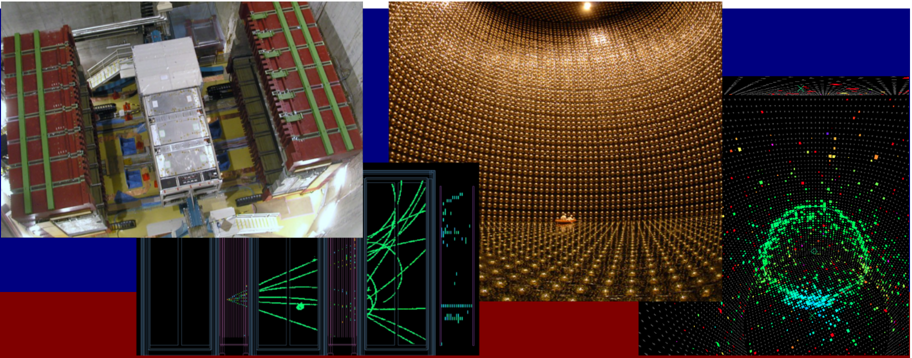
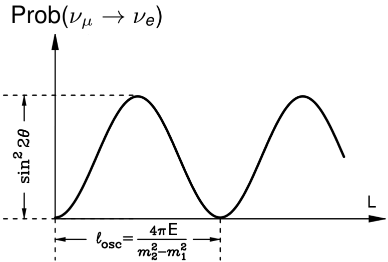


T2K: Recent results and TPC operation (and cross section measurements)

17 December 2014, Anthony Hillairet

The neutrino oscillation recipe



The neutrino oscillation recipe

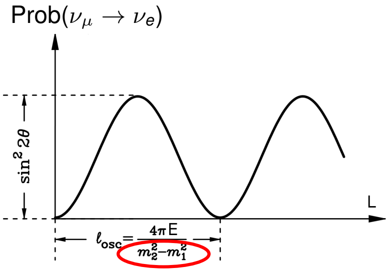
The mass states appear in the oscillation probabilities only in the form of differences:

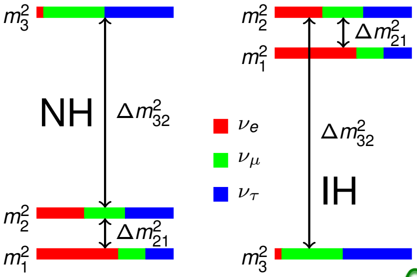
- $m_2^2 - m_1^2 = \Delta m_{21}^2 = (7.58^{+0.22}_{-0.26}) \times 10^{-5}\text{eV}^2$
- $|m_3^2 - m_2^2| = |\Delta m_{32}^2| = (2.35^{+0.12}_{-0.09}) \times 10^{-3}\text{eV}^2$

The sign of Δm_{32}^2 is currently unknown.

$\Longrightarrow$ Two possible mass hierarchies:

- Normal Hierarchy (NH)
- Inverted Hierarchy (IH)

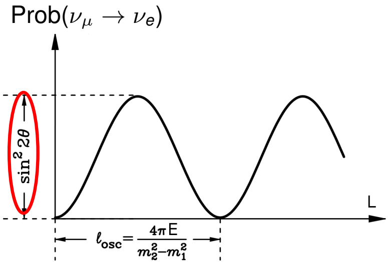




The neutrino oscillation recipe

3 mixing angle:

- $\sin^2 2\theta_{12} = 0.846 \pm 0.021$
  From $\nu_e \to \nu_x$
  (SNO, Super-K, KamLAND)
- $\sin^2 2\theta_{23} > 0.95 (90\% C.L.)$
  From $\nu_\mu \to \nu_x$
  (Super-K, K2K, MINOS, T2K, NOνA)
- $\sin^2 2\theta_{13} = 0.093 \pm 0.008$
  From $\nu_e \to \nu_x$
  (Daya Bay, RENO, Double Chooz)
  From $\nu_\mu \to \nu_e$
  (T2K, NOνA)



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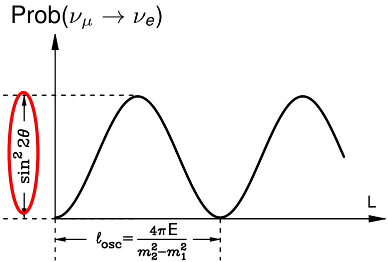
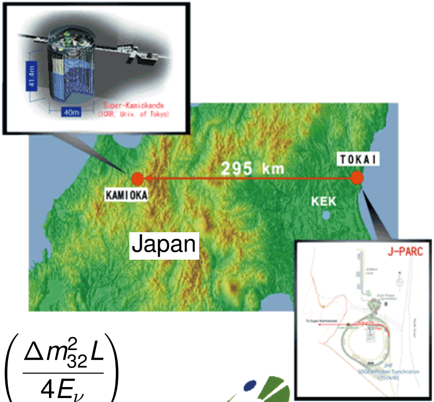


1 CP violating phase

- δ_{CP} : Totally unknown
  From $\nu_\mu \rightarrow \nu_e$
  (T2K, NOνA)

$\Longrightarrow$ Search for CP violation in the lepton sector

The Tokai to Kamioka experiment



The T2K experiment was designed to measure:

- ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)$$

- ν_μ disappearance

$$P(\nu_\mu \to \nu_x) \approx 1 - (\cos^4\theta_{13} \cdot \sin^2 2\theta_{23} + \sin^2\theta_{23} \cdot \sin^2 2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)$$

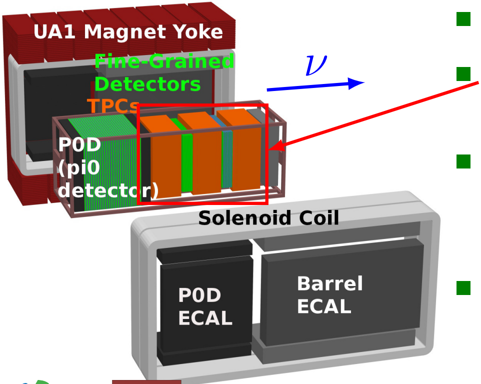
T2K measurement setup, J-PARC

- 30 GeV protons to neutrino beamline
- Design goal of 750 kW
- 250 kW reached recently
- 90 cm long graphite target
- Pions decaying in flight producing ν_μ
- Positive (negative) pions focussed by 3 magnetic horns for neutrino (anti-neutrino) beam mode

T2K's near detector: ND280

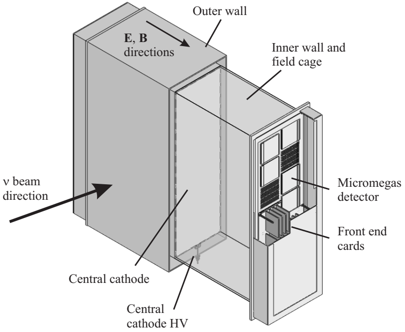
ND280 is located 280m from the production target to measure the characteristics of the unoscillated neutrino beam:

- ν_μ interaction rate
- ν_μ energy spectrum
- Intrinsic ν_e contamination
- The neutral current π^0 background



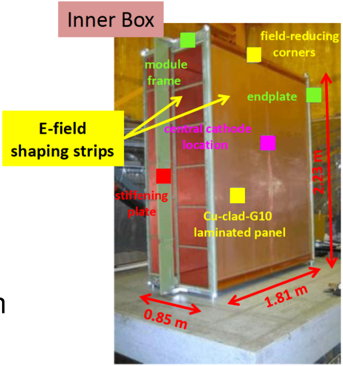
- 0.2T magnetic field
- Central component is the tracker Composed of 3 TPCs and 2 FGDs
- FGDs (Fine-Grained Detectors): active targets made of layers of scintillator bars $\Longrightarrow$ provides detailed vertex information
- TPCs: momentum measurement and particle ID using dE/dx

ND280's time projection chambers (TPCs)



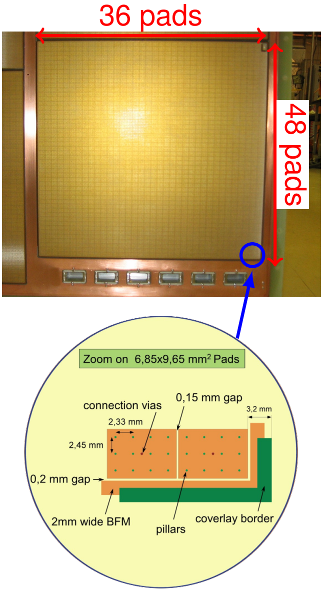
3 identical TPCs:

- Active tracking region: ($L \times H$) 720 mm $\times$ 2016 mm
- Drift distance 897 mm
- Drift field 279 V/m



- MicroMegas detectors
- Inner volume: Argon (95%), CF_4 (3%), isobutane (2%)
- Outer volume: CO_2 for electric insulation
- Drift velocity: 7.8 cm/μs

ND280's time projection chambers (TPCs)



