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

# Neutrino Interaction Results from T2K

MO Wascko
*Imperial College London*
on behalf of the T2K Collaboration

Fermilab Wine and Cheese Seminar
2014 11 07

# Outline

- Motivation
- Interaction model
- Cross section analysis methods
- Introduction to T2K experiment
- Recent cross section results
- Upcoming results

# Accelerator Neutrinos

*first accelerator neutrino beam*

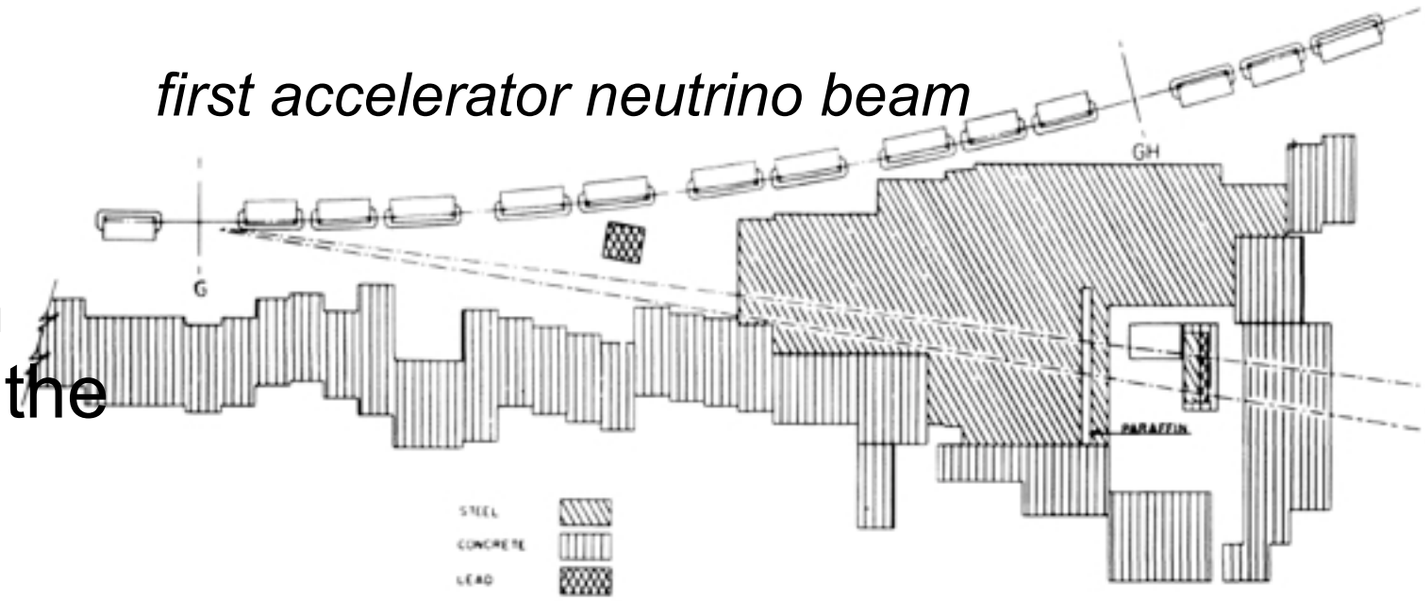
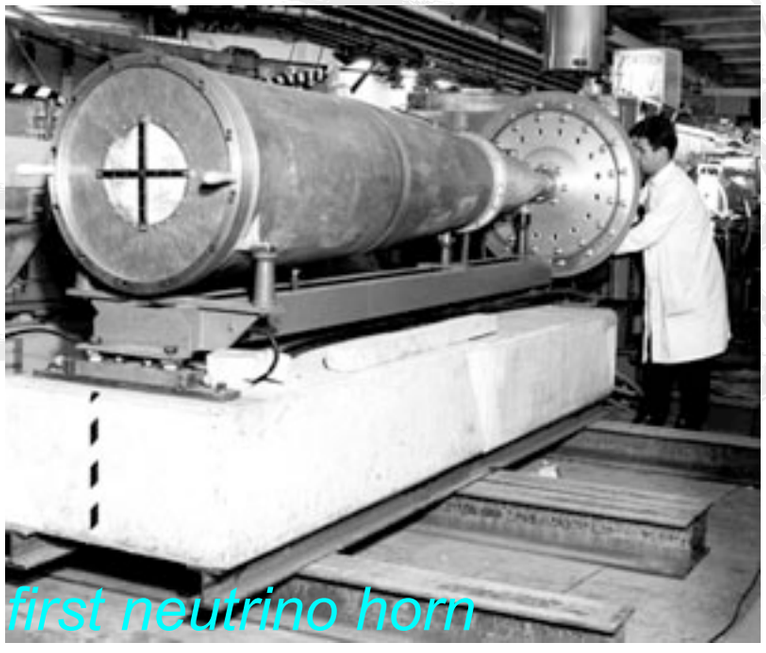


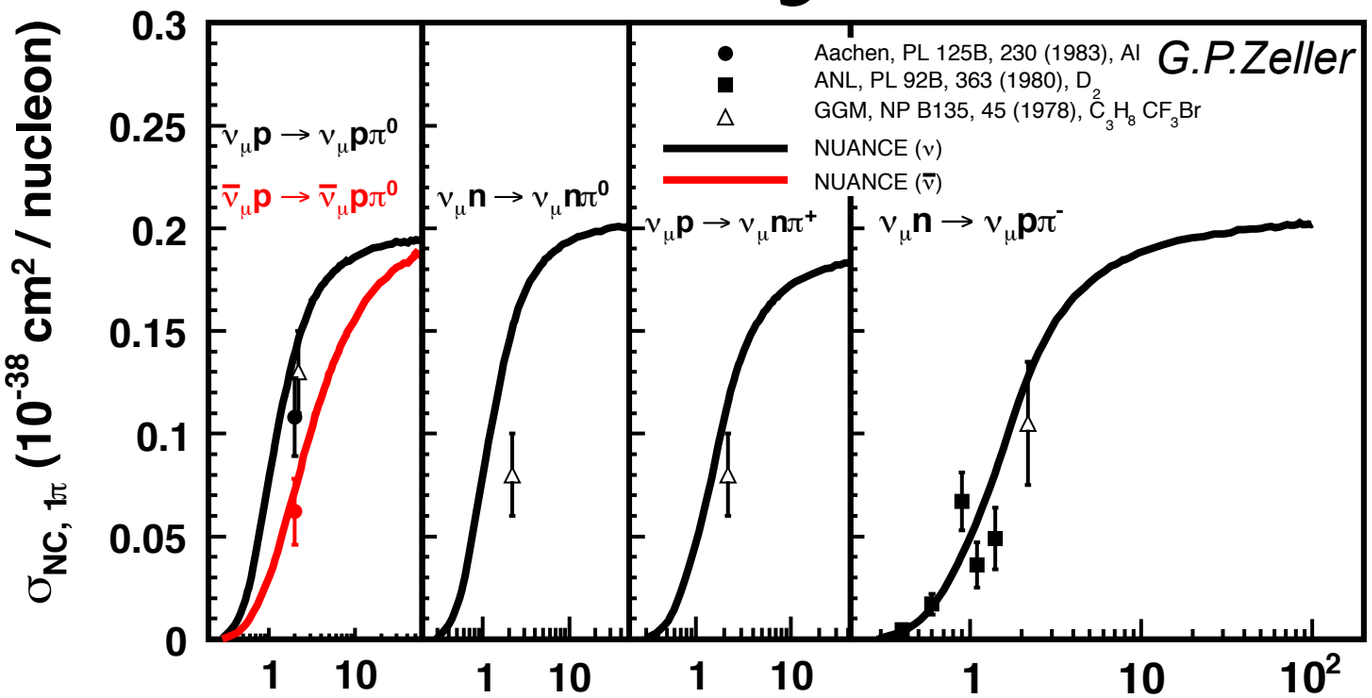

FIG. 1. Plan view of AGS neutrino experiment.

- Accelerator neutrino experiments were born in the 1960s and came of age in the 1970s
- 1960s - First pion decay beam, first focussing horns
- 1970s - Development of big bubble chambers
- Discovery of 2nd generation of neutrinos and neutral currents

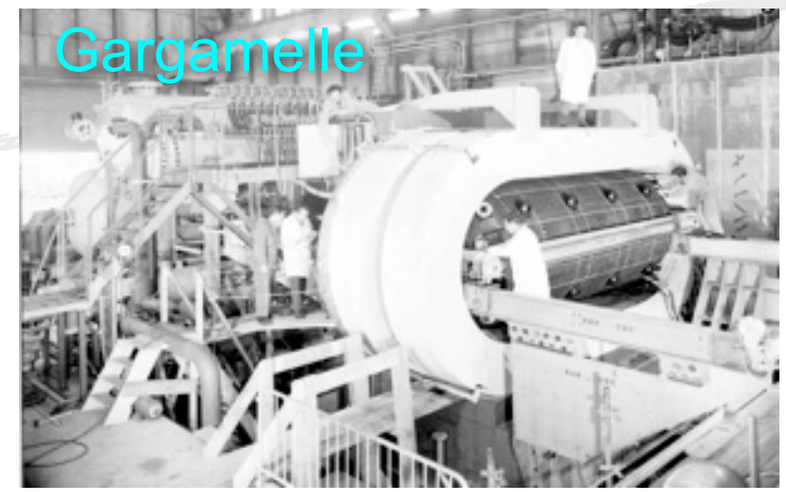


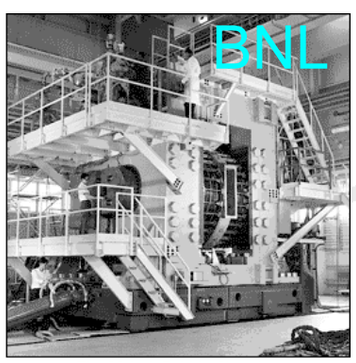
*first neutrino horn*

# Early neutrino data

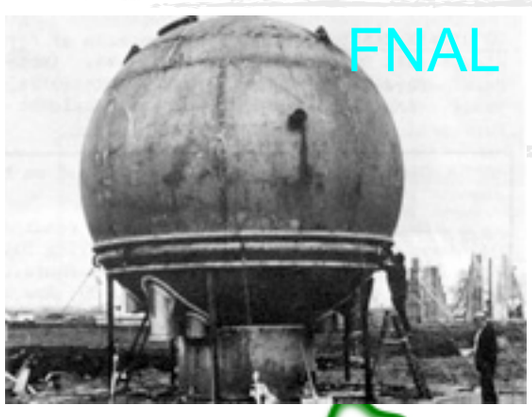


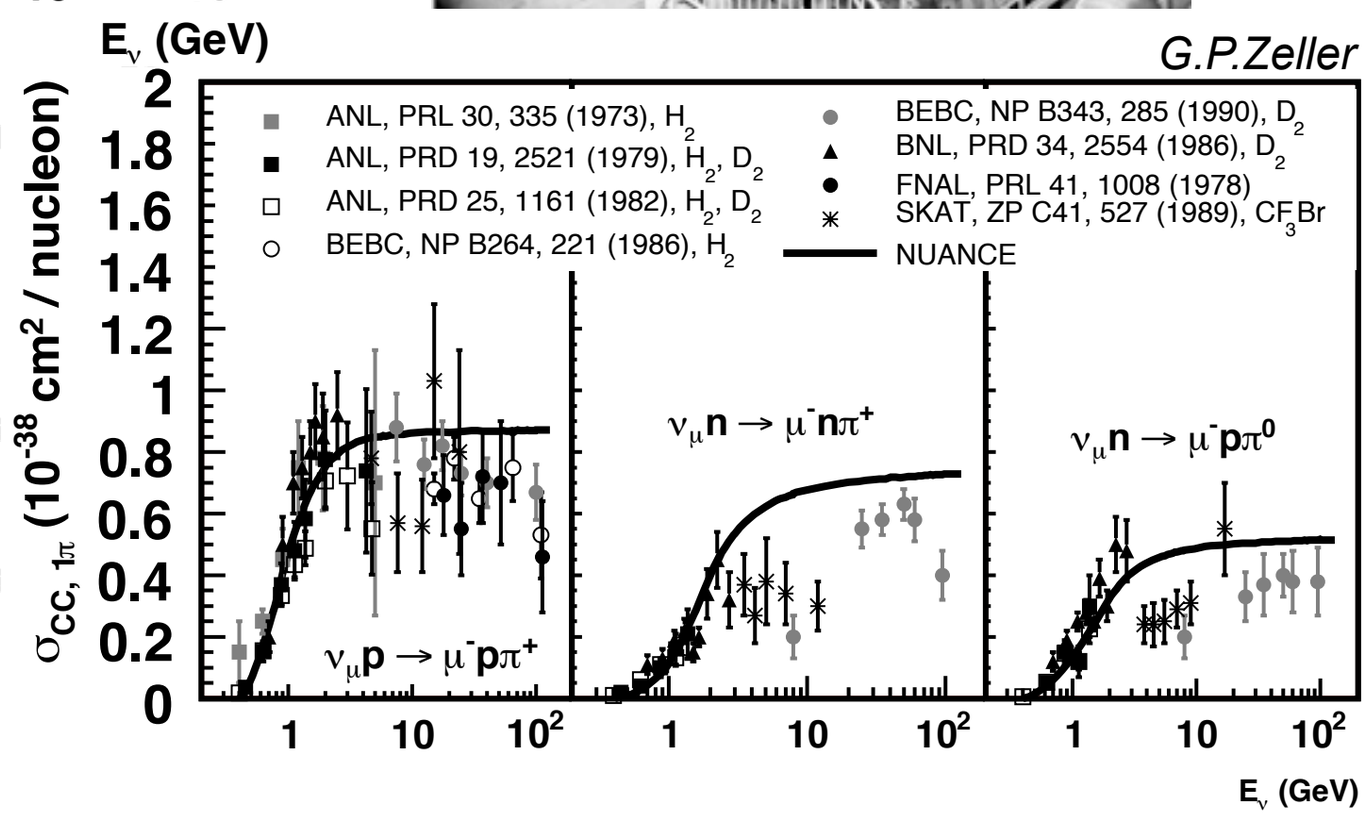

From discovery to (precision) measurements...



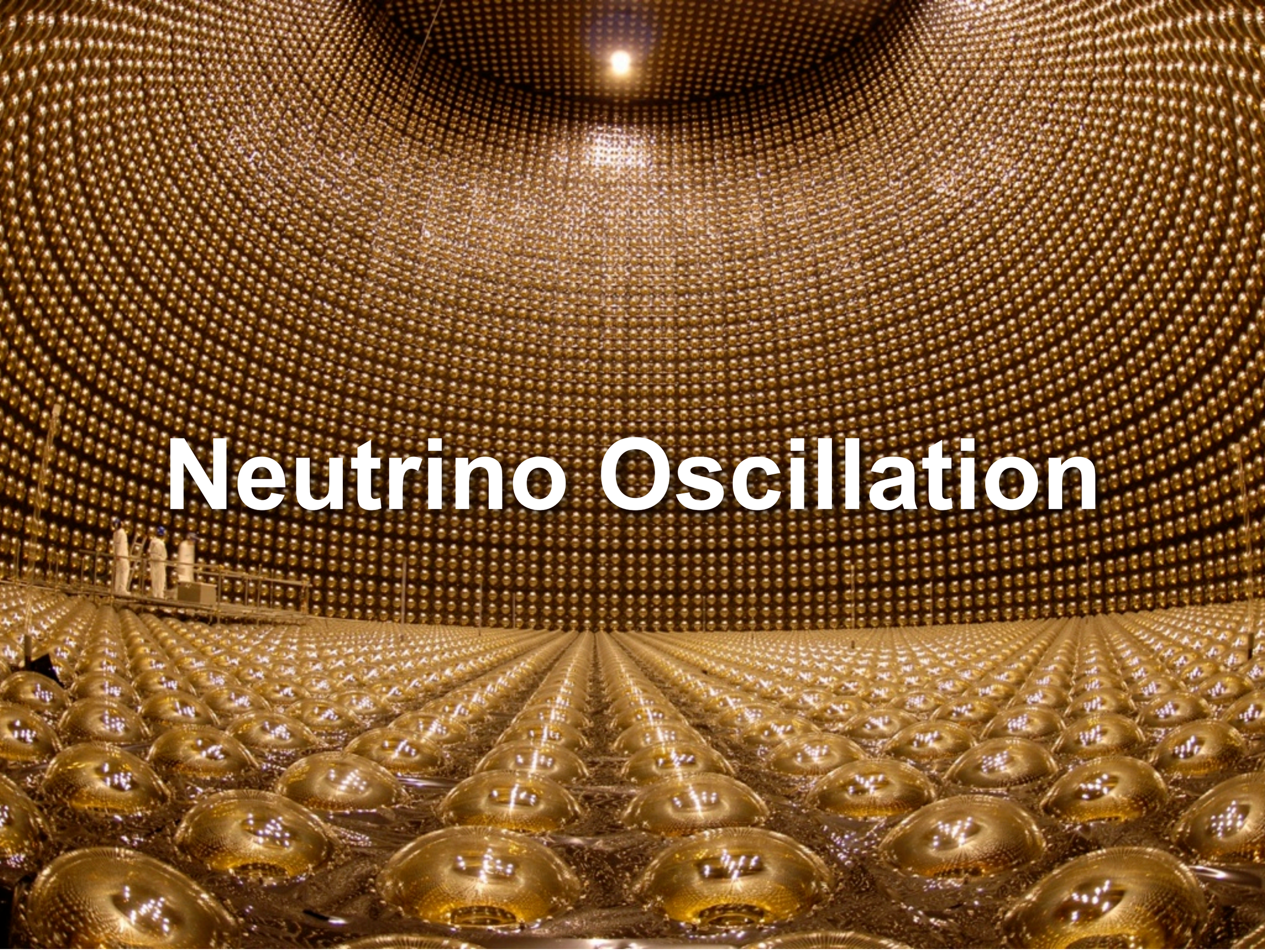




The 80-inch Bubble Chamber






*Plots from the PDG!*



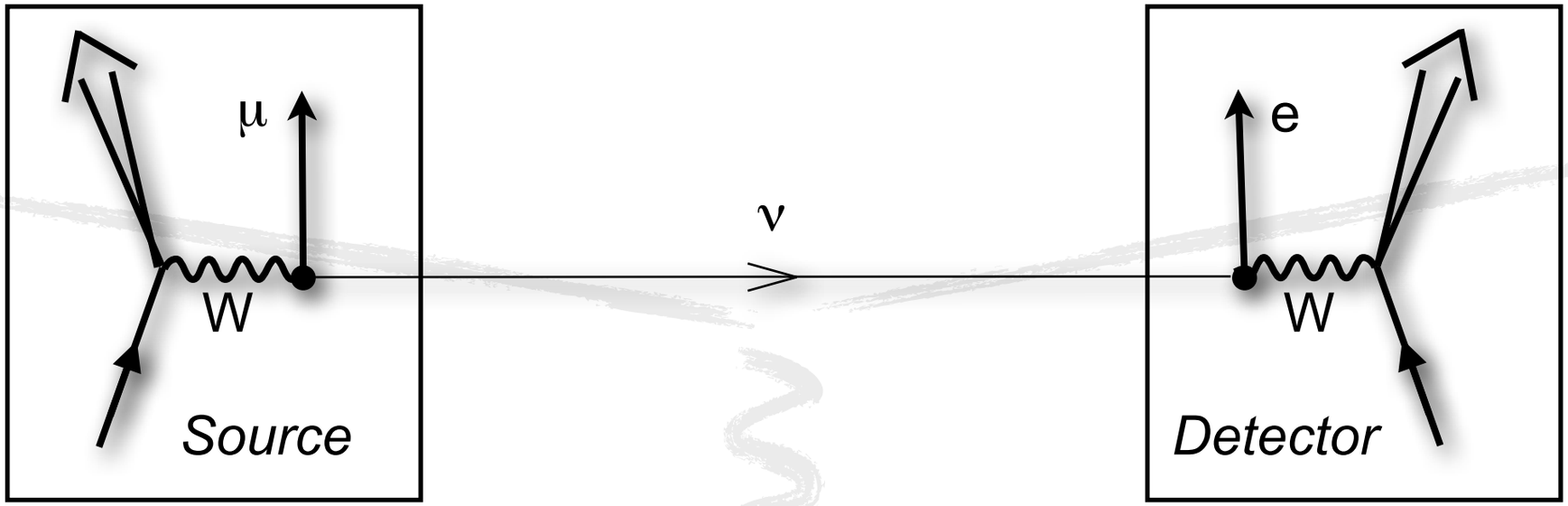
# Neutrino Oscillation

# Neutrino oscillation

Pontecorvo

Sov.Phys.JETP 6:429,1957

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

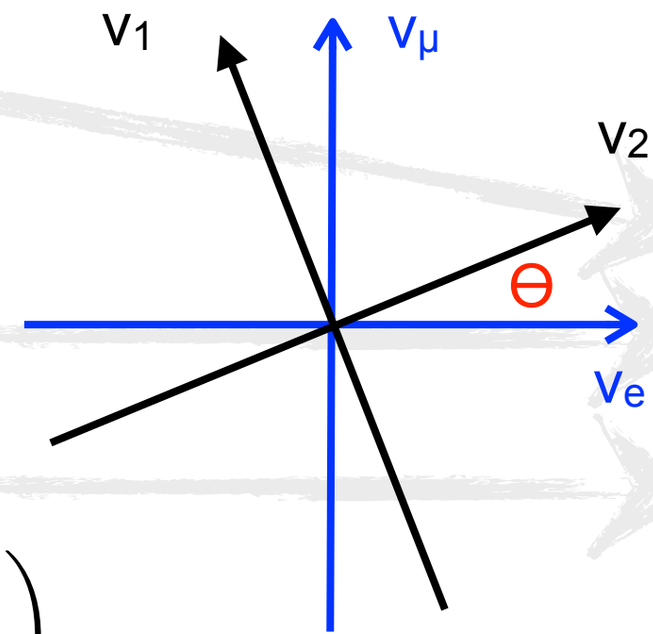


Maki, Nakagawa, Sakata

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

Simple 2 neutrino example-
if weak eigenstates ($\nu_e$, $\nu_\mu$) differ from mass eigenstates ($\nu_1$, $\nu_2$):

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

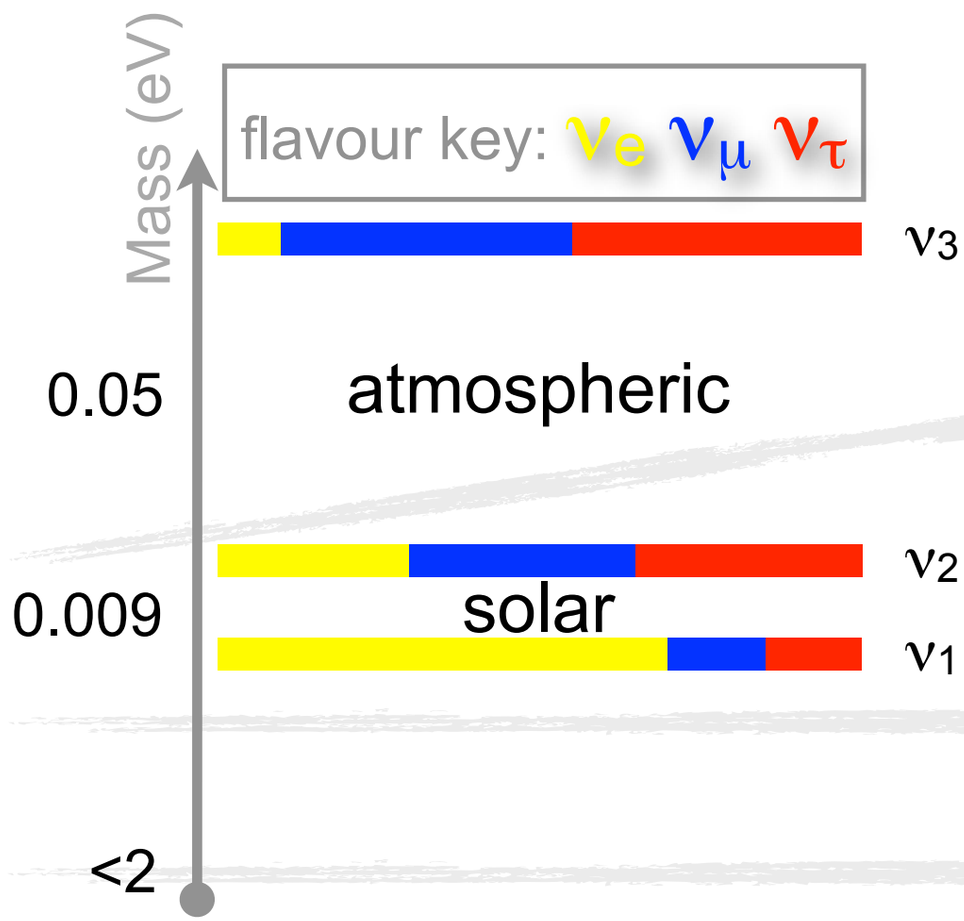



$$P_{oscillation}(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2 \left( \frac{1.27\ \Delta m^2(eV^2)\ L(km)}{E_\nu(GeV)} \right)$$

# 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 |
|---|---|
| $\lvert\Delta m^2_{32}\rvert$ | 2.35±0.12 E-03 ($eV^2$) |
| $\Delta m^2_{21}$ | 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 |
| $\delta_{CP}$ | (-0.5±0.62)$\pi$ ? |

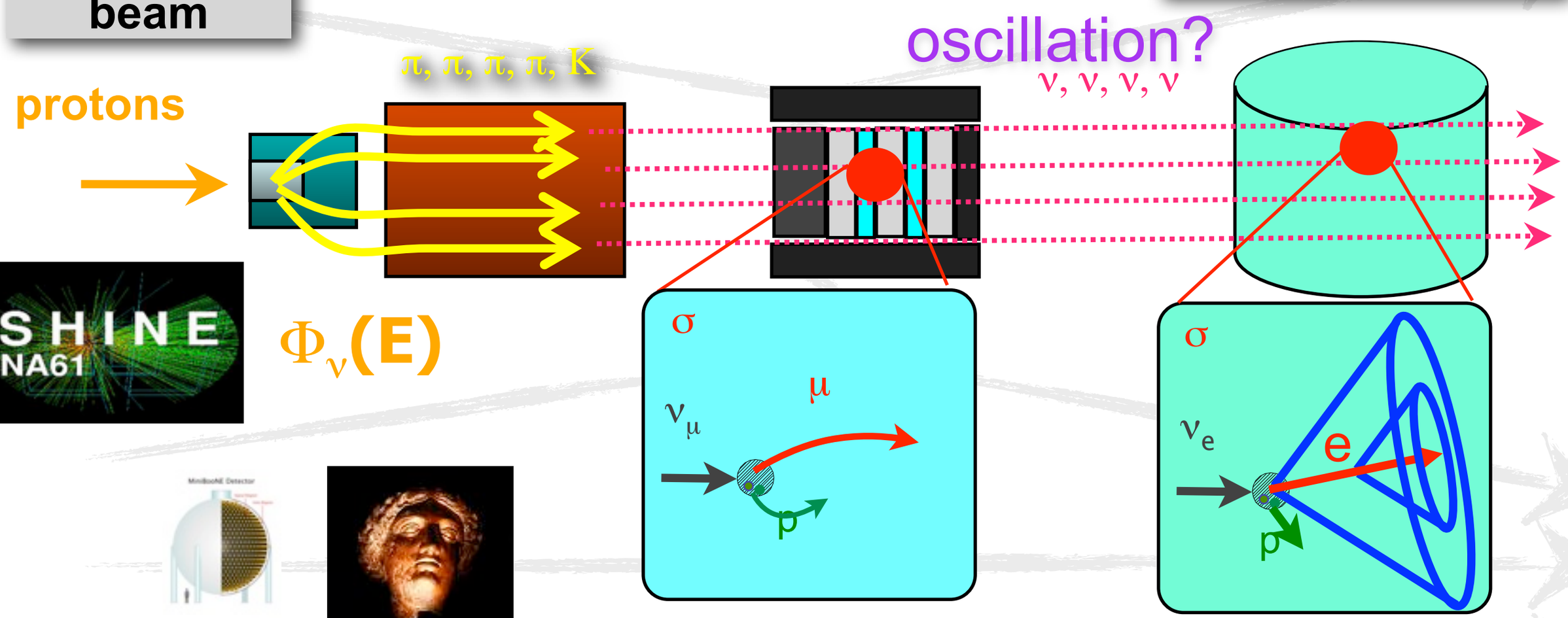
Accelerator experiments measure: $\Delta m^2_{32}$ (including sign), $\sin^2\theta_{23}$, $\sin^2\theta_{23}$ & $\delta_{CP}$

# Accelerator ν Experiments

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

**Intense beam**

**Gigantic detector**



$\Phi_\nu(E)$

SciBooNE

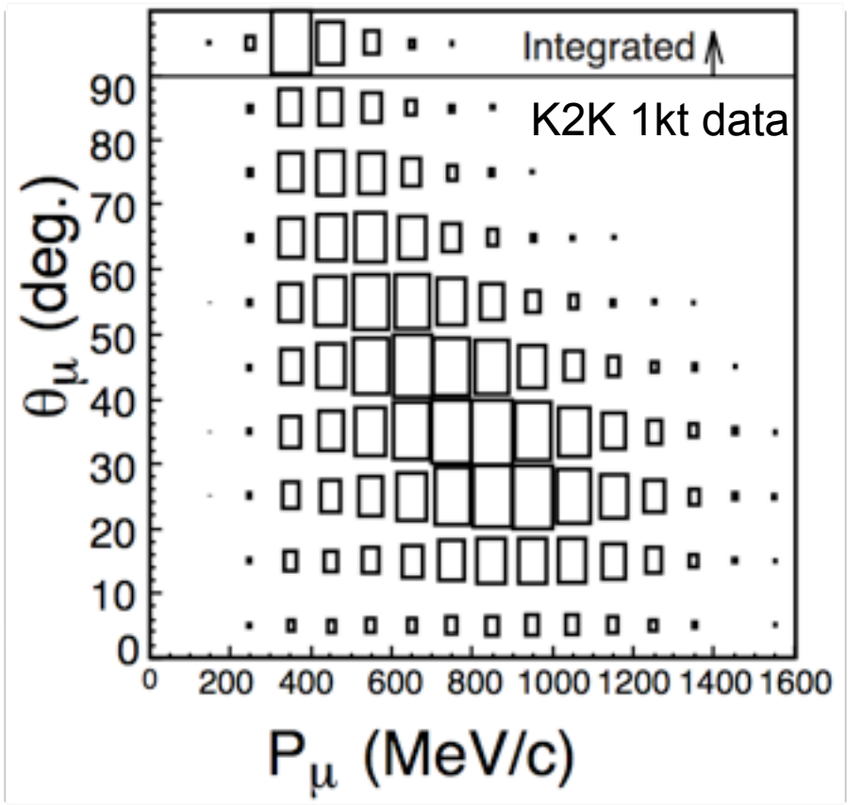
$$\Phi_\nu^{near}(E)\cdot\sigma^{near}(E)\cdot\varepsilon^{near}(E) \Leftrightarrow \Phi_\nu^{far}(E,\theta,\Delta m^2,\delta)\cdot\sigma^{far}(E)\cdot\varepsilon^{far}(E)$$

# What do we need?

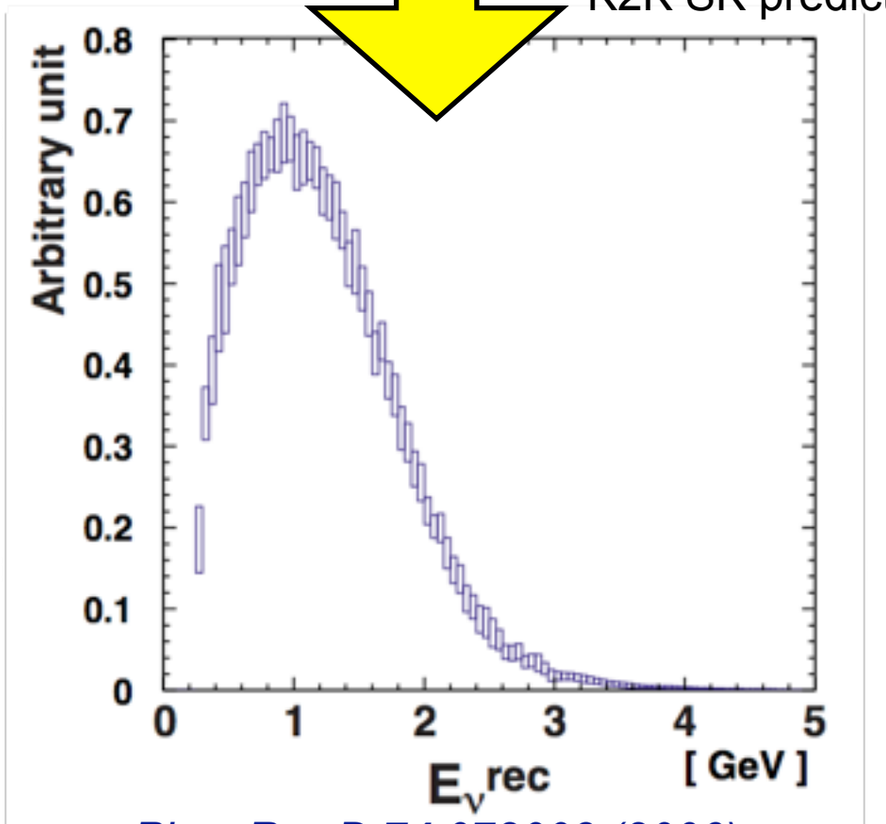
- Need to predict event rates and kinematics of final state particles;
- to reconstruct neutrino energy accurately;
  - both kinematic and calorimetric reconstruction;
- to accurately predict background contamination.

