Cross section measurement of the muon neutrino charged current single positive pion interaction on Hydrocarbon using the T2K near detector with 4π solid angle acceptance

PhD defense

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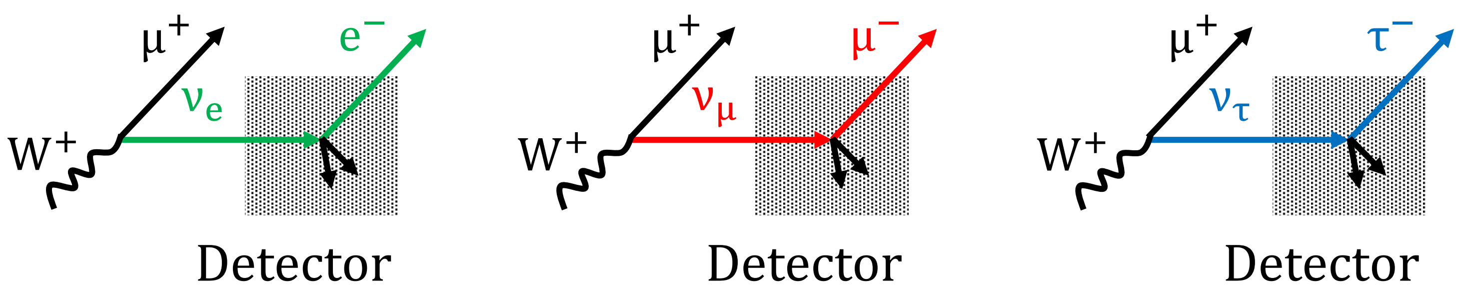
Overview

- Neutrino oscillations
- Neutrino interactions
- The T2K experiment
- Motivation
- CC1π^+ analysis overview
  - Selection development
  - Adler angles
  - Data and MC input
  - Likelihood fit and unfolding
  - Calculate cross section
  - Results
- Conclusions

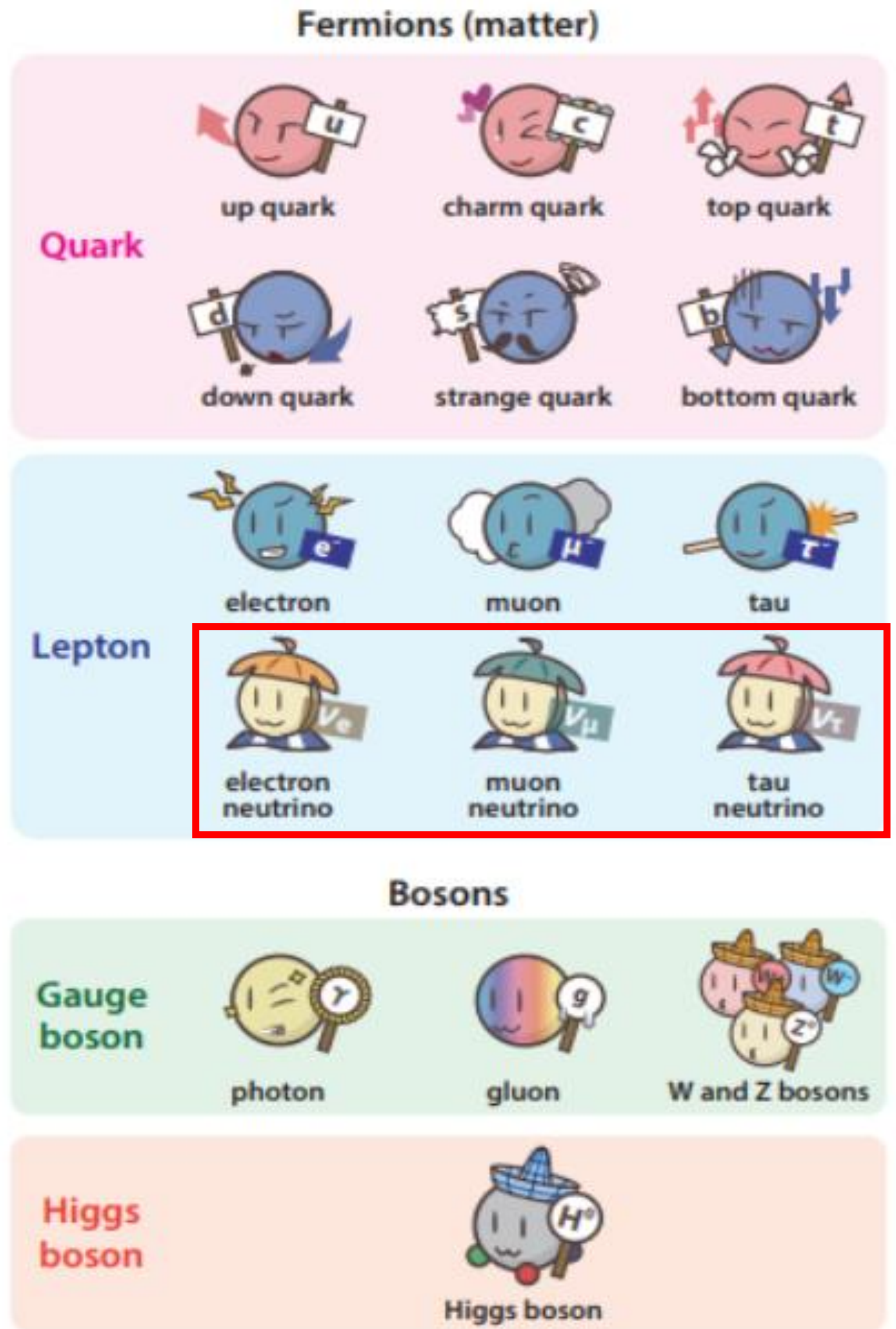
Neutrino in the Standard Model

Neutrino Facts:

- Have no charge
- Are nearly massless
- Are spin ½ leptons
- Only interact weakly
- Only left-handed interact



Neutrinos interact with matter and produce a lepton of the same flavor of the neutrino.



https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/

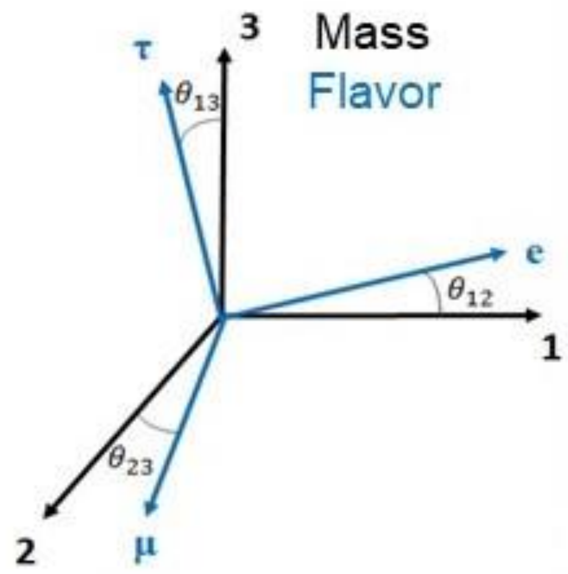
Neutrino oscillations

Neutrino oscillation

PNMS (Pontecorvo–Maki–Nakagawa–Sakata) rotation matrix.

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

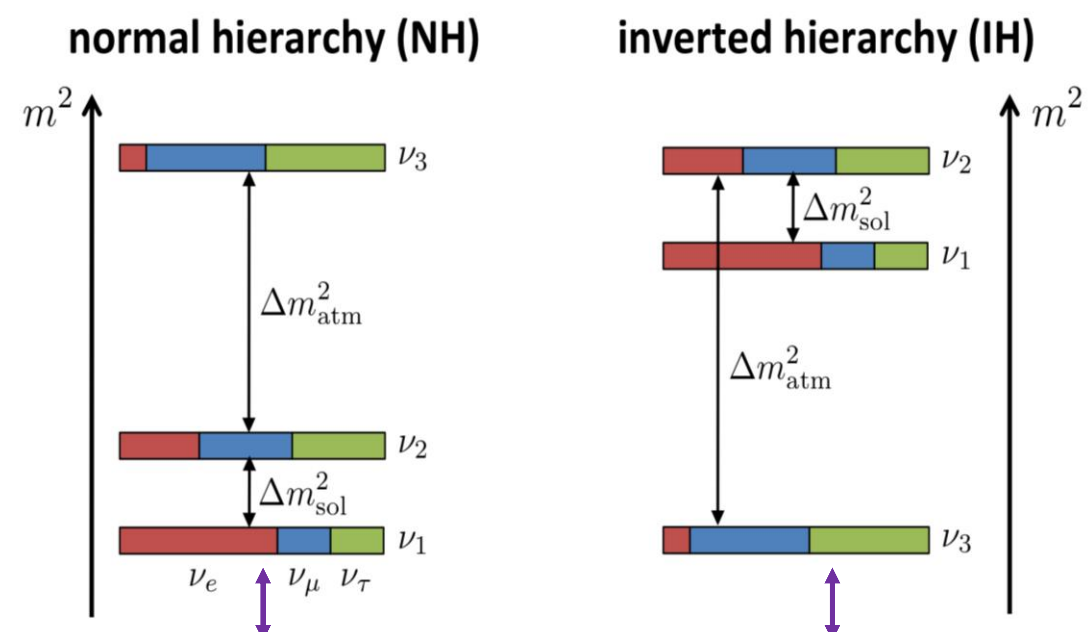
Atmospheric — Reactor — Solar



Where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ and $\Delta m^2_{ij} = m^2_i - m^2_j$

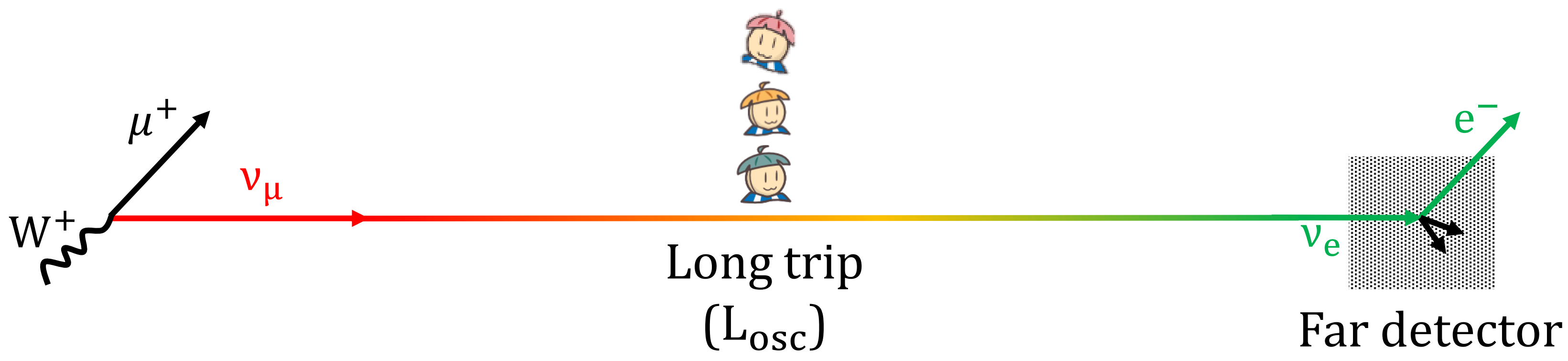
The oscillation depends of:

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

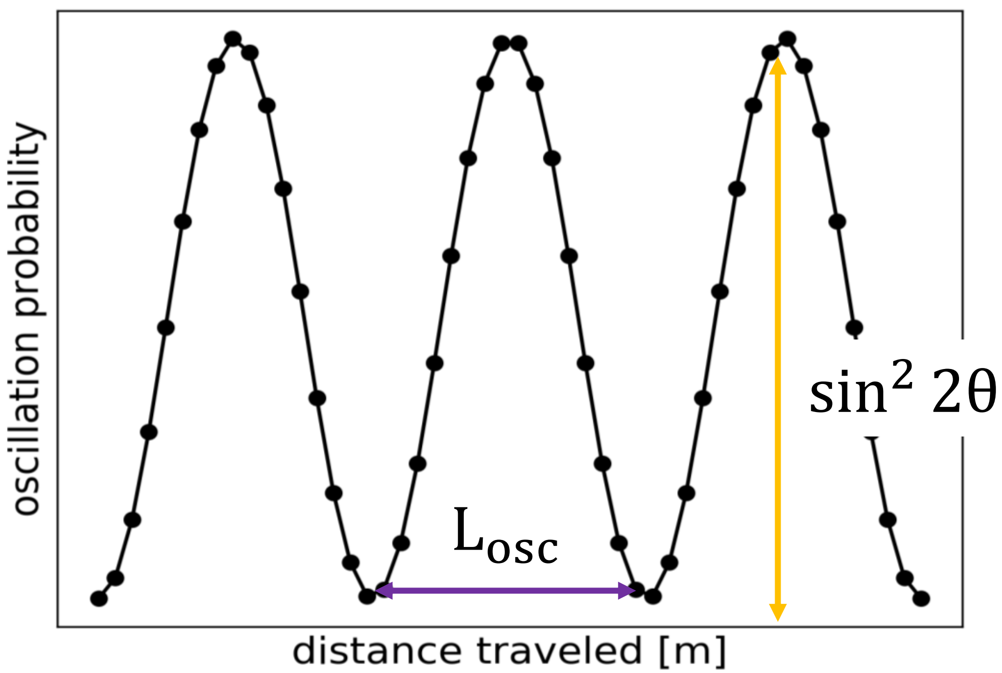


Absolute scale of neutrino masses unknown

Two flavor oscillation



All oscillation experiments live in the 0.1-10 GeV transition region.



The oscillation is described by equation:

$$P_{osc}(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L_{osc}}{4E_\nu}\right)$$

We extract: Rotation angle

We calculate: Probability of the oscillation

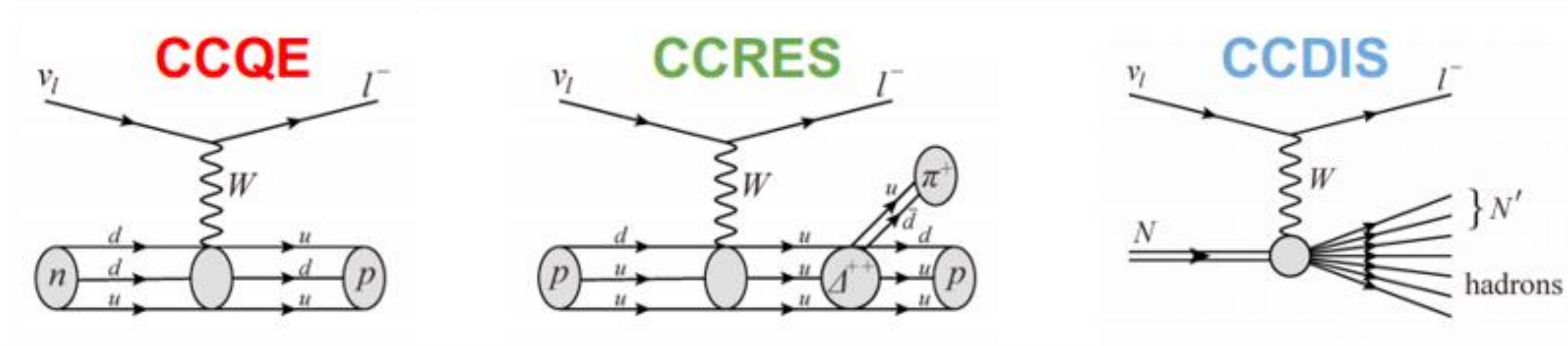
We calculate: Neutrino flux energy

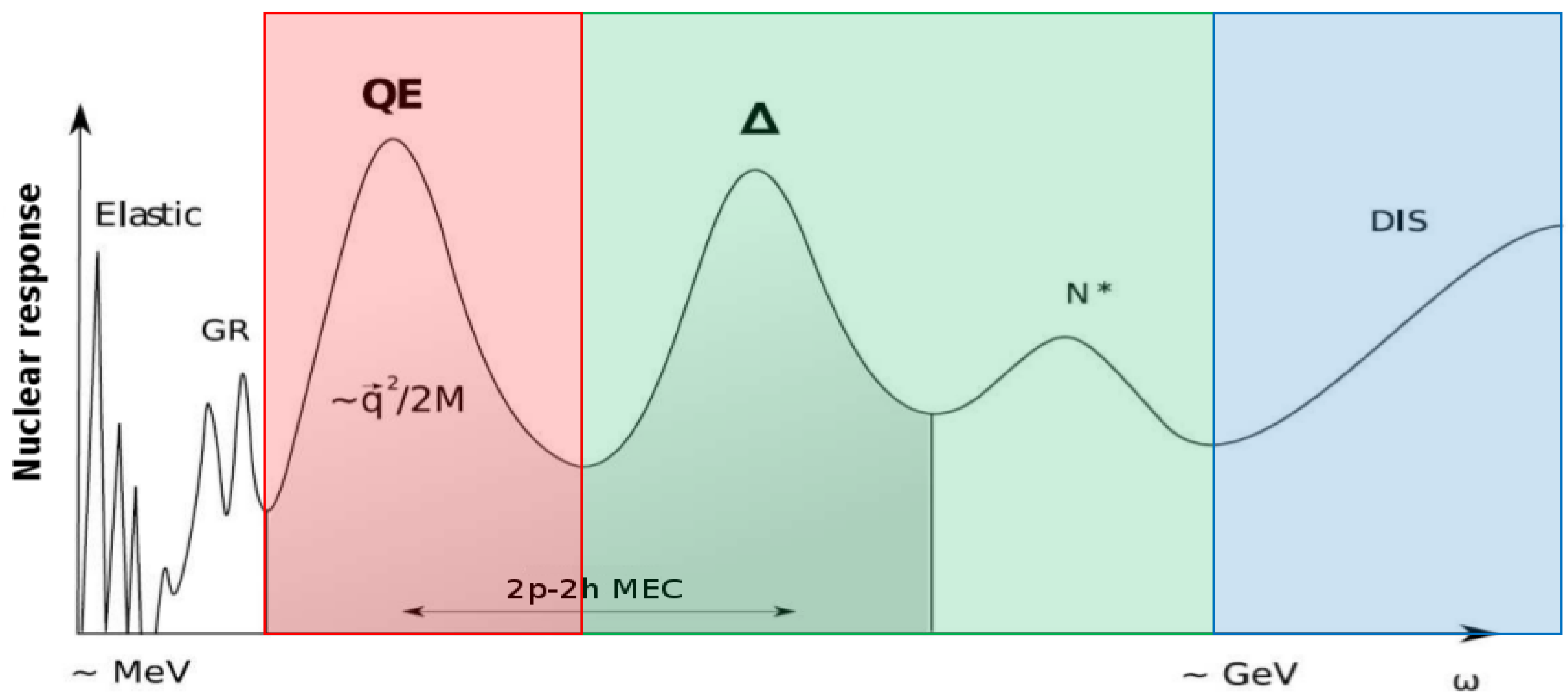
We know: length of the neutrino's long journey

Neutrino interactions

Neutrino-nucleon interactions

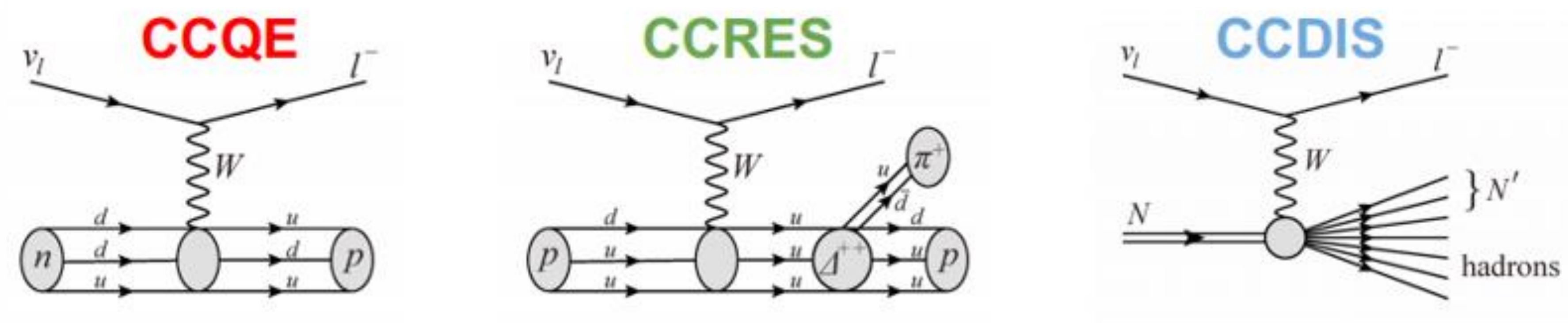
Interaction
Modes
(nucleon level)



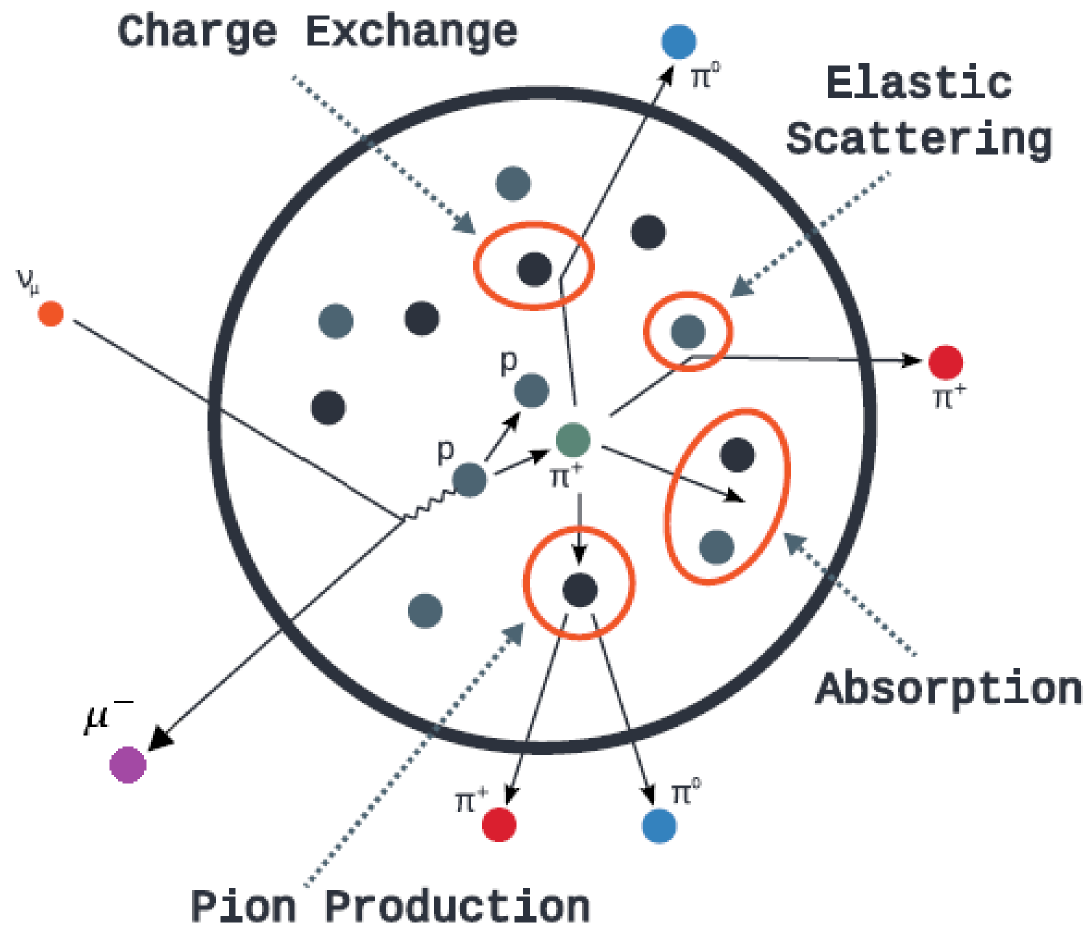


Nuclear effects and final state interaction

Interaction Modes (nucleon level)



As consequence of this, the kinematics and/or interaction topology can be altered.



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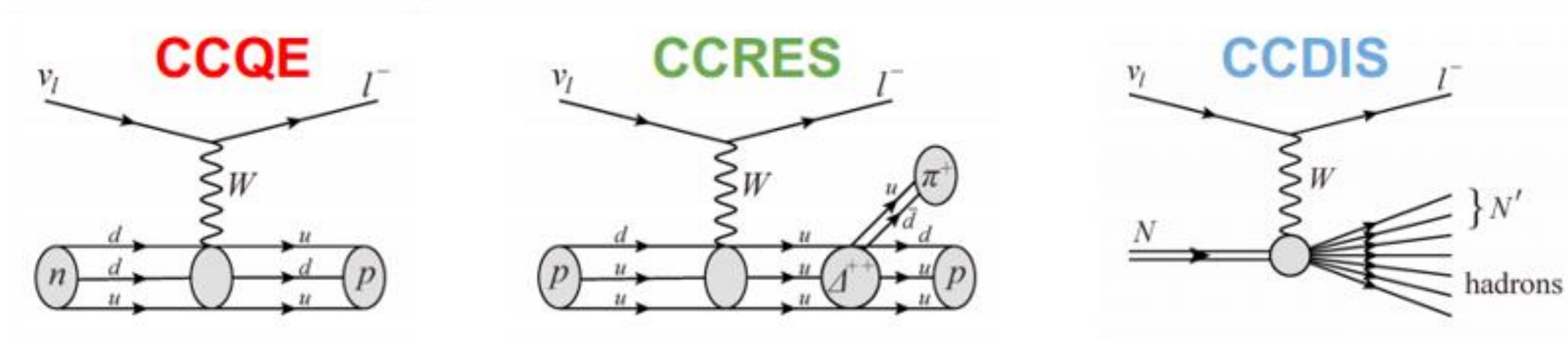

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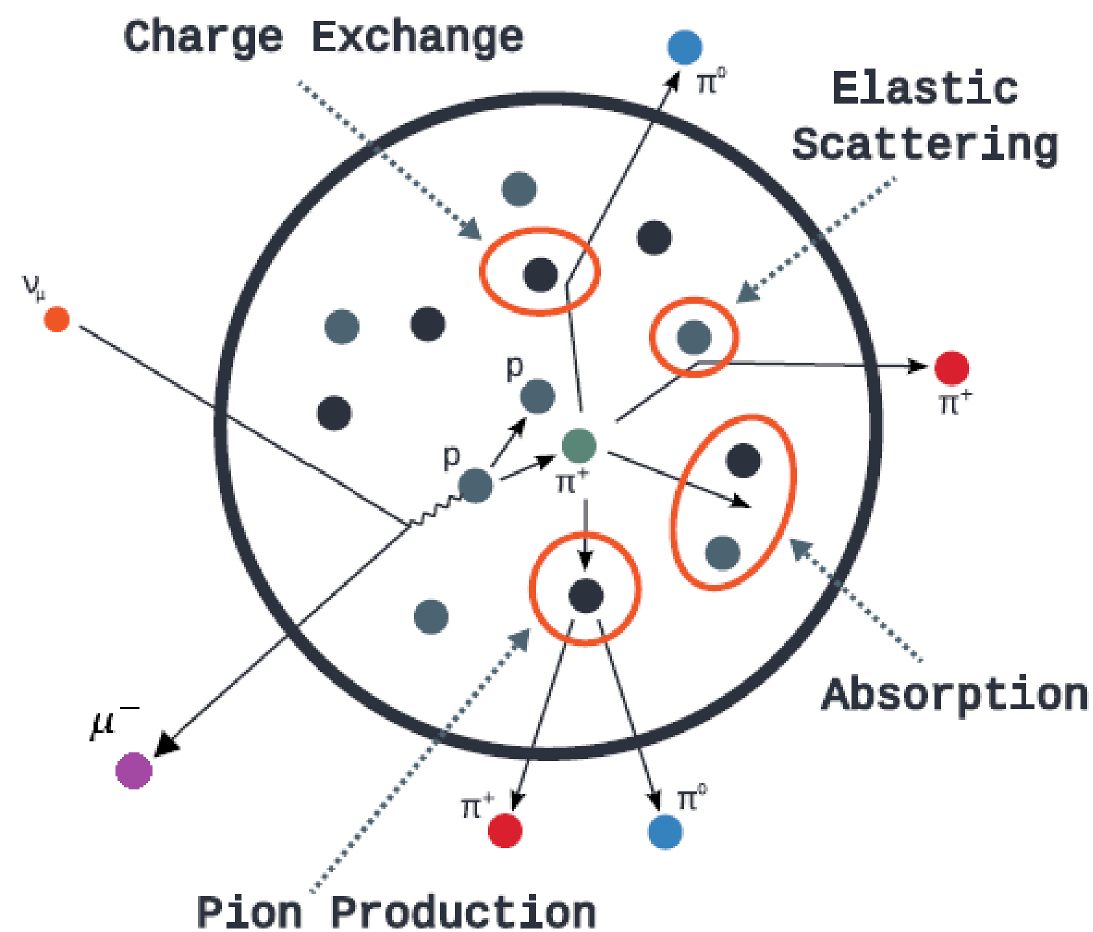

