Lecture 4

To Infinity and Beyond!

Question : What would you observe if you were able to know what mass state propagated from source to detector?

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$$Prob\left(\nu_\alpha \rightarrow \nu_\beta\right) \propto \left|\sum_i U^*_{\alpha i} \mathrm{Prop}\left(\nu_i\right) U_{\beta i}\right|^2$$

Question : What would you observe if you were able to know what mass state propagated from source to detector?

$$Prob(\nu_\alpha \rightarrow \nu_\beta) \propto \sum_i |U^*_{\alpha i} \mathrm{Prop}(\nu_i) U_{\beta i}|^2$$
$$\rightarrow \sum_i |U^2_{\alpha i}| |U_{\beta i}|^2$$

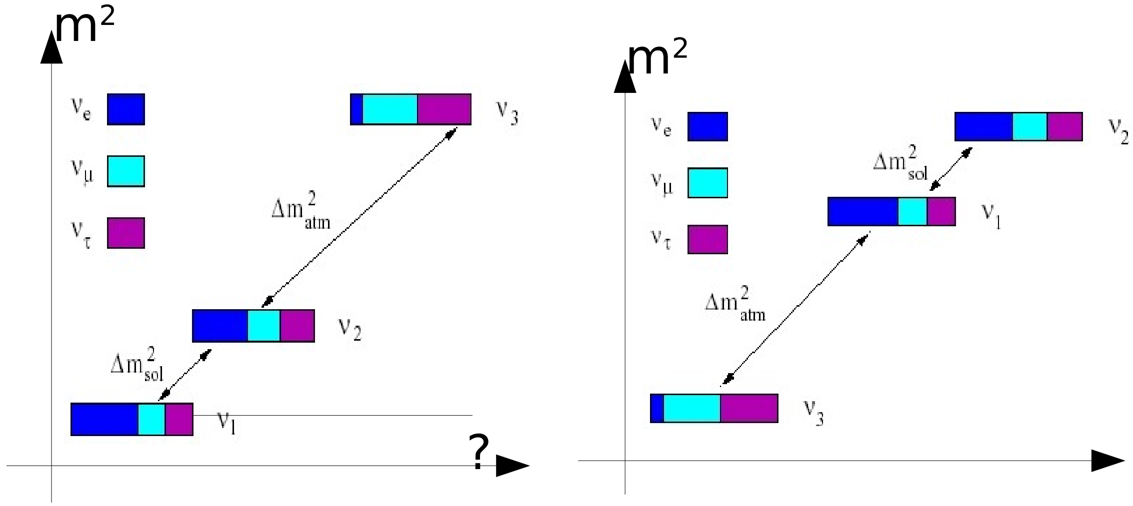
- The Prop term is just a phase rotation so vanishes
- The probability is now a constant – there is flavour change if mixing can still happen – but now the oscillation has vanished, as the interference between mass states no longer exists…

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?



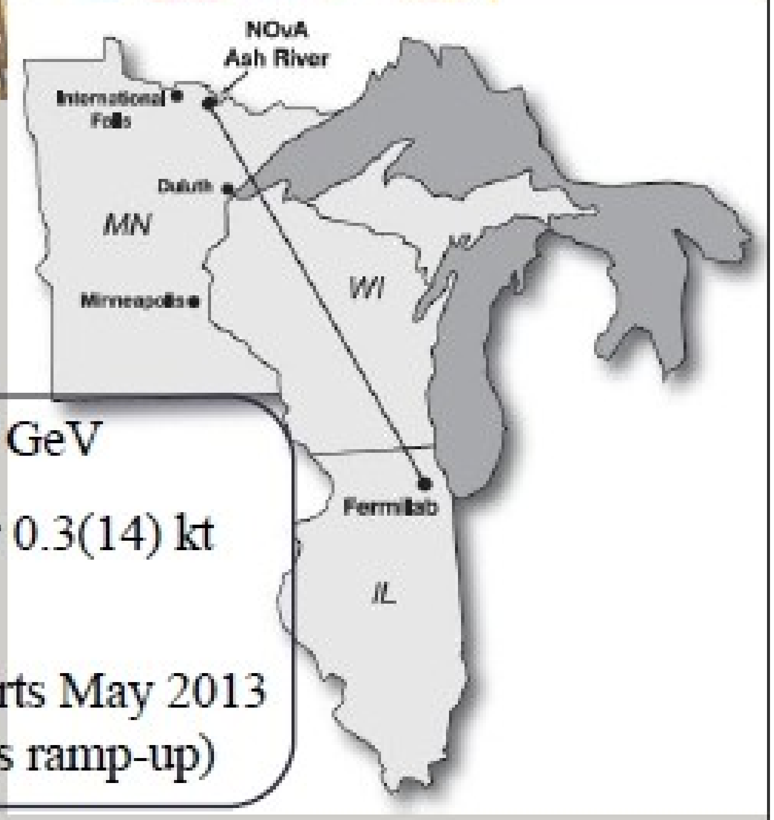
- Better estimates of the oscillation parameters using accelerators
- Is θ_{23} maximal?
- Is the neutrino Majorana?
- What is the absolute mass?

$$U_{PMNS} \approx \begin{pmatrix} 0.82 & 0.54 & 0.14 \\ 0.35 & 0.56 & 0.68 \\ 0.35 & 0.55 & 0.69 \end{pmatrix} \quad ?$$

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

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)



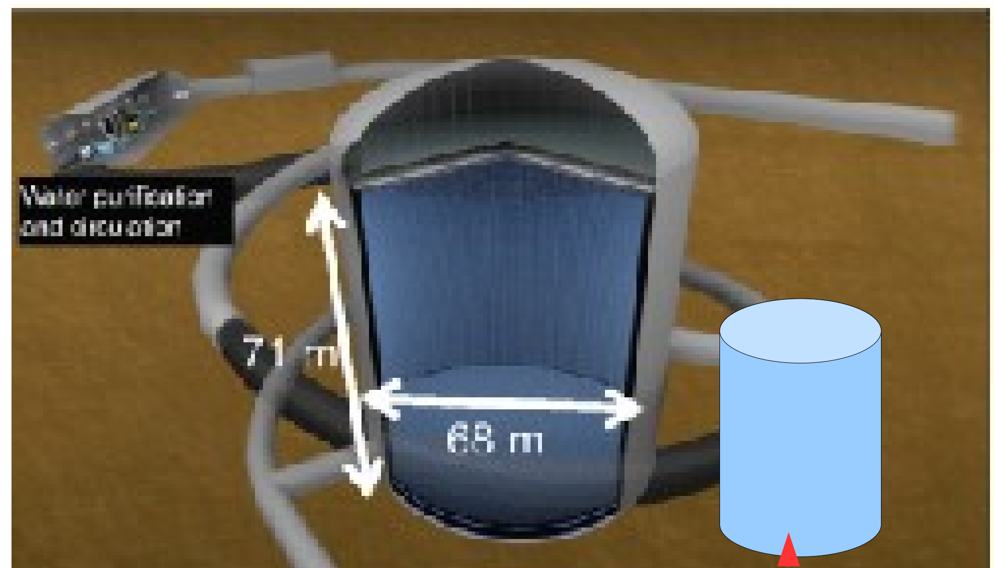
- L=810 km, <E>=2 GeV
- Near(Far) Detector 0.3(14) kt liquid scintillator
- NUMI beam re-starts May 2013 @ 700 kW (6 months ramp-up)

Next generation

DUSEL Underground
Neutrino Experiment (DUNE)

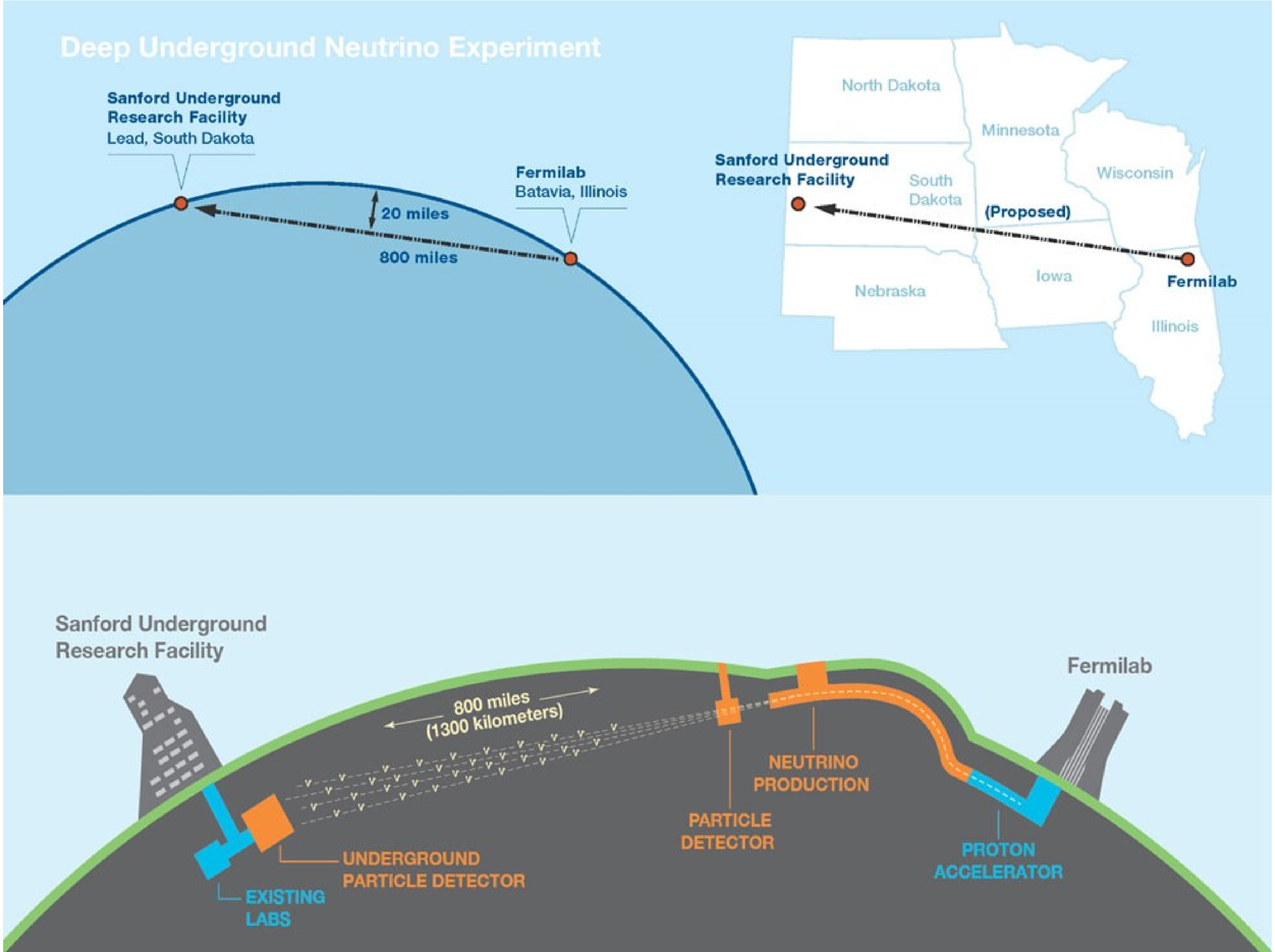
- MW beams
- multi-kton far detectors

Hyper-Kamiokande
300 km baseline

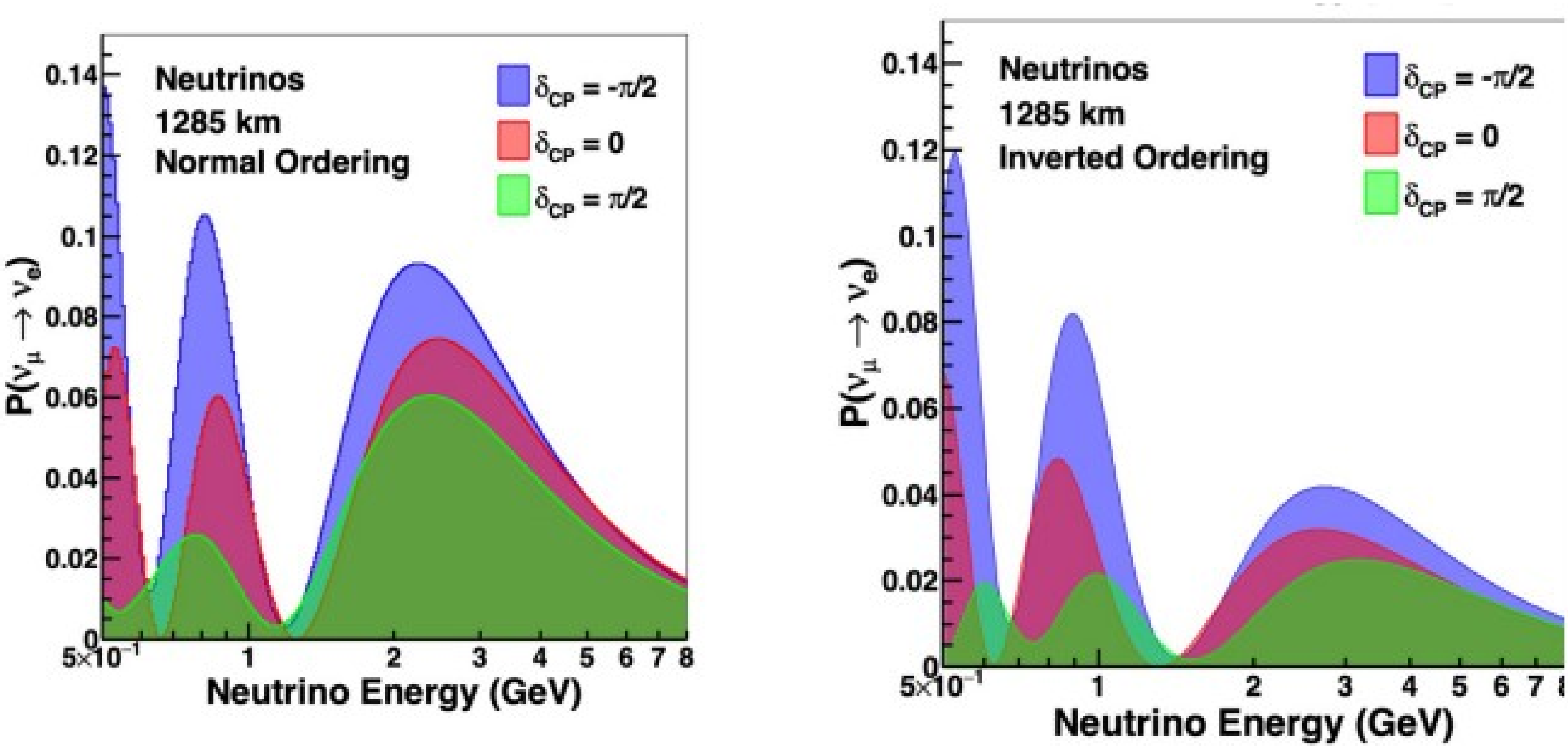


SK (to scale'ish)

DUNE in the USA

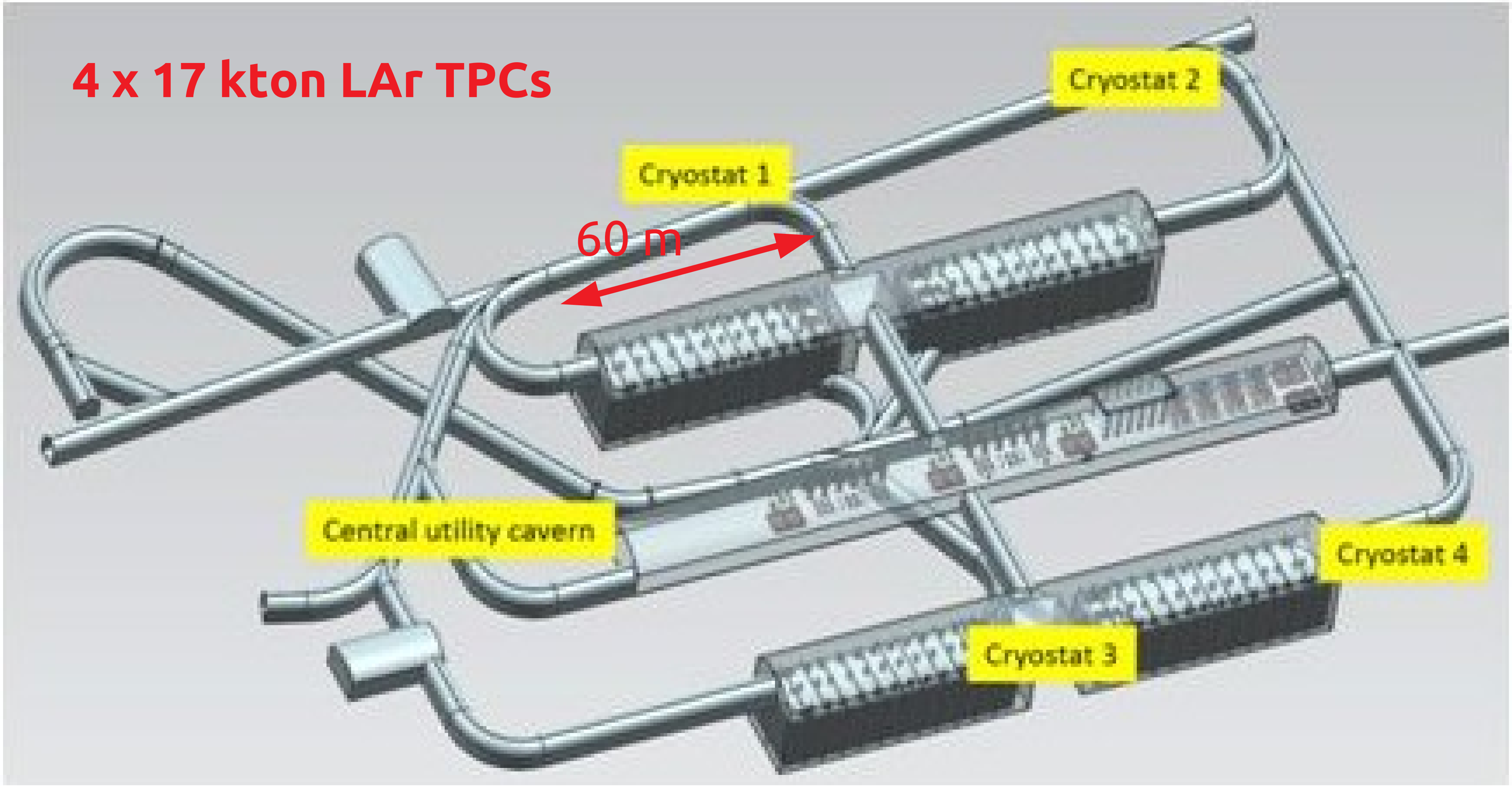


DUNE Beam

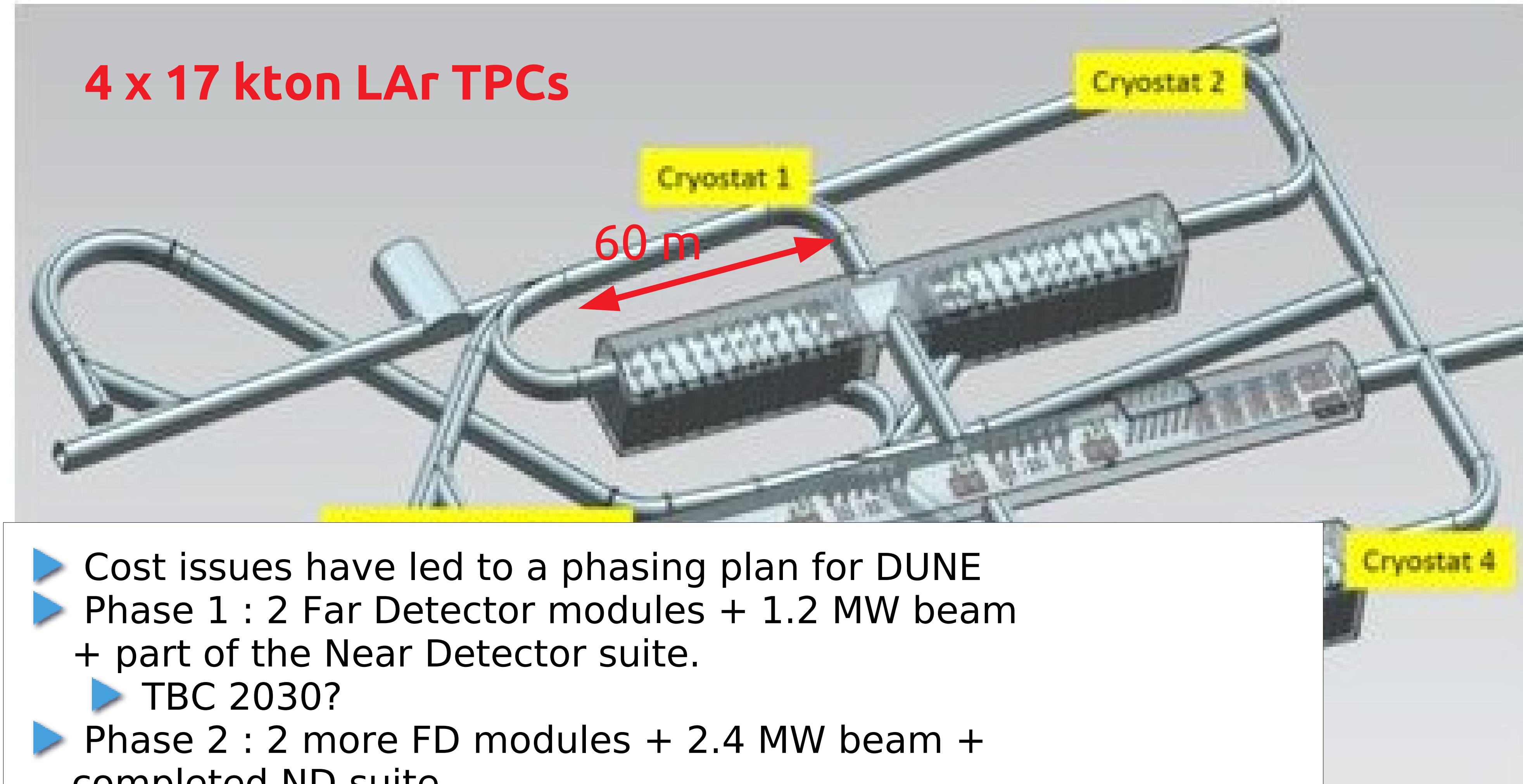


- DUNE operates a wide-band beam
- Comparison of the peaks of the first AND second oscillation maxima can be used to measure the mass ordering and δ_{CP}

DUNE Far Detector

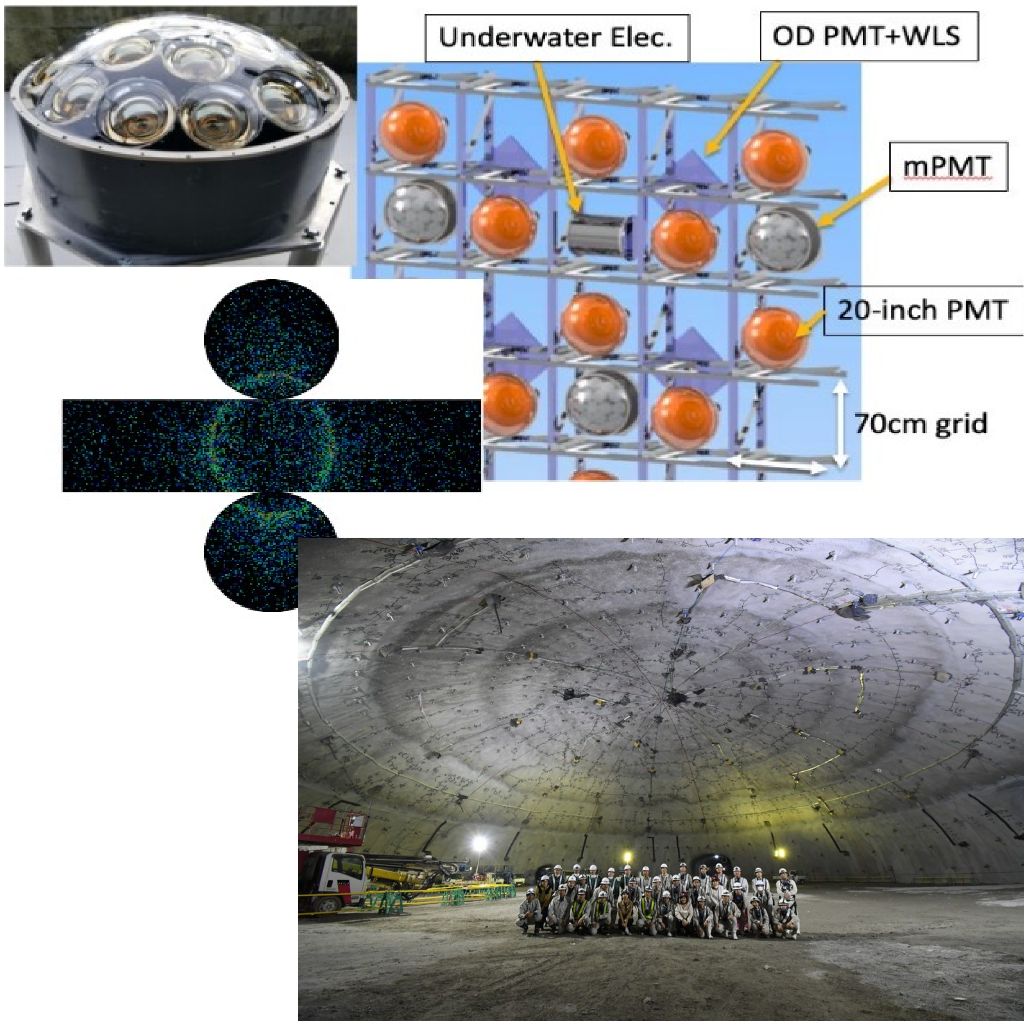


DUNE Far Detector



- Cost issues have led to a phasing plan for DUNE
- Phase 1 : 2 Far Detector modules + 1.2 MW beam + part of the Near Detector suite.
  - TBC 2030?
- Phase 2 : 2 more FD modules + 2.4 MW beam + completed ND suite
  - TBC 2032???

