Probing neutrino-nucleus interactions using the T2K off-axis near detector.

Kevin Fusshoeller
ETH Zurich

Zurich PhD Seminar
10 October 2019
PSI, Switzerland

Outline

1. Introduction
2. The T2K experiment
3. Measuring cross sections in neutrino experiments
4. Building a selection
5. Outlook

1. Introduction

What are neutrinos?

- Neutral particles (Q = 0).
- Extremely abundant.
- 3 different flavours:

ν_e ν_μ ν_τ

- Very light mass (m_ν < 1 eV).
- Only interact via the weak force.

Why are they interesting?

- Mass of neutrinos is the first evidence of physics beyond the Standard Model (m_ν = 0 in the SM).
  → Neutrino oscillations.
  → Possible CP violation in the leptonic sector.
    → Matter/Antimatter asymmetry in the universe.
- Sterile (non-interacting massive) neutrinos.
  → Dark matter candidate.

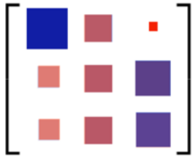
Neutrino oscillations?

Neutrinos have two different eigenstates:

- ***Flavor*** eigenstates → interactions
- ***Mass*** eigenstates → propagation

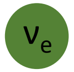
Credit: Fermilab/Sandbox Studios

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



$$\begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

Example:



An **electron-neutrino** is created in the fusion reactions of the sun.

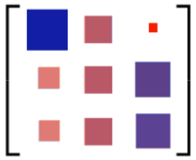
Neutrino oscillations? 

Credit: Fermilab/Sandbox Studios

Neutrinos have two different eigenstates:

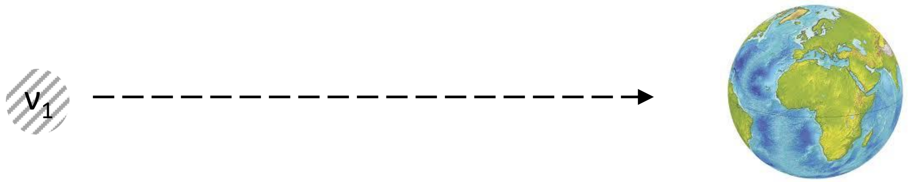
- ***Flavor*** eigenstates → interactions
- ***Mass*** eigenstates → propagation

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



$$\begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

Example:



The neutrino will propagate as one of the possible **mass states**.

Neutrino oscillations?

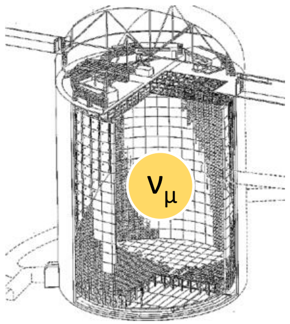
Credit: Fermilab/Sandbox Studios

Neutrinos have two different eigenstates:

- ***Flavor*** eigenstates → interactions
- ***Mass*** eigenstates → propagation

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} = [\text{matrix of coloured squares}] \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

Example:



The neutrino *interacts* within a neutrino detector. Since the mass state is a linear combination of the flavor states, it‘s possible that we measure a **muon-neutrino**.

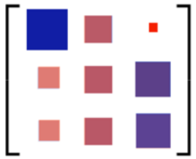
Neutrino oscillations?

Neutrinos have two different eigenstates:

- ***Flavor*** eigenstates → interactions
- ***Mass*** eigenstates → propagation

Credit: Fermilab/Sandbox Studios

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



$$\begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

We can describe neutrino oscillations with 6 parameters:

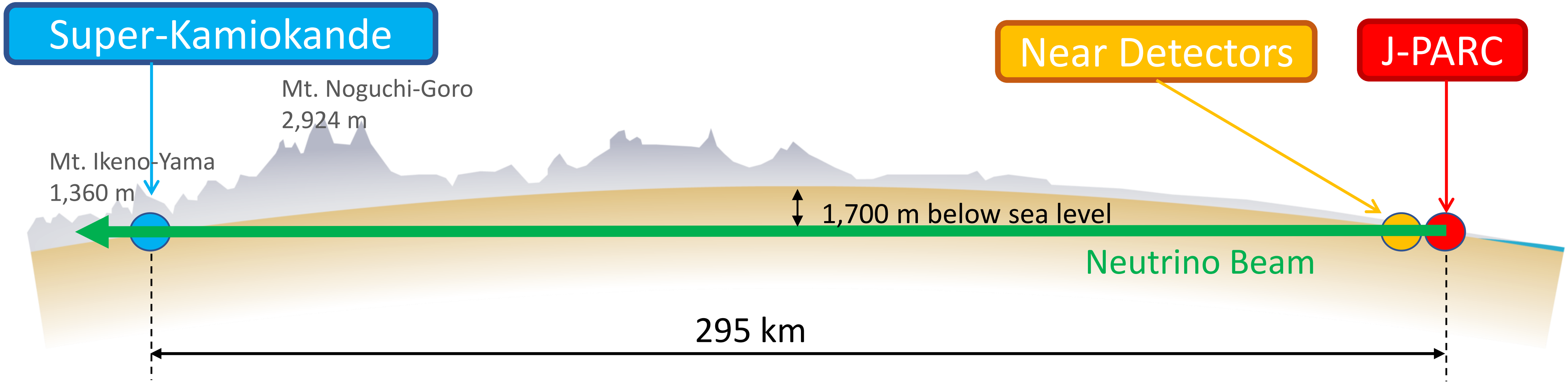
- 2 mass differences: Δm^2_{31} , Δm^2_{21} ($\Delta m^2_{ij} = m^2_i - m^2_j$)
- 3 angles: θ_{12} , θ_{13} , θ_{23} ($c_{12} = \cos\theta_{12}$, $s_{12} = \sin\theta_{12}$)
- 1 CP-violating phase: δ_{CP}

