Measuring $\nu_\mu CC1\pi^+$ on Carbon using the ND280 with 4π solid angle acceptance (summary)

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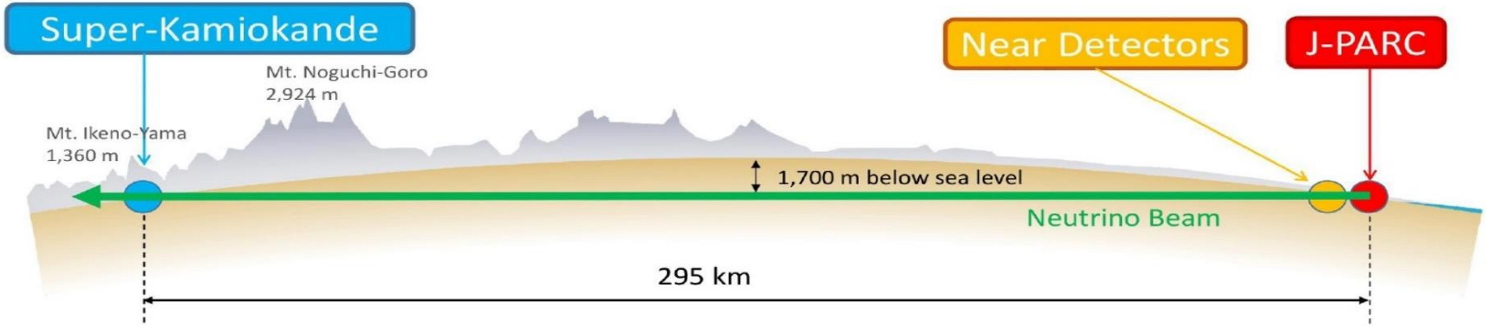
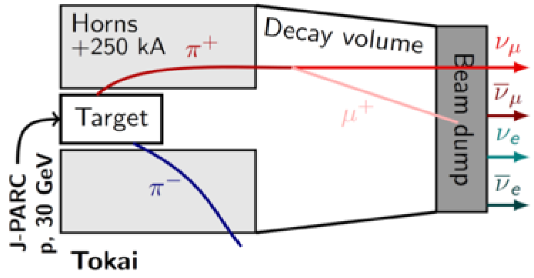
Part 1.

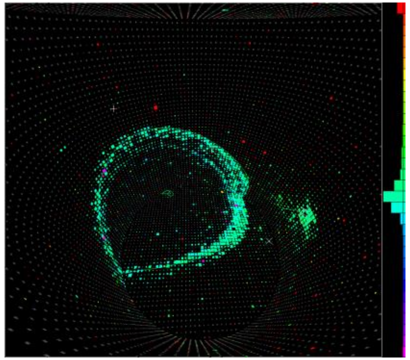
Measuring $\nu_\mu CC1\pi^+$ on Carbon using the ND280 with 4π solid angle acceptance

T2K experiment

- T2K is a long-baseline neutrino oscillation experiment.
- Goal: make precise measurements of oscillation parameters via observation of $\bar{\nu}_\mu/\nu_\mu$ disappearance and $\bar{\nu}_e/\nu_e$ appearance.







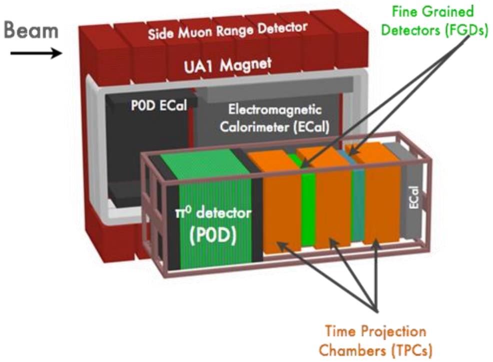
Flux: Depends on the neutrino source

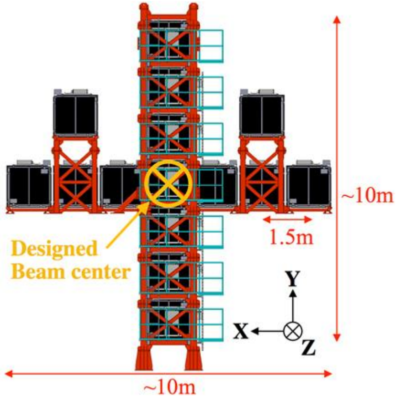
Number of protons on targets: Depends on the detector

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

Ratio of interactions in the detector

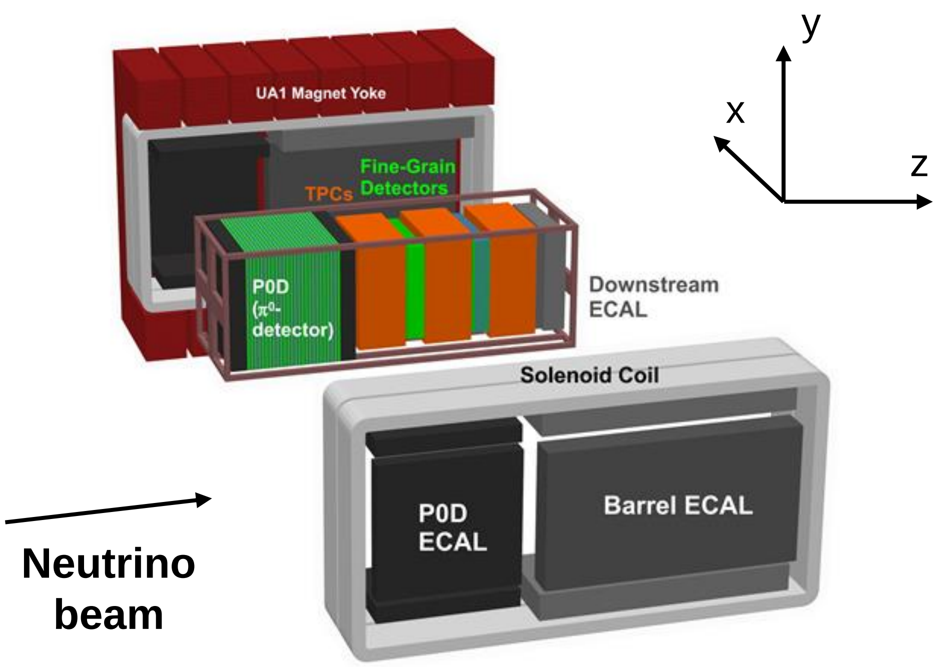
Cross section: It is very small and depends on energy

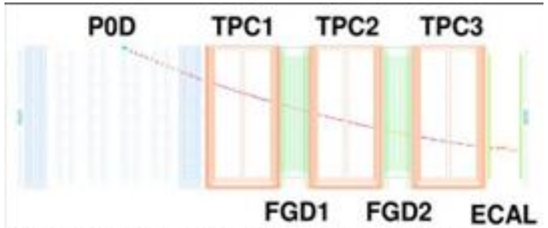




Off-axis ND280 detector

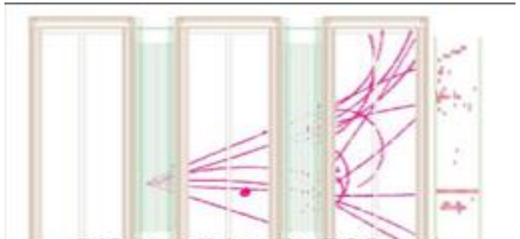
- 0.2 T magnetized tracking detector
- π^0 detector (P0D)
- Electromagnetic calorimeters (ECals)
- Side Muon Range Detectors (SMRD)
- The tracker (located downstream of the P0D) is made up of :
  - 3 gas Time Projection Chambers (TPCs)
  - 2 Fine Grained Detectors (FGDs)





