Probing the Nuclear Effect with a CC0π+Np Differential Cross Section Measurement

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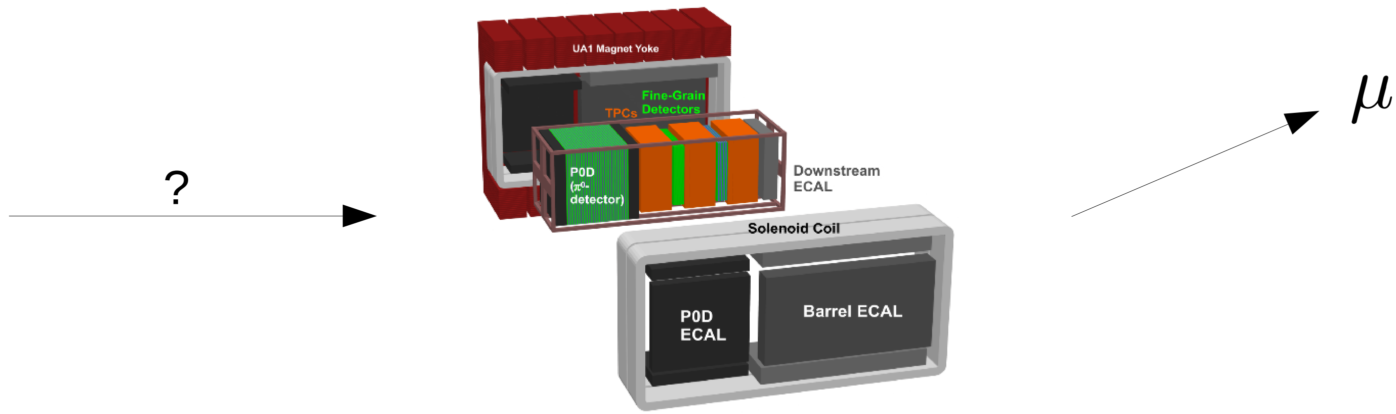
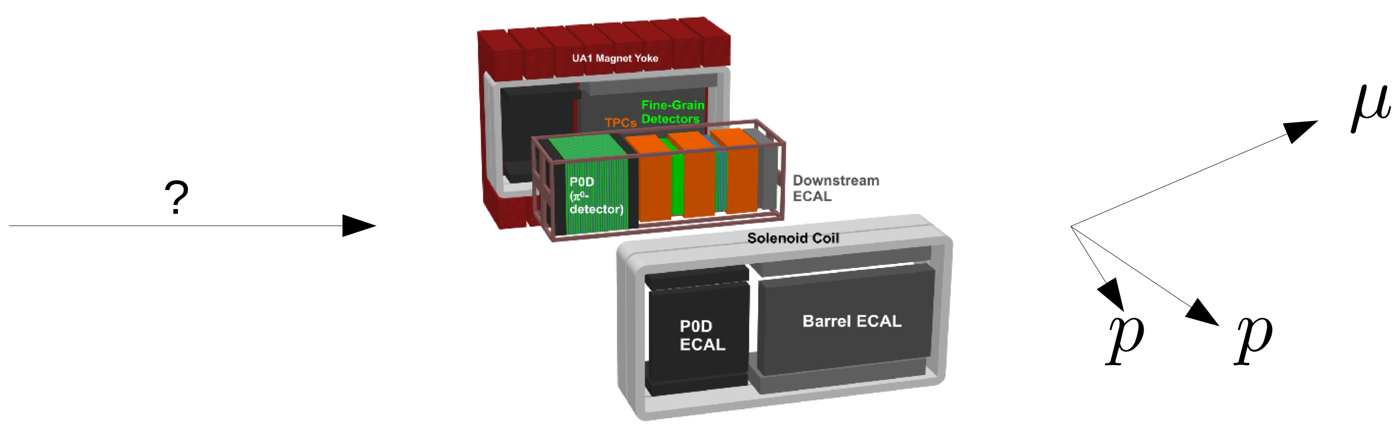
Overview



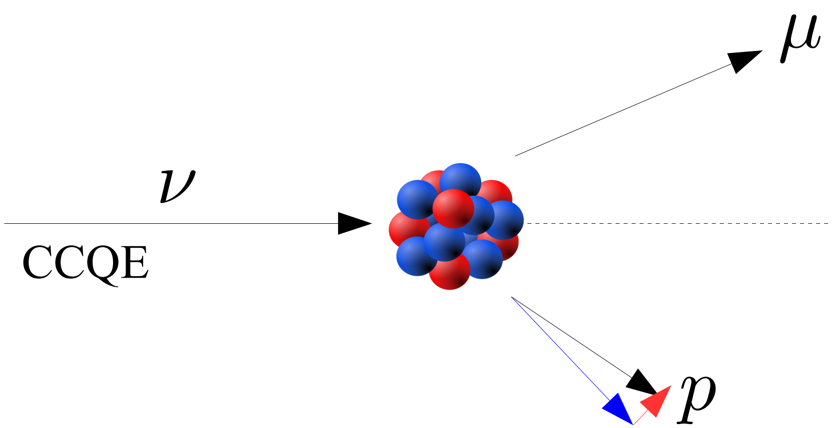
- We do not know the incoming neutrino energy. Instead we do only see the final topology to reconstruct it. We have claimed the topology of CC0π as :
  - One muon and no pion in the final state
  - The rest, we don't know.
- This topology was considered reasonable equivalence to CCQE interaction. But actually all the following would fall into the selection :
  1. CCQE
  2. CCRES followed by a pion absorption
  3. CC2p2h where a neutrino is scattered off more than one nucleon rather than a single nucleon.

