Highlights from the T2K experiment

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(for the T2K collaboration)

GDR Neutrino 2014
Marseille, 26 - 27 November

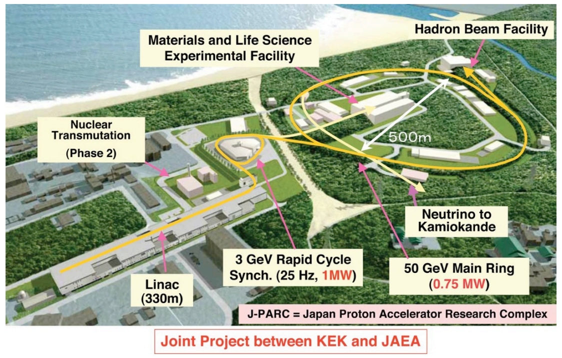
The T2K experiment

- Long baseline neutrino oscillation experiment in Japan (Tokai to Kamioka)
- Muon neutrinos produced from a 30 GeV proton beam (JPARC)
- Neutrinos detected at 2 points :
  - the near detector (**ND280**) at 280 m
  - the far detector (**Super-Kamiokande**) at 295 Km

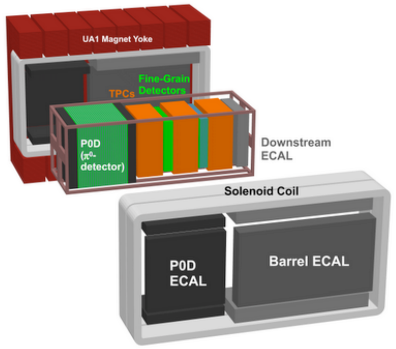
Two main goals :

- **ν_μ disappearance $P(\nu_\mu \rightarrow \nu_\mu)$:** measure Δm^2_{32} and ϑ_{23}
- **ν_e appearance $P(\nu_\mu \rightarrow \nu_e)$:** measure ϑ_{13} and constrain δ_{CP}

Japan Proton Accelerator Research Complex **(JPARC)**



Far Detector
(~300Km)

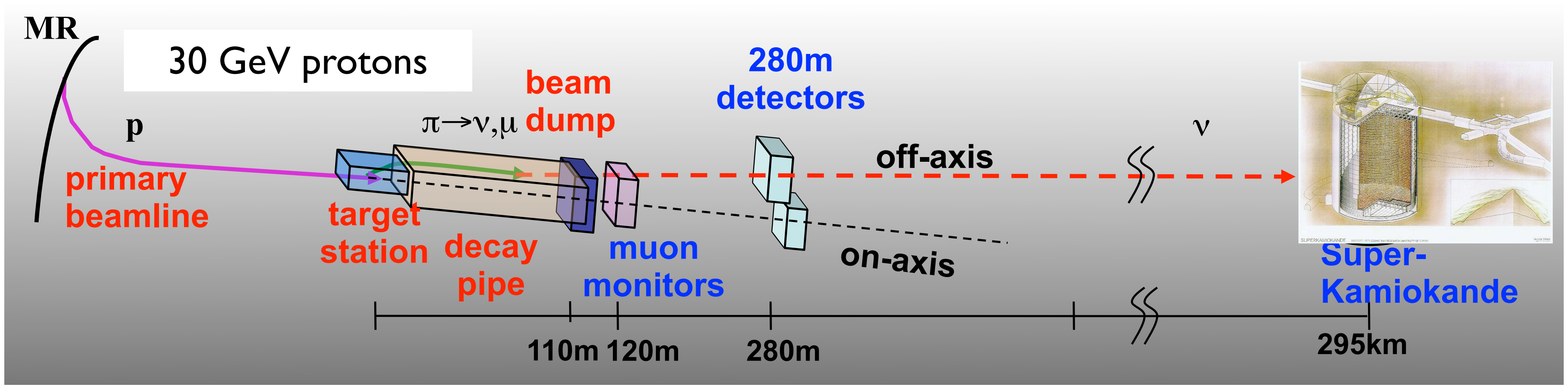


Near Detector
(@~280m)

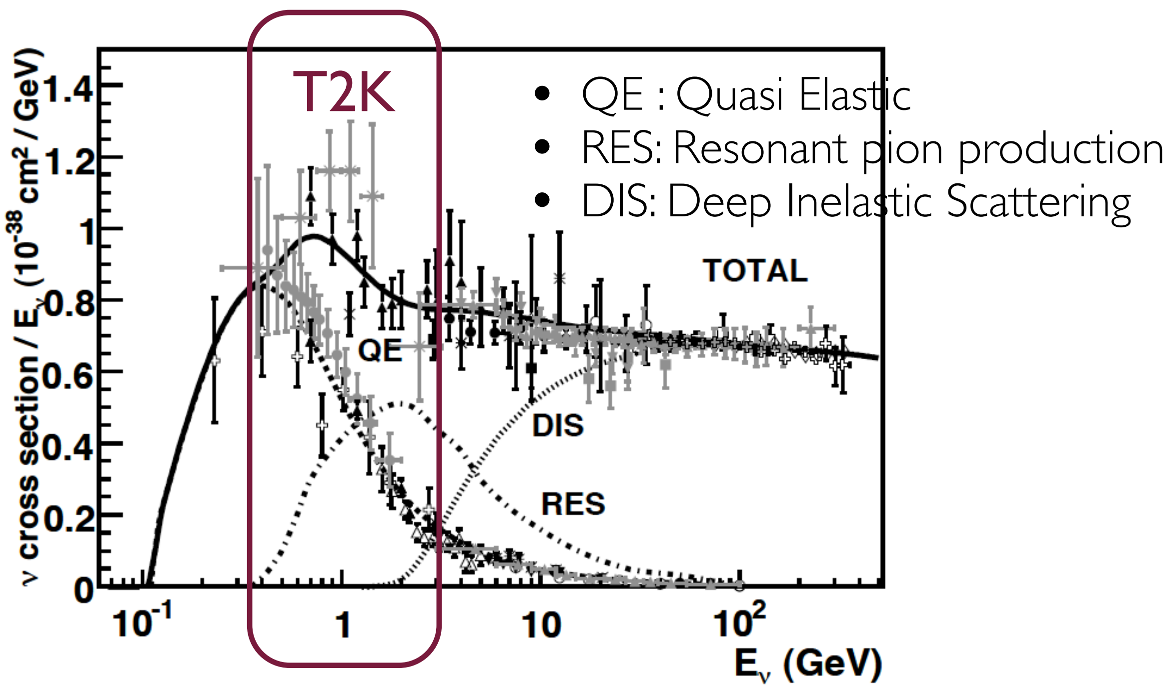
Overview of the talk

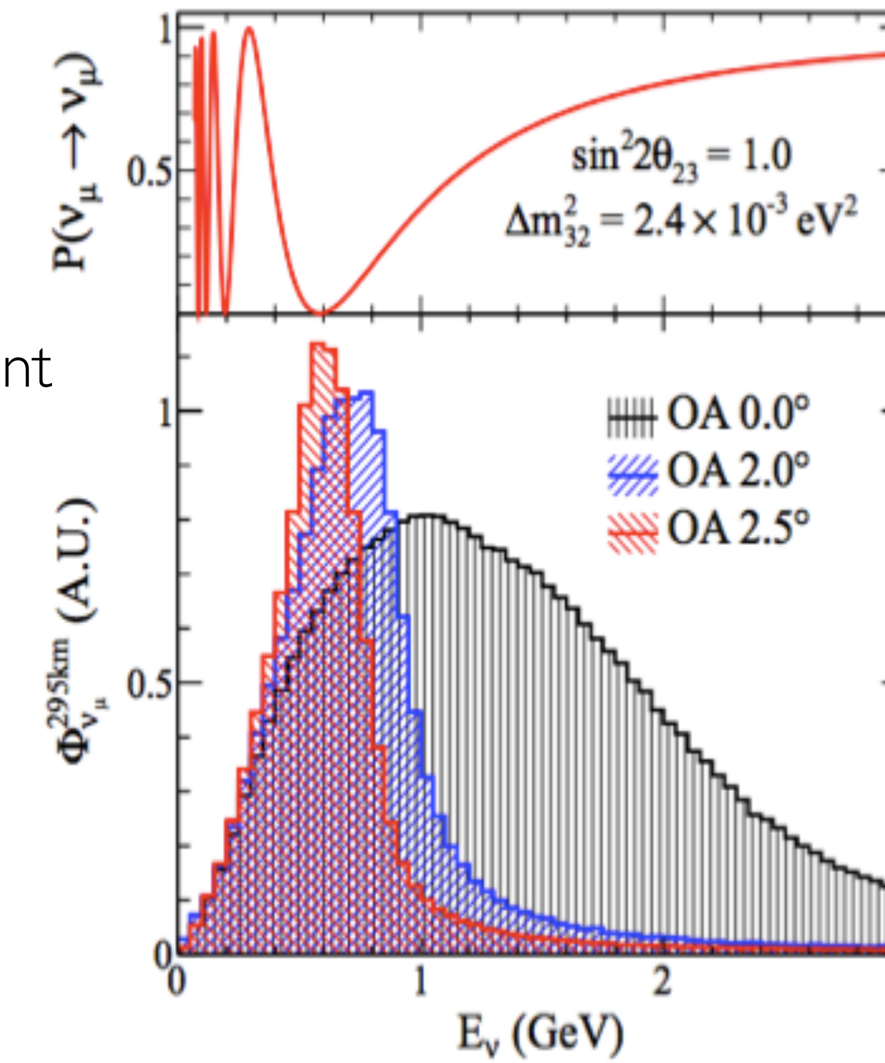
- **The T2K experiment** : design principle and the T2K detectors
- **The T2K analysis strategy**
- **Oscillation analyses**
  - ν_e appearance
  - ν_μ disappearance
  - joint ν_e-ν_μ analyses
- **Exotic physics**
- **Toward the future**

The design principle



- First experiment using an **off-axis technique (2.5°)**
  - **Narrow-band beam** peaked at the oscillation maximum
  - Reduce the high-energy tail of the spectrum: **reduction of the background** to oscillation analyses: DIS, RES and Neutral Current





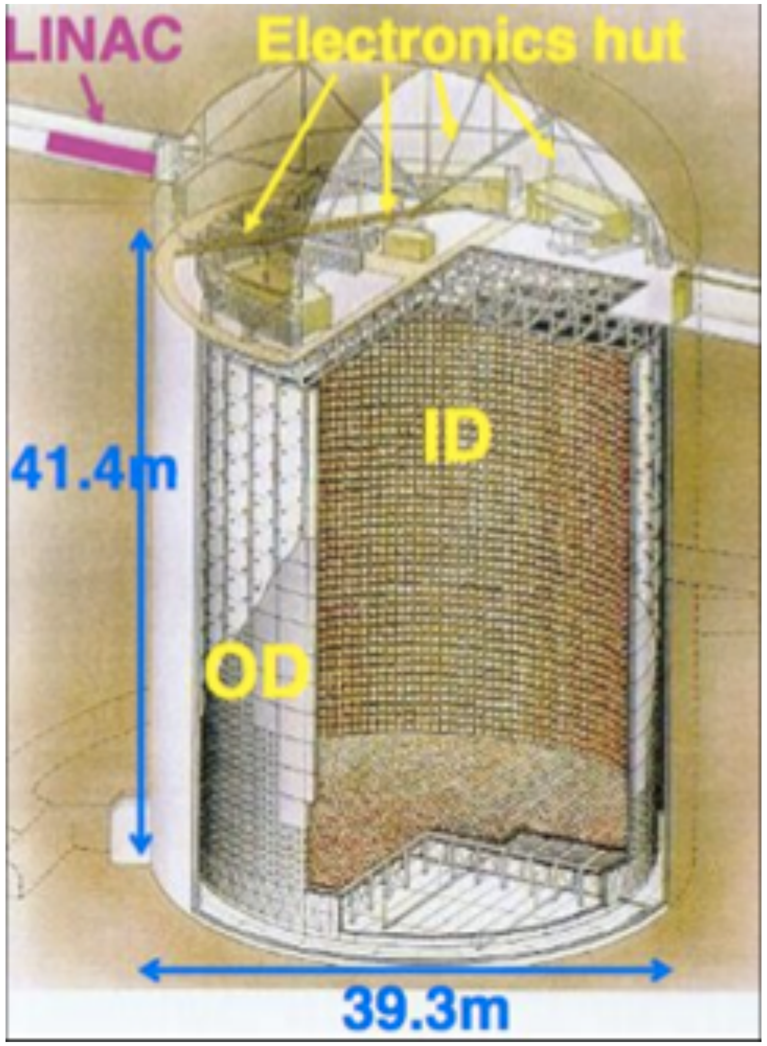
The SK detector

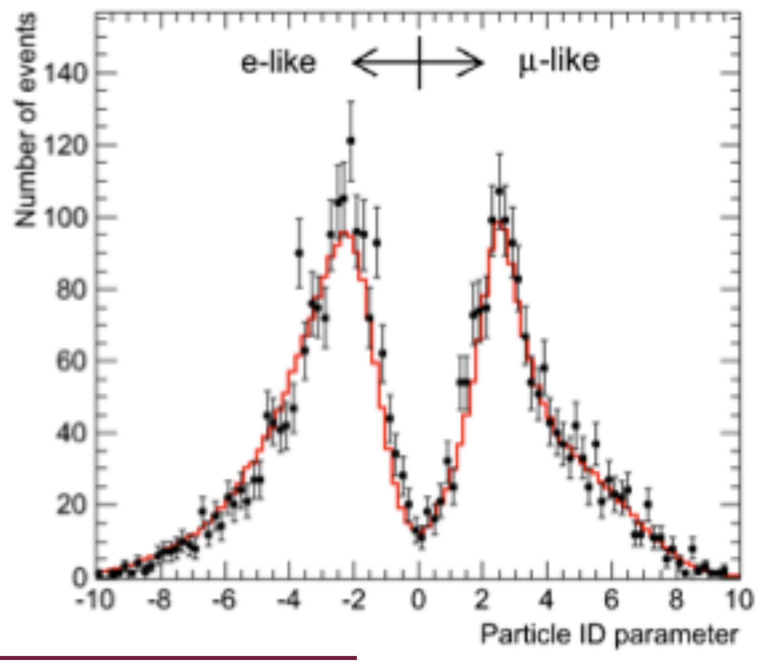
- Cylindrical detector located at ~1Km underground in the Kamioka mine (295 Km from the proton target)

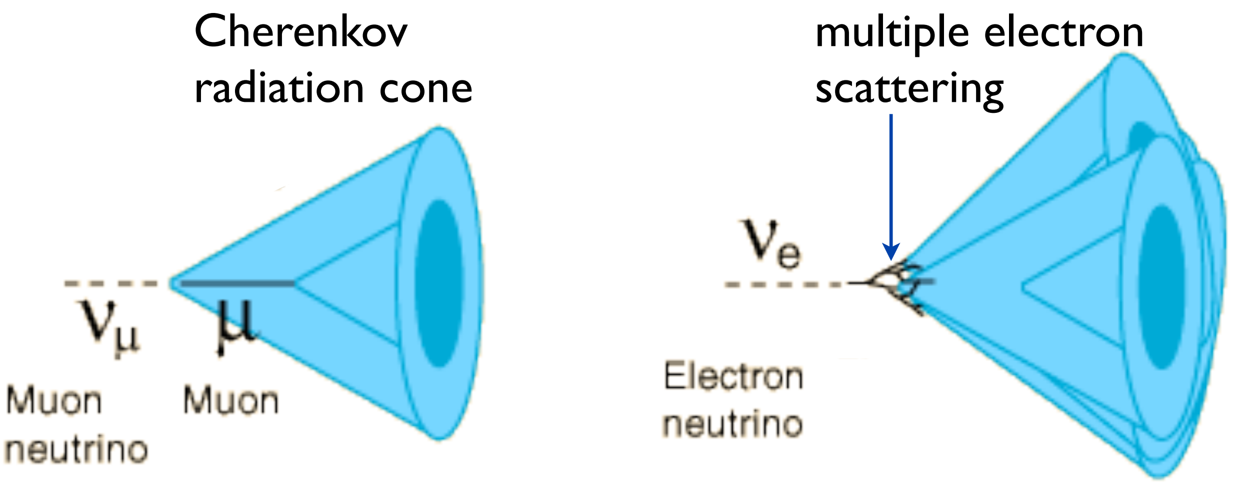
- Filled with 50 kton of ultra pure water (**22,5 kton FV**)
  - Inner detector (ID) : ~11 000 inward facing PMTs
  - Outer detector (OD): ~2 000 outward facing PMTs to veto external background

- Detection based on **Cherenkov technique**

- Very good capabilities to **distinguish electrons from muons**



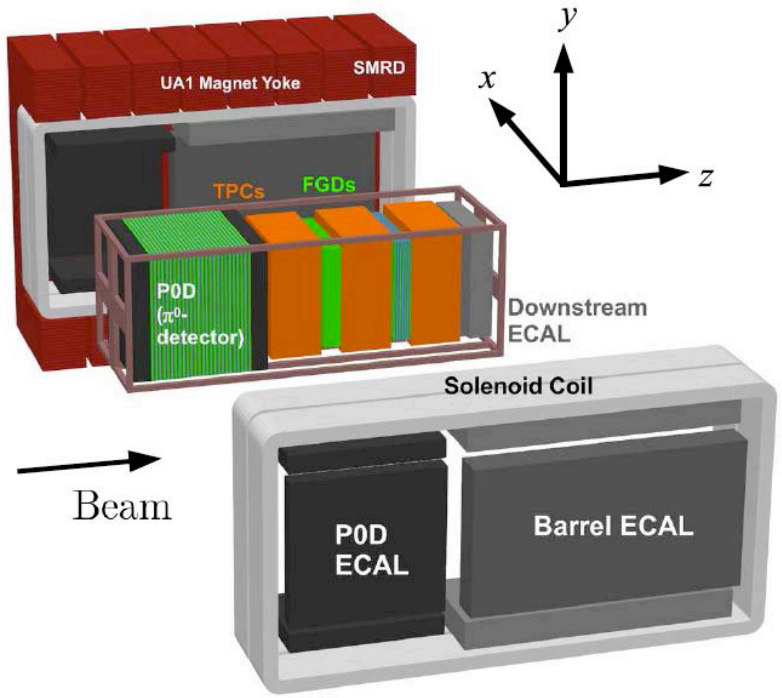




The T2K near detectors

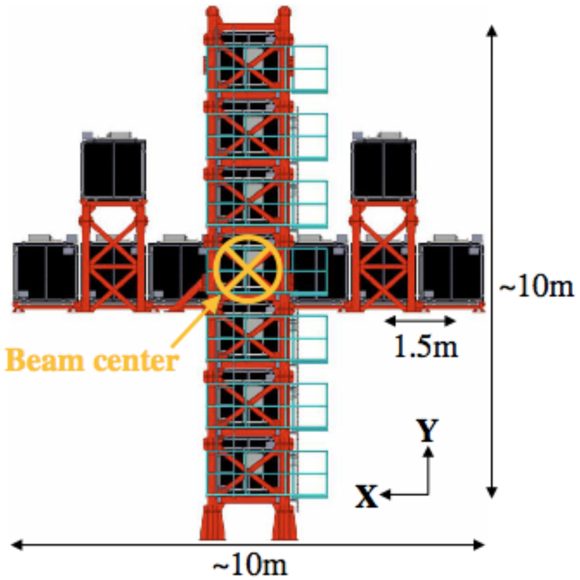
ND280 detectors

- **Same off-axis angle as SK →** cancelation of the shared systematics
- Located inside the UA1/NOMAD magnet (0.2 T magnetic field)
  - ✦ Dedicated π^0 detector (P0D)
  - ✦ Tracker :
    - ✦ Fine Grained detectors (FGDs) as active target
    - ✦ Gas TPCs for momentum measurements and PID
  - ✦ Surrounded by EM calorimeters and muon detectors (SMRD)



INGRID detector

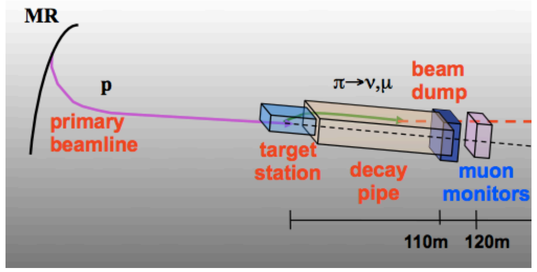
- **On-axis near detector**
- Monitor the beam stability day by day using neutrino interactions
  - ✦ 16 identical modules arranged as a cross composed by iron and scintillators
  - ✦ 1 proton module only composed of scintillators for neutrino cross section measurements



The T2K analysis strategy

Neutrino Flux prediction :

- Simulation of hadronic interactions in target and propagation of secondary particles
- Hadron production data from NA61/SHINE



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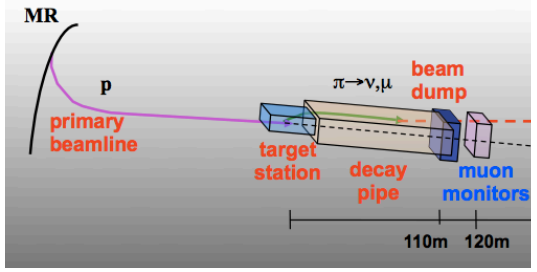

Cross section models:
- Interaction generator (NEUT)
- External data (MiniBooNE)

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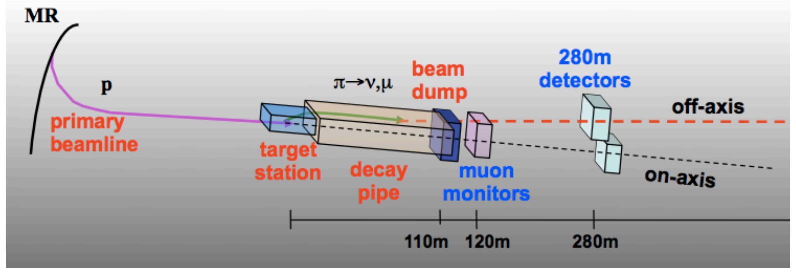
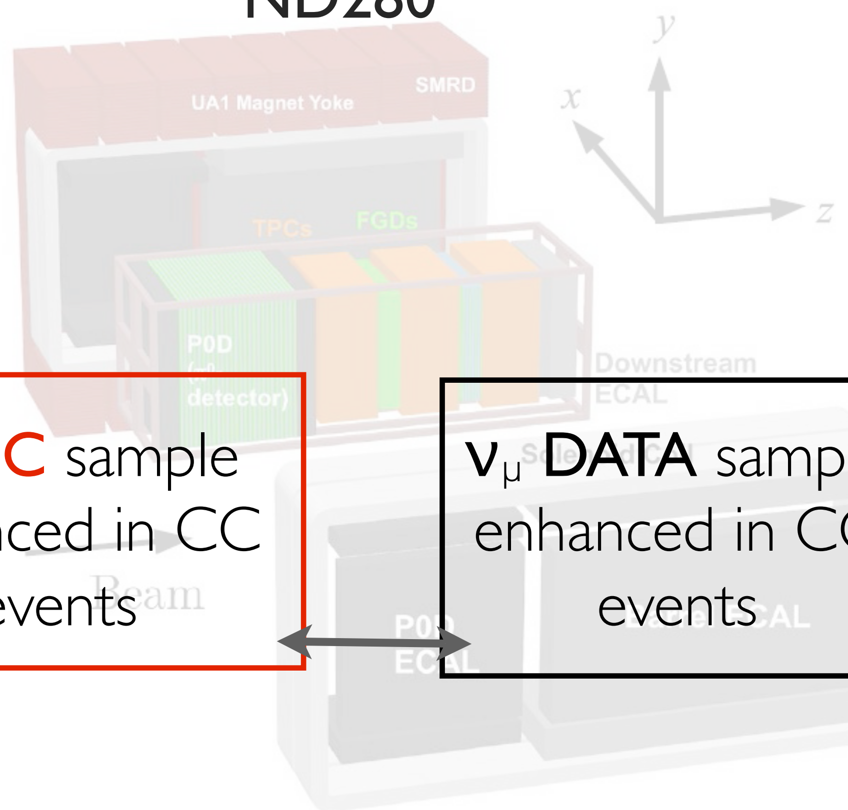


