# Neutrino-induced Single-Pion Production with Light Nuclei

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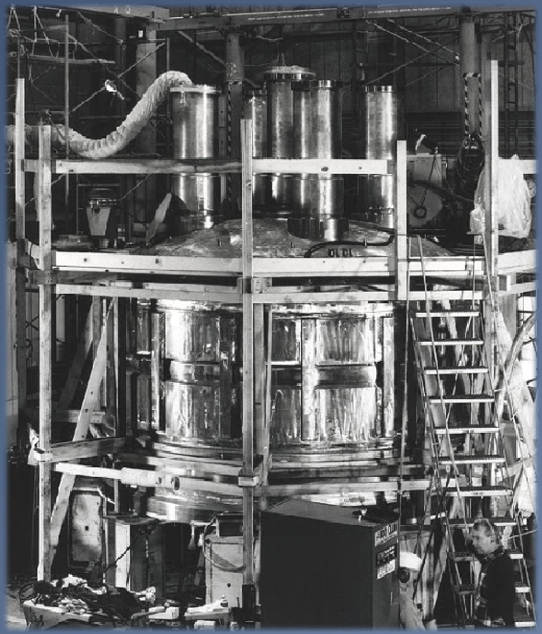
# Project Goals

12ft Bubble Chamber at the
Argonne National Lab



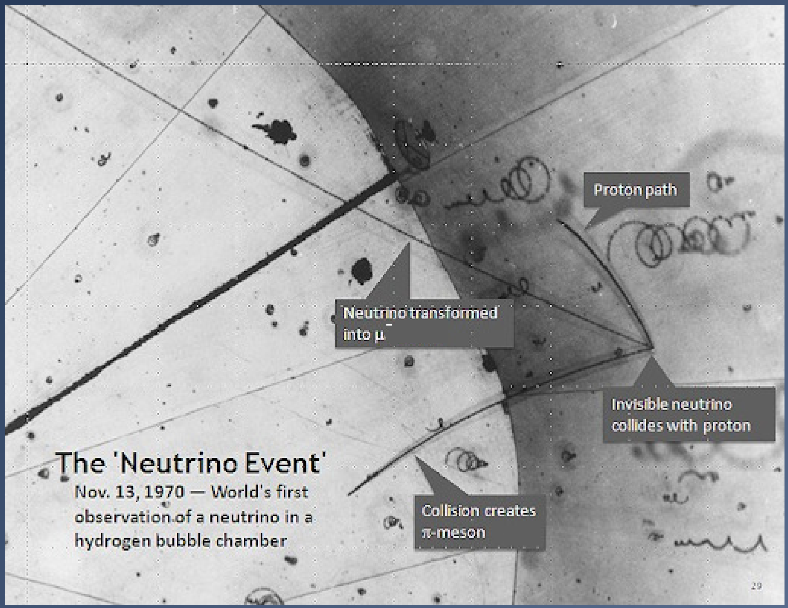
- Look for disagreements between the NEUT-predicted* neutrino interactions and the single-pion production data obtained with muon neutrinos on Deuterium at the Argonne & Brookhaven National labs

- Best-fit the data and try to design a new set of empirical parameters for governing the theoretical prediction.

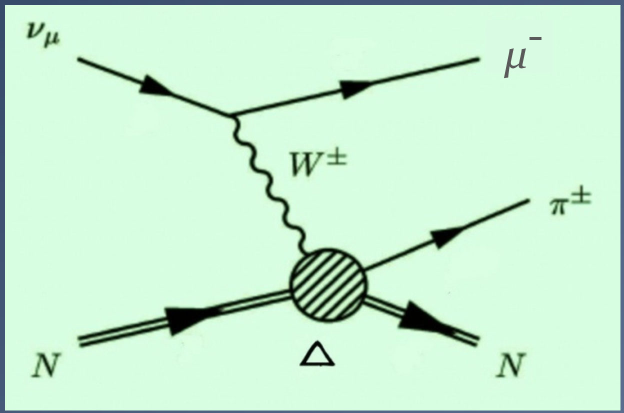
* NEUT is a Monte Carlo event generator – provides executables for simulating neutrino reactions that are used for comparisons to cross-section data. For more details, refer to:
*Hayato, Yoshinari. "A Neutrino Interaction Simulation Program Library NEUT." Acta Physica Polonica B 40.9 (2009).*

# Relevant events

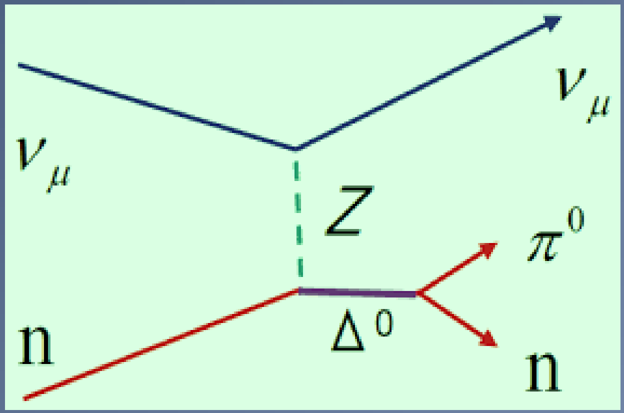
Exchange of $W^{+/-}$ and $Z^{o}$ bosons in neutrino-nucleus interactions result in charged and neutral current single-pion production via nucleon resonances, with small non-resonance contributions too:




The first event photographed in the ANL bubble chamber detector




**Charged Current**
**ν changes to charged lepton**

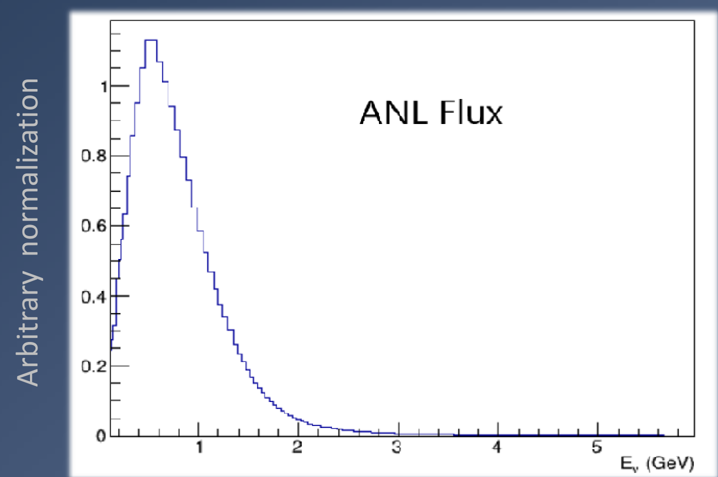


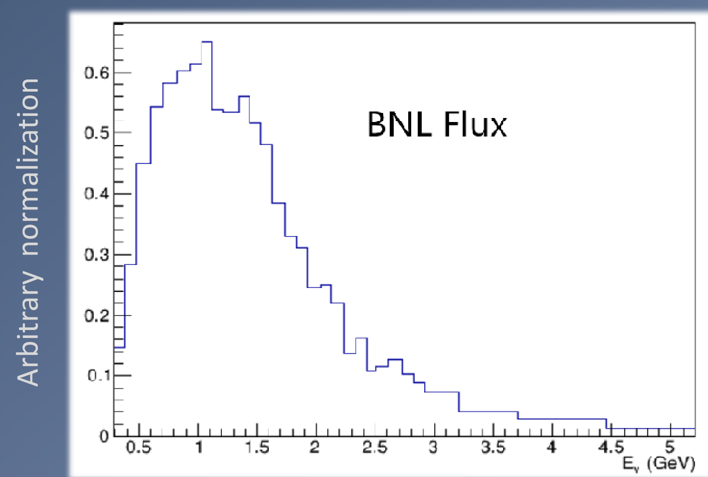

**Neutral Current**
**ν re-emerges as ν**

# Nuclear effects

- Heavy targets → nucleons not at rest → reconstruction of $E_\nu$ etc. not accurate
  Light target nucleus, such as deuterium → bound nucleons are quasi-free → negligible nuclear effects

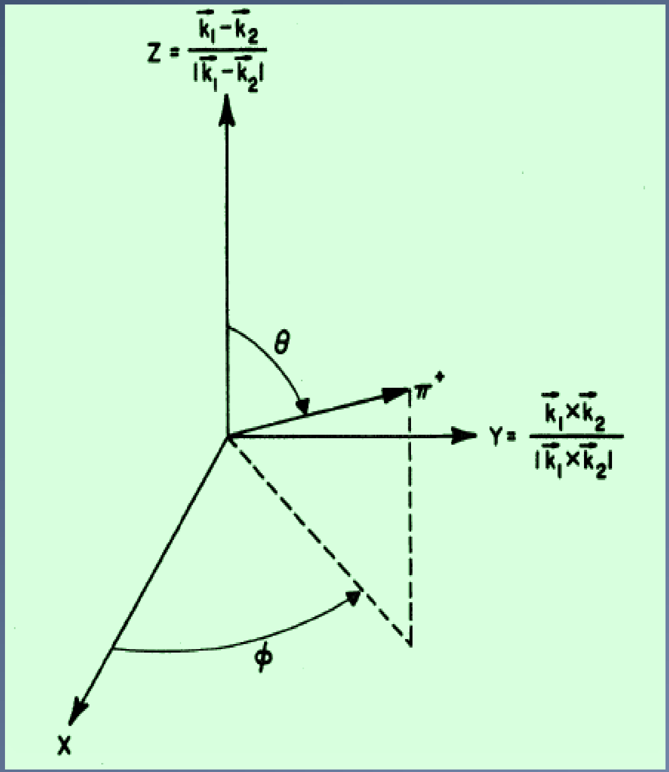
- ANL and BNL bubble chamber experiments of the 1980s → used deuterium and low-energy (few-GeV) neutrinos → reduced probability of non-resonance processes like Deep Inelastic Scattering → very significant source of info



# Variables of interest

The Adler coordinates; k1 and k2 are vectors along the ν and π directions, respectively, in the N-μ rest frame




- $E_\nu$ : Incoming neutrino energy
- **W** : Invariant masses of N-pi, N-mu & mu-pi systems
- $\theta^*$ : Polar angle of the muon in the neutrino-nucleon ref. frame
- $Q^2$ : Four-momentum transferred
- $p_\pi$ : Outgoing pion momentum
- $\theta_{Adler}$ $\phi_{Adler}$ : Polar and azimuthal angles of pions in the nucleon-pion reference frame

# Experiment summary

| Conditions/Statistics | ANL | BNL |
|---|---|---|
| Incoming neutrino beam energy spectrum | Peaks at 0.5 GeV<br>Extends to 6 GeV | Peaks at 1.2 GeV<br>Extends to 15 GeV |
| Total measured CC-inclusive events | ~ 5000 | ~ 10000 |
| Fiducial volume | 8.64 $m^3$ | 4 $m^3$ |
| Types of events<br>(i.e. the different channels in this study) | CC1ppip : $\nu_\mu d \rightarrow \mu^- p^+ \pi^+$<br>CC1npip : $\nu_\mu d \rightarrow \mu^- n^0 \pi^+$<br>CC1pi0 : $\nu_\mu d \rightarrow \mu^- p^+ \pi^0$<br>NCppim : $\nu_\mu d \rightarrow \mu^- p^+ \pi^-$ | CC1ppip : $\nu_\mu d \rightarrow \mu^- p^+ \pi^+$<br>CC1npip : $\nu_\mu d \rightarrow \mu^- n^0 \pi^+$<br>CC1pi0 : $\nu_\mu d \rightarrow \mu^- p^+ \pi^0$ |

# Monte Carlo Event generation

- 1 million neutrino-deuterium scattering events → four generators (NEUT, Nuwro, GENIE Version-2 & Version-3) → use different theoretical models.

  We provided the generators with ANL and BNL flux distributions from *https://nuisance.hepforge.122 org/trac/wiki/ExperimentFlux*.

- NUISANCE framework used to compare the generator predictions with published results.