➡Need precise neutrino-nucleus cross-sections predictions

➡Need good models

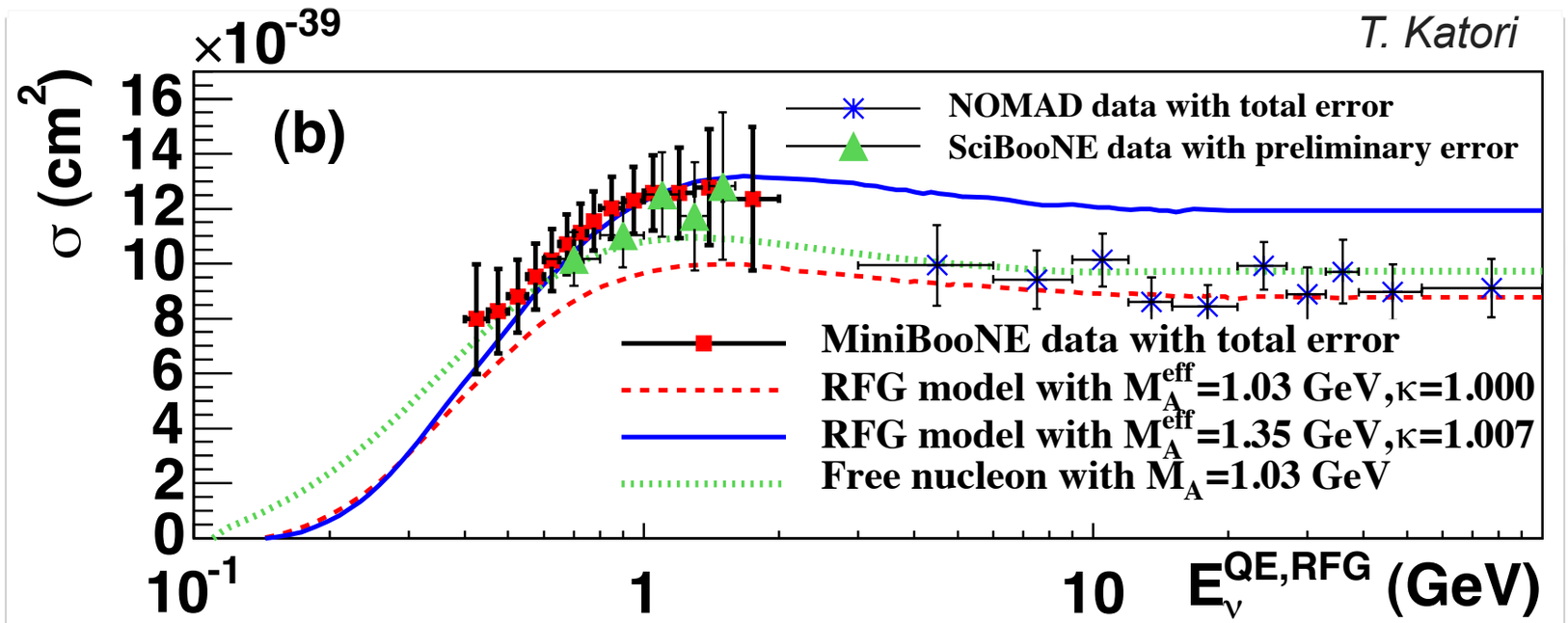



K2K SK prediction



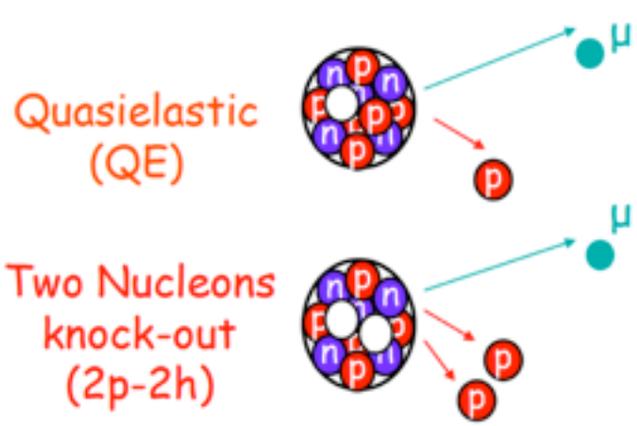

Phys.Rev.D **74** 072003 (2006)

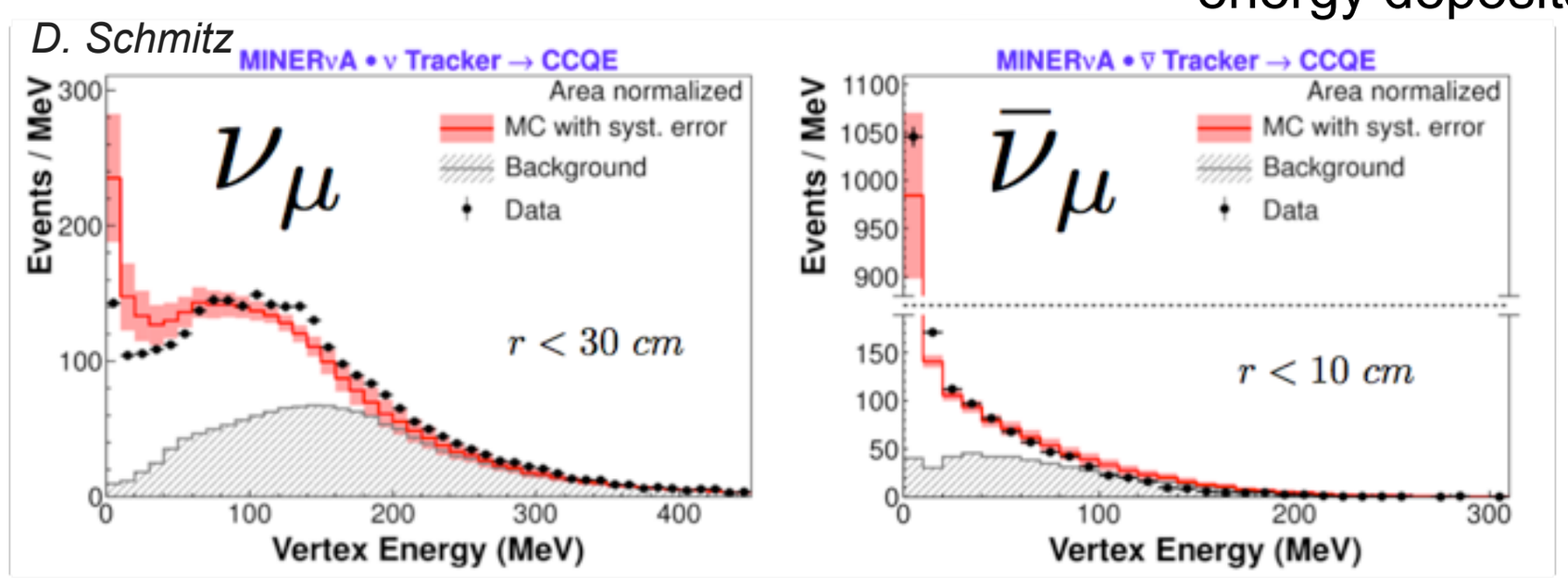
# Utility of models: Recent CCQE data




Significant discrepancies between BooNEs (~1 GeV) and NOMAD (~10 GeV).

MINERvA data show clues in recoil hadron energy deposits



# The effect of models on oscillations

- Cross section models currently used by experiments cannot describe K2K, MiniBooNE, SciBooNE, MINERvA, T2K observations.
  - Leads to larger systematic uncertainties.
- Model dependence will always be injected into data analysis
  - Energy, $Q^2$ reconstruction
  - Background subtraction
- Using these models will always give such uncertainties.
  - Need to develop better models!

*Systematic uncertainties reported by the world's most sensitive $\nu_e$ appearance experiments: MiniBooNE and T2K*

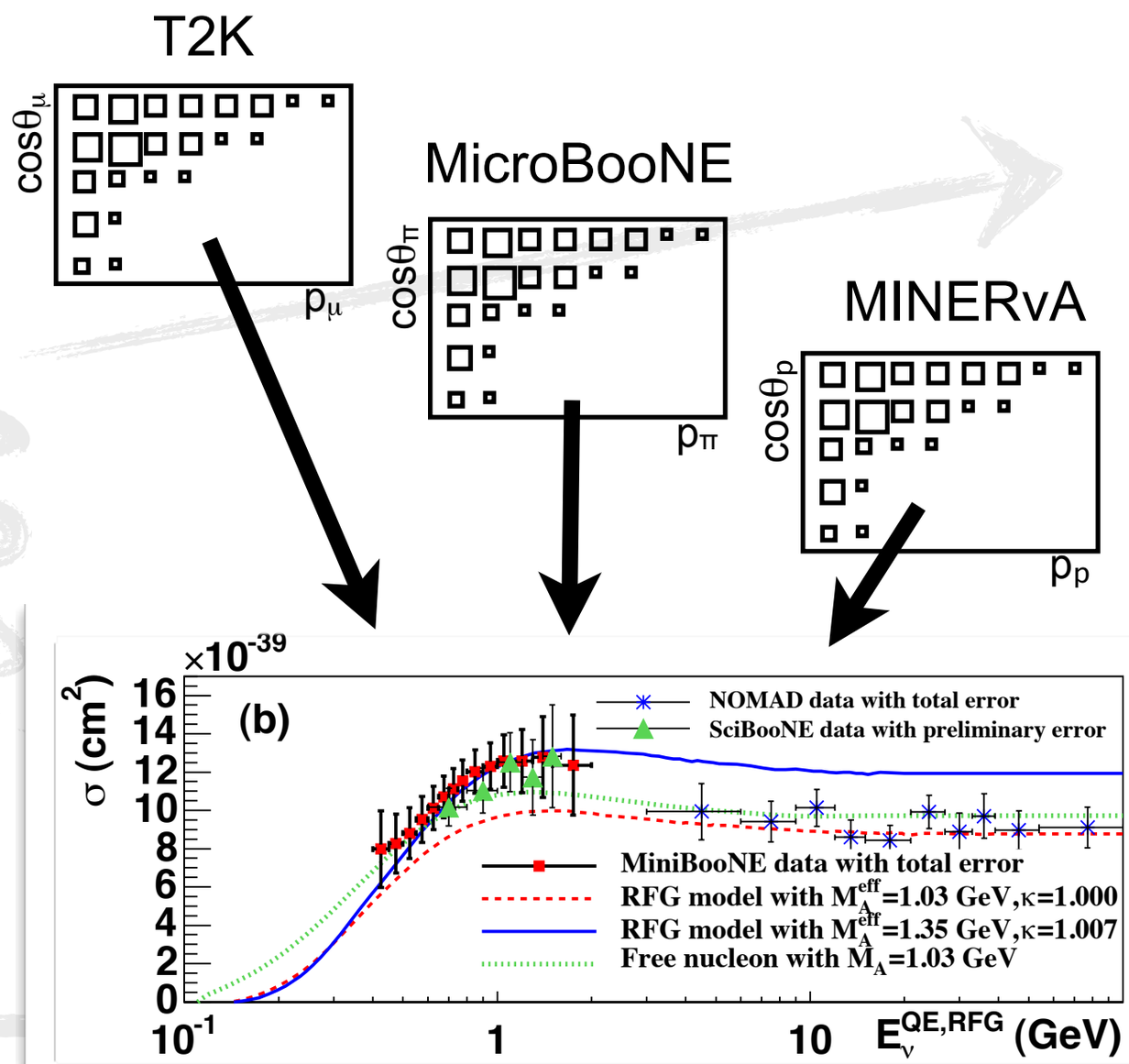
| Experiment | xsec err (%) | total err (%) |
|---|---|---|
| MiniBooNE (2007) | 12.3 | 17.6 |
| T2K (2012) | 7.5 | 10.3 |

*Conrad & Louis, FNAL Wine and Cheese Apr 11 2007*

*T. Nakaya, Neutrino 2012, Kyoto*

# Growing Consensus

- We need broad coverage
  - Model independent measurements at many energies, nuclei
- Differentiate between process cross-sections...
  - $\sigma$(CCQE), $\sigma$(CC res $\pi$), $\sigma$(CC coh $\pi$)
- ...and final state particle cross-sections
  - $\sigma$(CC), $\sigma(\mu)$, $\sigma(\mu+p)$, $\sigma(\mu+\pi)$




*Must succeed to achieve 1-2% total errors for Hyper-K and LBNF!*

*Today: progress by T2K on multiple xsec fronts.*

*Alex Himmel will present oscillation results Dec 12.*

# Interaction model

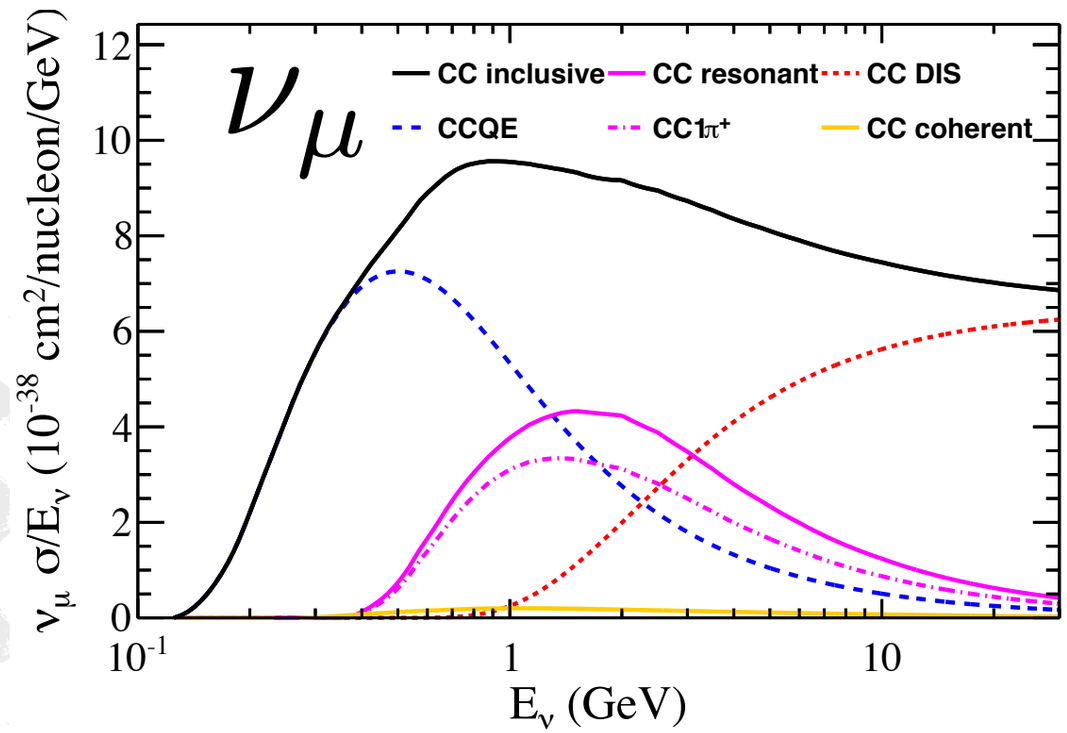
# $\nu$-nucleus interaction models

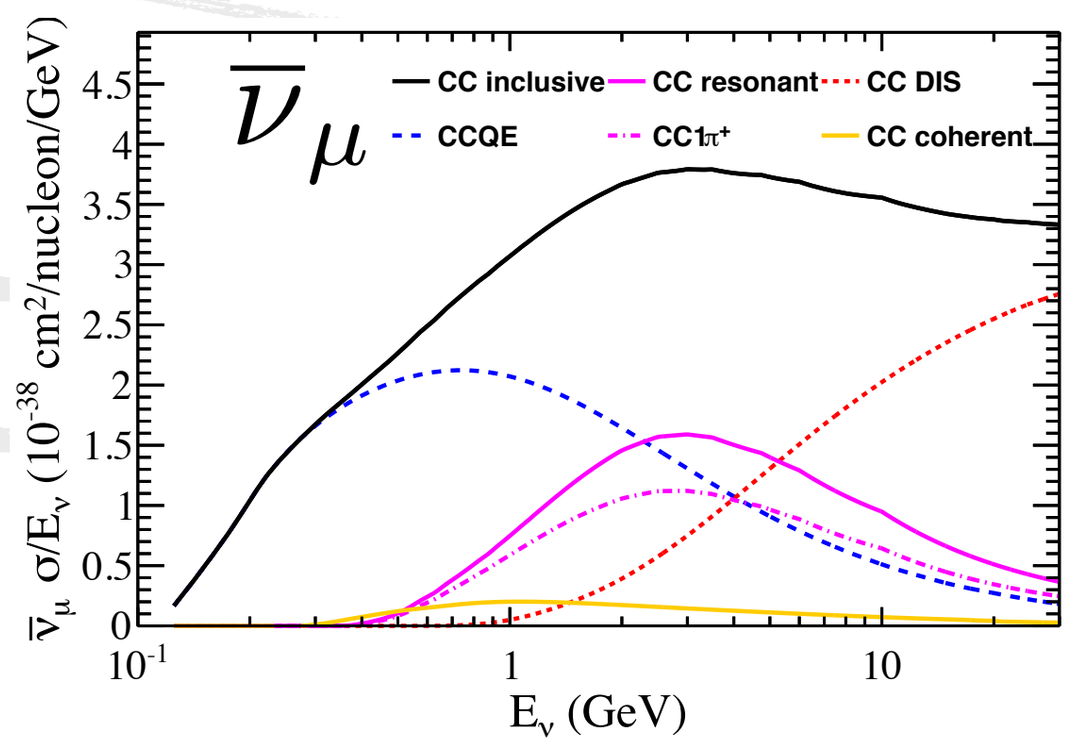
- T2K's primary neutrino generator MC is NEUT
  - Used by SK, SciBooNE, K2K
  - Tuned with fits to external data sets
  - 2012: mainly MiniBooNE CCQE, CC1$\pi^+$, CC1$\pi^0$, NC1$\pi^0$
    - Fits used to tune model parameters for prior inputs to oscillation analysis
    - Constrained and cross-checked with SciBooNE and K2K data
  - 2014: MiniBooNE and MINERvA $\nu$ and $\bar{\nu}$ data sets
    - Fits used to down select default interaction model and tune parameters for prior inputs to oscillation analysis
  - Working on a publication to describe the model and the fit procedure
- Also use GENIE and NuWro for cross-check analyses, systematic errors studies, and deeper inquiries into neutrino interactions

# NEUT interaction model

## *2012 model & parameters (v5.1.4.2)*

- CCQE: Llewellyn Smith, $M_A^{QE}$=1.2 GeV/$c^2$
- CC resonant $\pi$: Rein-Sehgal, $M_A^{RES}$=1.2 GeV/$c^2$
- 2p2h: not simulated
- Nuclear model: Smith-Moniz RFG
- RPA effects not included
- Coherent pion: Rein-Sehgal with lepton mass effects
- DIS with Bodek-Yang corrections
- Neutrino and antineutrino interactions simulated
- $\nu_\mu$ and $\nu_e$ simulated
  - Only differ at low energy

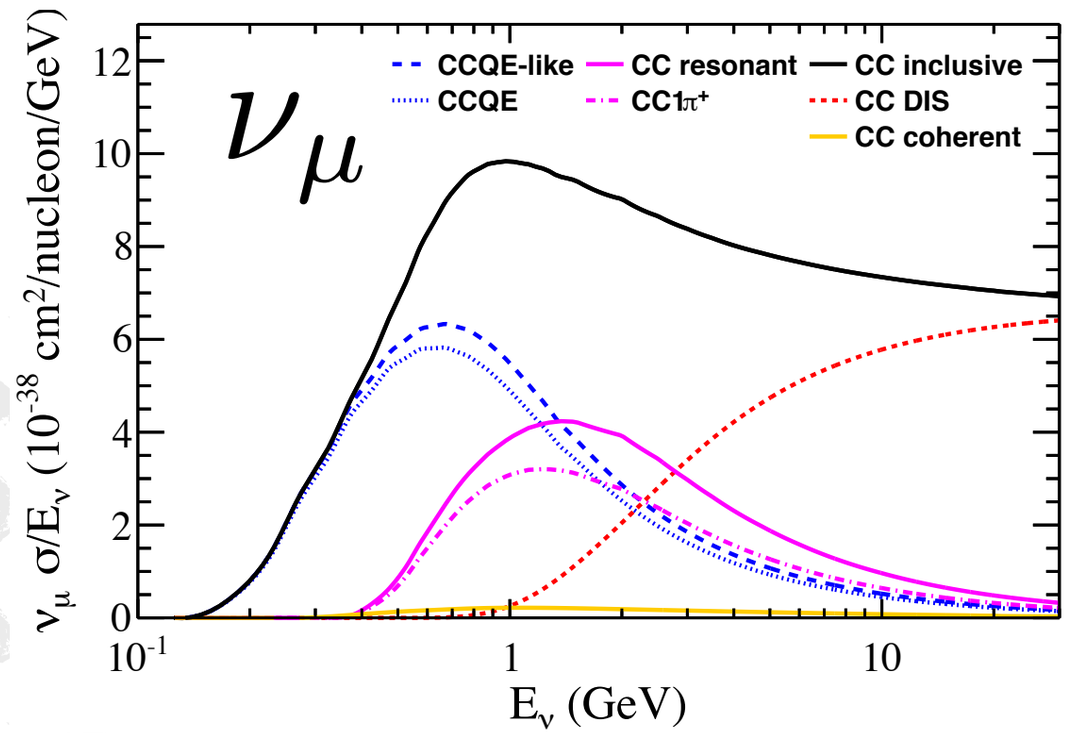


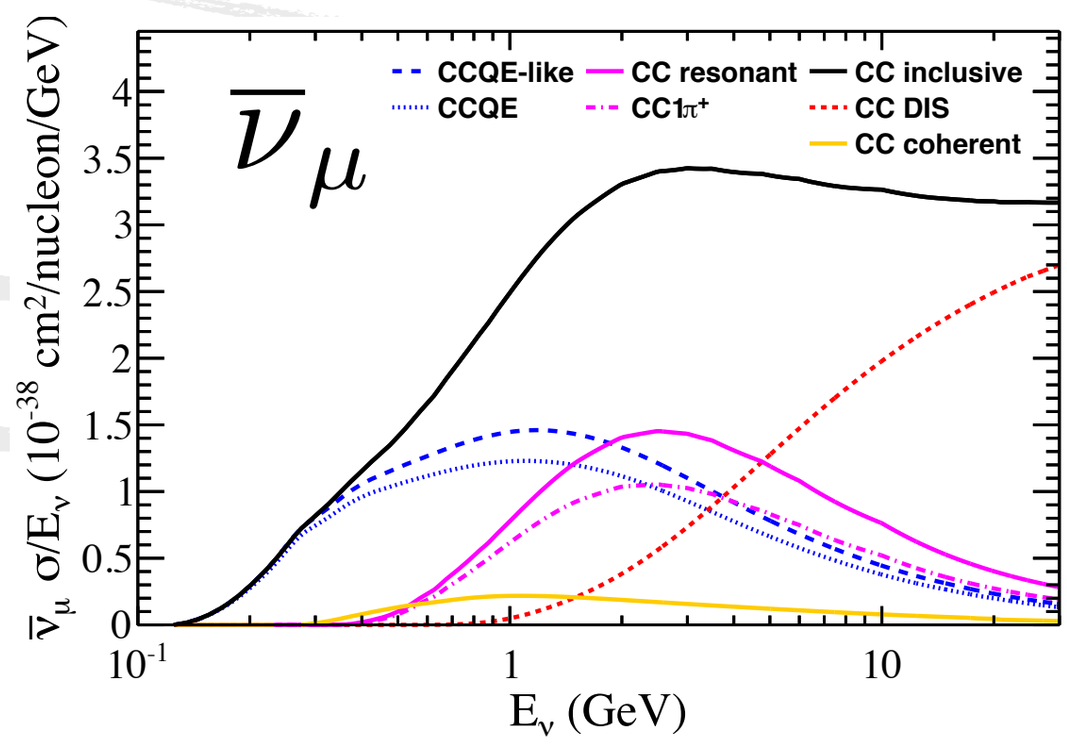



# NEUT interaction model

## *2014 model & parameters (v5.3.3)*

- CCQE: Llewellyn Smith, $M_A^{QE}$=1.0 GeV/$c^2$
- CC resonant $\pi$: 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
- $\nu_\mu$ and $\nu_e$ simulated
  - Only differ at low energy
  - Radiative corrections
- Second class currents



# Analysis Methods

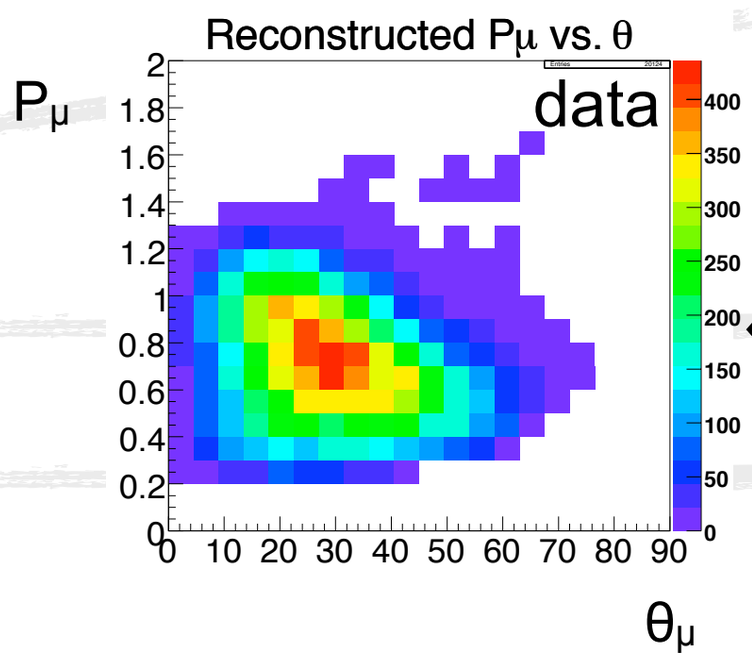
# Method 1: template fit

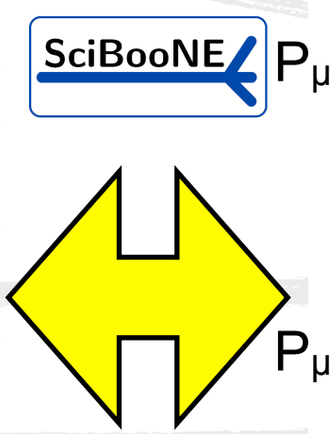
*Compare data to MC, within context of a model, using templates.*

$$\sigma_i = f_i < \sigma^{pred} >_i = \frac{f_i N_i^{pred} P_i}{\epsilon_i T \Phi_i}$$

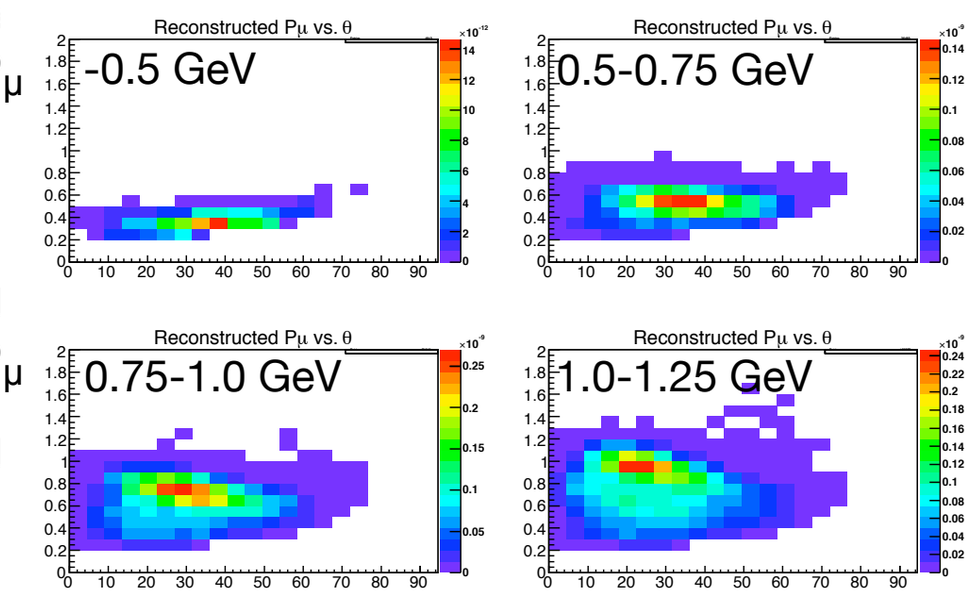
i = bin of xsec variable
$f_i$ = normalisation factor
$N_i^{pred}$ = predicted # of events
$P_i$ = purity
$\epsilon_i$ = efficiency
T = number of nuclear targets
$\Phi_i$ = neutrino flux per bin

Templates can be produced in observed dynamical variables, different from xsec variable.




MC template (MRD-stop)

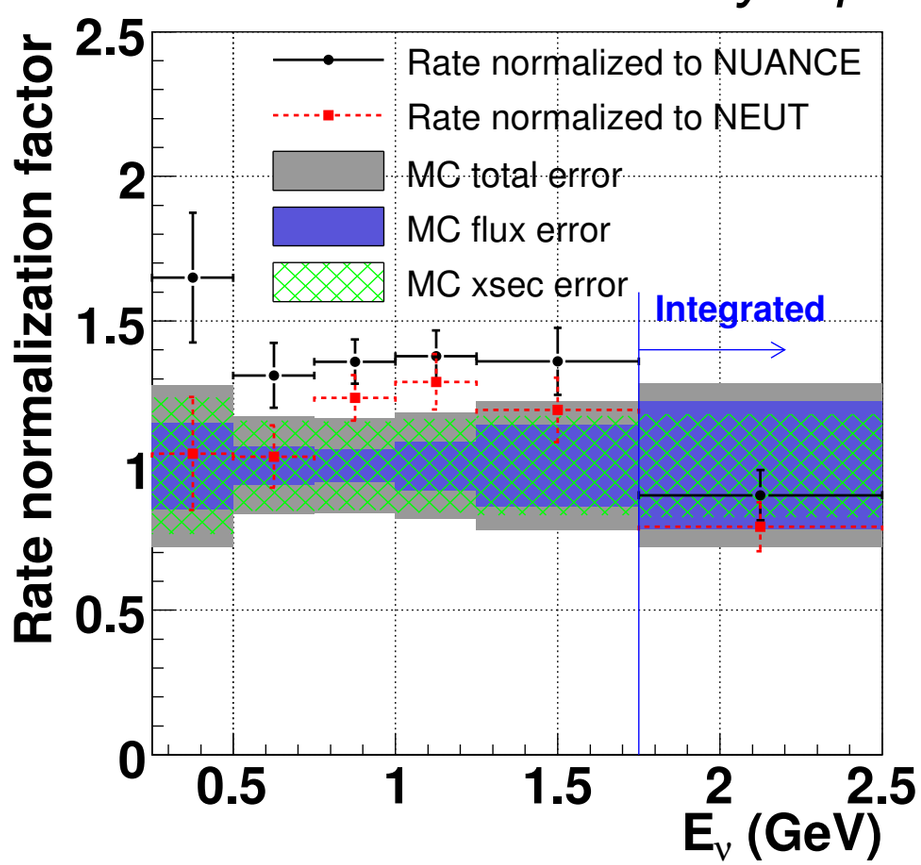


# Method 1: template fit

*Fit for values of $f_i$ that minimise some GoF parameter ($\chi^2$, likelihood), and use MC to infer the measured value of cross section.*

$$\chi^2 = \sum_{j,k}^{Nbins} (N_j^{obs} - f_j N_j^{pred})(V^{sys} + V^{stat})^{-1}_{jk}(N_k^{obs} - f_k N_k^{pred})$$

*Uncertainties: estimated with fake data studies by repeating the template fit with MC variants.*




**Advantage**: This method is especially useful for measuring cross sections as functions of input variables (like $E_\nu$) or internal variables (like $Q^2$).

**Drawback**: This method is susceptible to model bias. If your MC model differs from nature in some important way, you can infer the wrong answer!

