
T2K NEAR DETECTOR ANALYSIS PRACTICE



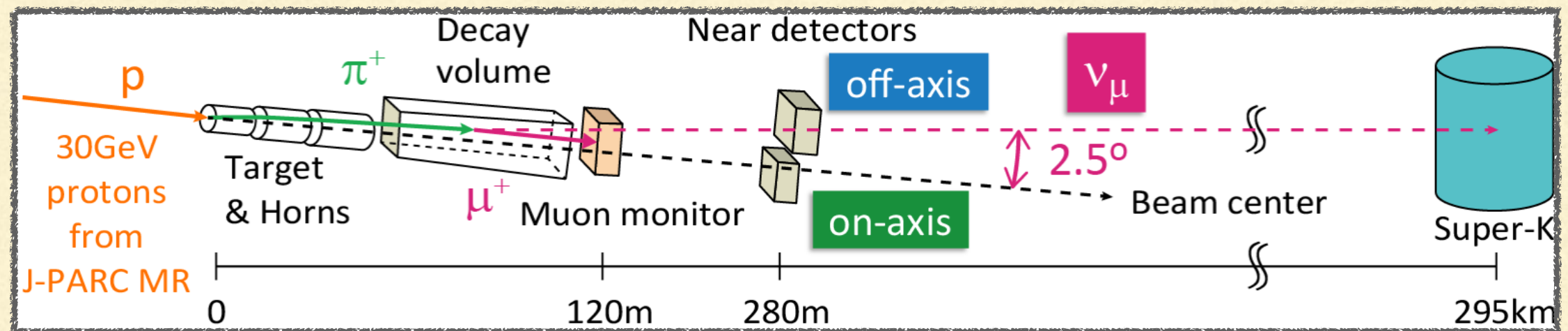
* hunting neutrinos
since 2010

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IFIC Summer School, July 2019

ACCELERATOR EXPERIMENT: DESIGN



- Near and Far detectors
- Neutrino/antineutrino beam
- **Energy adjusted to maximise oscillations (E~0.6 GeV)**
- Neutrino and antineutrino enhanced modes via horn polarity switching
- Many projects: K2K (Japan), MINOS (USA), T2K (Japan), NOVA (USA) ... Hyper-K (Japan), DUNE (USA)

$$N_{ND} \sim \Phi_{ND} \cdot \sigma_{ND} \cdot \epsilon_{ND}$$

Observable Flux Cross section Detector response

$$N_{FD} \sim \Phi_{FD} \cdot \sigma_{FD} \cdot \epsilon_{FD} \cdot P_{Osc}$$

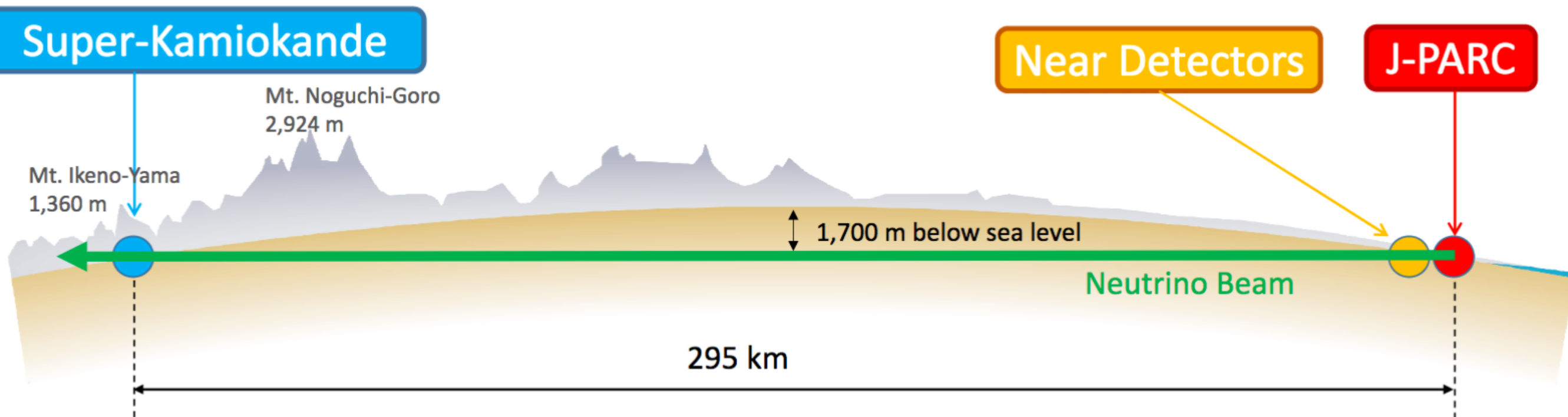
T2K NEUTRINO EXPERIMENT IN JAPAN

- Neutrino beam from Tokay to Kamioka across Japan



T2K (TOKAI-TO-KAMIOKA) EXPERIMENT

- World-leading neutrino oscillations physics project
- T2K — long-baseline neutrino oscillation accelerator experiment in Japan
- International collaboration:
 - ~500 members, 67 institutes, 12 countries



NEUTRINO OSCILLATIONS IN T2K

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23}) \sin^2 \left(\Delta m_{31}^2 \frac{L}{4E} \right)$$

“Disappearance” channel

- Precise measurement of “atmospheric” parameters θ_{23} and Δm_{32}^2 and CPT test via ν vs anti- ν analysis

From Phys. Rev. D64 (2001) 053003

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \quad \text{Leading term}$$

CP-violating “+” sign for anti- ν $-\alpha \sin \delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$

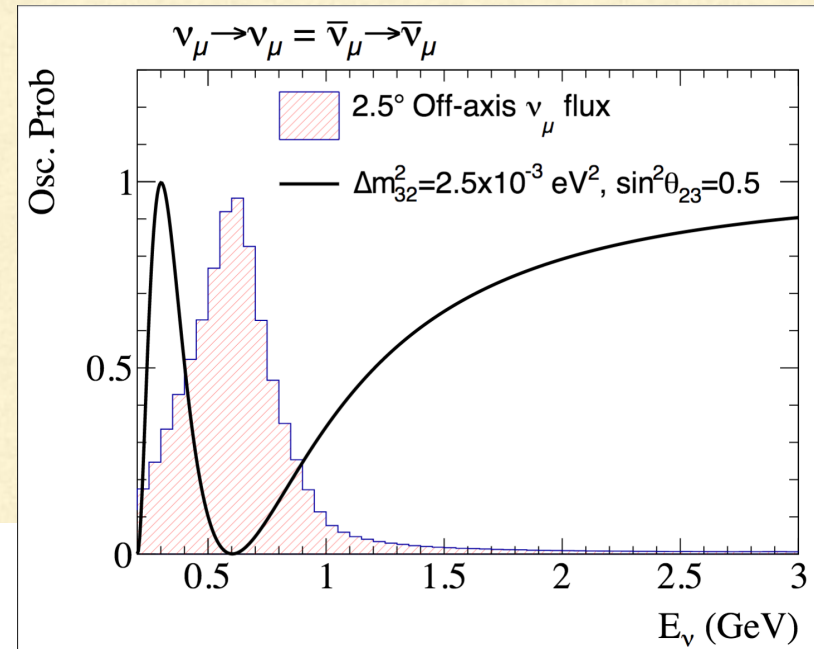
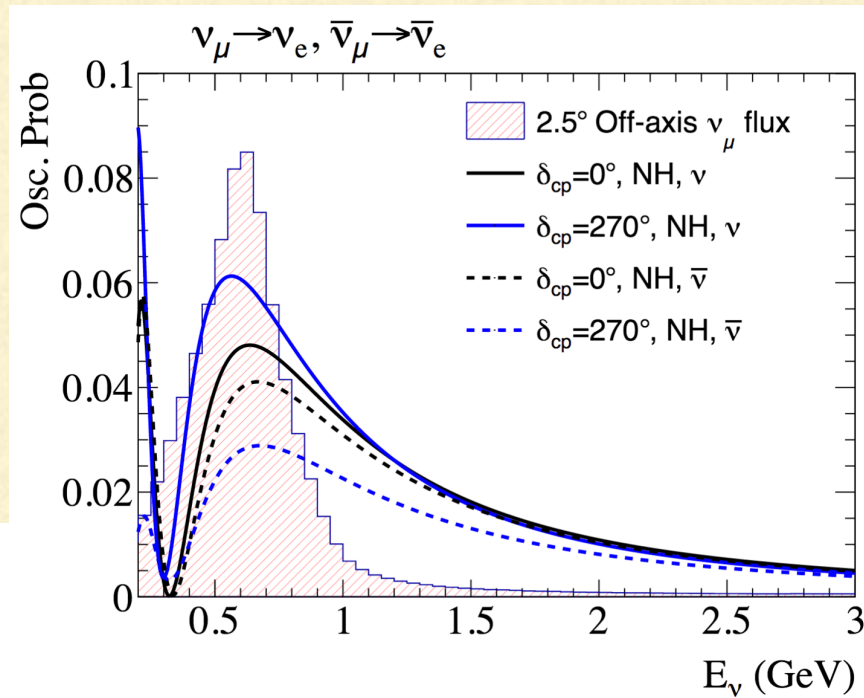
CP-conserving $+\alpha \cos \delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$

$+O(\alpha^2)$ $\alpha = \left| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right| \sim \frac{1}{30}$ $\Delta = \frac{\Delta m_{31}^2 L}{4E}$ $x = \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}$

“Appearance” channel: measuring θ_{13} and probing CP-violation (CPV)

- Leading term defines the octant of θ_{23} : $<$, $>$ or $= 45^\circ$ * T2K leading efforts
- Sub-leading term accounts for CPV: enhanced effect when comparing neutrino and antineutrino data

T2K (TOKAI-TO-KAMIOKA) EXPERIMENT



Super-Kamiokande

Near Detectors

J-PARC

Mt. Noguchi-Goro
2,924 m

Mt. Ikeno-Yama
1,360 m

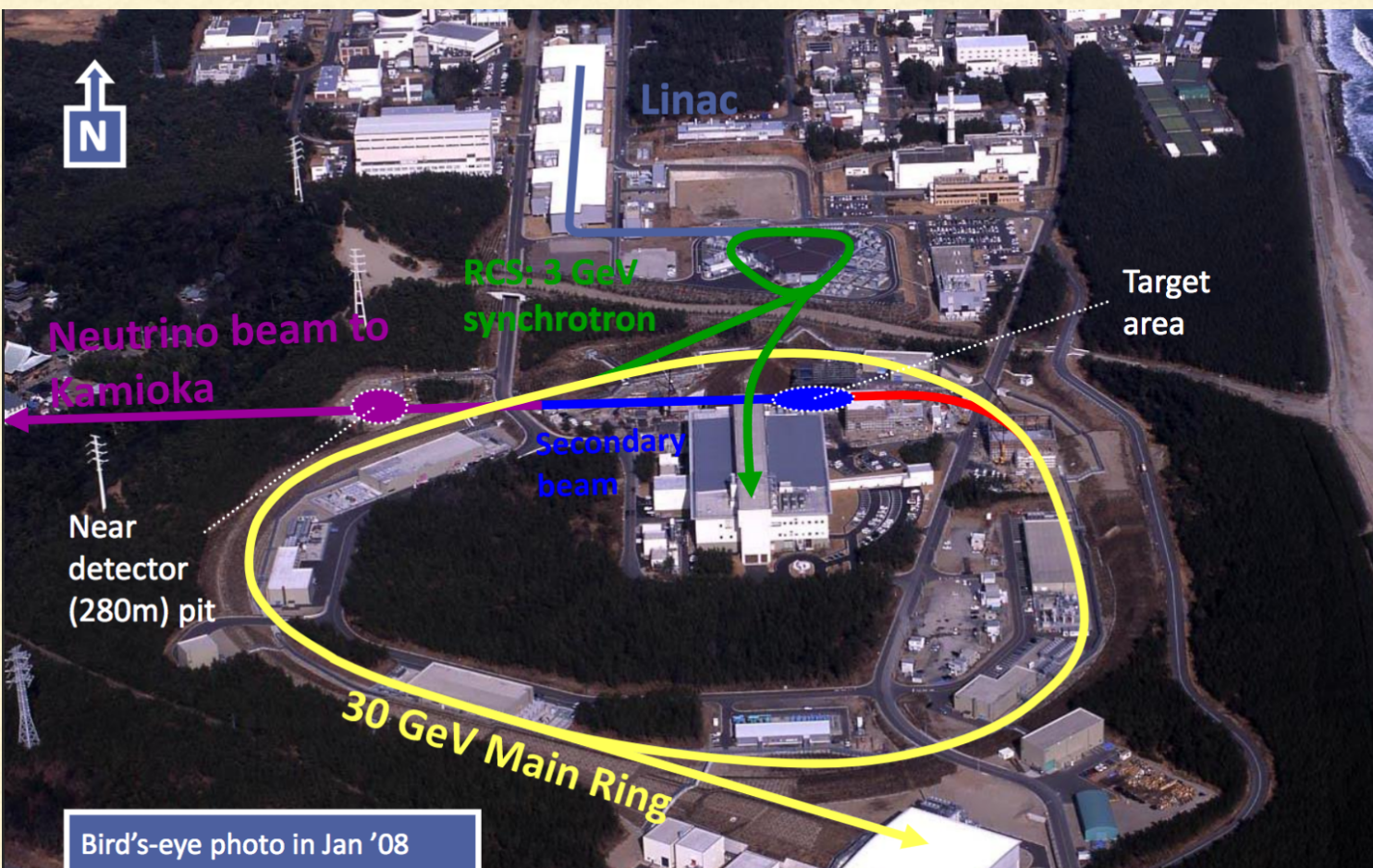
1,700 m below sea level

Neutrino Beam

295 km

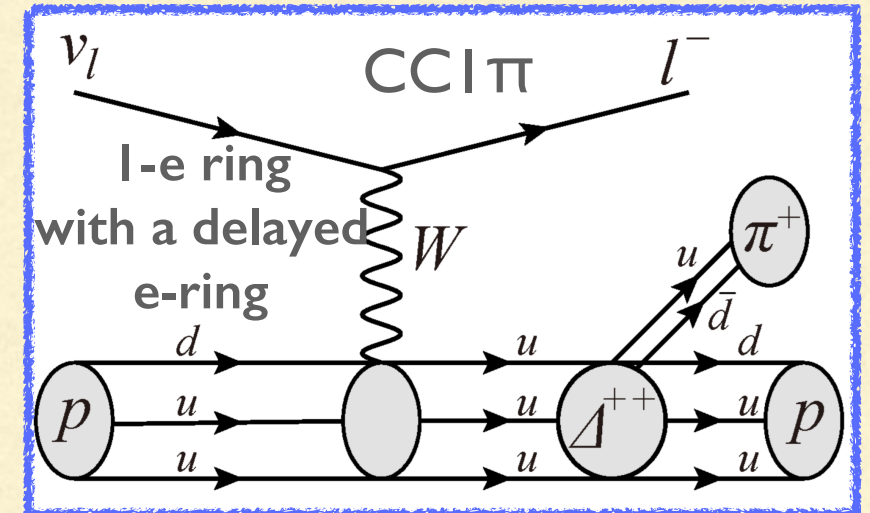
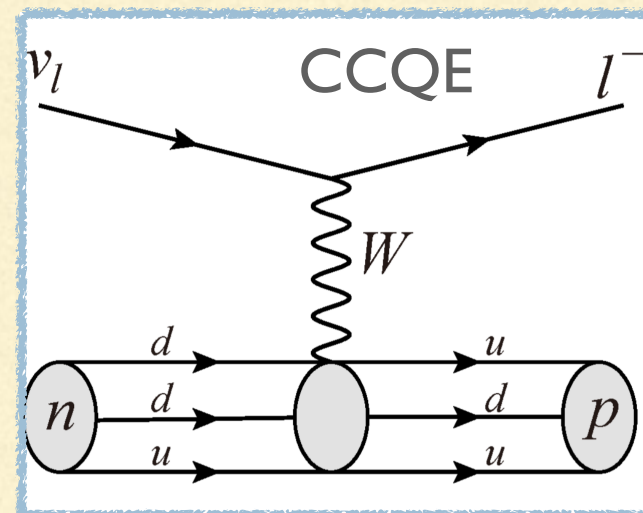
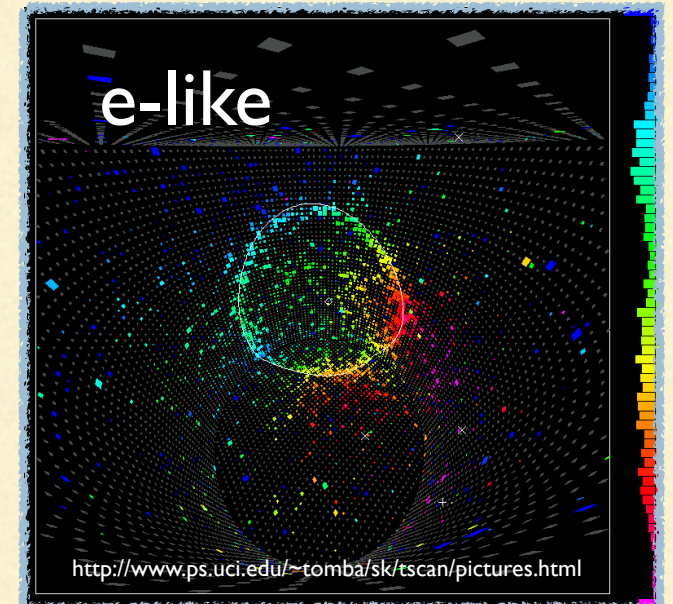
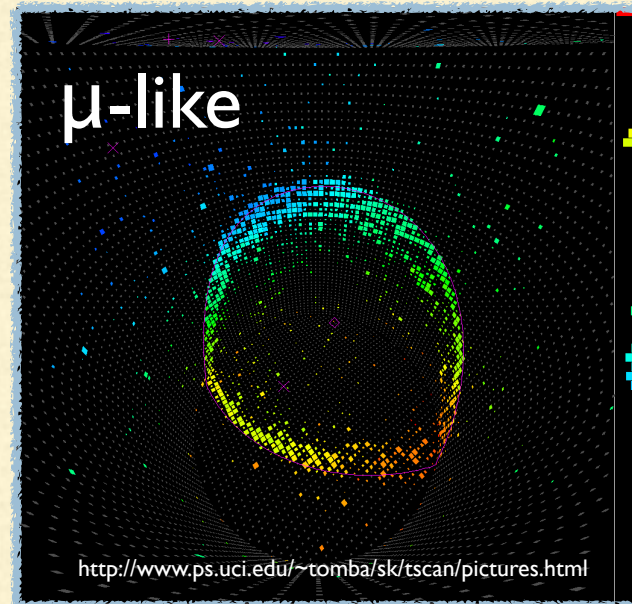
T2K (TOKAI-TO-KAMIOKA) EXPERIMENT

- Collecting data since 2010
- First discovery of $\nu_\mu \rightarrow \nu_e$ oscillations
- Hints for CP-violation in neutrino/lepton sector
- Officially attacked by Godzilla in 2000



FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

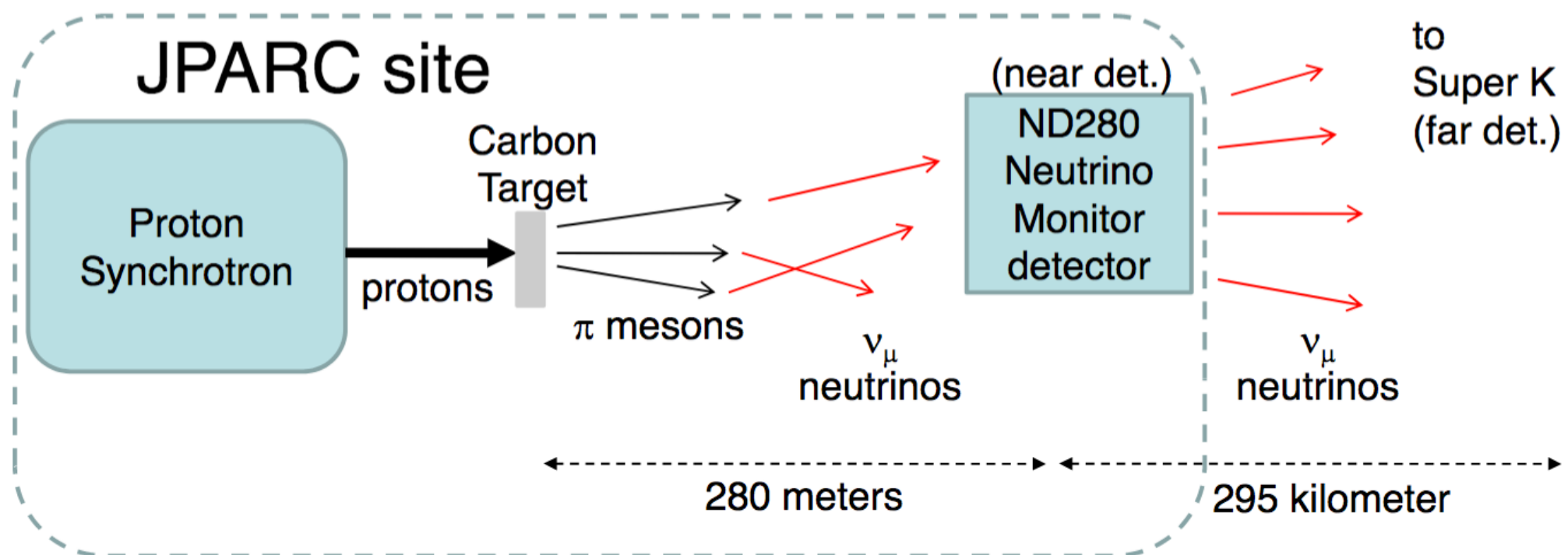
- 50 kton water-Cherenkov tank
- Separate e/ μ -like rings:
 - <1% misidentified μ as e
- π^0 rejection
- No magnetic field



- 5 Super-K samples used for analysis
- l-ring μ and e-like events in $\bar{\nu}$ and anti- $\bar{\nu}$ modes + CCI π e-like for $\bar{\nu}$ mode

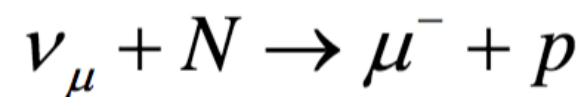
T2K NEAR DETECTOR

Simplified Schematic Diagram of the T2K Expt

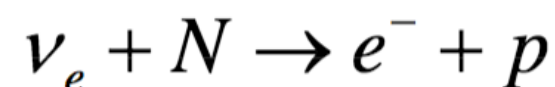


π mesons decay into neutrinos in the process; $\pi^+ \rightarrow \mu^+ + \nu_\mu$

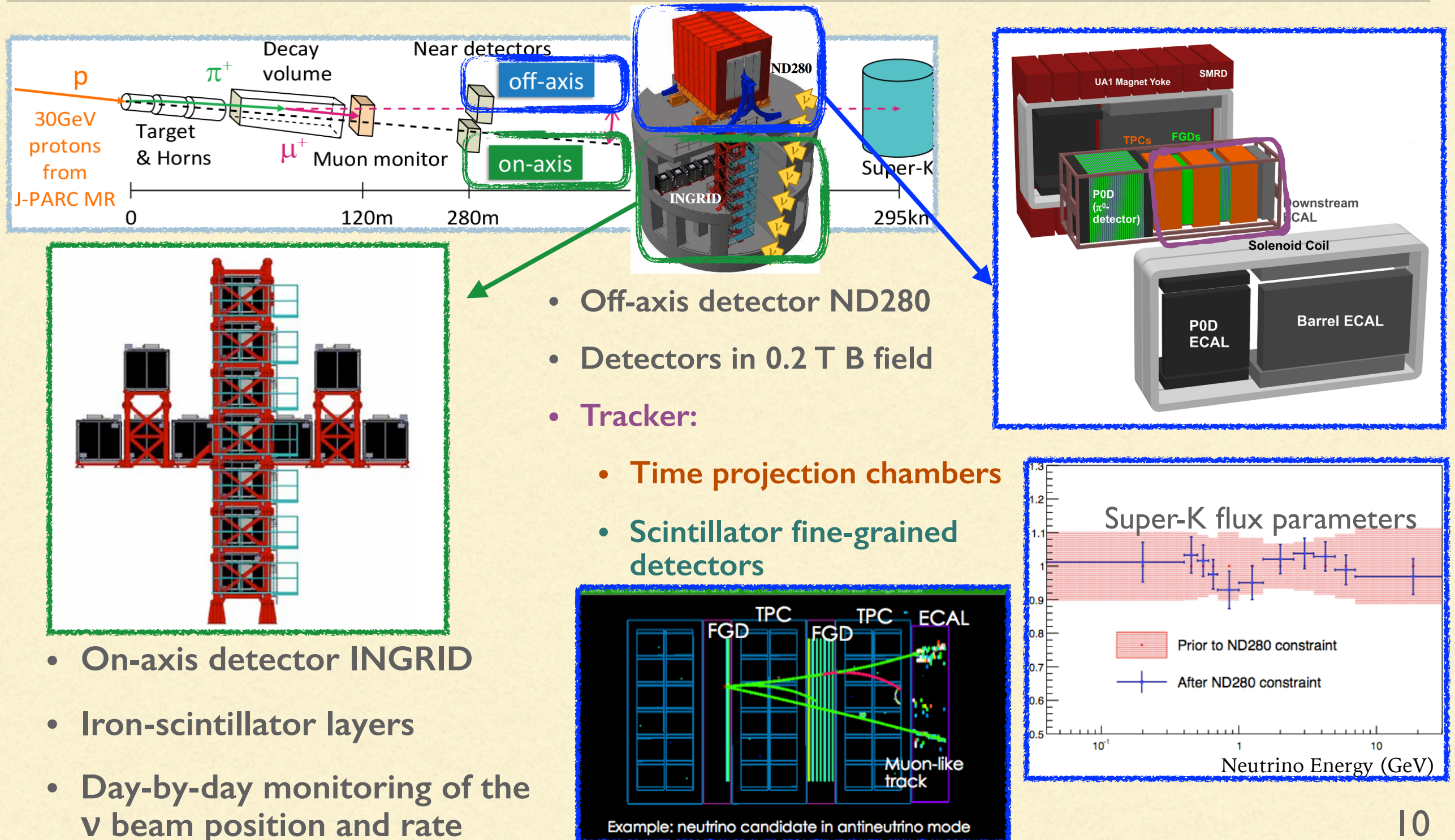
ν_μ neutrino are detected in the process ;



