er : 27404 | Run number : 8115 | Spill : 51004 | Time : Mon 2012-01-23 06:04:28 JST |Trigger

Neutrino Frontier Workshop 2016

平成28年 11月 29日

Status of T2K and Neutrino Interaction Measurements

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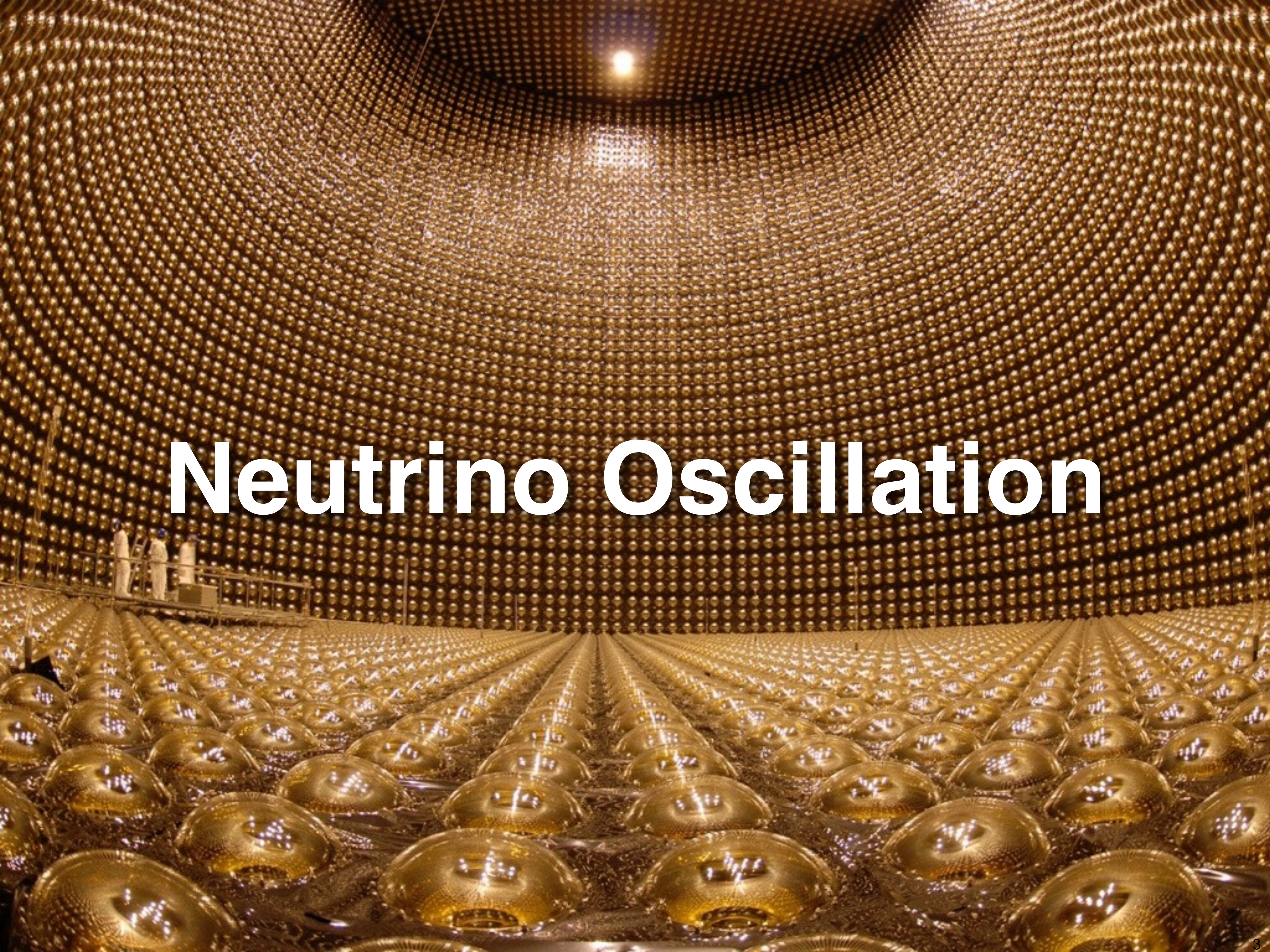
Imperial College London & KEK

Outline

- Introduction
    - Neutrino oscillation & CPV
    - Key issues for modelling neutrino interactions
- T2K experiment
- T2K neutrino interaction model
- T2K neutrino Interaction measurements
- Conclusion

Neutrino Oscillation

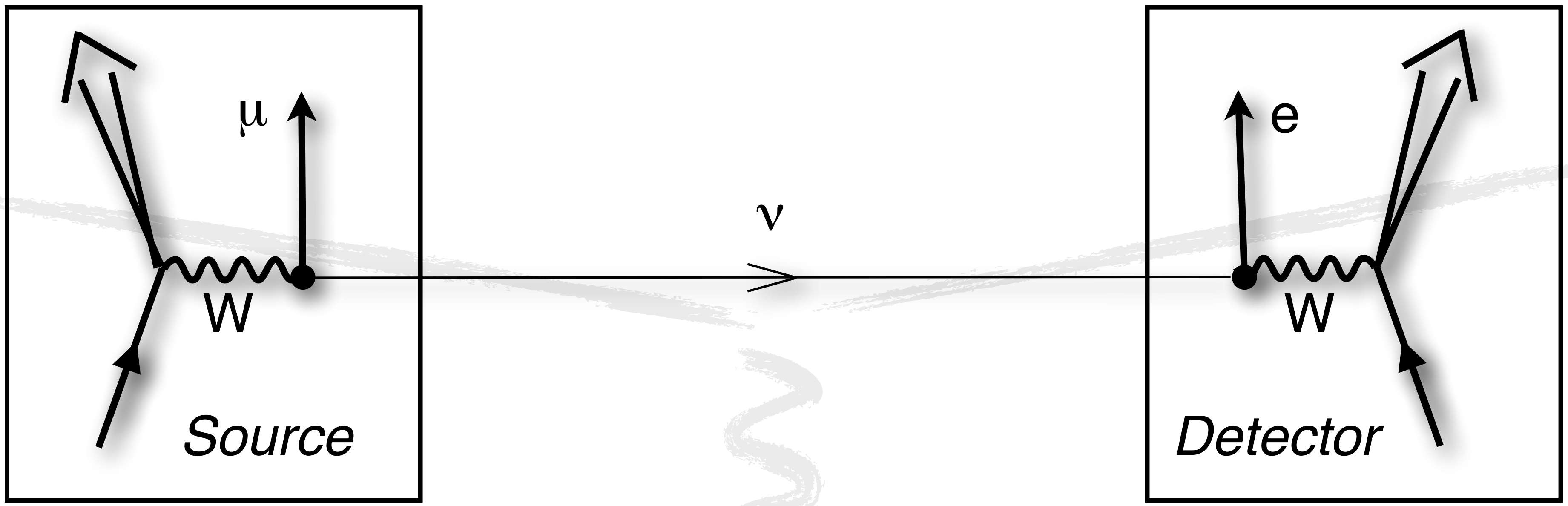


Neutrino oscillation

Pontecorvo

Sov.Phys.JETP 6:429,1957

Sov.Phys.JETP 26:984-988,1968

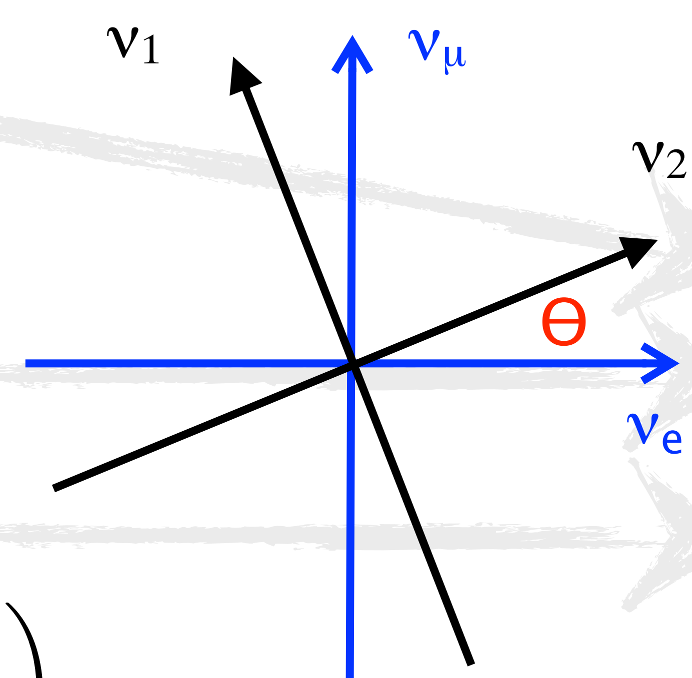


Maki, Nakagawa, Sakata

Prog.Theor.Phys. 28, 870 (1962)

Simple 2 neutrino example-
if weak eigenstates (ν_e, ν_μ) differ from mass eigenstates (ν_1, ν_2):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

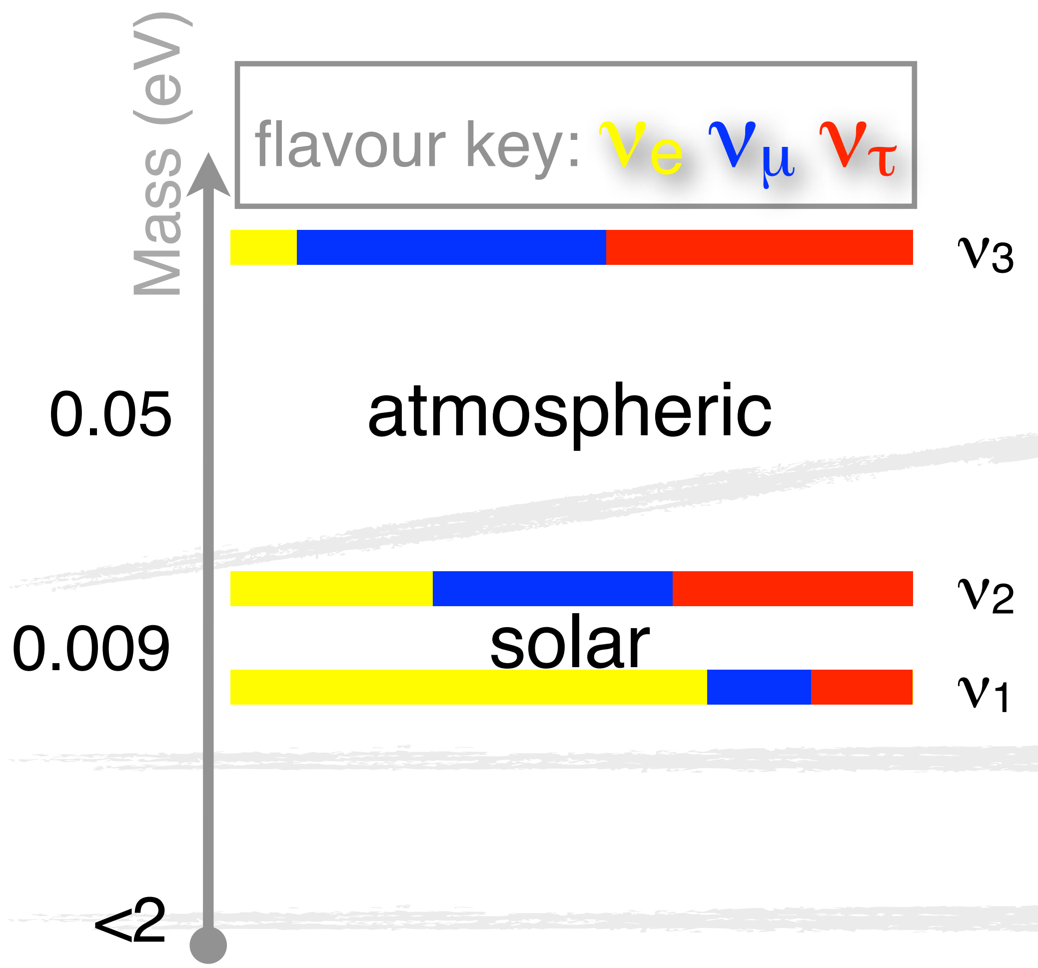


$$P_{oscillation}(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2\left(\frac{1.27\,\Delta m^2(eV^2)\,L(km)}{E_\nu(GeV)}\right)$$

Current neutrino picture

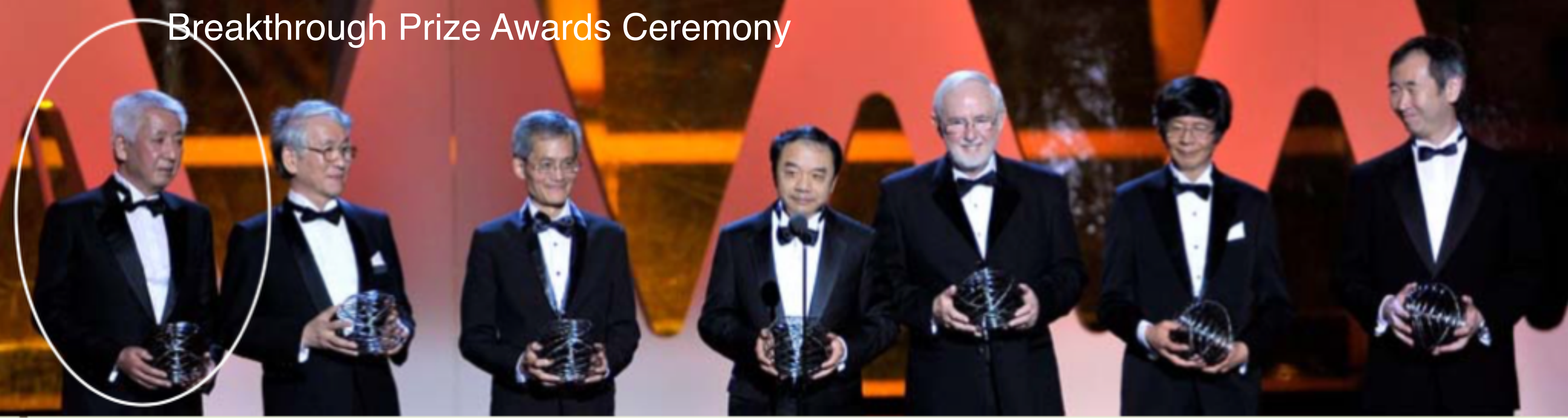
flavour — *atmospheric* — *accelerator* — *solar* — *Majorana* — mass

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0\\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



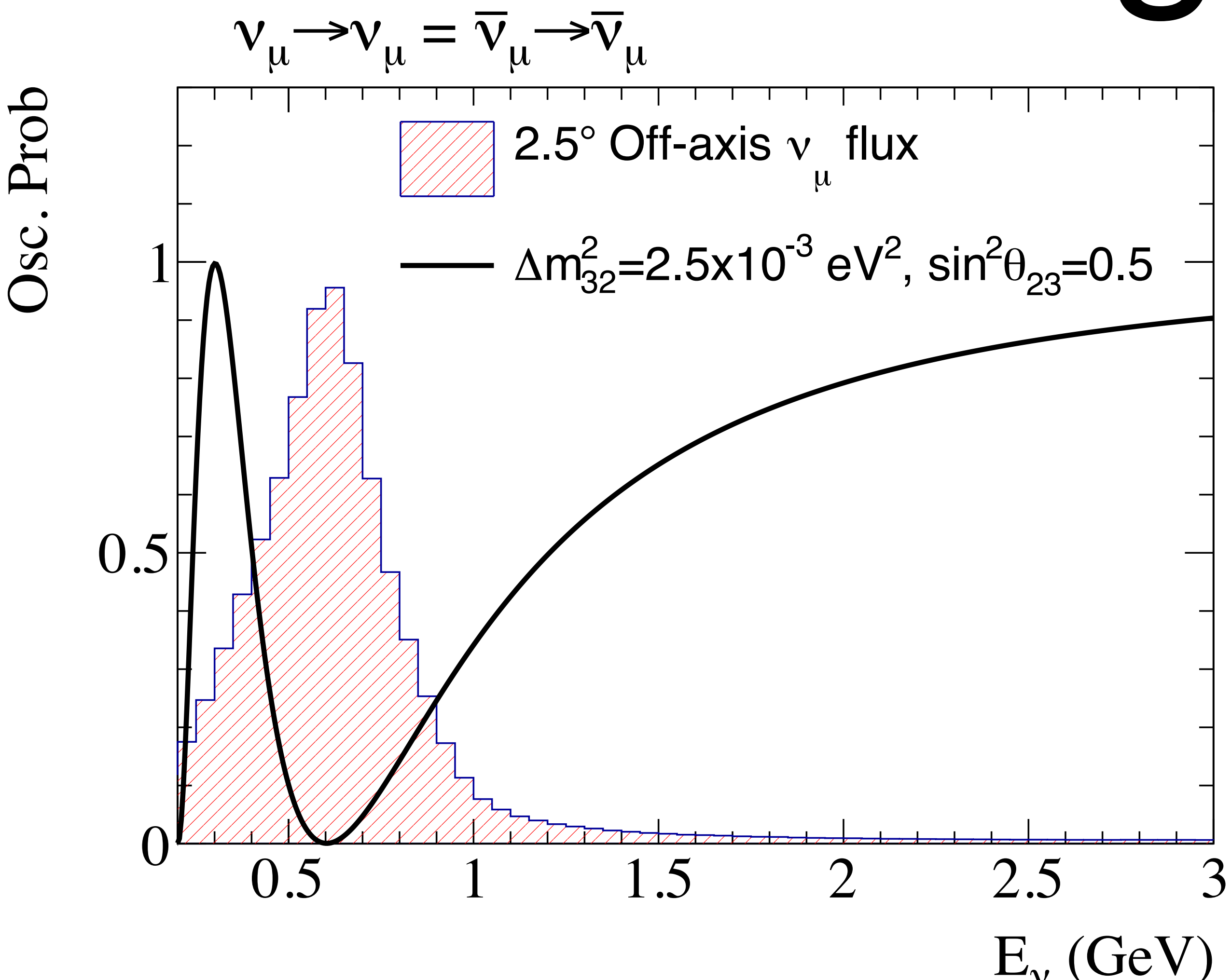
	VALUE
$\|\Delta m^2_{32}\|$	2.35±0.12 E-03 (eV^2)
Δm^2_{21}	7.58±0.24 E-05 (eV^2)
$\sin^2\theta_{12}$	0.31±0.018
$\sin^2\theta_{23}$	0.42±0.08
$\sin^2\theta_{13}$	0.02±0.007
$\boldsymbol{\delta_{CP}}$	$3\pi/2$?

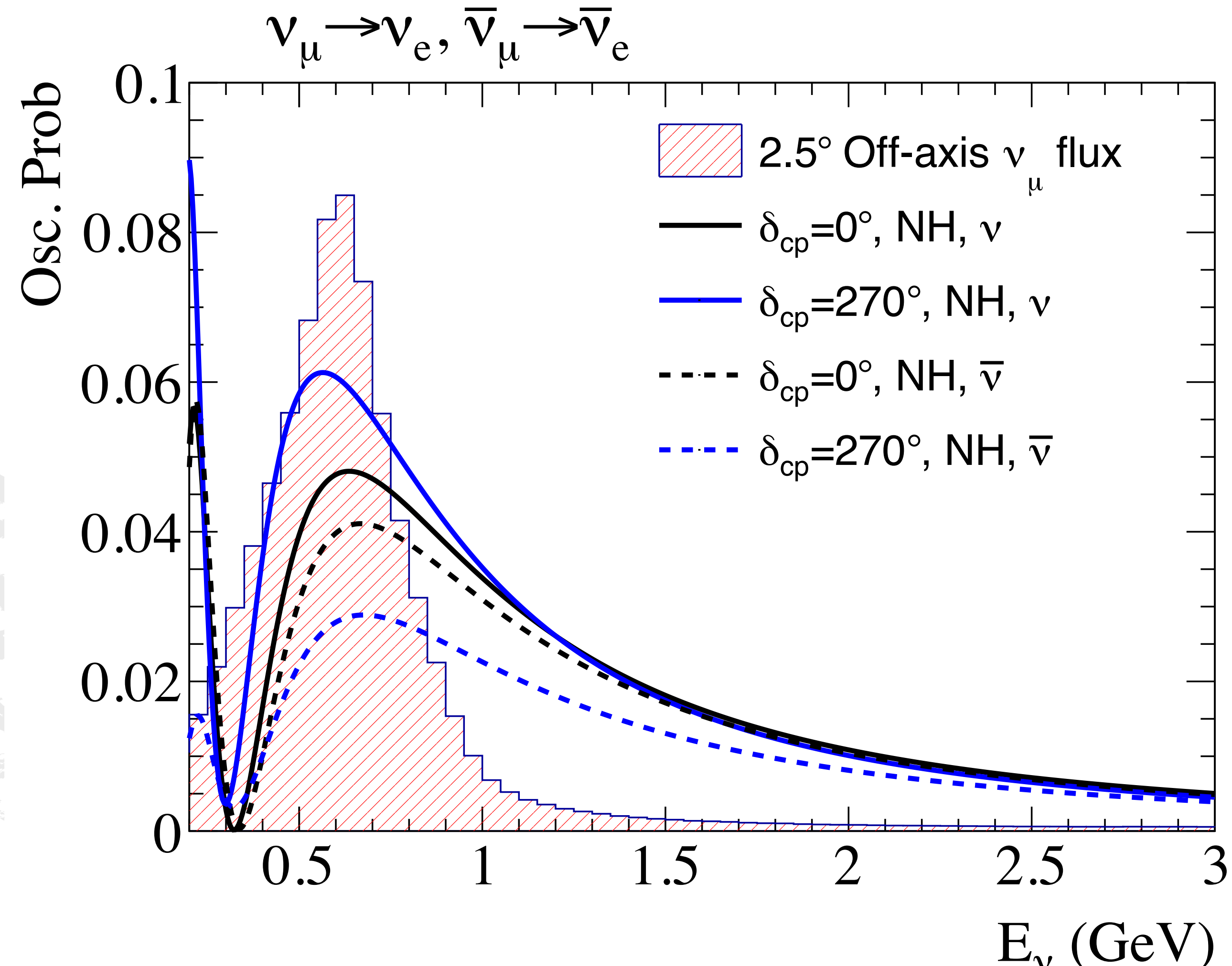
Accelerator experiments measure: Δm^2_{32} (including sign), $\sin^2\theta_{23}$, $\sin^2\theta_{23}$ & $\boldsymbol{\delta_{CP}}$



T2K founding spokesperson Ko Nishikawa and all T2K collaboration members won the 2016 Breakthrough Prize for fundamental physics!

