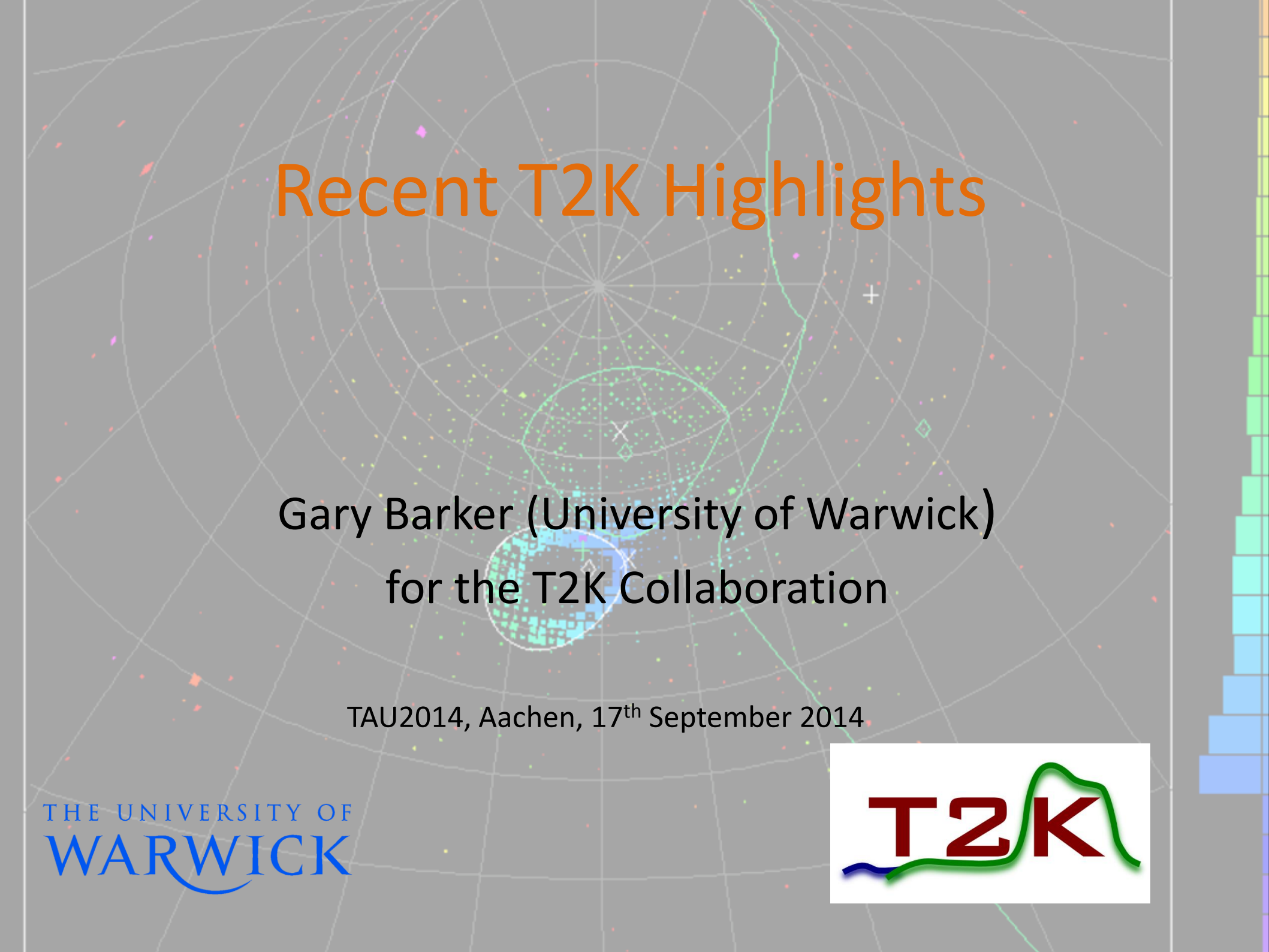
Recent T2K Highlights



Gary Barker (University of Warwick)

for the T2K Collaboration

TAU2014, Aachen, 17th September 2014

THE UNIVERSITY OF WARWICK

T2K

Contents

- Neutrino mixing/oscillations
- The T2K project and detectors
- Latest results from oscillation and cross section measurements
- Current run status and future plans
- Conclusion

Neutrino Mixing

- Flavour eigenstates ≠ mass eigenstates:

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

- U_{PMNS} parameterised in terms of 3 angles and a CP-violating phase:

$$\boldsymbol{\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}}$$

Oscillation Probabilities

- Leading order ν_e appearance probability:

$$P_{\mu\to e} \approx \sin^2\theta_{23}\cdot\sin^2 2\theta_{13}\cdot\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$$\Delta m^2 \approx \Delta m^2_{32} \approx \Delta m^2_{31}$$

=> Determine θ_{13}

- Leading order ν_μ disappearance probability:

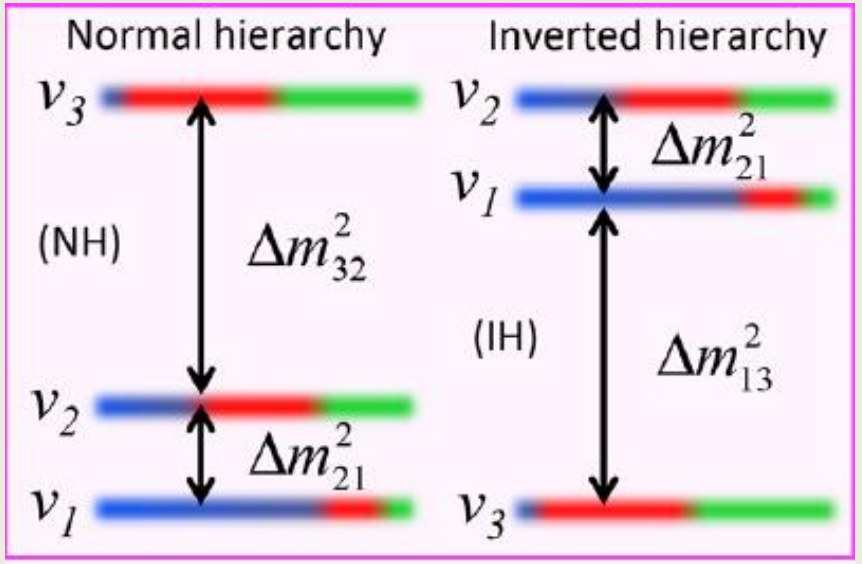
$$P_{\mu\to x} \approx 1-\left(\cos^4\theta_{13}\cdot\sin^2 2\theta_{23}+\sin^2\theta_{23}\cdot\sin^2 2\theta_{13}\right)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

=> Determine θ_{23} and Δm^2_{32}

Unknowns

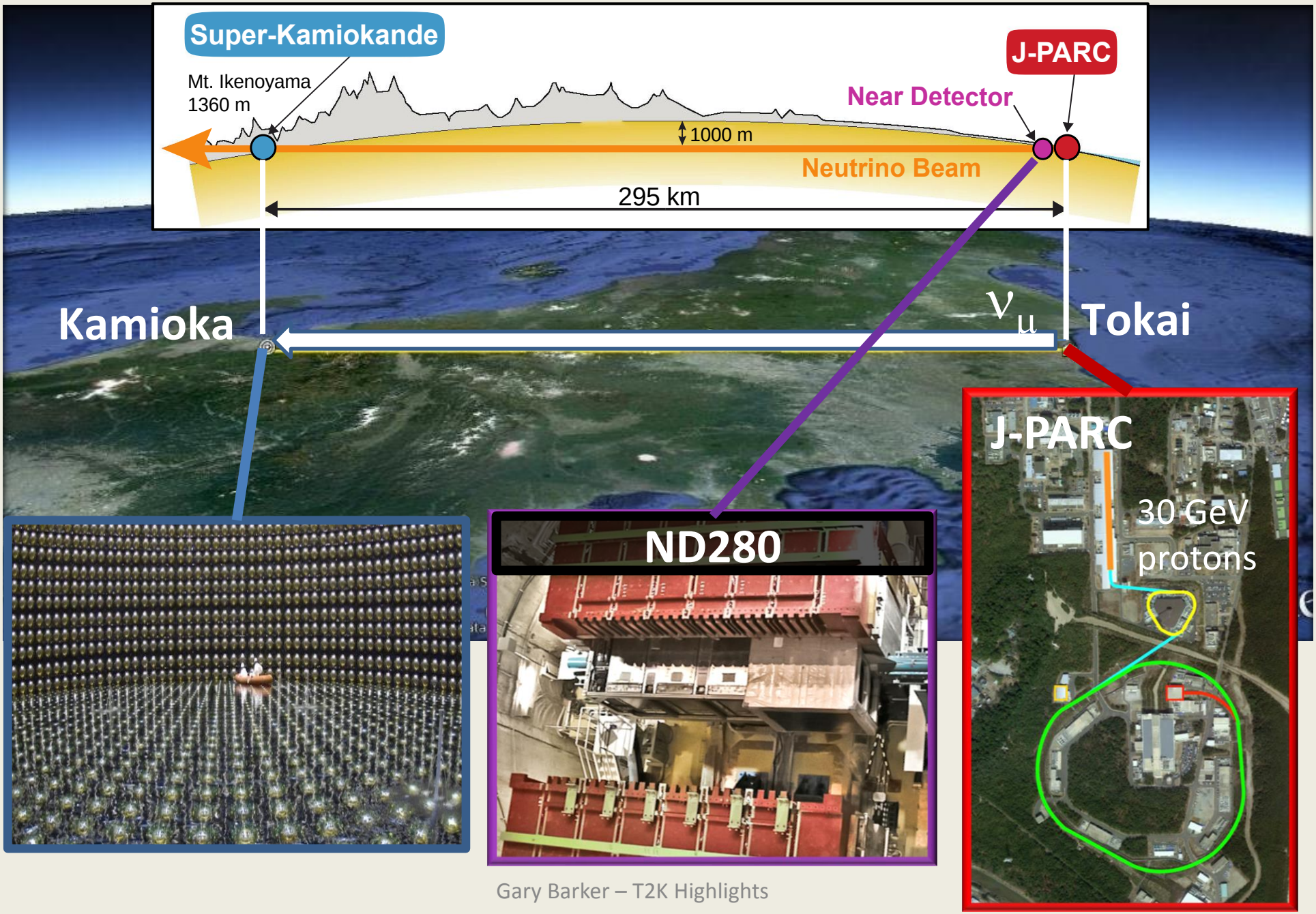
- $\theta_{23} \neq 45^{o}$? Which octant ? ($\theta_{23} < 45^{0}$, $\theta_{23} > 45^{0}$)
  - Through combination of disappearance and appearance

- δ_{CP} (=0?) ; Mass Hierarchy ?
  - Through higher order corrections to $P_{\mu \rightarrow e}$