Hyper-Kamiokande



- Three detectors:
- HK Far Detector
- Upgraded Near detector
- New “Intermediate” detector

- FarDet complete : 2028
- Beam upgrades complete : 2028
- First data : 2028-2029

Construction through to 2028’ish

Super-K : 25 kton water
Hyper-K : 200 kton

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	1.2 MW	0.5 MW
Type of Beam	Wideband	Off-axis	Off-axis
Mass of far detector	40 kton (P1) up to 80 kton (P2)	190 kton	22.5 kton
Technology	Liquid Ar TPC	Water Cerenkov	Water Cerenkov
Running from	2030'ish	2028'ish	Now

CP violation and the Mass Hierarchy

Measuring δ_{CP} is the ultimate goal of neutrino oscillation experiments. How? δ_{CP} shows up in the imaginary part of the PMNS matrix.

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

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

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

CP violation can only take place in *appearance* experiments

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

In all it's naked glory

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

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

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

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

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

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

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

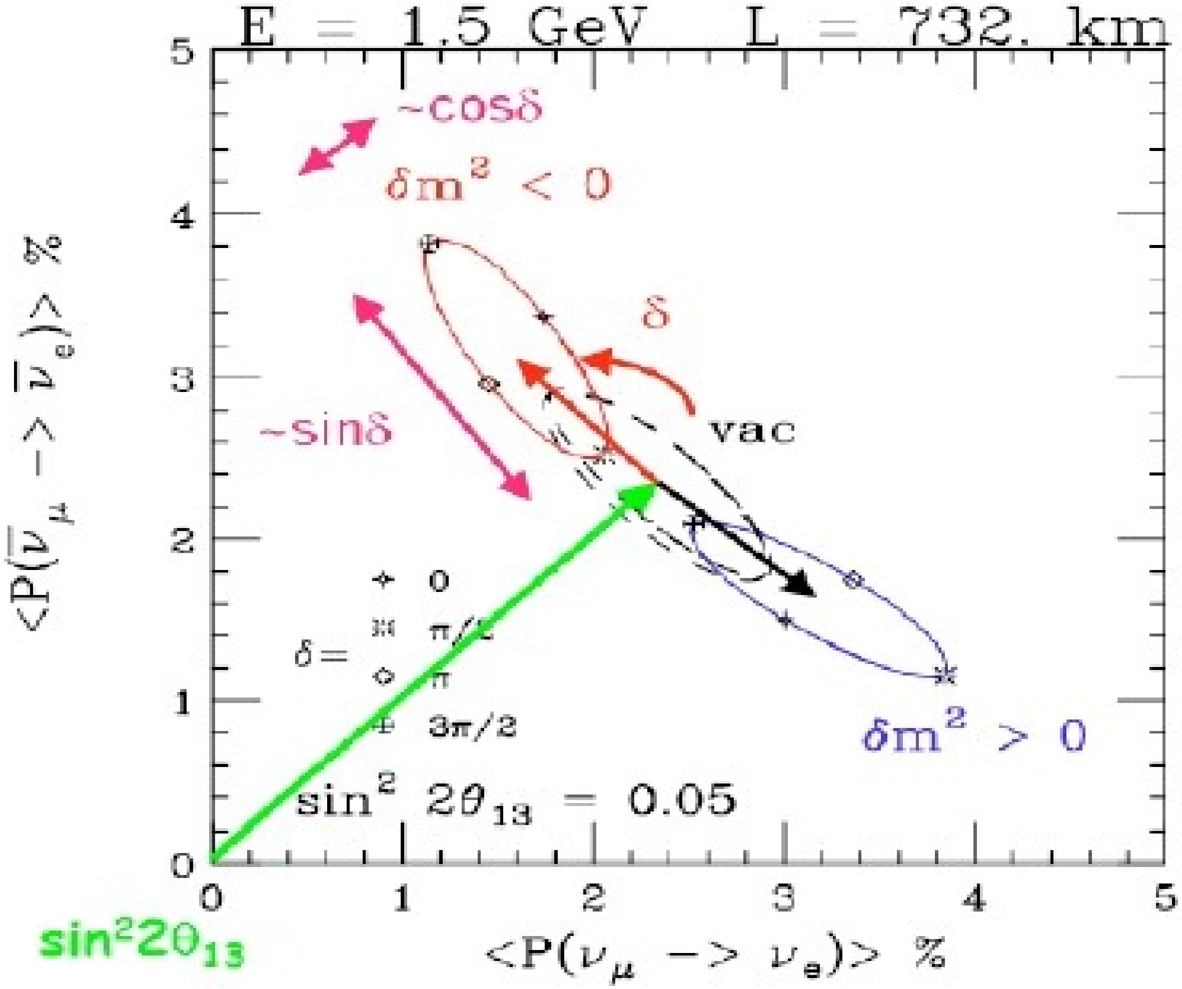
$$B_{-+} = |\Delta_{13} \mp A|$$

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

- θ_{13}
- $\theta_{23} > 45$ or $\theta_{23} < 45$
- Sign(Δm_{23}^2)
- $\delta_{\chi\pi}$

Degeneracies

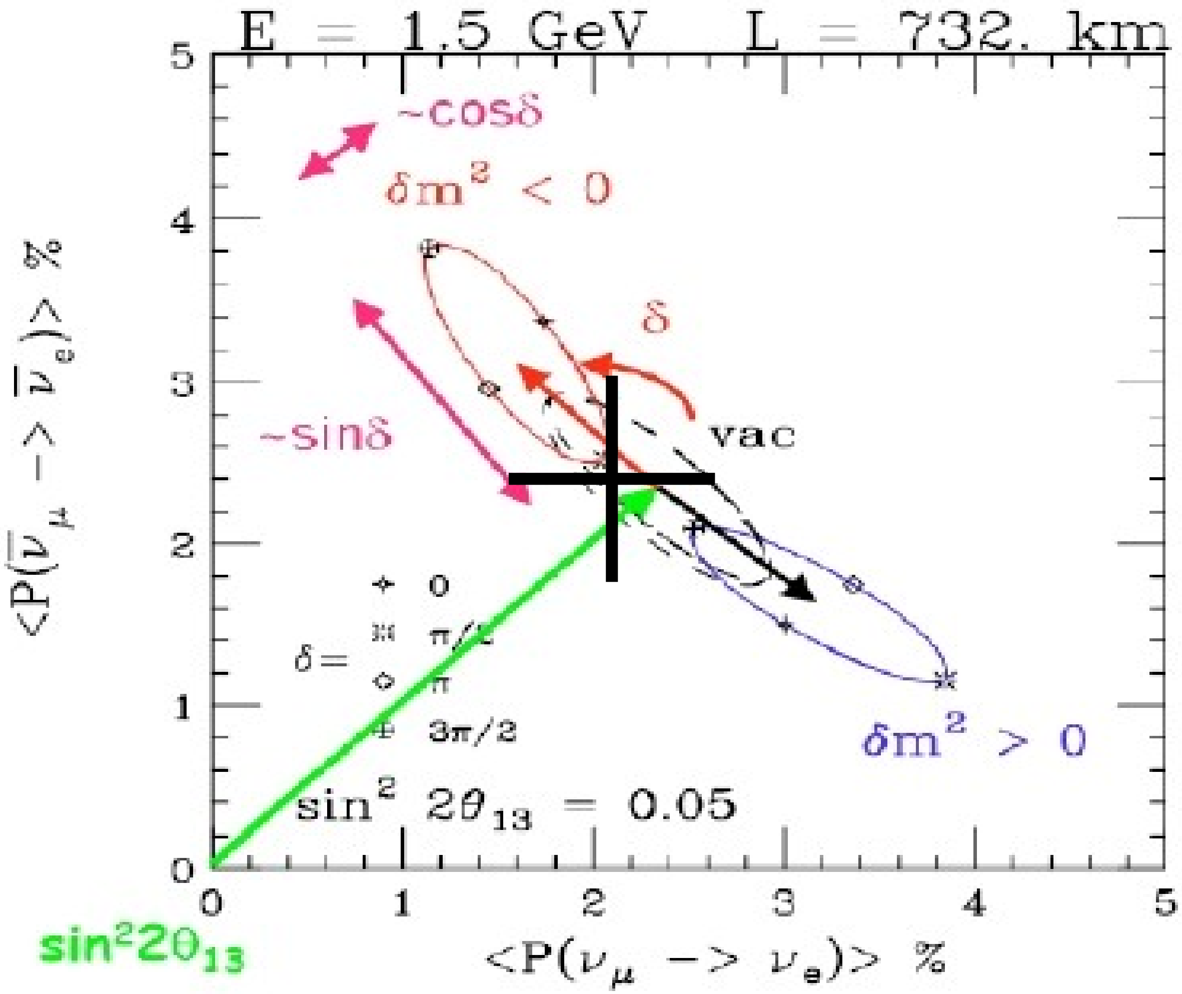
Experiments only measure at most two numbers; but probability has three unknowns and parameters with errors.



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

Degeneracies

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



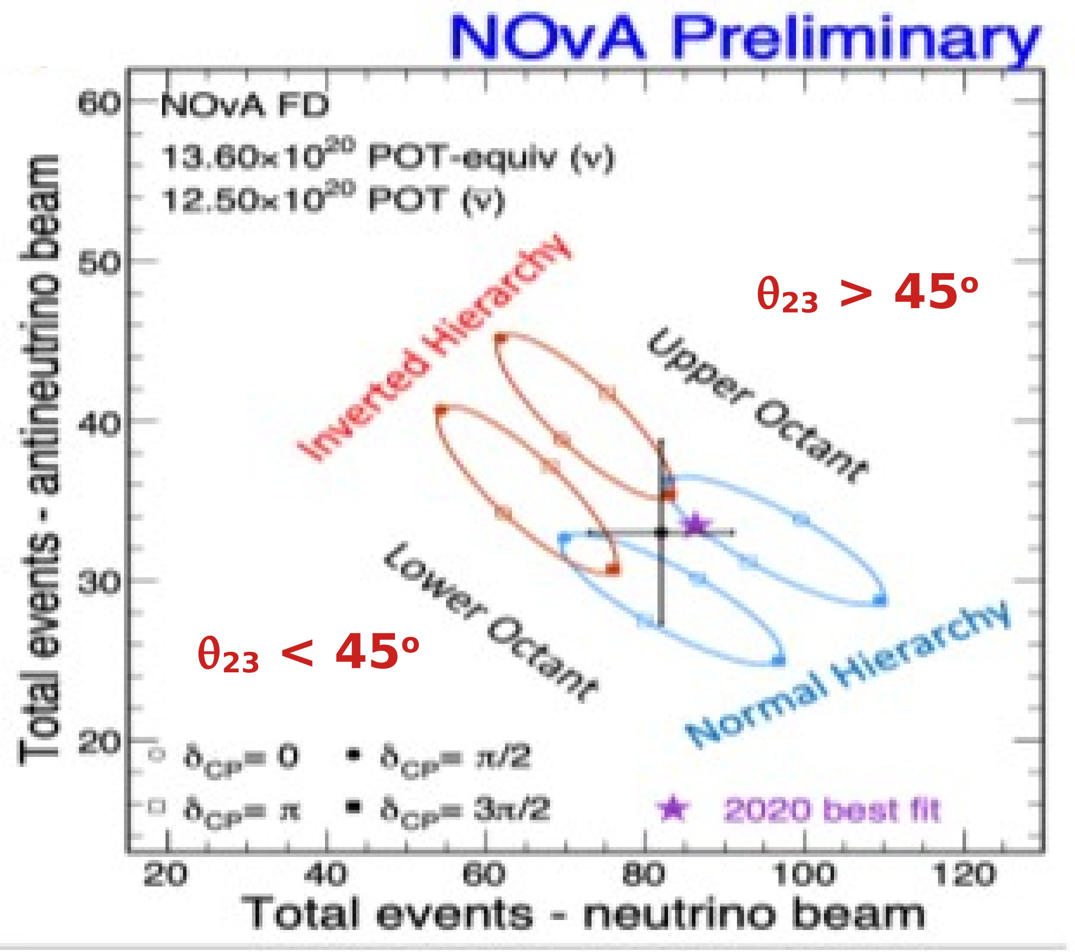
Need more than one measurement at different L/E to disentangle the parameter space

Mass Hierarchy measurements

As baseline grows, matter effects increase

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

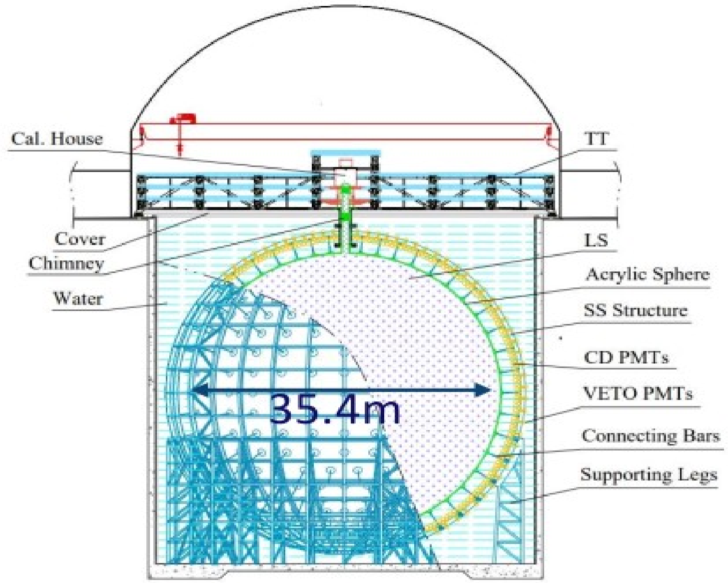
Once we've done that we need to determine CP phase

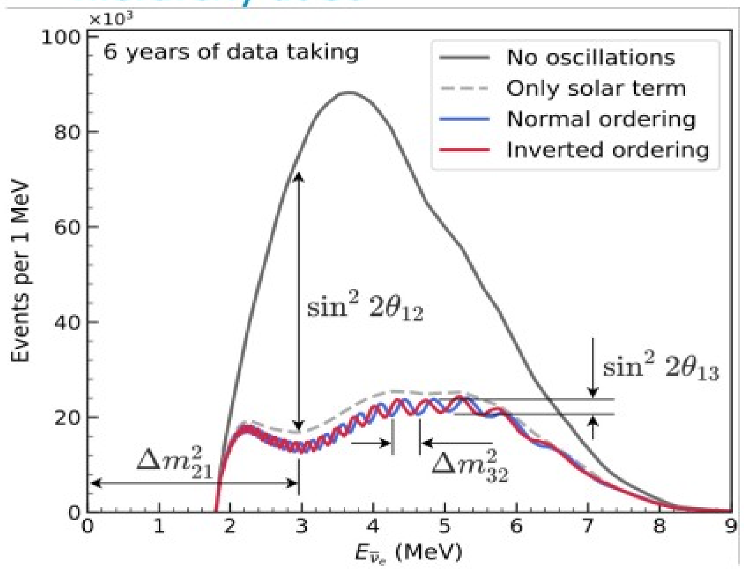


JUNO

Neutrino source: 26.6 GW_{th} from nuclear reactors
Experiment location: Jiangmen, China
Baseline: 53km
Main detector technology: Liquid Scintillator
Current Status: Under construction

- JUNO will measure $\bar{\nu}_e$ from Yangjiang and Taishan power plants
- Main goal: Neutrino Mass ordering
  - Simultaneous measurement of Δm^2_{31} and Δm^2_{32}
  - Independent of δCP and octant of θ_{23}
    - 6 years operation to determine mass hierarchy at 3σ

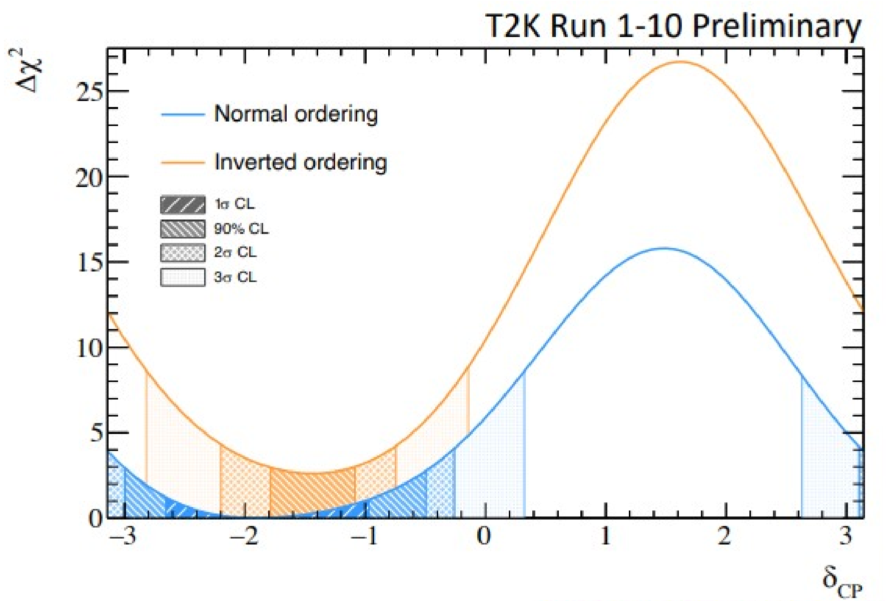




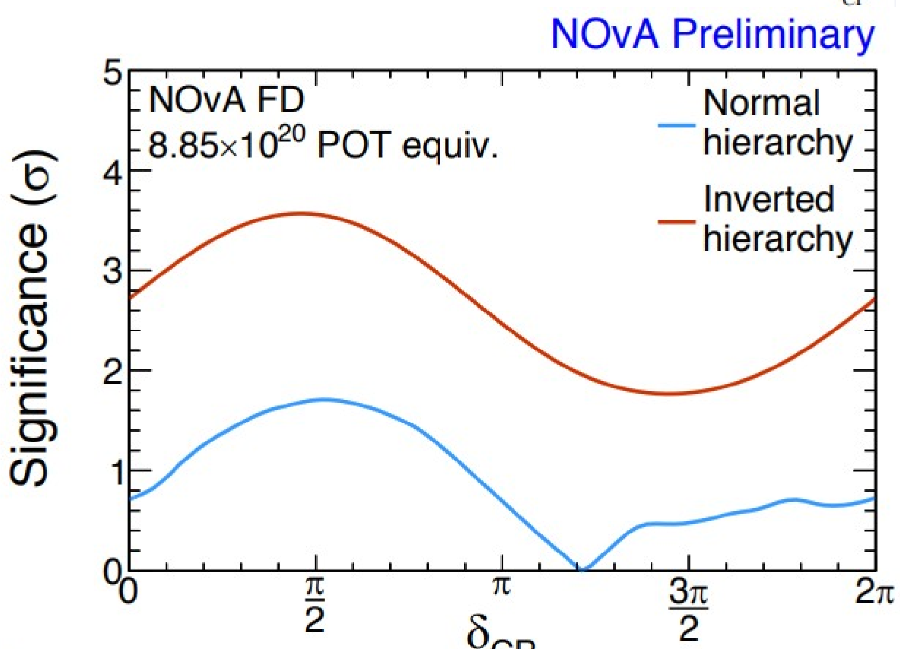
Largest liquid scintillator detector ever build

Data taking to begin this year

Hints of δ_{CP}? T2K & NOvA

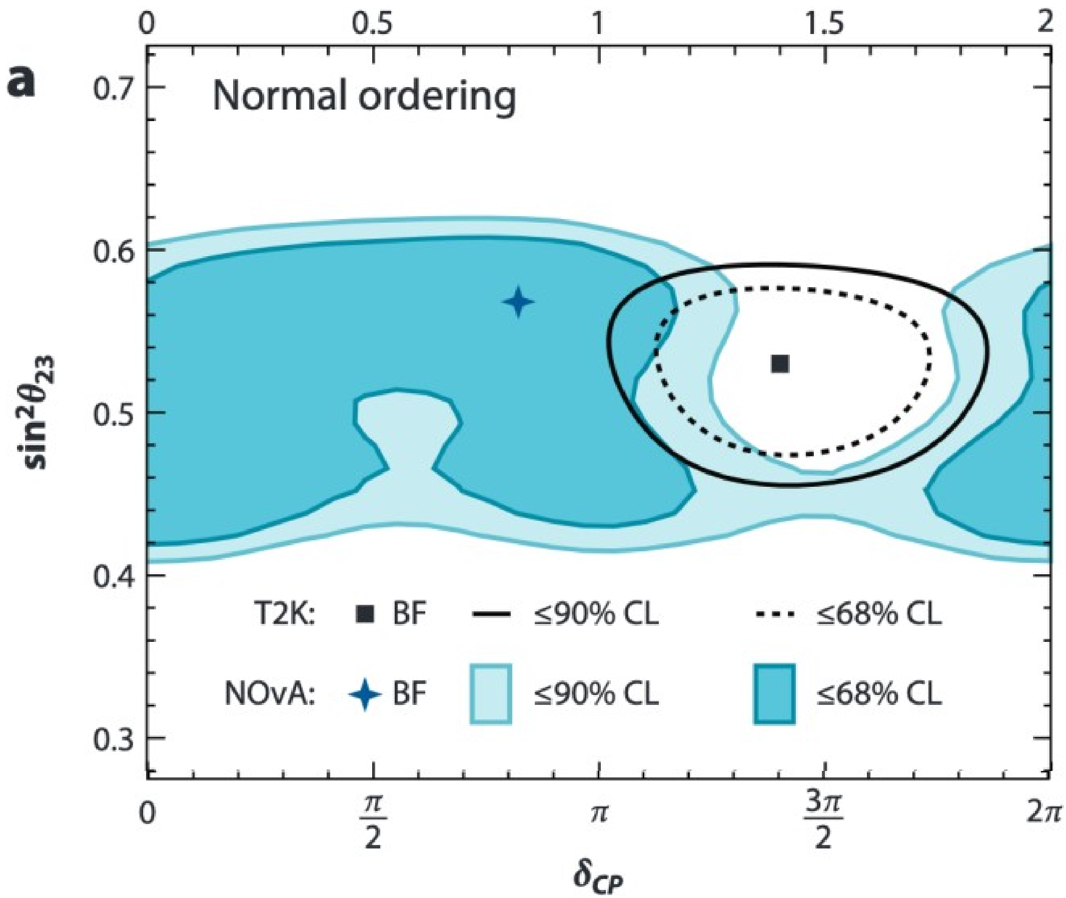


- Normal ordering weakly favoured
- δ_{CP}= 0 disfavoured at 2σ
- δ_{CP} > 0 disfavoured at 3σ



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

Slight tension



- Experiments are complementary : different baselines and energies mean that size of the mass ordering and δ_{CP} effects are different
- A combined fit of T2K and NOVA data is in the works.

