Modifying single pion production hadronic dists.

UNIVERSITY of ROCHESTER

Clarence Wret

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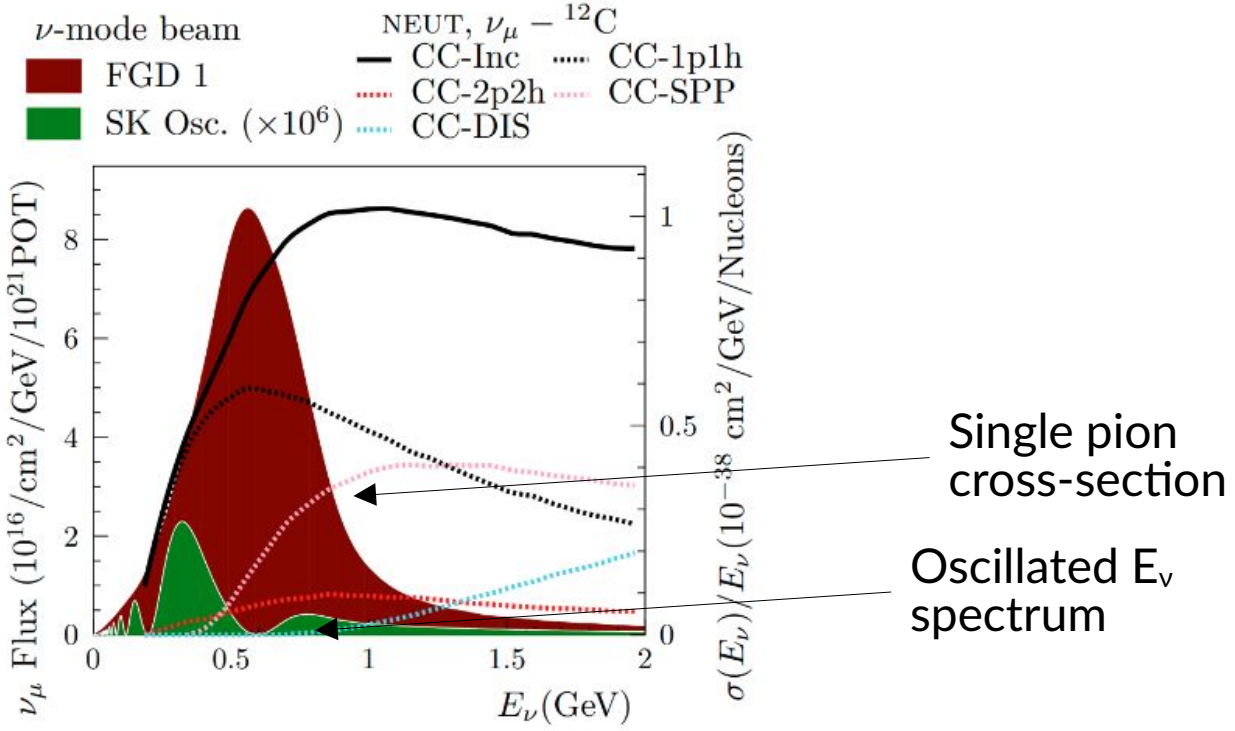
Background

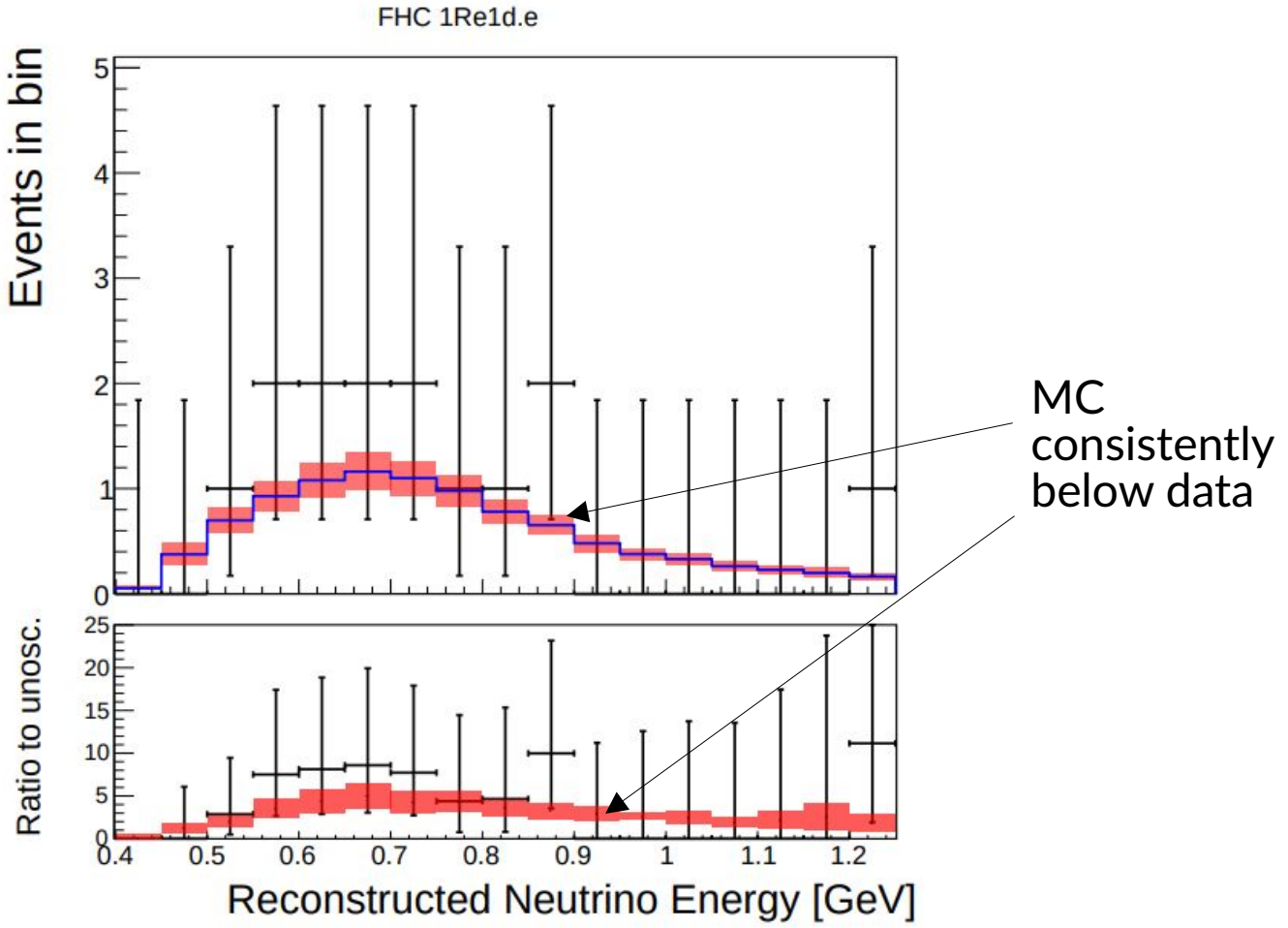
- T2K is introducing new “2 ring” selections this year
  - One ring from muon, one ring from pion above Cherenkov threshold
  - One ring from muon, one below-Cherenkov pion (Michel tagged)
- → Large number of 1π events into next oscillation analysis



- About 130-150 ν_μ MC events will be added (have ~340 1Rμ)
- Higher E_ν → smaller oscillation effect, but will contribute to the constraint at the maximum

Background

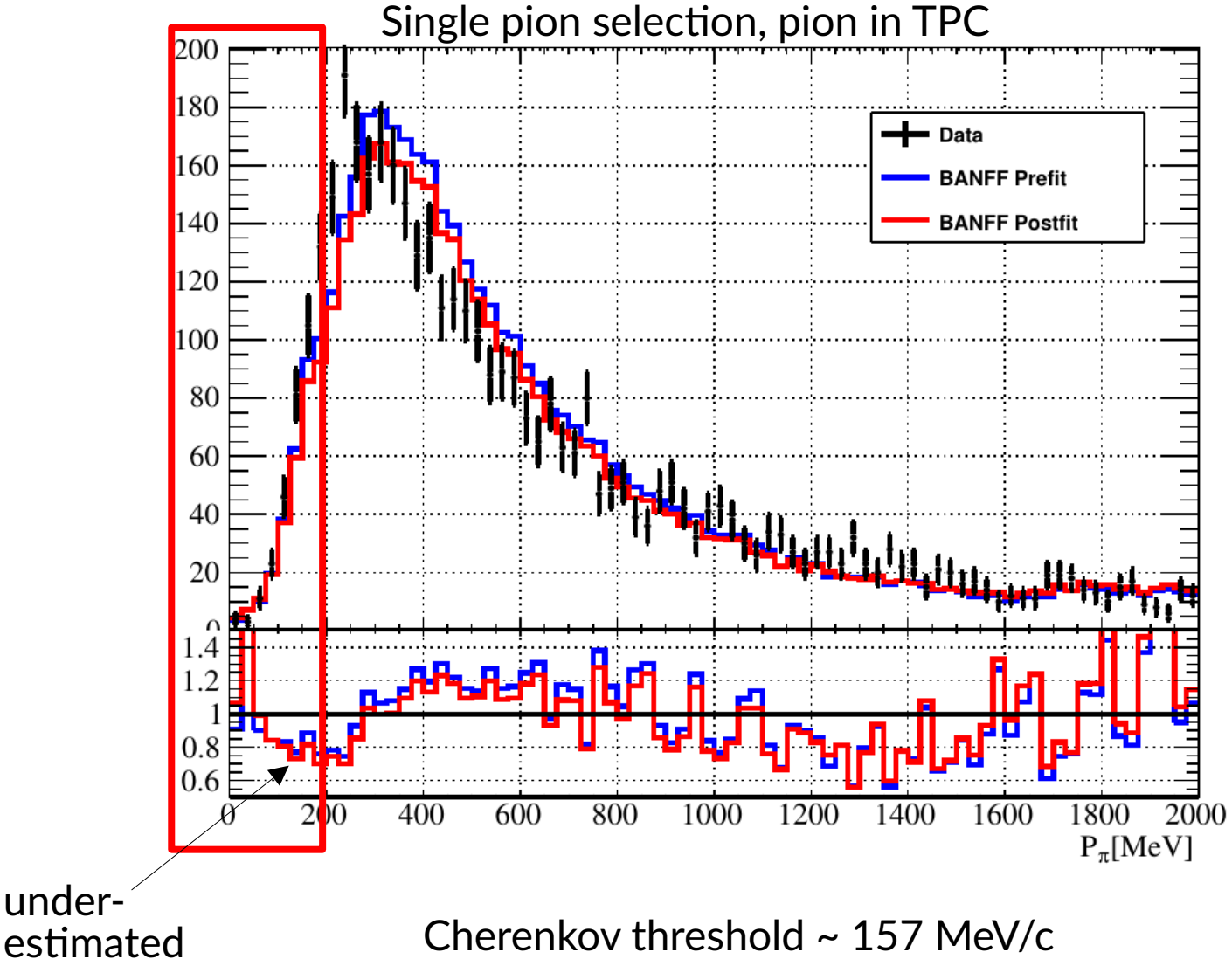
- Preliminary studies of atmospheric samples and current 1Re1de electron indicate low momentum pions may be underestimated



- Not binning in pion momentum in analysis, but are sensitive to pion momentum spectrum through selection cuts
  - e.g. does an event with a pion produce a ring or a Michel electron? → goes into selection A or selection B

