Selection of muon neutrino interactions with an increased acceptance for the updated T2K oscillation analysis

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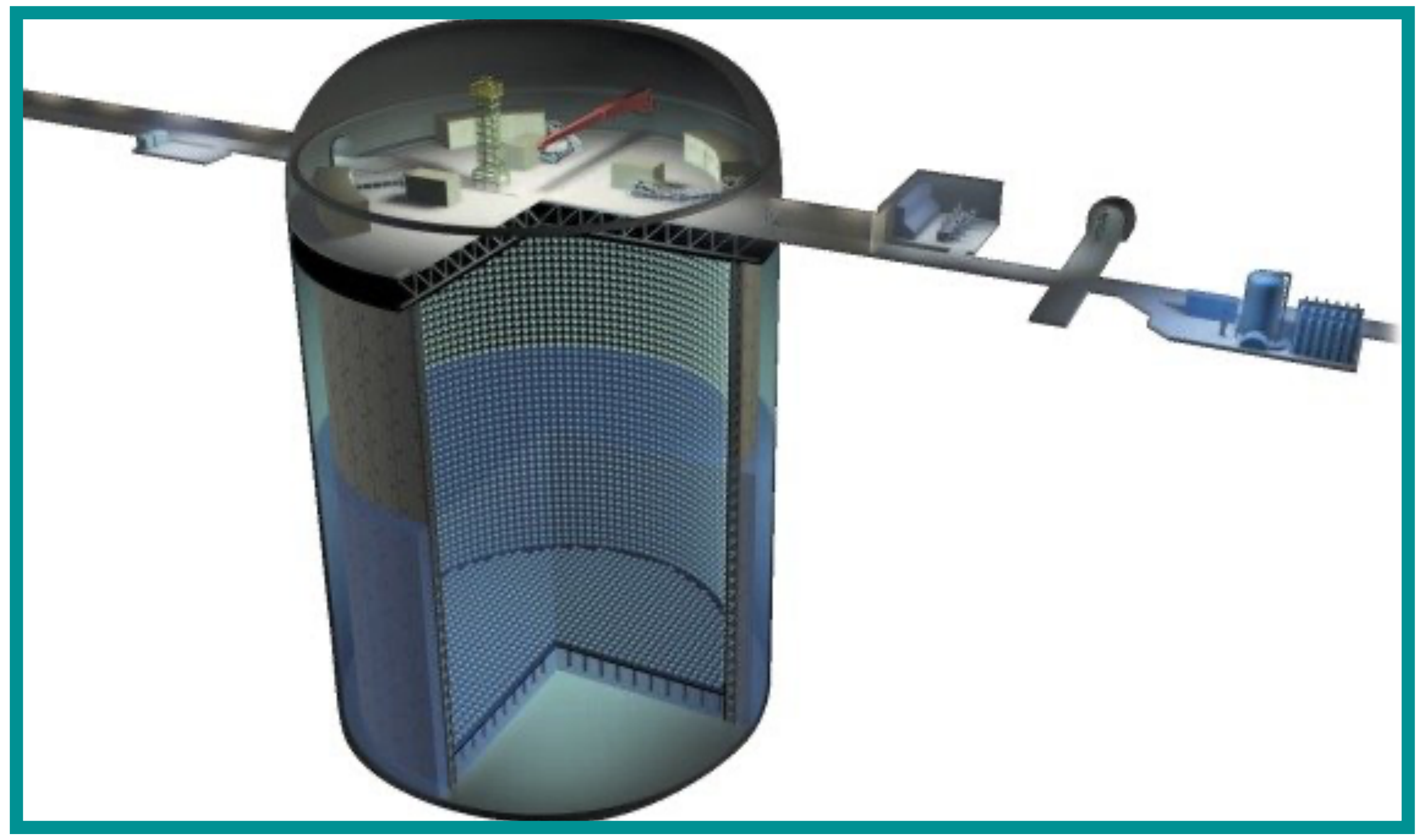
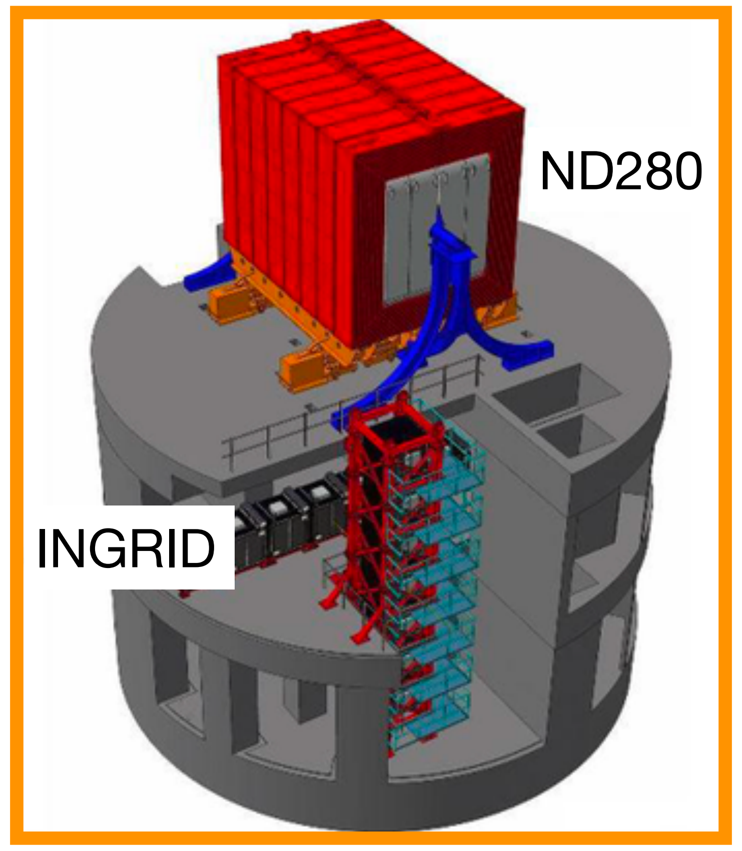
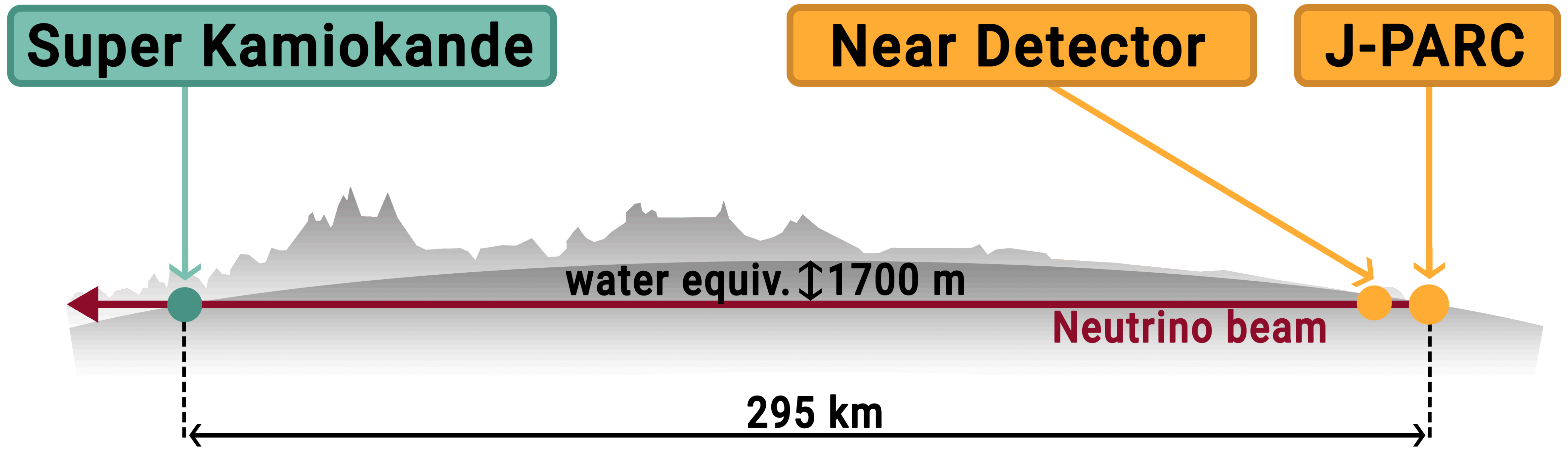
Tokai-to-Kamioka (T2K) experiment in Japan

