Measuring The ν_μ and $\bar{\nu}_\mu$ induced Charged-Current Coherent Pion Production Cross Sections on Carbon Using The T2K Near Detector ND280

Mitchell Yu
York University
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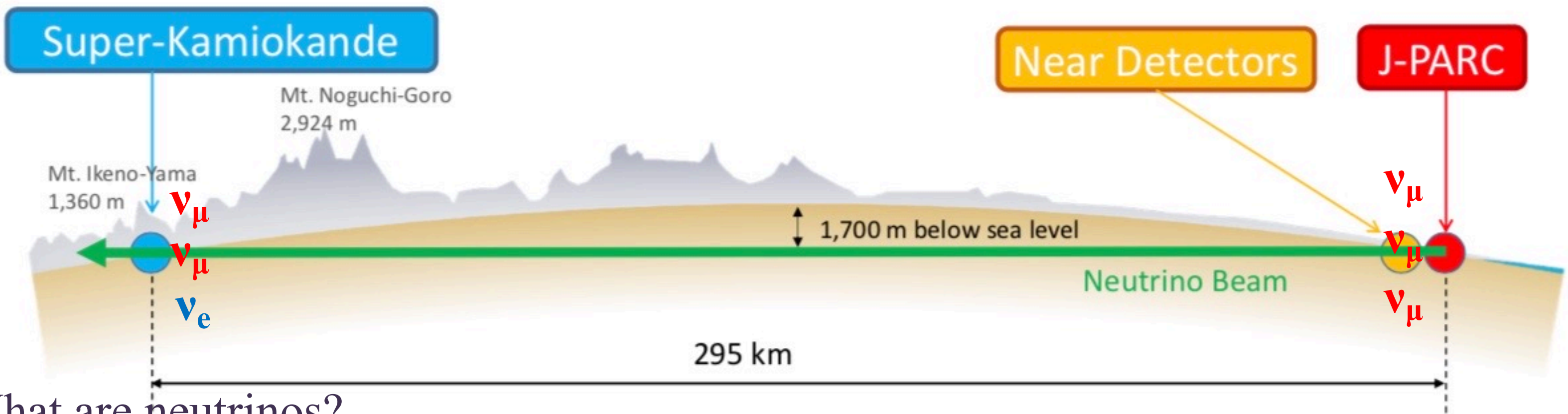
Overview

- The T2K experiment
- Neutrino interactions
- Coherent pion production
  - A rare yet important interaction channel to study
- Analysis highlights
  - Sample selection
  - Likelihood fitter
  - Systematic uncertainties
  - Analysis validations
- Results outlook and summary

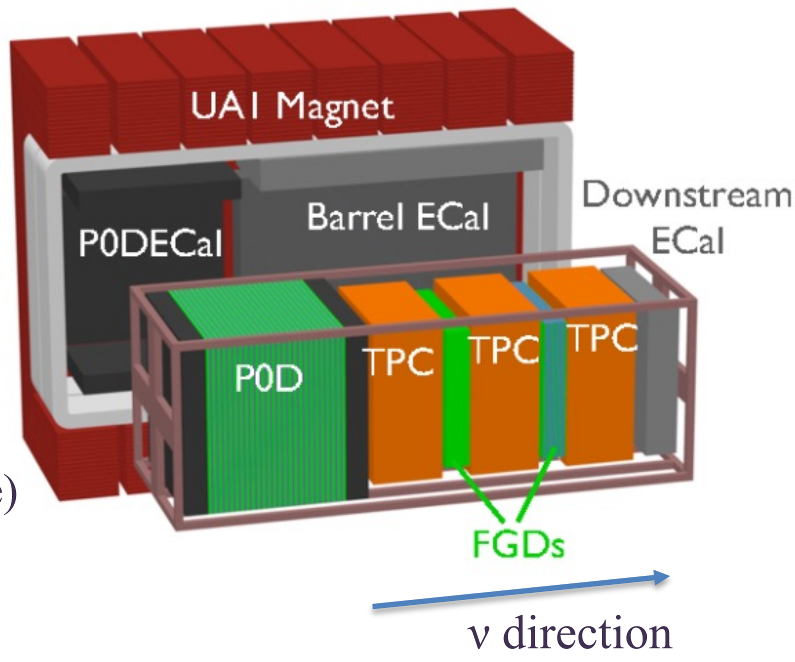
The T2K Experiment



- What are neutrinos?
  - The most abundant massive particles and they rarely interact
  - Neutrinos can also change identities while they propagate through space (neutrino oscillation)
- The Tokai-to-Kamioka (T2K) long baseline neutrino oscillation experiment
  - For more details on T2K, see Patrick de Perio's talk (TS4-3)
  - Utilizes the muon neutrinos and antineutrinos from the J-PARC proton accelerator facility
  - The near detector complex measures (un-oscillated) muon neutrino properties
  - The far detector Super-Kamiokande (SK) measures the the appearance of electron neutrinos (to study neutrino oscillation)
- T2K near detector complex ND280 provide rich neutrino interaction programs (this talk)
  - Better understanding of neutrino interactions

T2K Off-axis Near Detector ND280

- FGD
  - 2 fine grained detectors
  - Carbon and Oxygen target mass
  - **FGD1: plastic scintillator layers**
  - FGD2: alternating plastic and water layers
  - Particle identification for stopped particles
- TPC
  - 3 time projection chambers (Argon gas)
  - Momentum reconstruction (by track curvature)
  - Particle identification (by dE/dx)

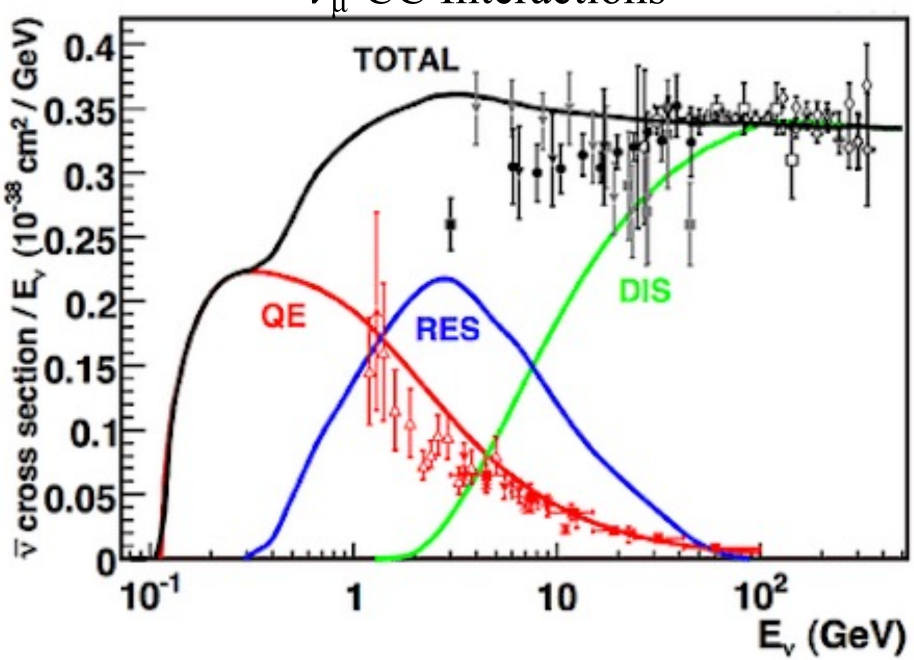


- P0D
  - Dedicated π^0 detector
  - Provide π^0 background constraints on Oxygen for Super-K (the main background)
- ECal
  - Electromagnetic Calorimeters (ECal) detectors surrounding
  - Particle identification (by electromagnetic shower)
- Magnet
  - All the detector components are surrounded a magnet (0.2 T)