72 MicroMegas

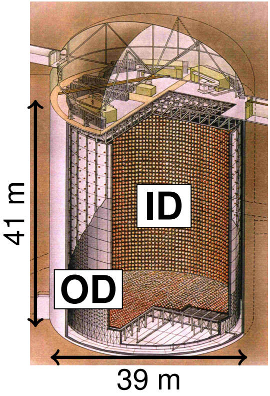
- ($L \times H$) 359 mm $\times$ 349 mm
- 1726 active pads:
  ($L \times H$) 9.8 mm $\times$ 7.0 mm
  $\Longrightarrow$ 124416 channels
- 128 μm amplification gap

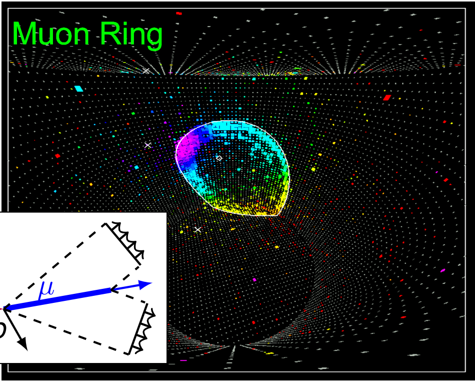
Front end electronics based on ASIC chip

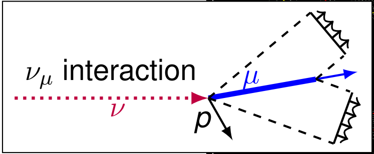
- 72 channels $\times$ 511 analog memory cells
- Sampling frequency at 25 MHz

T2K's far detector: Super Kamiokande

SK is located 295km from the production target to measure the neutrino beam <u>after oscillation</u>

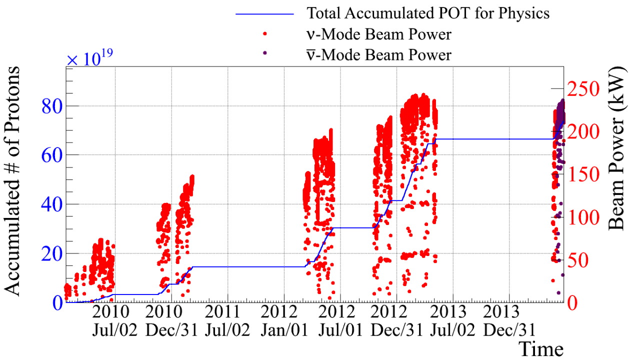






- 50 kton water Cherenkov detector
- 22.5 kton fiducial volume
- Inner detector (ID) ∼11000 20" PMTs, 40% coverage
- Outer detector (OD) ∼2000 8" PMTs facing outward, used to veto cosmics, radioactivity, . . .

Data collected and analyzed



- Results possible due to the efforts of J-PARC accelerator division and other related people.

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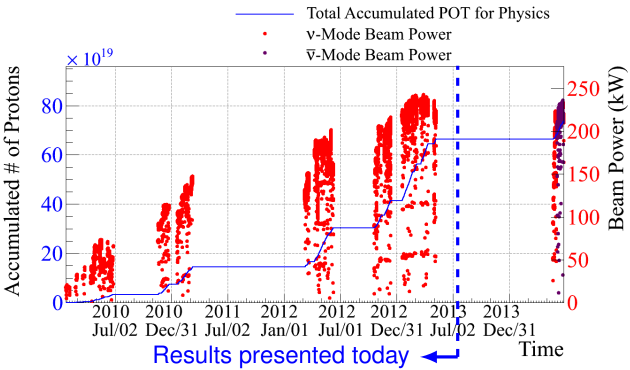

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- Results presented today correspond to $6.57 \times 10^{20}\, POT$ (Protons On Target)

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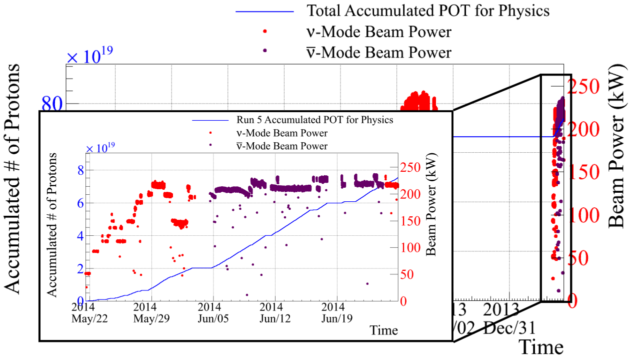

- Results possible due to the efforts of J-PARC accelerator division and other related people.
- Results presented today correspond to 6.57×10^{20} *POT* (Protons On Target)
- First data taking in anti-neutrino beam mode last June.
  $\Longrightarrow$ First results for anti-neutrino oscillations coming soon !
- Taking more anti-neutrino beam mode data as we speak !

Simultaneous ν_μ and ν_e analysis

ν flux predictions and their uncertainties

How many incoming neutrinos ?

Simultaneous ν_μ and ν_e analysis

Cross section uncertainties on ν-C and ν-O from external sources (MiniBooNE)

How many neutrinos will interact ?

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+ Statistic and systematic uncertainties for selection and detector

can constrain

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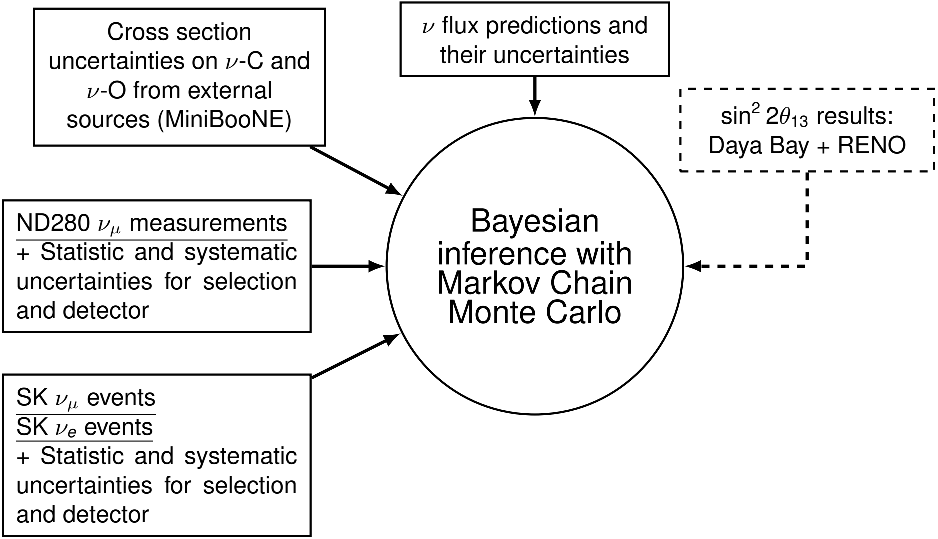

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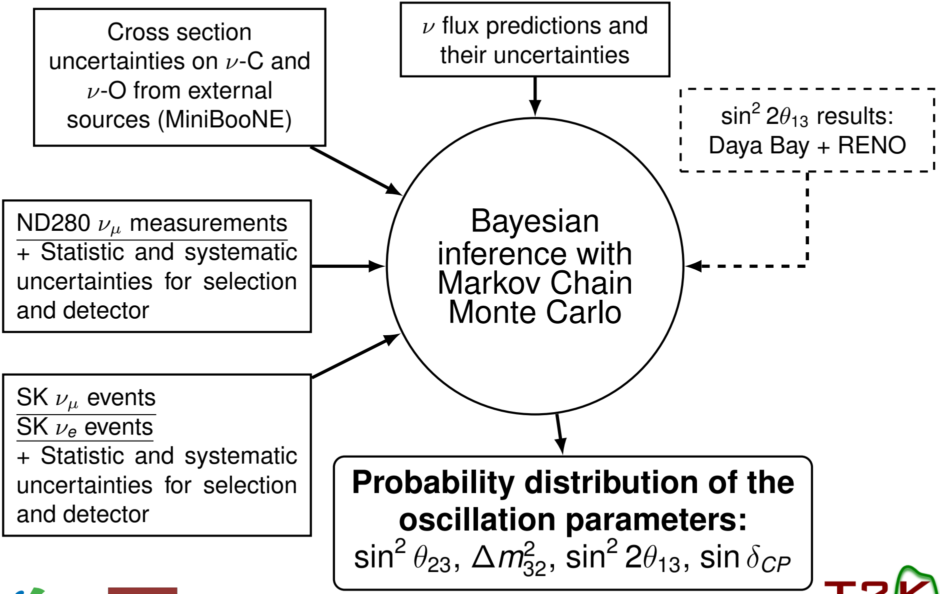
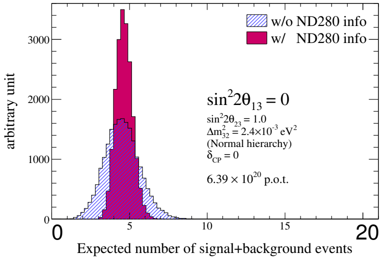
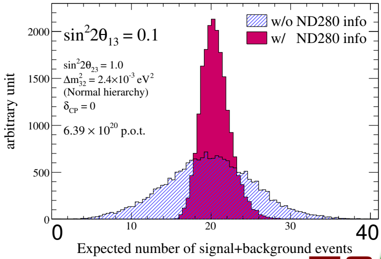


