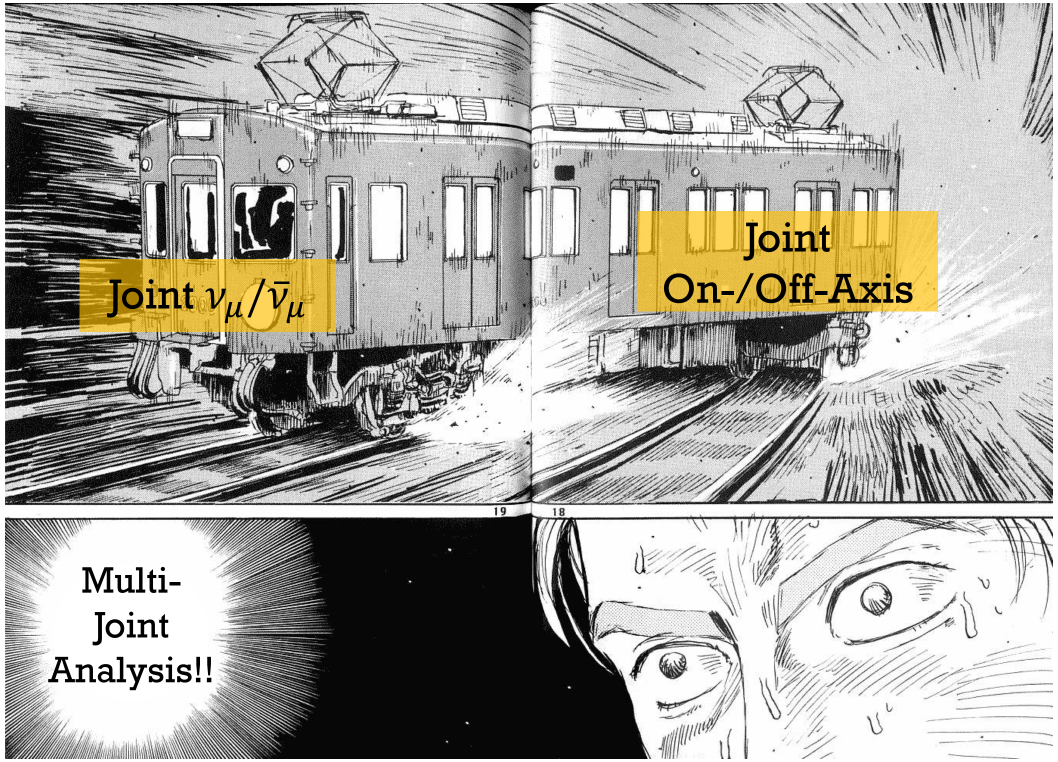
Combined ν_μ / $\bar{\nu}_\mu$ CC0π Cross Section in the T2K On-/Off-Axis Near Detectors



NuINT 2022

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T2K

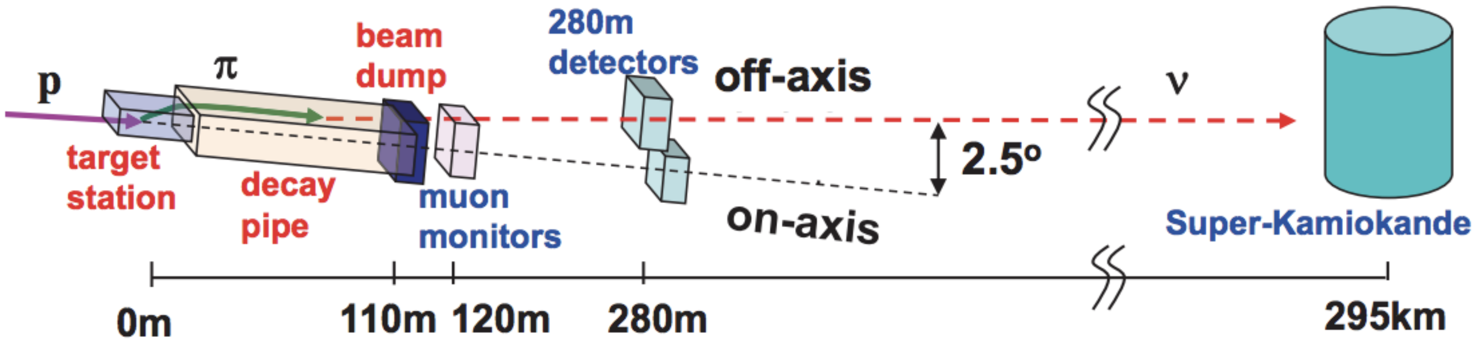
NuINT 2022, Seoul, Korea

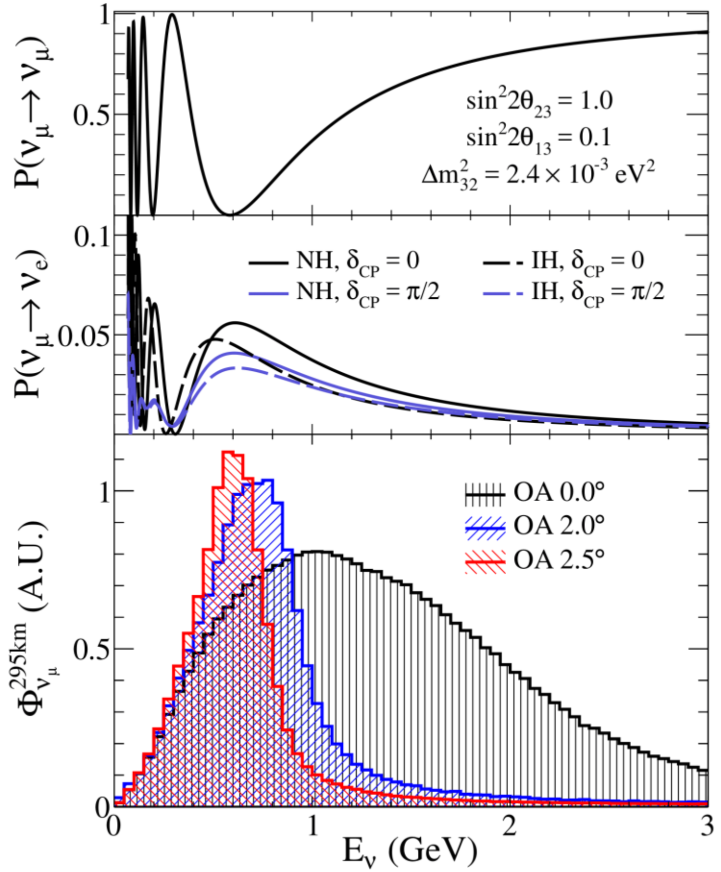
26.October.2022

Caspar Schloesser

The T2K Experiment

- Long-baseline neutrino oscillation experiment
- $\nu_\mu \rightarrow \nu_\mu$ / $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ disappearance
- $\nu_\mu \rightarrow \nu_e$ / $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
- First experiment to use off-axis technique





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Cross Section Measurements at T2K

Near Detector

Event rate = $\Phi_\nu(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times P(\nu_\mu \rightarrow \nu_{\mu,e})$

Far Detector

Neutrino Flux | Interaction Cross Section | Detector Efficiency | Oscillation Probability

Fractional uncertainty on event rate in %

	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
Flux and (ND unconstrained)	14.3	11.8	15.1	12.2	12.0	1.2
cross-section (ND constrained)	3.3	2.9	3.2	3.1	4.1	2.7
SK Detector	2.4	2.0	2.8	3.8	13.2	1.5
SK FSI + SI + PN	2.2	2.0	3.0	2.3	11.4	1.6
Nucleon Removal Energy	2.4	1.7	7.1	3.7	3.0	3.6
$\sigma(\nu_e)/\sigma(\overline{\nu}_e)$	0.0	0.0	2.6	1.5	2.6	3.0
NC1γ	0.0	0.0	1.1	2.6	0.3	1.5
NC Other	0.3	0.3	0.2	0.3	1.0	0.2
$\sin^2\theta_{23}$ and Δm^2_{21}	0.0	0.0	0.5	0.3	0.5	2.0
$\sin^2\theta_{13}$ PDG2018	0.0	0.0	2.6	2.4	2.6	1.1
All Systematics	5.1	4.5	8.8	7.1	18.4	6.0

PRD 103, 112008 (2021)

- Different flux, target and acceptance for near and far detectors
- Φ_ν, σ constrained by near detector → reduce far detector systematics
- Interaction cross section uncertainty is dominant one for oscillation analysis
- Need for reliable model and better understanding of neutrino interactions
  - Neutrino physics is entering high precision era

