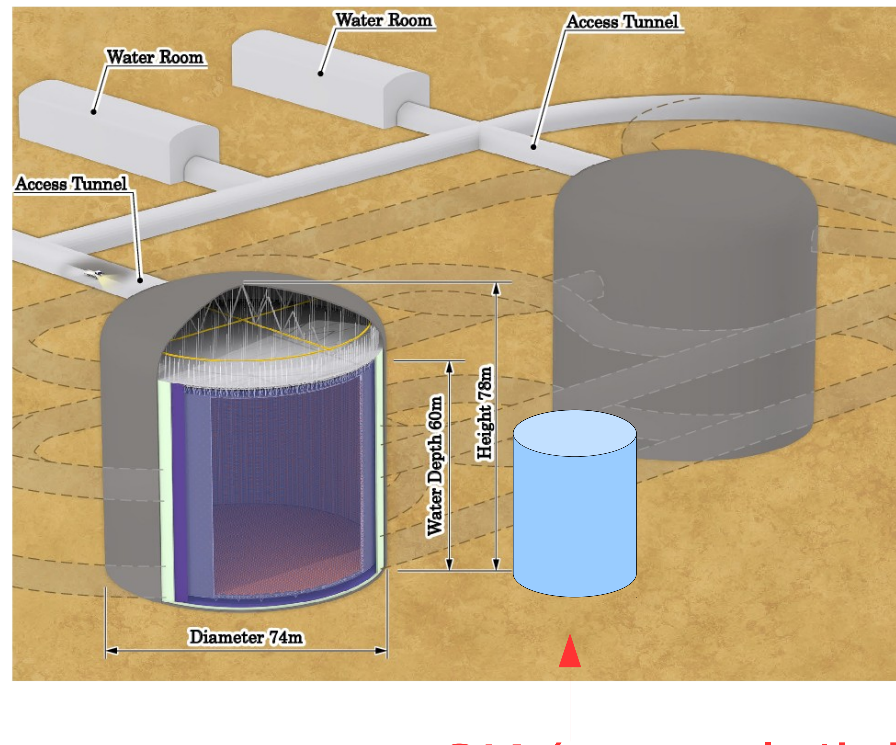
Next generation of experiments

DUSEL Underground Neutrino Experiment (DUNE)



- MW beams
- multi-kton far detectors

Hyper-Kamiokande

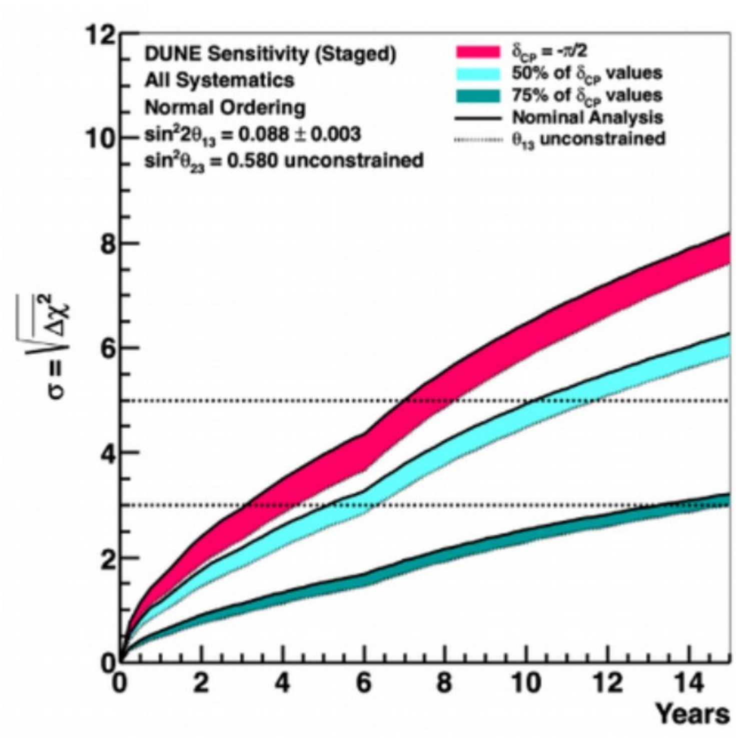


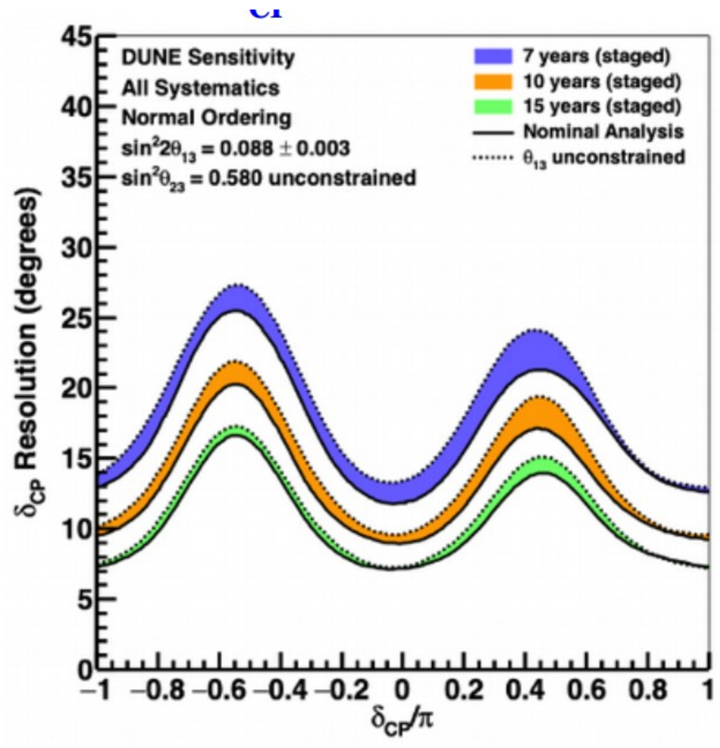
SK (to scale'ish)

Dune / HK Comparison

	DUNE	Hyper-K
Beam Energy	3 GeV	0.7 GeV
Baseline (L)	1300 km	295 km
Beam Power	1.2 MW	0.75 MW
Type of Beam	Wideband	Off-axis
Mass of far detector	70 kton	560 kton
Technology	Liquid Ar TPC	Water Cerenkov
Running from	2027	2027

DUNE Sensitivity

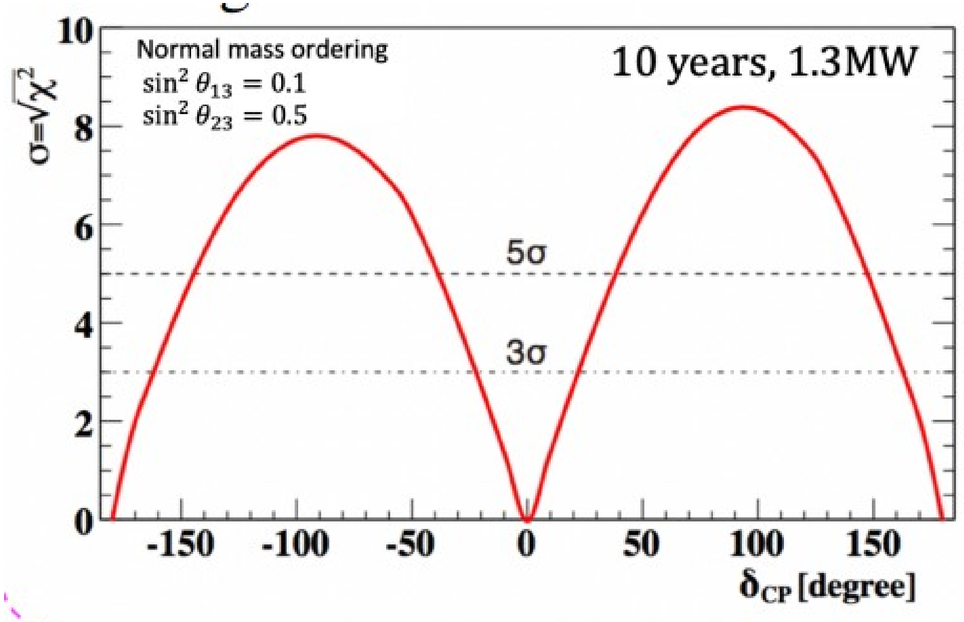


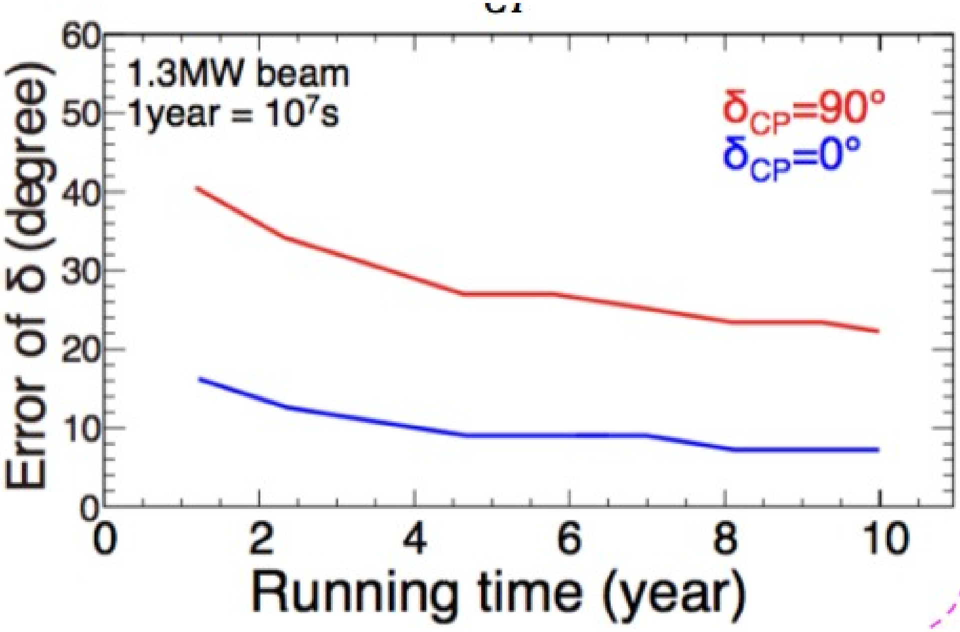


- $6\ \sigma$ discovery if $\delta_{CP} = -\pi/2$ in 10 years
- 5σ CP discovery over 50% of δ_{CP} in 10 years
- Determination of mass order in 3 years

- δ_{CP} precision 10-20% in 10 years

Hyper-K Sensitivity

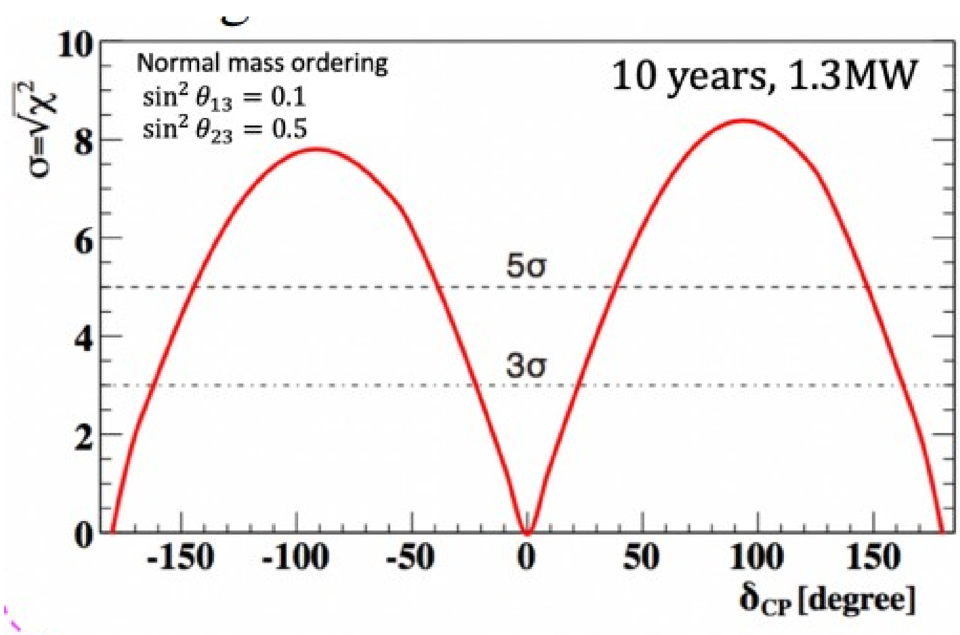


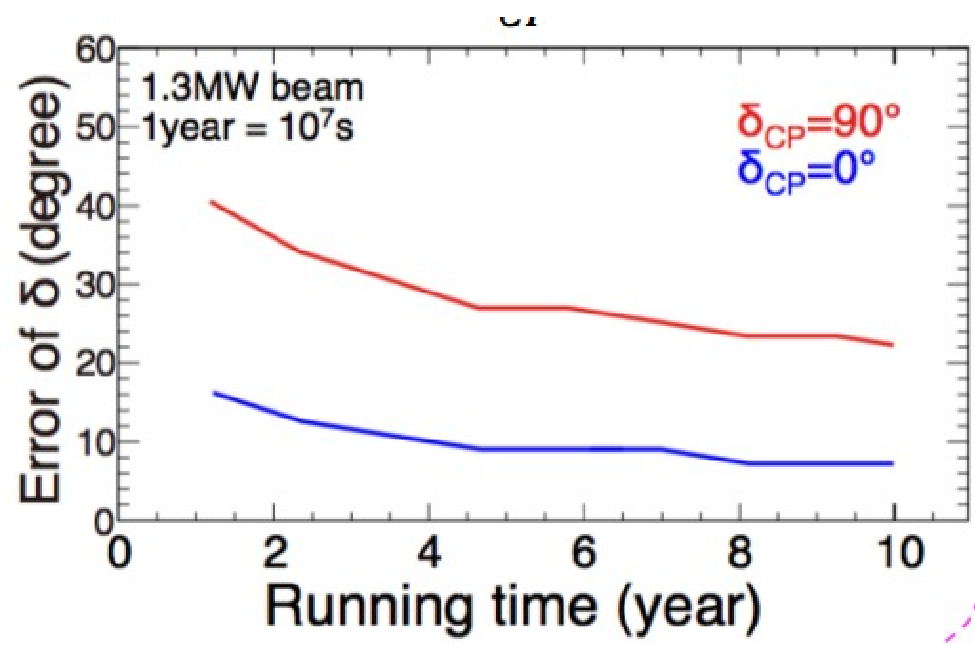


- 8 σ discovery if $\delta_{CP} = -\pi/2$ in 10 years
- 5 σ discovery over 50% of δ_{CP} range
- 10-20% δ_{CP} precision in 10 years

Both experiments also have substantial other-physics programs : solar neutrinos, proton decay searches, supernova searches, BSM searches.

