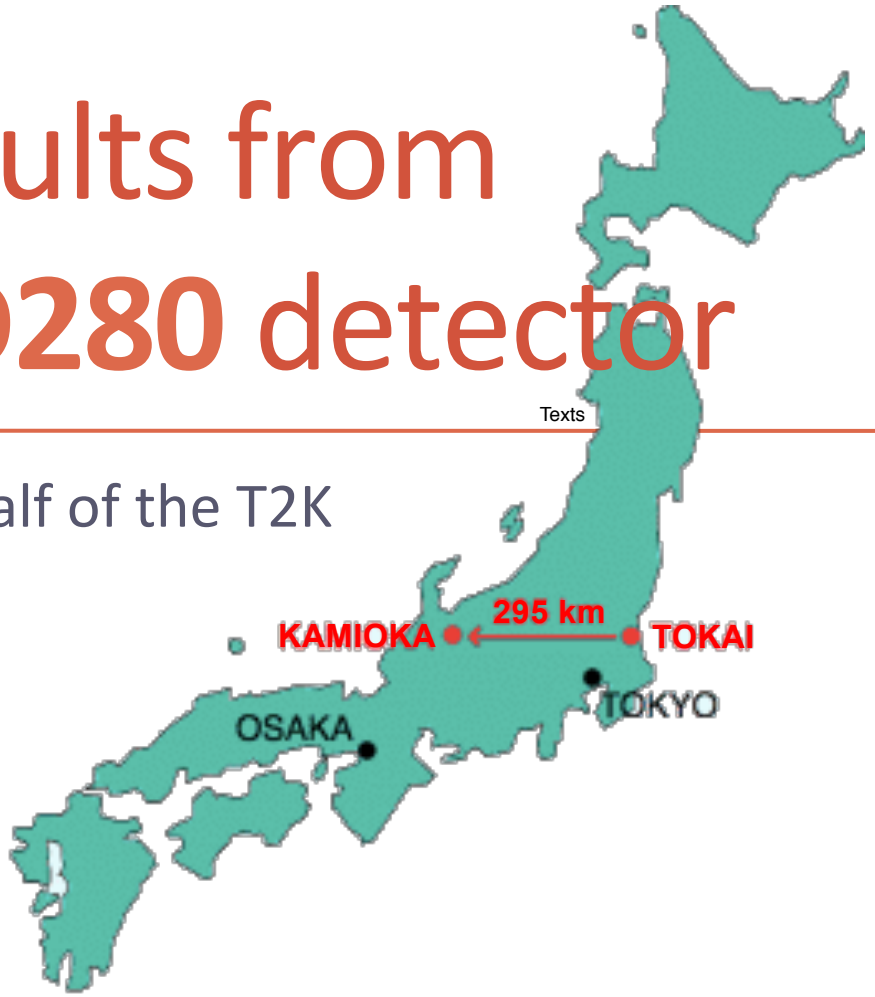
Recent Results from the T2K **ND280** detector

Jonathan Perkin on behalf of the T2K collaboration



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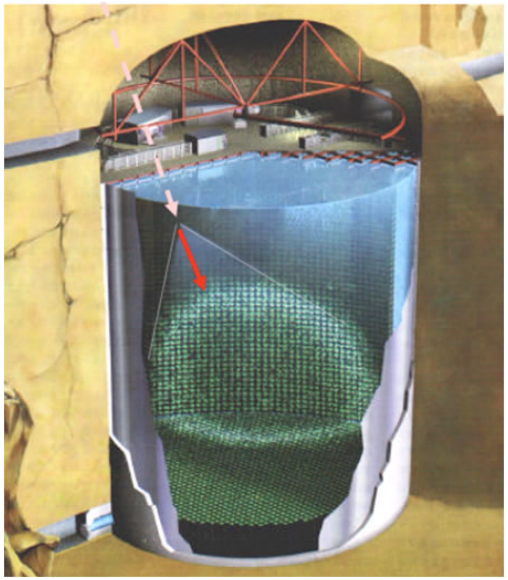
The T2K Experiment

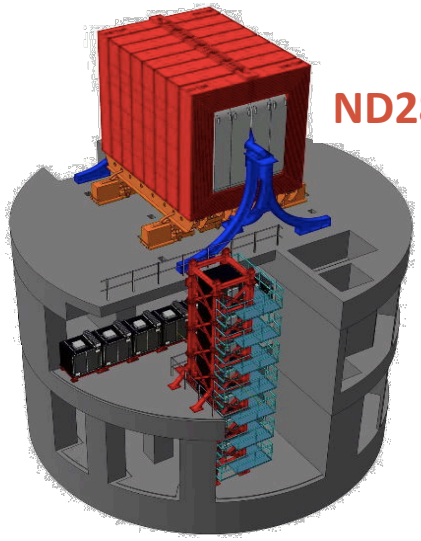
Tokai to Kamioka

$\nu_\mu \rightarrow \nu_e$ $\nu_\mu \rightarrow \nu_\mu$

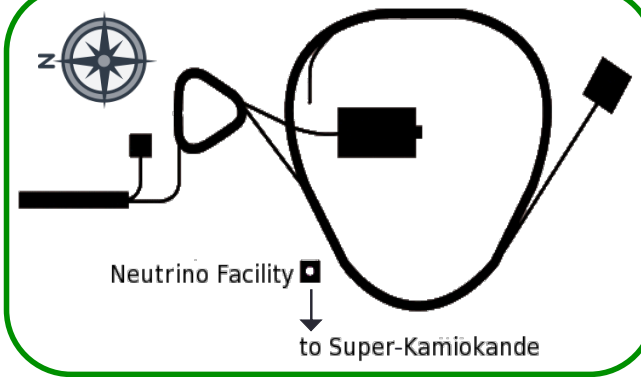
~500 Collaborators
59 Institutions
11 Countries



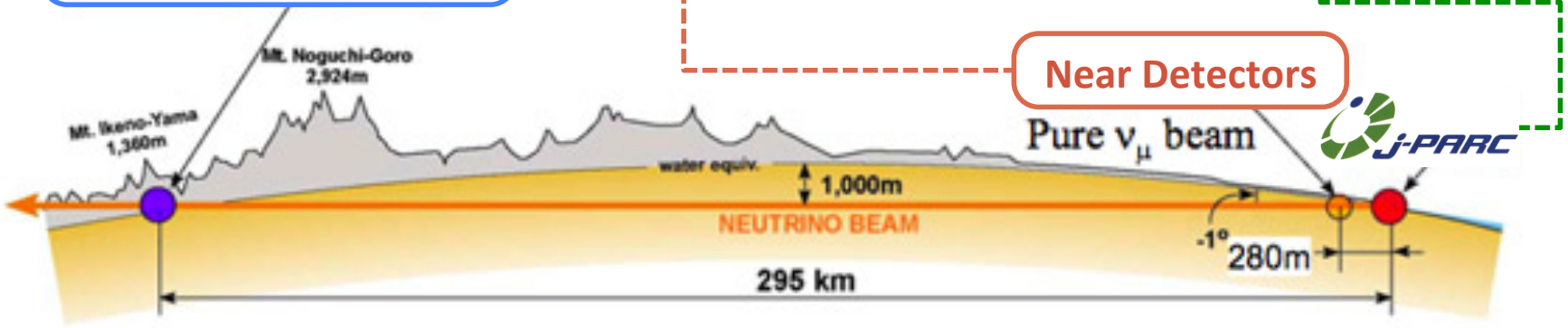
Super-Kamiokande



INGRID



Near Detectors



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T2K Analysis Concept

- $\nu_\mu \rightarrow \nu_x$ oscillation measurement
  - initially a counting experiment – how many of each flavour detected?
    - parameters also extracted from reconstructed energy spectrum
  1. measure source flux at near detector
  2. extrapolate flux to far detector and predict observed rate
  3. measure ν_μ deficit (disappearance) or ν_e excess (appearance)
  4. use deficit/excess to exclude null oscillation hypothesis
- Sounds simple, but…
  - many inputs required
  - many sources of uncertainty
  - many correlations to consider
  - several independent analyses

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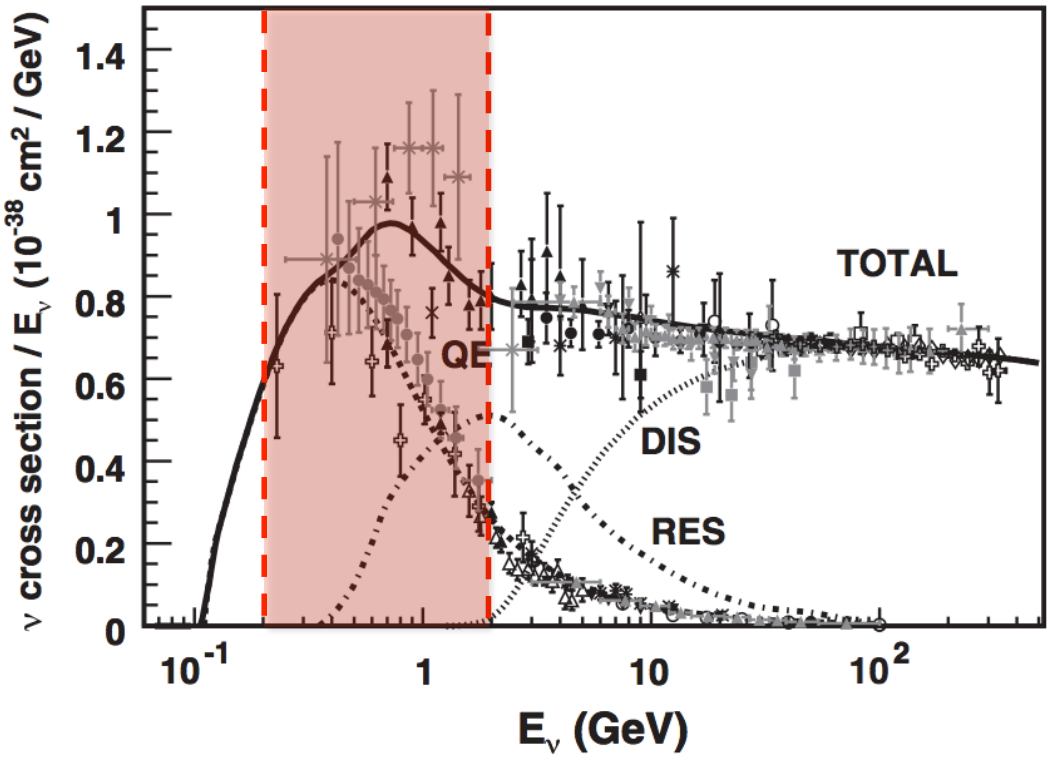
T2K Physics : ν + n(p) @ 0.1-2GeV