# Method 2: Matrix unfolding

- Calculate cross section directly from number of events

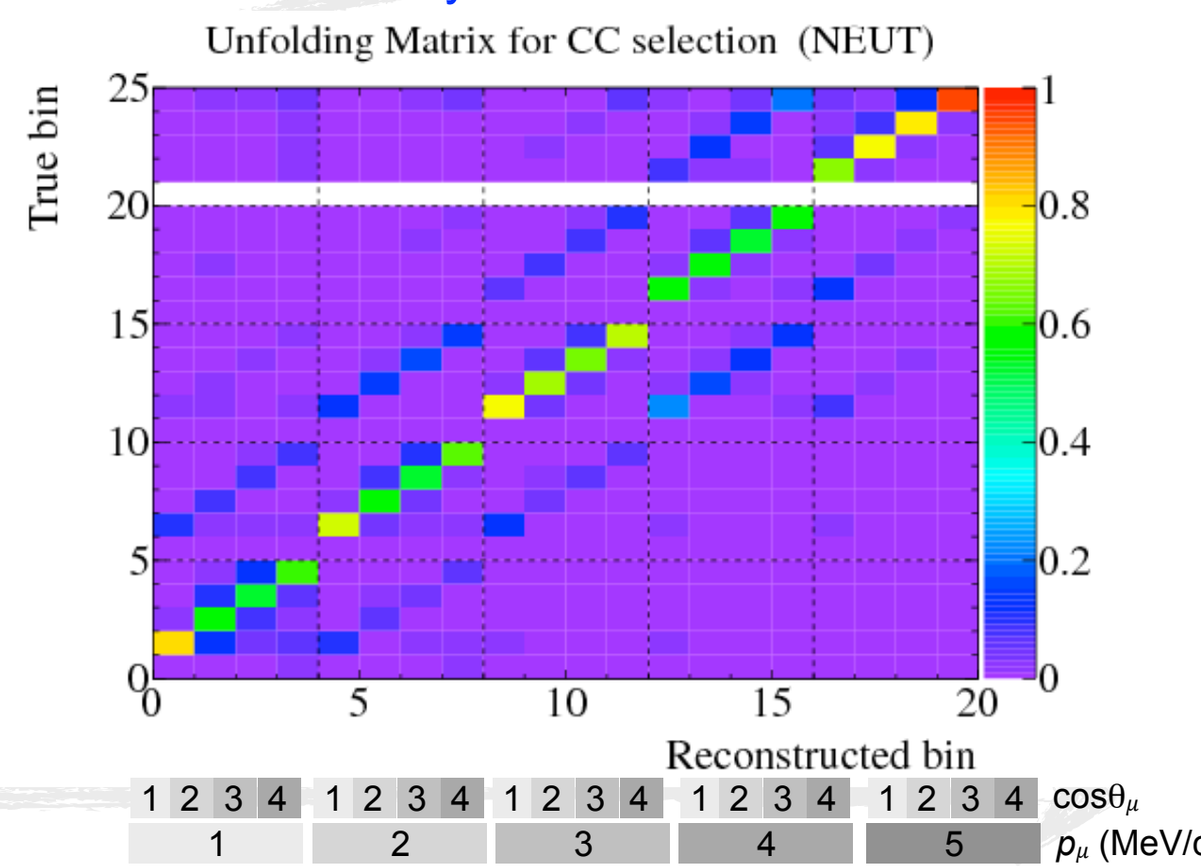
$$\hat{N}_i = \frac{\sum_j U_{ij}(N_j^{obs} - B_j)}{\epsilon_i}$$

1. Apply purity correction
2. Unfold to correct detector smearing
3. Apply efficiency correction

- Normalise with neutrino flux and number of nuclear targets to get cross section

➡Result is flux averaged differential cross section

j = bin of reconstructed variable
i = bin of corrected ("true") variable
$N_j^{obs}$ = observed # of events
$B_j$ = background events
$U_{ij}$ = unfolding matrix
$\epsilon_i$ = efficiency




$$\frac{d\sigma}{dx_i} = \frac{1}{T\Phi_\nu}\frac{\hat{N}_i}{\Delta x_i}$$

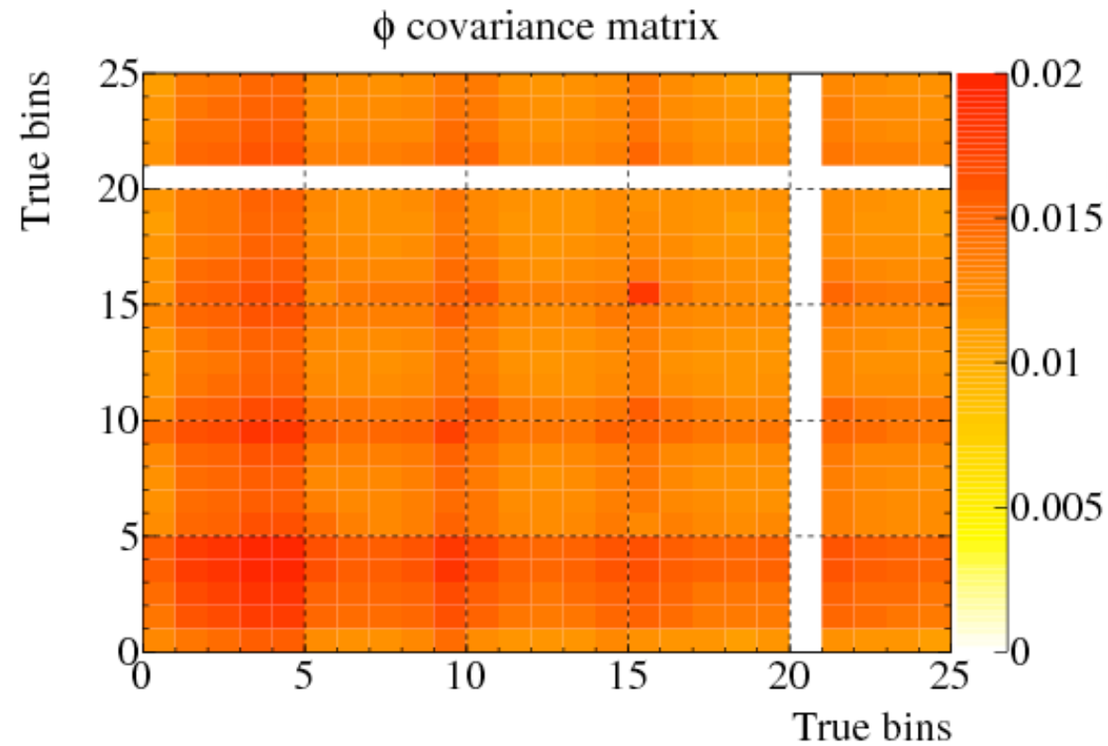
T = number of nuclear targets
$\Phi_\nu$ = total integrated neutrino flux
$\Delta x_i$ = bin width

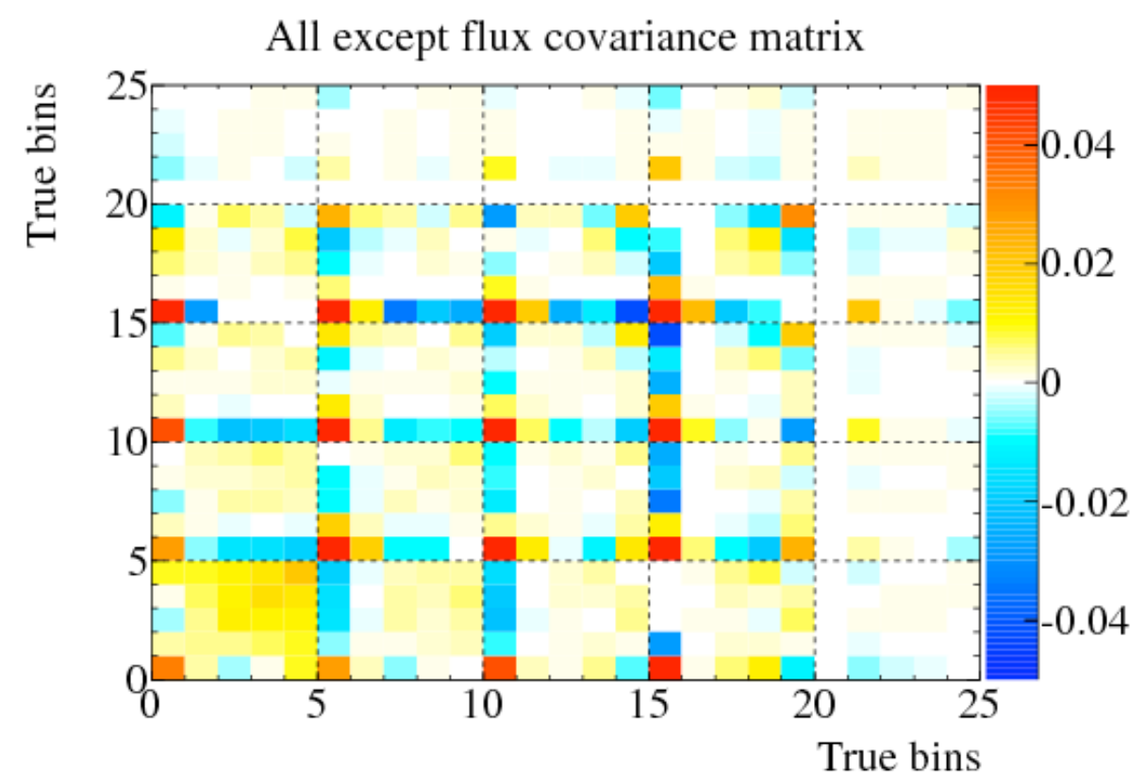
# Method 2: Matrix unfolding

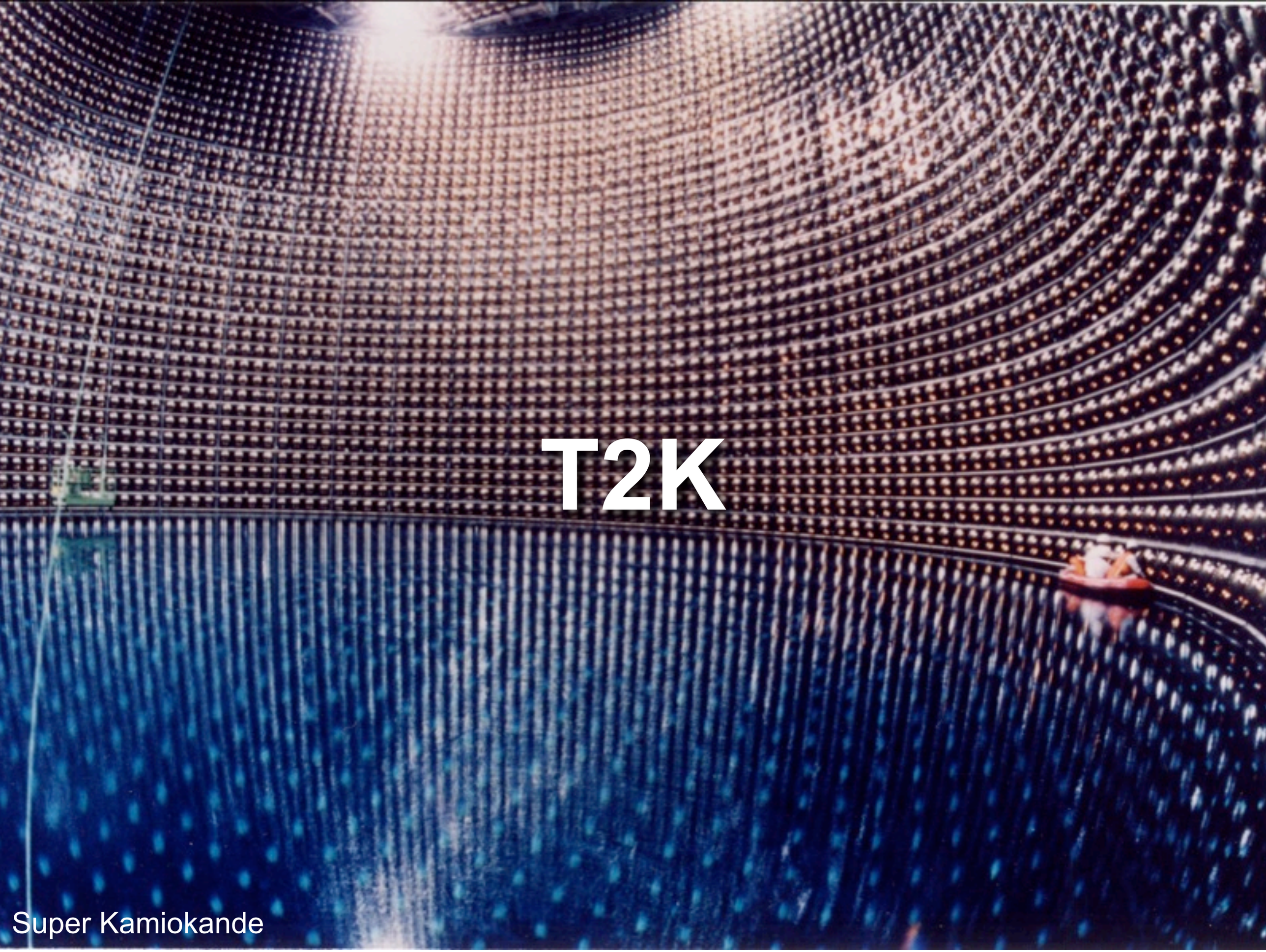
$$V_{kl} = \frac{1}{N_{var}} \sum_{s}^{N_{var}} (\sigma_k^s - \sigma_k^{nom})(\sigma_l^s - \sigma_l^{nom})$$

- Use MC variants to create covariance matrix
- Neutrino flux is (usually) just a normalisation error
  - We do, of course, propagate the full shape covariance
- Very useful to separate out the flux error

➡Potential for reducing model dependence with this method

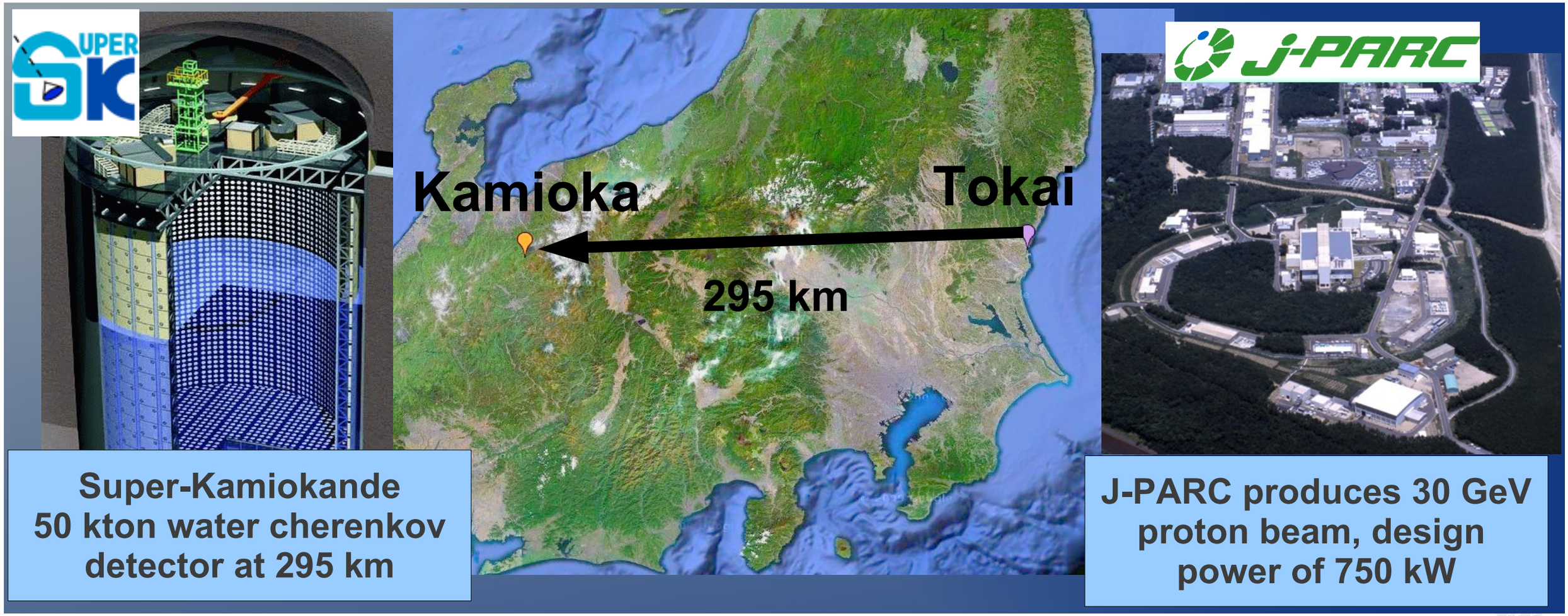



T2K
Super Kamiokande

# T2K (Tokai to Kamioka) Experiment

*First experiment purposely built for $\theta_{13}$ measurement*




- High intensity $\nu_\mu$ beam from J-PARC to Super-K
- Discovery of $\nu_e$ appearance ➠ determine $\theta_{13}$
  - Now, try to observe $\bar{\nu}_e$ appearance
- Precise measurements of $\theta_{13}$, $\theta_{23}$, $\Delta m^2_{32}$; ...$\delta_{CP}$?

# T2K Collaboration

~500 members, 59 Institutes, 11 countries

**Canada**
TRIUMF
U. Alberta
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.
U. Tokyo
Tokyo Metro U.

**Poland**
A. Soltan, Warsaw
H.Niewodniczanski, Cracow
T. U. Warsaw
U. Silesia, Katowice
U. Warsaw
U. Wroclaw

**Russia**
INR

**Spain**
IFIC, Valencia
U. A. Barcelona

**Switzerland**
U. Bern
U. Geneva
ETH Zurich

**United Kingdom**
Imperial College
Queen Mary U. L.
Lancaster U.
Liverpool U.
Oxford U.
Sheffield U.
Warwick U.
STFC/RAL
STFC/Daresbury

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

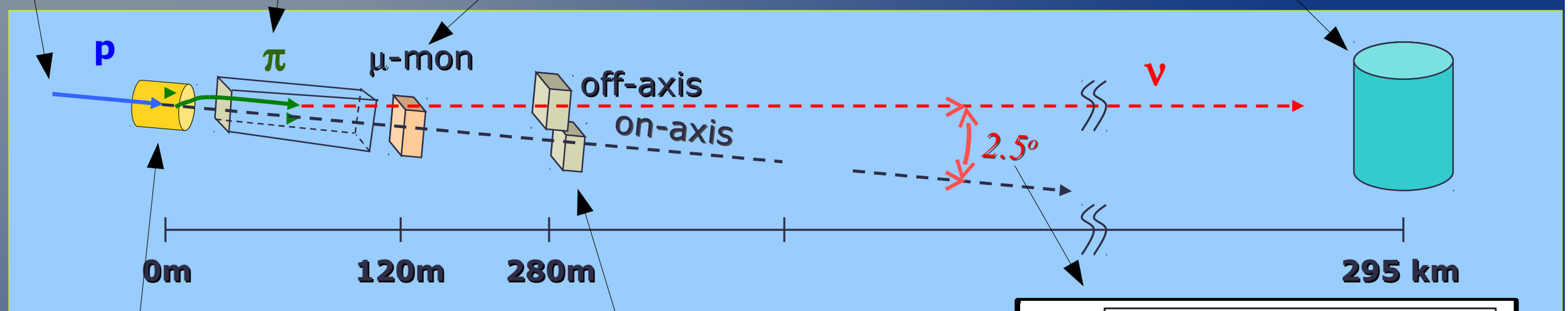
# T2K Overview

30 GeV proton beam from J-PARC Main Ring (MR)

Pions decay in 109 m decay volume

MUMON monitor measures muons from pion decay

Off-axis at 295 km, Super-Kamiokande (SK) water cherenkov detector measures oscillated flux

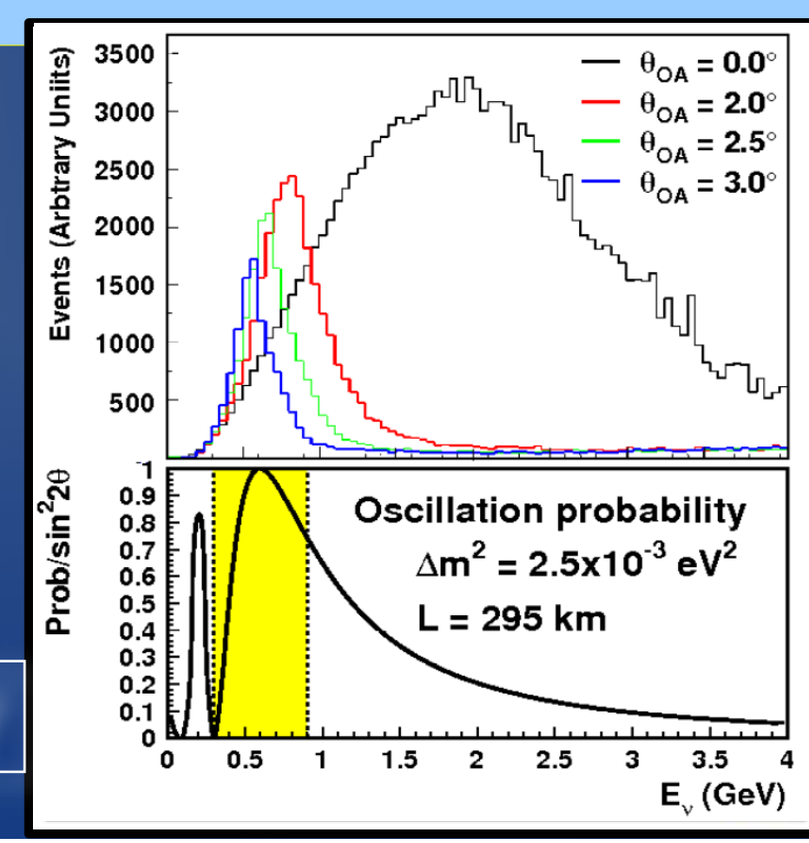



Beam on 90 cm graphite target

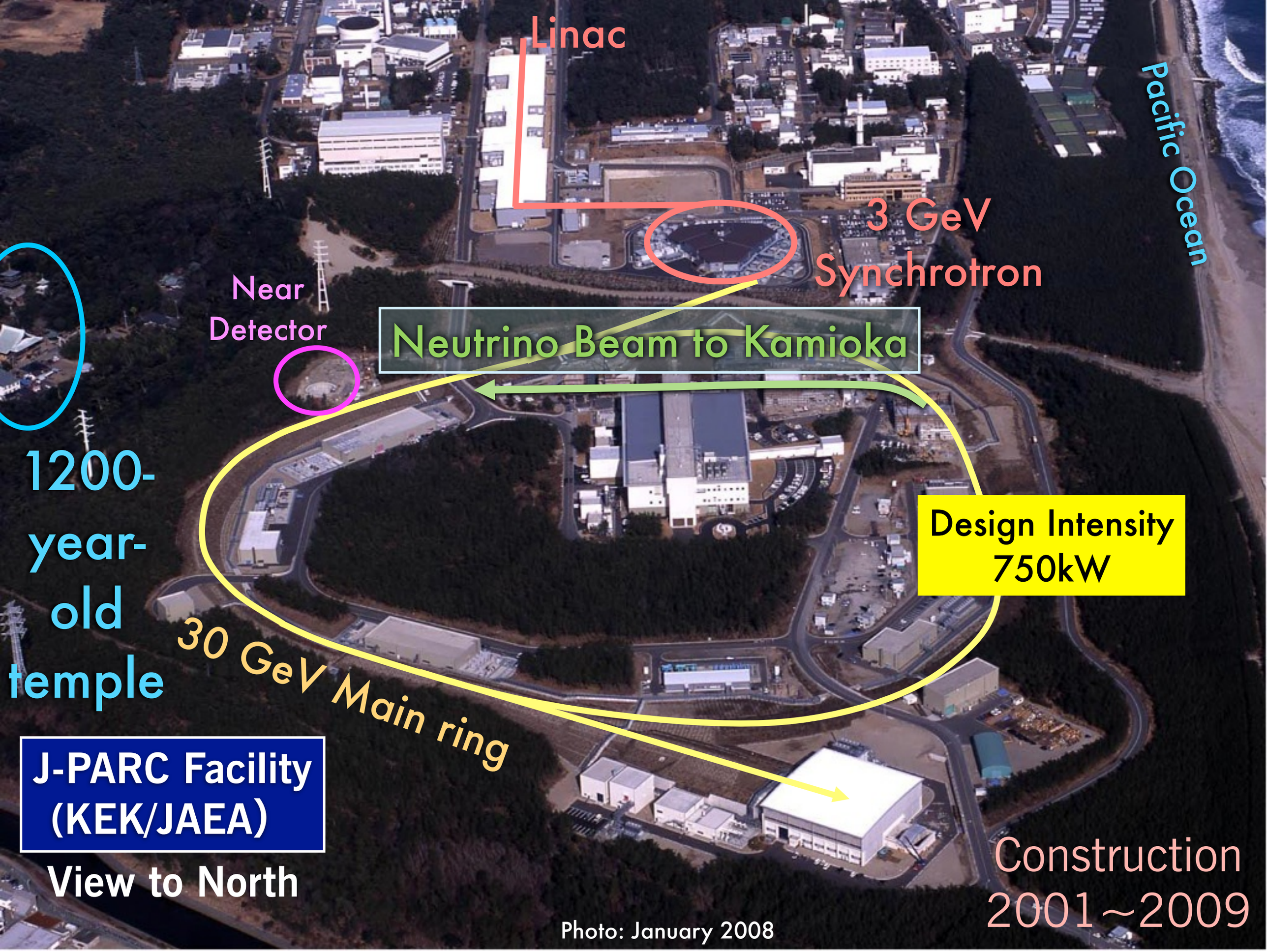
3 magnetic horns focus positively charged hadrons

At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

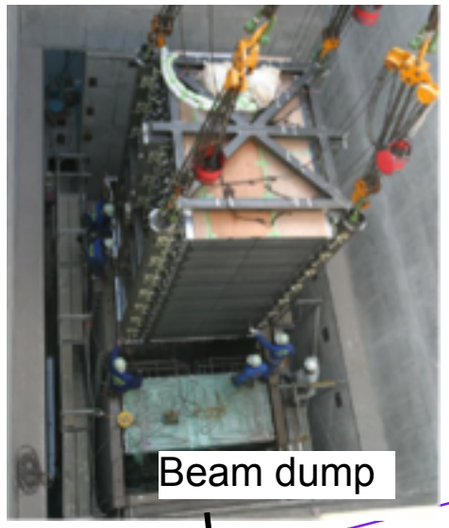
Off-axis ND280 detector measures spectra for various neutrino interactions




*Beam peaked at 1st max E≈600 MeV*

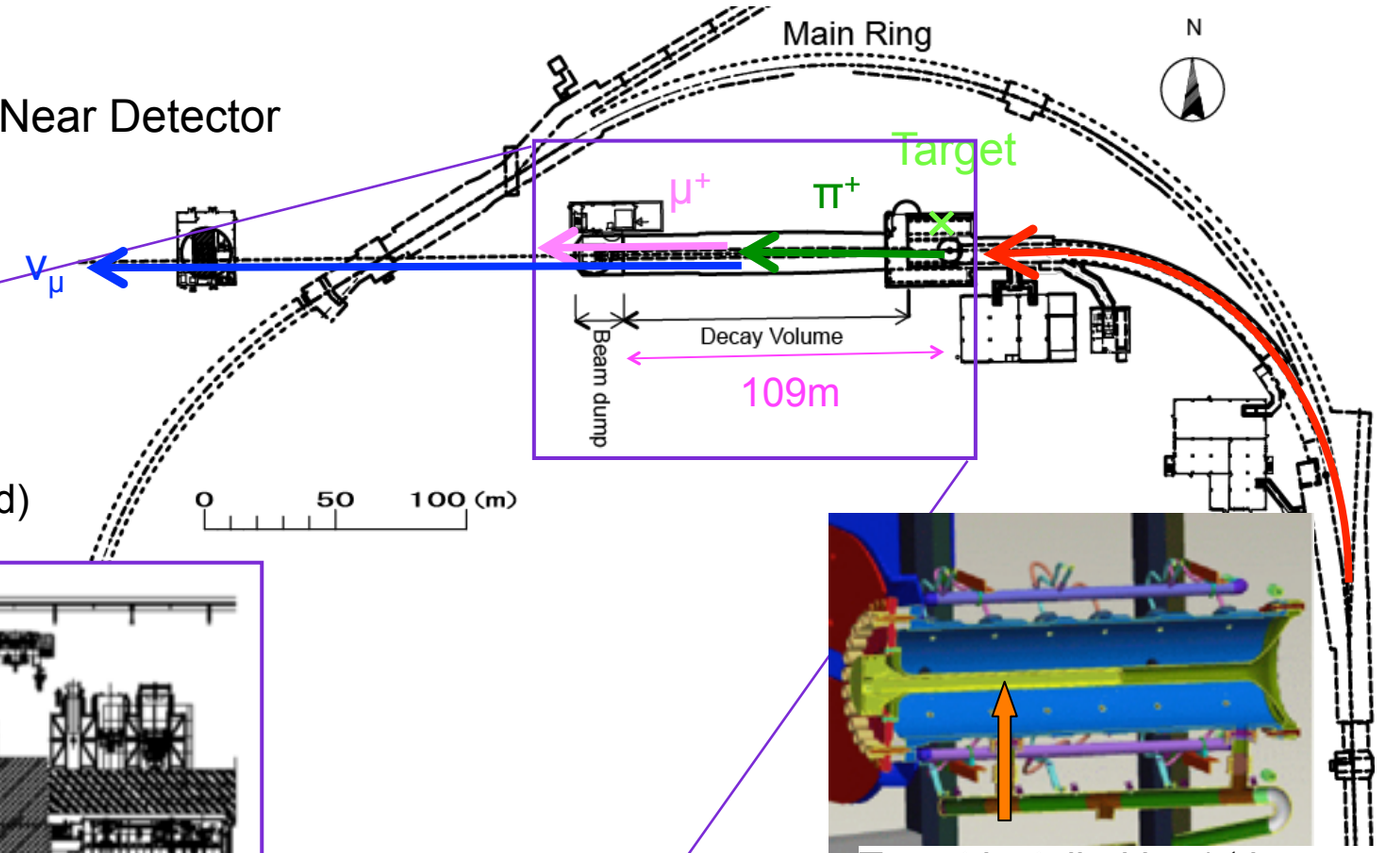

Linac
3 GeV
Synchrotron
Pacific Ocean
Near
Detector
Neutrino Beam to Kamioka
1200-
year-
old
temple
Design Intensity
750kW
30 GeV Main ring
J-PARC Facility
(KEK/JAEA)
View to North
Construction
2001~2009
Photo: January 2008

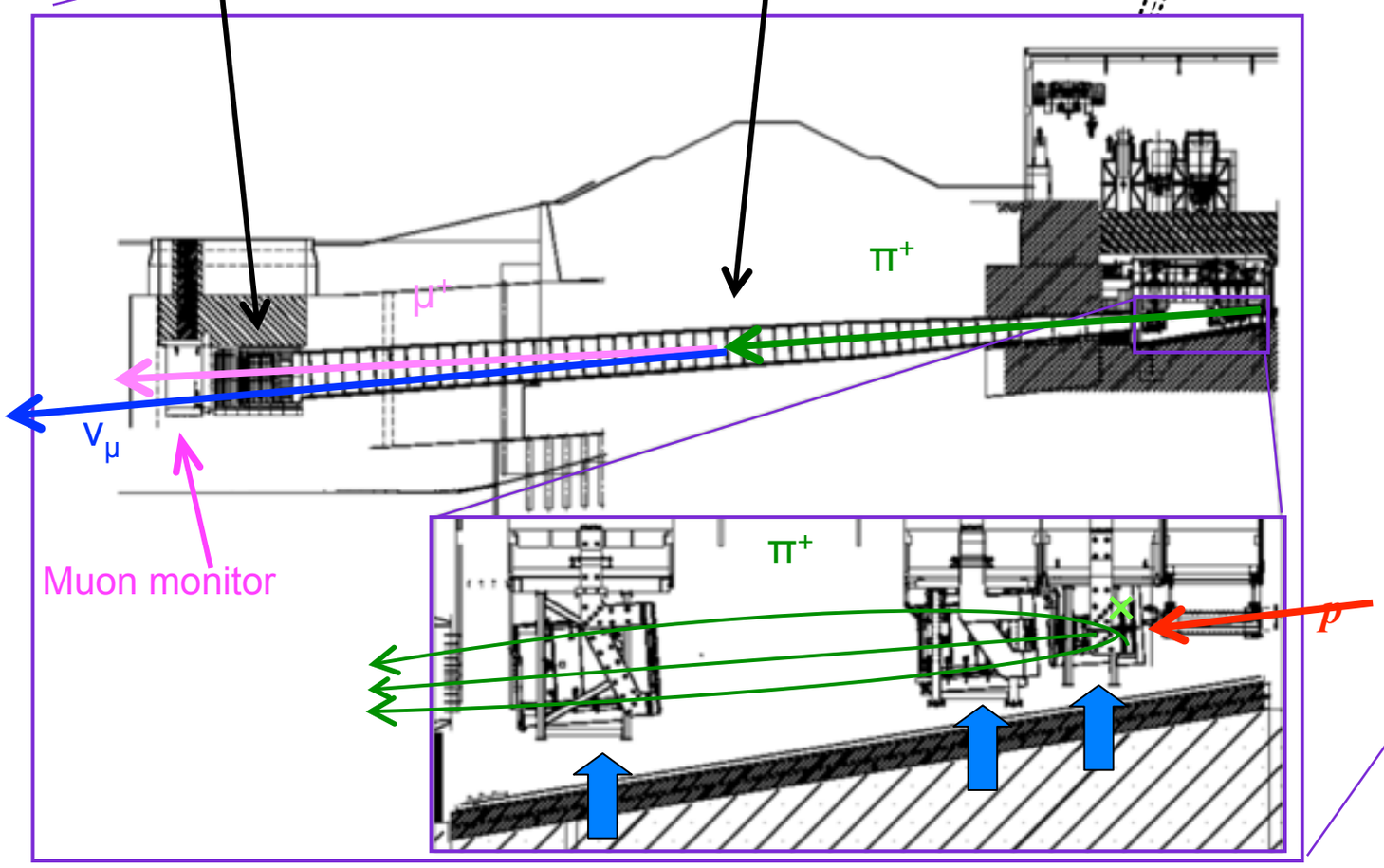
# J-PARC neutrino beamline overview



Decay volume (He gas filled)

Near Detector



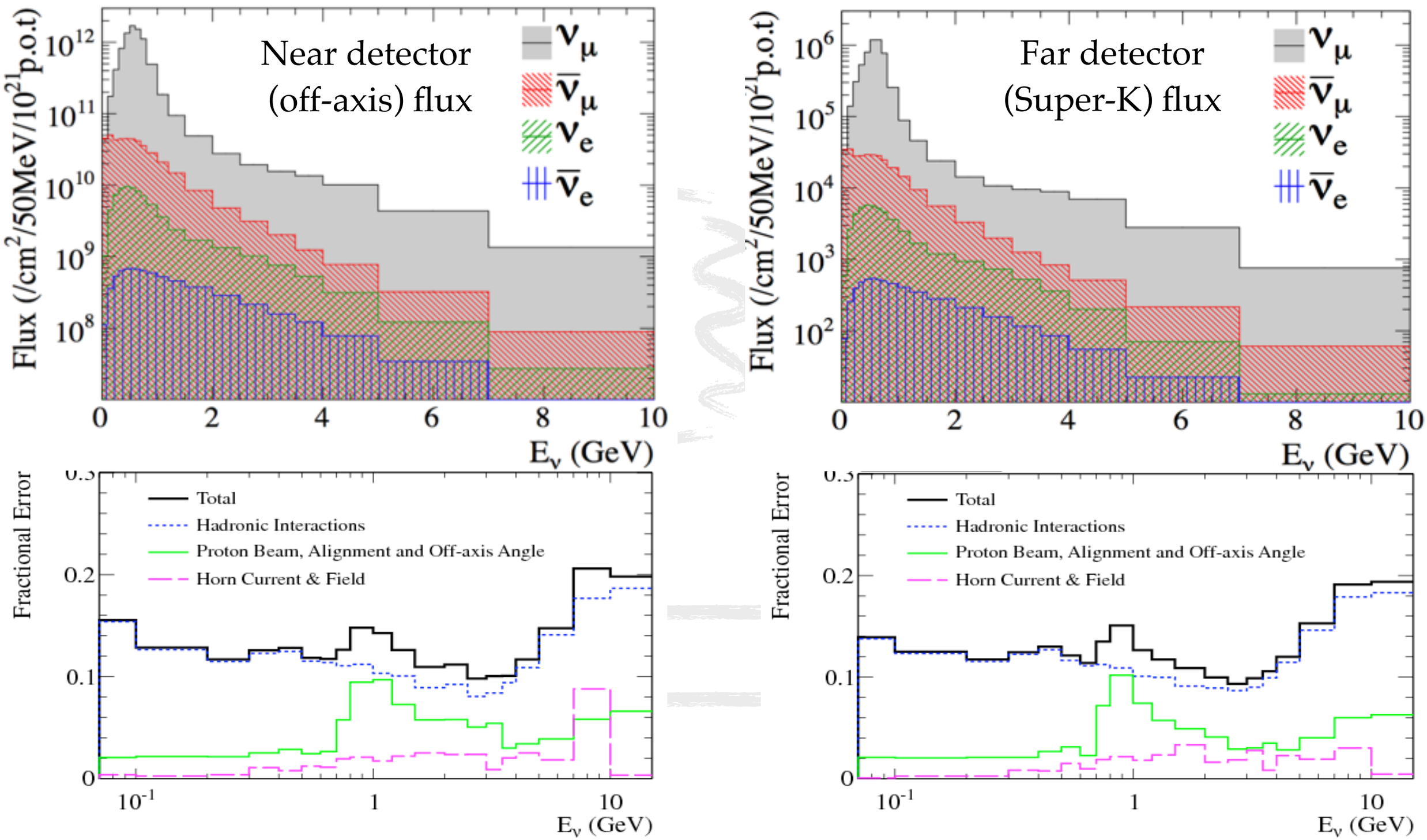






Target installed in 1st horn.