Measuring CPV in T2K

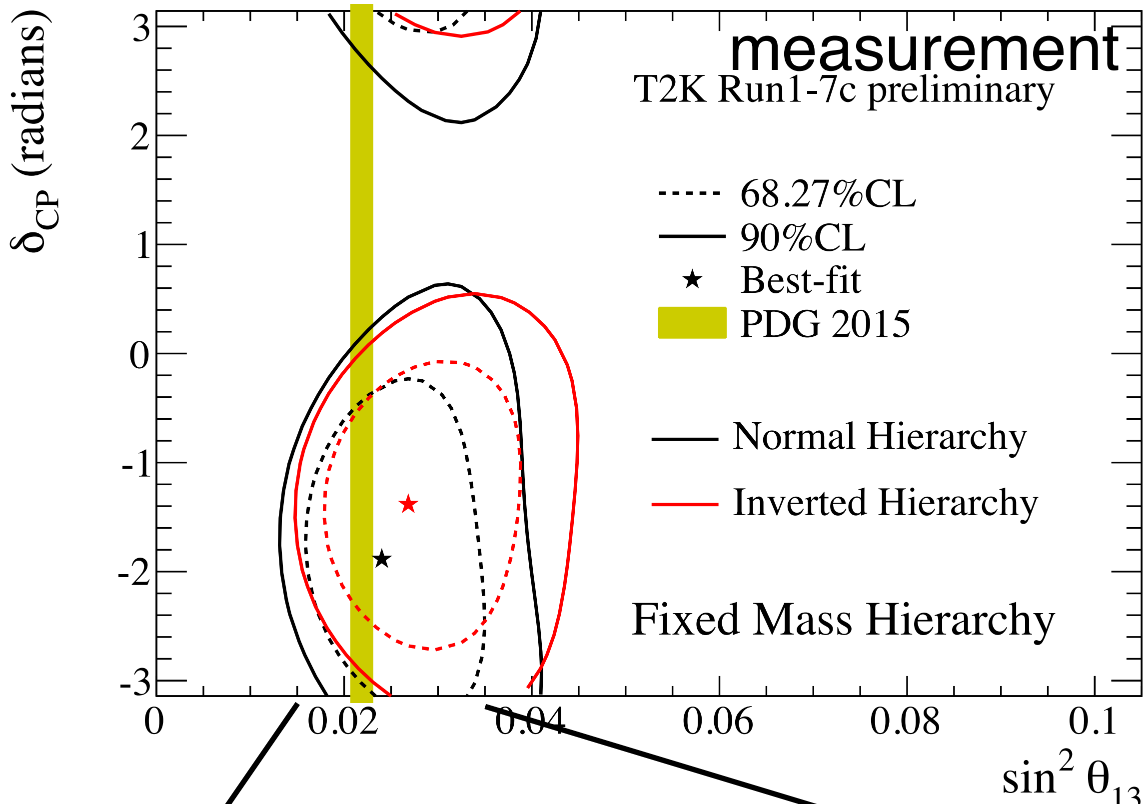




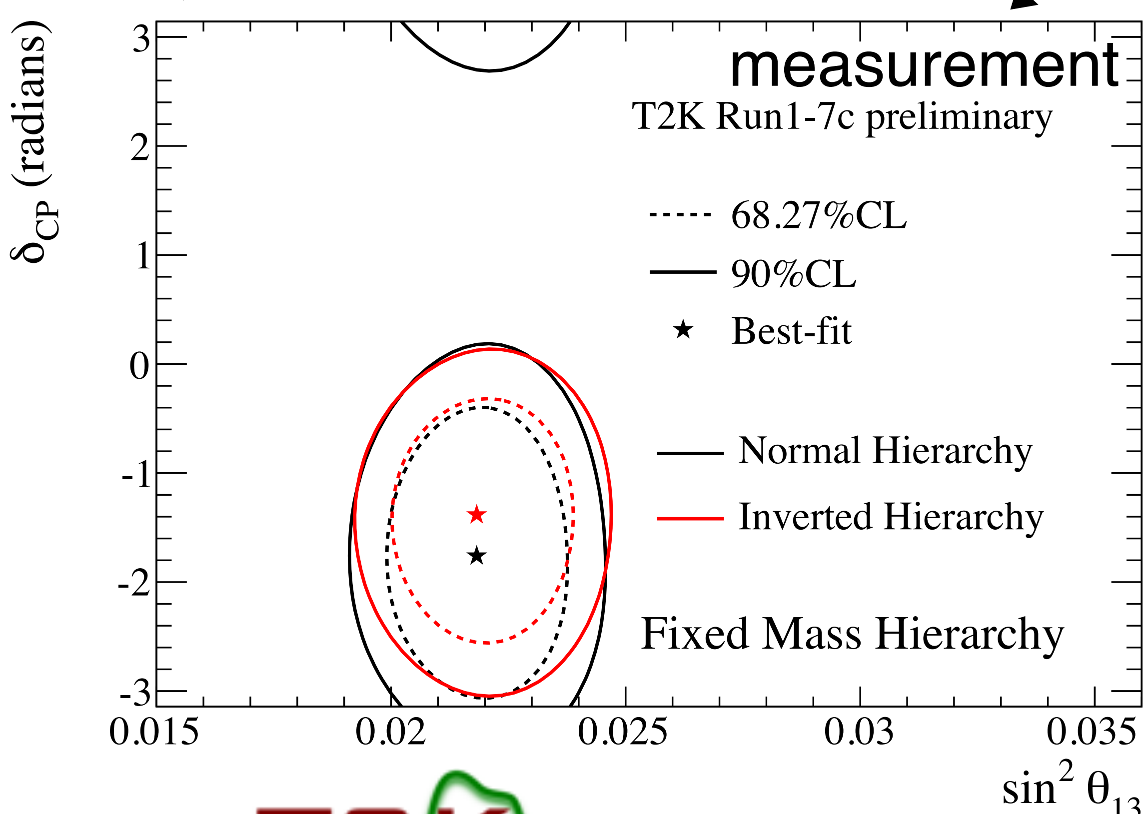
- Tests CPT symmetry
- Leading order dependence on $\sin^2 2\theta_{23}$
  - Can't separate θ_{23}>45° from θ_{23}<45°
- Leading order dependence on $|\Delta m^2_{32}|$
  - Doesn't depend on the sign of the mass splitting (hierarchy)

- Tests CP symmetry
- Leading order dependence on $\sin^2 2\theta_{13}$
- Leading order dependence on $\sin^2\theta_{23}$
  - Can separate θ_{23}>45° from θ_{23}<45°
- Sub-leading dependence on $\sin(\delta_{cp})$
  - Can detect CP violation
- Sub-leading dependence on Δm^2_{32} through matter effect
  - Relatively small in T2K due to baseline

Data T2K 2016: δ_{CP} vs. θ_{13}

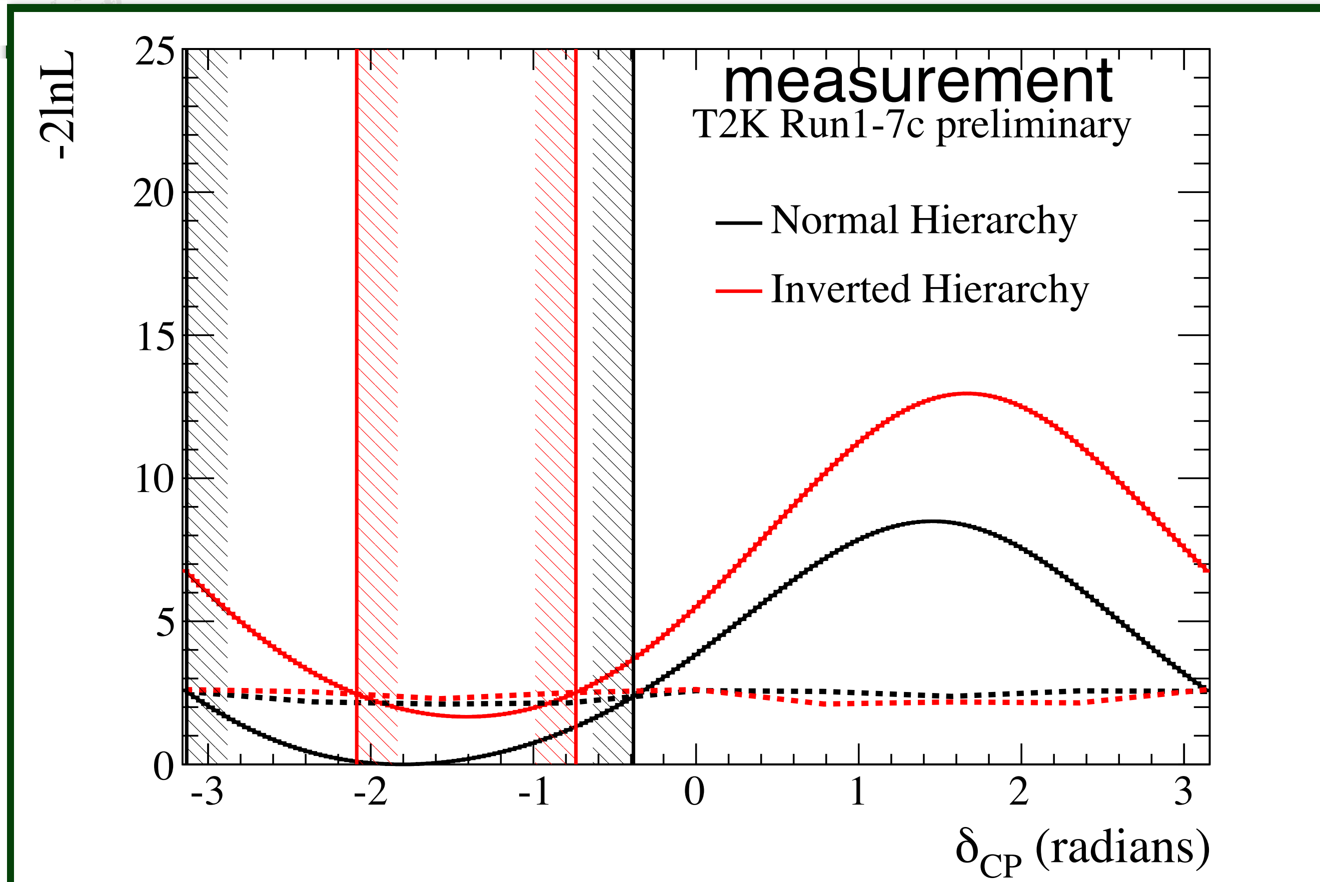


note change in horizontal scale



- Left: δ_{CP} vs. θ_{13} (fixed $\Delta\chi^2$, fixed hierarchy)
  - T2K-only
  - T2K with reactor $\sin^2 2\theta_{13}$= 0.085±0.005
- Below: δ_{CP} with Feldman-Cousins critical values and reactor θ_{13}

δ_{CP} = [-3.13, -0.39] (NH), [-2.09, -0.74] (IH)@90% CL

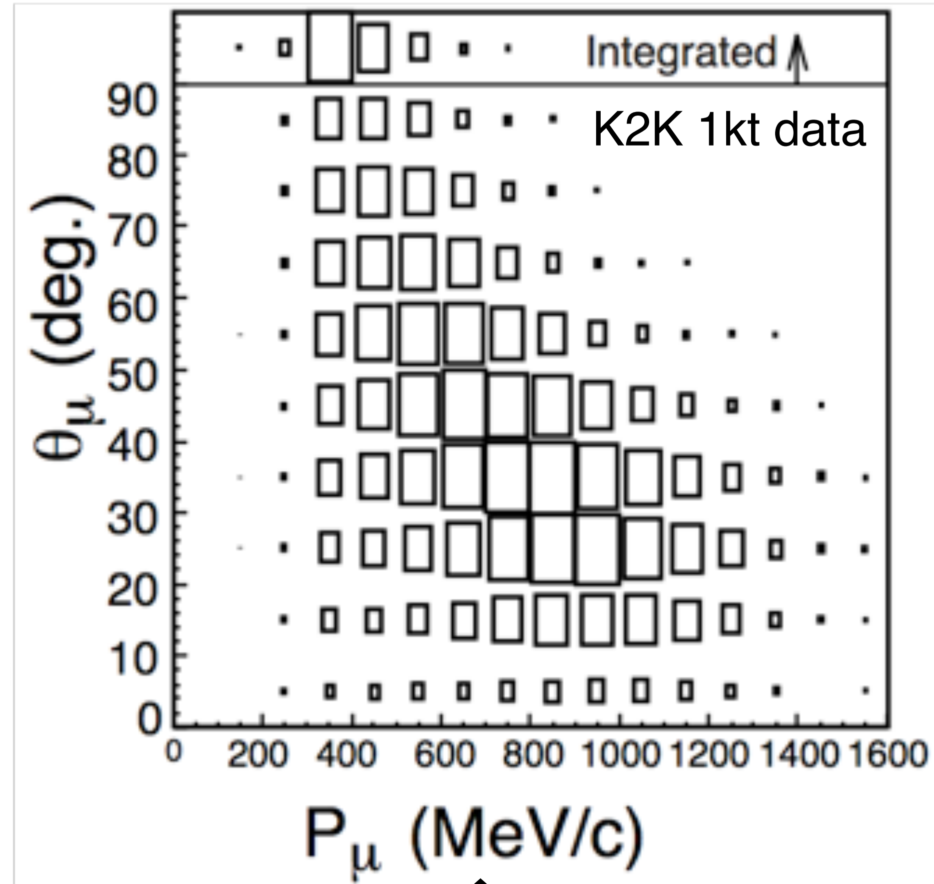


Xsecs: what do we need?

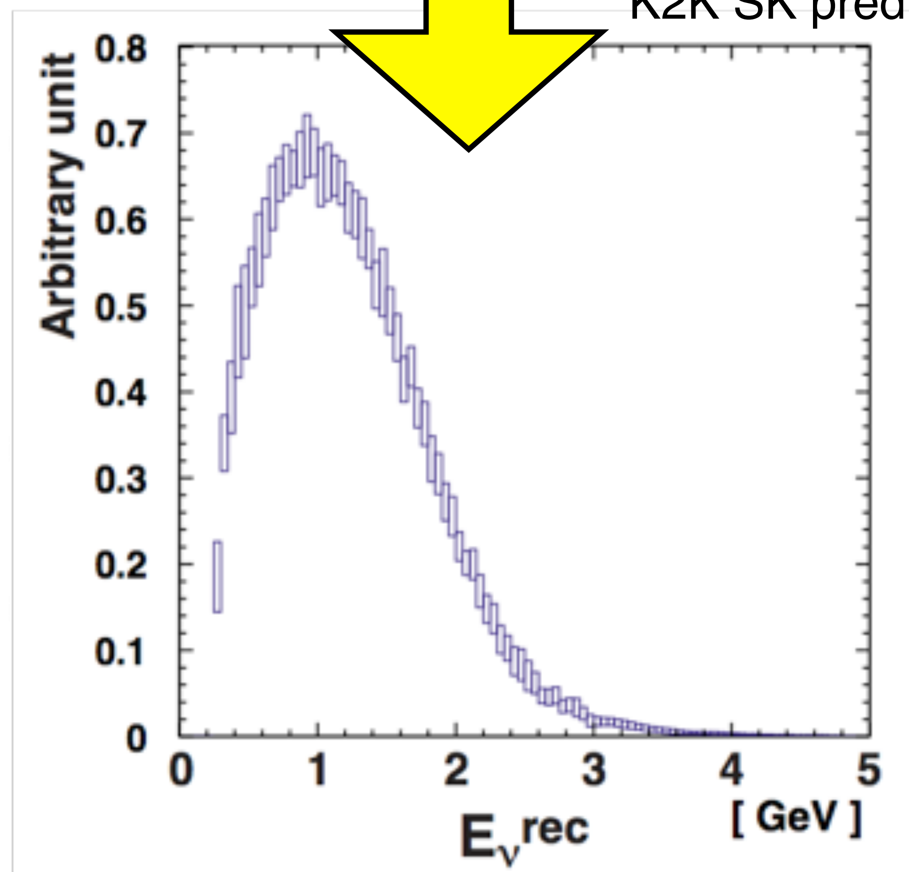
- Need to predict event rates and kinematics of final state particles
- Need to accurately calculate inferred (physics) variables from our observed variables
    - For oscillations, need to reconstruct neutrino energy
        - different ways to do this
            - *All methods need good models*
        - all beams are relatively wideband
- Need to accurately predict background contamination

➡Need to understand neutrino-nucleus cross-sections precisely

➡Need good models, tuned with good data!



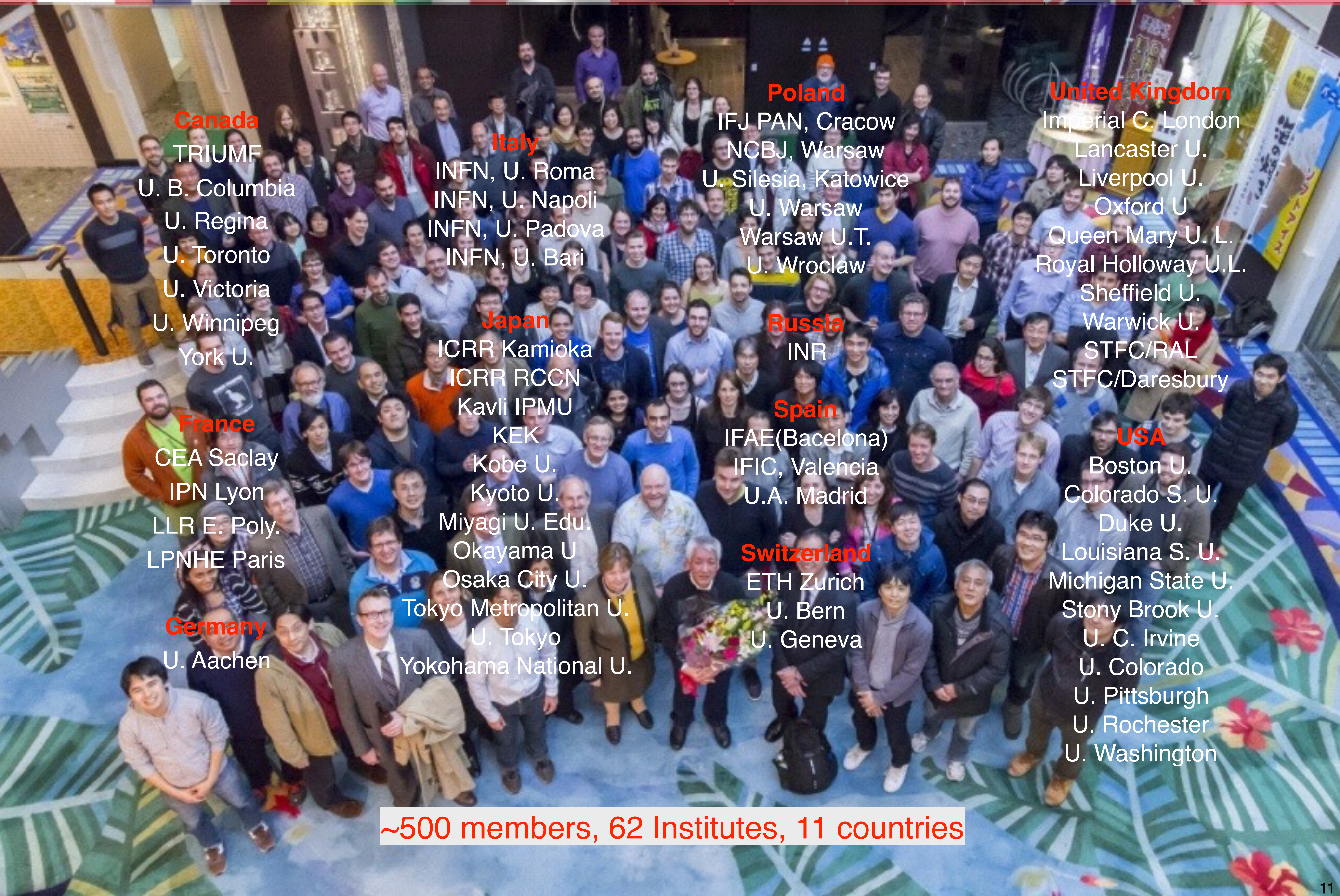
K2K SK prediction



[Phys.Rev.D **74** 072003 (2006)]

T2K Experiment

The T2K Collaboration



Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
U. Aachen

Italy
INFN, U. Roma
INFN, U. Napoli
INFN, U. Padova
INFN, U. Bari

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U
Osaka City U.
Tokyo Metropolitan U.
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Poland
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NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
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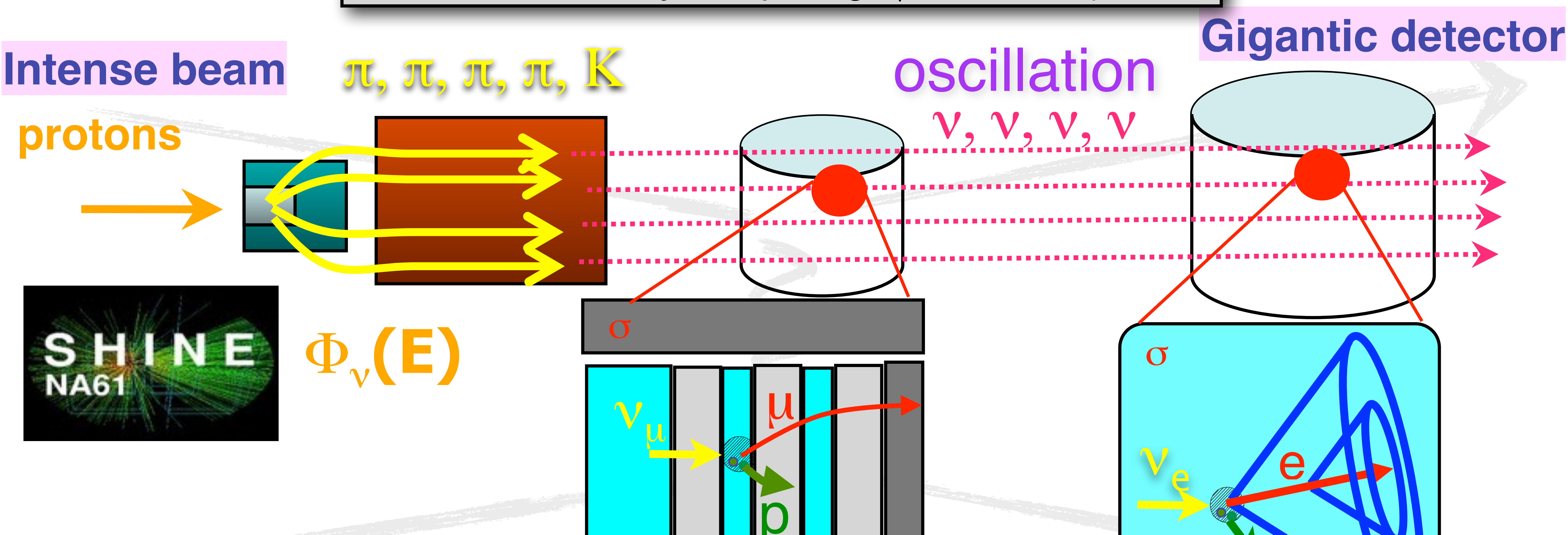
Royal Holloway U.L.
Sheffield U.
Warwick U.
STFC/RAL
STFC/Daresbury

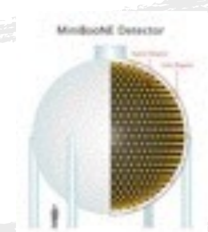
USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Michigan State U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

~500 members, 62 Institutes, 11 countries

T2K strategy

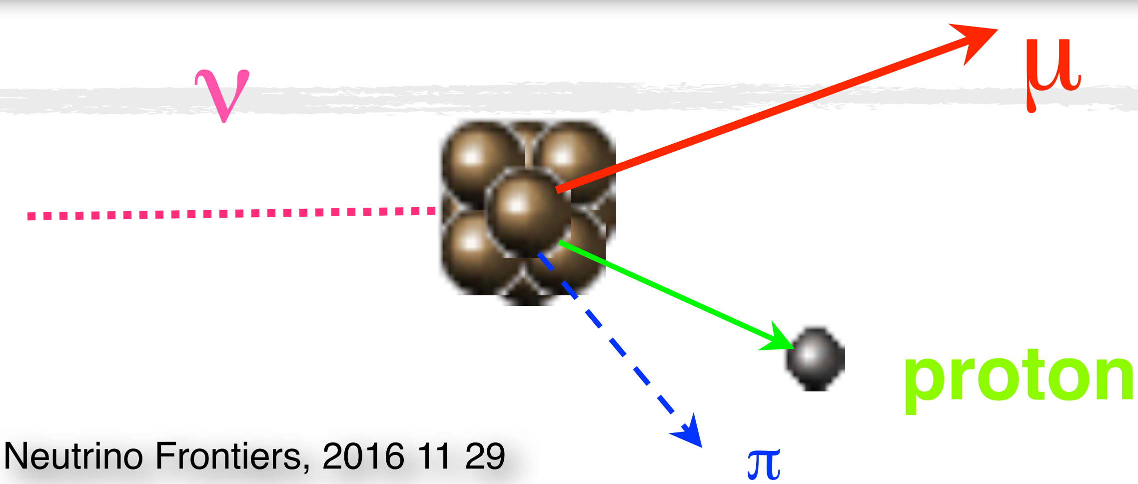
Search for δ_{CP} by comparing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.



