Experimental Overview on Neutrino (Oscillations) Physics

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The Future of Particle Physics: A Quest for Guiding Principles
KIT, Oct 2018

Neutrino Mixing
The PMNS Matrix

- Assume that neutrinos do have mass:
  - mass eigenstates ≠ weak interaction eigenstates
  - Analogue to CKM-Matrix in quark sector!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

with $c_{ij} = \cos(\theta_{\mathrm{ij}})$, $s_{ij} = \sin(\theta_{ij})$, θ_{ij} = mixing angle and $\Delta m_{ij}^2 = \mathrm{mass}^2$ difference

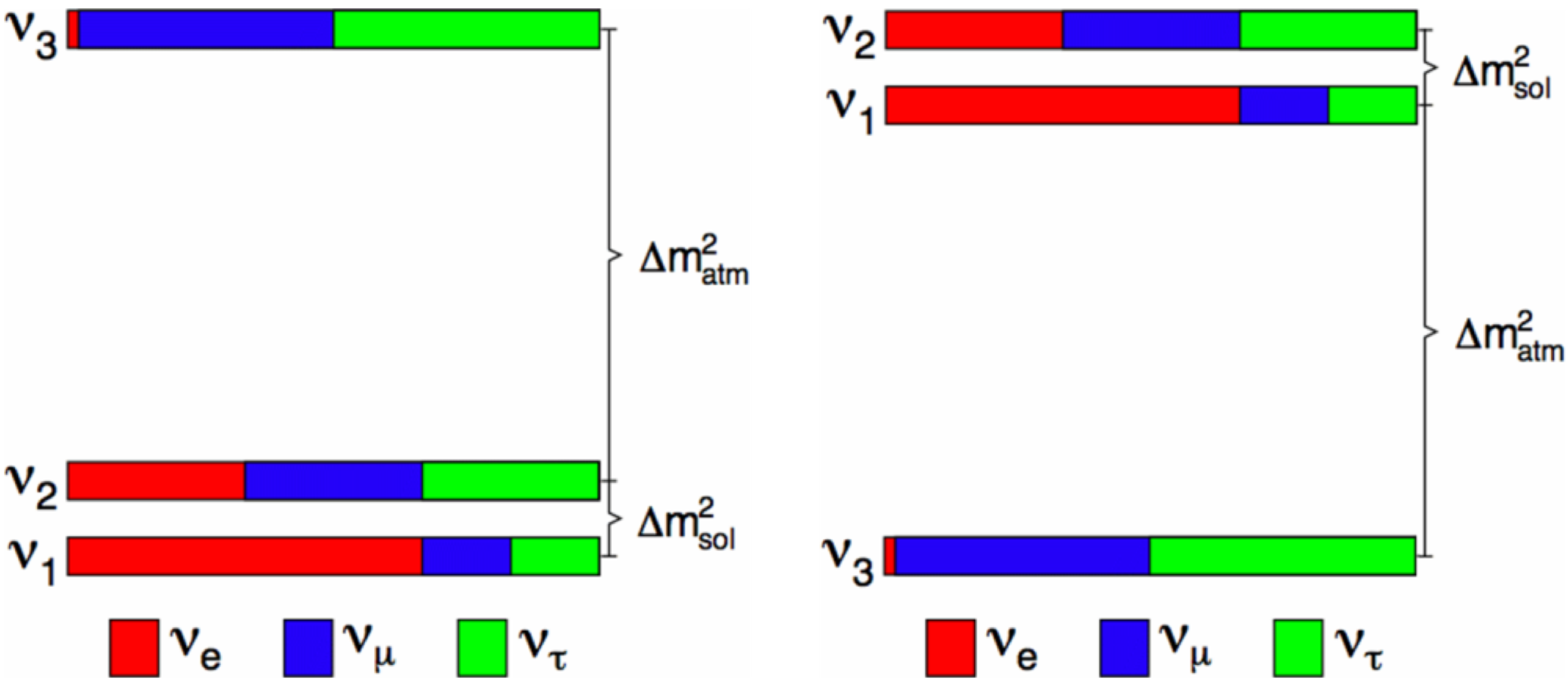
The Who-is-Who

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

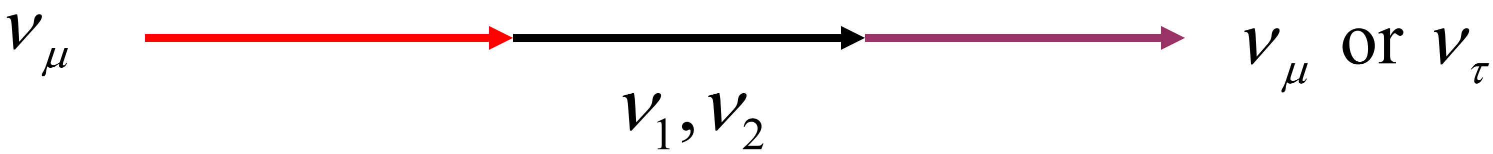
- ν_μ disappearance (first matrix)
- ν_e appearance in ν_μ beam Or reactor neutrino experiments (second matrix)
- Solar neutrino oscillation (third matrix)
- ν–less double beta decay (fourth matrix)

Mass Ordering

Normal Inverted

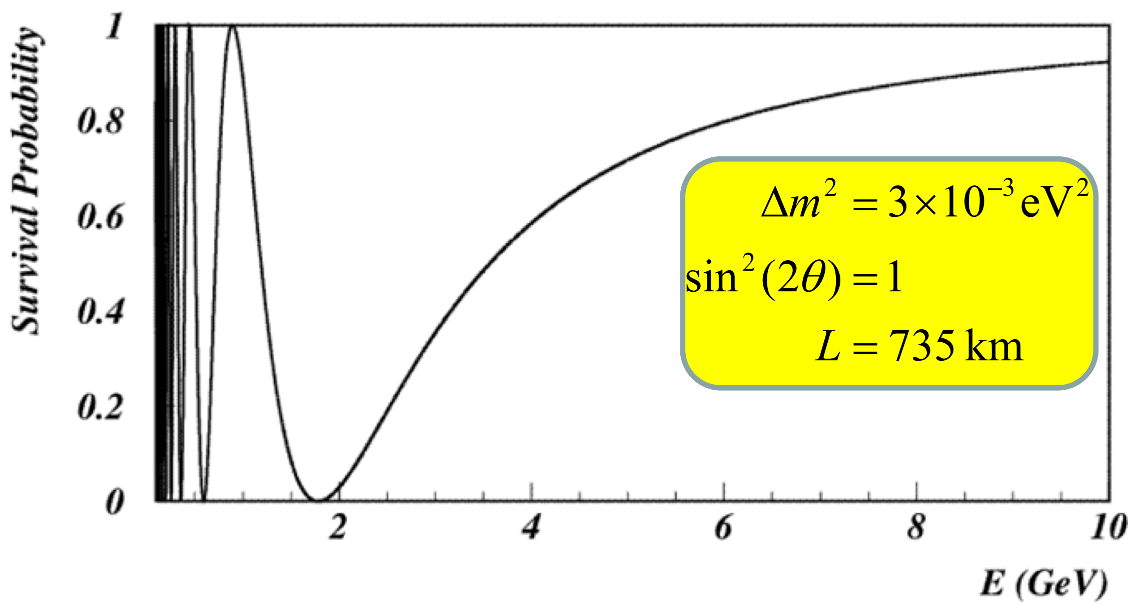


Oscillations for Dummies



$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

- Measure prob.
  - Survival
  - Appearance
- Result
  - Mixing angle
  - Mass differences



Matter Effects

- Simplified treatment: two neutrinos only
- In vacuum / in matter

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_m)\sin^2\left(\frac{\Delta m_m^2 L}{4E}\right)$$

$$\text{with } \sin(2\theta_m) = \frac{\sin(2\theta)}{\sqrt{(\cos 2\theta - A)^2 - \sin^2(2\theta)}}$$

$$\Delta m_m^2 = \Delta m^2 \sqrt{(\cos 2\theta - A)^2 - \sin^2(2\theta)}$$

$$A = \pm \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}$$

- Matter modifies oscillation probability
  - Sign of mass difference matters (opposite for anti-ν)
  - Larger effect at higher energies

The Full Monty

- Life isn't that easy
  - 3 Flavour oscillations
  - Matter effects
- The full formula

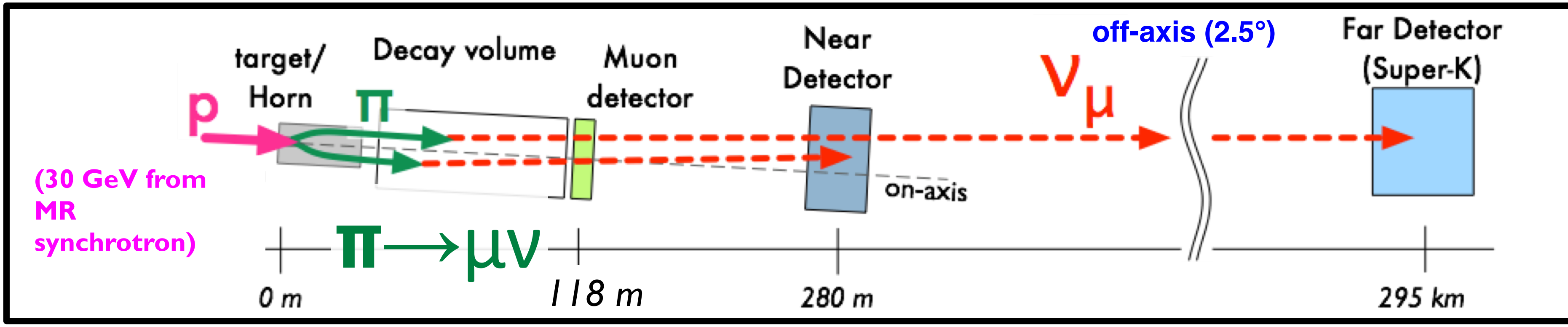
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

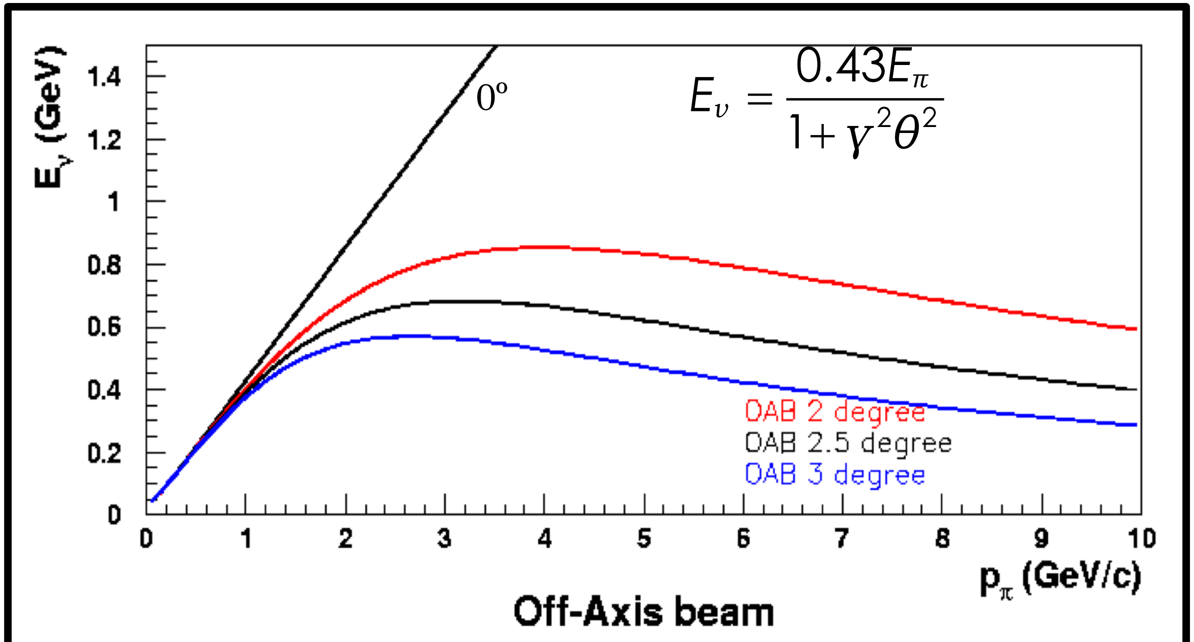
$$\begin{aligned}
P(\nu_\mu \to \nu_e) = & \; 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\left(1 - 2S_{13}^2\right)\right) \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
& + 4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \left(1 - 2S_{13}^2\right)
\end{aligned}$$

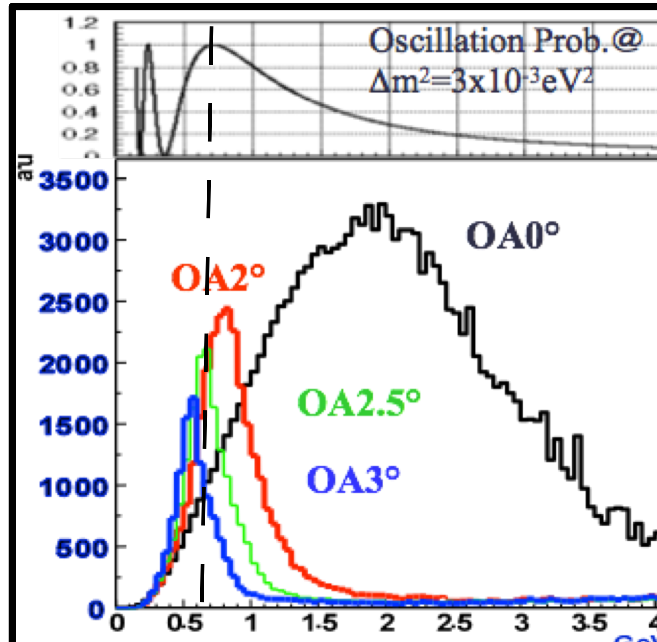
The T2K Experiment

- Neutrino Beam from j-parc
  - Beam power 50 – 480 kW
- Far Detector
  - SuperKamiokande
  - 40 kton water Cherenkov