Hyper-K Sensitivity

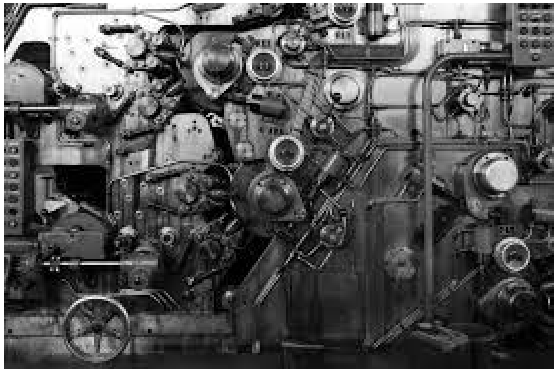




- 8 σ discovery if $\delta_{CP} = -\pi/2$ in 10 years
- 5 σ discovery over 50% of δ_{CP} range
- 10-20% δ_{CP} precision in 10 years

- Good indications of mass heirarchy in next few years; precision determination in 10 years
- T2K/NOVA can't get much further : δ_{CP} measurement in 10 years

+



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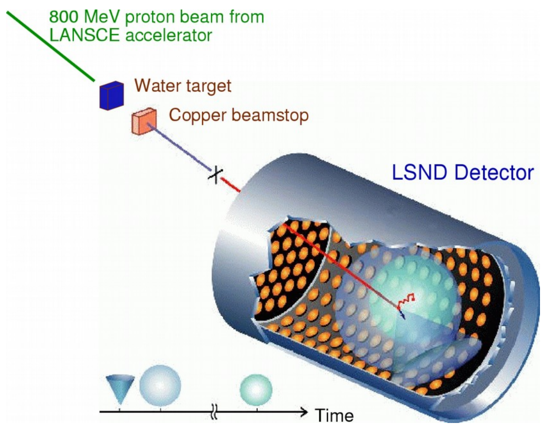
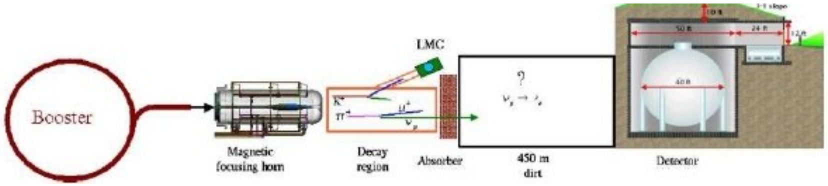
Anomalies

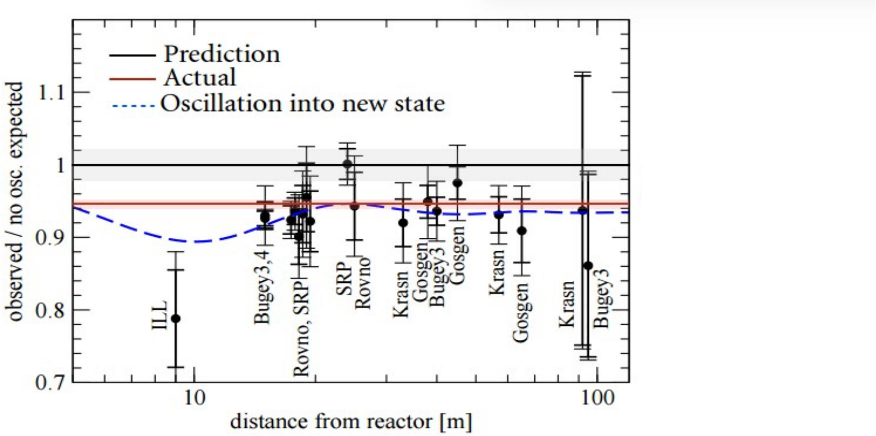
LSND



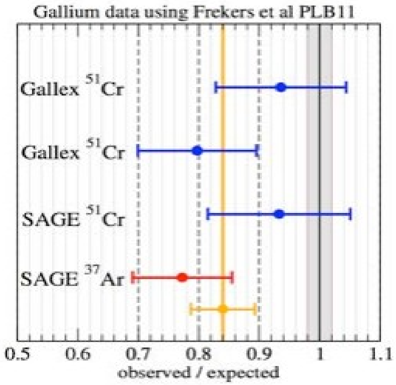
MiniBooNE



Reactors

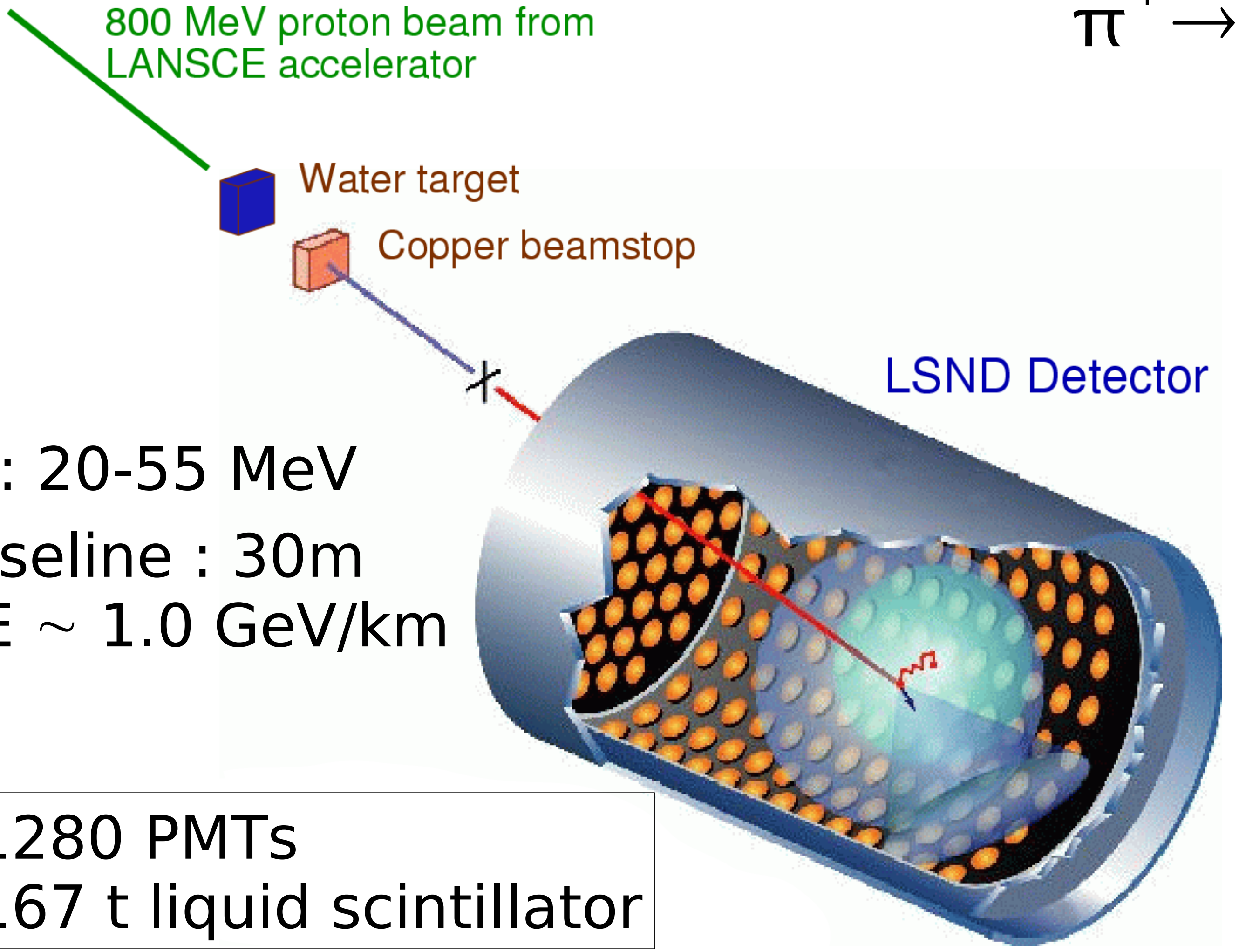


Gallium



LSND

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



$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$
$$\Updownarrow$$
$$\overline{\nu}_e$$