ν_e neutrino are detected in the process

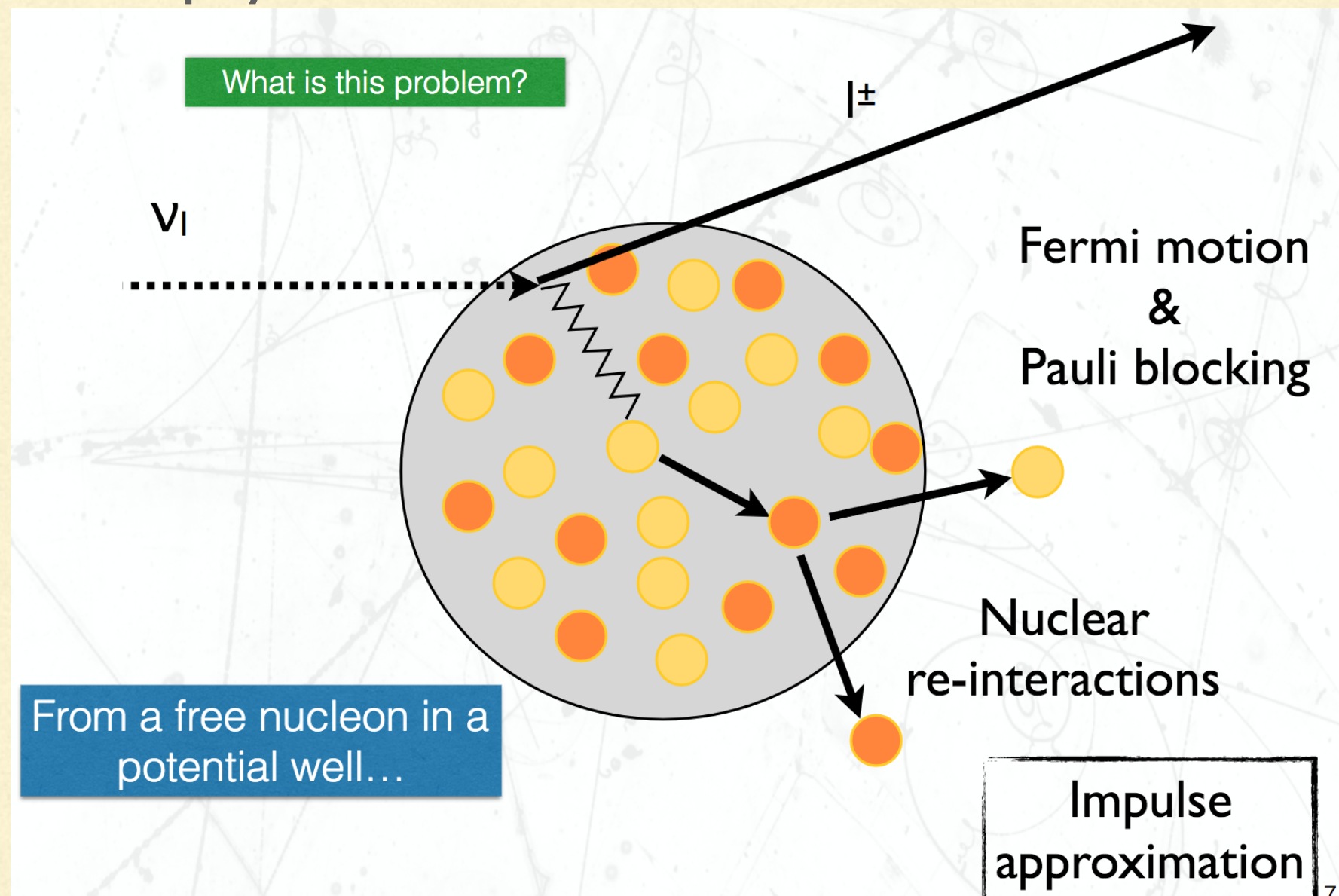


NEAR DETECTOR MEASUREMENTS



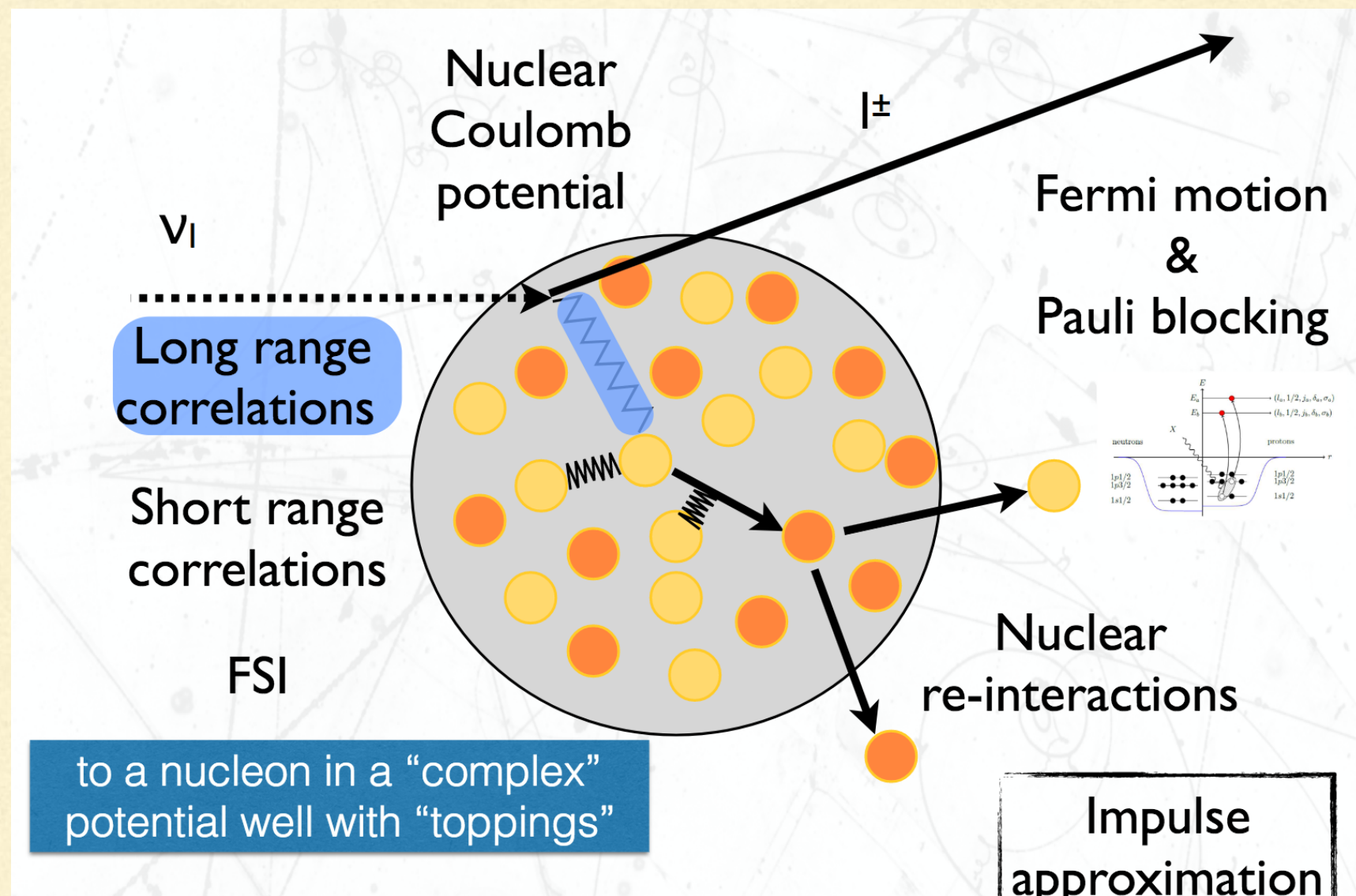
ROLE OF NEAR DETECTOR

- Neutrinos interact with nuclei!
- All nuclear physics is involved



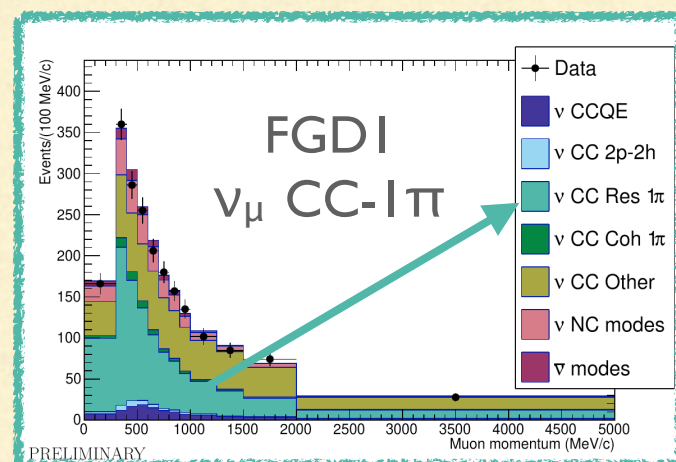
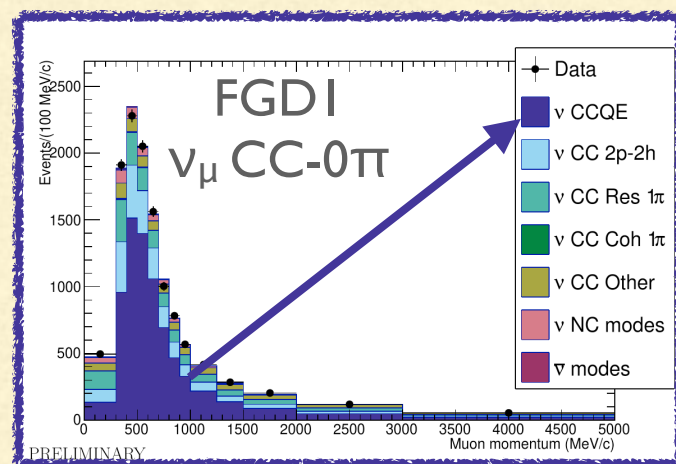
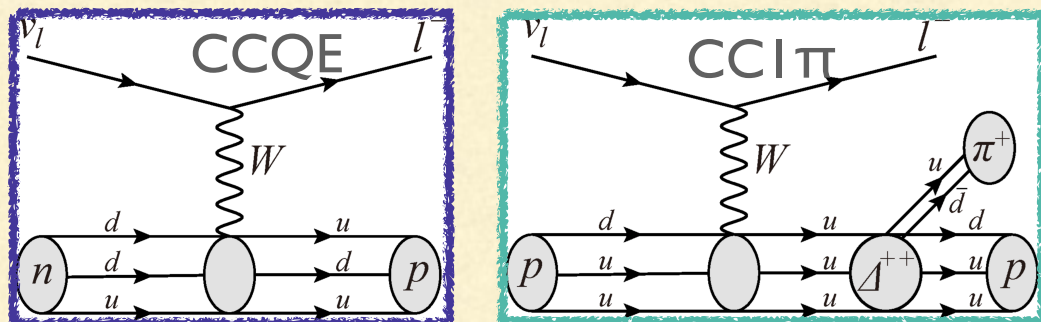
ROLE OF NEAR DETECTOR

- Neutrinos interact with nuclei!
- All nuclear physics is involved

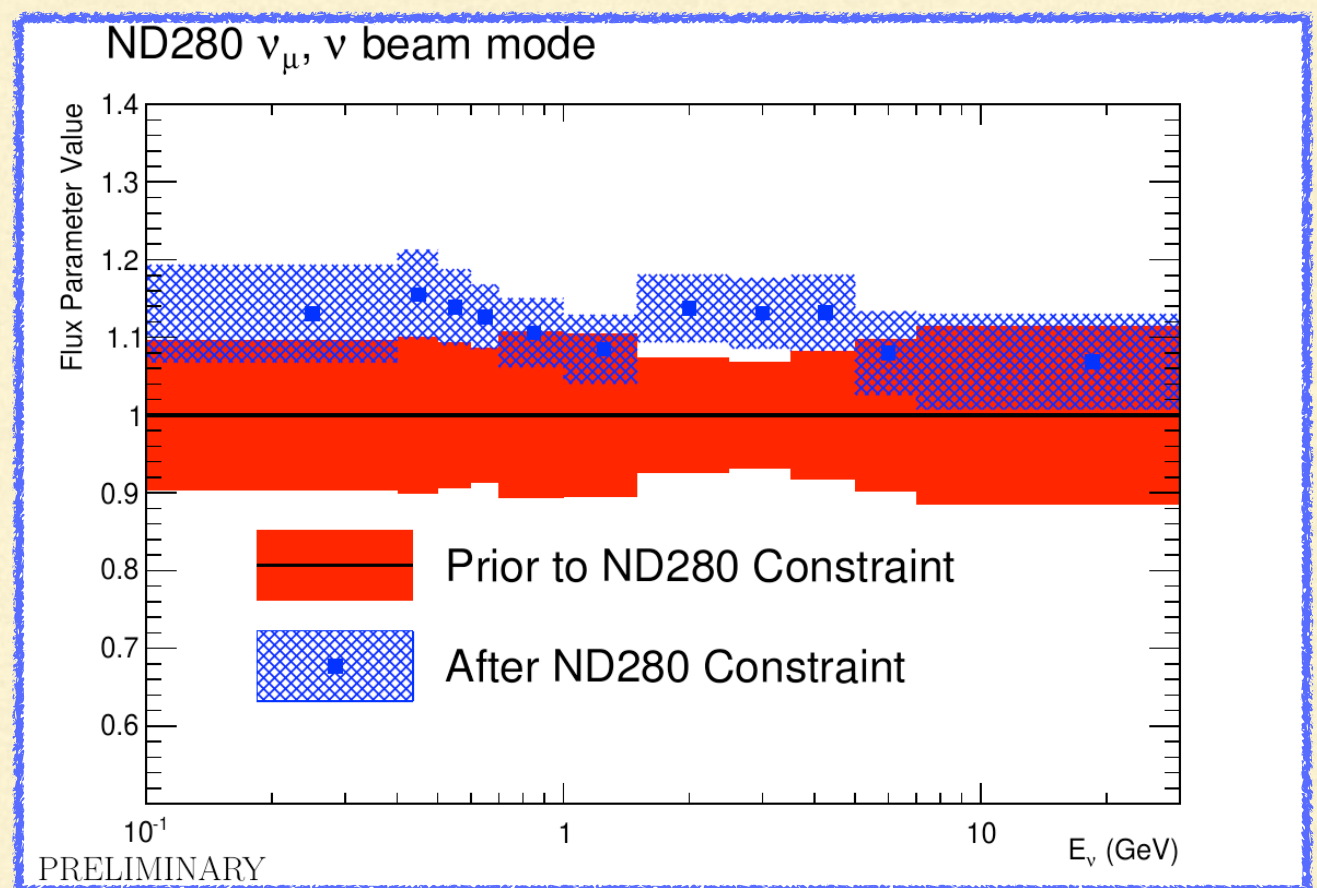


ND280 ANALYSIS

Example samples

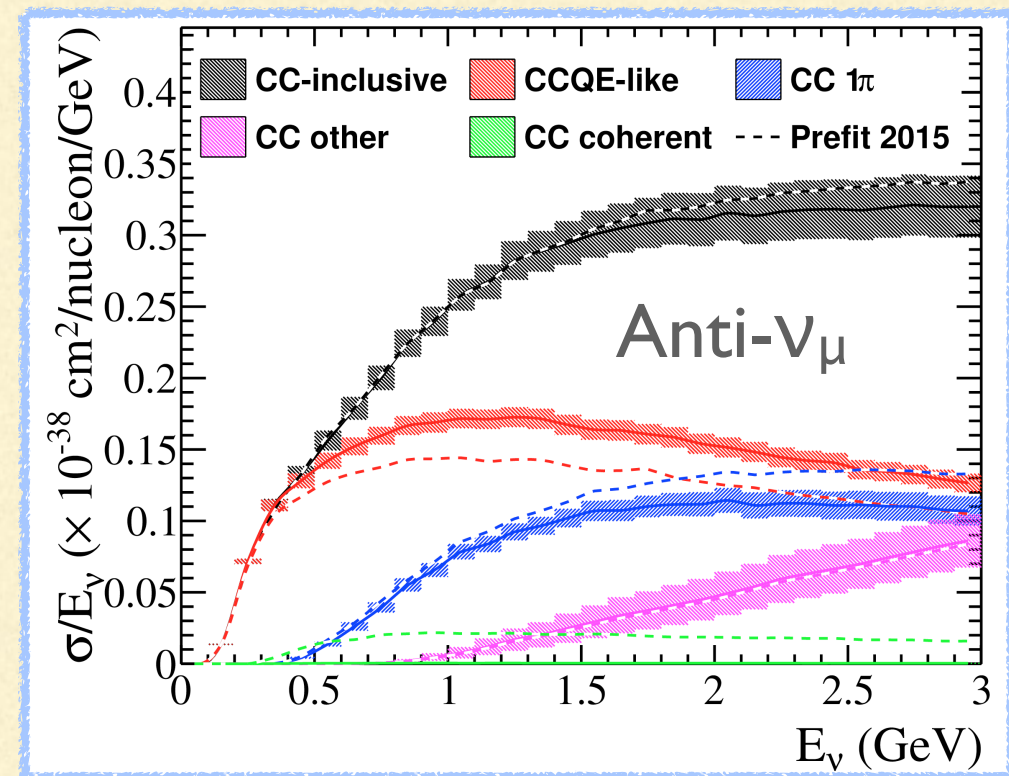
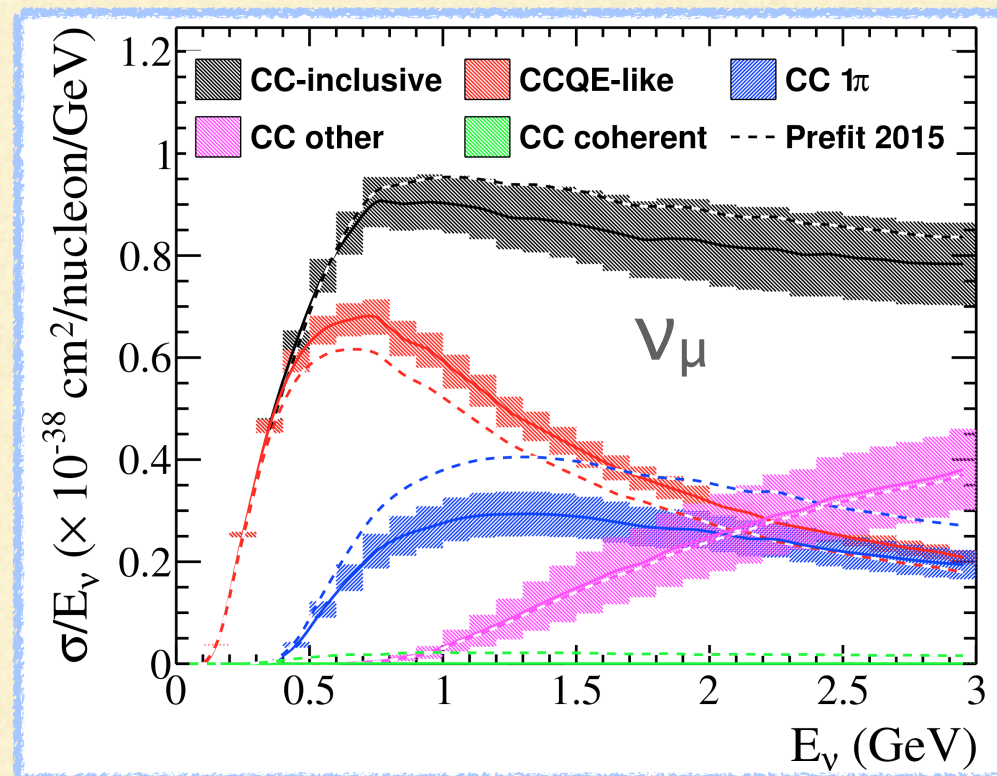


- Fit to ND280 samples constrains neutrino flux and cross-section model
- Reduce systematic uncertainty for oscillation analysis: $\approx 12\% \rightarrow \approx 6\%$
- +Many cross-section results with ND280 data



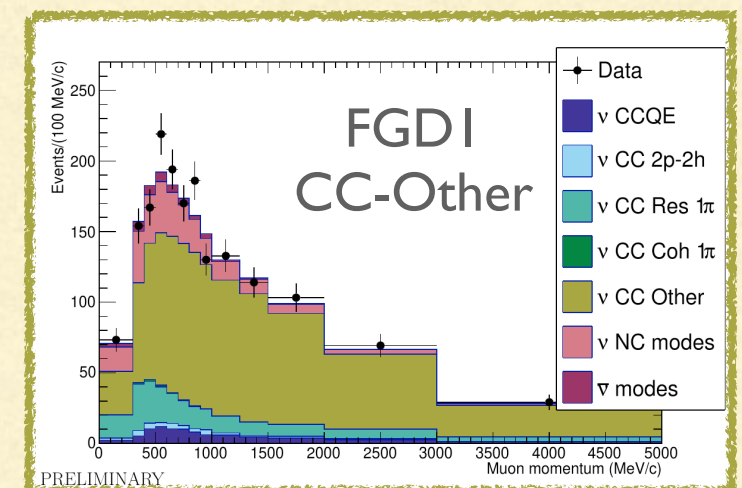
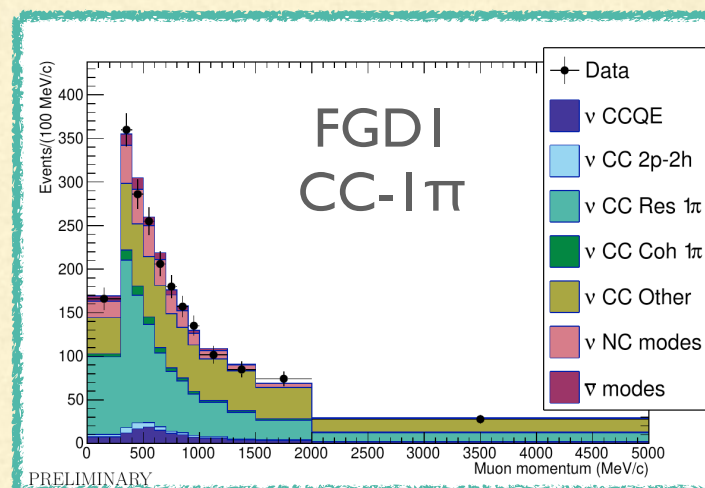
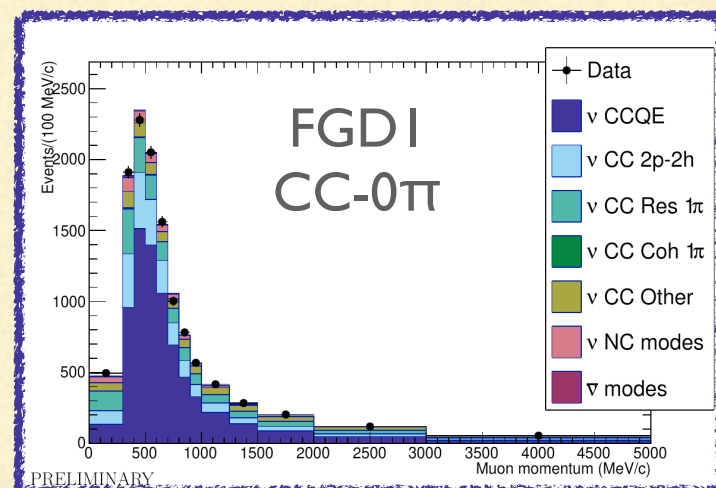
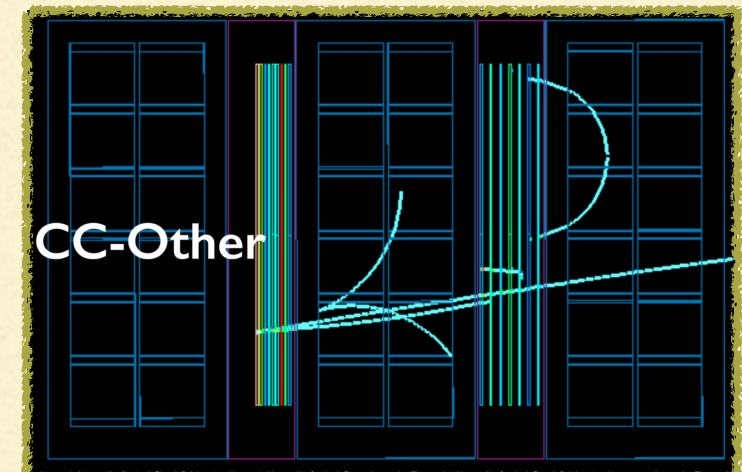
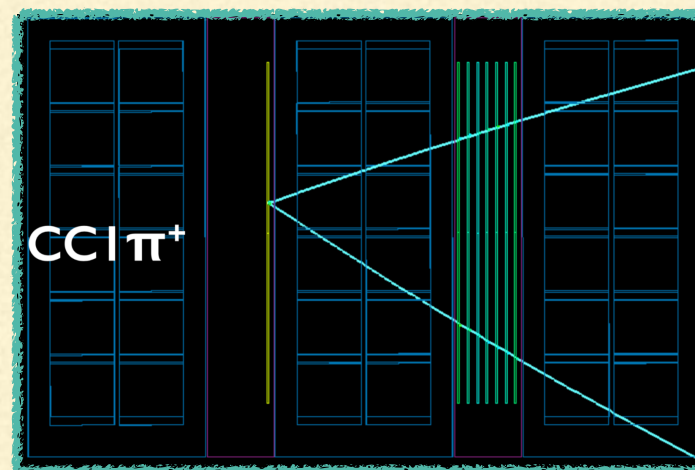
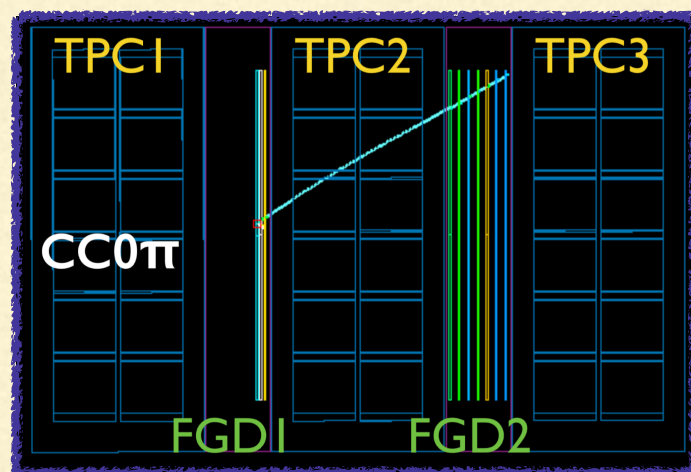
T2K NEUTRINO INTERACTIONS MODEL

- NEUT neutrino generator
- Model tuned to external data: MiniBooNE, MINERvA, bubble chambers`
- CCQE: Relativistic Fermi Gas (weighted from Spectral Function) + relativistic Random Phase Approximation for nuclear system
- Multinucleon processes (2p2h) included based on J.Nieves model, Phys. Lett. B 707, 72 (2012)
- Pre-(ND280)fit uncertainty for Super-K: $\sim 7.5\%$

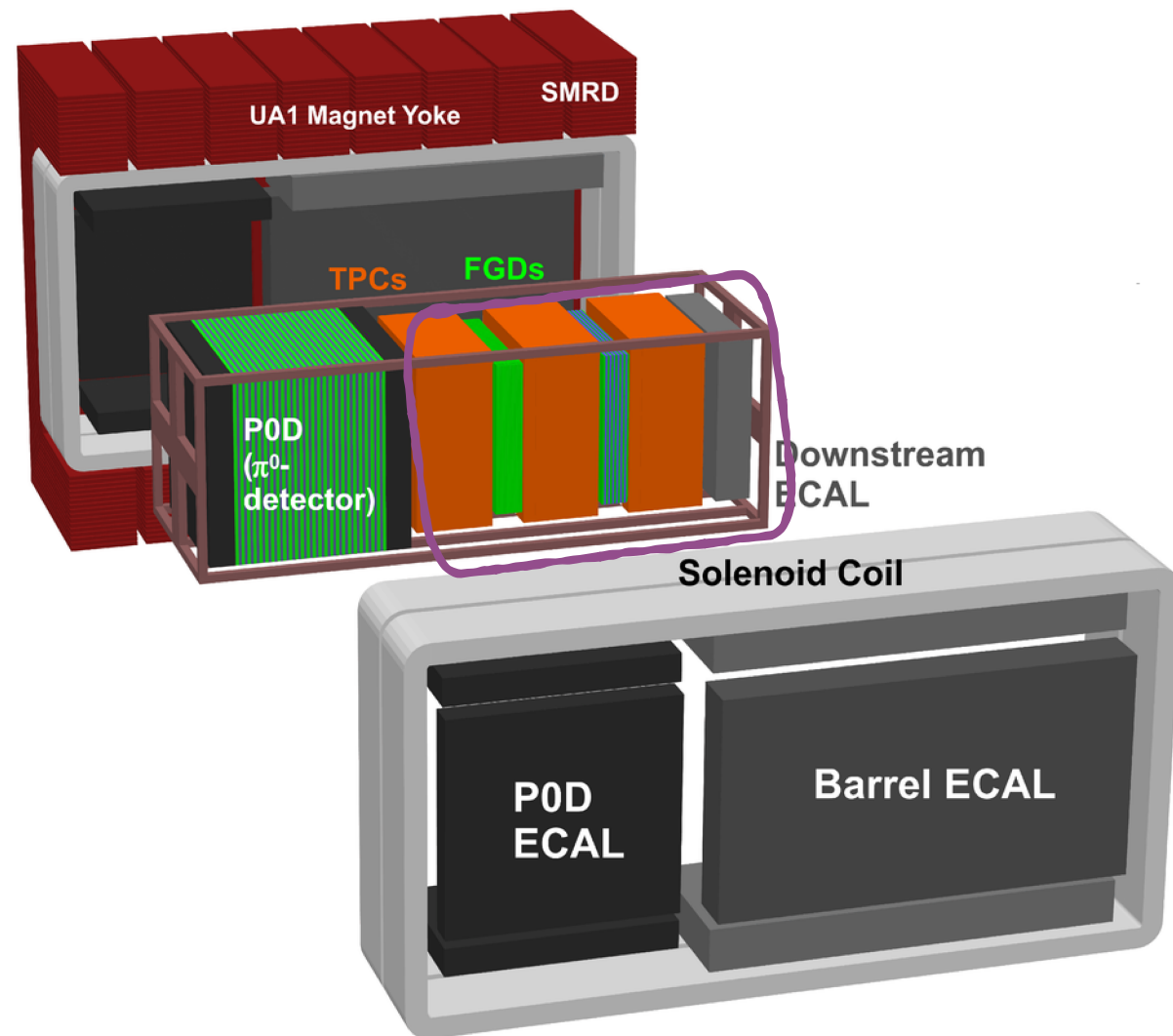


ND280 ANALYSIS

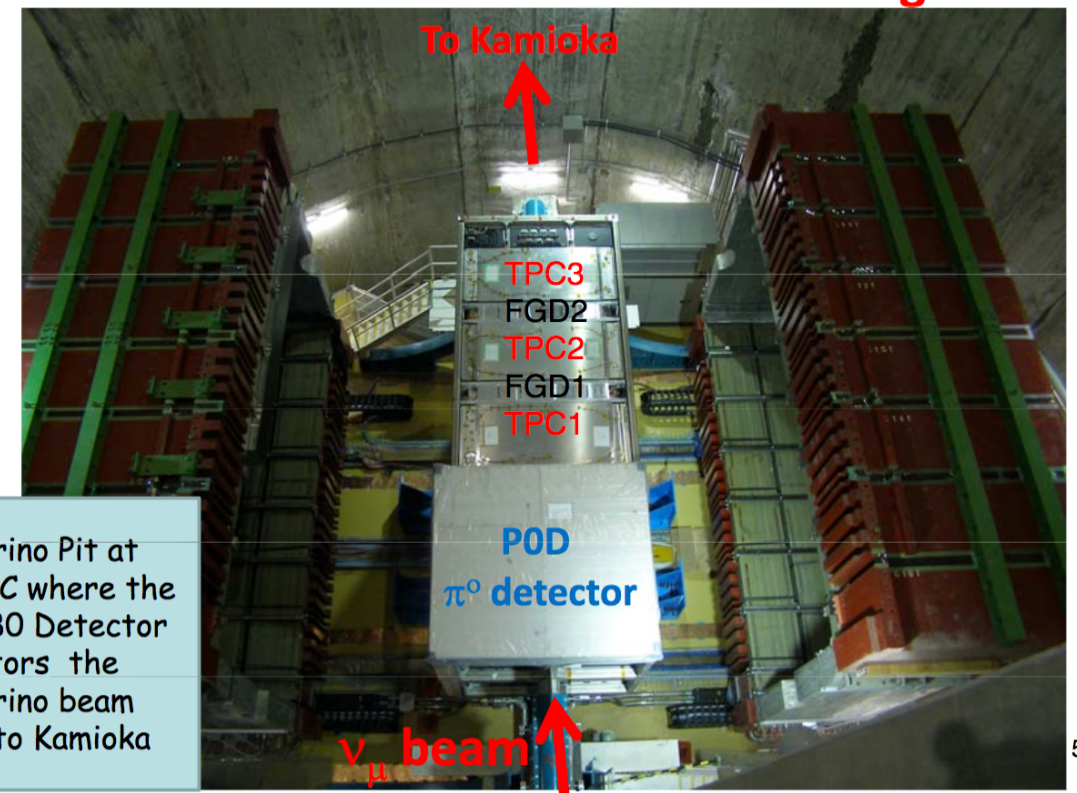
- In this course we'll get acquainted how to select signal events
- Develop our own selection of neutrino interactions in T2K ND280