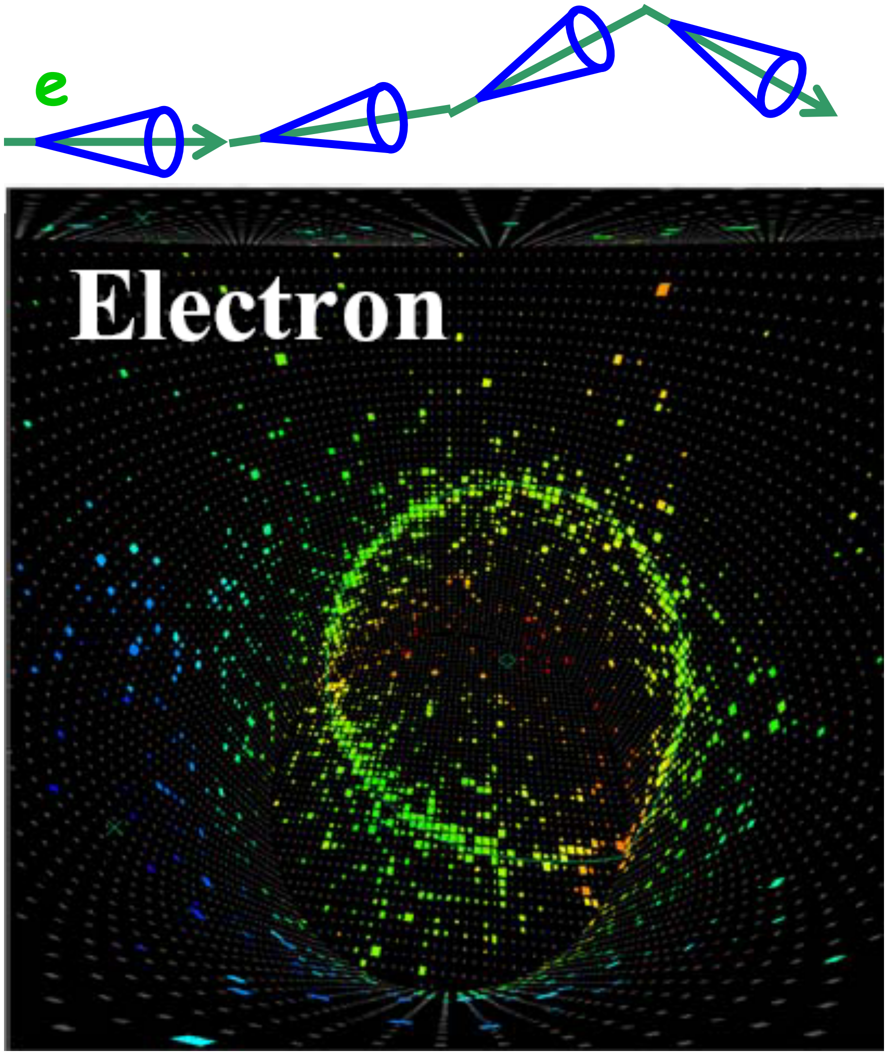
Producing Neutrinos

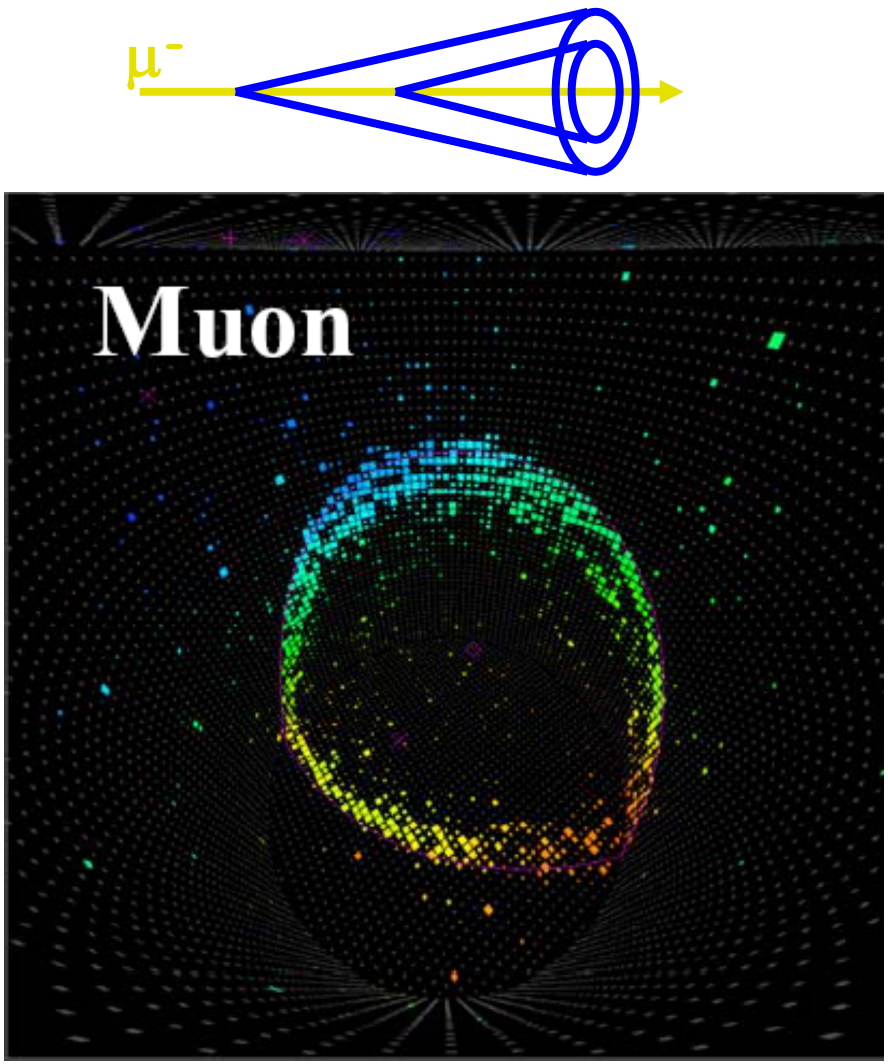




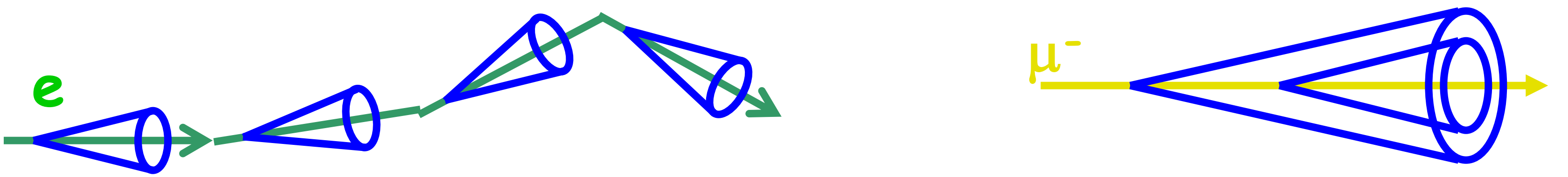


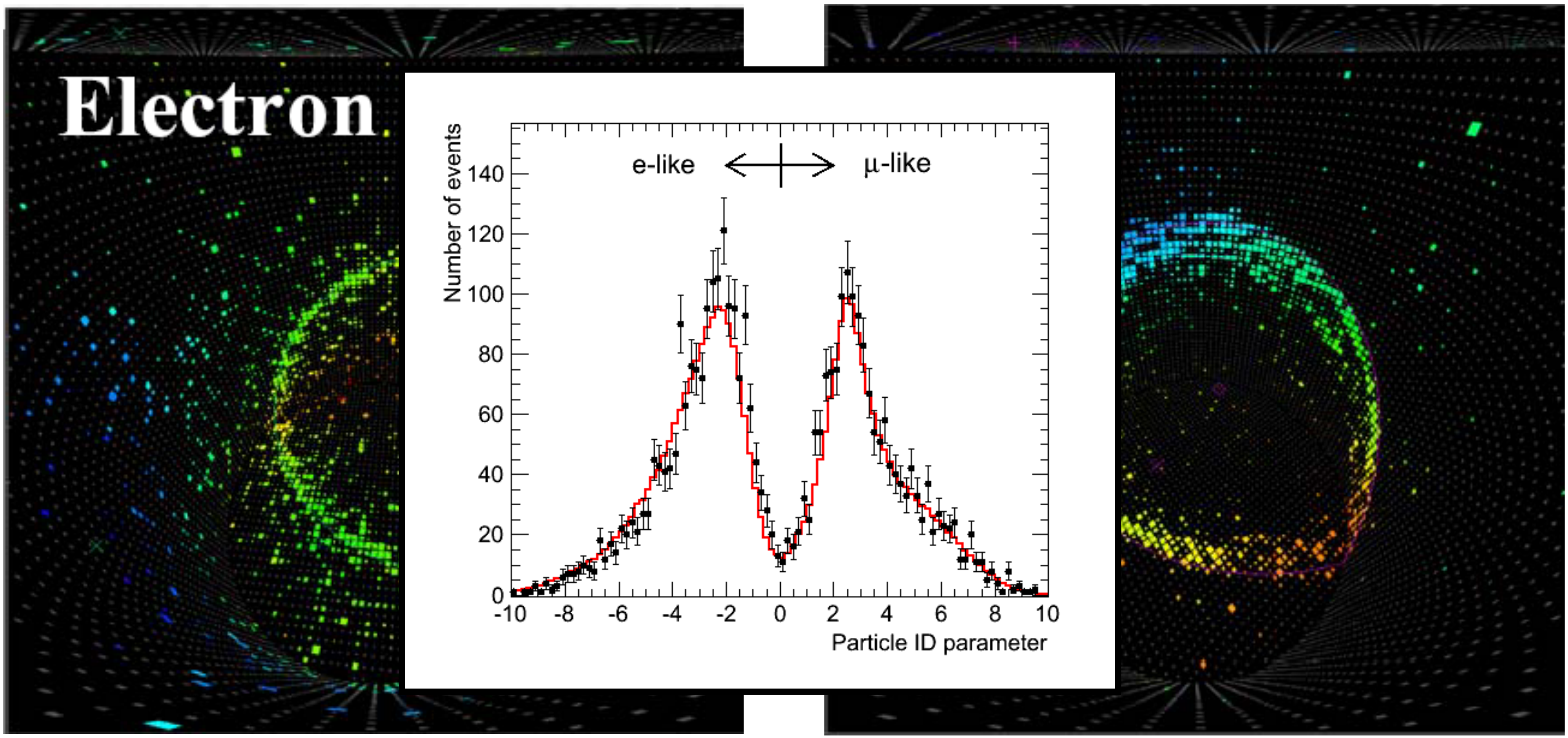
Super-Kamiokande PID



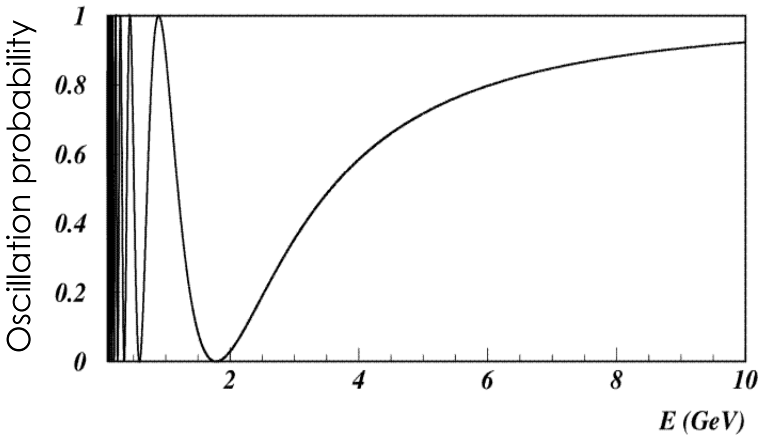


Super-Kamiokande PID

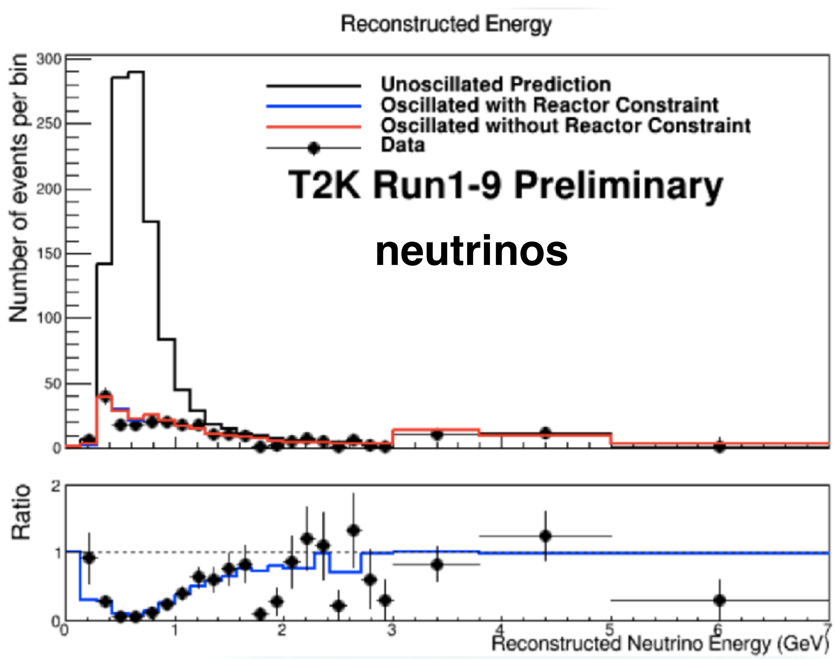


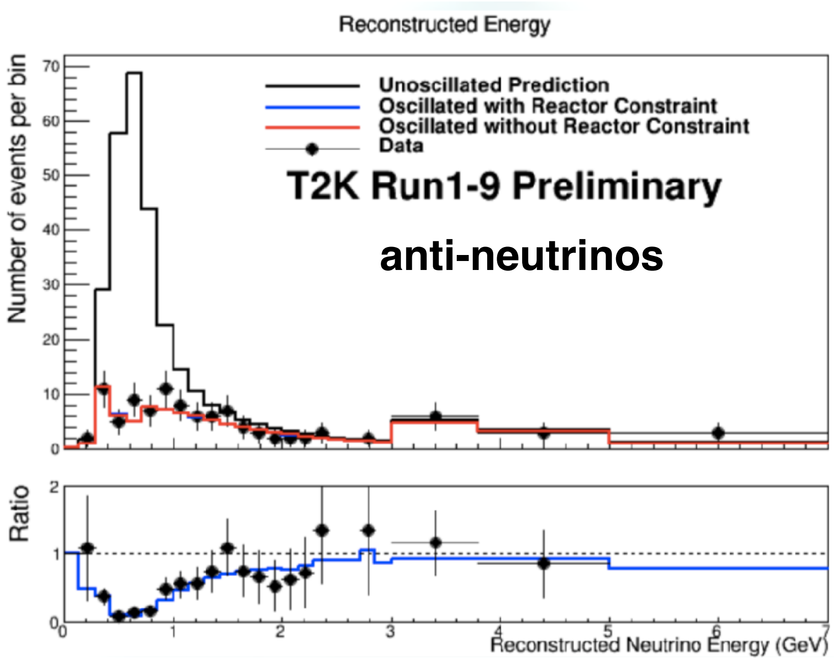


Muon Neutrino Disappearance



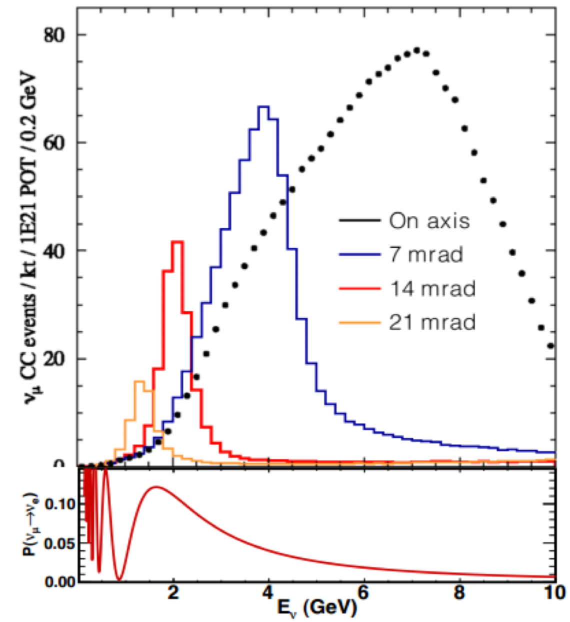
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E_\nu}\right)$$

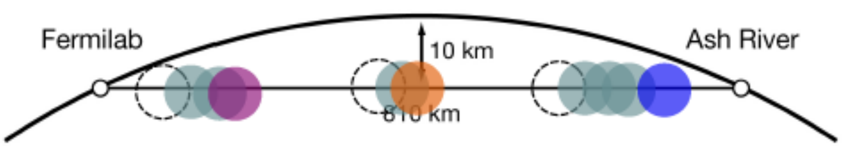




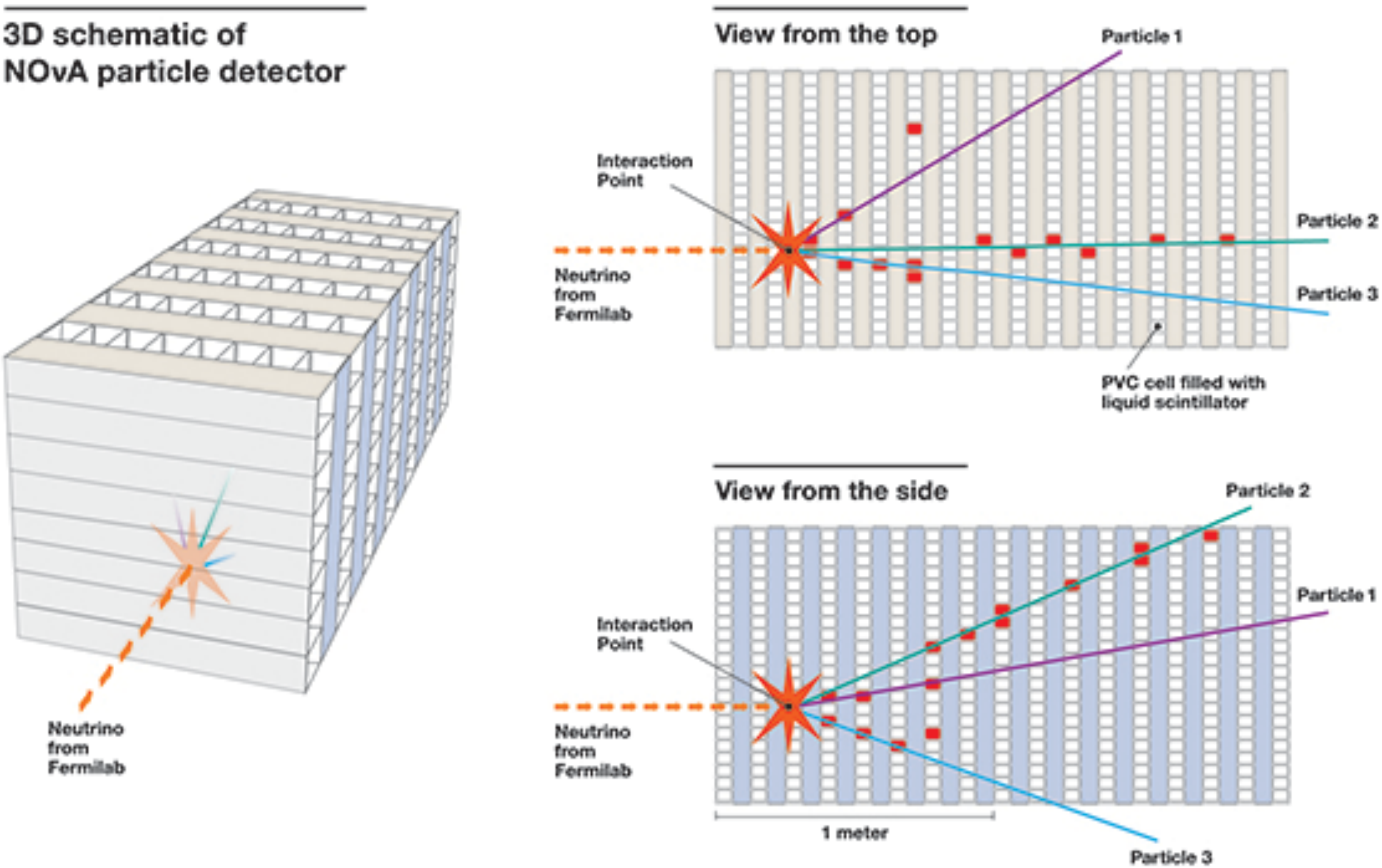
NOvA


NOvA
Ash River
International Falls
Duluth
MN
Minneapolis
WI
Fermilab
IL

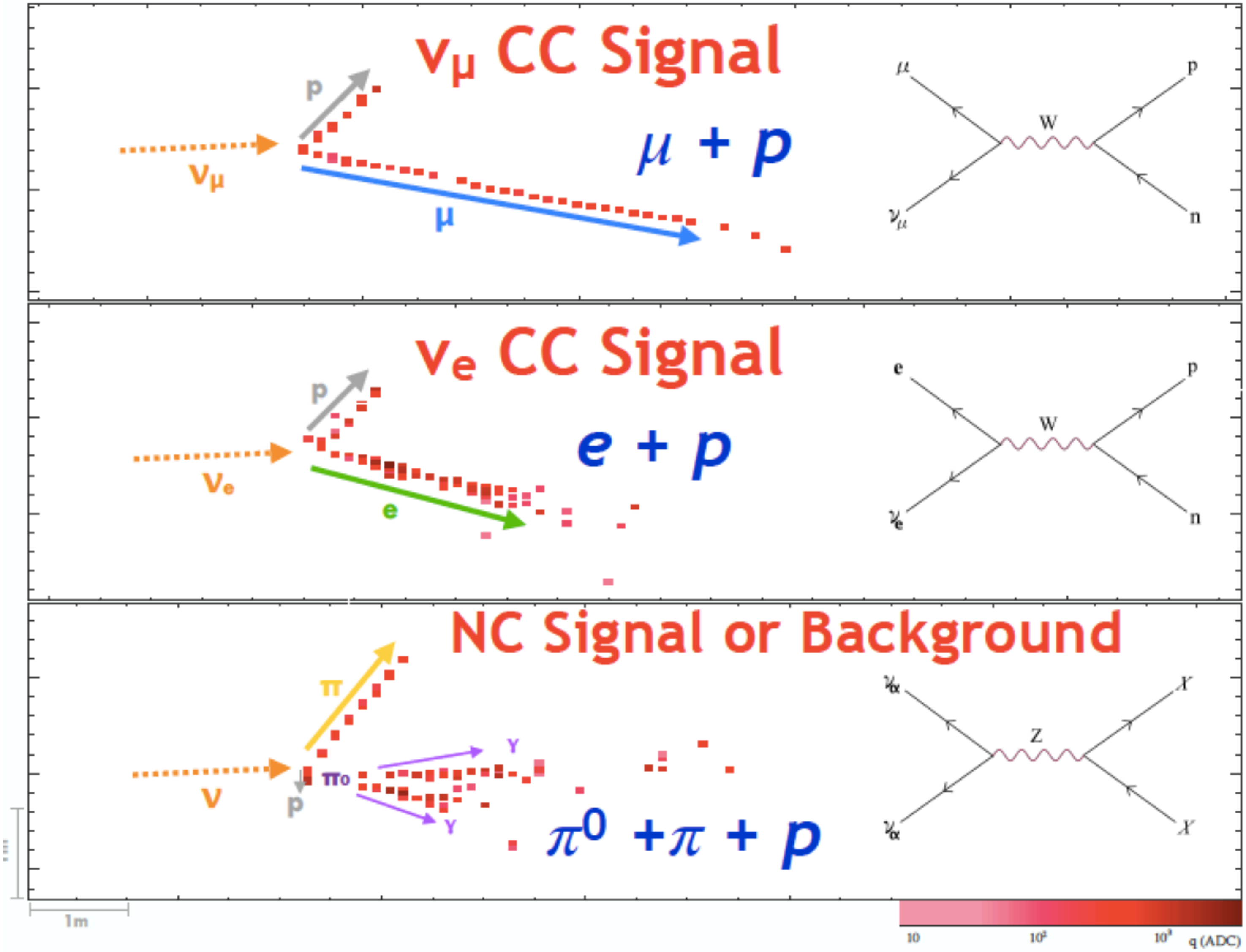

80
60
40
20
0
ν_μ CC events / kt / 1E21 POT / 0.2 GeV
On axis
7 mrad
14 mrad
21 mrad
0.10
0.05
0.00
$P(\nu_\mu \to \nu_e)$
2
4
6
8
10
E_ν (GeV)


Fermilab
Ash River
10 km
810 km

NOvA Detector Concept

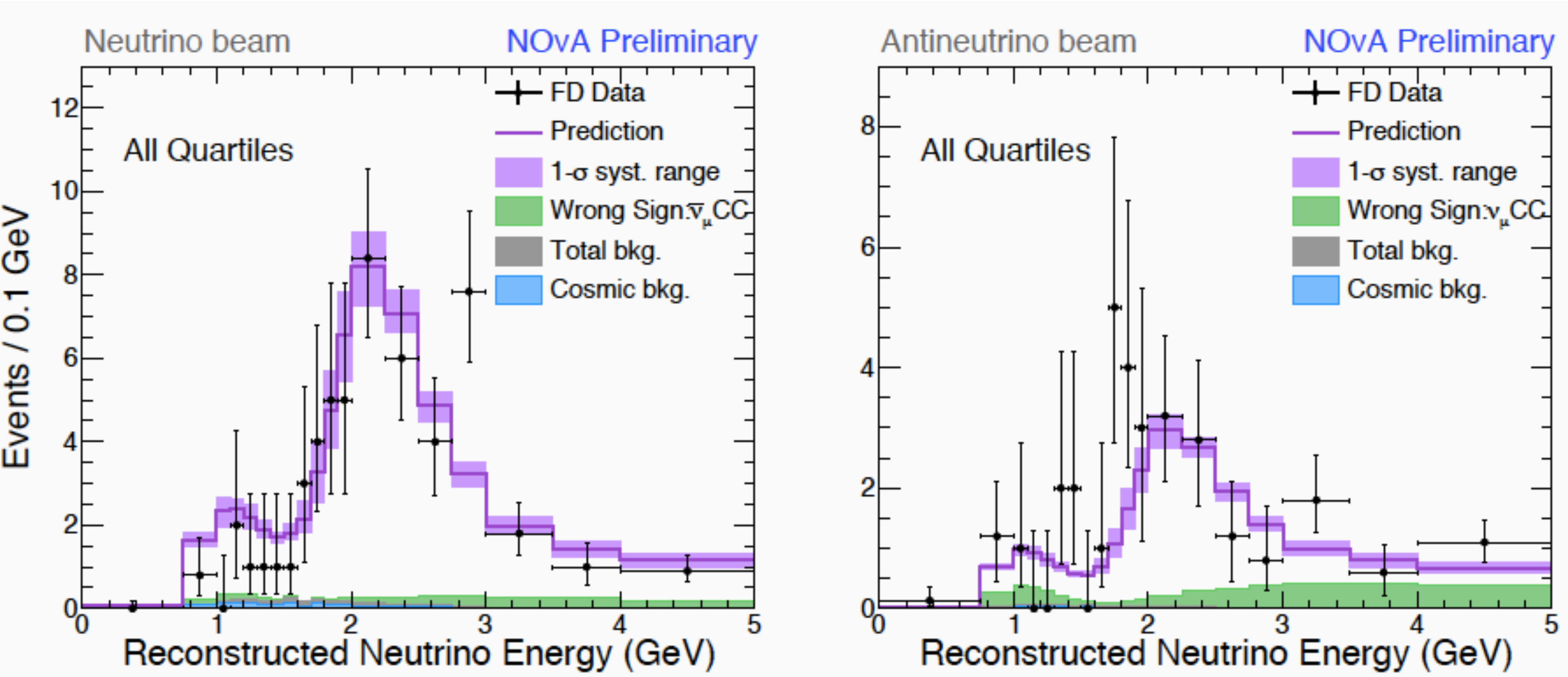


NOvA Events

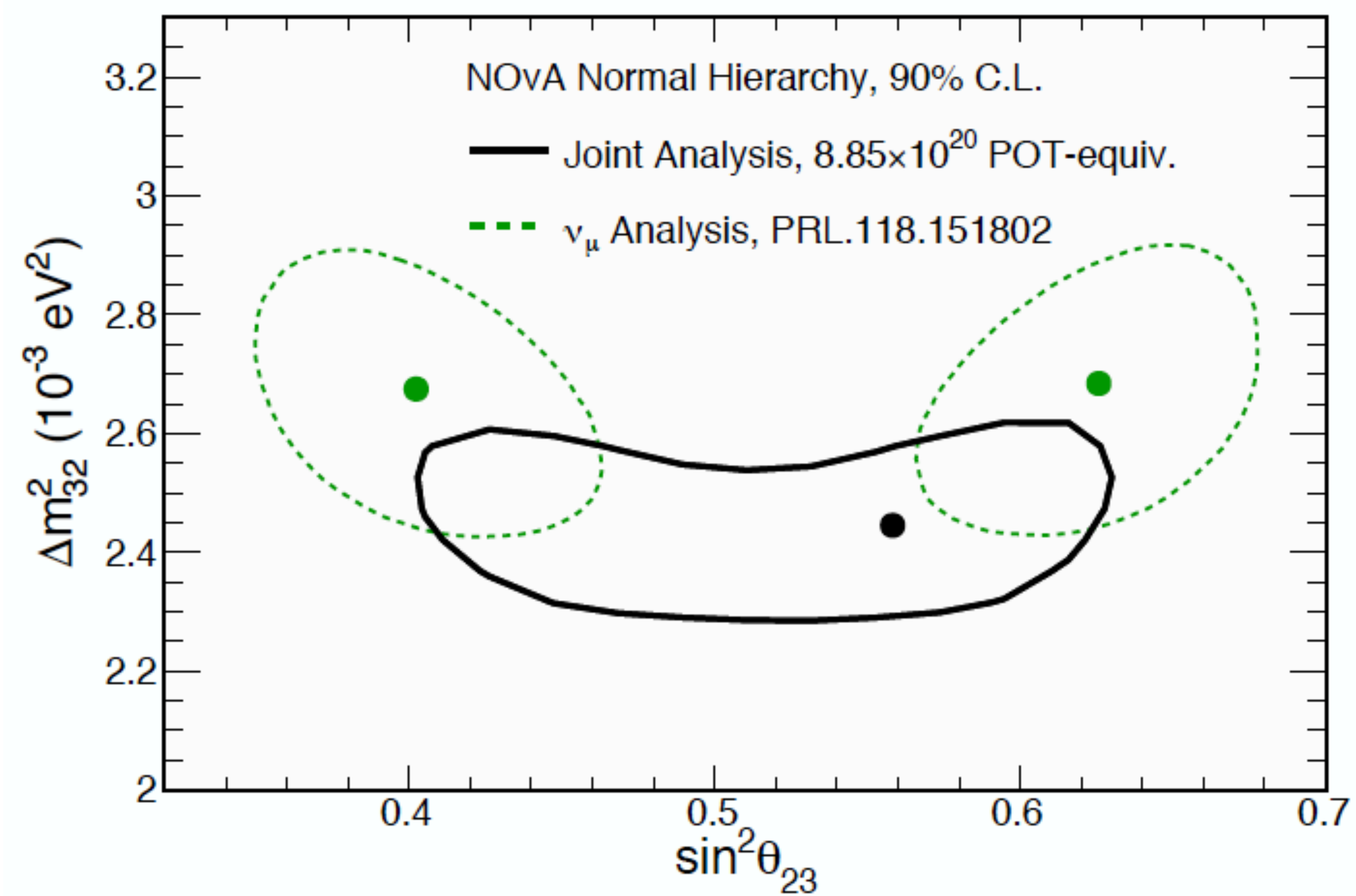


νμ CC Signal
p
νμ
μ
μ + p
μ
p
W
νμ
n
νe CC Signal
p
νe
e
e + p
e
p
W
νe
n
NC Signal or Background
π
γ
ν
π0
p
γ
π0 +π + p
να
X
Z
να
X
1m
10
10²
10³
q (ADC)

