The CC1π^+ Cross Section
in the P0D sub-detector of ND280, the T2K ND

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T2K

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Overview

- Motivation

- Signal Definitions

- ND280 and the P0D

- Track reconstruction and event selection

- Fitter strategy

- Mock data studies

- Results

Motivation

- **Results from previous experiments do not agree**
  - Different kinematic regions
  - Model dependent results
  - New restricted phase space result with limited model dependence √

- **New models in T2K MC (NEUT) being considered**
  - New coh. model: R-S→B-S (top)
  - New res. model: R-S→MK (bottom)
  - New result with sensitivity to model changes √

Paul Martins arXiv:1605.00095

$$\nu_\mu p \to \mu p \pi^+$$

Minoo Kabirnezhad
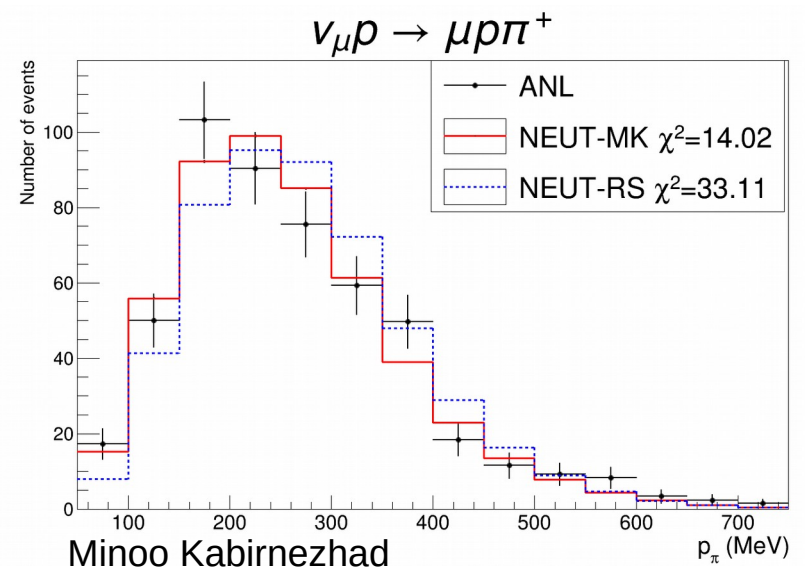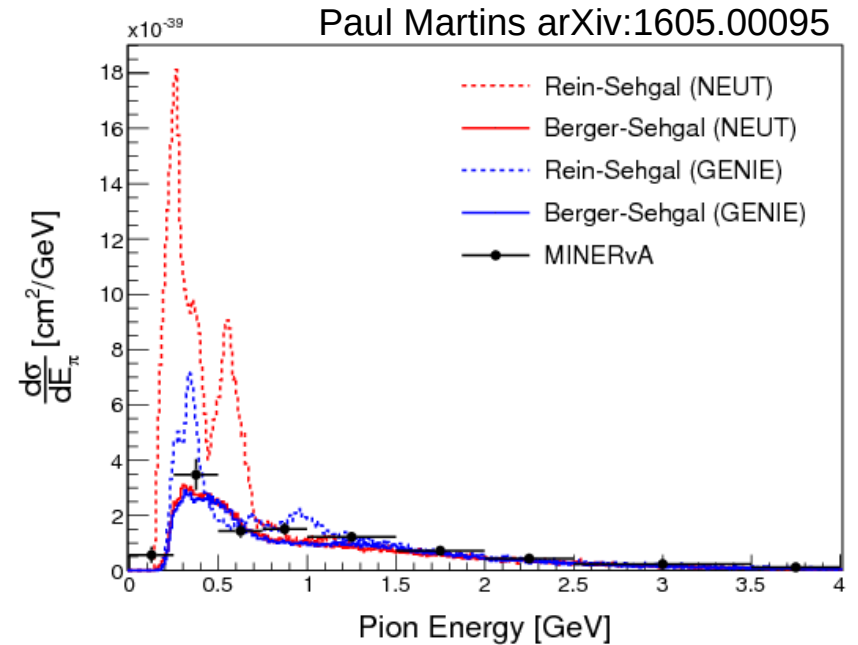
Signal Definition

- Interaction model: resonance production
  - Weak interaction physics
  - Requires 'unfolding' nuclear model

- AfterFSI model: $1\mu1\pi$ escapes the nucleus
  - Useful for oscillation analyses on same nucleus
  - Requires unfolding the detector model (and phase space restrictions)

- Topological model: $1\mu1\pi$ detected
  - What is actually measured
  - Well defined phase space
  - Inefficiencies are due to containment, and misreconstruction
 - Must convert to physics of interest

ν_μ

μ

Vertex activity

Tracked hadrons

FSI

Unseen particles

Detector Thresholds

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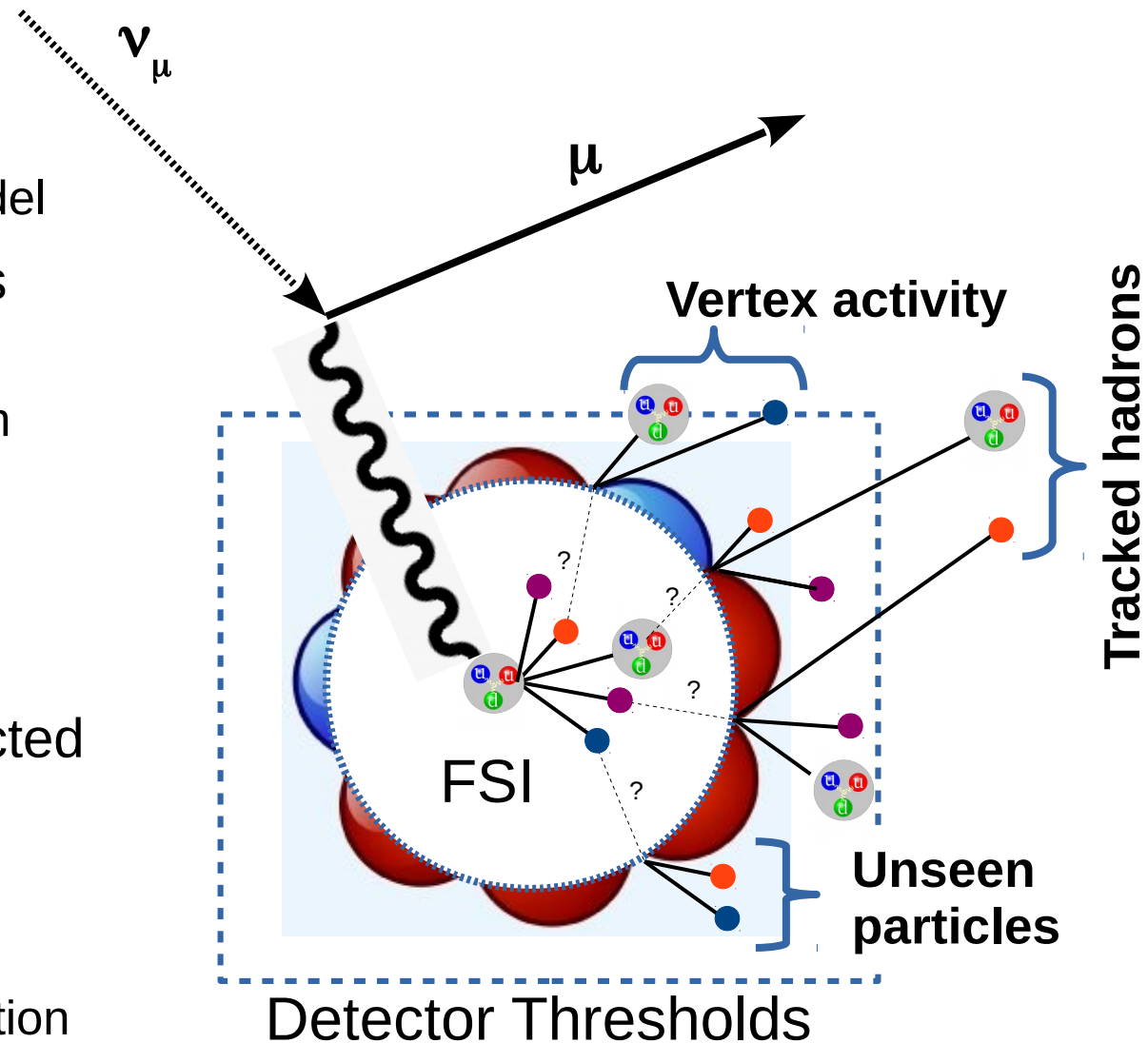
ND280 and the P0D

- ND280 is the T2K off-axis ND
- Same off-axis angle as SK, 2.5°
- Contained in a 0.2 T magnetic field
- Three CH and H_2O target modules
  - **P0D** (**water-in** / water-out)
  - FGD1 (CH)
  - FGD2 (CH+H_2O)
- Three TPC trackers downstream from each target module

5
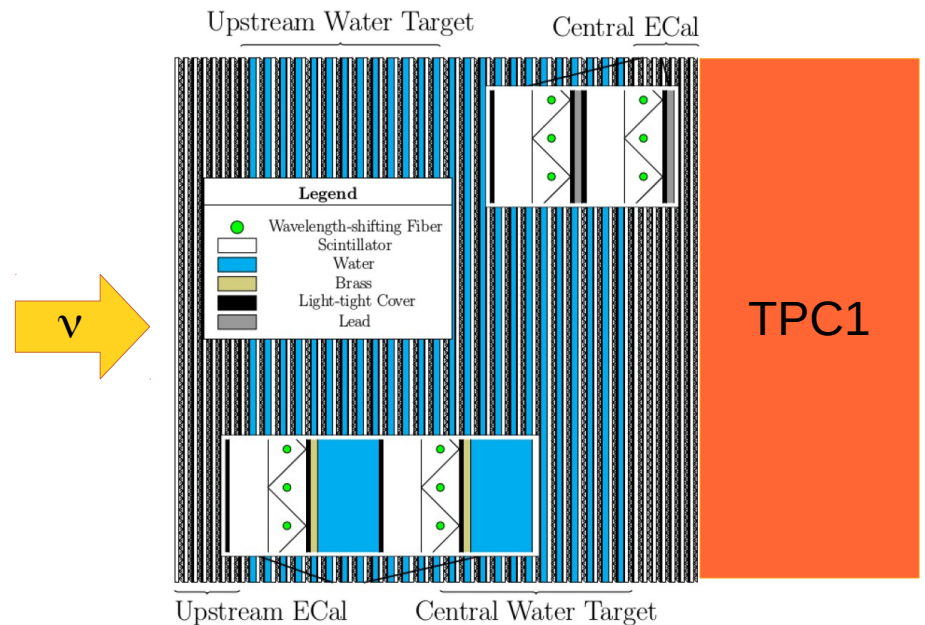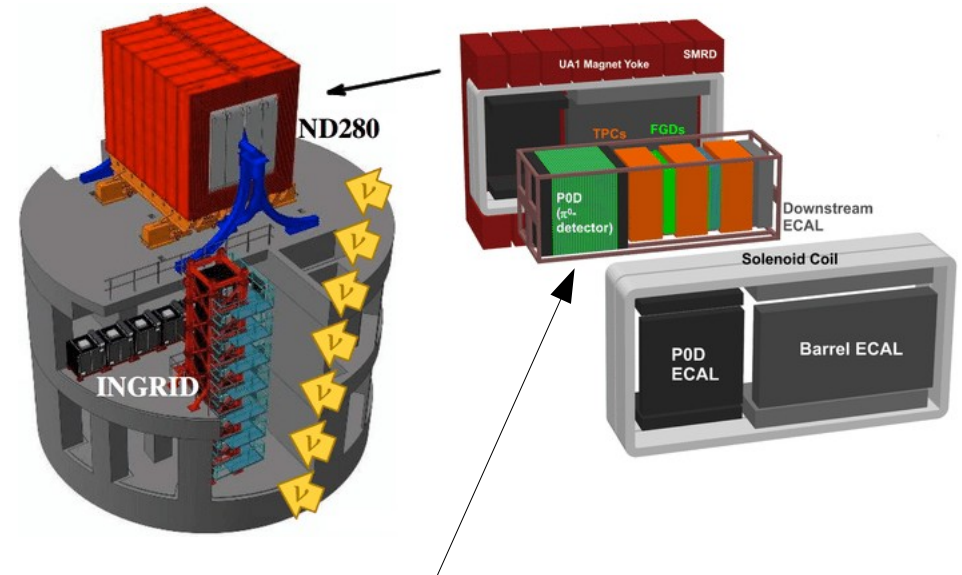
Track Reconstruction

- Three types of tracks
  - Kalman Contained
    - Long track traversing >= 5 scintillator planes
    - Contained in the P0D
  - Kalman Exiting
    - Long track traversing >= 5 scintillator planes
    - Enters TPC1
  - Cluster
    - Short or high angle tracks
    - Does not cross 5 P0D planes
   - Does not enter TPC1
- No Side-exiting tracks
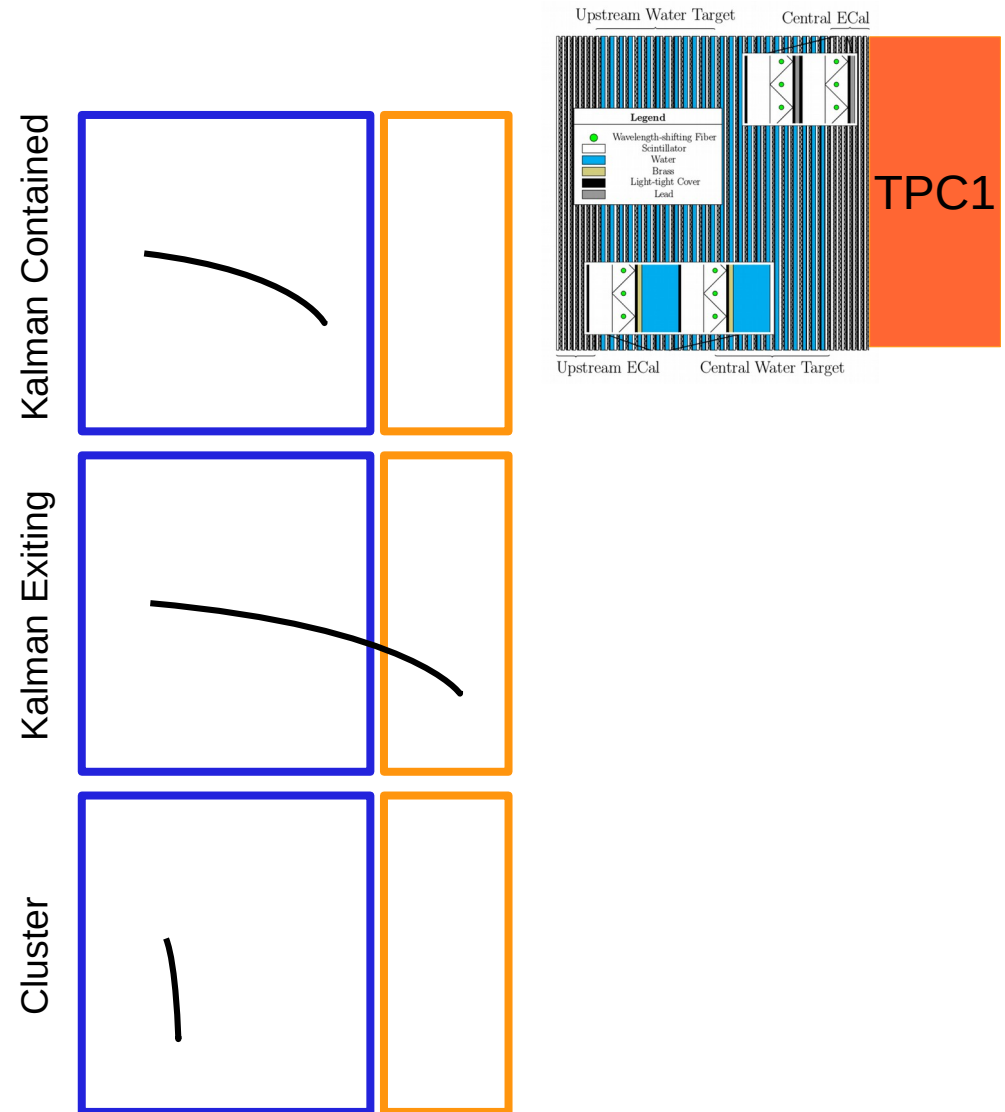
Kalman Contained
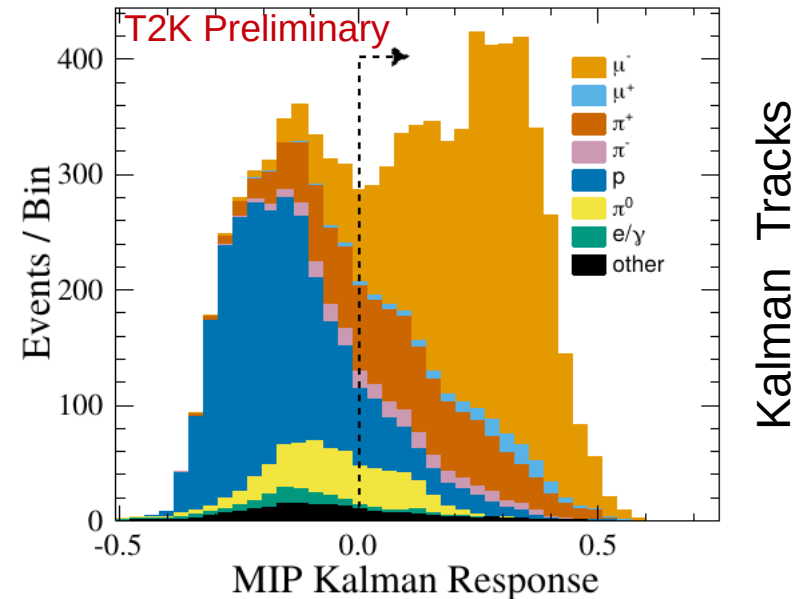
Kalman Exiting