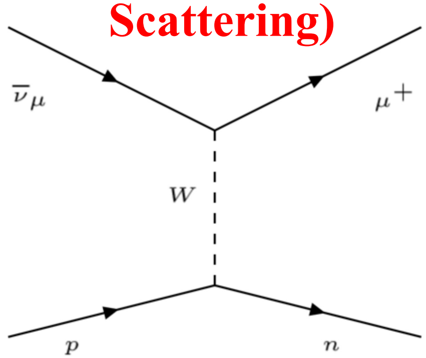
Neutrino Interactions

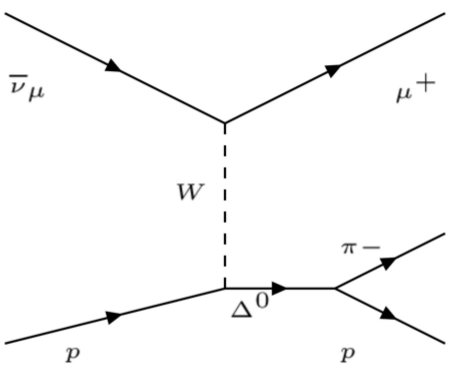
- Neutrino interactions are weak interactions
  - Neutral-current (NC) mediated by Z^0 boson
  - Charged-current (CC) mediated by $W^{\pm}$ boson
- Subcategorization based on the particles produced
  - QE, RES, and DIS are the dominant channels

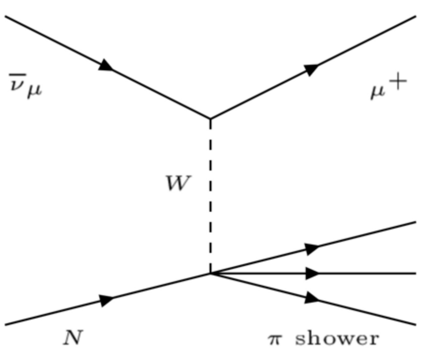
$\bar{\nu}_\mu$ CC Interactions



$\bar{\nu}_\mu$ CCQE (Quasi-Elastic Scattering)





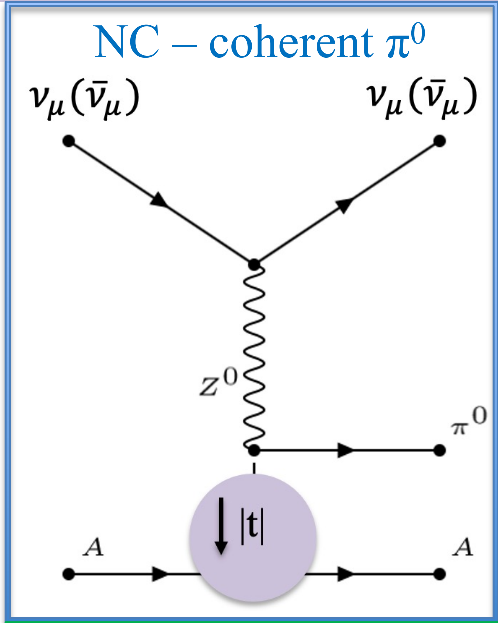


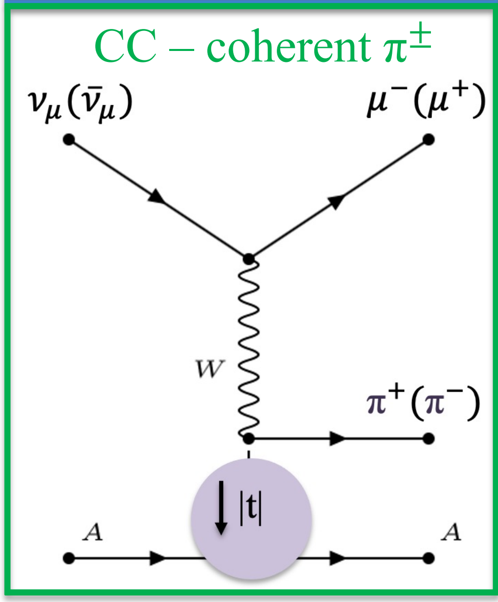
$\bar{\nu}_\mu$ CC-RES (Resonance Pion Production)

$\bar{\nu}_\mu$ CC-DIS (Deep Inelastic Scattering)

Coherent Pion Production

- Neutrino induced coherent pion production (COH)
  - Rare interaction channel (less than one percent)
  - A neutrino scatters off an entire nucleus
  - Produces 1 lepton and 1 pion
    - Both with small angle with respect to the neutrino direction
    - NC-coherent (NC-COH) has an outgoing π^0
    - CC-coherent (CC-COH) has an outgoing $\pi^\pm$
  - no fragmentation of the nucleus
    - Small four-momentum transferred squared (|t|)
    - No nucleons produced to deposit energy in the detector (vertex activity)