ND280



ν_μ MC sample enhanced in CC events

ν_μ **DATA** sample enhanced in CC events

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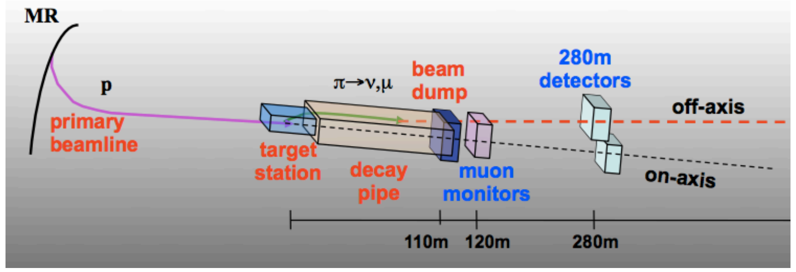
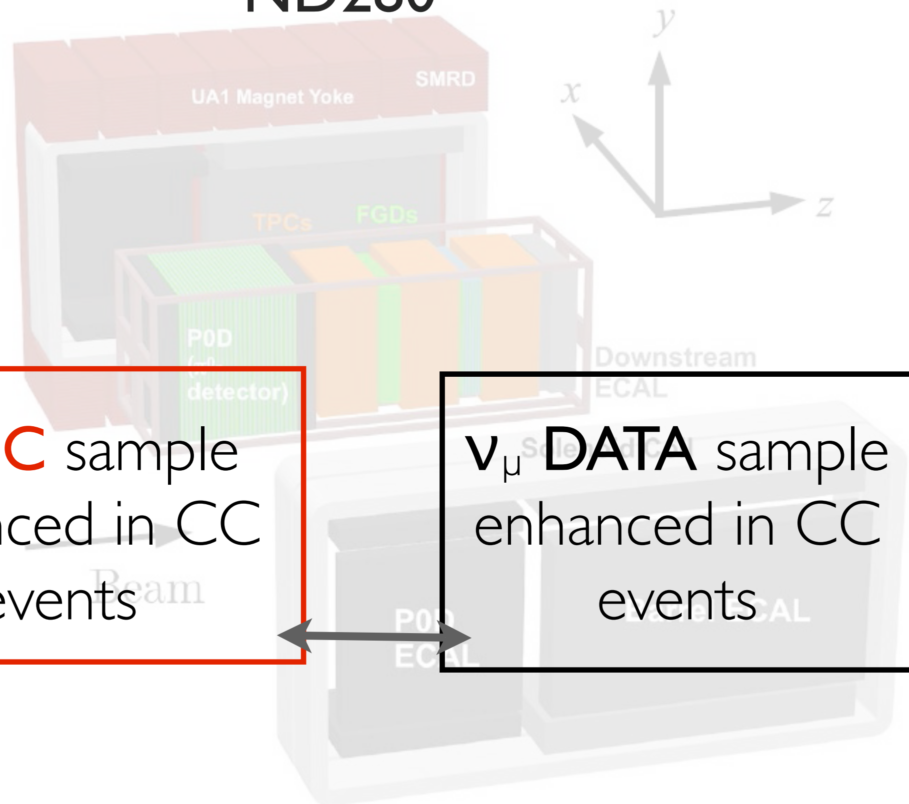


ND280



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ν_μ **DATA** sample enhanced in CC events

Fit to ND280 data constrains flux and cross section parameters

Cross section models:
- Interaction generator (NEUT)
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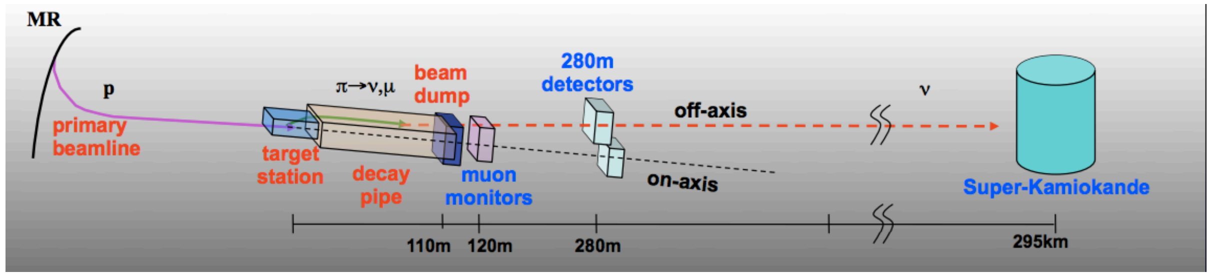


ND280

ν_μ MC sample enhanced in CC events

ν_μ DATA sample enhanced in CC events

Fit to ND280 data constrains flux and cross section parameters

Super-Kamiokande

expected ν_e (ν_μ) events for unosc. spectra in MC

ν_e (ν_μ) events selection in DATA

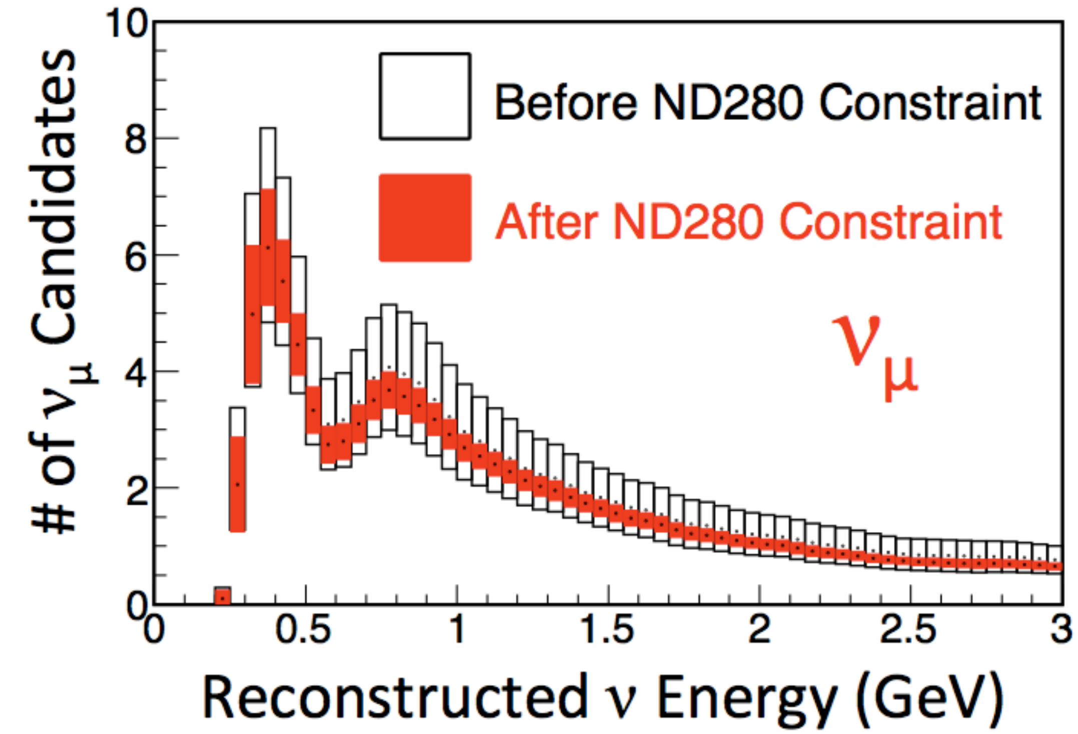
Cross section models:
- Interaction generator (NEUT)
- External data (MiniBooNE)

Extraction of the oscillation parameters

Systematic uncertainties

- Strong reduction of the systematic uncertainties to the event rate at Super-Kamiokande thanks to the ND280 data

- Current systematics already < 10%



		ν_μ sample	ν_e sample
ν flux and cross section	w/o ND measurement	21.8%	26.0%
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ν cross section due to difference of nuclear target btw. near and far		5.0%	4.7%
Final or Secondary Hadronic Interaction		3.0%	2.4%
Super-K detector		4.0%	2.7%
total	w/o ND measurement	23.5%	26.8%
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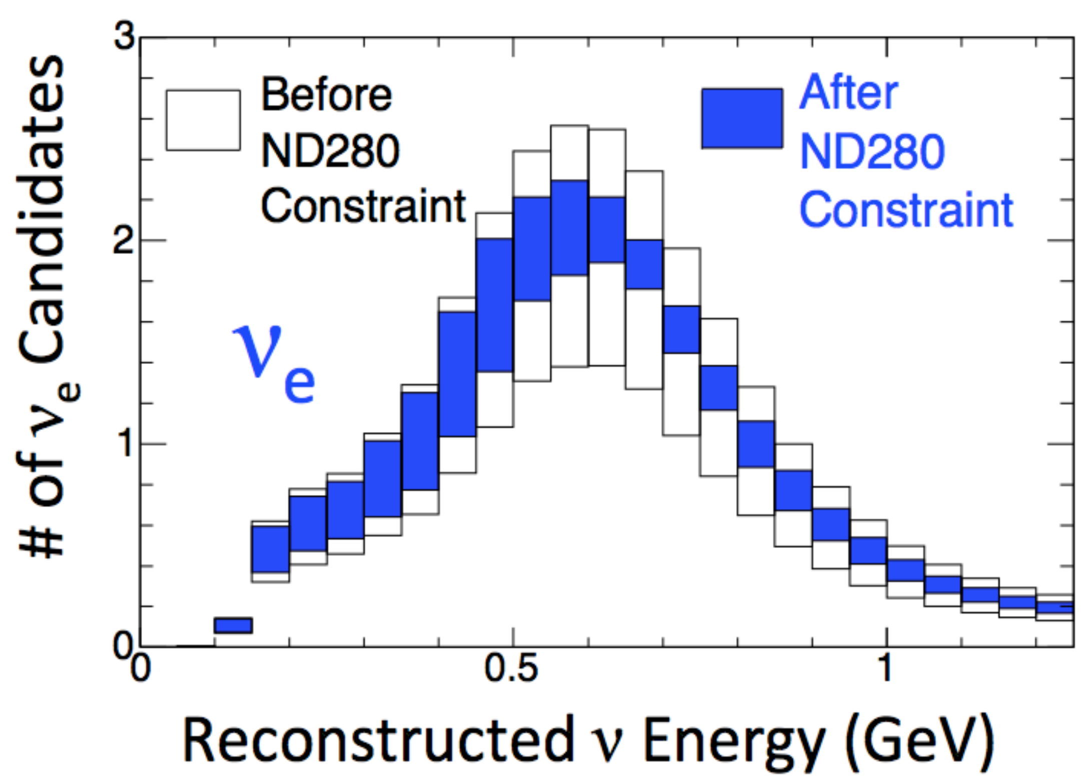
Fractional error on number-of-event prediction

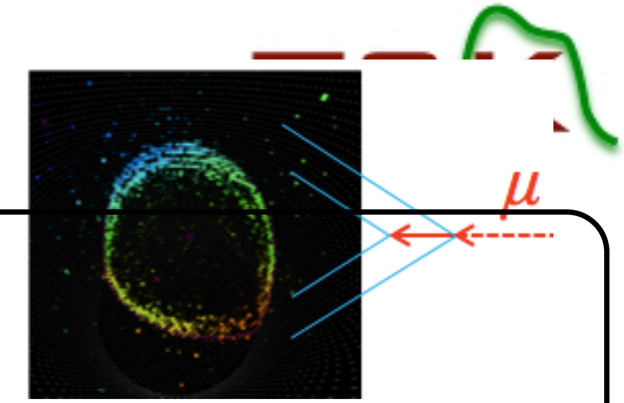


Note: Systematics error updated for joint analyses

SK events selection

- Fully contained
- Inside the FV
- 1 ring

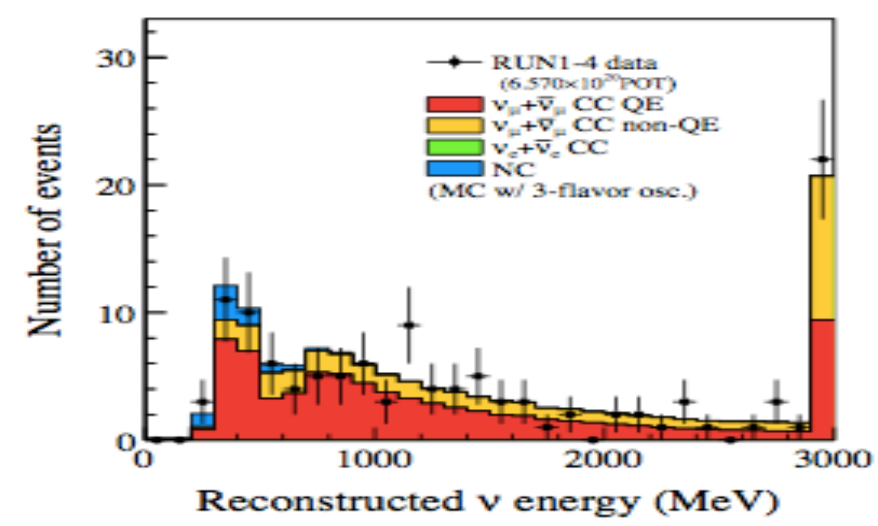
ν_μ selection



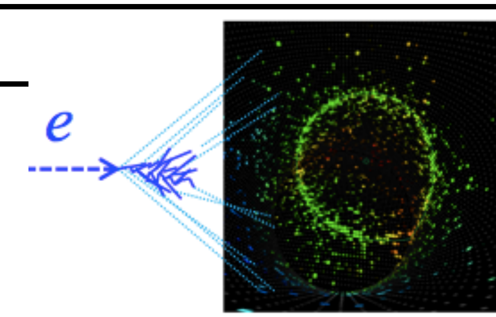
- Muon like
- p_μ > 200 MeV/c
- Decay-e <= 1

120 events observed

Expected events : 446±23 (syst)



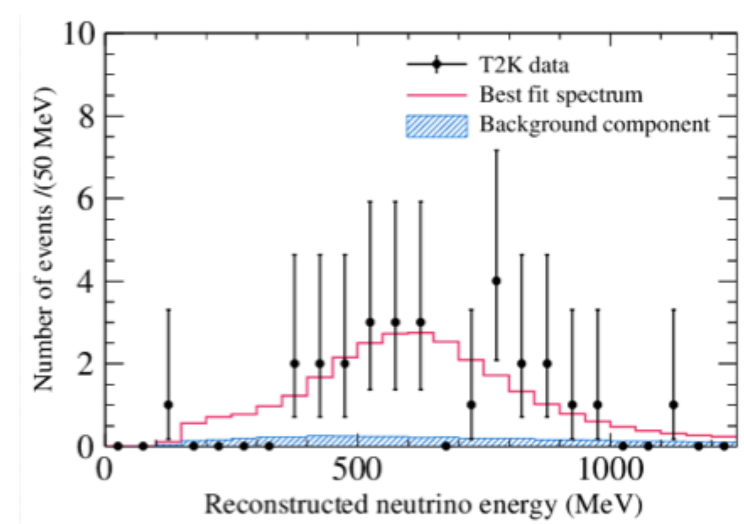
ν_e selection



- Electron like
- p_e > 100 MeV/c
- No Decay-e
- π^0 rejection
- Erec < 1250 MeV

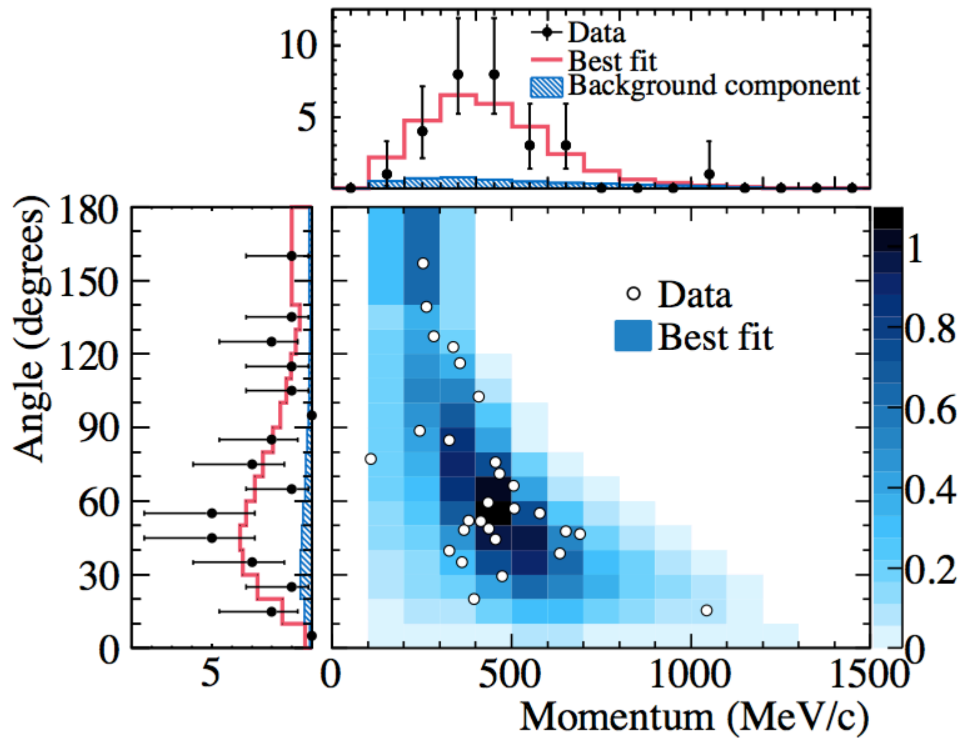
28 events observed

Expected events : 4.9±0.6 (syst)



Oscillation analyses results

ν_e appearance results

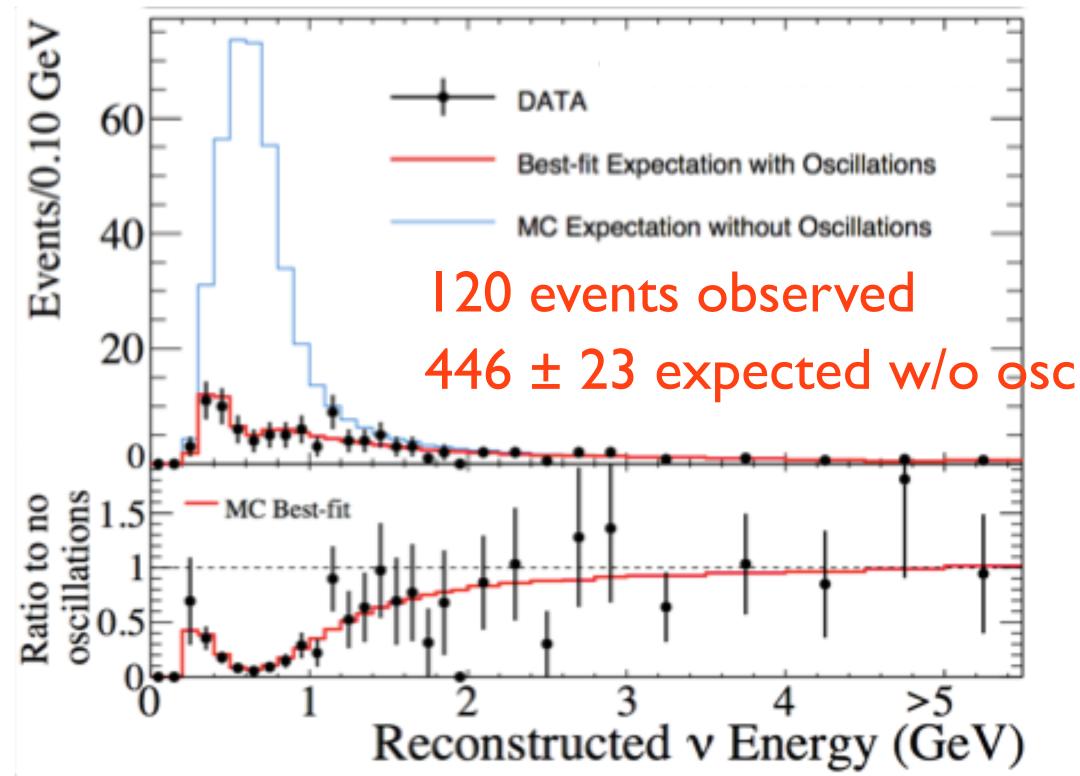


- Maximum likelihood fit in $\{p_e, \vartheta_e\}$
- Consistent with analysis based on E_{reco}

7.3σ significance to non-zero ϑ_{13}
Discovery of ν_e appearance!

