Measuring charged current ν_μ interactions with an outgoing π^+ using the ND280 detector of T2K

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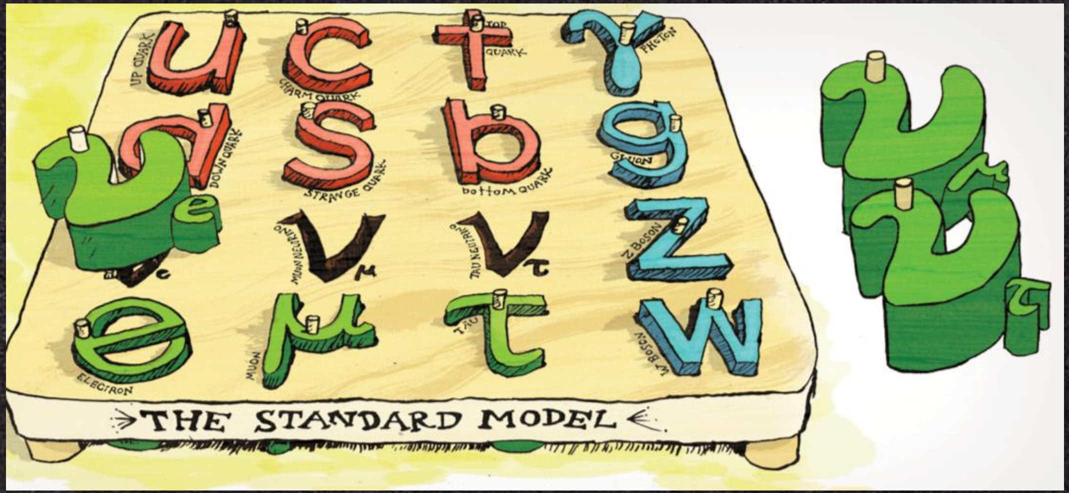
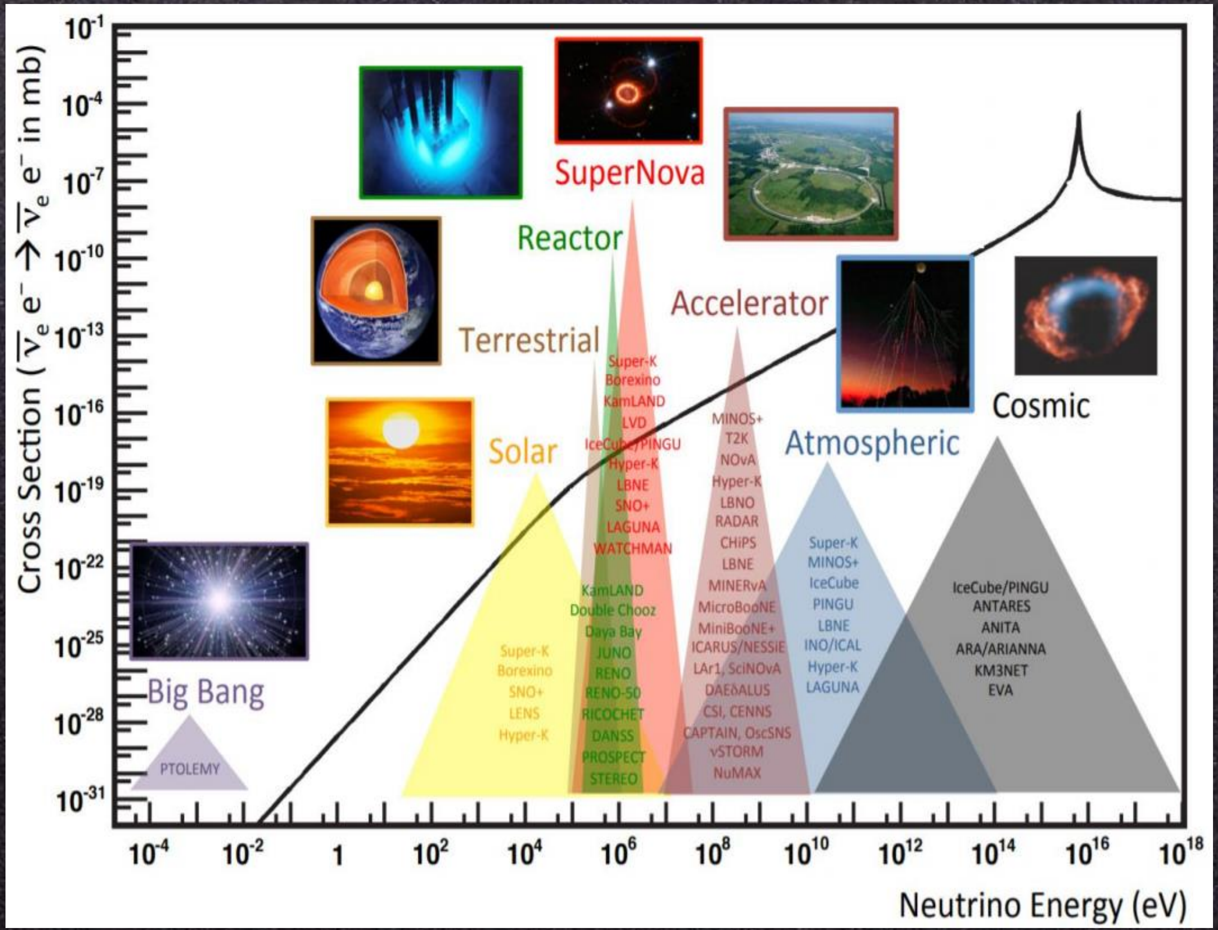
January 20th, 2021

Neutrinos in the standard model

- ✓ 3 flavors (ν_e, ν_μ, ν_τ) matched to charged leptons (e ,μ ,τ)
- ✓ Have no charge
- ✓ They have no mass ← **But this isn't true**
- ✓ They only interact through the weak force
- ✓ All this makes them basically… **INVISIBLE**



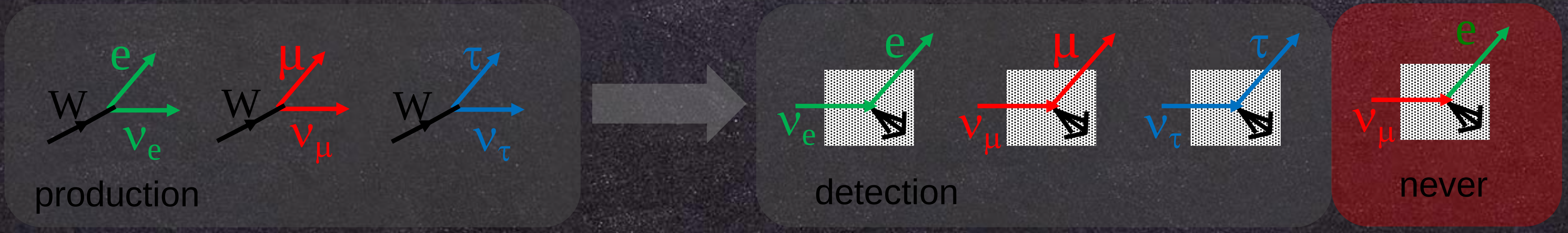


✓Neutrinos cover a wide spectrum of energy.

✓Detecting them involves using different techniques and detectors.

Neutrino (flavor) oscillation

The weak interaction couples the lepton of a flavor to the neutrino of its corresponding flavor.



Neutrino (flavor) oscillation

We extract: Rotation angle

We extract: Mass difference

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta_{23}) \sin^2\left(1.27 \frac{\Delta m^2_{32} L}{4E_\nu}\right)$$

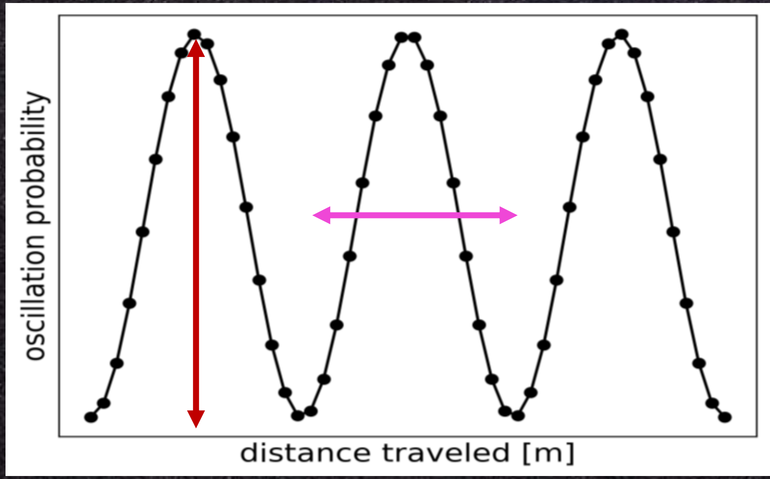
We know: Distance to the far detector (length of the neutrino's long journey)

We calculate: Probability of the neutrino changing flavor

We calculate: Neutrino flux energy

Note: Which means that at least one of them has to have mass for the oscillation to occur.

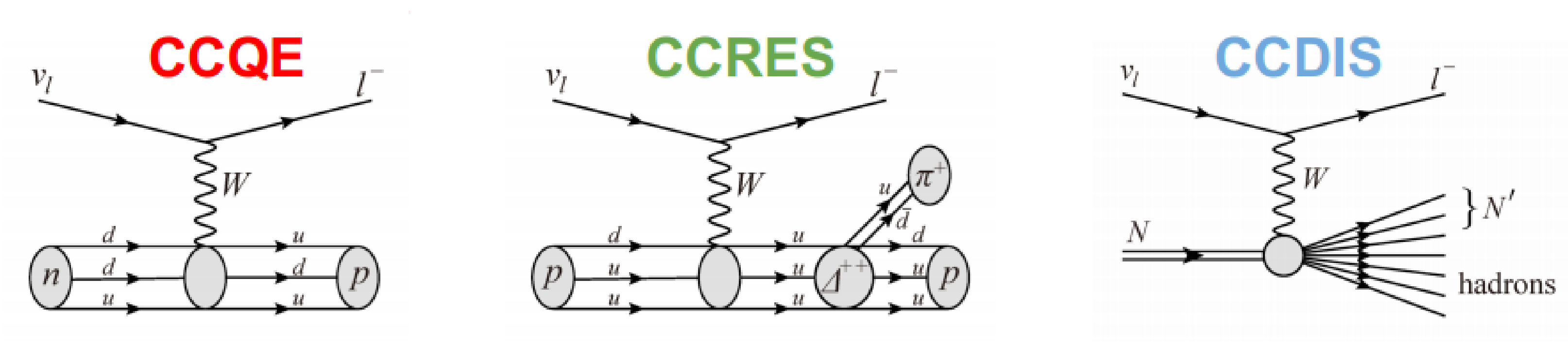
$$A = \sin^2(2\theta_{23}) \qquad \lambda = 1.27 \frac{\Delta m^2_{32}}{4E_\nu}$$



