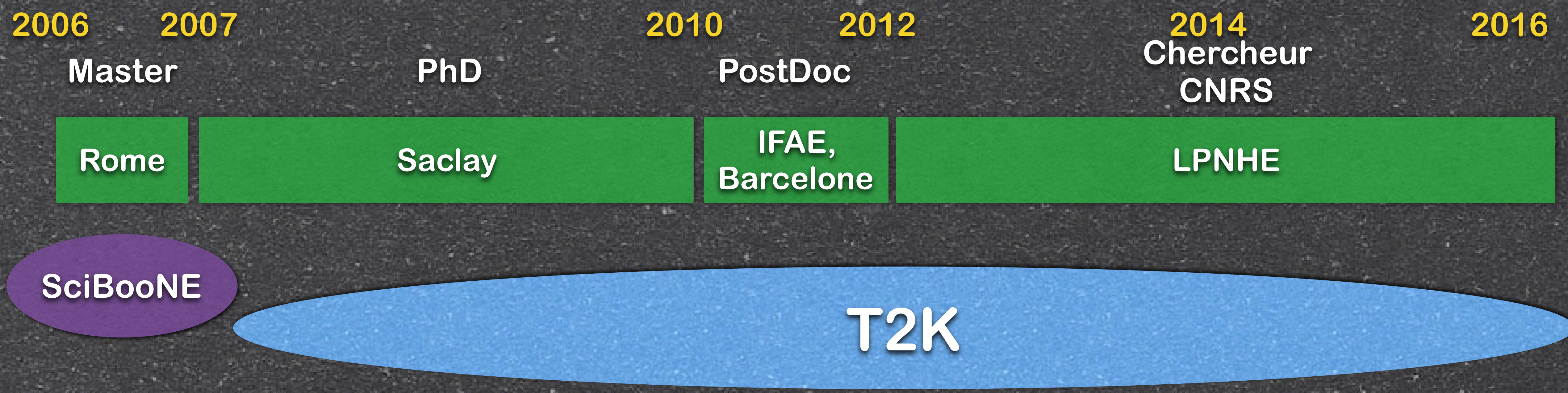
The quest for CP violation in the leptonic sector with the T2K experiment

Claudio Giganti

Soutenance HDR - 24/06/2016

My scientific activities



SciBooNE: experiment at Fermilab to measure neutrino cross-sections

T2K: Long baseline neutrino oscillation experiment in Japan

LAGUNA/LBNO/WA105: design study and R&D for next generation long baseline experiments

DarkSIDE: Liquid Argon detectors for Direct Dark Matter detection

Tutoring

2006 2007 2010 2012 2014 2016

Master — PhD — PostDoc — Chercheur CNRS

Rome — Saclay — IFAE, Barcelone — LPNHE

SciBooNE

T2K

LAGUNA/ LBNO/WA105

DarkSIDE

T2K

2011-2014 PhD co-supervisor Javier Caravaca (IFAE)
2013-2016 PhD supervisor Pierre Bartet
From 2015 PhD co-supervisor Simon Bienstock
+ 1 M2 stage and L3 stages

DarkSIDE

From 2015 M1+M2+PhD(?) Anyssa Navrer-Agasson
+1 L3 and 1 M1 stage

Responsibilities

2006 | 2007 | 2010 | 2012 | 2014 | 2016

Master | PhD | PostDoc | Chercheur CNRS

Rome | Saclay | IFAE, Barcelone | LPNHE

SciBooNE

T2K

2011-2014 ND280 ν_e co-convener

2015 - now T2K Oscillation Analysis co-convener

2014-2015 ND280 exotics convener

LAGUNA/ LBNO/WA105

DarkSIDE

Main results (presented in this HDR)

Measurement of the beam ν_e component
Phys. Rev. D 89, 092003

Electron neutrino CC cross-section
Phys. Rev. Lett. 113, 241803

Search for sterile neutrinos at ND280
Phys. Rev. D 91, 051102(R)

ND280 ν_μ selection to increase angular acceptance and measurement of ν cross-sections
arXiv:1602.03652, submitted to PRD

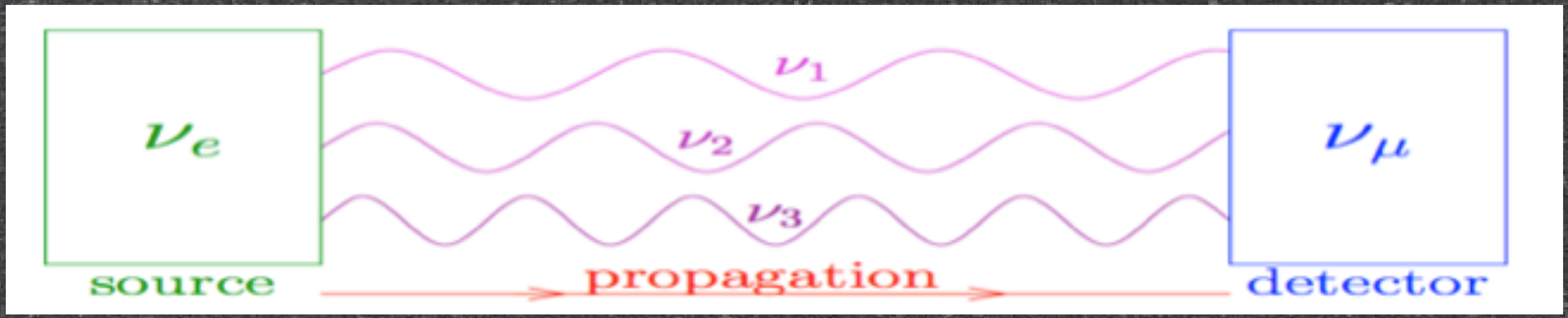
T2K joint ν-$\bar{\nu}$ oscillation analysis
(not published yet, will be presented at Neutrino2016 in two weeks)

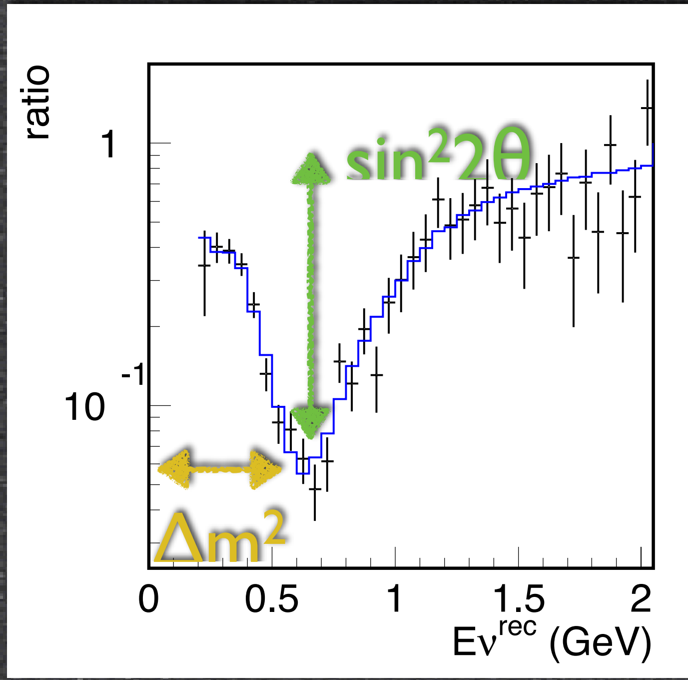
Plan

- (Quick) introduction to neutrino oscillations
  - Neutrino oscillations in ~2010
  - θ_{13} and CP violation
- The T2K experiment
- ND280 results
  - Measurements with CC ν_μ selections
  - Measurements with CC ν_e selections
- T2K oscillation analysis
- Next steps

Neutrino oscillations in a nutshell

- First introduced by Bruno Pontecorvo in 1957
- Neutrinos are produced in flavor eigenstates ν_e, ν_μ, ν_τ that are linear combination of mass eigenstates ν_1, ν_2, ν_3
- Neutrinos propagate as mass eigenstates
- At the detection a flavor eigenstate is detected → it can be different from the one that was produced





ν_e produced in a mixture of $\nu_{1,2,3}$

$\nu_{1,2,3}$ travel at different speed because they have different masses → interference

Different mixture of $\nu_{1,2,3}$ → μ from ν_μ is detected

Neutrino oscillation implies massive neutrinos

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2(\Delta m^2_{12} L/E)$$

3 flavor neutrino mixing: PMNS matrix

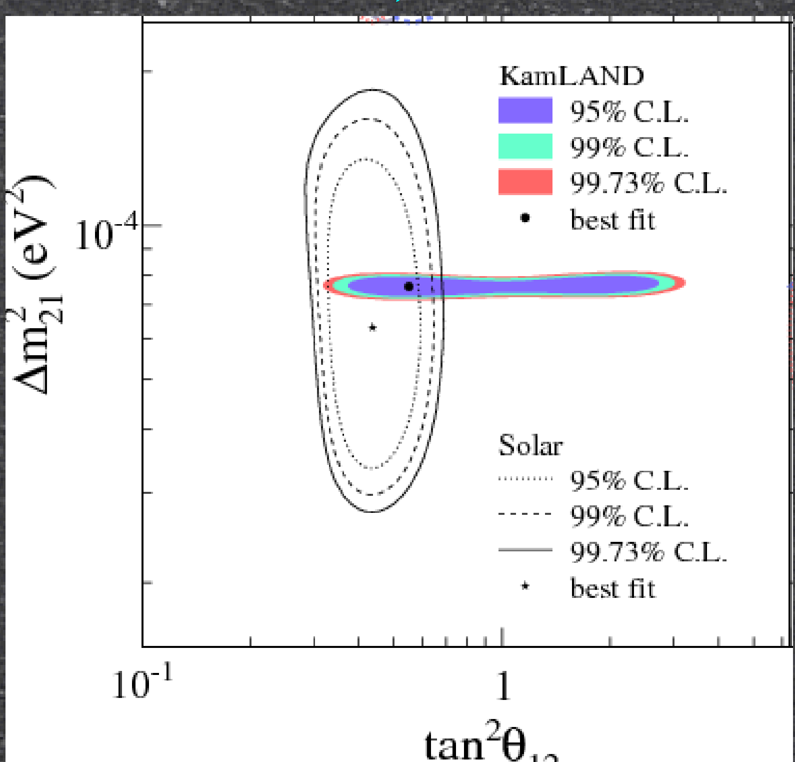
Solar — Interference — Atmospheric

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{+i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

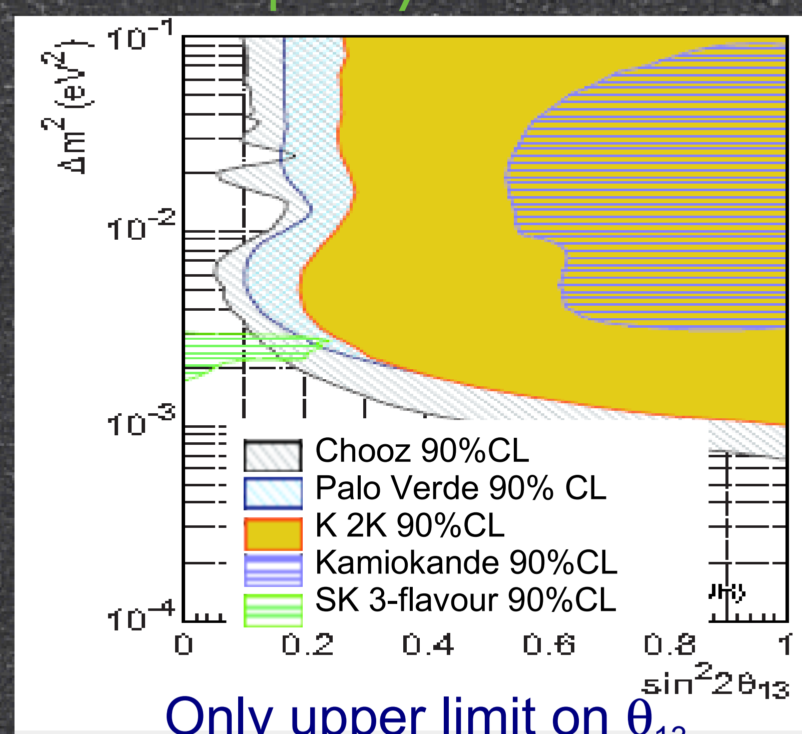
- 3 mixing angles
- 2 independent mass differences
- 1 CP violation phase

Once upon a time (~2010)

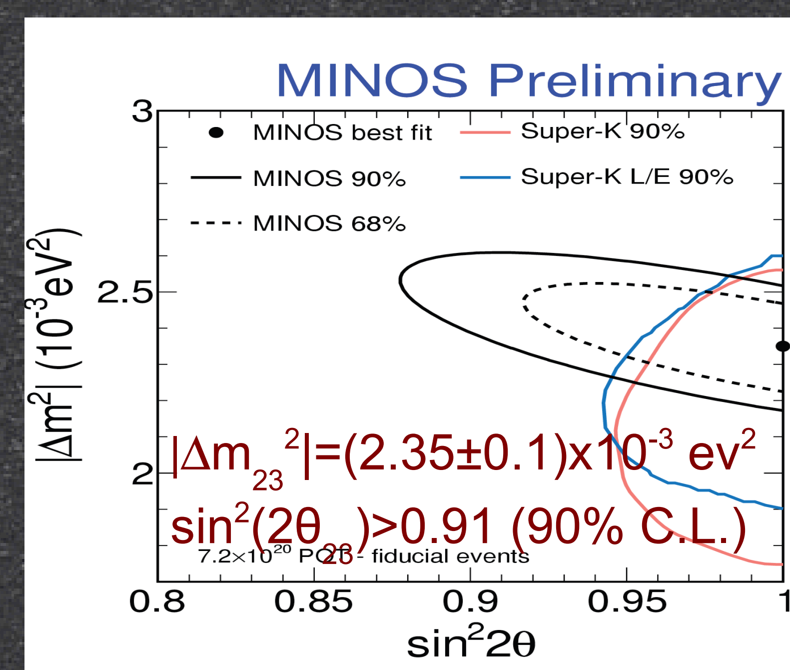
Solar (SNO, SK, KamLand) → θ_{12}, Δm_{12}



Interference θ_{13}, δ_{CP} Completely unknown



Atmospheric (SK, Minos) → θ_{23}, Δm_{32}



How to measure θ_{13}

Reactors (DChooz, RENO, Daya Bay)

- ✓ Disappearance of $\bar{\nu}_e$ $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$
- ✓ $\bar{\nu}_e$ produced in nuclear reactors
  - ✓ Neutrino energy few MeV
  - ✓ Distance L ~ 1 km
- ✓ Signature: disappearance of the $\bar{\nu}_e$ produced in the reactor → depends on θ_{13}

Accelerators (T2K, Nova):

- ✓ Appearance experiment: $P(\nu_\mu \rightarrow \nu_e)$
- ✓ ν_μ neutrino beam
  - ✓ Neutrino energy ~1 GeV
  - ✓ Distance L >~ 300 km
- ✓ Signature: ν_e appearance in ν_μ beam
- ✓ Degeneracy of θ_{13}, δ_{CP}, sign of Δm^2

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - sin^2 2\theta_{13} sin^2 \Delta_{13} - cos^4\theta_{13} sin^2 2\theta_{12} sin^2 \Delta_{12}$$

Simple dependence on θ_{13} (and Δm_{31}^2

1st order → θ_{13}

$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2\theta_{23} \frac{sin^2 2\theta_{13}}{(\hat{A}-1)^2} \sin^2((\hat{A}-1)\Delta)$$
$$+ \alpha \frac{8 J_{CP}}{\hat{A}(1-\hat{A})} \sin(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)$$
$$+ \alpha \frac{8 I_{CP}}{\hat{A}(1-\hat{A})} \cos(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)$$
$$\alpha^2 \frac{cos^2\theta_{23} \sin^2\theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta)$$

J_{CP} → CPV term
A depends on the sign of Δm^2

$\Delta = \Delta m_{32}^2 L/4E$ $\alpha = |\Delta m_{32}^2|/|\Delta m_{21}^2| \sim 1/30$

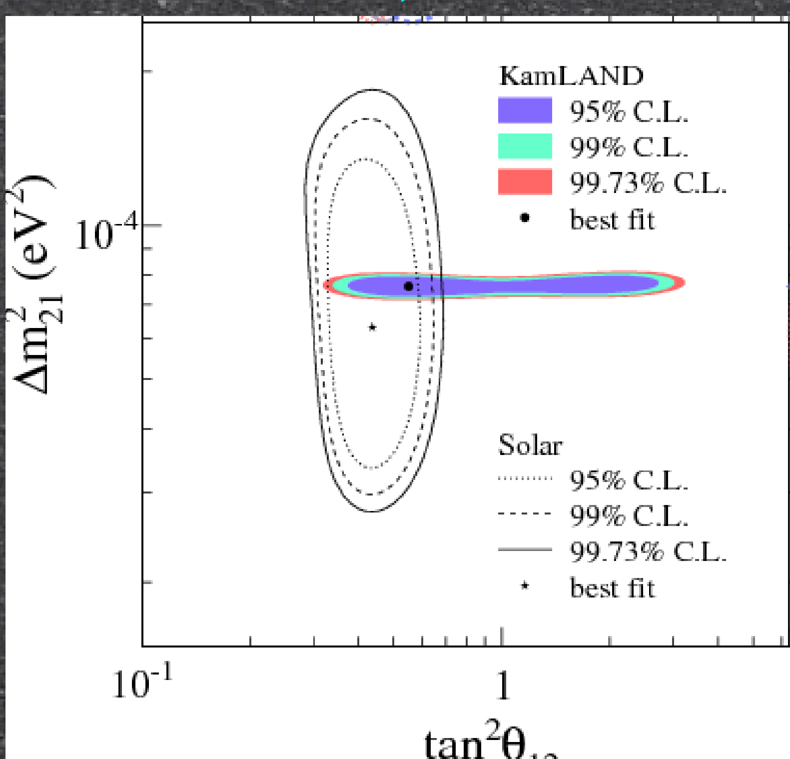
3 flavor neutrino mixing today

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{+i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

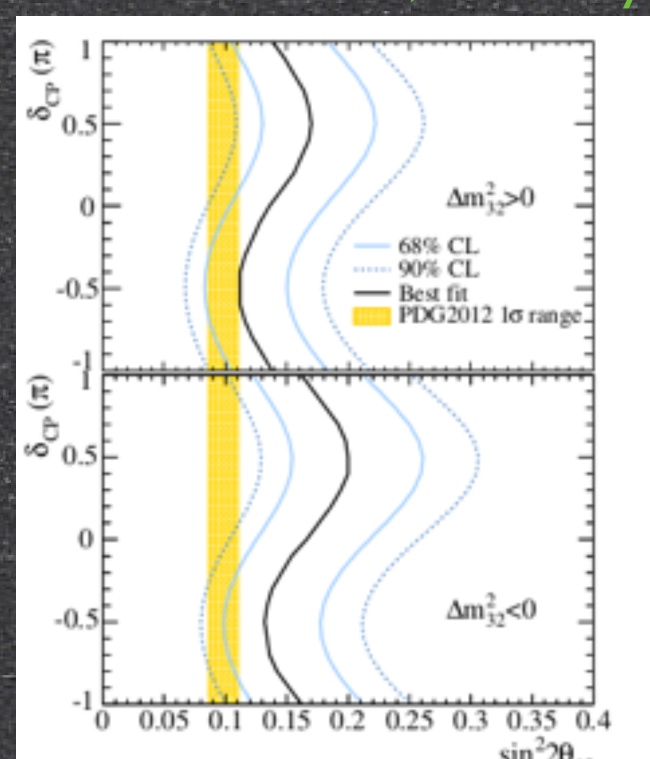
- 3 mixing angles
- 2 independent mass differences
- 1 CP violation phase

Today: θ_{13} is precisely known, some indications also for δCP

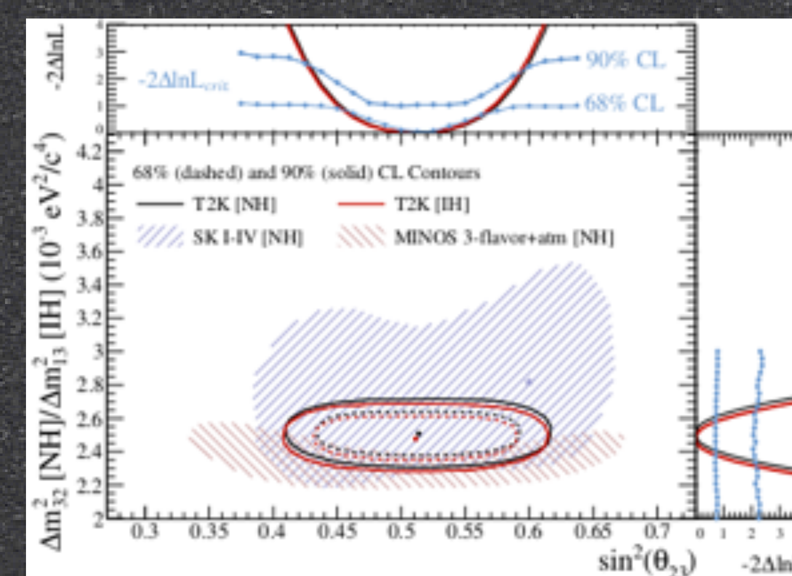
Solar (SNO, KamLand)
→ θ_{12}, Δm_{12}



Interference (Daya Bay, T2K)
→ θ_{13} measured, δ_{CP} not yet



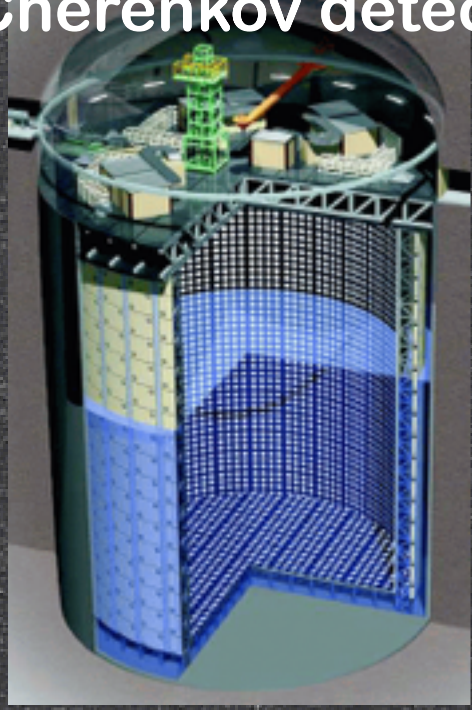
Atmospheric (SK, K2K, Minos, T2K)
→ θ_{23}, Δm_{32}

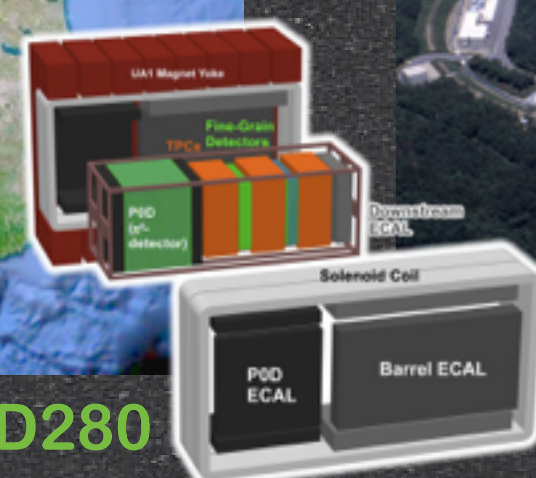


T2K experiment

- High intensity ~600 MeV ν_μ beam produced at J-PARC (Tokai, Japan)
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector (Super-Kamiokande) 295 km from J-PARC
- Main physics goals:
  - Observation of ν_e appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ disappearance → θ_{23} and Δm^2_{32}

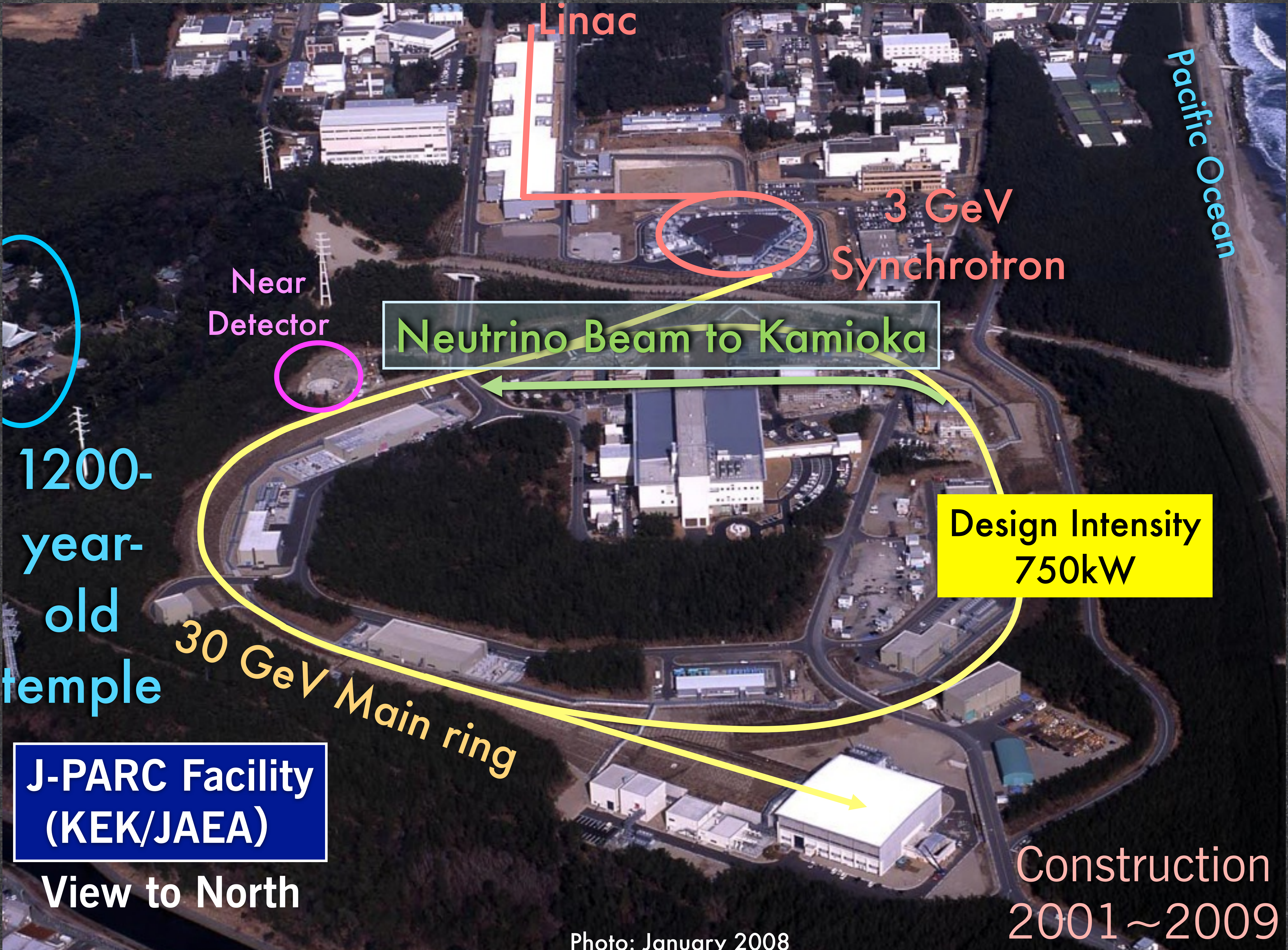
Super-Kamiokande: 22.5 kt fiducial volume water Cherenkov detector





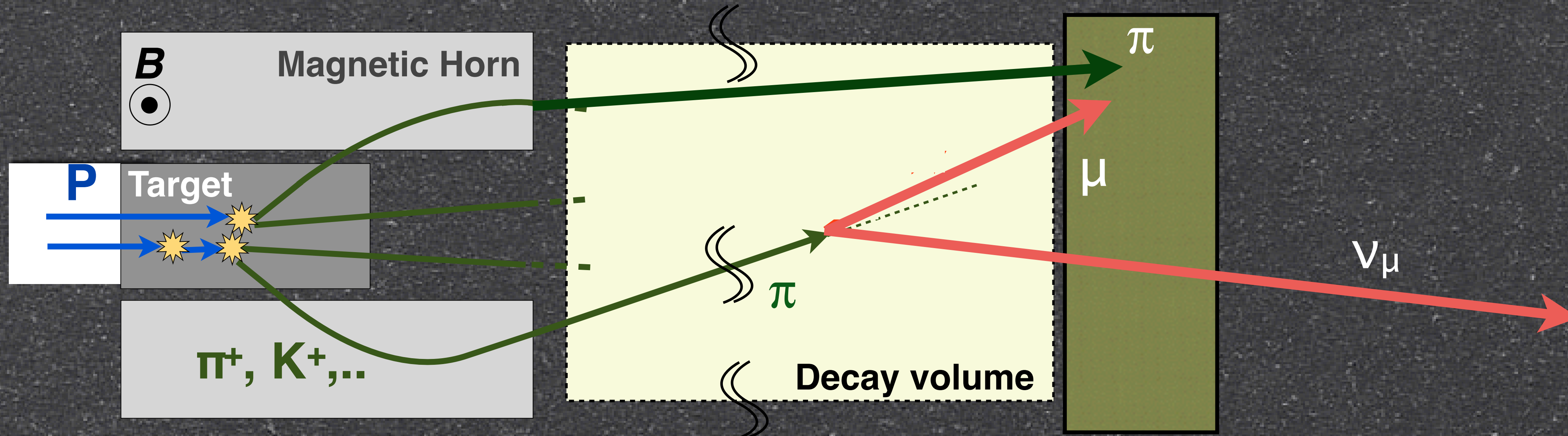
ND280

J-PARC accelerator: Design power: 750 kW



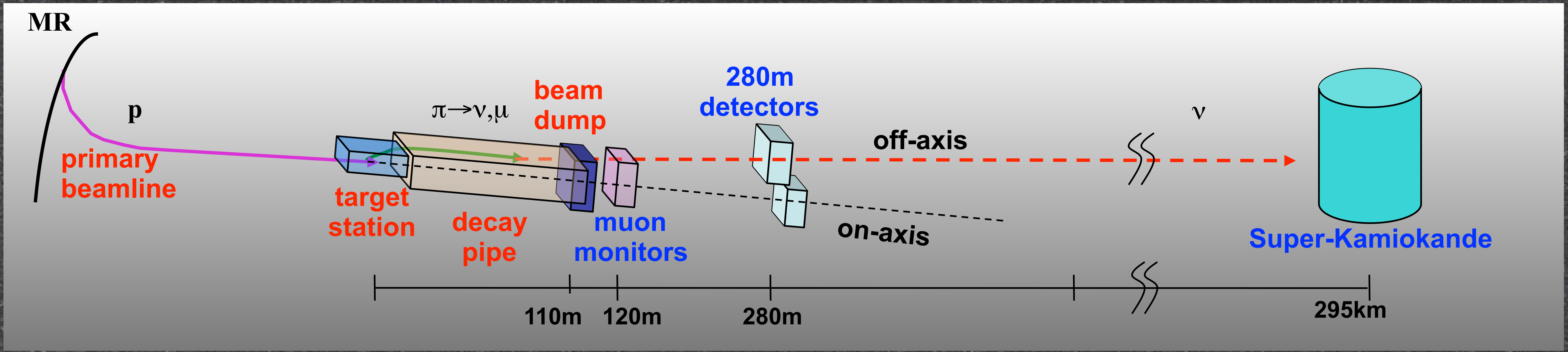
Linac
3 GeV
Synchrotron
Pacific Ocean
Near
Detector
Neutrino Beam to Kamioka
1200-
year-
old
temple
Design Intensity
750kW
30 GeV Main ring
J-PARC Facility
(KEK/JAEA)
View to North
Construction
2001~2009
Photo: January 2008

T2K neutrino beamline

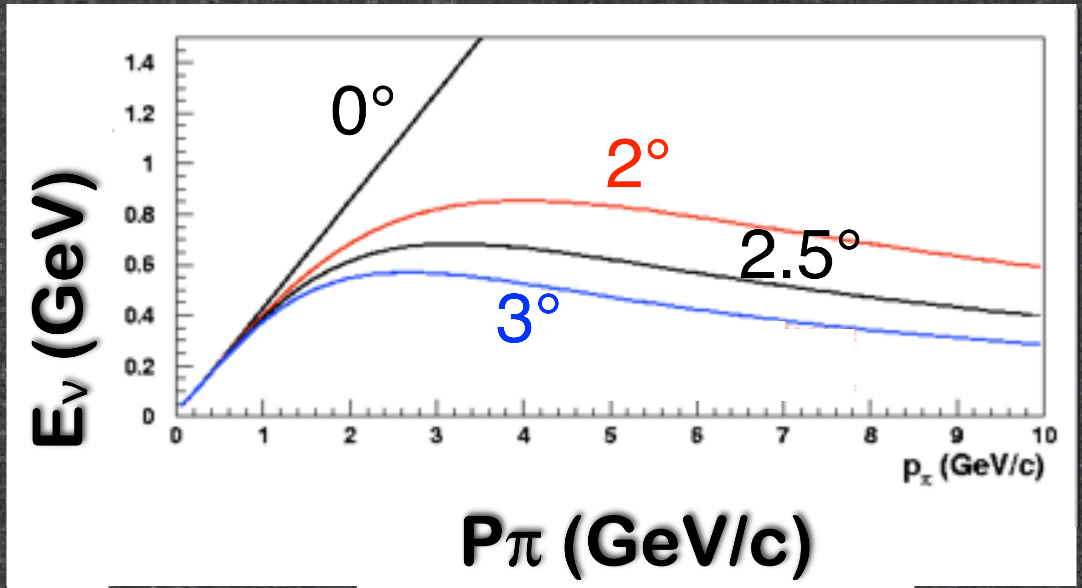


- 30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target
- p+C interactions producing hadrons (pions and kaons)
- Hadrons are focused and selected in charge by 3 electromagnetic horns
- ν_μ mainly produced by pion decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- Changing the sense of the current in the magnetic horns π^- can be focused and a beam of $\bar{\nu}_\mu$ can be produced
- I will often talk about POT (proton-on-target) → equivalent of luminosity for collider experiments

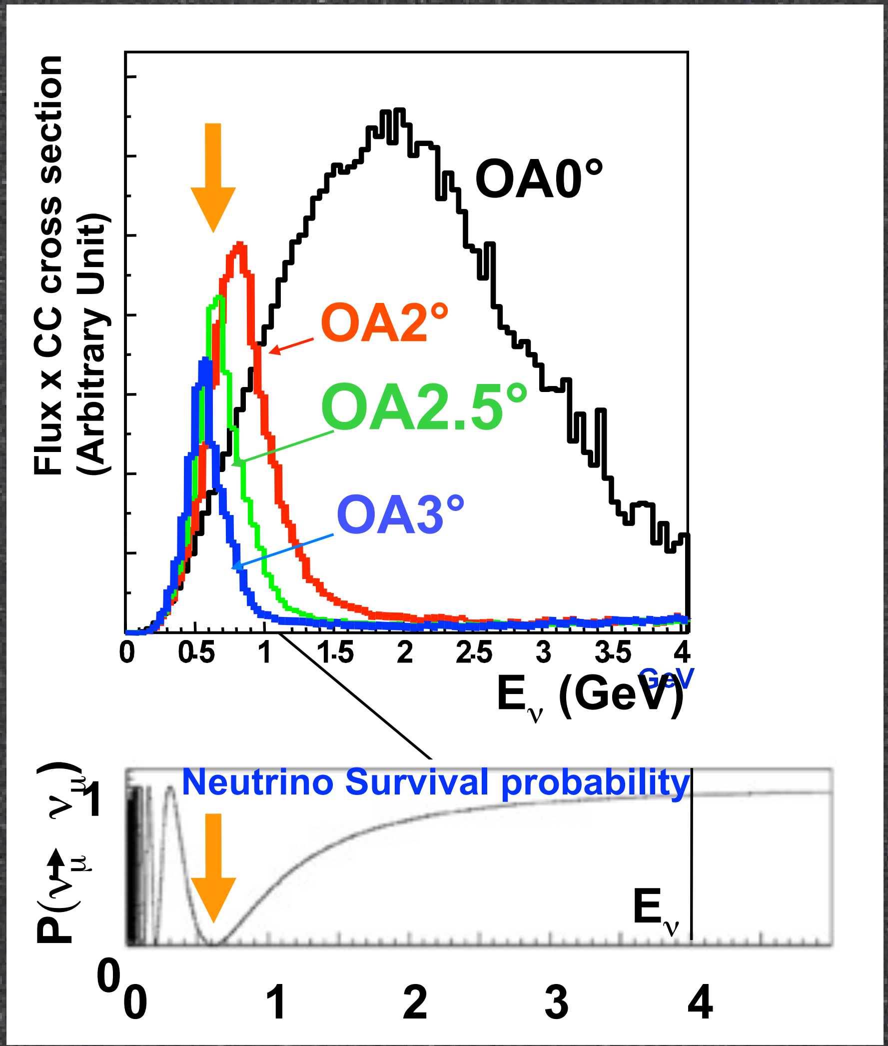
Off-axis beam



- T2K uses an off-axis technique (detectors at 2.5° from the center of the beam)
- Increase the intensity of the beam at the desired L/E → maximize the oscillation probability