Current status

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$
$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$	$0.582^{+0.015}_{-0.018}$	$0.433 \to 0.623$
$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$	$49.7^{+0.9}_{-1.0}$	$41.2 \to 52.1$
$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$	$0.02263^{+0.00065}_{-0.00066}$	$0.02067 \to 0.02461$
$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$	$8.65^{+0.12}_{-0.13}$	$8.27 \to 9.03$
$\delta_{CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$	$-2.512^{+0.034}_{-0.031}$	$-2.606 \to -2.413$

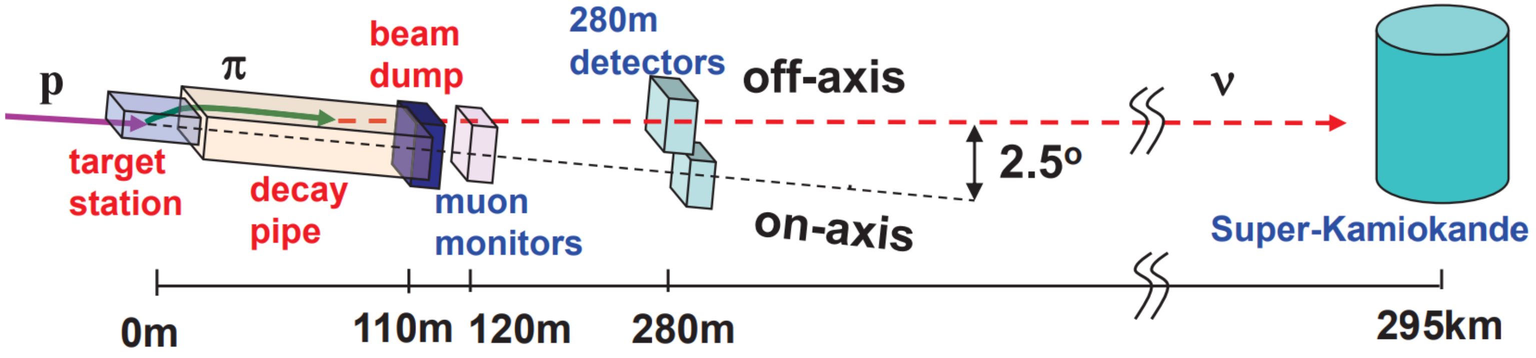
Still unknown: sign of Δm^2_{31} , value of δ_{CP} .

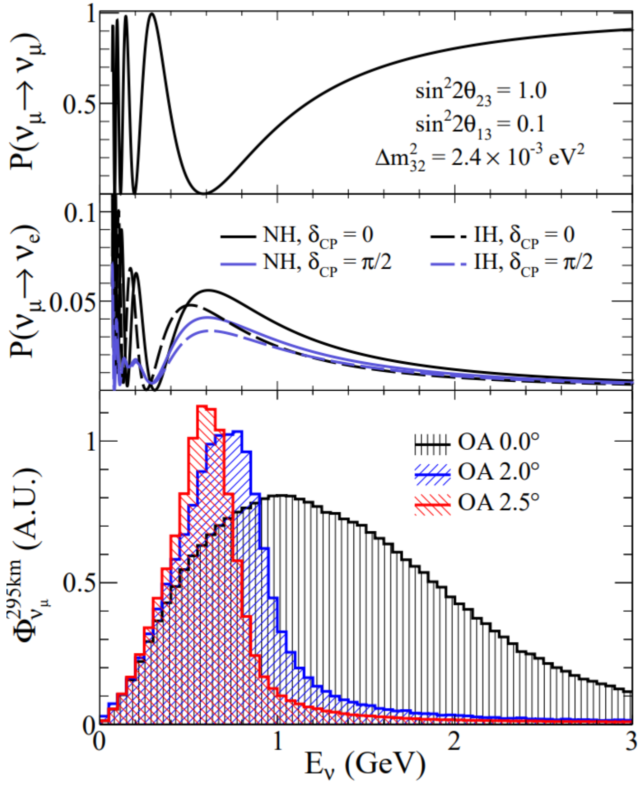
2. The T2K Experiment



- T2K is a long baseline neutrino experiment measuring oscillations of neutrinos as they travel through Earth.
- Goals: measure θ_{13} , θ_{23} , δ_{CP} and neutrino-nucleus cross sections.
- **J-PARC:** high-intensity neutrino beam factory.
- **Far Detector**: measures the oscillated neutrino beam.
- **Near Detectors:** measure the unoscillated neutrino beam.

How do you create a neutrino beam?