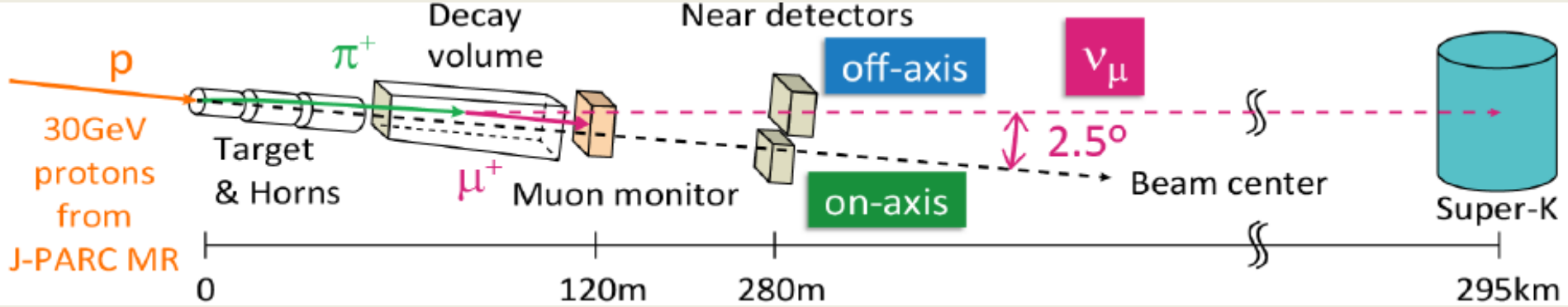


=> All questions that T2K is in the hunt to answer

The Tokai-to-Kamioka (T2K) Experiment



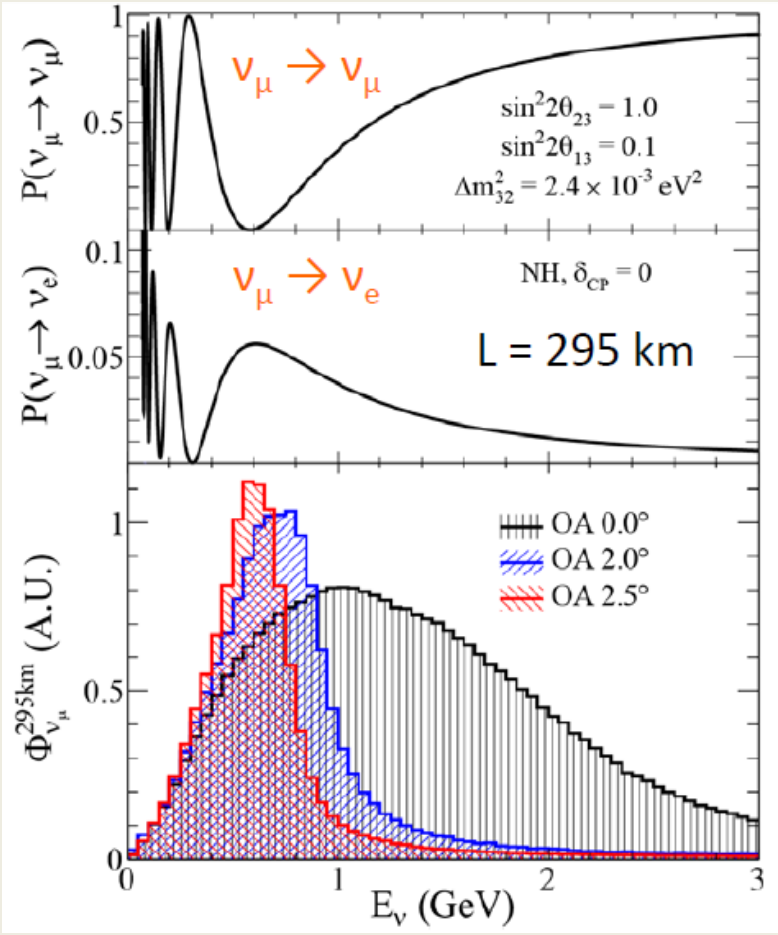
Neutrino Beam



- Proton beam incident on graphite target
- π^+ focussed by system of 3 magnetic `horns'
- π^+ -> μ^+ ν_μ decay in decay volume

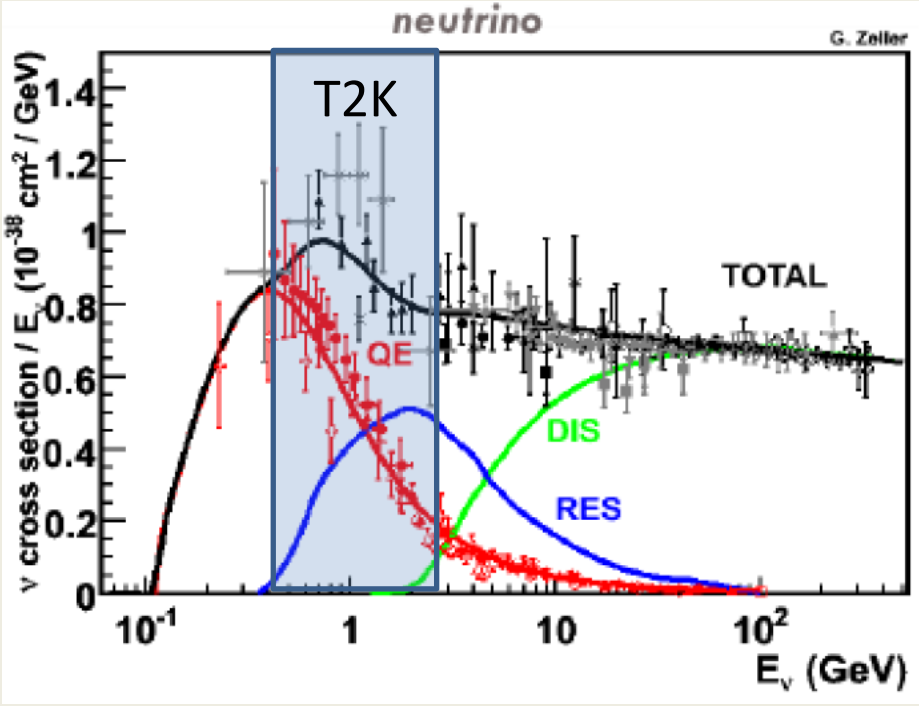
- Beam aligned with SK with a 2.5° off-axis angle
- 2-body kinematics of π-decay produces narrow band beam => lower backgrounds
- Mean beam energy 0.6 GeV => peak of oscillation probabilities

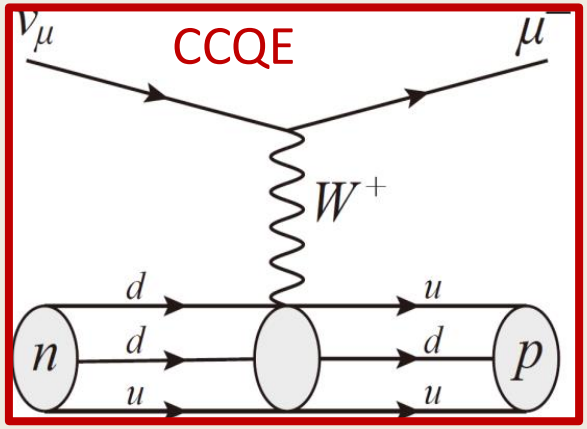
- Near detectors (on and off-axis) measure ν_μ flux before any oscillations occur

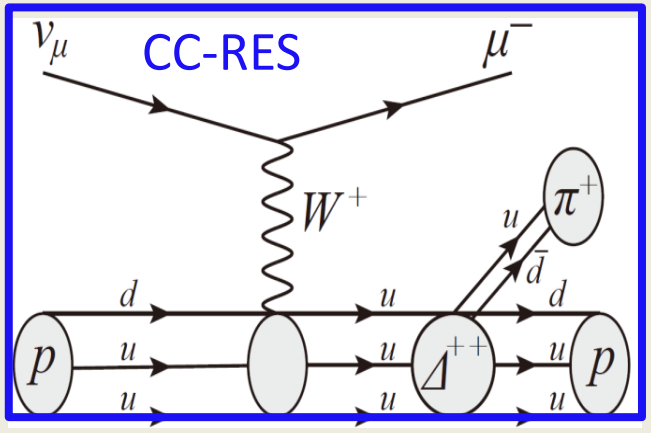


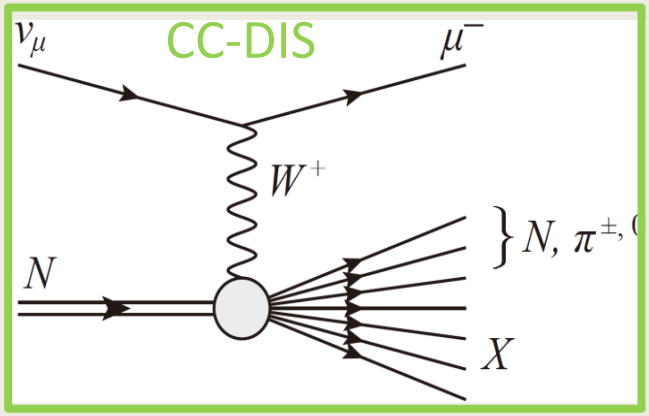
Neutrino Interactions

- The Charged Current Quasi Elastic (CCQE) process dominates at T2K energies



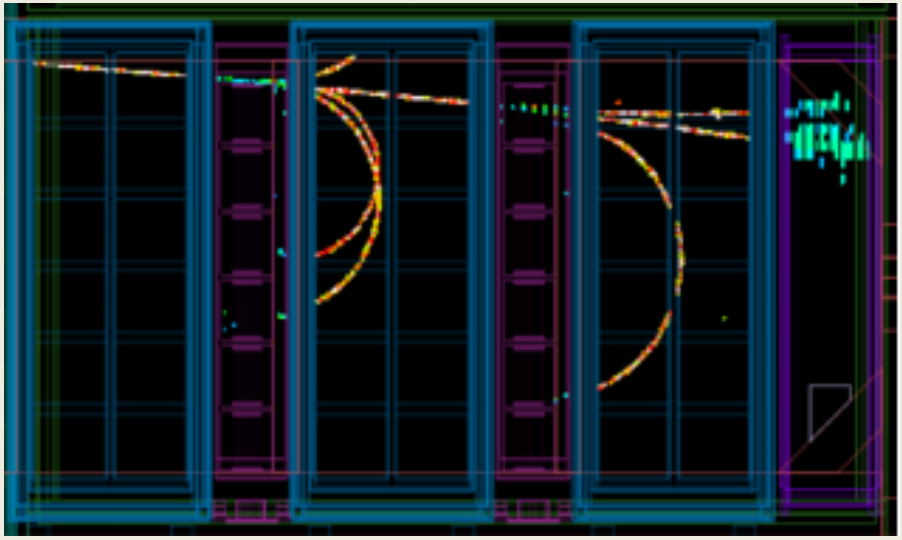


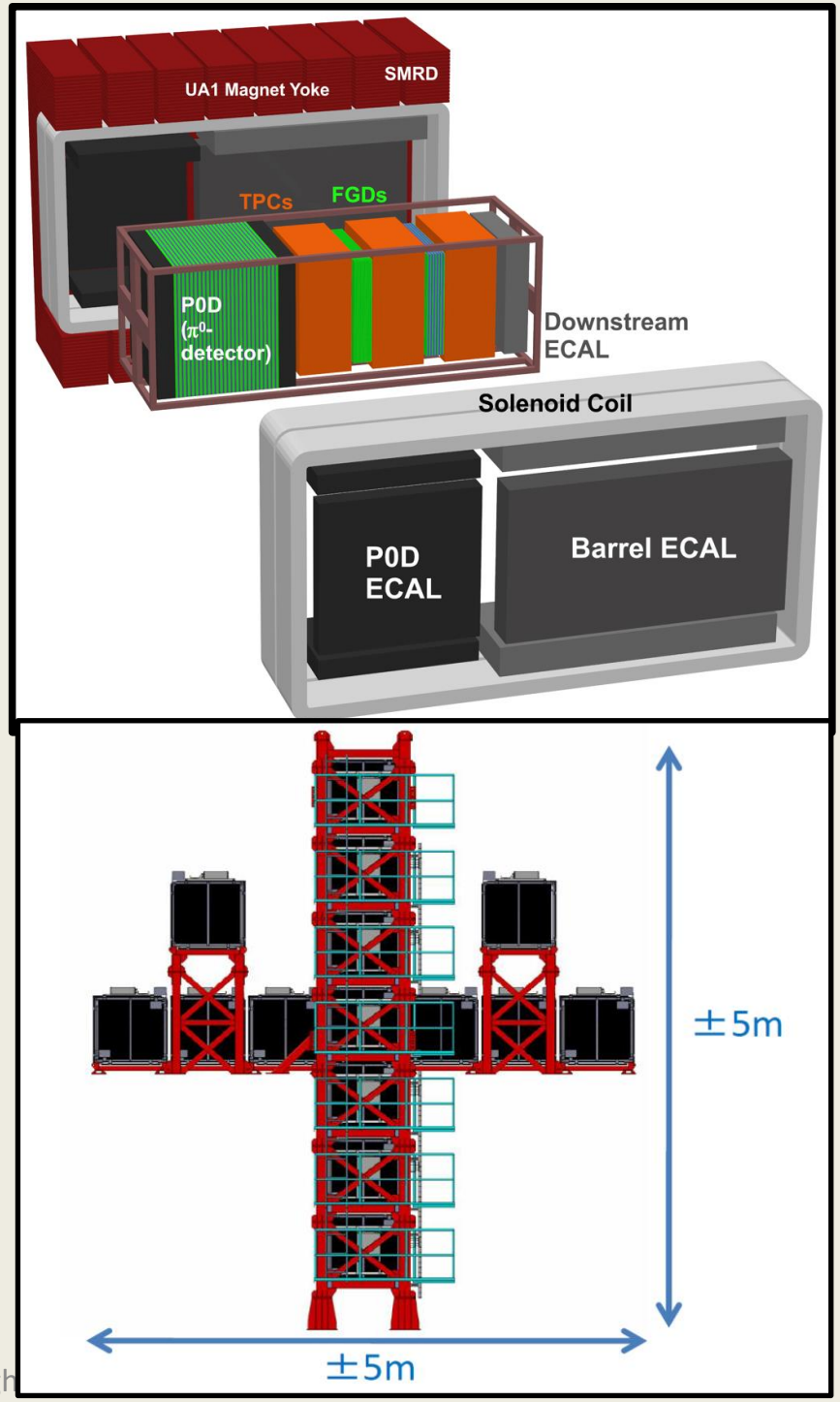




Near Detectors

- ND280 (Off-Axis): Collection of tracking detectors and calorimeters inside the UA1 magnet (B=0.2T)
- Measure flux, ν_μ energy and momentum, ν cross sections and ν_e contamination
- Plastic and water targets