Neutrino-nucleus interactions

Interaction
Modes
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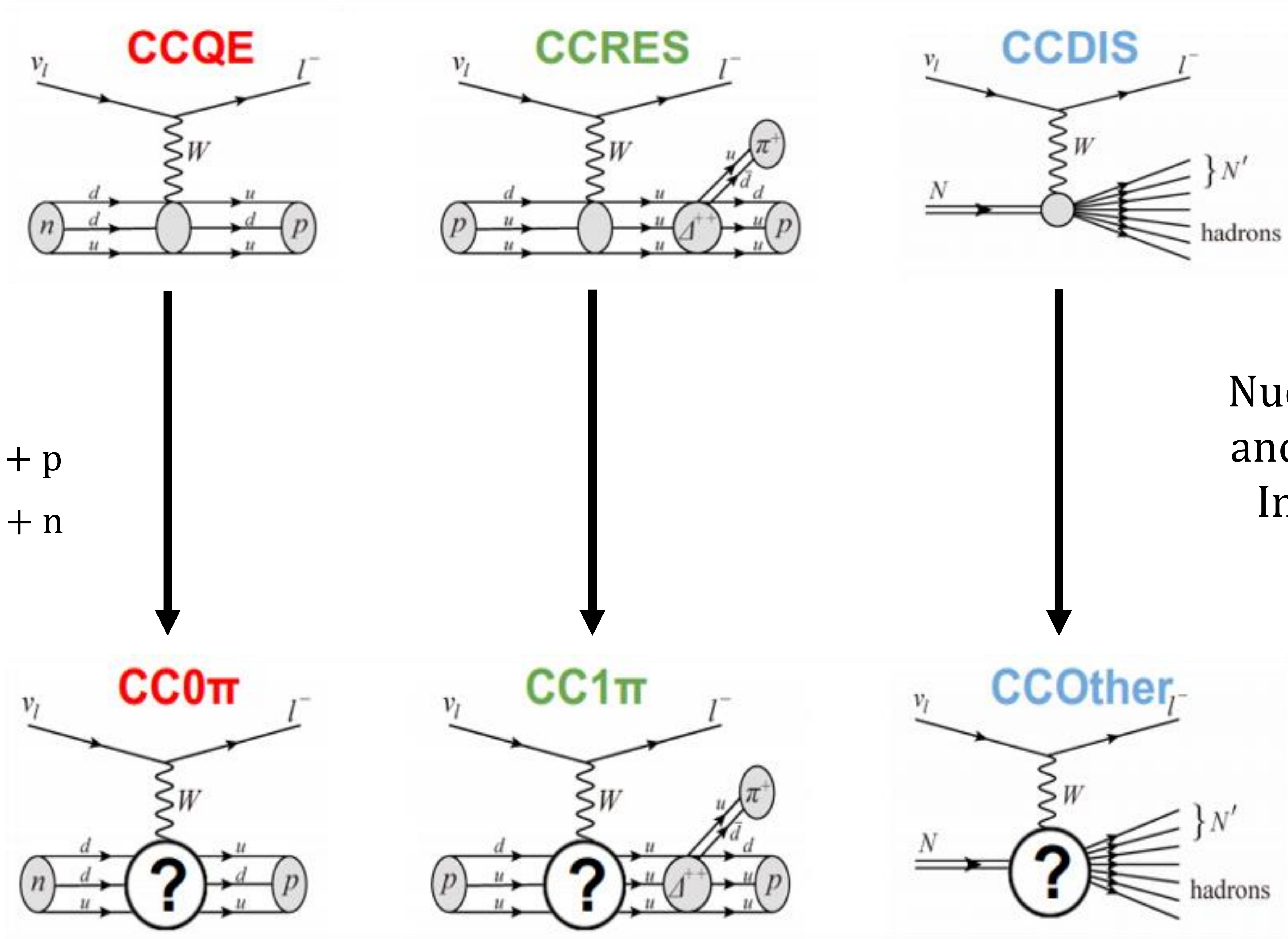

CCQE: $\nu_\mu + n \rightarrow \mu^- + p$

CCRES: $\nu_\mu + p \rightarrow \mu^- + \pi^+ + p$

$\nu_\mu + n \rightarrow \mu^- + \pi^+ + n$

Nuclear Effects
and Final State
Interactions

Interaction
Topologies
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Neutrino-nucleus interactions

Interaction
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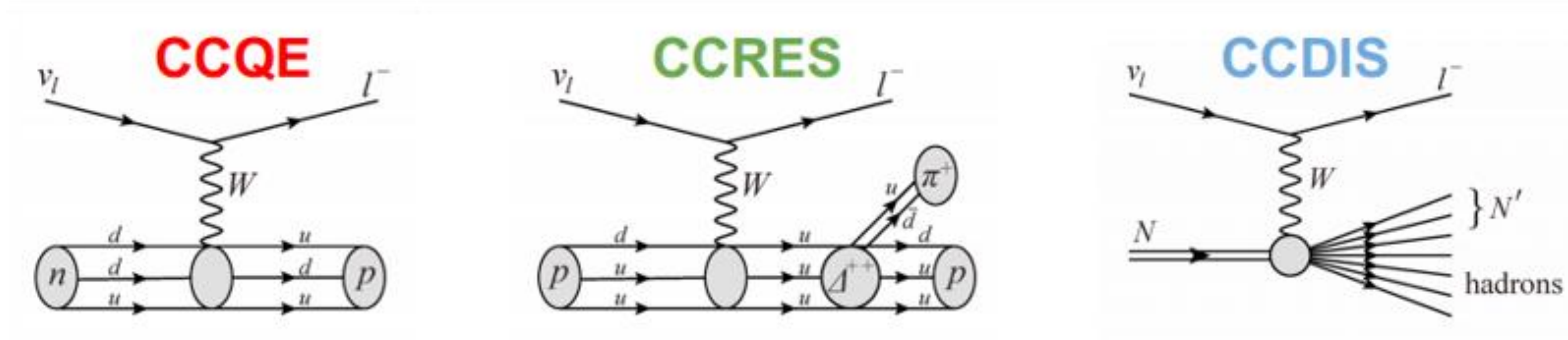

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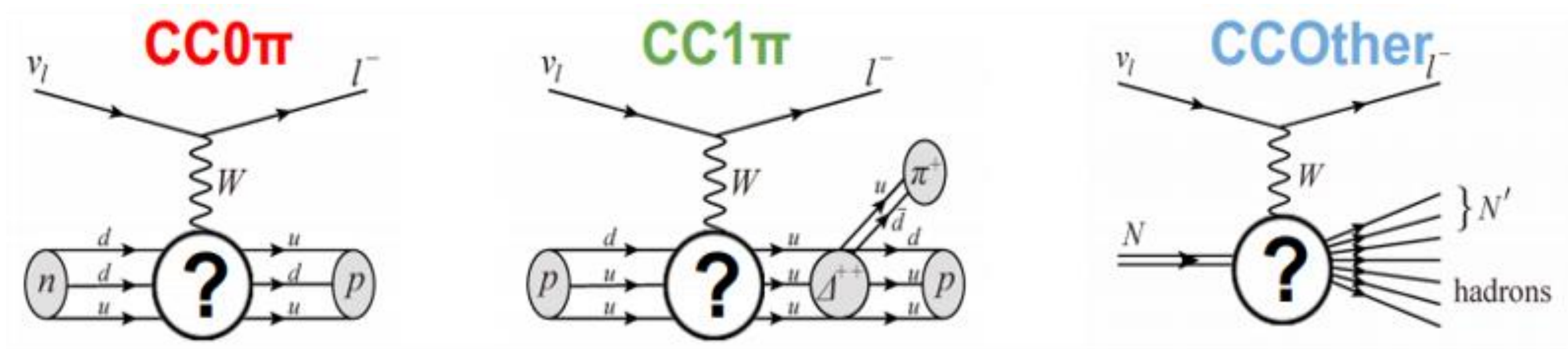

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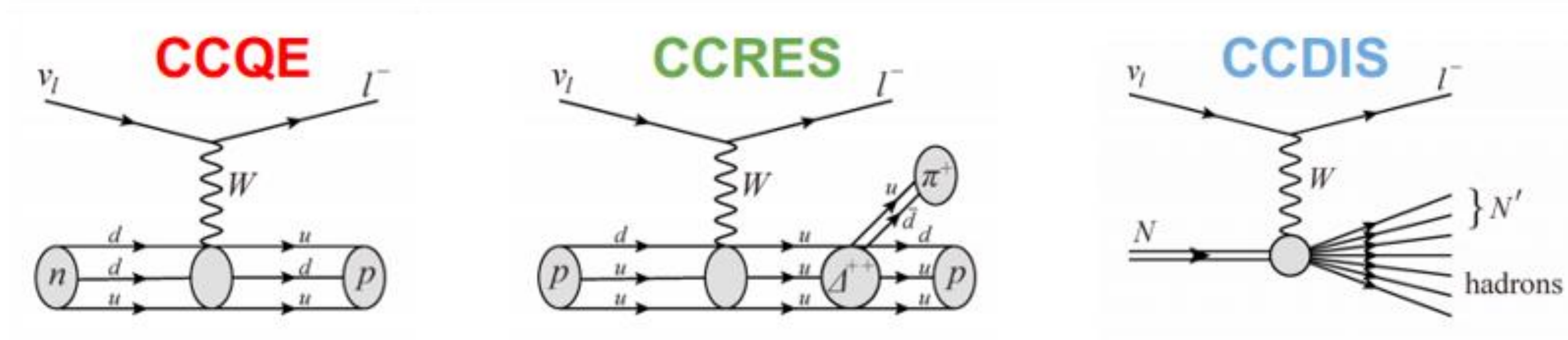

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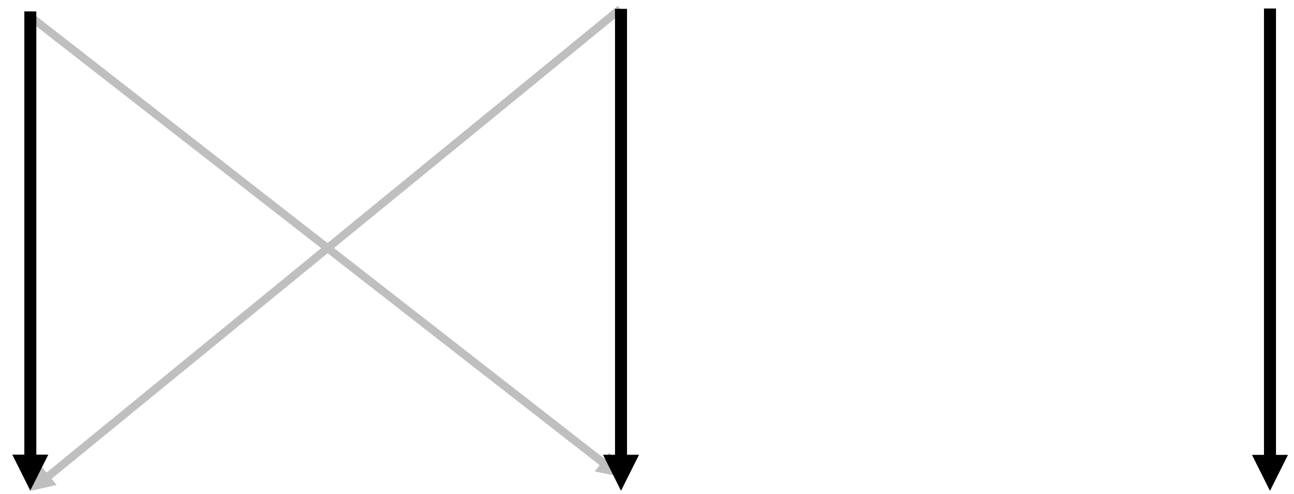
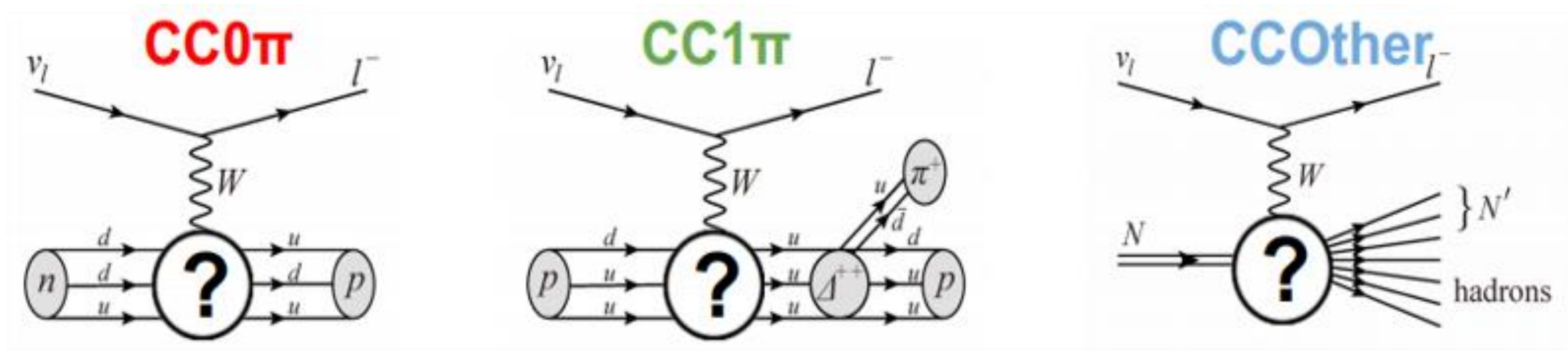


Nuclear Effects and Final State Interactions

Interaction Topologies (nucleus level)



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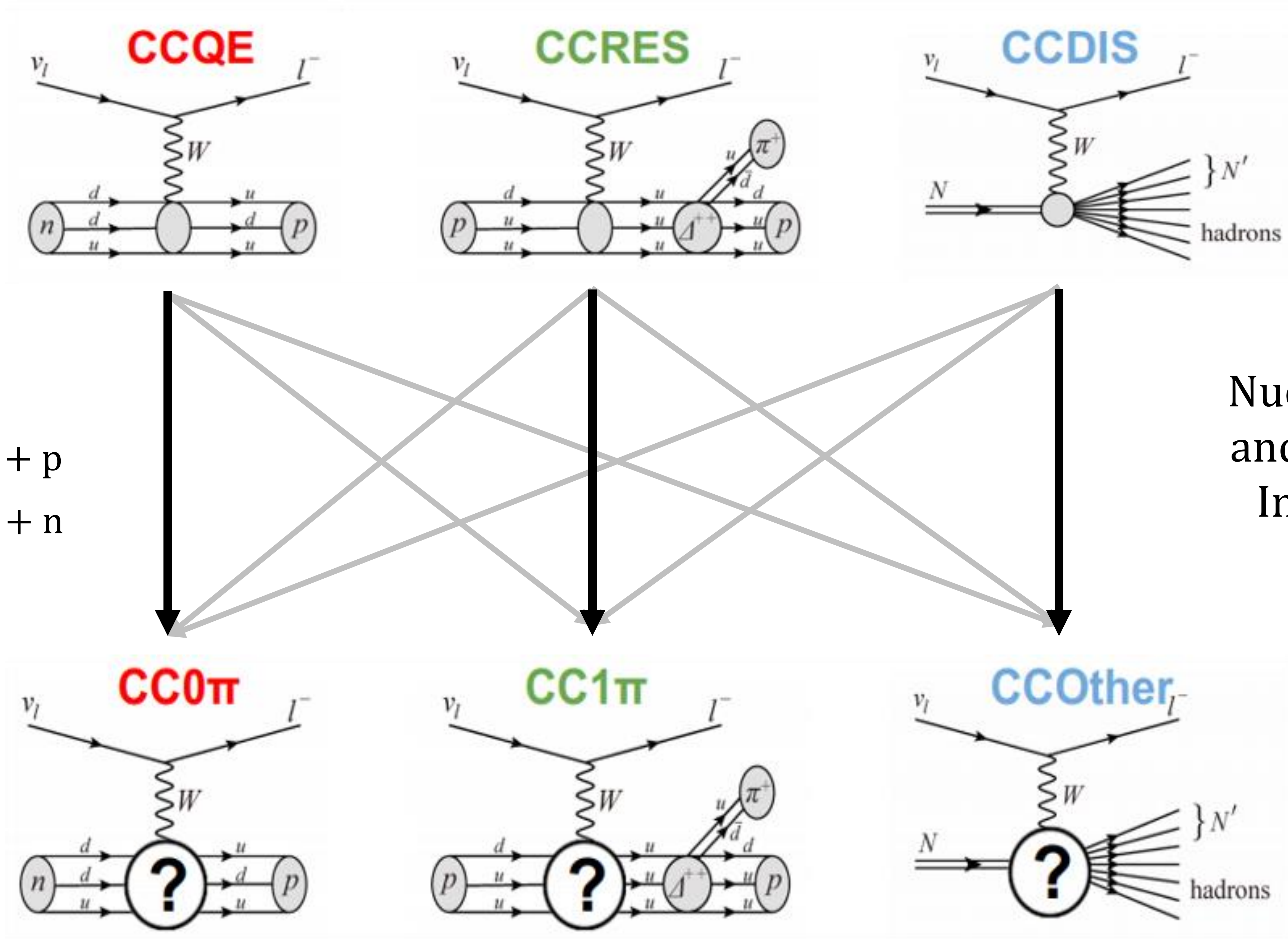


Nuclear Effects
and Final State
Interactions

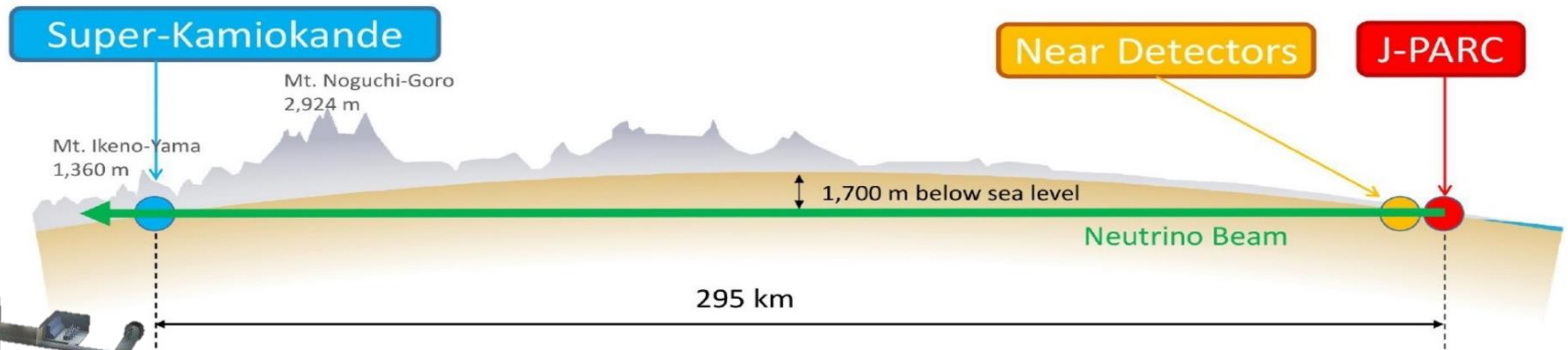
Interaction
Topologies
(nucleus level)

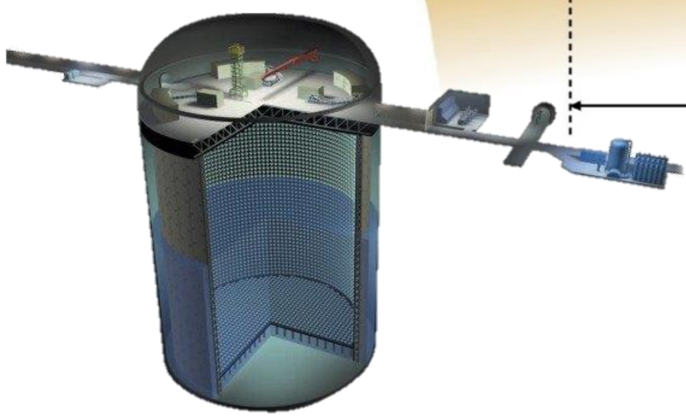
The T2K experiment

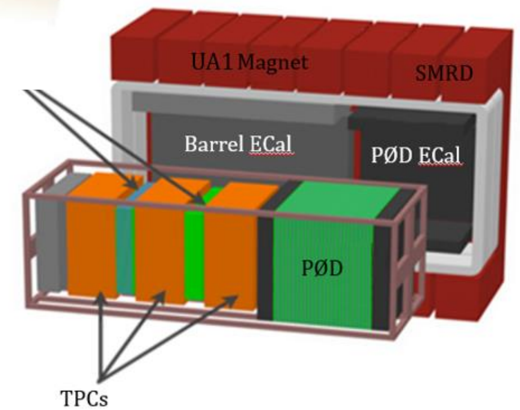
The T2K experiment

$N_x \rightarrow$ Number of neutrino-matter interactions
$E_\nu \rightarrow$ Neutrino energy
$\Phi \rightarrow$ Neutrino flux
$\sigma \rightarrow$ Cross section
$\epsilon \rightarrow$ Detector efficiency
$P \rightarrow$ Oscillation probability

- Measure neutrino oscillations: $\bar{\nu}_\mu/\nu_\mu$ disappearance and $\bar{\nu}_e/\nu_e$ appearance.
- Measure the oscillation parameters $\theta_{13}, \theta_{23}, \delta_{CP}$ and Δm^2_{32}



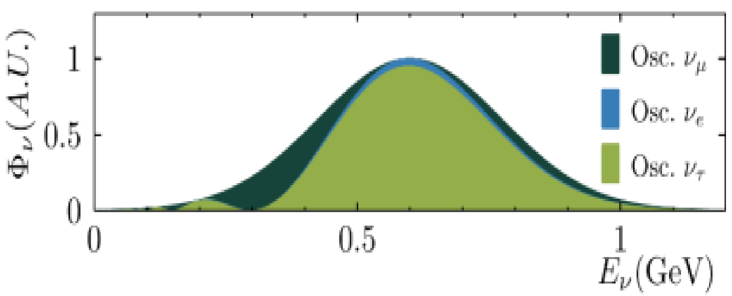


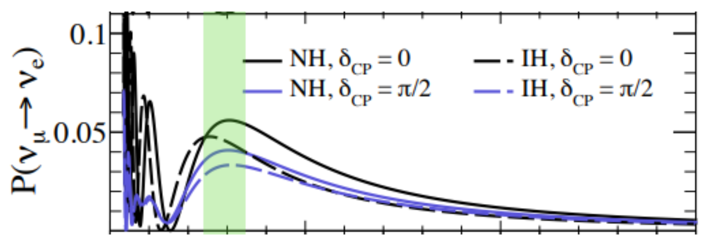


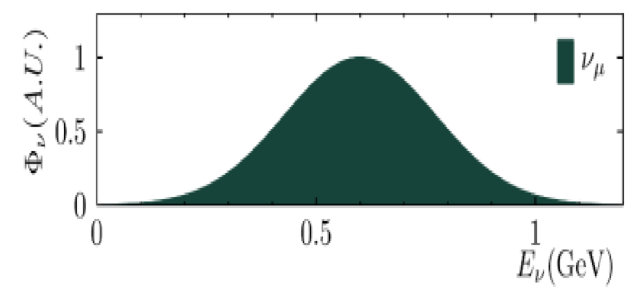
Near detector

$$N_x(E_\nu) = \phi(E_\nu)\,\sigma(E_\nu)\,\epsilon(E_\nu)\,P(\nu_\mu \rightarrow \nu_x)$$

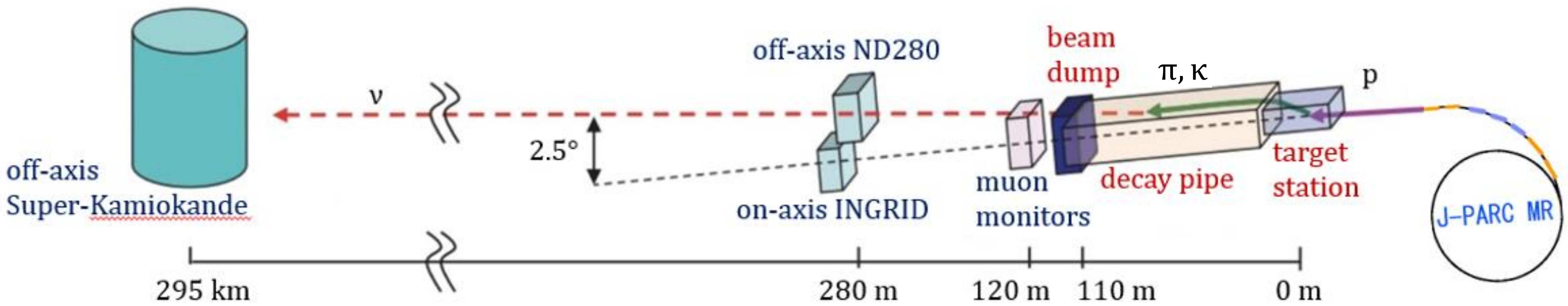
Far detector





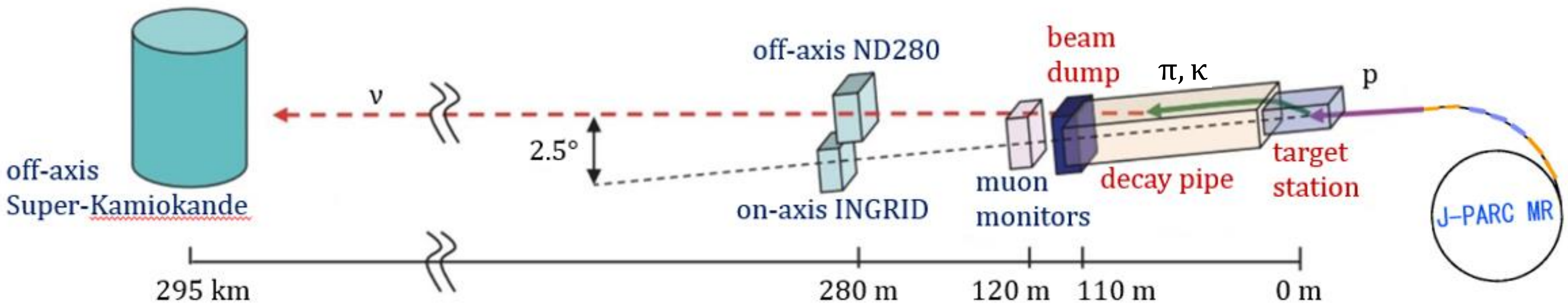


Beam

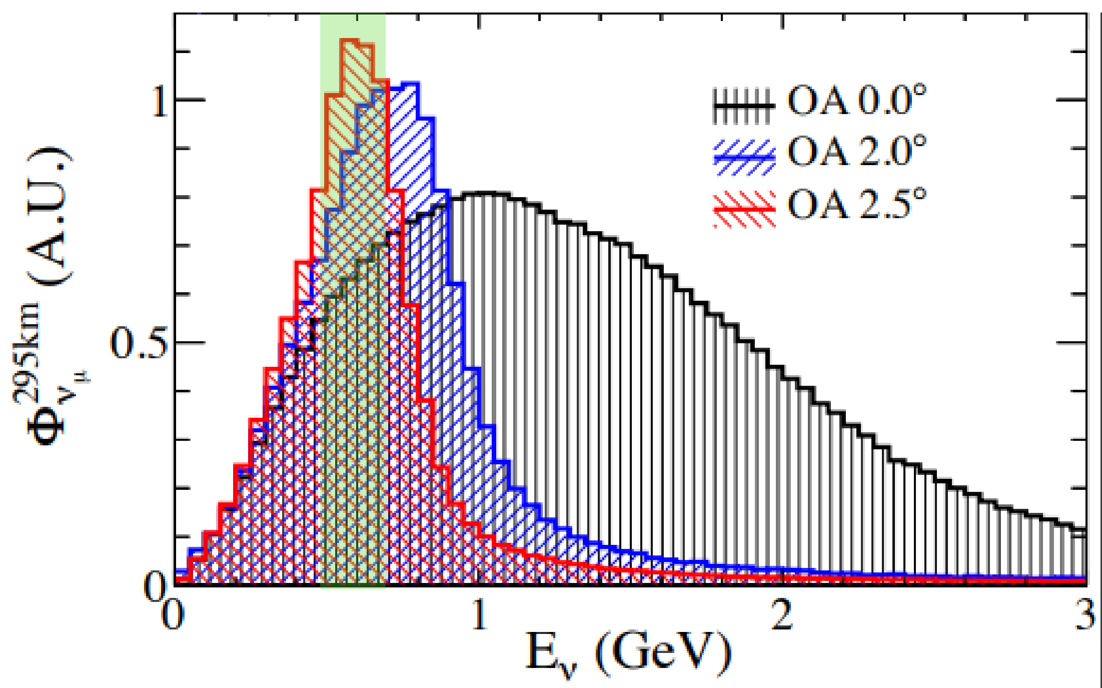


- 30 GeV protons collide with a graphite target and produce pions and kaons
- magnetic horns will focus the pions:
  - Forward horn current (FHC): $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - Reverse horn current (RHC): $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- all particles except neutrinos stopped in beam dump

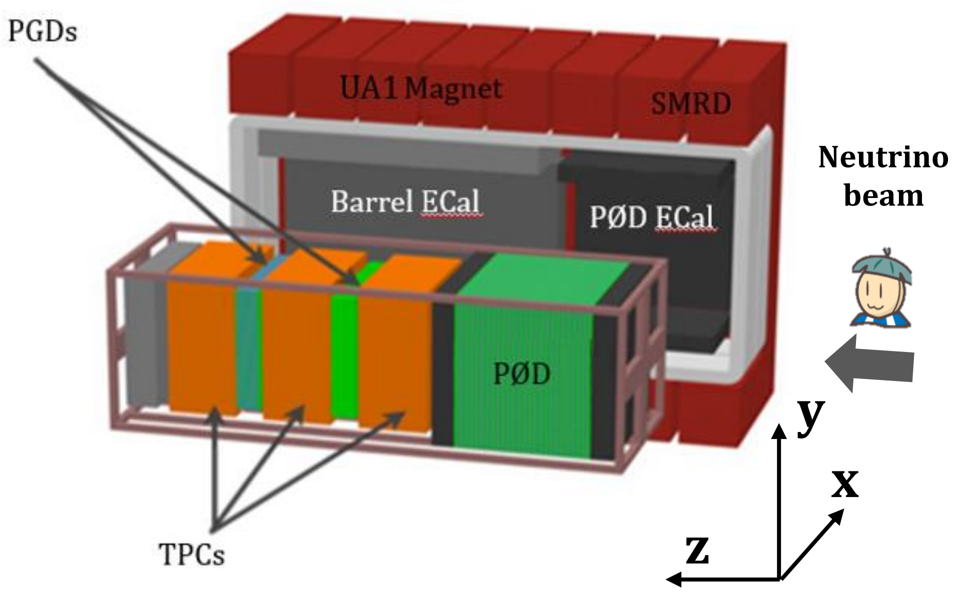
Flux

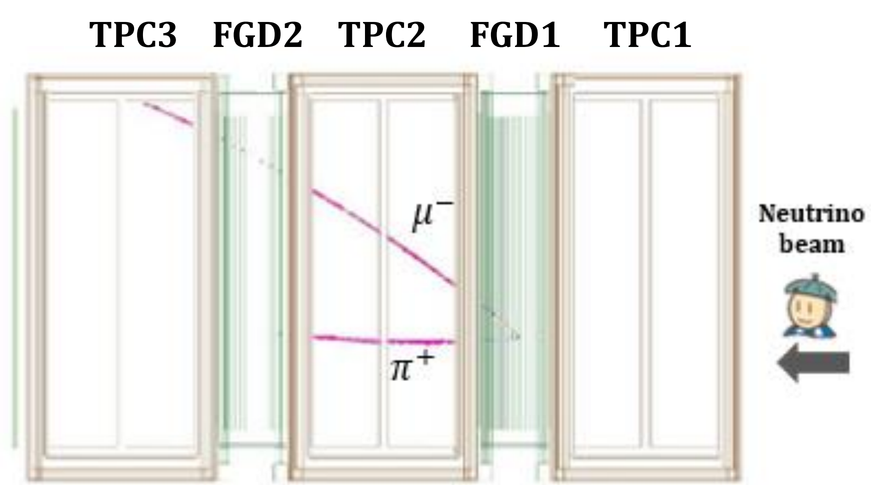


- Use off-axis beam for narrower energy spectrum.
- Off-axis angle flux peaked at 0.6 GeV, which is at an oscillation maximum.
- Only one oscillation maximum can be measured at a fixed distance.