E_ν : 20-55 MeV
baseline : 30m
L/E ~ 1.0 GeV/km

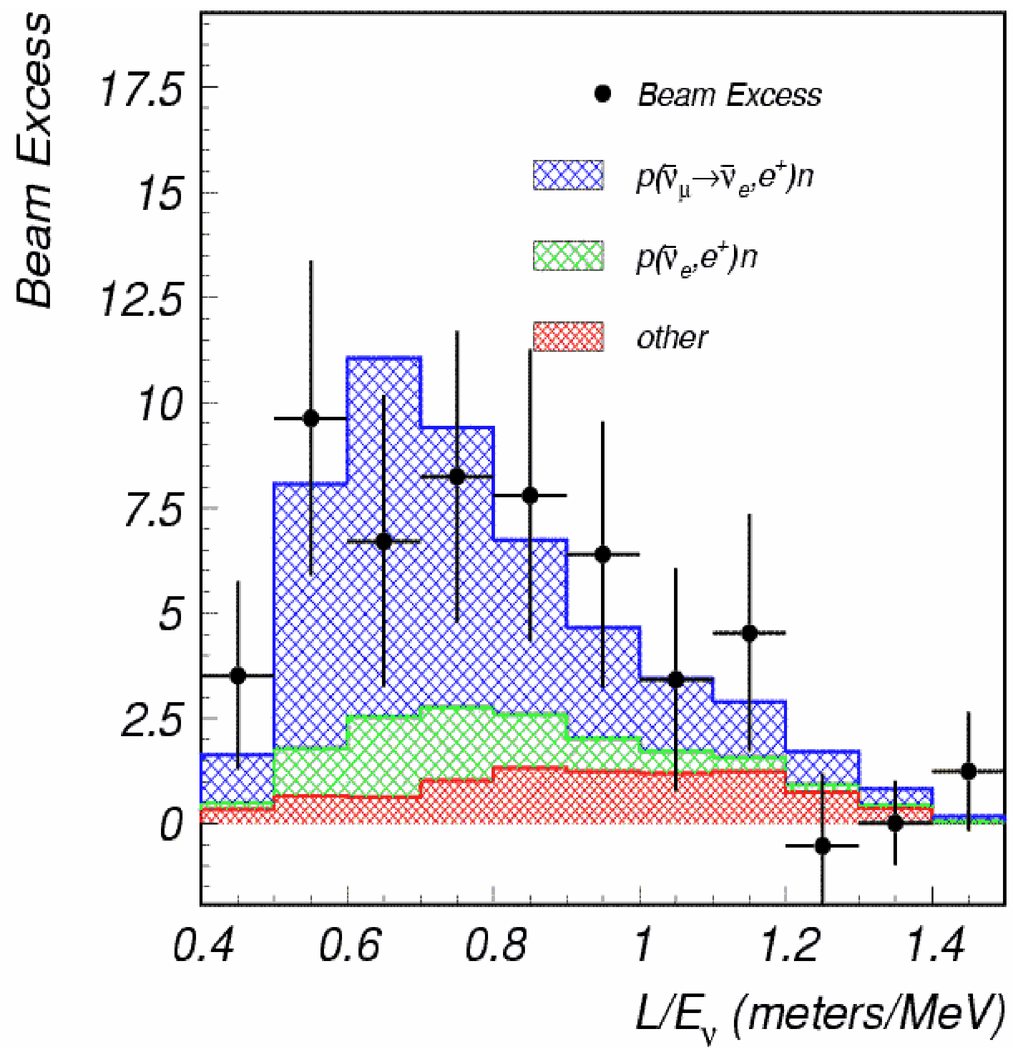
1280 PMTs
167 t liquid scintillator

$$\overline{\nu}_e\, p \to e^+ n$$
20-60 MeV

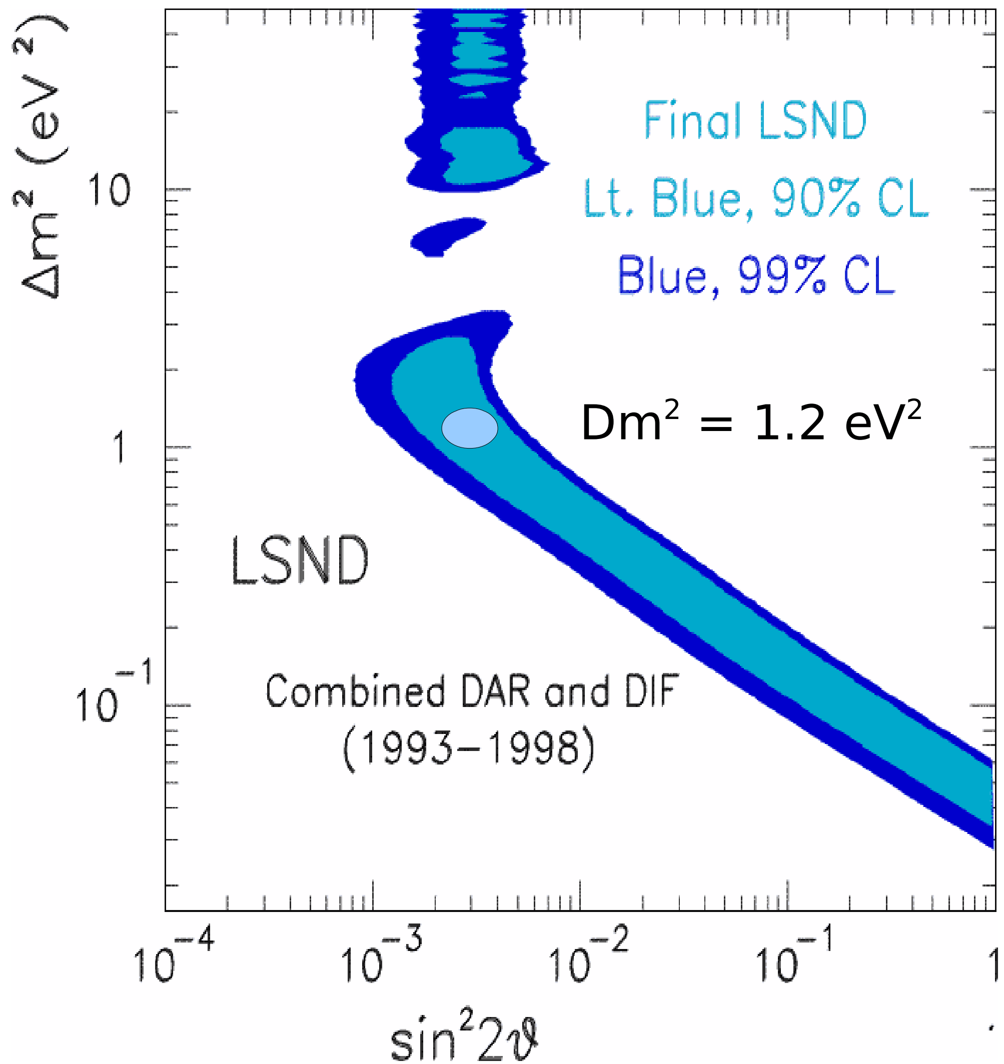
$$n\, p \to \gamma\, d$$
2.2 MeV

LSND Result (1997)

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



3.3 σ evidence for oscillations



LSND Result (1997)

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

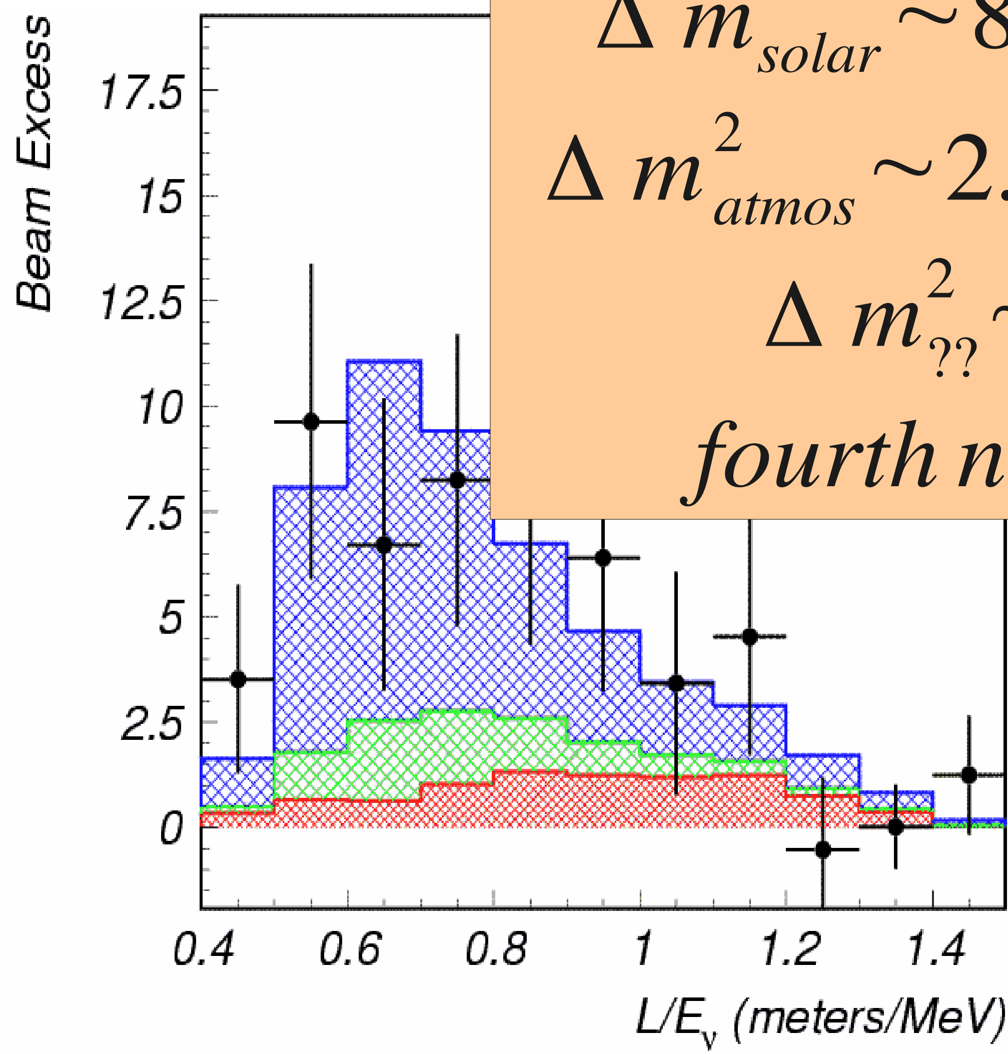
3.3 σ evidence for oscillations

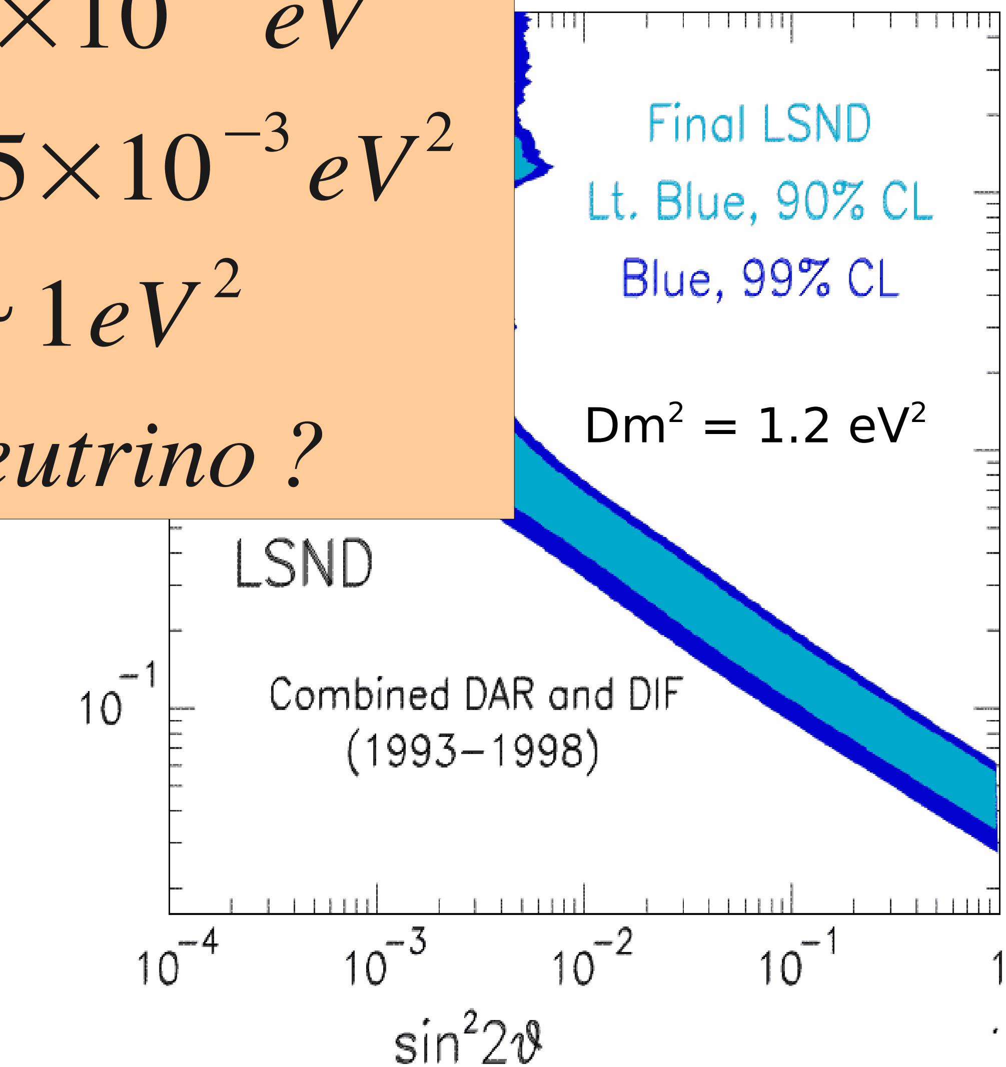
$$\Delta m^2_{solar} \sim 8\times10^{-5}\,eV^2$$

$$\Delta m^2_{atmos} \sim 2.5\times10^{-3}\,eV^2$$

$$\Delta m^2_{??} \sim 1\,eV^2$$

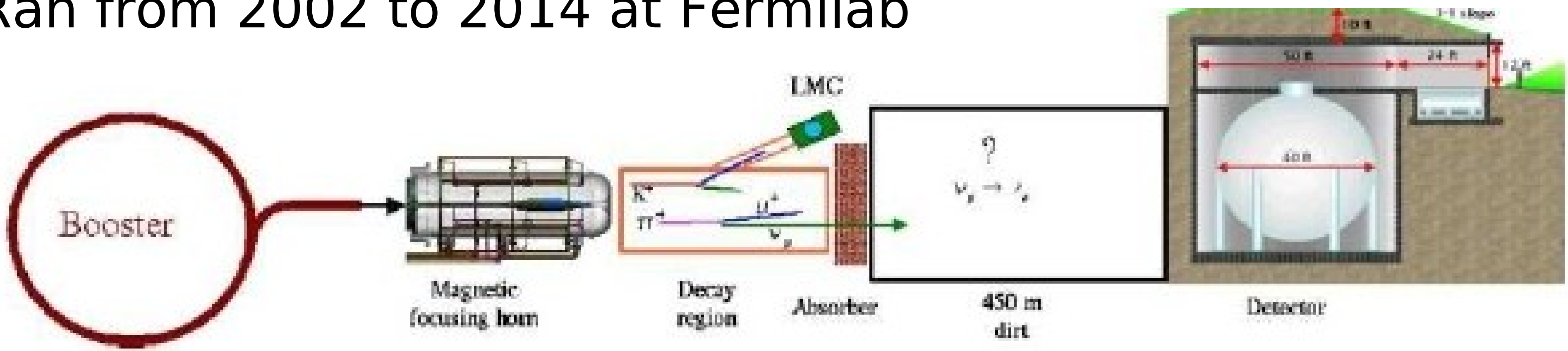
fourth neutrino ?





