# Playing with T2K ND280 selections

Towards a better separation of resonant/multi-pi/DIS?


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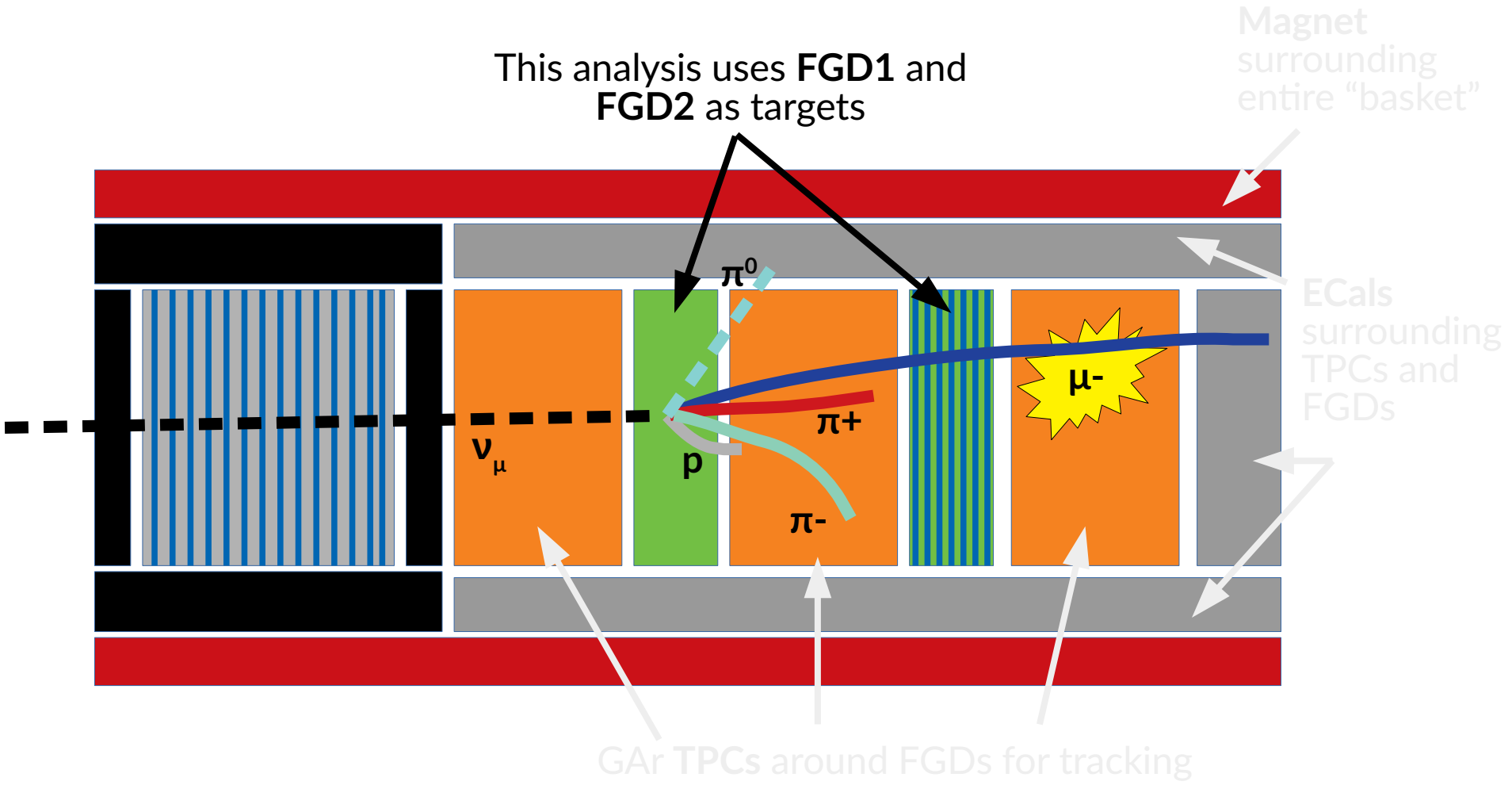
Rochester meeting
13 July 2020

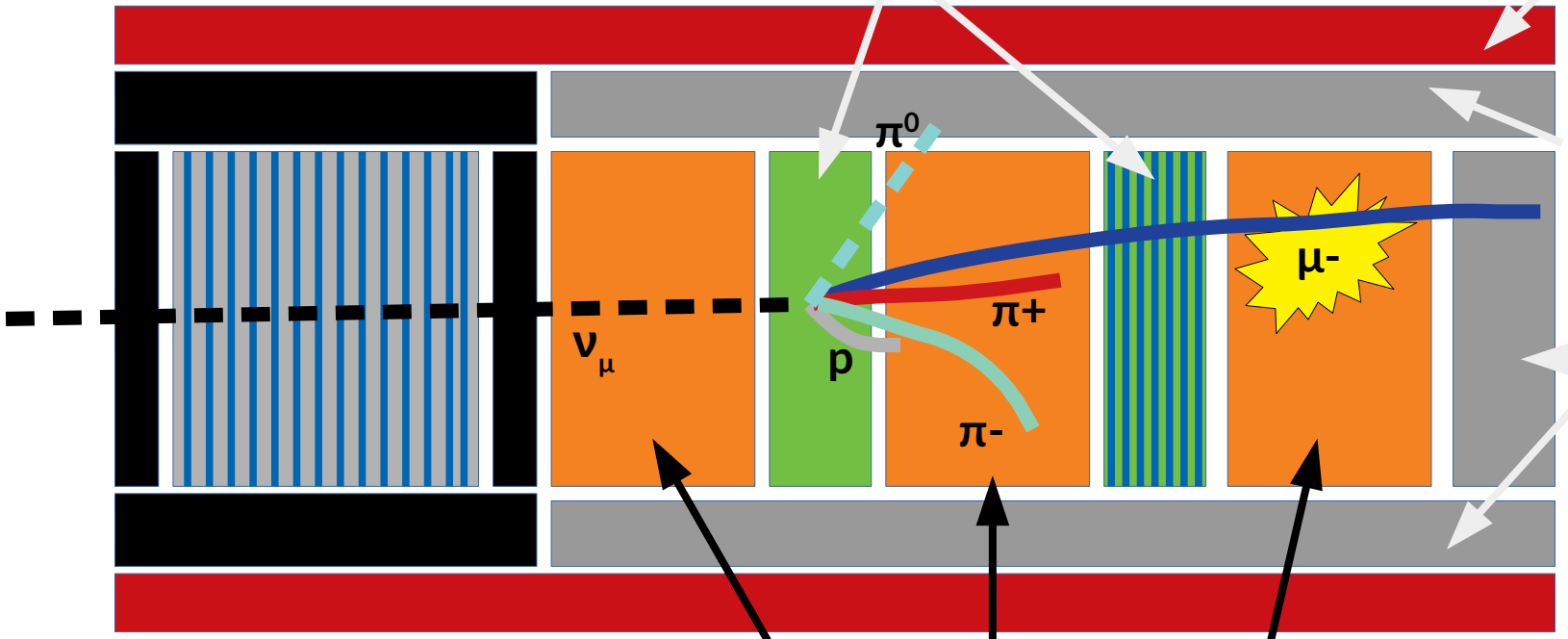
# Introduction

- Exciting path ahead for T2K; starting to focus on π model
  - Multi-ring samples incoming in T2K oscillation analysis (1 ring from lepton, 1 ring from pion)
  - Multi-GeV, multi-ring samples in the joint T2K+SK atmospheric oscillation analysis
  - T2K-NOvA joint fit may require better understanding of QE/2p2h/RES fractions, energy scaling, nuclear target differences…
- We know our 1π, multi-π and DIS models need love
  - From external data (e.g. MINERvA) and ND280 selections
- Working towards the future ND280 fit, we will likely have to provide justifiable constraints using
  - Pion production selections
  - Pion kinematics
  - Proton kinematics

# ND280 reminder



# ND280 reminder



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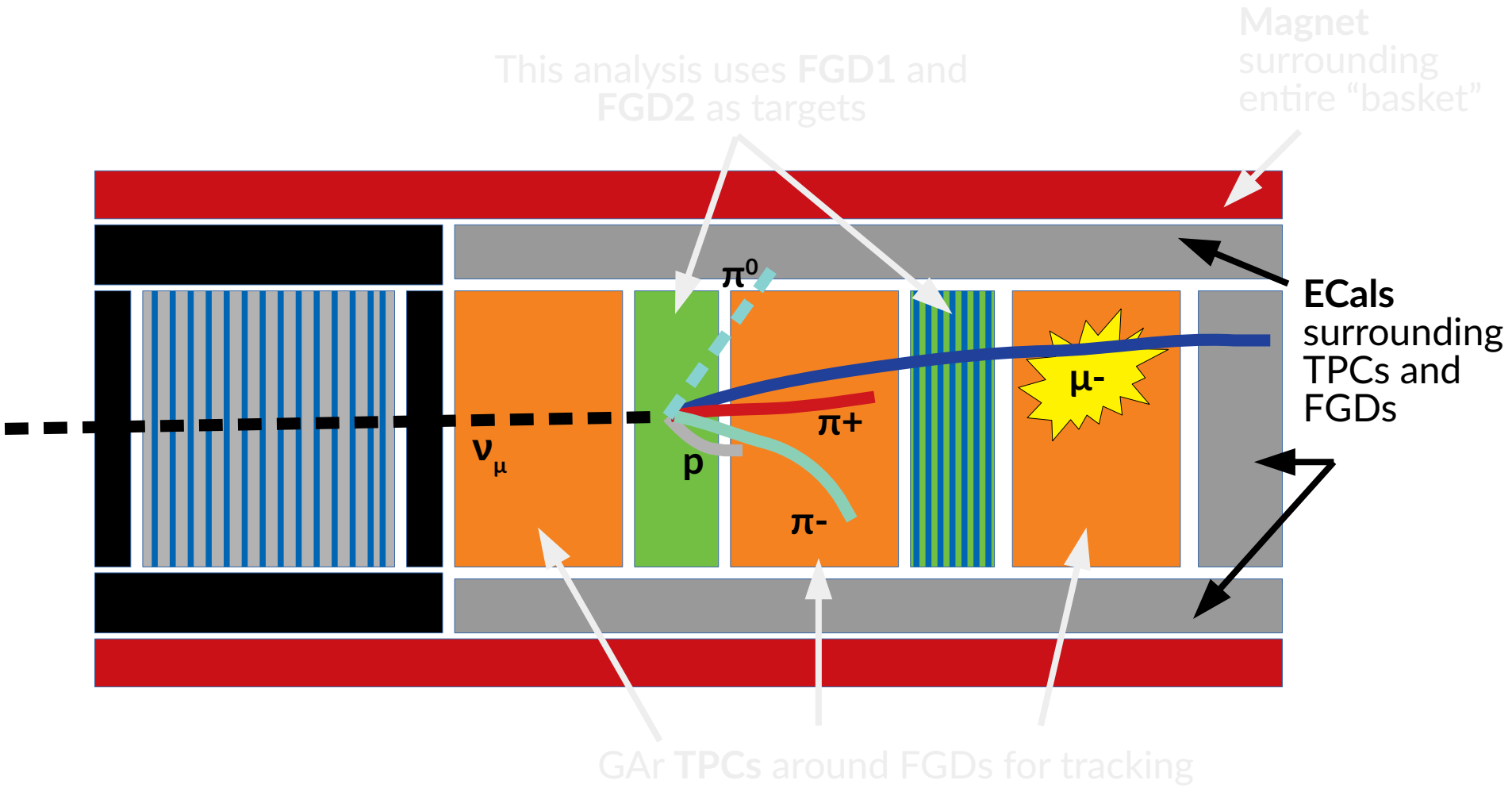