ν_e measurement results

Predicted number of events with $6.57 \times 10^{20} POT$

- Non-oscillation hypothesis $\sin^2 2\theta_{13} = 0.0$
  $\Longrightarrow$ MC prediction: 4.9
- Oscillation hypothesis based on reactor experiment results $\sin^2 2\theta_{13} = 0.1$
  $\Longrightarrow$ MC prediction: 21.6





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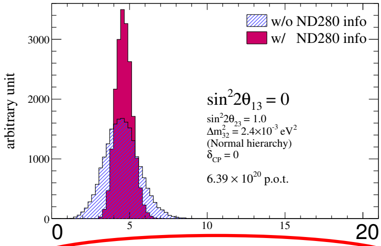
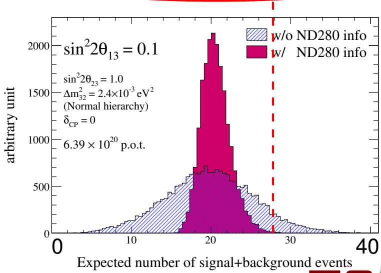
Non-oscillation hypothesis rejected at 7.3 σ

First ever confirmed observation of a lepton flavor appearance

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

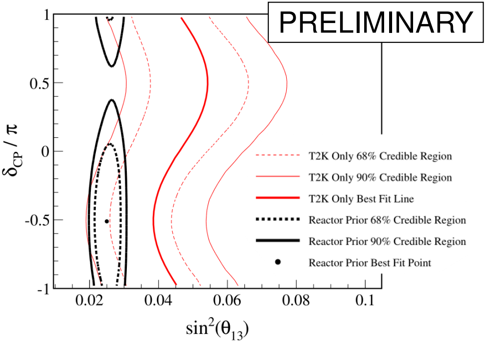


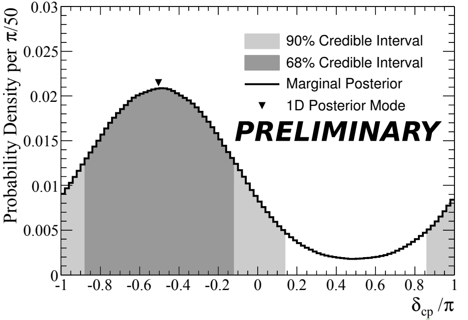
28 events observed



Results of the joint analysis

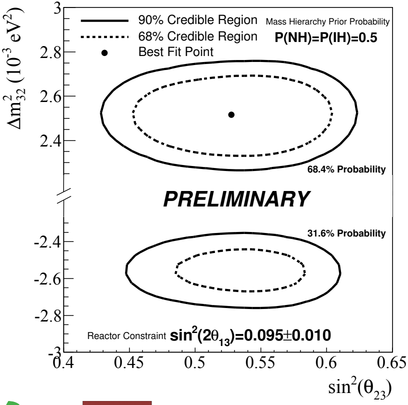
- ν_e appearance sensitive to $\sin^2 2\theta_{13}$ and δ_{CP} but there is a degeneracy between them
- Reactor neutrino experiments ($\bar{\nu}_e$ disappearance) are sensitive to $\sin^2 2\theta_{13}$ only
  $\Longrightarrow$ degeneracy can be resolved





Results of the joint analysis

- ν_μ disappearance sensitive to $\sin^2\theta_{23}$ and $|\Delta m^2_{32}|$
- Currently most precise measurement on $\sin^2\theta_{23}$ and $|\Delta m^2_{32}|$
- Very little sensitivity to the sign of Δm^2_{32}

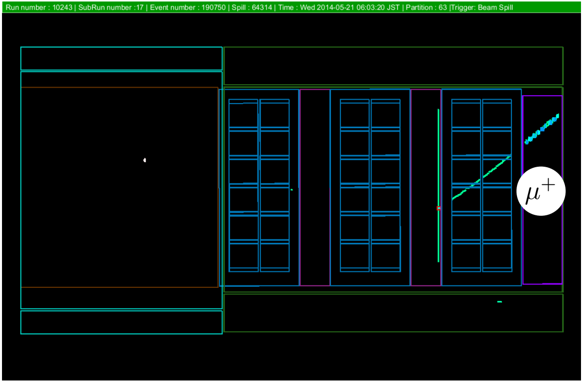


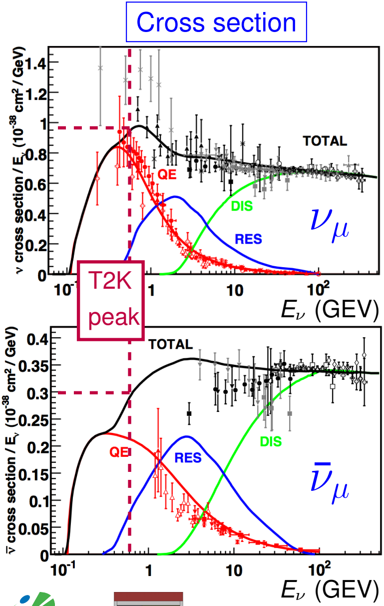
	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	0.179	0.078	0.257
$\sin^2\theta_{23} > 0.5$	0.505	0.238	0.743
Sum	0.684	0.316	1.0

Small preference for normal hierarchy

New data: $\bar{\nu}$ beam mode started !

- T2K will now measure $\bar{\nu}_\mu$ disappearance, $\bar{\nu}_e$ appearance $\Longrightarrow$ search for CP violation
- anti-neutrino beam mode run last June (Run5) and since November (Run6)
- Run5 results coming soon !





- $\bar{\nu}_\mu$ cross section has never been measured at T2K E_ν range
- Expected $\sigma_{\bar{\nu}_\mu} \sim 1/3\ \sigma_{\nu_\mu}$
  $\Longrightarrow$ ν_μ interaction rate not negligible compared to $\bar{\nu}_\mu$
- SK is a water Cherenkov detector
  $\Longrightarrow$ No reconstruction of lepton charge
- ND280 has charge reconstruction from the TPCs
  $\Longrightarrow$ ND280 can measure the interaction rate ratio $\bar{\nu}_\mu / \nu_\mu$

T2K TPCs: always improving

Constant effort to improve the calibration and reconstruction of the TPCs

- New MicroMegas timing calibration
- Reconstruction improvements for vertical tracks
- Using vertical tracks for better gain calibration
- Better parametrization of the dE/dx for particle identification
- Understanding the $\vec{E}$ Field distortion
- ...

A much more significant source of systematic uncertainties:

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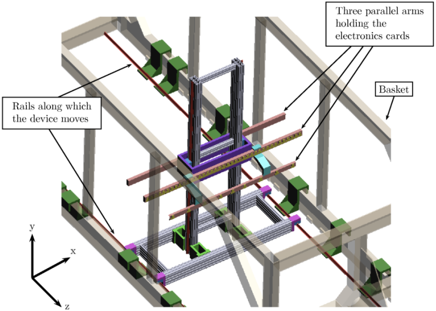
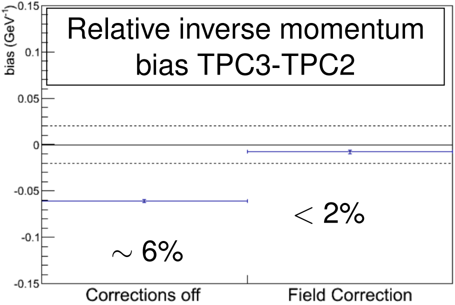
A much more significant source of systematic uncertainties:

Mapping and correcting $\vec{B}$ Field

- The $\vec{B}$ Field was mapped prior to installing the detectors in the ND280 magnet
- $\vec{B}$ Field map used to correct the charge position in the track reconstruction

$\Longrightarrow$ Relative bias between TPC2 and TPC3 reduced



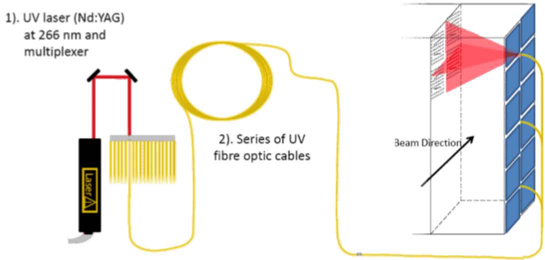


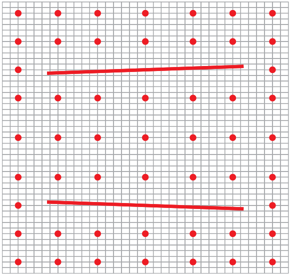
Laser system to measure distortions

- The laser system illuminates aluminium dots on the cathodes
- Photo-electrons are measured by MicroMegas
- Comparison of known and measured dot positions provides field distortion integrated over the whole drift distance