Pions are focused by
3 electromagnetic Horns.

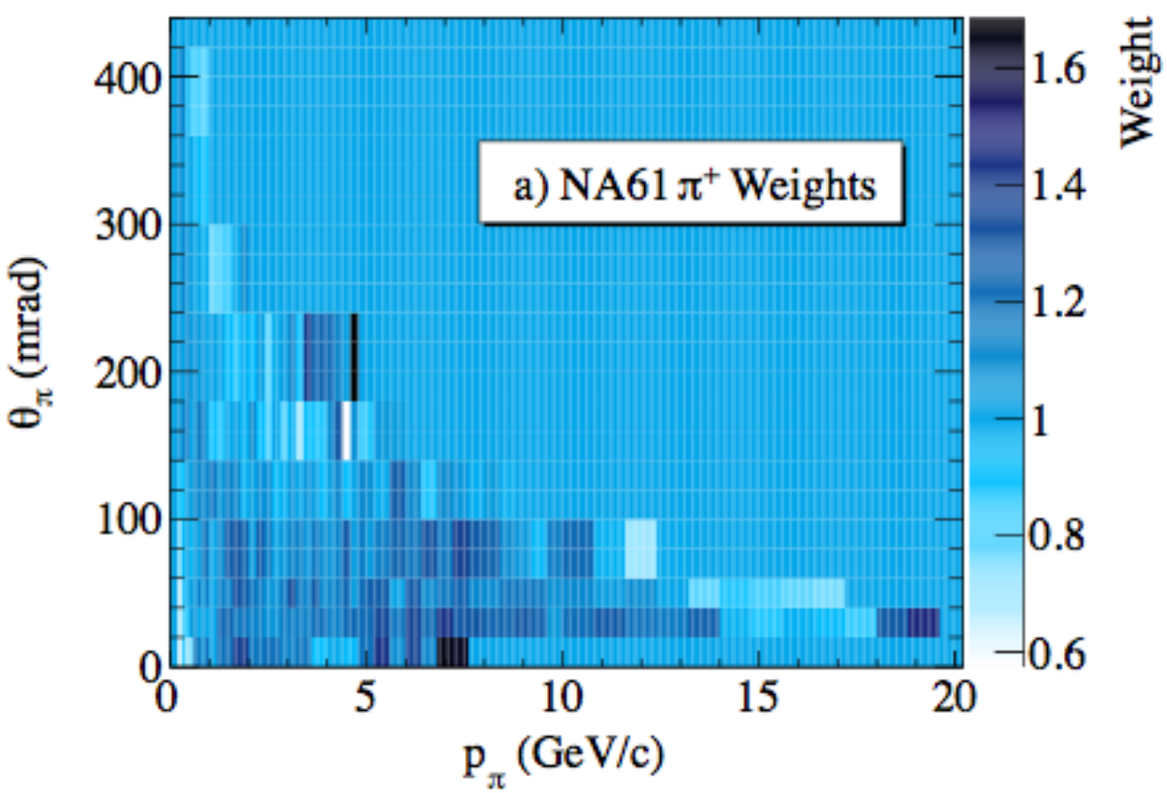
# Flux and Uncertainties

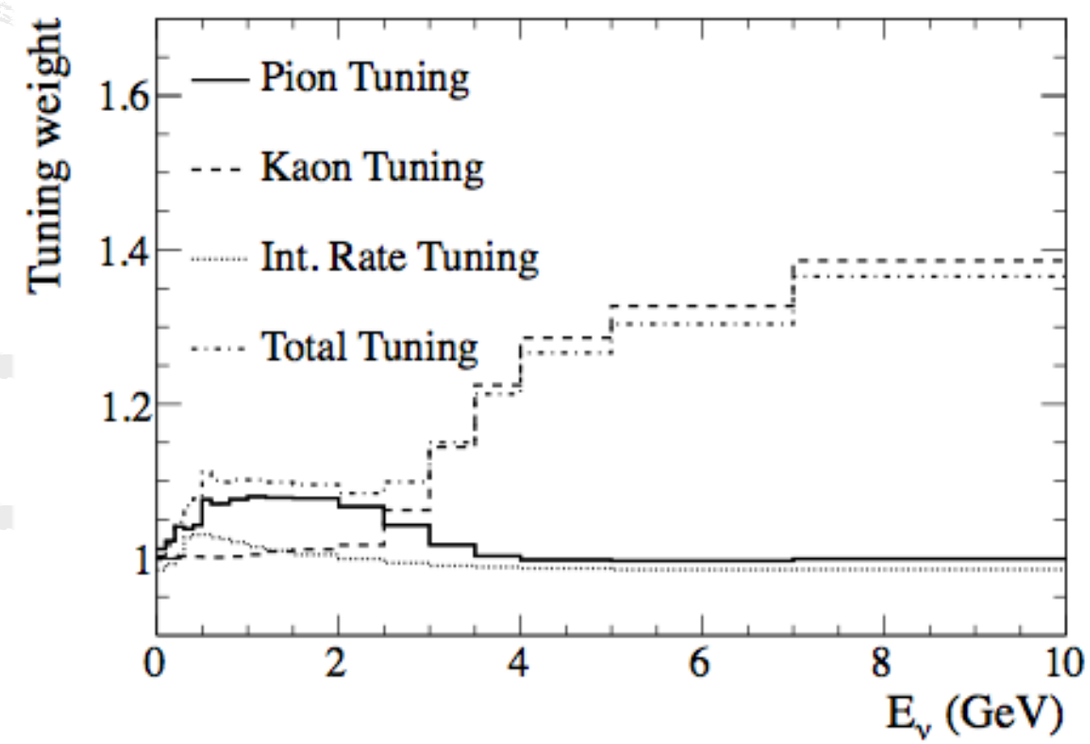


# External Data and Flux

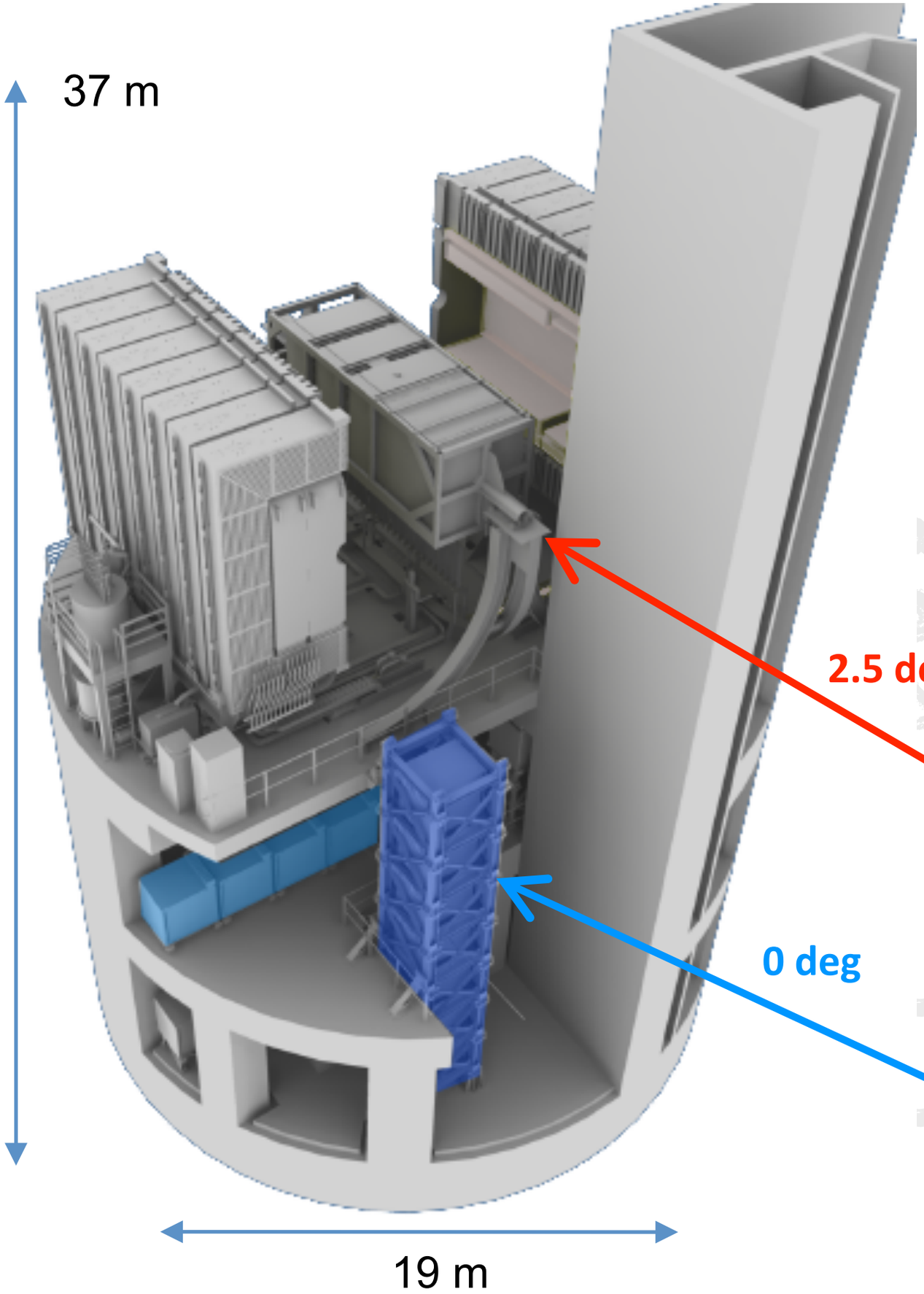
- Hadroproduction simulated with FLUKA2008.3d, weighted so that interactions match external data **[1]**
  - NA61/SHINE (CERN) **[2][3]**, Eitchen *et al.* **[4]**, and Allaby *et al.* **[5]**

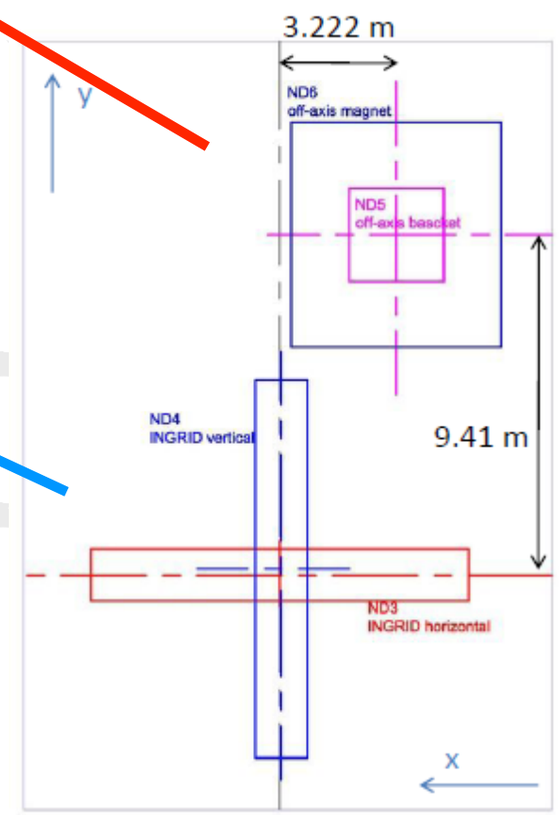

**[1]** K. Abe et al. (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).
**[2]** N. Abgrall *et al*. (NA61/SHINE Collaboration), Phys. Rev. C 84, 034604 (2011)
**[3]** N. Abgrall *et al*. (NA61/SHINE Collaboration), Phys. Rev. C 85, 035210 (2012)
**[4]** T. Eichten *et al.*, Nucl. Phys. B 44 (1972)
**[5]** J. V. Allaby *et al.*, Tech. Rep. 70-12 (CERN,1970)

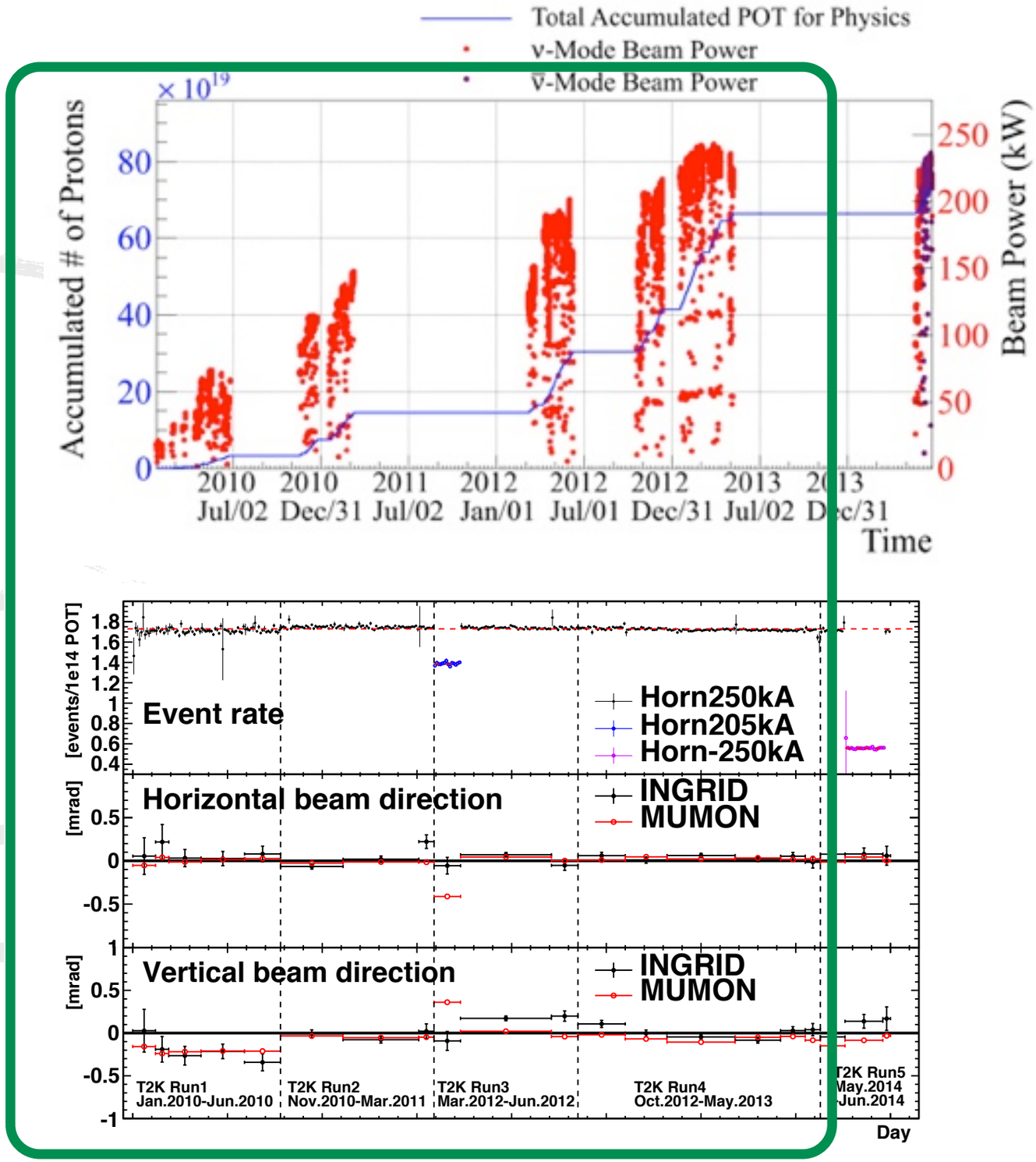
# The Near Detector pit houses both the off-axis (ND280) and on-axis (**INGRID**) detectors



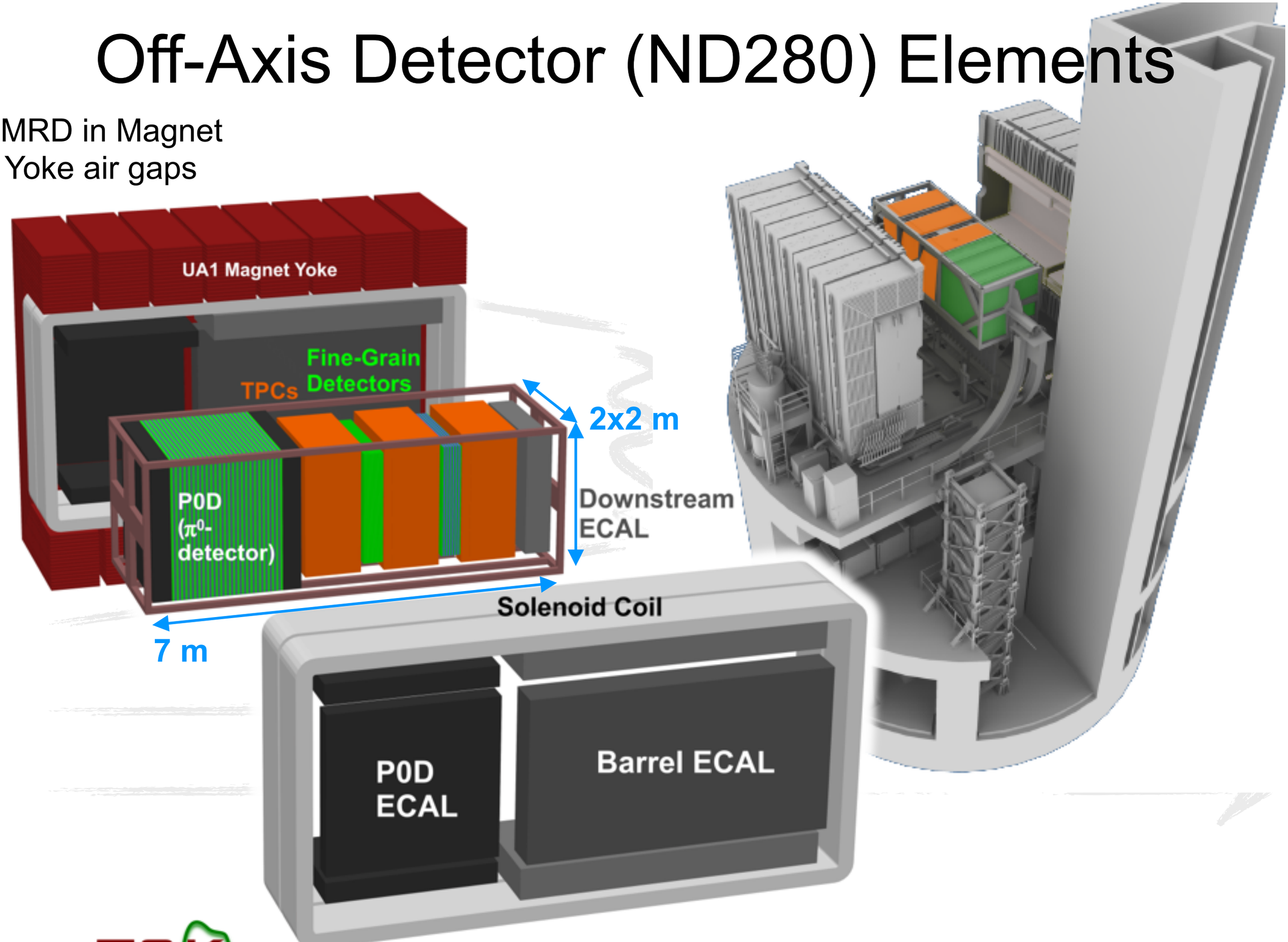
# Beam delivery & stability

- Beam operating stably at ~225 kW since 2012
- Beam delivery
  - 7.4e20 POT TOTAL
    - ~10% of expected total
  - 6.9e20 POT nu
  - 0.5e20 POT nubar
- Stability monitored by INGRID and MUMON
  - Event rates drop during 205 kA and −250 kA running



# Off-Axis Detector (ND280) Elements

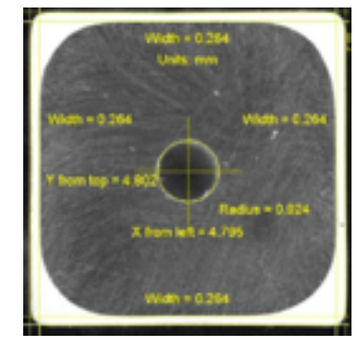
SMRD in Magnet
Yoke air gaps



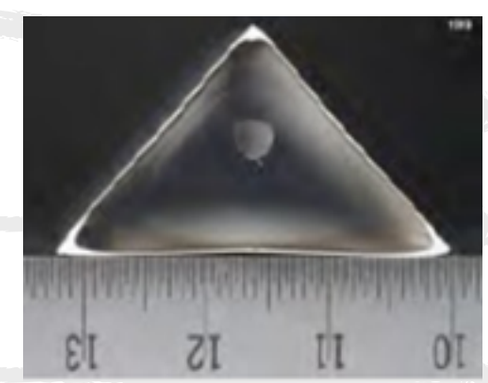
# Comparison of scintillator sub detectors:

| *sub detector* | *bar dimensions (mm)* | *channels* |
|---|---|---|
| Ingrid | 10 x 50 x 1203 | 8560* |
| P0D | 33 x 17 x 2200<br>33 x 17 x 2340 | 10400 |
| DSEcal | 10 x 40 x 2040 | 3400* |
| FGD | 9.6 x 9.6 x 1864 | 8448 |
| SMRD | 7 x 167 x 8750<br>7 x 175 x 8750 | 4016 |

FGD



P0D



All use 1 mm Kuraray Y11 double clad WLS fibers; either mirrored at one end, or read out at both ends (DSECal and SMRD); either inserted in central hole in bar, or in S-shaped groove (SMRD)

SMRD

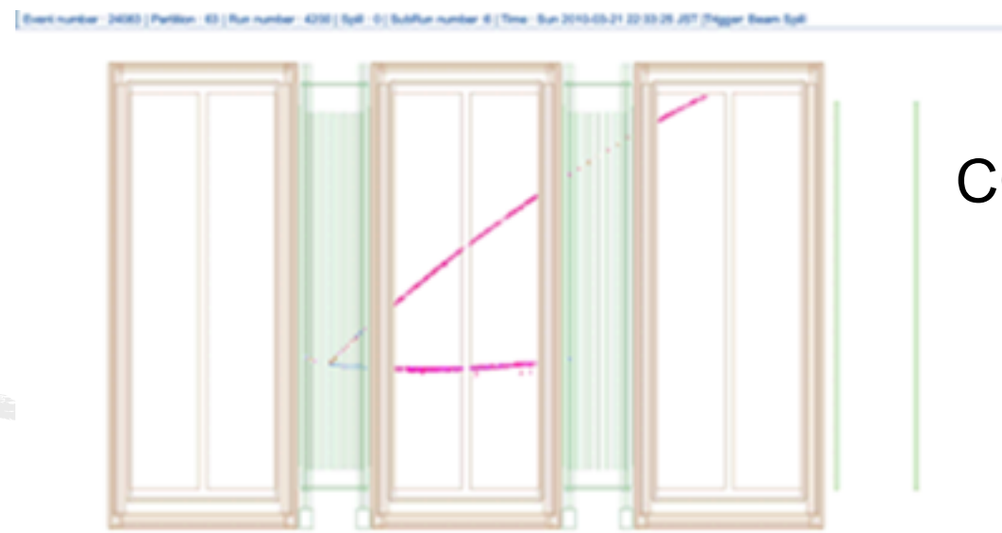
(photos not to scale)

*Ingrid has 10796 channels with new modules

*Complete Ecal has 22336 channels

# ND280 event selection

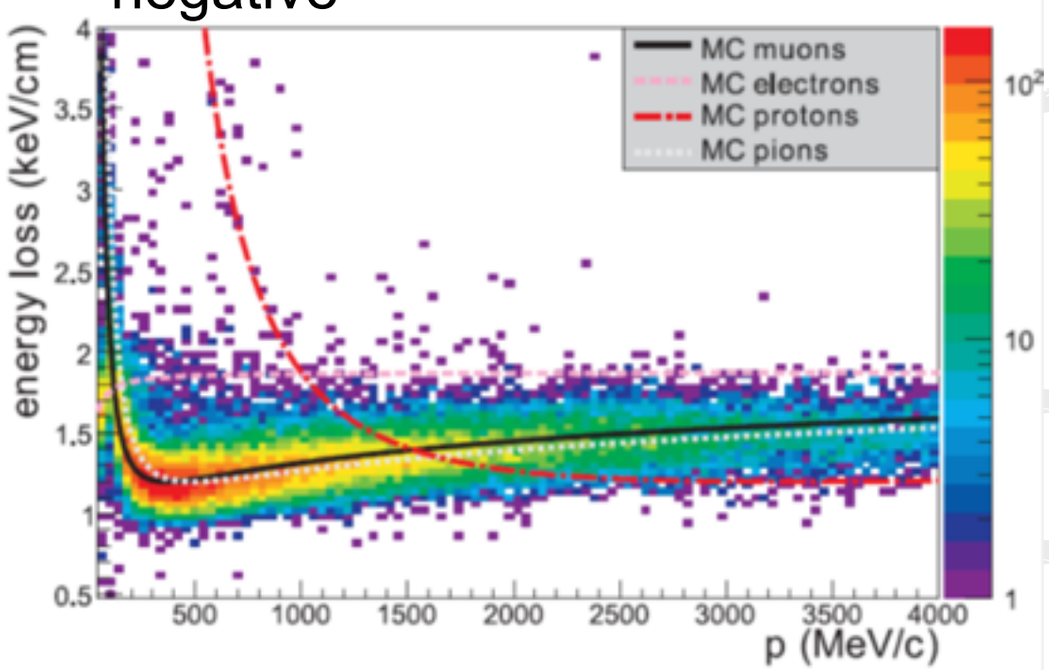
Event selection for CC analyses relies on separation of e−, μ−, $\pi^+$, p



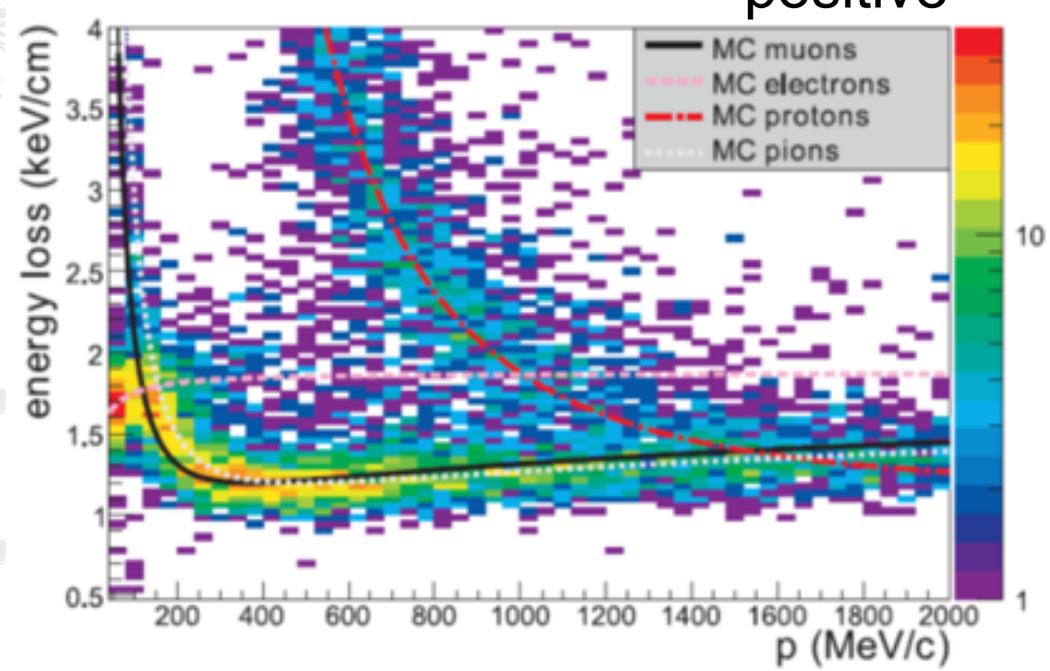
CC interaction in FGD1

TPC PID for particles from $\nu$ interactions

negative

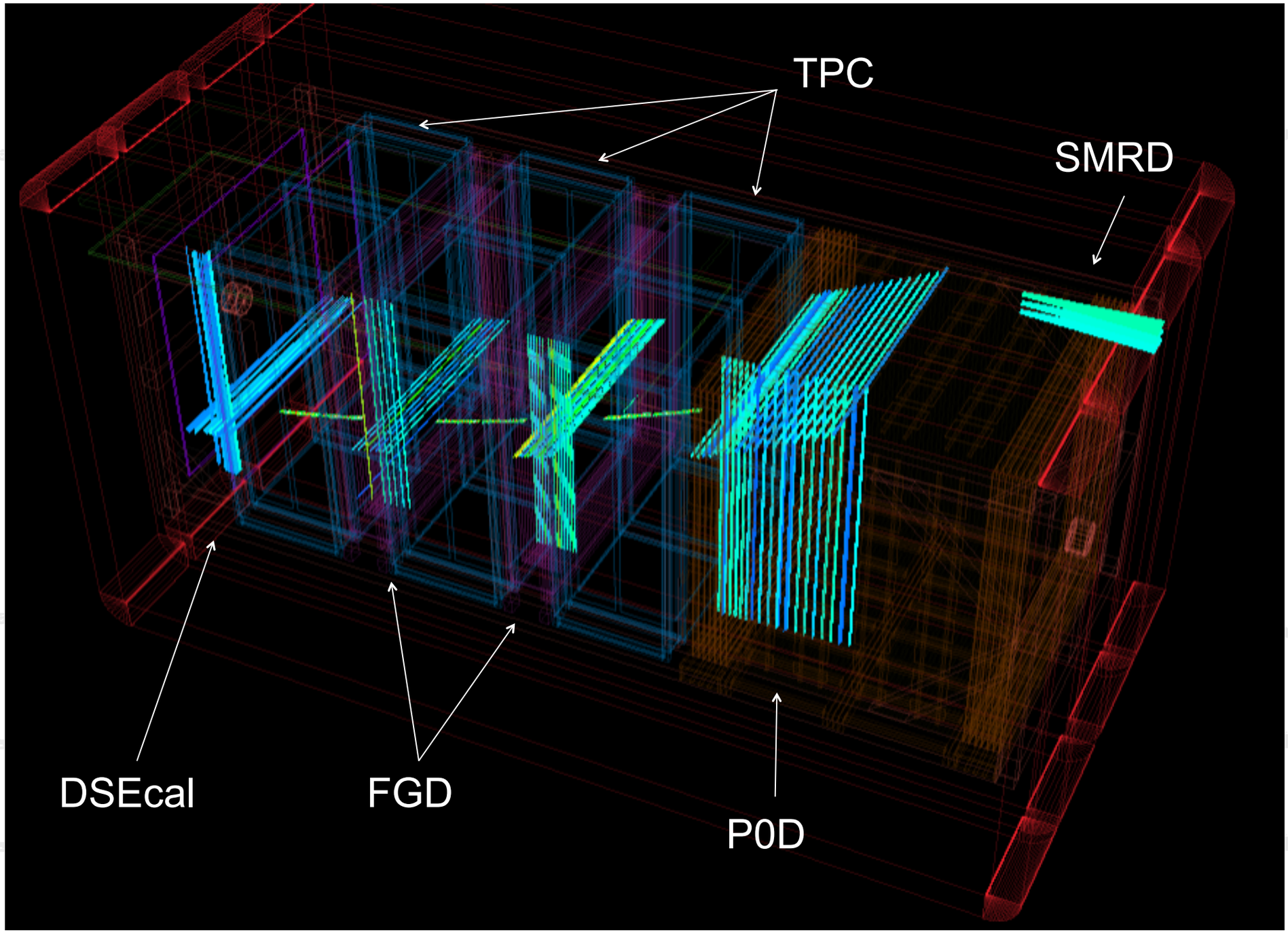



positive



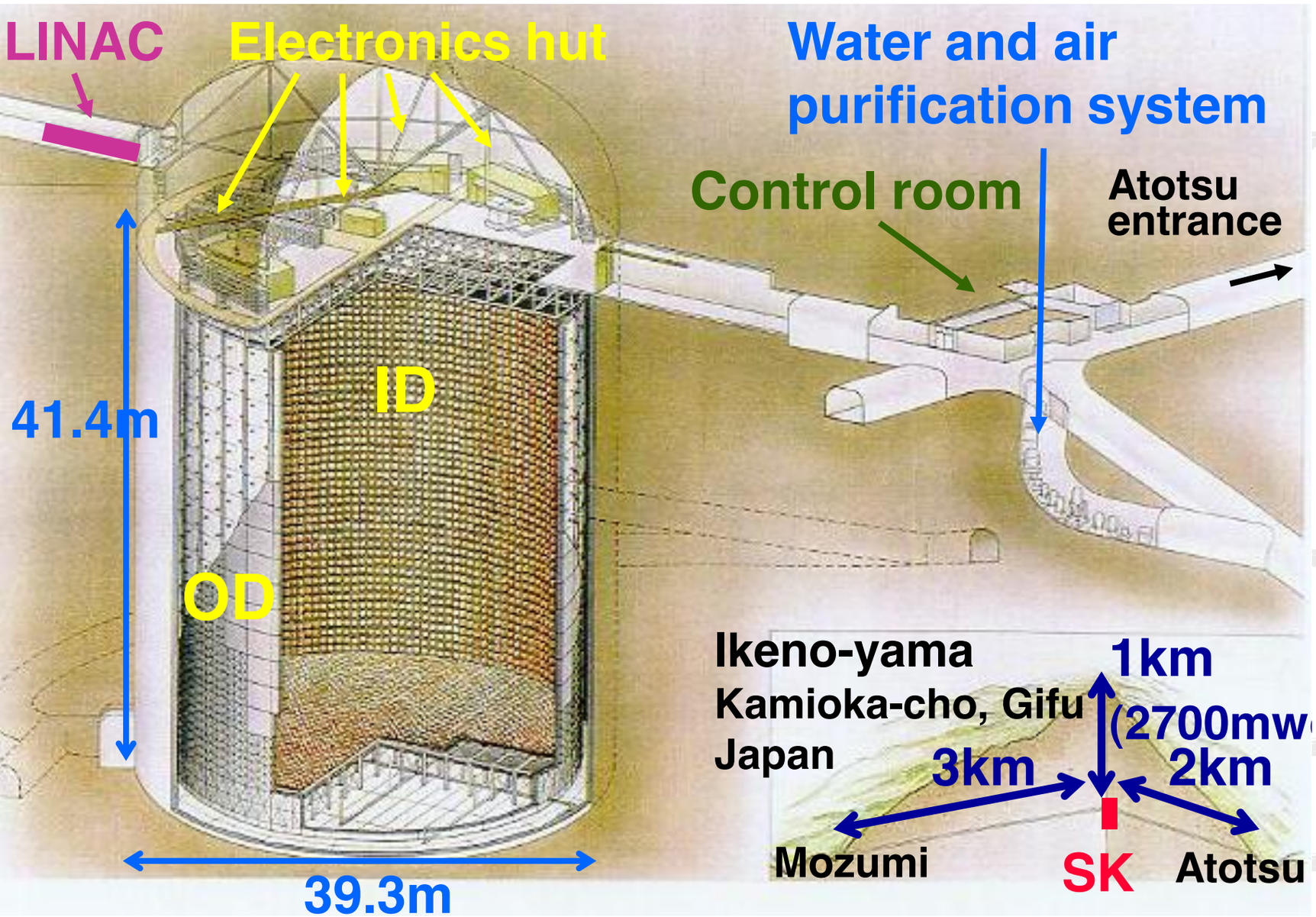

resolution for deposited energy is ~8% for MIPs better than the design requirement of 10%