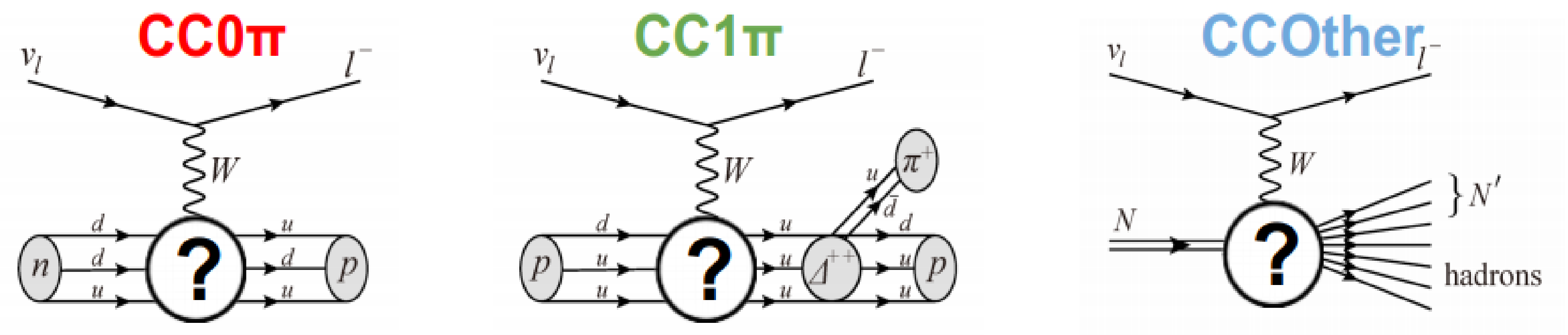
Neutrino interactions

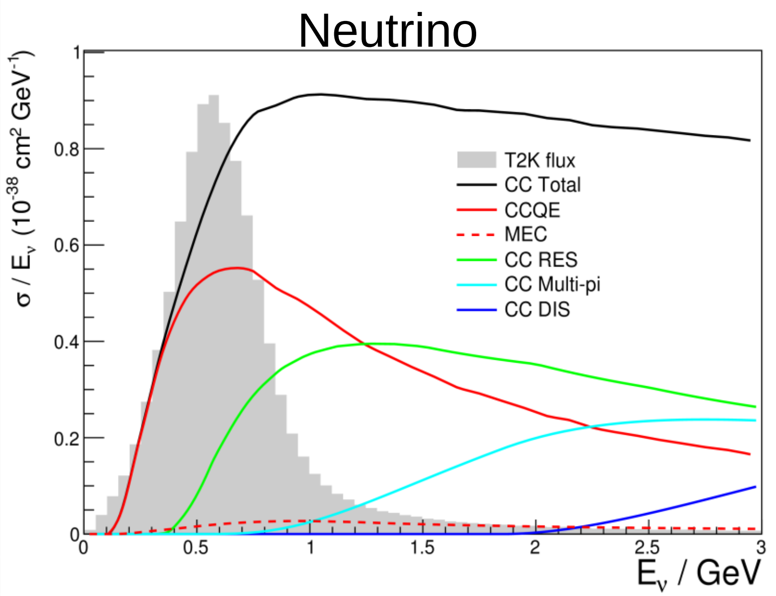
Three dominant scattering processes: Charged Current Quasi Elastic, Charged Current Resonant Pion Production, Charged Current Deep Inelastic Scattering

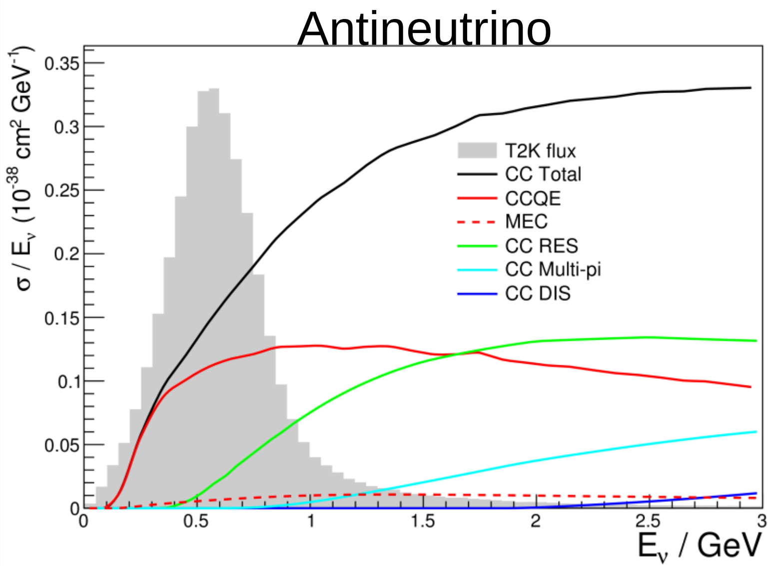
Interaction Modes (nucleon level)



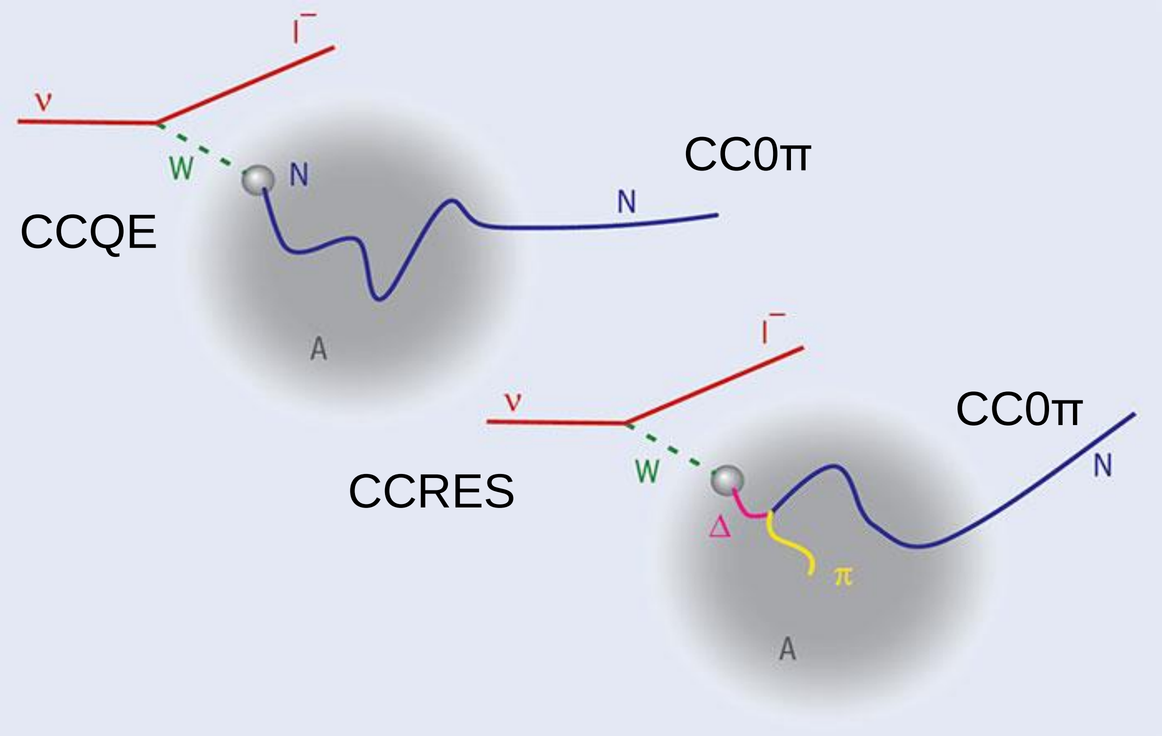
Interaction Topologies (nucleus level)