Cluster

TPC1

Event Selection

- Require 2 selected tracks

- Select tracks based on BDT score

  - BDT seperates MIP tracks from non-MIP tracks

  - Different BDTs for Kalman and Cluster tracks

  - Inputs: topological variables describing detector response
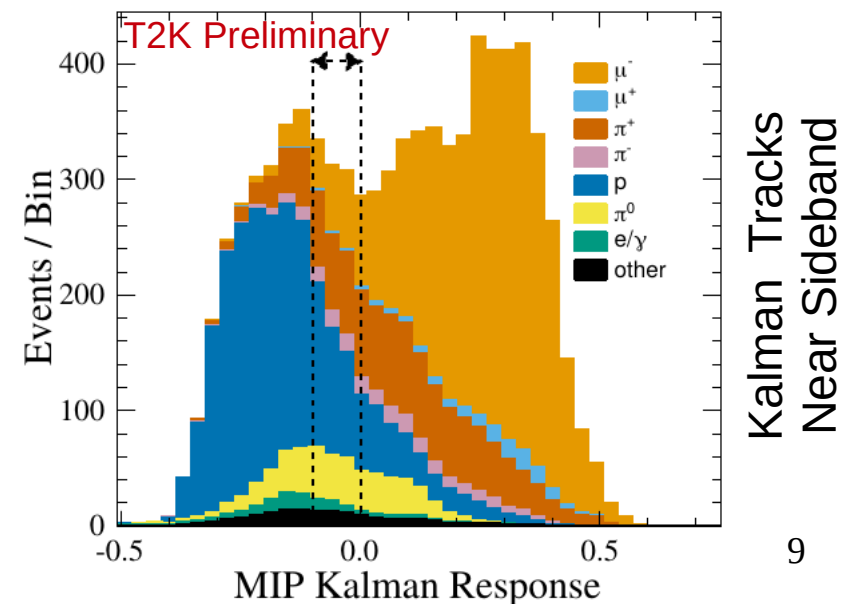
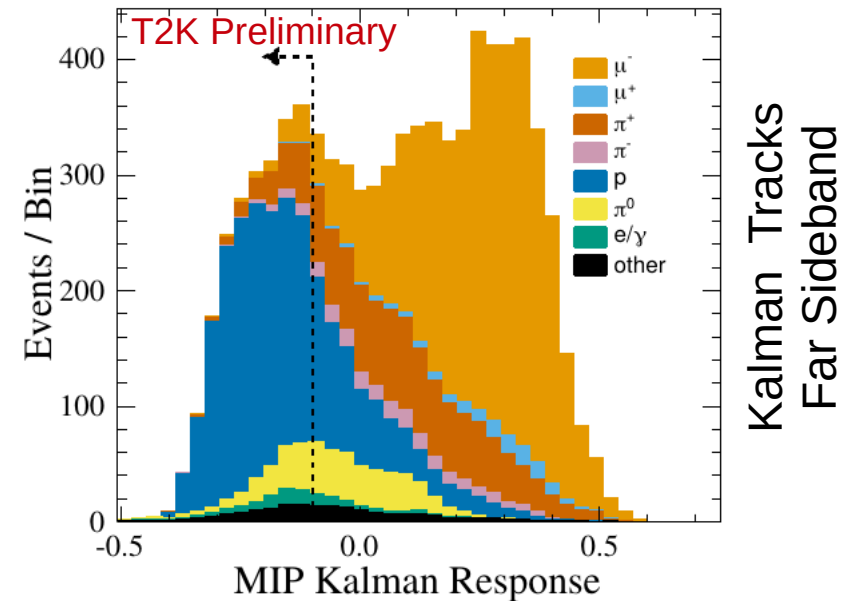- Select 1st track: high BDT score required
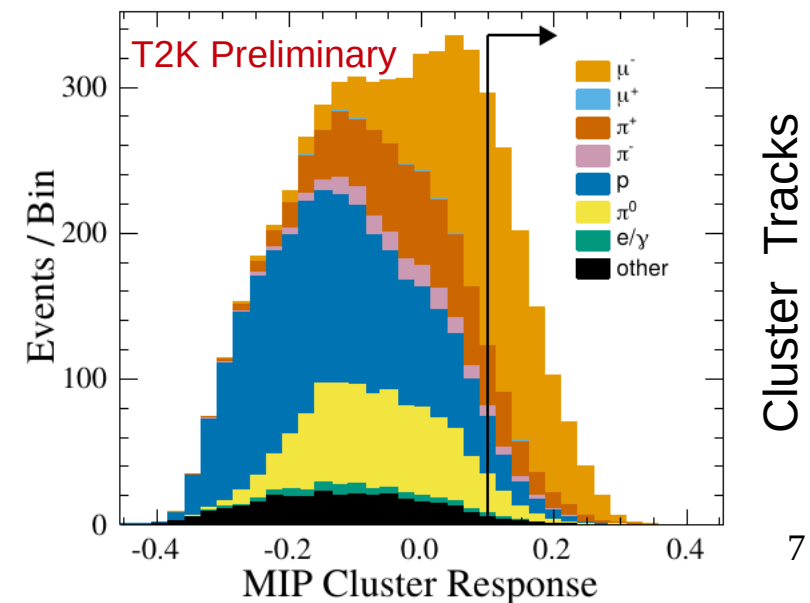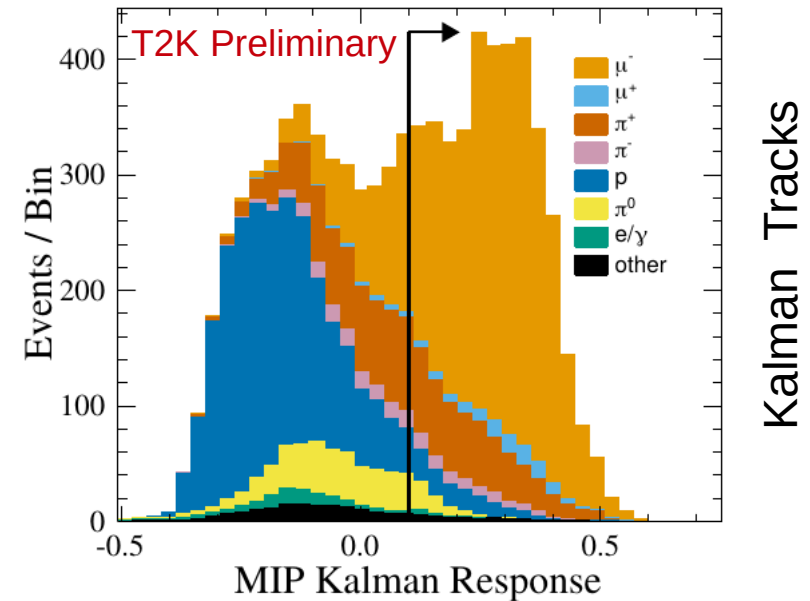
Event Selection

- Require 2 selected tracks

- Select tracks based on BDT score

  - BDT seperates MIP tracks from non-MIP tracks

  - Different BDTs for Kalman and Cluster tracks

  - Inputs: topological variables describing detector response

- Select 1st track: high BDT score required

- Select 2nd track: more relaxed BDT score to improve pion efficiency
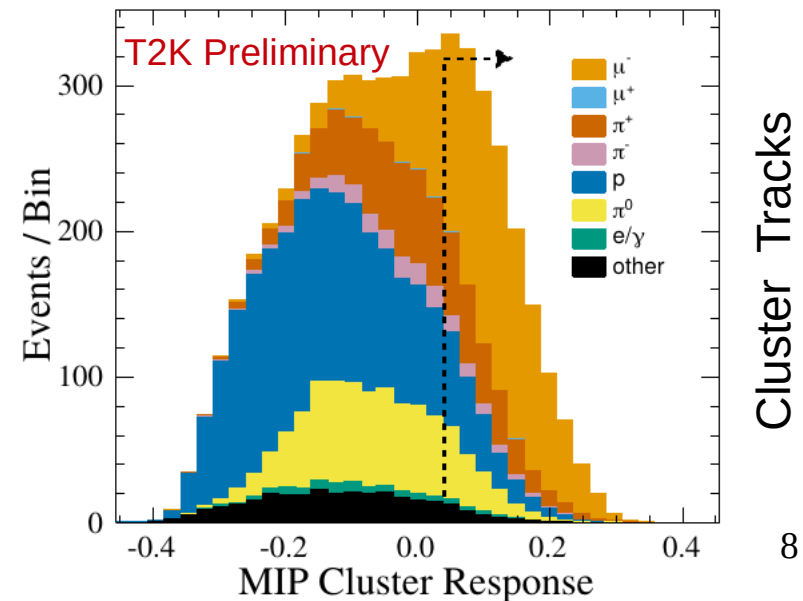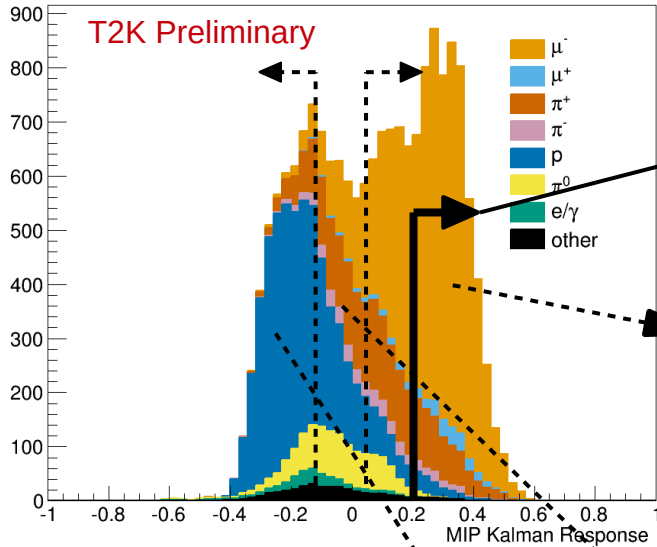
Sideband Selections

- Require 2 selected tracks

- Select tracks based on BDT score
  - BDT seperates MIP tracks from non-MIP tracks
  - Different BDTs for Kalman and Cluster tracks
  - Inputs: topological variables describing detector response

- Select 1st track: high BDT score required

- Select 2nd track: more relaxed BDT score to improve pion efficiency

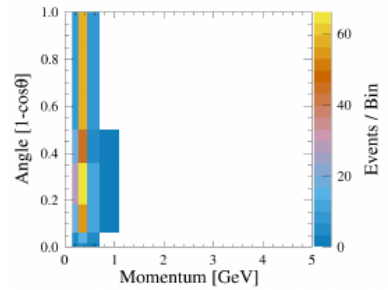- Reverse 2nd track cut to select sideband samples

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Analysis Samples

T2K Preliminary

μ⁻
μ⁺
π⁺
π⁻
p
π⁰
e/γ
other

MIP Kalman Response

Contained μ   Exiting μ   Cluster μ

Selected

Near Sideband

Far Sideband

T2K Preliminary
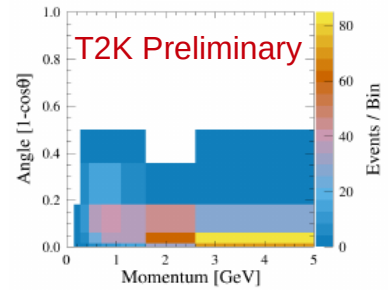
- Analysis done in 2D space
- Show projections
- Result in projections
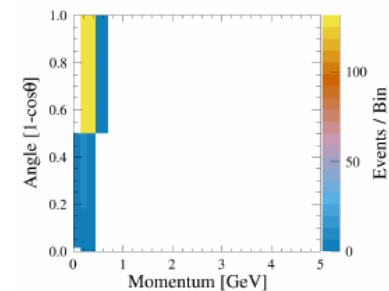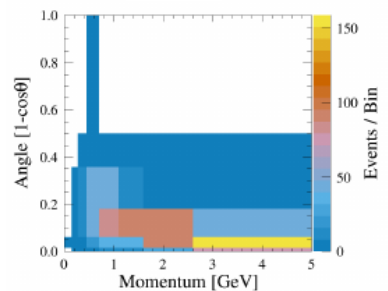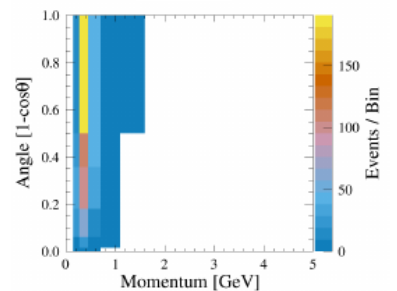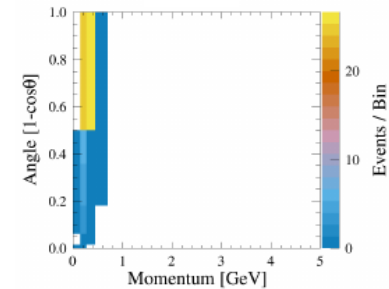- Binning balanced stats and resolutions
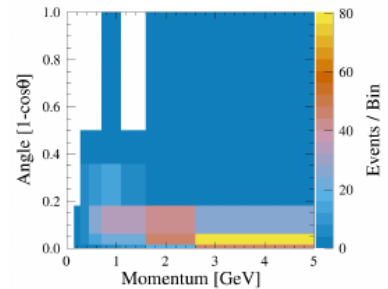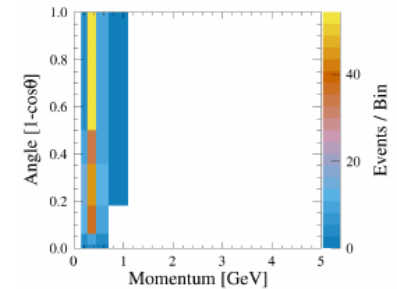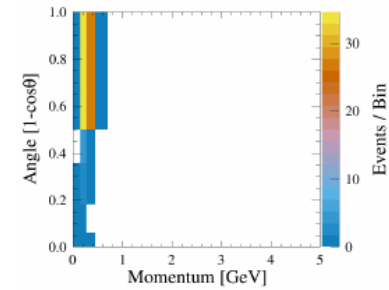
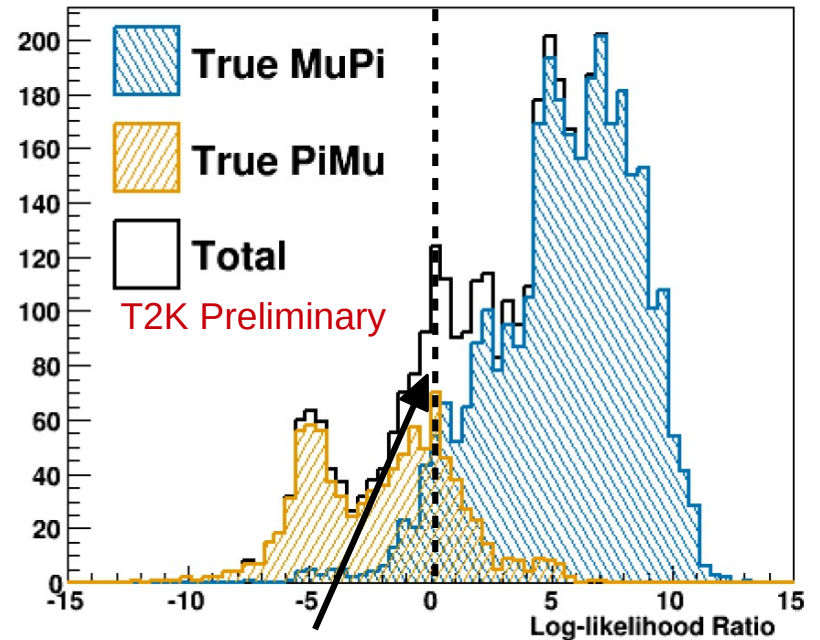Muon Angle (1 − cosθ) [0.0 − 1.0]
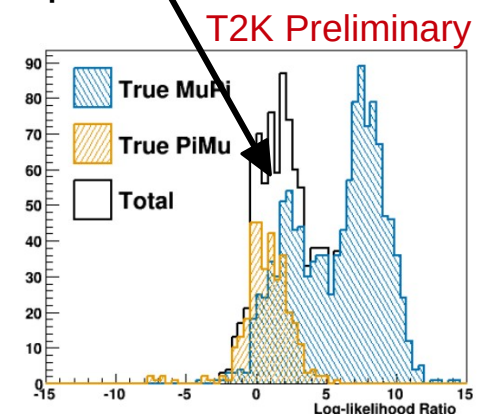
Muon Momentum [0.0 - 5.0 GeV]

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Track PID

- Identify a two track sample ✓
- Which is the μ, which is the π?
- Develop a likelihood function to decide
- Different likelihoods for:
  - Two Kalman tracks
  - One Kalman + one Cluster
- Mis-identified track pairs:
  - Blue pairs w/ negative likelihood
  - Orange pairs w/ positive likelihood
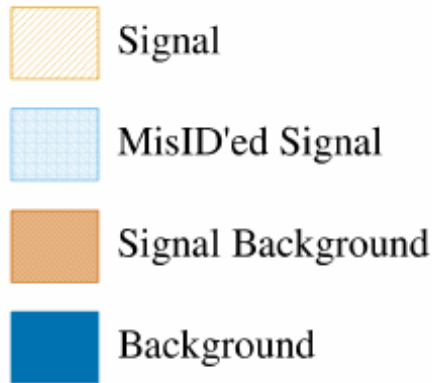
Two Kalman Tracks
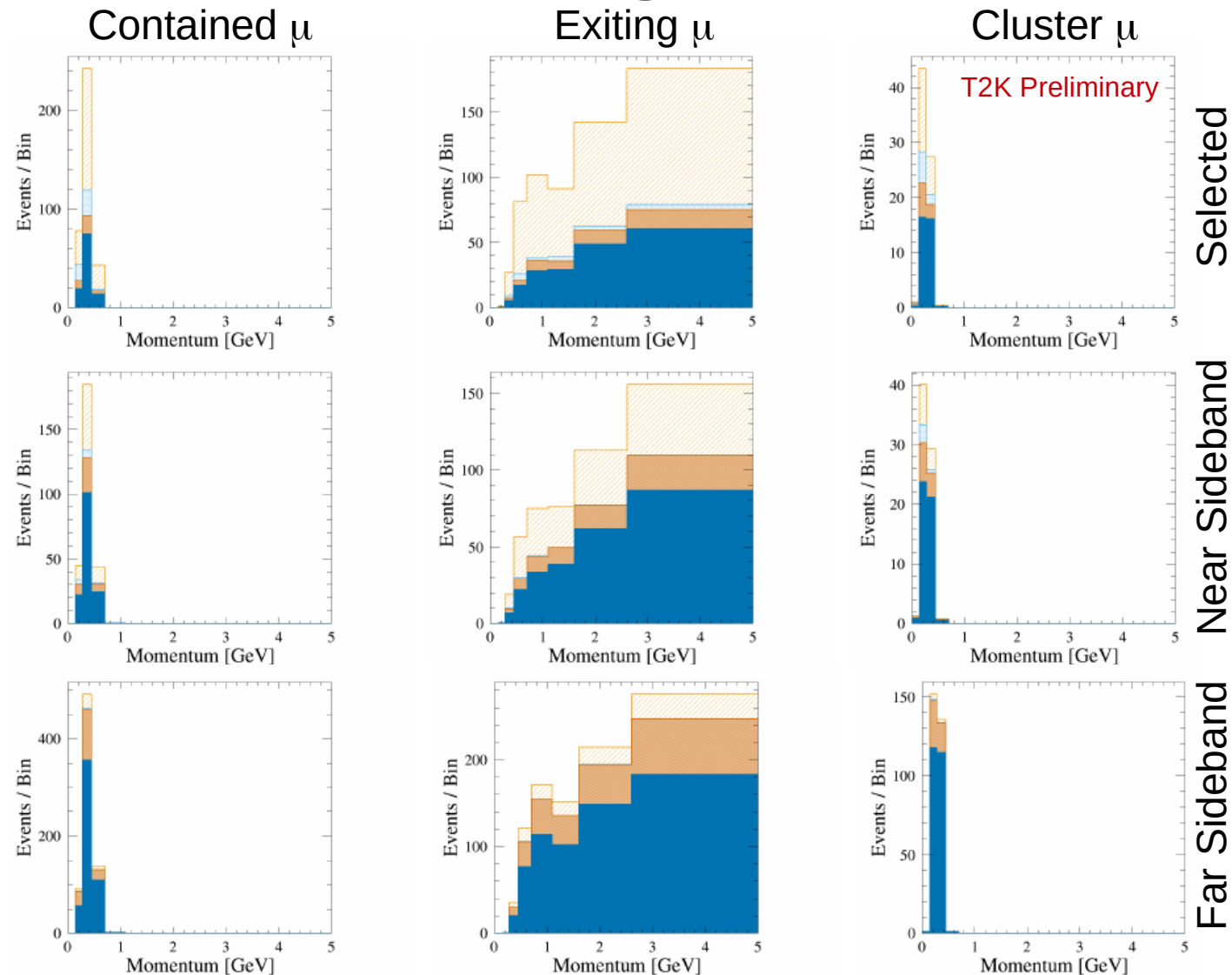