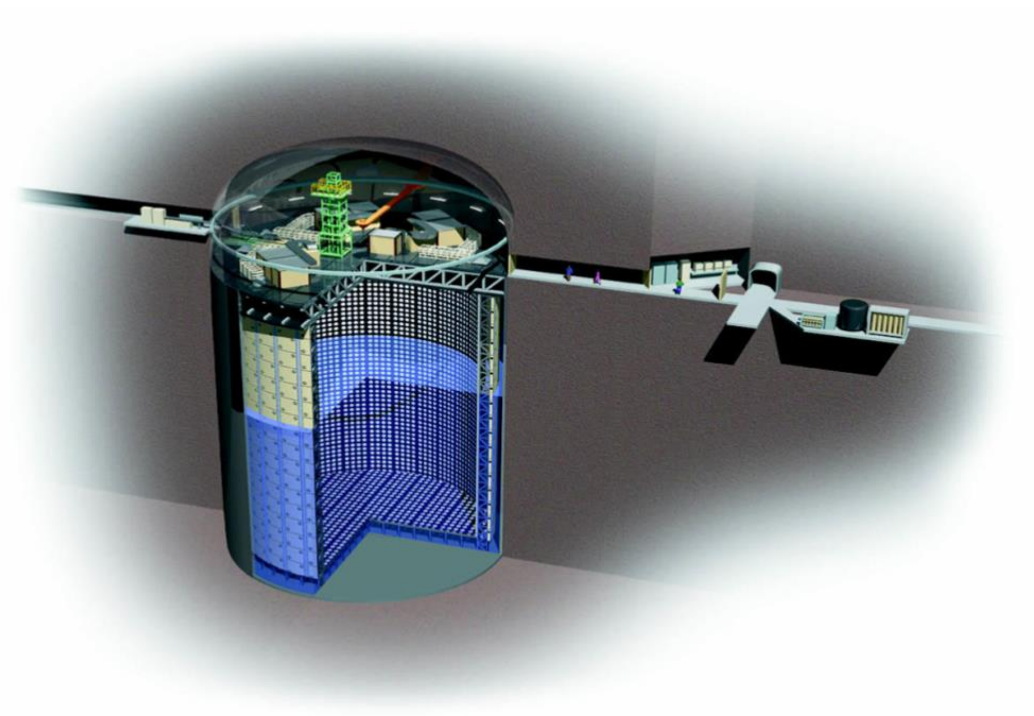


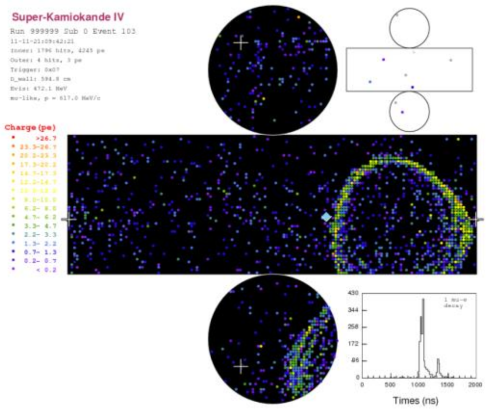


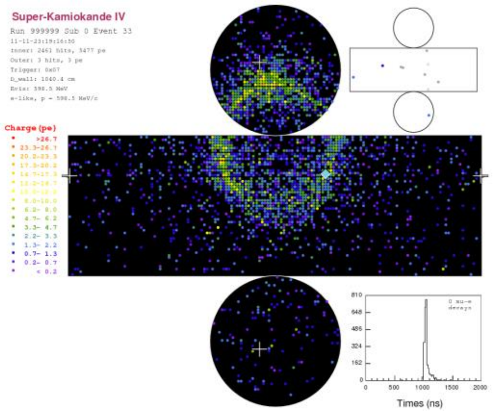
- 30 GeV protons collide with a carbon target.
- Positive (negative) pions decay into anti-muons (muons) and (anti-) muon-neutrinos.
- Two modes of neutrino beams can be created thanks to magnetic horns focusing negative or positive pions.
- All particles except the neutrinos are stopped in a beam dump.
- Beam is sent at a 2.5° angle for a narrower energy spectrum peaking at the oscillation maximum.

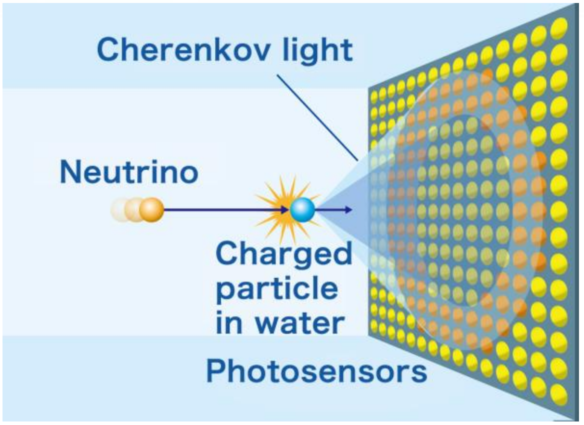
The Far Detector: Super-Kamiokande

- Water Cherenkov detector situated 1000 m underground in the Kamioka-mine.
  → Low cosmic background.
- 50000 tons of ultra-pure water.
  → Low radioactive background.
- Detector split into inner detector with 11129 PMTs and outer detector with 1885 PMTs.
  → Additional protection against cosmic rays.
- Muons and electrons distinguished by „fuzziness“ of ring.



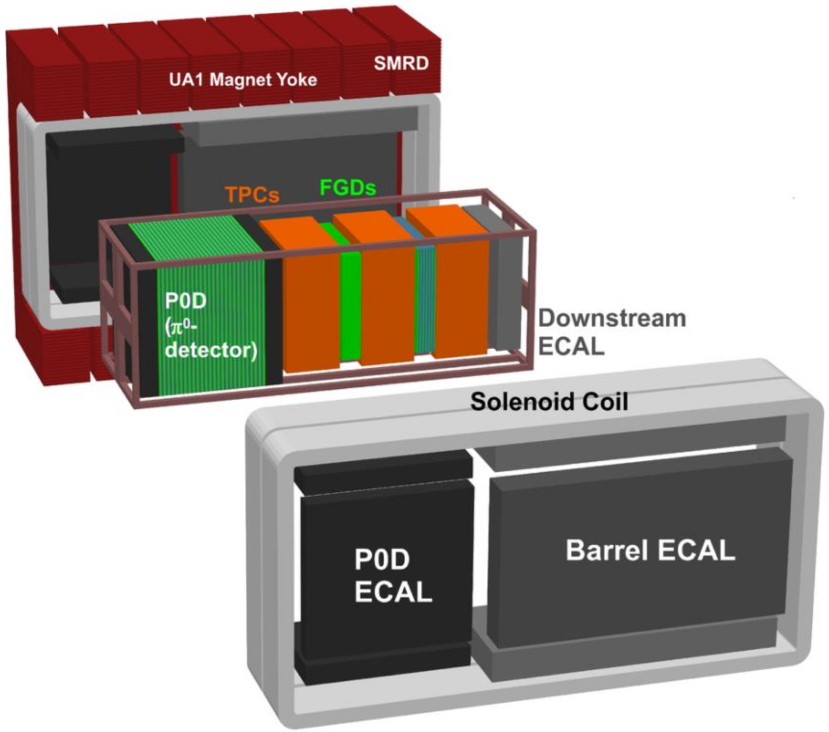






The off-axis Near Detector: ND280

- Situated at 280 m from the accelerator.
- Fully magnetised detector.
  → Can measure if anti-/neutrino.
- 2 fine-grained detectors (FGDs) act as target for the neutrinos.
- 3 argon time projection chambers (TPCs) act as tracker.
  → Measure momentum and charge of particles.
- π^0-detector measures neutral pions.
- The detector is encased in electromagnetic calorimeters (ECALs).
  → Measure photons.
- Goals:
  - Measure unoscillated neutrino spectrum.
  - Measure neutrino-nucleus cross sections.



