Adler's angles and asymmetry studies for CC1π^+

Neutrino Group Meeting

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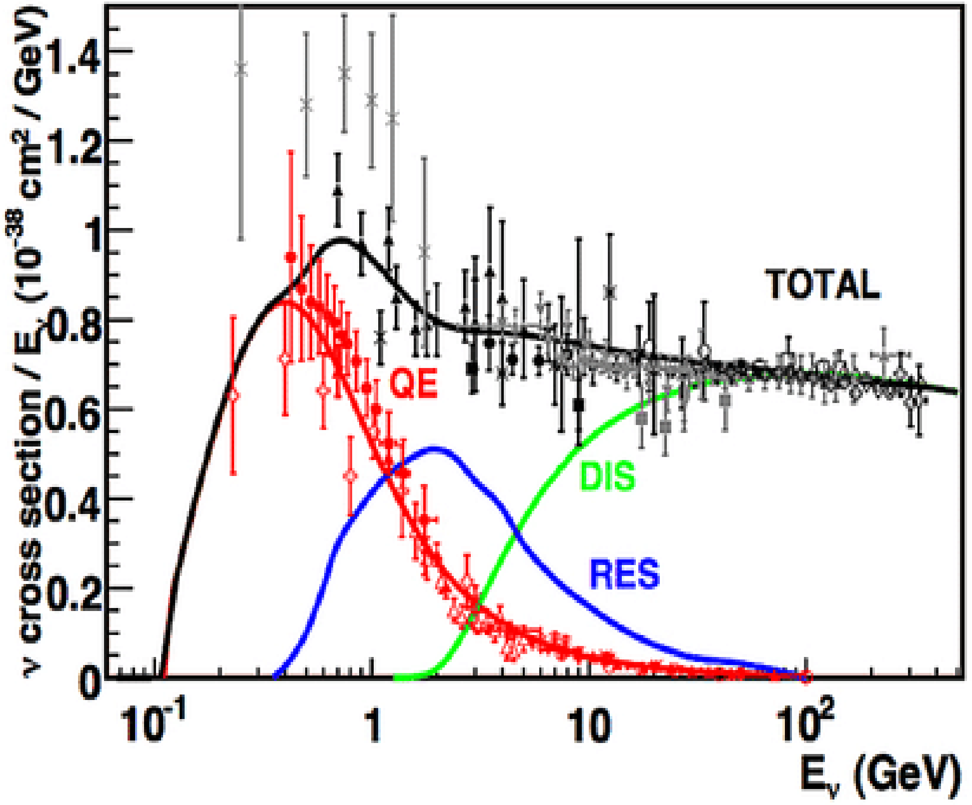
Adler's Angles

Motivation

Neutrinos interact with nuclei via neutrino-nucleon quasi-elastic scattering (QE), resonant production (RES), and deeply inelastic scattering (DIS).

Challenges:

- ❖ Our incomplete understanding of the nuclear effects contributing to the cross section
- ❖ Inaccuracies in reconstructing the neutrino energy



Related to neutrino cross-section knowledge we have three levels of uncertainties:

1. Cross sections at the nucleon level are not perfectly known.
2. Cross sections are modified by effects due to the nuclear medium.
3. These primary interactions are embedded in the nucleus, where nuclear effects can modify the event topology.

Current status:

- ❖ QE is well study.
- ❖ We now need to accurately model interactions occurring at higher energies such as single pion production.
- ❖ Current and future measurements can be performed only on nuclei.
- ❖ Explore the possibility of measuring Adler's angles in neutrino charged-current pion production on nuclei.

Adler's Angles

Introduction

- The Adler's angles carry information about the polarization of the Δ resonance, the interference with non resonant single pion production and they can provide hints of parity violation due to the lack of preference in the Δ direction.
- 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 that are computed with particles leaving the nucleus (Adler's Angles at the nuclear level) keep the information about the interaction at the nucleon level.

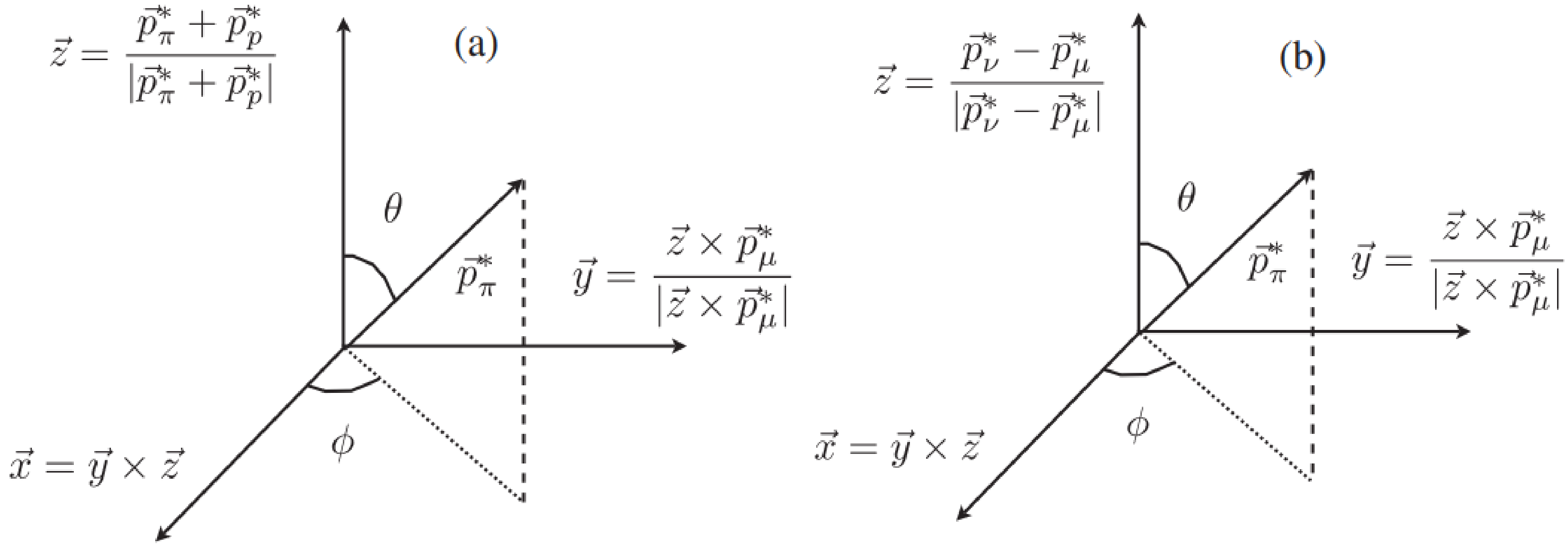


FIG. 1. Definition of the Adler Angles at the nucleon (true) level (a) and the nuclear level (b). The momenta of the particles are defined in the $\vec{q} = \vec{p}_\nu - \vec{p}_\mu$ rest frame.

Adler's Angles

Fermi momentum and final state interactions

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:

1. 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,
2. 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,
3. 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.

