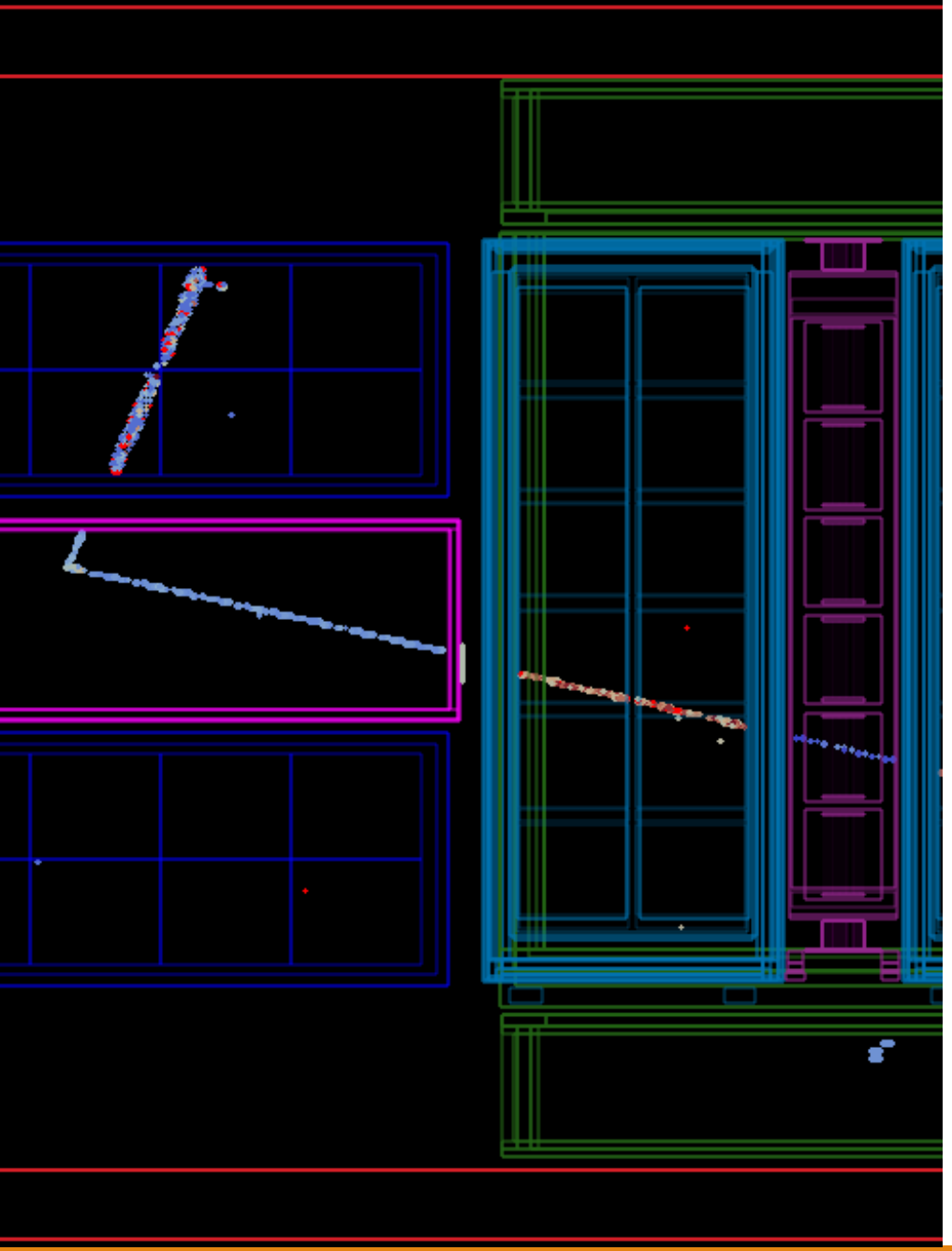


Latest Developments in Near Detector Analyses at T2K

Dominic Langridge

IOP APP/HEPP Edinburgh

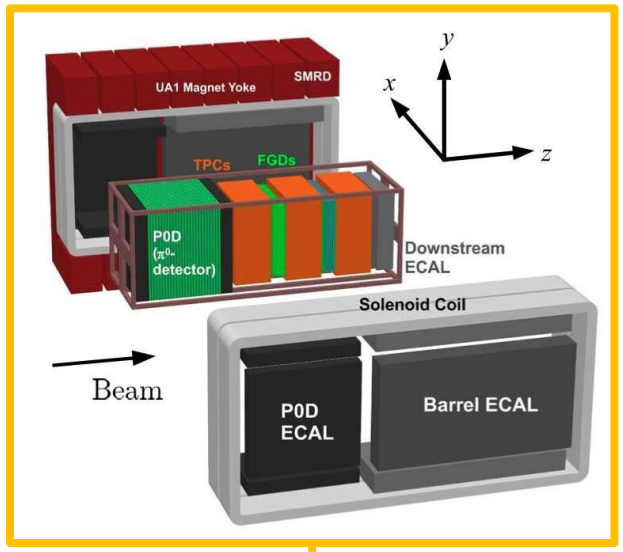
10/04/2026

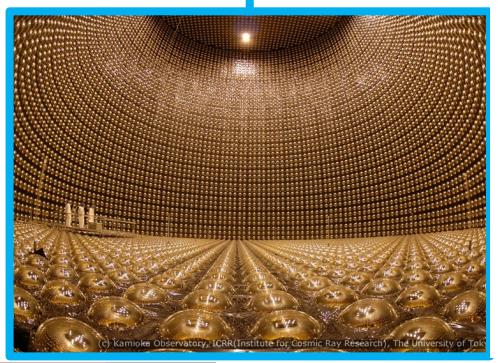
Tokai-to-Kamioka

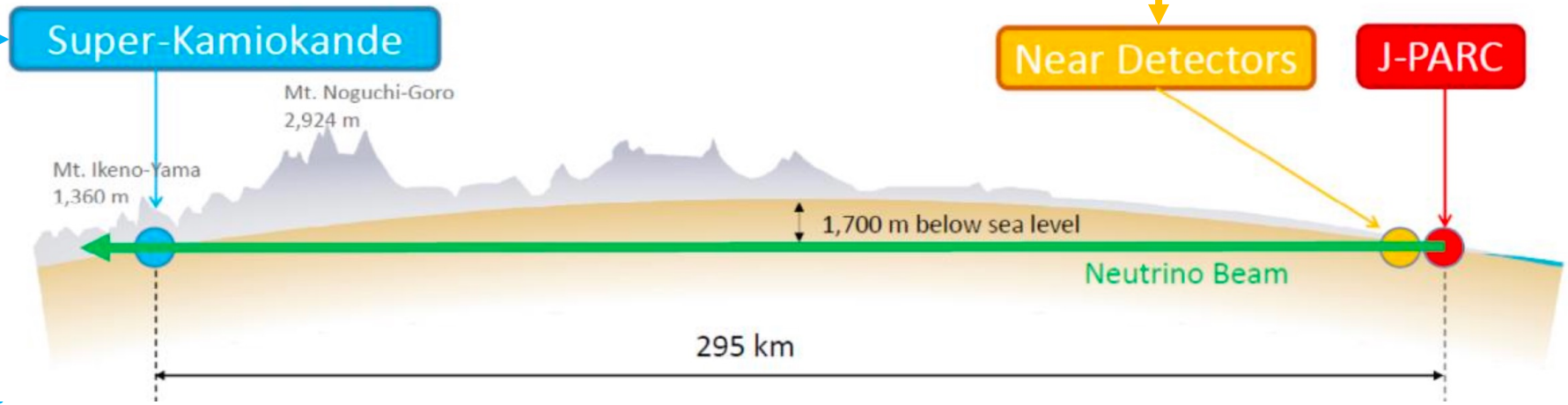
- Long-baseline neutrino oscillation experiment
- Uses a neutrino beam from J-PARC in Tokai, Japan
- Two beam modes: ν_μ and $\bar{\nu}_\mu$

- Two main detectors: **Super-Kamiokande** & **ND280**
- Measures oscillation at **SK** using constraint from **ND280**

ND280
(Near Detector @ 280m)