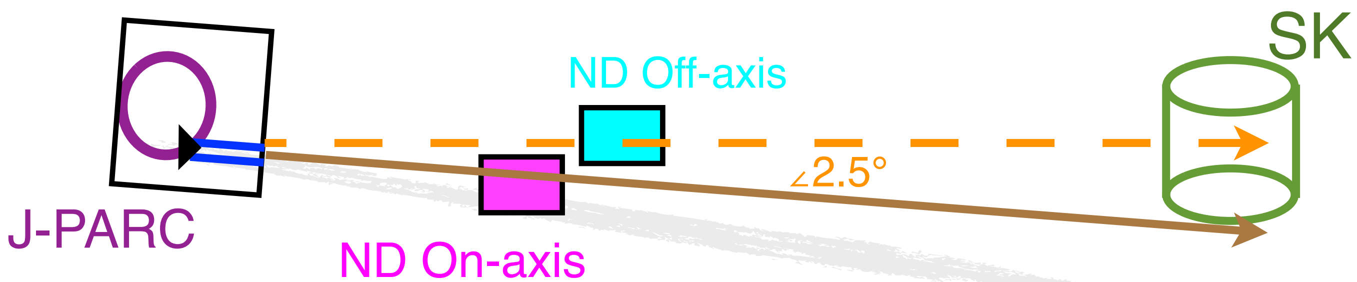


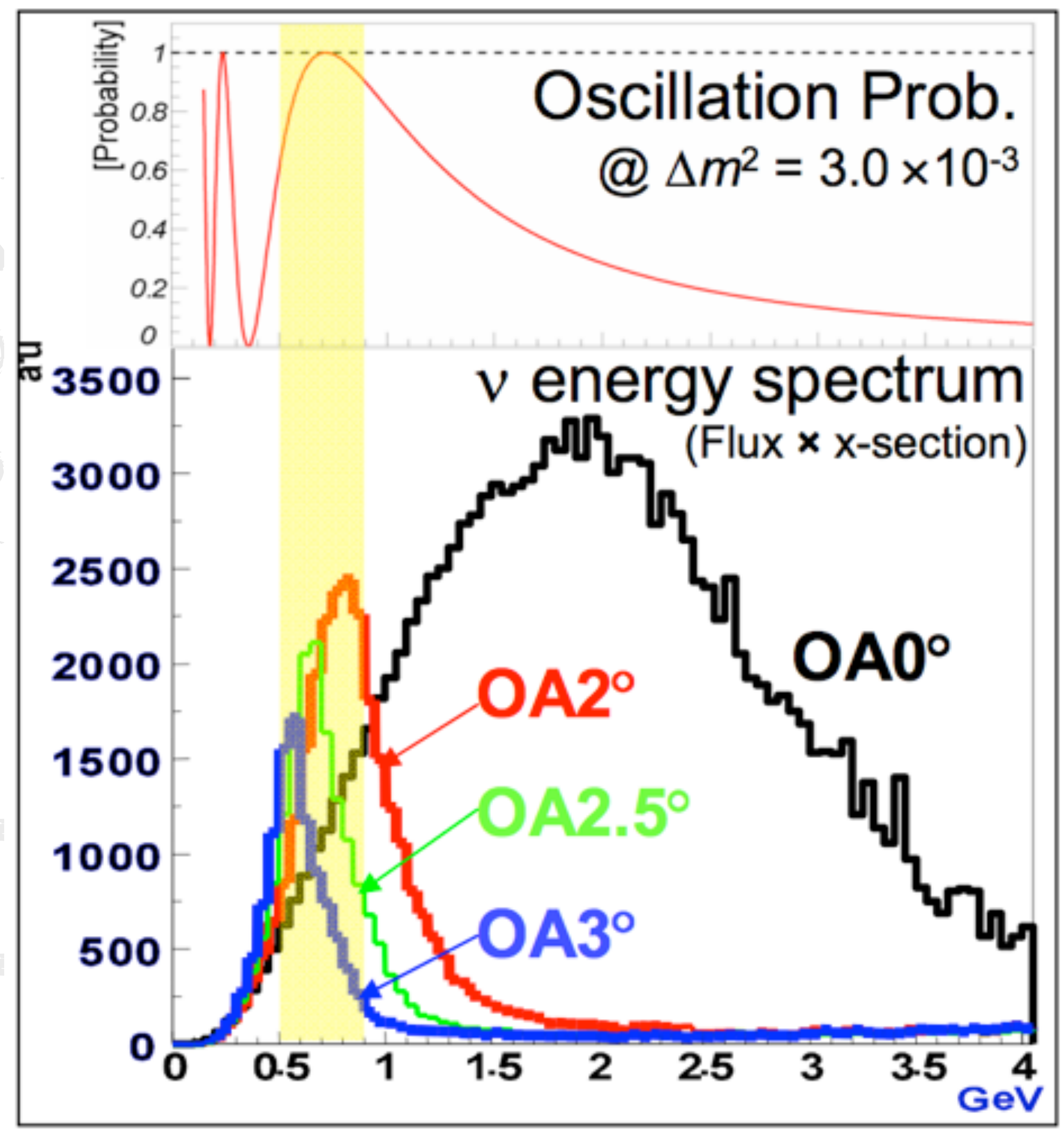
$$\Phi_{\nu near}(E)\cdot\sigma_{near}(E,Q^2)\cdot\varepsilon_{near}(E) \Leftrightarrow \Phi_{\nu far}(E,\theta,\Delta m^2,\delta)\cdot\sigma_{far}(E,Q^2)\cdot\varepsilon_{far}(E)$$

SciBooNE

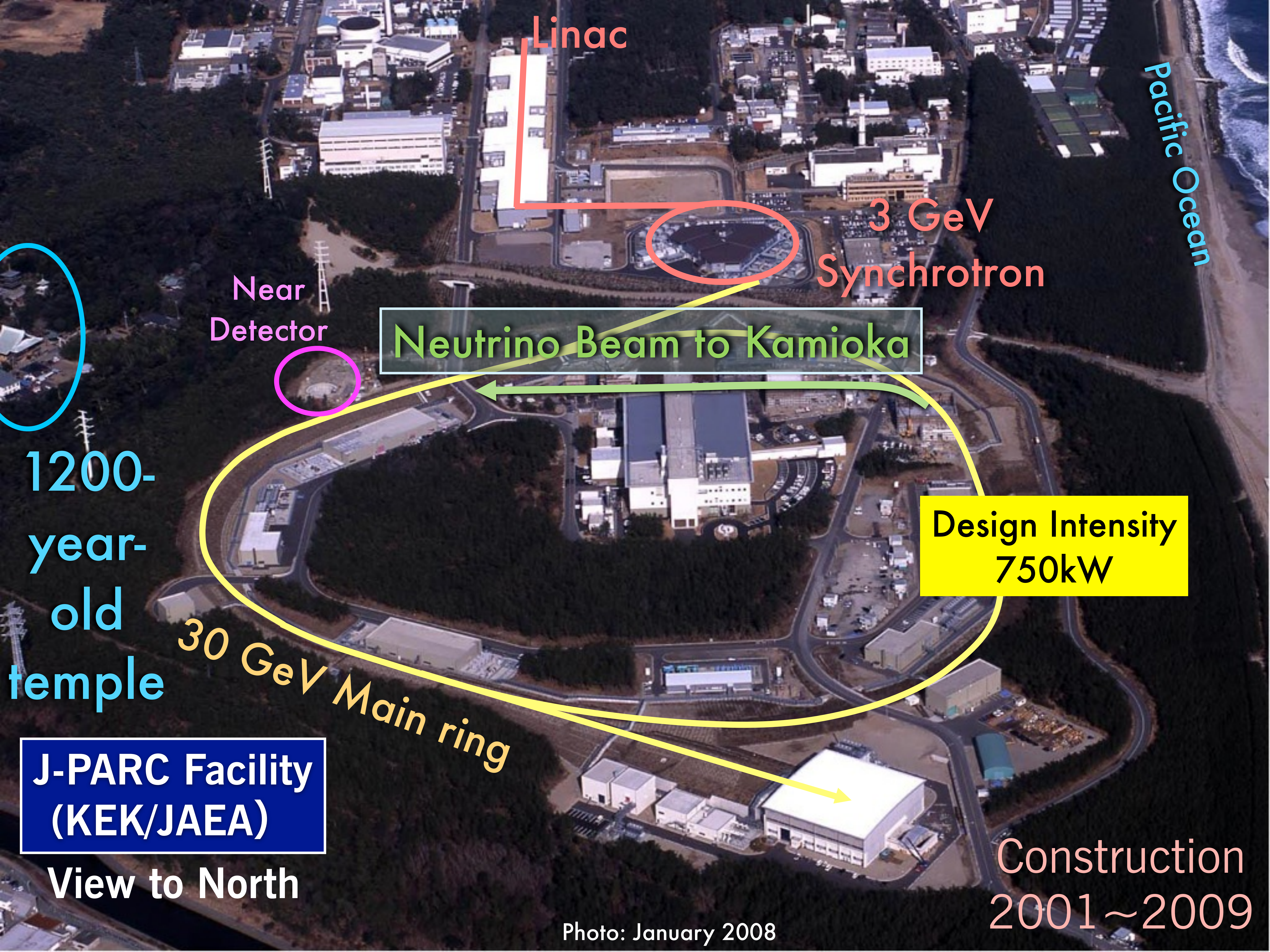


Off-Axis Beam



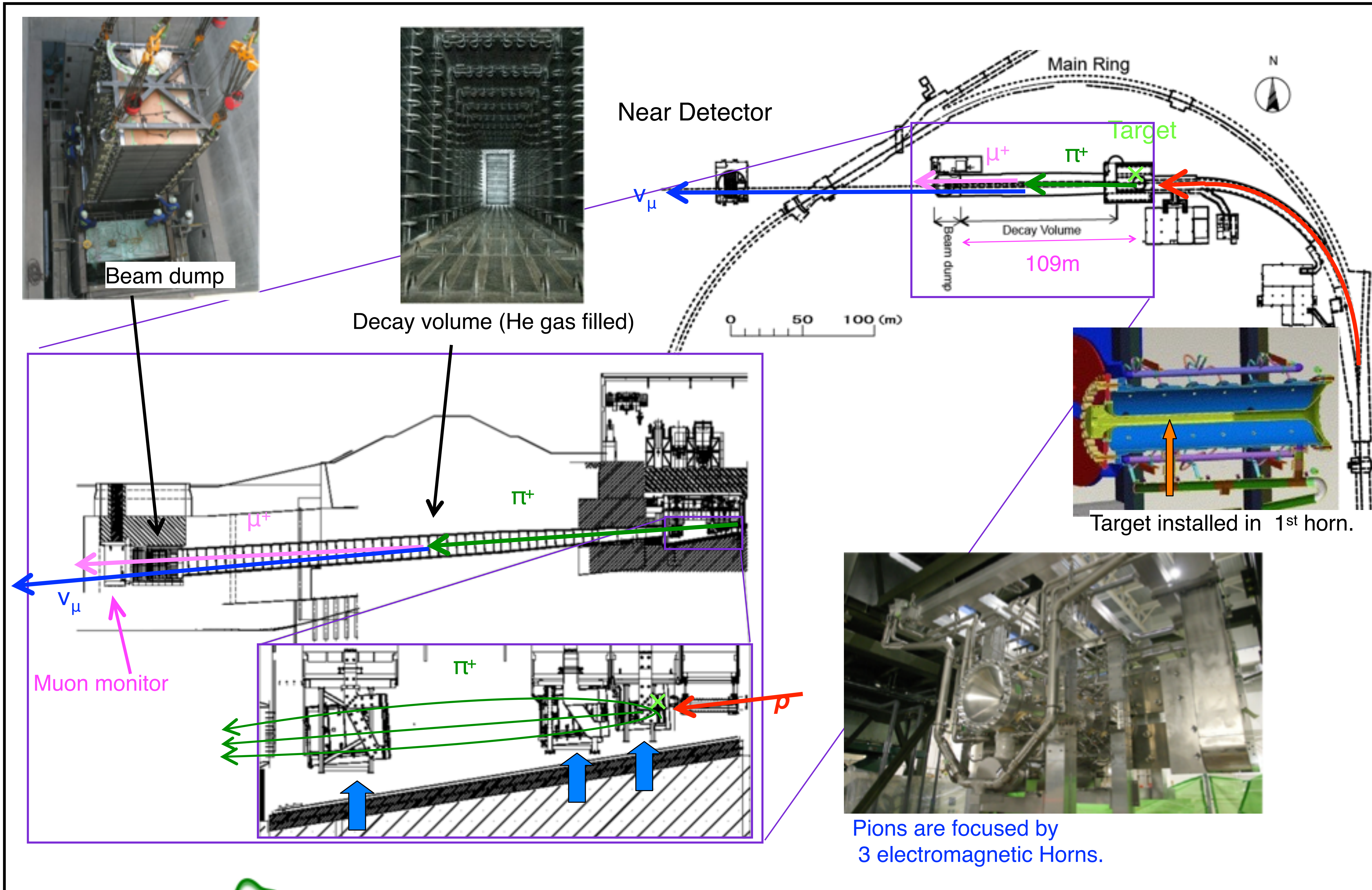


- Use kinematics of pion decay to tune the neutrino energy
- Flux peak at target energy for desired value of L/E
  - Eν well matched to Super-K

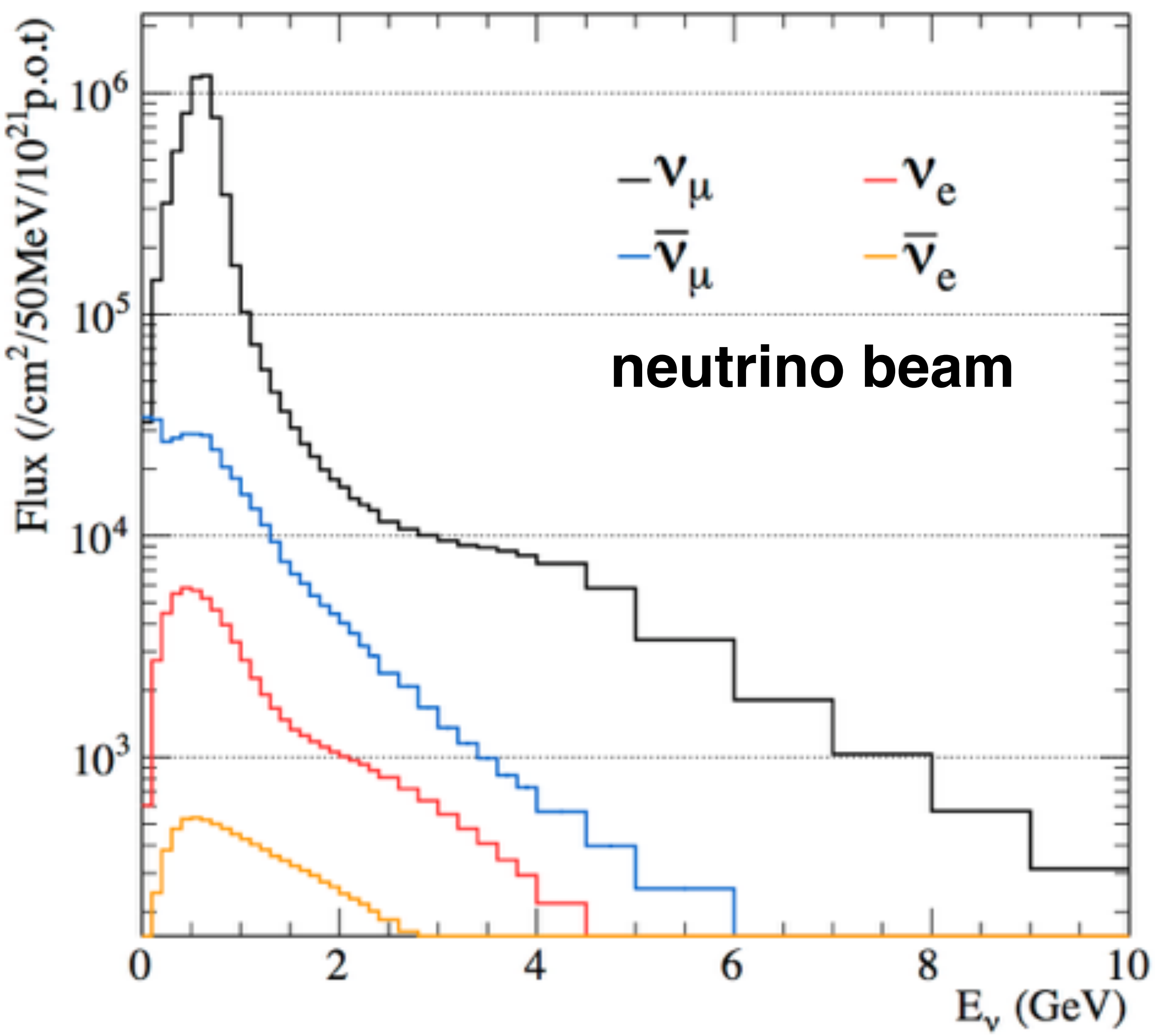


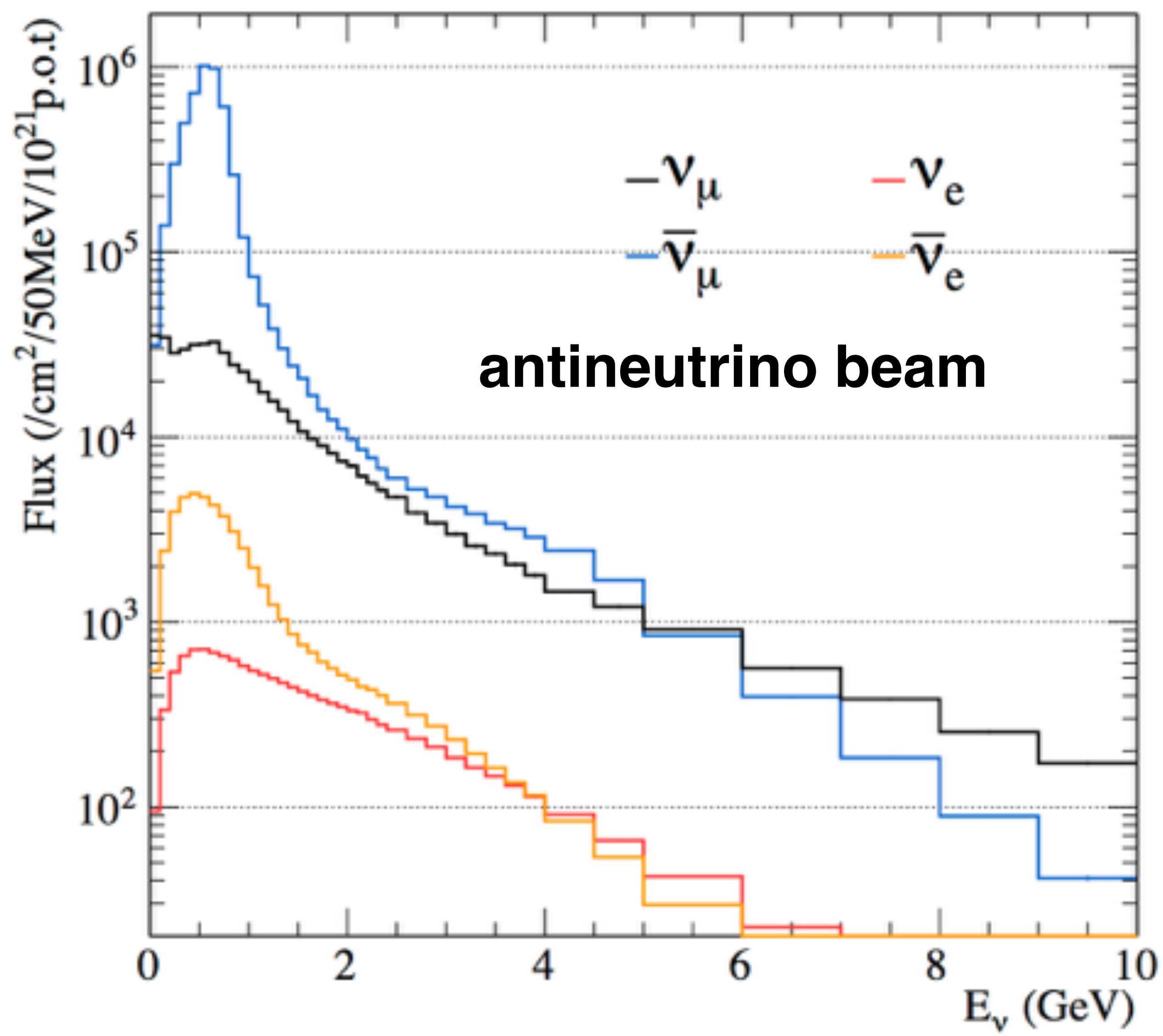
Linac
3 GeV
Synchrotron
Pacific Ocean
Near
Detector
Neutrino Beam to Kamioka
1200-
year-
old
temple
Design Intensity
750kW
30 GeV Main ring
J-PARC Facility
(KEK/JAEA)
View to North
Construction
2001~2009
Photo: January 2008