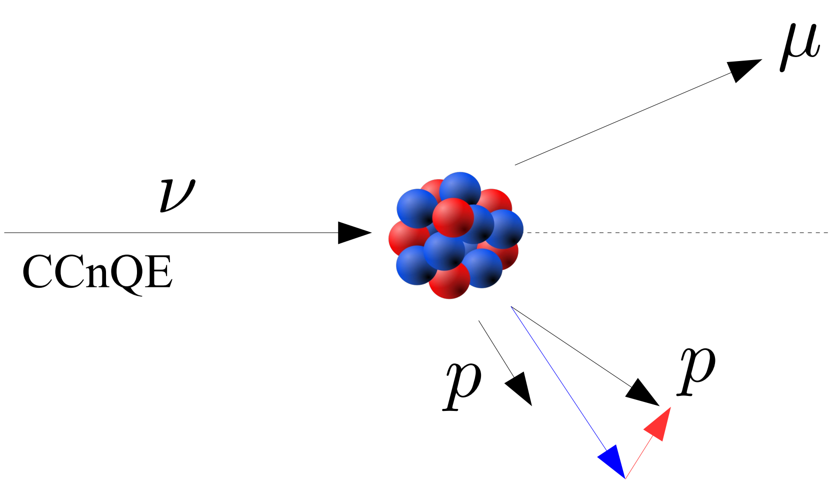
Overview



- Instead of CC0π, we narrow down the selection to CC0πNp requiring reconstructed proton tracks.
- Not only the muon kinematics, but also the proton kinematics now play a role in an analysis.
- How should we play with this additional information?

Observables





1. Inferred proton kinematics from the muon

$$E_\nu^{rec} \approx \frac{m_p^2 - m_\mu^2 + 2E_\mu(m_n - V) - (m_n - V)^2}{2[(m_n - V) - E_\mu + p_\mu \cos\theta_\mu]}$$

$$E_\mu = \sqrt{(p_\mu^2 + m_\mu^2)}$$

$$E_p = E_\nu - E_\mu + m_p$$

2. Reconstructed proton kinematics
3. Differences

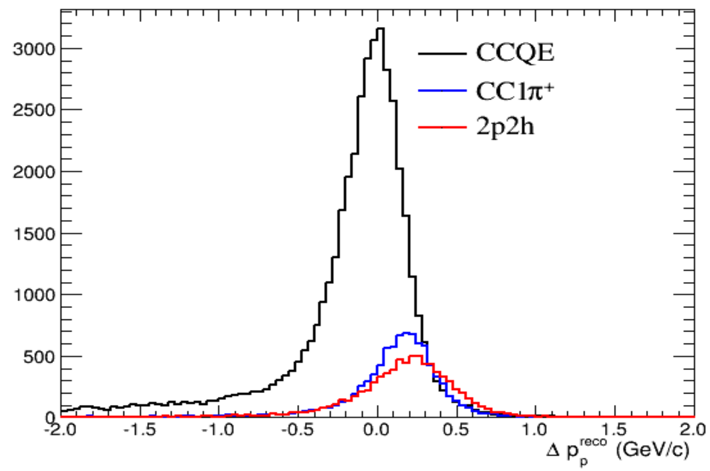
$$\Delta p_p = p_p^{measured} - p_p^{inferred}$$

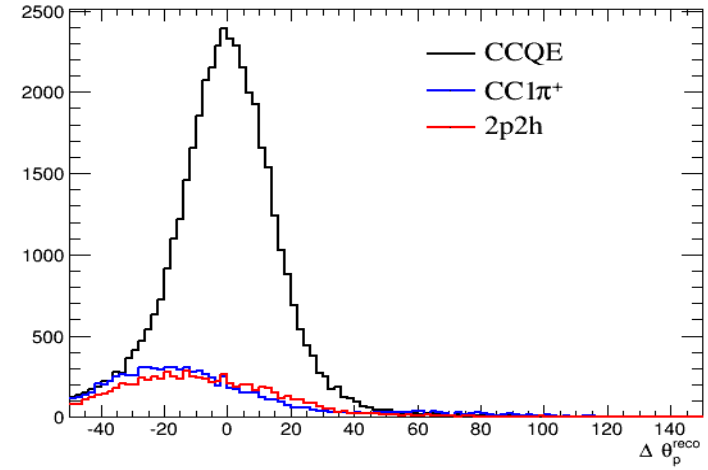
$$\Delta\theta_p = \theta_p^{measured} - \theta_p^{inferred}$$

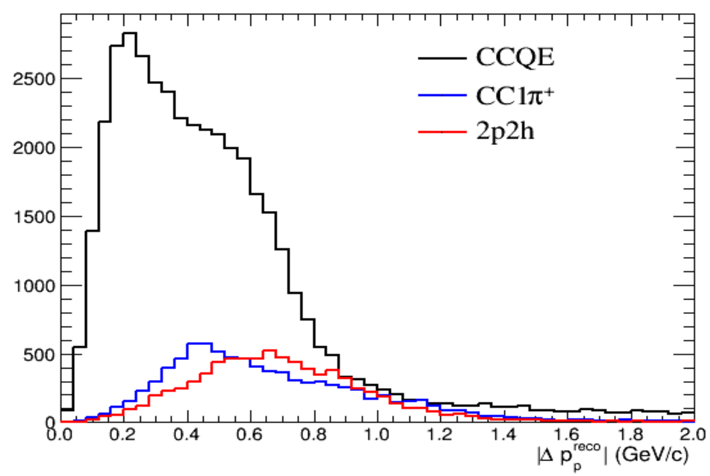
$$|\Delta p_p| = |\vec{p}_p^{measured} - \vec{p}_p^{inferred}|$$