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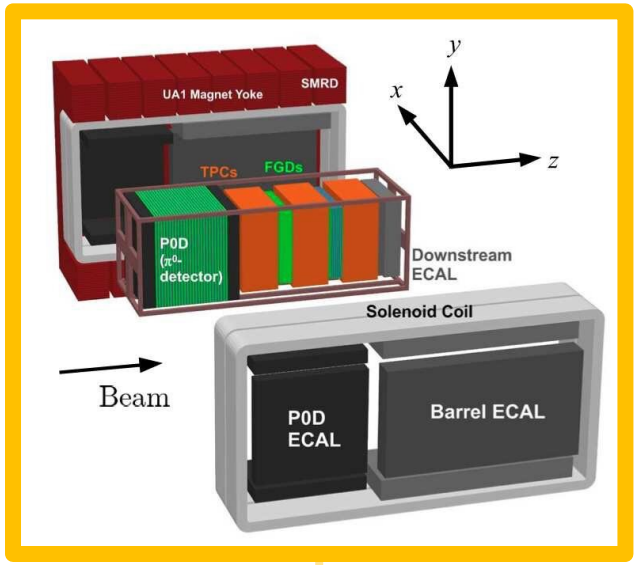
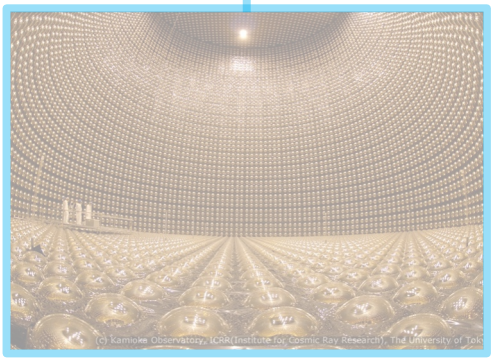
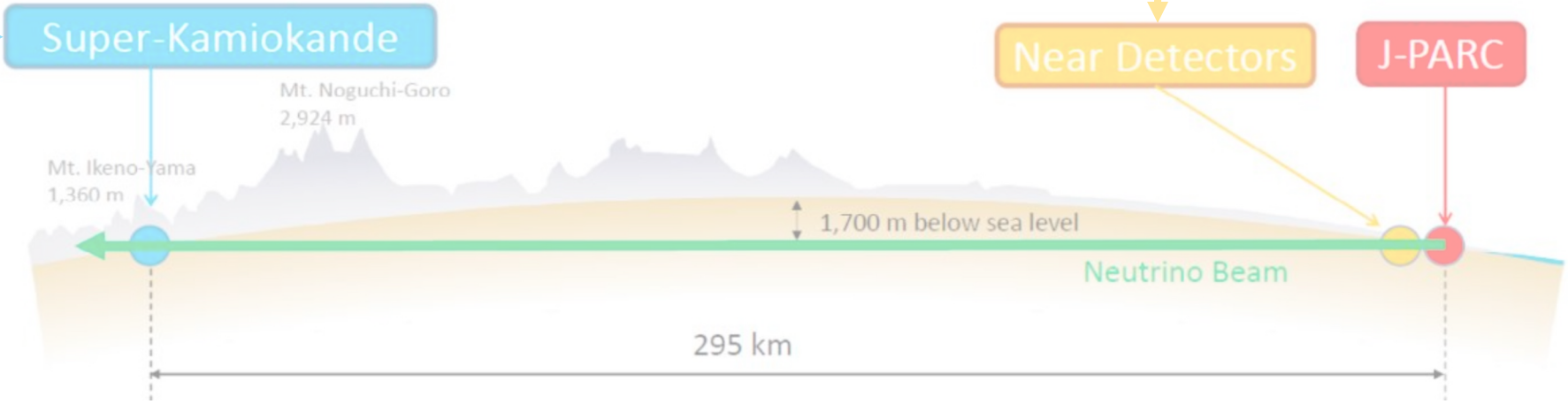




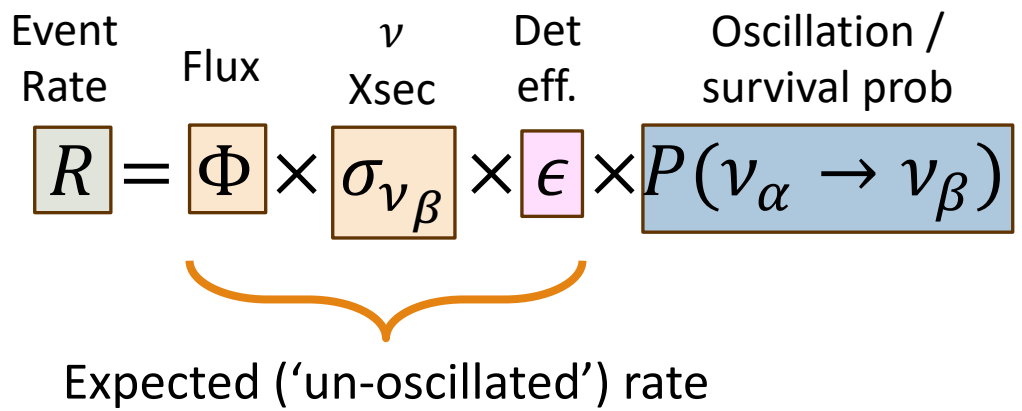


Why Do We Use Near Detectors?

- Oscillation measurements rely on the **Far Detector** (FD) – in this case **SK**

- **SK** alone has significant systematic uncertainties in interaction and flux models

- This is where the **Near Detector** comes in:
  - Much higher statistics
  - ***No oscillation effects***



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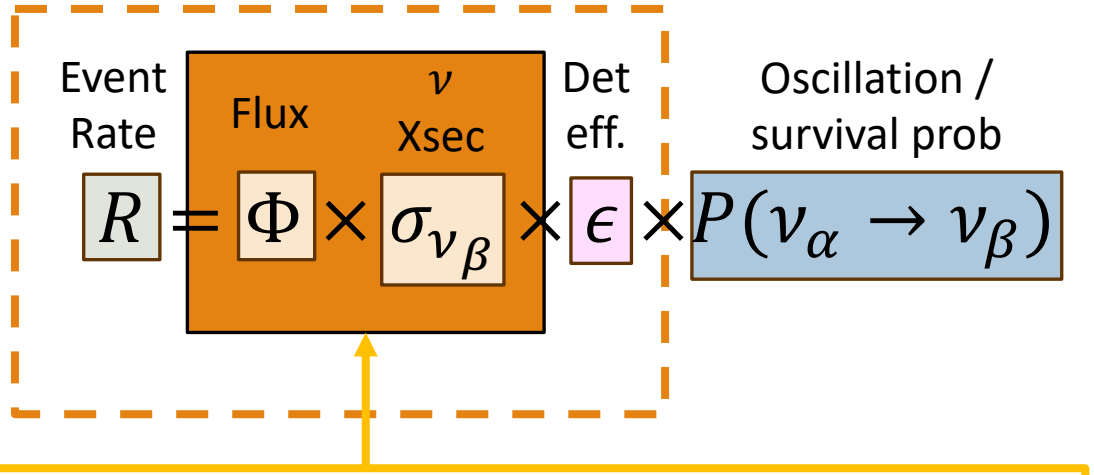


ND Only Analysis lets us **constrain flux & cross-section** parameters *before* the **FD oscillation analysis**

ND+FD Fit then uses this for reduced uncertainty from these factors

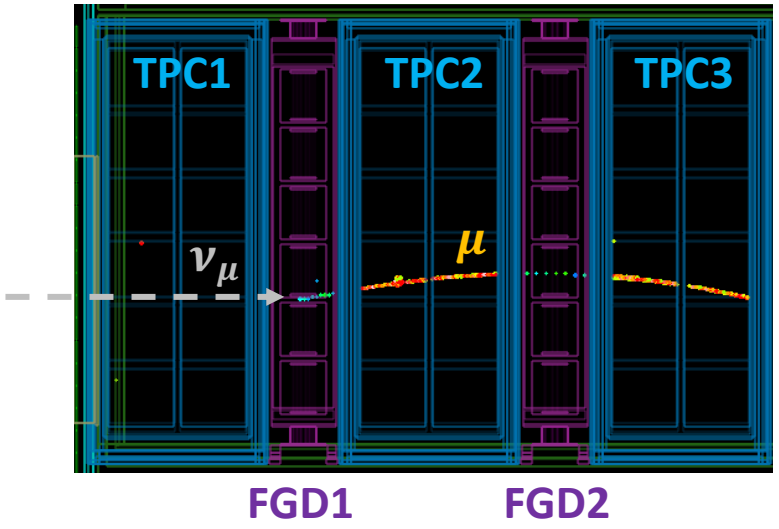
ND280: The T2K Near Detector

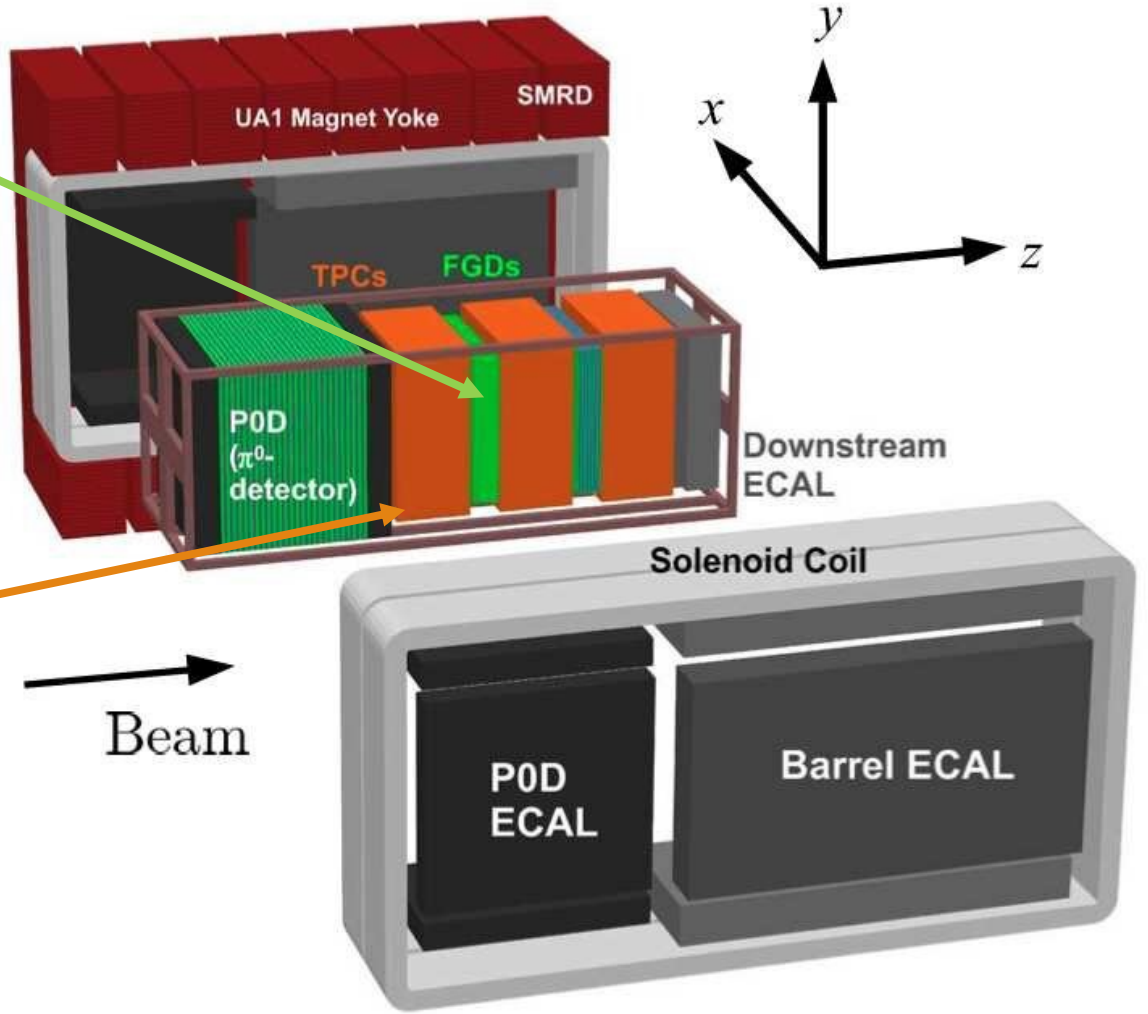
Fine Grained Detectors (FGDs)