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Possibility of measuring Adler angles in charged current single pion neutrino-nucleus interactions

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Adler's Angles

Results and future

- ✓ It is possible to measure the Adler's angles in neutrino-nucleus scattering.
- ✓ The results based on the NEUT Monte Carlo show:
  - ❖ That one can determine the transverse polarization of the Δ resonance because the information is reasonably well maintained despite the FSI and the need to reconstruct the energy of the incoming neutrino from the experimental data.
  - ❖ The longitudinal polarization is shown to depend strongly on the kinematics of the emerging pion, but it appears, on the $CC1\pi^+$ tracks emerging from the nucleus, to allow investigation of:
    1. the effects of pion re-scattering,
    2. high mass resonances,
    3. deep inelastic processes.
  - ❖ The results indicate that current high-statistics experiments can explore complex observables like the Adler's angles as a function of the kinematic parameters of the scattering process such as the energy of the neutrino, the hadronic invariant mass and four-momentum transfer.

Near Future

We plant to study also the influence FSI by:

1. Running with different generators like NEUT , GENIE and NuWro
2. Running different FSI models

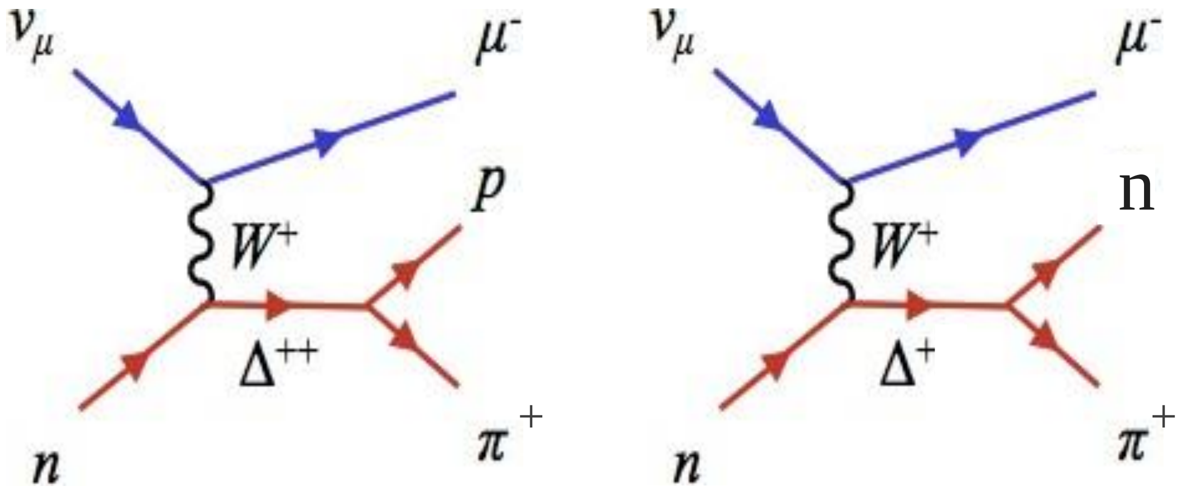
Selection

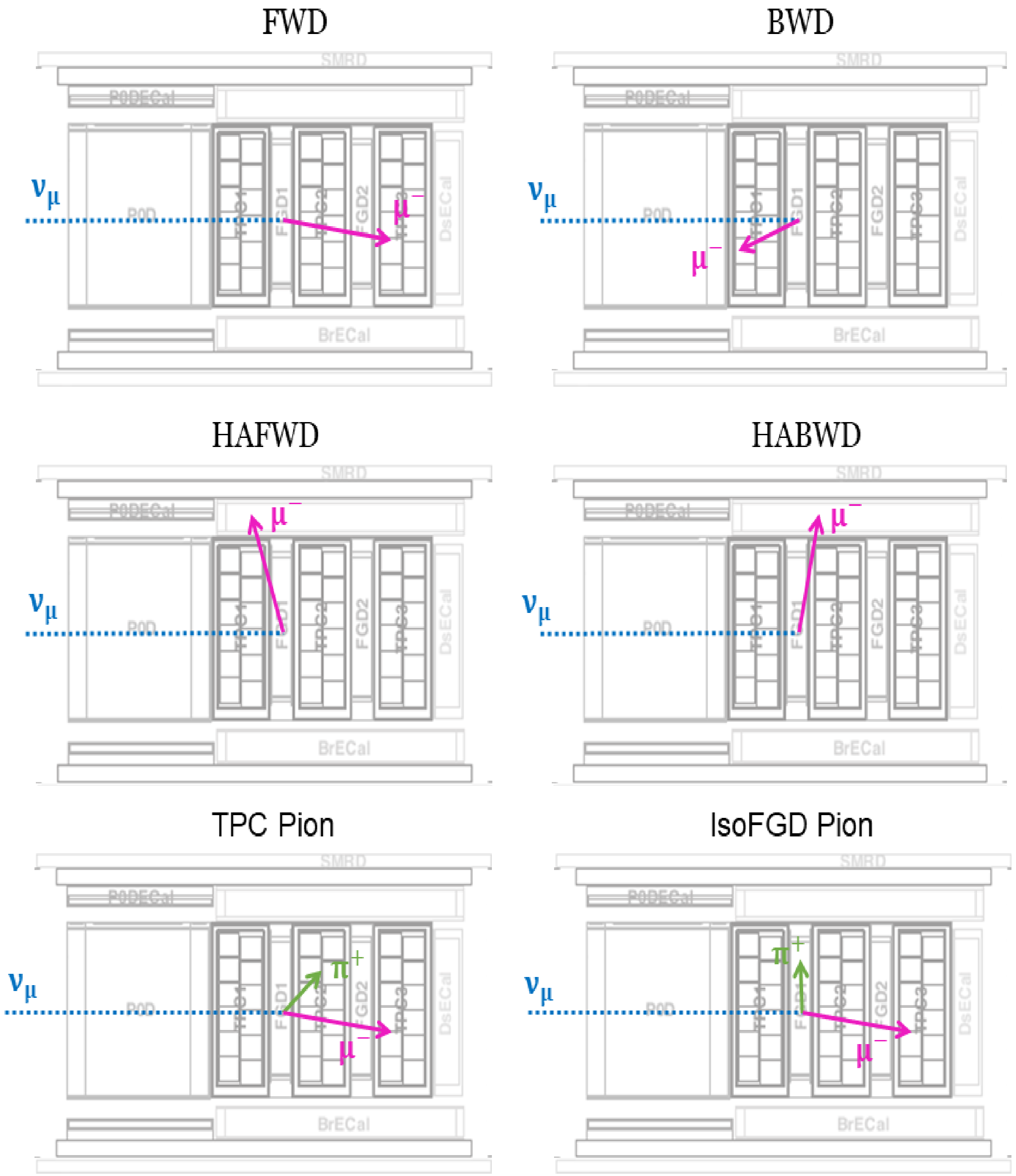
Signal

✓ Selecting events with a CC1π^+ topology in FGD1

- 1 muon (in 4π acceptance)
- 1 positive pion in TPC or contained in FGD1

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





Selection

Reconstructed variables

The neutrino energy is reconstructed using energy-momentum conservation:

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

Were $(E_\mu, \mathbf{P}_\mu)$ and $(E_\pi, \mathbf{P}_\pi)$ are the four-momenta of the muon and the pion, is the neutrino direction, $\mathbf{E_{bind}}$ is the target nucleon binding energy (≈ 25 MeV in NEUT for a carbon target) and $\mathbf{m_p}$ is the free proton mass. This definition of the neutrino energy is with the assumption that the target nucleon is at rest what allow us to calculate the invariant mass of the $p - \pi$ system:

$$W^2 = \left((E_\nu + m_p) - E_\mu\right)^2 - \left(|\mathbf{P}_\nu| - |\mathbf{P}_\mu|\right)^2$$

the value of the momentum transfer:

$$Q^2 = -q^2 = (\mathbf{P}_\mu - \mathbf{P}_\nu)^2$$

the angle between the $p - \pi$ system and the $\boldsymbol{q}$ approximation at the level of the nucleus.