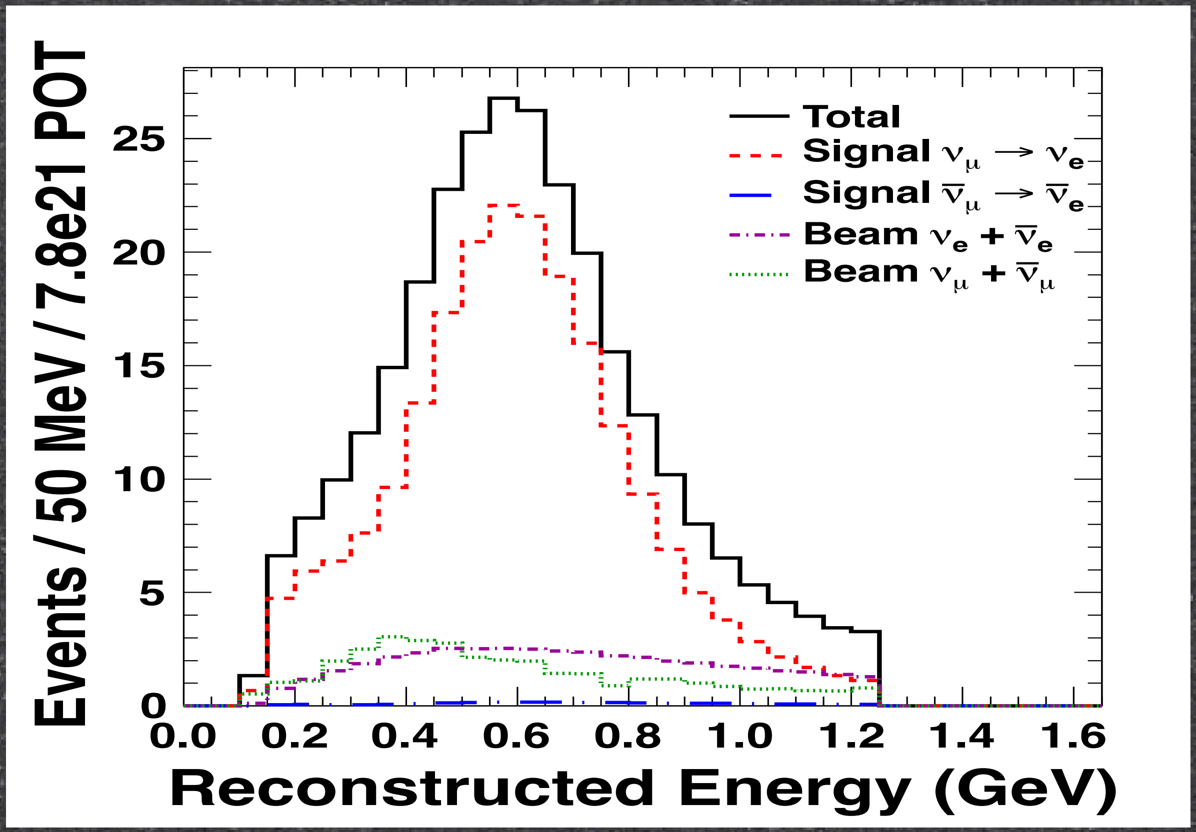
On-axis: E_ν proportional at P_π
Off-axis: different P_π contribute to the same E_ν



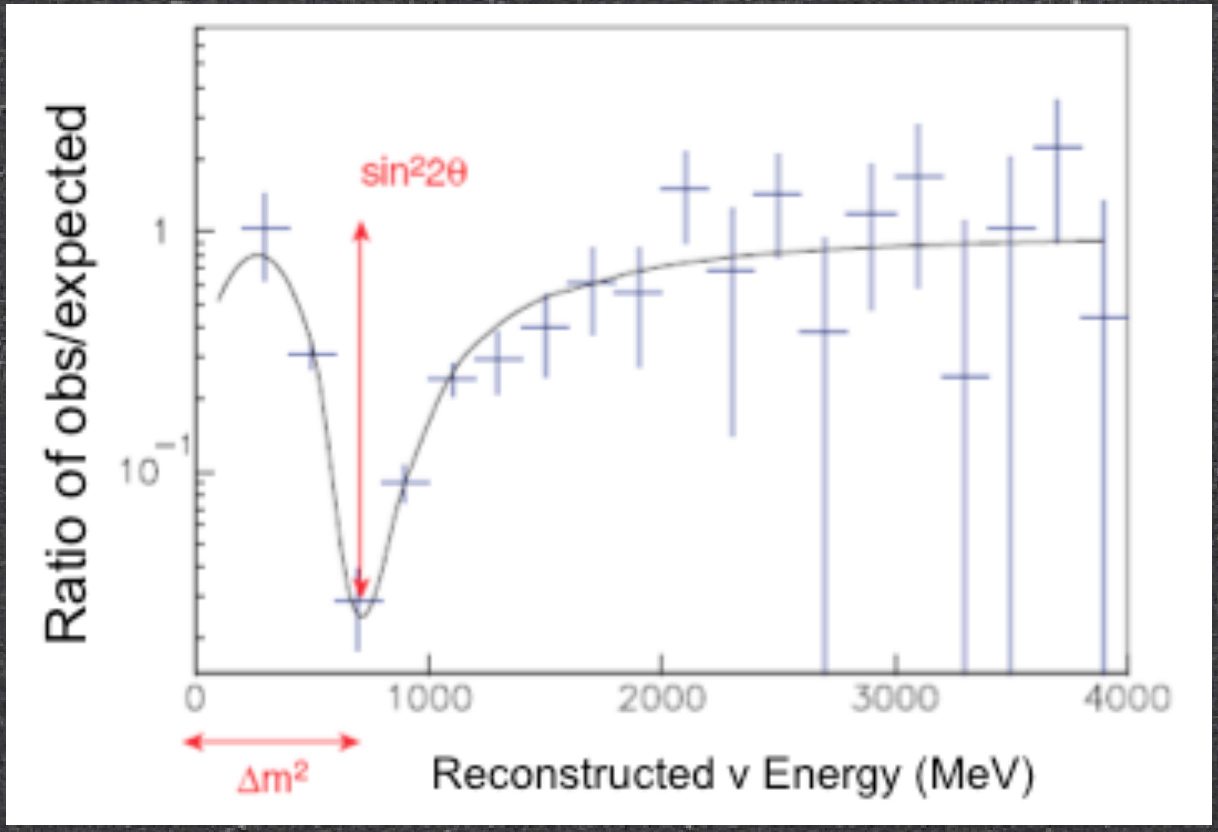
Physics goals

- The T2K experiment was designed to have Super-Kamiokande at the maximum of the oscillation probability
  - Ideal place to look for ν_e appearance (mainly driven by θ_{13}) and ν_μ disappearance (θ_{23} and Δm^2_{32})
- If negative pions are focused the beam is predominantly composed of $\overline{\nu}$ and this maximize the δ_{CP} sensitivity

ν_e appearance → θ_{13} and δ_{CP}



ν_μ disappearance → θ_{23} and and Δm^2_{32}



Why anti-neutrinos

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4\boxed{C_{13}^2 S_{13}^2 S_{23}^2} \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} \boxed{S_{23} \sin\delta} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& \boxed{\begin{aligned} & -8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\ & +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31}, \end{aligned}}
\end{aligned}
$$

Leading term → θ_{13}

CPV term

Matter effects ∝ distance

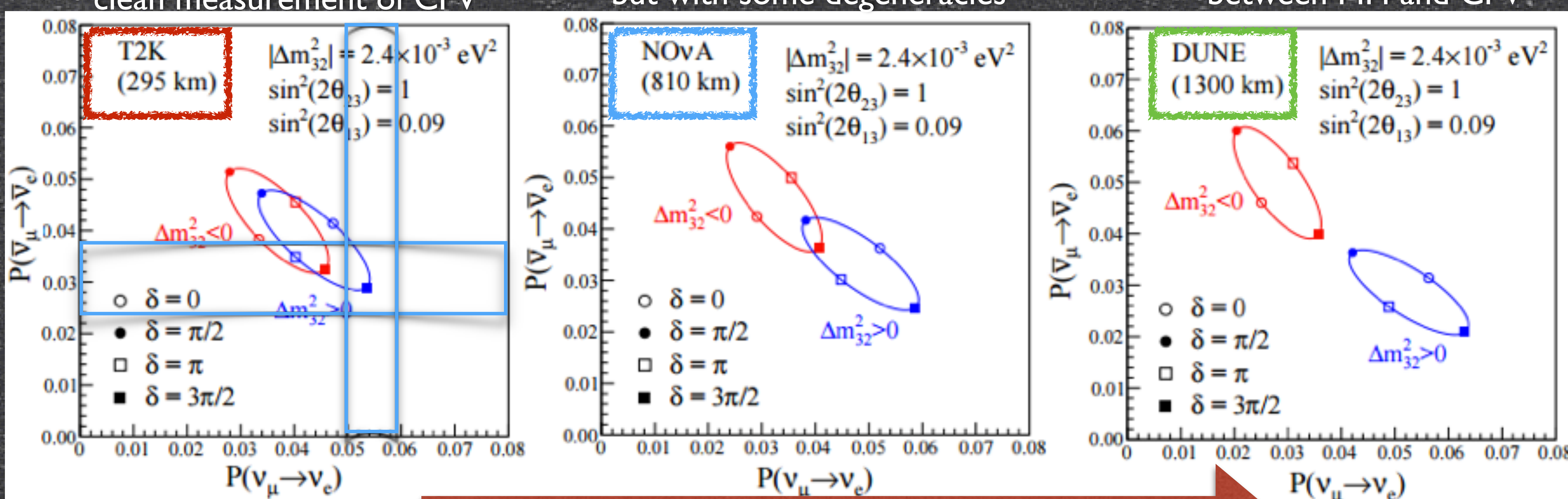
Experimentally we measure an appearance probability

sinδ and a change sign from neutrino to antineutrino

T2K almost no MH —> ~ clean measurement of CPV

NOVA sensitive to MH and CPV but with some degeneracies

DUNE breaks the degeneracy between MH and CPV



increasing baseline

Why antineutrinos

Leading term → θ_{13}

$$P(\nu_\mu \to \nu_e) = 4\boxed{C_{13}^2 S_{13}^2 S_{23}^2} \cdot \sin^2 \Delta_{31}$$

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

CPV term

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},$$

Matter effects

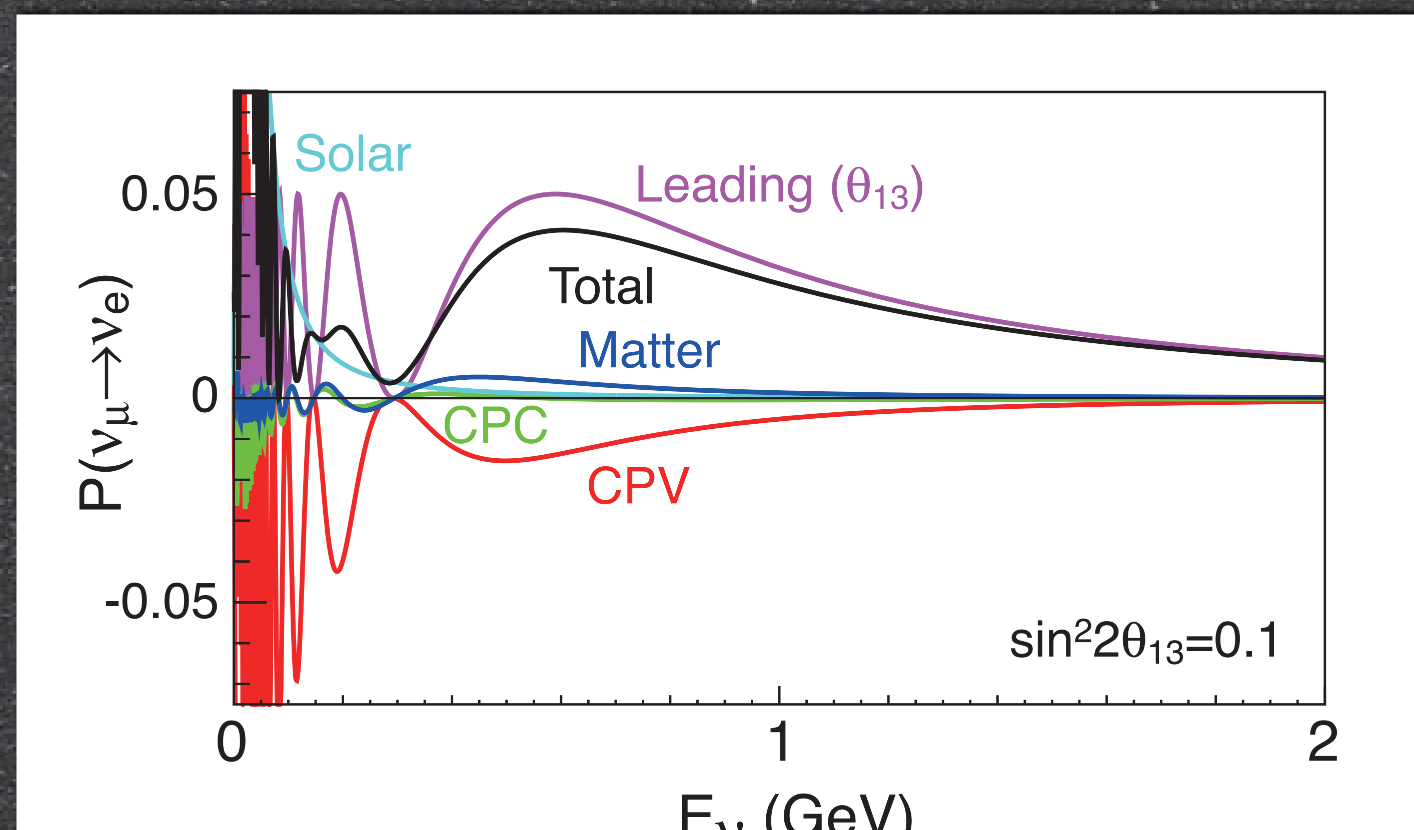
∝ distance

Experimentally we measure an appearance probability

sinδ and a change sign from neutrino to antineutrino

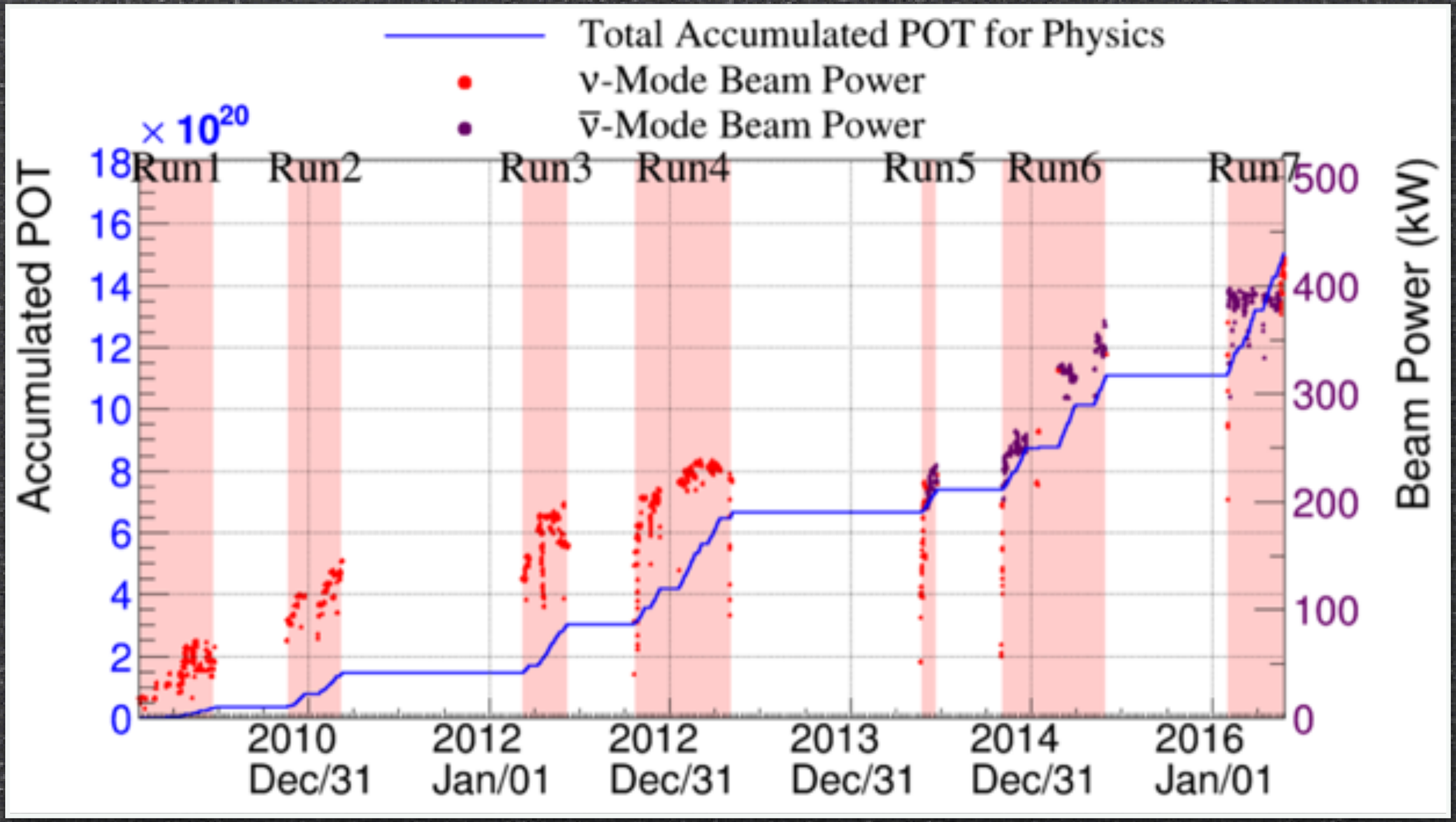
In case of T2K where the baseline is short we have:

δ_{CP} effect ±30%
MH effect ~10%



Data taking

- T2K started the data taking in 2010
- Collected proton on target so far ~15×10^{20} POT
  - Reached steady beam power of 410 kW (nominal beam power would be 750 kW)
- Equal amount of ν and $\bar{\nu}$

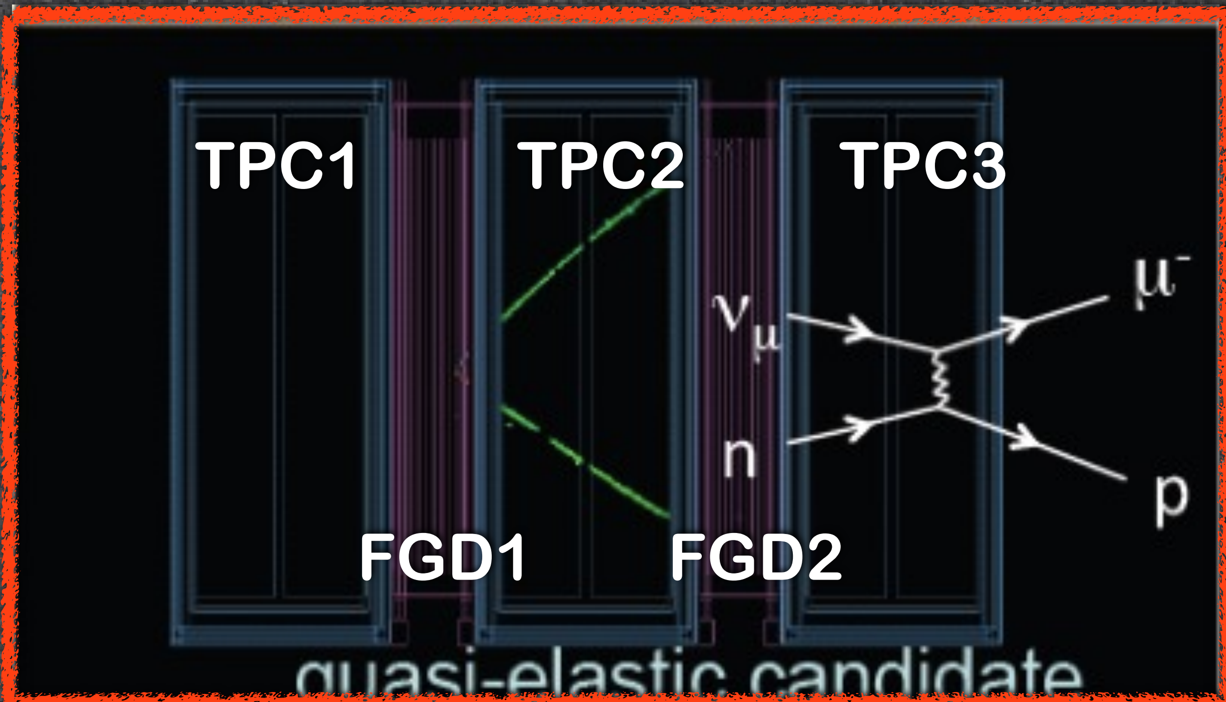


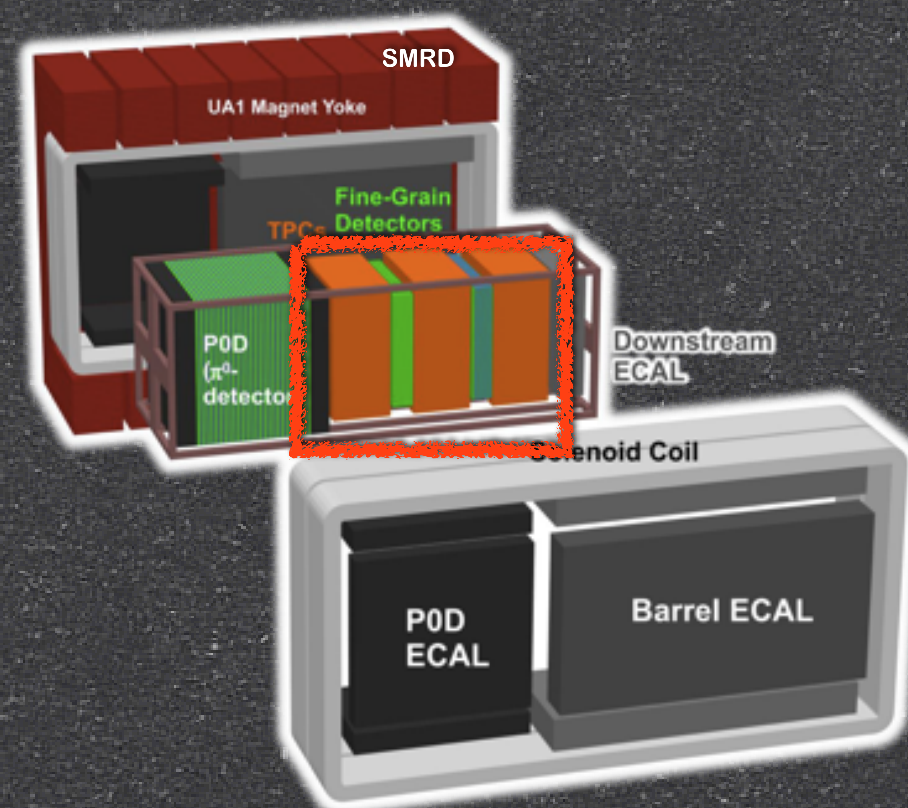
Today's analyses
6.9×10^{20} POT in ν
4.0×10^{20} POT in $\bar{\nu}$

Will be shown at Neutrino
7.0×10^{20} POT in ν
7.5×10^{20} POT in $\bar{\nu}$

ND280

Tracker

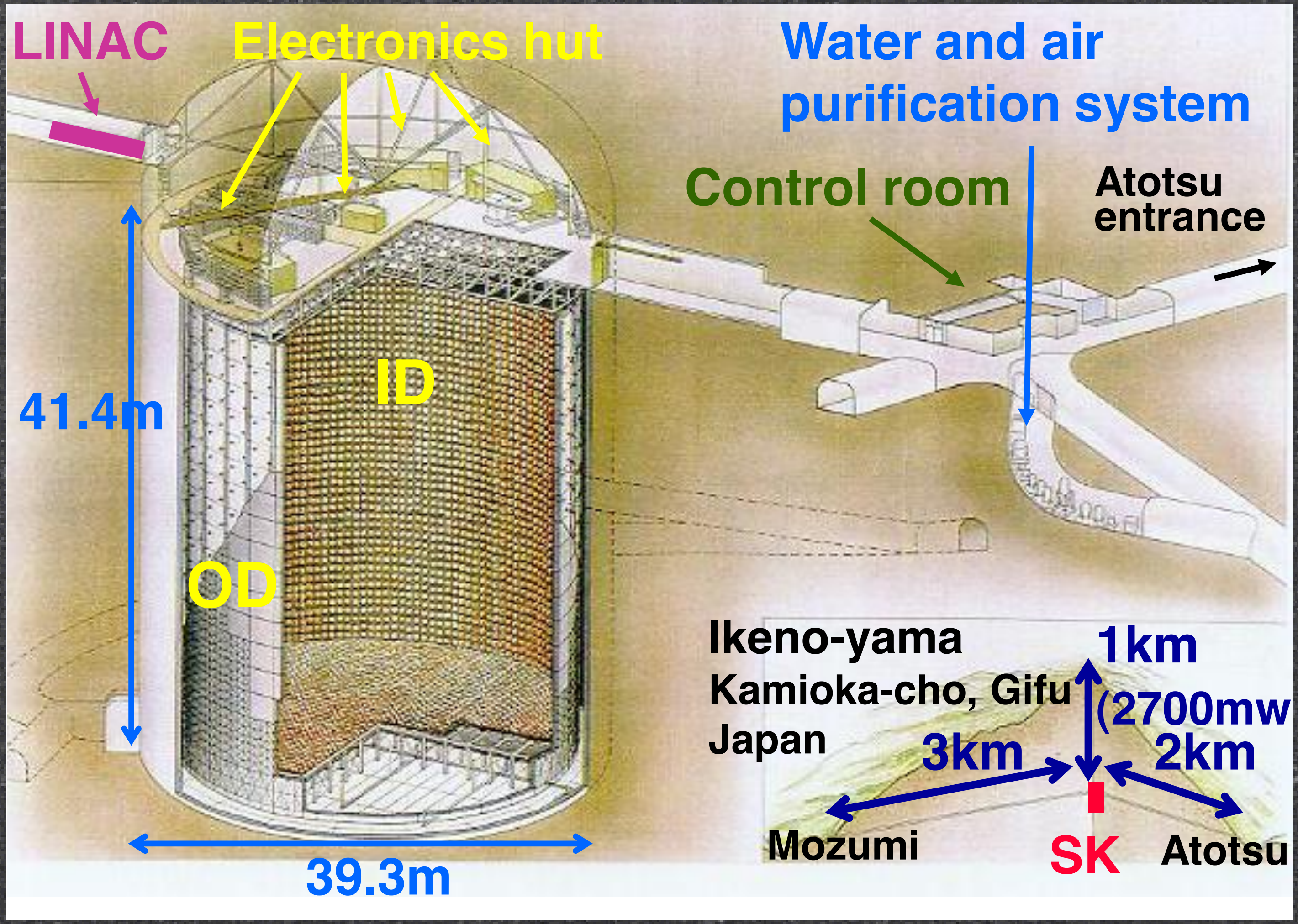




- Detector installed inside the UA1/NOMAD magnet (0.2 T magnetic field)
- A detector optimized to measure π^0 (P0D)
- A tracker system composed by:
  - 2 Fine Grained Detectors (target for ν interactions). FGD1 is pure scintillator, FGD2 has water layers interleaved with scintillator
  - 3 Time Projection Chambers: reconstruct momentum and charge of particles, PID based on measurement of ionization
  - Electromagnetic calorimeter to distinguish tracks from showers

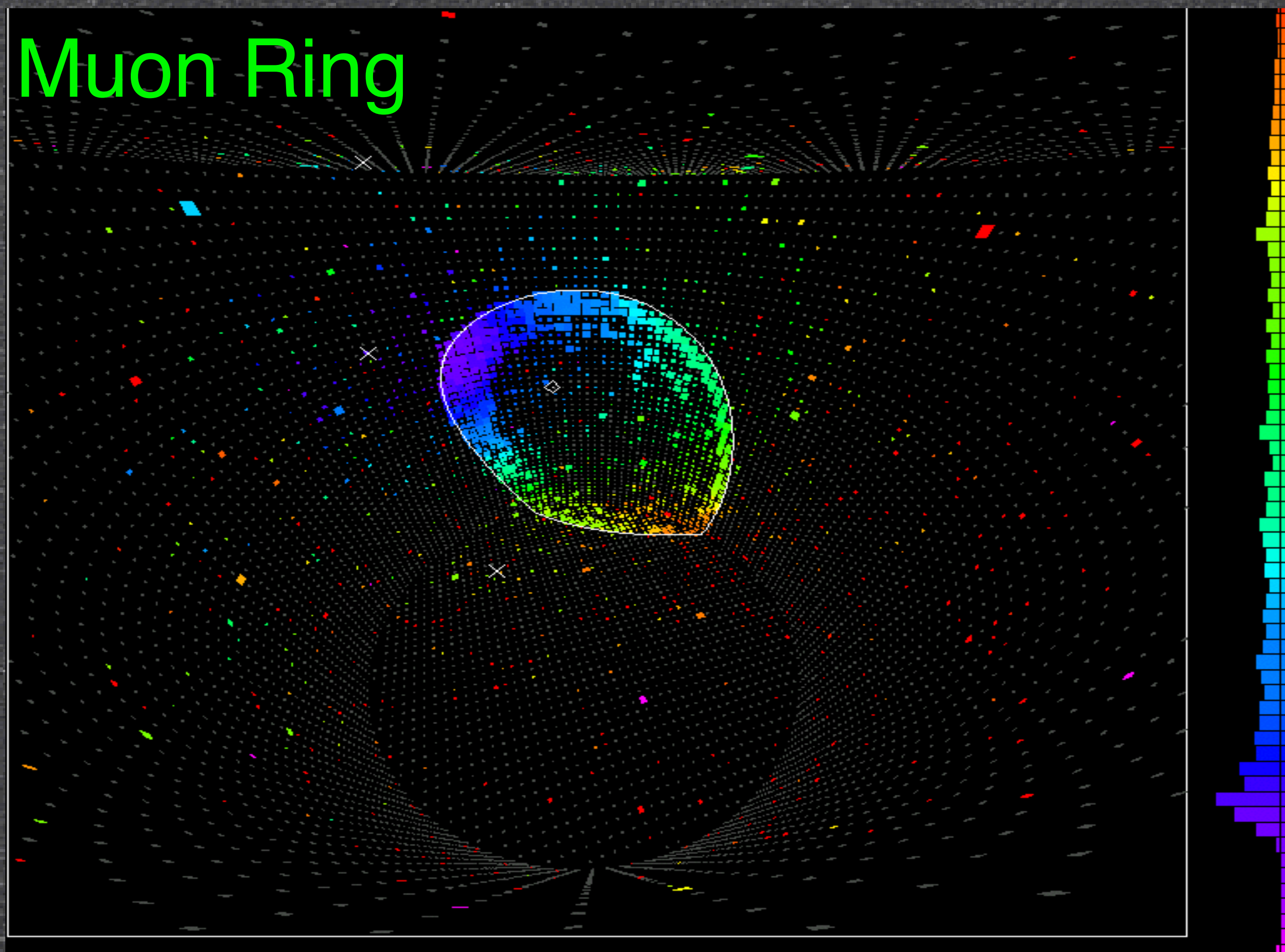
Super-Kamiokande

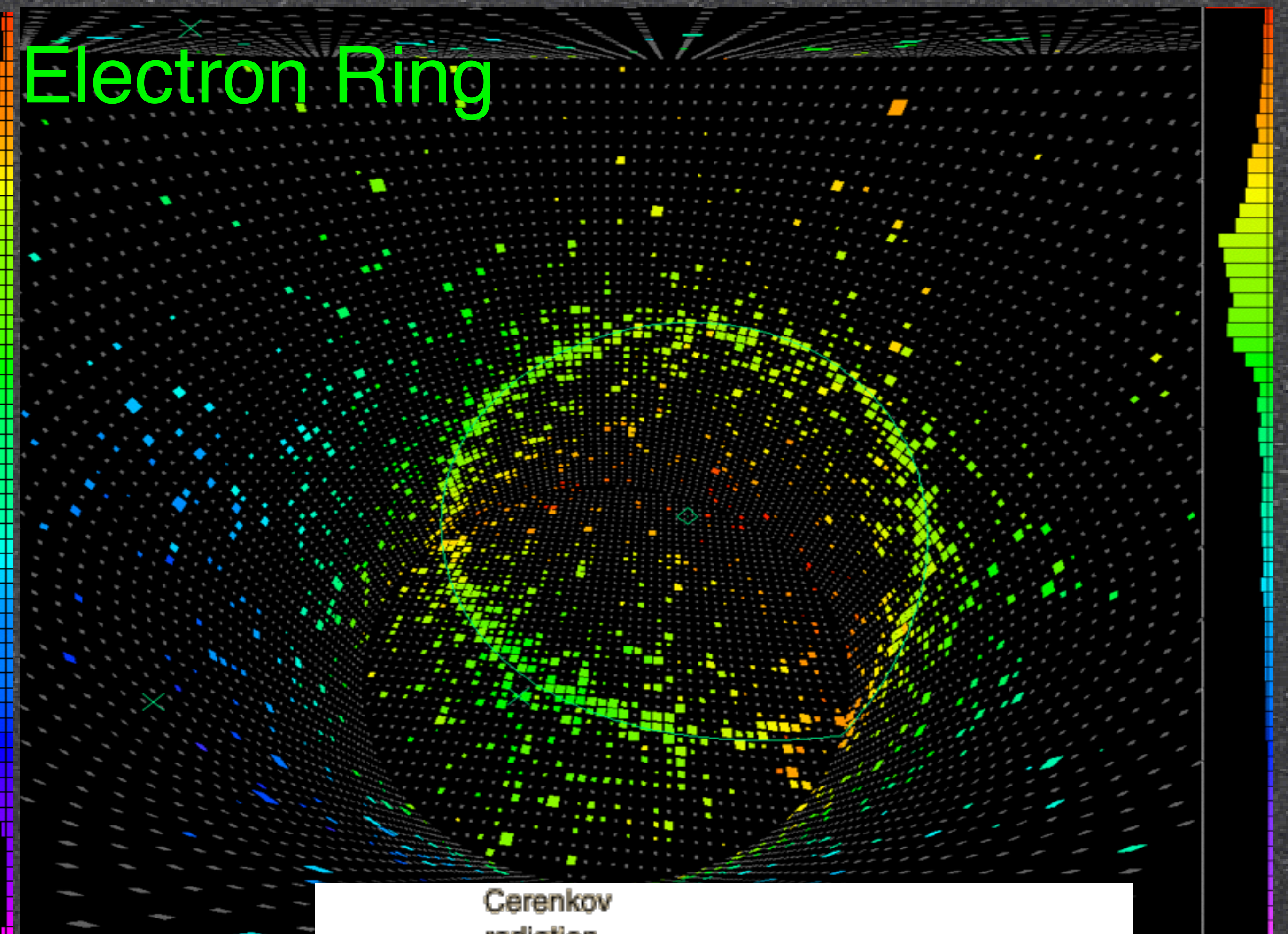
- 50 kton water Cherenkov detector (22.5 kton FV)
  - ~11000 20'' PMT inner detector (~2000 8'' PMT outer detector used as veto) → 40% photocathode coverage
- ~1000 meters underground in the Kamioka mine



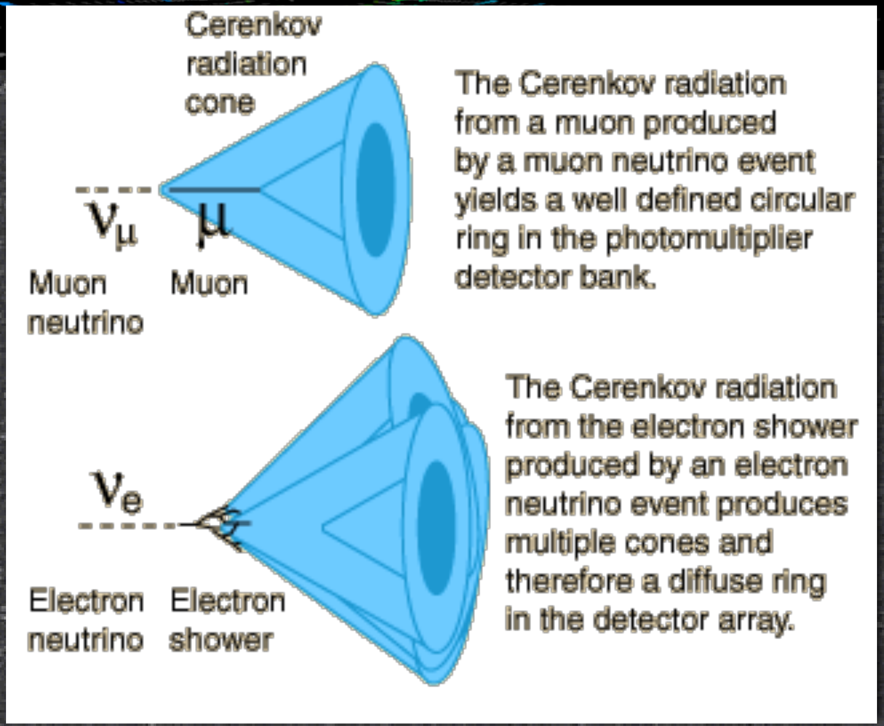
- Operated since 1996 (upgraded for T2K)
- Reconstruct vertex position, charged track direction and energy

SK PID capabilities





- Different shape of Cherenkov rings allow to clearly distinguish e-like rings from μ-like rings
- PID discrimination power > 99%



T2K oscillation analysis chain

Flux prediction:
- ✓ Proton beam stability
- ✓ Hadron production (NA61 and others external data)

ND280 measurements:
- ✓ ν_μ selection to constrain flux and cross-sections
- ✓ Measure ν_e beam component

Neutrino interactions:
- ✓ Interaction models
- ✓ External cross-section data

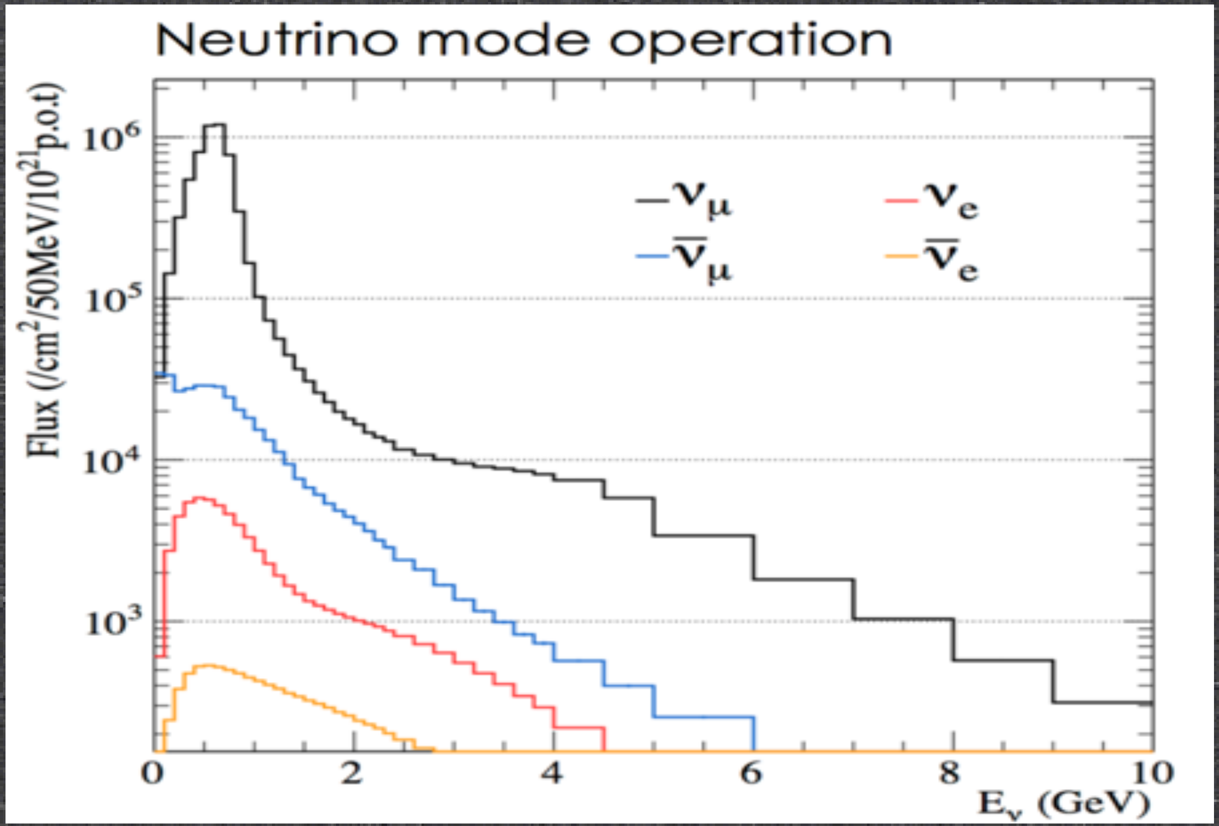
Prediction at the Far Detector:
- ✓ Combine flux, x-section and ND280 to predict the expected events at SK

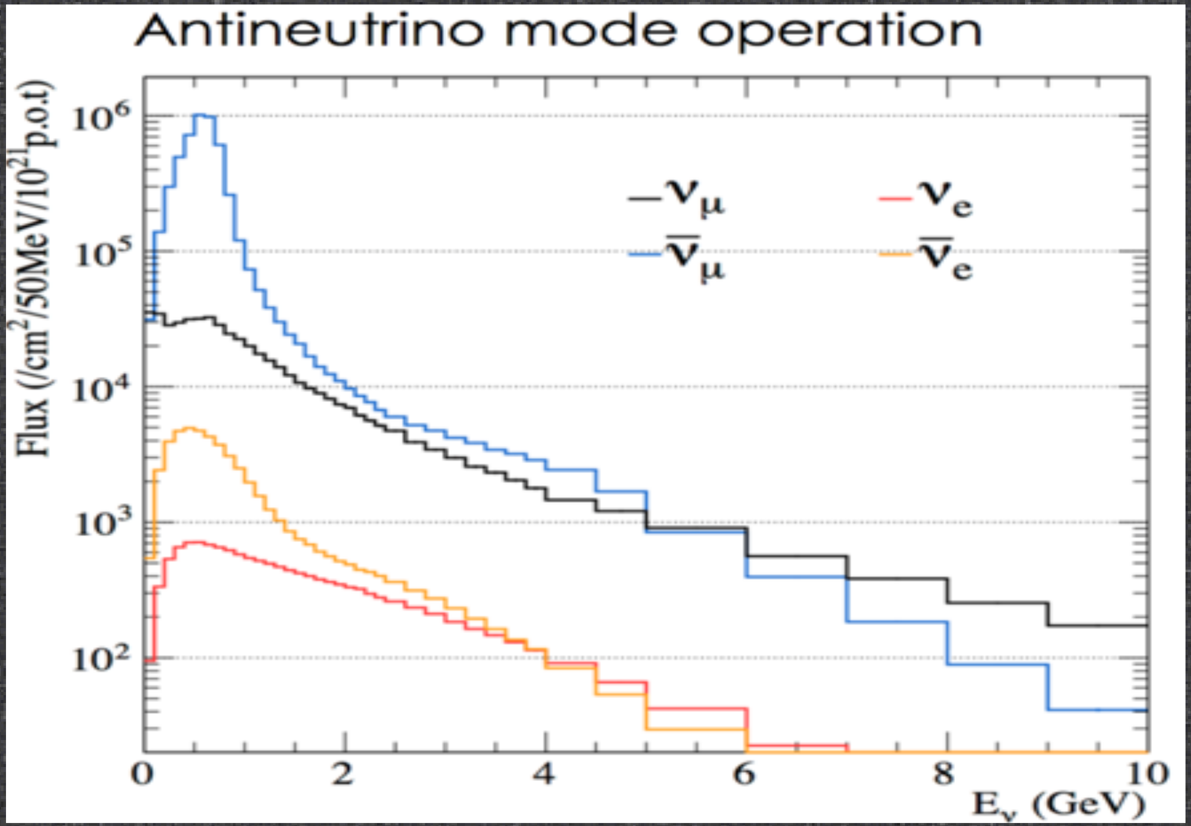
Extract oscillation parameters!!