Future project sensitivities

δ_{CP} : DUNE Sensitivity

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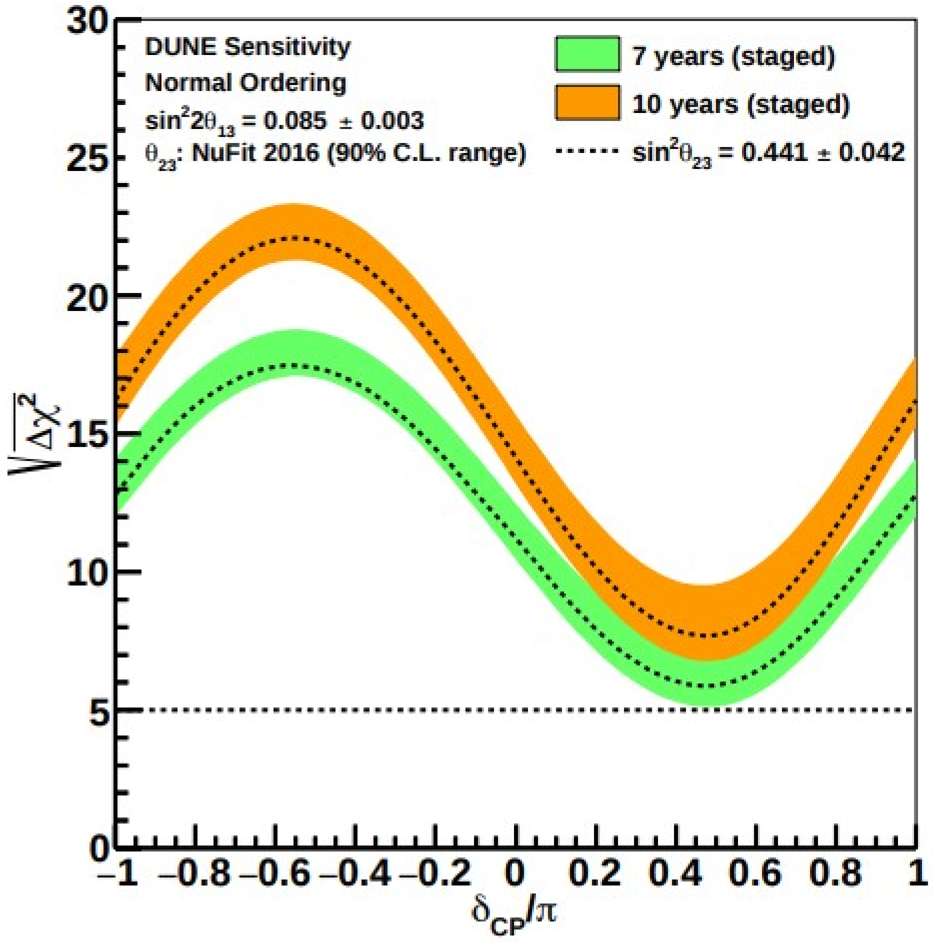
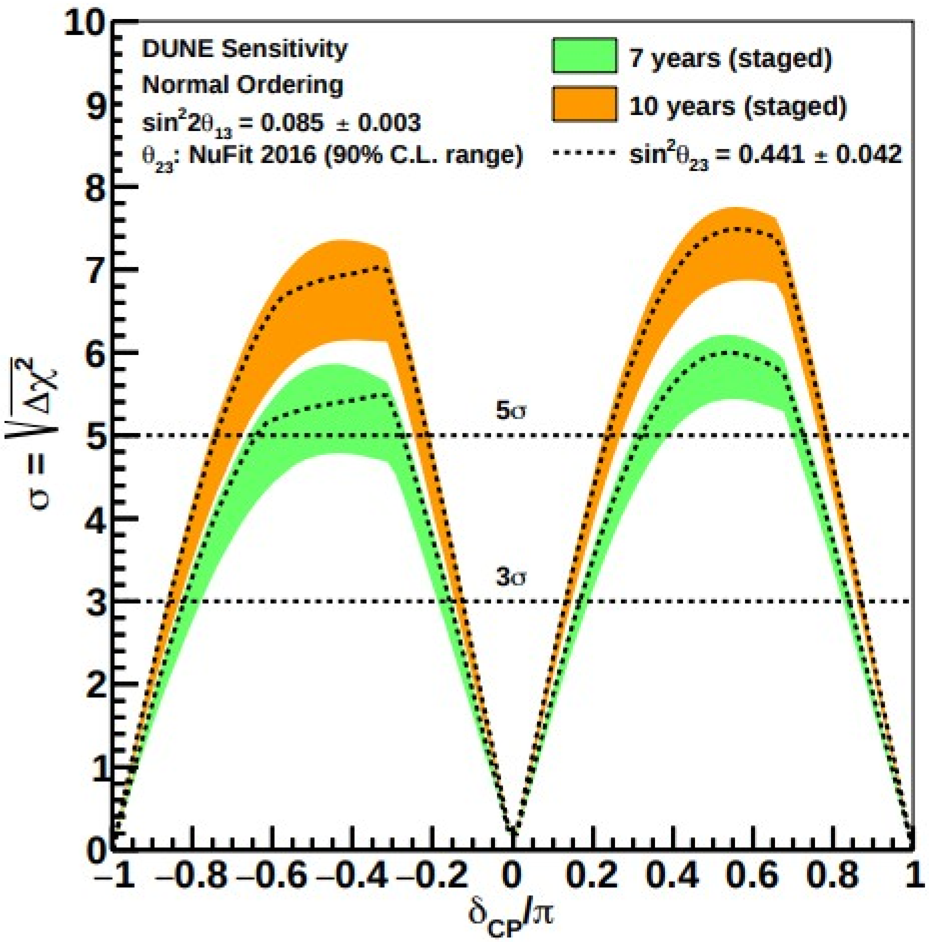
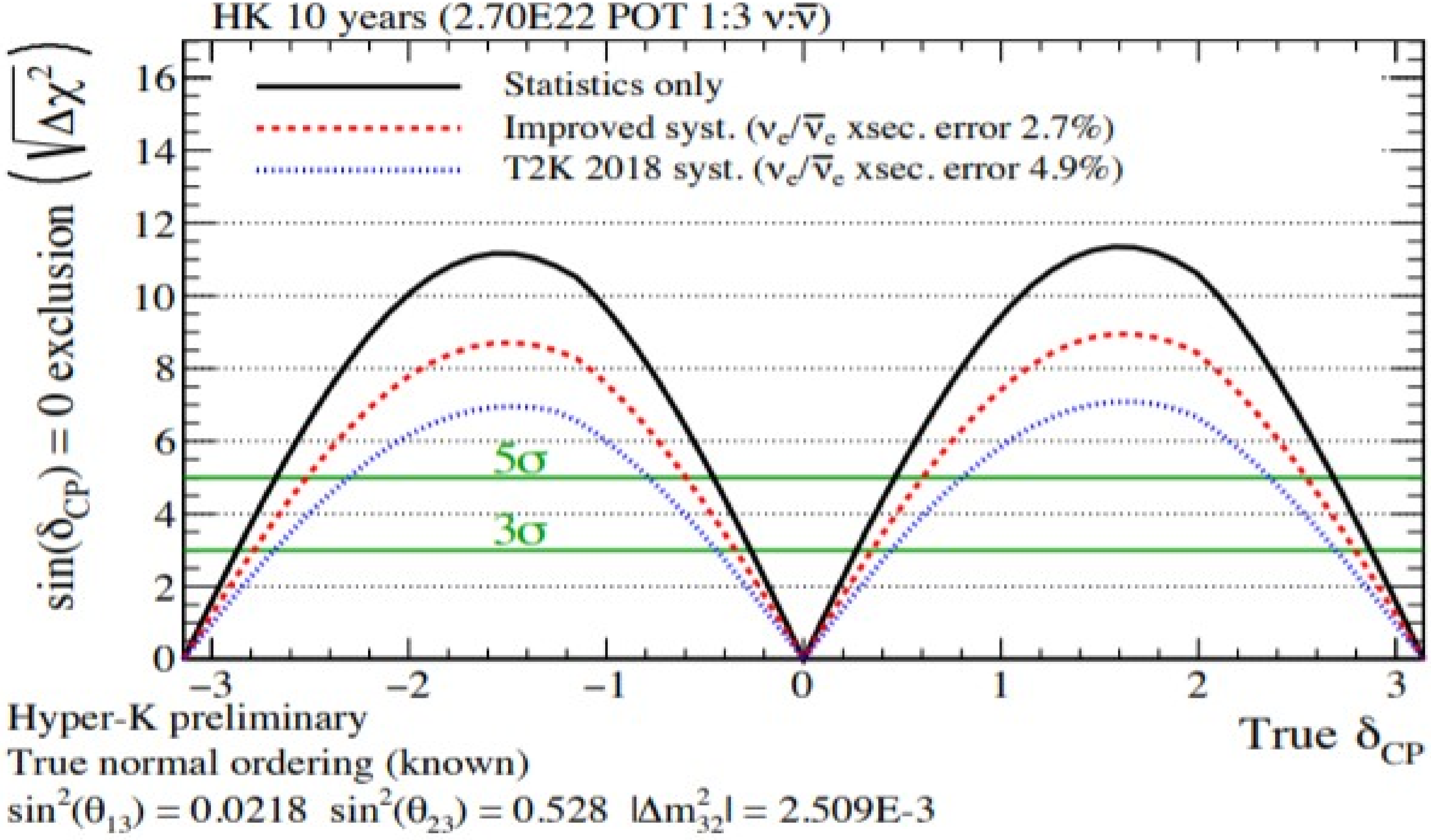




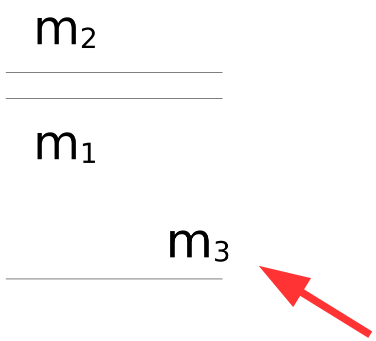
> 5 σ reach after 7 years of running over entire δ_{CP} range

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

HK δ_{CP} Sensitivity



A return to 0νββ decay



$$\Gamma(0\nu\beta\beta) \propto |\langle m_{\nu_e} \rangle|^2 = \left|\sum_i |U_{ei}^2| m_i e^{i\phi_i}\right|^2$$

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

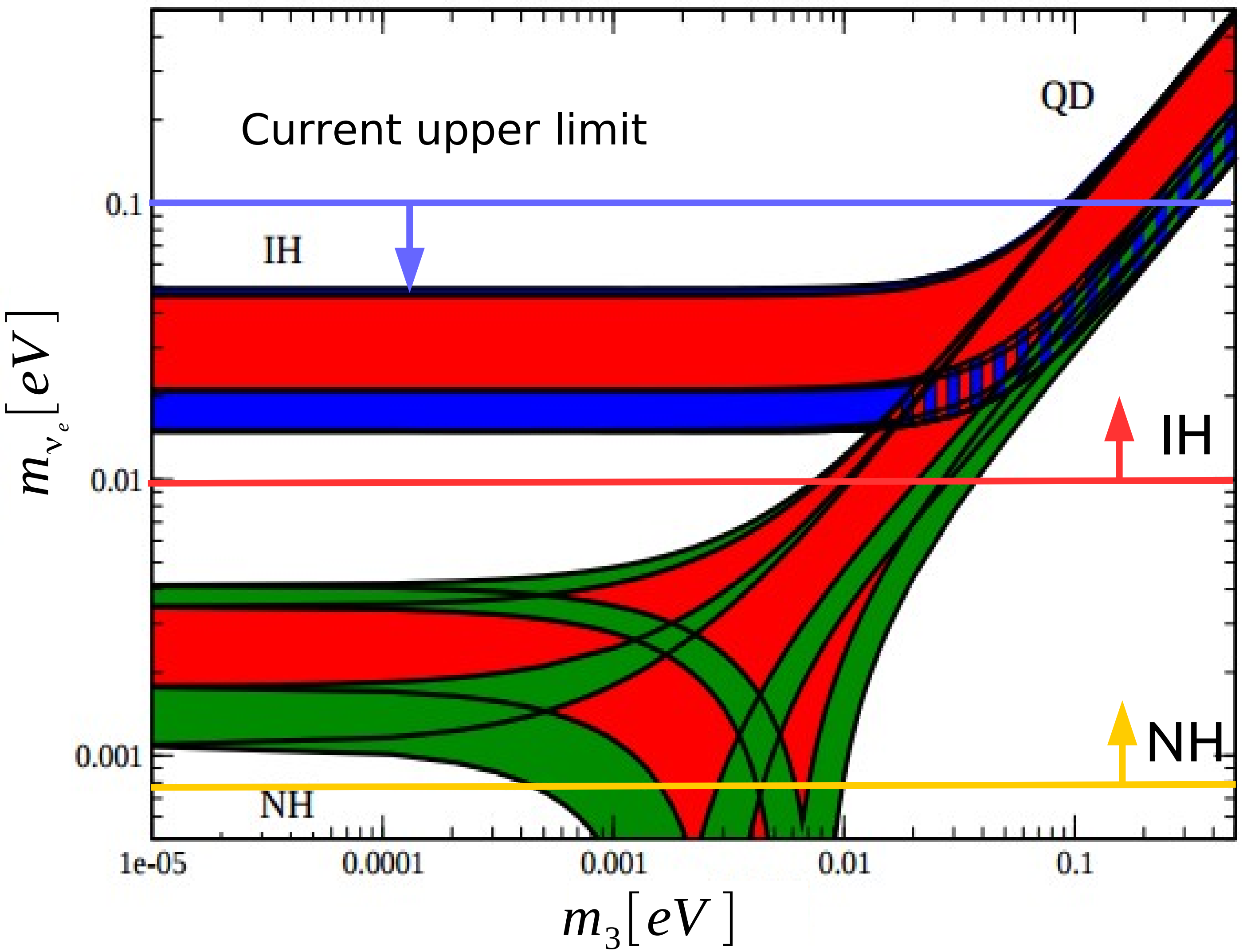
$$m_{\nu_e}^2 = \left| |U_{e1}|^2 \sqrt{m_3^2 + \Delta m_{23}^2} + |U_{e2}|^2 e^{i\alpha_2} \sqrt{m_3^2 + \Delta m_{23}^2} + |U_{e3}|^2 e^{i\alpha_3} m_3^2 \right|^2$$

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

$$m_{\nu_e} > \sqrt{\Delta m_{23}^2} \cos^2\theta_{13} (1 - 2\sin^2\theta_{12})$$

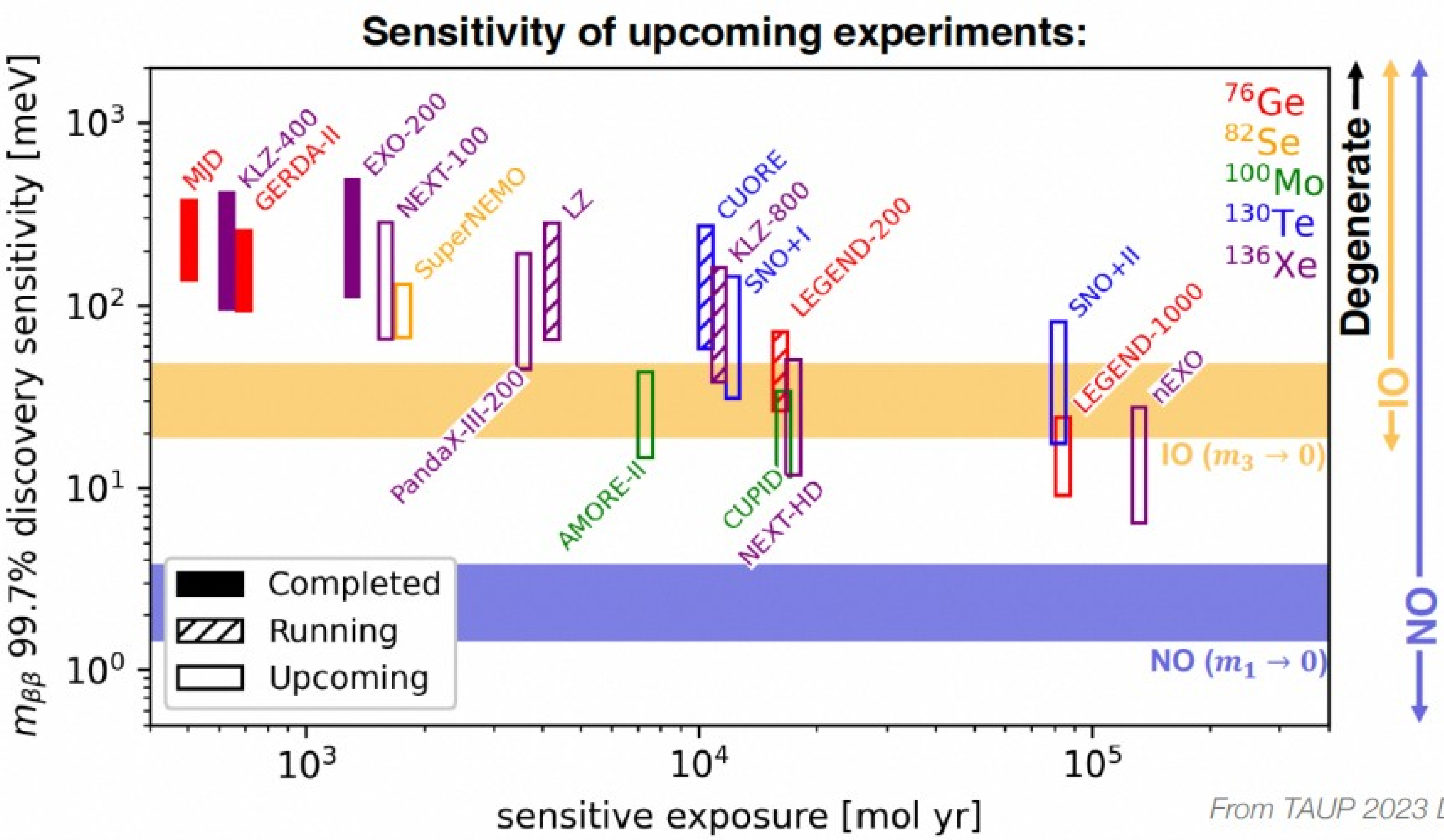
i.e for the inverted hierarchy, the average electron neutrino mass would have a *lower limit at small m_3*

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.

Exp. sensitivities



From TAUP 2023 D. Moore

Mass Hierarchy Determination

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

Timescale : ~ 5 years from now for 4 σ good indication from NOVA + T2K + JUNO

Measurement of δ_{CP}

Next generation of experiments are being planned to measure this

Timescale : 6-8 years from now (including 5 for construction) for 3σ sensitivity to distinguish from no CP-violation scenario (if true δ_{CP} is $\pi/2$).

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

The Roadmap - 2005

We are at the beginning of a global coordinated effort to unravel the neutrino sector

Now → Measure 23 sector to 10%
MINOS, K2K, OPERA, miniBoone

2009 → Measure θ_{13}; Probably need 2 measurements at different L/E and an antineutrino measurement to unravel ambiguities.
T2K/NOvA, Reactor experiments

2015 2020 → Precision measurements of all parameters
Phase 2 Superbeams, β beams, Neutrino Factories

The next 20 years – 2009

Measurement	Method	Experiments	Why?	When
$\|\Delta m_{23}^2\|$	ν_μ Disapp.	MINOS	More precise Estimates	2007
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
$\mathrm{Sgn}(\Delta m_{23}^2)$ δ_{CP}	ν_e / anti-ν_e	T2KK, neutrino Factory, ???	Unification, GUT Lepton asymmetry	2025?

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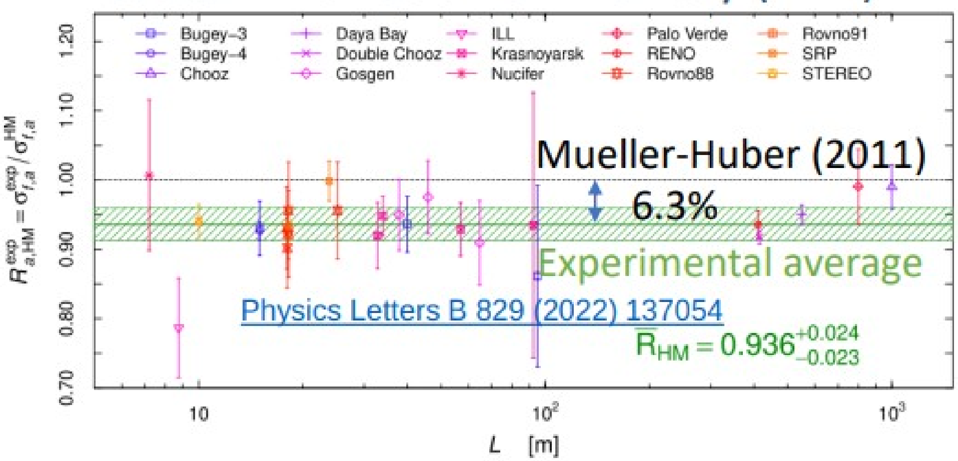
$Sgn(\Delta m_{23}^2)$ δ_{CP}	ν_e / anti-ν_e	T2KK, neutrino Factory, ???	Unification, GUT Lepton asymmetry	2025?	✘

The next 20 years – 2024

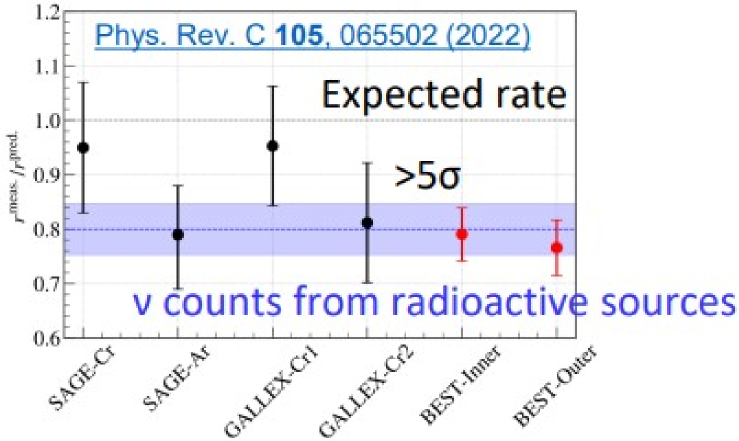
Measurement	Method	Experiments	Why?	When	
$\|\Delta m_{23}^2\|$	ν_μ Disapp.	MINOS	More precise Estimates	2007	✔
θ_{23}	ν_μ Disapp.	DUNE, HK, JUNO		2030's	✘
θ_{13}	ν_e Appear.	T2K, NovA	Equal to 0? Can't measure δ_{CP} if it is	2012	✔
	Anti-ν_e Disapp.	Reactor		2012	✔
$Sgn(\Delta m_{23}^2)$ δ_{CP}	ν_e / anti-ν_e	DUNE, HK, JUNO		2030's	✘