J-PARC neutrino beamline overview

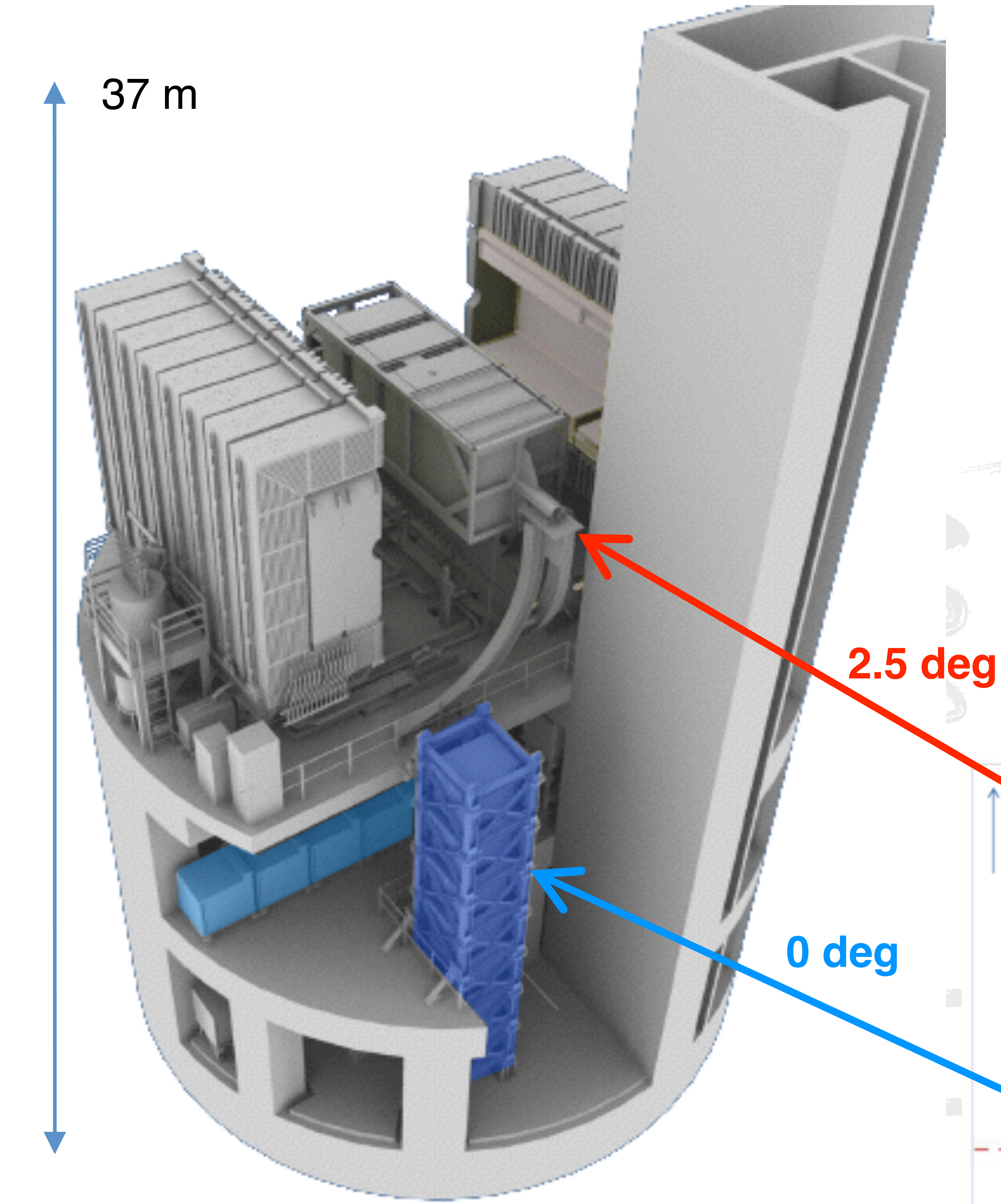


Neutrino flux predictions

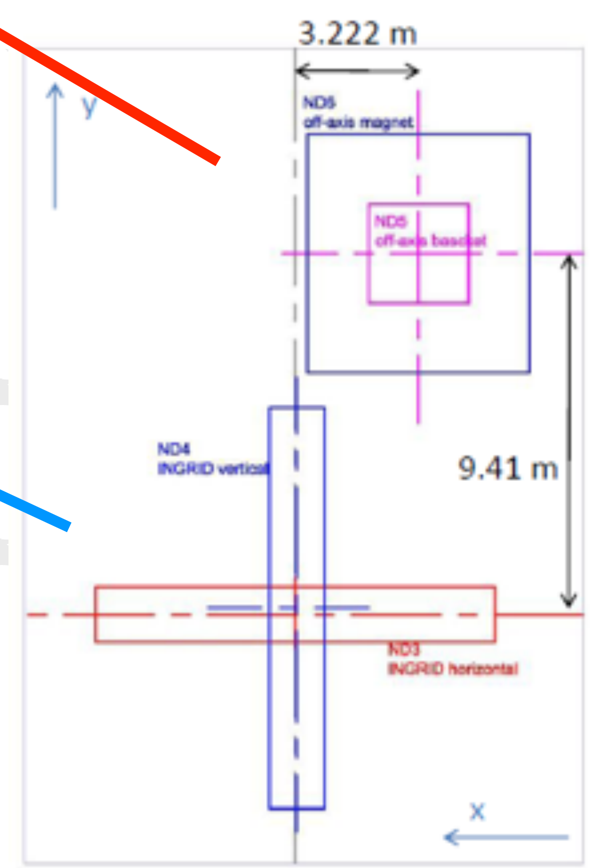




- <1% impurity from $\nu_e(\bar{\nu}_e)$ at energy peak; important background for $\nu_e(\bar{\nu}_e)$appearance
- "wrong sign" component: neutrinos contaminating antineutrino beam, vice versa.



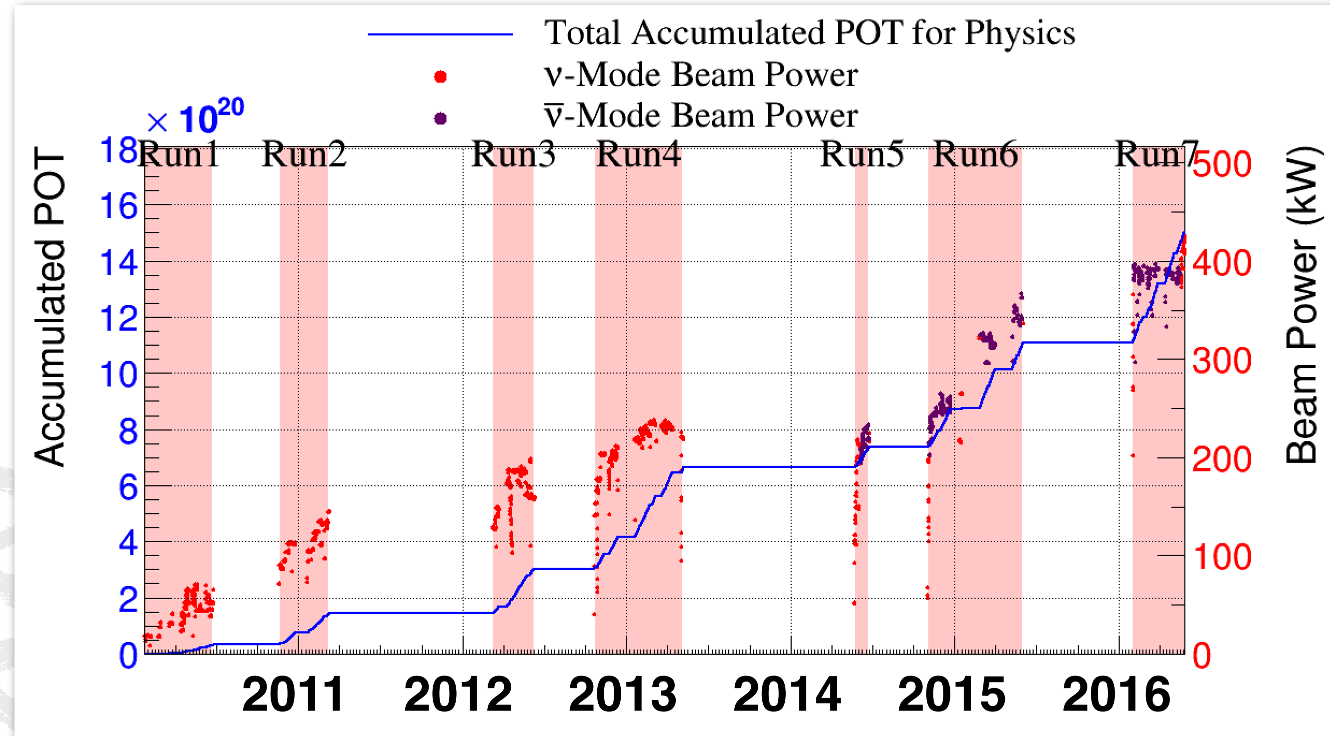
The Near Detector pit houses both the off-axis (ND280) and on-axis (**INGRID**) detectors

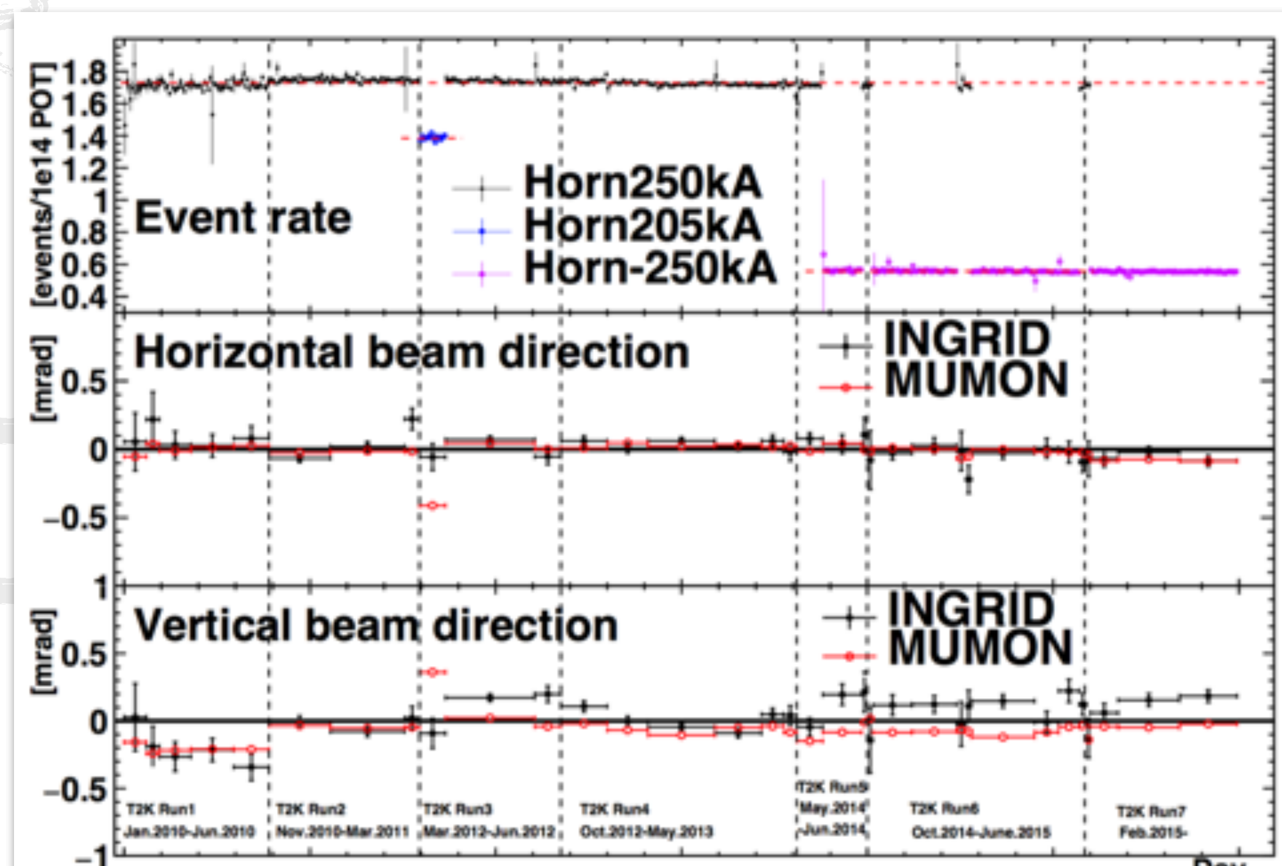


Beam delivery & stability

- Beam delivery until Jun'16
    - **1.51e21 POT TOTAL**
    - 7.57e20 POT nu
    - 7.53e20 POT nubar
- Expect ~7.5e20 POT in 2016-17 data run
- Beam operated stably at **420 kW**!

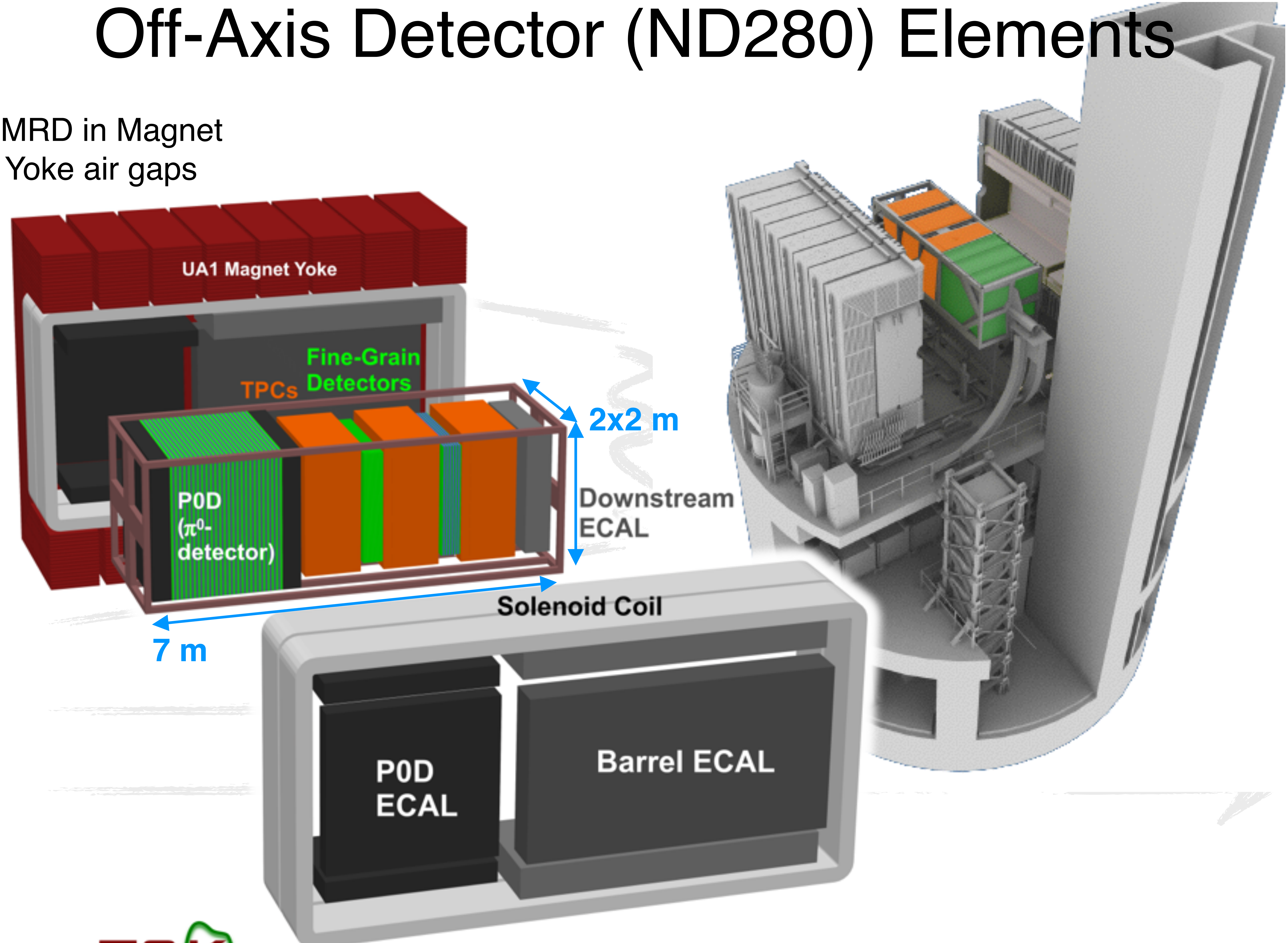
- **Main Ring power supply upgrade approved by MEXT**
- Will allow operation up to and beyond 750 kW in 2018