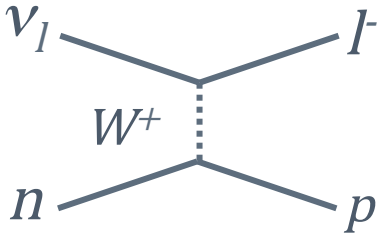
- $\nu_\mu \rightarrow \nu_e$ ***appearance*** and $\nu_\mu \rightarrow \nu_\mu$ ***disappearance***

Recent results from the T2K ND280 Detector

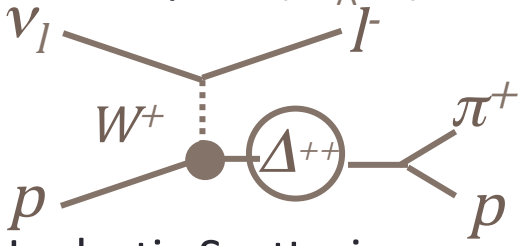


Formaggio & Zeller, Rev. Mod. Phys. 84 (2012)

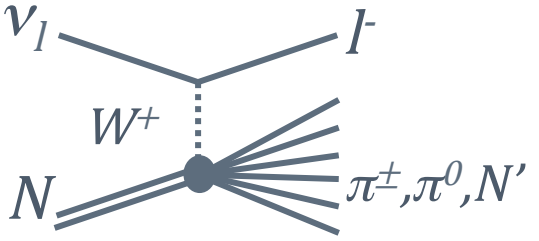
- Dominated by **C**harged **C**urrent **Q**uasi **E**lastic (M_A^{QE})



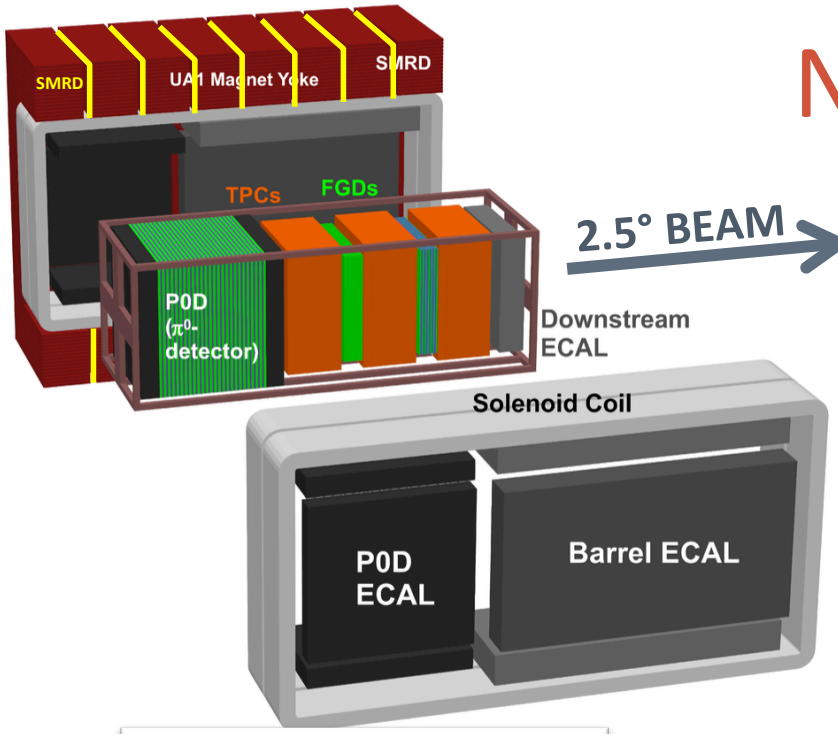
- Resonant CC pion (M_A^{Res})

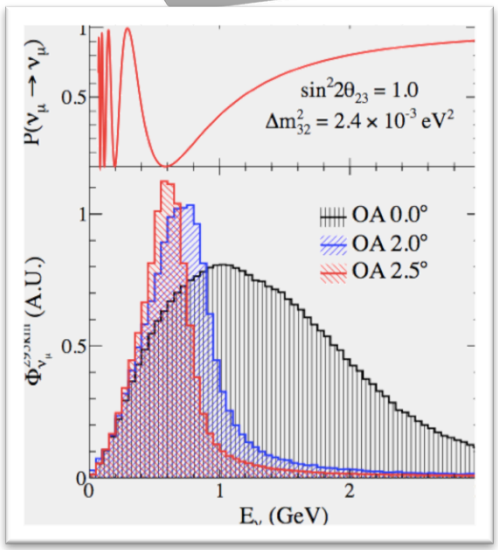


- Deep Inelastic Scattering



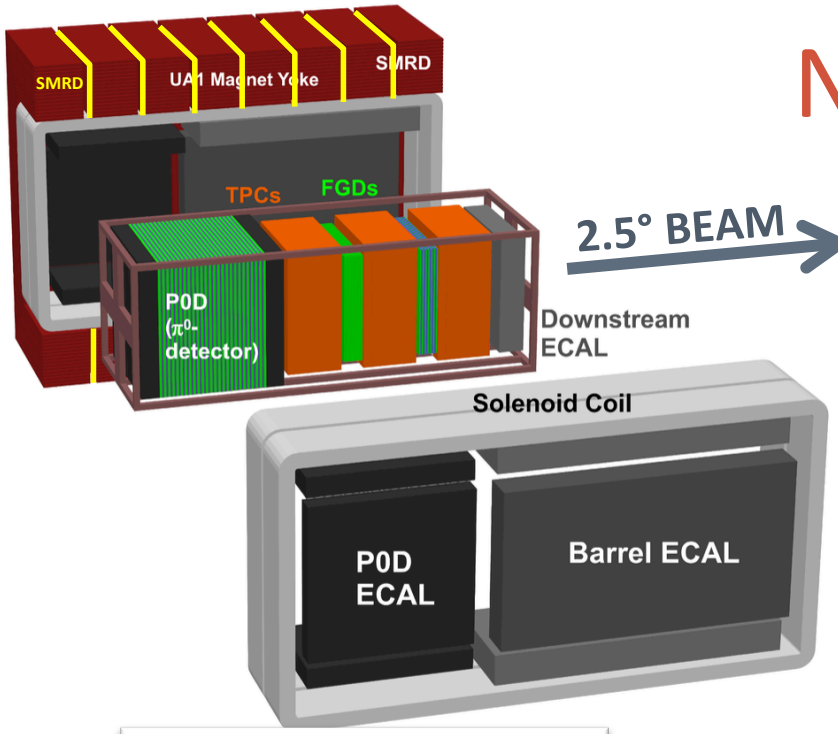
Near detectors constrain **cross section** and **ν flux prior** to oscillation

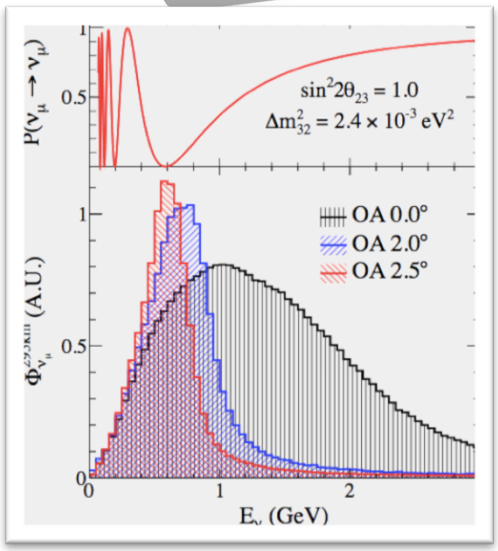




Near Detector @ 280m

- **280m from target**
  2.5° from beam axis
- **Upstream π^0 detector (P0D)**
  scintillator interleaved with C and H_2O targets and scintillator/brass in ECal PODules
- **2x 0.8ton Fine Grained Detectors (FGD)**
  scintillator interleaved with C (FGD1) and H_2O (FGD2) target
- **3x Time Projection Chambers (TPC)**
  for accurate dE/dx based PID
- **Electromagnetic Calorimeters (ECAL)**
  hermetic lead/scintillator
- **Side-Muon Range Detector (SMRD)**
  scintillator paddles interleaved with magnet flux return
- **0.2T magnetic field**
  refurbished UA1/NOMAD magnet





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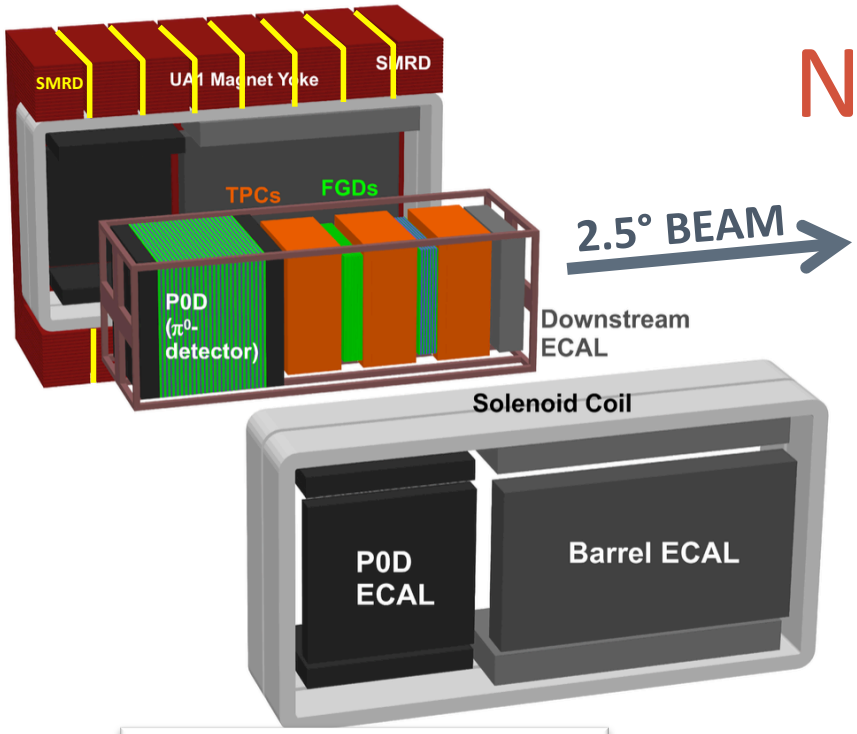