Off-axis (2.5 degrees) ND280





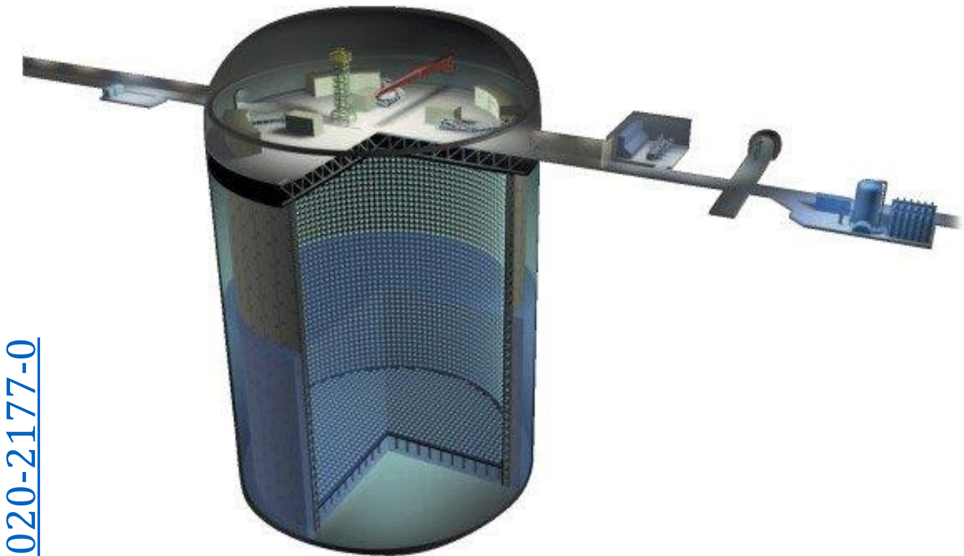
ND280 is used to:

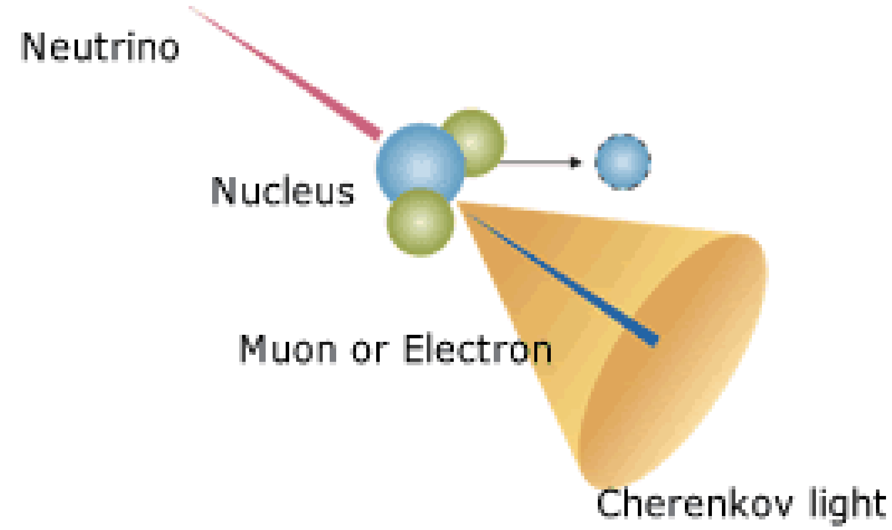
- constrain the flux and cross section parameters.
- measure background processes to oscillation.

ND280 is form by:

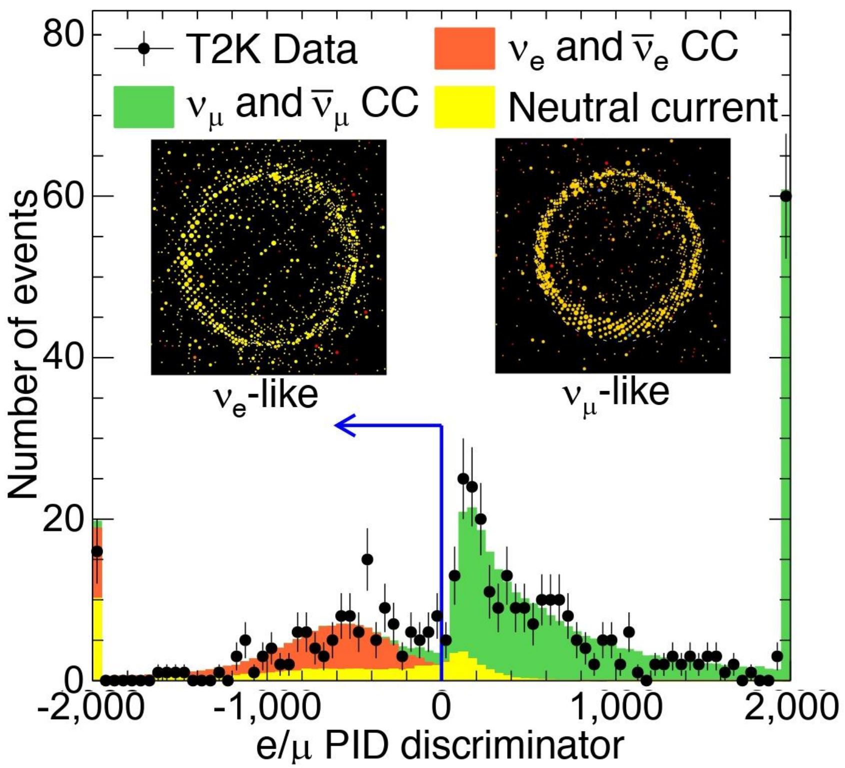
- π^0 Detector (PØD): neutral pion detector, optimized for NC interactions.
- Time Projection Chambers (TPCs): energy, angle and identification
- Fine grained detector (FGDs): active target
  - FGD1: Hydrocarbon
  - FGD2: Hydrocarbon + Water
- Electromagnetic Calorimeters (ECals): separated tracks from showers and as veto.
- Side Muon Range Detector (SMRD): energy of muons based on the range and as veto.
- Magnet: charge of the particles and momentum.

Off-axis (2.5 degrees) Super-Kamiokande





Water Cherenkov detector
- 50 kton of ultra-pure water
- ~11000 20 inch PMTs
- 1 km underground

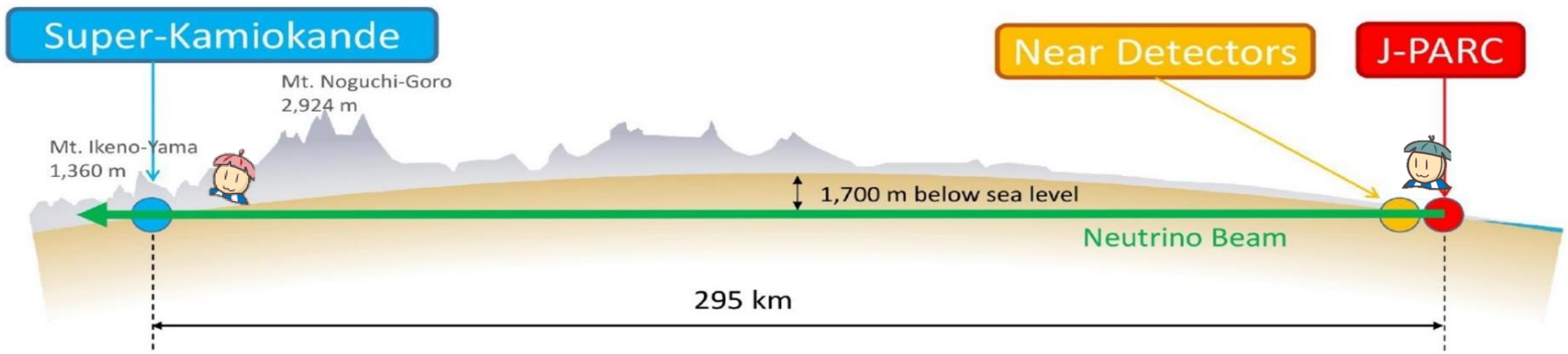


https://www.nature.com/articles/s41586-020-2177-0

- Particle identification
- Particle range
- Interaction vertex reconstruction
- Electromagnetic energy reconstruction
- Track Multiplicity

Milestones

https://link.aps.org/doi/10.1103/PhysRevLett.112.061802
https://www.nature.com/articles/s41586-020-2177-0
https://arxiv.org/abs/1901.03750
https://iopscience.iop.org/article/10.1088/1742-6596/888/1/012020



2004 — Start of construction ν beamline

2010 — Start of data taking

2014 — $\theta_{13} \neq 0$

2015 — Nobel Prize in Physics to neutrino oscillations

2016 — Breakthrough Prize in Fundamental Physics

2020 — Constraint on the Matter-Antimatter Symmetry-Violating Phase in Neutrino Oscillations

2023 — Second phase of data taking (T2K-II)

2027 — Start of Hyper-Kamiokande detector

Motivation

Why we look at ND280 4π solid angle acceptance?

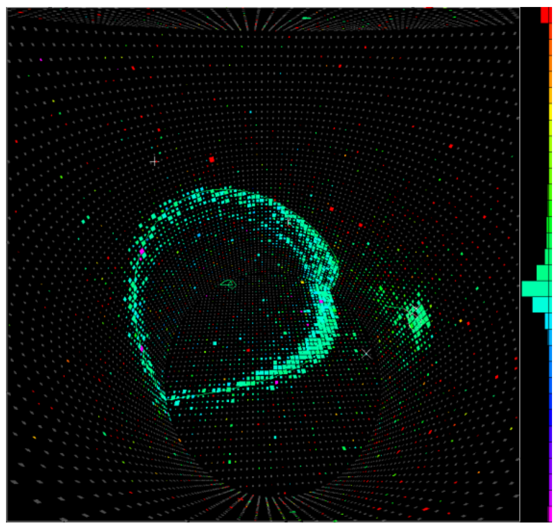
Near/far detector ratios don't fully cancel systematics:

- Different near/far detector design acceptance.

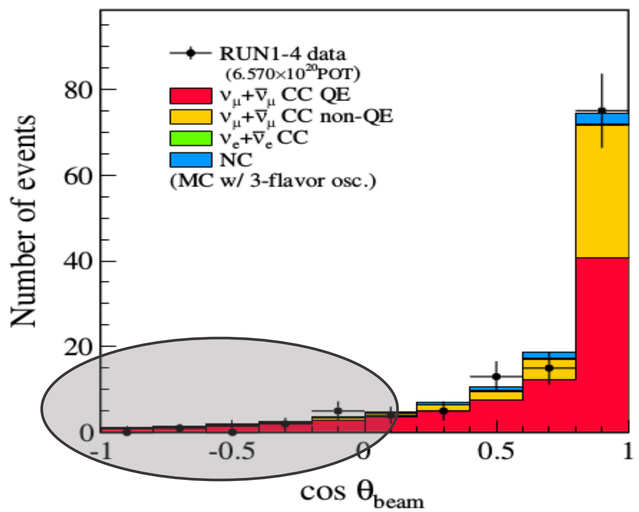
SK detector

↓

4π acceptance



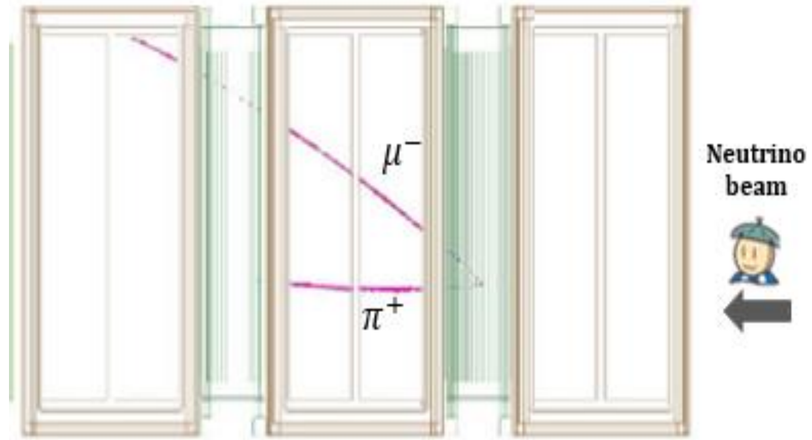
The cos θ_{beam} distribution in the events selected for the ν_μ disappearance analysis at SK



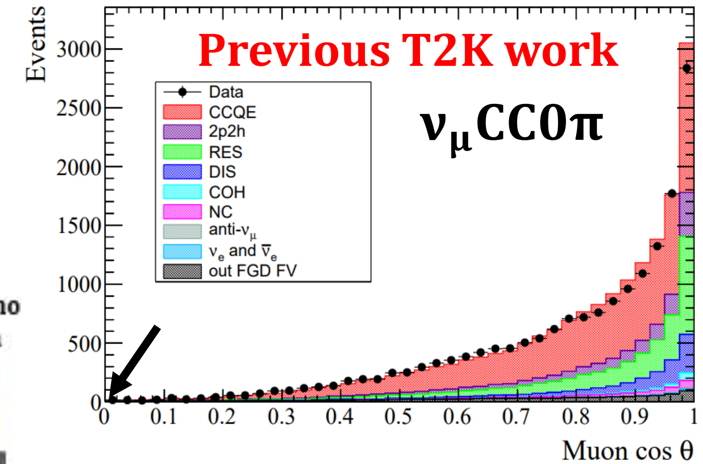
ND280

↓

Forward-going tracks



The cos θ_μ distribution



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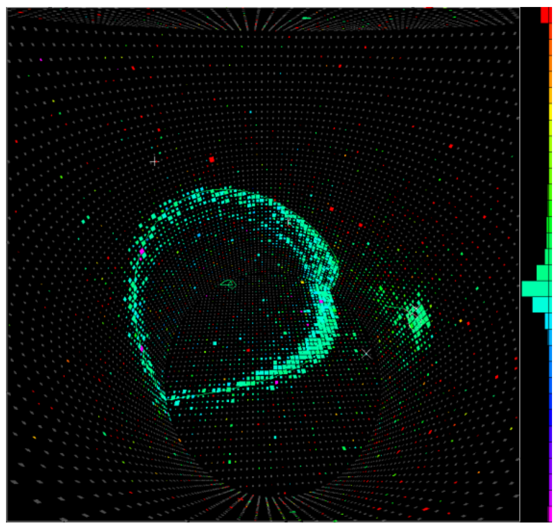

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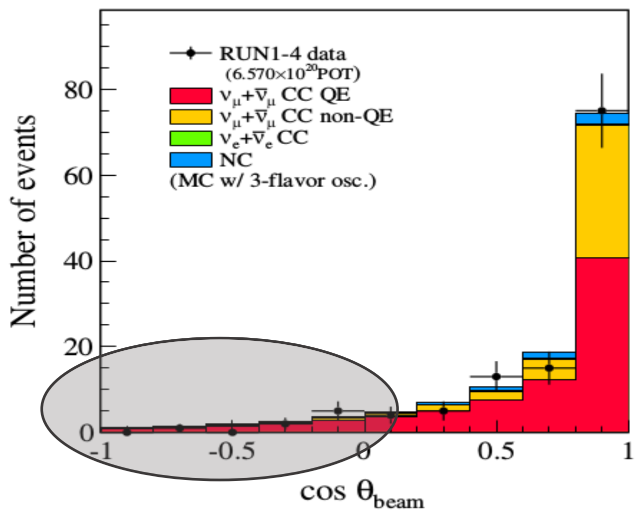

ND280

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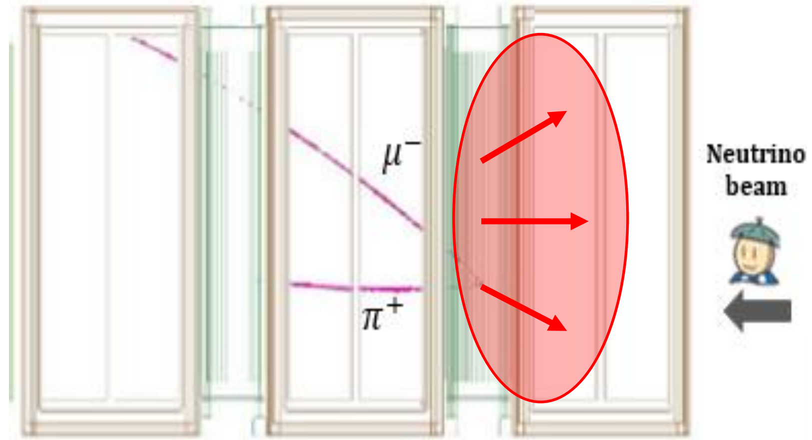

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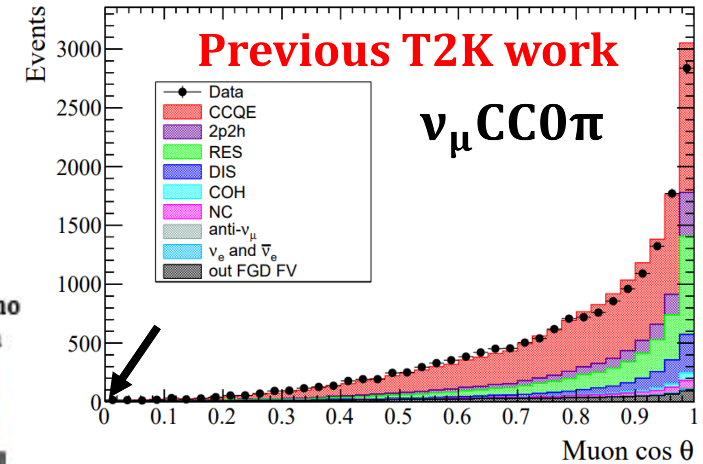
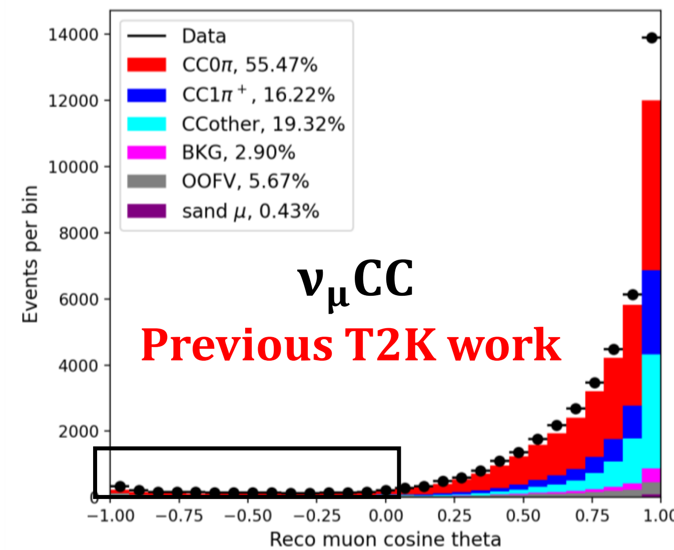




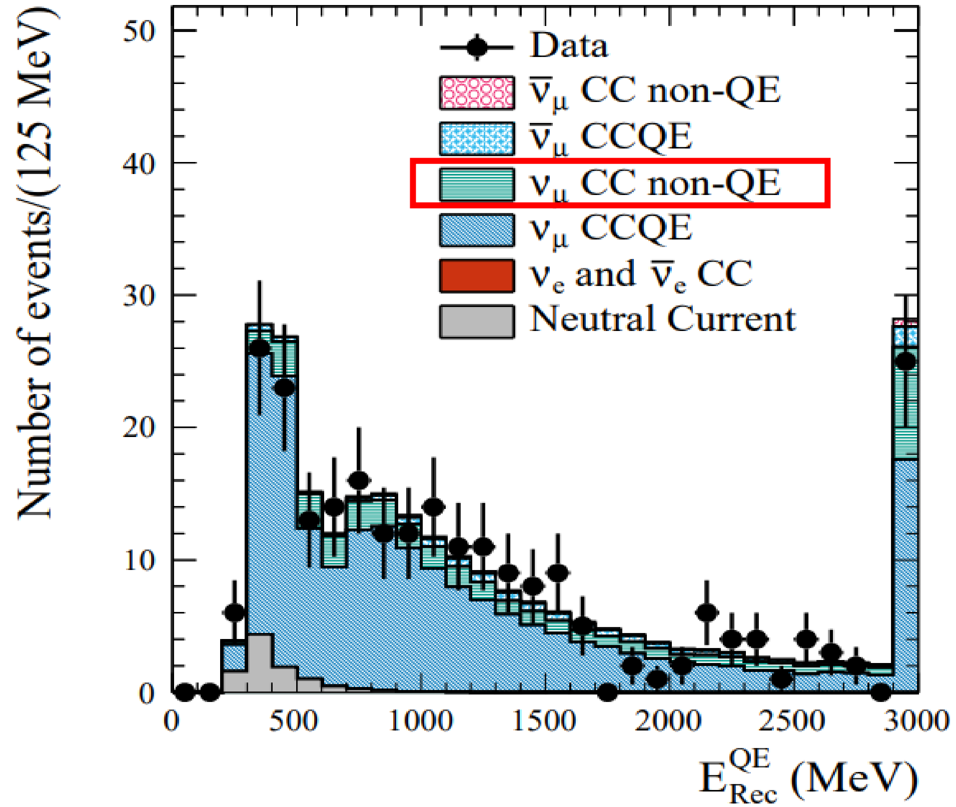
ND280

↓

4π acceptance

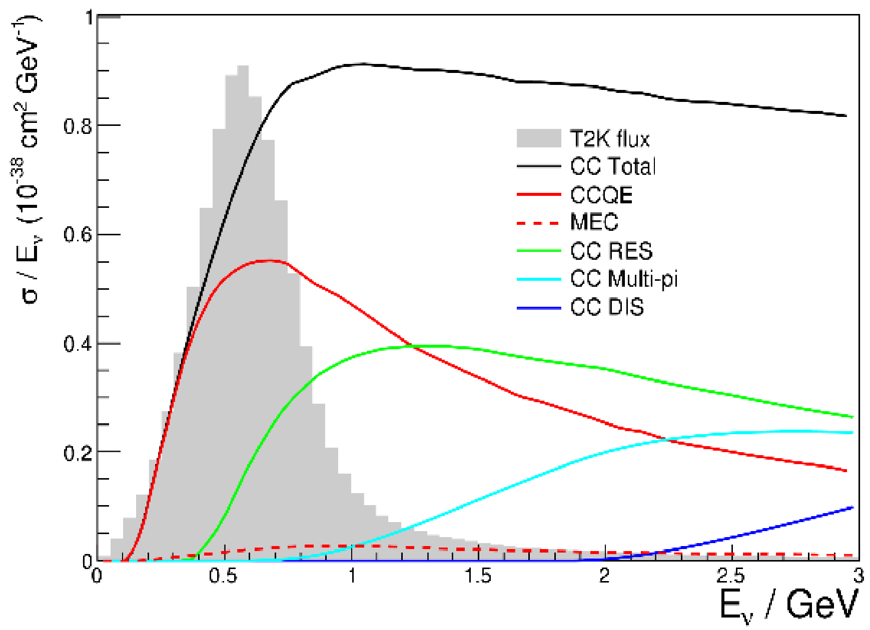
Why ν_μCC1π^+ events?

- ν_μCC1π^+ events constitute the main background for the ν_μ disappearance measurement.
- CC1π^+ events (2 rings) is a new signal at SK.
- Pion production is dominated by resonant interactions in the T2K energy range.



Single pion production issues

- Missing models of nuclear effects
- No consistent way to model RES/DIS transition
- Nucleon-level model is much shakier that CCQE



Why measure the cross section?

Neutrino oscillation parameters require a precise knowledge of the interaction cross section

Systematic errors are currently dominated by cross section and flux uncertainties

- Cross sections are used to:
  - understand how neutrinos interact with matter.
  - control the bias on the reconstructed energy
  - reduce uncertainties on the event rate at Super-Kamiokande.

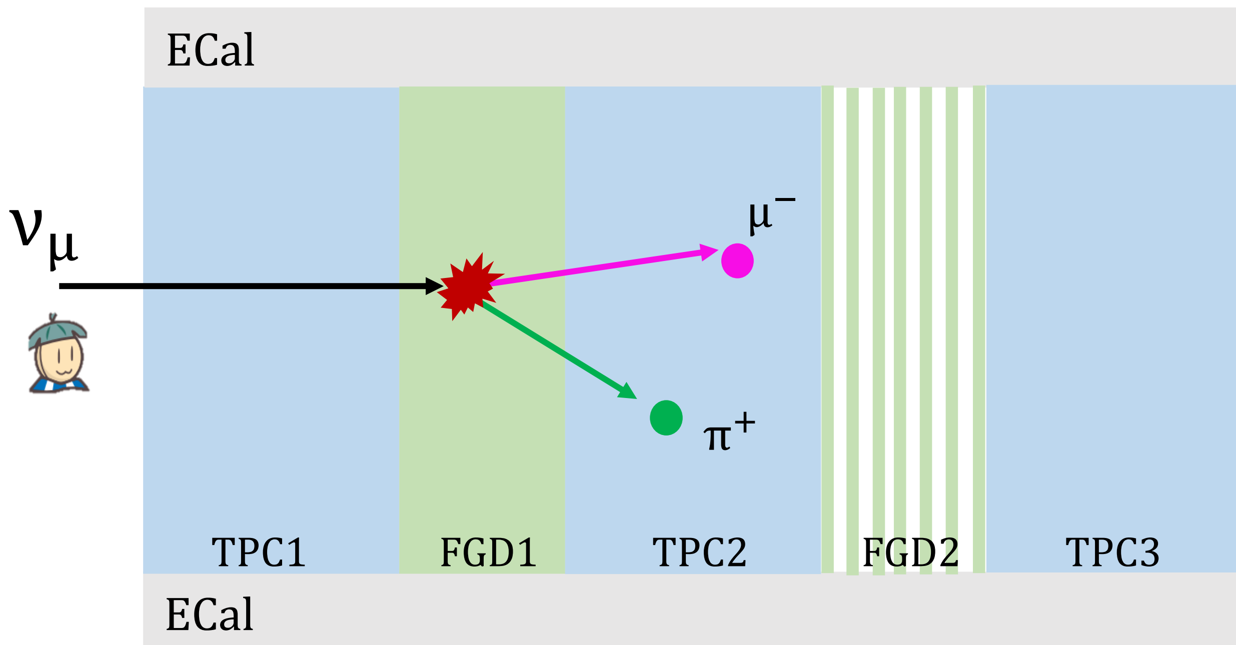
	1-Ring μ	
Error source	FHC	RHC
SK Detector	2.4	2.0
SK FSI+SI+PN	2.2	2.0
Flux + Xsec (ND unconstrained)	14.3	11.8
Flux + Xsec (ND constrained)	3.3	2.9
Nucleon Removal Energy	2.4	1.7
$\sigma(\nu_e)/\sigma(\overline{\nu}_e)$	0.0	0.0
NC1γ	0.0	0.0
NC Other	0.3	0.3
$\sin^2\theta_{23} + \Delta m^2_{21}$	0.0	0.0
$\sin^2\theta_{13}$ PDG2018	0.0	0.0
All Systematics	5.1	4.5

CC1π^{+} analysis overview

Signal definition

Target:

- Hydrocarbon (C_8H_8) → carbon



CC1π^+ signal:

- one negatively charged muon,
- one positively charged pion,
- no other pions,
- any number of nucleons.