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Measurement

- Joint ν_μ / $\bar{\nu}_\mu$ cross section measurement on carbon
- Charged current with zero pions in the final state
- Using the T2K on- and off-axis near detectors

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Measurement

- Joint ν_μ / $\bar{\nu}_\mu$ cross section measurement on carbon
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Joint ν_μ / $\bar{\nu}_\mu$ cross section measurement

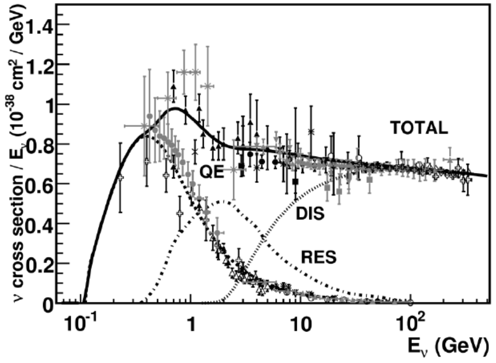
Charged-current quasi-elastic cross section:

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 M^2 \cos^2\theta_C}{8\pi E_\nu^2}\left[A(Q^2) \pm \frac{(s-u)}{M^2}B(Q^2) + \frac{(s-u)^2}{M^4}C(Q^2)\right]$$

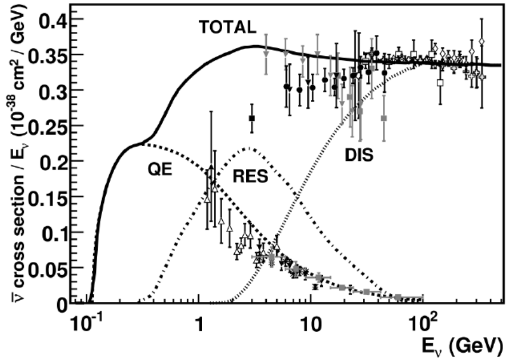
$+$ for ν
$-$ for $\bar{\nu}$

- Multinucleon excitations are expected to be less significant for $\bar{\nu}$
- Models can be assessed by measuring $\sigma^{\nu} - \sigma^{\bar{\nu}}$

ν Cross Section



$\bar{\nu}$ Cross Section



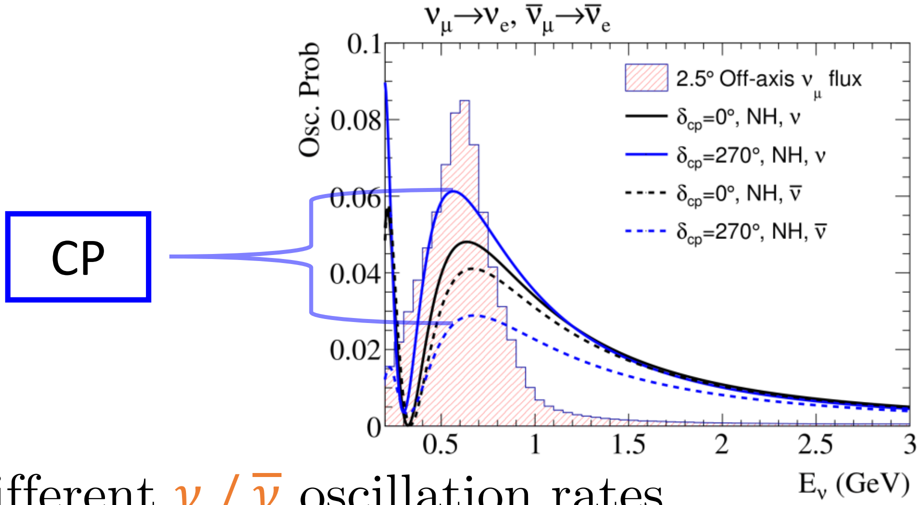
Interaction Asymmetry

VS

Oscillation Asymmetry

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$
$$\mp \frac{1.27\Delta m_{21}^2 L}{E} 8J_{CP}\sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$

(Matter effects not considered in this formula)



Different ν / $\bar{\nu}$ oscillation rates

if CP symmetry is violated ($\delta_{CP} \neq 0, \pi$)

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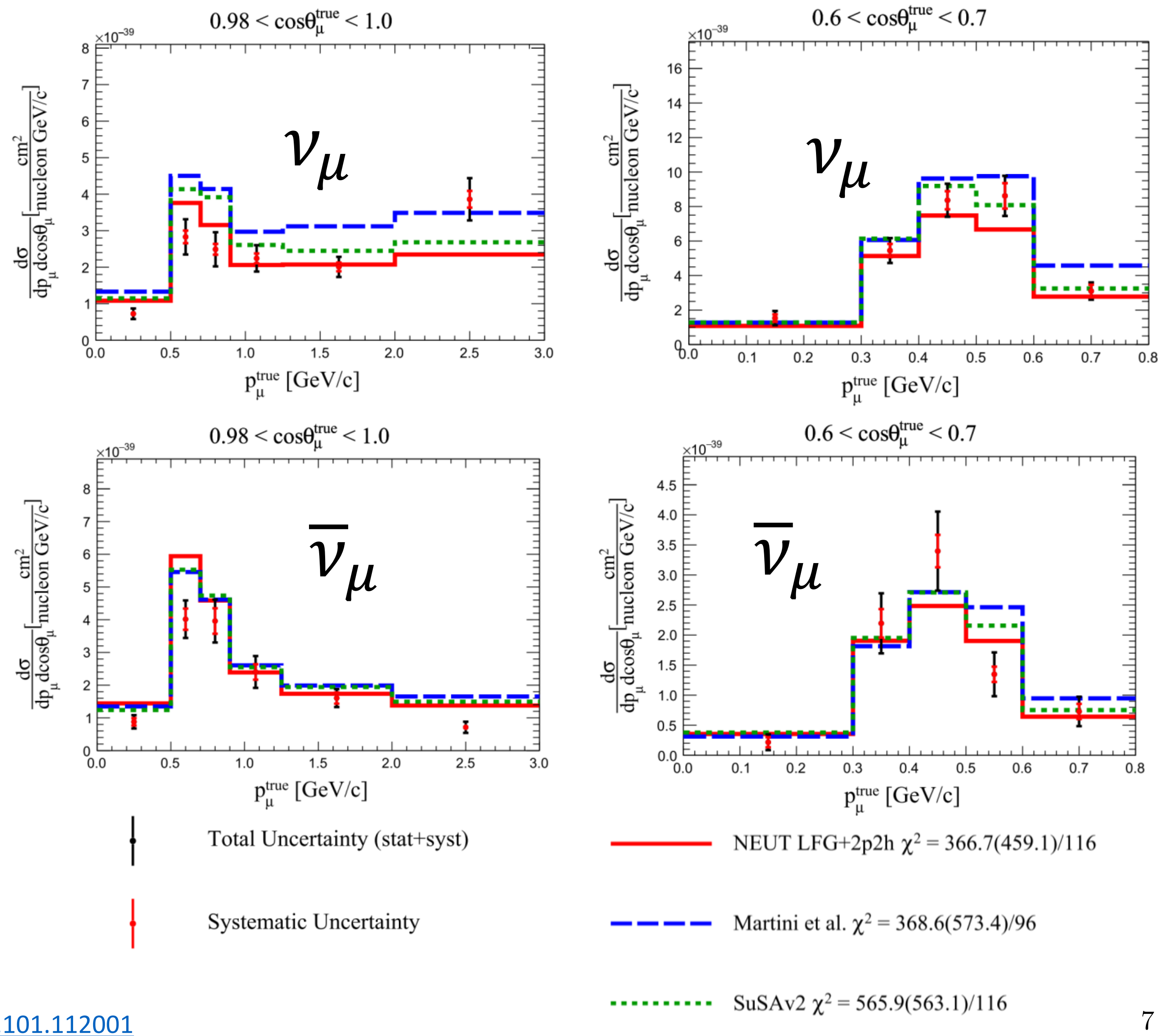
Joint ν_μ / $\bar{\nu}_\mu$ cross section measurement

- Simultaneous fit to ν_μ / $\bar{\nu}_\mu$ events (off-axis only)
- MC overestimates cross section in forward direction at medium momentum
- MC underestimation for high angles and low momentum
- No model describes the data well