T2K NEAR DETECTOR: ND280



ND280 Detector (down stream det. 280m) at JPARC in front of the neutrino beam target



Neutrino Pit at JPARC where the ND280 Detector Monitors the Neutrino beam sent to Kamioka

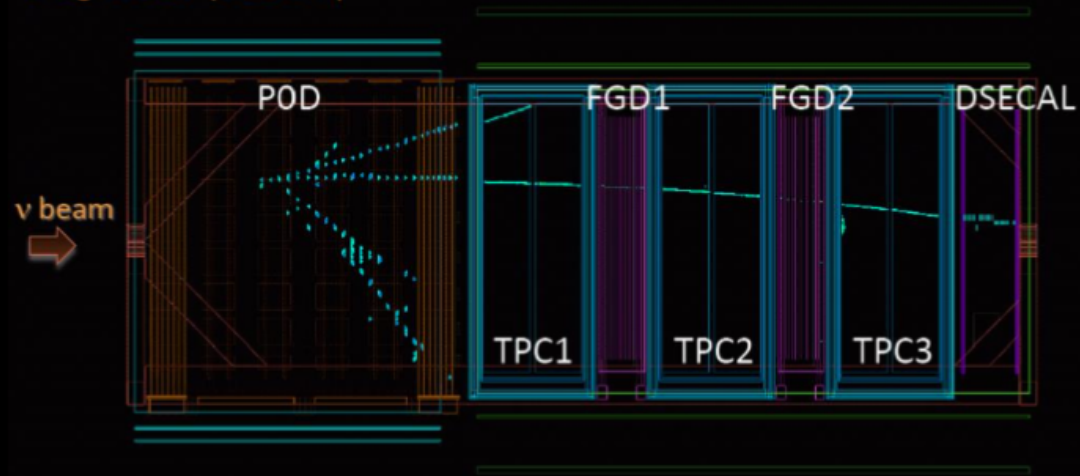
5

T2K NEAR DETECTOR

Event number : 1609 / Partition : 63 / Run number : 2553 / Spill : 7205 / SubRun number : [INVALID] / Time : Fri 2010-02-05 01:57:45 JST

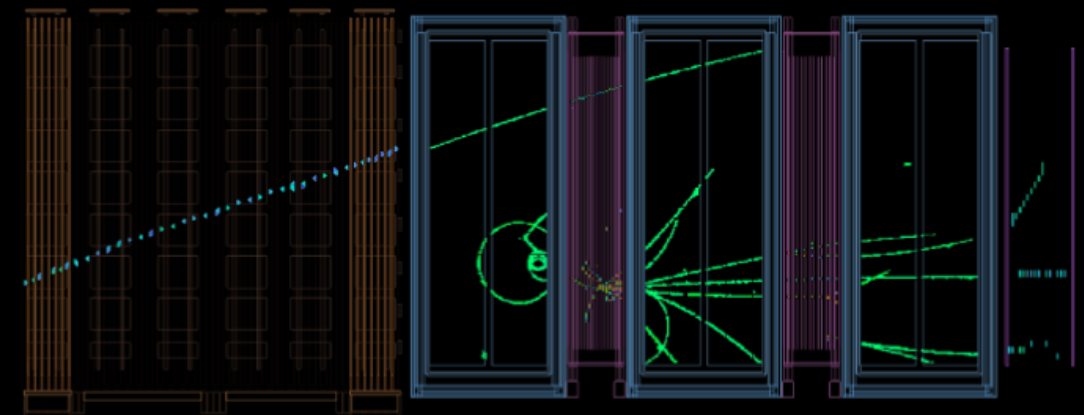
Magnet on (0.188 T)

01:57 JST, Feb. 5, 2010



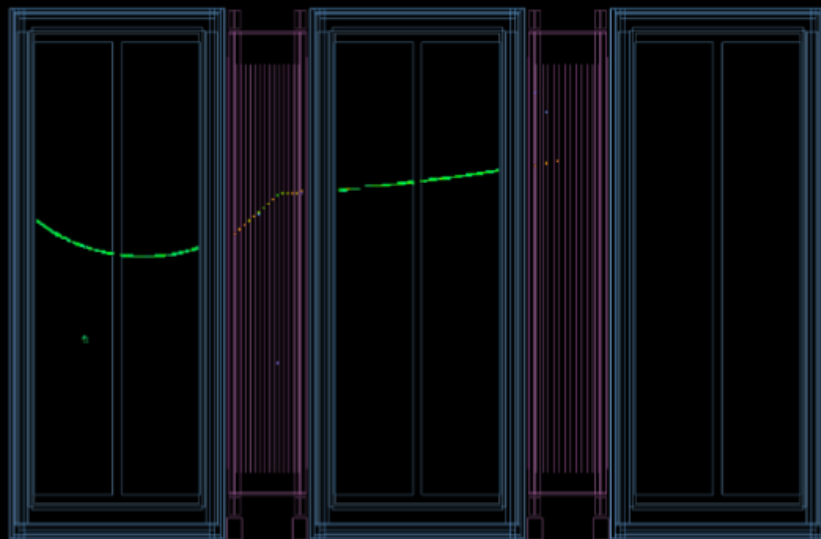
Interaction in POD: View from (north) side

Event number : 19211 / Partition : 63 / Run number : 4200 / Spill : 0 / SubRun number : 30 / Time : Mon 2010-03-22 15:10:44 JST / Trigger : Beam Spill



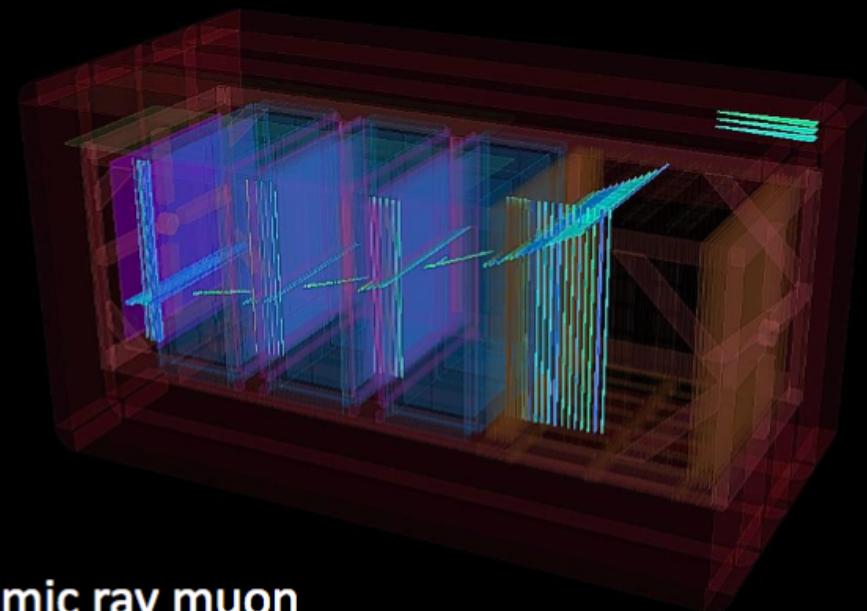
Sand Muon & FGD interaction

Event number : 16215 / Partition : 63 / Run number : 4200 / Spill : 0 / SubRun number : 15 / Time : Mon 2010-03-22 01:04:20 JST / Trigger : Beam Spill



FGD interaction with backward track

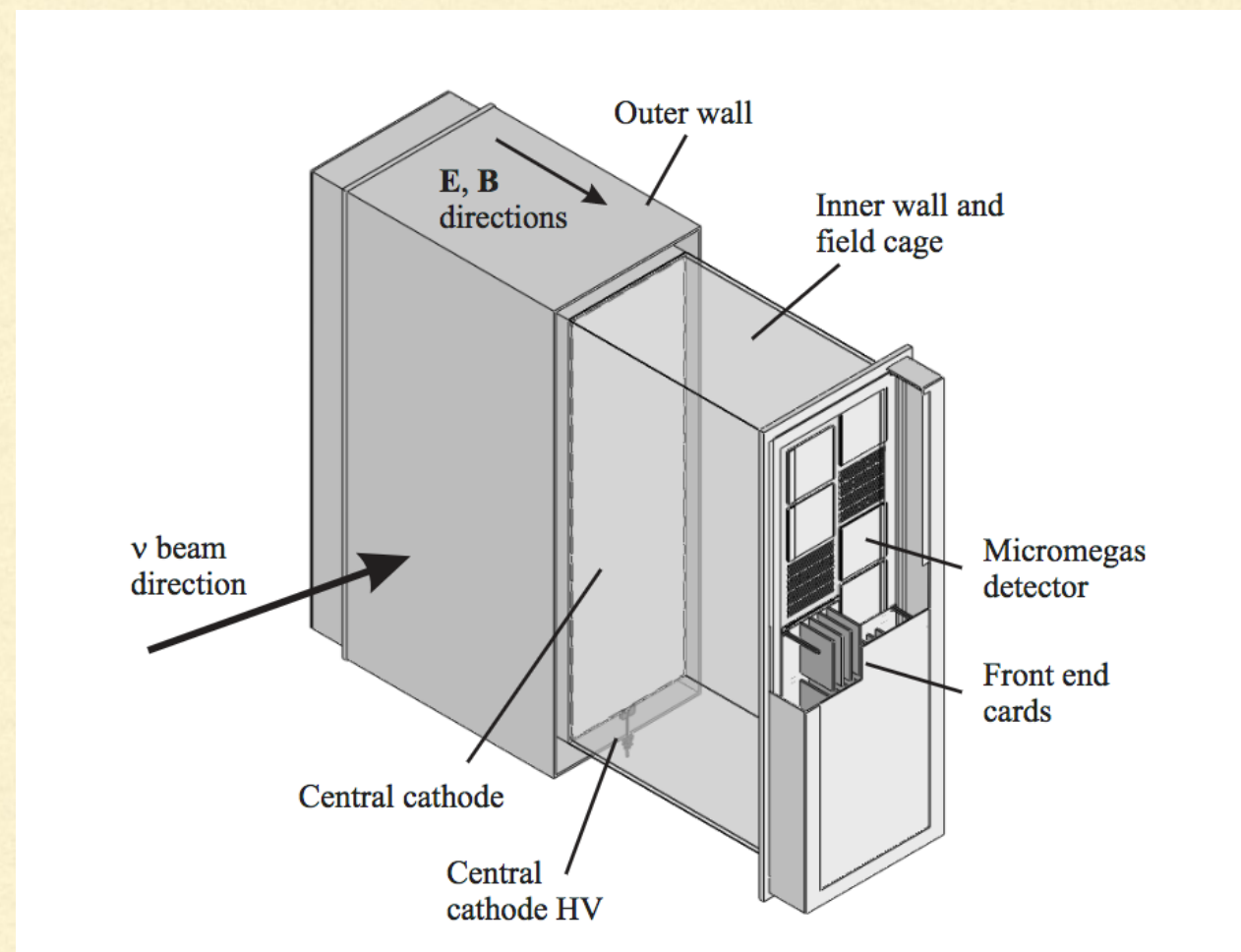
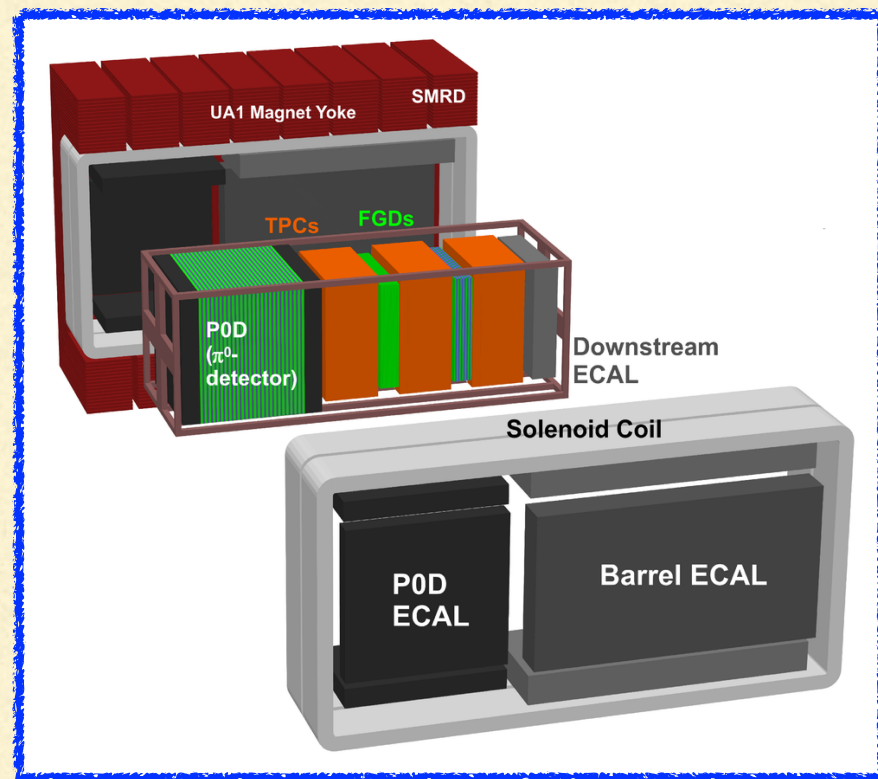
Event number : 7 / Partition : 63 / Run number : 2536 / Spill : 0 / SubRun number : 0 / Time : Wed 2010-02-24 15:47:58 JST / Trigger : TFB Cosmic



Cosmic ray muon

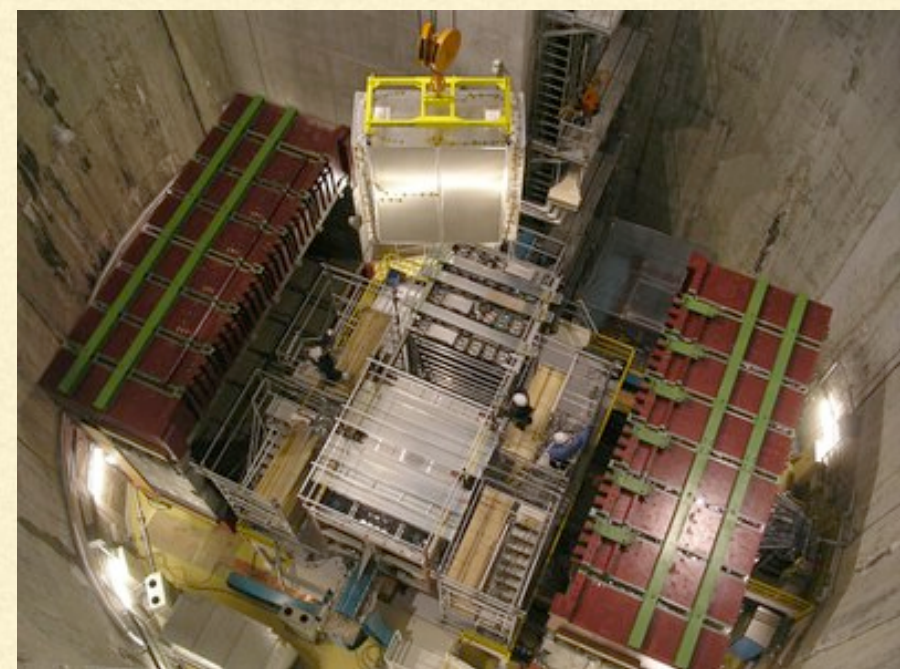
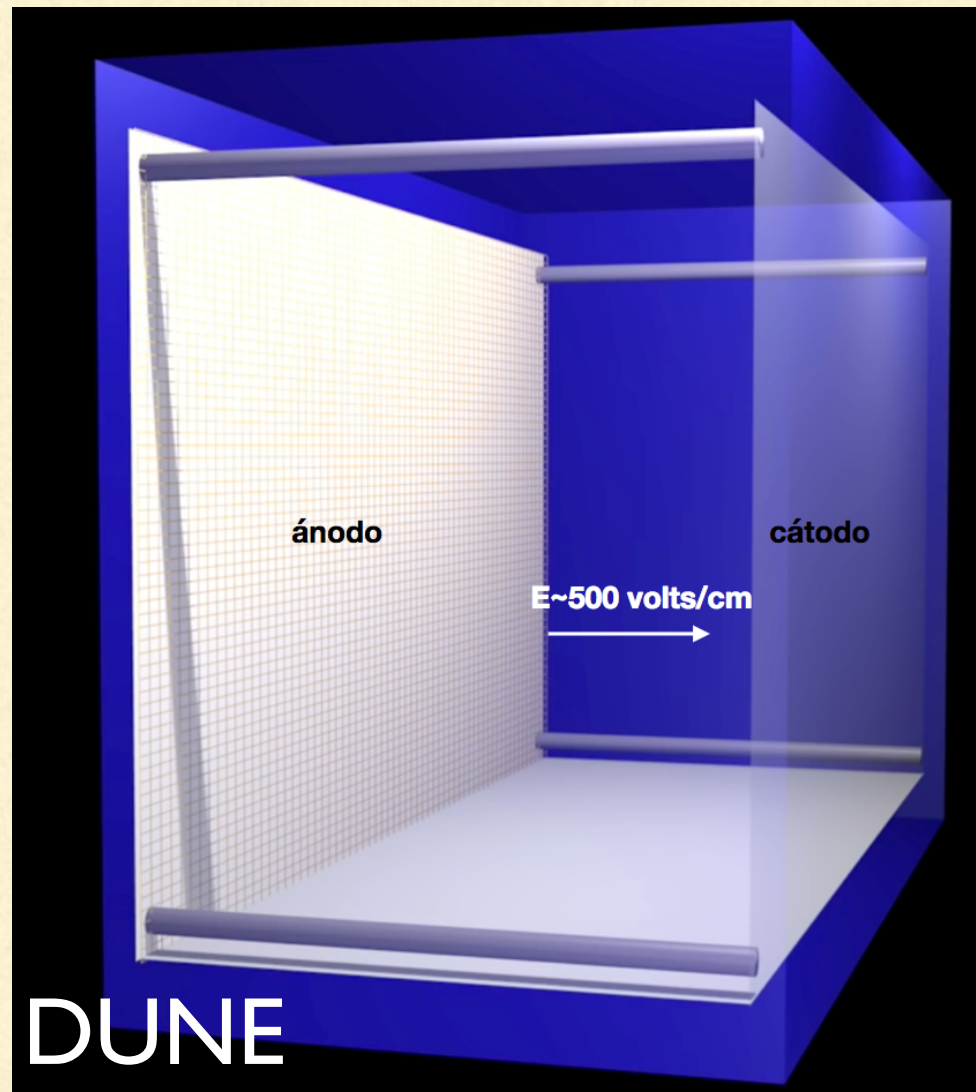
ND280 ANALYSIS

- At T2K energies the dominant processes are so-called quasi-elastic interactions: $\nu + N \rightarrow N' + \text{lepton}$
- We want to reconstruct kinematics of interactions: momentum, direction etc
- TPC is a key element!



ND280 TPC

- Argon filled → similar to DUNE - but gaseous argon
- B-field → can measure momentum and charge of particles



ND280 TPC

- Argon filled → similar to DUNE - but gaseous argon
- But we want also to know a type of the particle: electron, proton, muon ?
 - Energy deposit!
 - When particle passes through media it loses energy

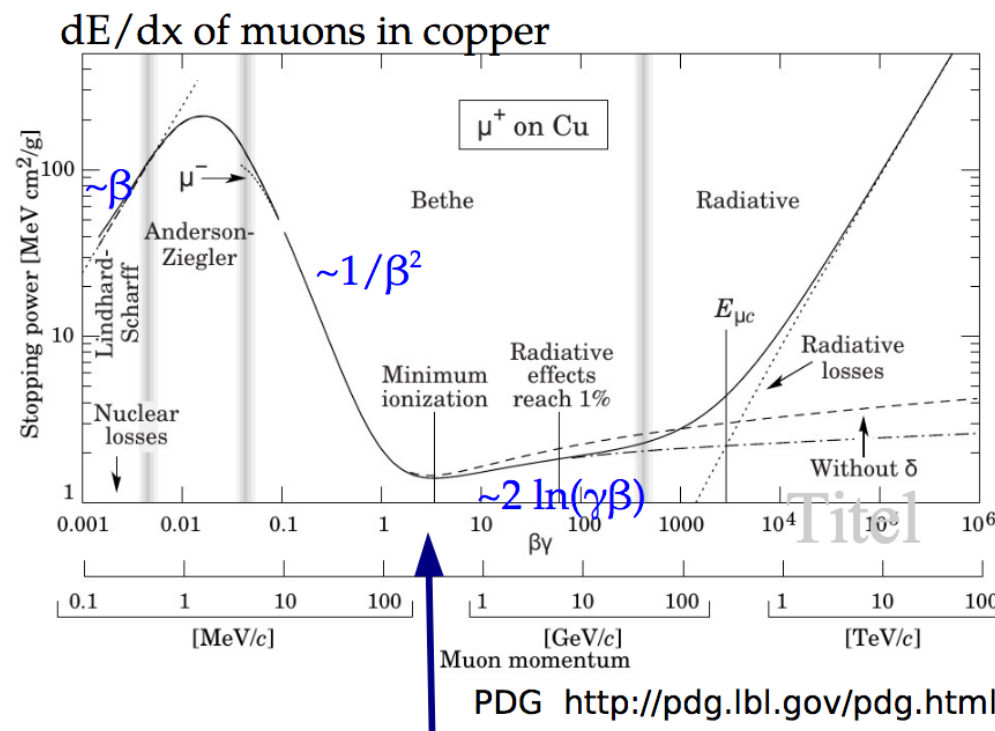
full quantum mechanical derivation: Bethe-Bloch Formula

$$\frac{-dE}{dX} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} \right]$$

$$K = \frac{4\pi e^4}{c^2 m_e} N_A = 0.31 \text{ MeV cm}^2/\text{g}$$

ND280 TPC

- When particle passes through media it loses energy
- And the energy loss dE/dX depends on its velocity
- Hence for the same momentum the energy loss can help to identify the mass $\rightarrow$ particle type

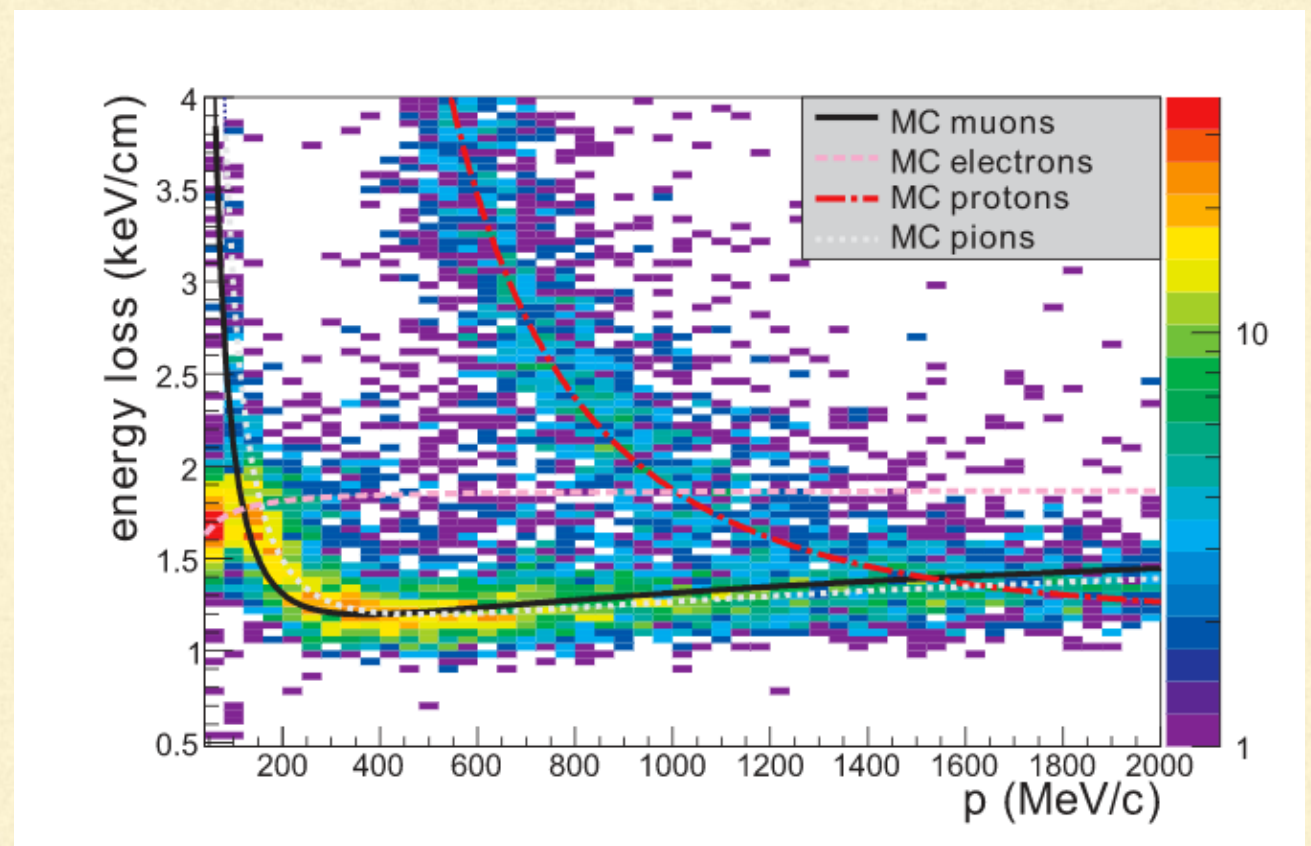
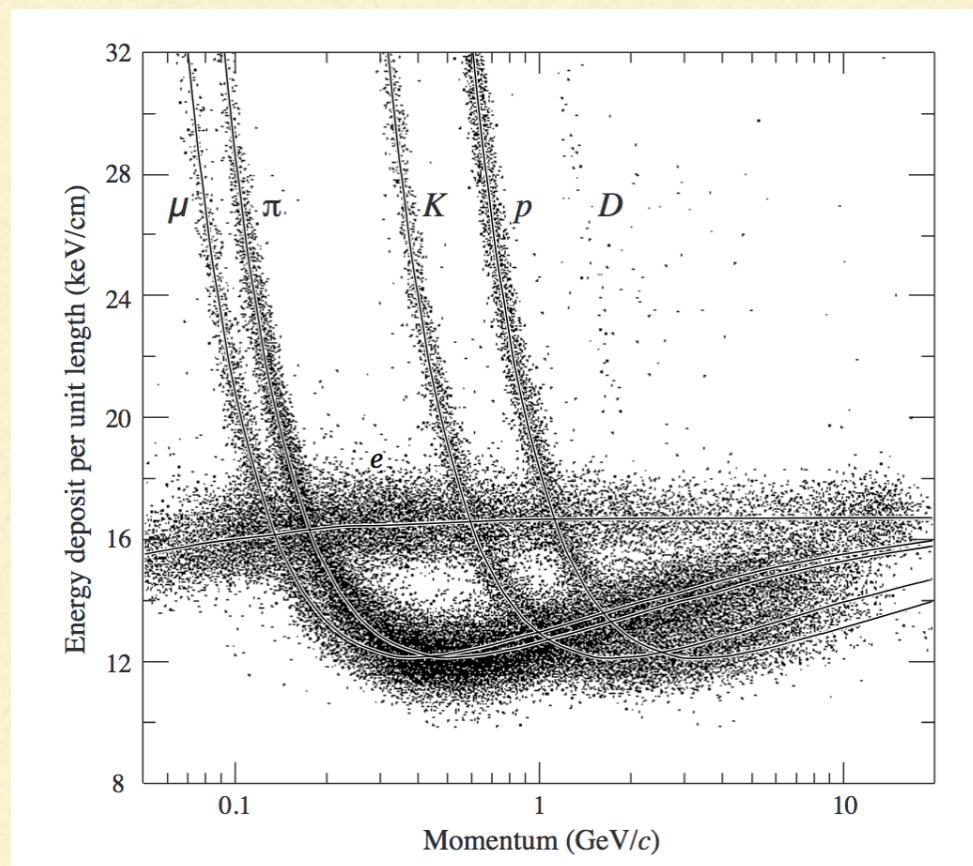


- $\beta\gamma < 3$ $dE/dX \propto 1/\beta^2$
- $\beta\gamma \approx 3.5$ minimum
 $dE/dX \approx 1-1.7 \text{ MeV cm}^2/\text{g}$
- $\beta\gamma > 3.5$ logarithmic rise
 $dE/dX \approx 2 \text{ MeV cm}^2/\text{g}$
- $\beta\gamma > 1000$ Bremsstrahlung dominant
- very low energy: BB not valid, empirical models
- low energies: shell corrections
- high energies: density corr.