- FGD1 (upstream), 5760 scintillating strips in 15 modules
- FGD2 (downstream), 7 modules alternated with 6 2.5cm water layers
- **Where the interactions used in this analysis happen**

Time Projection Chambers (TPCs)

- TPC1 (upstream), TPC2 (after FGD1), TPC3 (downstream)
- Gaseous argon
- **Tracks and identifies particles produced in the FGDs**





ND280: The T2K Near Detector

Other Subdetectors:

Side Muon Range Detector (SMRD)

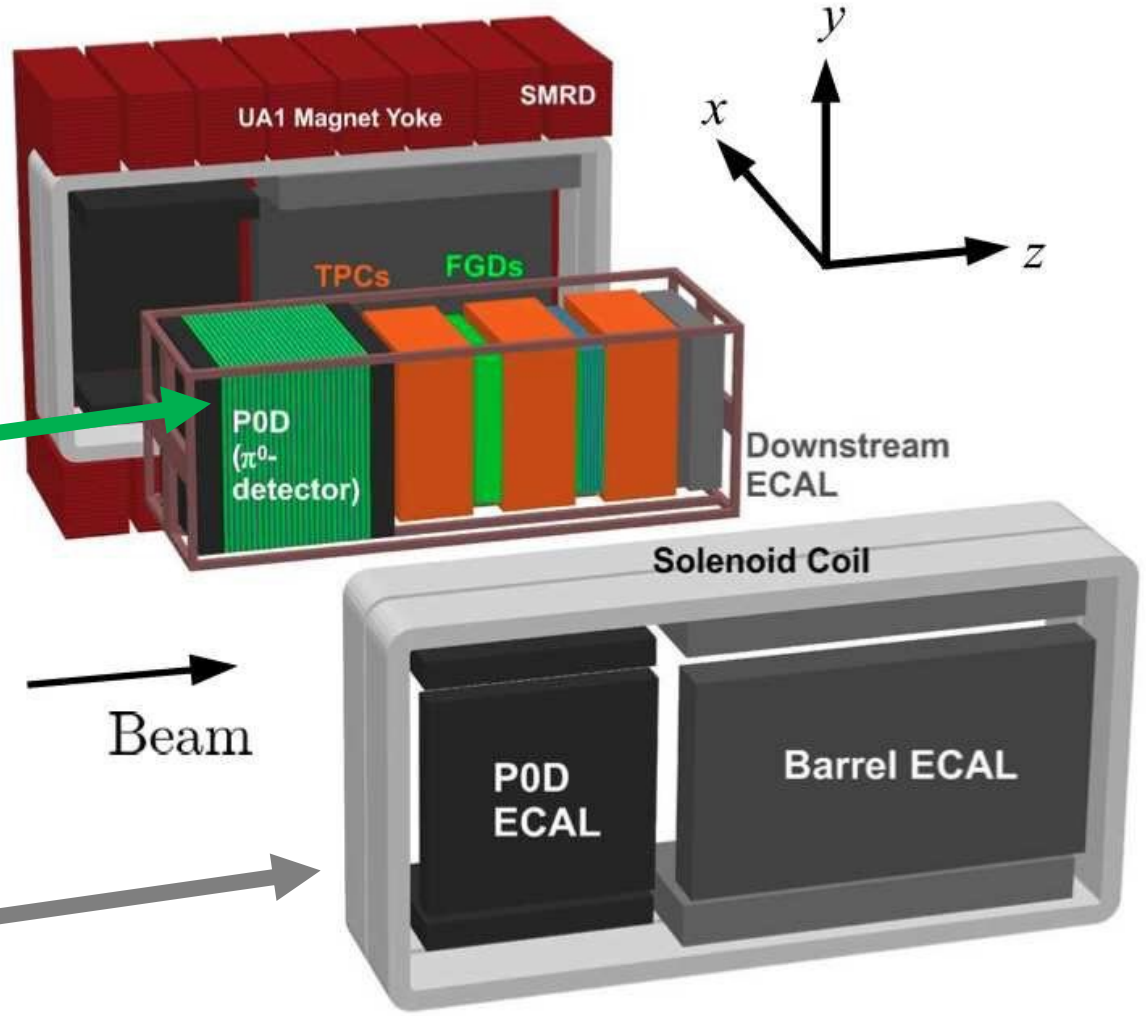
- Vetoes cosmic ray muons

π^0 Detector (P0D)

- Studies neutral-current π^0 background
- Removed in 2022

Electromagnetic Calorimeters (ECals)

- Identifies particles leaving the detector



The ND Fit

ND constraint comes from a parameterised fit, with three parameter groups:

Neutrino Beam Flux
Correlated between ND280 & SK

Interaction Cross Section
Direct constraint for SK

ND280 Detector Systematics

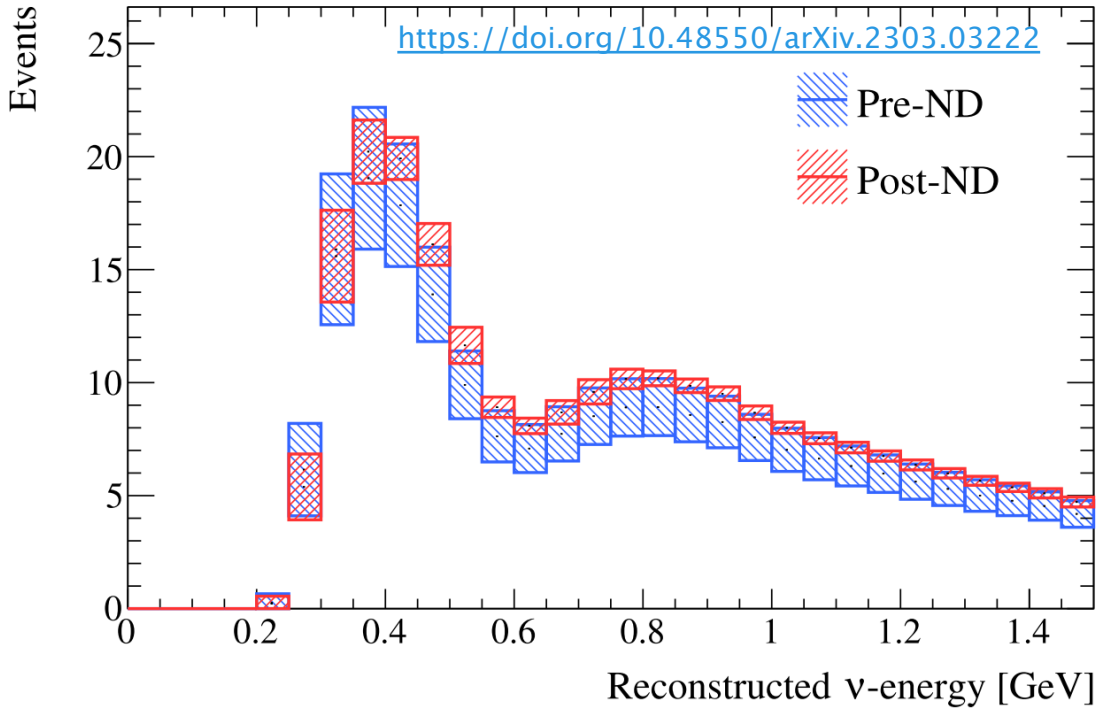
Three fit types:

Asimov Fit (MC to MC)
- Tests central prediction response

Data Fit (MC to Data)
- The actual model constraint

Alternate Model Study (MC to alternate MC)
- Checks for model-dependent biases

MC = Monte Carlo simulated data



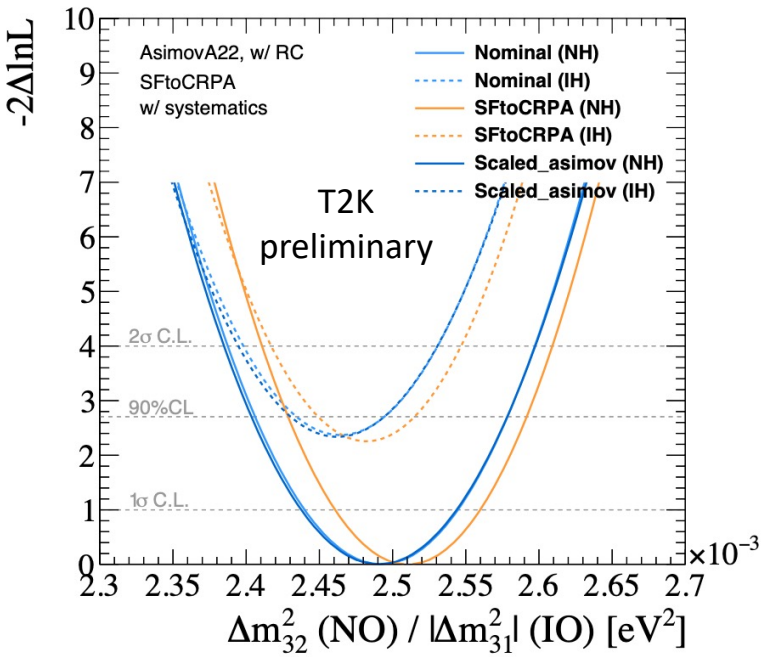
Example SK ν-mode 1Rμ prediction before and after an ND data fit