Background

- The T2K near detector (ND280) also sees something similar

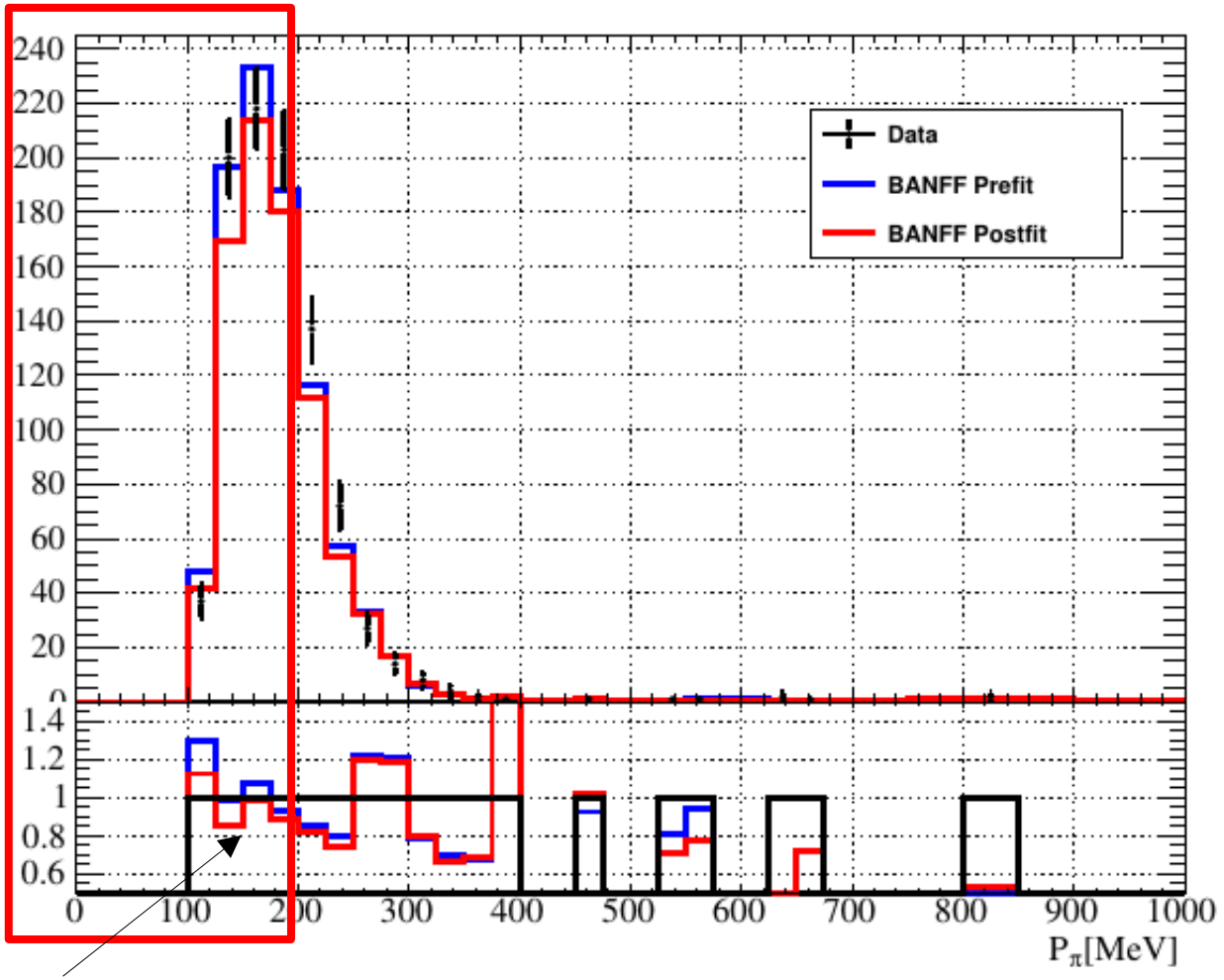


Cherenkov threshold ~ 157 MeV/c

Background

- The T2K near detector (ND280) also sees something similar

Single pion selection, pion in FGD



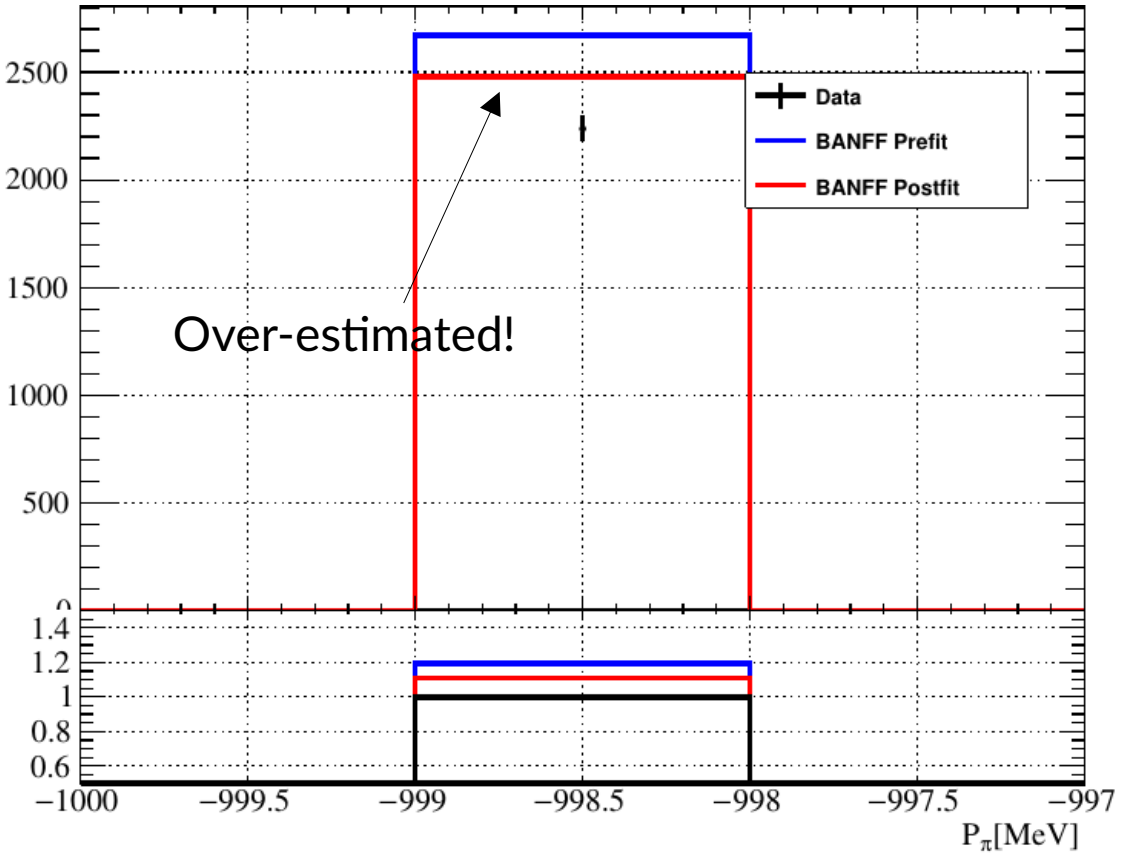
under-estimated

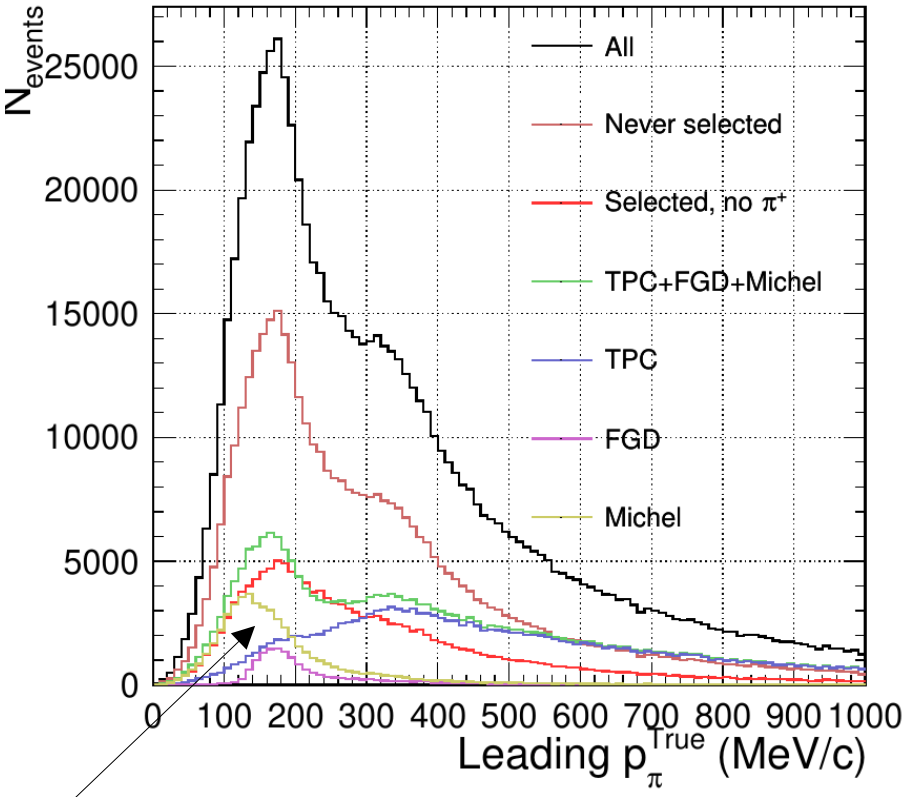
Cherenkov threshold ~ 157 MeV/c

Background

- The T2K near detector (ND280) also sees something similar?

Single pion selection, pion Michel tagged (no track)

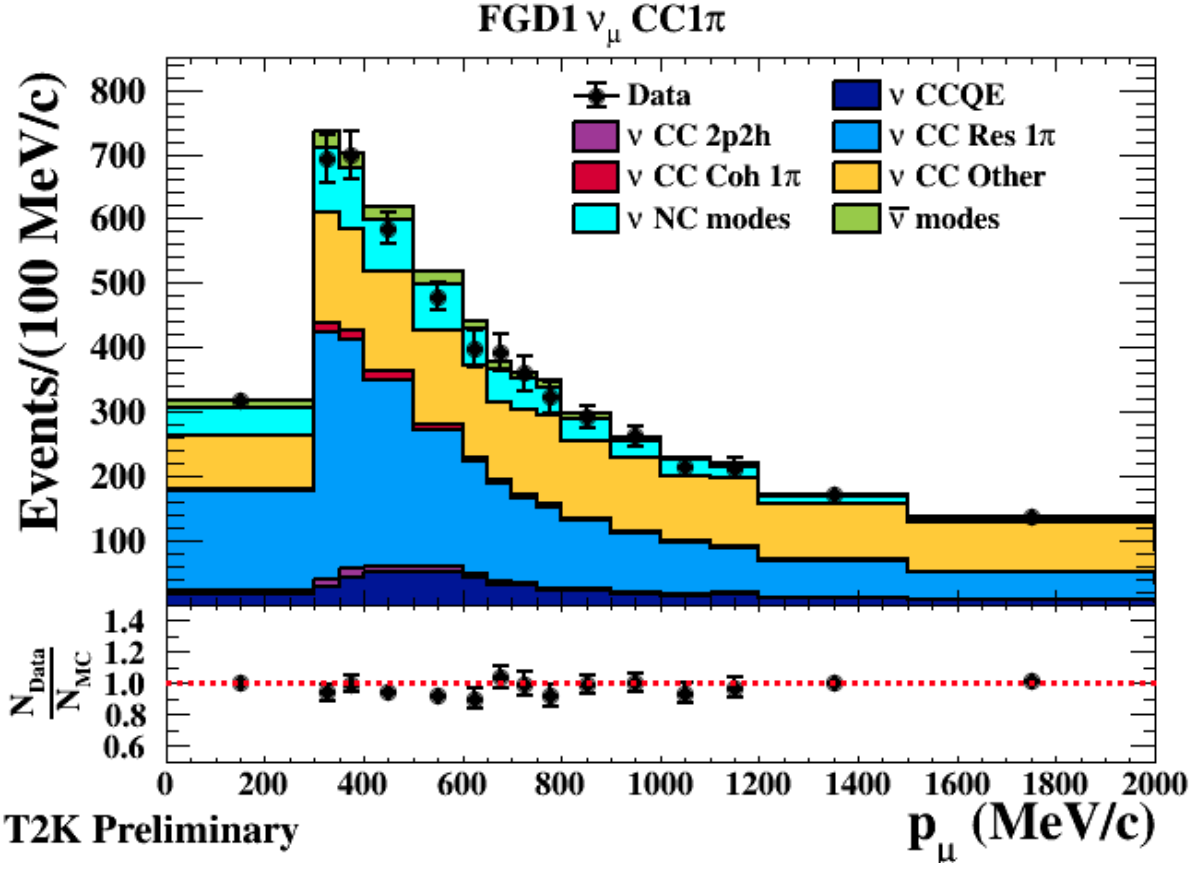




Most of Michel-tagged pions are below Cherenkov threshold

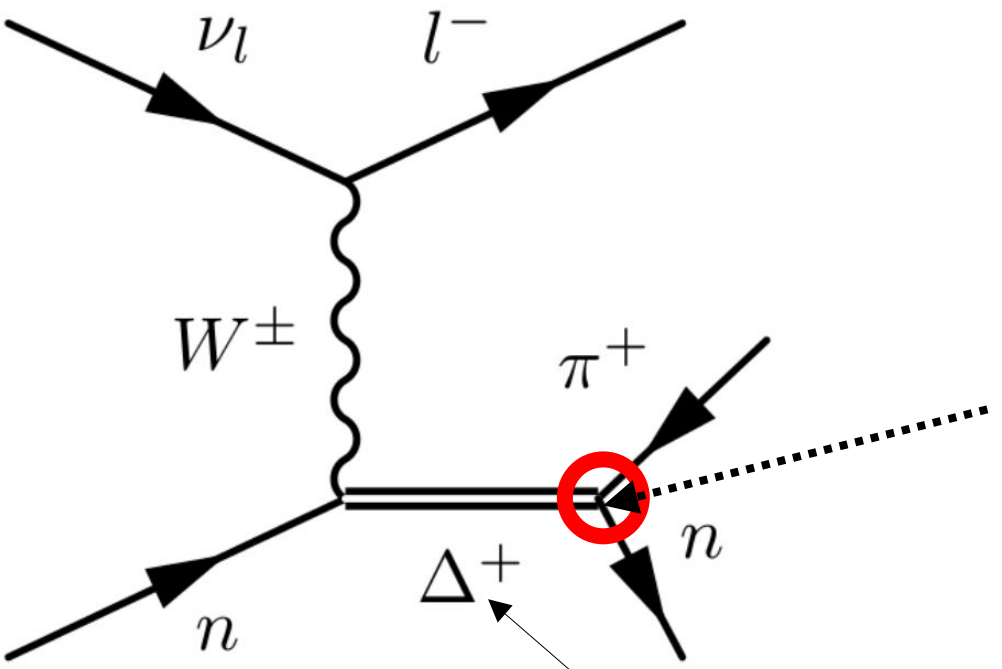
Background

- Most of our 1π systematics (M_A^{RES}, non-resonant background, C^A_5, FSI parameters) have little shape effect on pion distributions
- Need some way to affect pion distributions!
- Better yet, a dial that has minimum effect on lepton distributions
  - Since the lepton distributions are relatively well described (as they are fit in the ND280 fit)



Developing a dial

- Rein-Sehgal model has several suggestions for decaying resonances into pion+nucleon



(a) CC1π^+1n

Concerned with the kinematics of this decay

Can be any resonance with good quantum numbers (not just Delta)