NOvA Disappearance



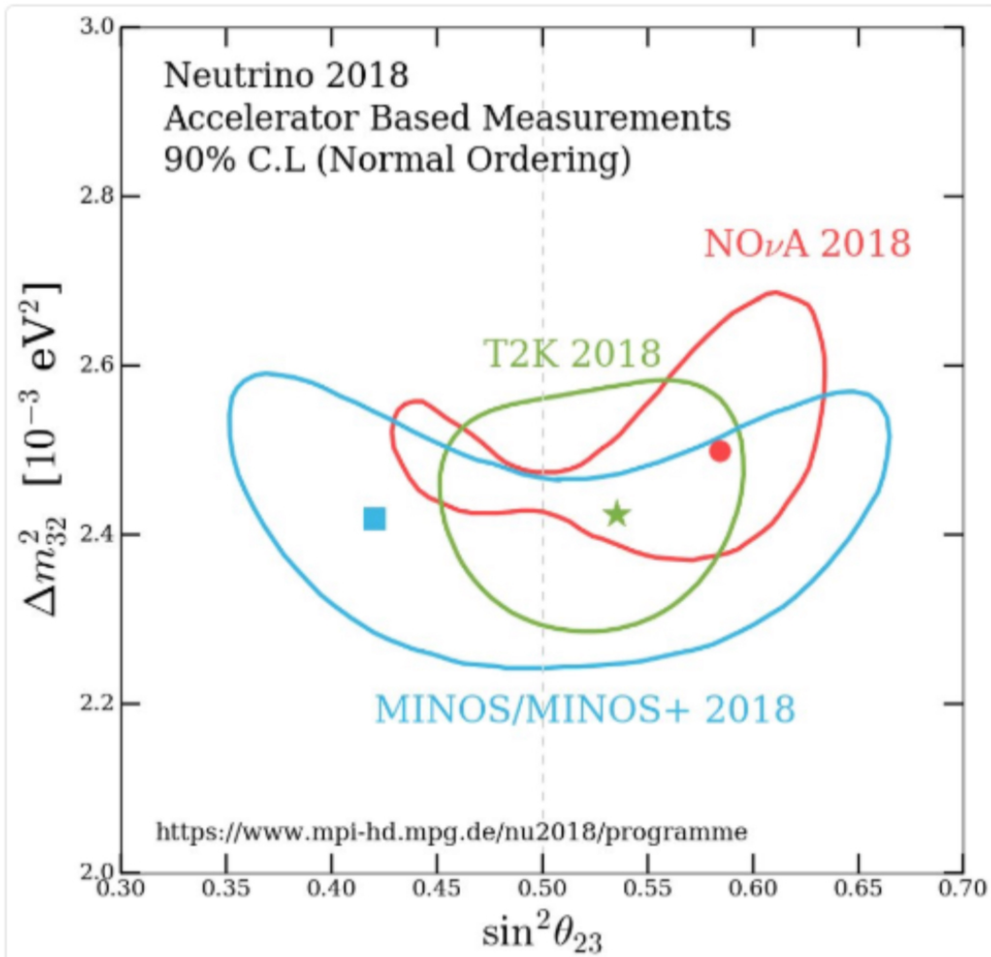
A word of caution



The Happy Family

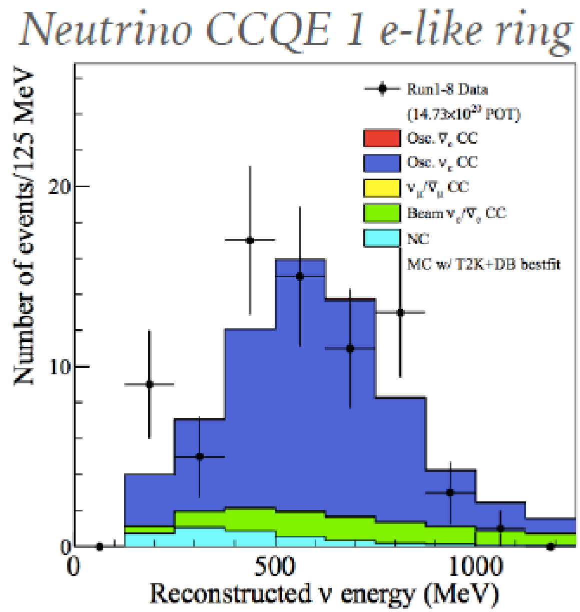
Mark Ross-Lonergan @mrossl · Jun 5

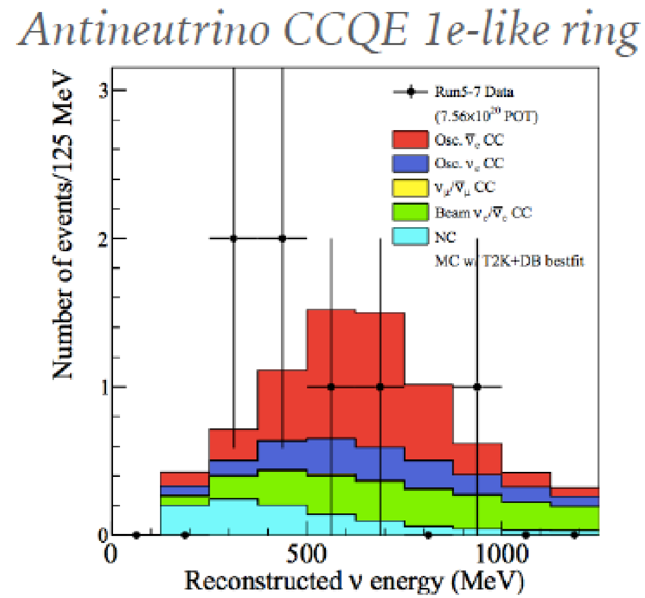
Although we will have to wait a bit for a combined analysis, we can easily take a look at yesterdays exciting accelerator updates to the atmospheric mixing parameters in one place! #neutrino2018



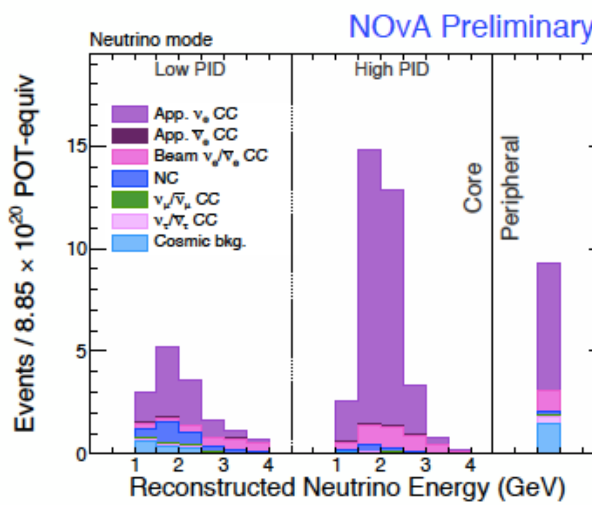
Electron Neutrino Appearance

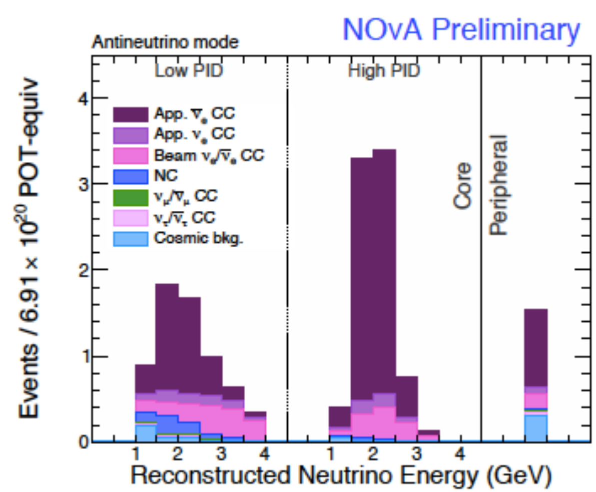
T2K





NOvA





The Full Monty

$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \; (1 - 2S_{13}^2)\right)$$

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

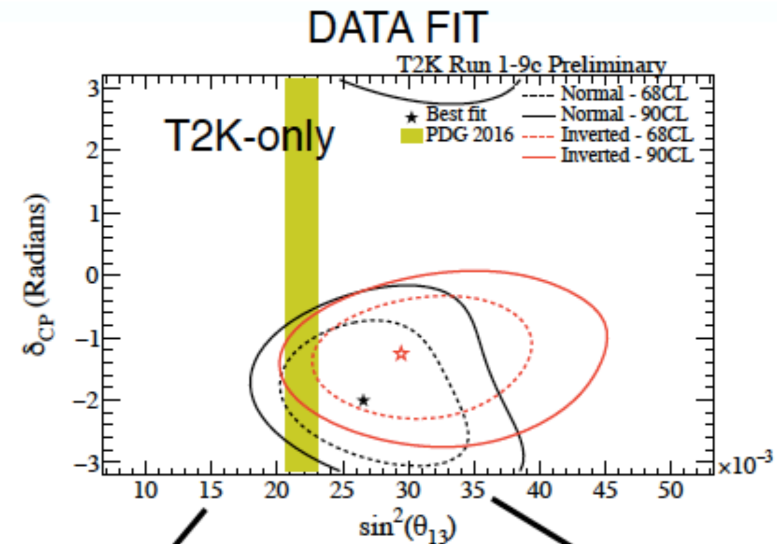
$$+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

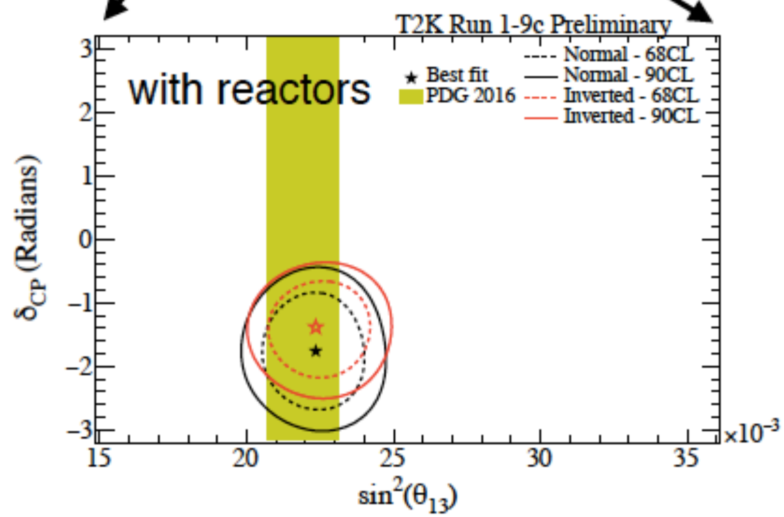
$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} (1 - 2S_{13}^2)$$

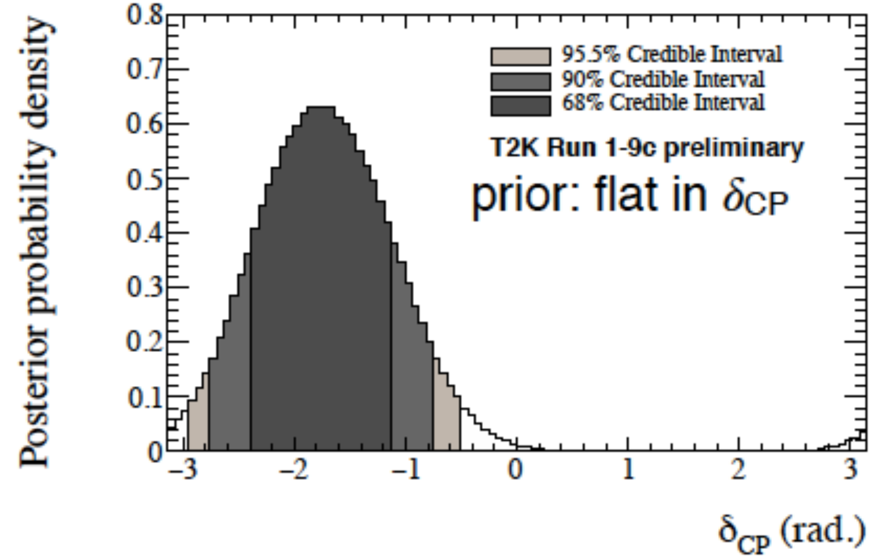
sin(δ) changes sign for anti-neutrinos

- δ is CP-violating phase
- Matter ⇔ anti-matter difference

T2K Results

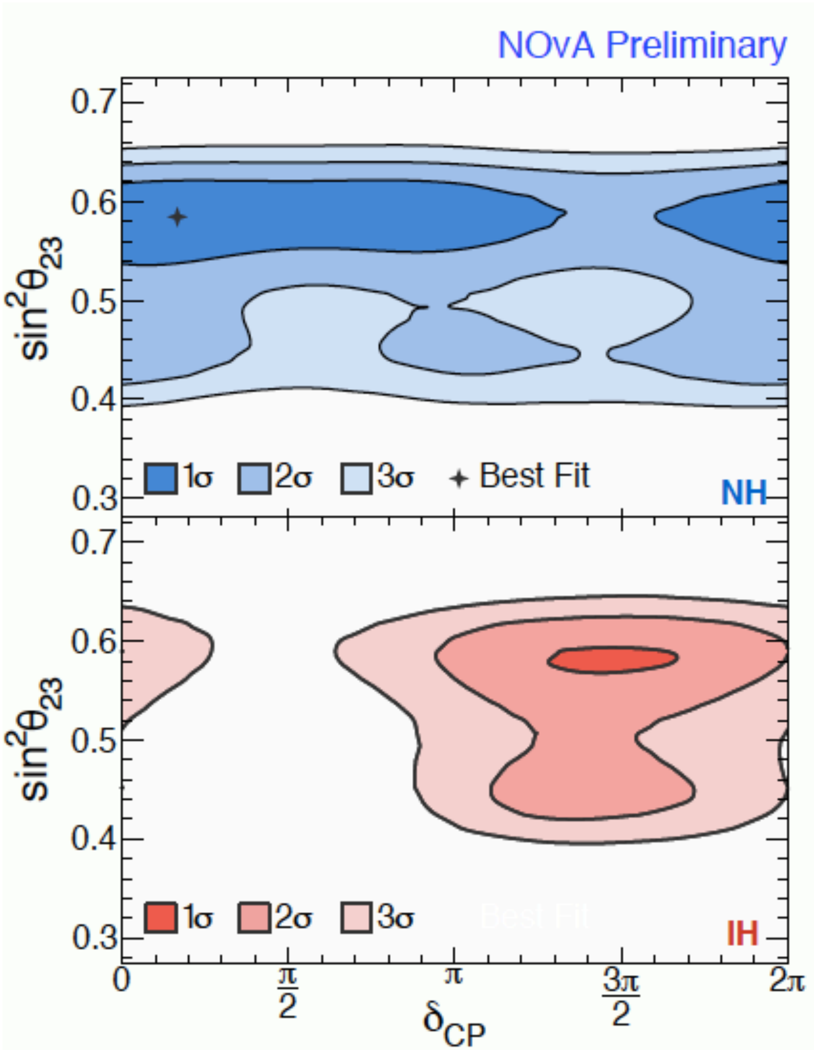


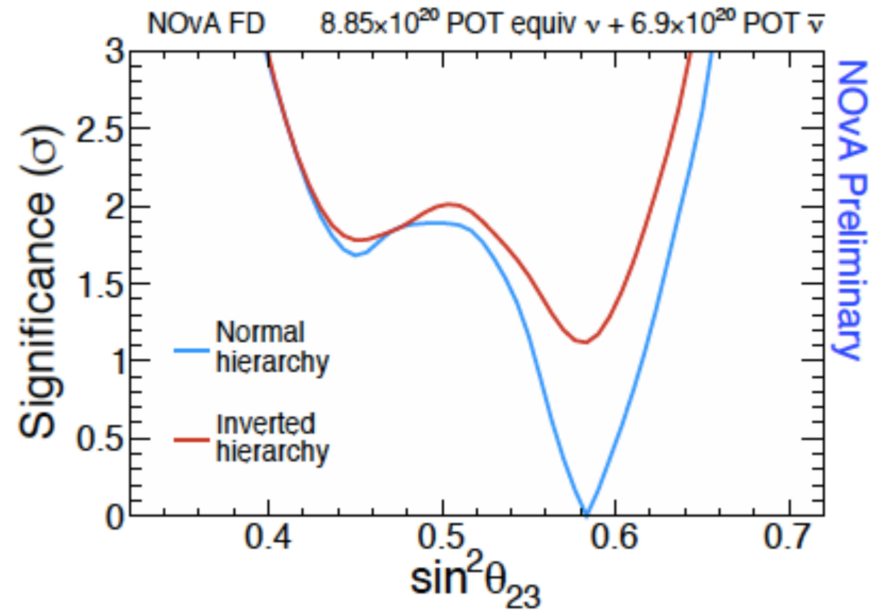




	$\sin^2\theta_{23} \leq 0.5$	$\sin^2\theta_{23} > 0.5$	SUM
NH ($\Delta m^2_{32} > 0$)	0.204	0.684	0.888
IH ($\Delta m^2_{31} < 0$)	0.023	0.089	0.112
SUM	0.227	0.773	1

NOvA Results





Best fit: Normal Hierarchy

$\delta_{CP} = 0.17\pi$

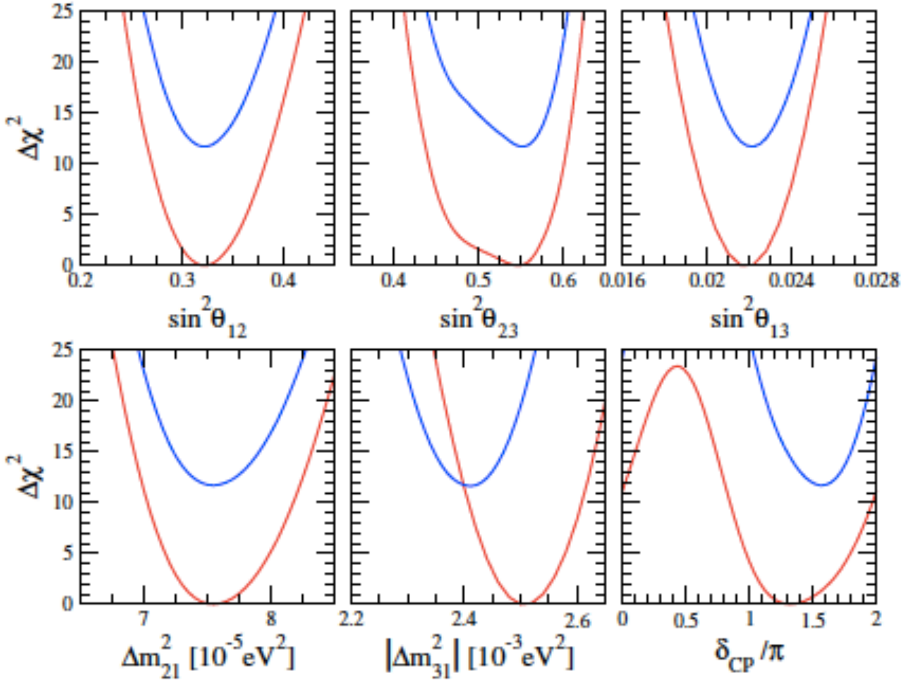
$\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)

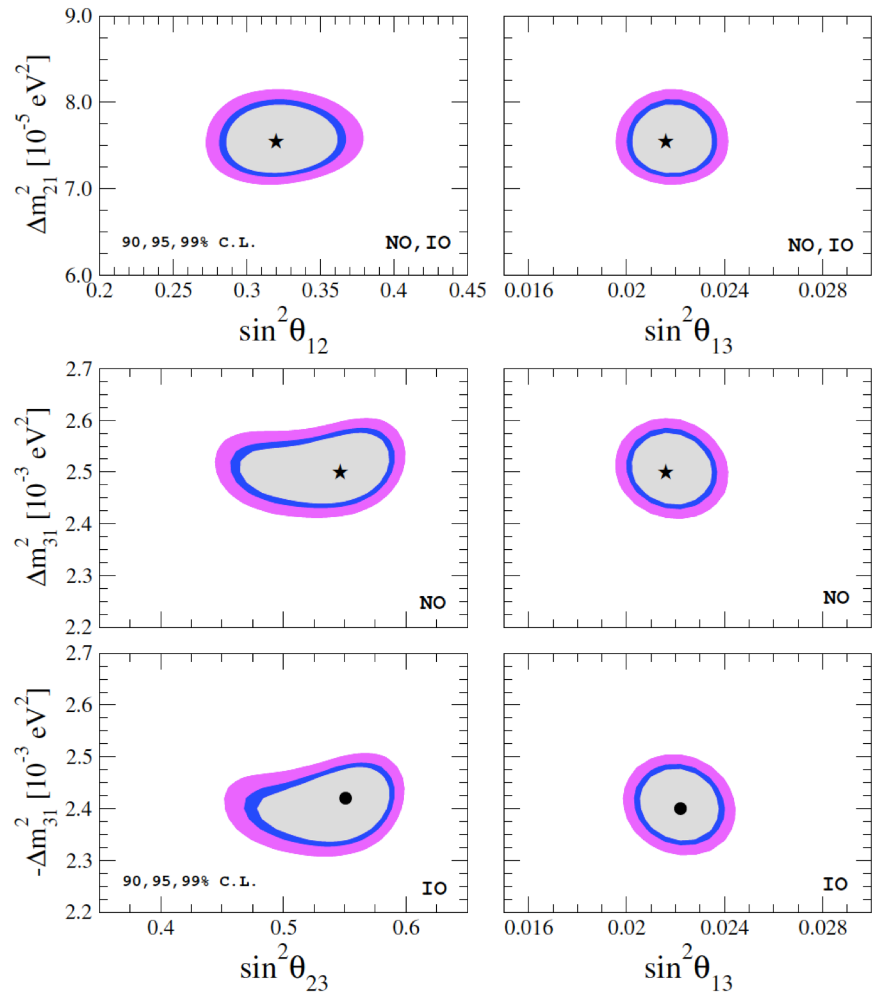
$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3}\ eV^2$

Solar & Reactor Neutrinos
In backup slides

Global Fits

[P. F. de Salas et al., Phys. Lett. B 782, 633 (2018)]





Normal Ordering

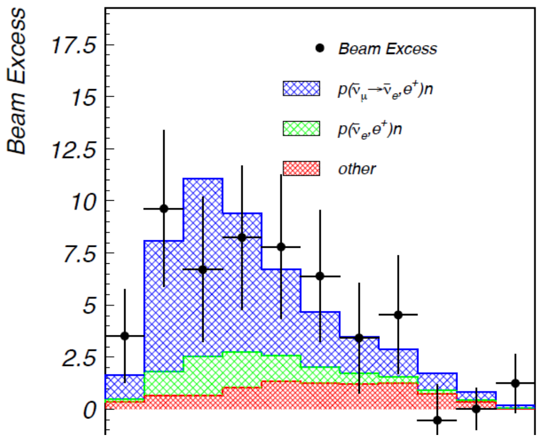
Inverted Ordering

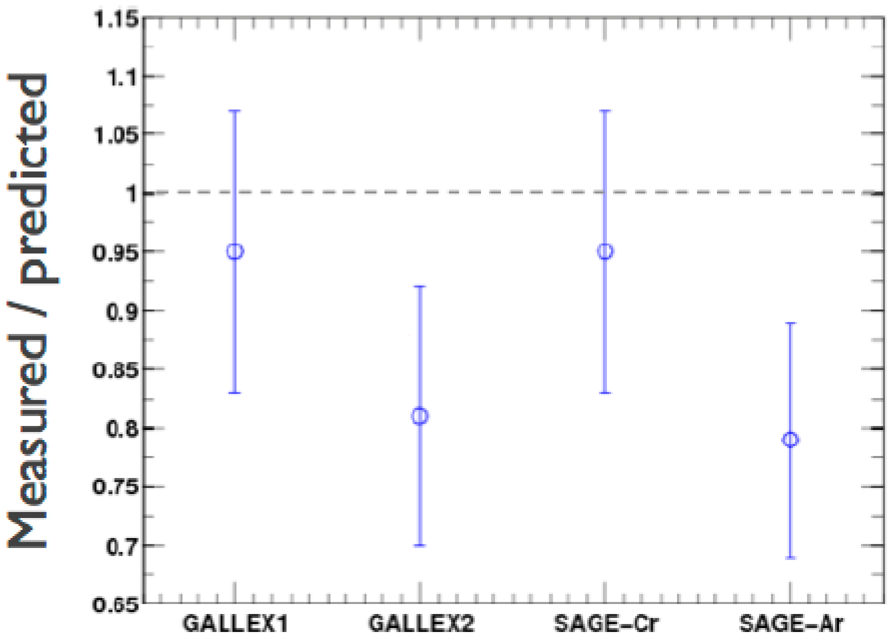
All is Fine?

Sterile Neutrinos

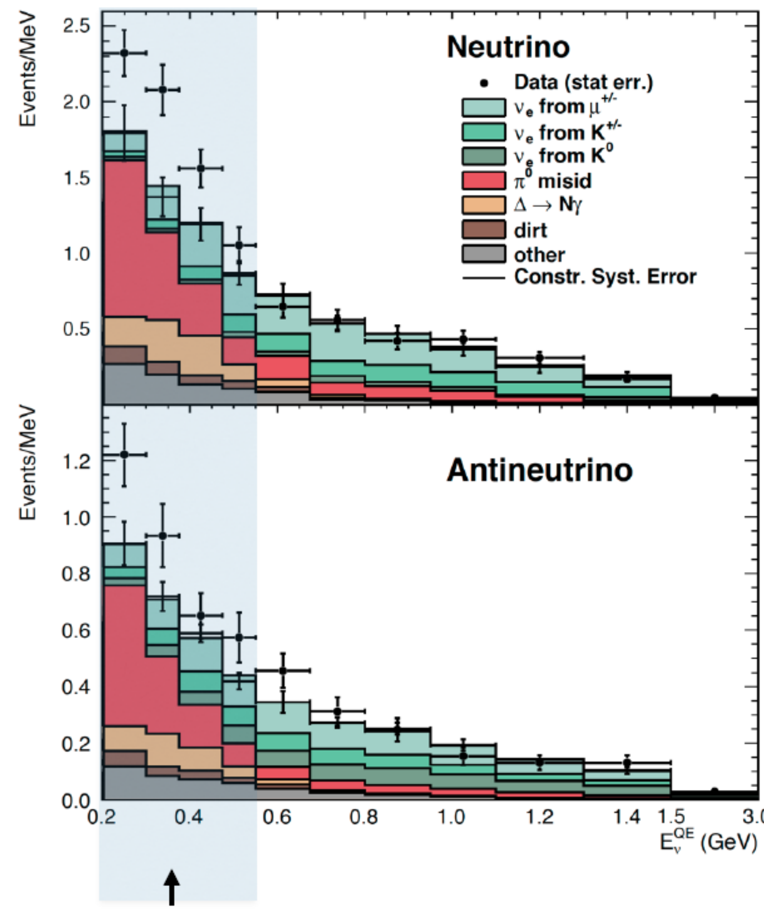
All is Fine?