Latest Developments

Two primary motivations for latest ND fit developments

Nuclear Model Bias

- Performed an alternate model study against a **Continuum Random Phase Approximation (CRPA)** nuclear model
- Comparison to **Asimov fit found significant bias in Δm^2_{32}**
- Represents single largest systematic on this measurement



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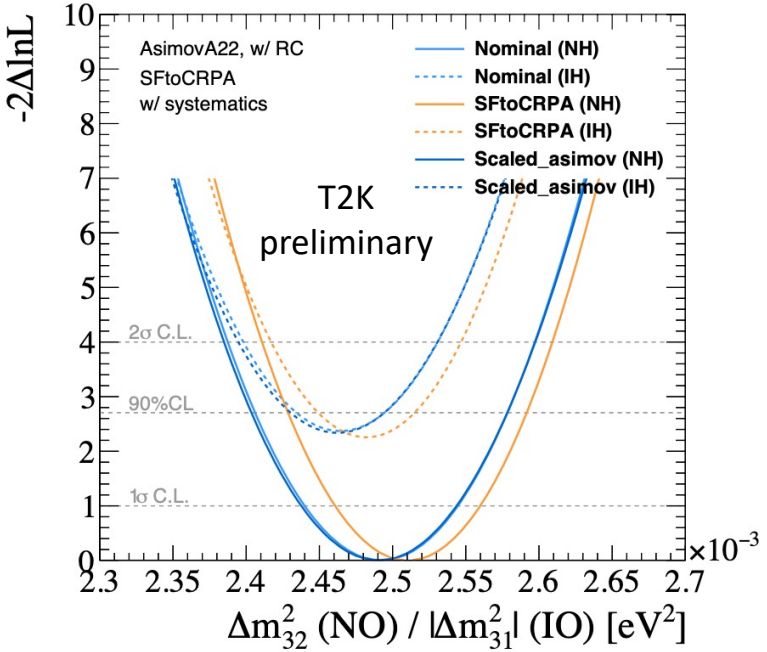
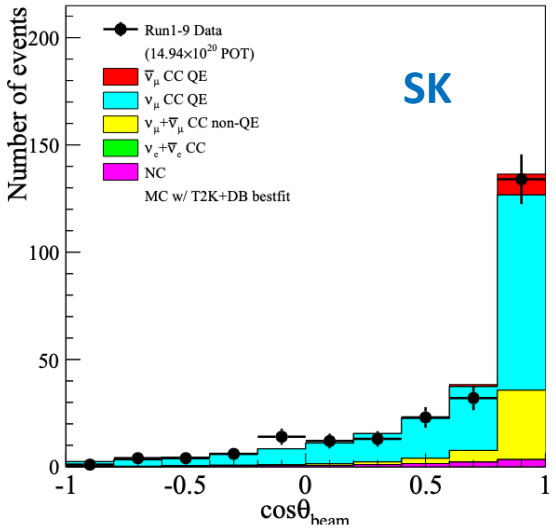
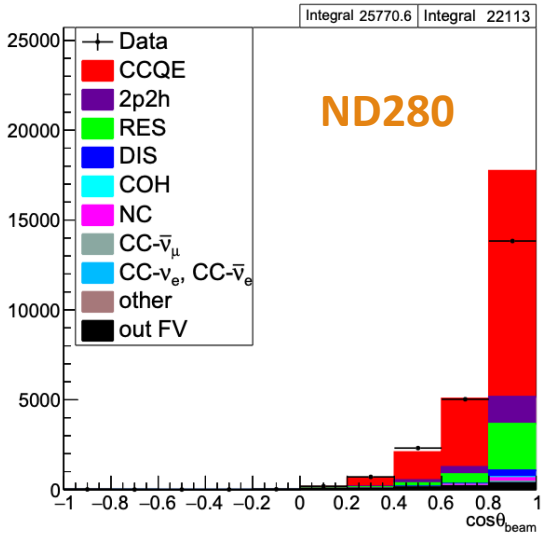






ND280 Angular Acceptance

- **SK**'s cylindrical geometry means no angular preference, unlike **ND280**'s forwards preference
- Results in **ND280** **giving limited constraint for low-energy neutrino interactions**

Nuclear Corrections

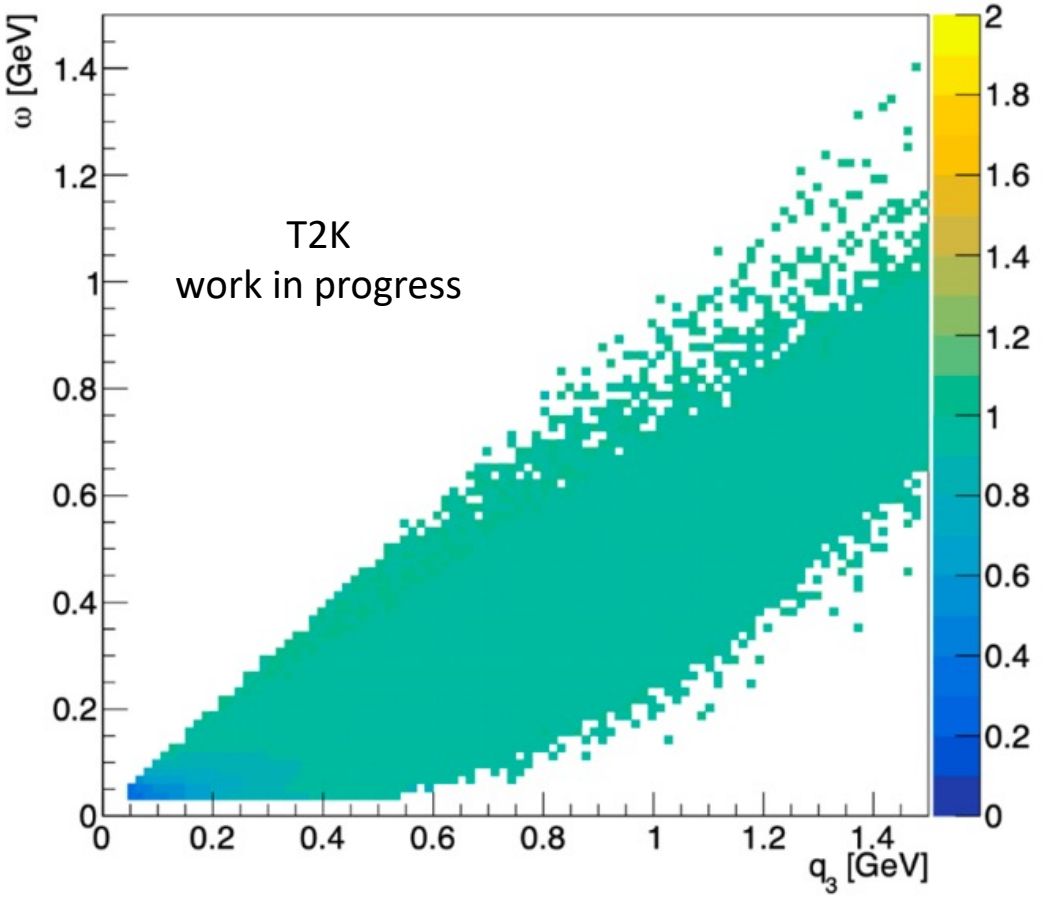
Current model struggles to account for nuclear effects on cross sections

- Significantly impacts interactions with **low energy transfer** (ω)

Continuum Random Phase Approximation (CRPA)[1]:

- Complex nuclear effects as **interactions happen inside a nucleus**, not with free particles
- Included via **two-body corrections to single particle wave functions**

