Recent results from the T2K experiment

Stefania Bordoni

Bologna, 15 May 2015

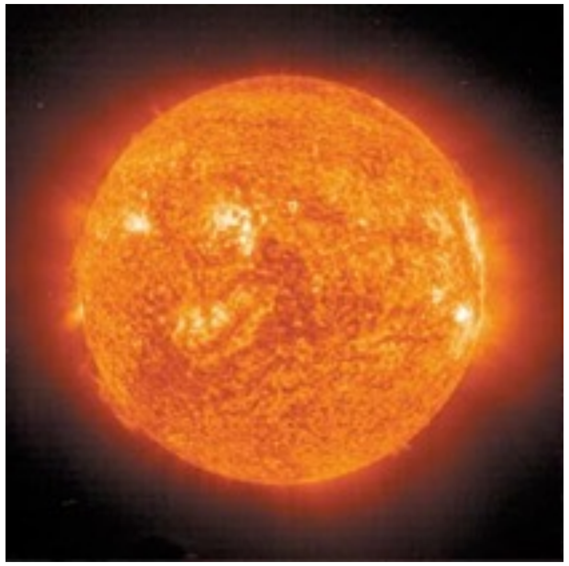
Overview of the talk

- Introduction to neutrino oscillations
- The T2K experiment
  - The experimental setup
  - Towards the oscillation analysis
  - The oscillation results
  - First look to anti-neutrino data

Neutrino oscillations

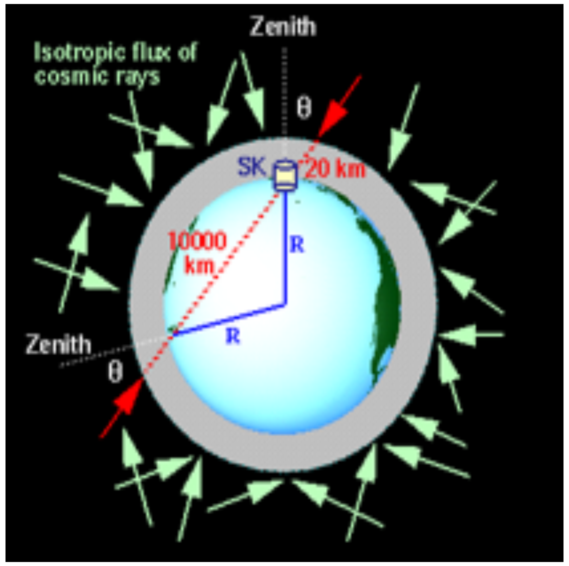
- Neutrino oscillations have a long history
- postulated by B. Pontecorvo in 1957
- First experimental evidence in 1968 observing a deficit in the expected solar neutrino flux
- First experimental evidence of atmospheric neutrino oscillation by Super Kamiokande in 1998
- Confirmation of the solar neutrino transition by SNO in 2001

Neutrino oscillations : various sources, vastly different energy and distance scales



solar neutrinos

E ~ [KeV, 10MeV]



atmospheric neutrinos

E ~ [MeV, 100TeV]

reactor neutrinos

E ~ [MeV, 10MeV]

accelerator neutrinos

E ~ [100MeV, 100GeV]

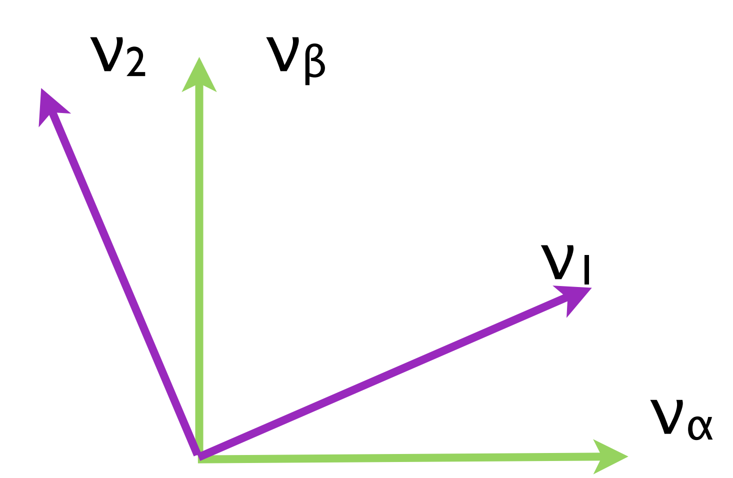
Neutrino oscillations

- Flavour states are coherent superposition of the mass states → flavour mixing
  - Similar to the CKM mixing matrix for quarks

2 neutrino scenario

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

flavor states mixing matrix mass states



Neutrino oscillations

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  - Similar to the CKM mixing matrix for quarks
- Neutrinos are always **produced** and **detected** as **flavour eigenstates**, while they **propagate** as **mass eigenstates**
- If mass eigenstates are different, they propagate with different phases → quantum interference changing the proportion of ν_1 and ν_2 at the detection

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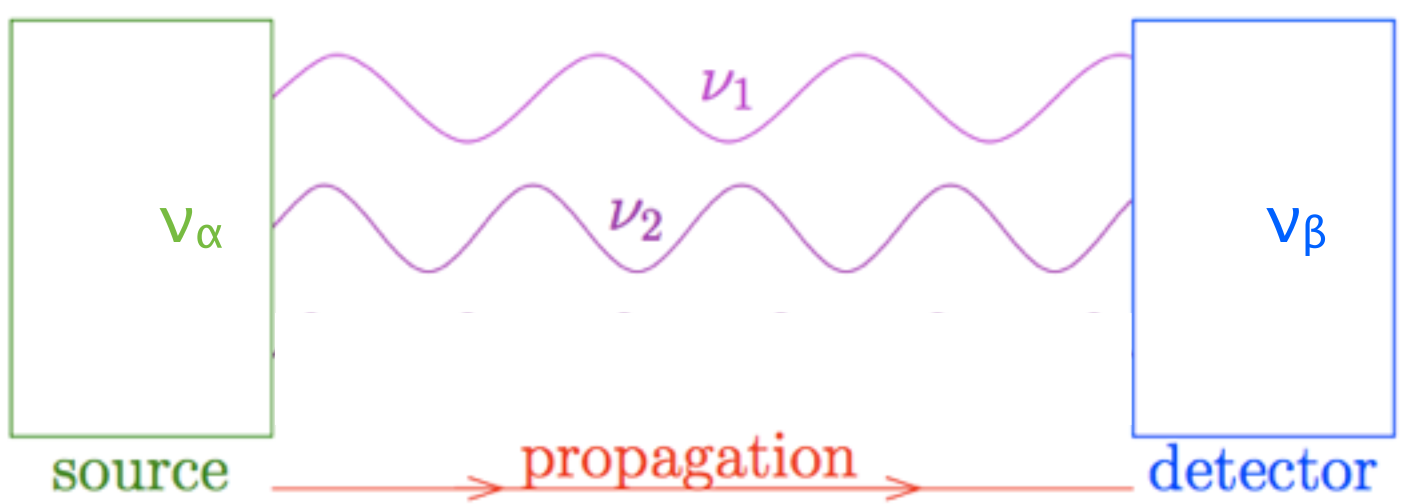

by C.Giunti

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2 neutrino scenario

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 [eV^2]}{E[GeV]} L[km]\right)$$

L = ν flight path

E = ν energy

Neutrino oscillations

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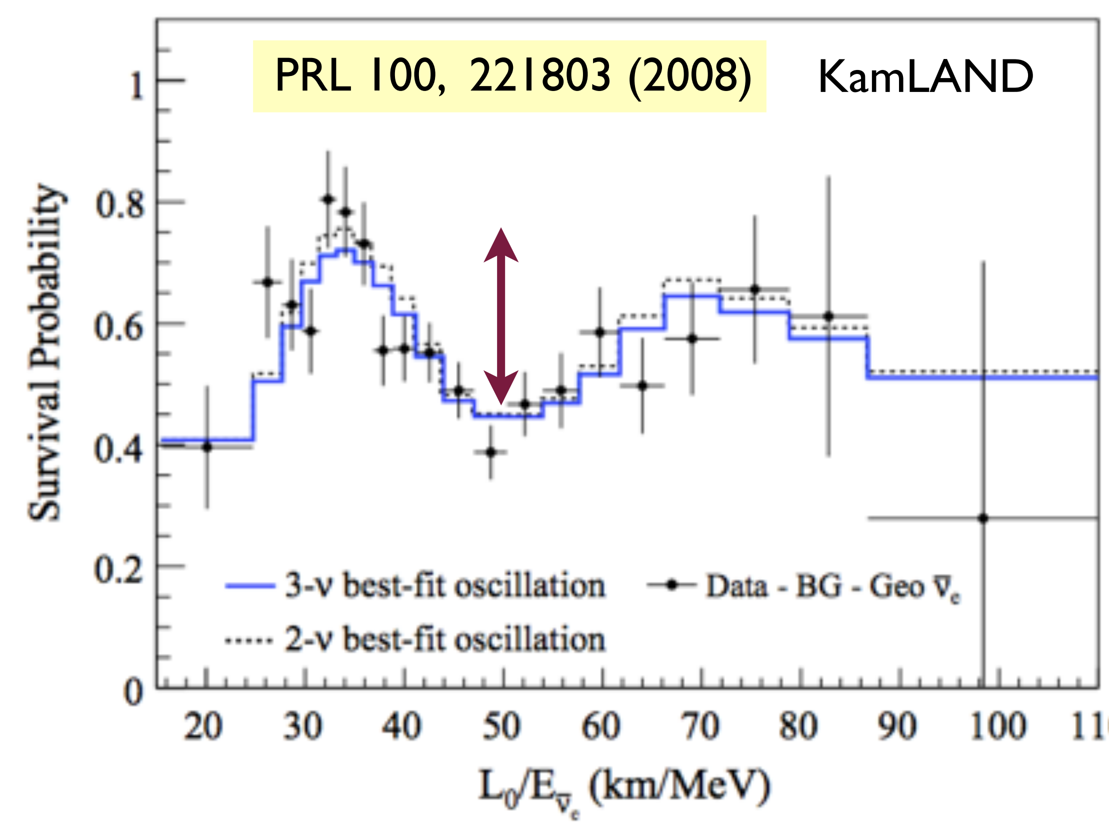
amplitude

anti-ν_e disappearance



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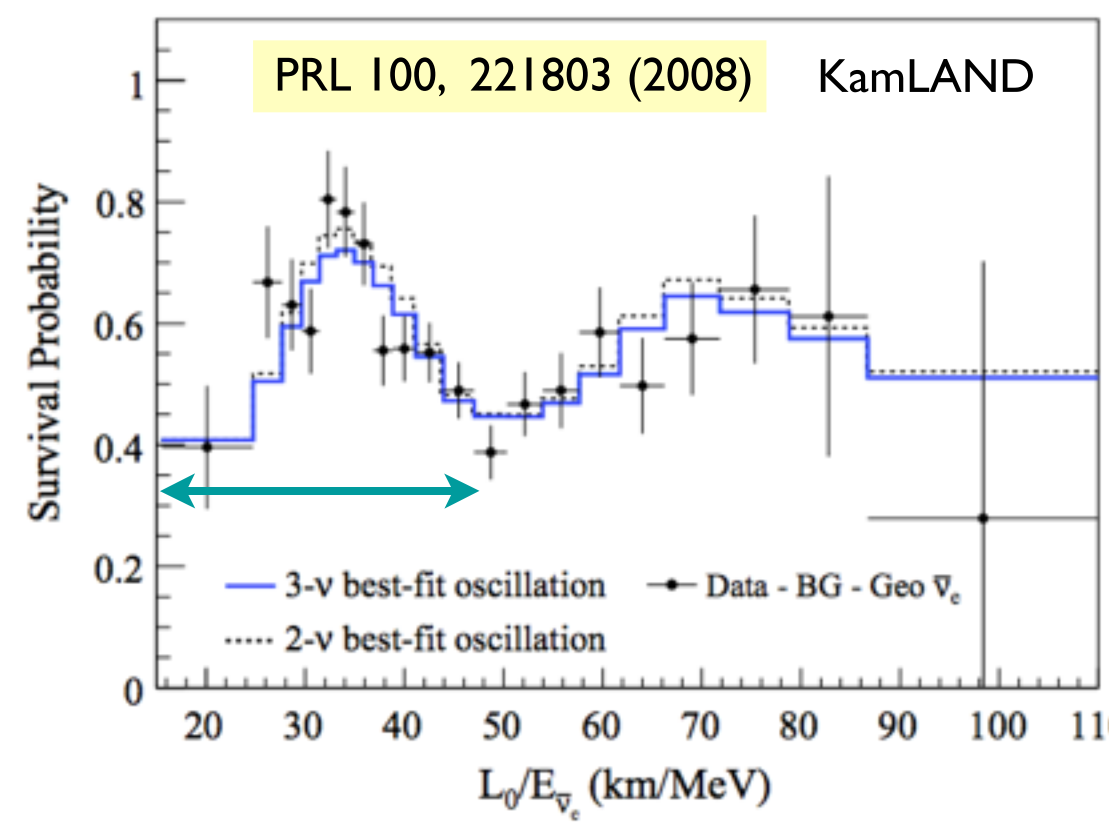
frequency

anti-ν_e disappearance



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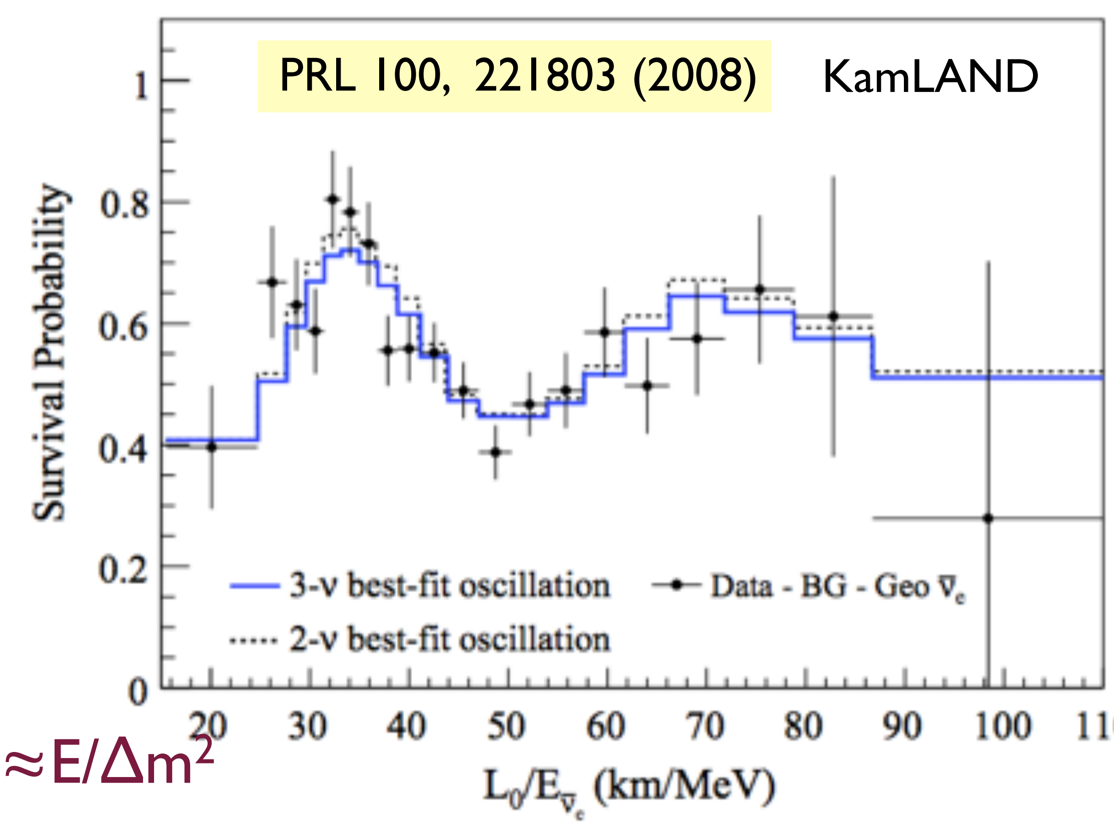

In order to determine both the oscillation parameters $L \approx E/\Delta m^2$

Neutrino oscillations

3 neutrinos scenario

PMNS matrix

cij = $\cos\theta_{ij}$
sij = $\sin\theta_{ij}$

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

flavor eigenstates | Atmospherics and accelerators | Interference | Solar and reactors | mass eigenstates

Pontecorvo Maki Nakagawa Sakata (PMNS) mixing matrix

- 3 angles (θ_{12}, θ_{23}, θ_{13})
- 1 imaginary phase (δ) allowing for CP violation
- **2 independent mass differences ($\Delta m_{ij}^2 = m_i^2 - m_j^2$)**

Neutrino oscillations

3 neutrinos scenario

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flavor eigenstates | Atmospherics and accelerators | Interference | Solar and reactors | mass eigenstates

Atmospherics and accelerators:

- Super Kamiokande
- K2K
- MINOS
- T2K

Interference:

- DoubleChooze
- Daya Bay
- RENO
- T2K
- MINOS

Solar and reactors:

- Super Kamiokande
- SNO
- Borexino

What do we (not) know about ν oscillations

PMNS parameter	Best Fit point (NH)	Best Fit point (IH)	Examples of experiments
Δm^2_{12} (10^{-5})	$7.50^{+0.19}_{-0.17}$	$7.50^{+0.19}_{-0.17}$	SK, SNO, KL, BOREX
$\Delta m^2_{3\ell}$ (10^{-3})	$+2.457^{+0.047}_{-0.047}$	$-2.449^{+0.048}_{-0.047}$	SK, K2K, MINOS, T2K
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.304^{+0.013}_{-0.012}$	SK, SNO, KL, BOREX
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$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0219^{+0.0011}_{-0.0010}$	T2K, DB,DC,RENO
δ_{CP}	306^{+39}_{-70}	254^{+63}_{-62}	MINOS, T2K

T.Schwetz et al. arXiv:1409.5439 [hep-ph]

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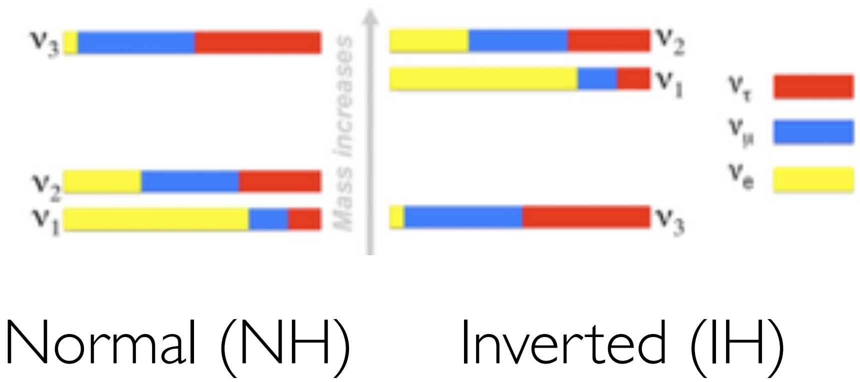
- **Mass hierarchy** still not known ($m_3 > m_2$?)



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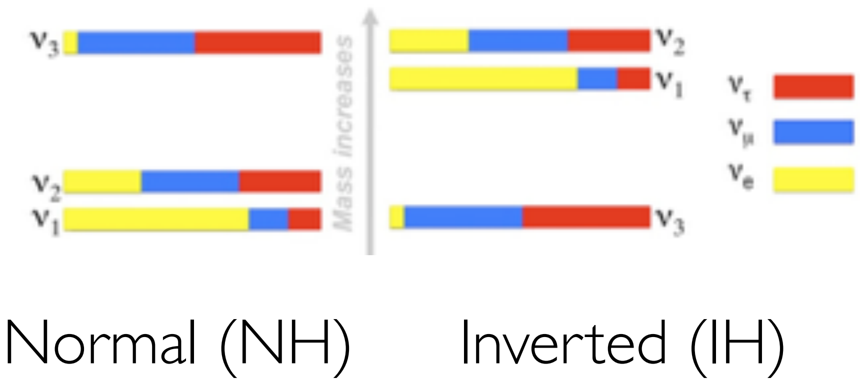

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- **θ_{23} octant** still not determined : (e.g. is it > or < 45° ? is **θ_{23} maximal**?)

What do we (not) know about ν oscillations

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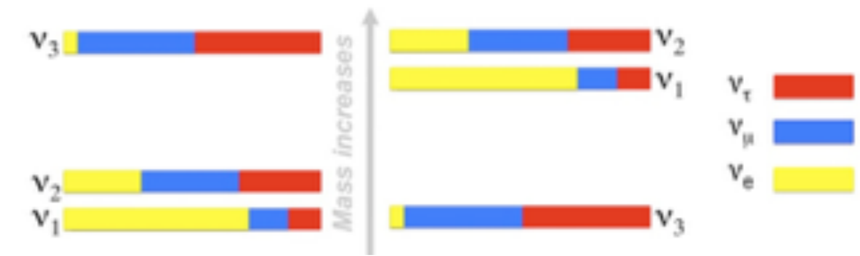

Normal (NH) Inverted (IH)

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- θ_{23} **octant** still not determined :
  (e.g. is it > or < 45° ? is θ_{23} **maximal**?)

- δ_{CP} still unknown (some hints..)

- Are they only three? (sterile neutrinos)

- Are they Dirac or Majorana particle

Overview of the T2K experiment

- Physics goals
- Experimental setup : beam-line, near detector, far detector

The T2K experiment

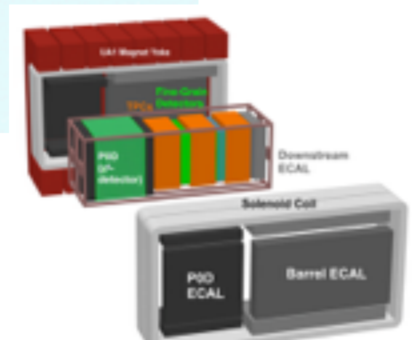
- Long baseline neutrino oscillation experiment in Japan (Tokai to Kamioka)
- Muon neutrinos produced from a 30GeV proton beam (JPARC)
- Neutrinos detected in 2 points :
  - at the **near detector** (**ND280**) at 280 m
  - at the **far detector** (**Super-Kamiokande**) at 295 Km

A bit of history...

- 1999 : idea of a ν_μ to νe experiment at JPARC
- 2000-2004: letter of Intent, formation of the collaboration and construction approved by the Japanese government
- 2009 : commissioning of the beam-line

Far Detector (~300Km)

Japan Proton Accelerator Research Complex (JPARC)



Near Detector (@~280m)

The T2K experiment

The T2K Collaboration

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Metropolitan U.
U. Tokyo

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia

Switzerland
ETH Zurich
U. Bern
U. Geneva

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

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

~500 physicists , 59 institutions, 11 countries

The T2K main physics goals

- ν_μ disappearance ($\nu_\mu \rightarrow \nu_\mu$)

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{13}L}{4E}\right) + (\text{matter terms})$$

- ν_e appearance ($\nu_\mu \rightarrow \nu_e$)

$$\begin{aligned} P(\nu_\mu \to \nu_e) \;\; \simeq \;\; & \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\frac{\Delta m^2_{31}L}{4E_\nu} \\ & -\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E_\nu}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E_\nu}\sin\delta_{CP} \\ & +(\text{CP even term, solar term, matter effect term}) \end{aligned}$$

The T2K main physics goals

- ν_μ disappearance ($\nu_\mu \rightarrow \nu_\mu$)

⚠ θ_{13} measured and ≠ 0 !
sub-leading terms are important to determine the θ_{23} octant

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{13}L}{4E}\right) + (\text{matter terms})$$

- ν_e appearance ($\nu_\mu \rightarrow \nu_e$)

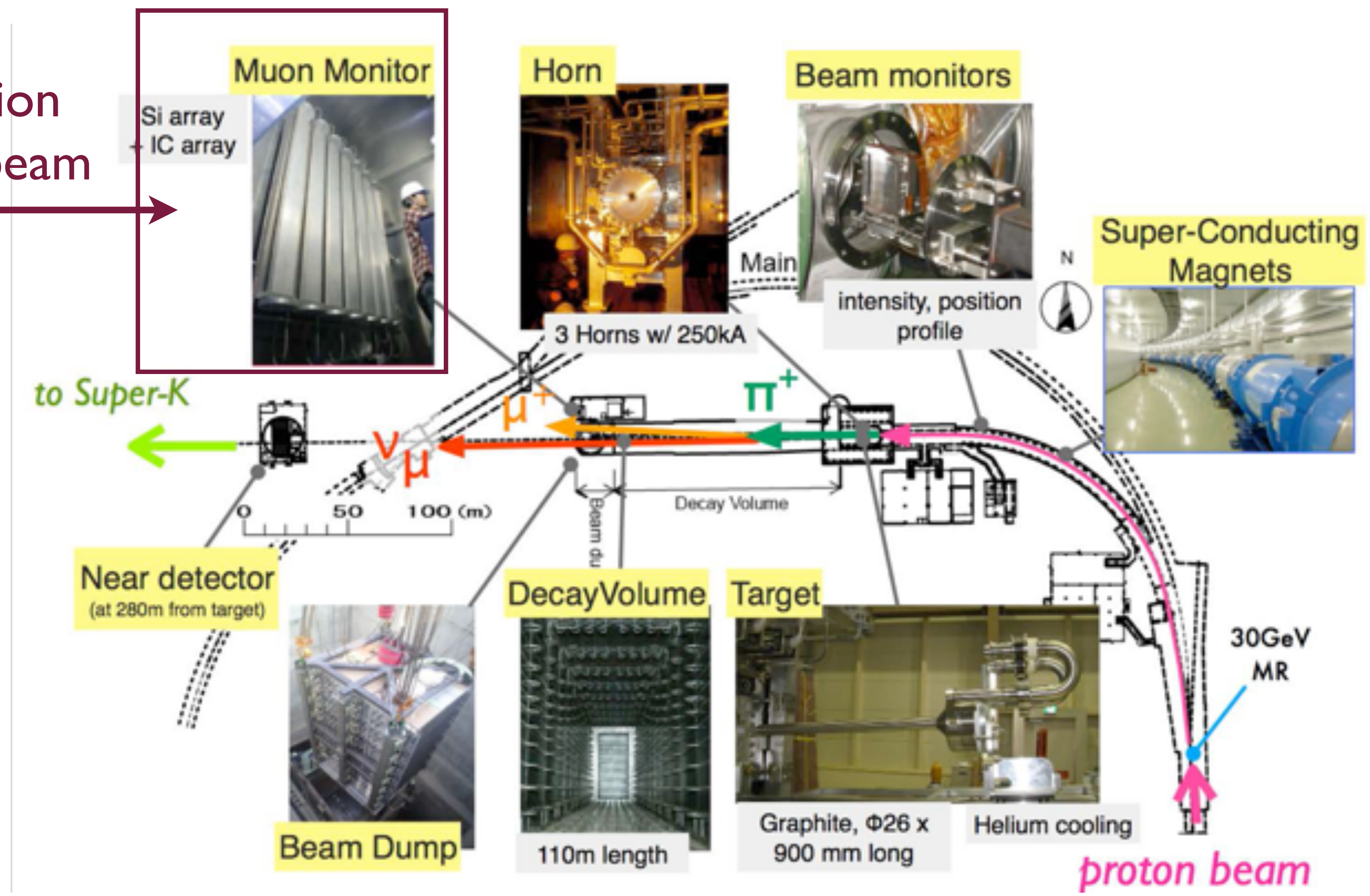
⚠ appearance probability also depends to θ_{23} !

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\frac{\Delta m^2_{31}L}{4E_\nu} - \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E_\nu}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E_\nu}\sin\delta_{CP} + (\text{CP even term, solar term, matter effect term})$$

Neutrino beam production

- 30 GeV protons from the main ring collides over a graphite target
- from proton collisions pions and kaons are produced
- 3 electromagnetic horns focus and select in charge the produced hadrons
- ν_μ are produced from the hadron decay (i.e. $\pi \rightarrow \mu\ \nu_\mu$)

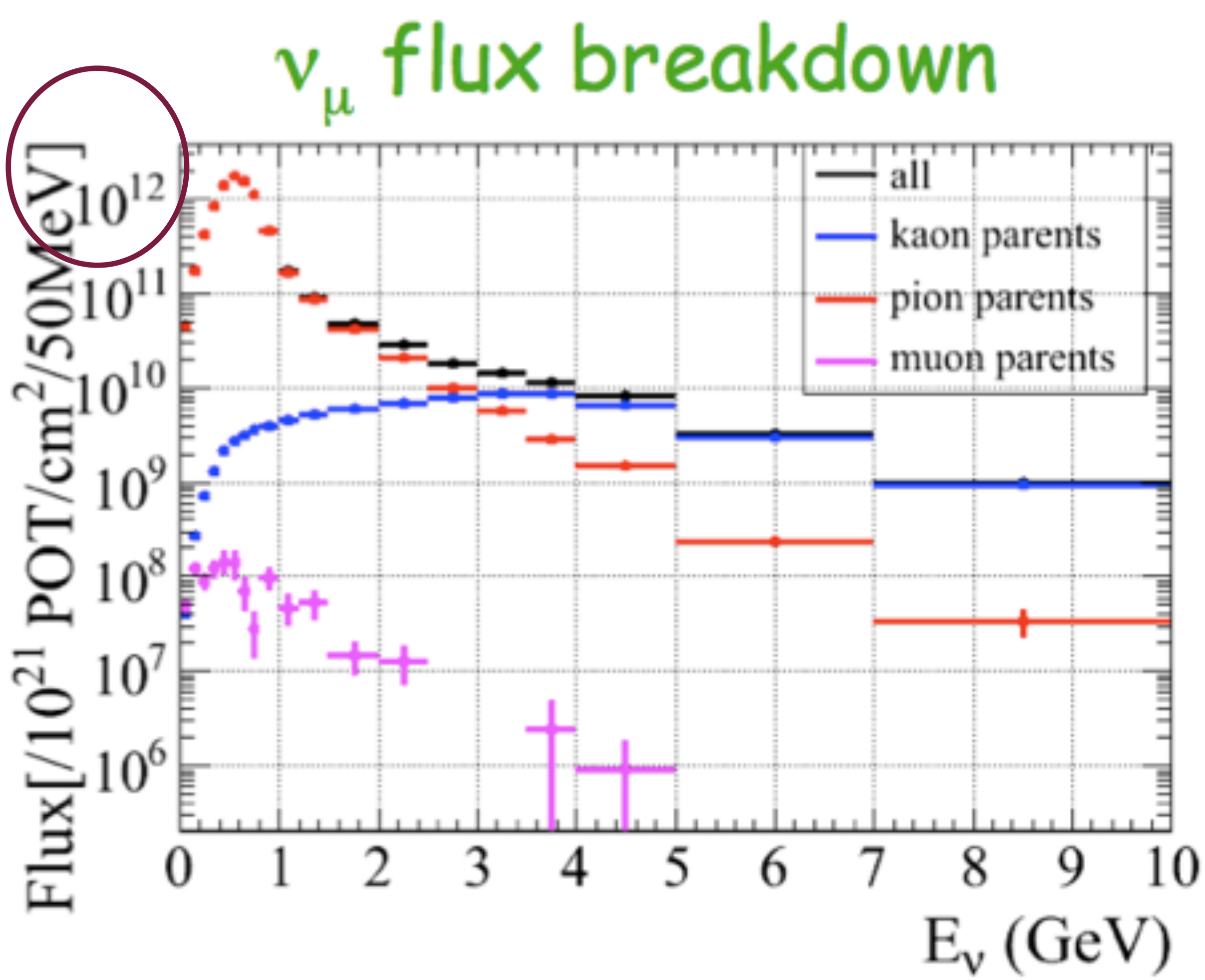
first information about the ν beam

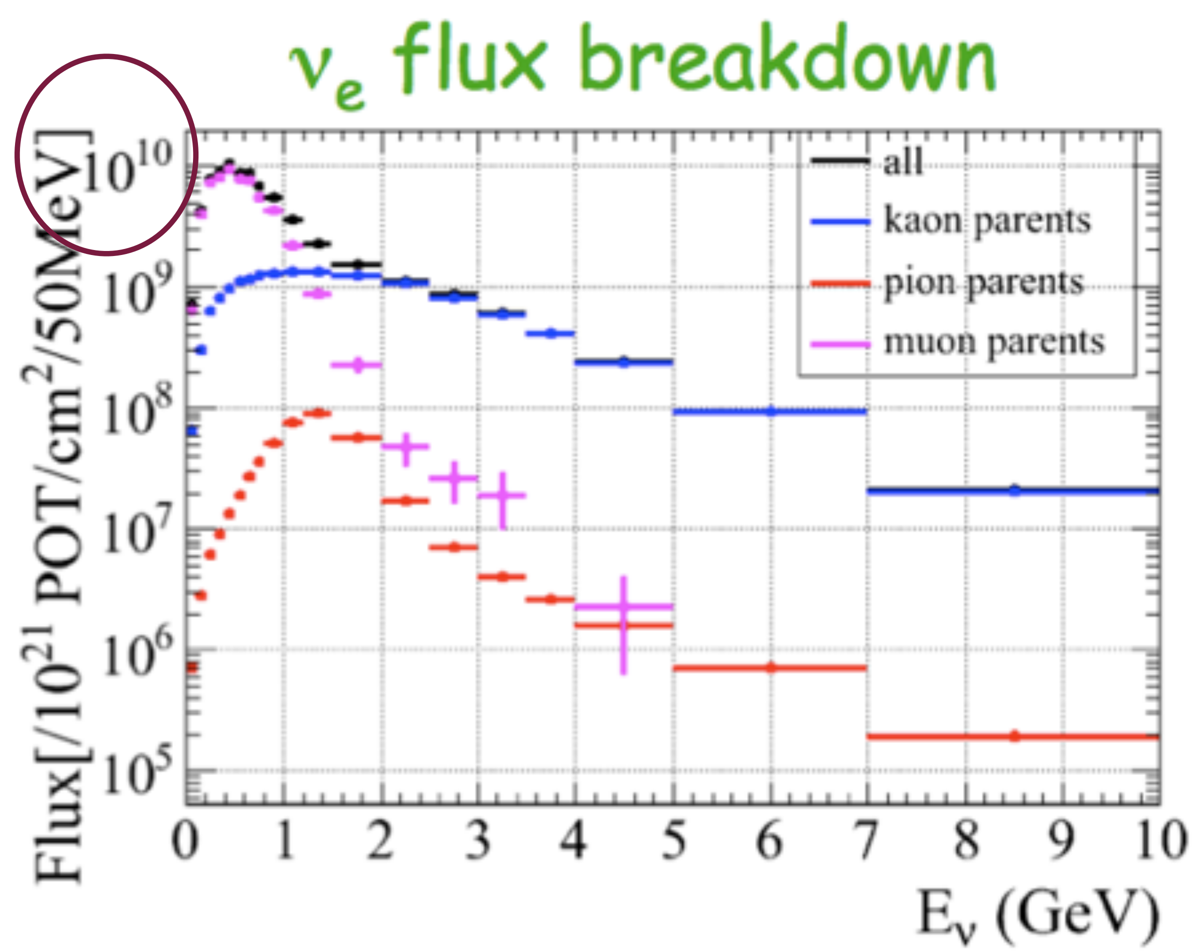


Neutrino beam production

Beam composition :

- mainly ν_μ : primarily from π decay, high energy tail from K decay
- contamination on ν_e (~1%): primarily from μ decay and high energy tail from K decay