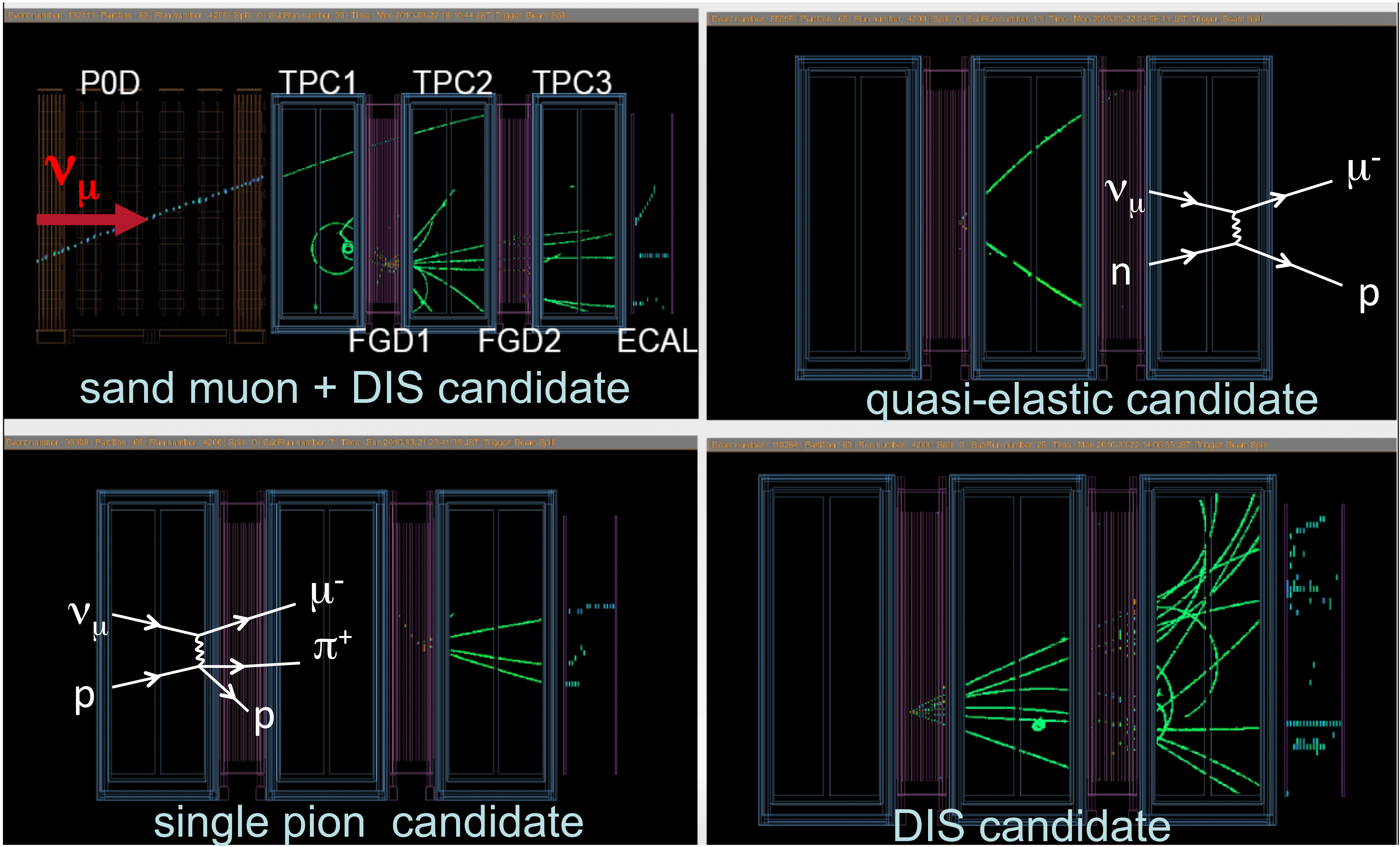


Off-Axis Detector (ND280) Elements

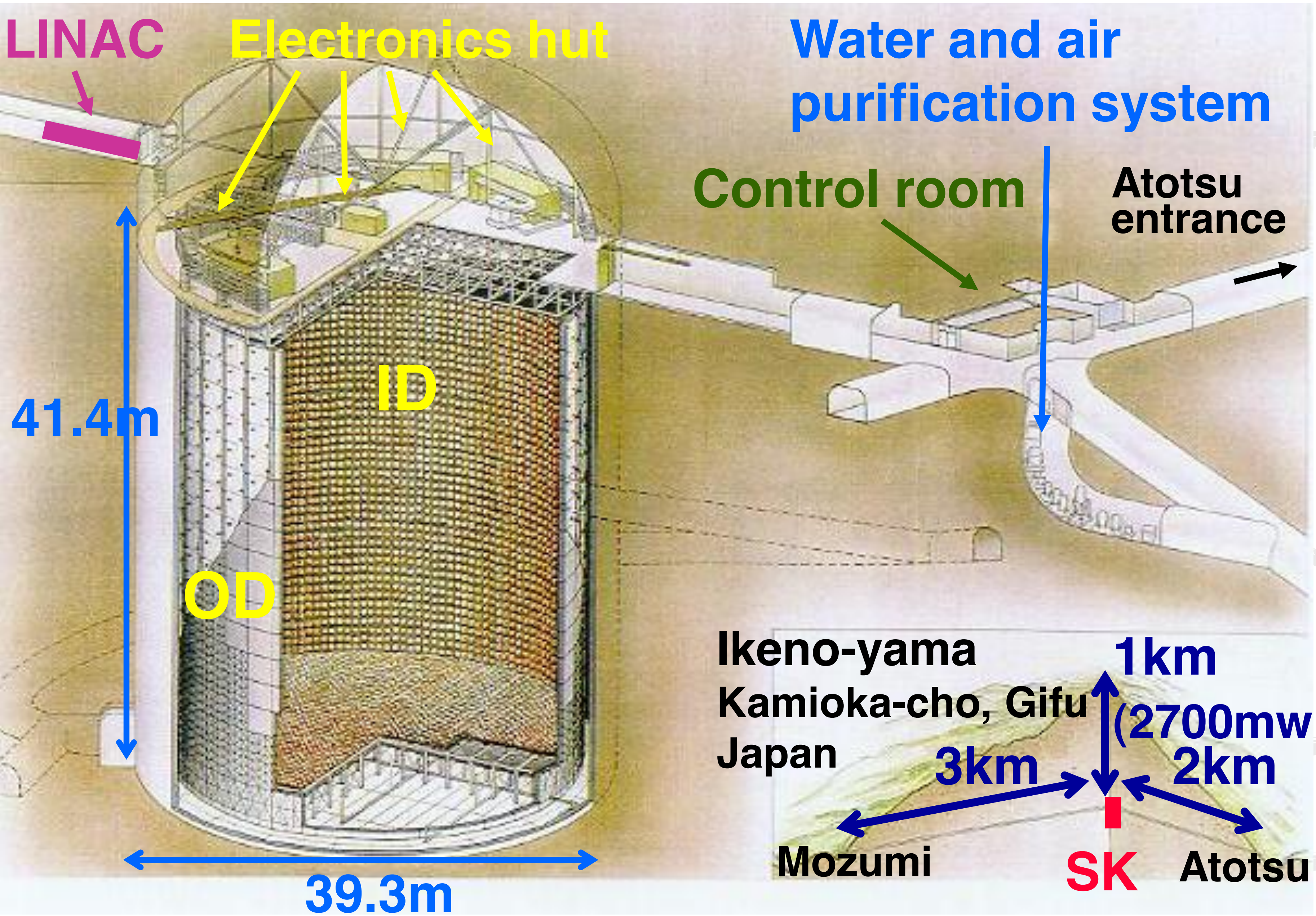
SMRD in Magnet
Yoke air gaps



ND280 neutrino events



Super-K (far) detector



- 50 kton (22.5 kton fiducial volume) water Cherenkov detector
- ~11,000 20" PMT for inner detector (ID) (40% photo coverage)
- ~2,000 outward facing 8" PMT for outer detector (OD): veto cosmics, radioactivity, exiting events
- Good reconstruction for T2K energy range
    - Threshold 4 MeV

T2K phase 2

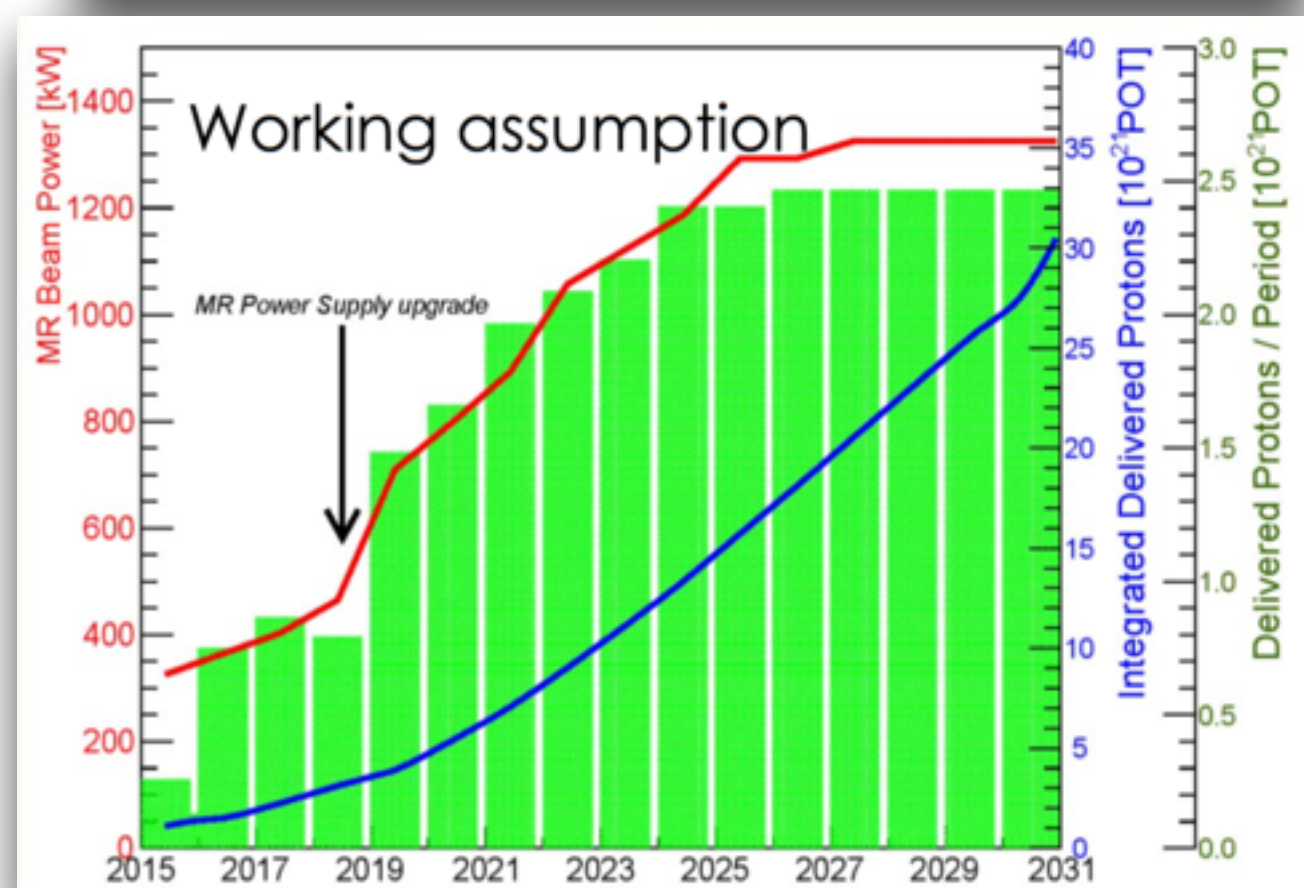
Expression of Interest for
an Extended Run at T2K to 20×10^{21} POT

T2K collaboration

January 8, 2016

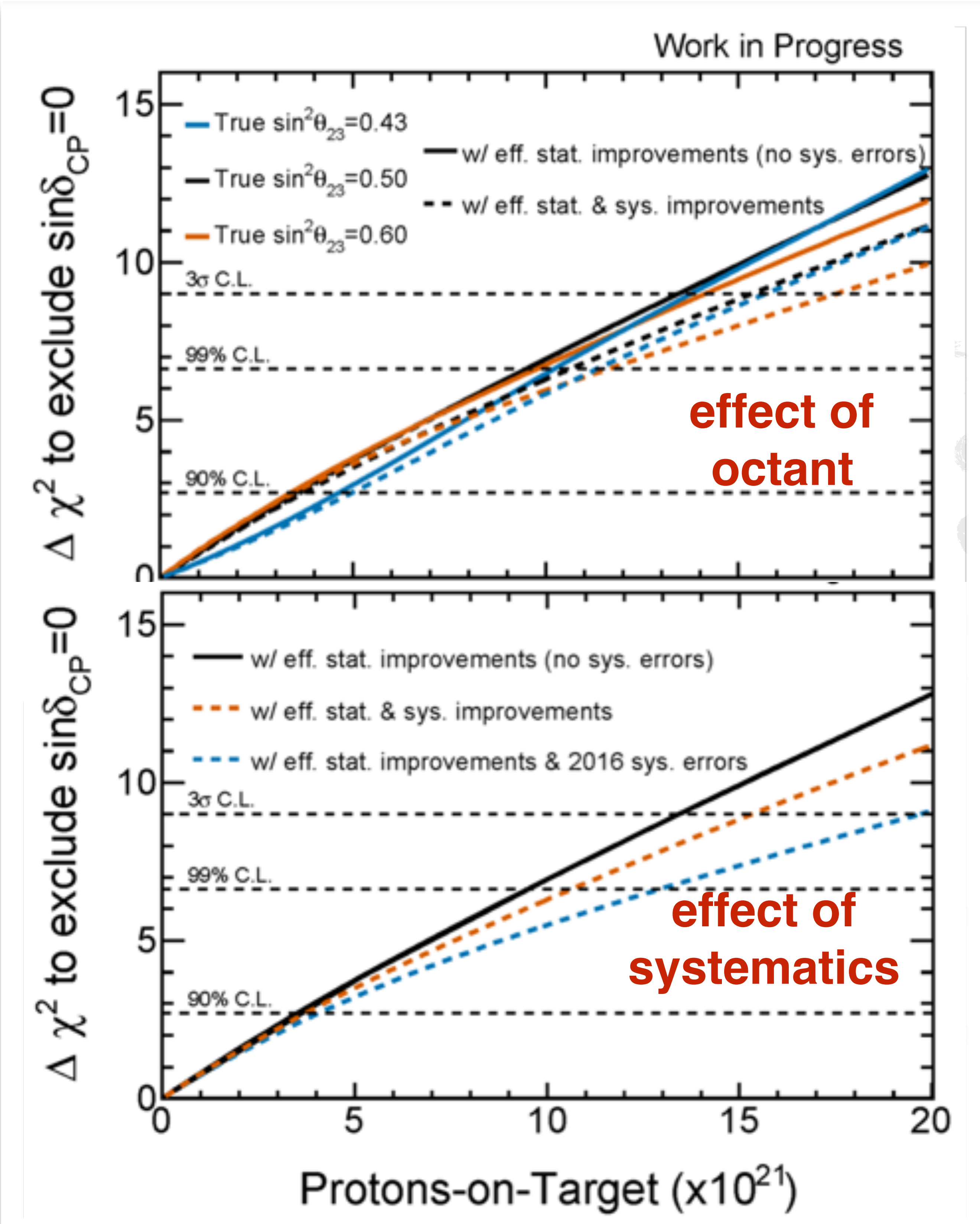
Abstract

Recent measurements at T2K indicate that CP violation in neutrino mixing may be observed in the future by long-baseline neutrino oscillation experiments. We explore the physics program of an extension to the currently approved T2K running of 7.8×10^{21} protons-on-target to 20×10^{21} protons-on-target, aiming at initial observation of CP violation with $3\,\sigma$ or higher significance for the case of maximum CP violation. With accelerator and beam line upgrades, as well as analysis improvements, this program would occur before the next generation of long-baseline neutrino oscillation experiments that are expected to start operation in 2026.



- T2K data favours maximal CPV
  - CPV may be observable in the near future!
- T2K will reach full stats in ~2021
  - Next gen experiments start in 2025, or later
- Let's extend T2K until ~2026
- With MR power upgrade, can achieve ~20E21 POT
  - >3 σ CPV sensitivity
  - Smoothly transition to next gen experiments with useful data
  - Can expand collaboration as well
- **T2K phase 2 given Stage 1 Status by KEK/J-PARC directorate**

T2K phase 2



- Expect up to 500 ν_e events, depending on value of δ_{CP}
- Sensitivity to excluding $\sin\delta_{CP}=0$ for:
  - ✓known true NH
  - ✓true $\sin\delta_{CP}=-\pi/2$
  - ✓effective statistical improvement from increased horn current, SK FV, SK data samples

- Two panels show:
  - effect of the true octant (value of θ_{23})
  - effects of systematics

➡**Significant sensitivity enhancements possible if systematics can be improved!**

Modeling ν-nucleus interactions

Processes in Neutrino Scattering

merely players

figure from Ref 1

- Charged Current Quasi Elastic (CCQE) and multinucleon processes (2p2h)

CCQE

Observable

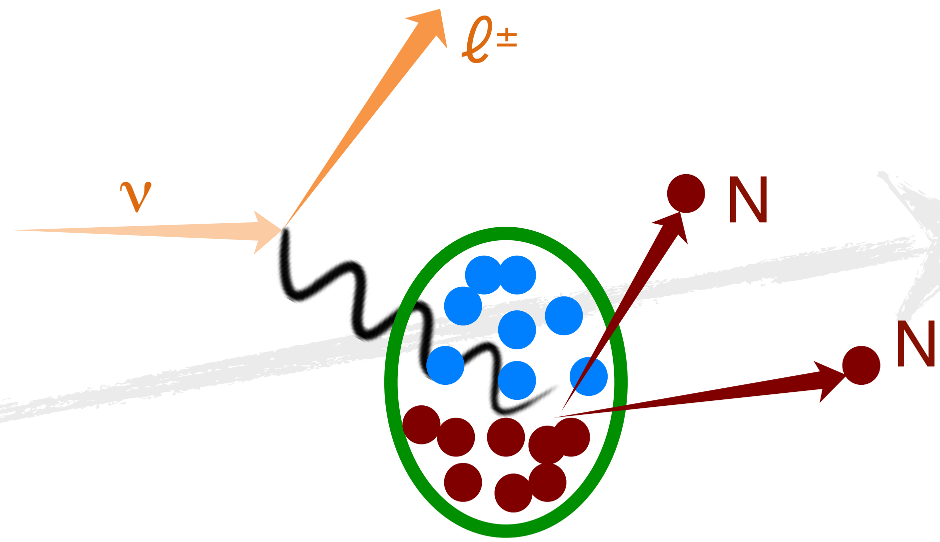
neutrino (anti)

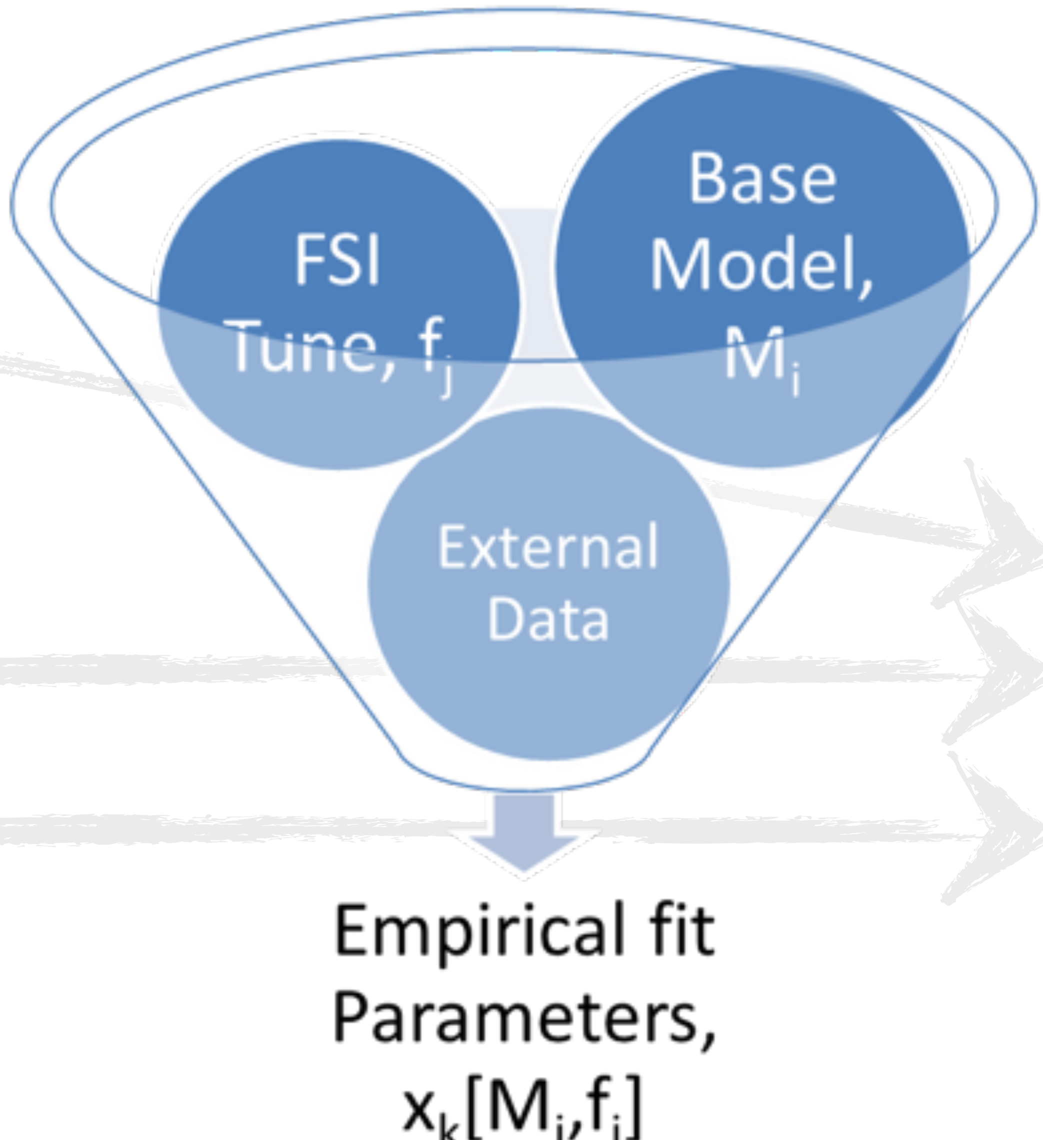
- muon or electron (+)
- proton (neutron)

2p2h

Ingredients for Interaction Model

- A "Base" physics model
  - Llewellyn Smith RFG w/ dipole vector FFs, Nieves 2p2h, R-S resonance region, duality (B-Y) DIS
  - Can use different base models for tests
- Empirical fit parameters
  - E.g., M_A^{eff}, κ, normalisation(Eν)
- FSI Model tune
  - Constrained by low energy hadron measurements
- External and (future) Internal Measurements
  - Must understand uncertainties
  - Measurements relevant to our physics model





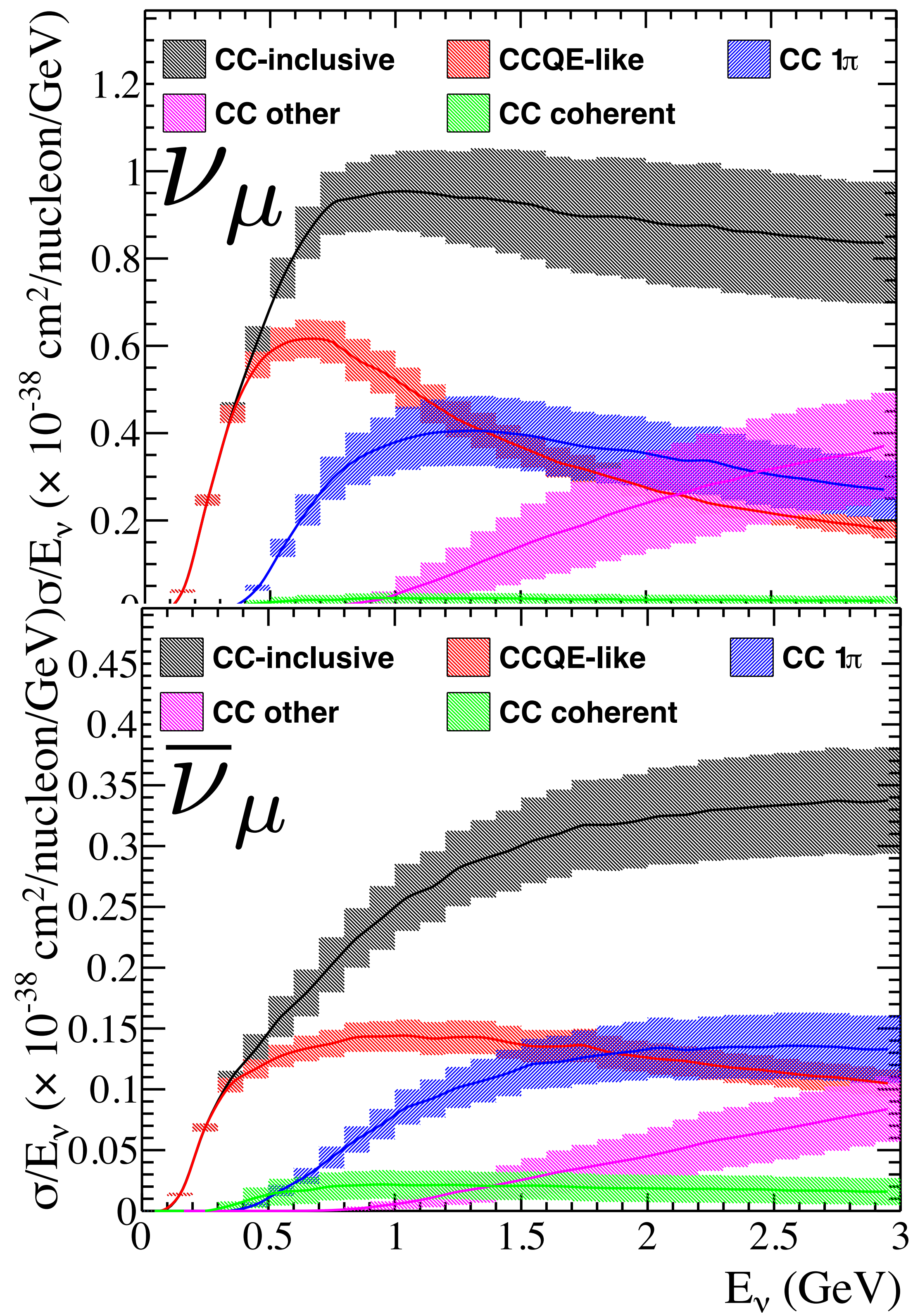
T2K ν-nucleus interaction model

- T2K's primary neutrino generator MC is NEUT
  - Simulates neutrino-nucleus interactions
  - Used by SK, SciBooNE, K2K
  - Tuned with fits to external data sets
  - 2012: mainly MiniBooNE CCQE, CC1π^+, CC1π^0, NC1π^0
    - Fits used to tune model parameters for prior inputs to oscillation analysis
    - Constrained and cross-checked with SciBooNE and K2K data
  - 2014: MiniBooNE and MINERvA *ν* and $\bar{\nu}$ data sets
    - Fits used to down select default interaction model and tune parameters for prior inputs to oscillation analysis
    - Published CCQE fits in early 2016
  - 2016: Expanding fits to include bubble chamber and other data
- Also use GENIE and NuWro for cross-check analyses, systematic errors studies, and deeper inquiries into neutrino interactions