Super-Kamiokande measurements:
- ✓ Select CC ν_μ and ν_e candidates after the oscillations

Flux prediction

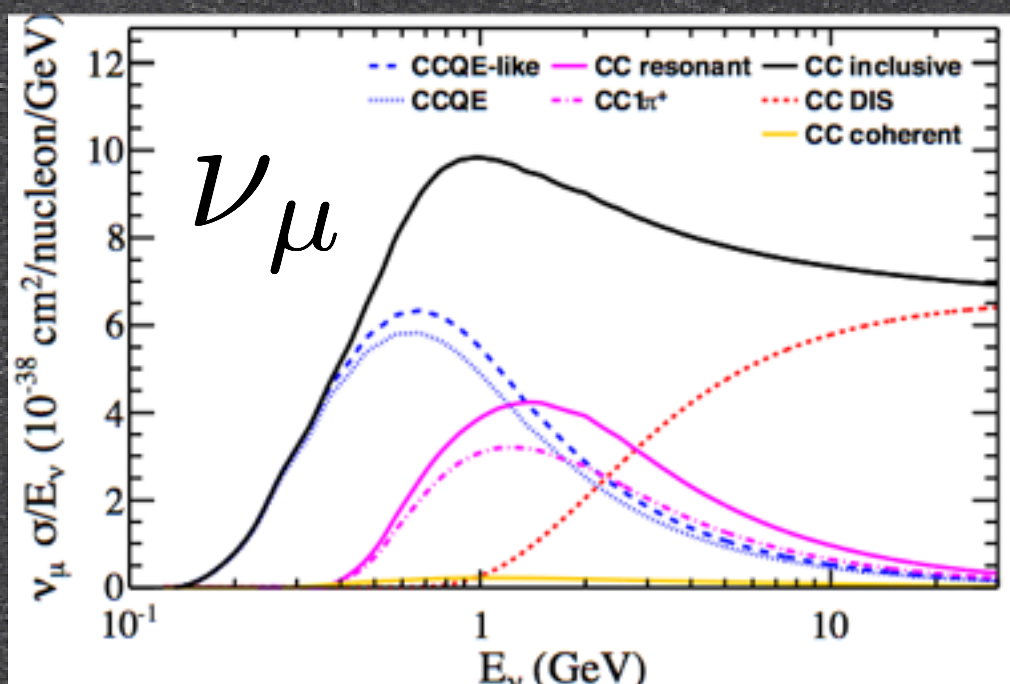
- In any long baseline experiment the main uncertainty on the flux prediction comes from the hadron production cross-section (in T2K case p+C→ π,K,..)
- T2K uses dedicated experiments at CERN (NA61) to predict fluxes in both, neutrino and antineutrino mode
- The uncertainties on the fluxes are at the 10% level when NA61 data are used

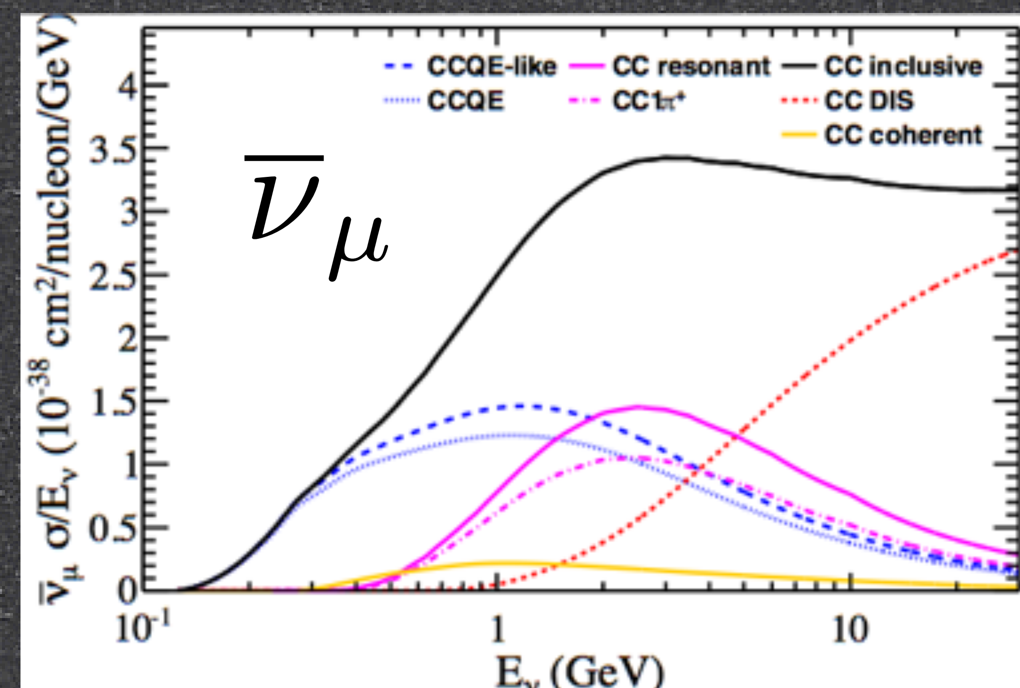




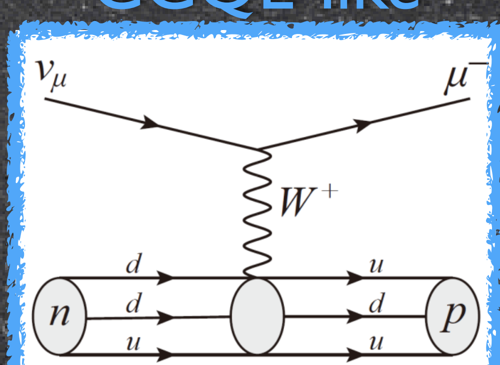
Cross-section model

- A lot of efforts done to include the most recent models in NEUT MC
- The Nieves 2p2h model has been now included in NEUT
- Fit to external data (MiniBooNE, Minerva) are used
- At T2K energies the ν and $\bar{\nu}$ cross-section differ of a factor of ~3

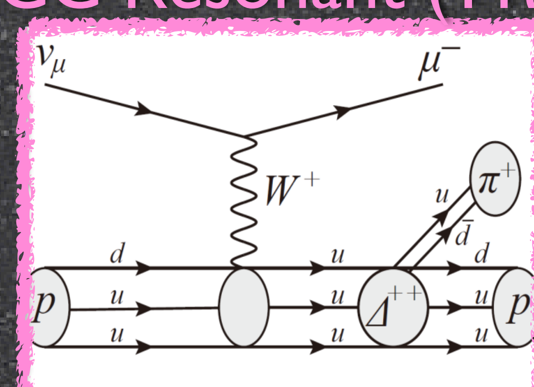




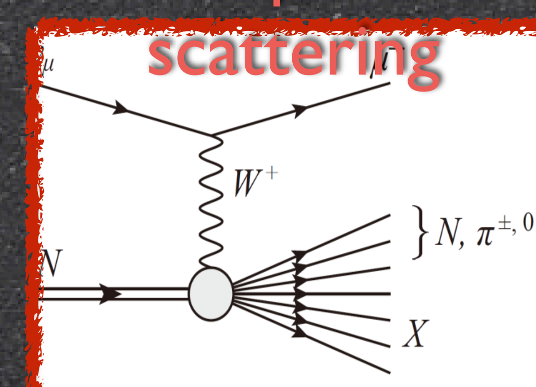
CCQE-like



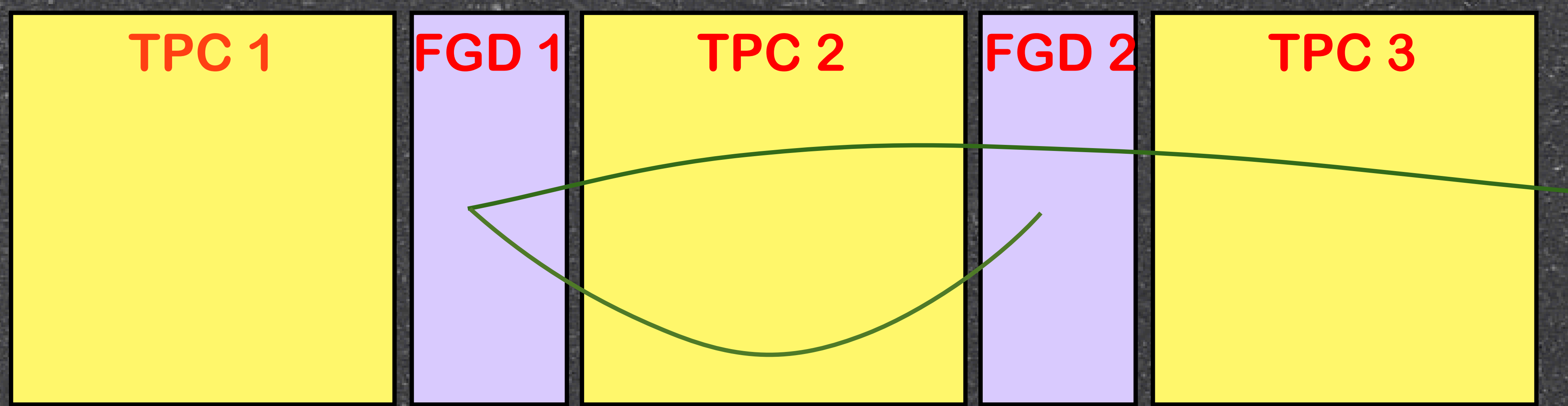
CC Resonant (1π)



CC Deep Inelastic scattering

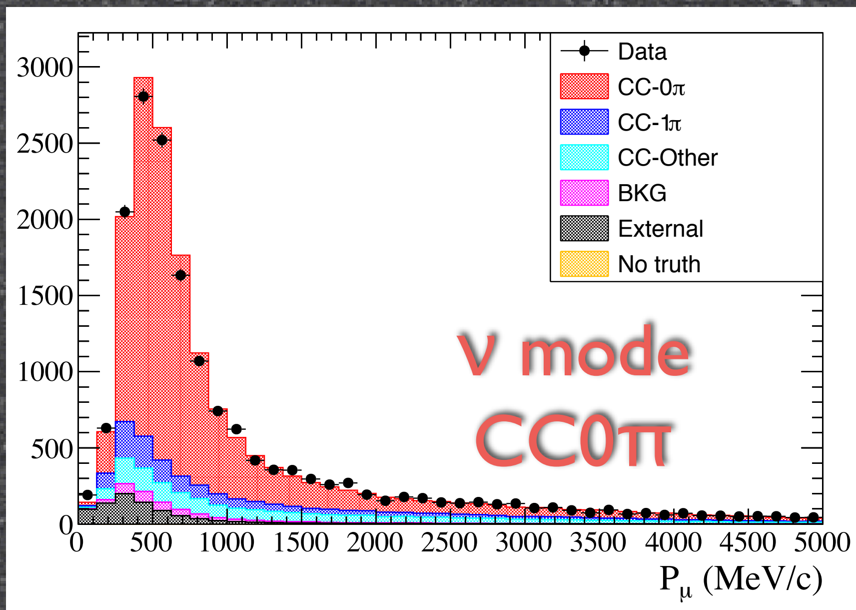


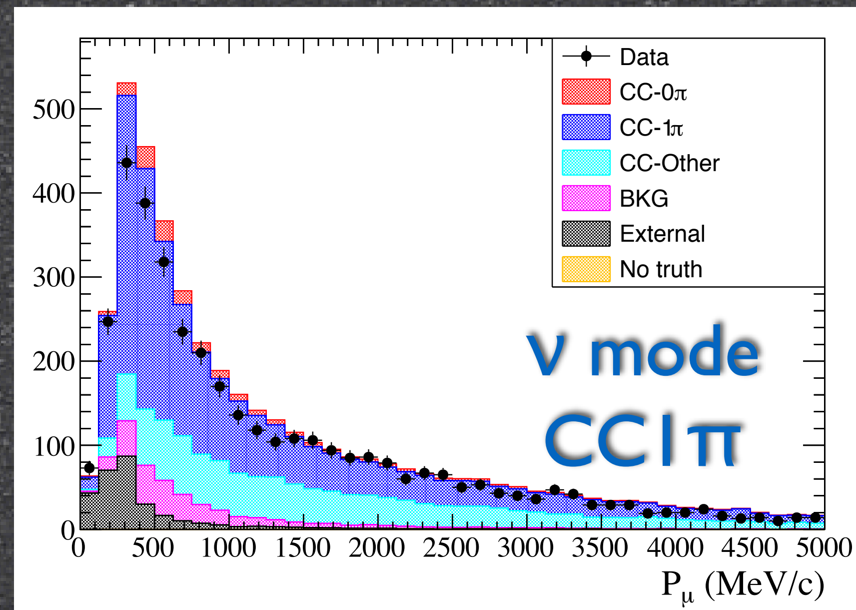
ND280 analyses

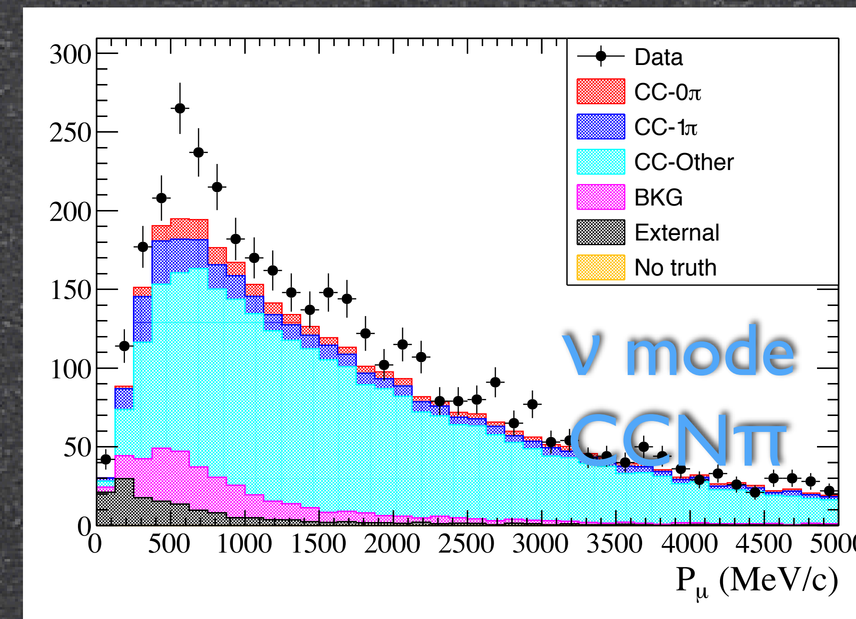


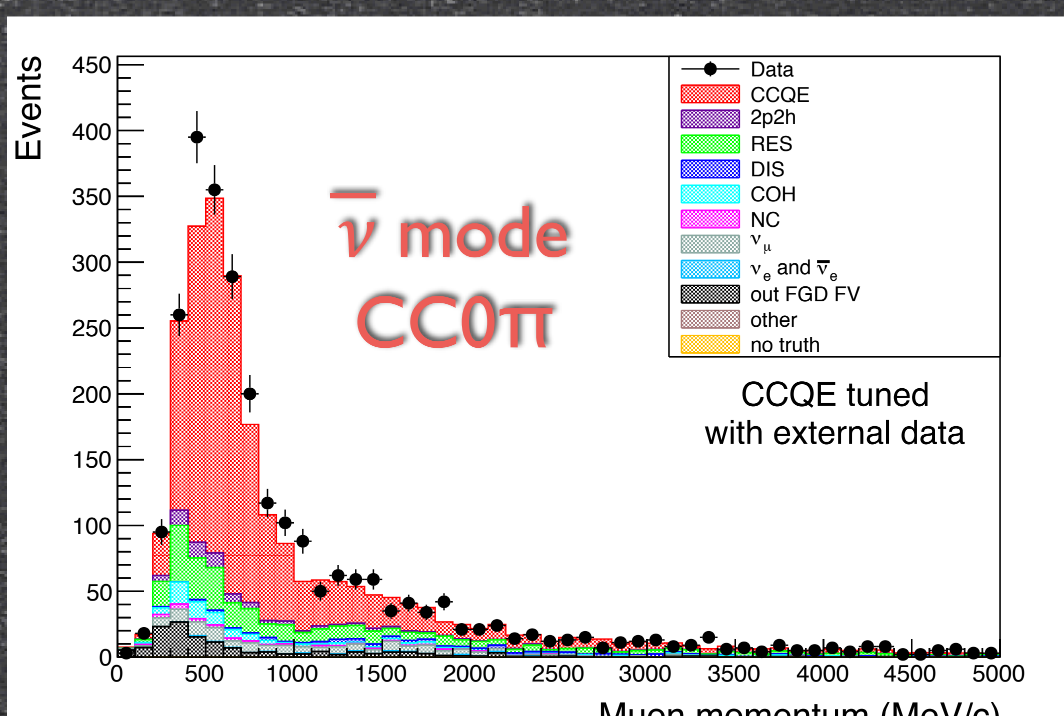
- The main use of ND280 is to constrain flux and cross-section uncertainties in the T2K oscillation analyses
- Neutrino interactions are selected in the FGD and the charged particles produced are tracked in the TPC
- The most energetic forward going negative track is selected as the lepton candidate
  - Positive track if we are taking data in $\overline{\nu}$ mode
- The inclusive sample is sub-divided according to the number of observed pions (0π, 1π, $N\pi$)

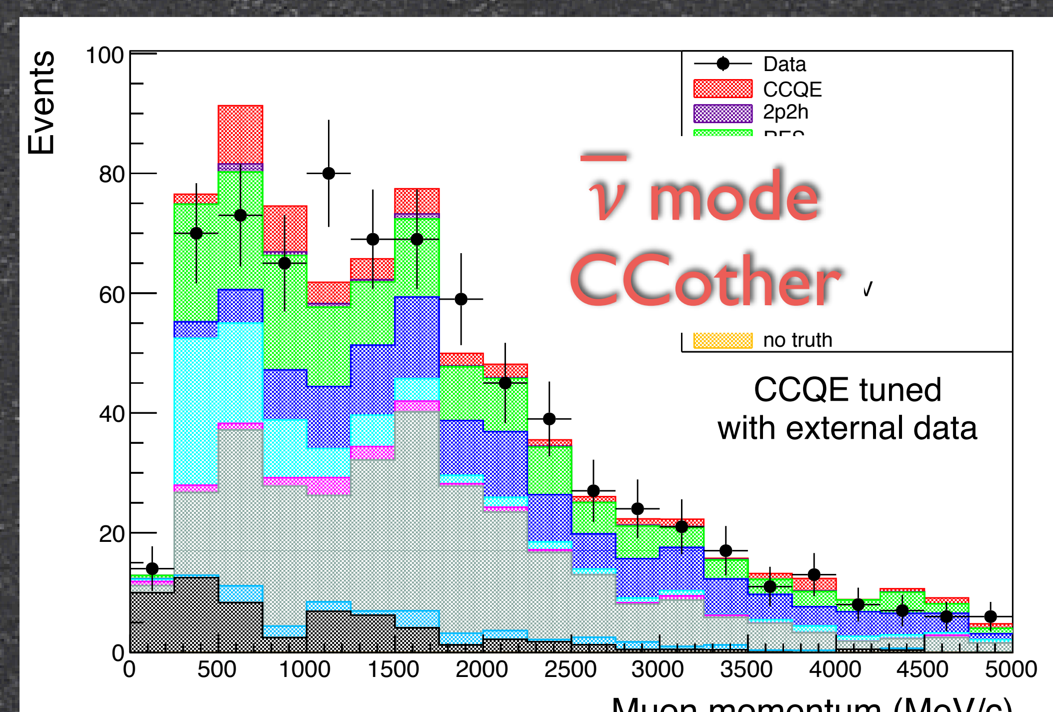
ND280 ν_μ analyses



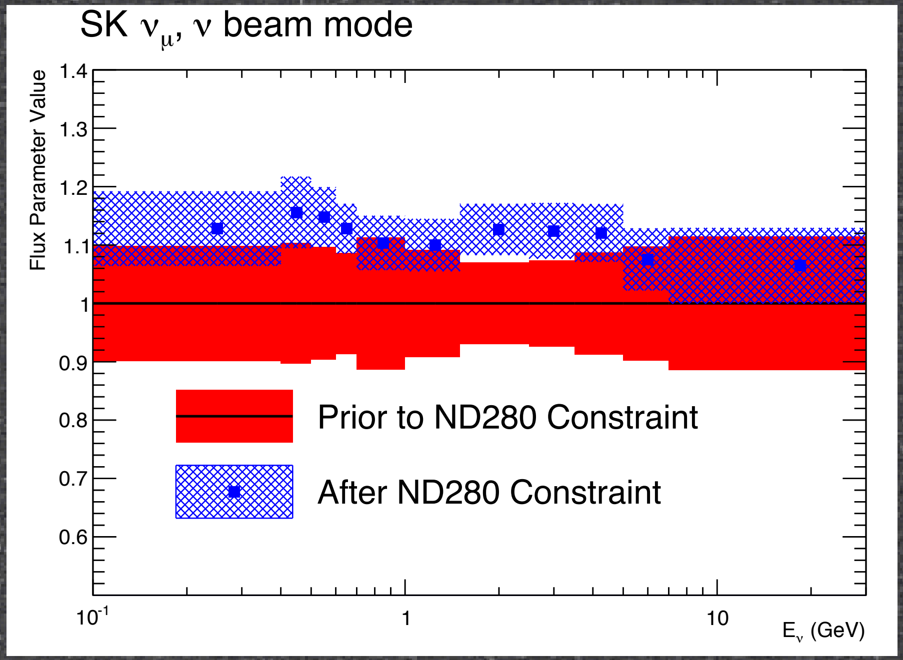


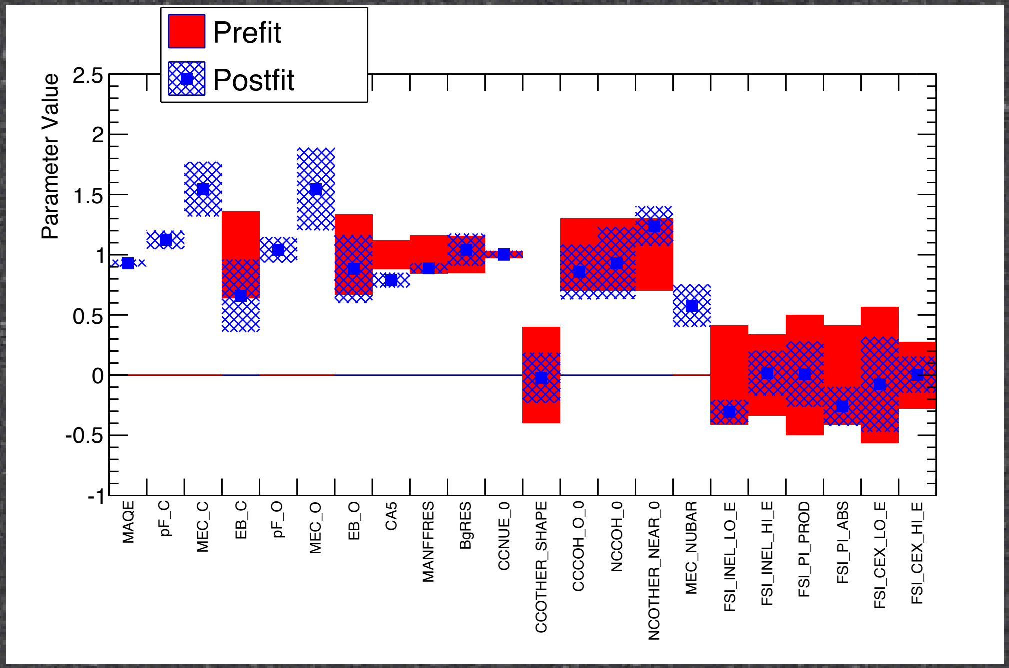






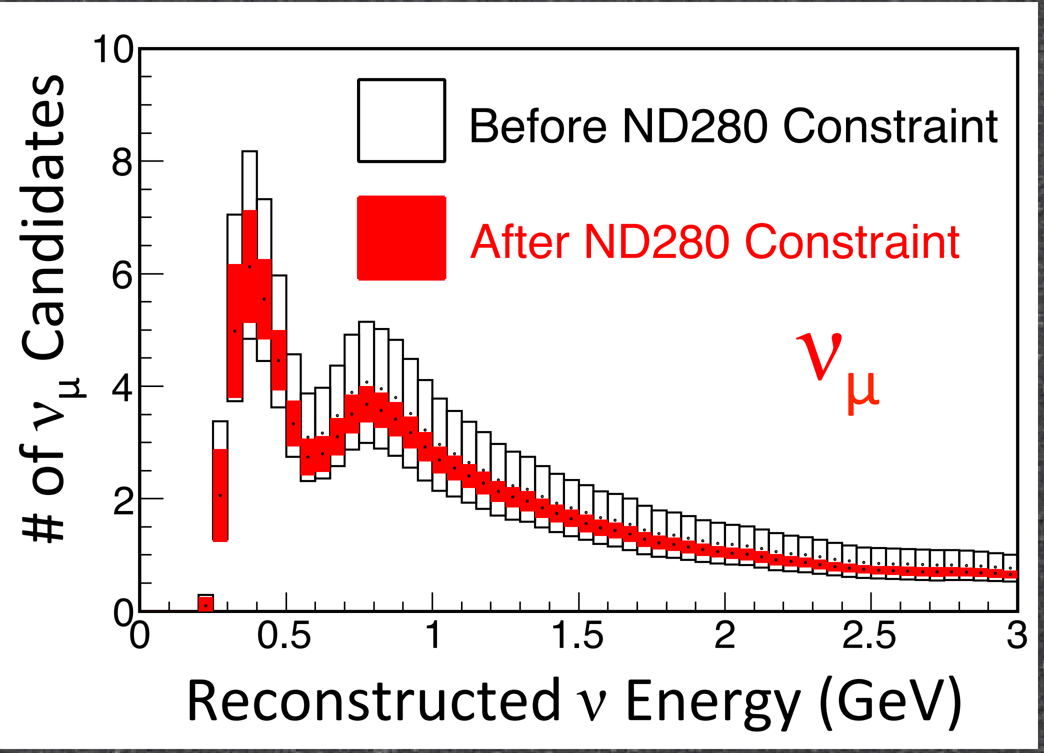
Systematic reduction

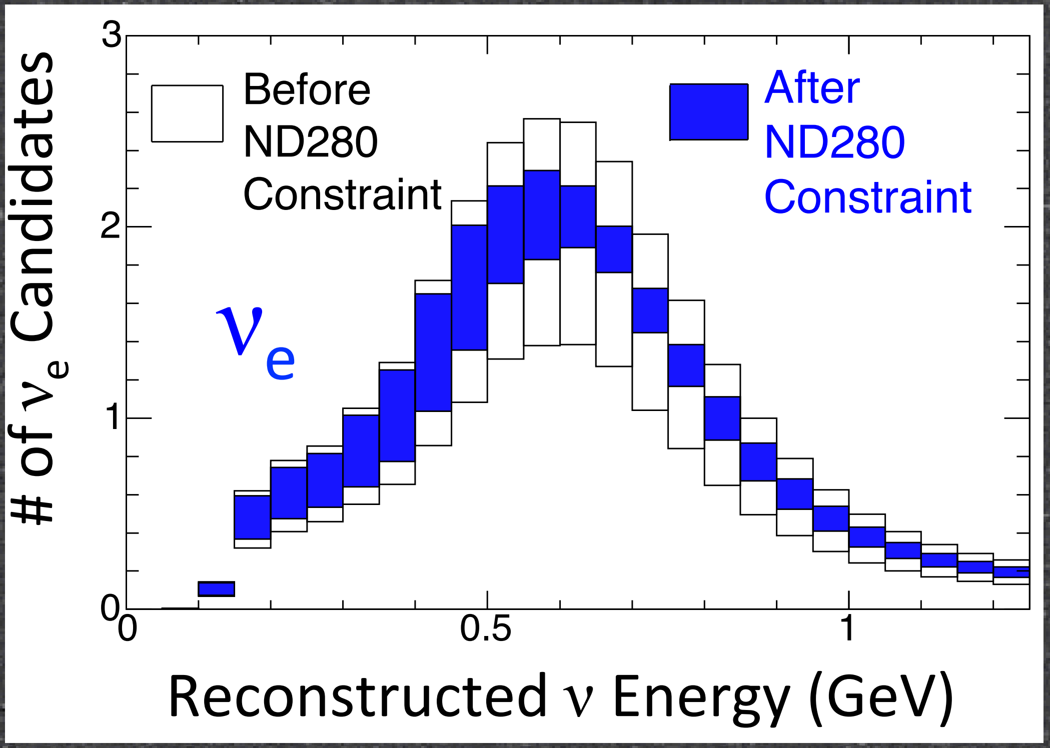




- The flux and cross-section models is fit using the ND280 data (CC0π, CC1π, CCNπ in ν-mode for both FGDs, CC0π and CCOther in $\overline{\nu}$ mode for both FGDs)
- This allow to greatly reduce the uncertainty in T2K oscillation analysis
  - From ~13% to ~6%, the dominant systematics being SK detector systematics

Systematic uncertainties at SK

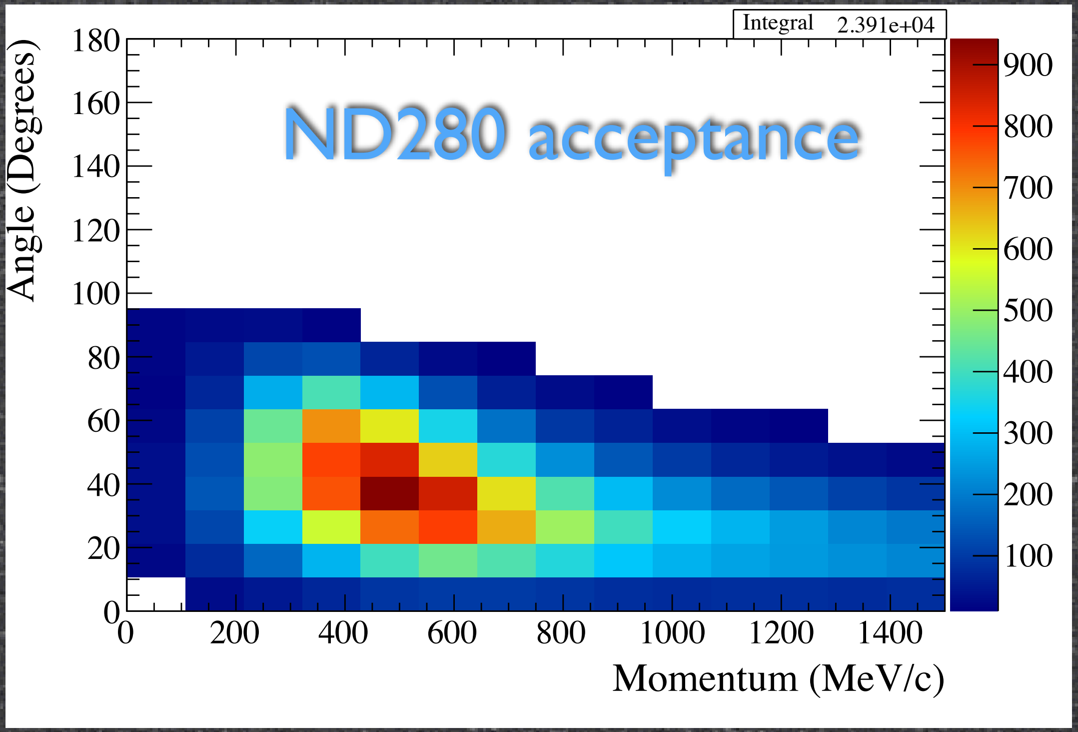


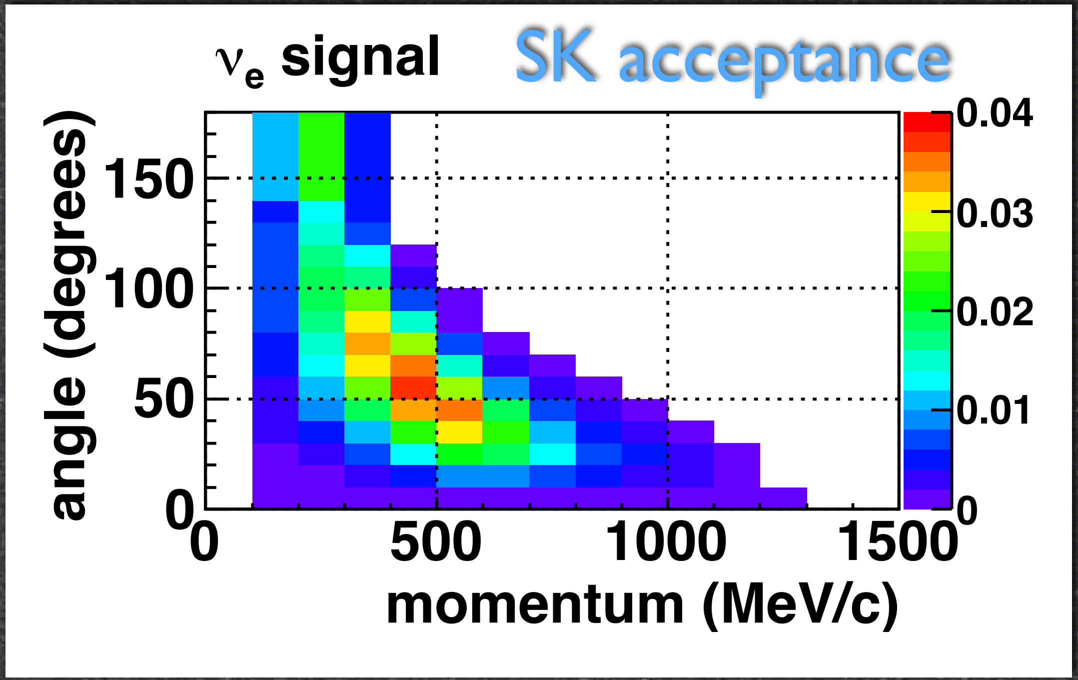


	$\delta_{N_{SK}}/N_{SK}$ (%)				
	1-Ring μ		1-Ring e		
Error Type	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	$\nu/\bar{\nu}$
SK Detector	4.6	3.9	2.8	4.0	1.9
SK Final State & Secondary Interactions	1.8	2.4	2.6	2.7	3.7
ND280 Constrained Flux & Cross-section	2.6	3.0	3.0	3.5	2.4
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.0	0.0	2.6	1.5	3.1
NC 1γ Cross-section	0.0	0.0	1.4	2.7	1.2
NC Other Cross-section	0.7	0.7	0.2	0.3	0.1
Total Systematic Error	5.6	5.5	5.7	6.8	5.9