Phys. Rev. D 101, 112001 (2020)
https://doi.org/10.1103/PhysRevD.101.112001

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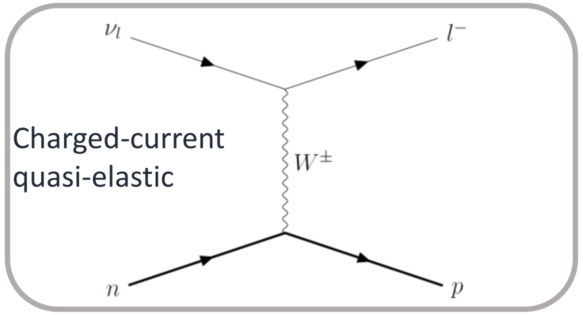
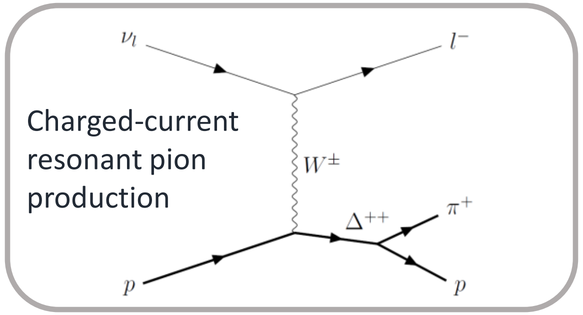
Measurement

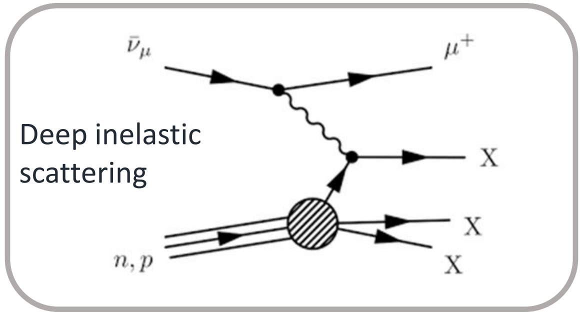
- Joint ν_μ / $\overline{\nu}_\mu$ cross section measurement on carbon
- Charged current with zero pions in the final state
- Using the T2K on- and off-axis near detectors

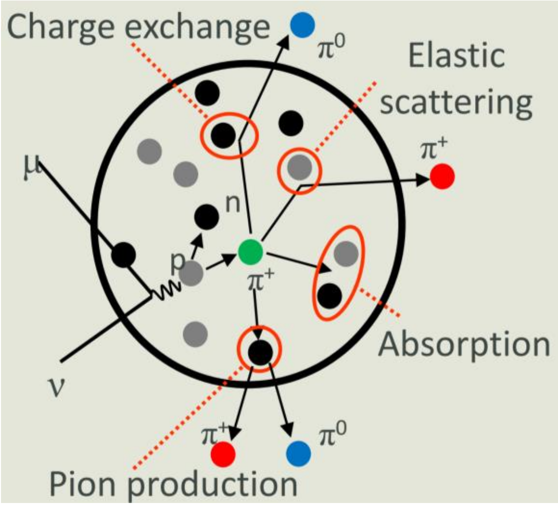
Signal Definition

Initial Neutrino Interaction

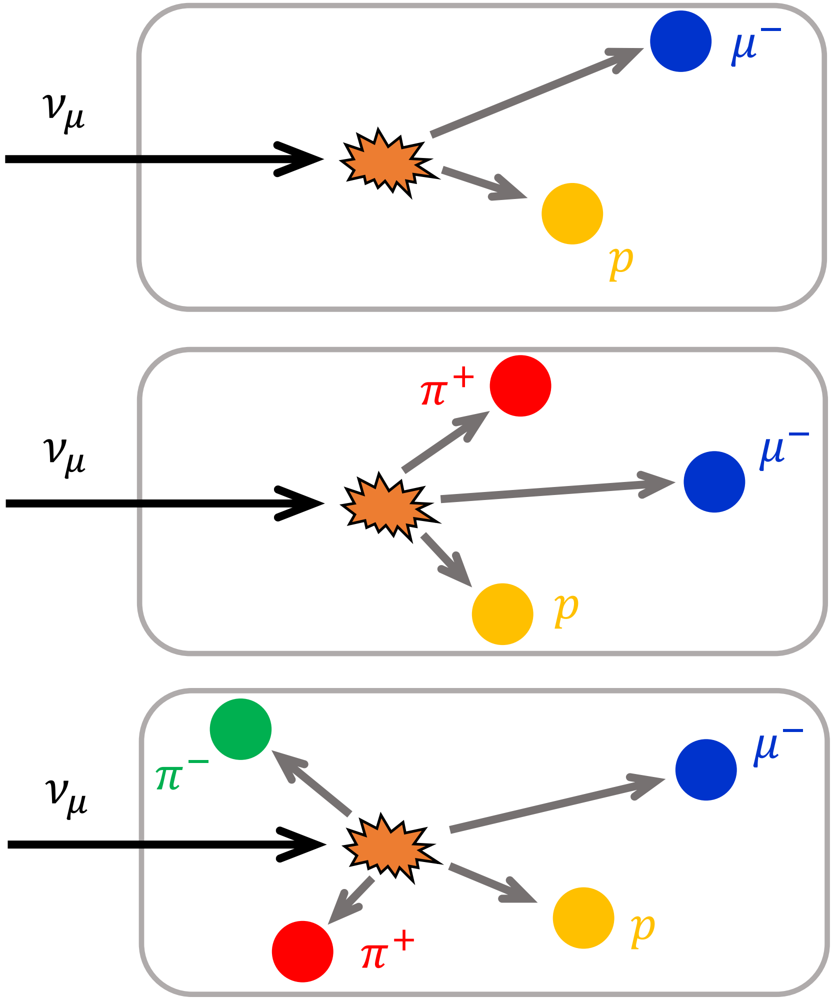




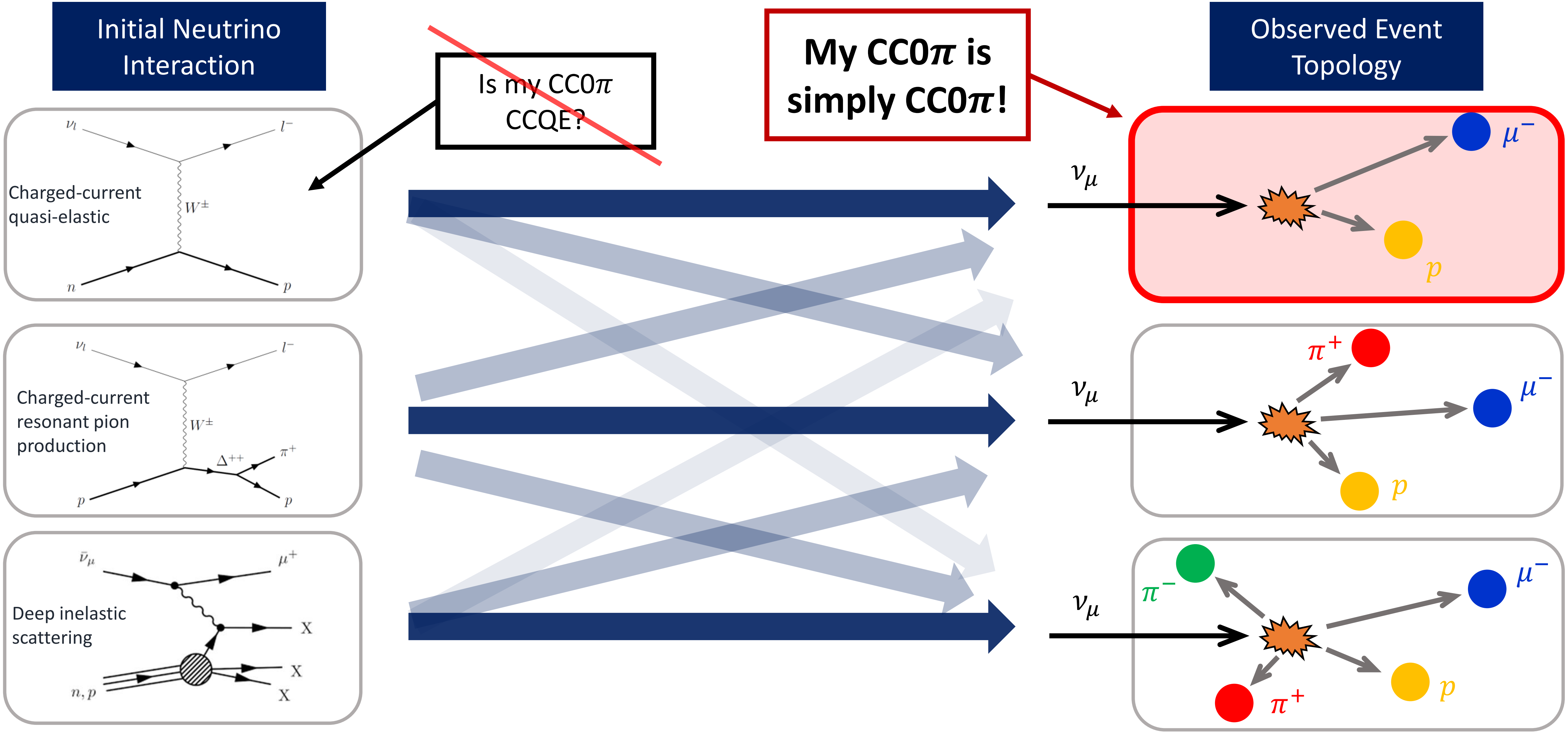




Observed Event Topology



Signal Definition



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Cross Section Extraction

Number of signal events from statistical fit (includes background constraints and unfolding)