$\Longrightarrow$ no details of the distortion versus drift distance

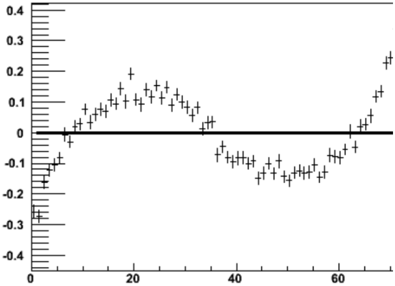
- This measured field distortion is used to evaluate the systematics

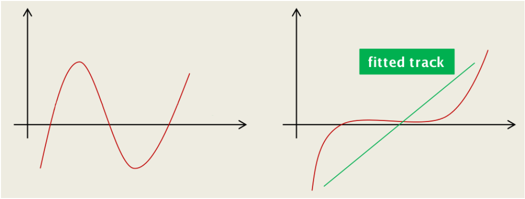




Another tool: Averaged track residuals

- The average residuals for through-going tracks (cosmics or beam) can test distortions for all drift distances
- Residuals have displayed an “S-Shape” behaviour for a long time
- Distortions on the upstream and downstream edges of the TPCs can explain this shape

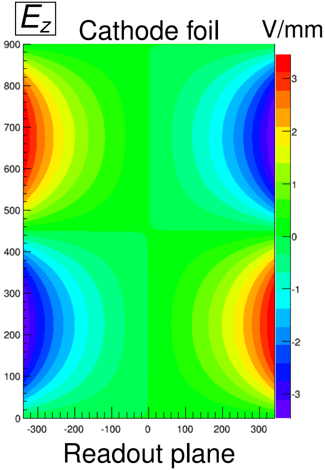




Neutrino beam direction →

$\vec{E}$ Field distortion

- An $\vec{E}$ Field distortion with the right shape can explain the residual patterns
- No clear source identified at the moment



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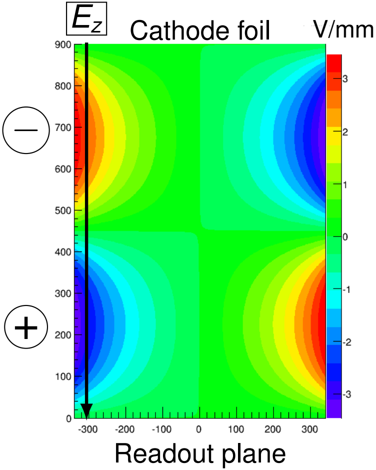

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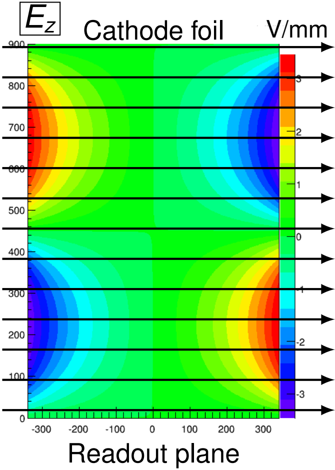

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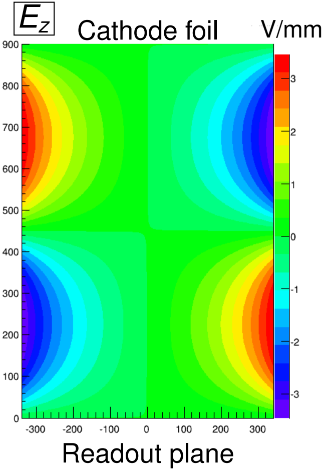
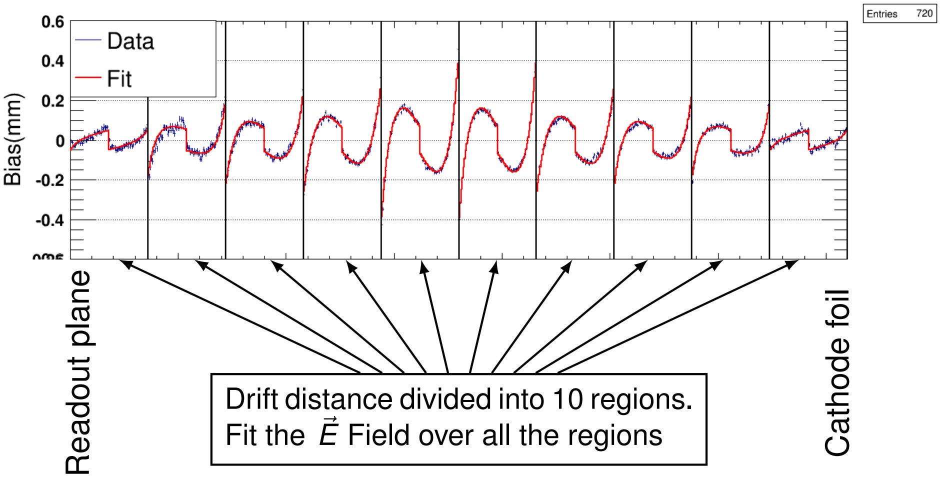
- No clear source identified at the moment
- The laser calibration is insensitive to this particular distortion pattern
- Empirical map can be fitted using the residuals from different drift distances
- For now simple empirical 2D model for the electric potential:
  x: drift direction; z: ν beam direction
  L: max drift distance = 897mm



$$\varphi(x,z) = A\left[\sin\left(\frac{2\pi}{L}x\right)\cosh\left(\frac{z}{b_1}\right) + c\sin\left(\frac{6\pi}{L}x\right)\cosh\left(\frac{z}{b_2}\right)\right]$$

$\vec{E}$ Field distortion empirical mapping



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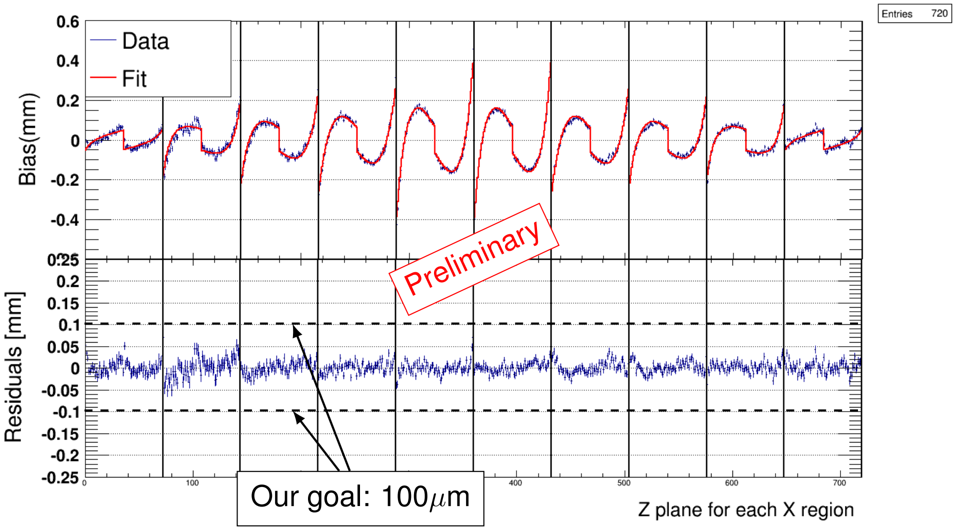
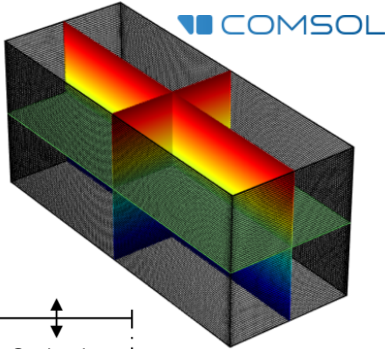
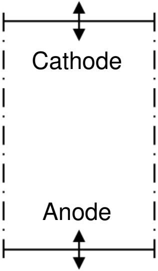


$\vec{E}$ Field distortion simulation

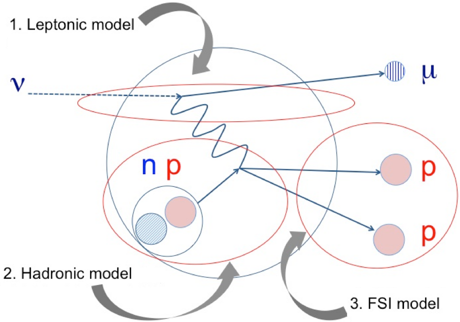
- In parallel to the mapping effort, we are also trying to simulate the distortion
- Various displacements, misalignments, bulging already tested
- Only promising test was displacing the anode and cathode inward
- However, the needed displacement is too big to fit the construction tolerance of $\sim 100\mu$m





The neutrino cross section challenge

- Neutrino cross sections are already and will be a major source of systematic uncertainties for accelerator neutrino experiments (range 0.2-5 GeV)
- Nuclear effects have significant impacts on neutrino energy reconstruction
- Final state interactions make it difficult to understand the neutrino interaction



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- To really understand the nuclear effects, we need to measure neutrino cross sections on various nuclei
- T2K can contribute because of its multi-detector structure !

