T2K Experiment
Results & Prospects

Alfons Weber
University of Oxford & STFC/RAL

For the T2K Collaboration

Content

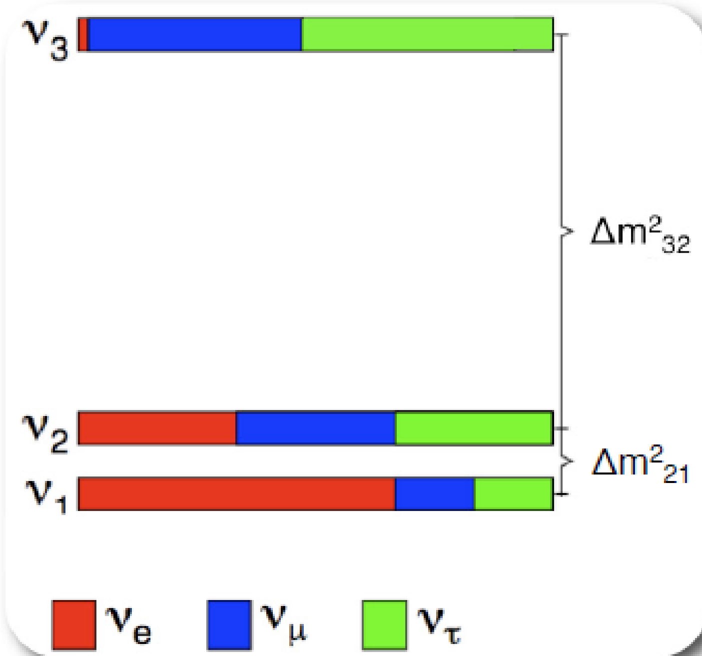
- Neutrino Oscillations
  - Introduction
- The T2K Experiment
  - Beam
  - Near Detector
  - Far Detector
- Results
  - Disappearance analysis
  - Appearance search
- Future potential
  - The hunt for CP-violation

Neutrino Mixing
The PMNS Matrix

FLASY 2014

Pontecorvo-Maki-Nakagawa-Sakata

- Assume th … ass:
  - mass eig … ction eigenstates
  - Analogu … rk sector!



weak "flavour eigenstates"

Mass eigenstates m_1, m_2, m_3

Unitary mixing matrix: 3 mixing angles & complex phases

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

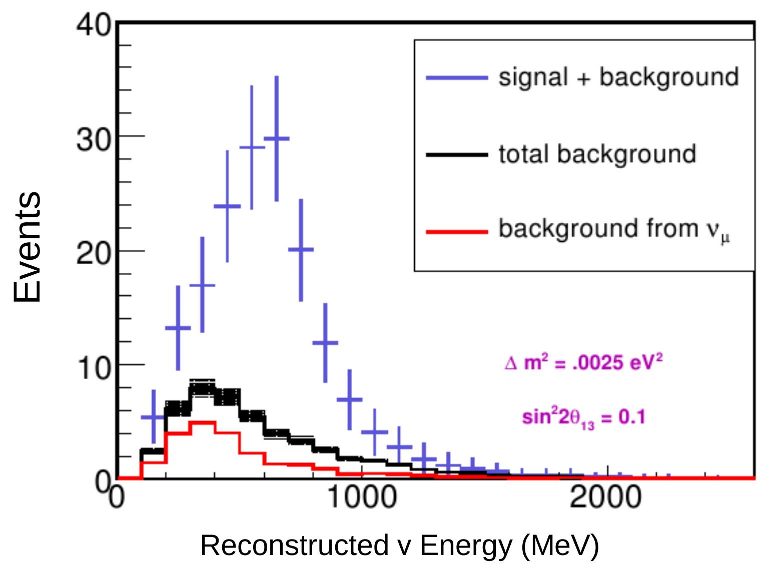
with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, θ_{ij} = mixing angle and Δm^2_{ij} = mass^2 difference

Oscillation Signatures

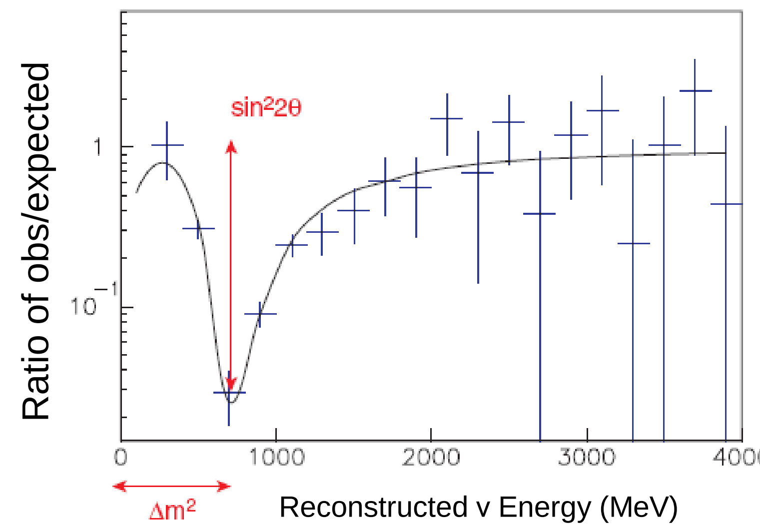
$\nu_\mu \longrightarrow \nu_1, \nu_2, \nu_3 \longrightarrow \nu_\mu,\ \nu_e$ or ν_τ

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

ν_e appearance: determine θ_{13} constrain δ_{CP}



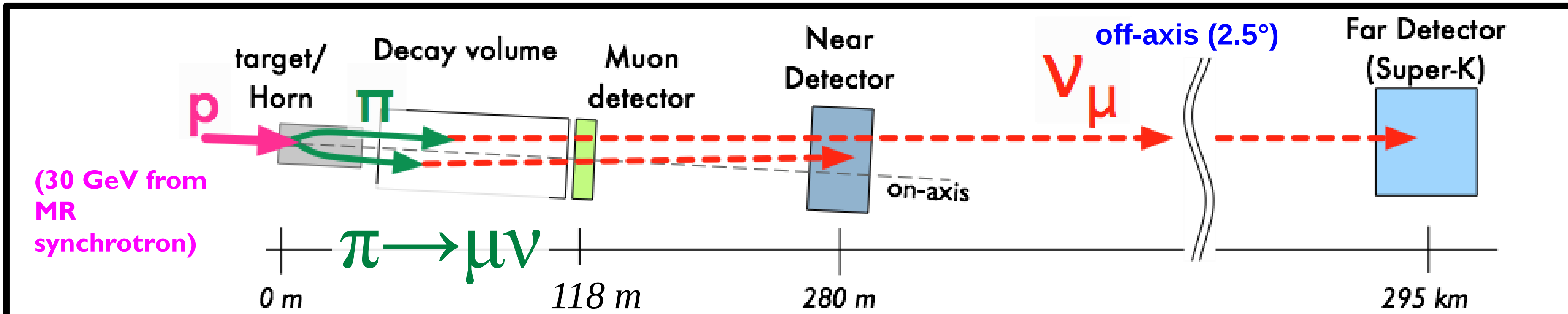
ν_μ disappearance: determine θ_{23} and Δm^2_{32}

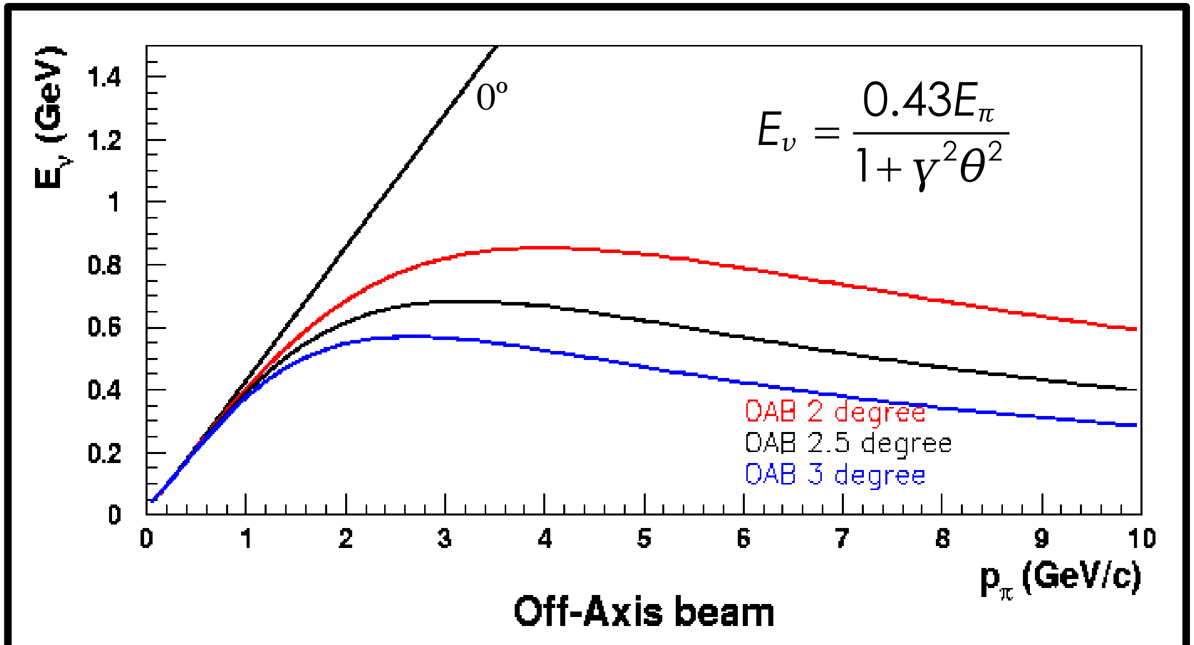


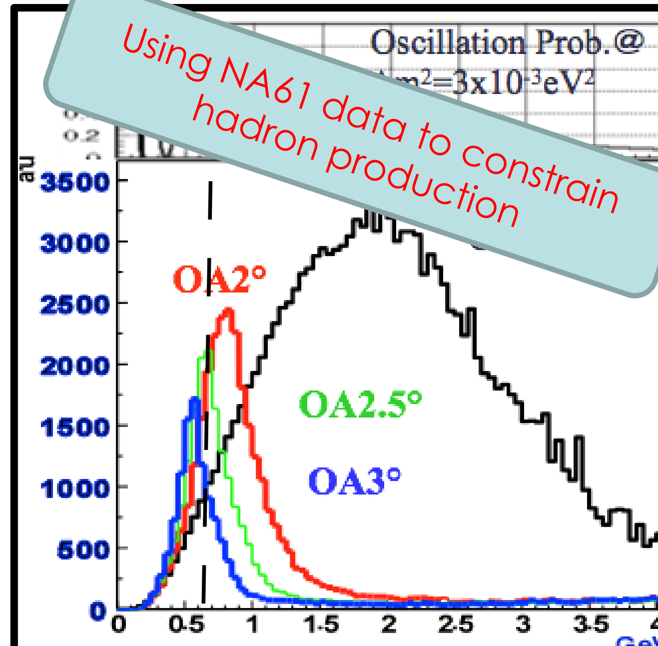
The T2K Experiment

- A Long-baseline Experiment to study neutrino oscillations
  - Baseline 295 km
  - Beam power up to 230 kW
  - Detectors Near and far