Differential cross section as a function of kinematic variable x in truth bin i

$$\frac{d\sigma}{dx_i} = \frac{N_i}{\epsilon_i \, T \, \Phi \, \Delta x_i}$$

Bin width correction

Efficiency correction in analysis binning

Integrated flux at detector

Number of target nuclei

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T2K

Measurement

- Joint ν_μ / $\overline{\nu}_\mu$ cross section measurement on carbon
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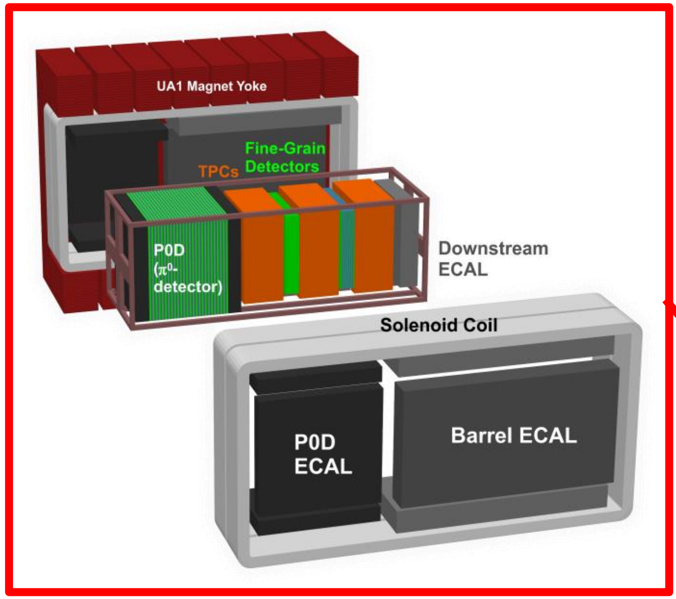
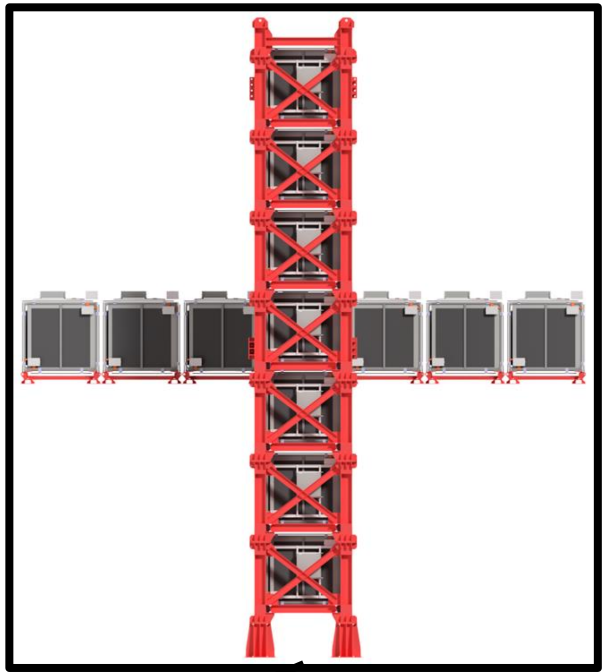
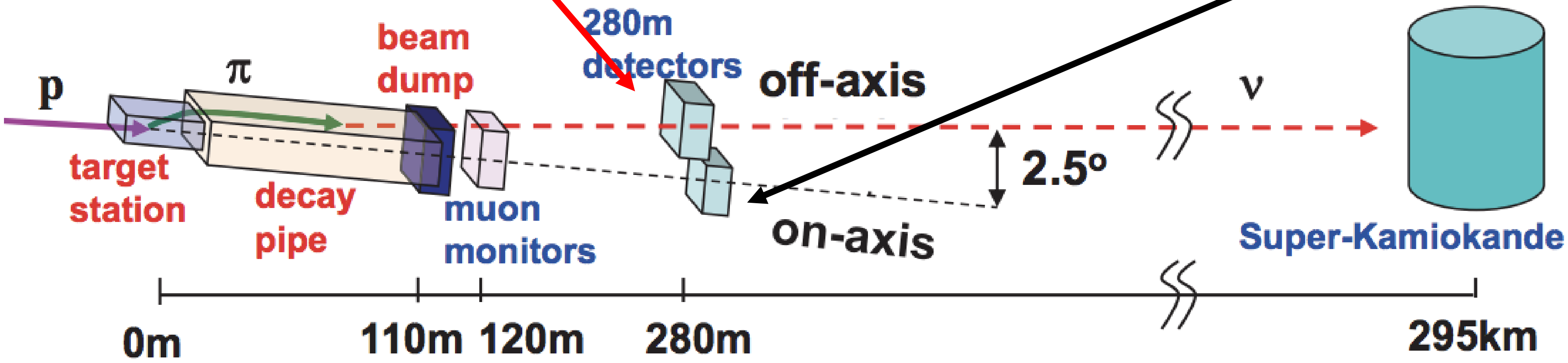
The Near Detectors