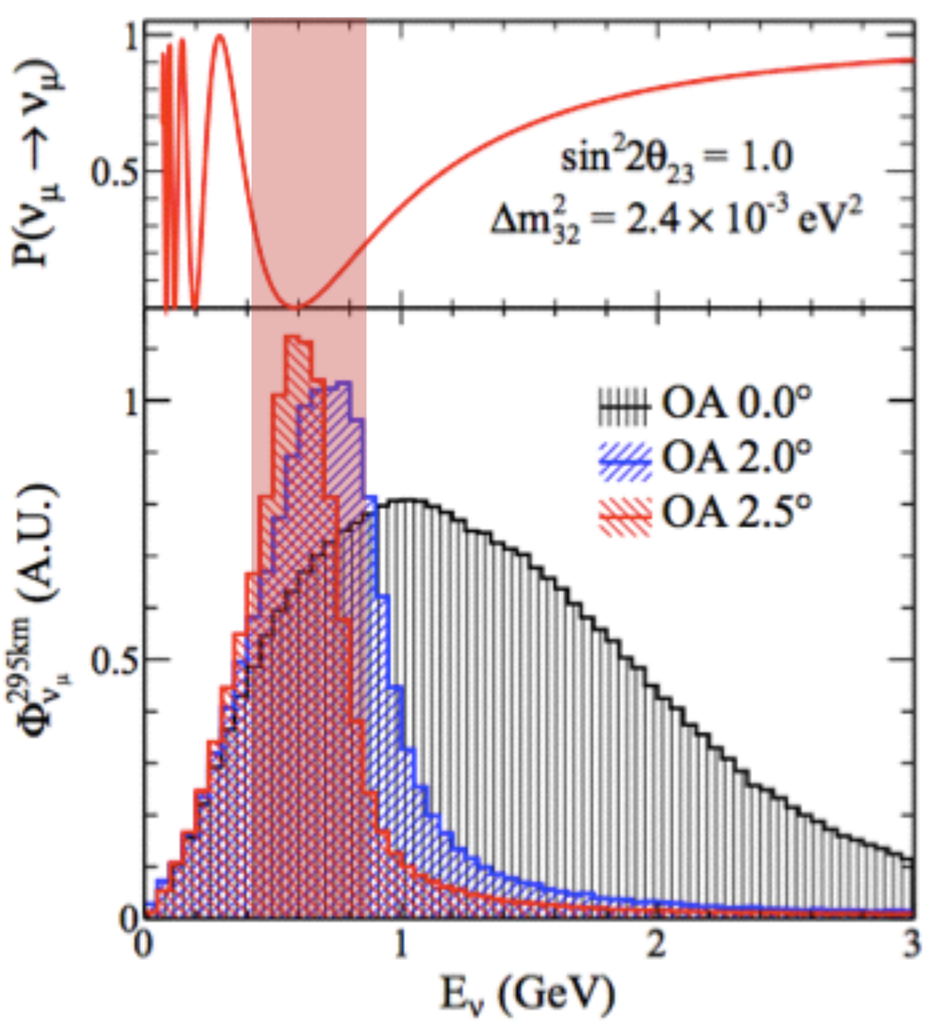


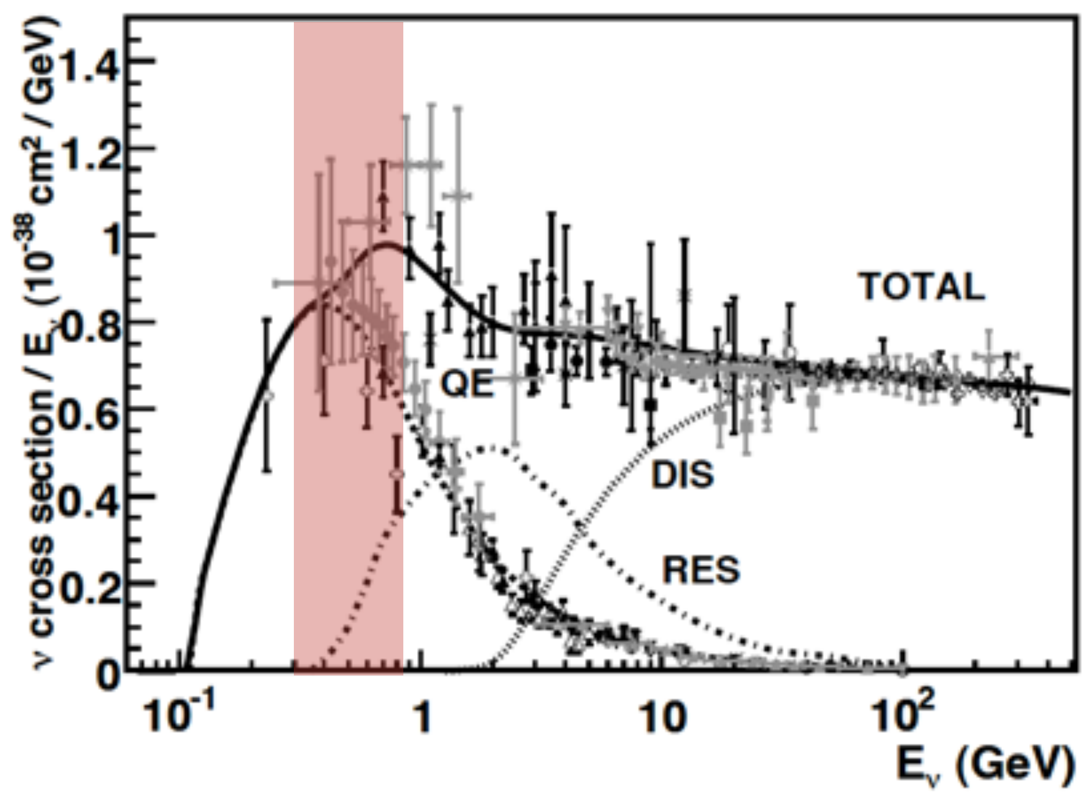
Off-axis technique

T2K runs 2.5° off-axis with respect to the initial proton beam

First experiment using the off-axis technique

- ν beam is picked at the maximum of oscillations
- ν interactions are dominated by QE processes → reduction of the backgrounds



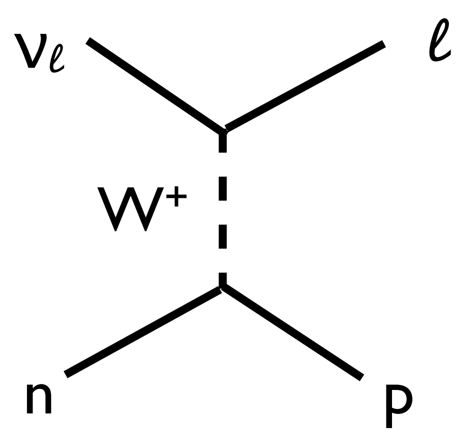


QE : Quasi Elastic
RES: Resonant pion production
DIS: Deep Inelastic Scattering

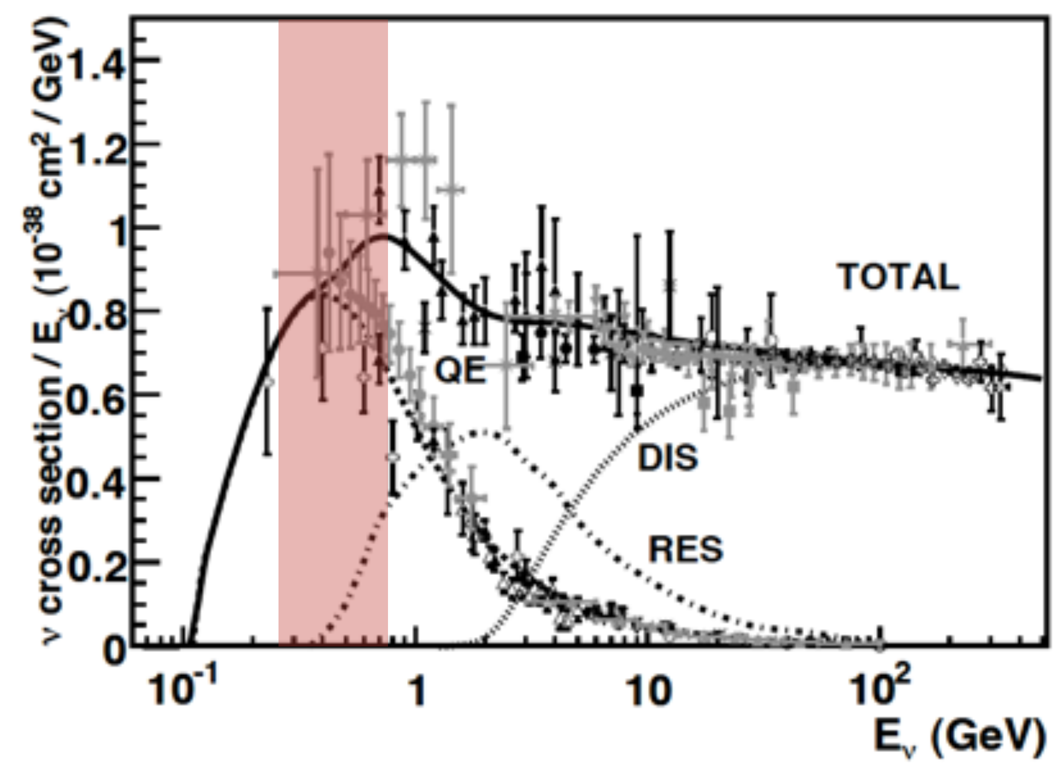
Signal and Background @T2K

- At 100 MeV< E_ν < few GeV , neutrino nucleon Quasi Elastic interaction dominate
- Resonance pion production is the second main contribution to the total cross section

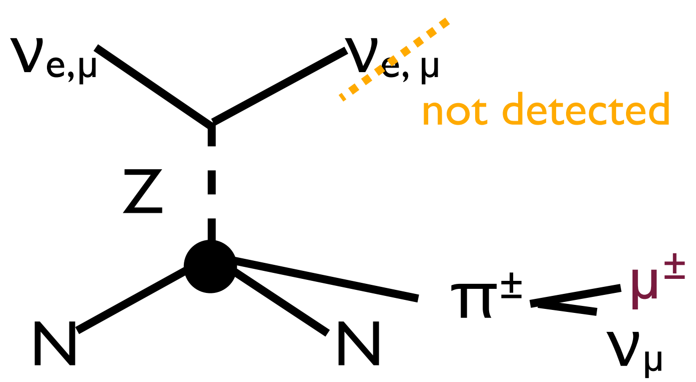
- Signal @ SK : CCQE interaction :
  μ^- from ν_μ or e^- from ν_e



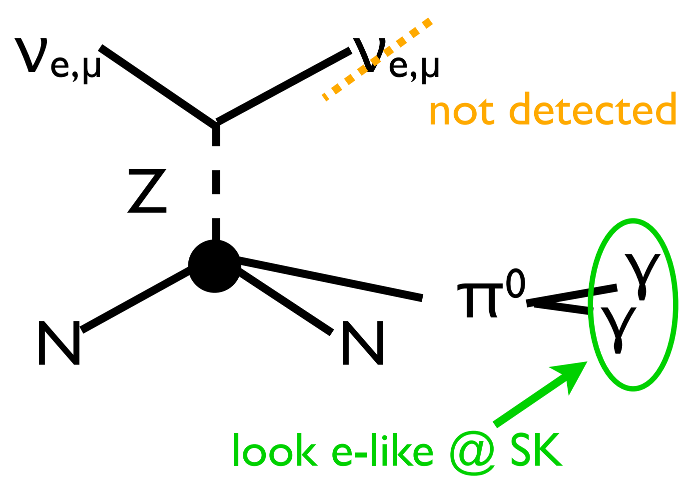
$\ell = \mu^-, e^-$



- Background @ SK



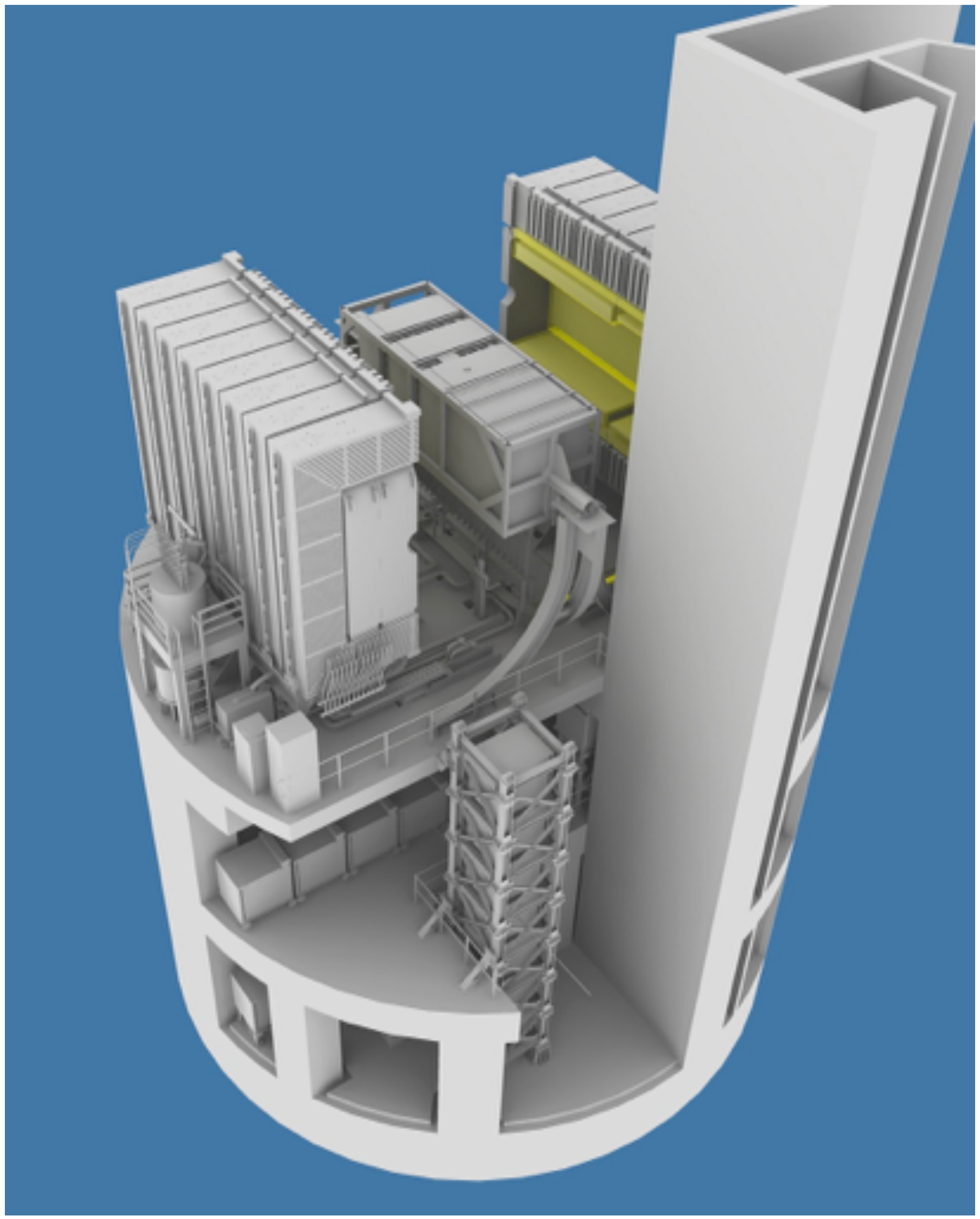
ν_μ disappearance bkg



\+ ν_e intrinsic beam contamination

ν_e appearance bkg

ND280 facilities



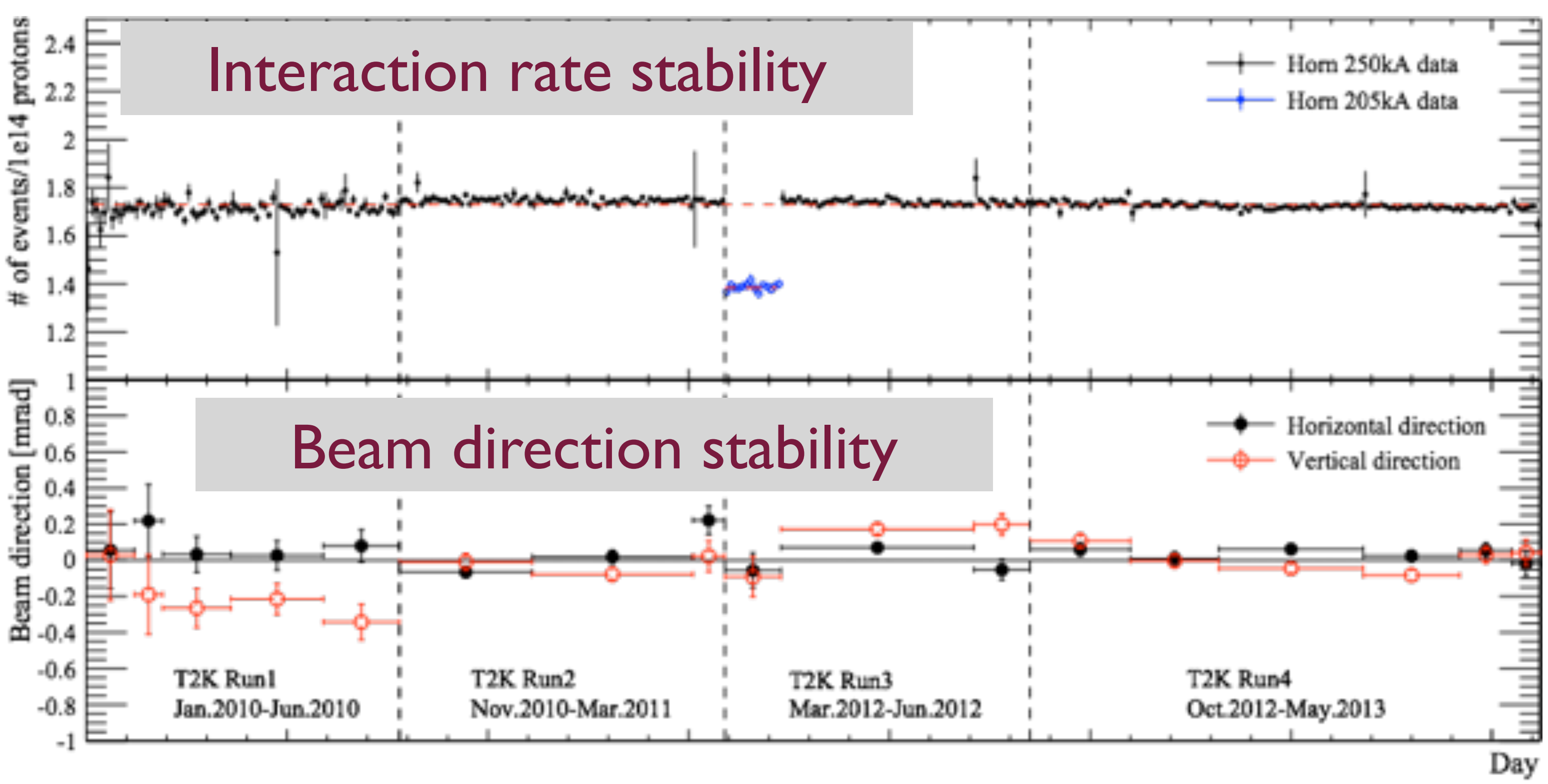
Two detectors located at 280 m from the target

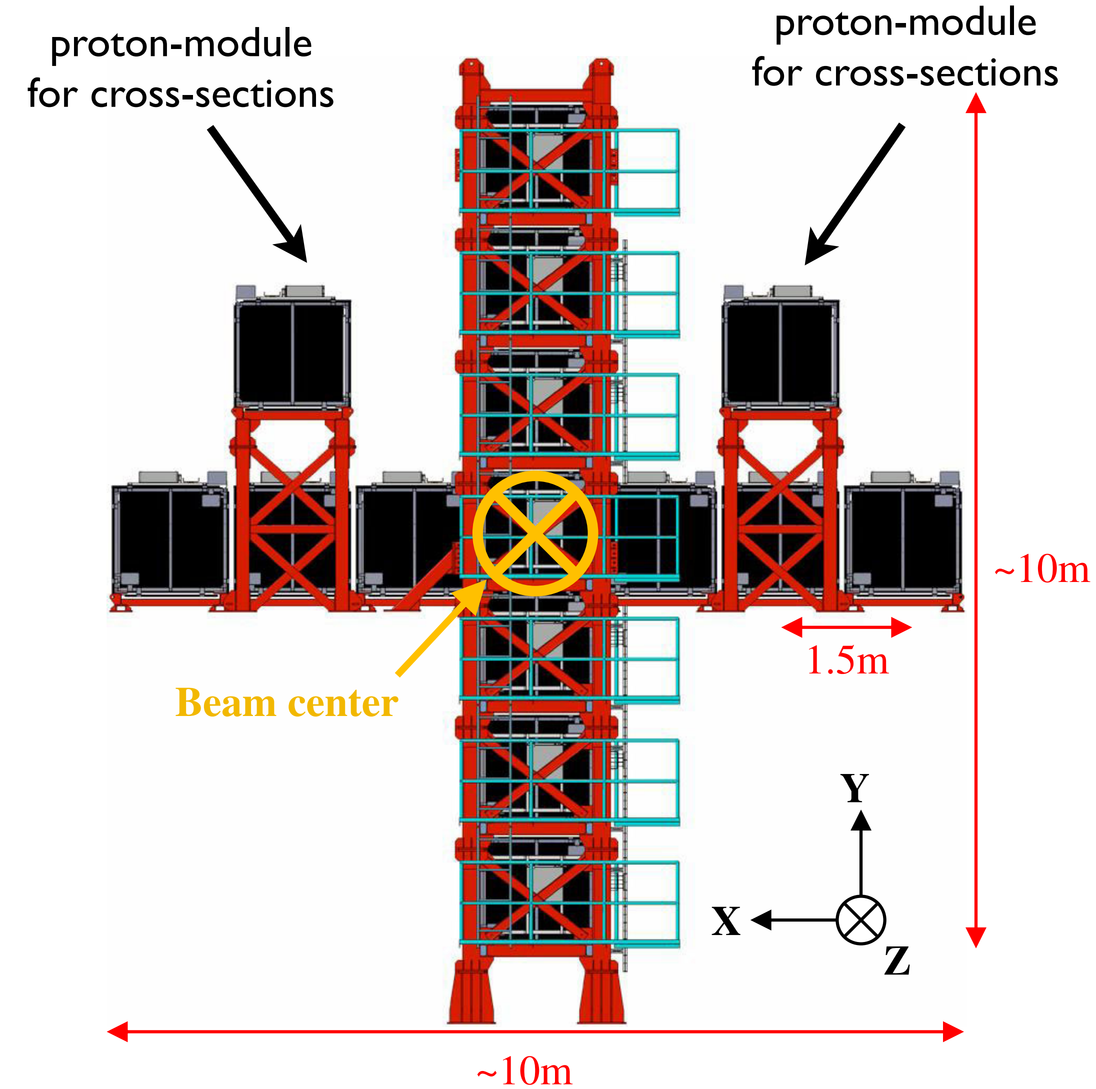
- **INGRID** : on axis detector → monitor the stability of the neutrino flux
- **ND280** : off-axis detector → measure the neutrino flux and cross section

INGRID: the on-axis near detector

- **14 identical modules** arranged as a cross, composed by iron (target) and scintillators (active region)
  - monitor of the **beam stability** in intensity (total rate)
  - monitor the beam **stability in direction** (rate per module)

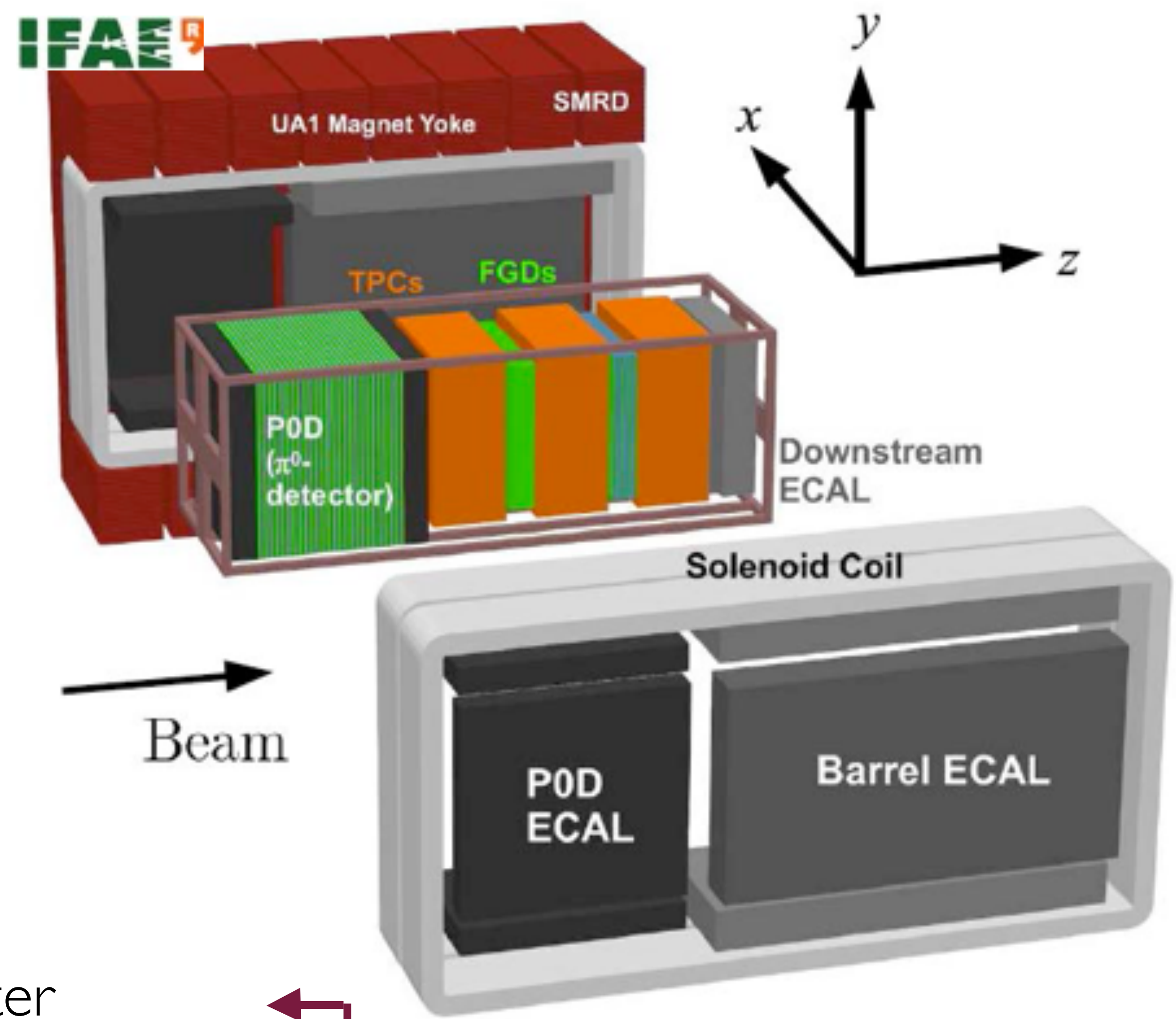
- **2 proton modules** only composed by scintillators for neutrino cross sections measurements





ND280: the off-axis near detector

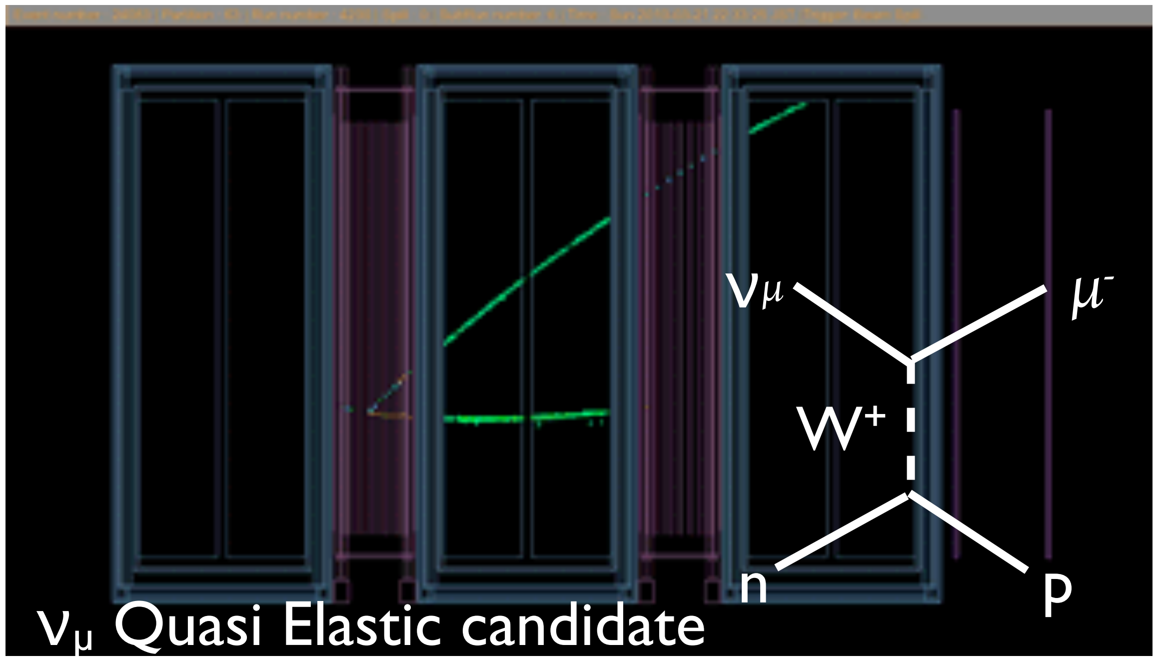
- Composite detector embedded in a 0.2T magnet field
- **Measure** the ν_μ and ν_e **spectrum before oscillations**
- **Neutrino cross-section measurements**



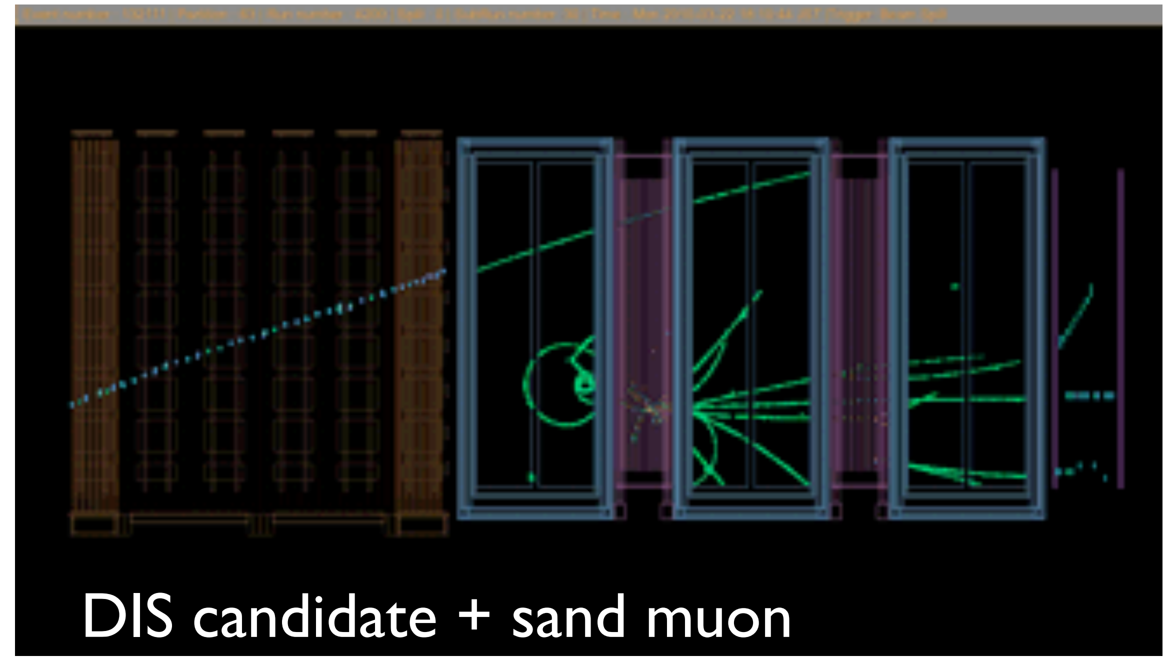
- P0D : π^0 detector for NCπ^0 CS measurements
- FGD: active target for ν interaction in carbon and water
- TPCs : measure of momentum, charge and high PID capabilities measuring dEdx
- Ecal: electron/gamma identification
- SMRD: measure of high angle muons

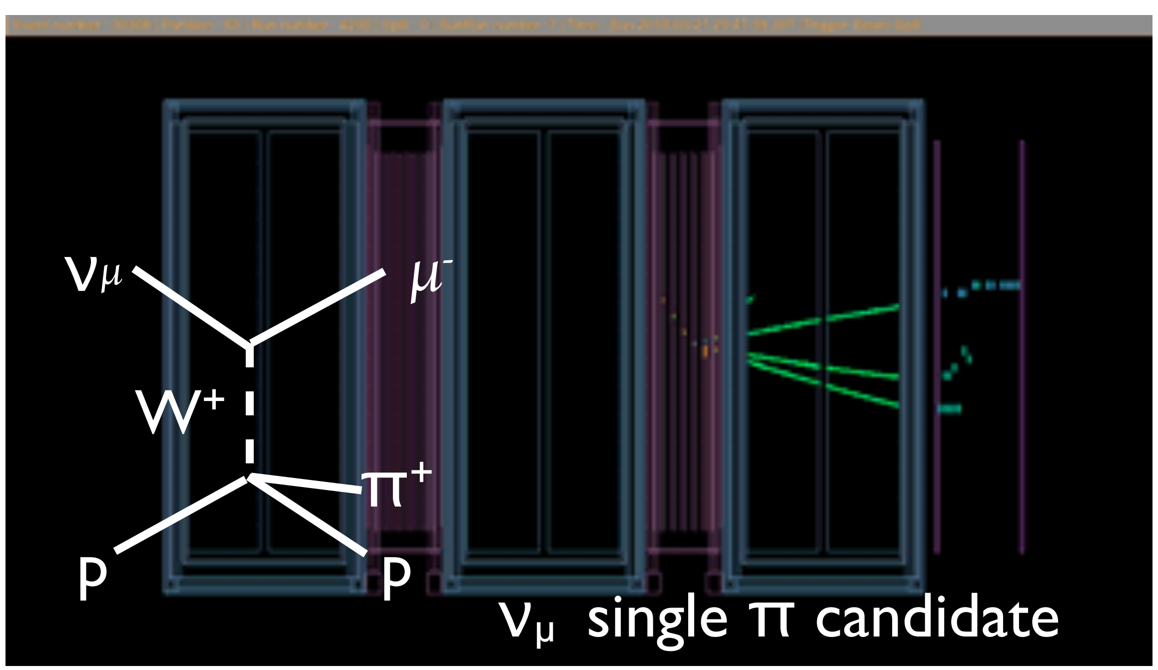
Tracker

ND280 detector events gallery

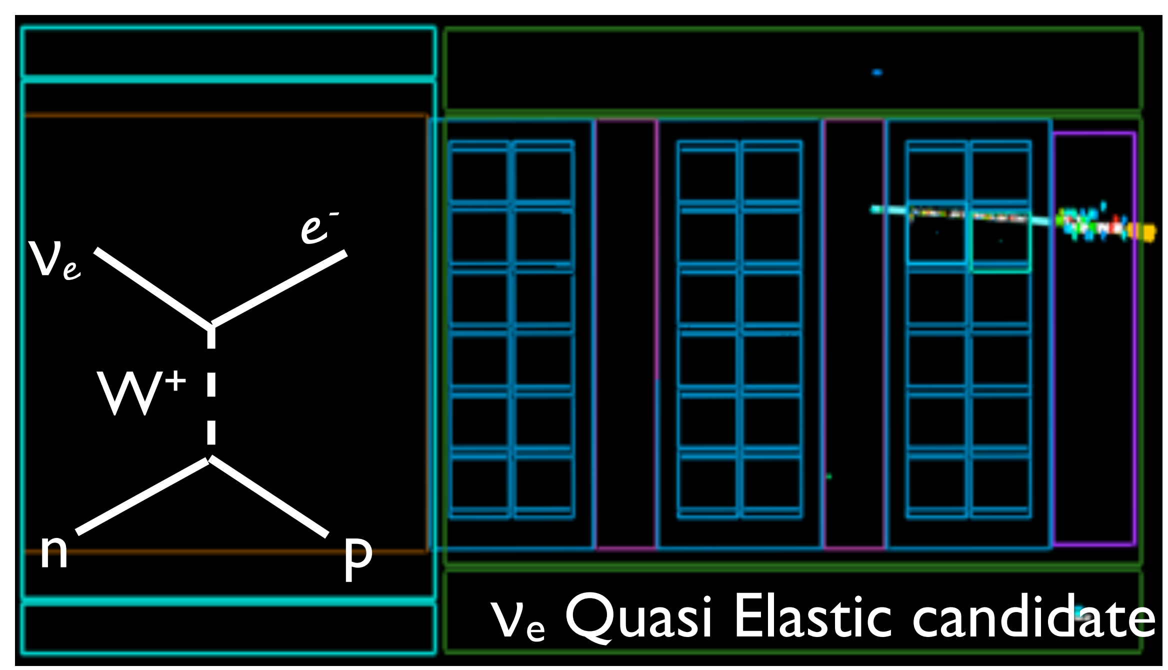


ν_μ Quasi Elastic candidate


DIS candidate + sand muon



ν_μ single π candidate



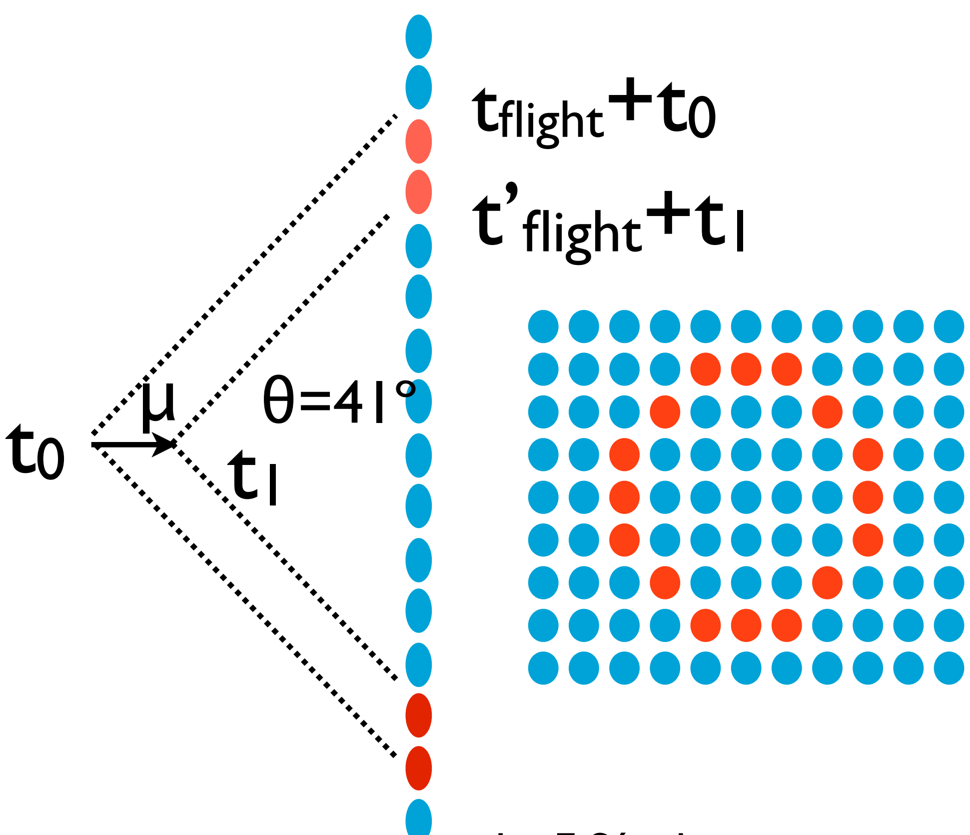
ν_e Quasi Elastic candidate

Super Kamiokande

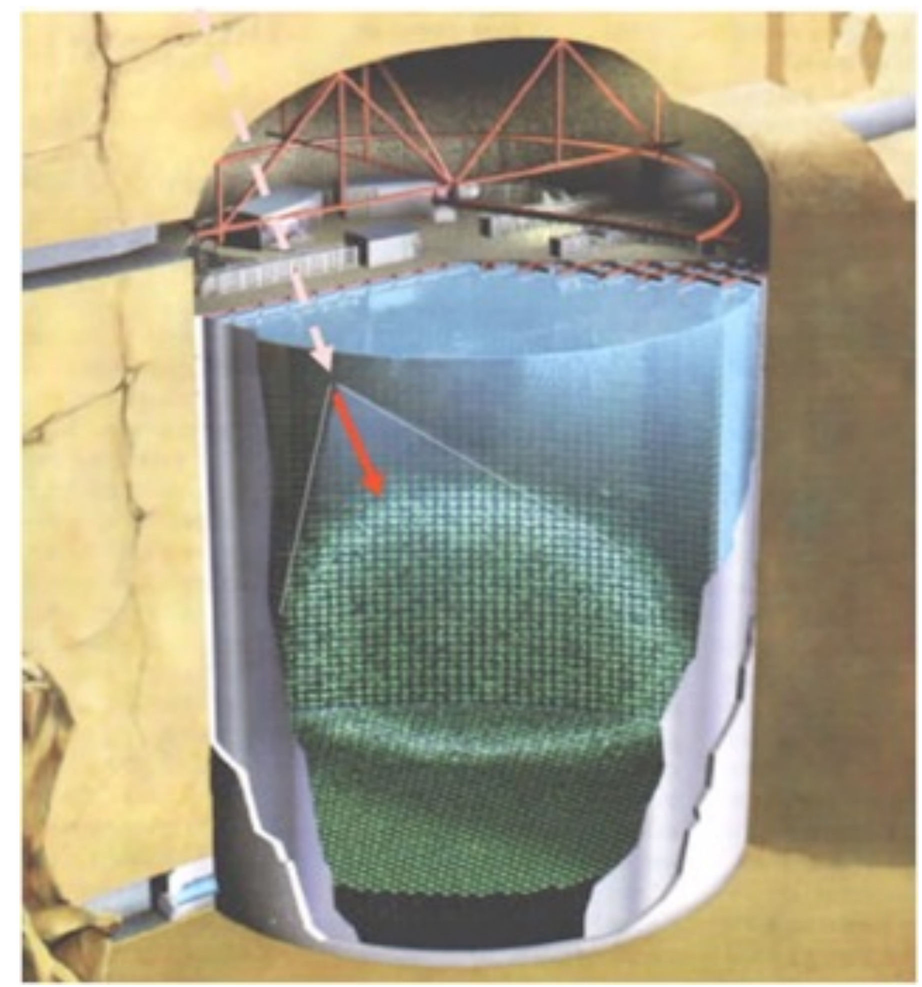
- Cylindrical detector located at ~1Km underground in the Kamioka mine (295 Km from the proton target)