- Flagship long-baseline accelerator neutrino project
- Study oscillations in both appearance and disappearance channels with muon (anti)neutrino beam
- Far detector: water Cherenkov Super-Kamiokande

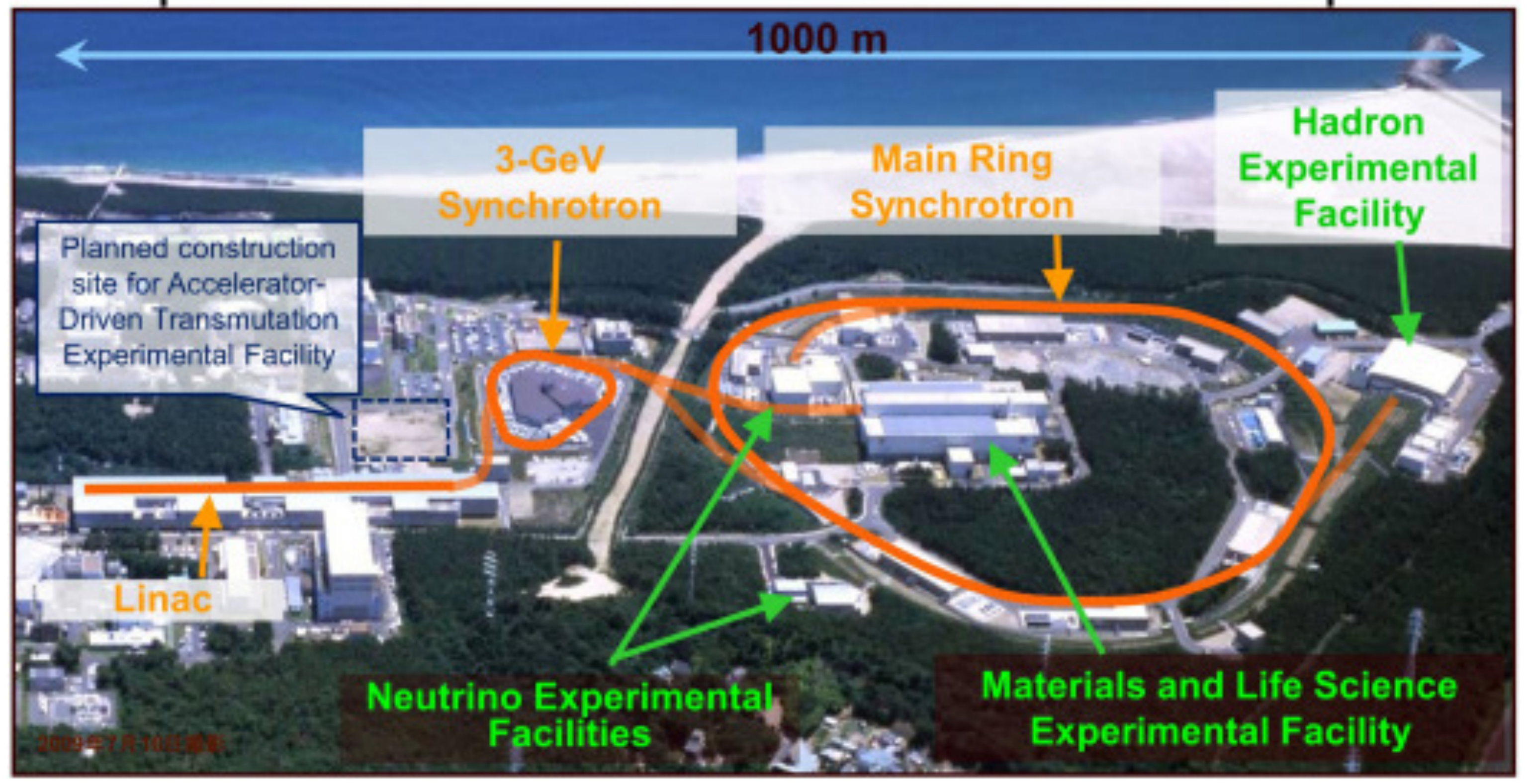
Nature volume 580, pages 339–344 (2020)