= Analysis Variables

Observables



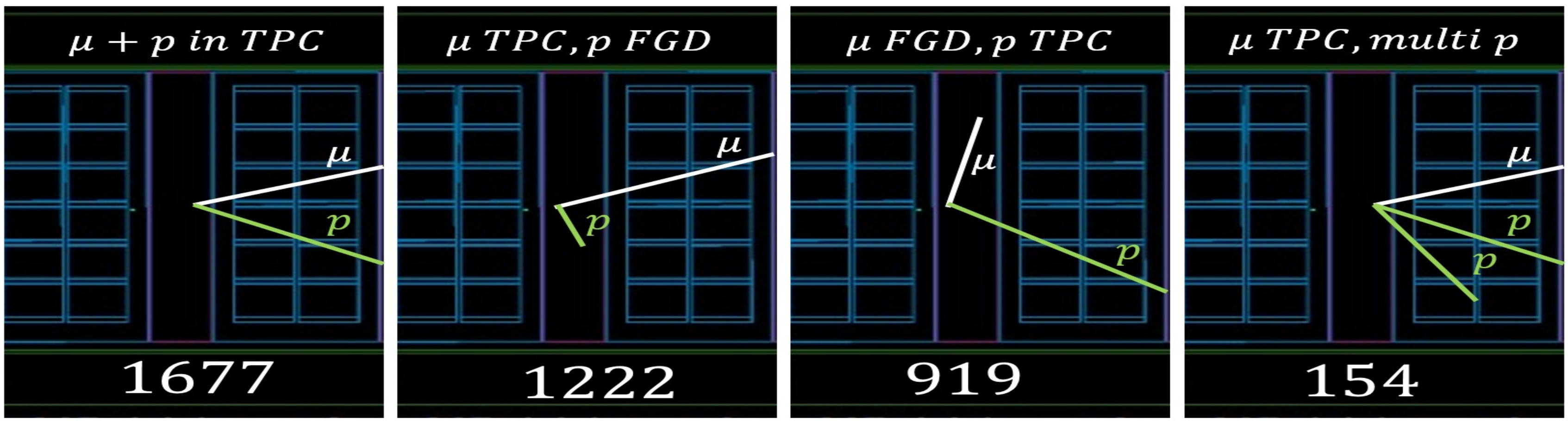




- Reconstructed distributions of three analysis variables for selected events breaking down into different neutrino interaction modes.
- There is nice separation between CCQE (black) and CCnQE (CCRES (blue) and 2p2h (red)).
- It is a bit harder to separate 2p2h from CCRES.
- Plot was produced with NEUT 6B.

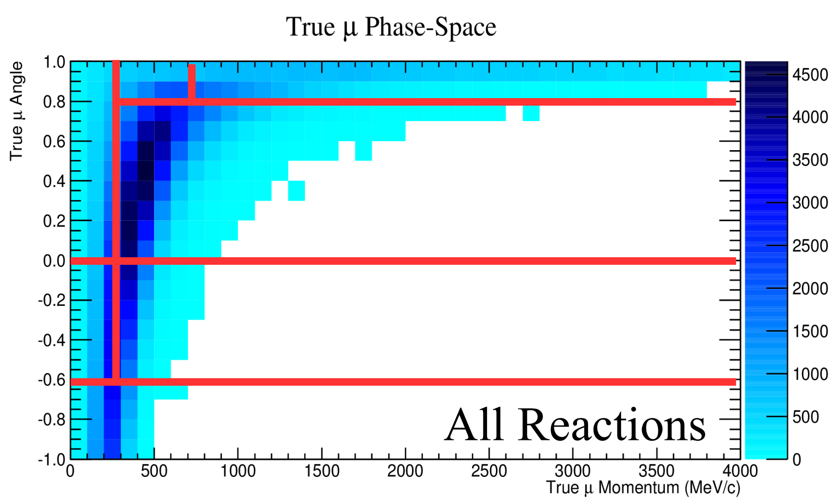
Strategy : Selection

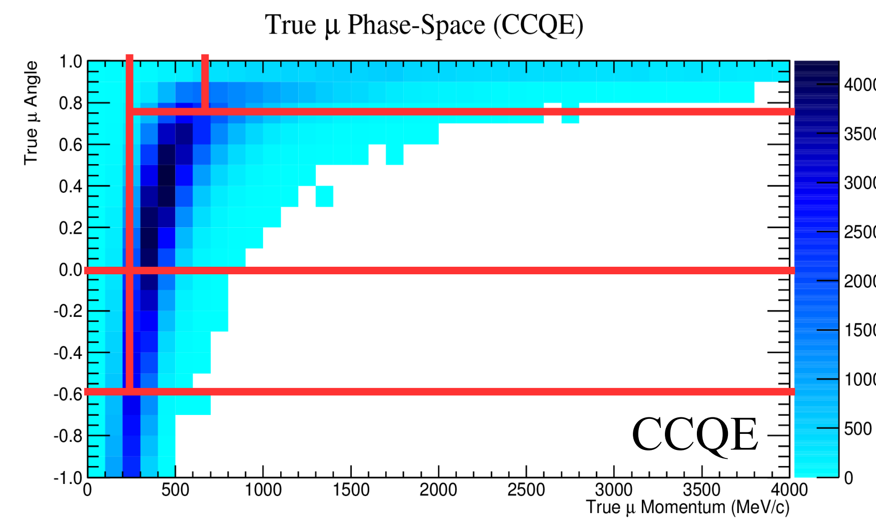
- **Selection**
  - CC0πNp with 4 reconstructed topologies :