- 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

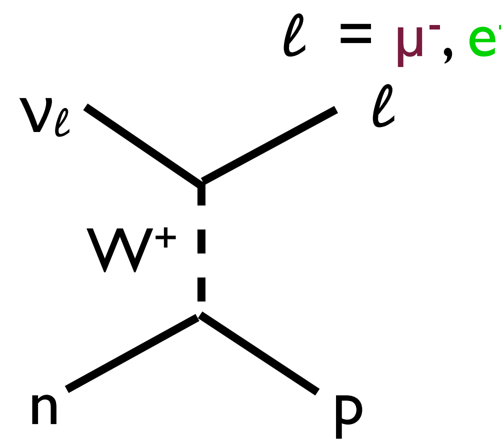
- Detection based on **Cherenkov technique**



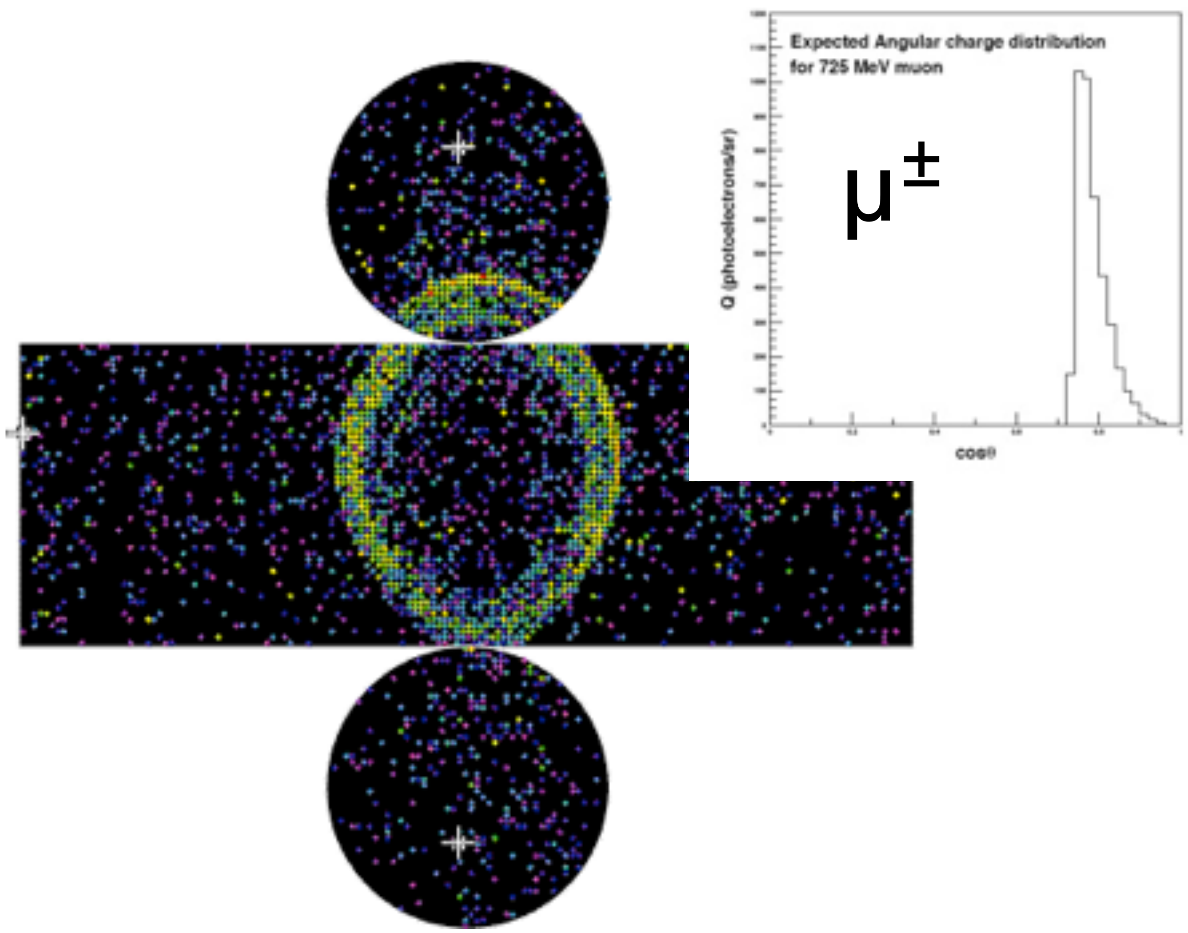
by F. Sánchez

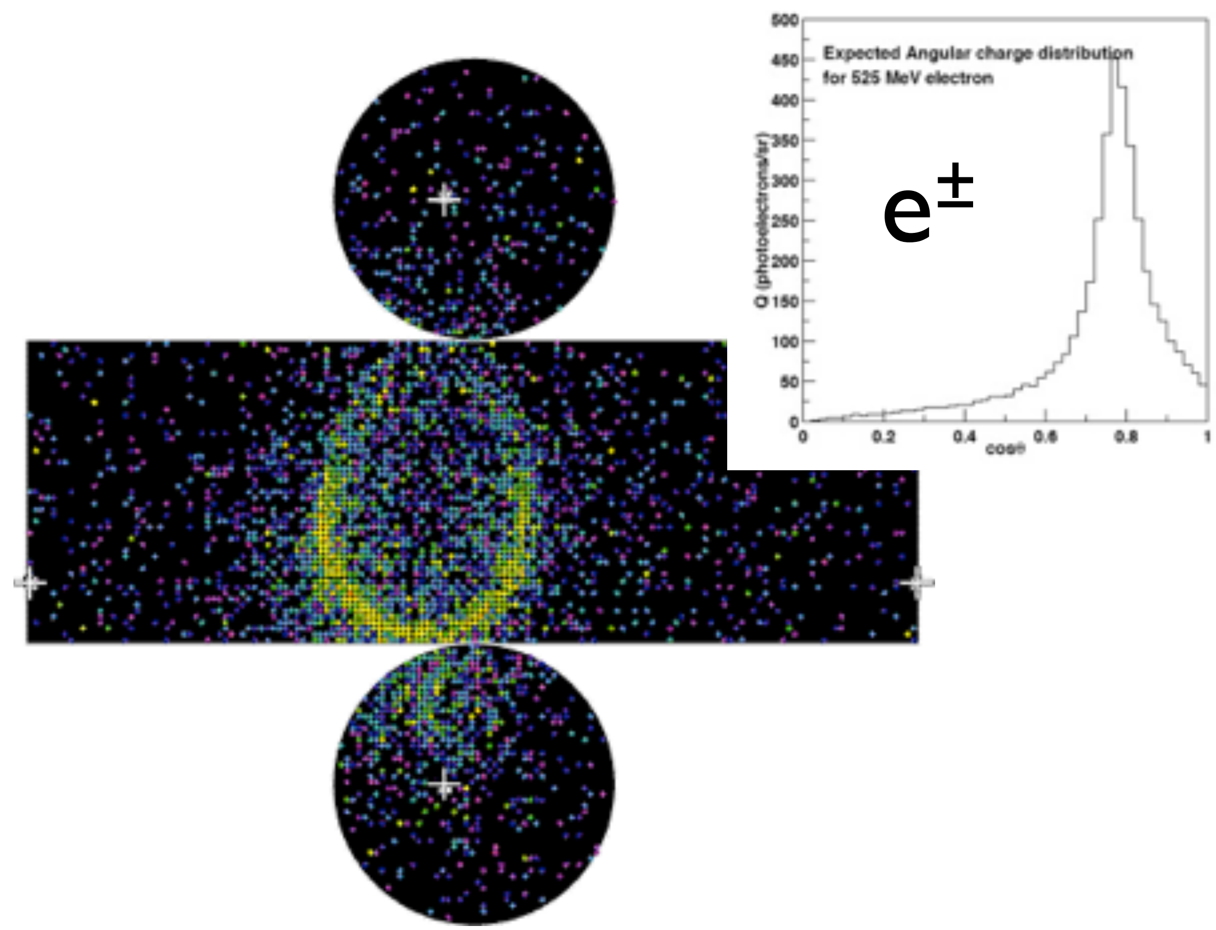


Particle identification with SK



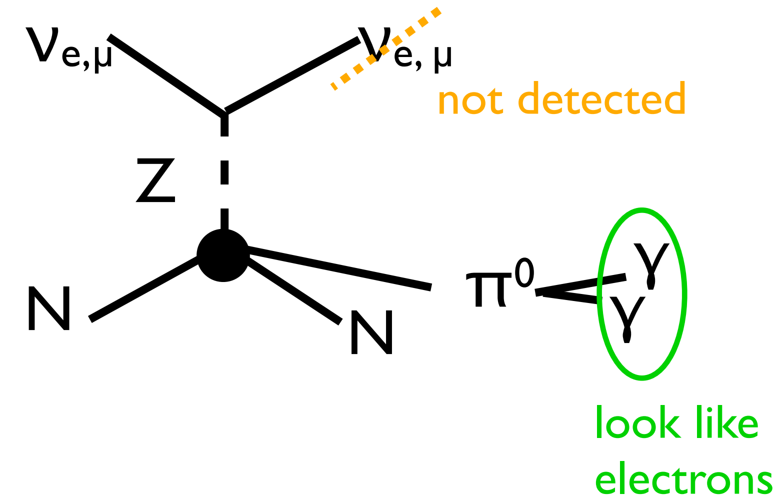
- Angular distribution of the Cherenkov photons along the primary particle direction provide a key to identify particles
- Signatures electron and muons are quite different at SK
  - **muons**: **sharp** and clear ring
  - **electrons**: **fuzzy** ring due to multiple scattering and showering





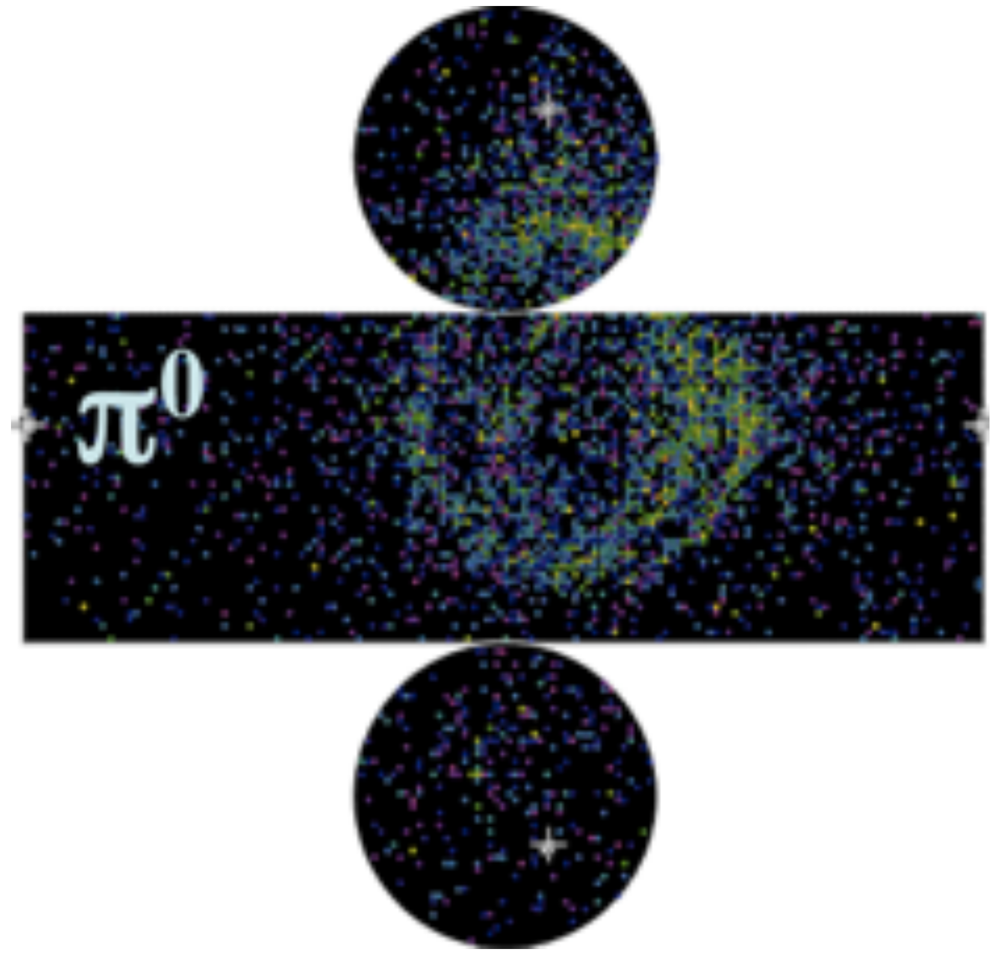
SK Neutral Current background

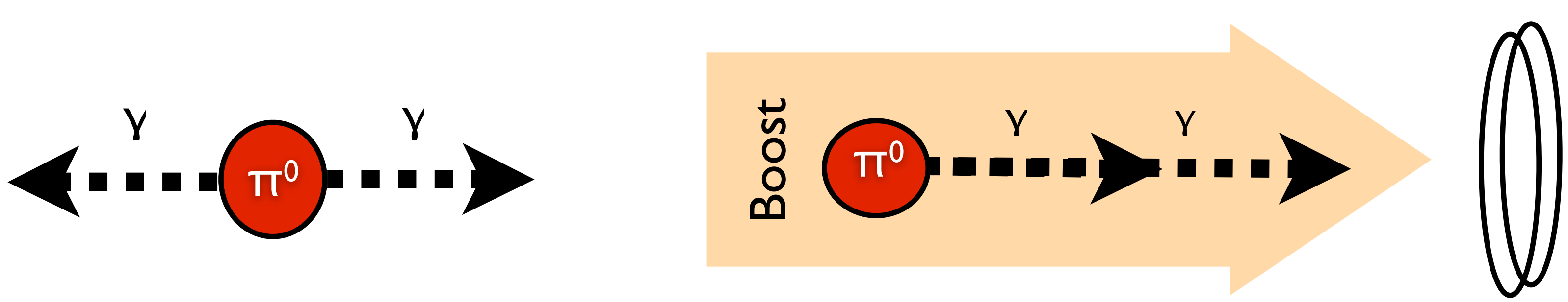
- π^0 are the main background source for appearance analysis
- gammas from π^0 decay shower as electrons
- multiple fuzzy rings that can be mis-identified as electrons



Mis-identification:

- If reconstructed as 1-ring event
  - photon rings overlap
  - 1 ring is faint and loss in the Cherenkov light of the other
- If both rings are reconstructed but poor invariant mass resolution

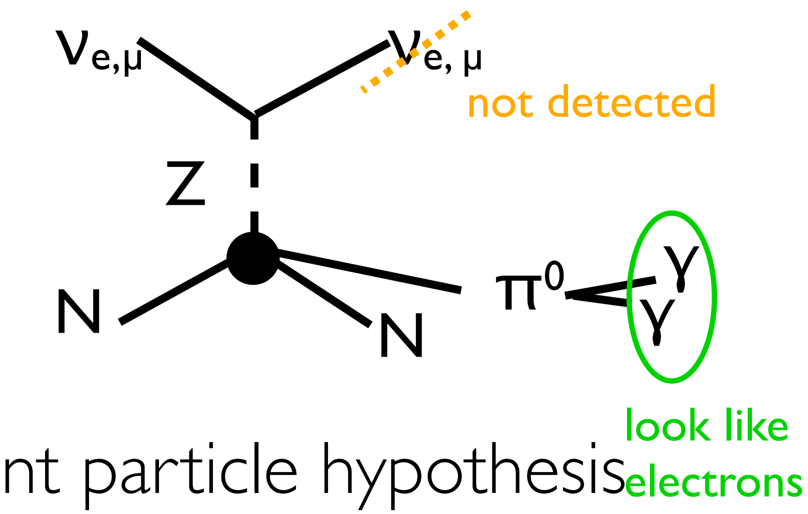


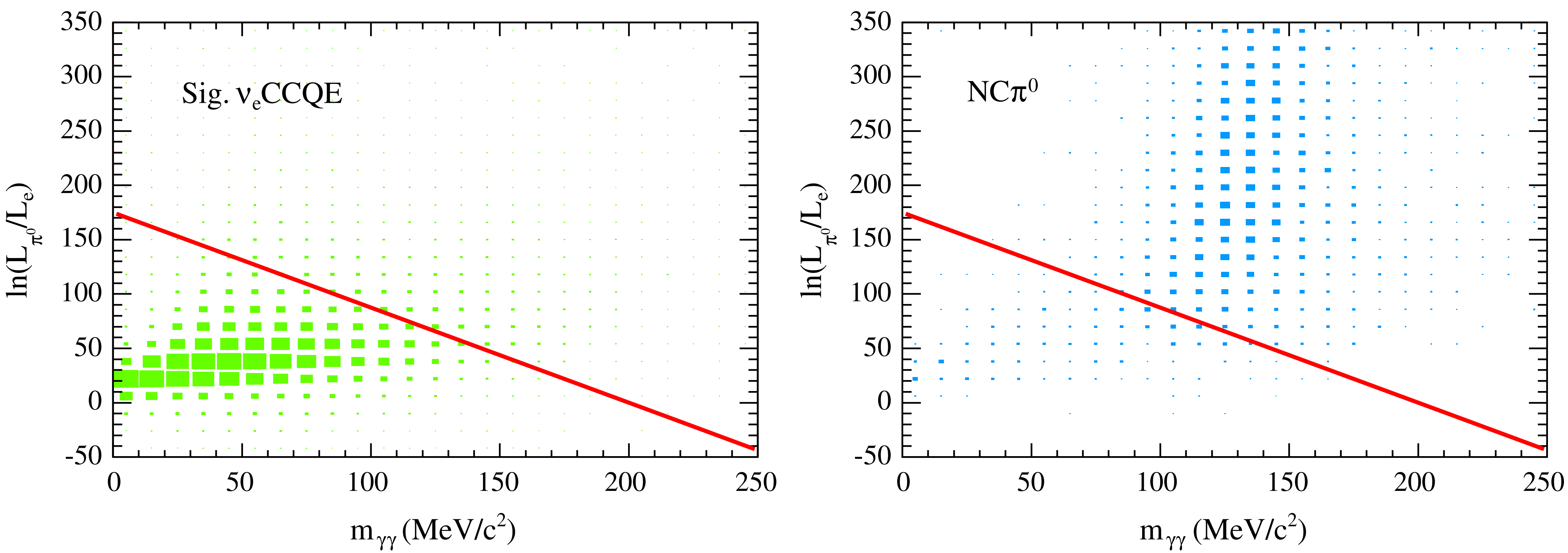


by F. Sánchez

SK Neutral Current background

- Very performing method to disentangle electrons from π^0
- Based on the ***new*** reconstruction algorithm
  - use of the charge and time information of each PMT
  - determination the kinematics of all final state particles
- For every event, maximization of a likelihood assuming different particle hypothesis
- Discrimination e-π based on $M_{inv}(\gamma\gamma)$ and the ratio of the e- π best-fit likelihoods (L_{π^0}/L_e)

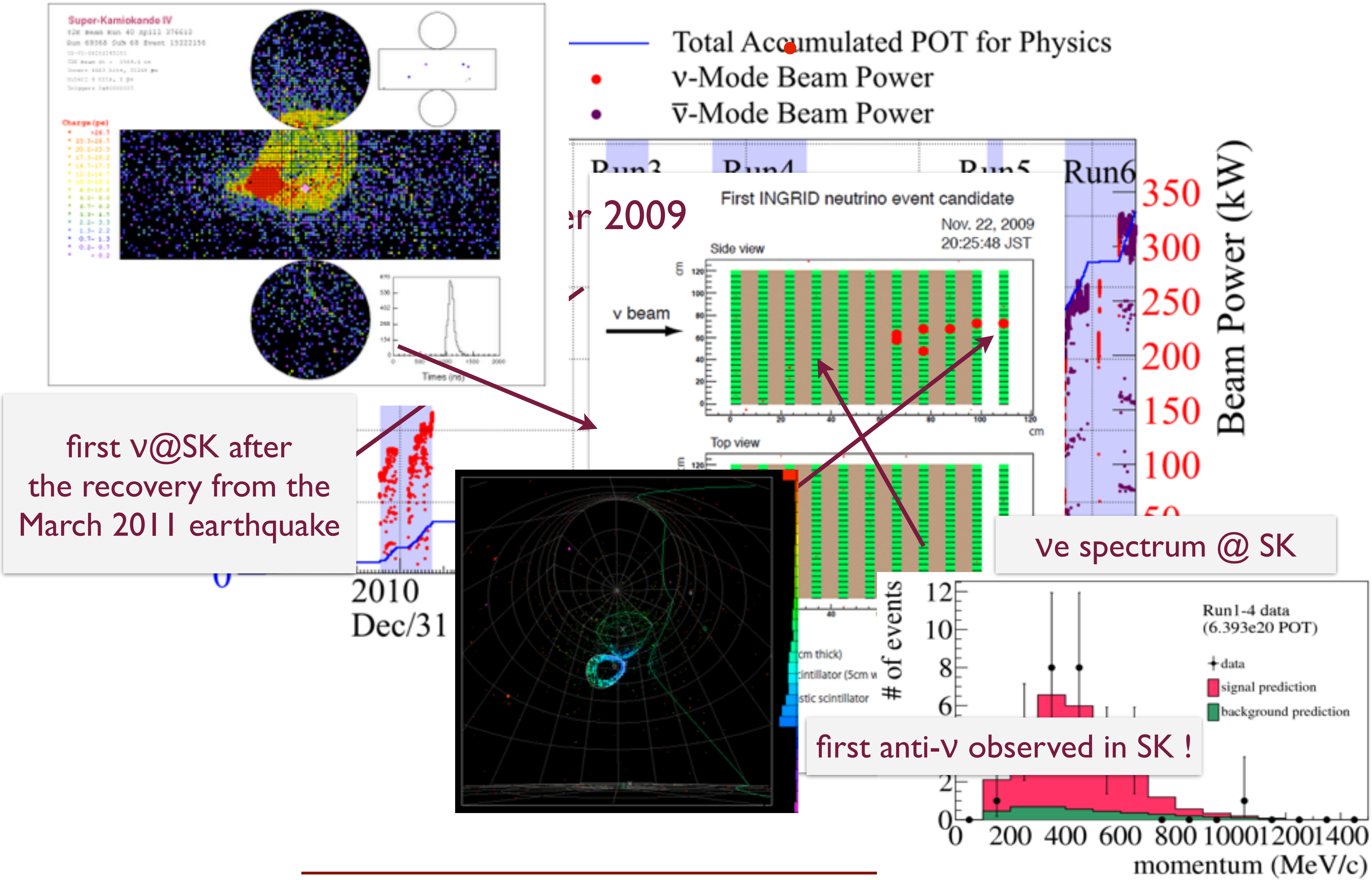




Phys. Rev. D. 91, 072010 (2015)

T2K @ work

Collected data

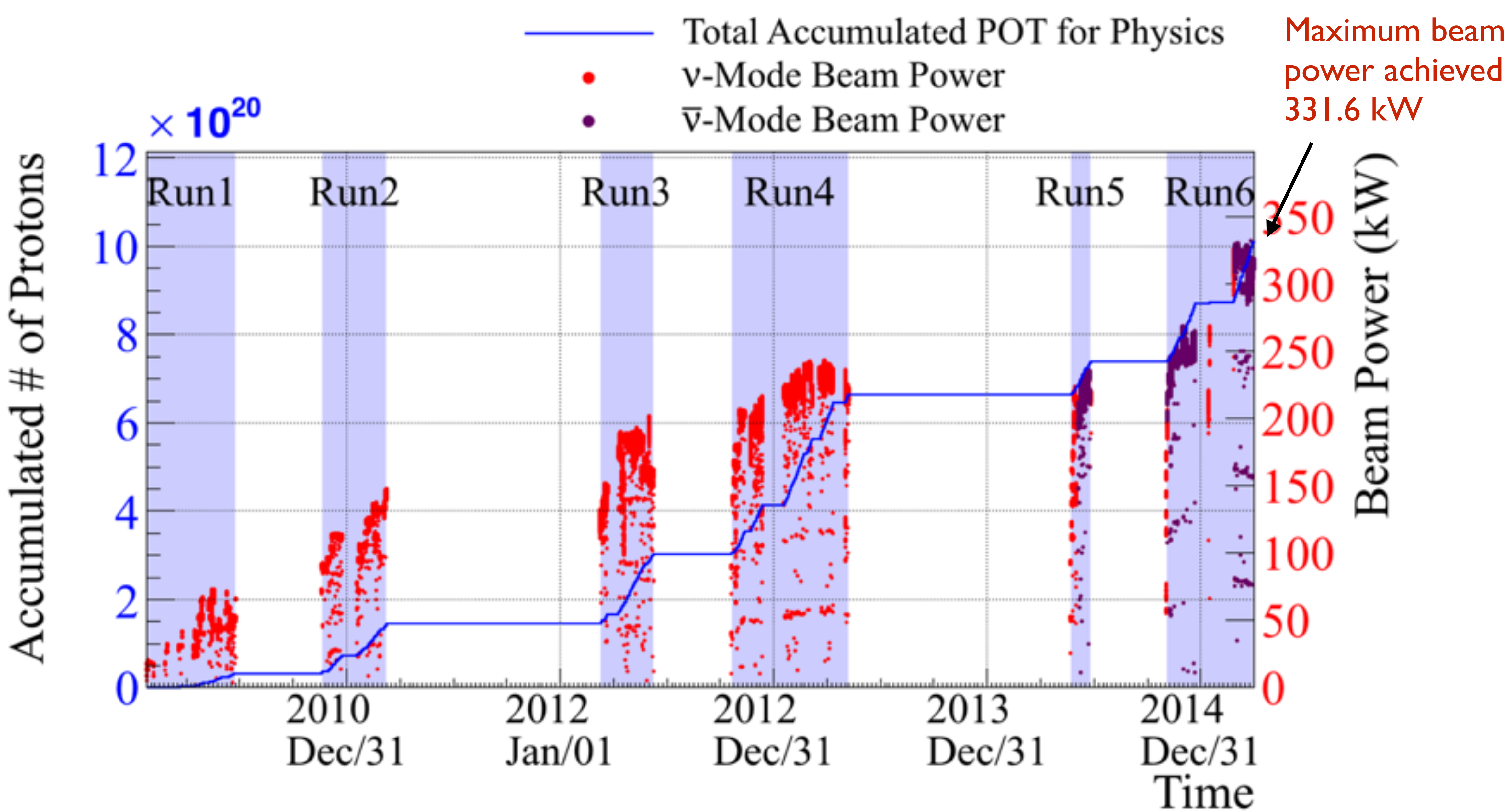


first ν@SK after the recovery from the March 2011 earthquake

νe spectrum @ SK

first anti-ν observed in SK !

Collected data



- Proton on target (POT) for physics :

  1.021×10^{21} **(tot)** = 7.0×10^{20} (ν) + 3.12×10^{20} (anti-ν)

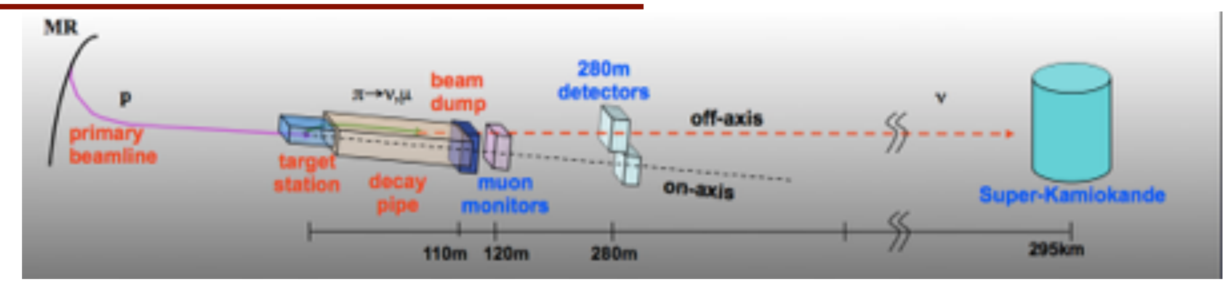
- In the following slides analyses for only 6.6×10^{20} POT : 8.3% of the total approved POT

Towards the oscillation analyses

- Flux constraints from beam-line and external sources
- Flux and cross-section constraints from ND280

Towards the oscillation analyses

Neutrino Flux prediction :
Beam line and hadron production simulation
Hadron production data from NA61/SHINE



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

Oscillation Fit

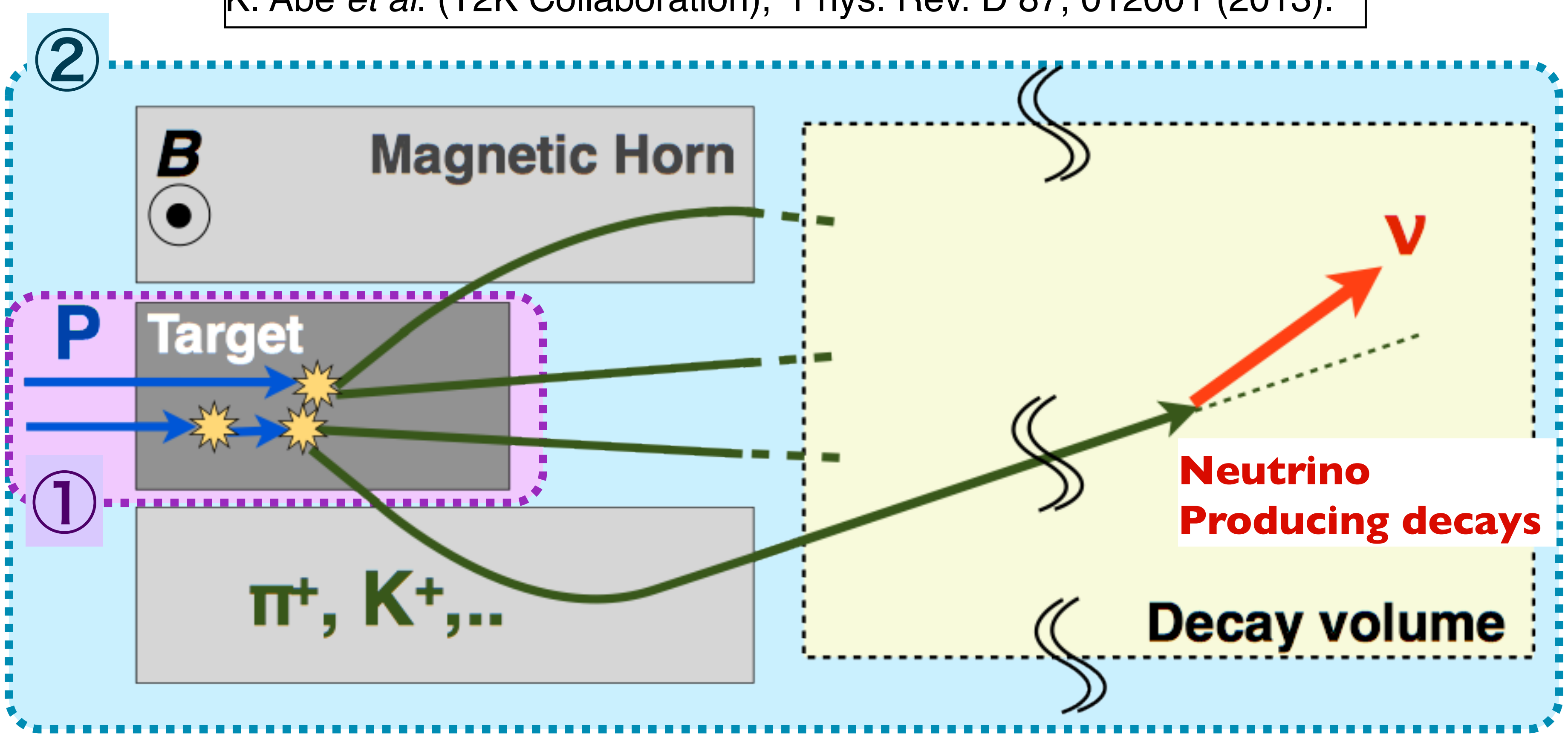
Cross section models:
Event generator (NEUT)
External data (MiniBooNE)

ν flux prediction

Simulation of the neutrino flux :

1. simulation of the proton interactions inside the carbon target (FLUKA2008.3d)
2. simulation of the particle passage through horn fields and decay volume (GEANT3+GCALOR)
   - propagation and decays of secondary pions and kaons
   - estimation of the flux at ND280 and SK