LSND



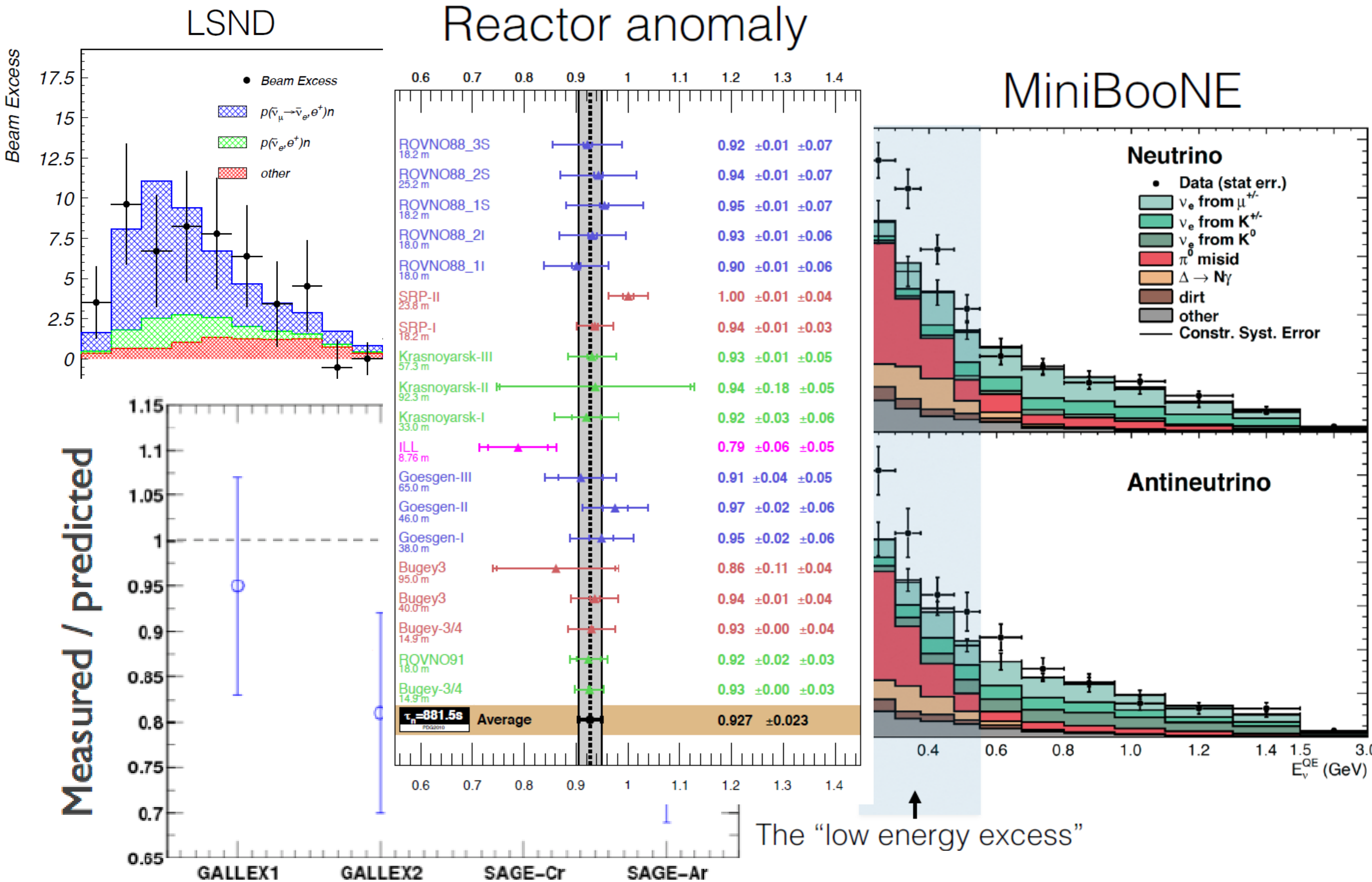


MiniBooNE



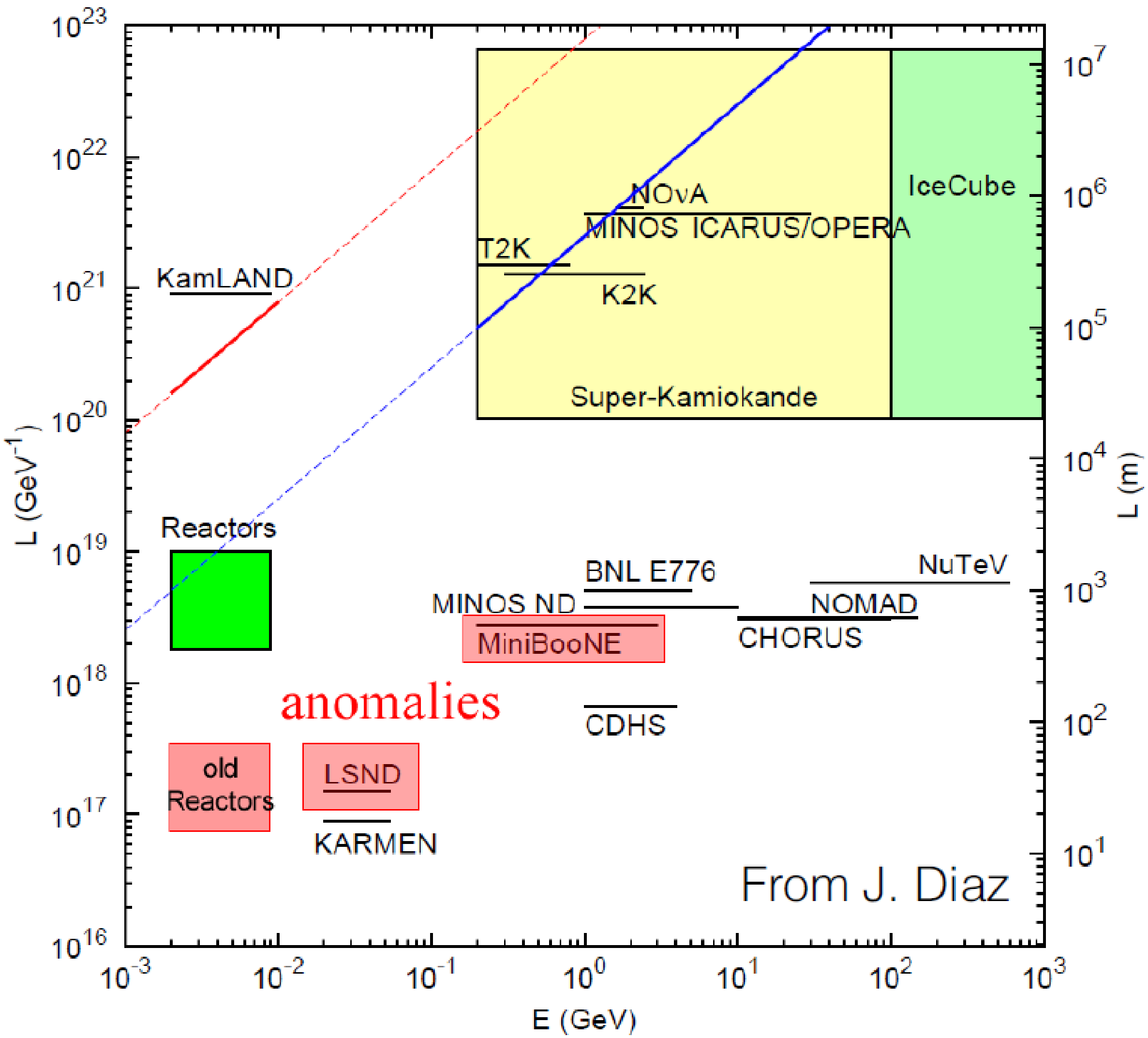
The "low energy excess"

All is Fine?



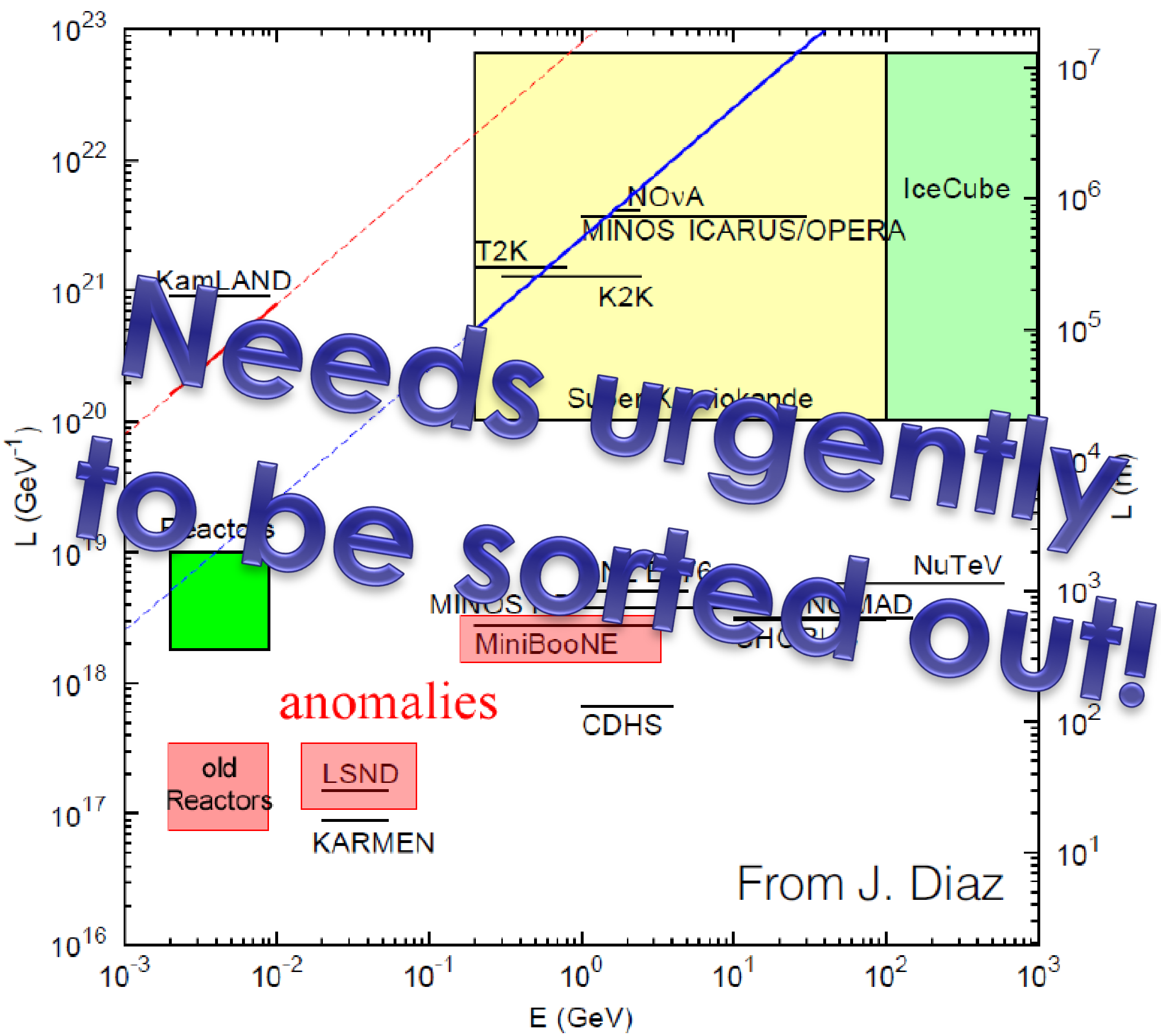
LSND
Beam Excess
Beam Excess
$p(\bar{\nu}_\mu \to \bar{\nu}_e, e^+)n$
$p(\bar{\nu}_e, e^+)n$
other
Reactor anomaly
ROVNO88_3S 18.2 m 0.92 ±0.01 ±0.07
ROVNO88_2S 25.2 m 0.94 ±0.01 ±0.07
ROVNO88_1S 18.2 m 0.95 ±0.01 ±0.07
ROVNO88_2I 18.0 m 0.93 ±0.01 ±0.06
ROVNO88_1I 18.0 m 0.90 ±0.01 ±0.06
SRP-II 23.8 m 1.00 ±0.01 ±0.04
SRP-I 18.2 m 0.94 ±0.01 ±0.03
Krasnoyarsk-III 57.3 m 0.93 ±0.01 ±0.05
Krasnoyarsk-II 92.3 m 0.94 ±0.18 ±0.05
Krasnoyarsk-I 33.0 m 0.92 ±0.03 ±0.06
ILL 8.76 m 0.79 ±0.06 ±0.05
Goesgen-III 65.0 m 0.91 ±0.04 ±0.05
Goesgen-II 46.0 m 0.97 ±0.02 ±0.06
Goesgen-I 38.0 m 0.95 ±0.02 ±0.06
Bugey3 95.0 m 0.86 ±0.11 ±0.04
Bugey3 40.0 m 0.94 ±0.01 ±0.04
Bugey-3/4 14.9 m 0.93 ±0.00 ±0.04
ROVNO91 18.0 m 0.92 ±0.02 ±0.03
Bugey-3/4 14.9 m 0.93 ±0.00 ±0.03
τ_n=881.5s
Average 0.927 ±0.023
Measured / predicted
GALLEX1
GALLEX2
SAGE-Cr
SAGE-Ar
MiniBooNE
Neutrino
Data (stat err.)
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
$\Delta \to N\gamma$
dirt
other
Constr. Syst. Error
Antineutrino
E_ν^{QE} (GeV)
The "low energy excess"

Signatures



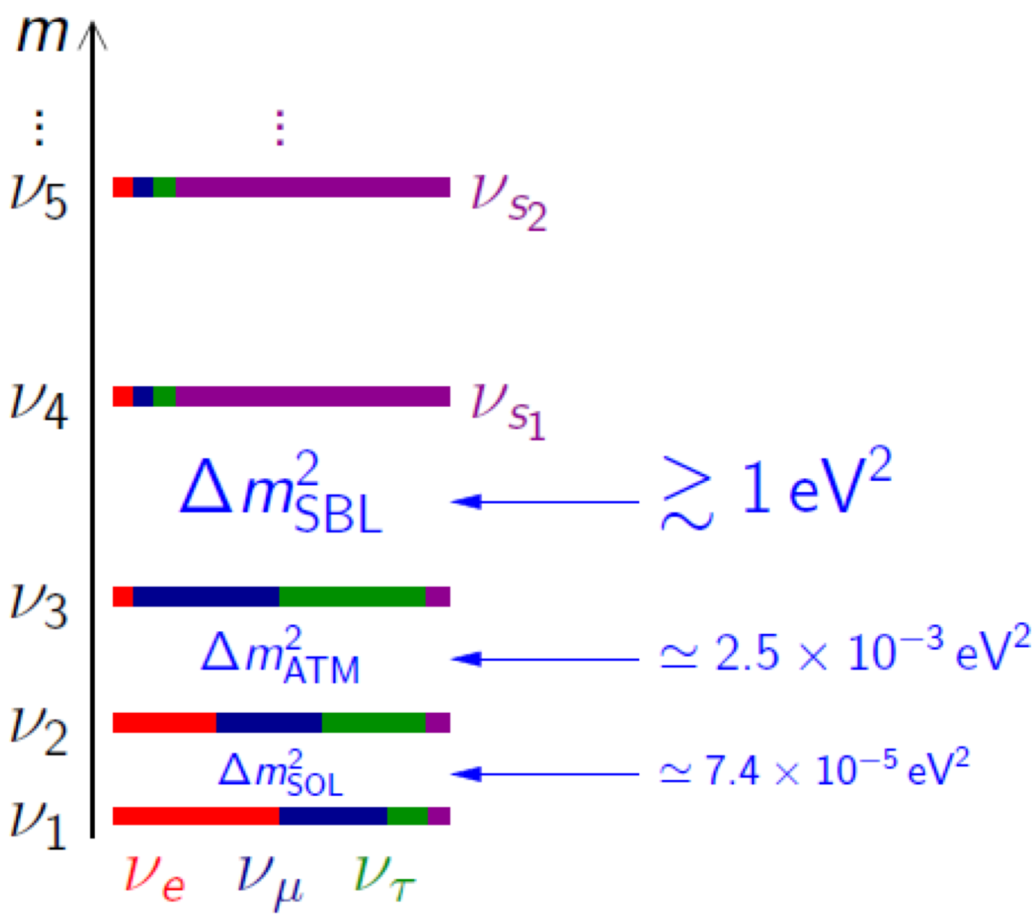
L (GeV^{-1})
L (m)
E (GeV)
KamLAND
Reactors
NOvA
MINOS ICARUS/OPERA
T2K
K2K
IceCube
Super-Kamiokande
BNL E776
NuTeV
MINOS ND
NOMAD
MiniBooNE
CHORUS
anomalies
CDHS
old Reactors
LSND
KARMEN
From J. Diaz

Signatures



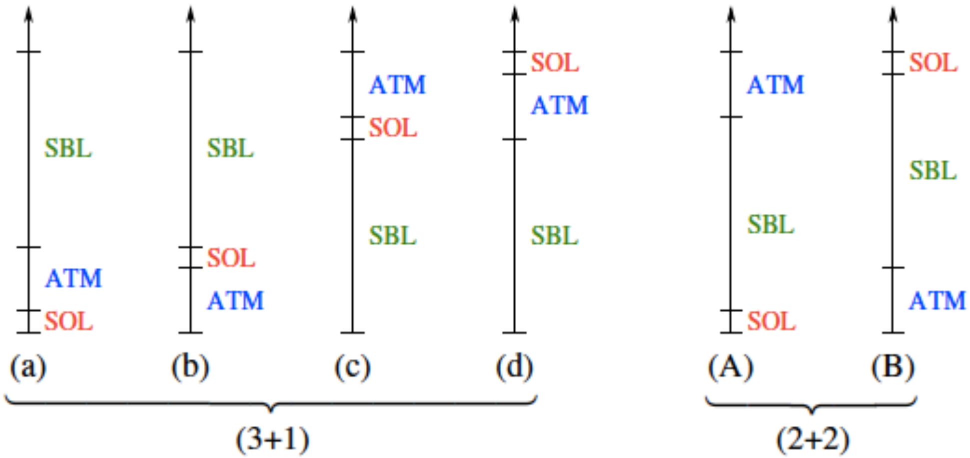
KamLAND
NOvA
MINOS ICARUS/OPERA
T2K
K2K
IceCube
Super-Kamiokande
Reactors
NuTeV
MINOS
NOMAD
MiniBooNE
CHORUS
anomalies
CDHS
old Reactors
LSND
KARMEN
From J. Diaz
L (GeV⁻¹)
L (m)
E (GeV)
Needs urgently to be sorted out!

More Neutrinos?



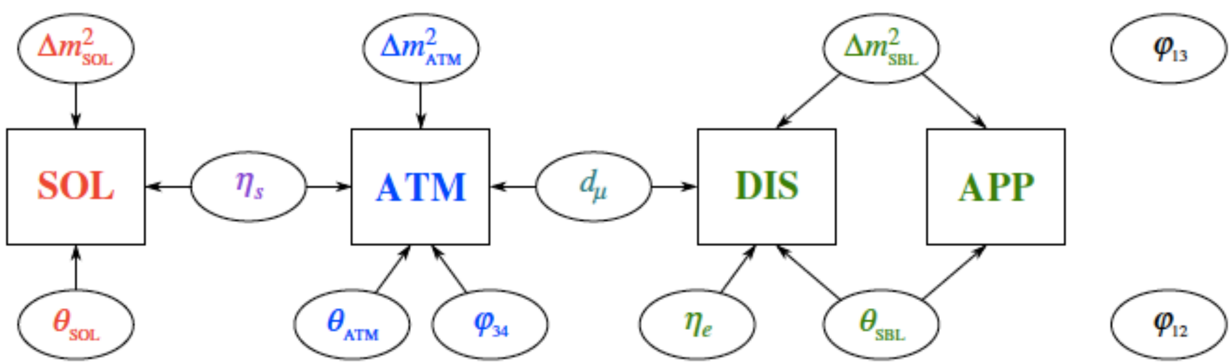
Global Sterile Picture

- Approximation: $\Delta m^2_{\text{SOL}} \ll \Delta m^2_{\text{ATM}} \ll \Delta m^2_{\text{SBL}} \Rightarrow$ 6 different mass schemes:



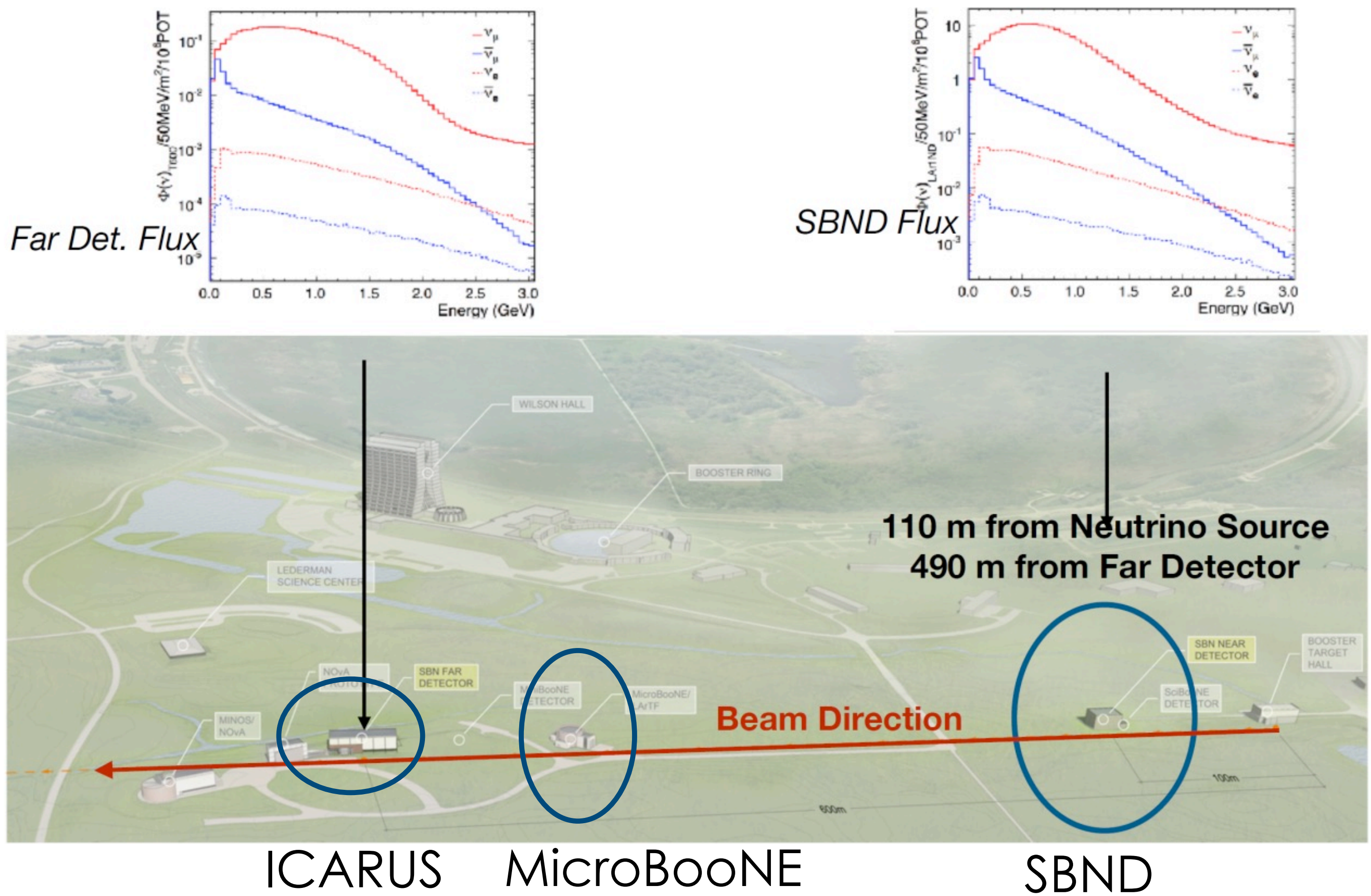
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- Total: 3 Δm^2, 6 angles, 3 phases. Different set of experimental data *partially decouple*:



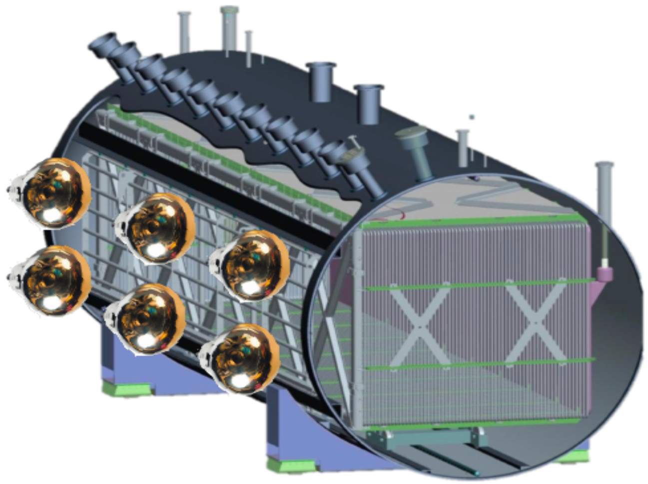
Michele Maltoni <michele.maltoni@csic.es>
Neutrino 2018, 8/06/2018

SNAL Short Baseline Programme

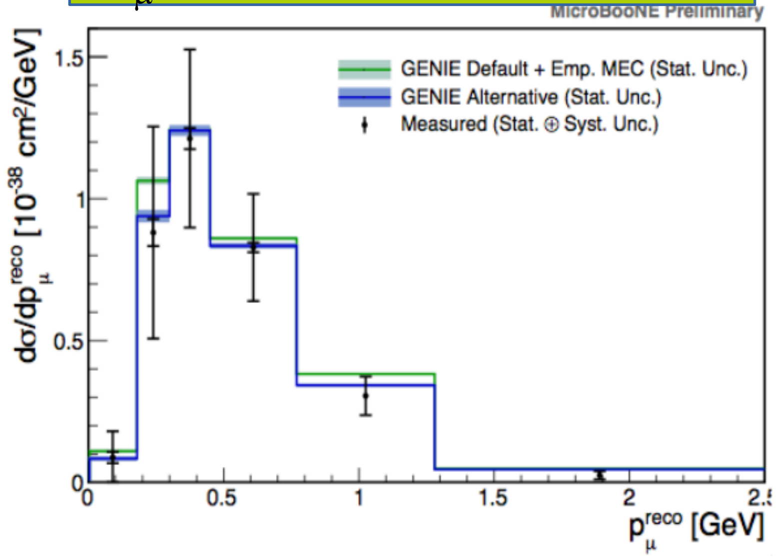


- Search for Sterile Neutrinos
- Neutrino interactions cross sections (7M CC events)

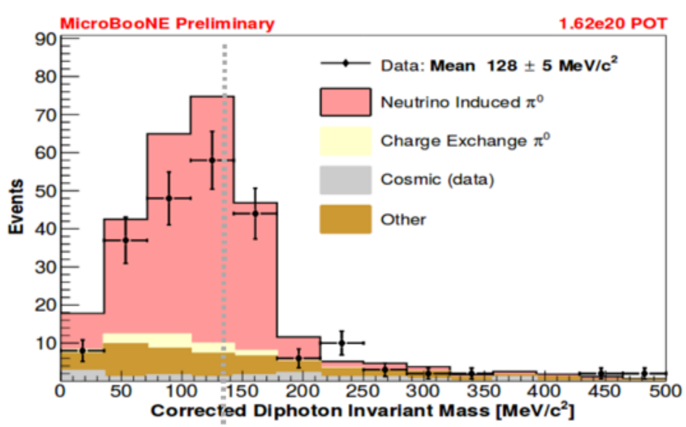
MicroBooNE First Results



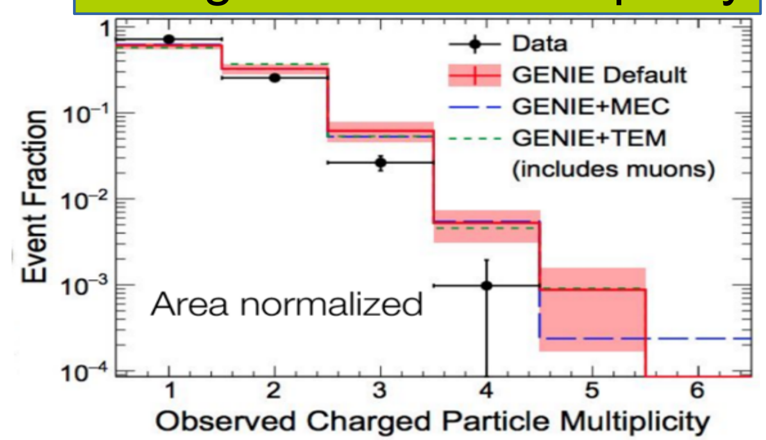
ν_μ -inclusive cross-section



CC-π^0 cross-section

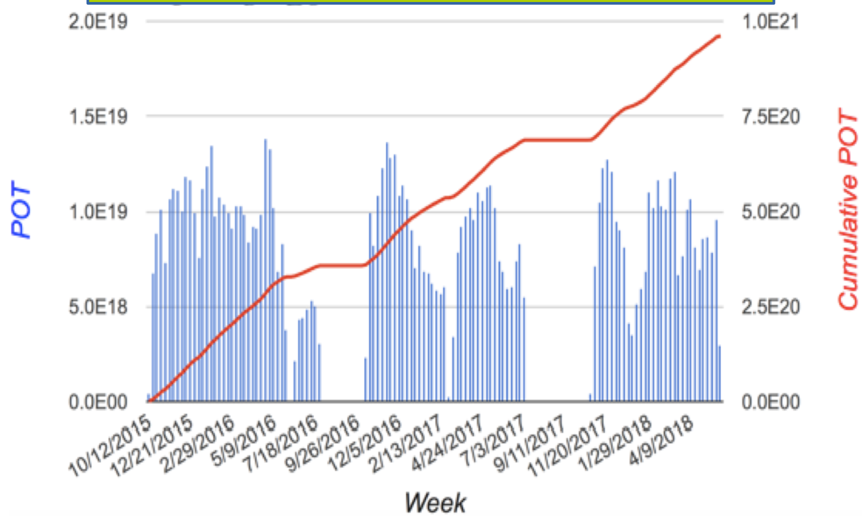


Charged Particle Multiplicity

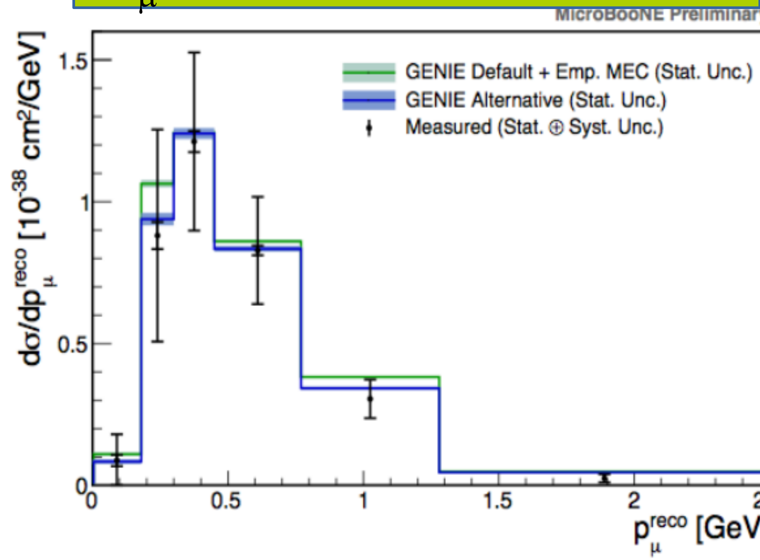


MicroBooNE First Results

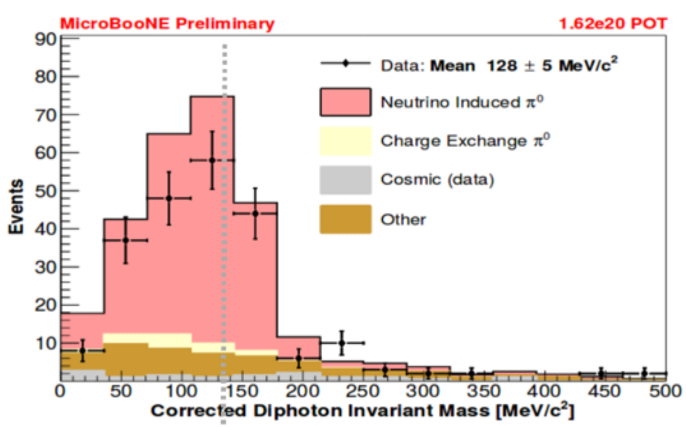
Data collected



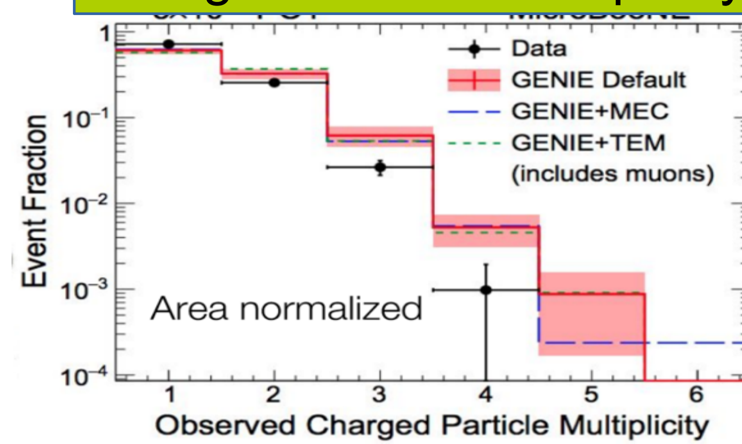
ν_μ -inclusive cross-section



CC-π^0 cross-section



Charged Particle Multiplicity

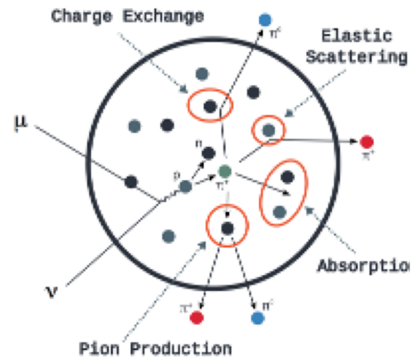


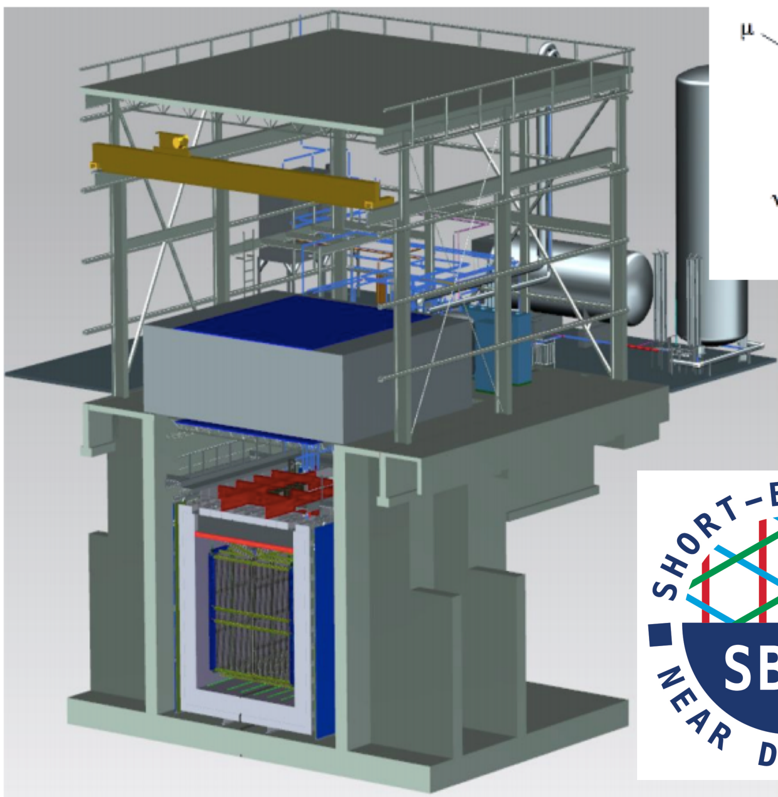
ICARUS


ICARUS Neutrino Detector Installation at Fermilab
ICARUS
Neutrino Detector
#IcarusTrip

SBND

- Near Detector for SBL program
- Detailed study of neutrino Argon interactions





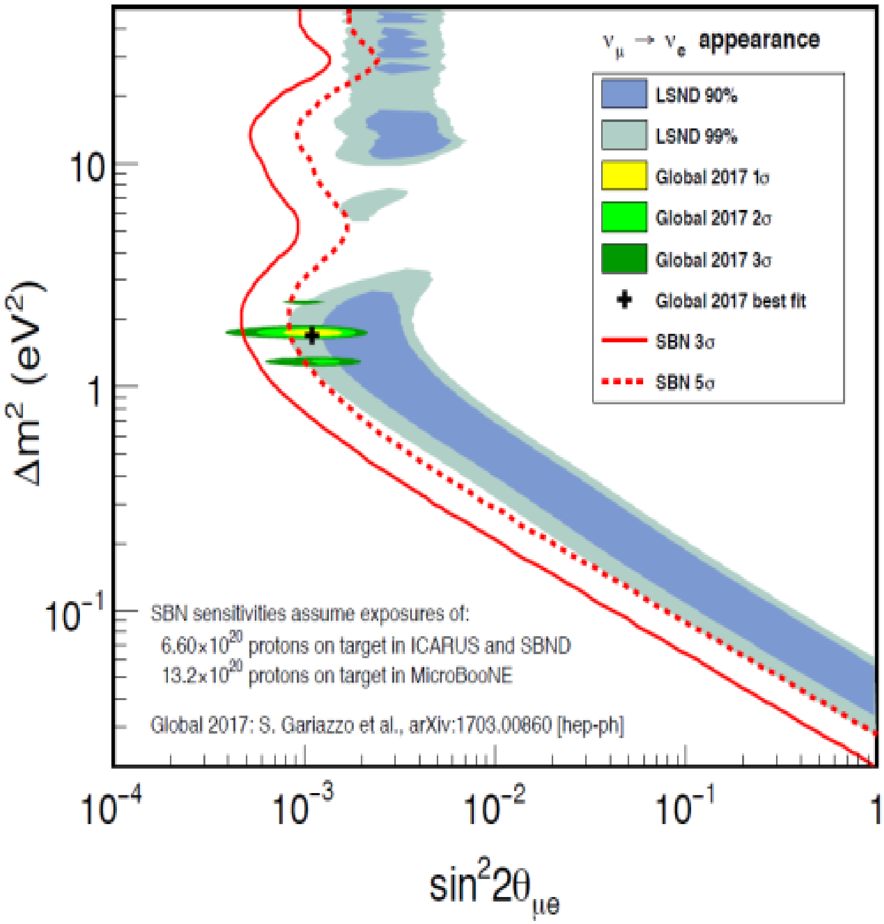
3 year event rates

Charged Current	
ν_μ Inclusive	5,389,168
$\rightarrow 0\pi$	3,814,198
$\longrightarrow 0p$	27,269
$\longrightarrow 1p$	1,261,730
$\longrightarrow 2p$	1,075,803
$\longrightarrow \geq 3p$	1,449,394
$\rightarrow 1\pi^+ + X$	942,555
$\rightarrow 1\pi^- + X$	38,012
$\rightarrow 1\pi^0 + X$	406,555
$\rightarrow 2\pi + X$	145,336
$\rightarrow \geq 3\pi + X$	42,510
$\rightarrow K^+K^- + X$	521
$\rightarrow K^0\bar{K}^0 + X$	582
$\rightarrow \Sigma_c^{++} + X$	294
$\rightarrow \Sigma_c^{+} + X$	98
$\rightarrow \Lambda_c^{+} + X$	672
ν_e Inclusive	**$\approx$ 12,000**

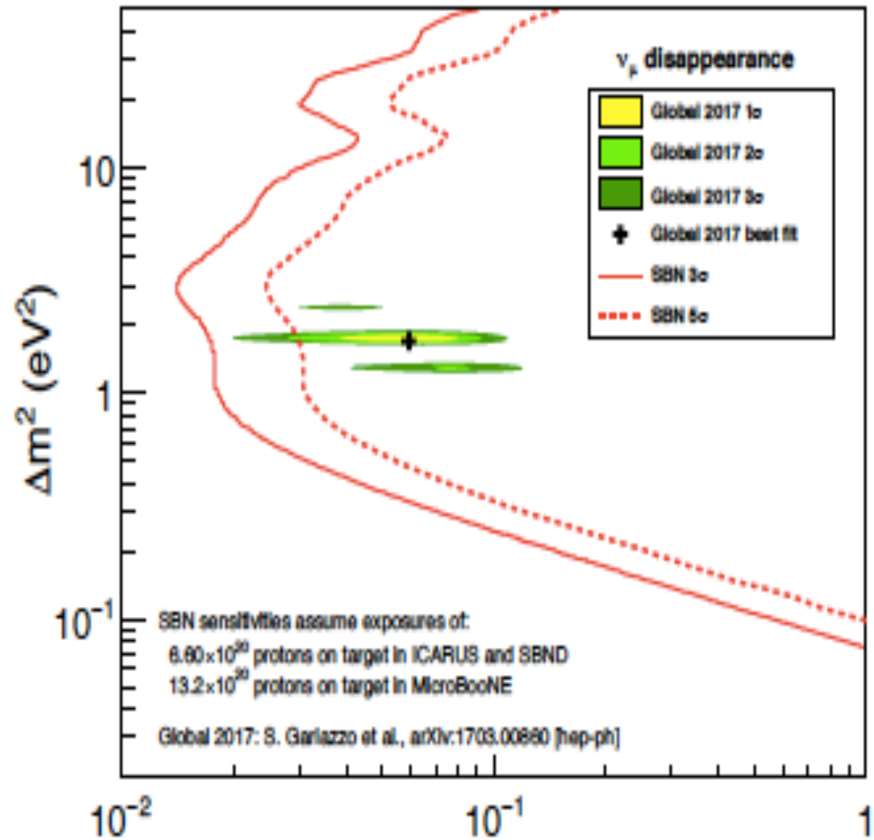
SBL Sensitivity

5 sigma test of allowed oscillation parameter regions

ν_e appearance



ν_μ disappearance



ν Global ~~Consistency~~ Inconsistency

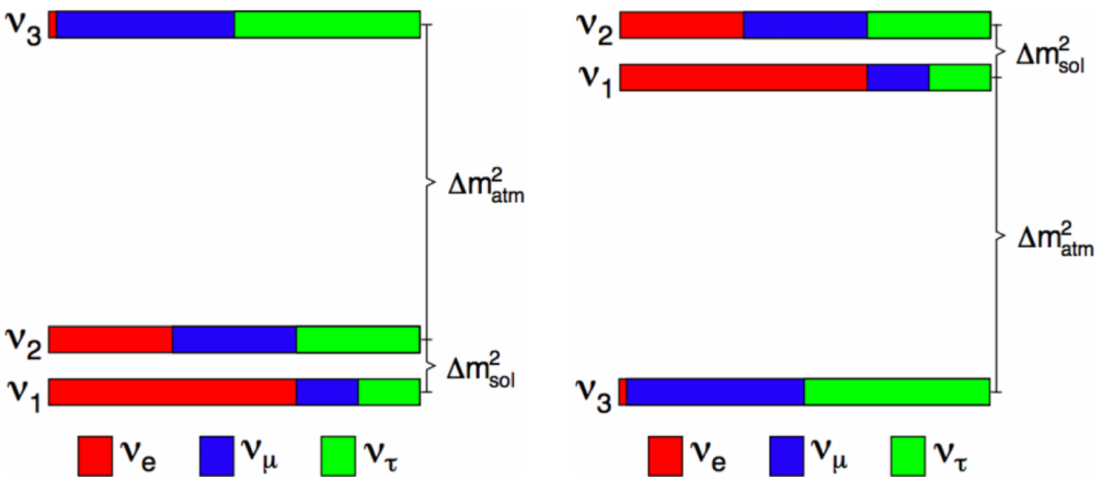
- The tension cannot be eliminated by discarding any *individual* experiment.

Analysis	$\chi^2_{\text{min,global}}$	$\chi^2_{\text{min,app}}$	$\Delta\chi^2_{\text{app}}$	$\chi^2_{\text{min,disapp}}$	$\Delta\chi^2_{\text{disapp}}$	χ^2_{PG}/dof	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.7×10^{-7}
Removing anomalous data sets							
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
w/o MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
w/o reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
w/o gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
Removing constraints							
w/o IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
w/o MINOS(+)	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
w/o MB disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$-dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$-dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
$\overset{(-)}{\nu}_\mu$-dis+solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

Michele Maltoni <michele.maltoni@csic.es> **Neutrino 2018, 8/06/2018**

The Big Question

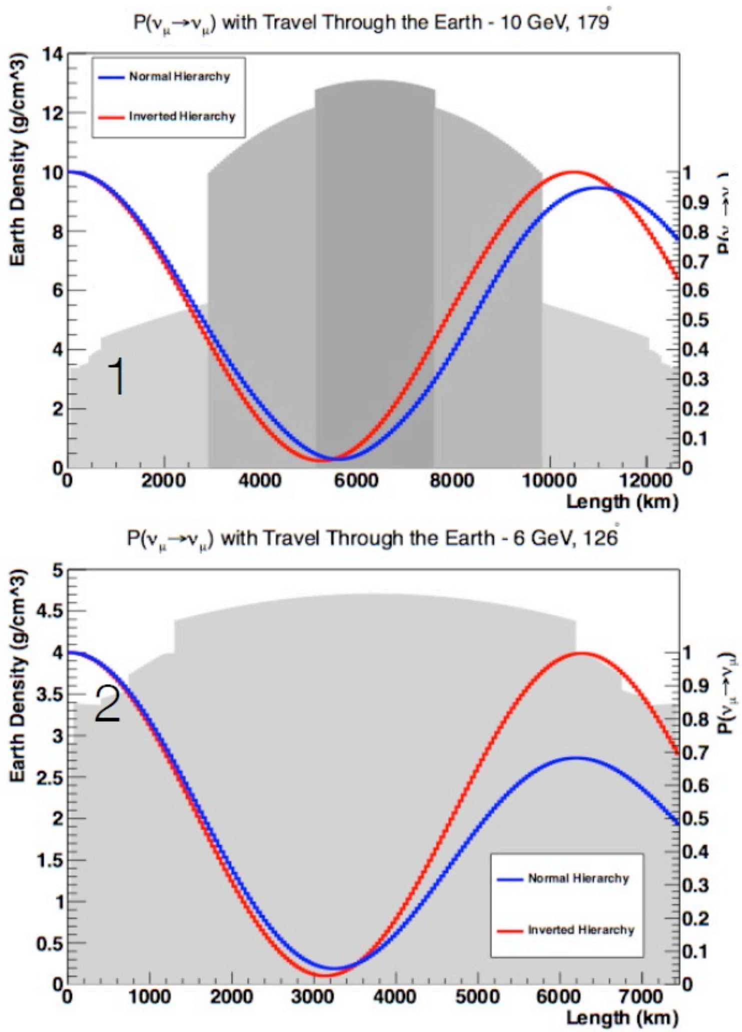
- Is θ_{23} maximal and if not, which octant is it in?
- What is the mass hierarchy/ordering?

