



# Observables and Systematics for the Oscillation Analysis

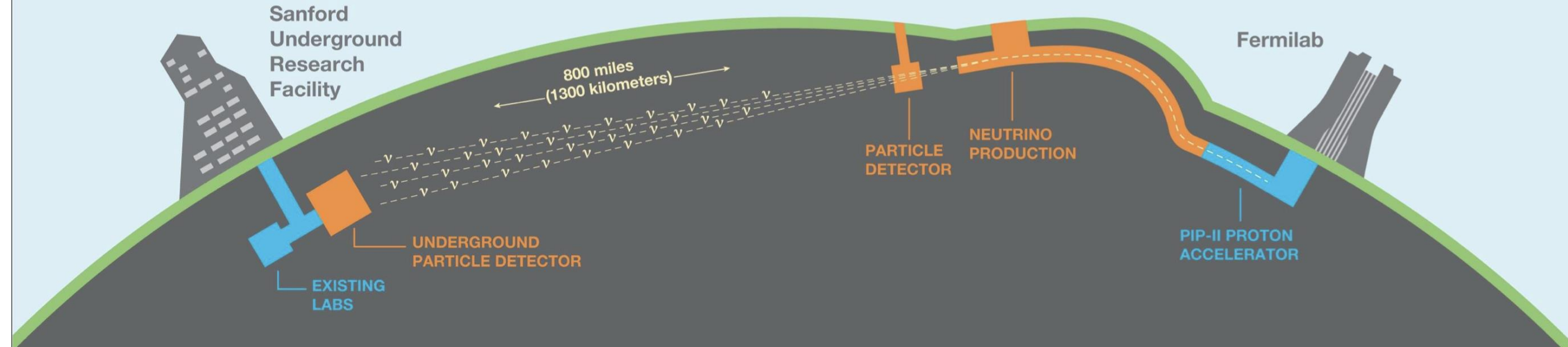
Abigail Peake

*On behalf of the DUNE Collaboration*

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# DUNE Overview

Observe  $\nu_\mu \rightarrow \nu_\mu$ ,  $\nu_\mu \rightarrow \nu_e$ ,  $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$   
Measure  $\delta_{CP}$ ,  $\Delta m_{32}^2$ ,  $\theta_{23}$ ,  $\theta_{13}$ , mass ordering



DUNE will also be able to observe  $\nu_\tau$

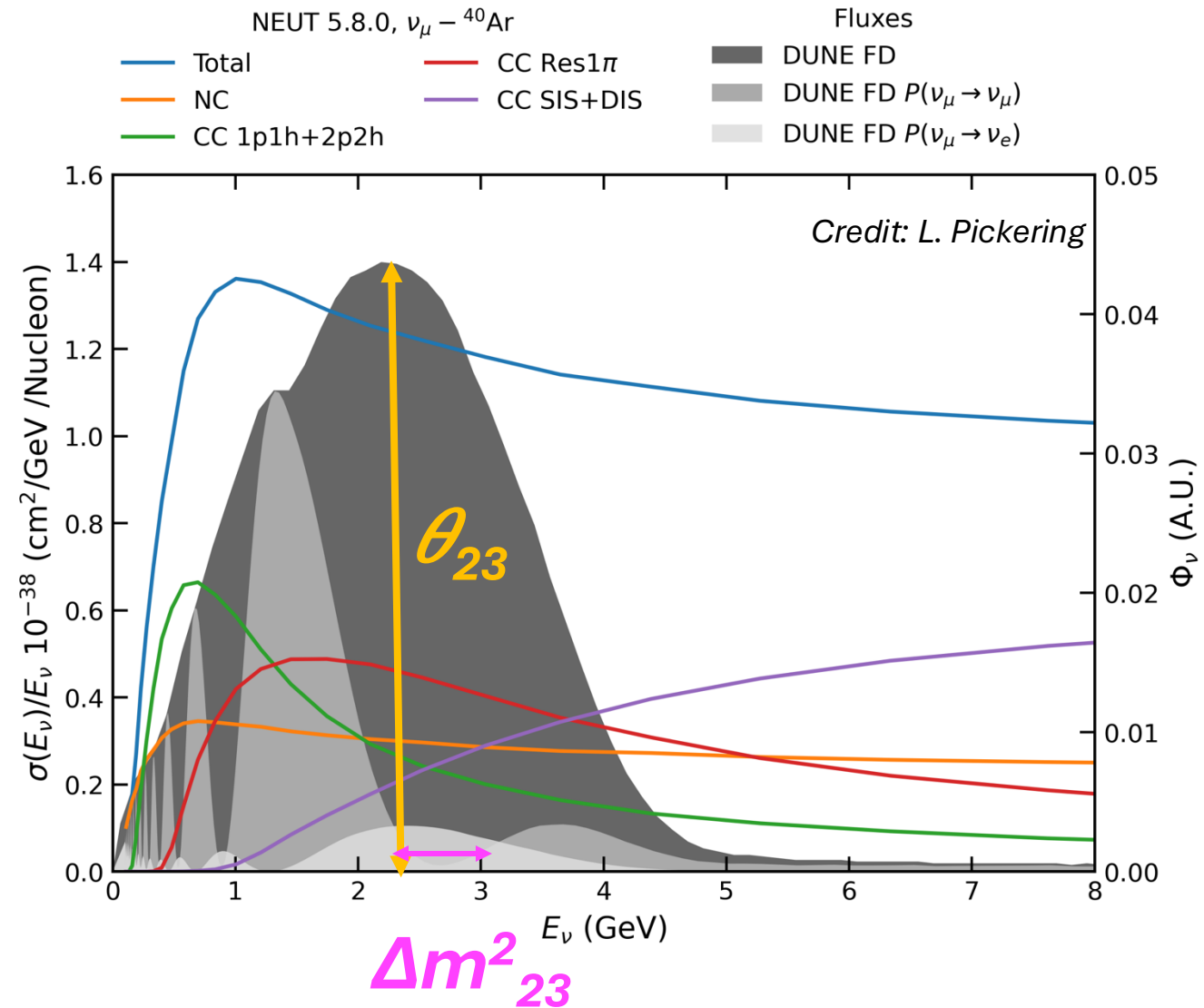
DUNE Far Detector (FD) will have a large fiducial mass, enabling a broad range of atmospheric and astrophysical neutrino measurements

# **DUNE Long baseline Analysis**

# Making an Oscillation Measurement

**Goal: Look for signature oscillatory shape in the observed neutrino flux at the DUNE Far Detector**

The precise shape of the oscillated flux will enable the measurement of the oscillation parameters

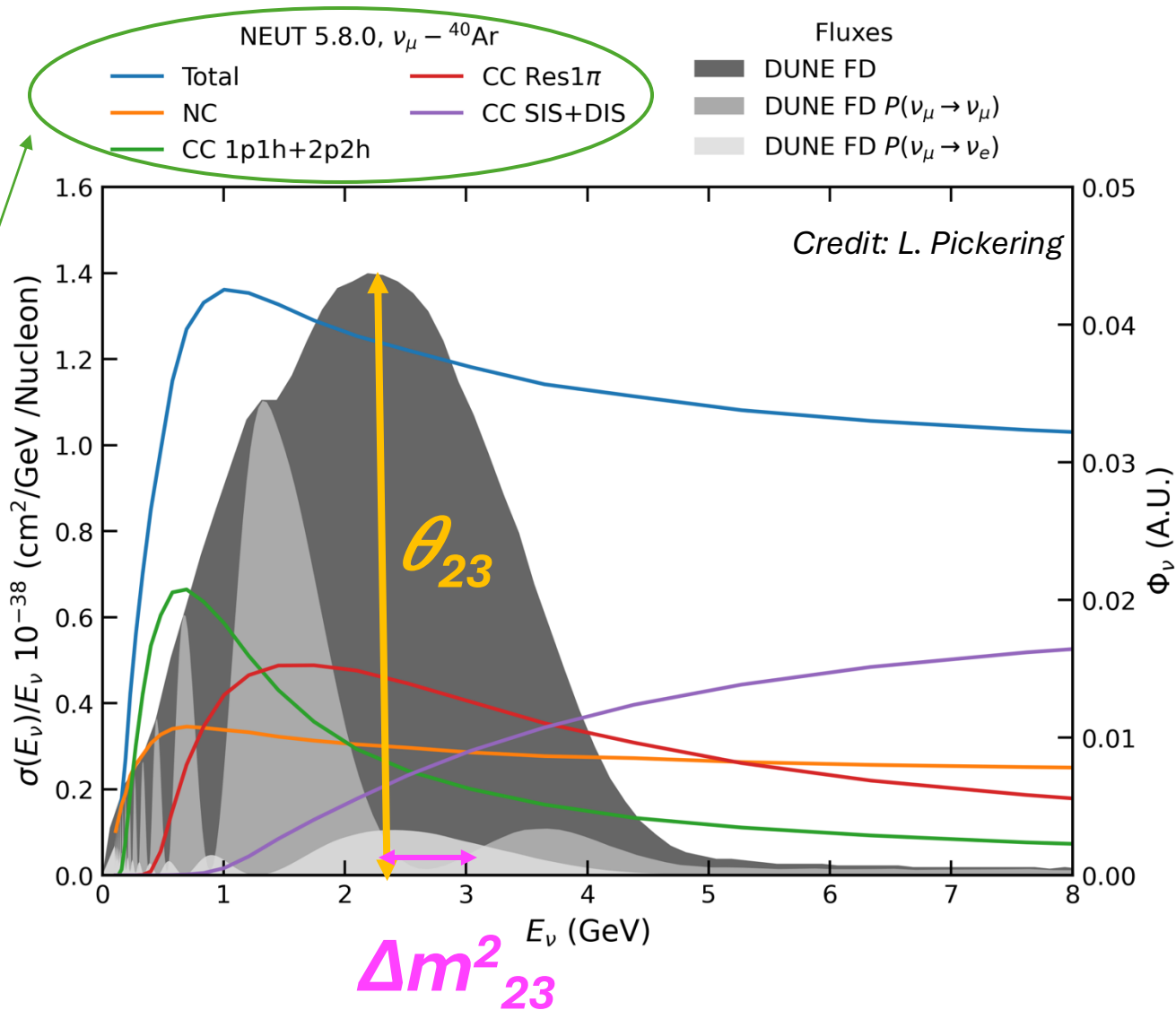


# Making an Oscillation Measurement

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Flux component predictions broken up by interaction channel