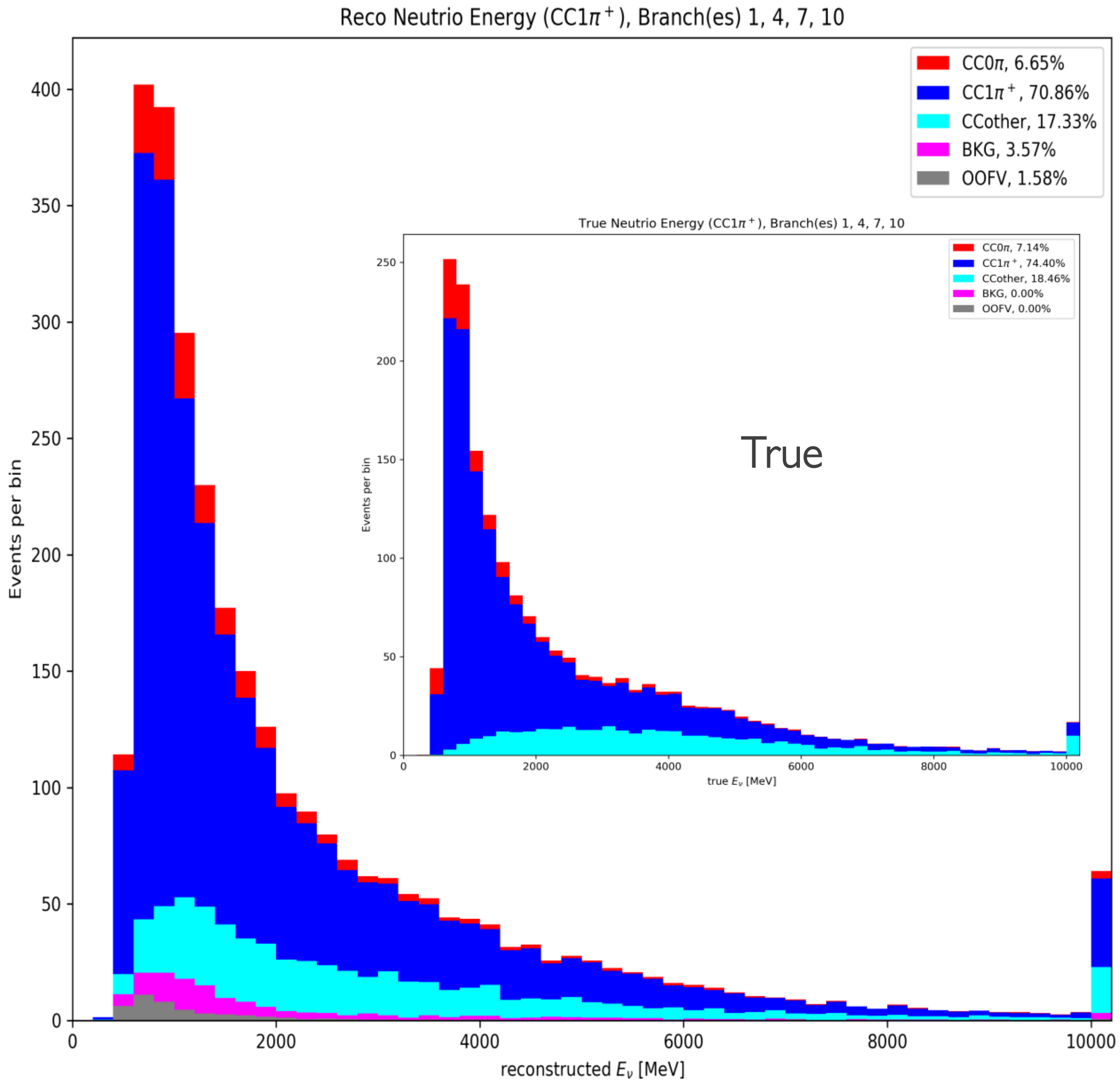
$$\cos\theta_{qP_{p\pi}} = \frac{\mathbf{k}_q * \mathbf{k}_{P_{p\pi}}}{|\mathbf{k}_q| * |\mathbf{k}_{P_{p\pi}}|}$$

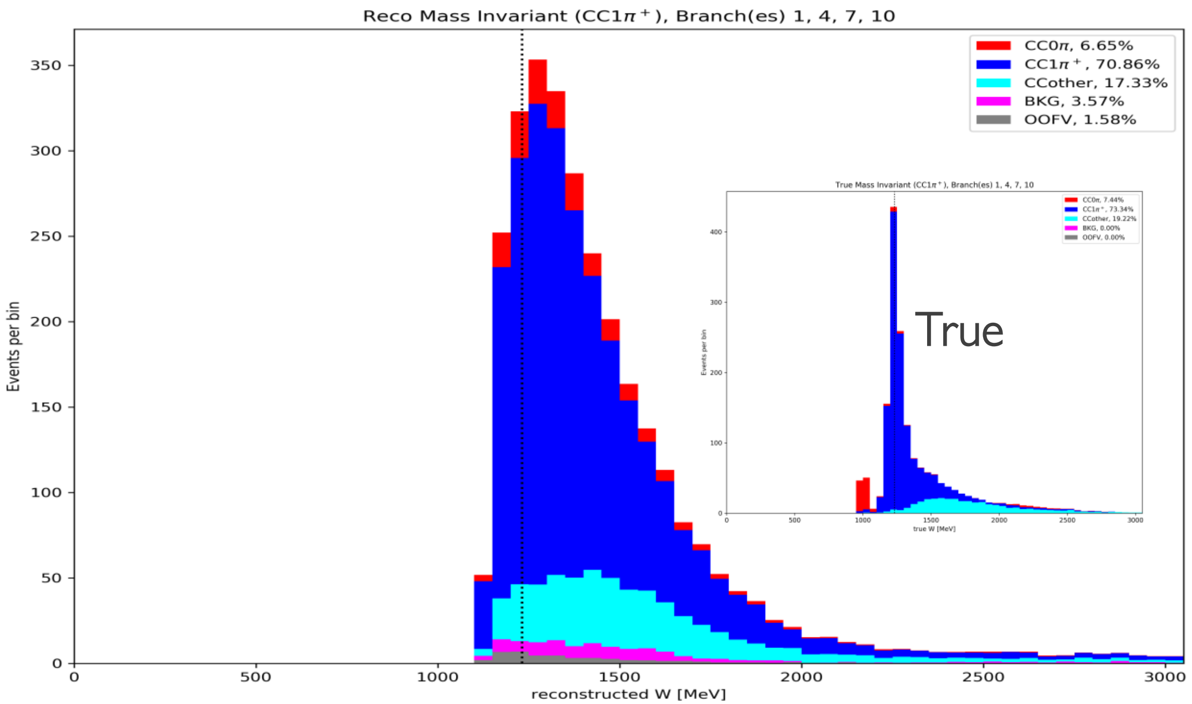
and angle between the muon and the pion will be:

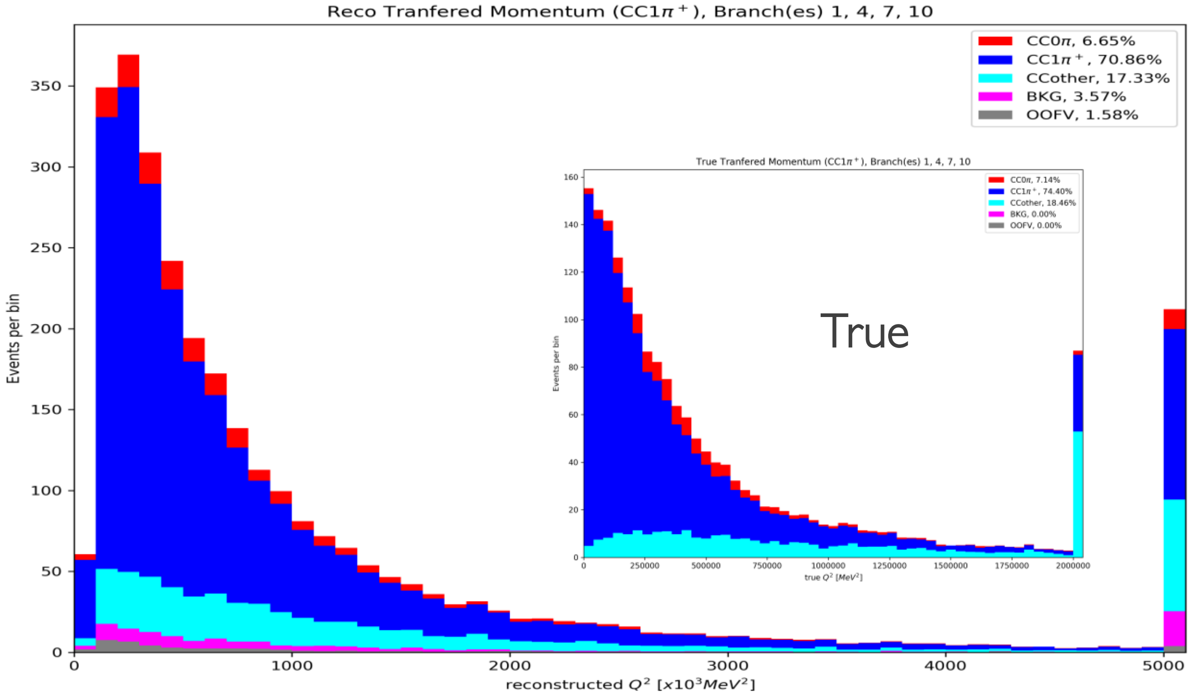
$$\cos\theta_{\mu\pi} = \frac{\mathbf{k}_\mu * \mathbf{k}_\pi}{|\mathbf{k}_\mu| * |\mathbf{k}_\pi|}$$

