Single pion uncertainties for T2K's oscillation analysis

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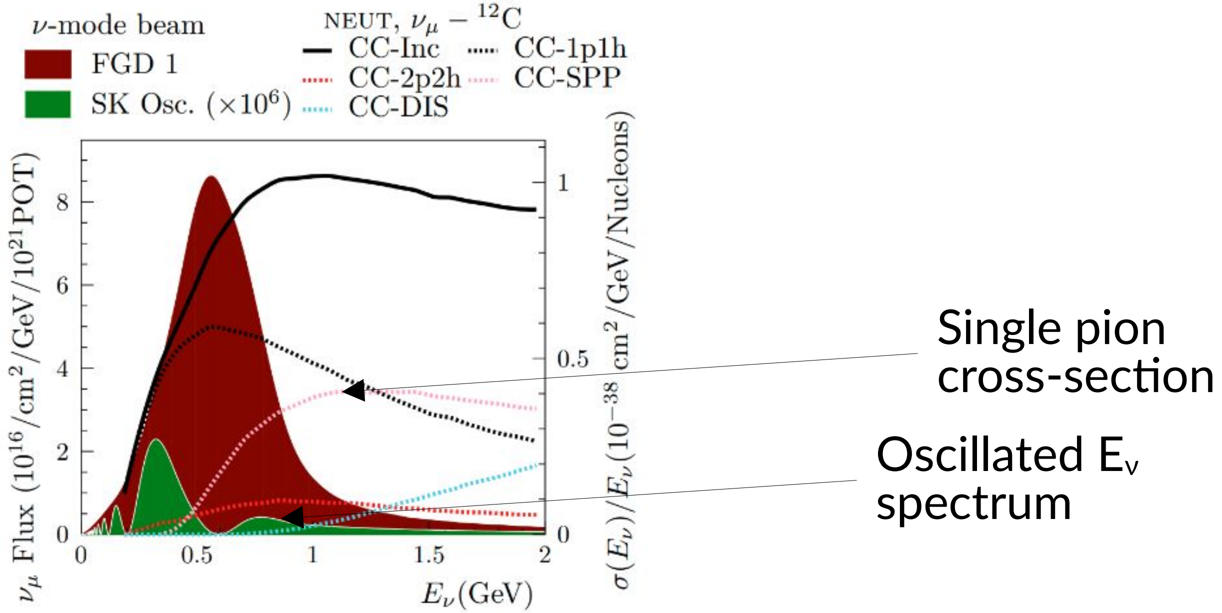
Introduction

- Single pion production uncertainties revised
  - Yet another pion kinematics uncertainty
  - $CC1\pi^+/CC1\pi^0$ scaling
  - Low Q^2 suppression

Background

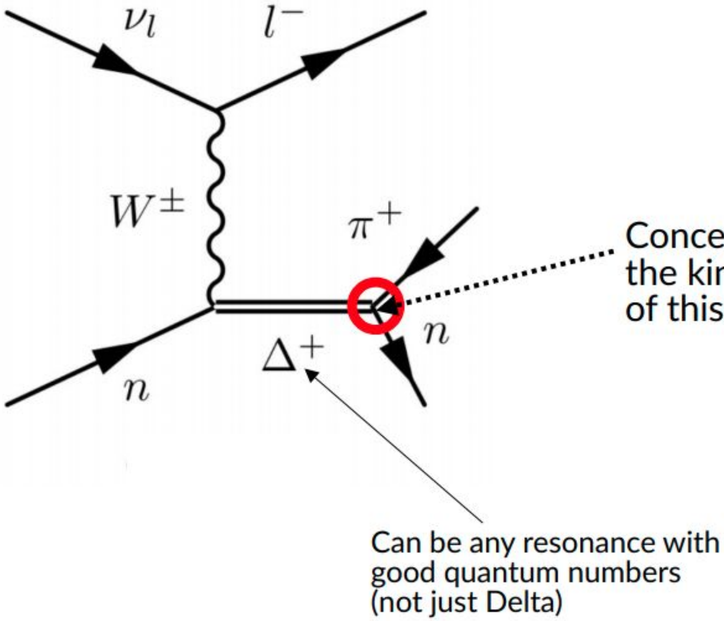
- T2K is introducing new “2 ring” selections this year
  - One ring from muon, one ring from pion above Cherenkov threshold
  - One ring from muon, one below-Cherenkov pion (Michel tagged)
- → Large number of 1π events into next oscillation analysis



- Higher E_ν → smaller oscillation effect, but will contribute to the constraint at the maximum
- Separately, joint T2K-SK atmospheric fit needs robust single pion uncertainty if we want to constrain sub-GeV atmospheric samples

Background

- Working on uncertainties that change the pion kinematics predominantly
- Focusing on when a resonance decays into πN system



If we only have a Delta resonance, this is the shape term

ϱ are combinations of matrix elements

$$W^\Delta(\theta,\phi) = \frac{1}{\sqrt{4\pi}}\frac{1}{\tilde{\rho}}\left\{Y_0^0\tilde{\rho} - \frac{2}{\sqrt{5}}Y_0^2\left(\tilde{\rho}_{33} - \frac{1}{2}\rho\right) + \frac{4}{\sqrt{10}}\left(\mathrm{Re}Y_1^2\mathrm{Re}\tilde{\rho}_{31} - \mathrm{Re}Y_2^2\mathrm{Re}\tilde{\rho}_{3,-1}\right)\right\}$$

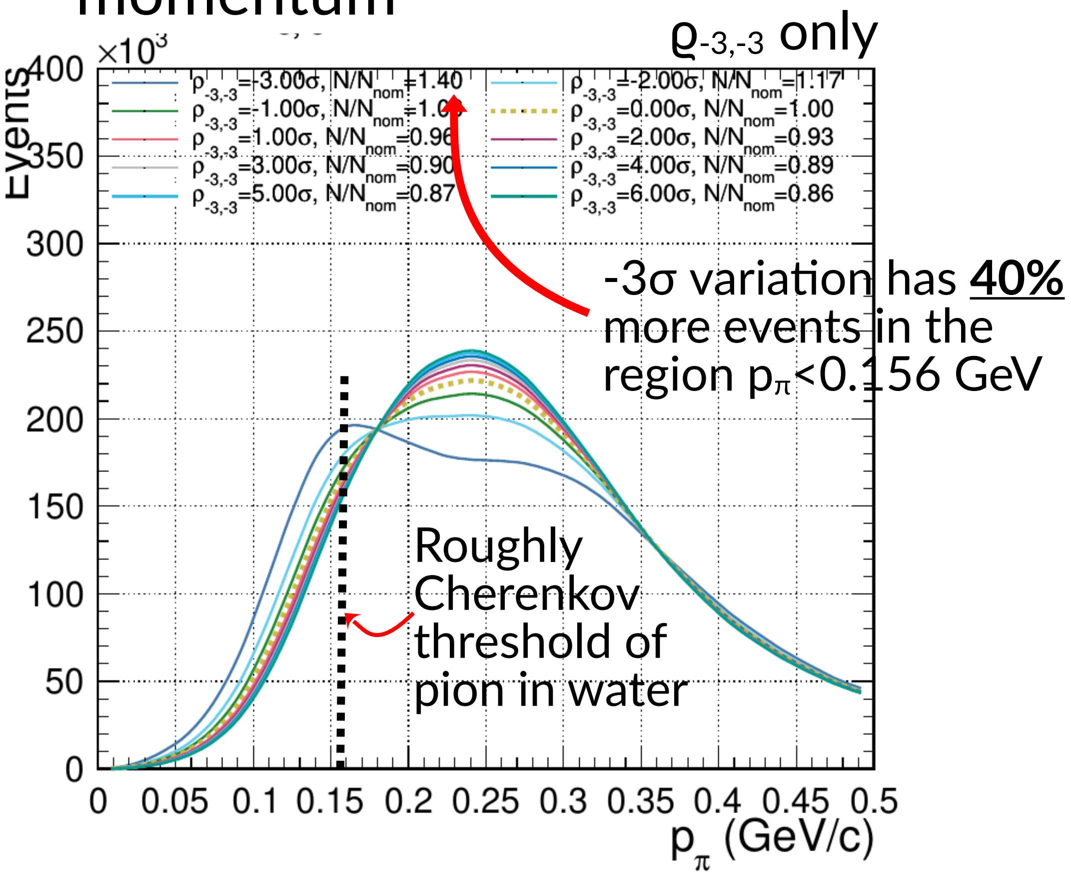
$$\tilde{\rho} = \sum_{j_z}\rho_{j_z j_z}\,,$$
$$\tilde{\rho}_{33} = \rho_{3/2\,3/2} + \rho_{-3/2\,-3/2}\,,$$
$$\tilde{\rho}_{31} = \rho_{3/2\,1/2} - \rho_{-1/2\,-3/2}\,.$$
$$\tilde{\rho}_{3-1} = \rho_{3/2\,-1/2} + \rho_{1/2\,-3/2}$$