# Making an Oscillation Measurement

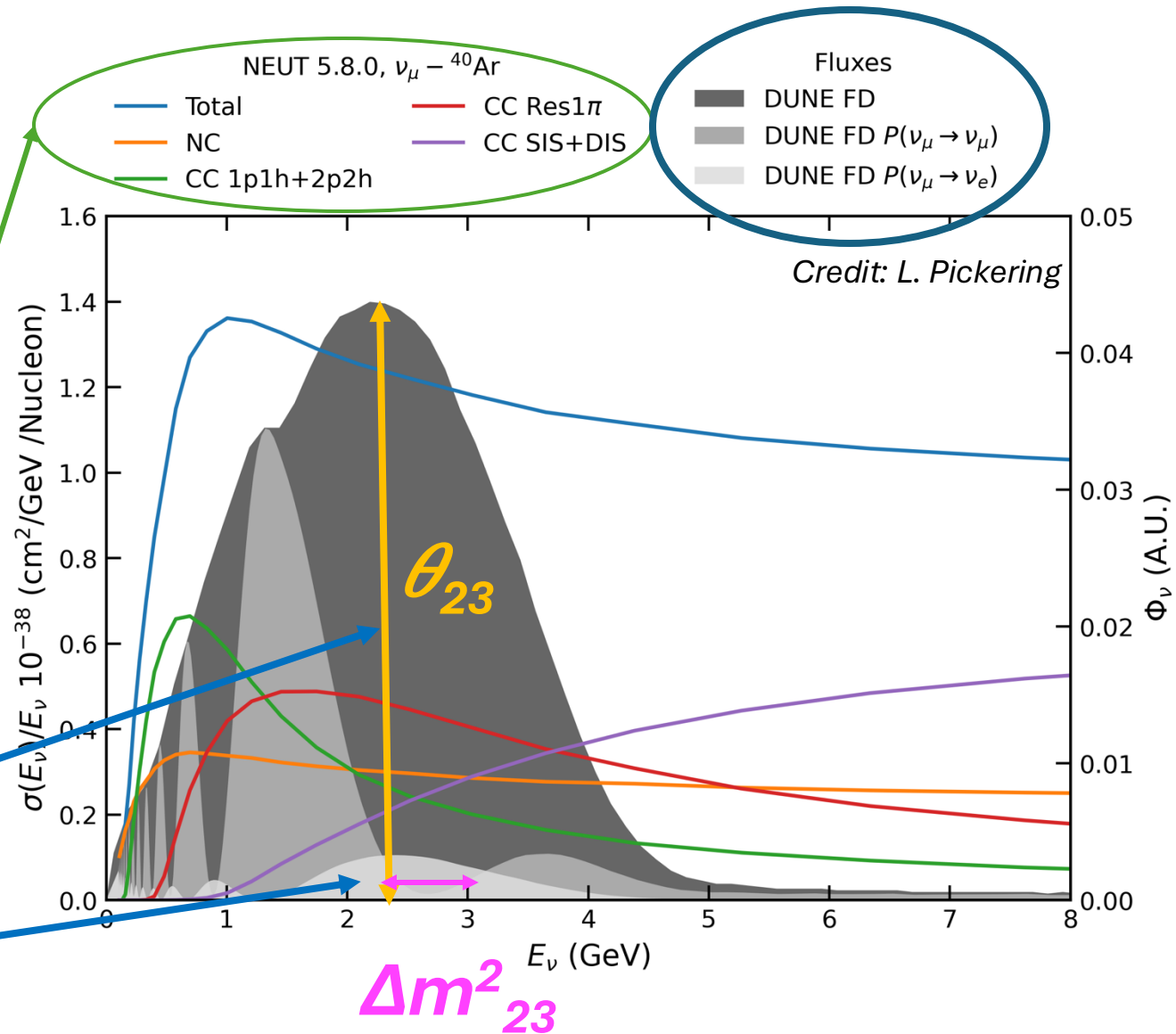
**Goal:** Look for signature oscillatory shape in the observed neutrino flux at the DUNE Far Detector

The precise shape of the oscillated flux will enable the measurement of the oscillation parameters

Cross-section predictions broken up by interaction channel

Disappearance of  $\nu_\mu$

Appearance of  $\nu_e$



# An Oscillation Analysis with DUNE

ND

$$\text{No. of events}_{\text{ND}}(E_\nu^{\text{measured}}) = \int dE_\nu \Phi_{\text{ND}}(E^\nu) \times \sigma(E^\nu) \times \epsilon_{\text{ND}}(E^\nu)$$

FD

$$\text{No. of events}_{\text{FD}}(E_\nu^{\text{measured}}) = \int dE_\nu P_{\text{osc.}}(E^\nu) \times \Phi_{\text{FD}}(E^\nu) \times \sigma(E^\nu) \times \epsilon_{\text{FD}}(E^\nu)$$

Event Rate

Measure

For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial!

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Event Rate

Measure

Flux

Detector Efficiency

Interaction cross-section

Model

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Event Rate

Measure

Oscillation Probability

**Want to determine!**

Flux

Detector Efficiency

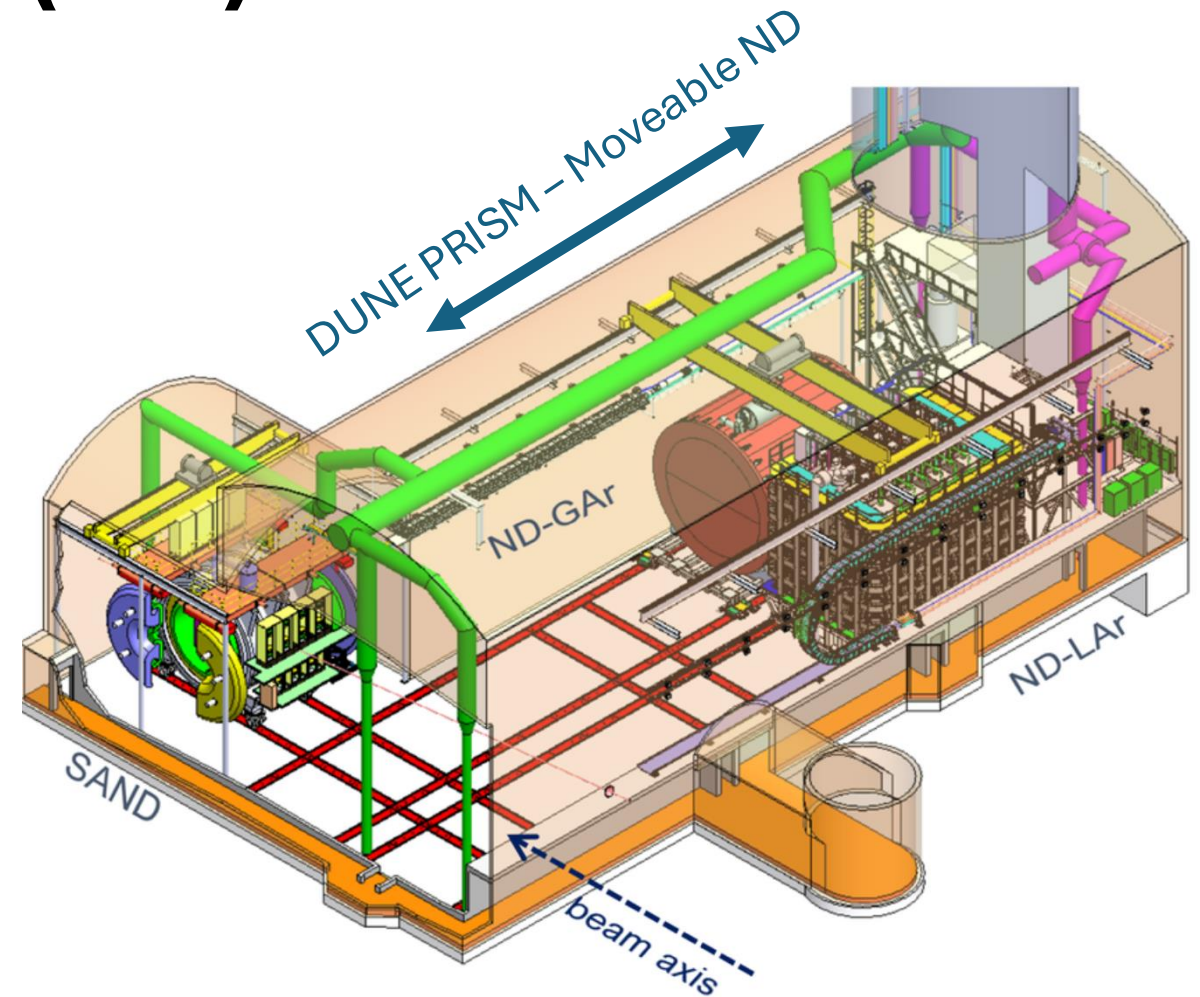
Interaction cross-section

Model

For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial !

# The DUNE Near Detector (ND)

- The DUNE ND is expected sample 60 million CC  $\nu_\mu$  interactions each year – highest flux produced in any experiment!
- DUNE ND will make high statistics measurements, which means we can constrain cross-section uncertainties with precision that has never been possible before!
- Need to plan how we can use the full capabilities of the ND to constrain flux uncertainties and detector efficiencies as well

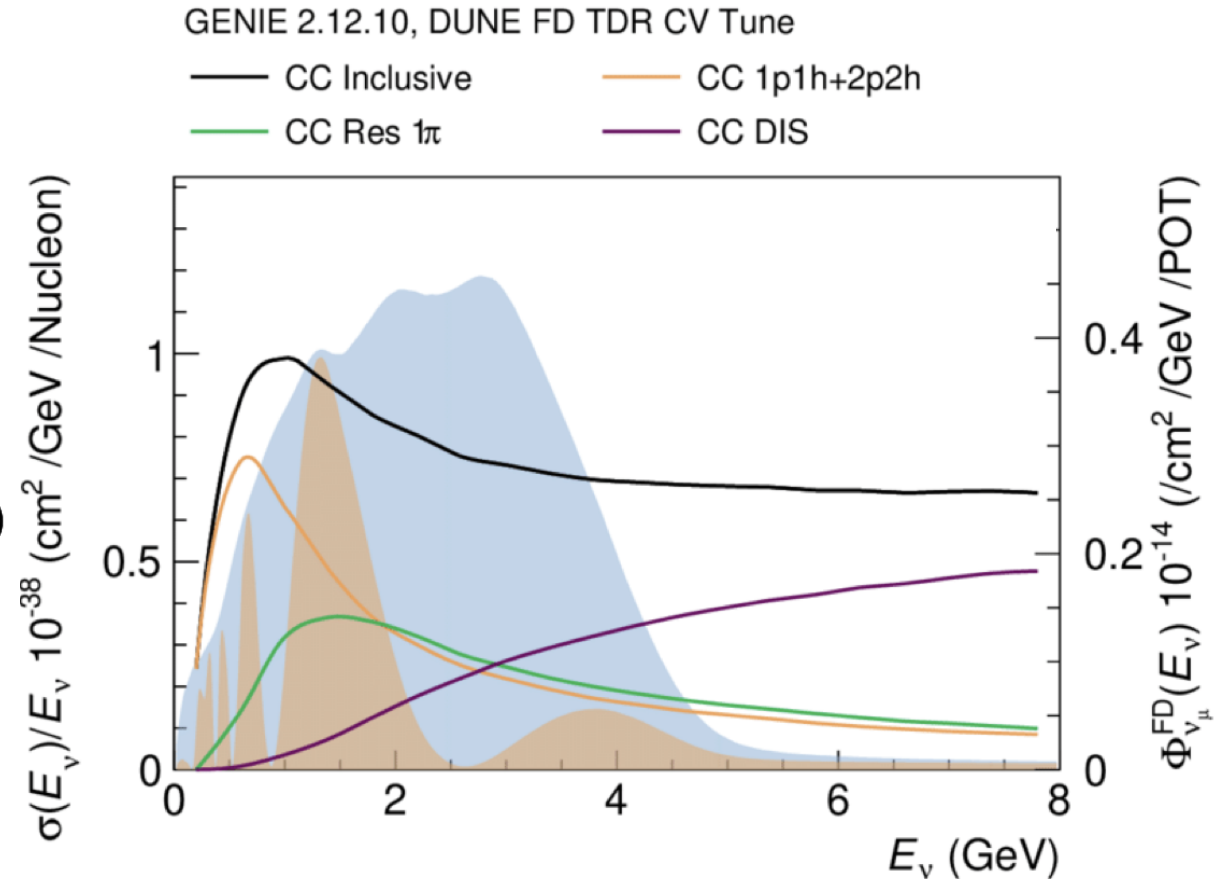


# Cross-section Uncertainties

- The  $E_\nu$  spectra at the Near Detector (ND) and Far Detector (FD) are different due to oscillations + detector effects
- It is impossible to separate the flux and cross-section contributions from the ND event rate:



$$\text{No. of events}_{\text{ND}}(E_\nu^{\text{measured}}) = \int dE_\nu (\Phi_{\text{ND}}(E_\nu) \times \sigma(E_\nu) \times \epsilon_{\text{ND}}(E_\nu))$$