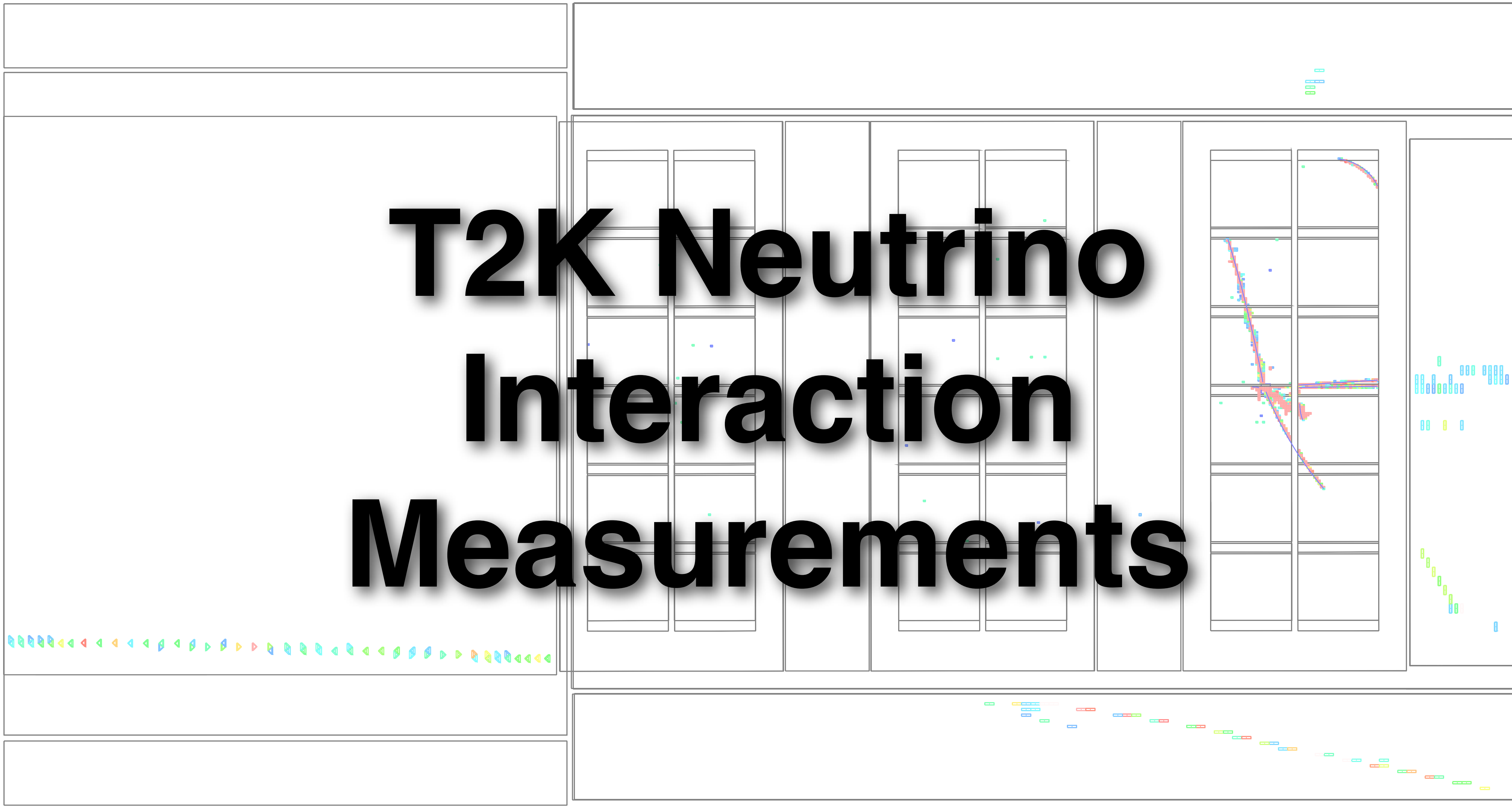
NEUT interaction model

2014 model & parameters (NEUT v5.3.3)

- CCQE: Llewellyn Smith, M_A^{QE}=1.0 GeV/c^2
- CC resonant π: Rein-Sehgal, M_A^{RES}=1.2 GeV/c^2
- 2p2h: Nieves model
- Nuclear model: Smith-Moniz RFG
  - Also have 2D spectral function implemented
- RPA effects included
- Coherent pion: Rein-Sehgal
- DIS with Bodek-Yang corrections
- Neutrino and antineutrino interactions simulated
- ν_μ and ν_e simulated
  - Only differ at low energy
  - Radiative corrections
- Second class currents

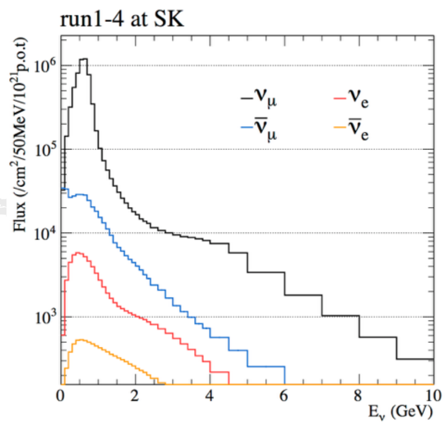


T2K Neutrino Interaction Measurements

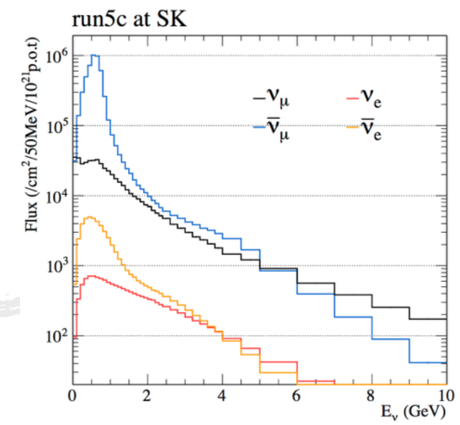


Many possible measurements

- Four neutrino fluxes

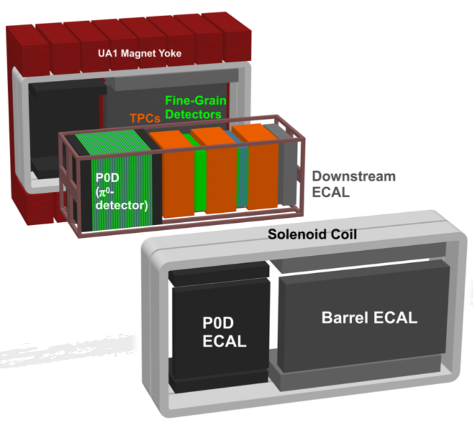


ν mode ("FHC")
- ν_μ
- ν_e

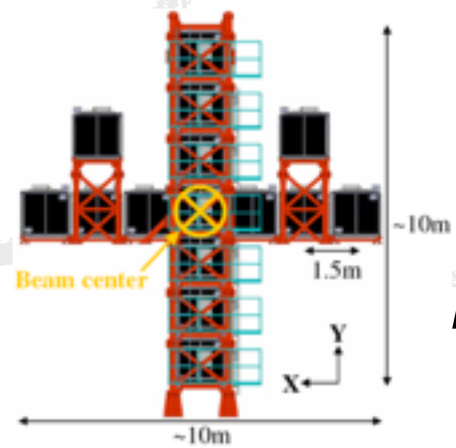


$\bar{\nu}$ mode ("RHC")
- $\bar{\nu}_\mu$
- $\bar{\nu}_e$

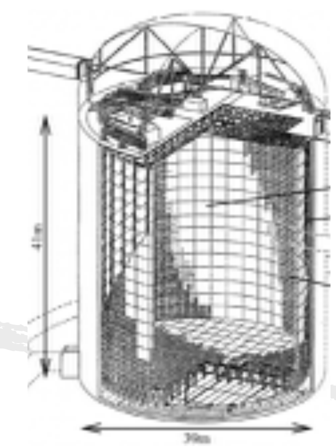
- Multiple detectors and target nuclei



CH
H_20
Cu/Sn
Pb
Ar



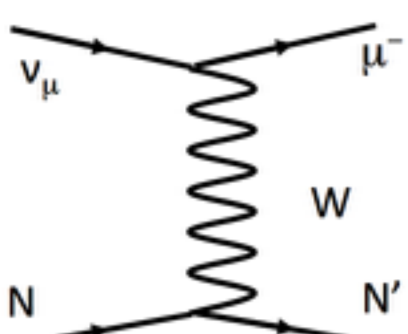
Fe
CH
H_20!