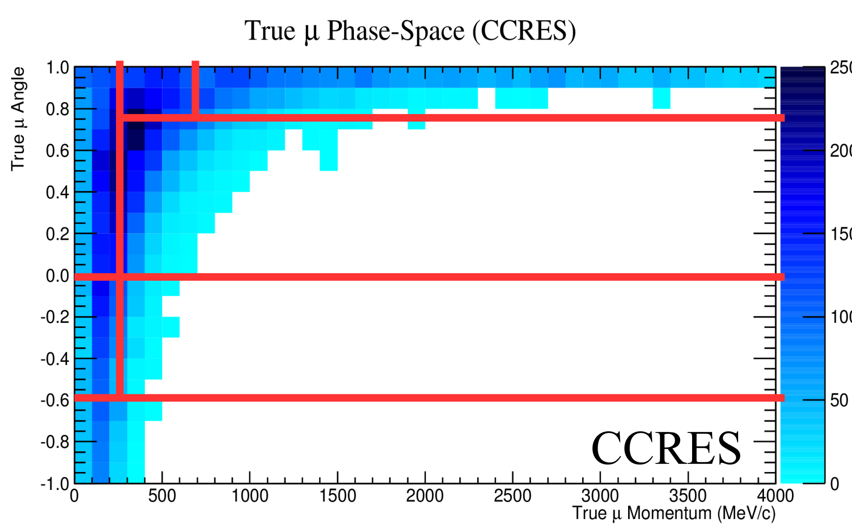


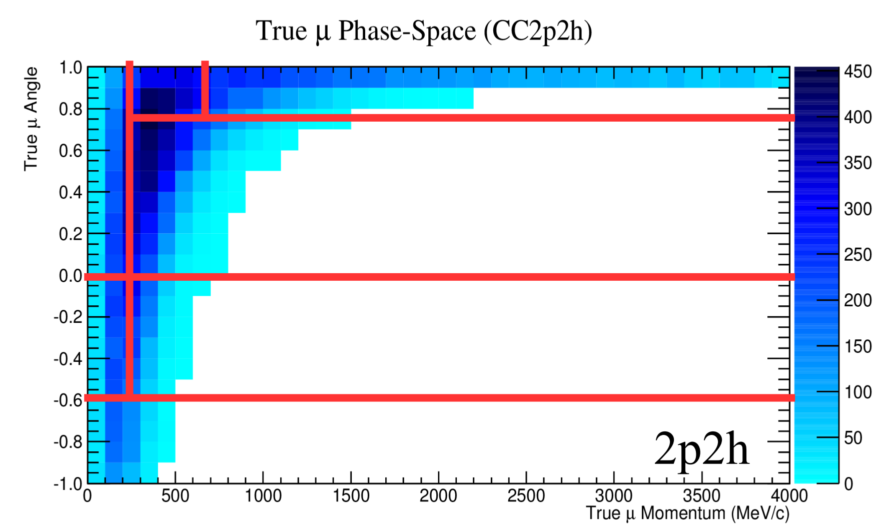
- **Signal Definition with Phase-space Constraints**
  - $1\ \mu + \ 0\ \pi + \ \mathrm{Np}$
  - Cuts on true proton phase-space (based on the detector acceptance)
    - $p_p > 450$ MeV/c
    - $cos\theta_p > 0.4$
  - Binned true muon phase-space

Strategy : Muon PS Binning









NEUT Prod6B

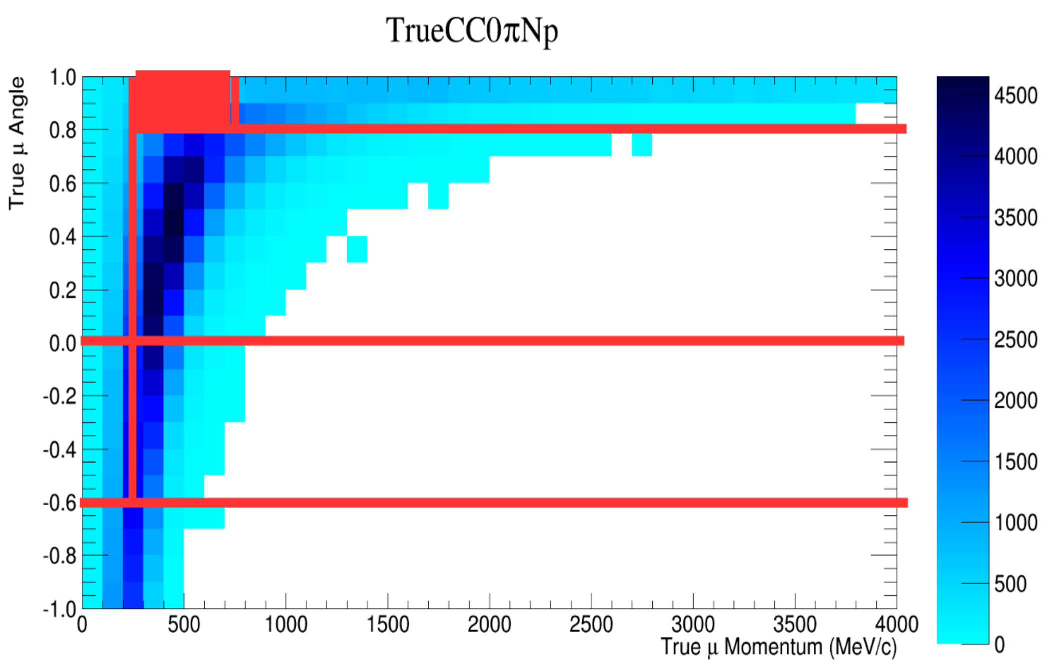
Strategy : Machinery

- **This analysis aims to unfold the observables of the selection.**
  - Main motivation of unfolding is to provide the true level information getting rid of detector effects, so that it can be compared to other experiments or theoretical calculations.
  - Method : Iterative Bayesian Unfolding
  - Data sets : nominal NEUT 6B (training MC) and nominal GENIE 6B (alternate model to validate the machinery).

Validation

- **What to answer**
  - how robust the machinery is : no matter what the MC prior is, the machinery should be able to recover the fakedata truth.
- **How to answer**
  - unfold GENIE fakedata to NEUT prior to see if the unfolding recovers the fakedata truth.
  - unfolded GENIE fake data to alternate prior to see if the unfolding gives the consistent results.