- **Constraints on δ_{CP}** combining with reactors
- **Dependency to ϑ_{23}** → joint ν_e - ν_μ analysis

ν_μ disappearance results



- **World leading measurement for ϑ_{23}** : first time for an accelerator-based experiment !
- Maximal mixing is favored
- $\sin^2\vartheta_{23} = 0.514 \pm 0.055$ (NH) → 10% uncertainties corresponding to 3° on the angle

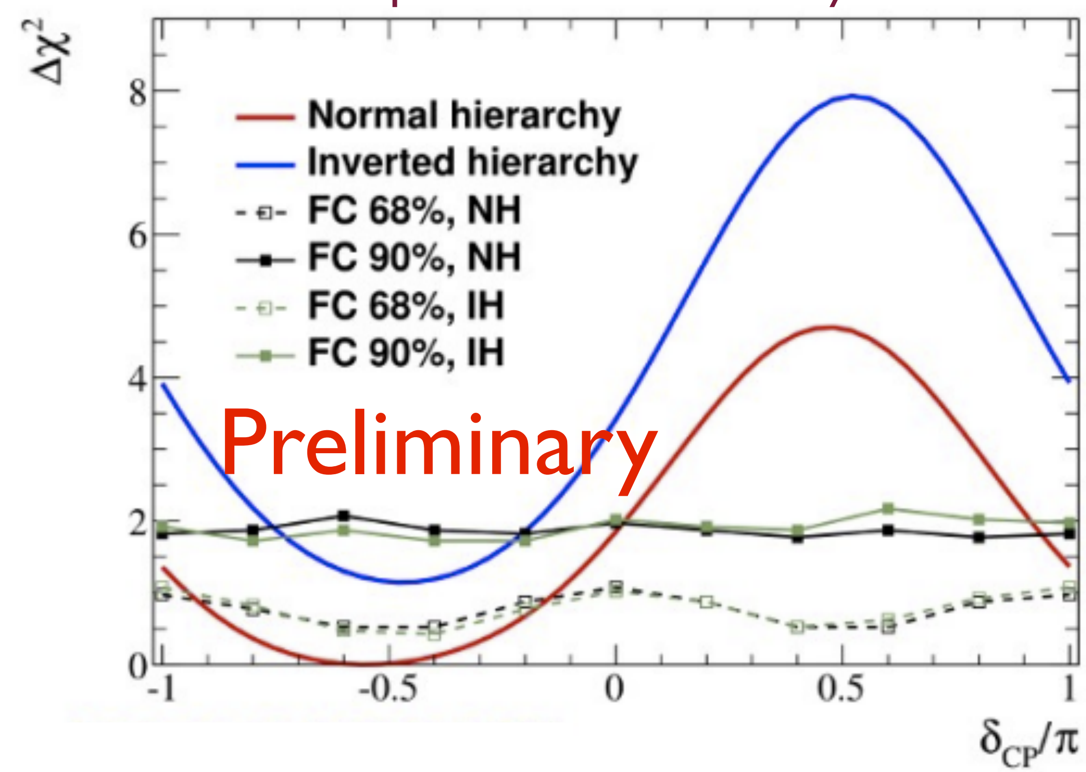
Joint ν_μ - ν_e fit analysis

- Two analyses: **frequentist** (w/ Feldman-Cousins) and **bayesian** (Markov Chain MC) approach
- The 4 oscillation parameters Δm^2_{32}, ϑ_{23}, ϑ_{13}, δ_{CP} are determined through a **simultaneous fit** of the reconstructed **energy spectra** of both ν_μ and ν_e samples (and ND280)
- Inclusion of reactor constraints (PDG 2013)
- **Best fit value for $\delta_{CP} \sim -\pi/2$**
- (Very) weak preference for NH and second octant

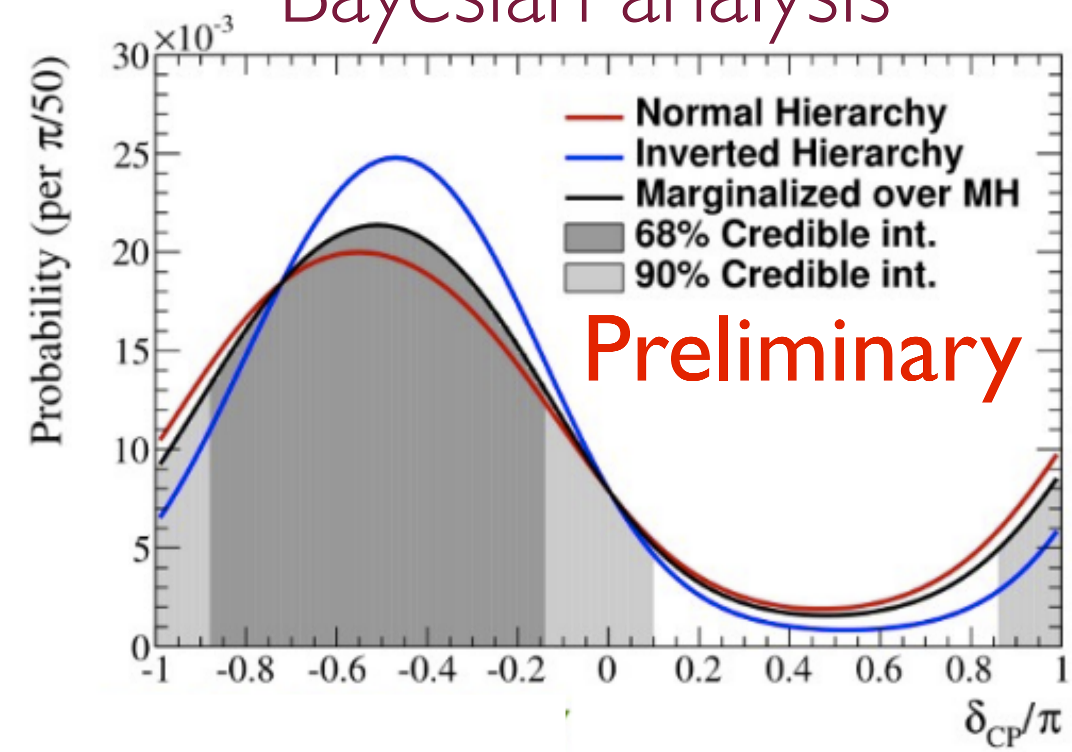
Posterior probability of different models (Bayesian analysis)

(%)	NH	IH	Sum
$\sin^2\vartheta_{23} \leq 0.5$	18	8	26%
$\sin^2\vartheta_{23} > 0.5$	50	24	74%
Sum	68%	32%	

Frequentist analysis



Bayesian analysis

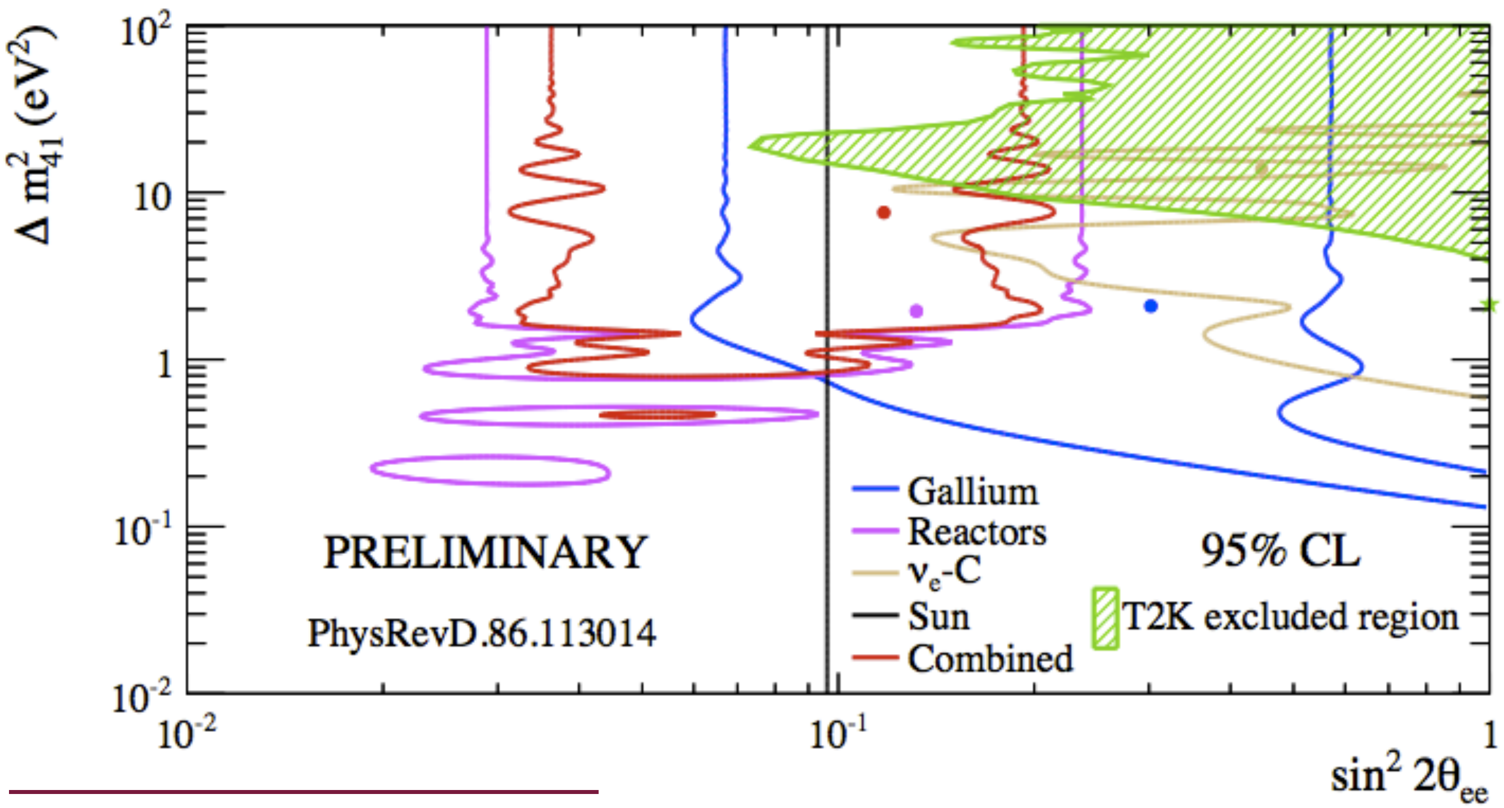


Exotic physics

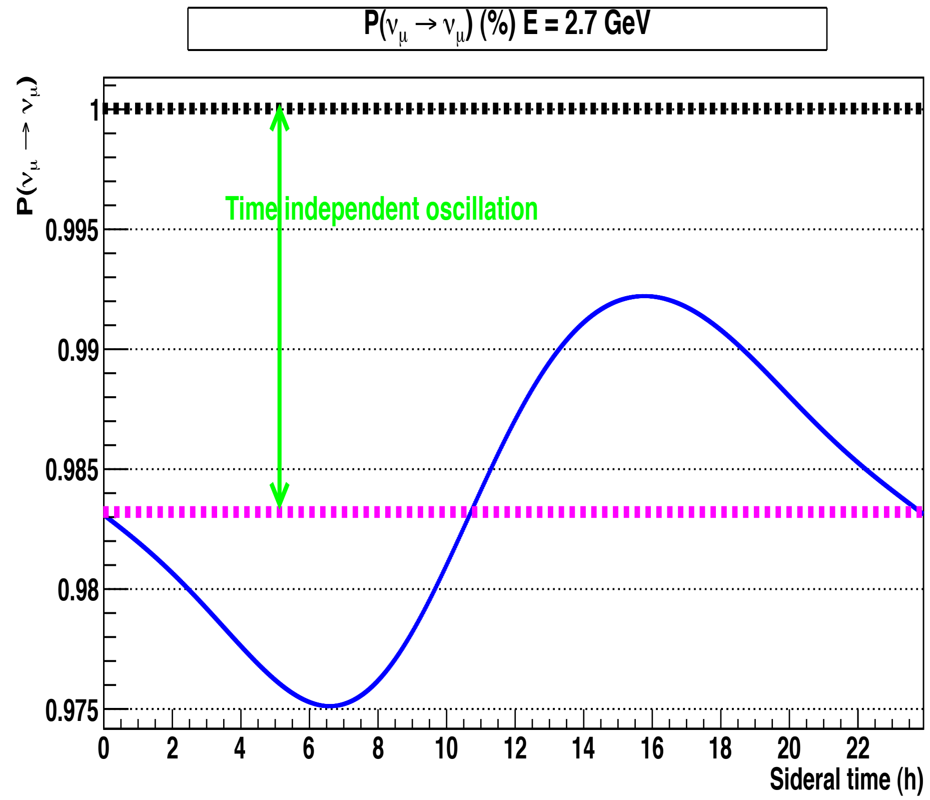
- The T2K collaboration is also performing searches for non standard physics processes :
  - Short baseline oscillations at ND280
    - **nue-disappearance:** published and presented at the previous GDR by Claudio
    - numu-disappearance: blind analysis, Monte Carlo sensitivity studies ongoing, not ready yet
  - Searches for Lorenz Violation with INGRID : blind analysis, Monte Carlo study almost ready for internal collaboration review

Search for SBL ν_e disappearance

arXiv:1410.8811 (submitted to PRD)



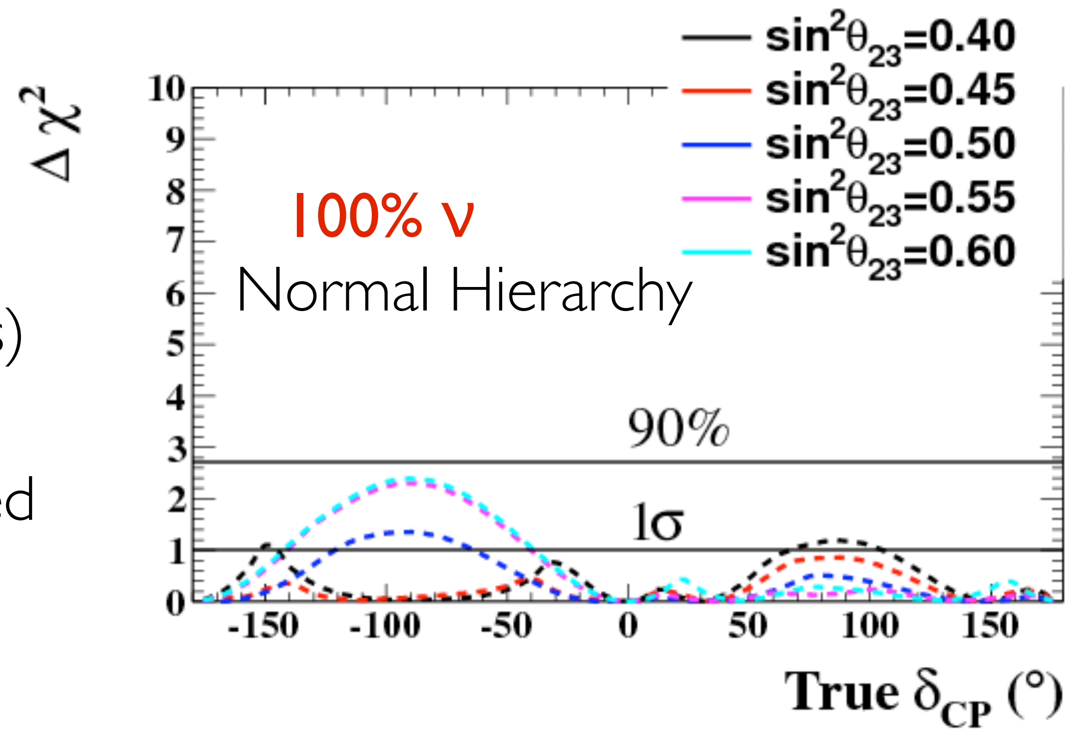
Search for Lorenz Violation



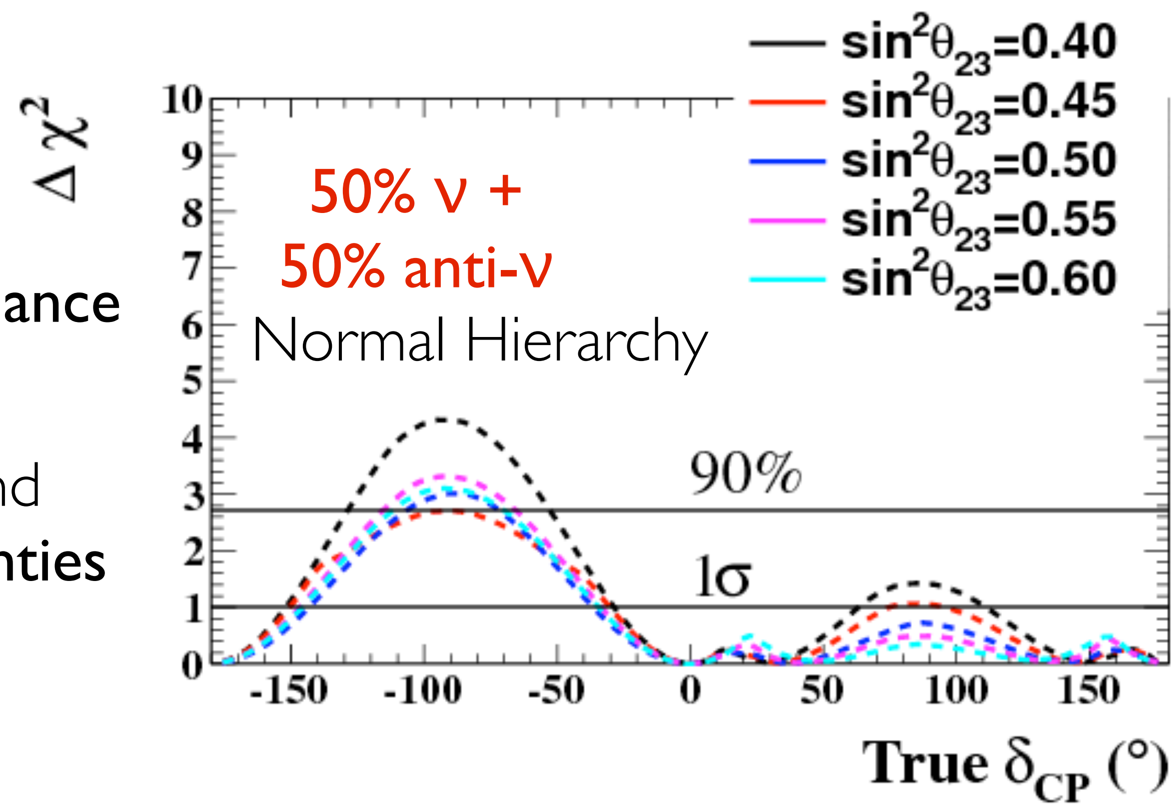
Toward the future

What's next ?

- World leading results with only 8% of the total expected statistics
  - First observation of the ν_e appearance
  - Best world measurement of $\sin^2\vartheta_{23}$ (10% uncertainties) through ν_μ disappearance
  - First hints of $\delta_{CP} \neq 0$ by joint ν_μ -ν_e analyses combined with reactor constraints

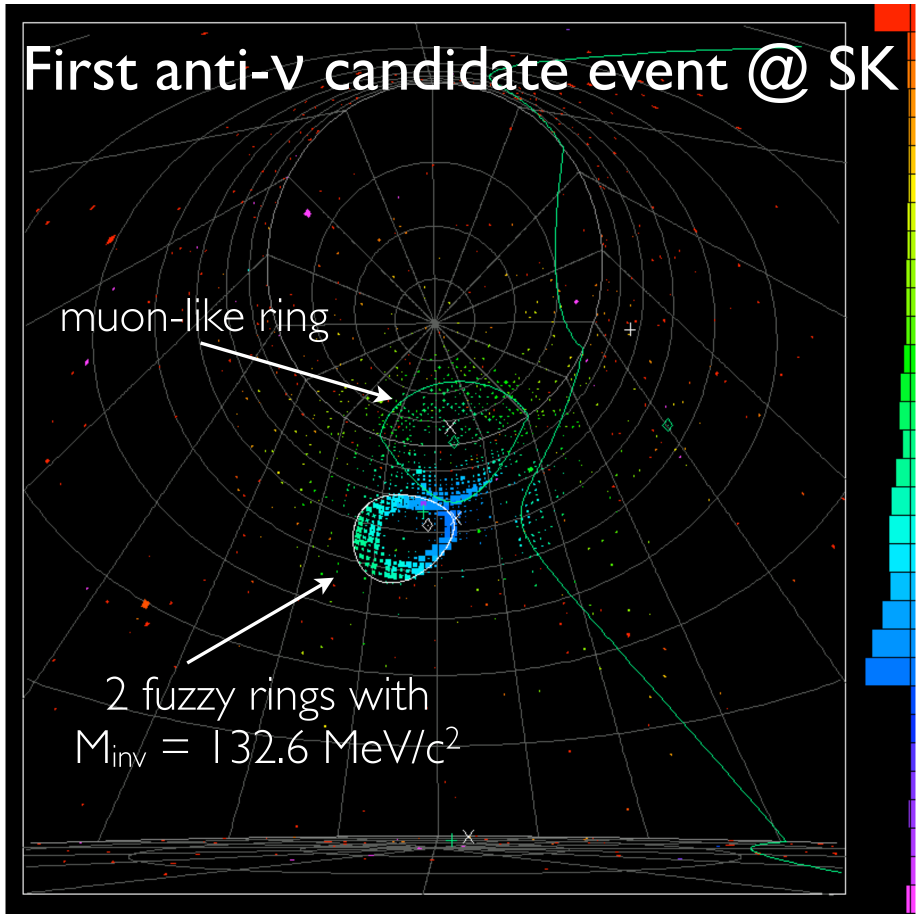


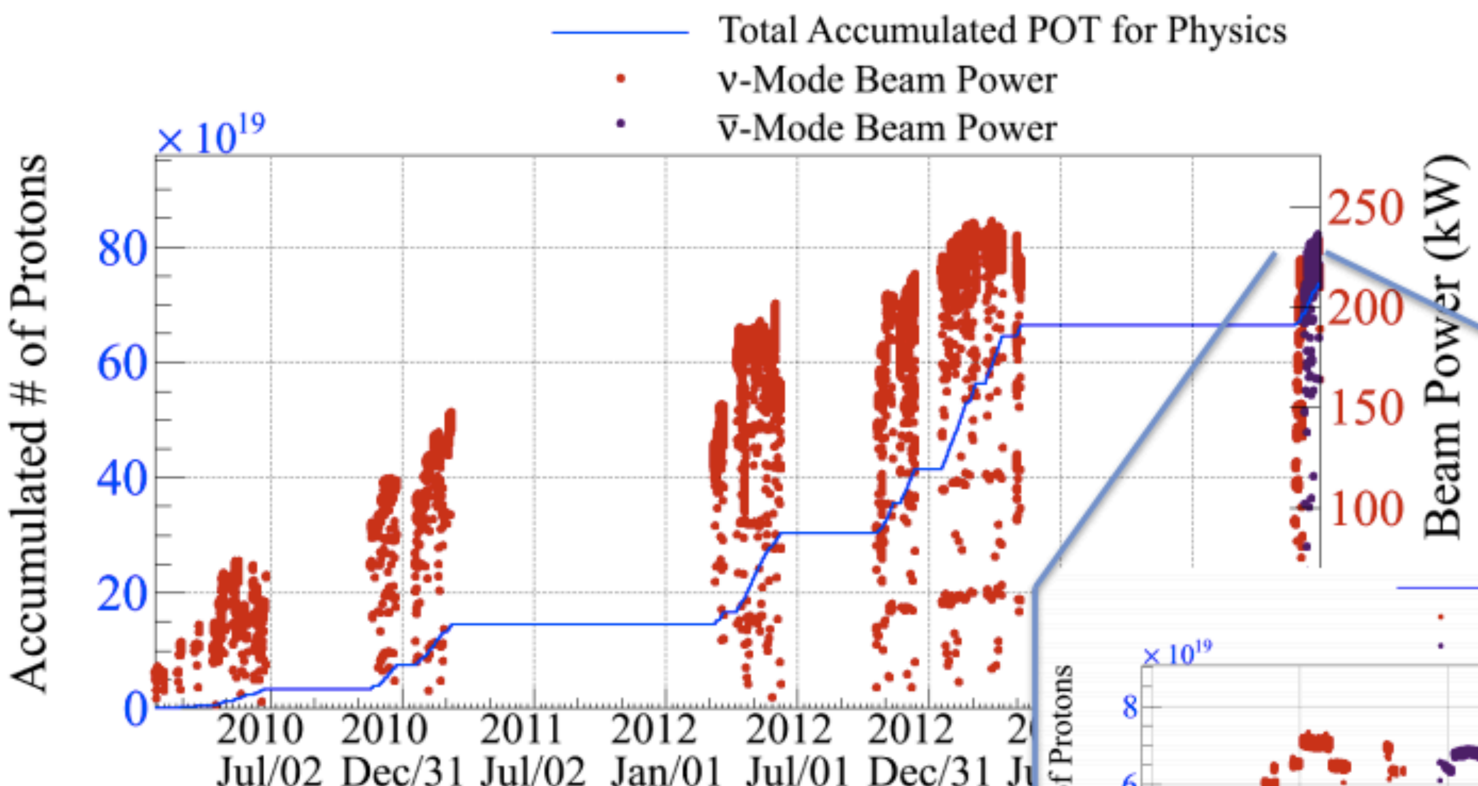
- Sensitivity studies have been performed to understand the physics potential of T2K
  - **Running 50% ν - 50% anti-ν mode will further enhance the T2K physics potential**
  - **To maximize the sensitivity to δ_{CP}**, with current and future generation experiment, **systematic uncertainties should be of the order of 2-3%**