- INGRID(On-Axis): monitor ν_μ direction, intensity and profile
- 16 modules of Fe-plastic scintillator sandwich

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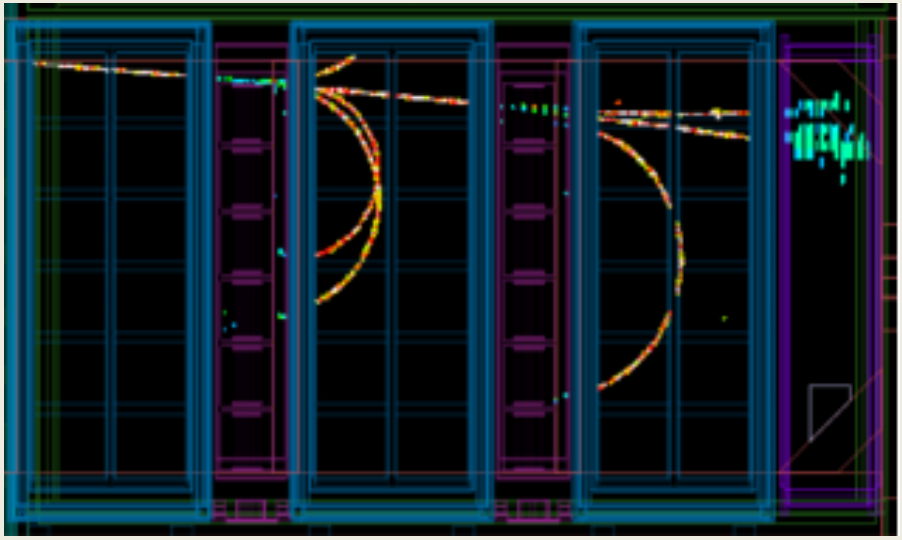

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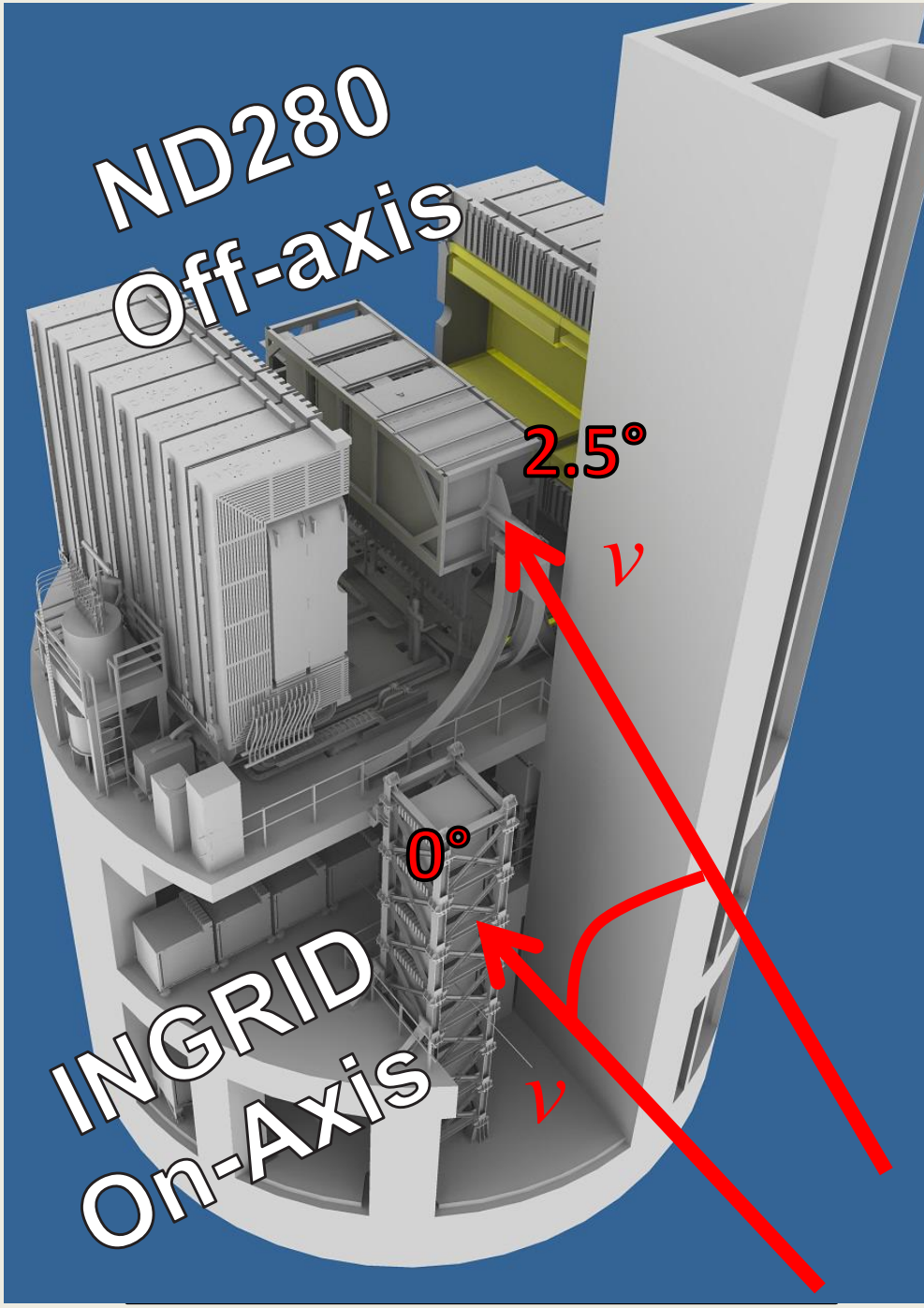
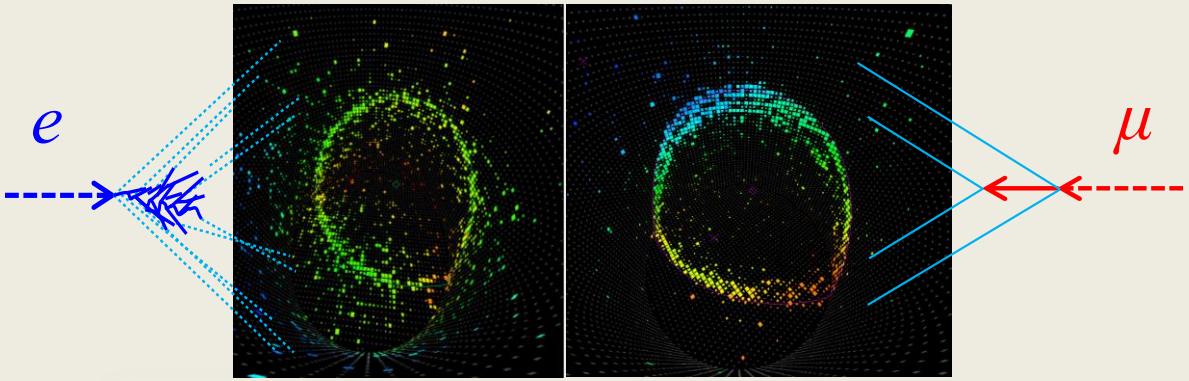
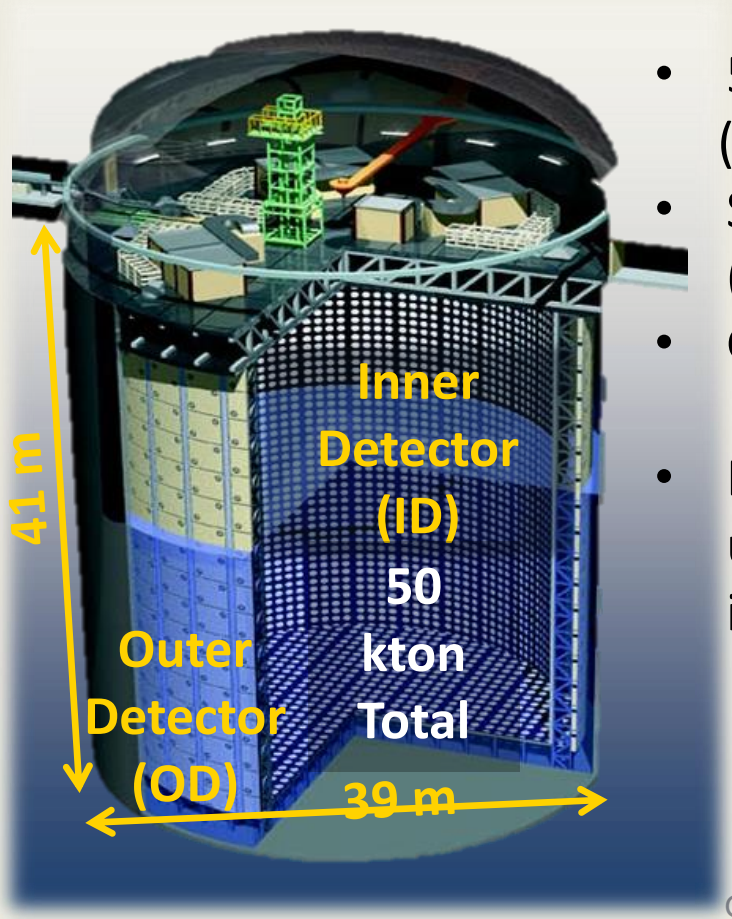
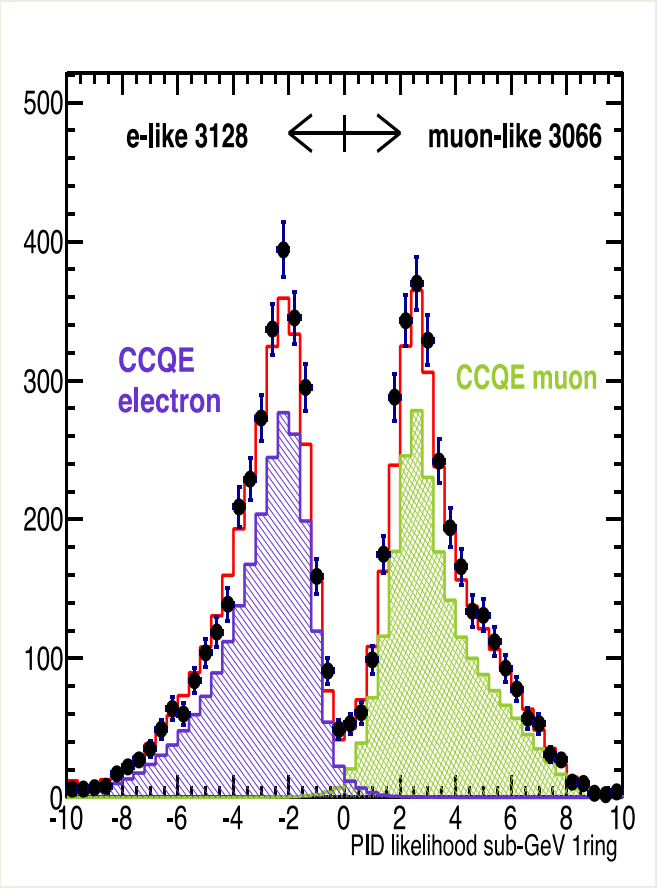