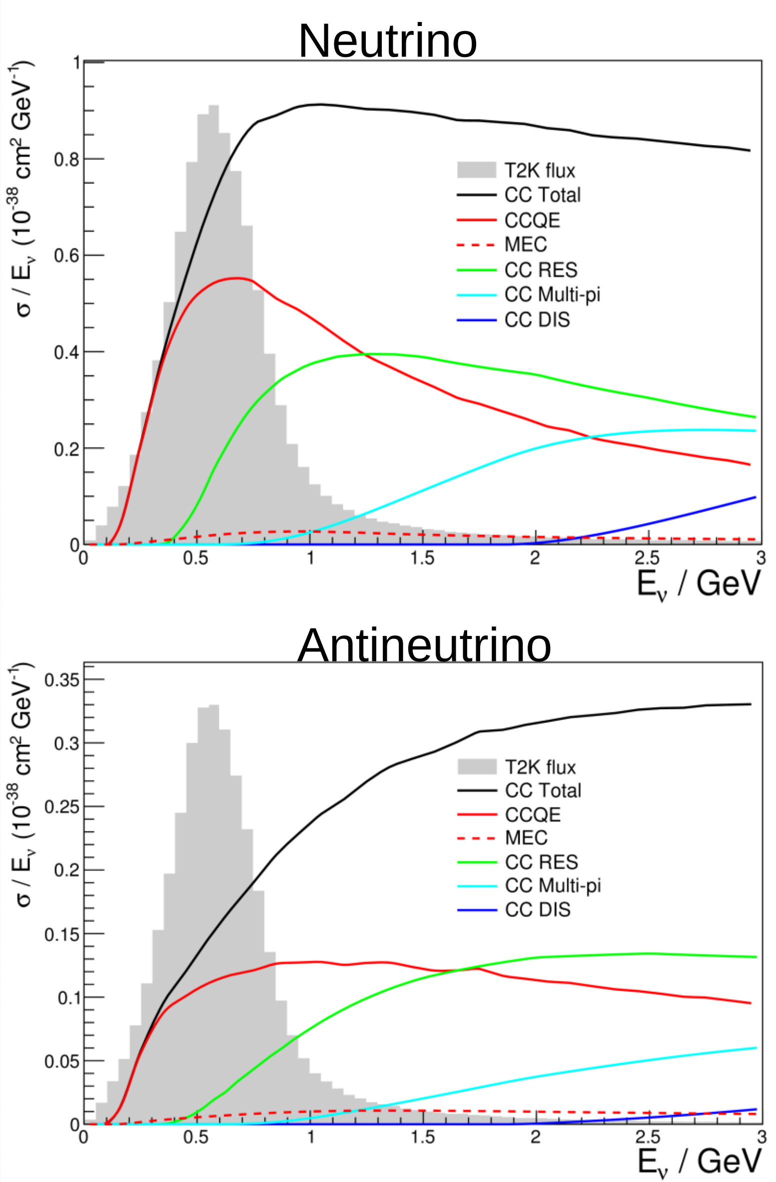






Final State Interaction

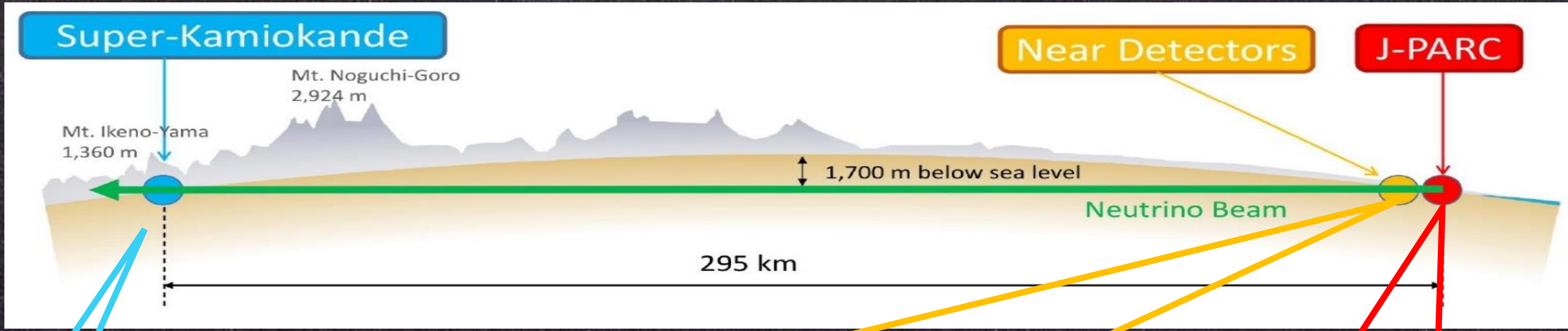


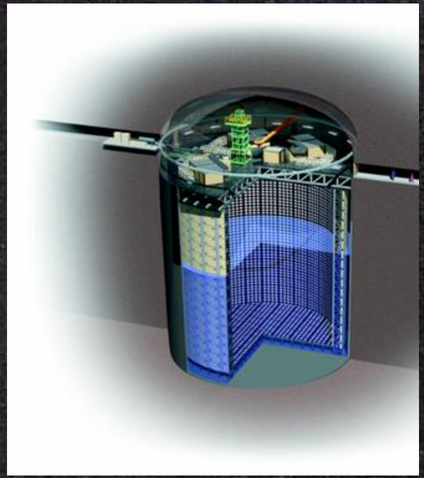


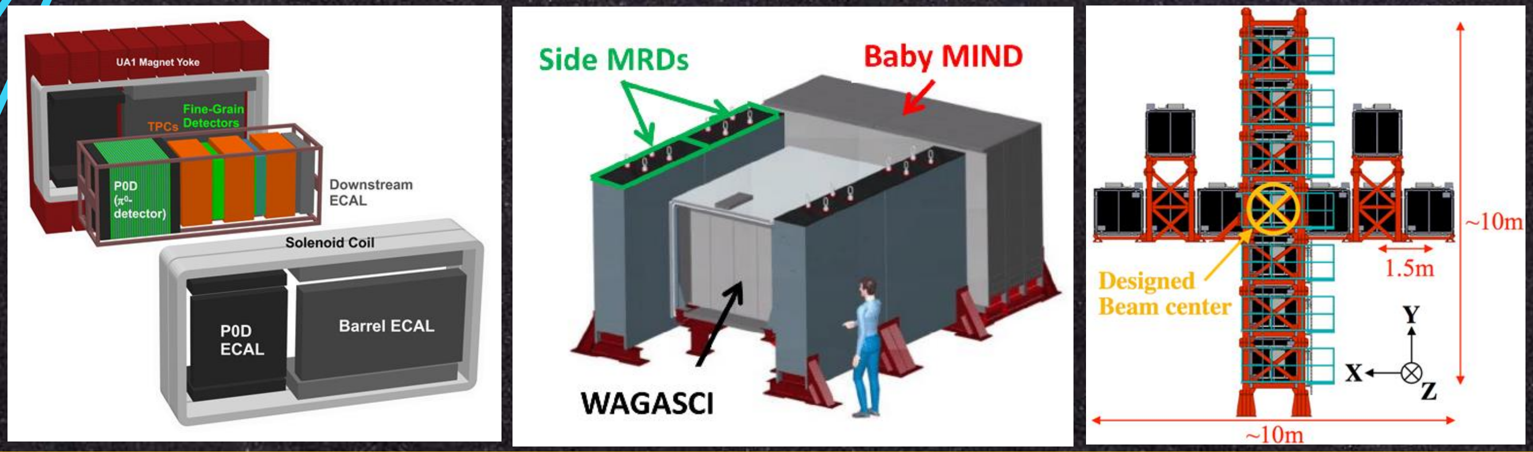
- Pions or nucleons can re-interact with the nuclear medium, or each other before leaving the nucleus.
- Changes outgoing particle content or kinematics in final state

T2K experiment

Main Goals: Measure the oscillation parameters $\theta_{13}, \theta_{23}, \Delta m^2_{32}, \delta_{CP}$







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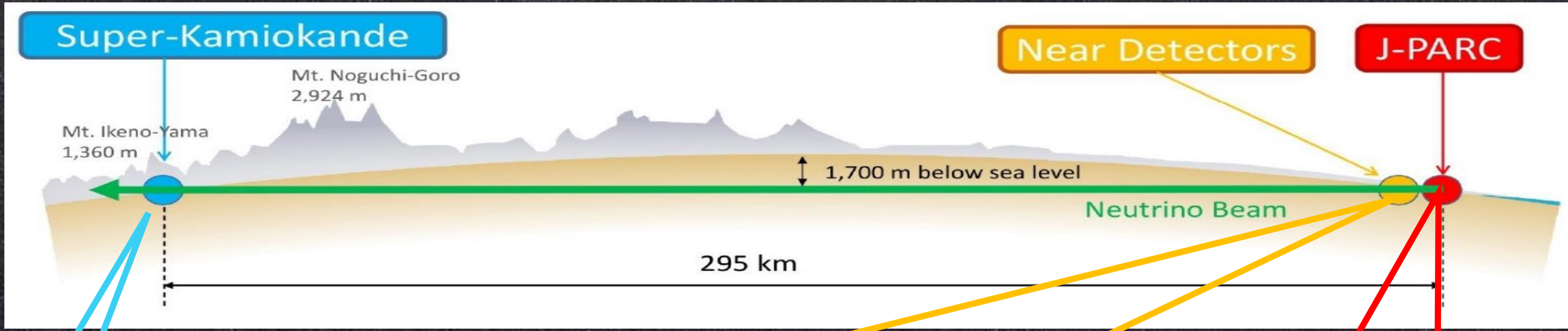
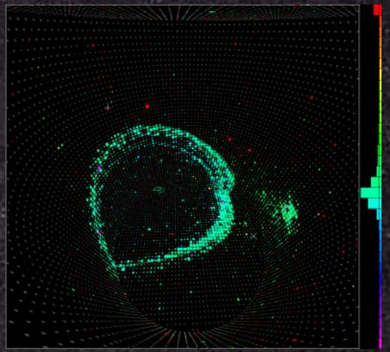


Measure oscillated spectrum



4π symmetry of the detector.

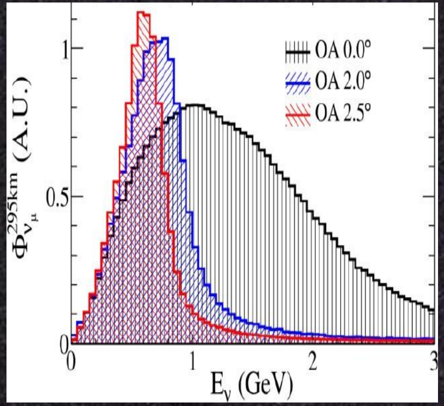
Measure unoscillated spectrum

Are used to constrain the flux and cross section parameters reducing the systematics errors in the T2K oscillation analyses.

4π acceptance

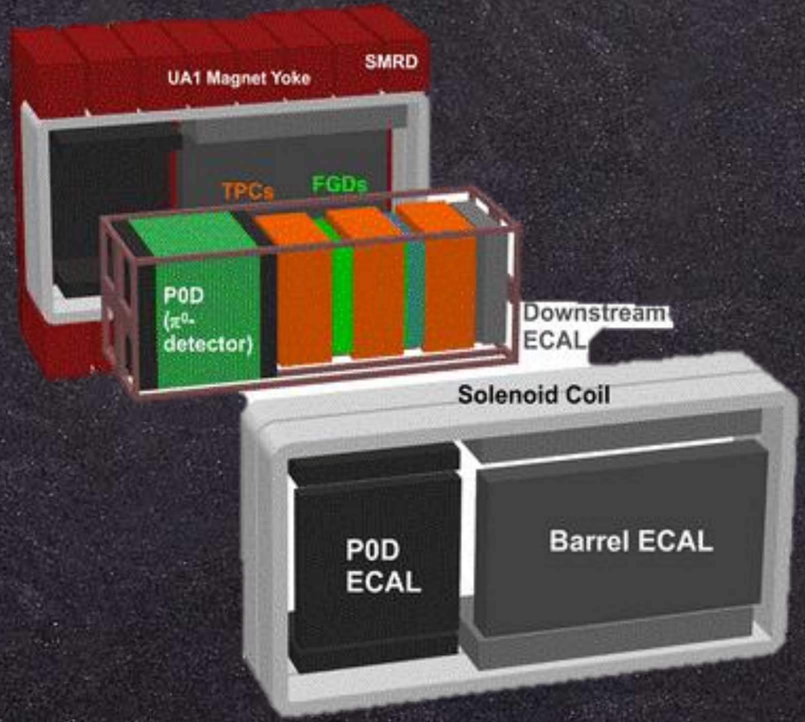
✓ making more use of ND280 to achieve a 4pi acceptance so we get a more representative constraint on neutrino interactions at SK

Production of high intensity $\nu / \bar{\nu}$ beam



T2K near detector: ND280

- **π^0 Detector (P0D):** neutral pion detector
- **Time Projection Chambers (TPCs):** energy, angle and identification
- **Fine grained detector (FGDs):** active target
  - **FGD1:** Carbon (target used for my study)
  - **FGD2:** Carbon + Water
- **Electromagnetic Calorimeters (ECals):** separated tracks from showers
- **Side Muon Range Detector (SMRD):** energy of muons based in the range
- **Magnet:** charge of the particles and momentum (when combined with TPCs)



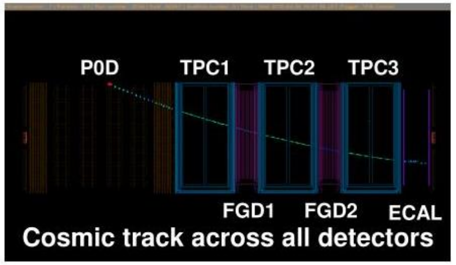
Flux: Depends on the source

Ratio of interactions in the detector

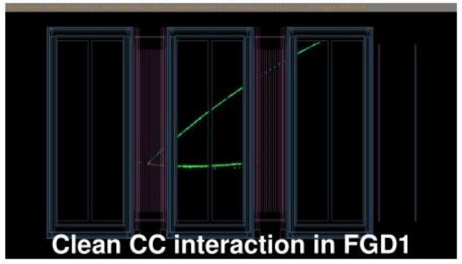
$$R = \phi(E_\nu) * \sigma(E_\nu) * N_t$$