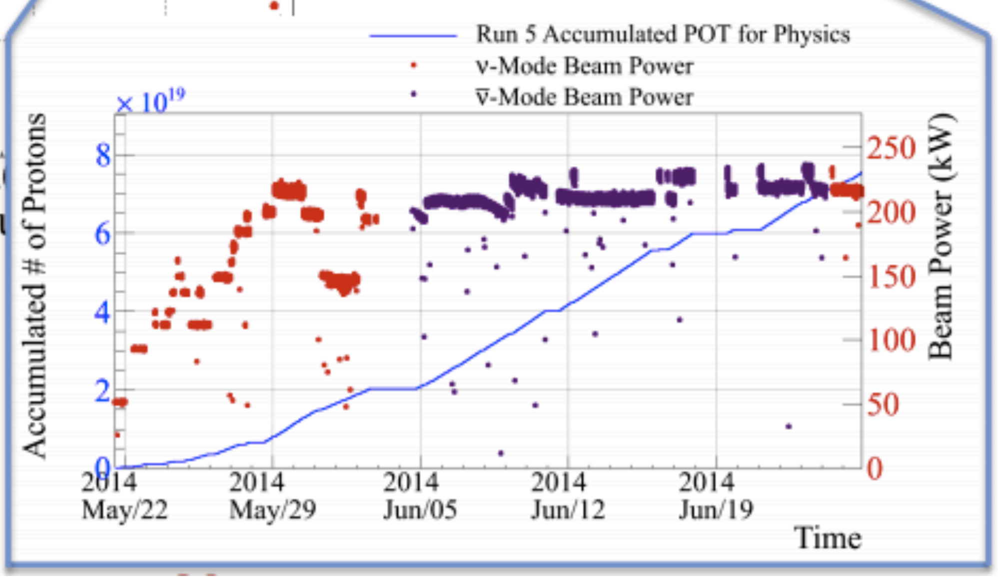


Anti-neutrino mode runs

- First data in anti-ν mode already recorded! Last summer we recorded ~0.5 × 10^{20} POT (Run 5)
- A new run in anti-ν mode has just started. We aim to collect soon the same statistic as in ν-mode
- Oscillation analyses with anti-ν mode data presented soon

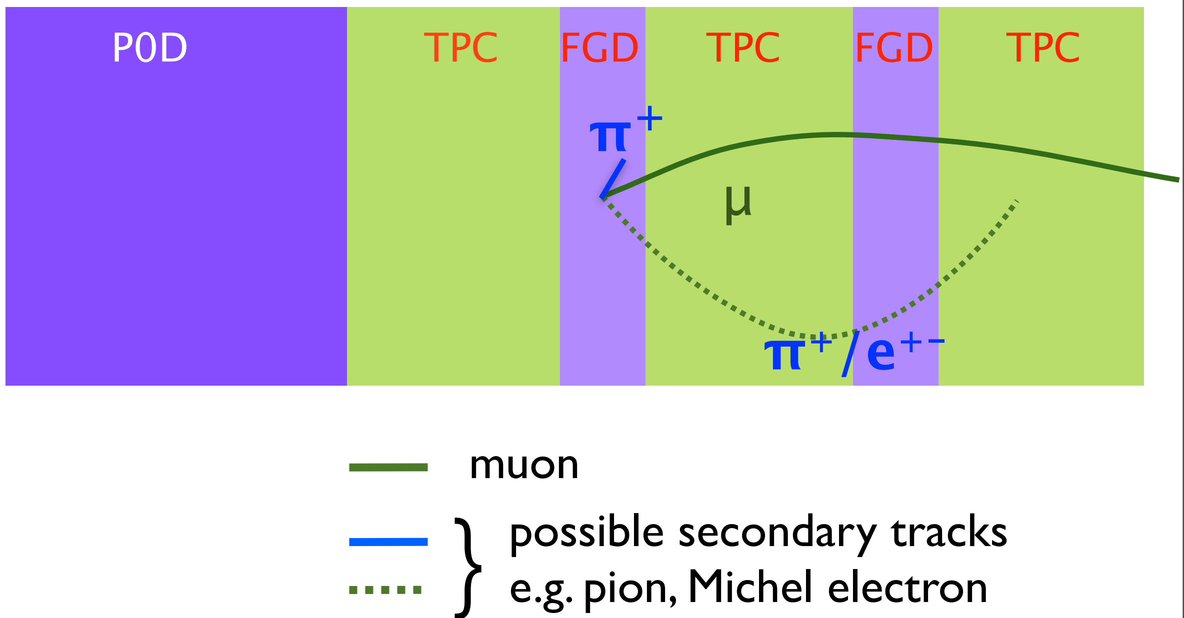






About the current systematics

- Current ND280 constraints:
  - Based on ν_μ-CC interactions in FGD1 (CH)
  - Categorization of the events based on the final state topologies (model independent)
  - Reduction of the flux and shared cross-section systematics from 20% to 2-3%



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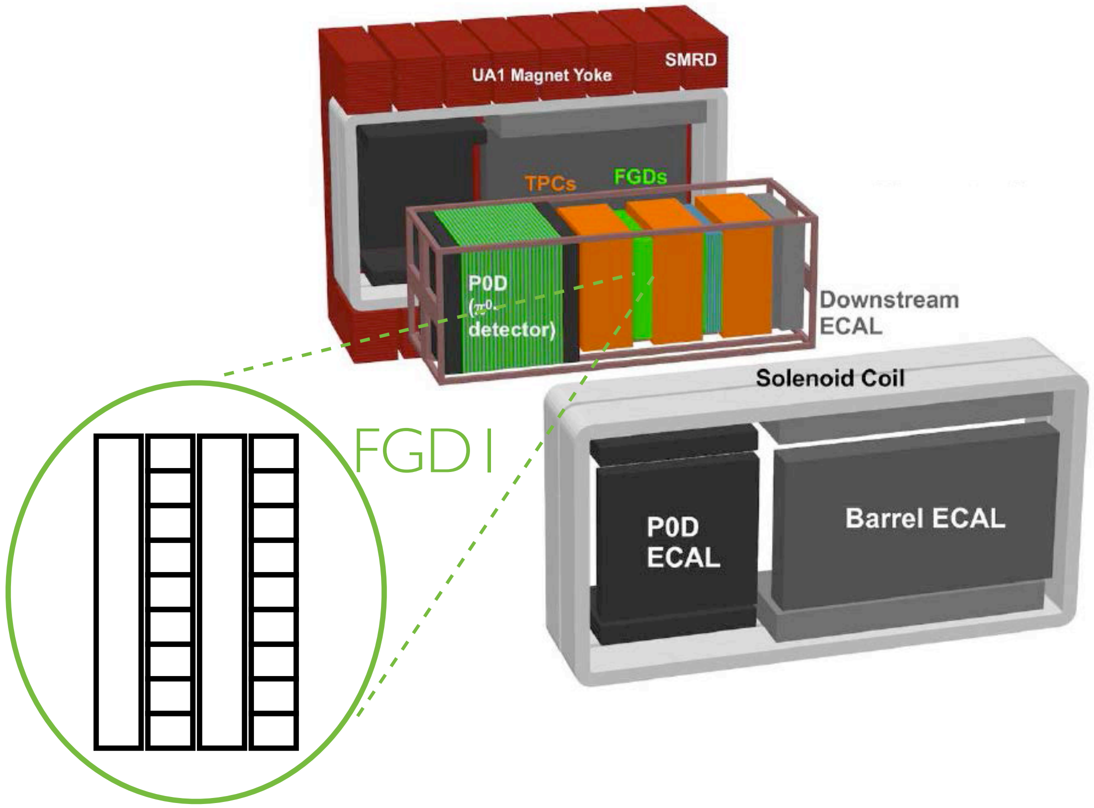
Fractional error on number-of-event prediction

However, **the potential of ND280 is still not fully exploited**

About the current systematics

Current ND280 constraints limitations :

- **Different target** between near (CH) and far detector (O)
- **Different acceptance** of the two detectors : near (mainly forward going tracks) and far (4**π**)
- **Deeply rely on cross-section models** to extrapolate the interaction rates at the far detector (where the neutrino flux has changed due to the oscillations)



- Main limitation: **unconstrained relation** between **the lepton kinematics** and the **neutrino energy**

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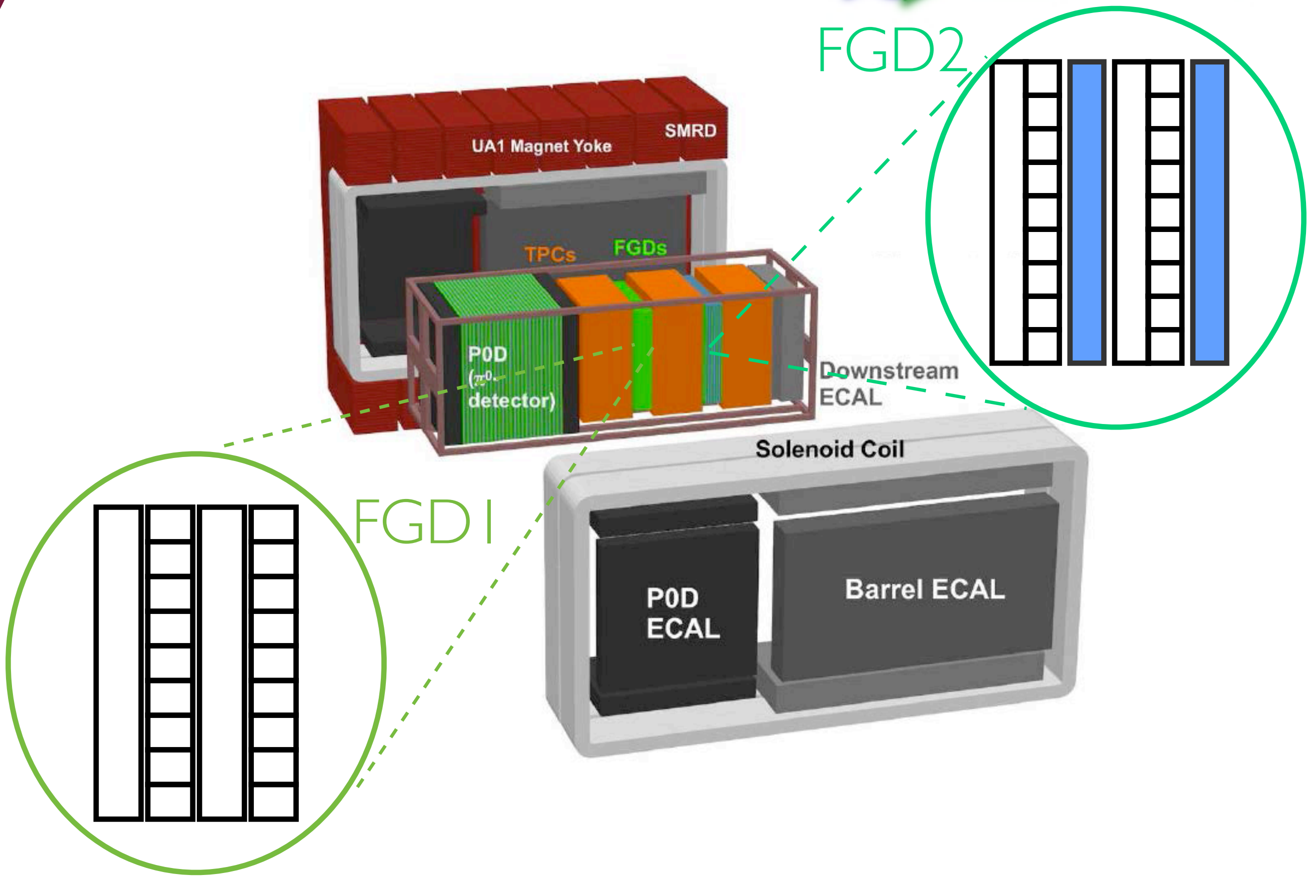

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On going developments for future analyses :

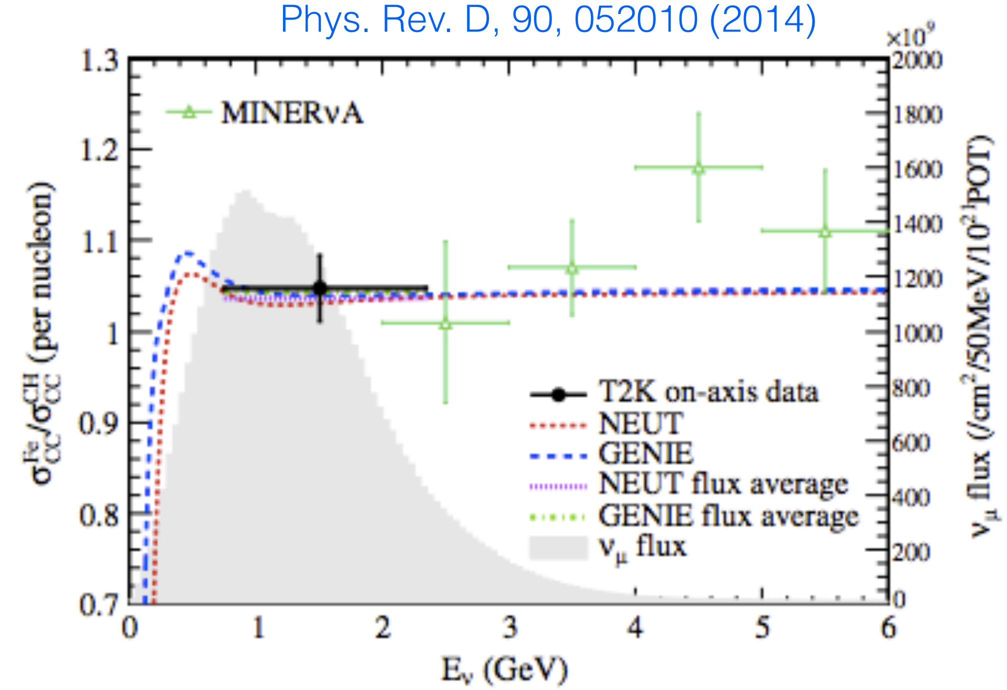
- Consider interactions in the FGD2 (water + carbon target)
- New reconstructions improvements : high angle and backward going tracks also in ND280
- Provide new cross-section measurements model independent to improve the current models
- ... new approach ?

Cross-section measurements

- Many cross-section measurements (published and ongoing) at T2K using all the three detectors **INGRID**, **ND280** and **SK**
- Not possible to report all of them. They would deserve a dedicated talk
- 3 results are reported here (arbitrary choice) as example of the effort done by the collaboration to provide new data to constrain the theoretical models

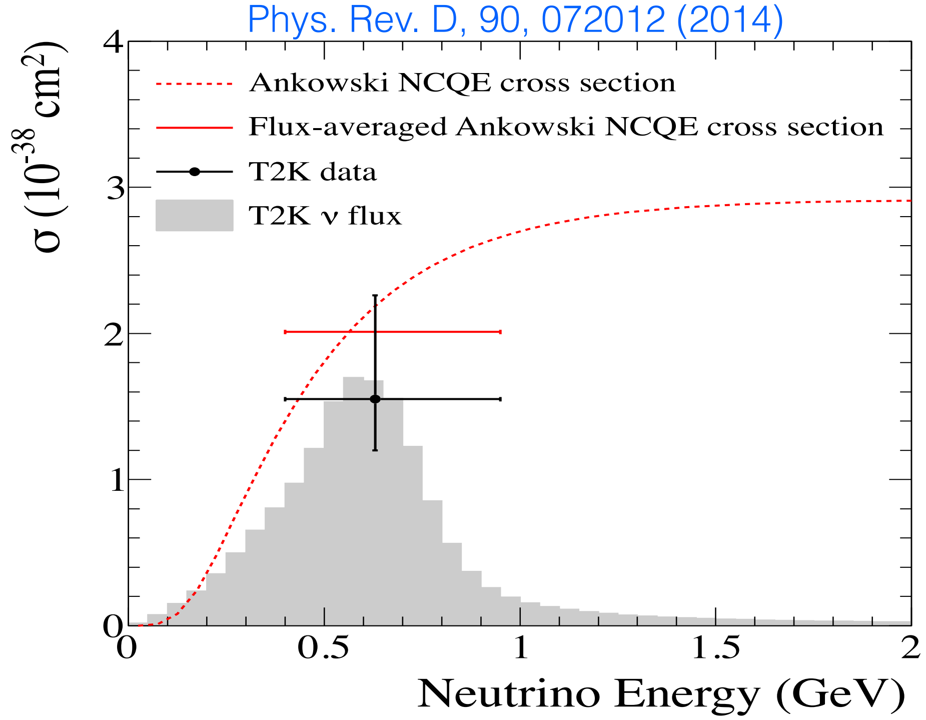
ν_μ cross section Fe/CH at **INGRID**

Phys. Rev. D, 90, 052010 (2014)



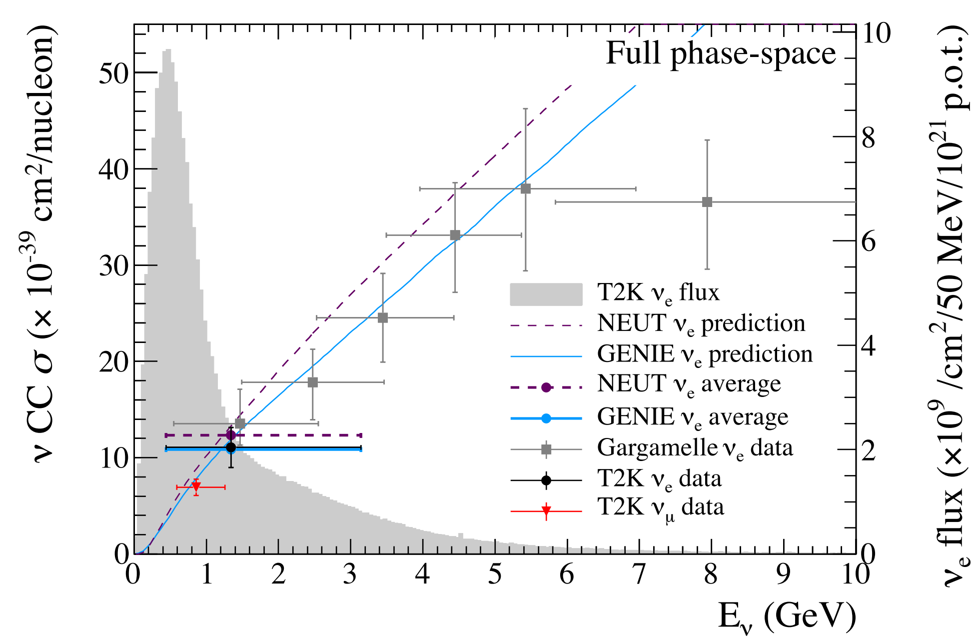
NC-QE cross section @ **SK**

Phys. Rev. D, 90, 072012 (2014)



ν_e CC cross section @ **ND280**

arXiv:1407.7389

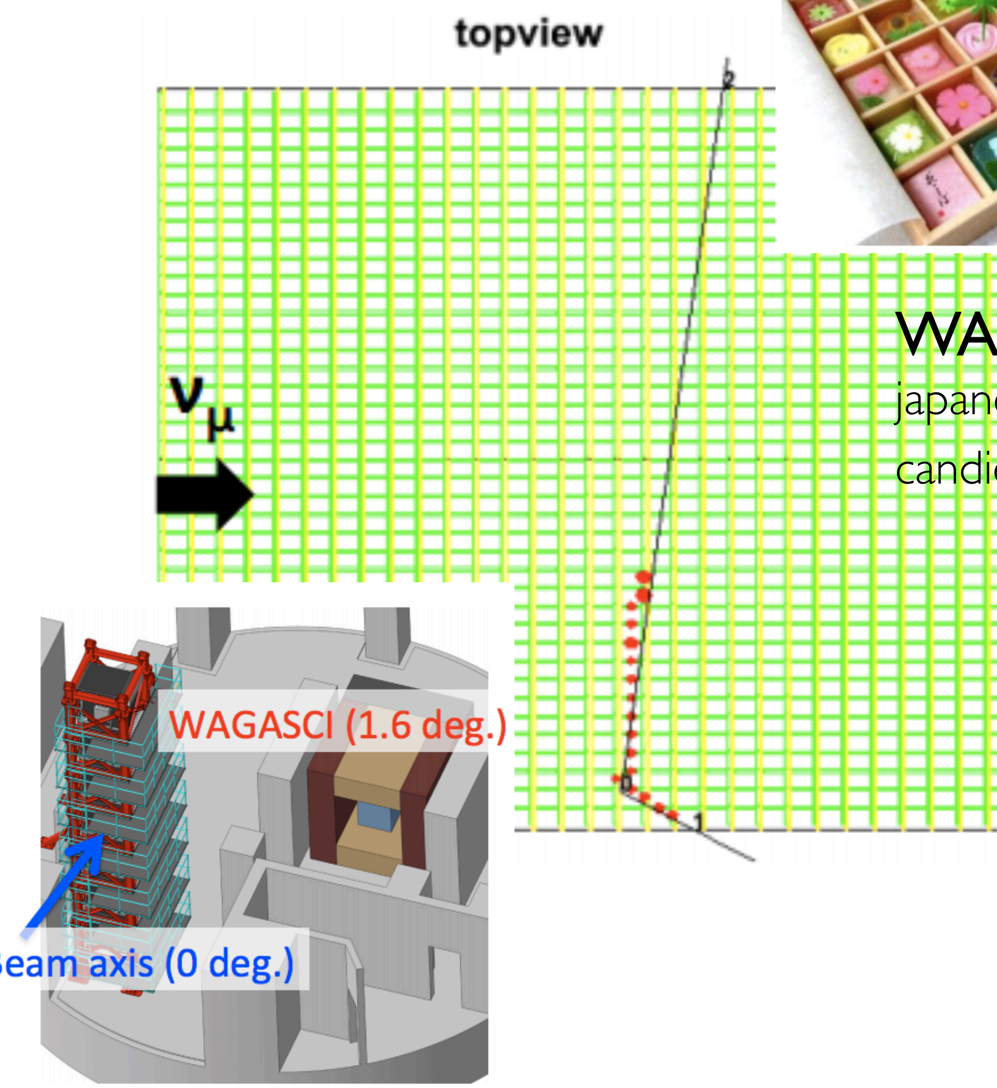


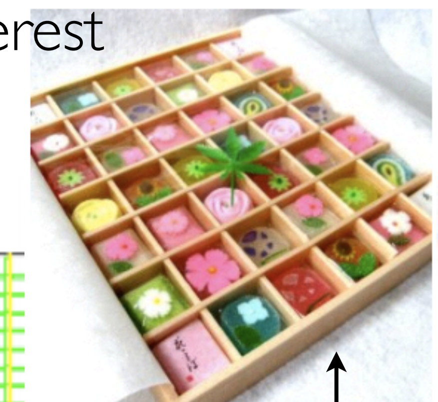
One step beyond

- The collaboration is already looking forward: call for new ideas and projects helping to improve the current measurements
- Among the several proposals, two ideas (**WAGASCI**, **nuPRISM**) have sufficiently grown up and recently become **independent collaborations**
- **WAGASCI** and **nuPRISM** are **no more T2K projects** (although significant overlap of personnel, place and purpose). Briefly mentioned here because of their physics interest