- Any mismodelling of  $\sigma$  could lead to:
  1. Oscillation features appearing in the wrong place in model
  2. Lowered sensitivity
  3. Biased measurements



# Why do we need DUNE PRISM ?

- The number of interactions at the ND means that DUNE will be limited by systematic uncertainties rather than statistical uncertainties
- The dominant source of systematic uncertainties for oscillation experiments comes from neutrino-nucleus interactions

<i>Uncertainty on <math>N_e^{rec}</math></i>		
Cross Sections	~4%	~3.5%
All Syst.	~5%	~3.5%

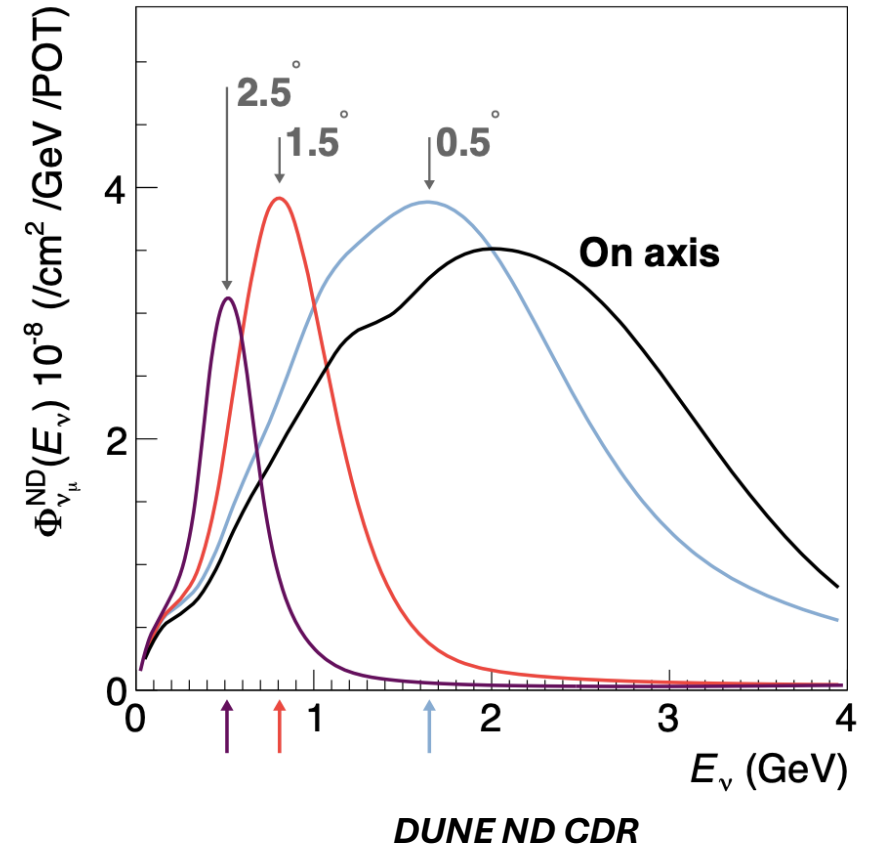
*S.Dolan*

- To make world leading measurement of the oscillation parameters, we need to constrain these systematic uncertainties to less than 1%
- PRISM is a key tool for DUNE to do this

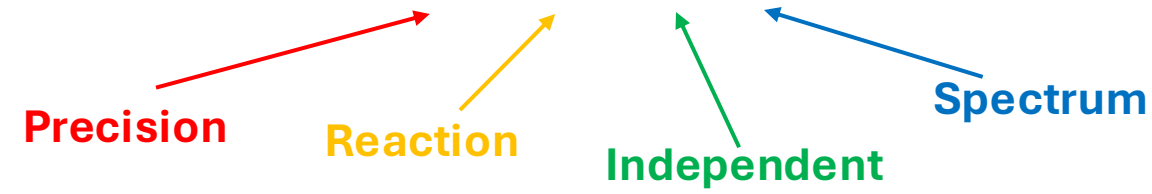
# DUNE PRISM

Precision → **P**
Reaction → **R**
Independent → **I**
Spectrum → **S**
Measurement → **M**

- The DUNE ND can move relative to the beam axis
- Means of controlling the range of energies the ND is exposed to
- At each OA position, there is a narrower band of  $E_\nu$ :



# DUNE PRISM

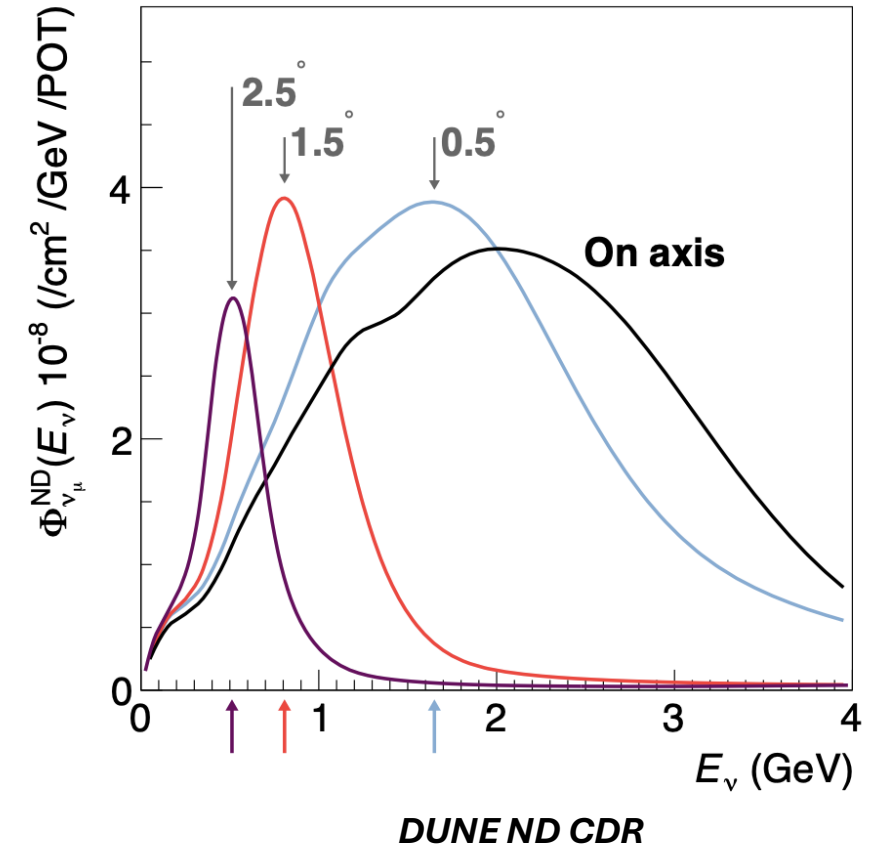


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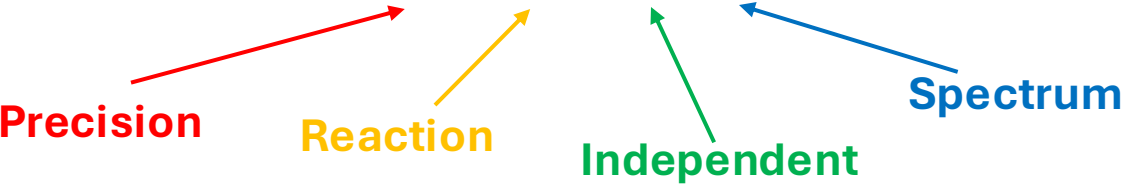
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Measure

Control using PRISM!



# DUNE PRISM



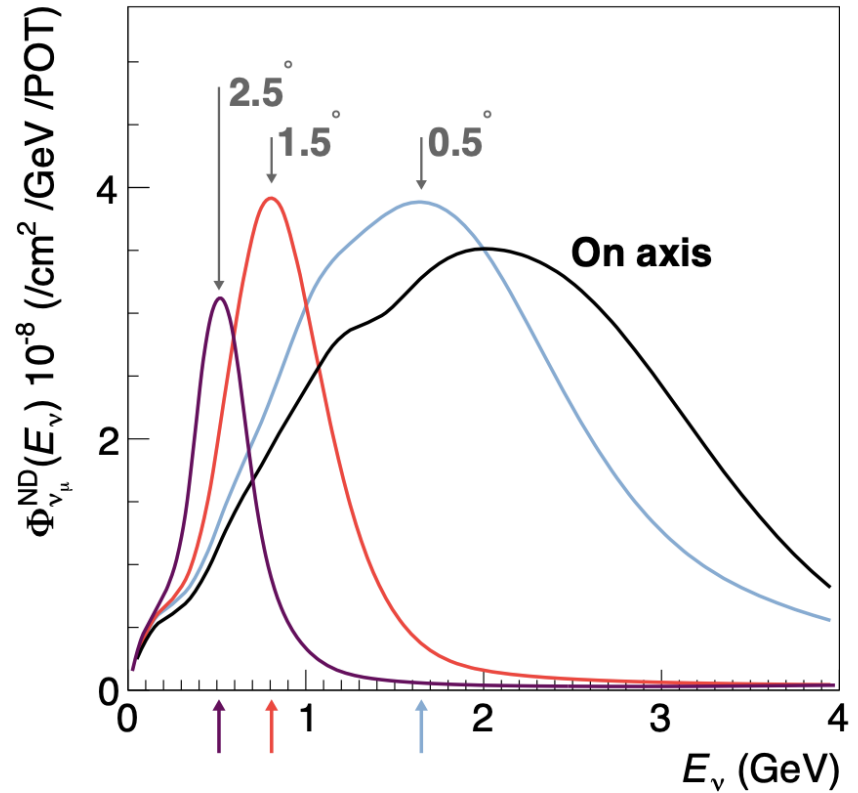
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- At each OA position, there is a narrower band of  $E_\nu$ :

$$\text{No. of events}_{\text{ND}}(E_\nu^{\text{measured}}) = \int dE_\nu \Phi_{\text{ND}}(E^\nu) \times \sigma(E^\nu) \times \epsilon_{\text{ND}}(E^\nu)$$

Measure

Control using PRISM!