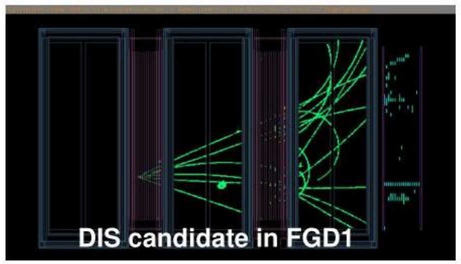
Number of targets: Depends on the detector

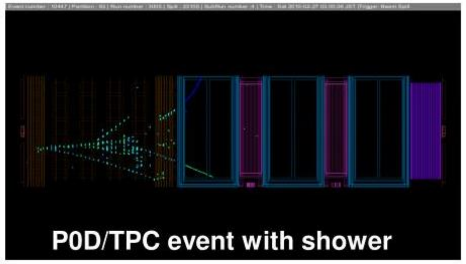
Cross section: It is very small and depends on energy



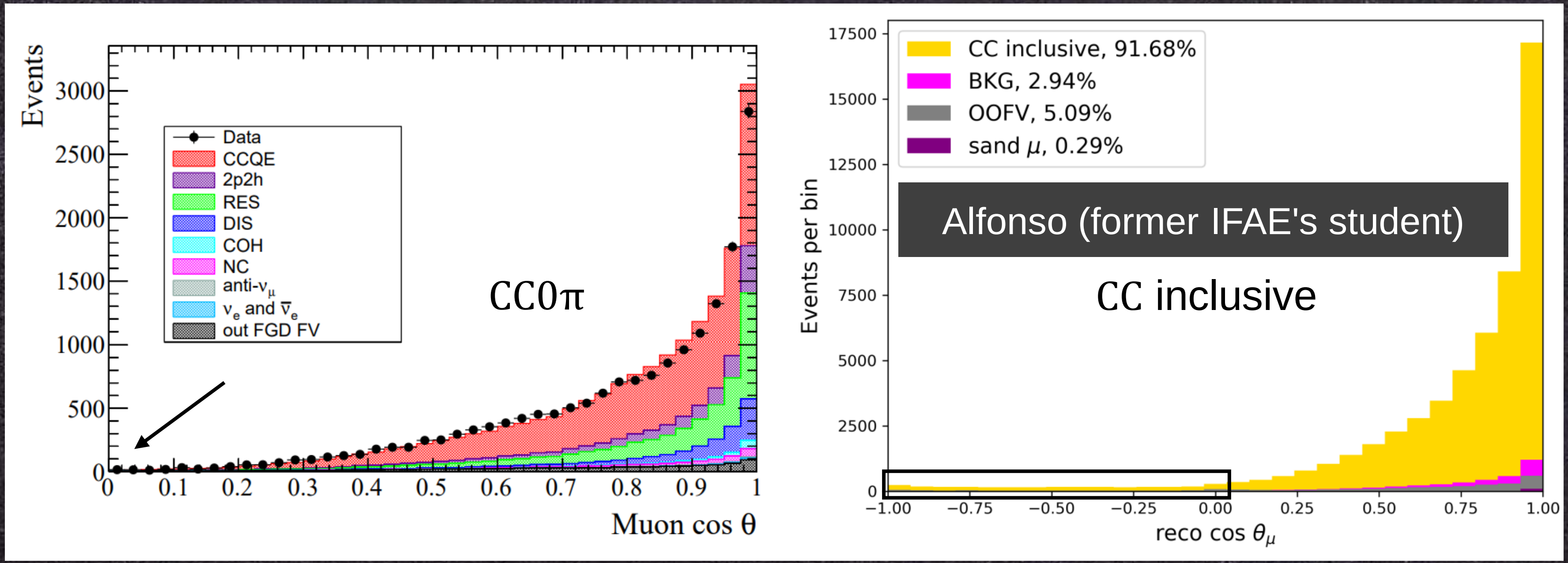
Cosmic track across all detectors


Clean CC interaction in FGD1


DIS candidate in FGD1


P0D/TPC event with shower

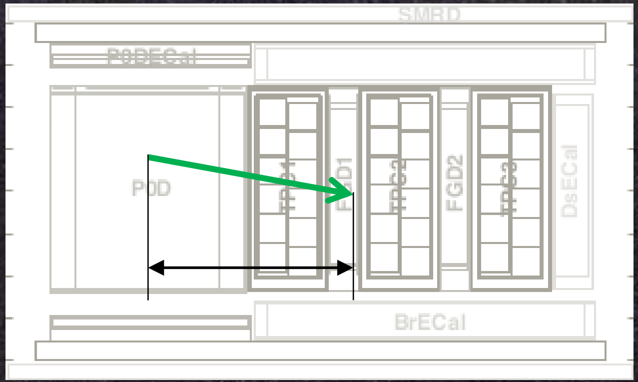
Motivation



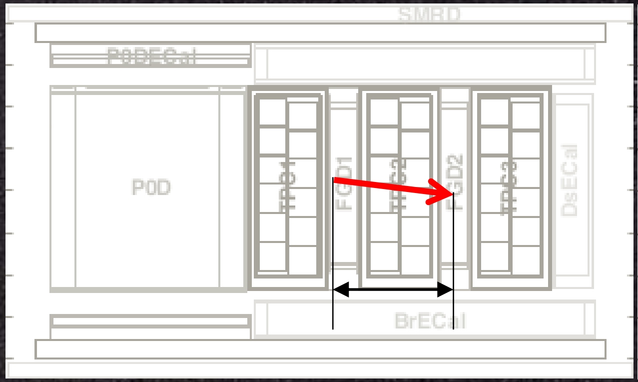
- $\mathrm{CC}1\pi^+$ constitutes the main background for the muon neutrino disappearance measurement when the charged pion is not observed.
- Its precise knowledge is relevant for all current and planned neutrino oscillation experiments.
- Single pion production is sensitive mainly to resonant processes but also to non-resonant contributions.
- Adler’s angles were measured with limited statistics in bubble chamber experiments but it is possible to measure them for single charged pion production in neutrino interactions with heavy nuclei as target.

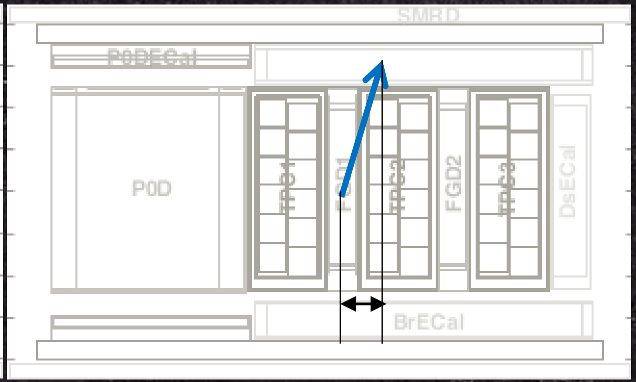
Selection developed

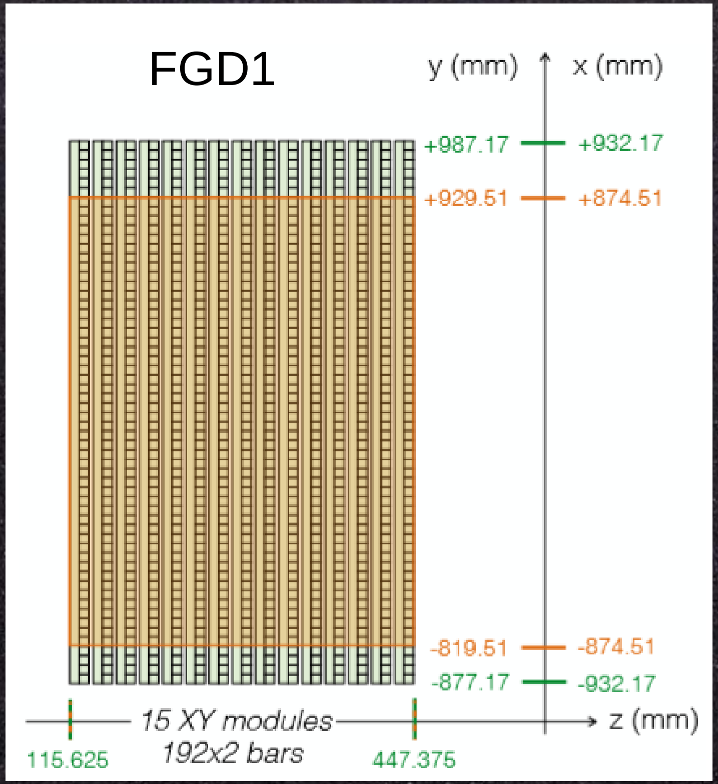
ND280 Events → General event quality, multiplicity, time of flight, fiducial volume → Selecting the direction of the main track and apply PID for muons → For each of the directions, we separated the events by pion multiplicity → Additional steps for improving the purity of the samples



Time of flight (ToF)







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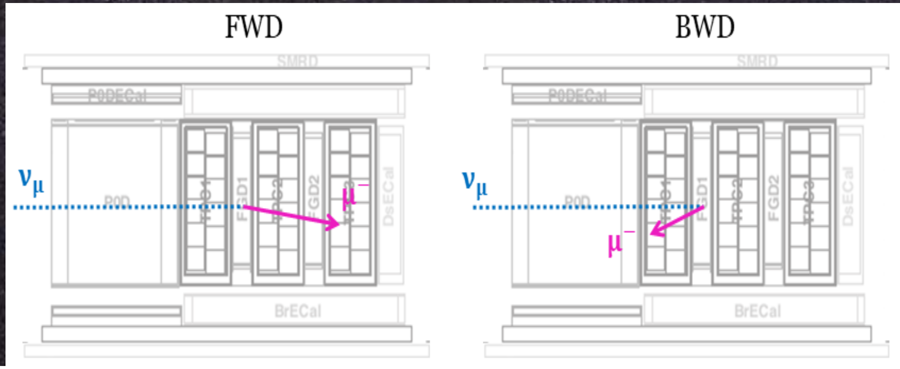