K. Abe *et al.* (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).



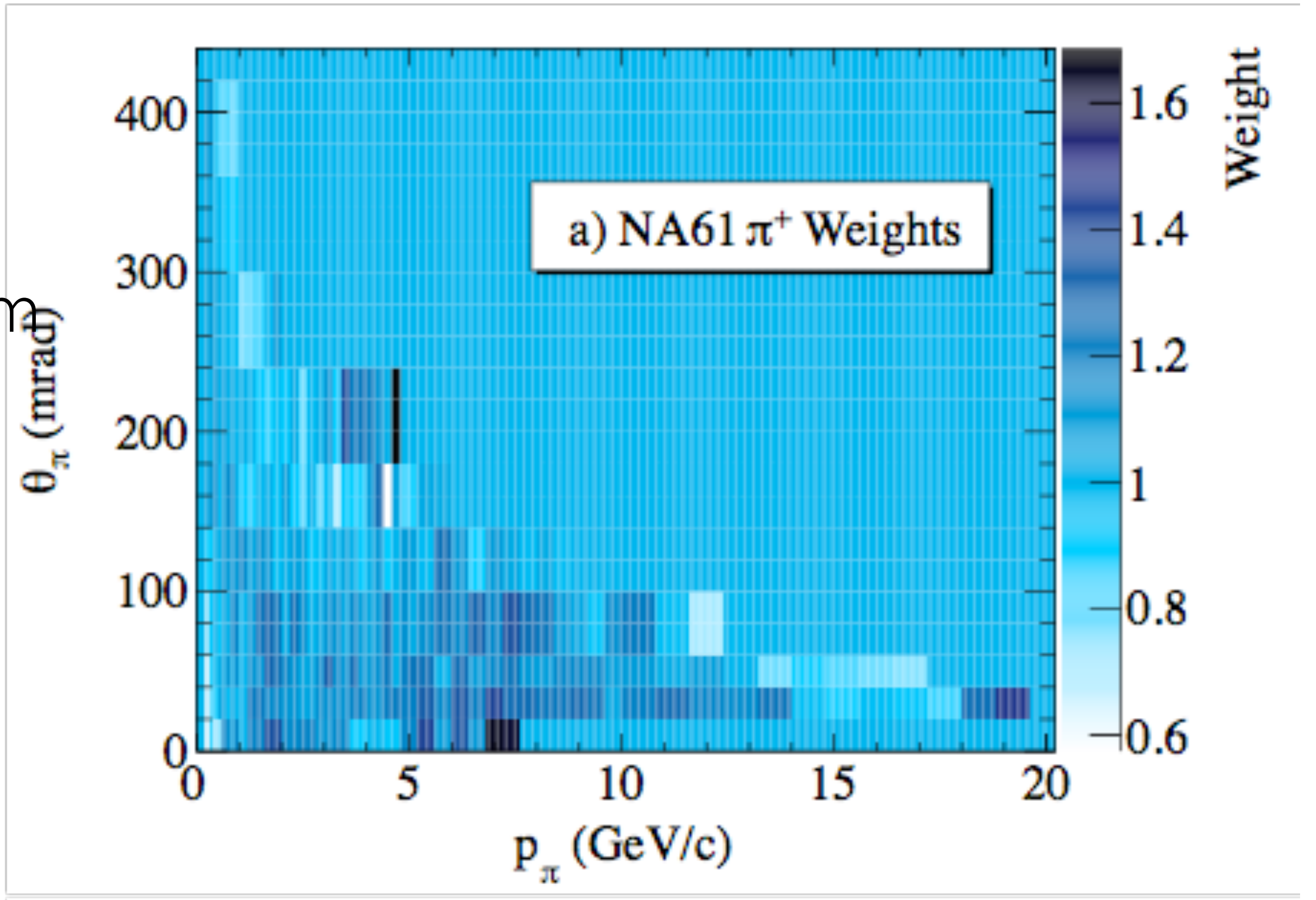
T2KCollaboration, PRD 87, 012001 (2013)

ν flux prediction

Improvement the MC simulation by re-weighting of the pion and kaon production using external data (NA61/SHINE)

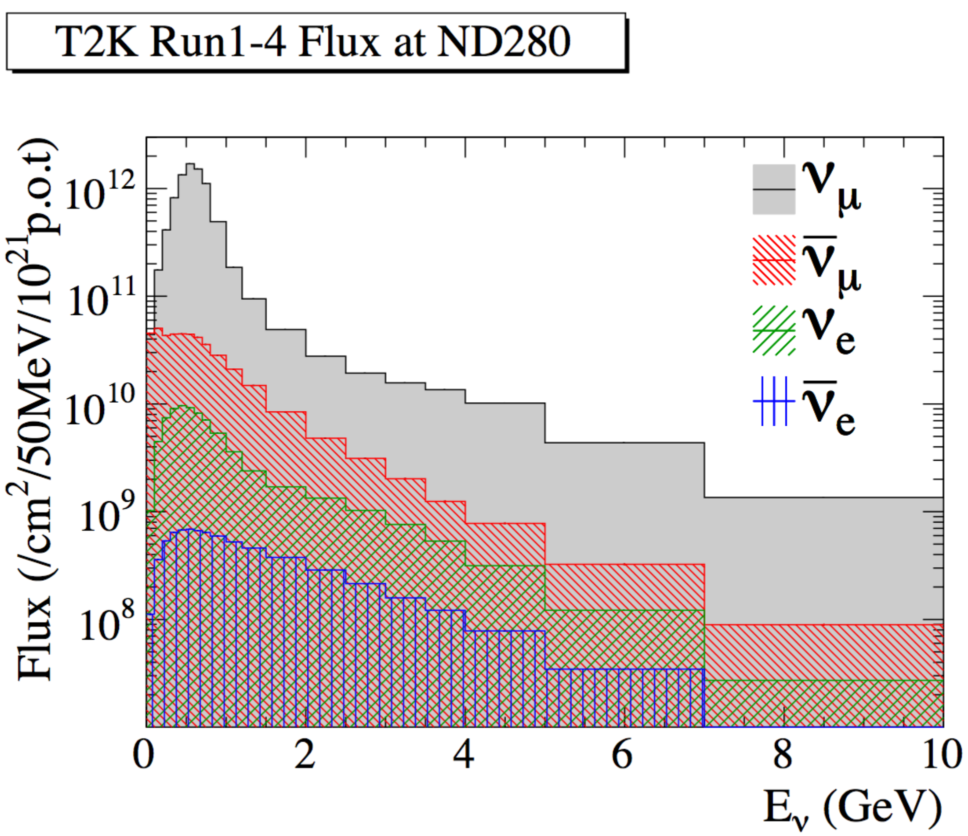
NA61/SHINE

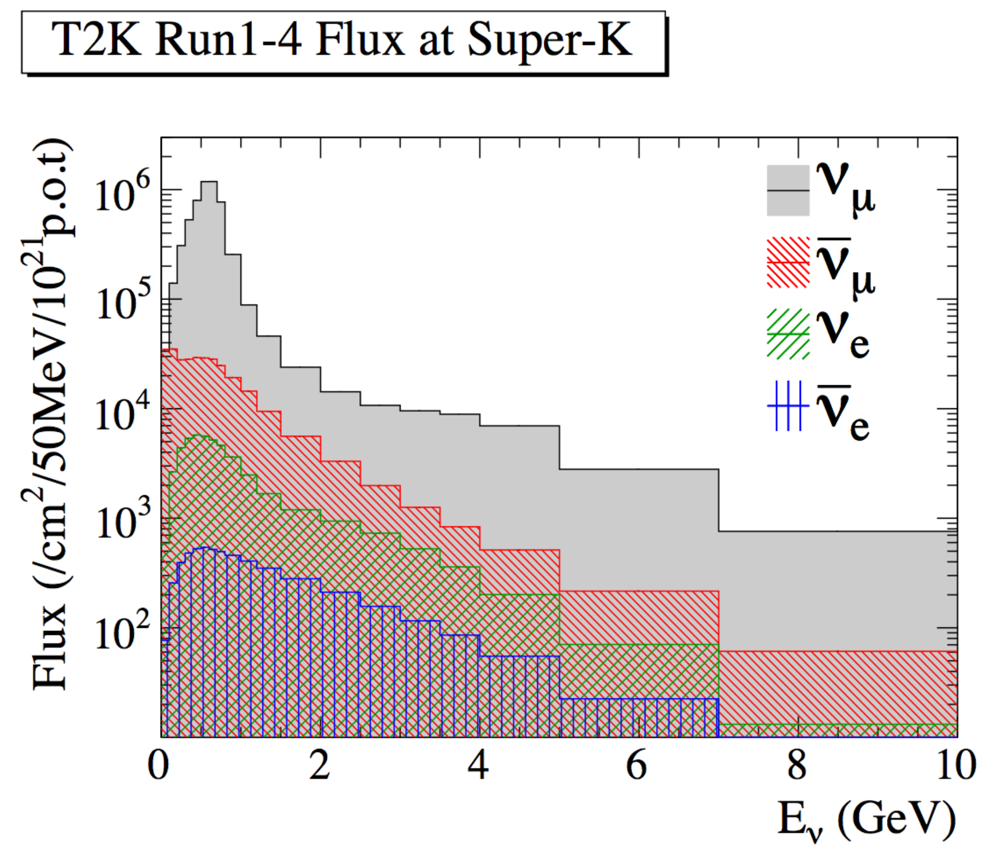
- Independent experiment located at CERN
- Study of the hadron production (π, K) from protons interaction in carbon target
  - momentum dependency
  - angle dependency



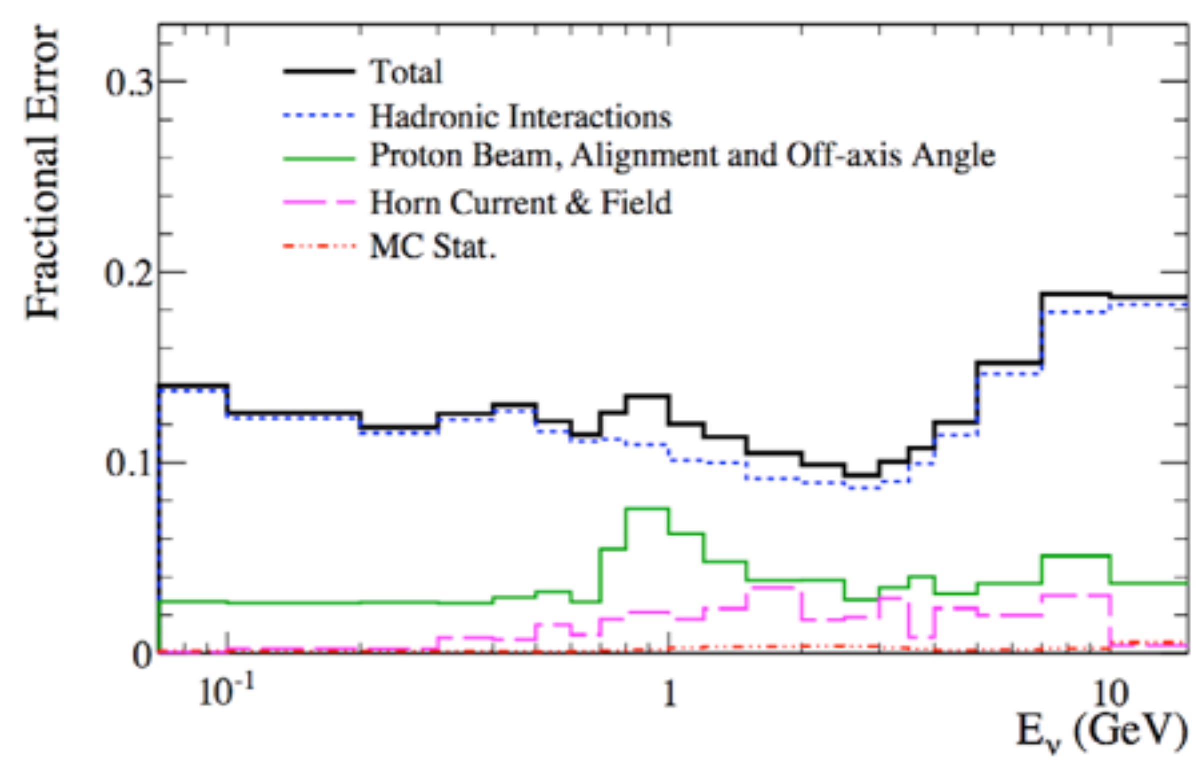
T2KCollaboration, PRD 87, 012001 (2013

ν flux prediction





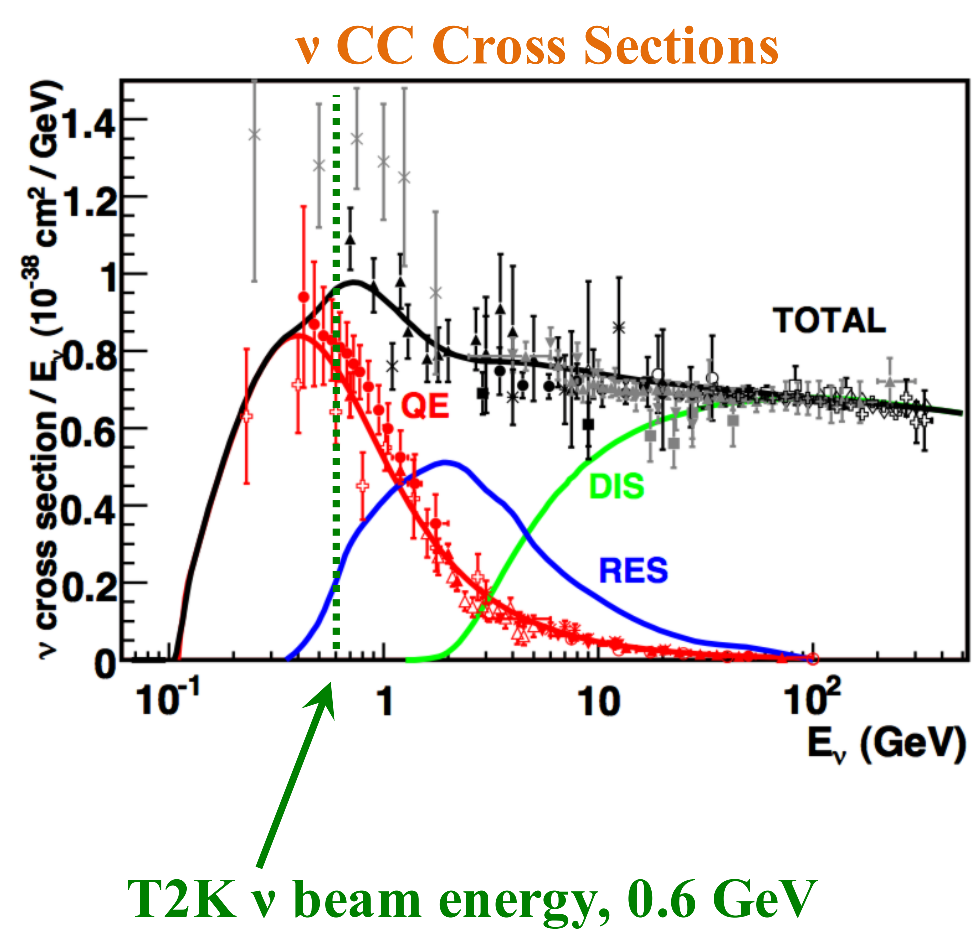
- Flux error below 15% in the relevant energy range (< 1 GeV)
- Flux error dominated by the hadron production uncertainties
- Strong correlation between ND280 and SK fluxes

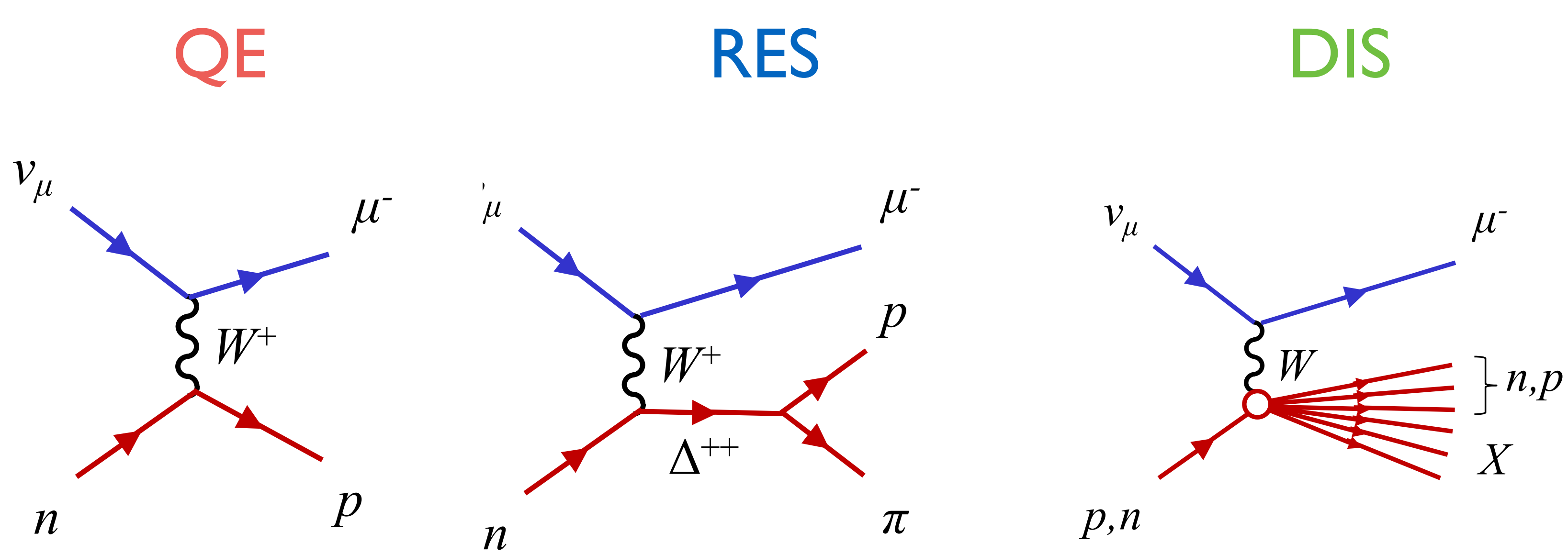


ND280 constraints

νμ CC interactions @ ND280

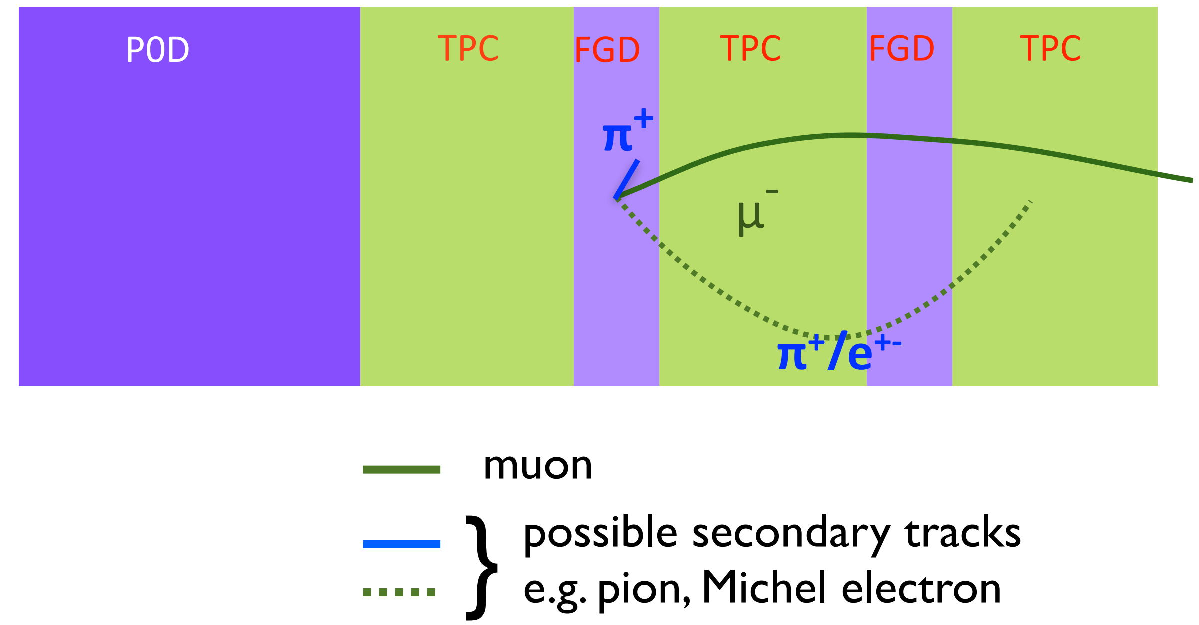
- Constraints to the flux and cross-section parameters for both the oscillation analyses
- Identification of the 3 main contributions to the total cross section
- Classification in 3 categories based on the reconstruction of pions in the events
  - **CC0π** : for Quasi Elastic (QE)
  - **CC1π⁺**: Resonant **π** production (Res)
  - **CCOthers** : Deep Inelastic Scattering (DIS)

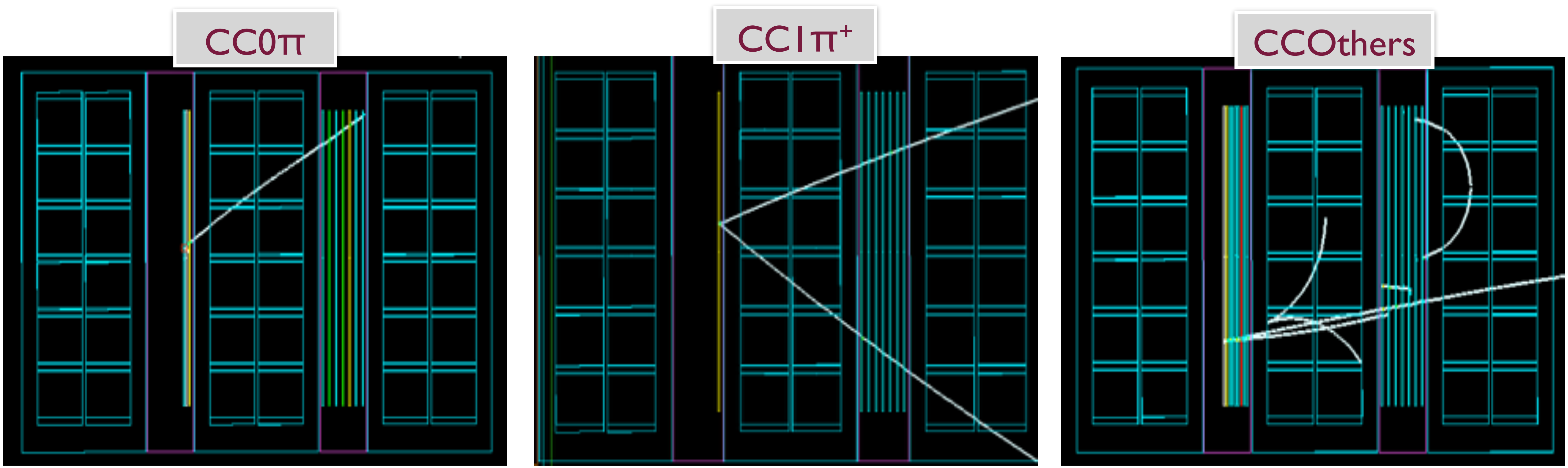




ν_μ CC interactions @ ND280

- 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





νμ CC interactions @ ND280

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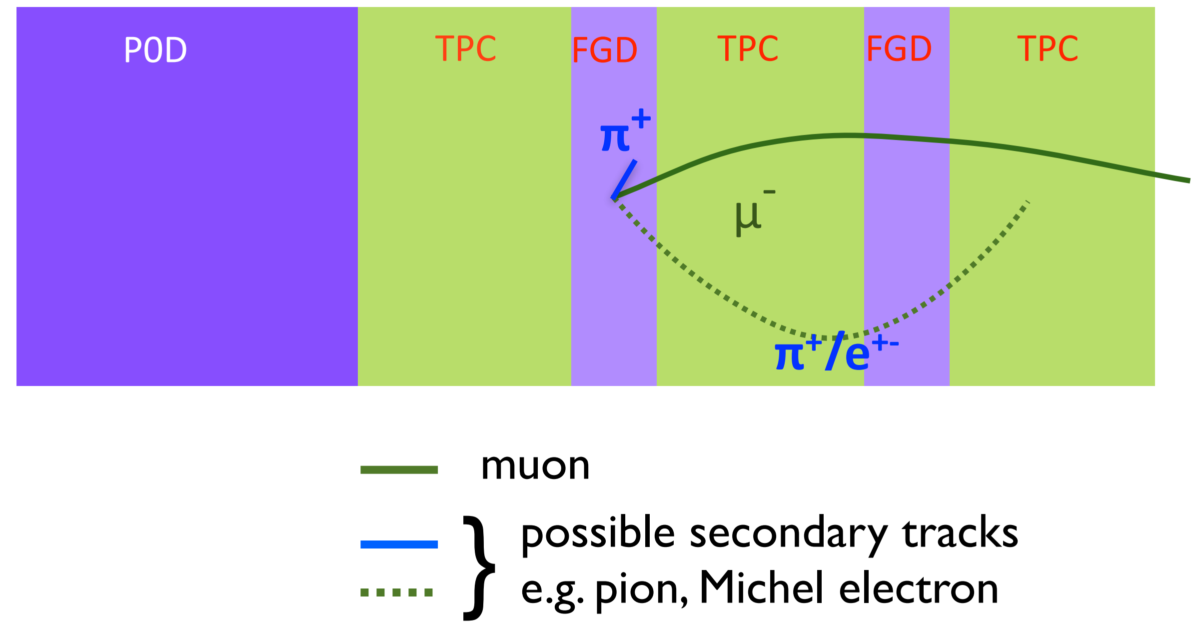
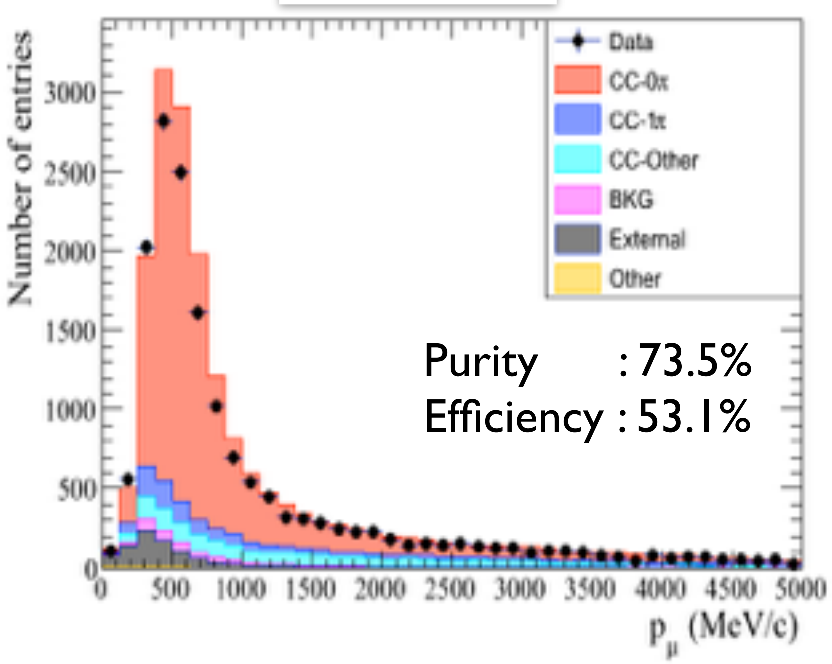
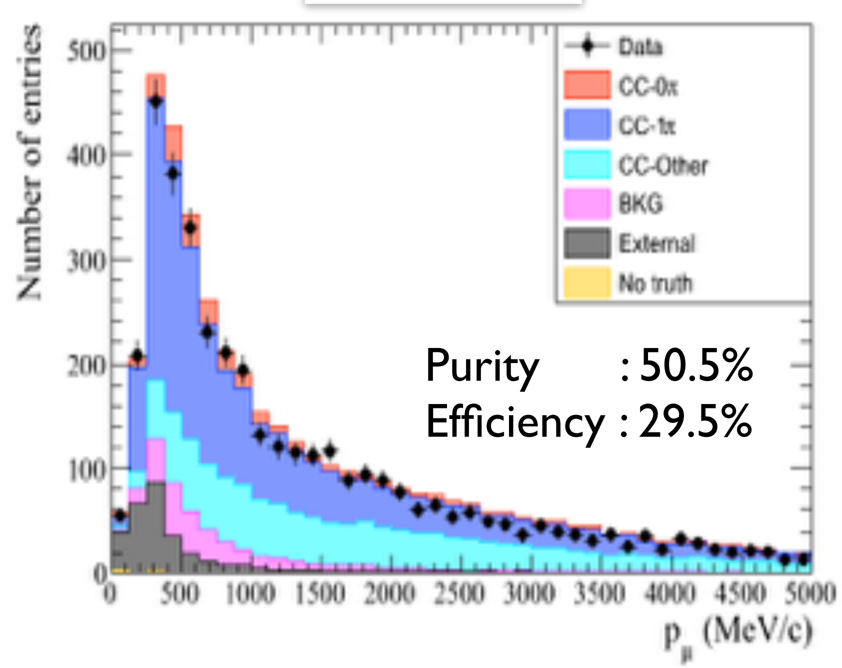


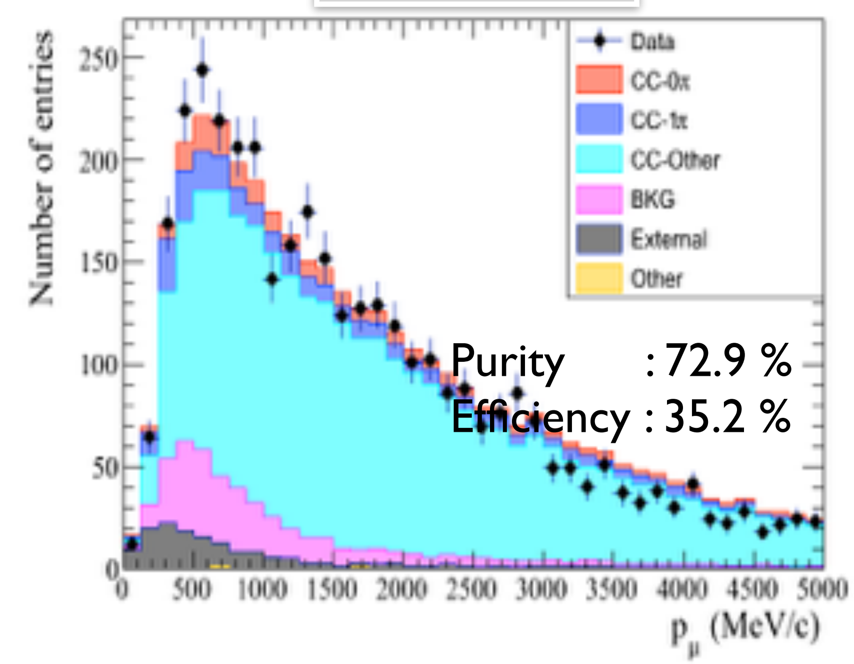
CC0π



CC1π+



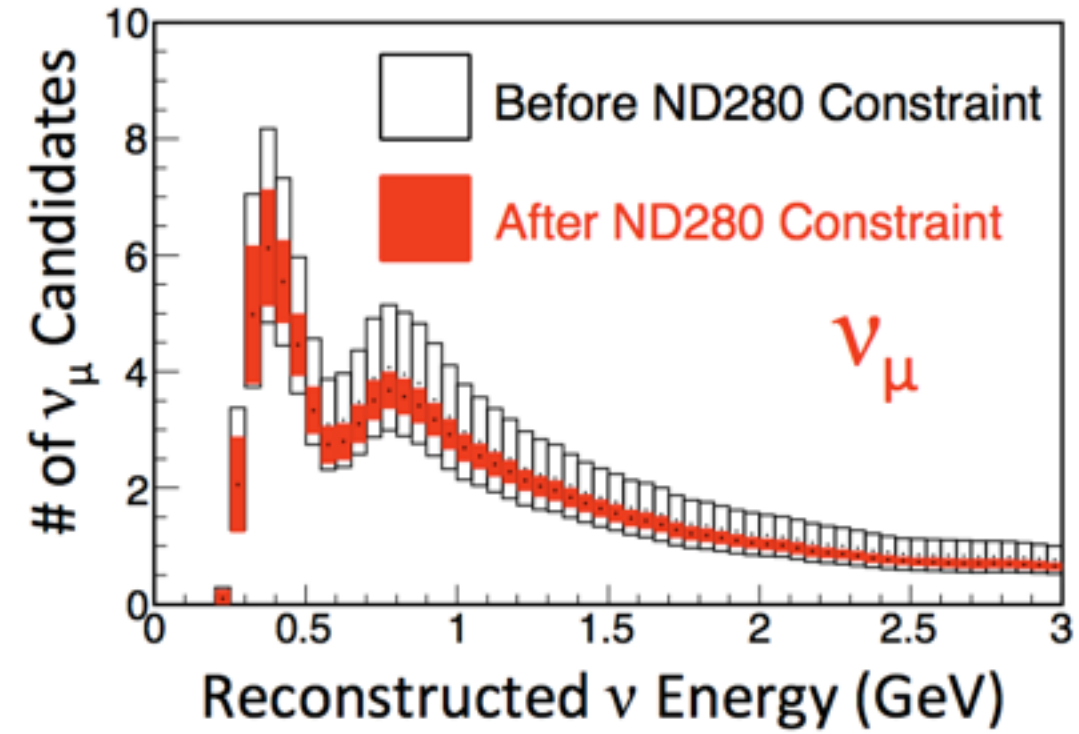
CCOthers



Constraining the ν flux and cross section (output)

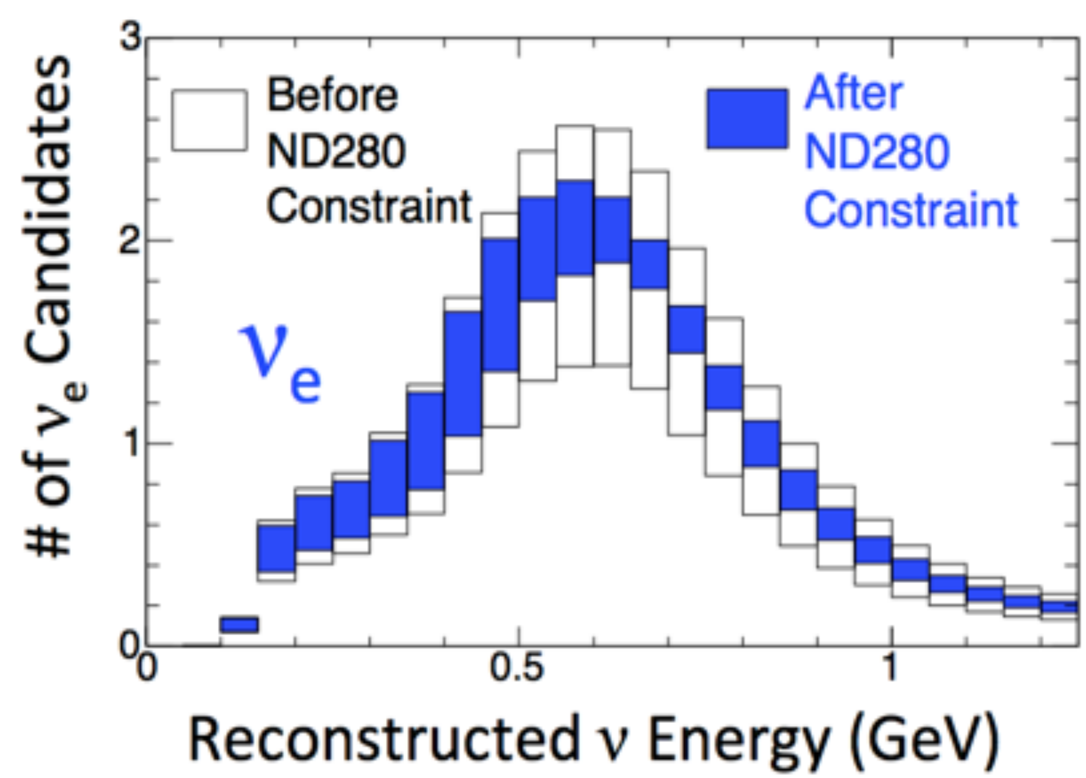
- Strong reduction of the systematic uncertainties to the event rate at Super-Kamiokande thanks to the ND280 data

- Current systematics already < 10%



		ν_μ sample	ν_e sample
ν flux and cross section	w/o ND measurement	21.8%	26.0%
	w/ ND measurement	2.7%	3.1%
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%
	w/ ND measurement	7.7%	6.8%