Ratio of model with vs. without CRPA



[1] https://doi.org/10.1103/PhysRevC.65.025501

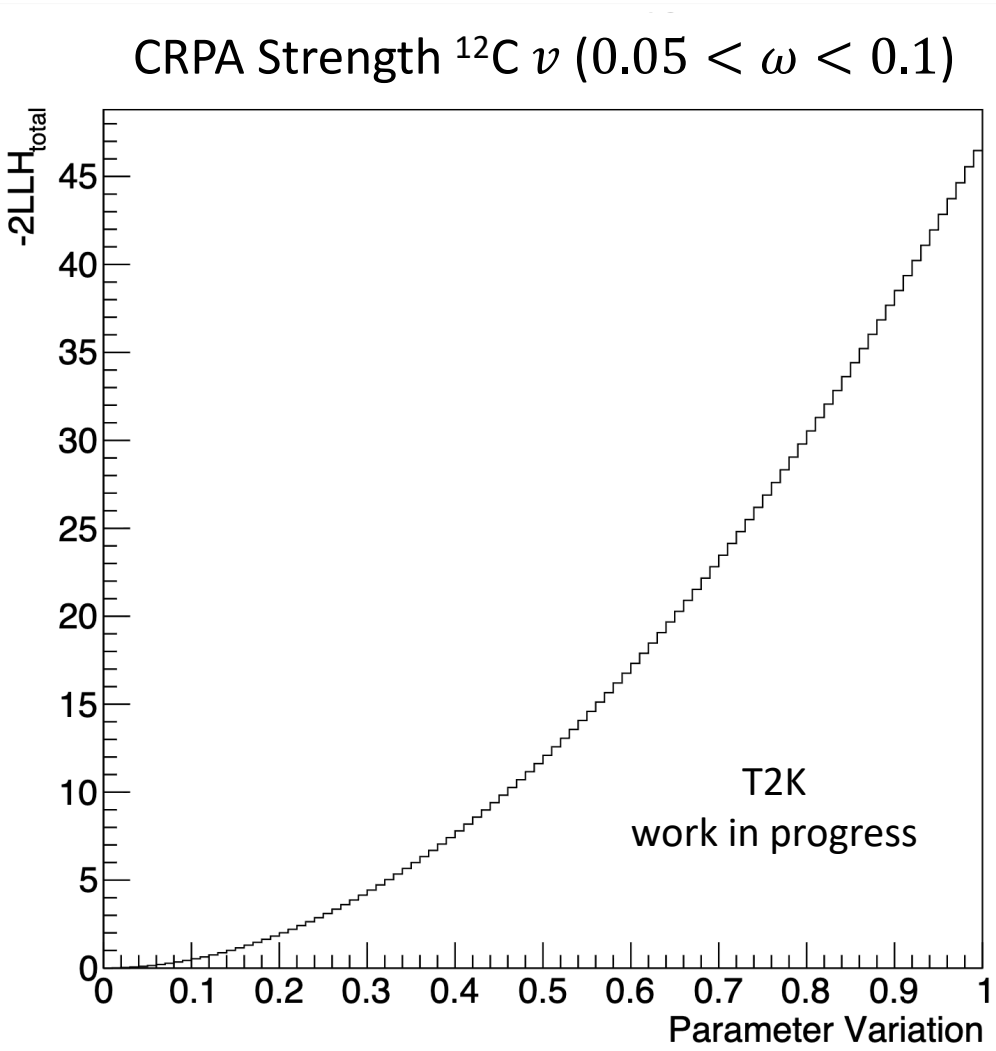
CRPA Reweight Systematics

We introduced new ***CRPA Strength*** **Systematics** to the parameterisation:

- "Activate" **nuclear corrections** as they increase

12 new CRPA systematics after splitting by:
- Interaction nucleus (C or O)
- Beam mode (ν_μ or $\bar{\nu}_\mu$)
- ω bin ([0.05, 0.1], [0.1, 0.2], [0.2, 10] GeV)

MC to MC Log-Likelihood

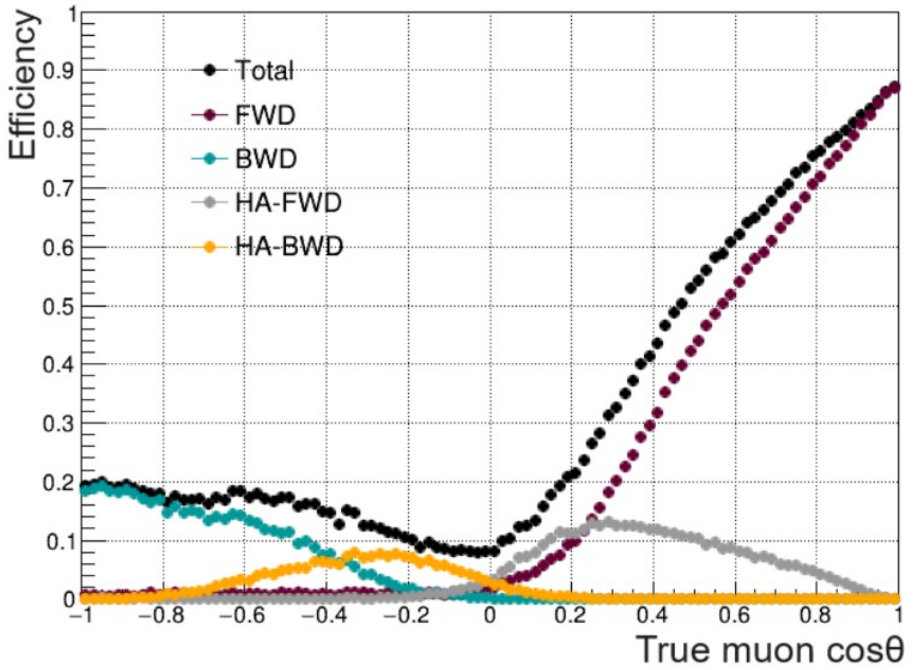


ND280 Angular Acceptance

To improve angular acceptance, we have updated our **event selection**:

- Use time-of-flight information to separate **Forwards (FWD)** and **Backwards (BWD) tracks**

- Use SMRD / ECal track reconstruction to include **new High-Angle (HA) tracks**



Also provides a 12.9% data stats increase

FWD

BWD

HA-FWD

HA-BBD

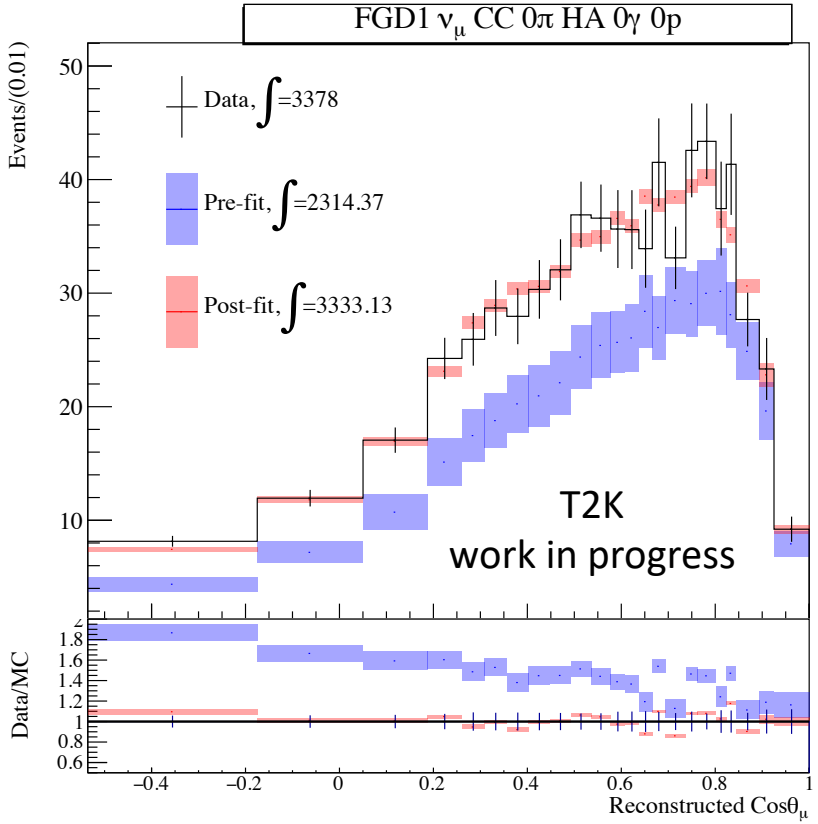
Latest Fit Results

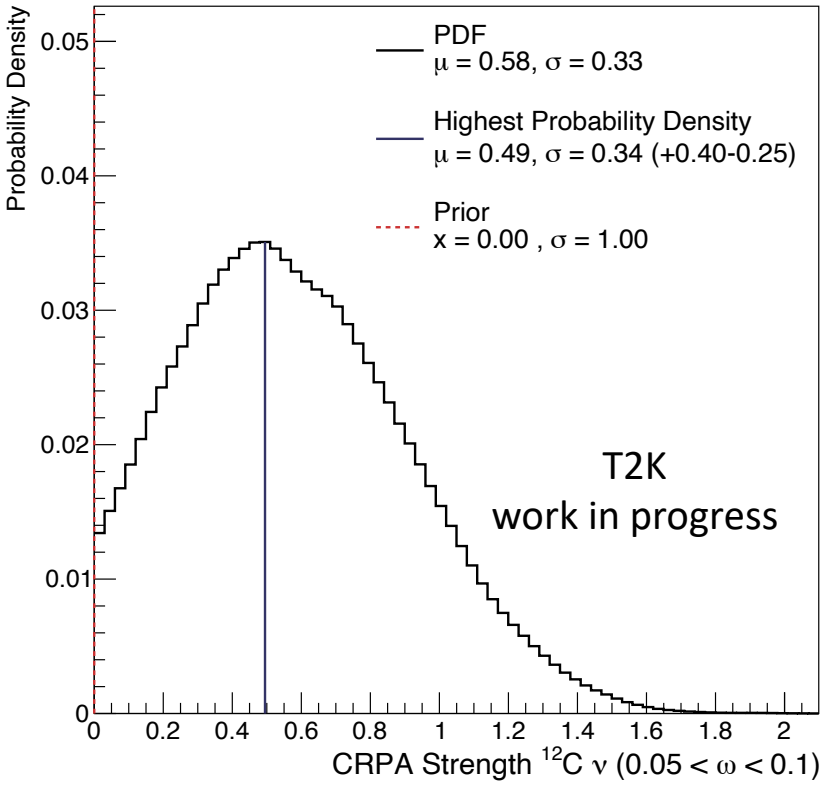
Both **CRPA systematics** and **new selection** have been included in the latest analysis

Good constraint in **High-Angle** and **Backwards samples**

CRPA systematics perform as expected

Post-fit model shows **some nuclear correction applied**





Full data results will be shown at Neutrino 2026 in June!