Constrain at each off-axis position



DUNE ND CDR

- Measurements less sensitive to neutrino interaction models
- Method to **constrain systematic uncertainties** that arise from interaction modelling

# Observables at the ND/FD

# Choosing the Right Analysis Observables

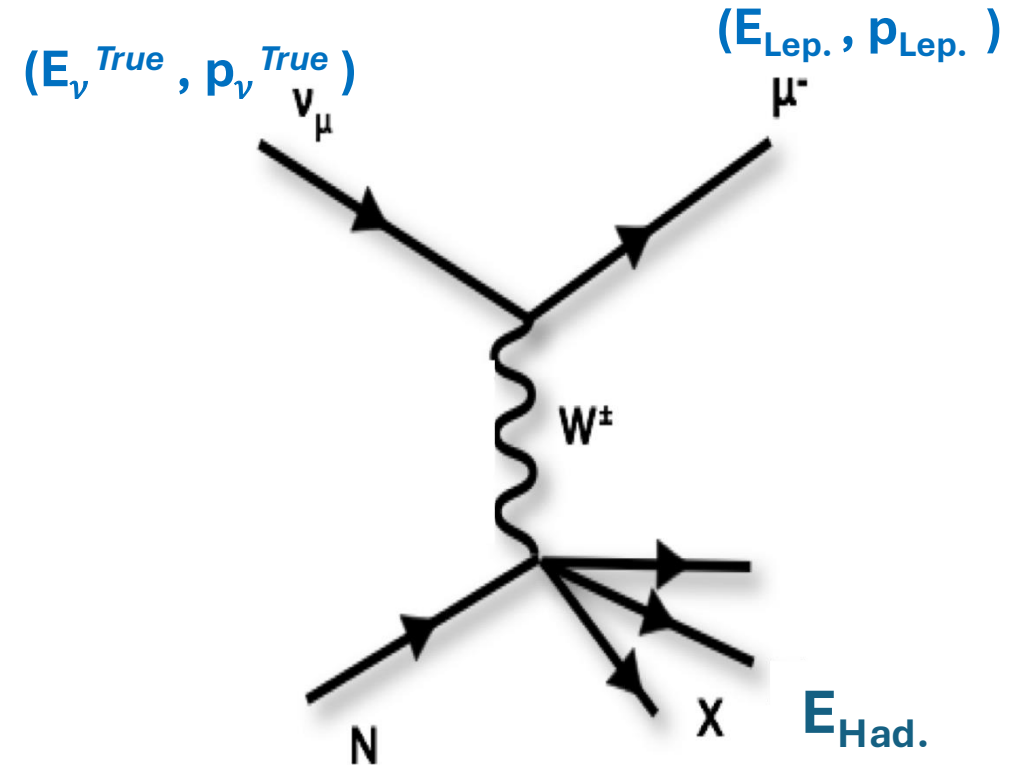
- Neutrino-nucleus interactions are complicated!
- They vary as a function of multiple quantities, which cannot be fixed in a neutrino beam experiment like DUNE
- In the theory basis, the inclusive cross-section needs three parameters, often these are chosen:

1.  $E_{\nu}^{True}$

2.  $q_0 = E_{\nu}^{True} - E_{Lep.}$

3.  $q_3 = |\mathbf{p}_{\nu}^{True} - \mathbf{p}_{Lep.}|$

...which cannot be measured directly!

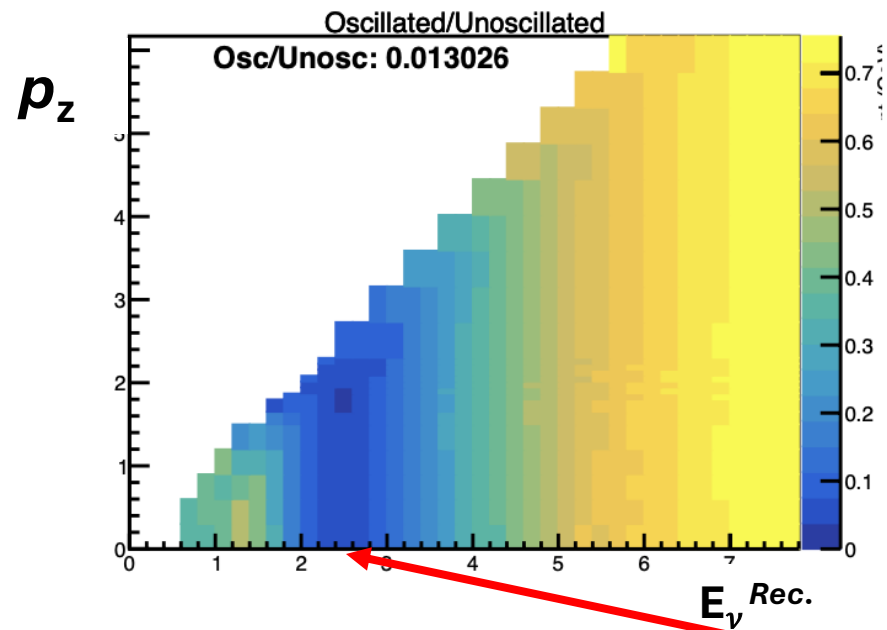


# True Variables → Reconstructed Estimators

- It is necessary to bin in variables that we can measure directly
- Reconstructed estimators can be used as a proxy for the true variables
- However, it is not always possible directly compare reconstructed and truth variables
- For example, it is impossible to exactly sum the energy from the hadronic shower

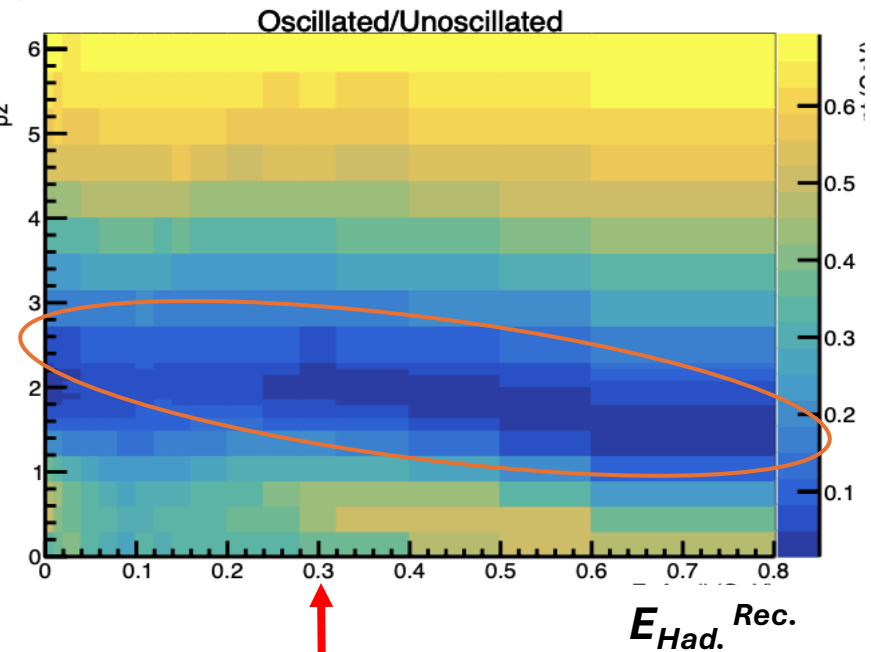
Truth Variable	Reconstructed estimator
$E_{\nu}^{True}$	$E_{\nu}^{Reco.}$
$q_3$	$p_T$ (Transverse Lepton Momentum)
$q_0$	$E_{\nu}^{Reco} - E_{lep.}^{Reco}$
$E_{Had}^{True}$	$E_{avail}$ – sum up energy from <b>visible</b> hadrons
$E_{lep.}^{True}$	$E_{lep.}^{Reco}$

# $E_{\nu}^{Rec.}$ vs. $E_{Had.}^{Rec.}$ for an Oscillation Analysis



Disappearance at DUNE oscillation maxima clear ( $E_{\nu} \sim 2.3$  GeV)