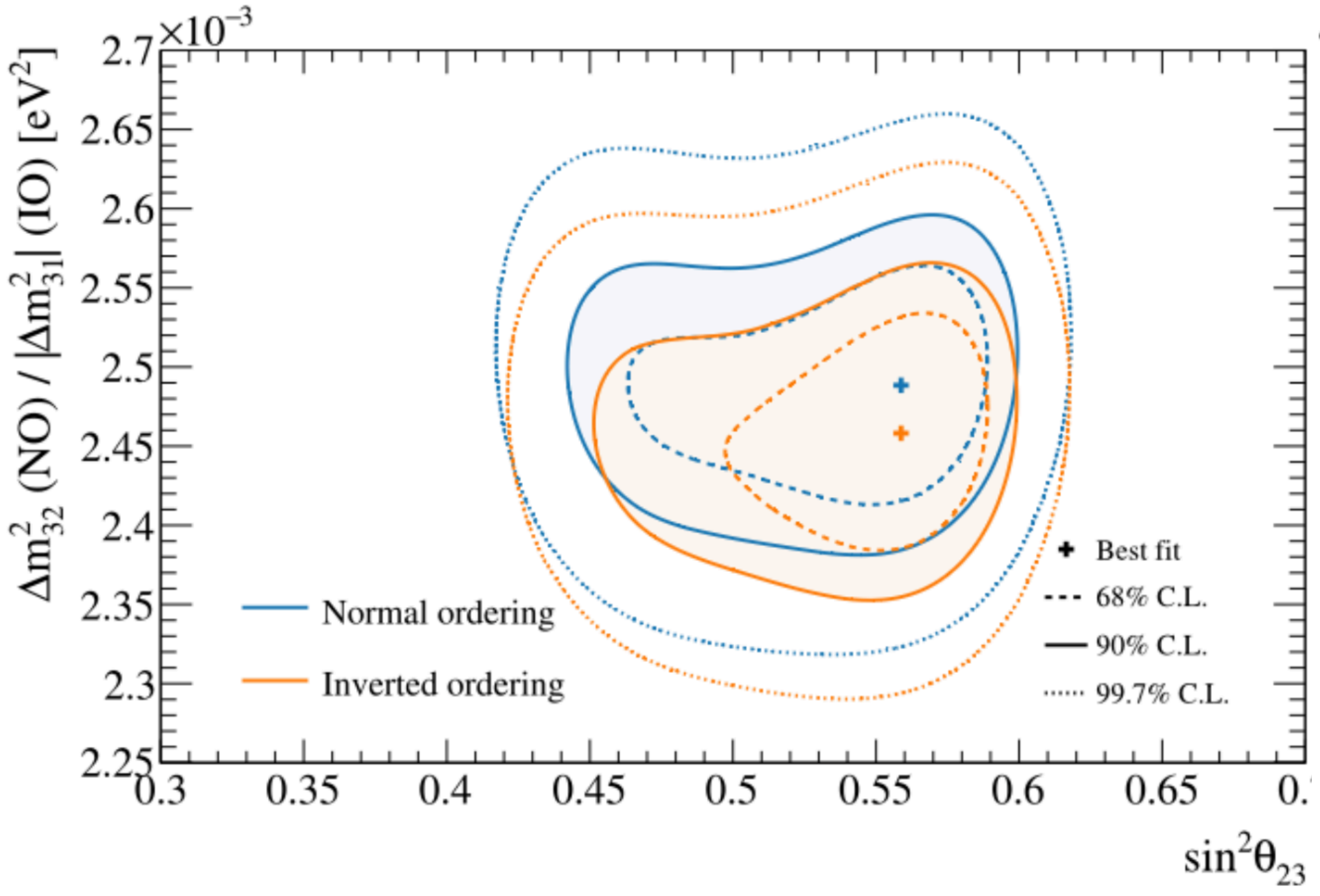
J-PARC
Japan Proton Accelerator Research Complex