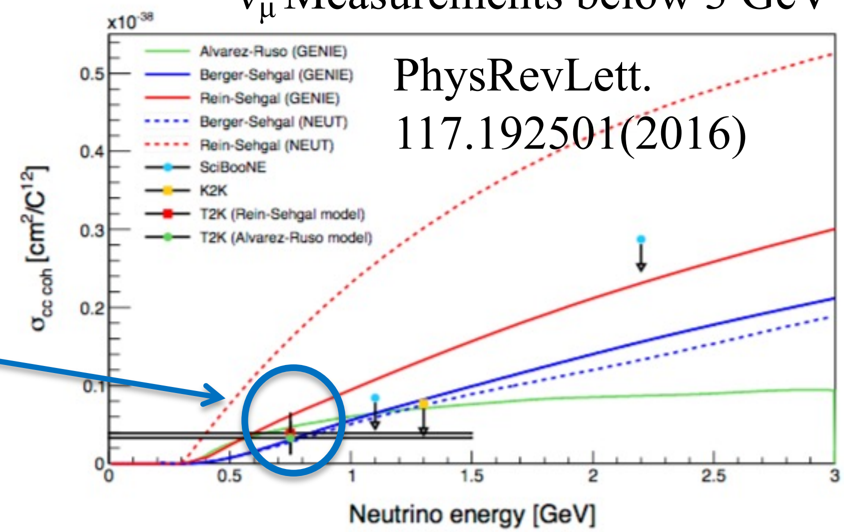
Analysis Motivation

- Why do we care about such an interaction?
  - This is not well understood theoretically - interesting measurement
  - π^0 from the neutral current coherent interaction can also mimic electron neutrino appearance in the T2K oscillation analysis
    - 3% background (simulation prediction) to the electron neutrino candidates at SK
    - 30% model uncertainty on the neutral current coherent pion production
- Measurements of the coherent pion production would help to constrain the physics model used in neutrino interaction generators
  - Underlying physics model for the neutral and charged current channels is the same

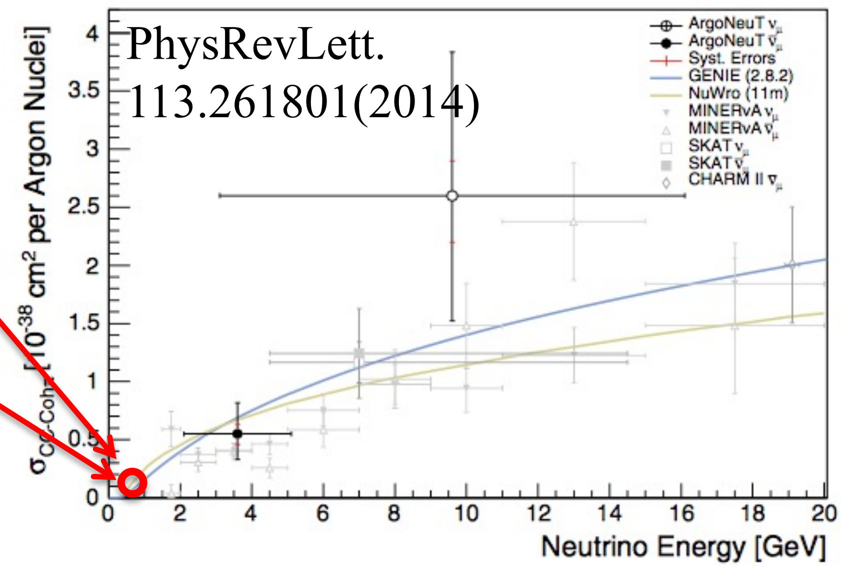
Current and New CC-COH Measurements

- ν_μ CC-coherent π^+ on ^{12}C
  - Only handful of successful global measurements
  - T2K CC-coherent π^+ on ^{12}C measurements (2016)
  - **New measurement #1**
    - Double the statistics
    - More sophisticated systematic uncertainty treatment
- $\bar{\nu}_\mu$ CC-coherent π^- on ^{12}C
  - **New measurement #2**
    - Using the T2K $\bar{\nu}_\mu$ data, the first observation of the process at sub-GeV region is possible
- Theoretical models explained in the backup slides

ν_μ Measurements below 3 GeV

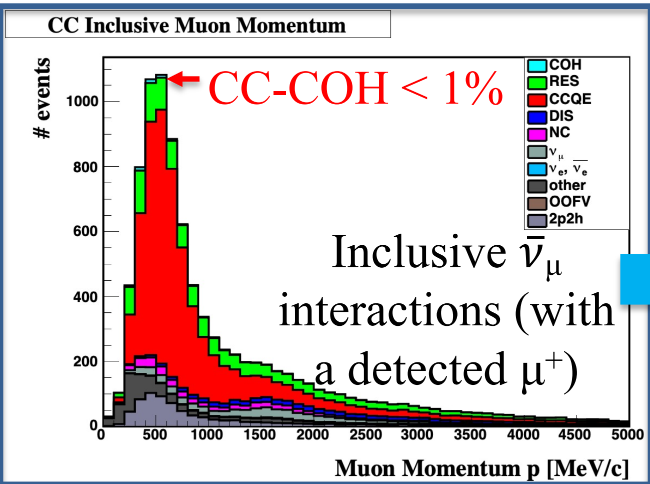


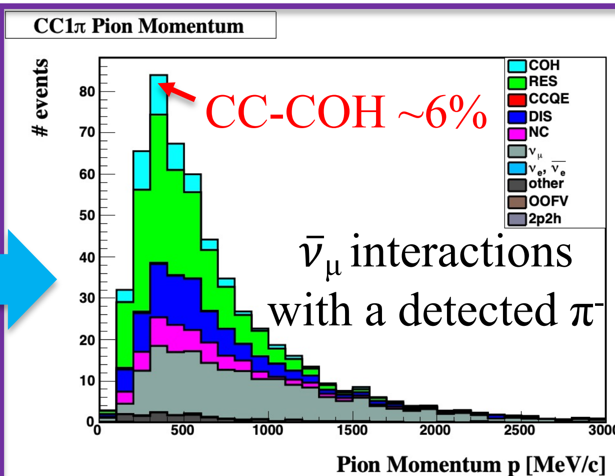
ν_μ and $\bar{\nu}_\mu$ Measurements Below 20 GeV