Selection

Reconstructed variables

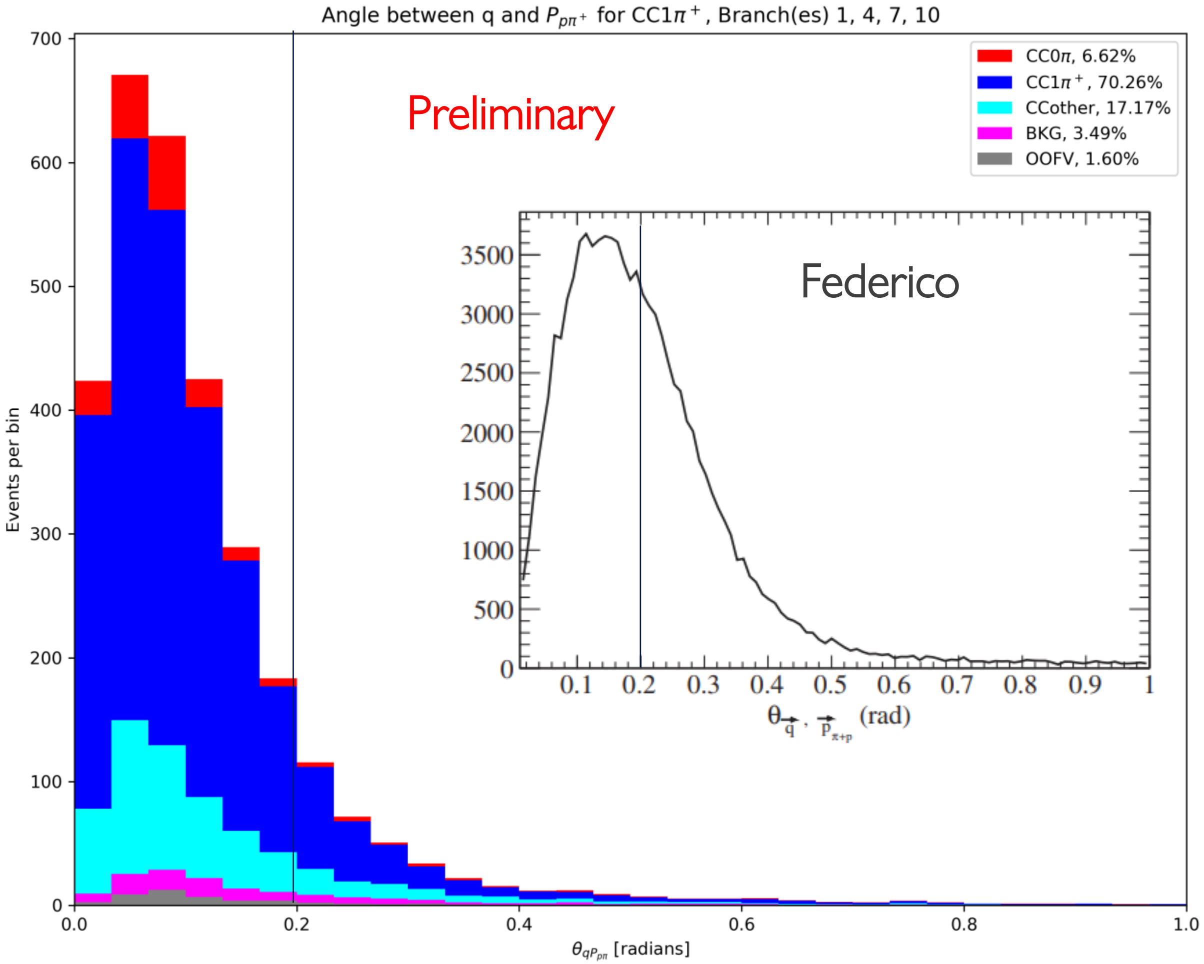


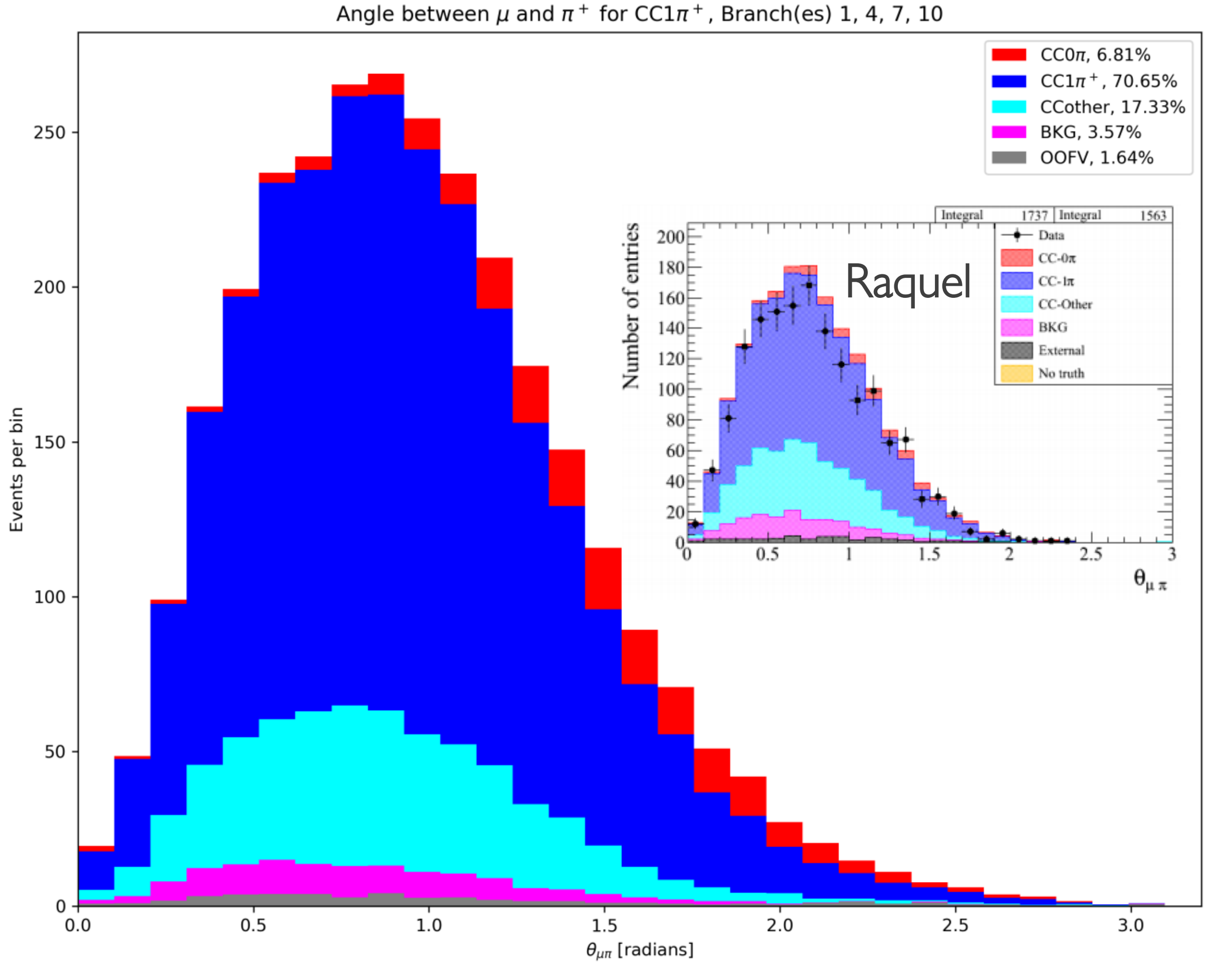




Selection

Reconstructed variables