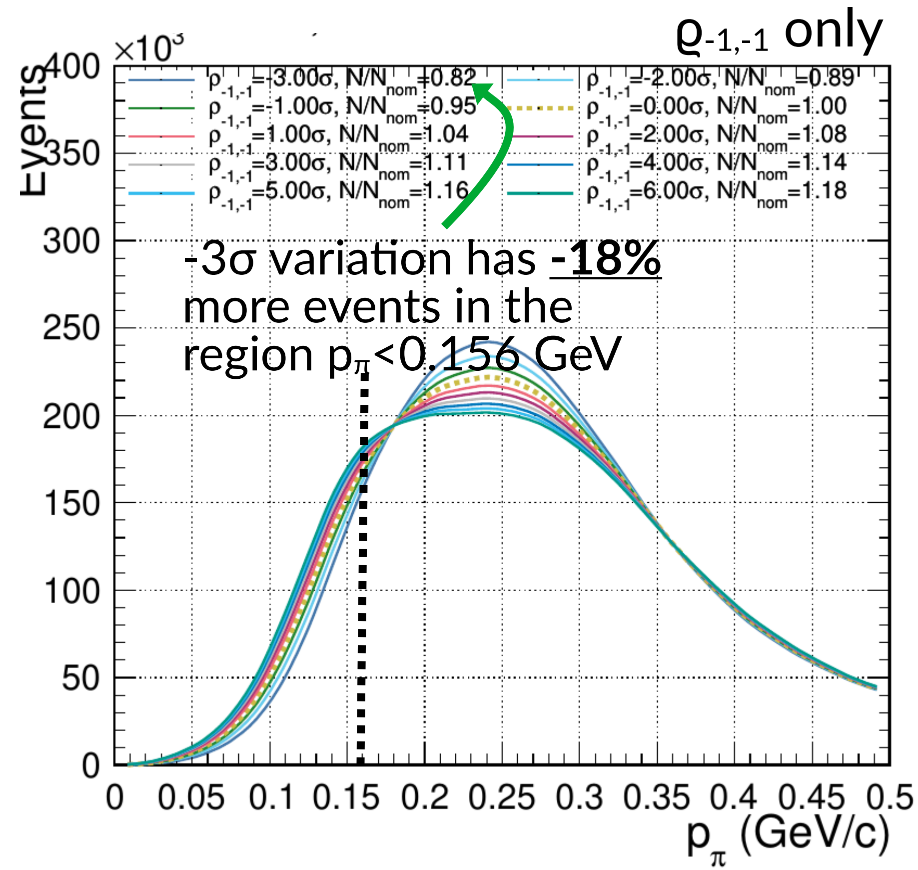
Y^l_m are spherical harmonics

- Previously showed that the number of resonances included in calculation produces uncertainty in pion kinematics
- This time looking at scaling the contributing **matrix elements** instead, using the Δ(1232)-only case

Combining elements

- Looking at individual variations of $\varrho_{mm'}$ and its effect on pion momentum

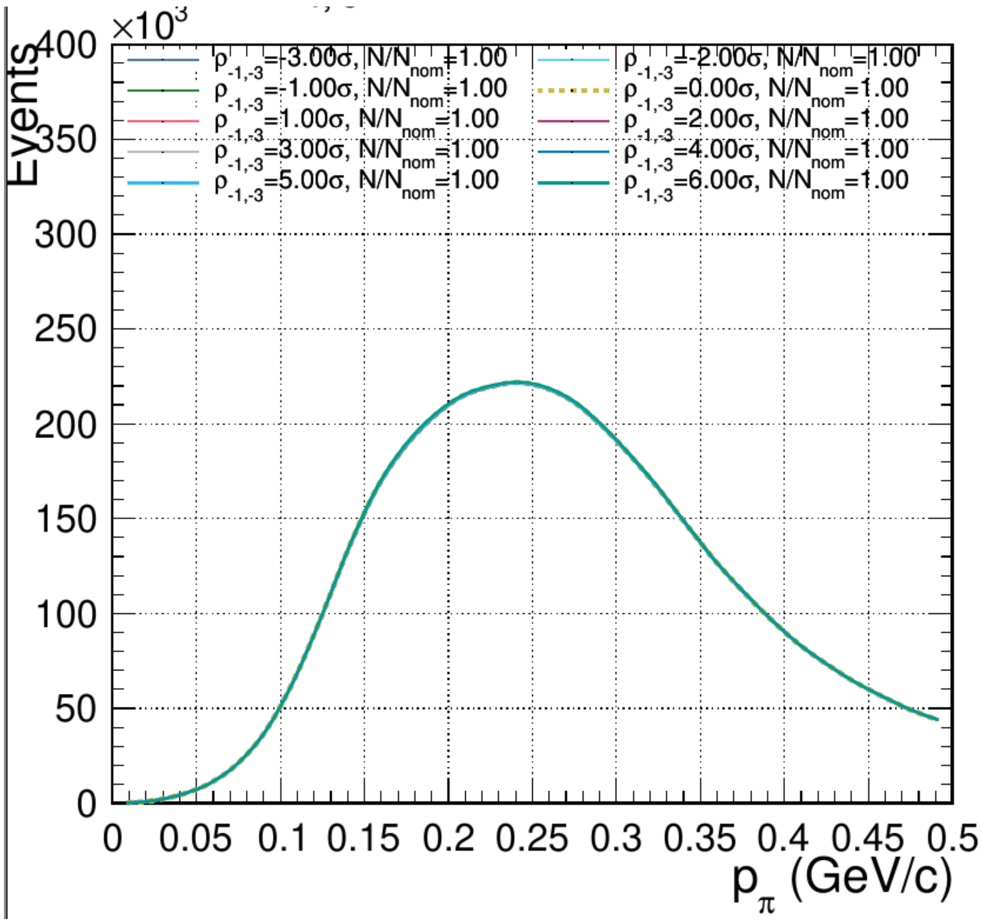


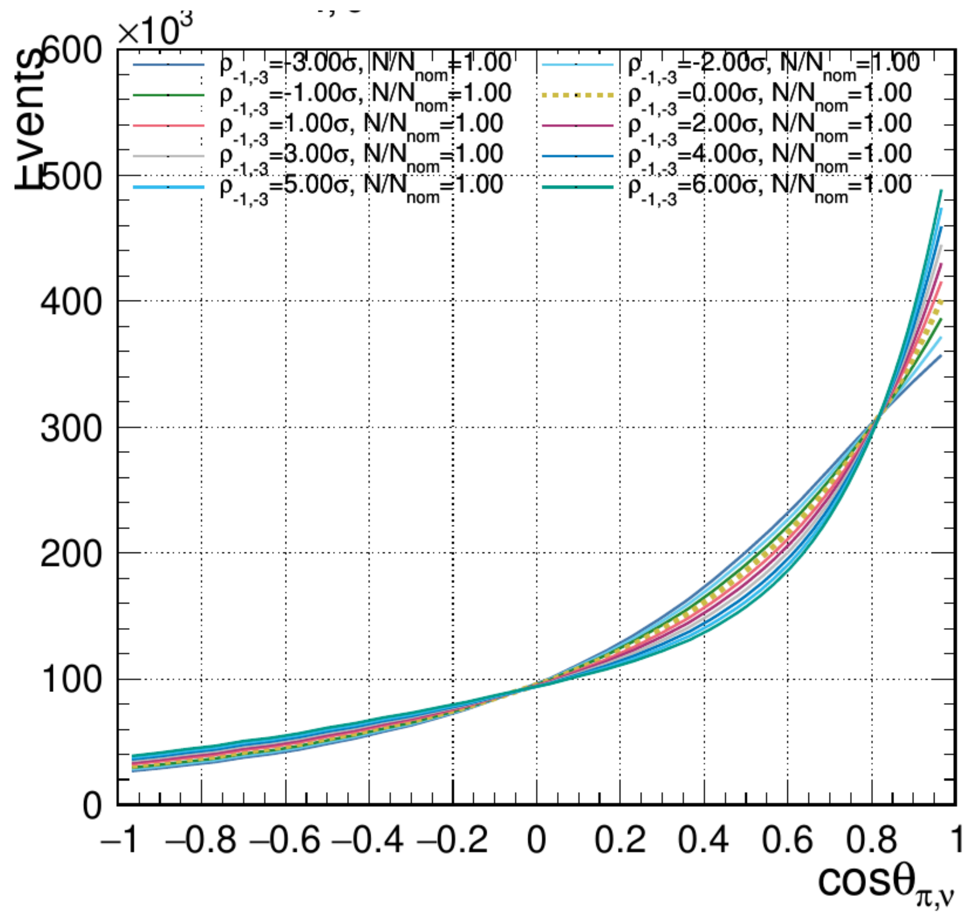


- In this example, +3σ for $\varrho_{-3,-3}$ goes in opposite direction to +3σ for $\varrho_{-1,-1}$ → a -3σ/+3σ combination would have a larger effect than -3σ/-3σ
  - Haven't studied the detailed correlations, could be improved
  - σ is defined as 30% change, roughly justifiable from original matrix element paper (FKR quark resonance model)