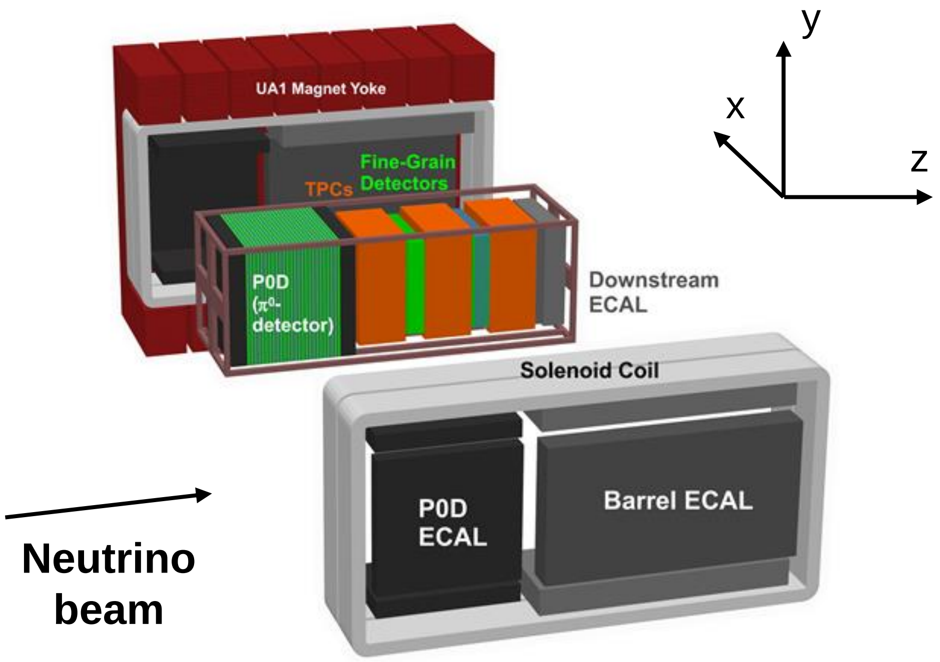
Cosmic track across all detectors


Clean CC interaction in FGD1

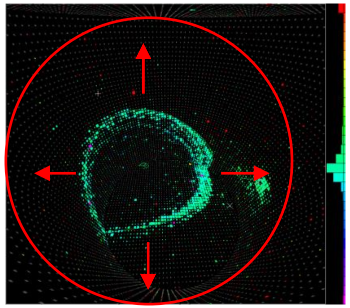

DIS candidate in FGD1

Motivation

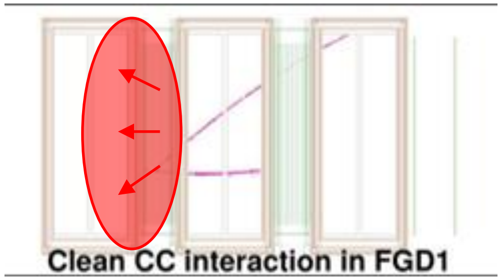
- $CC1\pi^+$ constitutes the main background for the muon neutrino disappearance measurement when the charged pion is not observed.
- Its precise knowledge is relevant for all current and planned neutrino oscillation experiments.
- The aim of the distributions presented here is to provide results in a model independent way, to make their comparison to other experiments easier and to contribute to the improvement of current models.
- The $CC1\pi^+$ cross section will be extracted using the present event selection (with 4π solid angle acceptance).
- Single pion production is sensitive mainly to resonant processes but also to non-resonant contributions.
- We can study the nuclear effects, FSI and Fermi momentum by computing and comparing the Adler angles.
- Adler's angles were measured for single charged pion production in neutrino interactions with heavier nuclei as target.

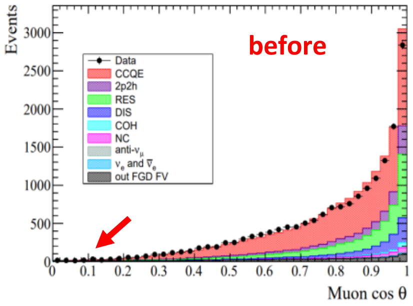


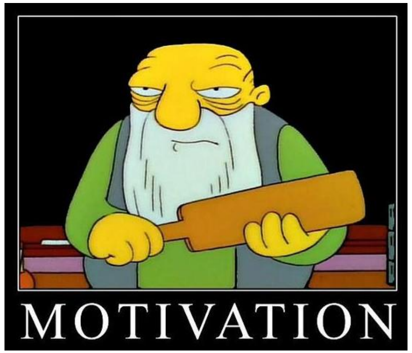
4π acceptance



4π acceptance



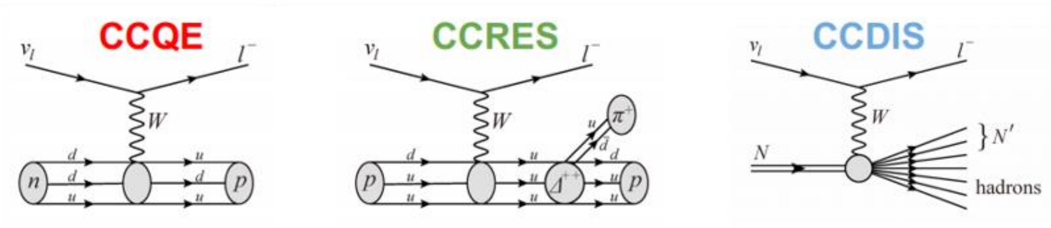




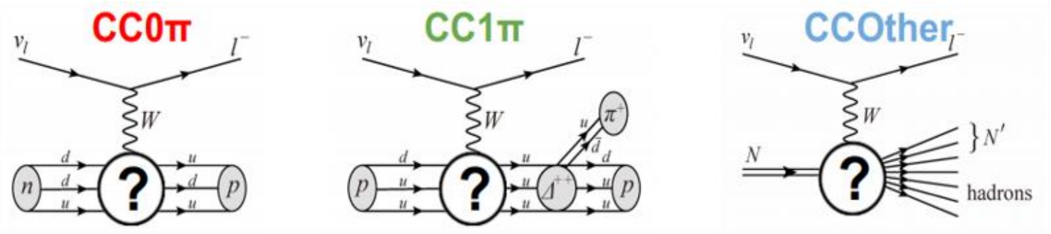
Neutrino interaction and Final state interaction role

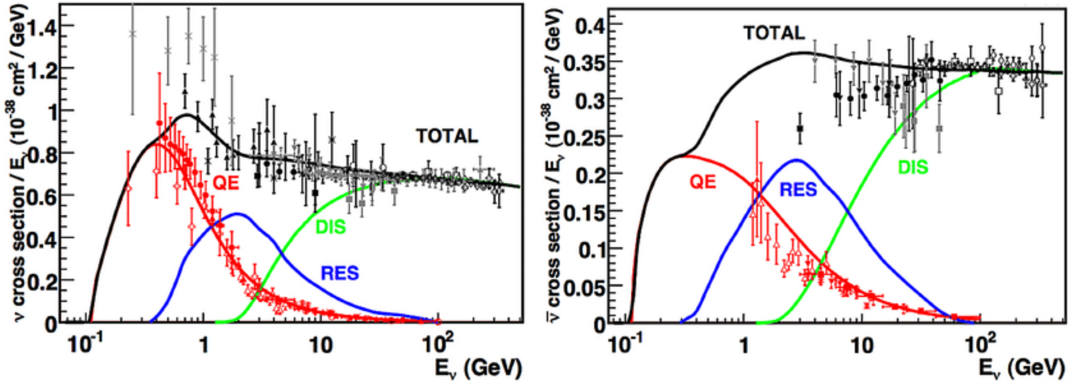
Three dominant scattering processes: Charged Current Quasi Elastic (CCQE), Charged Current Resonant Pion Production (CCRES), Charged Current Deep Inelastic Scattering (CCDIS).

Interaction Modes (nucleon level)

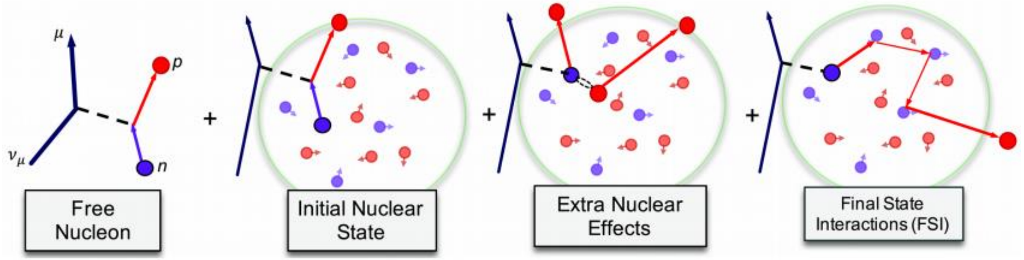


Interaction Topologies (nucleus level)





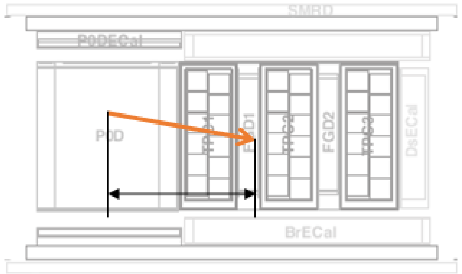
- Pions or nucleons can re-interact with the nuclear medium, or each other before leaving the nucleus.
- Changes outgoing particle content or kinematics in final state.