ND280 off-axis

INGRID on-axis





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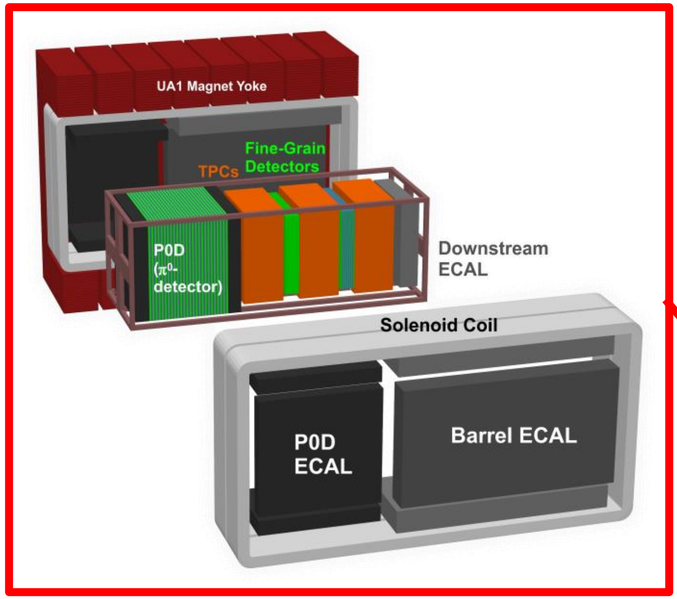
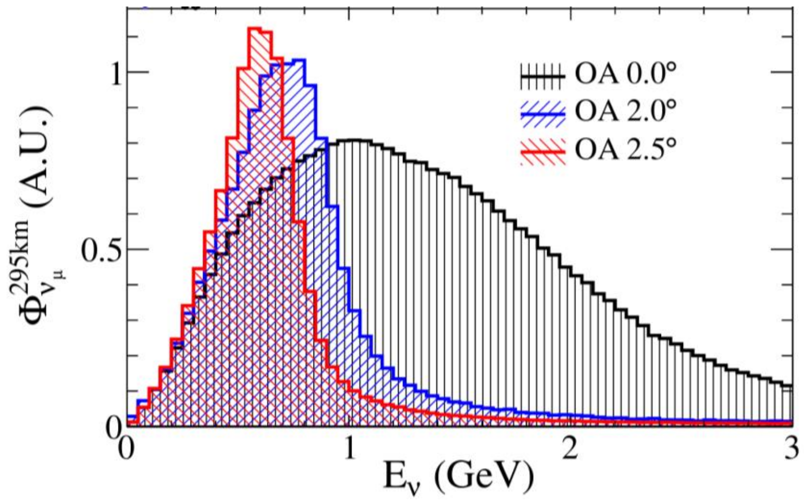
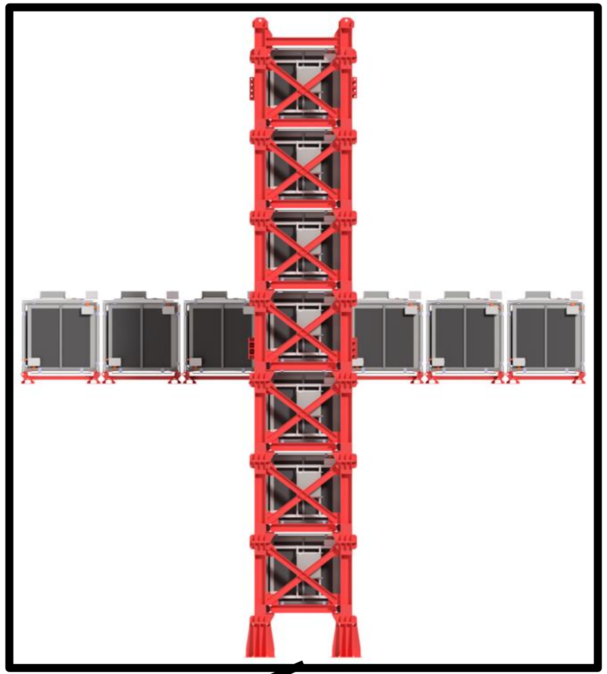
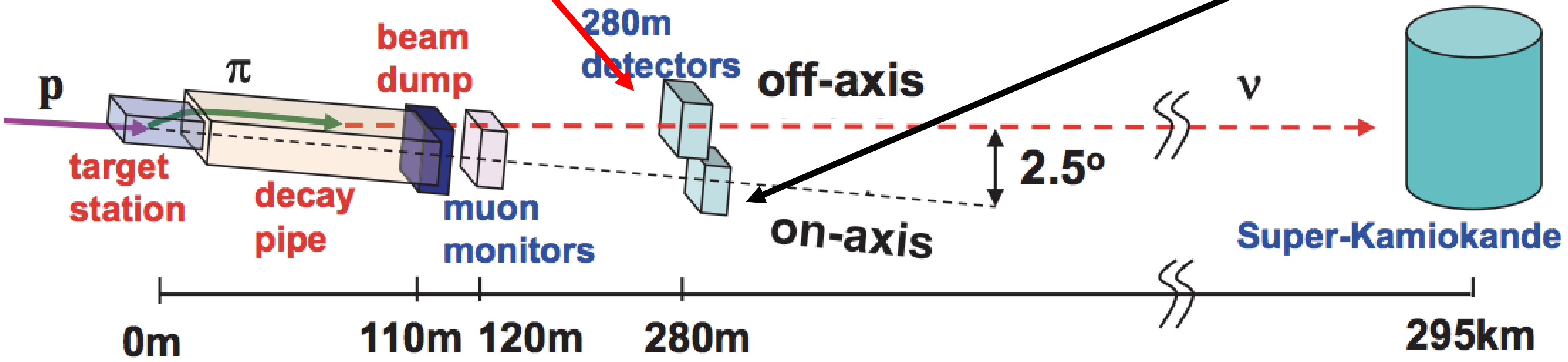
The Near Detectors