- Total Chi-square test: Add each sample included in the fit → 1σ uncertainties, uncorrelated between data-points: $S_1$ ✗ $S_2$ ✓ → Gaussian for $S_2$ and Poisson for $S_1$

$$\chi^2 = \sum_{S_1} \left\{ 2 \sum_{i=1}^{N} \left[ \mu_i(x) - n_i + n_i \ln \frac{n_i}{\mu_i(x)} \right] \right\} + \sum_{S_2} \left\{ \sum_{i=1}^{N} \frac{[n_i - \mu_i(x)]^2}{\sigma_i^2} \right\} \quad \text{(for each fit)}$$

$S_1$ = the set of all event distributions

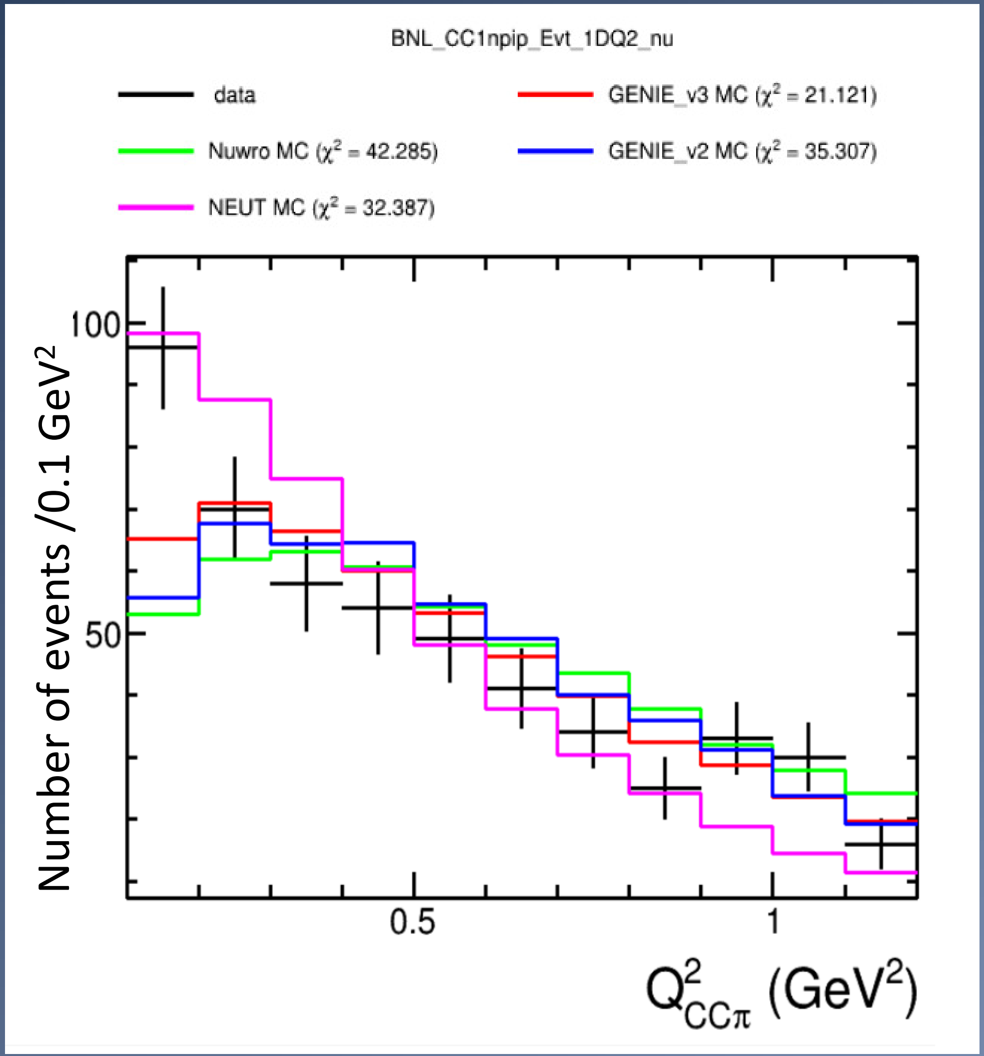
$S_2$ = the set of all cross-section distributions

# Predictions vary with generators

This is a comparison of the $Q^2$ predictions by the four different generators for the BNL $\nu_\mu d \rightarrow \mu^- n^0 \pi^+$ channel

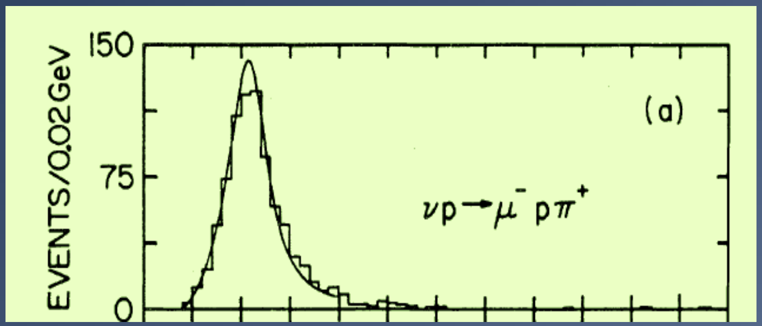
Here we can see :

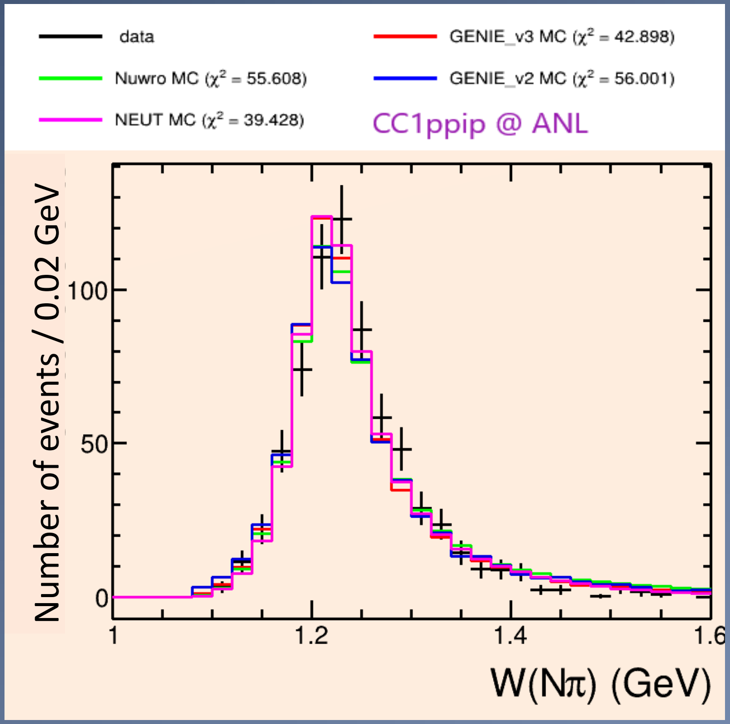
- NEUT prediction agrees best at low $Q^2$ .
- But with regards to the chi-square, the GENIE v3 prediction does better across the entire range.