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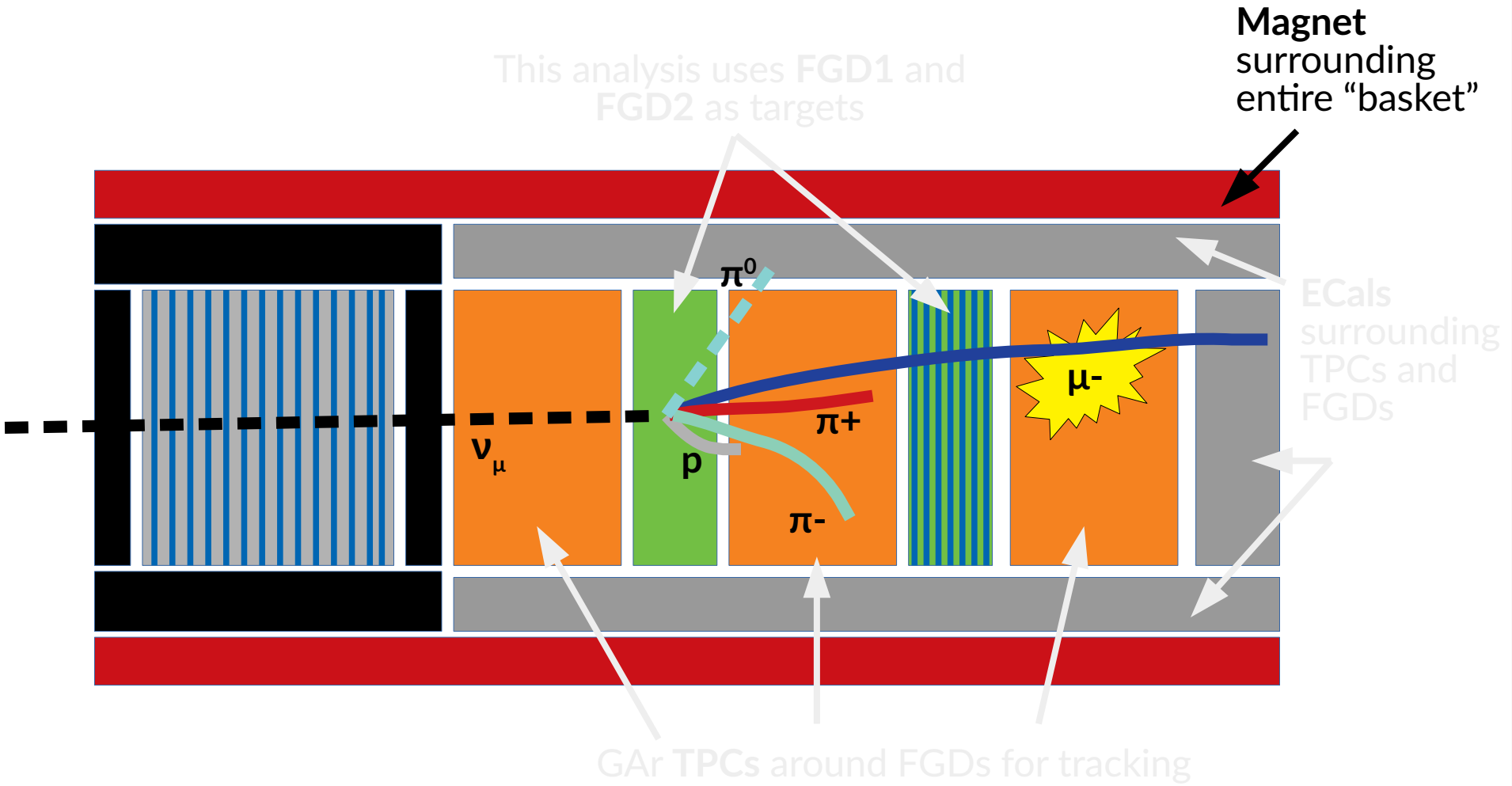
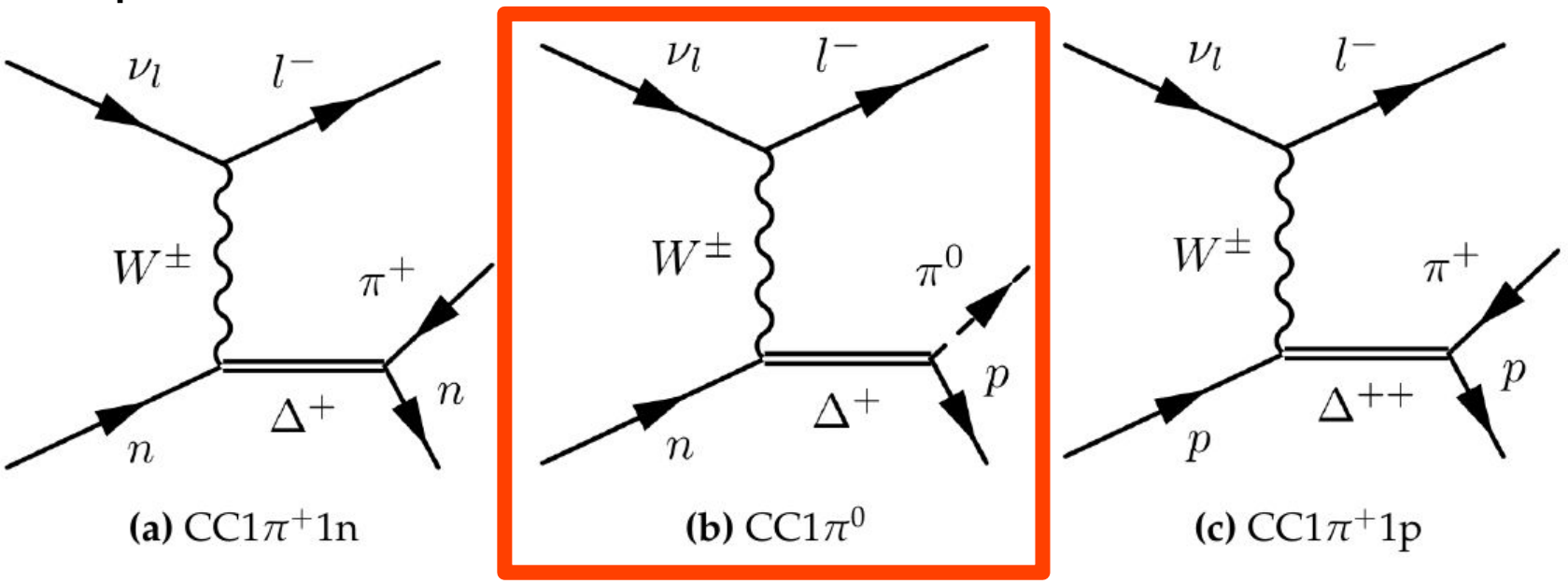


# Overview

- Analysis bins in $p_\mu$, $\cos\theta_\mu$ splits into pion multiplicity
  - Only CC selections: looks for correctly bent highest momentum track, required to have a muon PID in TPC
  - CC0π: there are no pions, any nucleons
  - CC1π: 1π with opposite charge to muon (e.g $1\pi^+$ in $\nu_\mu$ mode)
  - CCOther: >1 right-signed π, >0 $\pi^0$, >0 wrong-sign π
- The fit decreases uncertainty on events at SK from ~14% to ~3%
- Wanted to refine these further to get better model constraints
  - e.g. CCOther contains single pion via resonance, multi-pi, DIS: not great for constraining individual systematics
- Played around with these, see if we can build a different ND selection
  - Chopping up CCOther; CC1π with at least one proton; CCQE with at least one proton

# First, CCOther

- Wanted to see what TPC $\pi^0$ separation could do in CCOther
- Plotted in true hadronic mass (*W*)
  - Allows for by-eye separation of CCQE, Delta-dominated resonance contributions, multi-pi and DIS
- Wanted to try to "isolate" two processes from the current CCOther selection
  - $\pi^0$ production via resonance
  - multi-pi/DIS "enhanced" selections



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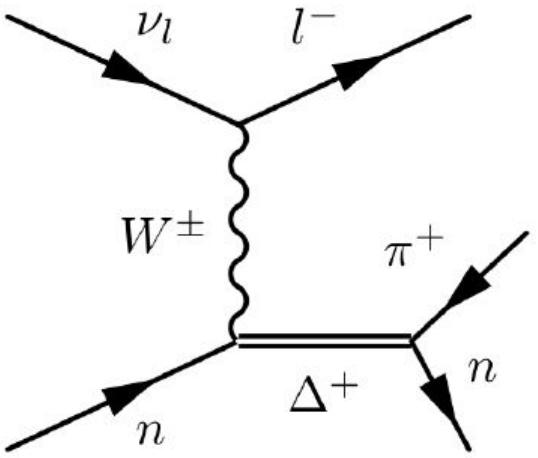
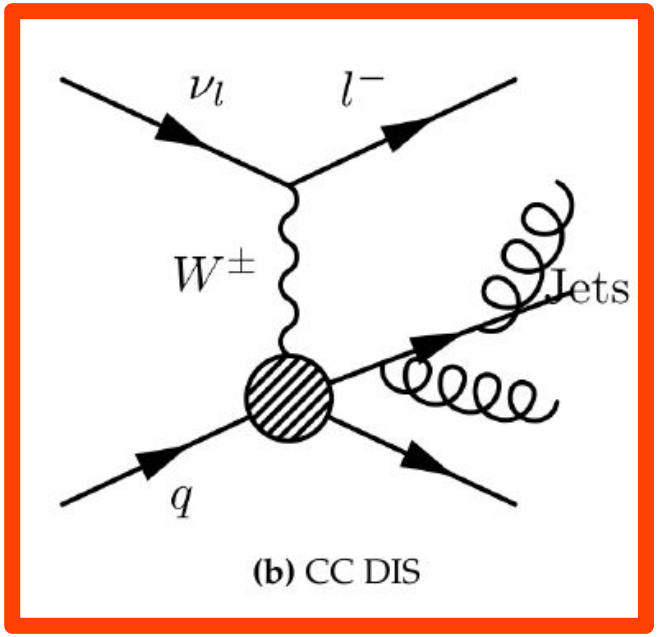