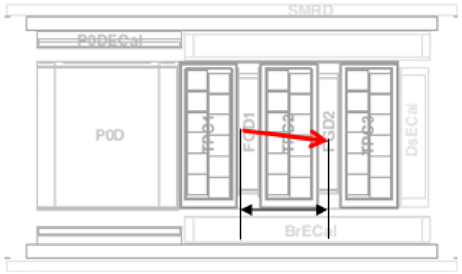
Selection development

ND280 Events → **General event quality, multiplicity, ToF, FV** → **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**

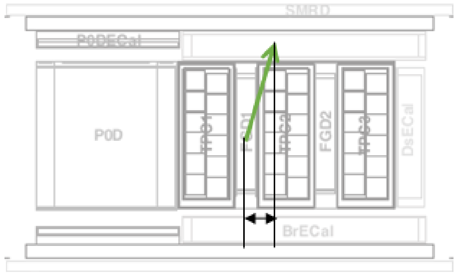
Time of flight (ToF)



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

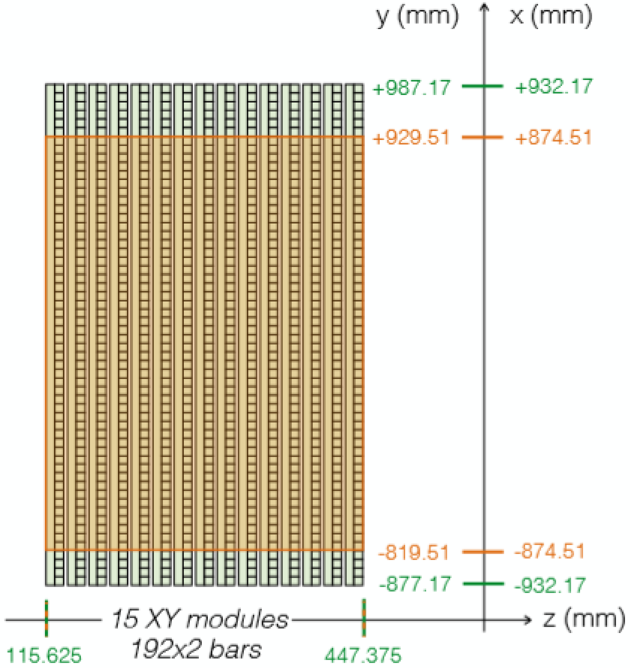


$$ToF_{FGD1-FGD2} = t_{FGD2} - t_{FGD1}$$



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

Fiducial Volume (FV)



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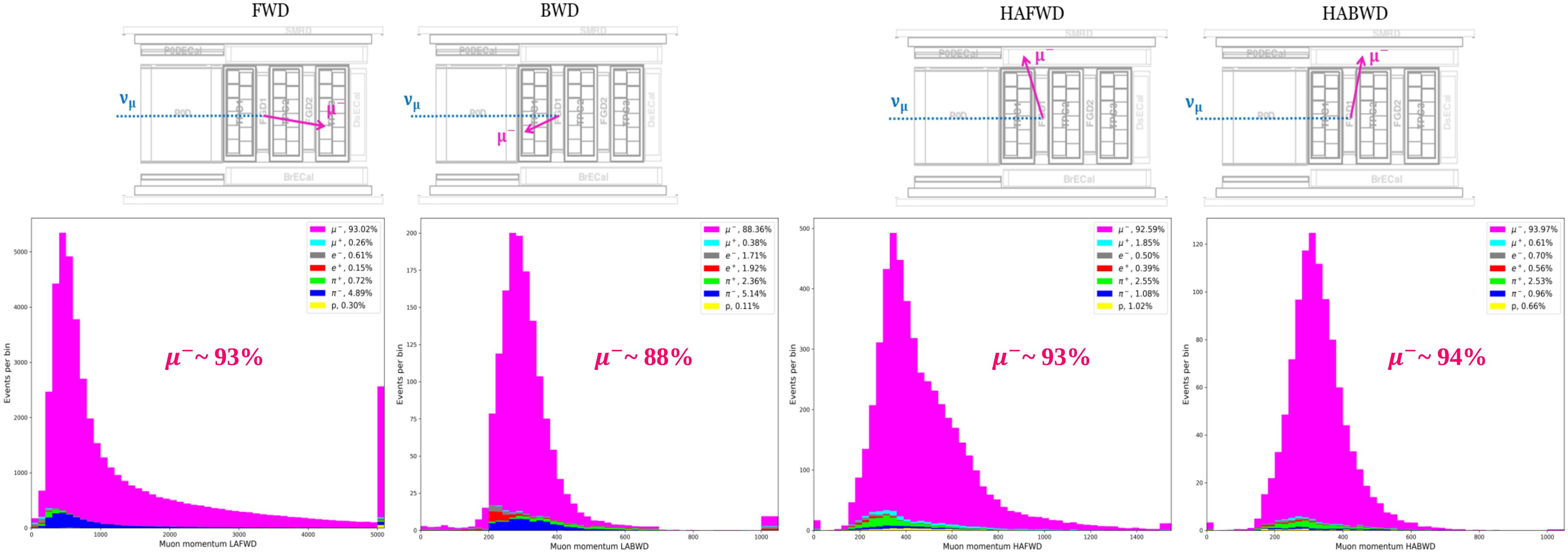

Selection development

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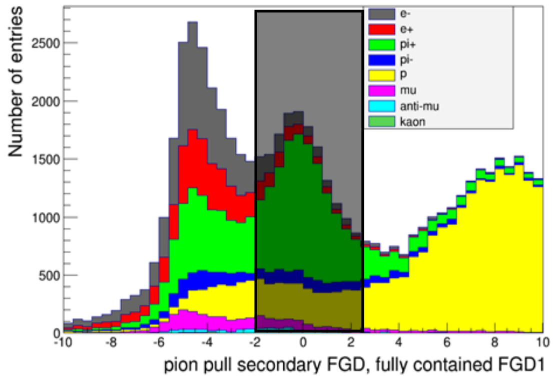
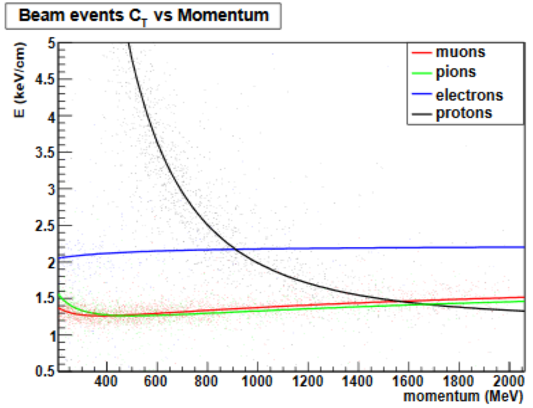
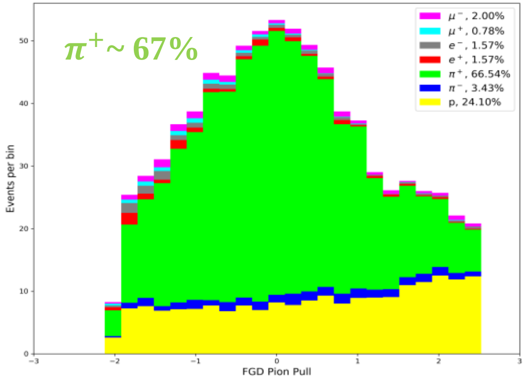
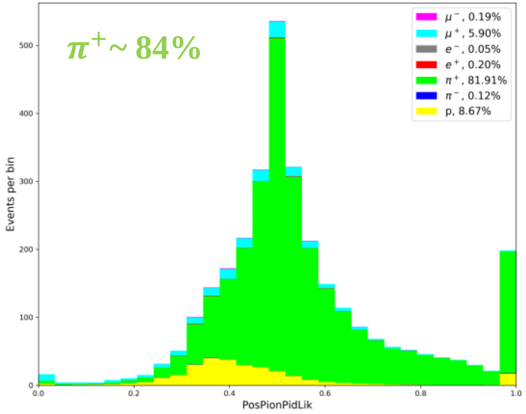
IsoFGD Pion