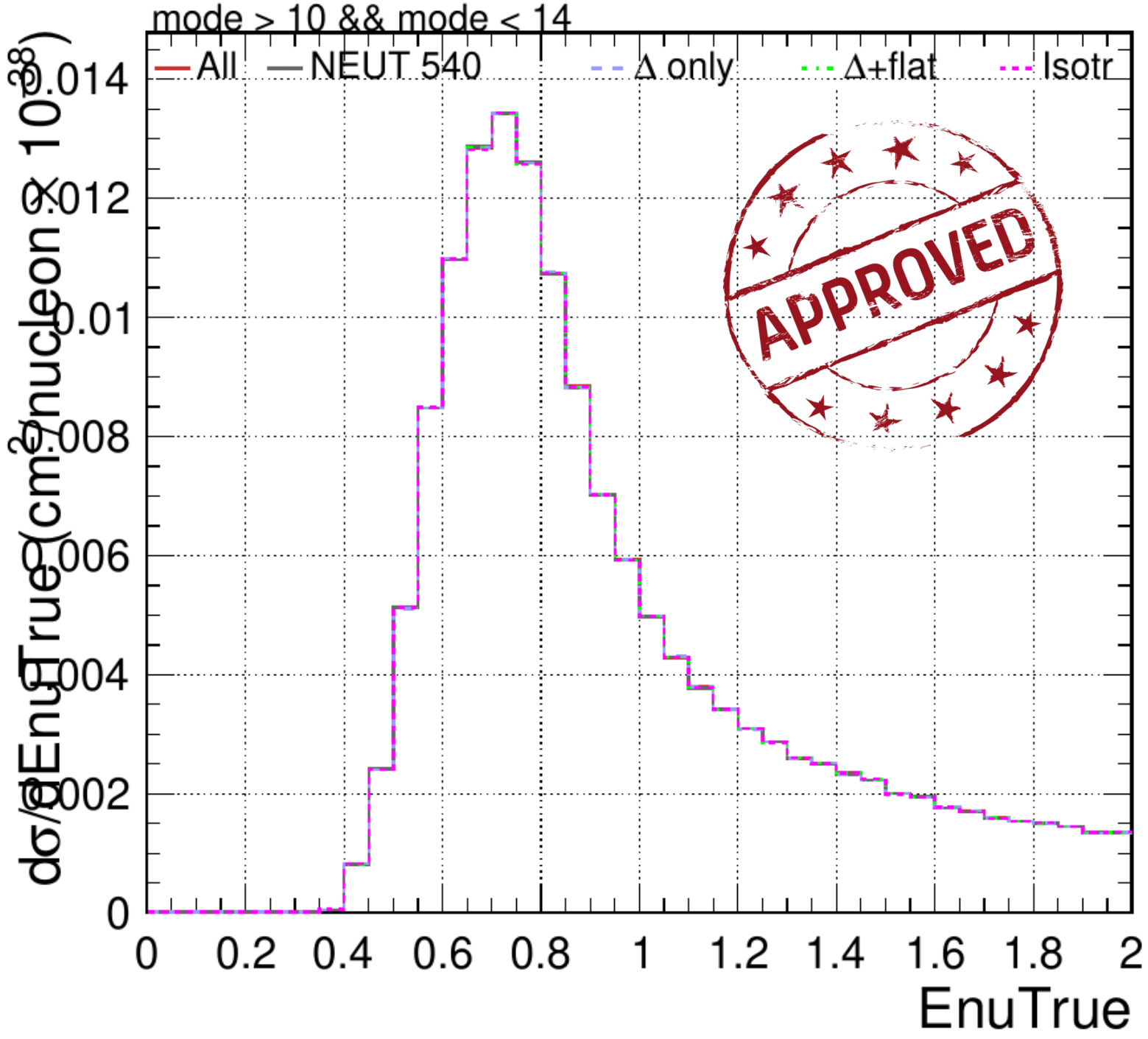
Developing a dial

- Construct $W(\theta,\varphi)$ in Adler/resonance frame which controls the process
- GENIE, NuWro and NEUT chose the simplest
  - Δ(1232)-only, or isotropic decay
- Recipe for multiple resonances and their interference is provided in Rein-Sehgal paper
- For pure $I_{3/2}$ channel (e.g. CC1π^+1p): consider Δ(1232) and Δ(1640)
- For mixed isospin channels (e.g. CC1π^+1n, CC1π^0): $\Delta_{33}(1232)$, $P_{11}(1450)$, $D_{13}(1525)$ and $S_{11}(1540)$
- A few thousand lines of code and 25 pages of calculation… and four years later, does it work?

Validating the dial

- Generated events on CH for T2K ND280 with nuclear effects in NEUT
- T2K energy means Δ(1232)-dominated, so don't expect **huge** change from including other resonances
- Simplest first validation is checking cross-section as function of muon variables, E_ν, Q^2, W, initial state, etc hasn't changed
- Also validate with NEUT before any of my changes to make sure I haven't changed the "reference" cross-section
  - And that I can replicate NEUT's pion+nucleon distributions with my new code

Validating the dial



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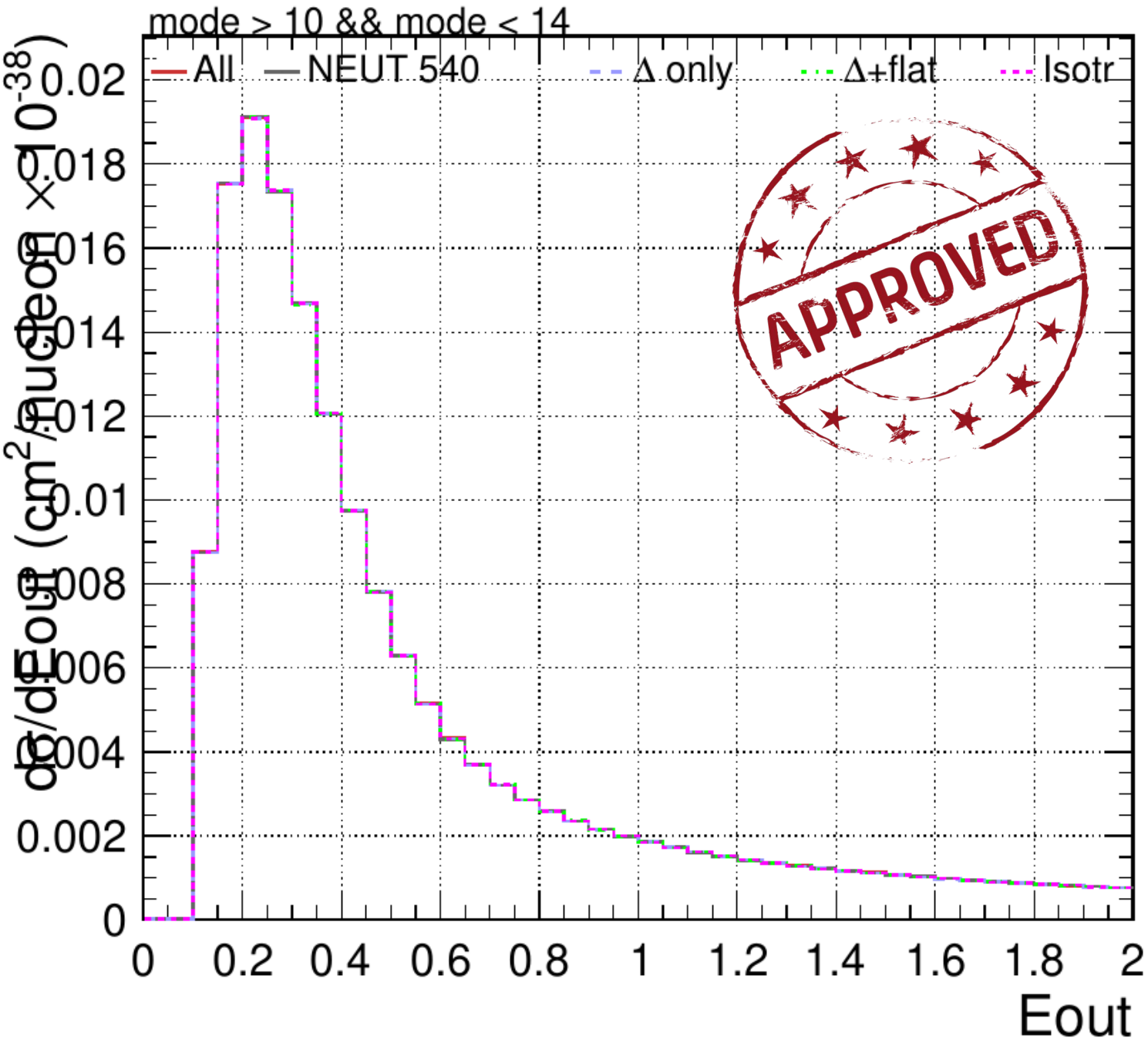

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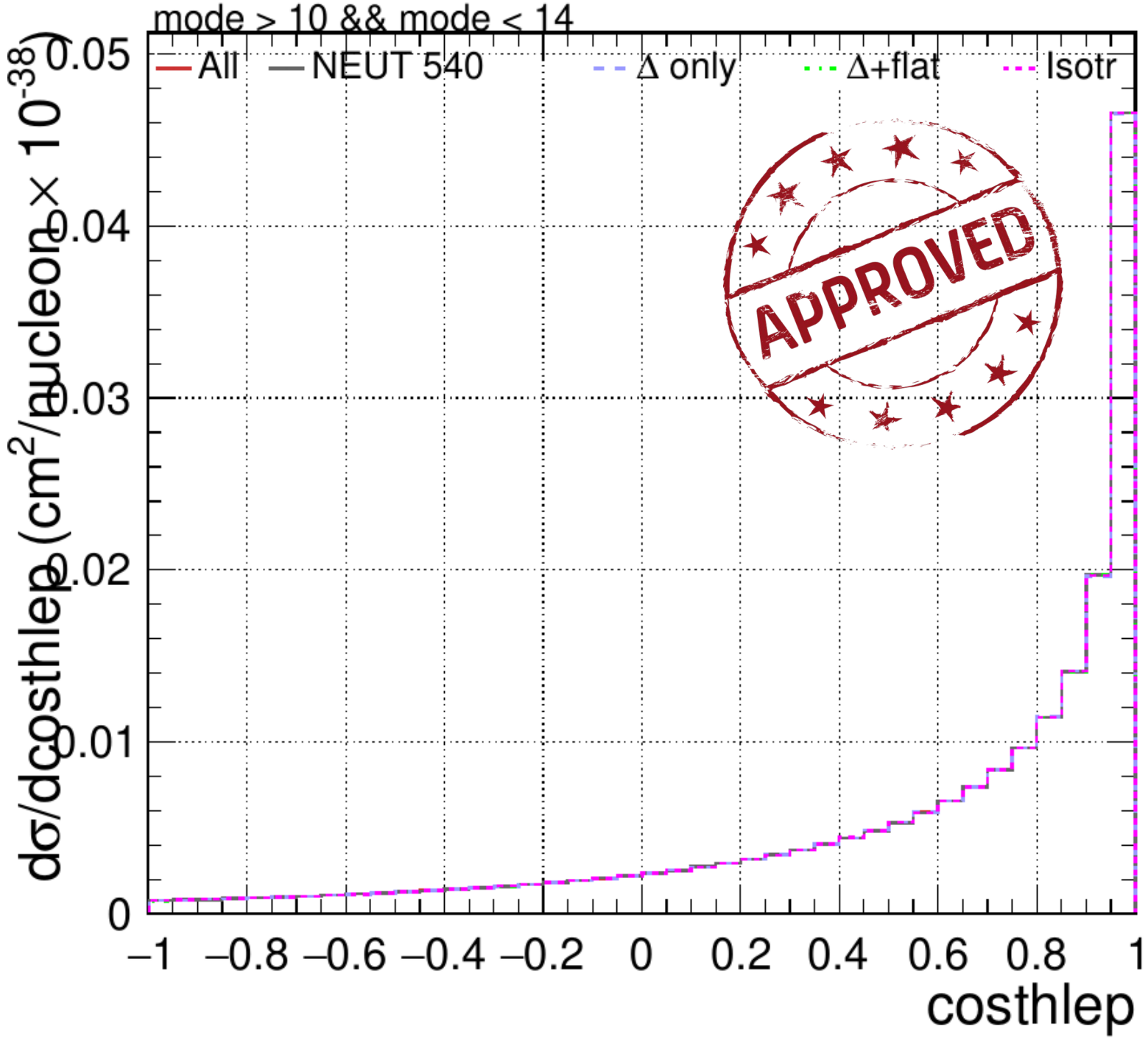