• WAGASCI

- H2O/CH off-axis (1.6°) detector with a 3D grid-like structure
- **7 institutes** (LLR!), **39 collaborators**
- Main goals : absolute and ratio cross section H2O/CH (4π acceptance, 3% accuracy)
- **Approved as test experiment, start operation on October 2016**

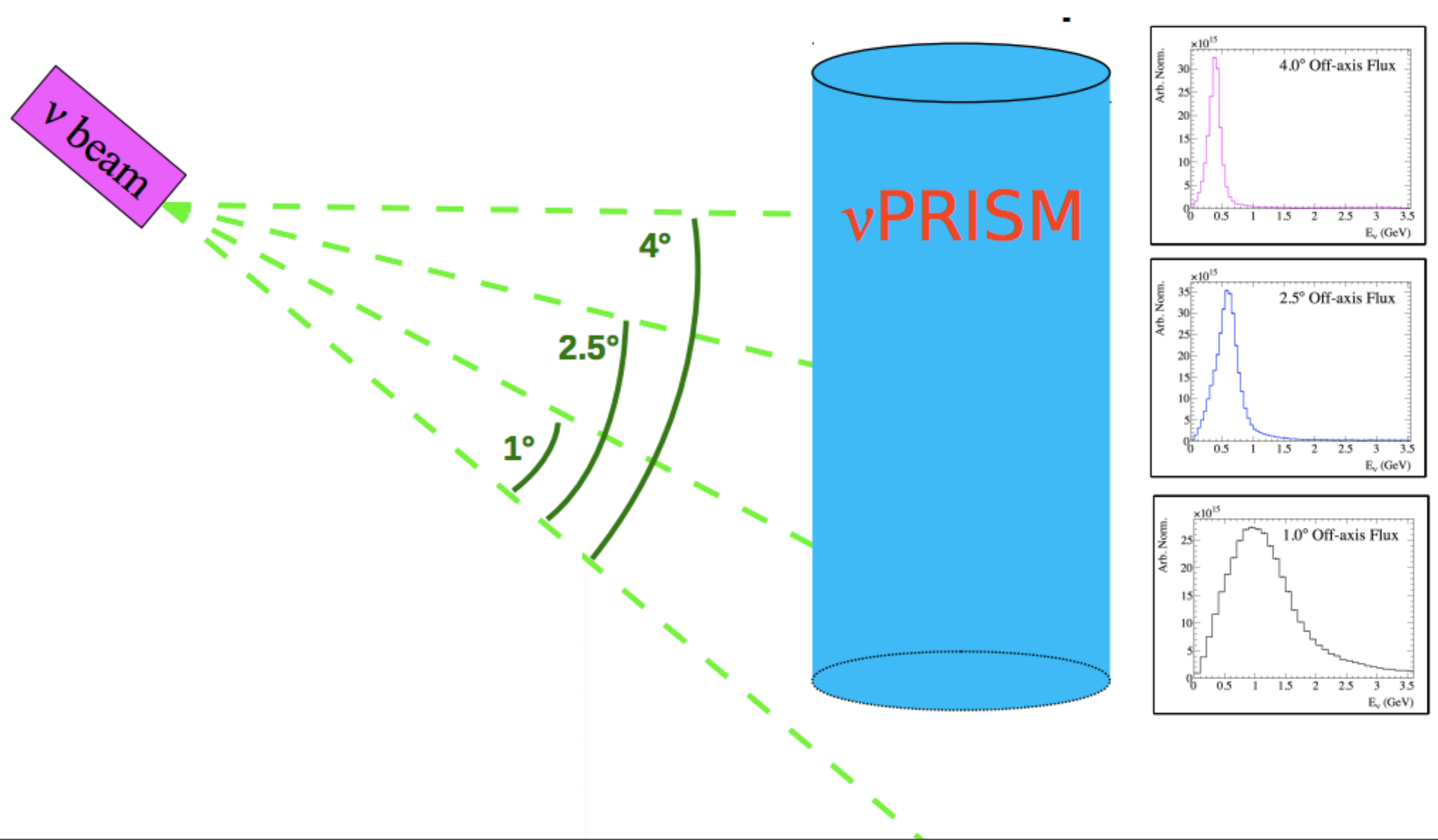




WAGASHI: japanese box for candies

One step beyond: nuPRISM

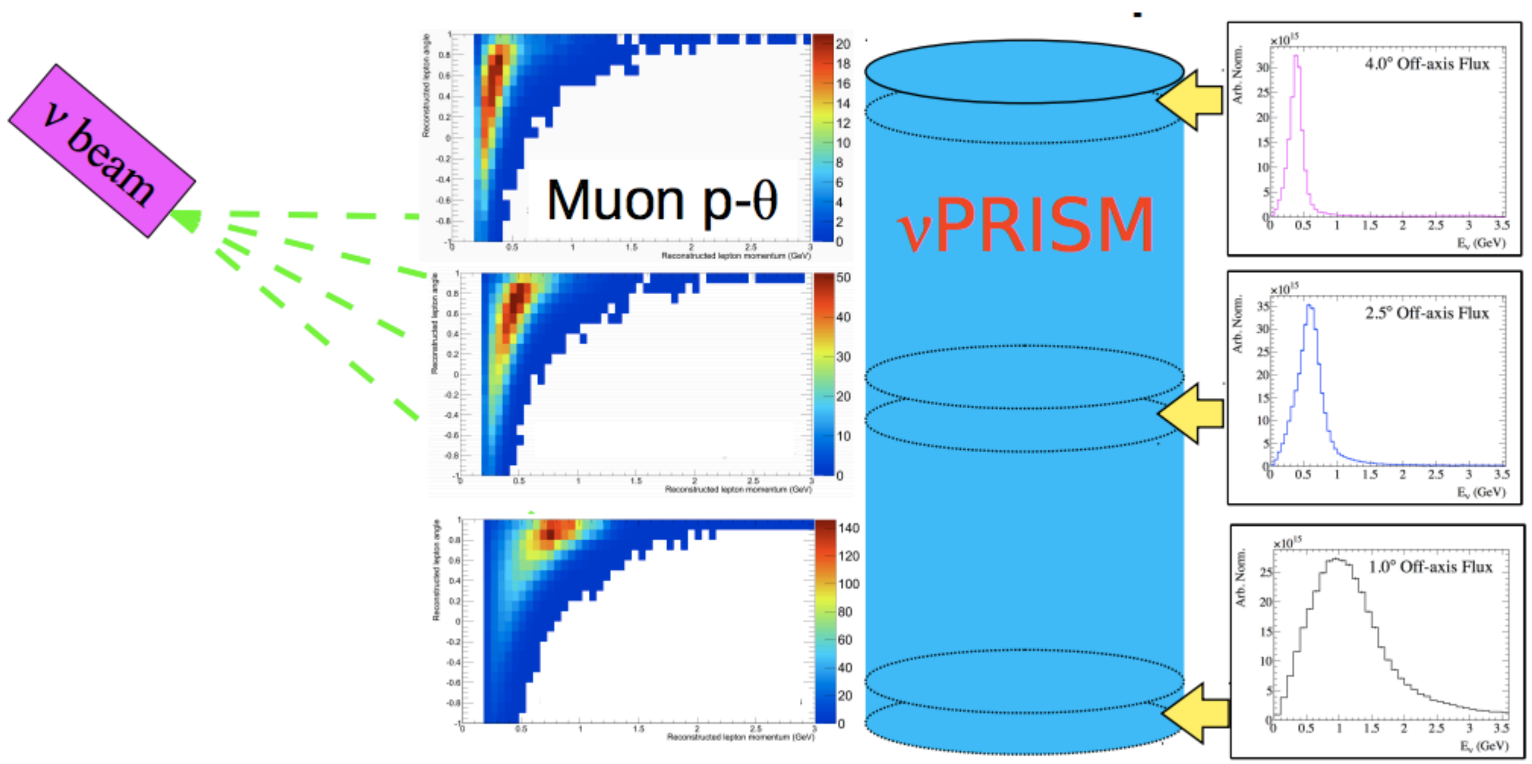
- Water Cherenkov detector as SK but with different off-axis angles (1°- 4°) @ 1Km
- 22 Institutes, 45 collaborators



Neutrino
Precision
Reaction
Independent
Spectrum
Measurement

One step beyond: nuPRISM

- Water Cherenkov detector as SK but with different off-axis angles (1°- 4°) @ 1Km
- 22 Institutes, 45 collaborators
  - Exploiting the off-axis angle (OAA) technique to have a **direct correspondence between the lepton kinematics and the neutrino energy** : "Neutrino spectrometer"
  - By (linear) combination of the fluxes at different OAA **any energy spectra can be built**
    - gaussian → cross section measurements
    - oscillated SK-like → minimize the dependency to cross-section models for osc. analyses
  - Physics potential to test the MiniBooNE results on **short baseline oscillations**



Neutrino
Precision
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Measurement

Conclusions

- World leading results with only 8% of the total expected statistics
  - First observation of the ν_e appearance
  - Best world measurement of $\sin^2\vartheta_{23}$ (10% uncertainties) through ν_μ disappearance
  - First hints of $\delta_{CP} \neq 0$ by joint ν_μ -ν_e analyses combined with reactor constraints

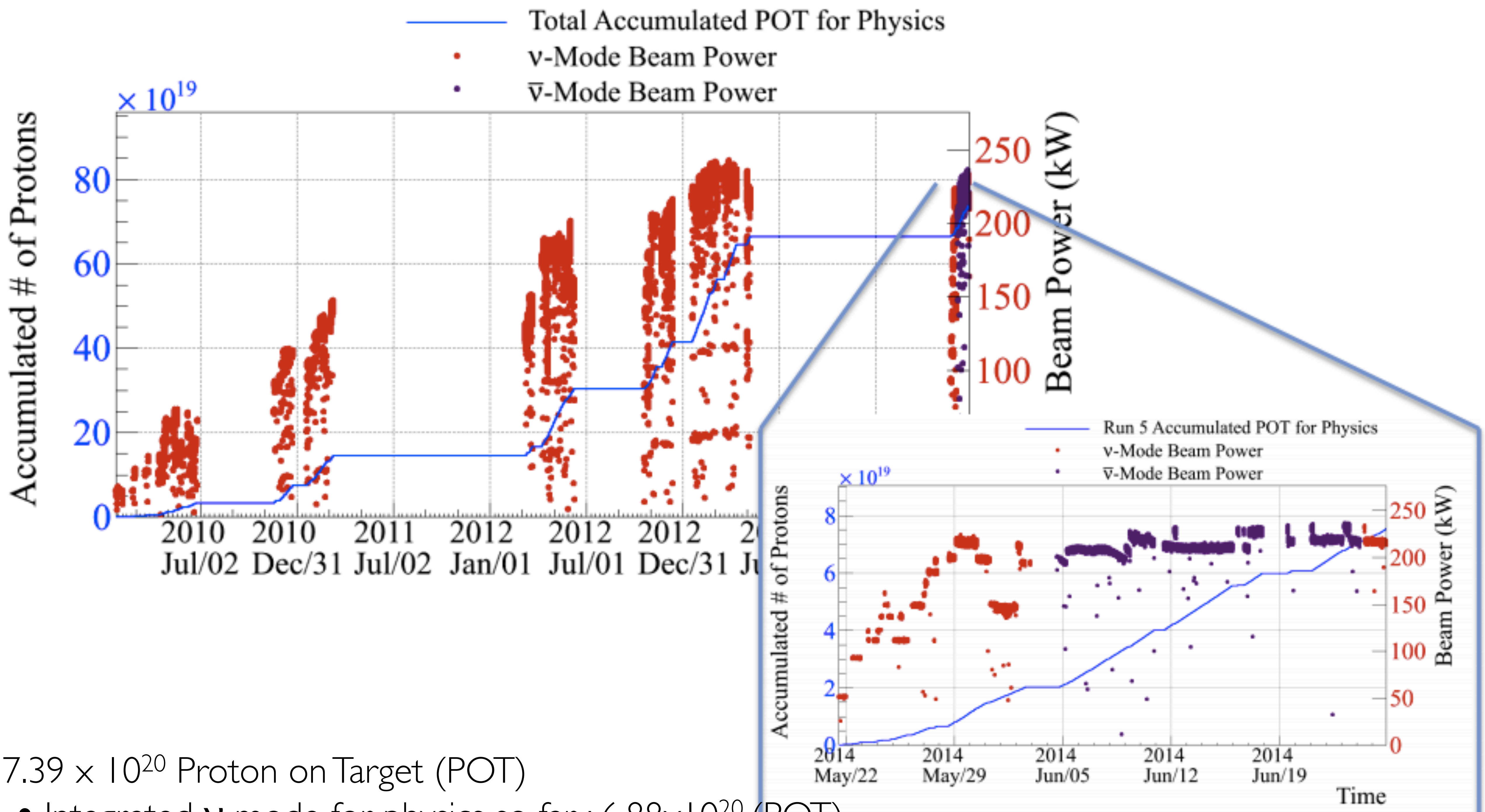
- T2K already collected anti-neutrino data
  - Measure anti-ν_e and anti-ν_μ oscillations in the near future
  - Aiming to collect 50% ν - 50% anti-ν to optimize the sensitivity to δ_{CP}

- Many other interesting measurements are performed: cross-section measurements and searches for non-standard processes

- New interesting and very promising ideas have already born : stay tuned!

Back-up

Summary of the data taking

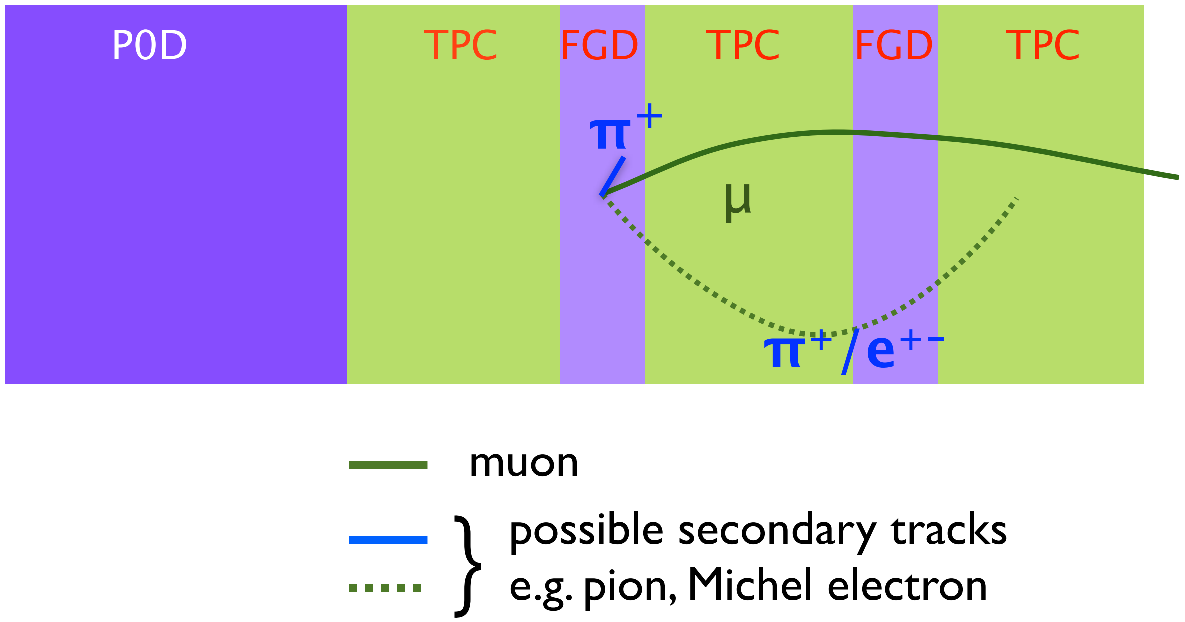


- 7.39×10^{20} Proton on Target (POT)
  - Integrated ν mode for physics so far : 6.88×10^{20} (POT)
  - Integrated anti-ν mode for physics so far : 0.51×10^{20} (POT)
- Reached stable beam at 235kW

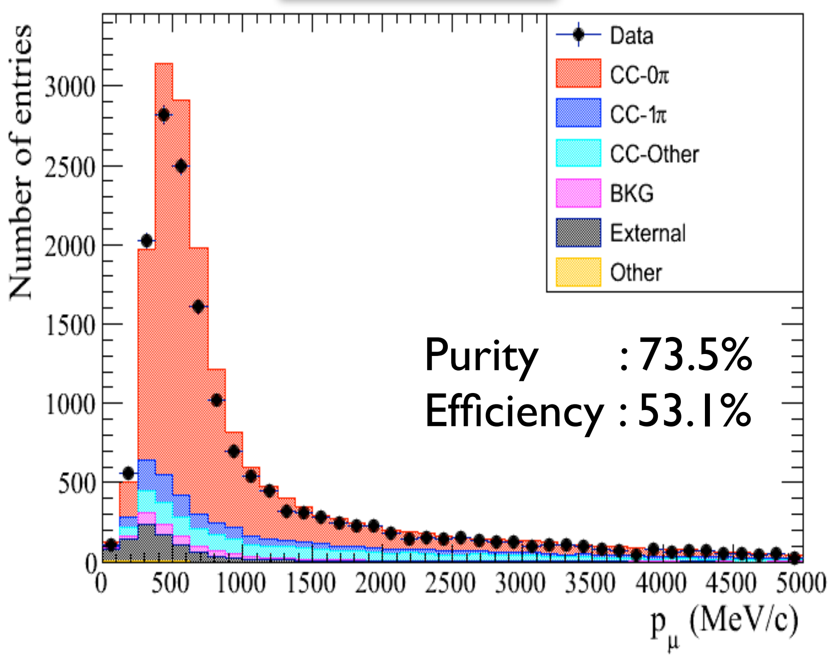
ν_μ CC interactions @ ND280

T2K

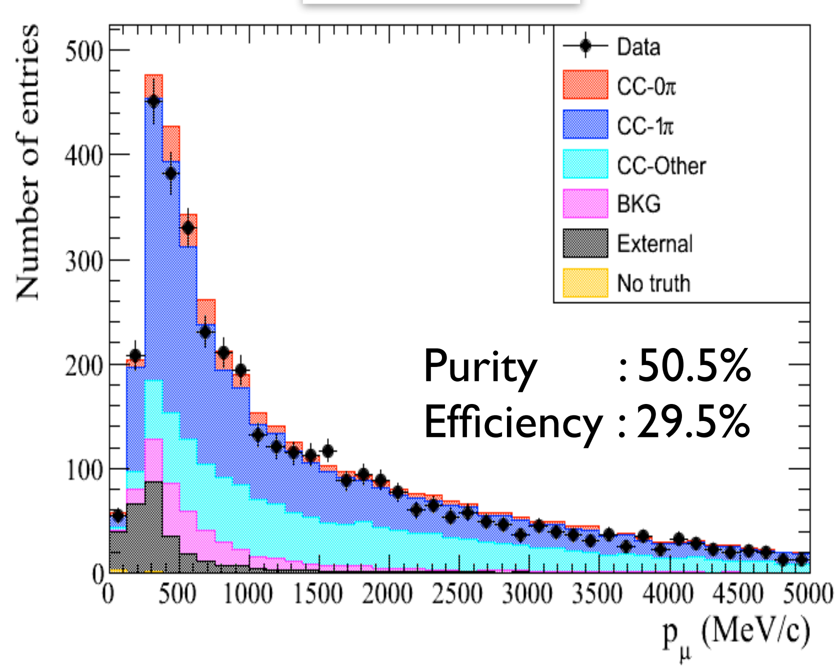
- Simple selection done using information coming from the tracker (FGD and TPCs)
- Muon as highest momentum negative track with energy deposition consistent with TPC muon hypothesis
- Momentum and identity of the secondary particles by TPC and FGD



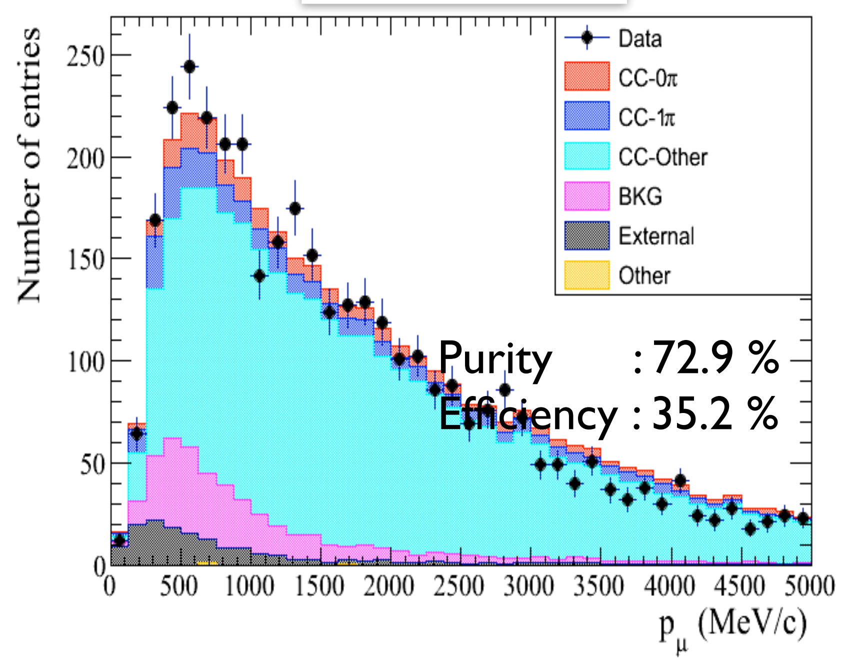
CC0π



CC1π+



CCOthers



Improving the event rate @SK

- Significant improvement of the prediction of the neutrino event rate at the far detector