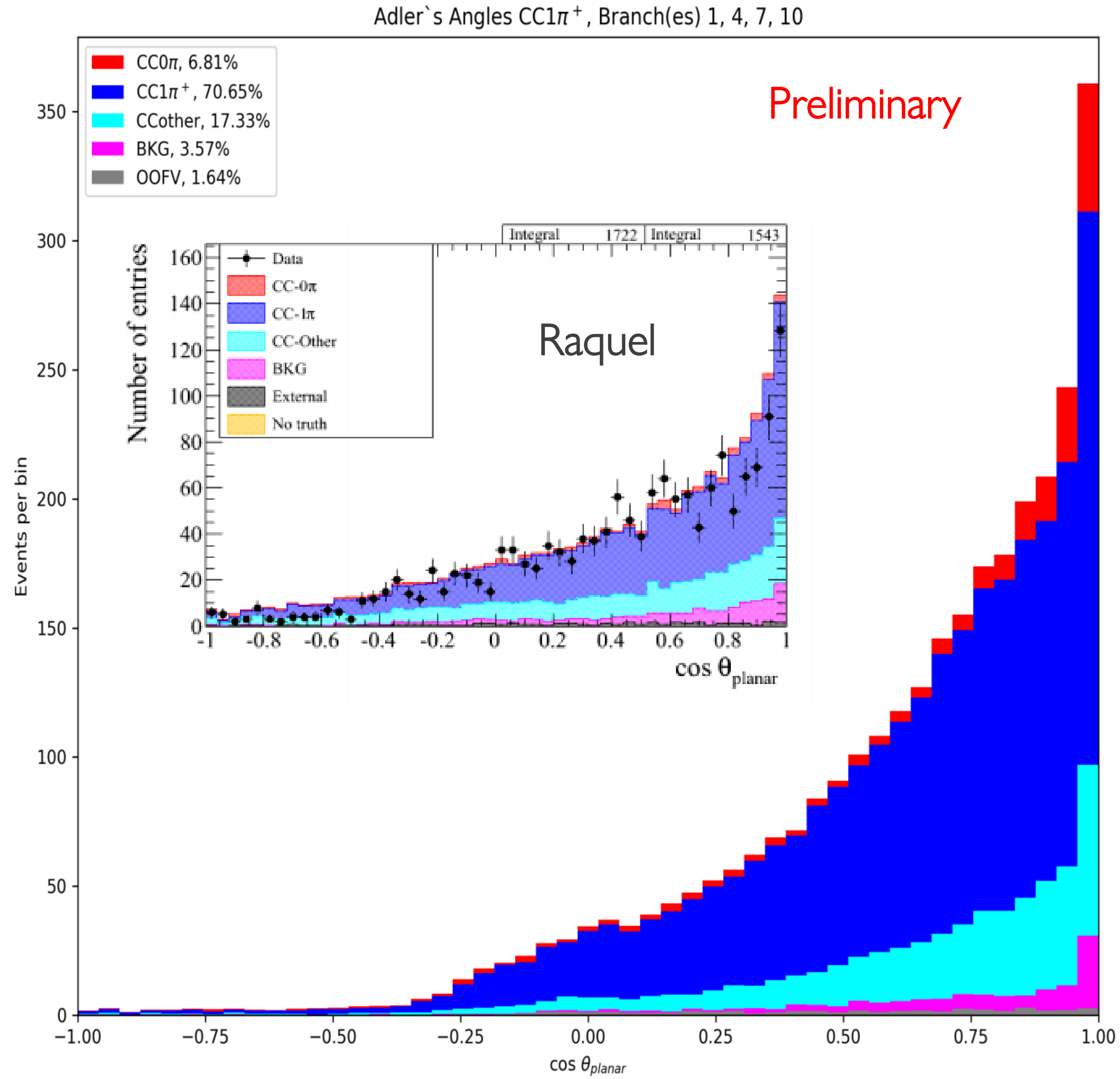


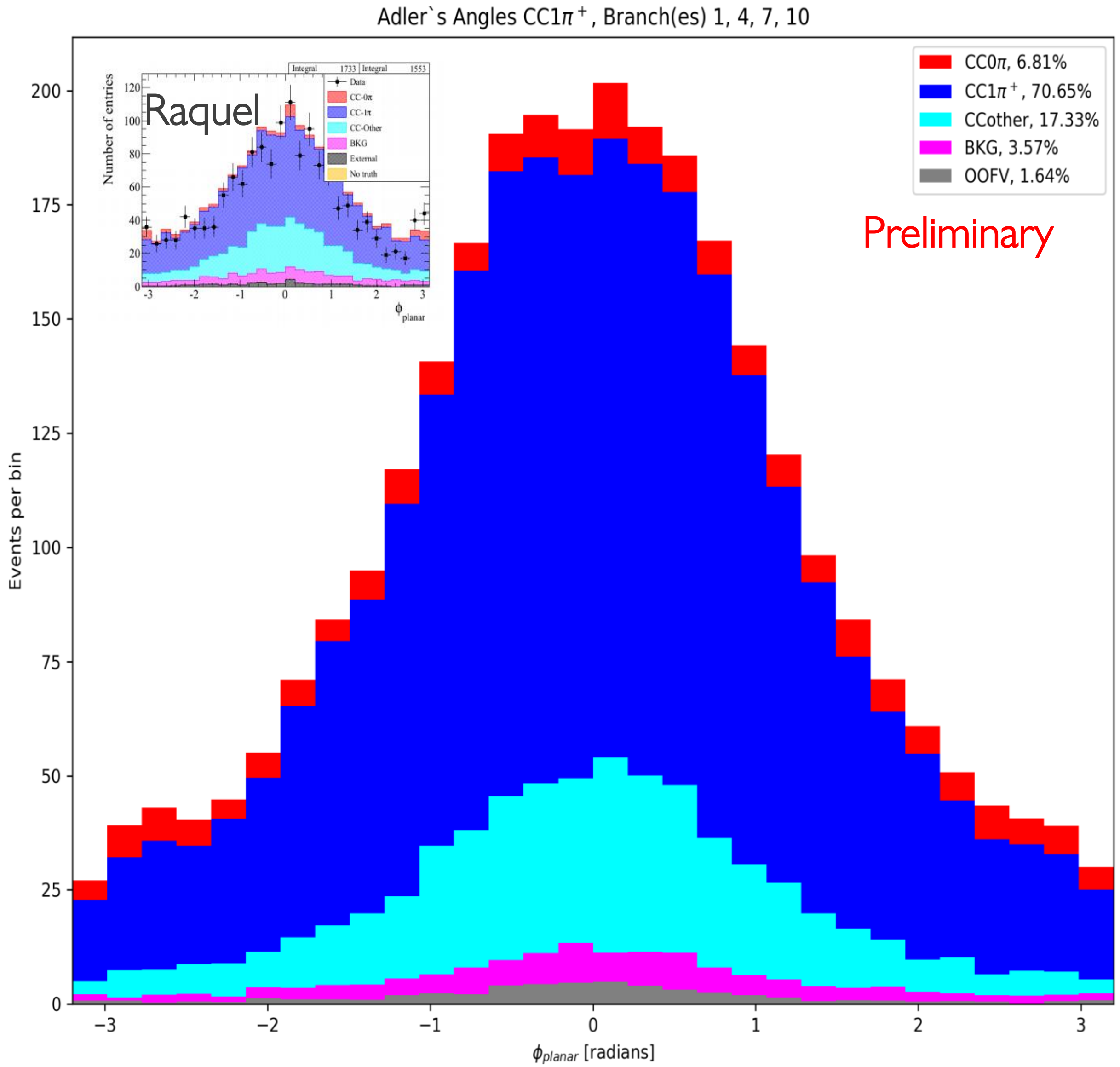


❖ Under the aforementioned assumptions this approximation a bias of about 0.2 rad was found before by Federico.