ANOMALIES
LIGHTYEAR
ANOMALIES EVERYWHERE

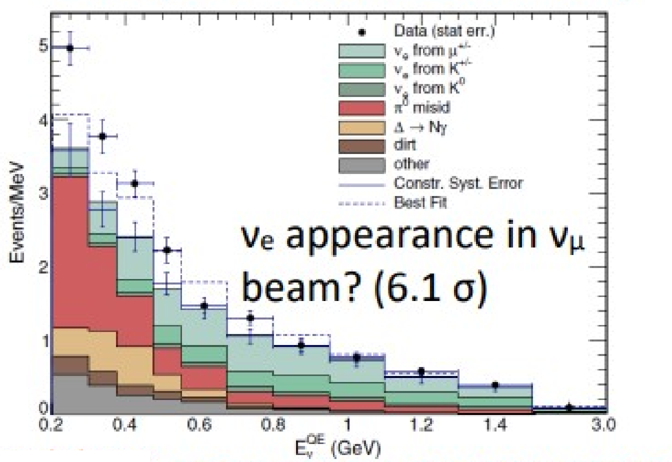
- Reactor Antineutrino Anomaly (RAA)



- Gallium Anomaly



- LSND/MiniBooNE Anomaly



Phys. Rev. Lett. 121, 221801 (2018)

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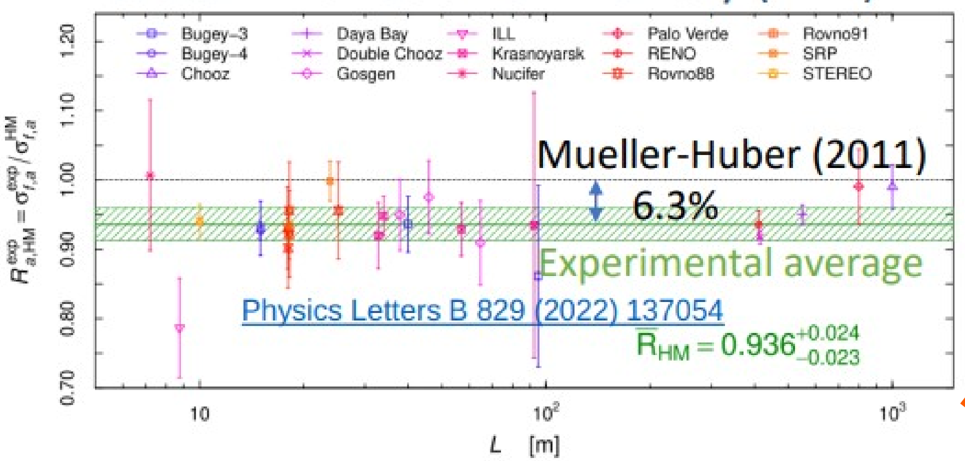

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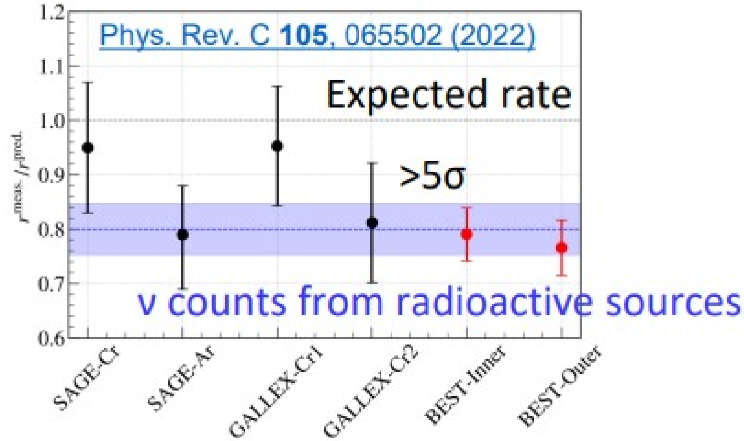

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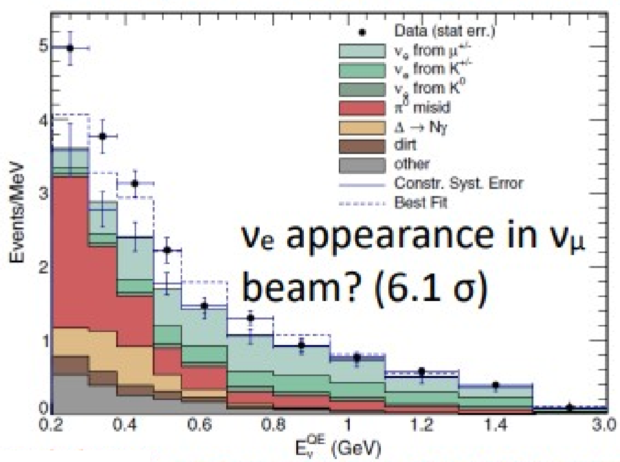
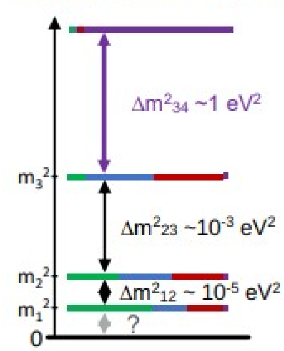
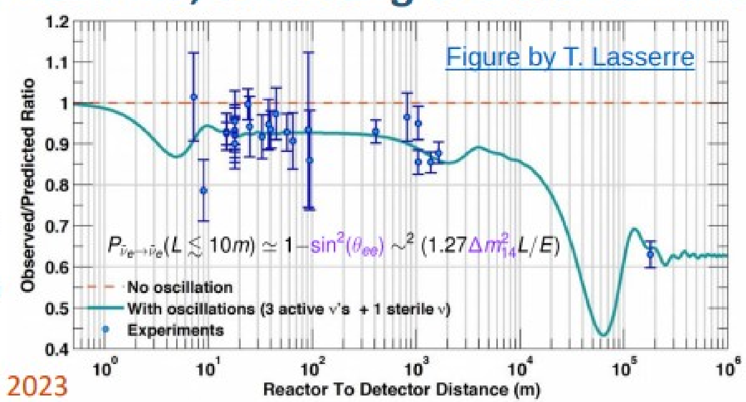


Phys. Rev. Lett. 121, 221801 (2018)

New 0.1-1 eV neutrino, consisting of a sterile flavor





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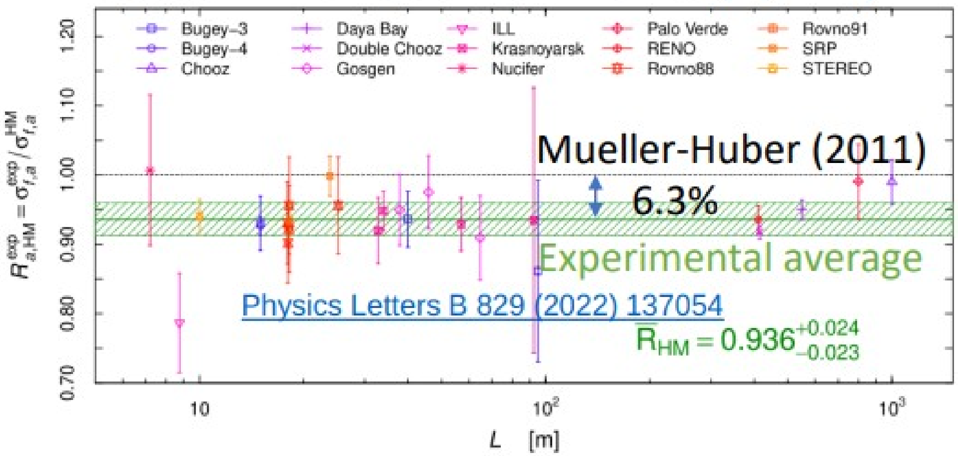

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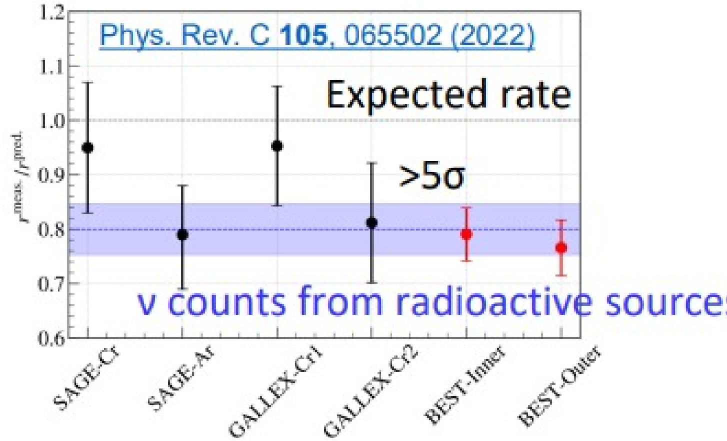

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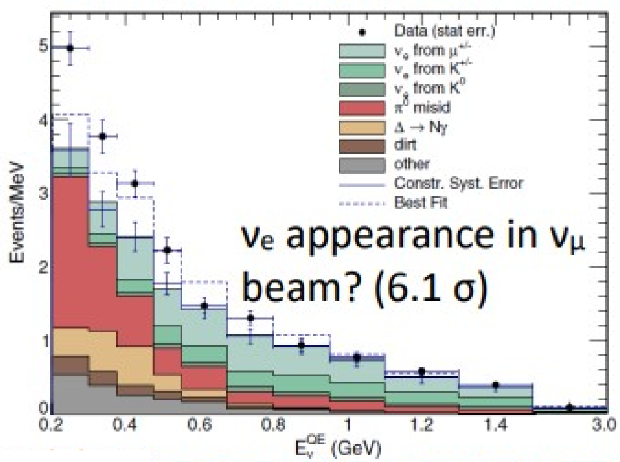

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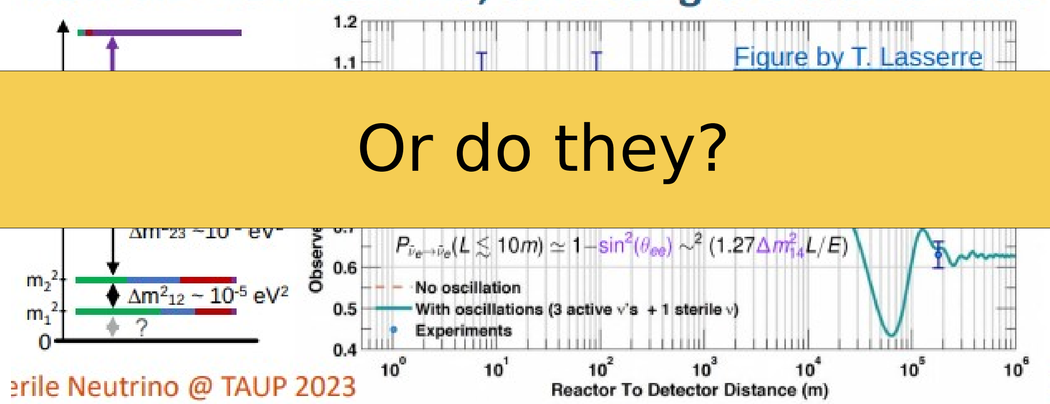


Or do they?

The Gallium Anomaly

We've discussed the Homestake experiment which studied

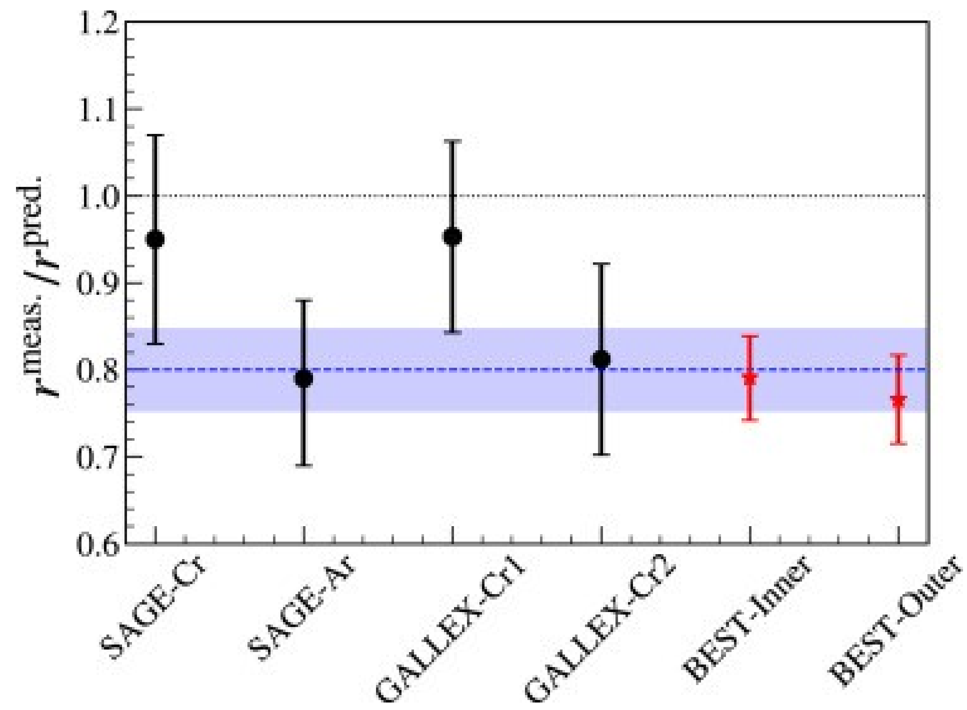
$$\nu_e + Cl^{37} \rightarrow Ar^{37} + e^-$$

A couple of experiments (SAGE and GALLEX) also studied

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

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.

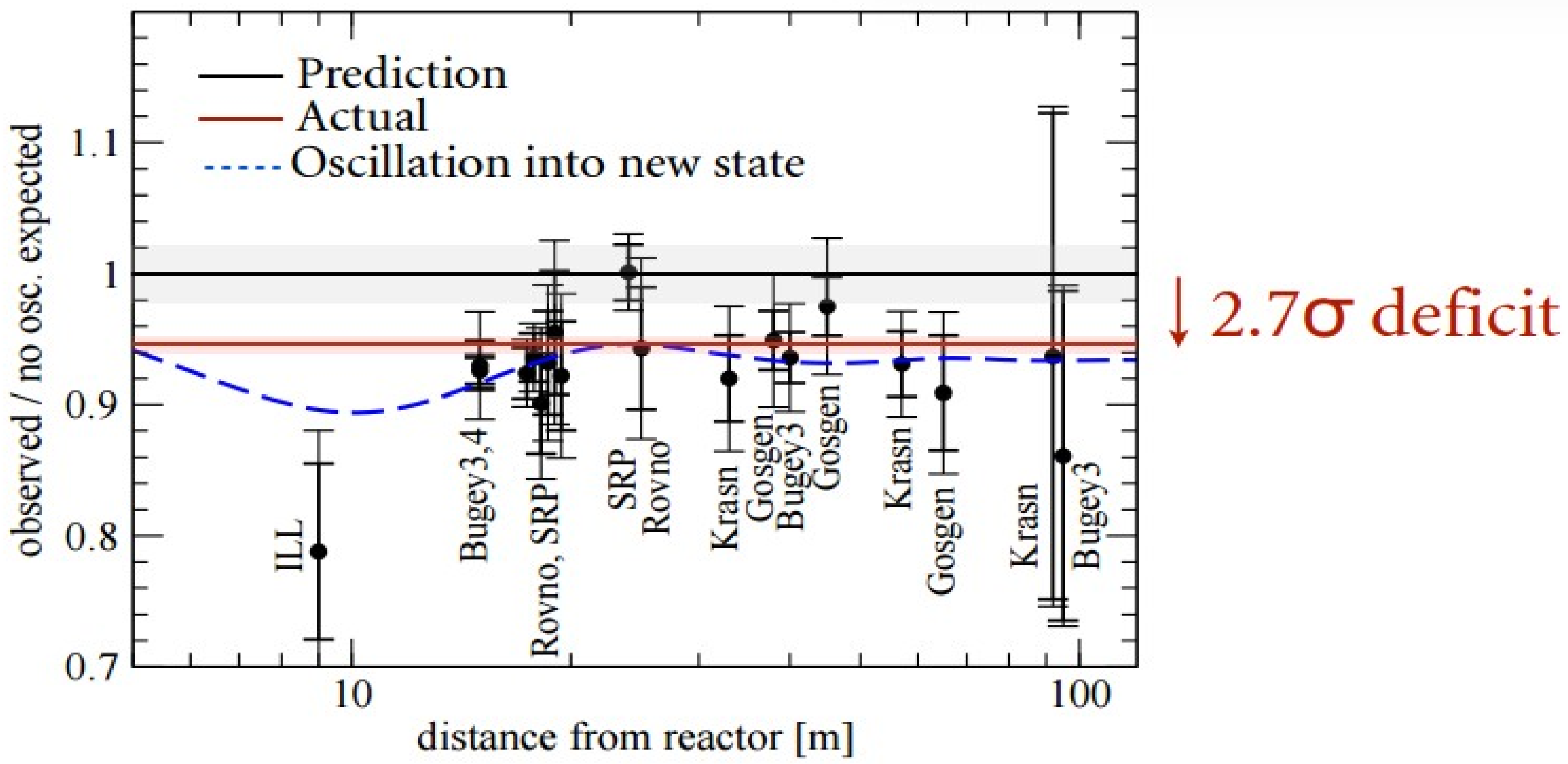
- In 2011, new techniques in modelling nuclear reactions led to a re-evaluation of the expected electron antineutrino flux. The new estimate was about 6% **higher** than the old.

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

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

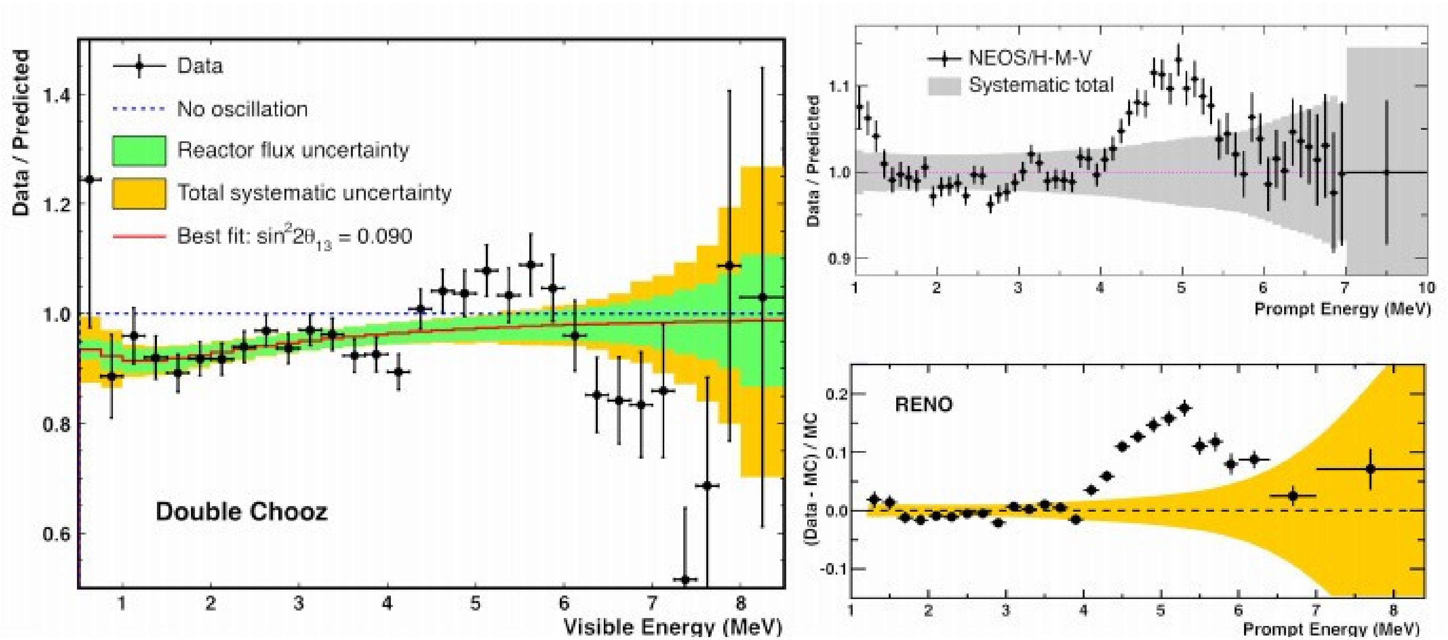
- Could this be (i) the new flux estimate is just a bit dodgy or (ii) we have short baseline neutrino oscillations to a sterile state?

Reactor Anomaly



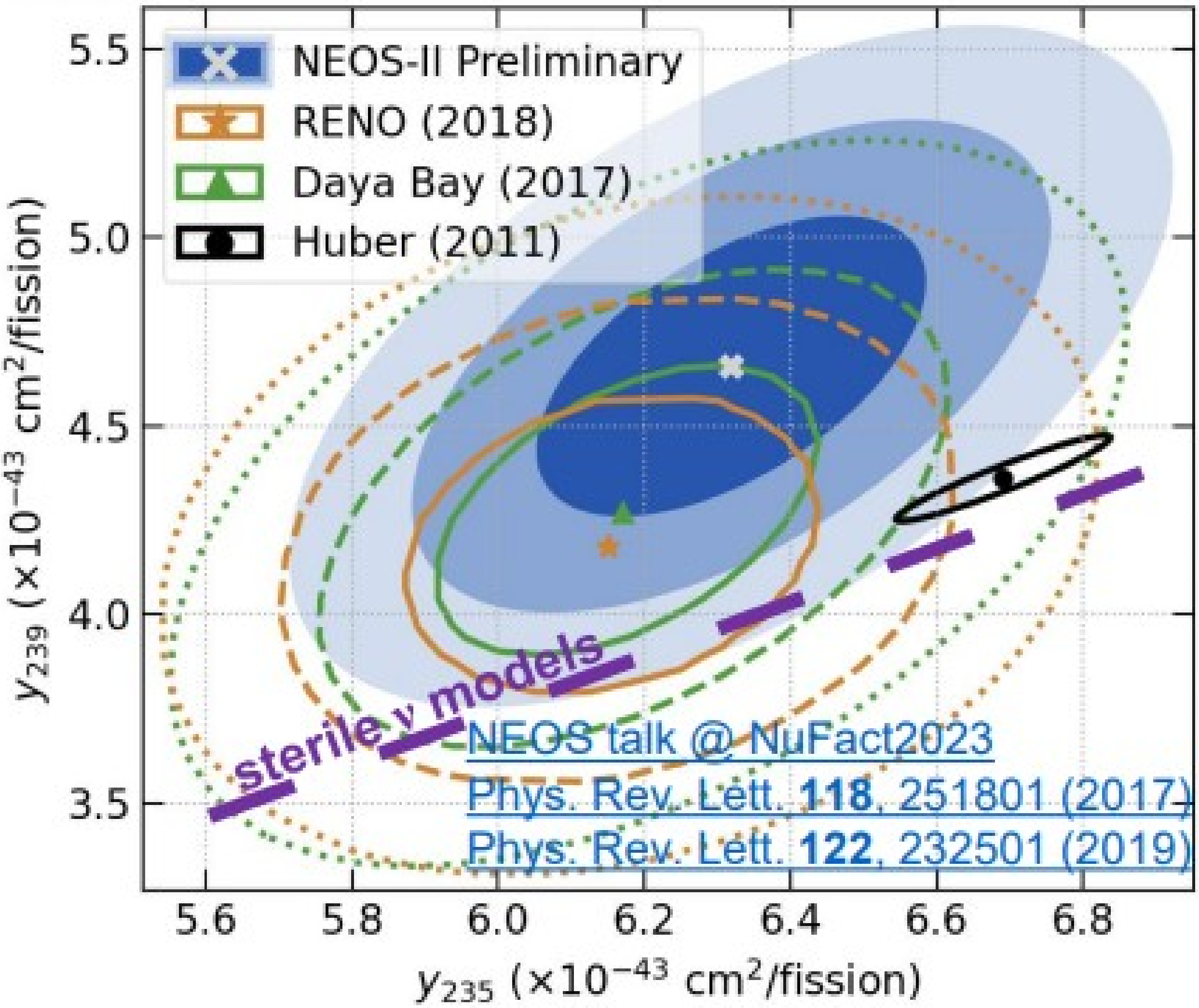
Deficit consistent with a sterile state with $\Delta m^2 \sim 1.5\ eV^2$
Reactor antineutrino flux calculations are VERY hard to do
It's almost certain that this is an issue with the calculation of the antineutrino flux NOT steriles.