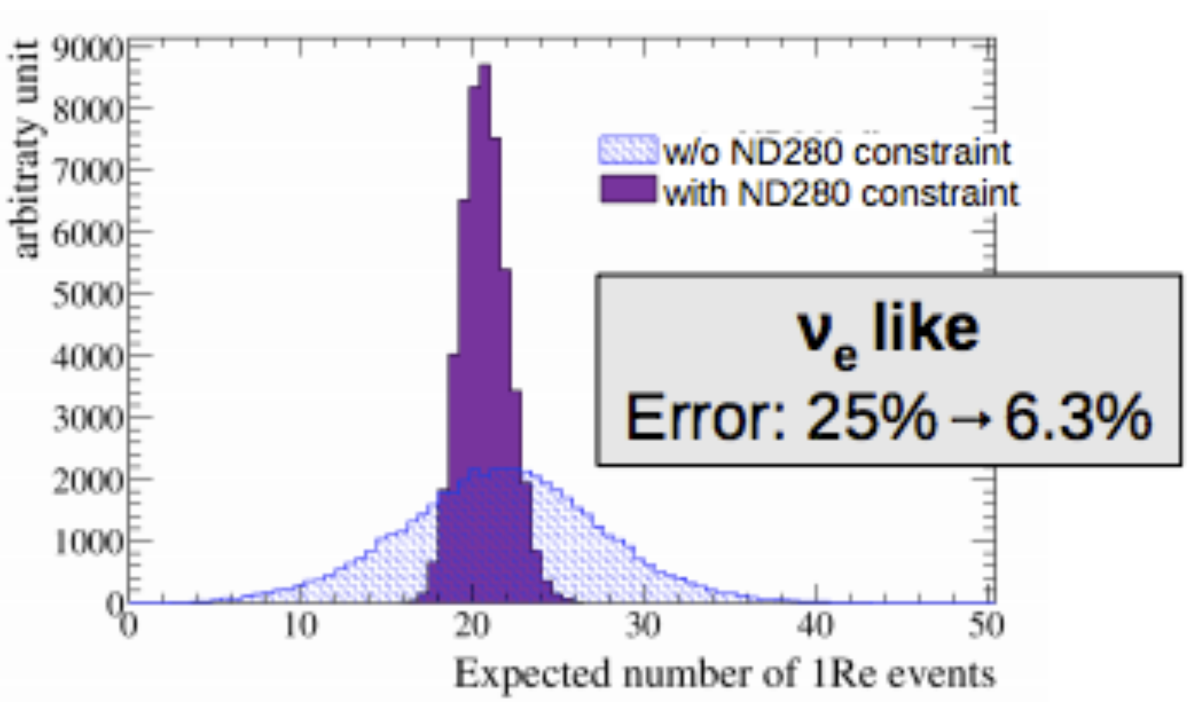
$\sin^2\vartheta_{13} = 0.1$

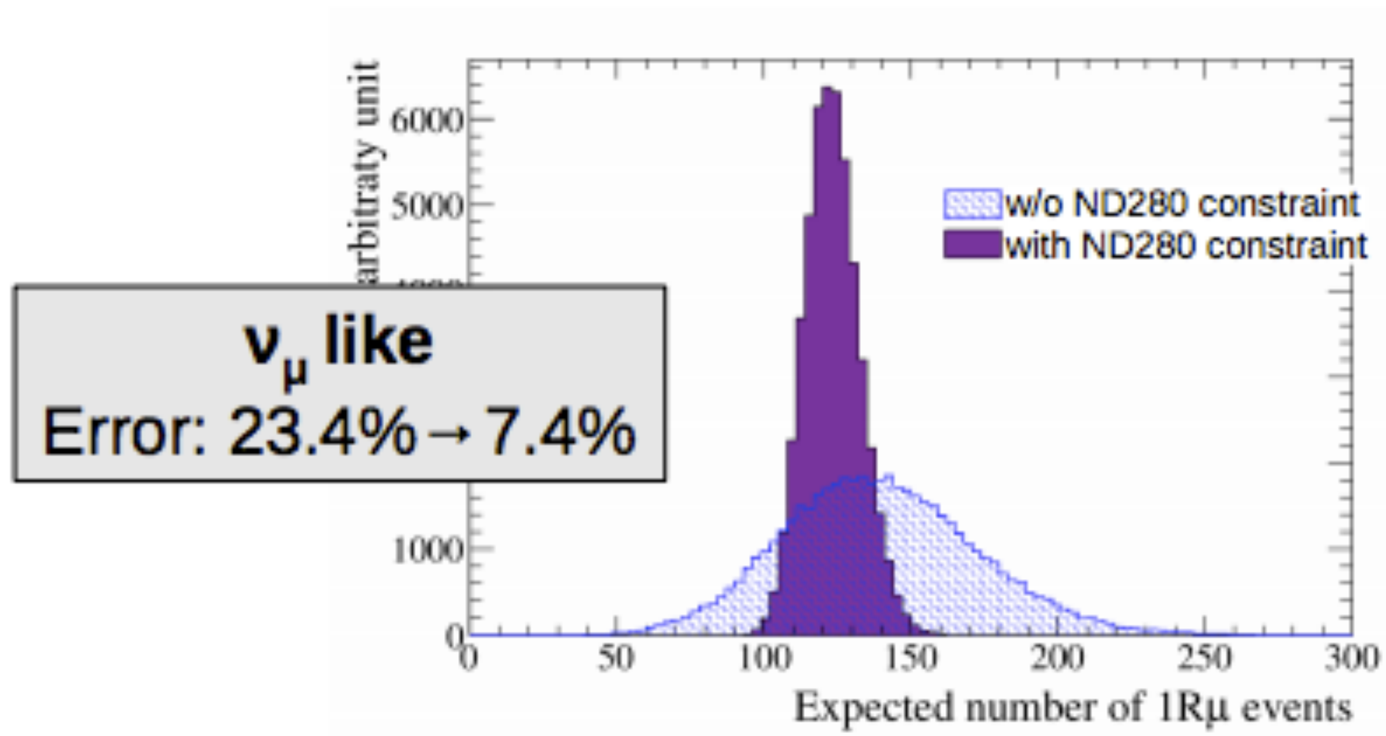
$\delta=0$

$\Delta m^2_{32} = 2.4\times10^{-3}\ eV^2/c^2$

$\sin^2\vartheta_{23} = 0.5$

Normal Hierarchy

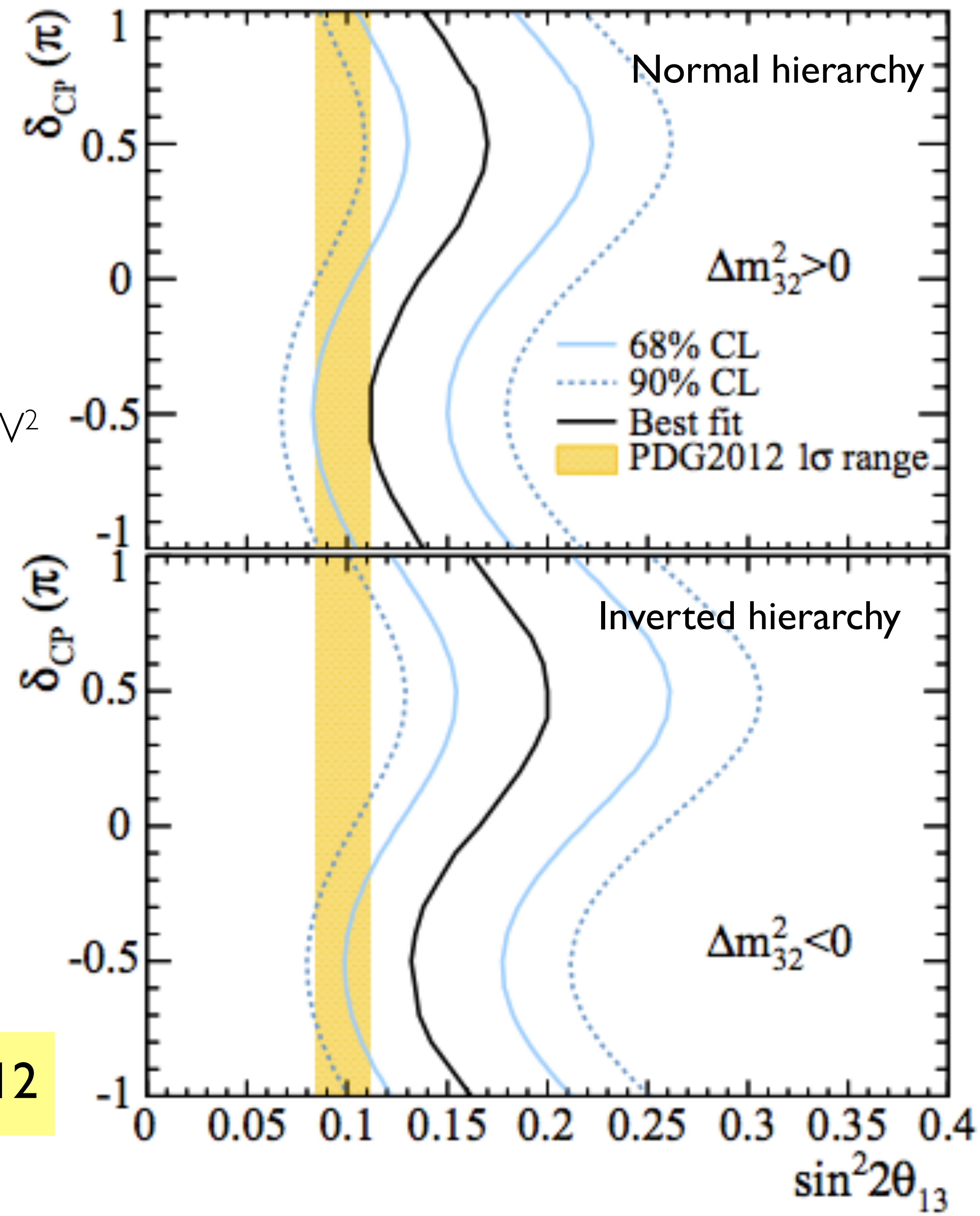




ν_e appearance

PRL 112, 061802 (2014)

Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}



NOTE: These are 1D contours for values of δ_{CP}

Best fit w/ 68% C.L. error @ δ_{CP}=0

$\sin^2\vartheta_{12}$=0.306, $\Delta m^2_{21}=7.6\times10^{-5}eV^2$, $\sin^2\vartheta_{23}$=0.5, $|\Delta m^2_{32}|=2.4\times10^{-3}eV^2$

Normal hierarchy: $\sin^2\theta_{13} = 0.140^{+0.038}_{-0.032}$

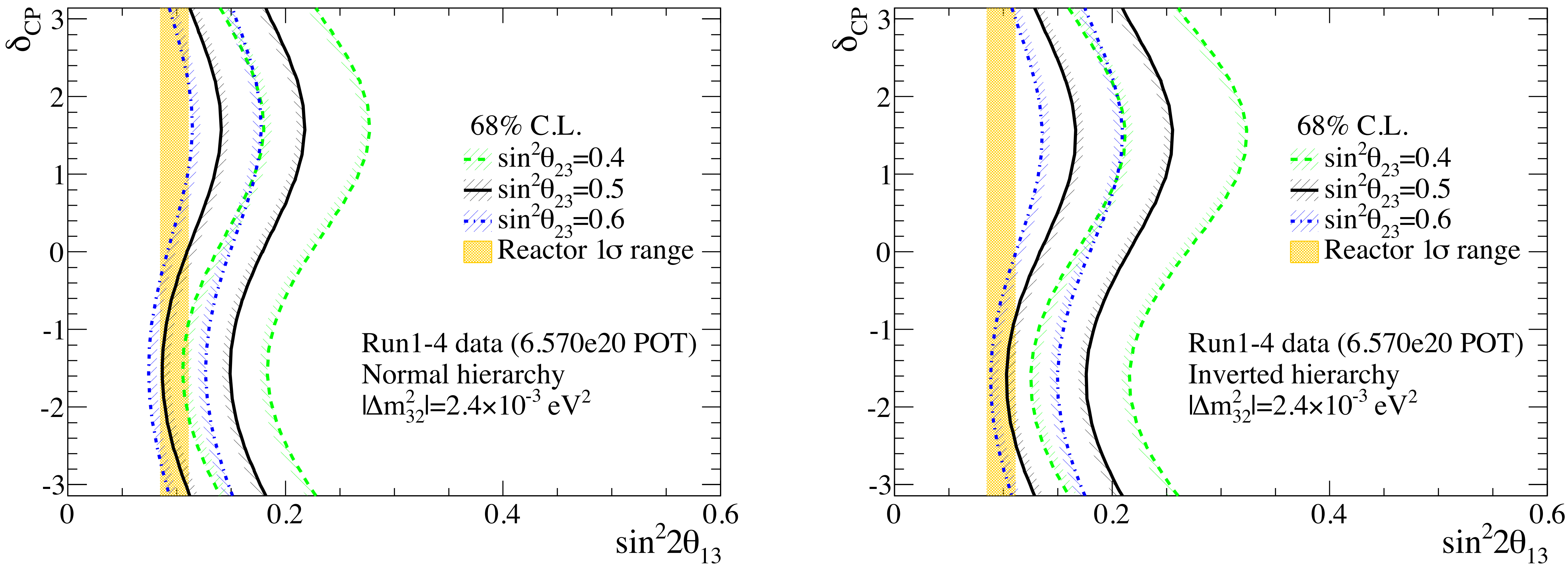
Inverted hierarchy: $\sin^2\theta_{13} = 0.170^{+0.045}_{-0.037}$

statistical significance of 7.3σ

Average θ_{13} value from PDG 2012

νe appearance analysis

Dependence of the best fit values to the ϑ_{23} angle



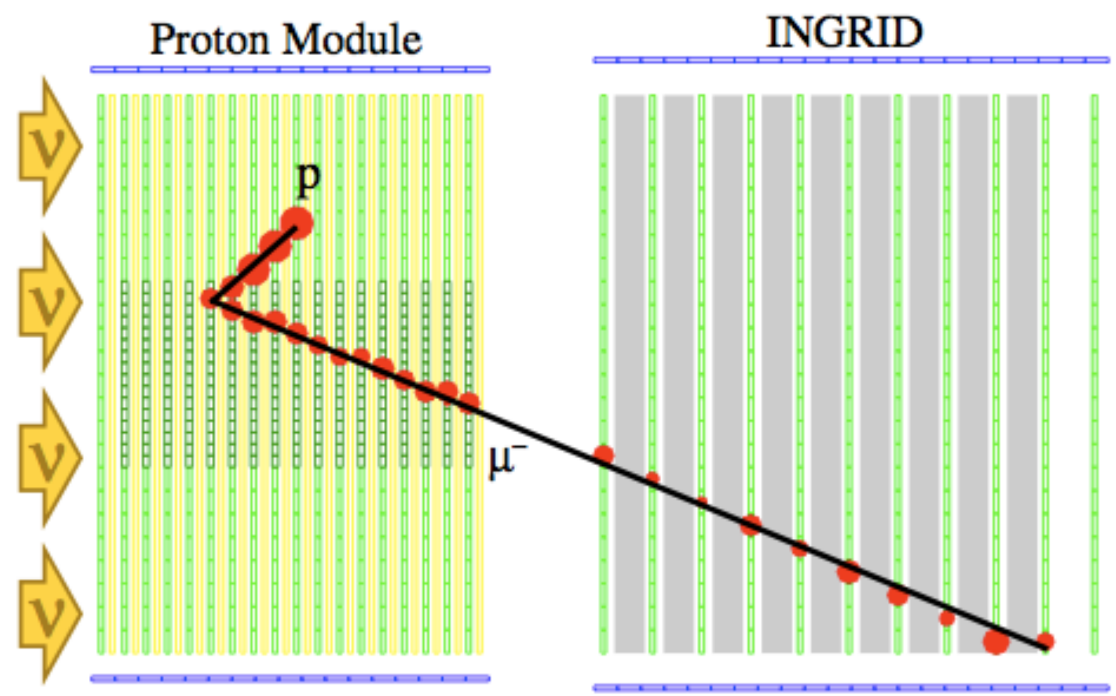
Yellow band: average ϑ_{13} value from PDG 2012

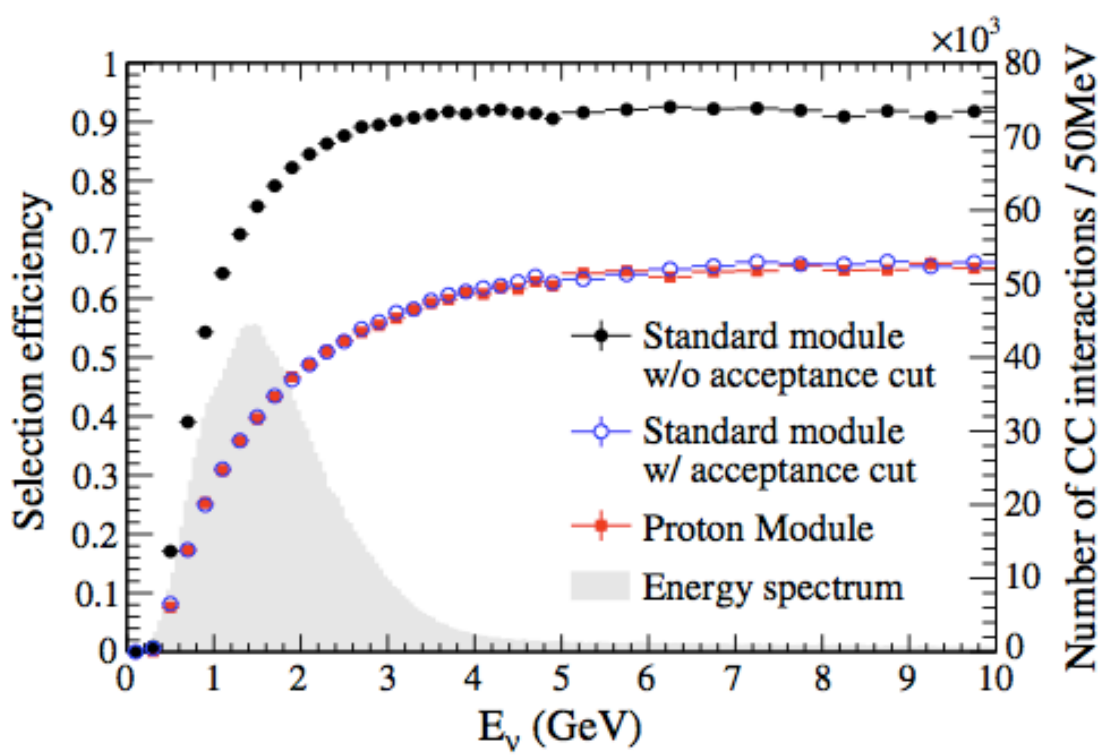
$\vartheta_{13} = 0.098 \pm 0.013$

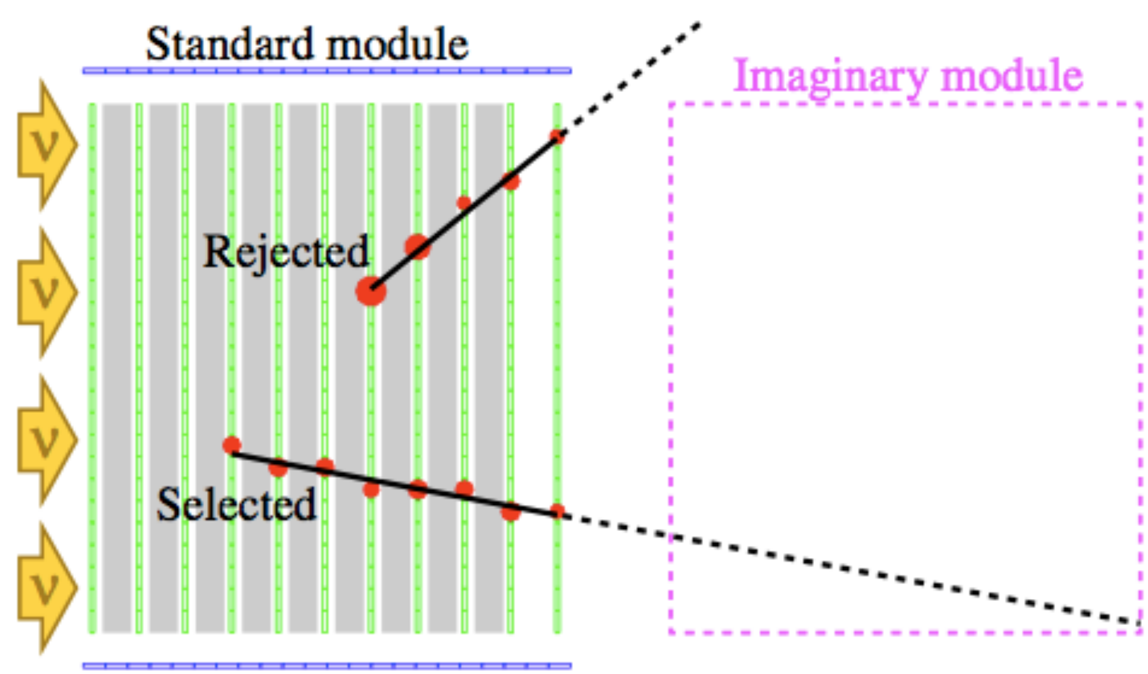
ν_μ Fe/CH x-sec @INGRID

Phys. Rev. D, 90, 052010 (2014)

- Proton module : only scintillators, 100% active target
- Standard module: sandwich of Fe and CH layers
- Both modules are on the central axis of the beam ar thus exposed to the same beam flux → cancelation some systematics







ν_μ Fe/CH x-sec @INGRID

Phys. Rev. D, 90, 052010 (2014)

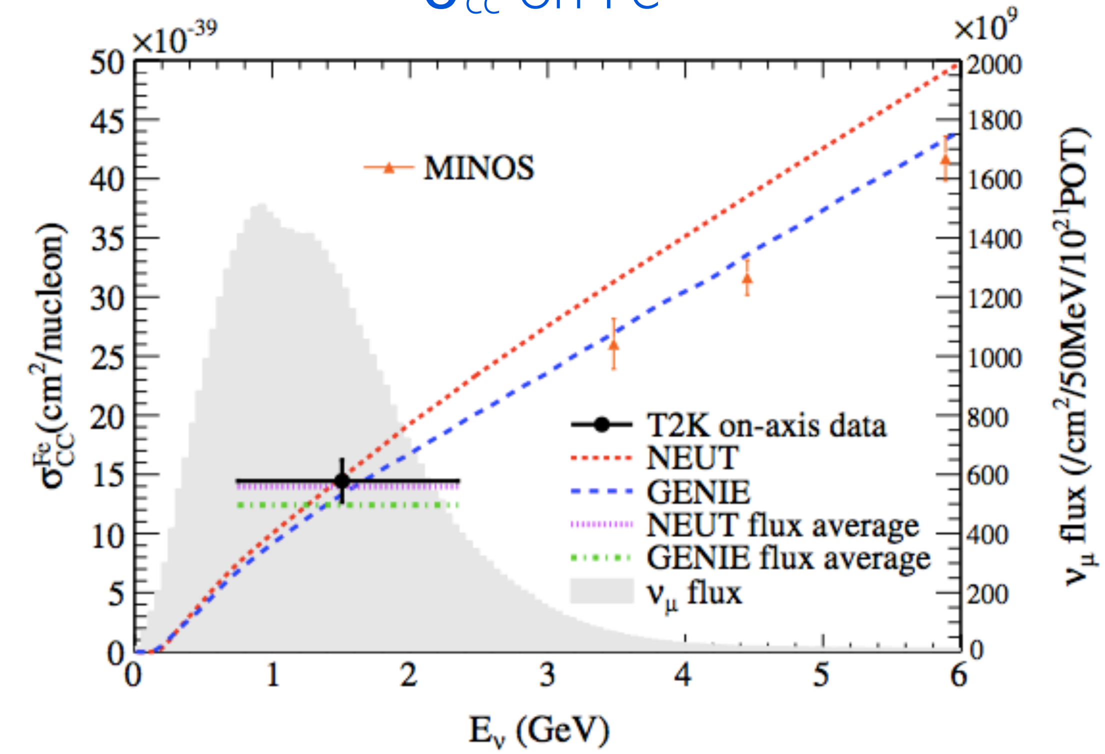
- CC Inclusive σ measurement on Fe @ 1GeV never measured before. Previous measurements from MINOS at higher energies
- CC Inclusive σ measurement on CH @ 1GeV already previously measured by ND280. Measurement at higher energy is possible for INGRID due to his position on-axix (higher <E$_\nu$>)
- σ ratio Fe/CH @ at lower energy than MINERνA

$$\sigma^{\mathrm{Fe}}_{\mathrm{CC}} = (1.444 \pm 0.002(\mathrm{stat})^{+0.189}_{-0.157}(\mathrm{syst})) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{nucleon},$$