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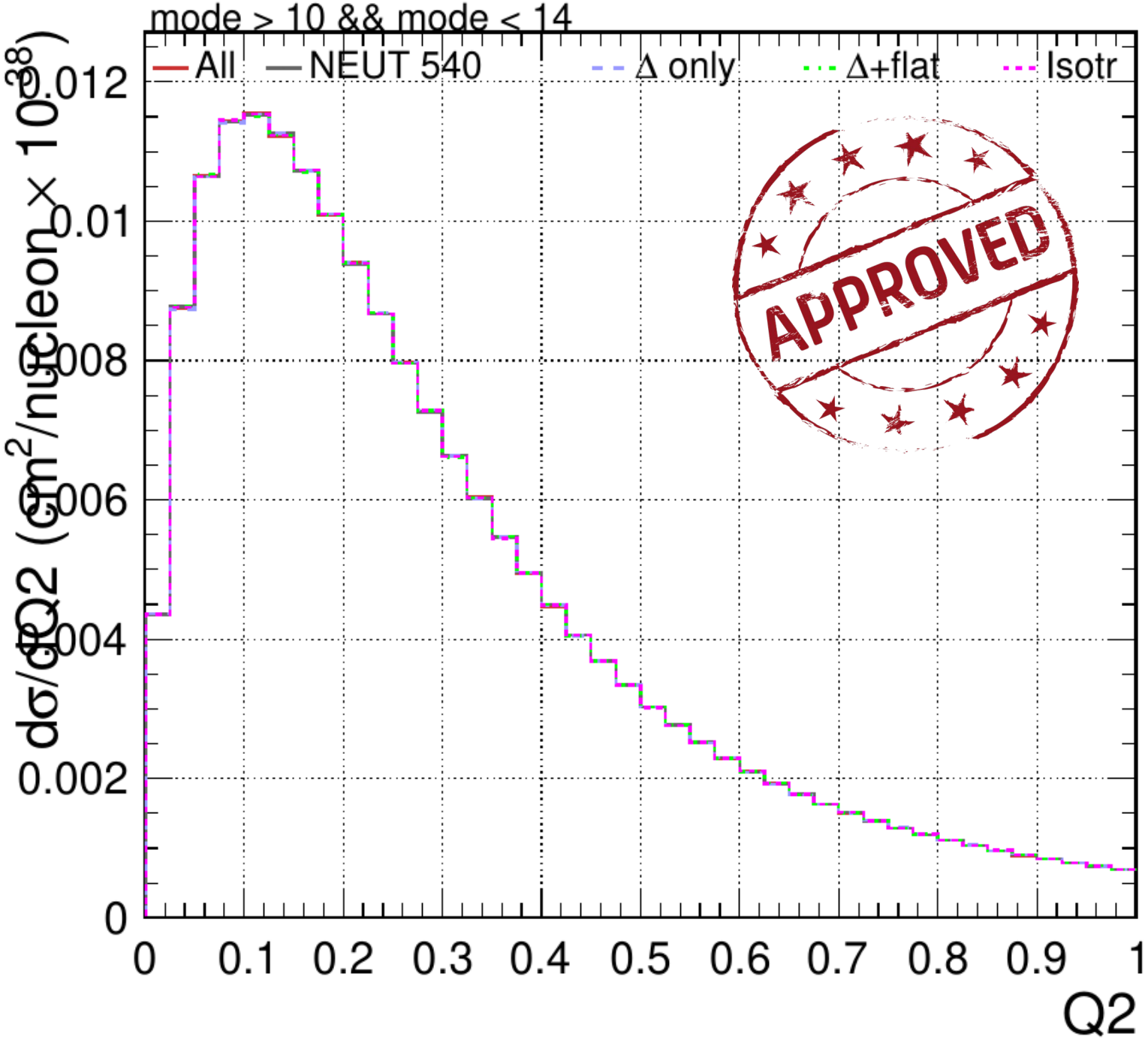
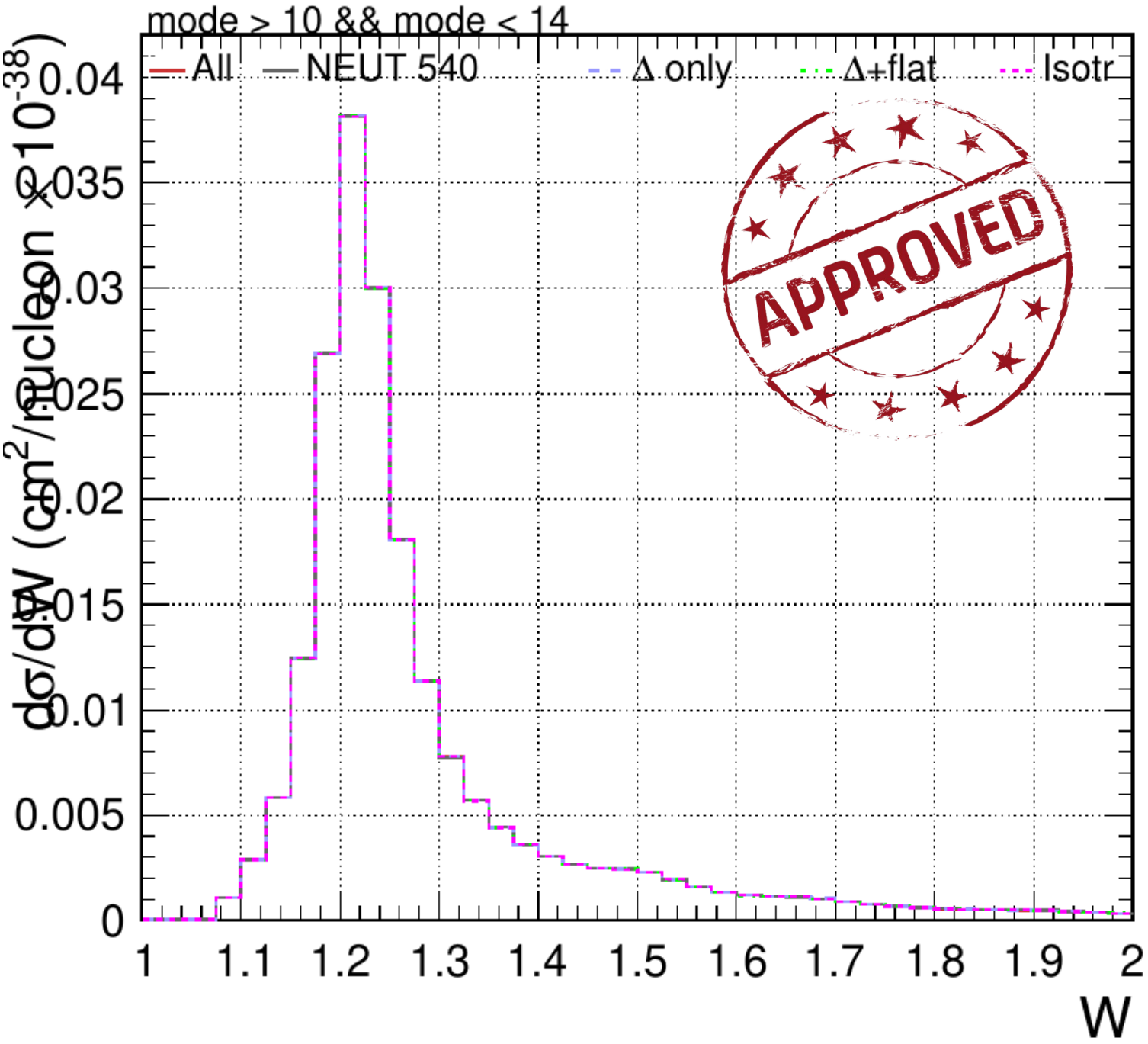


Validating the dial



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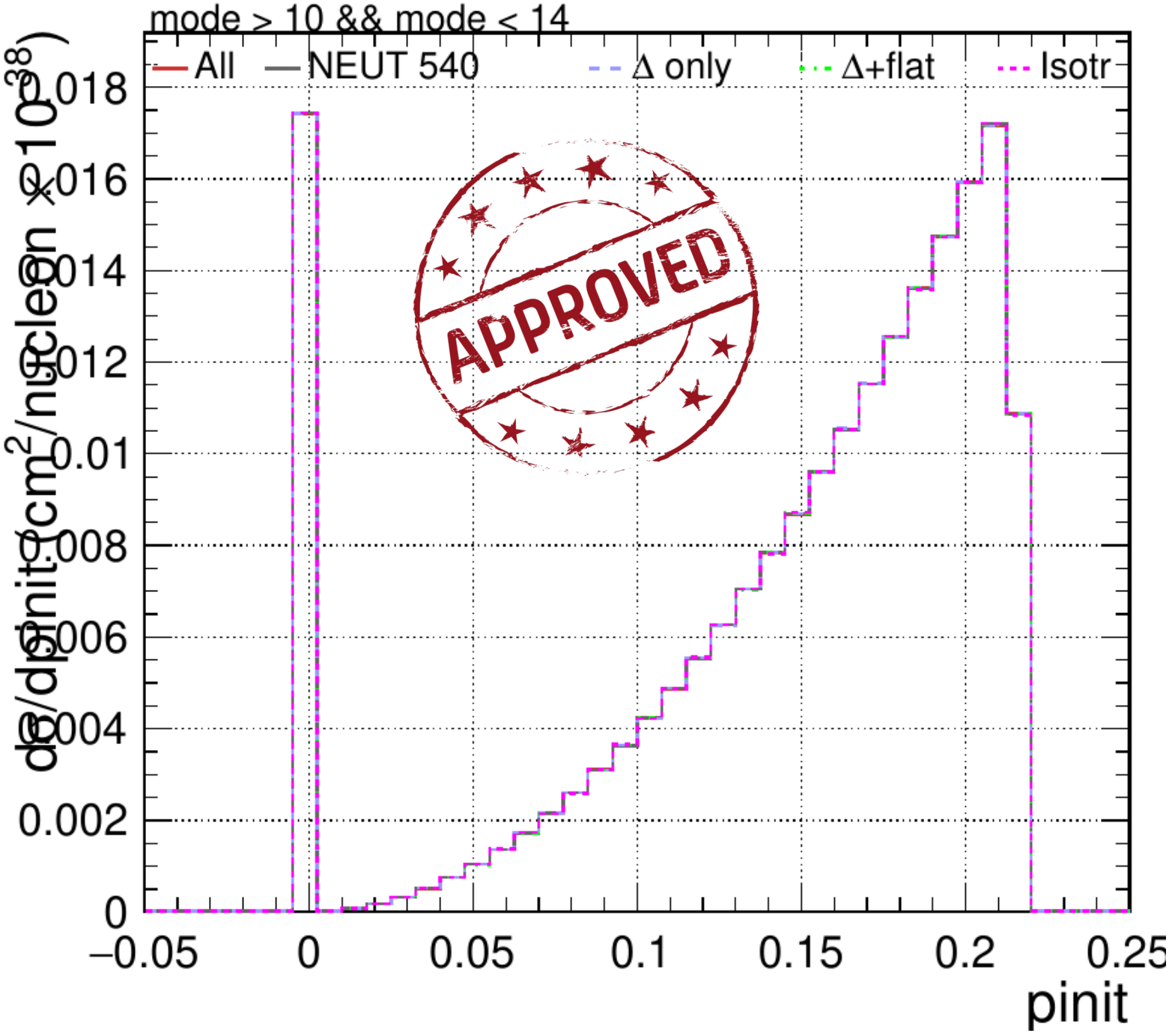
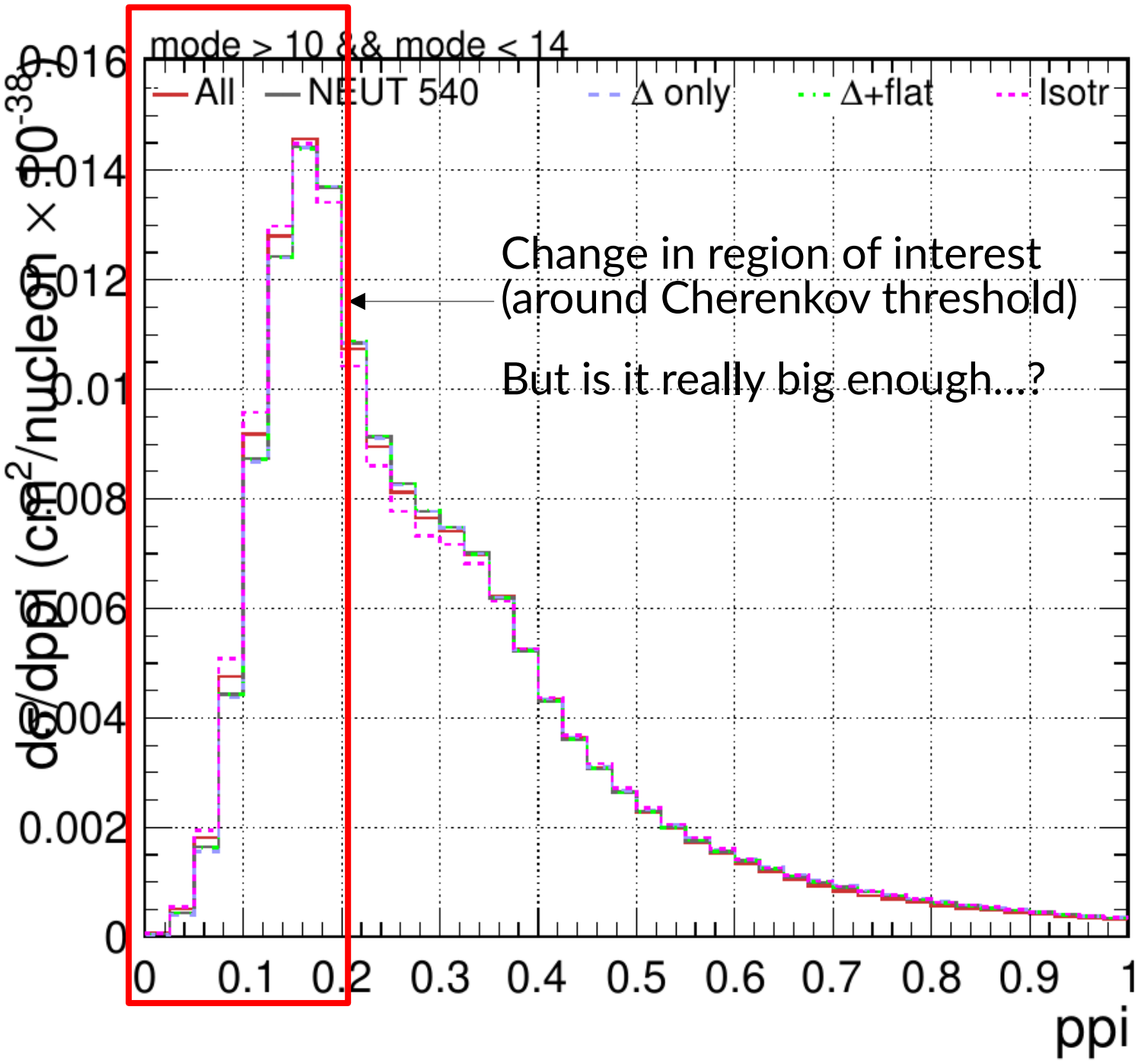


Validating the dial

- Looks like we're not changing anything in the leptonic variables
- And we're agreeing with previous NEUT 540

- What about the pion+nucleon system?

Validating the dial



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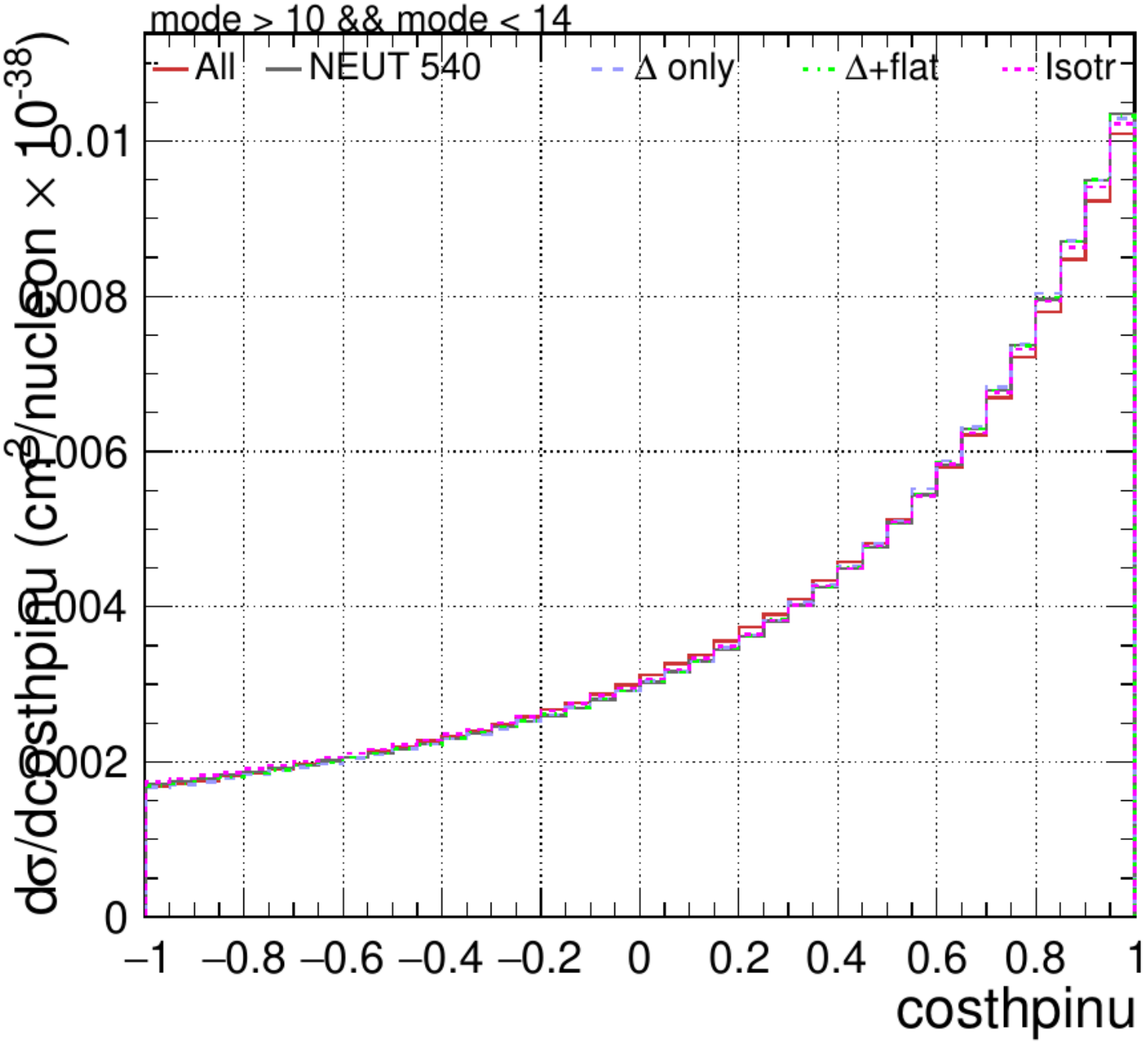