# ND280 Tracker



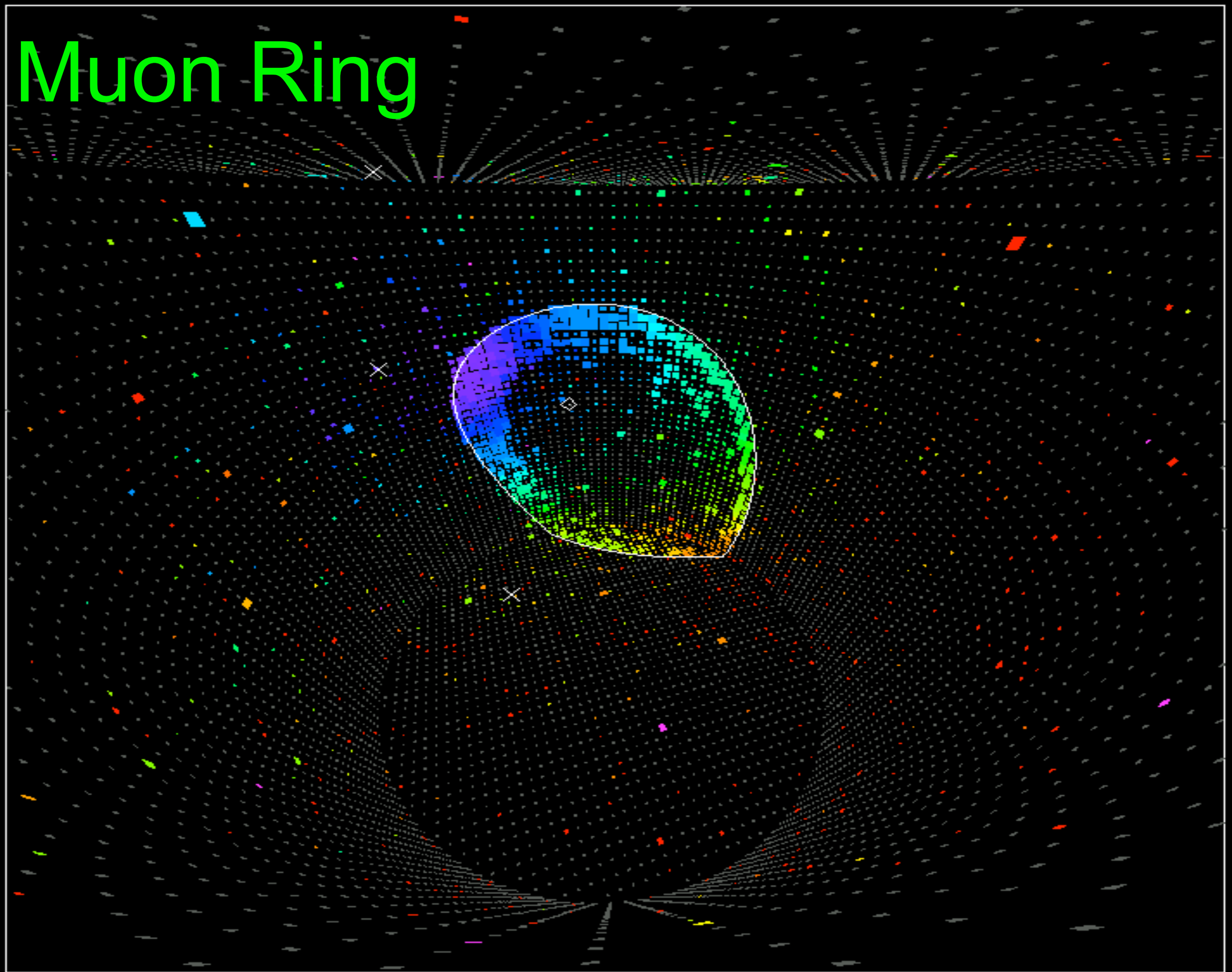

ECals, FGD, P0D have alternating horizontal and vertical bars forming x-y layers

# Super-K (far) detector

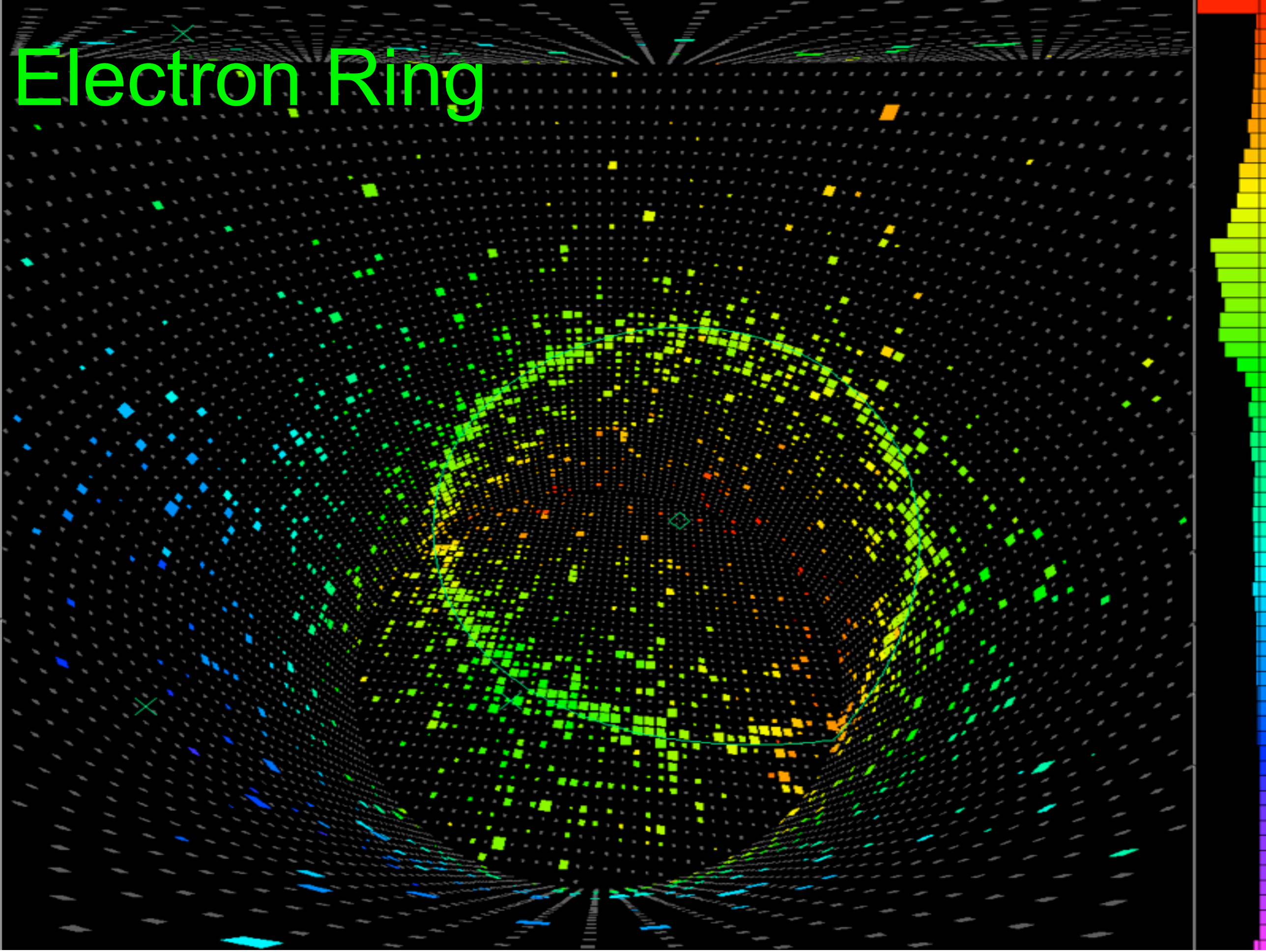



- 50 kton (22.5 kton fiducial volume) water Cherenkov detector
- ~11,000 20" PMT for inner detector (ID) (40% photo coverage)
- ~2,000 outward facing 8" PMT for outer detector (OD): veto cosmics, radioactivity, exiting events
- Good reconstruction for T2K energy range
  - Threshold 4 MeV

# Muon Ring



# Electron Ring



# $\nu$-nucleus cross section results

- ★ $\nu_e$ CC- inclusive
- ★ $\nu_\mu$ CC quasi-elastic

} ND280 tracker

- ✳ $\nu_\mu$ NC$\pi^0$
- ✳ $\nu_\mu$ NC elastic

} ND280 P0D

- ✦ $\nu_\mu$ CC-inclusive Fe & CH
- ✦ $\nu_\mu$ CCQE
- ✦ $\nu_\mu$ CC-inclusive vs Enu
- ✦ $\nu_\mu$ CC coherent pion

} INGRID

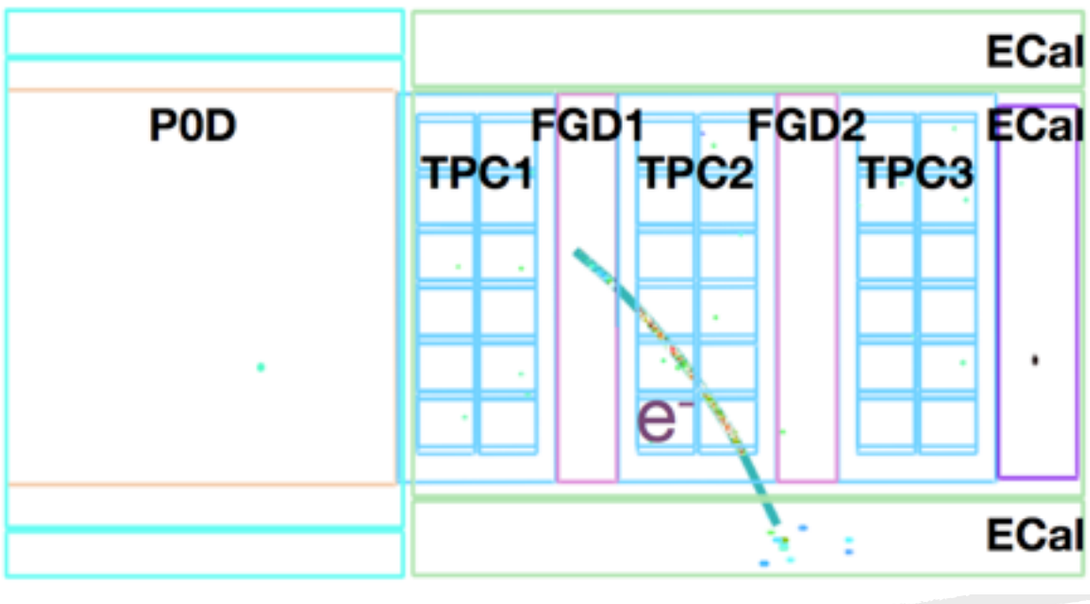
- ✤ $\nu_\mu$ NC Elastic via $\gamma$ emission

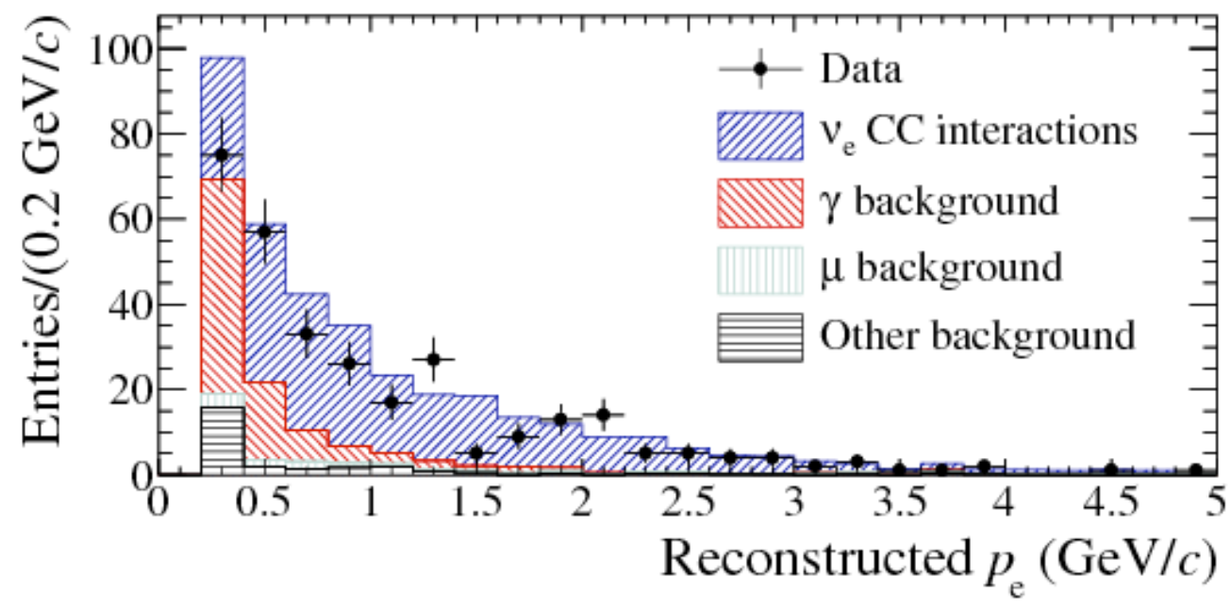
} SK (!)

$\nu_e + C \rightarrow e^- + X$

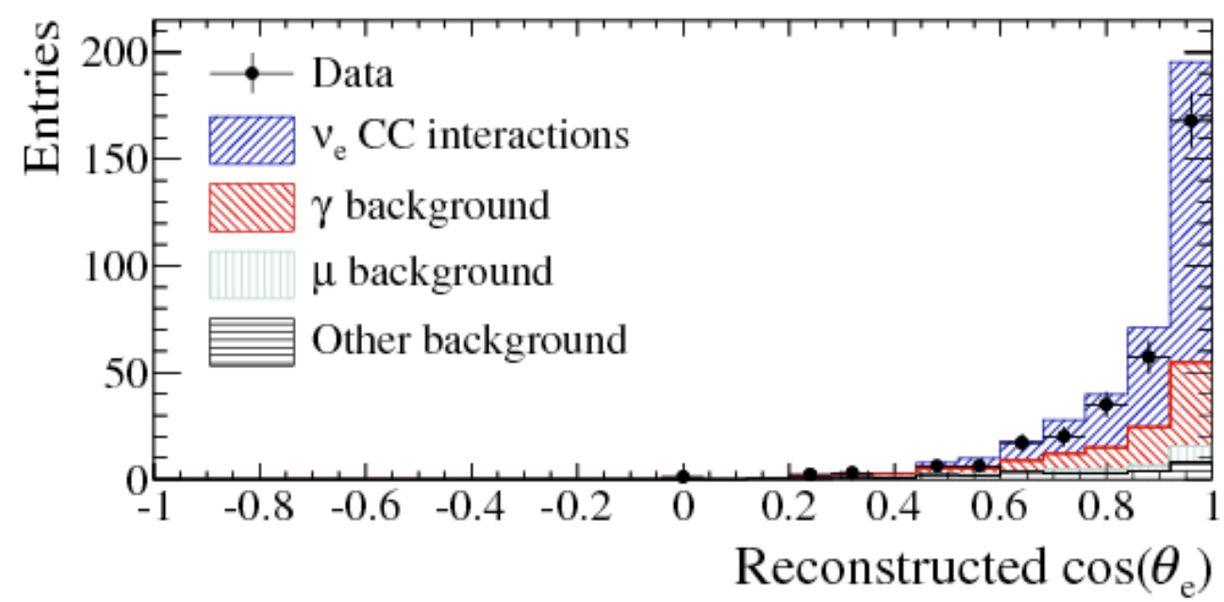
# ND280 $\nu_e$ analysis

arXiv:1407.7389 [hep-ex]. Accepted by PRL today.



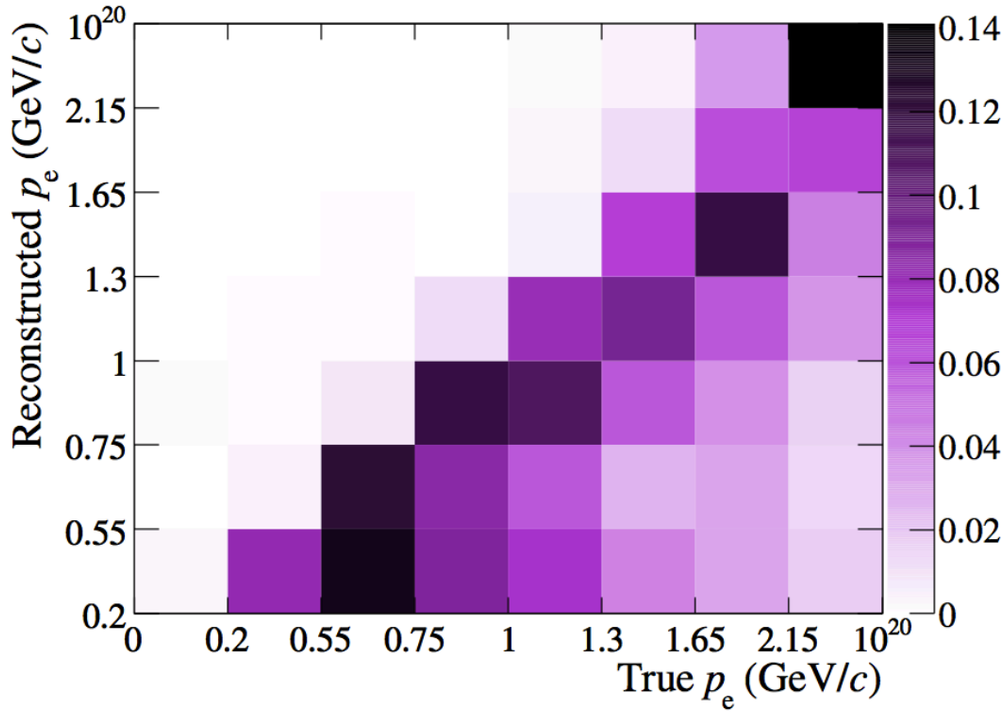



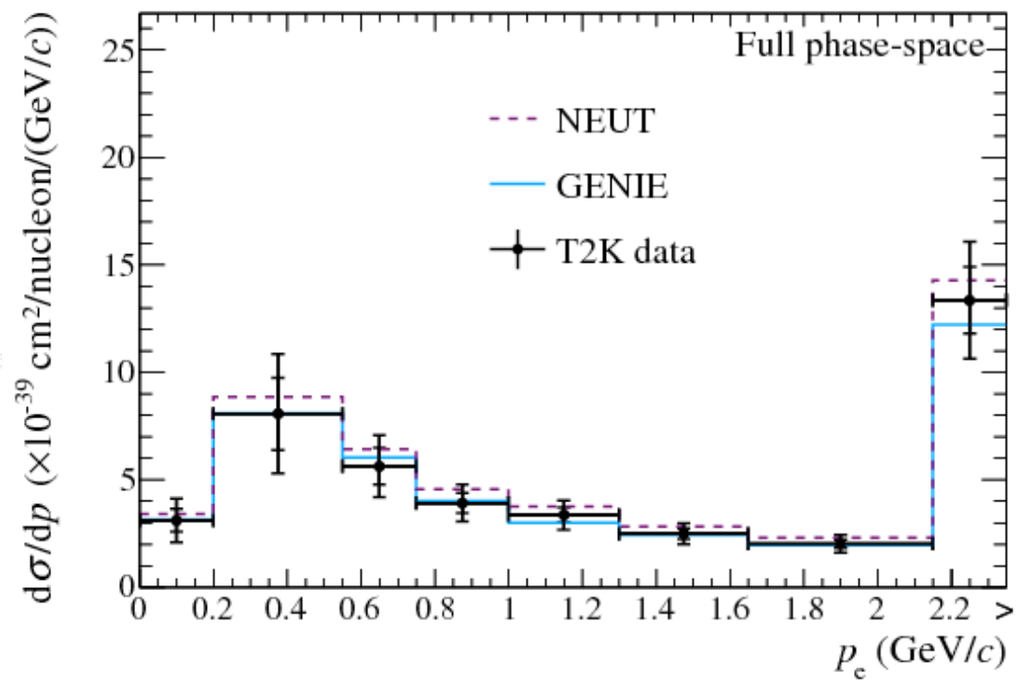

- Select e⁻ tracks starting in FGD
  - Use TPC & ECal PID
- Constrain $\gamma$ BG (from $\pi^0$) with $e^+e^-$ sample

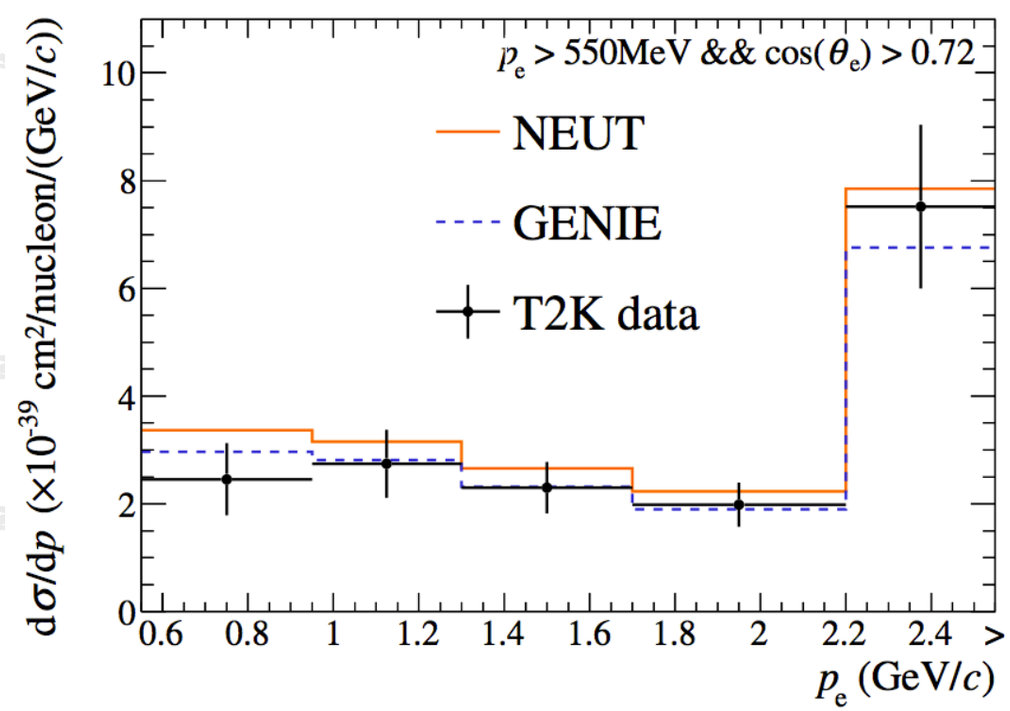


$\nu_e + C \rightarrow e^- + X$

# $\nu_e$ CC-inclusive cross section



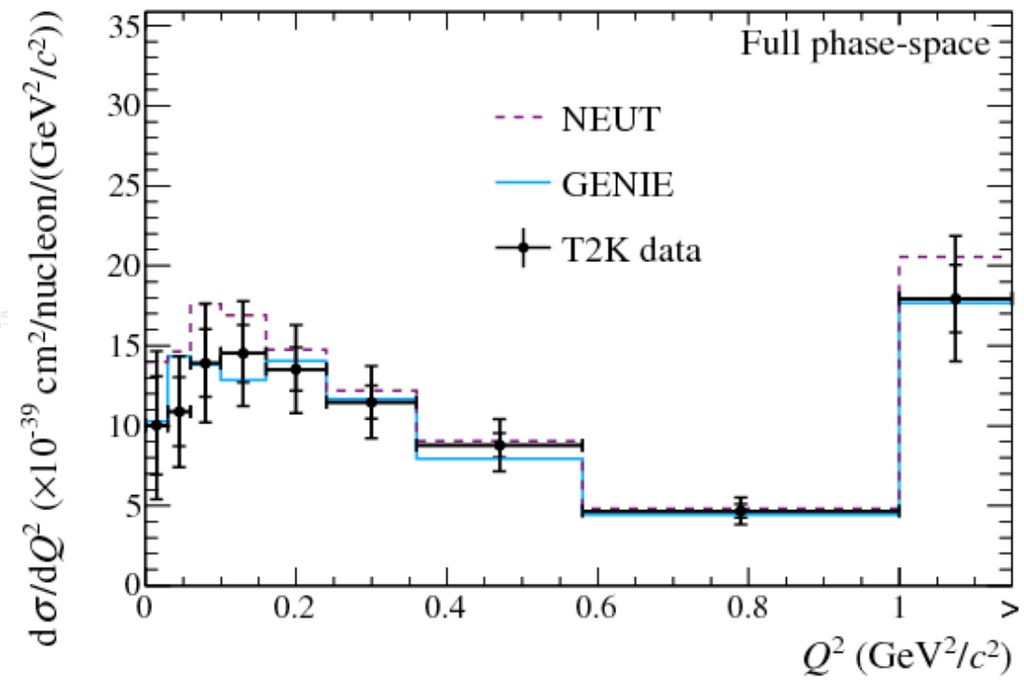

- Use Bayesian unfolding
  - Quite a bit of smearing in momentum due to Bremsstrahlung
- Differential measurements of $p_e$ and $\theta_e$
- Full phase space and restricted phase space
  - reduces model dependence

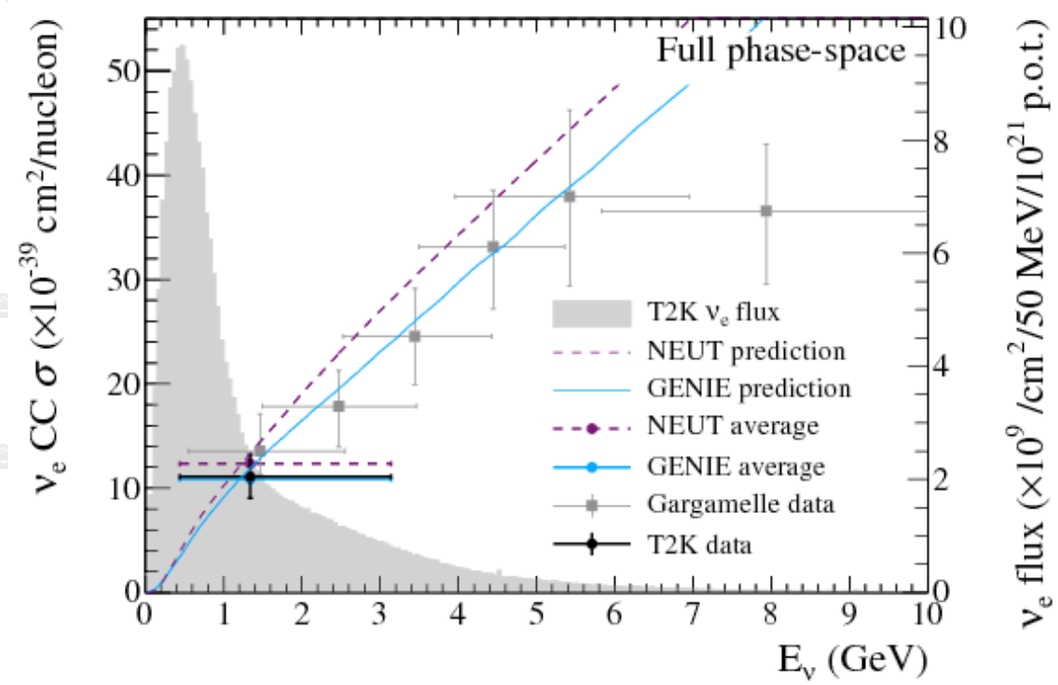
$\nu_e + C \rightarrow e^- + X$

# $\nu_e$ CC-inclusive cross section

- Also initial/internal variables
  - Calculated with Bayesian matrix method
- Largest uncertainties are
  - Flux (12.9%)
  - Statistics (8.7%)
  - Detector (8.4%)
- First measurement of $\nu_e$ near 1 GeV in 30 years