Fractional error on number-of-event prediction



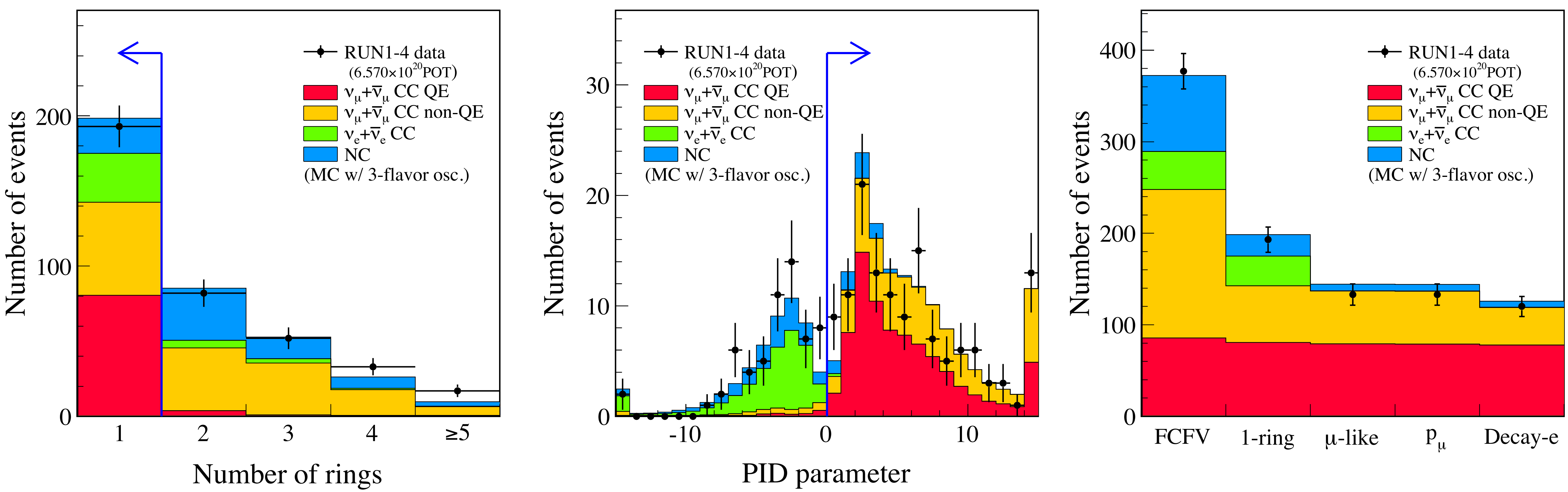
Note: Systematics error updated for joint analyses

Oscillation analyses: ν_μ disappearance

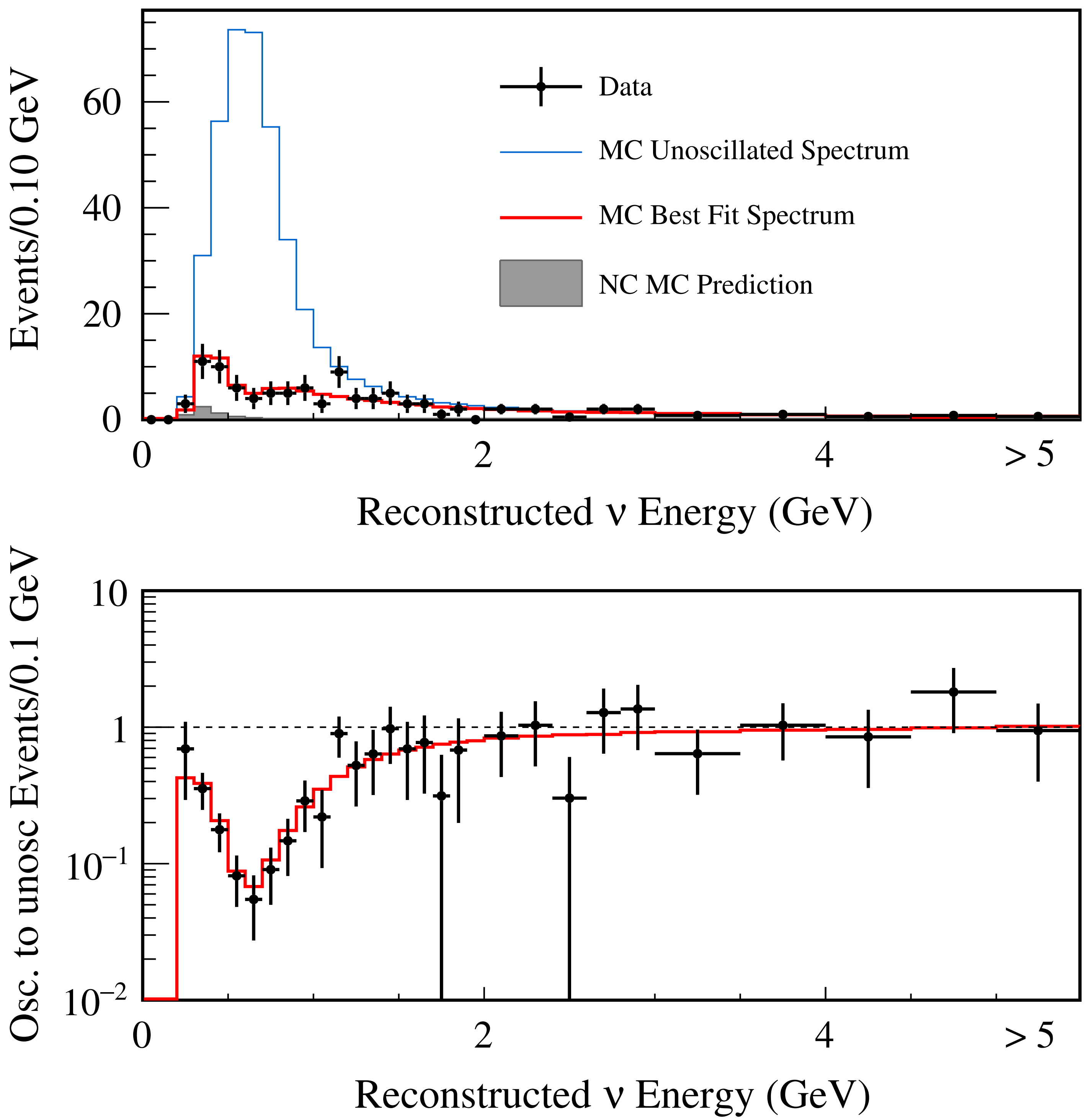
ν_μ disappearance

CCQE candidates at SK selected looking for "one-muon-only" events

- Fully contained single muon-like ring
- p_μ > 200 MeV and no more than one decay e^-
- E_ν reconstructed using the QE approximation



ν_μ disappearance

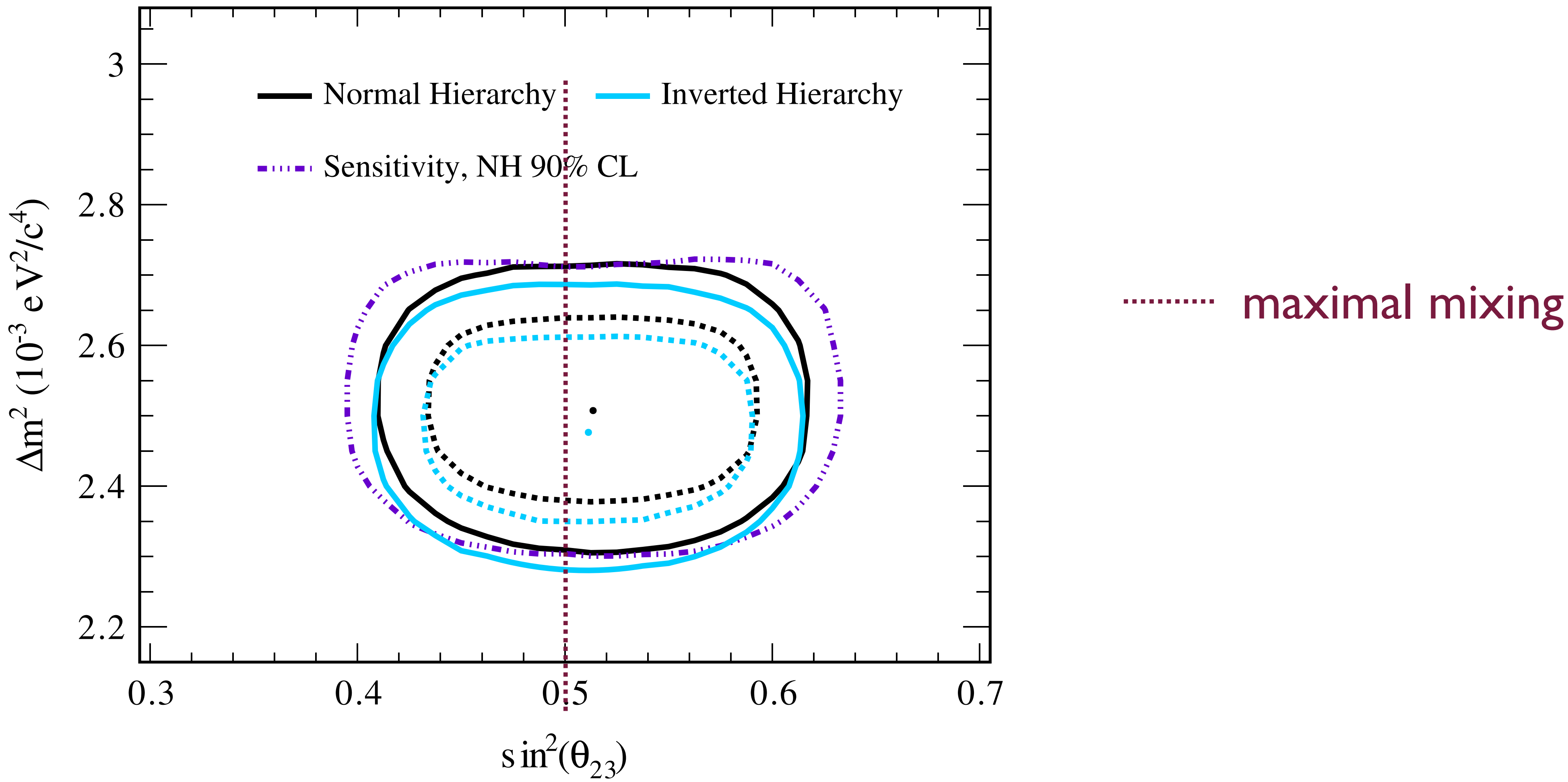


120 events observed

446.0 ± 22.5 (syst) expected if No oscillation

Phys. Rev. D. 91, 072010 (2015)

ν_μ disappearance



Best fit point NH :

$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$

$$\Delta m^2_{32} = 2.51 \pm 0.10 \times 10^{-3}\ \text{eV}^2/\text{c}^4$$

Best fit point IH :

$$\sin^2\theta_{23} = 0.511 \pm 0.055$$

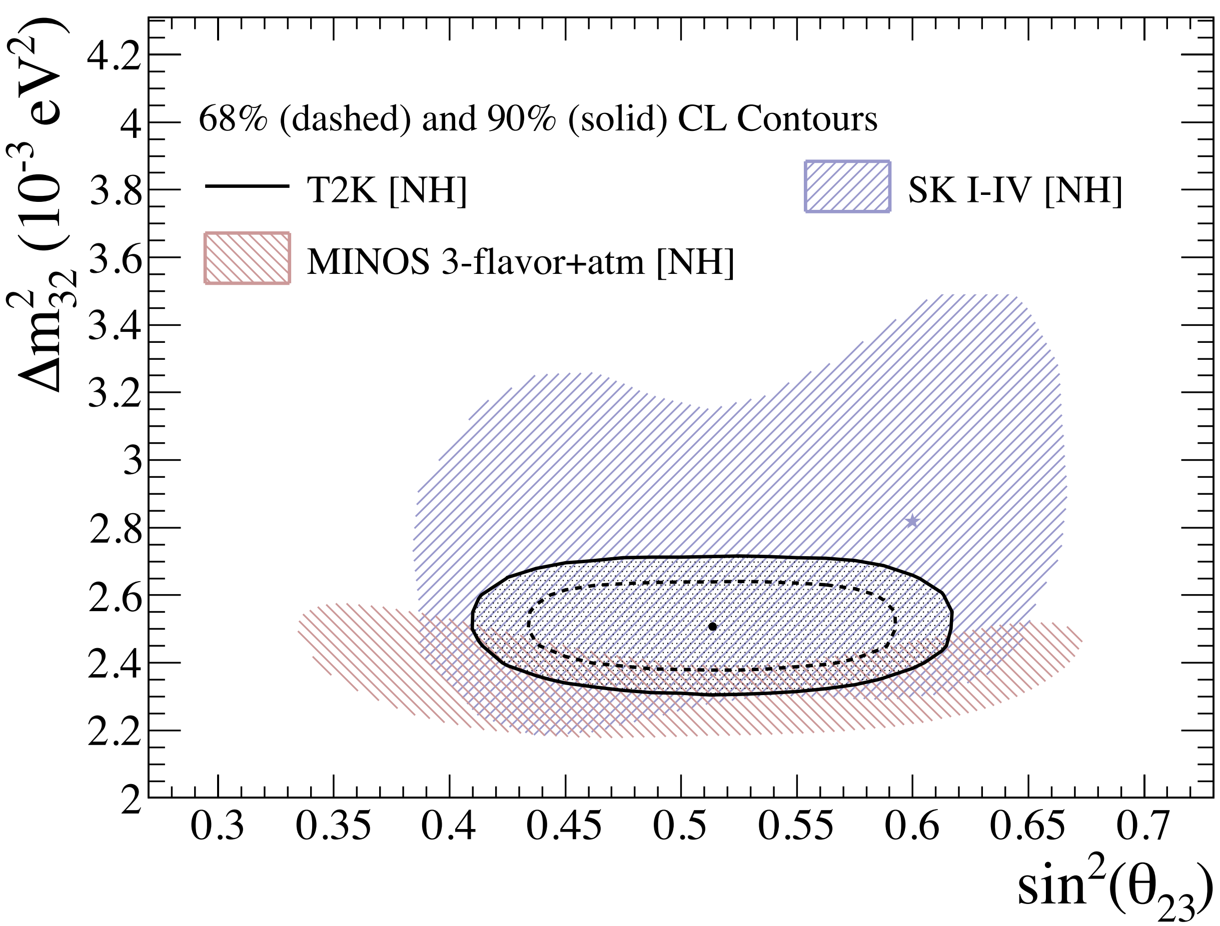
$$\Delta m^2_{13} = 2.48 \pm 0.10 \times 10^{-3}\ \text{eV}^2/\text{c}^4$$

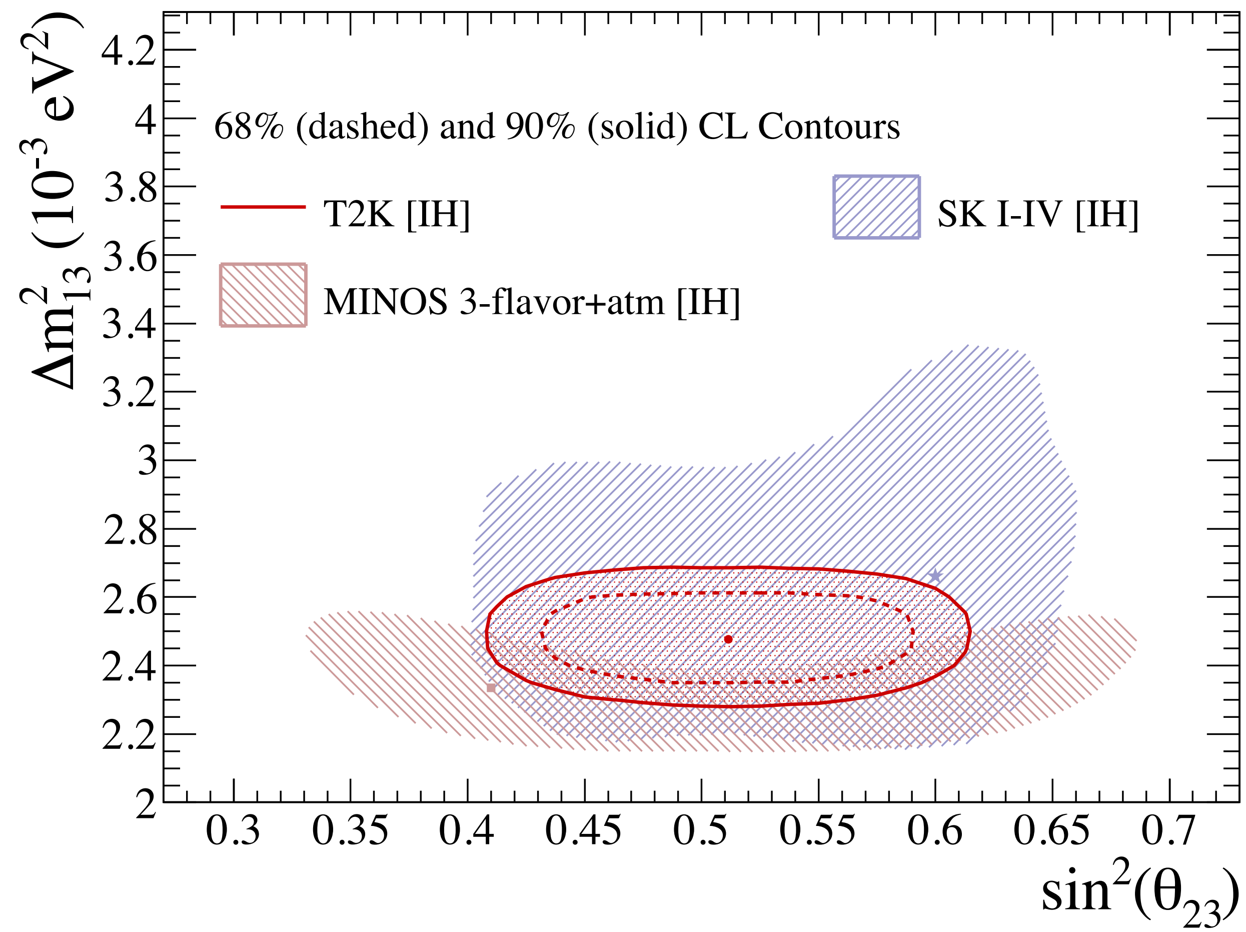
- Fit to data performed with the three flavours framework
- Maximal mixing is favored

Phys. Rev. D. 91, 072010 (2015)

νμ disappearance

Phys. Rev. Lett. 112, 181801





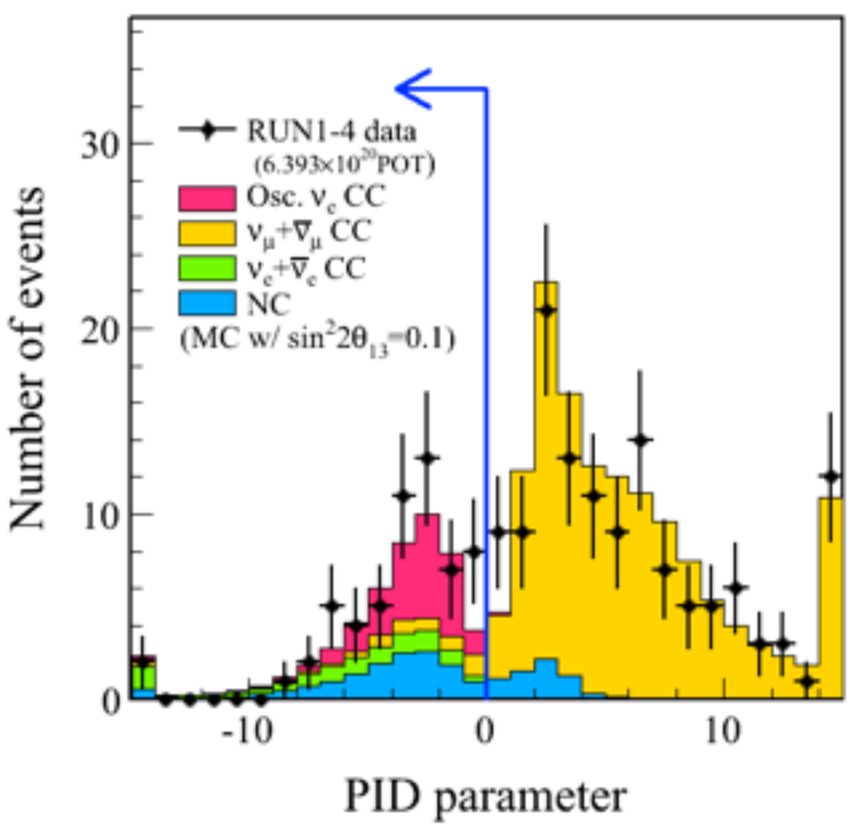
World's best measurement in ϑ_{23} !

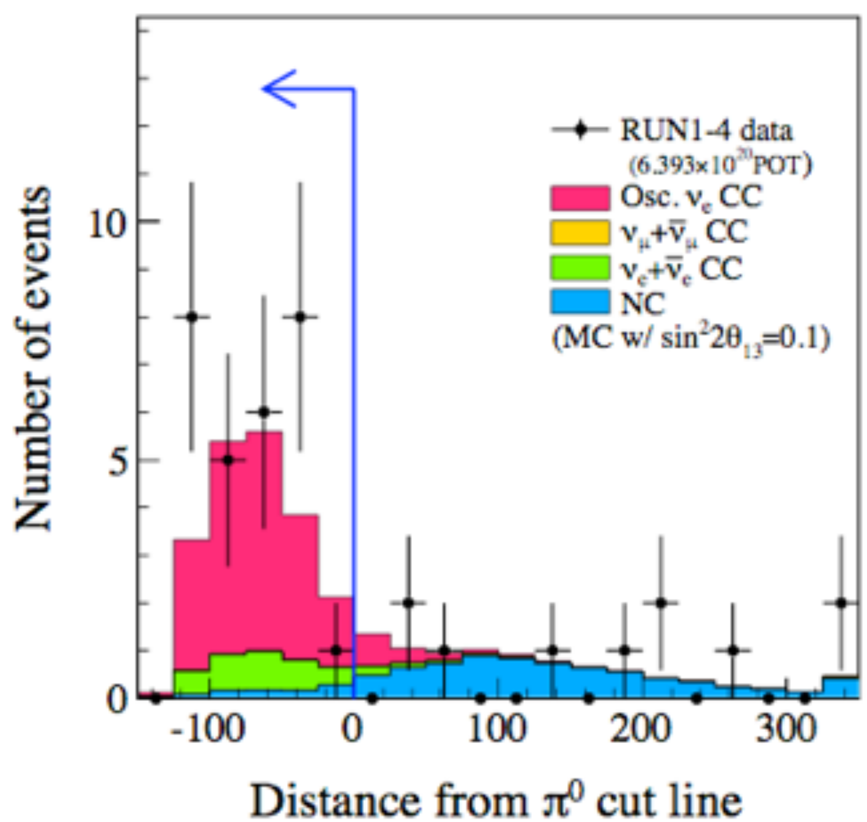
Oscillation analyses: ν_e appearance

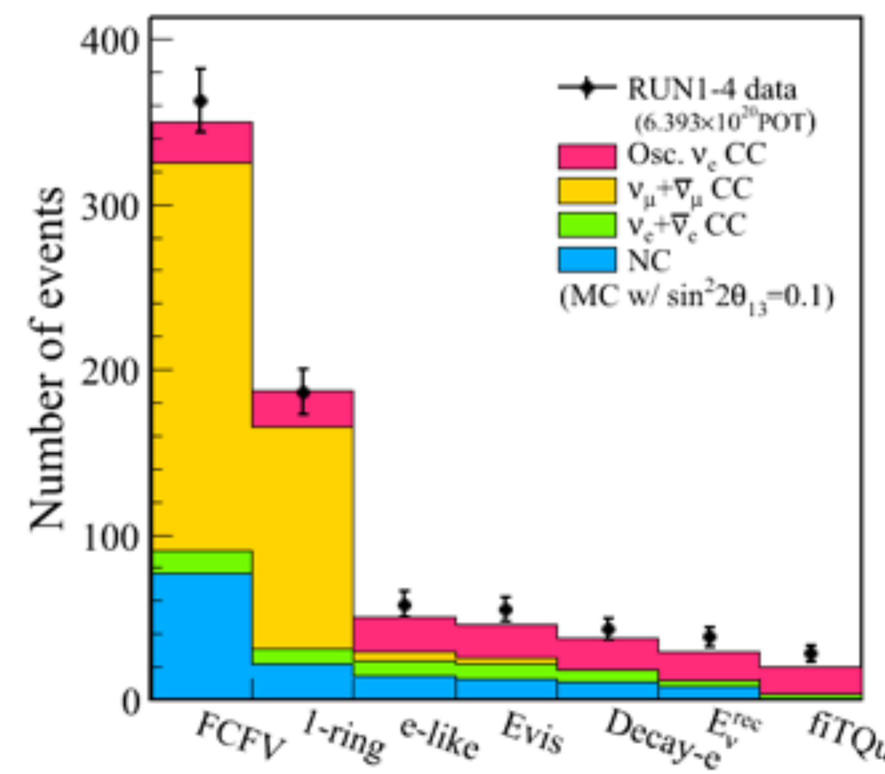
ν_e selection @ SK

CCQE candidates at SK selected looking for "one-electron-only" events

- fully contained single electron-like ring
- p_e > 100 MeV and no decay e^- (Michel electrons)
- E_ν reconstructed using the QE approximation
- π^0 background rejection







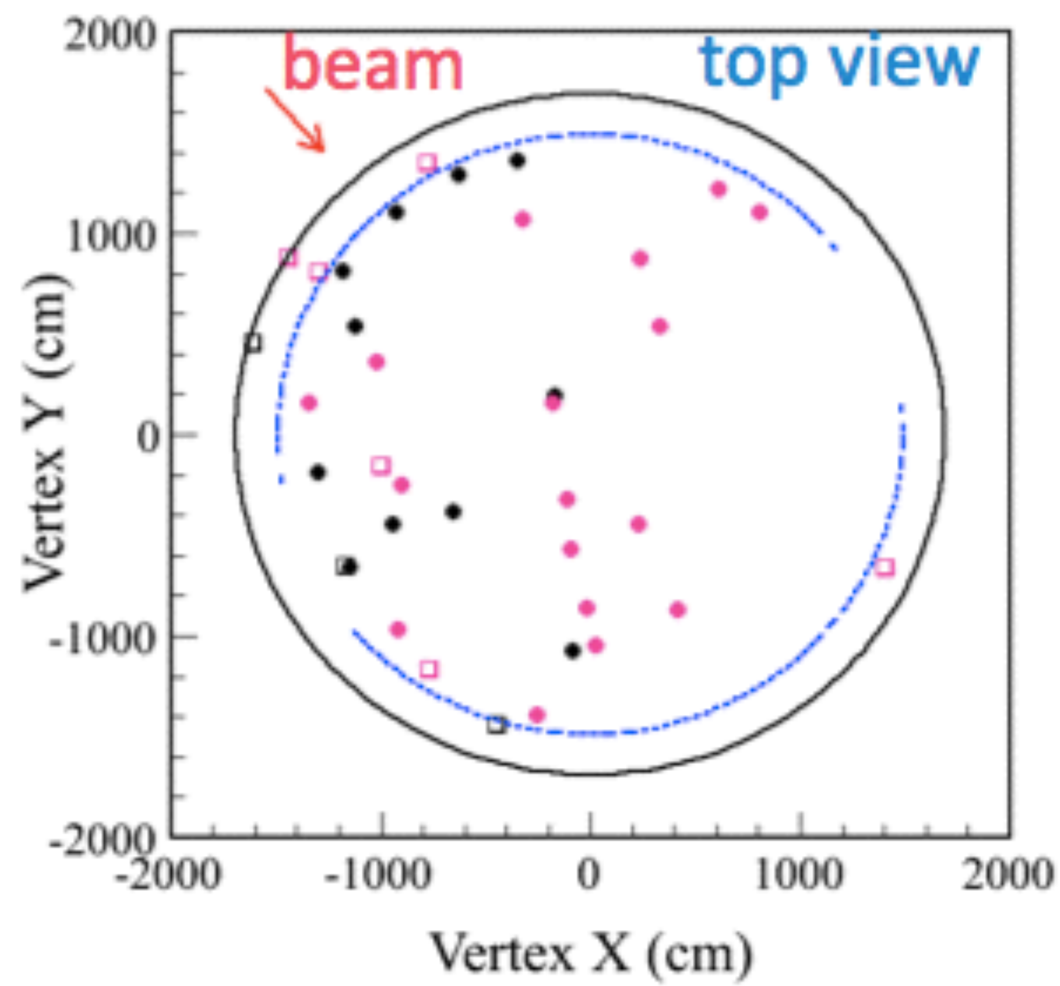
νe oscillation analyses review

T2K νe appearance results

	$N_{\nu e}^{Obs}$	N_{bkg}^{exp}	collected data
2011: first indication	7	1.5 ± 0.3	1.43×10^{20} POT
2013: further evidence	11	3.3 ± 0.4	3.01×10^{20} POT
2013: firmly established	28	4.9 ± 0.6	6.57×10^{20} POT

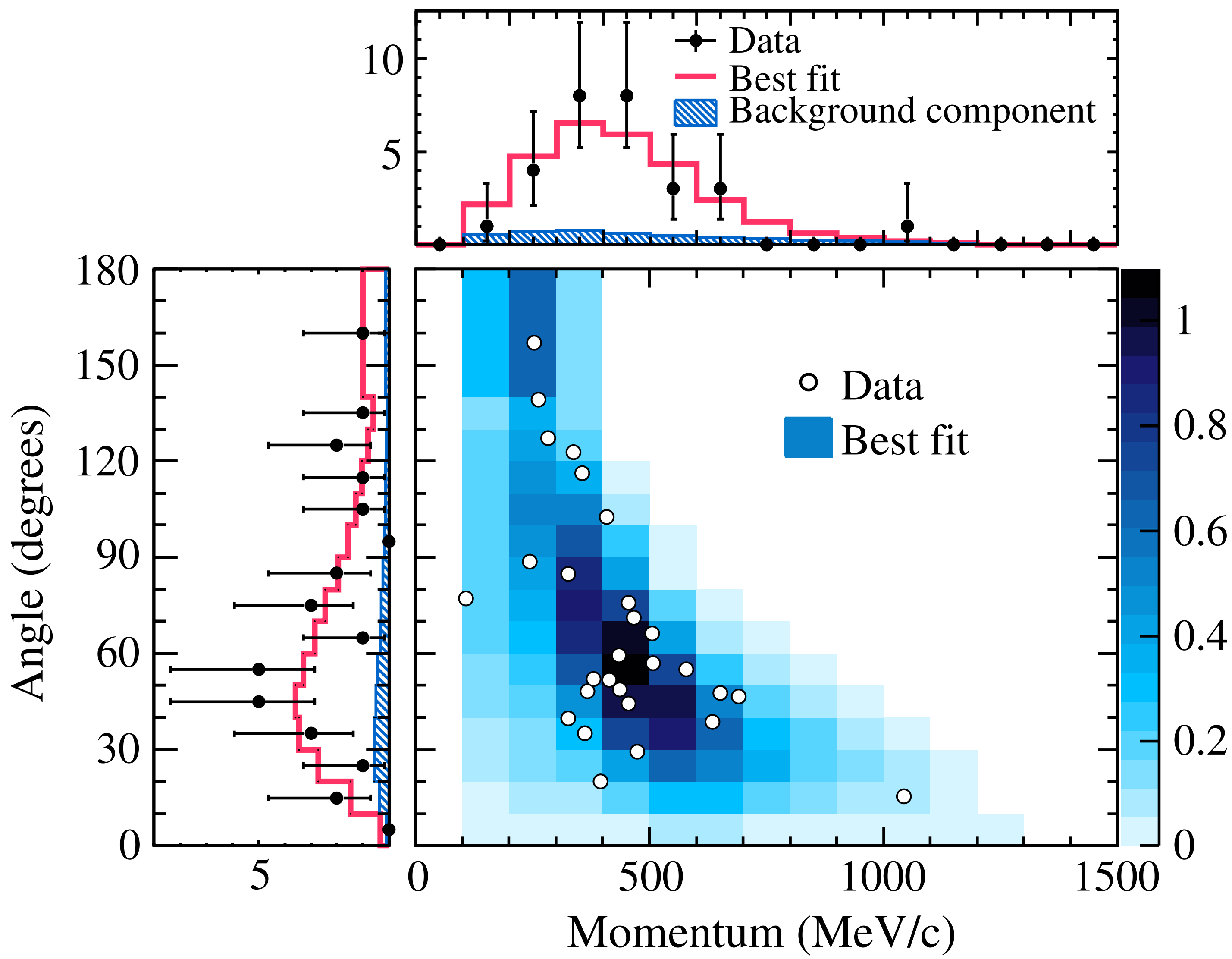
- early 2013 publication
- summer 2013

28 ν_e events
6.57×10^{20} proton on target



ν_e appearance

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



28 Observed evts

4.92 ± 0.55

expected w/ No osc.