T2K's wide cross section program

ND280 FGDs	ν_μ CC inclusive on carbon ν_e CC inclusive on carbon ν_μ CC quasi-elastic ν_μ CC0π, CC1π ν_μ CCπ coherent	Phys. Rev. D 87, 092003 (2013) PRL 113, 241803 (2014) arXiv: 1411.6264
ND280 P0D	ν_μ NCπ^0 ν_μ NC elastic	
ND280 ECals	ν_μ on lead	
ND280 TPCs	ν_μ on argon	
INGRID	ν_μ CC inclusive on Fe & CH ν_μ CC quasi-elastic on Fe ν_μ CC inclusive vs E_ν	arXiv: 1407.4256
Super-K	ν_μ NC elastic via γ emission	Phys. Rev. D 90, 072012 (2014)

Most of these cross sections will be evaluated for $\bar{\nu}_\mu$ as well !

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First ν_e cross section results since Gargamelle in 1978 !

Most of these cross sections will be evaluated for $\bar{\nu}_\mu$ as well !

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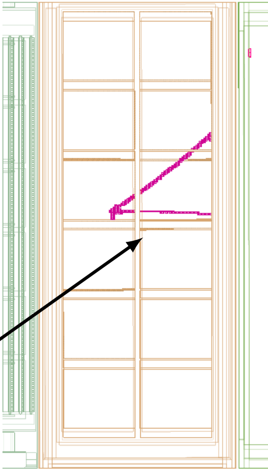
Most of these cross sections will be evaluated for $\bar{\nu}_\mu$ as well !

Argon is very popular these days !

- LBNE $\rightarrow$ Liquid argon (LAr) TPC
  $\Longrightarrow$ A lot of effort going into studying ν-Ar interactions and LAr TPCs:
  ArgoNeut, CAPTAIN, MicroBooNE, ...
- But there are only 3 argon gas TPCs in a neutrino beam. $\Longrightarrow$ All of them in ND280 !
- 16 kg of a mix of Ar:CF_4:iC_4H_{10} (95:3:2)
- Already one event found by chance in our data.
- 2 ν interaction generators used in T2K.



$\Longrightarrow$ Number of ν_μ-Ar CC inclusive in our $5.9 \times 10^{20}\,POT$:

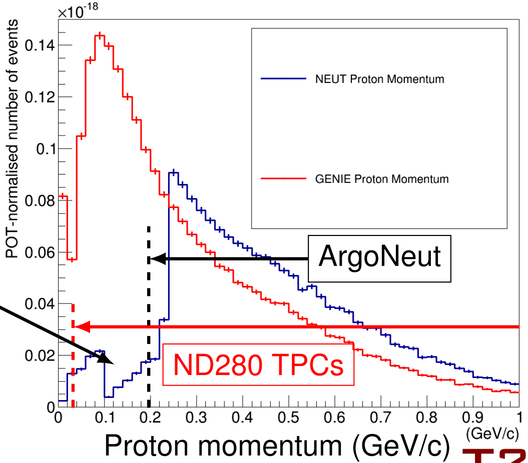
NEUT = 600 events GENIE = 552 events

Direct observation of nuclear effects

- Thanks to the very low density of the gas (at 1 atm), the ND280 TPCs can measure very low energy protons

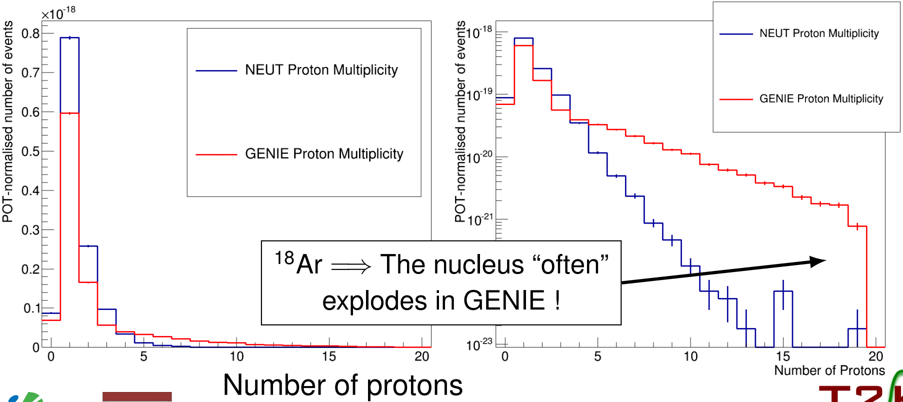
	threshold
ArgoNeut	200 MeV/c
ND280 TPCs	30 MeV/c

Region dominated by final state interactions !



A great test for the generators

- The number of emitted protons is another observable sensitive to nuclear effects
- The GENIE prediction seems already problematic
  $\Longrightarrow$ Developers already contacted.



Specialised reconstruction for vertices

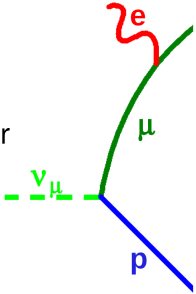
- Previous reconstruction in the TPCs:
  - No concept of vertex
  - Designed to find tracks crossing the TPCs

  $\Longrightarrow$ New reconstruction needed

- Complete rewrite: TREx
  (TPC Reconstruction Extension)

- The challenge is to remove the massive background of tracks coming from the surrounding detectors
  $\Longrightarrow$ New pattern recognition searching for vertices.

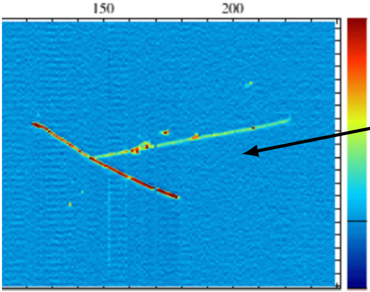
- Reusing previous maximum likelihood fit:
  Bias < 2%, resolution < 10% à 1 GeV/c



T2K's ARGONUTS

ARgon Gas Outgoing NUcleon Tracking Studies.

- First ν_μCC inclusive cross section in 2015 with proton multiplicity and momentum distributions.
- Cross section measurement to be followed by "exotic" event search.



- "exotic" event presented by ArgoNeut:
  1 muon and 2 protons back-to-back
- Interpretation : The neutrino interacted with a correlated neutron-proton pair

arXiv: 1405.4261

Summary

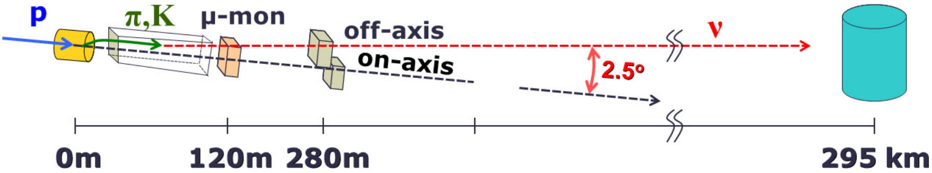
- T2K continues to improve on it's oscillation parameter measurements
- The new joint analysis of the ν_μ disappearance and ν_e appearance channels provides an optimale determination of the oscillation parameters from the T2K data.
- The ND280 TPCs are a crucial component of the T2K apparatus
- The TPCs performance is constantly improved with increasing understanding of the TPC features
- Many cross section measurements already performed and published, including the first ν_eCC cross section since 1978 !
- And soon the first neutrino-argon gas cross section measurement from the TPCs !

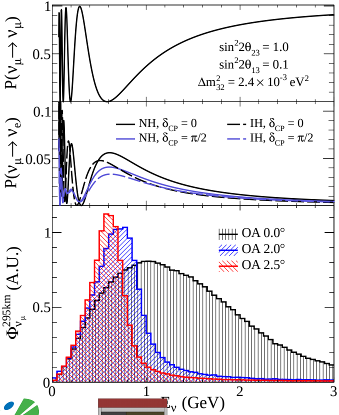
T2K has only collected 10% of the expected total data.

$\Longrightarrow$ a lot more cool results to come !