Combining elements

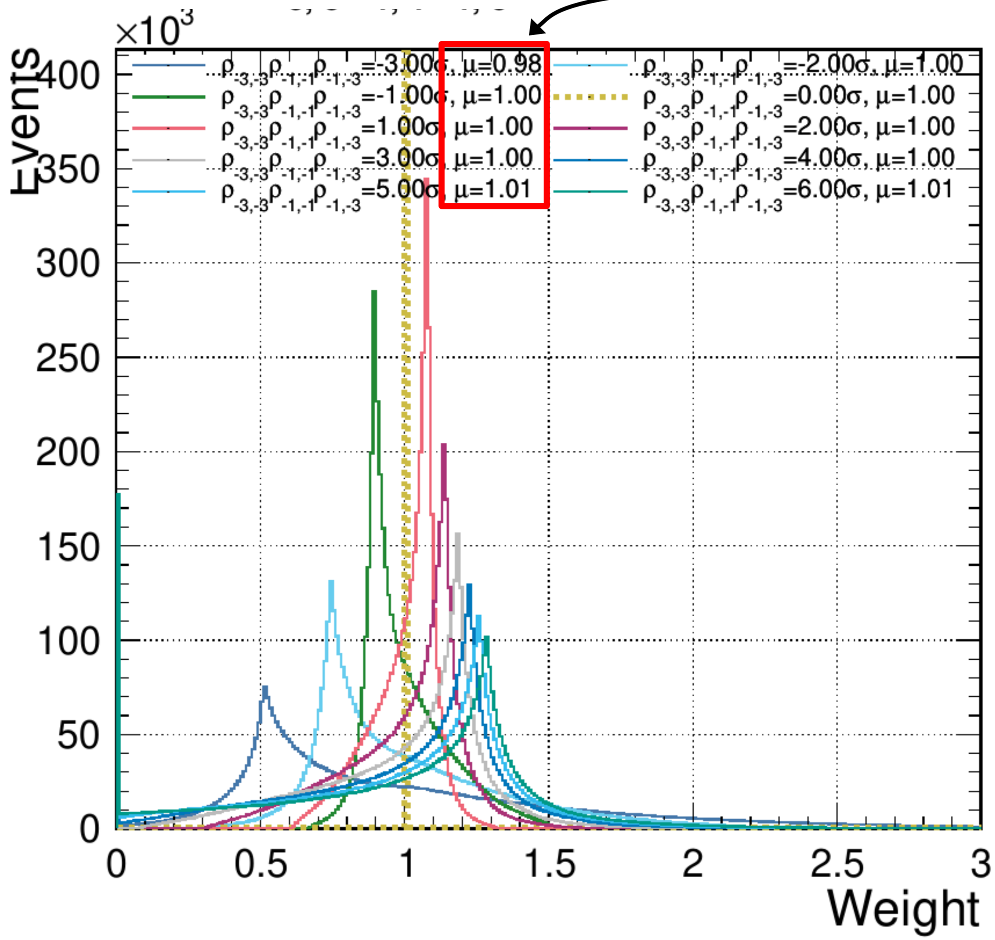
- Also found the $\rho_{-1,-3}$ had small effect on pion momentum, but large effect on angle, so included it too