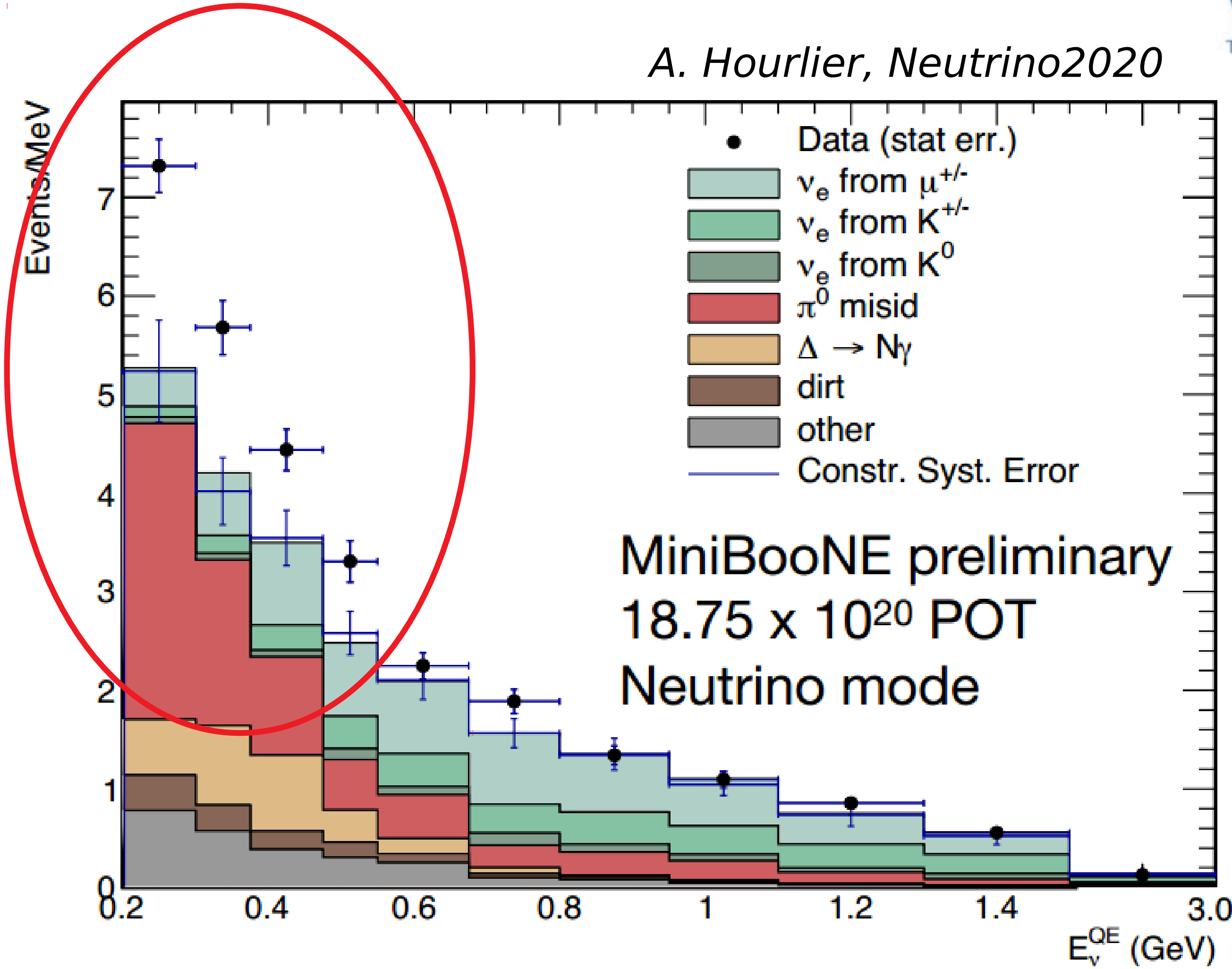
MiniBooNE

Ran from 2002 to 2014 at Fermilab



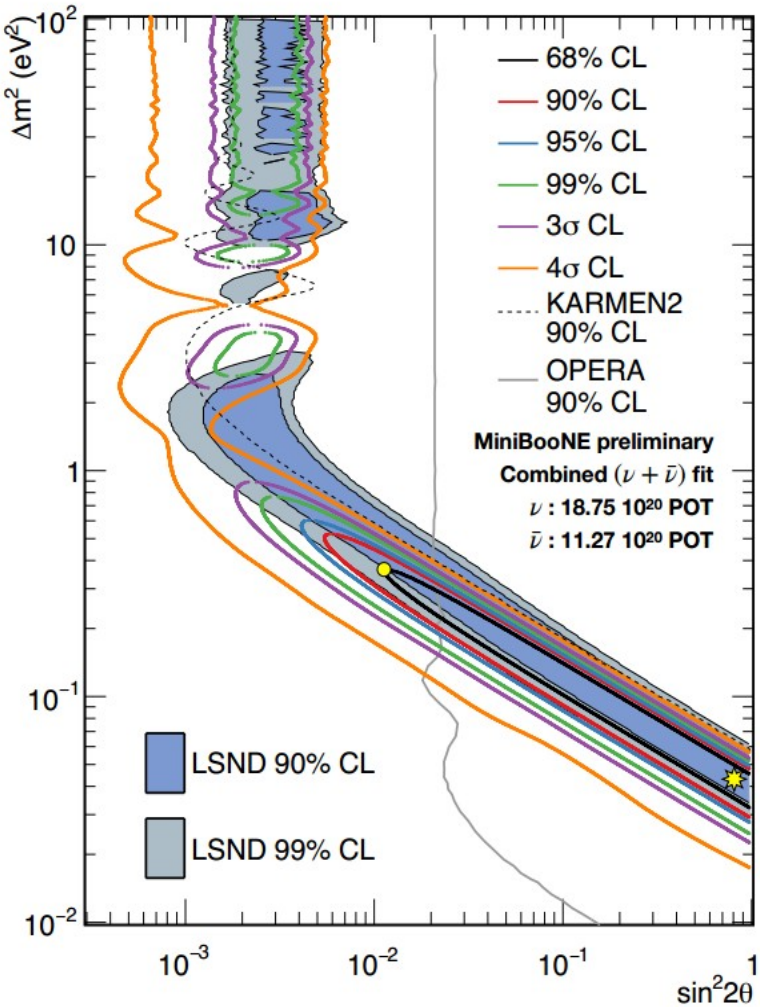
- Average neutrino energy ≈ 1 GeV
- L/E the same as LSND
- Same technology as LSND
- Different energy = different event types = different systematics

A. Hourlier, Neutrino2020

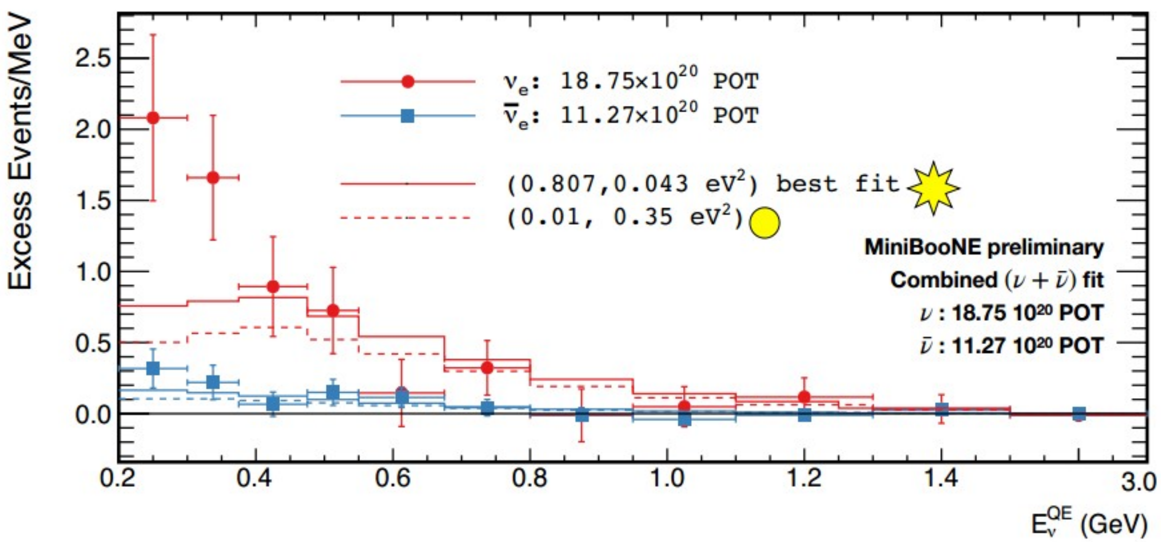


- 4.7 σ excess of ν_e-like events observed at low neutrino energy

- Event excess is stable over 17 years of data-taking
- No background hypothesis has been found to explain it



- Neutrino mode excess 4.7σ,
- **Neutrino+Anti-neutrino modes excess : 4.8σ**



Neutrino + Anti-Neutrino Mode

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

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

The Gallium Anomaly

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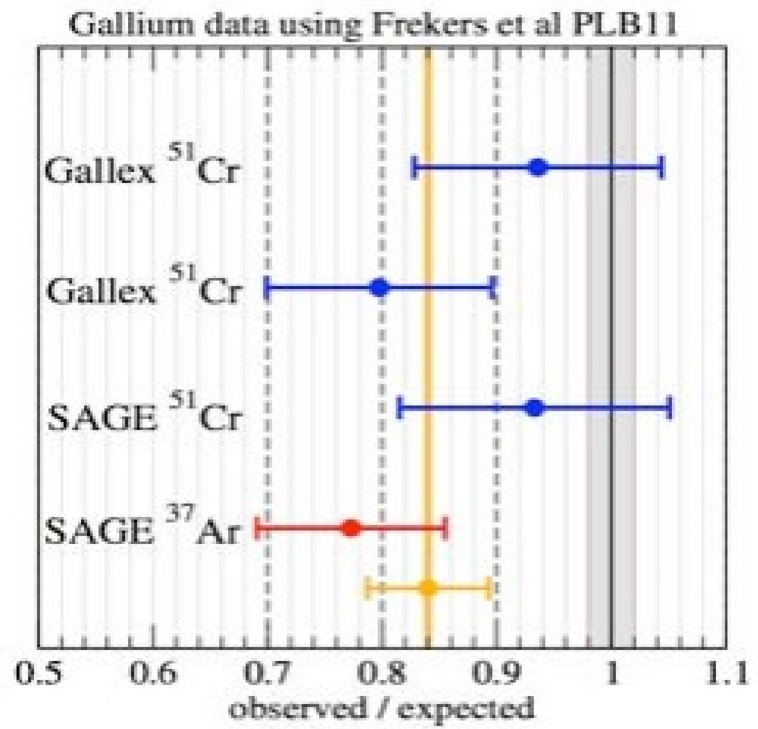
We've discussed the Homestake experiment which studied the reaction

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

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 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 nuclear β decay?

Reactor Anomaly

Over the years there have been lots of reactor experiments who measured the electron antineutrino flux from reactors and found that observed rates matched expected rates.

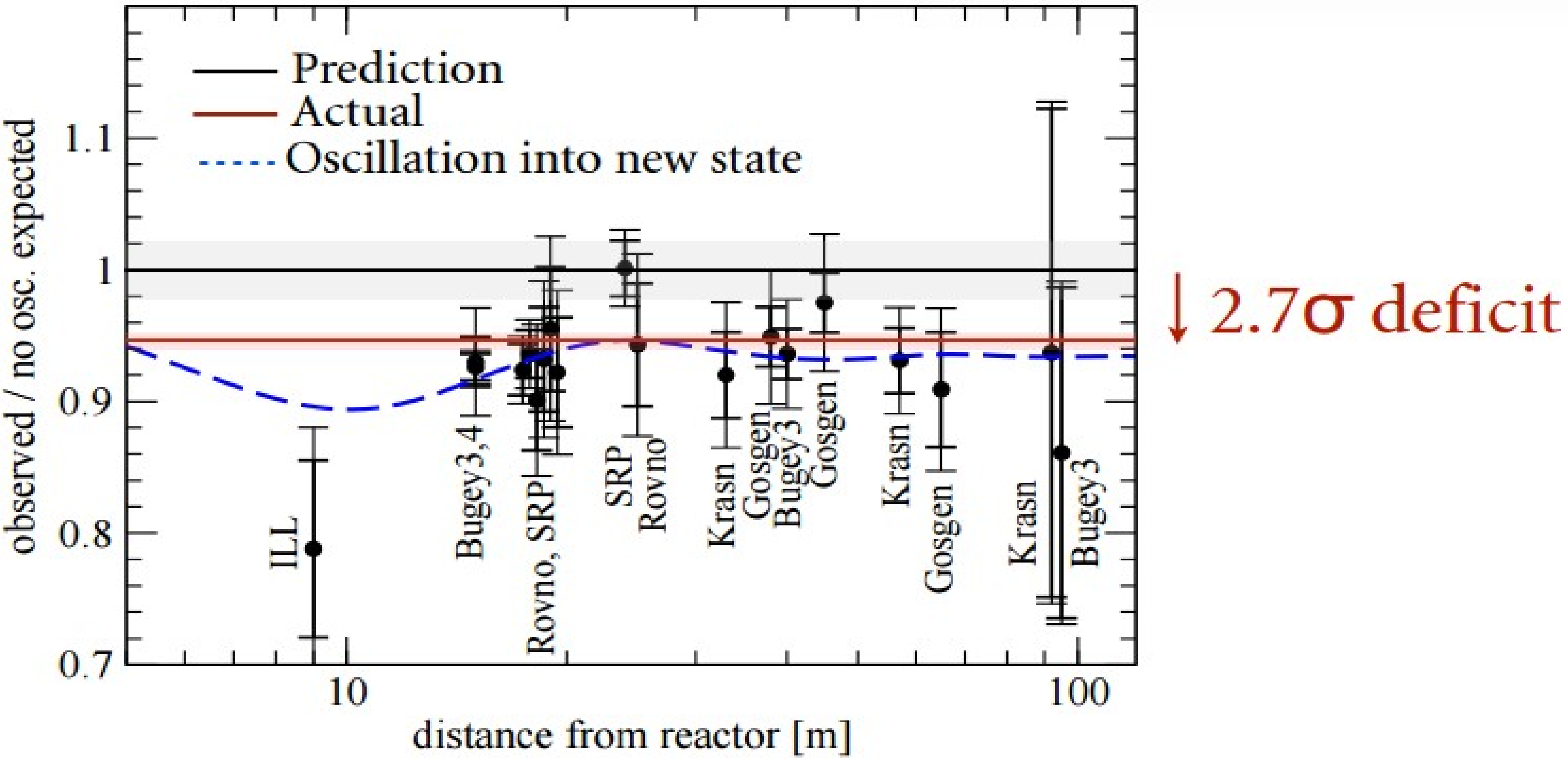
In 2011, new techniques in modelling nuclear reactions led to a re-evaluation of the expected electron antineutrino flux. The new estimate was about 6% **higher** than the old.