Mis-identified track pairs
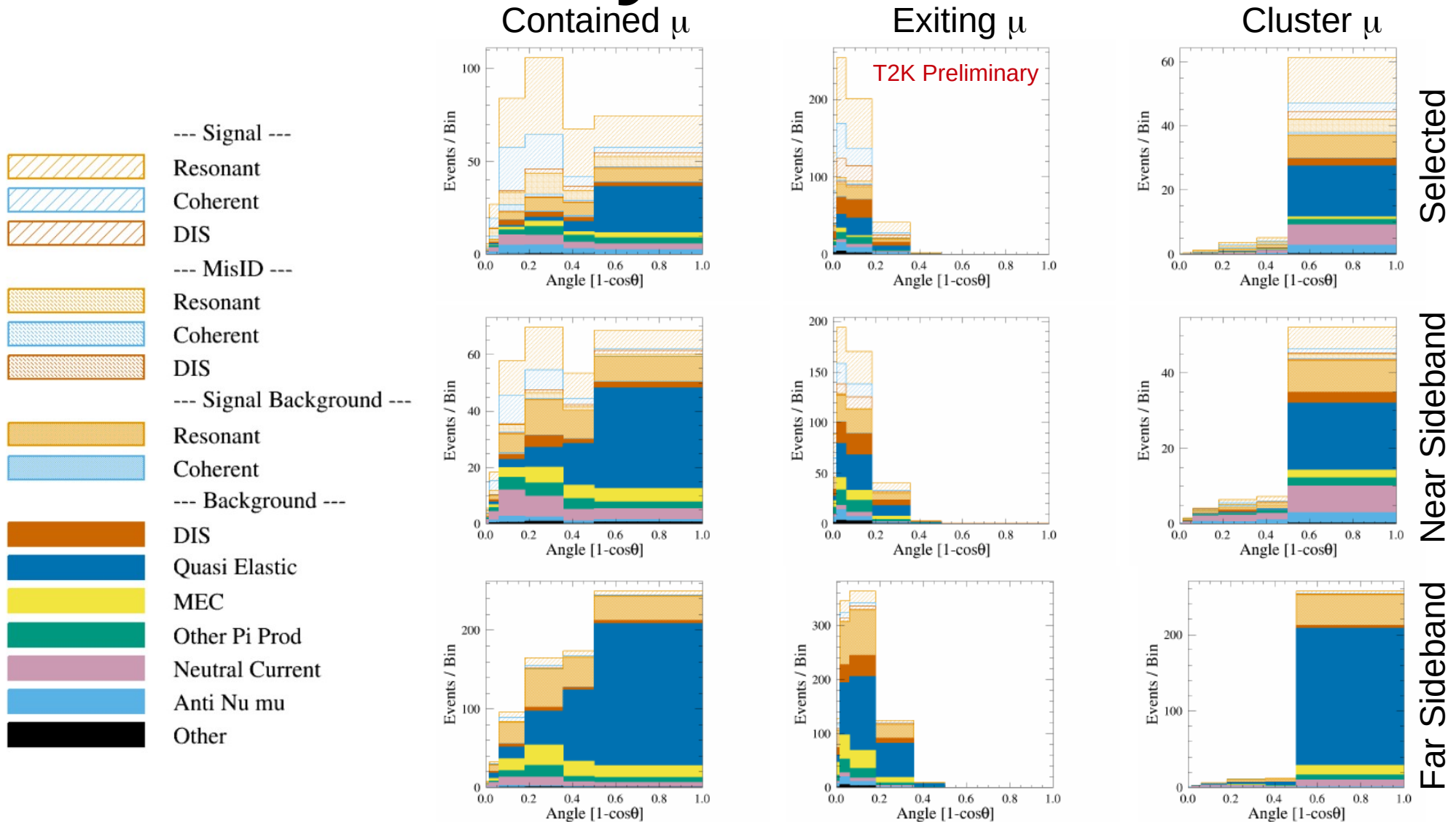
One Kalman + One Cluster Track

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Signal and Background

Contained μ   Exiting μ   Cluster μ

Selected   Near Sideband   Far Sideband

T2K Preliminary

Legend:
- Signal
- MisID'ed Signal
- Signal Background
- Background

- High purity in the selected sample
- **Signal Background: coh or res event but not 1μ1π selected**
- Mostly background in the Far Sideband
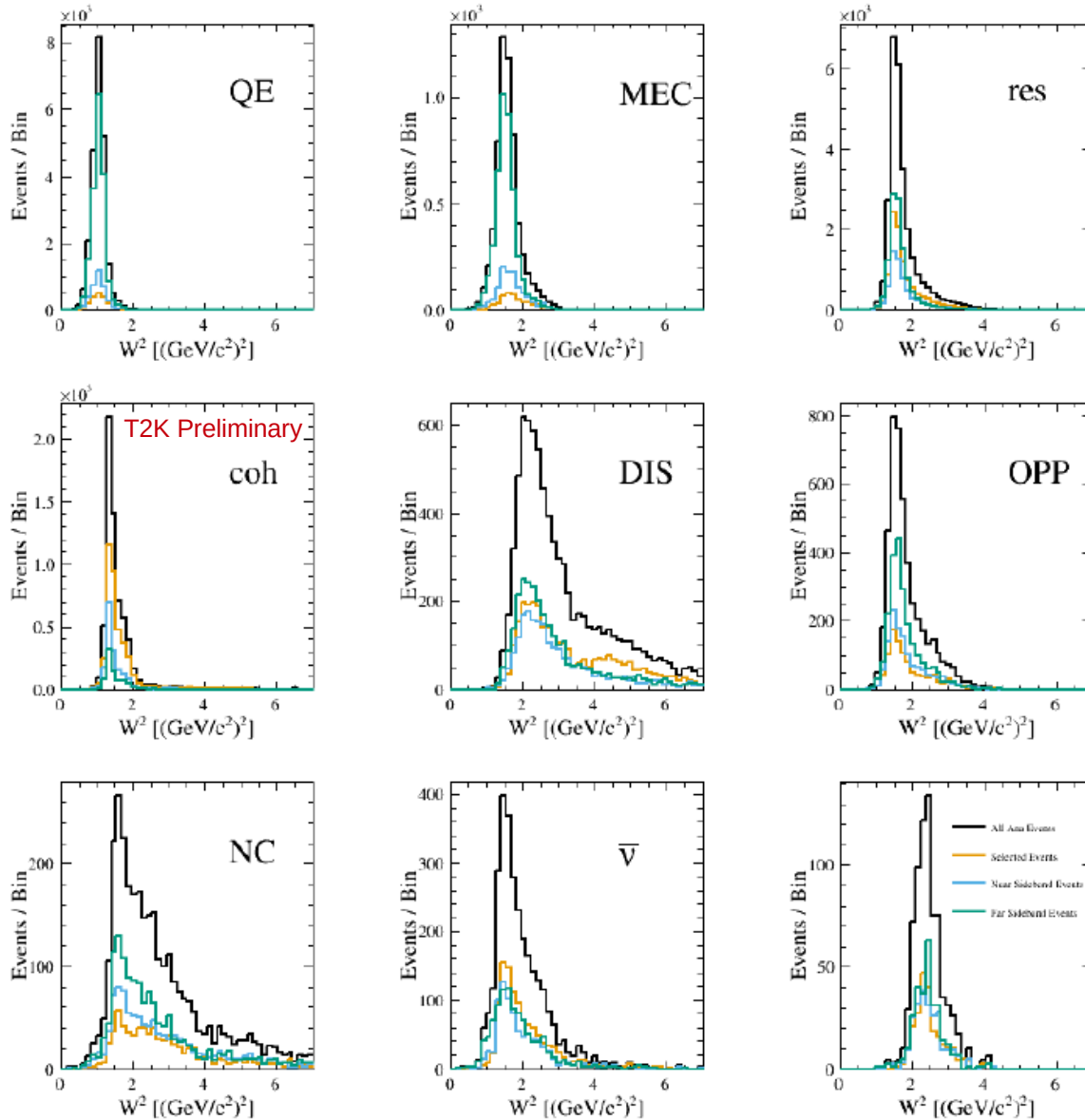- Useful information in the Near Sideband

Muon Momentum [0.0 - 5.0 GeV]

Events by Interaction

Contained μ   Exiting μ   Cluster μ

--- Signal ---
Resonant
Coherent
DIS
--- MisID ---
Resonant
Coherent
DIS
--- Signal Background ---
Resonant
Coherent
--- Background ---
DIS
Quasi Elastic
MEC
Other Pi Prod
Neutral Current
Anti Nu mu
Other

Selected

Near Sideband

Far Sideband

Muon Angle (1 – cosθ) [0.0 – 1.0]

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Kinematic Coverage

Legend: All Ana Events (black), Selected Events (orange), Near Sideband Events (light blue), Far Sideband Events (teal)

Panels: QE, MEC, res, coh (T2K Preliminary), DIS, OPP, NC, $\bar{\nu}$, and a final panel. All with axis W^2 $[(GeV/c^2)^2]$ vs Events / Bin.

- Check to see that the selected and sideband events cover the same regions of kinematic space

- Look at each channel separately

- Backgrounds are most important

- Right: W^2 distribution

- Also checked:
  - Q^2
  - Bjorken x
  - Bjorken y
  - Q^2-W plan
  - q_0-q_3 plane

- Coverage is quite good across all kinematic quantities

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Efficiencies

- Sig def 1: $1\mu 1\pi$ detected

- Sig def 2: $1\mu 1\pi$ after FSI

- First: correct data to sig def 1

- Next: subtract events that do not meet sig def 2

- Last: eff correct data to sig def 2

- Overall efficiency (right)
  - Selected → $1\mu 1\pi$ after FSI (def 2)
  - Grey: MC signal distribution (A.U.)
  - Black lines: analysis bins
  - Relatively flat across analysis bins

- Muon phase space:
  - Momentum (top): 0.0 – 5.0 GeV
  - Angle (bottom): All forward angles
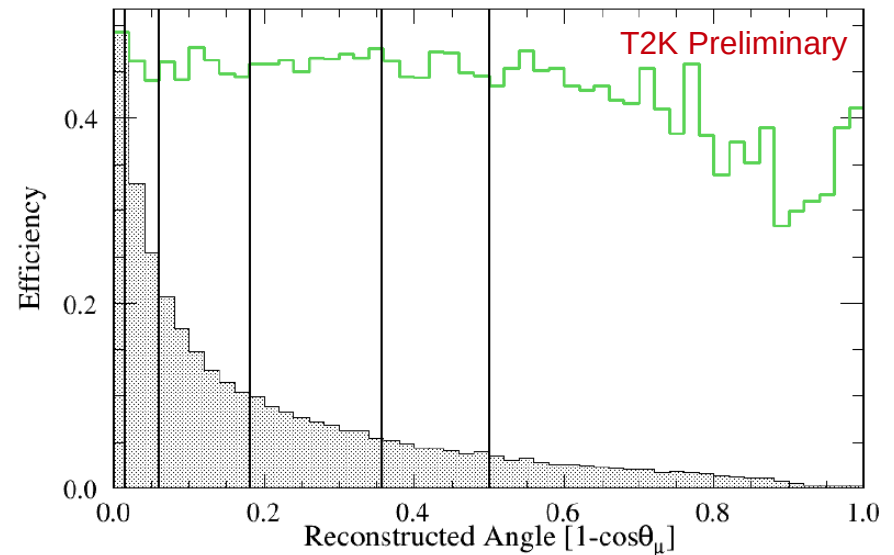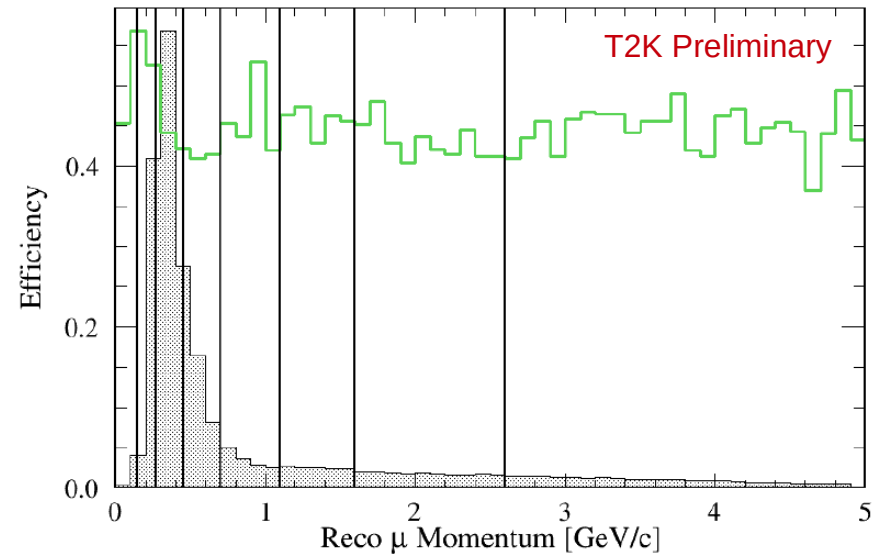
T2K Preliminary

T2K Preliminary

Efficiencies

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- Last: eff correct data to sig def 2
- Overall efficiency (right)
  - Selected → $1\mu 1\pi$ after FSI (def 2)
  - Grey: MC signal distribution (A.U.)
  - Black lines: analysis bins
  - Relatively flat across analysis bins
- Pion phase space:
  - Momentum (top): > 250 MeV
  - Angle (bottom): All forward angles
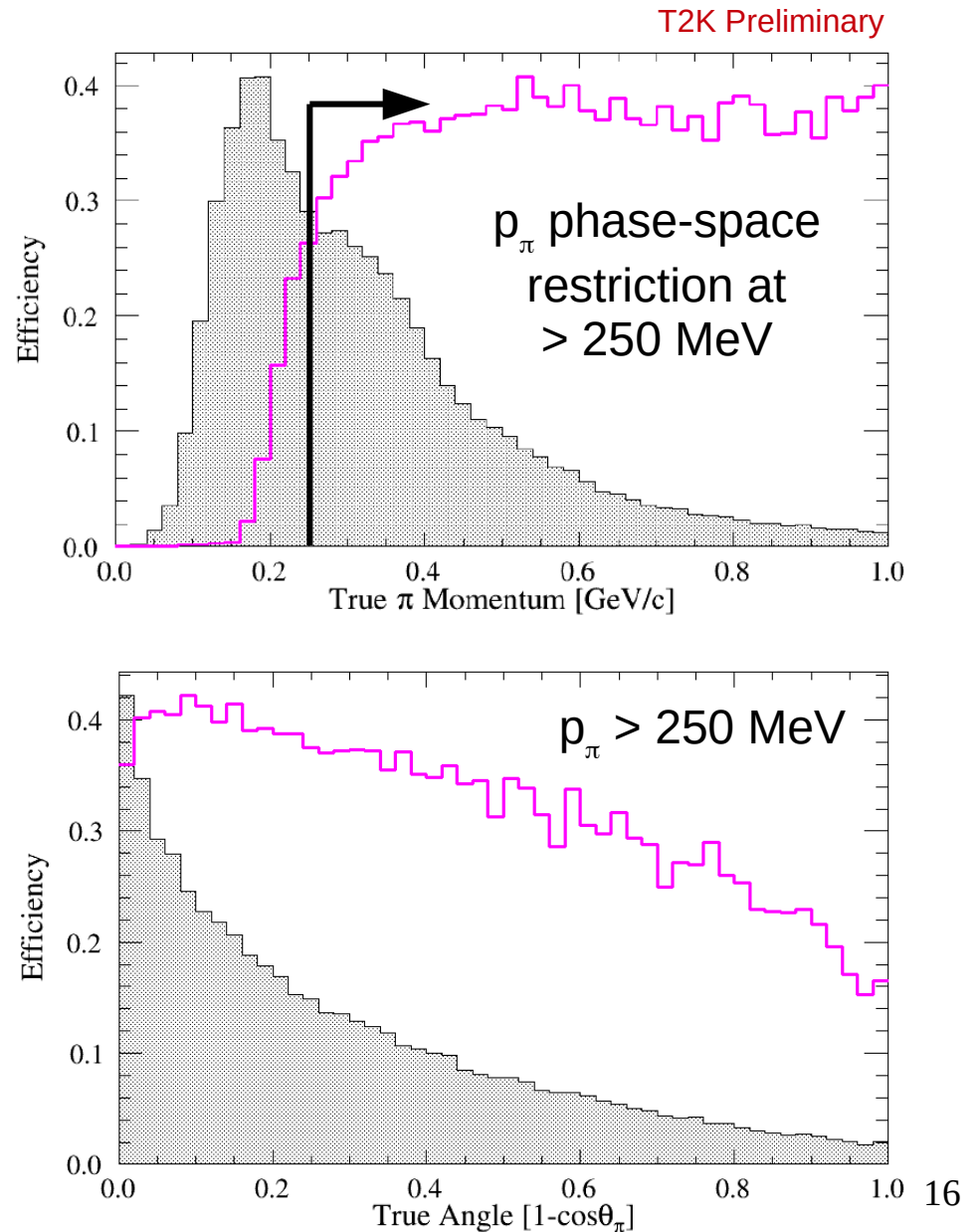
p_π phase-space restriction at > 250 MeV

p_π > 250 MeV

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Fitter Strategy

- MINUIT χ^2 minimization

- Fit in the reconstructed p_μ-θ_μ space (forward folded)

- Signal parameters
  - One per p_μ-θ_μ bin
  - 100% correlated across 9 samples
  - Unconstrained
  - Used to determine misID signal and Signal Background

Results

- Nuisance parameters
  - Flux model
  - Cross section models (bkg only)
  - FSI model
  - Detector response model
  - Priors used to determined penalty

$$\chi^2_{\text{total}} = 2 \sum_i^{\text{bins}} N_i^{\text{Data}} \ln \left(\frac{N_i^{\text{Data}}}{\left(Z_i N_i^{\text{Nom. Sig.}} + \left(1 + \sum_k^{systs} \left(W_i^k - 1\right)\right) N_i^{\text{Nom. Bkg.}} \right)} \right)$$

$$- N_i^{\text{Data}} + Z_i N_i^{\text{Nom. Sig.}} + \left(1 + \sum_k^{systs} \left(W_i^k - 1\right)\right) N_i^{\text{Nom. Bkg.}}$$

$$+ \sum_k^{uncorrelated} \left(\frac{\delta_k}{\sigma_k}\right)^2 + \hat{\delta}_{\text{flux}} C^{-1} \hat{\delta}_{\text{flux}}^T$$
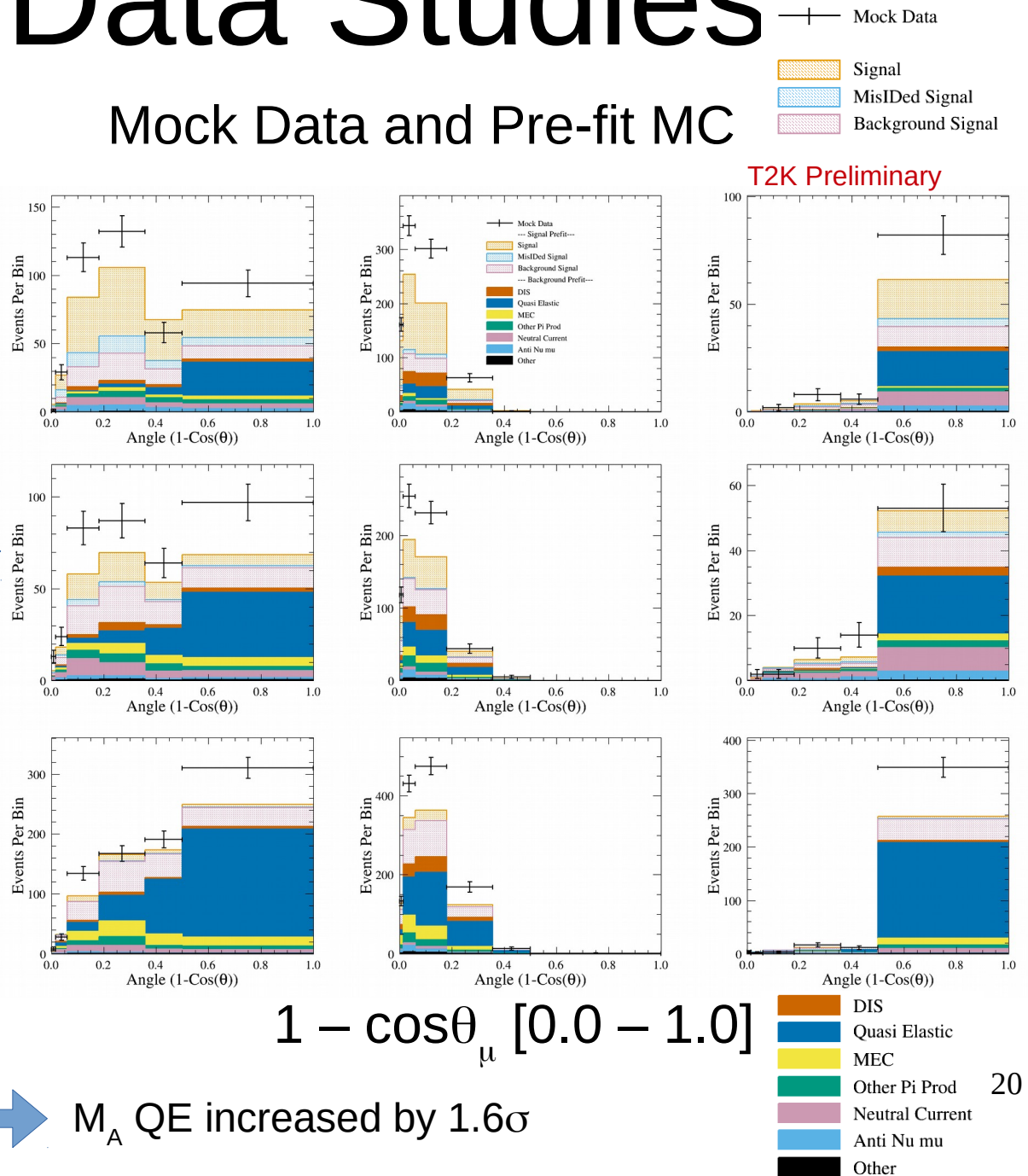
17