Minimum: $\beta\gamma$ 3-4 minimum ionising particle (MIP)
loses $\sim 1-1.7 \text{ MeV}/(\text{g}/\text{cm}^2)$

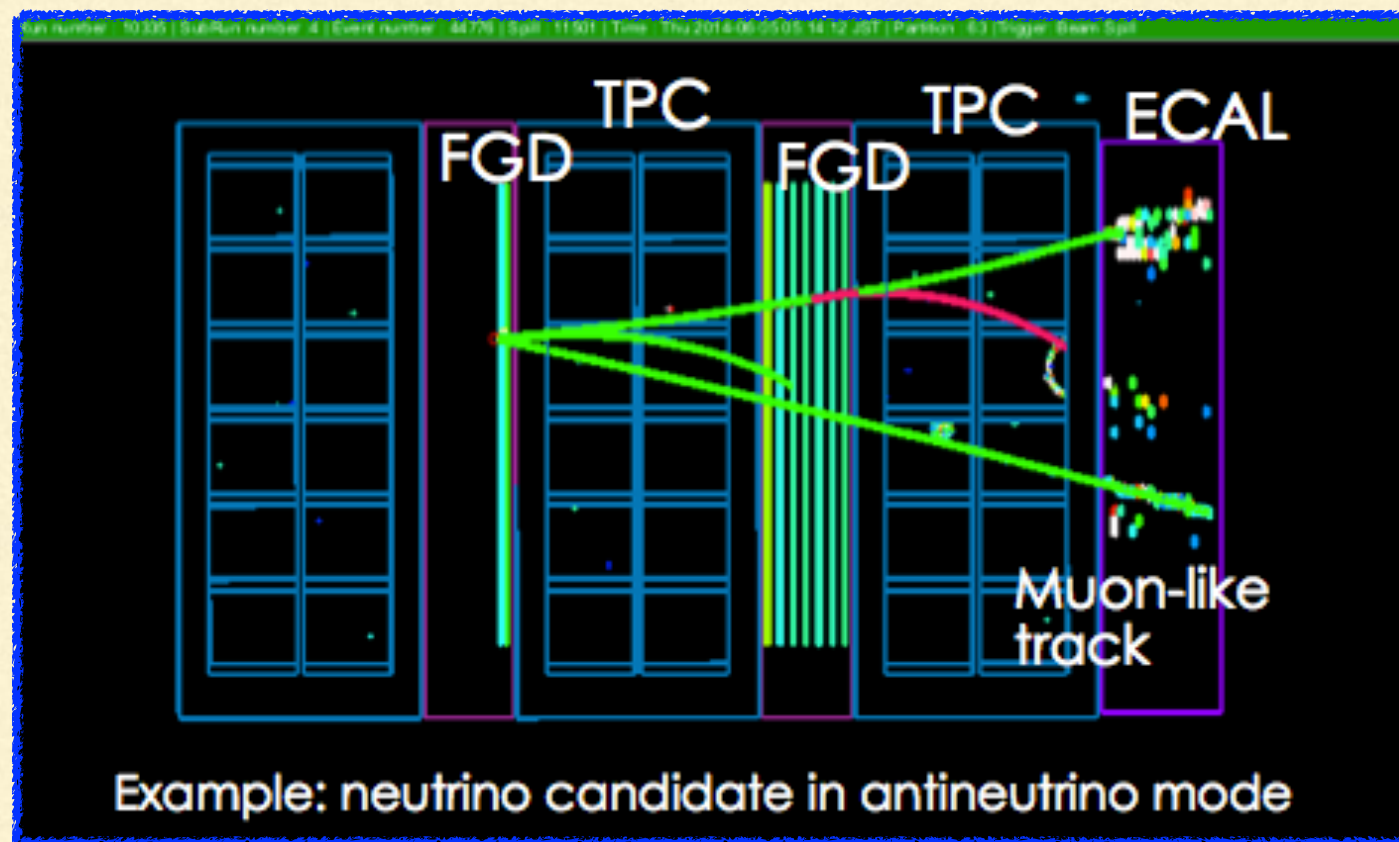
ND280 TPC

- And the energy loss dE/dX depends on its velocity
- Hence for the same momentum the energy loss can help to identify the mass $\rightarrow$ particle type
- Energy loss in TPC!



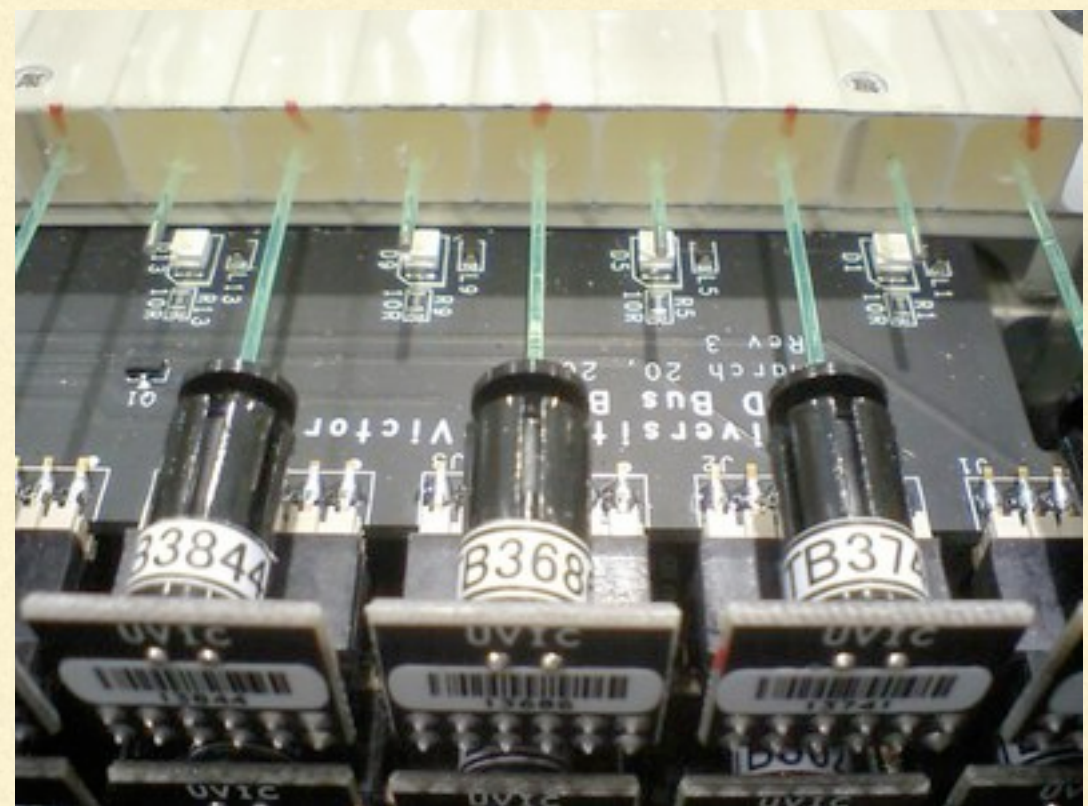
ND280 FGD

- TPCs are good to measure kinematics
- But neutrinos need a mass to interact
- In DUNE TPCs are heavy but in T2K not
 - Need other detectors as targets



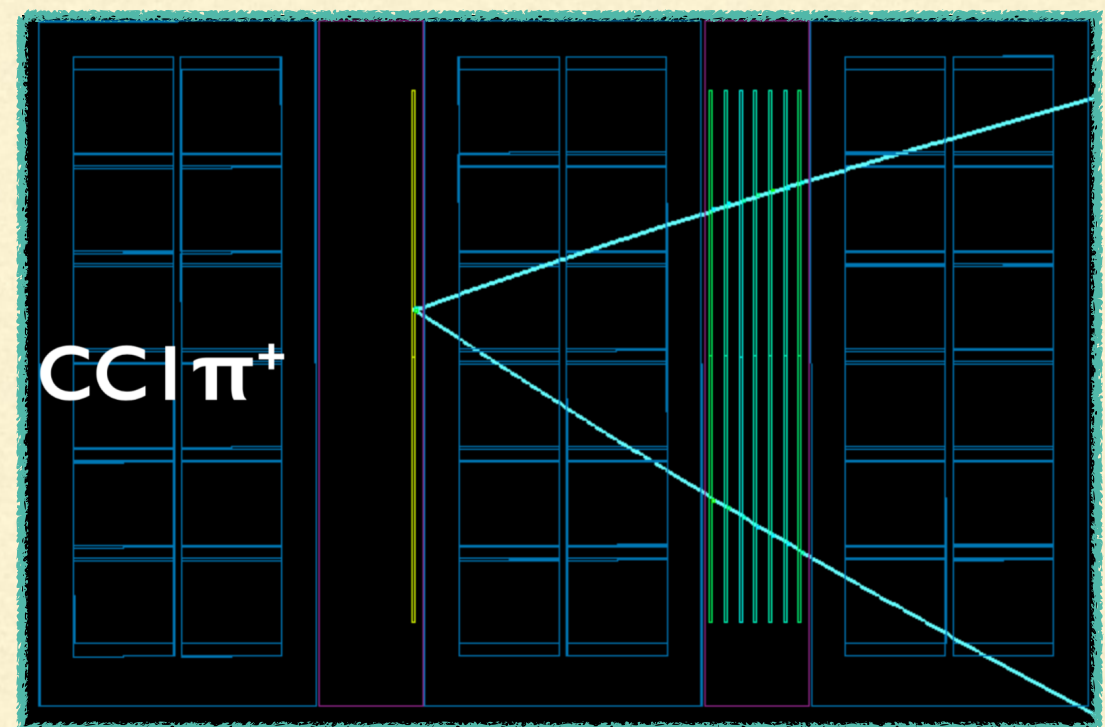
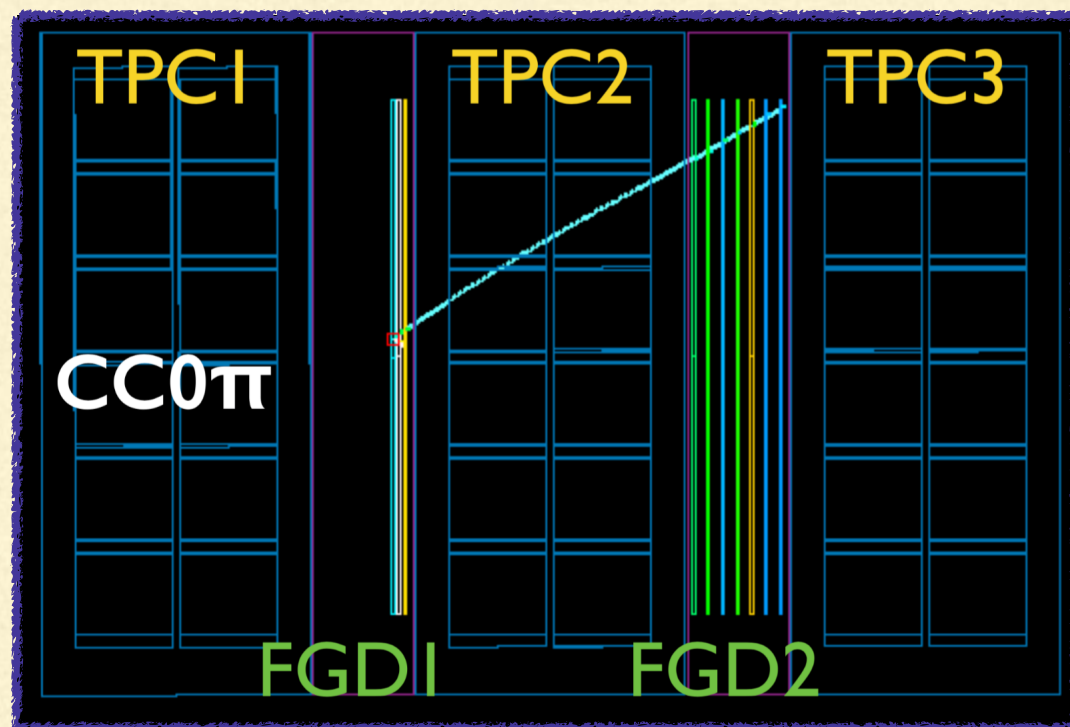
ND280 FGD

- Made out of plastic scintillator bars ~1 cm thick
- Particle crosses a bar → bar emits light → light is collected by WLS fibers → light reaches photon detectors → signal: a bar was fired by a crossing particle!



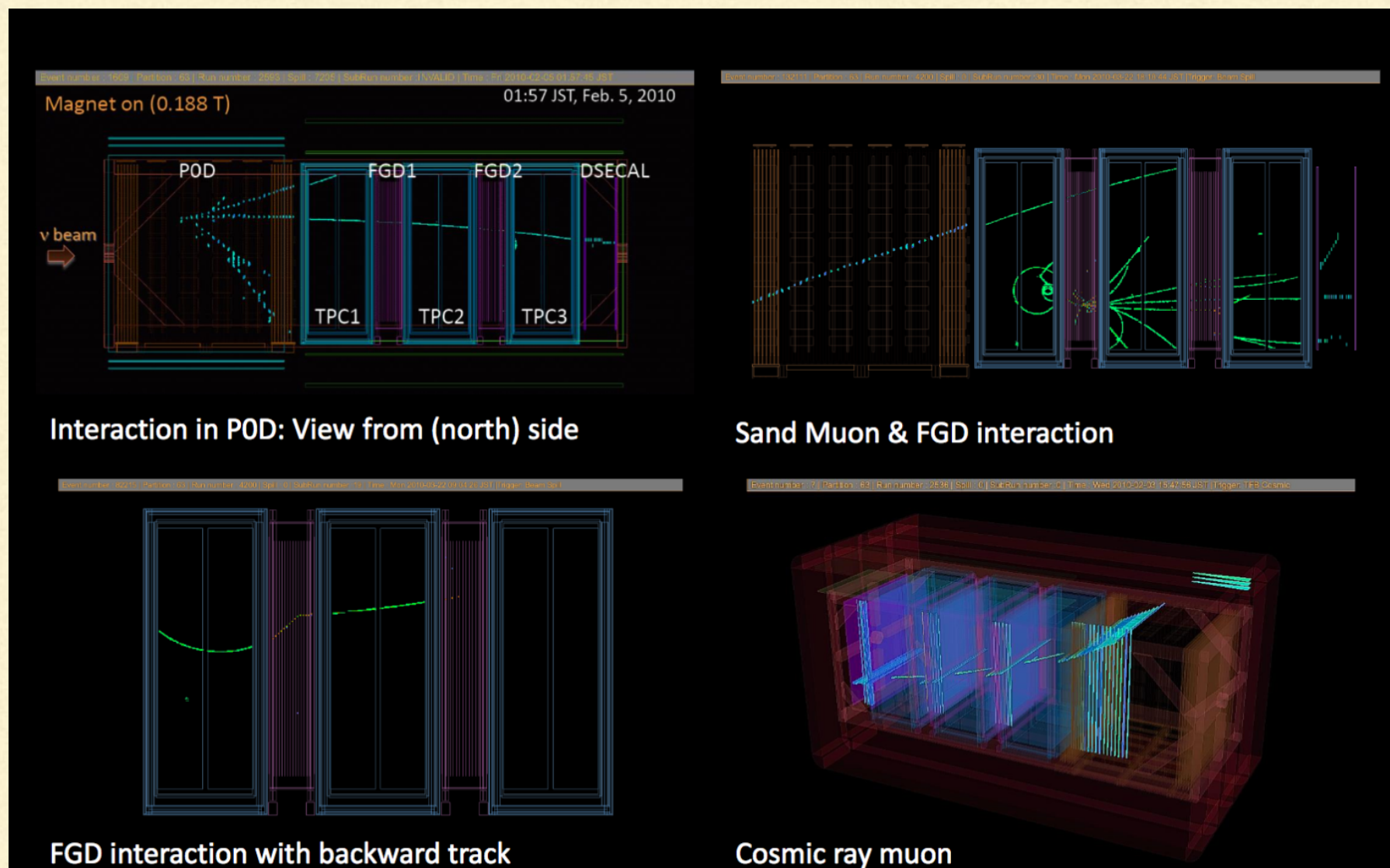
ND280 FGD

- Our target for interactions
- Thin bars $\rightarrow$ give us ~ 1 cm resolution of neutrino interaction vertices



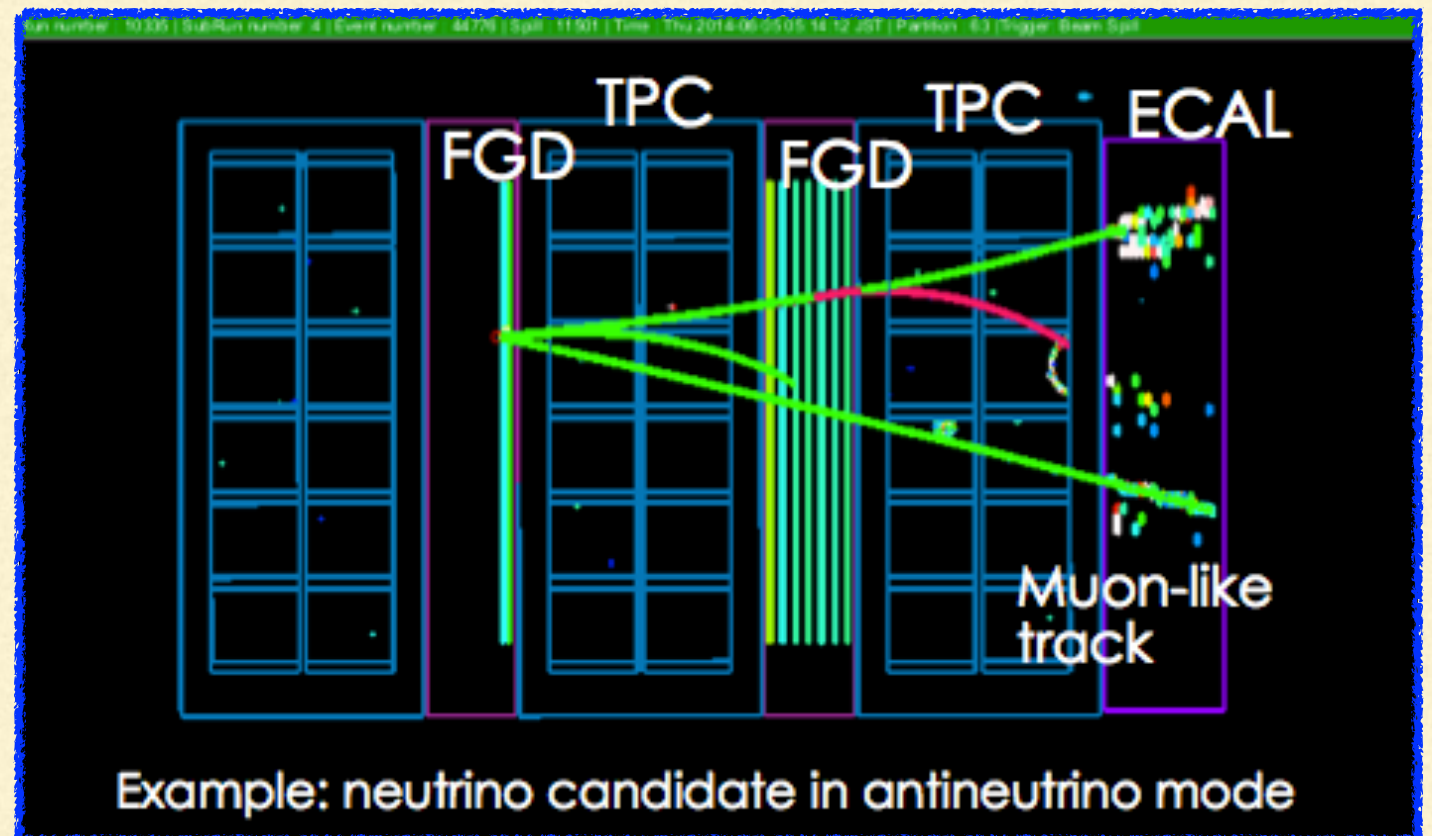
ND280 FGD

- Neutrino interactions can produce many products
- Since various other detectors to fully reconstruction what was going on



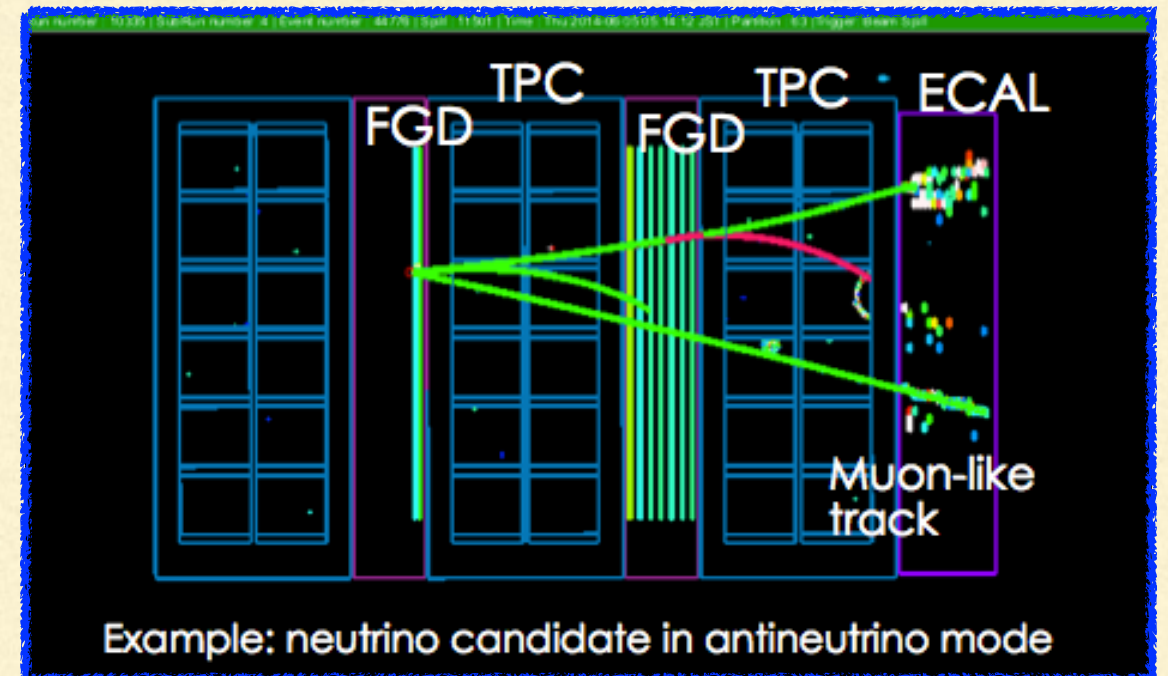
ND280 FGD

- What we will do?
- The idea is to start with is:
 - Select neutrino interactions in ND280 FGDs
 - Tracks that start from FGDs
 - Interactions that have a muon product
 - Using TPC dEdX information



ND280 FGD

- What do we have so to do it?
- Files were produced for ND280
- The have the following info
 - Total number of tracks
 - Total number of positive and negative tracks
 - Kinematic + TPC dEdX information for each track



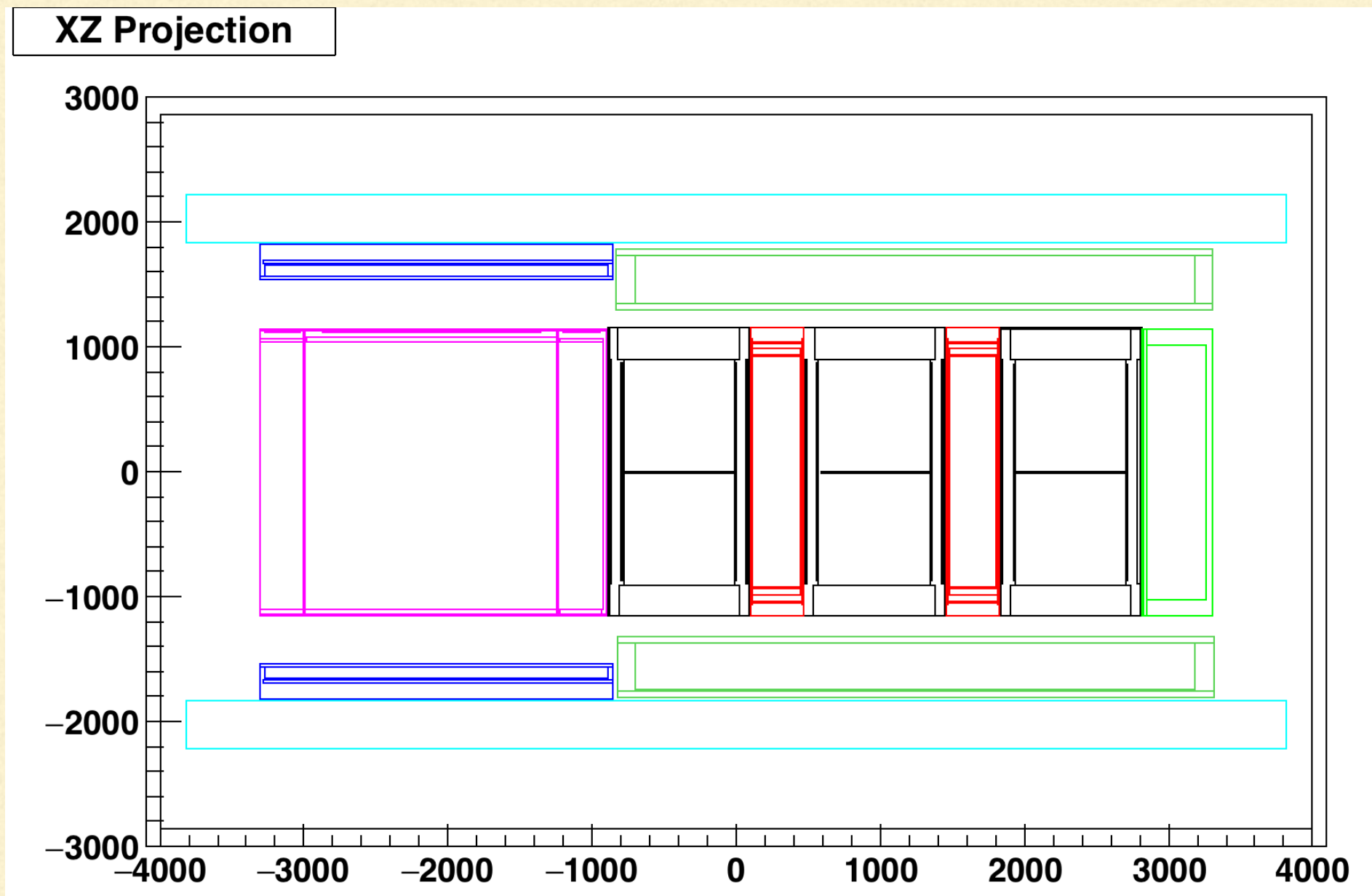
ND280 FGD

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```
sel_charge
sel_dir
sel_mom
sel_pos
sel_tpc_dedx
sel_tpc_dedx_exp_sigmaele
sel_tpc_dedx_exp_sigmap
sel_tpc_dedx_exp_sigmapsi
sel_tpc_dedx_exp_sigmae
sel_tpc_dedx_exp_mu
sel_tpc_dedx_exp_p
sel_tpc_dedx_exp_psi
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sel_truemom
sel_truepos
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sel_negtracks
sel_postracks
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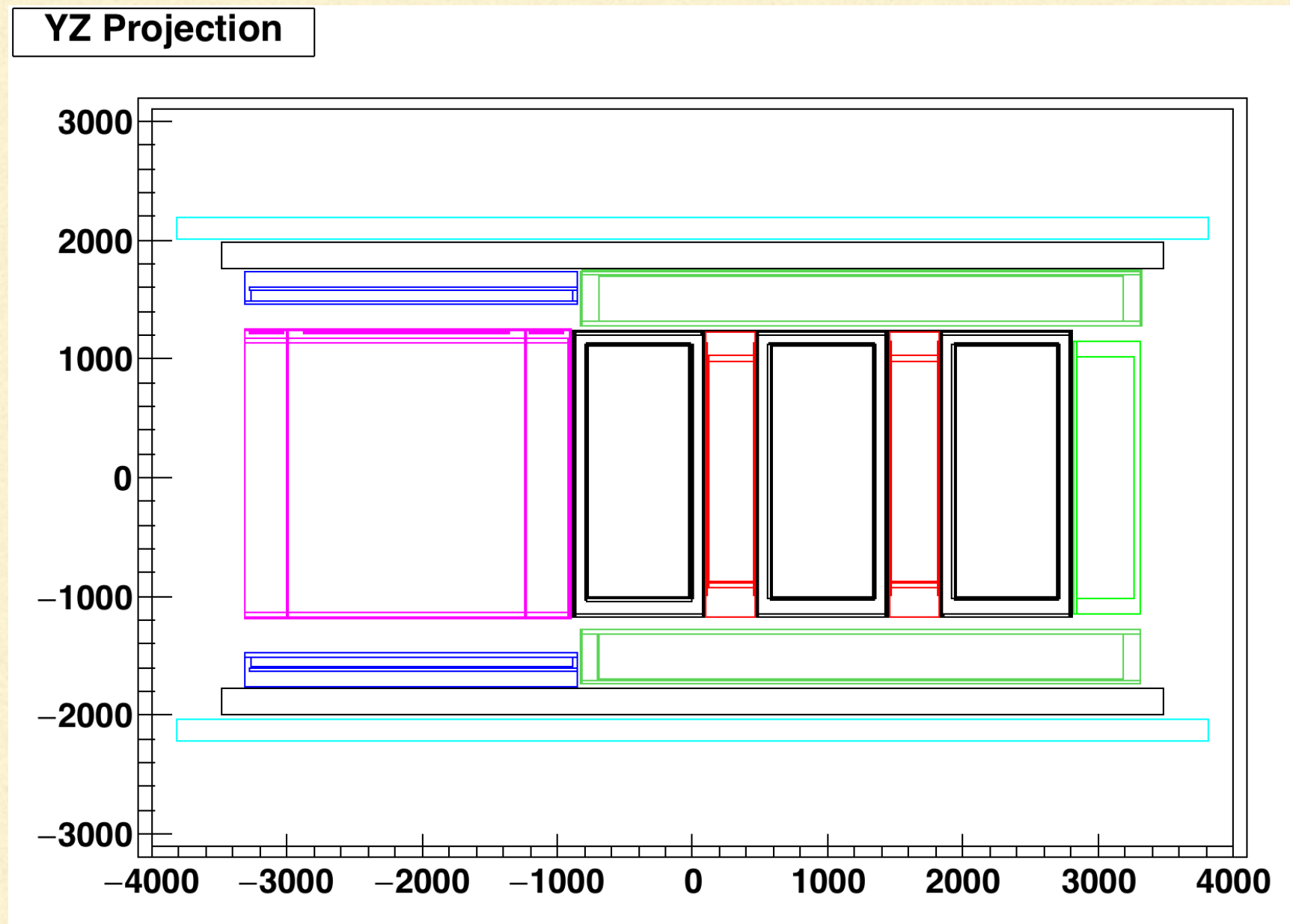

ND280 FGD

- We start with selecting tracks that start in FGDs...