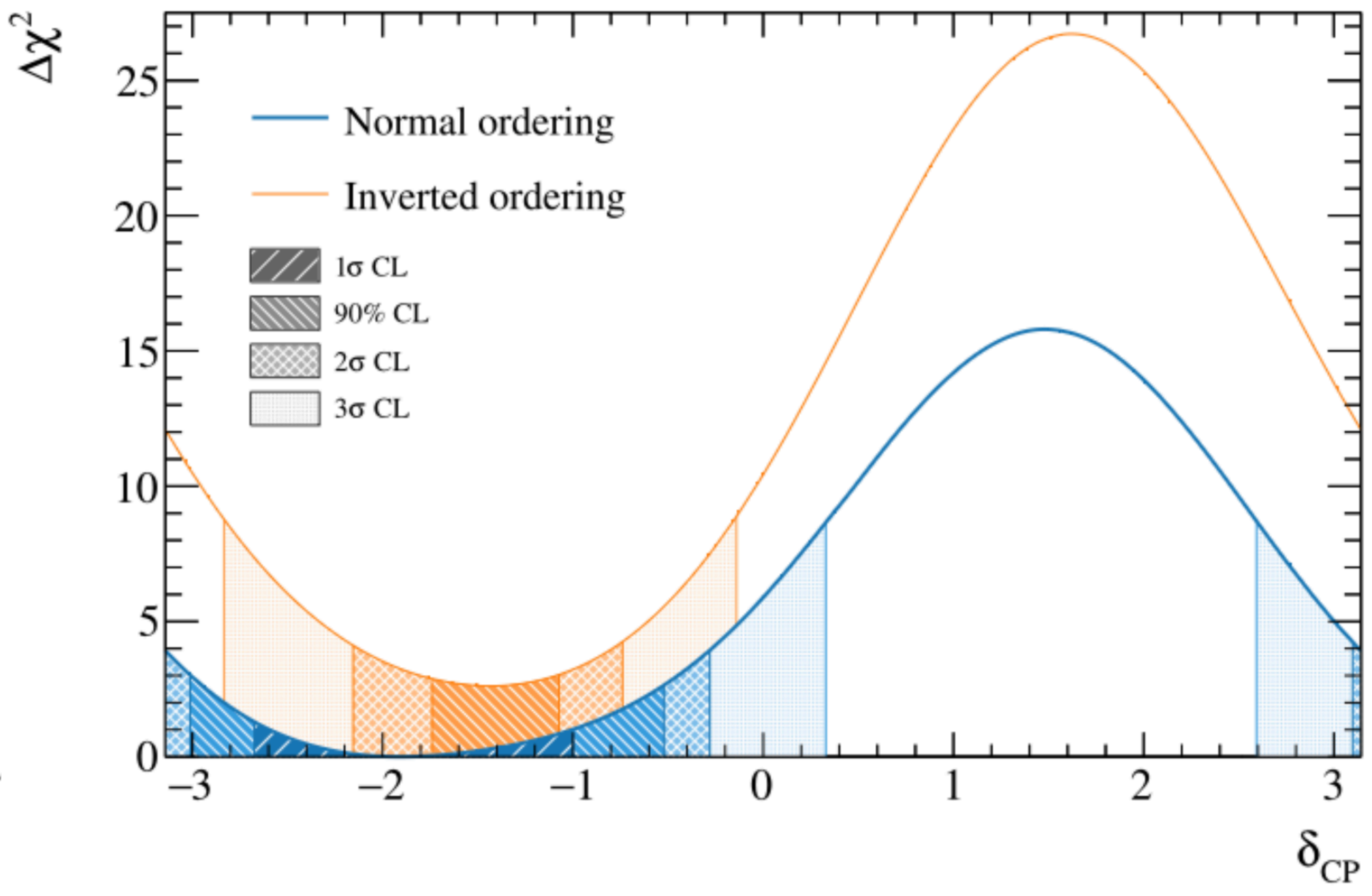


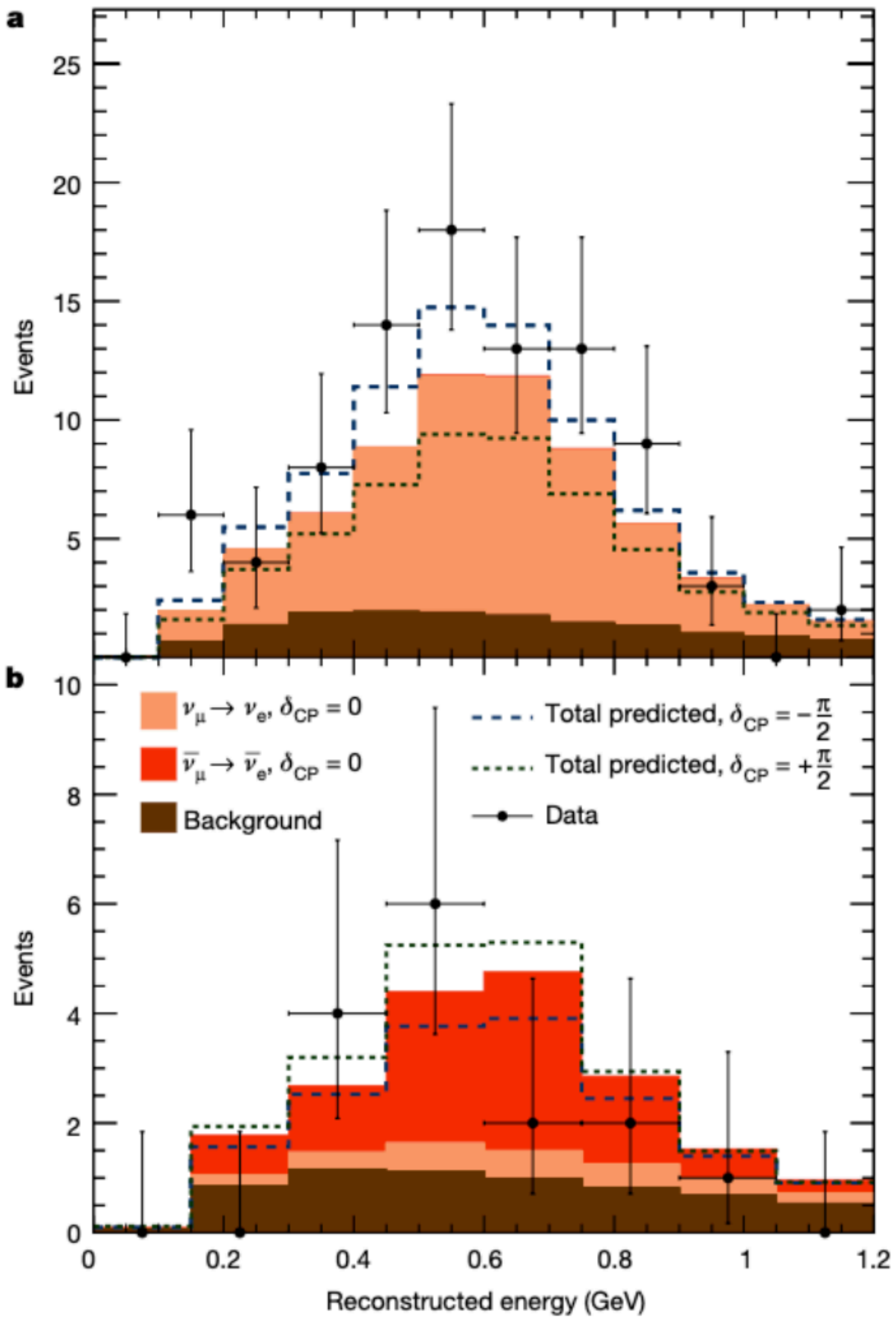
Latest T2K results

- World-leading measurements of θ_{23} and Δm^2_{32}:
  - Mild preference for upper octant of θ_{23} and normal mass hierarchy