Fitter Strategy

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$$\chi^2_{\text{total}} = 2 \sum_i^{\text{bins}} N_i^{\text{Data}} \ln \left(\frac{N_i^{\text{Data}}}{\left(Z_i N_i^{\text{Nom. Sig.}} + \left(1 + \sum_k^{systs} \left(W_i^k - 1 \right) \right) N_i^{\text{Nom. Bkg.}} \right)} \right)$$

$$- N_i^{\text{Data}} + Z_i N_i^{\text{Nom. Sig.}} + \left(1 + \sum_k^{systs} \left(W_i^k - 1 \right) \right) N_i^{\text{Nom. Bkg.}}$$

Penalty $\rightarrow$ $+ \sum_k^{uncorrelated} \left(\frac{\delta_k}{\sigma_k} \right)^2 + \hat{\delta}_{\text{flux}} C^{-1} \hat{\delta}_{\text{flux}}^T$

Signal Backgrounds

- Events that have $1\mu1\pi$ after FSI, but not $1\mu1\pi$ detected

- No signal xsec parameters in the analysis

- Must connect prediction to measurement

- Use value of "Signal Parameters"
  - Number of signal events in bins of reco p_μ-θ_μ
  - Map Signal Params to true muon p_μ-θ_μ
  - Reweight Signal Backgrounds in true muon p_μ-θ_μ
  - Fold reweighted true p_μ-θ_μ Signal Background to back to reco space

- Only relies on true $\rightarrow$ reco mapping of μ kine. (to 1st order)

Mock Data Studies

Signal
MisIDed Signal
Background Signal

Mock Data and Pre-fit MC

- Mock Data samples
  - Asimov
  - Changes to underlying model parameters
  - Swapping in new models
  - Different generators
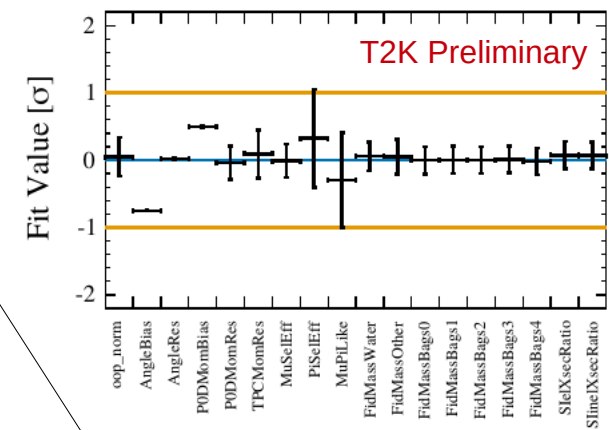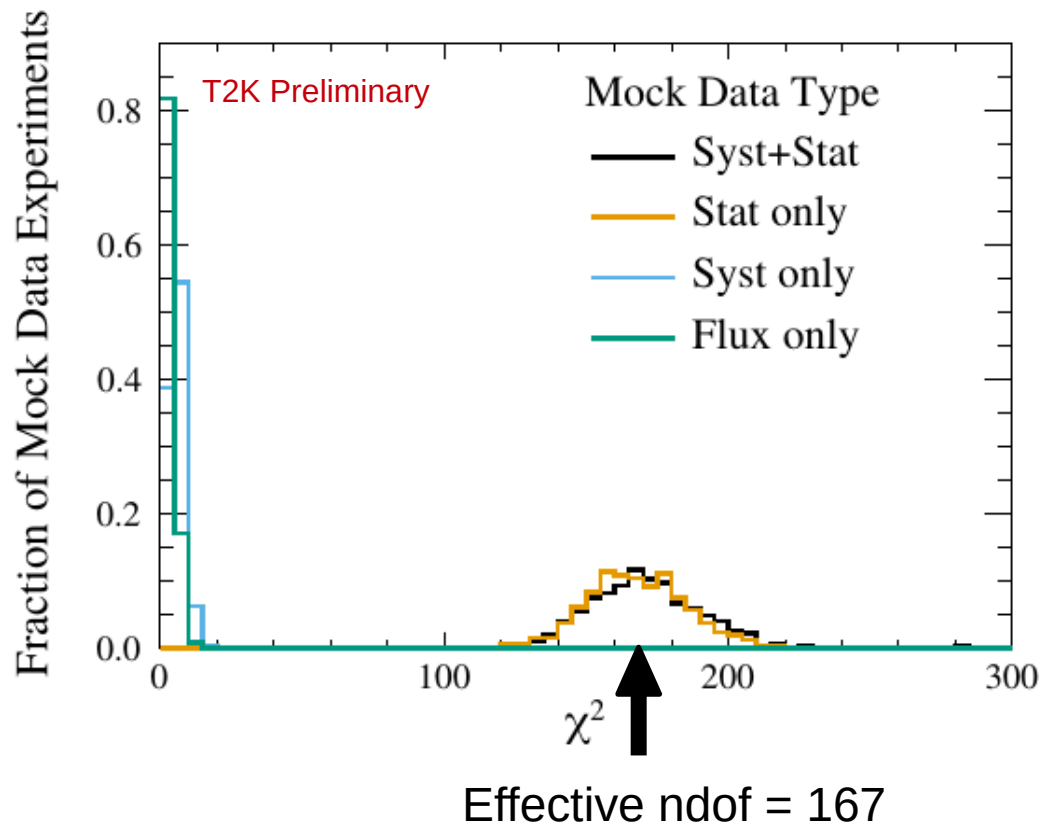 - Random stat throws
  - Random Syst+Stat throws
- Fit as if it was data
- Does best-fit match MC?
- Is true signal within errors?
- No large model biases?
- Are best fit parameter values reasonable?

T2K Preliminary

$1 - \cos\theta_\mu$ [0.0 – 1.0]

DIS
Quasi Elastic
MEC
Other Pi Prod
Neutral Current
Anti Nu mu
Other

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M_A QE increased by 1.6σ

Mock Data Studies

Data and Post-fit MC

- Mock Data samples
  - Asimov
  - Changes to underlying model parameters
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  - Different generators
  - Random stat throws
  - Random Syst+Stat throws
- Fit as if it was data
- Does best-fit match MC? ✓
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T2K Preliminary

$$1 - \cos\theta_\mu \ [0.0 - 1.0]$$

Legend:
- Mock Data
- Signal
- MisIDed Signal
- Background Signal
- DIS
- Quasi Elastic
- MEC
- Other Pi Prod
- Neutral Current
- Anti Nu mu
- Other

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Mock Data Studies

- Mock Data samples
  - Asimov
  - Changes to underlying model parameters
  - Swapping in new models
  - Different generators
  - Random stat throws
  - Random Syst+Stat throws ➡
- Fit as if it was data
- Does best-fit match MC? ✓
- Is true signal within errors? ✓
- No large model biases? ✓
- Are best fit parameter values reasonable?

Extracted Signal and Fit Errors
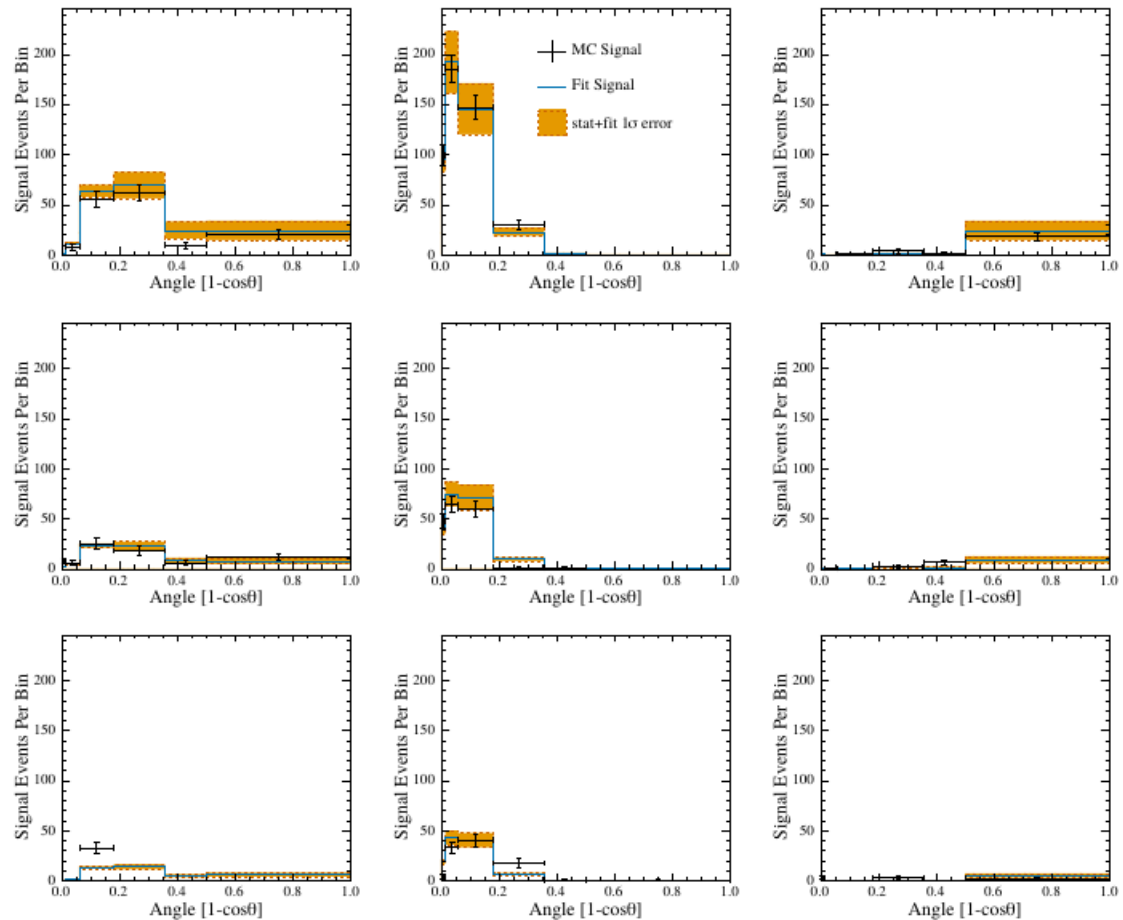
$$1 - \cos\theta_\mu\ [0.0 - 1.0]$$

Mock Data Studies

- Mock Data samples
  - Asimov
  - Changes to underlying model parameters
  - Swapping in new models
  - Different generators
  - Random stat throws
  - Random Syst+Stat throws

- Fit as if it was data

- Does best-fit match MC? ✓

- Is true signal within errors? ✓

- No large model biases? ✓

- Are best fit parameter values reasonable? ✓

Best-fit Nuisance Parameter Deviations

Cross Sections

True M_A MD value
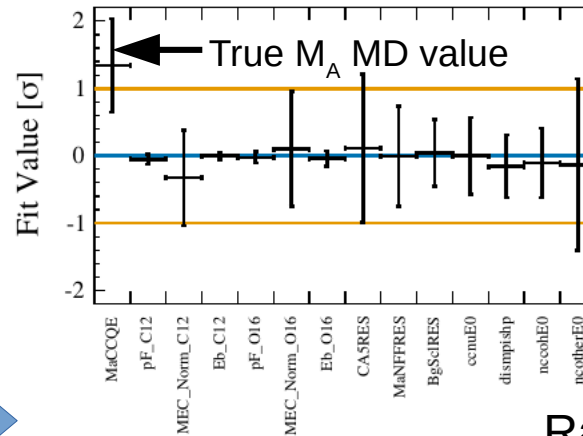
FSI
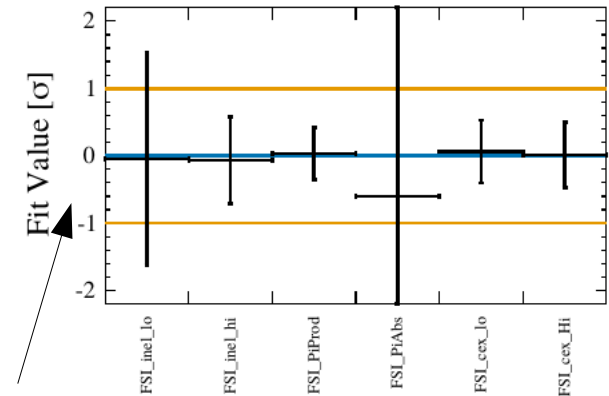
Ratio to prior central value

Flux

Detector

T2K Preliminary
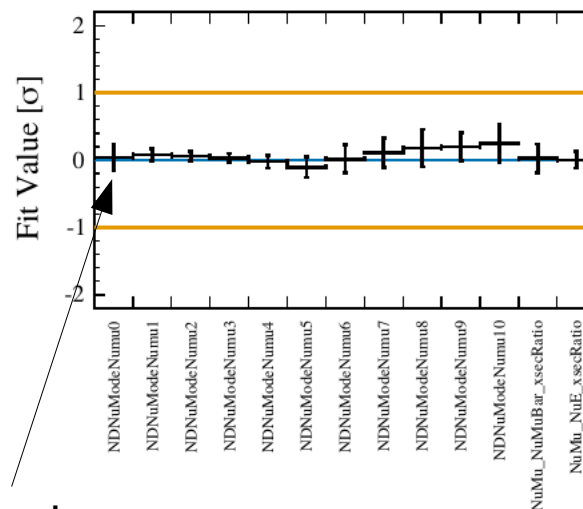
Best fit value and 1σ error

Prior 1σ uncertainty

Mock Data and Data χ^2

T2K Preliminary

Mock Data Type
- Syst+Stat
- Stat only
- Syst only
- Flux only

Effective ndof = 167

- Compare data fit with ensemble of Mock Data sets
- Random throws
  - Flux parameters
  - All systematics
  - Statistics
  - Statistics+systematics
- Mock data shows that results should be statistics limited

Data Fit Results

Data and Pre-fit MC

Data

Signal
MisIDed Signal
Background Signal

T2K Preliminary
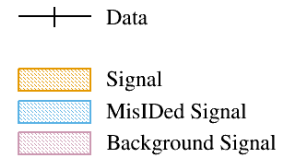
- Pre-fit MC greatly overestimates the data

- Especially at low angle

- The size of discrepancy decreases with the amount of signal predicted

$1 - \cos\theta_\mu$ [0.0 – 1.0]

DIS
Quasi Elastic
MEC
Other Pi Prod
Neutral Current
Anti Nu mu
Other

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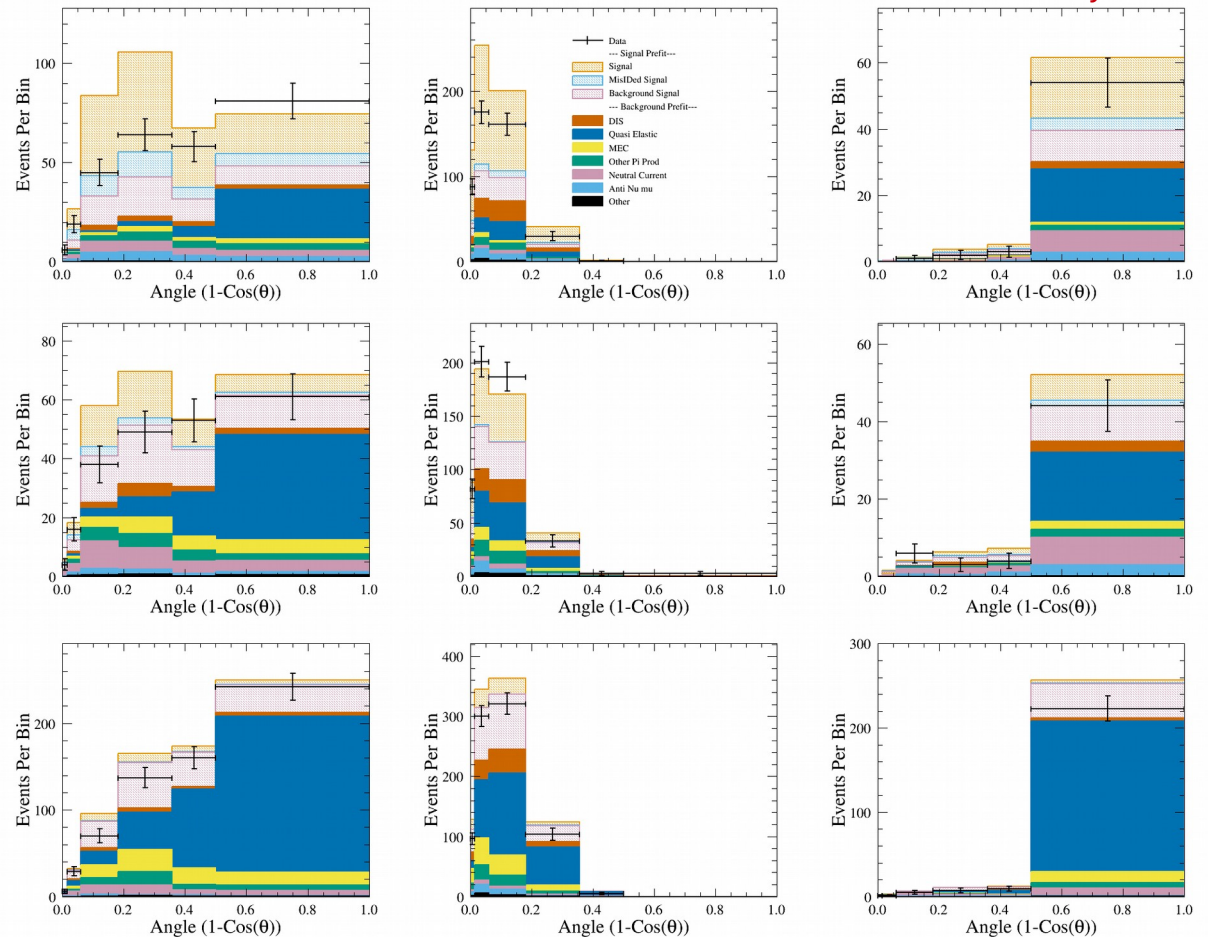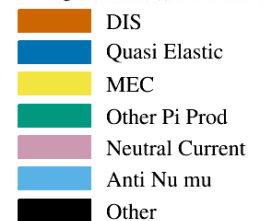
Data Fit Results

Data and Post-fit MC
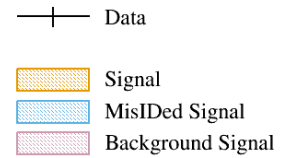
- Post-fit MC agrees well with data