ND280 FGD

- We start with selecting tracks that start in FGDs...

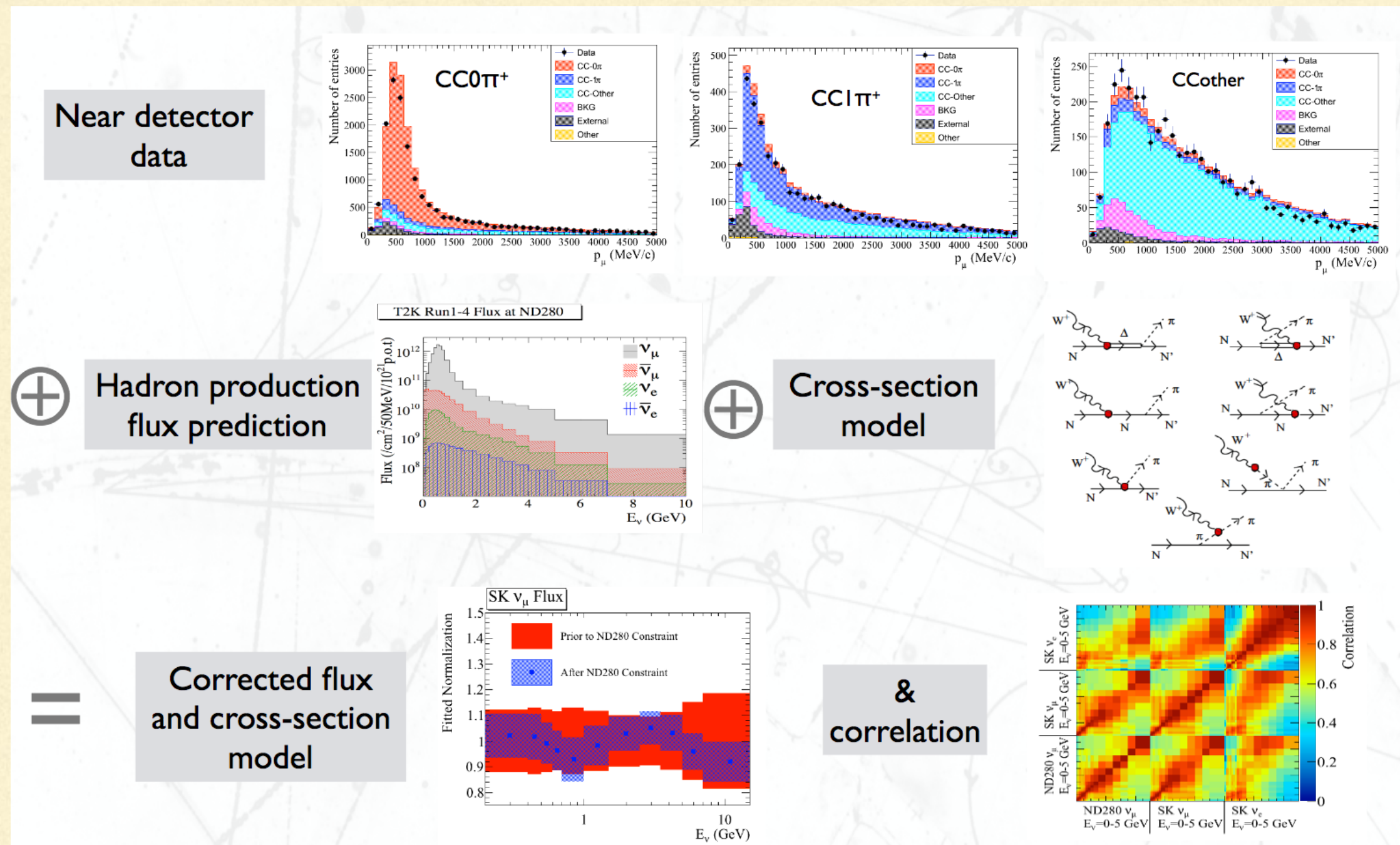


ND280 FGD

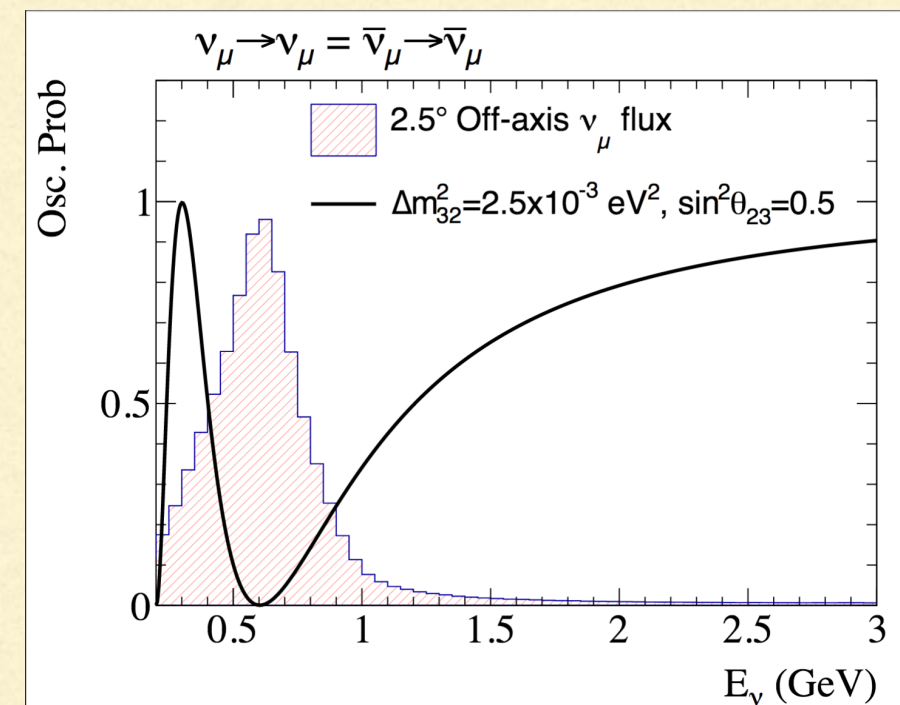
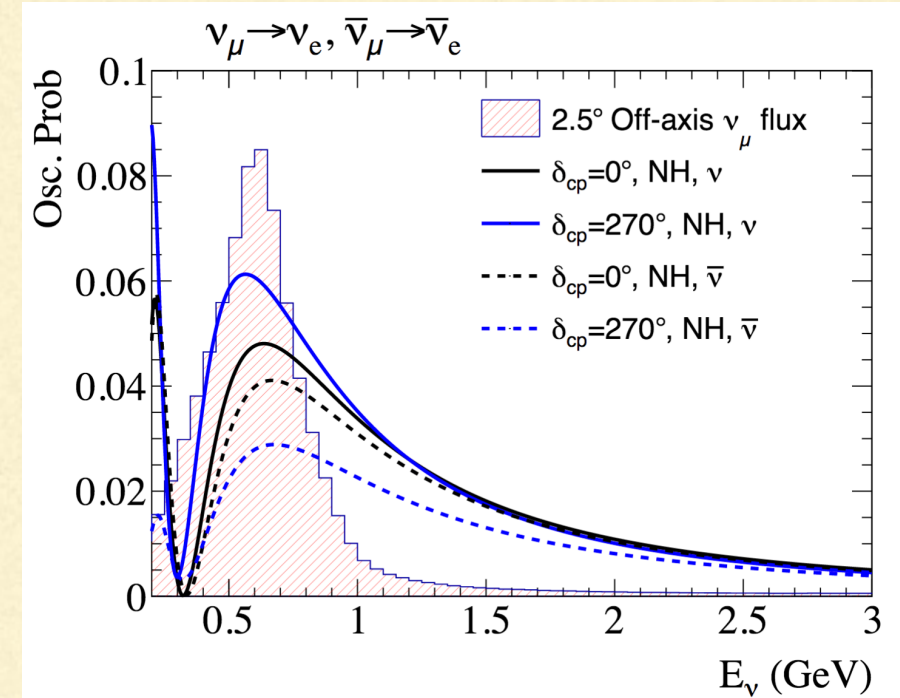
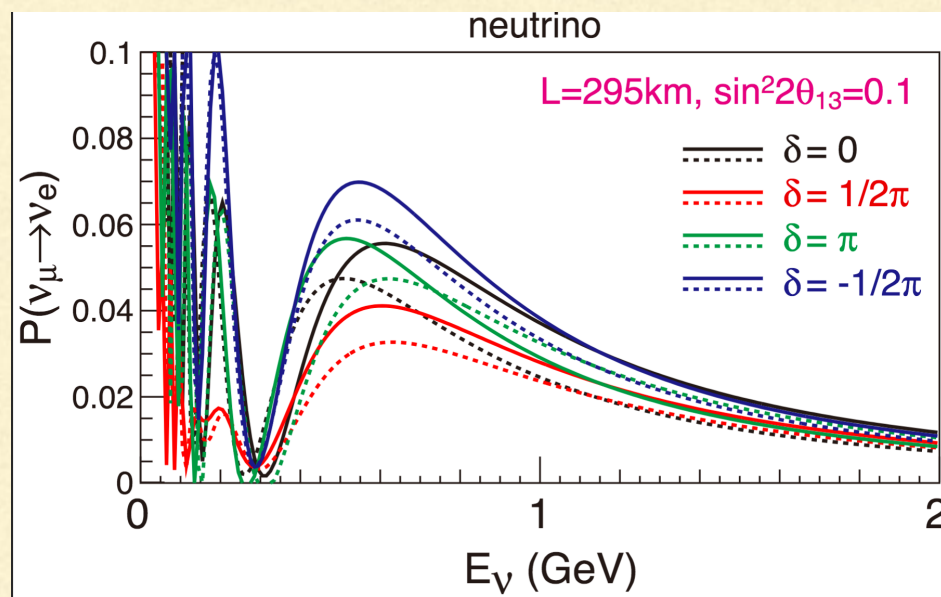
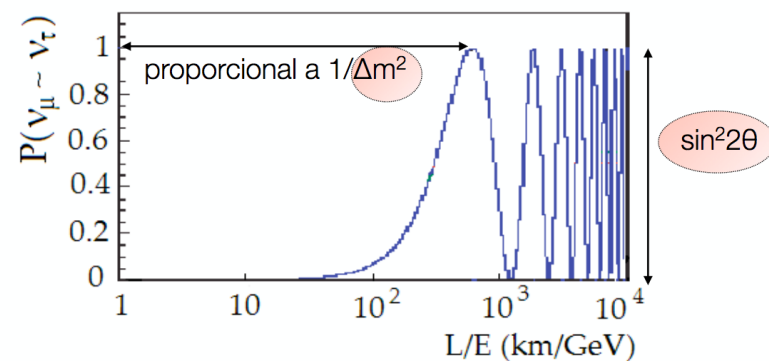
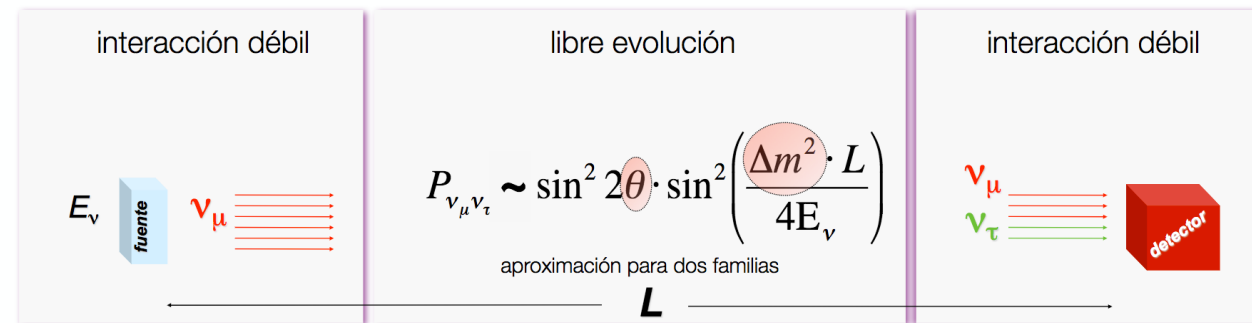
- We start with selecting tracks that start in FGDs...

ROLE OF NEAR DETECTOR

- Understand neutrinos prior to as they travel and oscillate

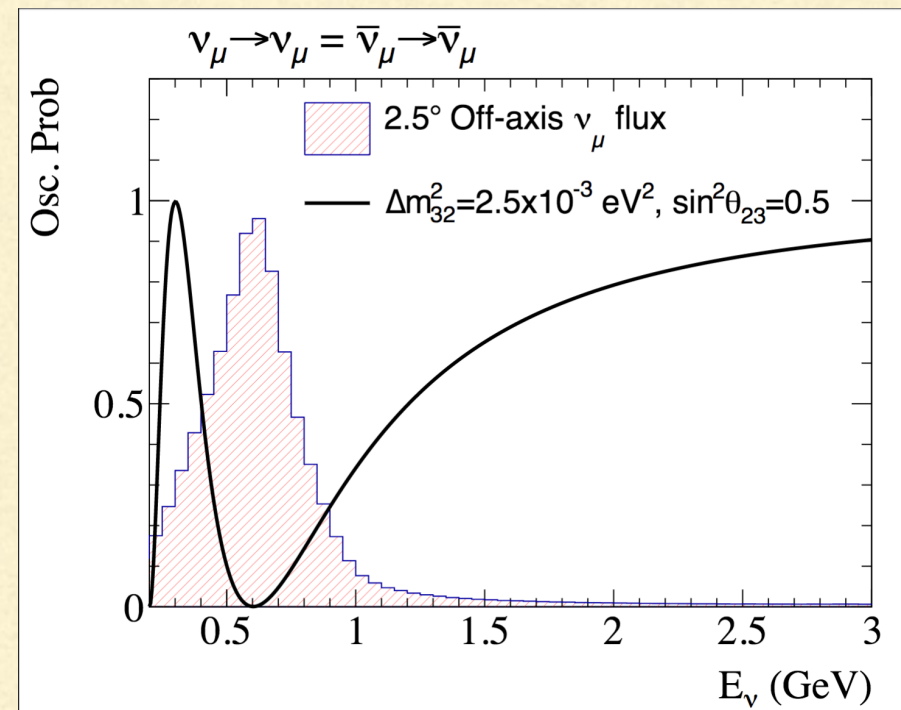
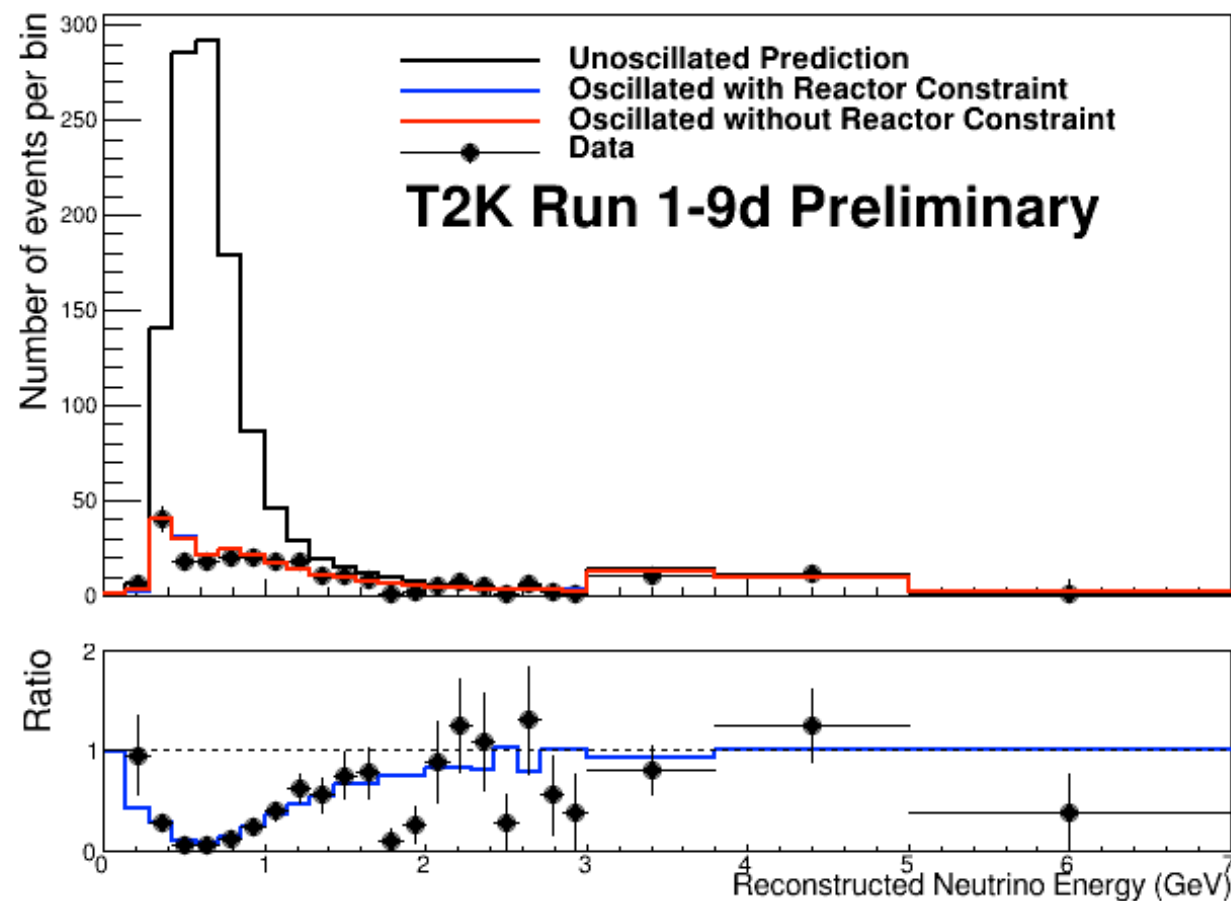


SEARCH FOR OSCILLATIONS



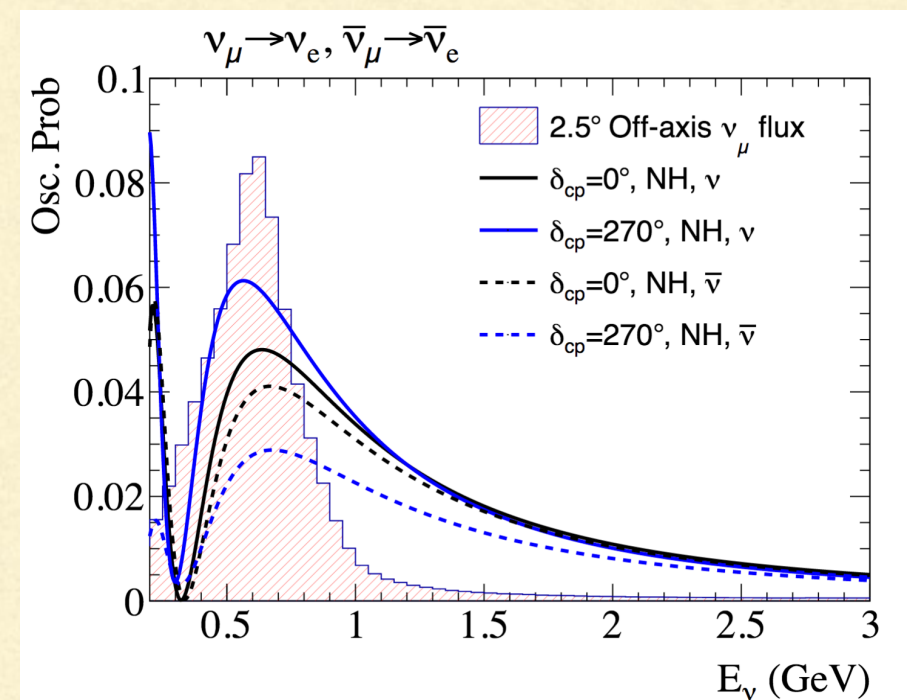
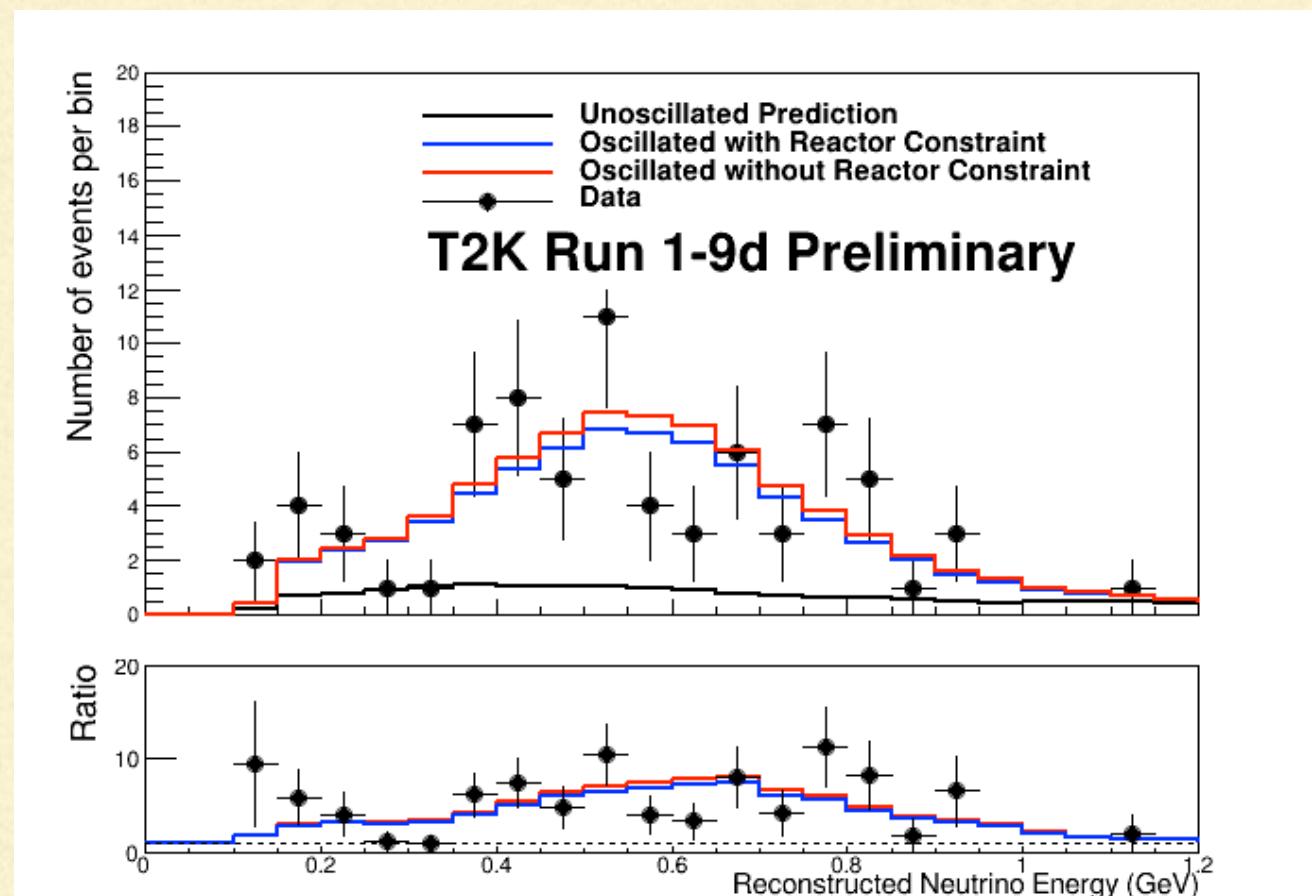
SEARCH FOR OSCILLATIONS

- Calculate observed μ -like and electron-like events
- And also profit from the change in the shape of the energy spectrum

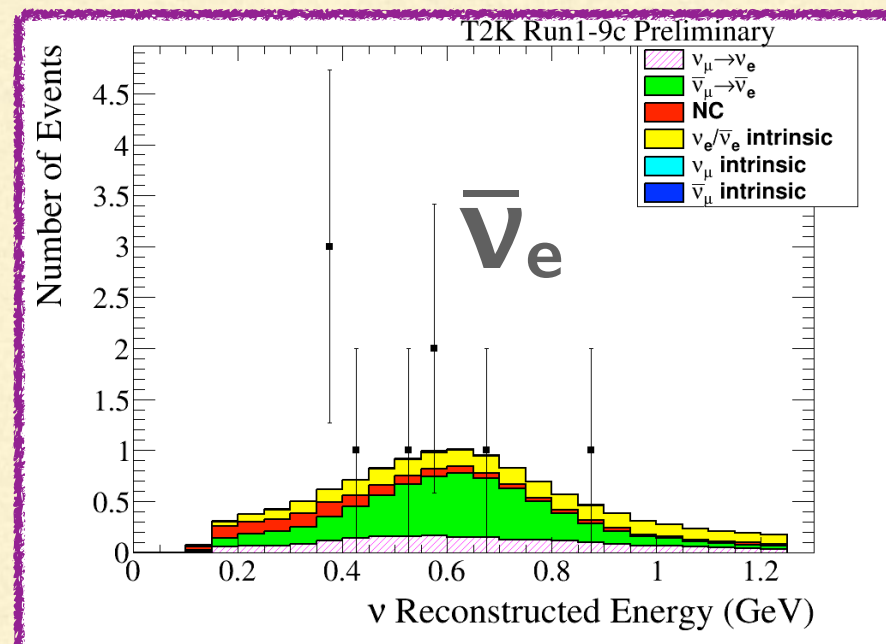
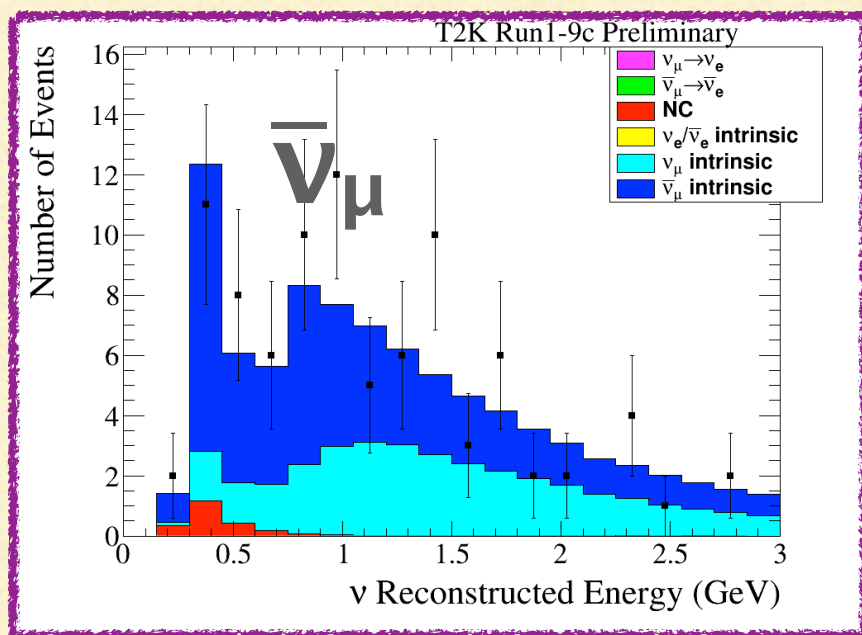
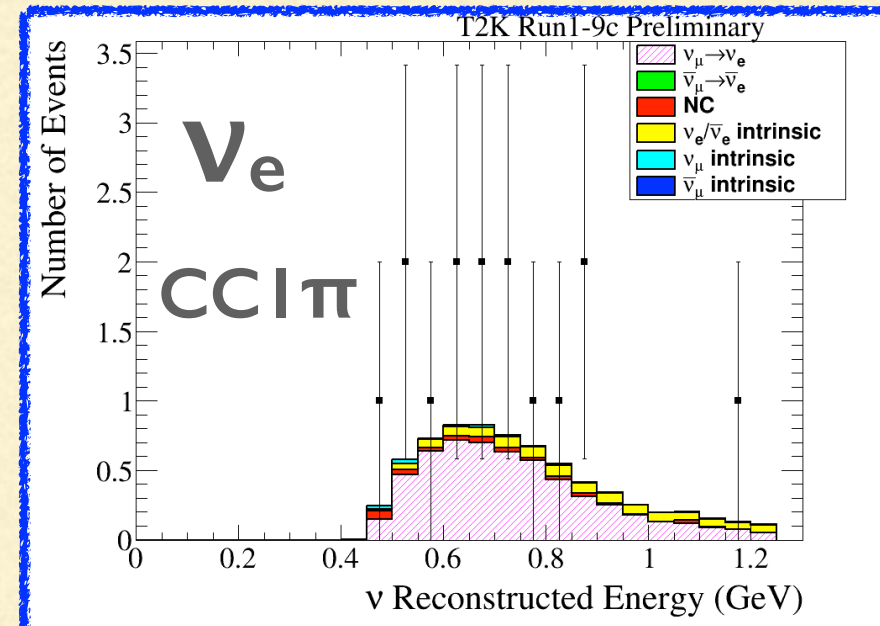
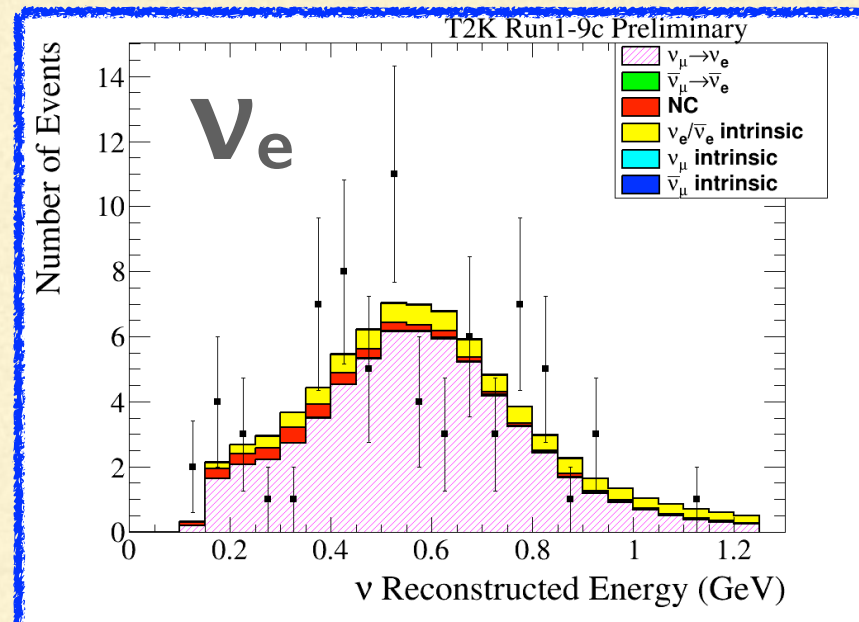
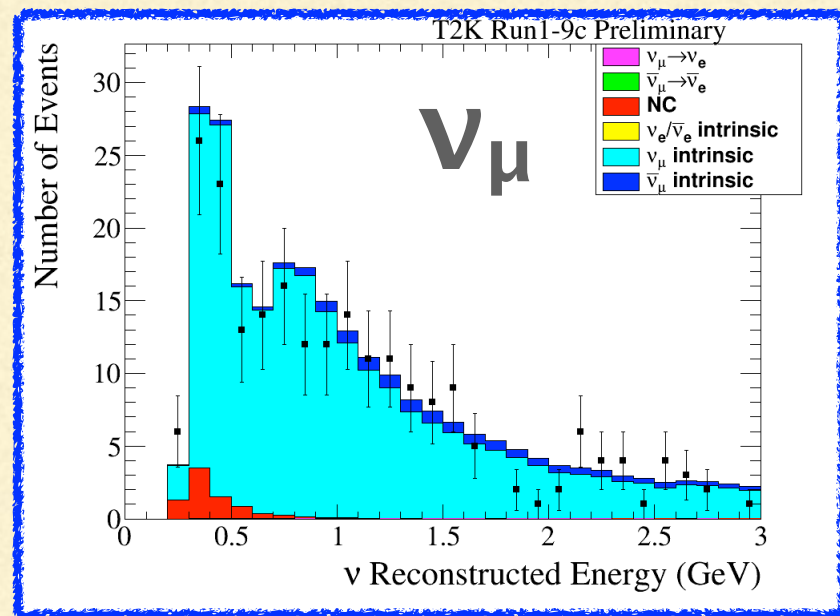