➡Possible because of excellent detector with magnetic field

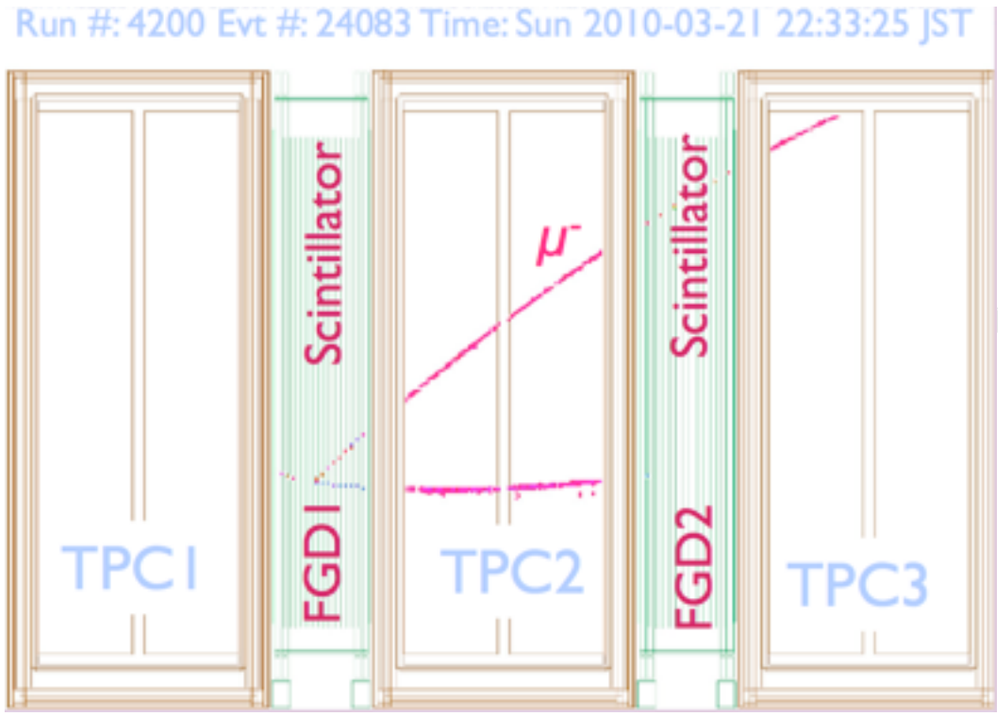


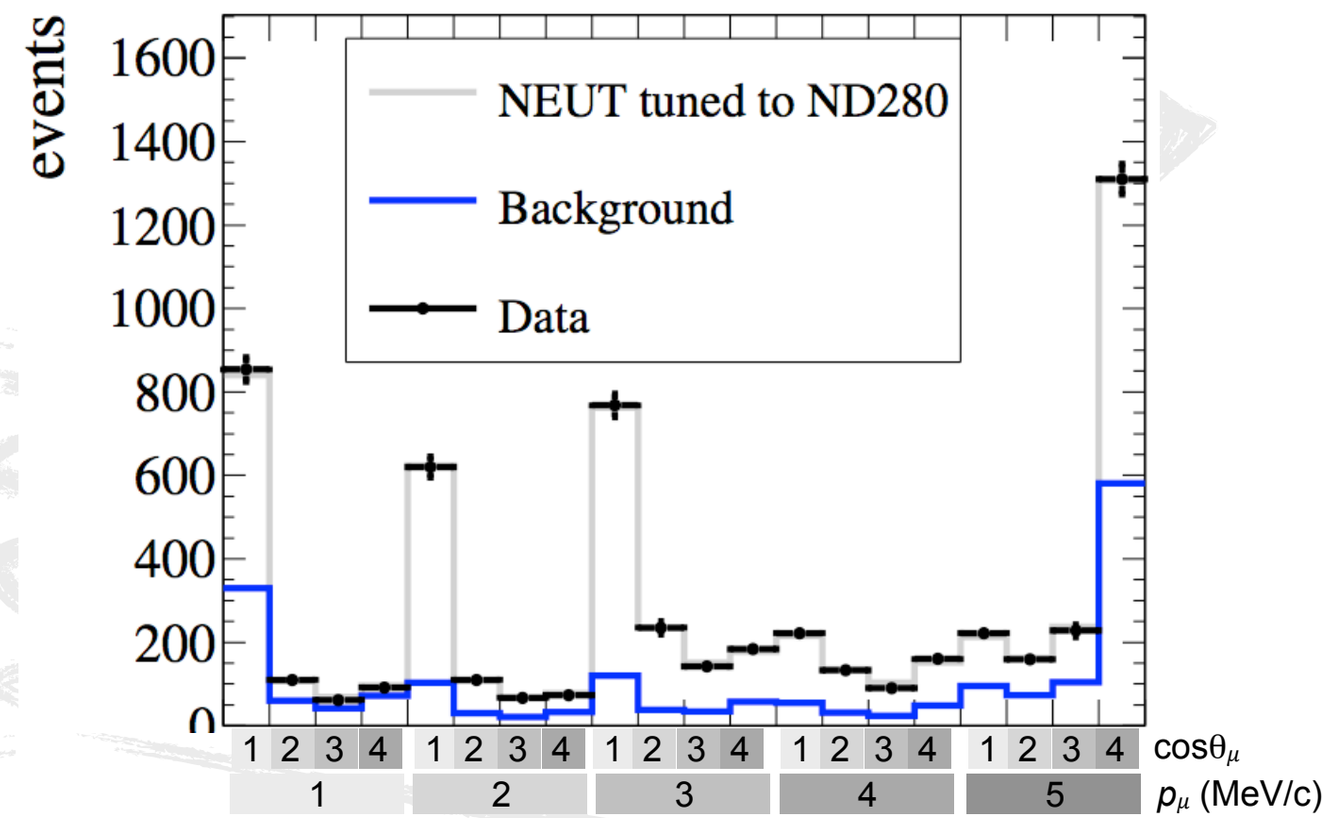



$$\nu_\mu + p \rightarrow \mu^- + n$$

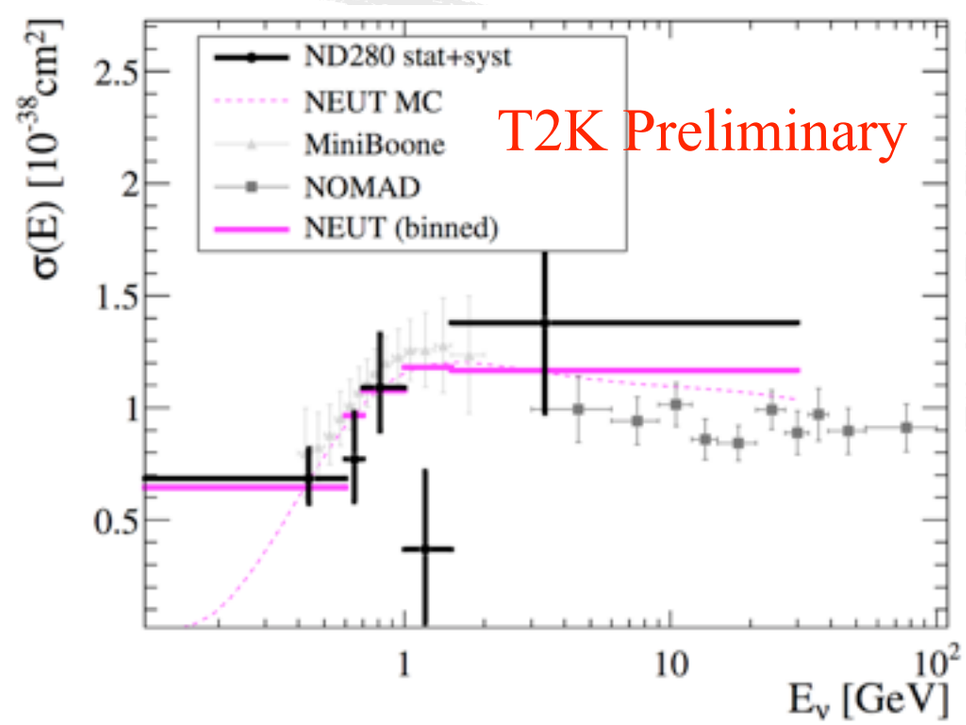
# $\nu_\mu$ CCQE

*To be submitted to IOP JoP G*



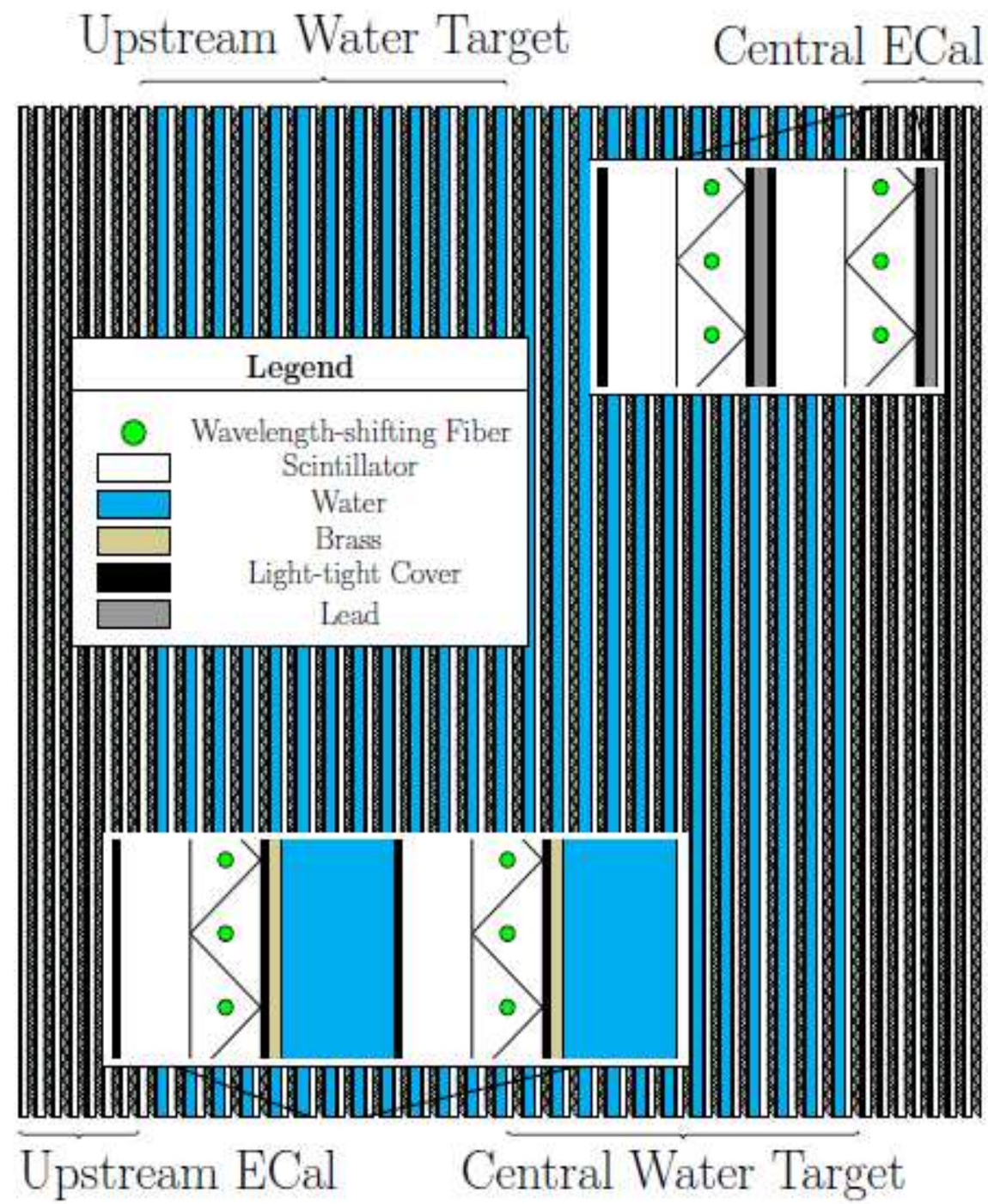




- Select mu- tracks starting in FGD
  - Require no pion-like tracks or muon decays
- Template fits in pmu-thetamu to extract CCQE xsec
  - $M_A^{QE}$ = 1.26 +0.21 -0.18 GeV/c2 (1.43 +0.28 -0.22 shape-only)



# $\pi^0$ detector (PØD)

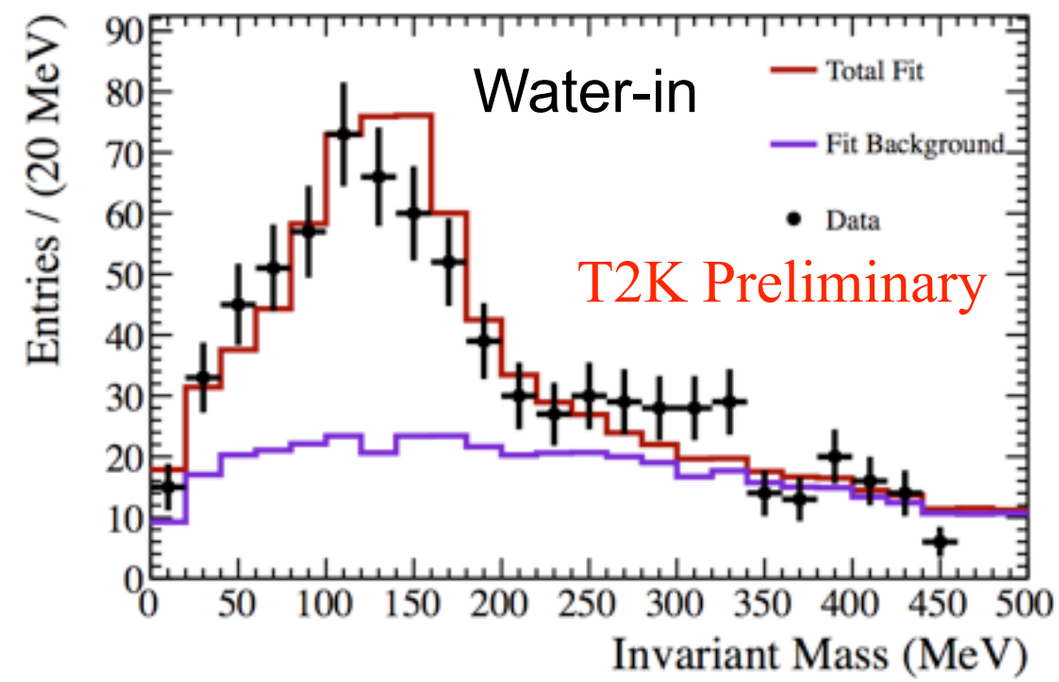
- Partially active volume
- Two EM Calorimeters (ECal)
  - Scintillator + lead
  - Helps contain EM showers
- Two water targets (WT)
  - Scintillator + brass + water(air)
  - Removable water to provide measurement of neutrino cross-sections on water
  - Brass to help initiate EM showers

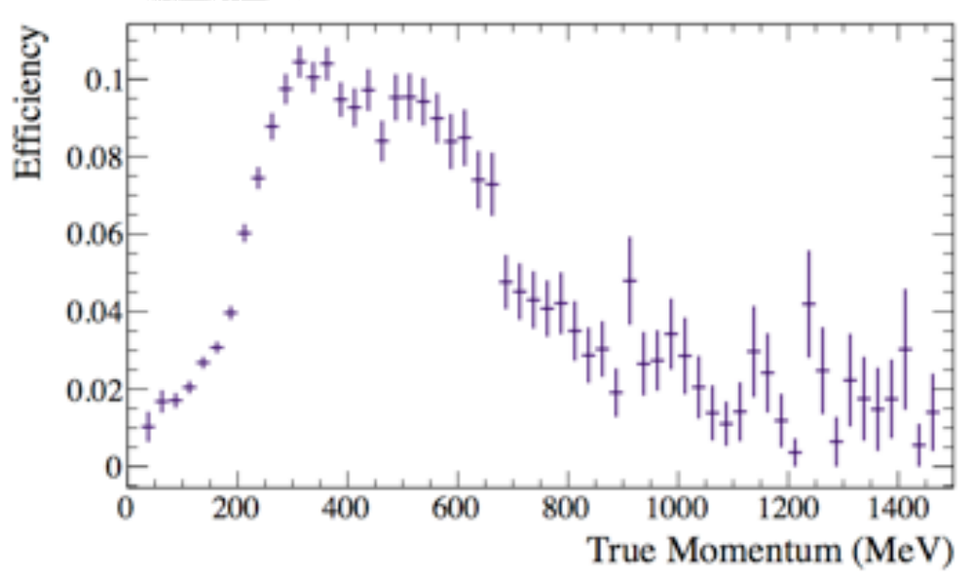


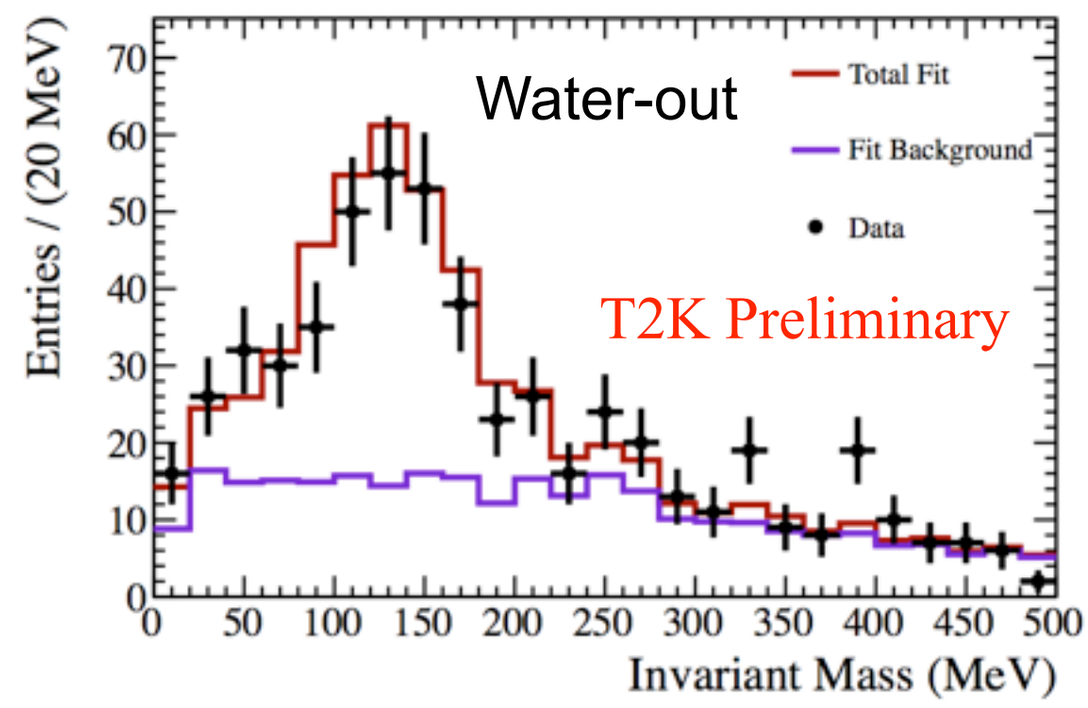
$$\nu_\mu + C, O \rightarrow \nu_\mu + \pi^0 + X$$

# PØD $\pi^0$ rate measurement

- Looking for NC events with one $\pi^0$ and no leptons or other mesons
- Select events with 2 showering clusters
- Reconstruct invariant mass
- Compare water-in and water-out data sets to extract events on O (statistically)
- Efficiency is a strong function of $\pi^0$ momentum

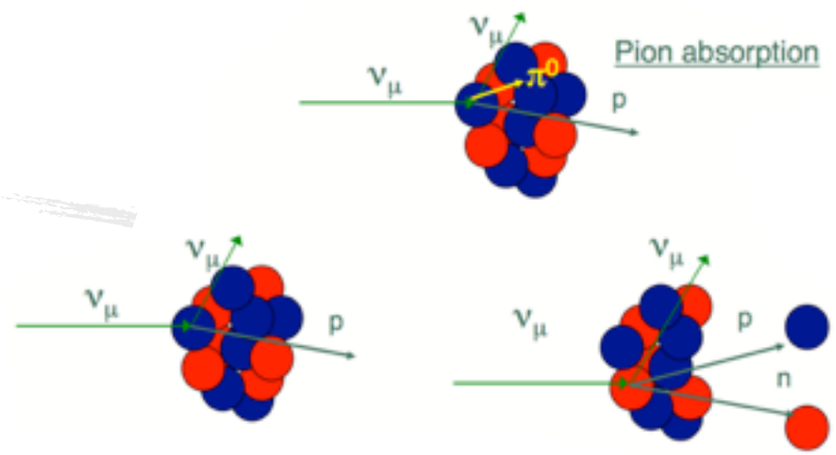


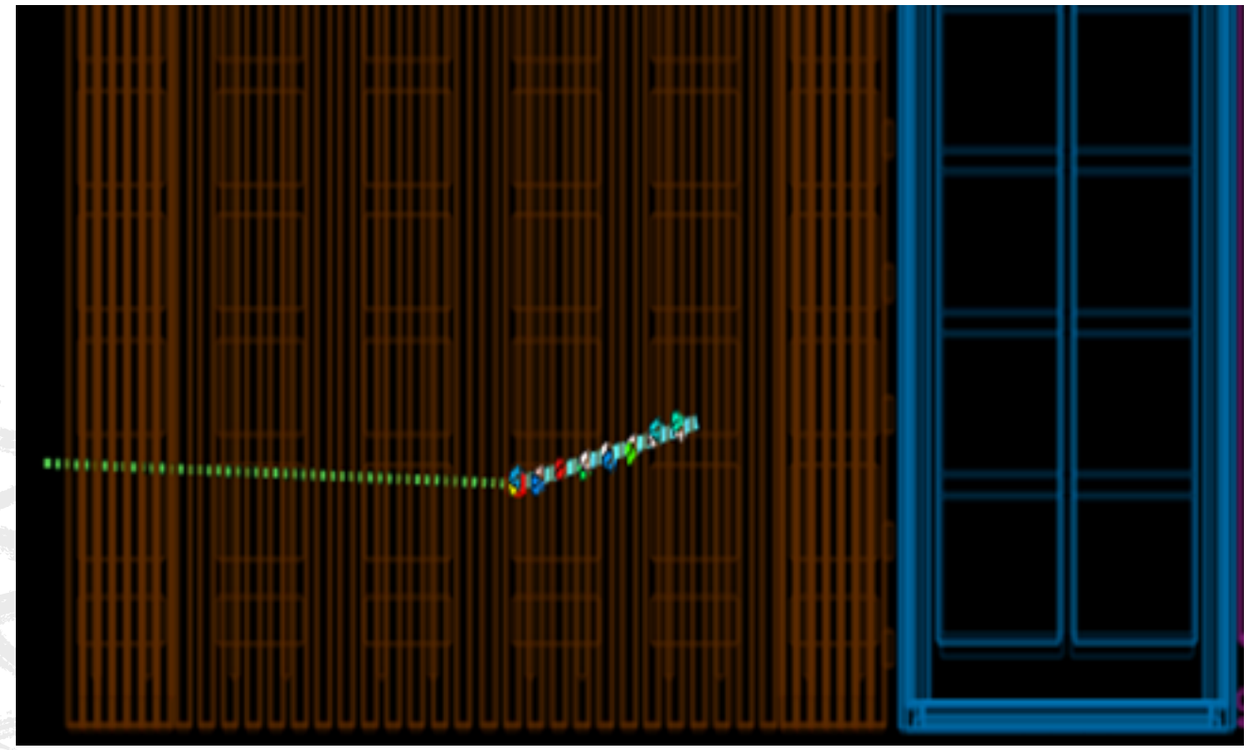



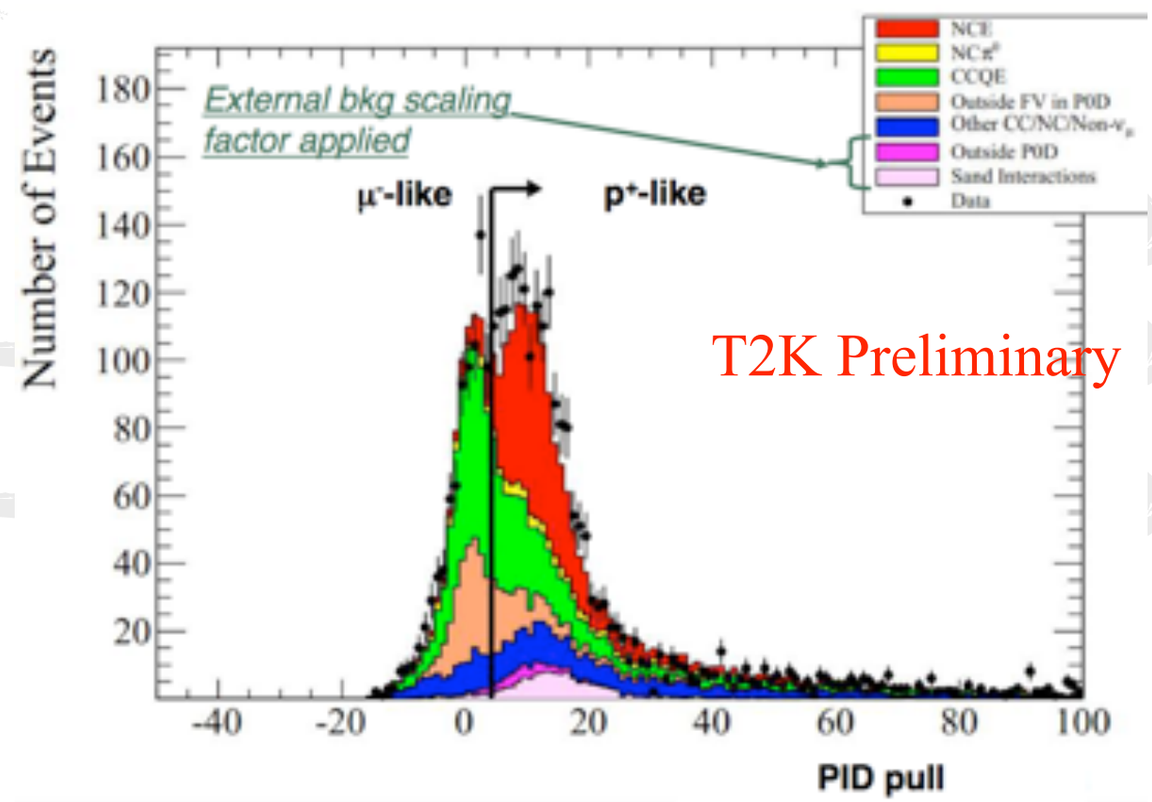
$$\nu_\mu + p, n \rightarrow \nu_\mu + p, n$$

# PØD NC elastic



- Looking for NC events with 1 proton and 0 mesons exiting nucleus
- Select highly-ionising tracks contained in P0D FV
- Main BGs
  - CCQE
  - neutrons from upstream



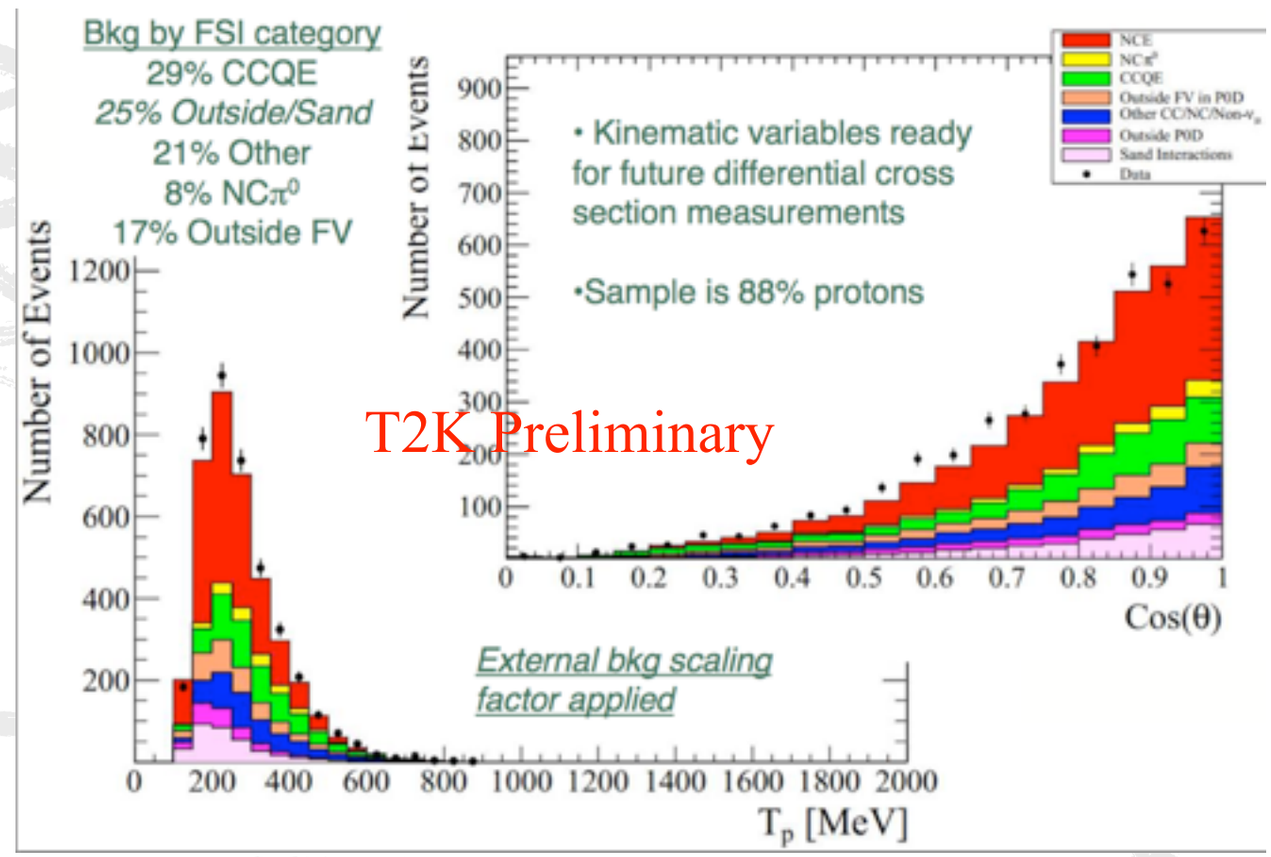
$$\nu_\mu + p, n \rightarrow \nu_\mu + p, n$$

# PØD NC elastic

$$< \sigma >_{flux} = \frac{N_{data} - B_{mc}}{T \Phi \varepsilon}$$

| | |
|---|---|
| $N_{data}$ | selected number of events in data |
| $B_{MC}$ | background prediction from MC |
| T | total number of target nucleons |
| $\Phi$ | Neutrino flux |
| $\varepsilon$ | Selection efficiency correction |

- Uses data with water in the P0D
- Reported as cross section per nucleon
  - Averages over carbon, brass, water
  - Background subtracted result
  - select 3936 events , 2016 BG
- Using $9.9 \times 10^{19}$ POT

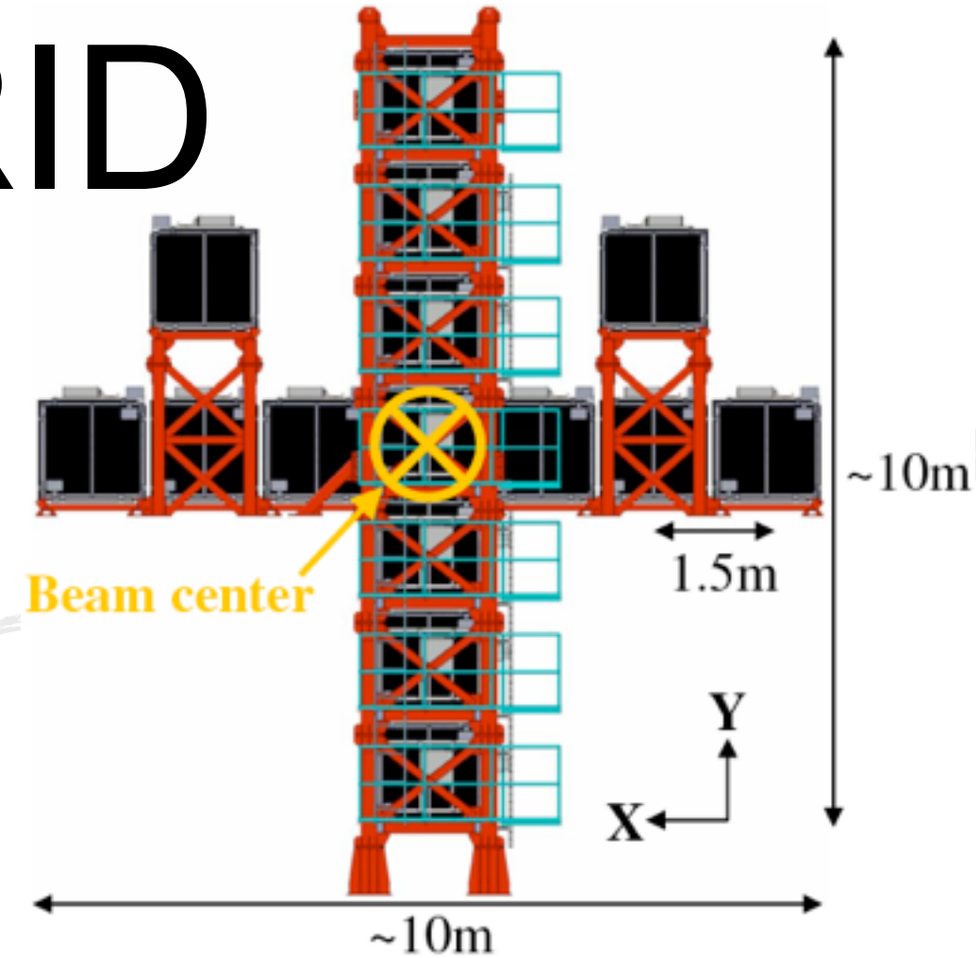



$$< \sigma >_{flux} = 2.24 \times 10^{-39} \pm 0.07(\text{stat.}) \begin{matrix} +0.53 \\ -0.63 \end{matrix} (\text{sys.}) \frac{\text{cm}^2}{\text{nucleon}}$$

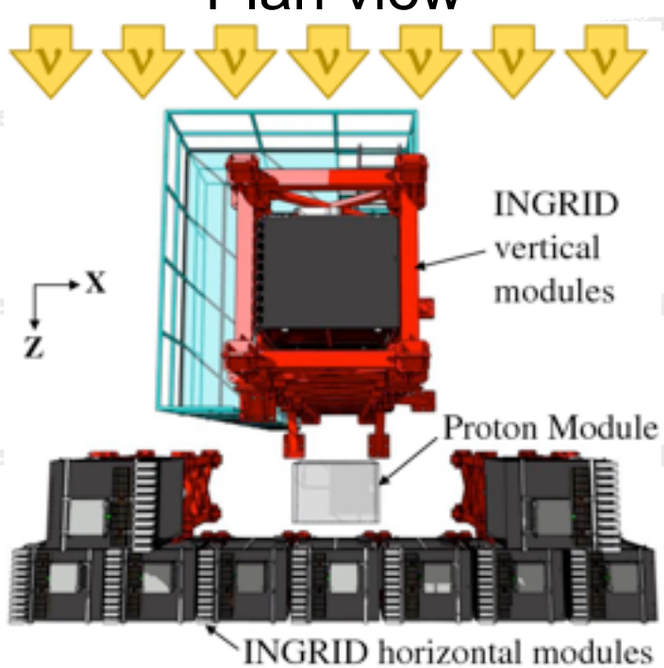
Consistent with NEUT and GENIE within errors.

# INGRID

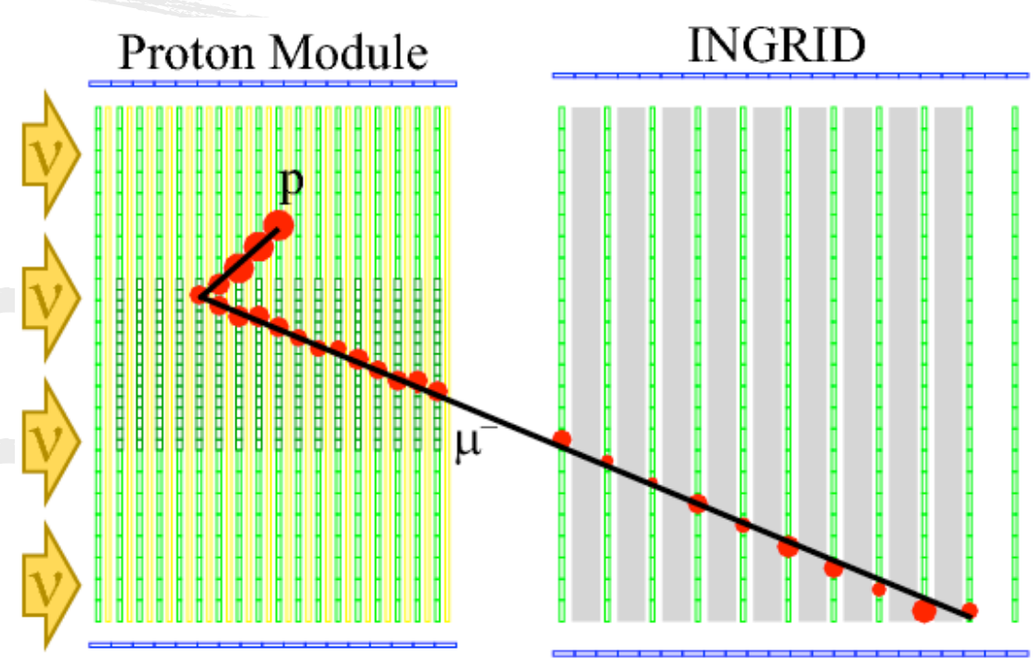
- 16 standard modules.
  - Alternating iron, scintillators layers.
  - Main purpose is beam monitoring.
- 1 extra module (Proton Module).
  - Fully active scintillator.
  - Developed for cross section studies.