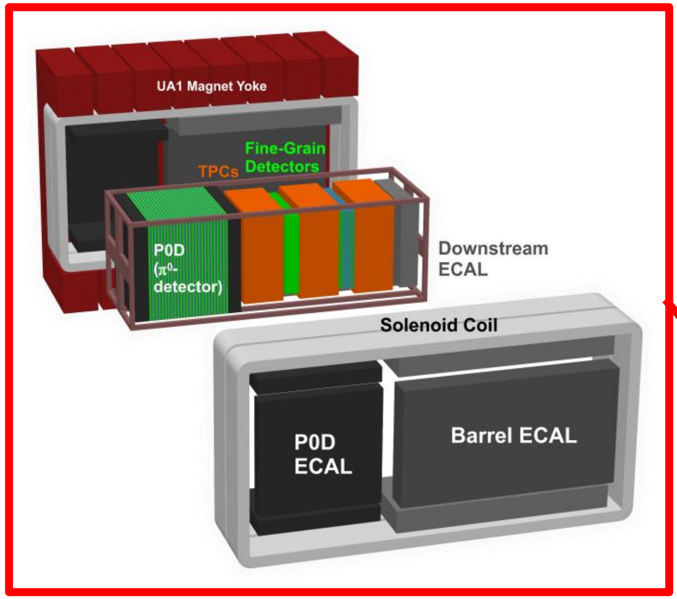




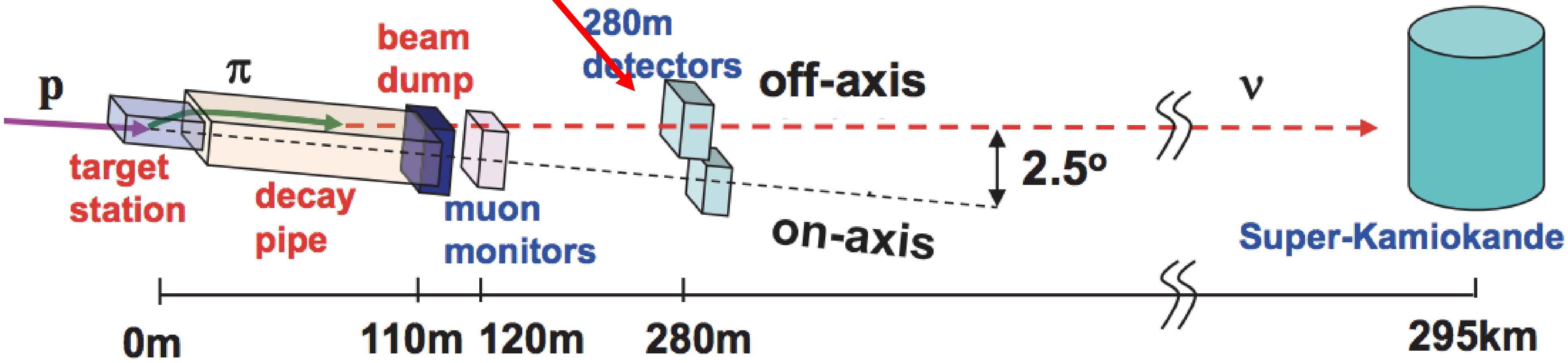




The Near Detectors

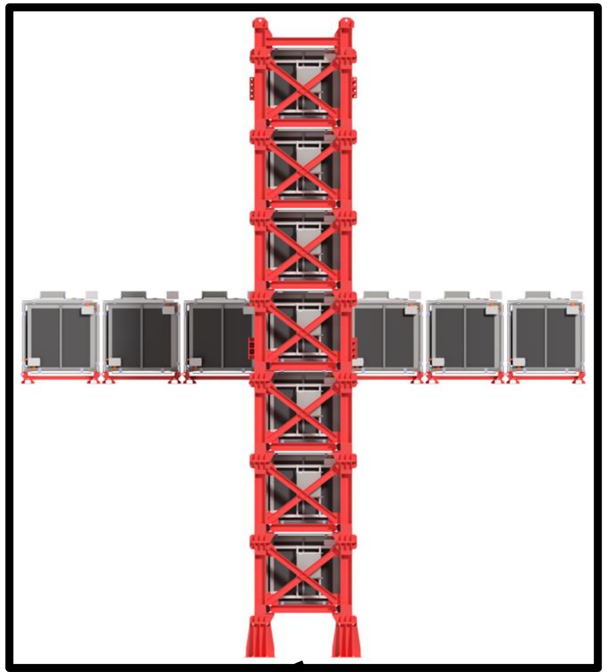


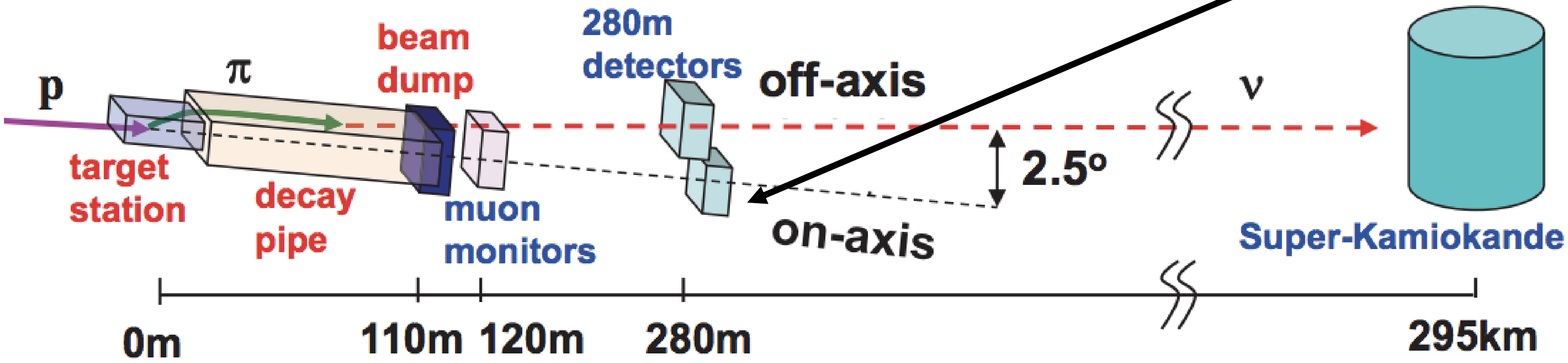
- ND280: the off-axis near detector
- Situated 280 m from the target station
- Fully magnetized detector
  - Can differentiate between $\nu/\overline{\nu}$
- 2 fine-grained detectors (FGDs) act as target for neutrinos
- 3 argon time projection chambers (TPCs) act as tracker and measure particle momentum and charge
- Detector encased in electromagnetic calorimeters (Ecals)
- Goals: Measure unoscillated neutrino spectrum and neutrino-nucleus cross sections



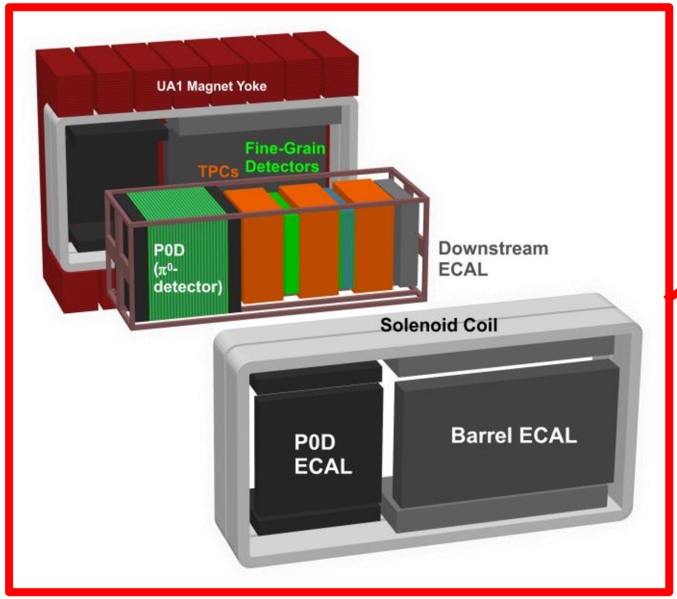
The Near Detectors

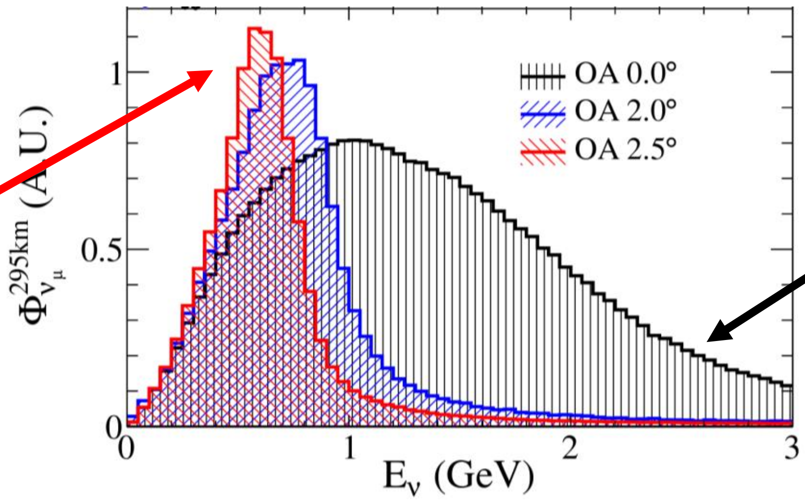
- INGRID: the on-axis detector
- Consists of 14 identical modules arranged in a cross
- Each module consists of sandwiched iron plates and tracking scintillator plates
- Goals: measure neutrino beam profile and neutrino-nucleus cross sections

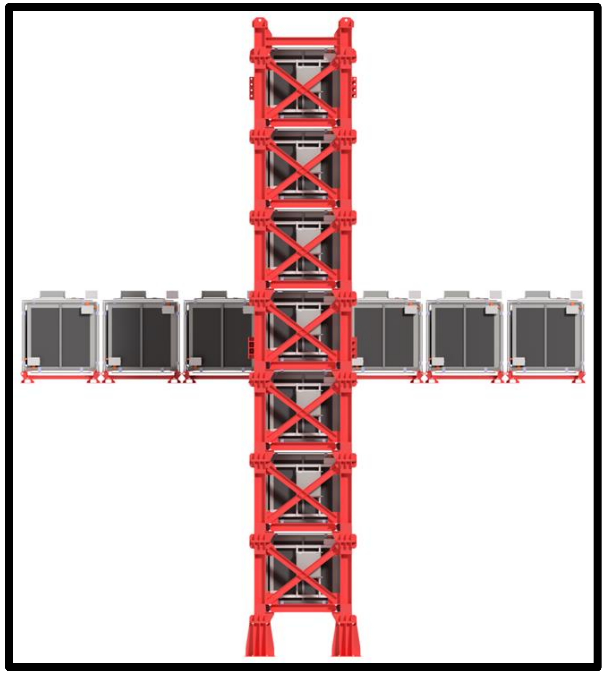




The Near Detectors







- Study cross section as a function of neutrino energy
- Measured ν interaction rate is product of flux and cross section → Degeneracy
- Difference in flux at the 2 near detectors gives better constraint
- Fluxes between detectors are correlated → Reduction of the flux uncertainty in the analysis
- Important step towards planned future multi-axis measurements with Hyper-K, DUNE

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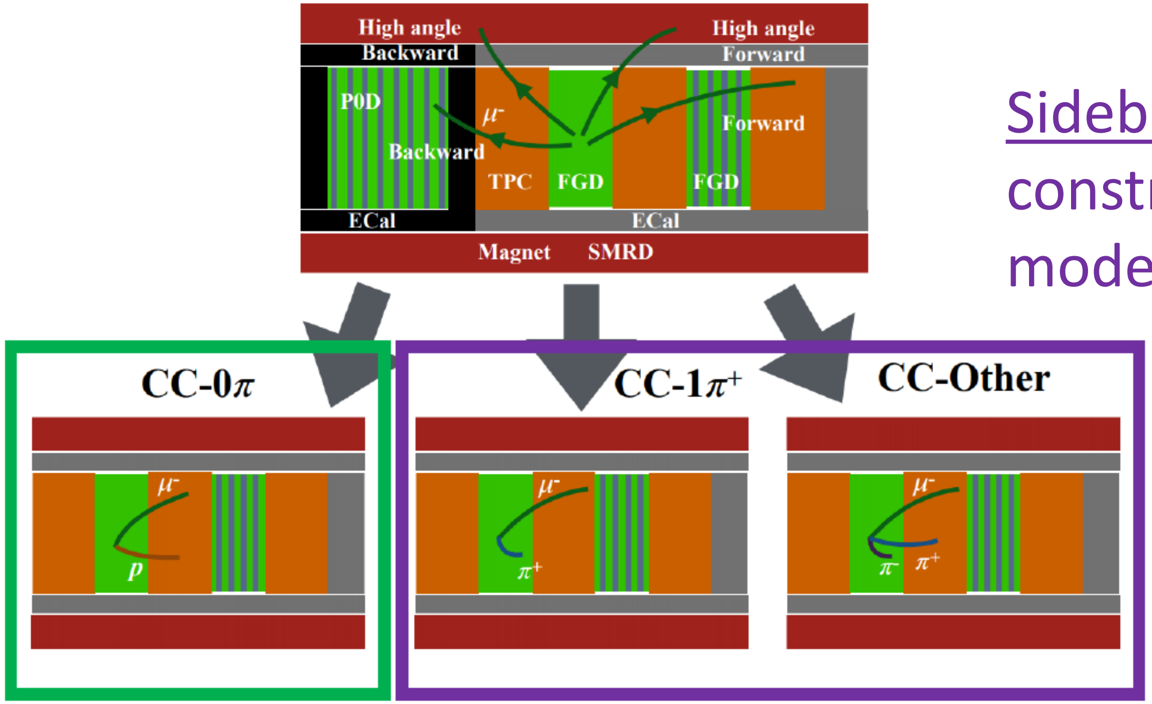
Event Selection