SEARCH FOR OSCILLATIONS

- Calculate observed μ -like and electron-like events
- And also profit from the change in the shape of the energy spectrum



T2K FAR DETECTOR SAMPLES



Energy distribution

ν -mode

anti- ν -mode

* T2K Preliminary

EVENT RATES

- Largely in line with the prediction for $\delta_{CP} = -\pi/2$

Sample	Predicted Rates				Observed
	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Rates
CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
CC1 π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ -like FHC	267.8	267.4	267.7	268.2	240
CCQE 1-Ring μ -like RHC	63.1	62.9	63.1	63.1	68

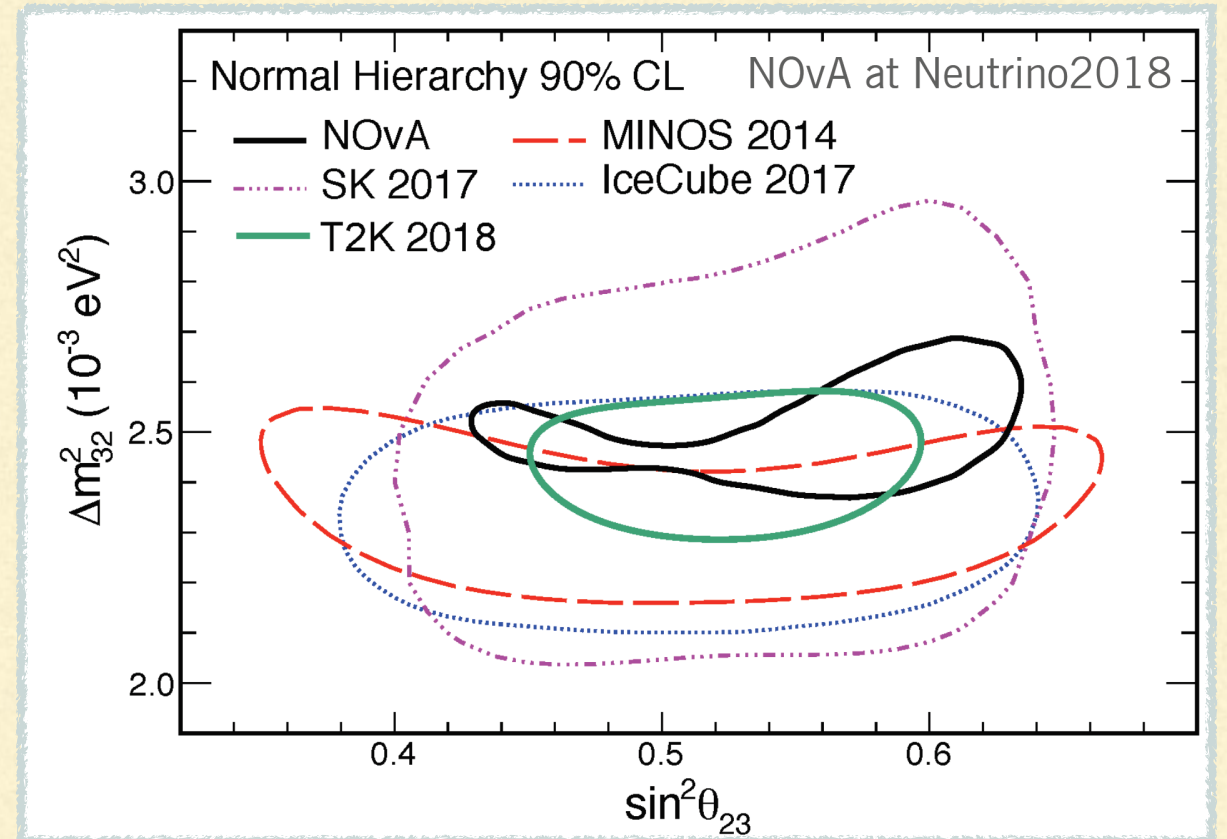
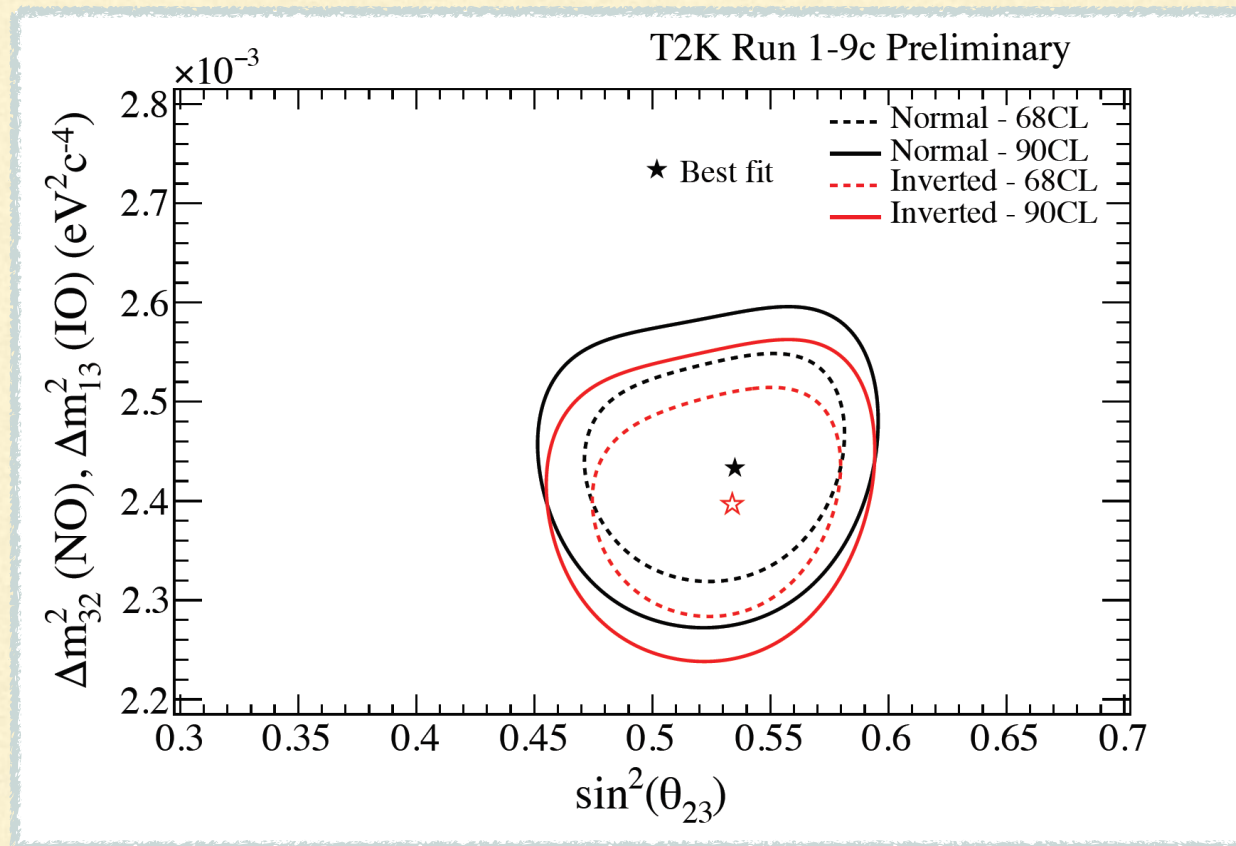
- Generally within statistical and systematic uncertainties
 - p-value: ~ 0.42
- More observed e-like CC1 π events **15** than maximum expectation **6.92₃₈**

T2K:VIDEOS

- Some nice T2K videos as well
- <https://youtu.be/u-UH3EwIEls>
- <http://scientific.ch/project/t2k/>

ANALYSIS RESULTS: ATMOSPHERIC PARAMETERS

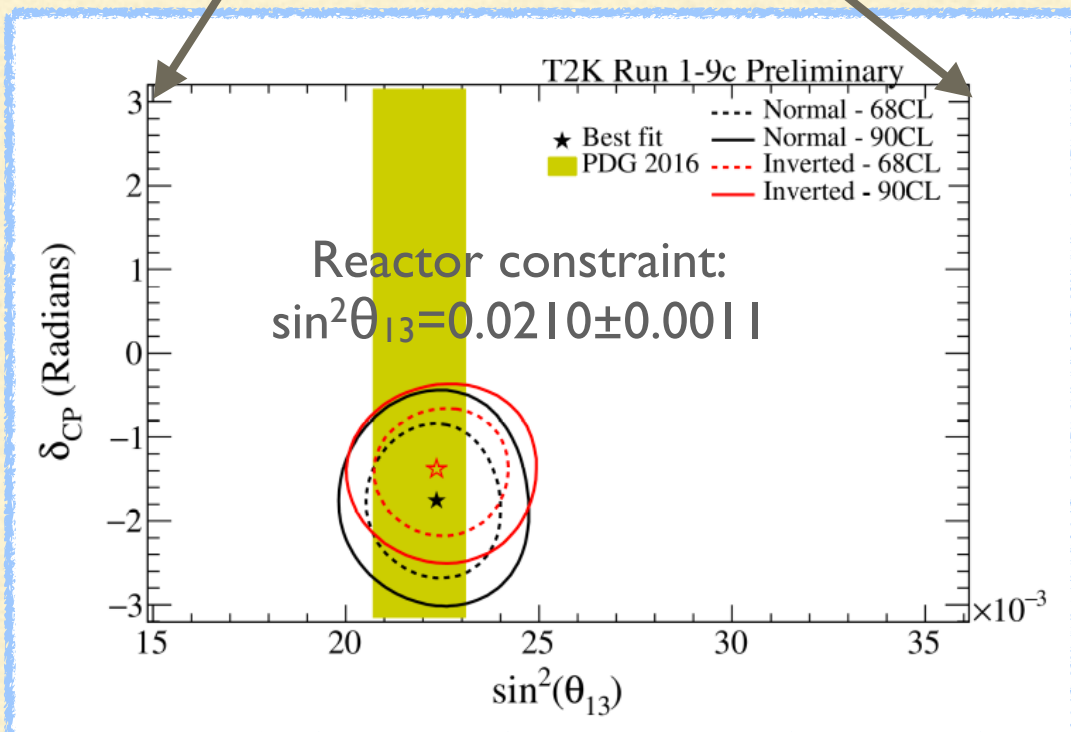
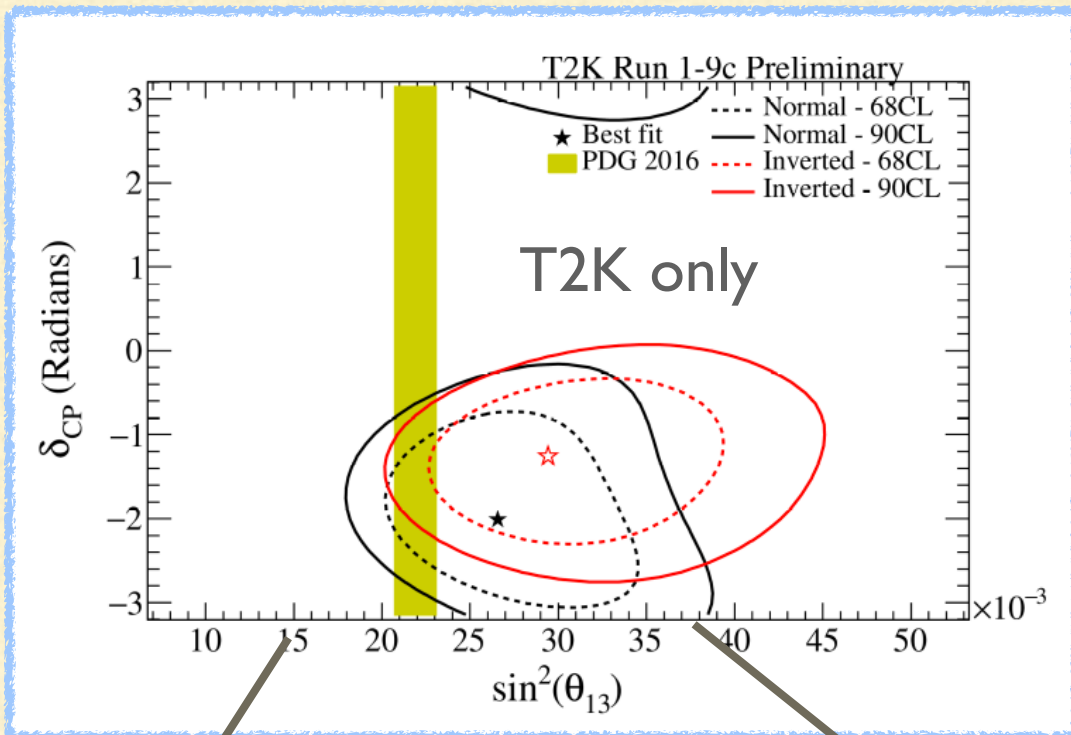
θ_{23} AND Δm_{32}^2



- T2K continues to favour maximal mixing
- Interesting tensions with NOvA
- More data needed to improve the results

	Normal	Inverted
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$ \Delta m^2 $ (10^{-3} eV^2)	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$

ANALYSIS RESULTS: θ_{13} and δ_{CP} MEASUREMENTS



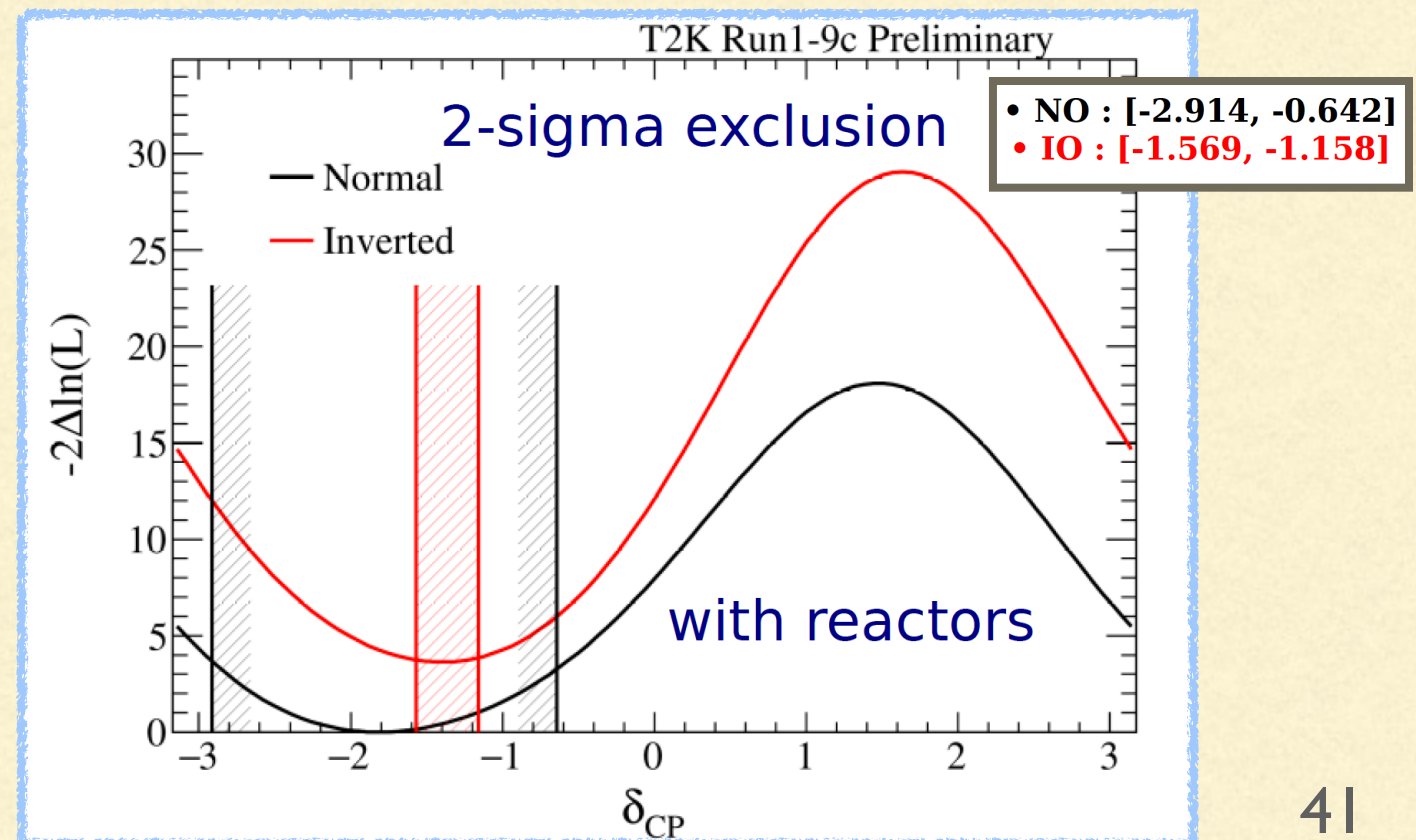
- Good agreement with reactor experiments

- T2K best fit (NH): $\sin^2 \theta_{13} = 0.0277^{+0.0054}_{-0.0047}$

- PDG 2016: $\sin^2 \theta_{13} = 0.0210 \pm 0.0011$

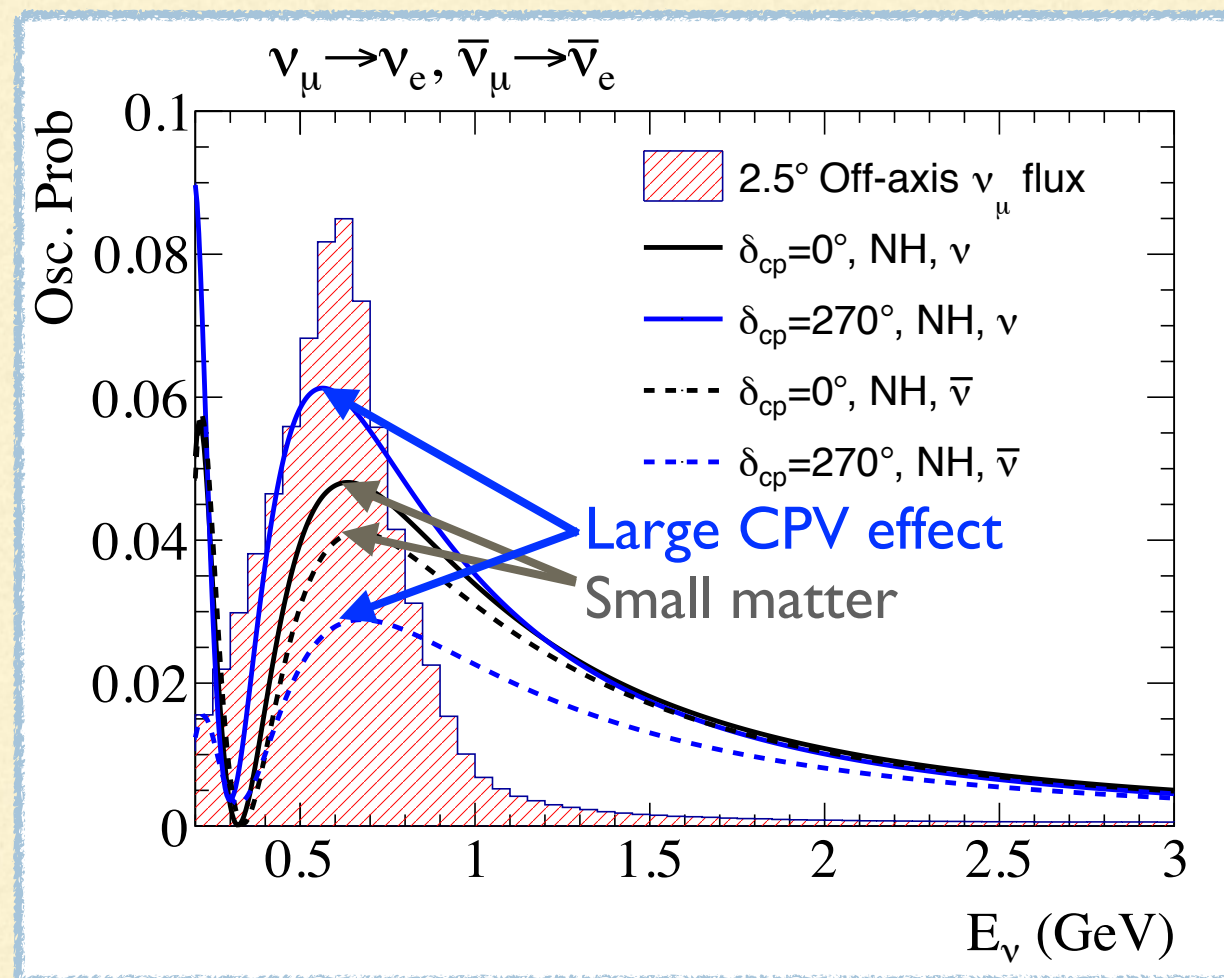
- 2σ exclusion for CP-conservation independent of OA

- Large CPV favoured



NEUTRINO OSCILLATIONS IN T2K

δ_{CP} and mass hierarchy (MH) both cause differences in ν and anti- ν oscillations



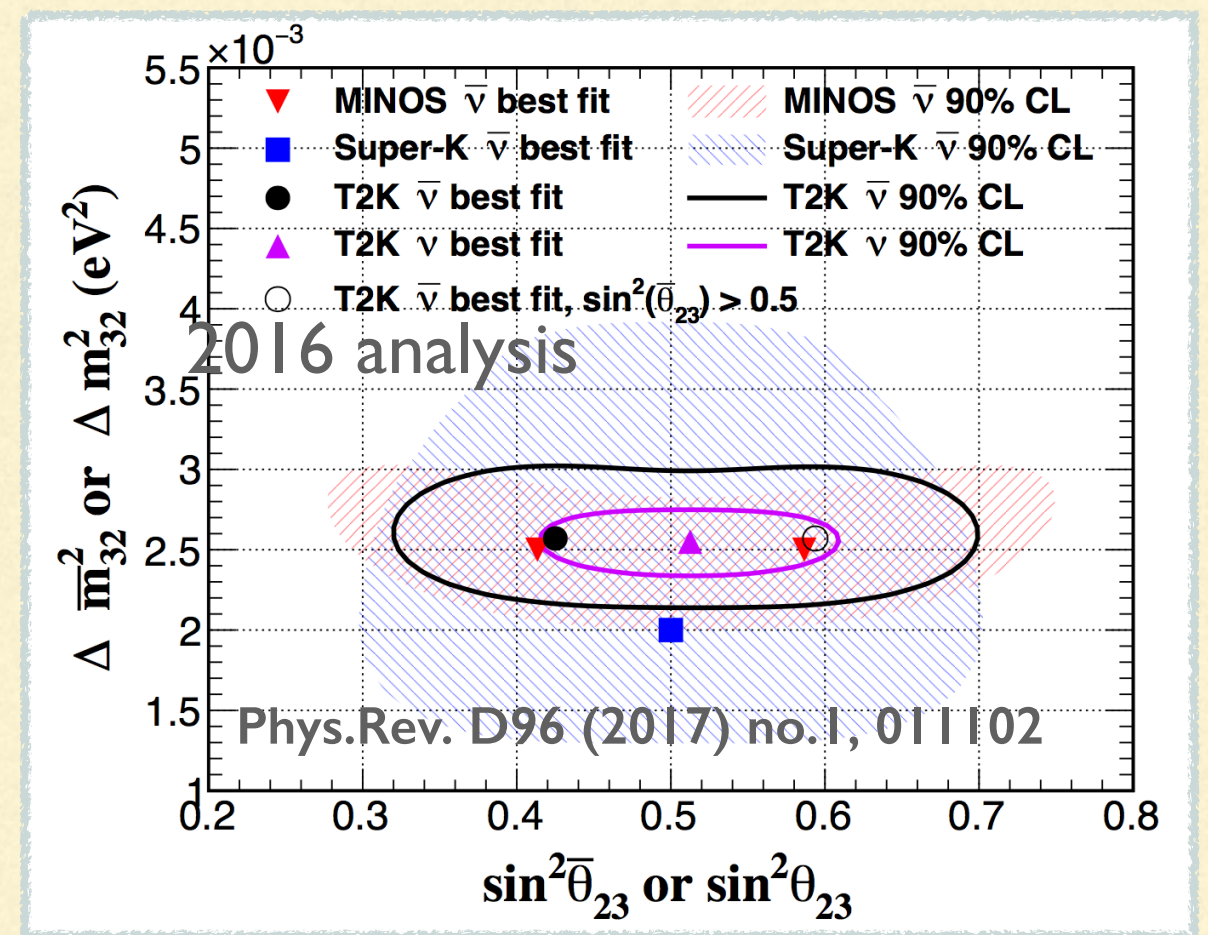
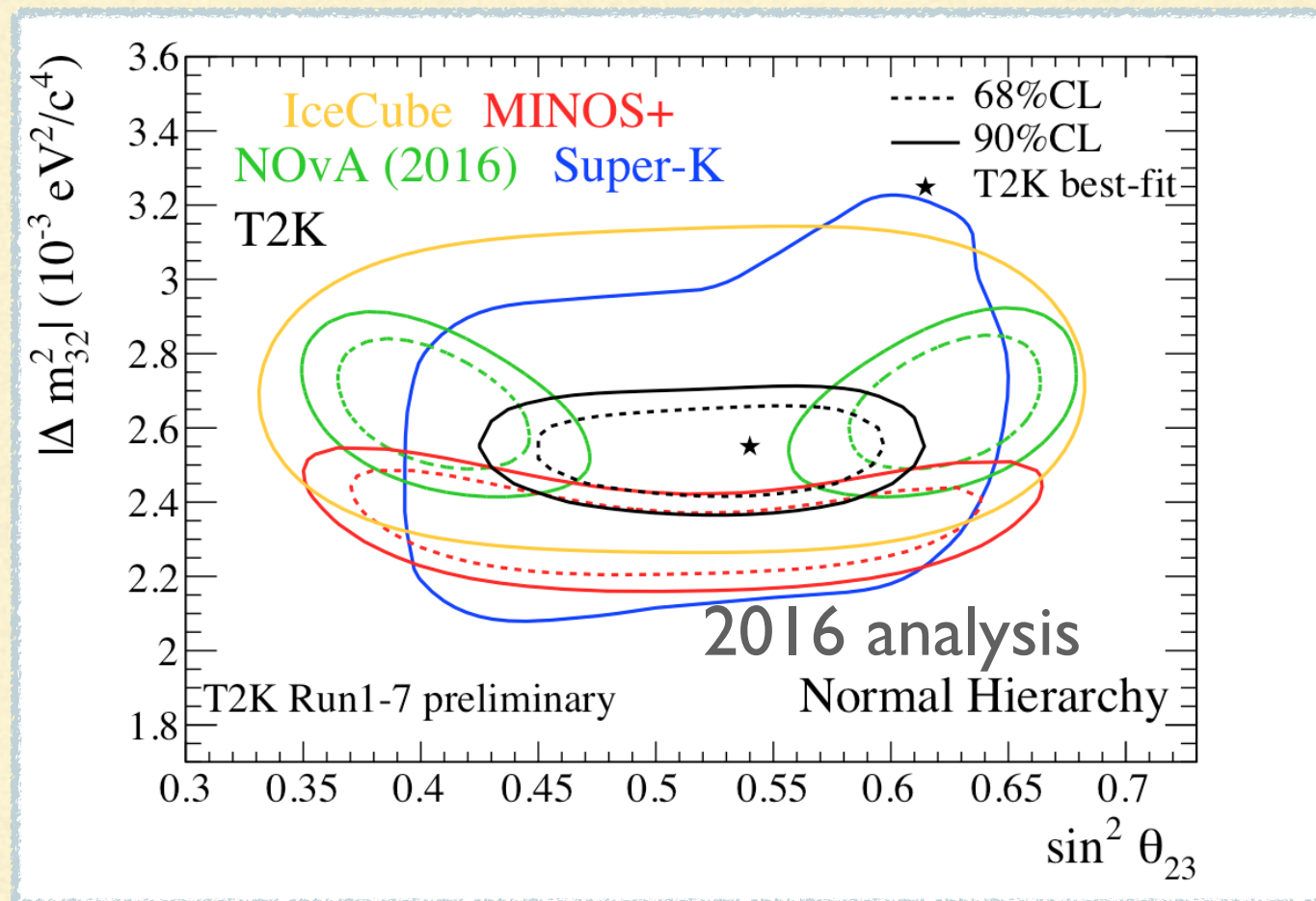
CP PHASE/ CHANNEL	$P(\nu_\mu \rightarrow \nu_e)$	$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
$\delta_{CP}=-\pi/2$	Enhance	Suppress
$\delta_{CP}=\pi/2$	Suppress	Enhance