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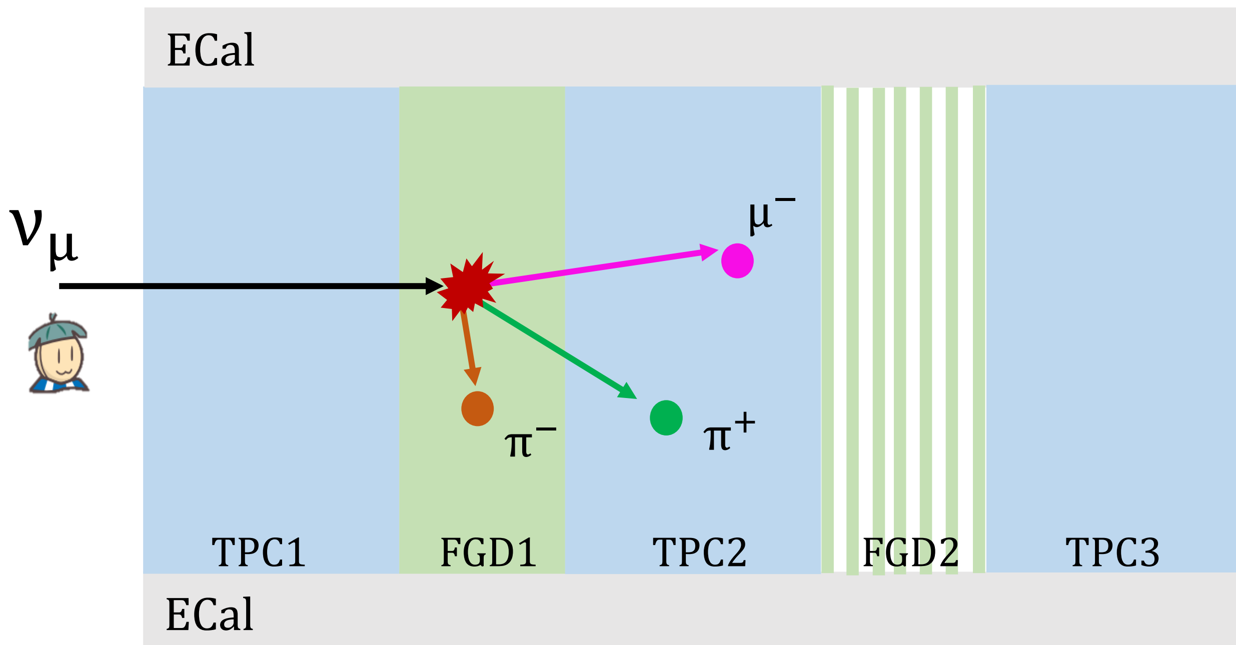


CC1π^+ signal:

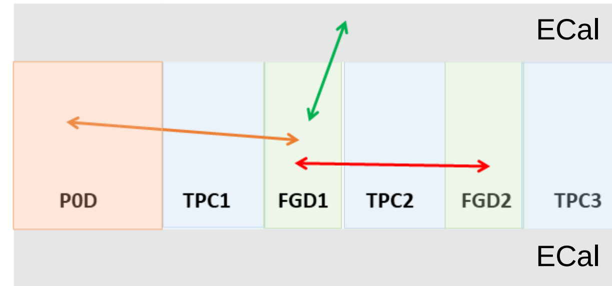
- one negatively charged muon,
- one positively charged pion,
- no other pions,
- any number of nucleons.

CC1π^+1$\pi^{\pm,0}$ side band or control region:

- one negatively charged muon,
- one positively charged pion,
- one other pion,
- any number of nucleons.

Selection development

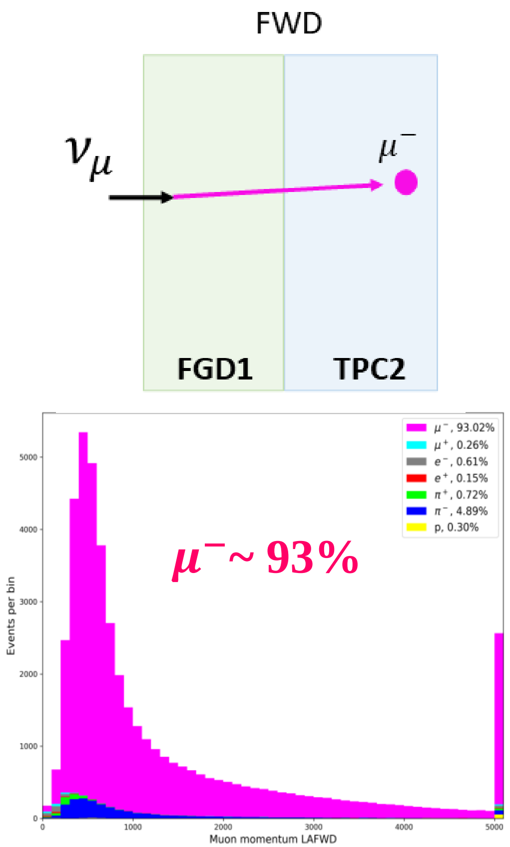
ND280 Events → general event quality, multiplicity, time of flight, fiducial volume → direction of the main track, apply PID for muons

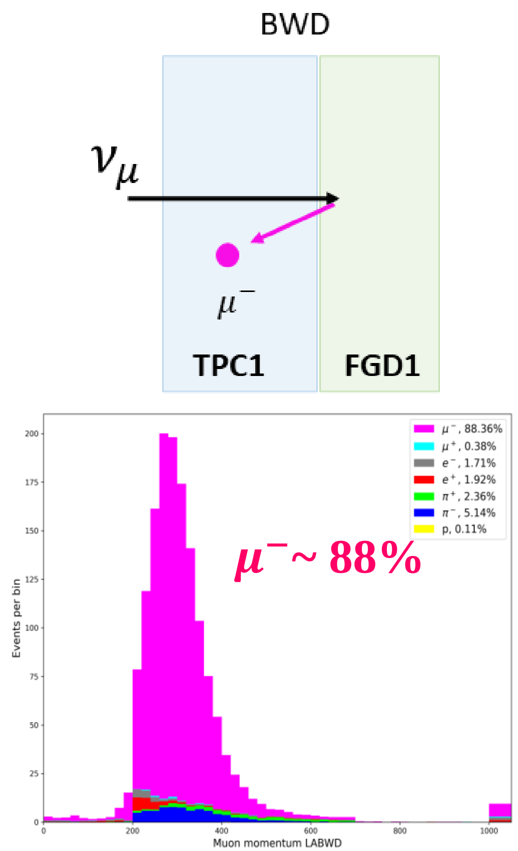


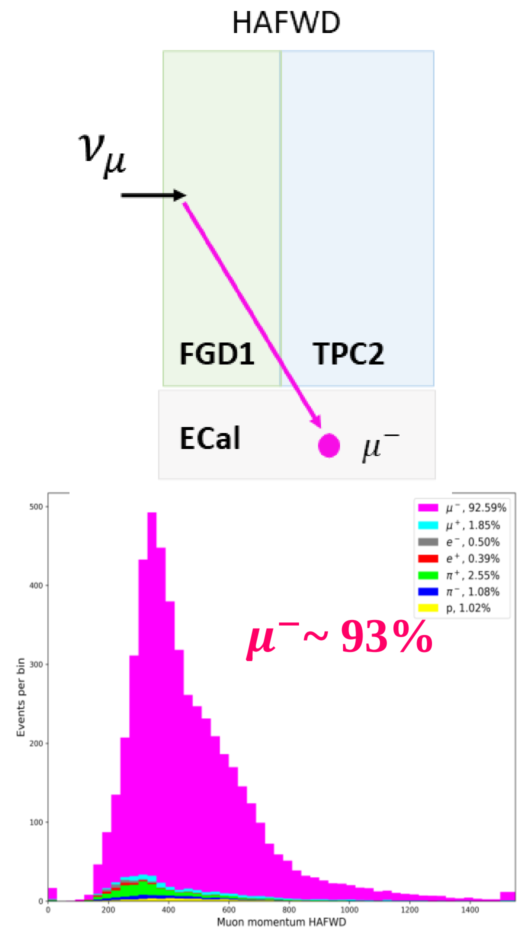
$$ToF_{P0D-FGD1} = t_{FGD1} - t_{P0D}$$

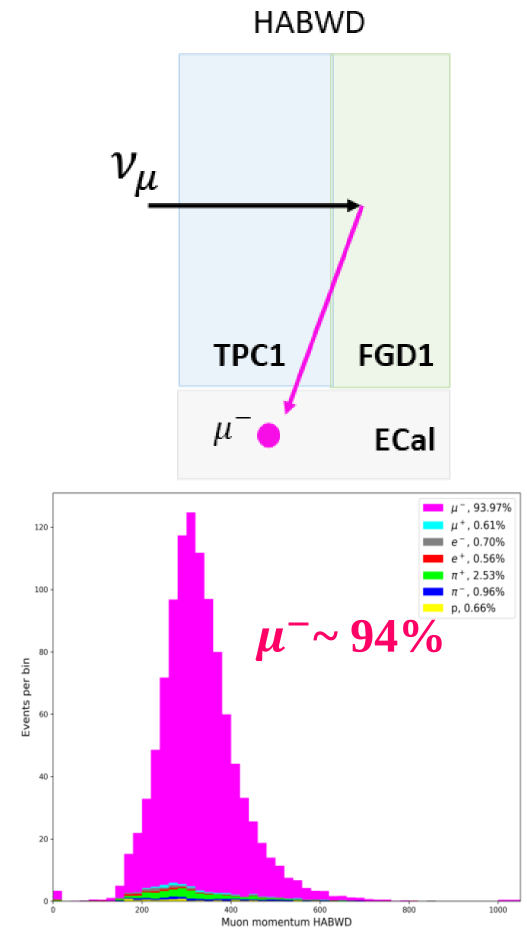
$$ToF_{ECal-FGD1} = t_{FGD1} - t_{BrECal}$$

$$ToF_{FGD1-FGD2} = t_{FGD2} - t_{FGD1}$$



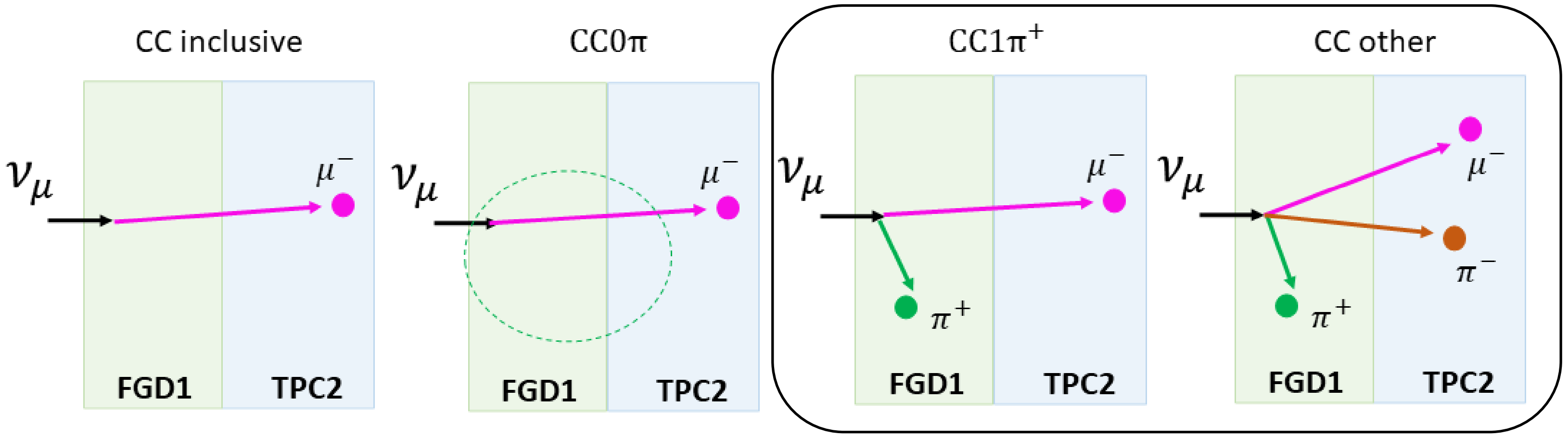


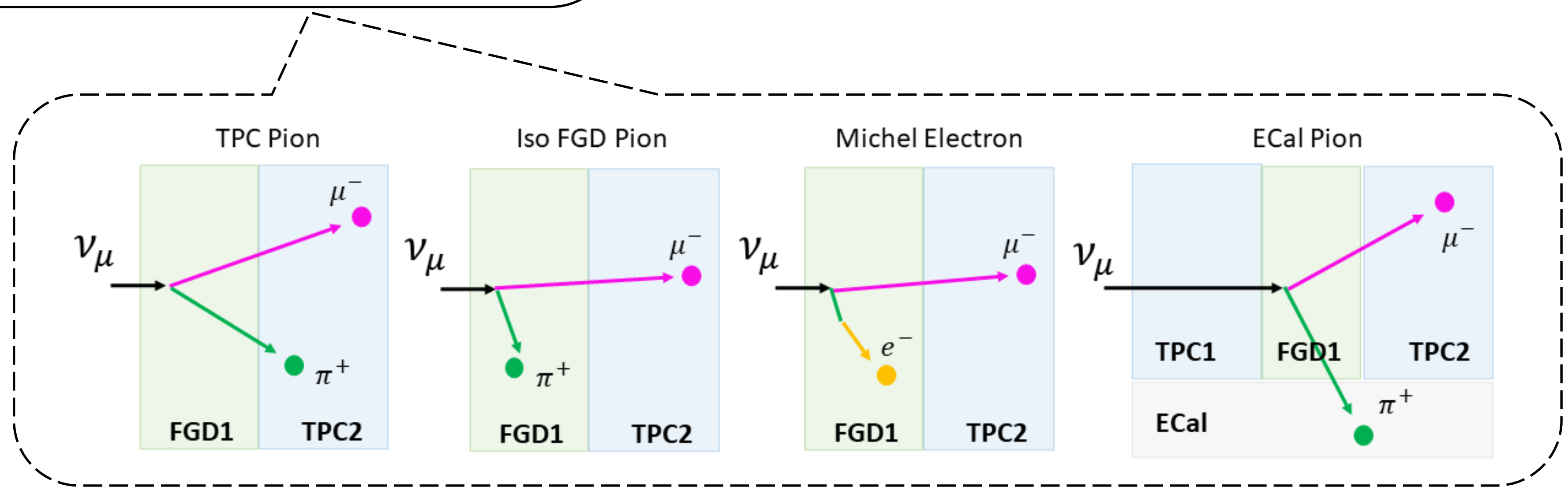




Selection development

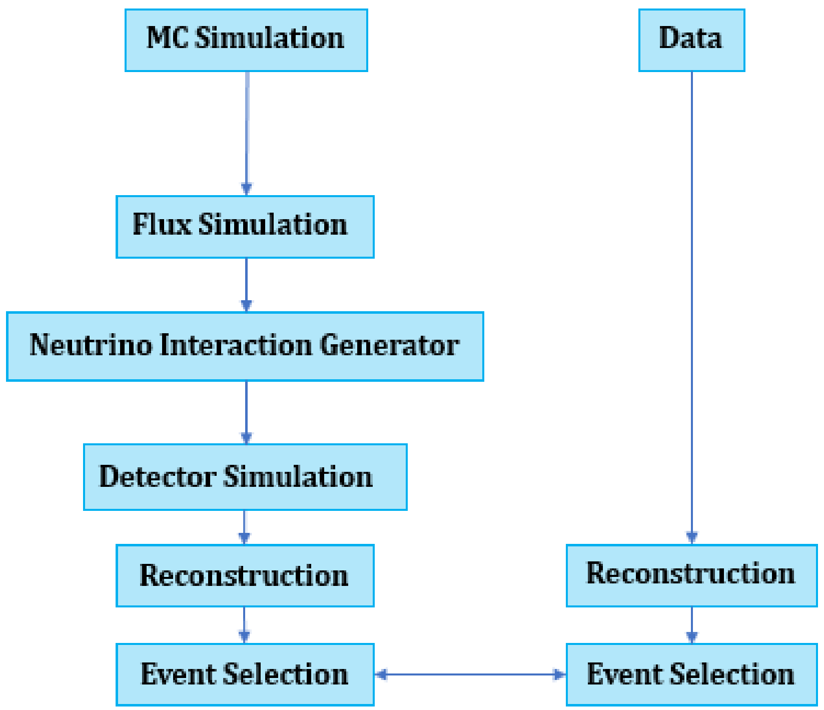
ND280 Events → general event quality, multiplicity, time of flight, fiducial volume → direction of the main track, apply PID for muons → Pion multiplicity → Additional steps for improving the purity of the samples

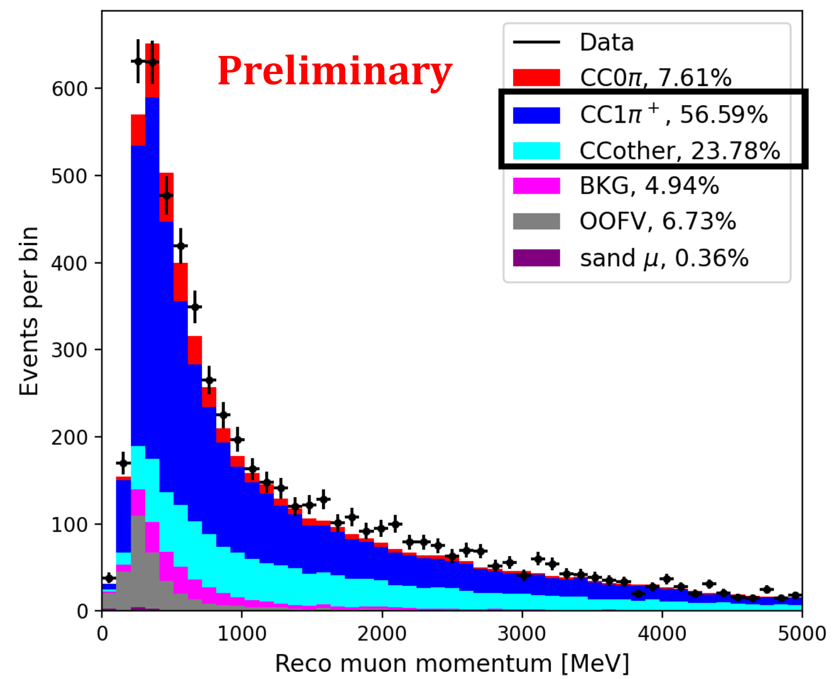


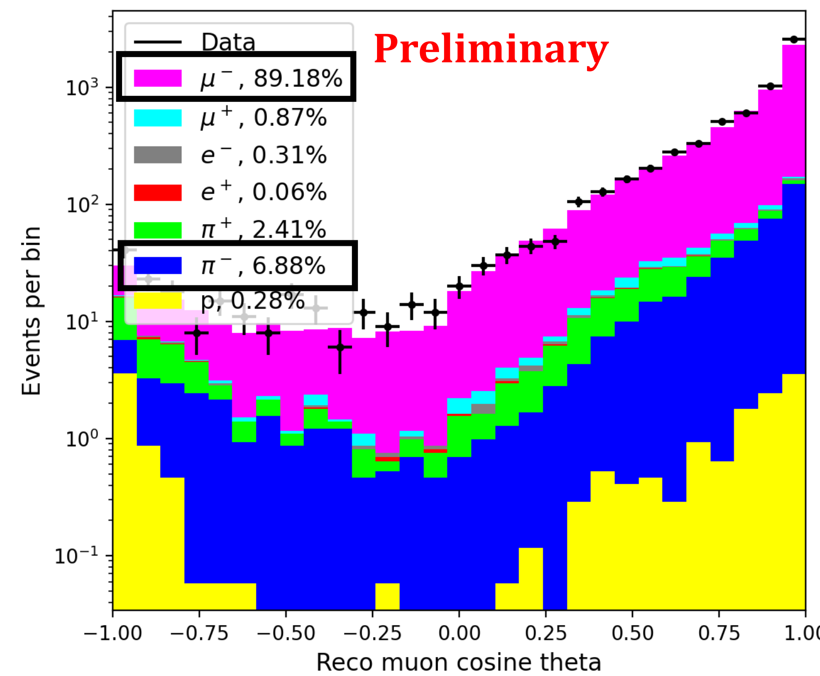


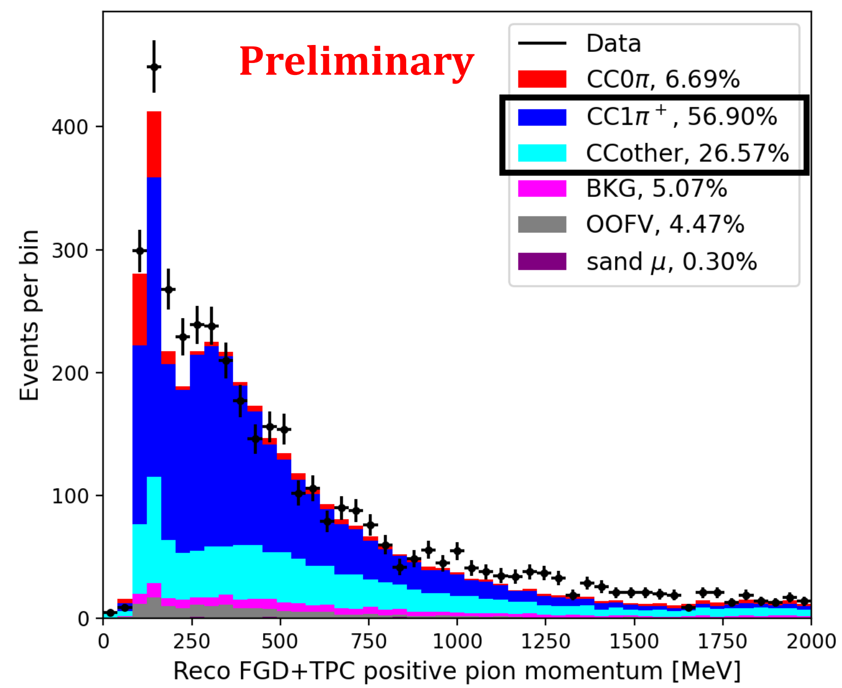
Input samples CC1π^+

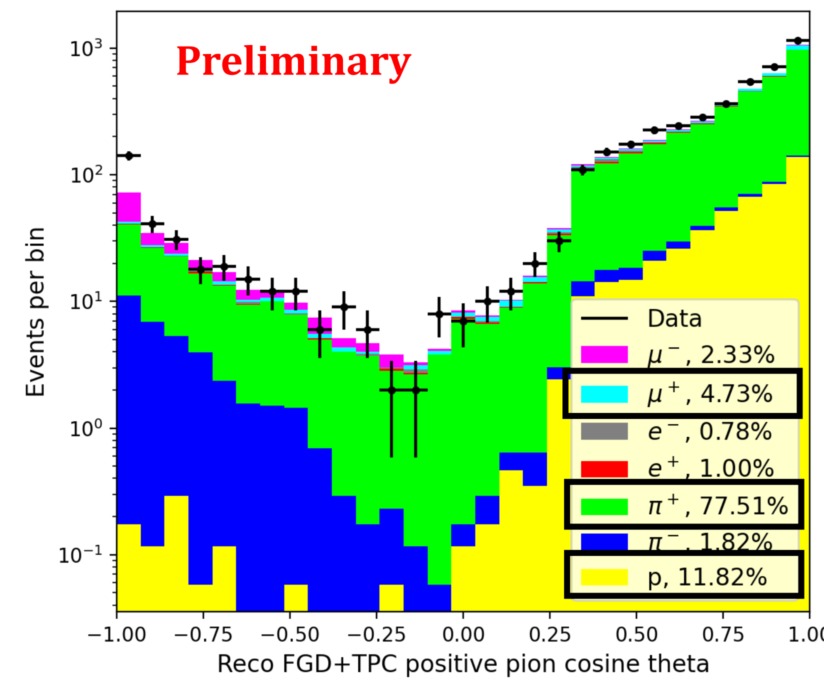
- model independent way
- comparison to other experiments
- improvement of current models





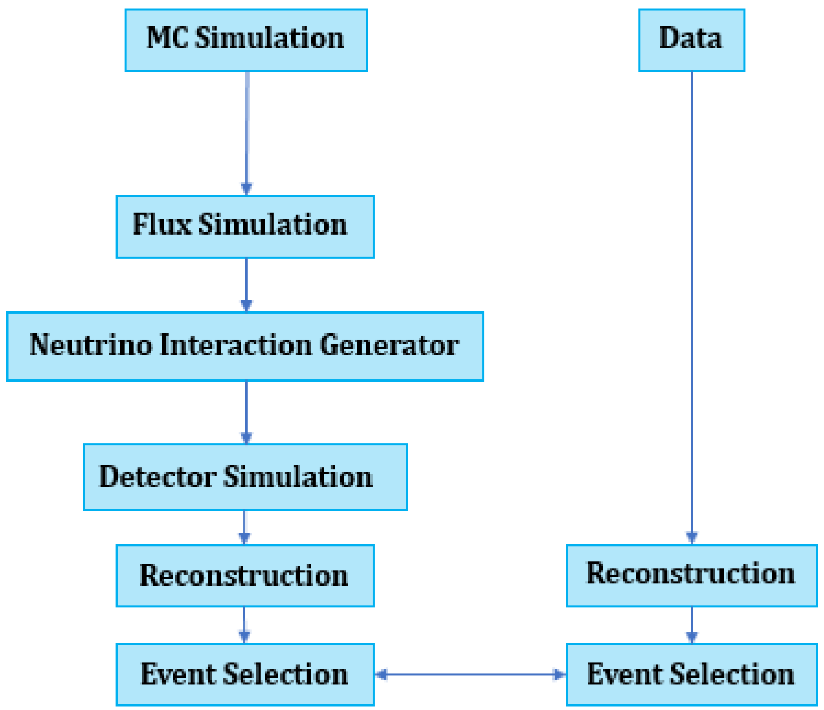


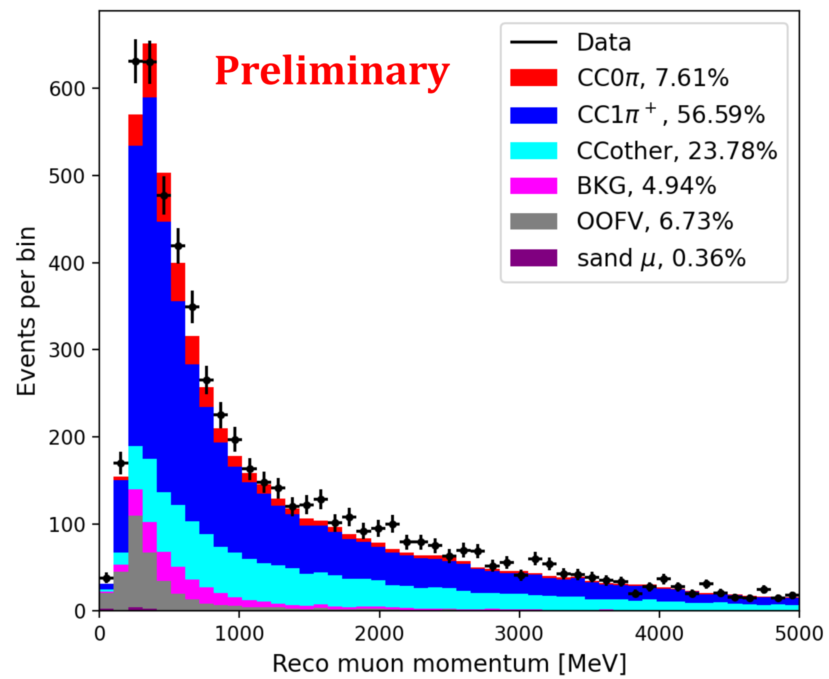


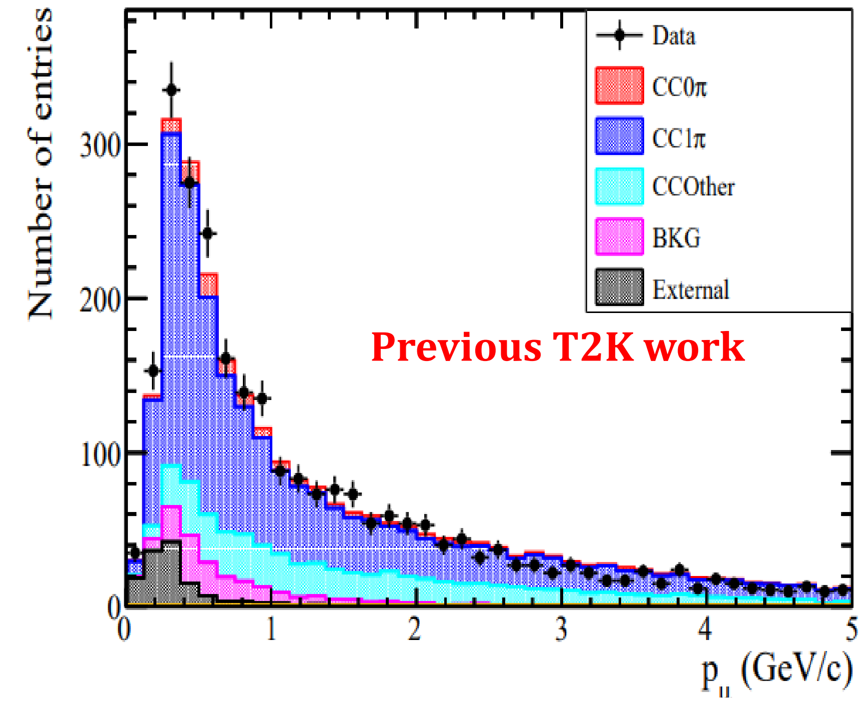


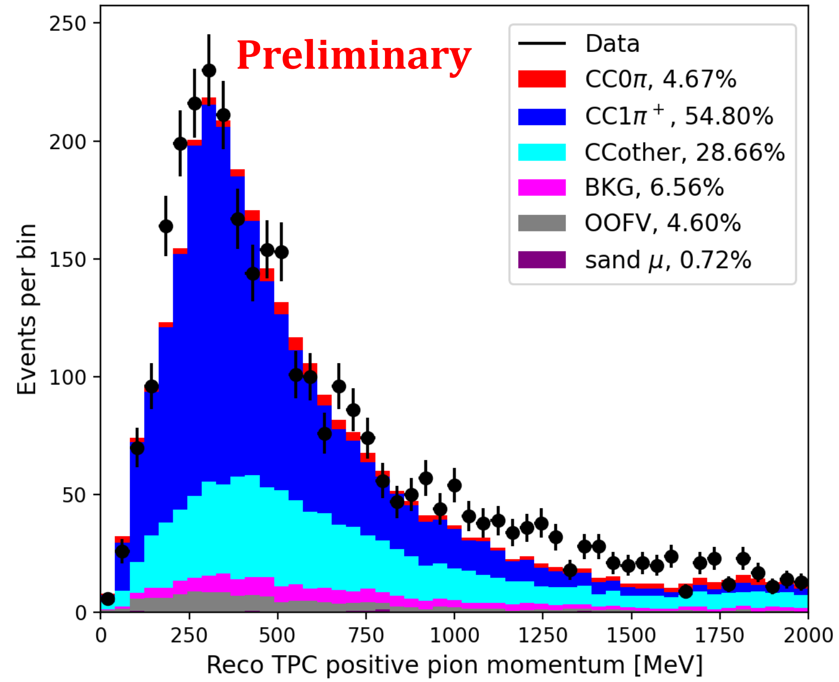
Input samples CC1π^+

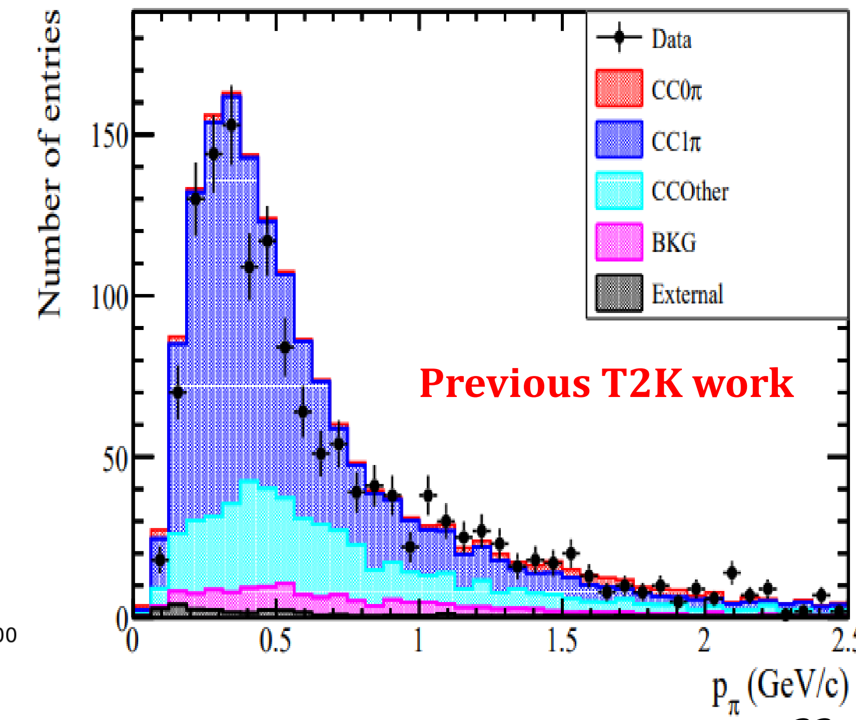
- More statistics
- Similar:
  - data agreement
  - distribution shape
  - purity