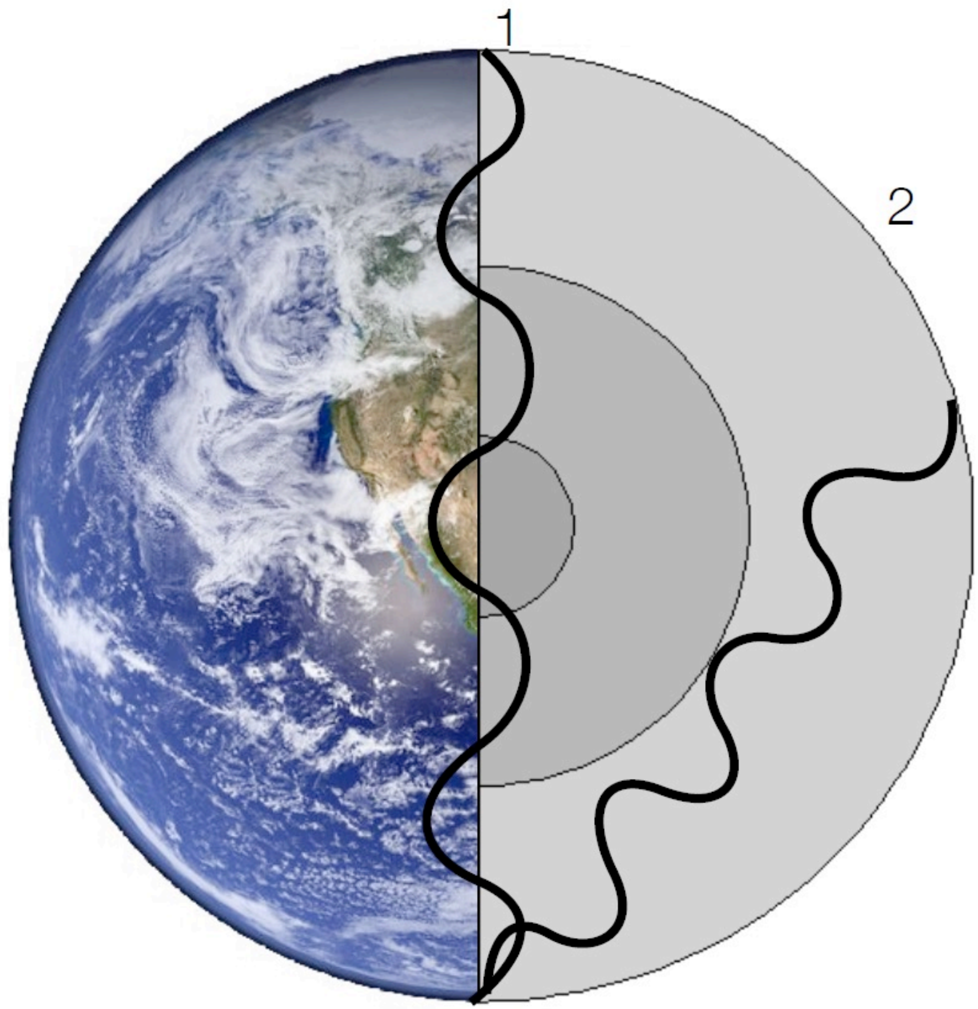


- Is CP violated in neutrino oscillations?

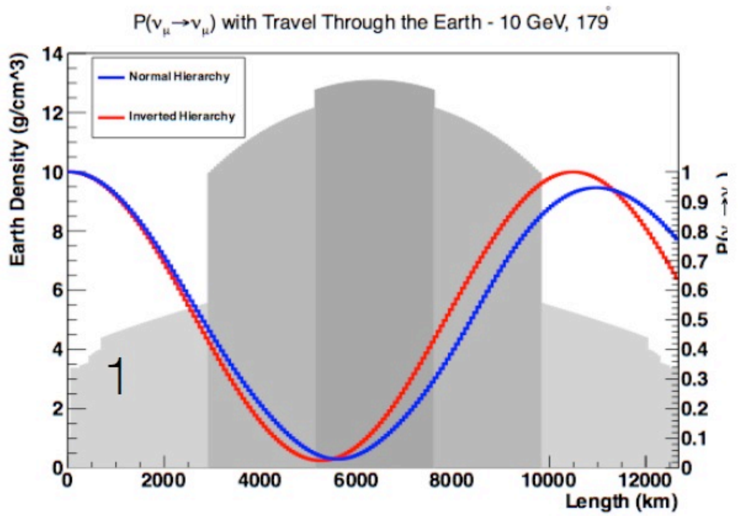
We need more than 1-2σ-effects!
Power comes from combining exp.

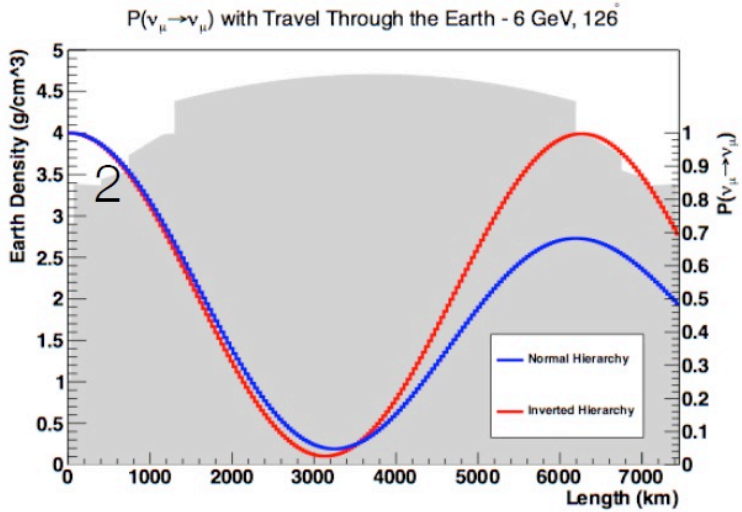
Using Atmospherics





Using Atmospherics





Reminder

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_m)\sin^2\left(\frac{\Delta m_m^2 L}{4E}\right)$$

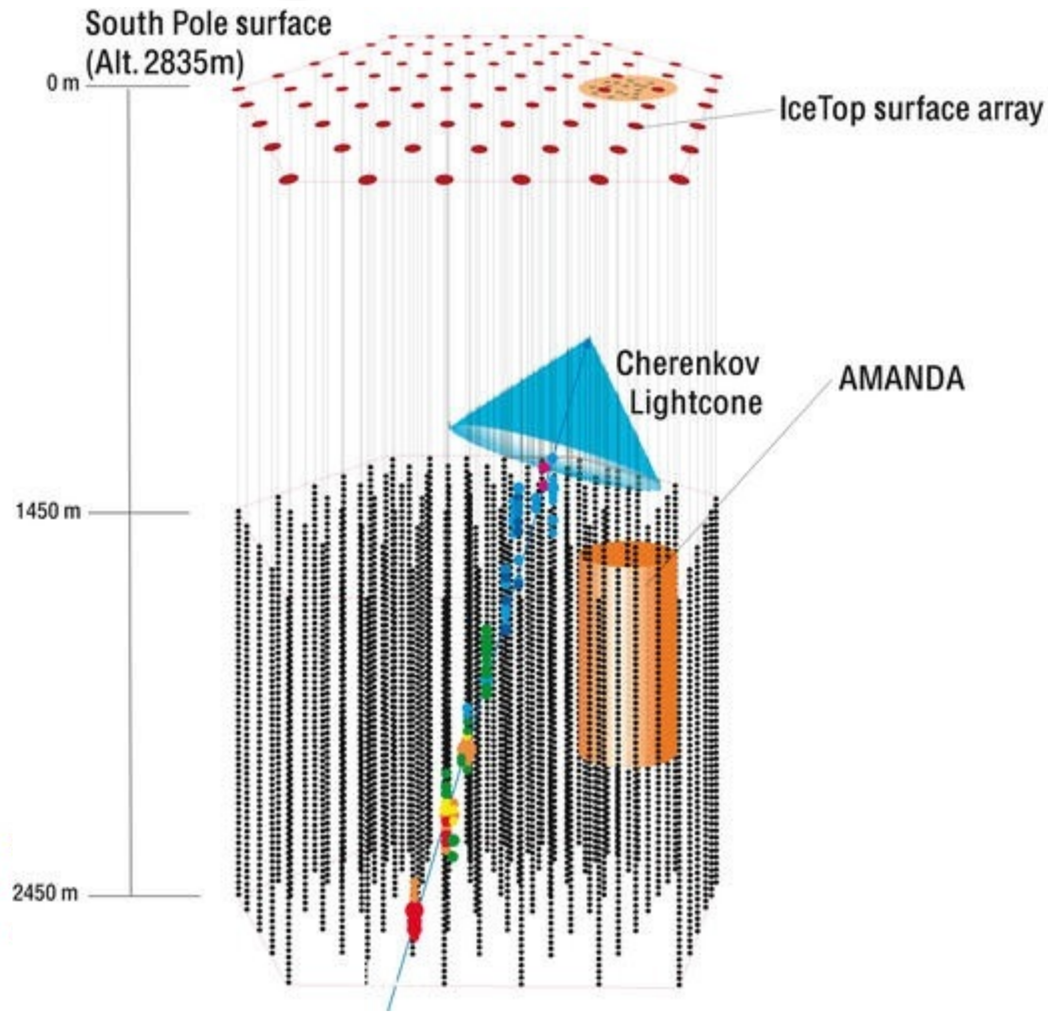
$$\text{with } \sin(2\theta_m) = \frac{\sin(2\theta)}{\sqrt{(\cos 2\theta - A)^2 - \sin^2(2\theta)}}$$

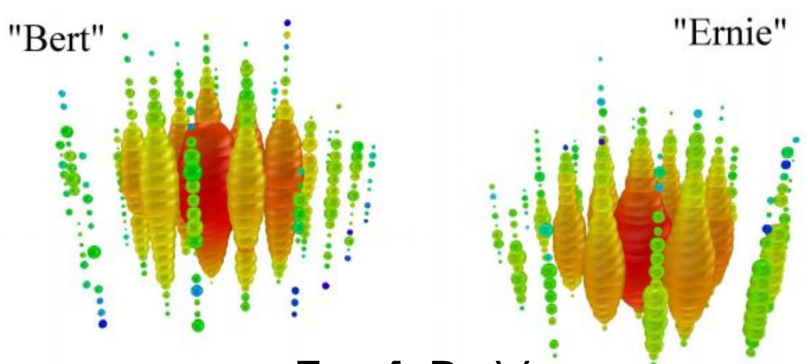
$$\Delta m_m^2 = \Delta m^2 \sqrt{(\cos 2\theta - A)^2 - \sin^2(2\theta)}$$

$$A = \pm \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}$$

Detecting Icy Neutrinos

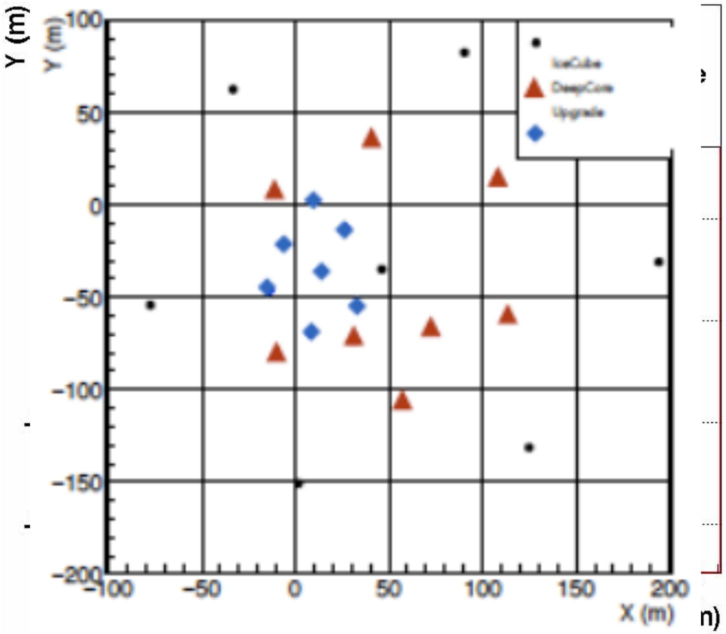
- Neutrinos interact with ice
  - E > 100 GeV
- Čerenkov light
- Reconstruction
  - Particle type
  - Energy
  - direction