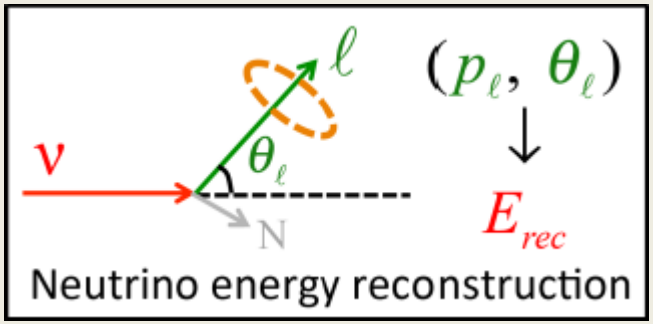
Far Detector: Super-Kamiokande



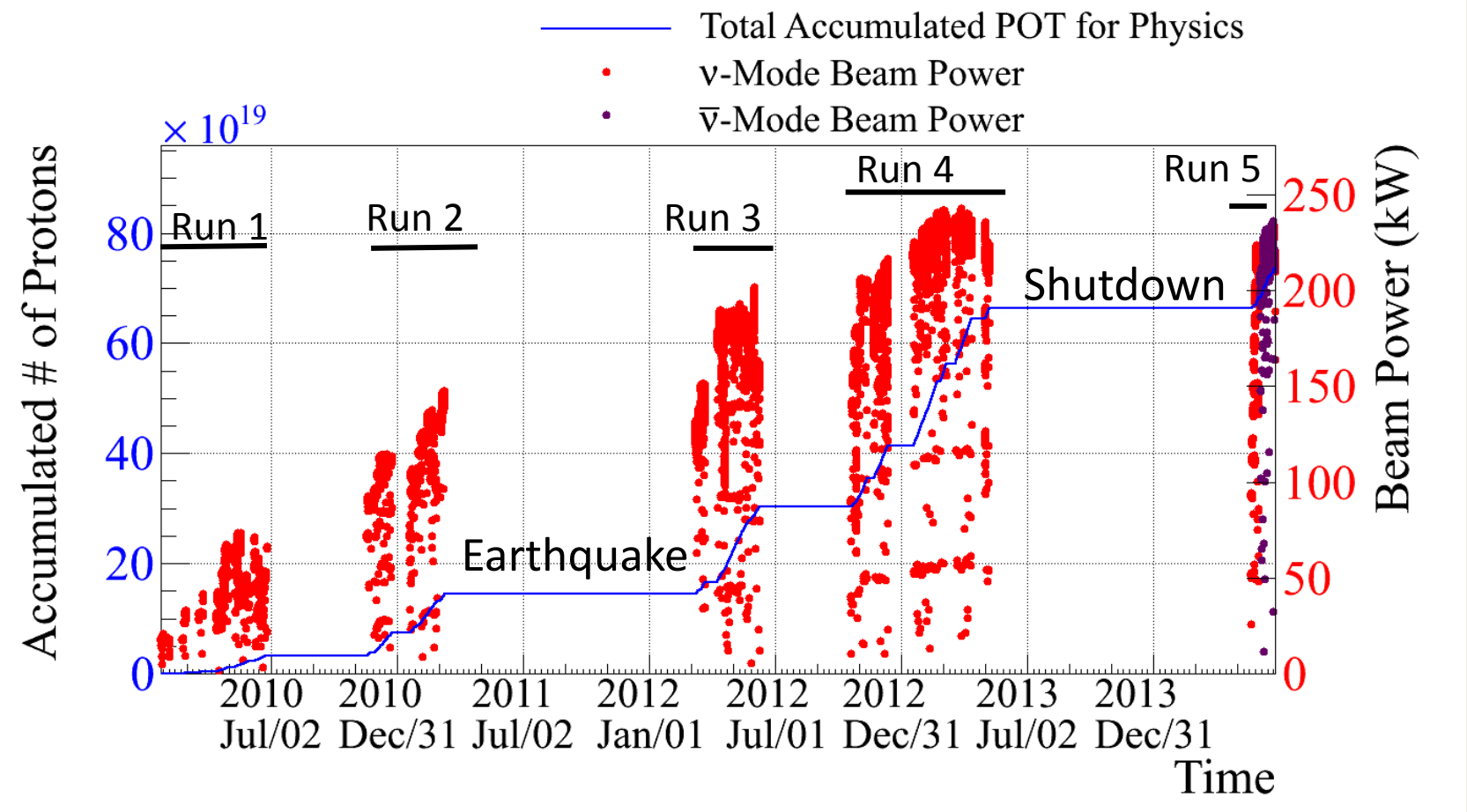


- 50kt water Cherenkov (22.5 kt fiducial volume)
- Superb e/μ identification (only 1% contamination)
- GPS synchronisation with J-PARC beam
- Energy reconstruction using kinematics of CCQE interactions





Beam delivered



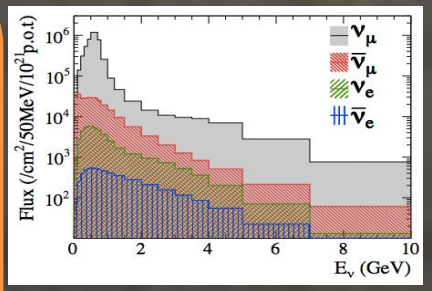
- So far delivered 6.57 x 10^{20} Protons On Target (POT) (8% of design goal)
- 97% of data used for analysis
- Achieved stable beam power of 235kW (a world-best 1.2 x 10^{14} protons per pulse)

Oscillation Analysis Chain

Simulate flux

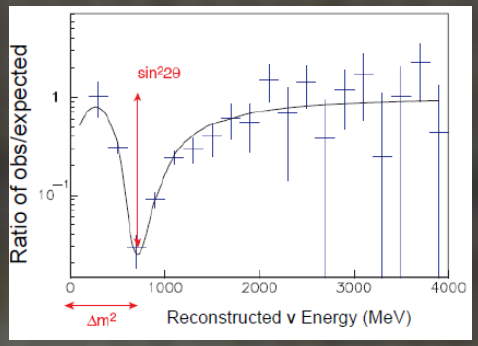
=> constrained by external hadron-production data e.g. NA61/SHINE

=> Proton beam stability (INGRID)



Fit to ND280 ν_μ data

Predict event rate at Super-K



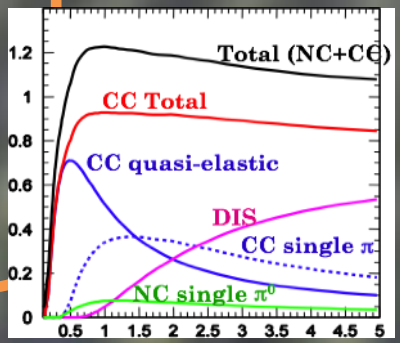
Extract oscillation parameters

Measure CC ν_μ and ν_e events at Super-K

Simulate neutrino interactions

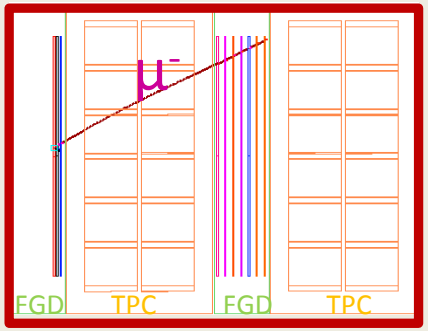
=> Interaction models

=> Constrained by external measurements (MiniBooNE)

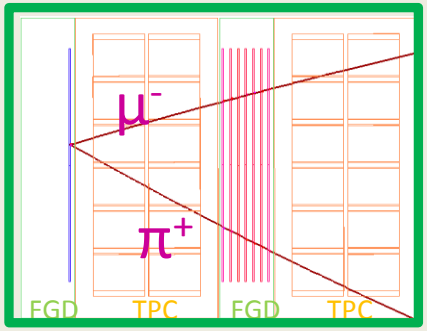


ND280 Fit to Topological Samples

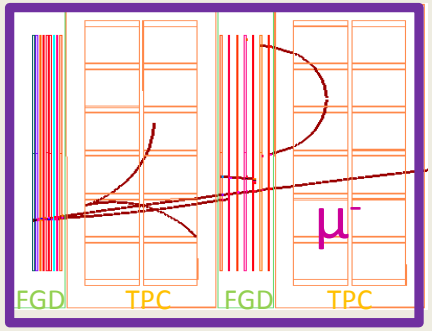
- Select CC ν_μ topological samples : 0π, 1π, `other'
- Fit (p_μ,cos θ_μ) distributions (marginalising over flux and cross section parameters)