- $\delta_{CP} = 0$ and π (CP-conservation) excluded at 90% CL

(**Eur. Phys. J. C 83, 782 (2023)**)







Near detector ND280

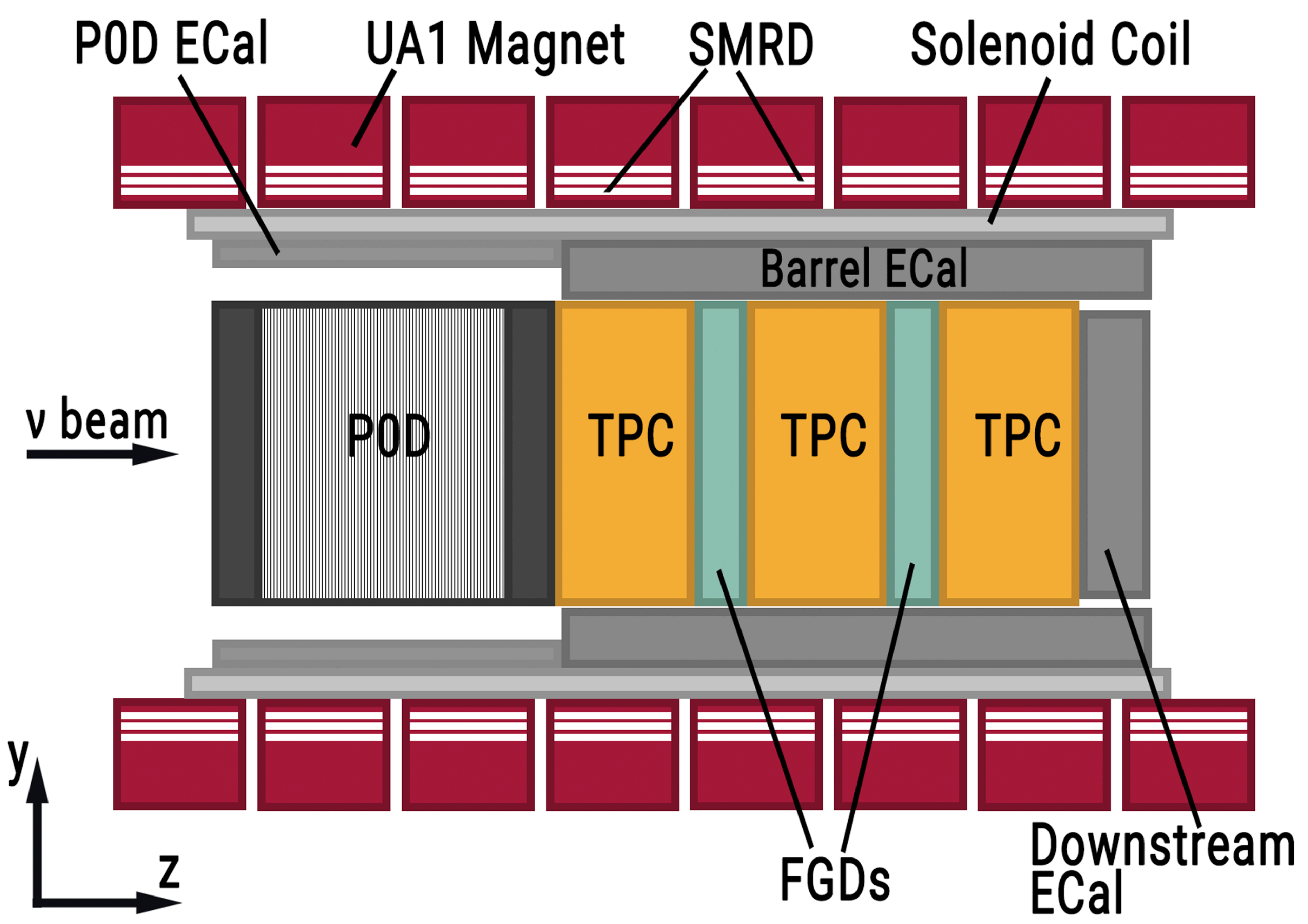
ND280:

- 2.5∘ off-axis (Super-K direction)
- Sub-detectors inside UA1 magnet (0.2 T magnetic field)
- Measure neutrino interactions, neutrino flux composition, intrinsic ν_e contamination
- Constrain cross-section and flux uncertainties for oscillation analysis (OA)

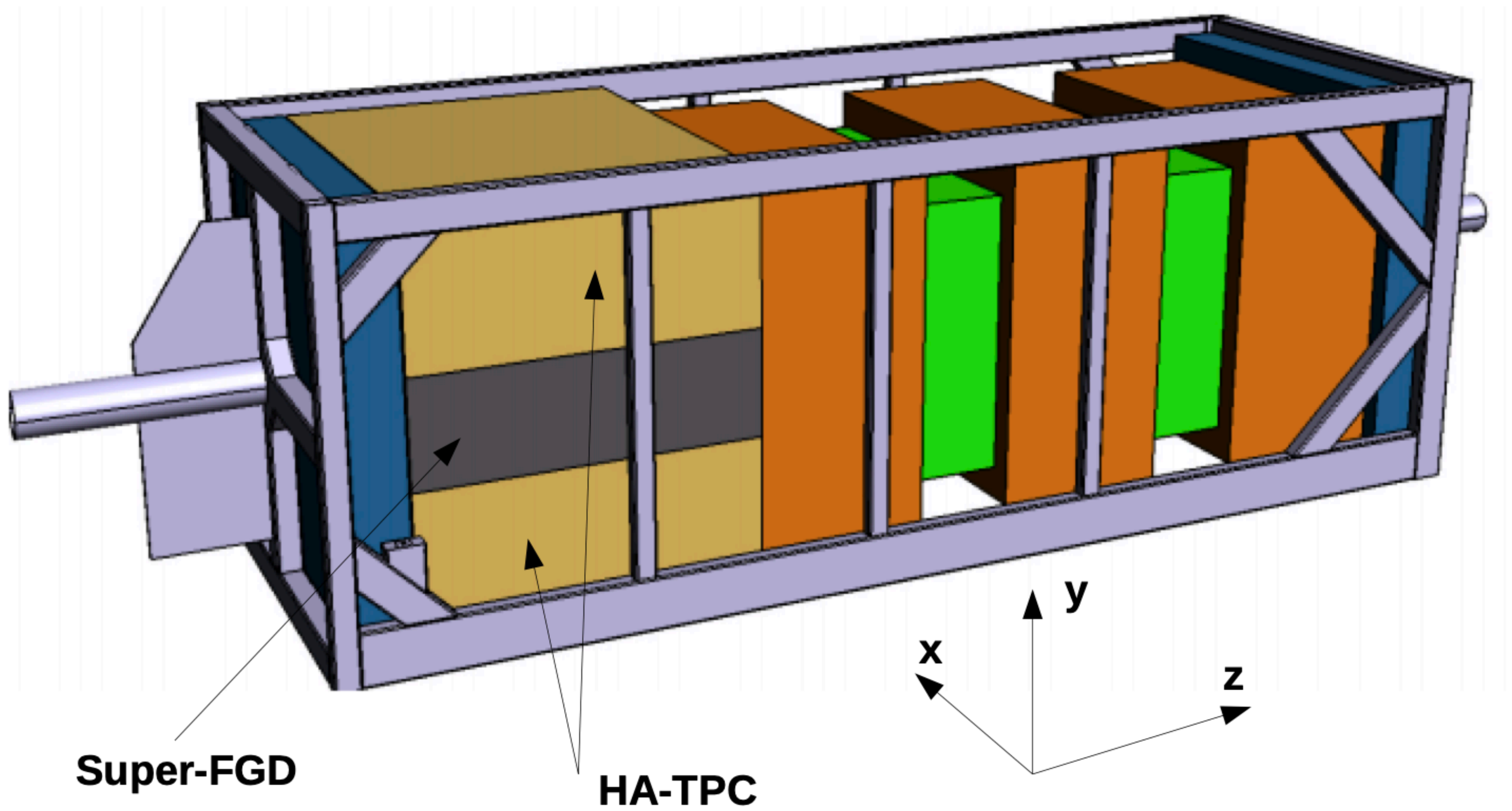
ND280 Upgrade — further reduction of systematic uncertainties for OA:

- Lower thresholds for neutrino interaction products, ability to reconstruct neutron kinematics, improved geometric acceptance
- Installation of new modules finished in May 2024
- See talks by **Angelina** and **Alexander**