Producing Neutrinos



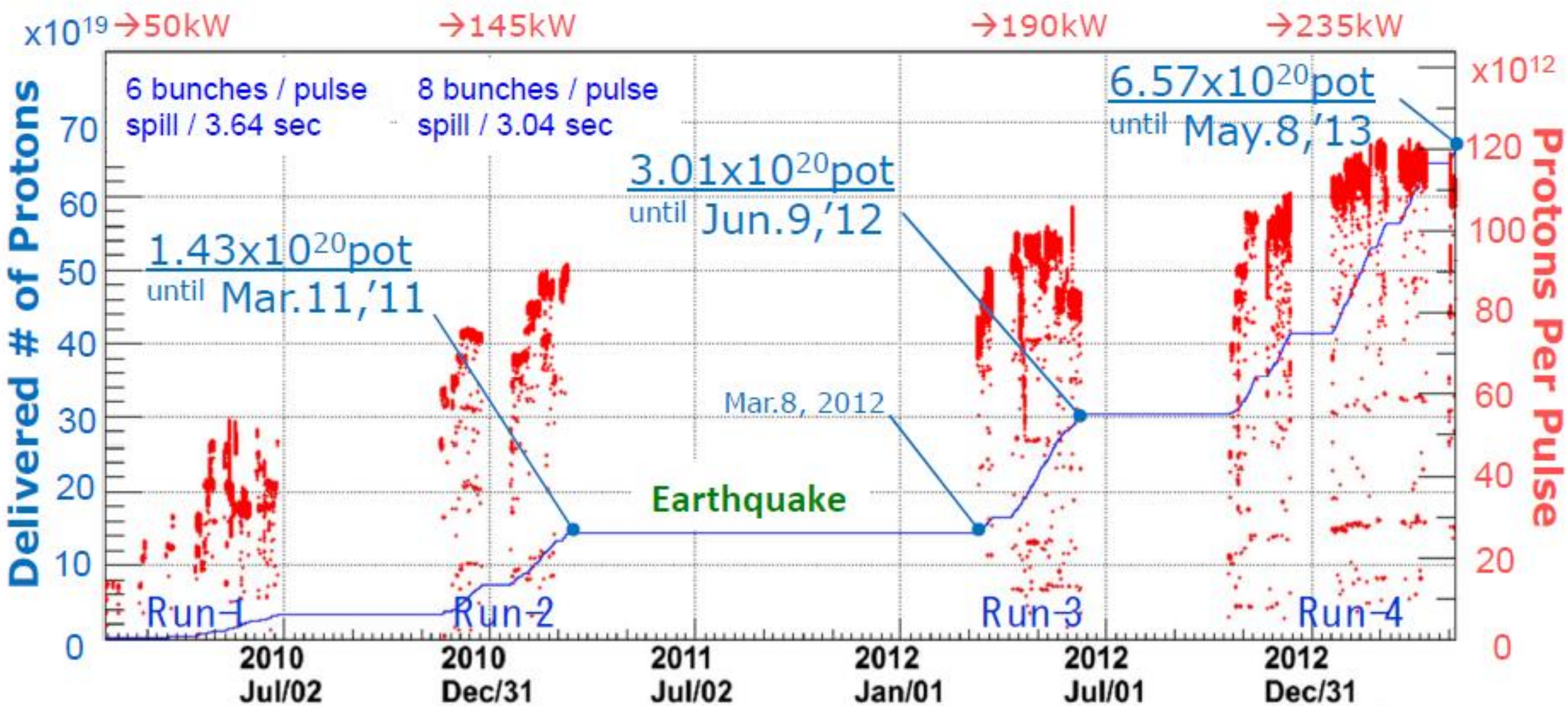




Using NA61 data to constrain hadron production

Data Taken

FLASY 2014

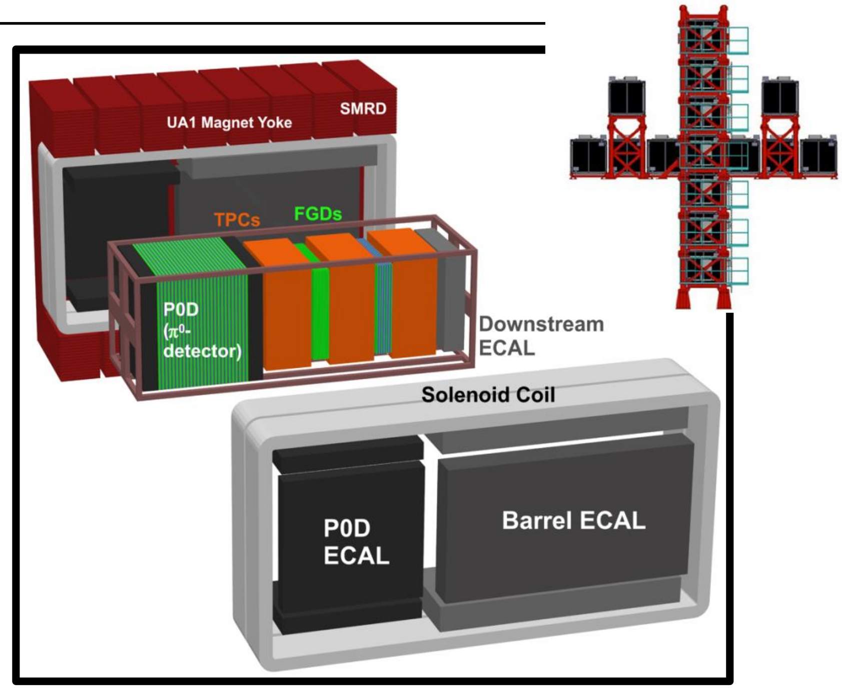


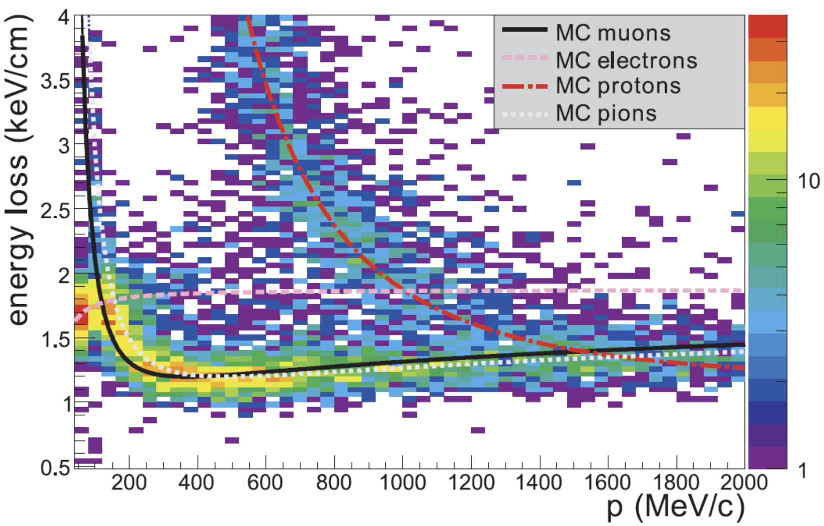
- Data Set: 6.57 x 10^{20} PoT (8% of design goal)
- Increase power in future
  - More protons / bunch
  - Higher repetition rate

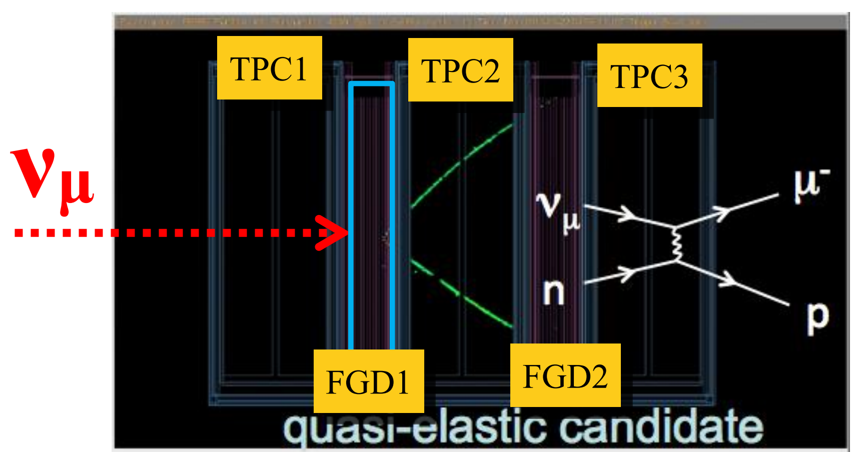
ND280 detector

FLASY 2014

- Off-axis: ND280
  - 0.2 T magnet (UA1/NOMAD)
  - Plastic scintillator detectors: Fine Grained Detector (FGD), π^0 detector (P0D), ECals and SMRD, Time projection chambers (TPC)
- On-axis: INGRID







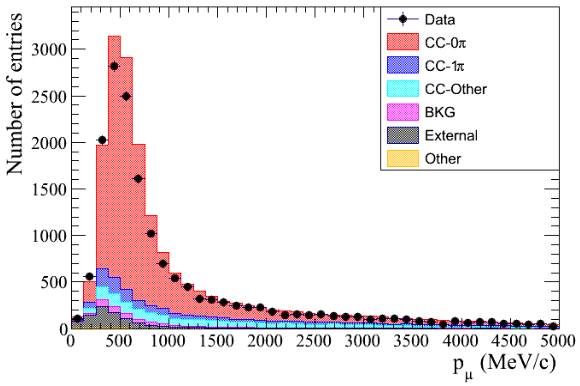
Some ND distribution

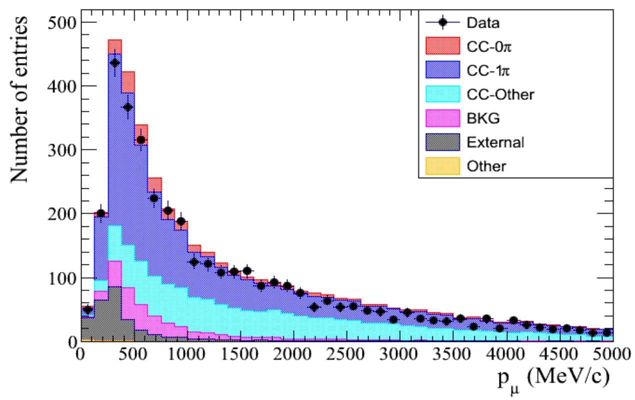
FLASY 2014

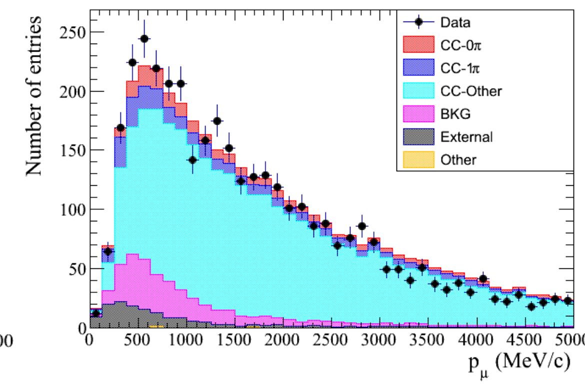
- Select different event classes in near detector
  - Negative muon & something/nothing
- Constrains flux and cross section uncertainties