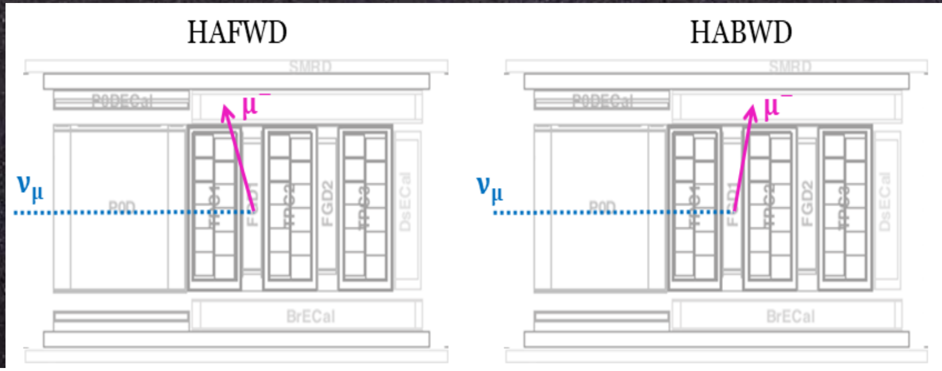

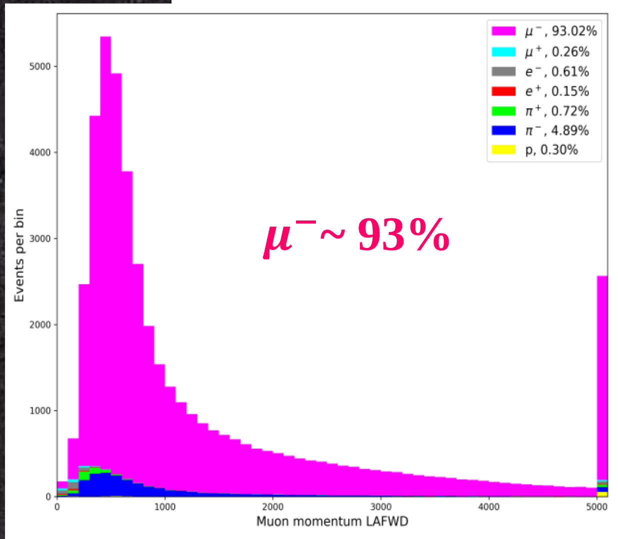

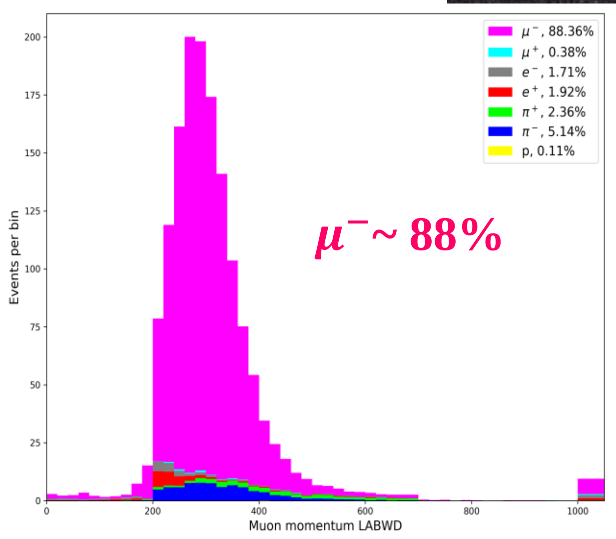

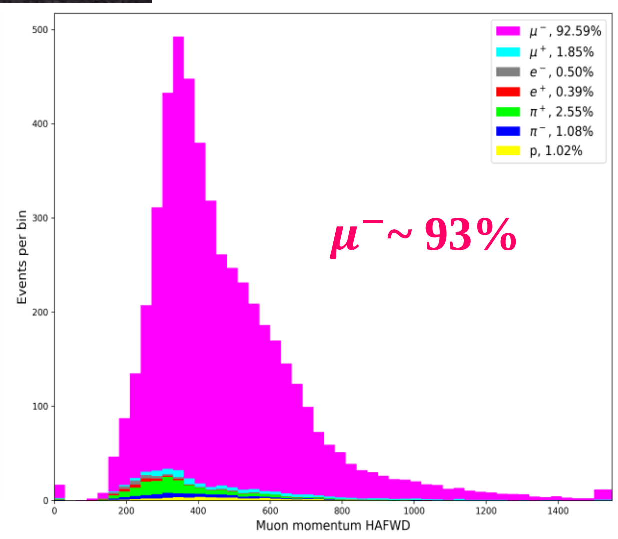

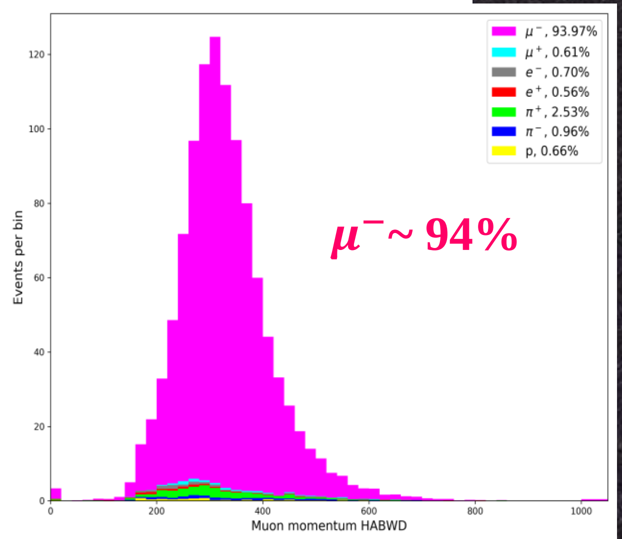

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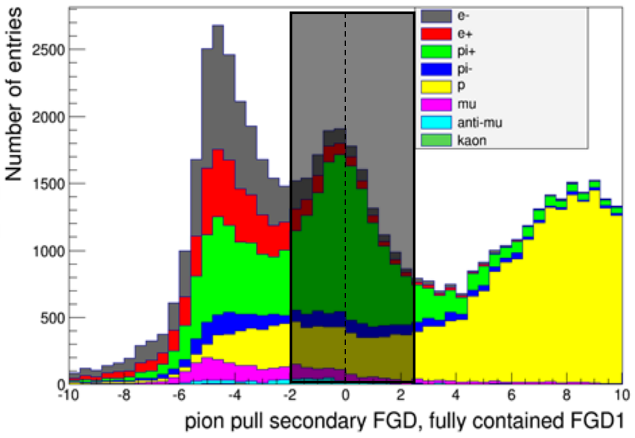
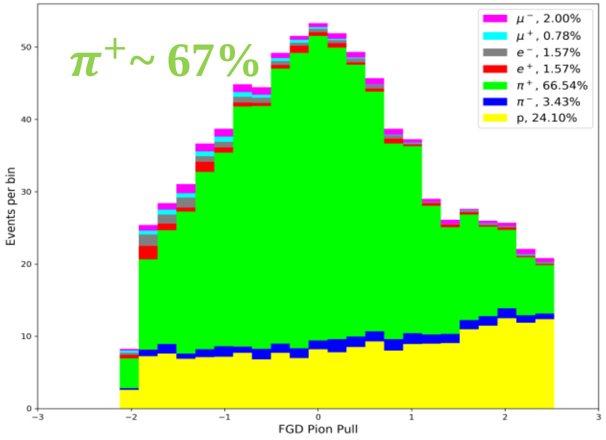
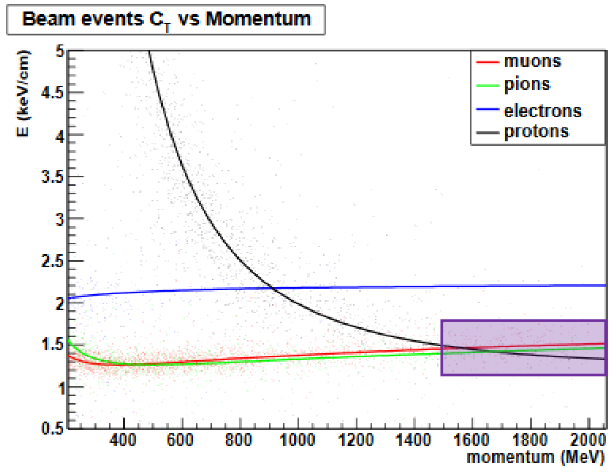
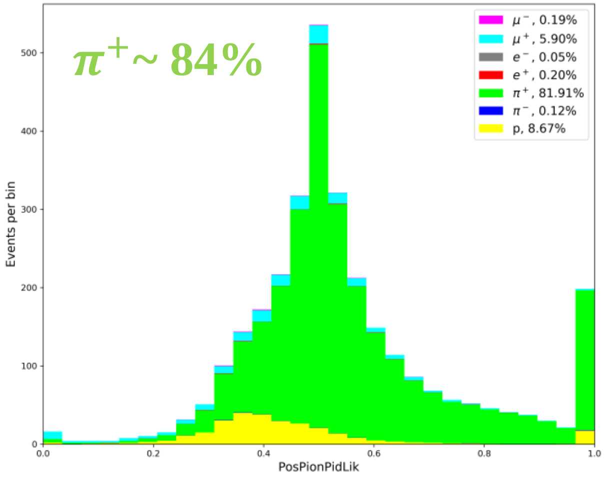
IsoFGD Pion