PRL 112, 061802 (2014)

Parameter fixed in the analysis: $\delta_{CP}=0$, Normal Hierarchy, $|\Delta m^2_{32}|= 2.4\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$

ν_e appearance

PRL 112, 061802 (2014)

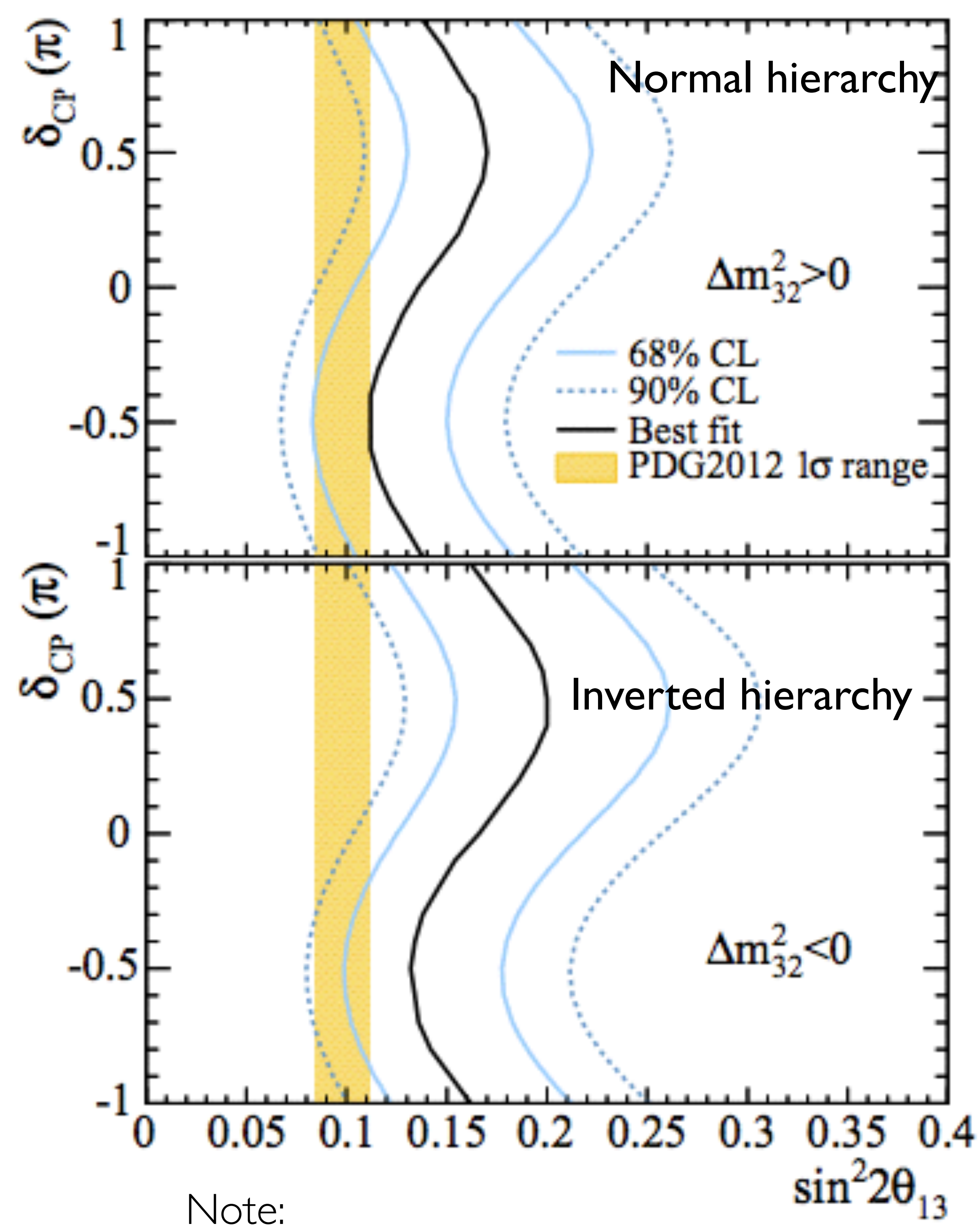
Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}

Best fit w/ 68% C.L. error @ δ_{CP}=0

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

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

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



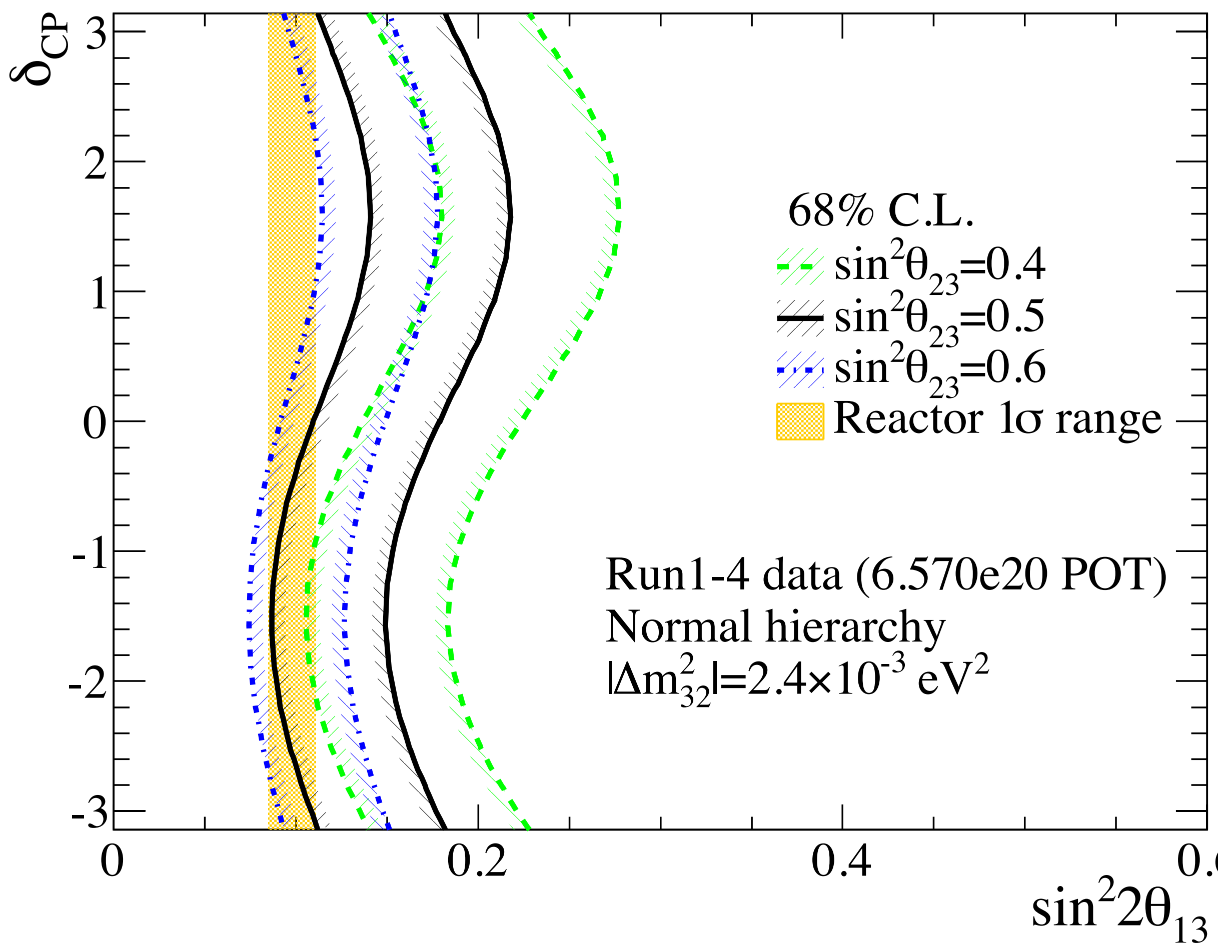
- Discovery of $\vartheta_{13} \neq 0$ with **7.3σ** significance!
- **Constraints on δ_{CP}** while combined with reactor results for ϑ_{13}

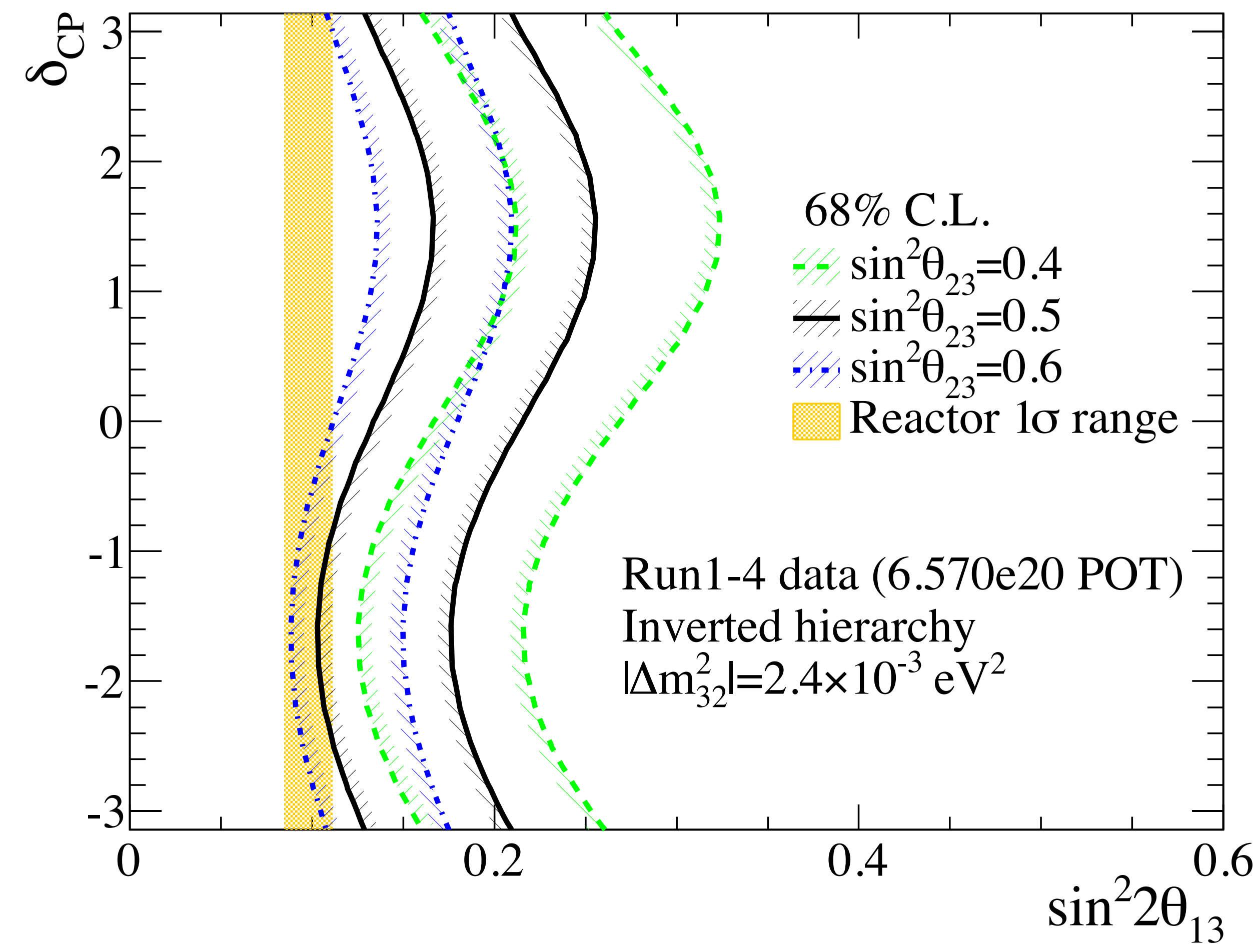
Average θ_{13} (PDG 2012)

Note:

- Marginalized over $\sin^2\vartheta_{23}$, $|\Delta m^2_{32}|$
- w/ T2K Run1-3 ν_μ results
- Raster scan: fit ϑ_{13} for fixed δ_{CP}

νe appearance

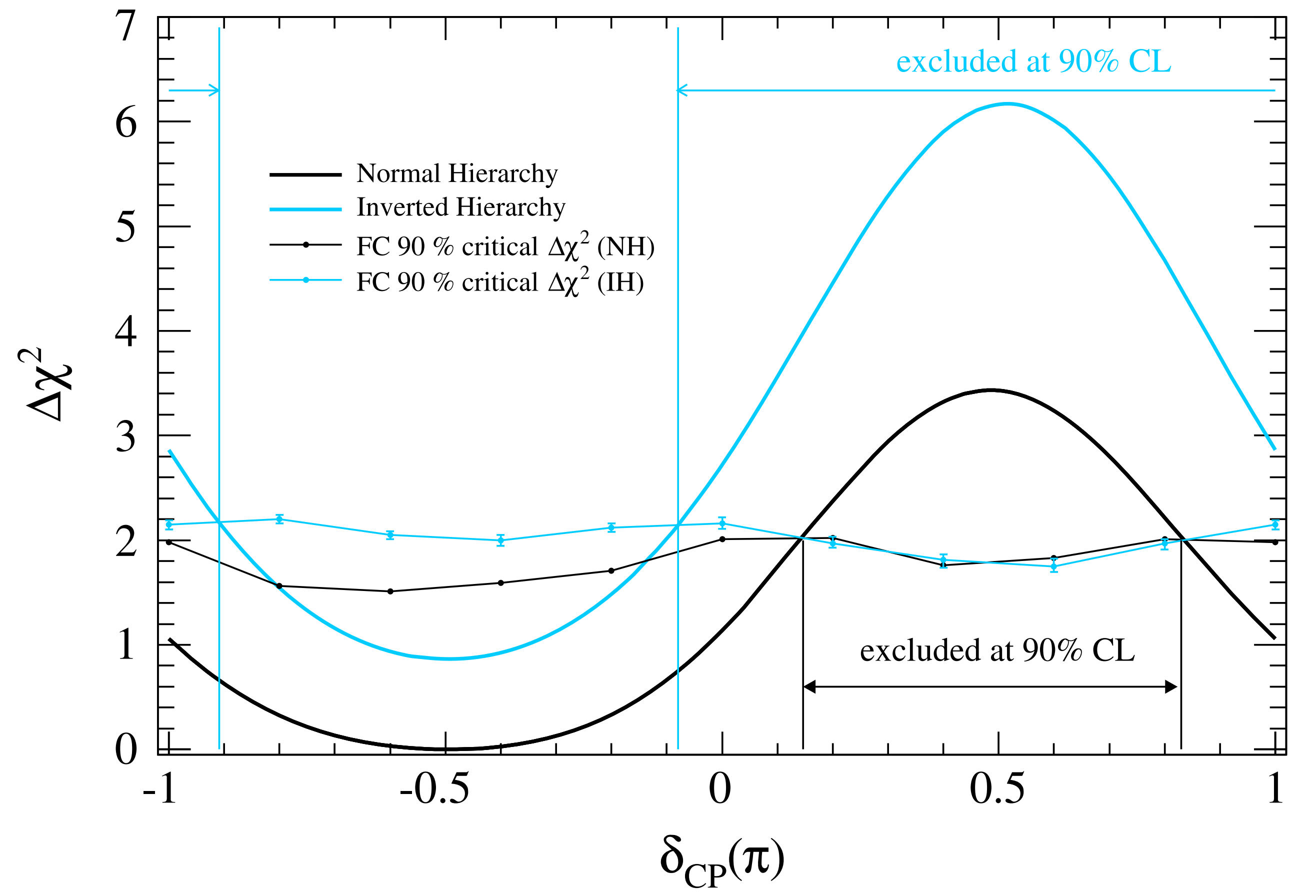


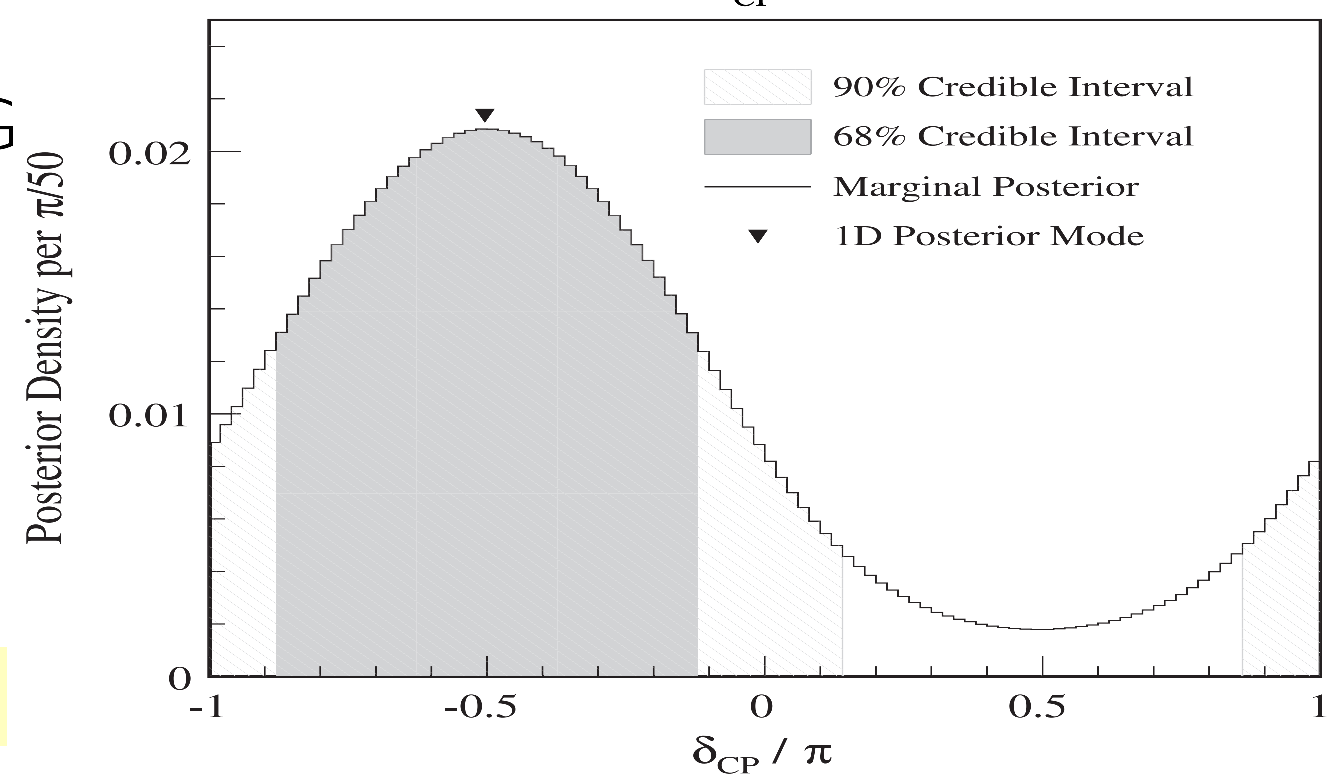


- Dependence of the appearance measurements on the ϑ_{23}
- Motivation for a **joint ν_μ+ ν_e fit**

Joint $\nu_\mu + \nu_e$ 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 $\delta_{CP} \sim -\pi/2$

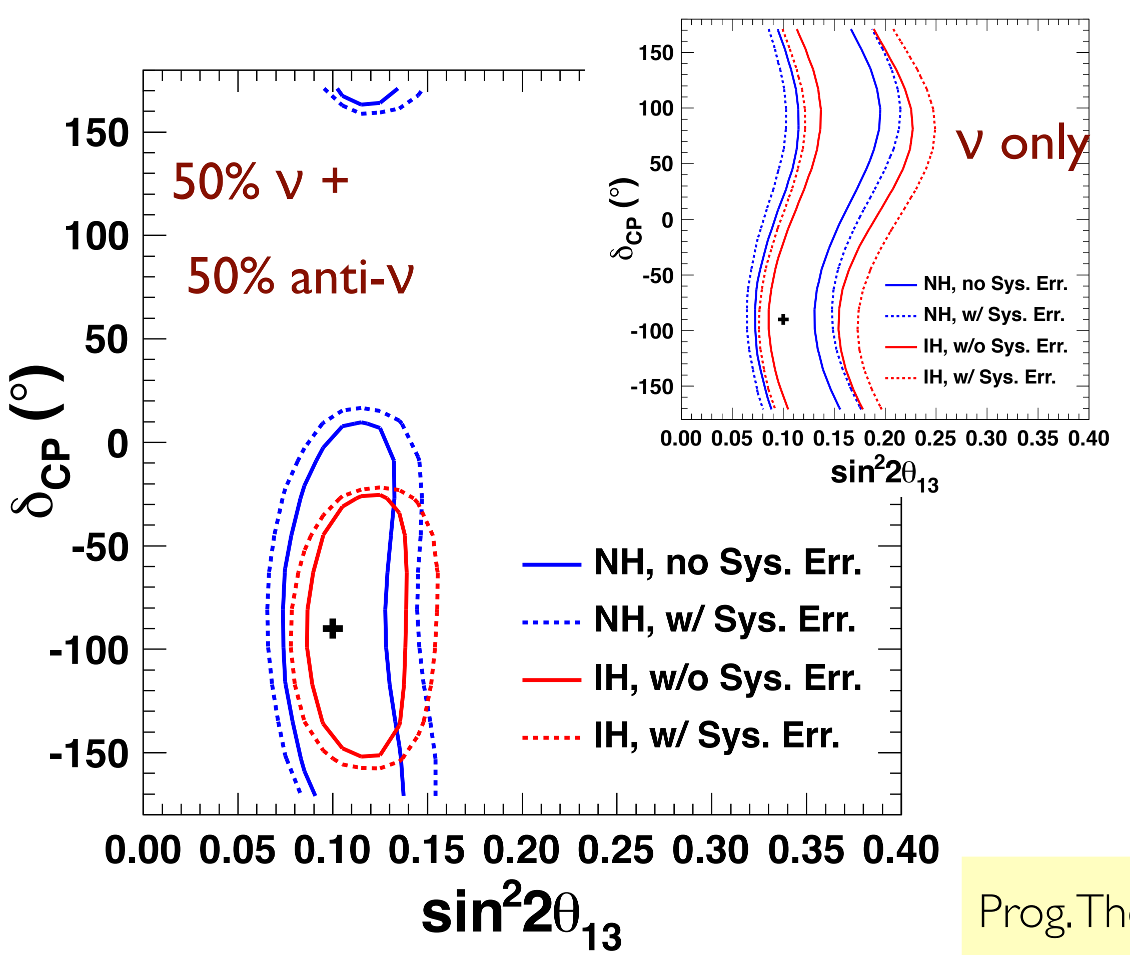


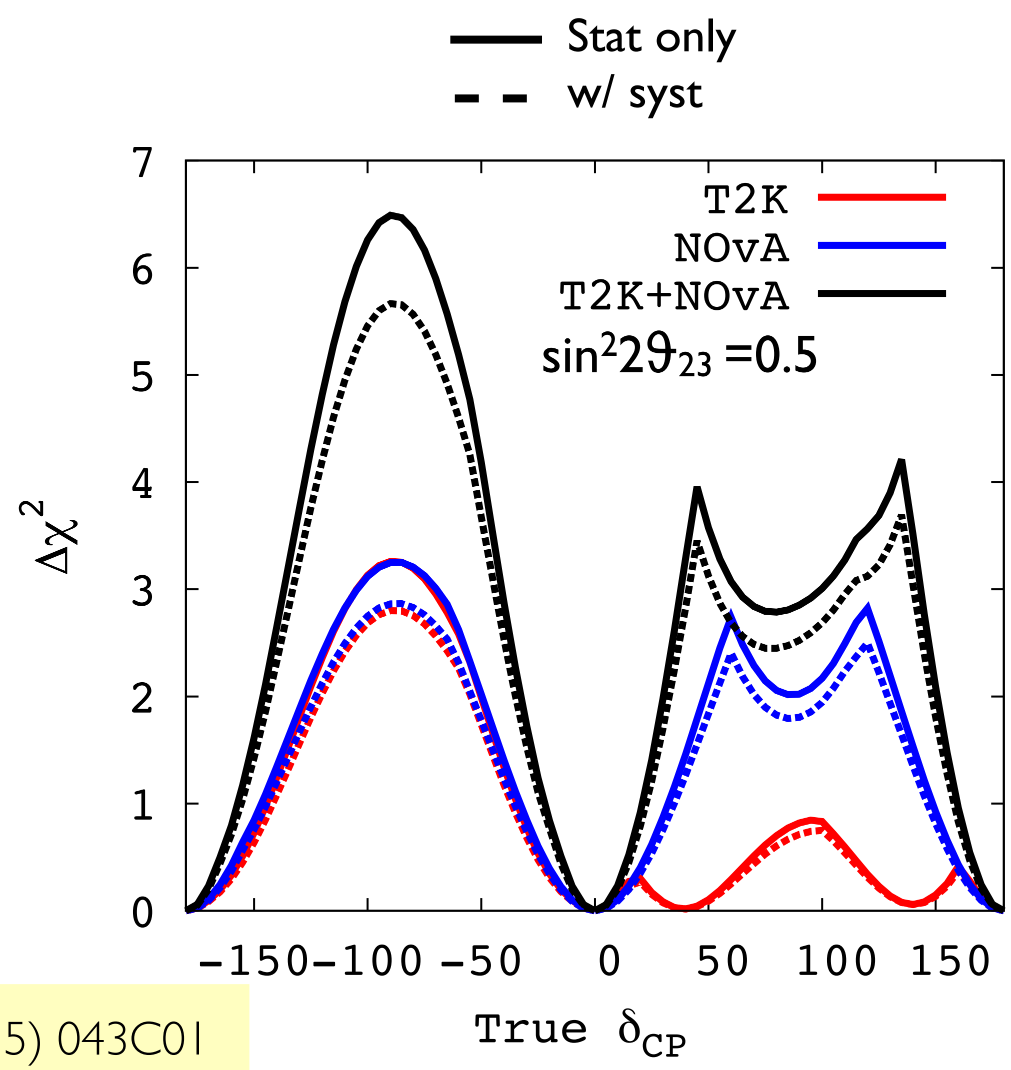


Phys. Rev. D. 91, 072010 (2015)

Future sensitivity studies

- T2K is aiming for 7×10^{21} POT (current data ~10%)
- Sensitivity studies has shown an **enhancement of the T2K physics potential** for **50%ν - 50% anti-ν mode**
- Combinations of the results w/ No**ν**a may help to disentangle the ϑ_{23} octant and (if lucky) discover δ_{CP} at 3σ





Prog. Theor. Exp. Phys. (2015) 043C01

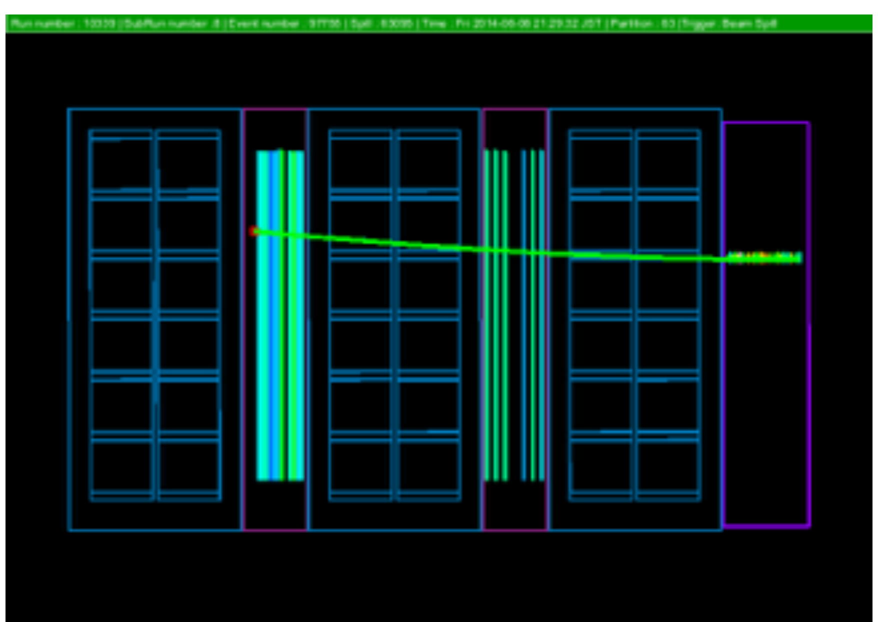
First look to anti-neutrino data

Anti-neutrino analyses

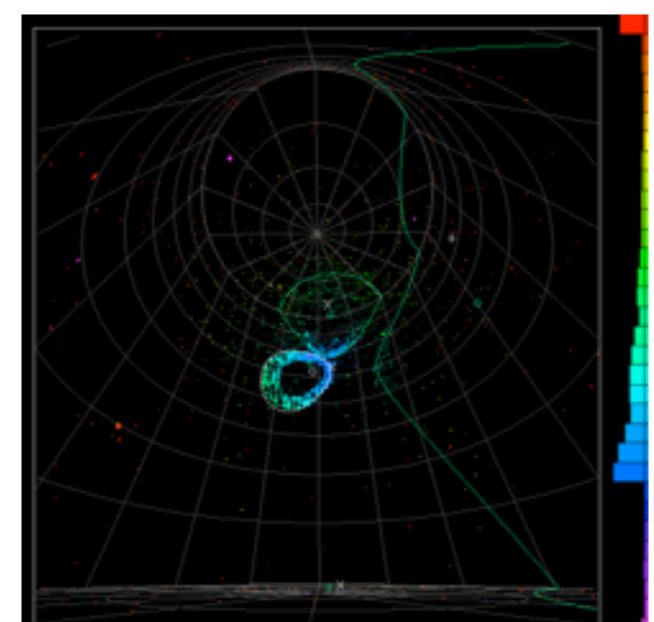
- Sensitivity studies have shown that running with 50% **ν** - 50% anti-**ν** mode will further enhance the T2K physics potential
- **3.12 x10^{20} POT** already recored in **anti-ν mode**!
- Same strategy as for the neutrino mode: use of ND280 data to constrain systematics
- **Oscillation analysis are ready** but still not public

  18th of May Seminar at KEK presenting the anti-νμ disappearance results

μ+ event in ND280



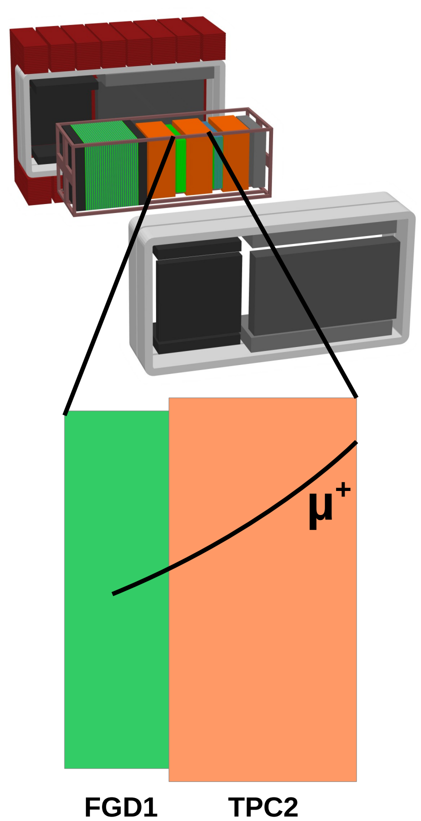
First anti-v in SK



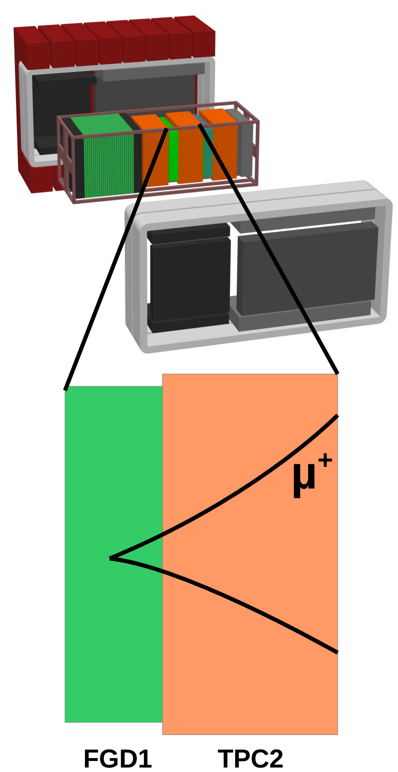
Anti-neutrino analysis at ND280

- The analysis performed at ND280 will perform a key role to reduce the systematics uncertainties also for anti-neutrino oscillation analyses
- For **4.3×10^{19} POT** (Run5 only) we observe **571 anti-$\nu\mu$** CC interaction candidates
- Simple selection: highest momentum positive track with mu-like PID
  - **CC-1-Track sample** : sensitive to T2K signal
  - **CC-N-Tracks sample**: sensitive to T2K background

CC-1 Track Sample

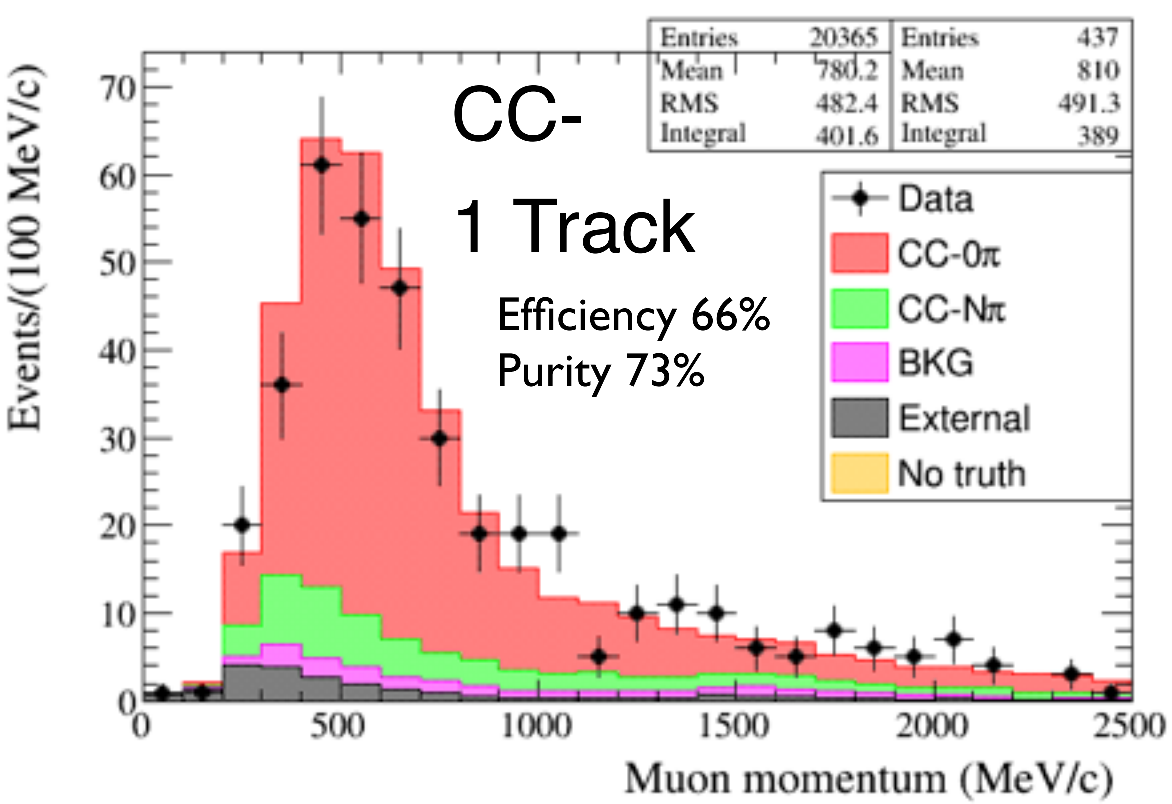


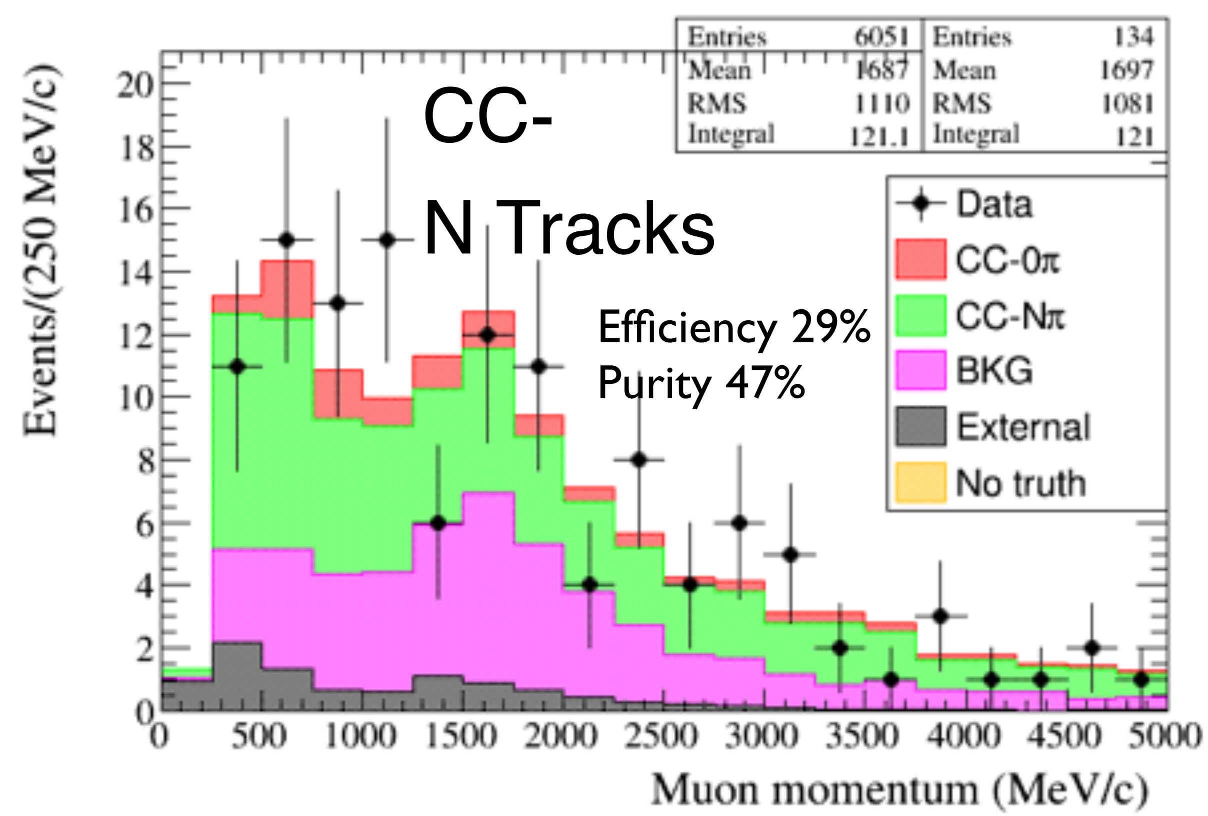
CC-N Tracks Sample



Anti-neutrino analysis at ND280

- The analysis performed at ND280 will perform a key role to reduce the systematics uncertainties also for anti-neutrino oscillation analyses
- For **4.3x10^{19} POT** (Run5 only) we observe **571 anti-νμ** CC interaction candidates
- Simple selection: highest momentum positive track with mu-like PID
  - **CC-1-Track sample** : sensitive to T2K signal
  - **CC-N-Tracks sample**: sensitive to T2K background