Impact of disappearance smeared out horizontally

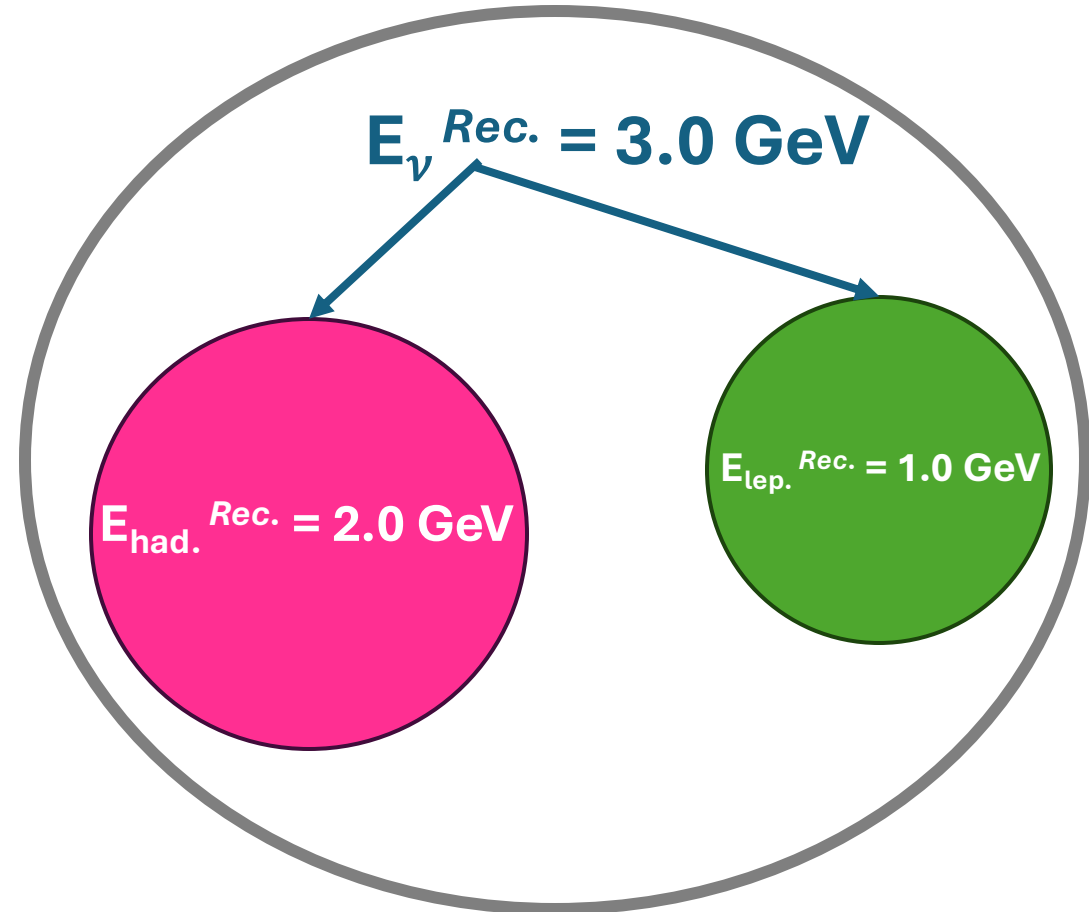
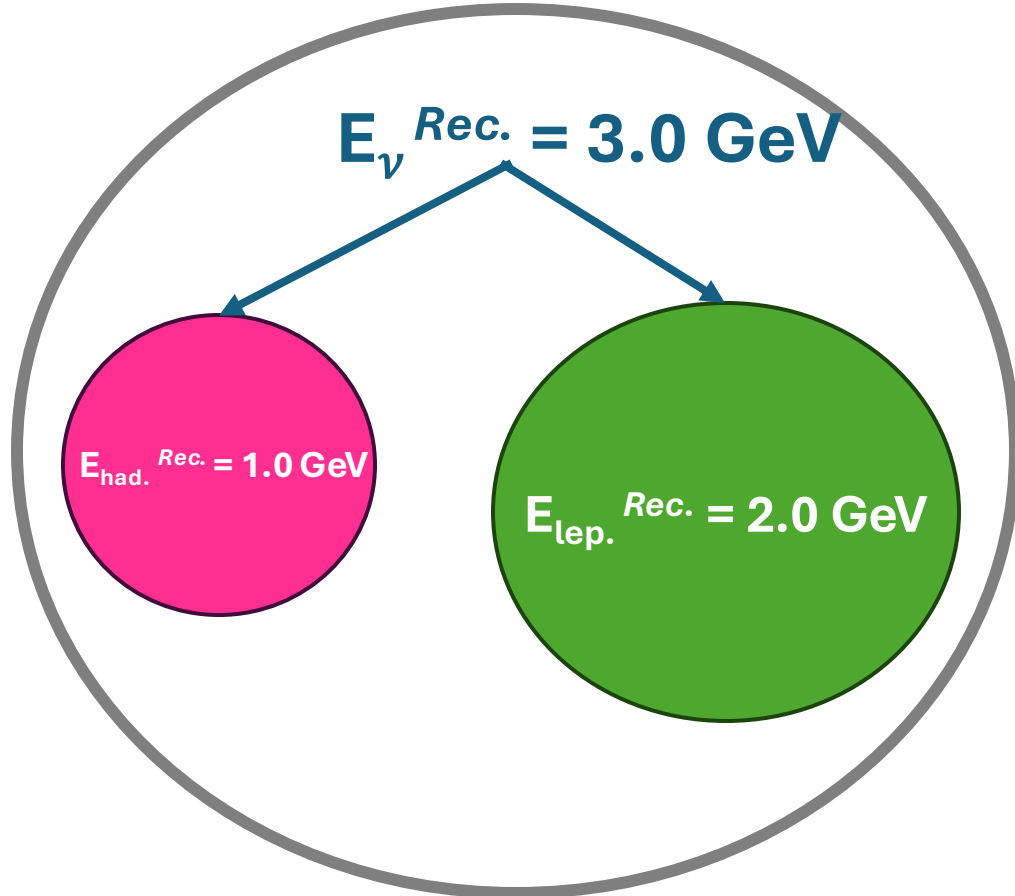


$$E_{\nu}^{Rec.} = E_{Lep.}^{Rec.} + E_{Had.}^{Rec.}$$

*These quantities have very different methods of reconstruction, so we apply different systematics*

# Why not just $E_\nu^{Rec.}$ ?

$$E_\nu^{Rec.} = E_{lep.}^{Rec.} + E_{had.}^{Rec.}$$



- If you just analyse in  $E_\nu^{Rec.}$  then these 2 events would seem identical
- However, the energy split between the hadronic and leptonic sides is **different**
- Splitting into  $E_{lep.}^{Rec.} + E_{had.}^{Rec.}$  means that we can apply the appropriate systematics

# “Who needs what?”

Need to choose the projection variables of physics analysis based on the constraints and needs of the analysis:

## Long Baseline

- $E_{\nu}^{Rec.}$  for measuring oscillation parameters
- The resolution of  $E_{\nu}^{Rec.}$  will vary, some variables will help separate these regions
- Make it easy to map systematics from the ND to FD

## Studying Neutrino Interactions

- Directly correlate to the interaction kinematics
- Measure the resolution between the measured and theoretical variables
- Quantities that demonstrate neutrino-nucleon interactions that may impact the neutrino energy spectrum

## Detector Simulation

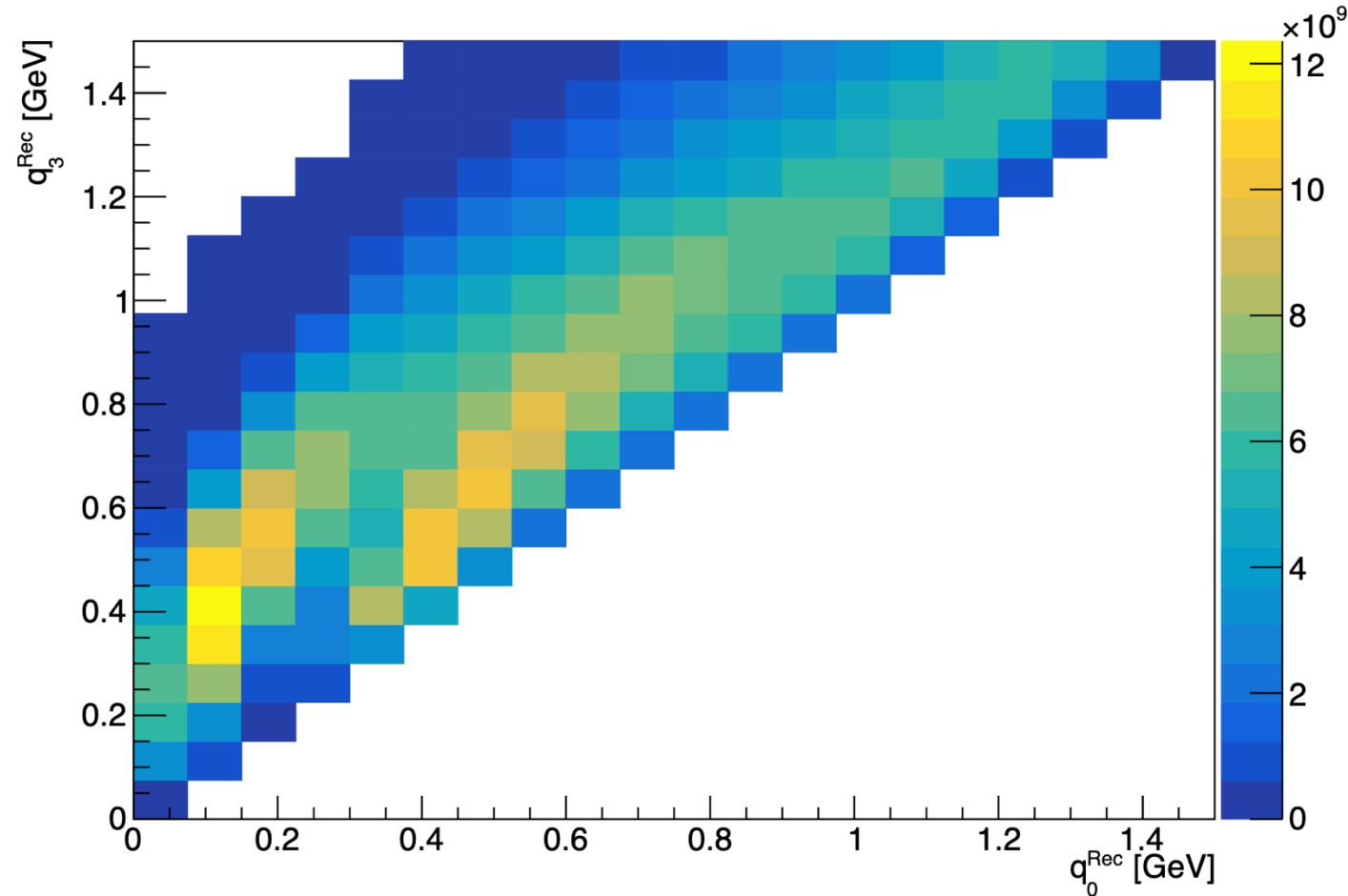
Quantities for which detector systematics can be well motivated  
e.g  
( $E_{lep.}$ ,  $\theta_{lep.}$ ,  $E_{Calorimetric}$ )

# A toy Cross-Section Uncertainty Model

- The cross-section uncertainty model is created using event generators (GENIE model)
- This is a way of adding freedom on top of the GENIE model, without making model dependent assumptions
- One way to do this is in terms of  $(q_0, q_3)$
- As a toy model, choose a uniform prior and vary the normalisations for each bin