CC 0π | **CC 1π^+** | **CC Other**

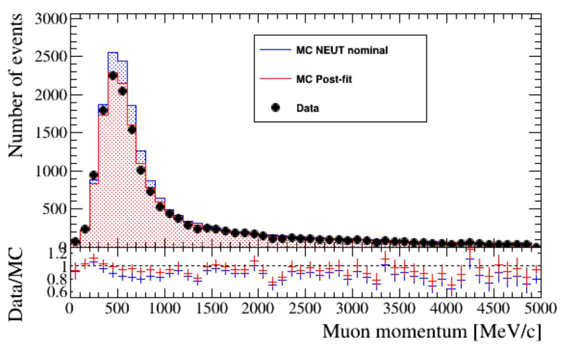
BEFORE FIT

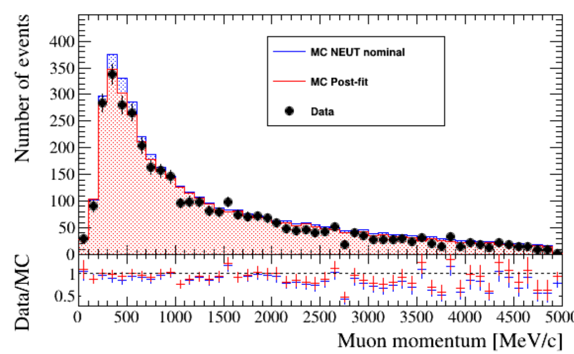


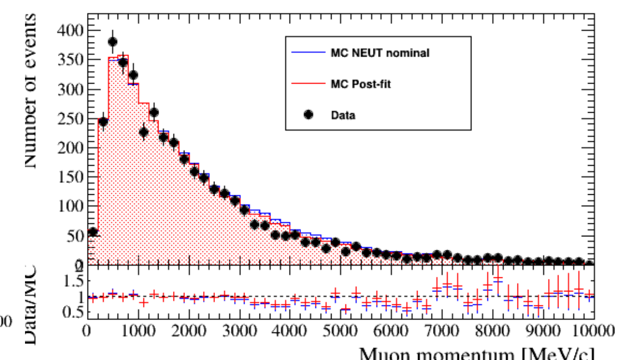




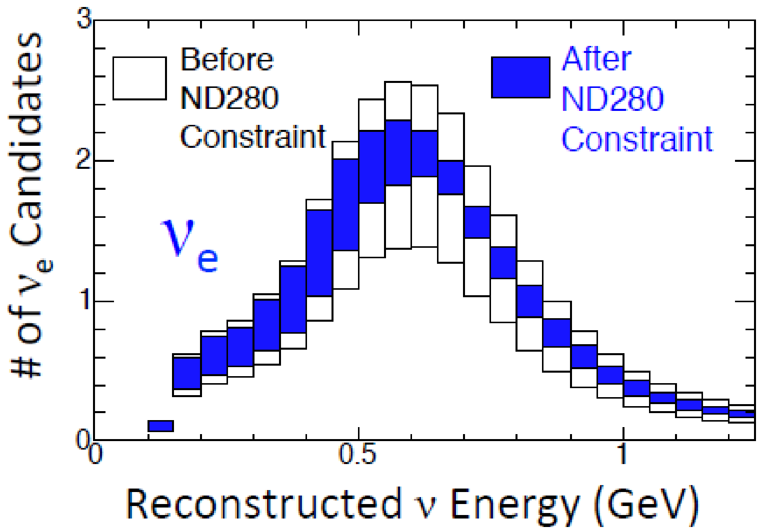
AFTER FIT

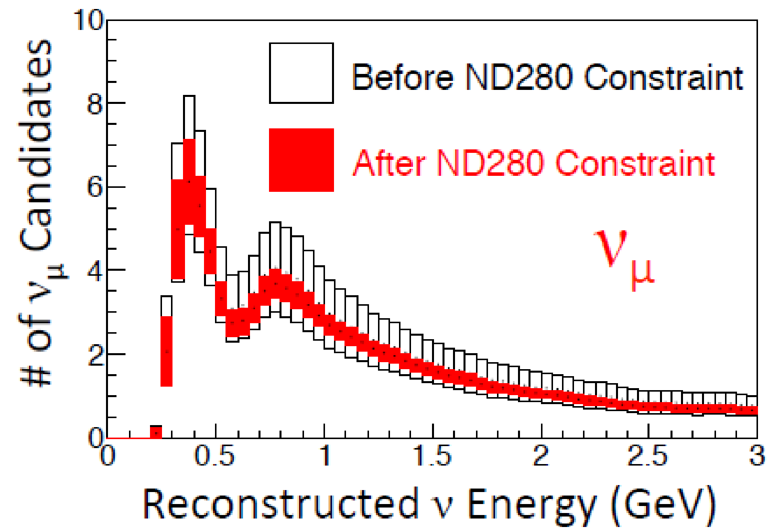






Reduced Systematics

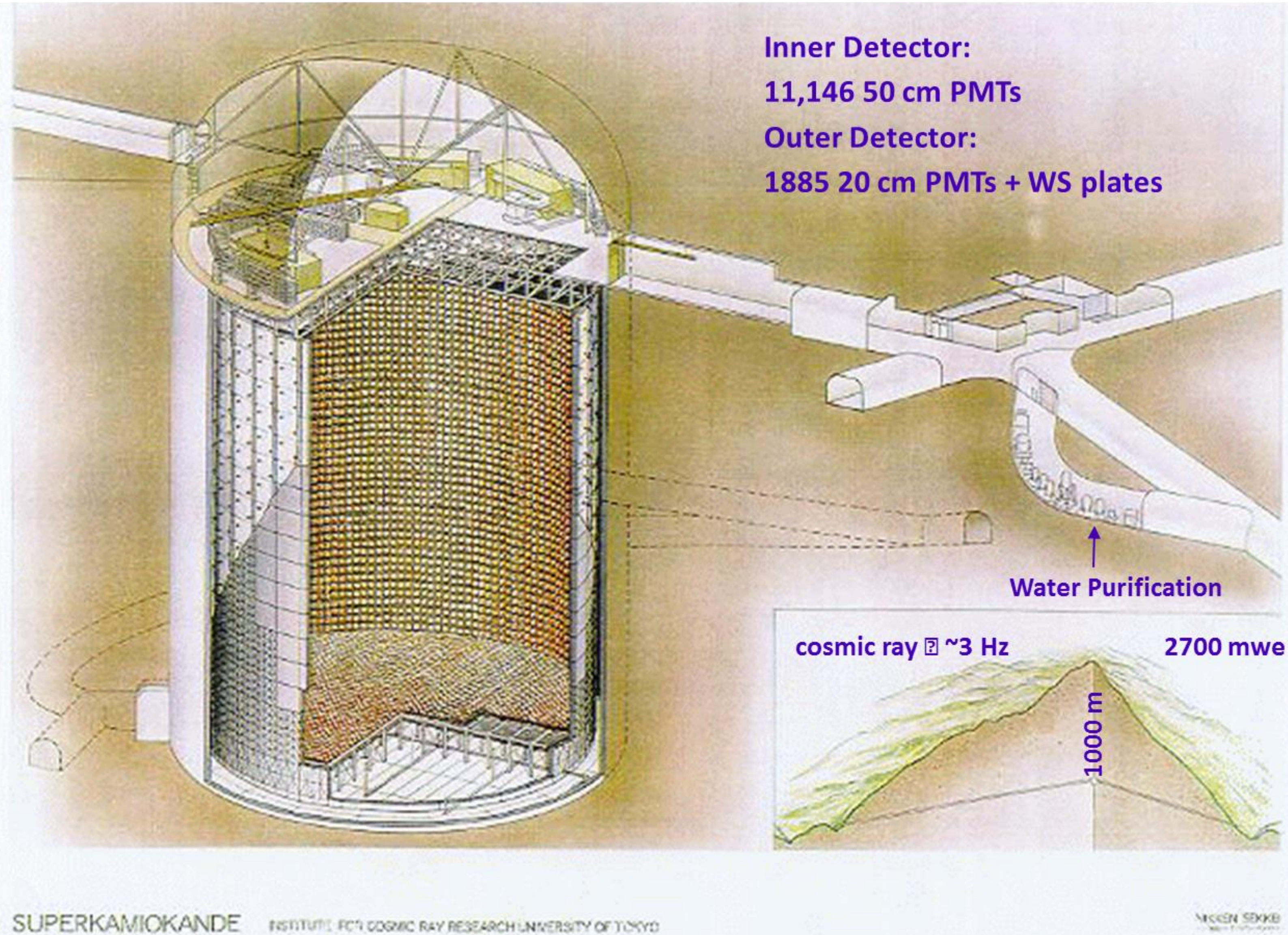




Systematic Source	Relative Uncertainty in # of ν_e Candidates (%)	Relative Uncertainty in # of ν_μ Candidates (%)
Flux + cross section (ND280 constrained)	3.1	2.7
Cross section (ND280-independent)	4.7	5.0
π Hadronic Interactions	2.3	3.5
SK Detector	2.9	3.6
Total	**6.8**	**7.6**