Anti-neutrino analysis at ND280

- The analysis performed at ND280 will perform a key role to reduce the systematics uncertainties also for anti-neutrino oscillation analyses
- For **4.3x10^{19} POT** (Run5 only) we observe **571 anti-νμ** CC interaction candidates
- Simple selection: highest momentum positive track with mu-like PID
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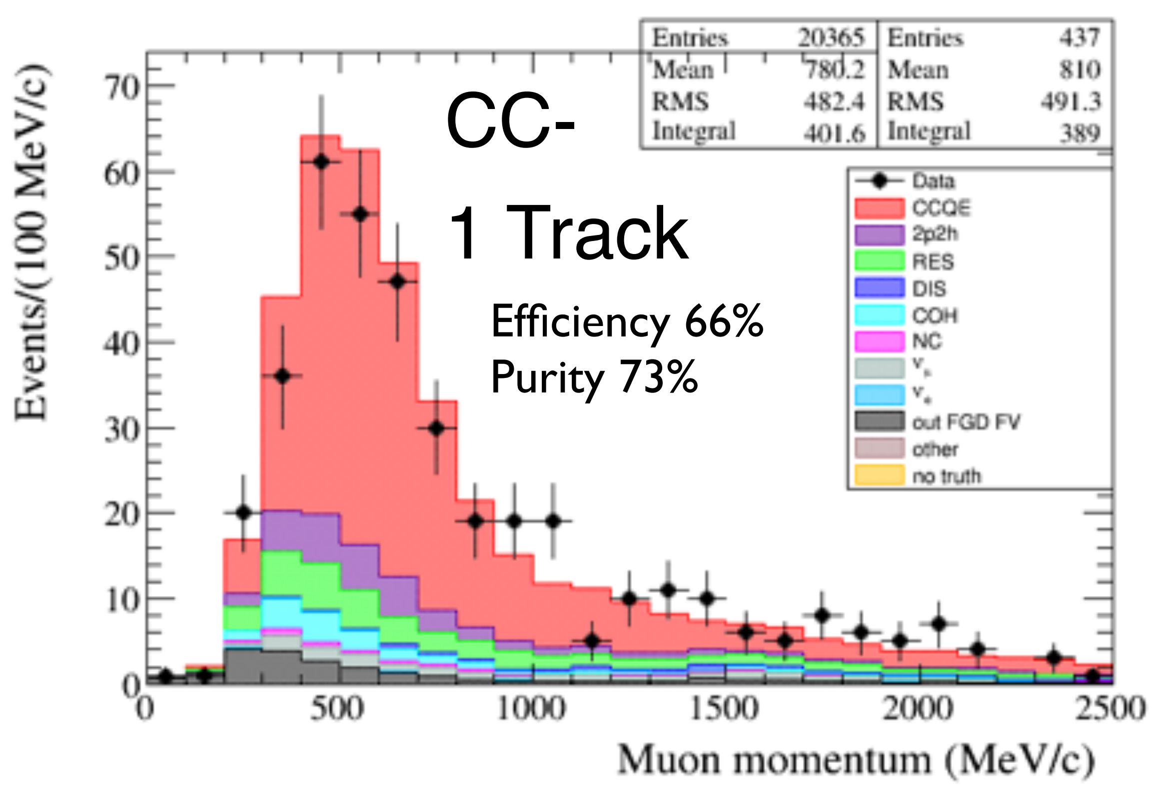
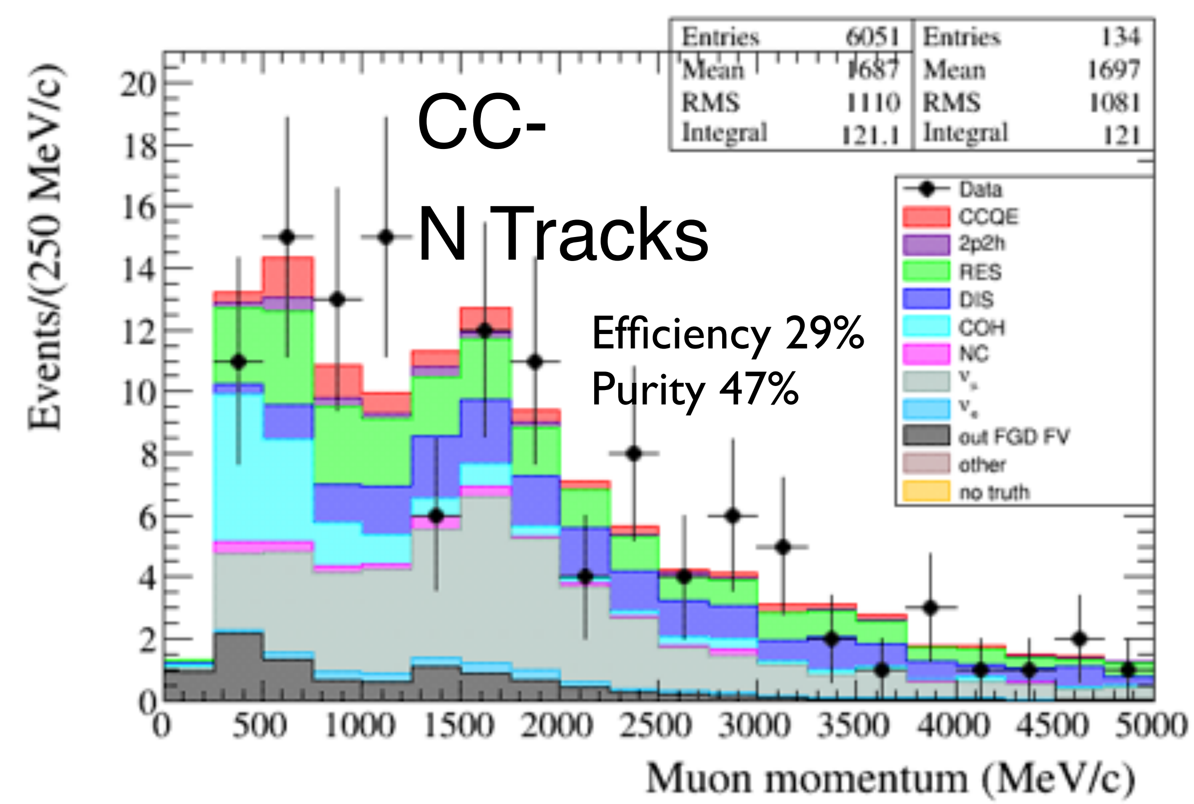
  - **CC-N-Tracks sample**: sensitive to T2K background





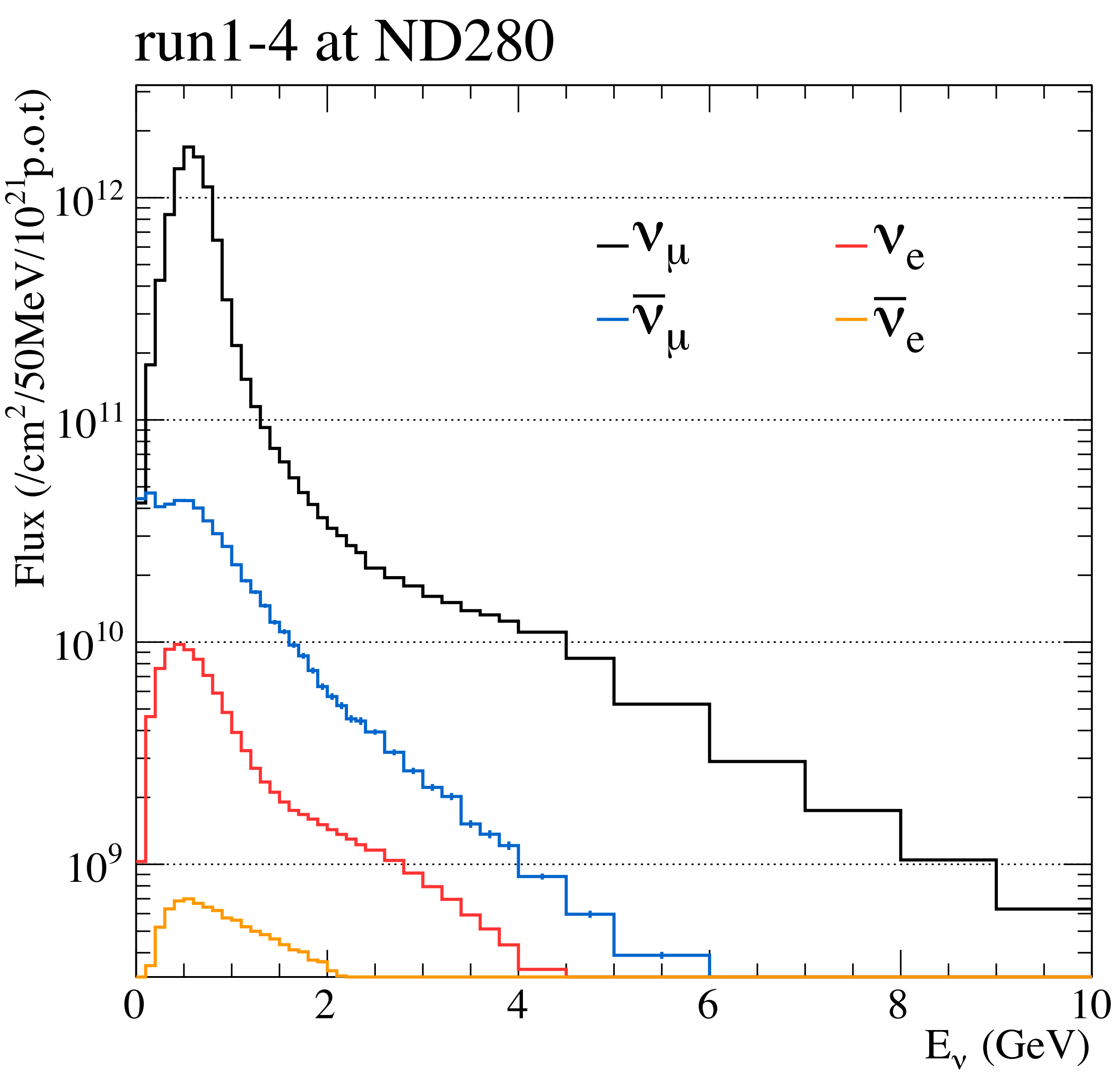
Conclusions

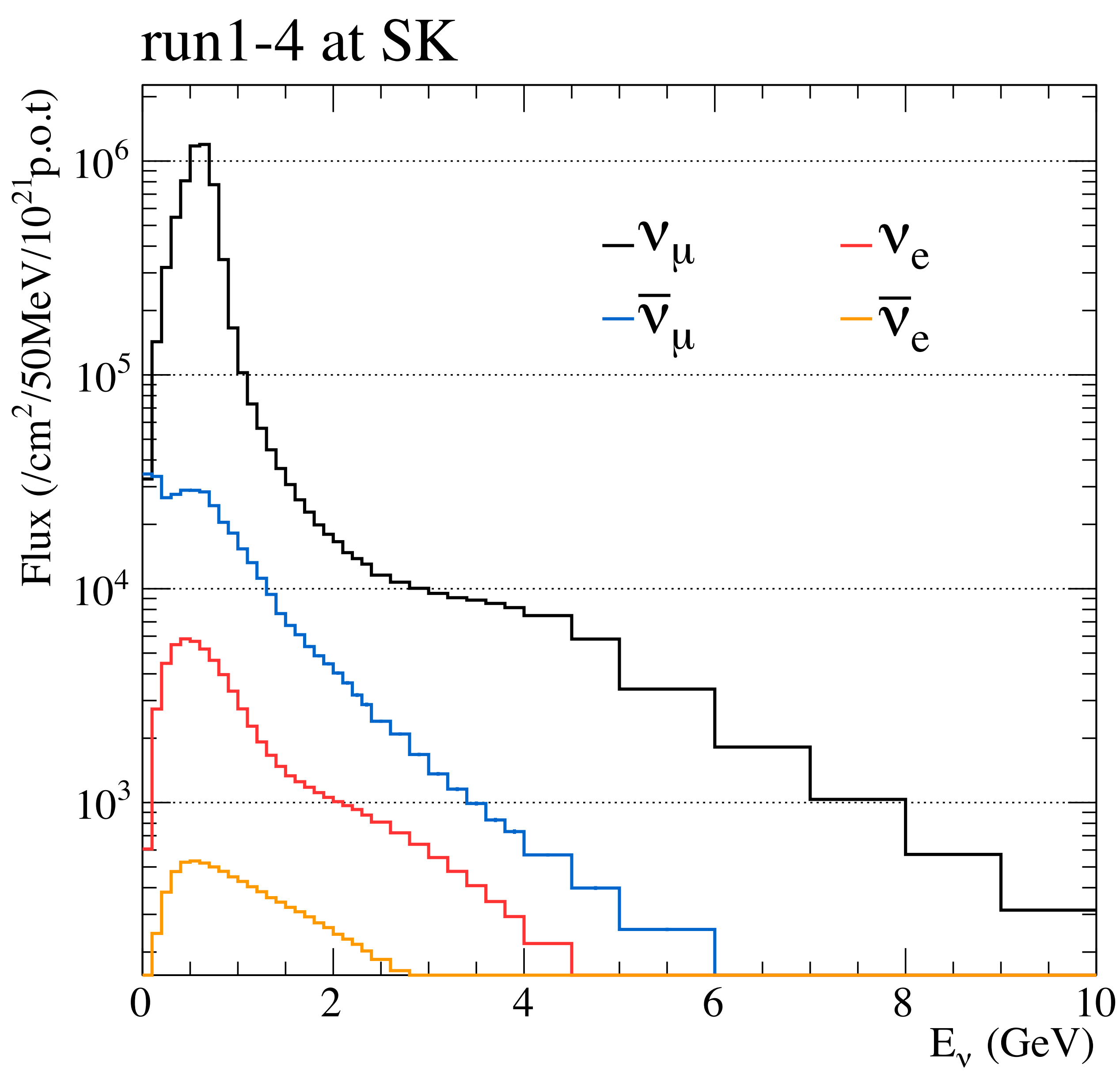
Conclusions

- 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
- A lot of interesting measurements are performed at the near detectors
  - ν_e and ν_μ cross sections
  - Search for Short Baseline oscillations (sterile neutrinos)
- T2K is collecting now also data in anti-neutrino mode
  - Sensitivity studies has shown an enhancement of the physics potential of T2K if we collect 50% ν - 50% anti-ν
  - anti-ν_μ disappearance results will be presented next week!
  - Other measurement (anti-ν_e appearance, joint analyses..) will be ready soon. Stay tuned!

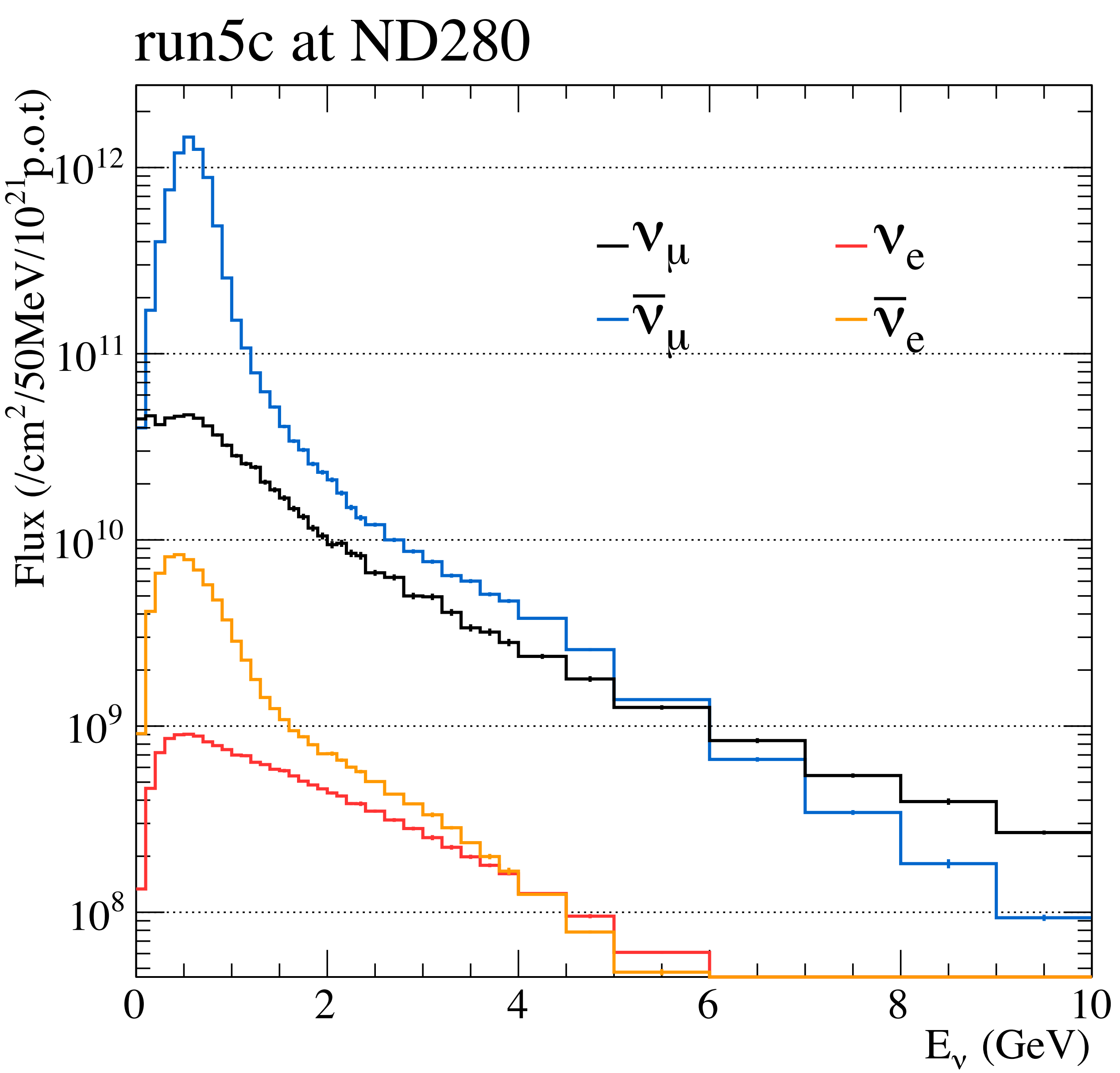
Supplementary

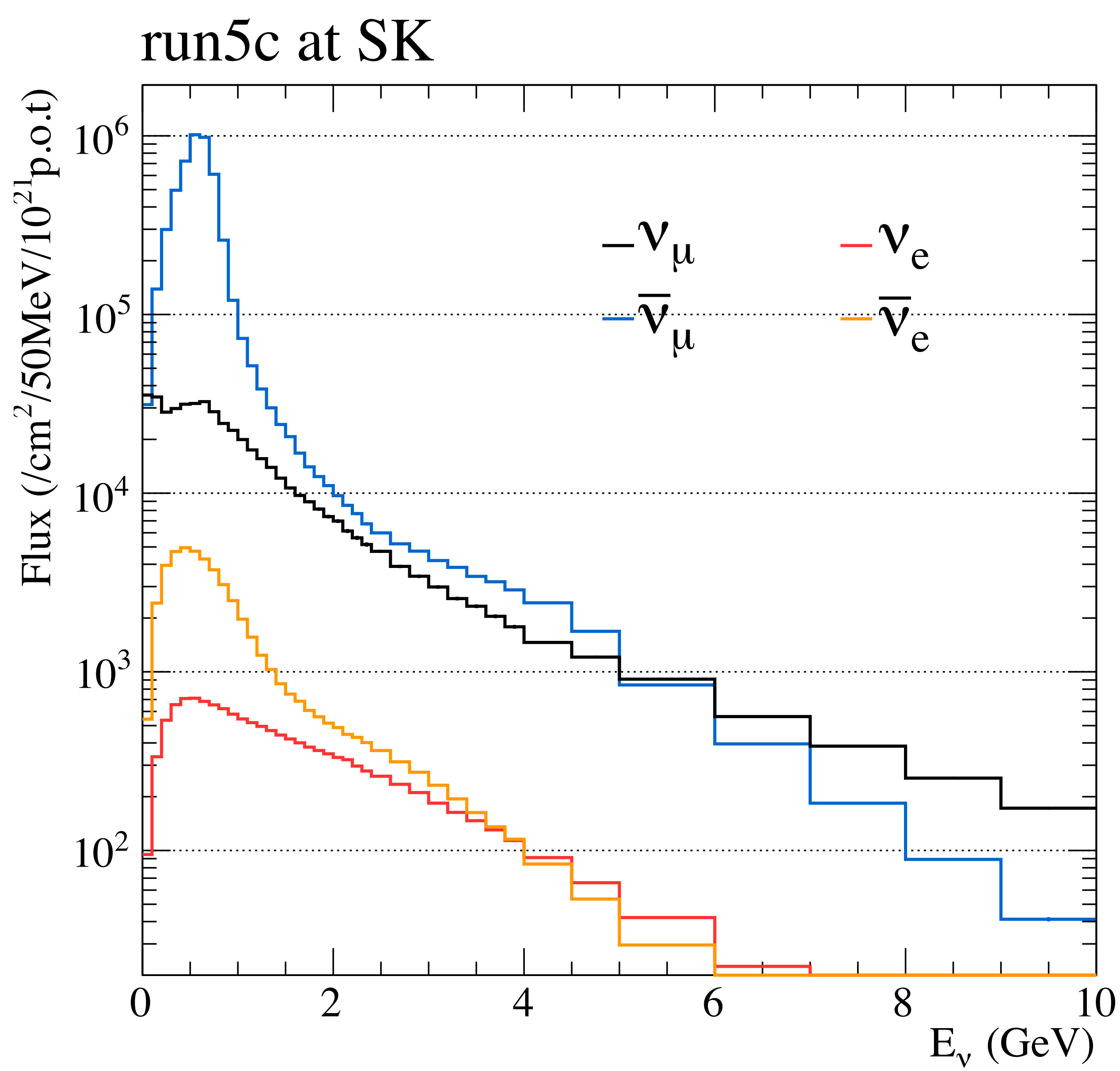
Flux prediction Run1-4



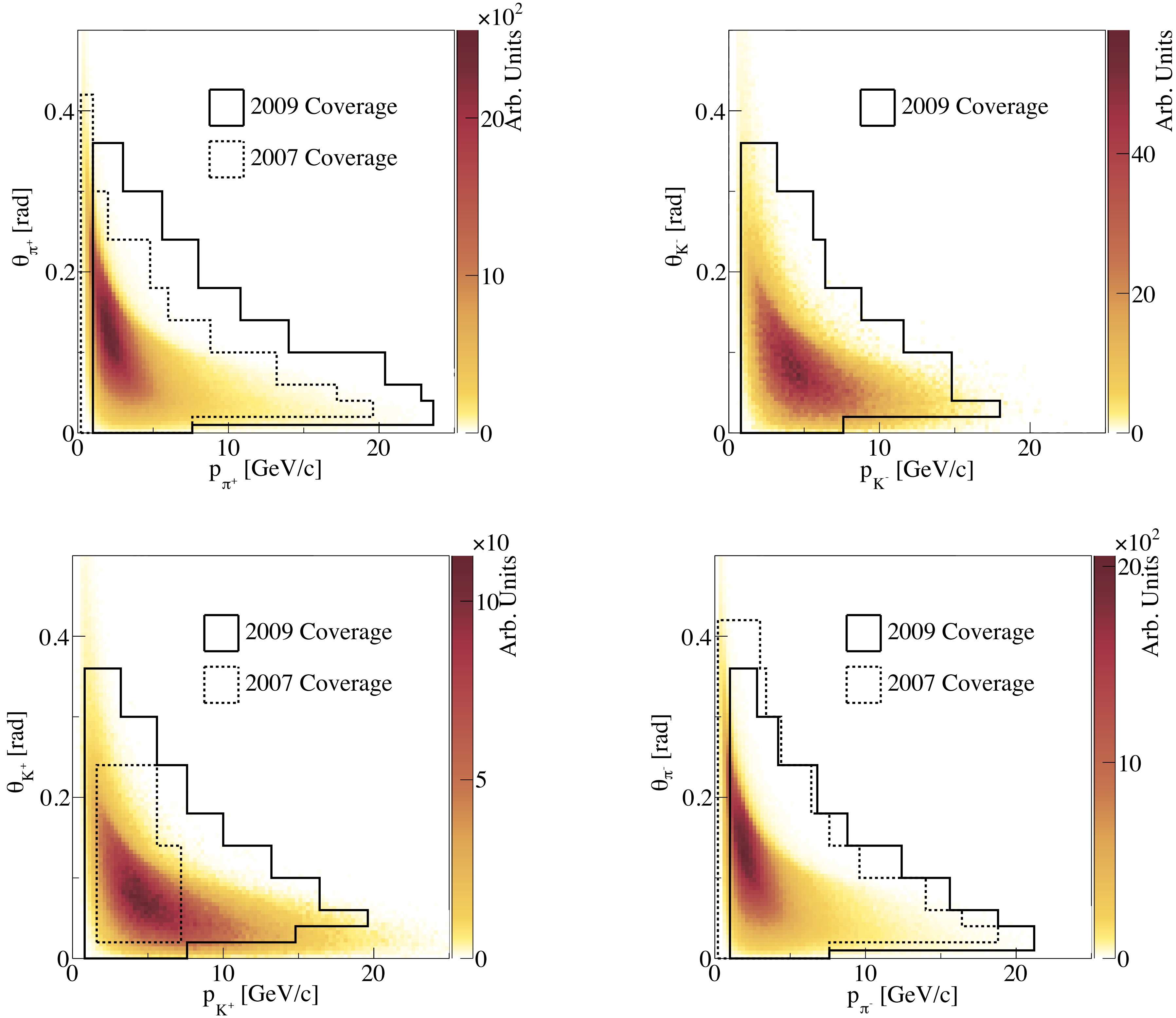


Flux prediction Run5c





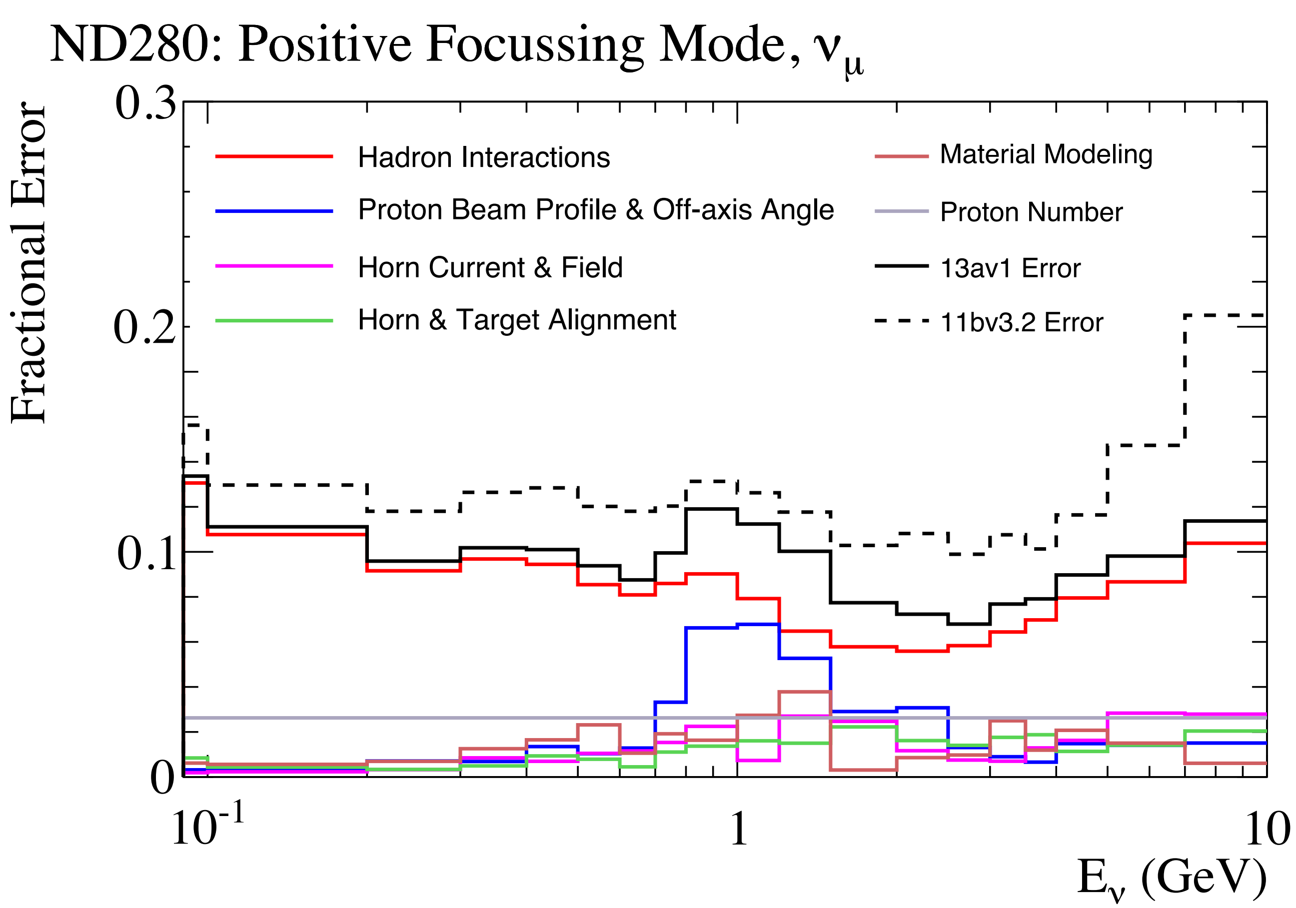
NA61 data

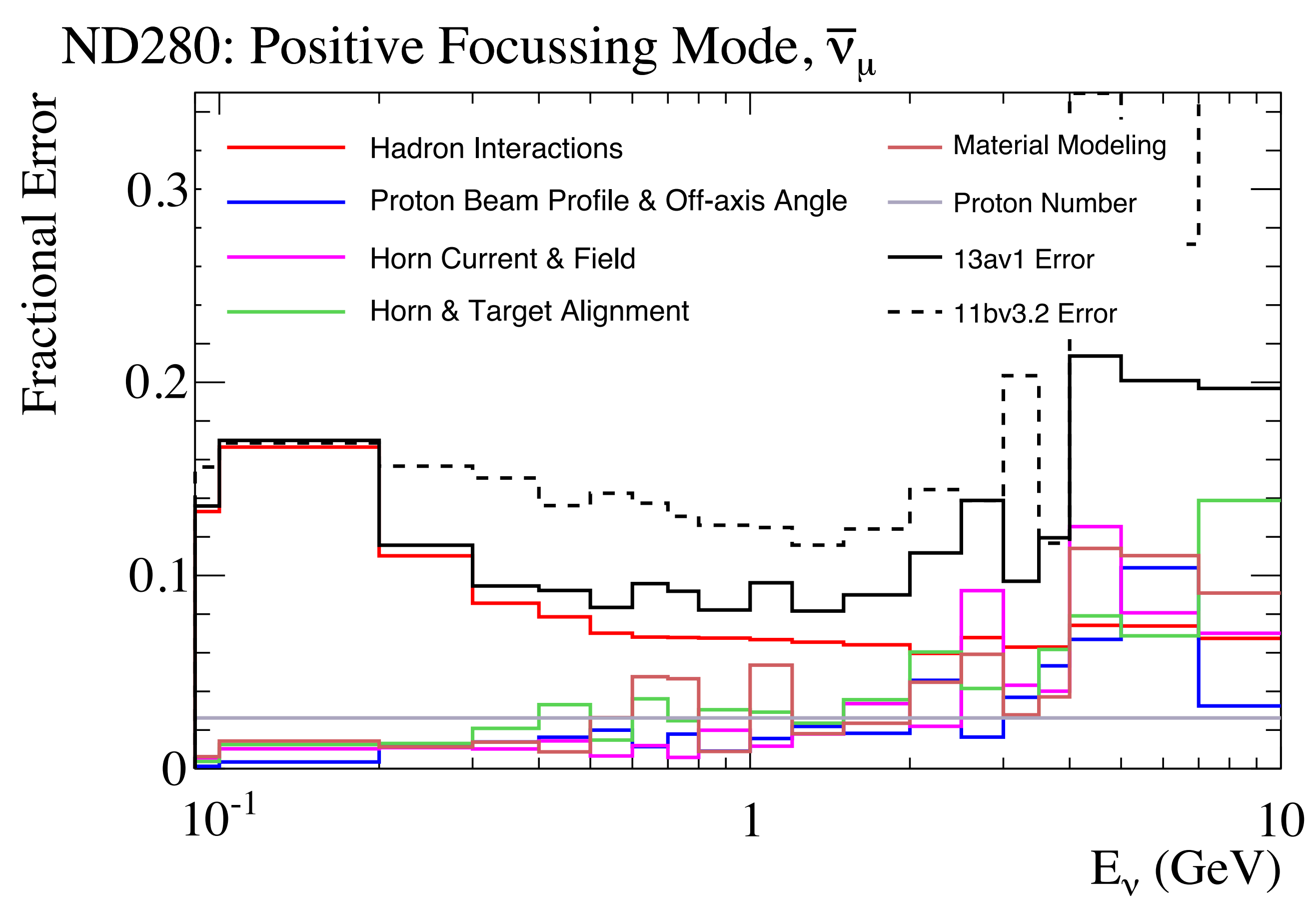

2009 Coverage
2007 Coverage
θ_{π^+} [rad]
p_{π^+} [GeV/c]
θ_{K^-} [rad]
p_{K^-} [GeV/c]
θ_{K^+} [rad]
p_{K^+} [GeV/c]
θ_{π^-} [rad]
p_{π^-} [GeV/c]
Arb. Units
$\times10^2$
$\times10$

Flux prediction error

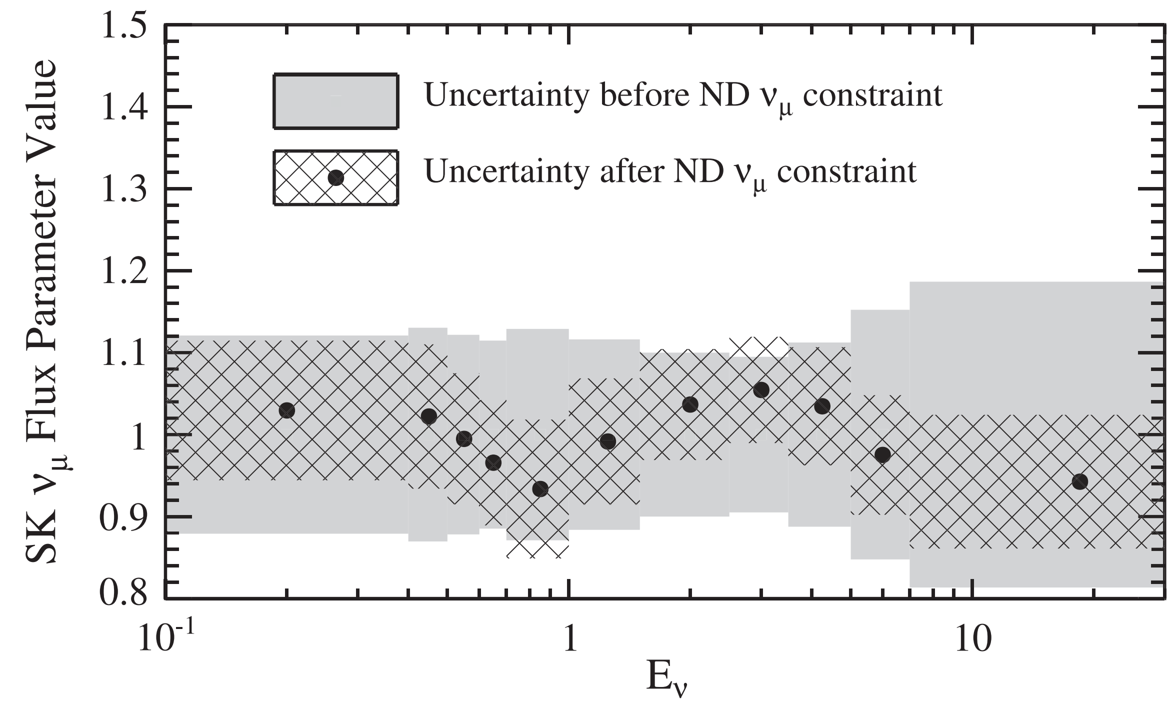
New NA61 data release:

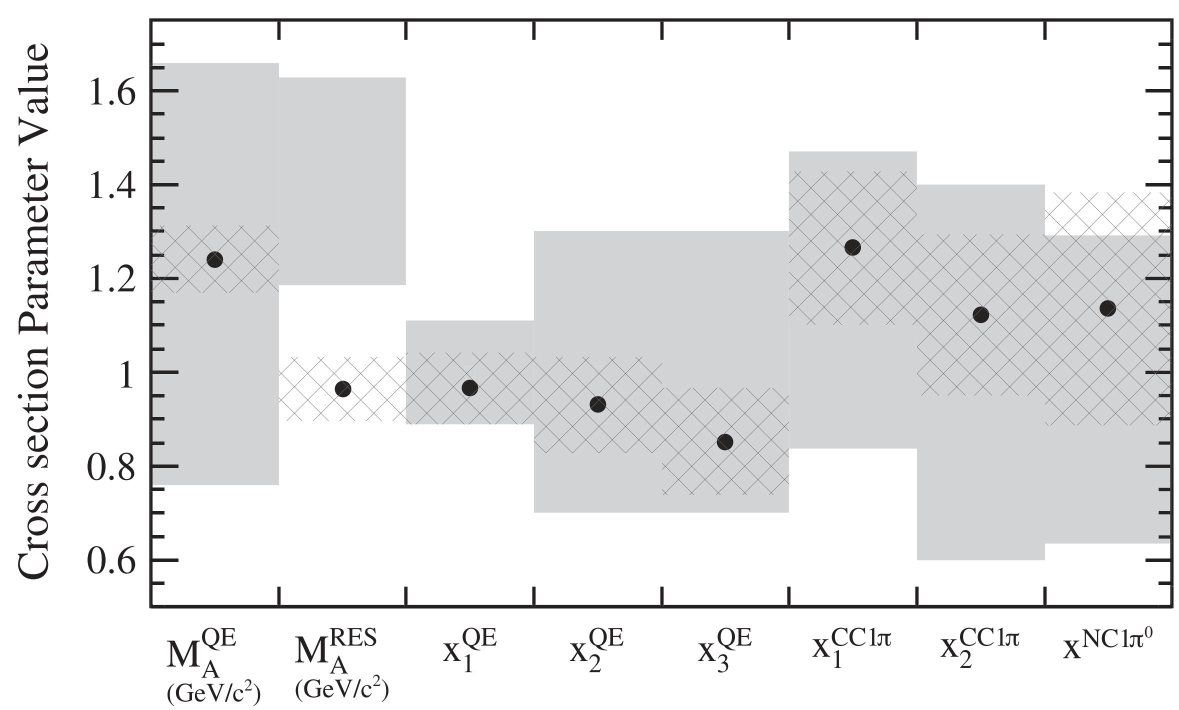
- Reduction of the error in n-mode at ~10% (15% with 2007 data release)
- Flux error in anti-nu mode < 15%