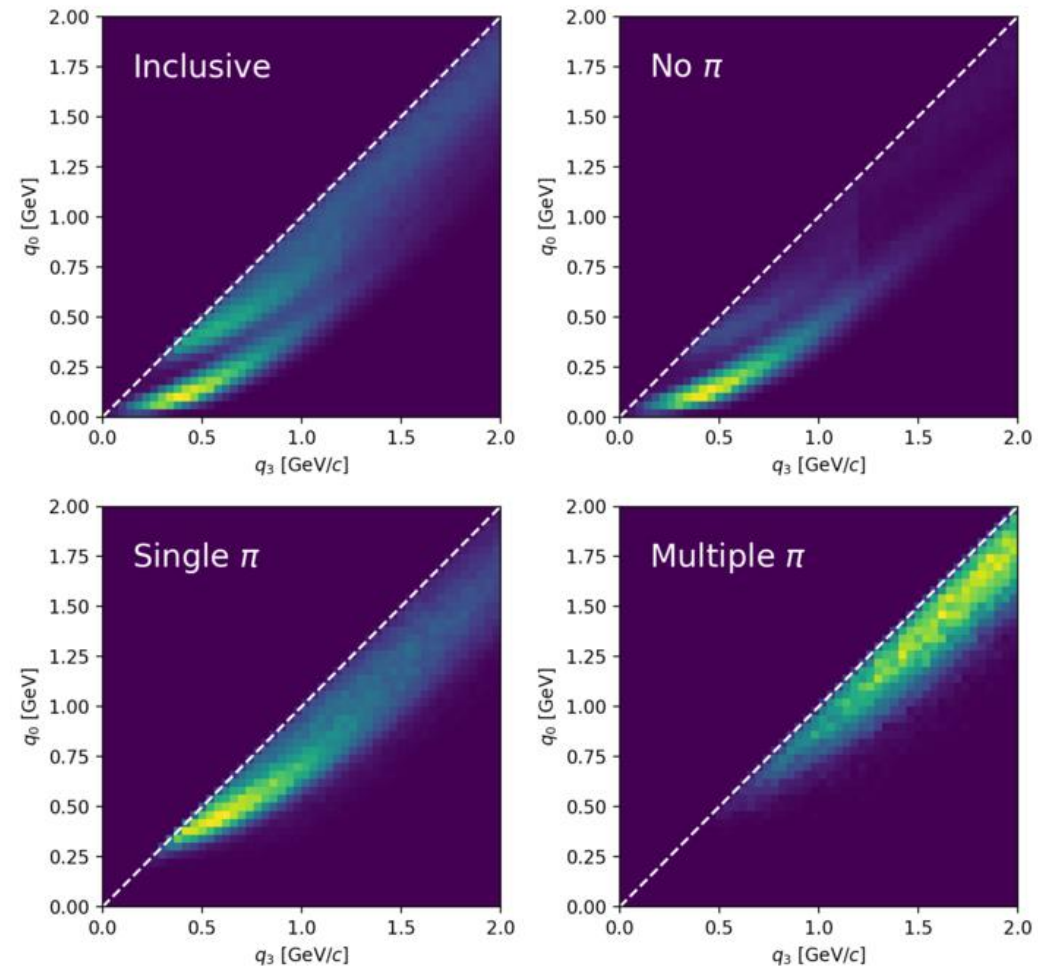
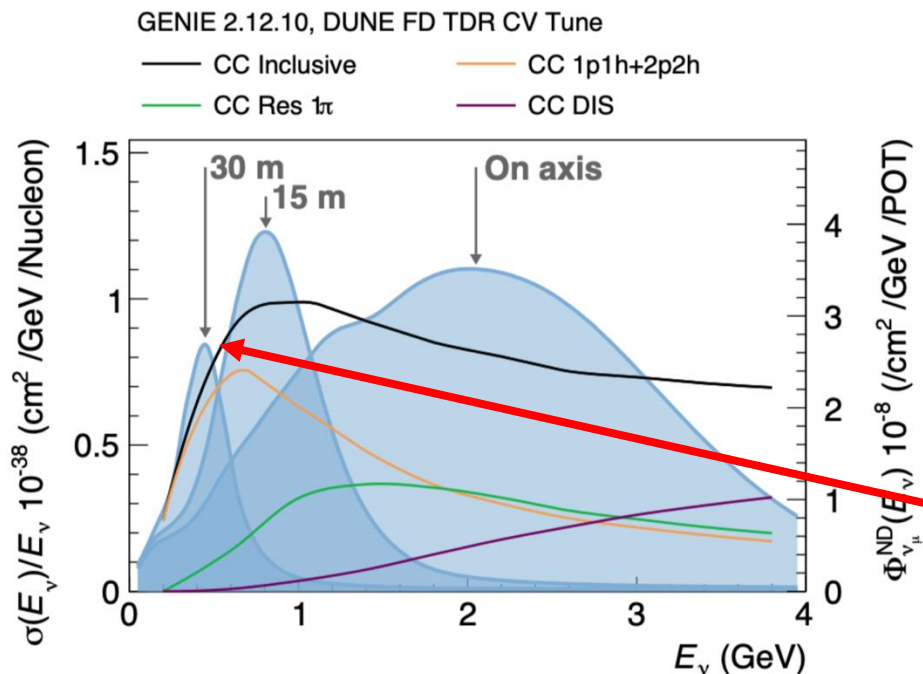
$$q_0 = E_\nu - E_{\text{lep}}$$

$$q_3 = |\mathbf{p}_\nu - \mathbf{p}_{\text{lep}}|$$



# ND Run-Plan and PRISM

- The amount of time the ND spends on-axis vs off-axis will impact the constraint in different regions of the cross-section uncertainty model
- Aiming to build intuition about how the run plan impacts the constraint on the uncertainty model



L. Pickering

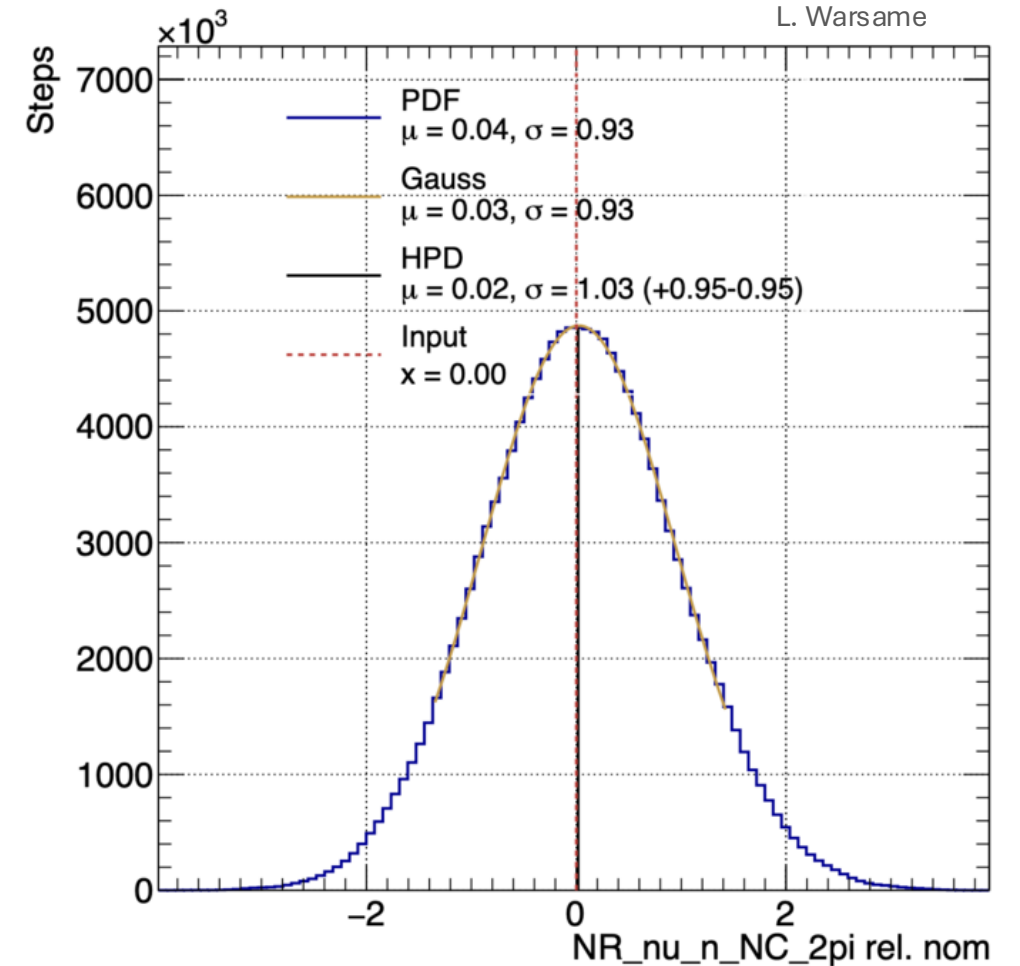
Spending time for off axis allows us to isolate QE rich sample

# Next Analysis Steps

Posterior Distribution of GENIE parameter from recent DUNE Bayesian analysis

Aim: make similar posterior distribution for new parameters

Investigate how the **run plan** and **binning variables** impacts the width of the posterior and correlations for each new parameter



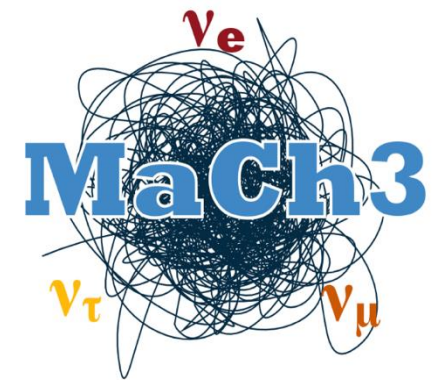
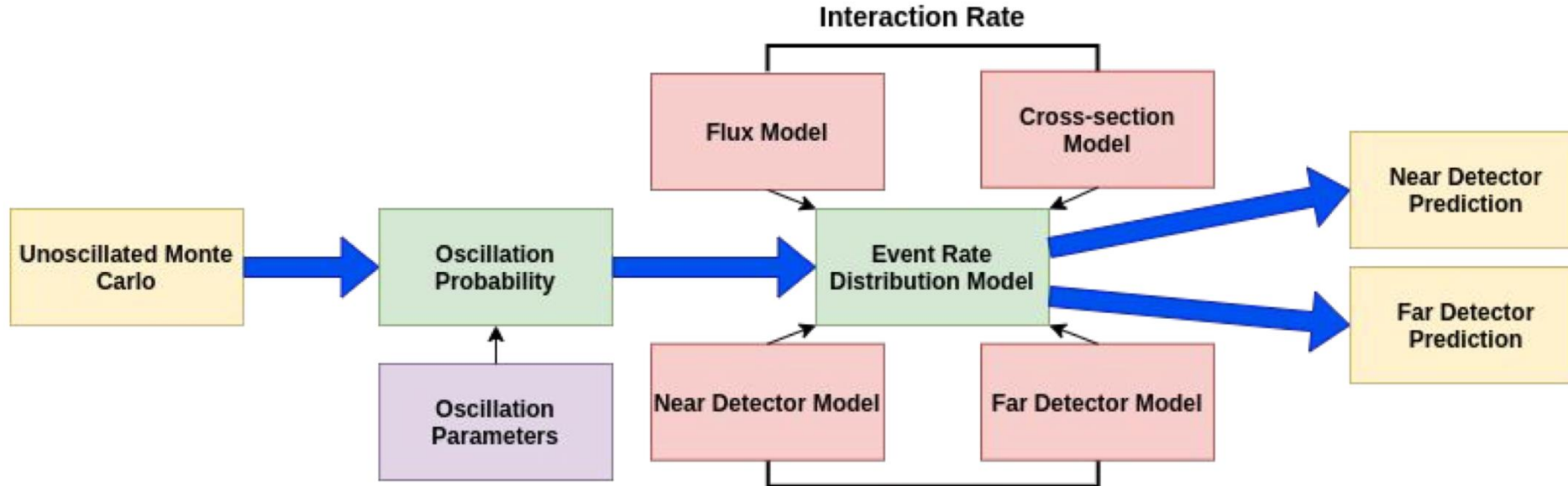
# Summary

- Investigations into projections are important in long baseline sensitivity studies, to ensure that DUNE could meet its physics goals, and make exciting measurements
- We need to use observables that are measurable in the detector, and useful in an oscillation analysis
- DUNE PRISM will play a vital role in determining which projections are best, and constraining cross-section systematics
- Currently building PRISM analysis in a way to assess the impact of new inputs for detector systematics, and cross-section uncertainties

# Backup Slides

# MaCh3 - The Oscillation Fitter

- Markov Chain Monte Carlo-based Bayesian fitter with integrated likelihood calculator
- **Software framework that enables systematic uncertainties to be incorporated in oscillation analysis**
  - In use on DUNE, T2K, HK, SK, T2K + SK, T2K + NOvA
- Use samples of likelihood to infer the oscillation parameters