Plan view



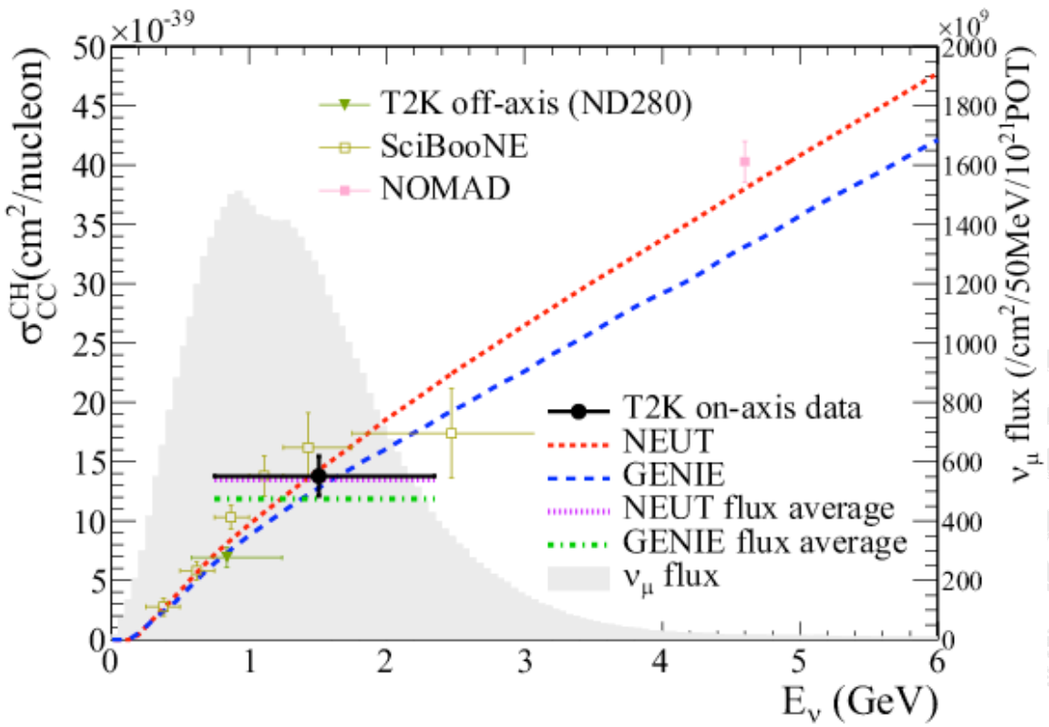

Beam's eye view

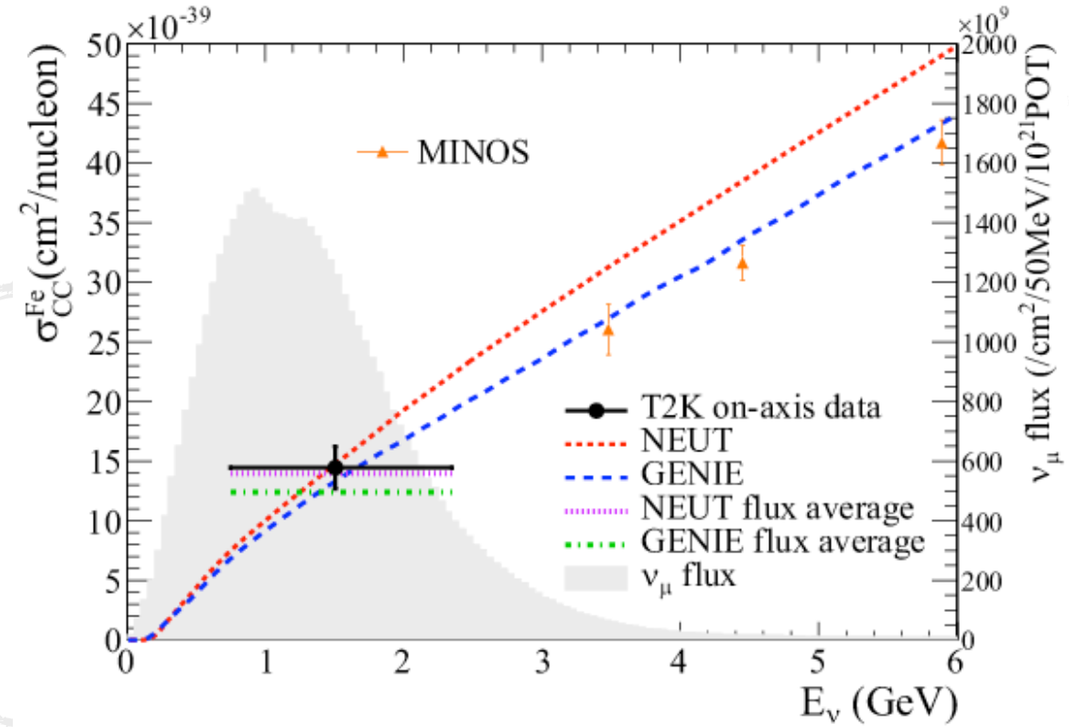


$\nu_\mu + C, Fe \rightarrow \mu^- + X$

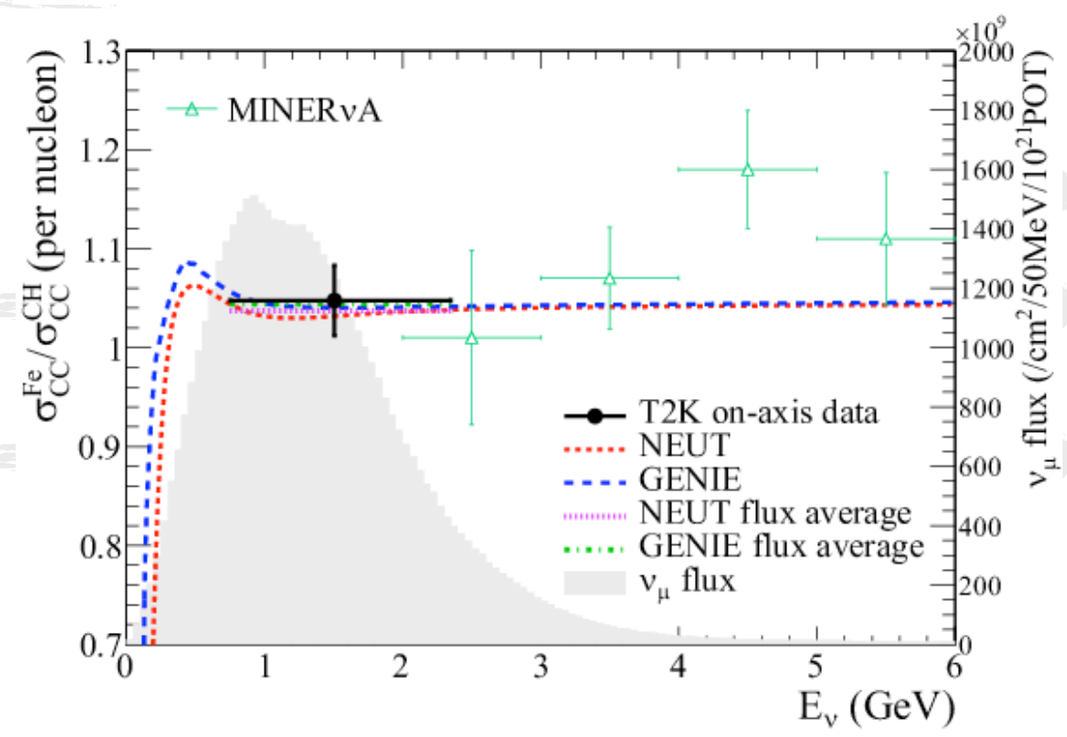
# INGRID C/Fe ratio

Phys Rev. D 90 (2014) 052010




- Select events in proton module (CH) and center modules (Fe)
- Extract cross sections on C and Fe with 1-bin “matrix unfolding” method
- Fe/CH xsec ratio also calculated



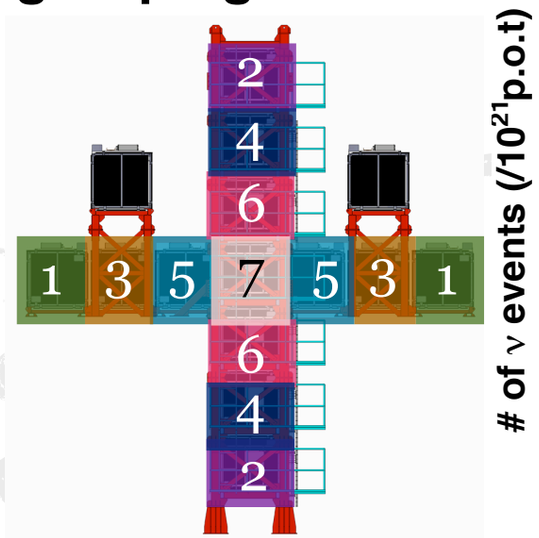
$\nu_\mu + Fe \rightarrow \mu^- + X$

# Extracting cross section vs. $E_\nu$

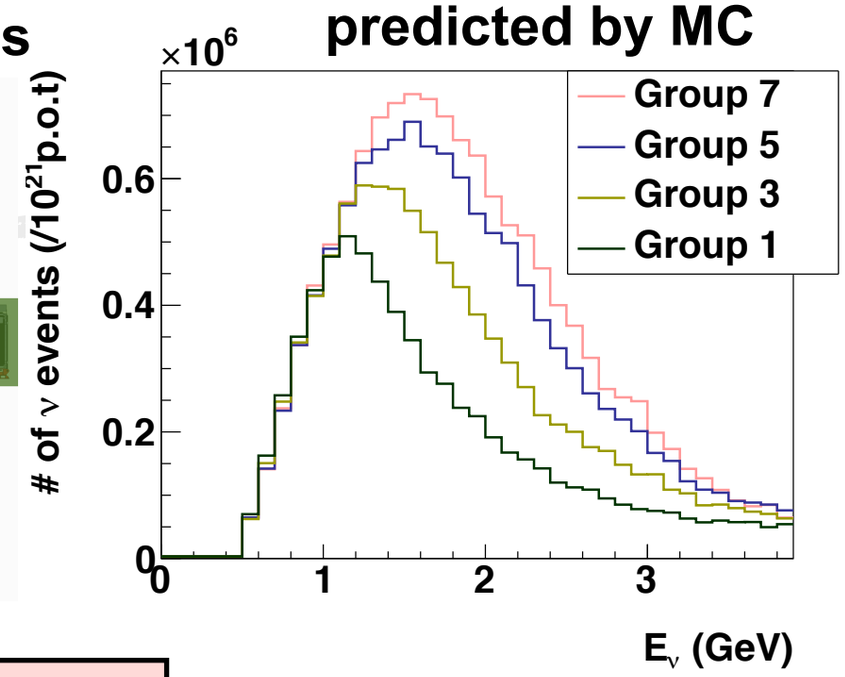
- Count events in different modules
  - Use off-axis effect to vary $E_\nu$ ($\theta_{OA}$=0-0.9°)
- Further categorise events:
  - Downstream(DS-) escaping
  - NonDS-escaping
  - z-position of interaction vertex

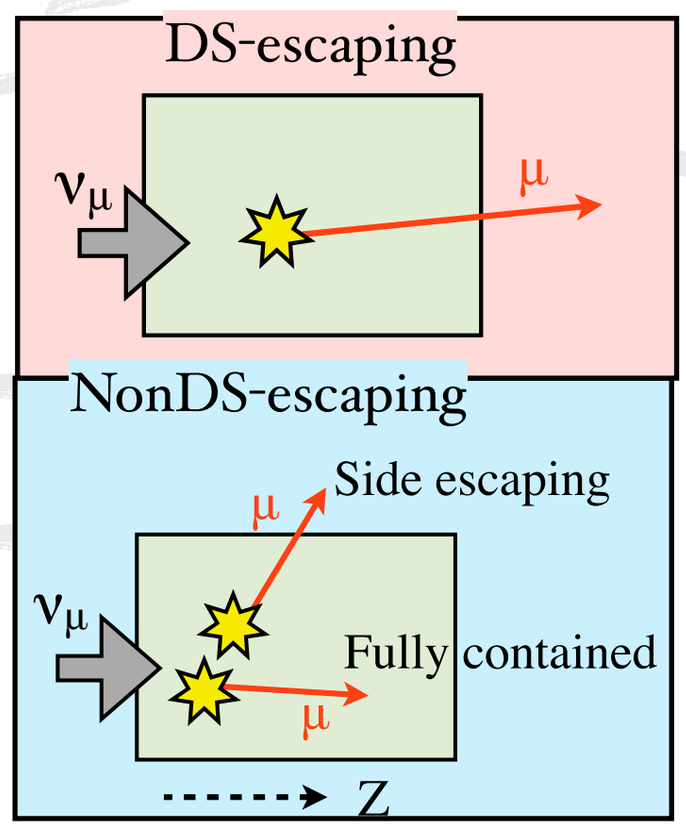
➡MC template method to measure xsecs

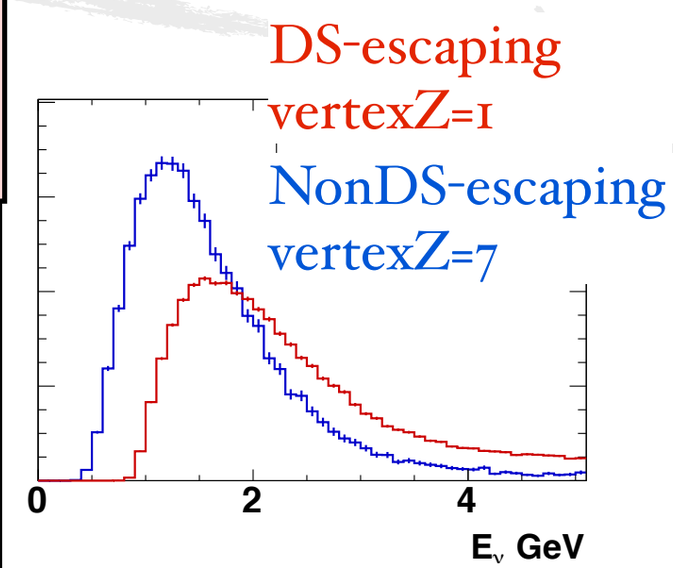
**Definition of grouping modules**




**Energy spectra predicted by MC**

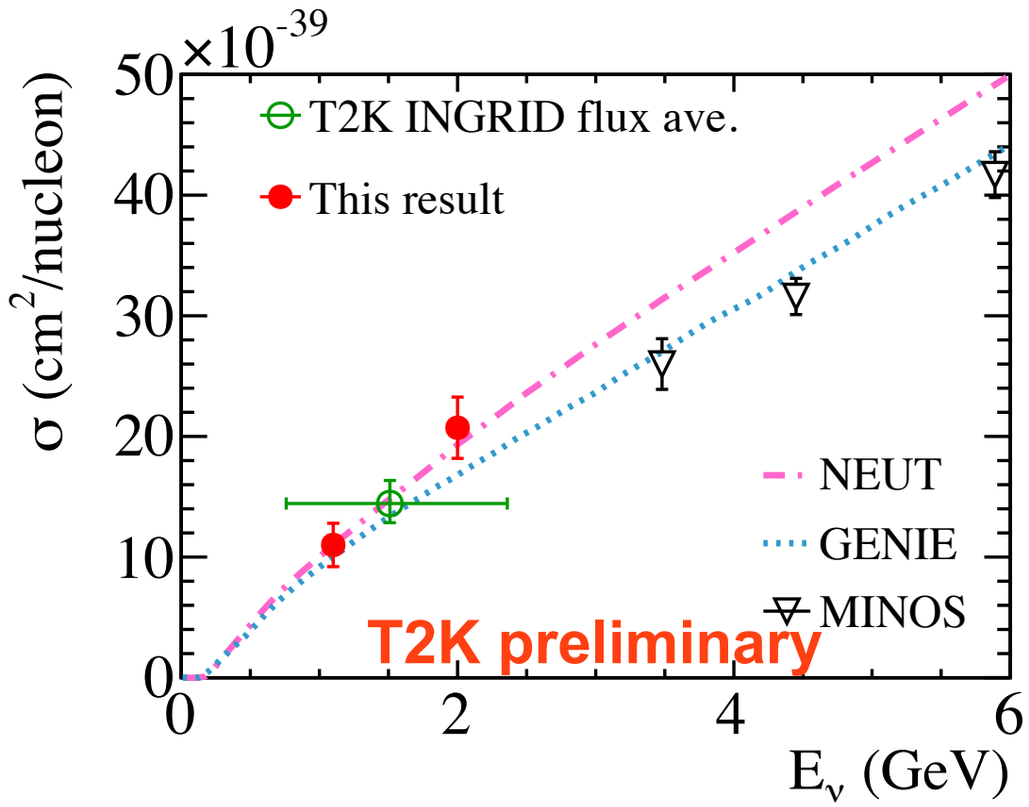


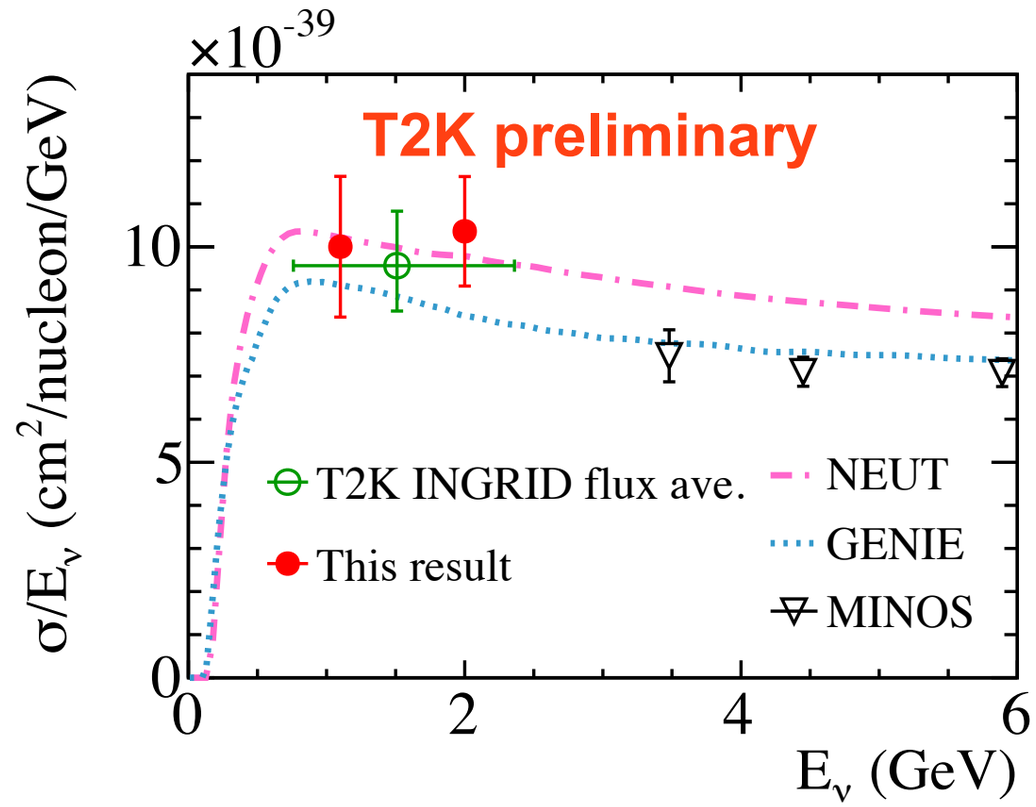



$\nu_\mu + Fe \rightarrow \mu^- + X$

# Energy dependent cross section




| | 1.1 GeV | 2.0 GeV |
|---|---|---|
| Cross section ($10^{-38}$cm$^2$/nucleon) | 1.10 ± 0.13 ± 0.12 | 2.07 ± 0.23 ± 0.06 |

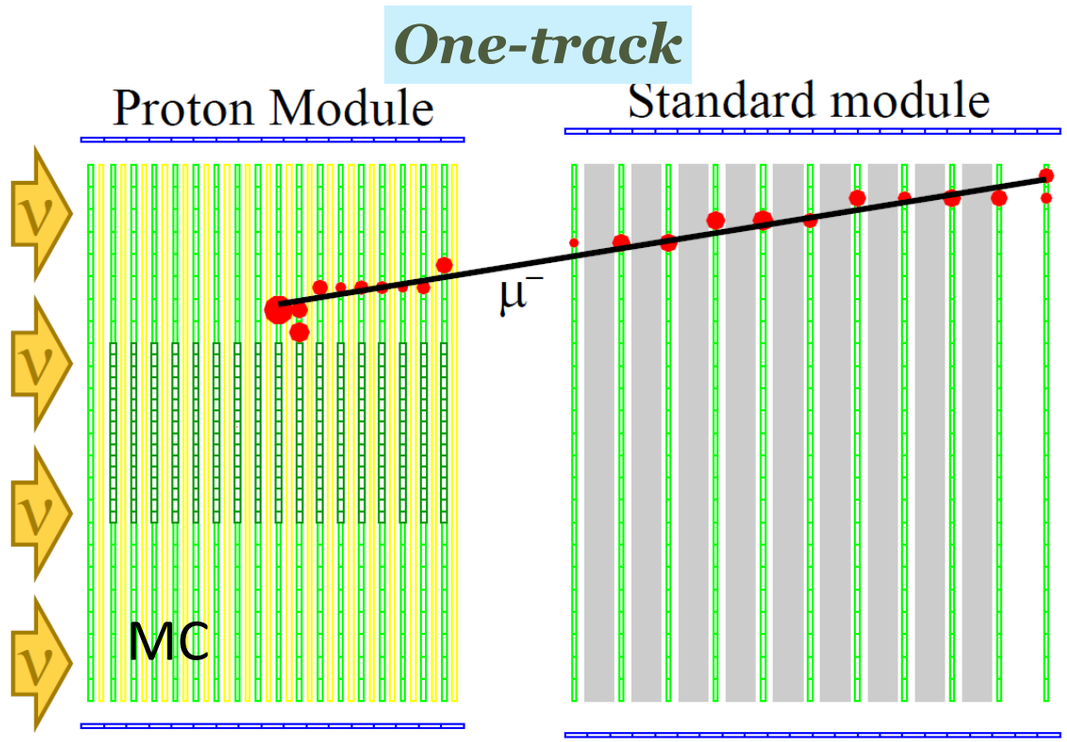
(Flux & Det. response & Neutrino interaction) ± Secondary interaction

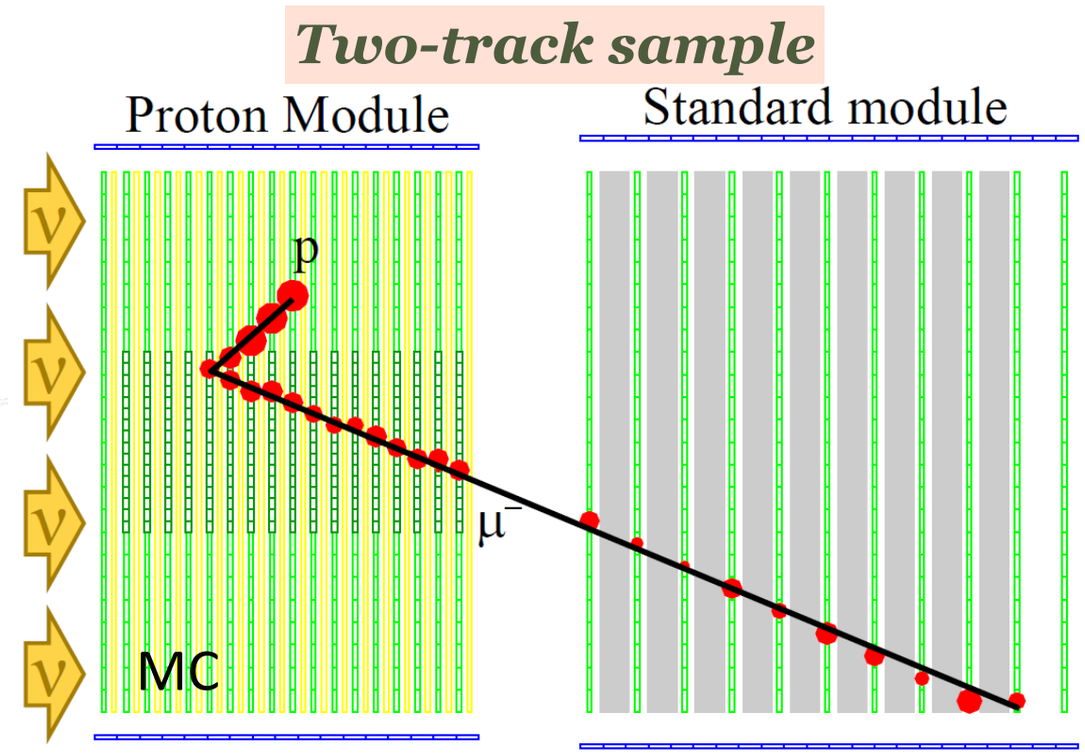
*We are now evaluating the systematic error for the cross section at 3.3 GeV*

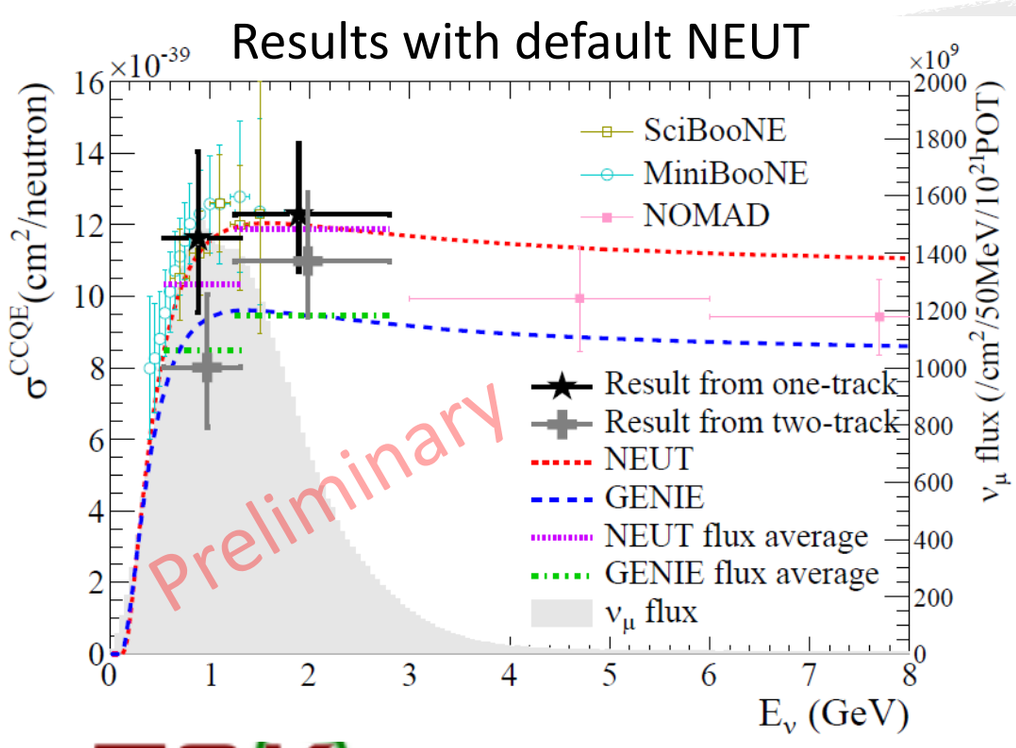
**Energy dependence is determined in a <u>model-independent</u> way!**

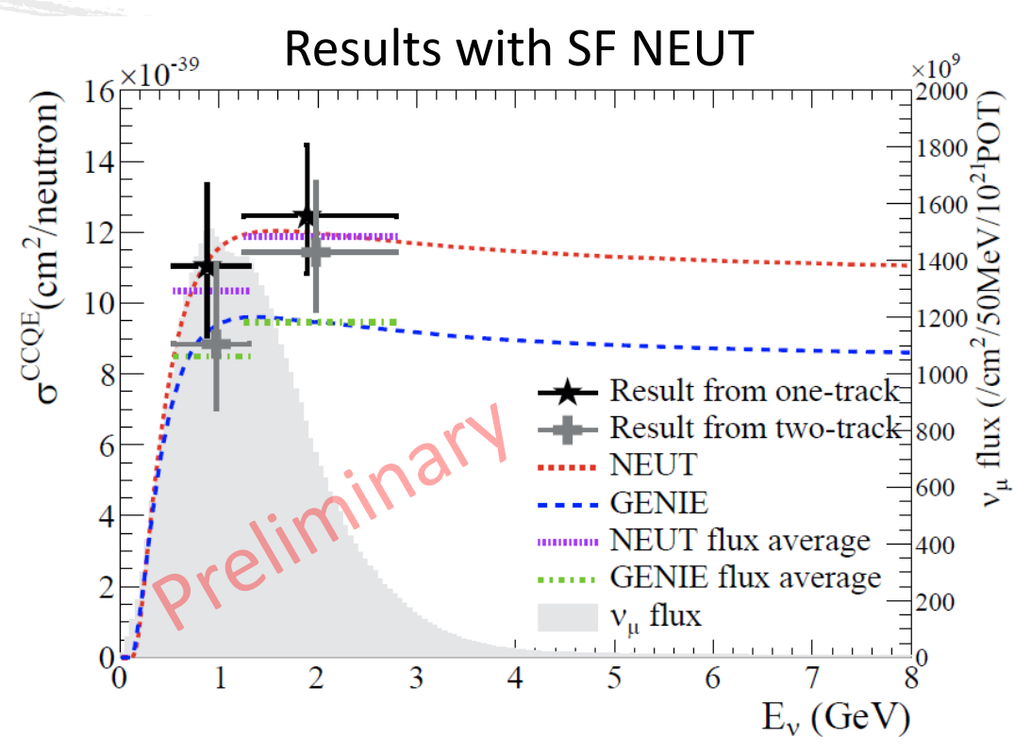
# INGRID CCQE

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



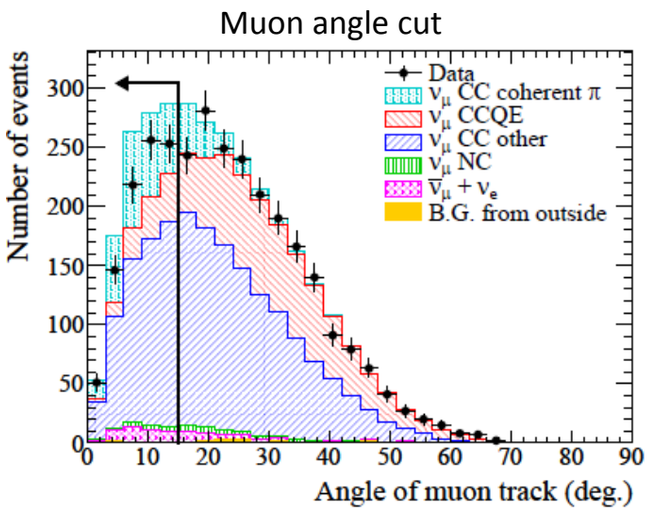



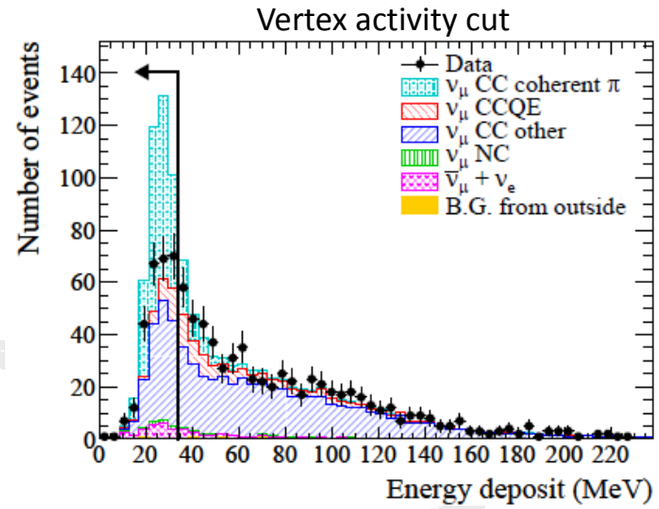



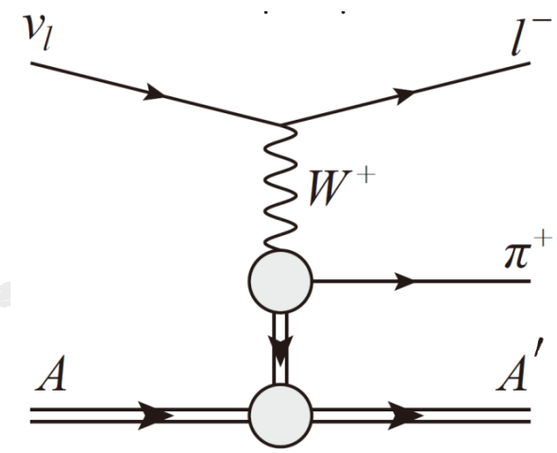



$$\nu_\mu + C \rightarrow \mu^- + \pi^+ + C$$

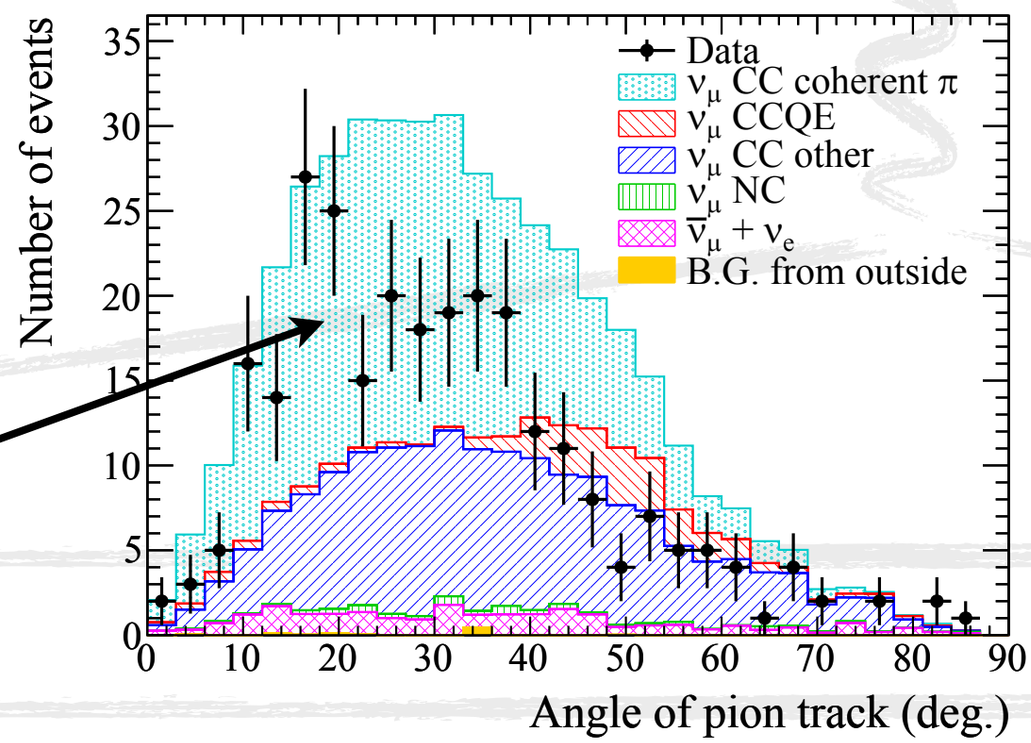
# INGRID CC coherent pion production

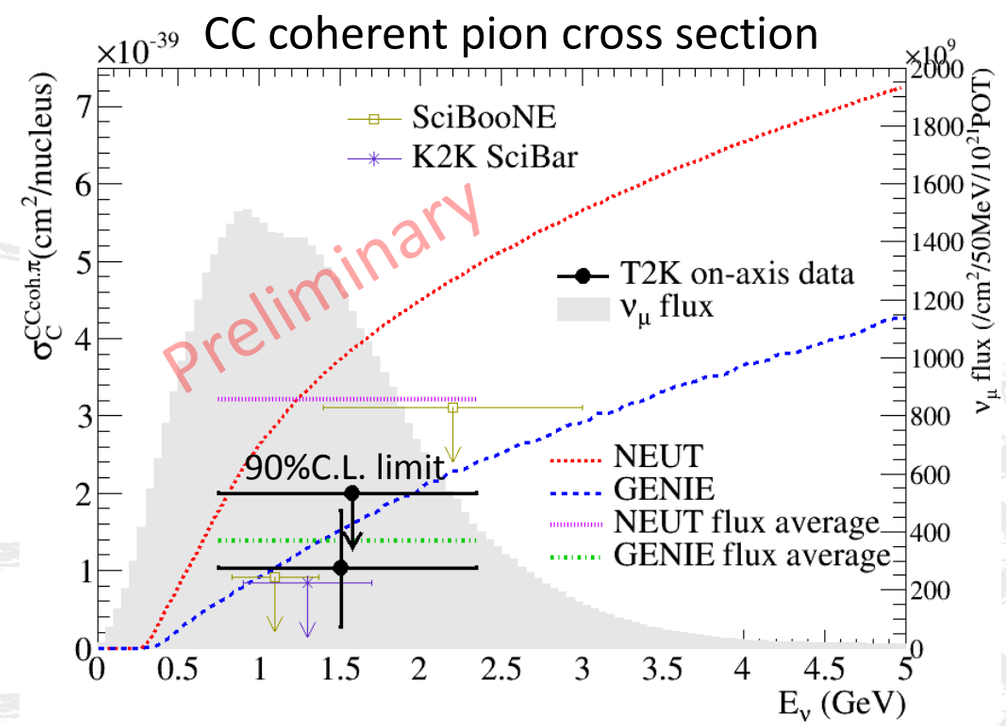



also seen by SciBooNE




**Cross section at mean energy of 1.5 GeV :**

$$\sigma_{CCcoh} = (1.03 \pm 0.25(stat.)^{+0.70}_{-0.68}(syst.)) \times 10^{-39}\ \text{cm}^2/\text{nucleus}$$