# Digitized histograms

- Produced 18 of them from images of W distributions in the Radecky *et al.* 1982 and Kitagaki *et al.* 1986 papers to perform new NUISANCE comparisons. These distributions have not been used for analysis in the past.
- Example from Radecky-1982:




TOP : From the paper
RIGHT : Results after digitizing

# Free parameters in NEUT's predictive model

- Nucleon form factor is a parameterized description of the nucleon's response to an external probe

- Graczyk-Sobczyk (GS) model → the axial hadronic (pion + nucleon) current can be described by the dipole parametrization of the axial form factor $C_5^A$

- NEUT's default theoretical model for pion production → defined with 3 parameters: $M_A^{RES}$ (axial mass), $C_A^5(Q^2 = 0)$, and $I_{1/2}$ (non-resonance background)

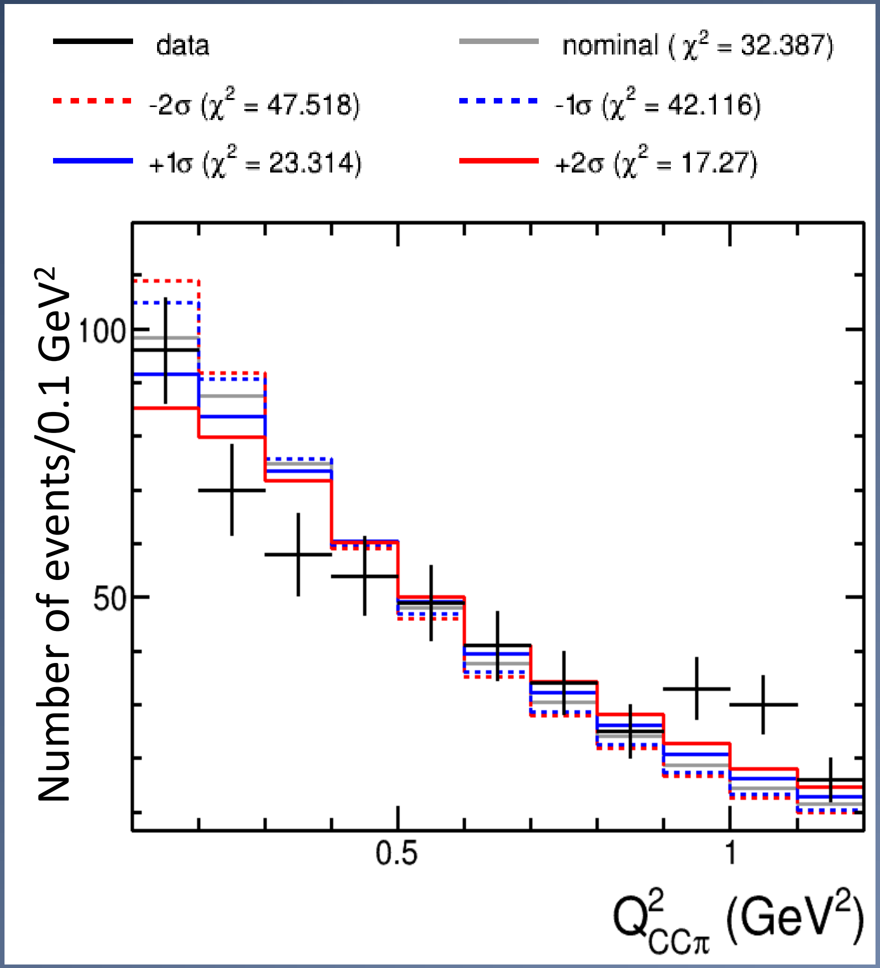
$$C_5^A(Q^2) = C_5^A(0)\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

| Parameter in NEUT | Default ± Uncertainty |
|---|---|
| $M_A^{RES}$ (GeV) | $0.95 \pm 0.15$ |
| $C_A^5(0)$ | $1.01 \pm 0.15$ |
| $I_{1/2}$ | $1.13 \pm 0.40$ |

# Exploring the parameter space

We examine how much and in what way every displacement (±2σ, ±σ) of the parameters from their default value affects the NEUT predictions for each of the ANL/BNL samples

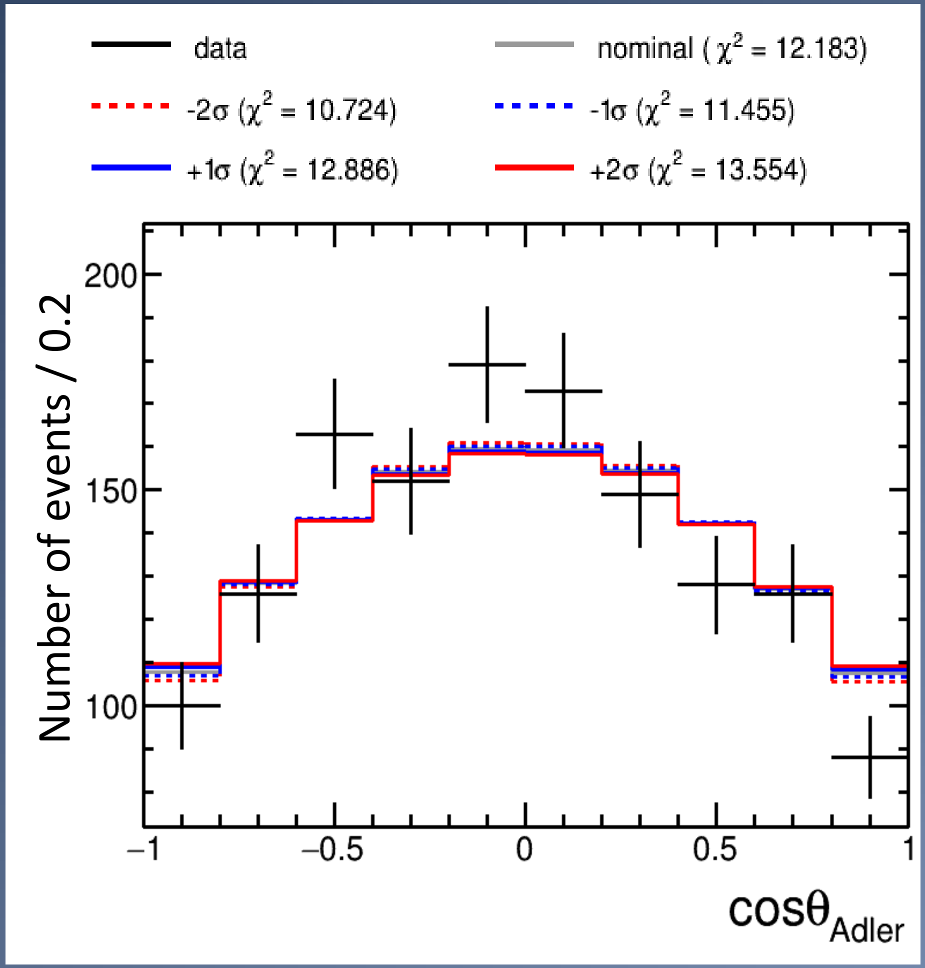
On the right : Change in the BNL $\nu_\mu d \rightarrow \mu^- n^0 \pi^+$ channel's $Q^2$ distribution prediction when $M_A^{RES}$ is displaced by us