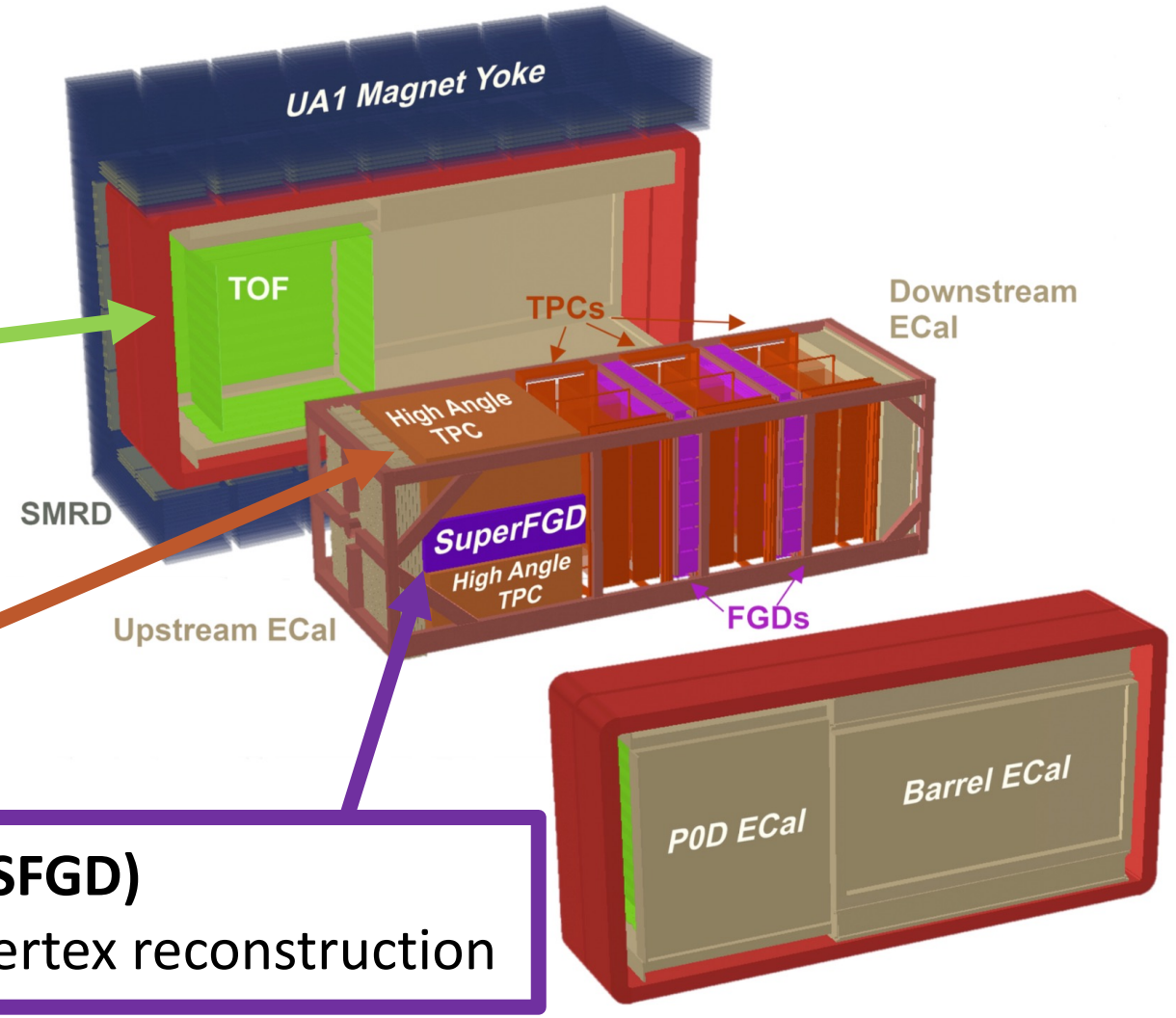
ND280 Upgrade

ND280 has been upgraded with new subdetectors (as of 2024):

Time Of Flight (ToF) Detectors
- Improved track direction reconstruction

High-Angle TPCs (HATs)
- Dedicated high-angle track reconstruction

Super Fine Grained Detector (SFGD)
- Improved resolution & 3D vertex reconstruction

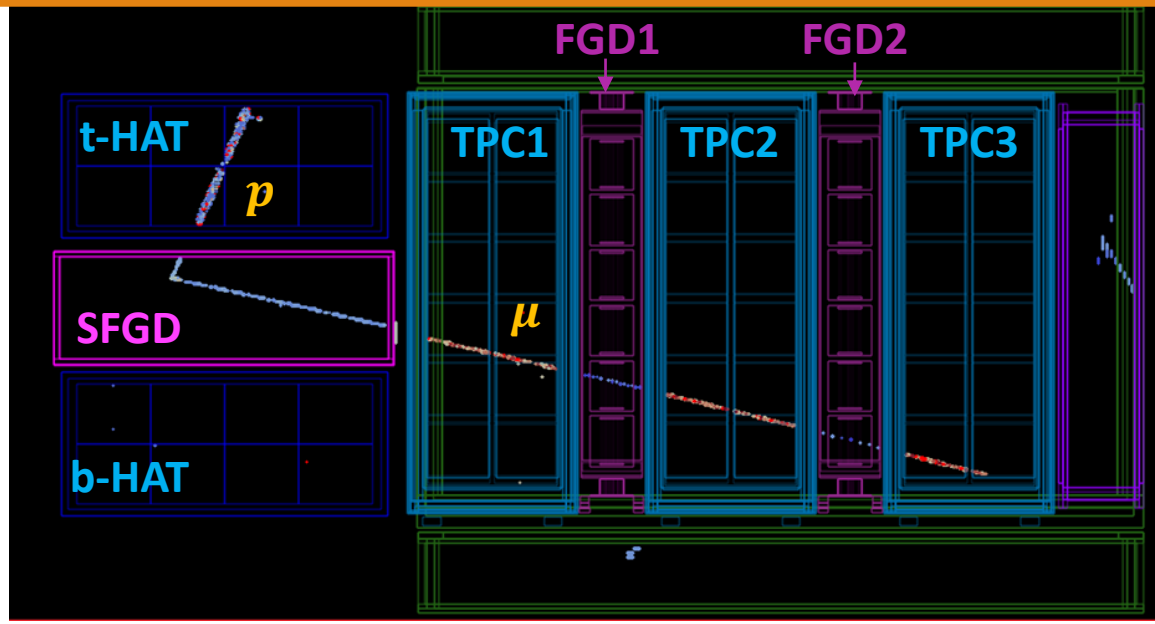


ND Fit Upgrade

ND280 upgrade can build on the latest ND fit developments:

- Dedicated high-angle & ToF detectors for greater angular acceptance

- Increases ability to study low-energy neutrino-nucleus interactions



First upgrade selections & detector systematics are currently being added into the analysis

- This will form the main body of my PhD Thesis

Summary

Latest Developments:

- New cross-section systematics introduced
  - Applies **CRPA corrections** to nuclear model
  - Corrects for bias seen in previous alternate model study
- New **ND280 selection** brings angular acceptance closer to that of **SK**

Fit Results:

- Good constraint in **new High-Angle & Backwards samples**
- **CRPA systematics** perform well
- **Full data results will be shown at Neutrino 2026**

ND280 Upgrade

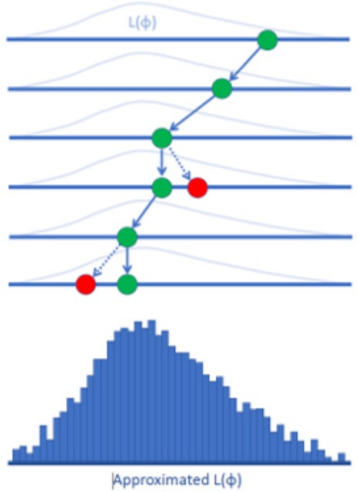
- Dedicated improvements to event reconstruction and acceptance
- **First selections & systematics are being added into the ND fit**

Backup

ND Fitters

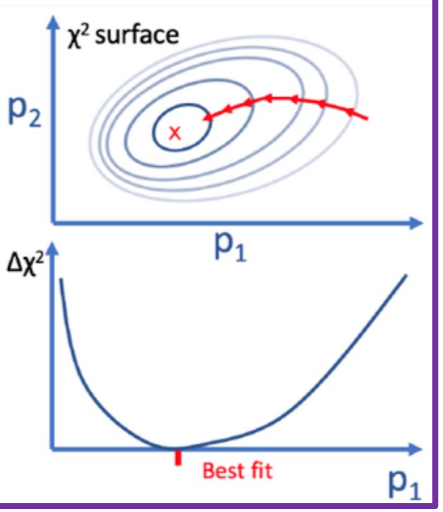
ND fit used to **constrain cross-section and flux parameters** for FD oscillation analysis

INPUTS:
Data, MC, samples, systematics



Bayesian approach
- *MaCh3*
- MCMC, using MR²T²* algorithm
- ND, FD, and ND+FD fits

Frequentist approach
- *GUNDAM, Ptheta*
- Gradient descent fit using Minuit2
- ND only fit, FD only fit with ND constraint