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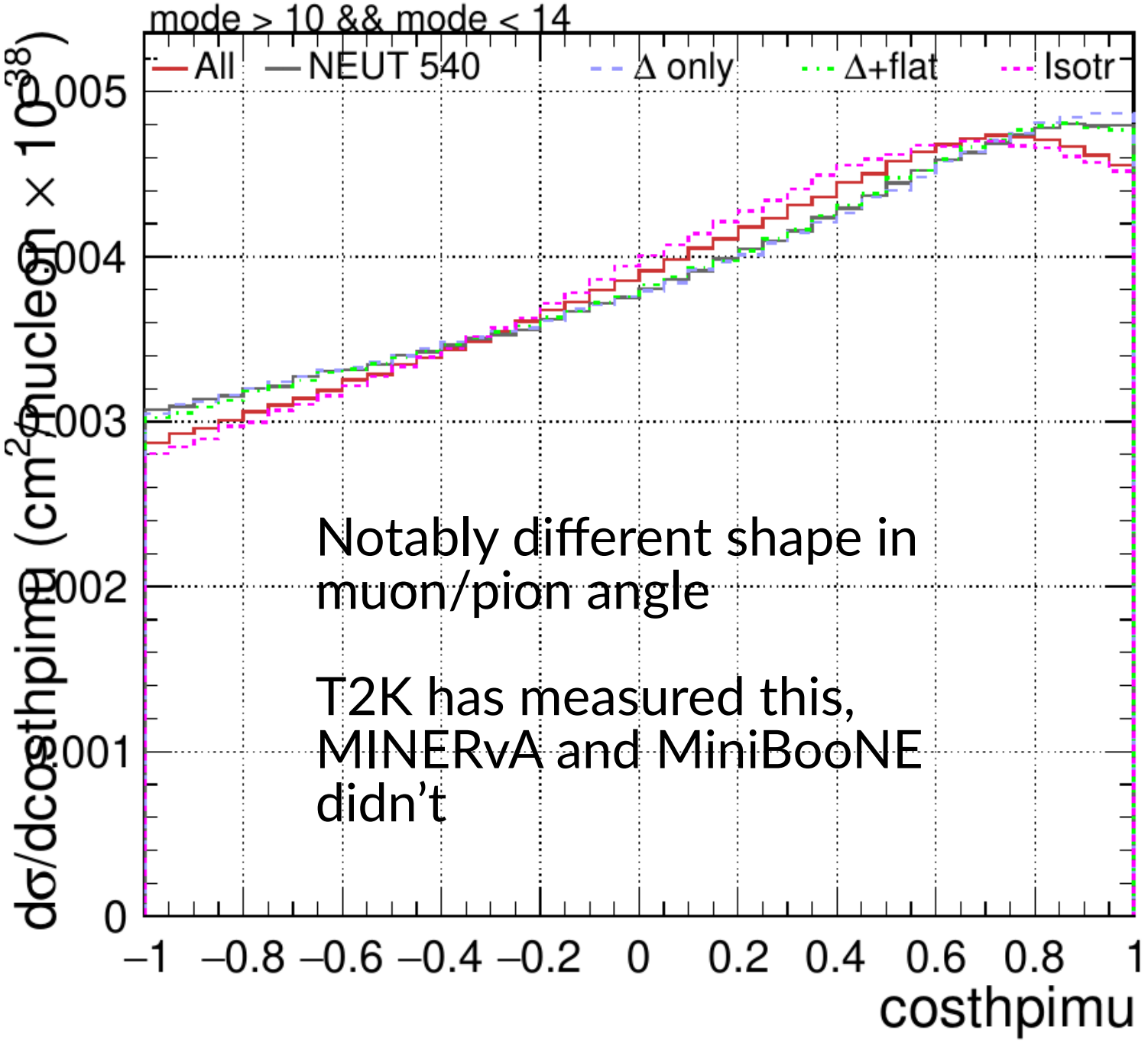
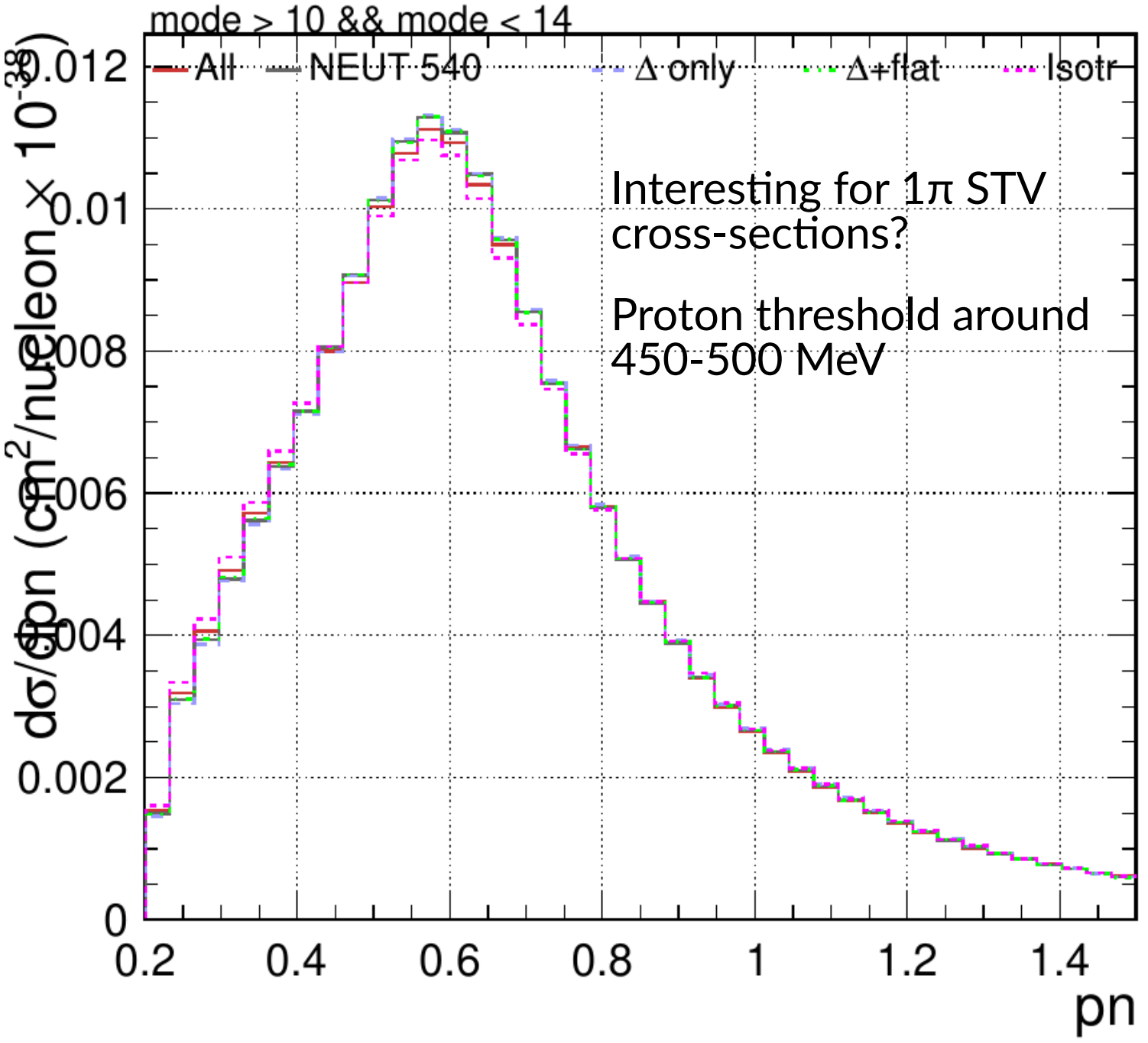


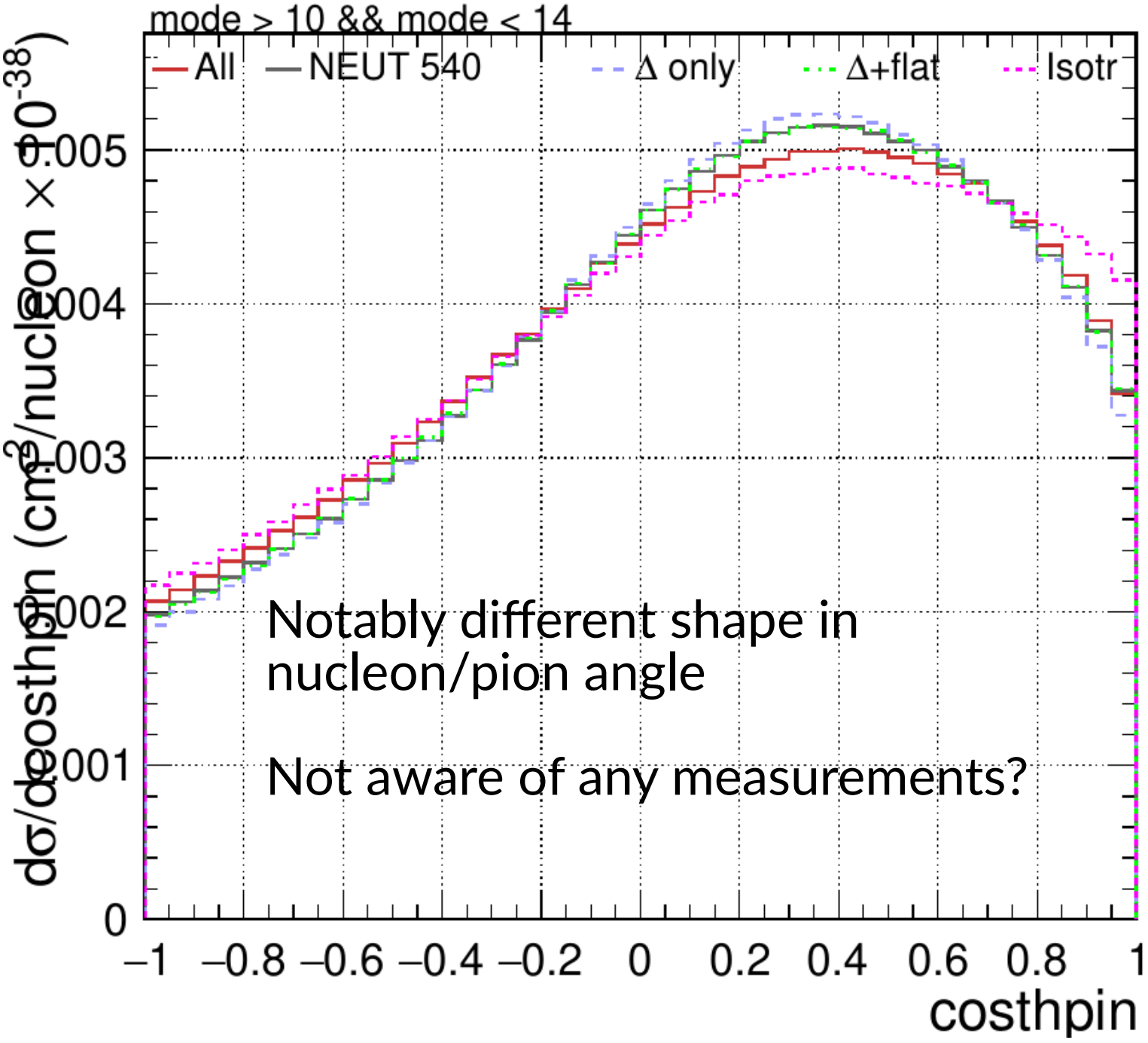
Notably different shape in muon/pion angle

T2K has measured this, MINERvA and MiniBooNE didn't

Validating the dial



Validating the dial



Validating the dial

- Looks like we're hitting the target
- Δ(1232)+flat is identical to NEUT 540, as expected
  - Additionally similar to Δ(1232) only

- pion/muon, pion/nucleon angles and pion momentum looks most affected, perfect!