3. Measuring cross sections in neutrino experiments

Why neutrino-nucleus cross sections? 😴

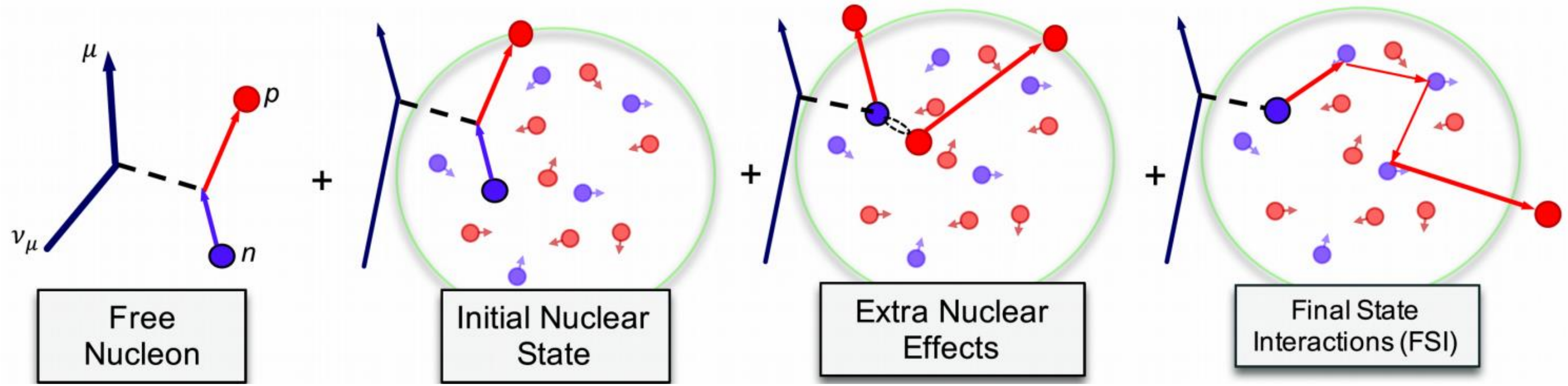
	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.80	13.15	1.47
SK FSI+SI+PN	2.21	1.98	3.00	2.31	11.43	1.57
Flux + Xsec constrained	3.27	2.94	3.24	3.10	4.09	2.67
E_b	2.38	1.72	7.13	3.66	2.95	3.62
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	0.00	0.00	1.09	2.60	0.33	1.50
NC Other	0.25	0.25	0.15	0.33	0.99	0.18
Osc	0.03	0.03	2.69	2.49	2.63	0.77
All Systematics	5.12	4.45	8.81	7.13	18.38	5.96
All with osc	5.12	4.45	9.19	7.57	18.51	6.03
Statistical	6.42	8.45	11.55	25.82	25.82	/

→ Statistical errors are approaching the systematic erros.

→ Just amassing more data will not help in the future.

Challenges of neutrino-nucleus cross section measurements

1. Neutrinos can interact with every nucleon inside a nucleus.
   → Need to know the initial state of the nucleon → nuclear models.
   → Excited nucleons can undergo other nuclear effects.
   → Ejected nucleons scatter repeatedly before exiting the nucleus (final state interactions).



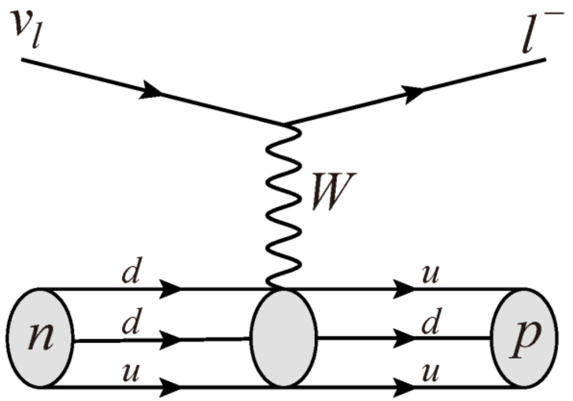
→ Difficult to infer the initial state of the neutrino from the final state.

Challenges of neutrino-nucleus cross-section measurements

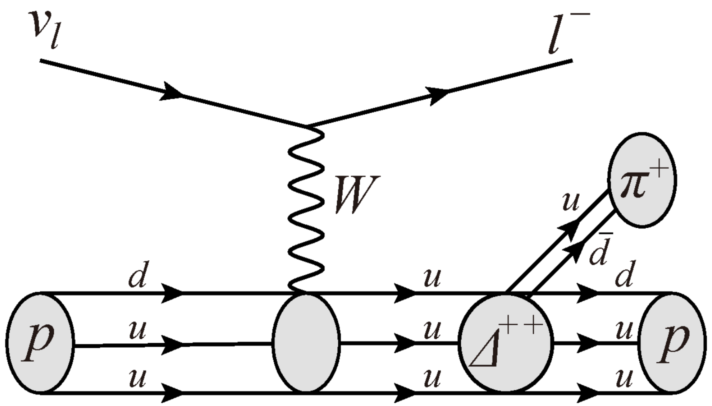
2. Neutrinos only interact weakly:
   → Many usely rare processes contribute to the cross section.
      → Not all the processes can easily be disentangled.