Post-Fit Parameter Estimations
Event Rate
ND Fit Cross-Validation

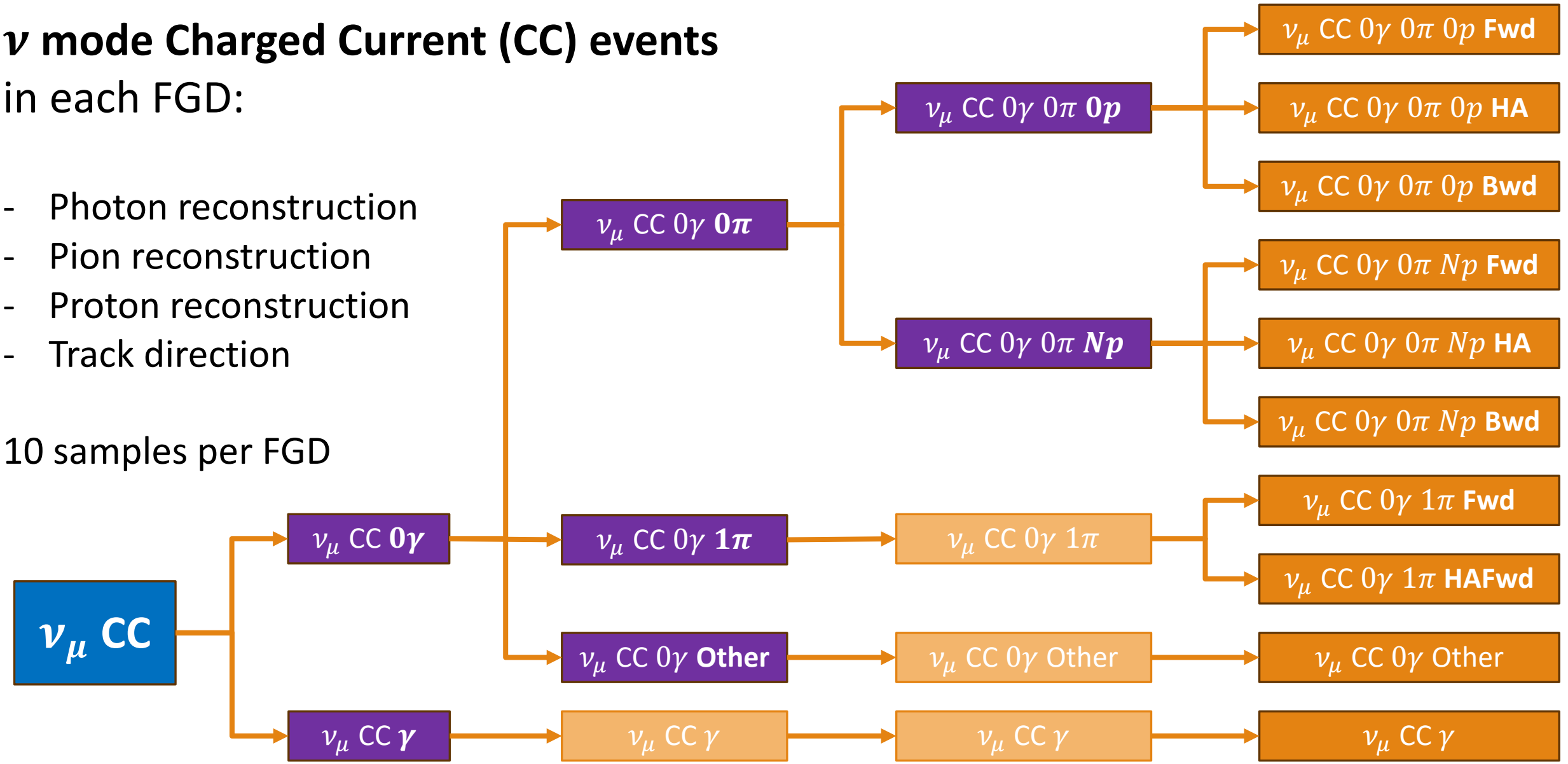
*Metropolis-Rosenbluth-Rosenbluth-Teller-Teller

ND280 ν Mode Event Selection

ν mode Charged Current (CC) events in each FGD:

- Photon reconstruction
- Pion reconstruction
- Proton reconstruction
- Track direction

10 samples per FGD

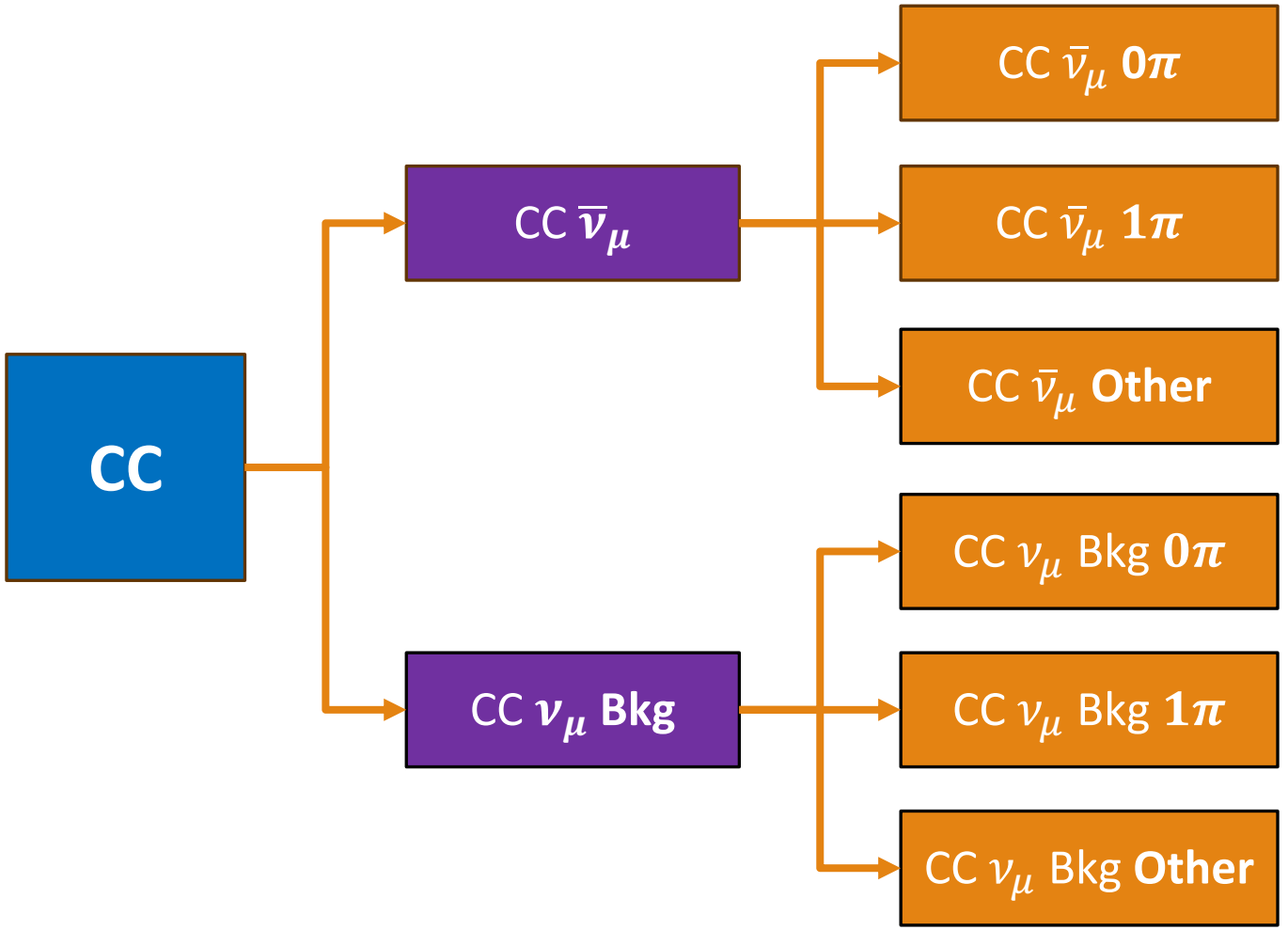


ND280 $\bar{\nu}$ Mode Event Selection

$\bar{\nu}$ mode Charged Current (CC) events
in each FGD:

- $\bar{\nu}_\mu$ vs. ν_μ background
- Pion reconstruction

6 samples per FGD



Δm^2_{32} Bias

Bias & 2σ interval definition, Alternate Model Study (AMS) vs. Asimov Fit

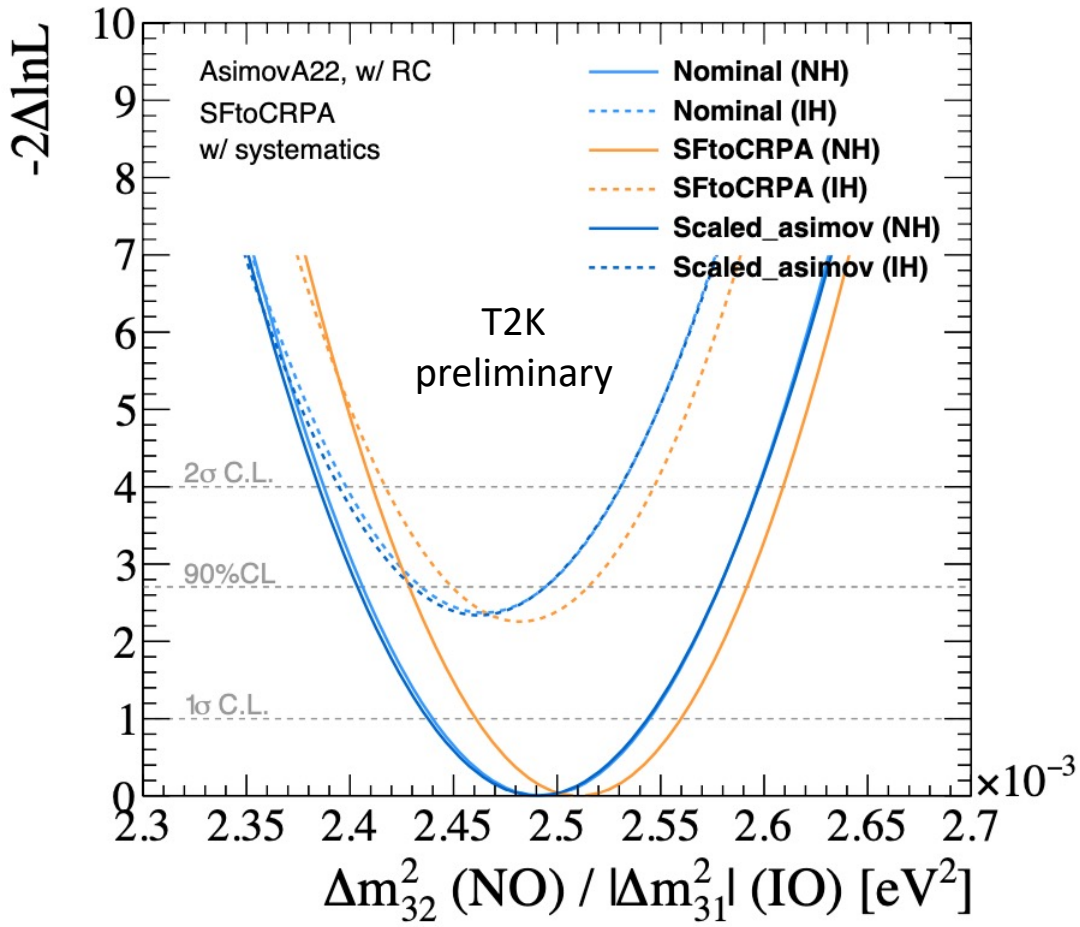
$$B_x^{syst} = \frac{\Delta_x^{2\sigma}}{1\sigma_{syst}^{Asimov}}, \qquad R_x^{2\sigma} = \frac{2\sigma_{tot.}^{AMS}}{2\sigma_{tot.}^{Asimov}}$$