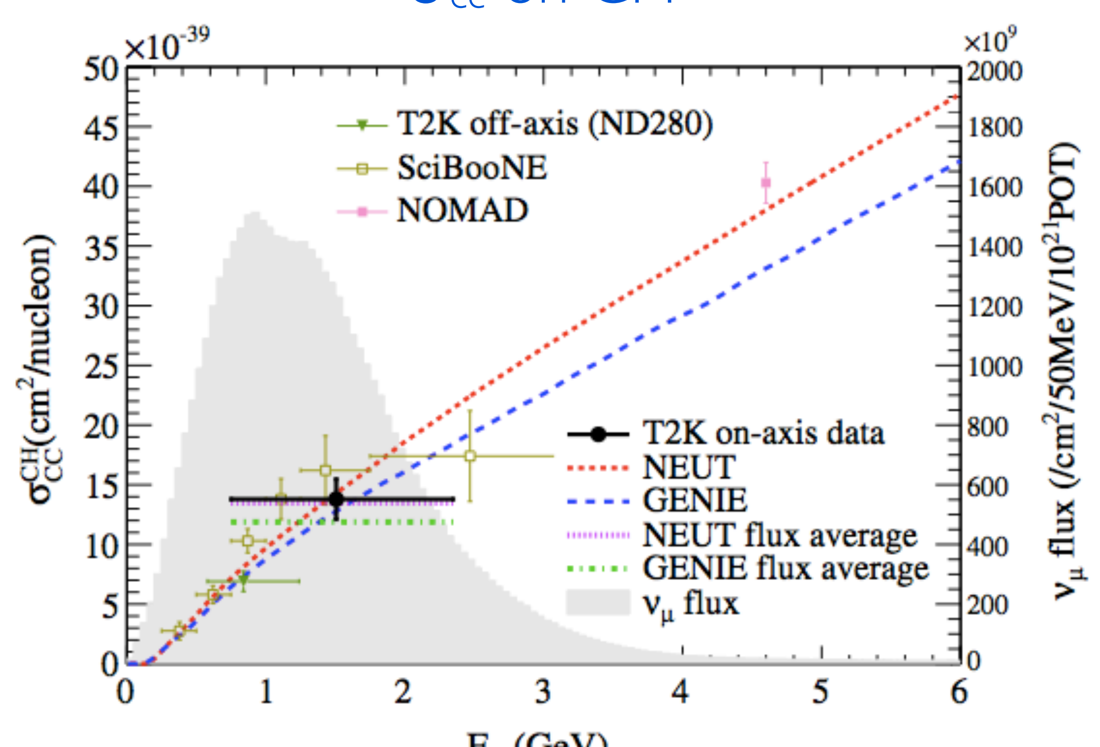
$$\sigma^{\mathrm{CH}}_{\mathrm{CC}} = (1.379 \pm 0.009(\mathrm{stat})^{+0.178}_{-0.147}(\mathrm{syst})) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{nucleon},\quad \mathrm{and}$$

$$\frac{\sigma^{\mathrm{Fe}}_{\mathrm{CC}}}{\sigma^{\mathrm{CH}}_{\mathrm{CC}}} = 1.047 \pm 0.007(\mathrm{stat}) \pm 0.035(\mathrm{syst}),$$

σ$_{CC}$ on Fe



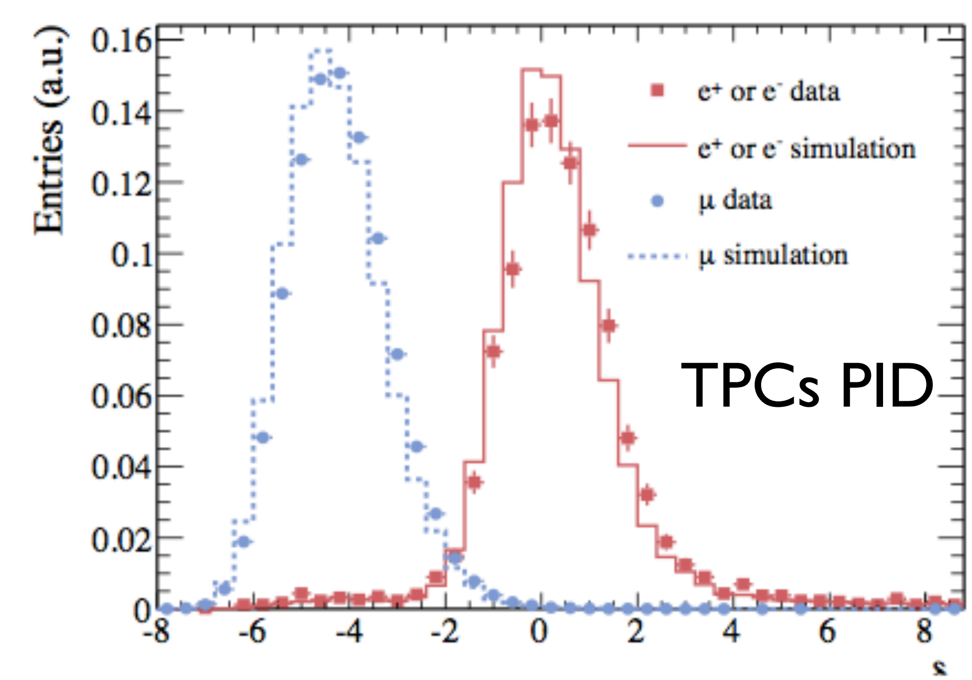
σ$_{CC}$ on CH



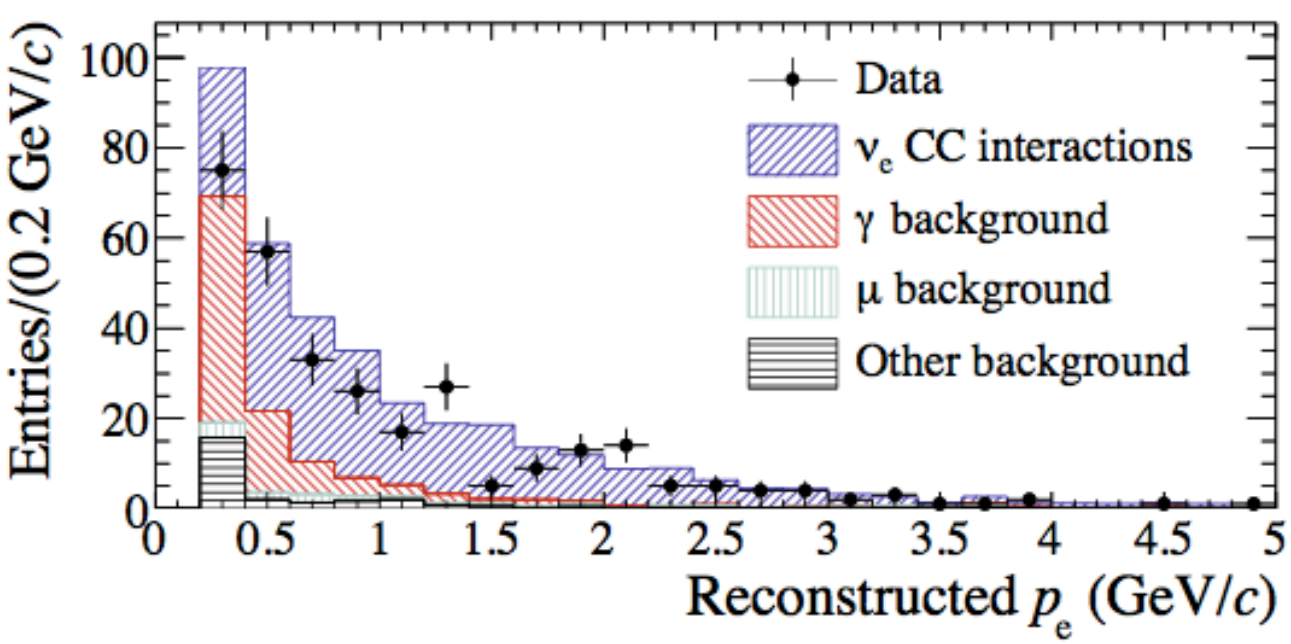
ν_e CC cross section @ ND280

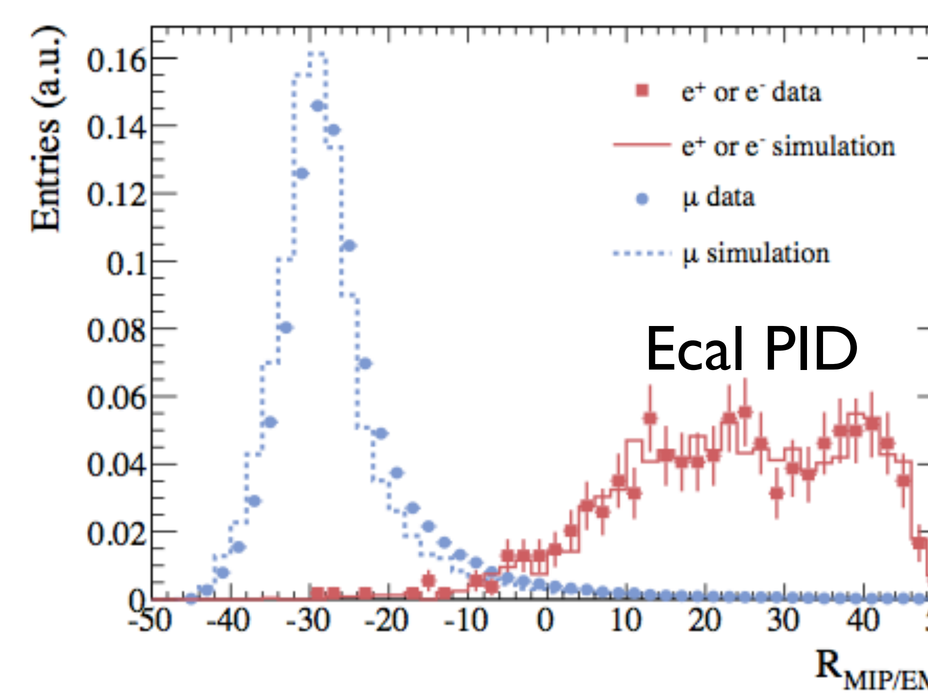
arXiv:1407.7389 (submitted to PRL)

- Difficult analysis because based on the ν_e beam component (1%)
- Search for negative electron-like track with vertex in the FGD1
- Selection based on the TPC and Ecal PID to reject muons
- Main background due to photon conversions



PRD 89, 092203 (2014)





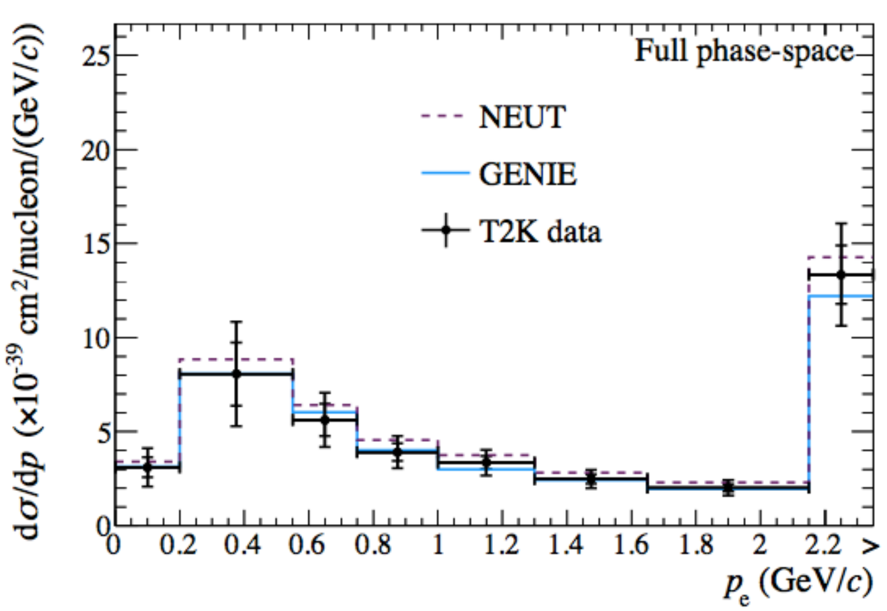
PRD 89, 092203 (2014)

ν_e CC cross section @ ND280

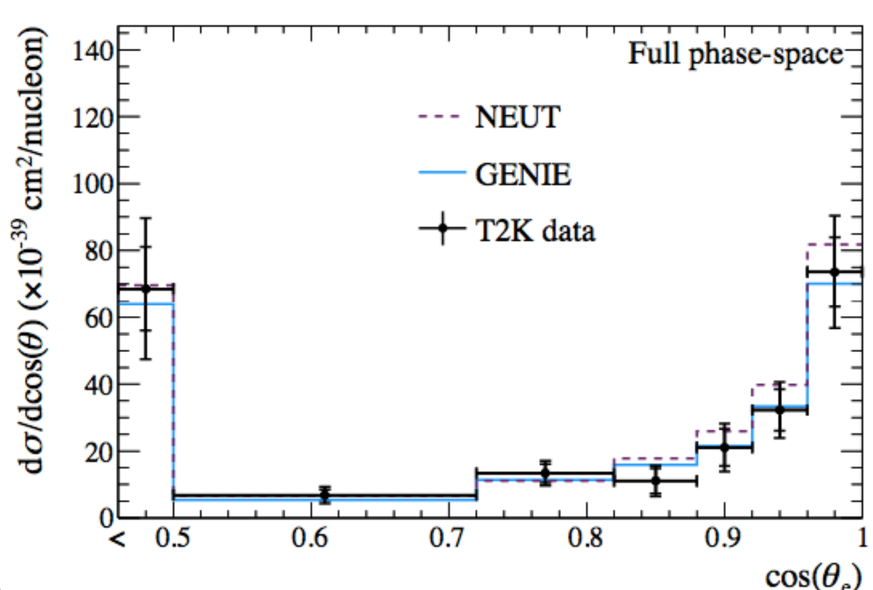
arXiv:1407.7389 (submitted to PRL)

- First ever ν_e differential cross section at the GeV scale
- Good agreement with data/MC (both GENIE and NEUT)
- Some discrepancies at low Q^2 : most interesting region to understand the differences between ν_e and ν_μ cross section: crucial for a LBL experiment to search for CP violation in the lepton sector

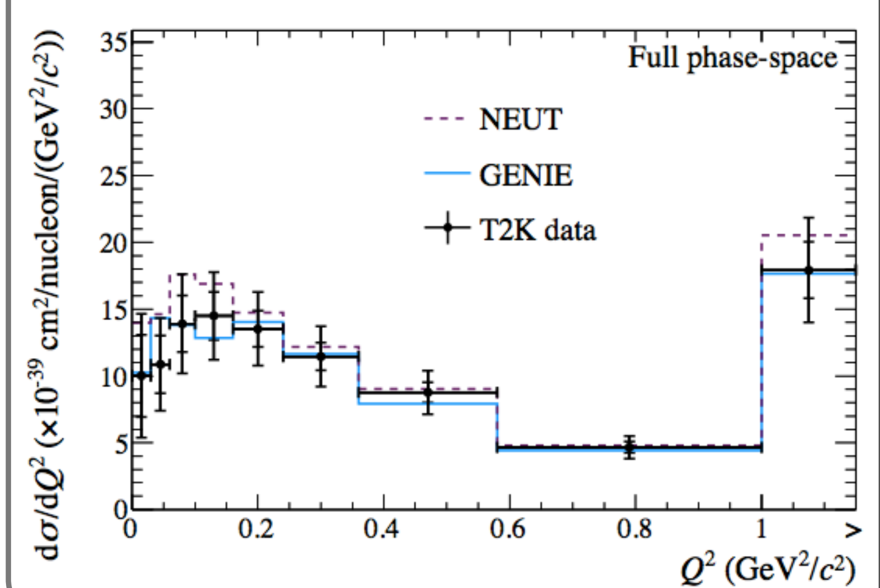
$d\sigma/dp$



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



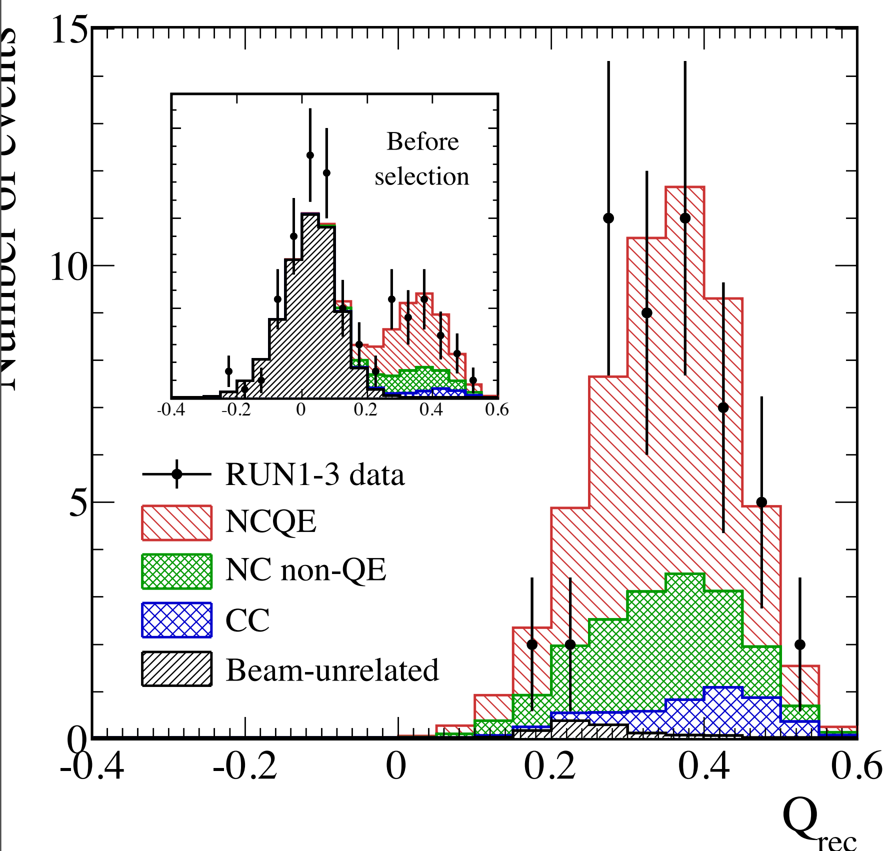
$d\sigma/dQ^2$

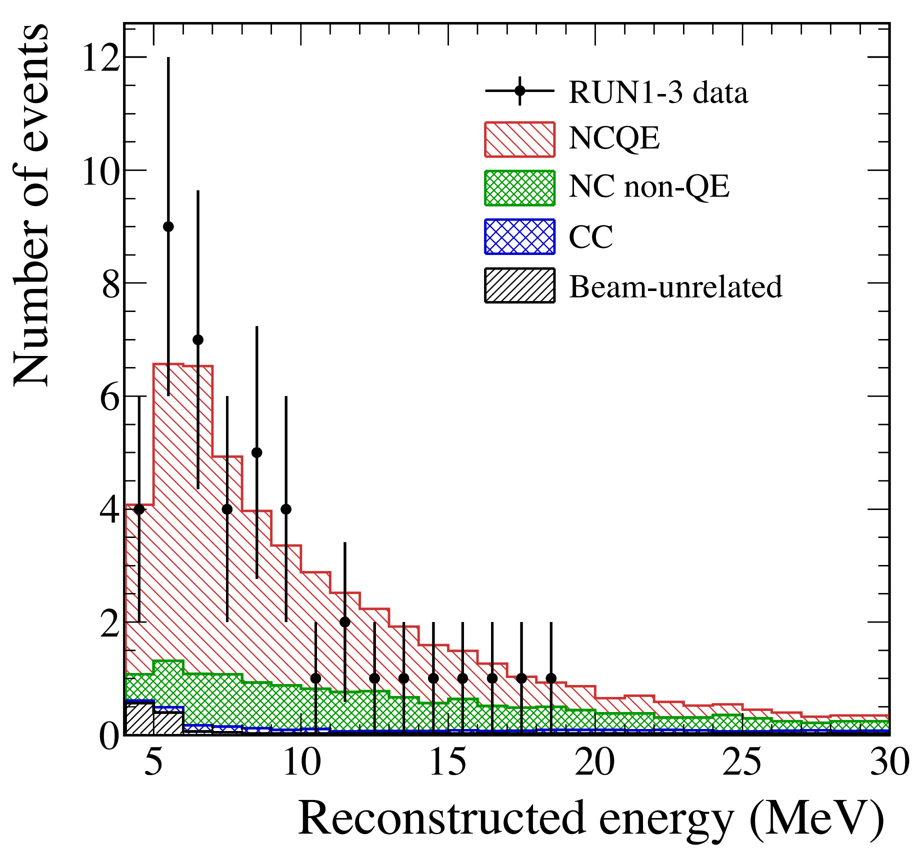


NCQE cross-section @ SK

Phys Rev D. 90, 07 2012 (2014)

- Measurement of NCQE by nuclear de-excitation gamma rays ($\nu + {}^{16}O \rightarrow \nu + p + {}^{15}O^*$)
  - **Signal:** - primary γ-rays from nucleus de-excitation
    - secondary γ-rays from the interaction of the knocked-out nucleon with water
  - **Motivation:** measurement of the γ-rays background from atmospheric neutrinos for the study of astrophysical neutrinos ($E_\nu \sim 10$ MeV)





Beam-related expectation	ν_μ	ν_e	$\bar{\nu}_\mu$
NCQE	34.33	0.46	0.69
NC non-QE	11.59	0.26	0.45
CC	2.01	0.0014	0.025
Signal		34.80	
Background (beam)		15.02	
Beam-unrelated		1.20	
Observed events		43	