We come up with some reasonable data groups & parameters that can be used in NUISANCE fits.

The resulting best fit parameter values and chi-squares determined if it was necessary to run a series of other fits with smaller subsets of the parameters & datasets.

On the right: varying $C_A^5$ (0) has minimal impact for $\cos(\theta_{Adler})$ in BNL's $\nu_\mu d \rightarrow \mu^- p^+ \pi^+$ channel



- Variations in $M_A^{RES}$ , $C_A^5(0)$ & $I_{1/2}$ show significant changes in final predictions , so these parameters were selected for fitting

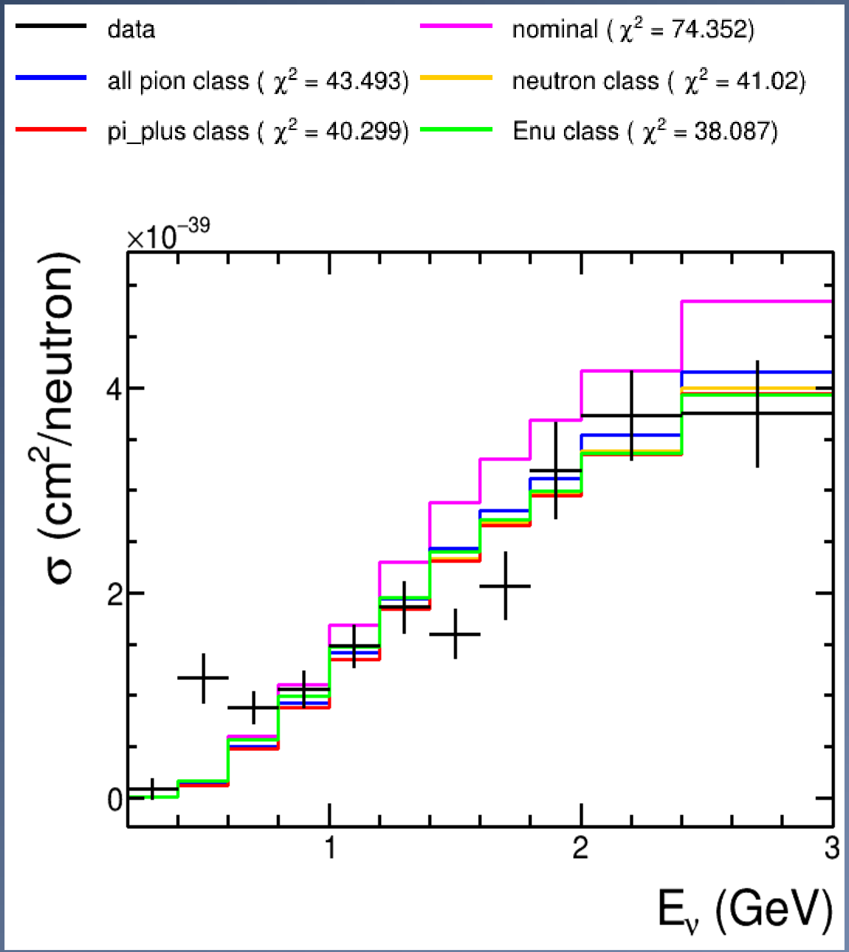
- Some other parameters related to DIS (Deep Inelastic Scattering), Multi-pion production and discrete model changes were found to have no effect on the predictions

- W distributions not been analysed much in the past and $E_\nu$ is most commonly used in study of the cross sections → So we eventually focus on tuning parameters by best-fitting various combinations of $E_\nu$ and invariant mass datasets.

# Partitions and Fits

- Full set of 44 data samples divided into subgroups defined by the final state particle(s) {$n^0$, $p^+$, $\pi^+$, $\pi^-$, $\pi^0$} and/or the measured variable
- Comparison done between fits on each group that a given sample features in
- The nuismin application uses the MIGRAD steepest gradient descent algorithm to minimize the $\chi^2$ w.r.t. to the specified tunable parameters.

EXAMPLE : CC1npip ($\nu_\mu d \rightarrow \mu^- n^0 \pi^+$) channel at BNL showing the different fit performances when the $E_\nu$ samples are sub-grouped at various levels



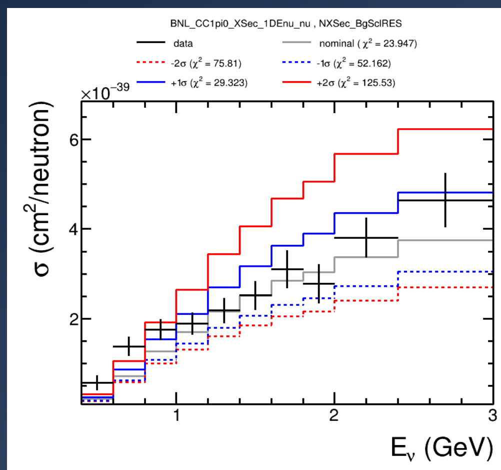
# Grouping $E_\nu$ with W

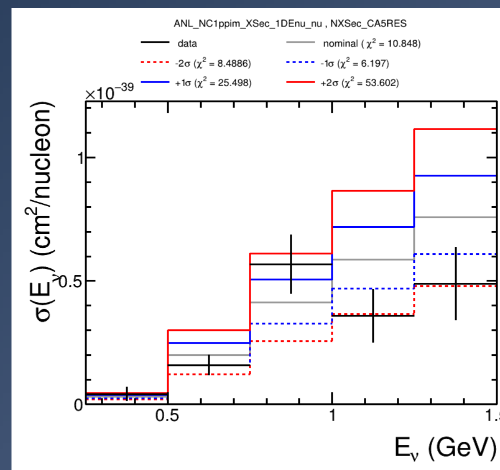
- 3 different groups of W distributions – $N\pi$, $N\mu$ and $\mu\pi$ → fit W group + all $E_\nu$ samples. To increase the complexity a bit more : a fourth fit involving all $E_\nu$ and all W distributions.