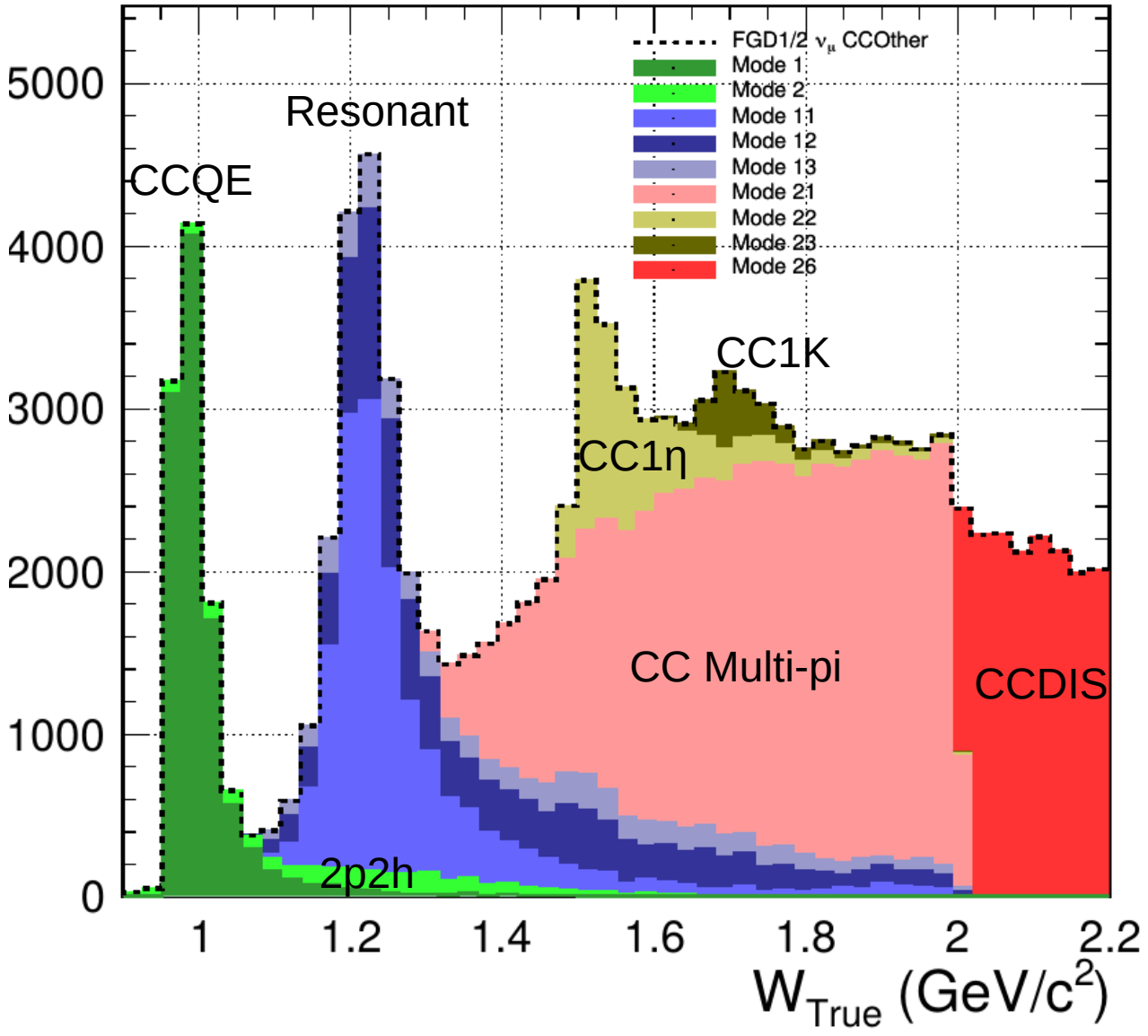
**(a)** CC1$\pi^+$1n



**(b)** CC DIS

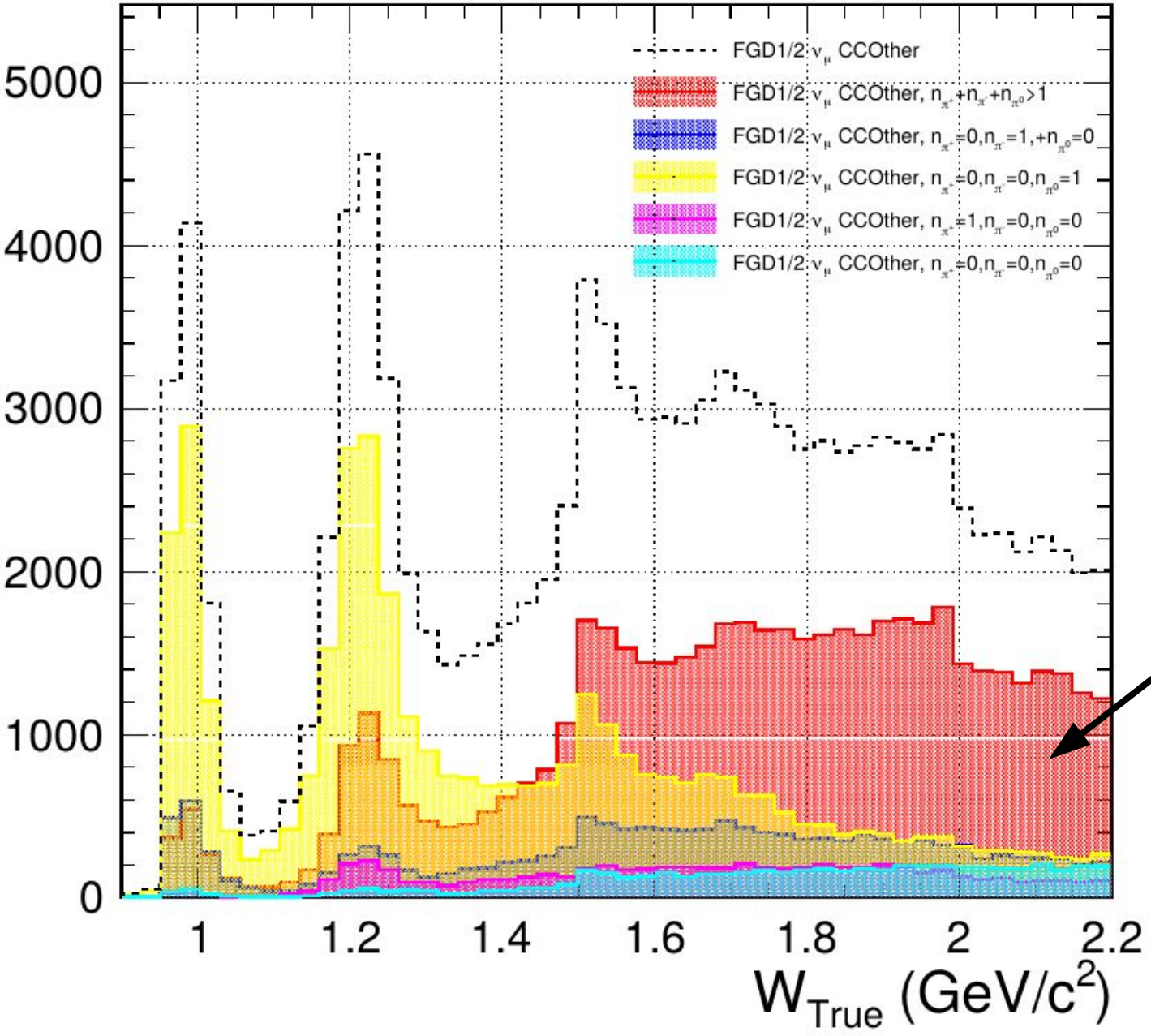
# CCOther by-mode

- Without any additional cuts, CCOther is a mish-mash of a lot of physics: let's separate them



# First, CCOther

- Simply counting number of reco TPC pions




**>1 reco pions**
Population at higher W: less Delta resonance, more multi-pi/DIS

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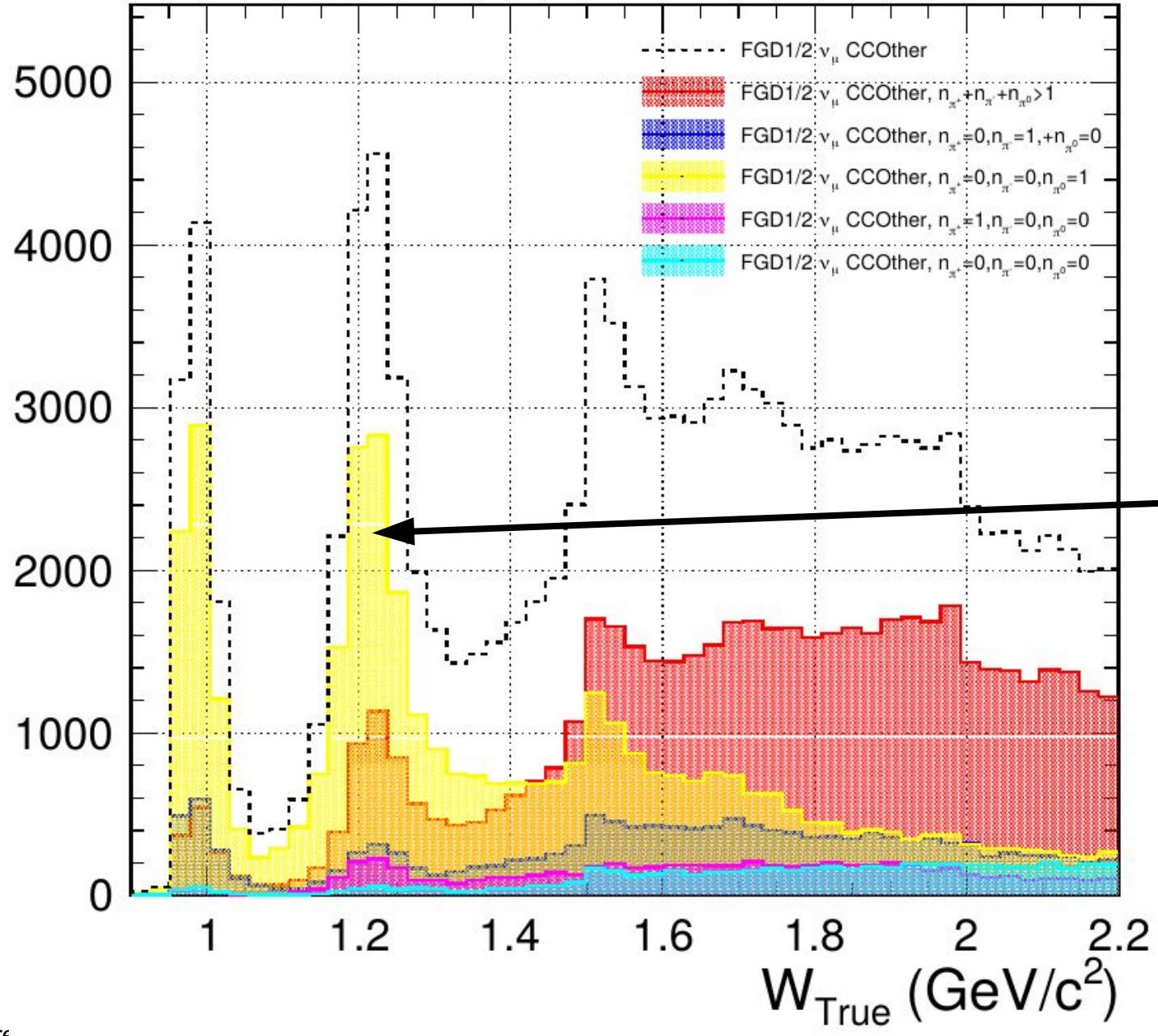
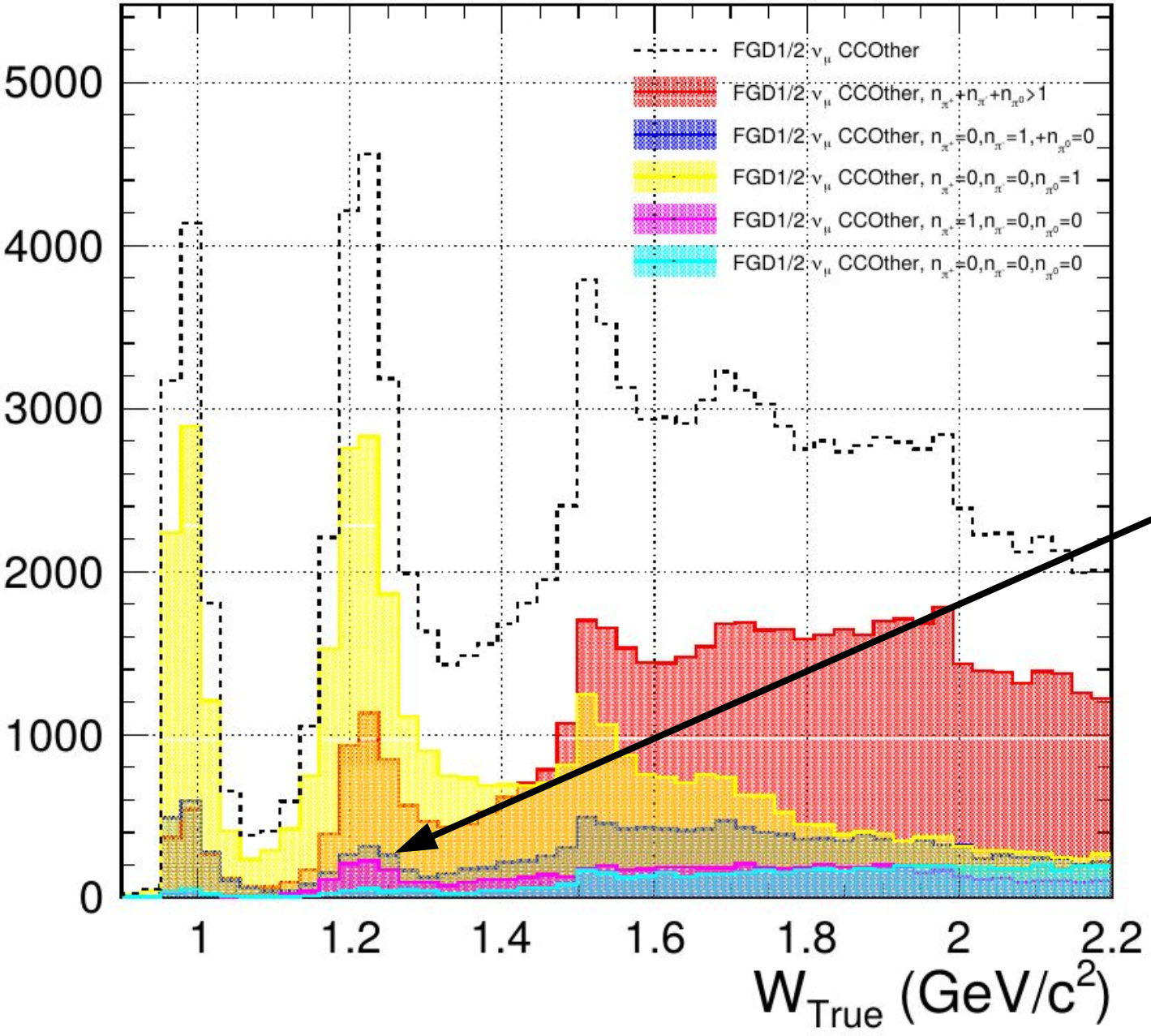