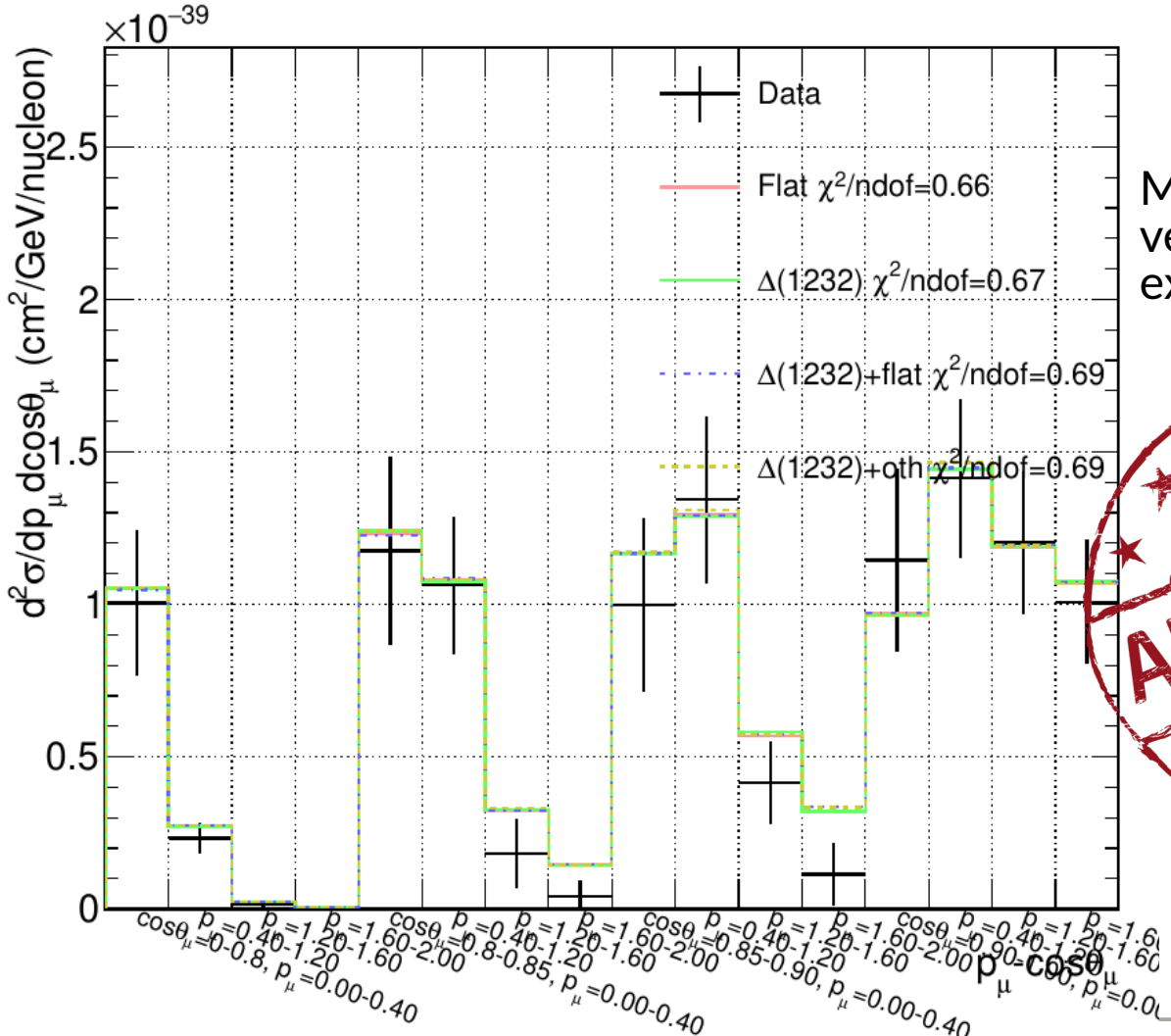
- Not shown: the different interaction channels ($CC1\pi^+1p$, $CC1\pi^0$, $CC1\pi^+1n$) has different responses
  - $CC1\pi^+1p$ being Δ(1232) dominated has smallest effect, other channels have bigger effect
  - $CC1\pi^+1p$ is dominant over $CC1\pi^+1n$ by ~ factor 3
  - Interesting to see what happens at higher energies where other resonances more important (e.g. MINERvA!)

Next steps

- Compare to some external data to gather constraints?
  - ANL and BNL H_2/D_2 can constrain these relatively well with Adler angles
  - But am more interested in pure pion kinematics, and nuclear data
- Ran on some T2K CH data to gauge the effect

T2K data

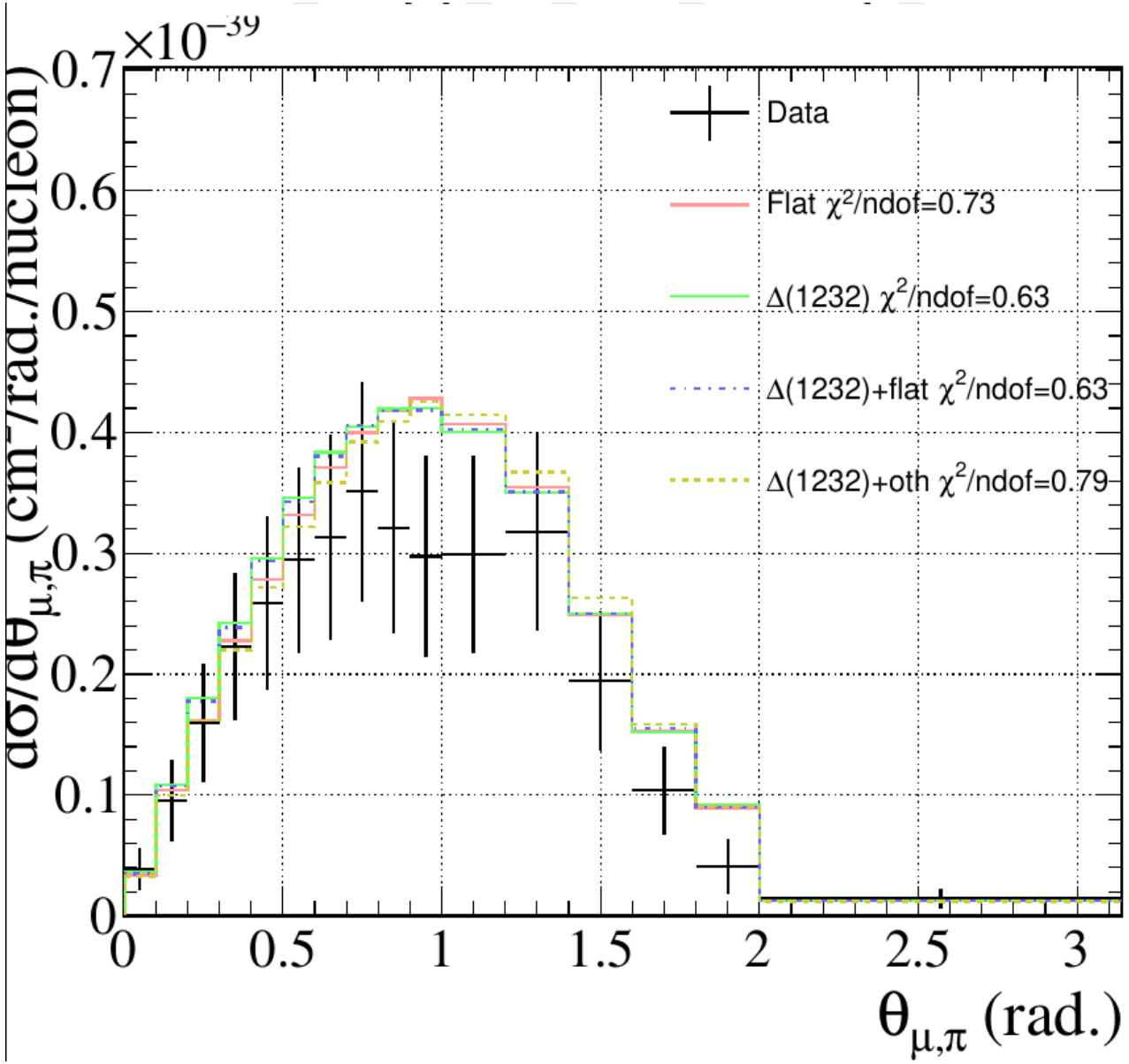
- Cross-section data may be relatively insensitive due to signal definition
  - e.g. many of T2K's measurements of pion kinematics cuts out $p_\pi < 0.2$ GeV, $\cos\theta_\pi < 0.2$: this is not the case for OA



Muon variables very similar, as expected

T2K data

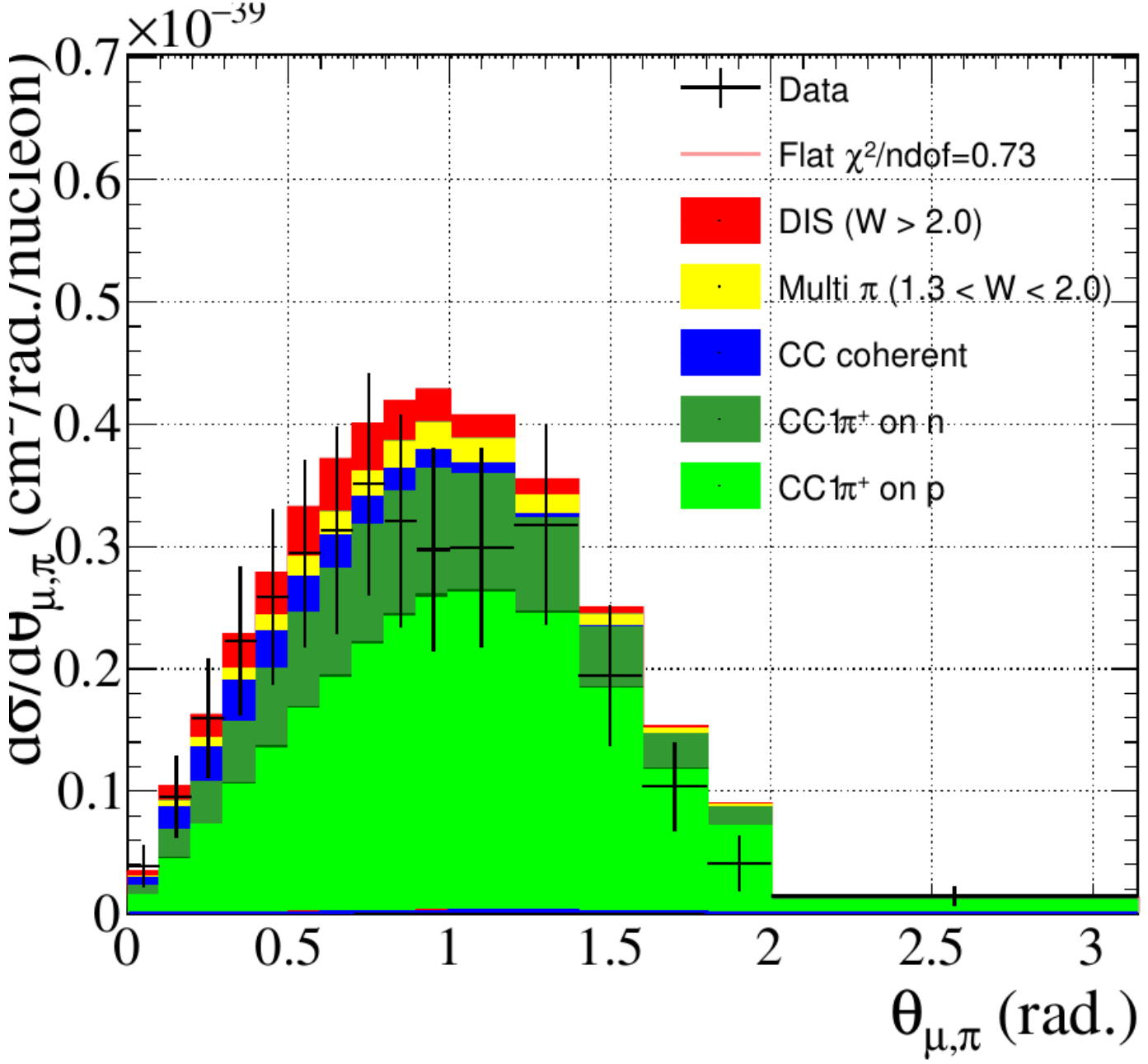
- Clear effect on prediction, and different to old NEUT using Δ(1232) only