TPC Pion

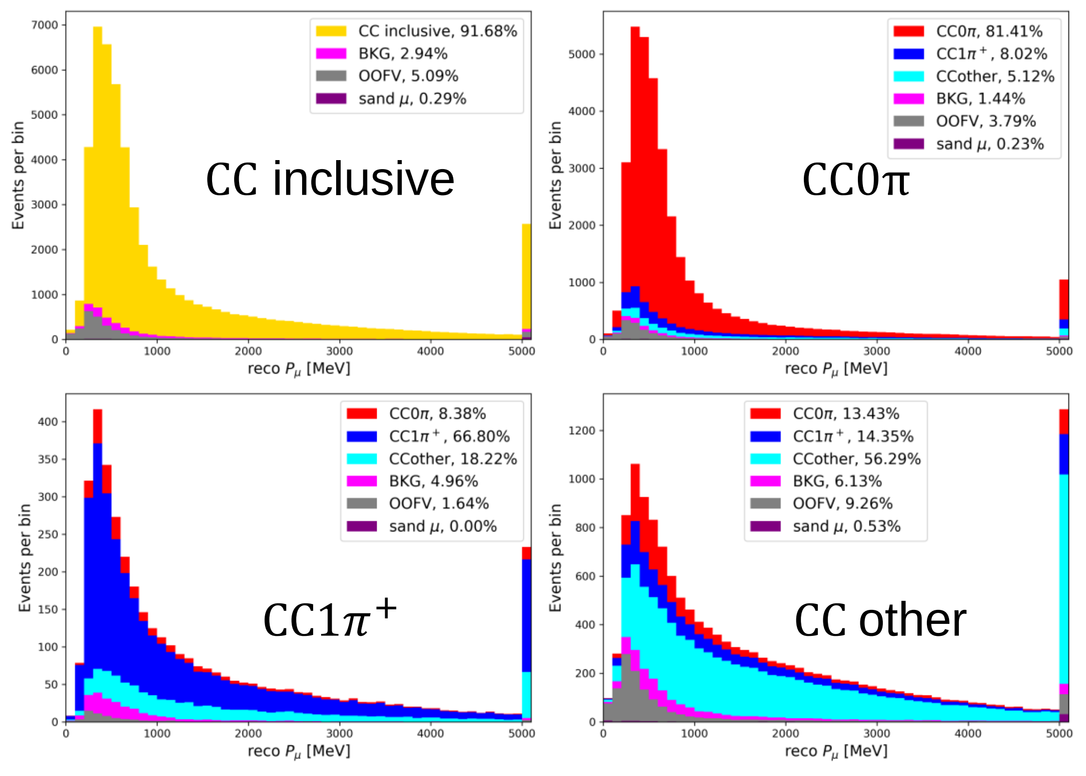




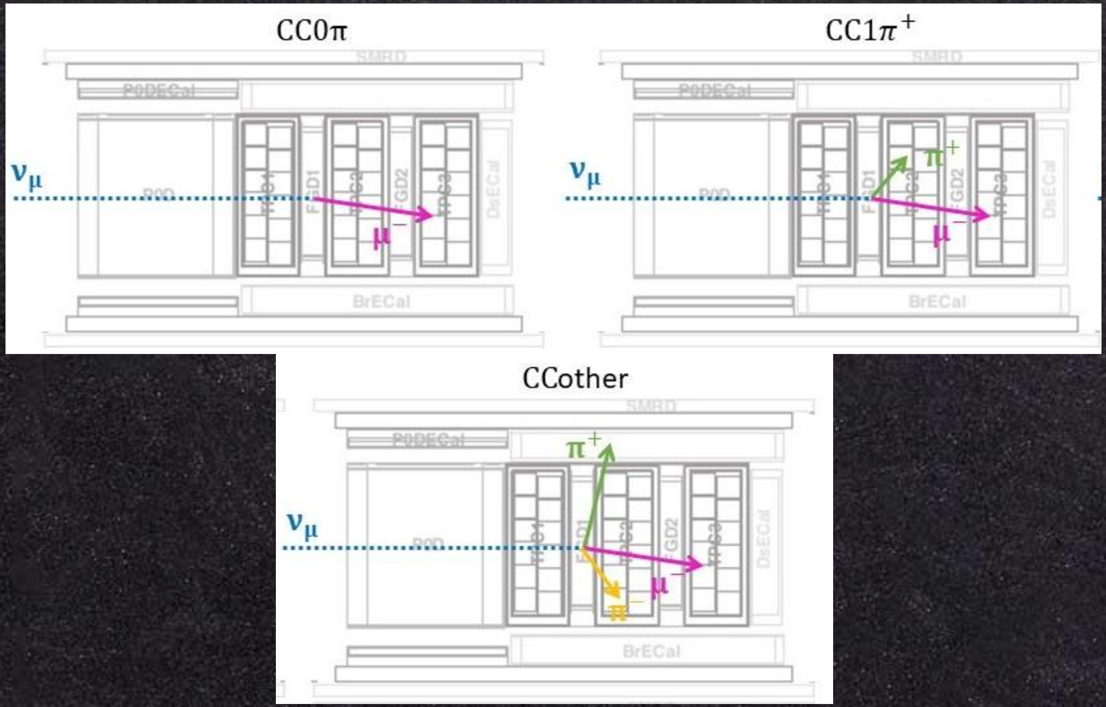
In the case of true protons that are identify as positive pion and vise-versa, this occur for energies superior to 1500 MeV in the TPC.
In the case of iso FGD tracks comes from the contamination of the pull.

Selection developed

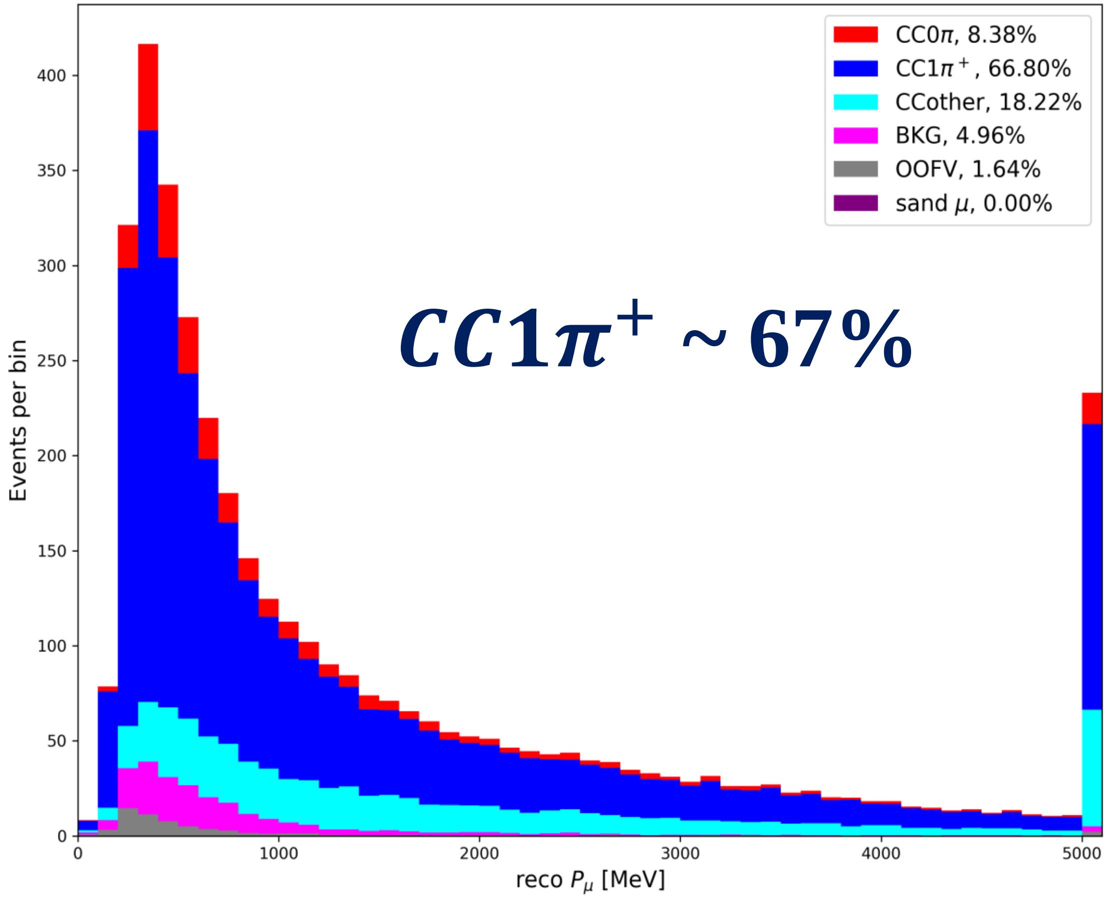
ND280 Events → **General event quality, multiplicity, time of flight, fiducial volume** → **Selecting the direction of the main track and apply PID for muons** → **For each of the directions, we separated the events by pion multiplicity** → **Additional steps for improving the purity of the samples**



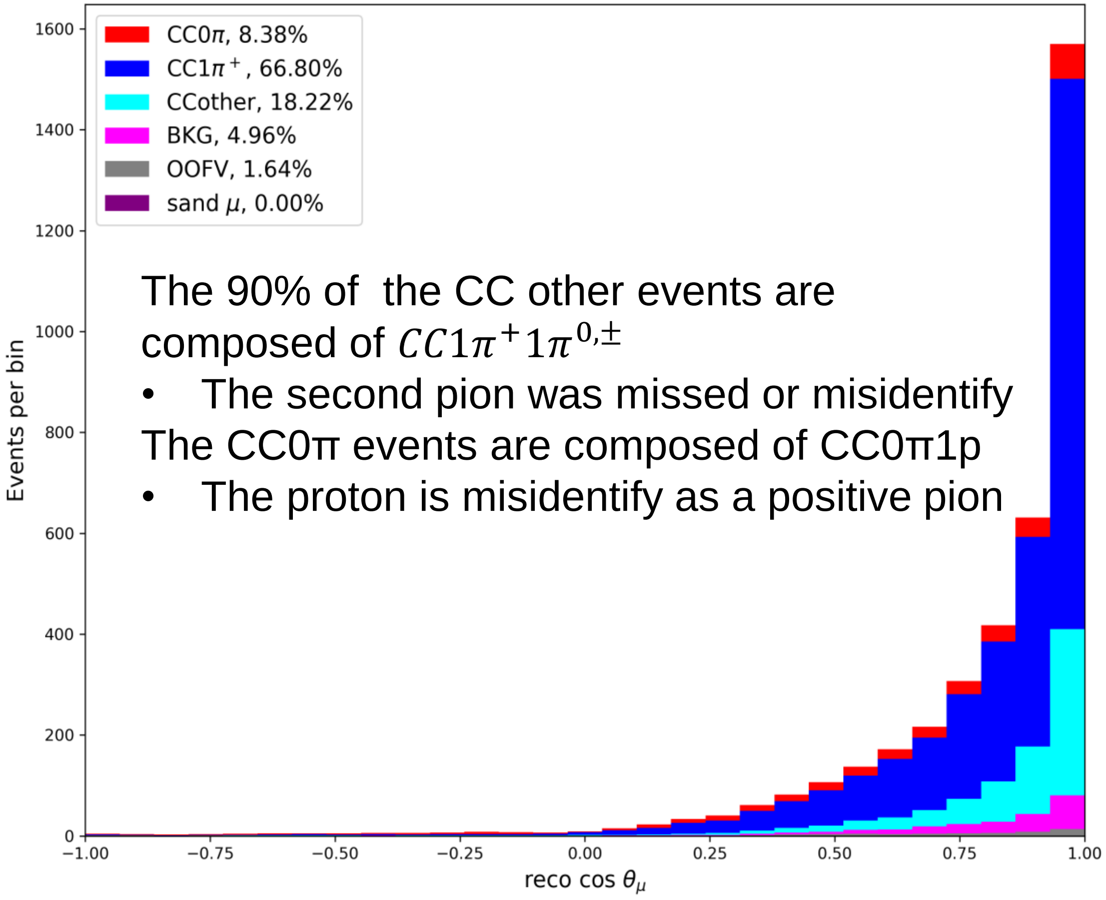
Distribution of the reconstructed muon momentum in the events selected at ND280 for CC inclusive, $CC0\pi$, $CC1\pi^+$ and CC other interactions by topology.



$CC1\pi^{+}$ kinematics



$CC1\pi^{+} \sim 67\%$



The 90% of the CC other events are composed of $CC1\pi^{+}1\pi^{0,\pm}$

- The second pion was missed or misidentify

The CC0π events are composed of CC0π1p

- The proton is misidentify as a positive pion

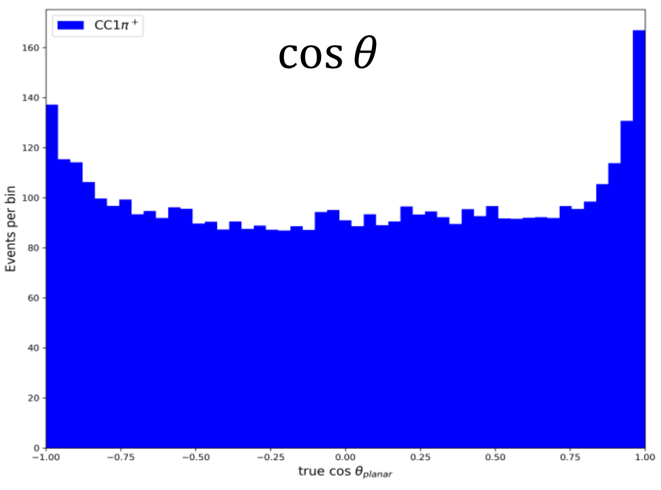
Distribution of the reconstructed muon momentum and muon cosine of theta in the events selected at ND280 for $CC1\pi^{+}$ interactions by topology.