Backup slides

T2K off-axis configuration

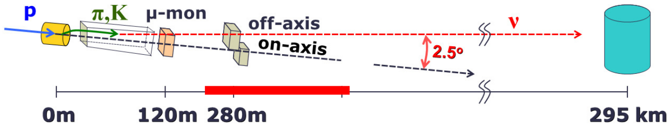


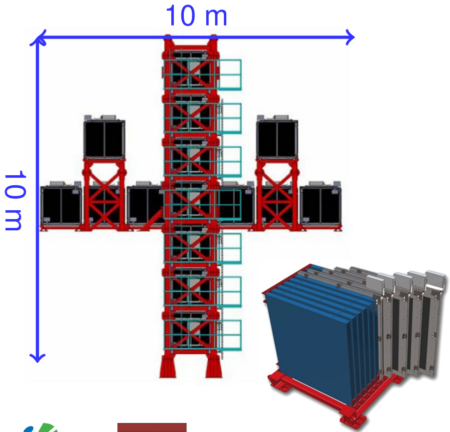


The 2.5° off-axis angle provides:

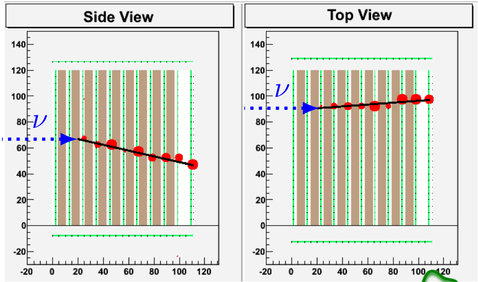
- narrow band of energy around the 1st oscillation maximum at ∼0.6 GeV
- increase of neutrino interactions of interest
- reduced background from high energy tail

T2K measurement setup, INGRID (on-axis)

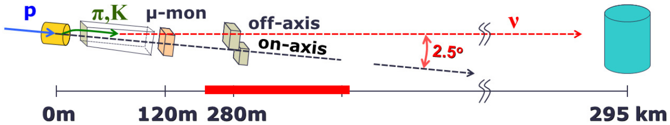




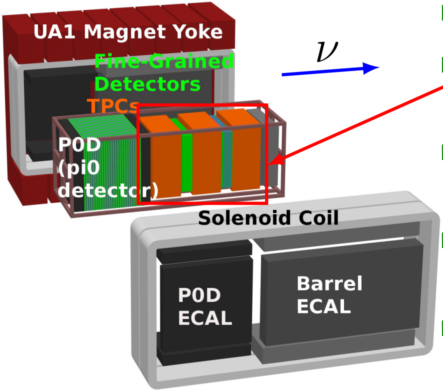
- INGRID monitors the neutrino beam direction and intensity
- Each module consists of iron and scintillator layers



T2K measurement setup, ND280 (off-axis)

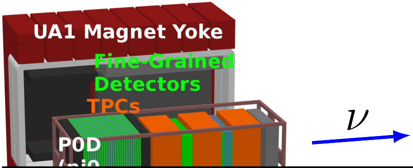


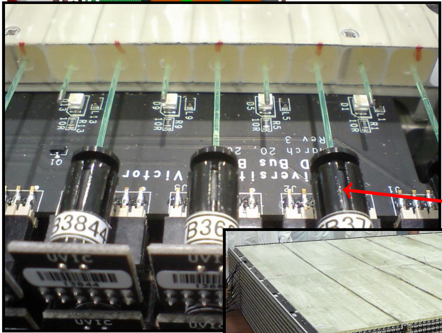
ND280 measures the characteristics of the unoscillated neutrino beam:

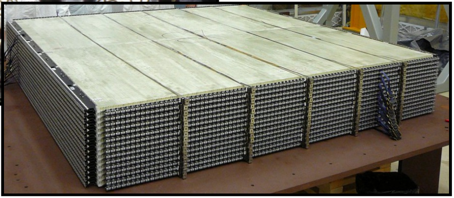


- 0.2T magnetic field
- Central component is the tracker
  Composed of 3 TPCs and 2 FGDs
- π^0 dedicated detector
  $\Longrightarrow$ P0D
- Electromagnetic calorimeters
  $\Longrightarrow$ ECal
- Yoke instrumented with scintillators
  $\Longrightarrow$ Side Muon Range Detectors (SMRDs)

Fine-Grained Detectors (FGDs)



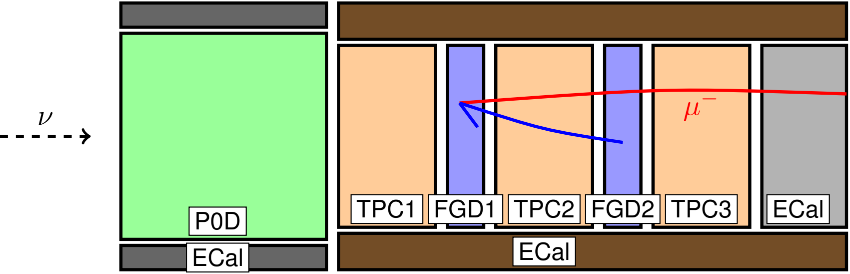




2 FGDs serving as active targets

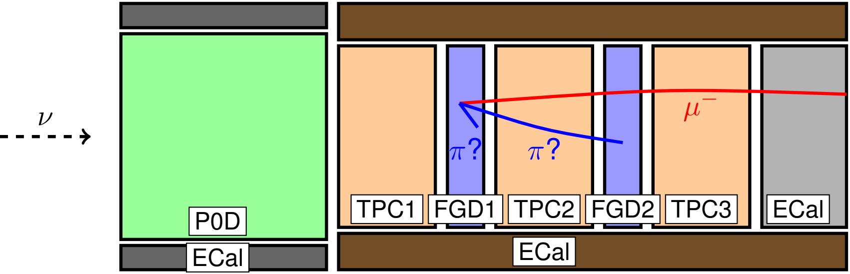
- FGD1: Layers of X and Y scintillator bars
- FGD2: Layers of X and Y scintillator bars alternated with water layers
- Provides detailed vertex information
- Multi-Pixel Photon Counter

2013 ND280 ν_μ event selection



One μ^- from FGD1 crossing TPC2 $\Longrightarrow$ **CC inclusive sample**

2013 ND280 ν_μ event selection



One μ^- from FGD1 crossing TPC2 $\Longrightarrow$ **CC inclusive sample**

- No pions found

$\Longrightarrow$ **CC0π sample**

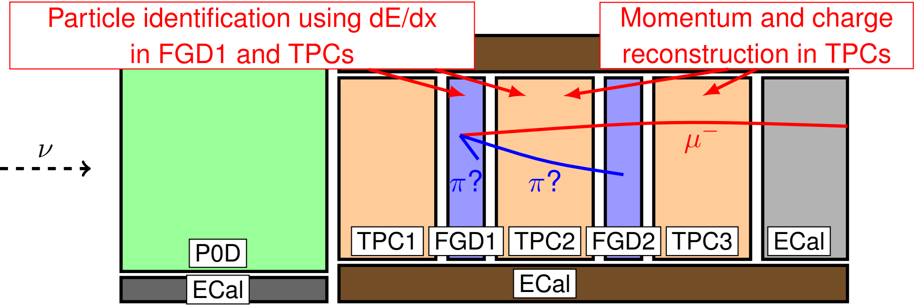
- $1\pi^+$ found

$\Longrightarrow$ **CC1π^+ sample**

- $> 0\pi^0$ or
- $> 0\pi^-$ or
- $> 1\pi^+$ found

$\Longrightarrow$ **CC-Other sample**

2013 ND280 ν_μ event selection



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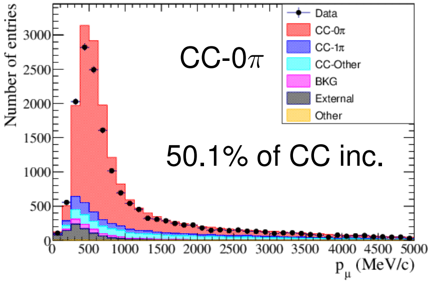
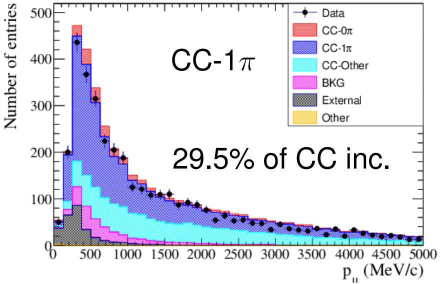
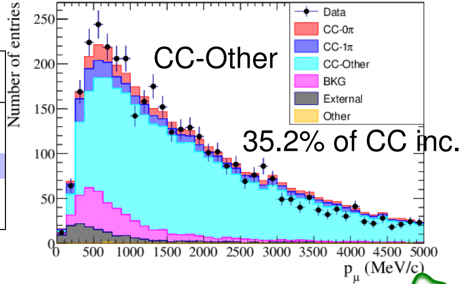
Results, 6.30×10^{20} *POT* ν beam mode





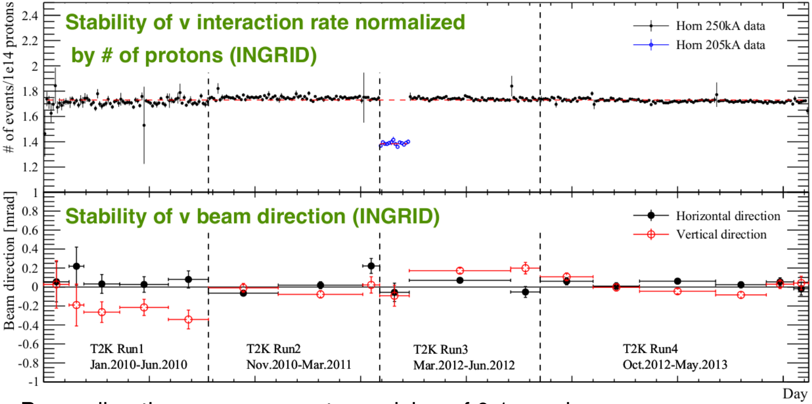
Distributions Data/MC before any fit

	Purity		
	CC-0π	CC-1π	CC-Other
CC-0π	72.6%	6.4%	5.8%
CC-1π	8.6%	49.4%	7.8%
CC-Other	11.4%	31.0%	73.8%
Bkg (NC+$\bar{\nu}_\mu$)	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%



Bkg (NC+$\bar{\nu}_\mu$) + Out FGD1 FV = 9.12% of CC inc.