- Almost all bins within 1σ error band

- Fraction with >1σ discrepancy consistent with expectations given number of bins

- Some tension between the Kalman Exiting Selected and Near Sideband samples

- Tension is at high momentum

$$1 - \cos\theta_\mu \; [0.0 - 1.0]$$

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Data Fit Results

Cross Sections

FSI
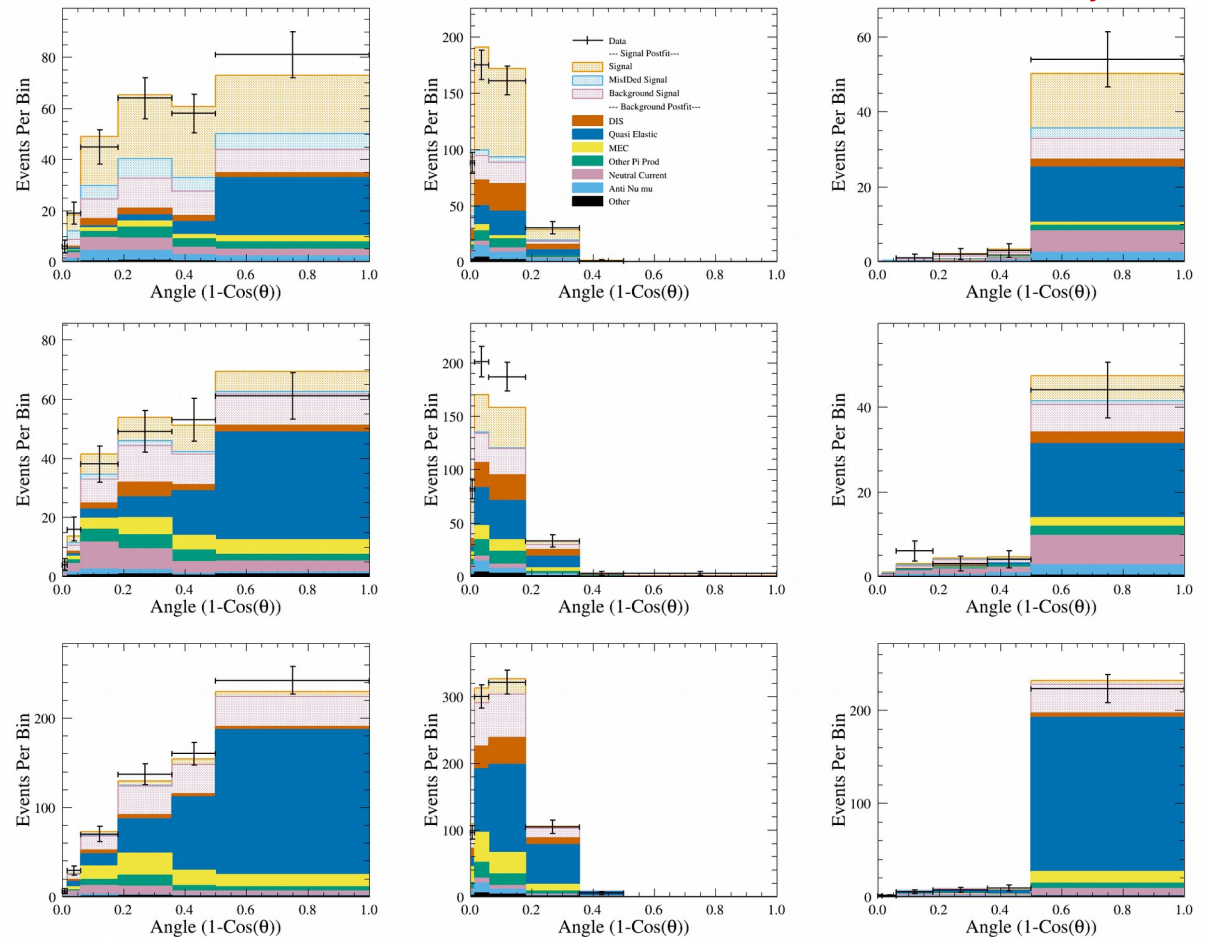
T2K Preliminary
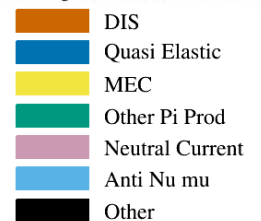
- Fairly insensitive to:
  - Most cross sections
  - FSI parameters
  - P0D mass uncertainties

- Constraints on:
  - M_A QE
  - p_μ-θ_μ resolution and bias
  - π selection efficiency
  - Flux: ~1.5% normalization increase

- Consistent with mock data study results
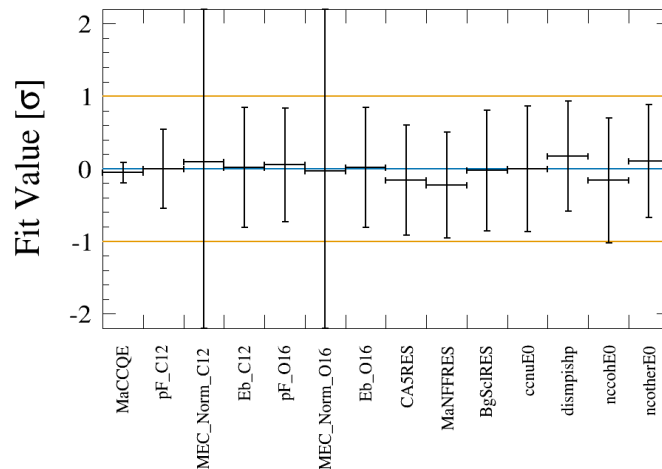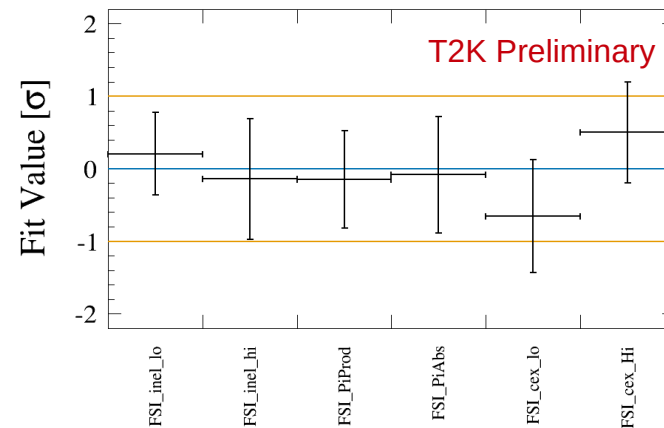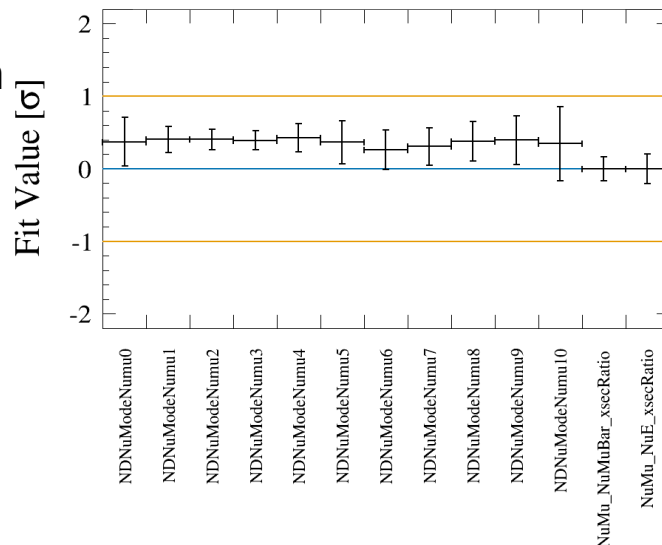
Flux

Detector
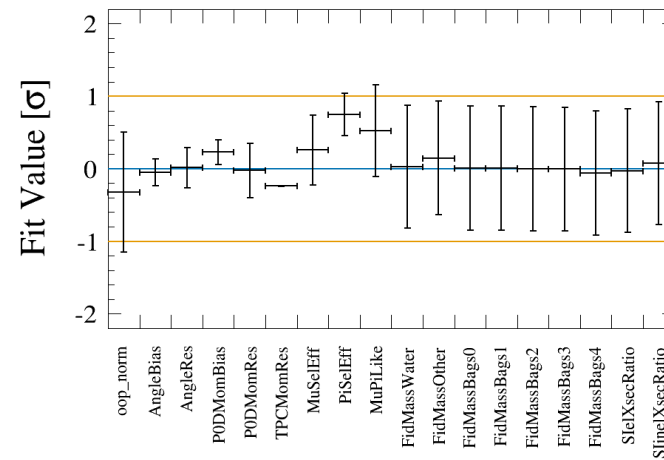
Best Fit Nuisance Parameter Values

Mock Data and Data χ^2
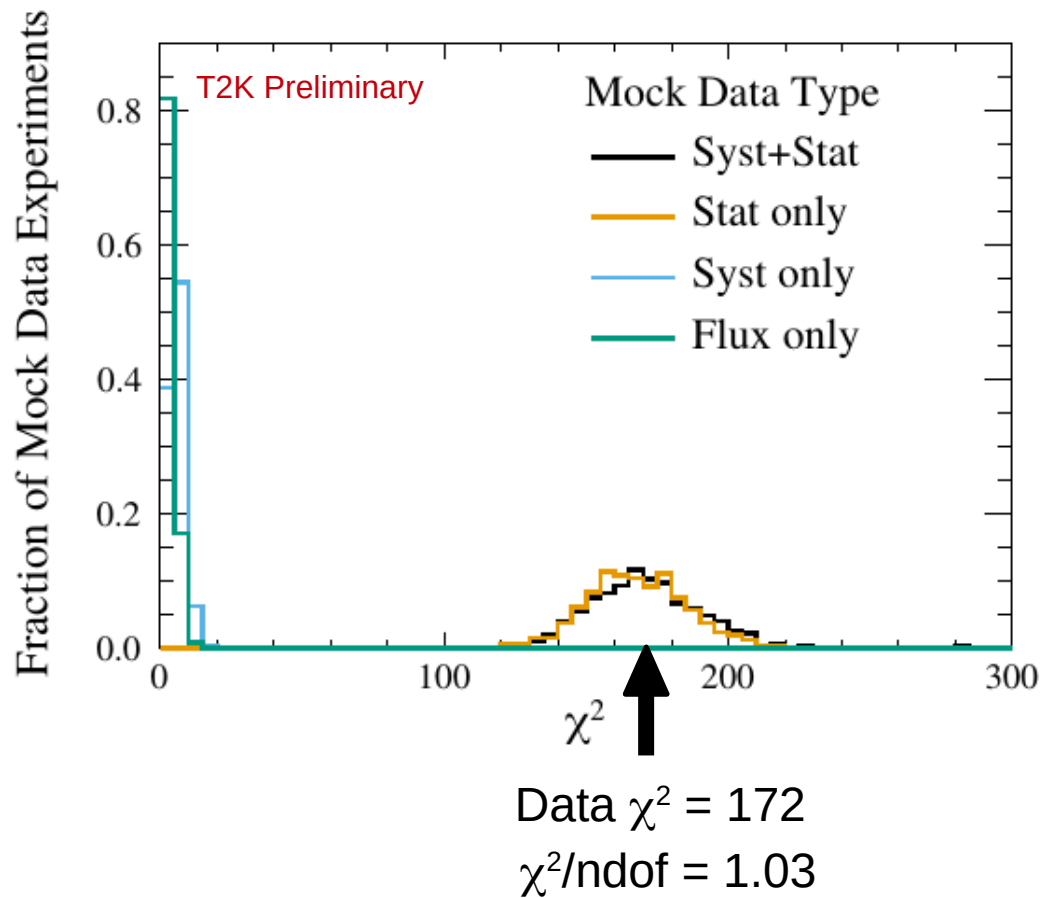
T2K Preliminary

Mock Data Type
— Syst+Stat
— Stat only
— Syst only
— Flux only

Data χ^2 = 172
χ^2/ndof = 1.03

- Compare data fit with ensemble of Mock Data sets
- Random throws
  - Flux parameters
  - All systematics
  - Statistics
  - Statistics+systematics
- Mock data shows that results should be statistics limited
- **Data χ^2 agrees with random statistical(+syst) fluctuation**

Event Rate Comparisons
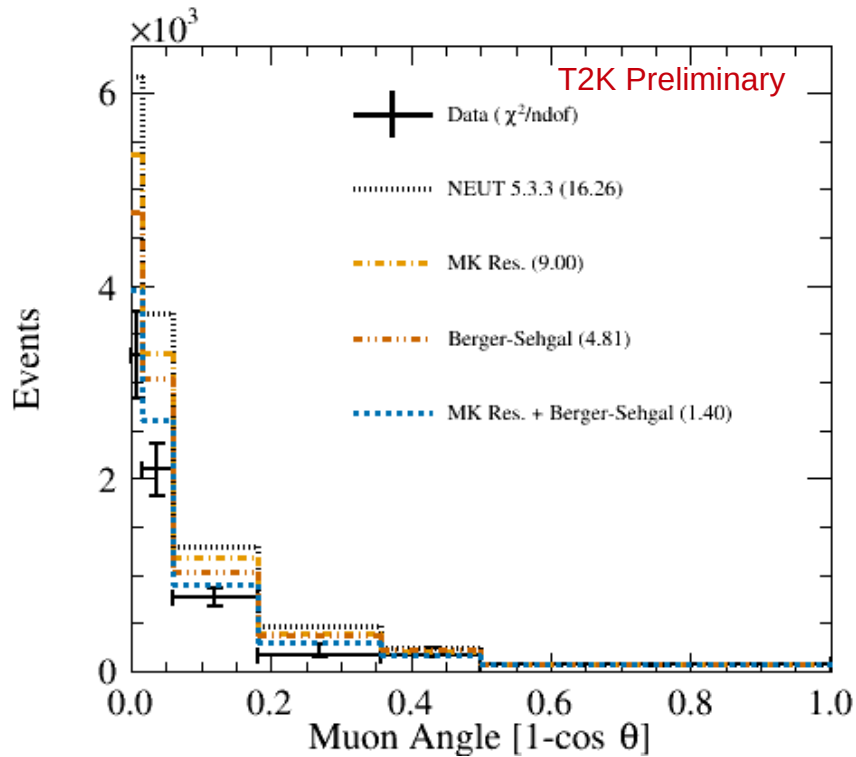
T2K Preliminary

Data (χ²/ndof)

NEUT 5.3.3 (16.26)

MK Res. (9.00)

Berger-Sehgal (4.81)

MK Res. + Berger-Sehgal (1.40)

- Compare data with various models
  - NEUT 5.3.3
  - NEUT with res RS→MK
  - NEUT with coh RS→BS
  - NEUT with both changes
- Track errors and correlations

T2K Preliminary

Error Source
Fit Error (+)
Fit Error (-)

T2K Preliminary

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1μ1π After FSI Cross Section

- Compare data with various models
  - NEUT 5.3.3
  - NEUT with res RS→MK
  - NEUT with coh RS→BS
  - NEUT with both changes
- Track errors and correlations

30
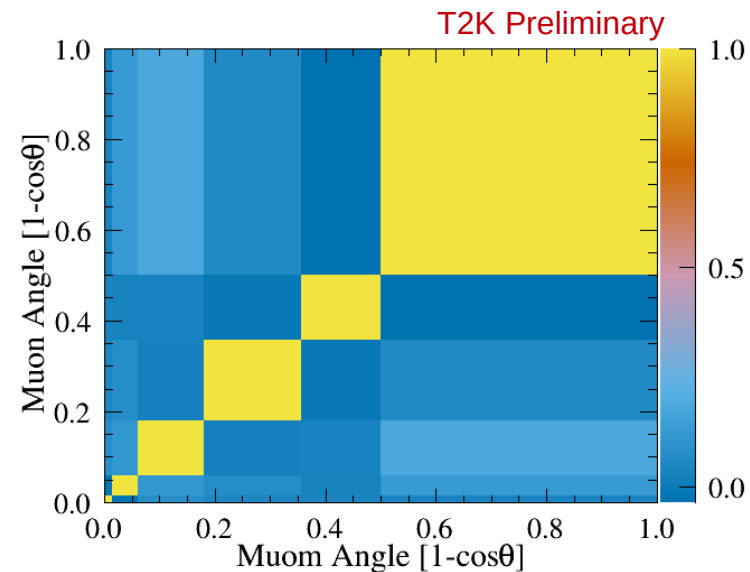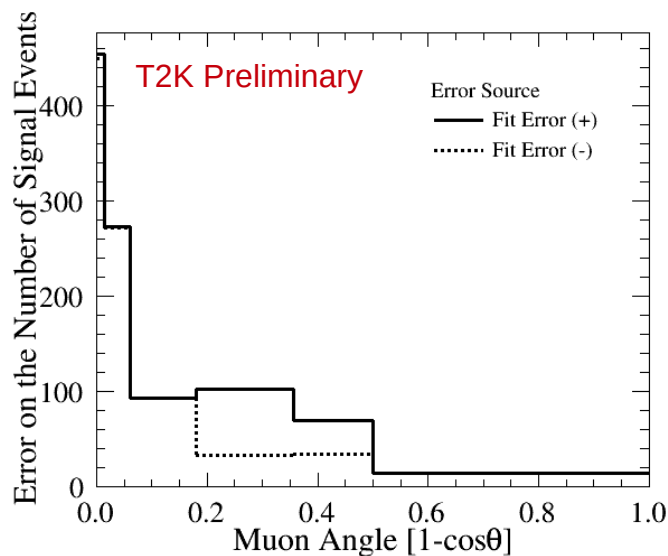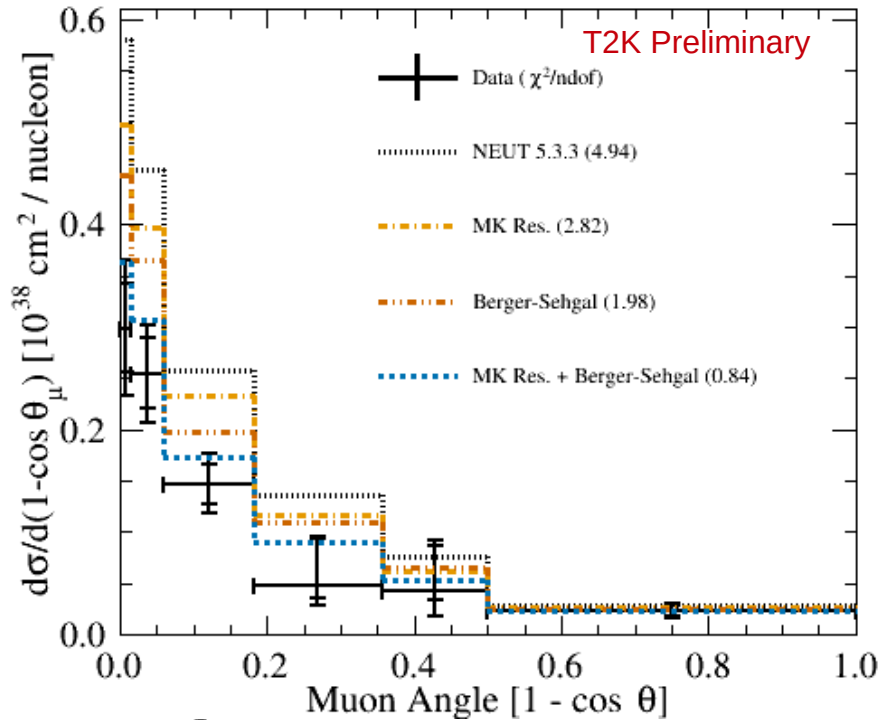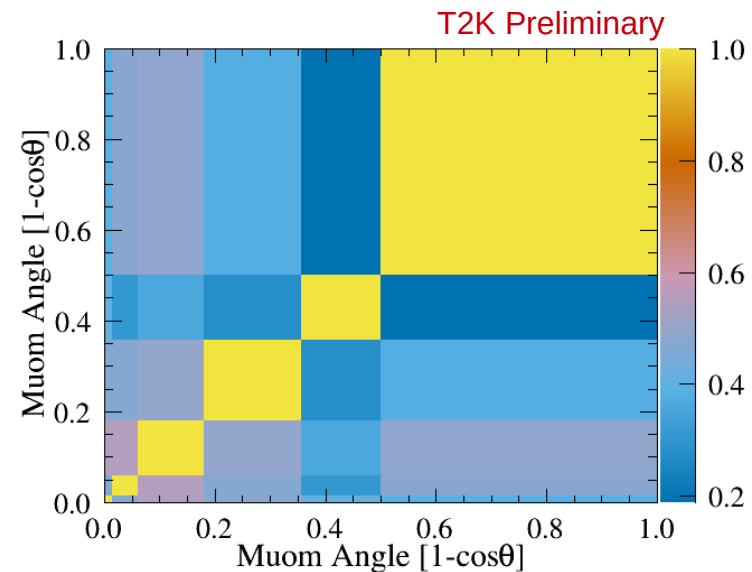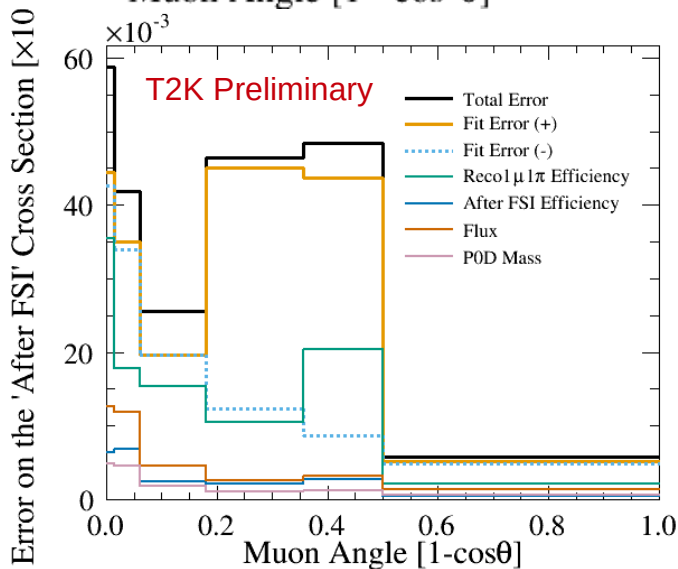
Summary and Conclusions