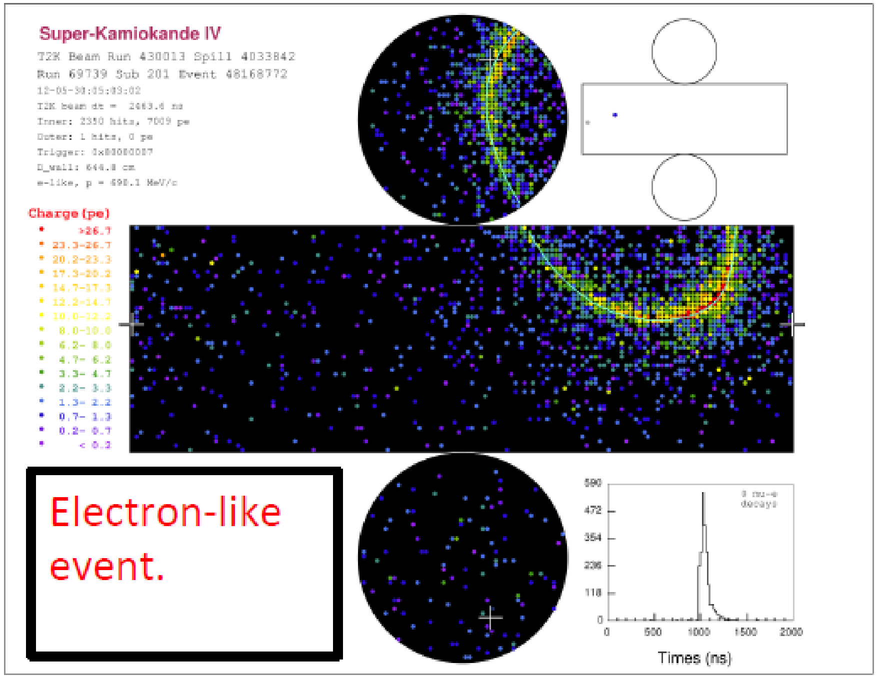
Far Detector

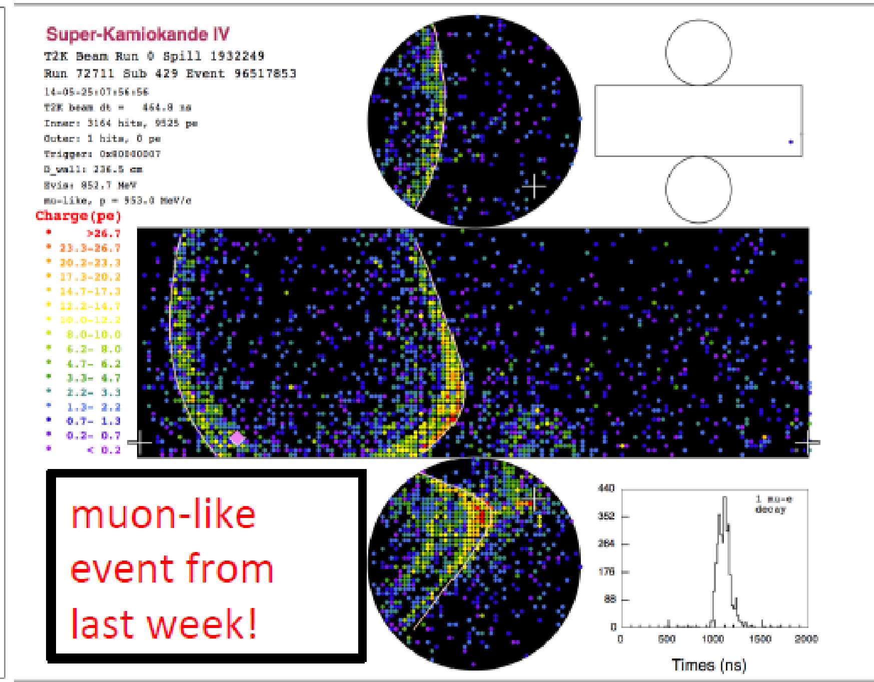
Super-Kamiokande Detector: 50,000 Ton Water Cherenkov Detector



Far Detector Events

FLASY 2014





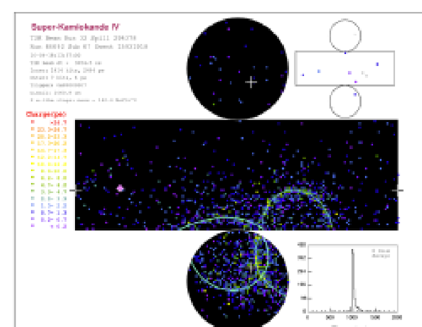
P_e = 690 MeV/c 0 decay-e

P_μ = 953 MeV/c 1 decay-e

Super-K has excellent particle ID

These events are split into three selected streams: ν_μ, ν_e and low energy events.

π^0 candidate.
M_{inv}=104 MeV/c^2



Electron Neutrino Appearance

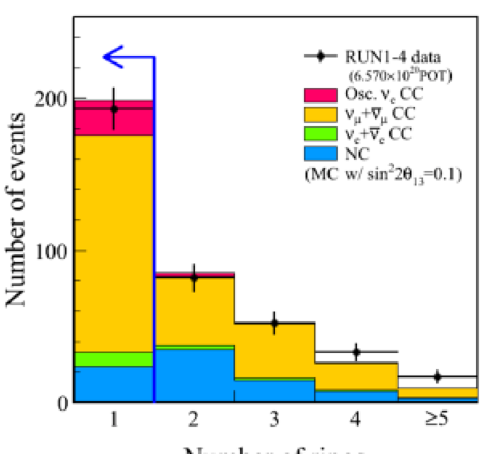
(Octant is here)

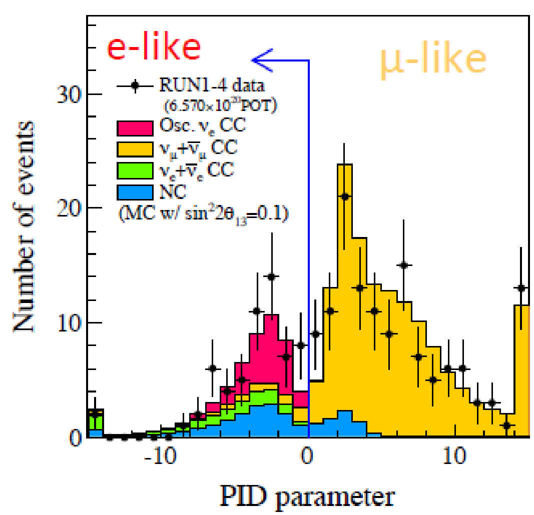
$$P(\nu_\mu \to \nu_e) \cong \boxed{\sin^2\theta_{23}\sin^2 2\theta_{13}}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu} - \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E_\nu}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}\boxed{\sin\delta_{CP}}$$

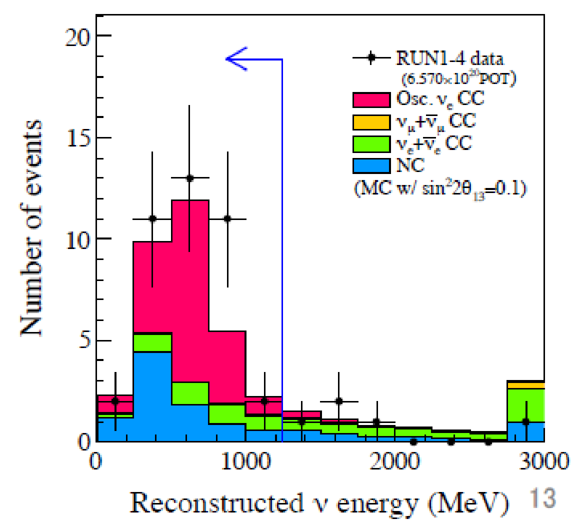
(sinδ is here)

+ (CP even term, solar tem, matter effect term)

- Event Selection
  - Fully contained,
  - no π^0
  - No decay electrons



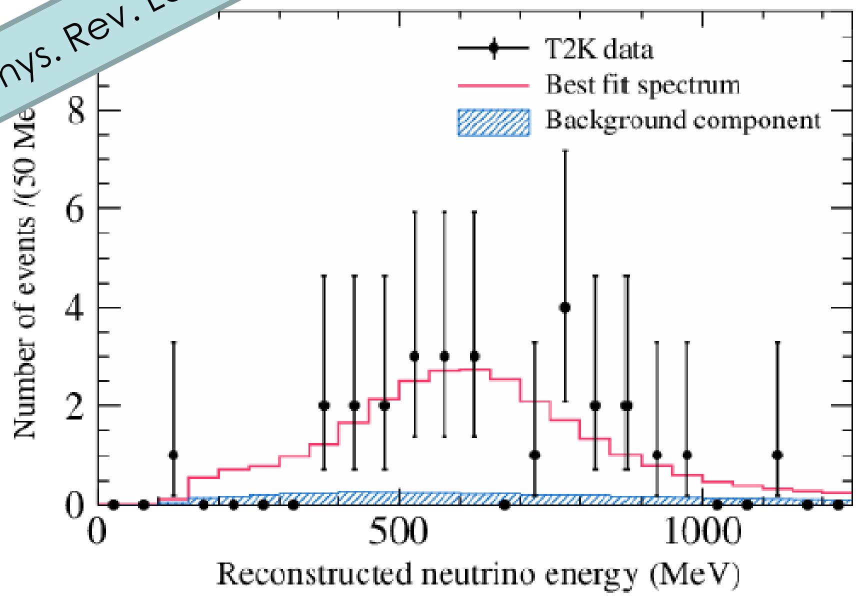


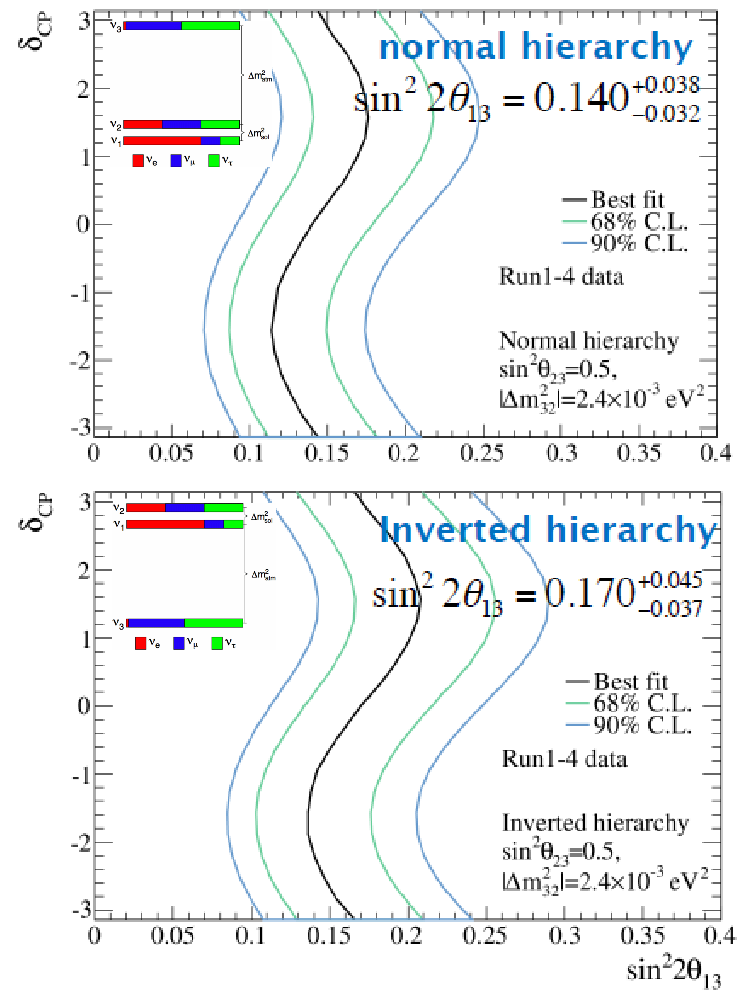


06/04/2014 13

Appearance Result

Phys. Rev. Lett. 112, 061802 (2014)