Summary

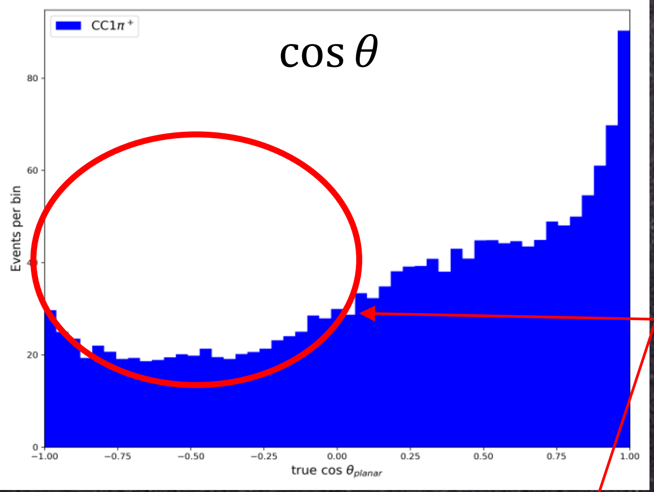
- Neutrino physics is entering high precision era.
- Improving $\mathrm{CC}1\pi^+$ measurements will lead to better oscillation analysis in the future.
    - Cross section uncertainty being a major one.
    - Good neutrino interaction model is essential to reduce systematics.
- My PhD has been focused on understanding and measuring $\mathrm{CC}1\pi^+$ interactions using the ND280 detector.
- Thanks to my work a new set of analysis, using the 4π acceptance of the ND280 detector, are possible (some already on the way).
- The analysis is close to being finished.


Thanks
See you all in ~7 moths for my defense.

Adler's angles

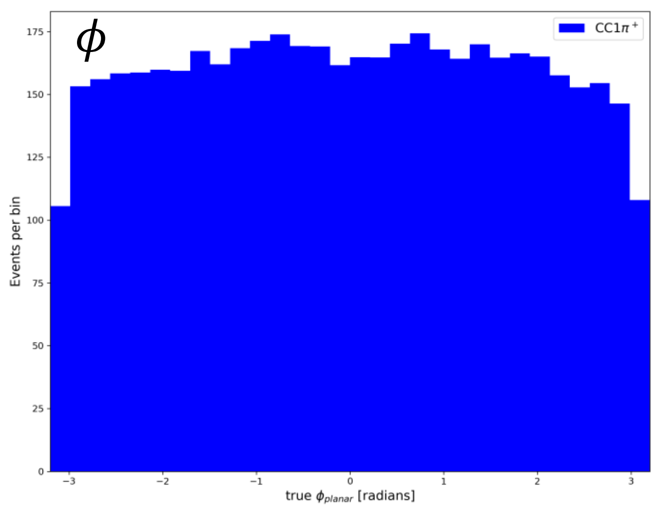


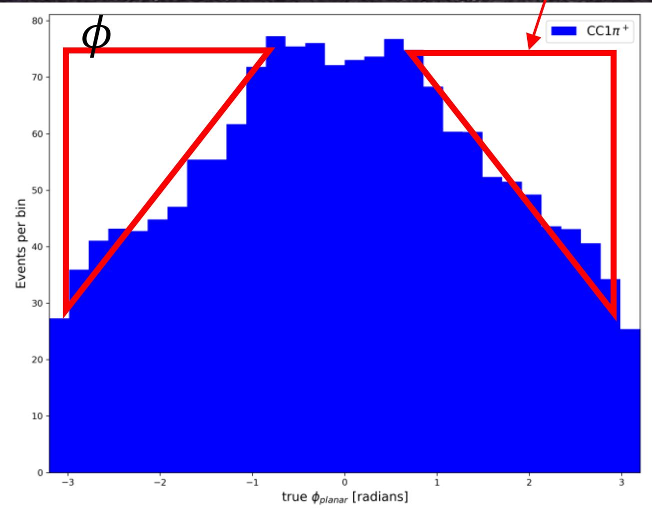
All true $CC1\pi^+$ events reconstructed in CC inclusive

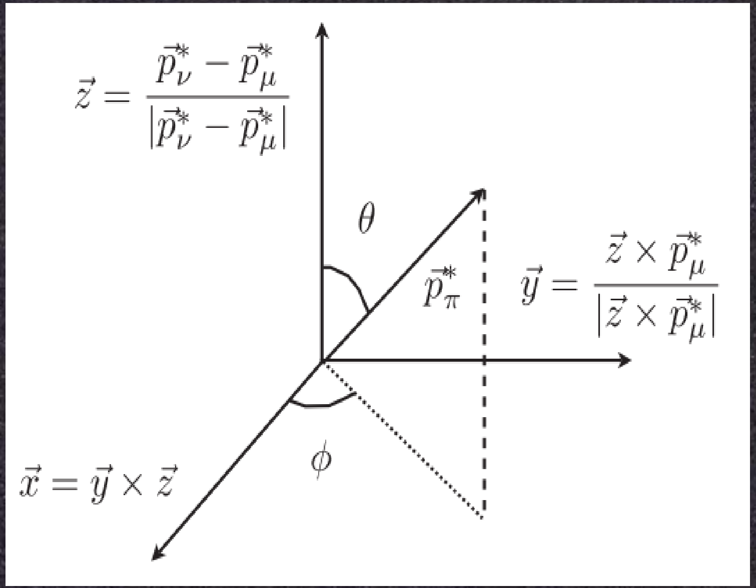


All true $CC1\pi^+$ events reconstructed in $CC1\pi^+$

Missing events when going from all events to the ones selected as $CC1\pi^+$







Definition of the Adler's Angles at the nuclear level. The momenta of the particles are defined in the $\vec{q} = \vec{p}_\nu - \vec{p}_\mu$ rest frame.

- The angles θ_{planar} and ϕ_{planar} are defined in the Adler's system which corresponds to the Δ rest frame.
- The Adler's angles carry information about the polarization of the Δ resonance and the interference with non resonant single pion production.

Neutrino Physics History

1930

Wolfgang Pauli postulated the “neutron” to compensate for the apparent loss of energy and conserve the moment of decay $\beta-$

1932

The Pauli neutron was renamed "neutrino" by Fermi when the real neutron was discovered by Chadwick

1956

Clyde Cowman and Federick Reines detected the neutrino experimentally from a reactor source

1962

Leon Max Lederman, Melvin Schwartz, and Jack Steinberger showed that more than one type of neutrino existed when the muon neutrino was first detected

2000

The DONUT collaboration at Fermilab announced the discovery of the tauonic neutrino

2015

Nobel Prize in Physics to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass.“

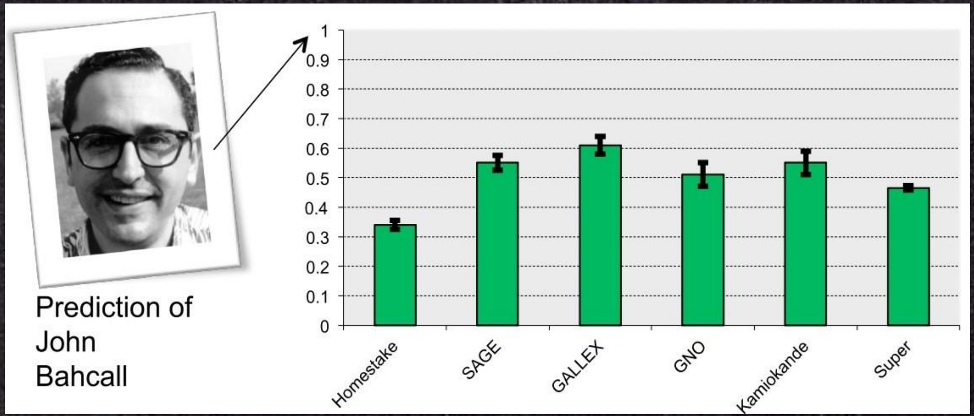
Solar neutrino problem

The sun produce only electron neutrinos by β decays.

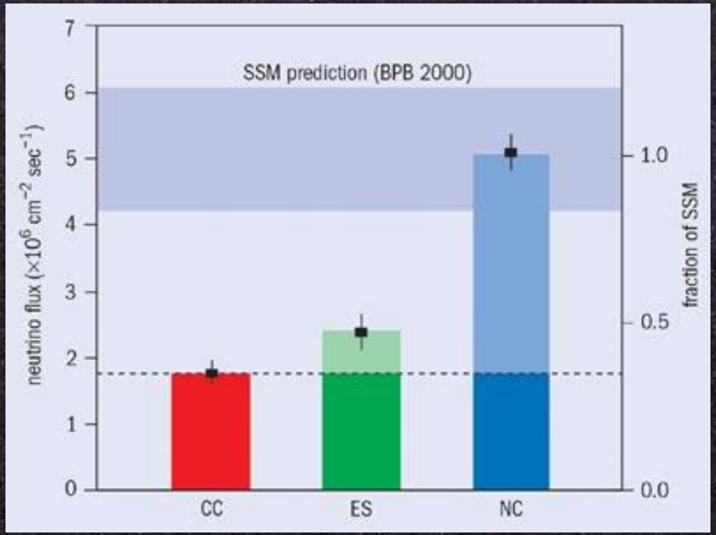
$$p^+ + p^+ \rightarrow \; ^2H + e^+ + \nu_e$$

Number of solar neutrinos measured experimentally is less than theoretically expected!!!

$$R = \frac{N_{experimental}}{N_{teorico}}$$



- **John Bahcall (rigth):** So my prediction was correct!!!
- **Ray Davis(left):** And my measurements too!!!

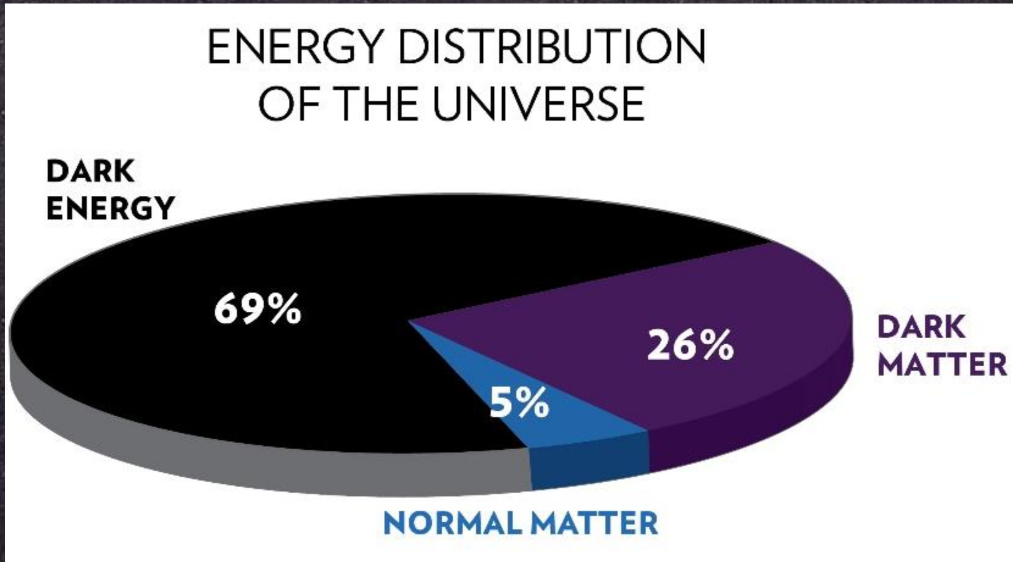


Charged Current (CC): $\mathbf{D} + \nu_e \rightarrow p + p + e^-$

Elastic Scattering (ES): $\mathbf{D} + \nu_{e,\mu,\tau} \rightarrow p + p + e^-$

Neutral Current (NC): $e^- + \nu_{e,\mu,\tau} \rightarrow e^- + \nu_x$

What's so interesting about neutrinos?