- A measurement of the CC1π^+ cross section in the P0D was presented

- The measurement was performed in the p_μ-θ_μ plane and results are given for the p_μ and θ_μ projections

- Great care was taken to remove any signal model dependent bias
  - Careful signal definition
  - Signal model independent fitting technique
  - Phase space restrictions

- The measured cross section:
  - Is much less than the NEUT 5.3.3 prediction
  - Agrees well with combined MK resonance + BS coherent model predictions

$v_\mu p \rightarrow \mu p \pi^+$

p_π phase-space restriction at > 250 MeV

T2K Preliminary
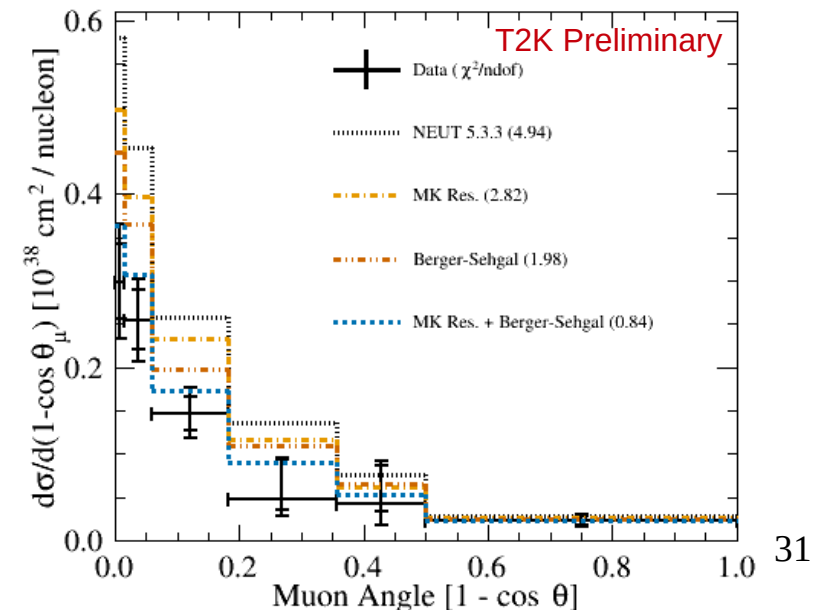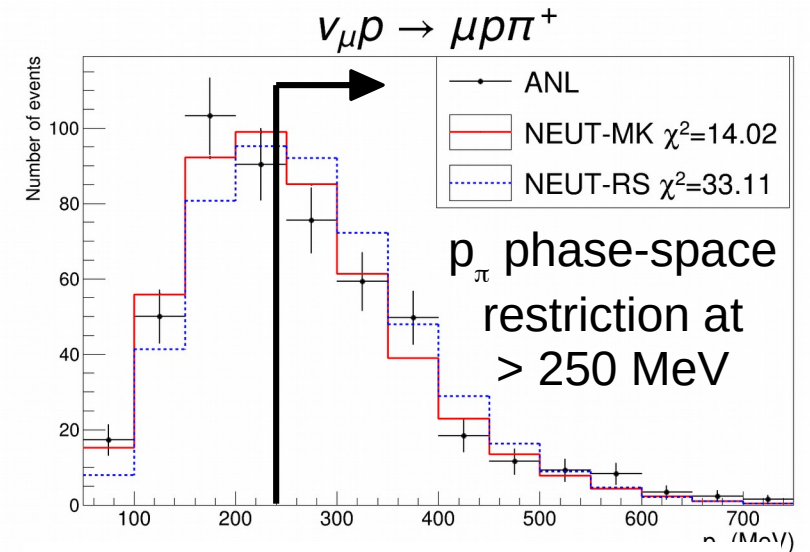
Thank you for your attention.

Questions?

Backup Slides

Avoiding Signal Model Dependence

- Signal definition
- Event selection technique
- Constraining backgrounds with sidebands
- Signal-like background treatment
- Efficiency corrections

Signal-like Backgrounds

Measure the signal in p_μ-θ_μ each bin
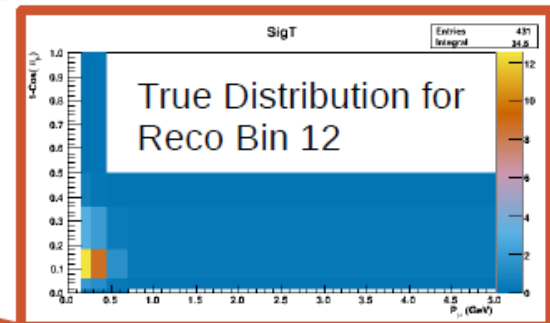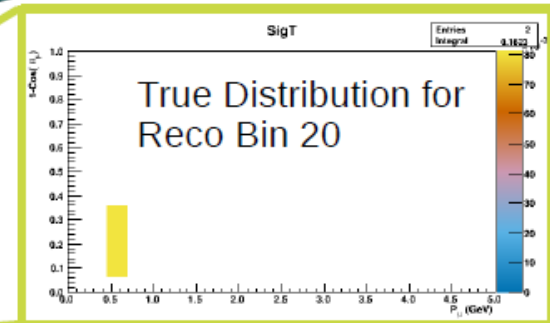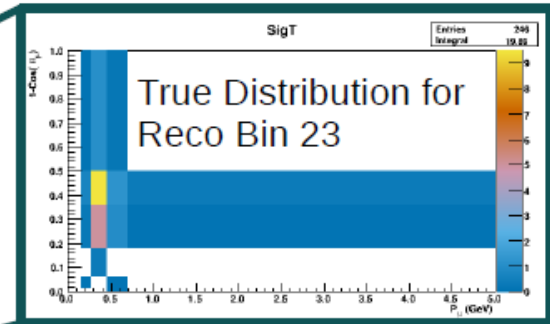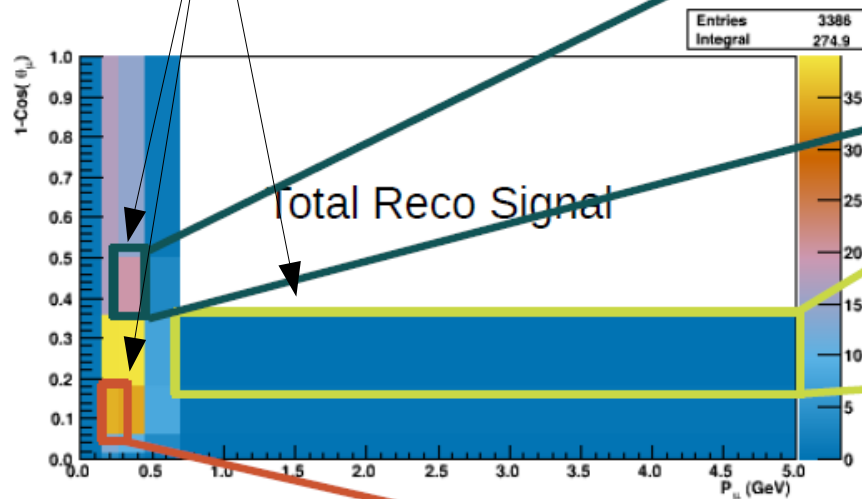
Use to weight background templates in true bins

Signal-like Backgrounds
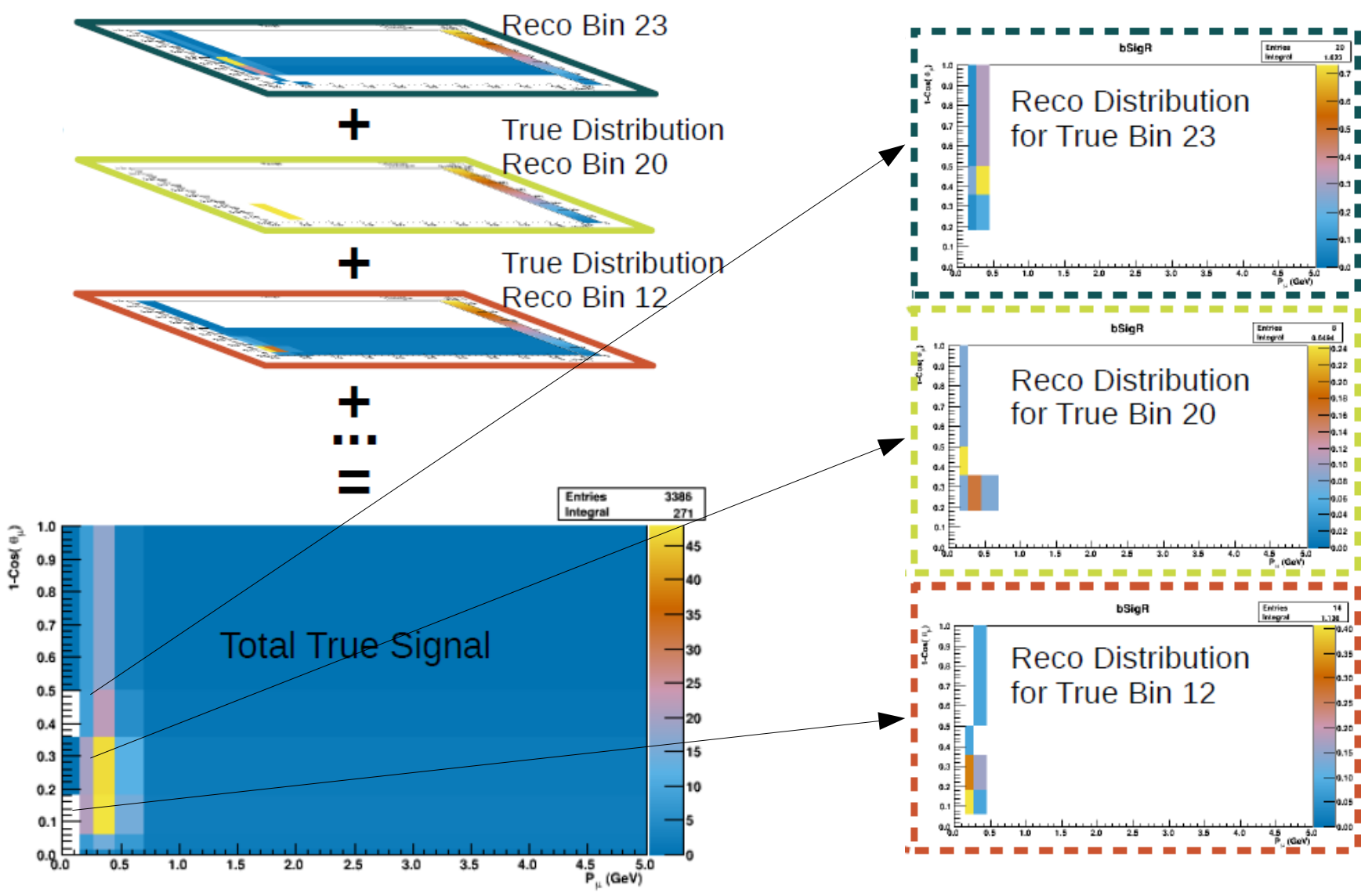
Signal-like Backgrounds
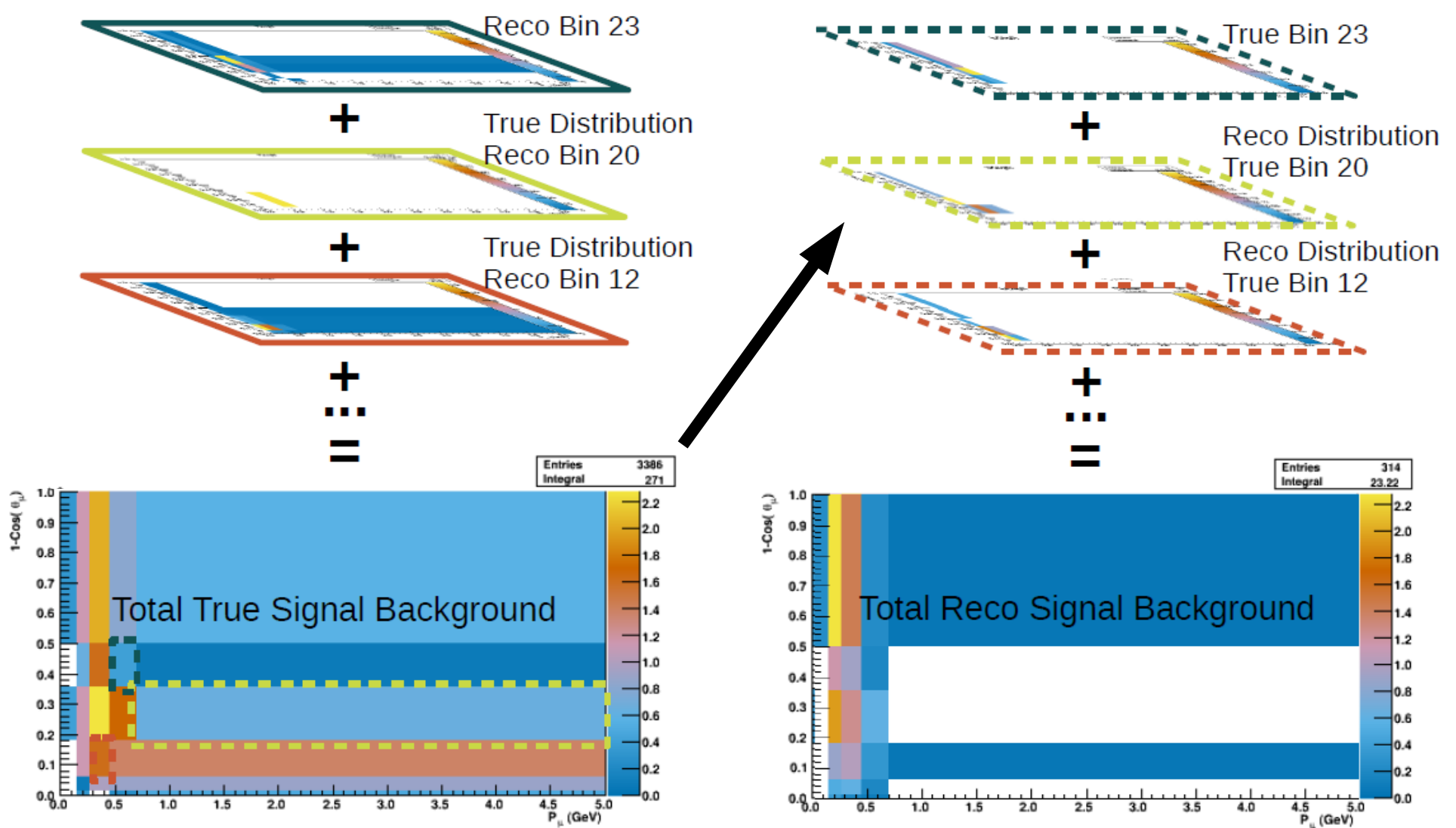
Efficiency Corrections (1μ1π detected)
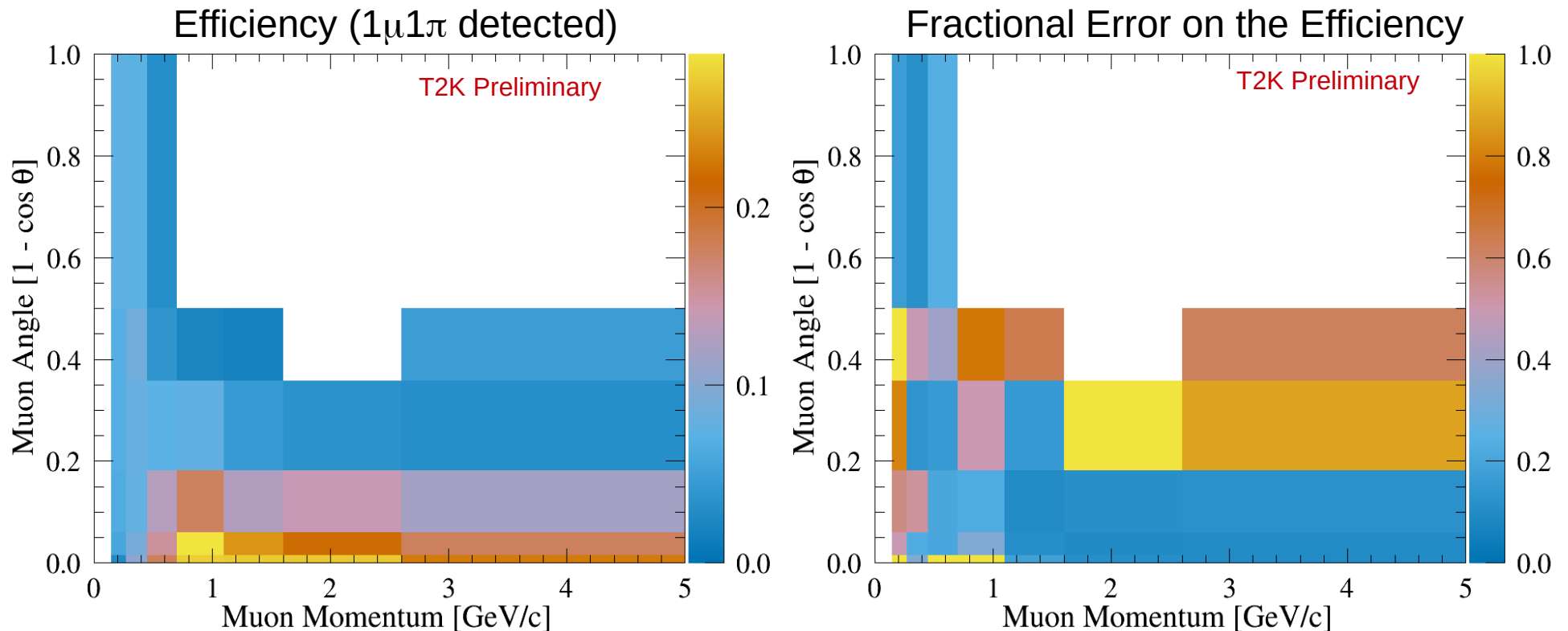
Efficiency for the 1μ1π detected signal definition, and associated uncertainties