4.92 ± 0.55 events expected background

28 events observed

21.6 events expected @ $\sin^2 2\theta_{13} = 0.1$

$\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

7.3 σ significance for non-zero θ_{13}

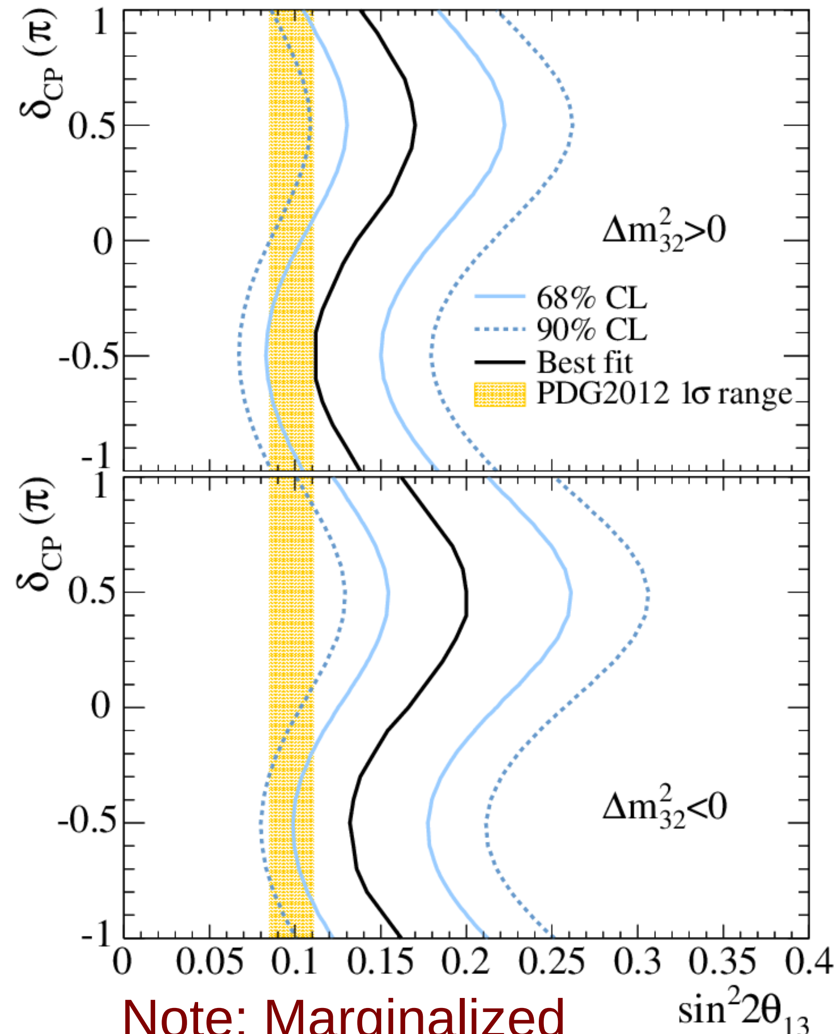
First ever observation (>5σ) of an explicit ν appearance channel

Compare with Reactors

- Comparing with reactor measurements
  - best overlap is for the normal hierarchy $\delta_{cp}=-\pi/2$.

Lucky point!

  - Need to increase θ_{23} to account for high event rate



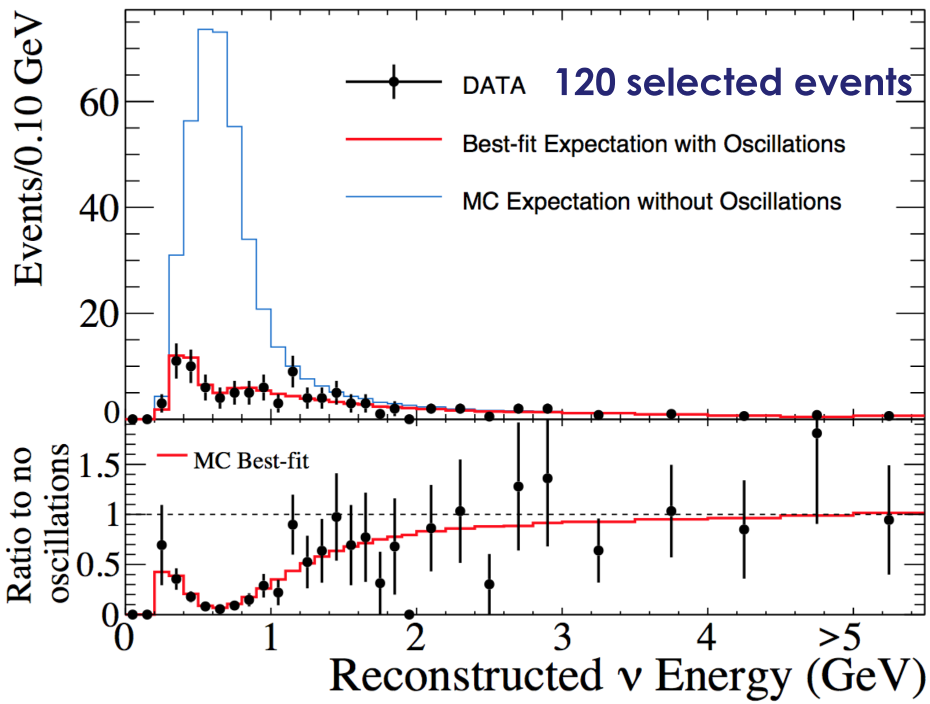
Note: Marginalized over θ_{23} and Δm^2_{32}

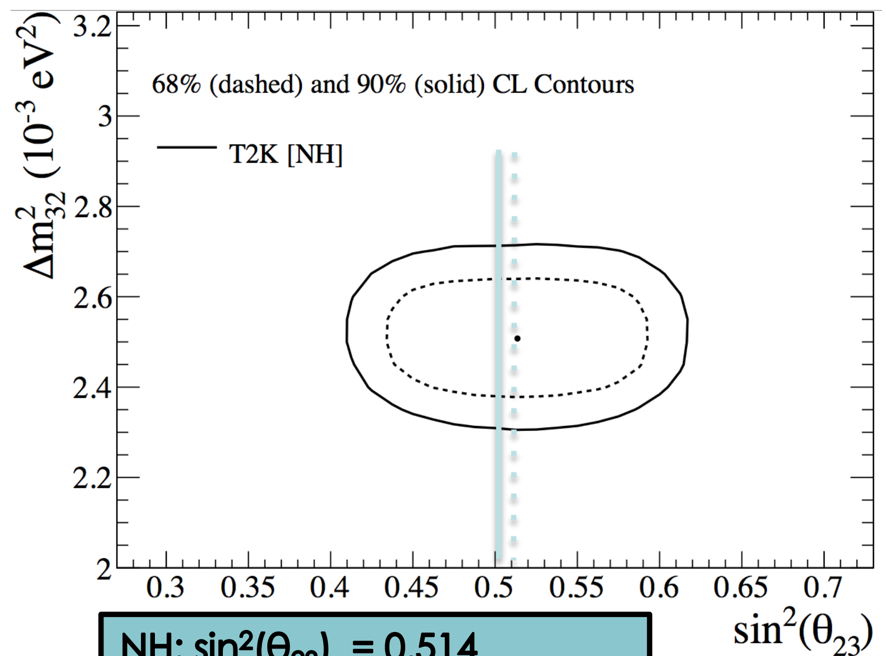
Disappearance Measurement

FLASY 2014

$$P_{\mu\rightarrow\mu} \approx 1 - \sin^2(\Phi) + \sin^2(\Phi) 4\cos^4\theta_{13}\left(\sin^2\theta_{23} - \frac{1}{2\cos^2\theta_{13}}\right)^2$$

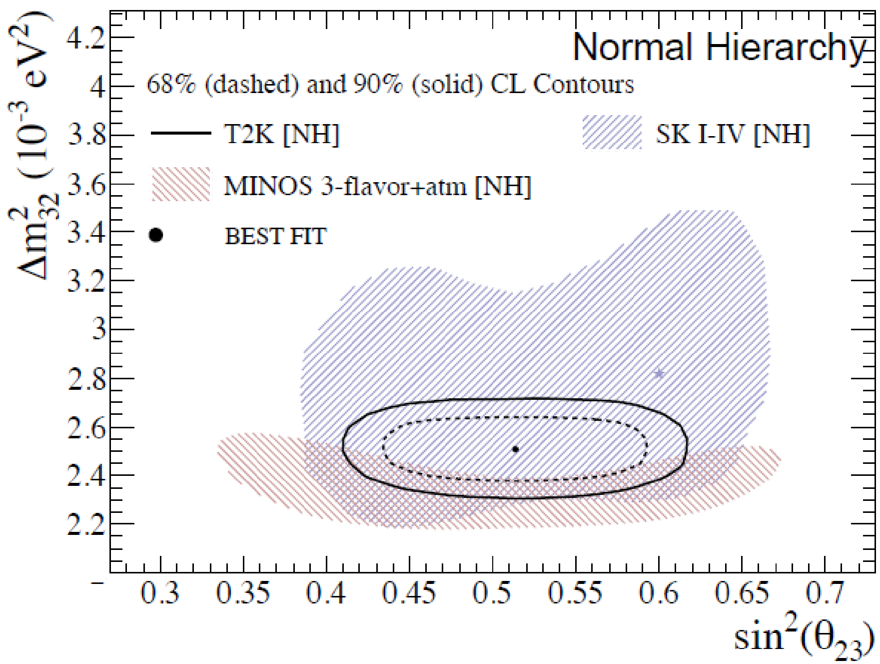
Maximal mixing is not the same as maximum disappearance if θ_{13} is not zero!