Validation

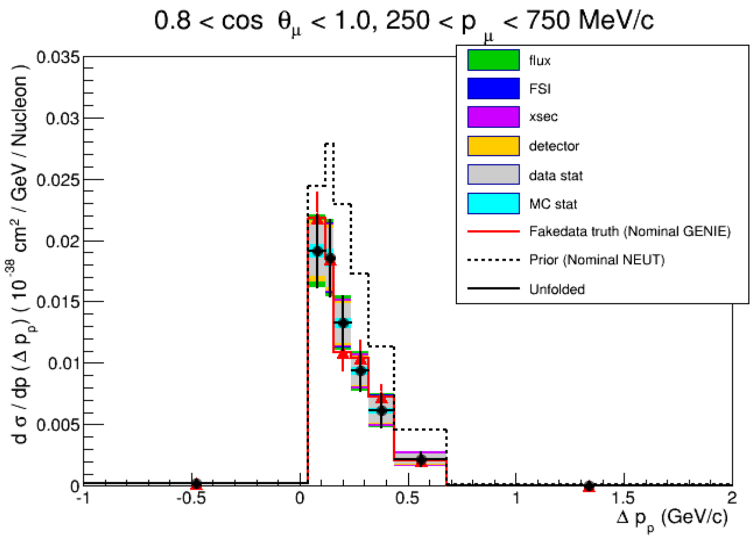


- **Sample bin**

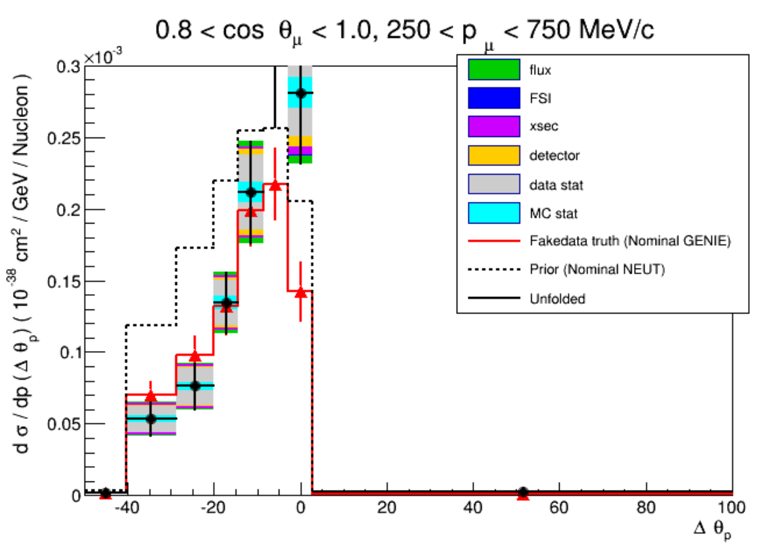
  $0.8 < cos\theta_{\mu} < 1.0$, $250 < p_{\mu} < 750$

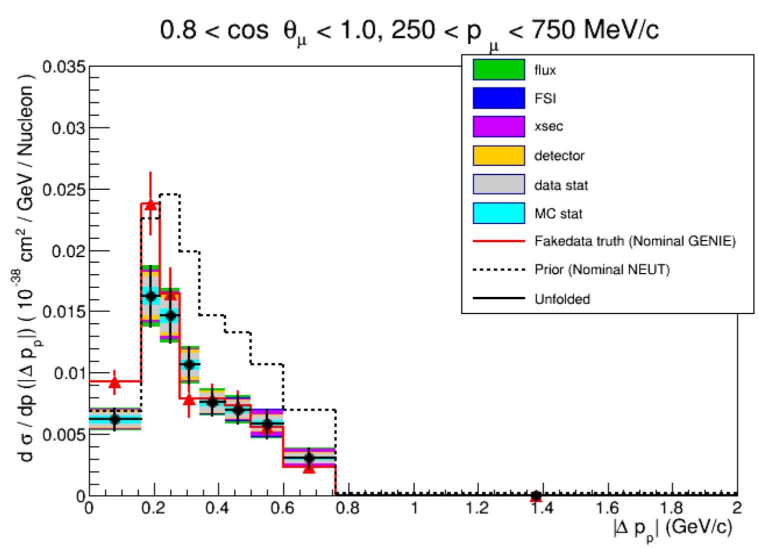
- Forward-going muons with medium momenta. This bin is where CCnQE contribution is enhanced.

Validation



- Unfolded results (black points) of GENIE (red solid) to NEUT (black dashed).





Decision Making

- How should we decide to reject or accept a given unfolded result? χ^2 is often used to qualify a fit, which is defined as :

$$\chi^2 = \Sigma(\text{unfolded}_i - \text{true}_i) cov_{ij}^{-1} (\text{unfolded}_j - \text{true}_j)$$

- The χ^2 values of all the results are shown in the Table on the right.

χ^2	Δp_p	$\Delta \theta_p$	$\|\Delta p_p\|$
bin0	19.07	44.30	5.04
bin1	38.39	22.33	47.37
bin2	40.07	53.23	93.48
bin3	14.61	42.51	15.77
bin4	27.19	11.70	24.42
bin5	12.77	29.58	37.83
bin6	3.47	27.33	44.42

Decision Making

- See the χ^2 values of nominal results along with Toy-MC driven χ^2 distributions. The idea is :