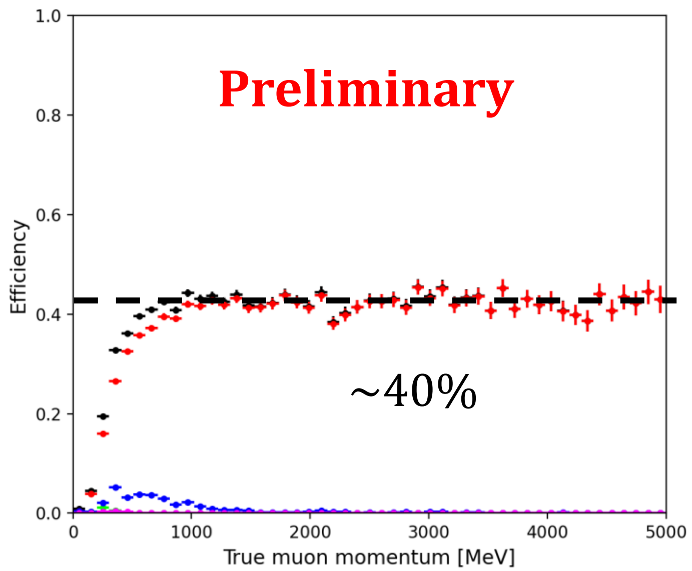


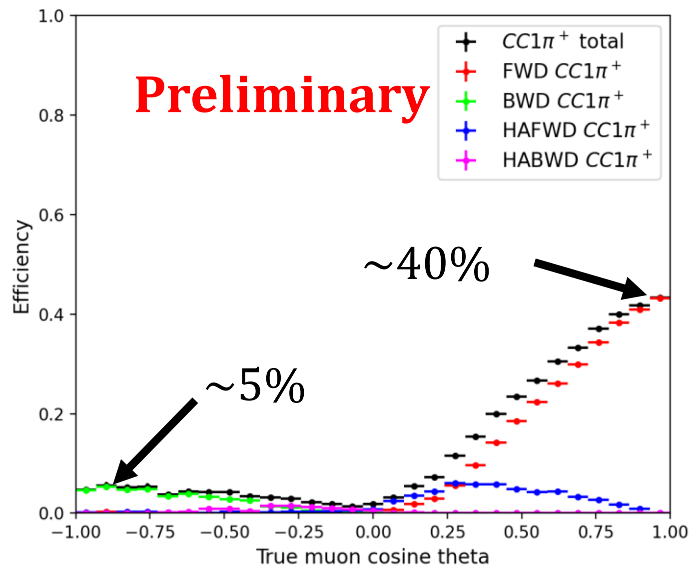


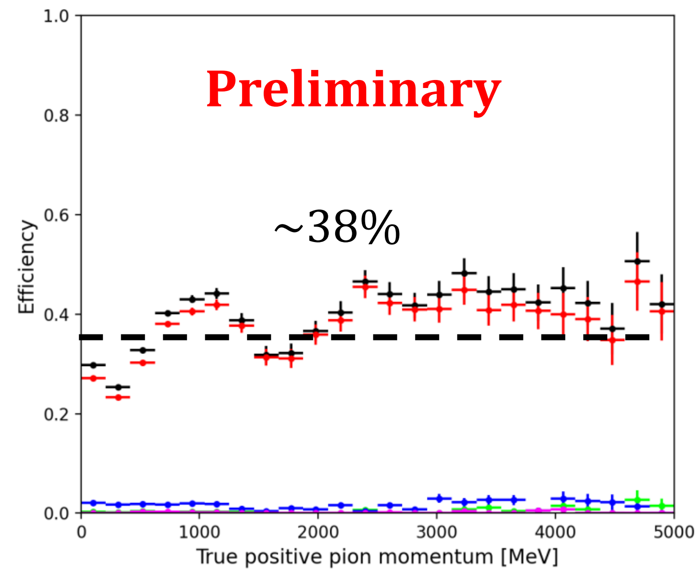


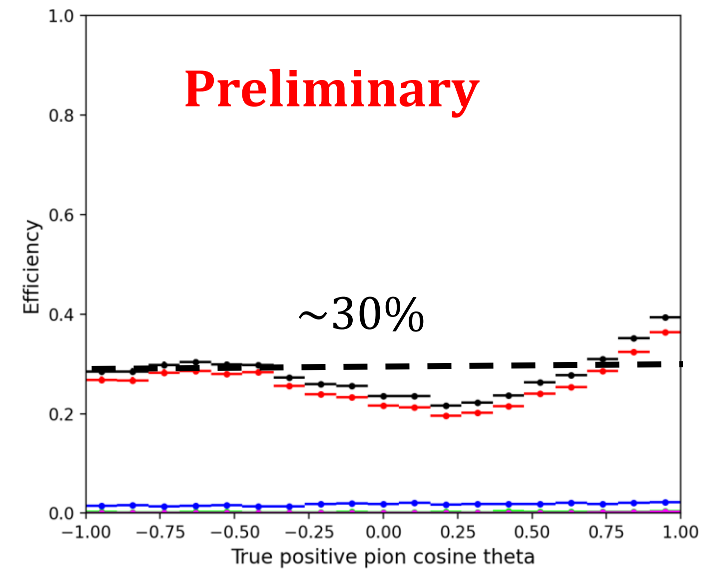


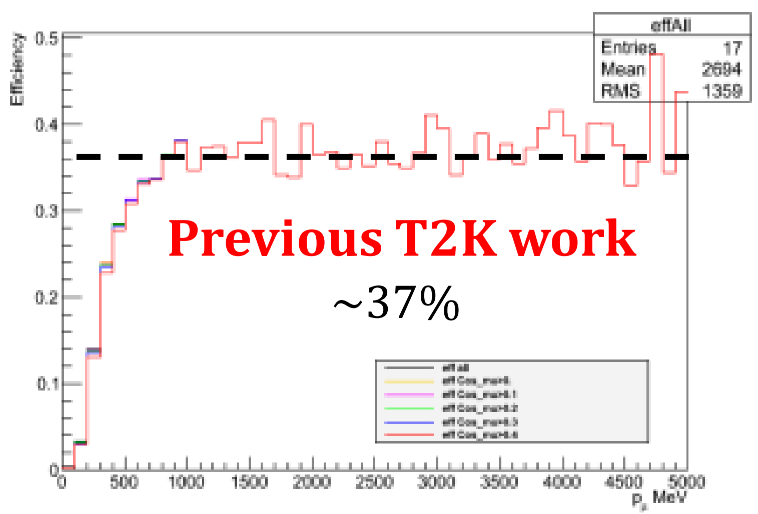
Detection efficiency

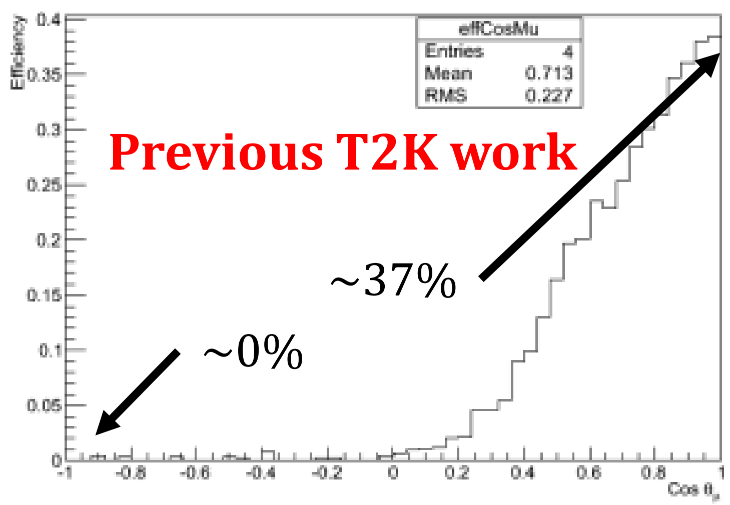








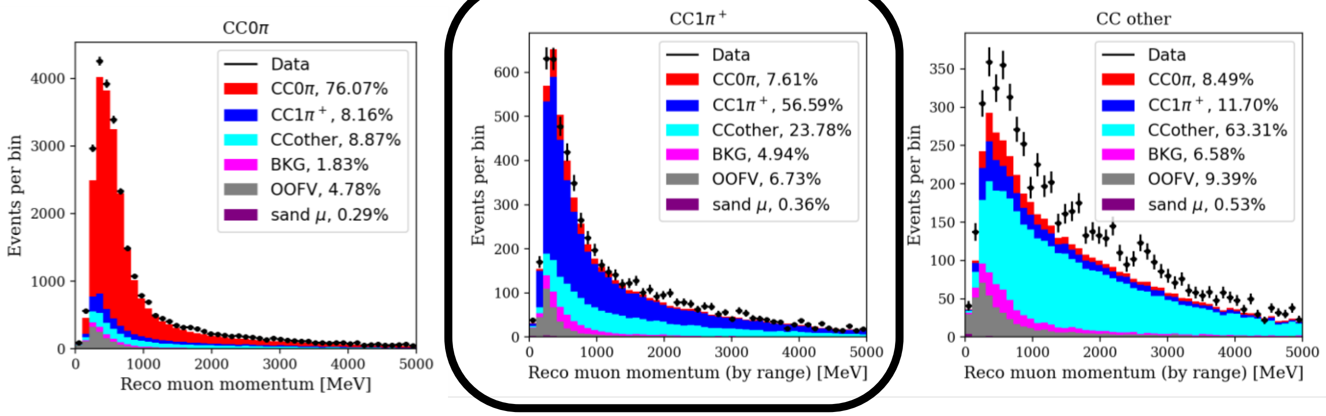




- For muons with momentum higher than 500 MeV the efficiency is quite flat.
- For BWD muons the efficiency is close to 5%
- For positive pions the efficiency is quite flat regardless of the direction.

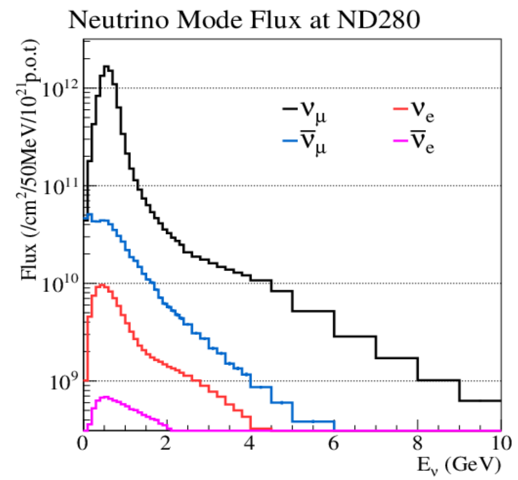
Beam And Nd280 Flux measurement task Force

ND280 data



+

Flux prediction



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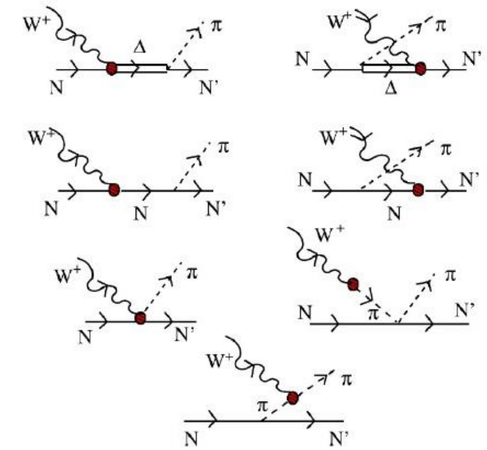
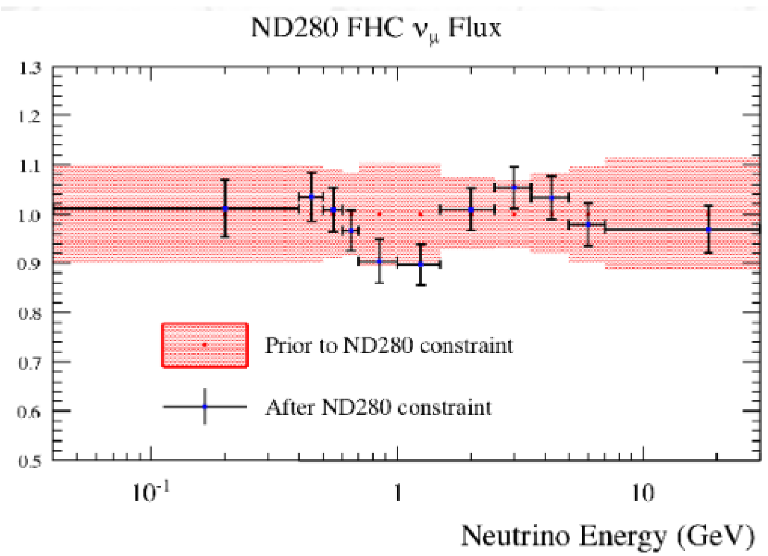
Cross section model



Corrected flux and cross-section model



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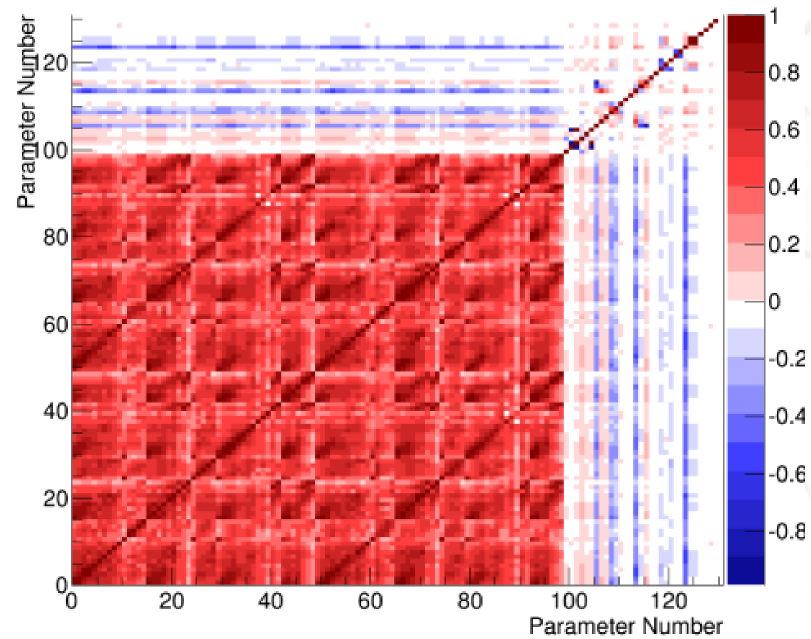
covariance matrix



BANFF

Adler angles and asymmetry definitions

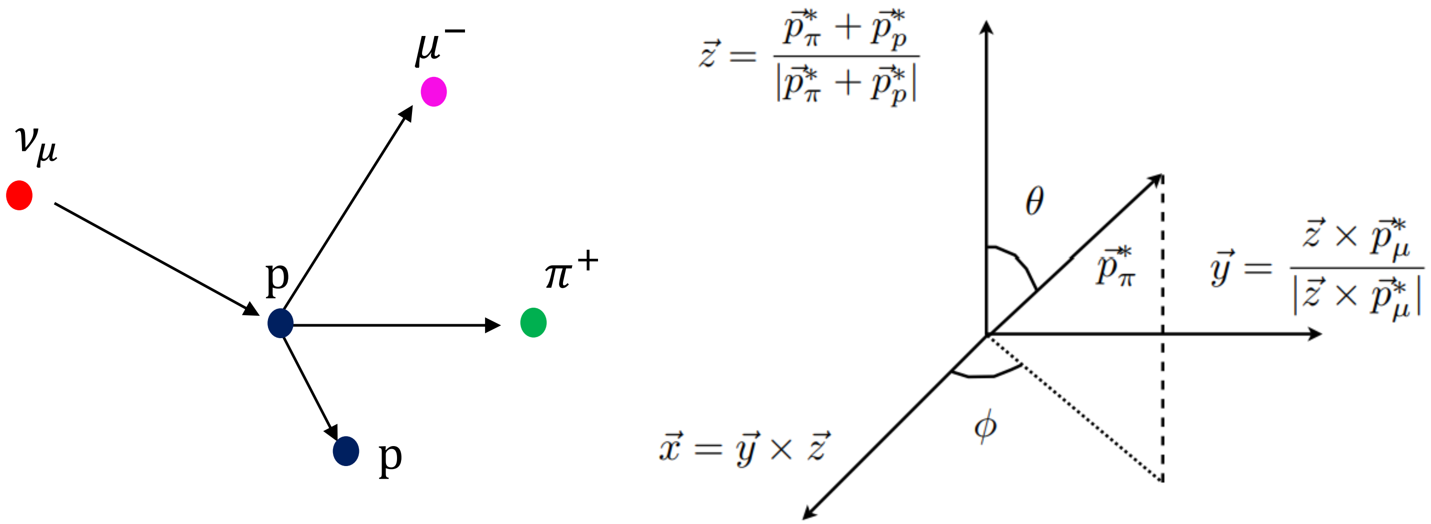
The angles θ and ϕ are defined in the Adler system which corresponds to the Δ rest frame.

- The Adler's angles carry information about:
  - the polarization of the Δ resonance
  - the interference with non resonant single pion production.
- These Adler angles can allow us to study nuclear effects, FSI and Fermi momentum by computing them at different levels.

- The FWD-BWD asymmetry of the two Adler angle with respect to the direction of the $p\pi^+$ plane:

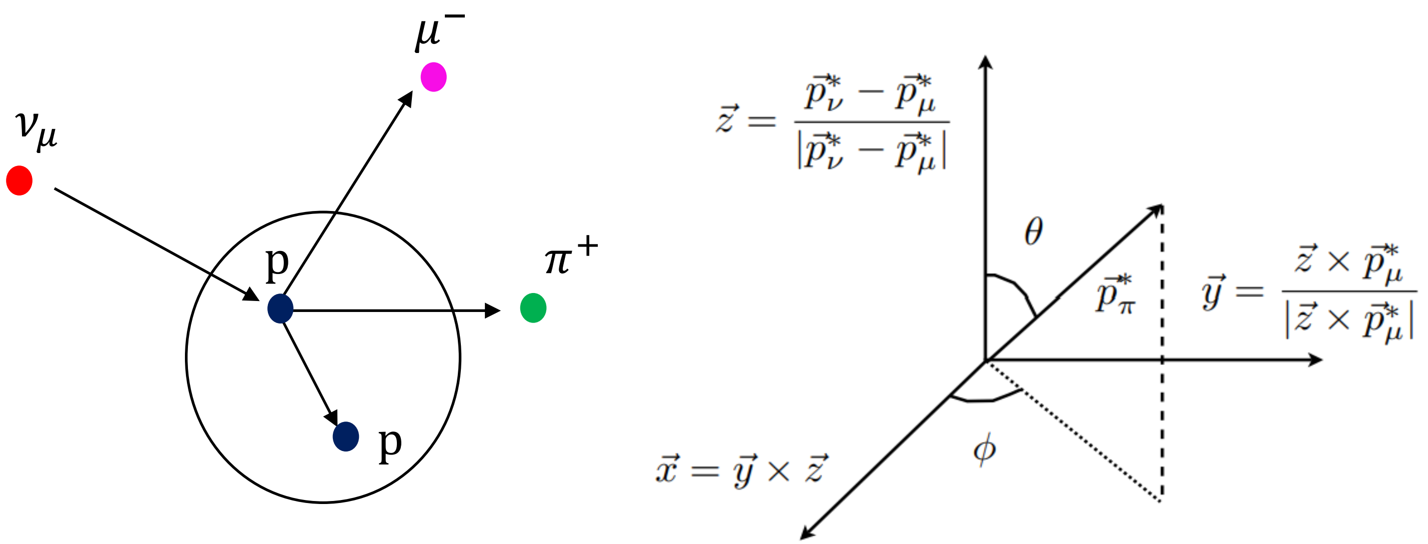
$$A_{FB}(\theta) = \frac{N_{\cos\theta>0} - N_{\cos\theta<0}}{N_{\cos\theta>0} + N_{\cos\theta<0}} \quad \text{and} \quad A_{FB}(\phi) = \frac{N_{\cos\phi>0} - N_{\cos\phi<0}}{N_{\cos\phi>0} + N_{\cos\phi<0}}$$

Adler angles definition



Level 1: Nucleon level

- Fermi momentum effect



Level 2: Nucleus level

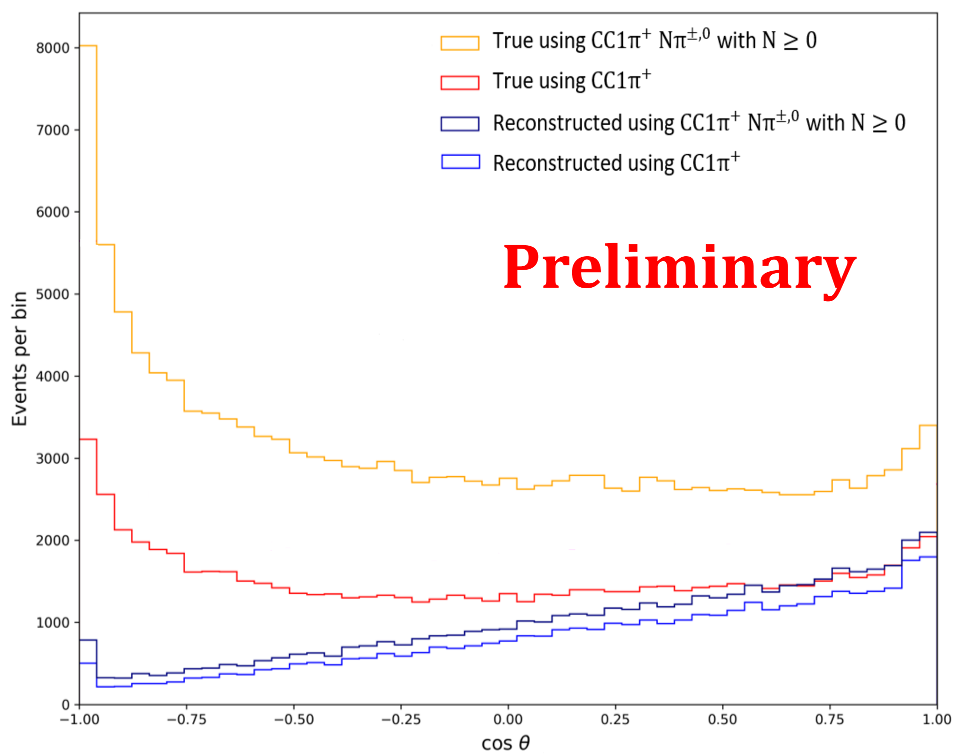
- Fermi momentum + FSI effects

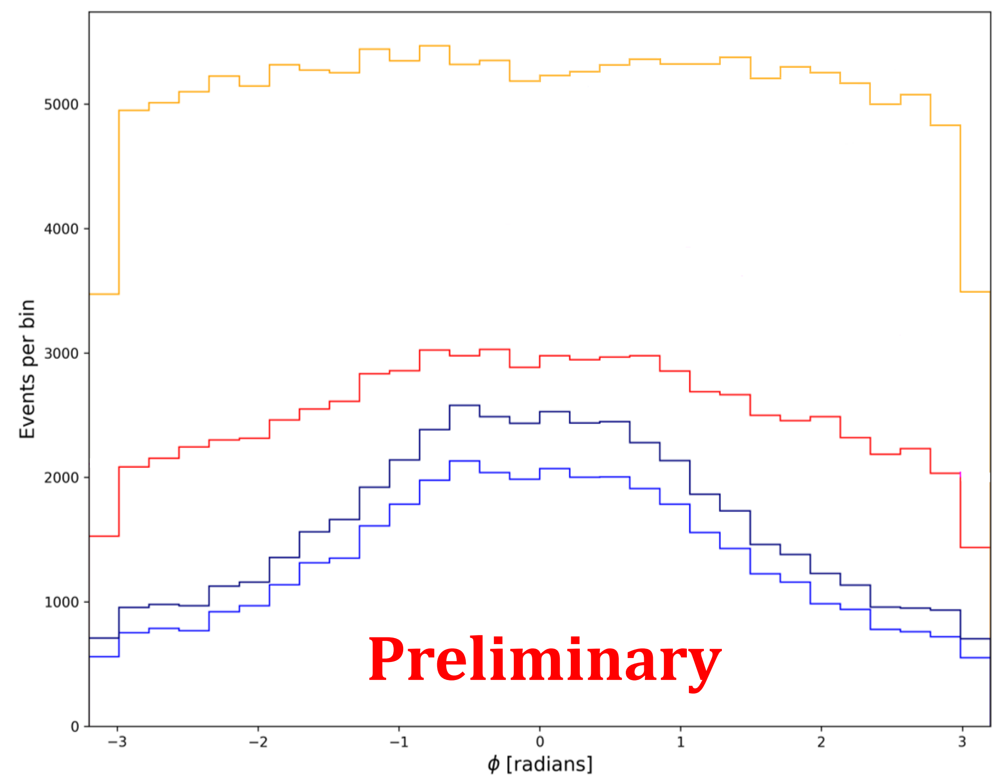
Level 3: Reconstructed nucleus level

- Fermi momentum + FSI + nuclear medium effects

Adler angles reconstruction

comparison between reconstructed and true Adler angles distributions for ϕ and $\cos\theta$ reconstructed in $CC1\pi^+$ or $CC1\pi^+N\pi^{\pm,0}$ $N \geq 0$.





cos θ distribution:

- Negative values will have low momentum after the boost.
- We miss low momentum pions in the reconstruction.

ϕ distribution:

- it shows a peak around zero
- This is due to FSI and nuclear effects

Asymmetry

Level		FWD-BWD asymmetry	
		$\cos\theta$	$\cos\phi$
	Reported by [39]		
1	True value	-0.007 ± 0.003	
	Reconstructed using true MC	-0.179 ± 0.003	
	Reconstructed using true MC with different NEUT configurations		
2	neut_C_noFSI_LFG	-0.305 ± 0.001	0.011 ± 0.003
	neut_CH_RFGRPA_lessNucFSI	-0.317 ± 0.001	0.011 ± 0.003
	neut_CH_RFGRPA_moreNucFSI	-0.244 ± 0.001	0.037 ± 0.003
	neut_CH_RFGRPA_noNucFSI	-0.251 ± 0.001	0.061 ± 0.004
	neut_CH_SF_MA103_flatSF	-0.283 ± 0.001	0.021 ± 0.003
	neut_CH_SF_MA103_lessNucFSI	-0.272 ± 0.001	-0.049 ± 0.003
	neut_CH_SF_MA103_moreNucFSI	-0.298 ± 0.001	-0.086 ± 0.003
	neut_CH_SF_MA103_noNuclFSI_noPB	-0.271 ± 0.002	0.095 ± 0.006
	neut_CH_SF_MA103_noNuclFSI_noPB_flatSF	-0.255 ± 0.002	-0.013 ± 0.006

FSI effects by comparing level 2 and 1.

Flux-integrated cross section measurement

- completely model-independent → no assumption needs to be made on the particular neutrino energy distribution in each kinematic bin.
- experiment-dependent results → no bin-by-bin correction for the flux is applied.

$$\left[\mathrm{cm}^2/\mathrm{nucleon}/\frac{\mathrm{MeV}}{\mathrm{c}}\right]$$

# of signal events in bin i

$$\frac{d\sigma_{signal}}{dP_\mu dcos\theta_\mu dP_{\pi^+} dcos\theta_{\pi^+}} = \frac{N_{signal,i}}{\epsilon_i \Phi N_{target}} \frac{1}{\Delta P_\mu \Delta cos\theta_\mu \Delta P_{\pi^+} \Delta cos\theta_{\pi^+}}$$

Detector efficiency in bin i

Incoming ν flux

# of targets (nucleons)

Bin i width

Likelihood fit and unfolding

- Binned maximum likelihood fit to ND280 data signal and control sample.
- Fitting control samples → constraint on the background contribution in the signal samples.
- Fit attempts to remove the detector effects from the data → unfolding

Simulation is not perfect:

- Includes systematic/nuisance parameters for the flux, interaction, and detector models.
- Parameters controlling number of signal events (template), as well as the flux, interaction model and detector response are simultaneously fit.