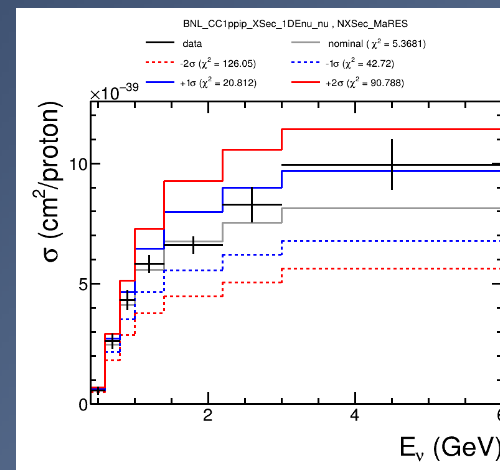
- Default model ("nominal") in NEUT takes values from an old $E_\nu$ + $Q^2$ fit; assumes that changes to the model over the years would not have had a big effect on the model's veracity.

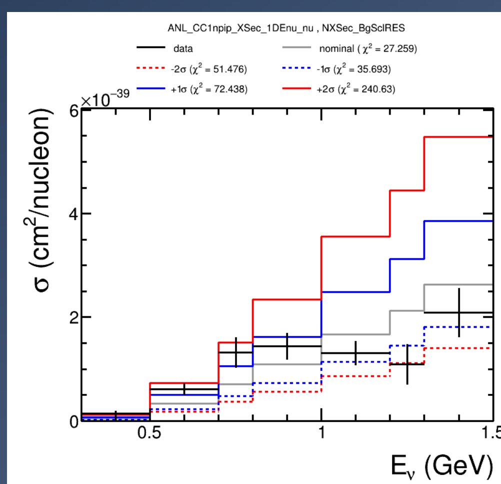
- The default model would need improvement if the fundamental W and $Q^2$ distributions yield predictions that greatly disagree with each other. To explicitly check this, we verify the presumption that the nominal fits will coincide with a current $E_\nu$ ($\sigma$) + $Q^2$ (event) fit.

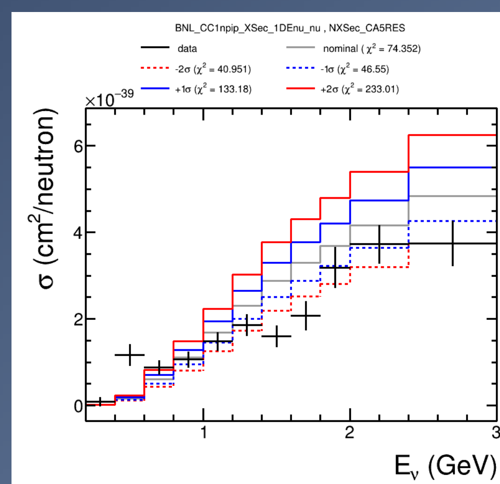
# A lot of info contributes to the $E_\nu$ + W fits...