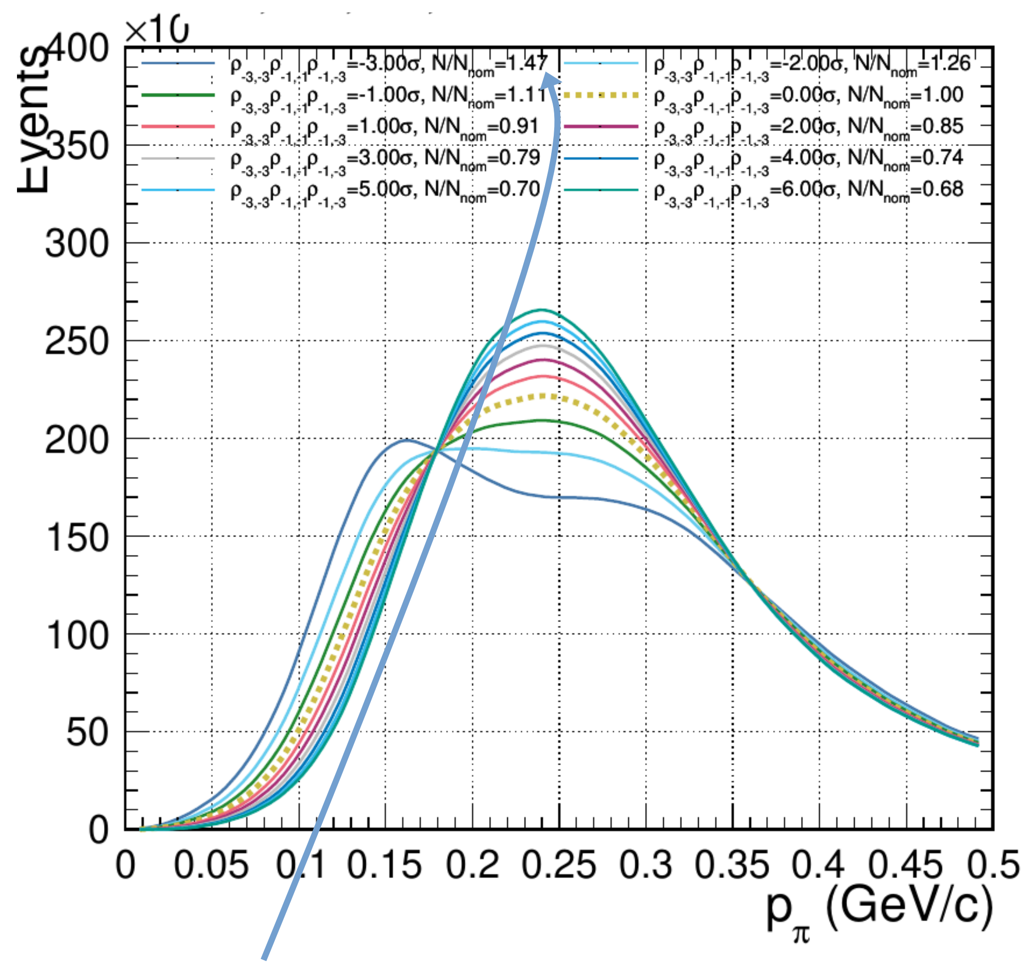




Result

- Weight distribution shows mean weight = 1; conserving cross-section

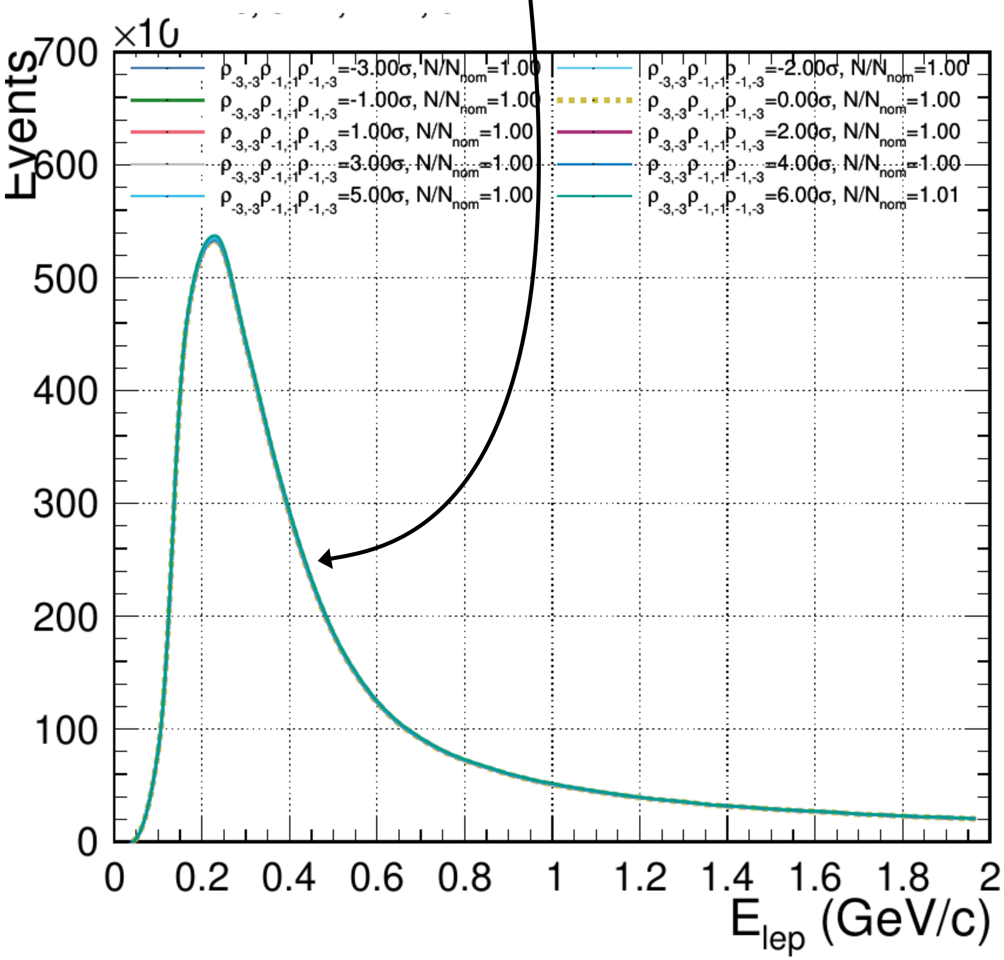


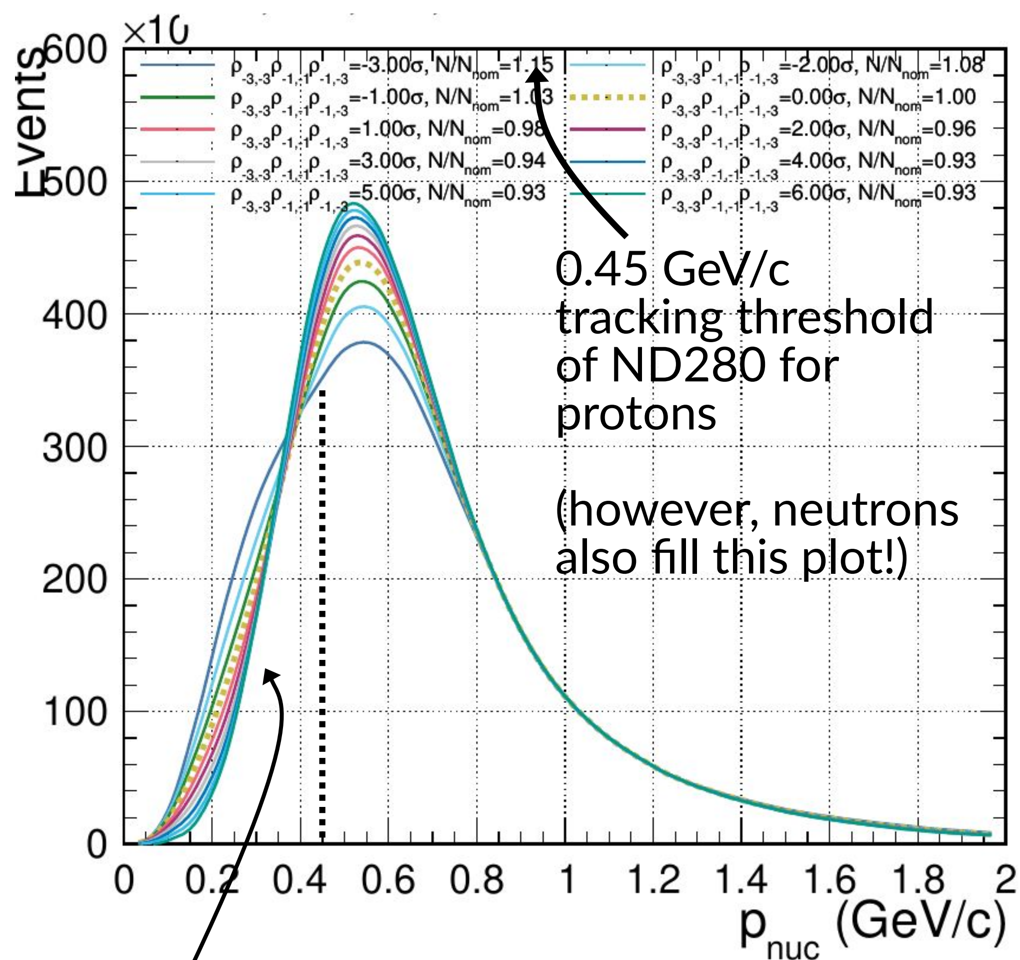


- -3σ has +47% more pions below threshold; -3σ/+3σ = 86%; -2σ/+2σ = 48%
  - → Under extreme variations dial allows for very large changes in low pion momentum behaviour

Result

- Has no effect on outgoing lepton distribution as intended (or E_ν, or W, or Q^2, etc)