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 reactor flux

New fluxes - again



- Reactor flux deficit has probably gone away now
- "New" 2011 flux overestimated the flux from U-235
- New flux measurements suggest that the reactor flux deficit was not real

Reactor Experiments

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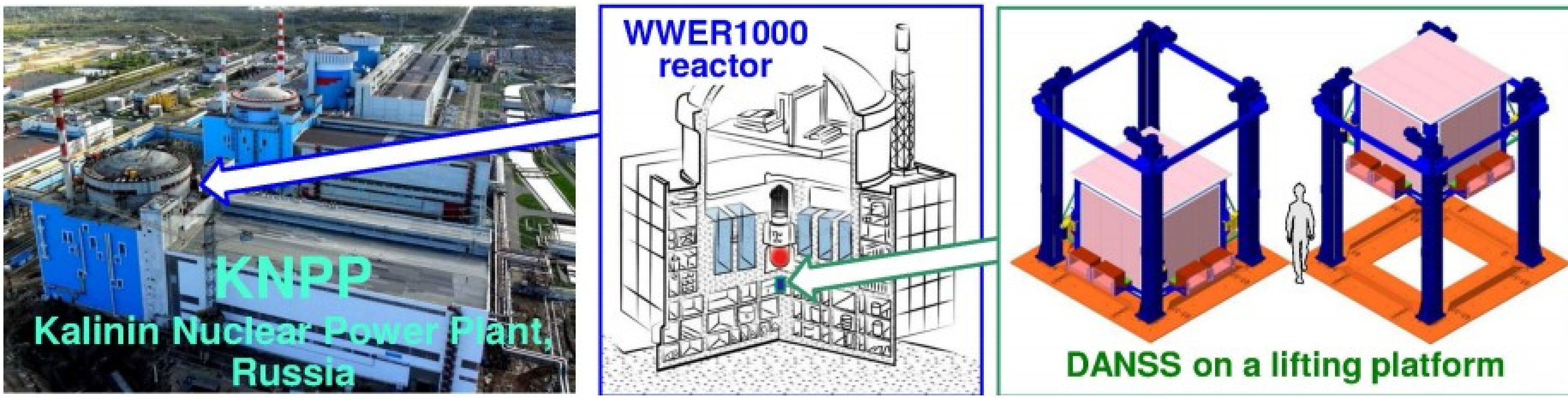
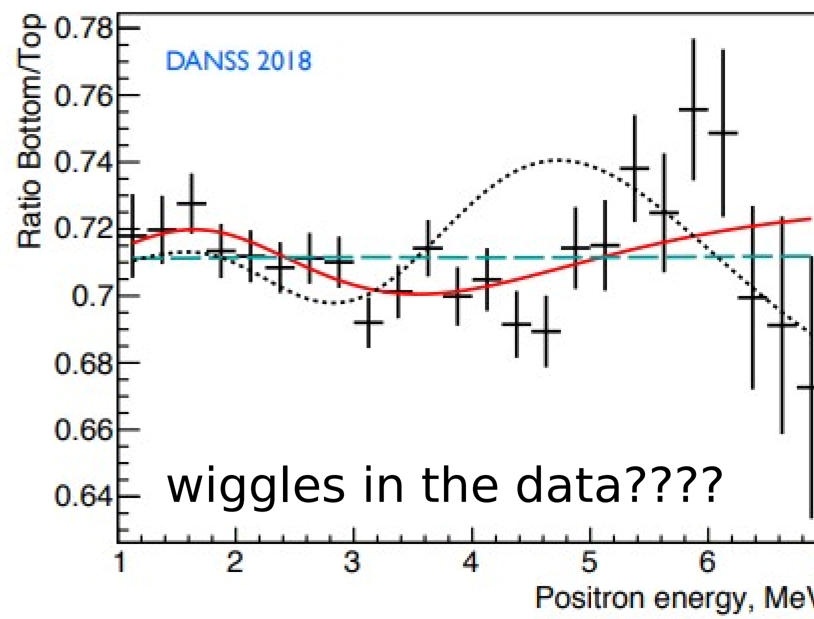
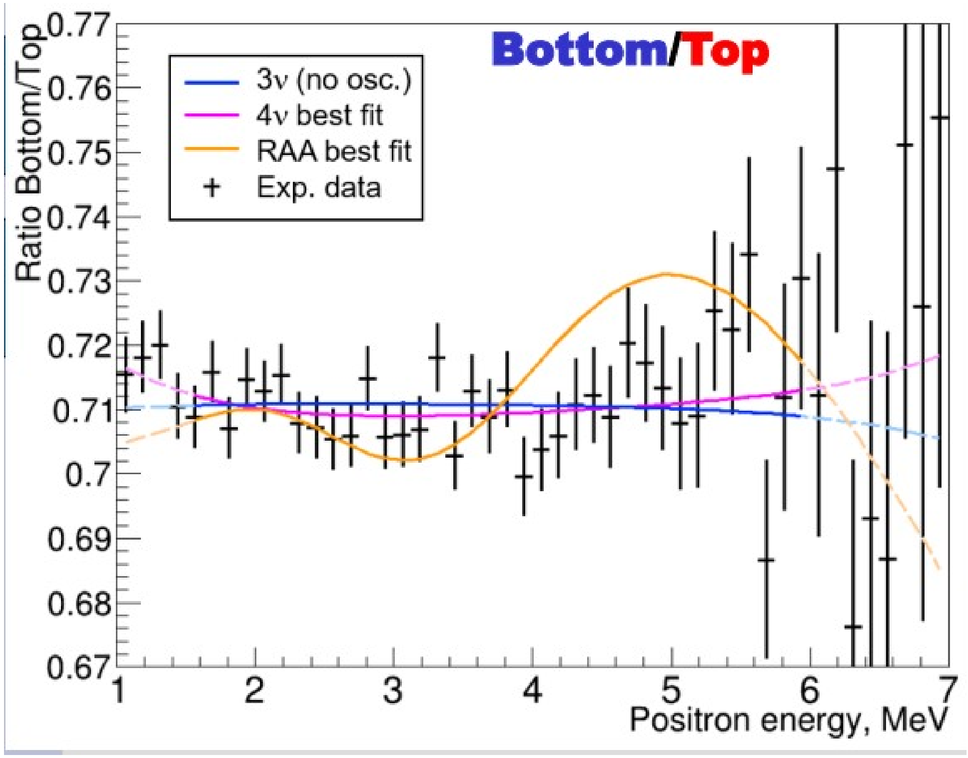
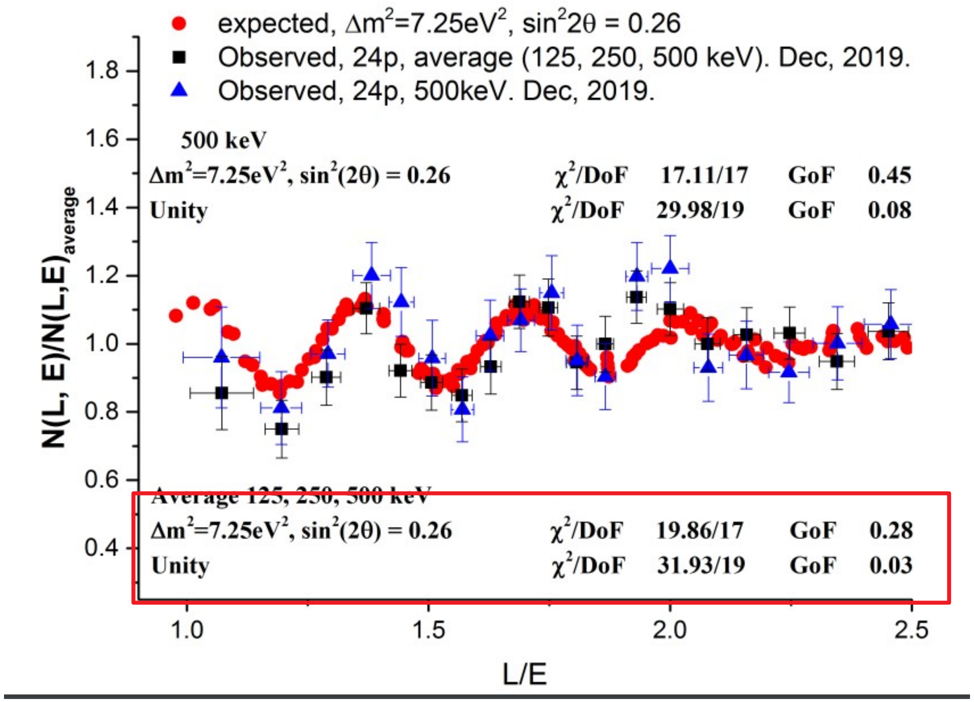


- Installed on a moveable platform under a 3 GW reactor
- Large neutrino flux
- Variable source-distance distance using the same detector
- Down : 12.7 m from reactor
- Up : 10.7 m from reactor



Reactor Experiments





DANSS (2020)
No visible effect

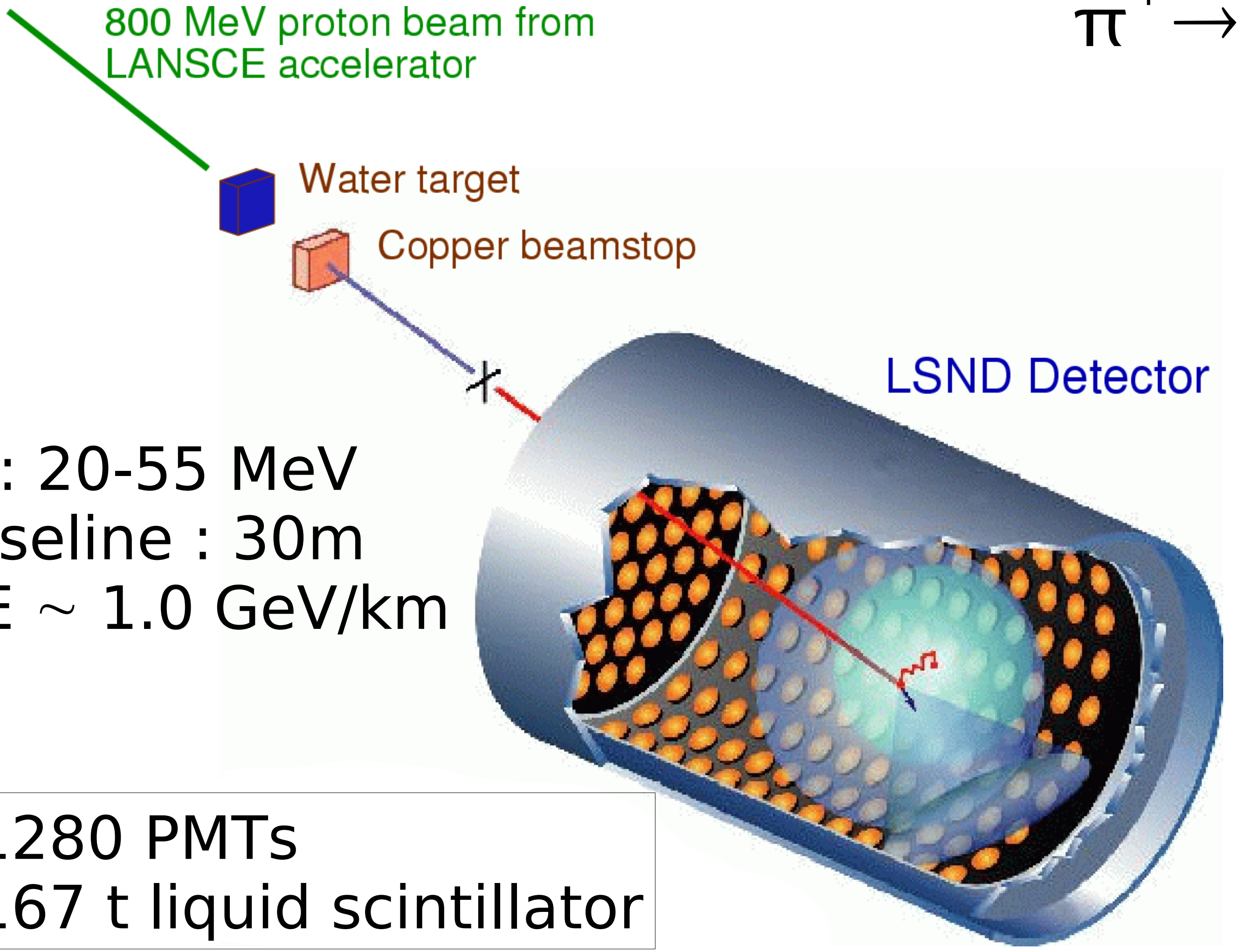
Neutrino4 (2020)
Claimed signal

Situation unclear : other experiments (Stereo, SoLiD, Prospect) don't see oscillations like this.

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)

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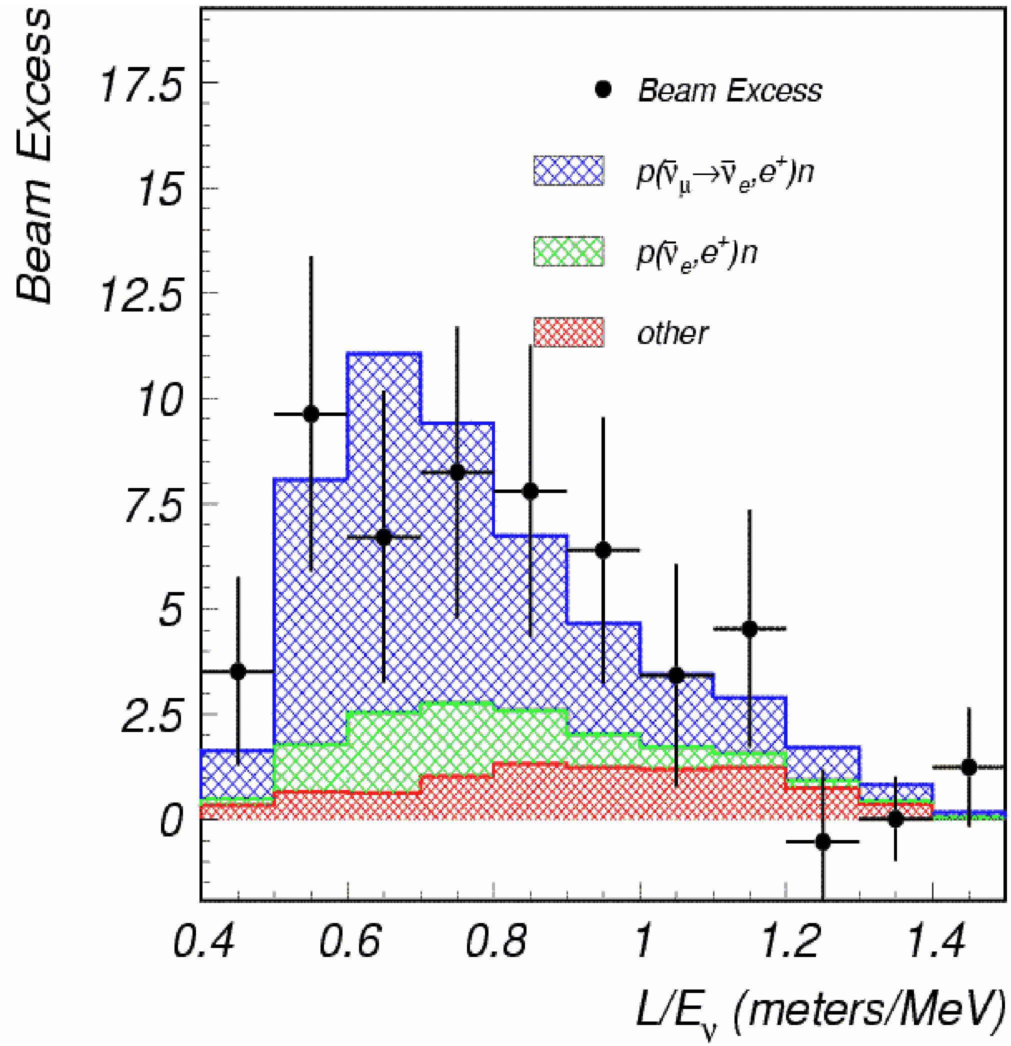
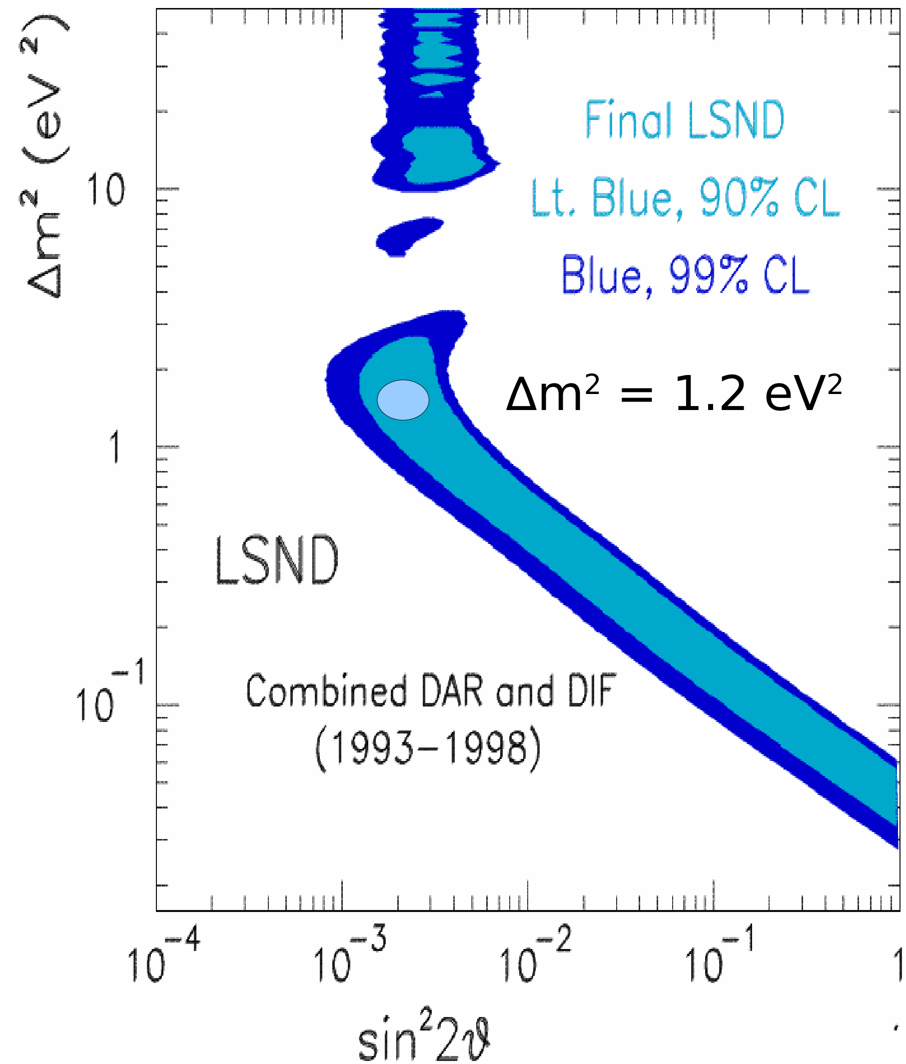
$87.9 \pm 22.4 \pm 6$ excess events from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

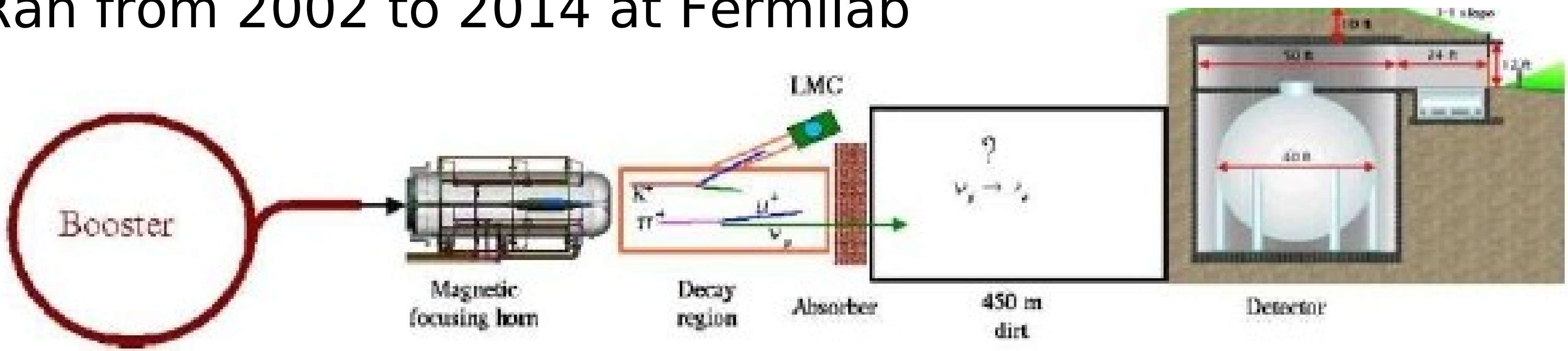
$3.3\ \sigma$ evidence for oscillations





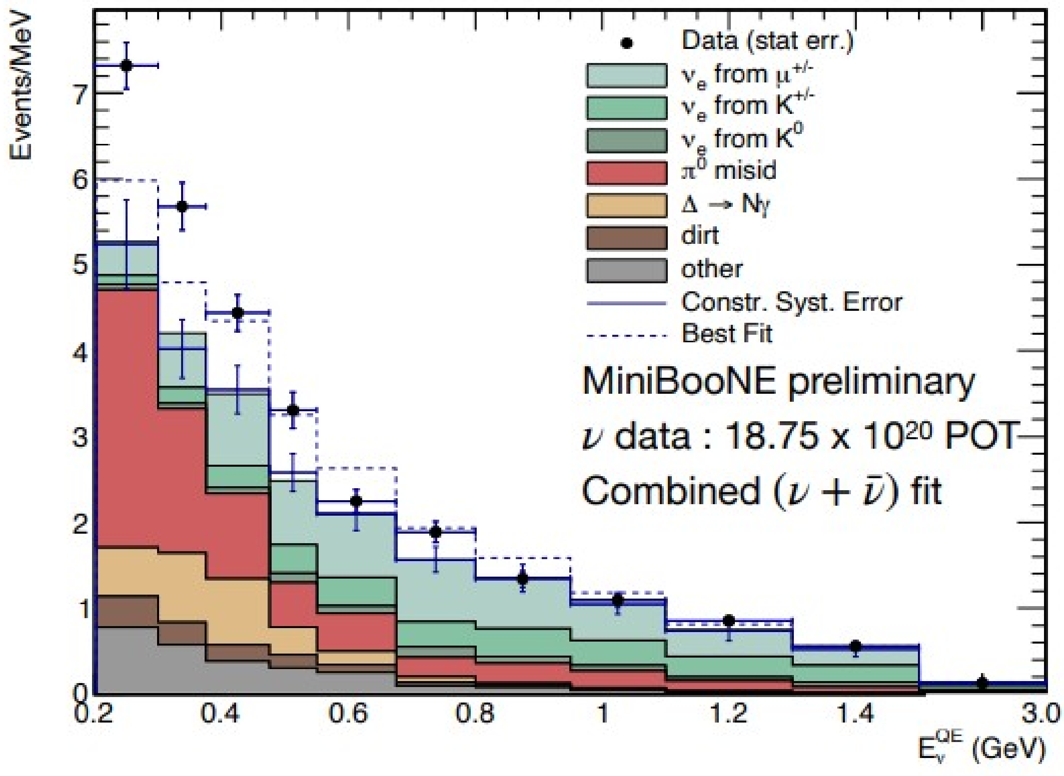
MiniBooNE

Ran from 2002 to 2014 at Fermilab

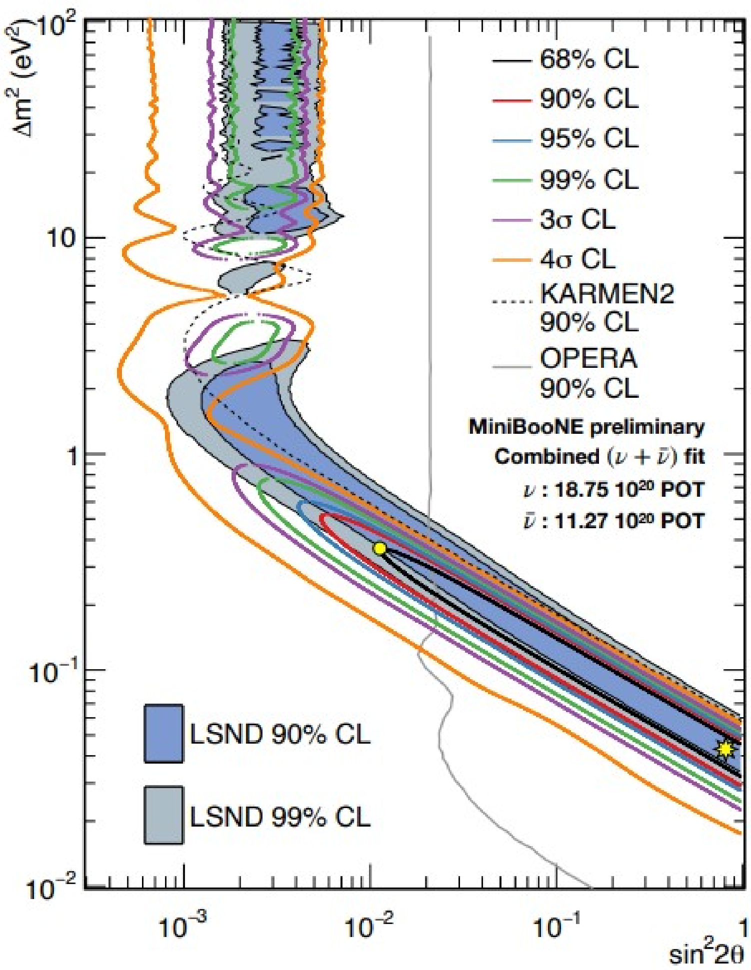


- Average neutrino energy ≈ 1 GeV
- L/E the same as LSND
- Same technology as LSND
- Different energy = different event types = different systematics