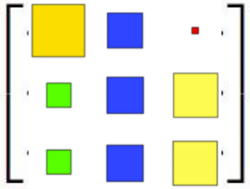
- First experimental observation of physics beyond the standard model.
- Discover supernovae and other astrophysical events.
- We could explain the matter/antimatter asymmetry.
- They help explain dark matter.
- Geologically study the interior of the earth.
- Monitor nuclear weapons on earth.
- Method of transmitting information.

In the distant future

Neutrino (flavor) oscillation

These are related through the PMNS matrix:

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



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

- 3 angles: $\theta_{12}, \theta_{13}, \theta_{23}$
- 2 mass differences: $\Delta m^2_{21}, \Delta m^2_{32}$ — Sign still unknown
- 1 CP violating phase: δ_{CP} — Value still unknown

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$
$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

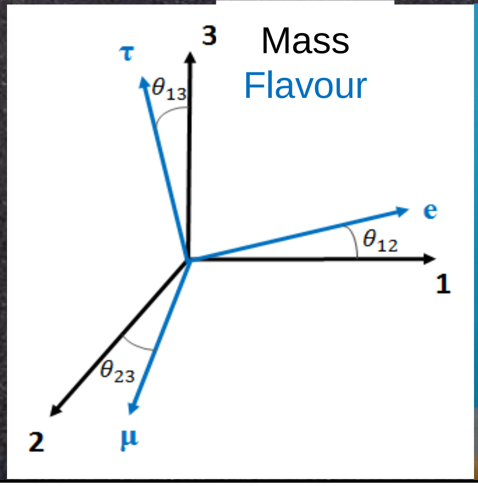
Neutrino Masses and Hierarchy

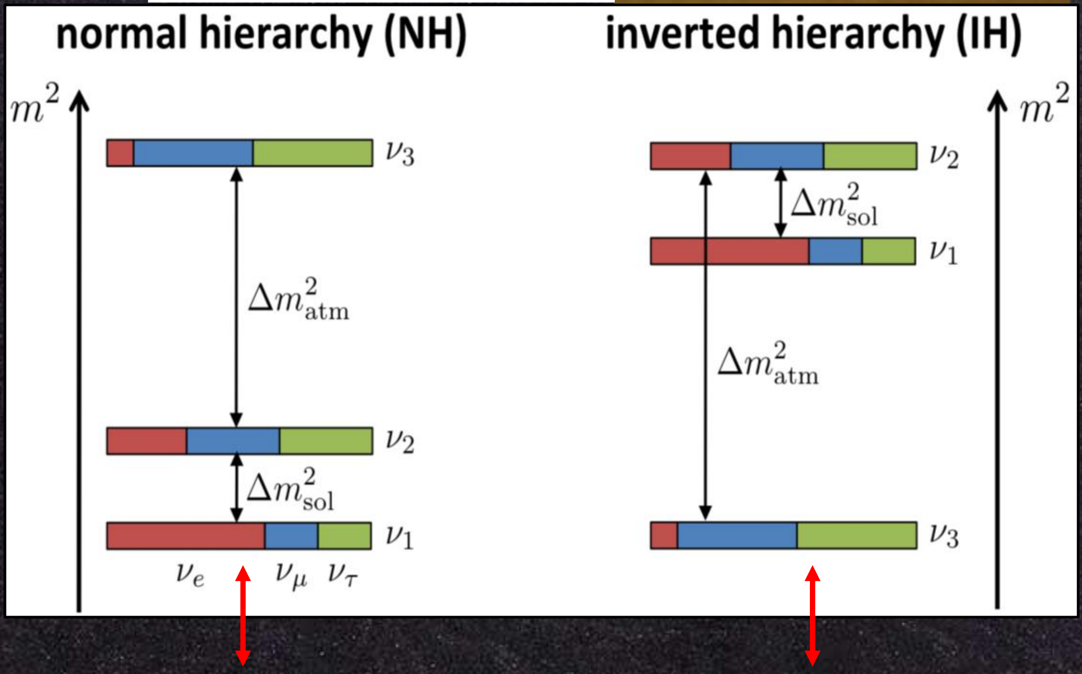
Neutrino mass is an evidence of physics the standard model. The mass difference involved in the neutrino oscillation are a combination of the neutrino masses.

$$|\nu_l> = \sum_{\alpha=1}^{3} U_{l\alpha}\,|\nu_\alpha>$$

Neutrinos have 2 sets of eigenstates: flavour ($l = e, \mu, \tau$) and mass ($\alpha = 1, 2, 3$) and $U_{l\alpha}$ is the leptonic mixture matrix known as Pontecorvo-Maki-Nakagawa-Sakata (PMNS)

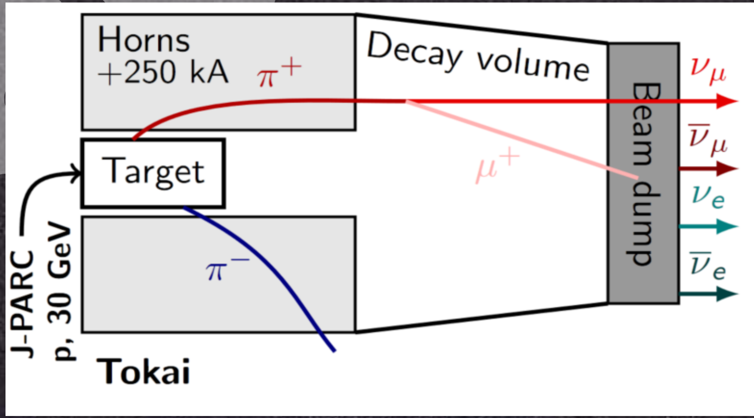
- ✓ Sign of $\Delta m_{32}^2 = m_3^2 - m_2^2$ unknown
- ✓ Two possible arrangements of neutrino masses
- ✓ Long baseline experiments sensitive to hierarchy through matter effect
- ✓ The differences have been measured
  - atmospheric neutrino
  - solar neutrino

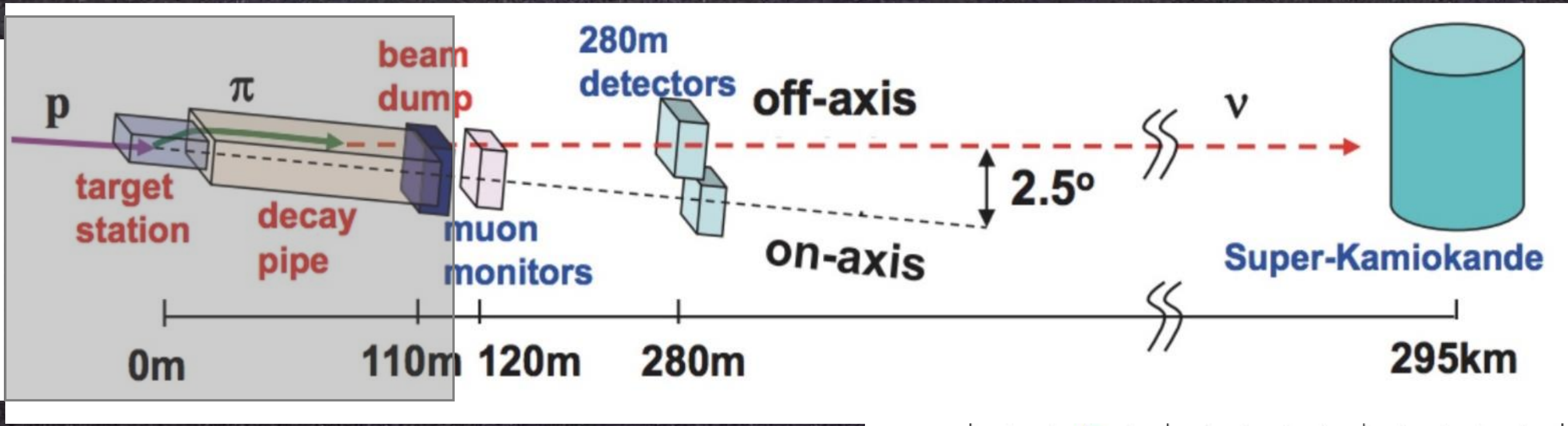




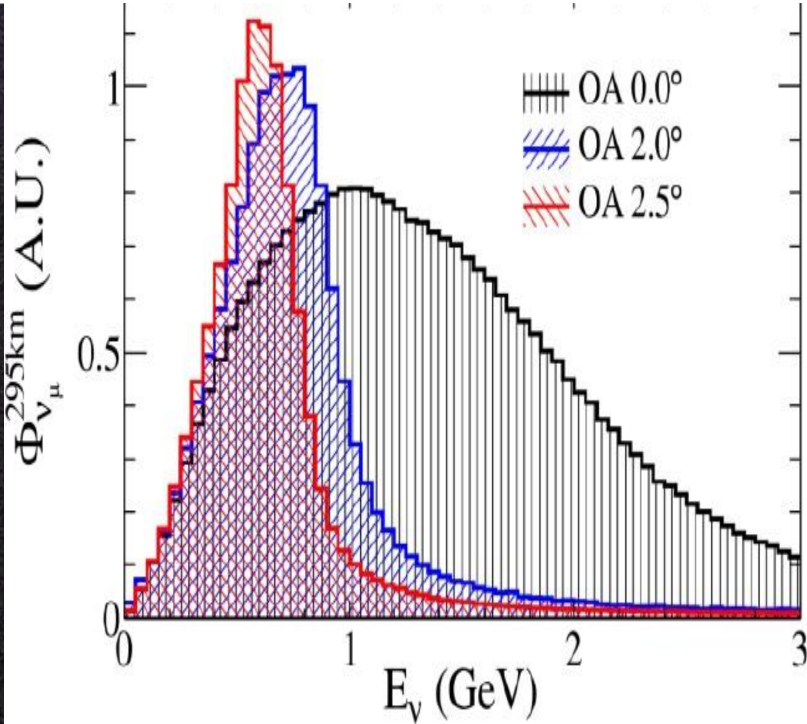
Absolute scale of neutrino masses unknown

T2K experiment





- 30 GeV protons collide with carbon target and produce pions
- Magnetic horns can focus either positive or negative pions
  - 2 different beam modes
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
    $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
  - All particles except neutrinos stopped in beam dump
- Use off-axis beam for narrower energy spectrum



The End