**1 reco $\pi^0$:**
Double peak: CCQE, Delta; some higher res/ multi-pi

# First, CCOther

- Simply counting number of reco TPC pions

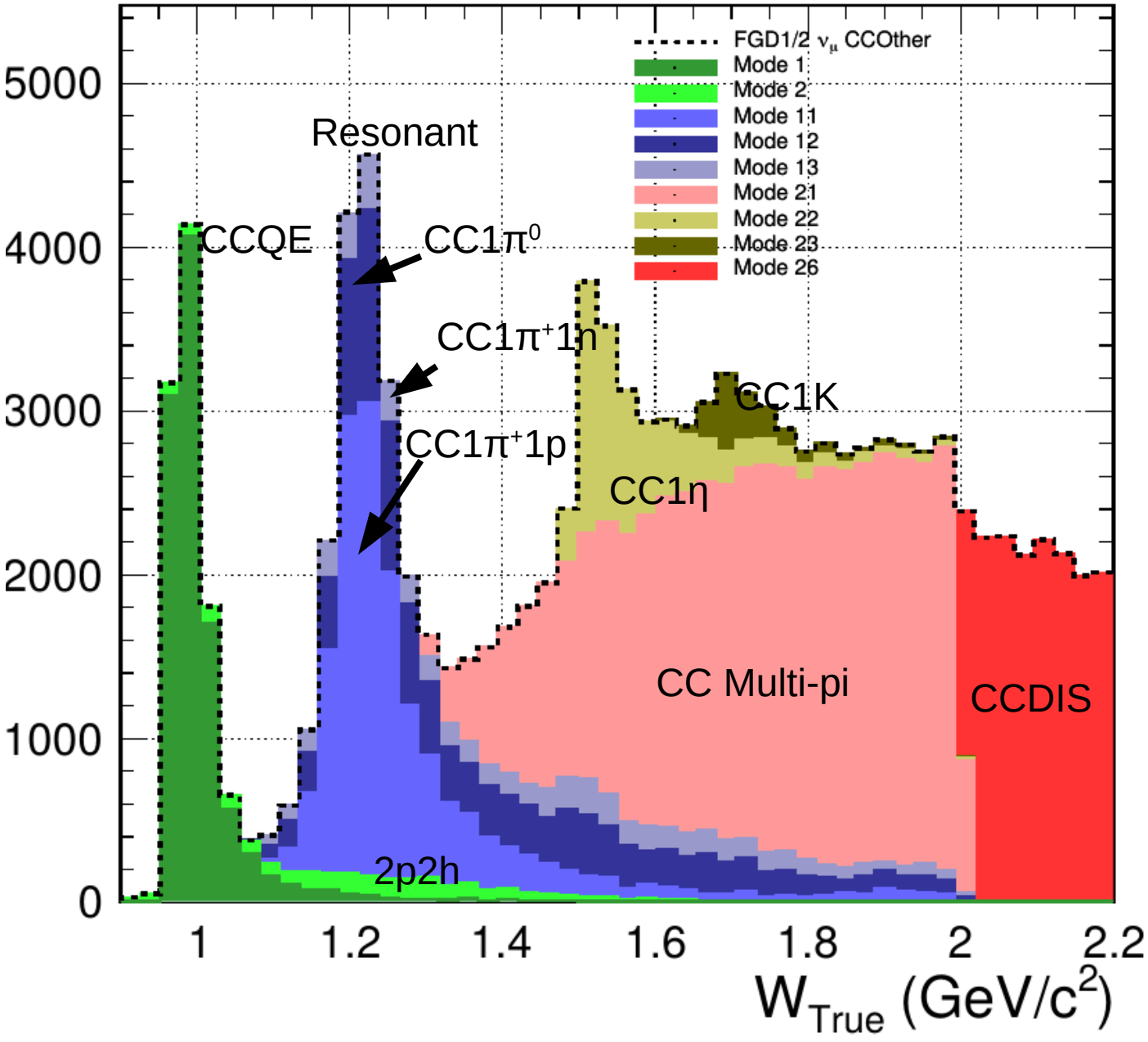



**1 reco $\pi^-$**:
Triple peak: CCQE, Delta, higher res/multi-pi

Clearly subleading

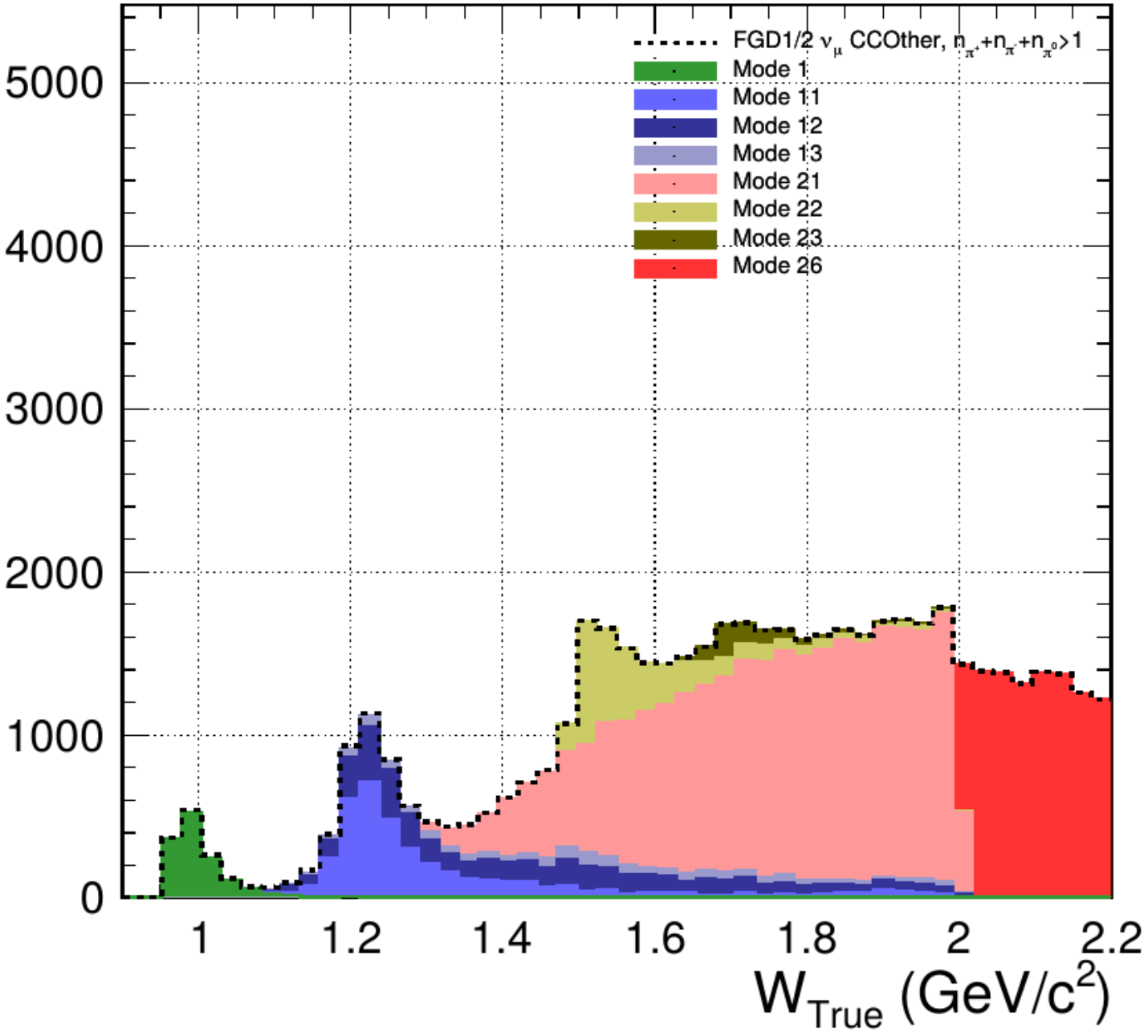
# CCOther by-mode

- Reminder of the by-mode distributions



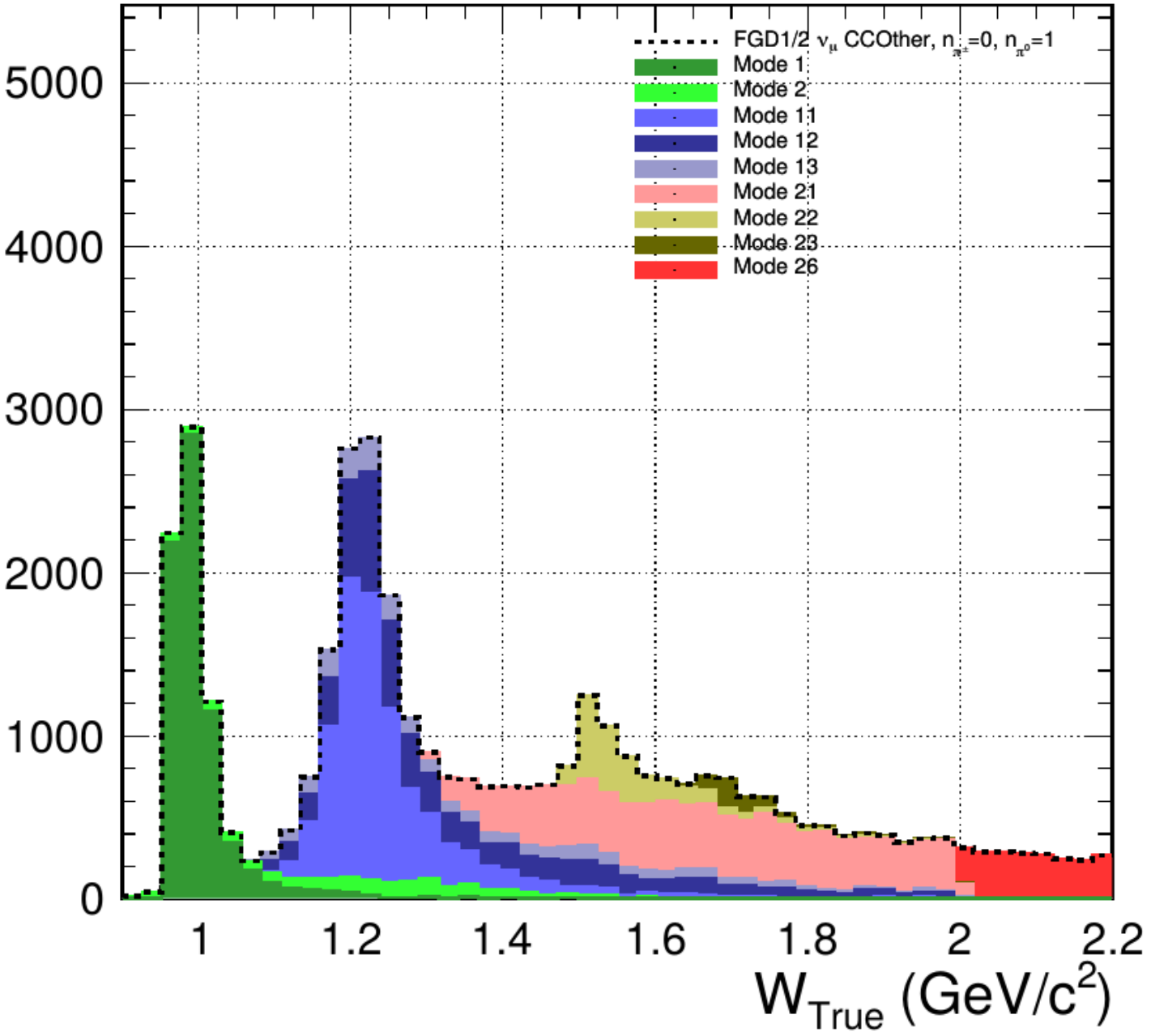
# Cut selections by mode

- At least 2 reco $\pi^{+,-,0}$



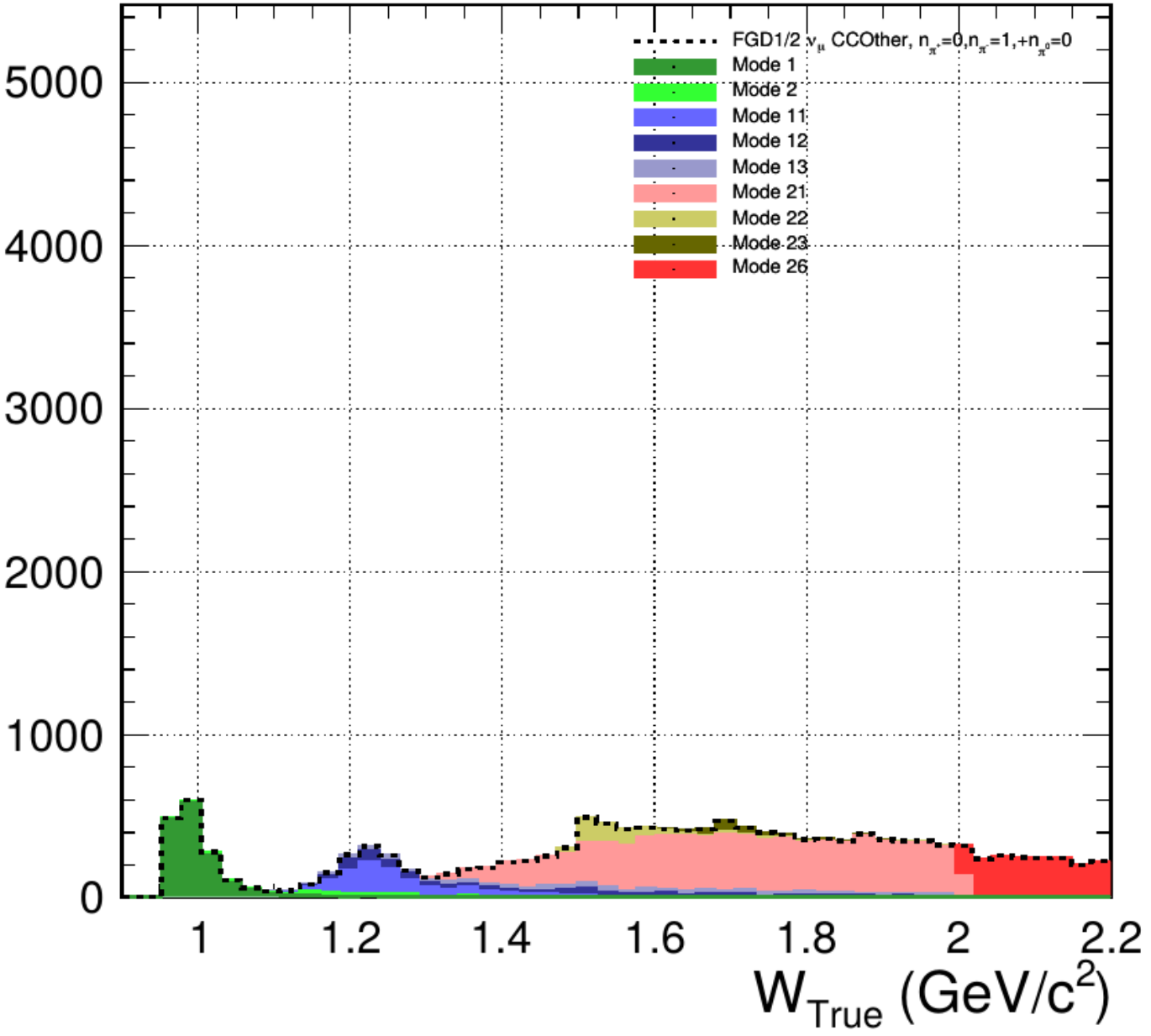