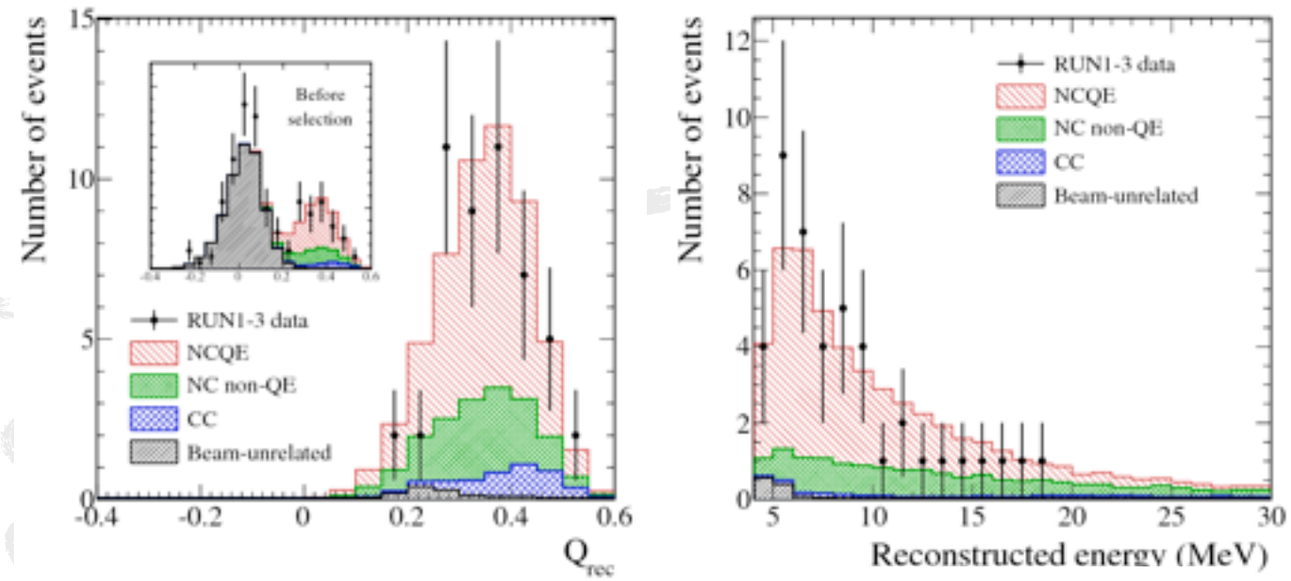
**T2K sets 90% C.L. upper limit** $\sigma_{CCcoh} < 1.98 \times 10^{-39}$ cm²/nucleus

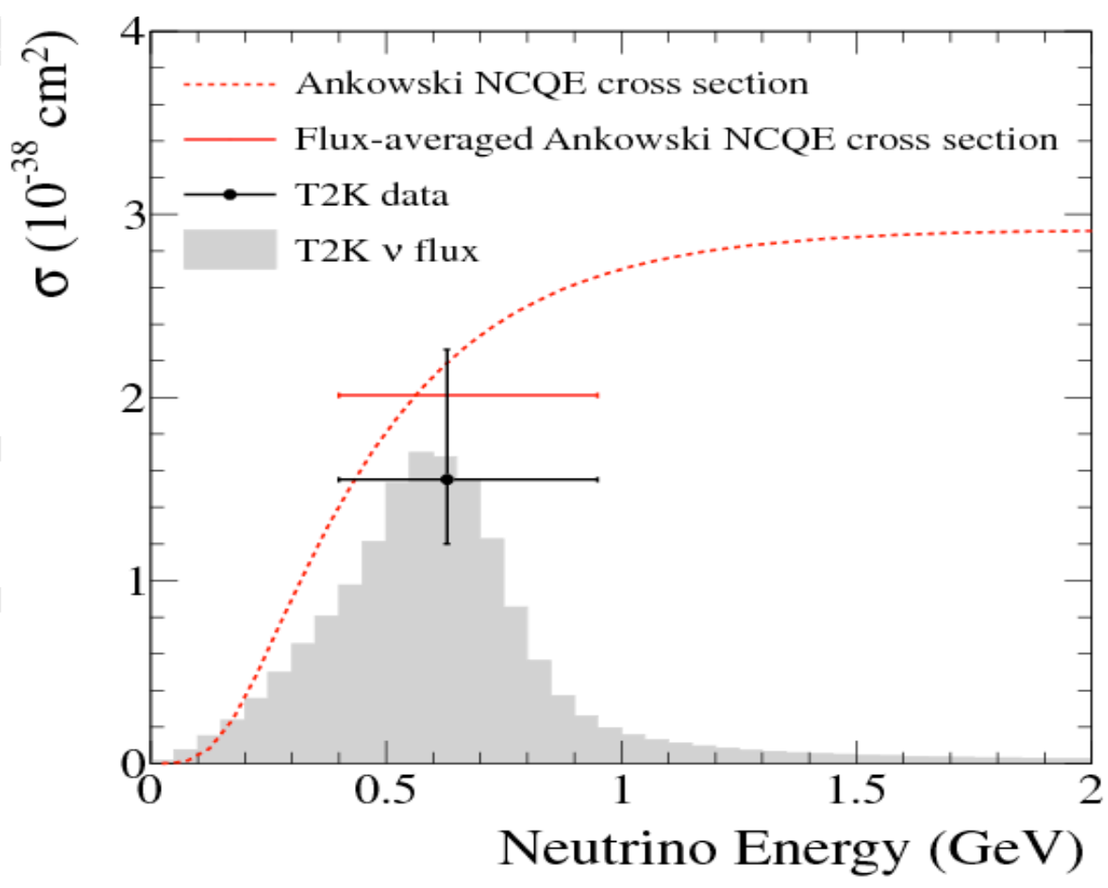
$$\nu_\mu + {}^{16}O \rightarrow \nu_\mu + p + {}^{15}N^*$$

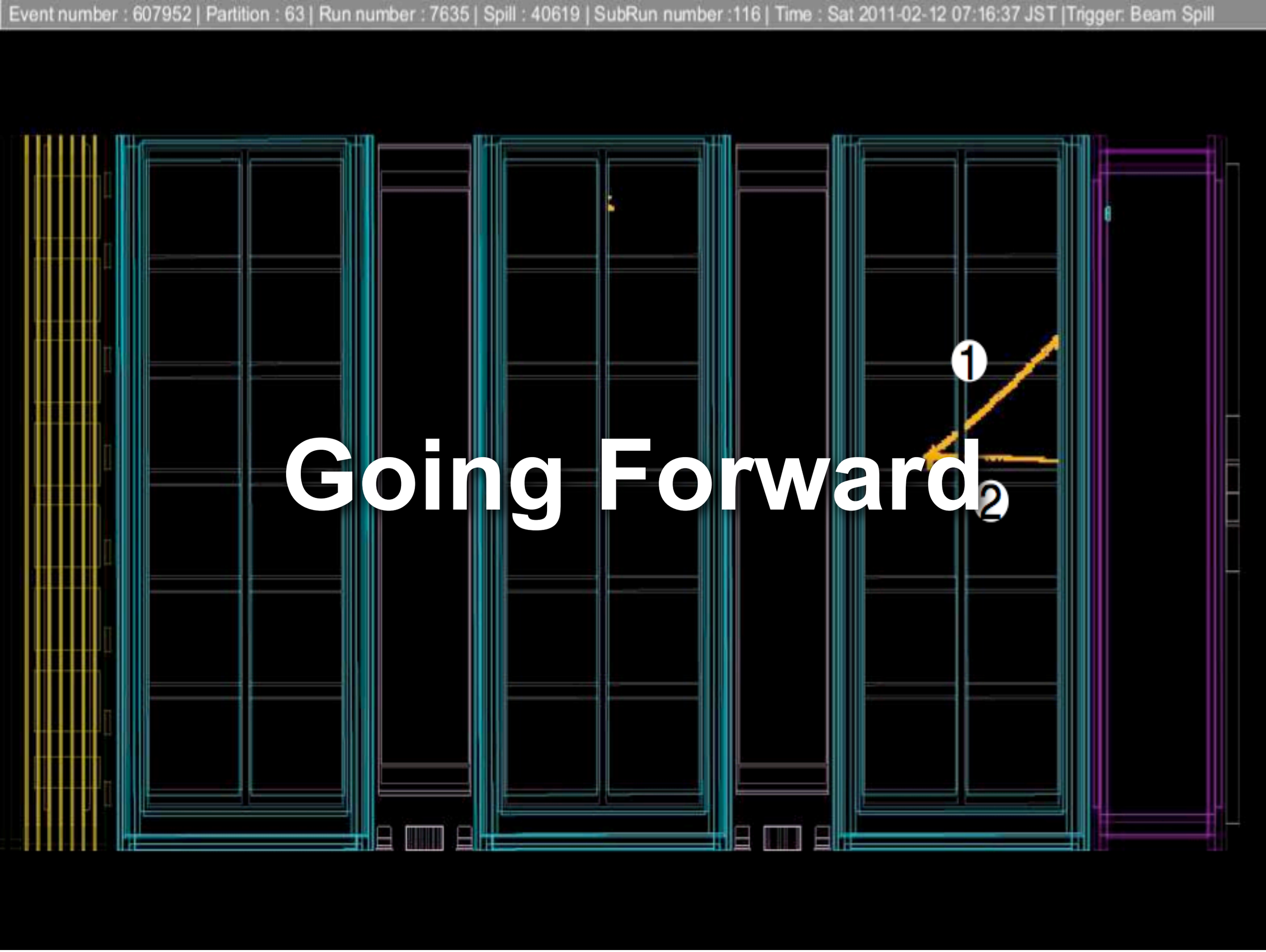
# SK NC QE

Phys Rev. D 90 (2014) 072012

- Measure NC QE scattering by detecting nuclear de-excitation gamma
- Select low energy 1-ring e-like events, with fiducial volume and beam-timing cuts
- Final cut on reconstruction quality parameter
  - Combines PMT hit position and timing
  - 43 events observed!
- Cross section extracted with template method (1 bin)



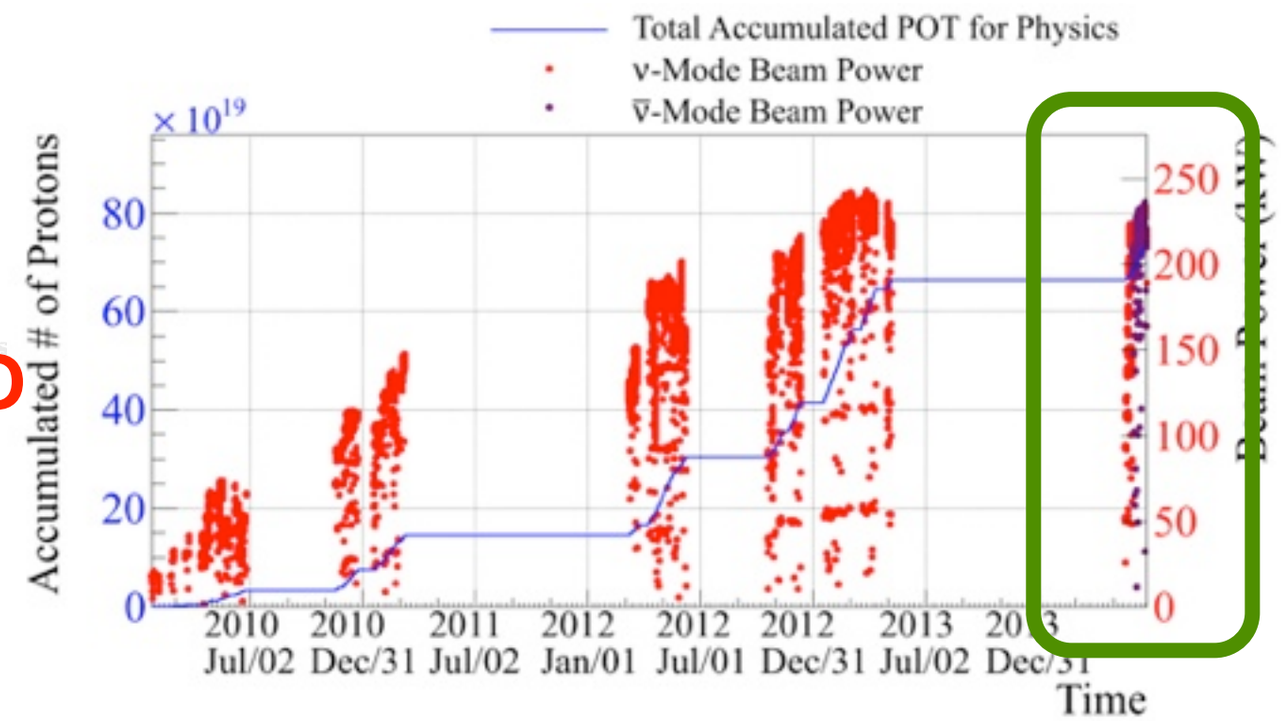






# Going Forward

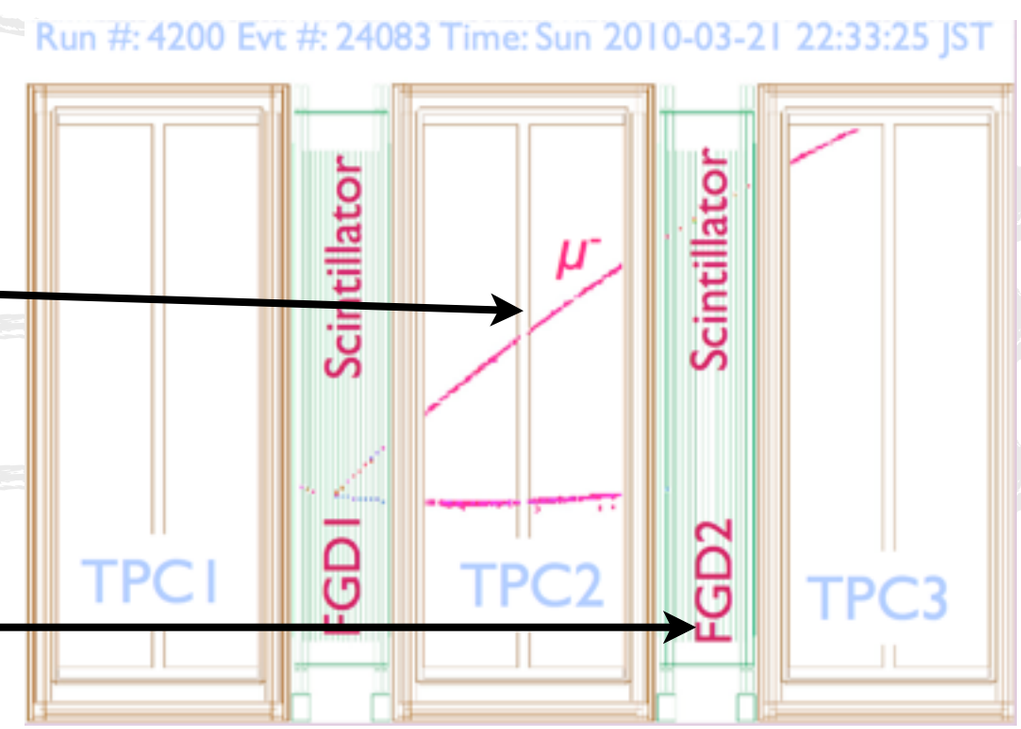
# Upcoming results

- **Antineutrino results**
- **$\nu$ and $\bar{\nu}$ measurements on O**
- CC coh pion in tracker
- $\nu_\mu$ CC0π / CC1π / CCother
- $\nu_\mu$-Pb in ECals
- $\nu_\mu$-Ar in gas TPCs



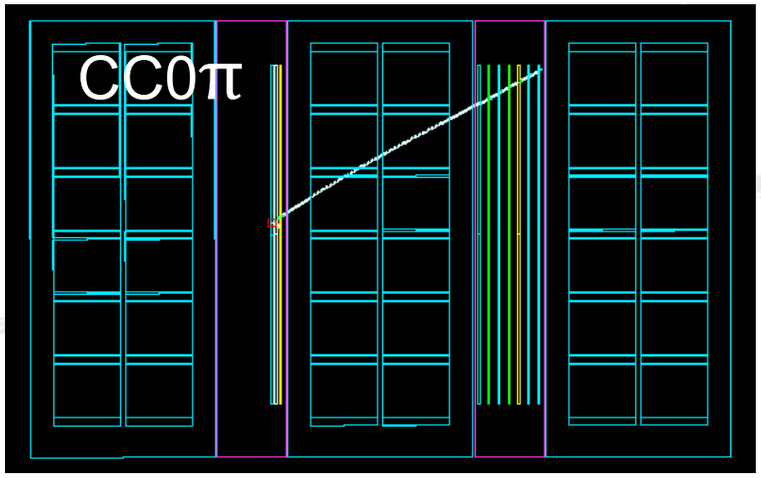

Look for $\mu^+$

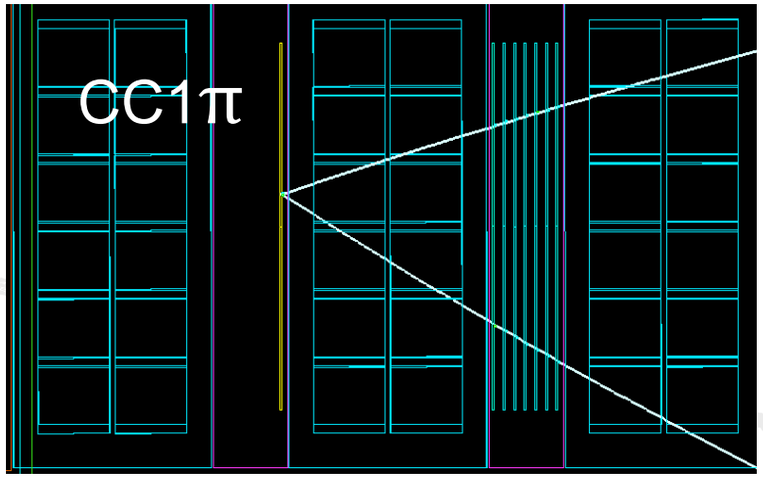
Contains inactive water layers

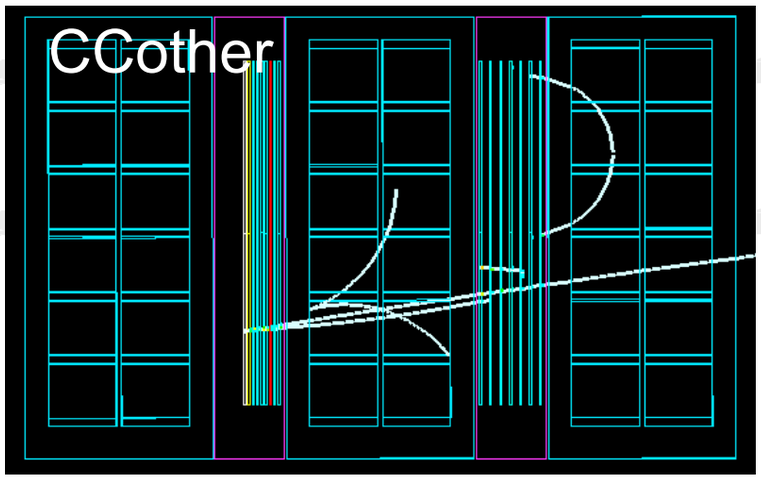


# Upcoming results

- Antineutrino results
- $\nu$ and $\bar{\nu}$ measurements on O
- CC coh pion in tracker
- **$\nu_\mu$ CC0π / CC1π / CCother**
- $\nu_\mu$-Pb in ECals
- $\nu_\mu$-Ar in gas TPCs

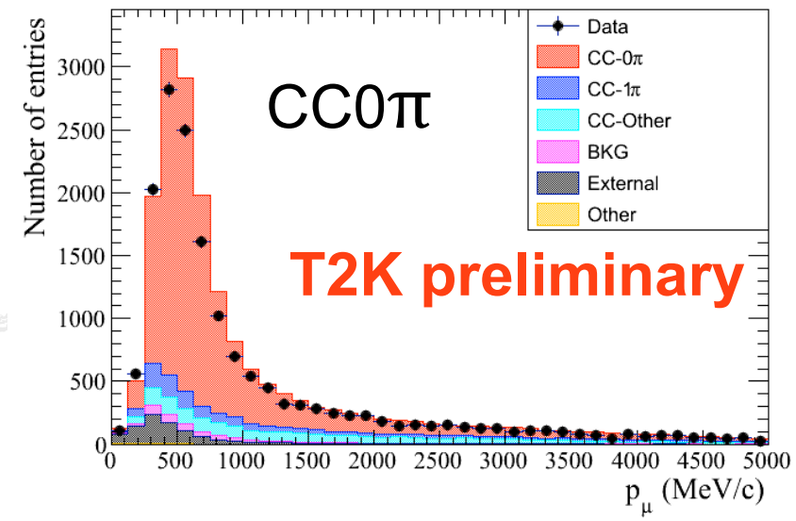


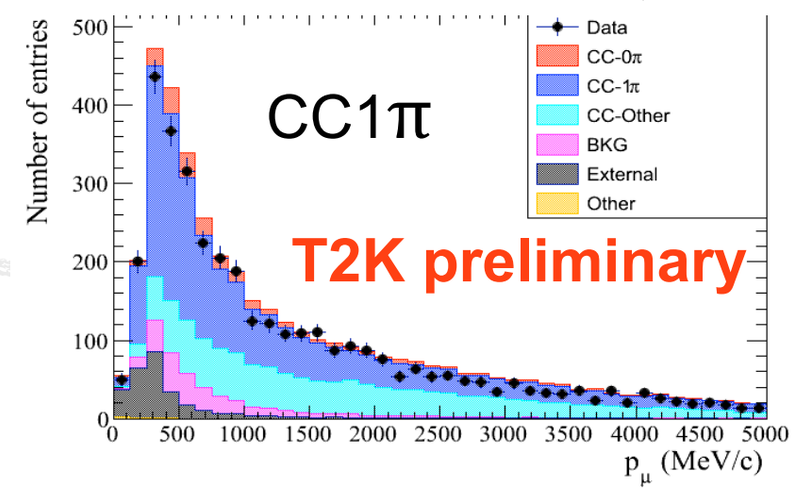



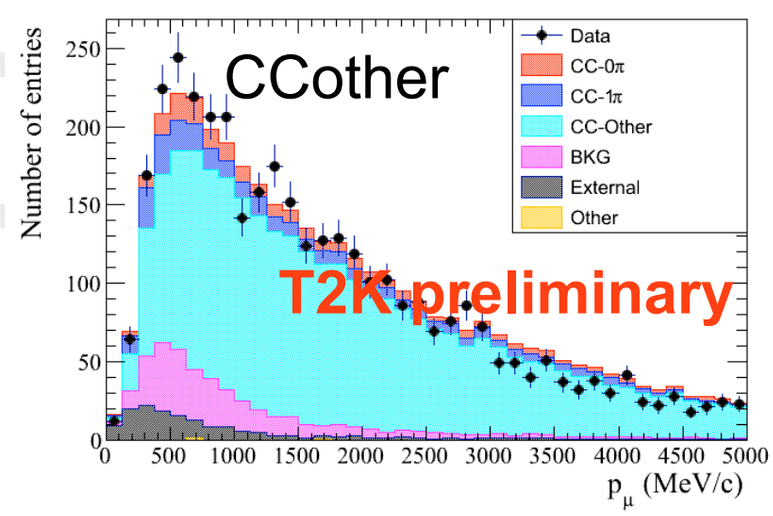



# Upcoming results

- Antineutrino results
- $\nu$ and $\bar{\nu}$ measurements on O
- CC coh pion in tracker
- **$\nu_\mu$ CC0π / CC1π / CCother**
- $\nu_\mu$-Pb in ECals
- $\nu_\mu$-Ar in gas TPCs



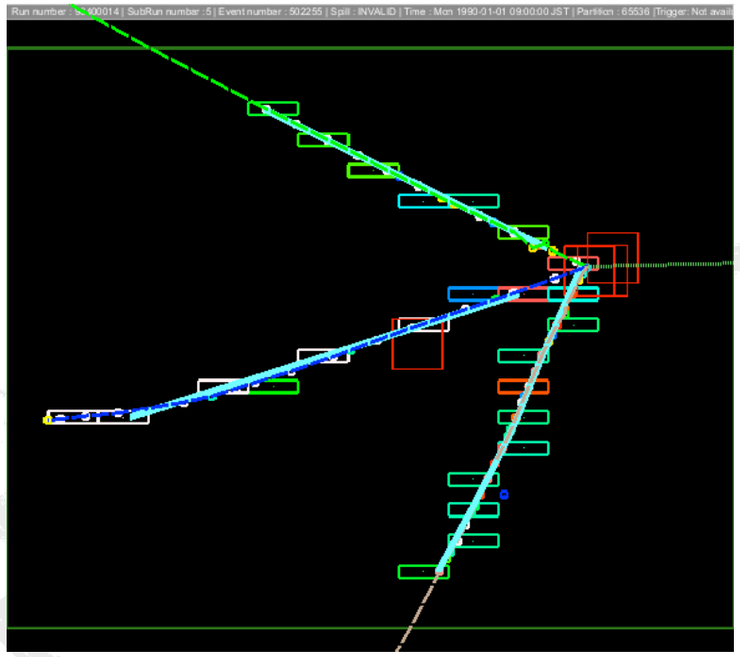




*Will test new NEUT model with improved ND280 event selections, and make differential cross section measurements*

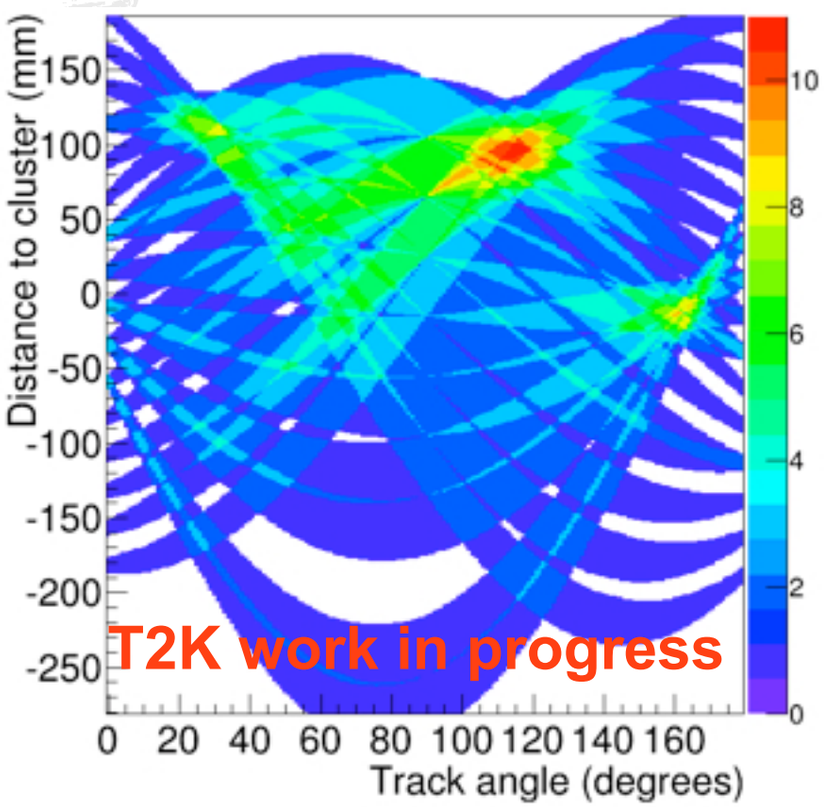
# Upcoming results

- Antineutrino results
- $\nu$ and $\bar{\nu}$ measurements on O
- CC coh pion in tracker
- $\nu_\mu$ CC0π / CC1π / CCother
- **$\nu_\mu$-Pb in ECals**
- $\nu_\mu$-Ar in gas TPCs



*New reconstruction in ECals based on Hough transform*

*Very good at separating tracks from same vertex*



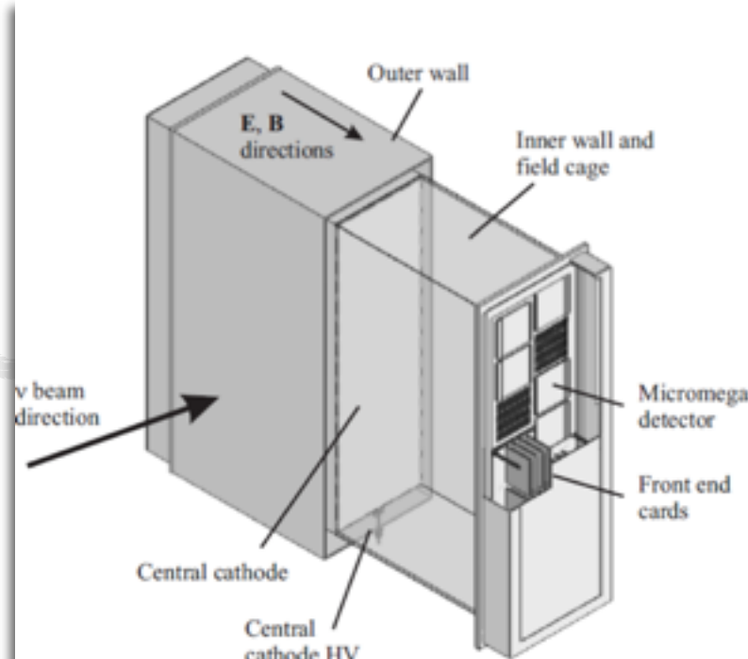

*Possible tracks traced out in distance-angle space; hot-spots show track candidates*

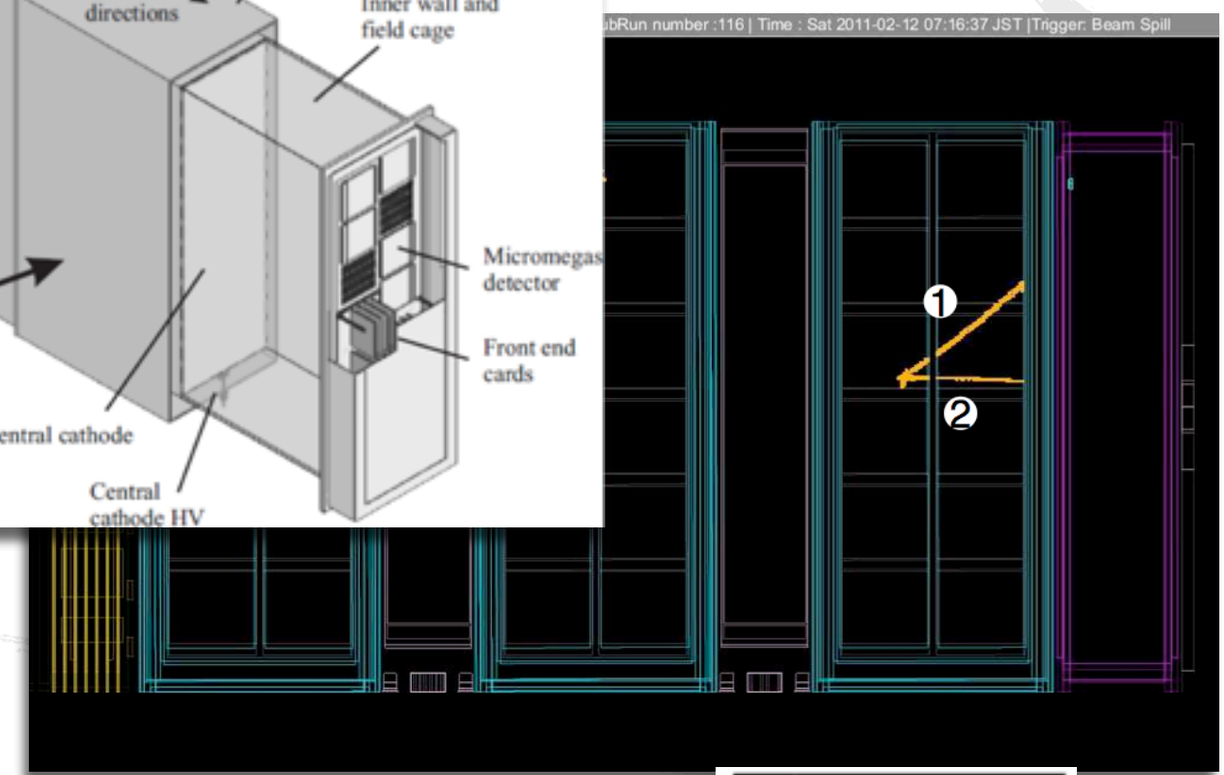
*Current ECal reconstruction would find a shower-like cluster for this event*

# Upcoming results

- Antineutrino results
- $\nu$ and $\bar{\nu}$ measurements on O
- CC coh pion in tracker
- $\nu_\mu$ CC0π / CC1π / CCother
- $\nu_\mu$-Pb in ECals
- **$\nu_\mu$-Ar in gas TPCs**

- *...and even more than that!*




TPC Reconstruction EXtension
processes TPC images
Looks for lines and junctions
with assigned PID values

# Summary

- The community needs newer and better neutrino-nucleus interaction measurements
- T2K has a wide variety of high precision subdetectors exposed to a wide variety of neutrino fluxes
- We are making unique, precise new measurements with
  - $\nu_\mu$, and $\nu_e$, $\nu$ and $\bar{\nu}$;
  - on-axis and off-axis detectors;
  - C, Fe, O, with Cu-Zn, Pb to come
  - baselines of 280 m and 295 km!
- There are more measurements with better precision on the horizon for T2K

See http://t2k-experiment.org/for-physicists/ for more information

# Thank you for your attention!

# ご清聴ありがとうございました

**Many thanks to:**
**A Himmel, J Holeczek,T Katori, M Khabibullin, P Litchfield, K Mahn, K McFarland, D Ruterbories, K Scholberg, B Smith, K Suzuki, R Tacik, H A Tanaka, C Wilkinson, K Yamamoto for valuable input**

水戸の梅の花