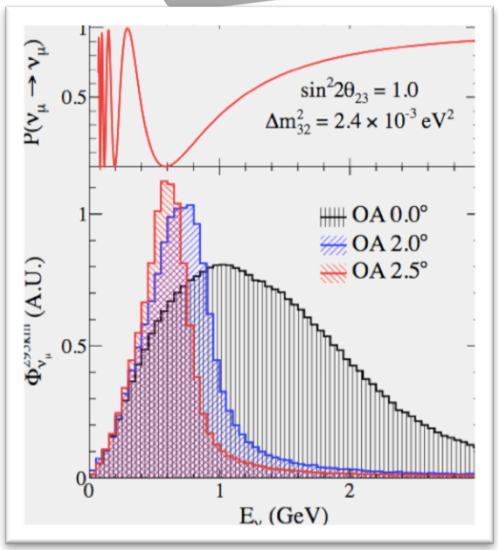

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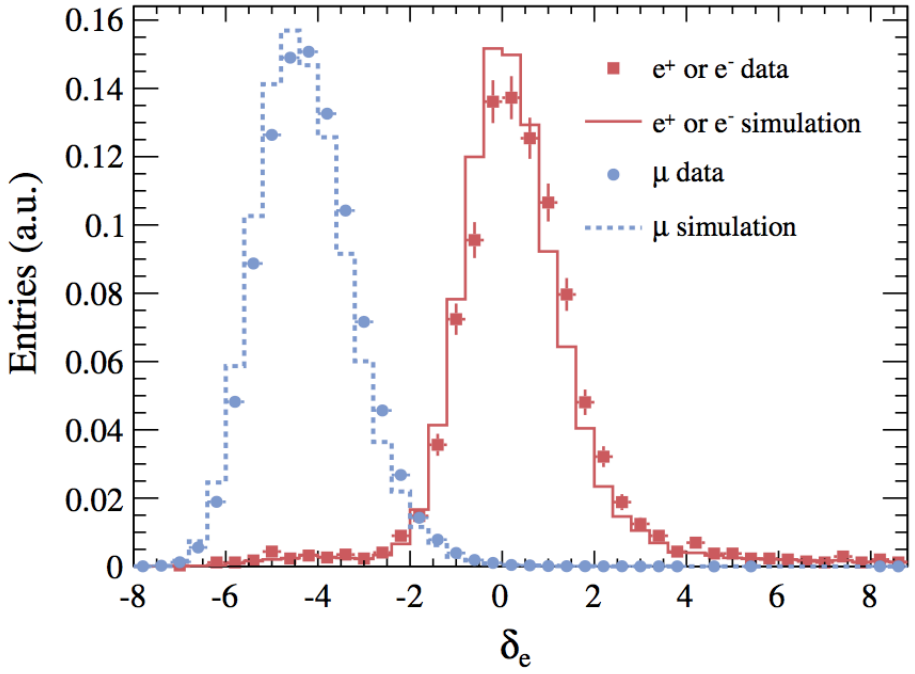
The ND280 TPC

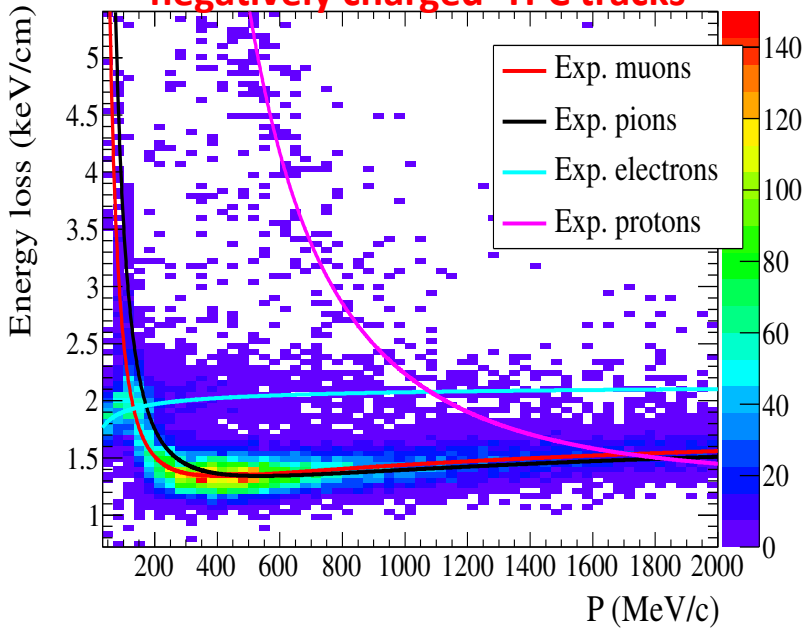
Recent results from the T2K ND280 Detector

TPC dE/dx

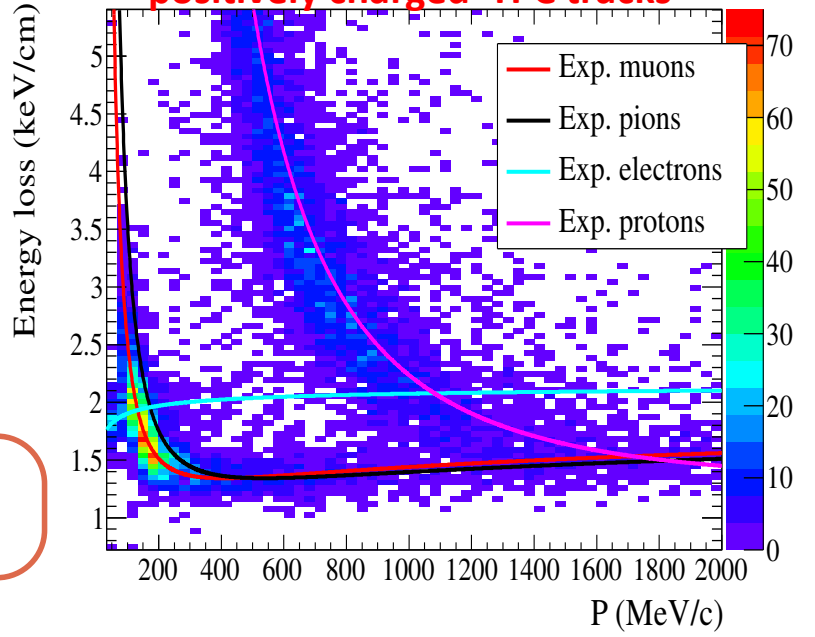
TPC electron likelihood for $e^{\pm}$ and μ



negatively charged TPC tracks

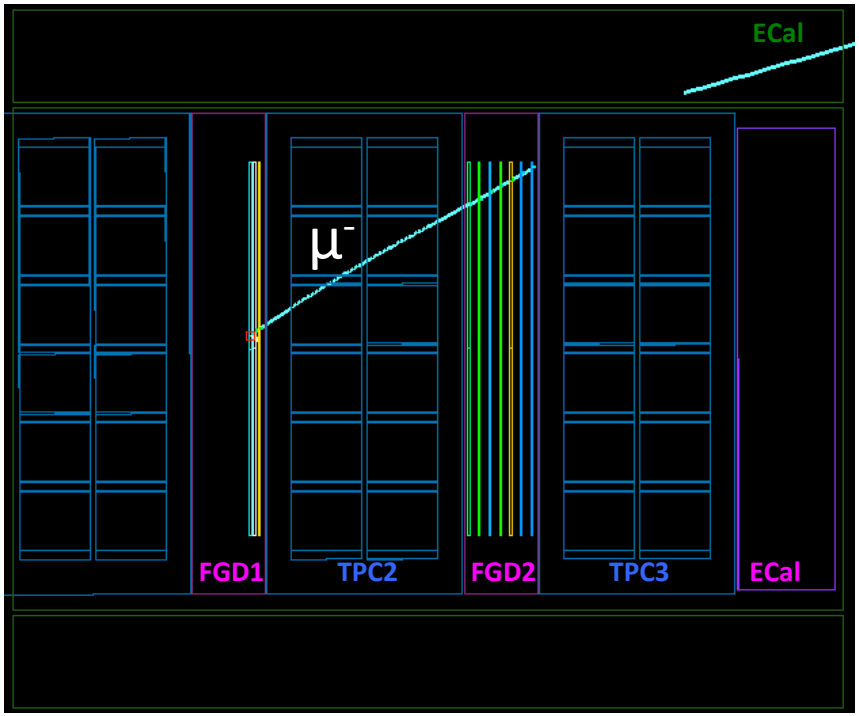


positively charged TPC tracks

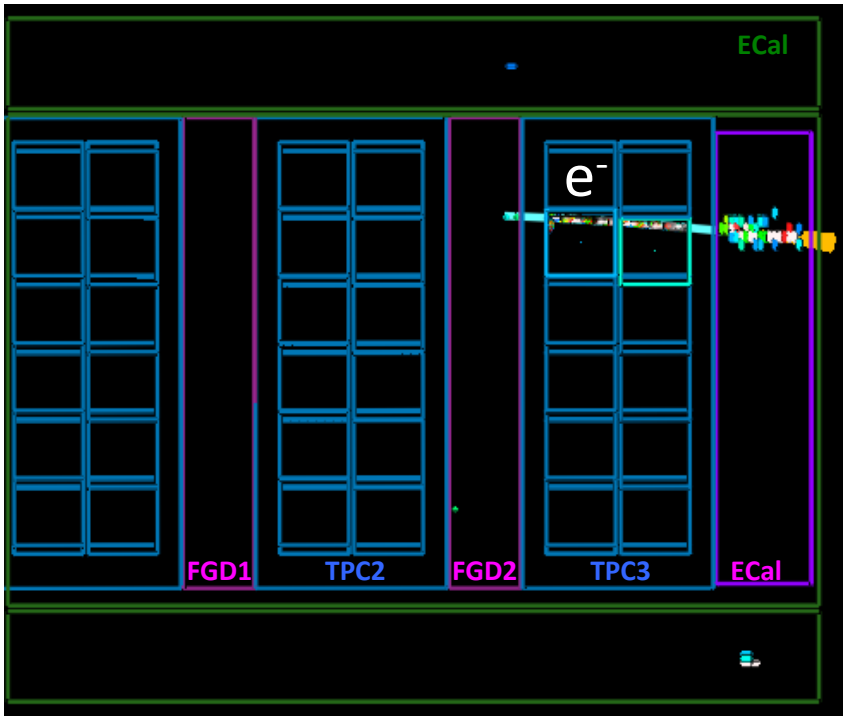


Excellent electron/muon separation from ND280

ND280 ν_μ candidate event



- Charged Current ν_μ in FGD1
  - no accompanying pions
  - muon-like TPC PID
  - ECal track



- Charged Current ν_e in FGD2
  - no accompanying pions
  - electron-like TPC PID
  - ECal shower