Example:

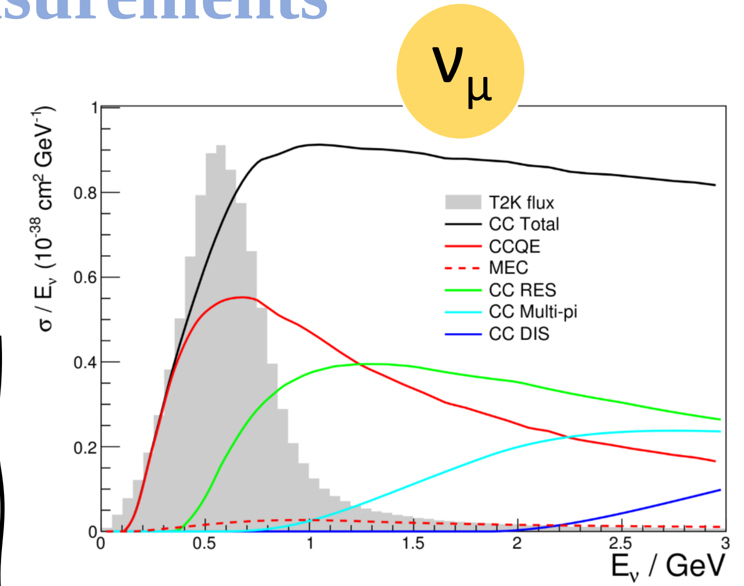
CCQE

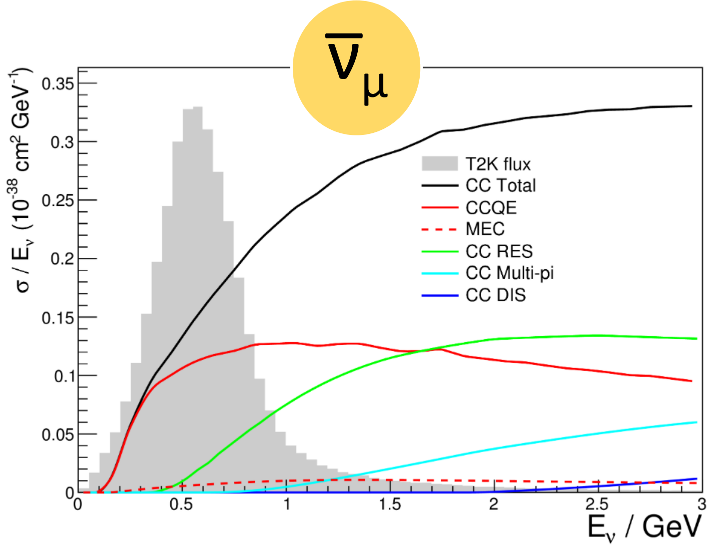


CCRes



Pion can be reabsorbed by the nucleus and fake a CCQE interaction.





Solving these challenges

Idea:

Define *model-independent samples* using final state signals:

- CC0pi: 1 muon, 0 pions. Most CCQE-like signal. Main background comes from CCRes interactions.
- CC1pi: 1 muon, 1 pion. Most CCRes-like signal. Main background comes from DIS.
- CCOther: all other. Many contributions.

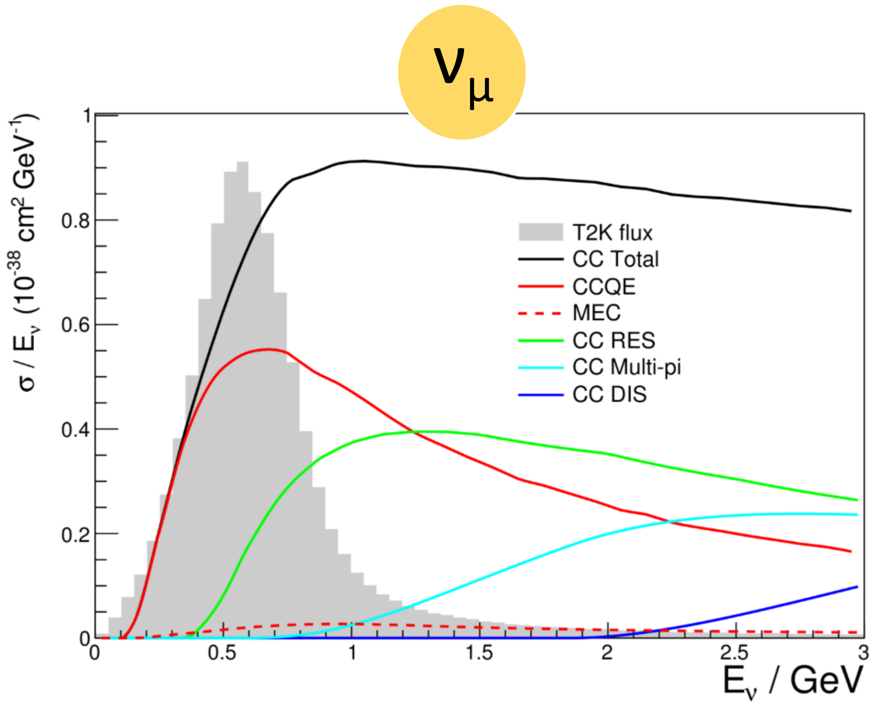
→ model-independent cross section measurement.

But: CC0pi and CC1pi share contributions from CCRES

→ Instead of treating the CC1pi sample as background, we could treat it as signal.

→ Fit CC0pi and CC1pi together and catch correlations between parameters.

→ Constrain interaction models.