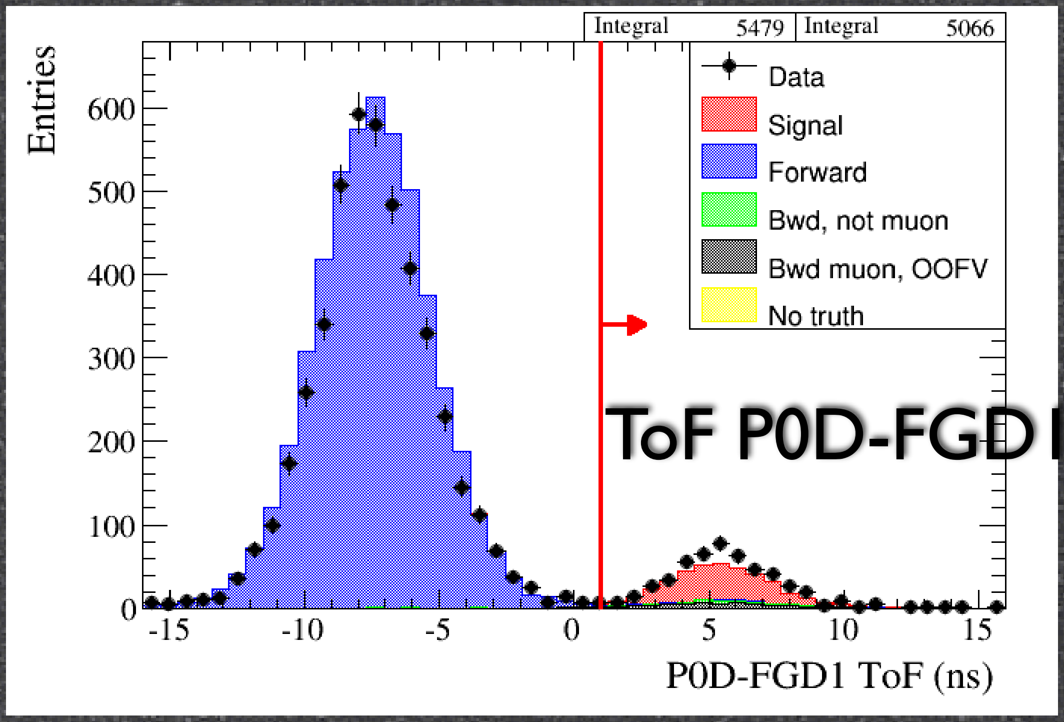
Angular acceptance

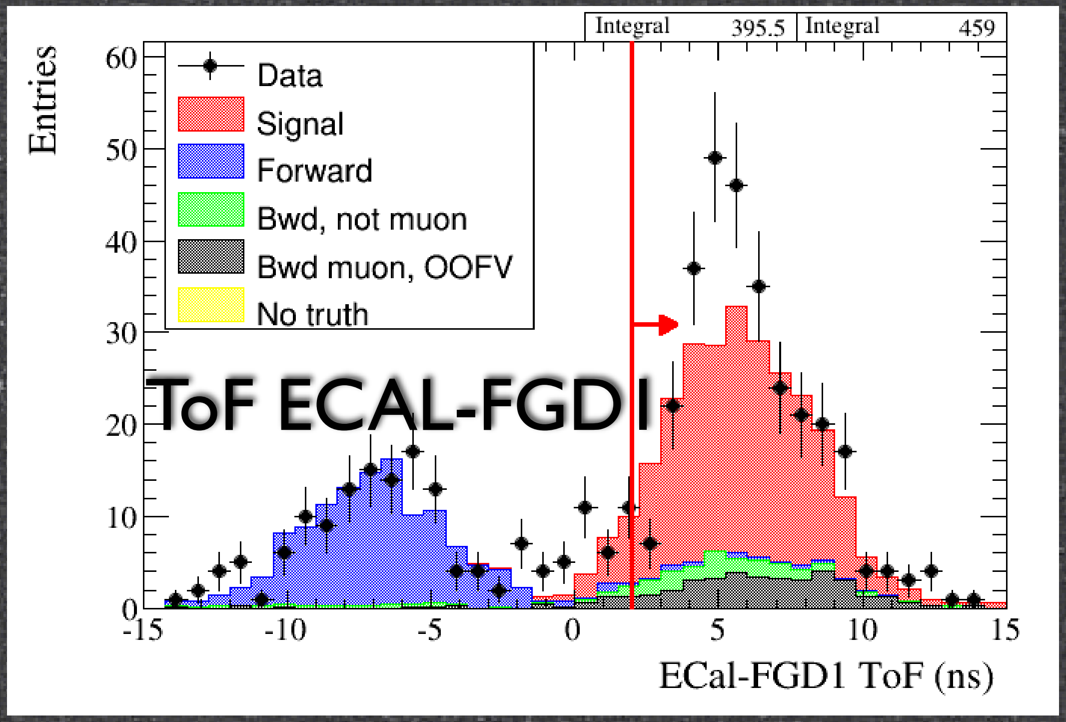
- One of the main limitation of current ND280 analyses is that it only select forward-going muons
- In SK the acceptance is flat with respect to the lepton angle and events with backward leptons are also selected
- Currently we constraint the models in the forward region and we let the model constraint the backward region → model dependent
- We developed a selection in ND280 to select backward tracks using the Time Of Flight between different ND280 detectors



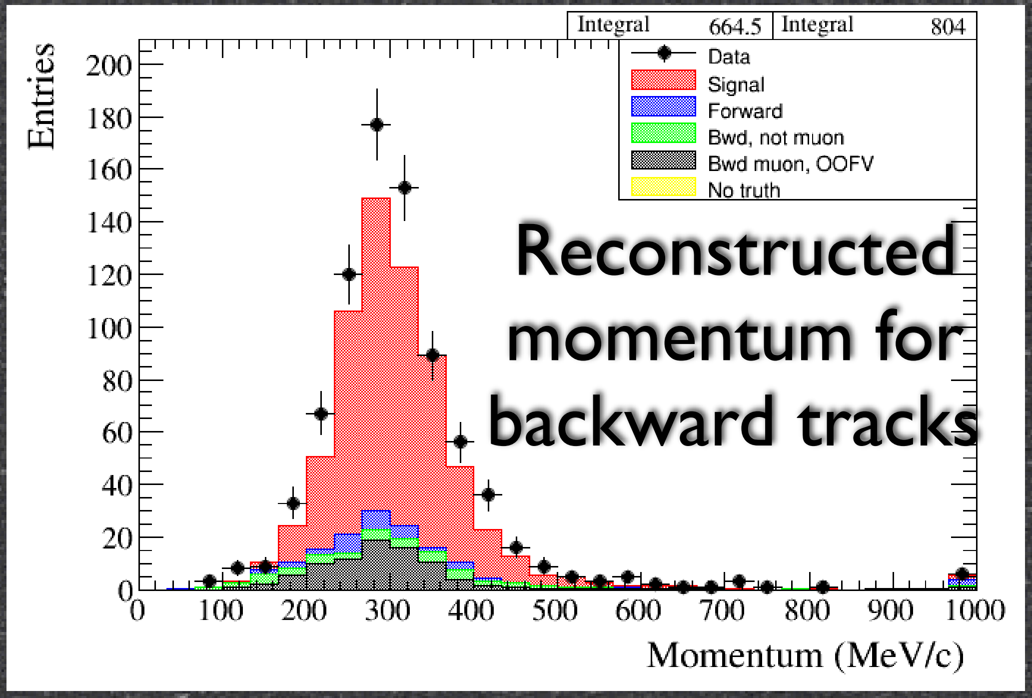


Time Of Flight cuts



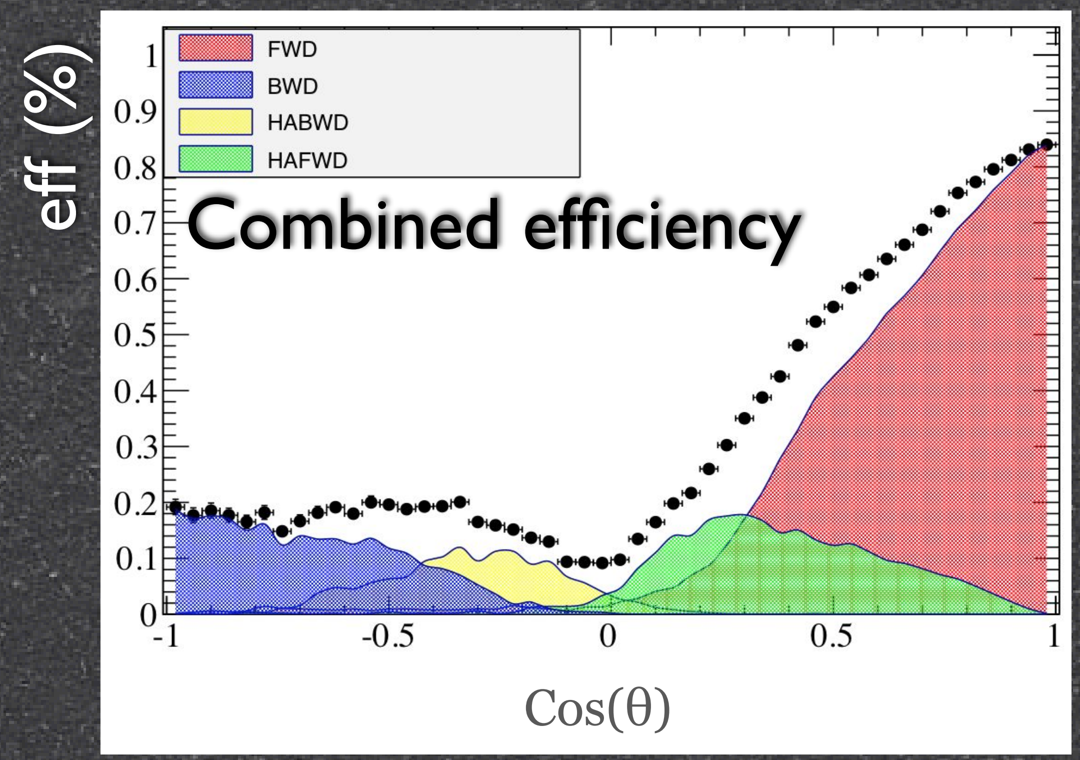


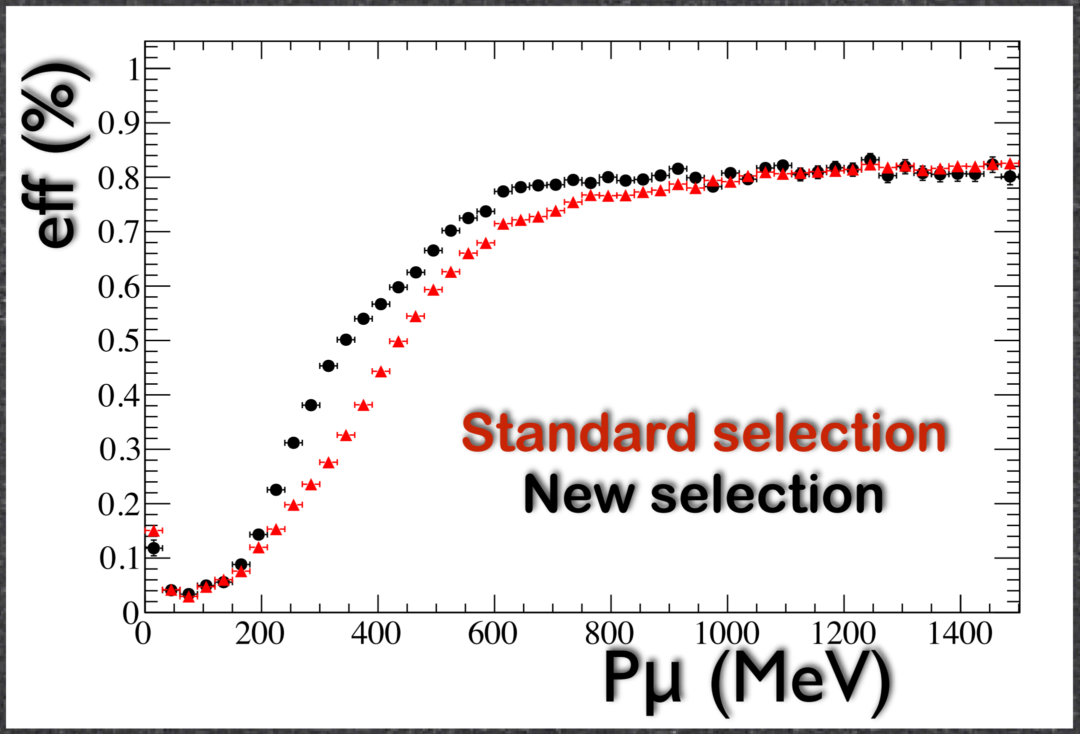
- Use TOF between detector to distinguish FGD interactions with backward going tracks from the dominant background of forward going tracks entering the FGD
- This select a clean sample of muons with low momenta (~300 MeV) due to the high momentum transfer to the nucleon

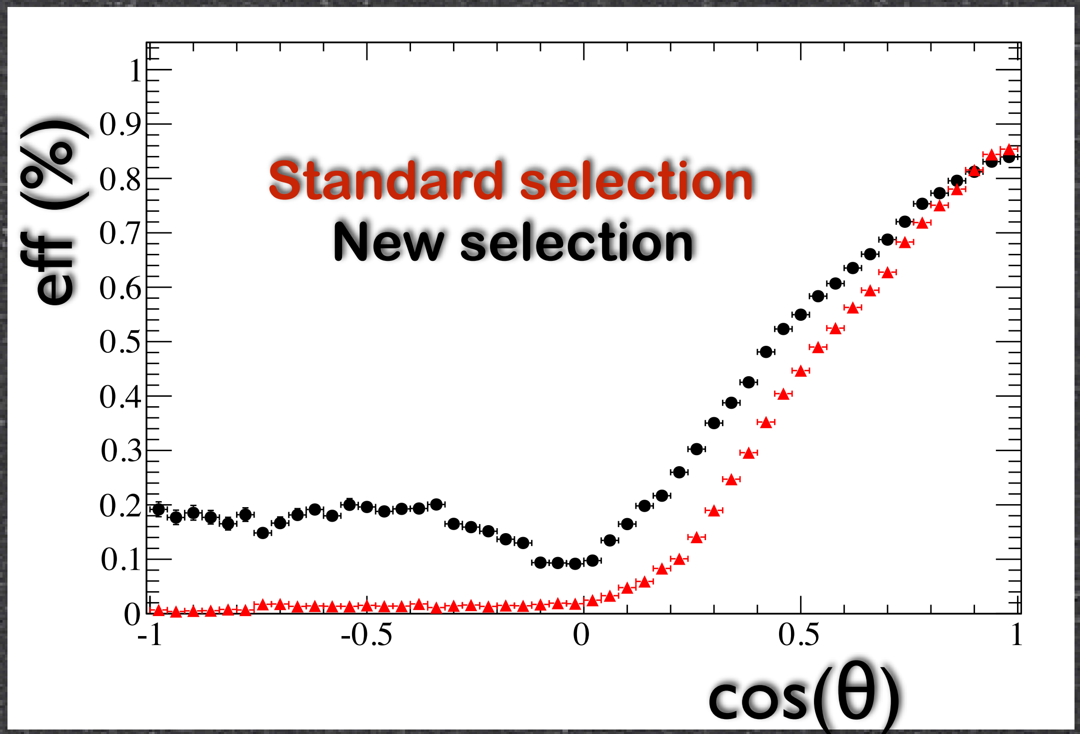


Increased angular acceptance

- Including this selection allow to increase the low momentum, high angle efficiency
- This selection will be included in the next round of T2K oscillation analyses
- Also being used to measure neutrino cross-sections → Pierre thesis

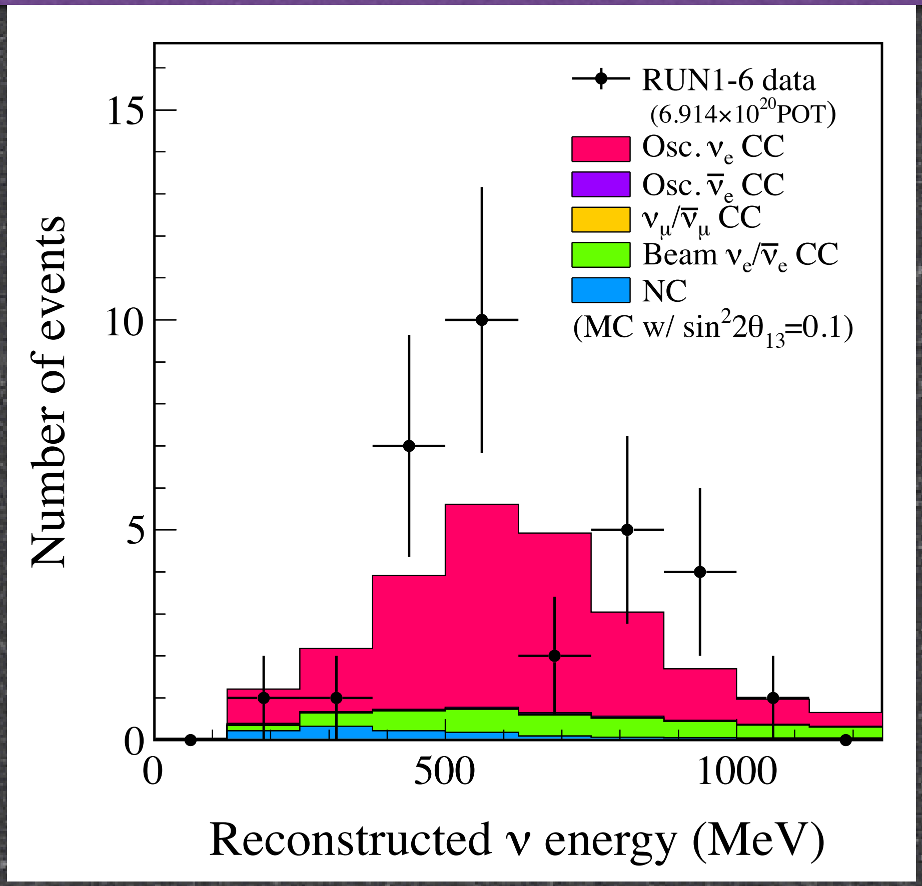


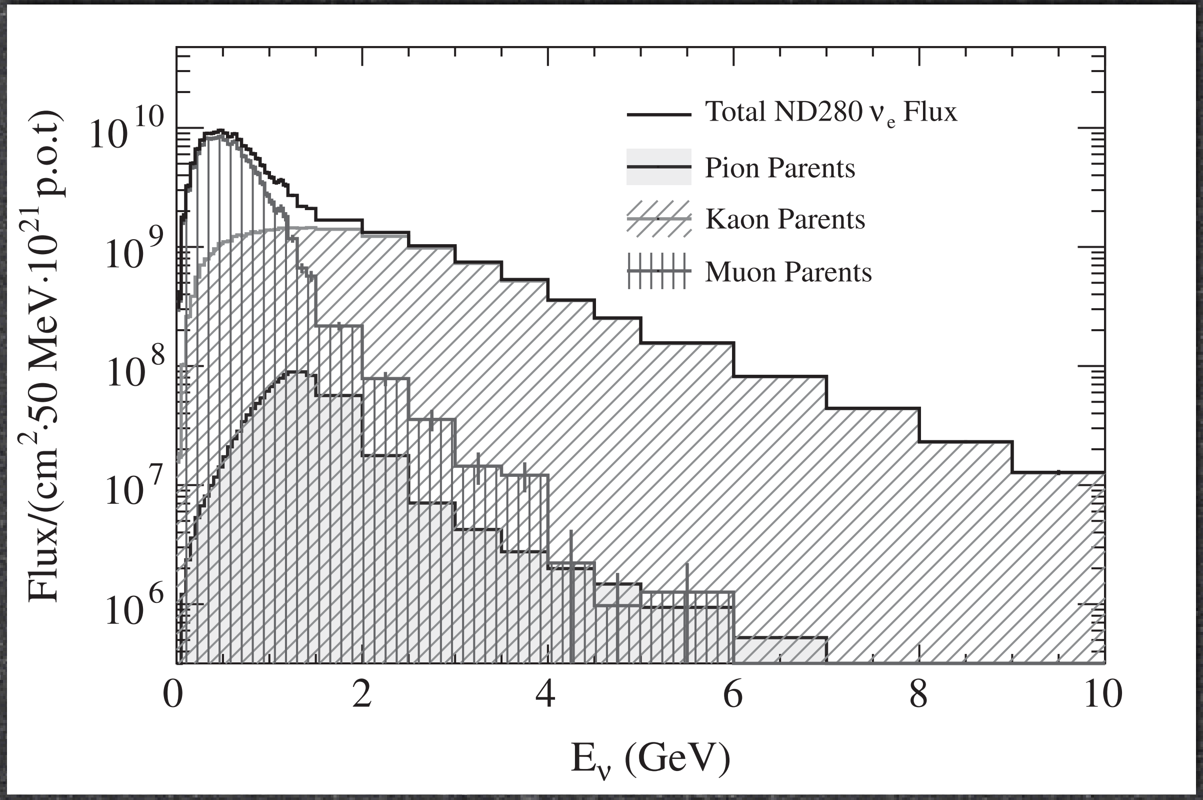




ND280 ν_e analyses

- The main background to the appearance signal at SK is due to the **intrinsic ν_e component** in the beam
- This is an unavoidable background in any neutrino beam (~1% of the total flux) where ν_e are mainly produced from μ or K decays

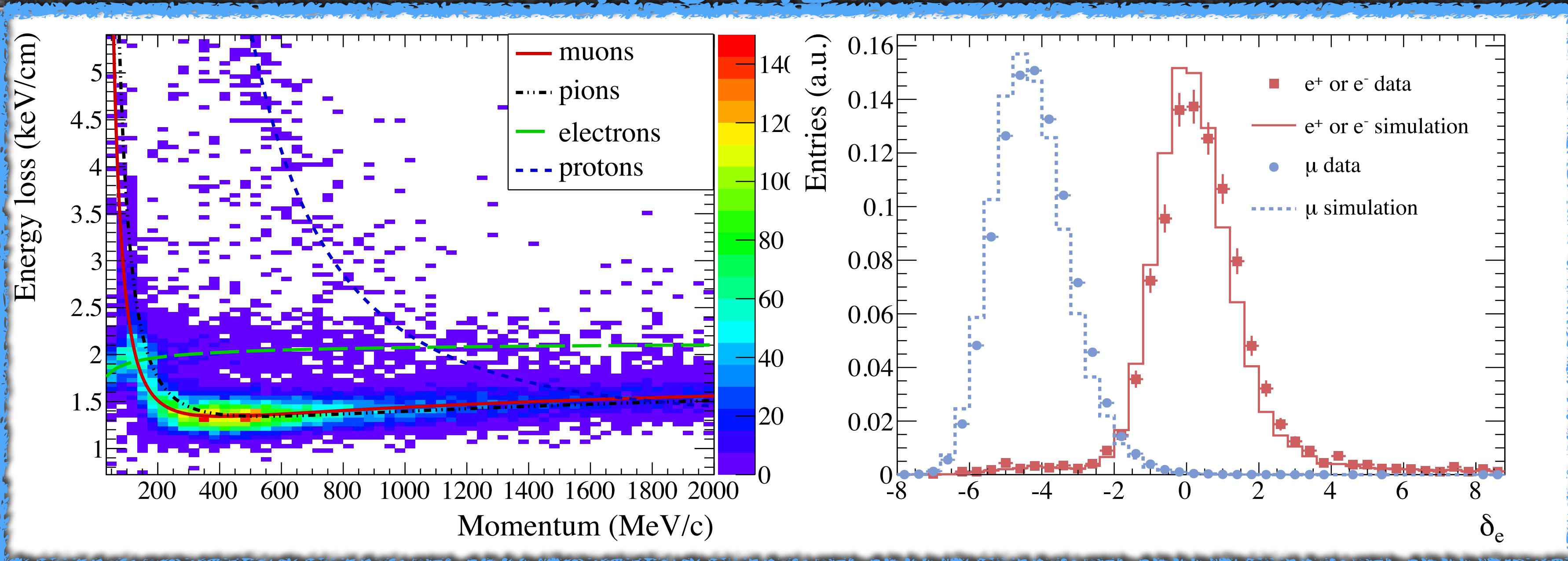


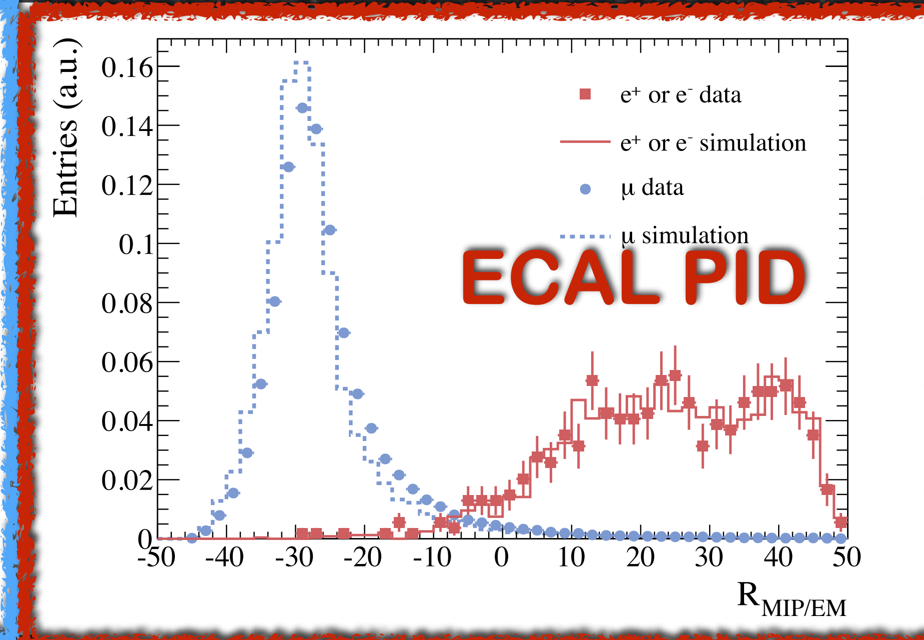


- We measured this component, before oscillations, using the Particle Identification capabilities of ND280 tracker
- The selected sample is also used to measure electron neutrino cross-section and to do sterile searches

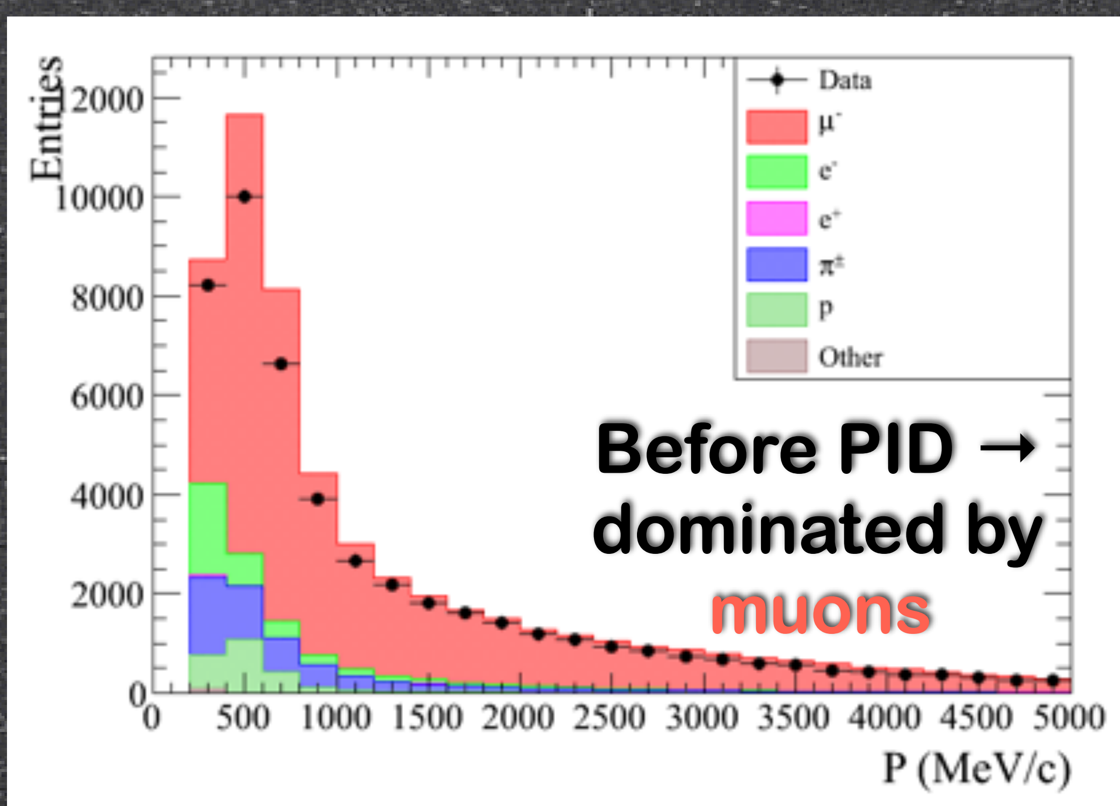
Particle Identification in ND280

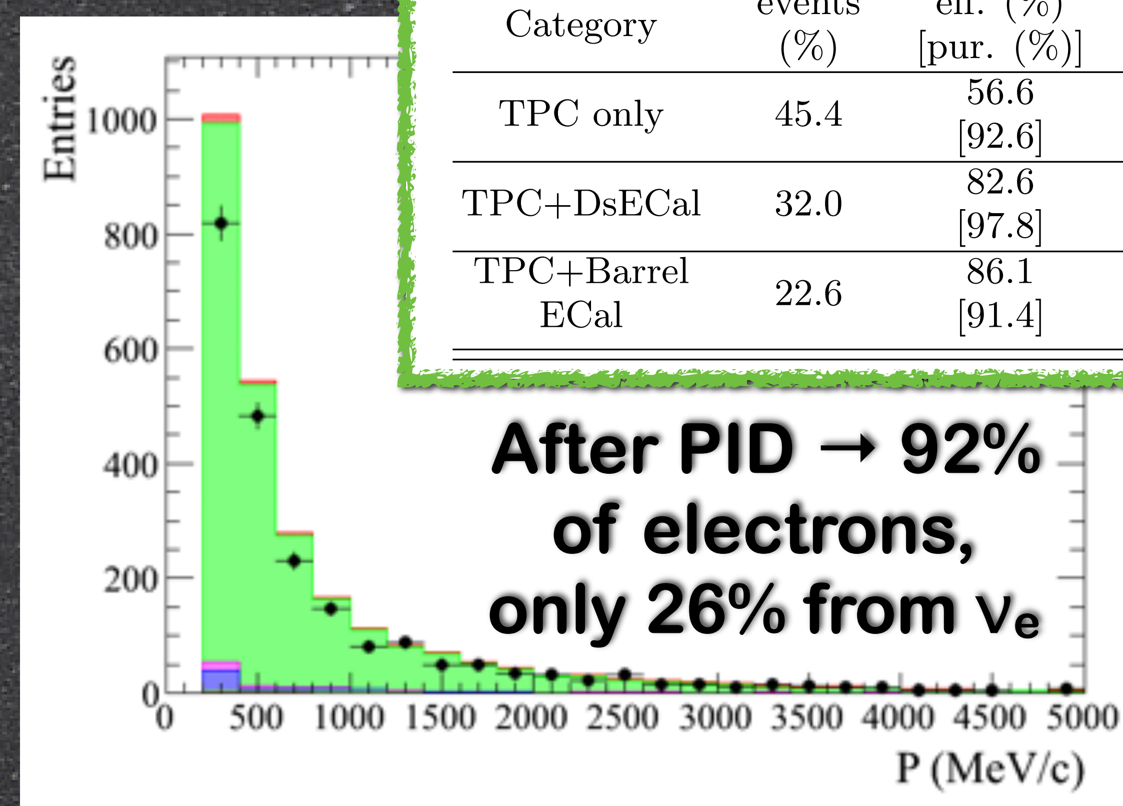
TPC PID



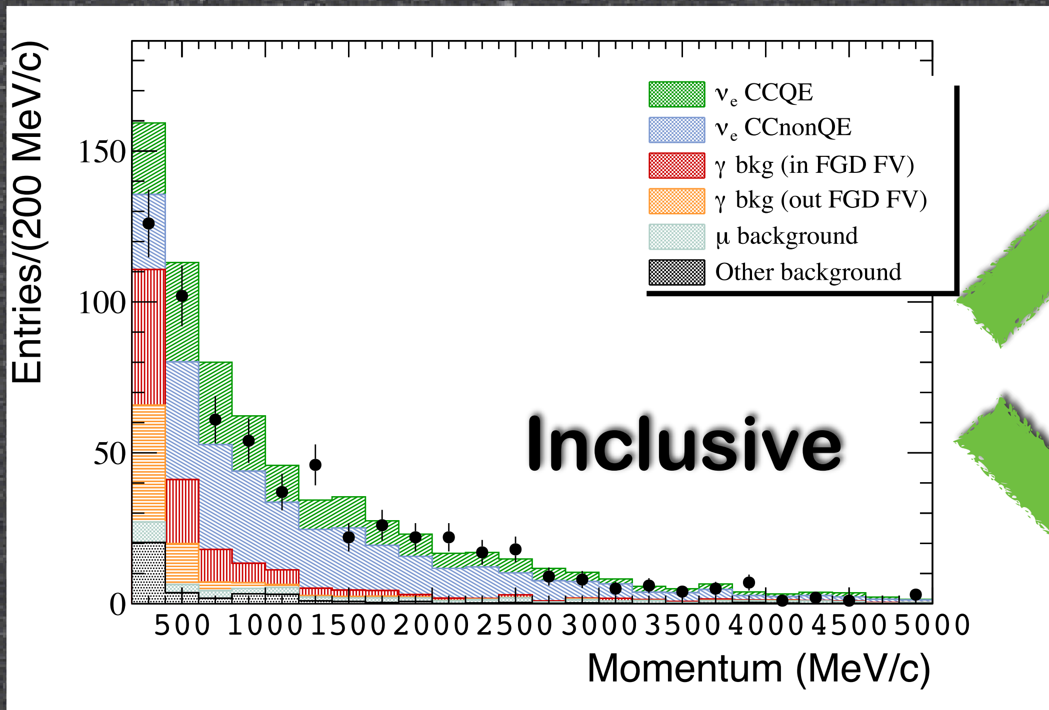


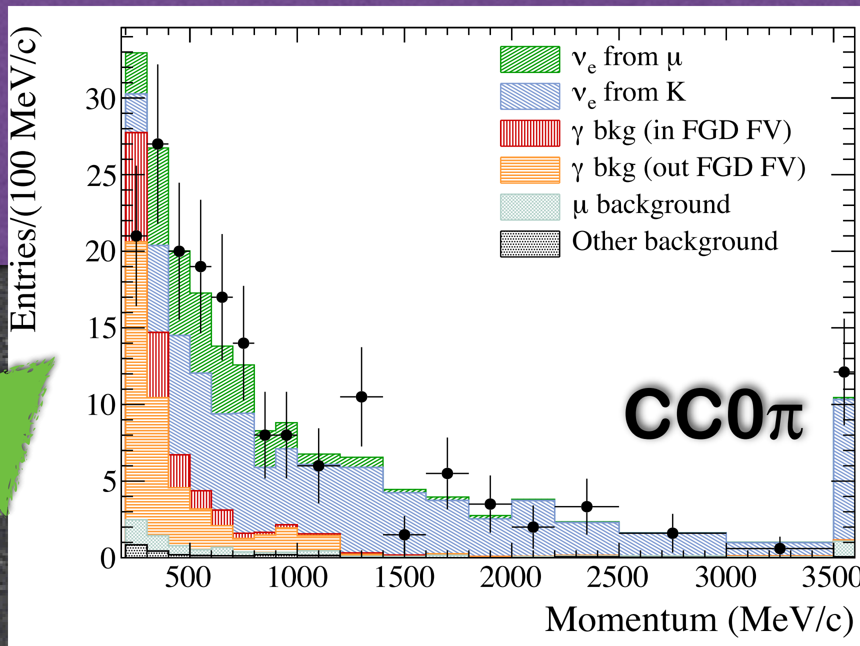
Category	FGD1 vertices events (%)	FGD1 vertices eff. (%) [pur. (%)]	FGD2 vertices events (%)	FGD2 vertices eff. (%) [pur. (%)]
TPC only	45.4	56.6 [92.6]	34.1	53.1 [90.9]
TPC+DsECal	32.0	82.6 [97.8]	59.0	89.1 [93.8]
TPC+Barrel ECal	22.6	86.1 [91.4]	6.9	88.6 [86.5]