ND280 ν_e candidate event

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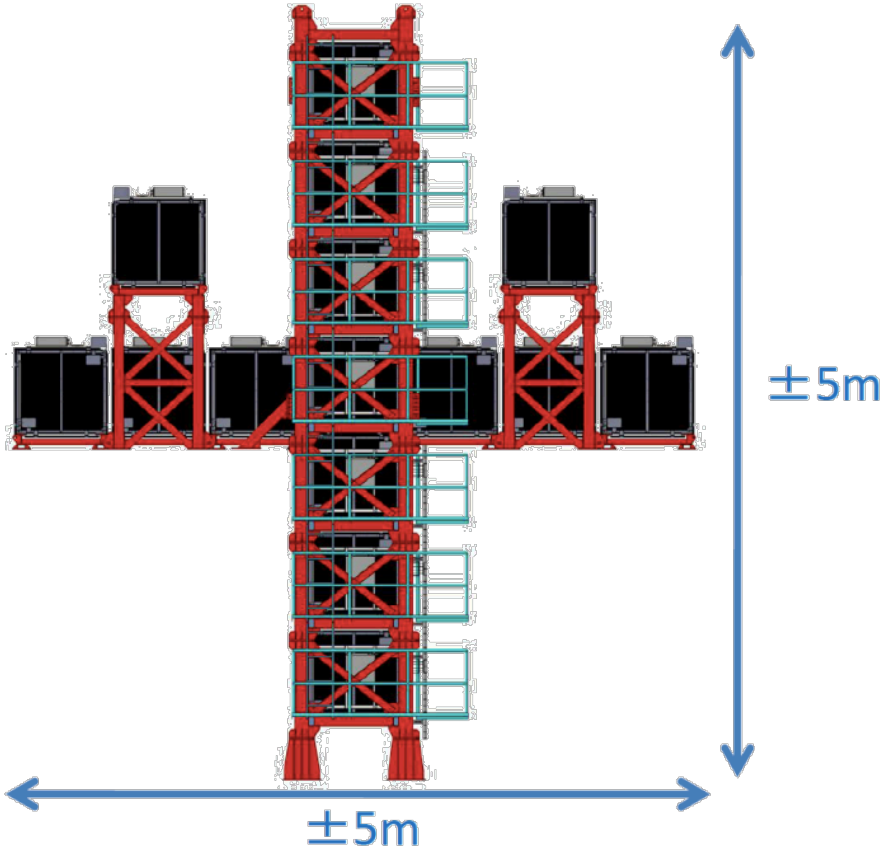
On Axis Near Detector

- **Interactive Neutrino Grid (INGRID)**
  - 280m from target on beam axis
  - 16x iron/scintillator tracking calorimeters
  - 1x all-scintillator proton module
  - monitors beam centre, profile and CC^{inc} rate
- **INGRID measurements:**
  - CC inclusive on Fe, C and Fe/CH [arXiv:1407.4256v1]
  - coherent CCπ on C
  - CCQE on CH
  - differential cross sections



Recent results from the T2K ND280 Detector

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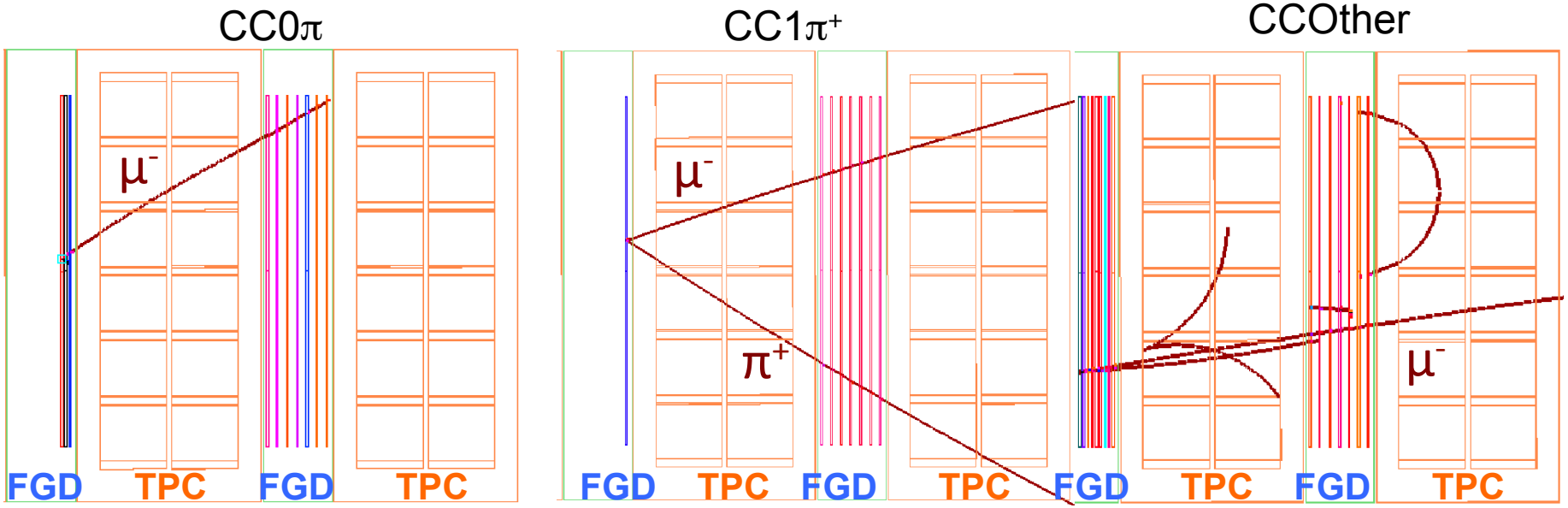
Charged Current Event Classifications



- The CC sample is separated into 3 classifications
  - defined by number of reconstructed pions from final state interactions (FSI)
    - CC0π = no charged or neutral FSI pions
    - CC1π+ = exactly 1 +ve FSI pion (no –ve or neutral)
    - CCOther = all other combinations of FSI pions (one or more –ve or neutral, >1 +ve)
- This allows for topology dependent systematics
  - featuring different combinations of sub-detector response
- Improves overall cross section + flux uncertainties

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The Near Detector Constraint

Neutrino Flux Model:

Data-driven: External (NA61/SHINE + others), beam monitor measurements [***priors***]

Uncertainties: modeled by variation of normalization parameters (*b*) in bins of neutrino energy and flavour

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Data-driven: External (NA61/SHINE + others), beam monitor measurements [***priors***]

Uncertainties: modeled by variation of normalization parameters (*b*) in bins of neutrino energy and flavour

Neutrino Cross Section Model (NEUT):

Data-driven: External neutrino, electron and pion scattering data [***priors***]

Uncertainties: modeled by variations of model parameters –

axial mass *(M_A),* Fermi-momentum *(p_F),* binding energy *(E_b), ad-hoc* parameters *(shape and normalization)*

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Data-driven: External neutrino, electron and pion scattering data [***priors***]

Uncertainties: modeled by variations of model parameters –

axial mass *(M_A)*, Fermi-momentum *(p_F)*, binding energy *(E_b)*, *ad-hoc* parameters *(shape and normalization)*

Constraint from ND280 Data:

Data Samples enhanced in CC interactions with 0, 1 or *N* pions

Fit to data constrains flux, *b,* and cross section, *x=(M_A, p_F, E_b, ad-hoc, etc.)*, parameters

Constrained SK flux parameters and subset of cross section parameters are used to predict SK event rates

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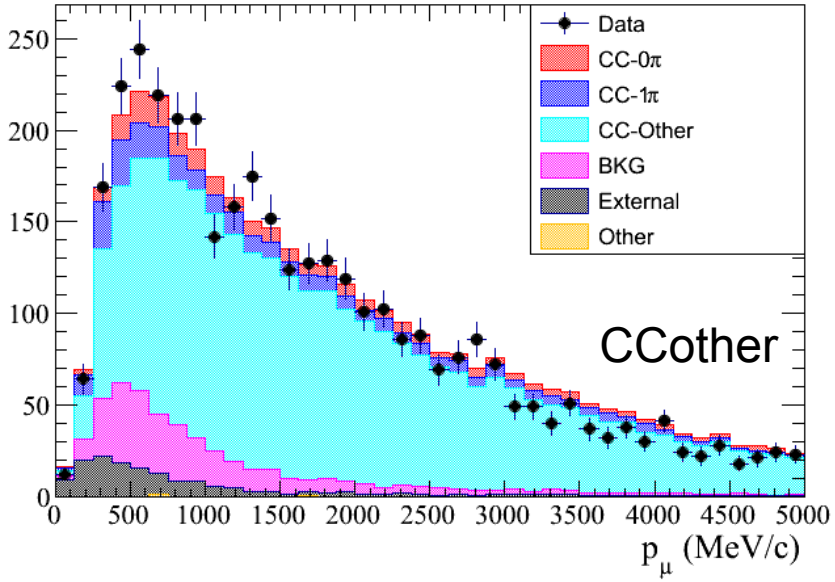
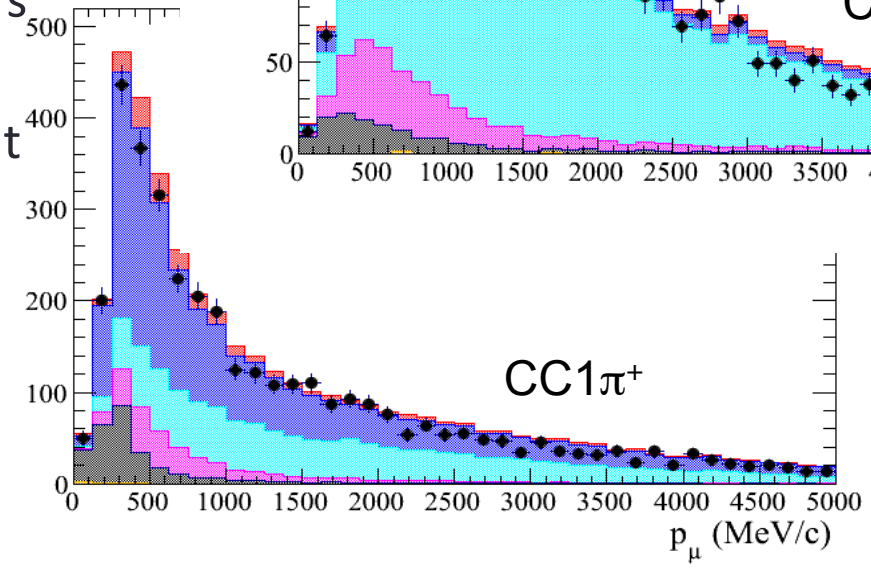
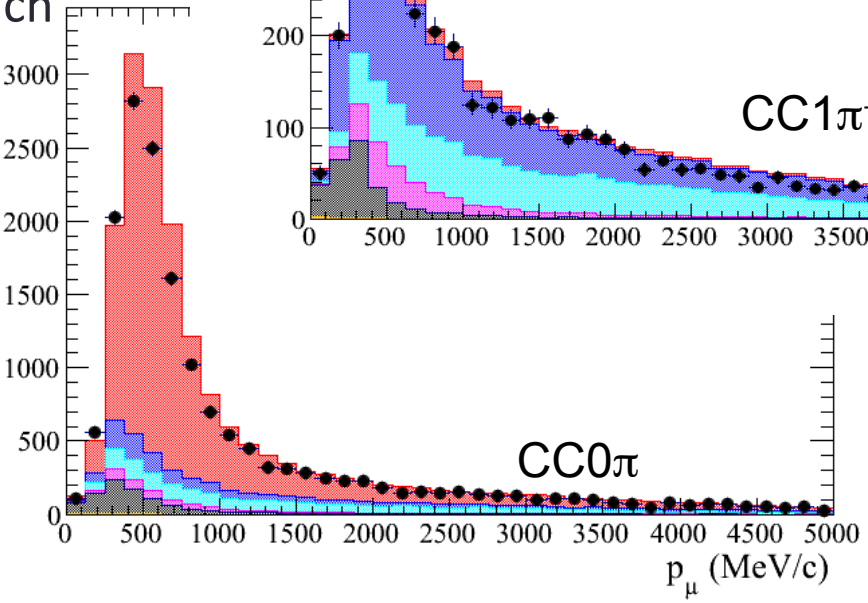
Near Detector Constraint