miniBooNE Results



Excess at the level of 4.8 σ

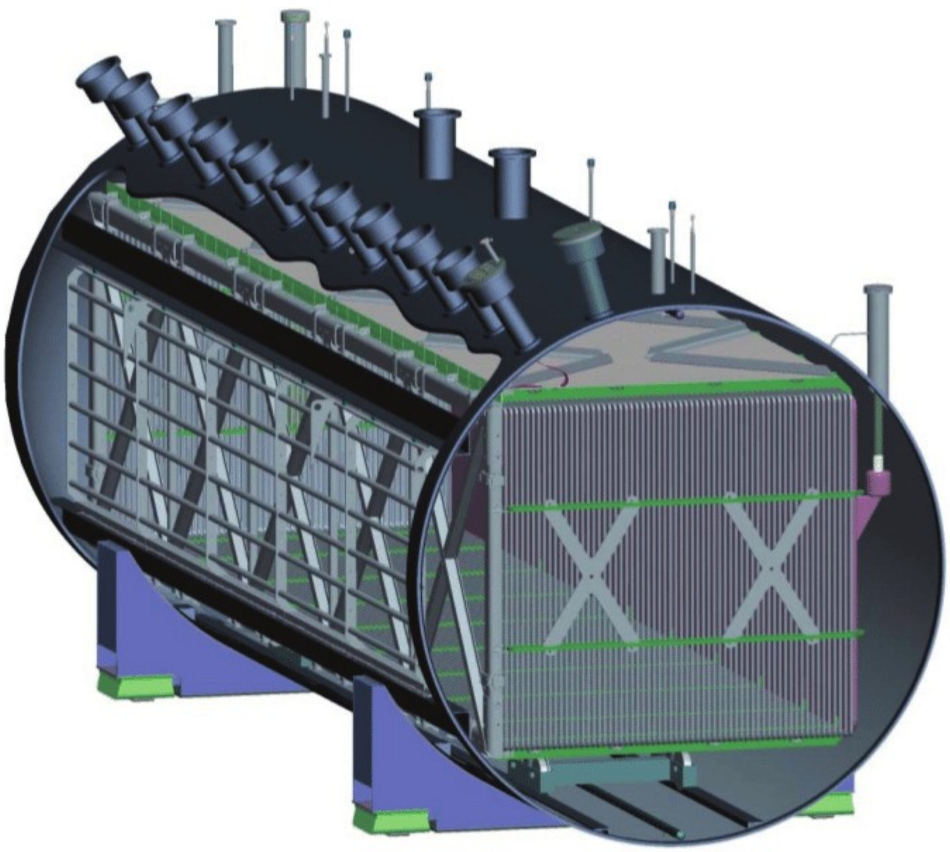


Neutrino + Anti-Neutrino Mode

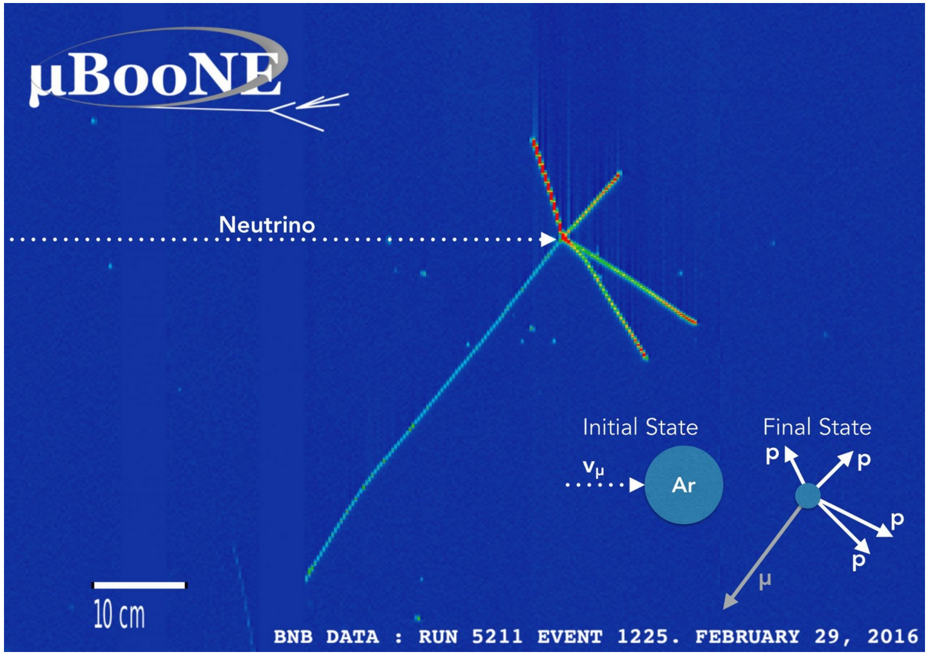
$(\Delta m^2, \sin^2 2\theta) = (0.043\ \mathrm{eV}^2, 0.807)$

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

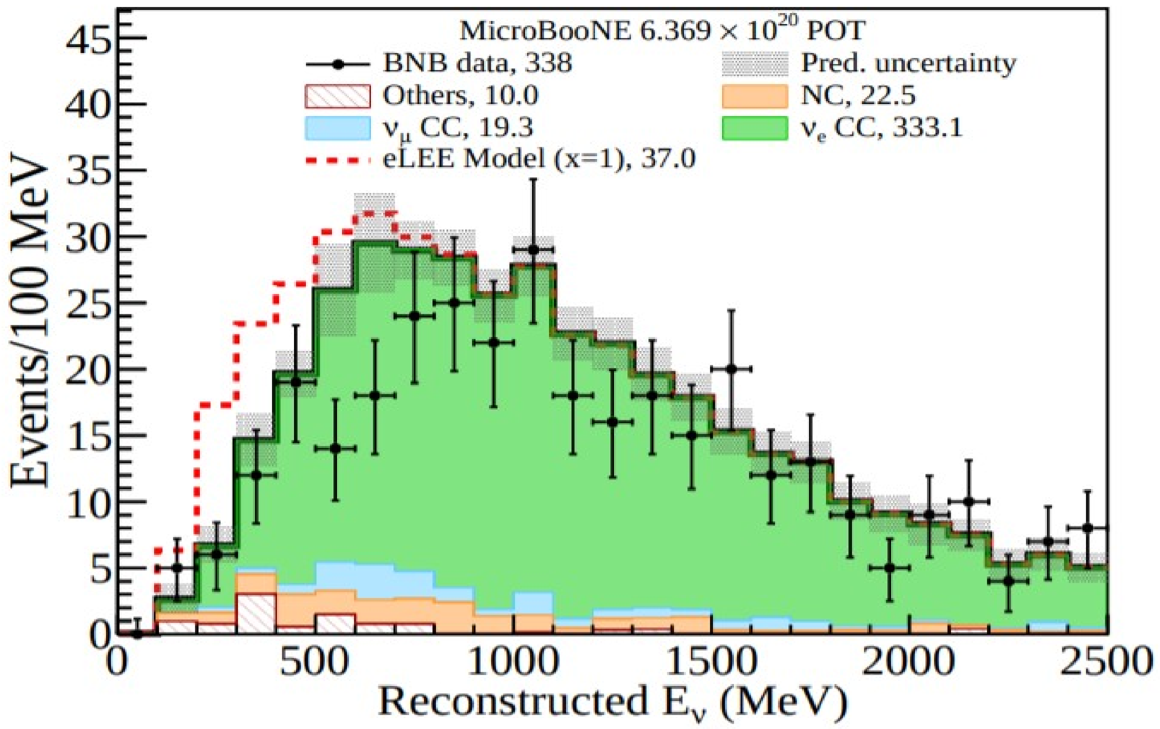
MicroBooNE



- 170 ton LAr TPC
- Operating in the same beam as LSND and miniBooNE
- Capable of reconstructing electrons and photons



Low Energy Excess



Reconstructed energy spectrum for inclusive ν_e event sample

- No sign of excess of low energy electrons or photons.
- ?????
- LSND/MiniBoone are seeing something though. What?
- Doesn’t rule out steriles though.

Decaying sterile neutrinos?

CPT Violation?

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

Lorentz violation?

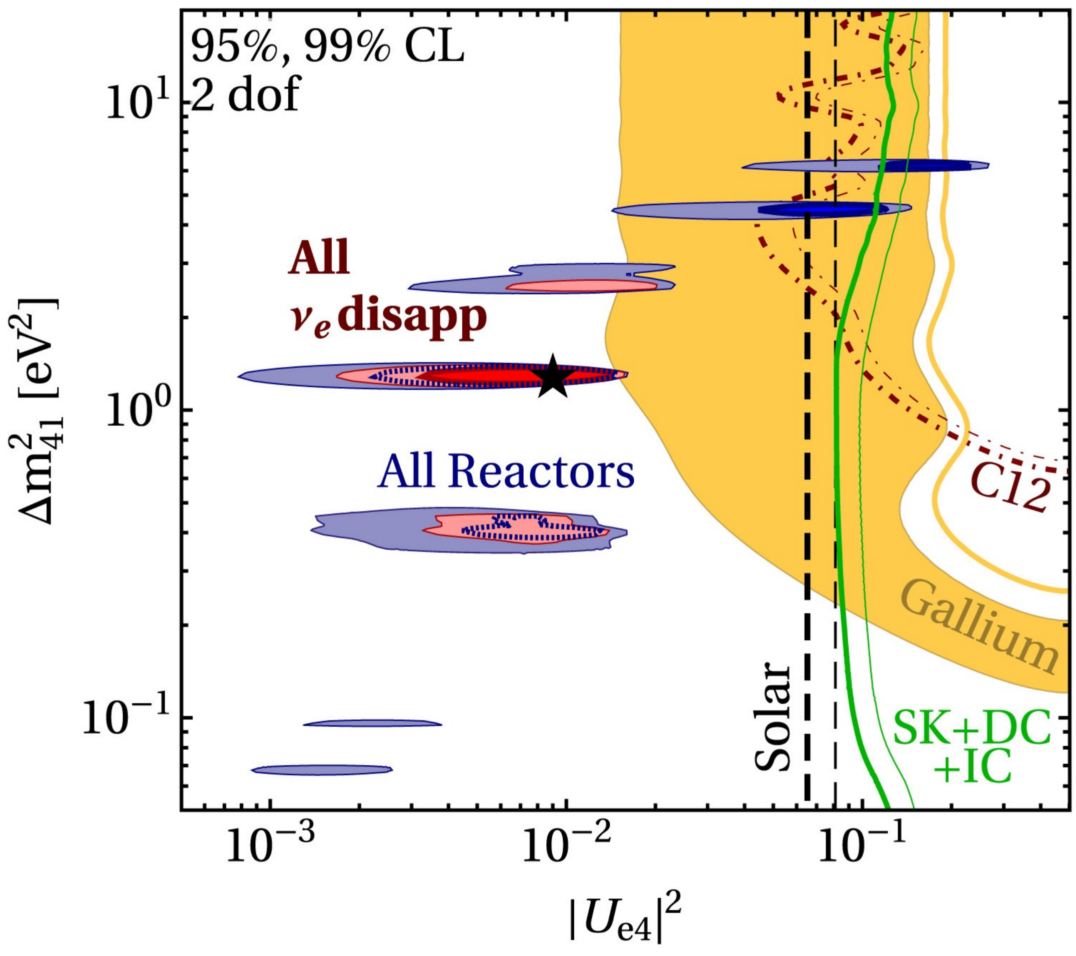
Extra dimensions?

Experimental problems?

No bleedin' idea

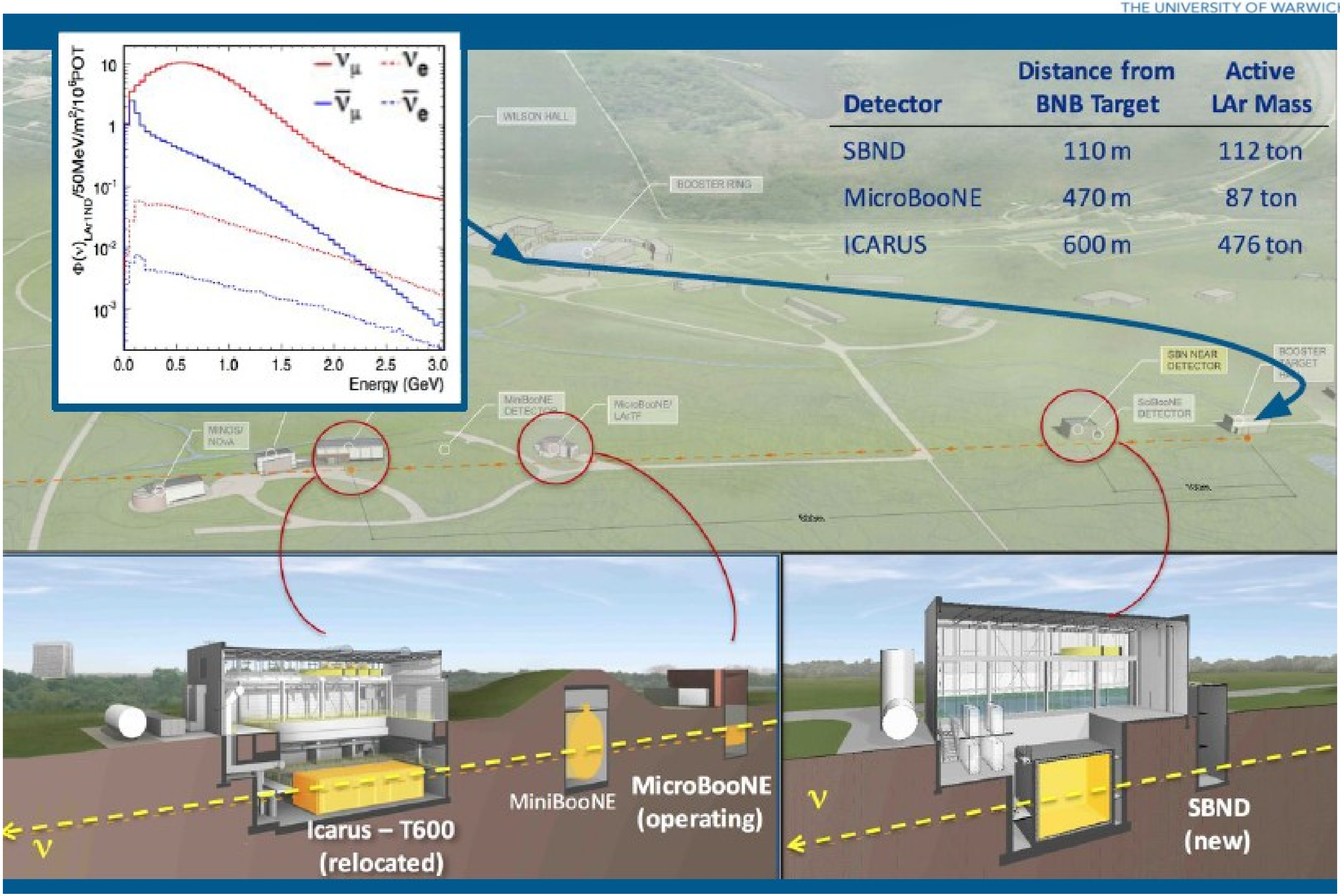
Wait for more data

Global analysis



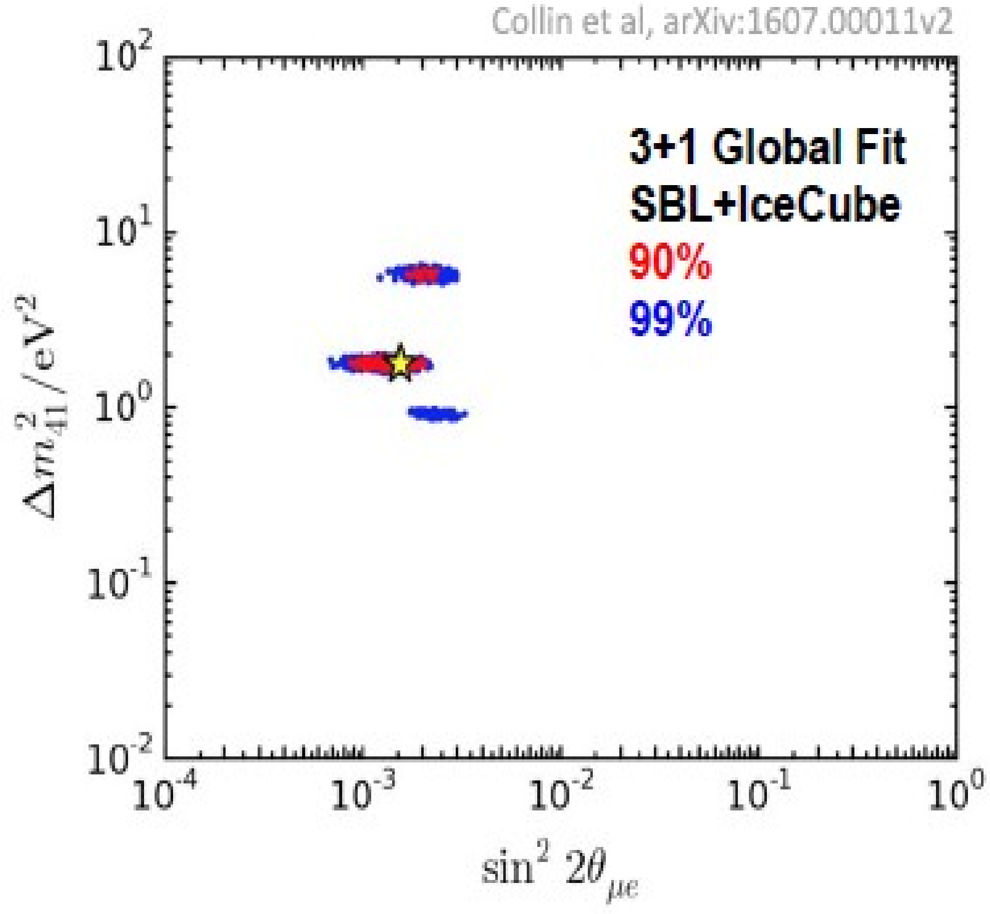
- It's very hard to fit all of the data to a 3+1 (or other) models.
- A consistent picture does not leap out from all these anomalies.