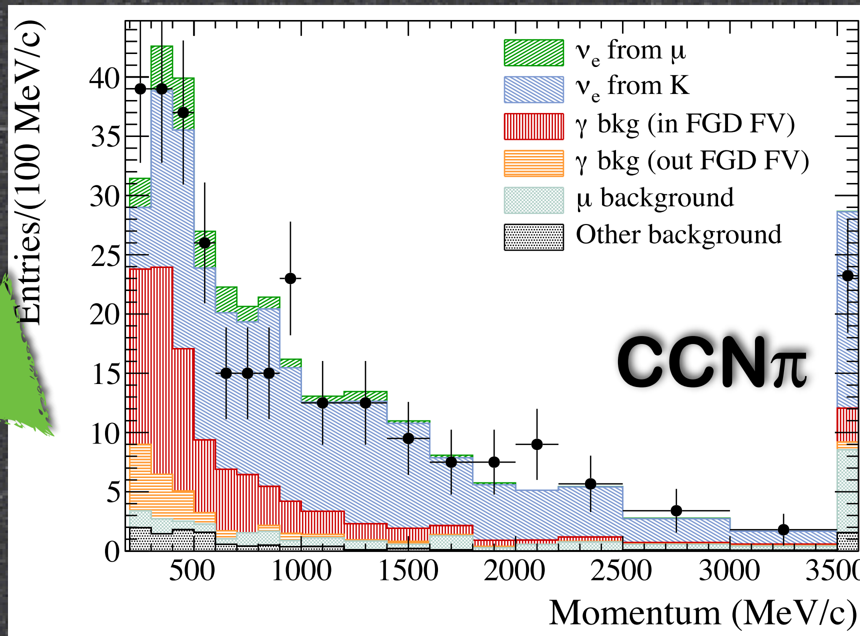




CC ν_e selection

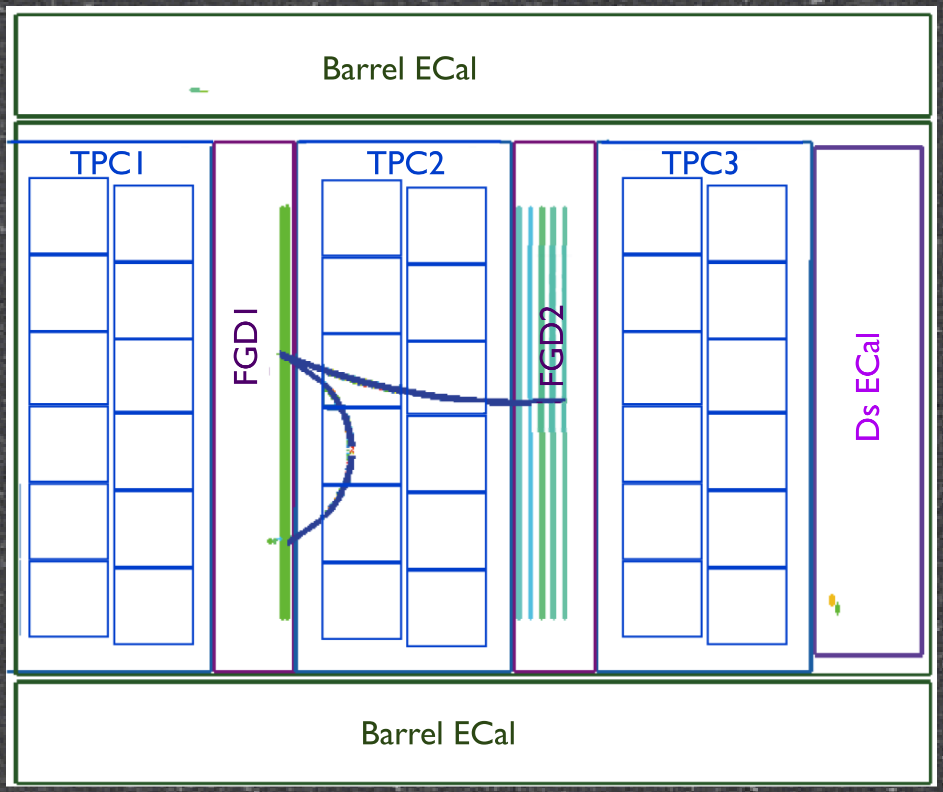


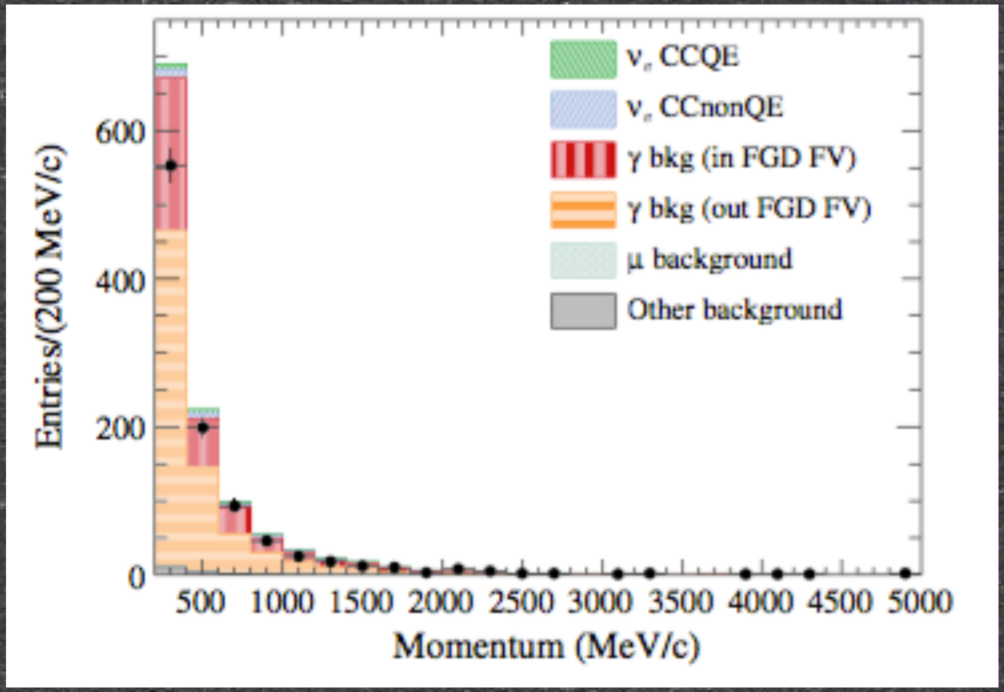




- Additional vetoes cut allow to increase the ν_e purity to ~65%
- The sample is then divided into 1 Track (mostly CCQE) and N track (CCnonQE) subsamples
- The remaining background is still mainly composed by γ conversions → develop a control sample in which we select γ conversions

Control samples



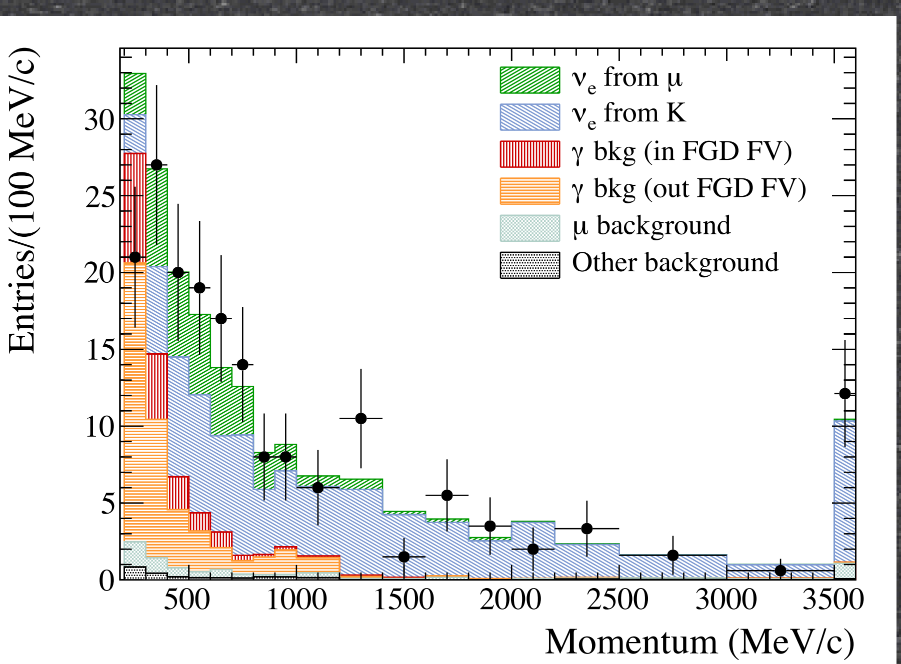


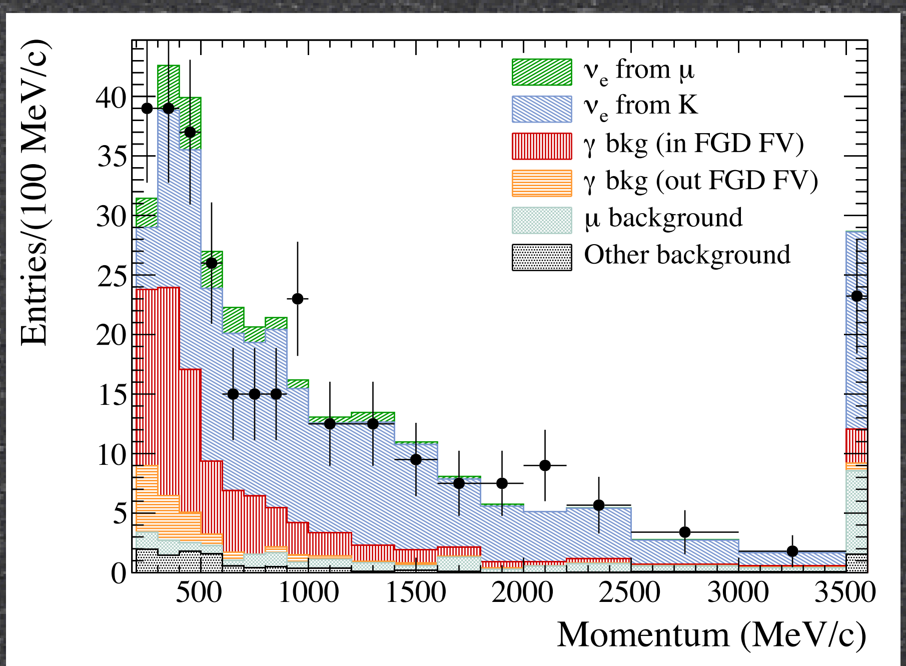
- Most of the background comes from γ conversions producing an electron in the TPC → additional vetoes cut → ν_e purity ~65%
- $\gamma \to e^+e^-$ sample is used to constrain the background in the fit (particularly the background coming from outside the FGDs
  - The control sample is particularly helpful to constrain the low energy deficit that we observe in the ν_e sample

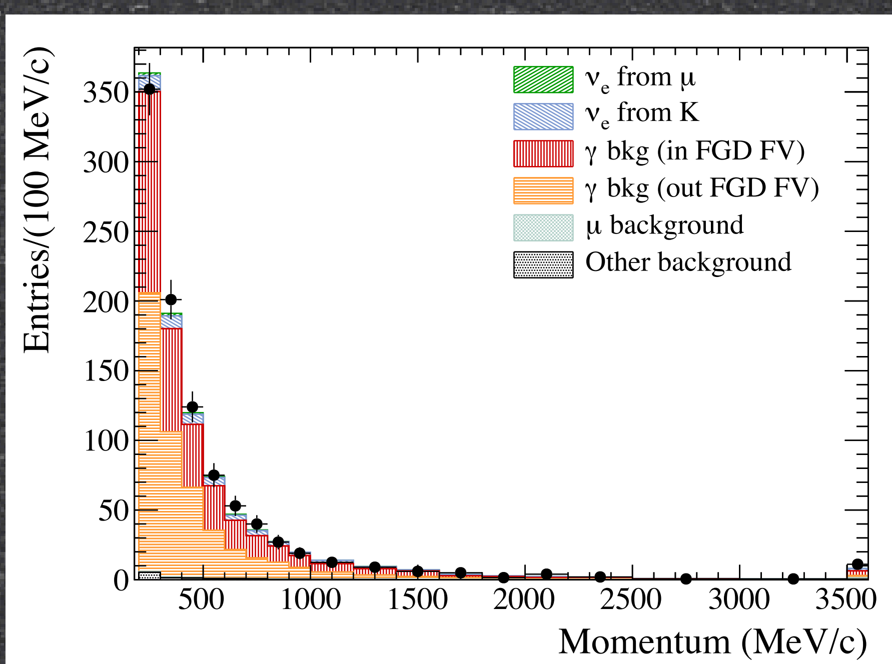
Measurement of beam ν_e component

- Likelihood fit to extract the beam νe component
  - Control sample is used to constraint the background → able to recover the low energy deficit of data
- Inclusive beam ν_e component
  - $R(\nu_e)$ = 1.01 ± 0.06 (stat.) ± 0.06 (flux + x-sec) ± 0.05 (detector) → 1.01 ± 0.10
- Separate ν_e from μ and from K decays
  - $R(\nu_e \text{ from } \mu) = 0.68 \pm 0.30$
  - $R(\nu_e \text{ from } K) = 1.10 \pm 0.14$

Phys. Rev. D 89, 092003



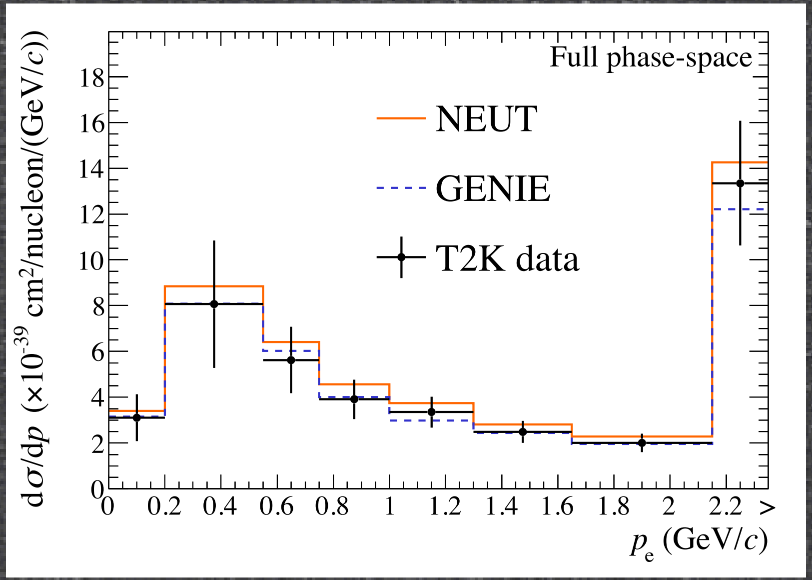




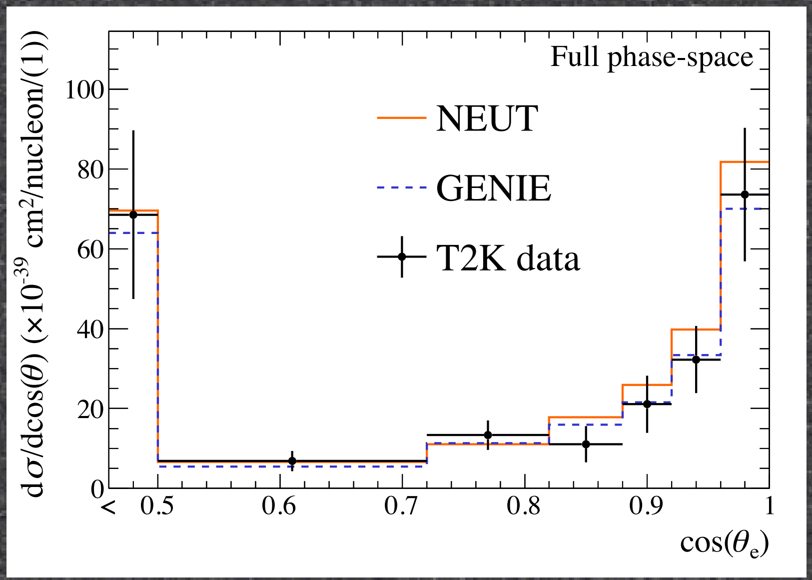
CC ν_e inclusive cross-section

Phys. Rev. Lett. 113, 241803

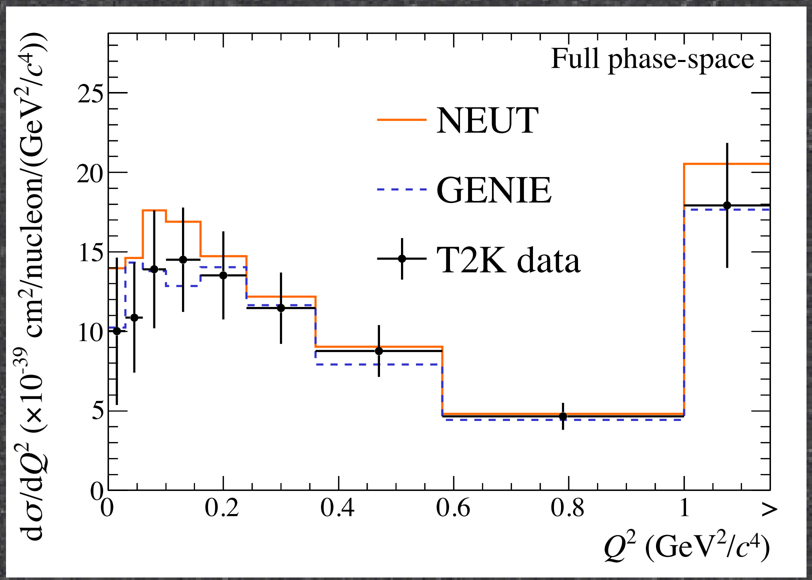
$d\sigma/dp$



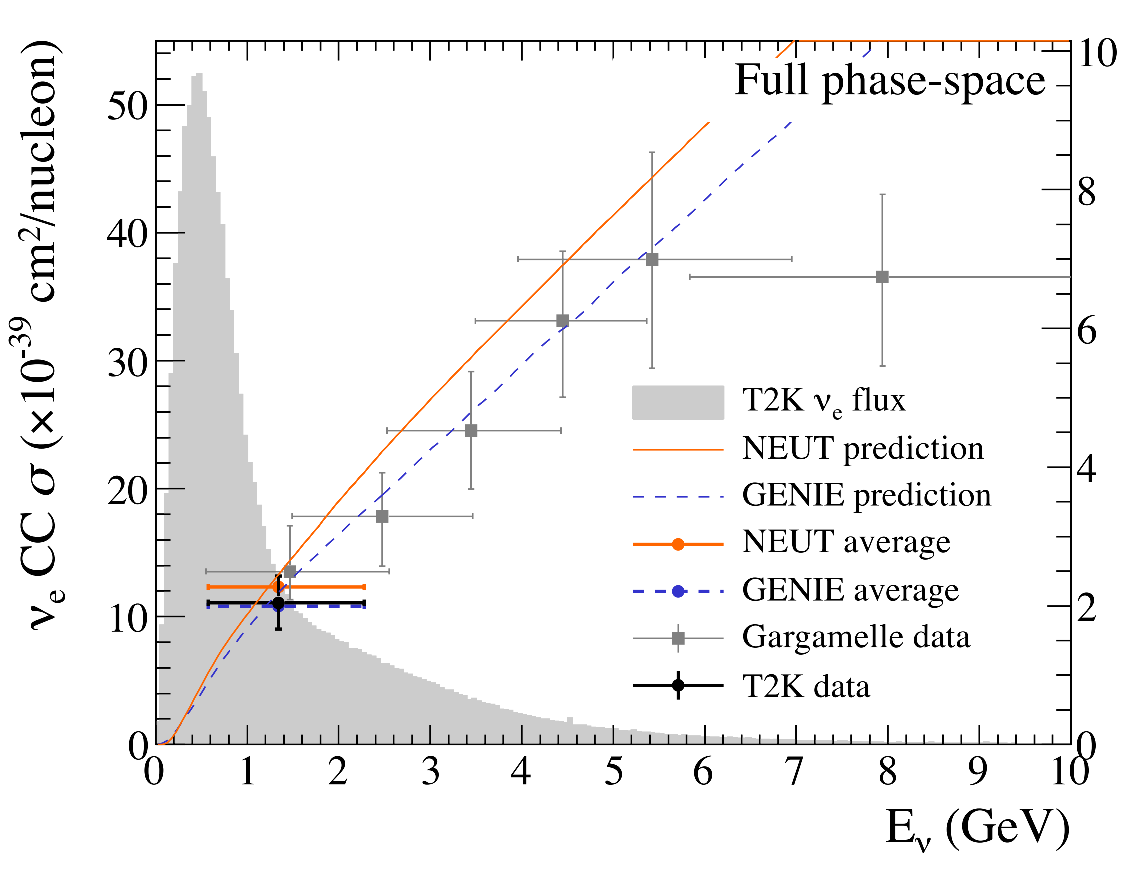
$d\sigma/d(\cos\theta)$



$d\sigma/dQ^2$



- First measurement of ν_e cross-section since Gargamelle (1978)
- Bayesian unfolding method is used to extract cross-section
  - Background is subtracted using the γ control sample
- Good agreement between data and MC (both GENIE and NEUT)



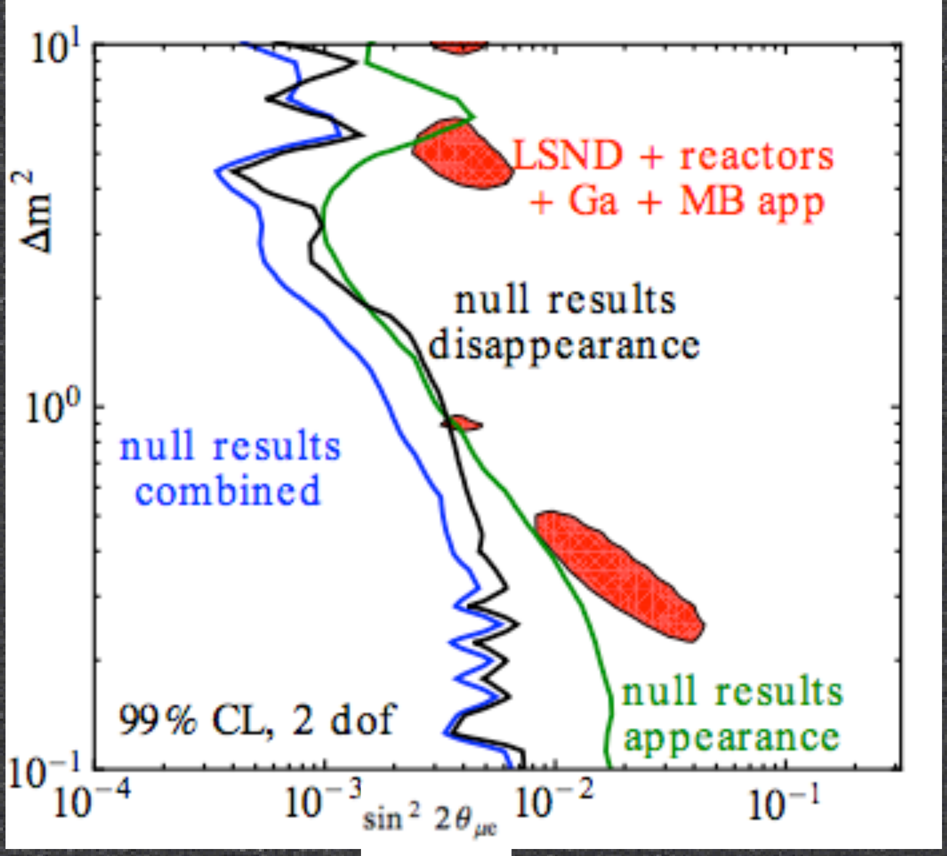
Search for sterile neutrinos

- Several "anomalies" exist in the neutrino sector
  - ν_e appearance ($P_{\mu e}$) → LSND, MiniBooNE
  - ν_e disappearance (P_{ee}) → reactor and gallium anomalies
  - No sign of ν_μ disappearance ($P_{\mu\mu}$)→ limits from several experiments at short baseline
  - All the three channels are related:
    - $2P_{\mu e} \sim (1-P_{ee})(1-P_{\mu\mu})$

Tensions when all the channels are combined together → some of them has to be wrong?

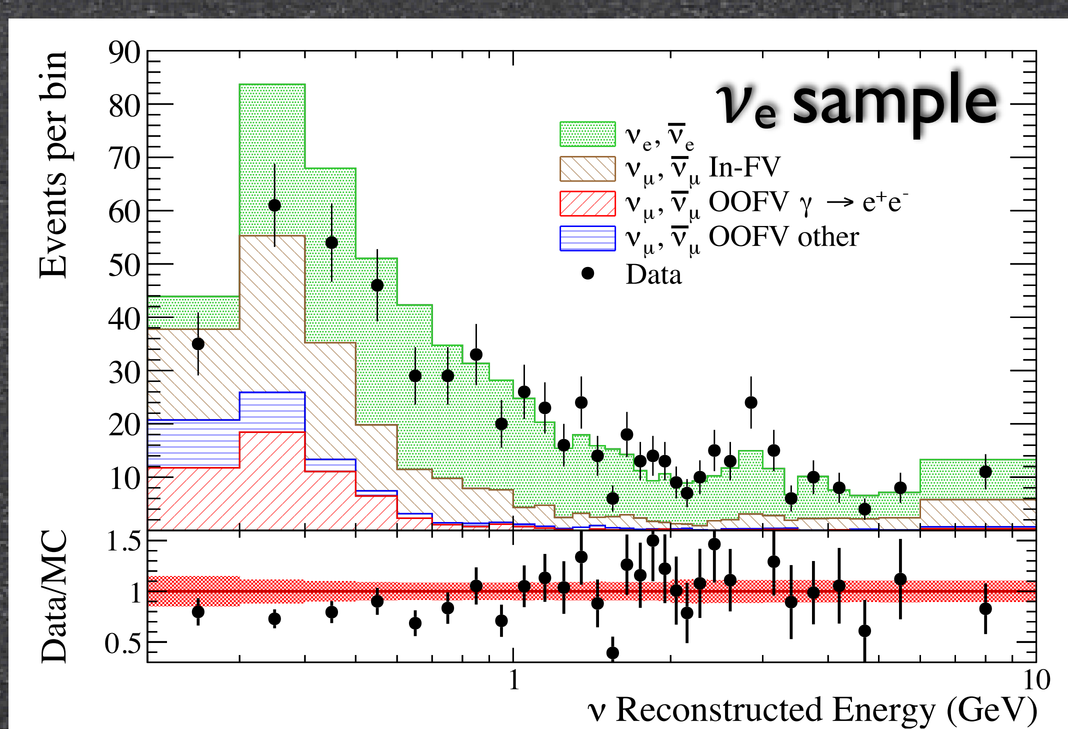
We decided to concentrate on the ν_e disappearance channel (reactor anomaly)

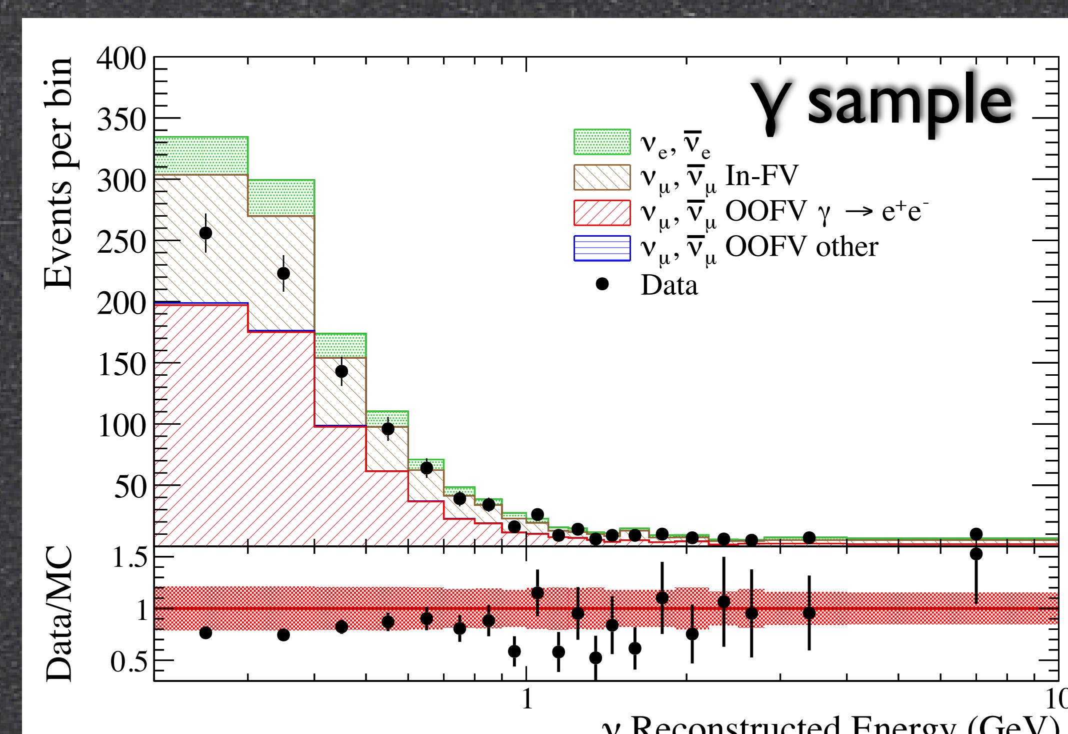
use ND280 ν_μ data to constrain the systematics (no ν_μ disappearance)



Search for ν_e disappearance @ND280

- 3+1 model: $$P_{\nu_e\to\nu_e} = 1 - \sin^2 2\theta_{ee} \cdot \sin^2\left(\frac{1.267\Delta m^2_{41} L_\nu}{E}\frac{\text{GeV}}{\text{eV}^2\text{km}}\right)$$
- No hints of ν_μ disappearance exist → $\sin^2(2\theta_{\mu\mu})=0$
- Look for ν_e disappearance in $(\sin^2(2\theta_{ee}), \Delta m^2_{41})$ plane
  - Study gallium and reactor anomaly
- Use ND280 ν_e and γ selections and fit E_{rec} distributions
  - γ selection used to constrain the out of FV backgrounds





Results

Phys. Rev. D 91, 051102(R)

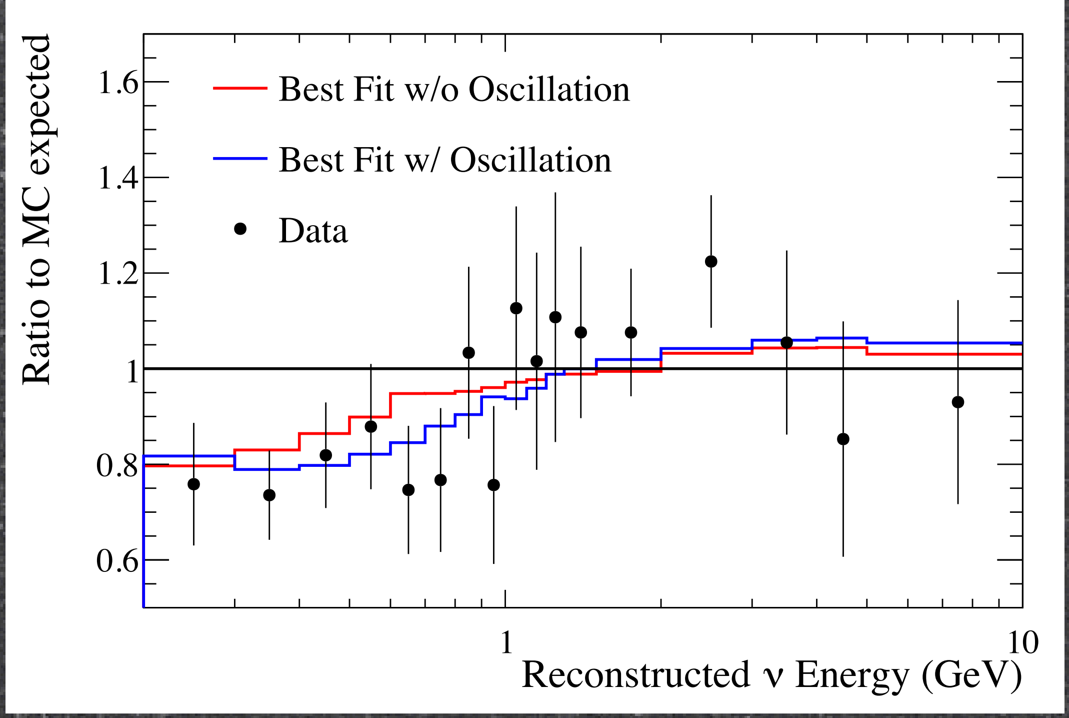
Frequentist method for confidence intervals (FC)

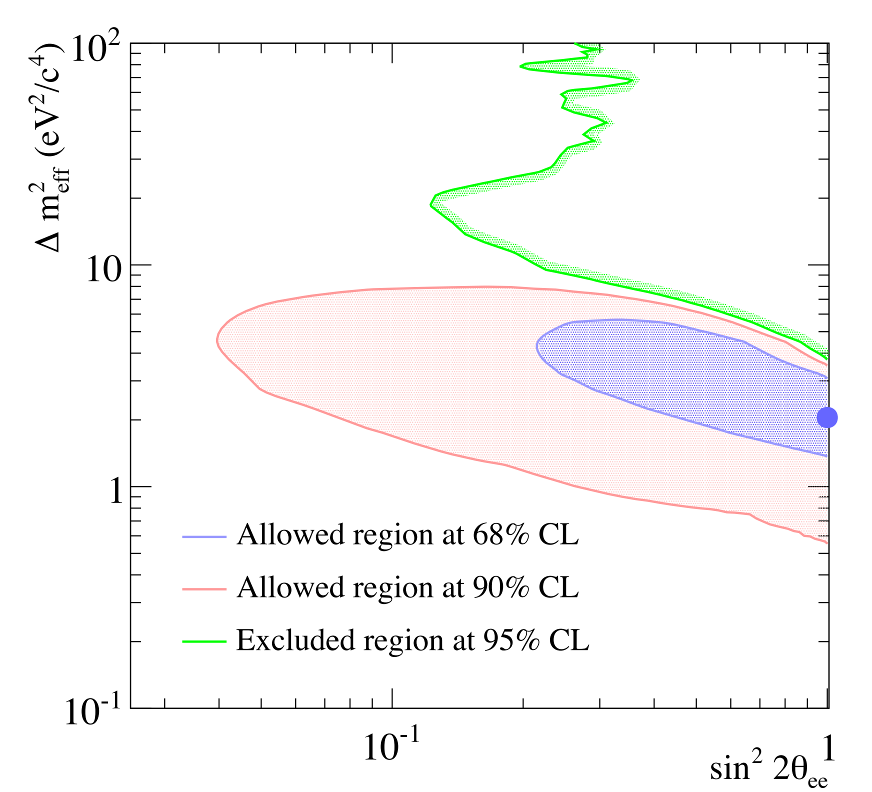
p-value with respect to null oscillation hypothesis: 8.4%

Best fit values $\sin^2 2\theta_{ee}=1$ and $\Delta m^2_{41}=2.14\ eV^2$

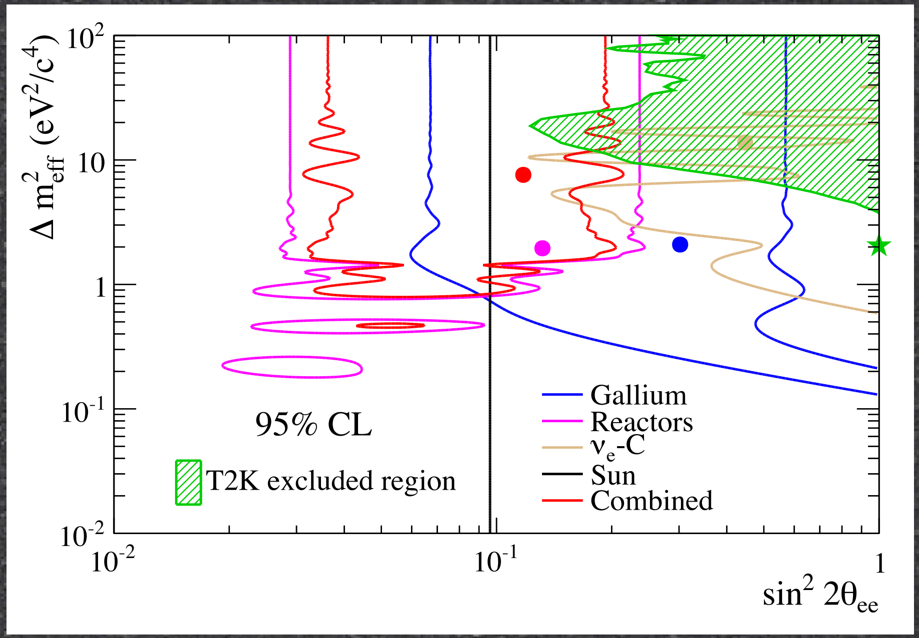
95% CL excluded intervals: $\sin^2 2\theta_{ee}$>~0.3 and Δm^2_{41}>~7 eV^2

Statistically limited → will repeat this analysis when more data will be available





95% CL comparison: T2K with reactor and gallium anomaly



Joint oscillation analysis

- I will show results from the joint T2K oscillation analysis
  - This analysis combine SK selections for μ-like and e-like events in both ν and $\bar{\nu}$ mode → 4 samples
- ND280 data are used to constraint flux and cross-section systematics
- Today I will show results from Run1-6
  - 6.9×10^{20} POT in neutrino mode
  - 4.0×10^{20} POT in anti-neutrino mode
- These results are not yet public! (please don't share!)
  - They will be released with 7.5×10^{20} POT in anti-neutrino mode at Neutrino2016 (July 4th)