- **$(p,\theta)_\mu$ distributions measured for each classification**
  - cross section and flux parameters floated to find best fit
  - far detector MC reweighted to fit results of near detector measurements for each classification







	efficiency	purity
CC0π	50.1%	72.6%
CC1π⁺	29.5%	49.4%
CCOther	35.2%	73.8%

ults from the T2K ND280 Detector

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2013 Near Detector Constraint

- **2013 analysis with CC0π, CC1π$^+$ and CCOther classifications** reduces parameter uncertainties

cross section parameters and uncertainties

Parameter	3.01x10^{20}POT (2012)	6.39x10^{20}POT (2013)
M_A^{QE} (GeV)	**1.33 ± 0.20**	**1.17 ± 0.09**
M_A^{RES} (GeV)	1.15 ± 0.10	0.97 ± 0.08
CCQE Norm.	0.96 ± 0.09	0.99 ± 0.08
CC1π Norm.	1.63 ± 0.29	1.18 ± 0.18

oscillation parameter uncertainties

Analysis	$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0.0$
2012	4.9%	6.5%
2013	3.5%	5.2%

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2014 Near Detector Constraint

- **2014 electron neutrino appearance**
  - flux and cross section parameter uncertainties

Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	**1.21 ± 0.45**	**1.240 ± 0.072**
M_A^{RES} (GeV)	1.41 ± 0.22	0.965 ± 0.068
CCQE Norm.*	1.00 ± 0.11	0.966 ± 0.076
CC1π Norm.**	1.15 ± 0.32	1.26 ± 0.16
NC1π^0 Norm.	0.96 ± 0.33	1.14 ± 0.25

* for $E_\nu < 1.5$ GeV ** for $E_\nu < 2.5$ GeV

  - uncertainty (RMS/mean in %) on predicted number of far detector ν_e events

Error source	$\sin^2 2\theta_{13} = 0.1$	$\sin^2 2\theta_{13} = 0$
flux and ND280 (w/o ND280 constraint)	**2.9(25.9)**	**4.8(21.7)**
ν interaction (external data)	7.5	6.8
Far Detector	3.5	7.3
Total	**8.8%**	**11.1%**

Recent results from the T2K ND280 Detector

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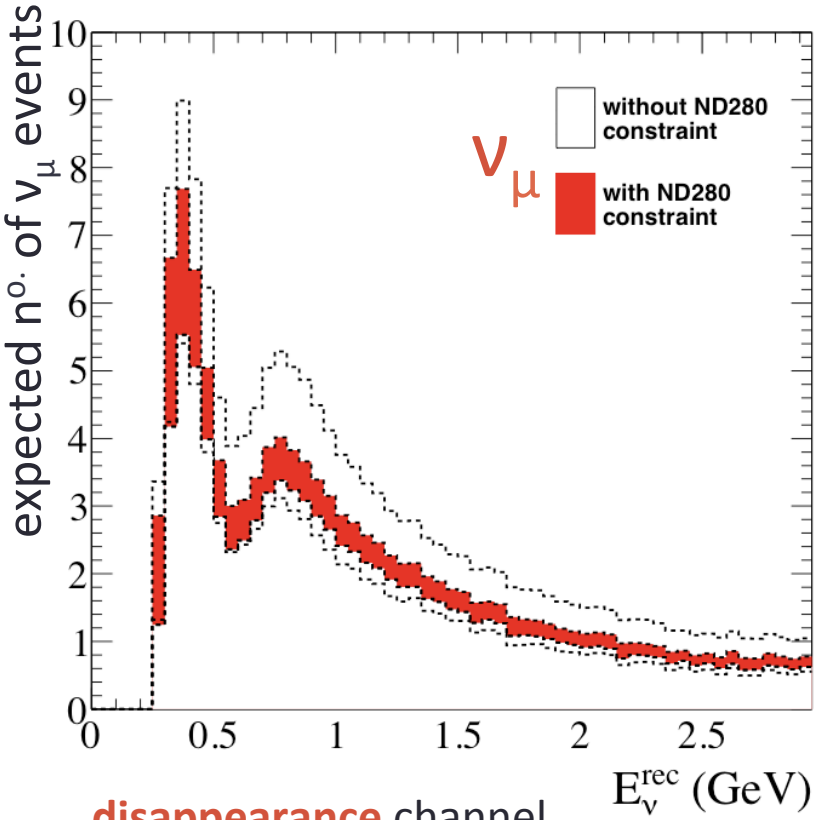
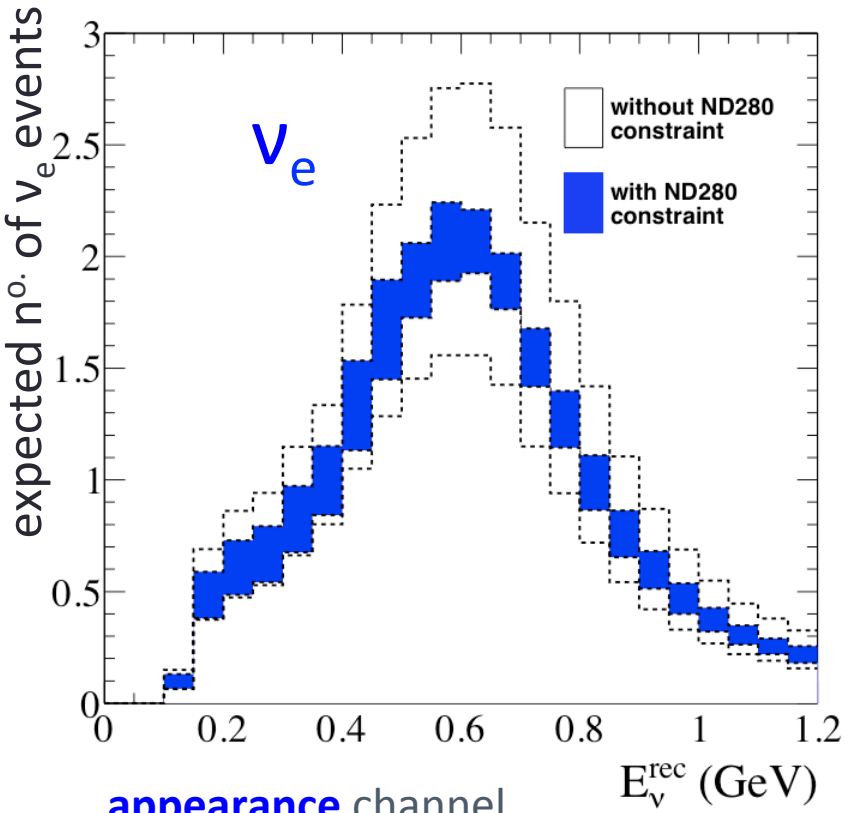
2014 Near Detector Constraint

- **Effect of near detector constraint**
  - on reconstructed neutrino energy at far detector

Recent results from the T2K ND280 Detector



disappearance channel



appearance channel

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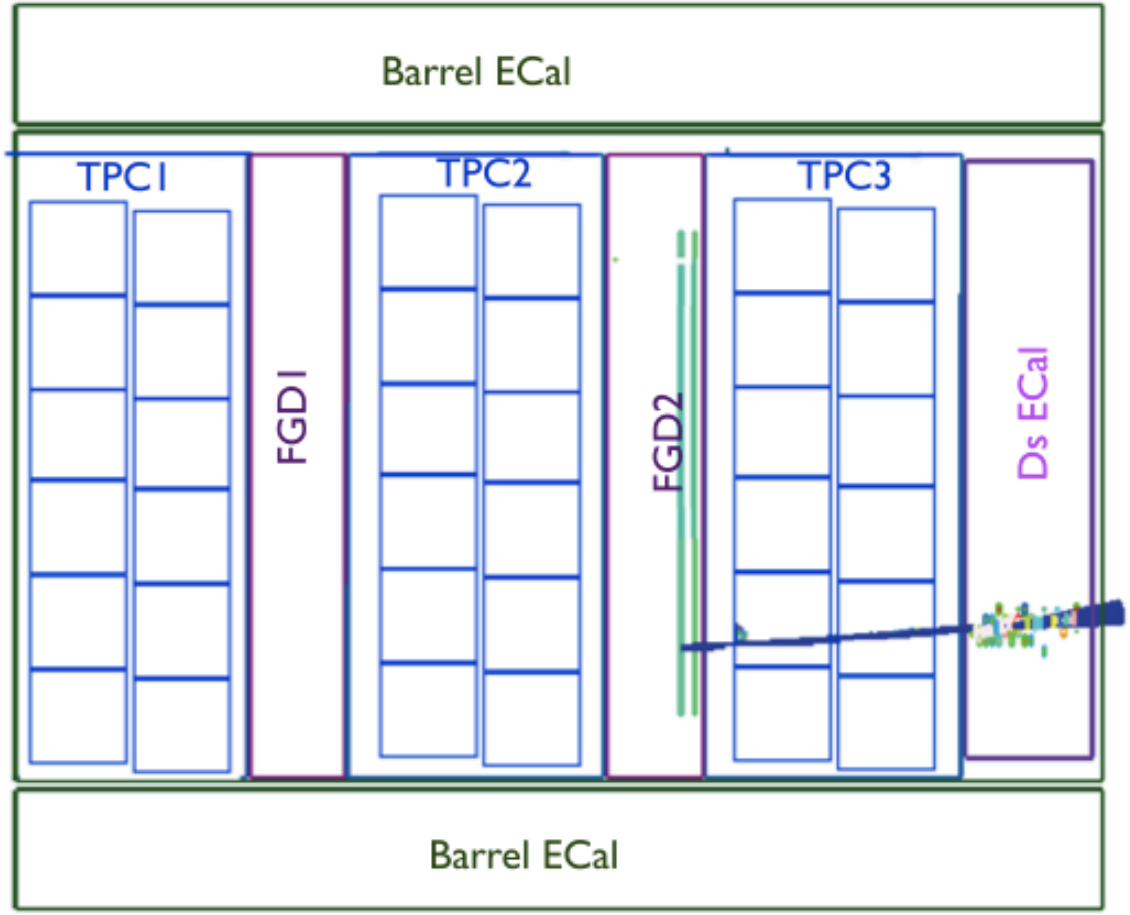
Measuring Intrinsic ν_e Component of Beam