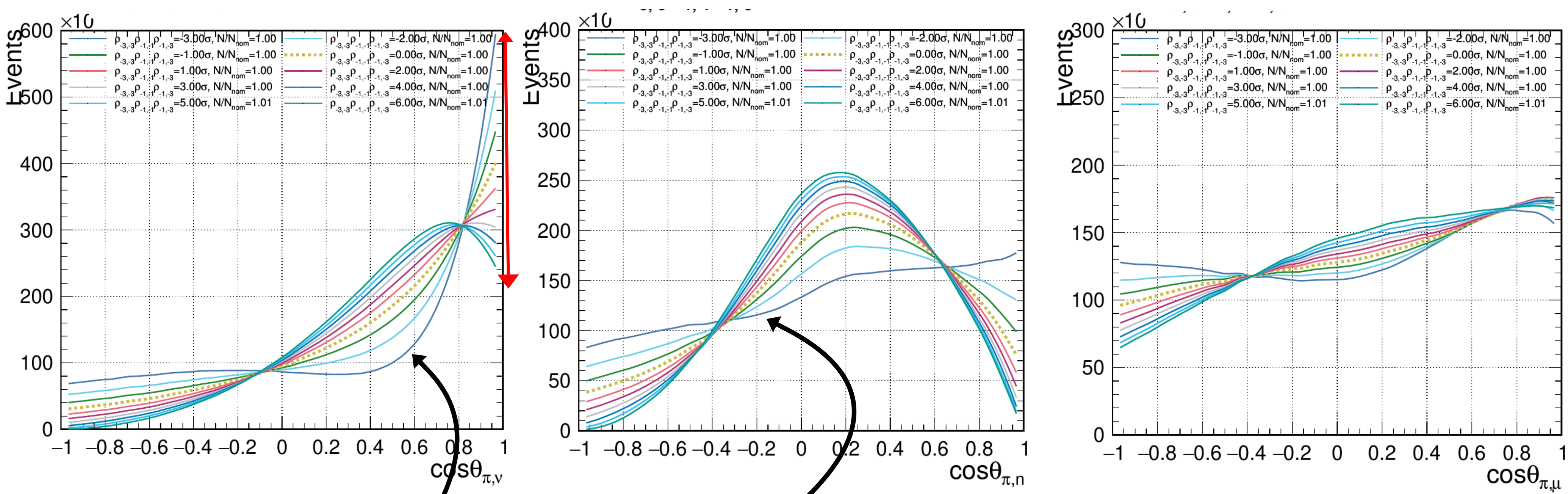




- Effect on outgoing nucleon is considerable

Results

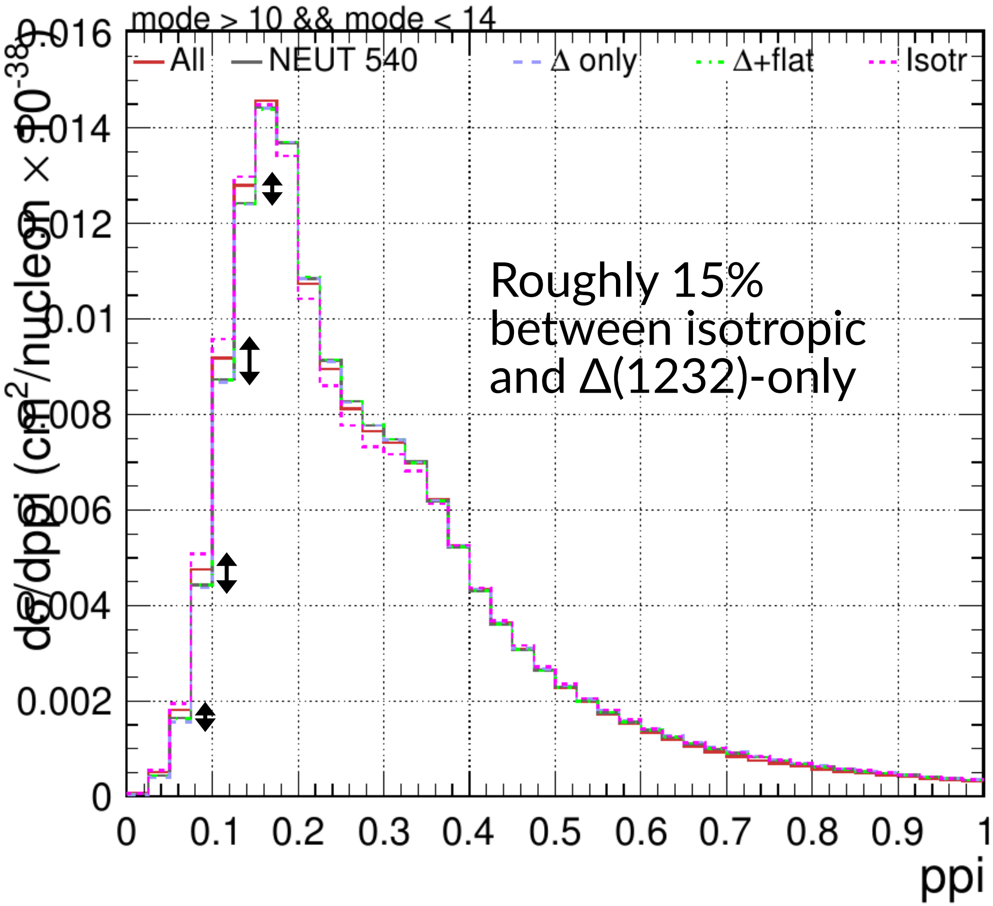
- Considerable effect on angular distributions, with clear intersection points for the variations
  - I think this is where the spherical harmonics may on average be maximised/minimised?

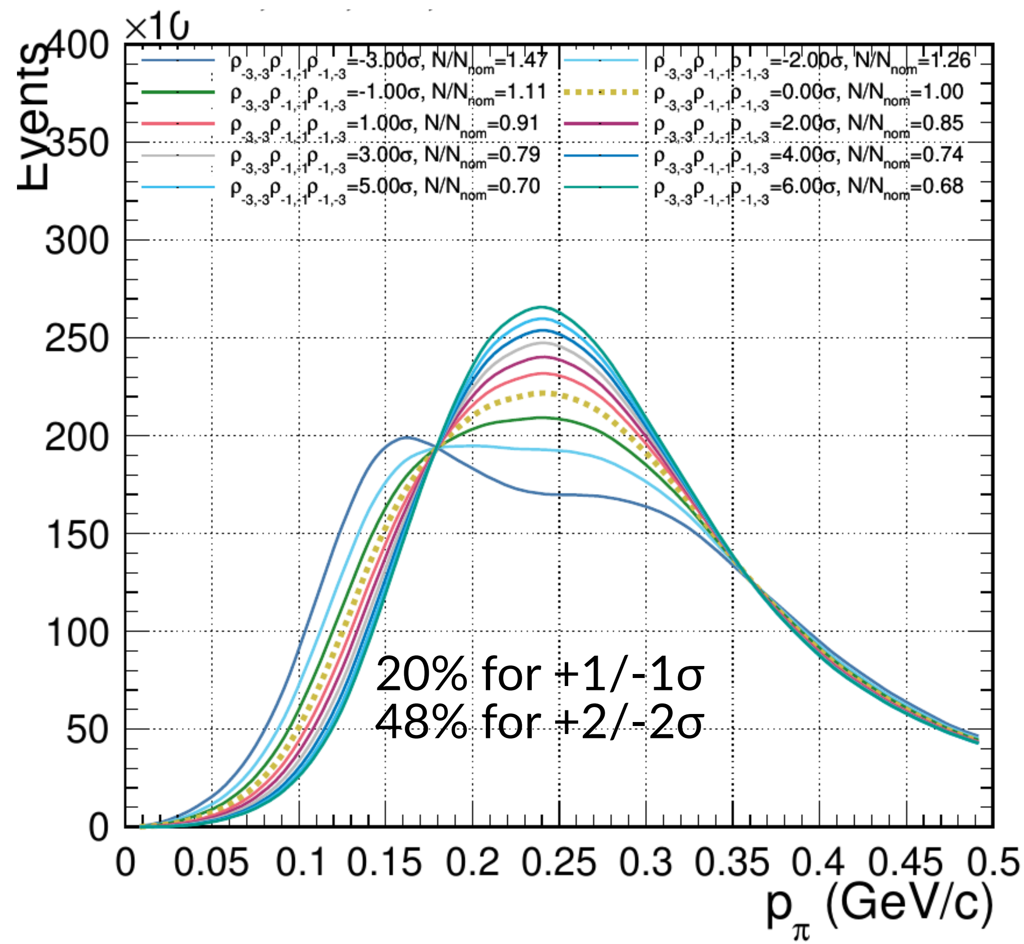


- Some variations clearly produce very “interesting” features
  - e.g. -3σ in $\cos\theta_{\pi\nu}$ and $\cos\theta_{\pi N}$
  - Probably pushing physicality of variation in this region?

Results

- Compare to other resonance decay dial developed for analysis





- Additional benefit of continuous parameter vs discrete parameter

Mini-summary

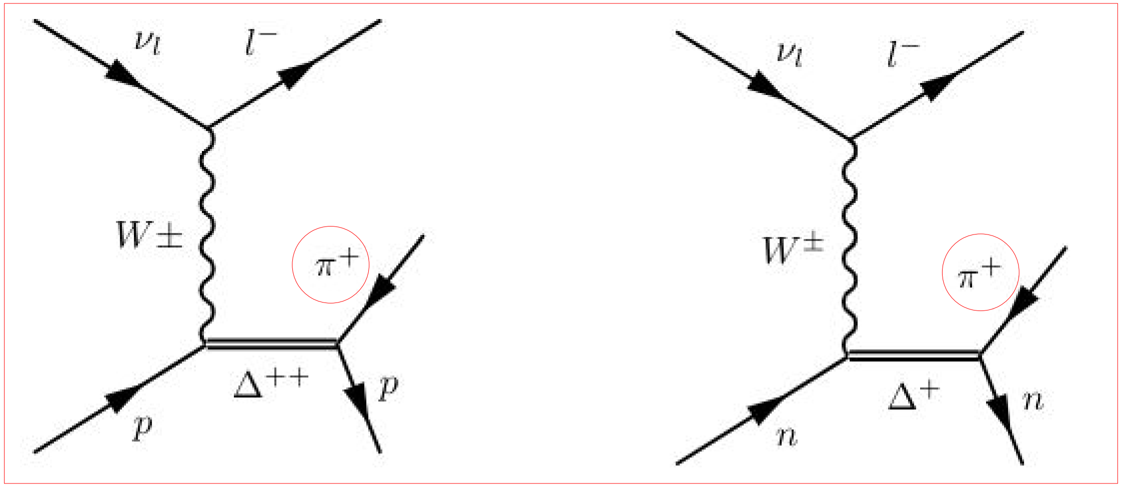
- Yet Another Source of Pion Kinematics Uncertainty™ found, this time from scaling matrix elements for Δ(1232) resonance
- Extends on previous work on trying isotropic (no resonance), Δ(1232)-only, and multiple resonances treatment
  - Will combine into one single uncertainty
- To my knowledge, no one is accounting for this or the isotropic/Δ(1232)-only, and multiple resonances uncertainty
- Has considerable effect on angular distributions and nucleon distributions too, and no effect on incoming/outgoing lepton, initial state nucleon, Q^2, W, etc