L. Warsame

# Proposed Solution 1

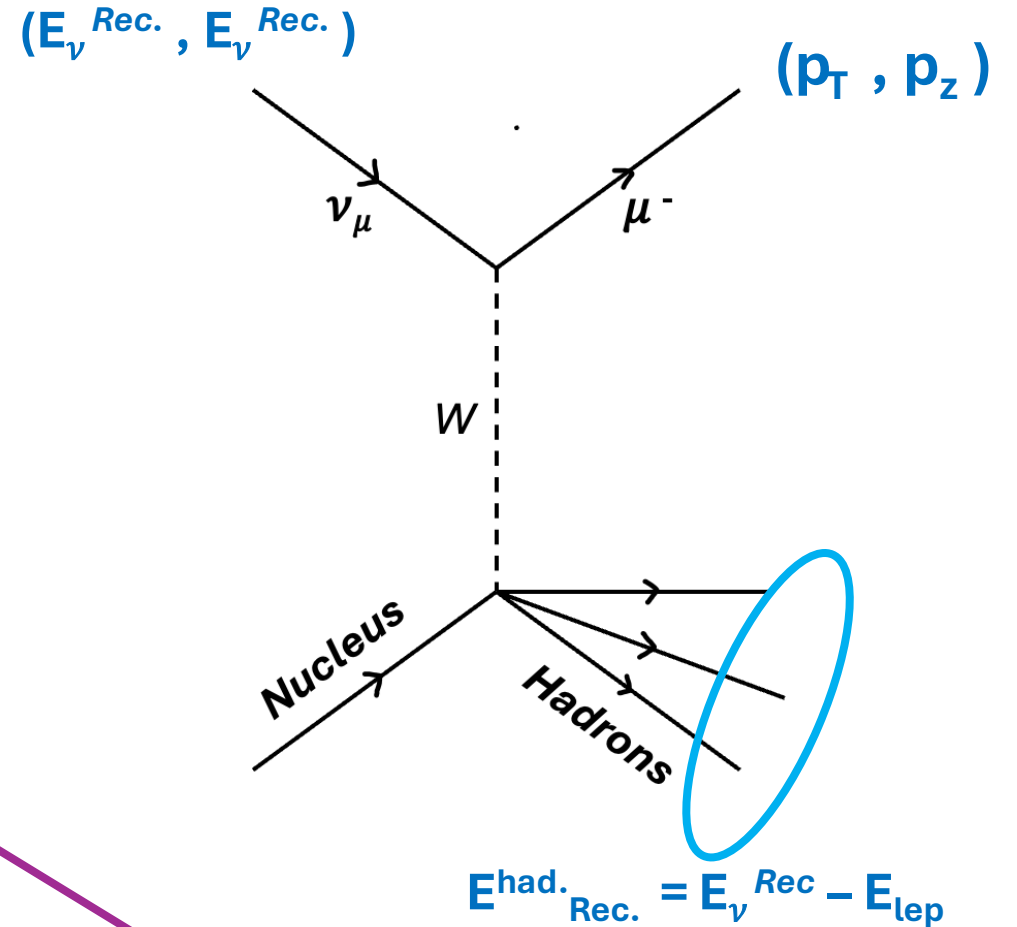
$$(E^{\text{Had.}}_{\text{Rec.}}, p_T, p_z)$$



**NIUWG**  
 Already studied by Minerva and MicroBooNe and NOvA exp.  
 $E^{\text{Had.}}_{\text{Rec.}}$  to indicate interaction type  
 $p_T$  correlated with  $q_3$   
 $p_z$  correlated with  $E_{\nu}^{\text{Rec}}$

**LBL**

$$E_{\nu}^{\text{Rec}} = \sqrt{(p_z)^2 + (p_T)^2} + M_{\mu} + E_{\text{Visible}}^{\text{Had.}}$$



**Detector Groups**  
 $E^{\text{Had.}}_{\text{Rec.}}$  measured calorimetrically

# Proposed Solution 2

$$(E_\nu^{Rec.}, p_T, p_z)$$

$$(E_\nu^{Rec}, E_\nu^{Rec})$$

$$\vec{P}_\nu$$

$$\nu_\mu$$

$$\vec{P}_\mu$$

$$(p_T, p_z)$$

$$\vec{P}_h$$

## NIUWG

Already studied by Minerva and MicroBooNe exp.  
 $E_{Visible}^{Had}$  to indicate interaction type  
 $p_T$  correlated with  $q_3$   
 $p_z$  correlated with  $E_\nu^{Rec}$

## LBL

Best for measuring oscillation parameters

## Detector Groups

$p_T$  and  $p_z$  can be measured directly

# Systematics

Neutrino Interaction Uncertainties Working Group

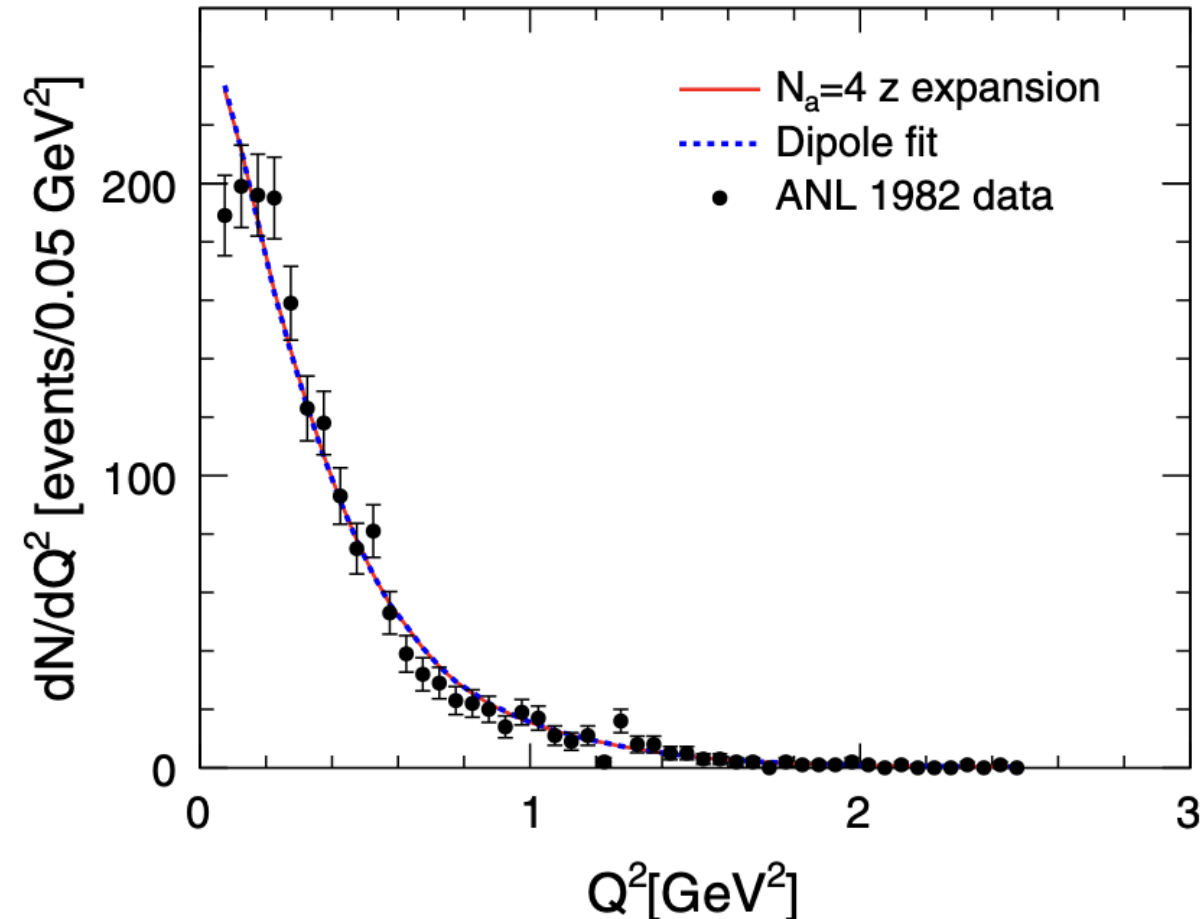
# Modelling Neutrino-nucleus Interactions

- Neutrino-nucleus interactions are a big source of systematic uncertainty for current oscillation experiments
- High statistics at the ND means it will be possible to model fine details of neutrino-nucleus interactions
- No model is currently capable of fully describing the neutrino cross-section over DUNE's energy range
- Flexibility needs to be built into the uncertainty model to cover the variations suggested by neutrino cross-section measurements

# Example: Axial Form Factor, $F_A$

PhysRevD.93.113015

- An important systematic for DUNE to model is  $F_A$  (*provides ~ 10% syst.*)
- $F_A$  characterises the weak charge distribution and is a key parameter when modelling CCQE interactions
- In the past it was modelled too simply with just one parameter
- Now that we have new measurements from MINERvA + Lattice QCD predictions
- We now have a better parameterisation for  $F_A$



Bubble Chamber Measurement of  $F_A$ , 1982

# Multiparameter z expansion - Disadvantage

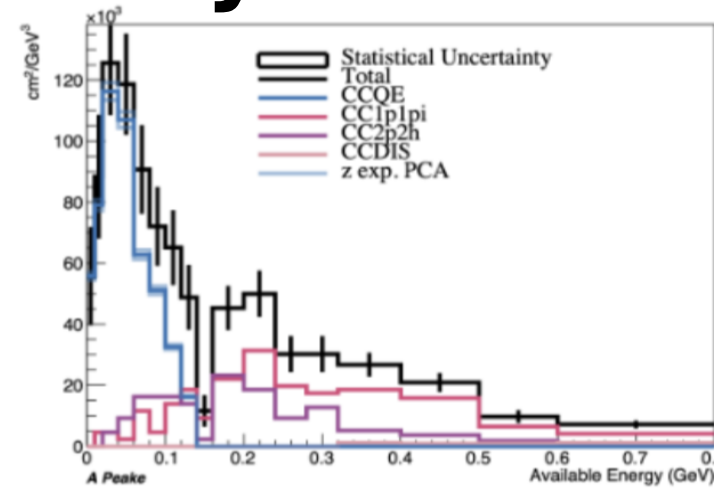
- Practically, oscillation analyses sample from likelihoods with 100s of parameters
- To make this procedure computationally tractable, it often helps to treat nuisance parameters as **independent**
- The  $a_k$  parameters are not factorizable in z expansion : 
$$F_A(q^2) = \sum_{k=0}^{k_{\max}} a_k z(q^2)^k$$
- Treating  $a_k$  as factorisable leads to divergences that grow with  $Q^2$

## Improvement:

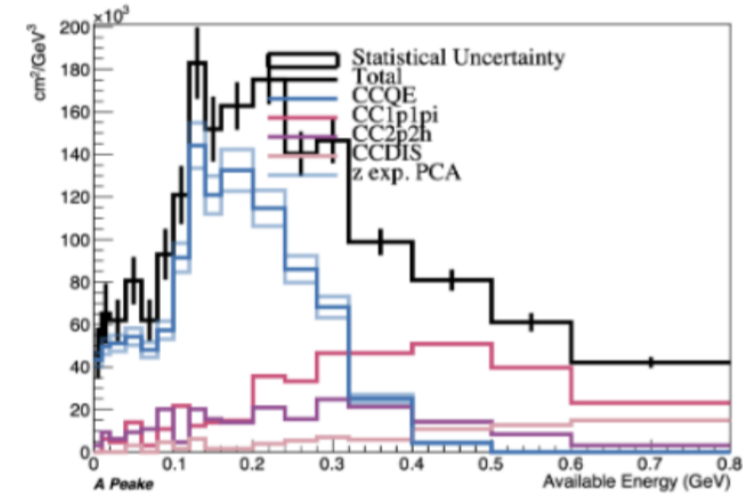
- Use a **Principal Component Analysis** to transform an uncorrelated basis into a new basis of  $a'_k$
- Diagonalise the parameter space, into orthogonal eigenvectors
- New parameters that can be treated independently, but preserve the correlations shown in the original basis