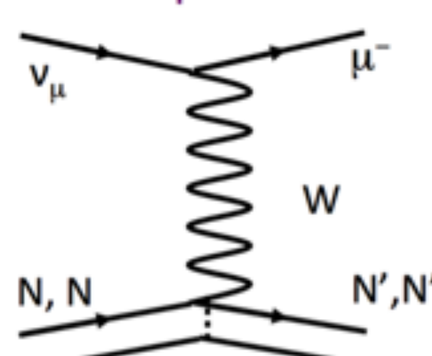
H_20

- Multiple interaction processes

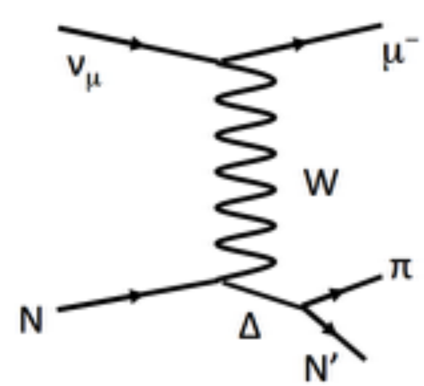
CCQE



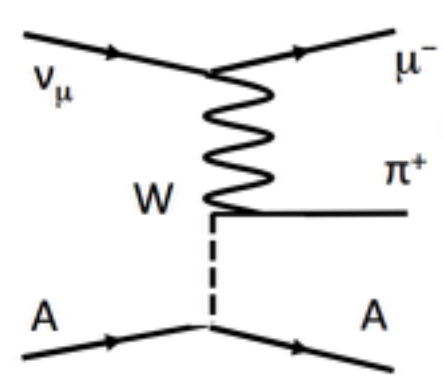
2p2h



CCπ

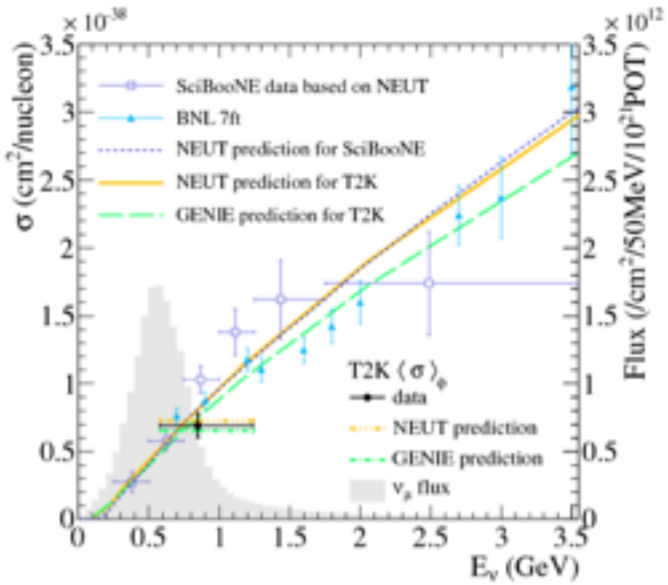


CCπ

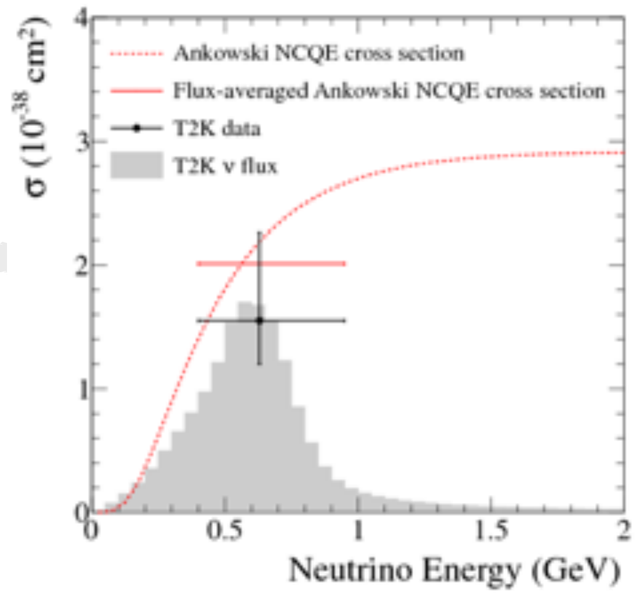


+ NC + …

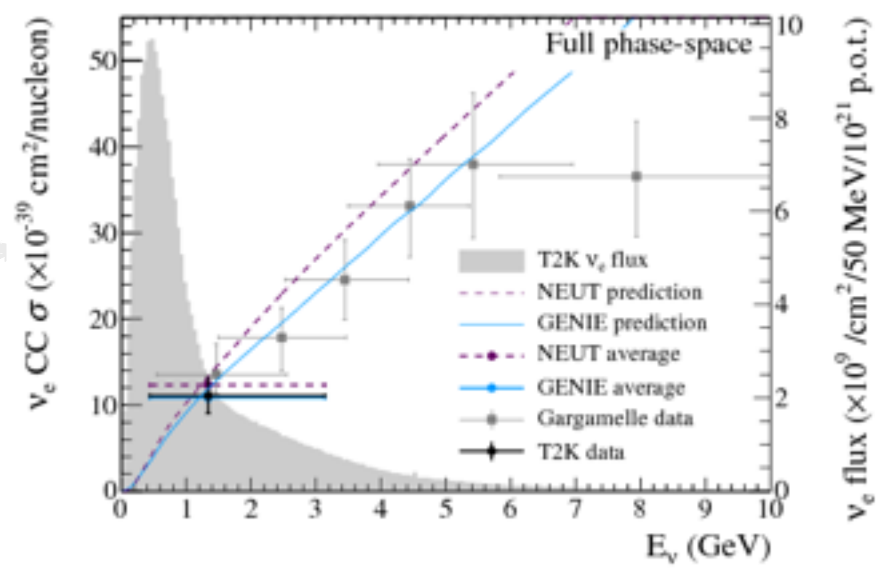
Previous T2K ν-nucleus results



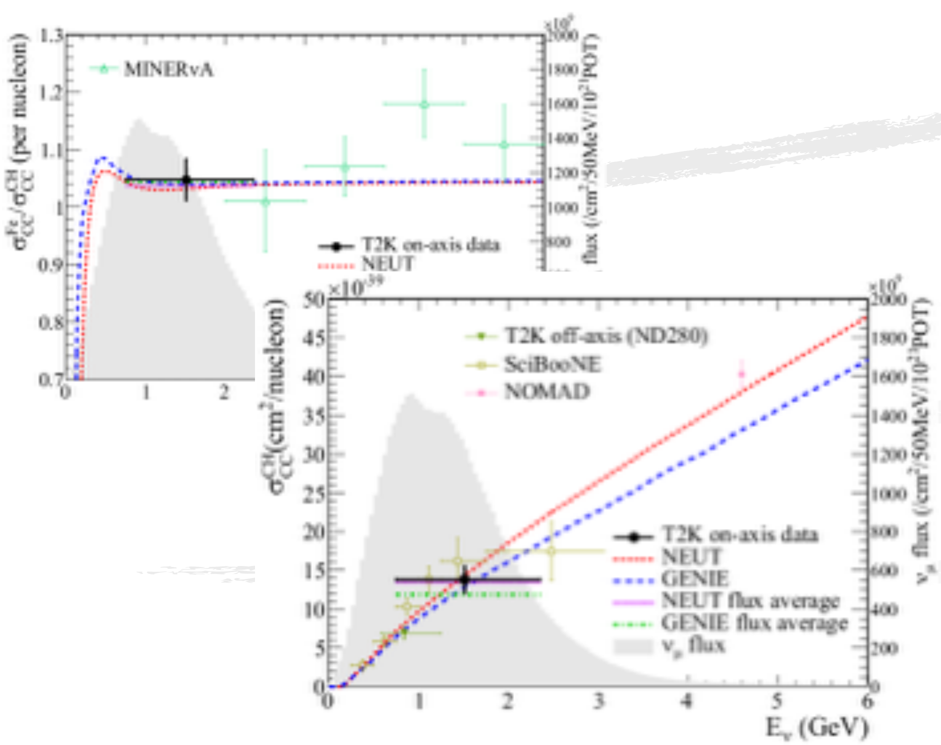
Phys.Rev. D87 (2013) no.9, 092003



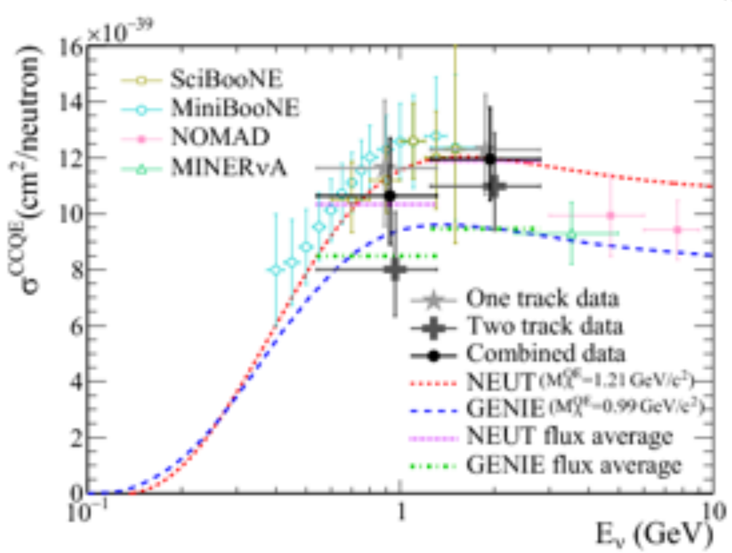
Phys.Rev. D90 (2014) no.7, 072012



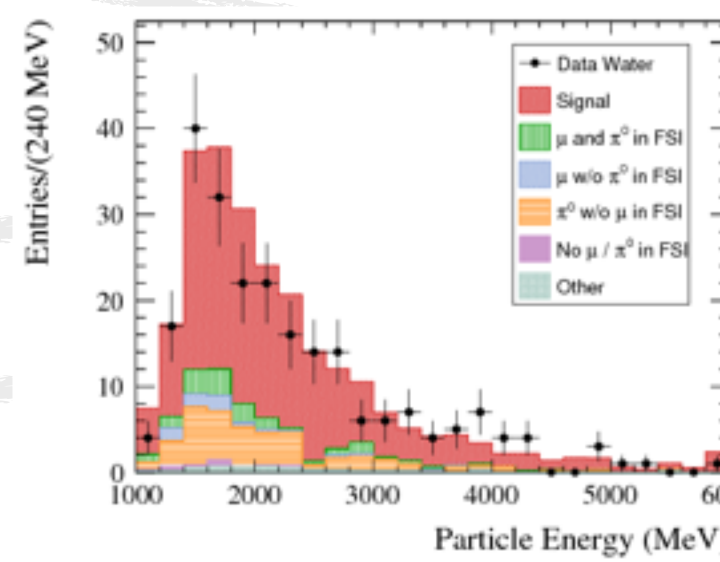
Phys.Rev.Lett. 113 (2014) no.24, 241803



Phys.Rev. D91 (2015) 112010



Phys.Rev. D91 (2015) no.11, 112002



Phys.Rev. D91 (2015) 112010

Recent ν-nucleus interaction results

➡ Results published within the past year

★ ν_μ CC QE on C

★ ν_μ CC coherent π^+ on C

★ ν_μ CC π^+ on H_2O

★ ν_μ CC 0π on C

} ND280 tracker

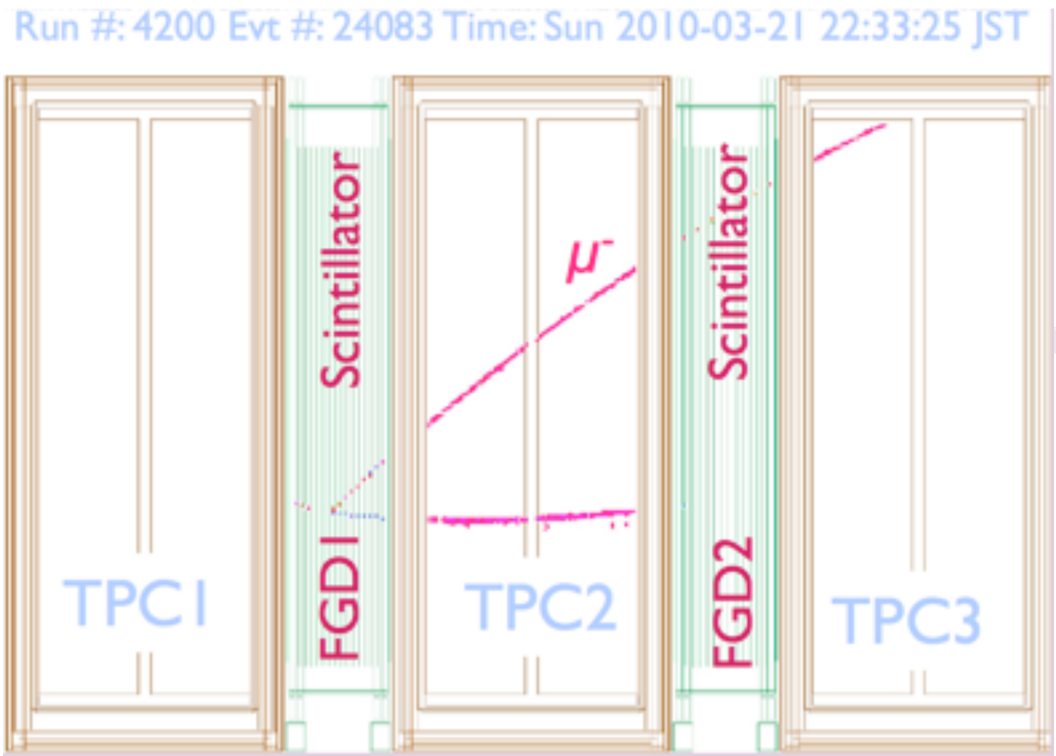
✦ ν_μ CC-inclusive vs E_ν

} INGRID

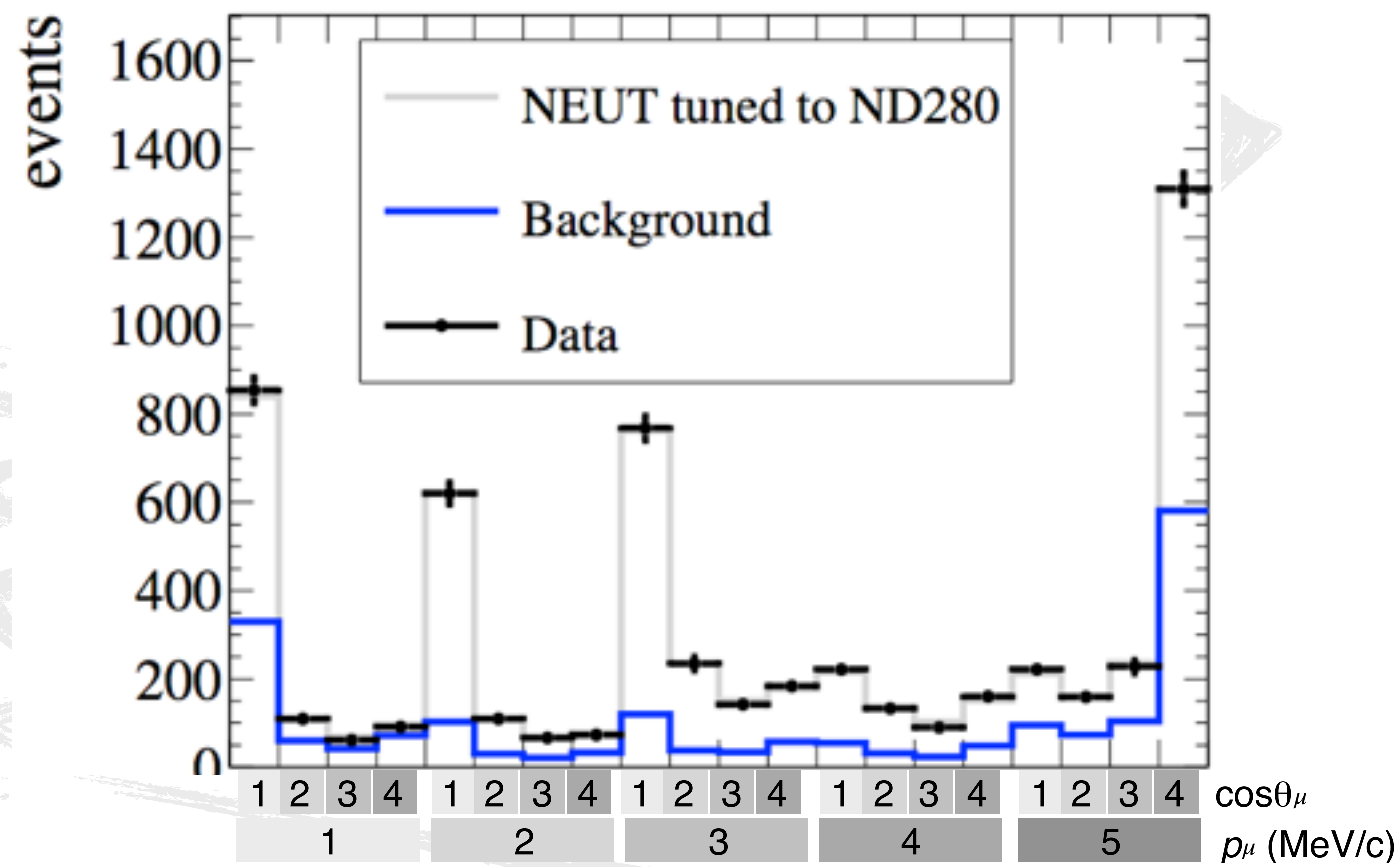
ν_μ CCQE on C

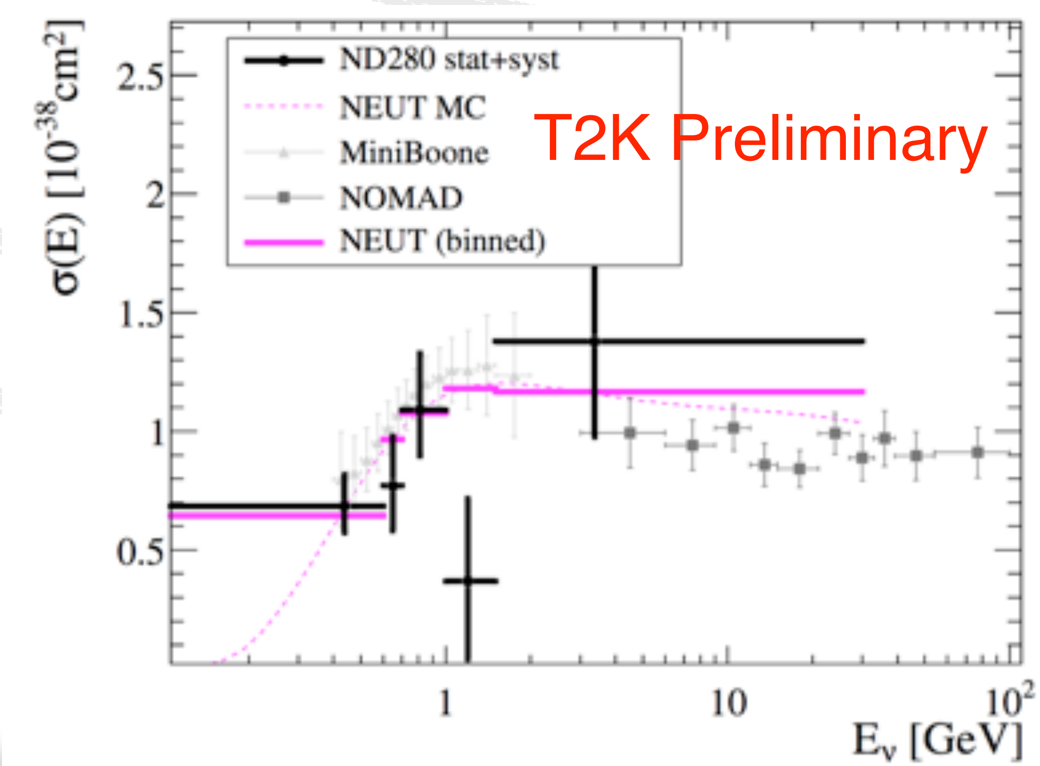
$$\nu_\mu + p \rightarrow \mu^- + n$$

*Phys. Rev. D **92 (2015)**112003*



- Select 1μ^- tracks starting in FGD
  - Require no pion-like tracks or muon decays
- Template fits in p_μ vs. $\cos\theta_\mu$ to extract CCQE xsec
  - M_A^{QE} = 1.26 +0.21 -0.18 GeV/c2 (1.43 +0.28 -0.22 shape-only)



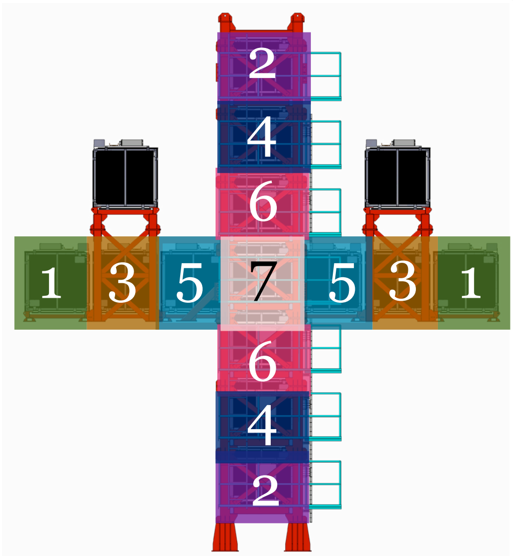


$$\nu_\mu + Fe \to \mu^- + X$$

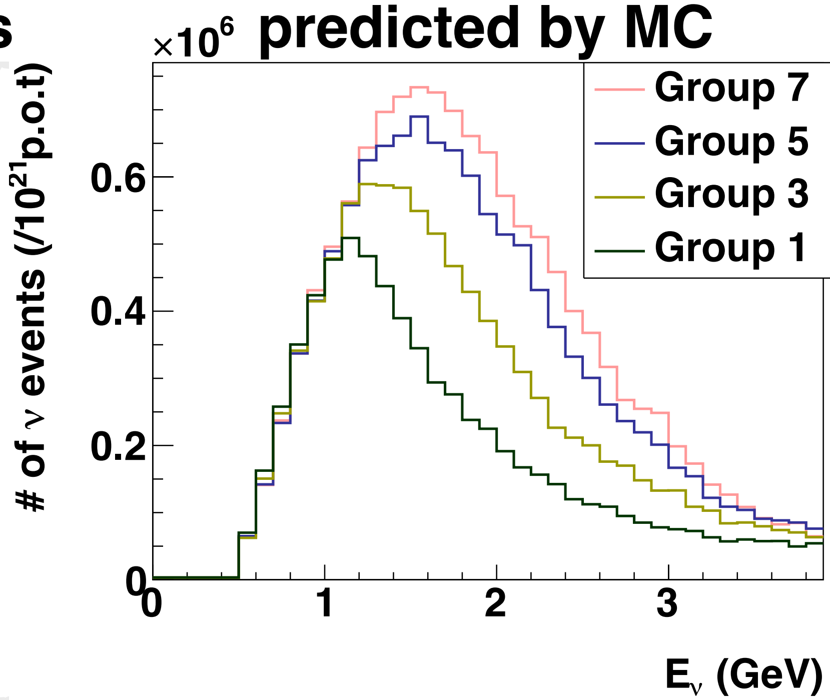
ν_μ CC on Fe vs. E_ν

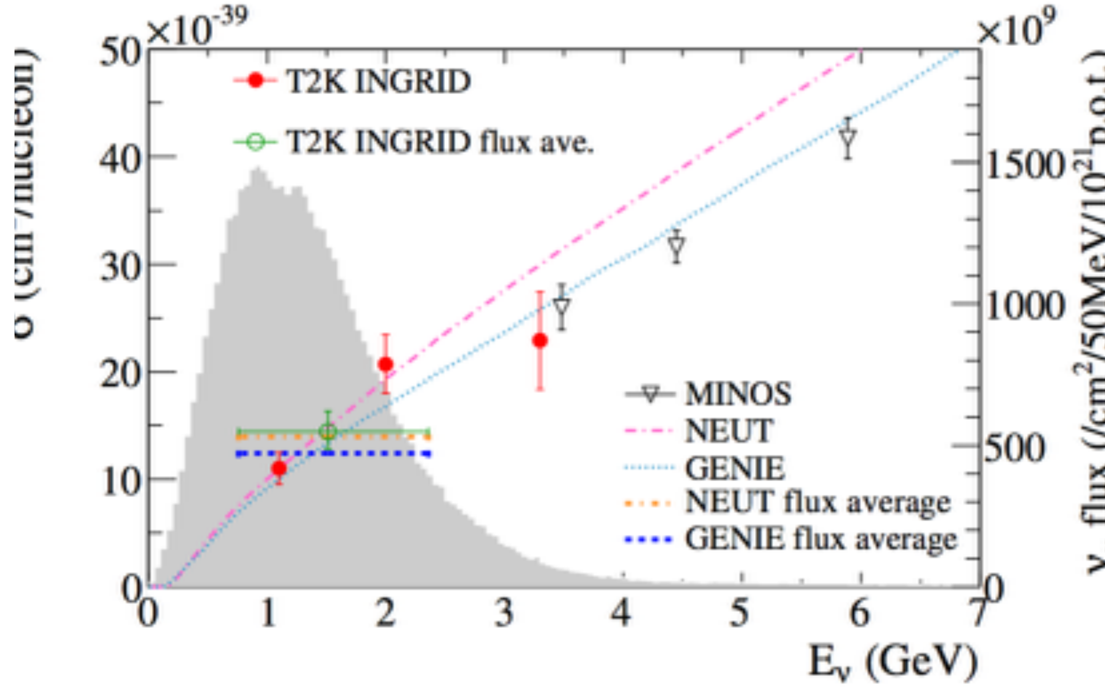
*Phys.Rev. D **93** (2016) no.7, 072002*

Definition of grouping modules



Energy spectra predicted by MC





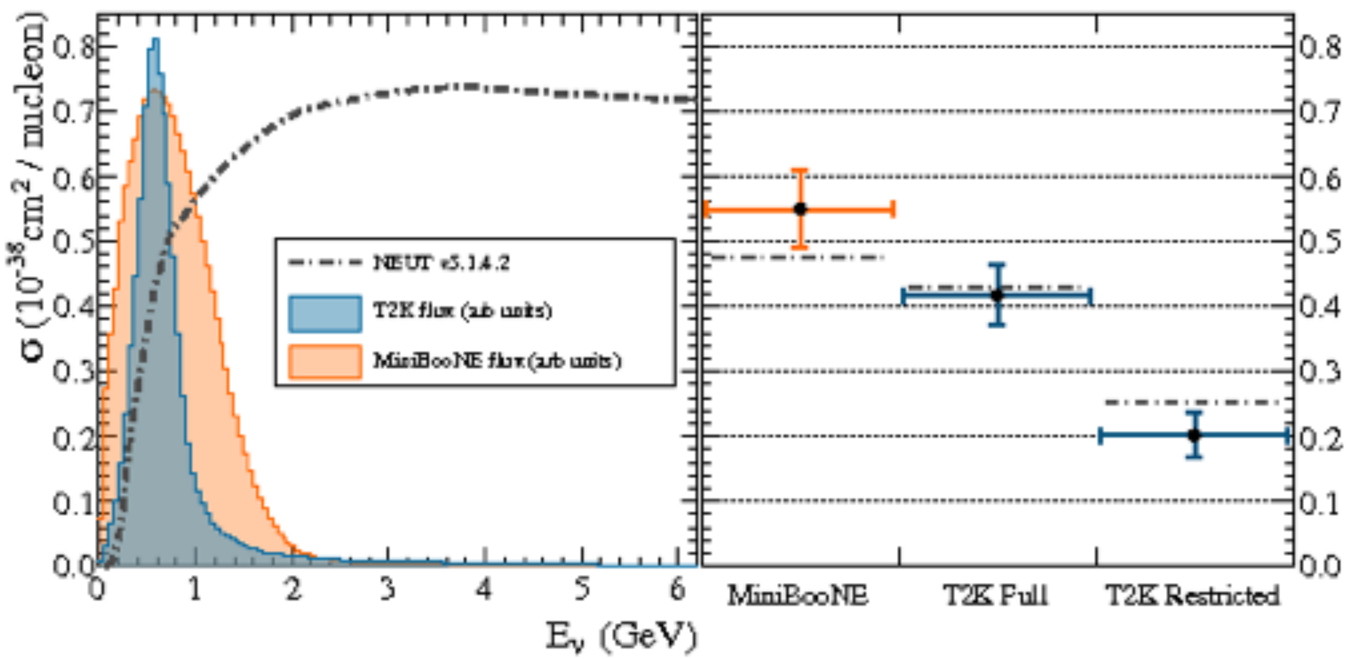
	1.1 GeV	2.0 GeV	3.3 GeV
Cross section ($10^{-38}cm^2$/nucleon)	1.10 ± 0.15	2.07 ± 0.27	2.29±0.45

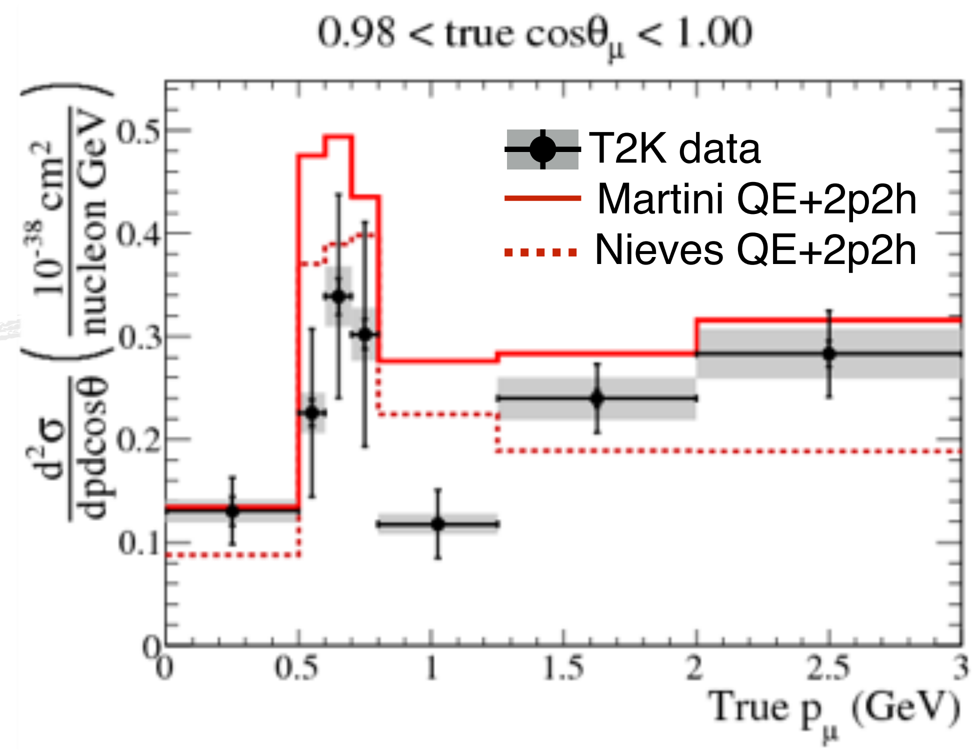
Energy dependence is determined in a model-independent way!

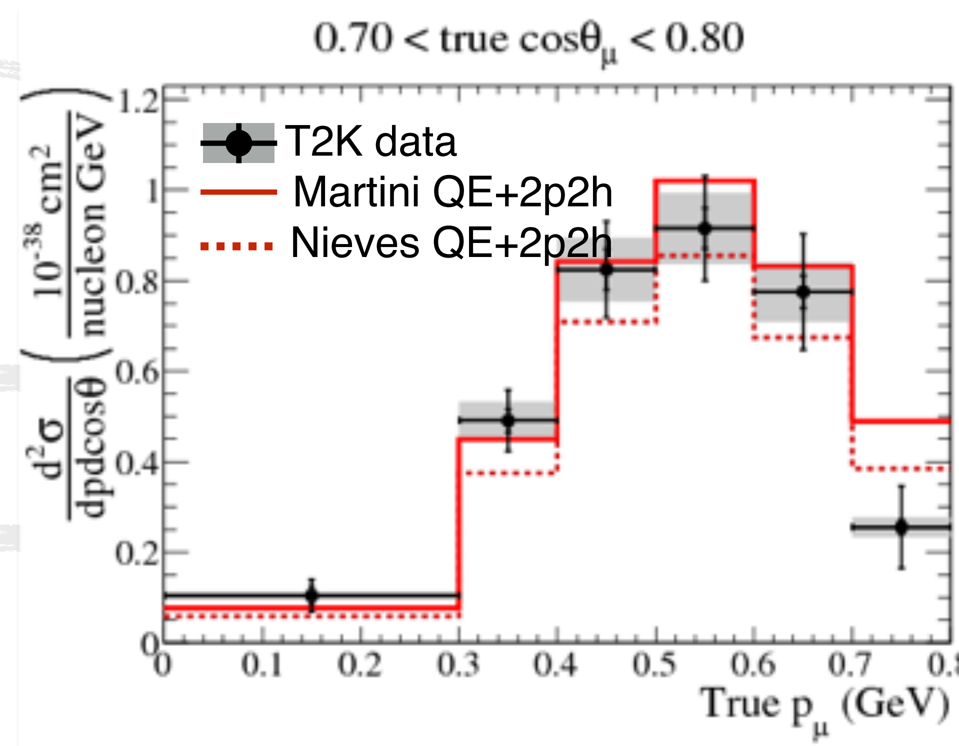
$\nu_\mu + C \rightarrow \mu^- + 0\pi^+ + X$