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

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

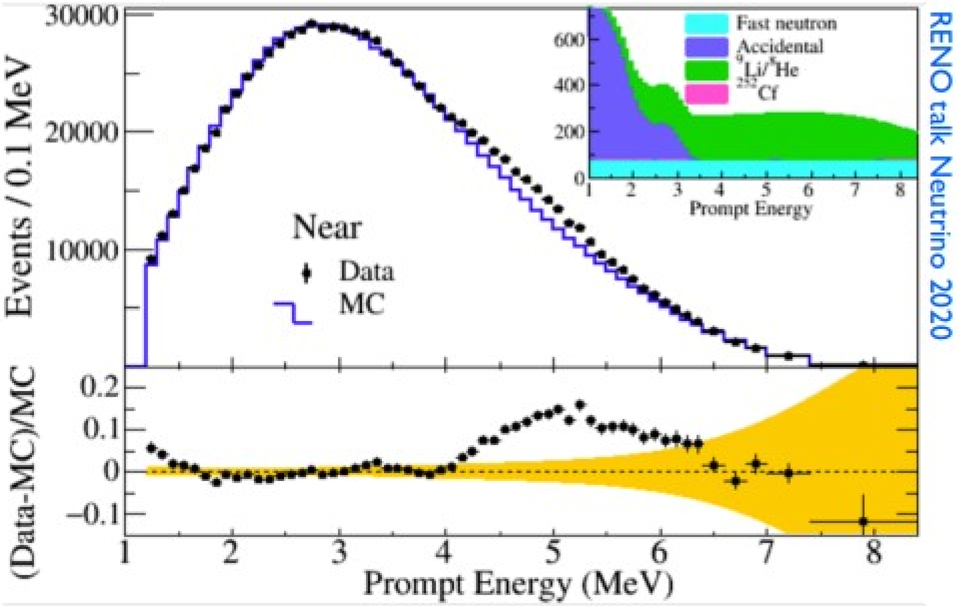
Could this be (i) the new flux estimate is just a bit dodgy or (ii) we have short baseline neutrino oscillations to a sterile state?

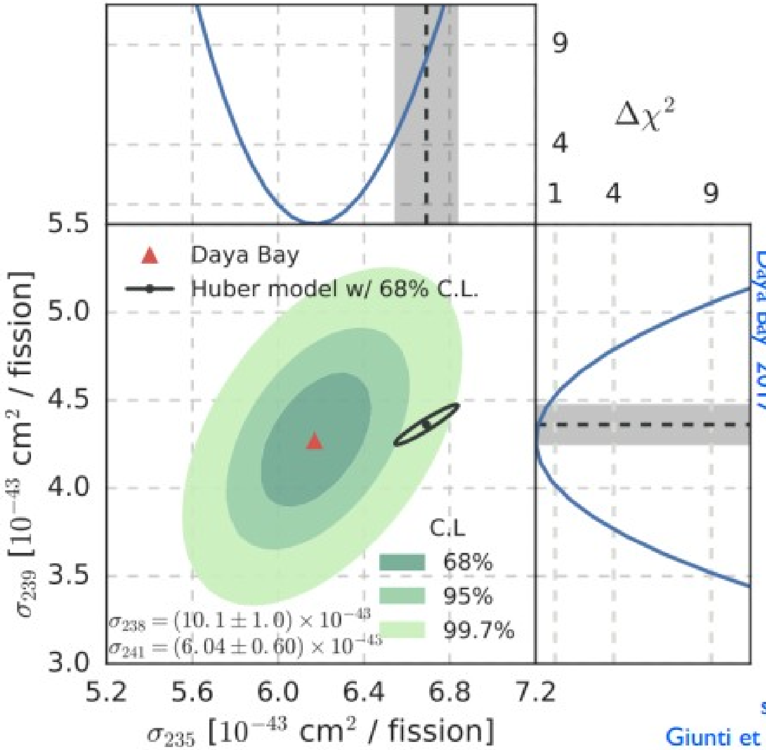
Reactor Anomaly



Deficit consistent with a sterile state with $\Delta m^2 \sim 1.5\ \text{eV}^2$

Odd observations...





see also
Giunti et al 2017
Berryman Huber 2020

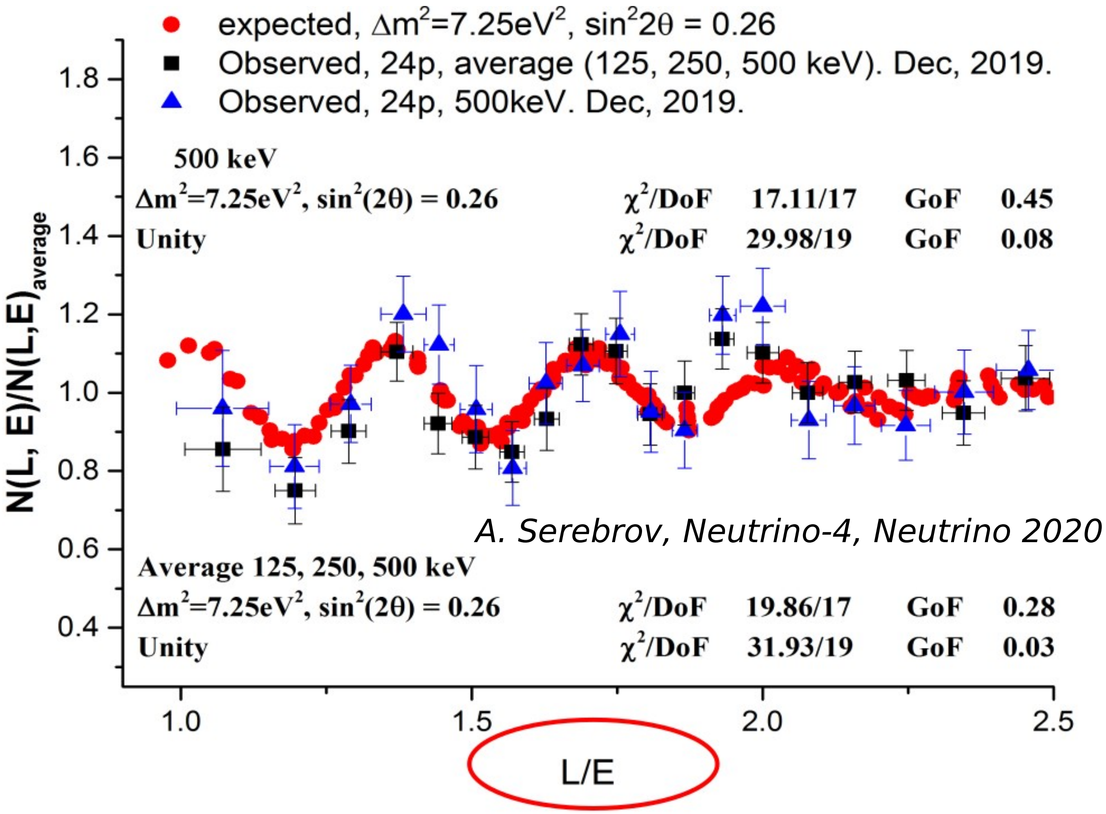
- All reactor experiments observe an excess of antineutrinos around 5 MeV

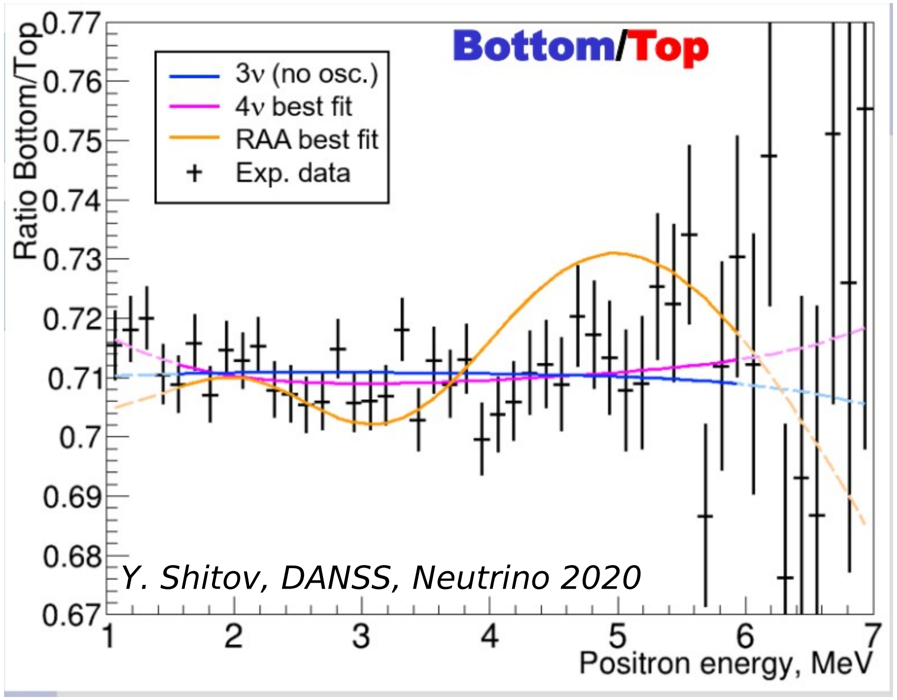
- Different isotopes burn at different rates. Can use the time evolution of the neutrino flux to measure β decay cross section from different isotopes.
- Looks like U-235 component is overestimated by model

- Suggestive that the reactor flux theoretical models need work.

...and wiggles???

- A number of very short baseline reactor experiments measure the antineutrino rate at different distances very close to the reactor core.





- Neutrino-4 claims to observe oscillations in reactor flux consistent with sterile neutrinos

- But not observed by similar DANSS experiment.

Summary

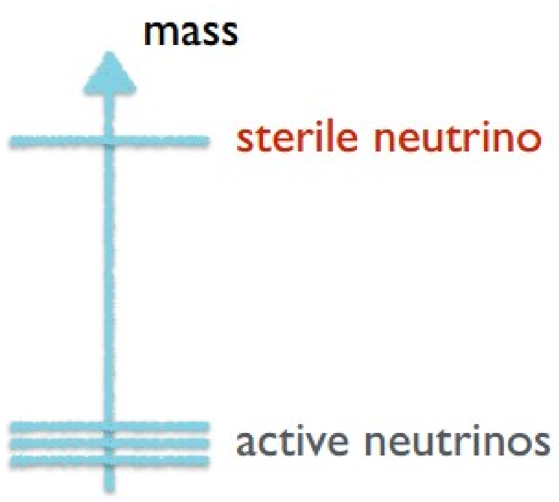
- Reactor and Gallium anomalies may indicate problems with flux theory (although the wiggles.....)

- LSND and MiniBooNE anomlies : same L/E, no obvious common backgrounds or culprits to explain excess

- All four anomalies come from very different experiments

Sterile hypothesis

- Posit existence of a 4th sterile neutrino with large mass compared to the 3 active neutrinos



Add 4th neutrino with mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

*Last line in 4x4 PMNS is unphysical

Δm^2_{21}, $|\Delta m^2_{31}|$ << Δm^2_{41} allows for approximate oscillation formula:

$$\boxed{P_{\alpha\beta} \simeq \delta_{\alpha\beta} - 4|U_{\alpha\beta}|^2(\delta_{\alpha\beta} - |U_{\alpha\beta}|^2)\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)}$$

$\nu_\mu \to \nu_e : \ \sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 4}|^2|U_{e4}|^2$ → LSND, MiniBooNE, OPERA, …

$\nu_e \to \nu_e : \ \sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1 - |U_{e4}|^2)$ → Reactors, solar, Gallium, …

$\nu_\mu \to \nu_\mu : \ \sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$ → MiniBooNE, MINOS, IceCube, …

Sterile hypothesis

ν_μ disappearance

MiniBooNE, ICECUBE,SK
MINOS/MINOS+,NOVA

NO anomaly observed

$\nu_\mu - \nu_e$ appearance

LSND, MiniBooNE, NOMAD,
KARMEN, ICARUS, OPERA

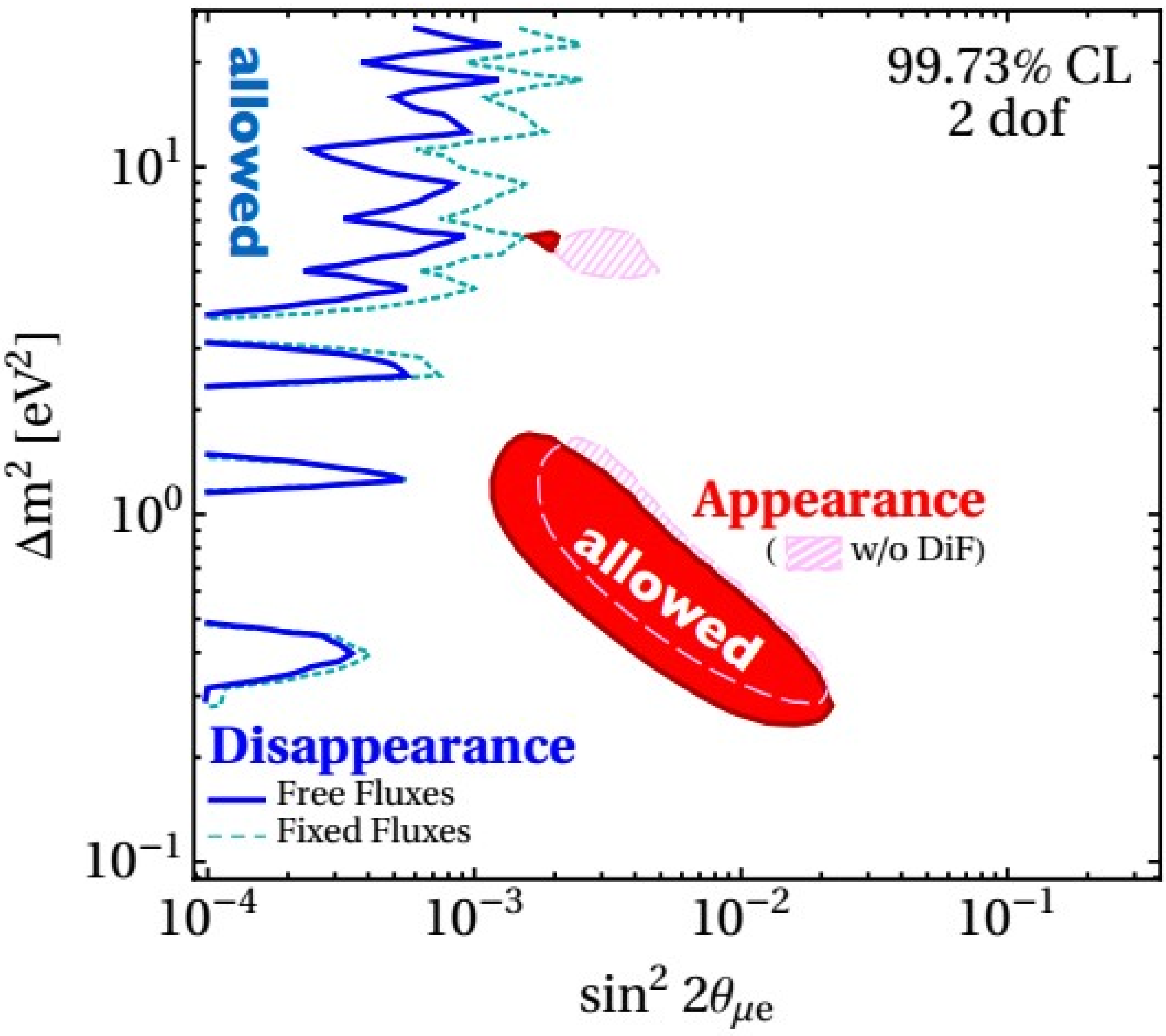
5σ anomaly dominated by LSND

ν_e disappearance

Reactor experiments, Source experiments,
Solar and atmospheric experiments

3σ anomaly dominated by DANSS/NEOS
BUT
Reactor best fit point is inconsistent with global best fit point

Sterile hypothesis



- Combined analysis displays significant tension between disappearance and appearance modes

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Decaying sterile neutrinos?