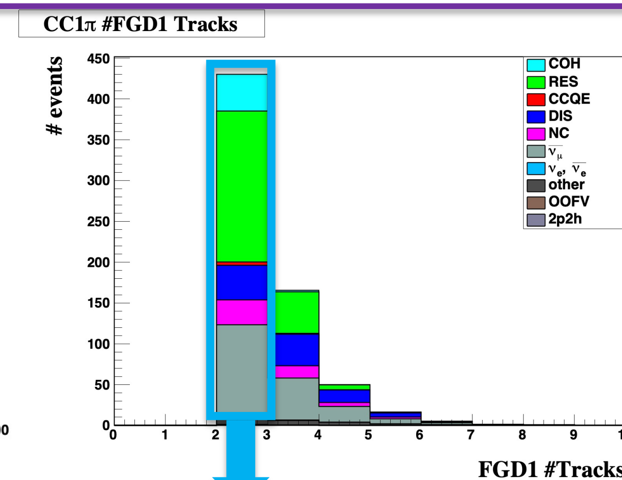


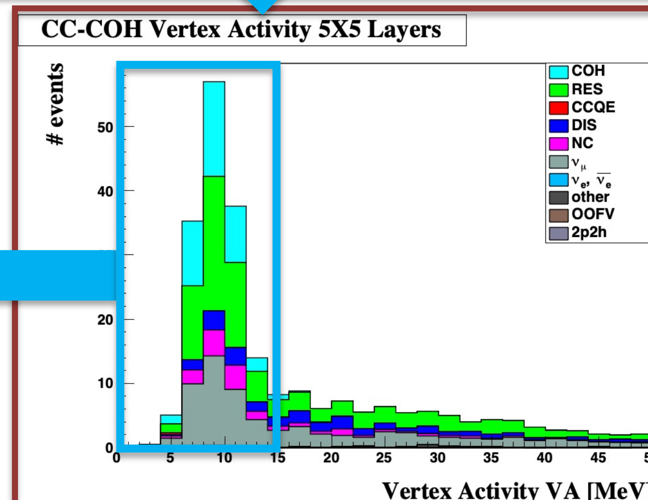
Coherent Pion Production Selection

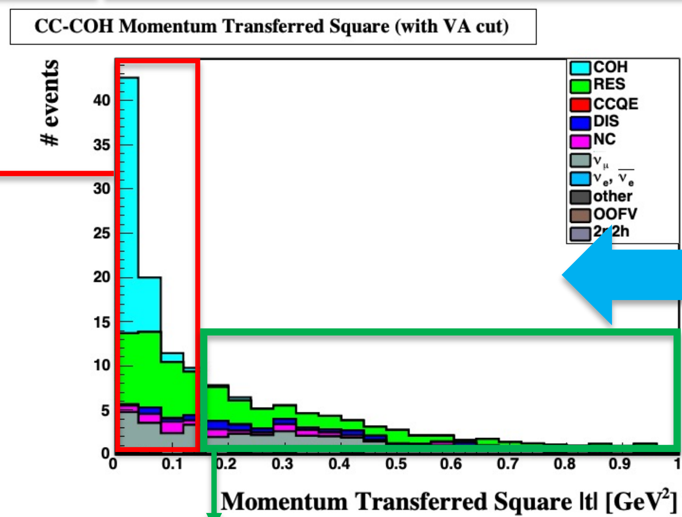
- $\bar{\nu}_\mu$ CC-coherent π^- selection (T2K MC only)











CC-COH Signal region

- 44% purity
- 36 $\bar{\nu}_\mu$ CC-coherent π^- events predicted in data
- MC stat. is 13.8 times data stat.
- Sample 0

Background control region

- For RES
- Sample 1

Cross-section Likelihood Fitter

- Likelihood fitter
  - Finds the measured number of CC-COH events
  - Adjust simulation prediction to data (best fit)
  - Minimizes the chi-square: $\chi^2 = \chi^2_{stat.} + \chi^2_{syst.}$

SELECTION

Selected Events (Data)

Selected Events (Simulation)

SYSTEMATIC UNCERTAINTIES

Detector Systematics Covariance

Neutrino Flux Covariance

Cross-section Model Covariance

Cross-section likelihood fitter

Best fit result of measured number of events (with stat. and syst. uncertainties)

$$\frac{N_{event}}{\varepsilon \cdot T \cdot \Phi} = \sigma$$

- ε: selection efficiency
- T: # of target nucleus
- Φ: # of incident neutrino per unit area

Cross section is the likelihood of the neutrino to interact

- $\nu_\mu + A \rightarrow \mu^- + \pi^+ + A$
- $\bar{\nu}_\mu + A \rightarrow \mu^+ + \pi^- + A$

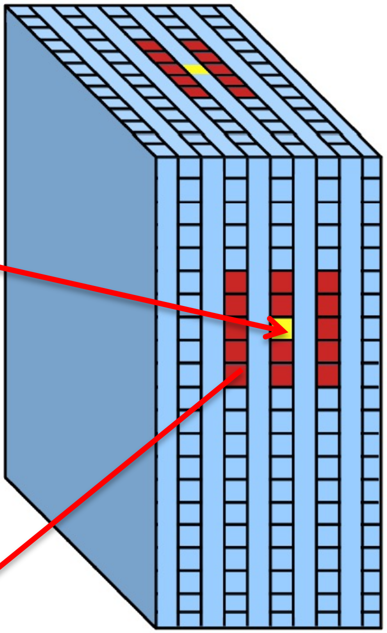
Systematic Uncertainties & Analysis Validations

- Fake data (also known as mock data or pseudo data) studies
  - Blind analysis to avoid bias to the results
  - Adjustments to the nominal MC simulation
    - Test specific aspects of the analysis framework, especially background events
    - Fake data cross section is known
  - Evaluate analysis framework performances
    - Does the fitter return the correct cross section?

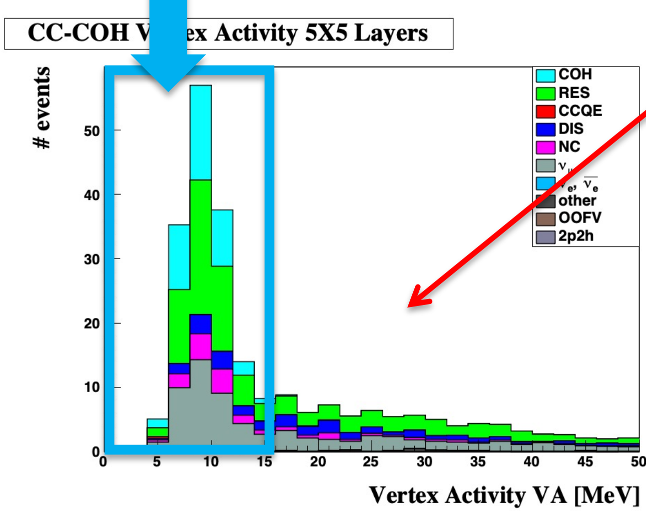
- Systematic uncertainties
  - Two will be highlighted in this talk
- The "known unknown"
  - Known sources of uncertainties
  - Need to be evaluated for the analysis
- The "unknown unknown"
  - Sources of uncertainties that are not yet studied and modelled by the analysis framework

Systematic Uncertainties

The T2K fine grained detector (FGD1)