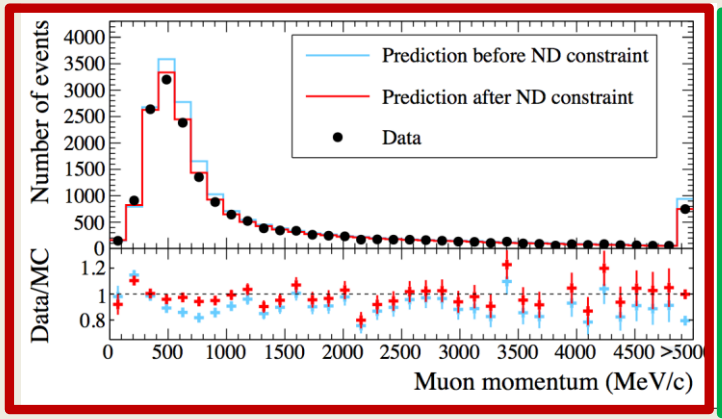
CC-0π
63% pure
in CCQE

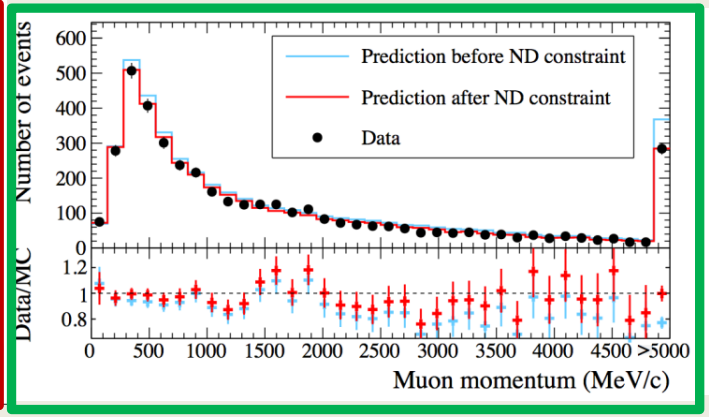


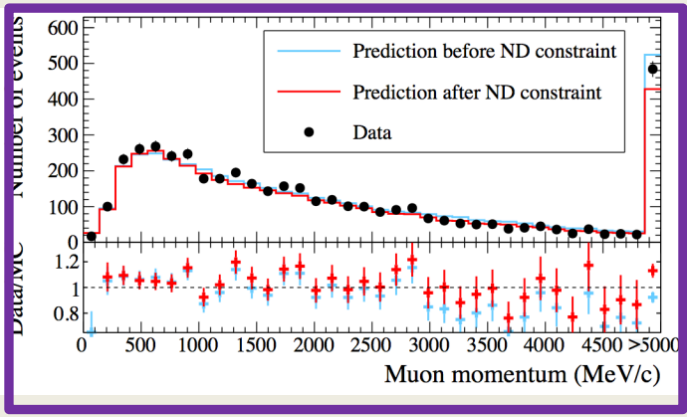
CC-1π⁺
39% pure
in CC-RES



CC-other
68% pure
in CC-DIS





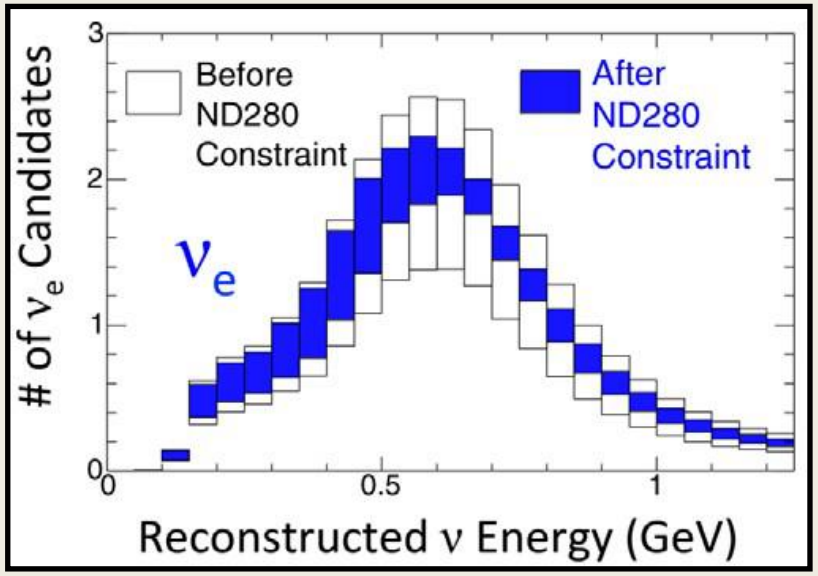


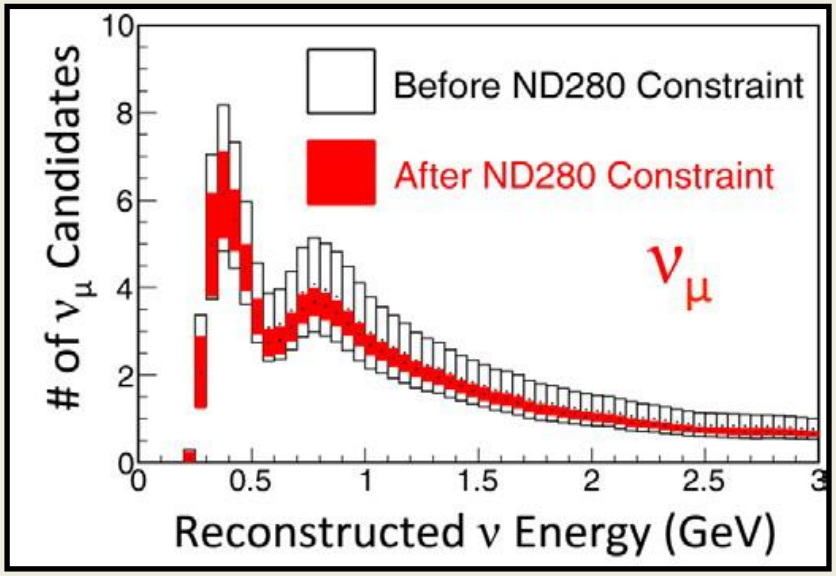
ND280 Constraint on Event Rates at Super-K

Relative Uncertainty in # of ν_e Candidates (%)	**Systematic Error Source**	Relative Uncertainty in # of ν_μ Candidates (%)
3.1(26)	Flux ✣ Xsec. (ND280 constrained)	2.7(21.8)
4.7	Xsec. (ND280-independent)	5.0
2.4	π Hadronic Interactions	3.0
2.7	SK Detector	4.0
6.8(26.8)	**Total**	**7.7(23.5)**

dePerio

(Errors from the joint ν_e-ν_μ analysis: $\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{23} = 1$, $\Delta m_{32}^2 = 2.4\times10^{-3}$ eV^2, NH, $\delta_{CP}=0$)

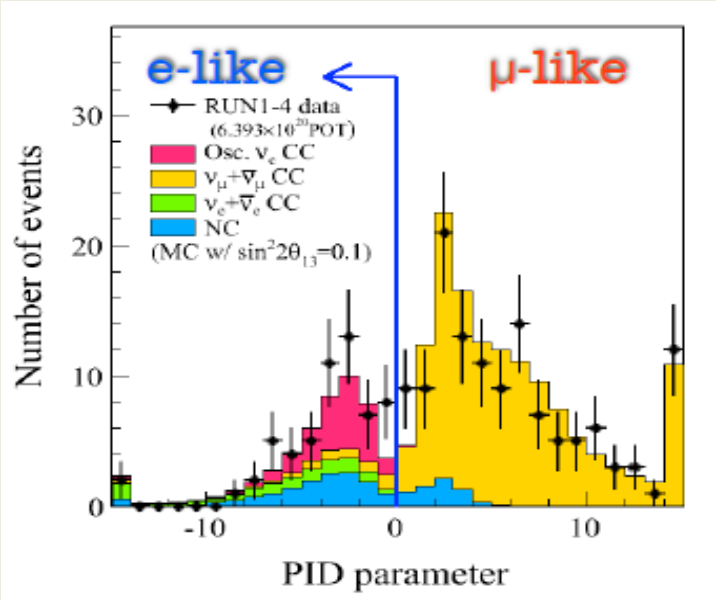




Super-K Event Selection: ν_e Appearance

Fully Contained & Fiducial Volume & 1-Ring

PID: *e*-like



$p_e > 100$ MeV/c

No decay-*e*

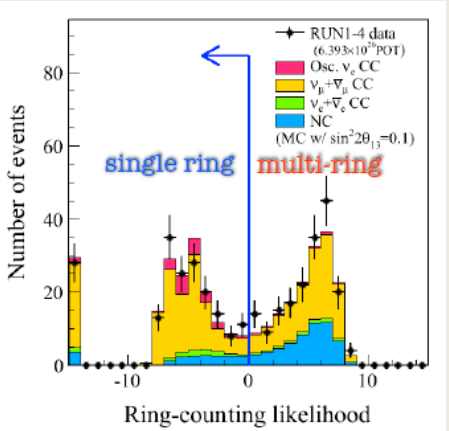
New π^0 Rejection

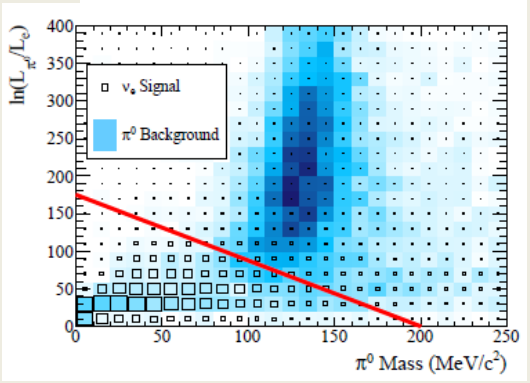
$E_{rec} < 1250$ MeV

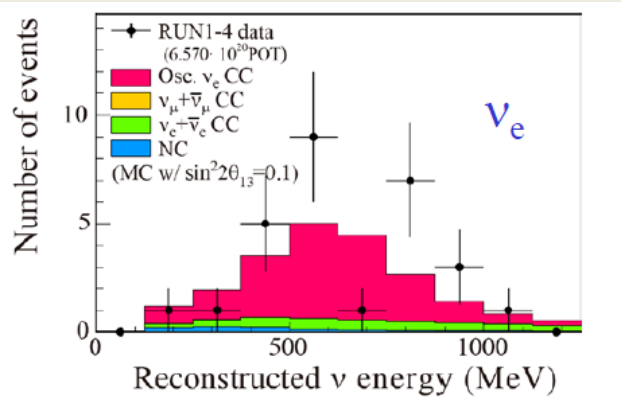
28 Events

Backgrounds (4.6 events) :
Beam ν_e
NC π^0

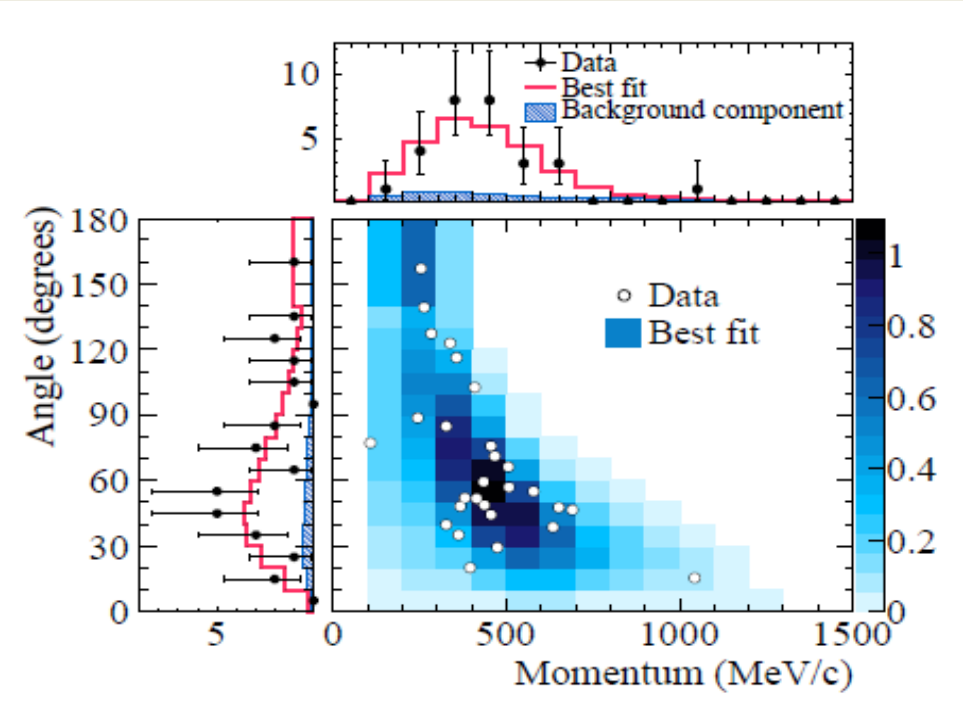
+



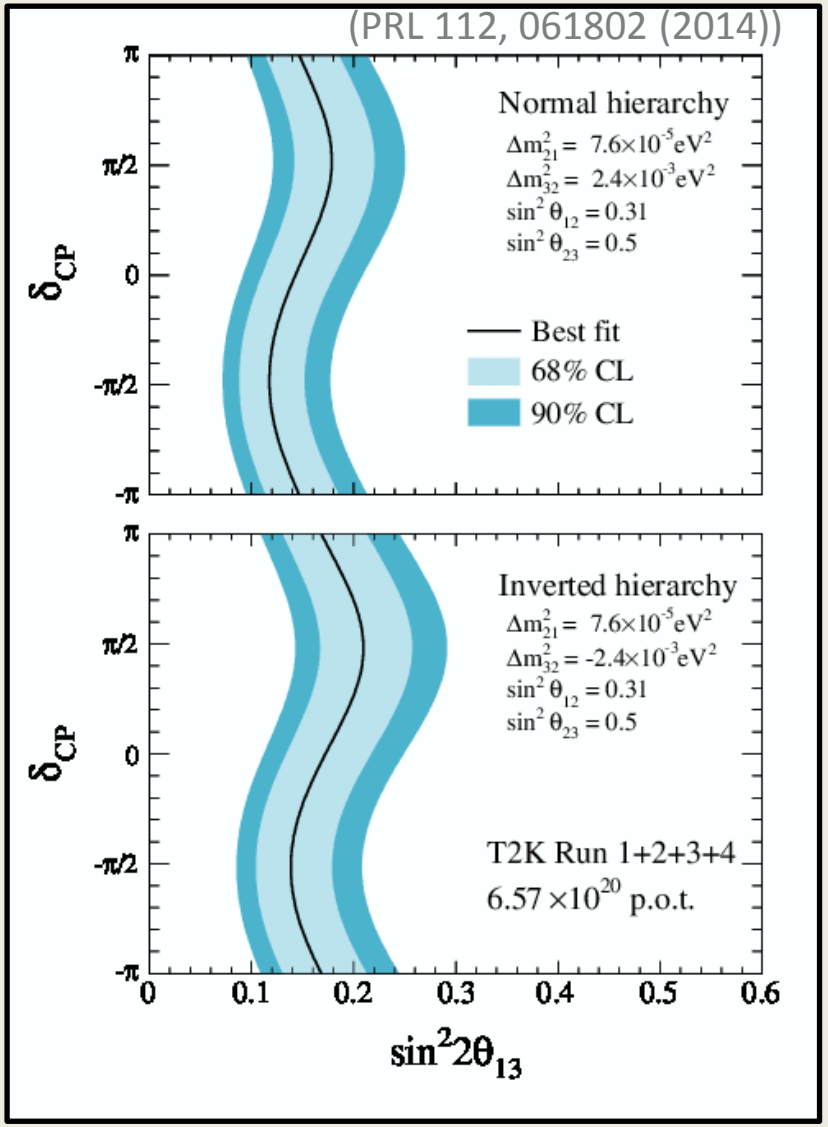




T2K Appearance Result



(PRL 112, 061802 (2014))