CPT Violation?

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

Lorentz violation?

Extra dimensions?

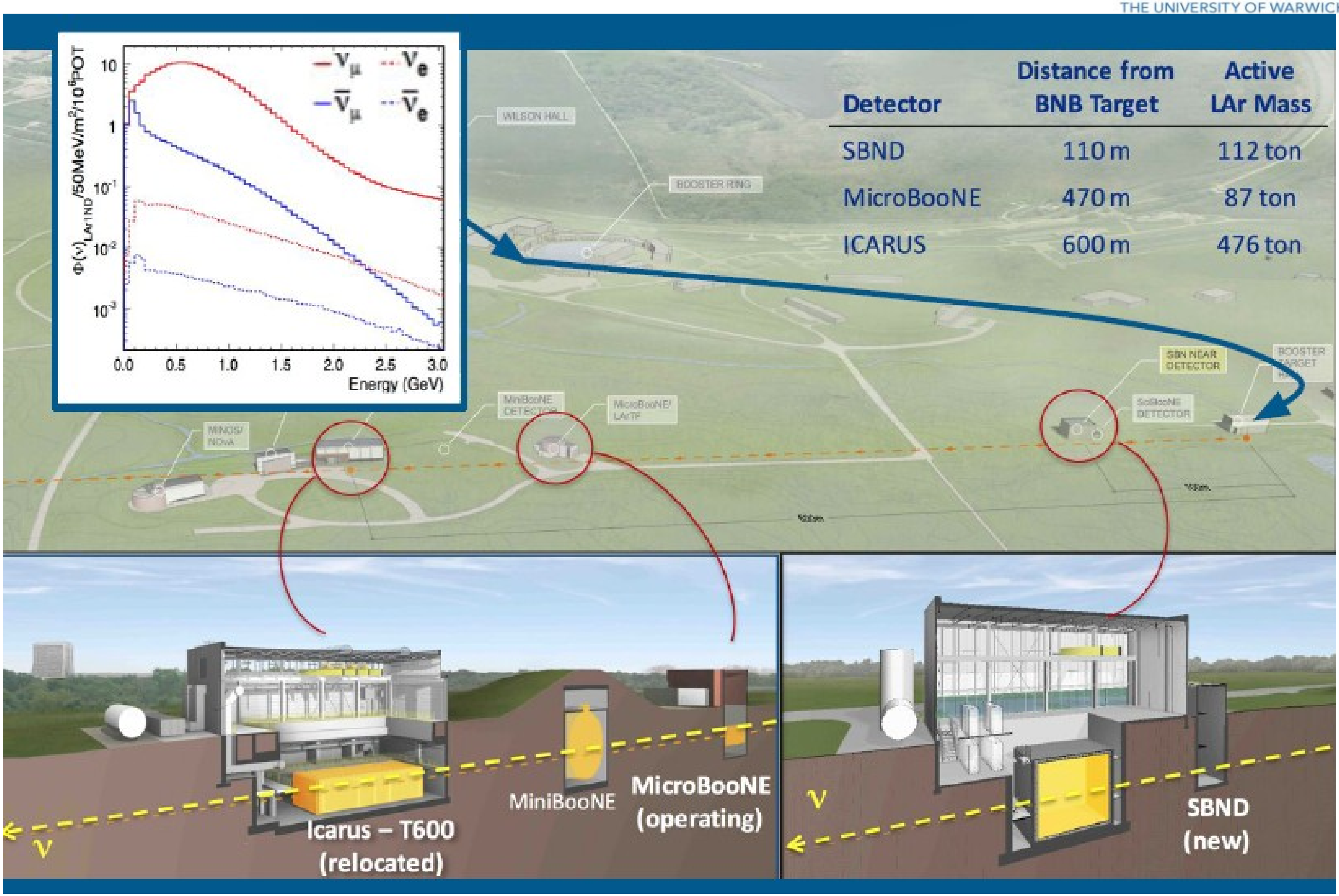
Experimental problems?

No bleedin' idea

Experimental Summary

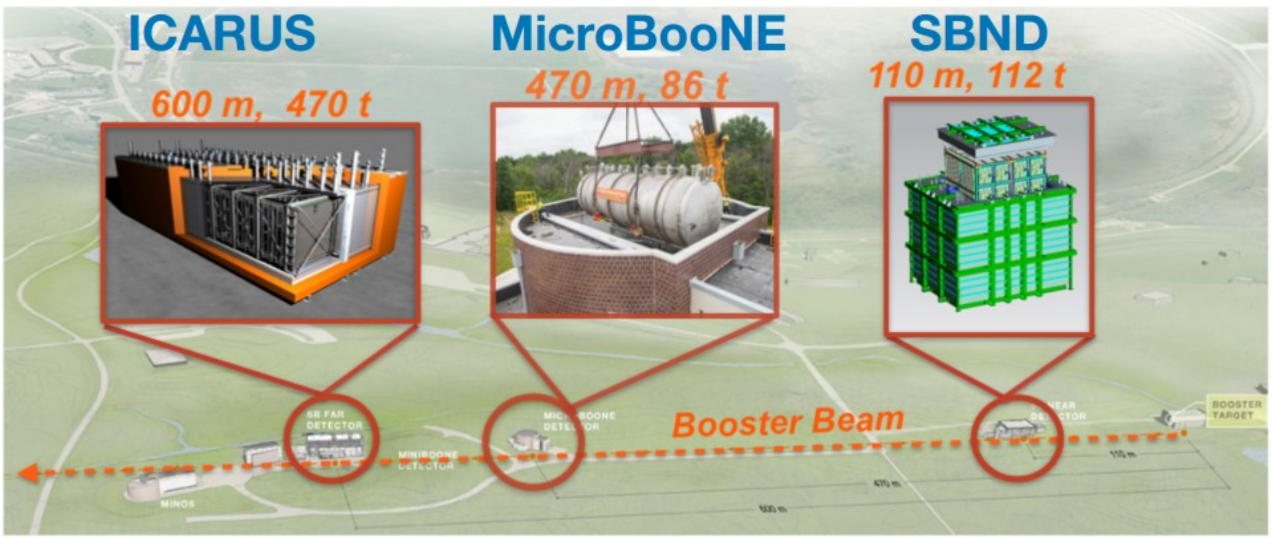
Reactor Experiments					
Name	**Location**	**Power (MW)**	**Distance (m)**	**Target mass (t)**	**Technology**
NEOS	China	2700	25	1	Gd – Liq. Scint.
DANSS	Russia	3000	9-12	0.9	Gd – Plastic. Scint.
Neutrino4	Russia	90	6-12	1.5	Gd – Liq. Scint.
Stereo	France	58	9-11	1.7	Gd – Liq. Scint.
Prospect	USA	85	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



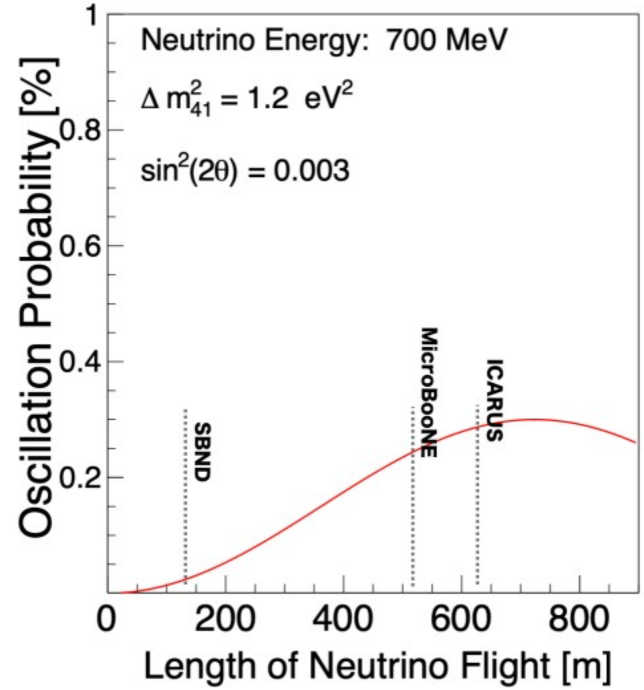
Detector
Distance from BNB Target
Active LAr Mass
SBND
110 m
112 ton
MicroBooNE
470 m
87 ton
ICARUS
600 m
476 ton
Energy (GeV)
WILSON HALL
BOOSTER RING
SBN NEAR DETECTOR
SciBooNE DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS/ NOvA
Icarus – T600
(relocated)
MiniBooNE
MicroBooNE
(operating)
SBND
(new)