TPC Pion





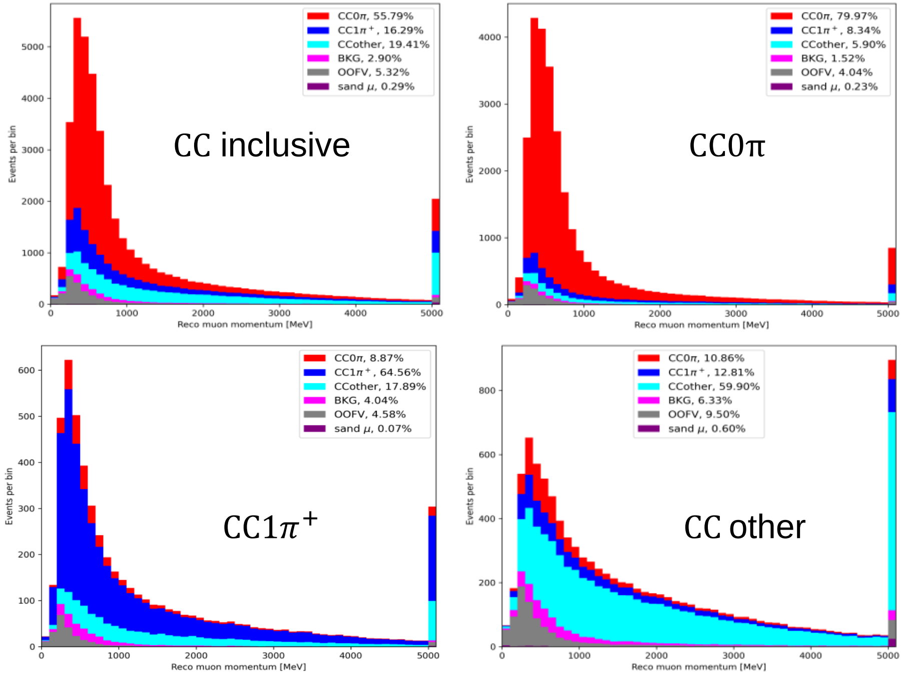




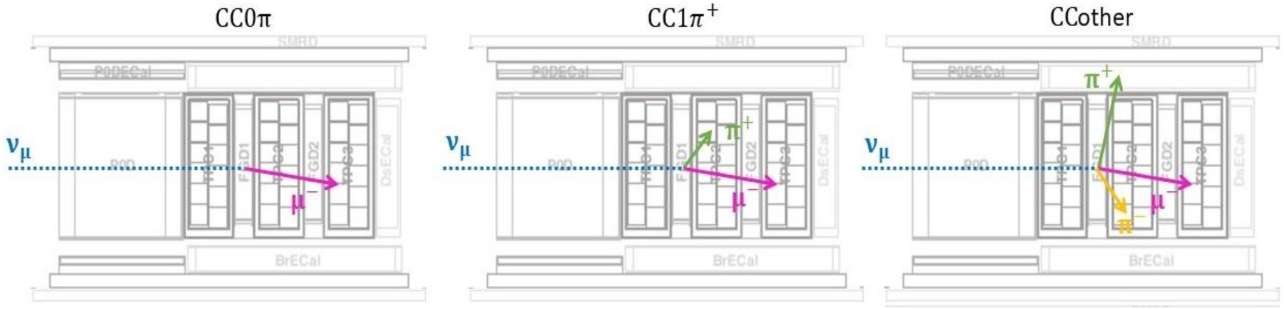
In the case of true protons that are identify as positive pion and vise-versa, this occur for energies superior to 1500 MeV in the TPC.
In the case of iso FGD tracks comes from the contamination of the pull.

Selection development

ND280 Events → **General event quality, multiplicity, ToF, FV** → **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**

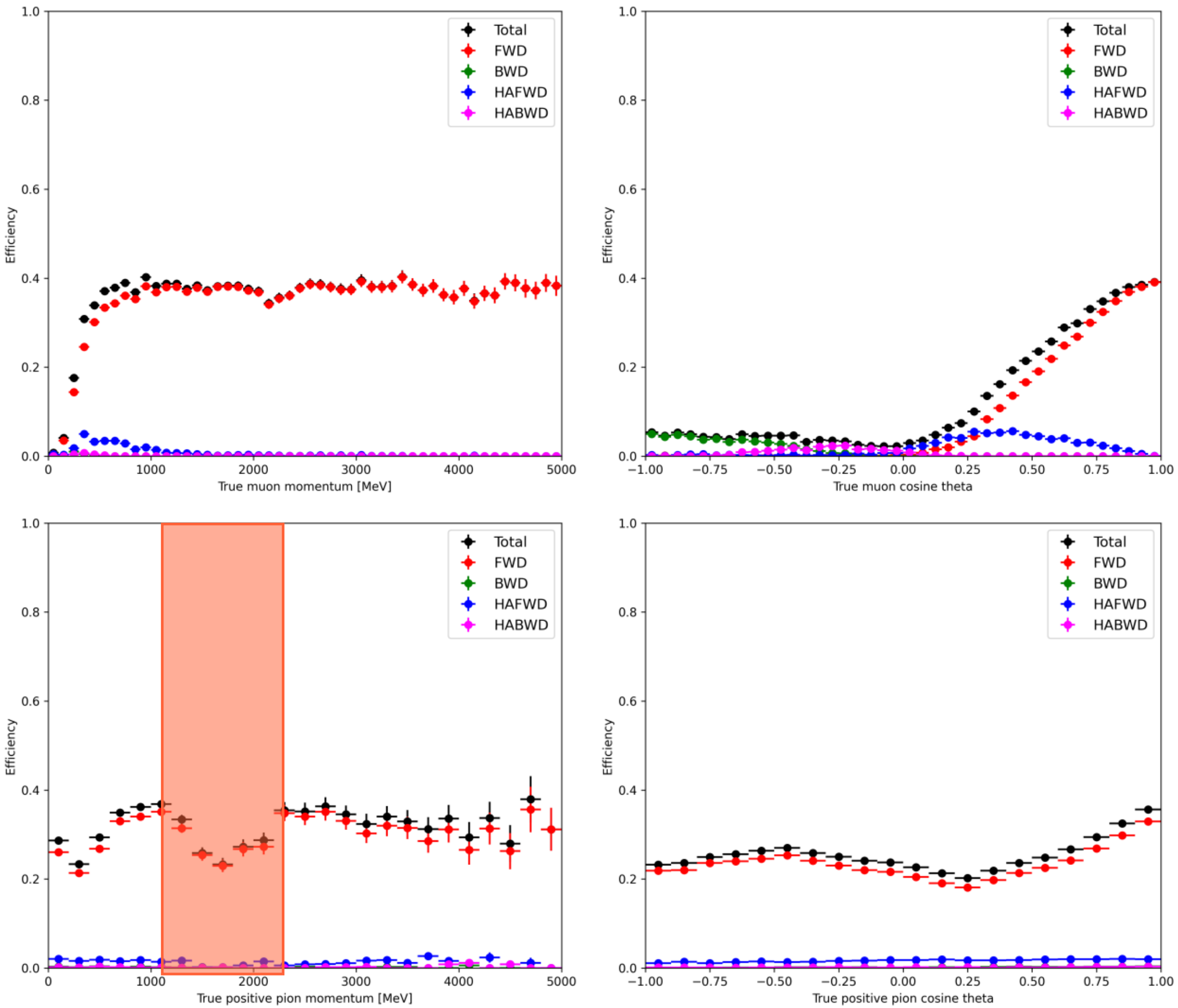


Distribution of the reconstructed muon momentum in the events selected at ND280 for CC inclusive, CC0π, CC1π^+ and CC other interactions by topology.