# Cut selections by mode

- One reco $\pi^0$, no other TPC $\pi^{+,-}$



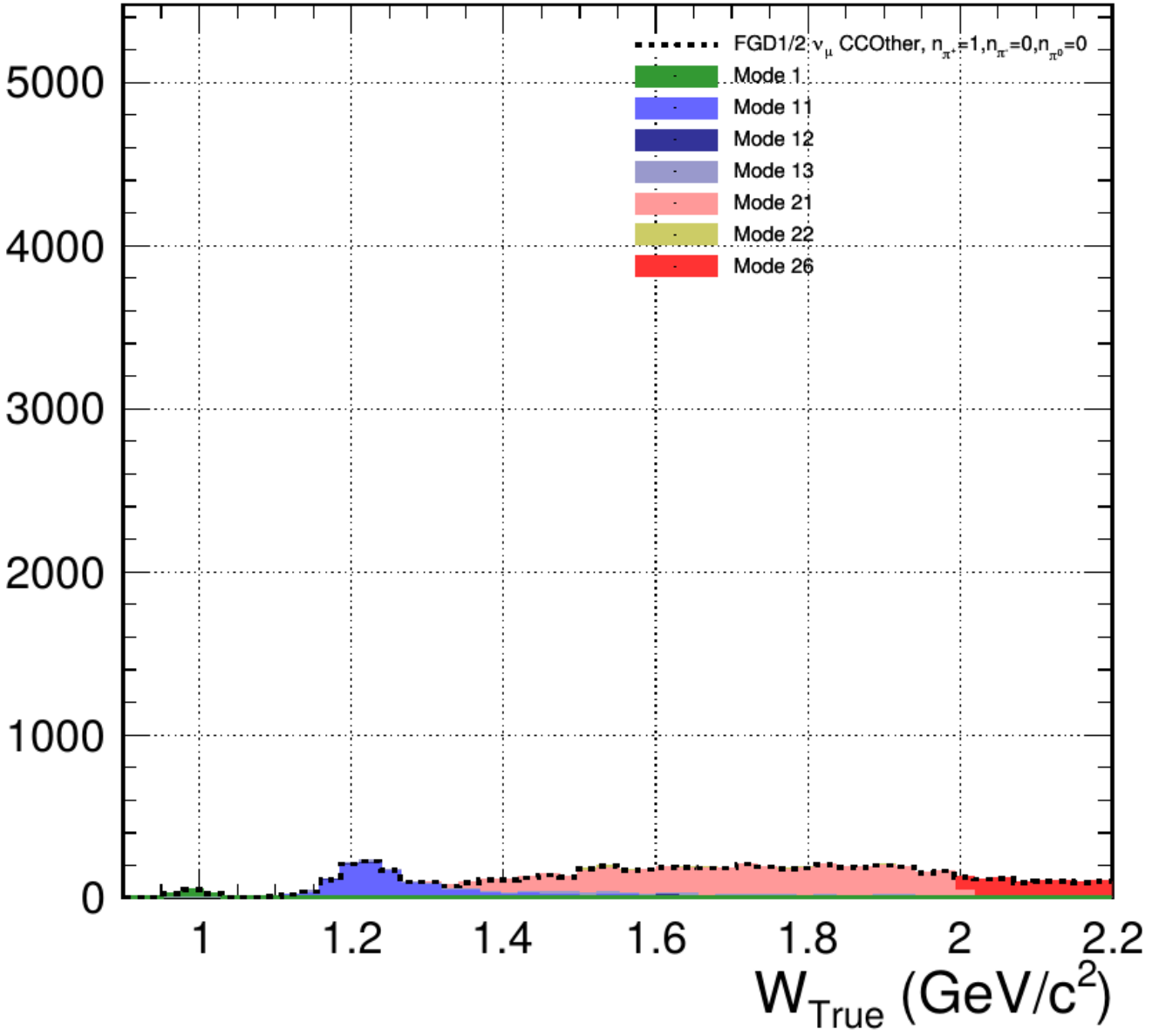
# Cut selections by mode

- Only $1\pi^-$, no other $\pi^{+,0}$



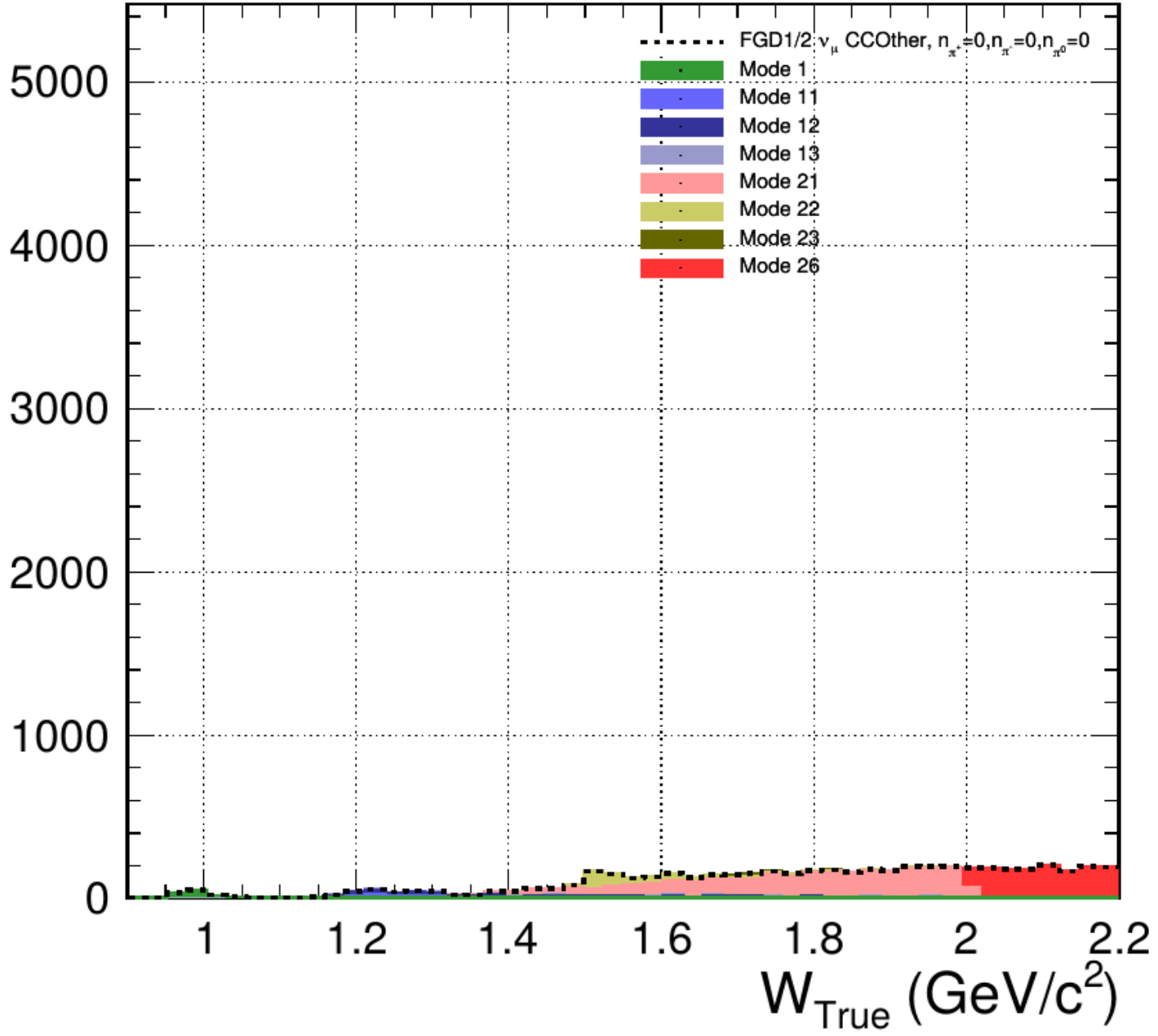
# Cut selections by mode

- Only one TPC $\pi^+$, no other TPC $\pi$ (Michel and FGD pions allowed, otherwise this would be zero)



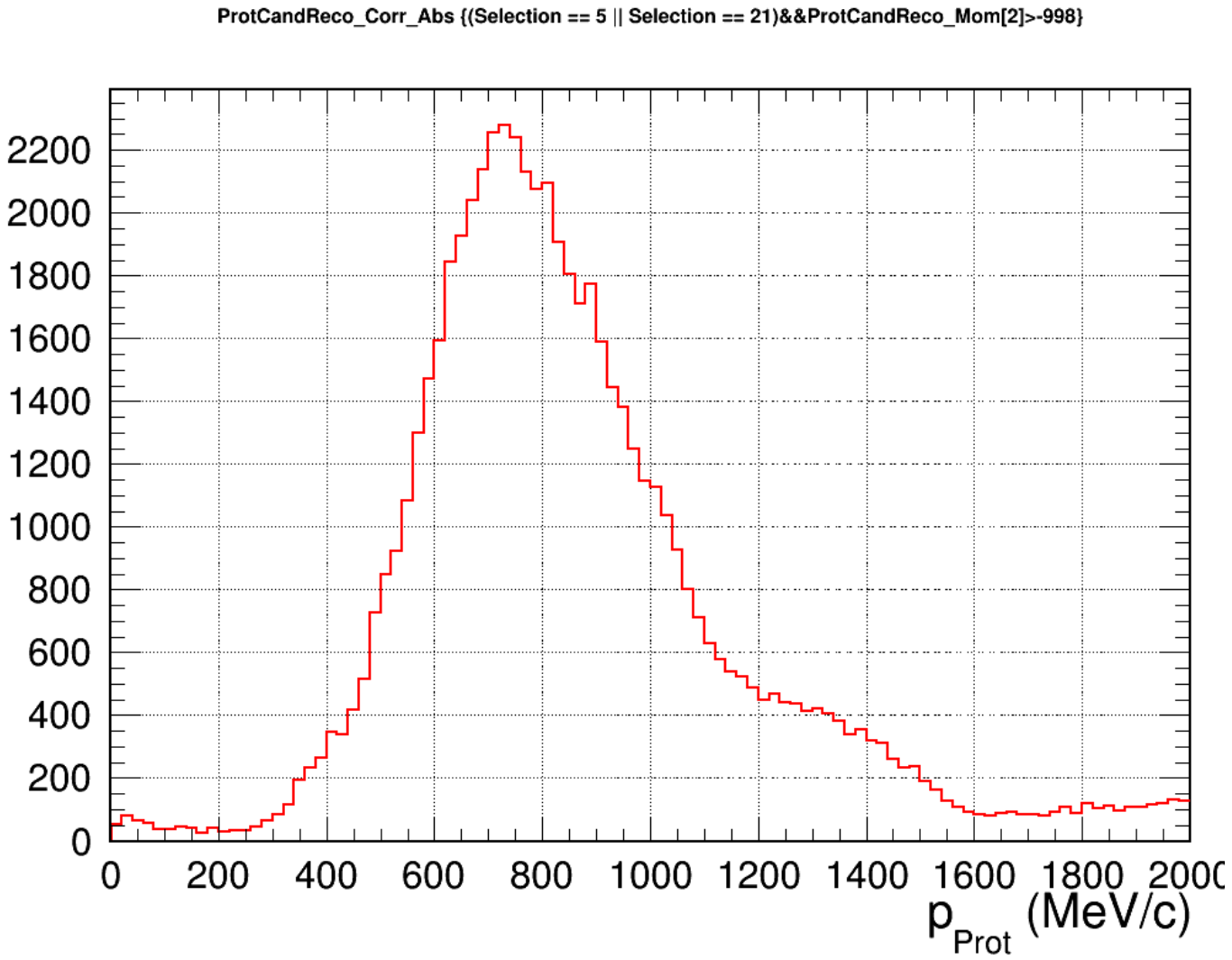
# Cut selections by mode

- No TPC $\pi^{+,-,0}$ tracks (but any FGD iso and Michel)



# CCOther and protons

- Could CC1$\pi^0$ isolation be better by including proton?