Efficiency Corrections (1μ1π After FSI)
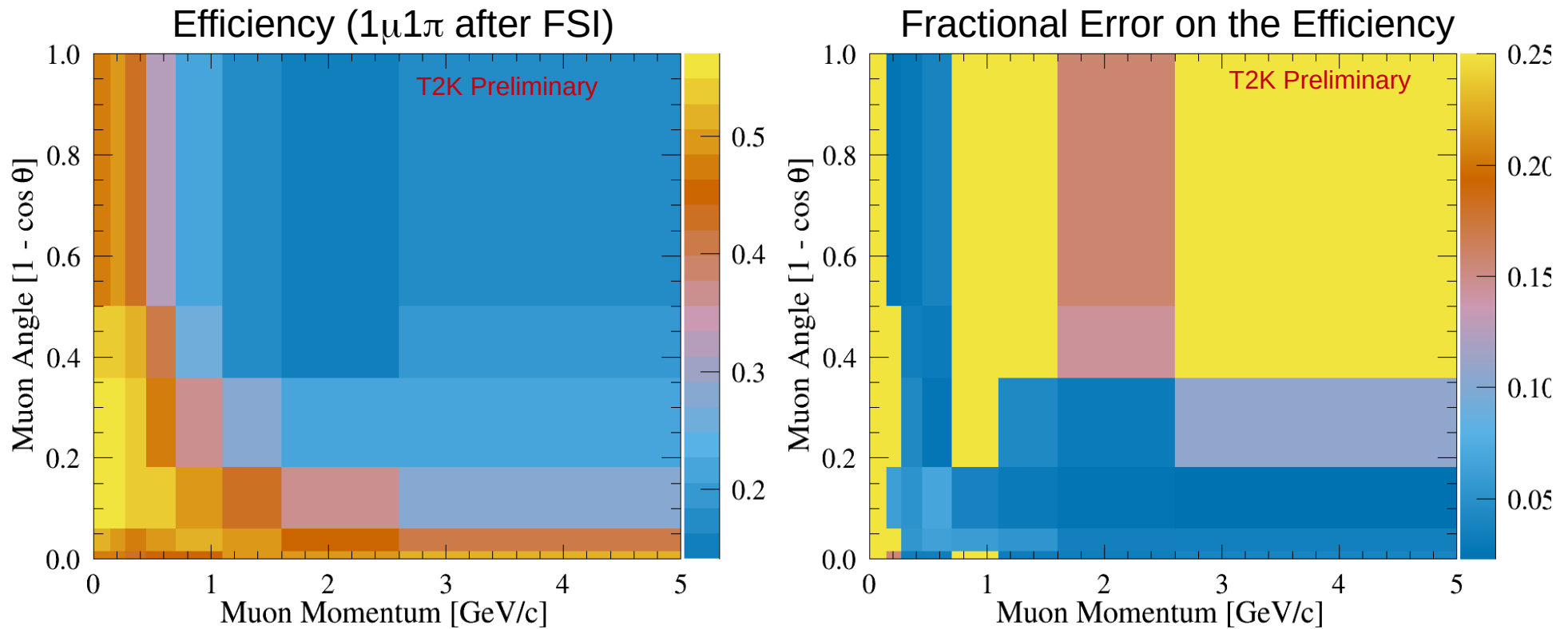
Efficiency for the 1μ1π afterFSI signal definition, and associated uncertainties

1μ1π detected ≠ 1μ1π after FSI
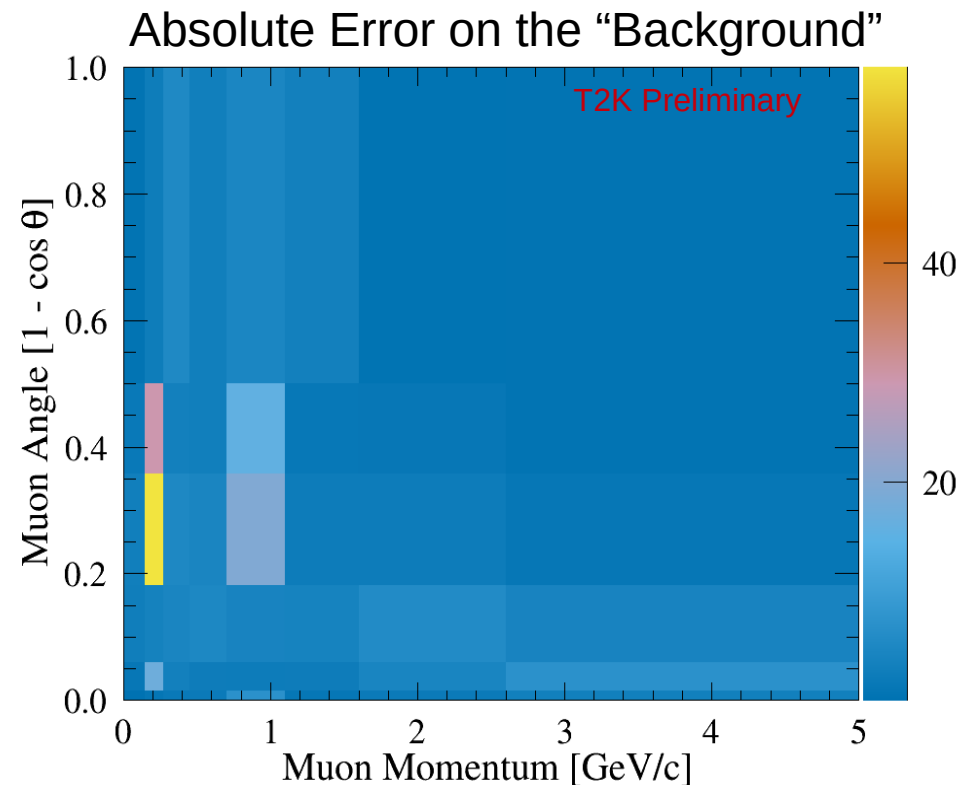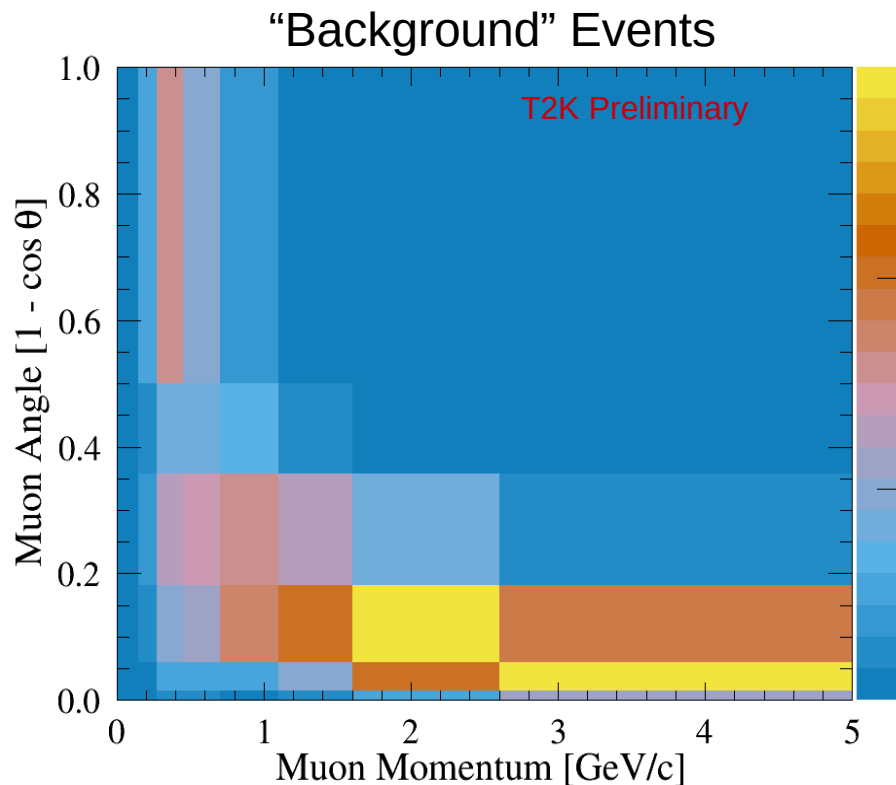
"Background" Events — T2K Preliminary

Absolute Error on the "Background" — T2K Preliminary

Events that pass sig def 1 but not sig def 2, and must be subtracted to convert from sig def 1 but to sig def 2

1μ1π detected ≠ 1μ1π after FSI

"Background" Events (p_μ)

"Background" Events ($1-\cos\theta_\mu$)

T2K Preliminary
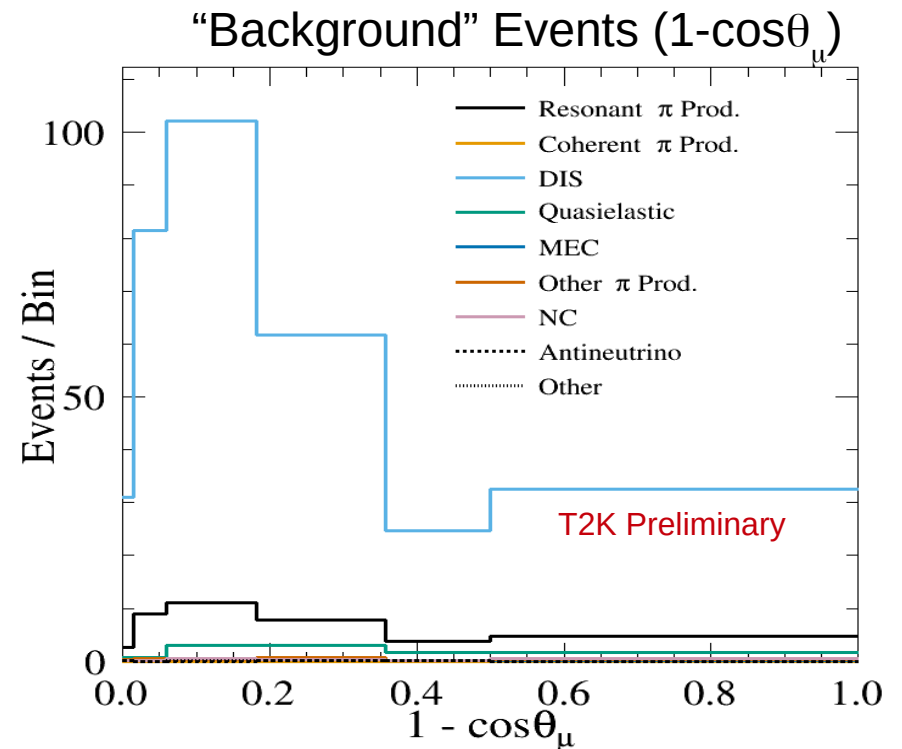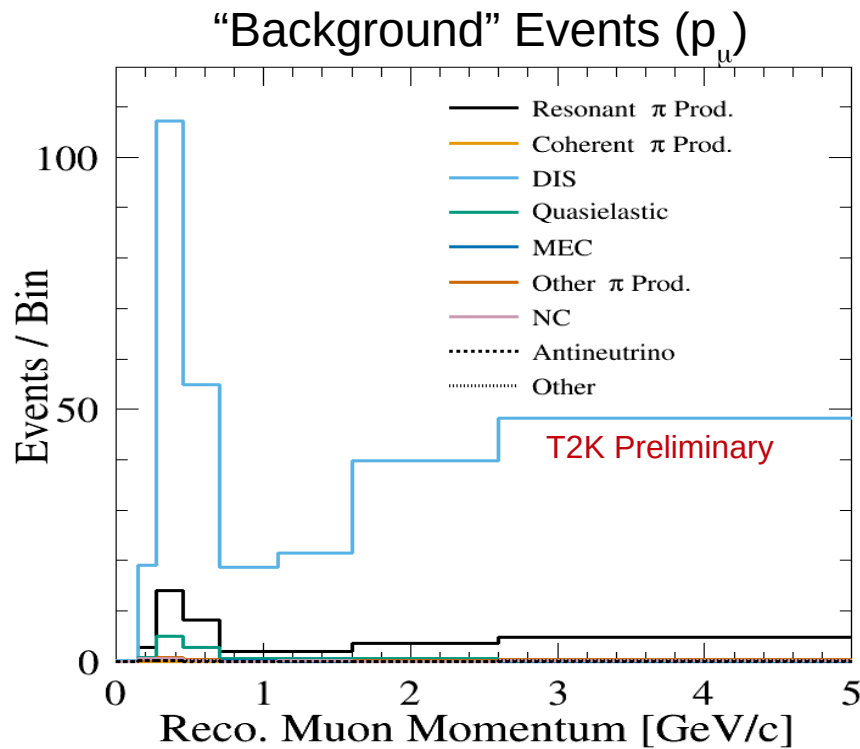
Breakdown by interaction type of events that pass sig def 1 but not sig def 2, and must be subtracted to convert from sig def 1 but to sig def 2

Data Fit Results

Data and Pre-fit MC
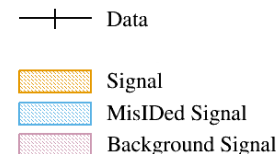
- Prefit MC greatly overestimates the data
- Overestimate roughly flat
- The size of discrepancy decreases with the amount of signal predicted
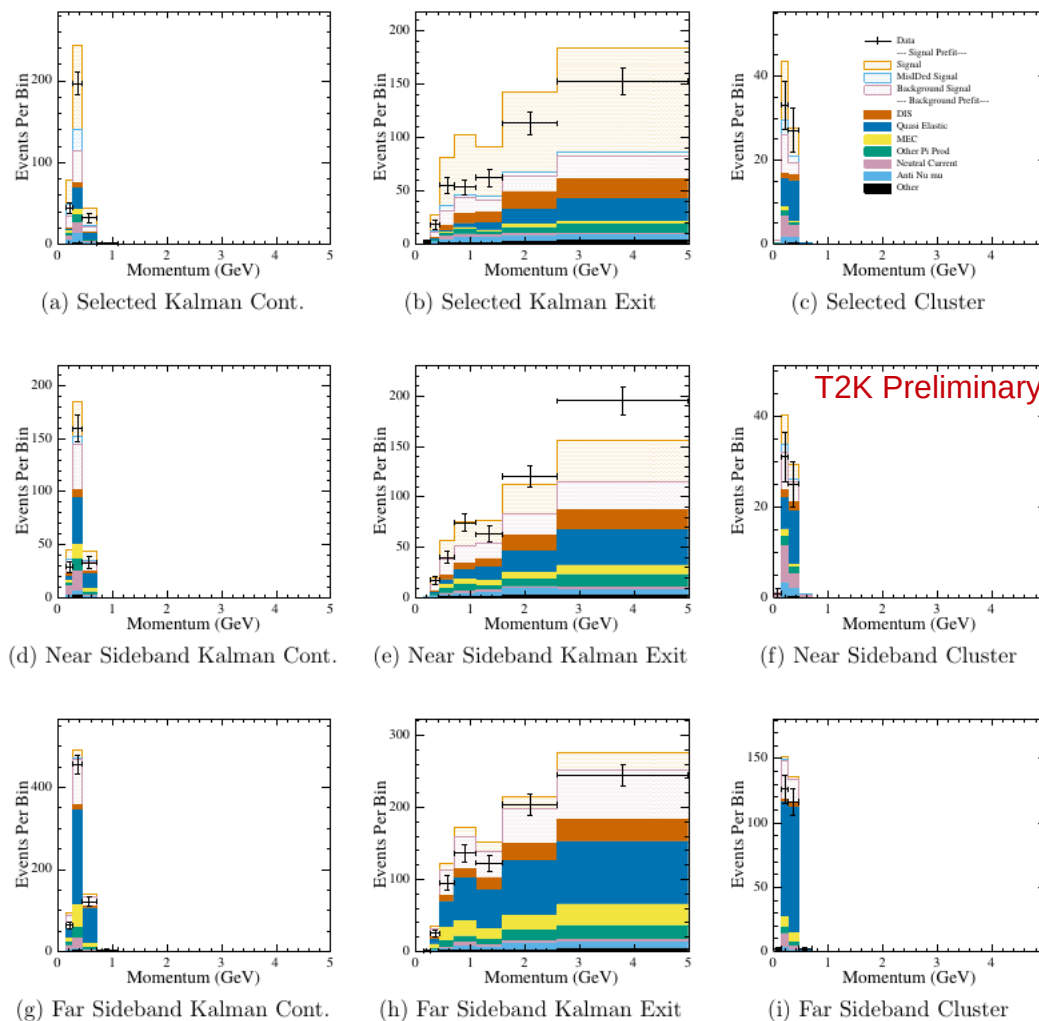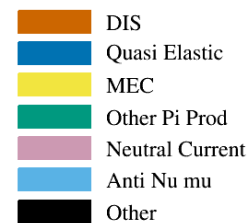
(a) Selected Kalman Cont. (b) Selected Kalman Exit (c) Selected Cluster

(d) Near Sideband Kalman Cont. (e) Near Sideband Kalman Exit (f) Near Sideband Cluster

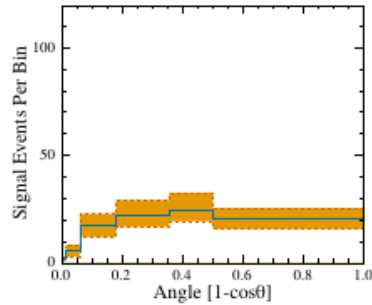(g) Far Sideband Kalman Cont. (h) Far Sideband Kalman Exit (i) Far Sideband Cluster

T2K Preliminary

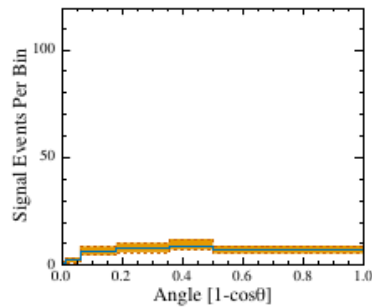p_μ [0.0 – 5.0 GeV]

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Data Fit Results

Data and Pre-fit MC

- Post-fit MC agrees well with data
- Almost all bins within 1σ error band
- Fraction with >1σ discrepancy consistent with expectations given number of bins
- Some tension between the Kalman Exiting Selected and Near Sideband samples
- Tension is at high momentum

(a) Selected Kalman Cont.   (b) Selected Kalman Exit   (c) Selected Cluster
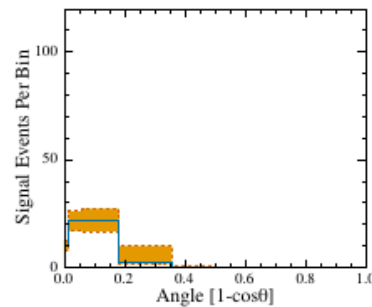
(d) Near Sideband Kalman Cont.   (e) Near Sideband Kalman Exit   (f) Near Sideband Cluster

(g) Far Sideband Kalman Cont.   (h) Far Sideband Kalman Exit   (i) Far Sideband Cluster

T2K Preliminary

p_μ [0.0 – 5.0 GeV]