- The signal is defined in terms of the experimentally observable particles exiting the nucleus.
- Using NEUT as the default MC generator. We select events with a CC1π^+ topology in FGD1:
  - 1 muon in 4π solid angle acceptance.
  - One and only one pion of positive charge is required.
- The event is rejected if additional pions, either charged or neutral, or photons are identified in the event either by looking at TPC tracks or electromagnetic showers in ECal.

Selection: efficiency



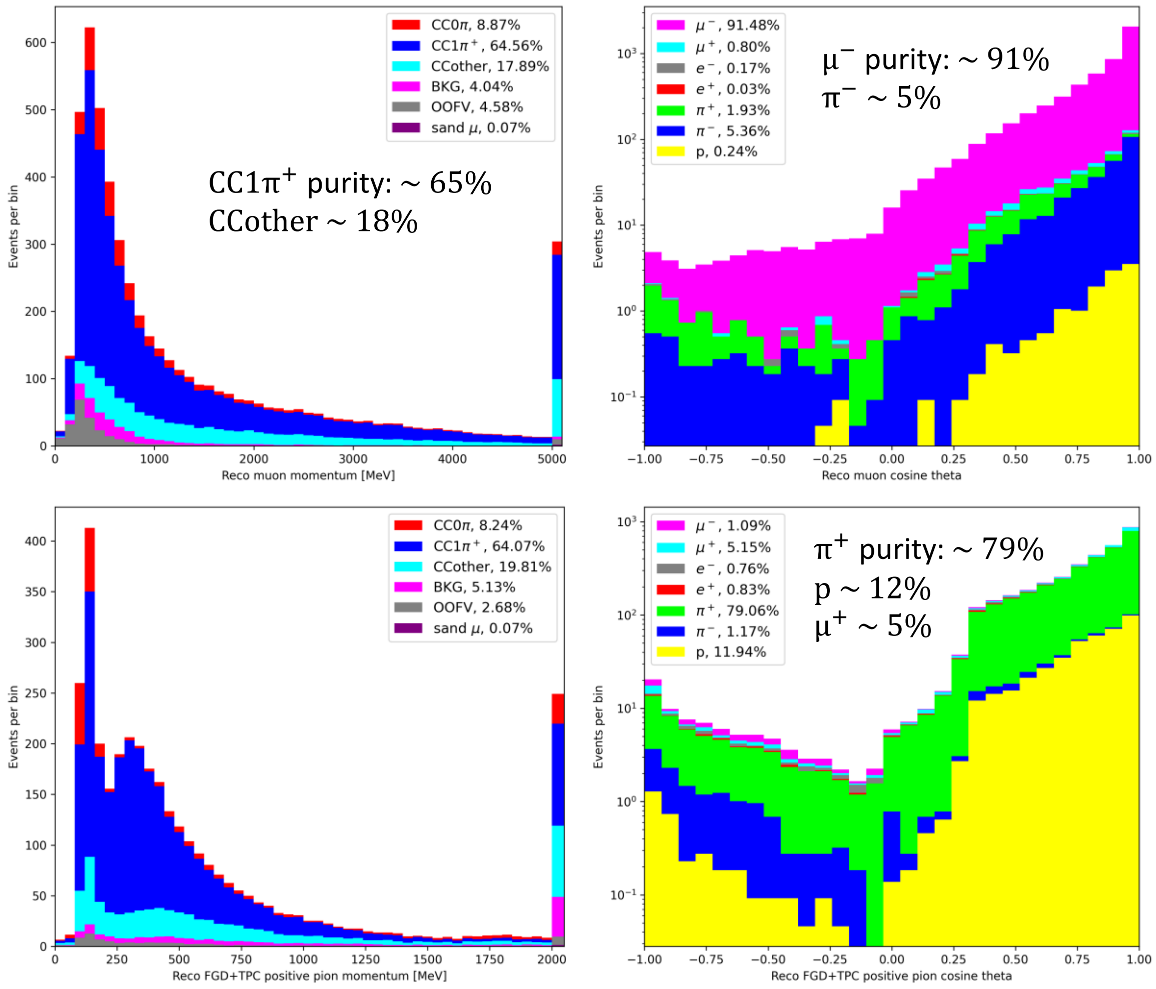
Efficiency distributions for $\mathrm{CC1}\pi^{+}$ with 4π solid angle acceptance vs. the muon and pion kinematics variables.

The efficiency is computed as:

$$\frac{\text{Number of selected true } \mathrm{CC1}\pi^{+} \text{ events in kinematic bin in branch}}{\text{Total number of true } \mathrm{CC1}\pi^{+} \text{in kinematic bin}}$$

- For muons with momentum higher than 500 MeV the efficiency is quite flat.
- For BWD muons the efficiency is close to zero but flat.
- For positive pions the efficiency is quite flat regardless of the direction.
- The positive pion momentum has a dip at $\sim 1600\ \mathrm{MeV}$.
    - that correspond to the energy where the TPC is incapable of distinguishing pions from protons based on the $\mathrm{d}E/\mathrm{d}x$.

Selection: purity

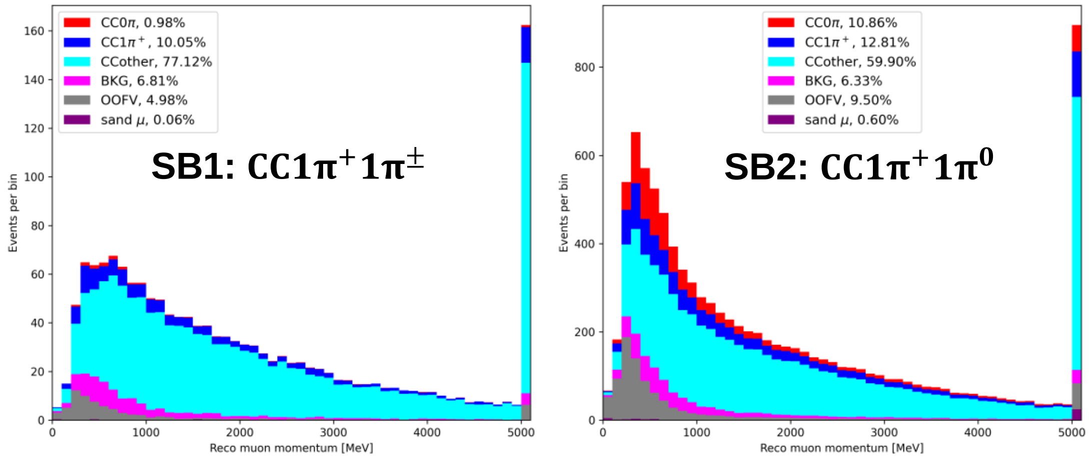


Kinematics distributions for $\mathrm{CC}1\pi^{+}$ with 4π solid angle acceptance. Using the true topology and particle definition.

Mains backgrounds:

- Topology: CCother
- Particle ID (muon): π^{-}
- Particle ID (pion): p, μ^{+}

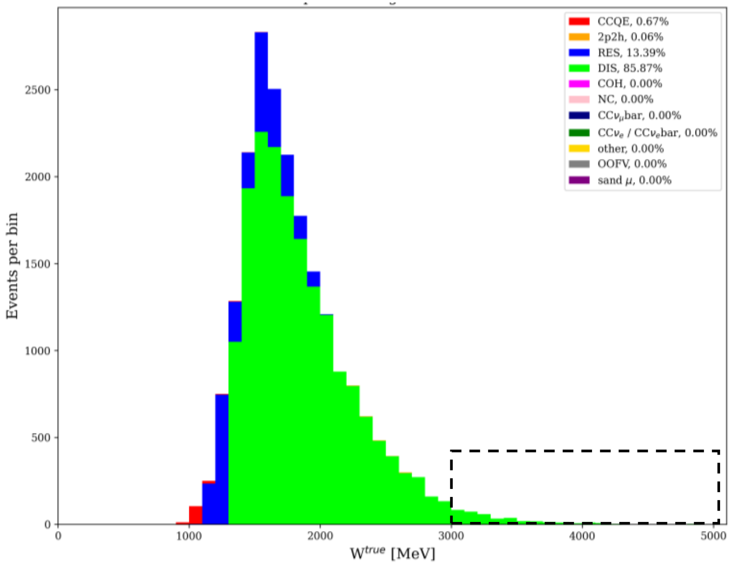
The two control samples that are subsamples of the $\mathrm{CCother}$:



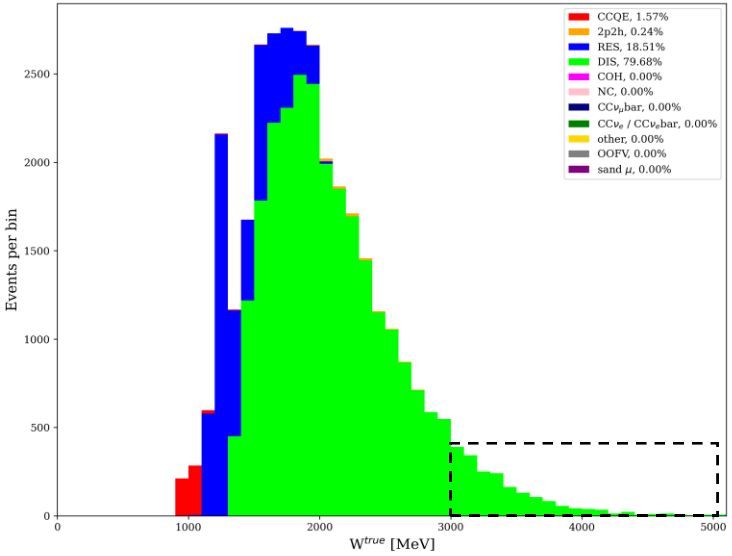
Muon momentum of $\mathrm{CC}1\pi^{+}1\pi^{\pm}$ (left) and $\mathrm{CC}1\pi^{+}1\pi^{0}$ (right) with 4π solid angle acceptance. Using the true topology definition.

Selection background

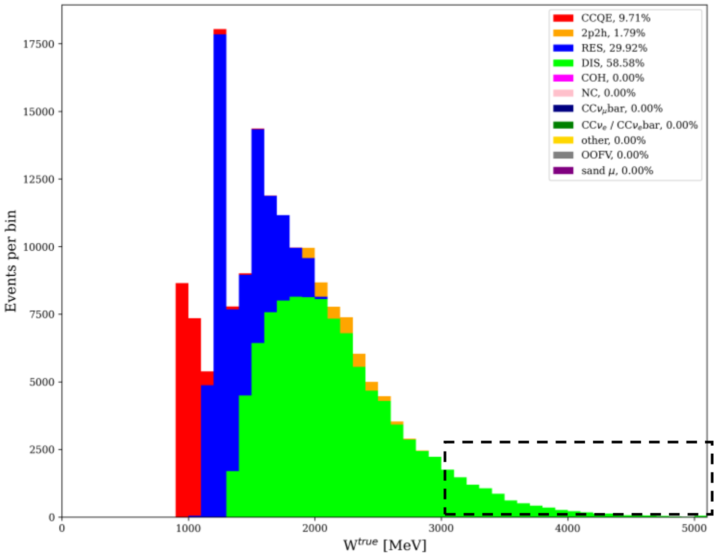
$CC1\pi^+1\pi^{\pm,0}$ in $CC1\pi^+$



$CC1\pi^+1\pi^{\pm}$



$CC1\pi^+1\pi^0$



True invariant mass of the $\mathrm{CCother}$ contamination of the samples $CC1\pi^+$(left column), $CC1\pi^+1\pi^\pm$ (central column), and $CC1\pi^+1\pi^0$ (right column) with 4π solid angle acceptance. Using the true reaction definition.

- Similar distribution of true invariant mass
- DIS purity is also similar between my contamination and $CC1\pi^+1\pi^\pm$.
- DIS purity is lower for $CC1\pi^+1\pi^0$

Part 2.
Interesting angular variables

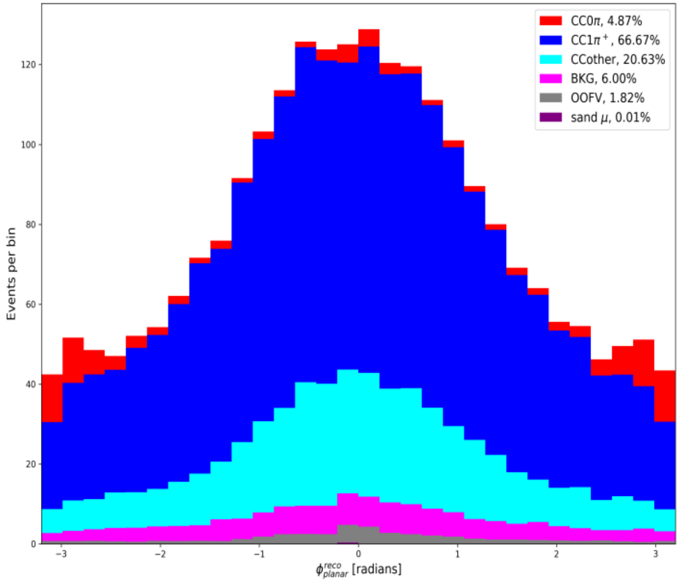
Adler's angles

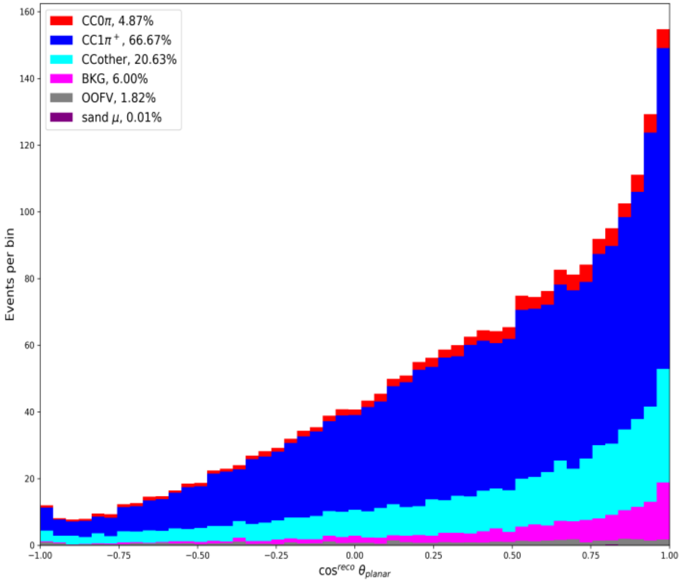
How are the Adler angles defined and calculated?

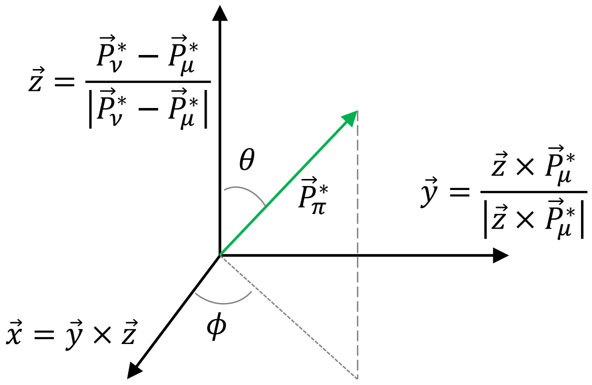
- The Adler reference system describes the $p-\pi^{+}$ final state in the Δ reference system (rest frame).
- The angles θ_{planar} and ϕ_{planar} are defined in this system.
- They are computed with particles leaving the nucleus (Adler angles at the nuclear level) keep the information about the interaction at the nucleon level.

What can we learn with them?

- They are altered by the final state interactions and the Fermi momentum of the target nucleon.
- They carry information about the polarization of the Δ resonance and the interference with non resonant single pion production
- They can provide hints of parity violation due to the lack of preference in the Δ direction.