Action required if:

$$\left|B_x^{syst}\right| > 0.5 \text{ and } \left|R_x^{2\sigma} - 1\right| > 0.1$$

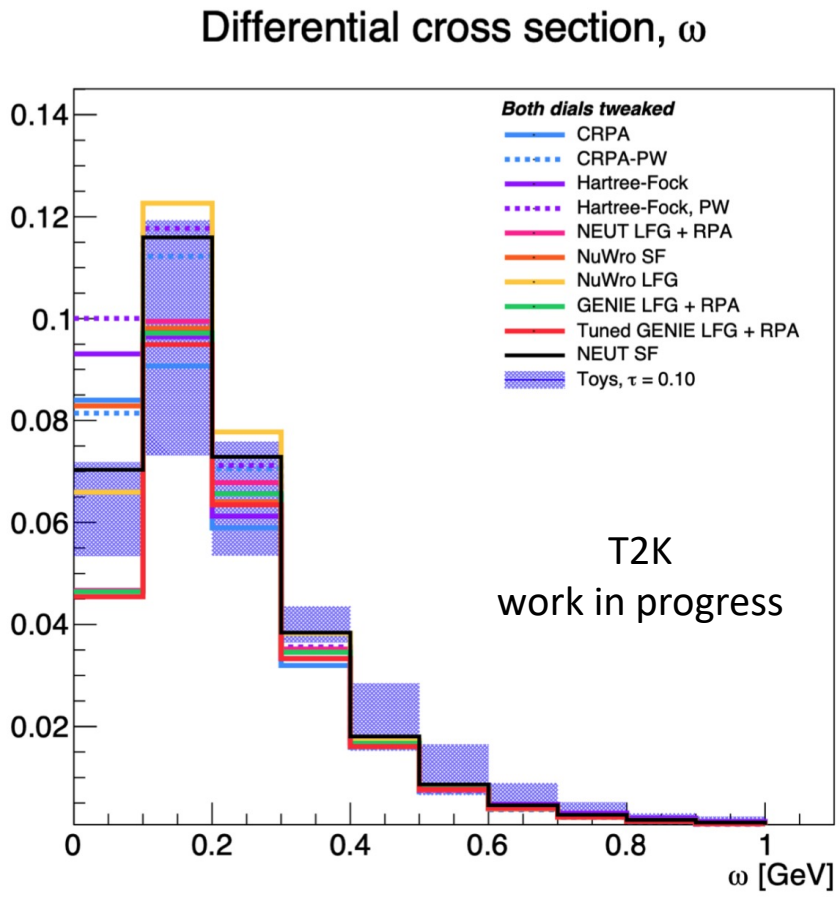
Alternate Model Study Δm^2_{32} bias:

$$B_x^{syst} \sim 0.85, \qquad R_x^{2\sigma} \sim 0.95$$

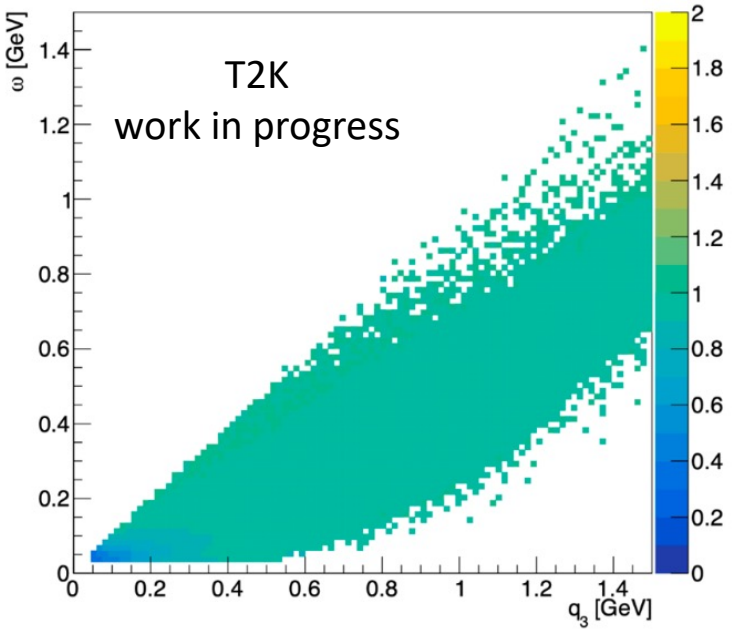


RPA Strength Systematics

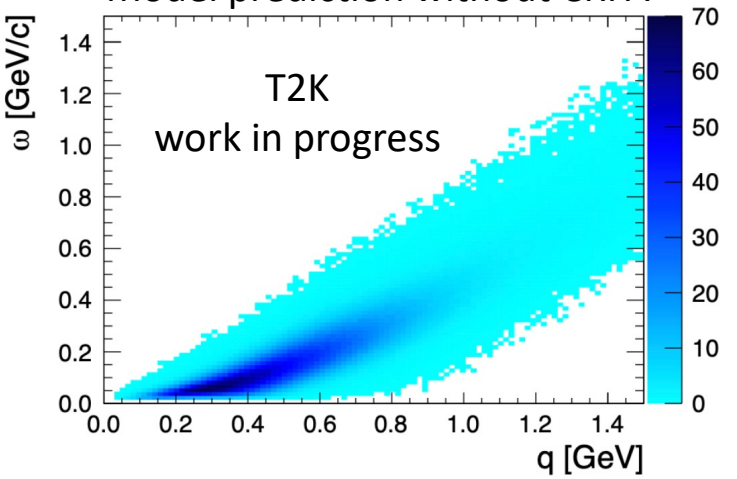
Ratio of prediction from **CRPA** model to **Hartree-Fock (HF)** model



Ratio of model with vs. without CRPA



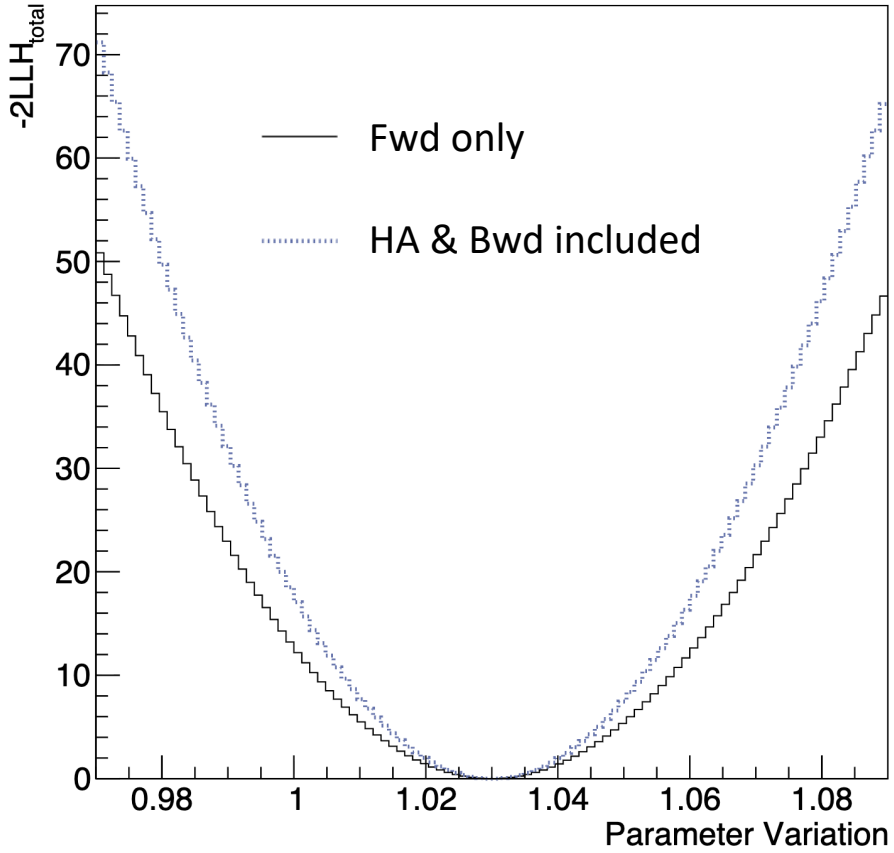
Model prediction without CRPA



Asimov Likelihoods with New Selection

Tighter Log-Likelihood constraint with new
High Angle and Backwards samples included

M_A^{QE}



T2K
work in progress

FGD1 Tracking Efficiency, ν mode p^+