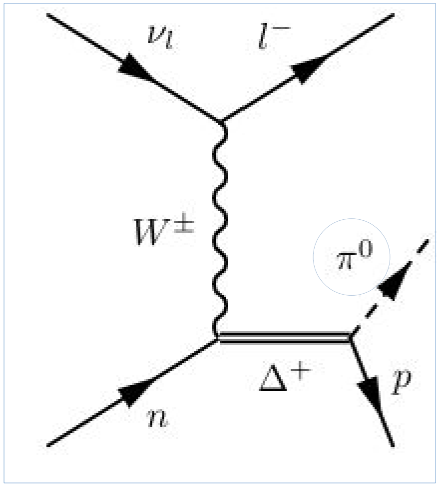
Background

- In addition to multi-ring selection at SK, T2K is introducing a "CCphoton" selection at ND280 to better target $CC1\pi^0$
  - Previously, events with a/many photons were lumped together with multi-π events
  - This year we want a better constraint on multi-π, since it contributes to multi-ring at SK
  - Separate out photon contribution to its own selection
  - Also, technically, get a better $CC1\pi^0$ constraint
- Additionally, photon tag improves purity and efficiency of other ND selections: CC0π → CC0π without a photon, and so on

Background

- The majority of CC1π^0 events on T2K are from resonance interactions, mostly Δ(1232)





- As such, they are constrained by the same parameters as the CC1π^+ events, which we have much more of
- But, is having CC1π^+ events constrain CC1π^0 events through our single pion model a good idea?
- Let's generate some events with the model, and compare to measured cross-sections from MINERvA, MiniBooNE and T2K using NUISANCE
- See how much we're off with simple normalisation

CC1π^0

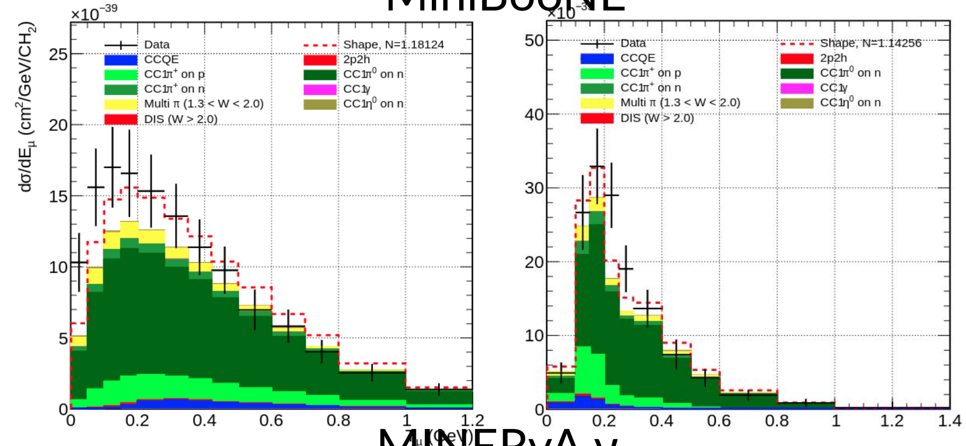
Experiment	Measurement	Final State	Distribution	Data/MC ratio
MINERvA	ν_μ CC	$1\pi^0$	T_π	1.19529
			θ_π	1.19562
			p_μ	1.20858
			θ_μ	1.35351
			Q^2	1.31784
			E_ν	1.41445
			W_{exp}	1.20911
			$M_{p+\pi^0}$	1.15151
			$M_{p+\pi^0,\Delta}$	1.28048
			$\cos\theta_{Adler}$	1.32757
			ϕ_{Adler}	1.27858
MiniBooNE	ν_μ CC	$1\pi^0$	E_ν	1.21867
			Q^2	1.17566
			T_μ	1.18124
			$\cos\theta_\mu$	1.15047
			$\cos\theta_\pi$	1.20636
			p_π	1.14256
MINERvA	$\bar{\nu}_\mu$ CC	$1\pi^0$	θ_π	1.09898
			p_π	0.941269
			T_π	1.13169
			Q^2	1.18317
			θ_μ	1.07292
			p_μ	1.08995
			E_ν	1.22334

Table 6: Data/MC ratios for recent CC1π^0 cross-section measurements on CH$_N$ targets, using NEUT. $N = 1$ for MINERvA and T2K, $N = 2.08$ for MiniBooNE.