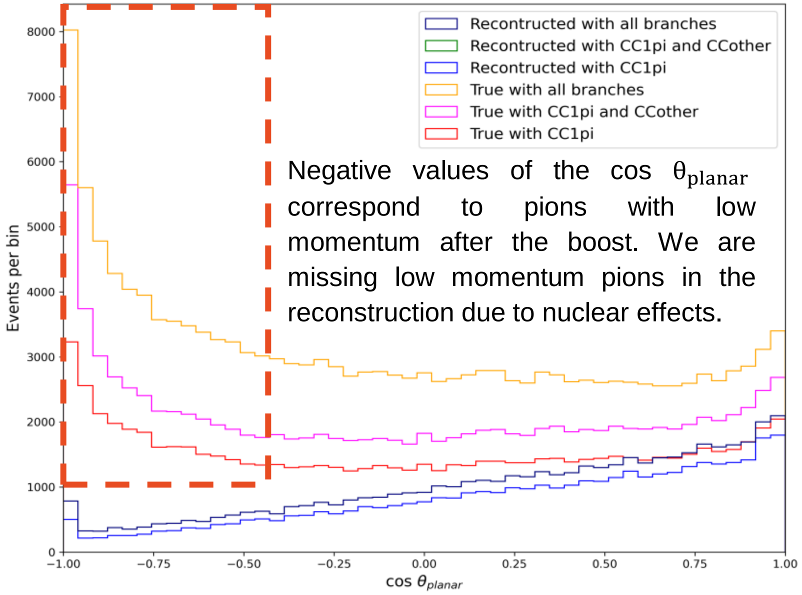


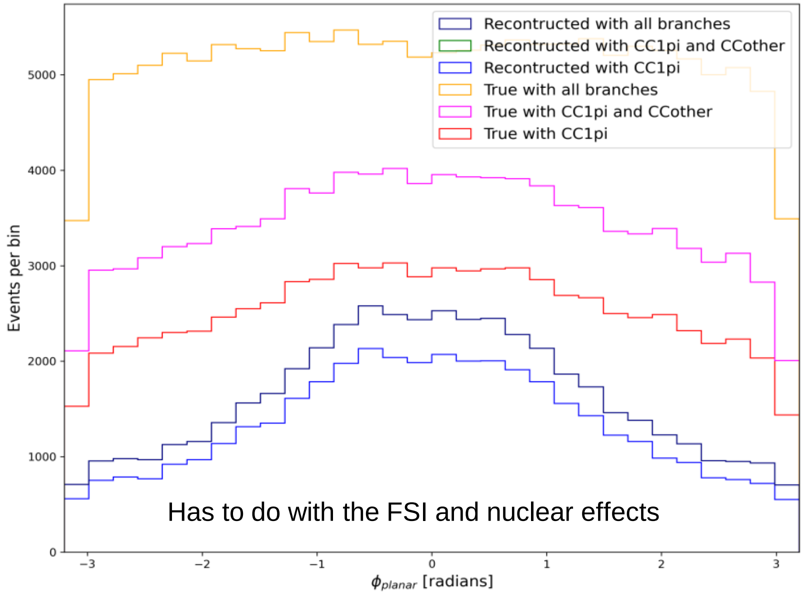
Definition of the Adler angles at the nuclear level. The momenta of the particles are defined in the $\vec{q} = \vec{P}_\nu - \vec{P}_\mu$ rest frame.

Adler's angles

To evaluate the relative contributions to the Adler's angles of the Fermi momentum and the FSI, we should compute the Adler's angles under three assumptions:

- True: We should estimate the parameters using the full kinematic information at the level of the nucleon. These results are experimentally measurable only with a hydrogen target,
- Pre-FSI: We should use the true kinematics of the pion at the level of the nucleon but we ignore the target nucleons momentum. In this case, the effect of the Fermi momentum is taken into account but the FSIs are ignored,
- Post-FSI: We should use the information of the pion leaving the nucleus and ignore the kinematic information of the target nucleon. These are the actual experimental observables and they contain the effect of both the Fermi momentum and of the FSI.





Underneath there is a nucleon-level effect that has information about the neutrino-nucleon interactions in relation to the polarization of the Δ. The problem is that the nuclear effects are large, but comparison of data with MC can still give valuable insights.

Summary

Part 1.

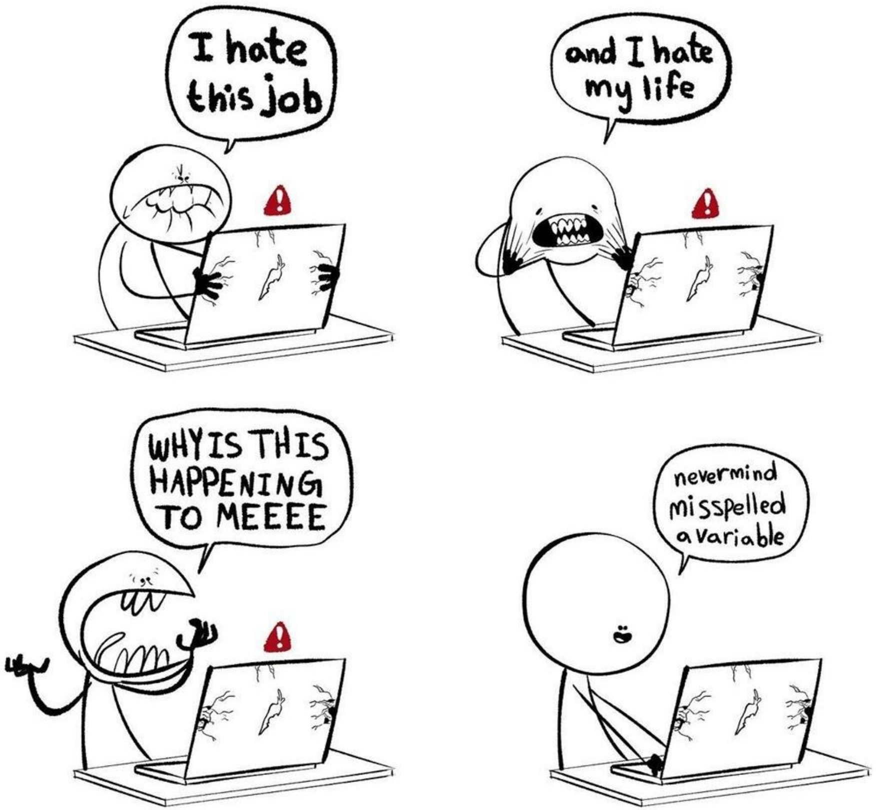
- The $CC1\pi^+$ cross section will be extracted using the present event selection (with 4π solid angle acceptance and for 4 dimensions).
- Using NEUT as the default MC generator we observe a purity of the $CC1\pi^+$ signal of ~65%. $CCother$ events being the main contamination.

Part 2.

- Negative values of the $\cos\,\theta_{planar}$ correspond to pions with low momentum after the boost. We are missing low momentum pions in the reconstruction due to nuclear effects.
- This is the second time those angles are measured in interactions of neutrinos on heavy nuclei (first time was also in ND280, 2 years ago in a constrained phase space and with less statistics).
- The Adler angles can be used to improve our interaction models.

General

- The selection review just started.
- Writing the thesis (defense in December)