ND280 constraints





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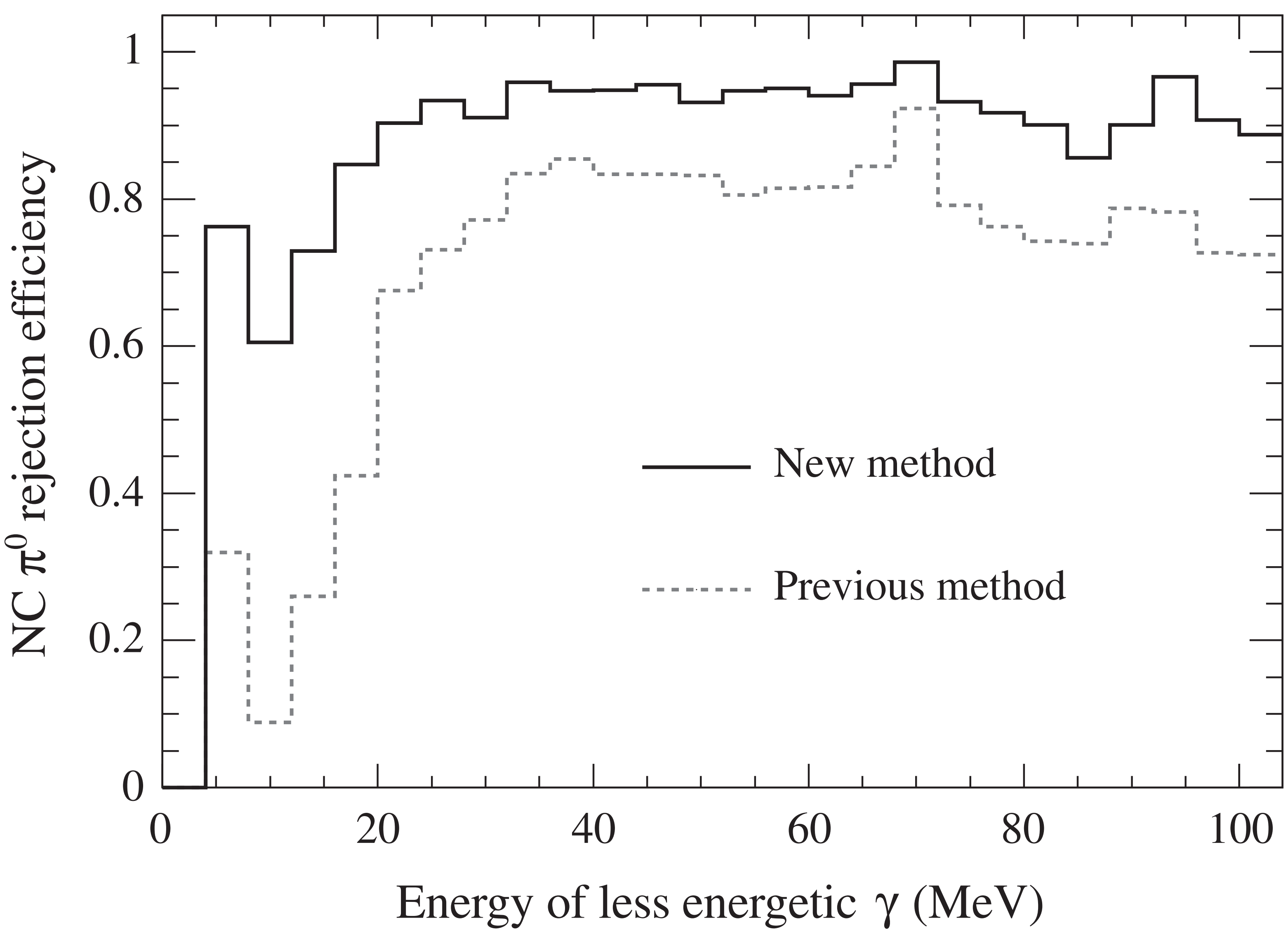
NCπ^0 rejection

With the new method:

- reduction of about 9x of the remaining NC background (after "1-ring" selection)
- reduction of 69% of the remaining background wrt to the previous method



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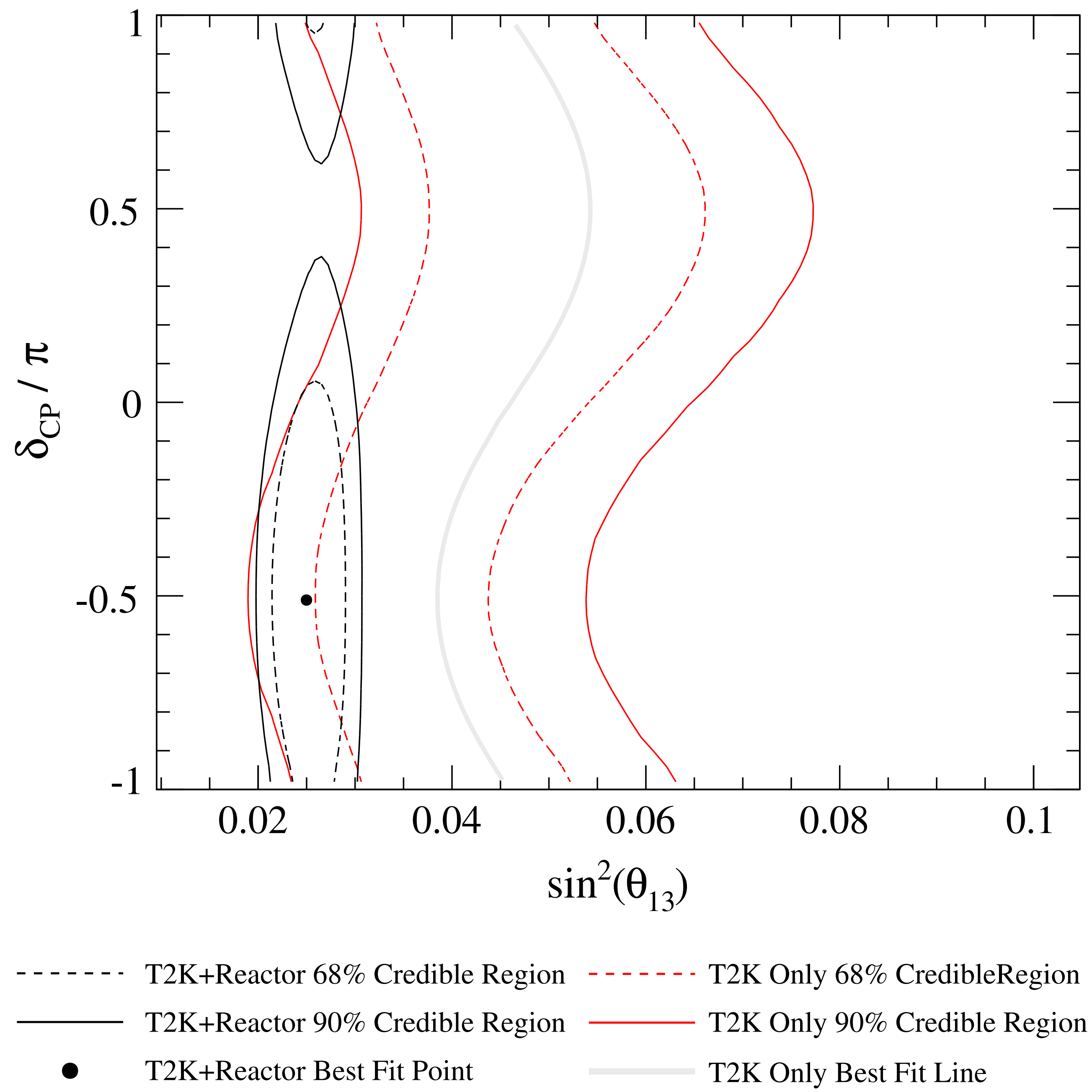
$\sin^2\theta_{13}$ - δ_{CP} credible region



Phys. Rev. D. 91, 072010 (2015)

Joint $\nu_\mu + \nu_e$ analysis :

Frequentist approach

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Excluded regions @ 90% CL

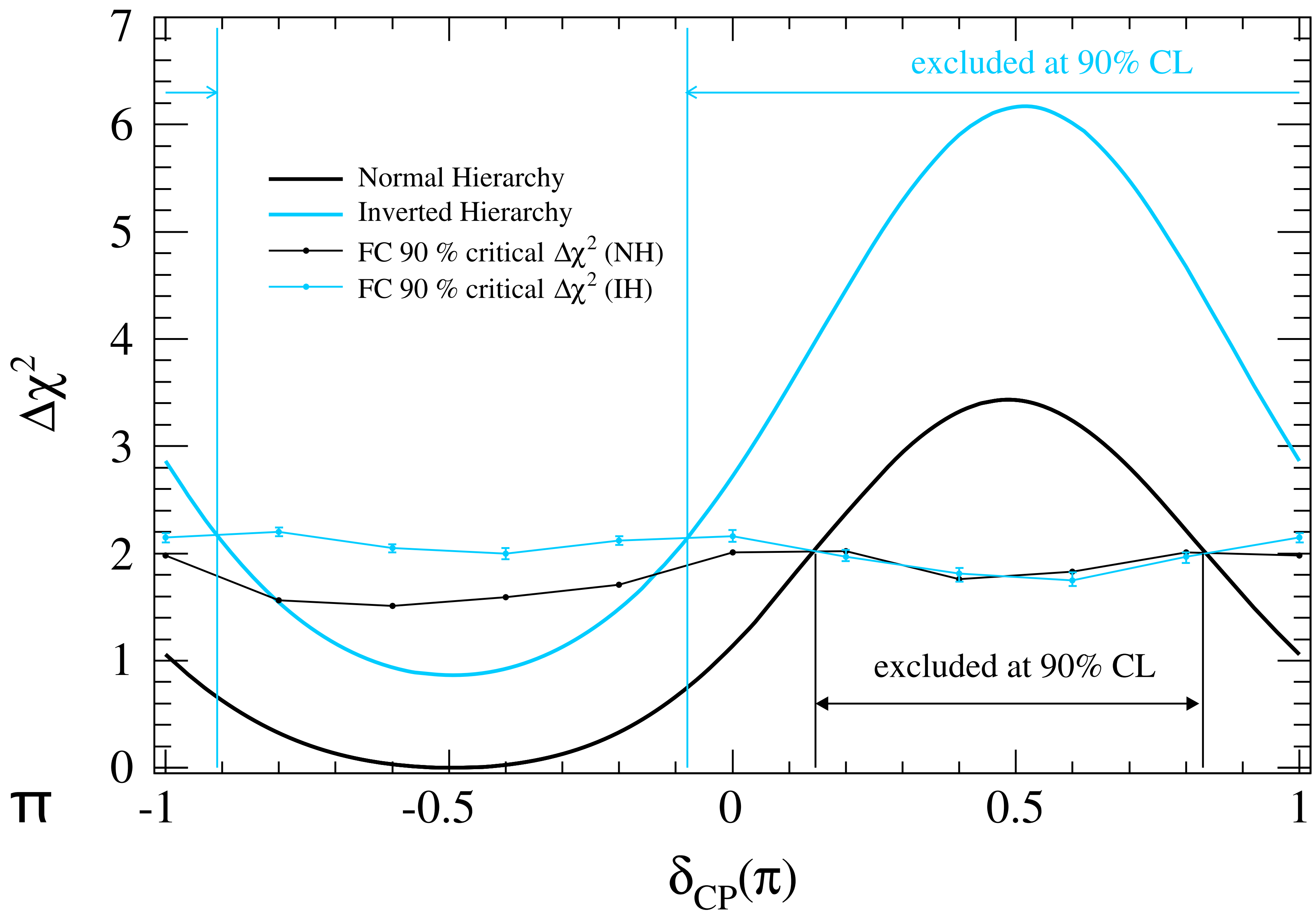
Normal hierarchy ($\Delta m^2_{32} > 0$):

$0.15\,\pi < \delta_{CP} < 0.83\,\pi$

Inverted hierarchy ($\Delta m^2_{32} < 0$):

$-0.08 < \delta_{CP} < \pi$

$-\pi < \delta_{CP} < -0.91\pi$



Reactor constraints from PDG 2013 $\sin 2\vartheta_{13} = 0.095 \pm 0.010$

Joint $\nu_\mu + \nu_e$ analysis :

Bayesian approach

- Markov Chain Monte Carlo method
- Simultaneous inclusion of ND280 and SK data
- Marginalize over the mass hierarchy
- Assuming flat prior of $\sin 2\vartheta_{23}$ $|\Delta m^2_{23}|$ and $P_{NH} = P_{IH} = 0.5$

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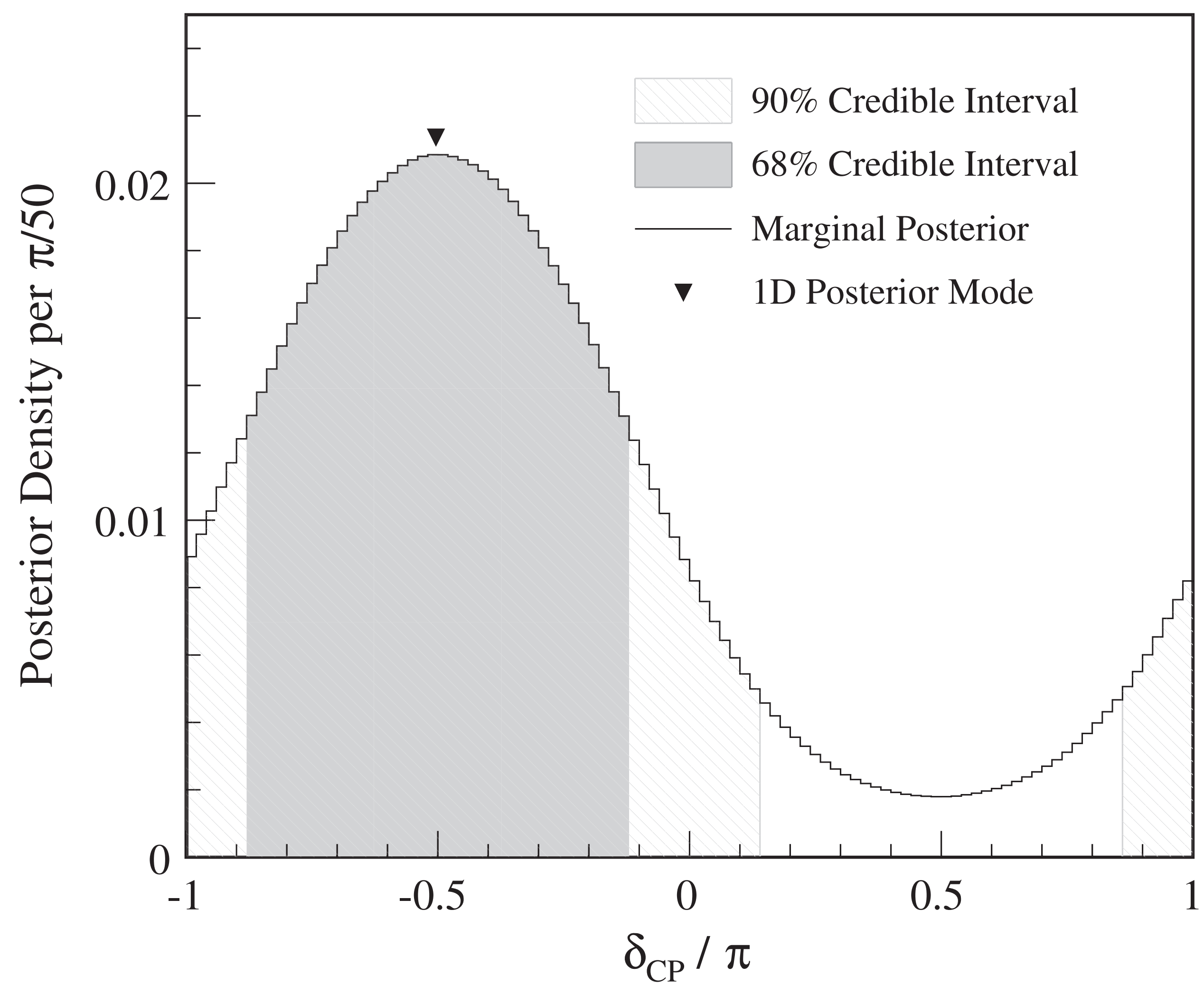
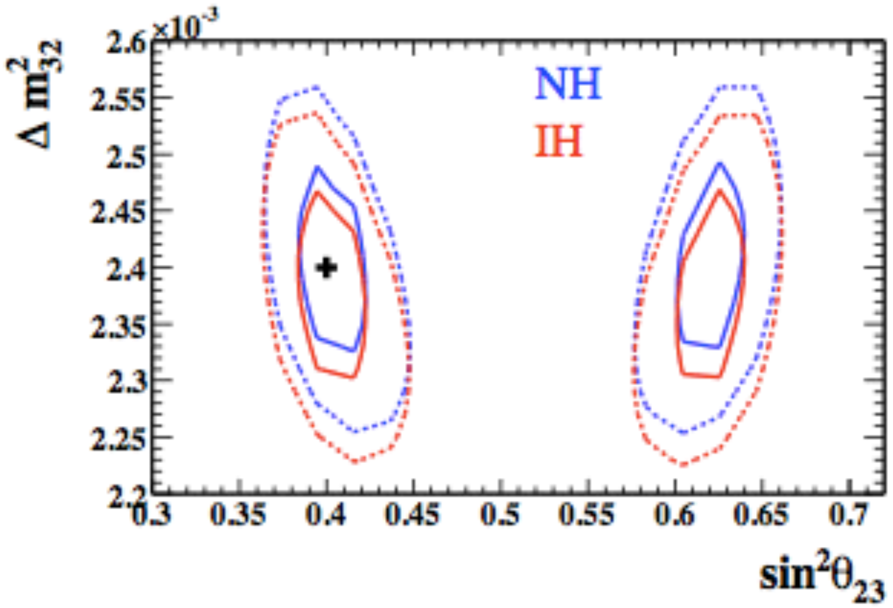
90% credible interval

$-1.11\ \pi < \delta_{CP} < 0.38\ \pi$

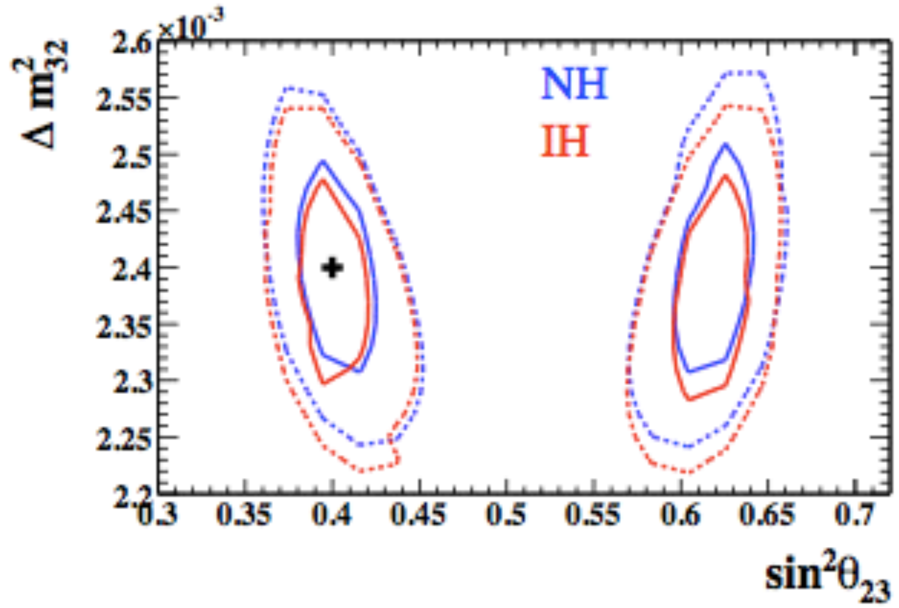
	NH	IH	Sum
$\sin^2\vartheta_{23} \leq 0.5$	0,179	0,078	0,257
$\sin^2\vartheta_{23} > 0.5$	0,505	0,238	0,743
Sum	0,684	0,316	1



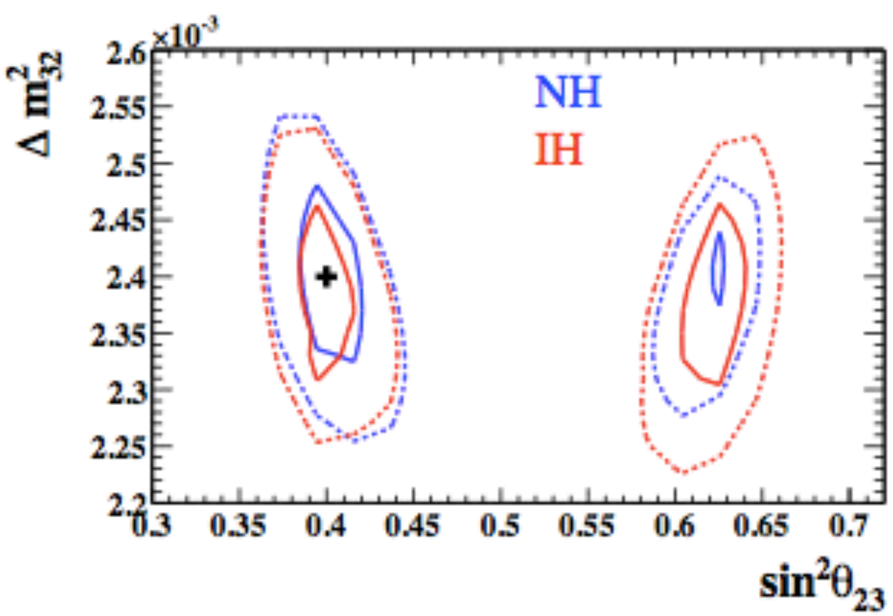
Future sensitivity studies



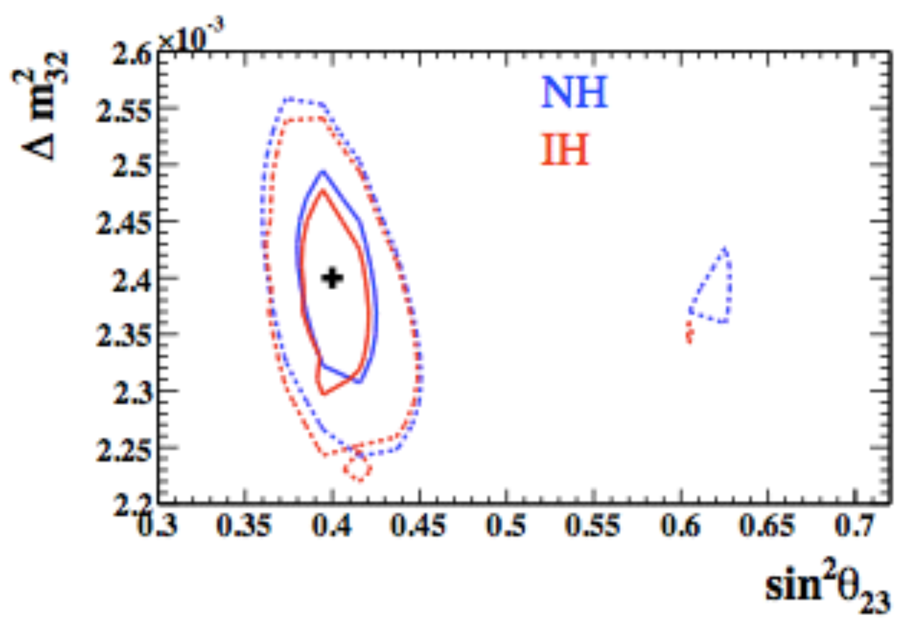
(a) 100% ν-running.



(b) 50% ν-, 50% $\bar{\nu}$-running.



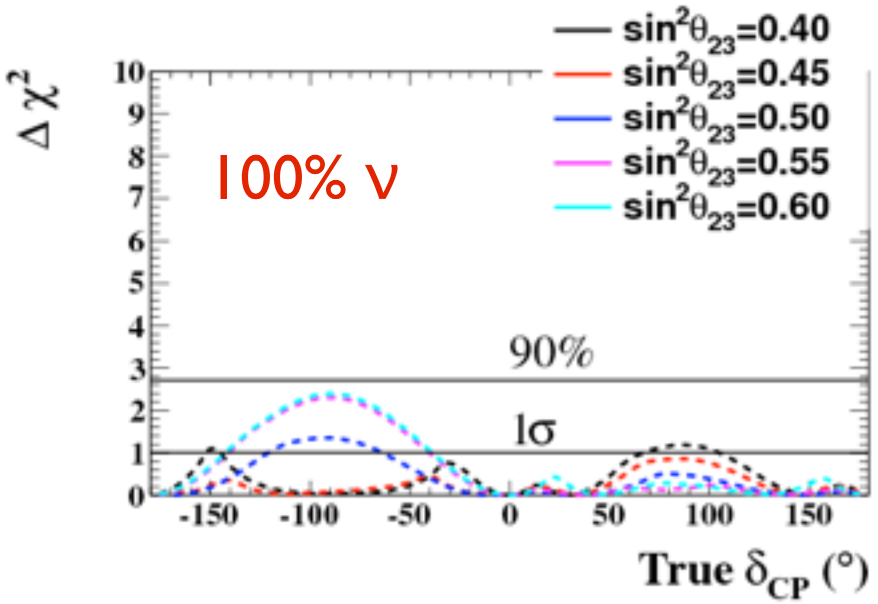
(c) 100% ν-running, with ultimate reactor error.

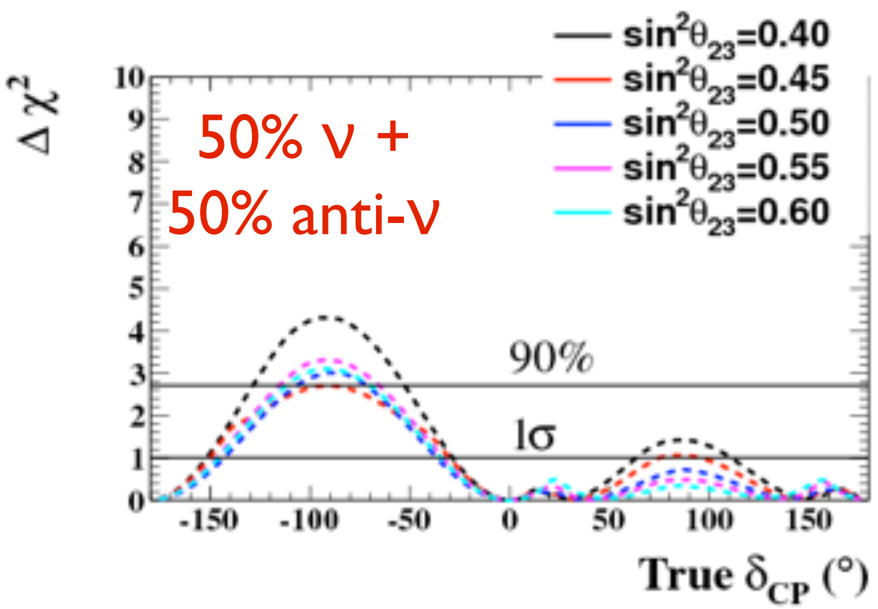


(d) 50% ν-, 50% $\bar{\nu}$-running, with ultimate reactor error.

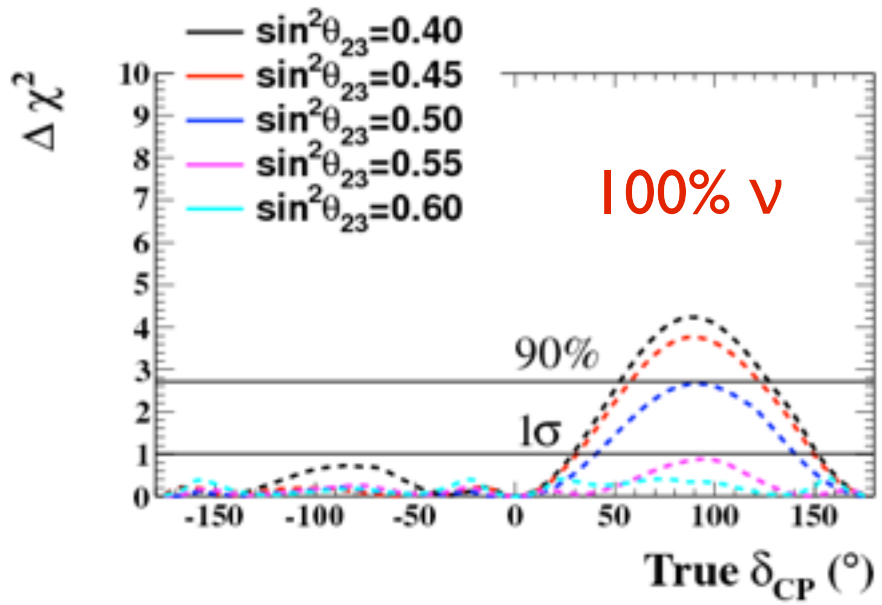
Sensitivity to resolve δ_{CP} /= 0

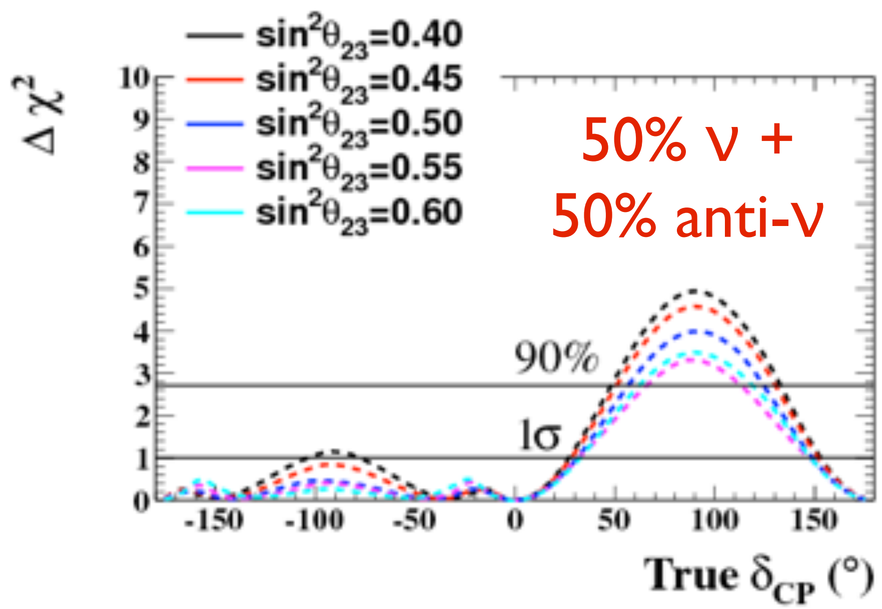
True NH





True IH

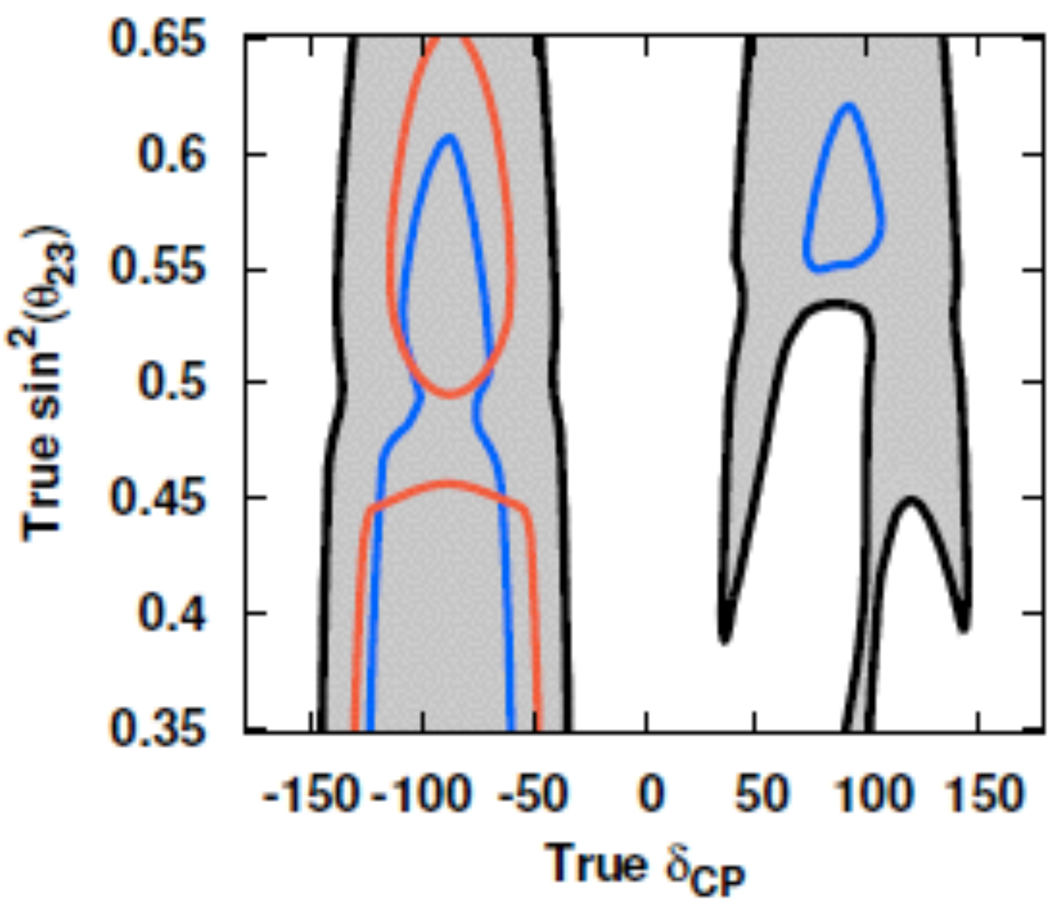




7.8×10^{21} POT $\sin^2 2\vartheta_{13}$ =0.1, δCP =0°, $\sin^2 2\vartheta_{23}$ =0.5, Δm^2= 2.4×10^{-3} eV^2 + 2012 systematics

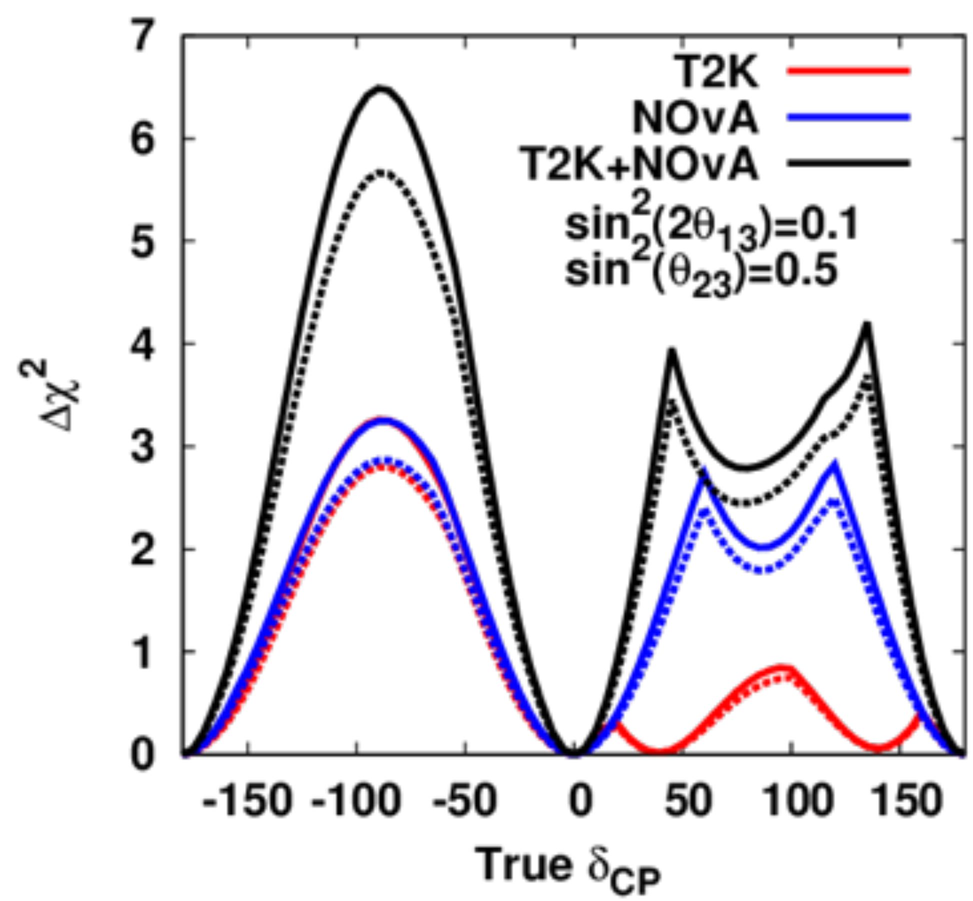
T2K + Nova

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

7.8×10^{21} POT $\sin^2 2\vartheta_{13} = 0.1$, $\delta CP = 0°$, $\sin^2 2\vartheta_{23} = 0.5$, $\Delta m^2 = 2.4 \times 10^{-3}$ eV^2 + with $\delta(\sin^2 2\vartheta_{13}) = 0.005$