15 template parameters

- Directly scale the cross section
- Free

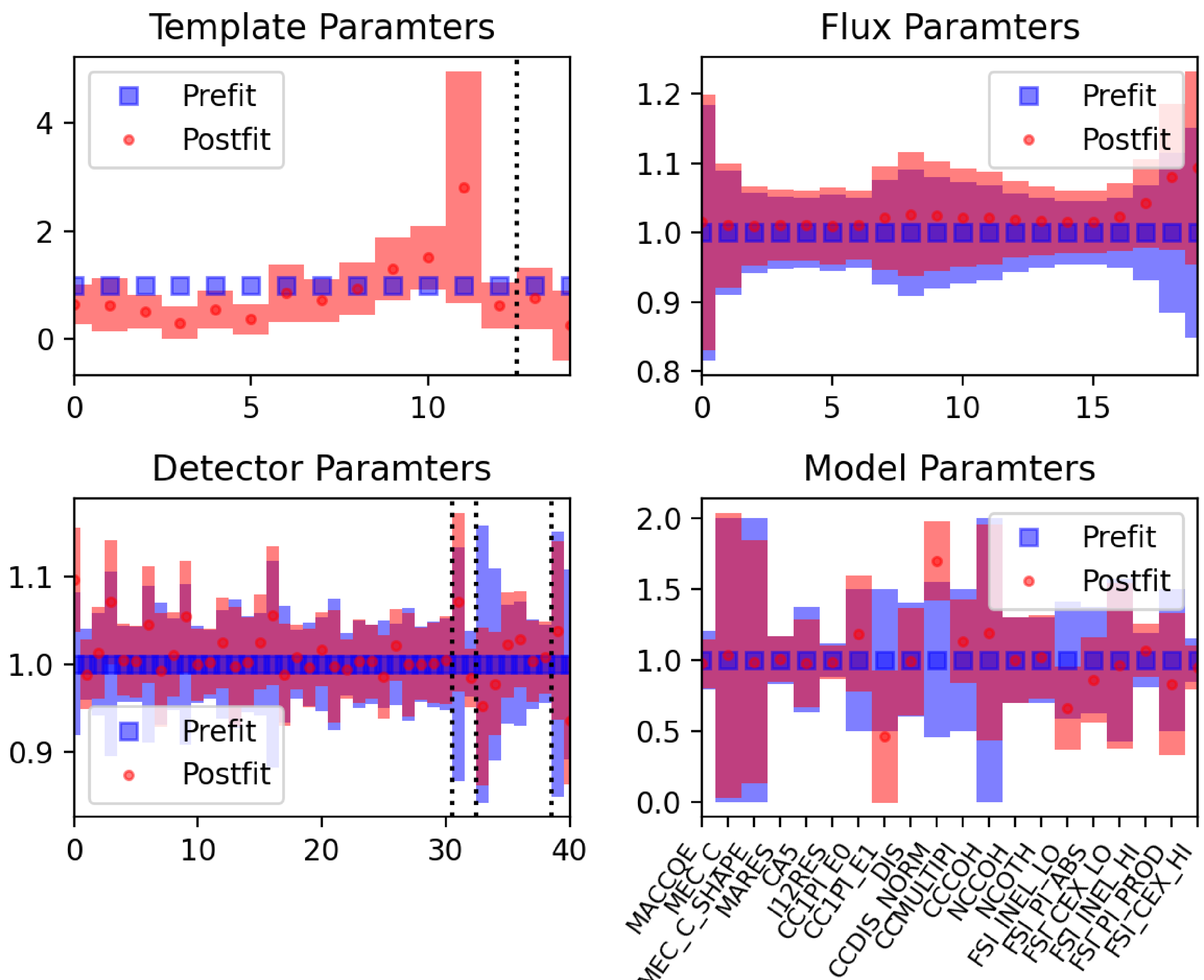
20 flux parameters

41 detector parameters

20 interaction model parameters

- constrained
- prior correlations → avoid very unphysical configurations

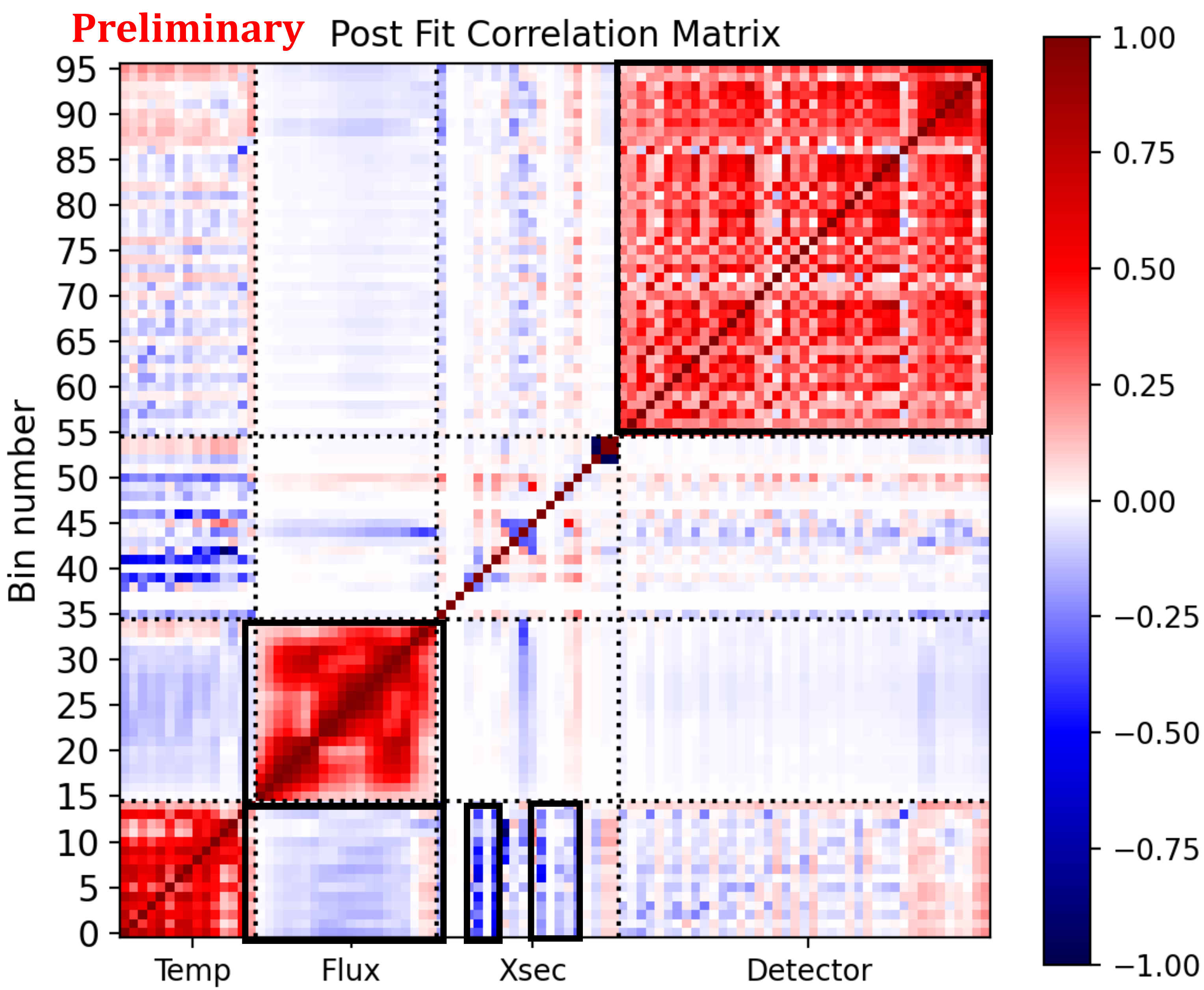
Fit results (NEUT)



- Flux and detector parameters:
  - deviations from nominal values
  - stay at 12%
  - within the pre-fit errors limit
- Detector parameters:
  - fit reduced the relative errors
- Cross section model parameters:
  - Impacted were those related to the signal.
    - CC Multi pions
    - CC1pi (E_ν > 2.5 GeV)
- Template parameters move to correct these values.

Phase space constrains:
$P_\mu \geq 200$MeV and $P_{\pi^+} \geq 160$MeV

Fit results (NEUT)

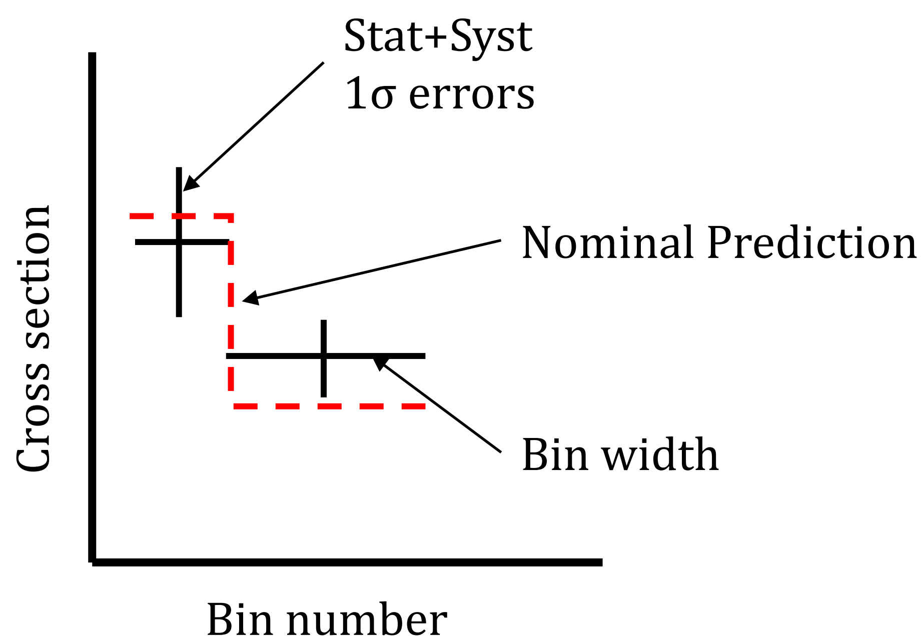


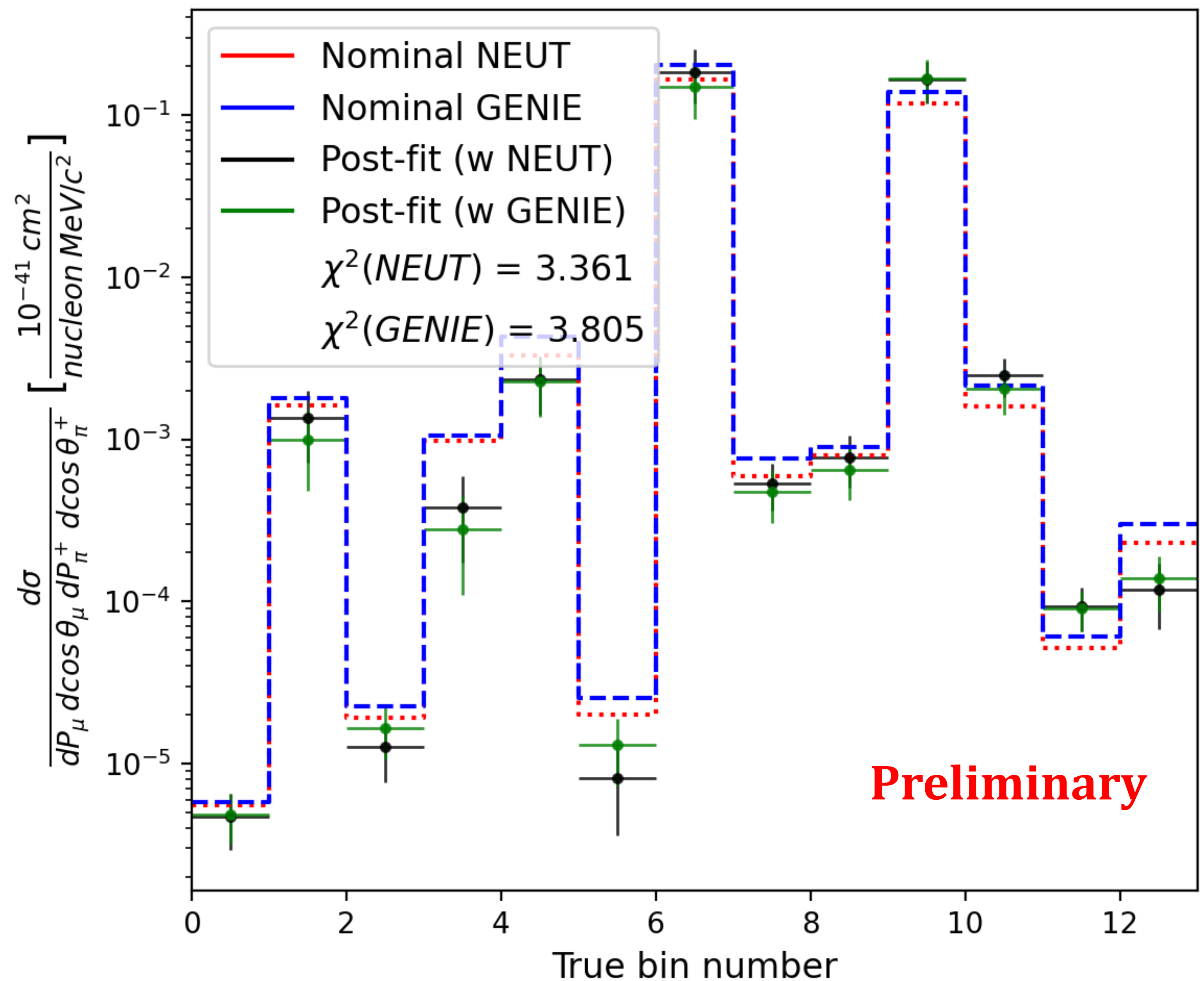
Red: correlated
Blue: anticorrelated

- Highly correlated flux
- Flux anticorrelated to template parameters
- Highly anticorrelation between template and some cross section model parameters that affect signal events
- Highly correlation between reconstructed detector bins

Quadruple differential cross section

How to read!





Quadruple differential cross section

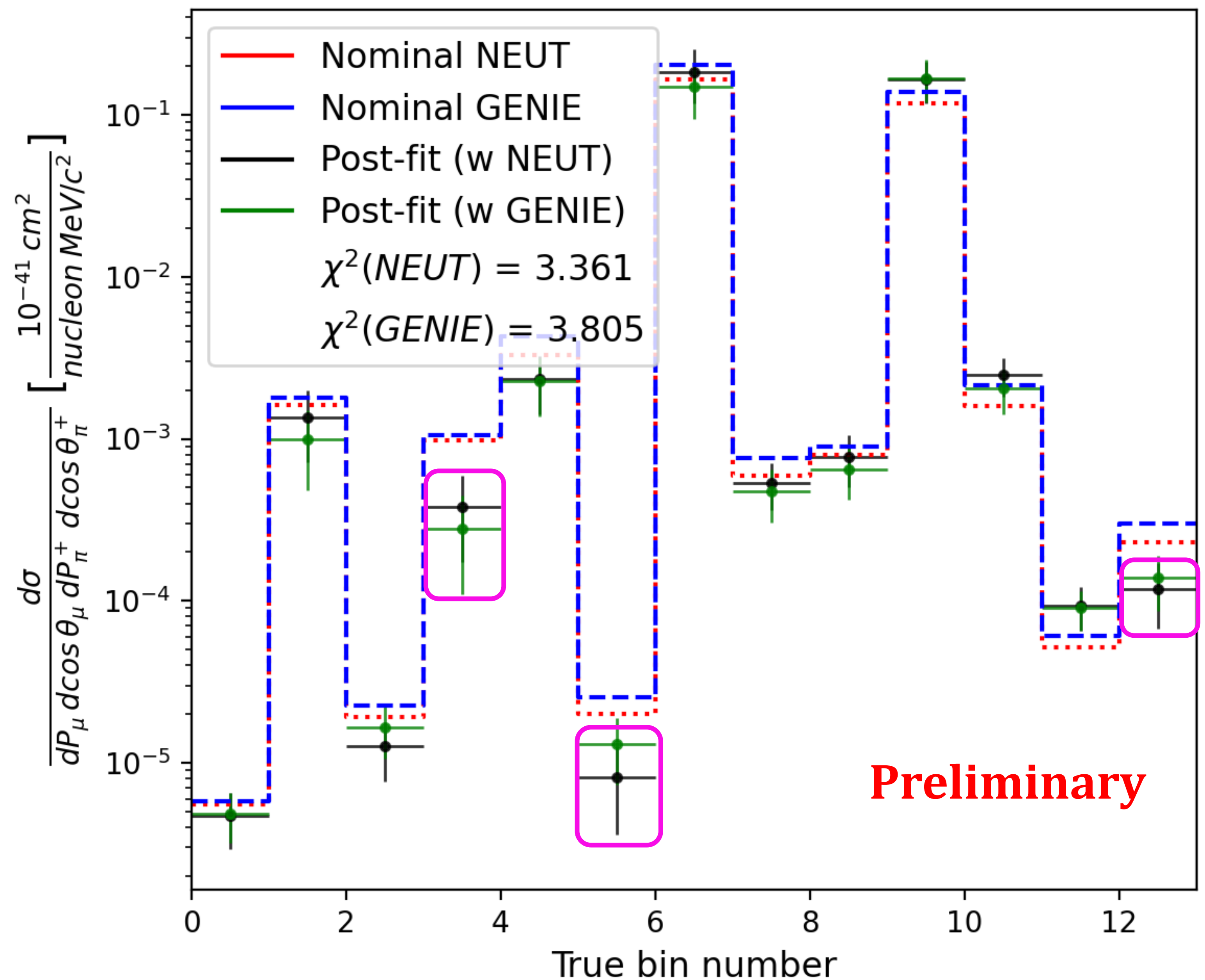
NEUT and GENIE → similar agreements with the data

Overestimation of the cross section in bins 3, 5 and 12:

- **Bin 3:** FWD μ^- ($P_\mu < 1$ GeV) and BWD & HA π^+
- **Bin 5:** FWD μ^- ($P_\mu > 1$ GeV)
- **Bin 12:** FWD μ^- ($P_\mu > 2.5$ GeV) and FWD π^+

Deficiency in our theoretical models when describing :

- RES to DIS transitions
- π absorption and production models (Rein-Sehgal)



Conclusions

Summary

- It directly addresses important challenges oscillation analyses.
  - interaction cross section → systematic errors are currently dominated by cross section and flux.
  - the main background for the ν_μ disappearance measurement.
  - new 2 ring signal at SK.
- I contributed significantly to general parts of ND280's analysis framework (Highland).
- New selection developed that has been added to BANFF.
- We reported the differential cross sections:

$$\frac{d\sigma}{dP_\mu dcos\theta_\mu dP_{\pi^+} dcos\theta_{\pi^+}}, \quad \frac{d\sigma}{dP_\mu dcos\theta_\mu}, \quad \frac{d\sigma}{dP_{\pi^+} dcos\theta_{\pi^+}},$$

Model independent

$$\frac{d\sigma}{dE_\nu}, \quad \frac{d\sigma}{dW}, \quad \frac{d\sigma}{dQ^2}$$

Model dependent

- The preliminary cross section results achieved showed some disagreements between the MC prediction and the post-fit results.
- Base on the results, our models still need a lot of work. Theoretical input will be essential.
- Some of the variables studied were the Adler angles and they asymmetry.

Looking forward

- The selection is currently being used by other analyzers.
- Analysis will enter T2K collaboration review → publication foreseen
- Improvements:
  - Michel electrons reconstructed kinematics information can be included.
  - reduce the systematics uncertainties.
  - better cut to reduce the contamination of protons when selecting the FGD pions.
  - timing information and the detector efficiency for BWD and HA tracks.

ND280 upgrade

Thank you for your time!!!

Backup slides

Neutrino physics breve history

1930 → Wolfgang Pauli postulated the “neutron” to compensate for the apparent loss of energy and conserve the moment of decay $\beta-$

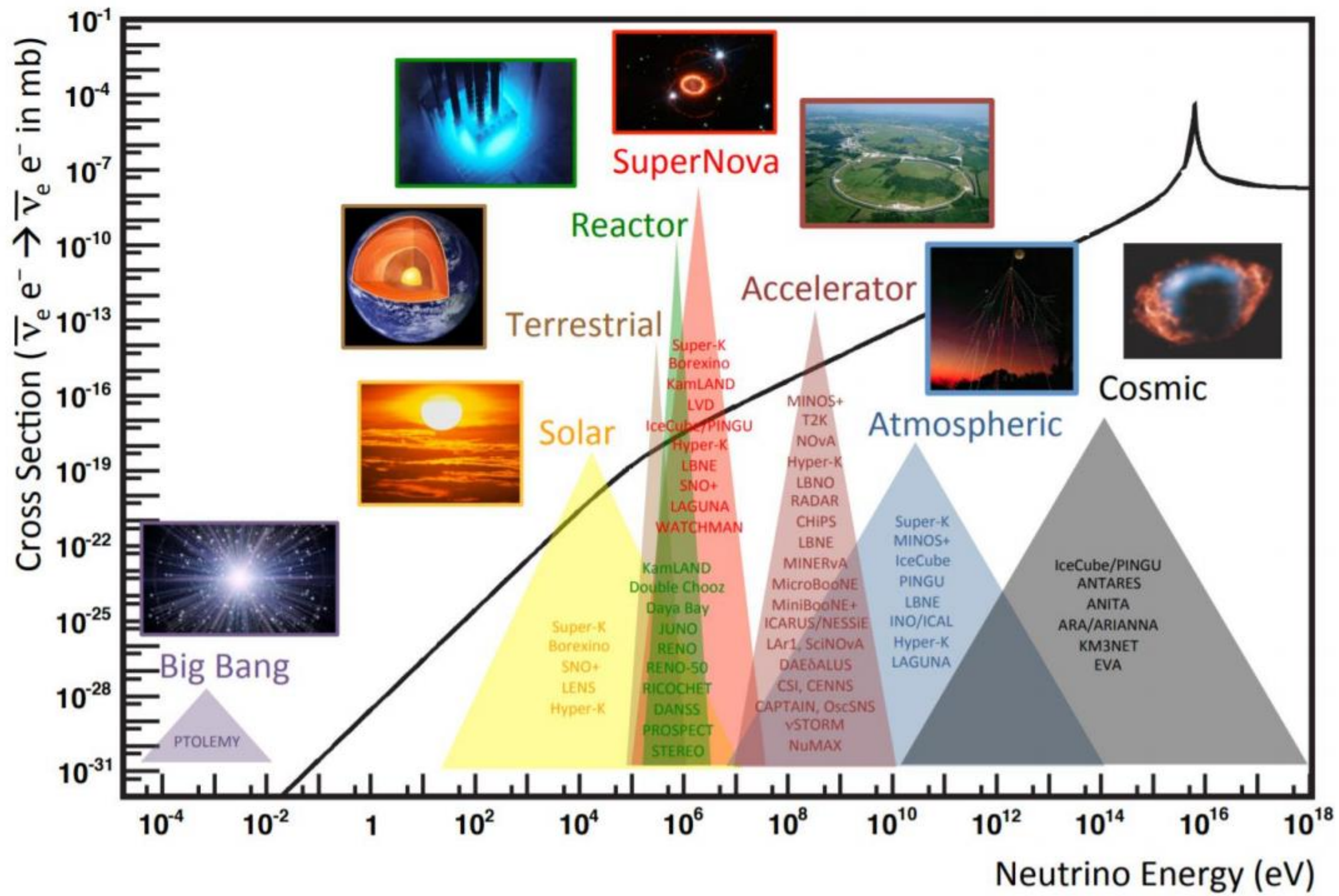
1932 → The Pauli neutron was renamed "neutrino" by Fermi when the real neutron was discovered by Chadwick

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.“

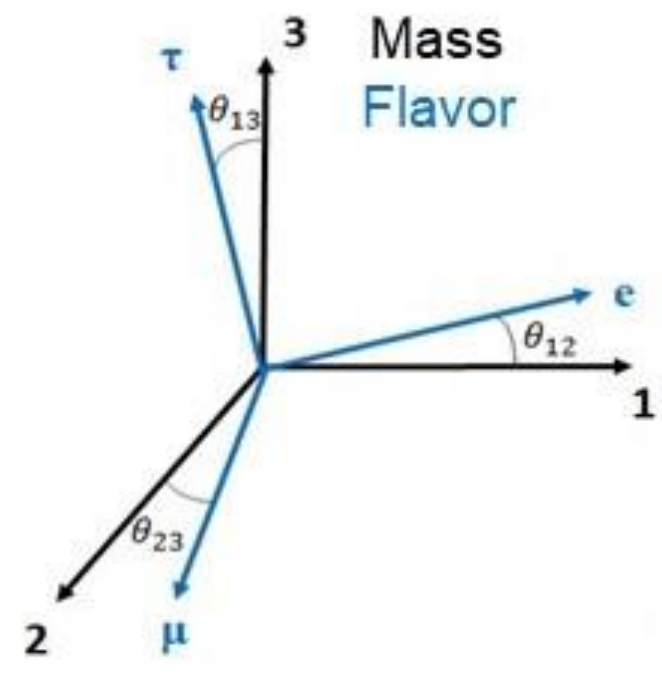


- Neutrinos cover a wide spectrum of energy.
- Detecting them involves using different techniques and detectors.

Neutrino oscillation

$$|\nu_l> = \sum_i U_{li} |\nu_i>$$

where flavour ($l = e, \mu, \tau$), mass ($i= 1, 2, 3$) and U_{PNMS} is the PNMS (Pontecorvo–Maki–Nakagawa–Sakata) rotation matrix:



$$U_{PNMS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}$$

Where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ and $\Delta m_{ij}^2 = m_i^2 - m_j^2$

3 mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$

1 CP violating phase: δ_{CP} Value still unknown

Neutrino oscillation

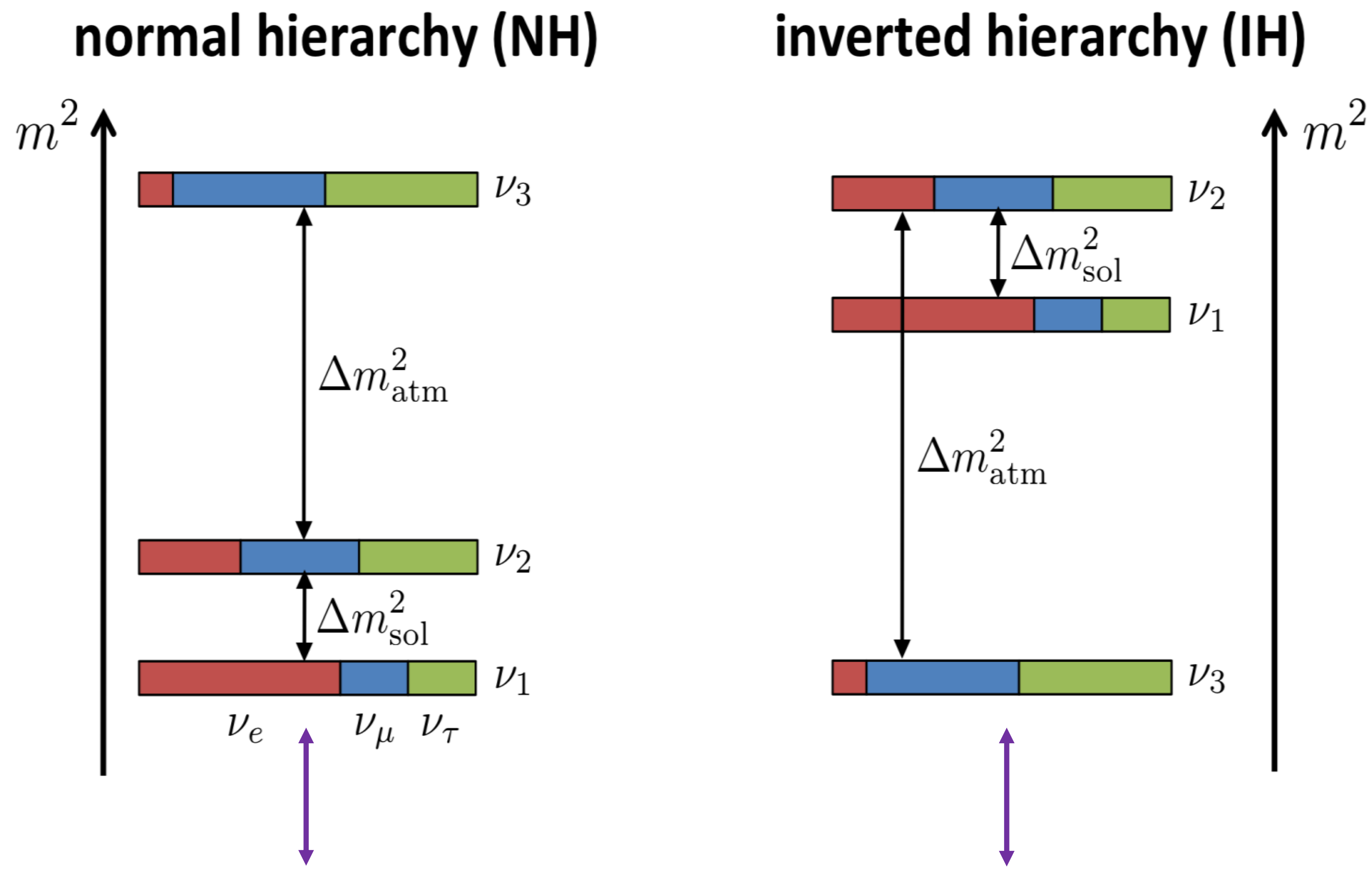
3 mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$

1 CP violating phase: δ_{CP} Value still unknown

2 mass differences: Δm^2_{21}, Δm^2_{32} Sign still unknown

Hierarchy determines the ordering of the masses:

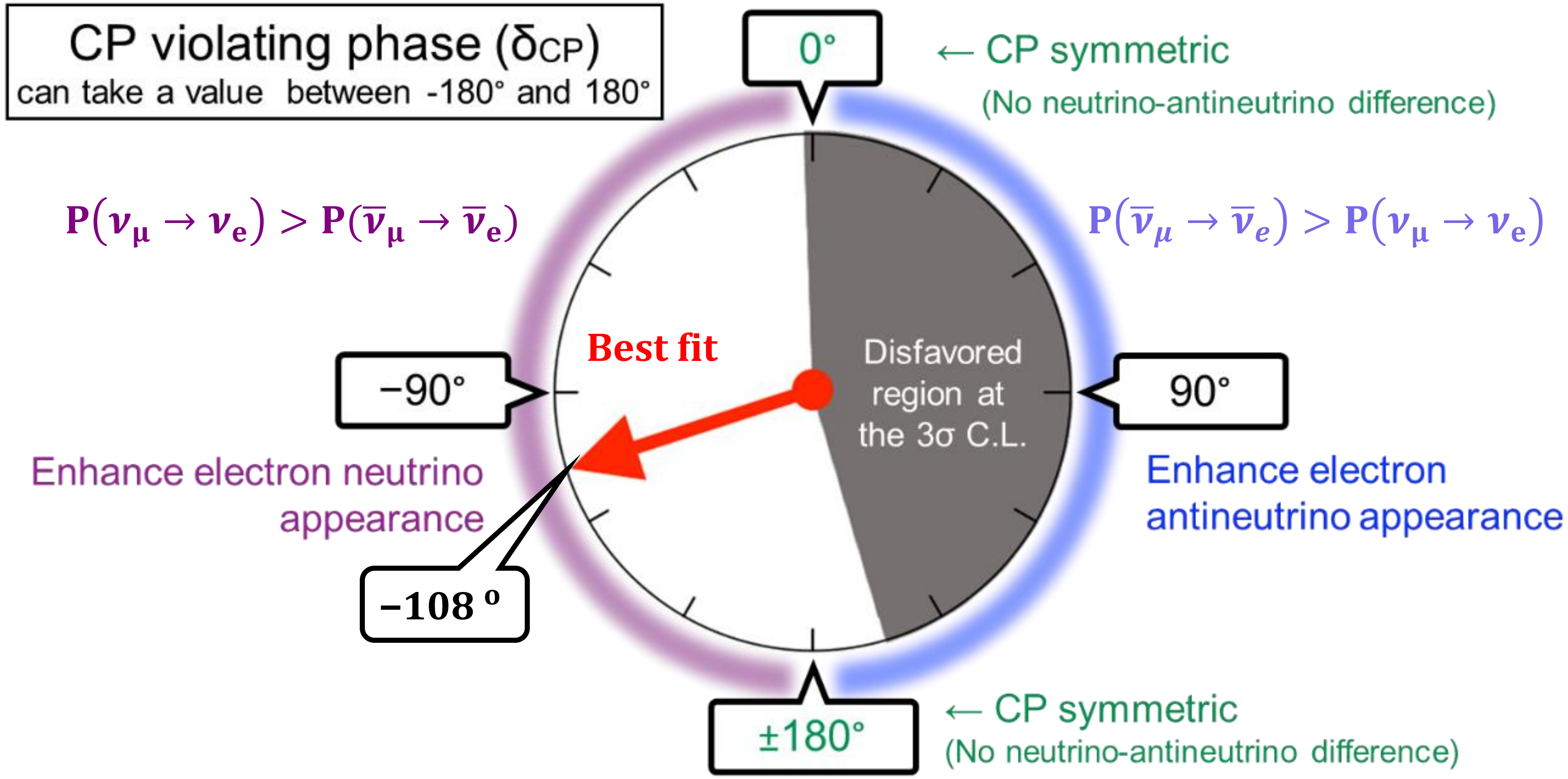
- Normal: $m_1 < m_2 < m_3$
- Inverted: $m_3 < m_1 < m_2$



Absolute scale of neutrino masses unknown

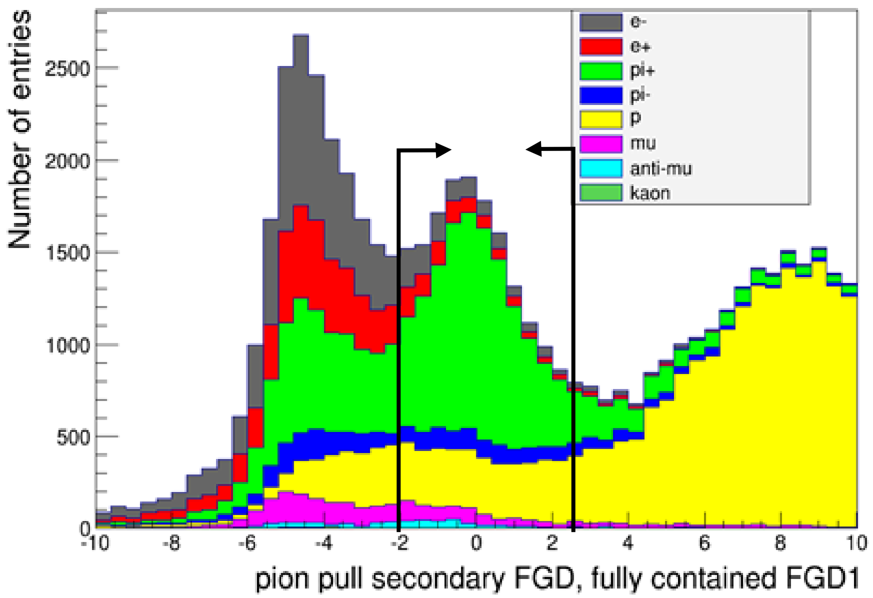
T2K resent results

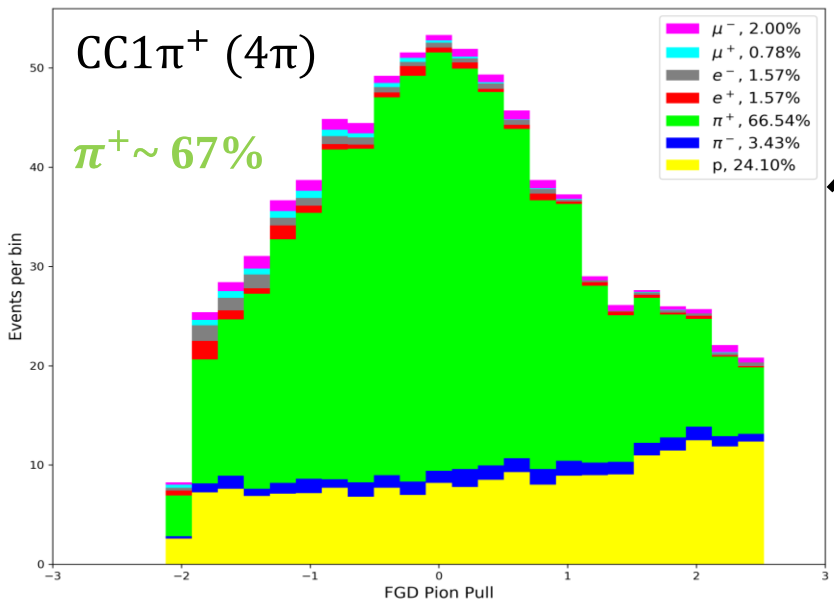
For the first time, T2K has disfavored almost half of the possible values at the 99.7% (3σ) confidence level, and is starting to reveal a basic property of neutrinos that has not been measured until now. https://www.nature.com/articles/s41586-020-2177-0

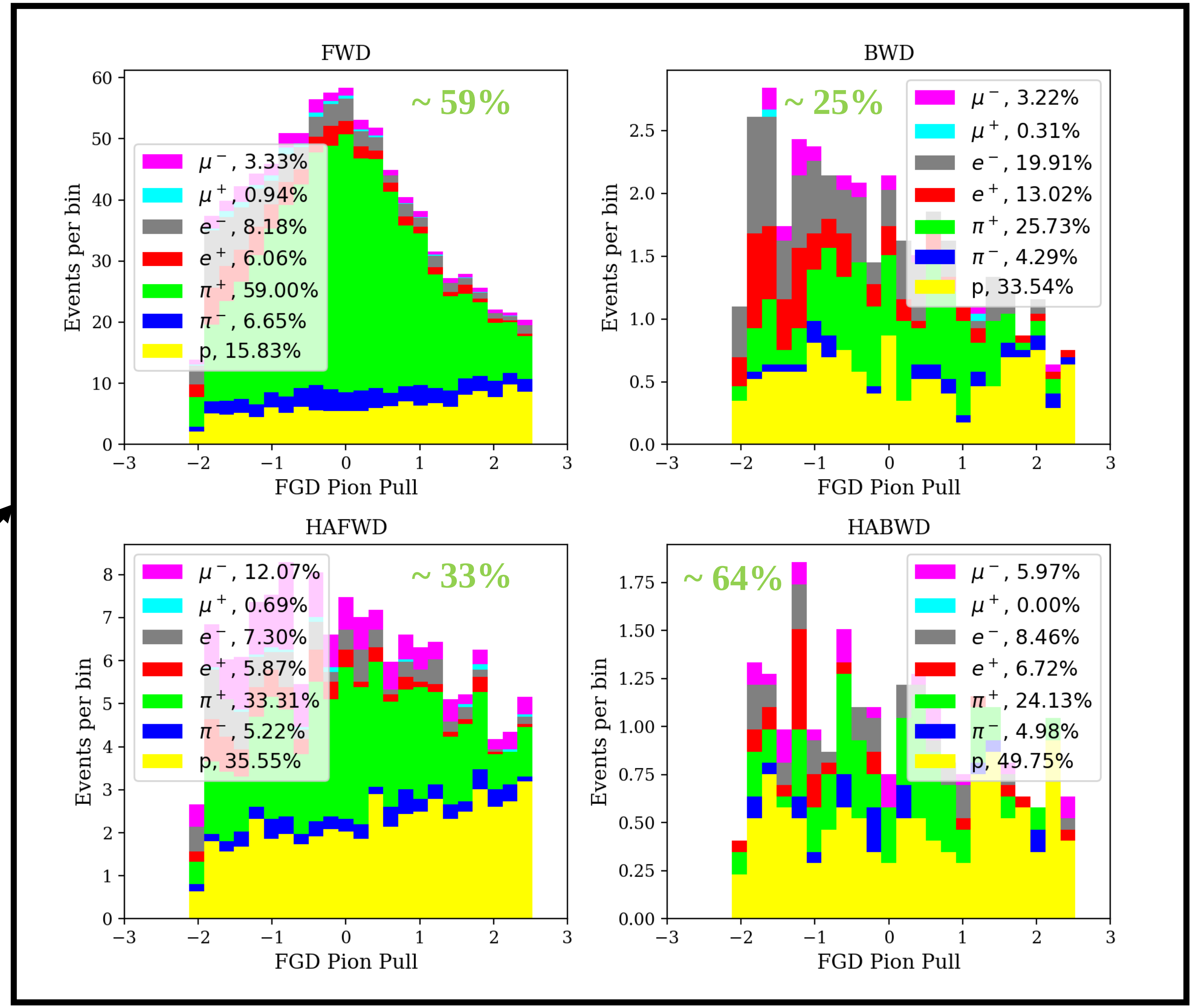


- Most of the parameters measured with <10% precision
- θ_{23} mixing angle is known with 15% precision
- Remaining parameters are δ_{CP} and mass hierarchy
- T2K result excludes most of the δ_{CP} >0 values a 99.7% Confidence Level

FGD pions

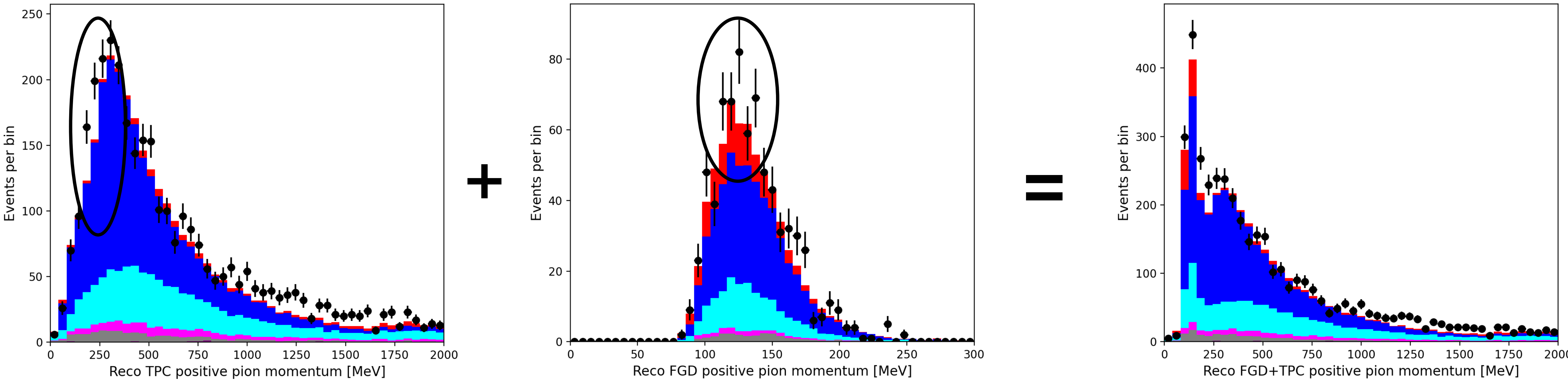






- A better reconstruction could improve the cut

Data agreements positive pions

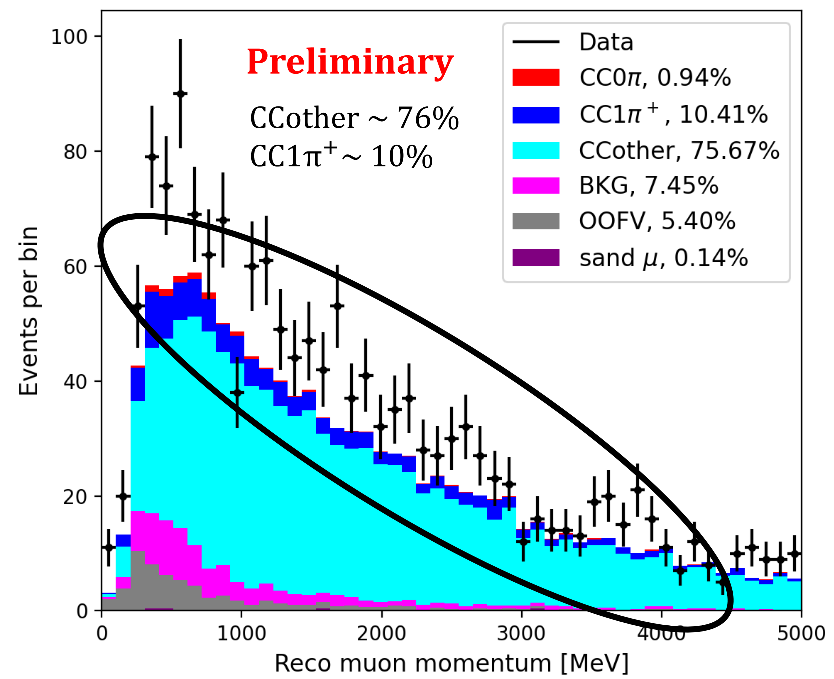


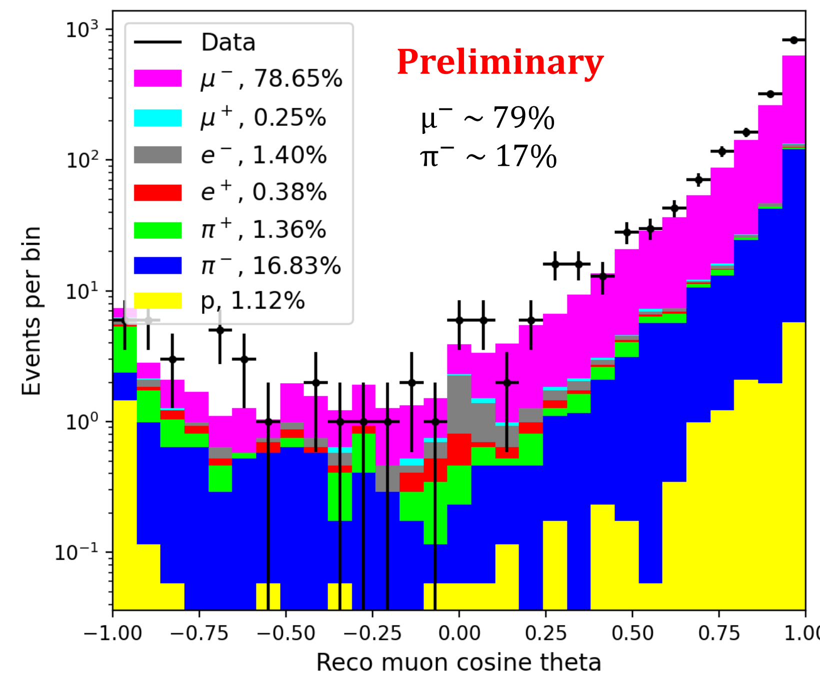
Resonance production: Rein-Sehgal model describes single pion production through baryon resonances below W = 2GeV

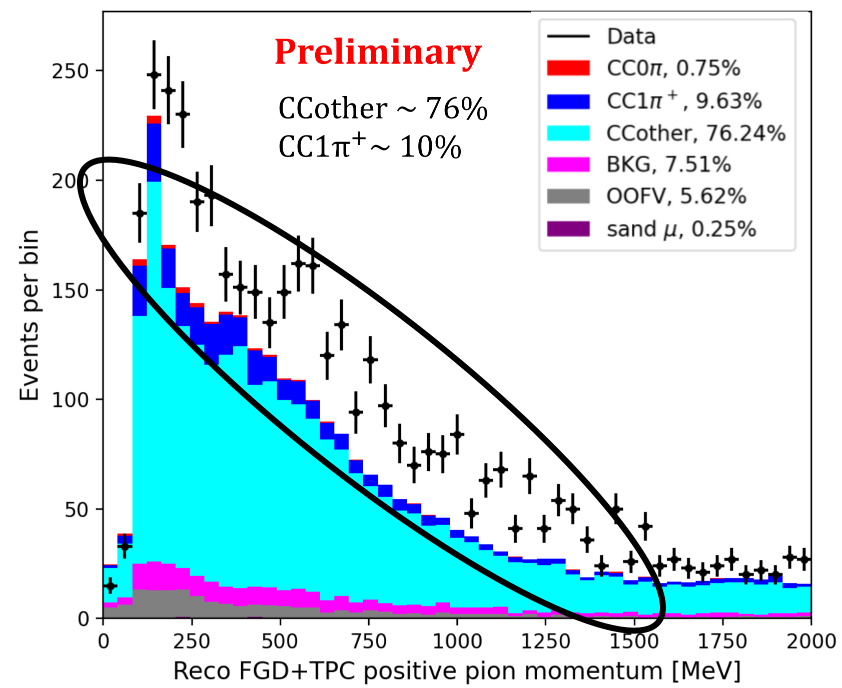
- the discrepancy must come from imperfect nuclear modeling.
- models predict more pion absorption that what it is in reality.

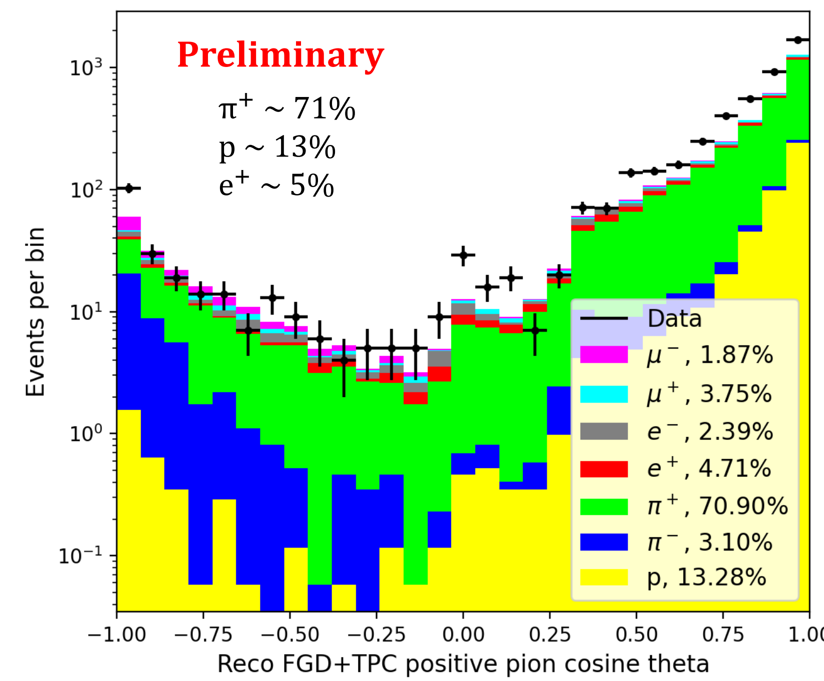
Input samples CC1π⁺1$\pi^{\pm,0}$

- Control samples are selected to constrain the MC background components
- The control sample is selected to be representative of a specific background
- It is required to minimize the content of CC1π^+ in order to be considered a side-band sample independent of the signal sample







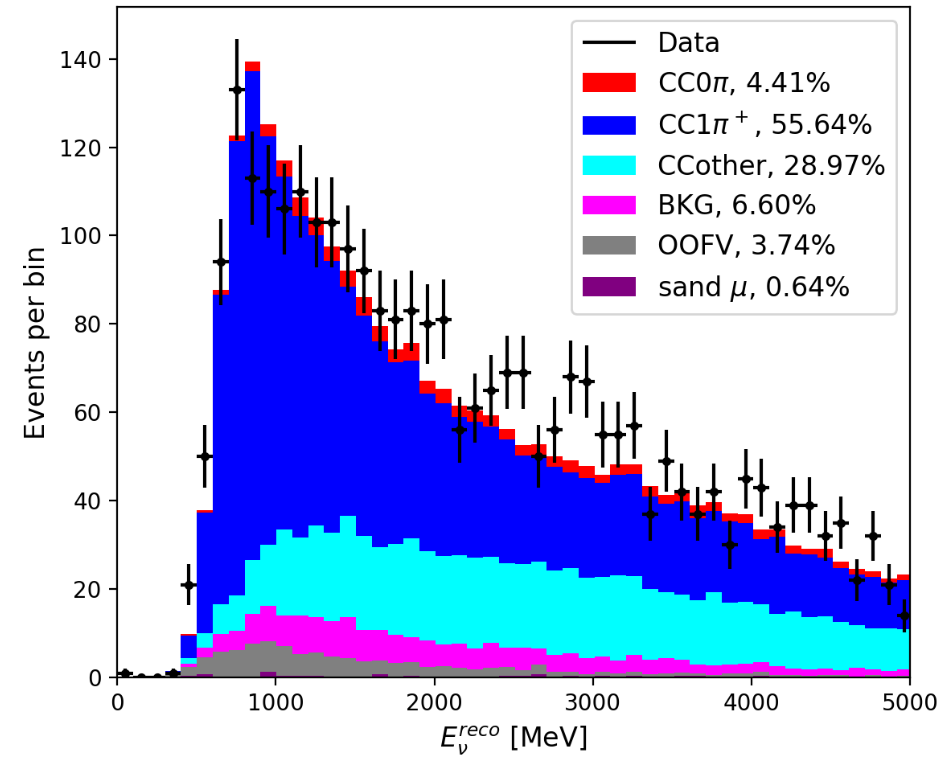


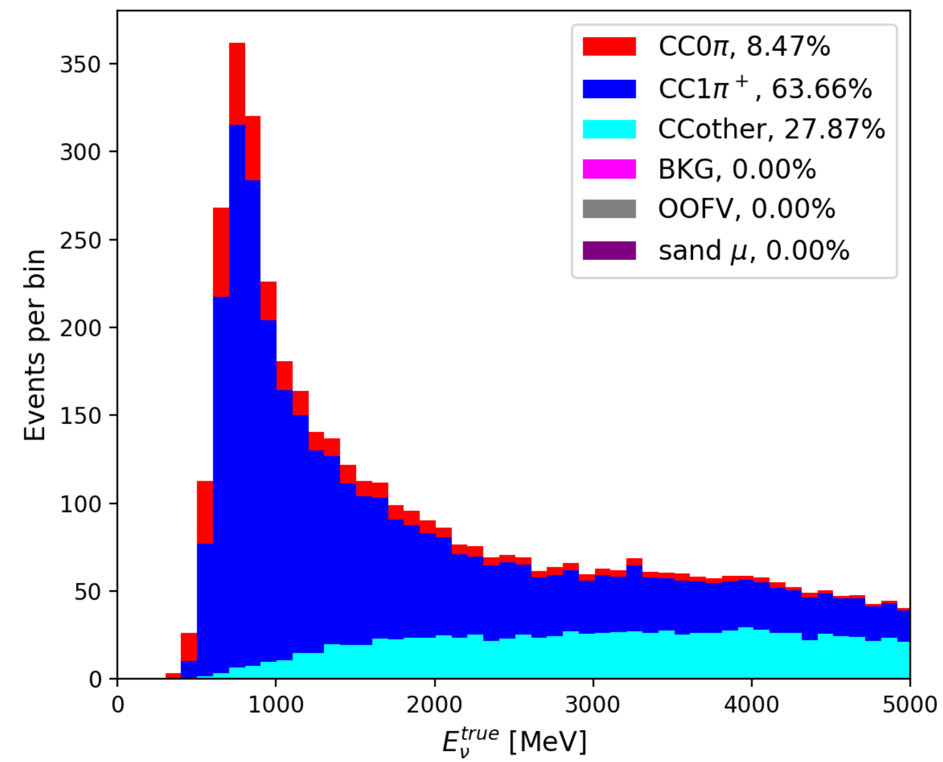
Measuring neutrino energy

Neutrino energy is reconstructed:

- using leptonic and hadronic kinematics,
- assuming stationary target (a nucleon)
- massless neutrino.

$$E_{\nu_{reco}} = \frac{m_p^2 - \left(m_p - E_{bind} - E_\mu - E_\pi\right)^2 + \left|\vec{P}_\mu + \vec{P}_\pi\right|^2}{2\left\{m_p - E_{bind} - E_\mu - E_\pi + \hat{k}_\nu\left(\vec{P}_\mu + \vec{P}_\pi\right)\right\}}$$





This introduce some biases:

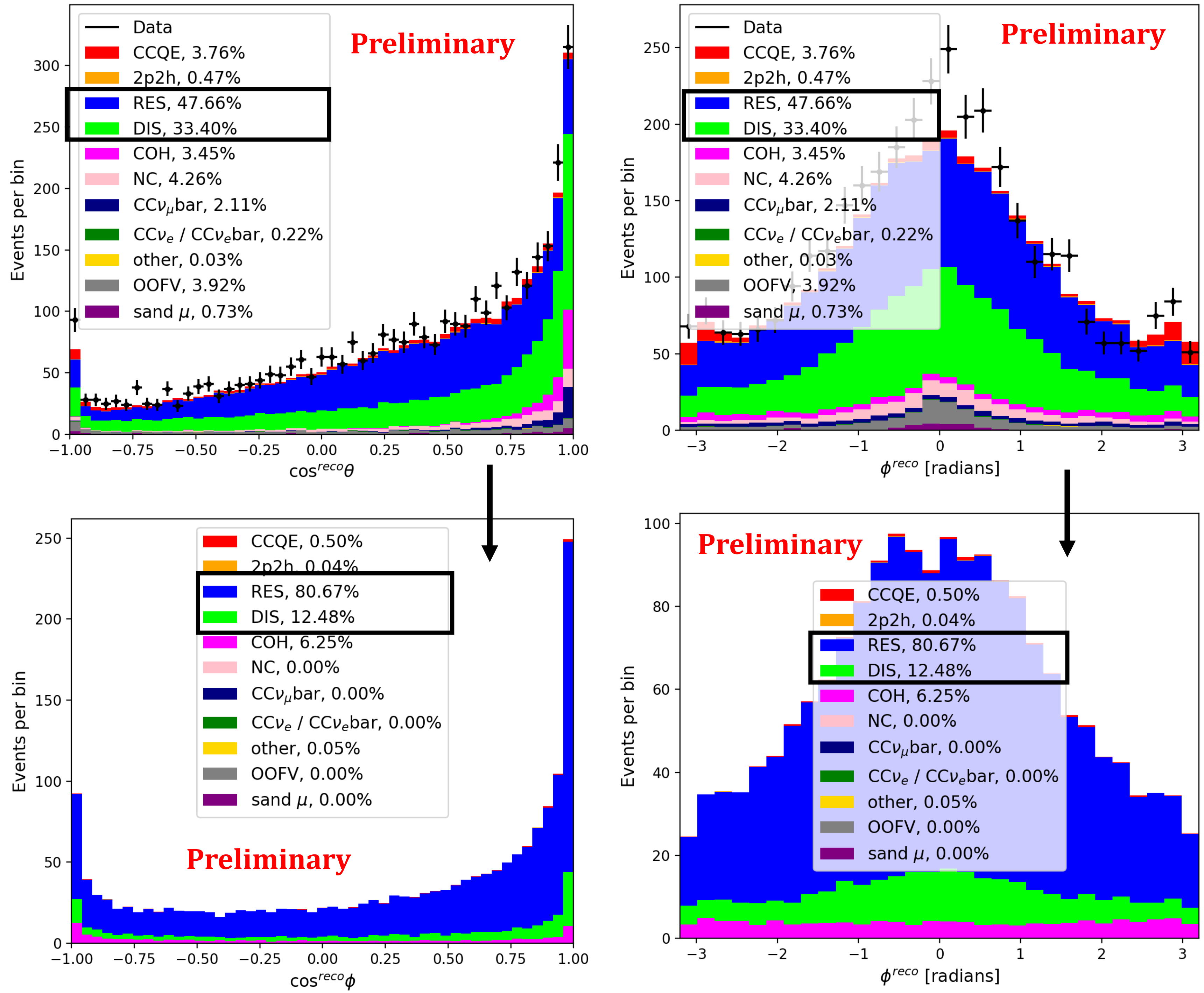
- Due to initial state interactions (Fermi motion),
- The detector miss neutral particles,

Adler angles reconstruction

CC1π$^+$ reconstructed events

Removing background (mis-reconstructed events)

using true CC1π$^+$ events reconstructed correctly

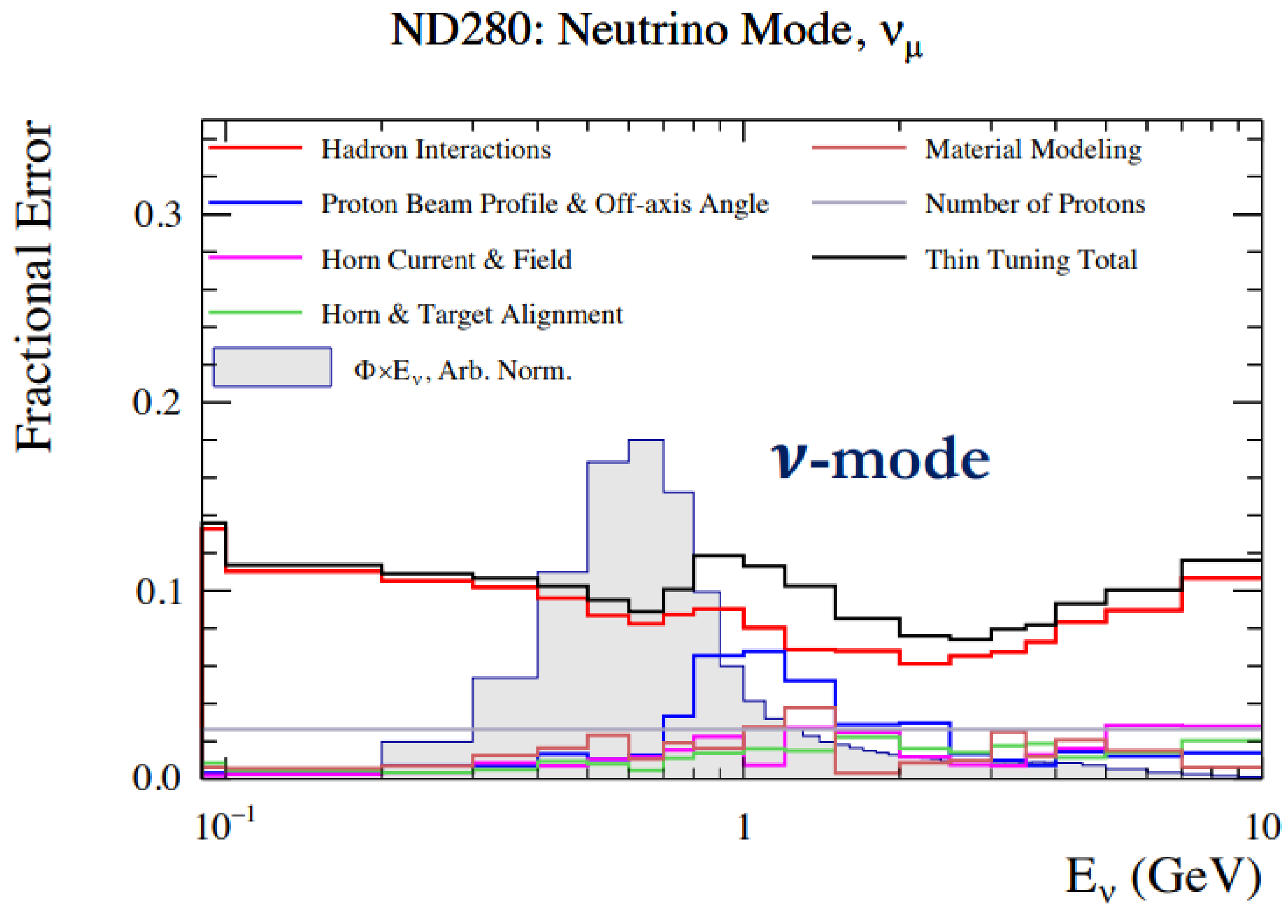


Flux model

The flux model is studied by comparisons to cross section and particle production data, and simulations of changing the characteristics of the beam and beamline.