Adler's Angles

Physics





FWD-BWD Asymmetry

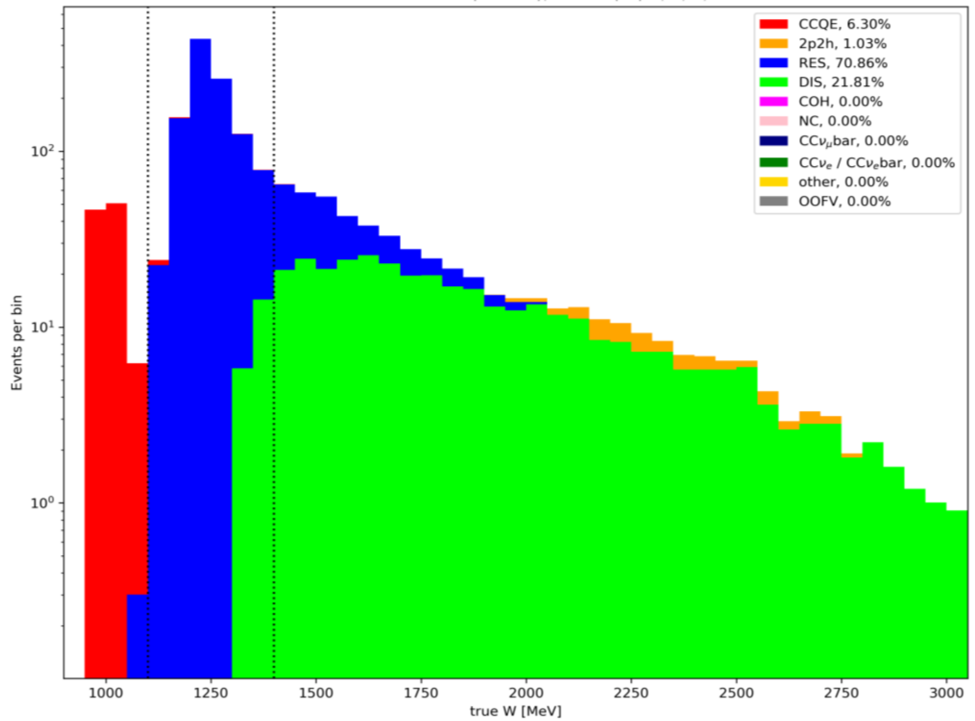
Introduction and Results

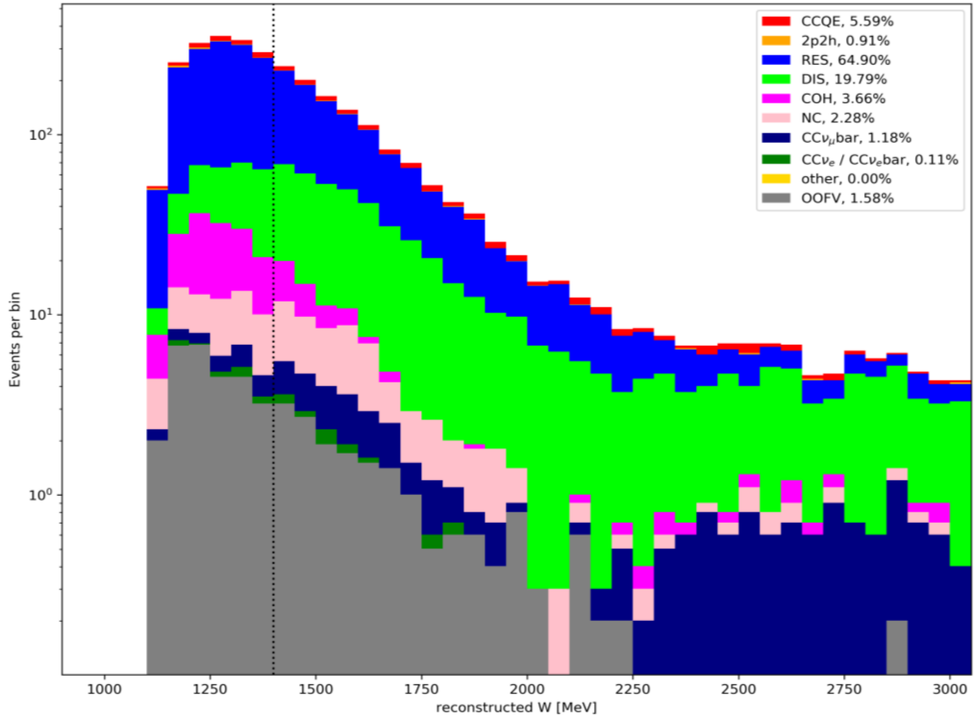
The FWD-BWD asymmetry of θ (Adler's angle) with respect to the direction of the plane $\vec{q} = \vec{p}_\nu - \vec{p}_\mu$:

$$A_{FB} = \frac{N_{\cos\theta>0} - N_{\cos\theta<0}}{N_{\cos\theta>0} + N_{\cos\theta<0}} = 0.164 \pm 0.002$$

with W below 1400 MeV in order to select events dominated by Δ^{++} and Δ^{+} resonant contributions. The A_{FB} value (as predicted by the NEUT MC) is -0.007 ± 0.003 and the one reporter by Federico's article is -0.179 ± 0.003 from the reconstructed observable.

- ❖ The observed bias is produced by the FSI and Fermi momentum within the nucleus because the Adler θ is modified.
- ❖ The dependence of the θ angle on the FSI and Fermi momentum makes it a very useful observable when investigating the nuclear effects on the results of the reaction.



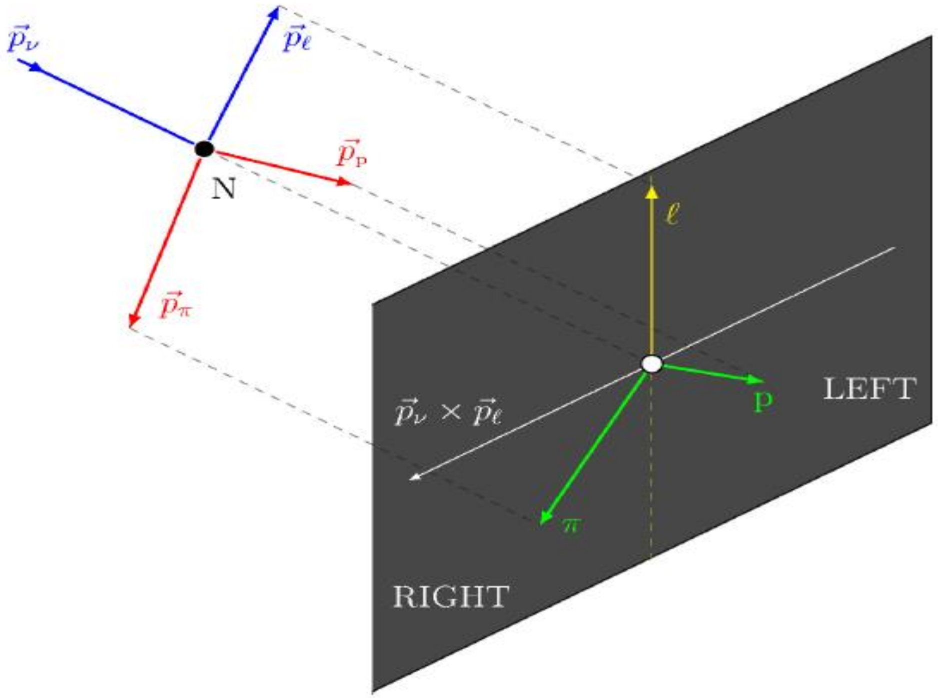


Left-Rigth Asymmetry

Introduction and Results

In neutrino-nucleus interactions, a proton produced with a correlated pion might exhibit a left-right asymmetry relative to the lepton scattering plane even when the pion is absorbed.

- ❖In $CC0\pi$ production could reveal the details of the absorbed-pion events that are otherwise inaccessible.
- ❖The idea was to use the final-state proton left-right asymmetries to quantify the absorbed-pion event fraction and underlying kinematics.
- ❖These asymmetries are ascribed to the interference between the resonant and non-resonant amplitudes and the correlation needs to survive nuclear effects, such as Fermi motion and nucleon FSIs.