    1. We weight nominal NEUT according to statistical, model, and detector uncertainties to get a toy-MC.

    2. We unfold the GENIE fakedata with a generated toy and compute the .

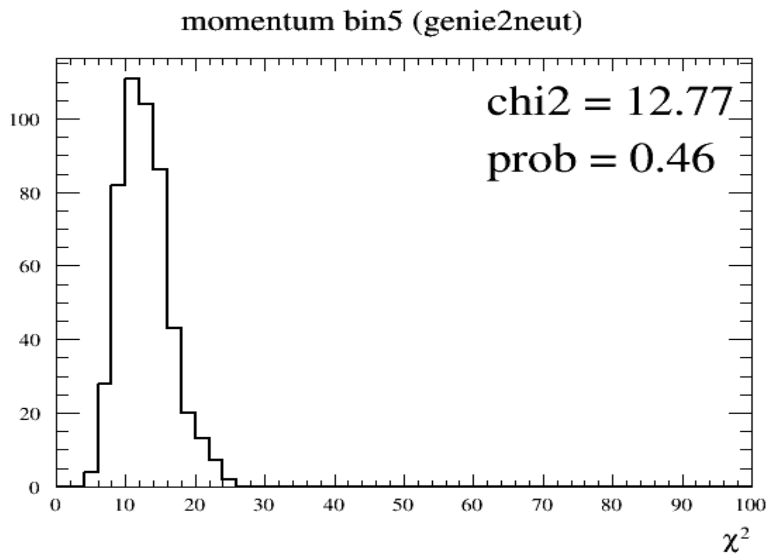
    3. Repeat steps 1 and 2 over 500 toys.

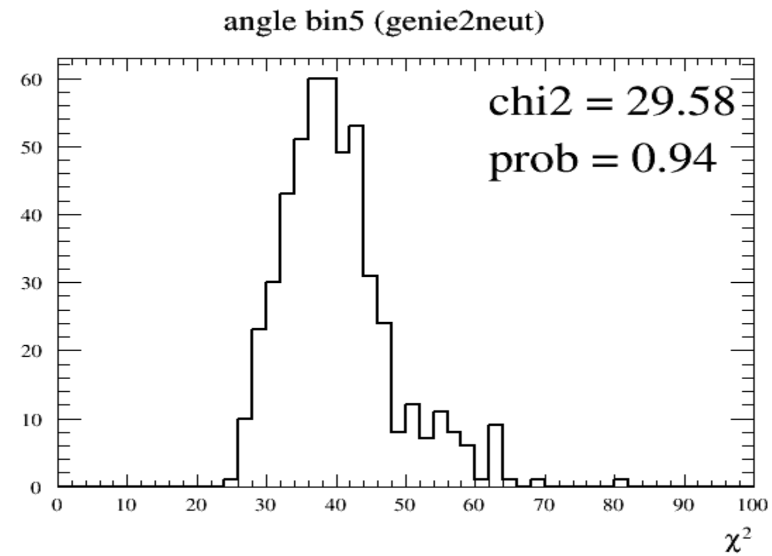
    4. Plot the values over the toys.

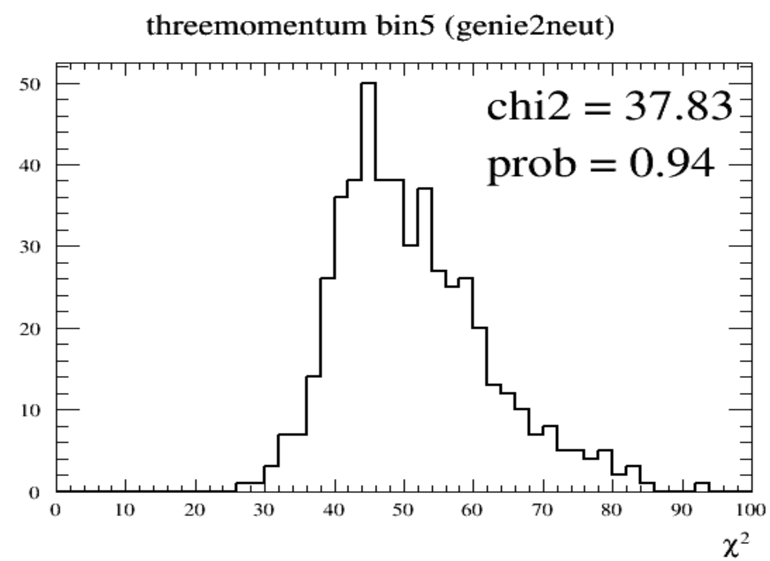
- χ^2 for each toy is defined as :

$$\chi^2 = \Sigma(\text{unfolded}_{toy,i} - \text{true}_i) cov_{ij}^{-1} (\text{unfolded}_{toy,j} - \text{true}_j)$$

Decision Making







- Here we can see where the nominal χ^2 sits on the χ^2 distribution. There is still some discussion going on how to interpret this. It can be seen in a way that : varying the model assumption within certain uncertainties, the can be varied as much as shown in the χ^2 distributions. If the nominal χ^2 is within the distribution, the given result can be accepted.
  - However, this does not tell you how much GENIE/NEUT model discrepancy (model dependency) gets into the unfolding.

Conclusions

- Unfold imbalance in proton kinematics to explore nuclear effects.
  - Analysis variables : Δp_p , $\Delta\theta_p$, $|p_p|$
  - Selection : $\mathrm{CC0}\pi\mathrm{N}p$
  - Machinery : iterative Bayesian unfolding
- The machinery looks in general working fine. However, we need more systematic way to make the final decision.
  - χ^2 studies using 500 toy-MC. It is still under discussion how to interpret the results.