- Proton threshold about p=450 MeV/c

# CCOther and protons

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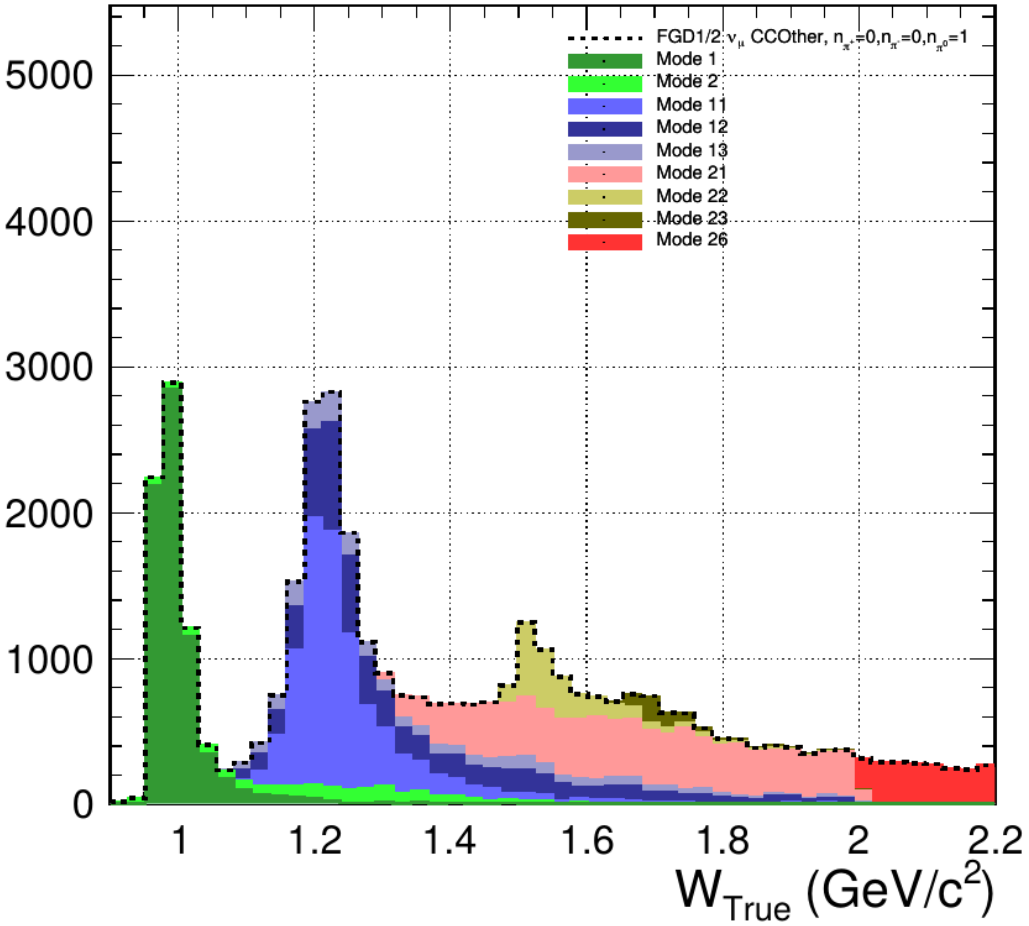
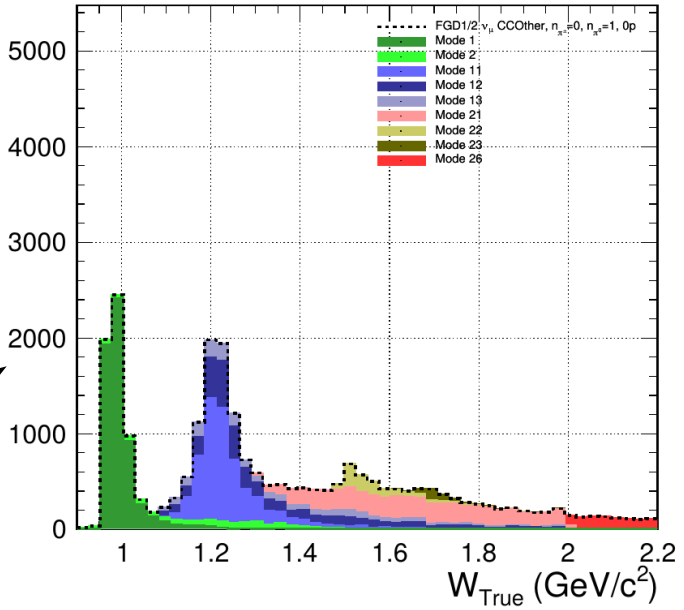
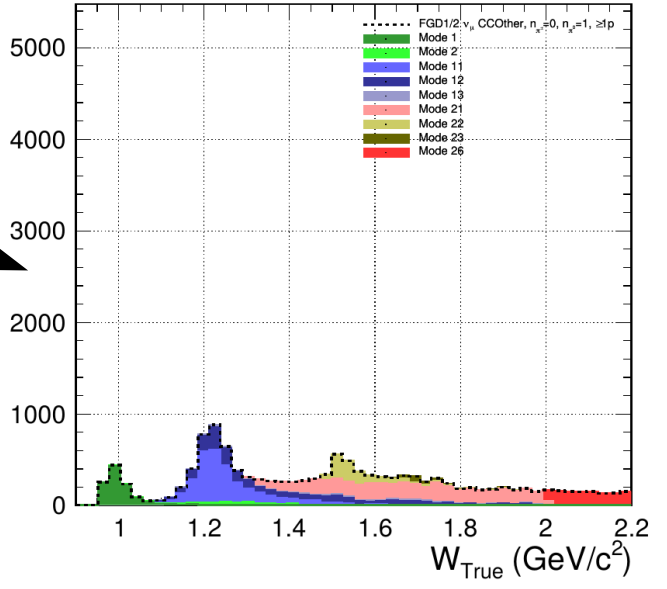
CCOther with only 1$\pi^0$




0 protons



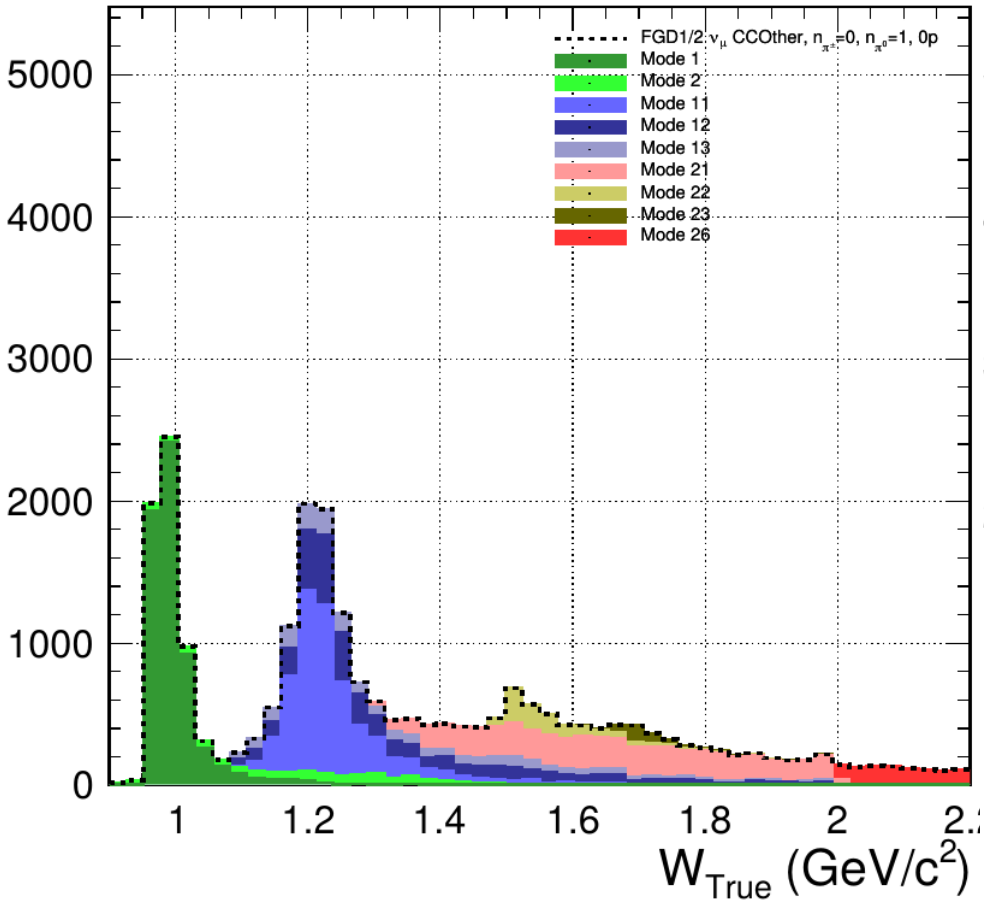

>0 protons



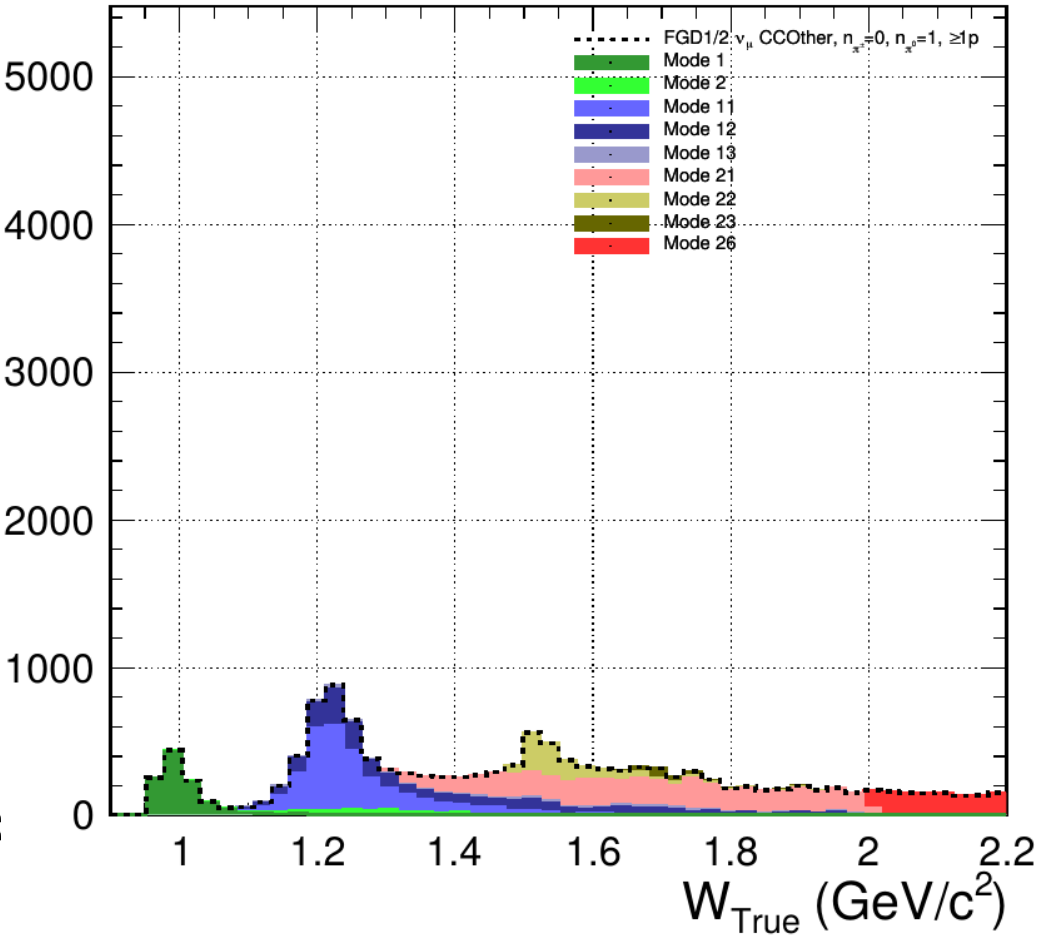
# CCOther and protons

- Proton requirement separates CCQE component
  - Largely from high proton momentum threshold
- Separates CC1$\pi^+$1n contribution fairly well