SBND



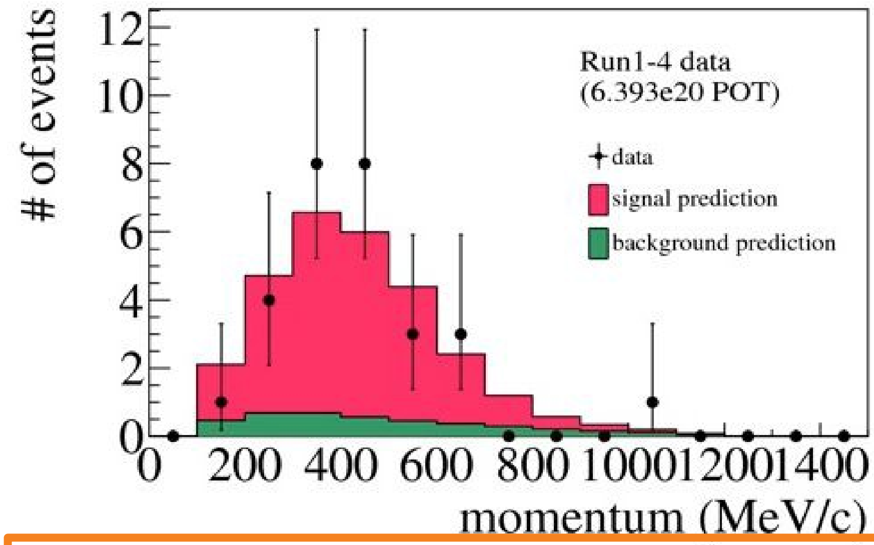
arXiv:1503.01520

Betancourt, Neutrino 2020



Neutrino Interactions

Systematic Problems



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

6-12%

Number of Targets

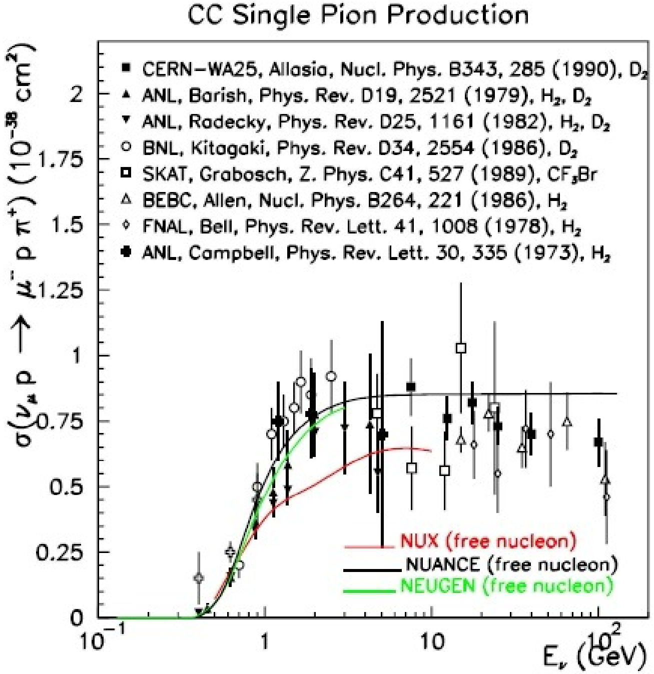
1-2%

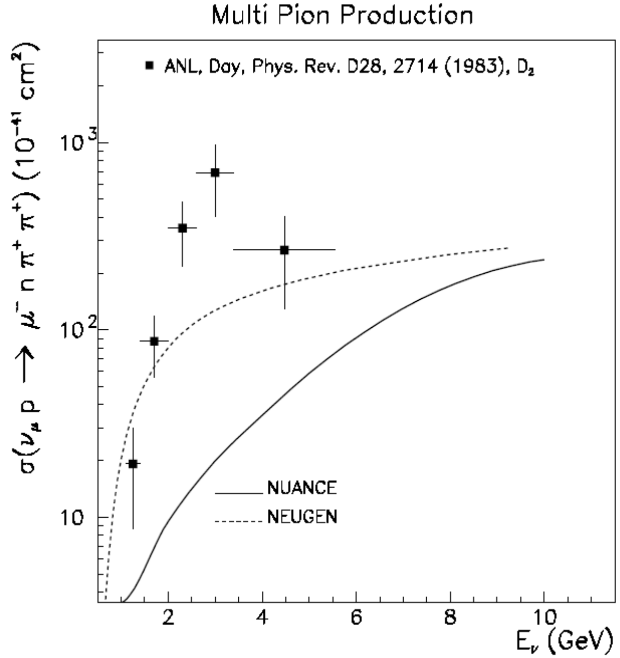
Selection Efficiency

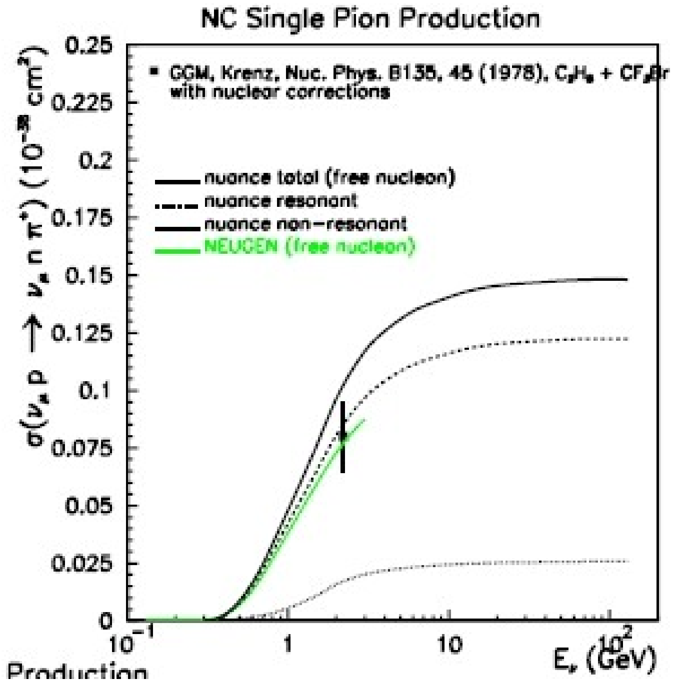
5-10%

Xsec data pre 2007

The data was impressively imprecise





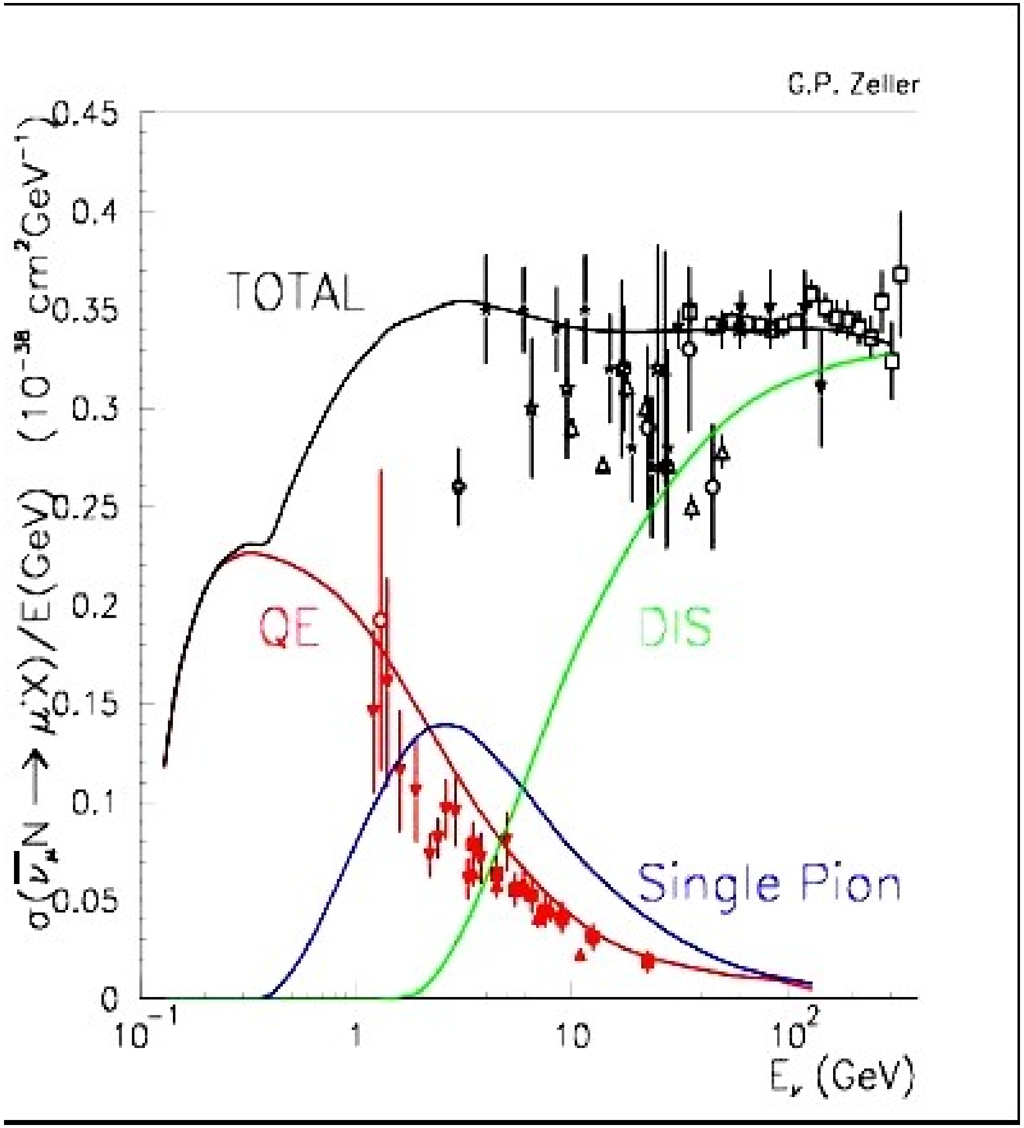


$\nu_\mu p \rightarrow \mu^- p \pi^+$ $\nu_\mu p \rightarrow \mu^- n \pi^+ \pi^+$ $\nu_\mu p \rightarrow \nu_\mu n \pi^+$

Added complication that the final state pions can (i) scatter (ii) be absorbed (iii) charge exchange within the nucleus before being observed (iv) nucleons rescatter producing p

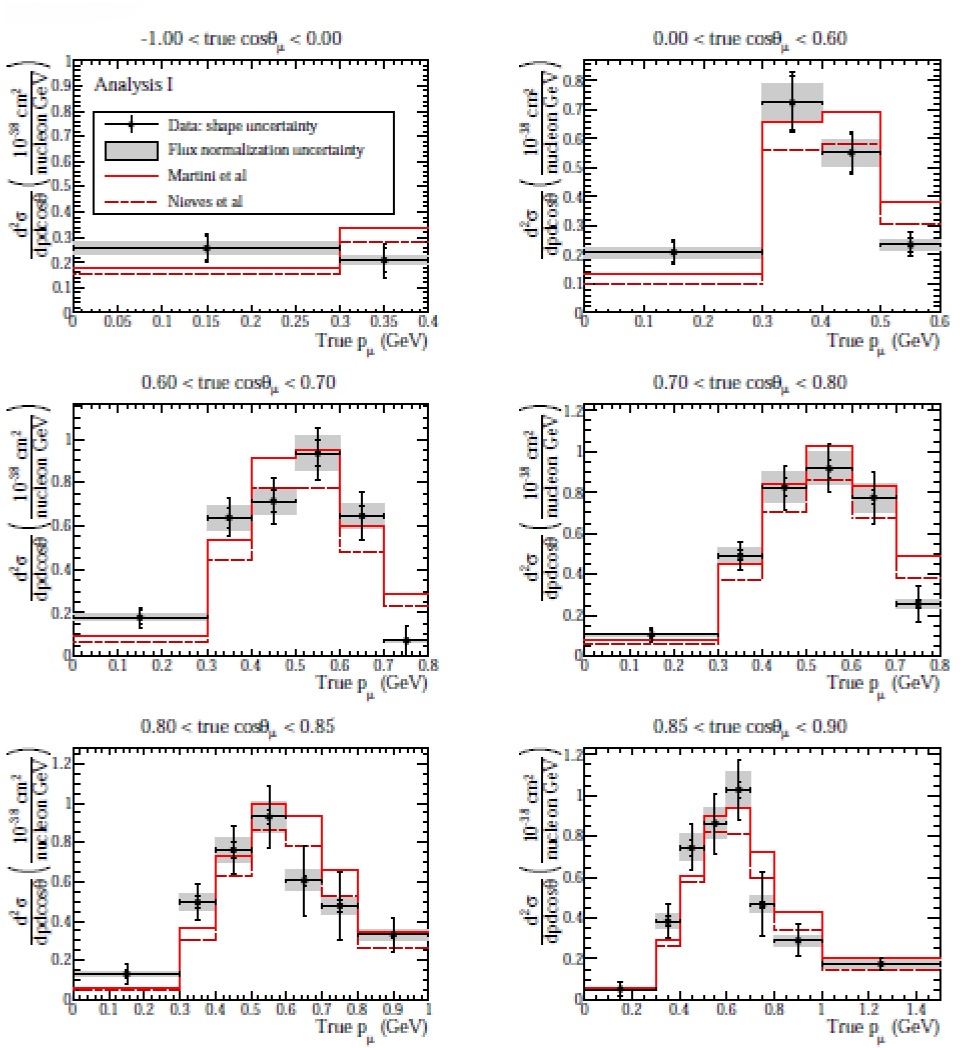
$\pi^+ n \rightarrow \pi^0 p$

World Data for Antineutrinos

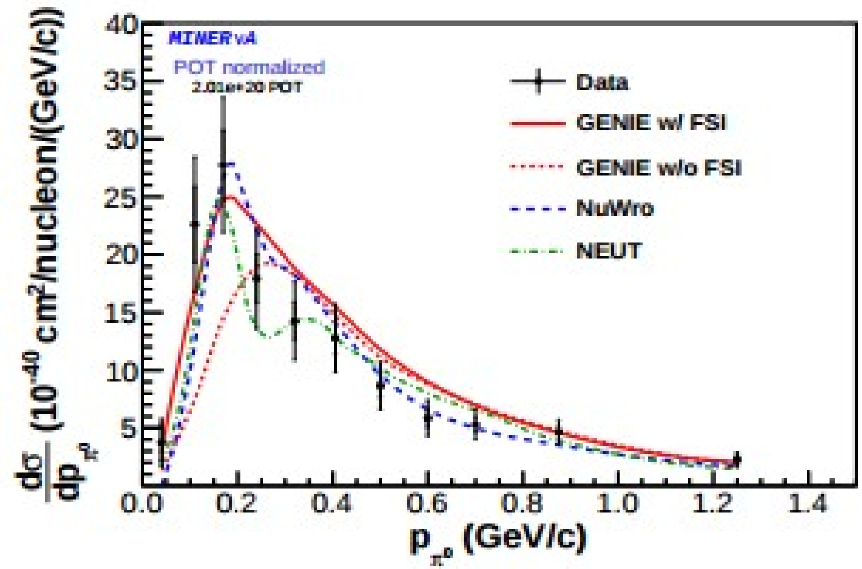


Getting better

WARWICK
THE UNIVERSITY OF WARWICK



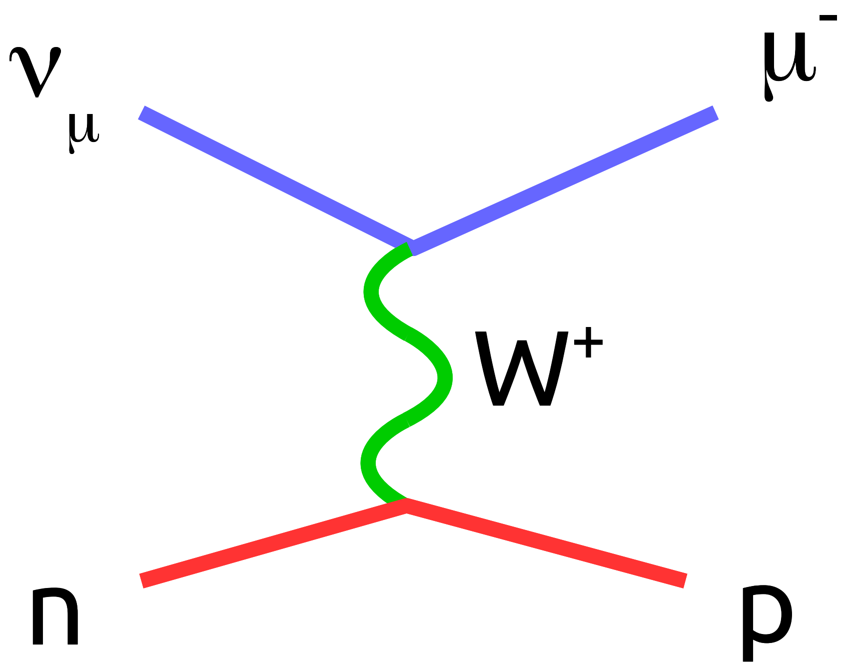
CC 0π differential Xsec from T2K
arXiv:1602.03652