Examples include:

- Proton--Carbon cross section
- Pion--Carbon cross section
- Horn current absolute value
- Horn alignment



Interaction model

- Based on a set of models for each neutrino interaction process, and includes nuclear effects.
- The fit includes a series of nuisance parameters which either change the underlying physics model parameters or act as a scaling on a given aspect of the interaction model.

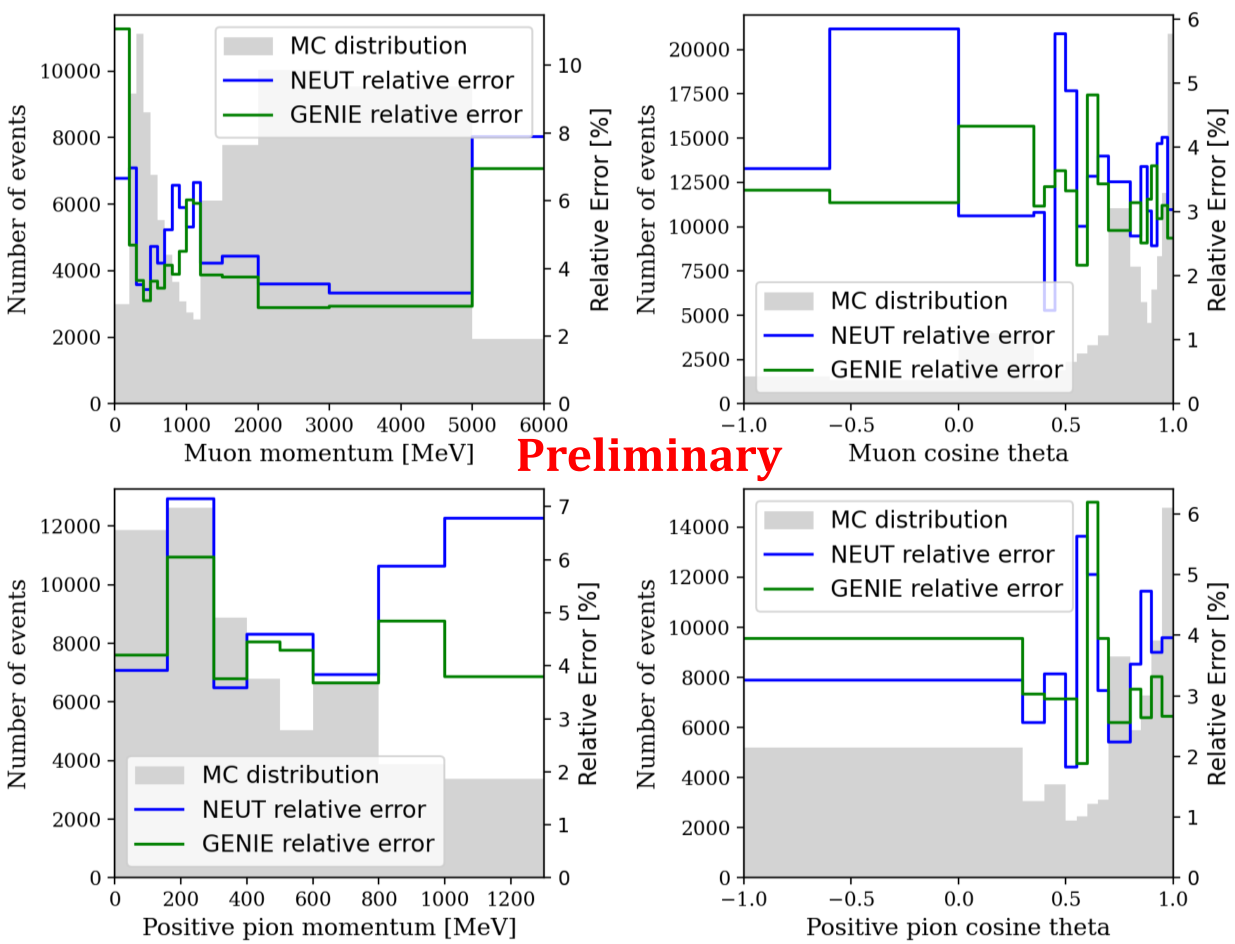
Examples include:

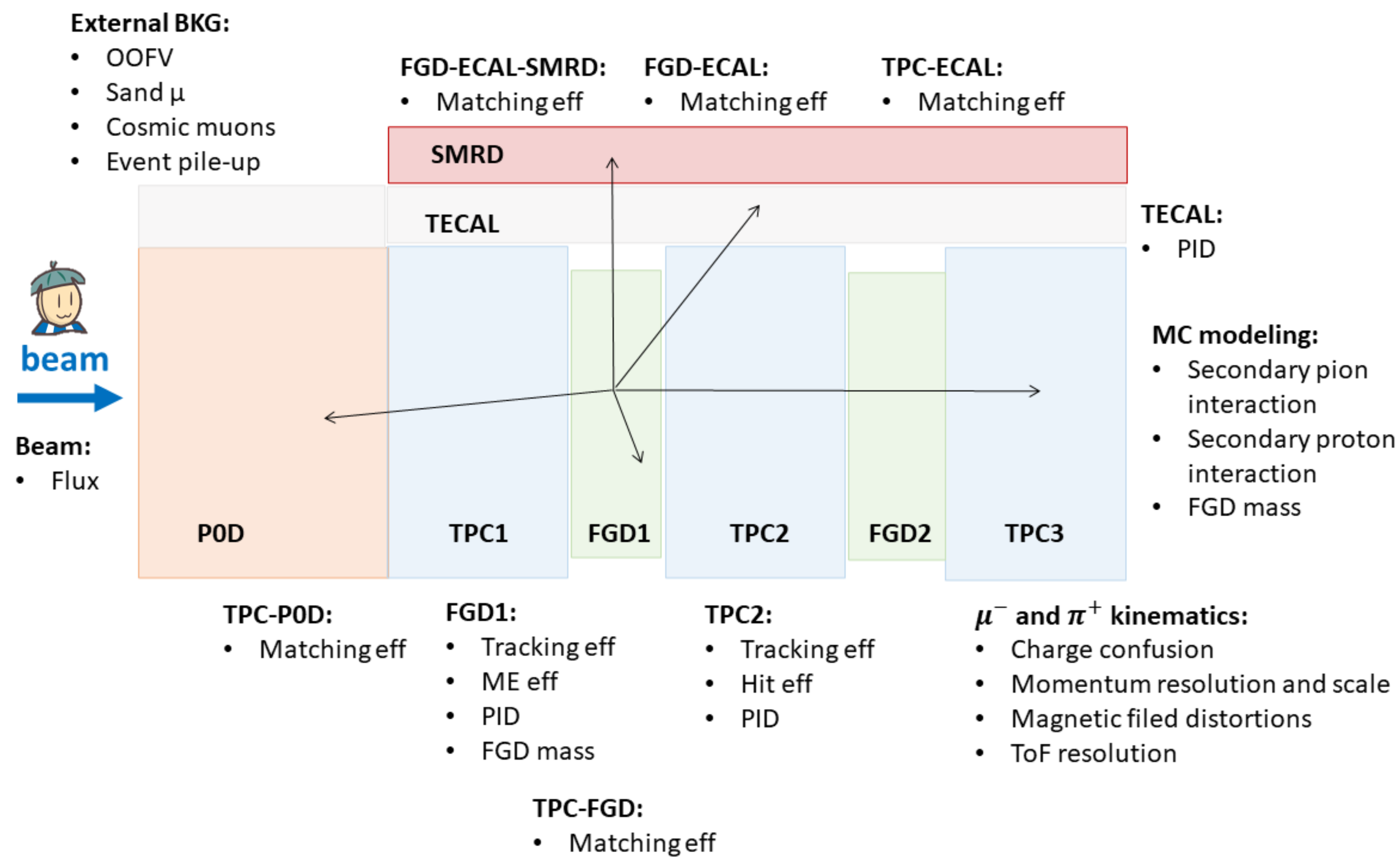
- Pion prod/ abs, that will affect FSI

Index	Parameter	Type	Prior	Error
0	M_A^{QE}	Signal shape	1.21	0.3
1	2p2h ν norm.	Signal normalization	1.0	1.0
2	2p2h ν shape	Signal shape	1.0	1.0
3	M_A^{Res}	Background shape	0.95	0.15
4	C_A^5	Background shape	1.01	0.12
5	$I_{1/2}$ Bkg Resonant	Background normalization	1.3	0.2
6	DIS Multiple pion	Background shape	1.0	0.4
7	CC-1π $E_\nu < 2.5$ GeV	Background normalization	1.0	0.5
8	CC-1π $E_\nu > 2.5$ GeV	Background normalization	1.0	0.5
9	CC DIS	Background normalization	1.0	0.5
10	CC Multi-π	Background normalization	1.0	0.5
11	CC Coherent on C	Background normalization	1.0	1.0
12	NC Coherent	Background normalization	1.0	0.3
13	NC Other	Background normalization	1.0	0.3
14	CC ν_e	Background normalization	1.0	0.03
15	FSI Inelastic, LE	Background shape	1.0	0.41
16	FSI π absorption	Background shape	1.1	0.41
17	FSI Charge exchange, LE	Background shape	1.0	0.57
18	FSI Inelastic, HE	Background shape	1.8	0.34
19	FSI π production	Background shape	1.0	0.50
20	FSI Charge exchange, HE	Background shape	1.8	0.28

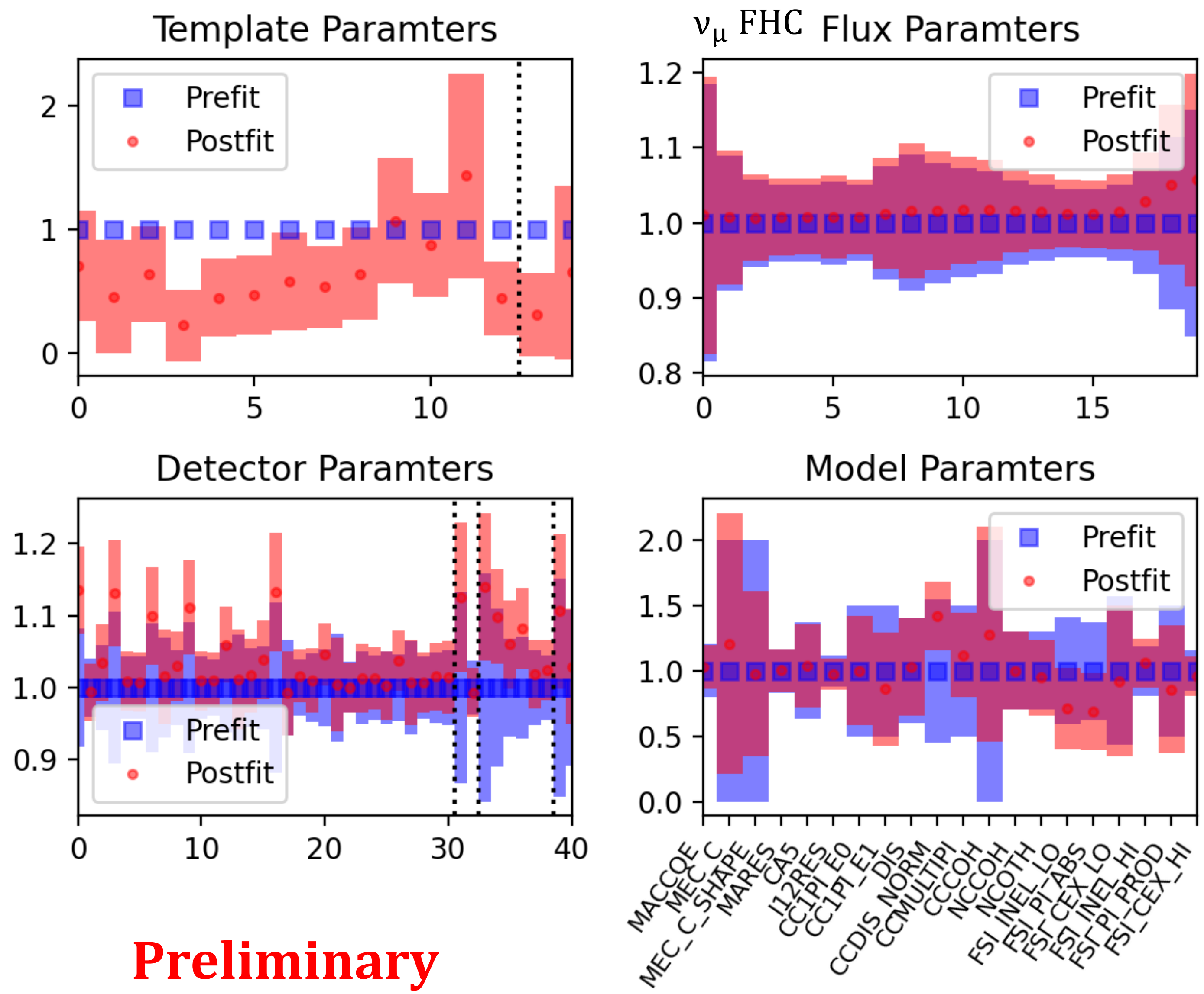
Detector model

- The detector model is studied through a series of control samples to evaluate the ND280 detector performance.
- The effects of the detector uncertainties are parameterized as a function of muon and pion kinematics and included in the fit.



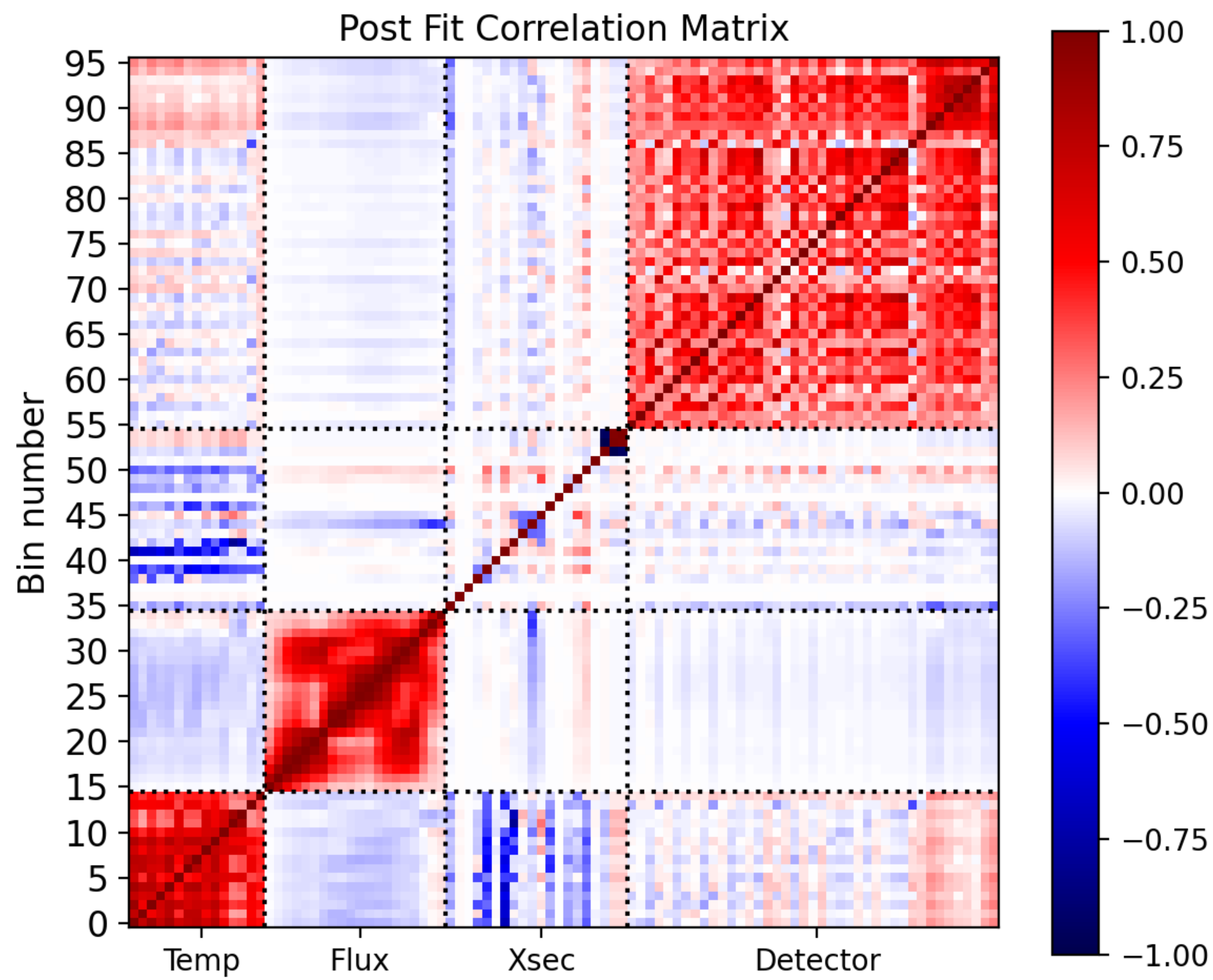


Likelihood fit and unfolding (GENIE)



Preliminary

Preliminary

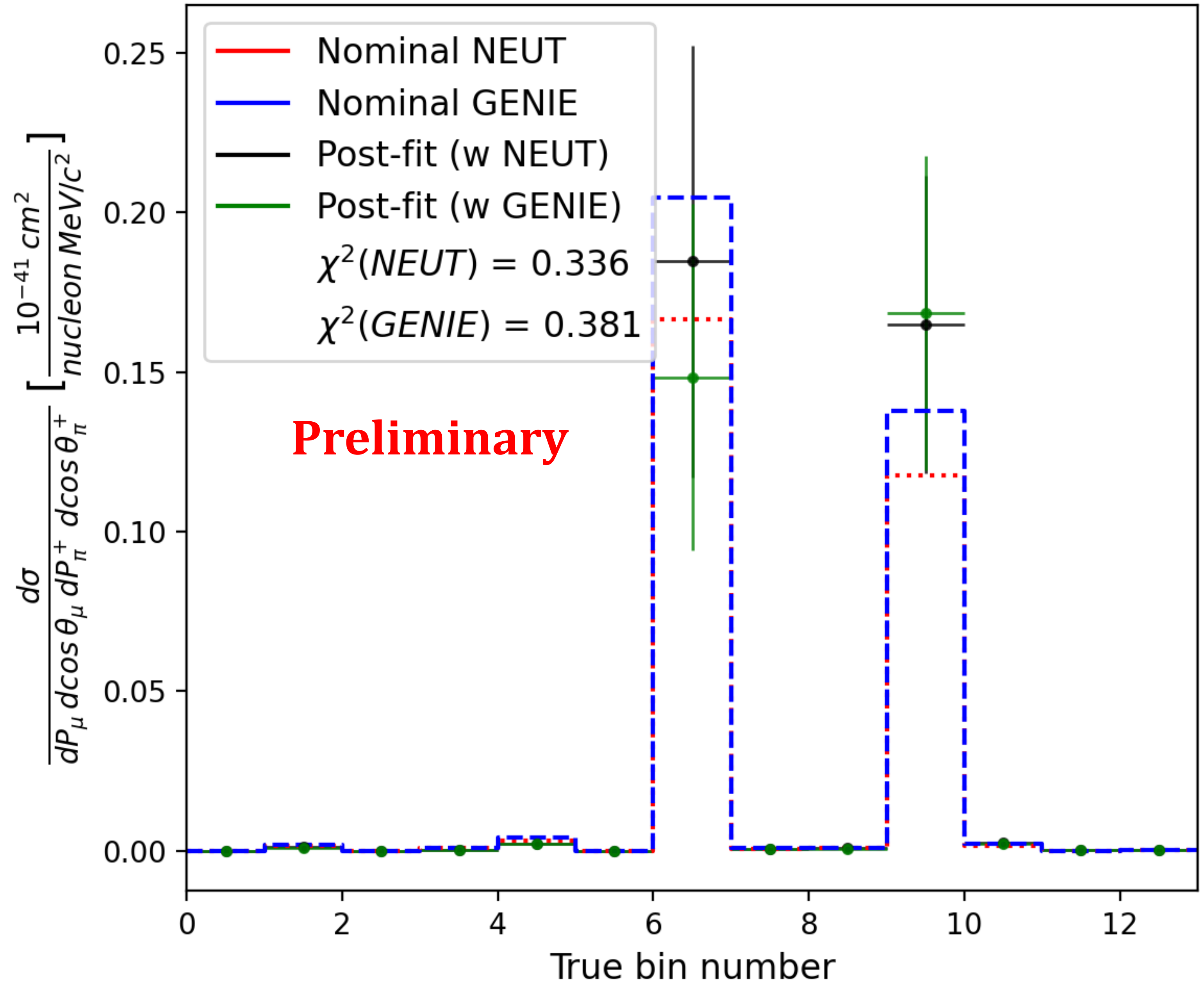


Quadruple differential cross section

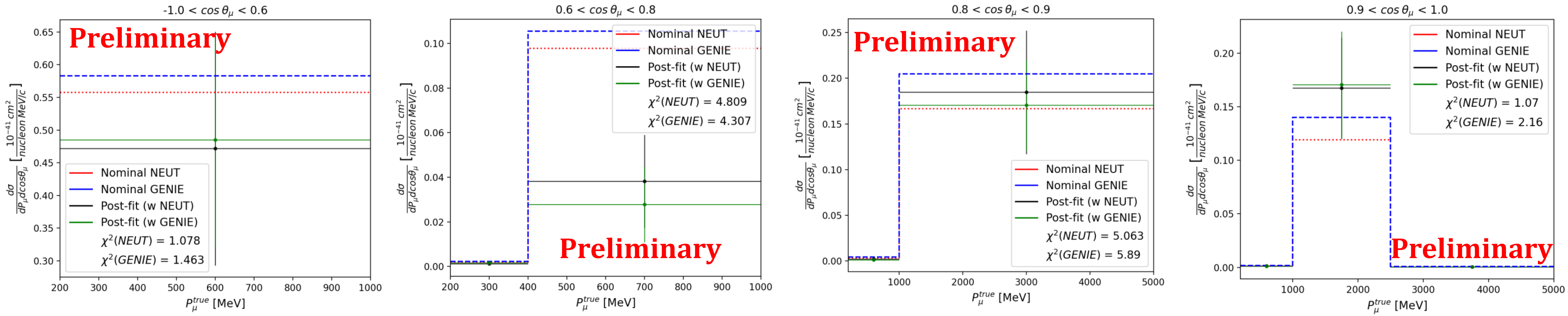
Template (truth)

Bin	$\cos\theta_\mu$		P_μ		$\cos\theta_{\pi^+}$		P_{π^+}	
0	-1.0	0.6	200	30000	-1.0	1.0	160	30000
1	0.6	0.8	200	400	-1.0	1.0	160	30000
2	0.6	0.8	400	30000	-1.0	1.0	160	30000
3	0.8	0.9	200	1000	-1.0	0.7	160	30000
4	0.8	0.9	200	1000	0.7	1.0	160	30000
5	0.8	0.9	1000	30000	-1.0	1.0	160	30000
6	0.9	1.0	200	1000	-1.0	1.0	160	300
7	0.9	1.0	200	1000	-1.0	1.0	300	30000
8	0.9	1.0	1000	2500	-1.0	0.7	160	30000
9	0.9	1.0	1000	2500	0.7	1.0	160	600
10	0.9	1.0	1000	2500	0.7	1.0	600	30000
11	0.9	1.0	2500	30000	-1.0	0.7	160	30000
12	0.9	1.0	2500	30000	0.7	1.0	160	30000

$$\chi^2 = (\vec{\sigma}_i^{fit} - \vec{\sigma}_i^{true}) V_{fit}^{-1} (\vec{\sigma}_i^{fit} - \vec{\sigma}_i^{true}),$$

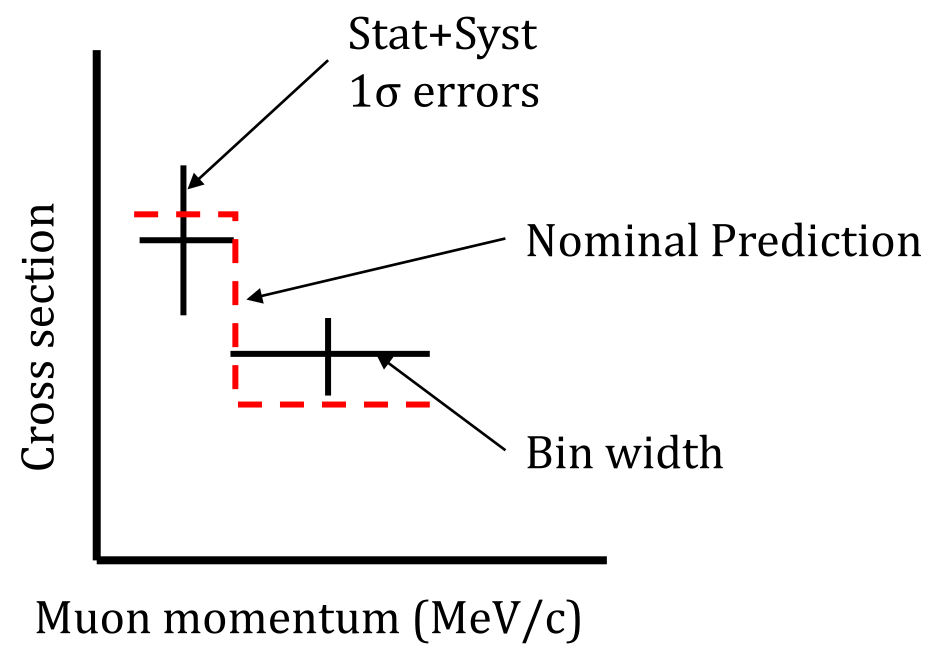


Double differential cross section (muon)



Note:

- NEUT MC (red line)
- GENIE MC (blue line)
- The last momentum bins extend all the way to 30 GeV.



Double differential cross section (positive pion)

Note:

- NEUT MC (red line)
- GENIE MC (blue line)
- The last momentum bins extend all the way to 30 GeV.