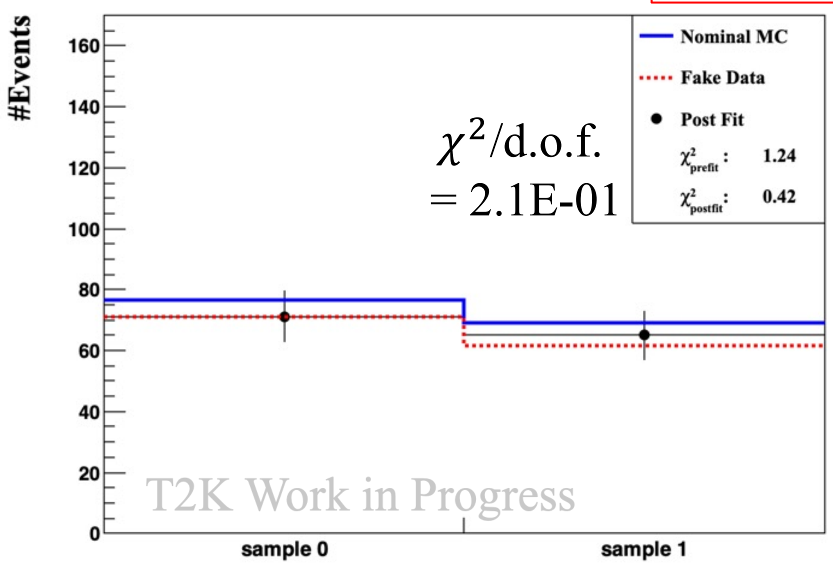
- The “known unknown”
  - Vertex activity (VA)
    - The energy deposition by particles around the neutrino interaction vertex in detector
    - Used as a selection variable for the analysis
  - Sources of uncertainties related to vertex activity
    - Detector reconstruction in the simulation
    - Modelling of particles produced from interactions



Example of $\bar{\nu}_\mu$ Analysis Validations

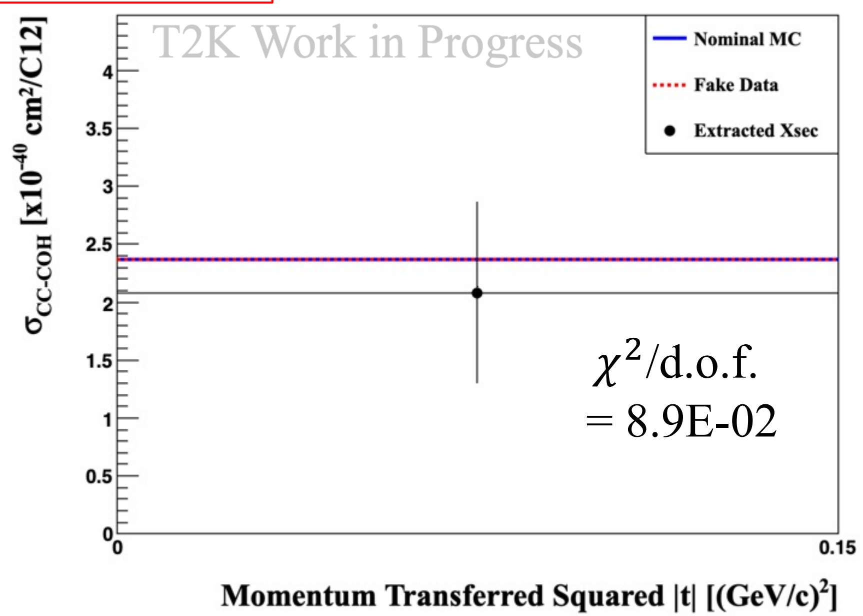
- Additional vertex activity fake data study
  - Motivated by another T2K analysis (see backup)
- Extracted cross section is very close to the fake data cross section
  - Existing systematic uncertainties covers the difference between cross sections
  - Analysis framework is robust against the change related to the vertex activity

Likelihood Fitter Results



Signal Region

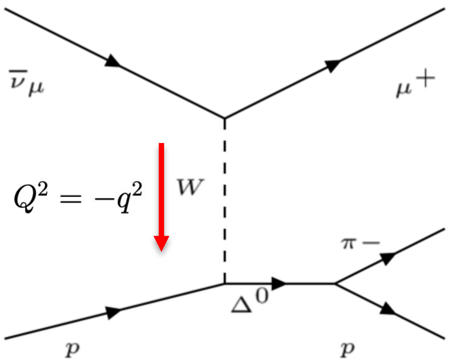
Background Control Regions



Extracted Cross-section based on the fake data

Systematic Uncertainties

- The "unknown unknown"
  - Low Q^2 suppression of the RES background
    - Results from other experiments (e.g. the MINERvA experiment, see backup) indicate an over prediction of RES at low Q^2 region ($Q^2 < 0.7$ GeV^2) in the simulation
    - Unclear yet whether the T2K simulation over predicts
  - The analysis need to be able to handle such a change
    - Currently no uncertainty assigned