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

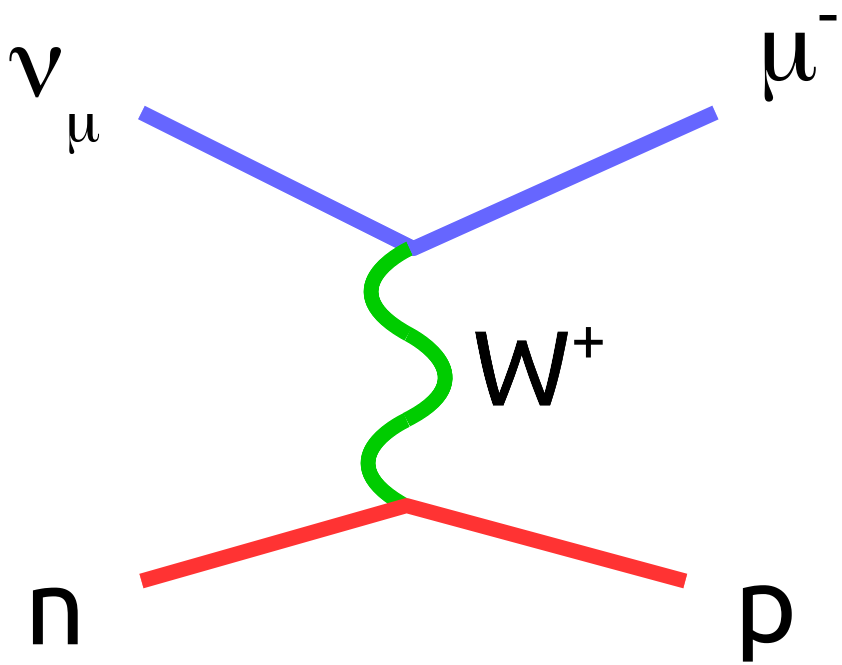
eg : Quasi-Elastic Scattering



- 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 contributes the most of the total cross section at a few GeV

Quasi-Elastic Scattering

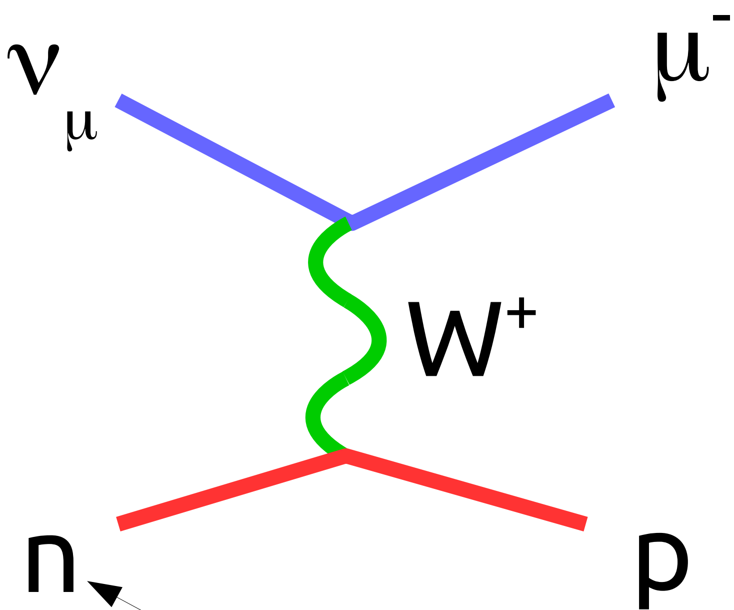


- Usually though of as a single nucleon knock-on process
- In the past has been used as a “standard candle” to normalise other cross sections
- Heavily studied in the 1970's and 1980's and considered to be “understood”

II. Energy reconstruction is unbiased assuming 2 body kinematics

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

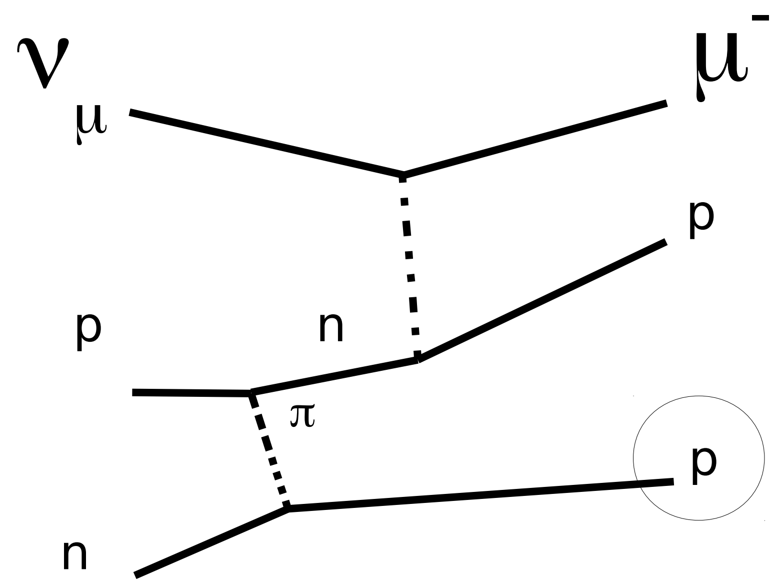
Extra processes contribute : e.g.



What is the momentum distribution of the neutron?

Initial state models (Fermi Gas, Relativistic Fermi Gas, Spectral Functions)

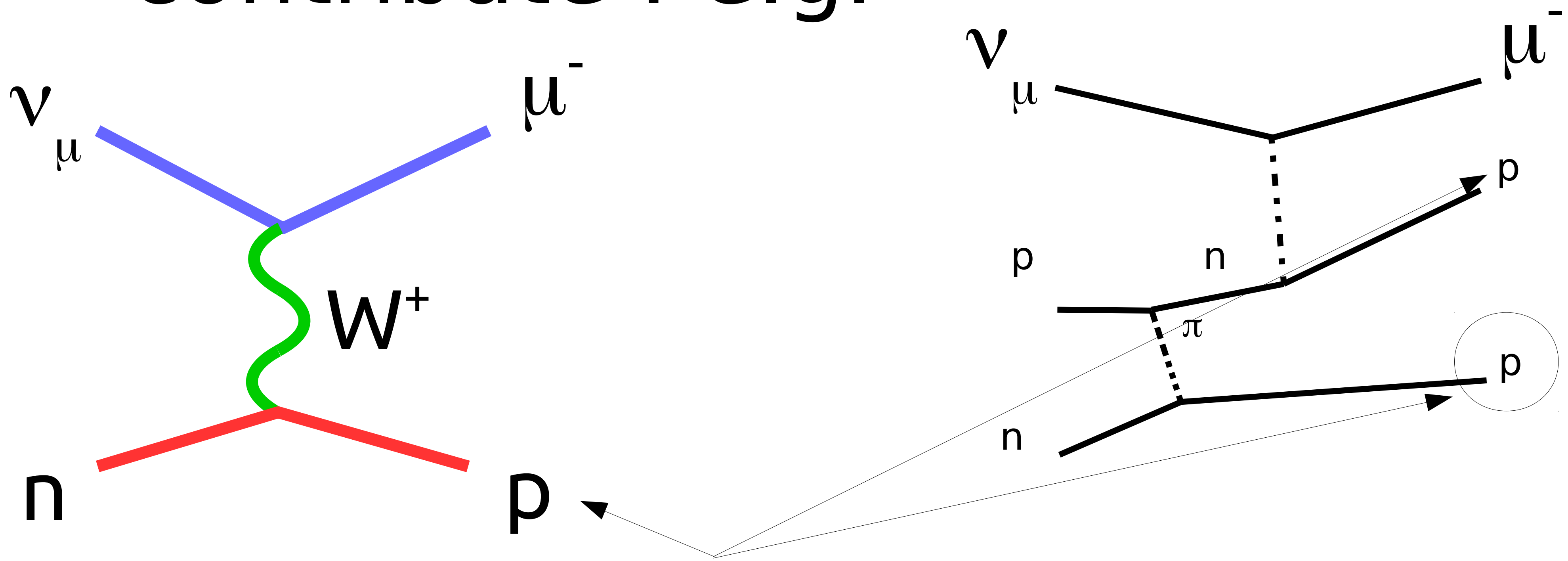
+=



unobserved final state proton

2p2h processes e.g.
Meson Exchange Current (MEC)

Extra processes contribute : e.g.



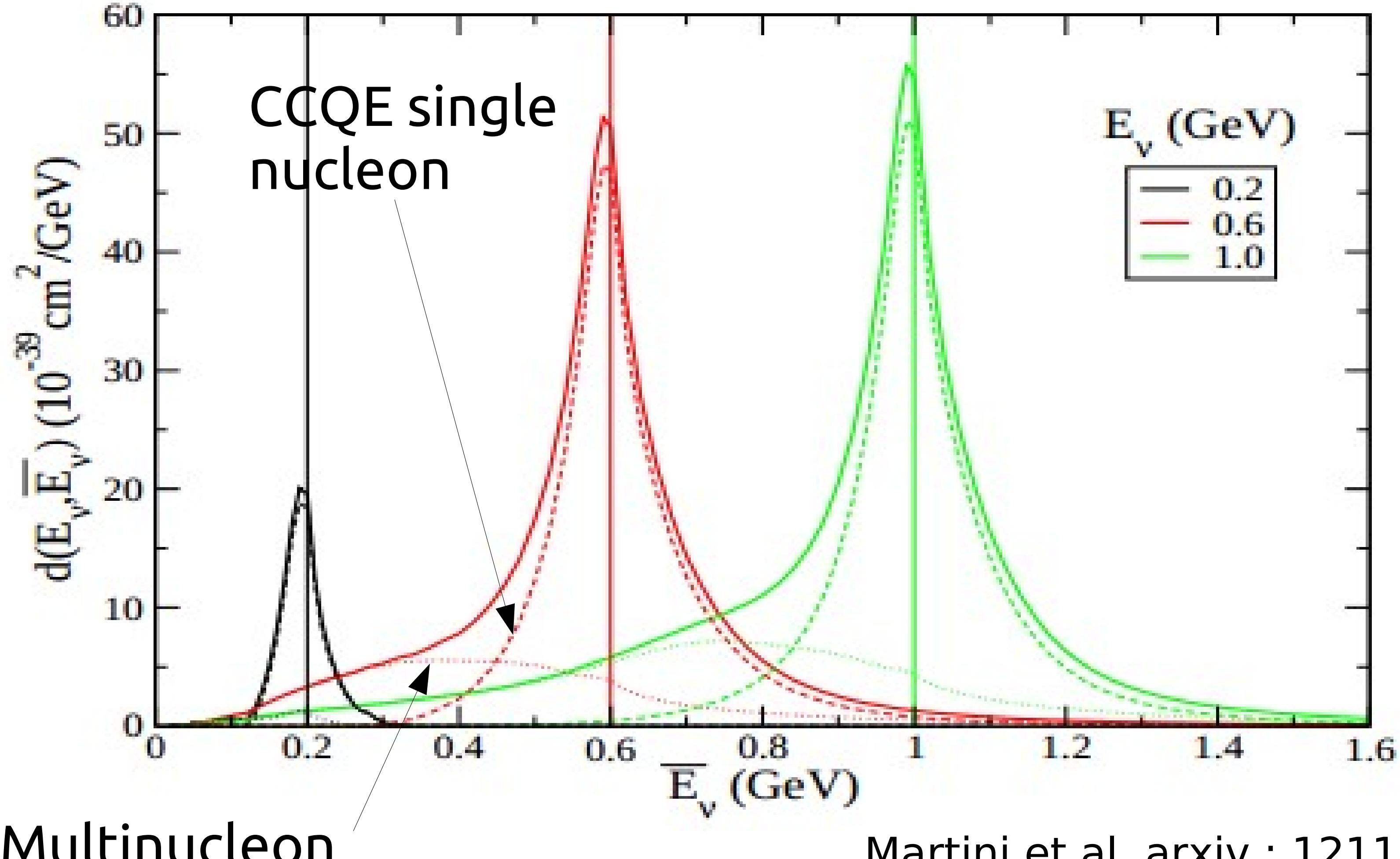
Protons can interact in the nucleus on their way out.
This will change the observed proton kinematics as well

What is your Final State Interaction (FSI) model?

- Intranuclear Cascade (INC) (not)including Formation Time, Pauli blocking,...
- Full hadronic transport through the nuclear field (GIBUU)

Note that initial state and final state are not independent!

Effect on energy reconstruction



Martini et al, arxiv : 1211.1523

Summary on xsec

- We measure events = flux*cross section
- We don't generally have a handle on the flux to better than 7% - it’s taken 10 years of work to get down to this.
- The other side of the coin, cross-sections, are even more poorly known.
- All experiments are now doing precision cross-section measurements and new experiments are being proposed to do them to better precision.

Concluding Remarks

- The history of neutrino physics is a history of anomalies
- Our knowledge of neutrino physics has exploded in the last 10-15 years
- We are in the era of precision neutrino measurements but there are still many things we need to find out:
    - what is the neutrino mass?
    - Is the neutrino Majorana or Dirac?
    - What is the CP violating phase and how does it connect to cosmology?
    - How do neutrinos interact at a few GeV?
    - Is there a sterile neutrino? How to account for the existing anomalies otherwise?
    - How can you explain leptonic CP violation?
    - Why does the weak interaction maximally violate parity?