4. Building a selection

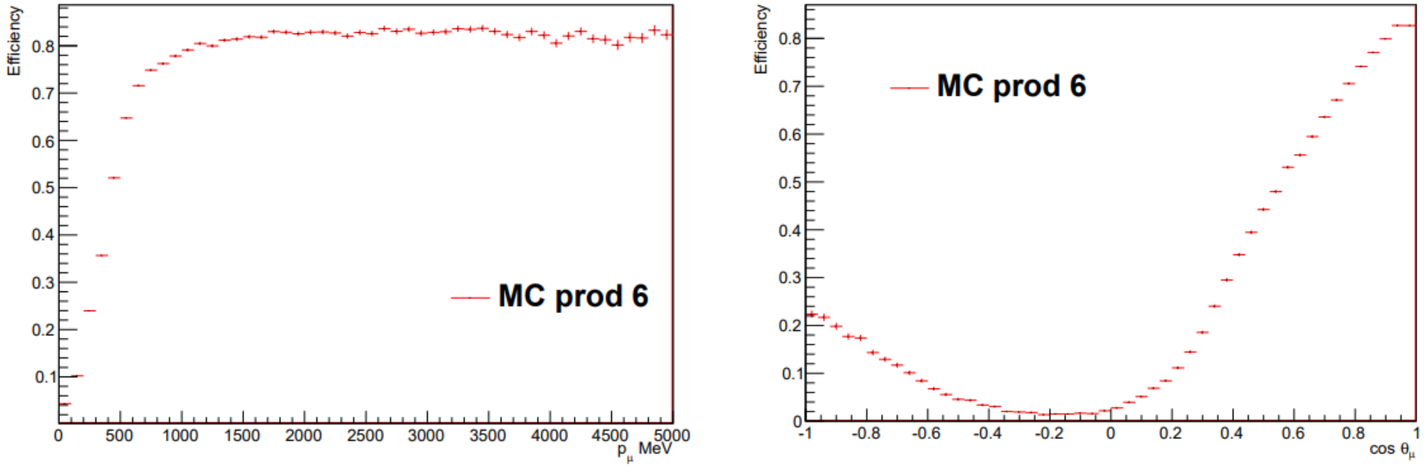
What do we want to select?

- CC0pi events: 1 muon, no pions.
- CC1pi events: 1 muon, 1 pion.

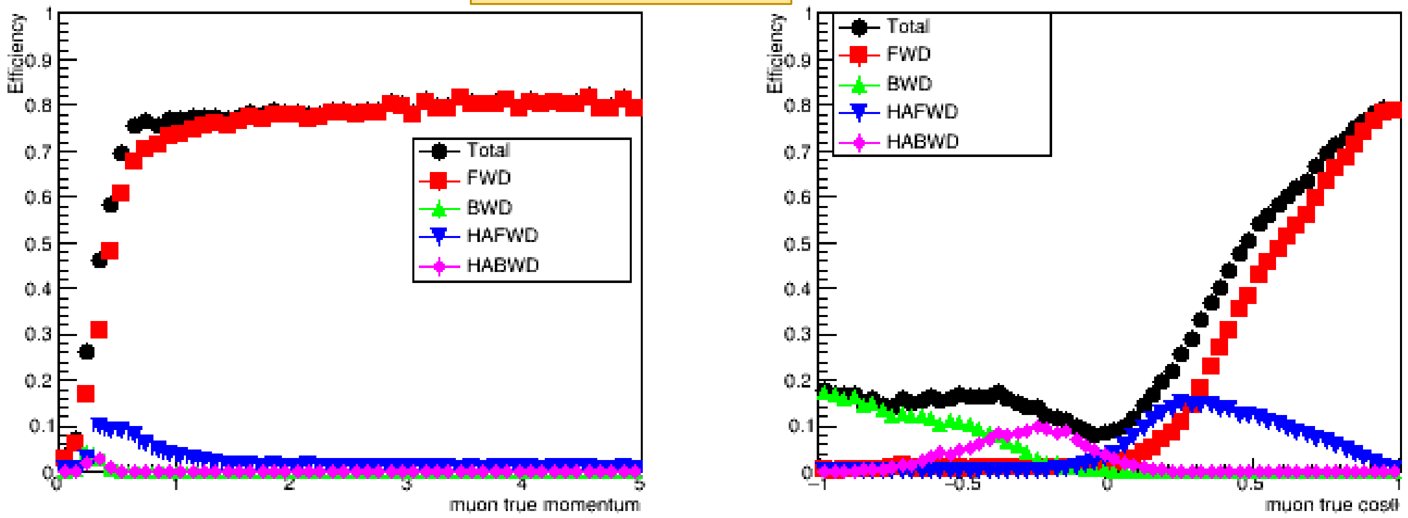
→ Start by selecting the muon (CC inclusive selection) and later the pions.

- Challenges:
  - No model dependance in cuts.
  - Purity of the samples.
  - Good coverage of full phase space.

Previous Selections



New Selection



- Efficiencies as a function of true muon kinematics for selections similar to the official selection (top) and for the new selection (bottom).
- Efficiency is increased by 15-20% for tracks going at high angle.

Purities and Backgrounds

CC0pi	Purity	CC1pi Background
FWD	79.99	9.5
HAFWD	79.91	7.04
BWD	74.05	1.87
HABWD	72.16	3.33

CC1pi	Purity	Main Background
FWD	76.40	CC Other
HAFWD	75.71	CC Other
BWD	58.81	CC Other
HABWD	67.55	CC Other

- Good purity in most samples.
- Combined with improved coverage, this represents a great improvement with respect to previous selections.

5. Outlook

Outlook

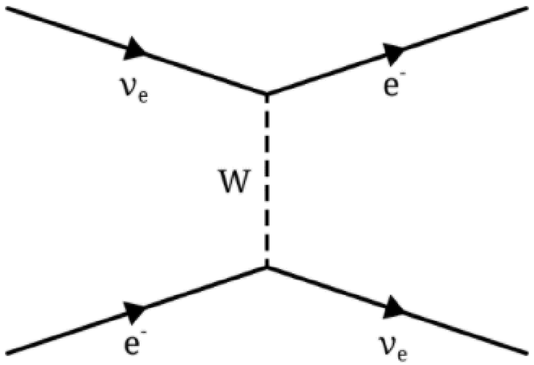
- After the events are selected, one can extract a cross-section.
- Method: take the data as input and unfold into truth space to compare to models.
- Unfolding done with template likelihood fitter.