Pion-Proton Correlation in Neutrino Interactions on Nuclei

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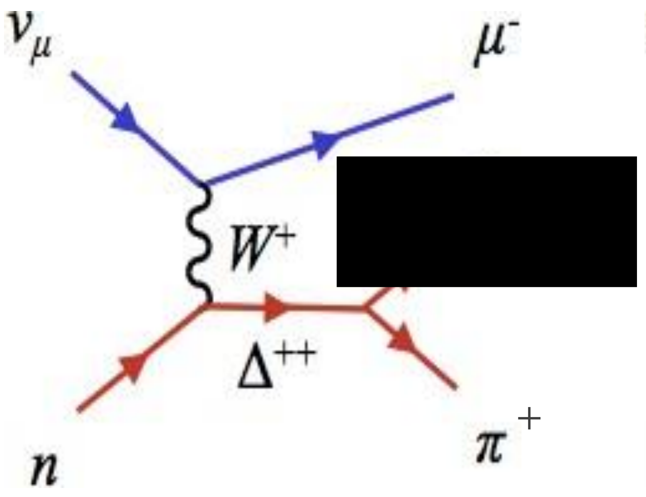
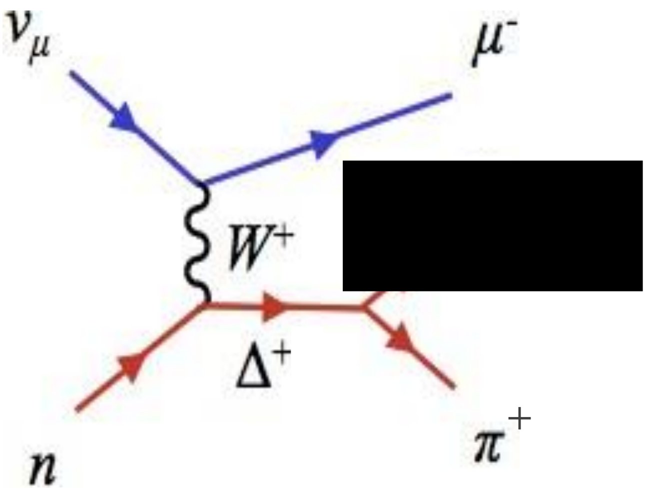
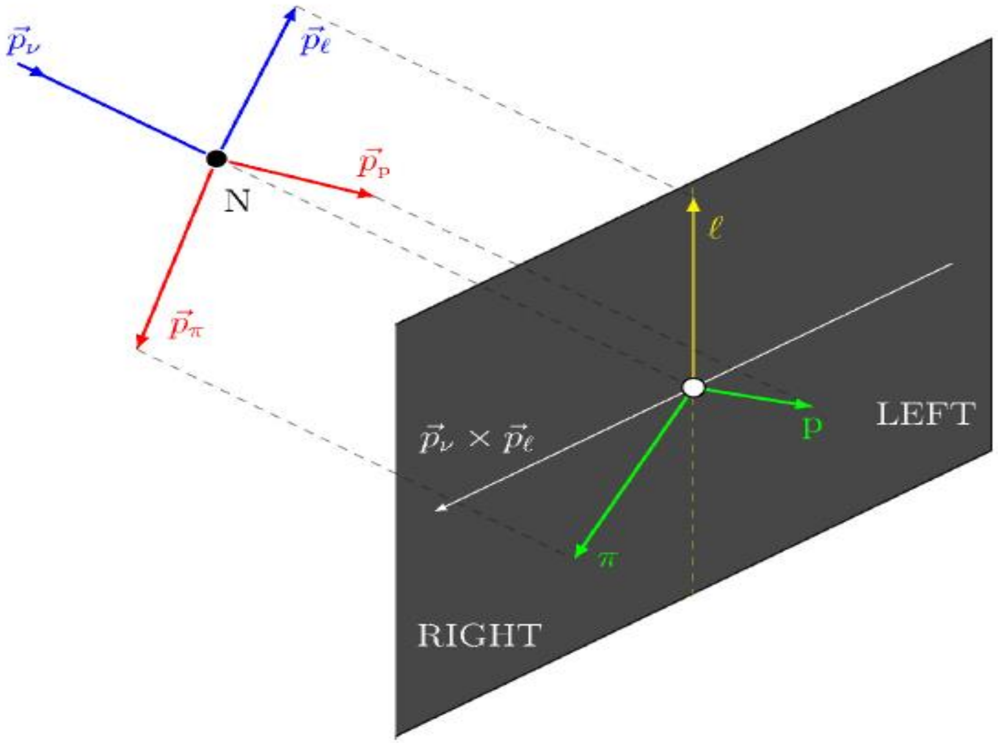
(Dated: July 26, 2019)

Left-Rigth Asymmetry

Introduction and Results







The left-right asymmetry of π^+ production with respect to the direction of the plane $\vec{p}_\nu \times \vec{p}_\mu$:

$$A_{LR} = \frac{N_L - N_R}{L + N_R} = 0.014 \pm 0.002$$

The A_{LR} value reporter for π^+ by ANL is 0.053 ± 0.035 (only for $\nu_\mu + p \rightarrow \mu^- + \pi^+ + p$).

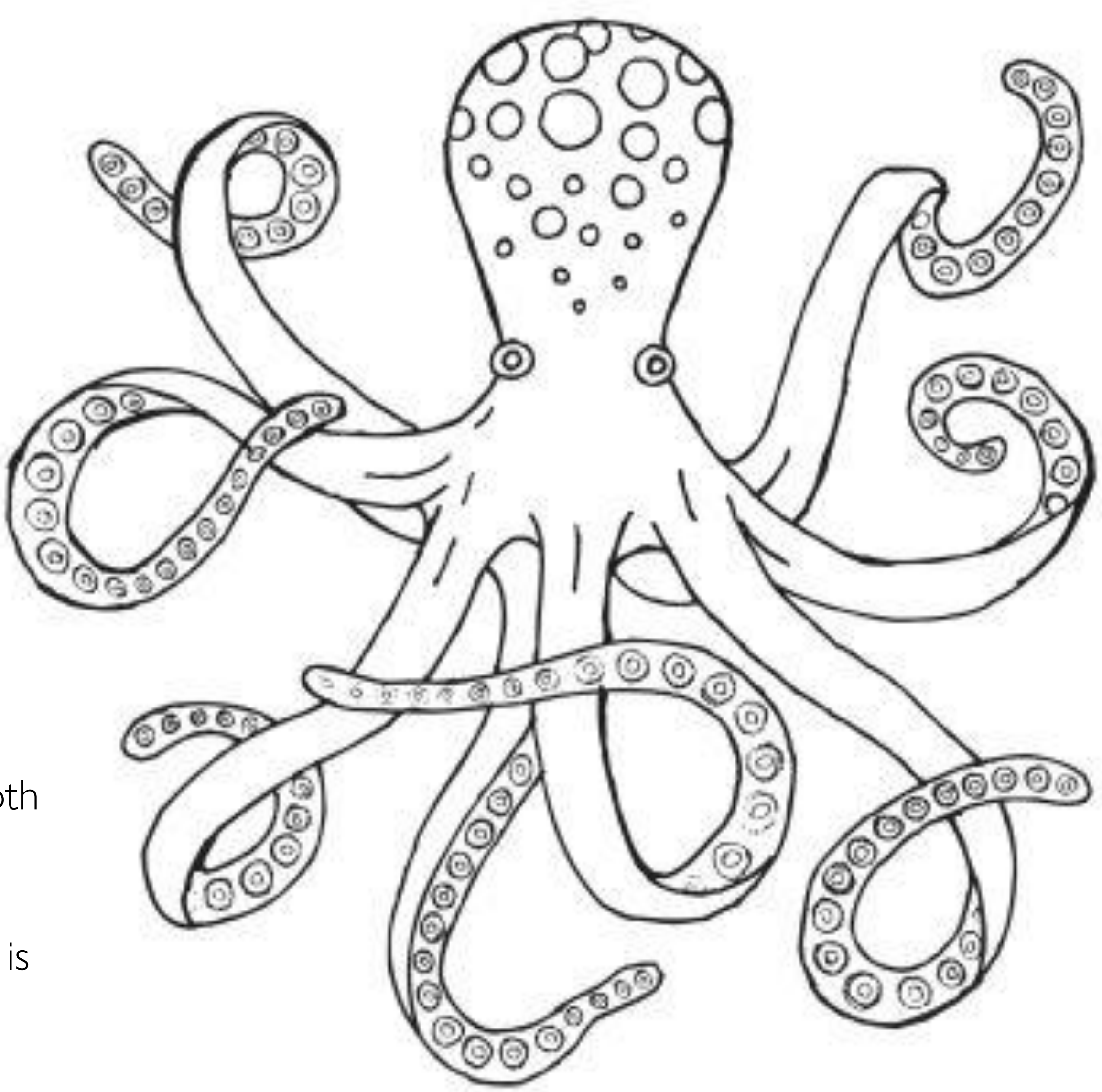
Summary

Adler's angles:

- ✓ Working on producing the different flies using the generators
- ✓ After that I will have to compute the Adler's angles for the different FSIs, and without FSI

Asymmetry:

- ✓ Reviewing the calculations of both asymmetries.
- ✓ Compared values when no FSI is used.



Selection systematics :

- ✓ Problem with the plotting have been solved!!! Running now the code.

4D binning:

- ✓ Still working in including the 4D binning on the detector covariance and correlation matrix code.

Thank you!!!