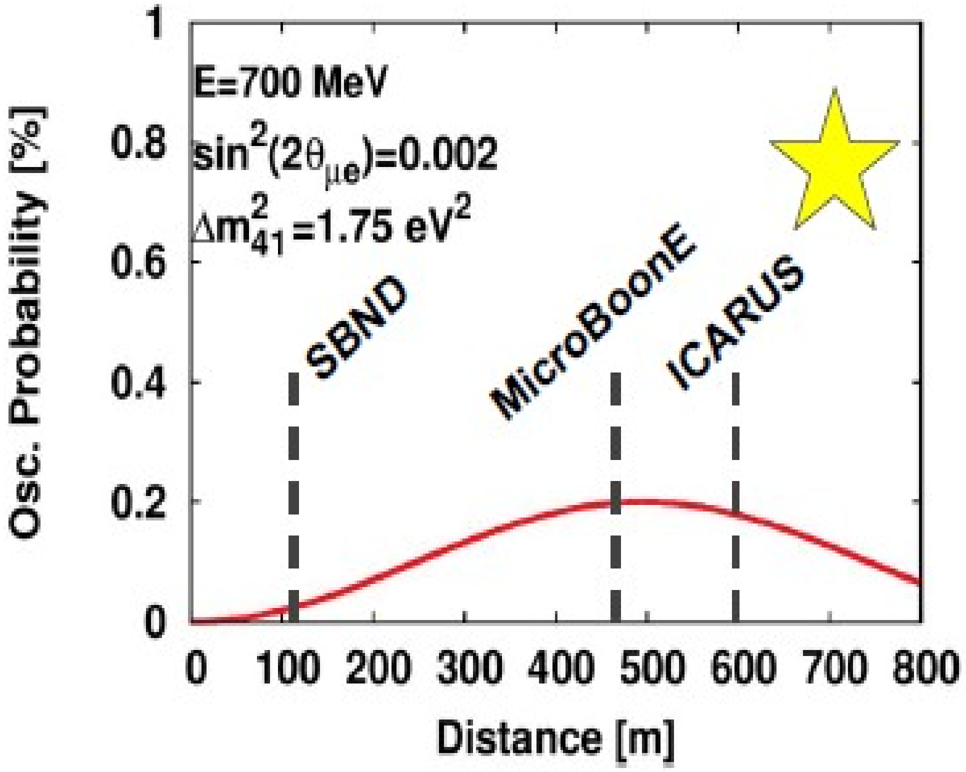
SBN Program



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

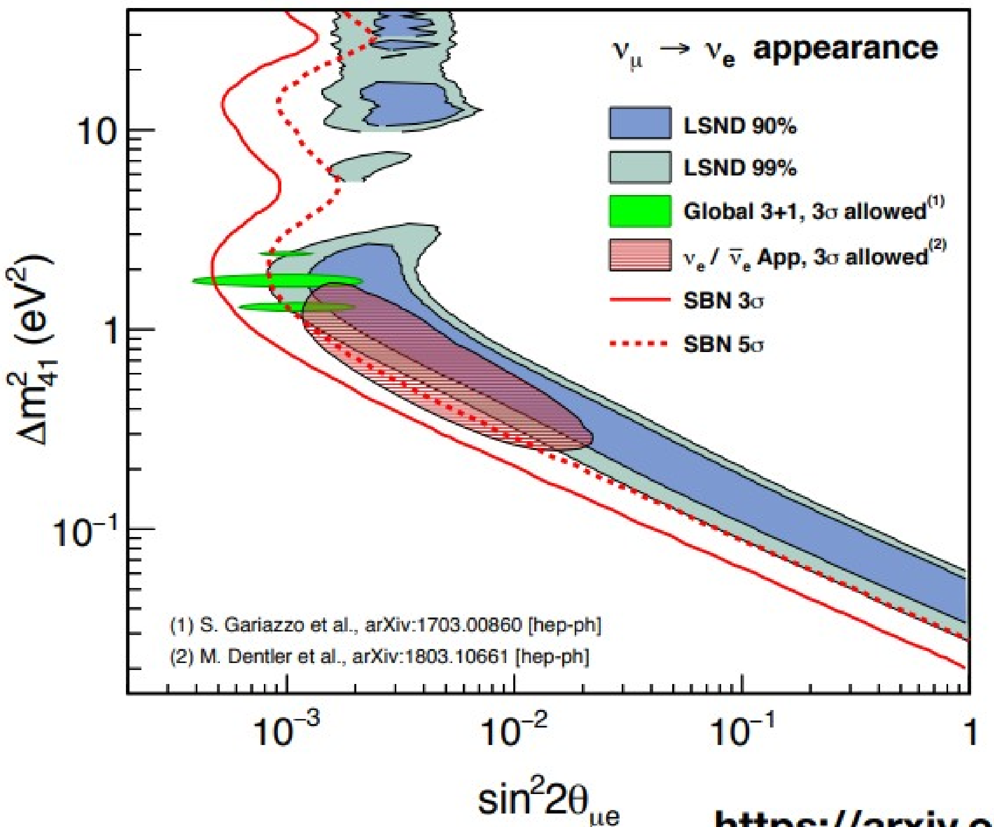
SBND


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

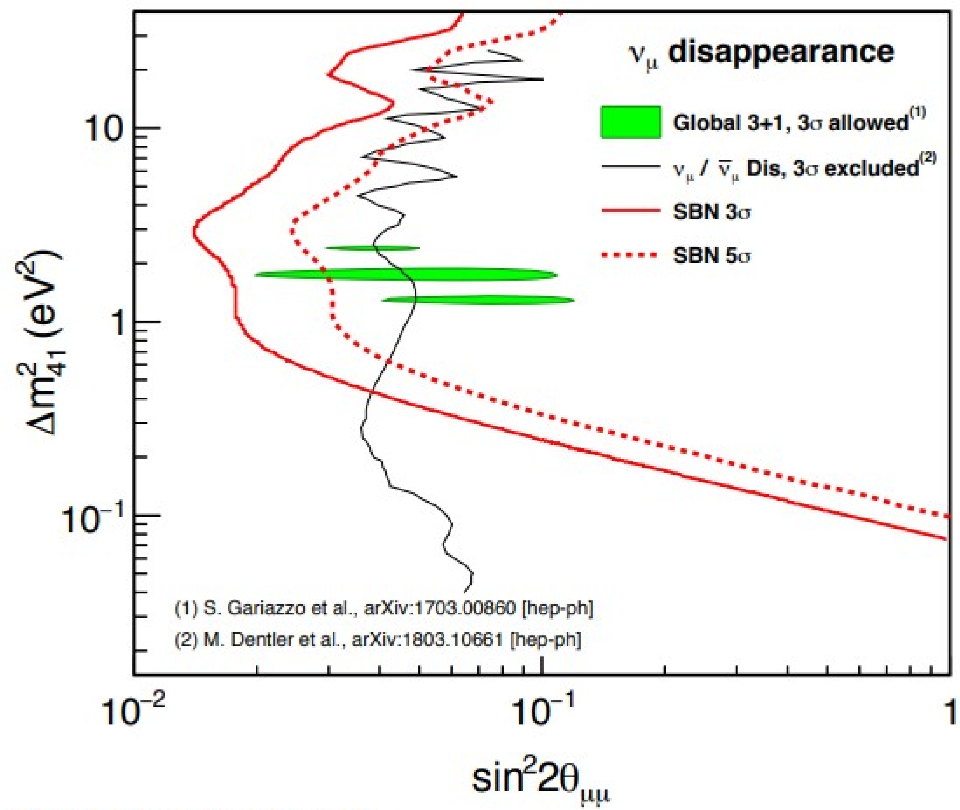

E=700 MeV
$\sin^2(2\theta_{\mu e})=0.002$
$\Delta m^2_{41}=1.75\ \mathrm{eV}^2$
SBND
MicroBooneE
ICARUS
Osc. Probability [%]
Distance [m]

SBND

ν_e appearance



ν_μ disappearance



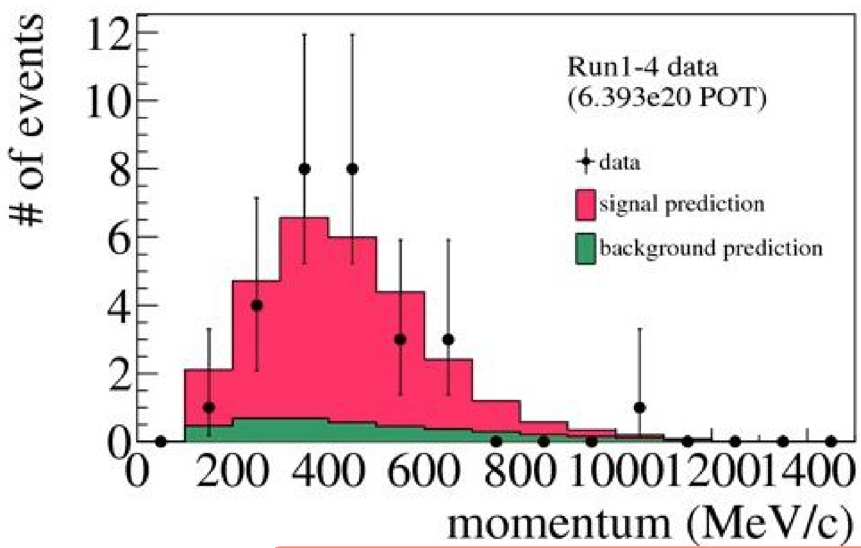
https://arxiv.org/pdf/1903.04608.pdf

- SBN cover much of the parameters allowed by past anomalies at >5σ significance

- Starts taking data soon

Neutrino Cross-sections

Systematic Uncertainties



To do these sort of measurements

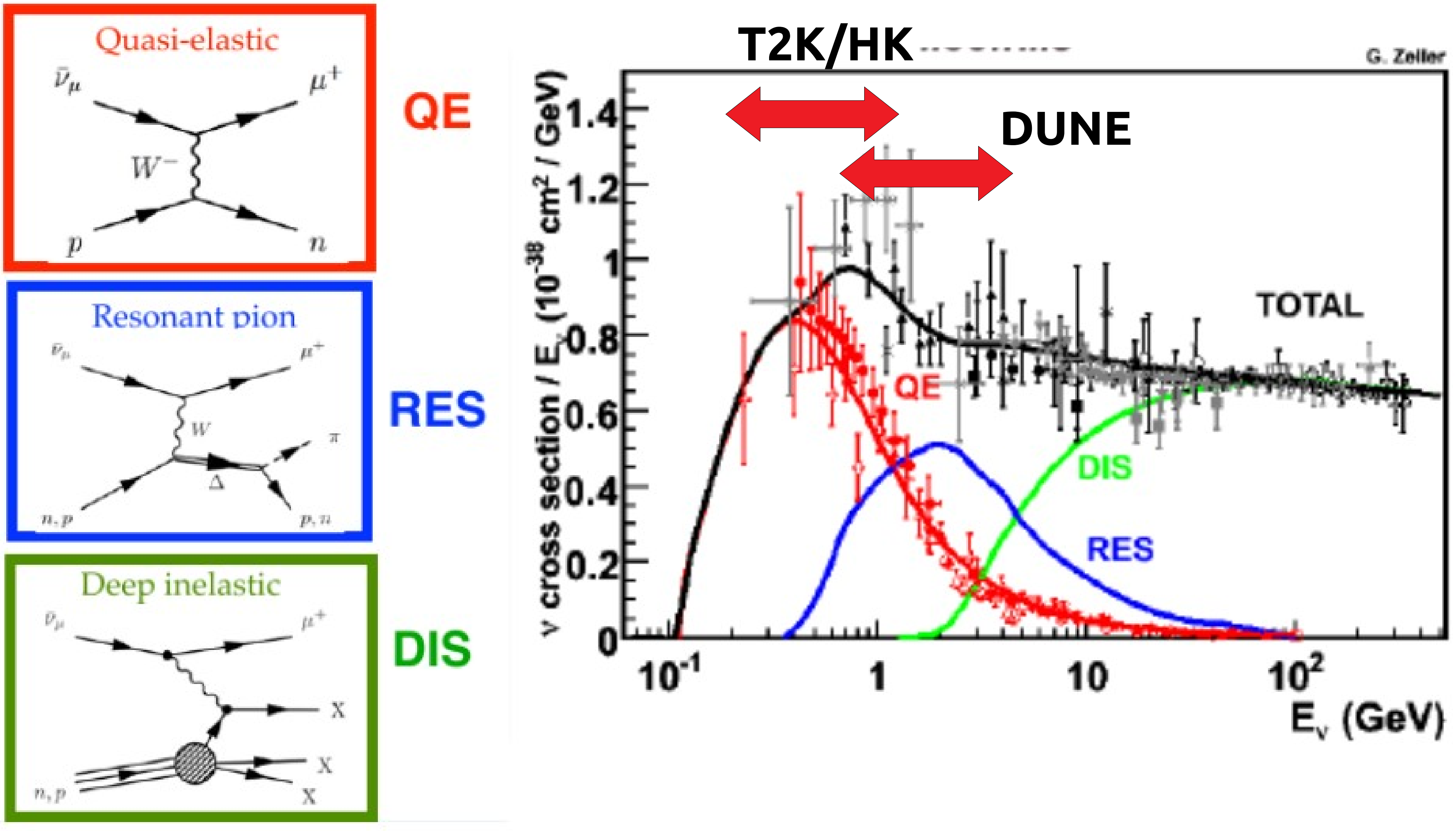
Measure number of events at Far Detector

Compare with expected number of events

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

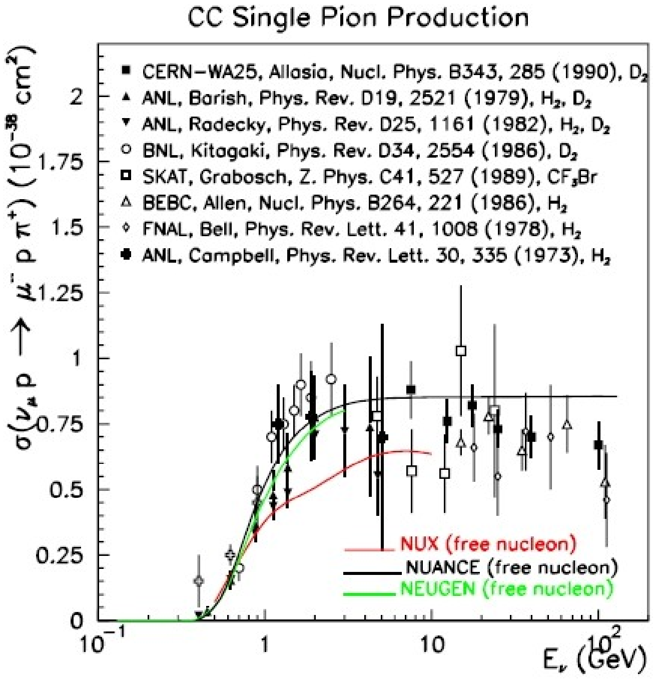
Cross Section	Neutrino Flux	Number of Targets	Selection Efficiency
10-100%	5-10%	1-2%	10%

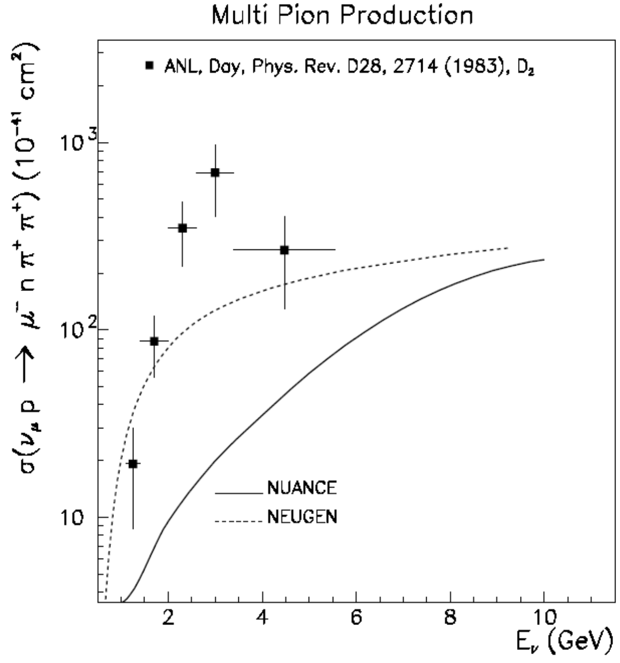
Neutrino Interactions

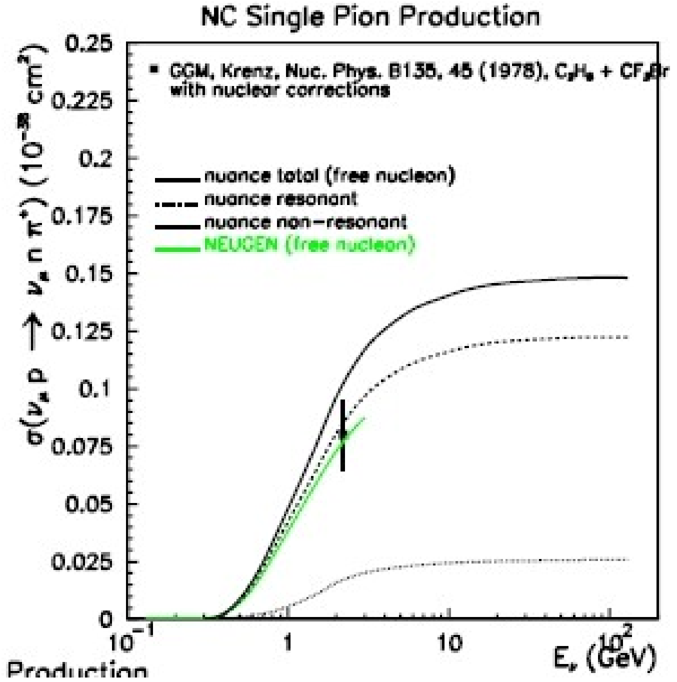


Xsec data pre 2007

The data was impressively imprecise





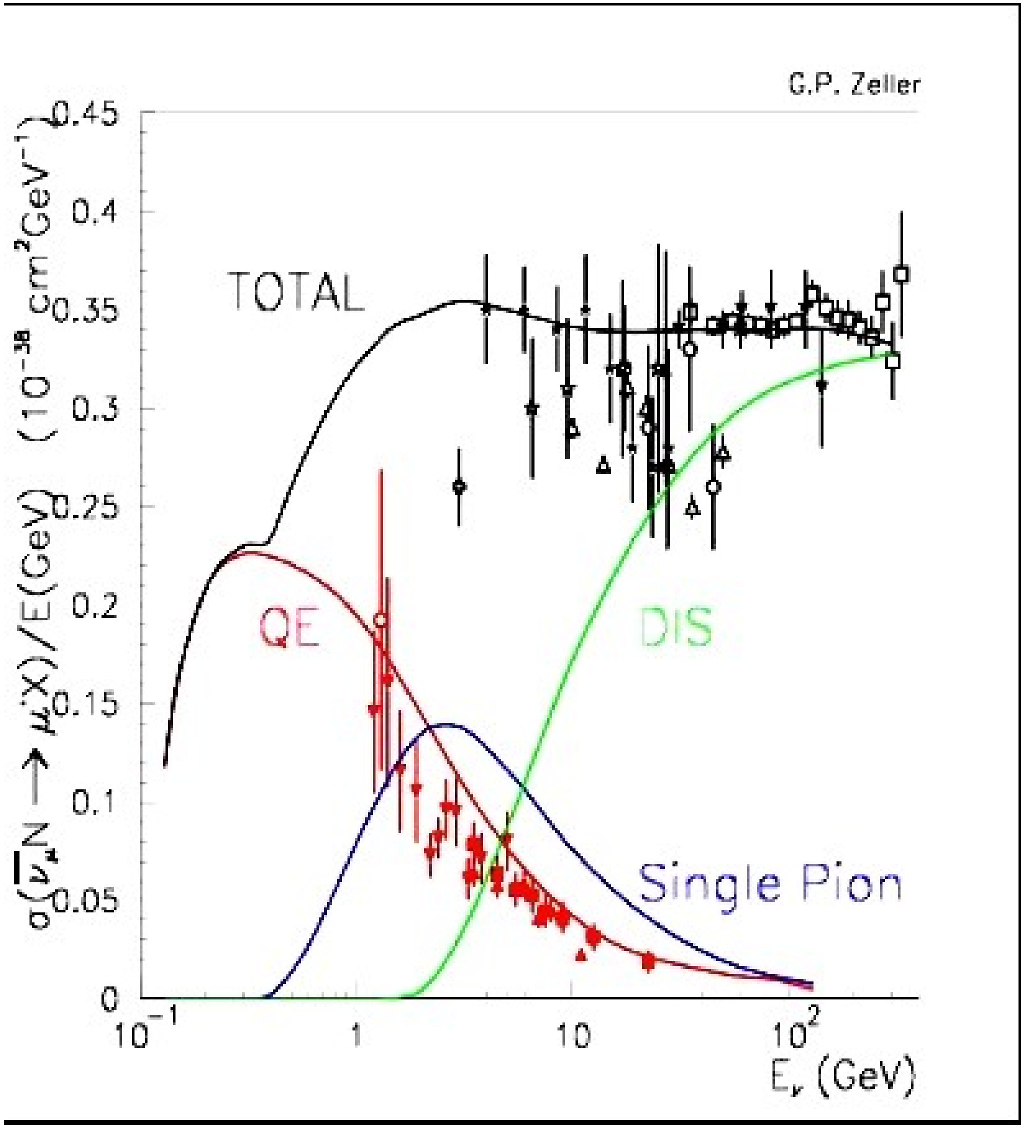


$\nu_\mu p \rightarrow \mu^- p \pi^+$

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

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

World Data for Antineutrinos



It’s slowly getting better

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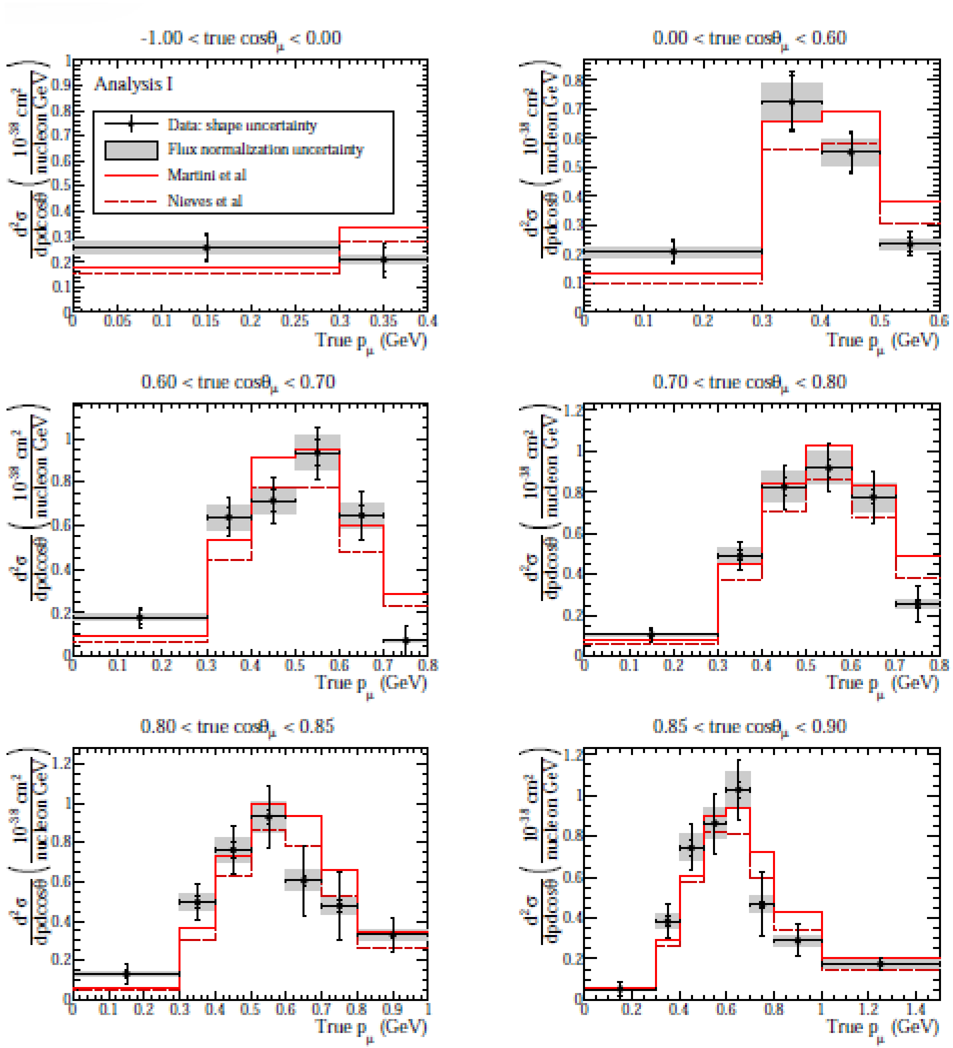
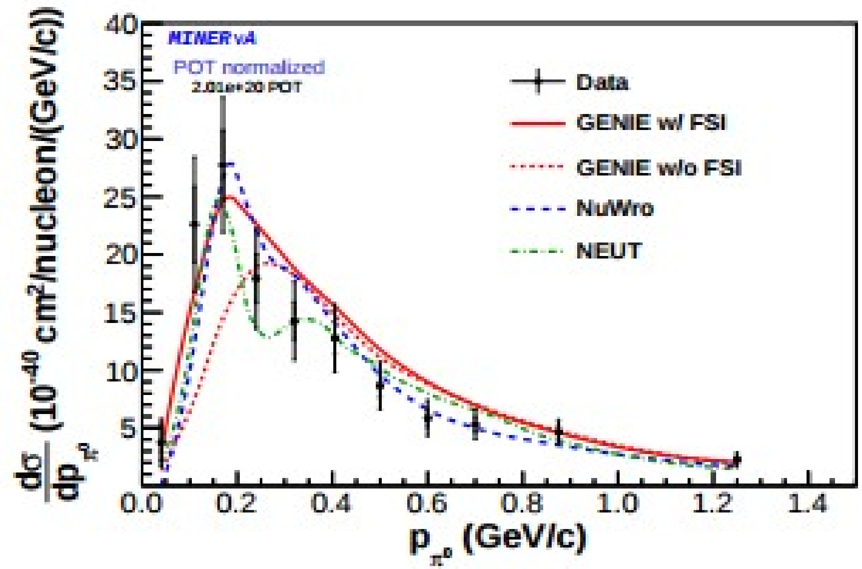


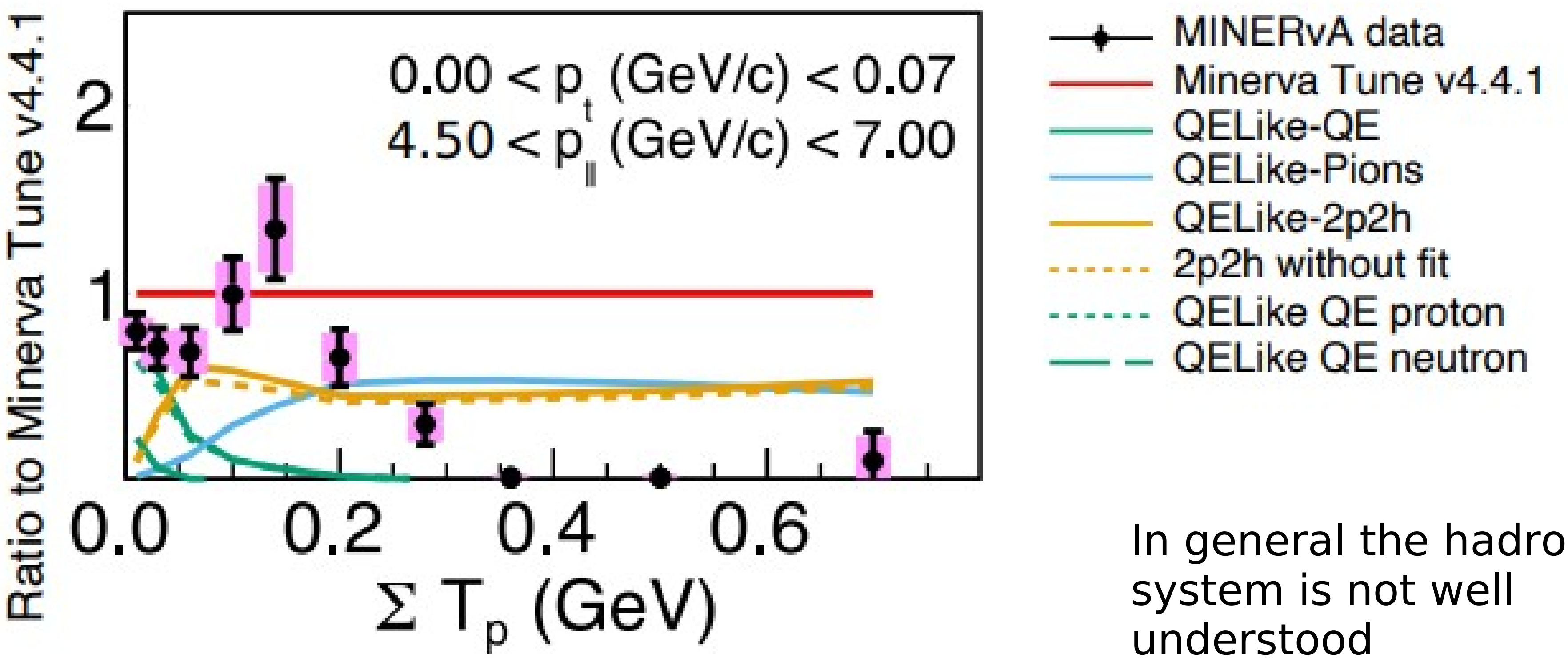
CC 0π differential Xsec from T2K
arXiv:1602.03652



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

But still not good



In general the hadronic system is not well understood

Total proton kinetic energy

D Ruterbories et al. Simultaneous measurement of proton and lepton kinematics in quasielasticlike ν μ-hydrocarbon interactions from 2 to 20 gev. Physical review letters, 129(2):021803, 2022.