At T2K baseline ($L \sim 295\text{km}$, $E \sim 0.6\text{GeV}$):

- CPV: $\approx \pm 30\%$ effect
- Mass hierarchy: $\approx \pm 10\%$ effect

ANALYSIS RESULTS: ATMOSPHERIC PARAMETERS

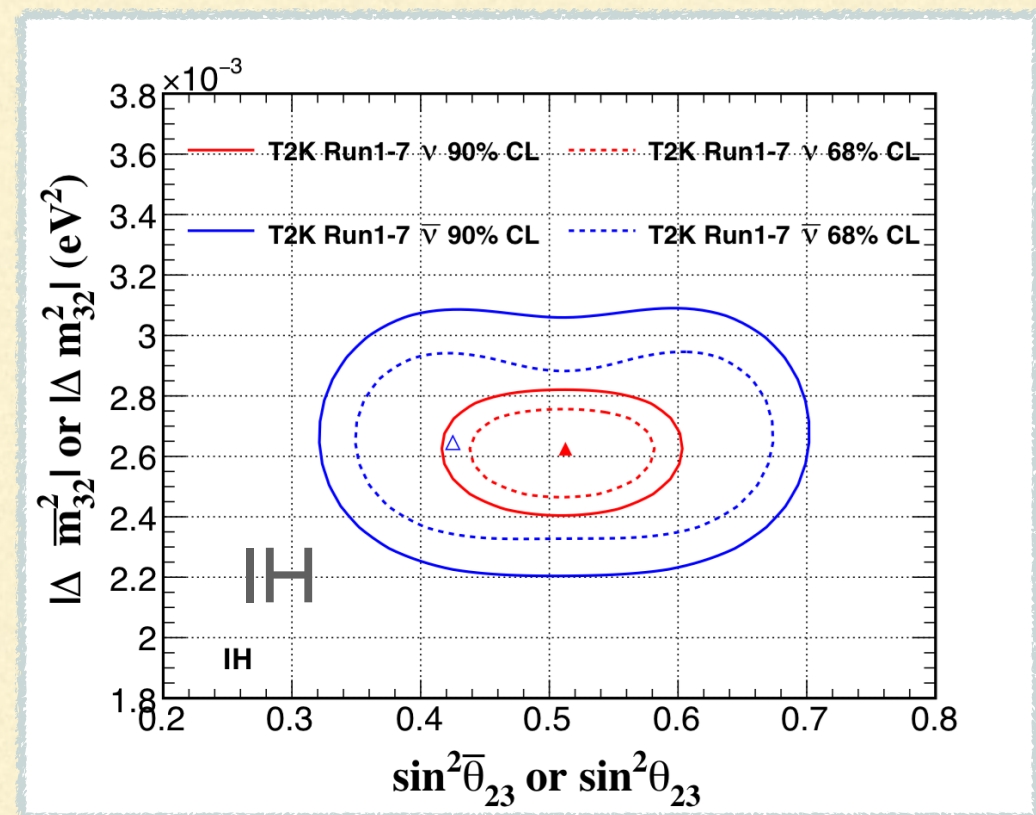
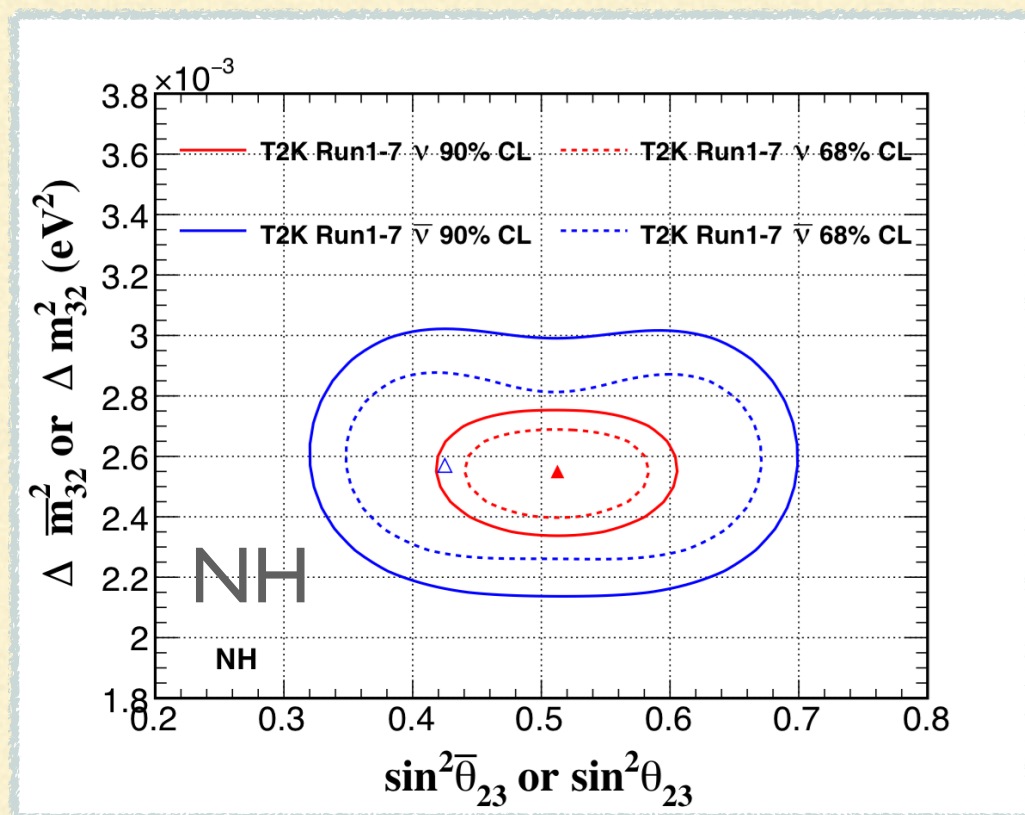
θ_{23} AND Δm_{32}^2



- 2016 analysis (joint fit of 5 samples with reactor constraint for θ_{13}):
 - Compatible and consistent results with other experiments
 - Consistent results for $P(\nu_\mu \rightarrow \nu_\mu)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$: CPT conserved

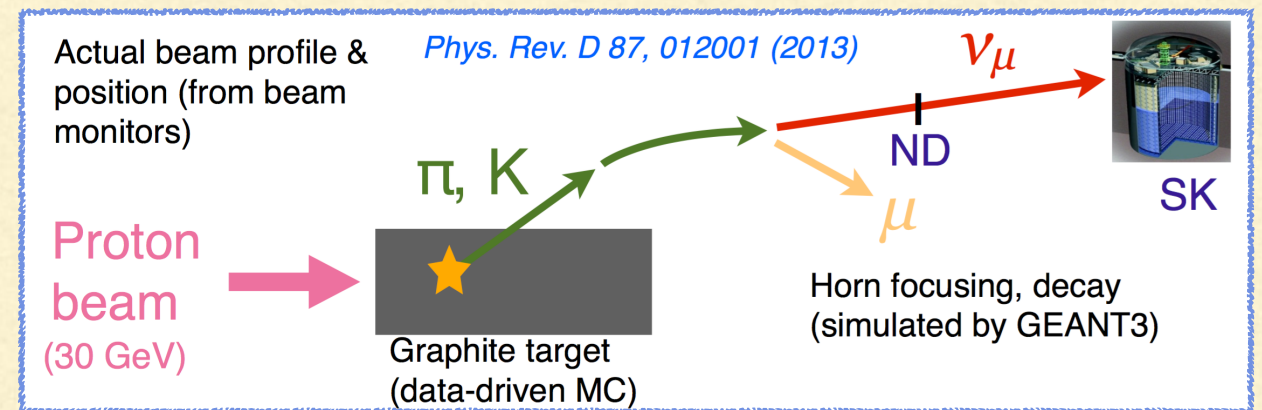
2016 CPT INVARIANCE TEST: ν_μ AND anti- ν_μ DISAPPEARANCE

- Strategy
 - Assign independent oscillation parameters for antineutrinos
 - Neutrino samples constrain “wrong-sign” background
 - Test CPT: $\theta_{23} \neq \bar{\theta}_{23}$ and $\Delta m_{32}^2 \neq \Delta \bar{m}_{32}^2$
- Consistent results for $P(\nu_\mu \rightarrow \nu_\mu)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$: CPT conserved

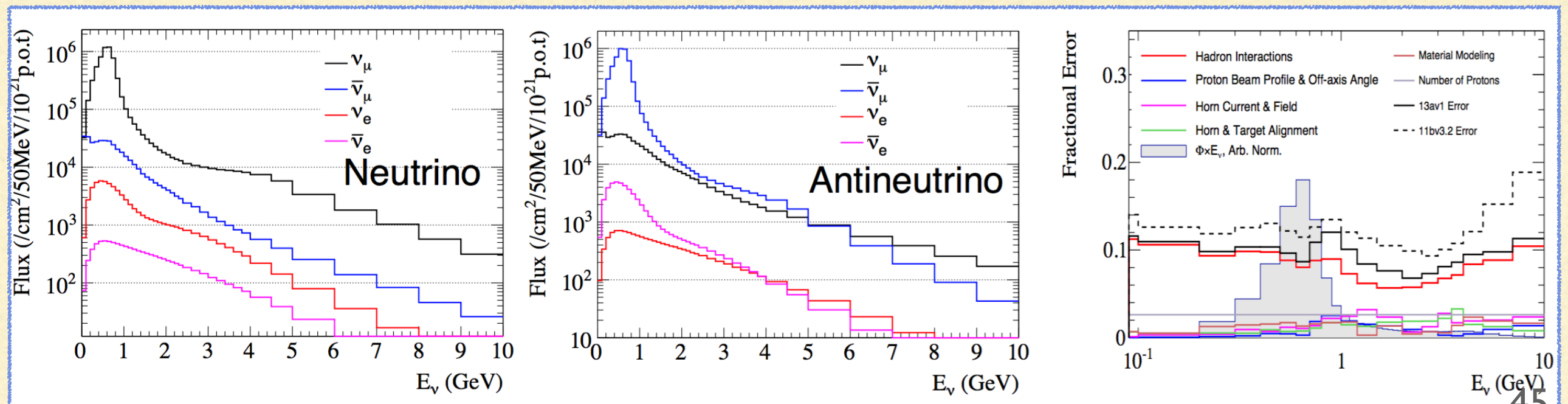


T2K NEUTRINO FLUX PREDICTION

- Simulation: FLUKA, GCALOR and GEANT3
- Tuned to external data: NA61/SHINE (CERN)
 - Measurement of pion/kaon production of 31 GeV/c proton beam with carbon target
 - Thin target (4λ) and T2K replica target
 - Reduction of uncertainties: $\sim 30\%$ to $\sim 10\%$
- Intrinsic ν_e background at $\sim 0.5\%$ level

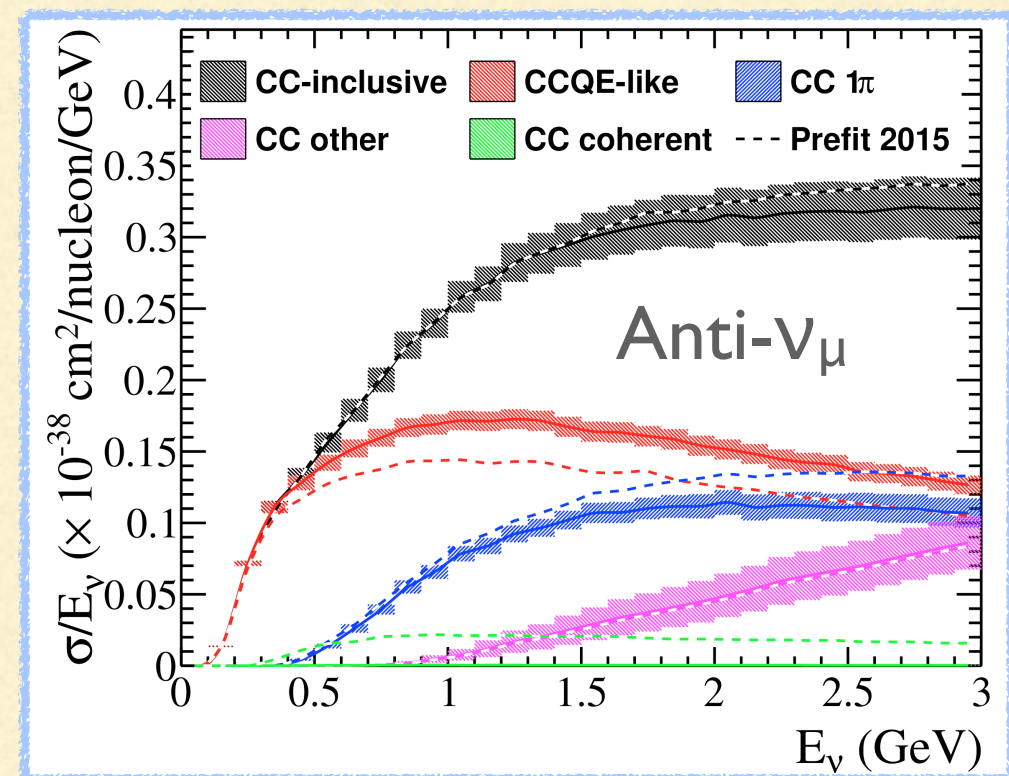
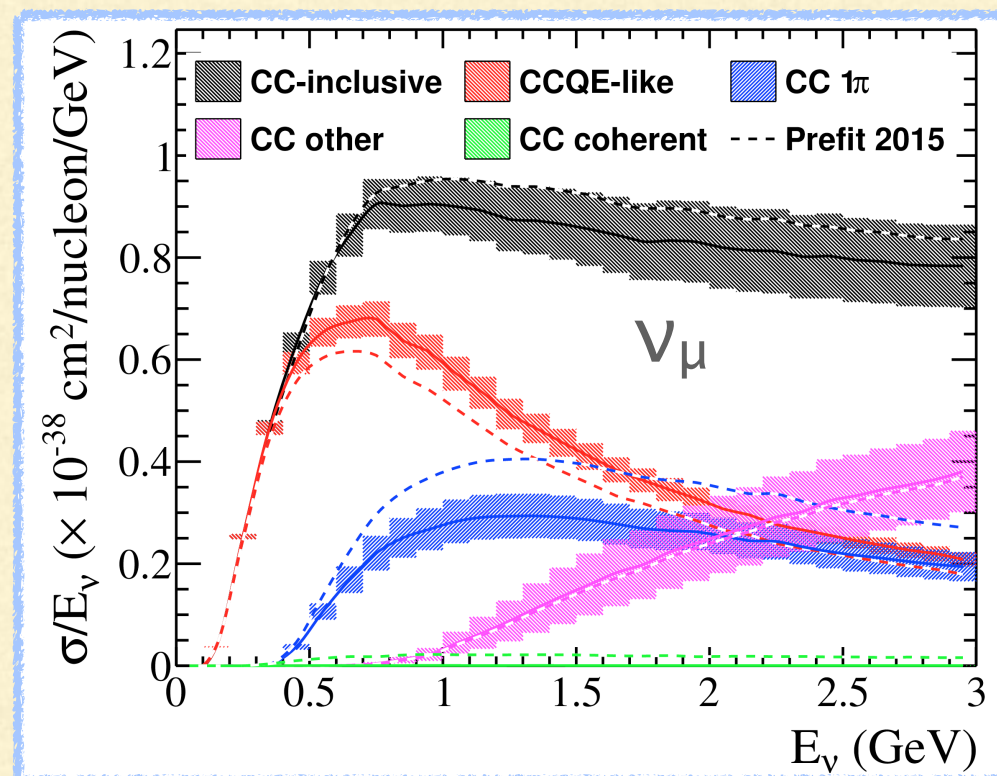


Replica target results are being incorporated into analysis

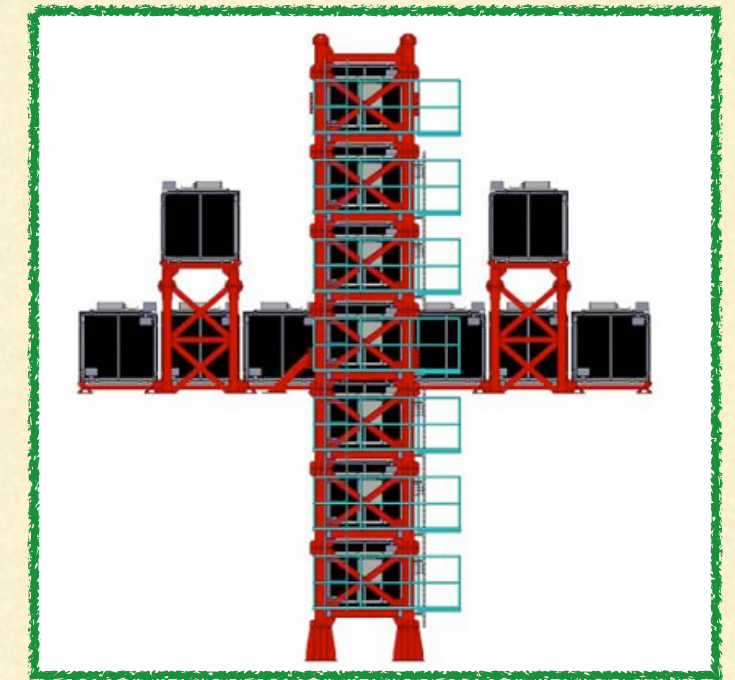
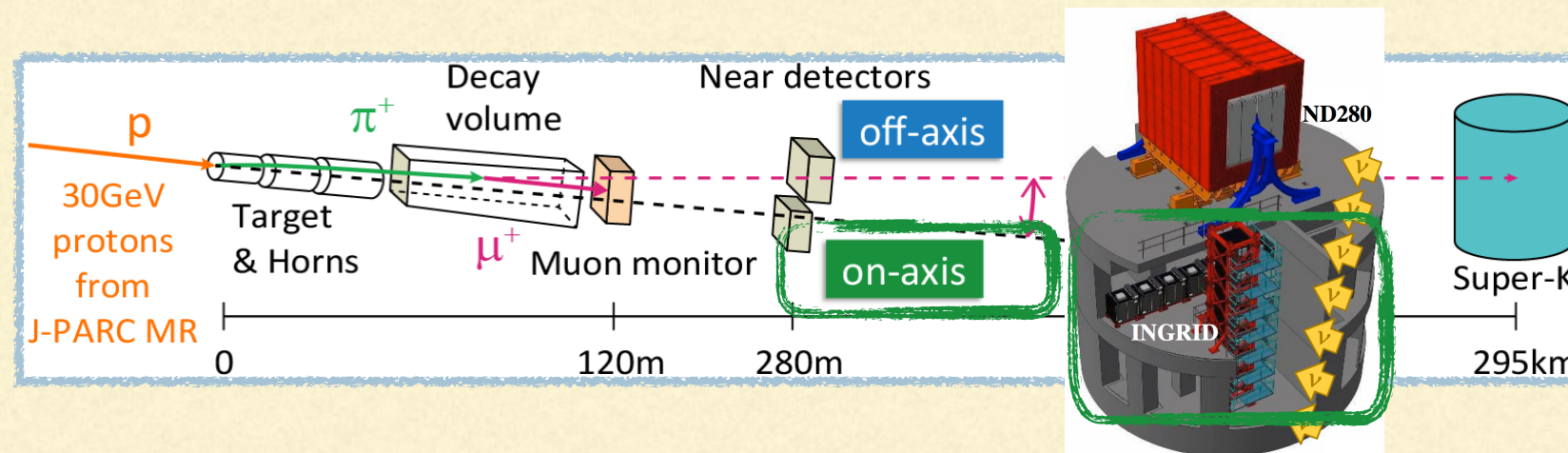


T2K NEUTRINO INTERACTIONS MODEL

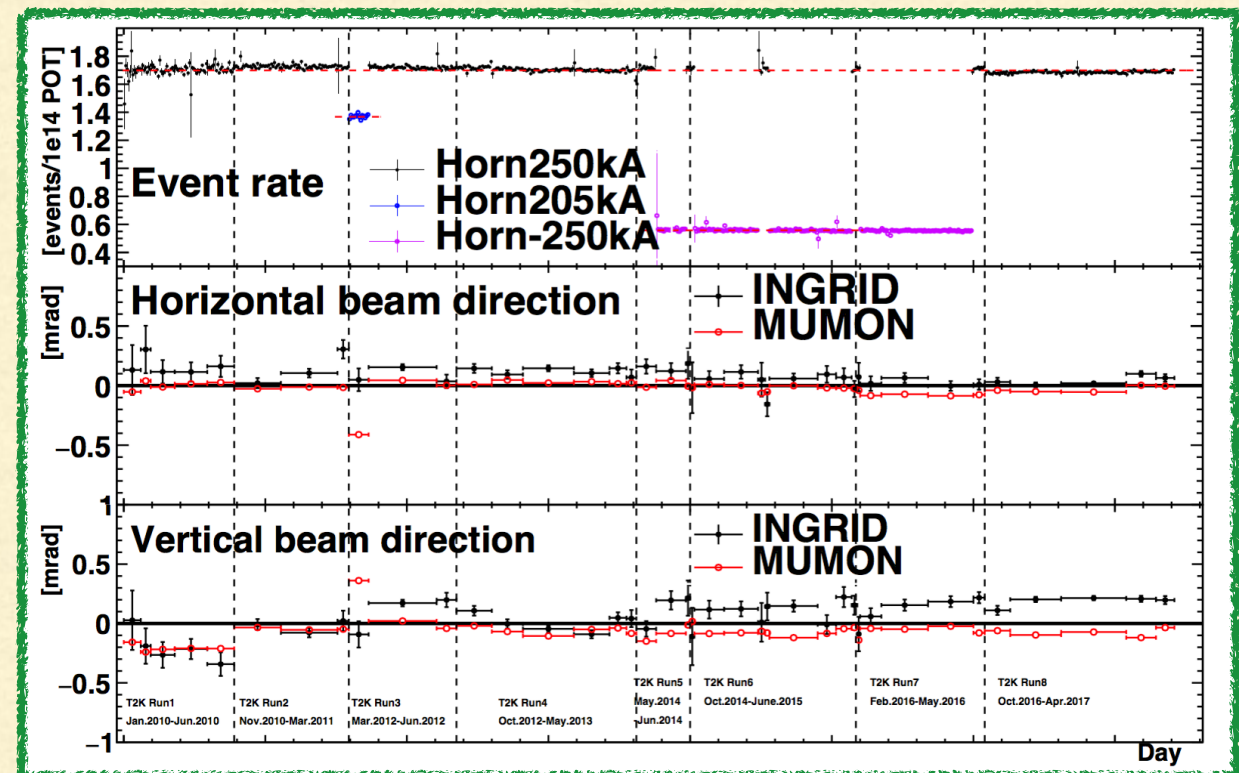
- NEUT neutrino generator
- Model tuned to external data: MiniBooNE, MINERvA, bubble chambers`
- CCQE: Relativistic Fermi Gas (weighted from Spectral Function) + relativistic Random Phase Approximation for nuclear system
- Multinucleon processes (2p2h) included based on J.Nieves model, Phys. Lett. B 707, 72 (2012)
- Pre-(ND280)fit uncertainty for Super-K: $\sim 7.5\%$



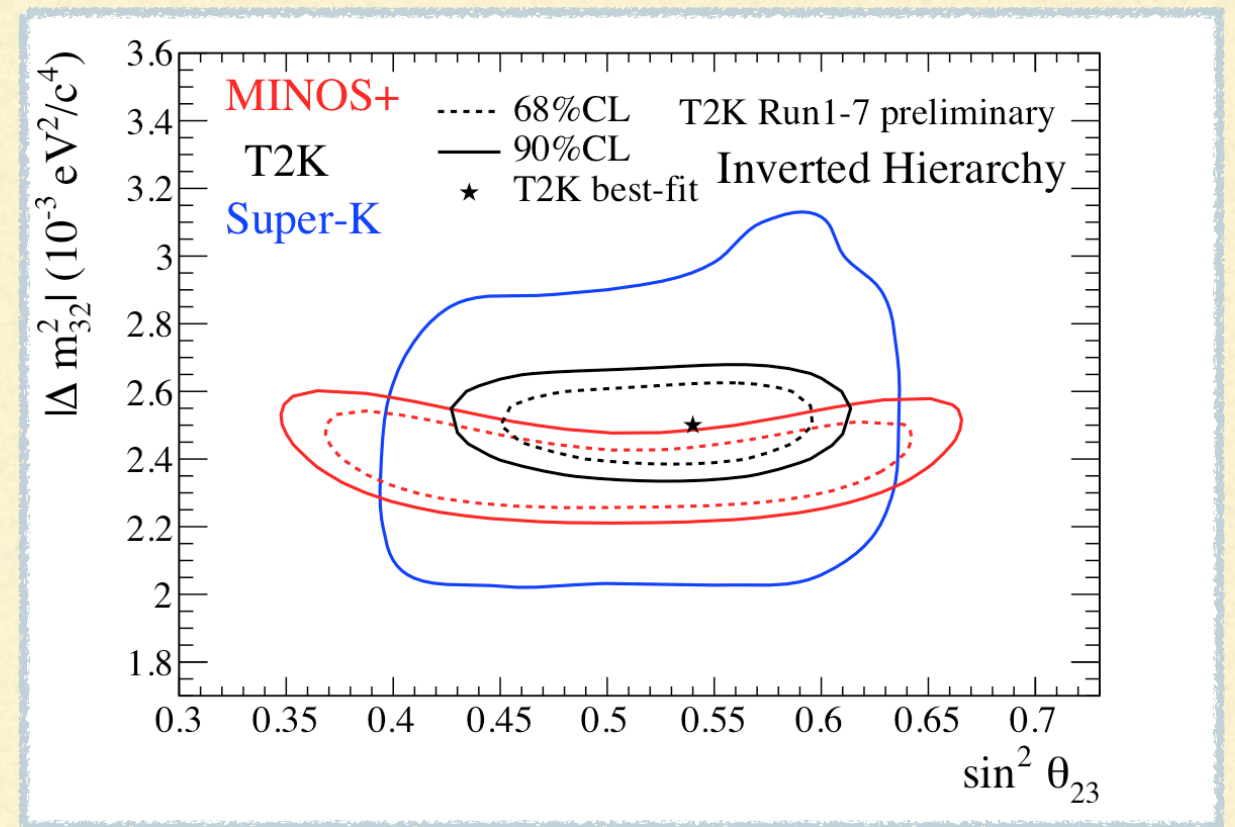
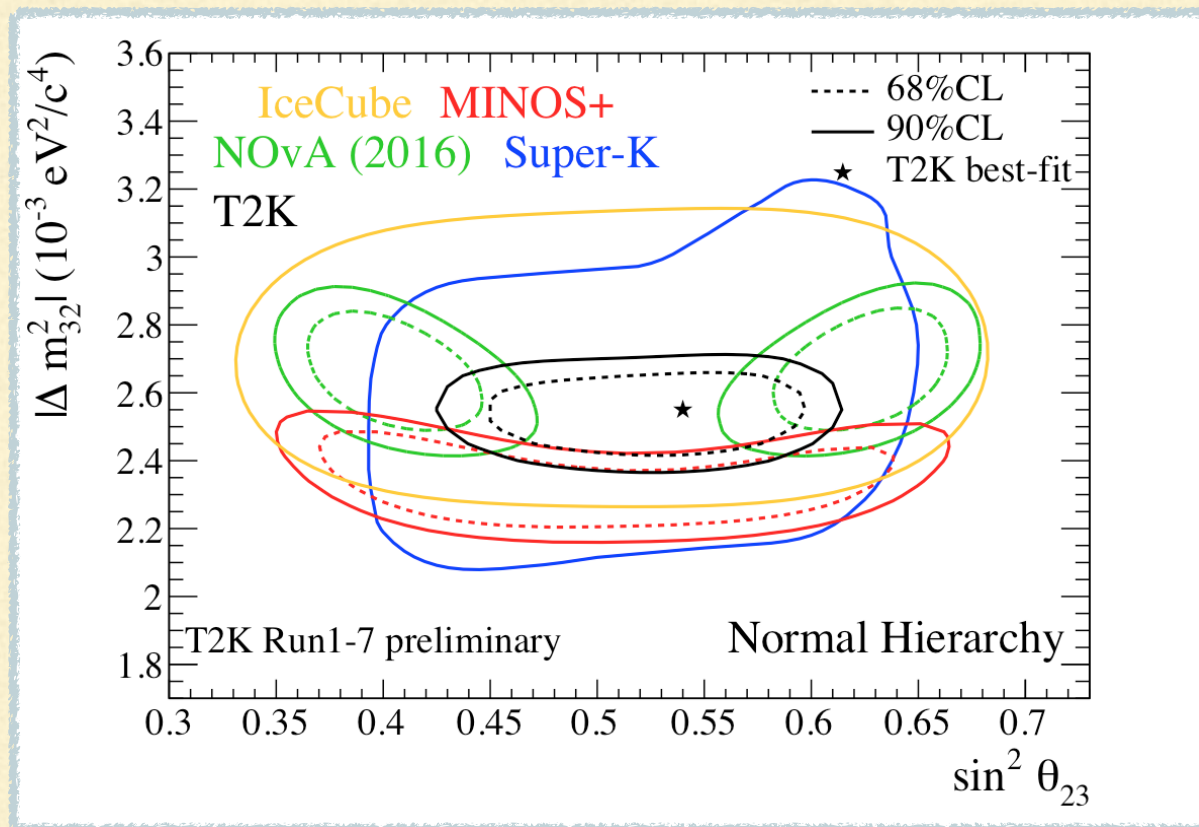
ON-AXIS NEAR DETECTOR INGRID