Reason for a joint analysis

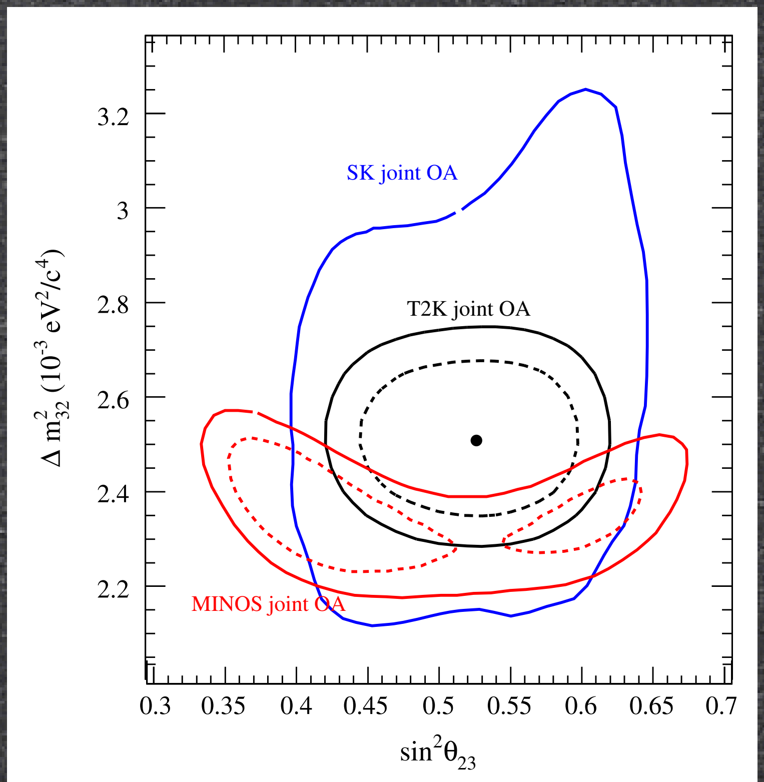
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \sim \quad & \sin^2 2\theta_{13} && \times \boxed{\sin^2\theta_{23}} \text{ constrain by } \nu_\mu \text{ disp.} \times \frac{\sin^2(1-x)\Delta}{(1-x)^2} \\
& -\alpha \sin 2\theta_{13} && \times \boxed{\sin\delta_{CP}} \sin 2\theta_{12} \boxed{\sin 2\theta_{23}} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& + \text{CP even term} && + \text{solar term}
\end{aligned}
$$

switches sign for $\bar{\nu}_\mu \to \bar{\nu}_e$

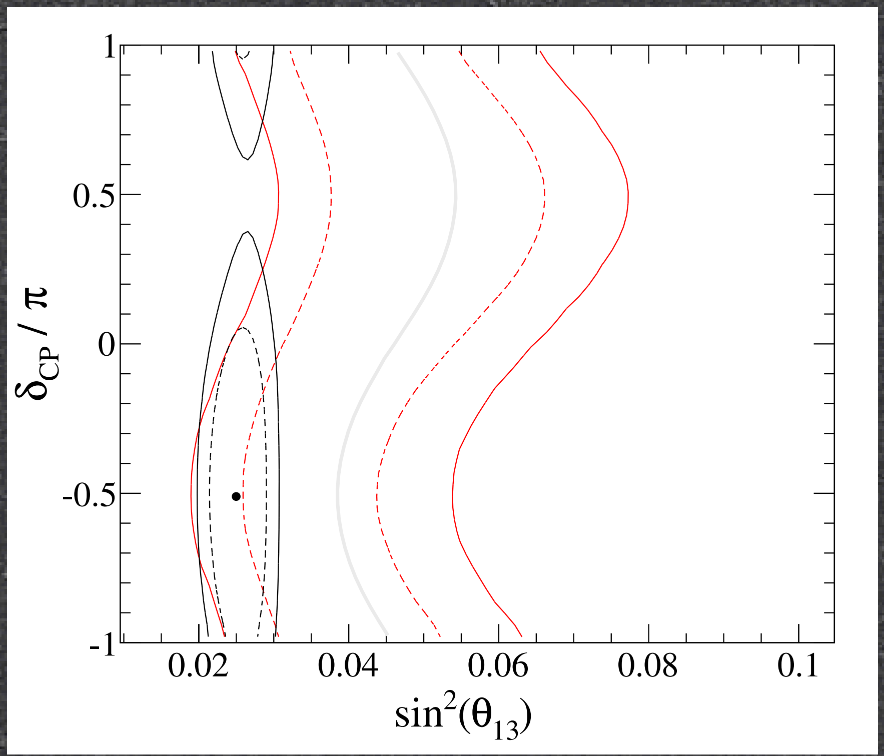
ν only results

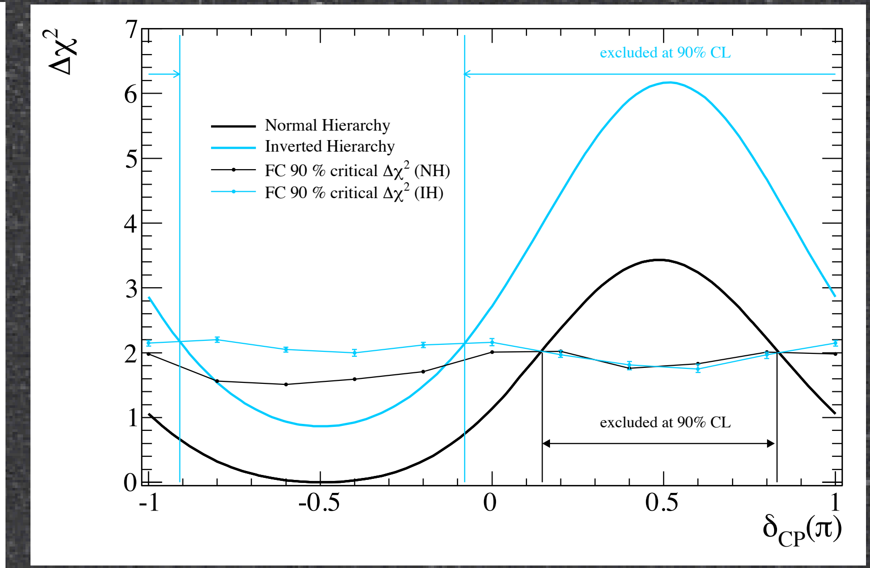
Phys. Rev. D 91 072010

Best measurement of θ_{23}



Start breaking degeneracy between δ_{CP} and θ_{13} when T2K is combined with reactors





SK μ-like selection

- SK is not able to reconstruct the charge of the lepton → cannot distinguish ν from $\bar{\nu}$ interactions
- Exactly same selection for both running mode
- Due to larger contamination and larger cross-section the wrong-sign contamination in $\bar{\nu}$ mode is much larger than the one in ν mode

<u>ν_μ **Selection Cuts**</u>

- Fully Contained FV events

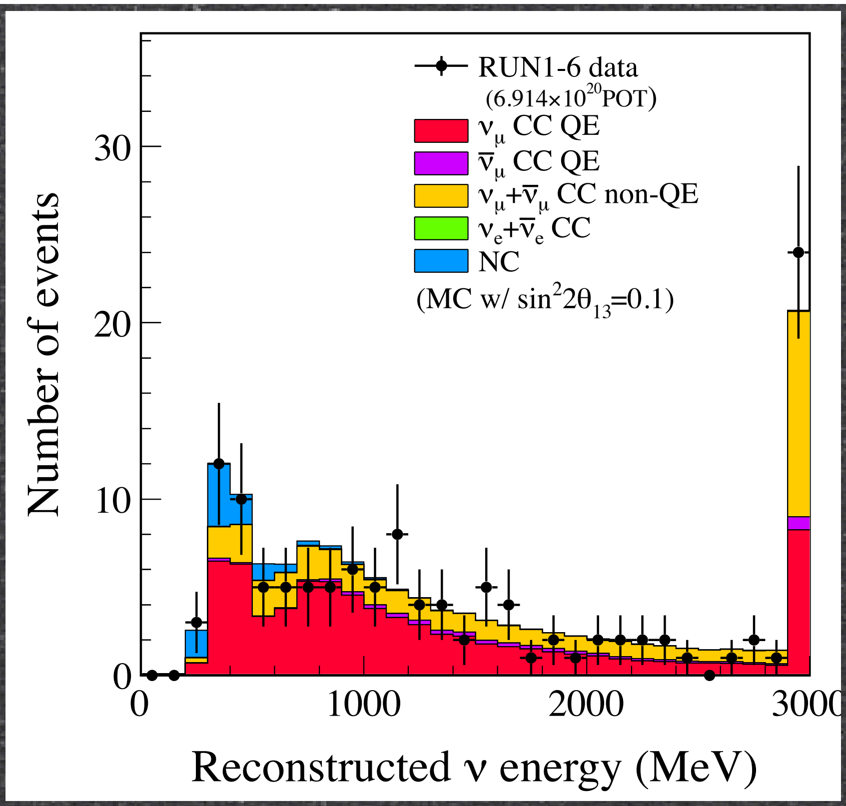
- # of rings = 1

- Ring is μ-like

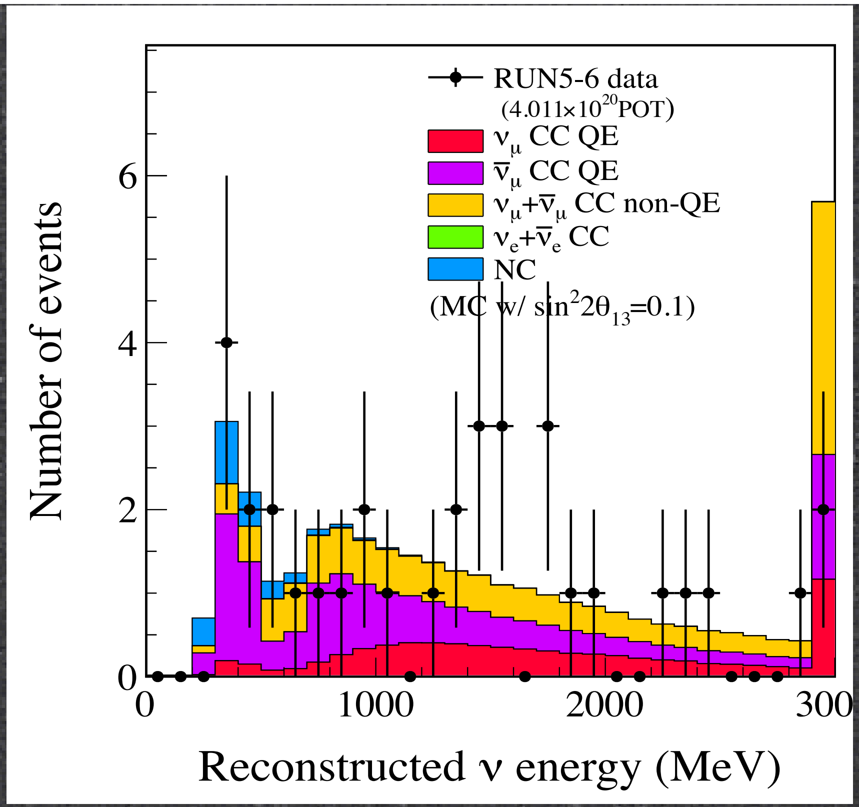
- P_μ> 200 MeV

- Less than 2 Michel electrons

ν mode μ-like: 6% of events from $\bar{\nu}$ interactions



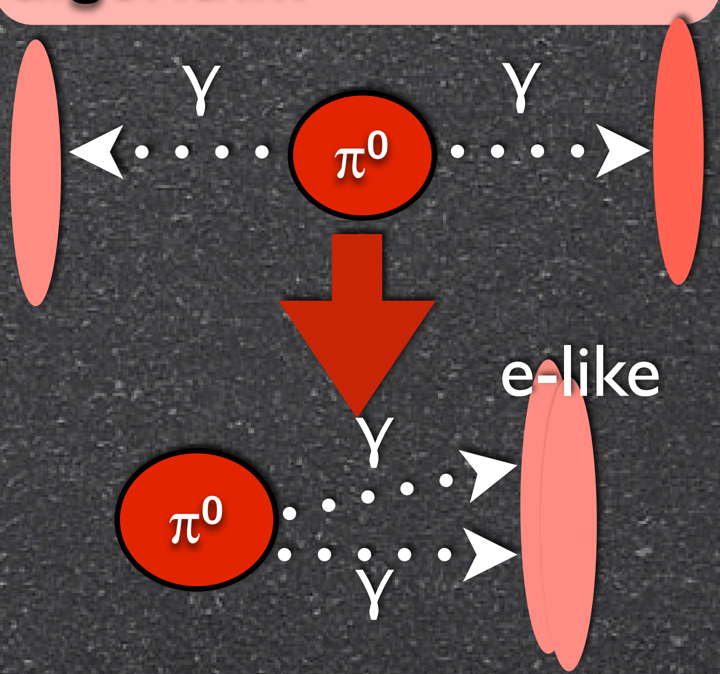
$\bar{\nu}$ mode μ-like: 35% of events from ν interactions

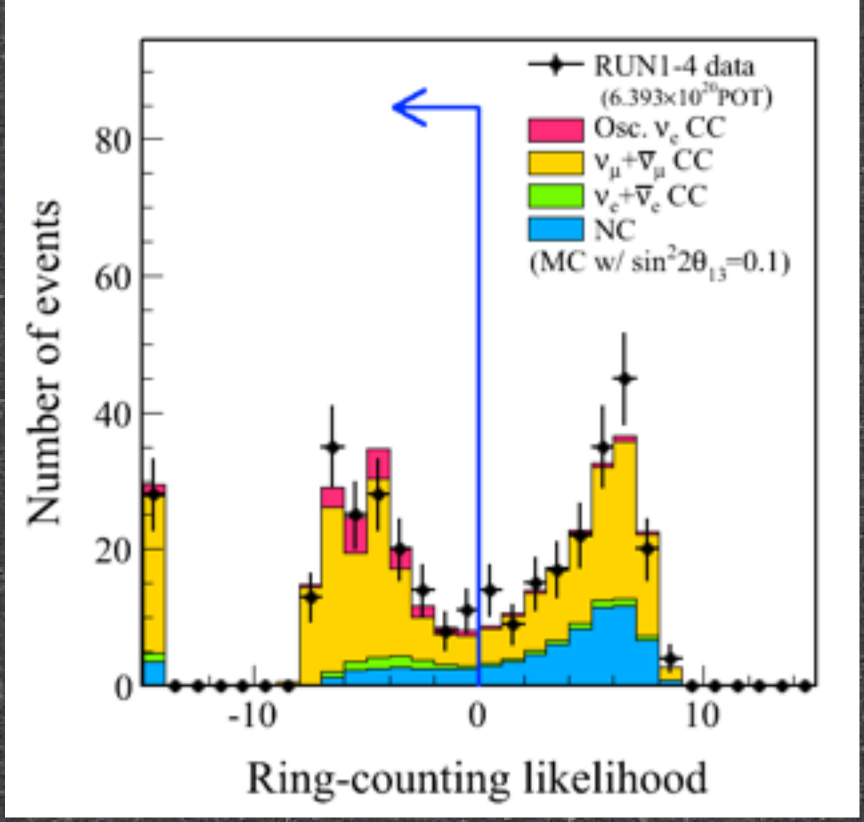


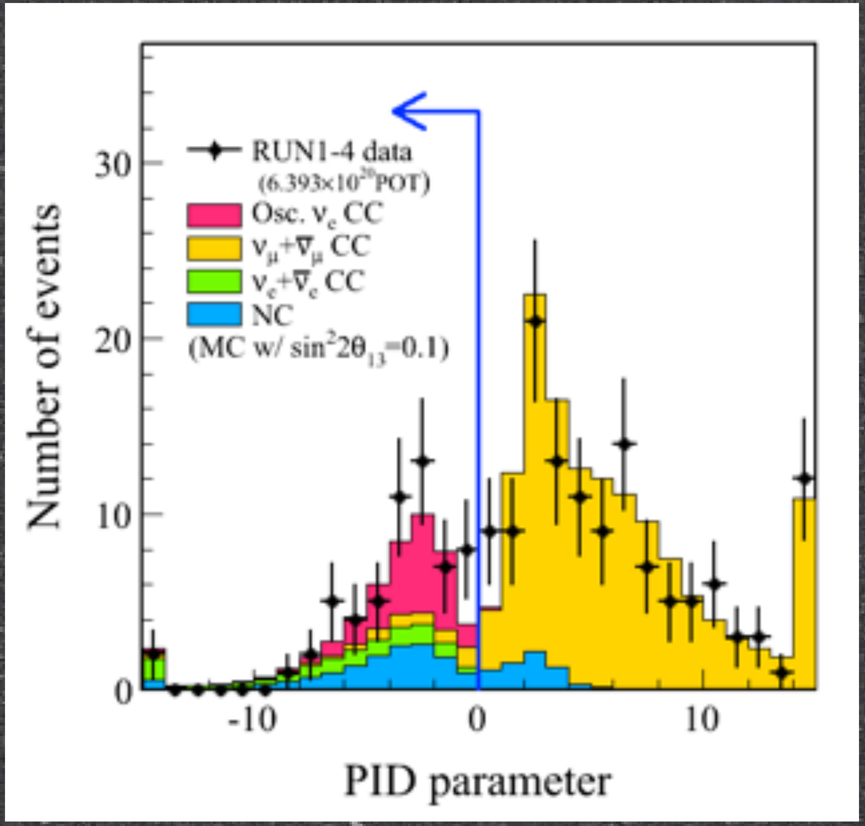
SK e-like selection

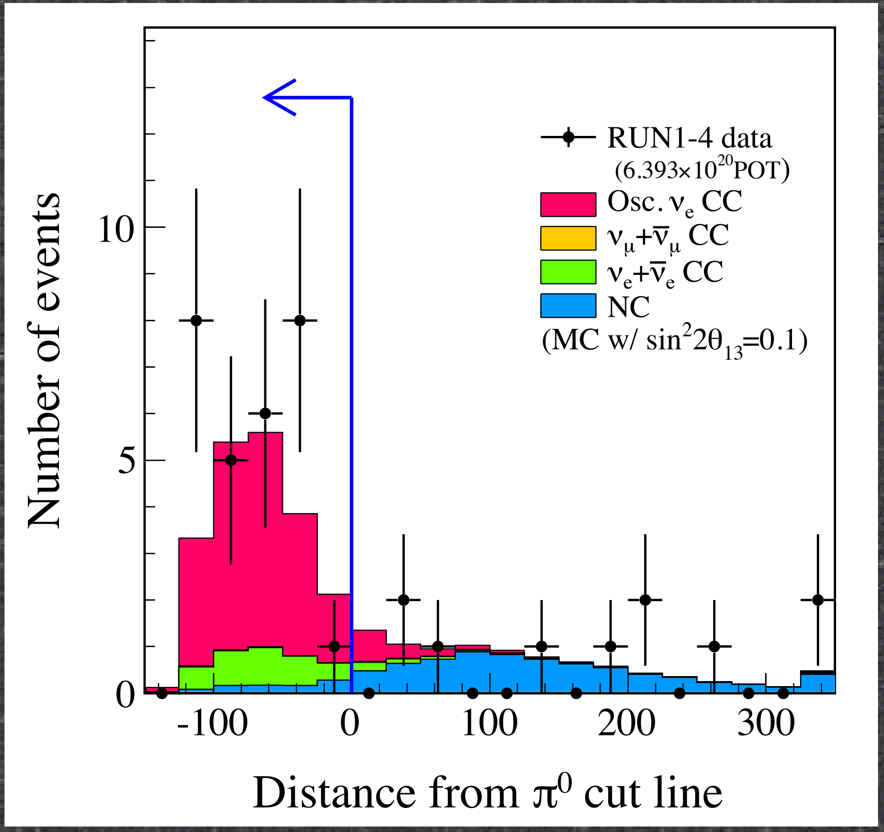
ν_e Selection Cuts

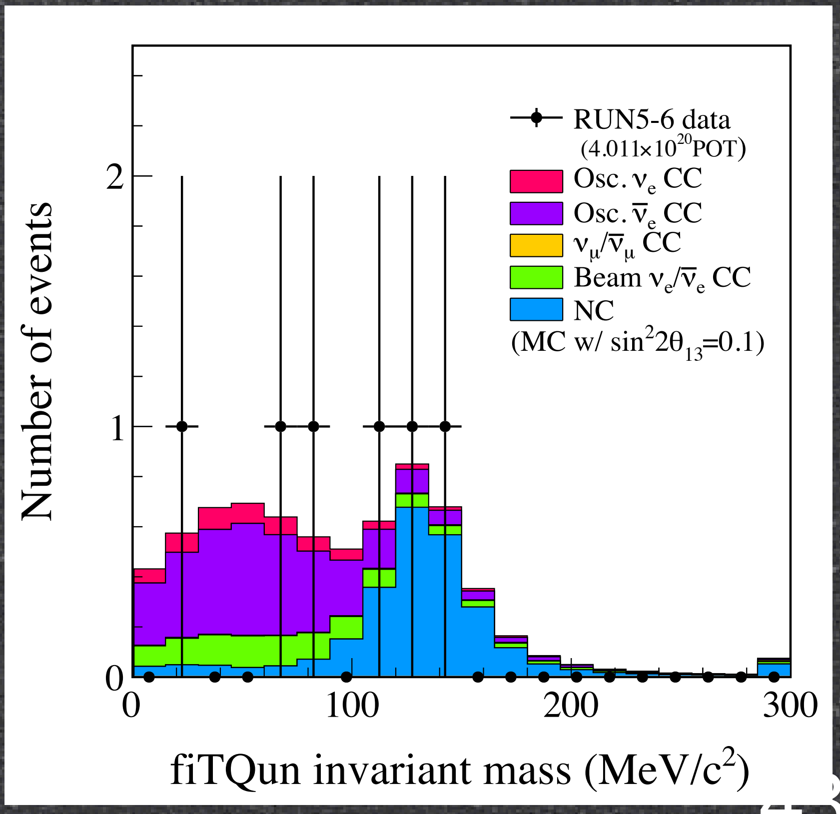
- **Fully Contained FV events**
- **# of rings = 1**
- **Ring is e-like**
- **$E_{visible}$ > 100 MeV**
- **no Michel electrons**
- **0 < E_ν < 1250 MeV**
- **new π^0 rejection algorithm**











Expected and observed events

$6.9\text{x}10^{20}$ POT in ν

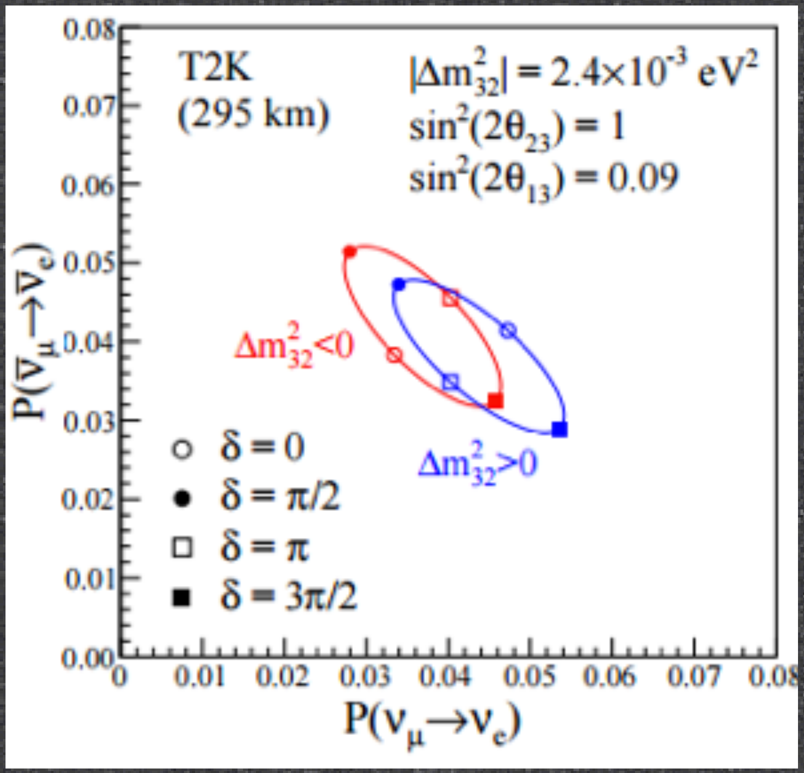
$4.0\text{x}10^{20}$ POT in $\overline{\nu}$

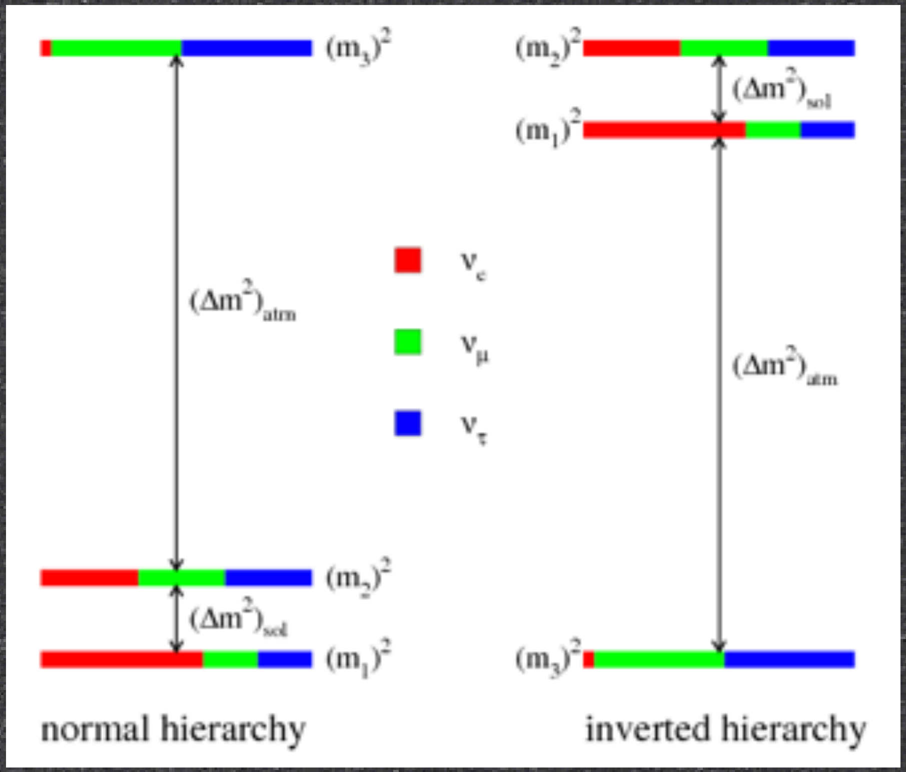
	1-Ring e		1-Ring μ	
Category	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode
$\nu_\mu \to \nu_e$	21.0	0.5	0.3	0.01
$\overline{\nu}_\mu \to \overline{\nu}_e$	0.1	1.5	0.0	0.02
ν_μ	0.0	0.0	105.3	12.8
$\overline{\nu}_\mu$	0.1	0.0	6.9	17.9
$\nu_e + \overline{\nu}_e$	3.3	0.8	0.1	0.0
NC	1.4	0.4	7.5	1.6
Total (oscillated)	25.9	3.1	120.1	32.5
Total (not oscillated)	5.5	1.2	466.6	94.9
Data	31	3	124	34

- $\sin^2(\theta_{23})=0.5$, $\delta_{CP}=-\pi/2$ and NH → maximize ν_e appearance, minimize $\overline{\nu}_e$ appearance
- Any other combination reduce the number of e-like events in neutrino mode and increase the number of e-like events in anti-neutrino mode

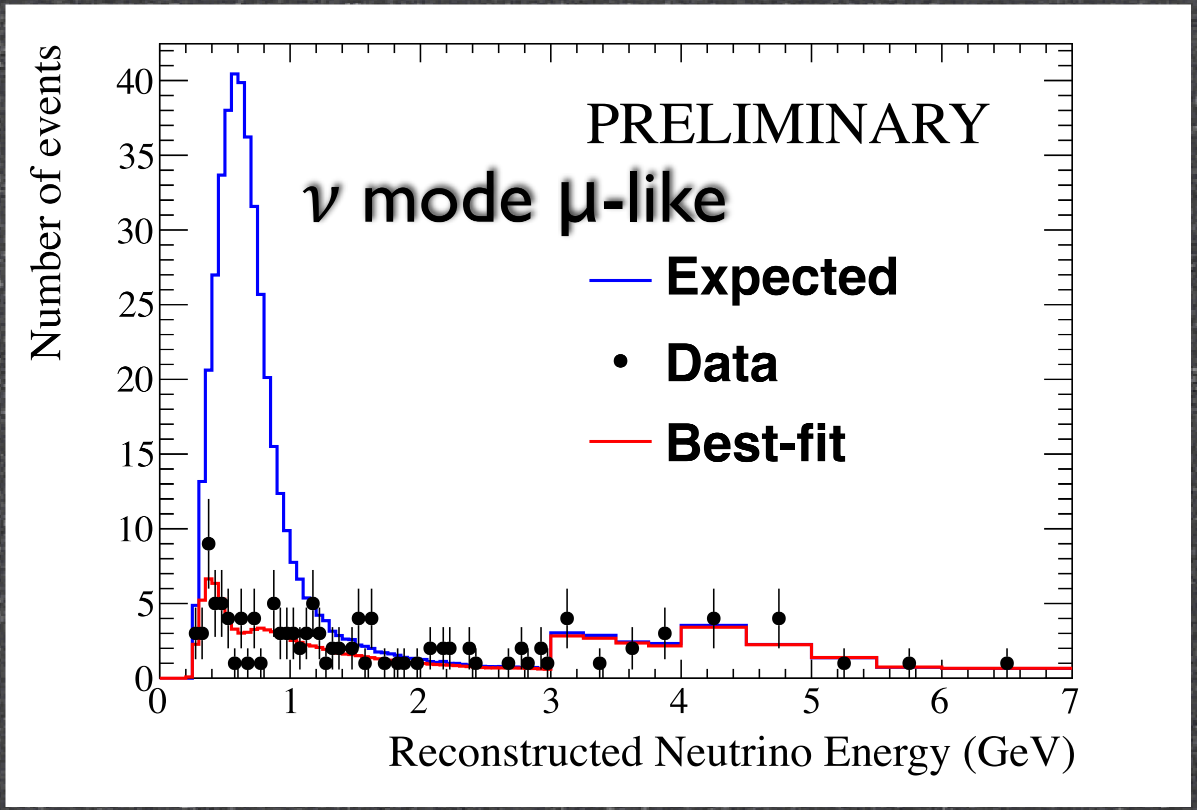
Effect of oscillation parameters

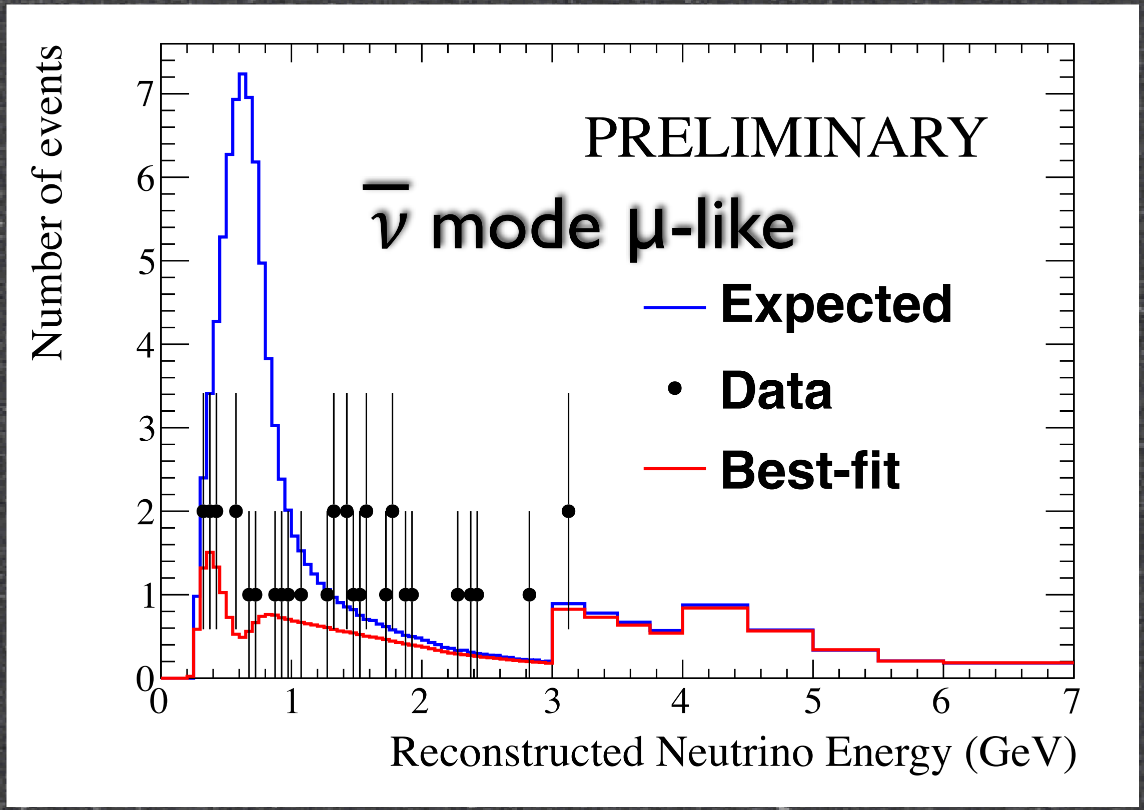
- CP violating term δ_{CP}
  - $\delta_{CP}=0,\pi$ → no CP violation
  - $\delta_{CP}=-\pi/2$ → enhance $\nu_\mu \rightarrow \nu_e$, suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - $\delta_{CP}=\pi/2$ → suppress $\nu_\mu \rightarrow \nu_e$, enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Normal hierarchy
  - enhance $\nu_\mu \rightarrow \nu_e$
  - suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Inverted hierarchy
  - suppress $\nu_\mu \rightarrow \nu_e$
  - enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- $\sin^2\theta_{13}$ and $\sin^2\theta_{23}$ → enhance/ suppress both cases in same way