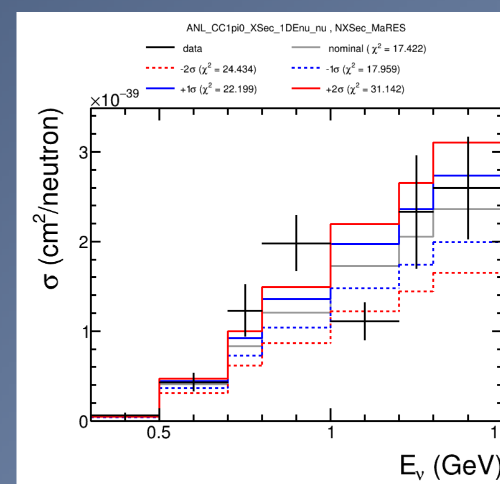


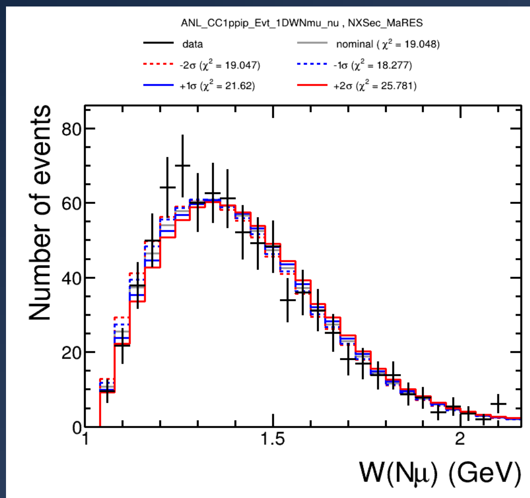



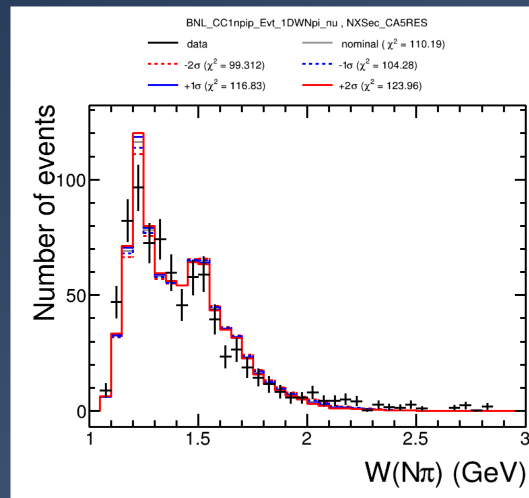



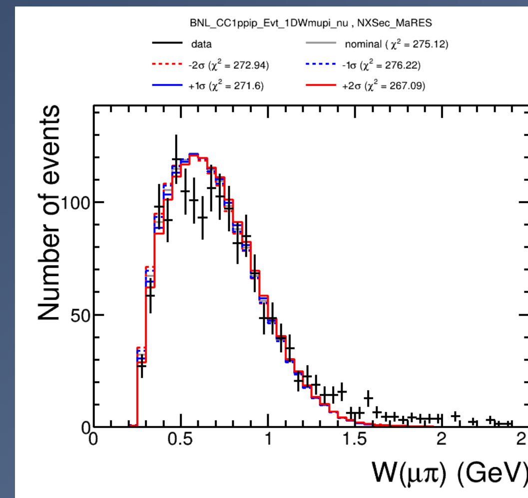



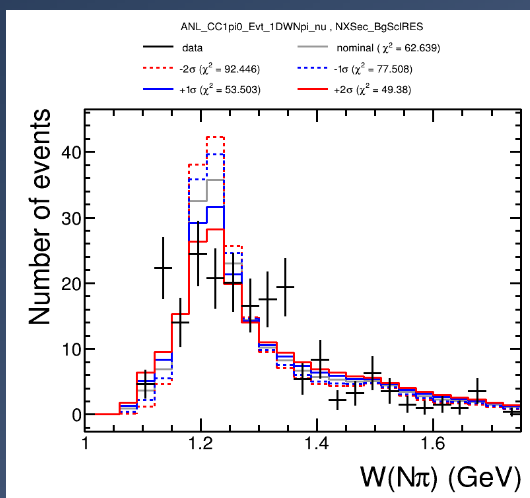



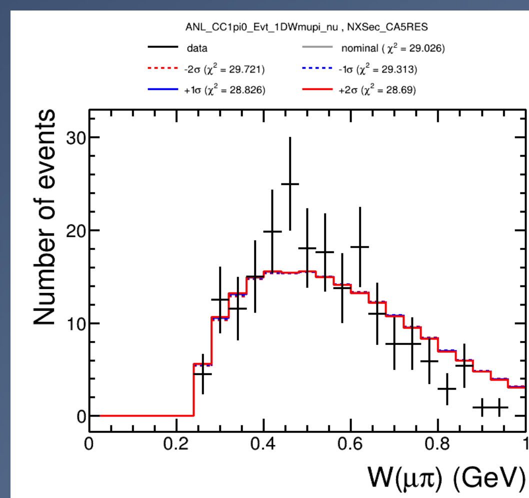



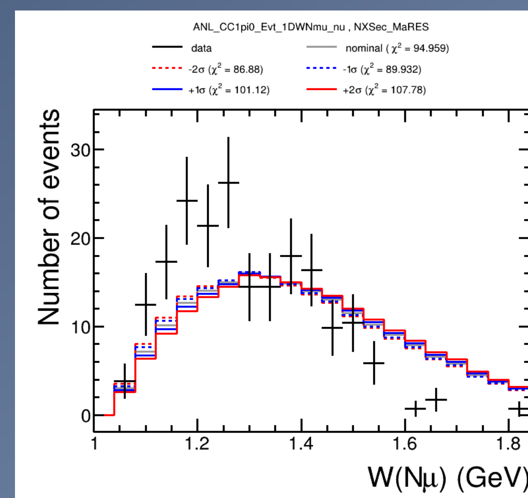

ANL_CC1ppip_Evt_1DWNmu_nu , NXSec_MaRES
data
nominal ( χ² = 19.048)
-2σ (χ² = 19.047)
-1σ (χ² = 18.277)
+1σ (χ² = 21.62)
+2σ (χ² = 25.781)
Number of events
W(Nμ) (GeV)


BNL_CC1npip_Evt_1DWNpi_nu , NXSec_CA5RES
data
nominal ( χ² = 110.19)
-2σ (χ² = 99.312)
-1σ (χ² = 104.28)
+1σ (χ² = 116.83)
+2σ (χ² = 123.96)
Number of events
W(Nπ) (GeV)


BNL_CC1ppip_Evt_1DWmupi_nu , NXSec_MaRES
data
nominal ( χ² = 275.12)
-2σ (χ² = 272.94)
-1σ (χ² = 276.22)
+1σ (χ² = 271.6)
+2σ (χ² = 267.09)
Number of events
W(μπ) (GeV)


ANL_CC1pi0_Evt_1DWNpi_nu , NXSec_BgSclRES
data
nominal ( χ² = 62.639)
-2σ (χ² = 92.446)
-1σ (χ² = 77.508)
+1σ (χ² = 53.503)
+2σ (χ² = 49.38)
Number of events
W(Nπ) (GeV)

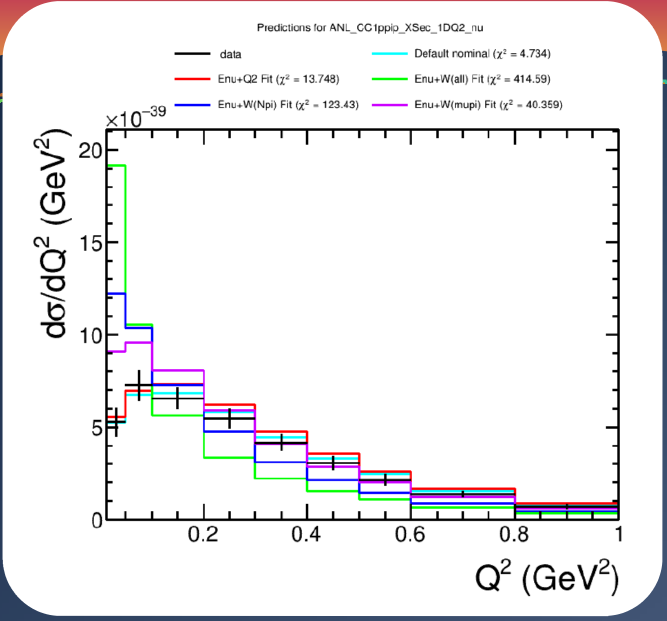

ANL_CC1pi0_Evt_1DWmupi_nu , NXSec_CA5RES
data
nominal ( χ² = 29.026)
-2σ (χ² = 29.721)
-1σ (χ² = 29.313)
+1σ (χ² = 28.826)
+2σ (χ² = 28.69)
Number of events
W(μπ) (GeV)