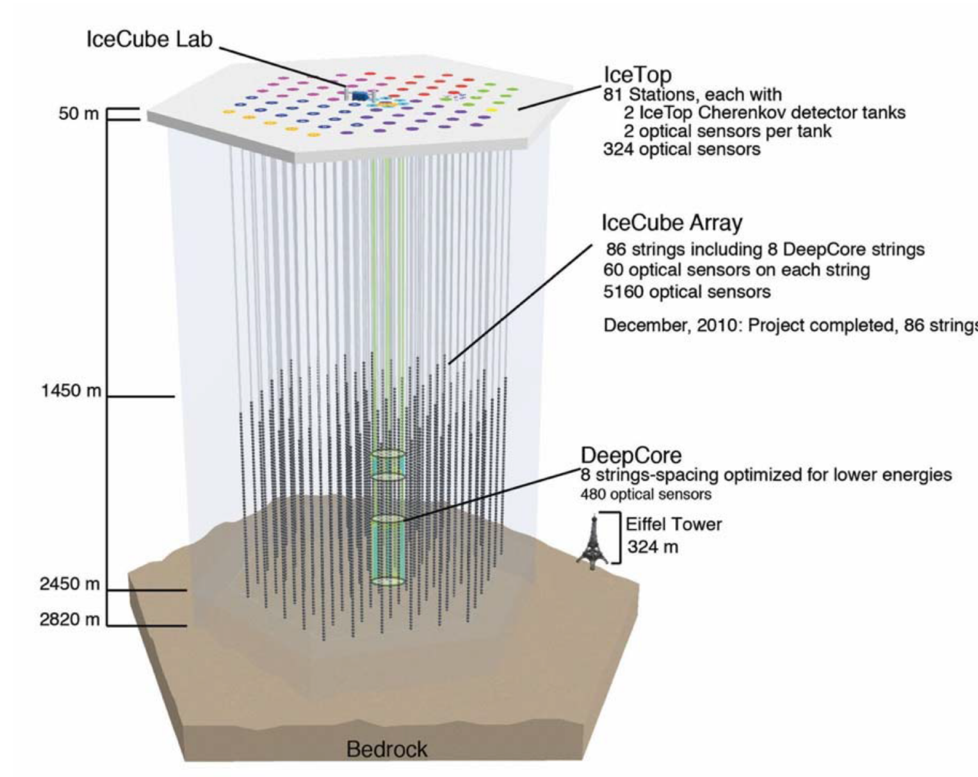


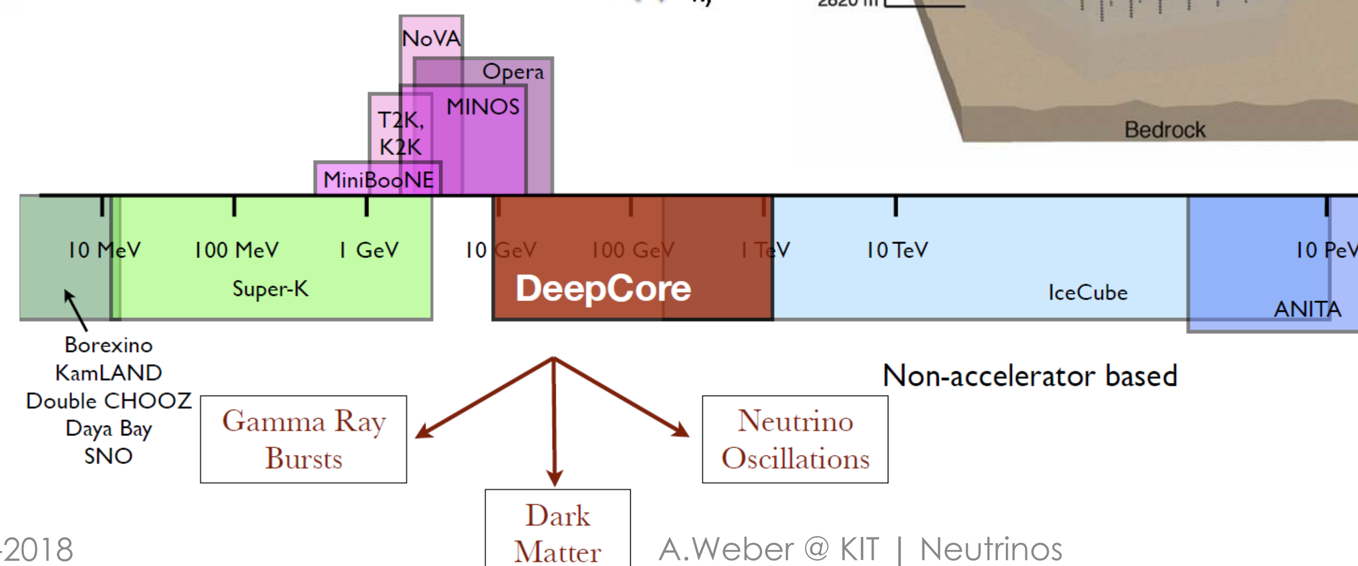


E ~ 1 PeV

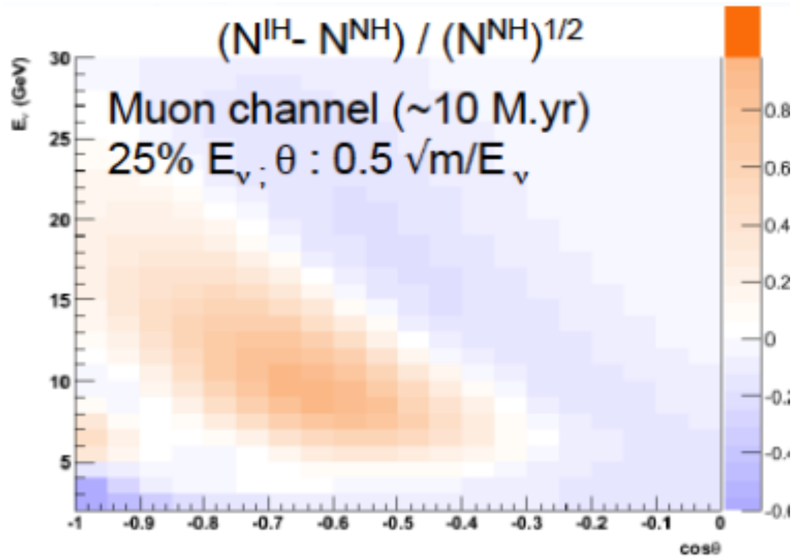
PINGU➔ IceCube Gen II

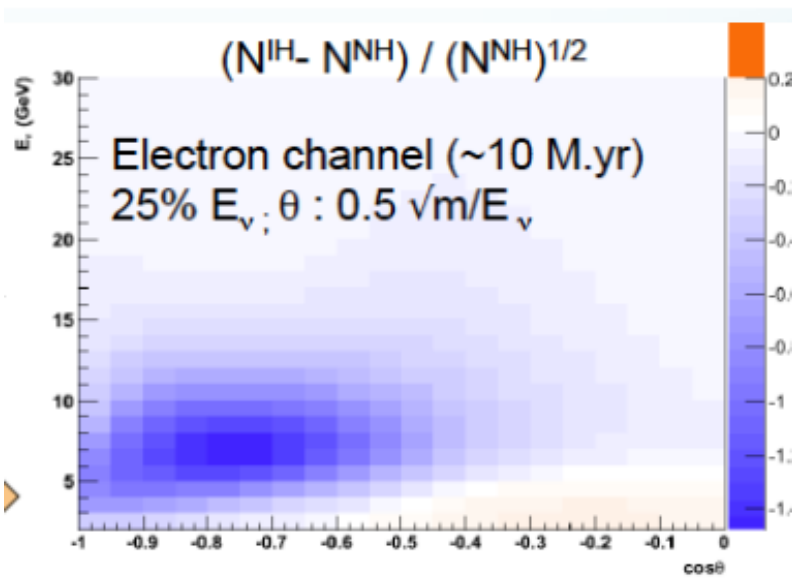


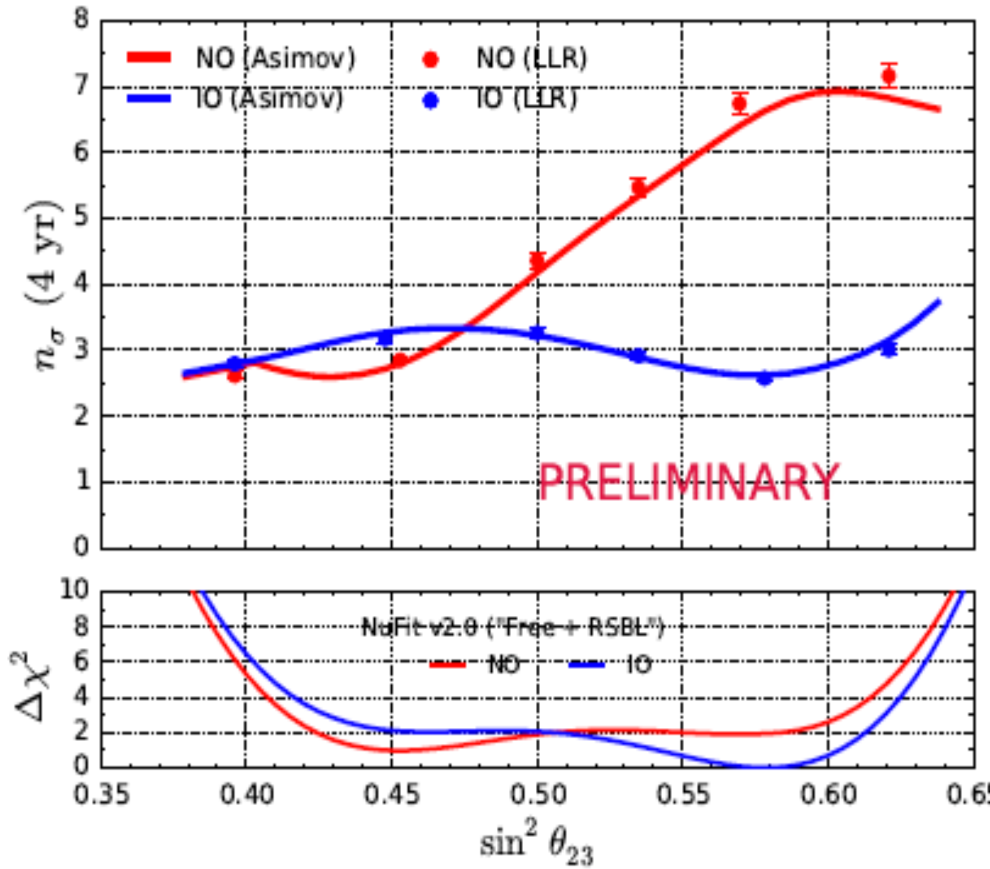




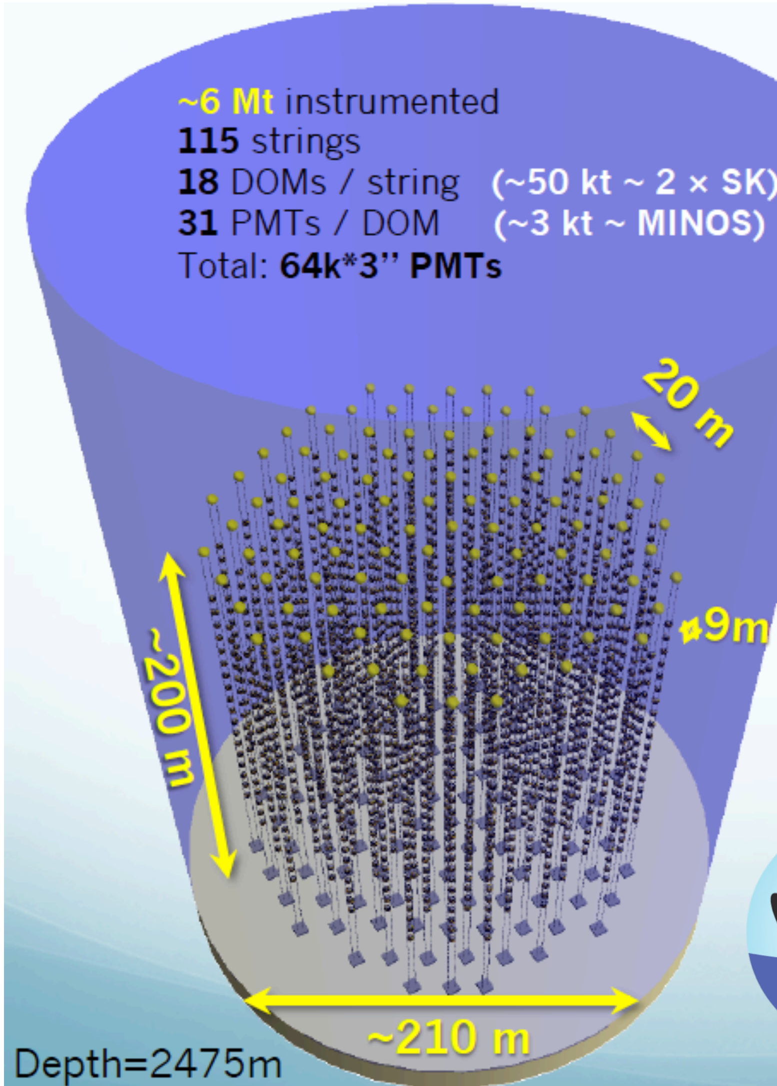
PINGU Sensitivity





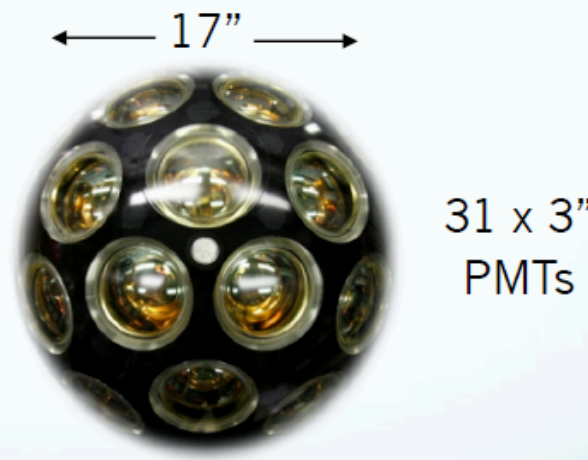


KM3NeT & ORCA



Digital Optical Module

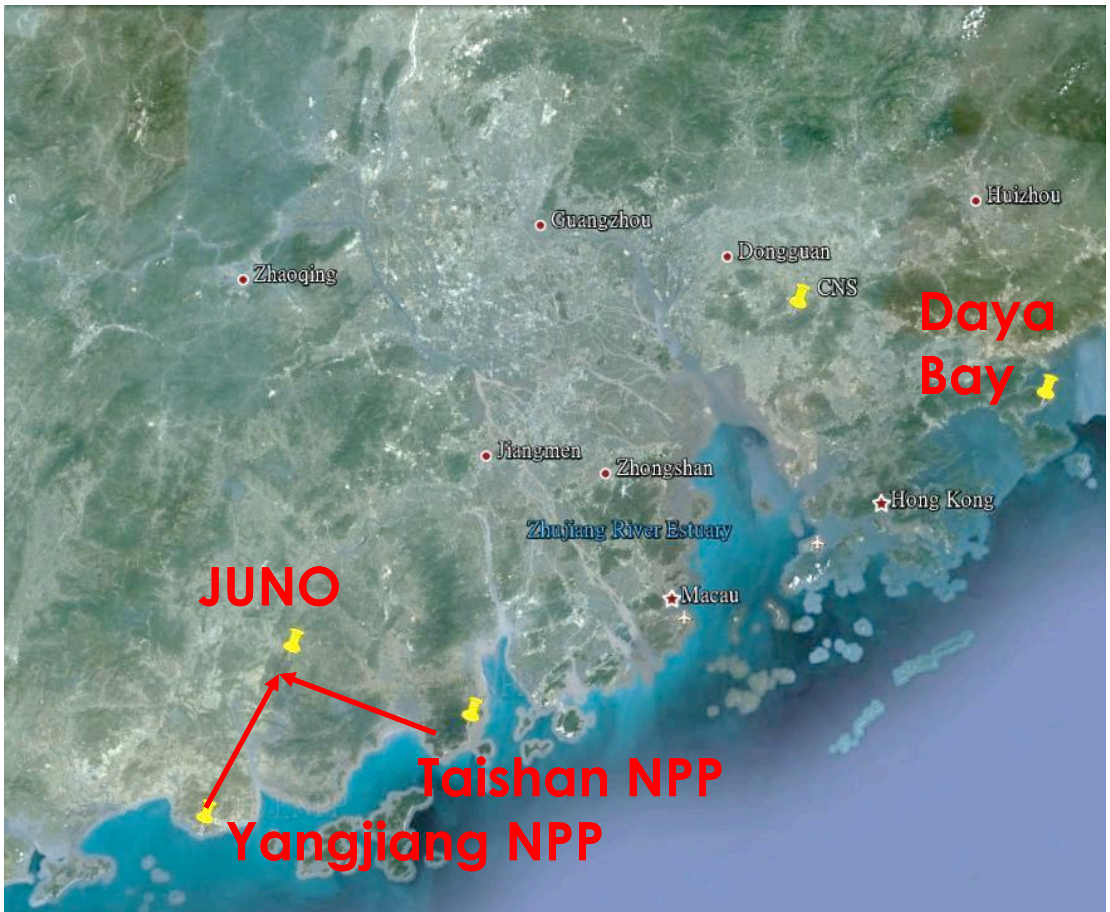
Optical background (mainly ^{40}K):
10kHz/PMT & 500Hz coincidences



- Uniform angular coverage
- Directional information
- Digital photon counting
- Wide angle of view
- Background rejection
- All data to shore

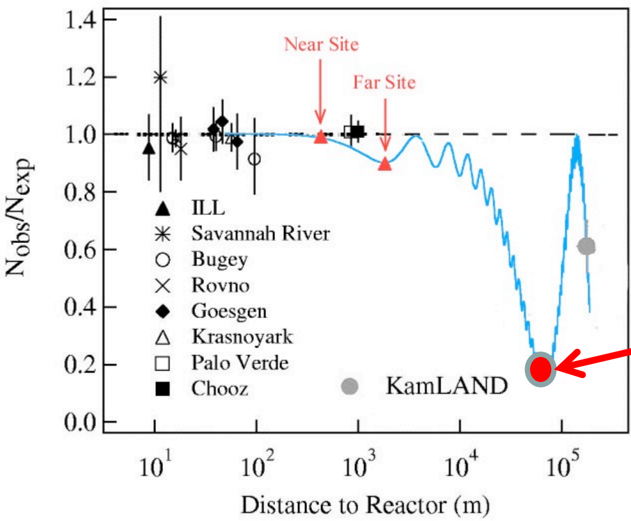
JUNO

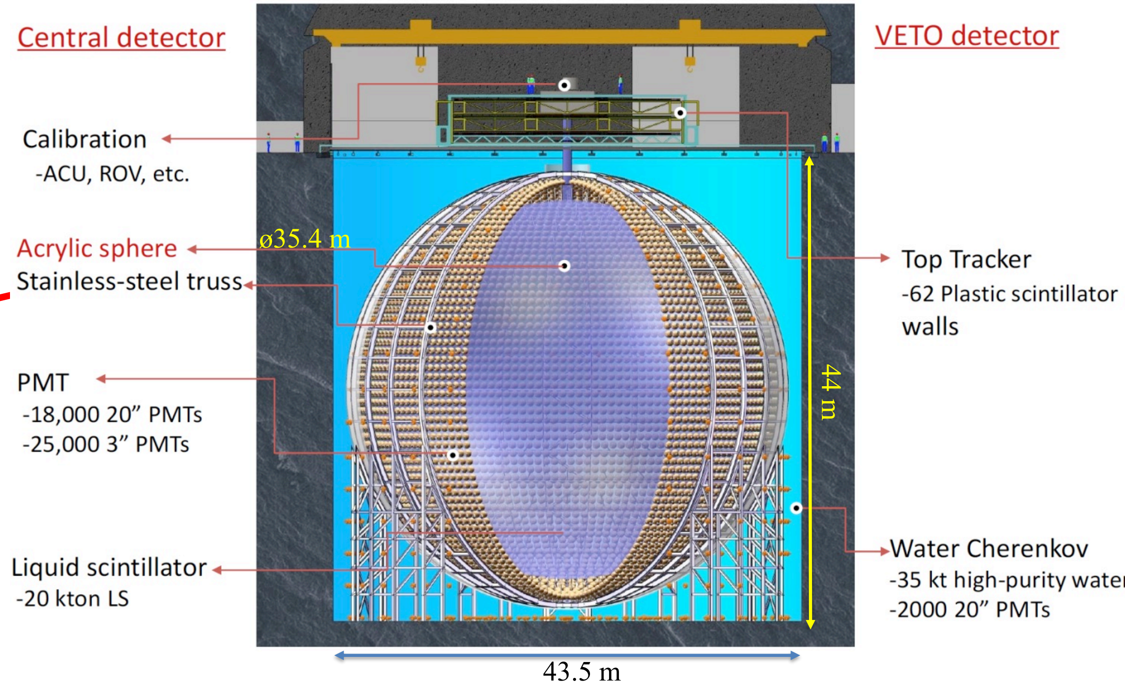
- Jiangmen Underground Neutrino Observatory
- Proposed in 2008, approved in 2013

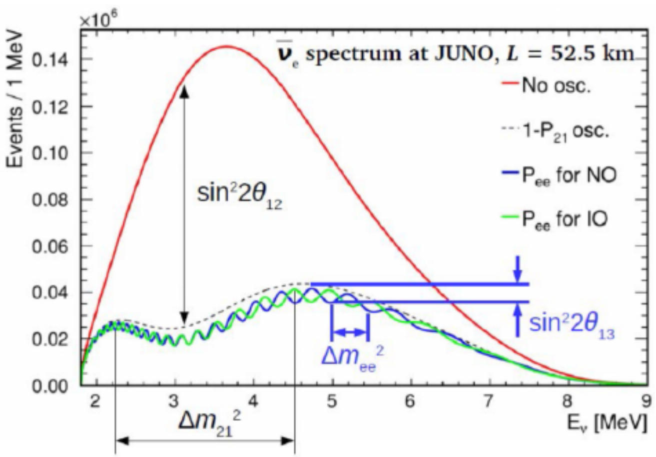


- Physics Program
  - Mass Hierarchy
  - Oscillation parameters
  - SN neutrinos
  - geo-neutrinos
  - solar neutrinos
  - atmospheric neutrinos
  - Sterile neutrinos
  - exotics

Future Reactors: JUNO

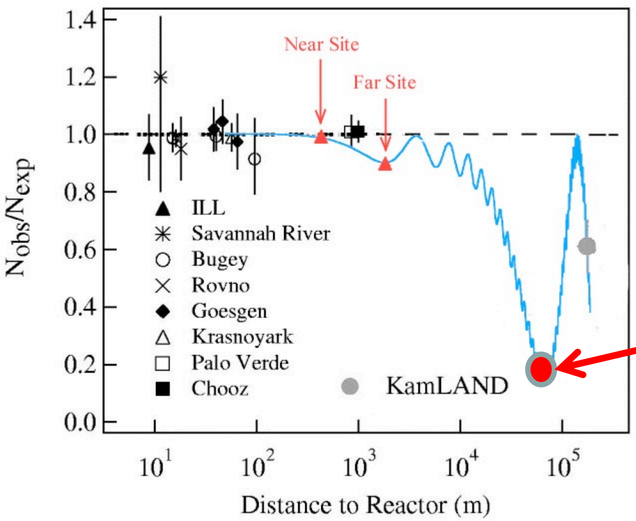


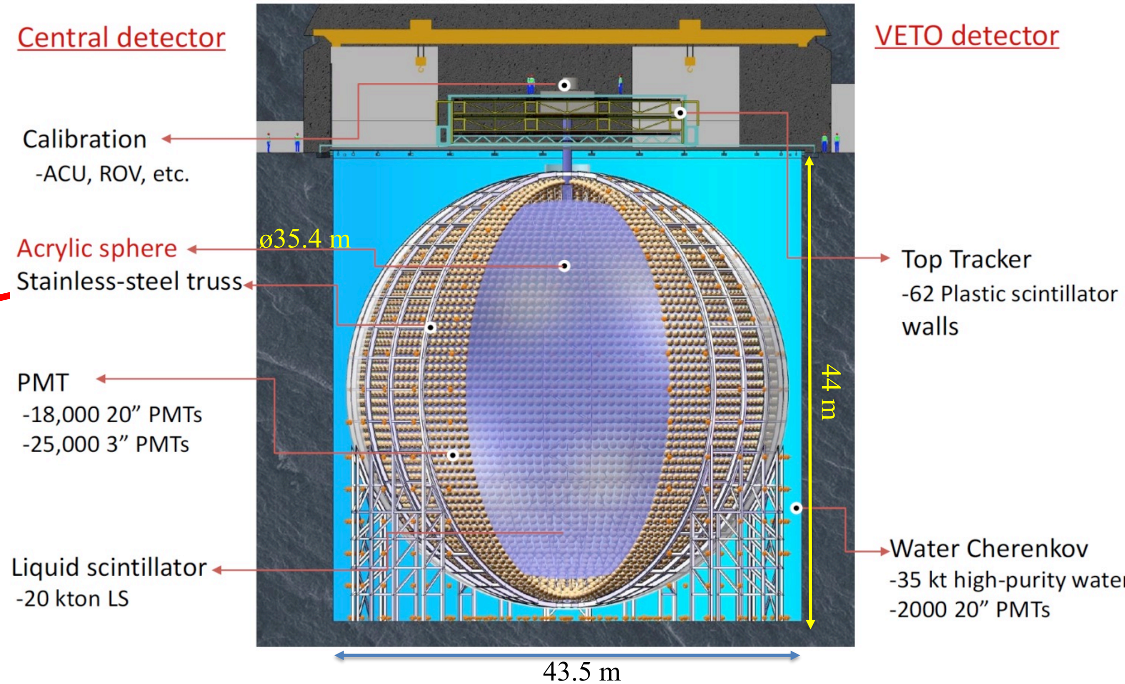


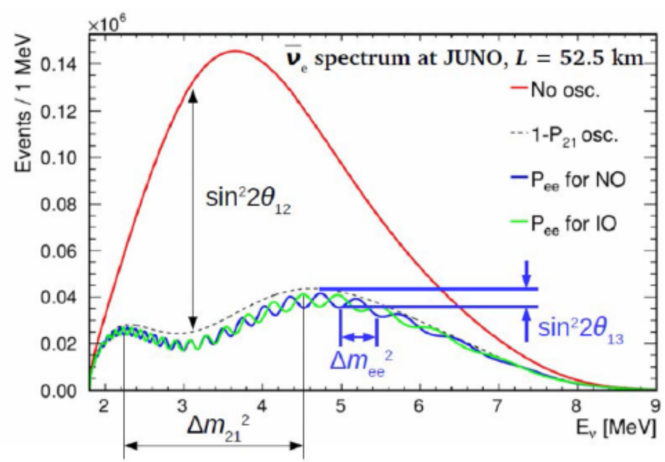


	KamLAND	Borexino	Daya Bay	JUNO
Target Mass	1 kt	300 t	20 t	20 kt
Light yield (p.e./MeV)	250	500	160	1200
Photocathode Coverage	34%	34%	12%	80%
Energy Resolution	6%/√E	5%/√E	7.5%/√E	3%/√E

Future Reactors: JUNO







MAIN PHYSICS:

- determination of the neutrino mass hierarchy with good sensitivity: 3σ after 6y
- precisely measure the neutrino mixing parameters
  - $\sin^2\theta_{12}$ current precision 4.1 % with **JUNO below 1%**
  - Δm_{21}^2 current precision 2.3 % with **JUNO below 1%**
  - Δm_{ee}^2 current precision 1.6 % with **JUNO below 1%**

Future Accelerator Experiments

HYPER K

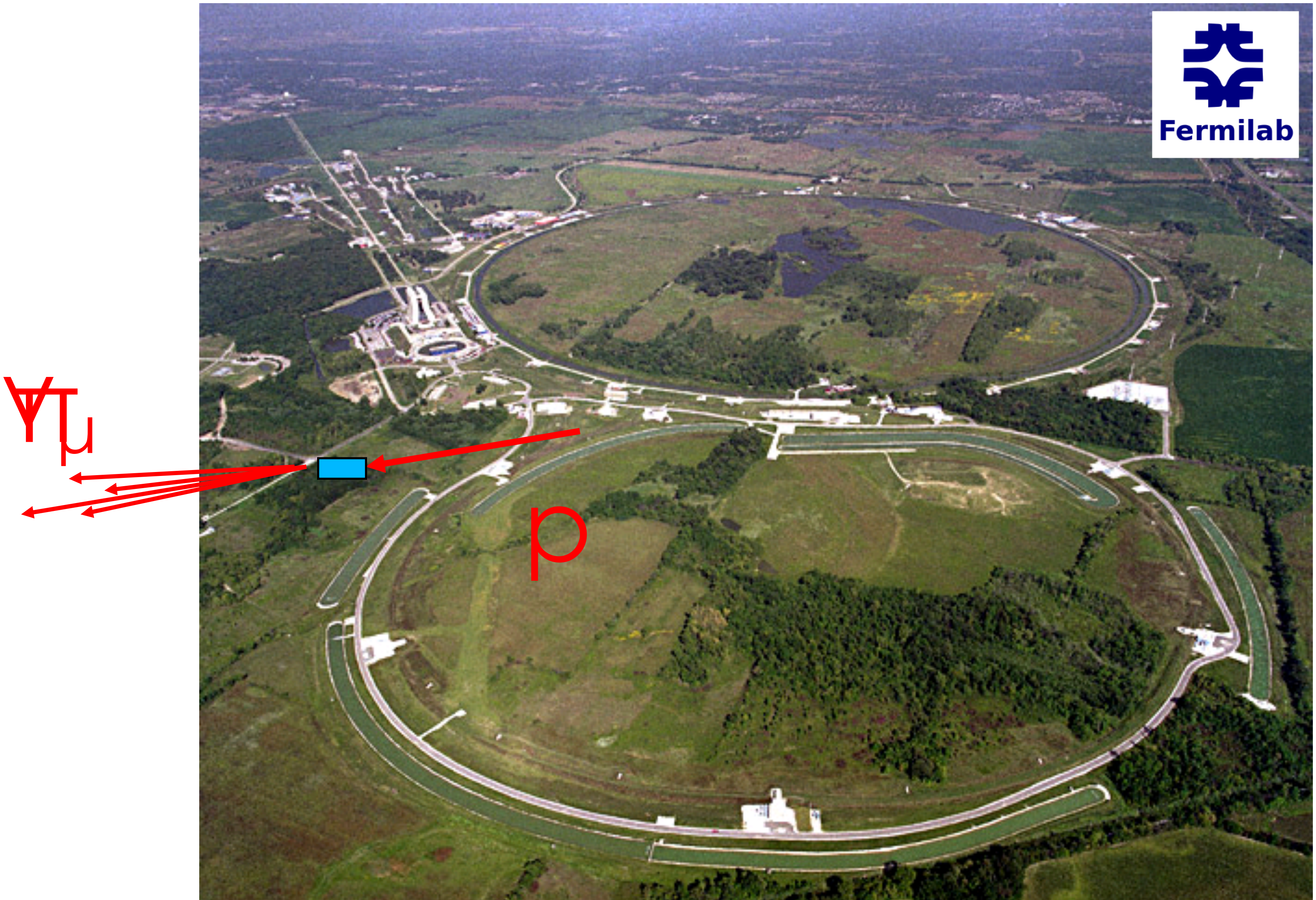
DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Summary

- A coherent picture emerges from
  - Reactors
  - Atmospheric neutrinos
  - Intense beams
- There are no sterile neutrinos! (Probably)
  - Large suite of experiments looking at different aspects
    - SBL, rector
- Next generation of experiments is needed
  - What is the mass ordering?
  - Is there CP violation in the lepton sector?
  - Precision parameter measurements

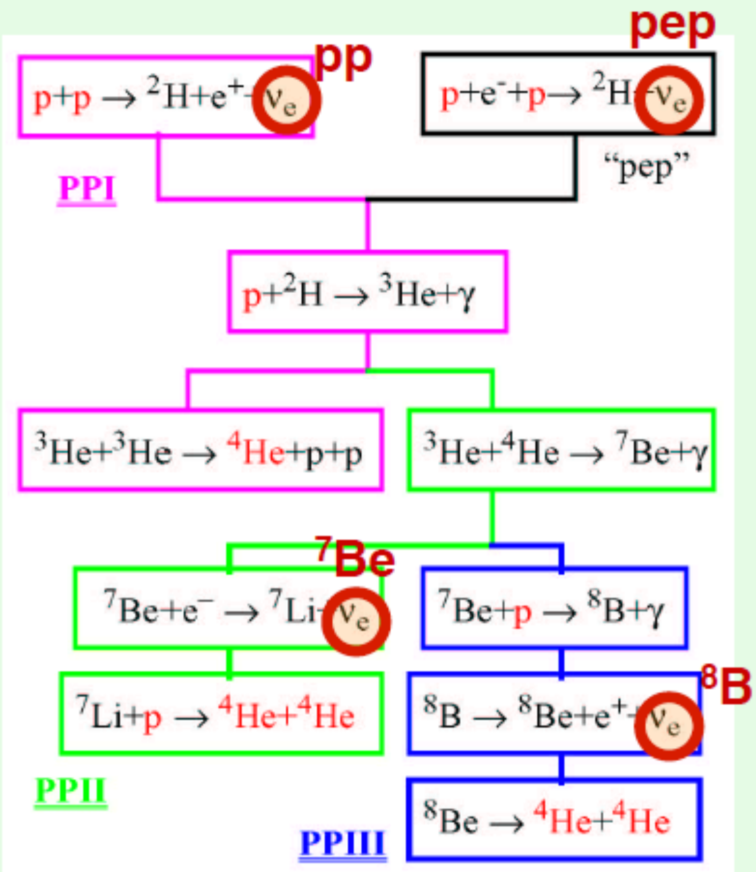
Thank you!