# Assessing the $F_A$ Uncertainty

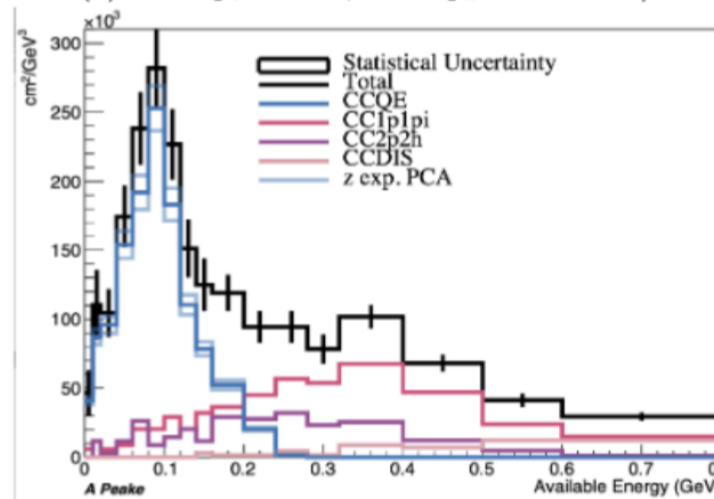
- z expansion (PCA) is now a reweighting tool in Nusystematics
- z expansion error band on CCQE events
- See the impact of uncertainty in different kinematic regions



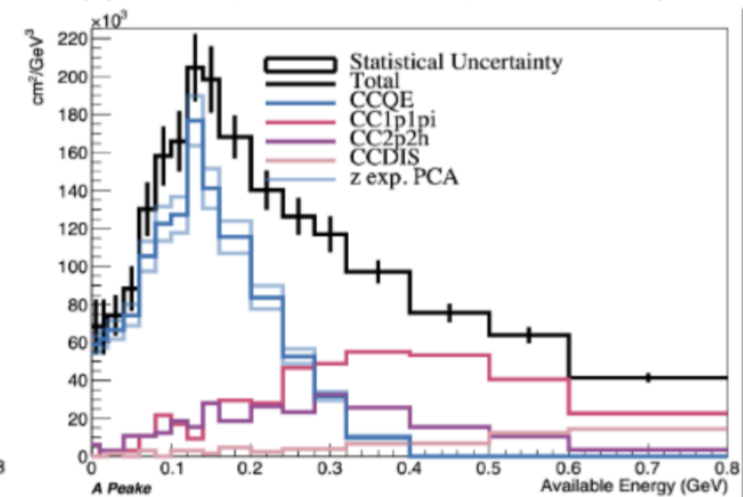
(a)  $0.1 < p_t < 0.15, 2.3 < p_z < 2.7$  GeV/c



(b)  $0.55 < p_t < 0.62, 2.3 < p_z < 2.7$  GeV/c



(c)  $0.36 < p_t < 0.40, 2.3 < p_z < 2.7$  GeV/c



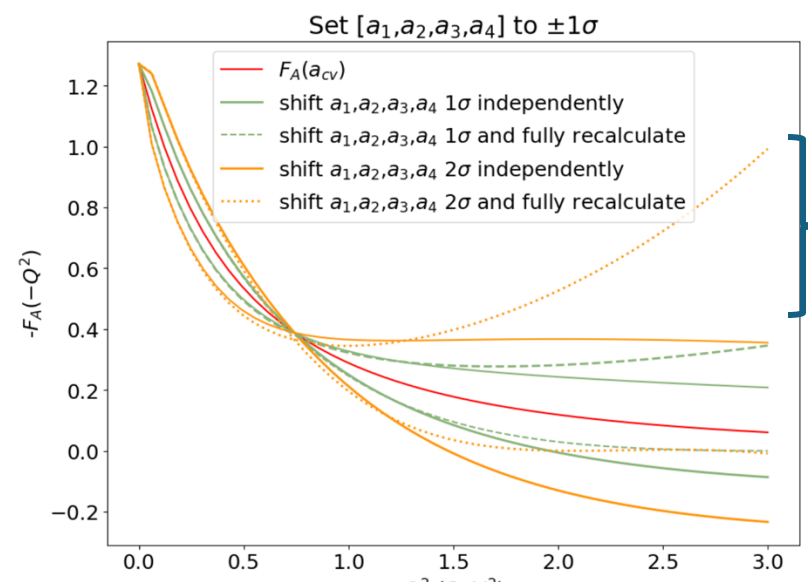
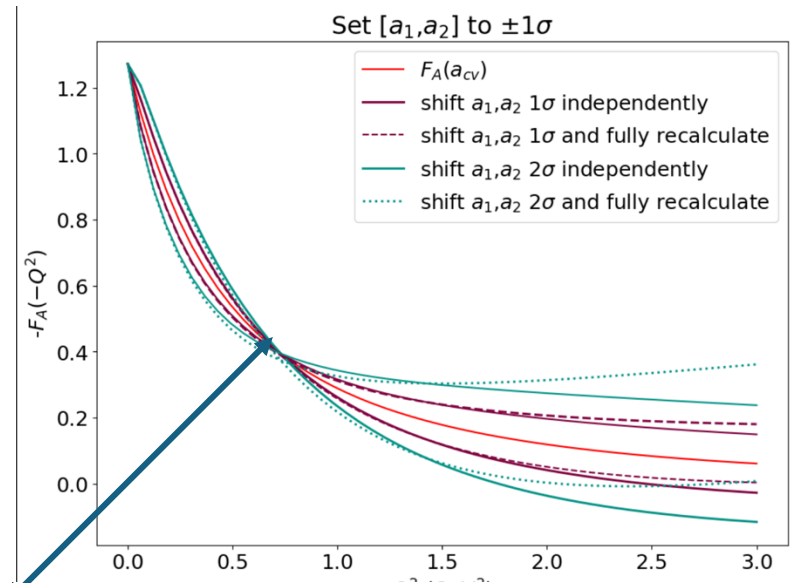
(d)  $0.48 < p_t < 0.55, 2.3 < p_z < 2.7$  GeV/c

Link to Latest  
Version on GitHub:



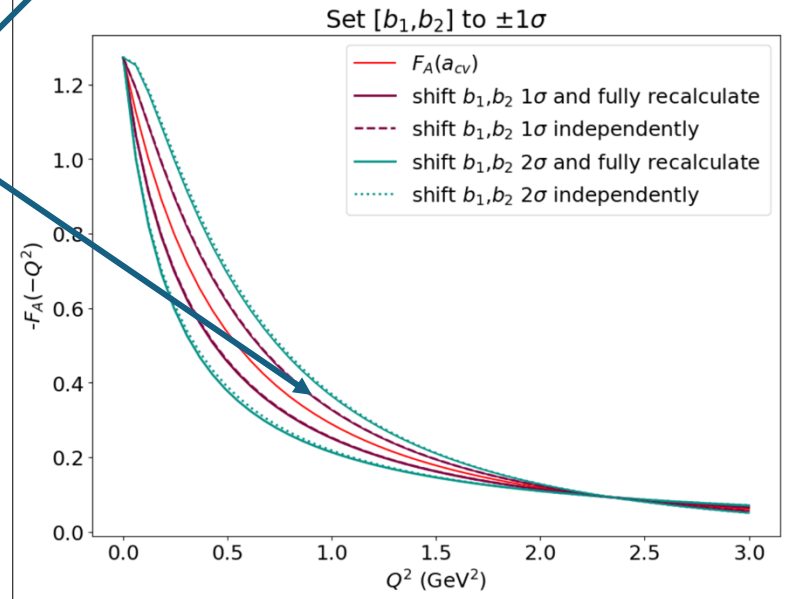
[https://github.com/jedori0228/nusystematics/blob/f44e8f1bb7992e6e1f140898633d6577a6a95d82/src/nusystematics/systproviders/ZExpPCAWeigher\\_tool.cc](https://github.com/jedori0228/nusystematics/blob/f44e8f1bb7992e6e1f140898633d6577a6a95d82/src/nusystematics/systproviders/ZExpPCAWeigher_tool.cc)

Original Basis

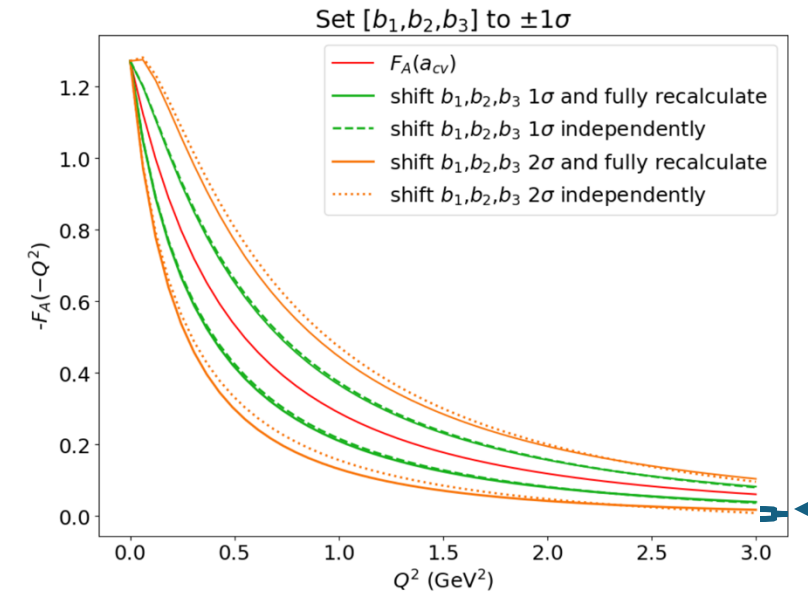


Weight  
x 2.5 larger  
@  $Q^2 \sim 3 \text{ GeV}$

More stable  
@ mid  $Q^2$



Uncorrelated  
Basis



Weight < 10%

# Conclusions about $F_A$ systematic

- Properly modelling neutrino-nucleus cross-section uncertainties is vital for DUNE
- It is important to correctly model the uncertainty of  $F_A$  for CCQE interactions
- The size of the  $F_A$  uncertainty band varies over momentum space
- In the future, we can redo using the fits to MINERvA  $F_A$ , to Lattice QCD  $F_A$  or any other combined fits in use
- In future also fit to vector form factor  $F_V$ , which also use  $z$  expansion
- We will treat every DUNE systematic in this way

# A Goal for DUNE ND

- Example from MINERvA, but it is now possible to bin DUNE ND data in this way
- Identify regions where different systematics are important
- DUNE can benefit from the experience of MINERvA, MicroBooNE and NOvA to build similar distributions
- We just need to optimize the binning for the DUNE ND