- T2K utilises off-axis neutrino beam:
 - Important to monitor beam intensity and direction
- Iron/scintillator detector to measure beam profile and rate
- Day-by-day monitoring
- Direction stable within 1 mrad (~2% shift in peak energy)



2016 ANALYSIS RESULTS: θ_{23} AND Δm^2_{32}



- Joint analysis with reactor constraint:
 $\sin^2 2\theta_{13} = 0.085 \pm 0.05$
- T2K data consistent with maximal mixing
- Compatible with other experiments
(intervals for fixed mass hierarchy)

PARAMETER/MASS HIERARCHY	NORMAL MASS HIERARCHY	INVERTED MASS HIERARCHY
$\sin^2 2\theta_{32}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.07}$
$ \Delta m^2_{32} $ ($\times 10^{-3} \text{ eV}^2/\text{c}^4$)	$2.545^{+0.081}_{-0.084}$	$2.51^{+0.081}_{-0.083}$

T2K: SPANISH GROUPS IMPACT

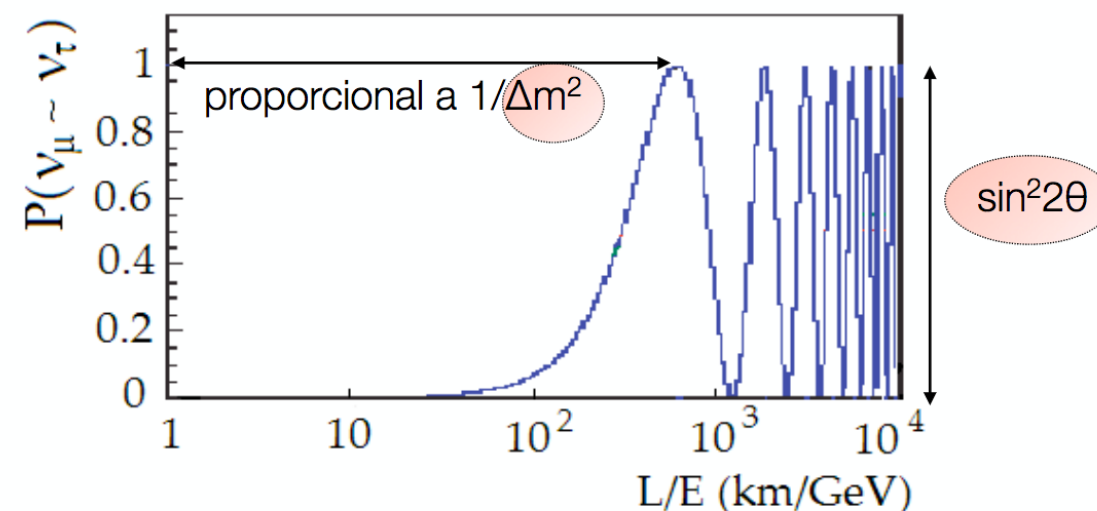
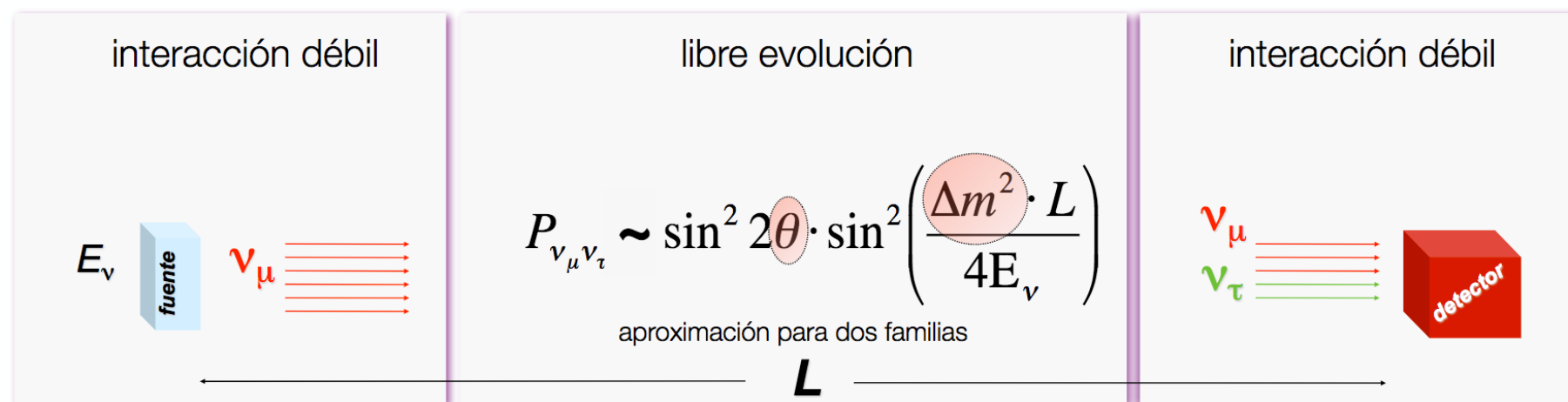
- Spanish groups provide important and in many ways crucial contributions to the T2K experiment
- Near Detector:
 - Magnet operations (IFAE), TPCs (IFAE and IFIC), near detector calibration, reconstruction and analysis
 - Conveners of the groups responsible of the data-taking coordination, neutrino interactions modelling, tracking, analysis framework development, “exotics” physics searches
- UAM actively participates in the Super-Kamiokande calibrations + work on Gd addition
- Further work beyond current activities:
 - T2K+SK+reactors global fit (IFIC+UAM with T2K-UK/Japan groups)
 - T2K ND280 analysis software for DUNE(-SP) analyses

NEUTRINOS...

- Chargeless and the very tiny pieces of matter, tiniest!
- Neutrinos provide a test-bench to probe physics beyond the Standard Model and further open horizons of mankind knowledge
- Search for the CP (charge-conjugation and parity) symmetry violation (CPV) in the neutrino(lepton) sector
 - Considered as a mandatory condition for the matter dominance (over antimatter) in the Universe
 - What is the nature of the neutrino itself? is it its own antiparticle?
 - Does neutrino have impact on the dark matter?
 - Are there “so far hidden” effects? sterile neutrinos, heavy neutrinos?
- Beckoning neutrino quest here in IFIC-UV-CSIC Valencia

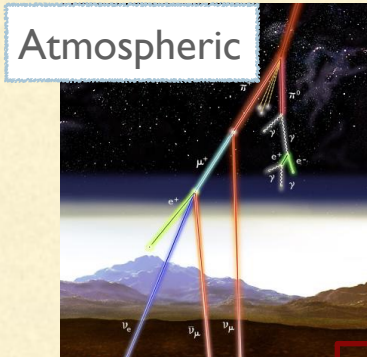
NEUTRINO OSCILLATIONS

- Neutrinos mix and can change their flavour
- Oscillations - first prove that neutrinos have masses!



NEUTRINO OSCILLATIONS - MANY DIFFERENT SOURCES

Neutrino mixing:
Pontecorvo-Maki-
Nakagawa-Sakata
(PMNS) matrix



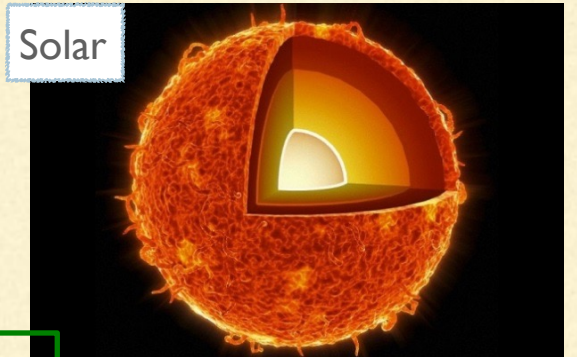
Atmospheric



Accelerator



Reactor



Solar

$$c_{ij} = \cos \theta_{ij}$$

$$s_{ij} = \sin \theta_{ij}$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

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

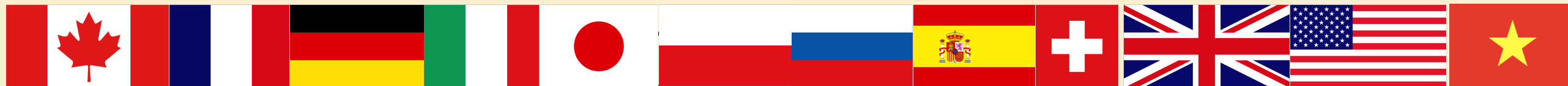
Oscillations governed by

- three mixing angles:
 - $\theta_{12} \approx 34^\circ$, $\theta_{13} \approx 9^\circ$, $\theta_{23} \approx 45^\circ$
- two mass squared differences:
 - $\Delta m_{21}^2 \approx 7.6 \times 10^{-5} \text{ eV}^2$ and $|\Delta m_{32}^2| \approx 2.4 \times 10^{-3} \text{ eV}^2$
- source-detector baseline and neutrino energy

NEUTRINOS WITH ACCELERATORS

- Neutrinos interact very rarely
- Need intense sources and big detectors
- Accelerators - a good option!
 - Neutrinos can be produced in (mostly) mesons decays
 - Powerful accelerators → intense beams
 - Does neutrino have impact on the dark matter?
 - Known energy → place a detector where expect maximum of oscillations probabilities

~500 members, 67 institutes, 12 countries



T2K Experiment International Collaboration

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.

Okayama U.

Osaka City U.

Tokyo Institute of Tech

Tokyo Metropolitan U.

U. Tokyo

Tokyo U. of Science

Yokohama National U.

Canada

TRIUMF

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

Poland

IFJ PAN, Cracow

NCBJ, Warsaw

U. Silesia, Katowice

U. Warsaw

Warsaw U. T.

Wroclaw U.

Russia

INR RAS

Spain

IFAE, Barcelona

IFIC, Valencia

U. Autonoma Madrid

Switzerland

U. Bern

U. Geneva

United Kingdom

Imperial C. London

Lancaster U.

Oxford U.

Queen Mary U. L.

Royal Holloway U.L.

STFC/Daresbury

STFC/RAL

U. Liverpool

U. Sheffield

U. Warwick

USA

Boston U.

Colorado S. U.

Duke U.

Louisiana State U.

Michigan S.U.

Stony Brook U.

U. C. Irvine

U. Colorado

U. Pittsburgh

U. Rochester

U. Washington

Vietnam

IFIRSE

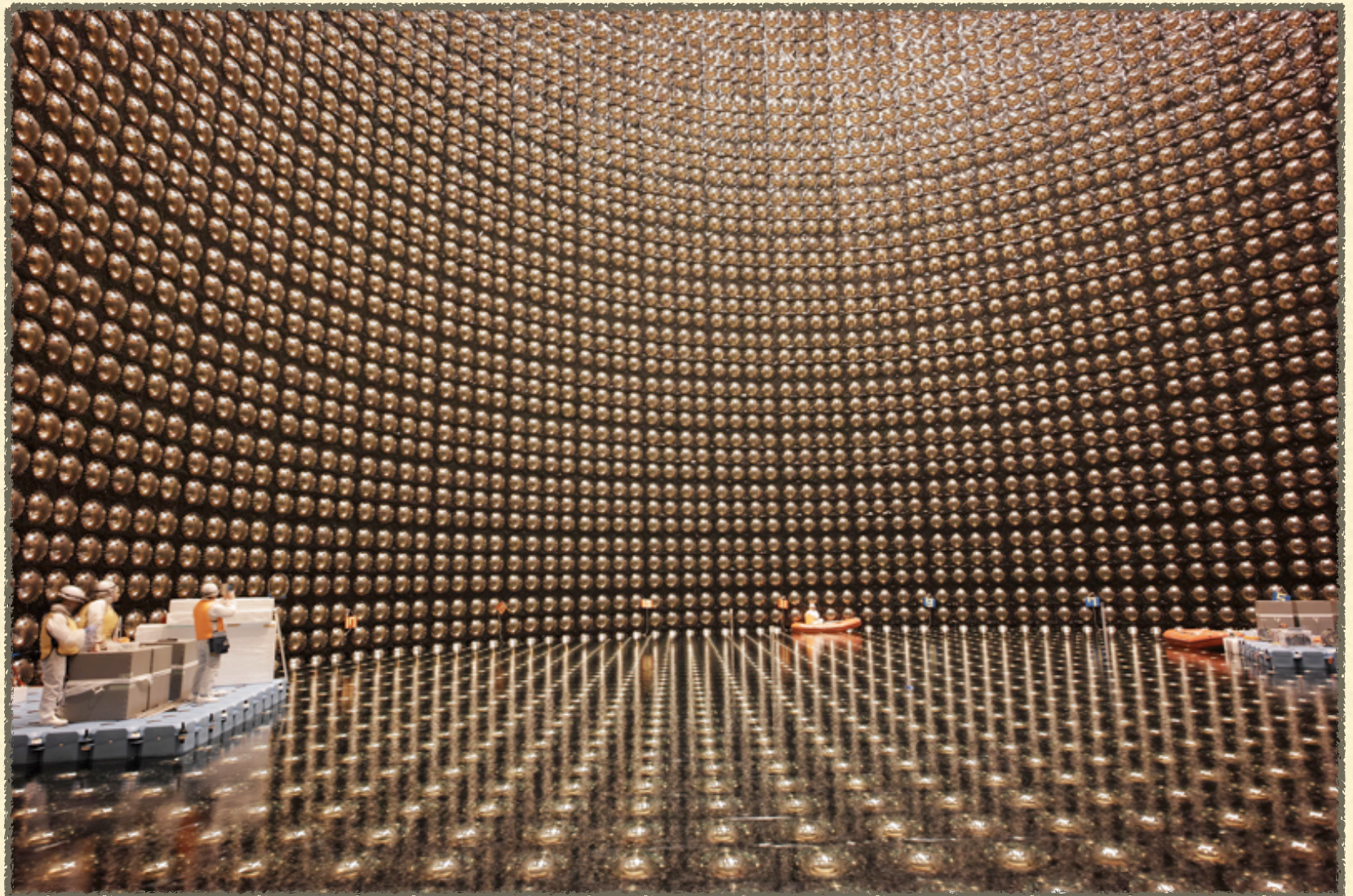
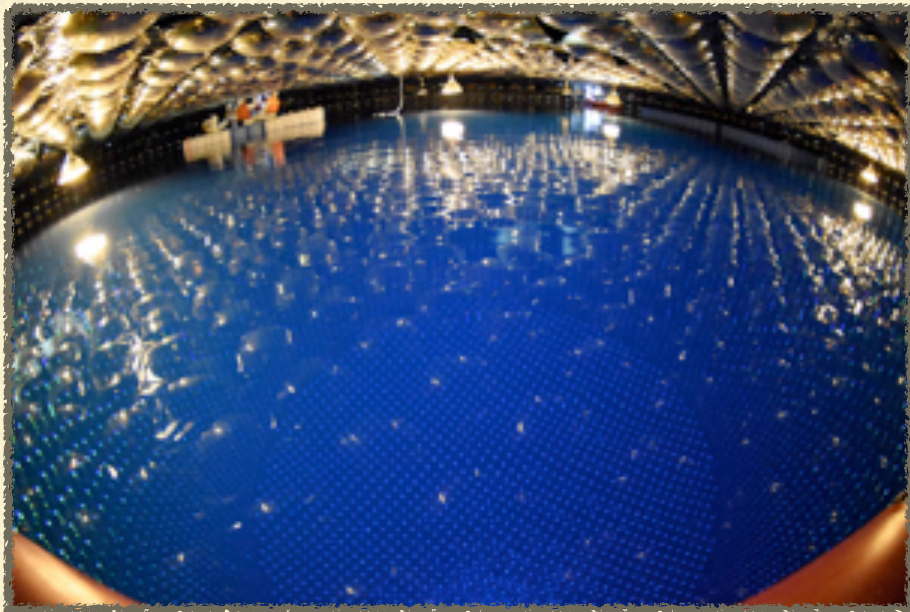
IOP, VAST

T2K IN JAPAN

- Why Japan?
- Neutrinos require large detectors to be detected + accelerators/reactors/stars/Universe as well
 - Significant efforts of engineers, scientists, constructors ...
 - Anselmo will explain the new DUNE project tomorrow
 - Better utilise multi-purpose detectors → more physics with less cost!
- And Japan has Super-Kamiokande!

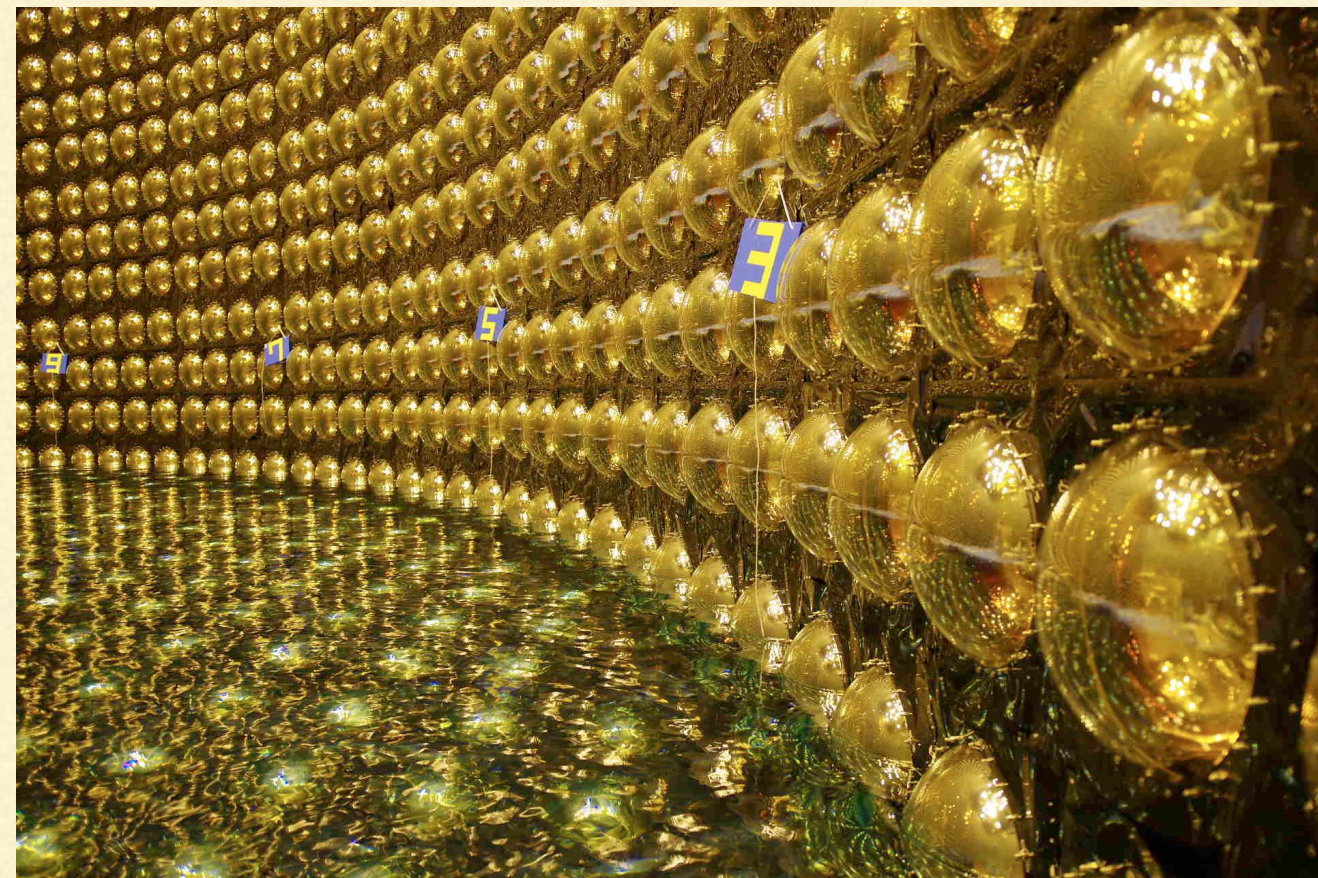
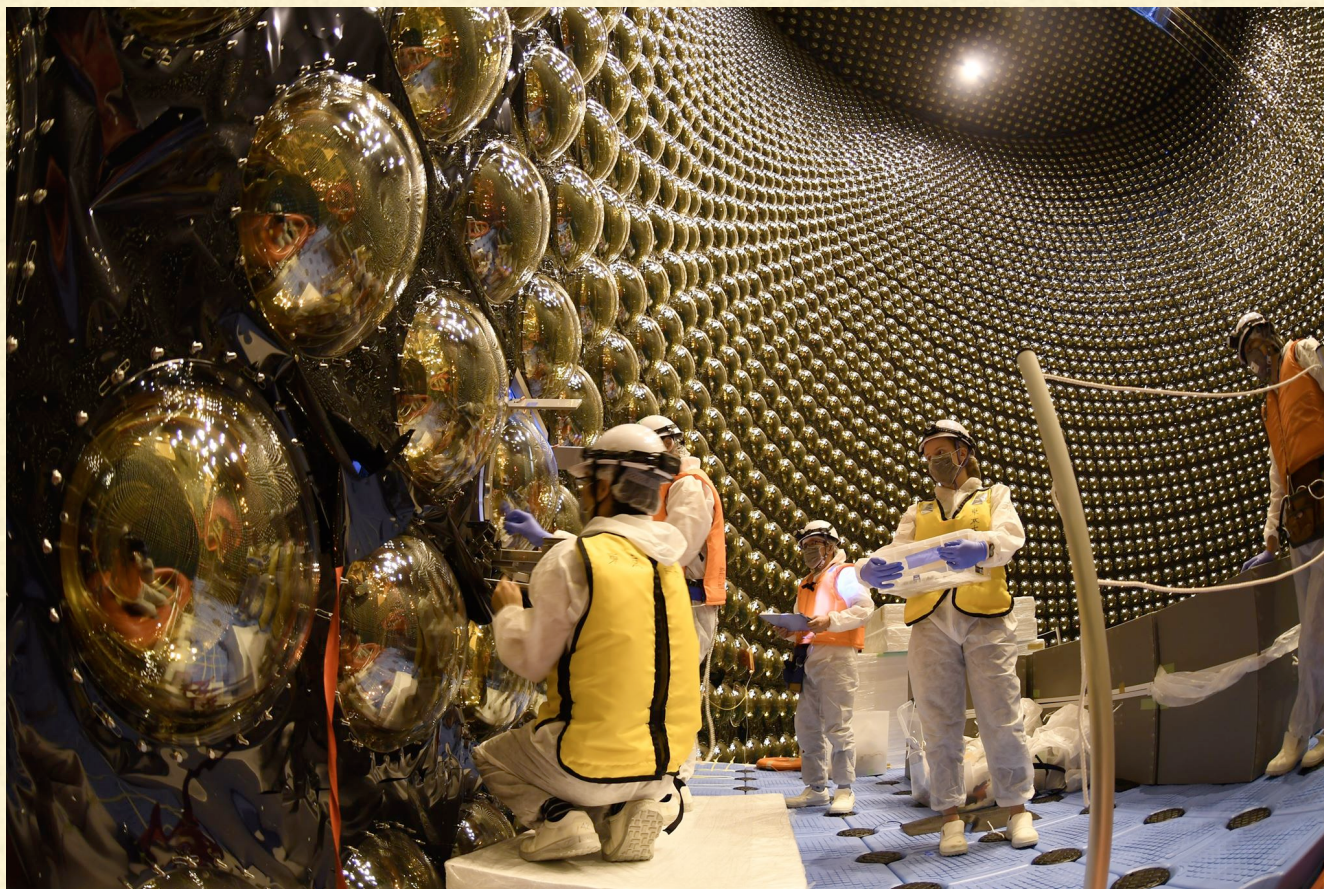
FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

- Originally started in 1980s to search for proton decays
- Then continued with solar, atmospheric and accelerator neutrinos
- KEK-to-Kamioka
- Tokai-to-Kamioka



FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

- Summer 2018 - new era with a well-cleaned and renewed detector



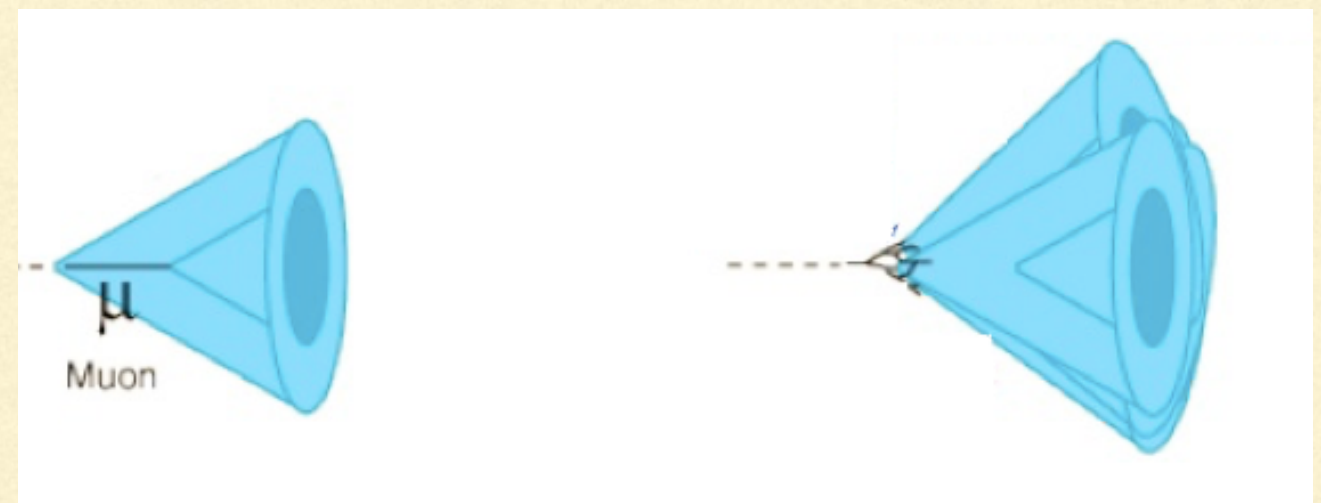
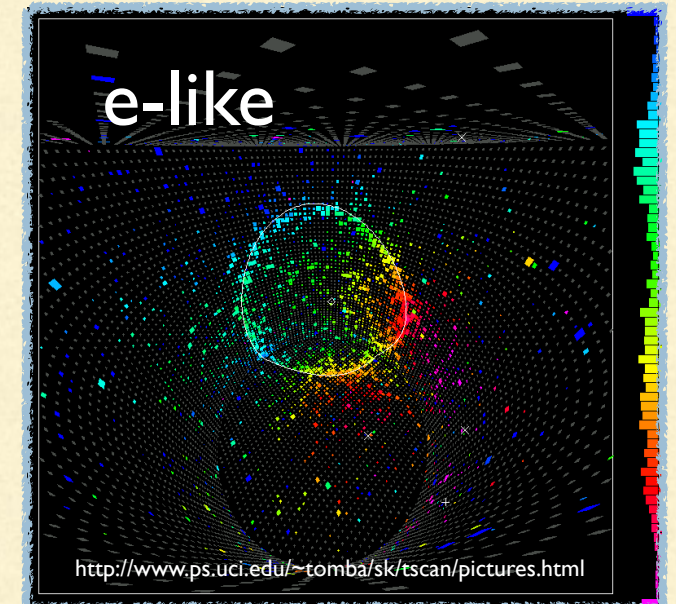
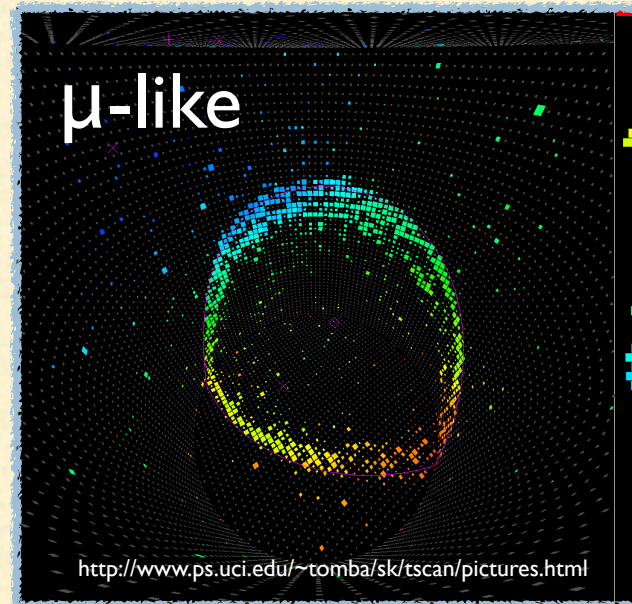
FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

- Summer 2018 - new era with a well-cleaned and renewed detector



FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

- 50 kton water-Cherenkov tank
- Separate e/ μ -like rings:
 - <1% misidentified μ as e
- π^0 rejection
- No magnetic field



- 5 Super-K samples used for analysis
- 1-ring μ and e-like events in ν and anti- ν modes + CC 1π e-like for ν mode

T2K IN JAPAN

- Deficiently some Japanese experiments
- <https://bit.ly/2LtrFc9>



T2K (TOKAI-TO-KAMIOKA) EXPERIMENT: NEAR DETECTORS

- Why near detectors?
- We need to understand our neutrino flux before they start to oscillate!
- We need to “tune” our models of neutrinos