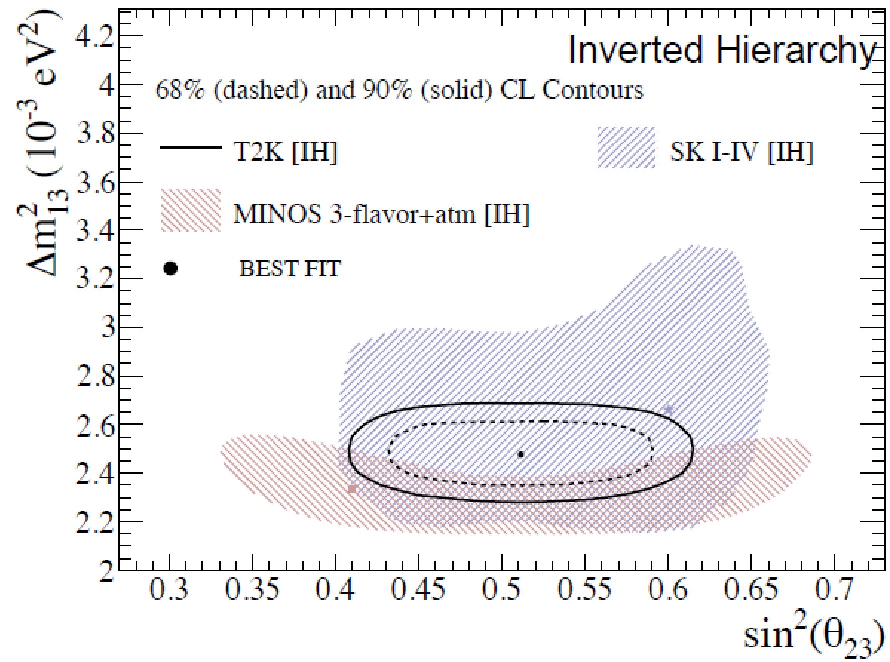




NH: $\sin^2(\theta_{23})$ = 0.514
NH: Δm^2_{32} = 2.51×10^{-3} eV^2

The World Scene





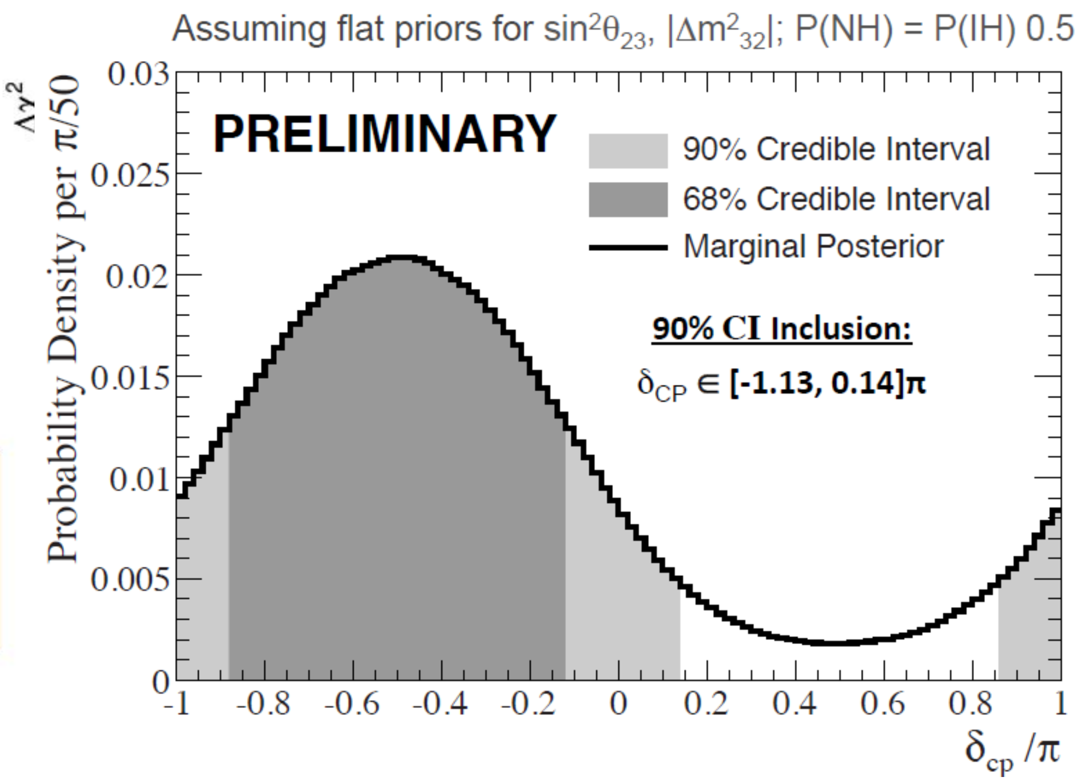
		Best-fit ± FC 68% CL (Δm^2 units 10^{-3} eV^2/c^4)
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32}	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{13}	2.48 ± 0.10

Putting it All Together

Likelihood ratio fit to both $\nu_\mu + \nu_e$ event samples

Plot includes constraint from reactor experiments as given by PDG 2013.

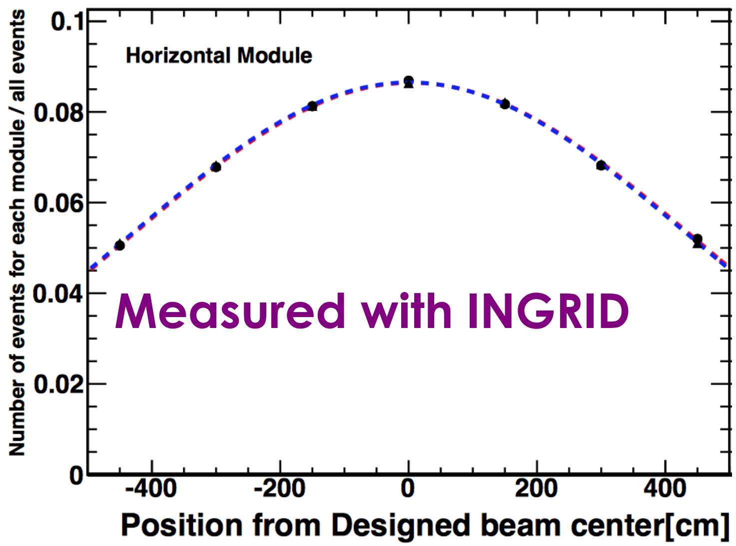
T2K has a slight hint for the normal hierarchy with a value of δ_{CP} of $-\pi/2$



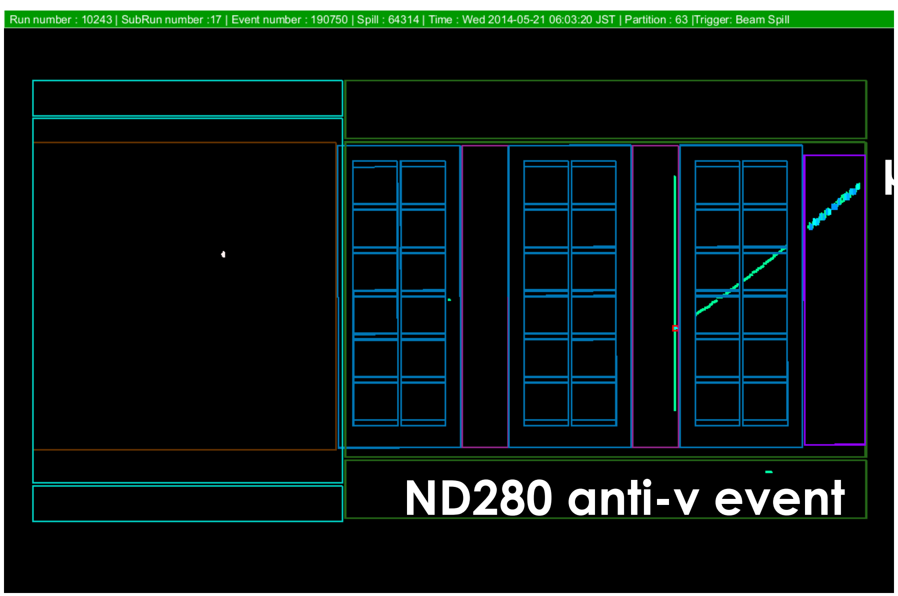
(%)	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	18	8	26%
$\sin^2\theta_{23} > 0.5$	50	24	74%
Sum	68%	32%	

PRELIMINARY

Run Status



The width of the beam is comparable to the measured Gaussians in the previous runs.



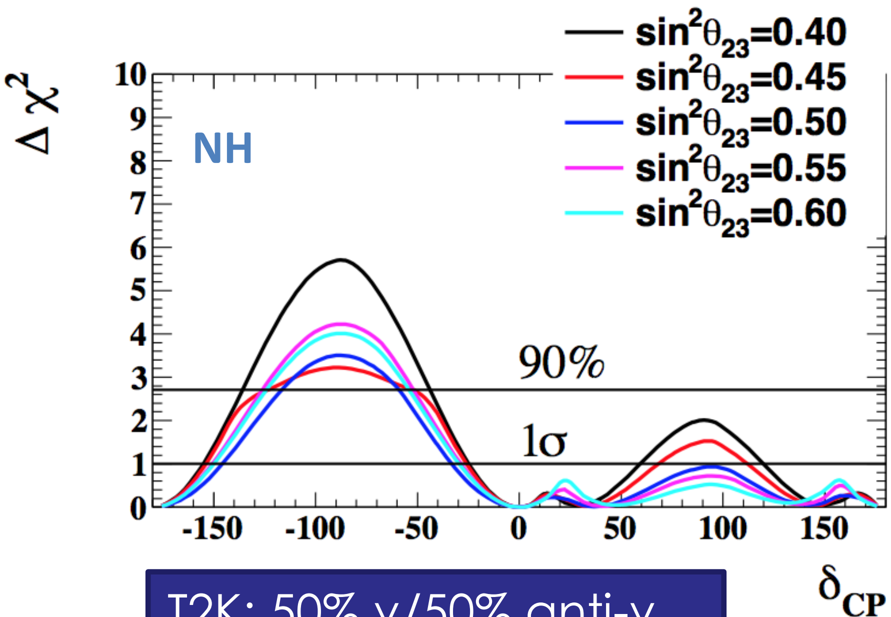
The detectors are all working well.

<u>Here is our first identified anti-neutrino event from an anti-neutrino test run!</u>

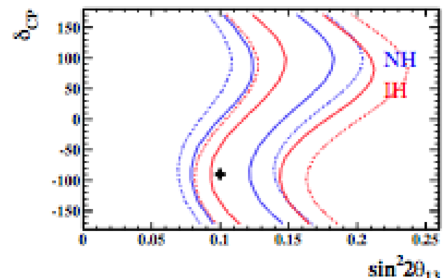
Future Sensitivity

FLASY 2014

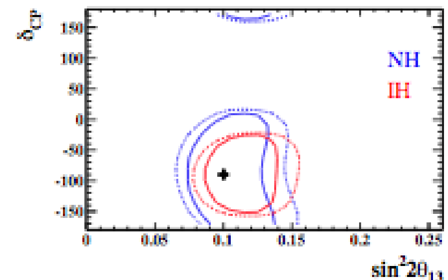
"Lucky! (+: $Sin^2 2\theta=0.1$, $\delta_{CP}=-90$)"



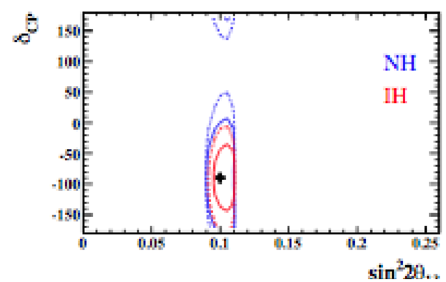
T2K: 50% ν/50% anti-ν



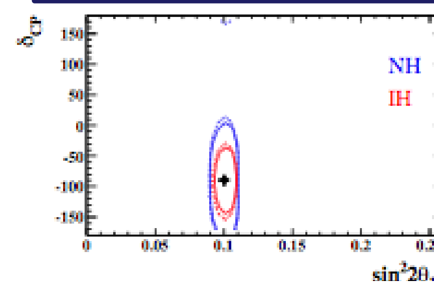
100% ν (true NH)