ν_μ CC0π on C

*Phys.Rev. D **93** (2016) no.11, 112012*





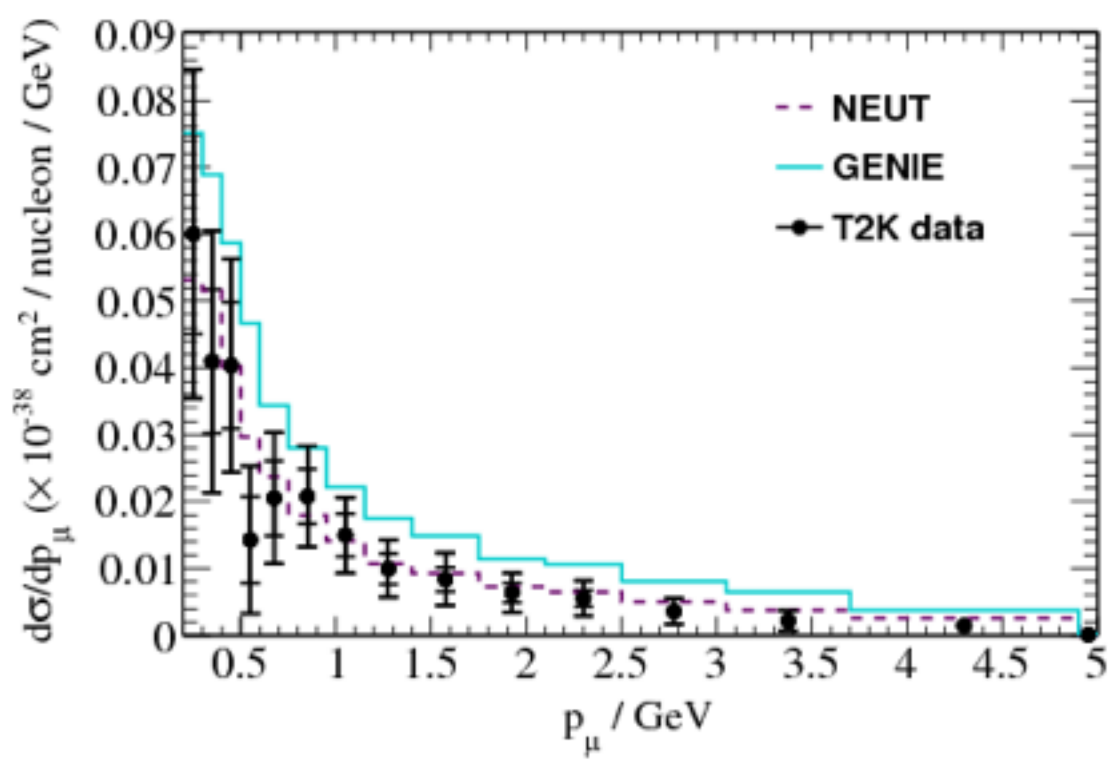


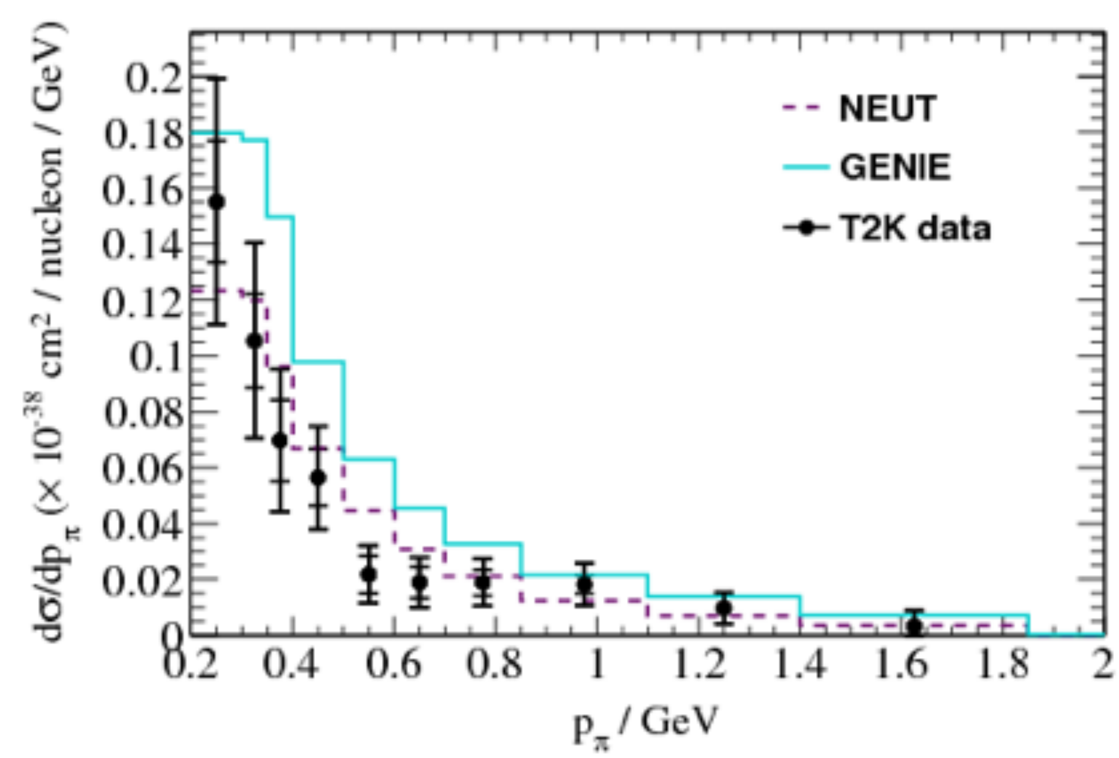
- Select events with 1μ^- and 0π
- Double differential xsecs
  - p_μ vs. $\cos\theta_\mu$
- Predominantly CCQE events
- Good data set for testing 2p2h models

$\nu_\mu + H_2O \rightarrow \mu^- + 1\pi^+ + X$

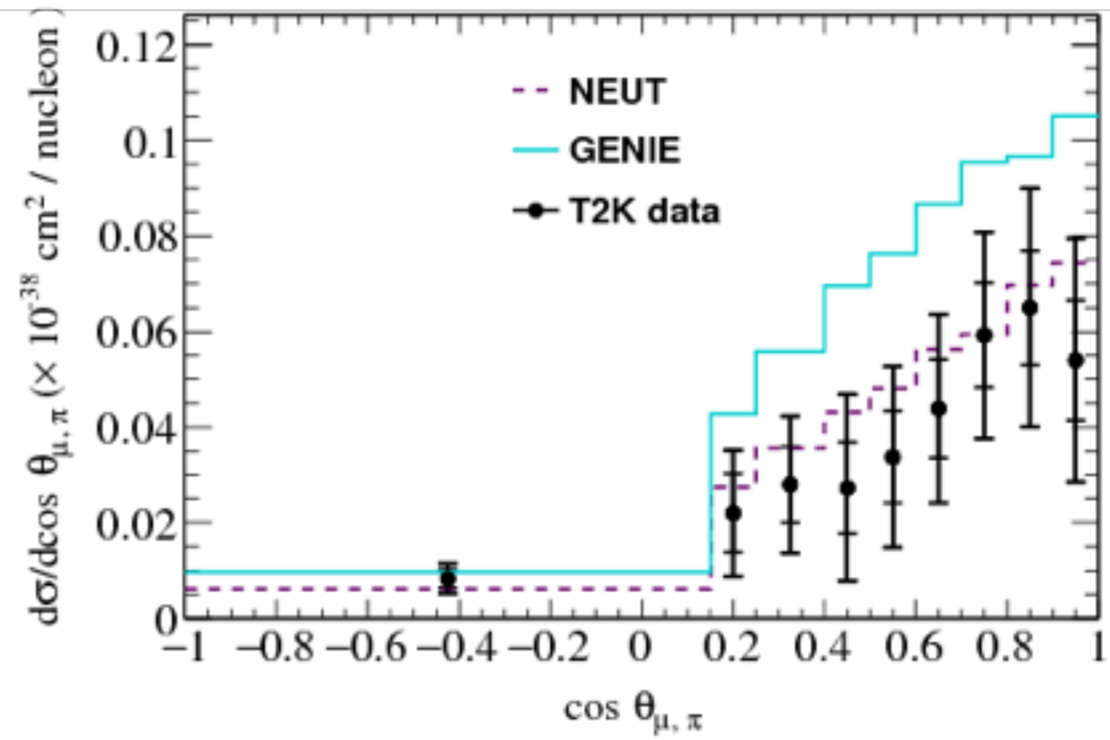
ν_μ CC1π^+ on H_2O

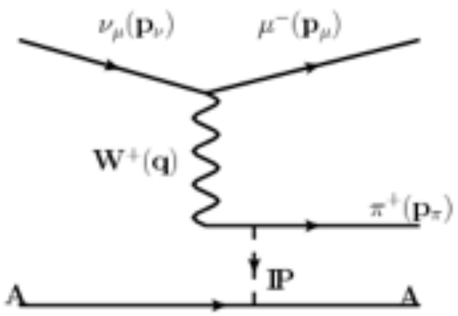
arXiv:1605.07964 [hep-ex] (accepted by PRD)





- Inclusive 1π production
- Select events with 1μ^- and 1π^+
- Differential xsecs
  - p_μ, $\cos\theta_\mu$, and now p_π, $\cos\theta_\pi$!
- Excellent new data set for model testing and tuning!



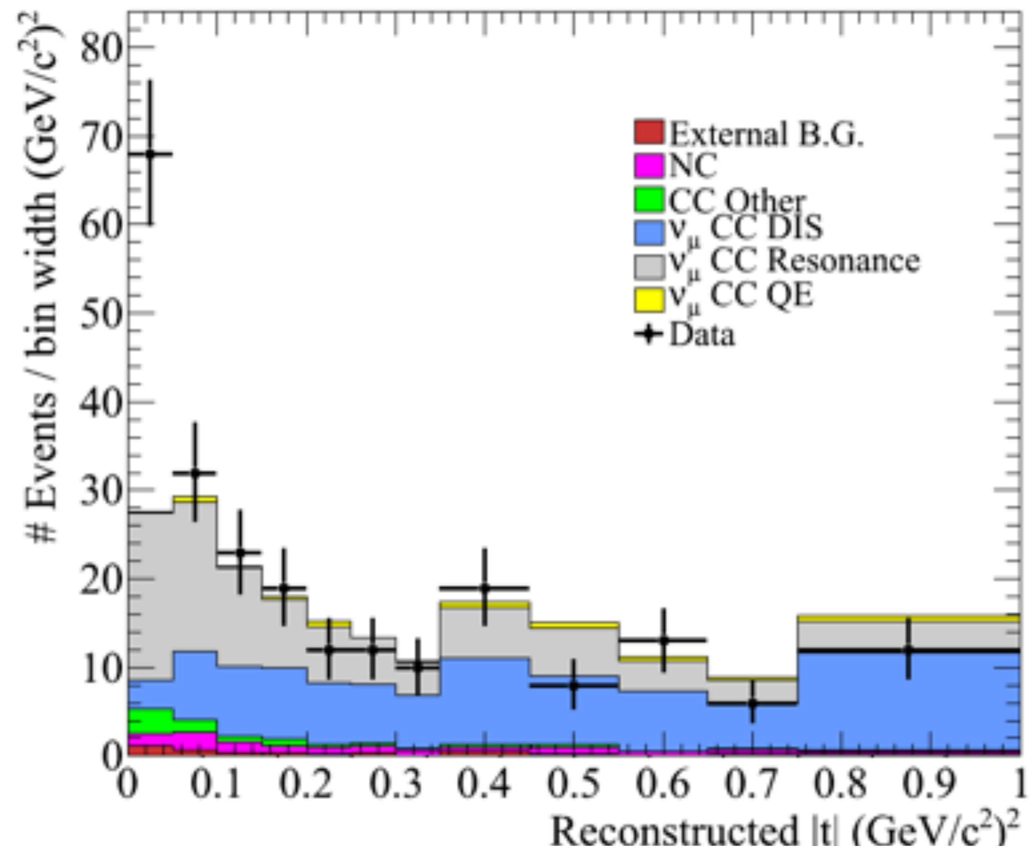


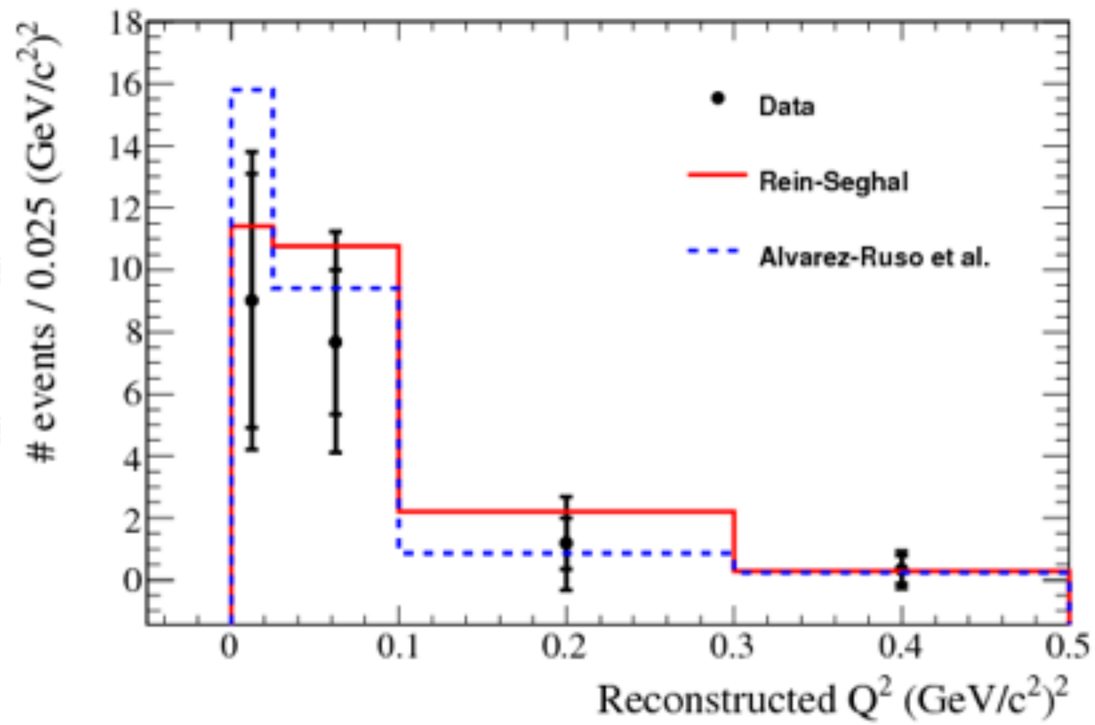
$$\nu_\mu + C \rightarrow \mu^- + \pi^+ + C$$

ν_μ CC coh π^+ on C

Phys.Rev.Lett. 117 (2016) no.19, 192501

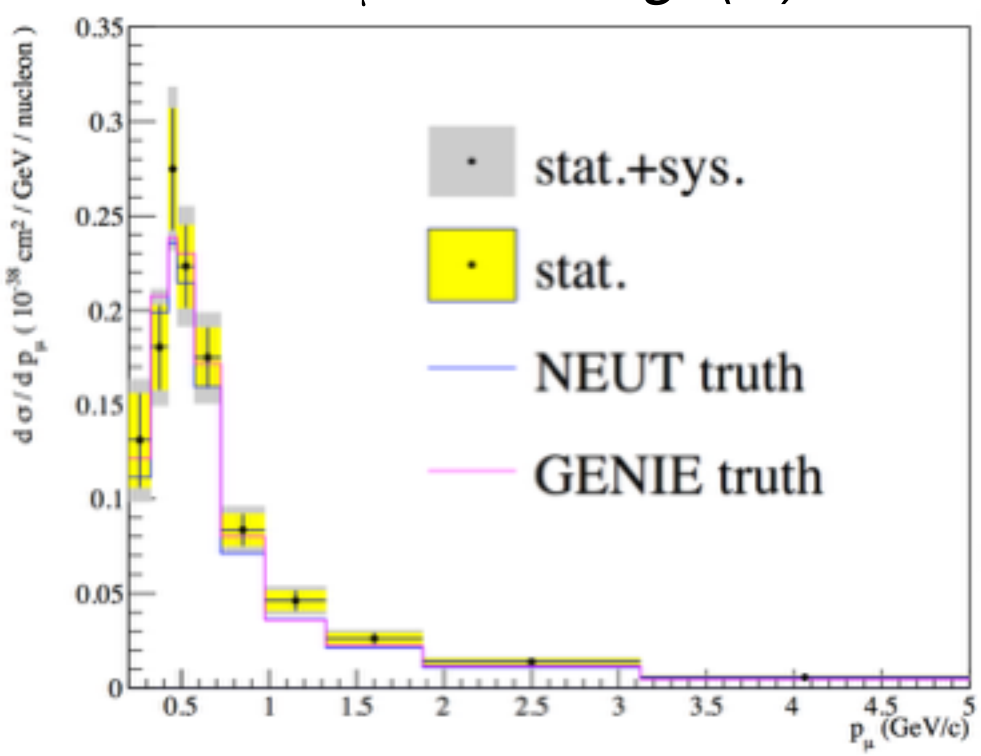
- In coherent processes, the weak propagator interacts with all nucleons *coherently*
  - leaves target nucleus in ground state
- Low energy transfer (" |t| ") is characteristic signature of coherent pion production, compared to incoherent
  - e.g. resonant production
- Signal definition is model-dependent, so data are analysed in context of two different models



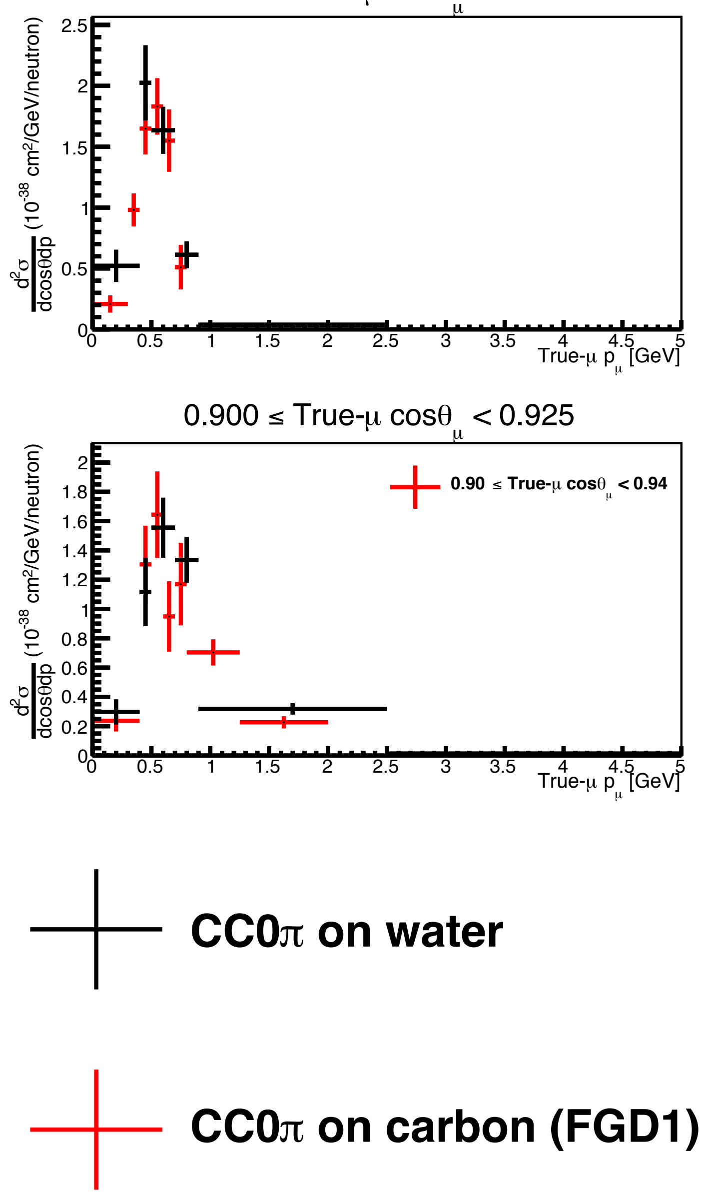


Future ν-nucleus measurements

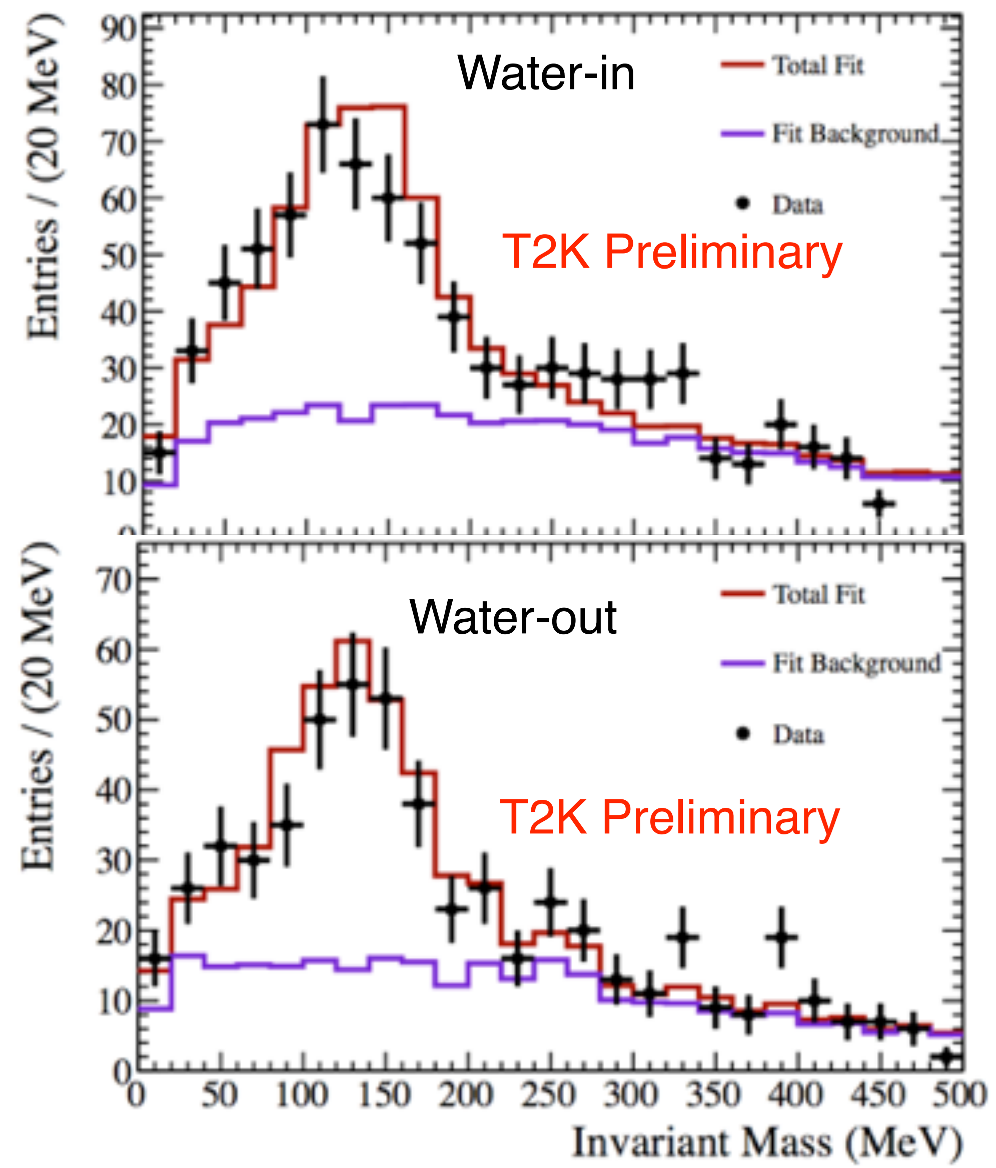
$\bar{\nu}_\mu$ scattering (C)



ν_μ CC0π (O)



NCπ⁰ production (C,O)



also working on CC-inclusive on Pb, CC-inclusive on Ar, and many more…

Conclusions

- T2K has made many competitive neutrino-nucleus interaction measurements
  - Dozens of possible measurements, so lots of interesting work ahead!
- T2K's sensitivity to CPV can be enhanced with better understanding of neutrino-nucleus interactions

➡ **Let's communicate more and find the best way to study neutrino-nucleus interactions!**

Thank you for your attention!

ご清聴ありがとうございました

水戸の梅の花