Neutrino beam stability



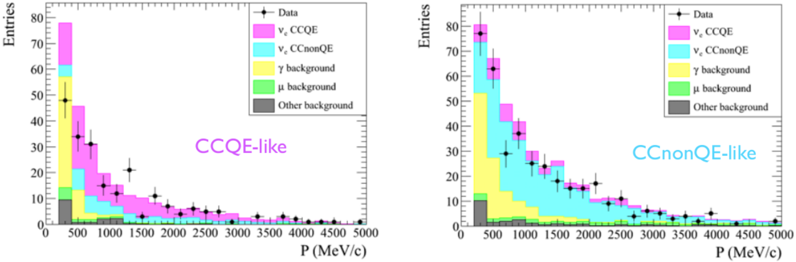
- Beam direction measurement: precision of 0.1 mrad
- For each run period, the beam is stable within 0.4 mrad
- Precision and stability much better than the 1 mrad of our initial goal

1 mrad change in ν beam direction lead to a 2-3% change in energy scale ($\approx$ 16MeV)

ND280 ν_e measurement (tracker analysis)

ND280 can verify the predicited ν_e intrinsic contamination by measuring this component of the beam directly

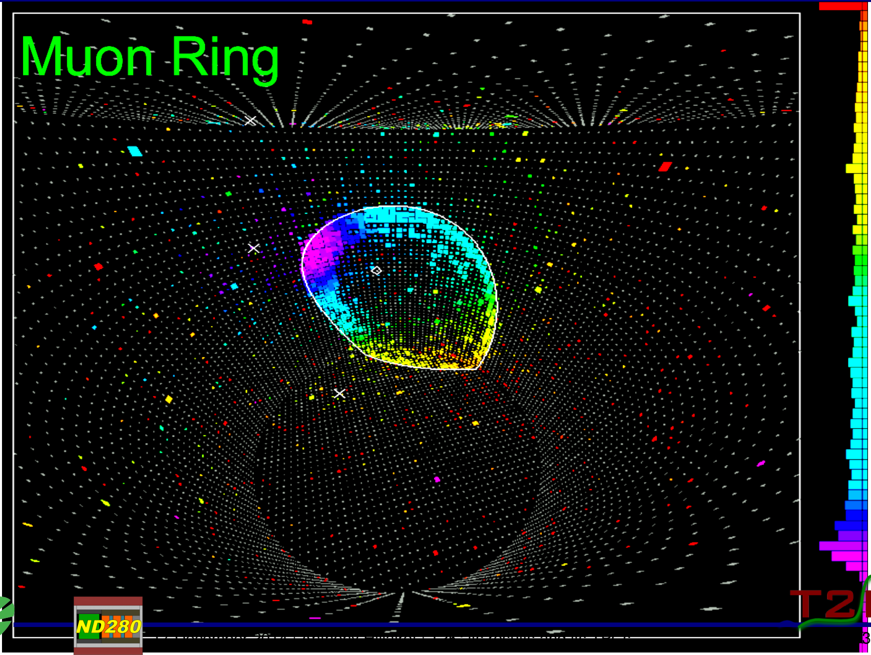
- First select CC inclusive ν_e interactions then split into:
  1. CCQE sample: only one TPC-FGD track
  2. CCnonQE sample: more than one TPC-FGD track
- Both samples have >65% ν_e purity



Likelihood fit to extract the ratio between observed and expected ν_e interactions:

$$\text{Data/MC ratio: } f(\nu_e) = 1.055 \pm 0.058(\text{stat.}) \pm 0.079(\text{syst.})$$

ν_μ interaction in Super-Kamiokande



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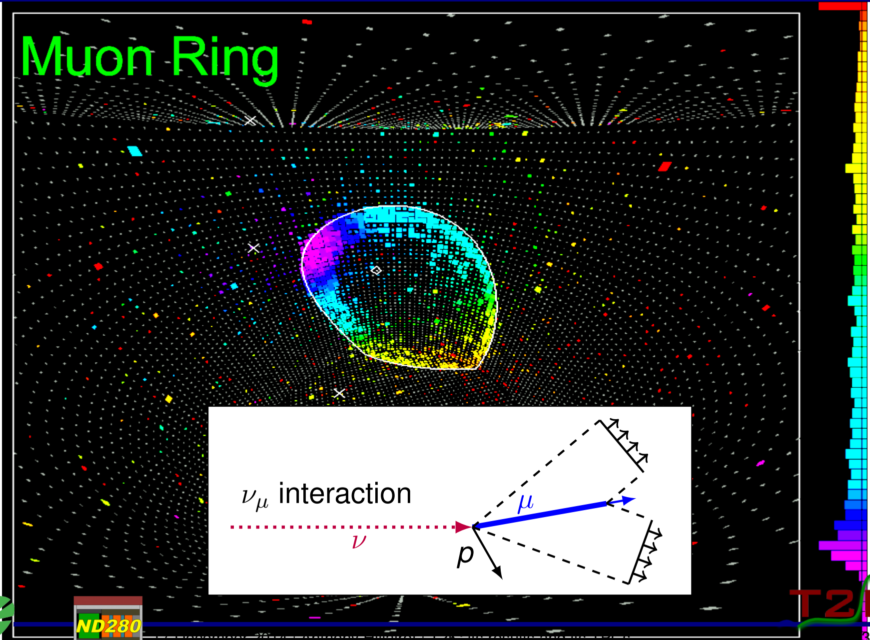
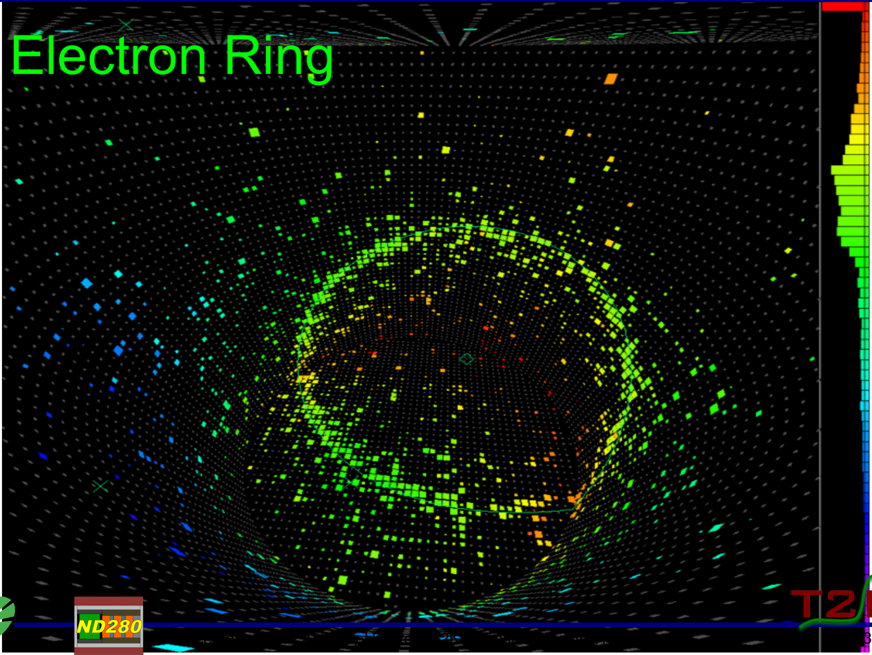
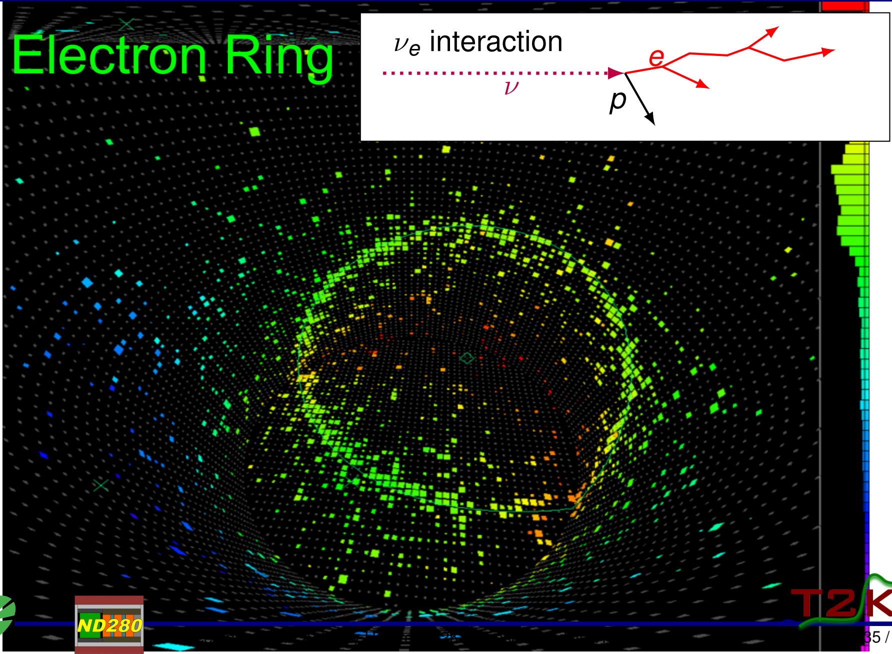