- Strategy: define multiple samples and bin events in outgoing muon momentum and angle

Signal



Sidebands: used to constrain background modeling in Monte Carlo

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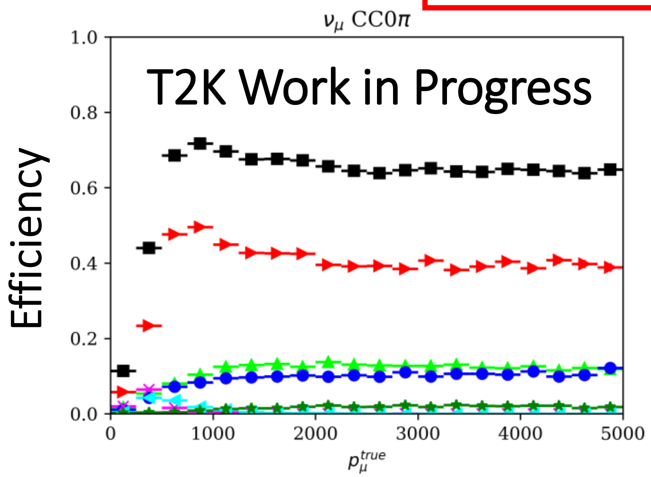
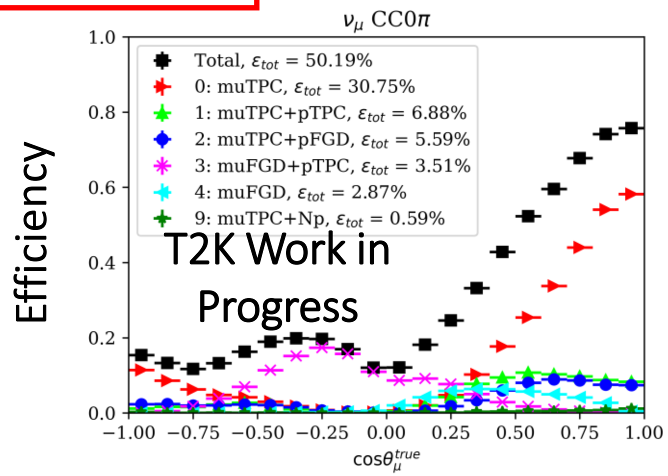
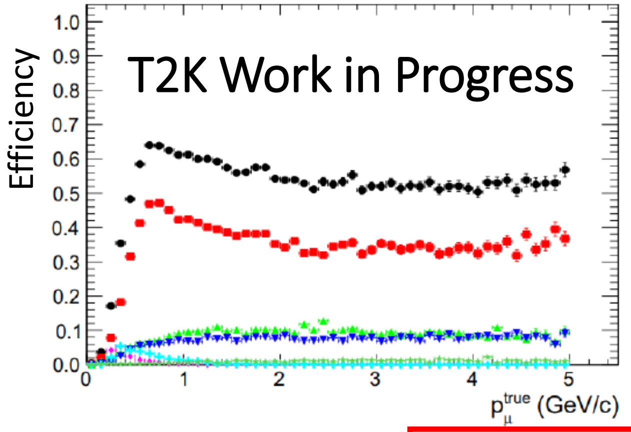
Event Selection - Improvements

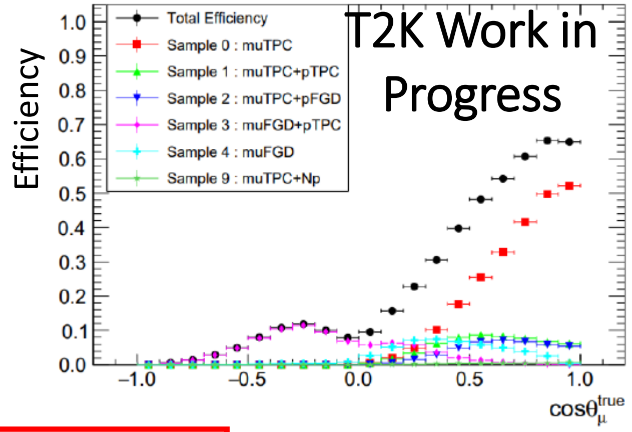
Time-of-flight information used to get correct track sense

New selection



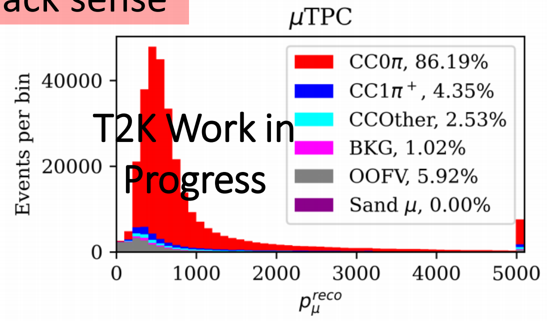


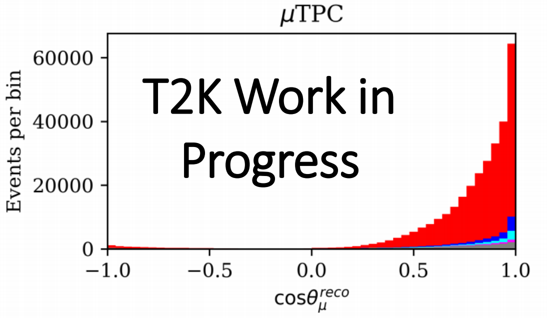




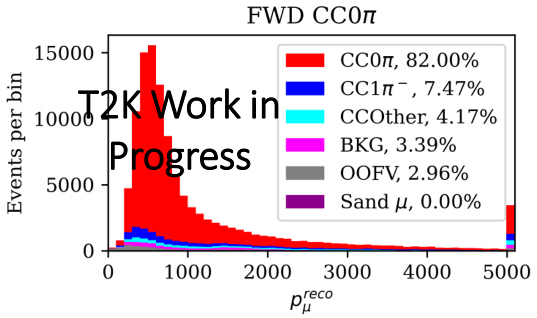
Previous selection

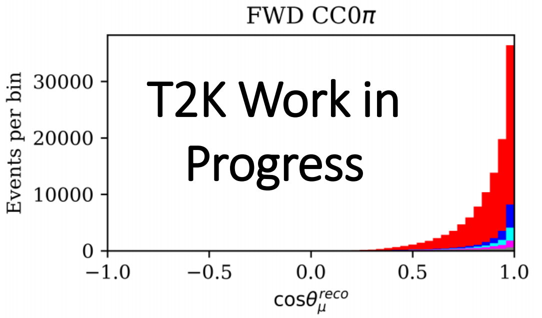
Off-axis ν_μ Selection





Off-axis $\bar{\nu}_\mu$ Selection





- Very similar purity for previous and improved selection
- But efficiency is greatly improved for high angle and backwards going tracks

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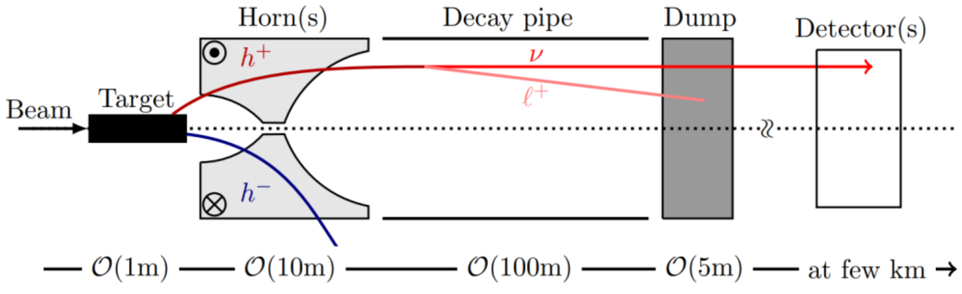
Flux Correlations

- Framework developed to determine flux correlations between different
  - ν flavors $(\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e)$
  - Beammodes (ν-mode, $\bar{\nu}$-mode)
  - Off-axis positions (0°, 1.5°, 2.5°, etc.)