- **Irreducible ν_e contamination**
  - due to muon and kaon decays
- **Important background for ν_e appearance**
  - affects predicted rate at far detector
  - split into **CCQE-like** and **CCnonQE-like** samples
- **CCQE-like ν_e event**
  - with electron like TPC track + ECal shower



PHYSICAL REVIEW D 89, 092003 (2014)

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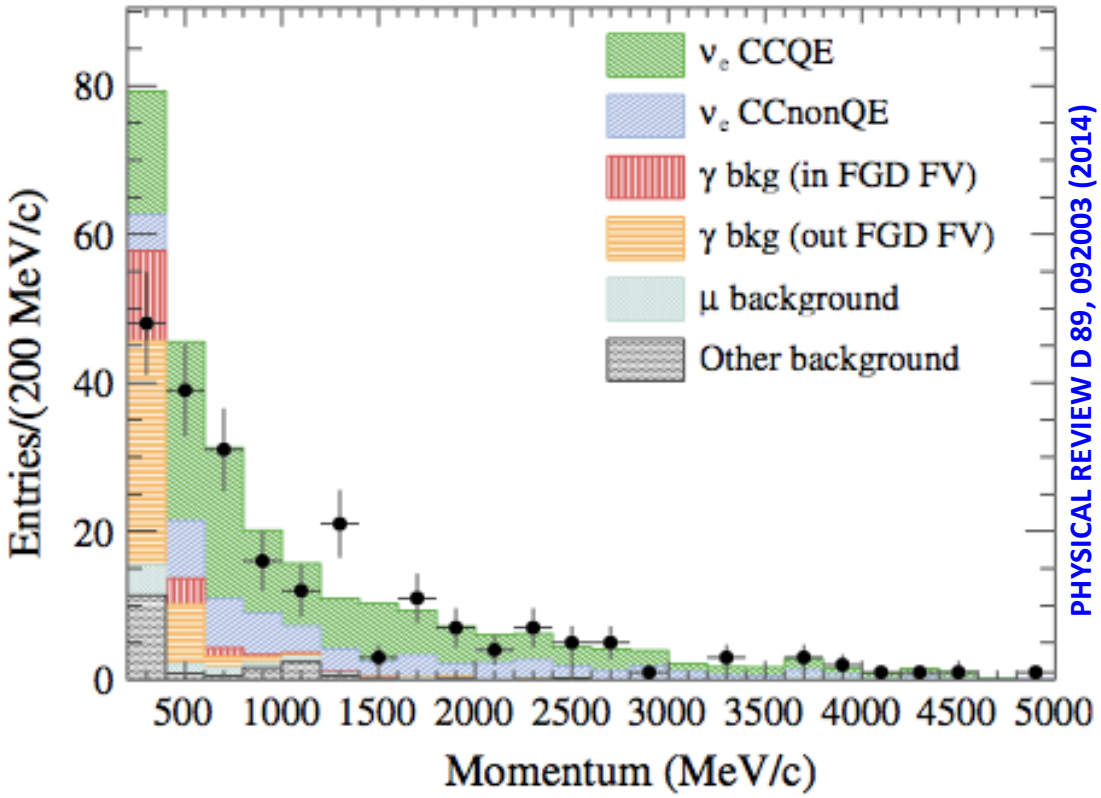
Measuring Intrinsic ν_e Component of Beam

Recent results from the T2K ND280 Detector

- **Reconstructed electron momentum** for **CCQE-like** sample
- **Expect** 1.2% ν_e component (from MC)
- $N\nu_e^{meas} / N\nu_e^{MC} = 1.01 \pm 0.10$
- **Constrain** using *in-situ* $e^{\pm}$ control samples



PHYSICAL REVIEW D 89, 092003 (2014)

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ND280 Cross Section Measurements

- **Cross-section uncertainties are a large source of error**
  - narrow band beam provides access to cross sections at ~1GeV
  - measurable at ND280
  - little existing experimental data

Systematic source	Relative uncertainty in no. of ν_e candidates (%)	Relative uncertainty in no. of ν_μ candidates (%)
flux + cross section (ND280-constrained[1])	3.1	2.7
cross section (ND280 independent)	4.7	5.0
hadronic interactions	2.3	3.5
far detector	2.9	3.6
Total	**6.8**	**7.6**

[1] : see slide 13

- **Several different targets in ND280**
  - *Hydrocarbons* **CH** (scintillator)
  - *Water* **H_2O** (target masses)
  - *Metals* **Fe**,**Pb**,**brass** (calorimetric absorbers)

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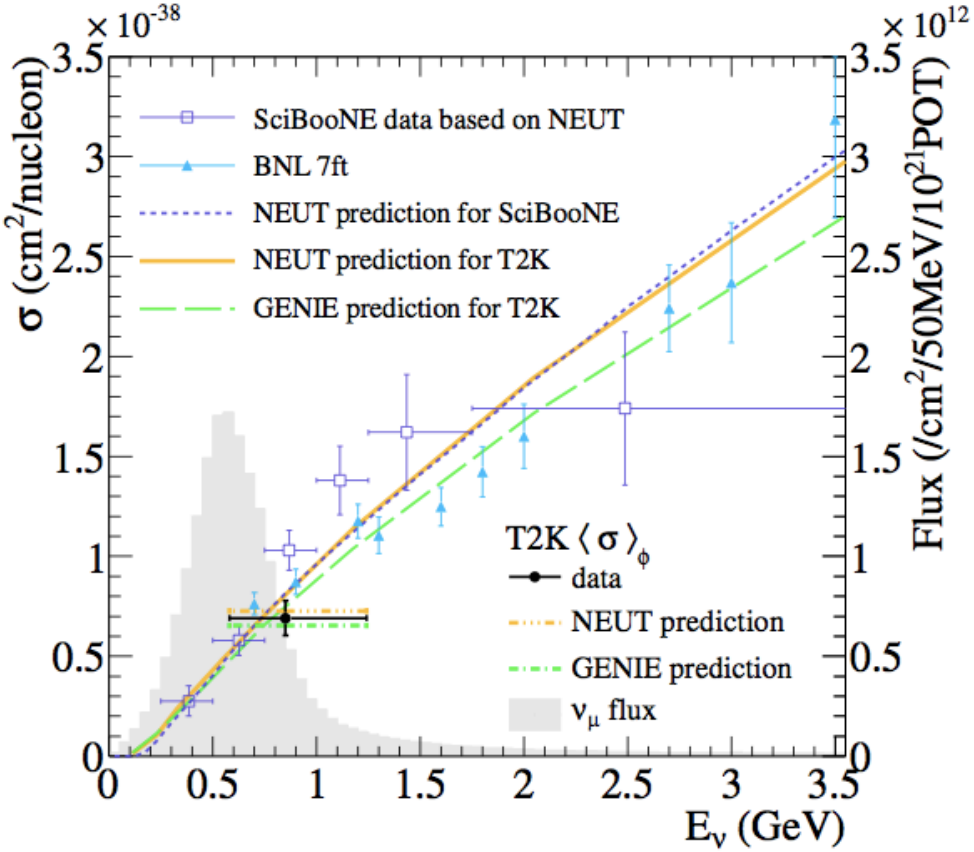
ND280 Cross Section Measurements

- ~1GeV measurement of differential CC^{inc} ν_μ on Carbon
  - total flux averaged:

$$\langle\sigma\rangle\phi = 6.91 \pm 0.13\ (stat) \pm 0.84\ (syst) \times 10^{-39}\ cm^2/nucleon$$



Recent results from the T2K ND280 Detector

Phys. Rev. D 87, 092003 (2013)

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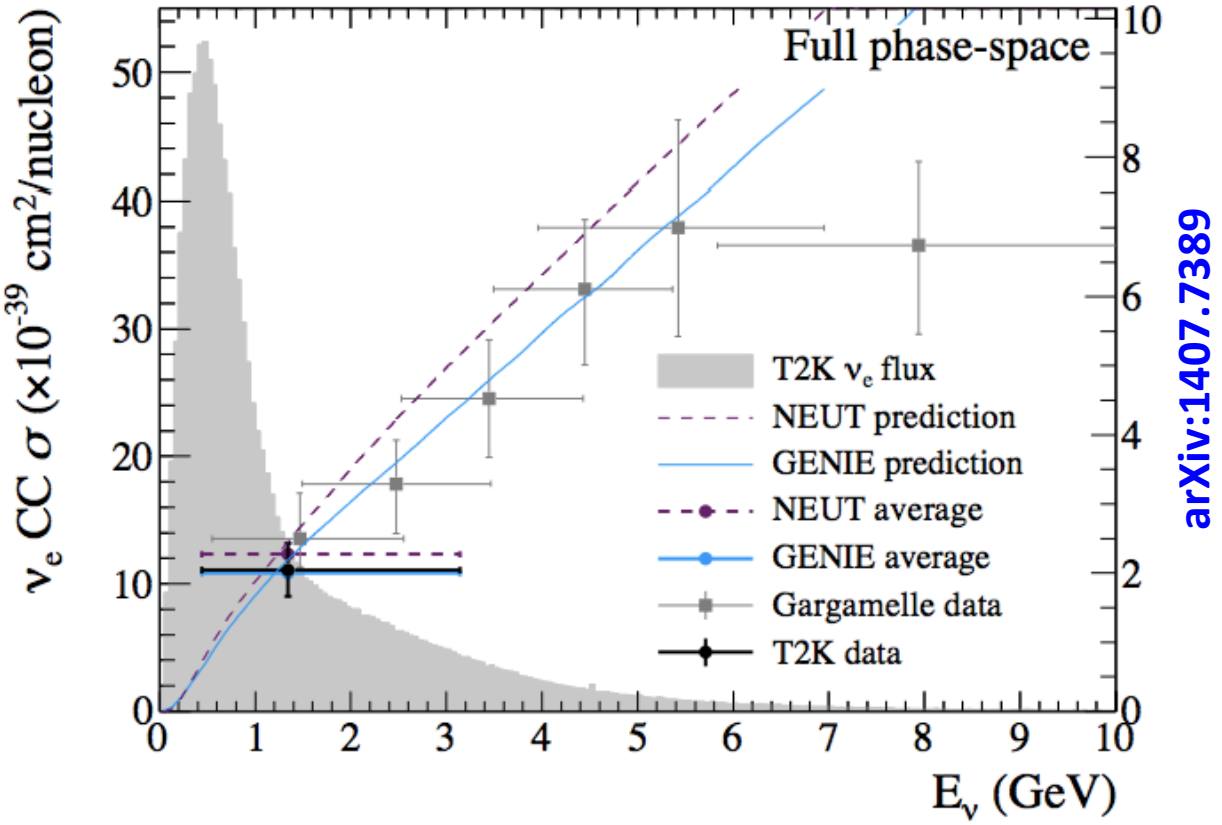
ND280 Cross Section Measurements