- Maximum likelihood fit in (p_e, θ_e)
- Best fit results (for $\delta_{CP}=0$):

NH	$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$
IH	$\sin^2 2\theta_{13} = 0.170^{+0.045}_{-0.037}$

- Only experiment able to a make direct observation of ν_e appearance:
  2011 (6 events) => 2.5σ (for non-zero θ_{13})
  2014 (28 events) => 7.3σ

- 1D contours for all δ_{CP} values
- Marginalised over θ_{23} and $|\Delta m_{32}|^2$

Super-K Event Selection: ν_μ Disappearance

Fully Contained & Fiducial Volume & 1-Ring

PID: μ-like

p_μ > 200 MeV/c

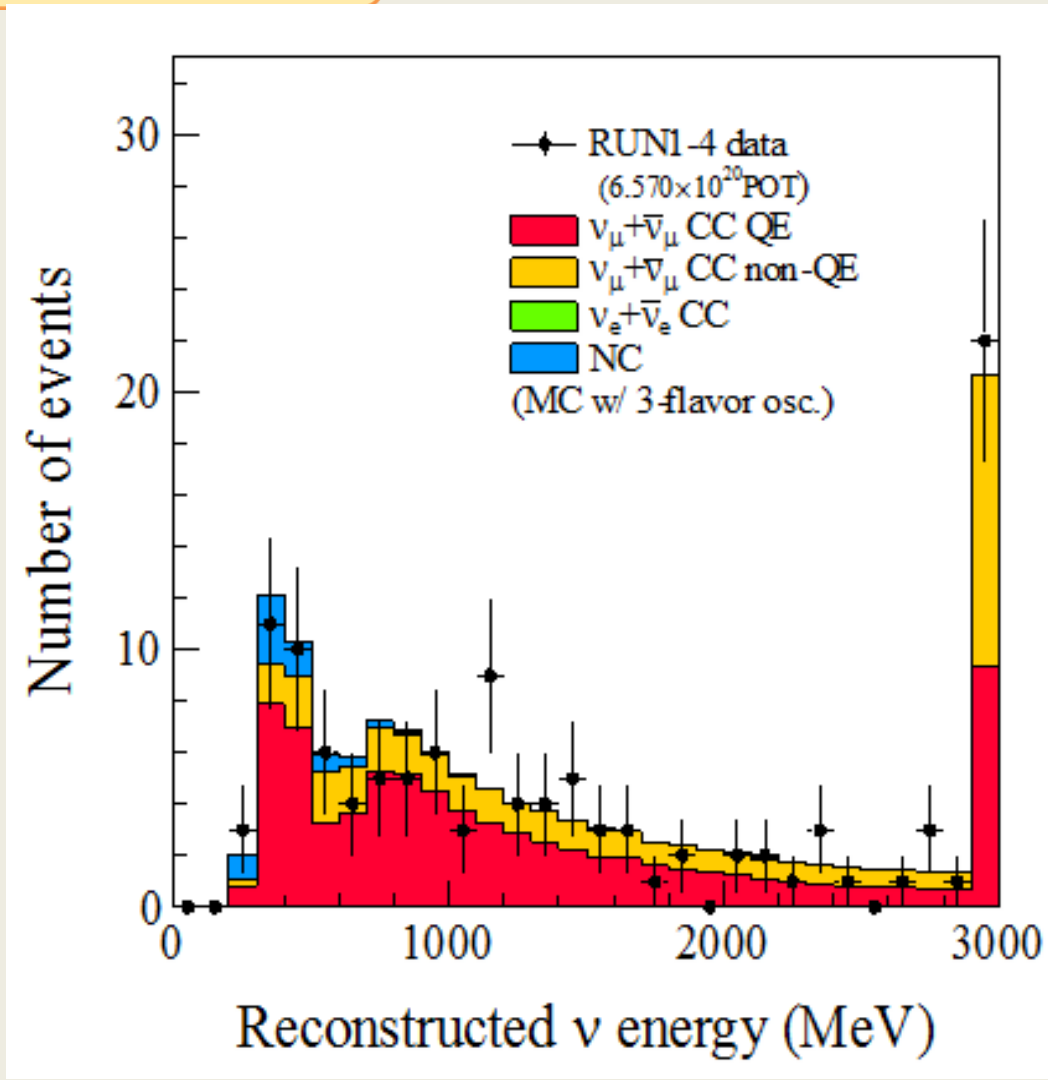
Decay-e ≤ 1

All E_{rec}

120 Events

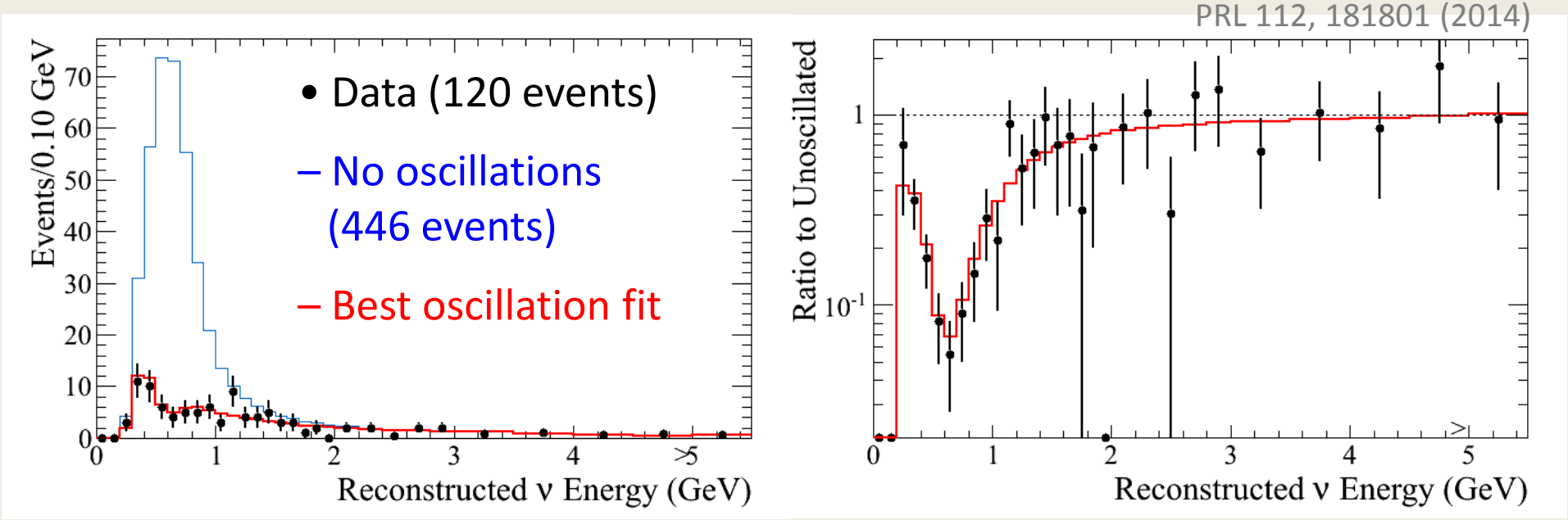
\+

Backgrounds:
CC non-QE
NC $\pi^{\pm}$

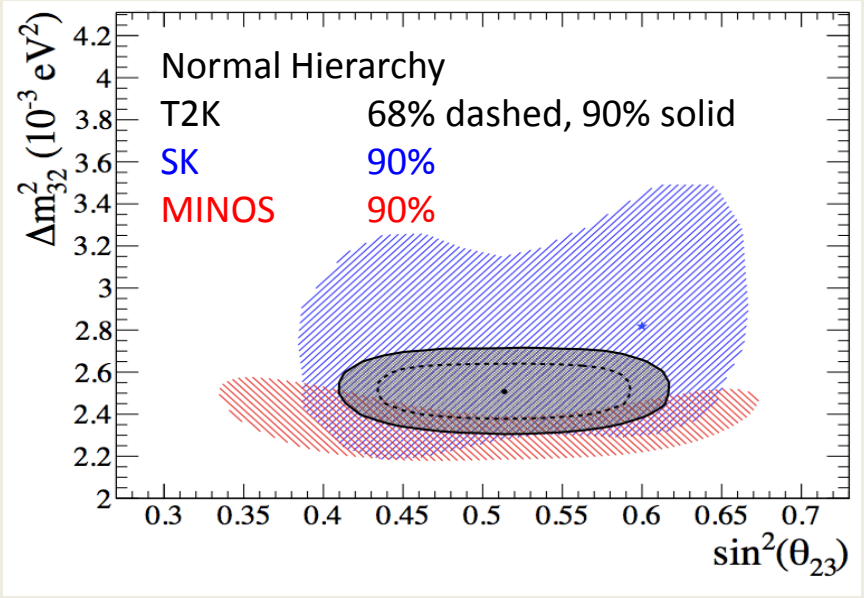


T2K Disappearance Result

PRL 112, 181801 (2014)



(Confidence intervals by Feldman-Cousins method)



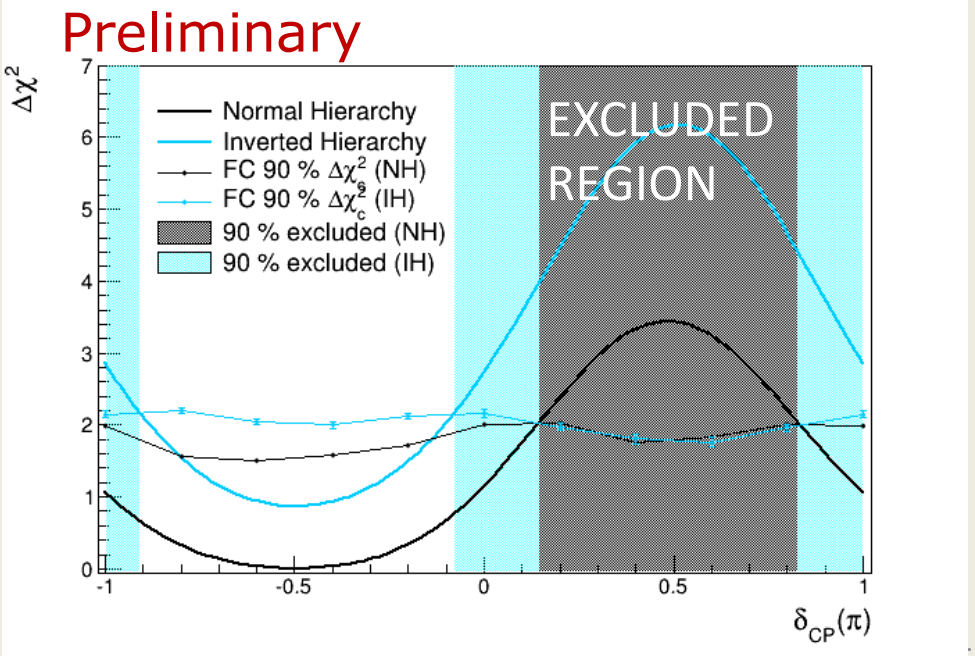
- World leading result:
  $\sin^2(\theta_{23})=0.514 \pm 0.055$
  (=> 3º uncertainty on the angle)
- For the first time, θ_{23} is better constrained by an accelerator experiment and not an atmospheric neutrino result