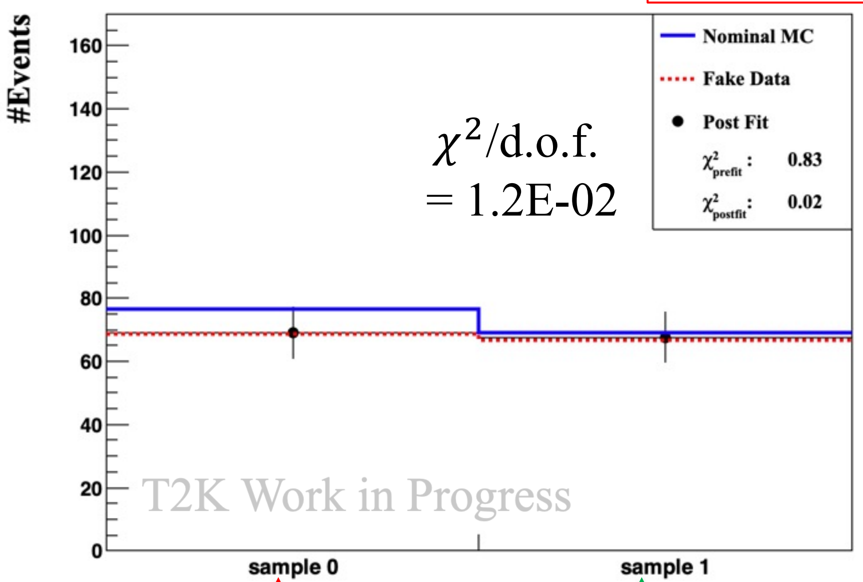


CC-RES

Example of $\bar{\nu}_\mu$ Analysis Validations

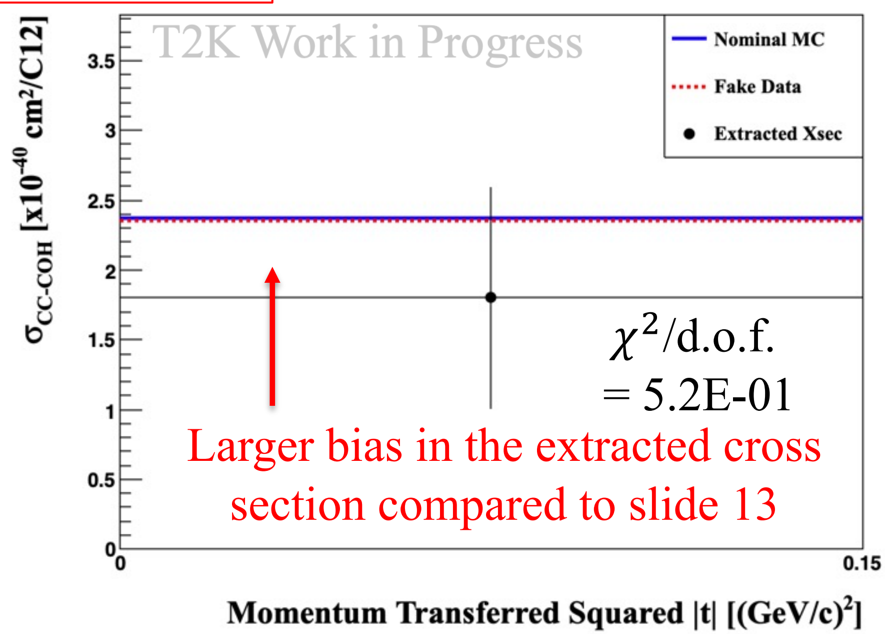
- Low Q^2 suppression of RES
  - Guidance from the MINERvA experiment results (see backup)
- A good fit does not necessarily mean an accurate extracted cross section
  - The bias in the extracted cross section indicate insufficient degree of freedom in the fitter
  - Additional systematic uncertainty needed to cover this bias

Likelihood Fitter Results



Signal Region

Background Control Regions



Extracted Cross-section based on the fake data

Results outlook & Summary

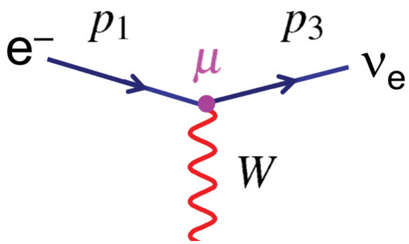
- The T2K near detectors provide opportunities to study neutrino interactions
- Coherent pion production
  - Background for the T2K oscillation analysis
  - New measurements (ν_μ and $\bar{\nu}_\mu$) to be performed
    - ν_μ CC-COH on ^{12}C: improved measurement (compared to the 2016 result)
    - $\bar{\nu}_\mu$ CC-COH on ^{12}C: first measurement at sub-GeV region
- Examples of the challenges to the analysis shown
- Status of the analysis
  - Analysis procedure finalized
  - Full data unblinding soon

Stay tuned for the results from T2K!

Back up

CVC and PCAC Hypothesis

- Weak interactions are experimentally determined to have the form of Vector – Axial-Vector (V-A)

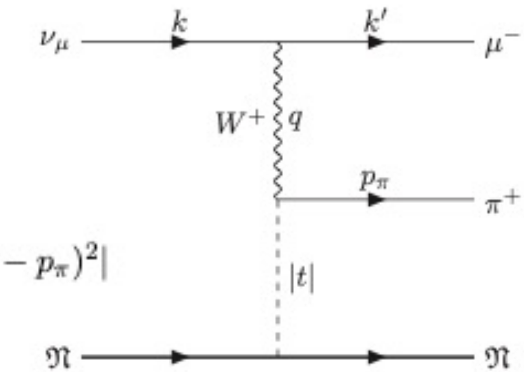


$$j^{\mu} \propto \bar{u}_{\nu_e}(\gamma^{\mu} - \gamma^{\mu}\gamma^{5})u_e$$

Vector   Axial-Vector

- In pure vector, or axial-vector interactions parity is conserved
- Weak interactions do not conserve parity due to the linear combination of vector and axial-vector
  - $\gamma^{\mu} - \gamma^{\mu}\gamma^{5} \rightarrow c_V\gamma^{\mu} - c_A\gamma^{\mu}\gamma^{5}$
  - c_V – correction to the vector ”weak charge”
  - c_A – correction to the axial vector “weak charge”
- Conserved Vector Current (CVC) hypothesis
  - Experimentally, $c_V = 1.000$
- Partially Conserved Axial Current (PCAC) hypothesis
  - Experimentally, $c_A = 1.270 \pm 0.003$ → ”Almost” conserved

Rein and Sehgal (1983)



- From Adler's theorem,

$$\frac{d^2\sigma(\nu + \mathfrak{N} \to \ell^- + \mathfrak{N}')}{dQ^2 dW} = \frac{G_F^2 W}{2\pi^2 M_{\mathcal{N}}} \frac{E_\ell}{E_\nu (E_\nu - E_\ell)} f_\pi^2 \sigma(\mathfrak{N} + \pi \to \mathfrak{N}')$$

$$x_B = \frac{Q^2}{2M_{\mathcal{N}}(E_\nu - E_\ell)} \quad , \quad y_B = \frac{E_\nu - E_\ell}{E_\nu} \qquad |t| = |(q - p_\pi)^2| = |(k - k' - p_\pi)^2|$$

$$\left(\frac{d\sigma}{dx_B\, dy_B\, d|t|}\right)_{Q^2=0} = \frac{G_F^2\, M_{\mathcal{N}}\, E_\nu}{\pi^2} \frac{1}{2} f_\pi^2 \,(1 - y_B)\, \frac{d\sigma(\pi\mathfrak{N} \to \pi\mathfrak{N})}{d|t|}\Big|_{E_\nu y = E_\pi}$$

- Adding nucleus dependencies

$$\frac{d\sigma(\pi\mathfrak{N} \to \pi\mathfrak{N})}{d|t|} = A^2\, |F_{\mathfrak{N}}(t)|^2 \frac{d\sigma(\pi\mathcal{N} \to \pi\mathcal{N})}{d|t|} \qquad \frac{d\sigma(\pi\mathcal{N} \to \pi\mathcal{N})}{d|t|} = \frac{1}{16\pi}\left[\sigma_{\rm tot}^{\pi\mathcal{N}}\right]^2 (1 + r^2)$$

$$|F_{\mathfrak{N}}(t)|^2 = e^{-b|t|} F_{\rm abs}, \quad \text{with } b = \frac{R_0^2}{3} A^{2/3} \qquad r = \mathbf{Re}[f_{\pi N}(0)]/\mathbf{Im}[f_{\pi N}(0)]$$

- Rein-Sehgal triple differential coherent cross section

$$\frac{\mathrm{d}\sigma^{\rm NC}}{\mathrm{d}x\, \mathrm{d}y\, \mathrm{d}|t|} = \frac{G_F^2\, M_{\mathcal{N}}\, E_\nu}{4\,\pi^2} f_{\pi^0}^2\, (1 - y_B) \left(\frac{m_A^2}{m_A^2 + Q^2}\right)^2 A^2\, F_{abs}\, e^{-b|t|} \frac{1}{16\pi}\left[\sigma_{tot}^{\pi^0 N}(Ey)\right]^2 (1 + r^2)$$