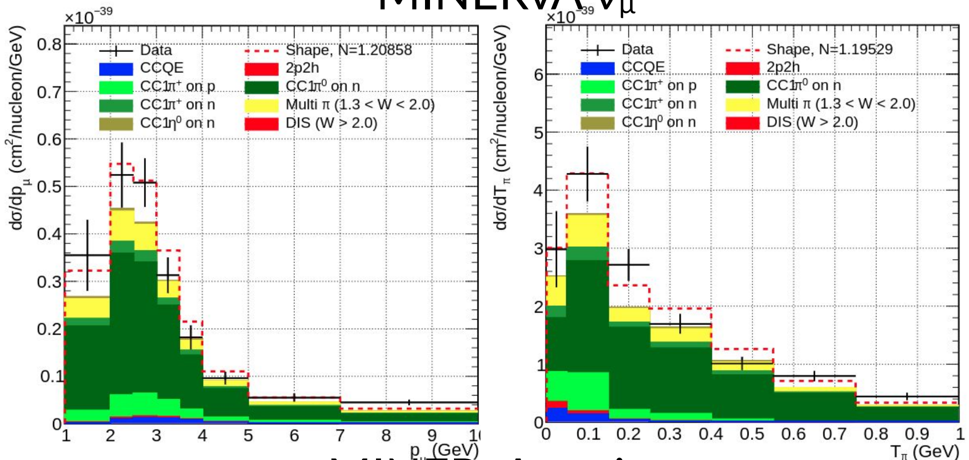
Looks consistently under-estimated

Shape isn't **too bad** after scaling

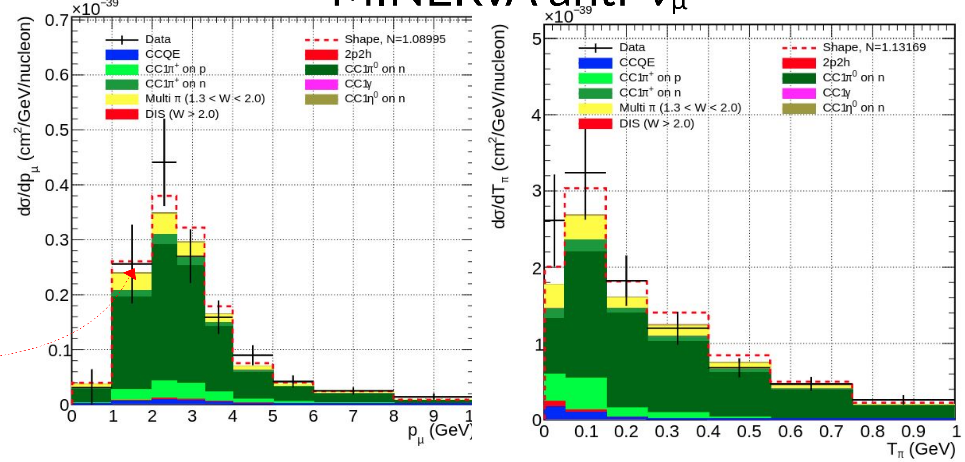
MiniBooNE



MINERvA ν_μ



MINERvA anti-ν_μ



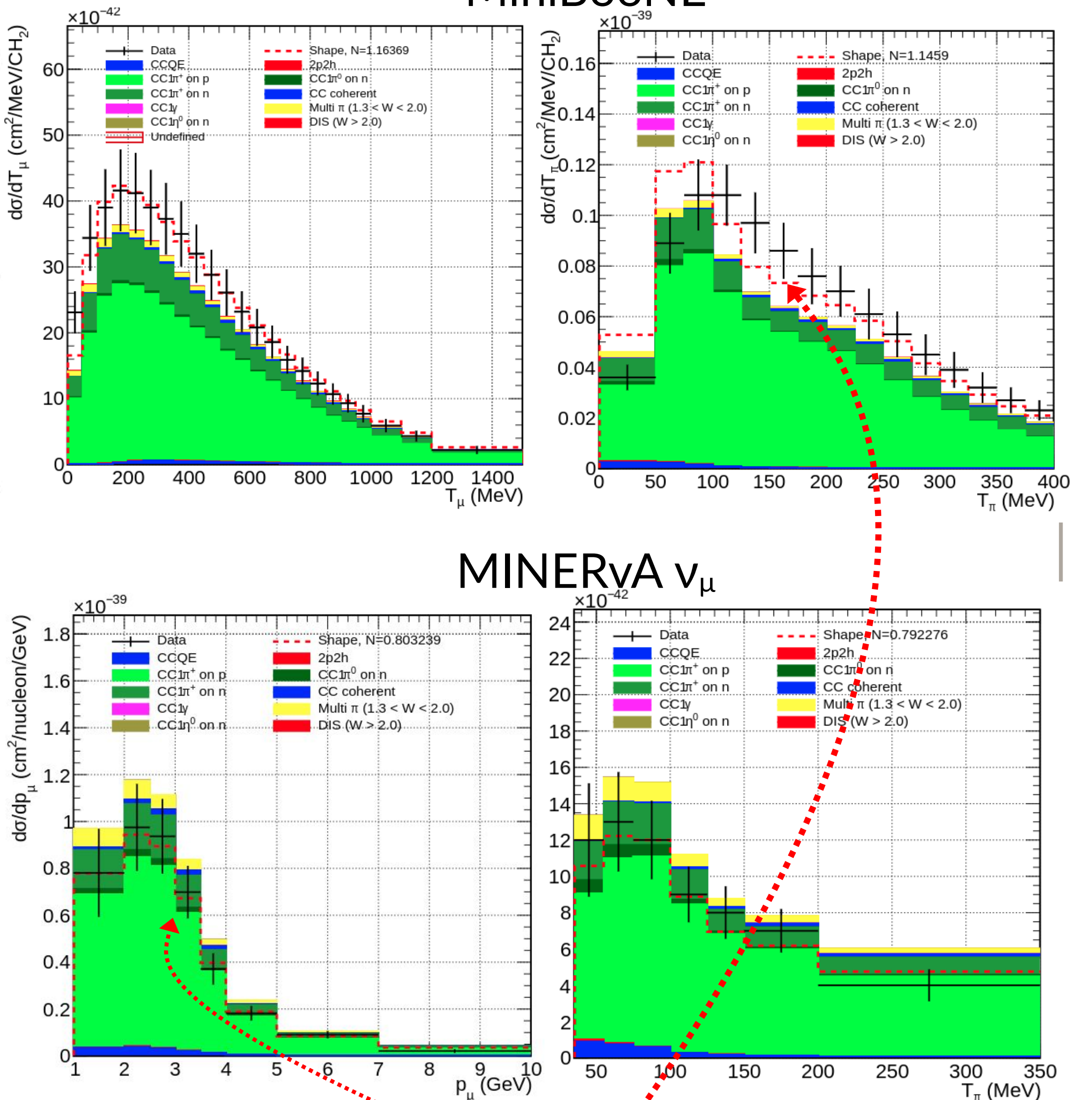
$CC1\pi^{+/-}$

Experiment	Measurement	Final State	Distribution	Data/MC ratio
MINERvA	ν_μ CC	$1\pi^+$	T_π	0.792276
			θ_π	0.785772
			p_μ	0.803239
			θ_μ	0.820134
			Q^2	0.809505
			E_ν	0.816158
T2K	ν_μ CC CH	$1\pi^+$	p_π	0.757429
			θ_π	0.763961
			$\theta_{\mu,\pi}$	0.806983
			Q^2	0.814487
			ϕ_{Adler}	0.790387
			$\cos\theta_{Adler}$	0.755398
MiniBooNE	ν_μ CC	$1\pi^+$	E_ν	1.26415
			Q^2	1.20402
			T_π	1.1459
			T_μ	1.16369
MINERvA	ν_μ CC	$N\pi^+$	θ_π	0.677343
			T_π	0.670601
			θ_μ	0.83082
			p_μ	0.736194
			Q^2	0.803409
			E_ν	0.755323
MINERvA	$\bar{\nu}_\mu$ CC	$1\pi^-$	E_ν	1.16361
			Q^2	1.05634
			T_π	1.10254
			p_μ	1.05884
			θ_π	0.866754
			θ_μ	1.14954

Table 5: Data/MC ratios for recent $CC1\pi^\pm$ cross-section measurements on C targets using NEUT. $N = 1$ for MINERvA and T2K, $N = 2.08$ for MiniBooNE.

MiniBooNE

MINERvA ν_μ



Not so consistent...
MINERvA and T2K is 0.7-0.8 (over-estimated)
MiniBooNE is under-estimated by 20%
MINERvA $CC1\pi^-$ less relevant, but still interesting (opposite to $CC1\pi^+$)

Shape is approximately adequate...

Mini-summary

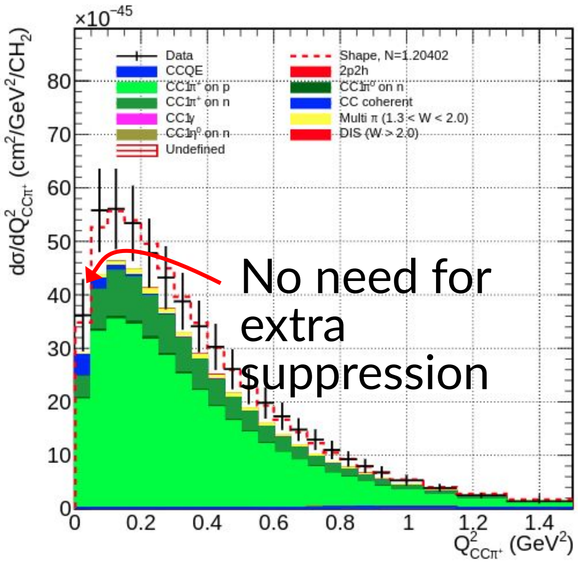
- If CC1π^+ is over-estimated, CC1π^0 is under-estimated
- Most of the shape of kinematics modelled well after scaling
- Looks like a CC1π^+/CC1π^0 relative scaling is a decent proposal, at least from inspecting external data
- More conservative to decorrelate than to correlate, so going ahead with this

$CC1\pi^{+/0/-}$ low Q^2

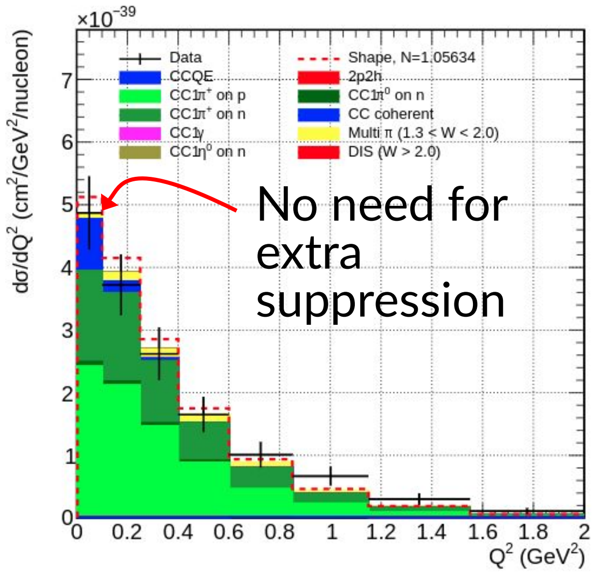
- Since we're at it, might as well check low Q^2 behaviour for the single-pion final sate; is a suppression needed?
  - Some literature (including yours truly) argues may need suppression low Q^2, but those studies used an old version of GENIE (2.8.6)
  - NOvA also **used to** need a $CC1\pi^+$ suppression, but after updating to GENIE 3 no longer do
- Here we primarily care about the $CC1\pi^+$ final state, since that will be included in both SK and T2K analyses