50% ν/50% anti-ν (true NH)



100% ν (true NH)
w/ Reactor constraint



50% ν/50% anti-ν (true NH)
w/ Reactor constraint

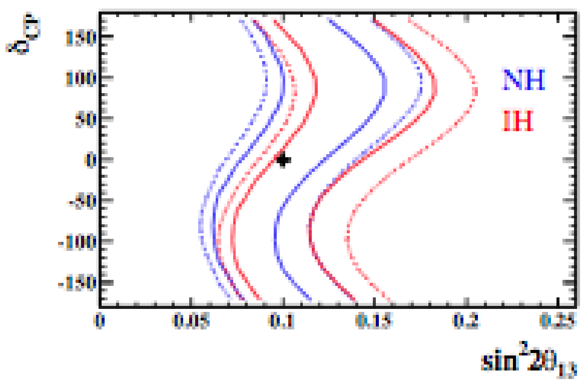
No systematics

5% error on signal, 10% on background

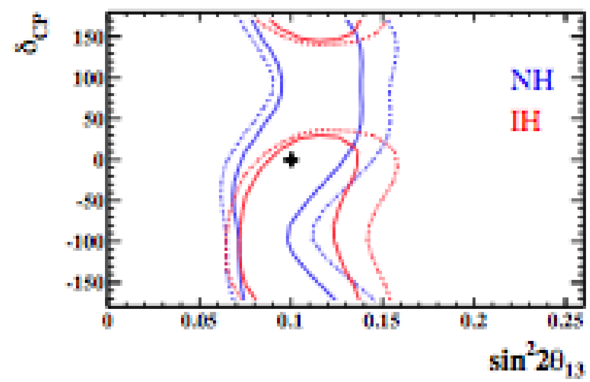
T2K best sensitivity: 50% ν/50% anti-ν
Anti-nu running: large new physics program.

Future Sensitivity (II)

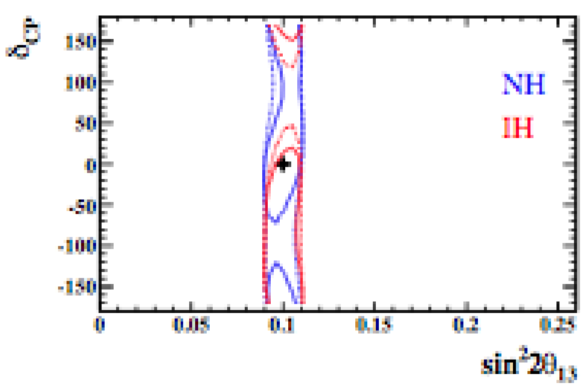
"Unlucky! (+: $Sin^2 2\theta$=0.1, δ_{CP}=0)"



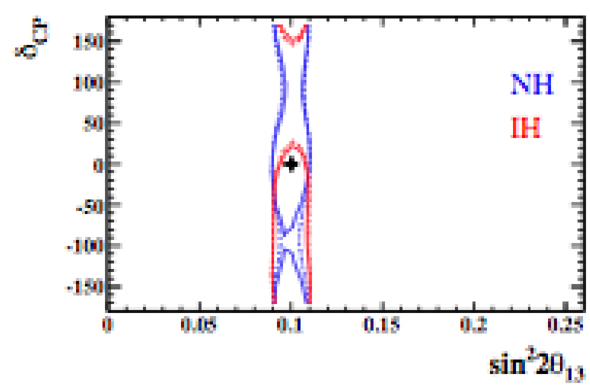
100% ν (true NH)



50% ν/50% anti-ν (true NH)



100% ν (true NH)
w/ Reactor constraint

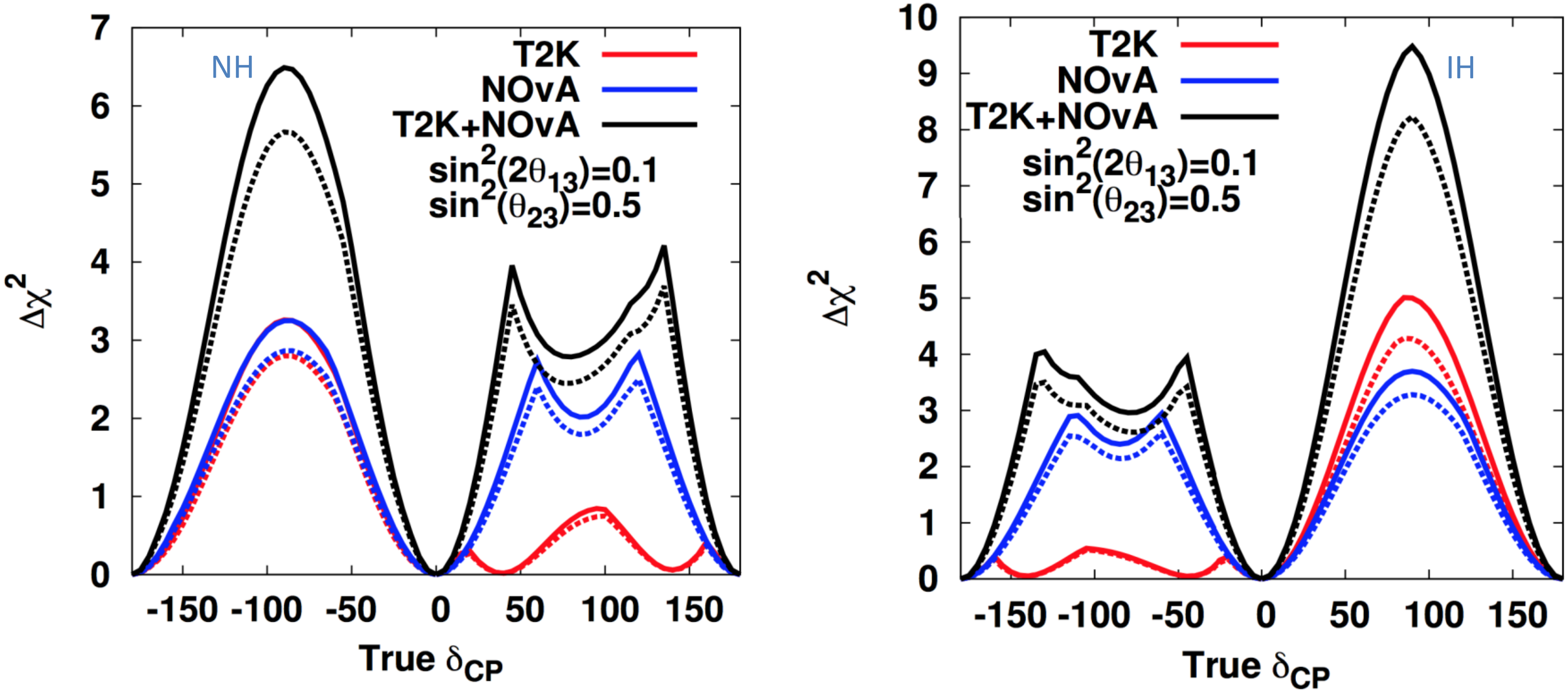


50% ν/50% anti-ν (true NH)
w/ Reactor constraint

T2K and NOvA

FLASY 2014

T2K: 50% ν/50% anti-ν



No systematics

5% error on signal, 10% on background

Summary and Conclusion

FLASY 2014

- T2K has taken 8% of its nominal PoT
- World leading results
  - 7.3σ electron neutrino appearance
  - Most precise measurement of θ_{23}
- Combination with reactor measurements
  - Hint that $\delta_{CP} = -\pi/2$
- Improved sensitivity with data to come
  - Can be lucky to "discover" CP violation
- More results to come
  - Cross sections, sterile neutrinos, exotics…

Backup

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

ν_e disappearance in ν_μ beam
Or
reactor neutrino experiments

Solar neutrino oscillation

ν–less double beta decay

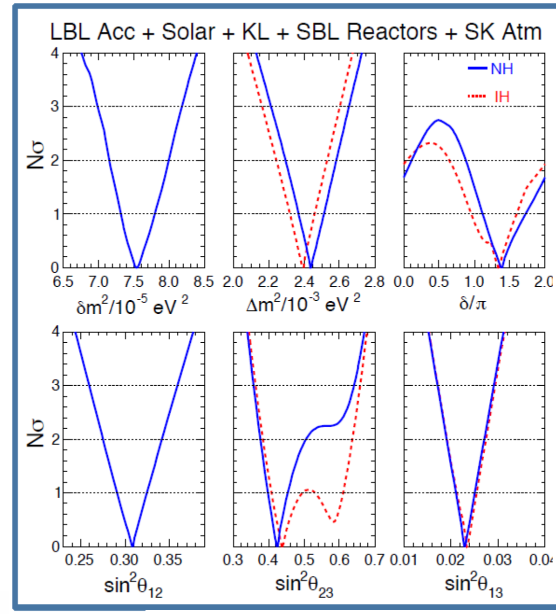
Ubi es?

FLASY 2014

$Dm_{21}^2 = 8 * 10^{-5} eV^2$ $\quad |\Delta m_{32}^2| = 2.4 * 10^{-3} eV^2$

$q_{12} \approx 34^\circ$ $\quad \theta_{23} \approx 45^\circ$ (or a little smaller)

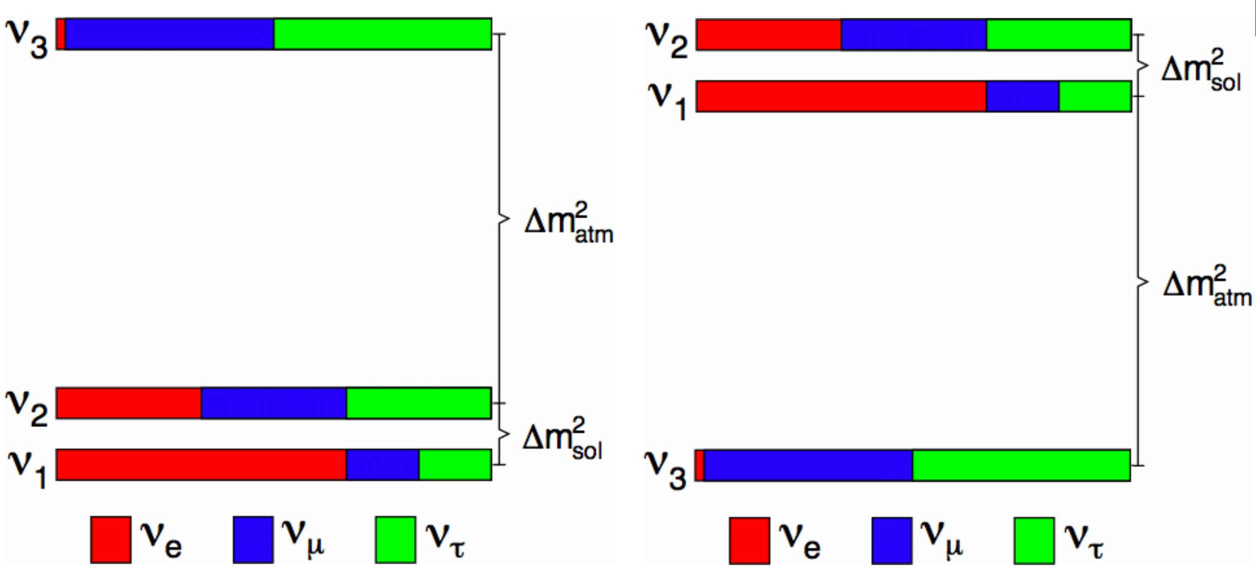
$\theta_{13} \approx 9^\circ$



Fogli et al. arXiv:1205.5254

Open questions:

Normal Hierarchy or Inverted Hierarchy?