- For charged-current cross section:
  - Substitute pion decay constant: $f_{\pi^+}^2 = 2\, f_{\pi^0}^2$

Rein and Sehgal (2007)

- Following the original RS formulization

$$\frac{d\sigma^{\rm NC}}{dx\,dy\,d|t|} = \frac{G_F^2\,M_N\,E_\nu}{4\,\pi^2}\,f_{\pi^0}^2\,(1-y_B)\left(\frac{m_A^2}{m_A^2+Q^2}\right)^2 A^2\,F_{abs}\,e^{-b|t|}\,\frac{1}{16\pi}\left[\sigma_{tot}^{\pi^0 N}(Ey)\right]^2(1+r^2)$$

- For CC-COH, deficit was found in forward going muon direction
  - Outgoing lepton mass is not assumed to be zero anymore
  - Correction factor was added

$$\mathcal{C} = \left(1 - \frac{1}{2}\frac{Q^2_{\rm min}}{Q^2 + m^2_{\pi^+}}\right)^2 + \frac{1}{4}y_B\frac{Q^2_{\rm min}(Q^2 - Q^2_{\rm min})}{(Q^2 + m^2_\pi)^2} \qquad Q^2_{\rm min} = m^2_{\rm lep}y_B/(1 - y_B)$$

  - The modified RS cross section:

$$\frac{d\sigma^{CC}}{dx_B\,dy_B\,d|t|} = \frac{d\sigma^{NC}}{dx_B\,dy_B\,d|t|} \times 2\mathcal{C}\theta(Q^2 - Q^2_{\rm min})\theta(y_B - y_{\rm B,\,min})\theta(y_{\rm B,\,max} - y_B)$$

  - A reduced valid phase space is defined:

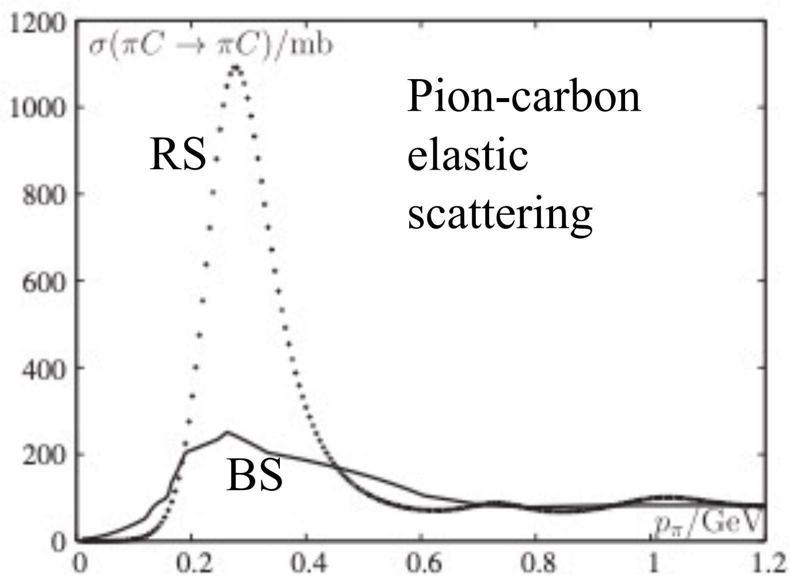
$$y_{\rm B,\,min} = m_\pi/E \qquad y_{\rm B,\,max} = 1 - m_{\rm lep}/E$$

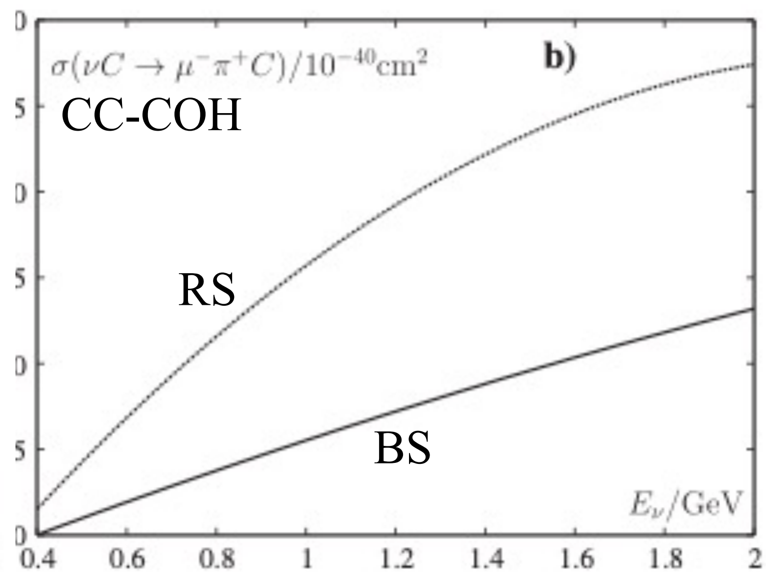
Berger and Sehgal (2009)

- The original and modified RS does not describe experimental measurements in the sub-GeV to few-GeV region
- 2 further modification was added by Berger and Sehgal
- Approximation of the kinematic term 1-y_B is replaced by the complete derived term

$$1 - y_B + \frac{y_B^2}{4}\left(1 - \left|\frac{Q^2}{(E_\nu - E_\ell)^2} + 1\right|\right)$$