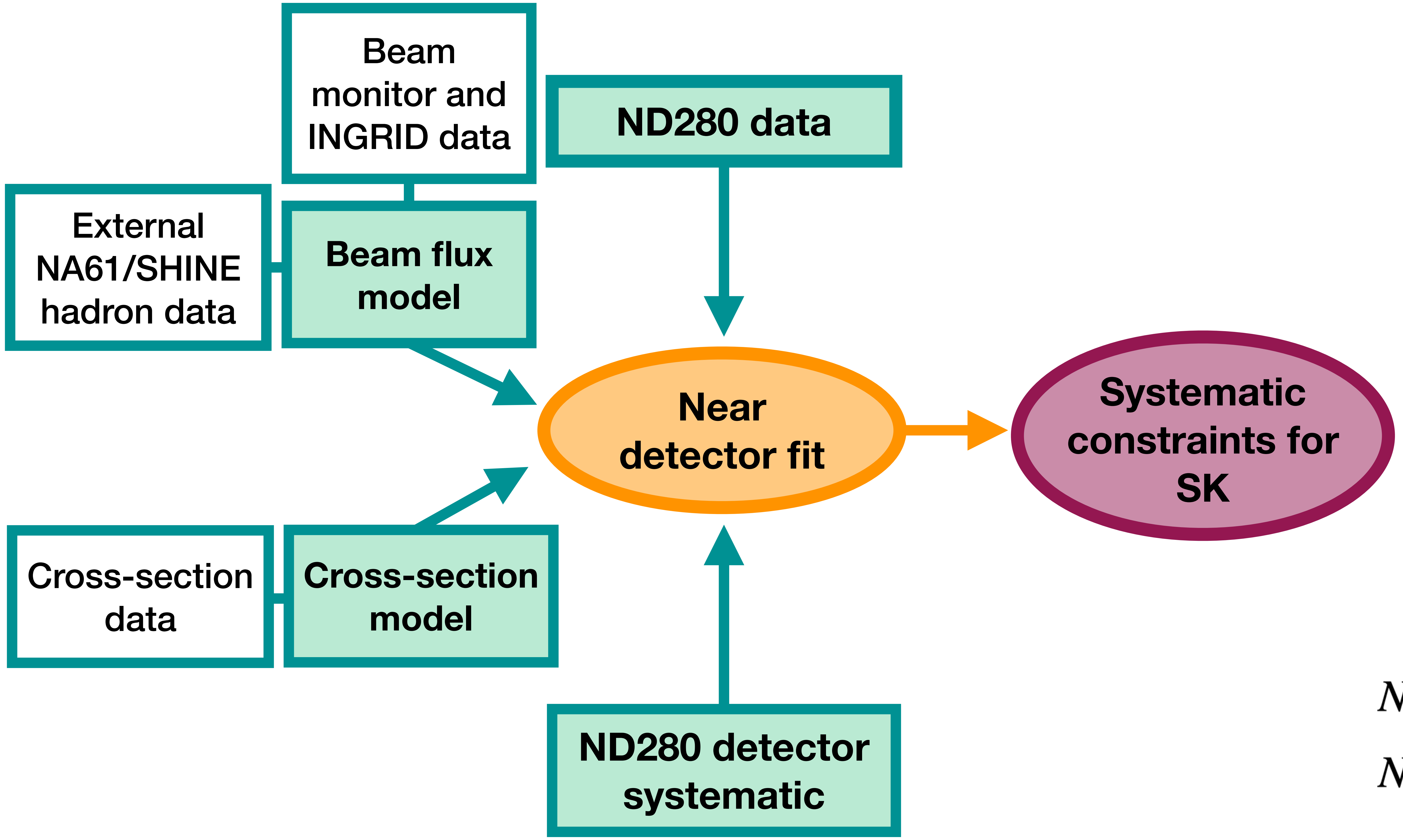
ND280 2010-2022

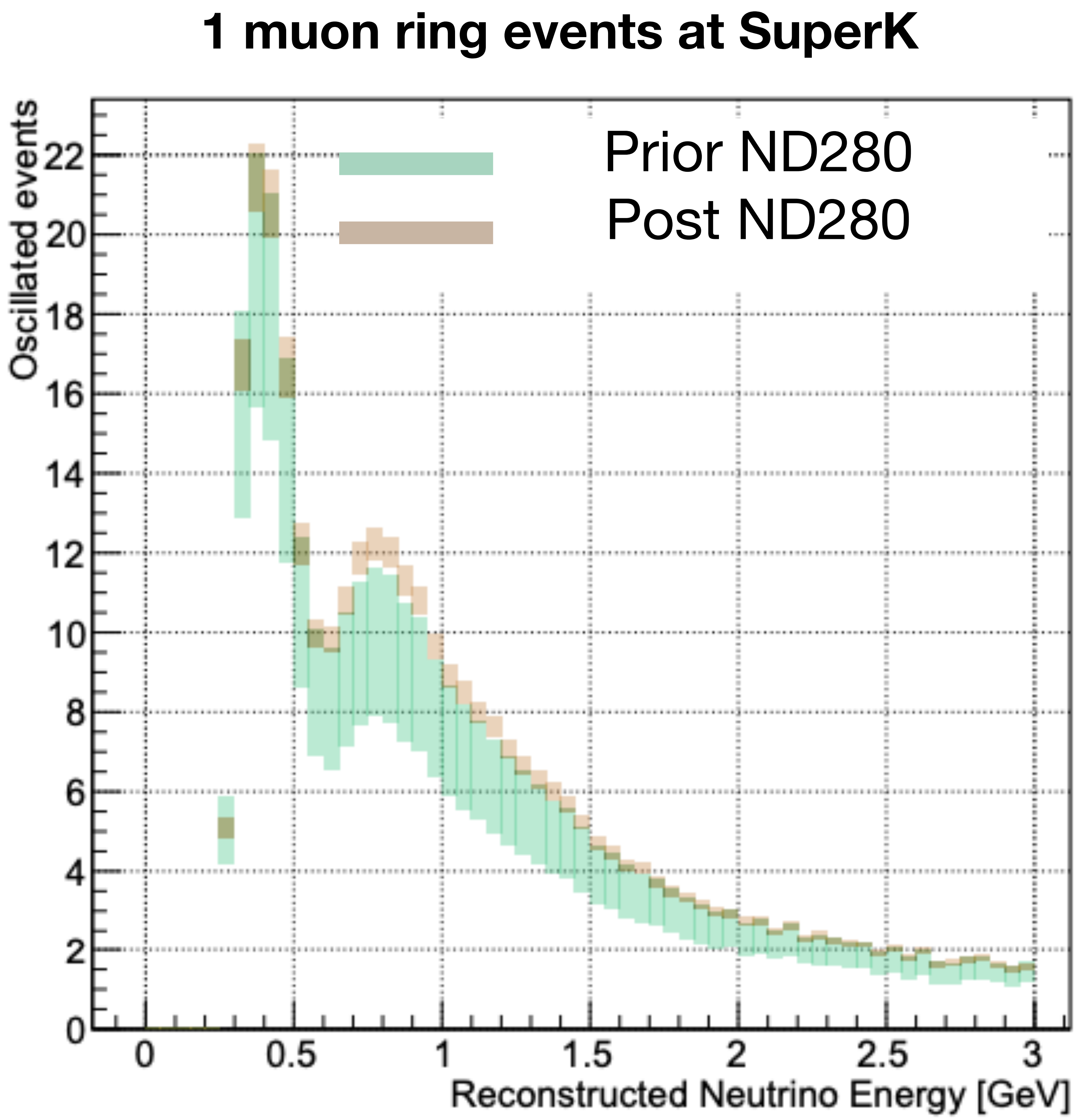


ND280 Upgrade 2024



ND280 analysis workflow





$$N^{ND}_{\nu_\alpha}(E_\nu) = \Phi^{ND}_{\nu_\alpha}(E_\nu) \times \epsilon^{ND}(E_\nu) \times \sigma^{ND}_{\nu_\alpha}(E_\nu)$$