Backup slides →

Part 3.
Backup slides

Binning

Bin Edges - Reconstructed CC1π^+

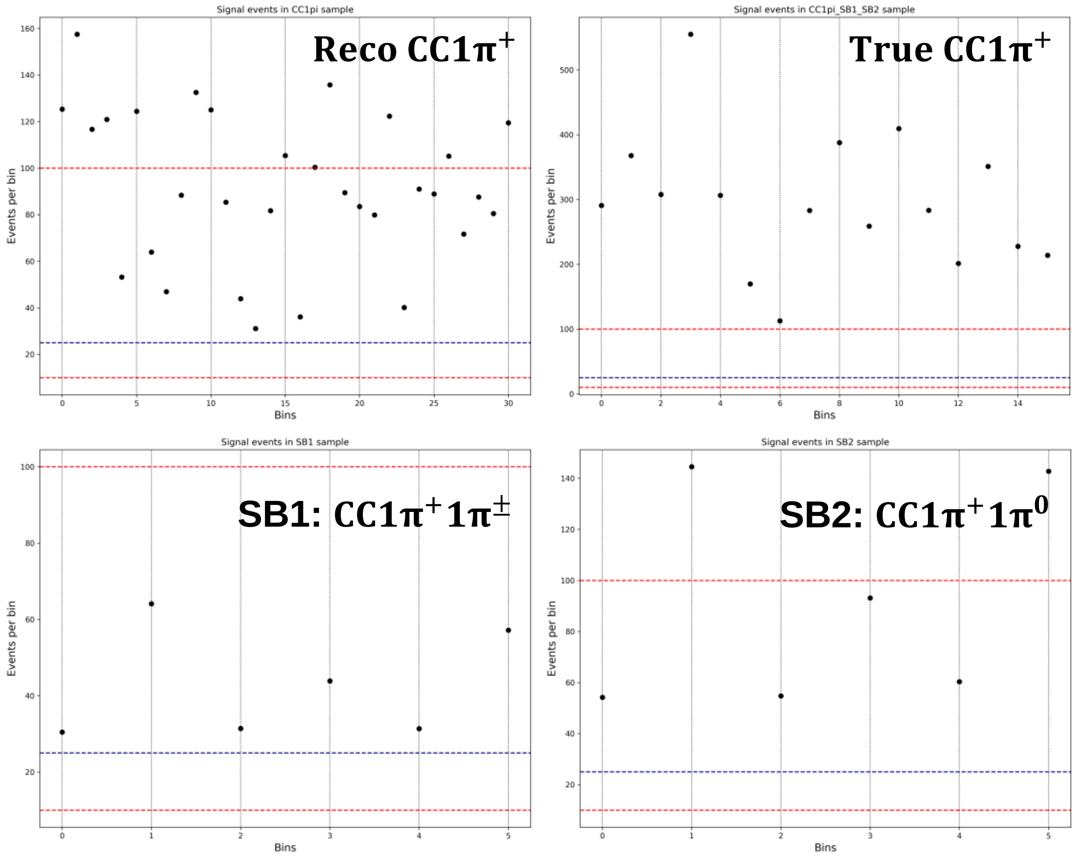
$\cos\theta_\mu$		P_μ		$\cos\theta_{\pi^+}$		P_{π^+}	
-1.0	0.6	0	30000	-1.0	0.7	0	30000
-1.0	0.6	0	400	0.7	1.0	0	30000
-1.0	0.6	400	30000	0.7	1.0	0	30000
0.6	0.8	0	600	-1.0	0.7	0	30000
0.6	0.8	600	30000	-1.0	0.7	0	30000
0.6	0.8	0	600	0.7	1.0	0	400
0.6	0.8	0	600	0.7	1.0	400	30000
0.6	0.8	600	30000	0.7	1.0	0	400
0.6	0.8	600	30000	0.7	1.0	400	30000
0.8	0.9	0	1000	-1.0	0.7	0	30000
0.8	0.9	0	1000	0.7	1.0	0	400
0.8	0.9	0	1000	0.7	1.0	400	30000
0.8	0.9	1000	30000	-1.0	0.7	0	30000
0.8	0.9	1000	30000	0.7	1.0	0	400
0.8	0.9	1000	30000	0.7	1.0	400	30000
0.9	1.0	0	1000	-1.0	0.7	0	300
0.9	1.0	0	1000	-1.0	0.7	300	30000
0.9	1.0	0	1000	0.7	1.0	0	300
0.9	1.0	0	1000	0.7	1.0	300	30000
0.9	1.0	1000	2500	-1.0	0.7	0	300
0.9	1.0	1000	2500	-1.0	0.7	300	30000
0.9	1.0	1000	2500	0.7	1.0	0	300
0.9	1.0	1000	2500	0.7	1.0	300	600
0.9	1.0	1000	2500	0.7	1.0	600	800
0.9	1.0	1000	2500	0.7	1.0	800	30000
0.9	1.0	2500	30000	-1.0	0.7	0	300
0.9	1.0	2500	30000	-1.0	0.7	300	30000
0.9	1.0	2500	30000	0.7	1.0	0	300
0.9	1.0	2500	30000	0.7	1.0	300	500
0.9	1.0	2500	30000	0.7	1.0	500	800
0.9	1.0	2500	30000	0.7	1.0	800	30000

Bin Edges - Reconstructed SB1 & SB2

$\cos\theta_\mu$		P_μ		$\cos\theta_{\pi^+}$		P_{π^+}	
-1.0	0.85	0	30000	-1.0	1.0	0	300
-1.0	0.85	0	30000	-1.0	1.0	300	30000
0.85	1.0	0	30000	-1.0	0.8	0	300
0.85	1.0	0	30000	-1.0	0.8	300	30000
0.85	1.0	0	30000	0.8	1.0	0	500
0.85	1.0	0	30000	0.8	1.0	500	30000

Bin Edges - Truth CC1π^+

$\cos\theta_\mu$		P_μ		$\cos\theta_{\pi^+}$		P_{π^+}	
-1.0	0.6	200	5000	-1.0	0.7	100	3000
-1.0	0.6	200	5000	0.7	1.0	100	3000
0.6	0.8	200	400	-1.0	1.0	100	3000
0.6	0.8	400	5000	-1.0	1.0	100	3000
0.8	0.9	200	1000	-1.0	0.7	100	3000
0.8	0.9	200	1000	0.7	1.0	100	400
0.8	0.9	200	1000	0.7	1.0	400	3000
0.8	0.9	1000	5000	-1.0	1.0	100	3000
0.9	1.0	200	1000	-1.0	0.7	100	3000
0.9	1.0	200	1000	0.7	1.0	100	300
0.9	1.0	200	1000	0.7	1.0	300	3000
0.9	1.0	1000	2500	-1.0	0.7	100	3000
0.9	1.0	1000	2500	0.7	1.0	100	600
0.9	1.0	1000	2500	0.7	1.0	600	3000
0.9	1.0	2500	5000	-1.0	0.7	100	3000
0.9	1.0	2500	5000	0.7	1.0	100	600
0.9	1.0	2500	5000	0.7	1.0	600	3000



- Where we have at least 25 event per reconstructed bin.
- Where we have at least 100 event per true bin.

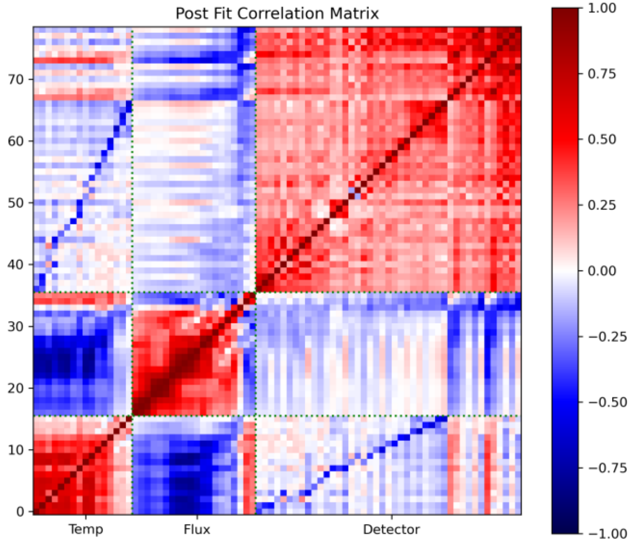
Detector systematics

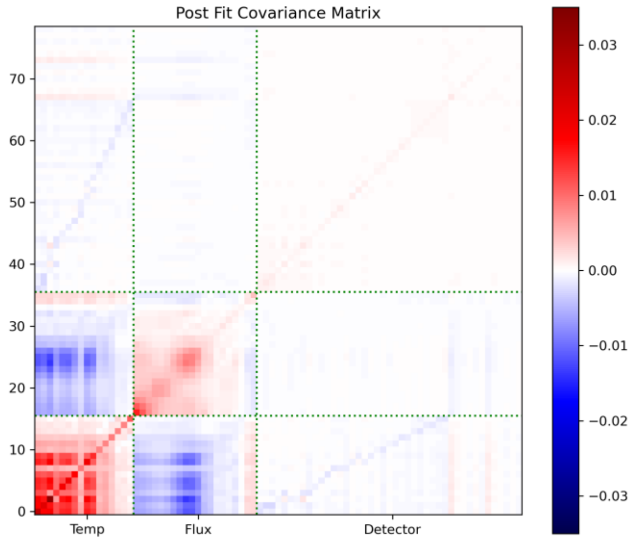
- 10 variation systematics
- 20 weigth systematics
- 500 toys

Relative errors (using NEUT) as function of kinematics variables when ToF systematics are thrown for $CC1\pi^+$ sample.

Still running syst plots,
Sorry

- 16 bins used for the template parameters.
- 20 bins used for the flux covariance matrix for muon neutrinos.
- 43 bins used for the detector covariance and correlation matrix.





Good news:

- The flux params are highly correlated and anticorrelated with templates.