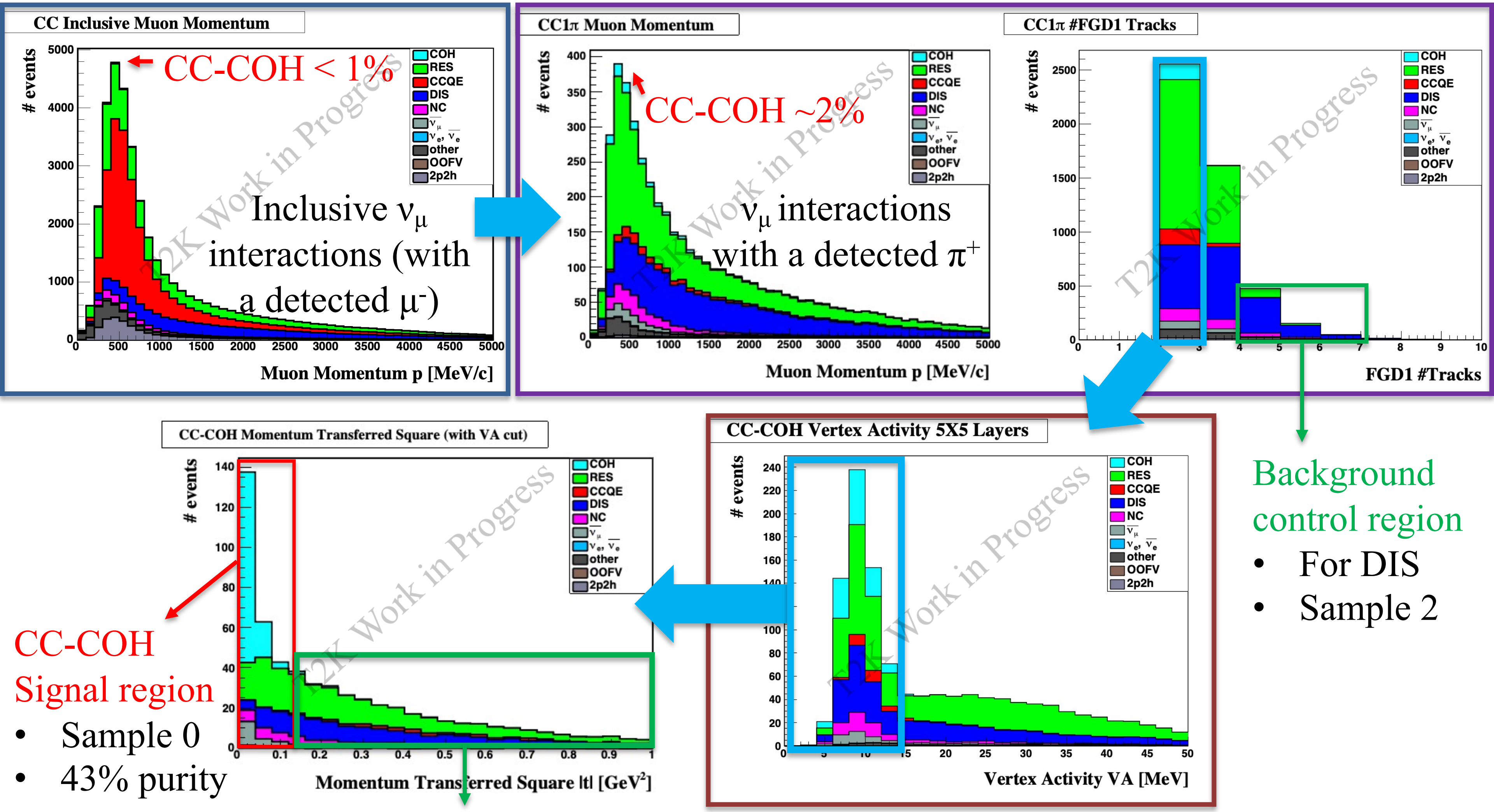
- BS used external pion-carbon scattering data to constrain the pion-nucleus cross section
  - RS tries to model the nuclear processes for the pion-nucleus elastic differential cross section used inside the model





Coherent Pion Production Selection

- ν_μ CC-coherent π^+ selection (T2K MC only)



Background control region

- For RES and DIS
- Sample 1

Motivation for the Additional VA Study

- Study performed at the T2K on-axis near detector (INGRID)
  - A sample of CC interactions with 0 π produced, and 2 tracks in the detector is selected
  - Difference seen in the data and MC comparison in vertex activity
    - Could be explained by additional {0-100MeV} of energy deposition added to 25% of background events with a neutron target

MINERvA Low Q^2 Suppression

- Phys. Rev. D 100, 072005 (2019)
- Indication of MC overprediction of CC-1π events at low Q^2 region

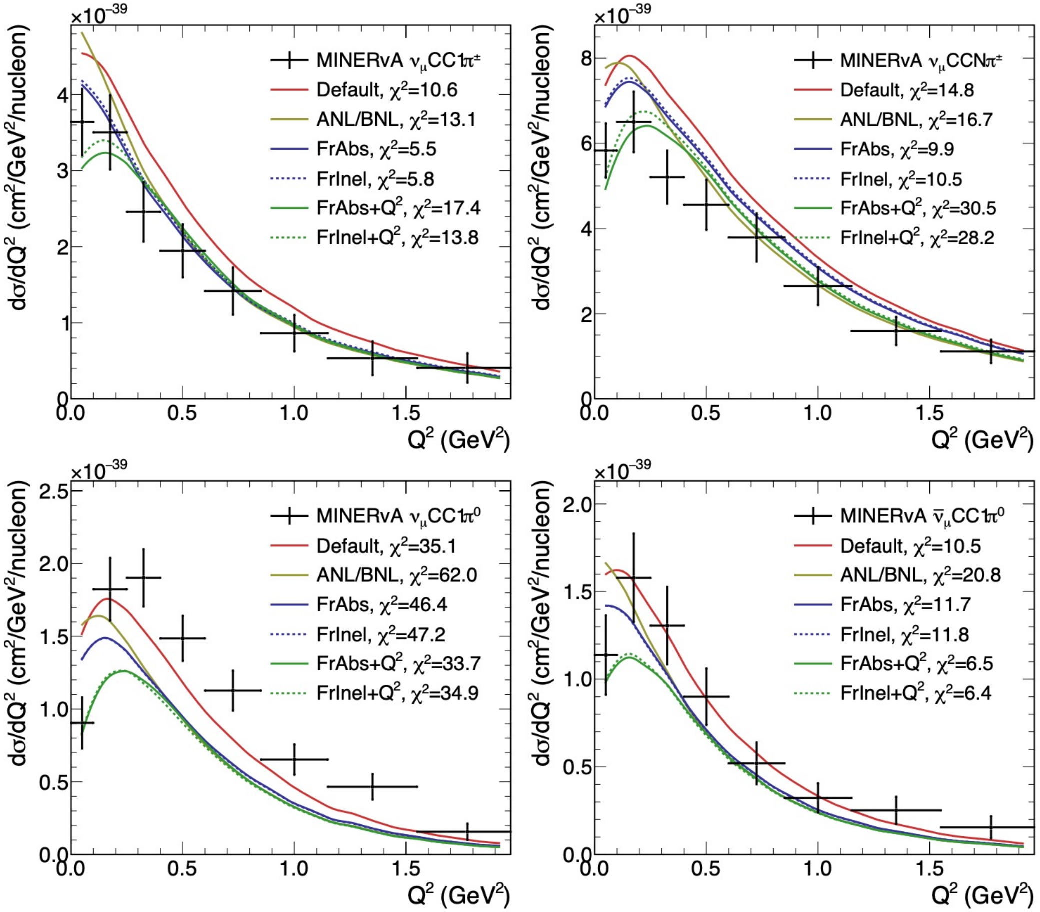


FIG. 11. Comparisons of the nominal and tuned models to MINERvA $\nu_\mu CC1\pi^\pm$ (left top), $\nu_\mu CCN\pi^\pm$ (right top), $\nu_\mu CC1\pi^0$ (left bottom) and $\bar{\nu}_\mu CC1\pi^0$ (right bottom) distributions in Q^2. The χ^2 is computed using the full covariance matrices. The distributions were not explicitly used in the tuning procedure.