Back Up

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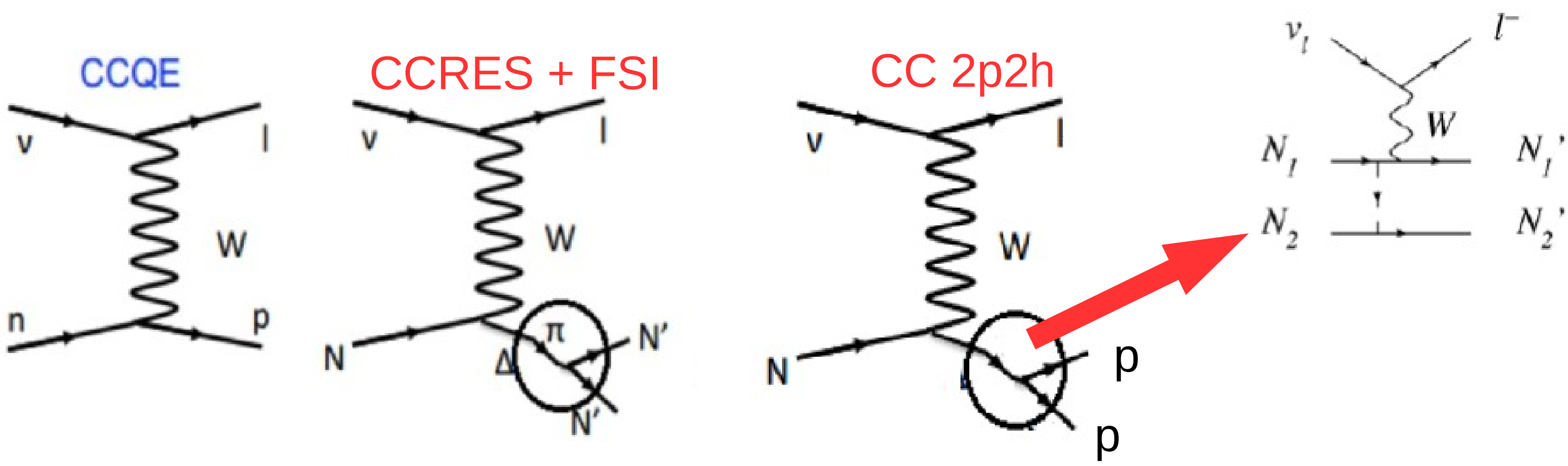
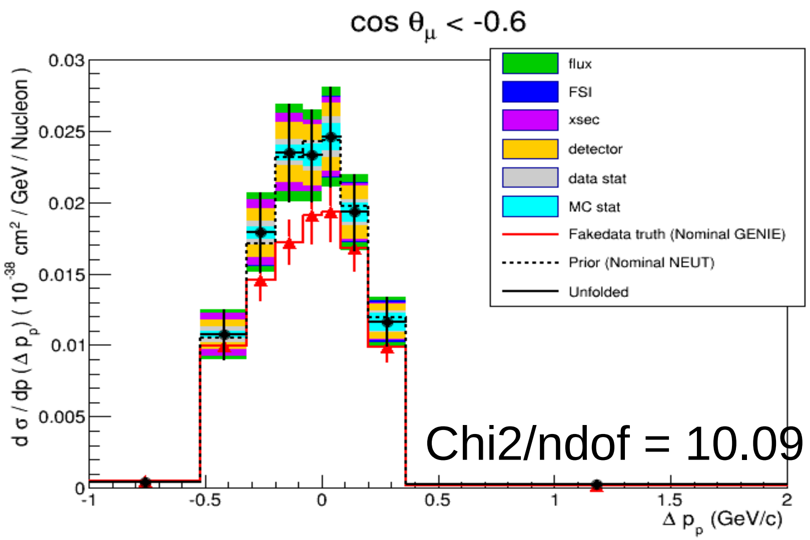
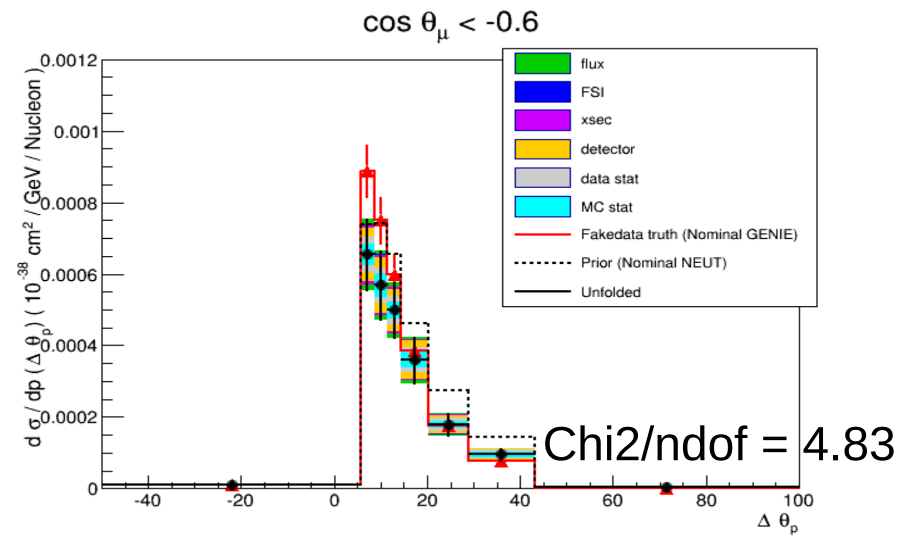
Observables

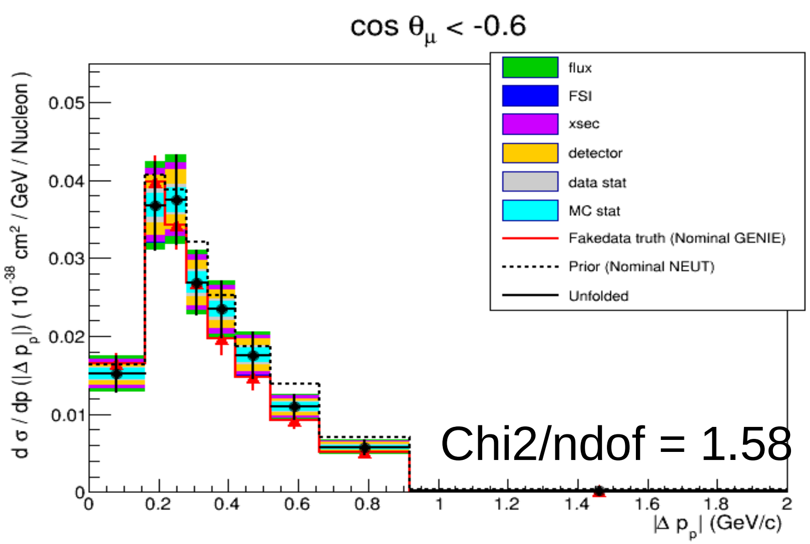


- If CCQE is identified as the topology of one lepton, no pion, without requiring any dedicated proton tracks, all the three above would appear as the same events.
  1. CCQE
  2. CCRES followed by the pion absoprtion.
  3. CC 2p2h where a neutrino is scattered off more than one nucleon rather than a single nucleon.