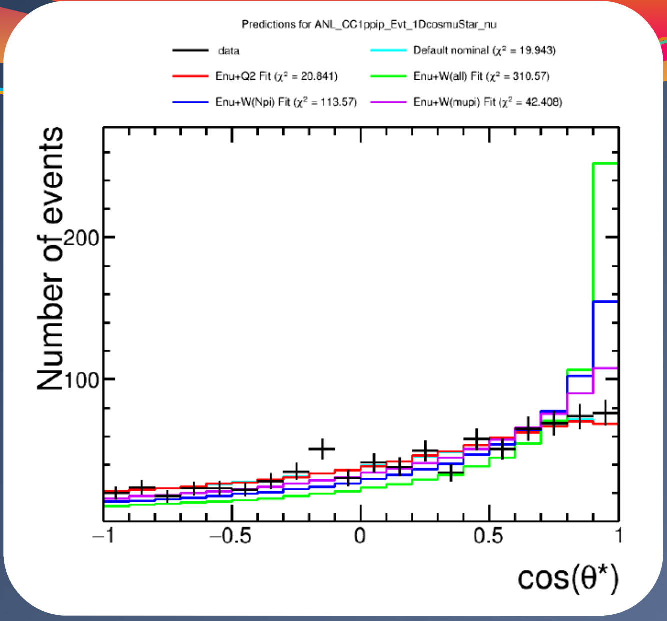

ANL_CC1pi0_Evt_1DWNmu_nu , NXSec_MaRES
data
nominal ( χ² = 94.959)
-2σ (χ² = 86.88)
-1σ (χ² = 89.932)
+1σ (χ² = 101.12)
+2σ (χ² = 107.78)
Number of events
W(Nμ) (GeV)

# Result of the (all) $E_\nu$ + (all) W group fits

| Parameter in NEUT | Pre-fit value ± uncertainty | Post-fit value (all $E_\nu$ and all W included) |
|---|---|---|
| $M_A^{RES}$ (GeV) | 0.95 ± 0.15 | 0.339 |
| $C_A^5(0)$ | 1.01 ± 0.15 | 3.145 |
| $I_{1/2}$ | 1.13 ± 0.40 | 1.227 |

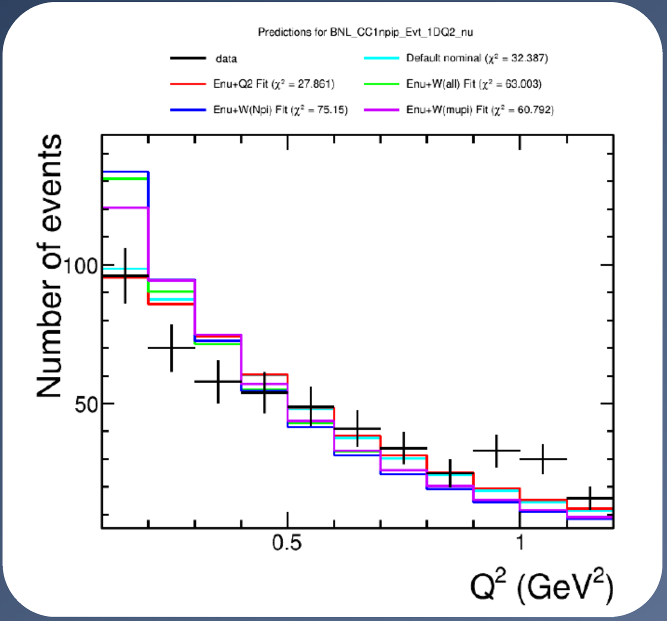
Sum of $\chi^2$ = 2534.15 and No. of Degrees of freedom (NDOF) = 683

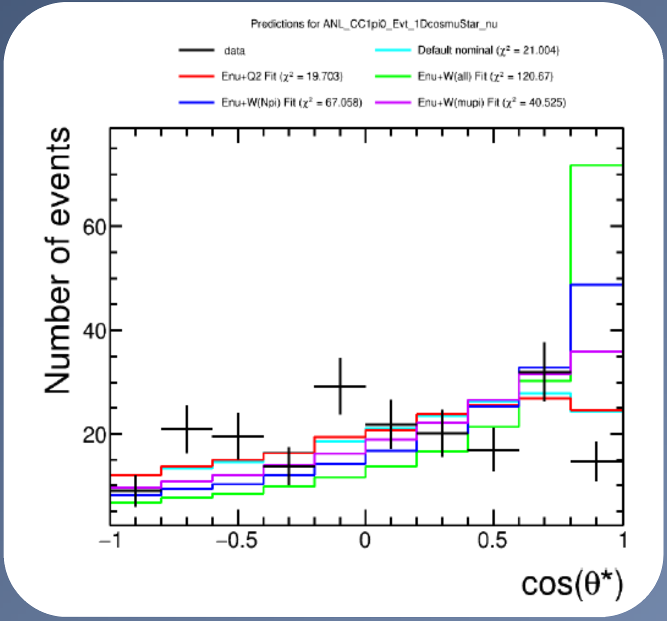



Over-estimate at low $Q^2$

Over-shoot at high $\cos(\theta^*)$



# Some Concerns with the $E_\nu$ + W group fits

- Bad agreement with other samples: at low $Q^2$ and very forward angles ($\theta^*$) of the muon in the neutrino-nucleon COM frame.

- Splitting simulation into resonance & non-resonance ($I_{1/2}$ background) contributions did not reveal any striking aberrations that would deem either component responsible for the observed discrepancies

- Comparing to the nominal or $E_\nu$ + $Q^2$ fits (which coincide), it is clear that predictions drawn from W & $Q^2$ distributions show disagreement when used to tune the NEUT model.

# Conclusions

- We will report the fitting results that we have obtained across multiple kinematic variables by using the unexplored W datasets in combination with the better-understood $E_\nu$ samples.

- Interesting problems for future research:

  - Figure out reasons behind the disagreement between two basic kinds of distributions in the context of the predictive model we have.

  - Try to construct improved parameter sets by fitting over combinations of other variables, or else look into how more freedoms can be introduced in the implementation.

  - A well-optimized set of $M_A^{RES}$ , $C_A^5(0)$, and $I_{1/2}$ parameters could help address uncertainties encountered in neutrino oscillation experiments.

# References


- Radecky, G. M., et al. "Study of single-pion production by weak charged currents in low-energy νd interactions." Physical Review D 25.5 (1982): 1161.
- Kitagaki, T., et al. "Charged-current exclusive pion production in neutrino-deuterium interactions." Physical Review D 34.9 (1986): 2554.
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# Thank You