Accelerator Neutrinos

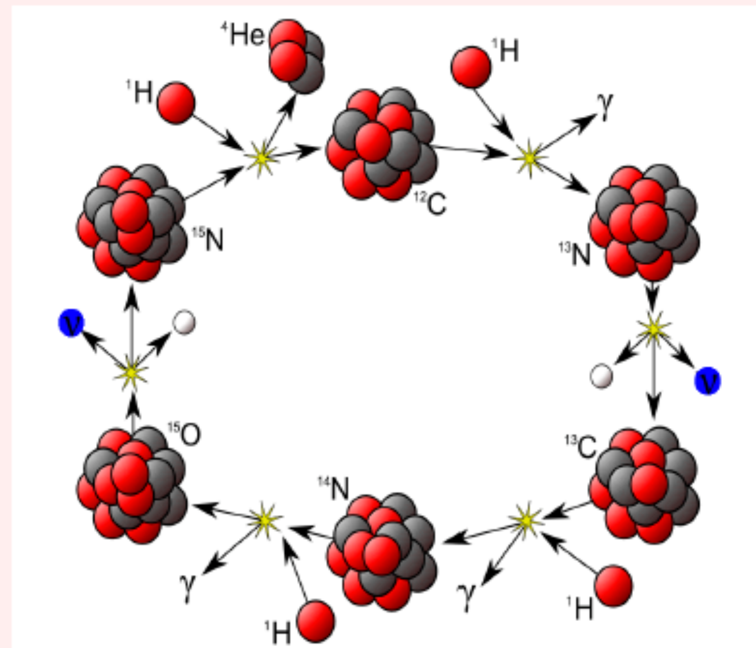


Solar Neutrinos

~99% **pp-cycle**

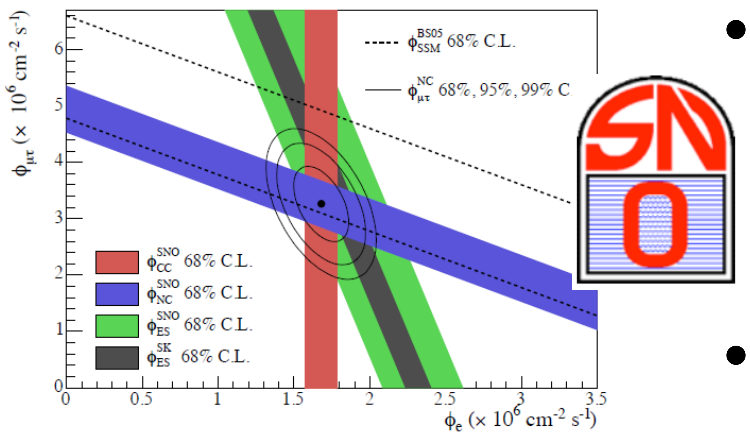


< 1% ? **CNO-cycle**

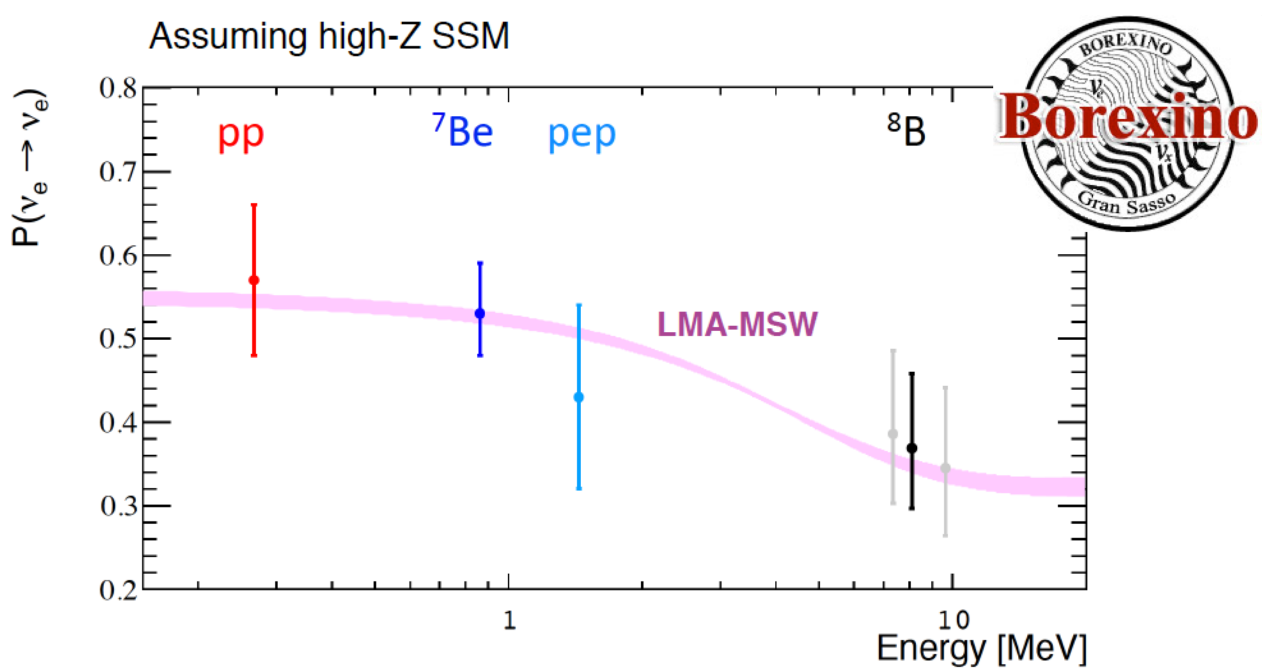


- Sun: should contribute <1%
- Heavy stars: should be dominant!
- Never observed until now

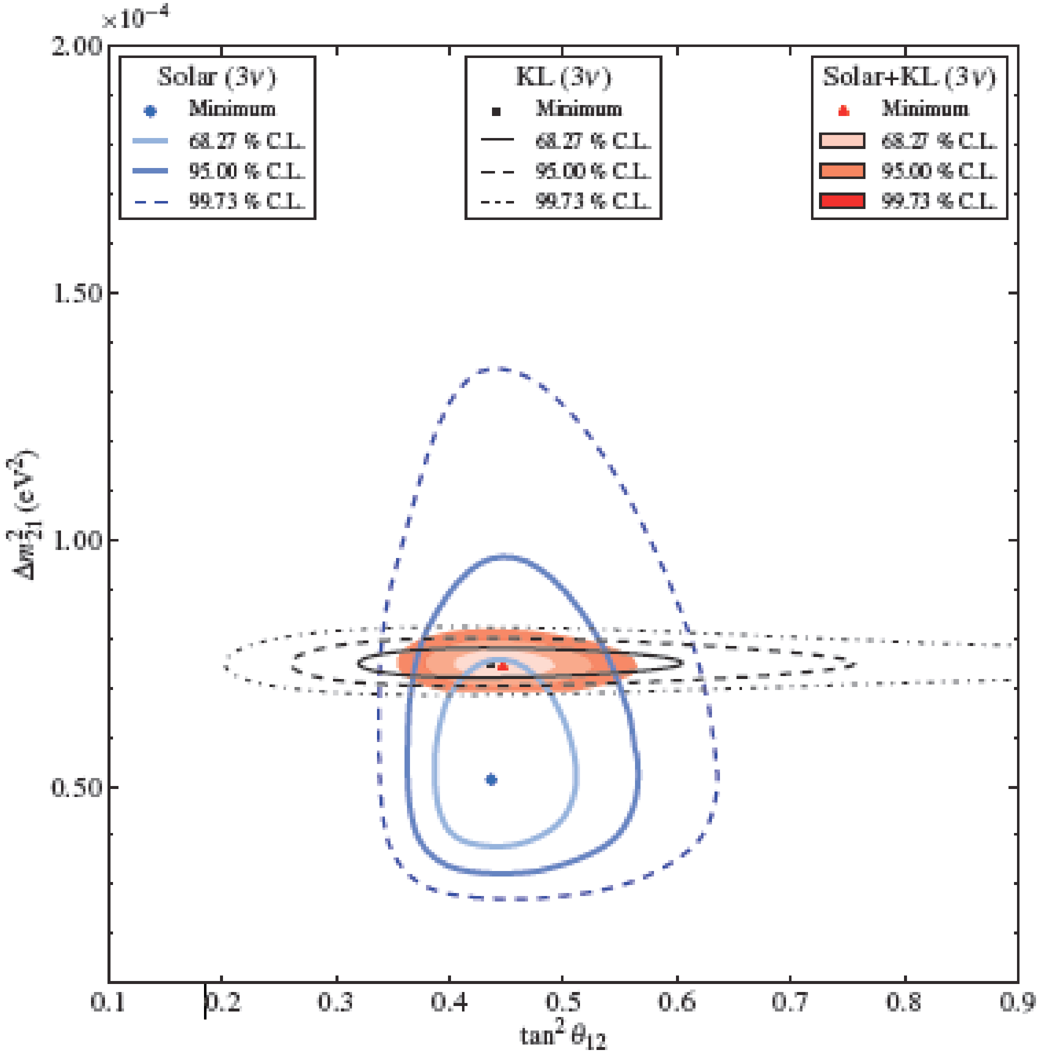
Solar Neutrinos



- Have been measured for many decades
  - Deficit ⇔ solar neutrino problem
- First indication of oscillations



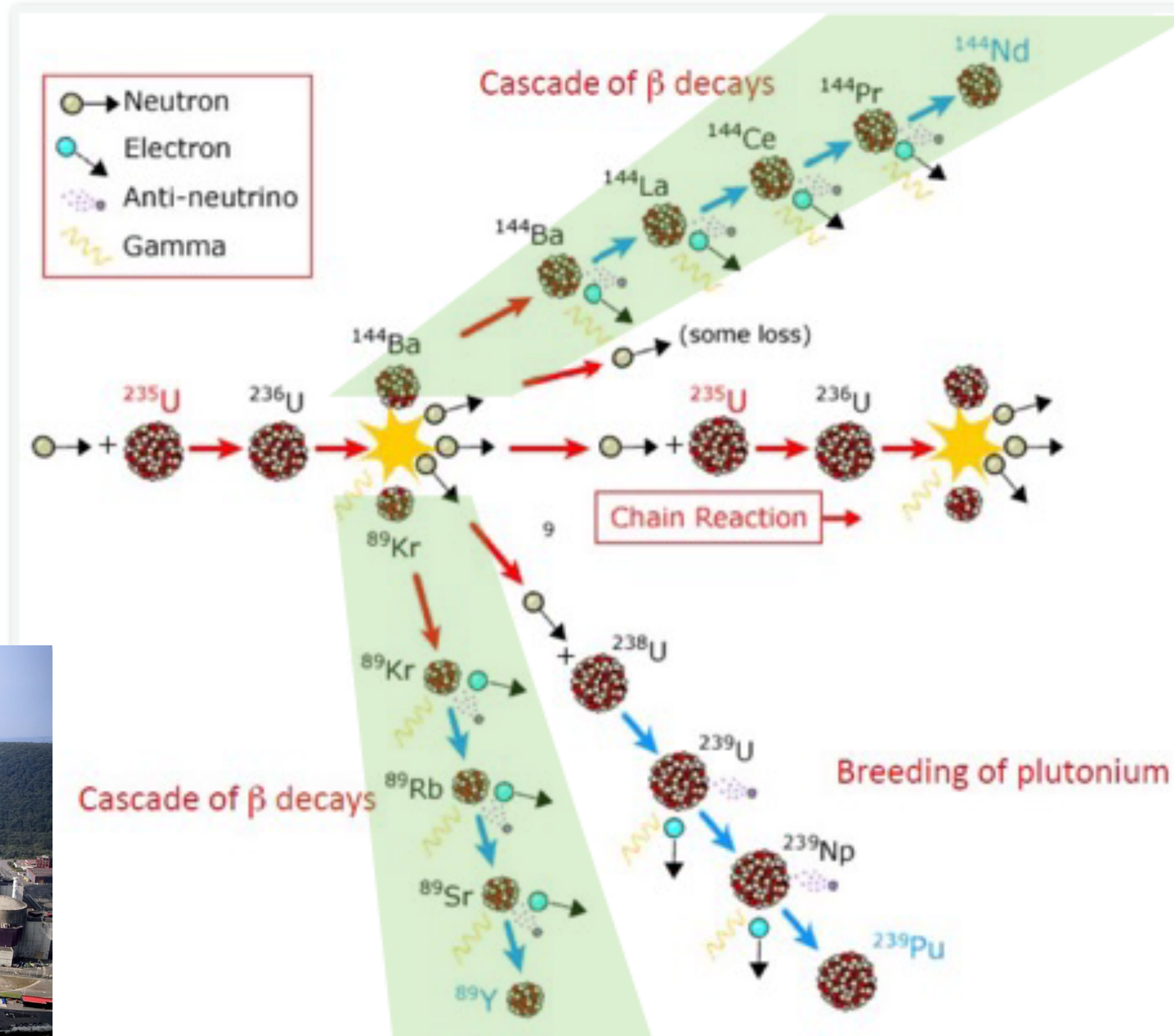
Solar Neutrino Summary



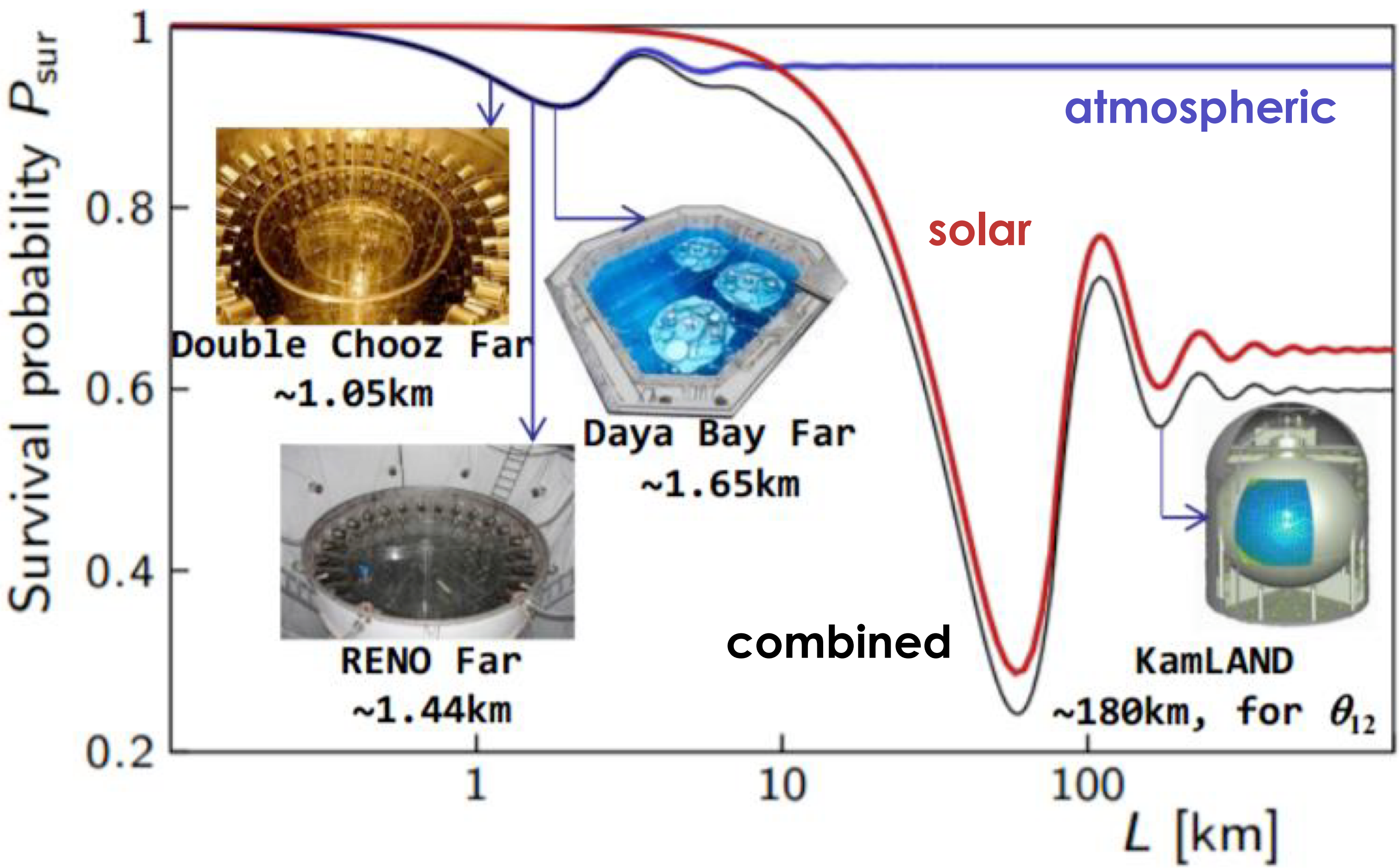
Reactor Neutrinos

- Most intense manmade neutrino source
- Neutron rich fission fragments undergo beta decay

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X' + e^{-} + \bar{\nu}_e$$

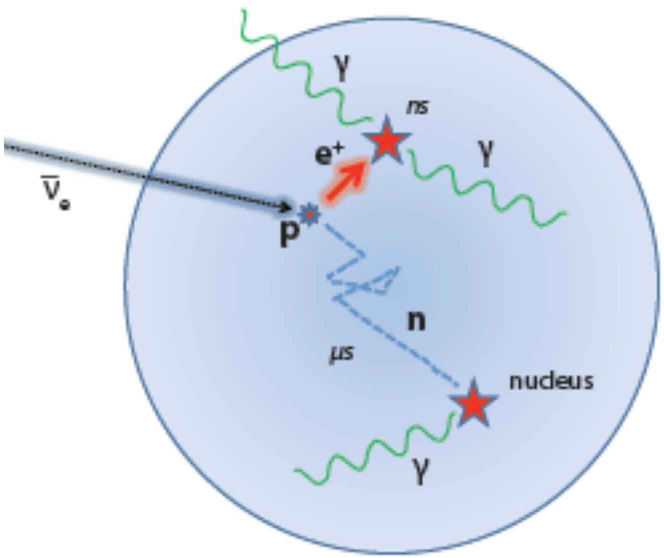


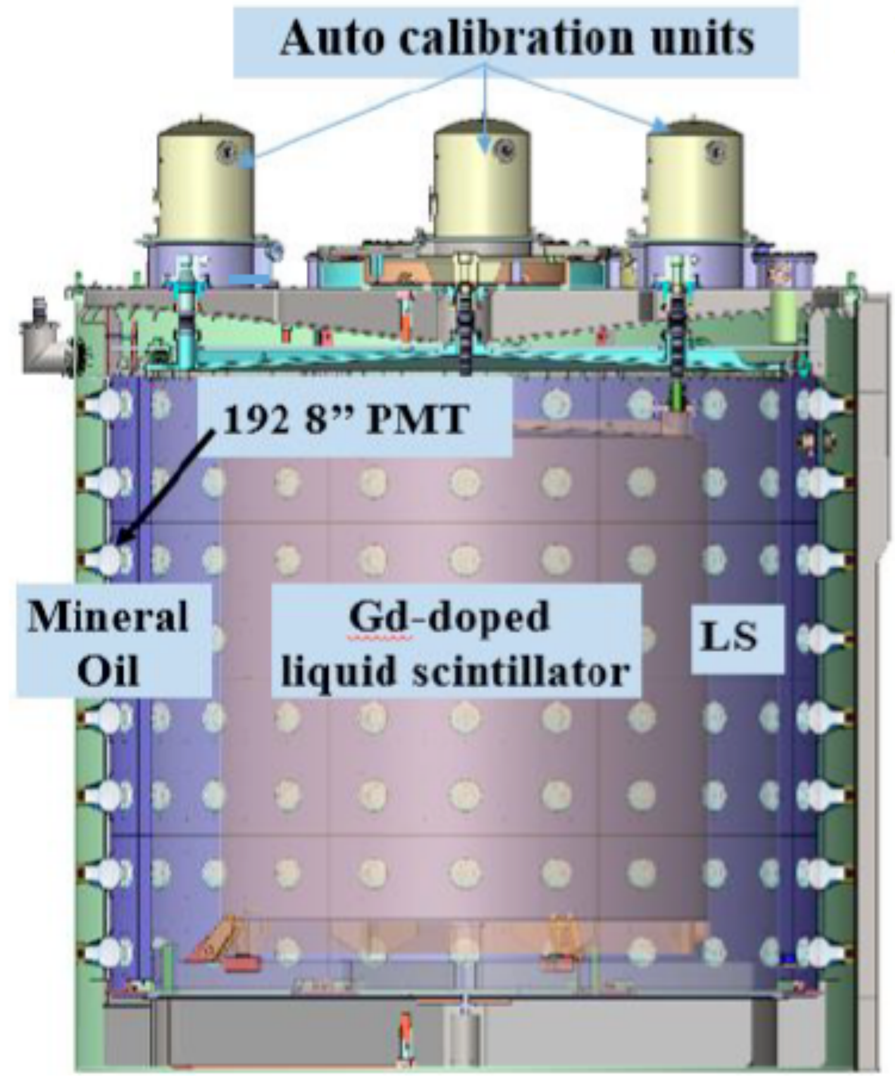
The Players



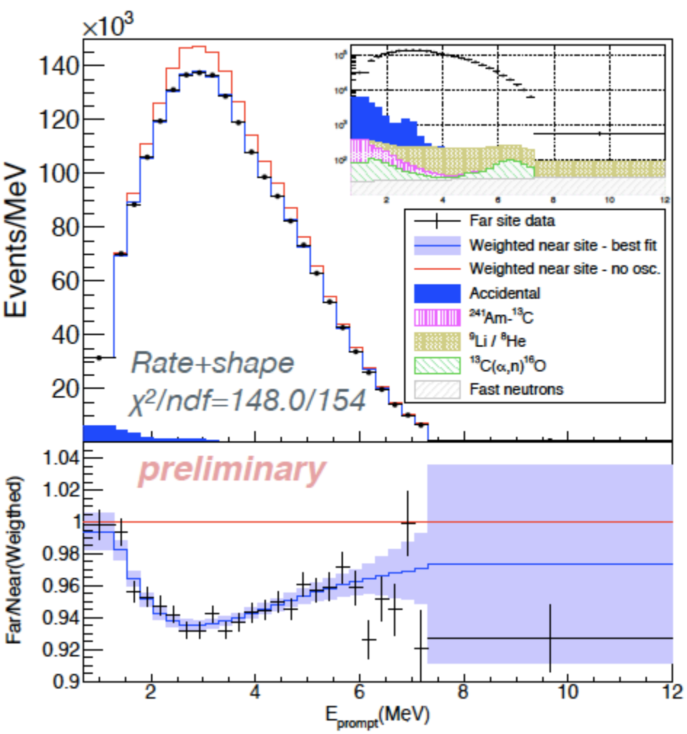
Survival probability P_{sur}
1
0.8
0.6
0.4
0.2
1
10
100
L [km]
atmospheric
solar
combined
Double Chooz Far
~1.05km
Daya Bay Far
~1.65km
RENO Far
~1.44km
KamLAND
~180km, for θ_{12}

Detection Concept

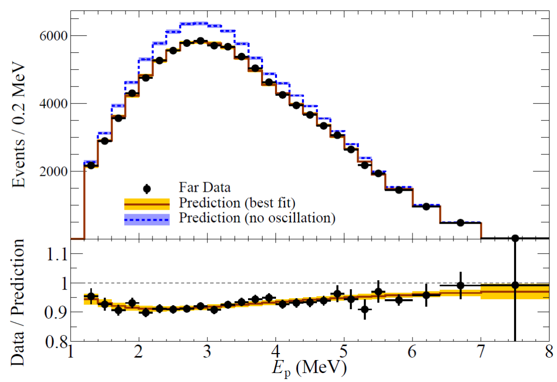




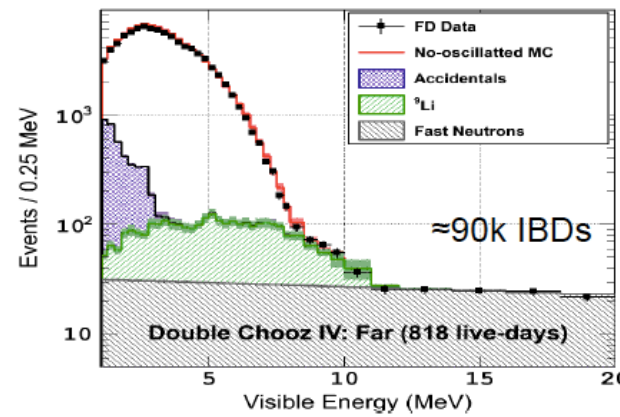
The data



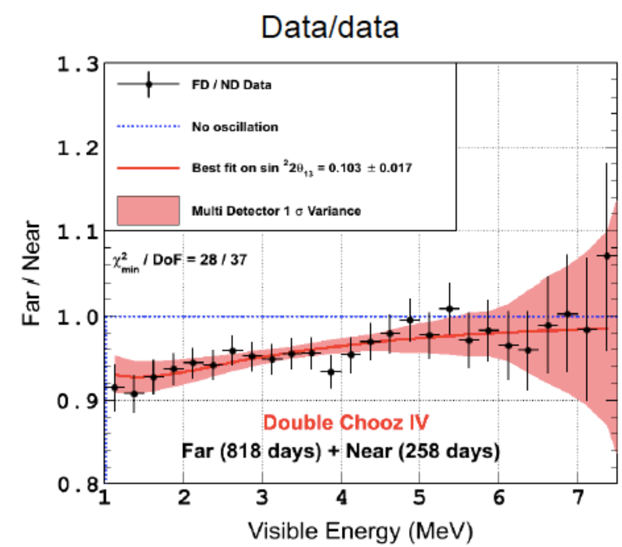
×10³
Events/MeV
Rate+shape
χ²/ndf=148.0/154
Far site data
Weighted near site - best fit
Weighted near site - no osc.
Accidental
241Am-13C
9Li / 8He
13C(α,n)16O
Fast neutrons
preliminary
Far/Near(Weigthed)
E_prompt(MeV)



Events / 0.2 MeV
Far Data
Prediction (best fit)
Prediction (no oscillation)
Data / Prediction
E_p (MeV)



FD Data
No-oscillatted MC
Accidentals
9Li
Fast Neutrons
≈90k IBDs
Events / 0.25 MeV
Double Chooz IV: Far (818 live-days)
Visible Energy (MeV)



Data/data
FD / ND Data
No oscillation
Best fit on sin²2θ13 = 0.103 ± 0.017
Multi Detector 1 σ Variance
χ²min / DoF = 28 / 37
Far / Near
Double Chooz IV
Far (818 days) + Near (258 days)
Visible Energy (MeV)

Oscillation Parameters