Summary

- Cross section measurements are important to reduce systematic errors for future neutrino experiments.
- Successfully built a selection with good purity in both CC0pi and CC1pi samples and an improved coverage of high angle tracks.

Backup Slides

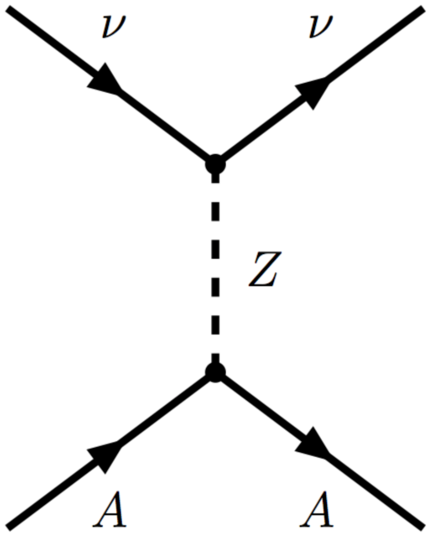
How can we measure the mass hierarchy



- We can measure the sign of a mass difference thanks *only* to the so-called matter effect or MSW effect.

What is the matter effect?

- Neutrinos travelling through matter can scatter elastically.
- Electron neutrinos more likely to scatter.
  → Symmetry between flavours is broken
  → Oscillation probability now also affected by density of medium that is being traversed.

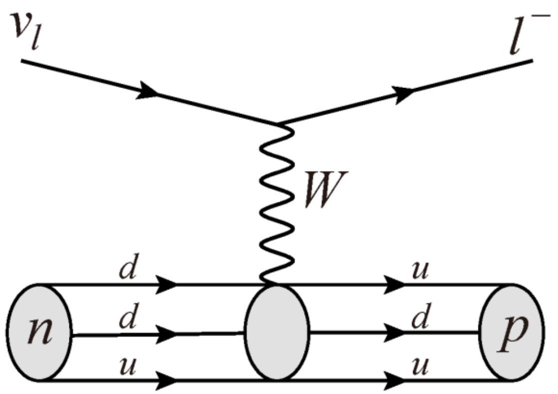


→ Δm^2_{21} known thanks to solar neutrinos (mostly electron-neutrinos at start).

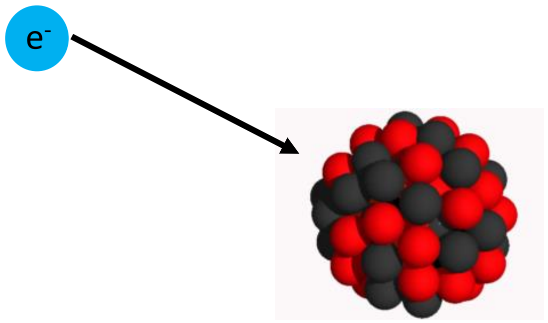
→ For Δm^2_{31} we need to shoot accelerator neutrinos (mostly muon-neutrinos at start) through Earth.

How to measure/detect a neutrino?

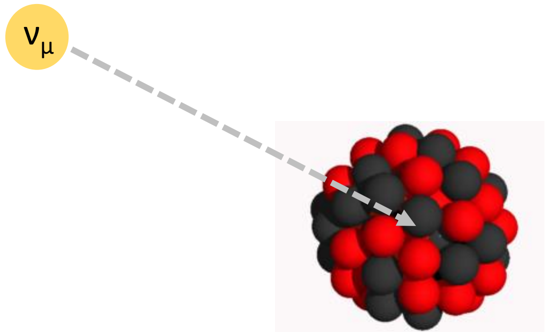
- We cannot detect the neutrino itself, but the product of its interactions.
- For a charged-current interaction, the signal is that of an ***appearing lepton***.
- Possible background:
  - Cosmic radiation
  - Radioactivity
  - Neutrinos
- Neutrinos have a very low cross-section (insert number here)
  → Need large detectors or high-intensity beams.
  → Need low backgrounds and an excellent background rejection.
    → Pure materials with stable isotopes.
    → Cosmic vetos.



Why is measuring neutrino-nucleon cross sections so different?



- Electron interacts with the nucleons mainly via electromagnetic charge.
- It will therefore interact preferably with the nucleons on the surface, which are not strongly subject to the nuclear potential.