Concluding Remarks

- Neutrinos are massive → extensions needed to the Standard Model
- Neutrino oscillation parameters still need to better measured; δ_{CP} and ordering have to be measured.
- Next generation of experiments will hopefully get a handle on these parameters : data coming from 2029 and the early 2030's.
- Many opportunities for BSM in the neutrino sector
- We are getting perilously close to a neutrino mass measurement – perhaps in the next 5-10 years?
- Majorana or Dirac? We may be lucky with an intensive $0\nu\beta\beta$ program; look out for LEGEND 1000
- New neutrino machines may be coming with muon storage ring technology

Quasi-Elastic Scattering

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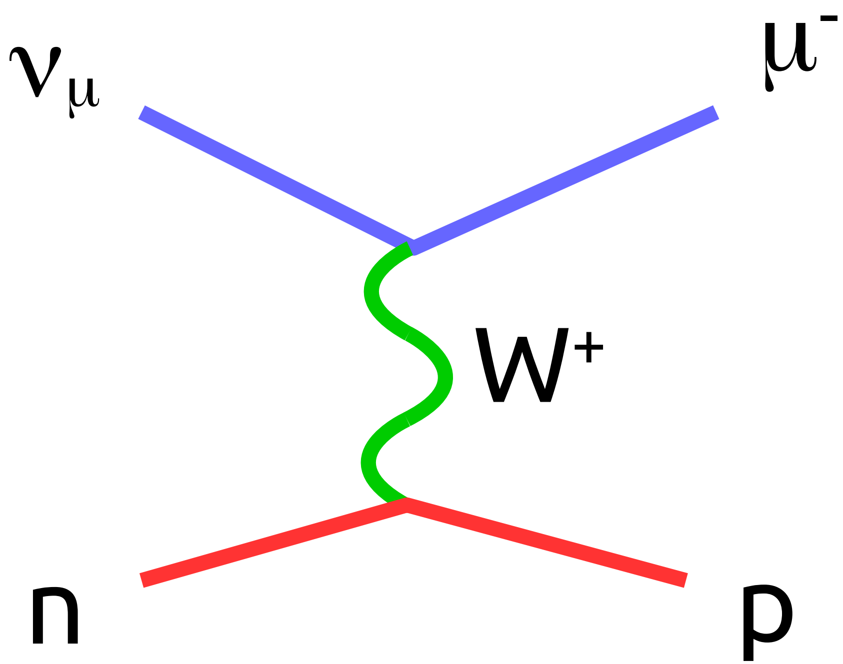
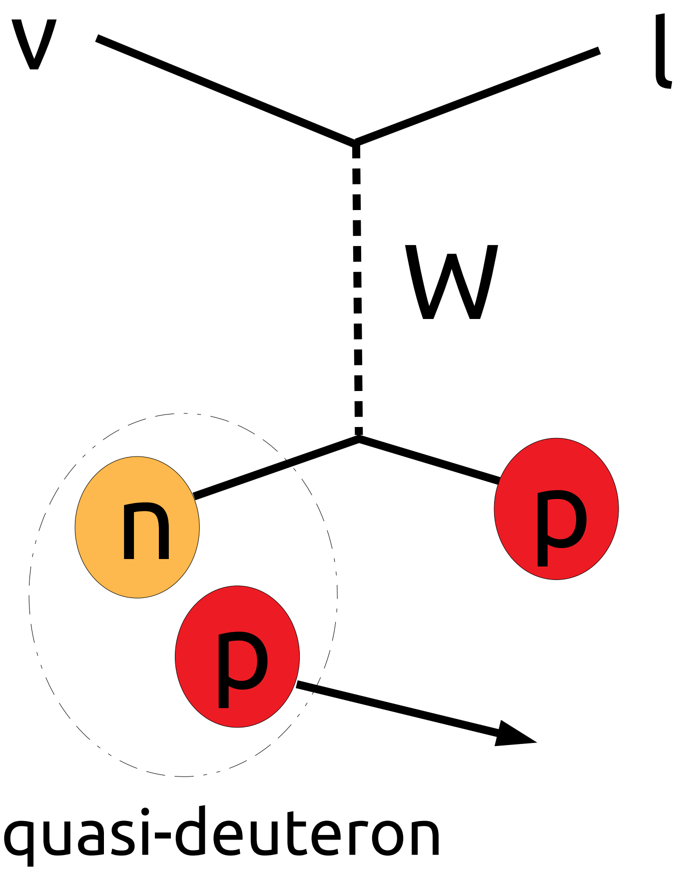


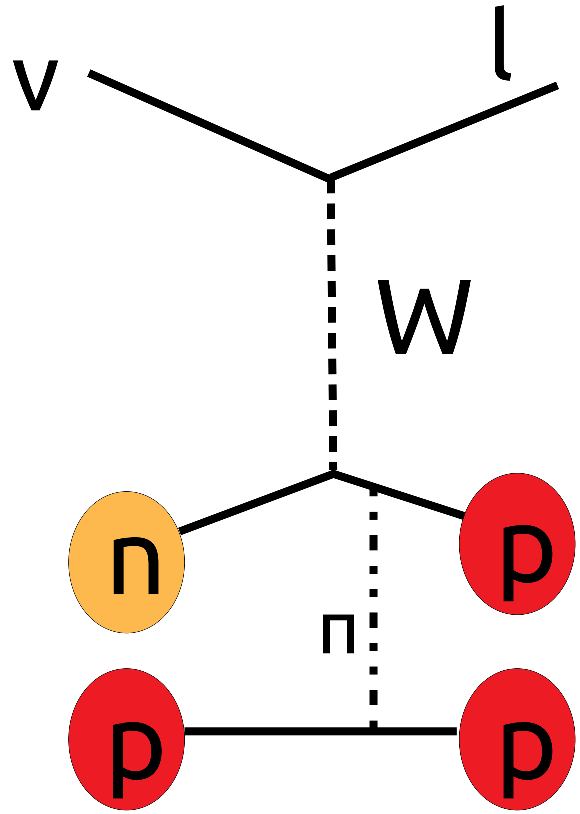
- Usually though of as a single nucleon knock-on process
- In the past has been used as a "standard candle" to normalise other cross sections
- Heavily studied in the 1970's and 1980's and considered to be "understood"

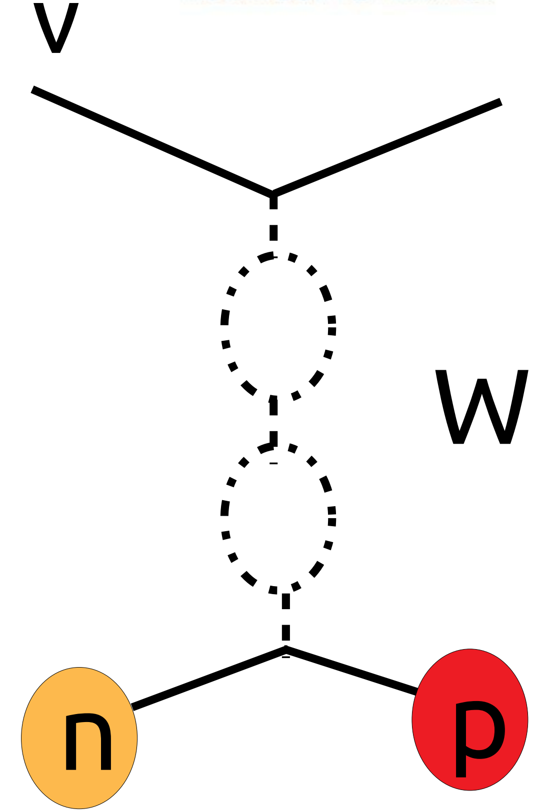
II. Energy reconstruction is unbiased assuming 2 body kinematics

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

Nuclear Effects







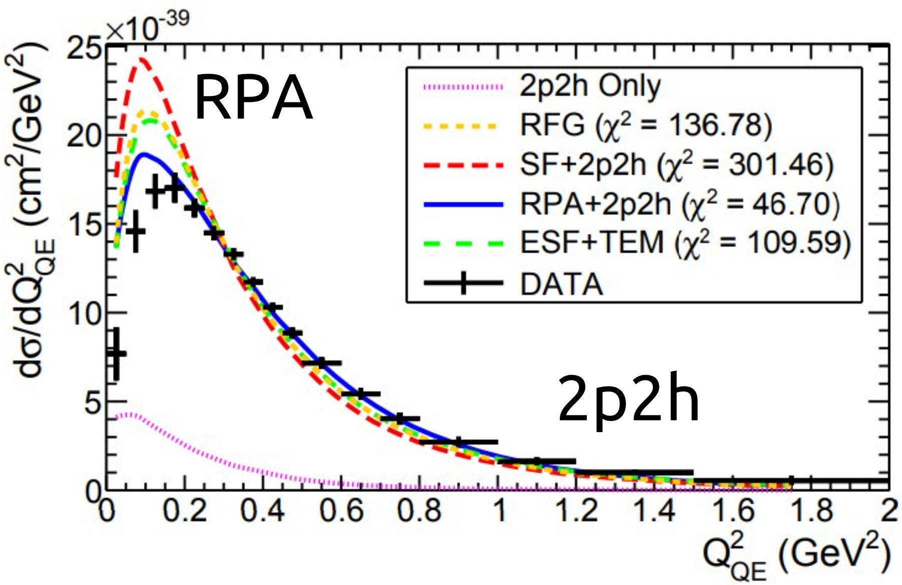
Short-range correlations (SRC)

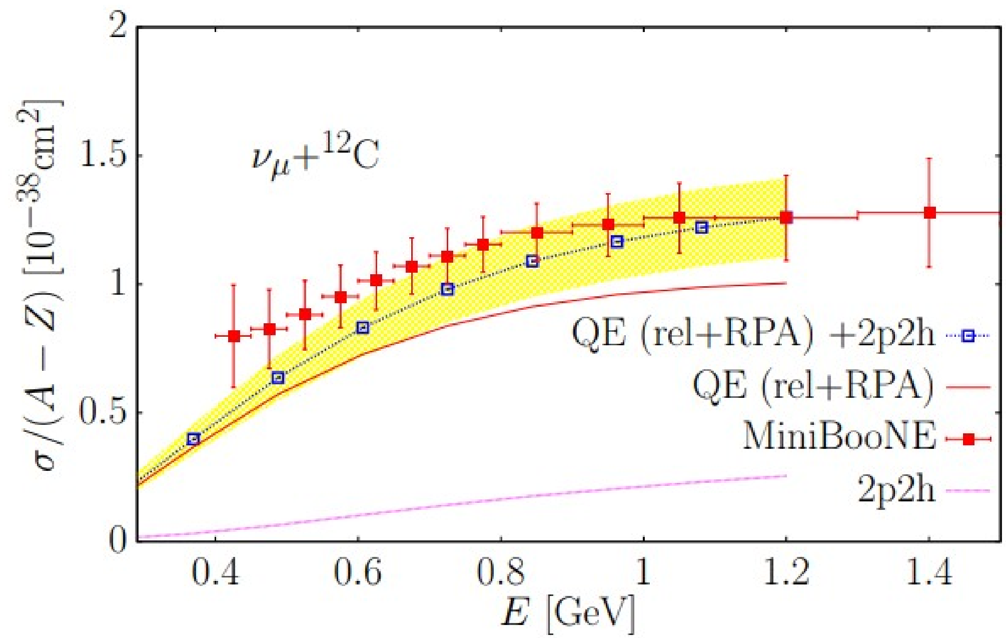
Meson Exchange Currents (MEC)

2p2h processes - medium to high Q^2

RPA effects
W polarisation changes strength of weak interaction

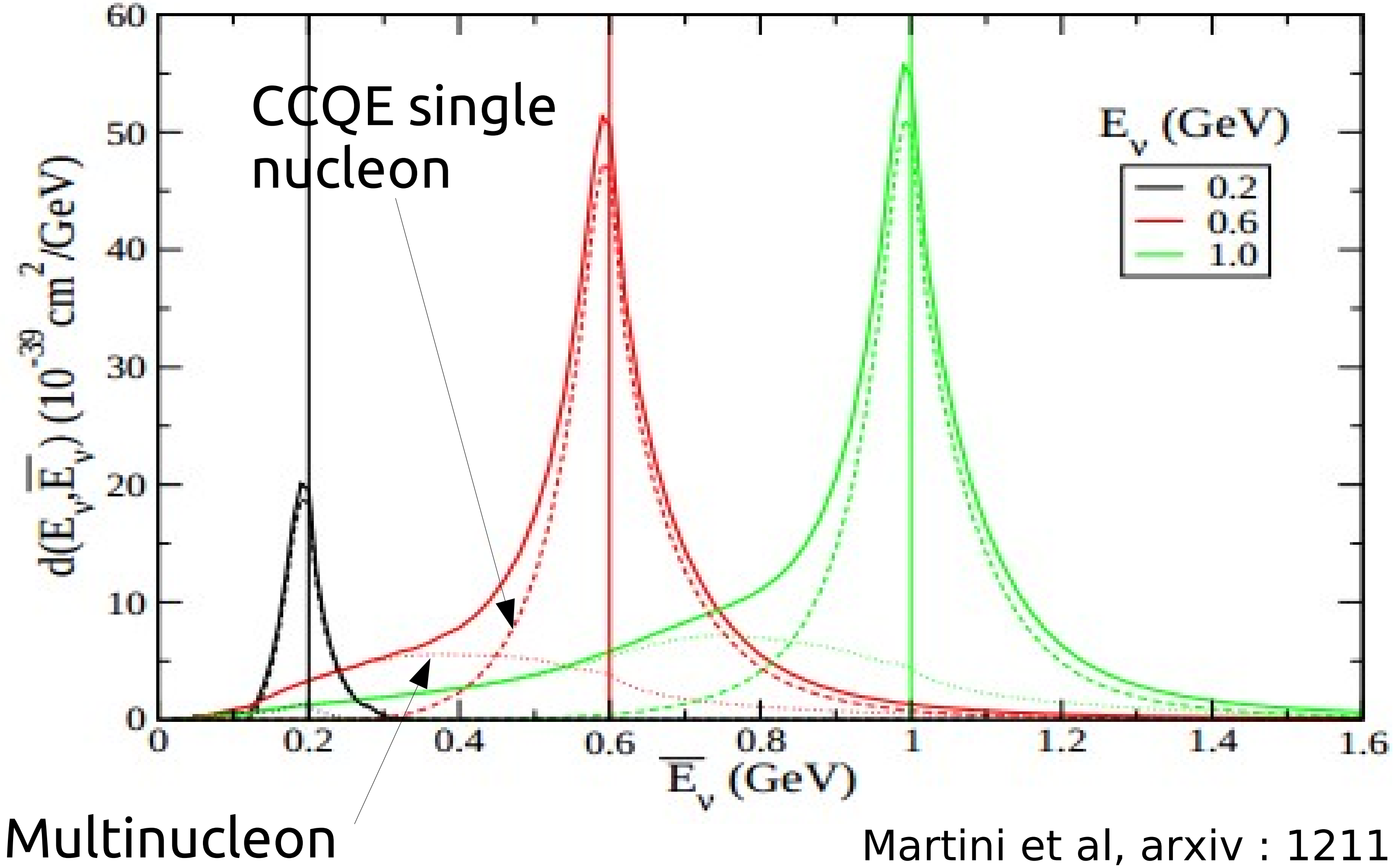
Effect of nuclear corrections





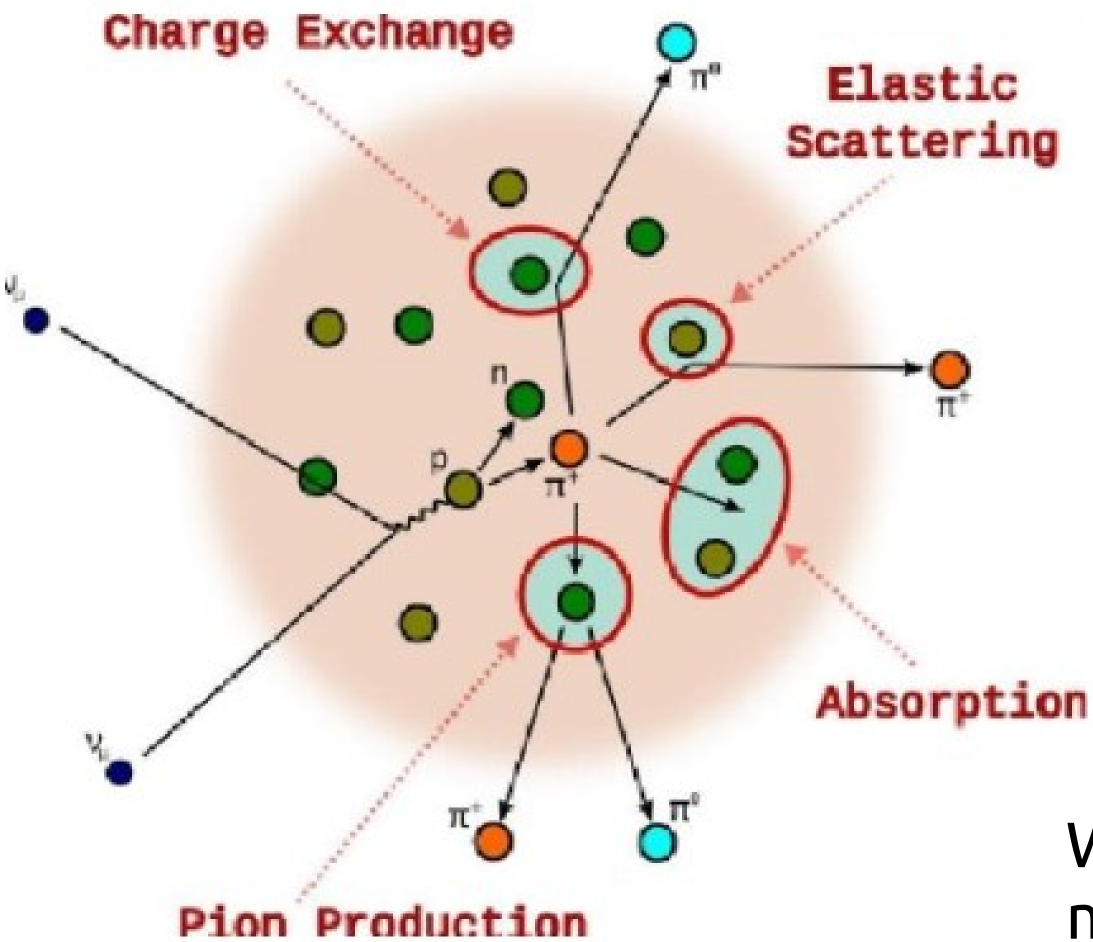
- Models change Q^2 shape in different regions
- Models add a new channel which increases the total cross section

Effect on energy reconstruction



Martini et al, arxiv : 1211.1523

Final State Interactions

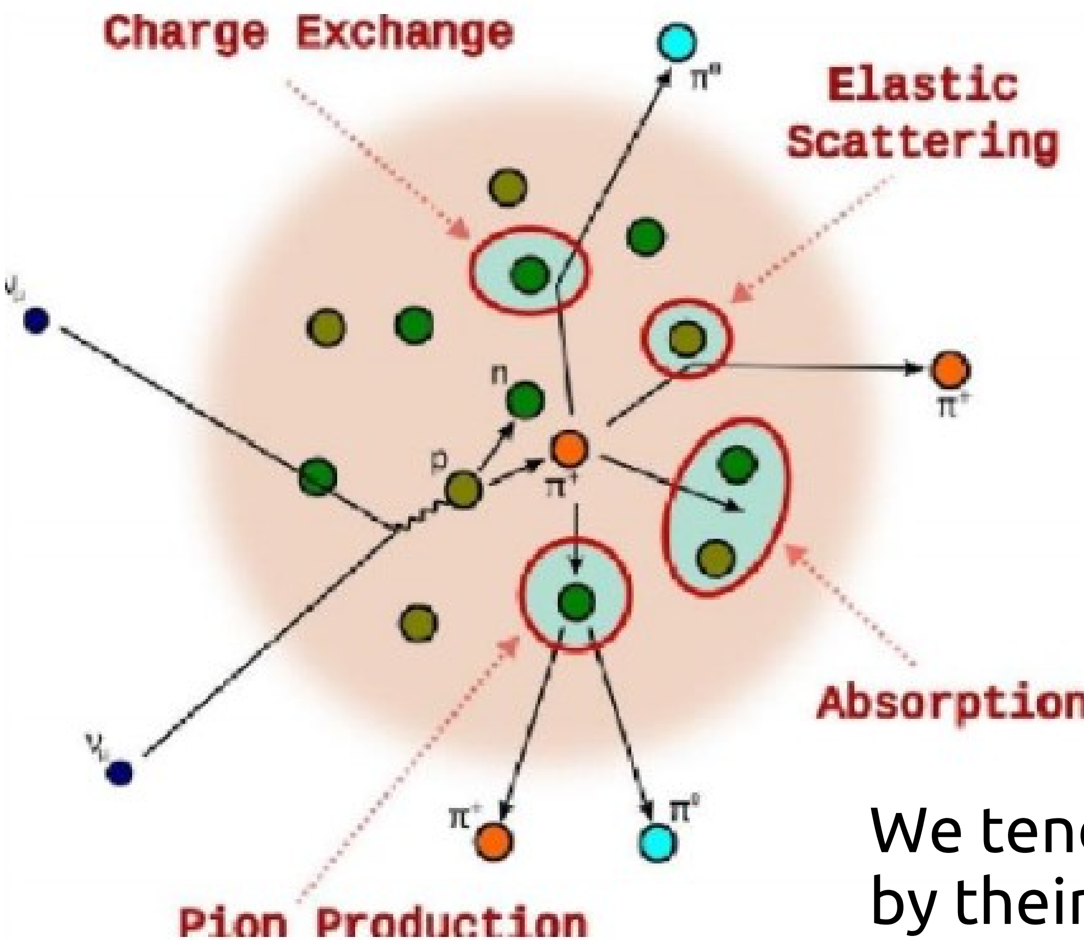


In the nuclear medium

- 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



In the nuclear medium

- Outgoing protons can
  - Scatter
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  - scatter
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  - create more pions
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We tend to categorise events by their final state content now rather than their theoretical "label"