Does cut on $p_\pi < 0.2$ GeV, $\cos\theta_\pi < 0.2$

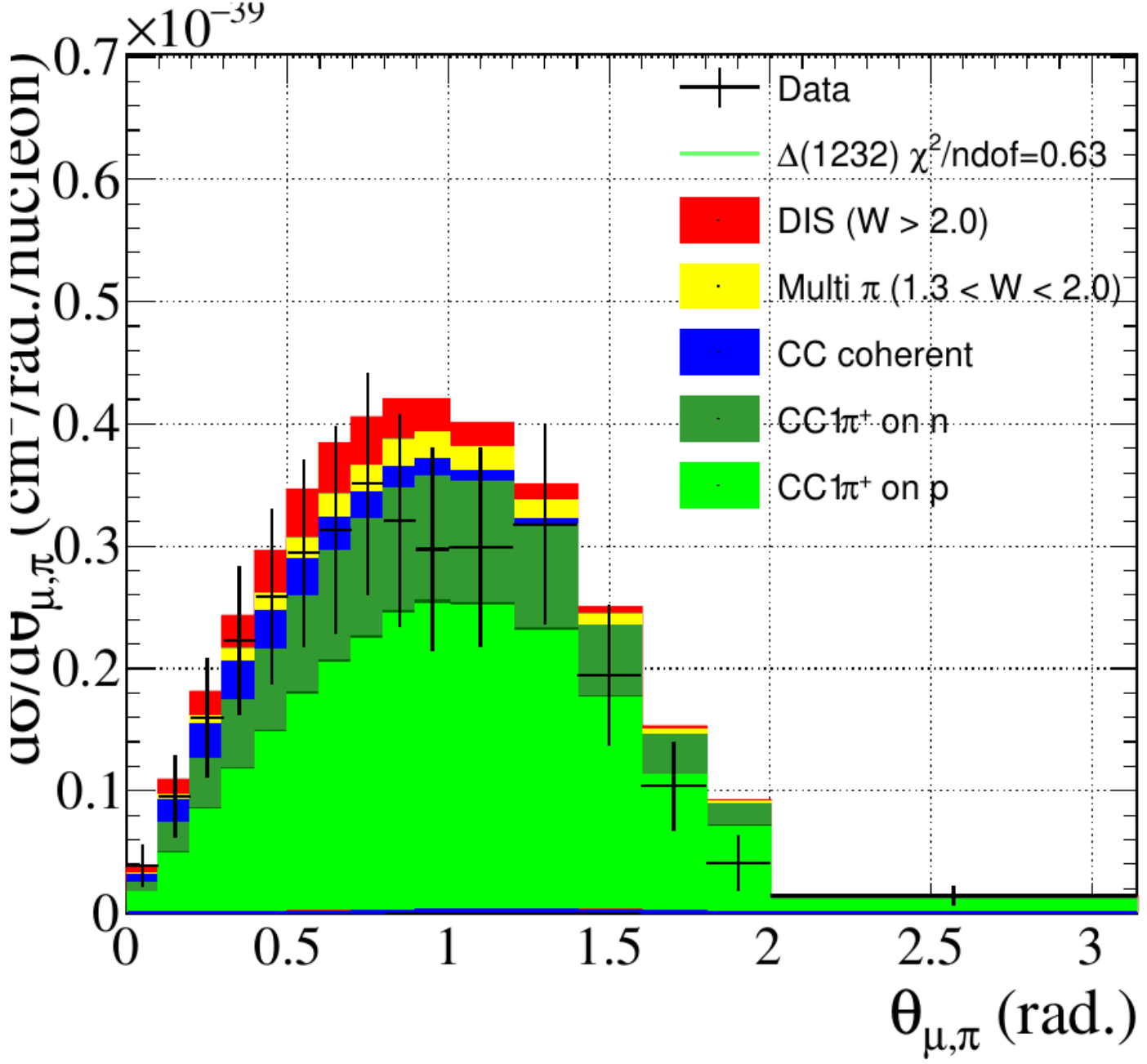
T2K data

- Looking by mode, flat/isotropic



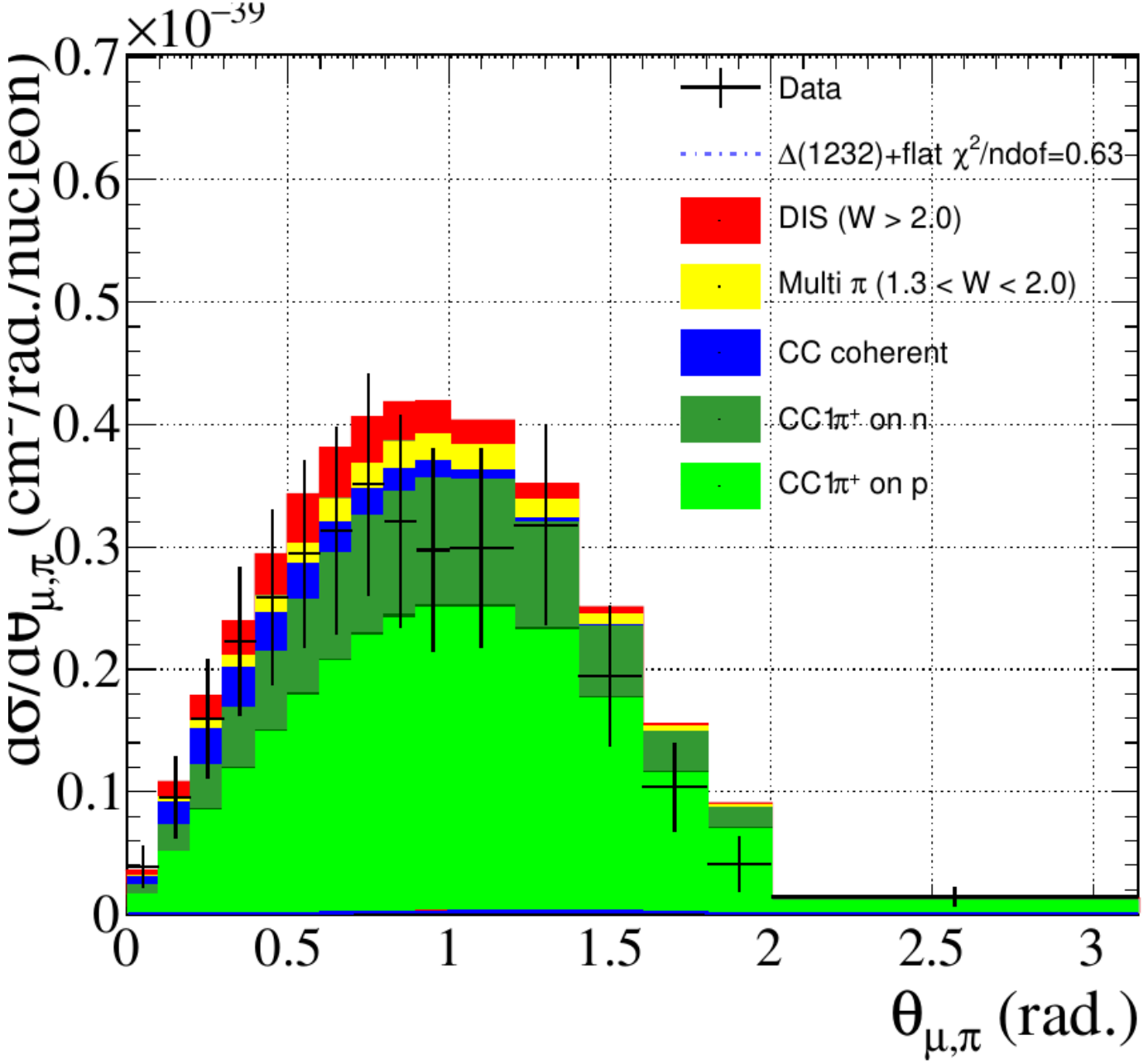
T2K data

- Looking by mode, Δ(1232) only



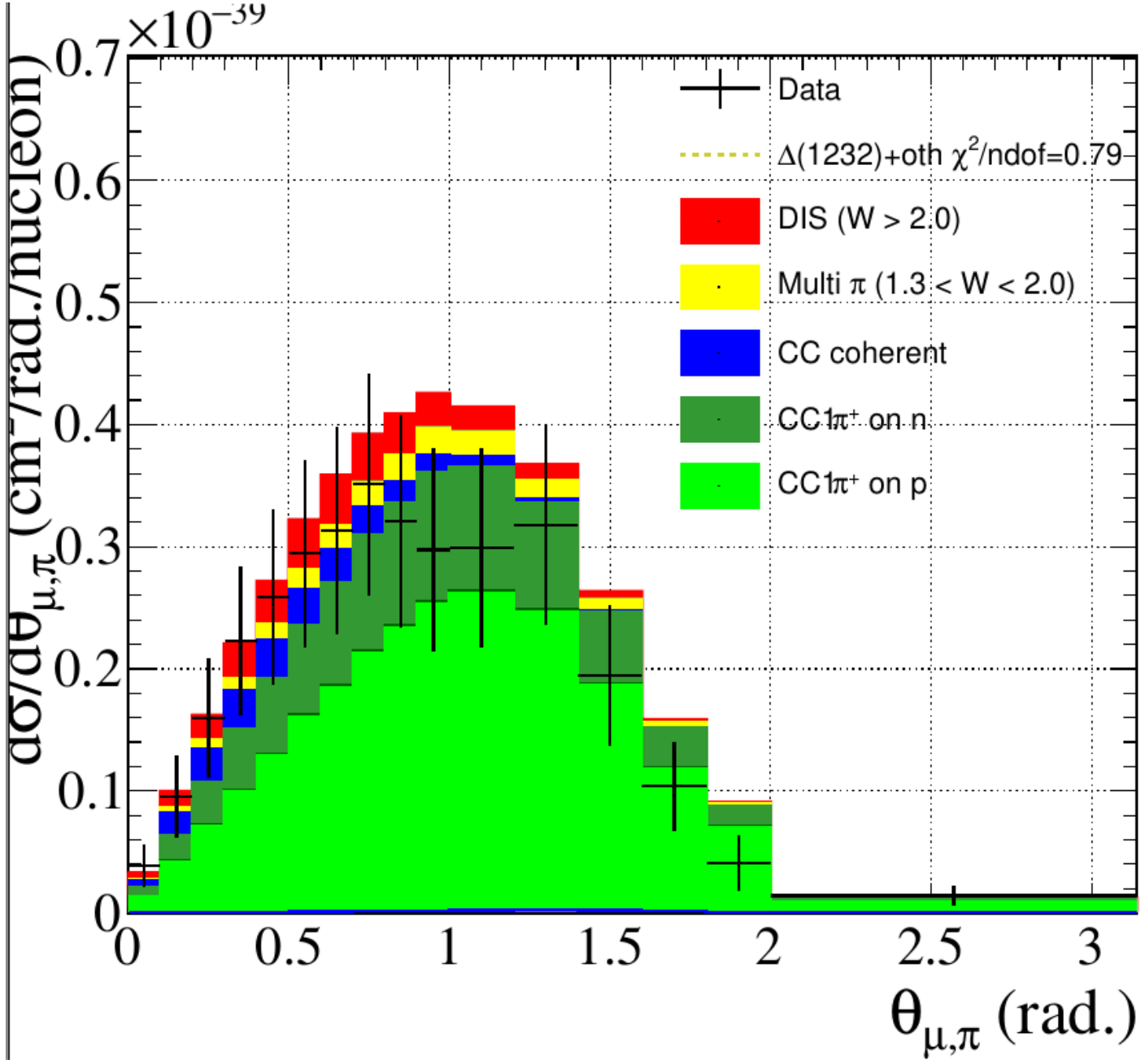
T2K data

- Looking by mode, Δ(1232)+flat



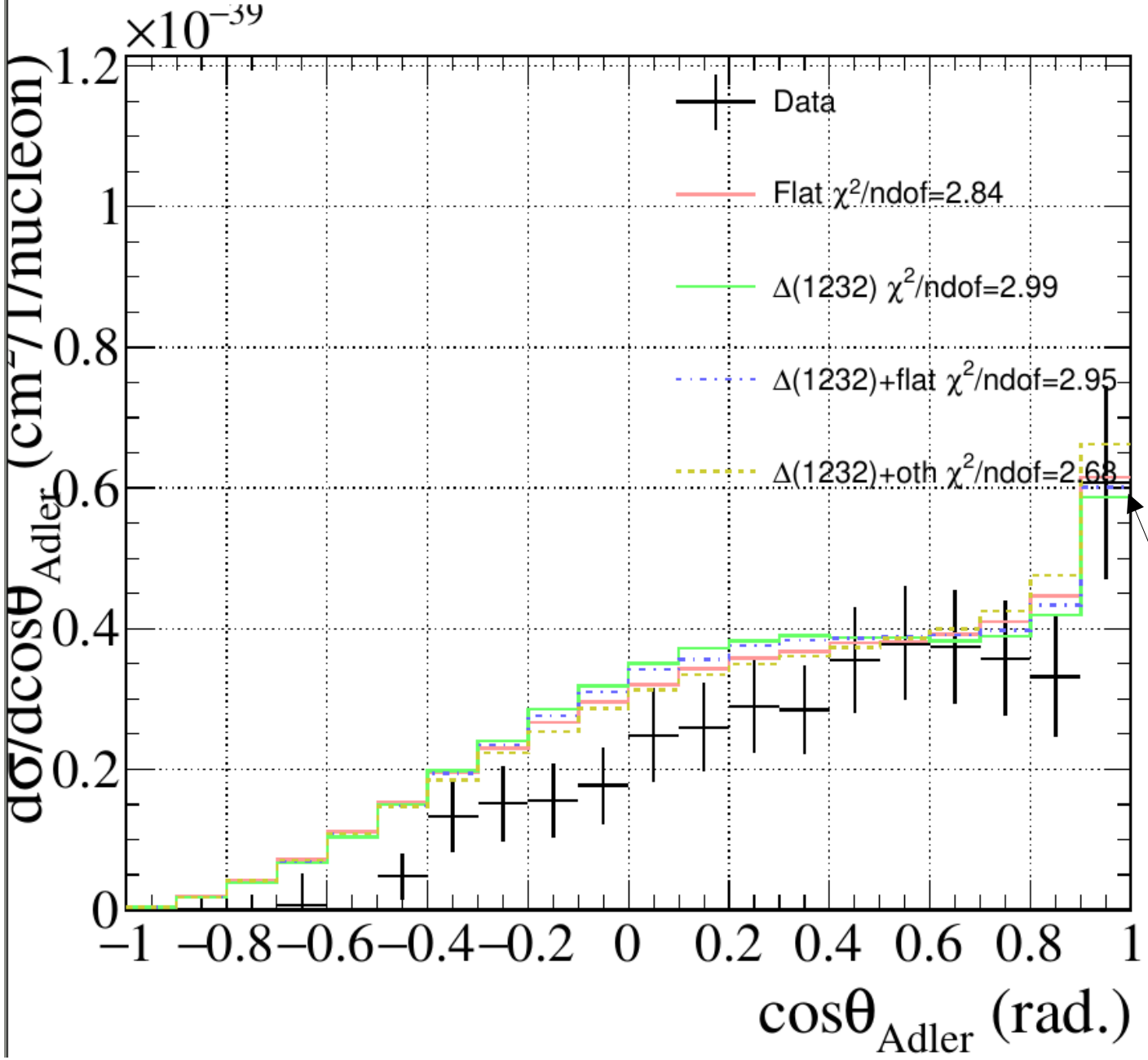
T2K data

- Looking by mode, Δ(1232)+other



T2K data

- T2K Adler angle using leptonic info

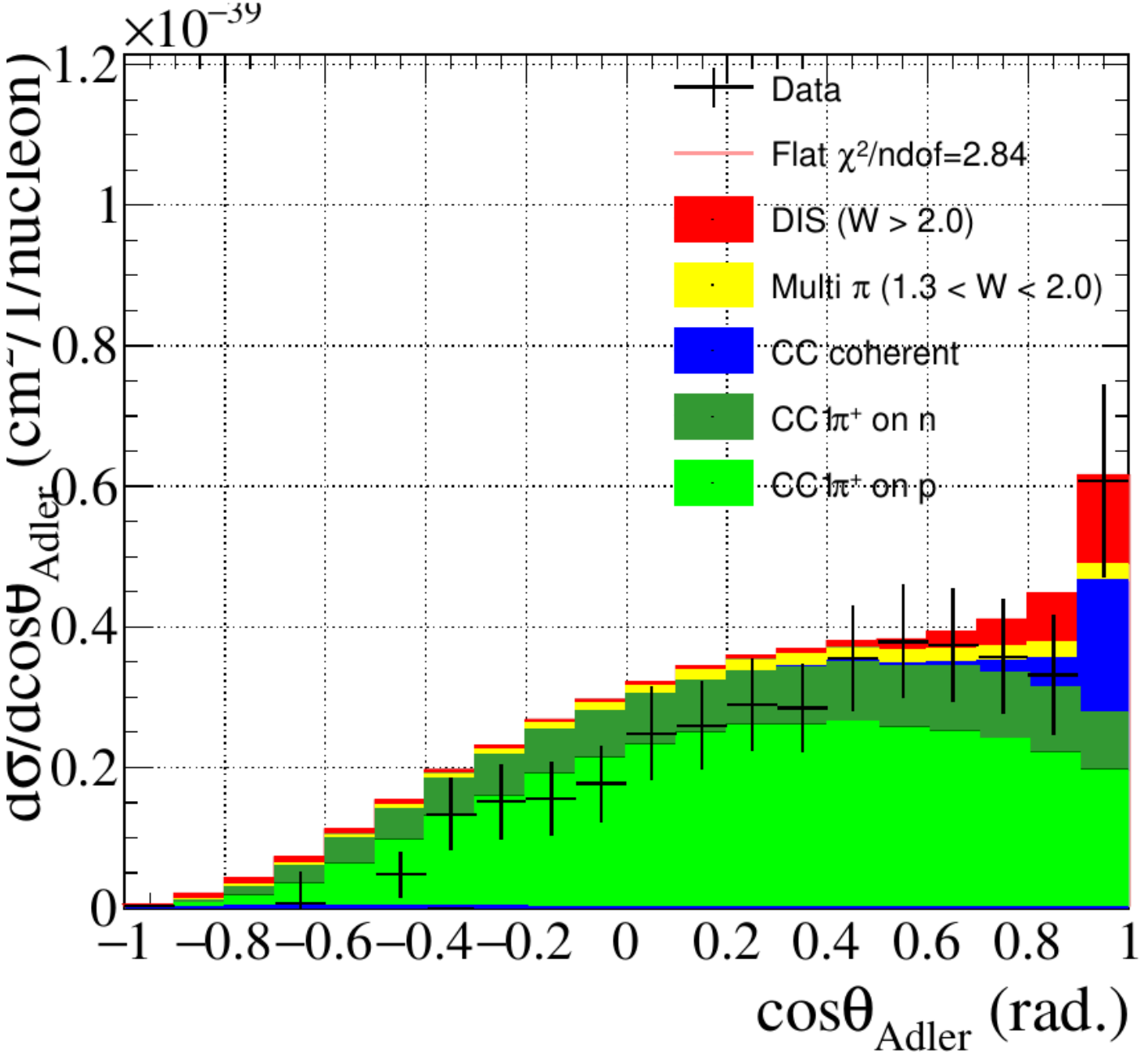


Does cut on $p_\pi < 0.2$ GeV, $\cos\theta_\pi < 0.2$

Biggest difference in forward

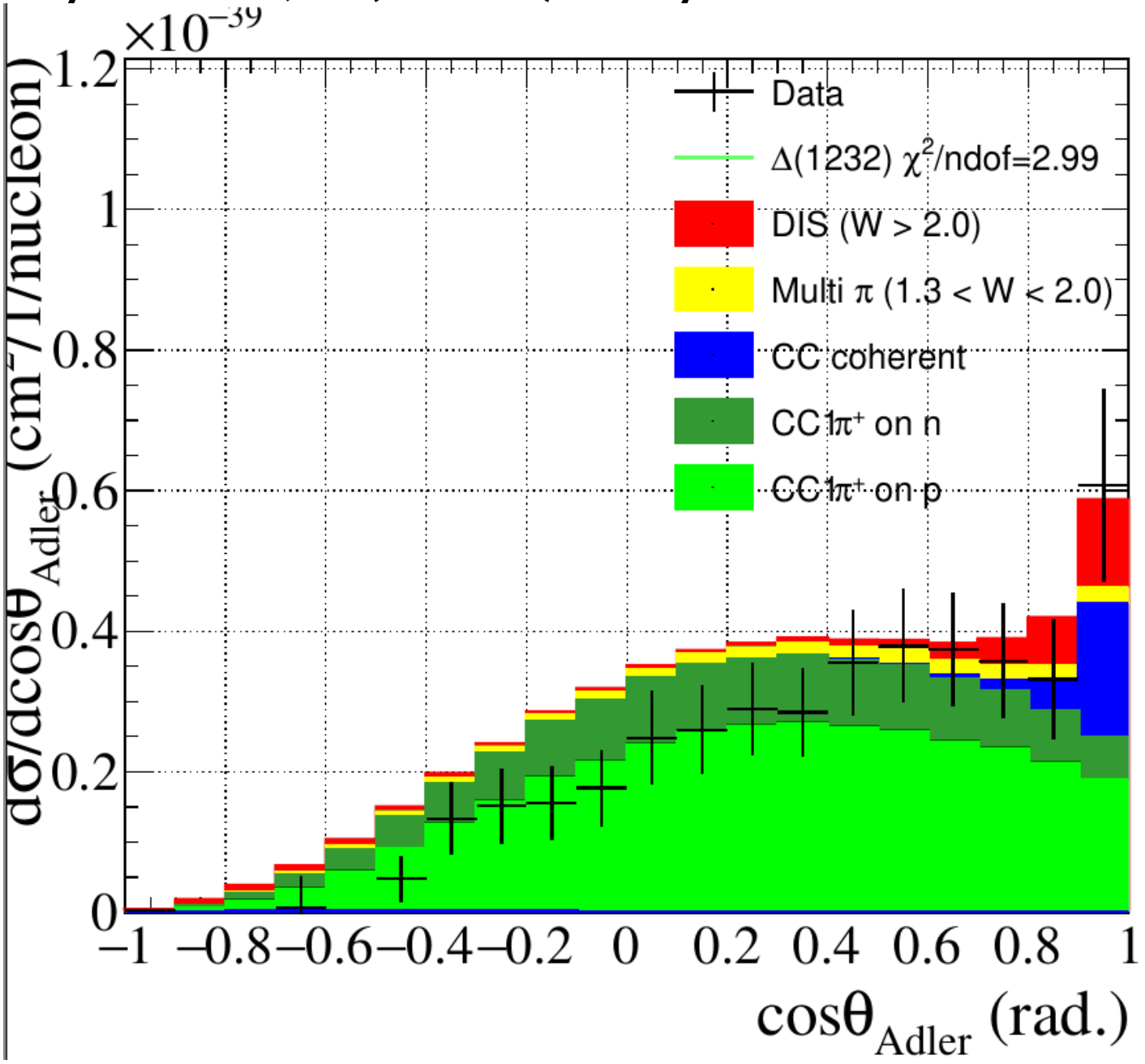
T2K data

- Looking by mode, flat/isotropic



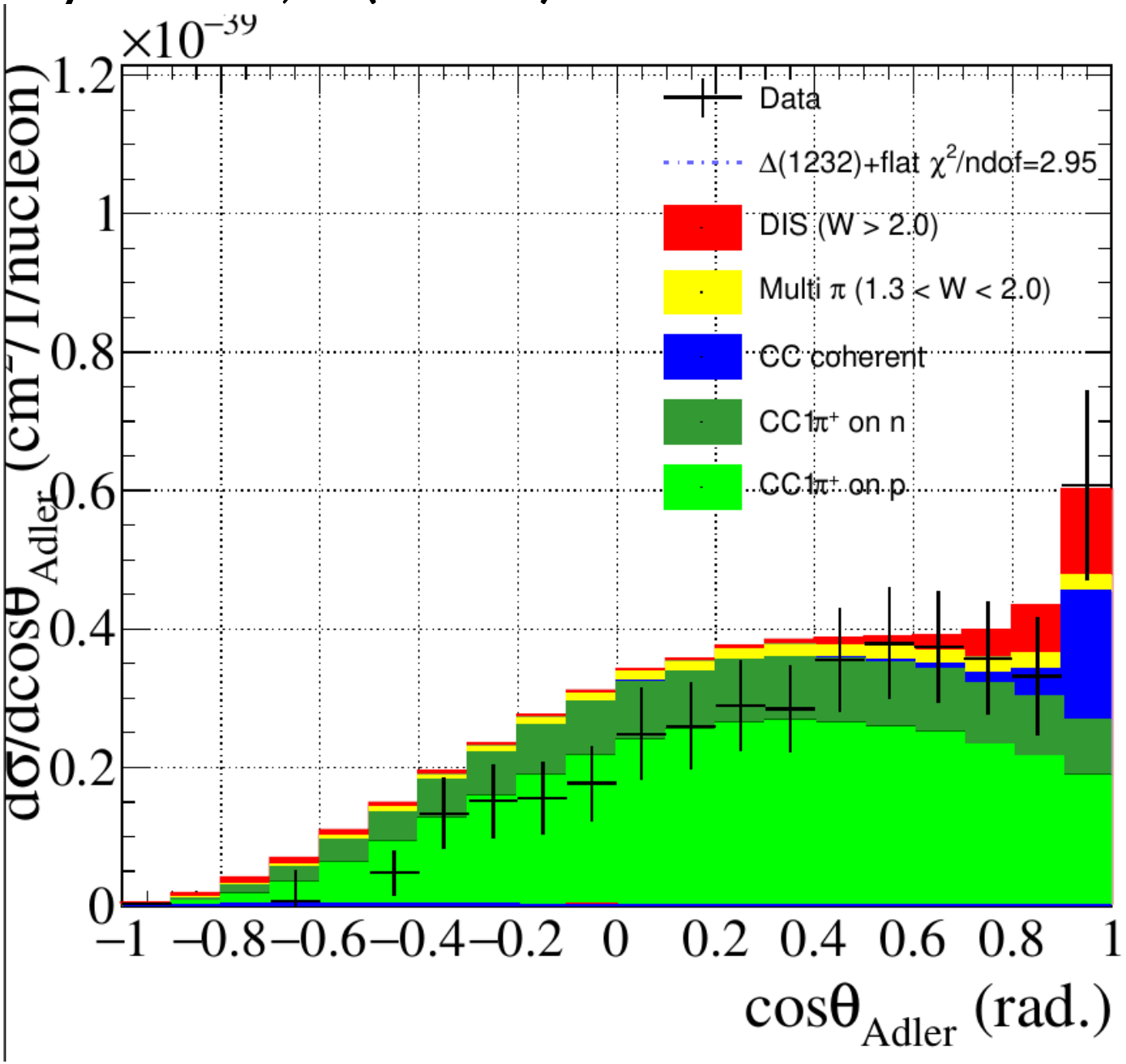
T2K data

- Looking by mode, Δ(1232) only



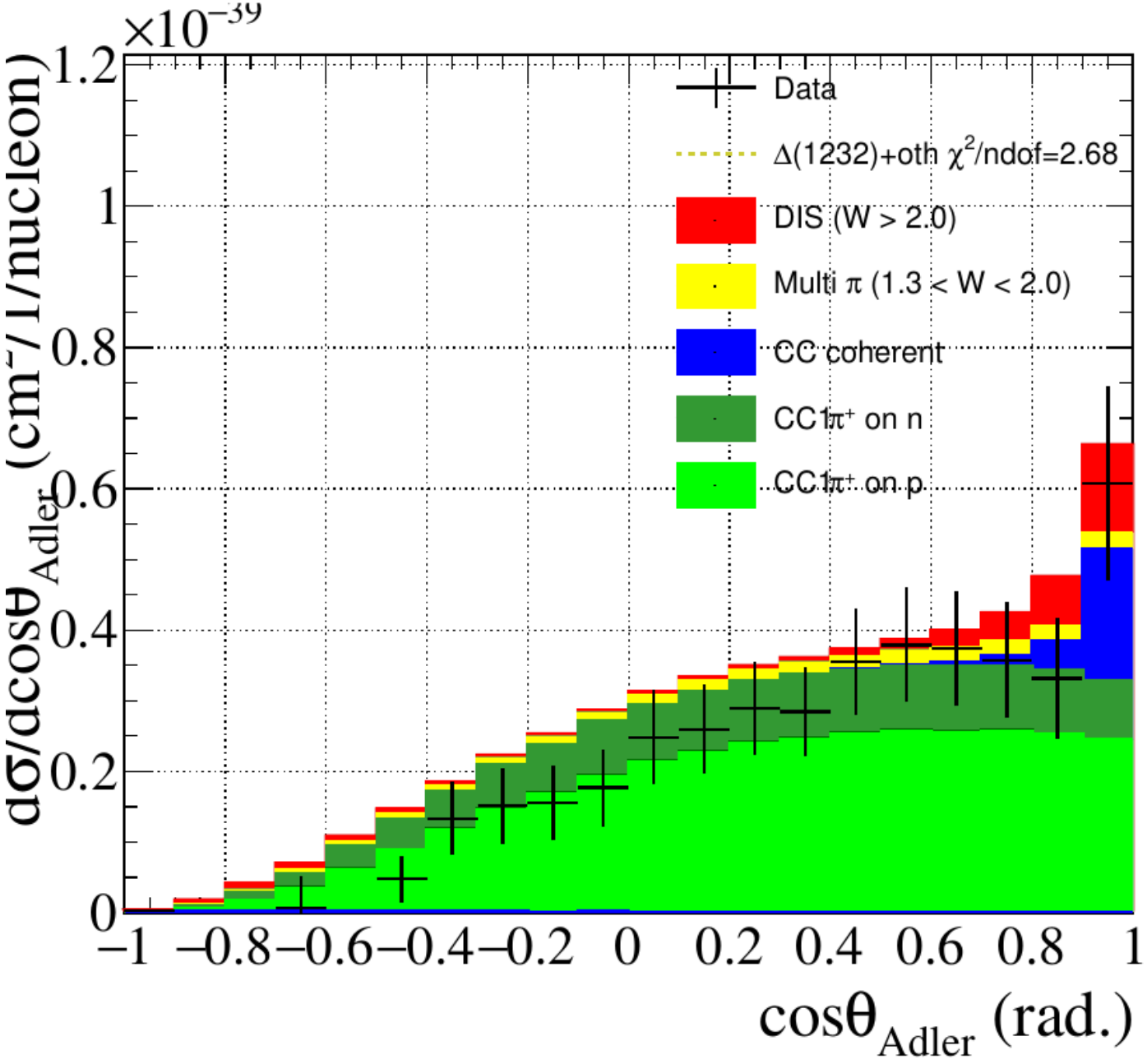
T2K data

- Looking by mode, Δ(1232)+flat



T2K data

- Looking by mode, Δ(1232)+other



Next steps

- (probably) not use external data to constrain, since little is available over whole region of interest
  - Instead leave as a free parameter
- Enhance effect beyond “realistic physics” to have ability to manipulate pion spectrum even more?
- Write reweighting routine to include in T2K analysis
  - Can’t be a “normal” reweight since the differential cross-section in W, E_ν, Q^2 doesn’t change
  - Need to use the $W(\theta,\varphi)$

Summary

- Devised a physics-sane single pion uncertainty, not currently included in any analyses I'm aware of
  - Hopefully included in next T2K analysis with pions
- Affects only pion/nucleon system by definition; invariant in lepton, Q^2, E_ν, initial state etc
- Effect is right at the intended region: Cherenkov/tracking threshold for pions and proton
  - But may not be big enough?
- For cross-section data, T2K results doesn't see full effect due to pion tracking requirement (cuts out largest part of effect at low momentum)
  - Will produce MINERvA comparisons too
- Writing a reweighting routine for this

Thanks