ν_e interaction in Super-Kamiokande

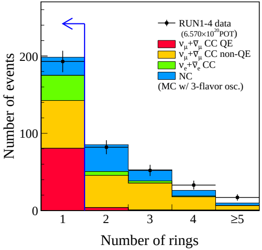


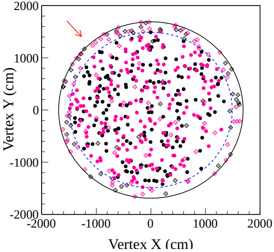
ν_e interaction in Super-Kamiokande

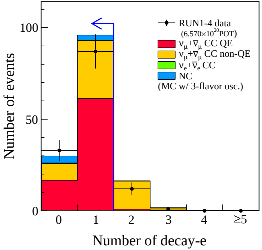


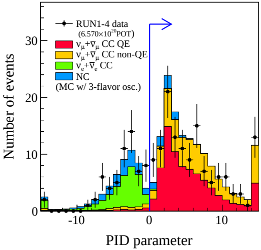
ν_μ selection in T2K SK

1. Event is fully contained in SK fiducial volume (22.5 ktonne)
2. Number of rings found = 1
3. Ring has muon-like particle ID
4. Reconstructed p_μ > 200 MeV/c
5. Nb decay electrons < 2



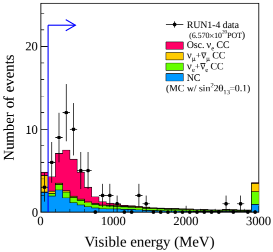


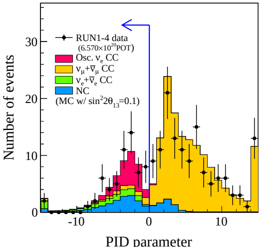


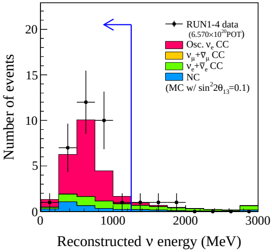


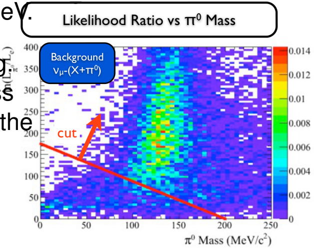
ν_e selection in T2K SK

1. Event is fully contained in SK fiducial volume (22.5 ktonne)
2. Number of rings found = 1
3. Ring has electron-like particle ID
4. Visible energy > 100 MeV
5. No decay electrons
6. Reconstructed neutrino energy (CCQE kinematic) < 1250 MeV.
7. π^0 cut: Force fit of a 2nd ring. $\Longrightarrow$ cut on the invariant mass and the likelihood fit ratio of the 2 rings.

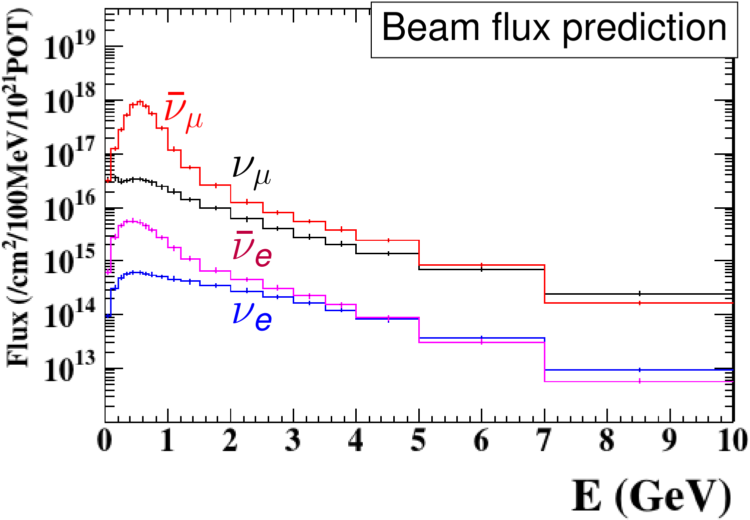








Flux in anti-neutrino beam mode



External neutrino cross section constraints

The fit to the ND280 data cannot start from scratch, it needs prior knowledge of neutrino cross sections

- MiniBooNE neutrino-nucleus scattering data is fitted to extract values and prior errors
- MiniBooNE data well-suited for T2K:
  - Wider neutrino energy spectrum
  - 4π open volume Cherenkov detector like Super-K
  - CH_2 target similar to T2K targets (mostly ^{12}C and ^{16}O)
- Many parameters constrained:
  - "Axial masses" M_A^{QE}, M_A^{RES}
  - CCQE and CC1π normalization factors
  - . . .
- Parameters which are nuclei dependent are uncorrelated between ND280 (^{12}C) and SK (^{16}O)

ν_e appearance analysis

ν_e appearance analysis

ν flux predictions and their uncertainties

How many incoming neutrinos ?

ν_e appearance analysis

Cross section uncertainties on ν-C and ν-O from external sources (MiniBooNE)

How many neutrinos will interact ?

ν flux predictions and their uncertainties

How many incoming neutrinos ?

ν_e appearance analysis

Cross section uncertainties on ν-C and ν-O from external sources (MiniBooNE)

ν flux predictions and their uncertainties

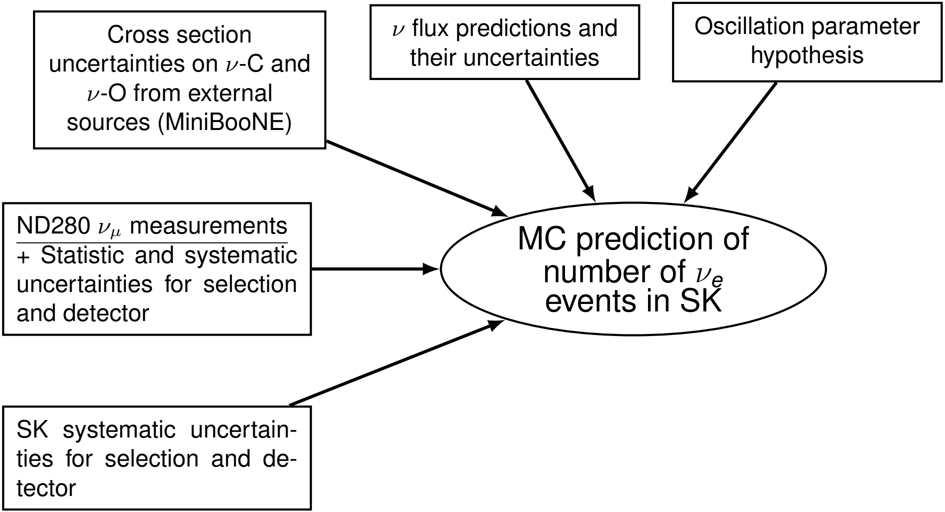
How many incoming neutrinos ?

How many neutrinos will interact ?

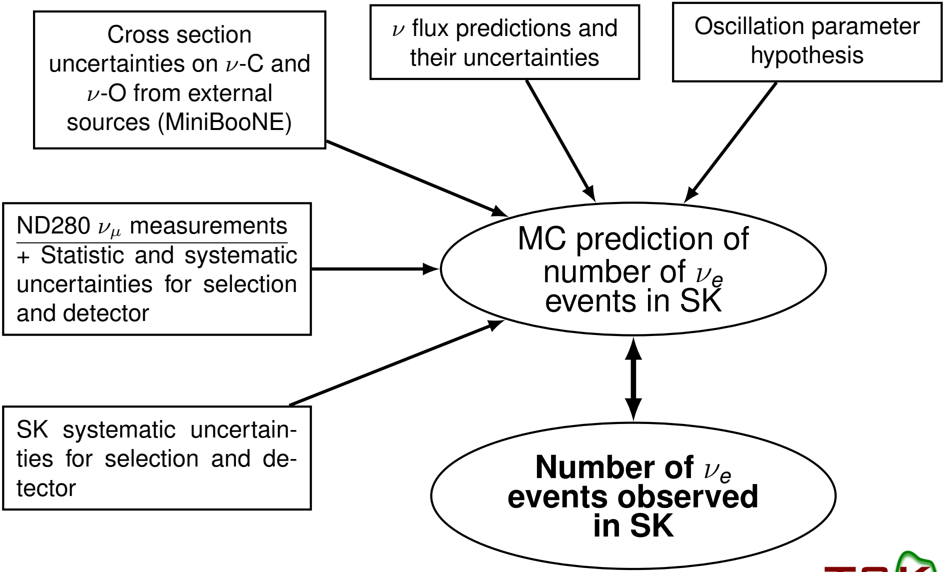
ND280 ν_μ measurements
+ Statistic and systematic uncertainties for selection and detector

can constrain

ν_e appearance analysis



ν_e appearance analysis



TREx event display