CC1$\pi^0$0p




CC1$\pi^0$Np (N>0)



# CCOther summary

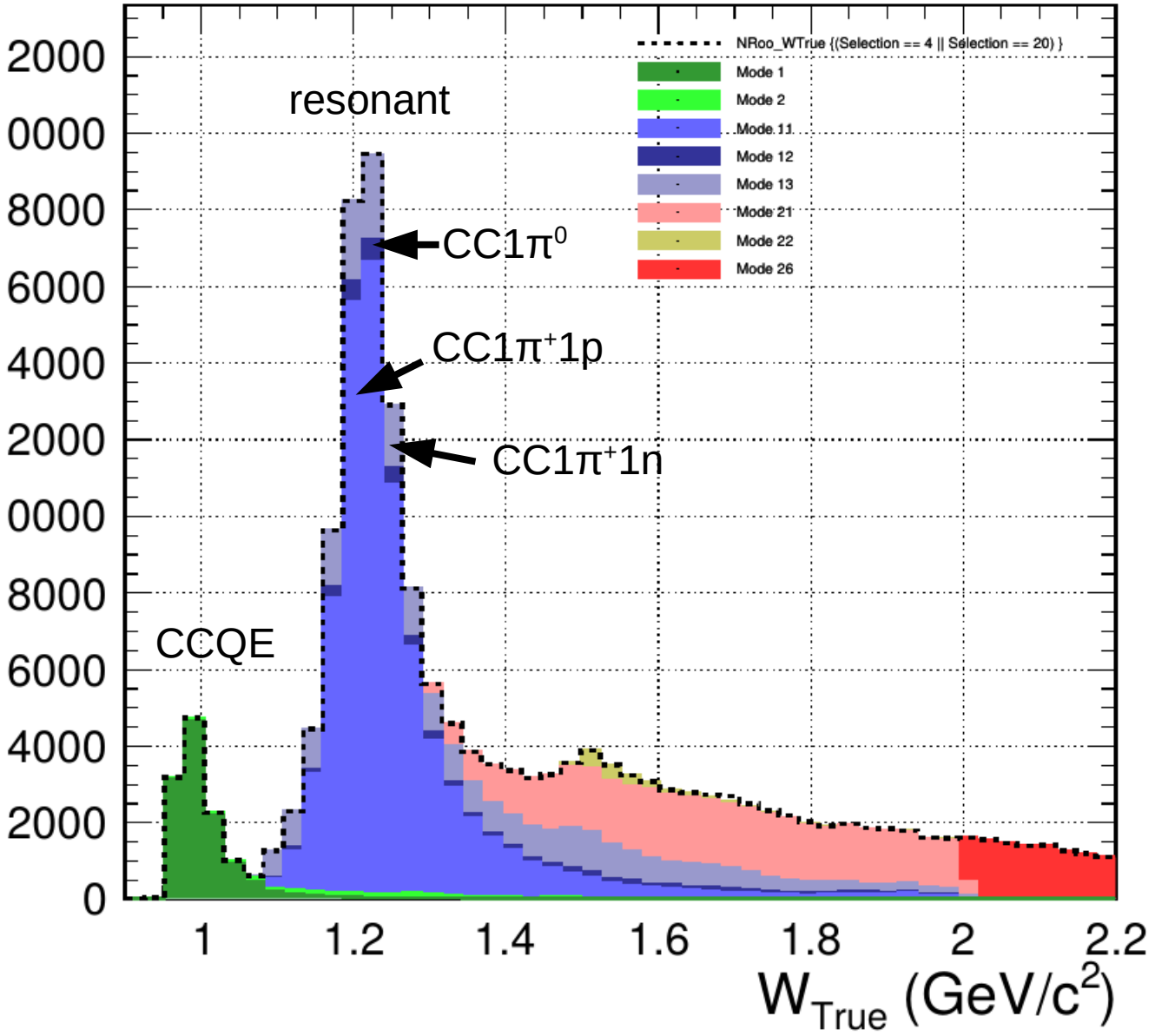
- Simply counting up the pions seems to work
- Separating out single $\pi^0$ events from wrong-sign and multiple pion events
- Including proton information helps isolate further, but leads to low statistics in >0p selection

- Want to also include FGD iso and Michel tag into the pion counting: small effect though
- Check biases in the true PDG of proton candidates

- Look at sensitivity studies to fitting the model parameters

# CC1π⁺ with protons

- The CC1π⁺ selection is a mix of resonant, CCQE/2p2h and multi-pi



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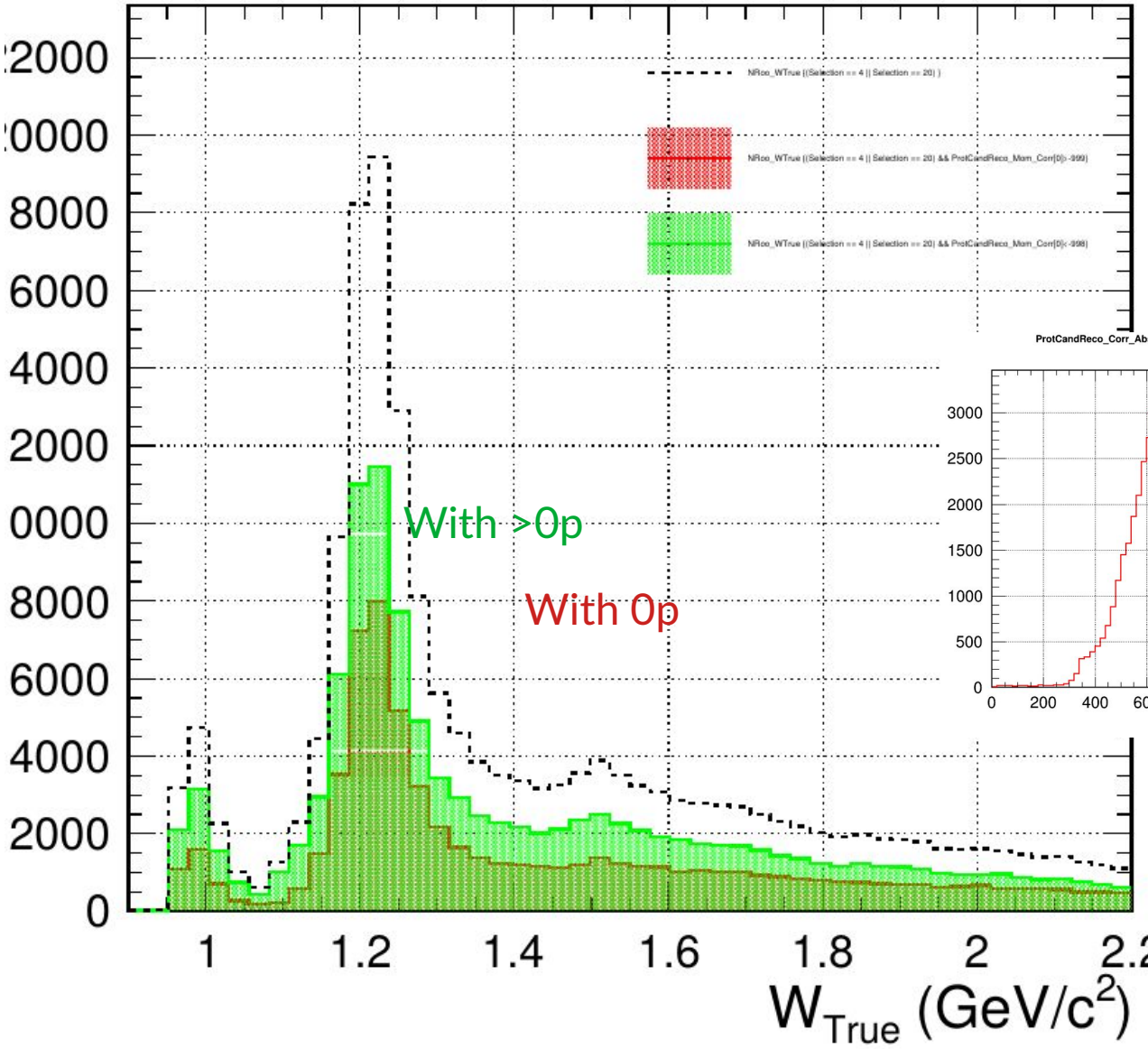
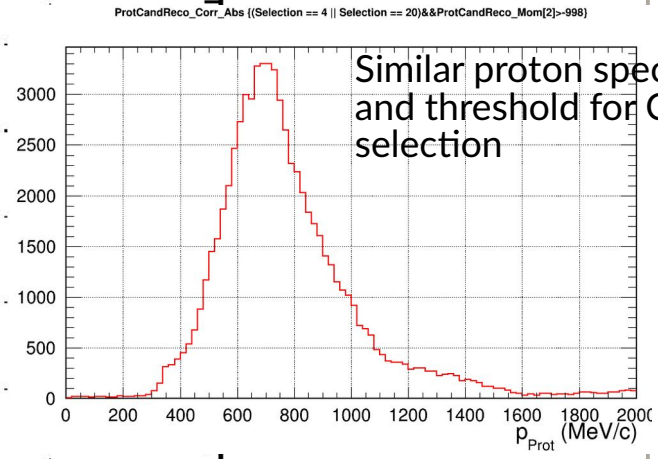
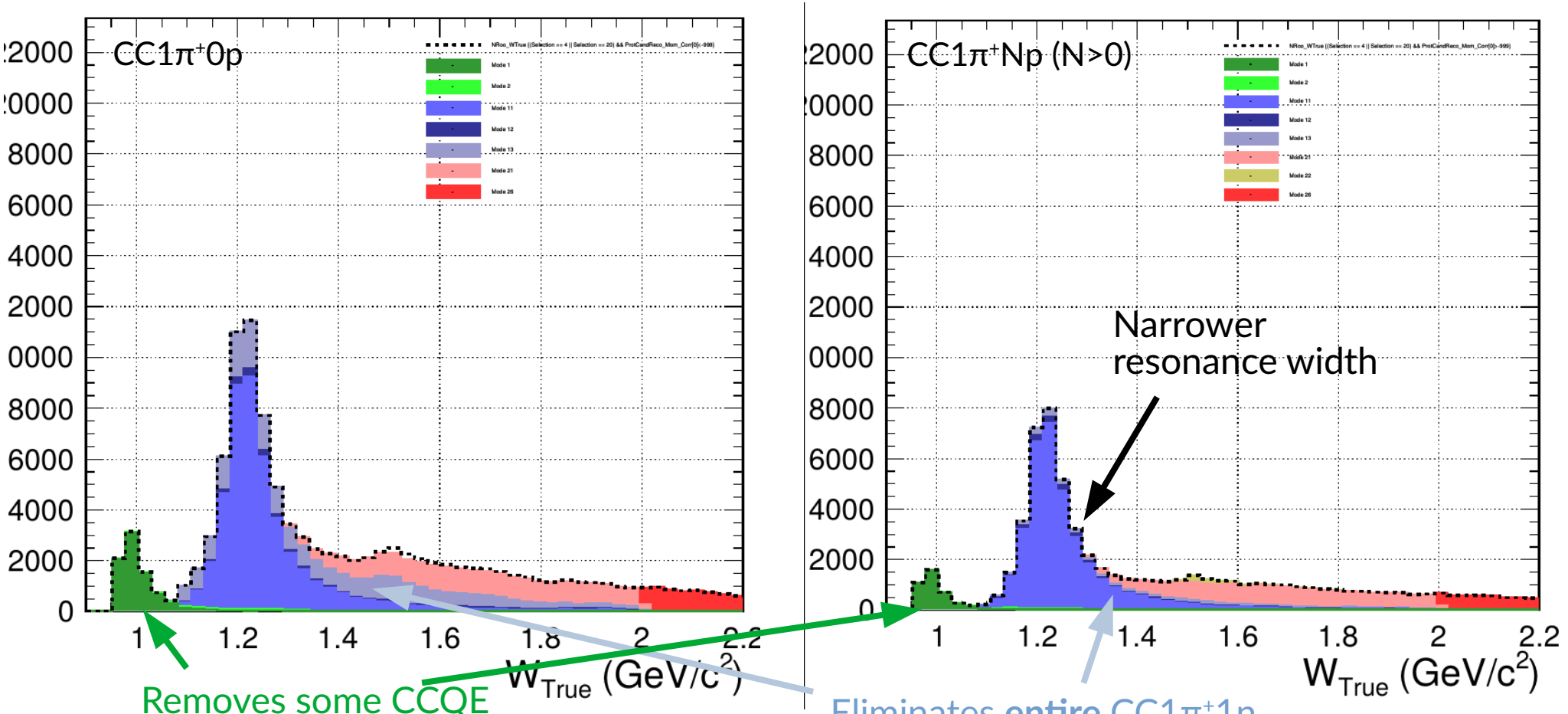