Data
Signal
MisIDed Signal
Background Signal

DIS
Quasi Elastic
MEC
Other Pi Prod
Neutral Current
Anti Nu mu
Other

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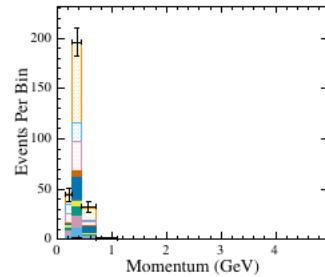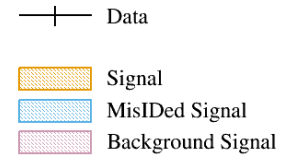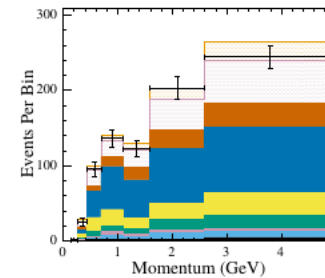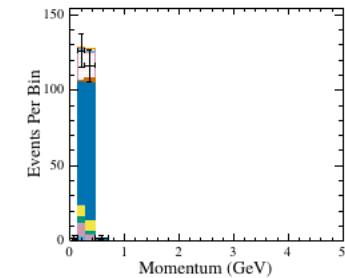
Data Fit Results

(a) Selected Kalman Cont.
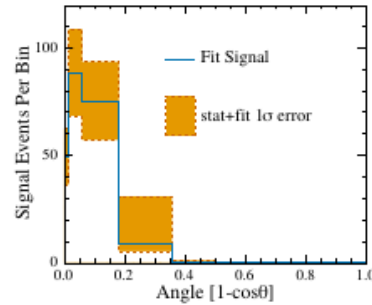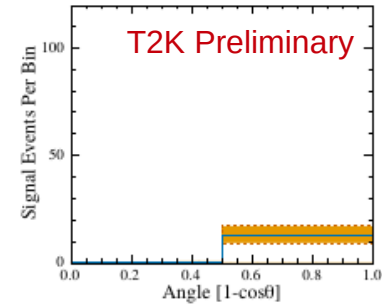
(b) Selected Kalman Exit

(c) Selected Cluster

(d) Near Sideband Kalman Cont.
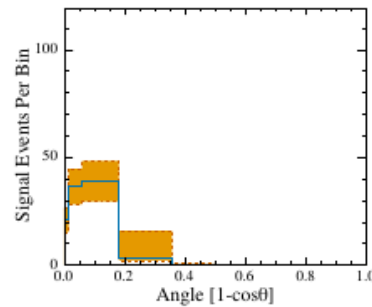
(e) Near Sideband Kalman Exit
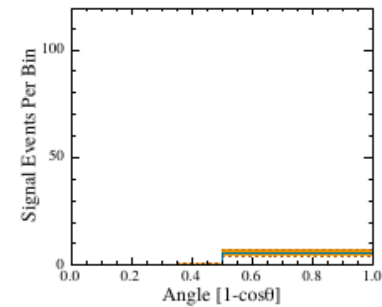
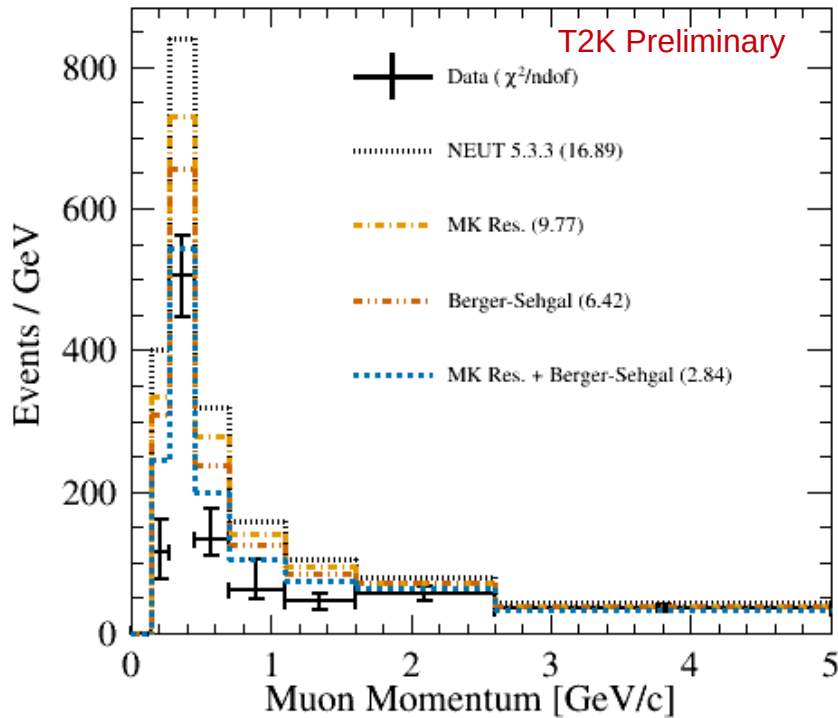(f) Near Sideband Cluster
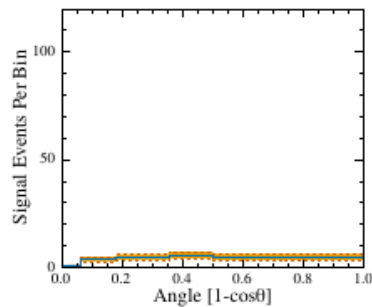
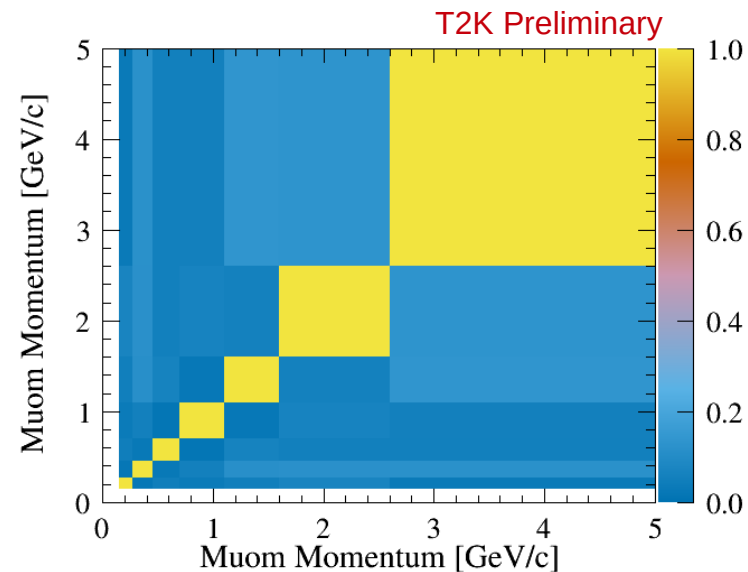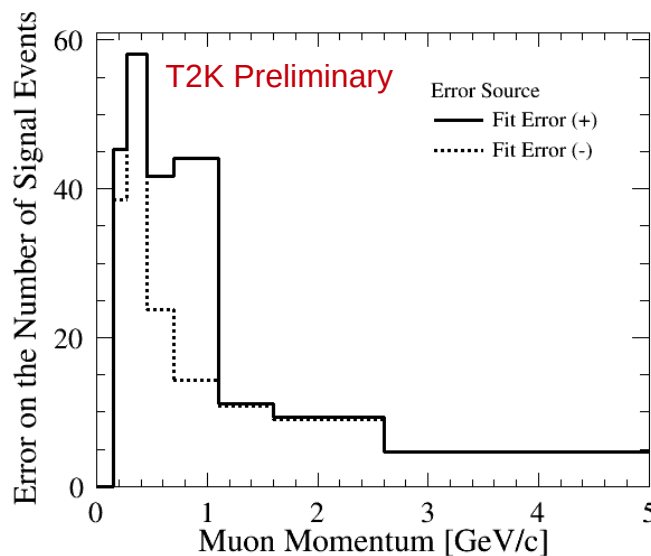(g) Far Sideband Kalman Cont.

(h) Far Sideband Kalman Exit
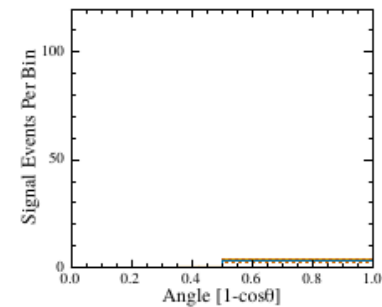
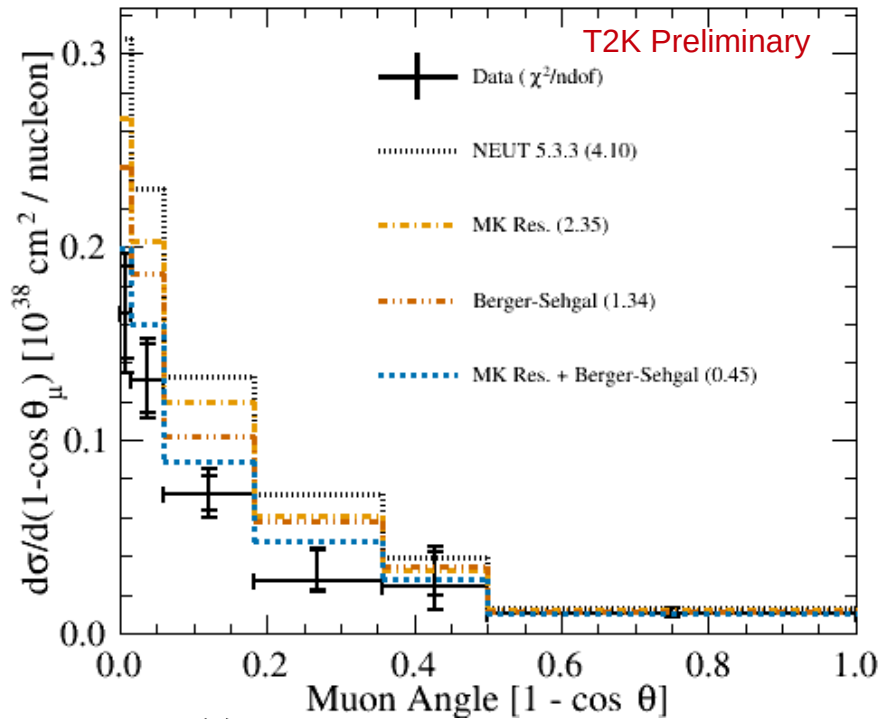(i) Far Sideband Cluster

Extracted Signal Events and Fit Errors

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Event Rate Comparisons

- Compare data with various models
  - NEUT 5.3.3
  - NEUT with res RS→MK
  - NEUT with coh RS→BS
  - NEUT with both changes
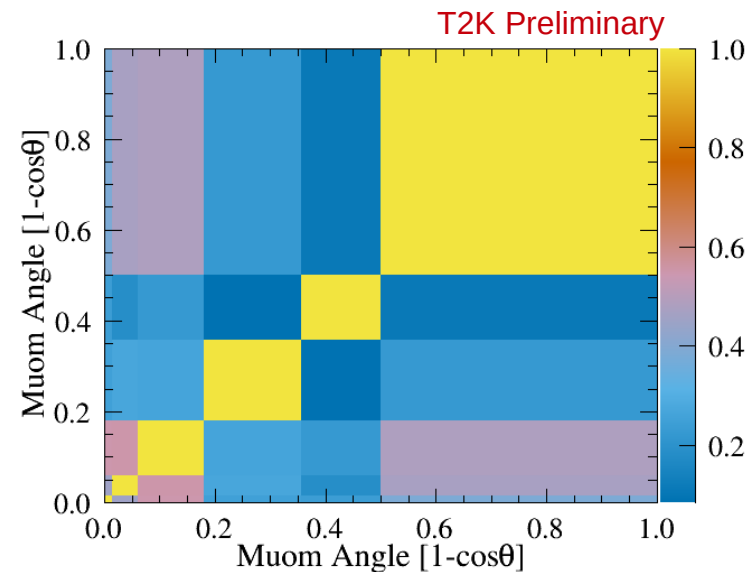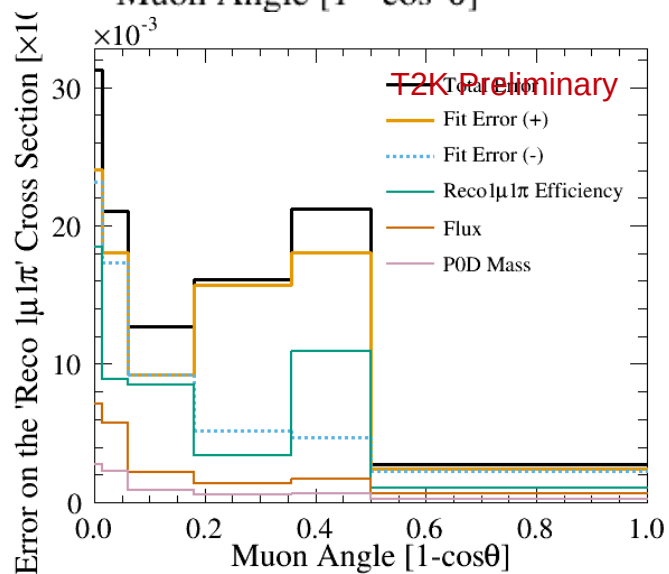- Track errors and correlations

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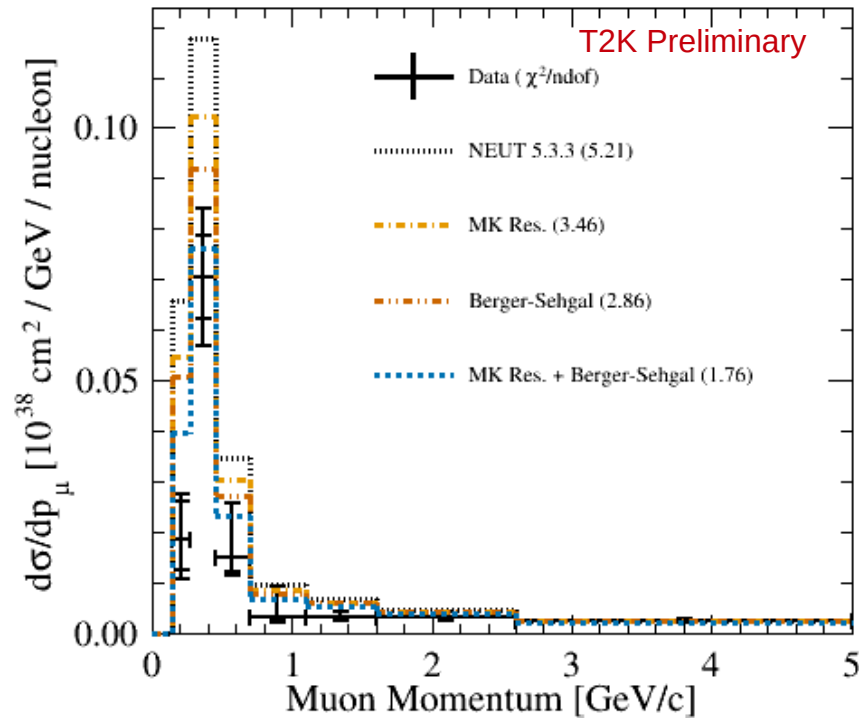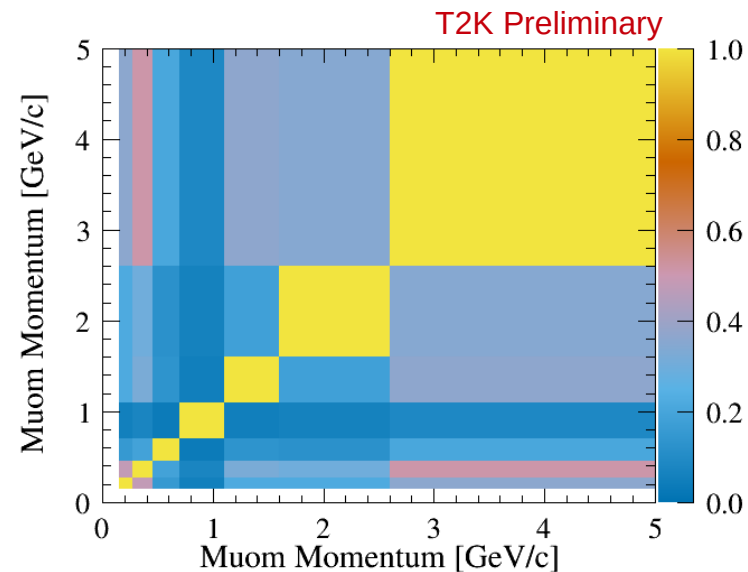# 1μ1π Detected Cross Section

- Compare data with various models
  - NEUT 5.3.3
  - NEUT with res RS→MK
  - NEUT with coh RS→BS
  - NEUT with both changes
- Track errors and correlations

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1μ1π Detected Cross Section
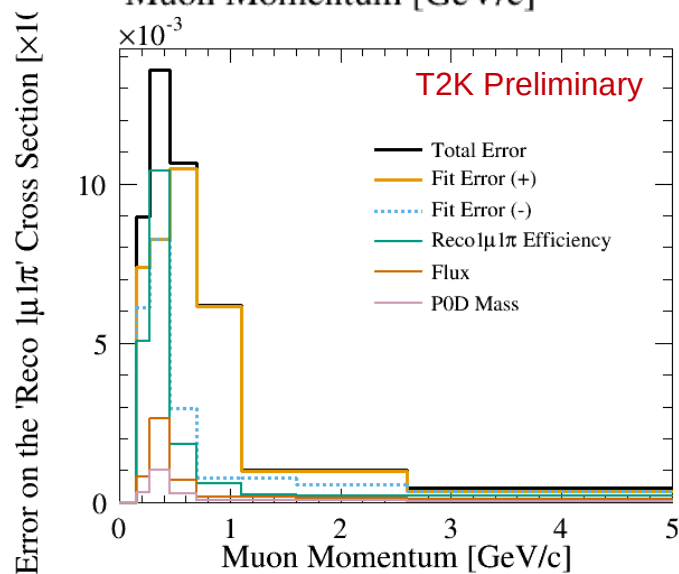

- Compare data with various models
  - NEUT 5.3.3
  - NEUT with res RS→MK
  - NEUT with coh RS→BS
  - NEUT with both changes
- Track errors and correlations

1μ1π After FSI Cross Section

- Compare data with various models
  - NEUT 5.3.3
  - NEUT with res RS→MK
  - NEUT with coh RS→BS
  - NEUT with both changes
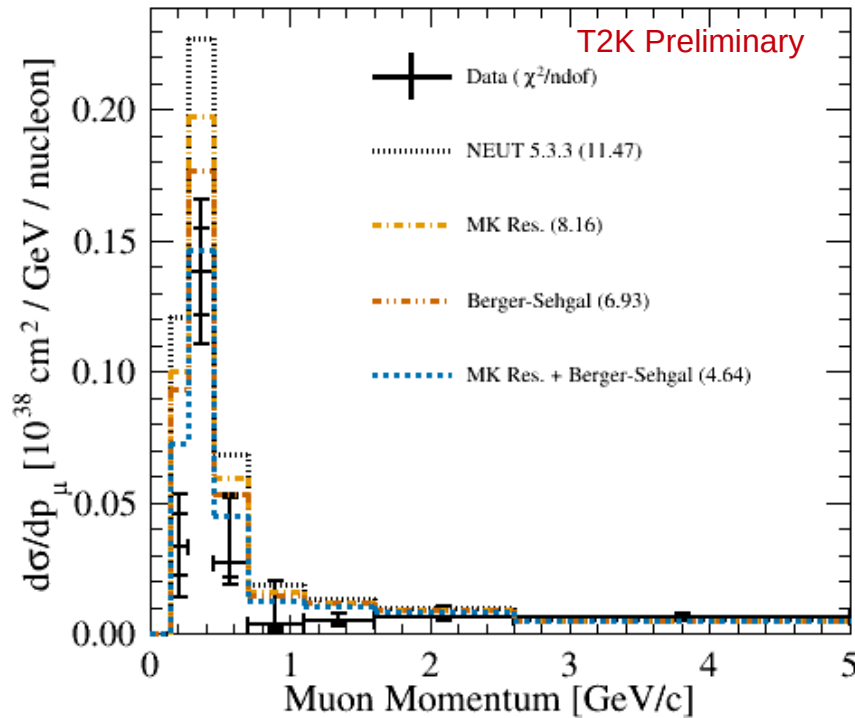- Track errors and correlations