- ~1GeV measurement of differential CC^{inc} ν_e on Carbon
  - total flux averaged:

$$\langle\sigma\rangle\phi = 1.11 \pm 0.09\ (stat) \pm 0.18\ (syst) \times 10^{-38}\ cm^2/nucleon$$



Recent results from the T2K ND280 Detector

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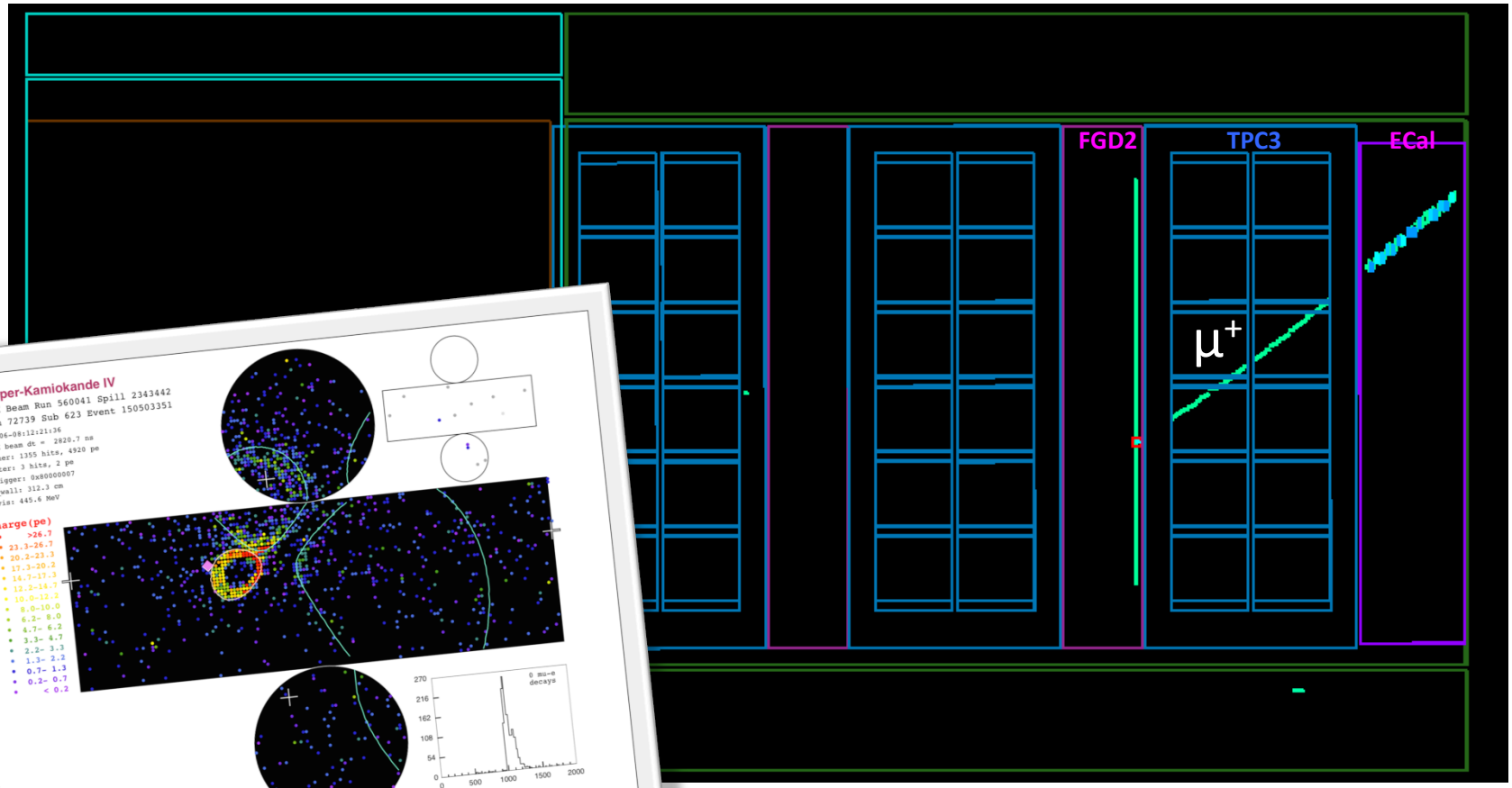
ND280 anti-neutrino events in 2014

- +ve muon in FG2-TPC3 and downstream ECal



Recent results from the T2K ND280 Detector

The University Of Sheffield.

Summary

- To date, T2K has recorded 6.9×10^{20} POT of neutrino-mode data
  - 6.57×10^{20} POT analysed
  - 8% of design goal
- First anti-neutrino mode data acquired in 2014
  - 0.5×10^{20} POT acquired
- ND280 measurements constrain the neutrino cross section and flux parameters
  - resulting in a reduction of predicted event rate uncertainties
- ND280 cross section measurements feedback into MC
  - CC inclusive flux integrated measurements for ν_μ and ν_e
  - differential measurements coming soon

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Thank You!

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Backup Slides

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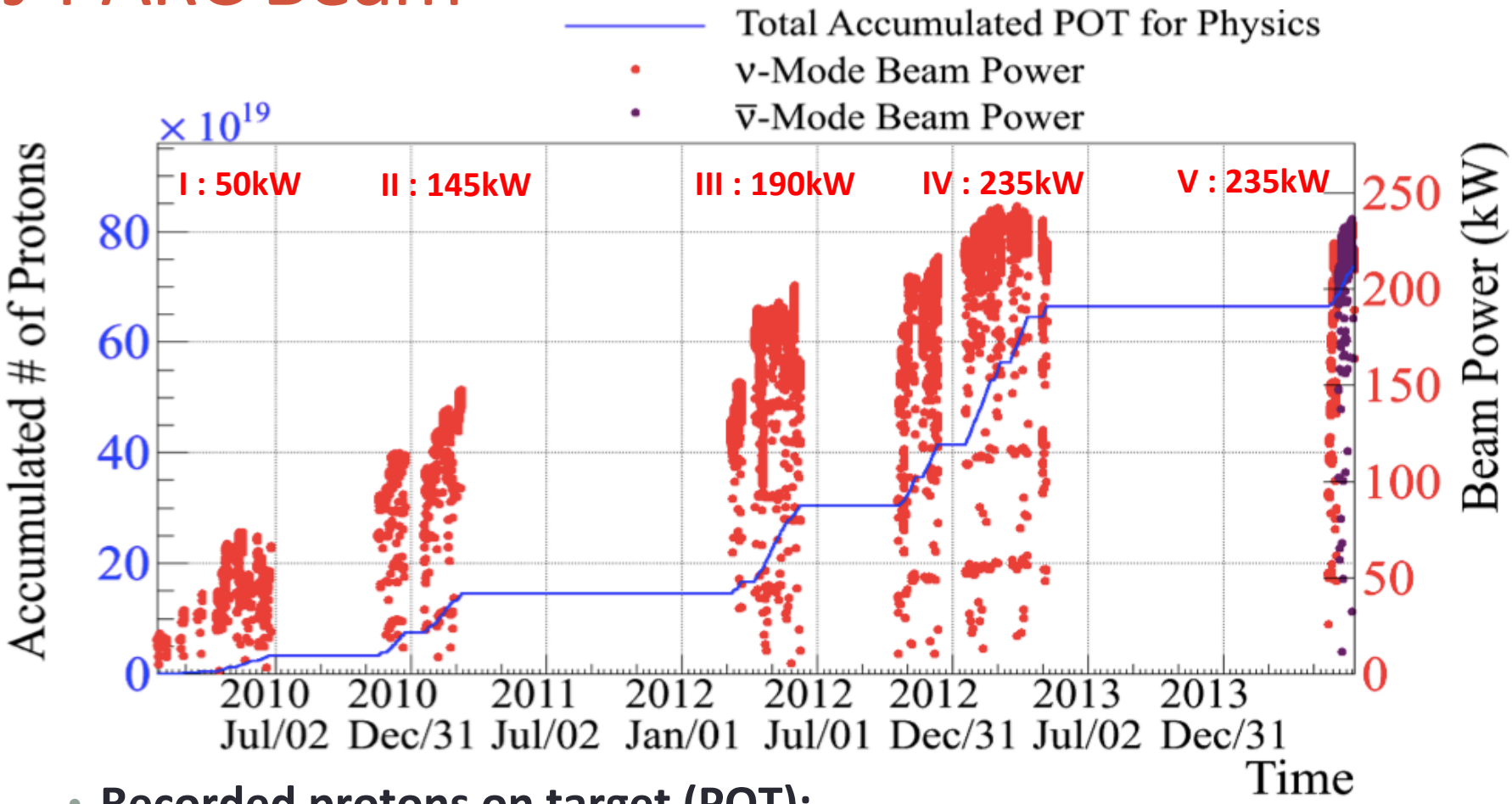
J-PARC Beam