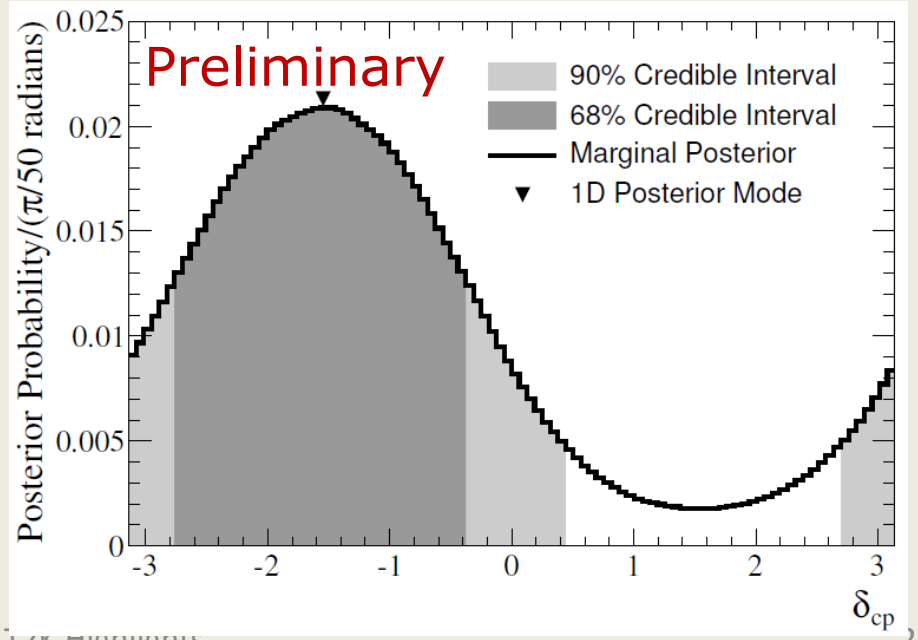
Sensitivity to δ_{CP}

- Correlations between θ_{23}, θ_{13} and δ_{CP} => highest sensitivity from a simultaneous fit to both ν_μ and ν_e spectra.
- Include constraint on θ_{13} from the reactor experiments (Daya Bay, Reno and Double Chooz): $\sin^2(2\theta_{13}) = 0.095 \pm 0.010$ (PDG 2013)
- Weak preference for $\delta_{CP} = -0.5\ \pi$ (would imply maximal CPV!)
- Consistent result seen from both a frequentist and Bayesian approach

❑ Frequentist: Likelihood ratio fit. Confidence intervals evaluated via Feldman-Cousins method

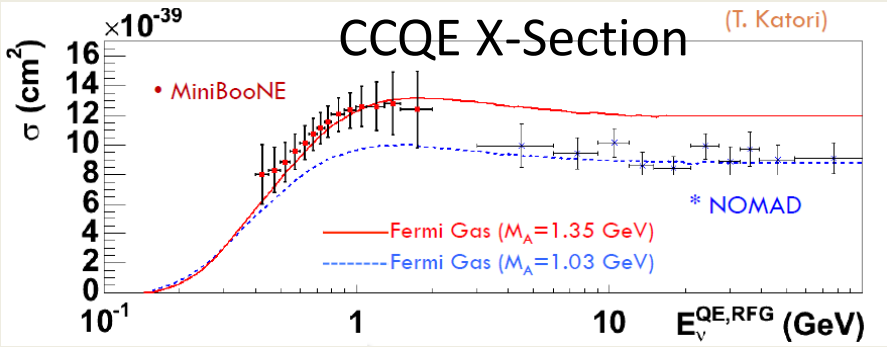
❑ Bayesian: Markov chain MC method. Marginalise over MH

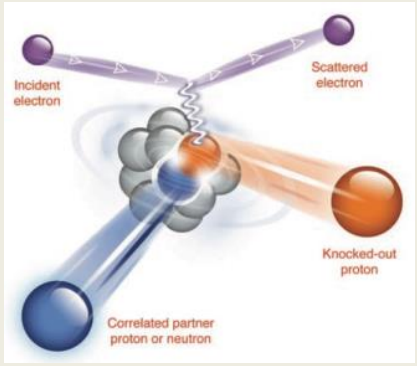


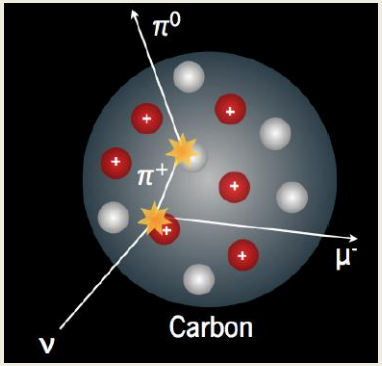


ND280 Analyses

- T2K has active programme of non-oscillation analyses with the ND280
- A primary motivation is to contribute ν cross section measurements: scarce at T2K energies and (nuclear) model effects poorly understood e.g.



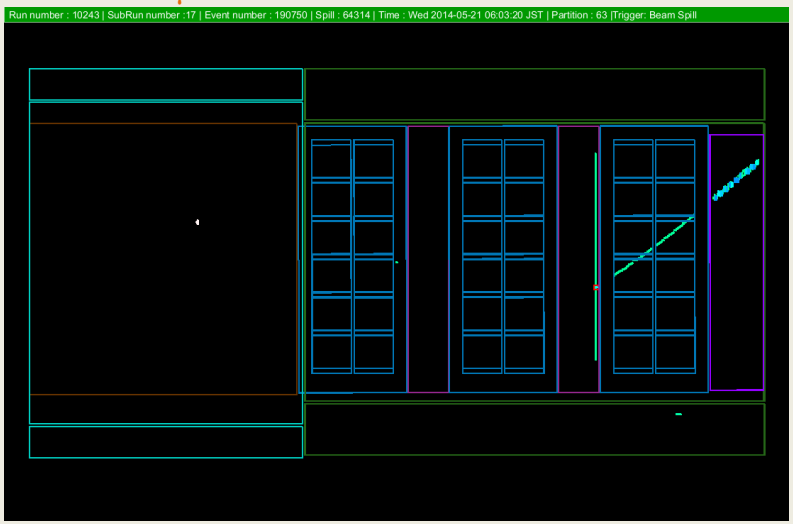




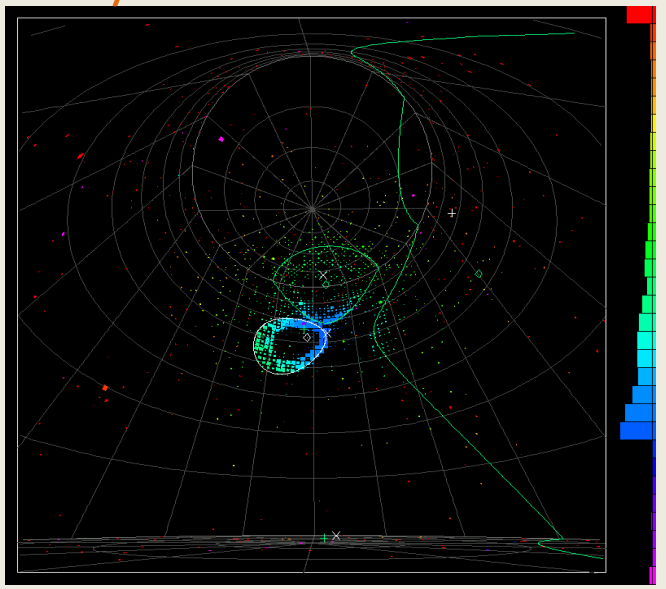
- Recent measurements:
  - ν_μ: inclusive cross section on C (off-axis) (PRD 87, 092003 (2013)) and Fe/CH(on-axis) (accepted for pub. in PRD, arXiv 1407.4256 [hep-ex])
  - ν_e: inclusive cross section (submitted to PRL, arXiv:1407.7389), ν_e beam component (PRD 89, 092004 (2014))
  - ν-O Neutral Current Quasi Elastic cross section in SK via the detection of nuclear de-excitation γ-rays (arXiv 1403.3140 [hep-ex])

Current Run Status

Anti-ν_μ CC candidate at ND280



Fully contained event at SK



- In May T2K successfully completed the first pilot run with anti-neutrinos
- All detectors running well
- Studies suggest best sensitivity to δ_{CP} for ν:anti-ν of 50:50

What Next From T2K?

- Continue to take data towards the approved design target of 7.8×10^{21} POT
- Expect a substantial fraction of the running time assigned to anti-ν running
  - Anti-ν interaction cross sections are down by factor 3-4 cf. neutrinos
- Planned J-PARC accelerator upgrades will speed-up the data taking rate
  - MR beam power: 235 kW (currently) will rise to 750 kW (design) over the next few years
- Combined oscillation results with the reactor experiments and, soon, NOνA also could provide a strong hint regarding one (or more) of:
  - δ_{CP}
  - Mass hierarchy
  - θ_{23} octant
- More valuable non-oscillation results from ND280:
  - Cross section measurements in preparation: CCQE, CC-0π, CC-1π, coherent π production and (in the future) anti-ν
  - Sterile SBL search, non-standard oscillations

In Conclusion

- With the existing data set of 6.57 x 10^{20} POT, T2K has achieved:
  - ν_μ disappearance: world-best precision on θ_{23}
  - ν_e appearance: unique direct measurement with 7.3σ significance
  - first hints of δ_{CP} unfavoured regions
- This has been achieved with only 8% of the design data total
- Important results on cross sections on a variety of nuclear targets now being reported
- Will collect ~12 times more data and continue to combine with results from the reactors and Nova

=> exciting times ahead!

Thanks for your attention

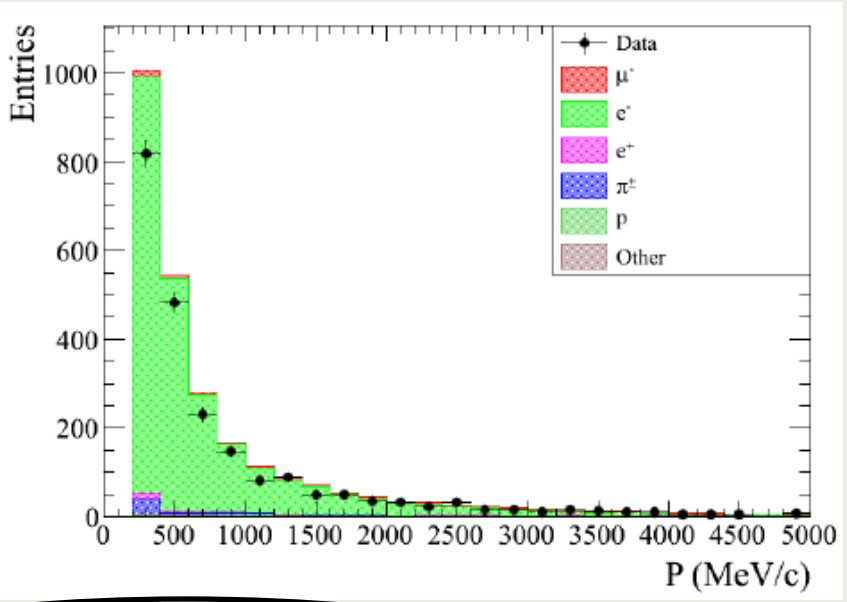
Back-up Slides

ND280 Analyses: ν_e Beam Component

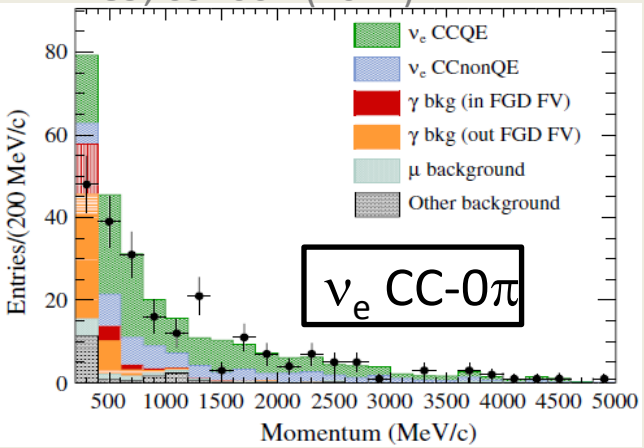
- The ~1% ν_e component of the ν_μ beam dominates the ν_e appearance uncertainties => is vital to measure precisely
- TPC and ECAL PID capability applied to reject muons in favour of electrons: final sample is 92% electrons (26% from the ν_e beam component)
- Data/MC ratio from simultaneous likelihood fit to topological samples: CCQE + non-QE (+ γ conversion background):