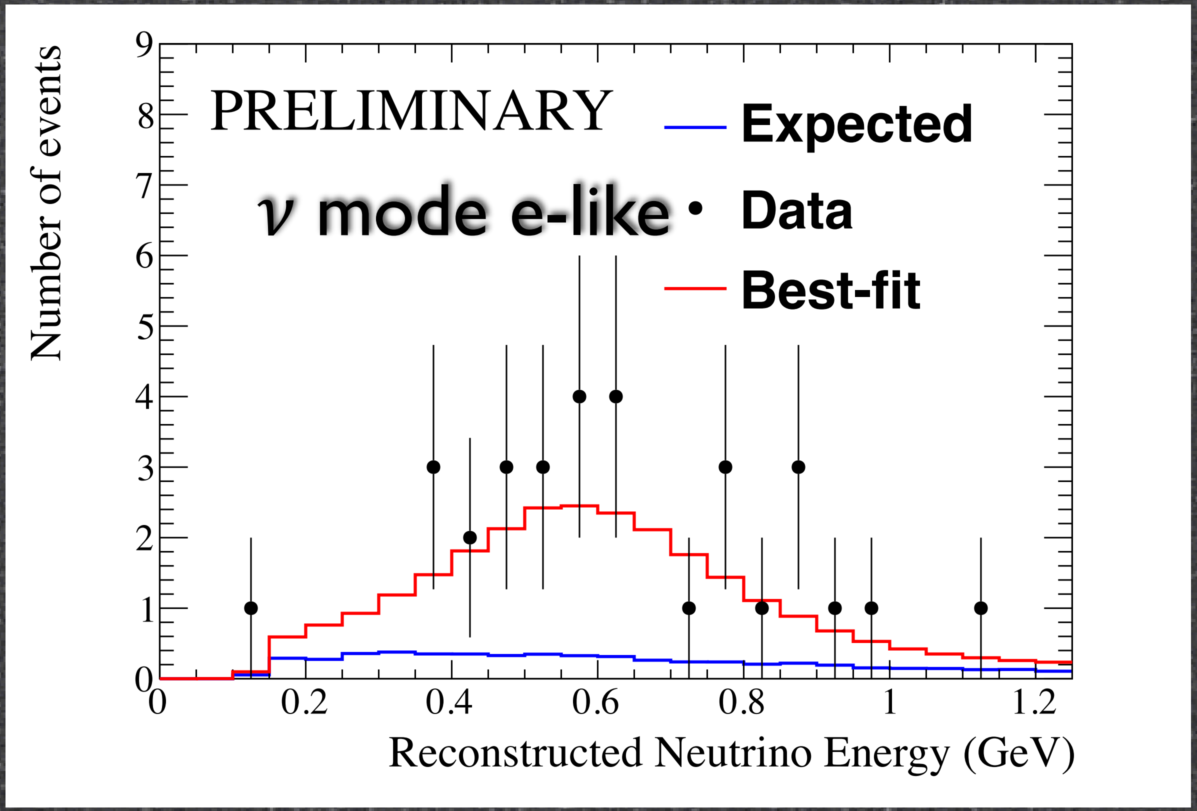


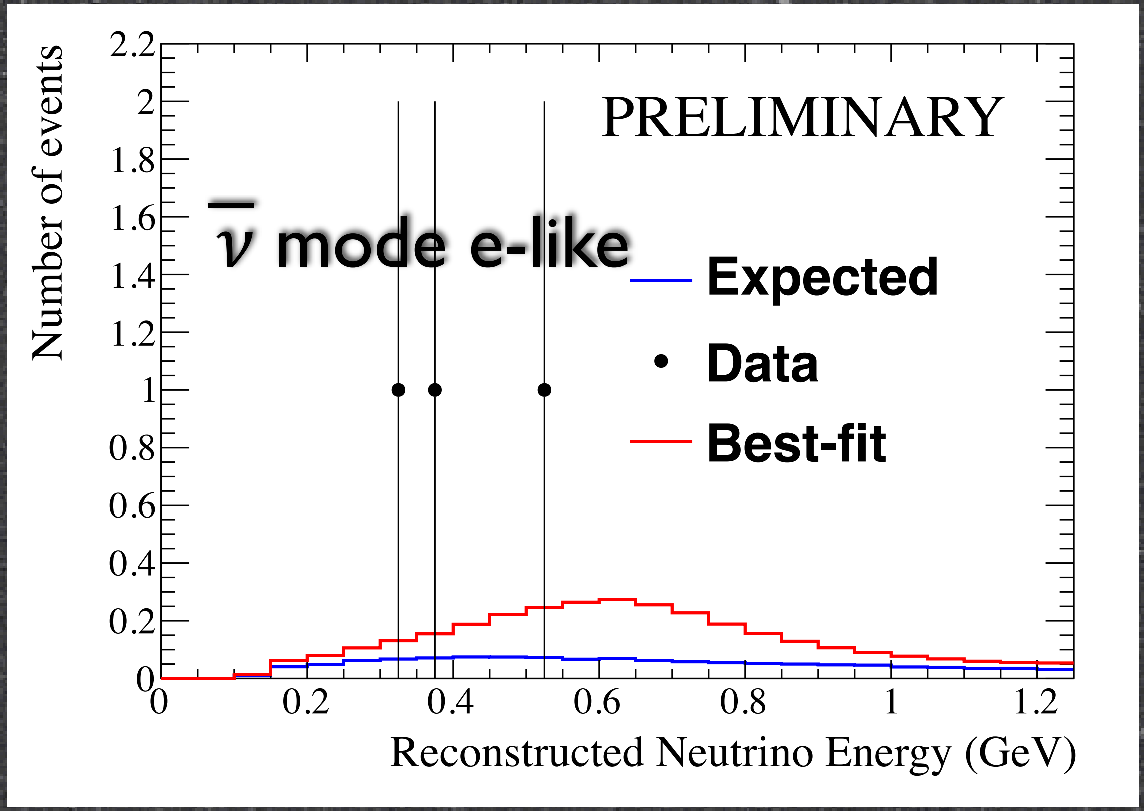


Observed spectra

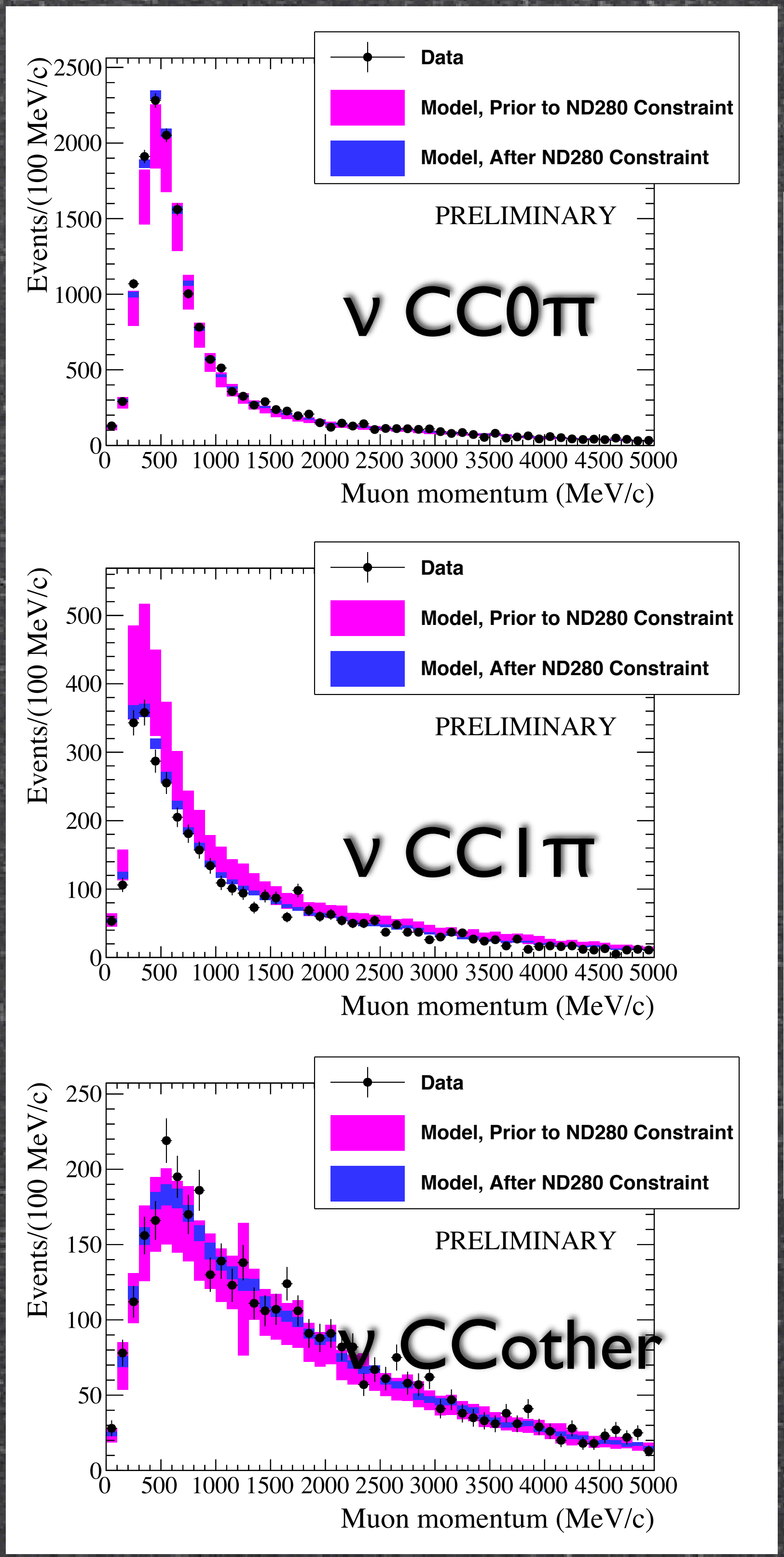




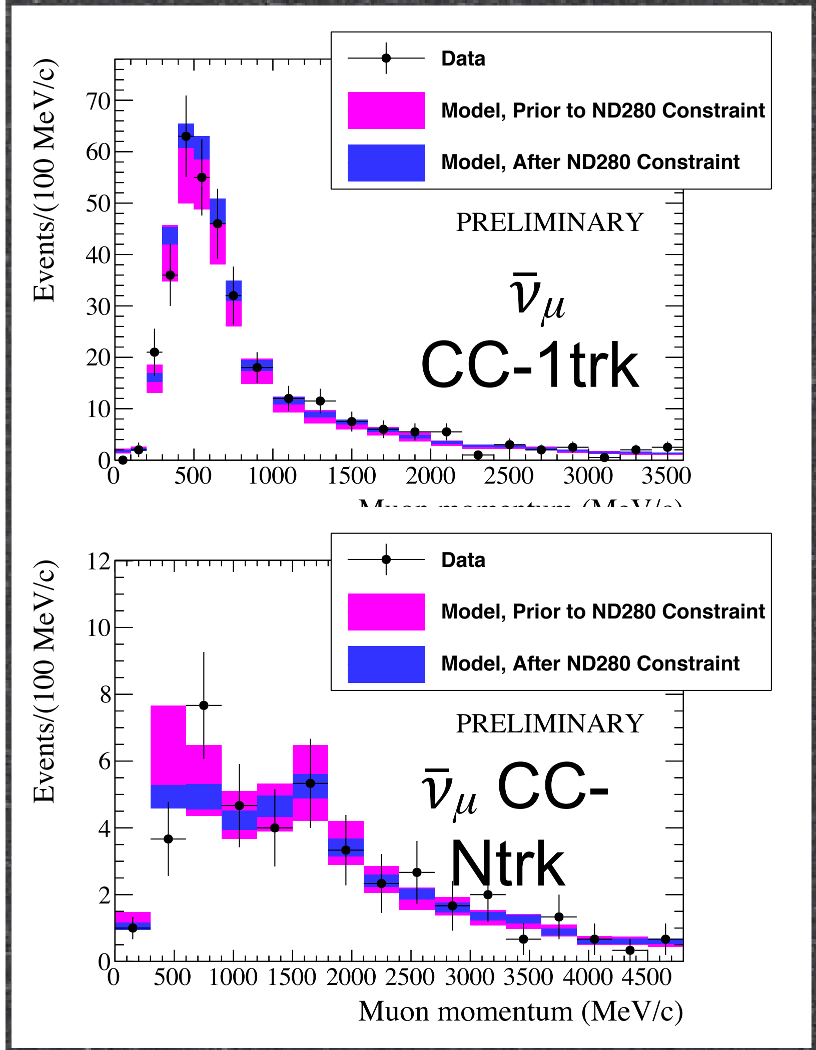


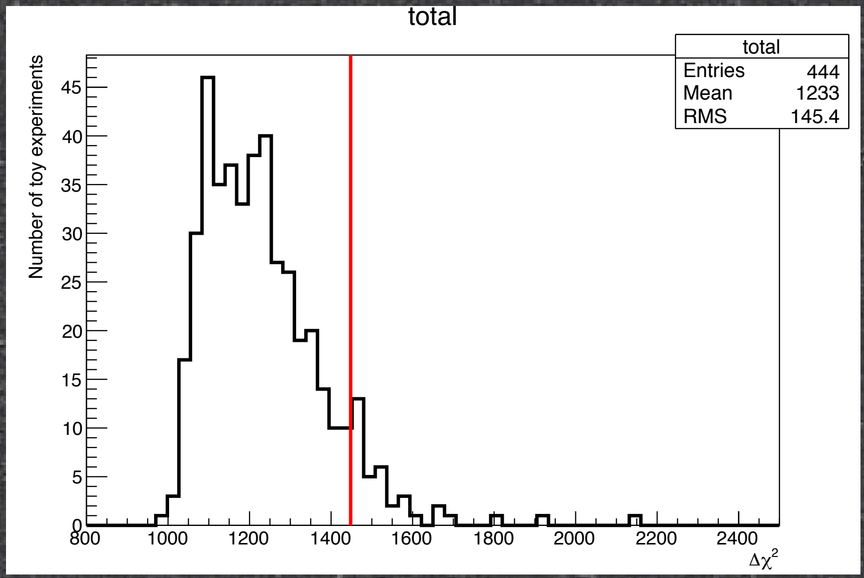


ND280 constraint on flux and x-sec



- ND280 constraint the parameters of the flux and cross-section model that we use as input



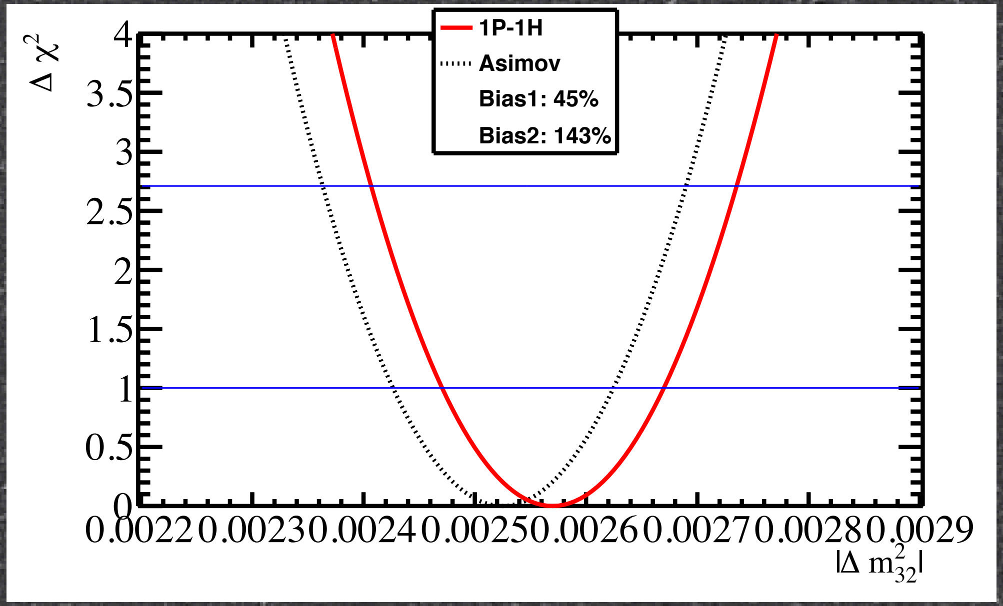


- The p-value of the data with the model is 8.5% → acceptable agreement but some work on the neutrino interaction model is needed

Fake data studies

- In order to study the dependence of our oscillation analysis on the cross-section model we used we performed some fake data studies:
  - Generate fake data at ND280 and SK (including oscillation) using a different model
  - Fit ND280 fake data with our default model
  - Propagate expected spectra at SK and fit oscillation parameters

1p-1h contribution (Nieves vs NEUT)

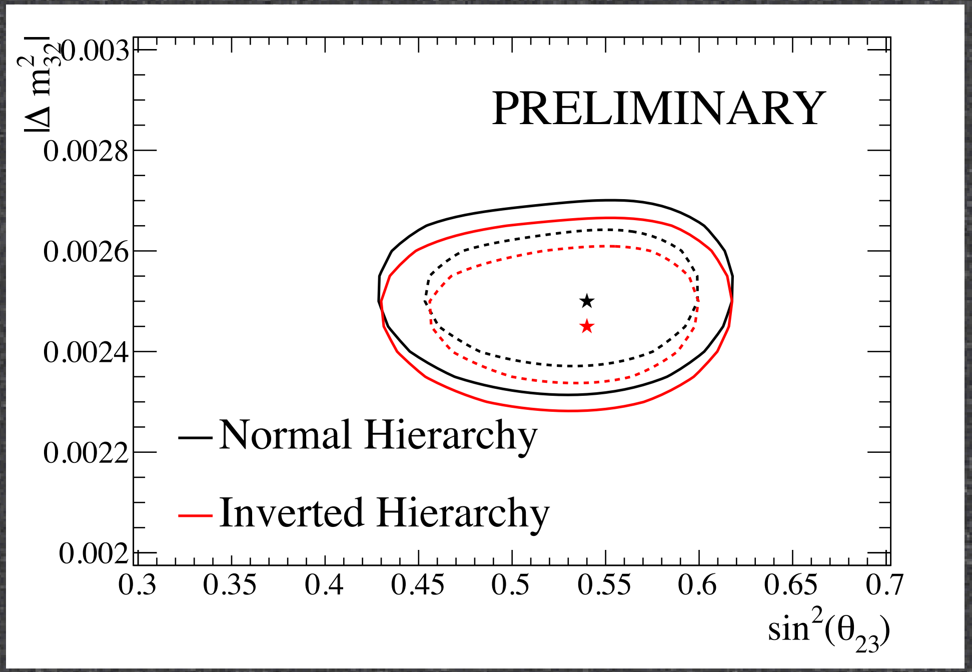


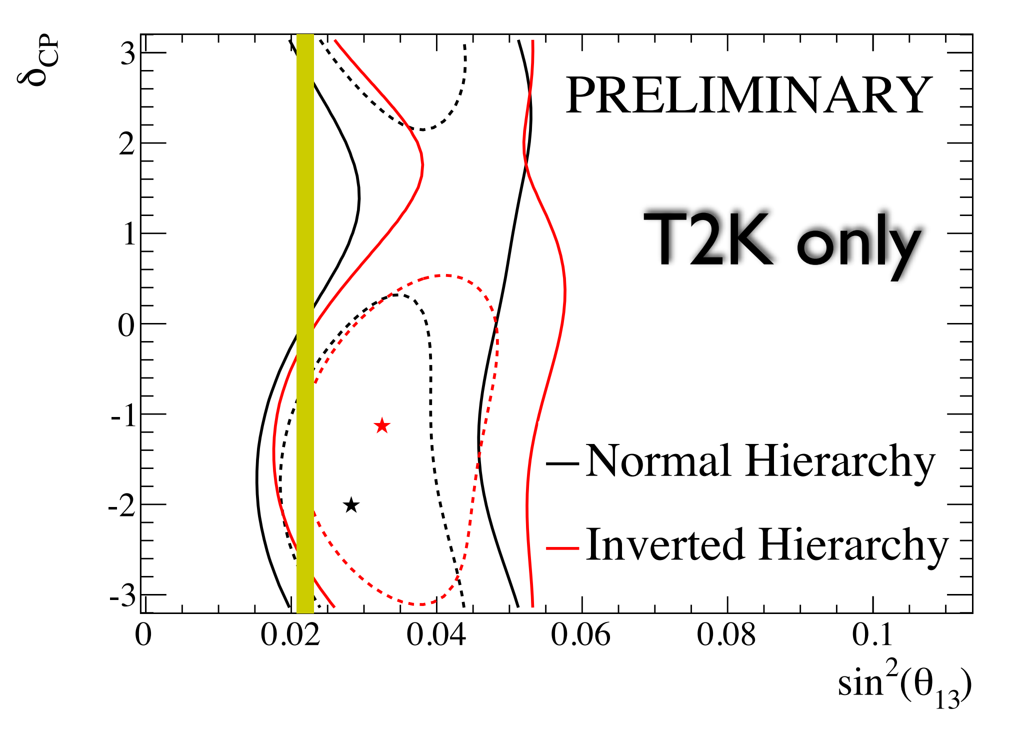
(a) $|\Delta m^2_{32}|$

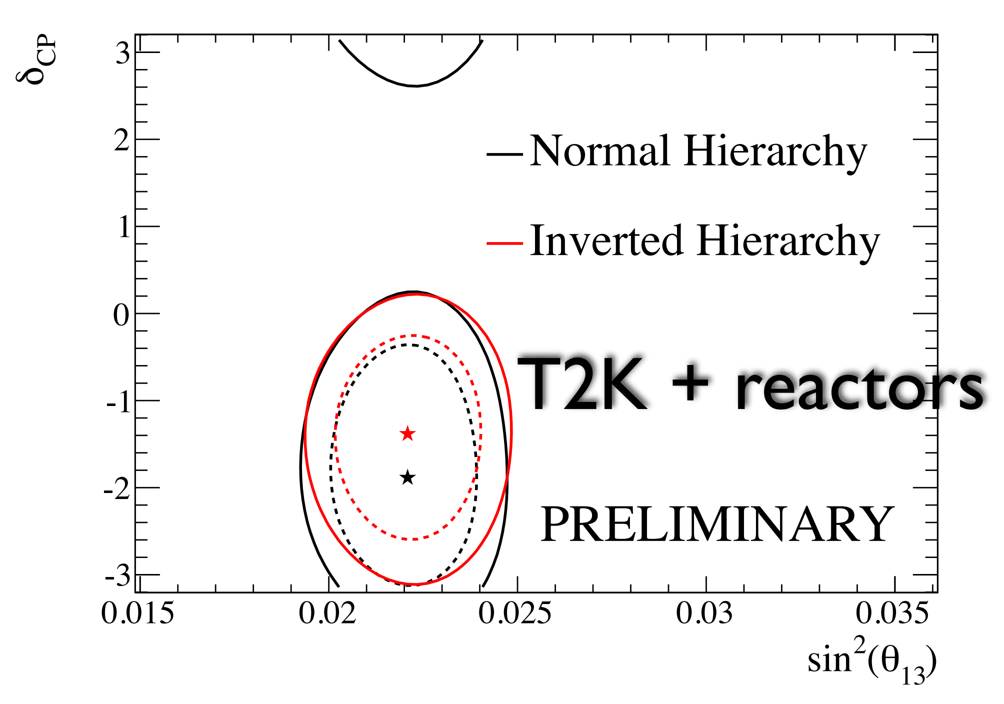
- Several models were used and the most sensitive parameters to the model is Δm_{32} (position of the oscillation dip)
- Largest bias is ~30% of the error
- All the other oscillation parameters are ~unaffected by the choice of the model

Oscillation results - 2D contours

- For θ_{23} and Δm_{32} the improvement due to the anti-neutrino runs is small
- For θ_{13} and δ_{CP} the addition of anti-neutrino allow to start breaking the degeneracy also when only T2K data are used

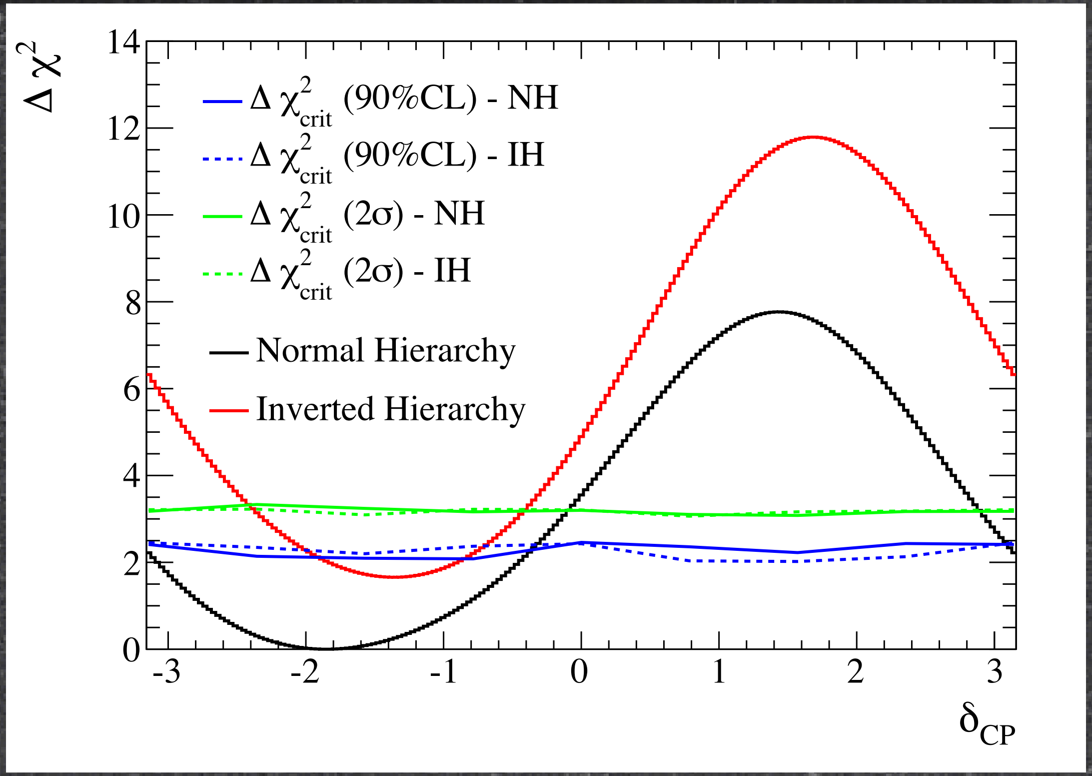






1D contour for δ_{CP}

- Exclude δ_{CP}=0 at >2σ
- Exclude δ_{CP}=π at <90% CL
- This is mainly driven by the excess of events in ν-mode (31 vs 26.6 expected for the most favorable value of δ_{CP} and NH)
- In anti-neutrino mode we observe 3 events while we expect [3.2 - 4.5] → double the statistics at Nu2016



e-like neutrino mode			
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Normal Hierarchy	26.596	22.407	18.179
Inverted Hierarchy	23.554	19.704	15.891

e-like antineutrino mode			
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Normal Hierarchy	3.219	3.704	4.122
Inverted Hierarchy	3.475	3.987	4.499

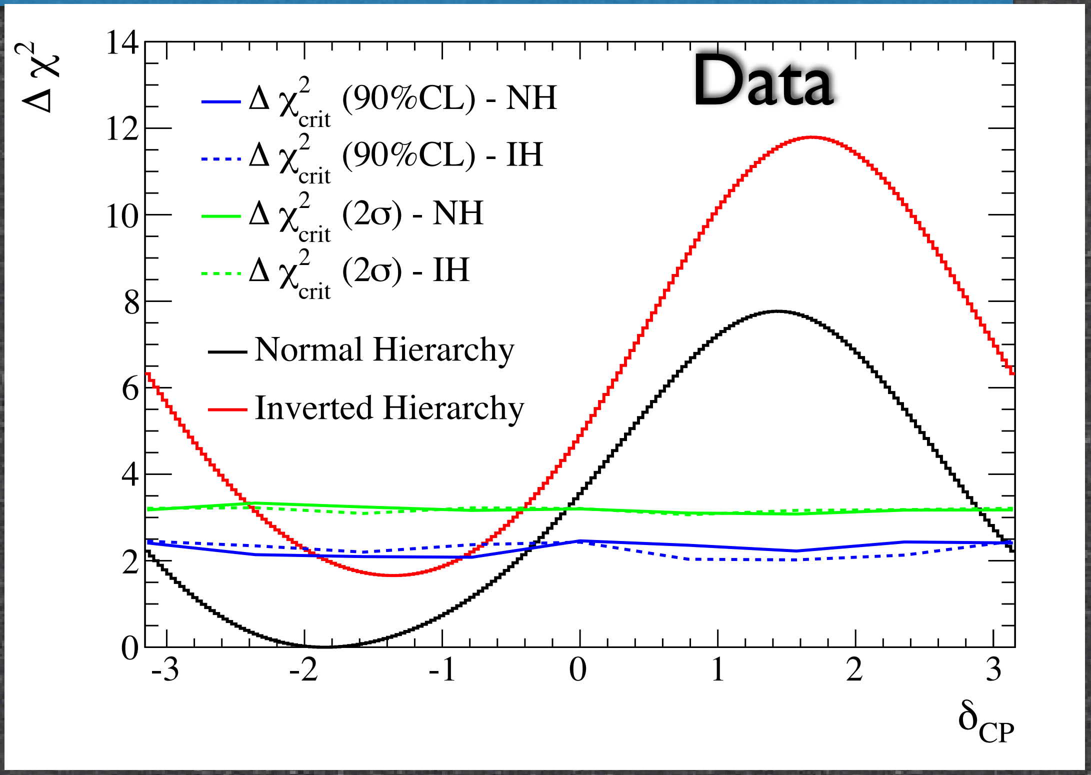
Observed events in e-like samples

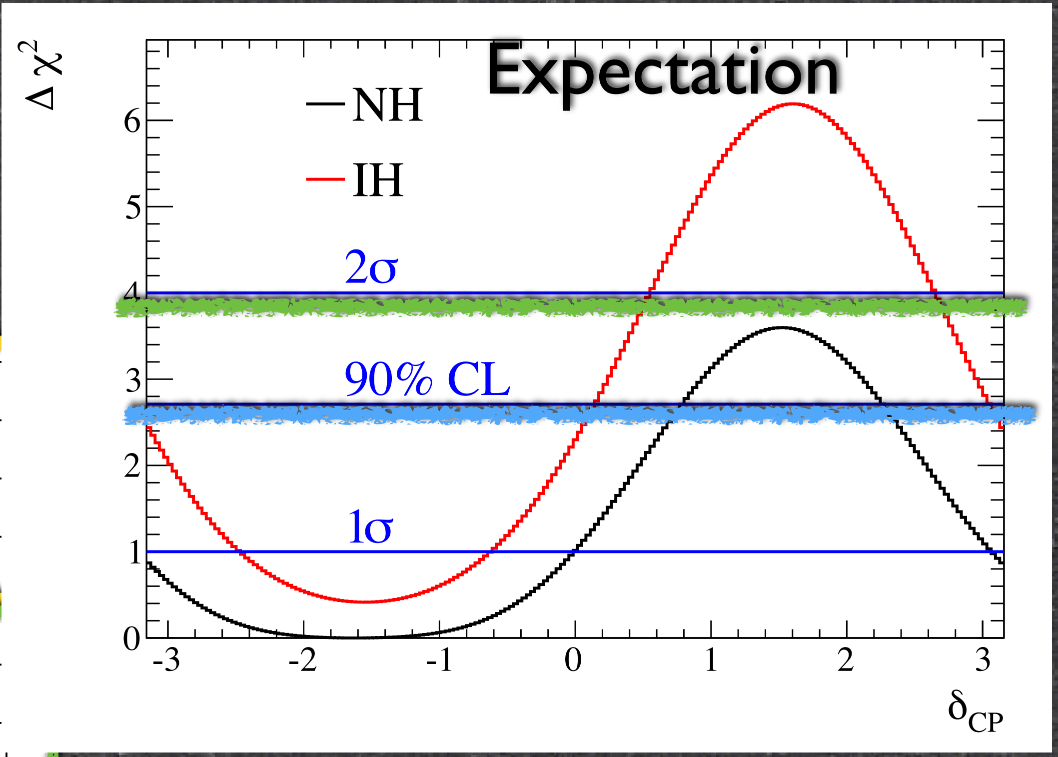
31 events in ν-mode

3 events in $\bar{\nu}$-mode

1D contour for δ_{CP}

- Exclude δCP=0 at >2σ
- Exclude δCP=π at <90% CL
- This is mainly driven by the excess of events in ν-mode (31 vs 26.6 expected for the most favorable value of δ_{CP} and NH)
- In anti-neutrino mode we observe 3 events while we expect [3.2 - 4.5] → double the statistics at Nu2016





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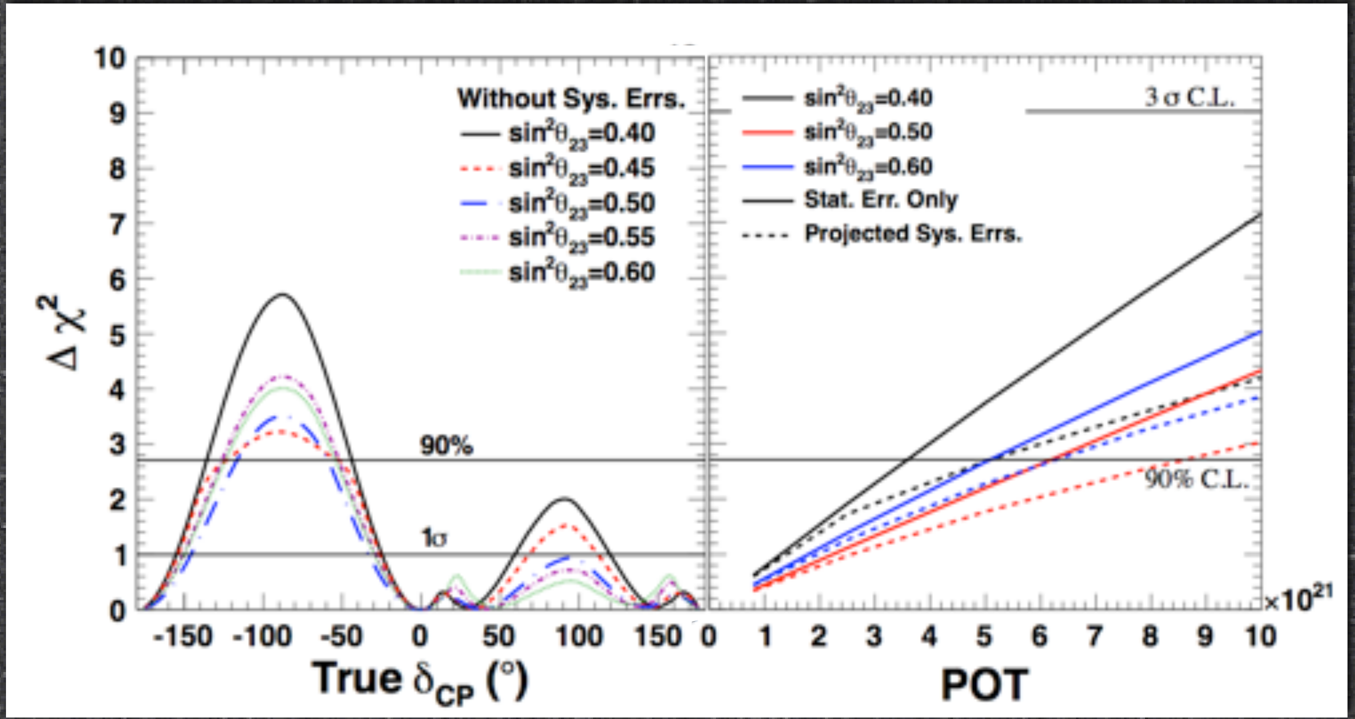
T2K short term prospects

- The main goal of T2K is to search for CP violation in the leptonic sector
- Currently our data show a preference for δCP~-π/2 but additional data are needed to confirm this preference
- T2K is approved to take 7.8×10^{20} POT and such statistics will be collected by 2020 → currently we collected ~20%
- The requested statistics was driven by the sensitivity to θ_{13} → now we know θ_{13} is large and our sensitivity to δ_{CP} will be greatly enhanced if we collect more statistics



Expect >90% sensitivity to δ_{CP} if δ_{CP}~-π/2

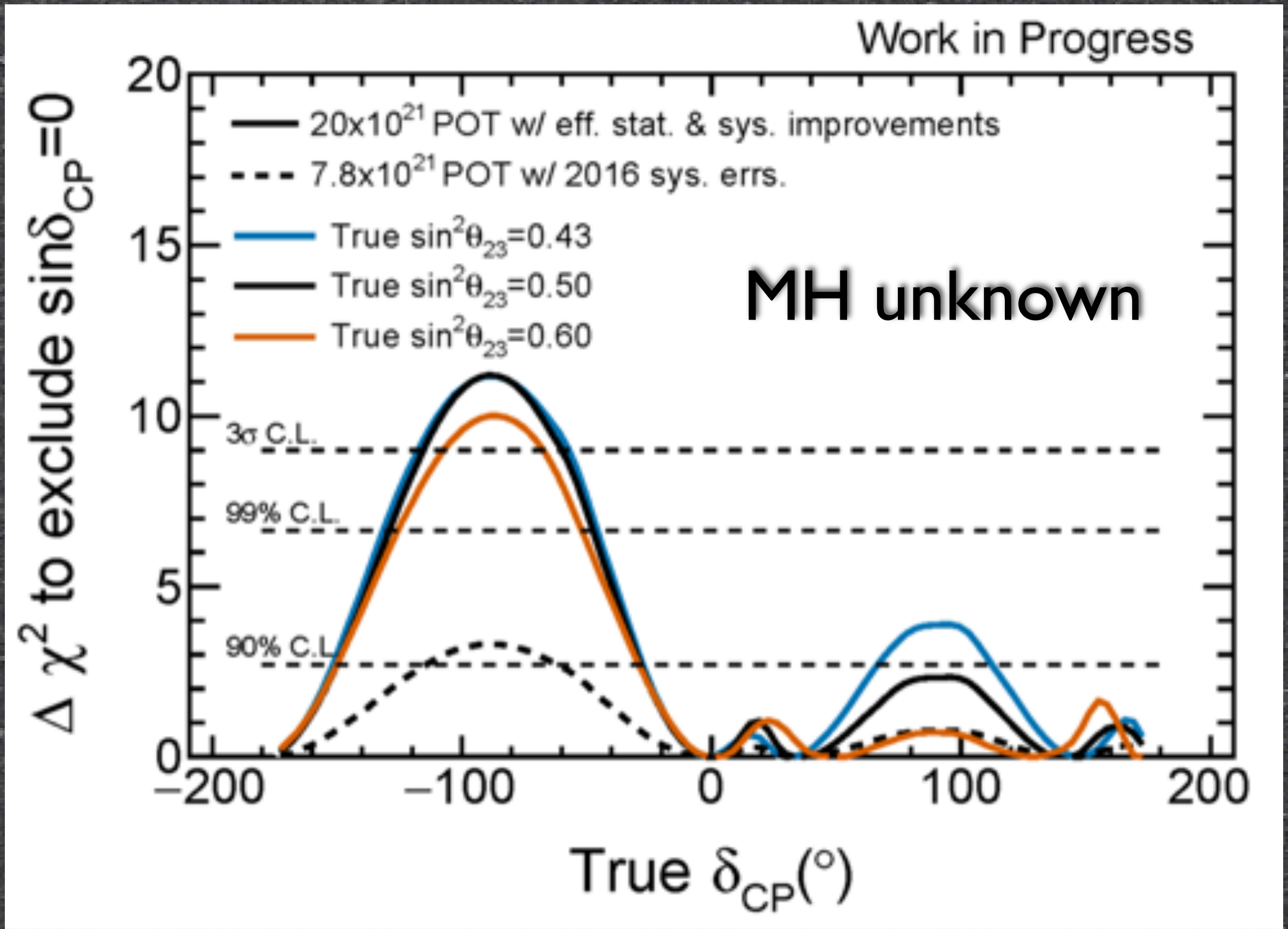
T2K phase-II

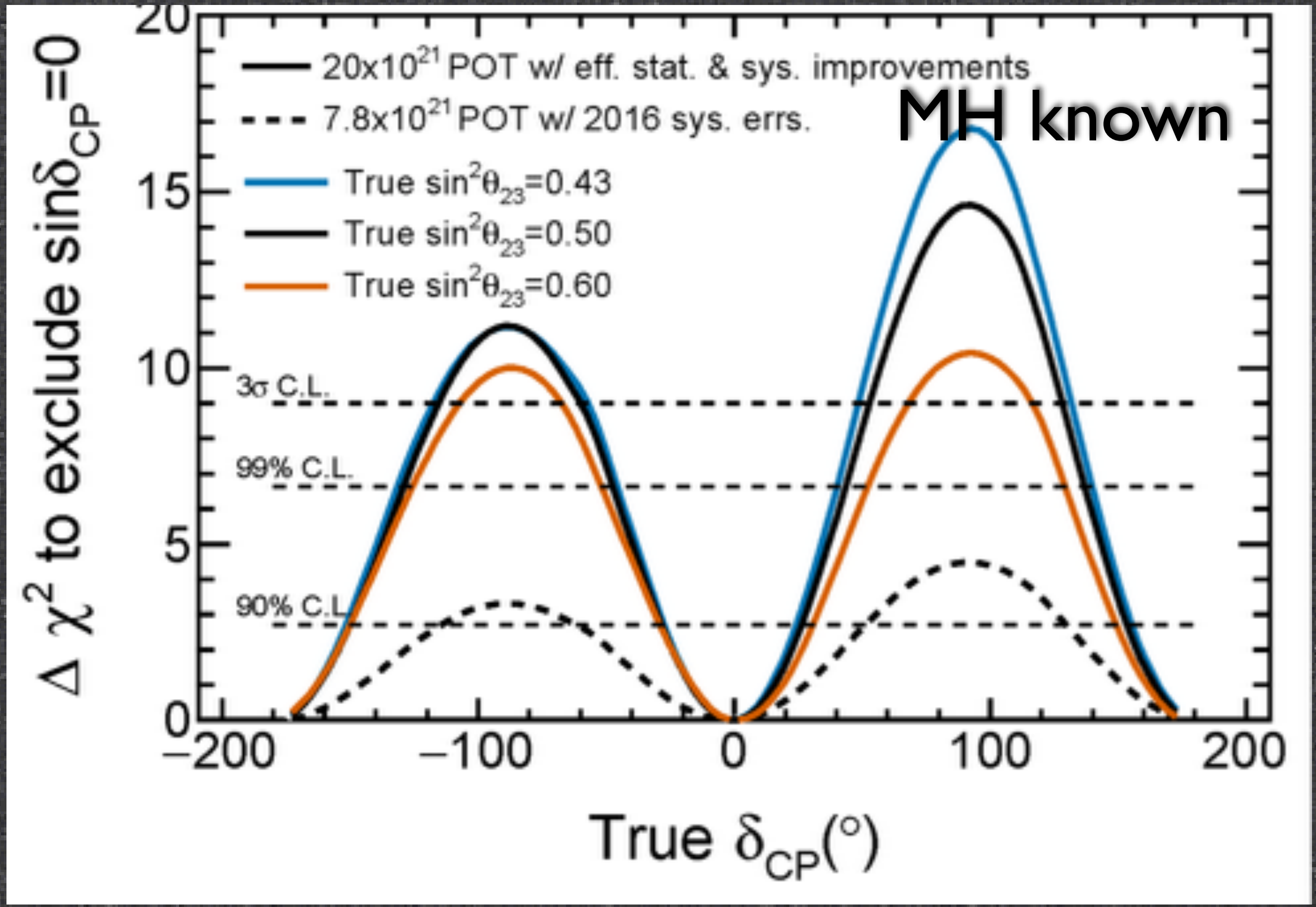
- T2K and NOVA are expected to complete their data taking by 2020
- The next-generation long-baseline neutrino oscillation experiment (DUNE or Hyper-Kamiokande) won't start data taking before 2027
- By 2020 we might have hints of CP violation but no new experiments before ~2026
- T2K has recently submitted a request for an extended running period (T2K-II) that will allow to collect 20×10^{20} POT by 2026