Backward-going Bin

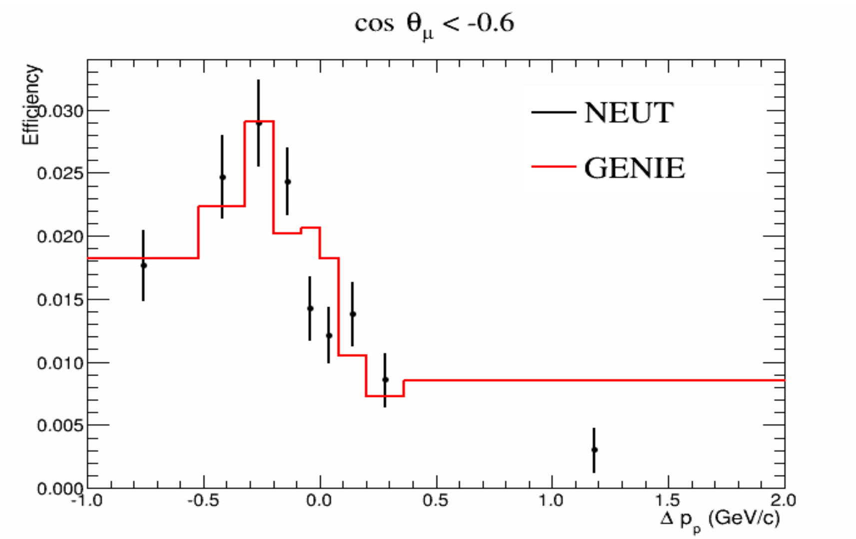


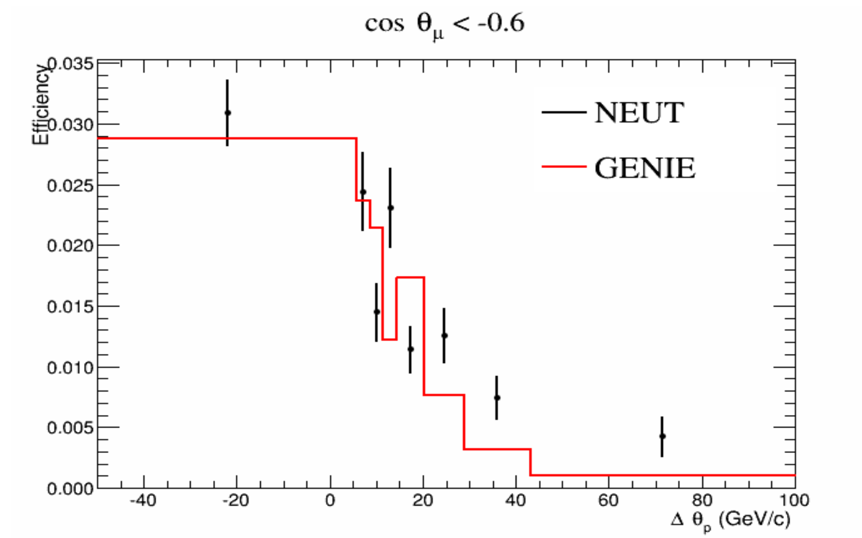


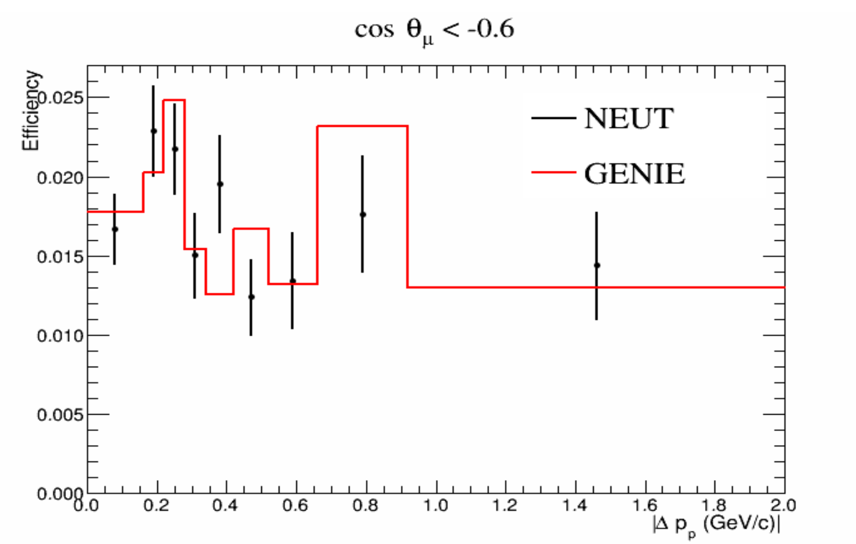


- Momentum difference (top left) : the unfolding does not recover the truth (red solid) at all. Instead it stays at the initial prior (black dashed).
- Angle difference (top right) : it seems that the unfolded result is well converged at the tail, but still there is big bias at the peak.
- Three-momentum difference (bottm left) : Even though there is some bias, it is well covered by the uncertainties.

Backward-going Bin







- The bins where the efficienci is low or the discrepancy is high are not always consistent with the unconverged bins on the previous slides.