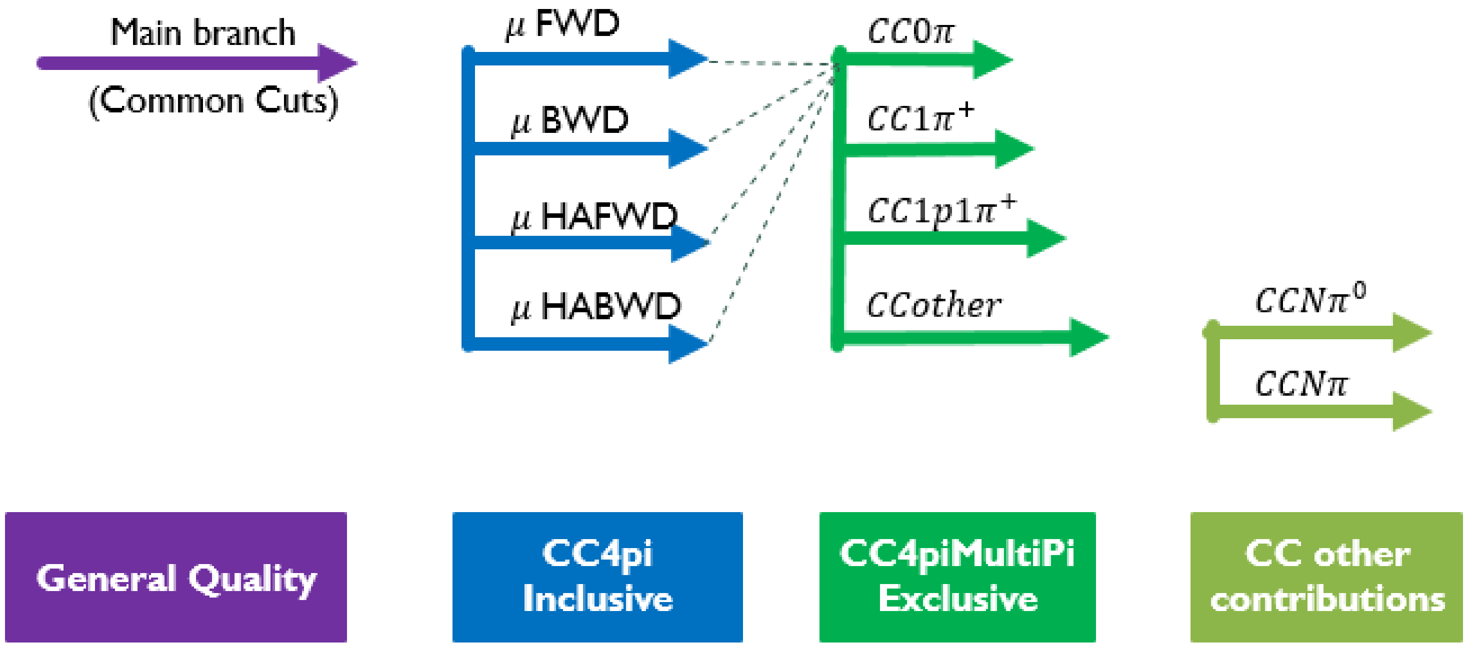


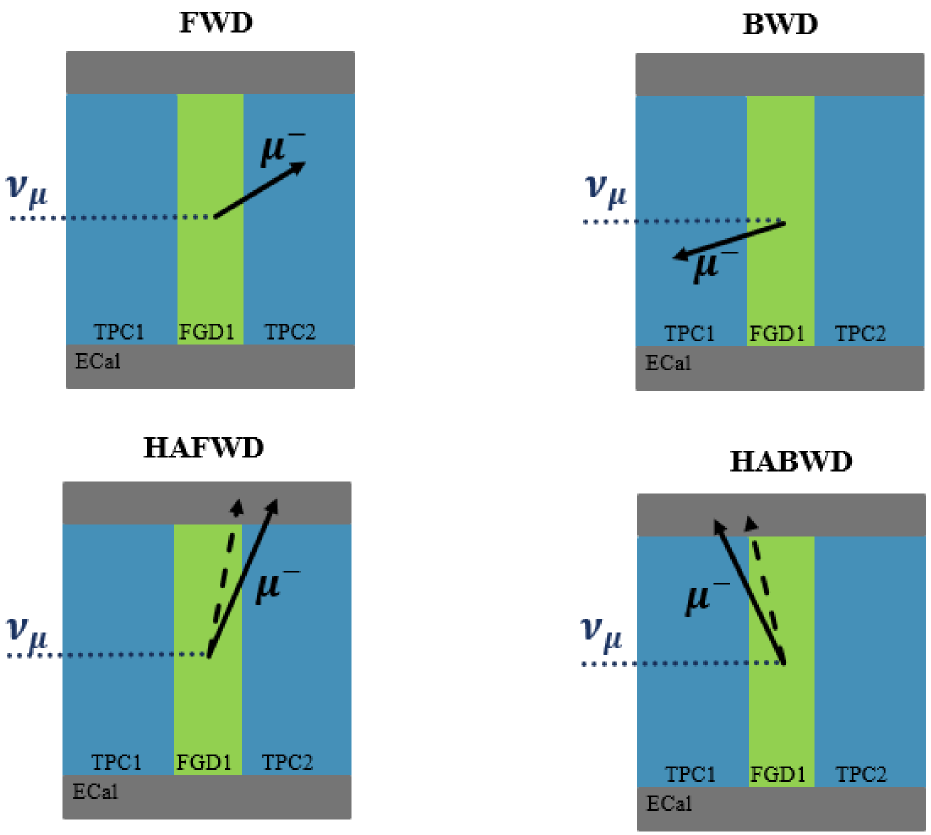
- Neutrino is neutral → does not see Coulomb potential.
- Interacts only weakly → does not see nuclear potential.

→ The neutrino can interact with nucleons deep inside the nucleus, which feel the nuclear potential strongly.

The selection

- The selection is implemented following the scheme below, where FWD mean forward, BWD backward and HA high angle.





→ In the end we have: 4 x (3+1 x 2) = 20 samples.

The selection cuts

General Quality	- Event Quality Cut - Total Multiplicity Cut - Sort Tracks Action - Track General Quality and FV Cut - Find Vertex Action - Veto Action - PID Action - Find Pions Action - FillSummaryAction_numuCC4piMultiPi			
CC4pi Inclusive	- Fwd Quality - Fwd Veto - Fwd PID	- Bwd Quality - Bwd Veto - Bwd PID	- HAFwd Quality - HAFwd Veto - HAFwd PID	- HABwd Quality - HABwd Veto - HABwd PID
CC4piMultiPi Exclusive	-No Pion Cut -ECal Pi0 Veto Cut	- One Pion Cut - Common Vertex 2 track FGD Cut - Find Correct Track Sense Action - ECal Pi0 Veto Cut	- One proton one Pion Cut - Common Vertex 3 track FGD Cut	- Others Cut
CC other contributions	-N number of neutral pions		-N number of pions (positive and negative))	