Physics case

T2K-II Expression of Interest (10E21 POT for nu and 10E21 POT for an

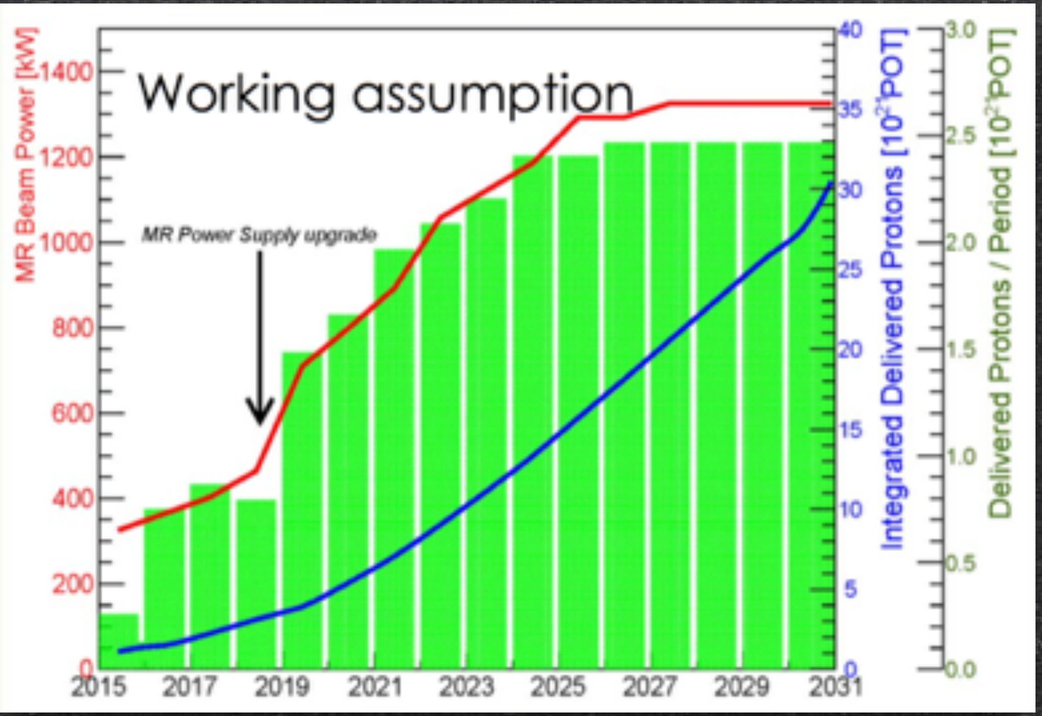
	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode	0	454.6	346.3	3.8	72.2	1.8	30.5
ν_e sample	$-\pi/2$	545.6	438.5	2.7	72.2	1.8	30.5
$\bar{\nu}$-mode	0	129.2	16.1	71.0	28.4	0.4	13.3
$\bar{\nu}_e$ sample	$-\pi/2$	111.8	19.2	50.5	28.4	0.4	13.3

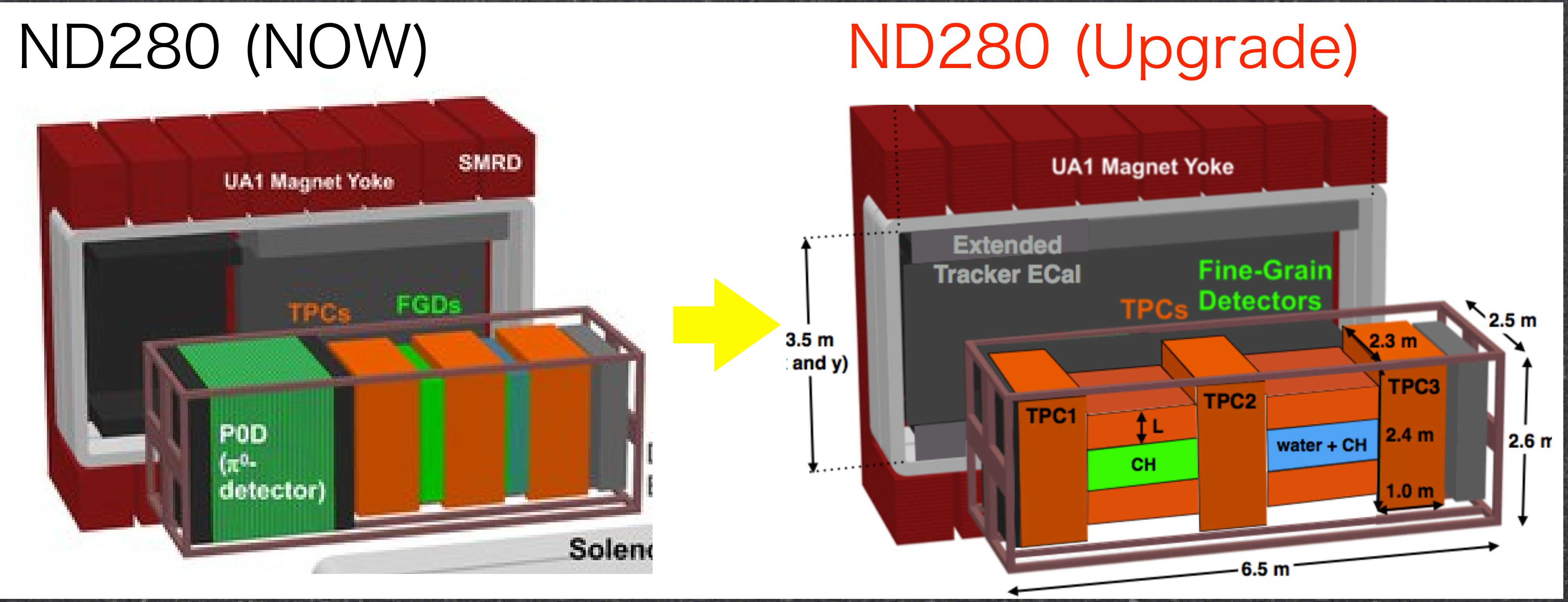




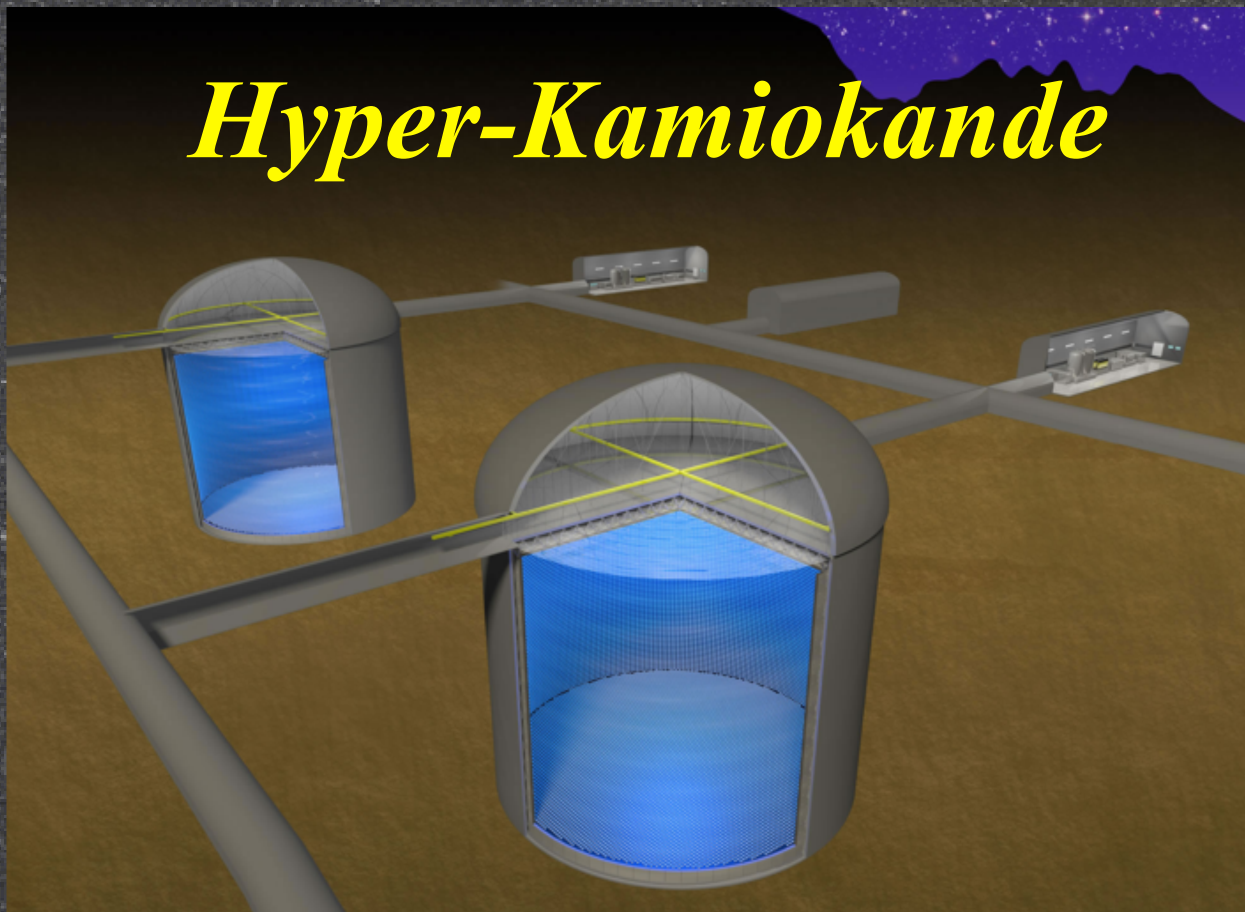
T2K-II upgrades

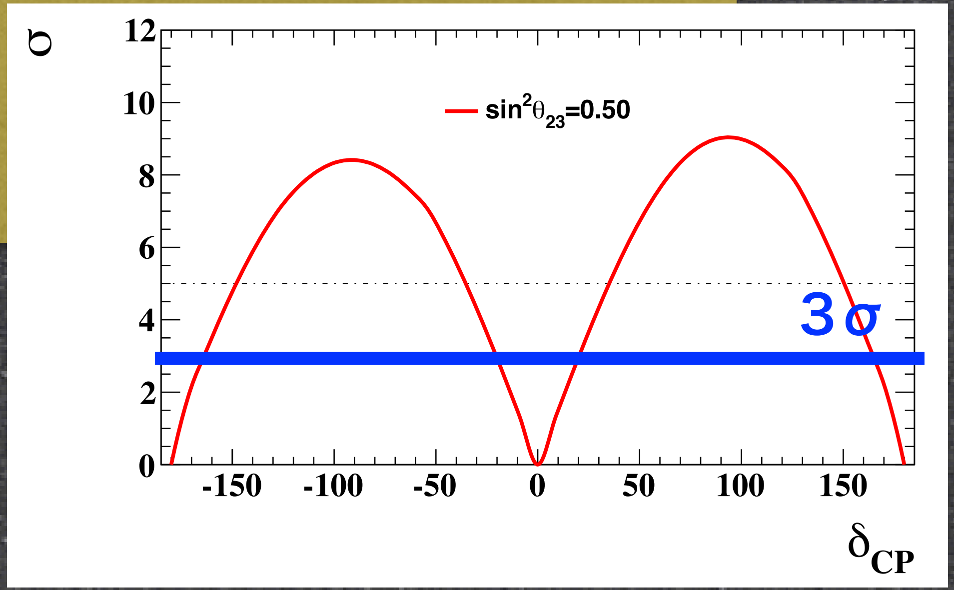
- In order to reach T2K-II physics goal there will be updates to the accelerator complex (from 400 kW to 1.3 MW)
- Possible ND280 upgrades are also being investigate to improve angular acceptance and measurements of neutrino interactions on water
- SK loading with Gadolinium to tag neutrons distinguishing ν from $\bar{\nu}$





Towards HyperKamiokande





Hyper-K Design Report (7E21 POT for nu and 20E21 POT for anti-nu)

		signal		BG						Total
		$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	BG Total	
ν mode	Events	2300	21	10	0	347	15	188	560	2880
	Eff.(%)	63.6	47.3	0.1	0.0	24.5	12.6	1.4	1.6	—
$\overline{\nu}$ mode	Events	289	1656	3	3	142	302	274	724	2669
	Eff. (%)	45.0	70.8	0.03	0.02	13.5	30.8	1.6	1.6	—

assuming δ_{CP}=0

- The next steps for neutrino physics in Japan will be Hyper-Kamiokande
- 500 kiloton water Cherenkov detector using J-PARC neutrino beam (1.3 MW power)
- Start data taking in 2027 → definite measurement of CP violation in the leptonic sector

Conclusions

- T2K is the leading long baseline neutrino oscillation experiment
  - First observation of (electron) neutrino appearance and measurement of θ_{13}
  - Best measurement of atmospheric mixing angle θ_{23}
  - Hints of CP violation in the leptonic sector → look forward for new results at Neutrino
  - Many nice measurements with the Near Detector
- It has been very exciting to be part of it!
- And it will still be
  - In the next 10 years we expect to increase by a factor of 20 the effective statistics
  - Have >3 sigma sensitivity to δ_{CP}
  - Open the way to the next generation → HyperKamiokande

Merci!
Grazie!
Thanks!

Back-up

ν OSCILLATIONS AT T2K

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4 2\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \Delta m^2_{31} \frac{L}{4E}$$

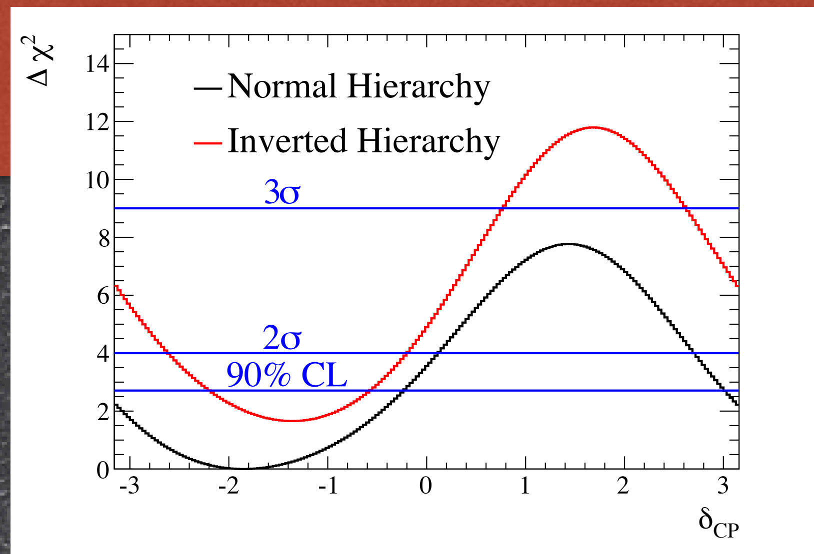
- Precision measurement of $2\theta_{23.}$
- CPT tests with antineutrino mode ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)

$$\begin{aligned} P(\nu_\mu \to \nu_e) \sim\ & \sin^2 2\theta_{13} && \times \boxed{\sin^2 \theta_{23}} && \times \boxed{\frac{\sin^2[(1-x)\Delta]}{(1-x)^2}} \\ & \boxed{-\alpha \sin\delta} && \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} && \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\ & +\alpha\cos\delta && \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} && \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\ & +\mathcal{O}(\alpha^2) \end{aligned}$$

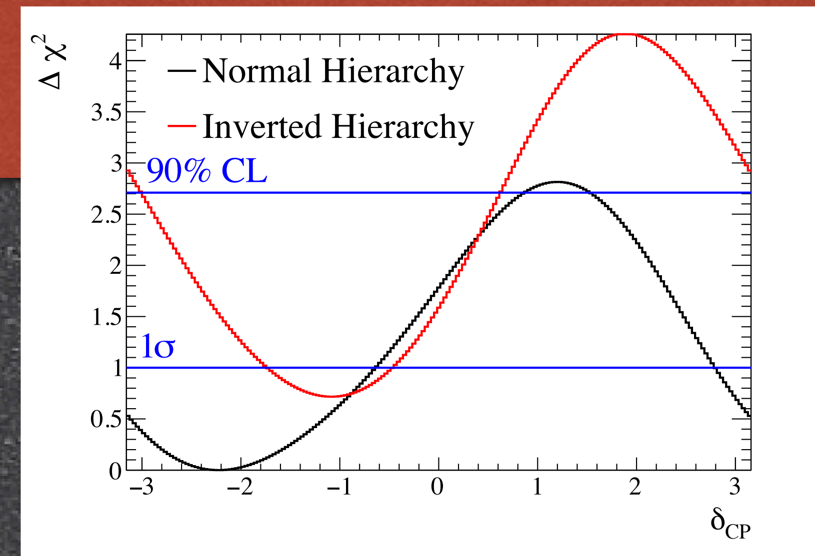
$$\alpha = \left| \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad \boxed{x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}}$$

M. Freund, Phys.Rev. D64 (2001) 053003

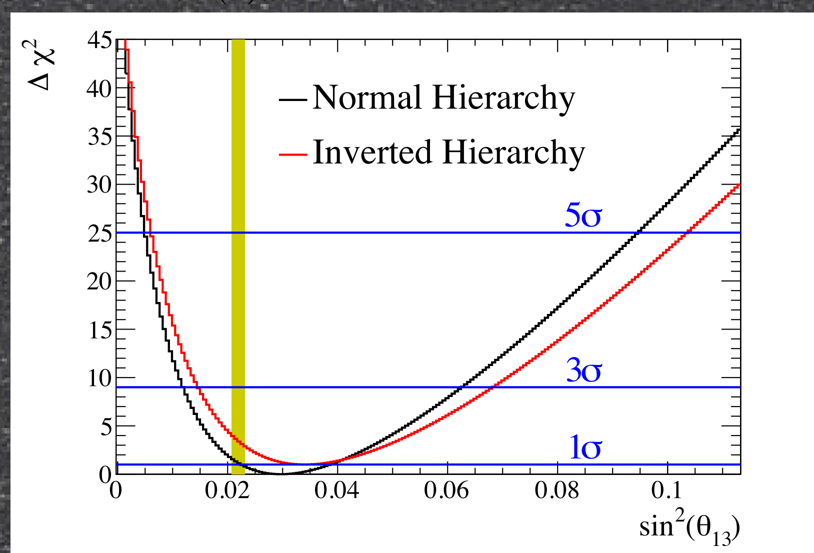
- **θ_{23} dependence of leading term: "octant" dependence (θ_{23}=/>/<45°?)**
- **CP odd phase δ: asymmetry of probabilities P($\nu_\mu \to \nu_e$) ≠ P($\bar{\nu}_\mu \to \bar{\nu}_e$) if sin δ ≠ 0**
- **Matter effect through x: ν_e ($\bar{\nu}_e$) enhanced in normal (inverted) hierarchy**



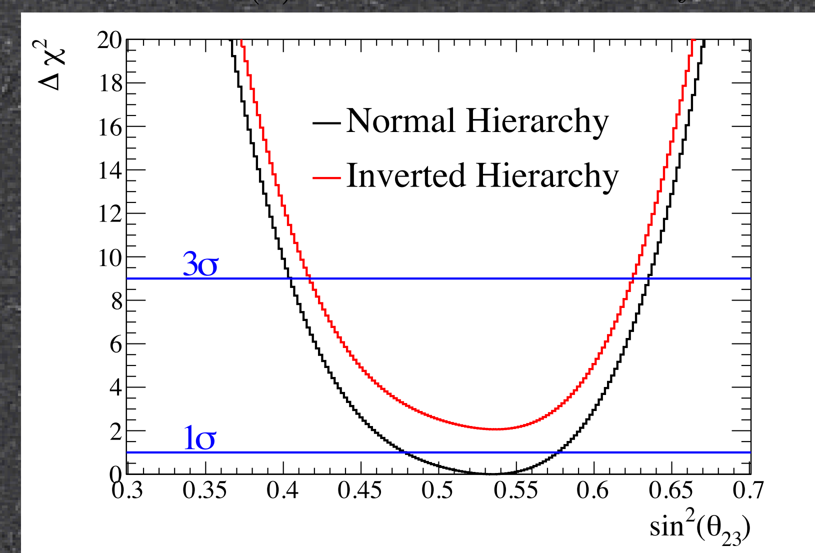
(a) δ_{CP} with reactor constraint



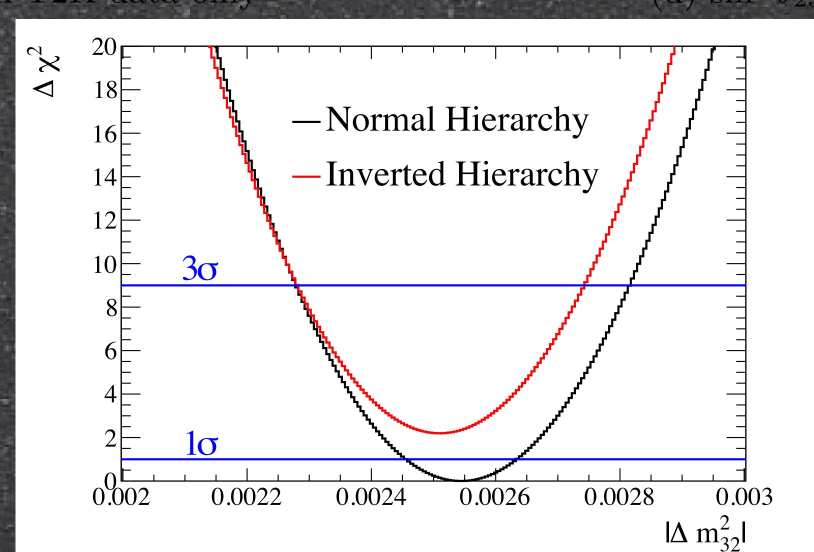
(b) δ_{CP} with T2K data only



(c) $\sin^2\theta_{13}$ with T2K data only

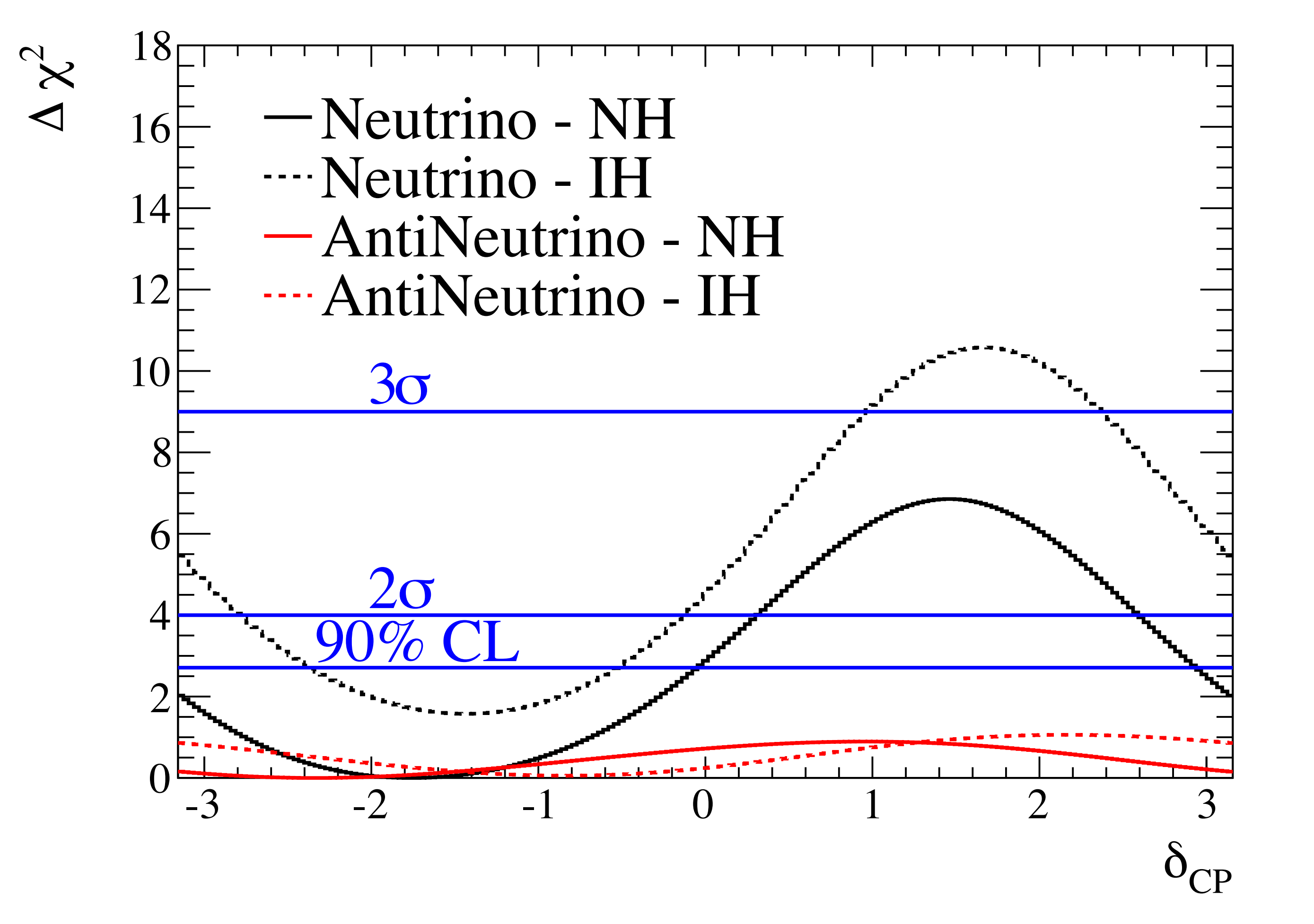


(d) $\sin^2\theta_{23}$ with reactor constraint



(e) Δm^2_{32} (Δm^2_{13}) with reactor constraint

Neutrino/Antineutrino



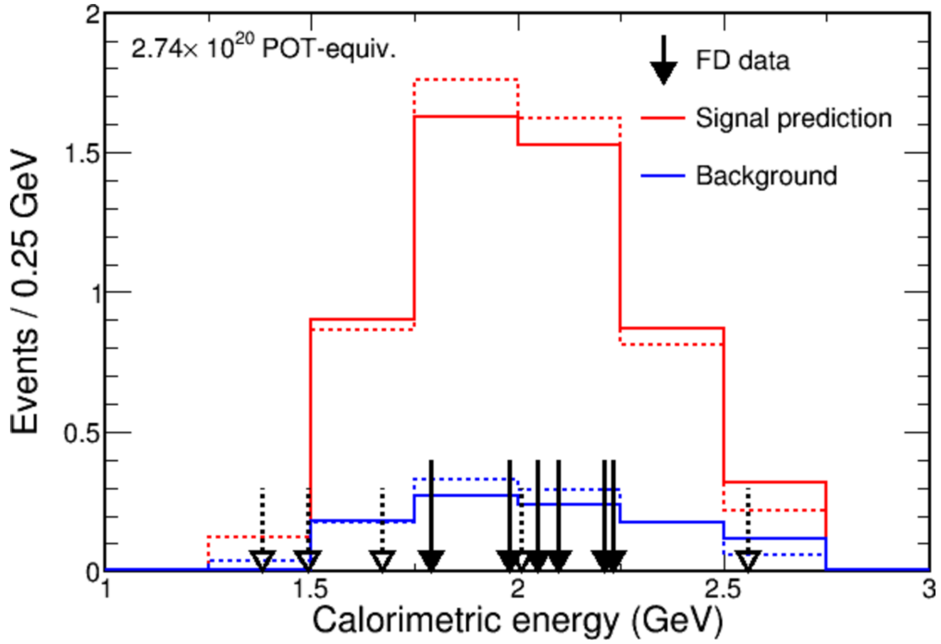
NOVA results

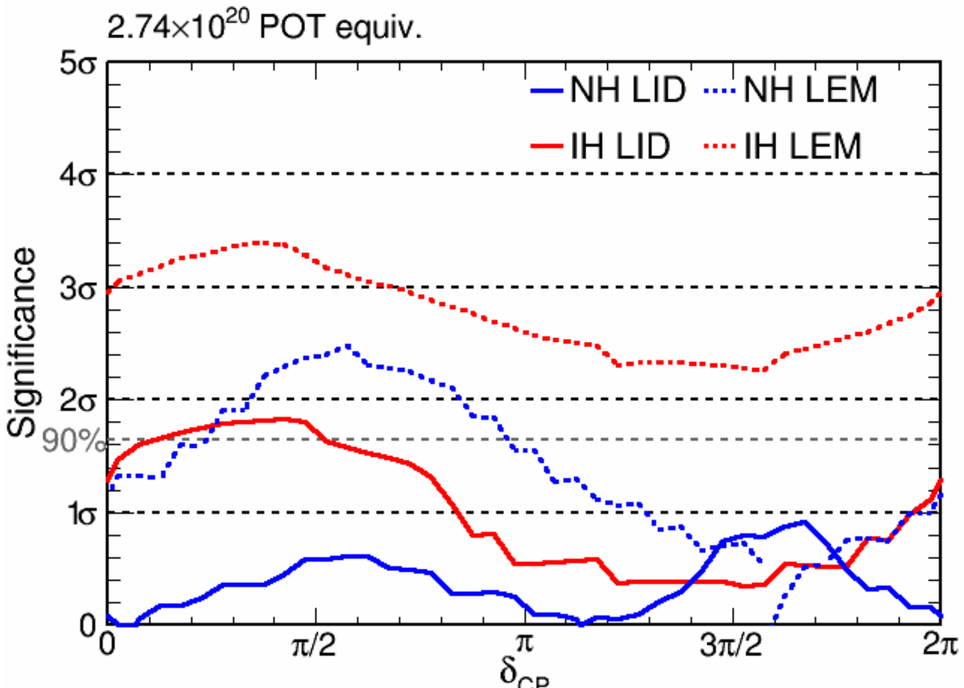
Two ν_e CC event selectors

- EM shower likelihood based – LID
- Library Event Matching - LEM
- Observe 6 LID, 11 LEM on BG of 1
  - 3.3 σ (LID), 5.3 σ (LEM)
- All LID events are in LEM
  - 7.8% P-value for this combination given expected overlap

Significance of NOvA result vs. Mass Hierarchy and δ_{CP}

- Use reactor θ_{13} constraint
- Marginalize over θ_{23}, other unknowns
- Hint in favor of Normal Hierarchy and δ_{CP}~$3\pi/2$

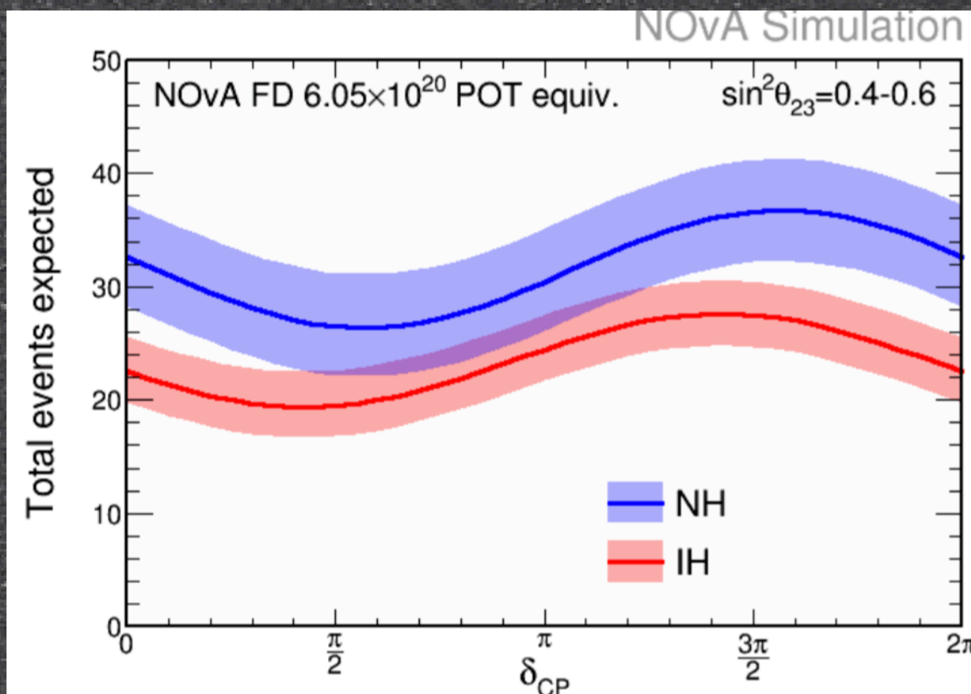




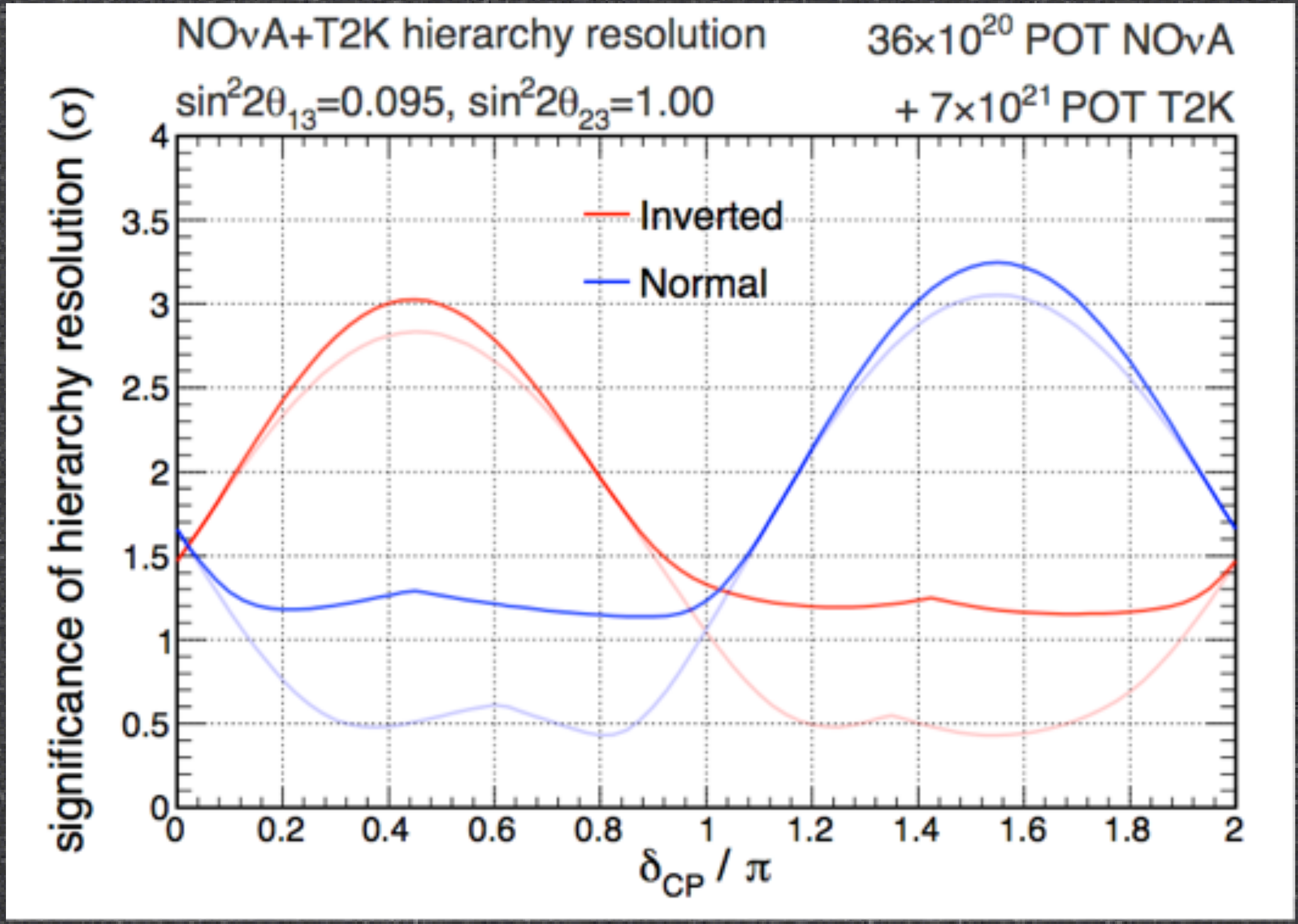
Phys. Rev. Lett. ***116****, 151806*

NOVA status

Expected events at Neutrino
→ increased efficiency by 40%



MH sensitivity at the end of the data taking
(with old efficiencies)



Stably running at 400-500 kW, already
collected 17% of their POT goal
Will probably run anti-neutrino
starting from next year