CC1π⁺ low Q²

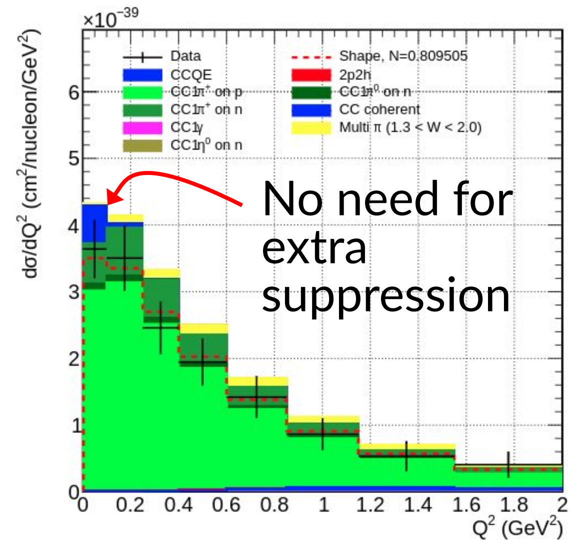
MiniBooNE CC1π⁺



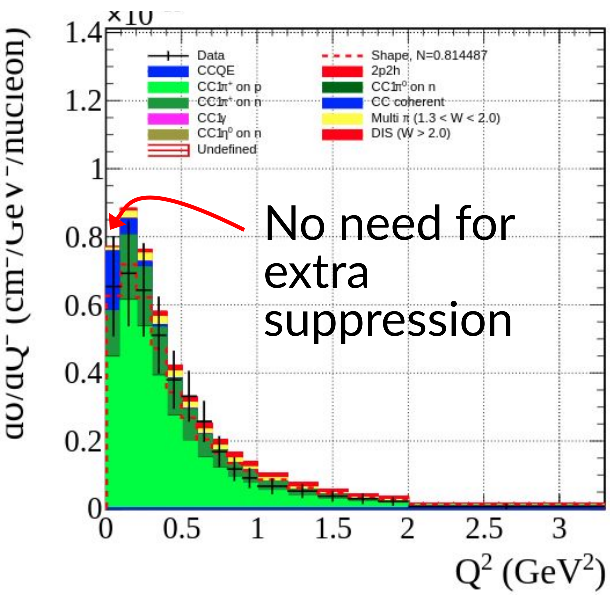
MINERvA CC1π⁻



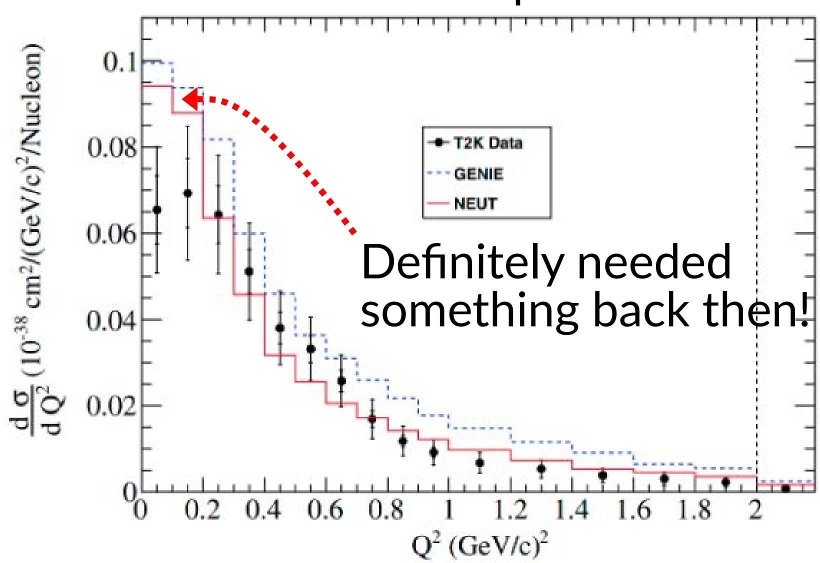
MINERvA CC1π⁺



T2K CC1π⁺



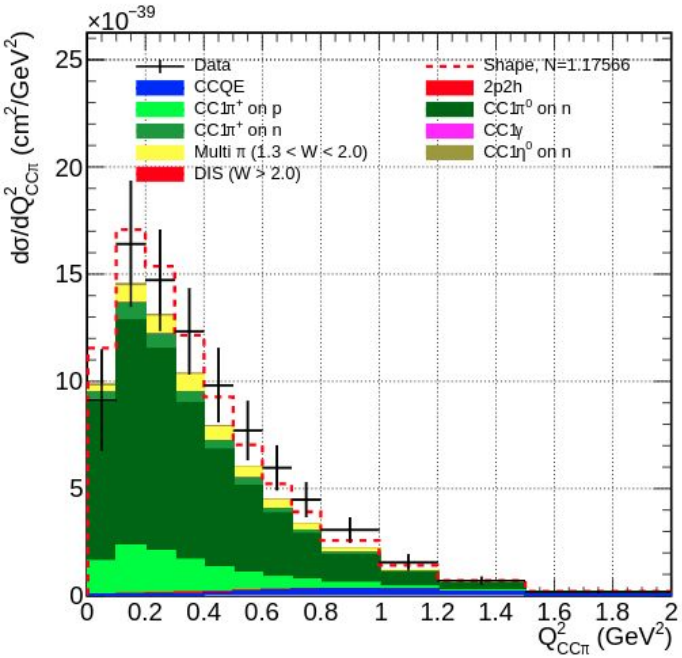
T2K CC1π⁺ in publication



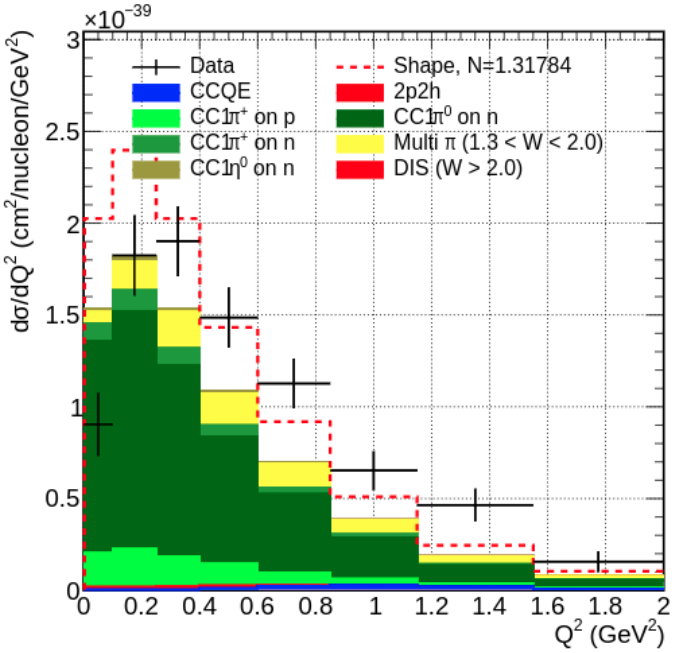
Looks like no suppression needed with a more **modern** NEUT version

CC1π^0 low Q^2

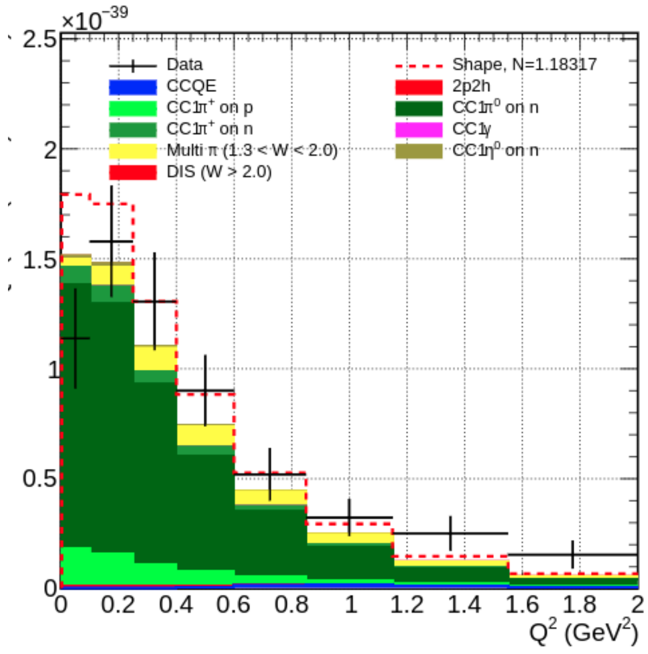
MiniBooNE CC1π^0



MINERvA CC1π^0



MINERvA CC1π^0 anti-ν_μ



- MiniBooNE looks fine, but MINERvA does not
- Different resonances contributing to final state (W<1.8 GeV, higher energy at MINERvA)
- More multi-π/transition/SIS events contributing at MINERvA
- Not quite as clear cut

Summary

- T2K is introducing a new pion kinematics shape uncertainty into analysis, developed either from effect of multiple resonances, or from scaling the matrix elements
- About 50% uncertainty on pions below Cherenkov threshold for a 2σ variation for the latter dial
- A separate $CC1\pi^0$ scaling parameter seems justified by comparison to external data from MINERvA, T2K and MiniBooNE
  - Uncertainty of about 30%
- Low Q^2 suppression for $CC1\pi^+$ interactions appears unnecessary against T2K, MINERvA and MiniBooNE data
- Low Q^2 suppression for $CC1\pi^0$ interactions may be warranted
  - But relatively few events enter the oscillation analysis, so leaving it for now

Thanks!