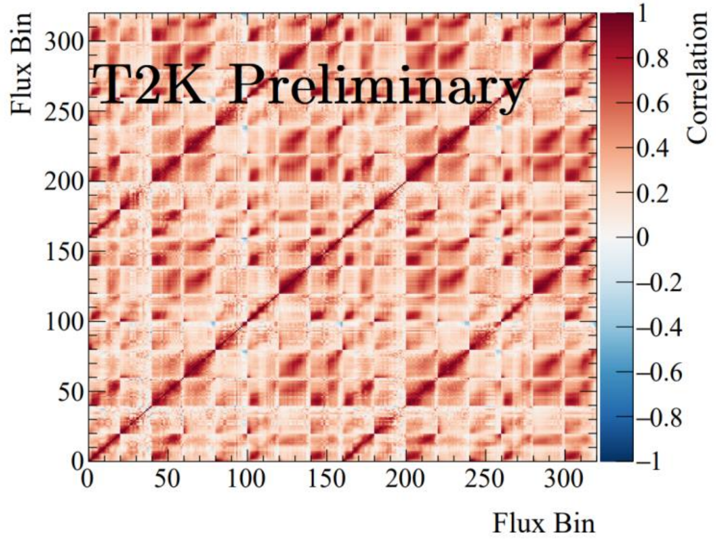


- ν-beamline is simulated many times
- Each time a variation is introduced
  - e.g., horn magnetic field, horn alignment, proton-carbon interactions
- Variations are propagated through simulation to determine correlations between flux energy bins

- Account for flux modeling uncertainties with nuisance fit parameters $\vec{p}$
- Correlations are considered through penalty term:

$$\chi^2_{\rm syst} = (\vec{p} - \vec{p}_{\rm prior})(V^{\rm syst}_{\rm cov})^{-1}(\vec{p} - \vec{p}_{\rm prior})$$

Correlations enter through covariance matrix



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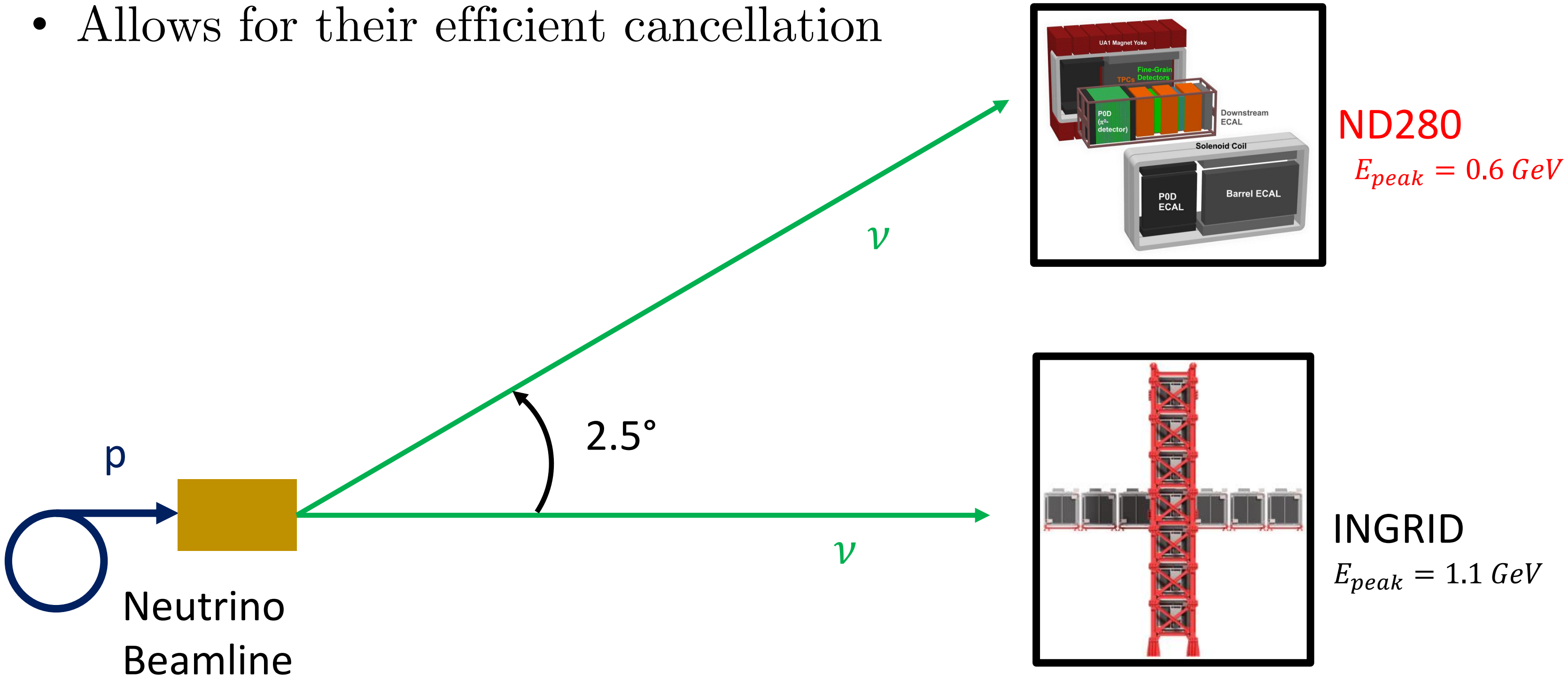
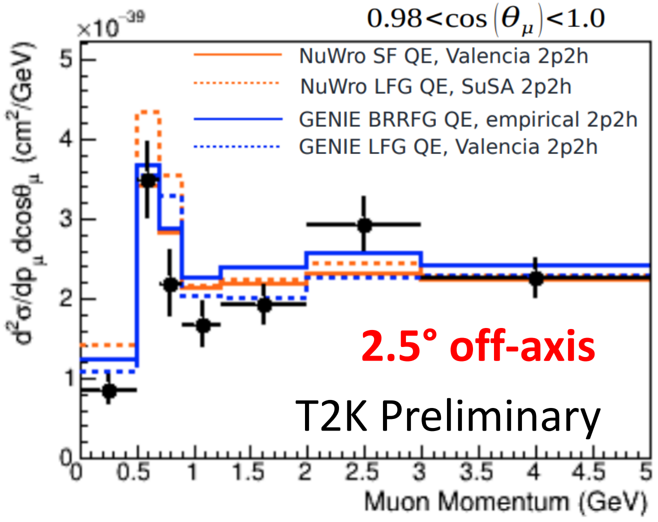
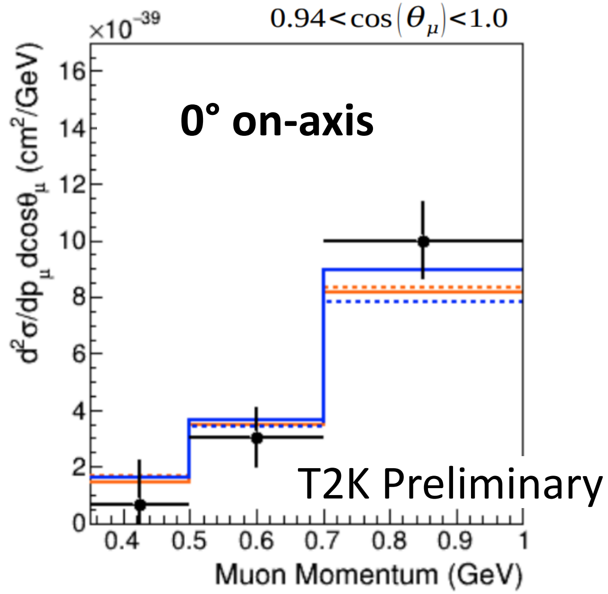
Sneak Peek: Joint On-/Off-Axis CC0π Cross Section

- First T2K multi-detector cross section measurement
- Direct probe of E_ν dependence
- Exploits correlations between the systematic uncertainties of the samples
  - Allows for their efficient cancellation







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Summary

- Joint measurements are the future of T2K's cross section group
- First doubly-joint cross section measurement at T2K is being completed
  - Multiple detectors
  - ν_μ and $\bar{\nu}_\mu$
- Development of joint fitting framework for near detector and cross section fits
- Working on minimizing model dependence and gain better handle on systematic uncertainties
- So far, all theoretical models hard pressed to accurately predict multiple data sets
- Further improvements from ND280 upgrade

THANK YOU!