# CC1$\pi^+$ with protons

- The CC1$\pi^+$1p final state is special in bubble chambers
  - Large $\Delta^{++}$ (pure $I_{3/2}$) contributions with barely any other resonances and minimal non-resonant background interference

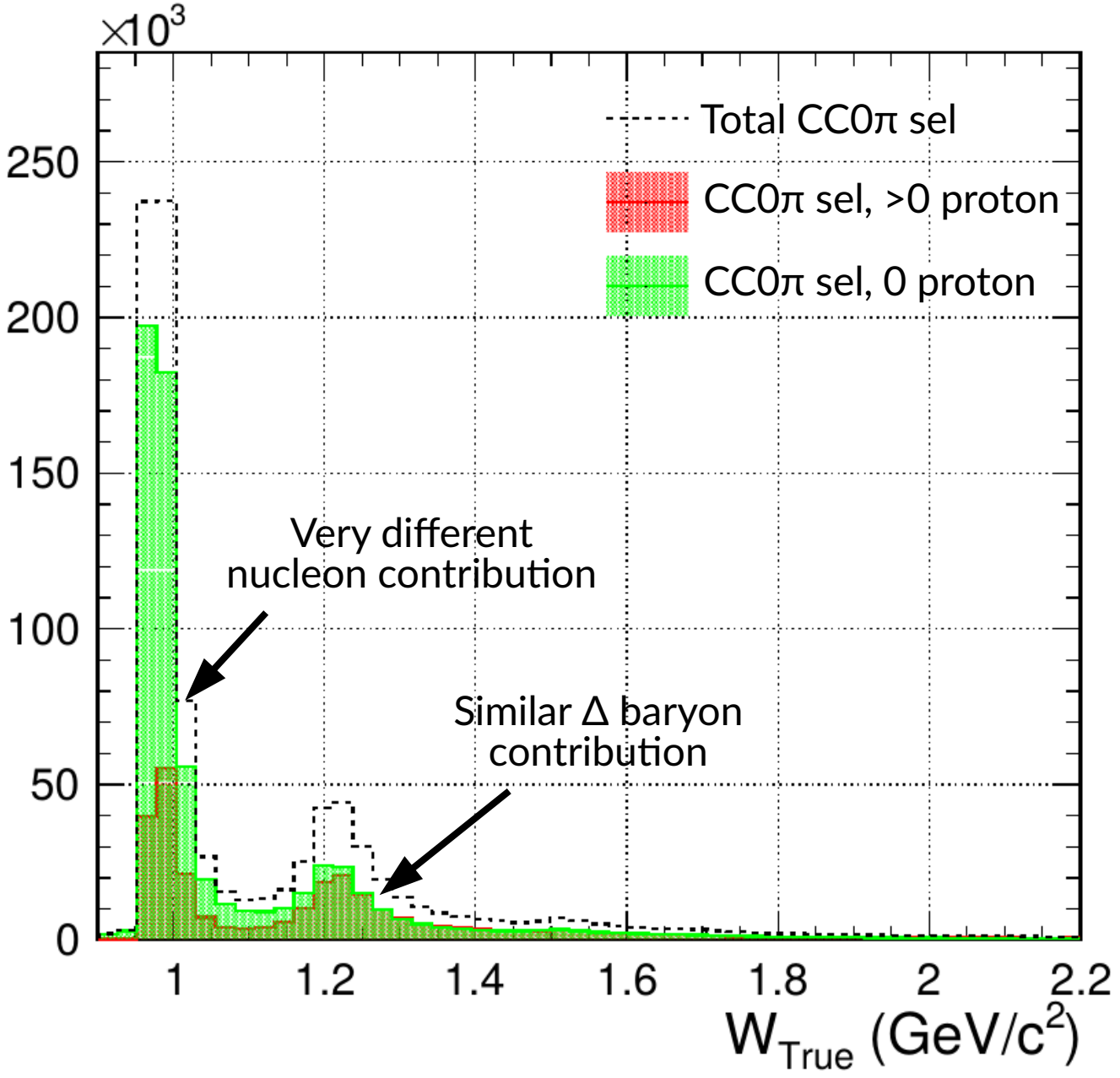


# CC1$\pi^+$ with protons summary

- Including proton track presence gives better separation of interaction modes as anticipated
- But there is still room for improvement
  - Including proton kinematics in the separation, or vertex activity (could separate coherent contribution perhaps?)
  - Including proton kinematics in fitting variable
- Happy to pursue this basic selection update to see improvements in e.g. likelihood scans and parameter sensitivity
  - However, don't have huge amount of free time, so am very happy to work in group with someone

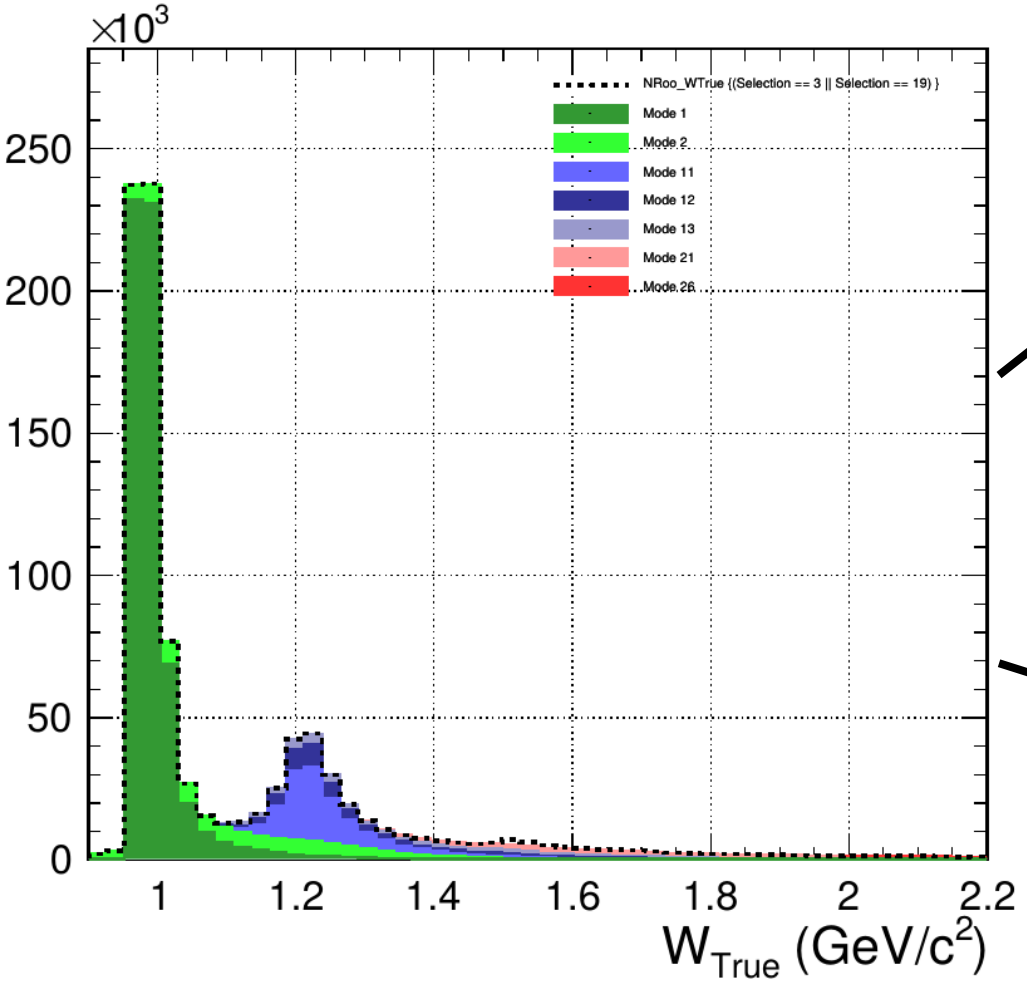
# CC0π with protons

- Repeating exercise but for CC0π selection

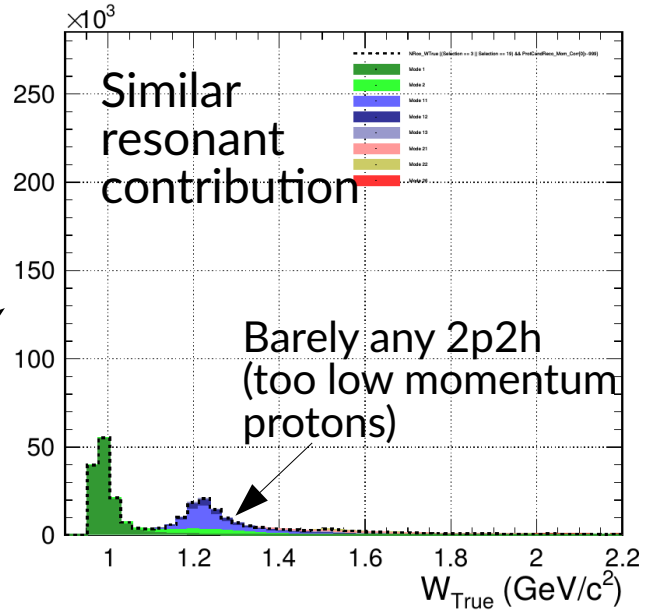


# CC0π with protons

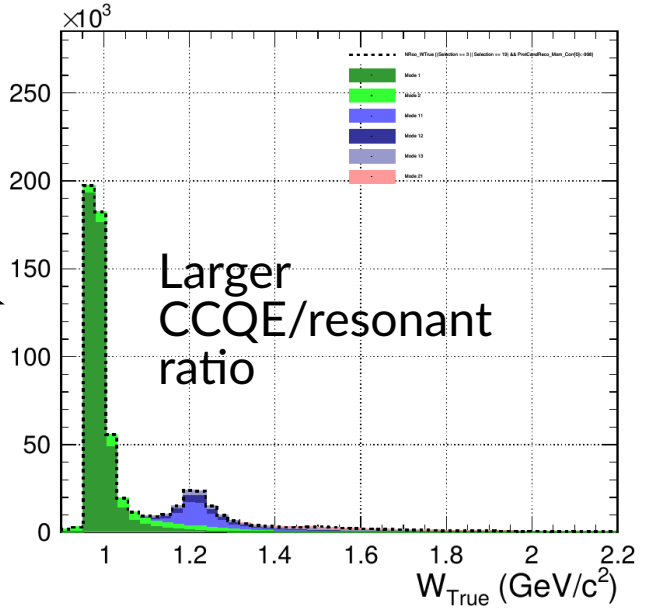
- Looking at the total by mode, see mostly 1π in Δ baryon peak




>0p




0p



# CC0π with protons summary

- Looking purely at the presence of proton tracks seems too crude for CC0π, due to high proton momentum threshold
  - Most CCQE **should** have protons, but most CCQE events end up in 0p selection → due to low momentum of proton
  - Most 2p2h **should** have protons, but most 2p2h events end up in 0p selection → due to low momentum of proton(s)
  - Resonant sometimes has protons → Higher $E_\nu$ → Higher proton momentum → More often detected
  - Provides some separation of CCQE and resonant
- This seems to indicate vertex activity is central to successfully separating the CCQE/2p2h interaction mode contributions?
  - No easy way to do this currently
- Can test statistical power of the two samples in sensitivity studies

# The elephant in the room

- Proton interaction systematics!
- Include “with proton” and “without proton” samples mitigate events migrating in/out of entire selection
  - Study migration between “with” and “without” proton is accounted for
- Secondary interaction (SI) systematic handled, will evaluate the size of this systematic on the selections
- Proton final state interaction (FSI) systematic handled in NEUT, but not presently included (not enough pass-through information in our production)
  - Wait for new production to evaluate this? Would prefer not…
  - Hash something out in the meantime comparing generators, or just doing mean free path

# Summary

- Naive first pass glance at slicing up ND280 selections included in T2K's ND280 fit

- CCOther and CC1$\pi^+$ updates seem reasonably easy for the additionally physics gain (I hope…)
  - Dedicated CC1$\pi^0$ selection from CCOther
  - Include proton tag to separate CC1$\pi^+$
- CC0$\pi$ benefits too, but relatively high momentum threshold of ND280 leads to poor CCQE/2p2h/resonant separation
  - Needs further studies, e.g. proton momentum slices, vertex activity


# Thanks