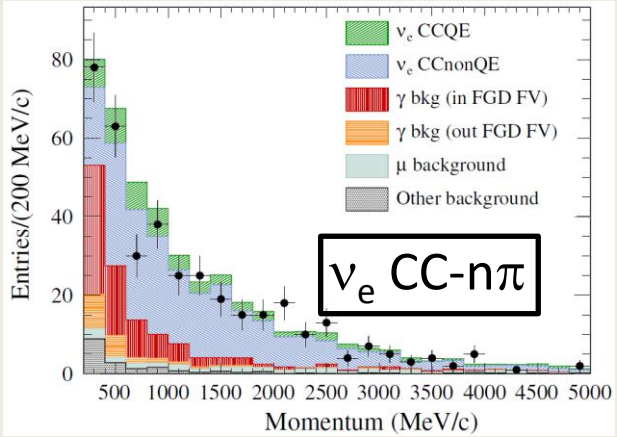
$R(\nu_e) = 1.01 \pm 0.06(stat) \pm 0.08(syst)$

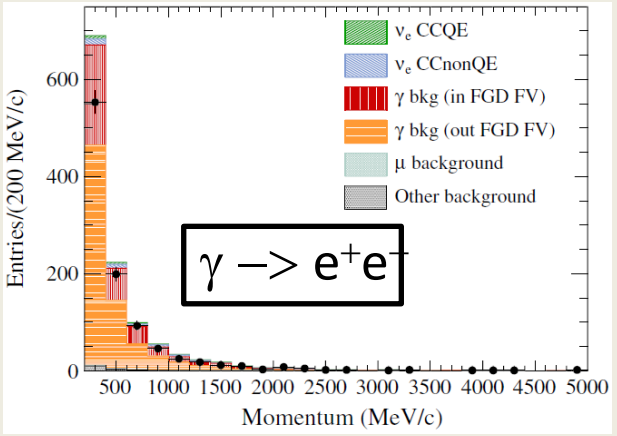
validation of T2K's simulation used in oscillation results



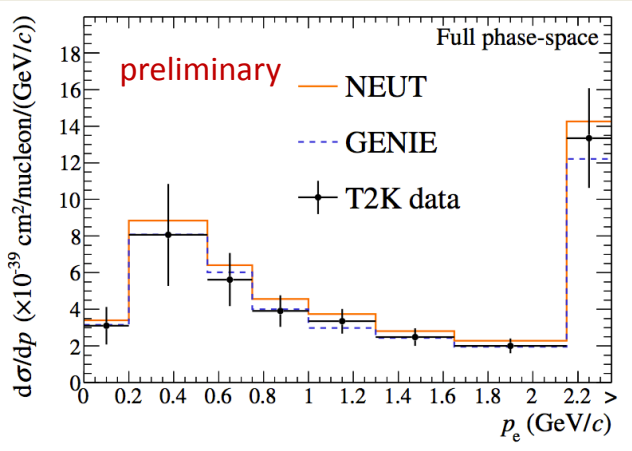
PRD 89, 092004 (2014)

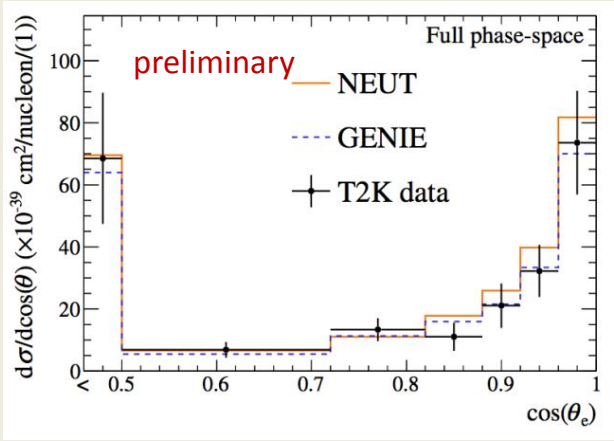


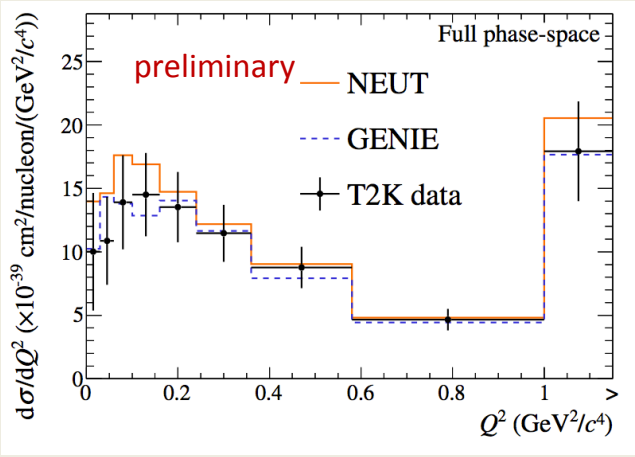




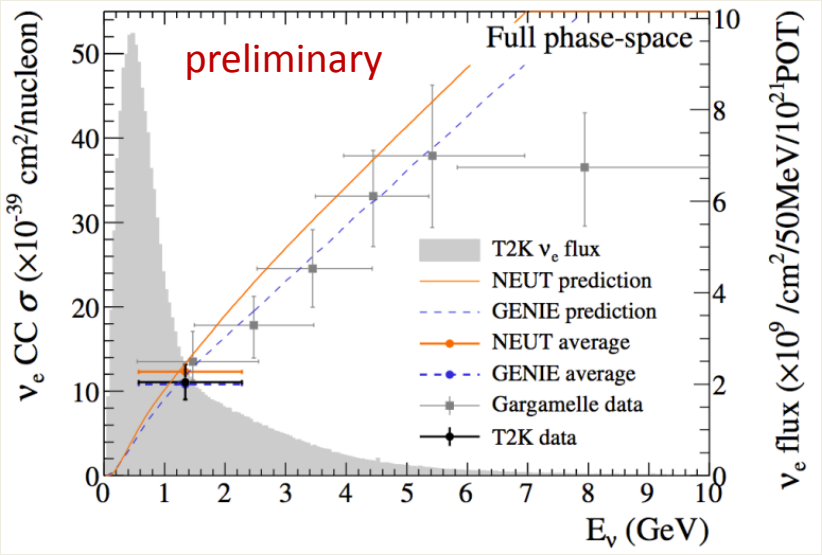
ND280 Analyses: CC Inclusive ν_e X-Section







- Differential and flux-averaged results:
  Φ_e^{tot}=1.11 ± 0.2 x10 $^{-38}$ cm^2/nucleon
- First ν_e x-section measurement at GeV scale since Gargamelle results in 1978!
- Good agreement with Gargamelle and with different generators within current statistics
- More precision results needed for future ν_e appearance experiments and to establish ν_e/ν_μ differences



Submitted to PRL, arXiv:1407.7389

T2K Collaboration

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U. Geneva
ETH Zurich

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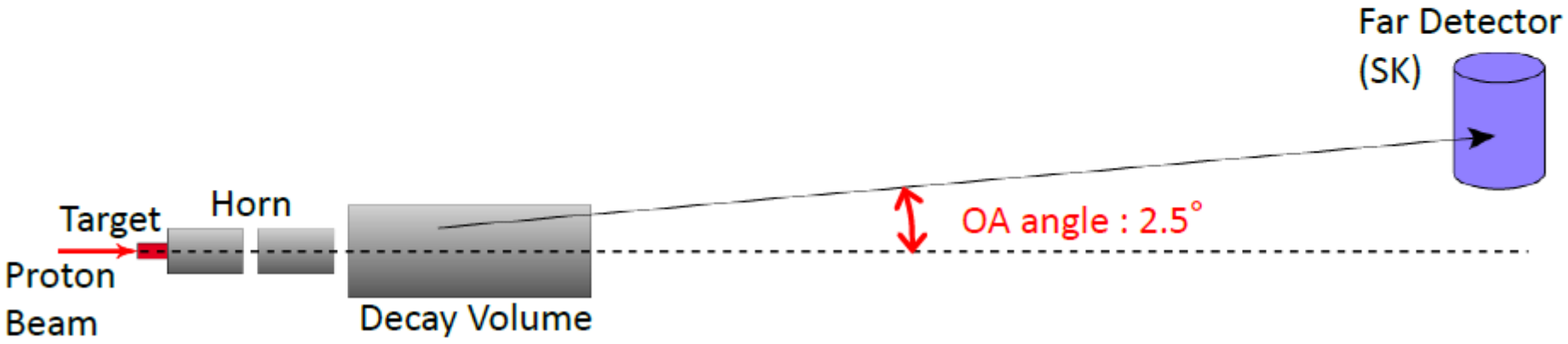
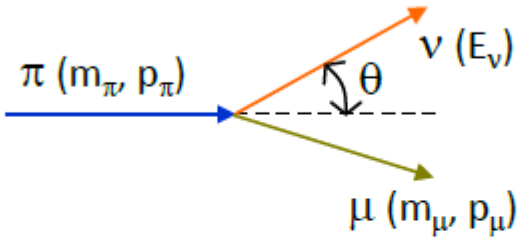
Oxford U.
Sheffield U.
STFC/Daresbury
STFC/RAL
Warwick U.

USA
Boston U.
Colorado S.U.
Duke U.
Louisiana S.U.
Stony Brook U.
U.C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

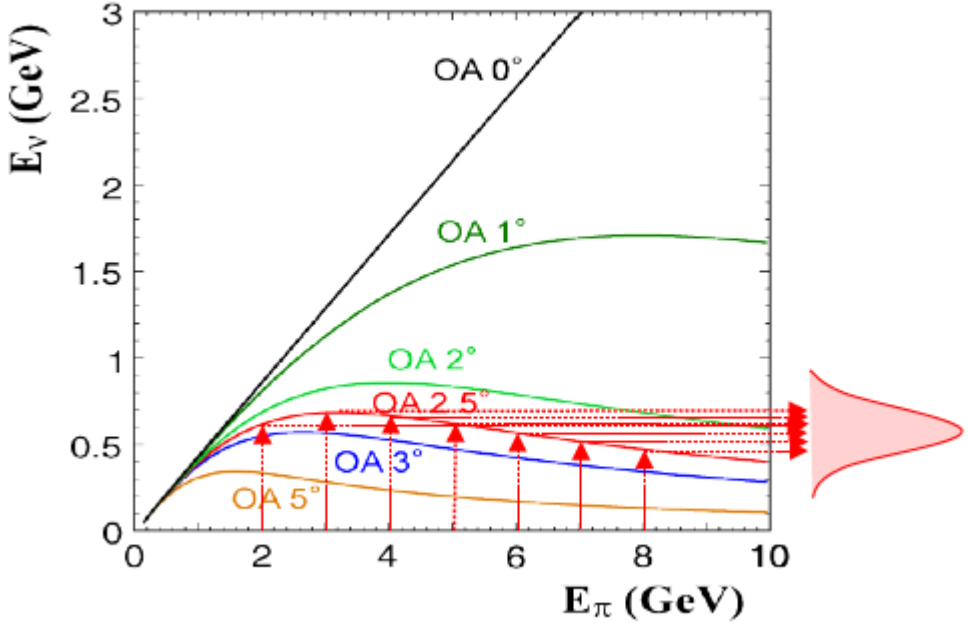
~500 members from 11 countries

Off-axis Beam





$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$



ν Beam Stability