- **Recorded protons on target (POT):**

  6.9×10^{20} nu mode, 0.51×10^{20} **anti-nu** mode

  <1mrad (~16MeV [2%]) beam stability for total period

  ~8% of design goal POT so far

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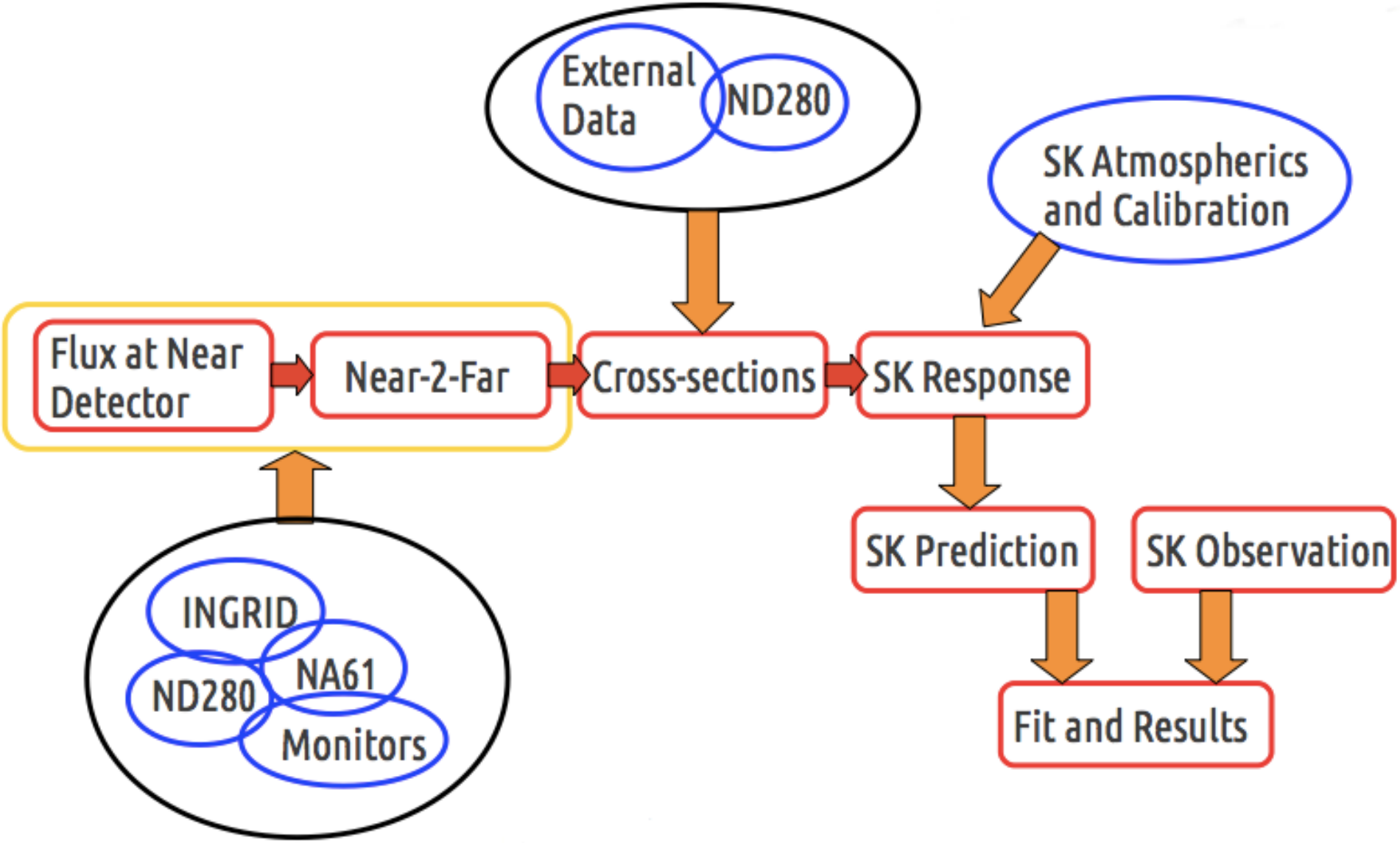
T2K analysis strategy



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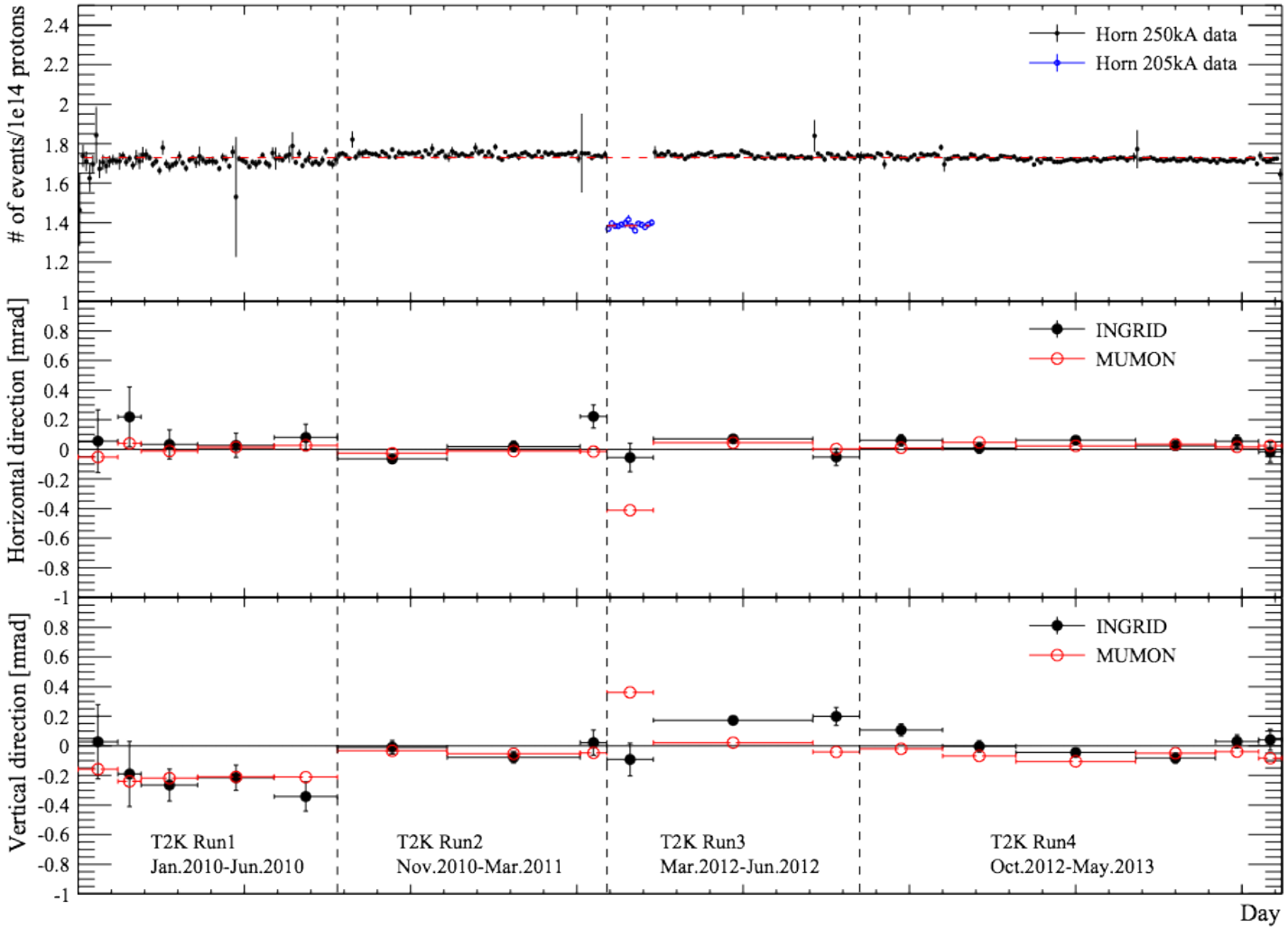
Beam Stability (ND280)



Recent results from the T2K ND280 Detector

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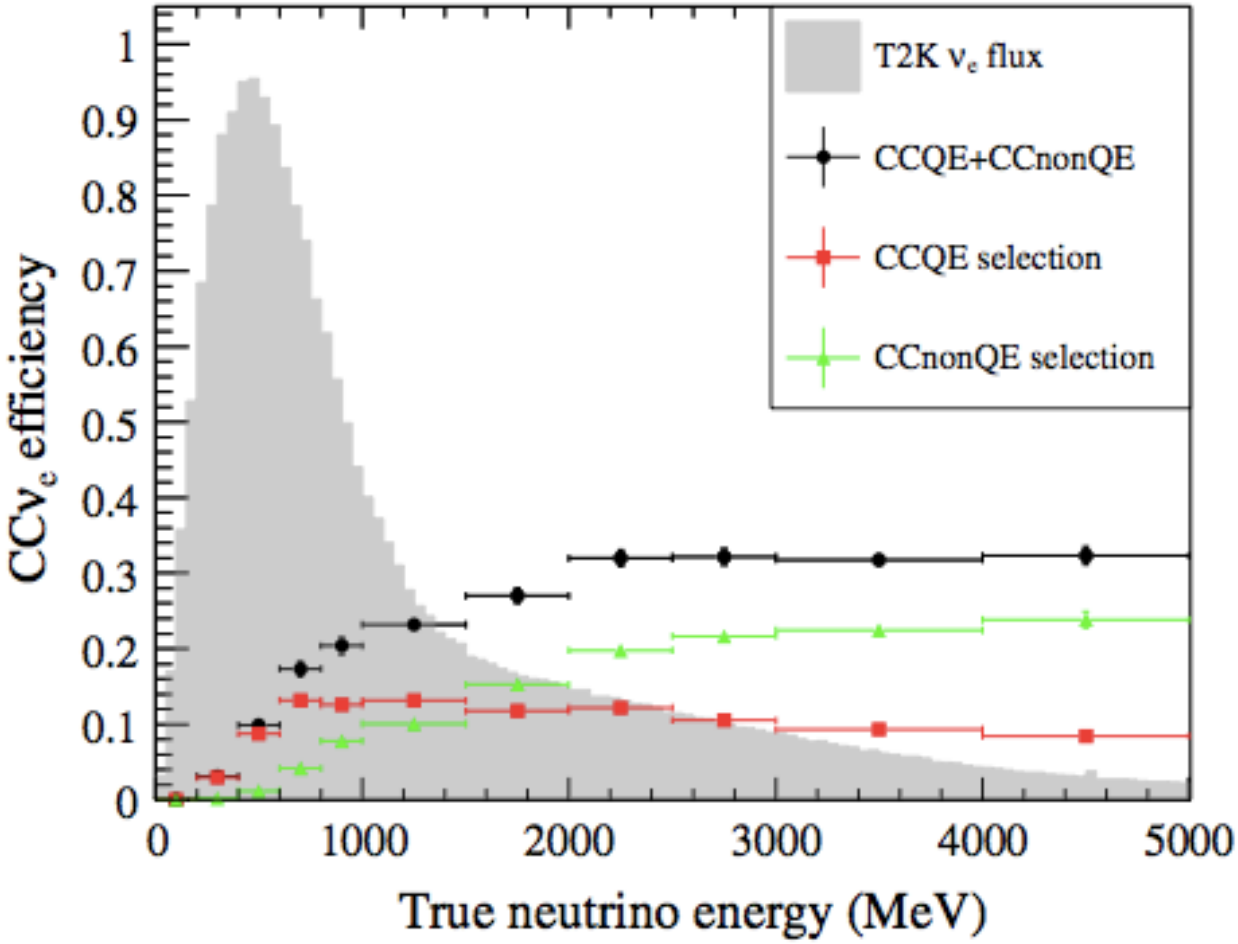
Charged Current ν_e Selection

- **CC selection efficiency** as a function of true neutrino energy



Recent results from the T2K ND280 Detector