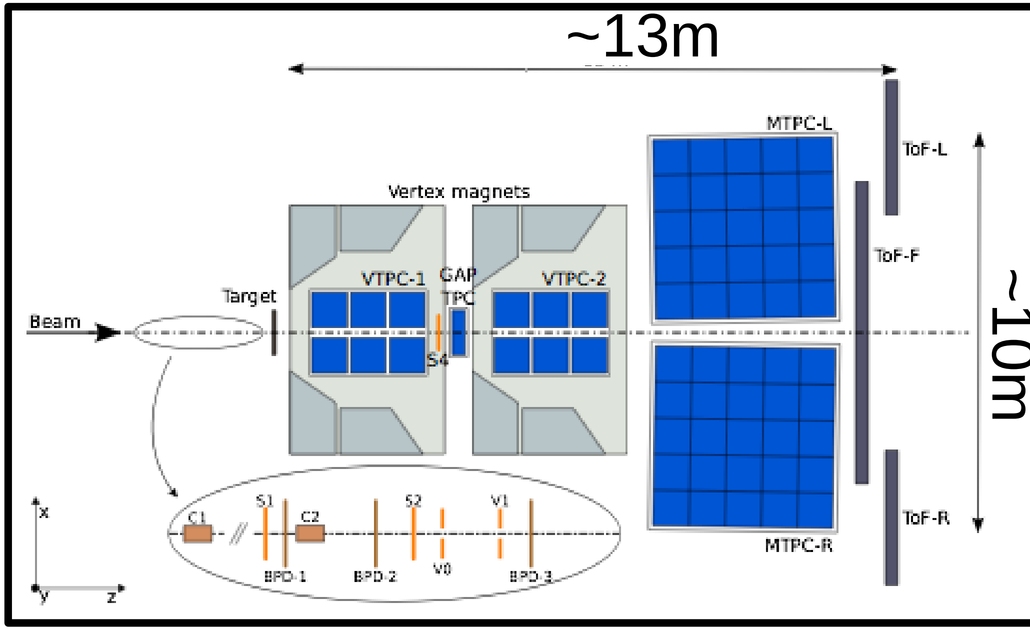


$\delta = ?$

$\Delta m_{32}^2 > 0\,?$

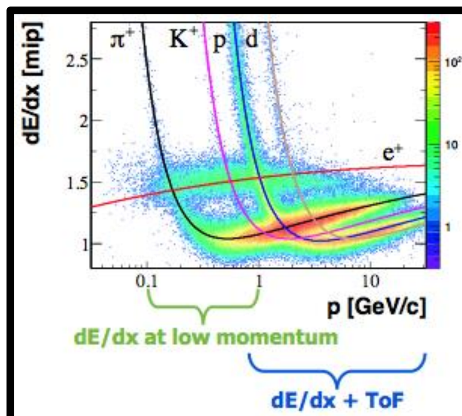
NA61/SHINE

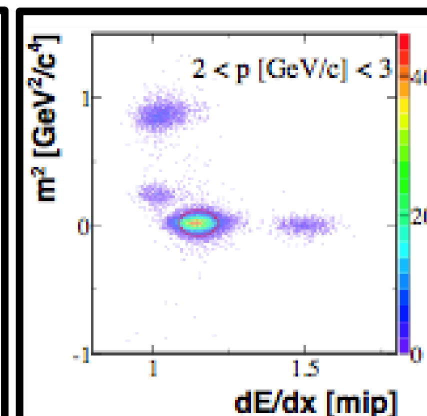
- hadron(π, K) yield
  - 30 GeV p + C
- High-acceptance
  - ToFs and spectrometers
- 2cm thin target (4%λ_I)
- π^+ analysis:
  - dE/dx only analysis low momenta (Phys.Rev.C84.2011.034604)
  - dE/dx+ToF analysis high momenta (Phys.Rev.C85.2011.035210)



$$\sigma(p)/p^2 \approx 2\times10^{-3},\ 7\times10^{-3},\ 3\times10^{-2}(\mathrm{GeV/c})^{-1}$$
$$\text{for } p>5,\ p=2,\ p=1\ \mathrm{GeV/c}$$

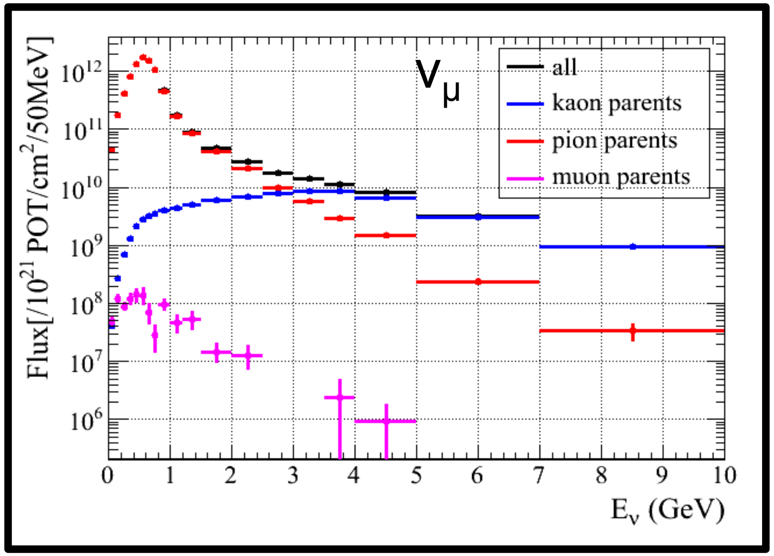
$$\sigma(\mathrm{dE/dx})/\langle\mathrm{dE/dx}\rangle \approx 0.04$$
$$\sigma(\mathrm{TOF\text{-}F}) \approx 115\ \mathrm{ps}$$

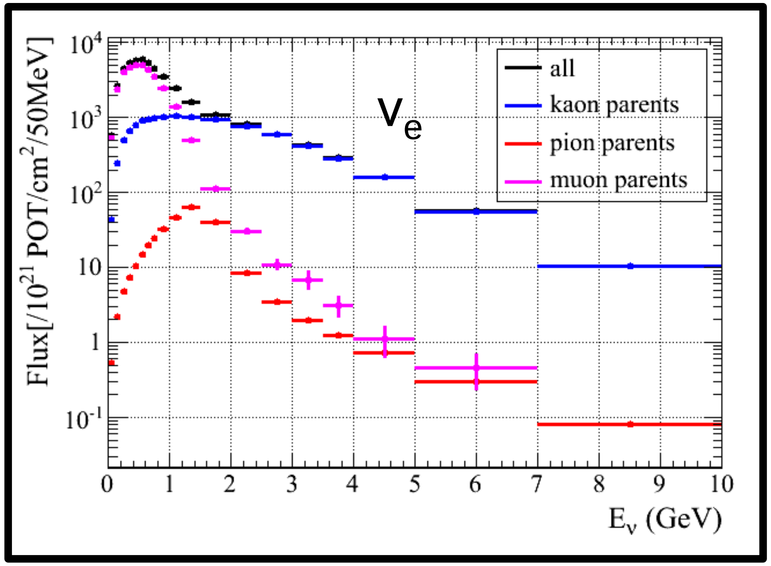


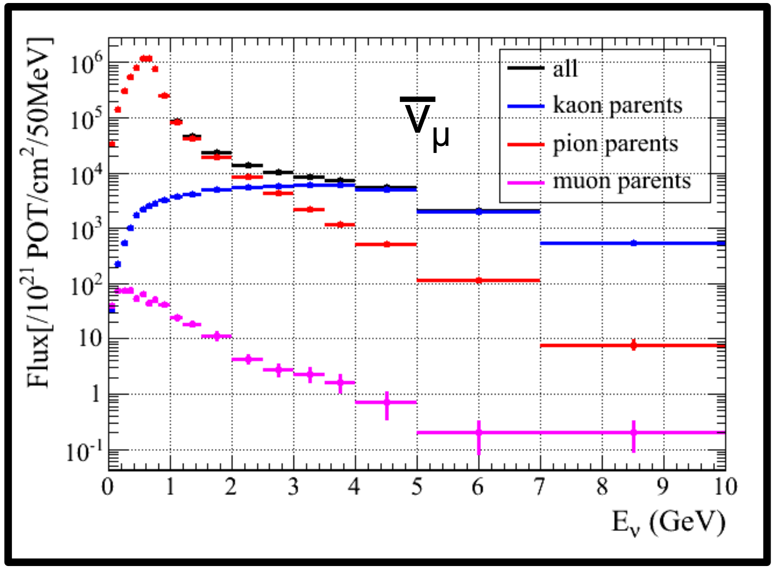


Predicted Flux

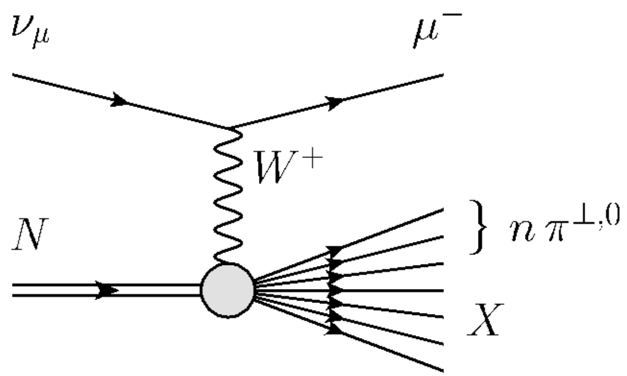
- Primary pions modelled with NA61 data
- ν_μ flux
  - Pions dominant at low energy
  - Kaons important in tail
- ν_e flux
  - For low energy from muons



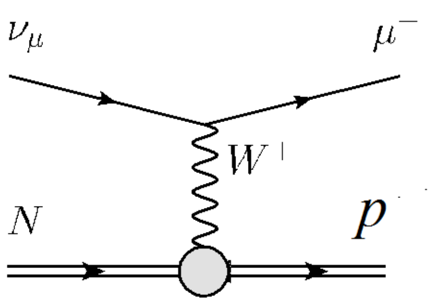




CC Interaction



CC-Quasi Elastic (CCQE)



CC-nonQE (CCnQE)

= all CC that is not QE