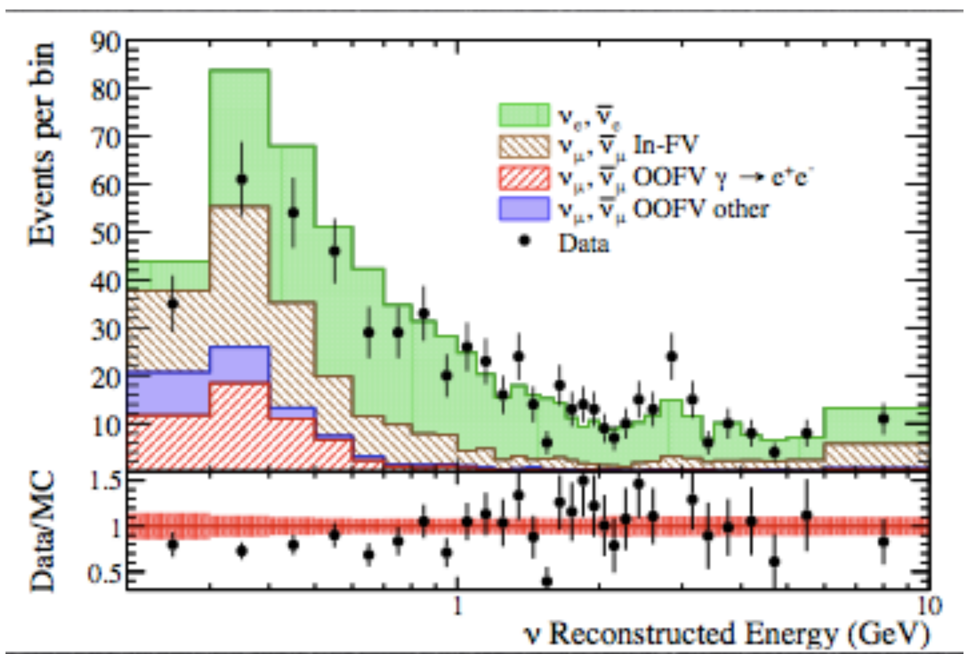
Search for SBL oscillations

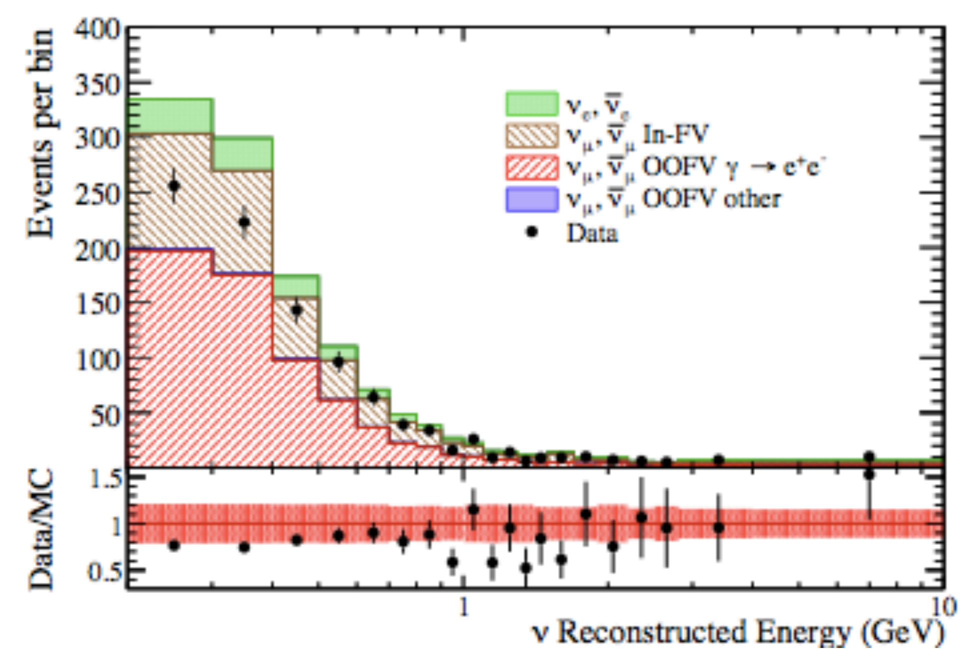
- 3+1 model $$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{ee} \cdot \sin^2\left(\frac{1.267\Delta m^2_{41} L_\nu}{E}\frac{\text{GeV}}{\text{eV}^2\text{km}}\right)$$

- No hints of ν_μ disappearance exists so far → $\sin^2(2\vartheta_{\mu\mu})=0$
- Search for ν_e disappearance in the $\sin^2(2\vartheta_{ee})$, Δm^2_{41} plane → Study Gallium and reactor anomalies

Analysis strategy

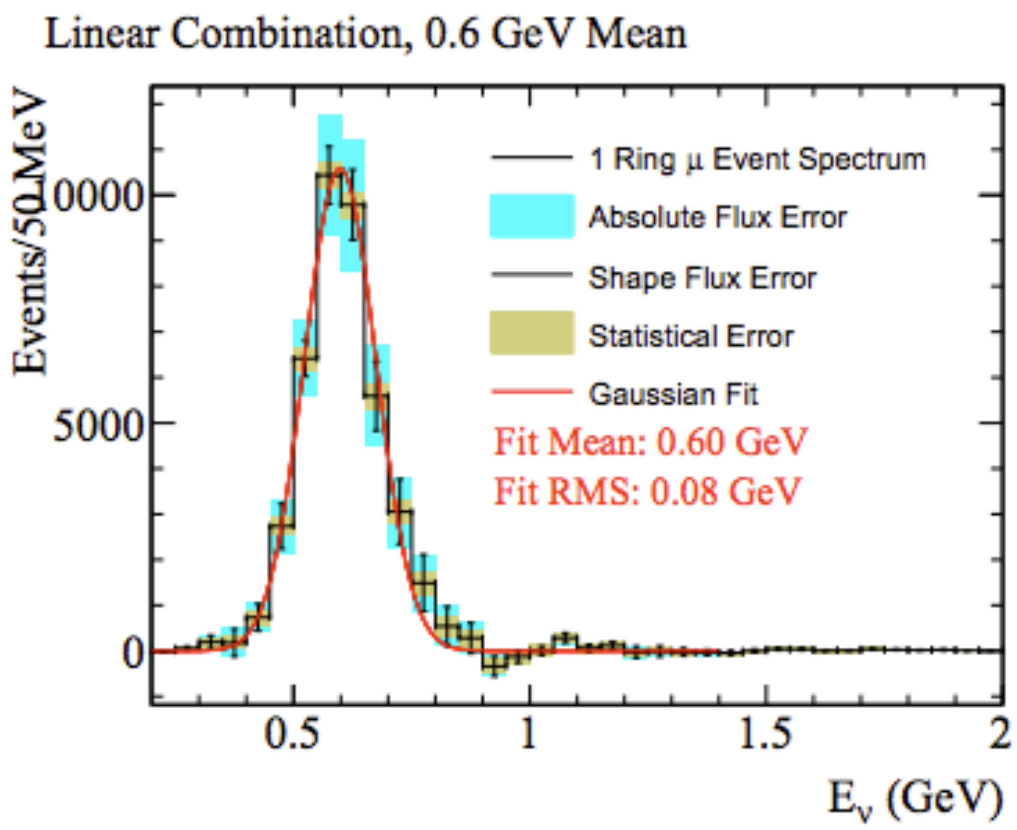
- Use the ν_e and γ selection (to constrain the background) at ND280 and fit the E_{reco} distribution
- Binned log-likelihood ratio method

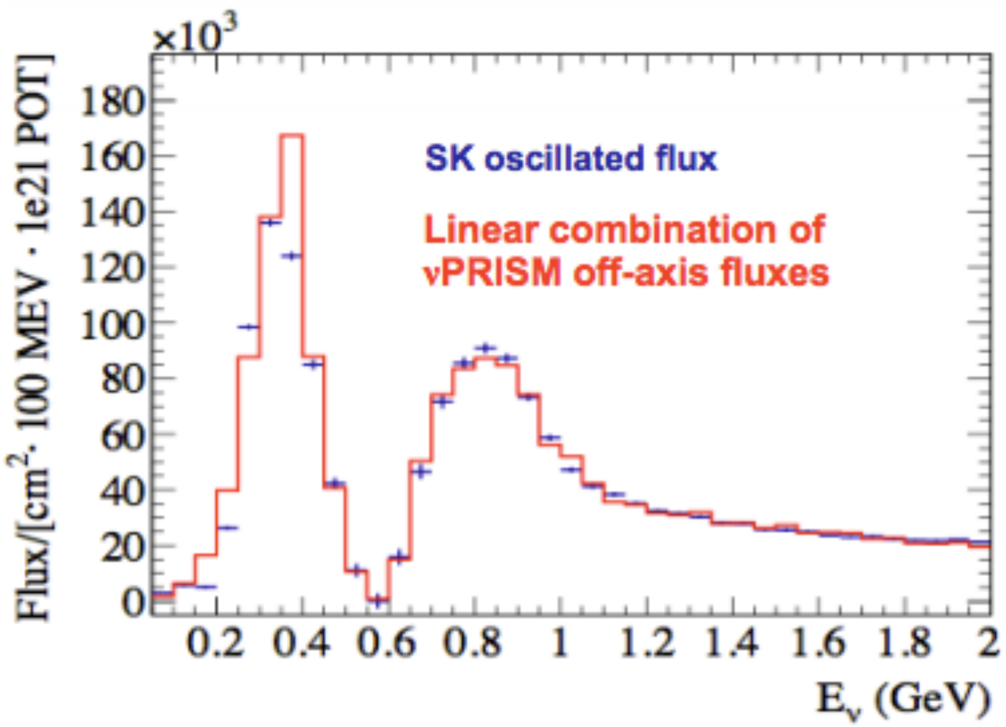




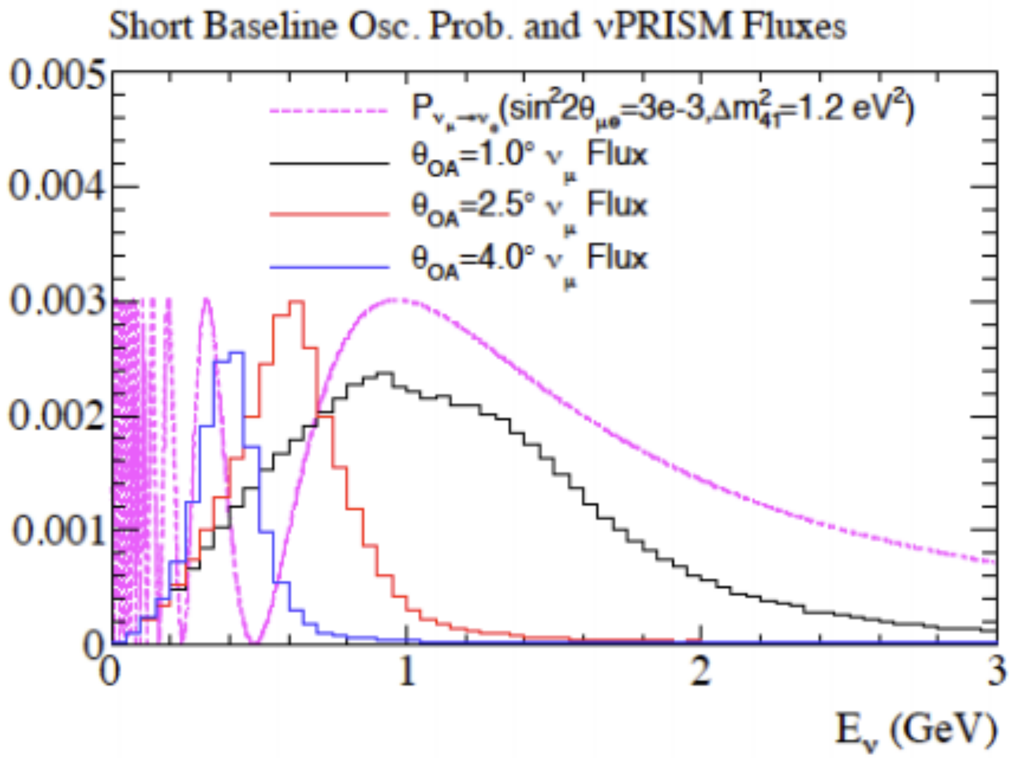
nuPRISM

- The detector can be logically divided into **slices of off-axis** based on the reconstructed vertex position
- Taking a linear combination of each of these slides a **pseudo-monochromatic beams** at any energy between 0.4 and 1 GeV
  - high energy tails subtracted using further off-axis measurements
  - low energy tails subtracted using further on-axis measurements
- nuPRISM technique can be expanded beyond monochromatic beams : it is possible to produce an **oscillated SK-like spectrum** → reduction of the uncertainties associated to cross section modeling

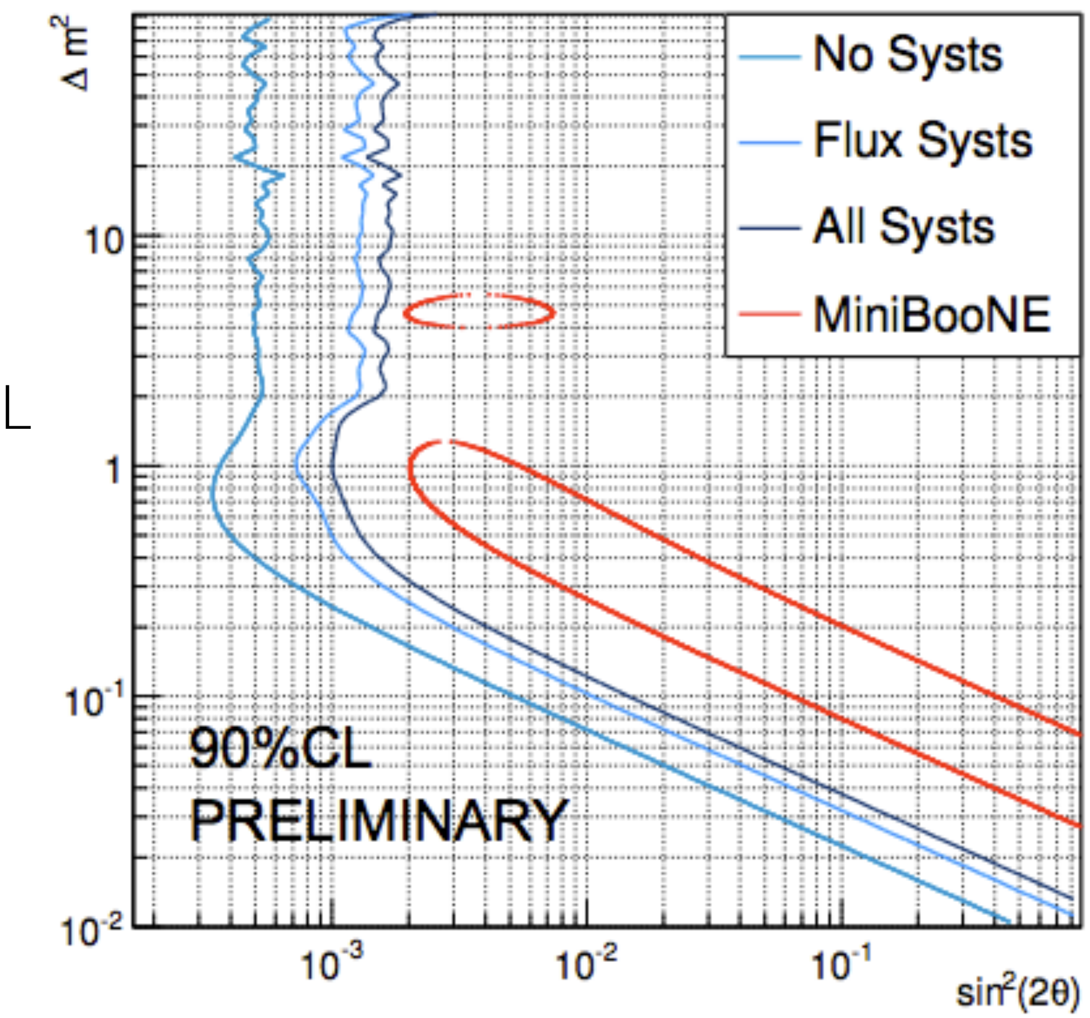




nuPRISM



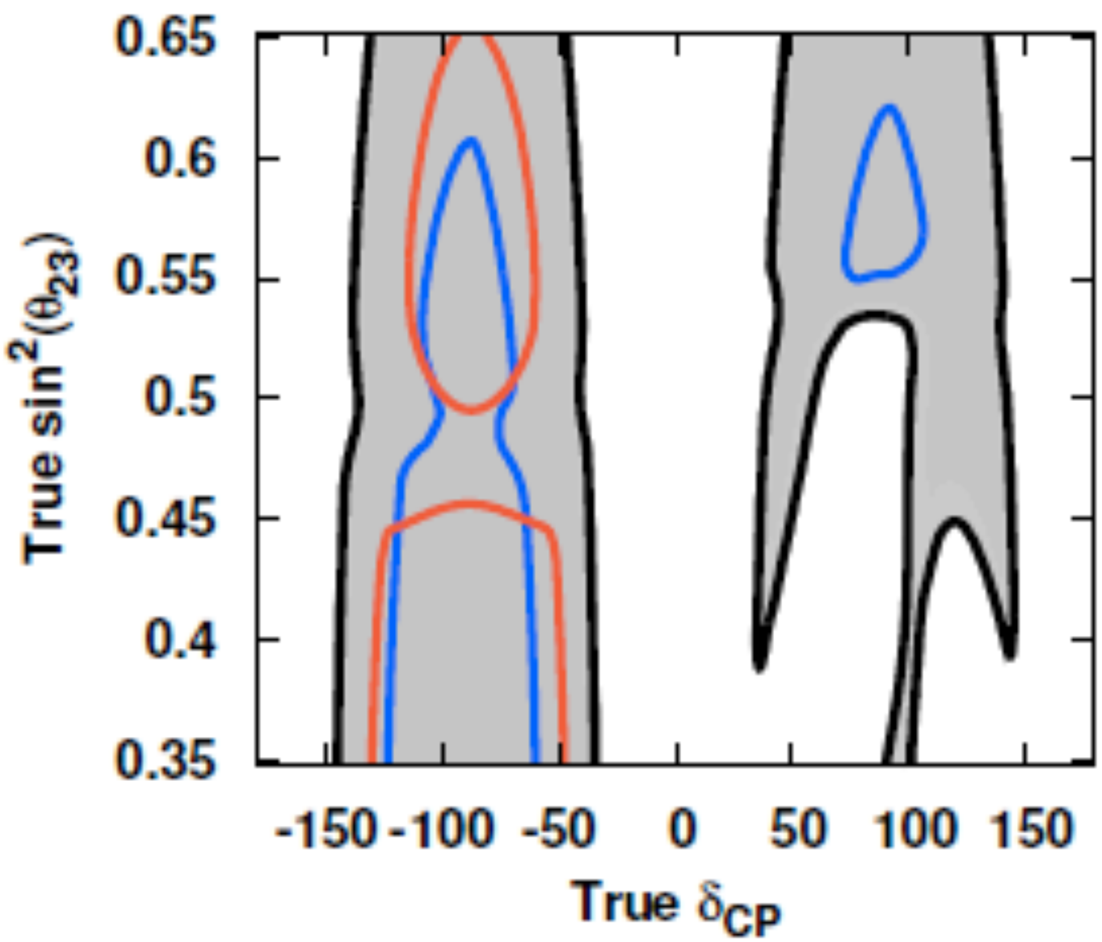
- 1Km baseline ideal to search for SBL oscillations through sterile neutrino
- The flux varies across nuPRISM giving unique capabilities
  - direct probe of the oscillation w/o relying on reconstructed energy
  - NC and CC background events will affect different off-axis slices differently



- 4.6×10^{20} POT
- nuPRISM can resolve MiniBOONE anomaly @ 90% CL
- Do not include existing constraints from ND280 measurements which will improve the sensitivity

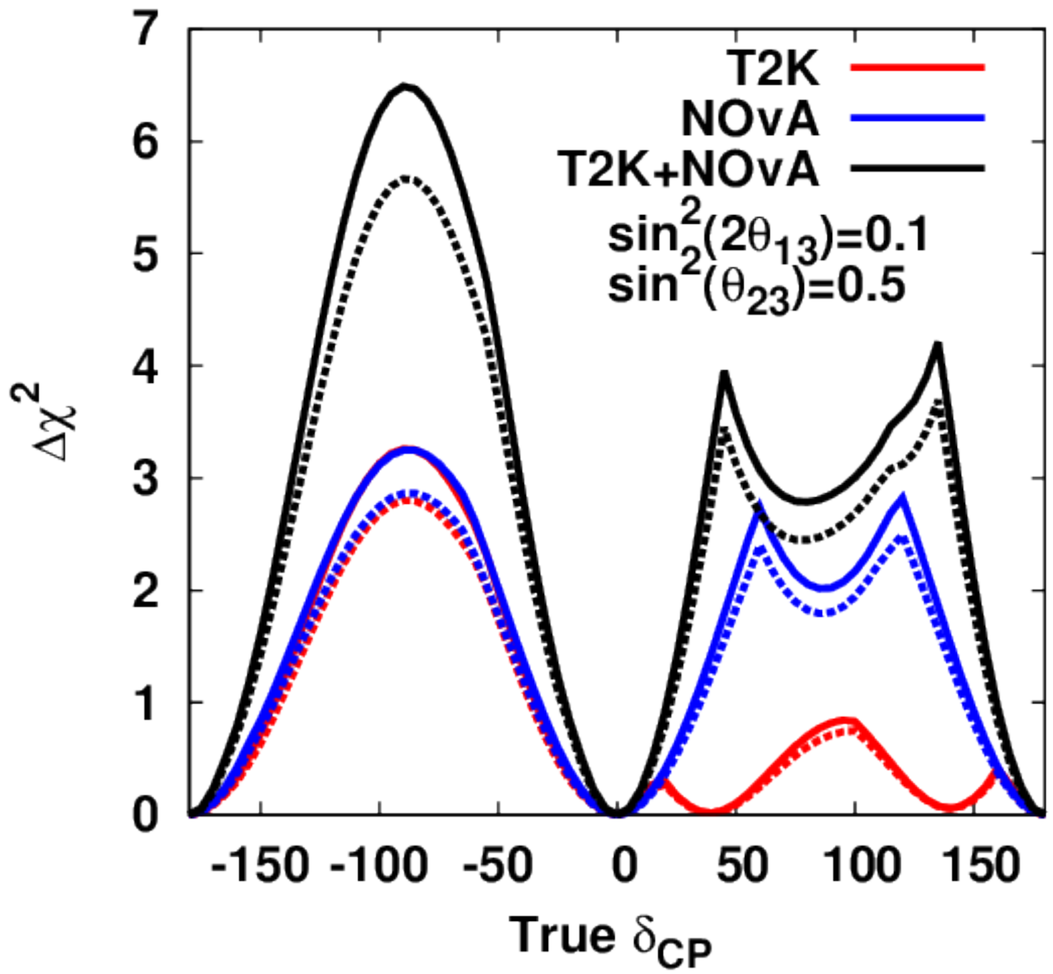
T2K+Nova Future sensitivity δ_{CP}

Region where δ_{CP} can be discovered at 90% CL



T2K alone | Nova alone | T2K+ Nova

Sensitivity to sinδ /= 0



solid (dash) : w/o (w/) systematics

Assuming true values : $\sin^2 2\vartheta_{13} = 0.1$, $\Delta m^2_{32} = 2.4\times10^{-3}\,\mathrm{eV}^2$