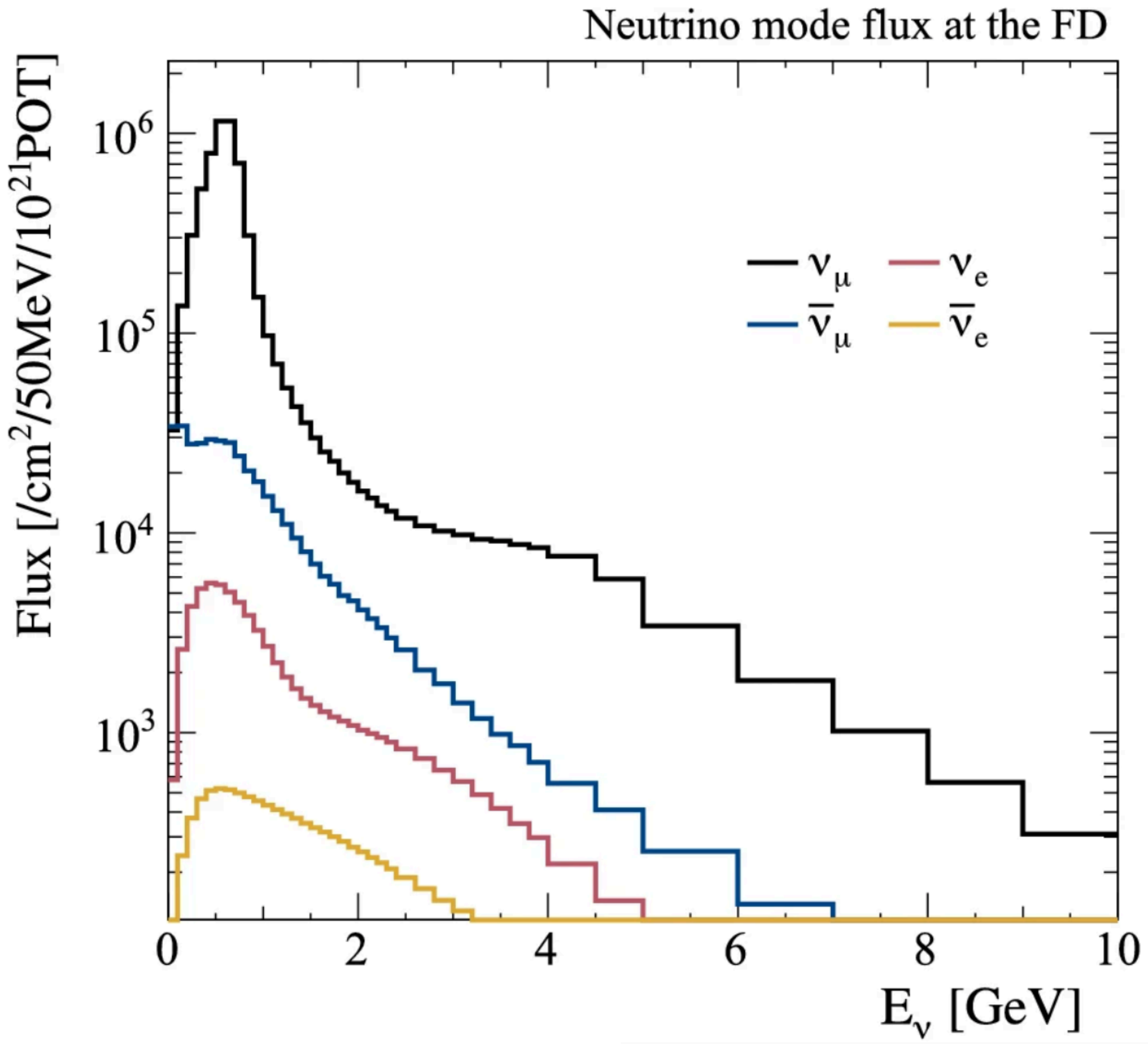
$$N^{FD}_{\nu_\beta}(E_\nu) = \Phi^{FD}_{\nu_\beta}(E_\nu) \times \epsilon^{FD}(E_\nu) \times \sigma^{FD}_{\nu_\beta}(E_\nu) \times P_{\nu_\alpha \to \nu_\beta}(E_\nu)$$

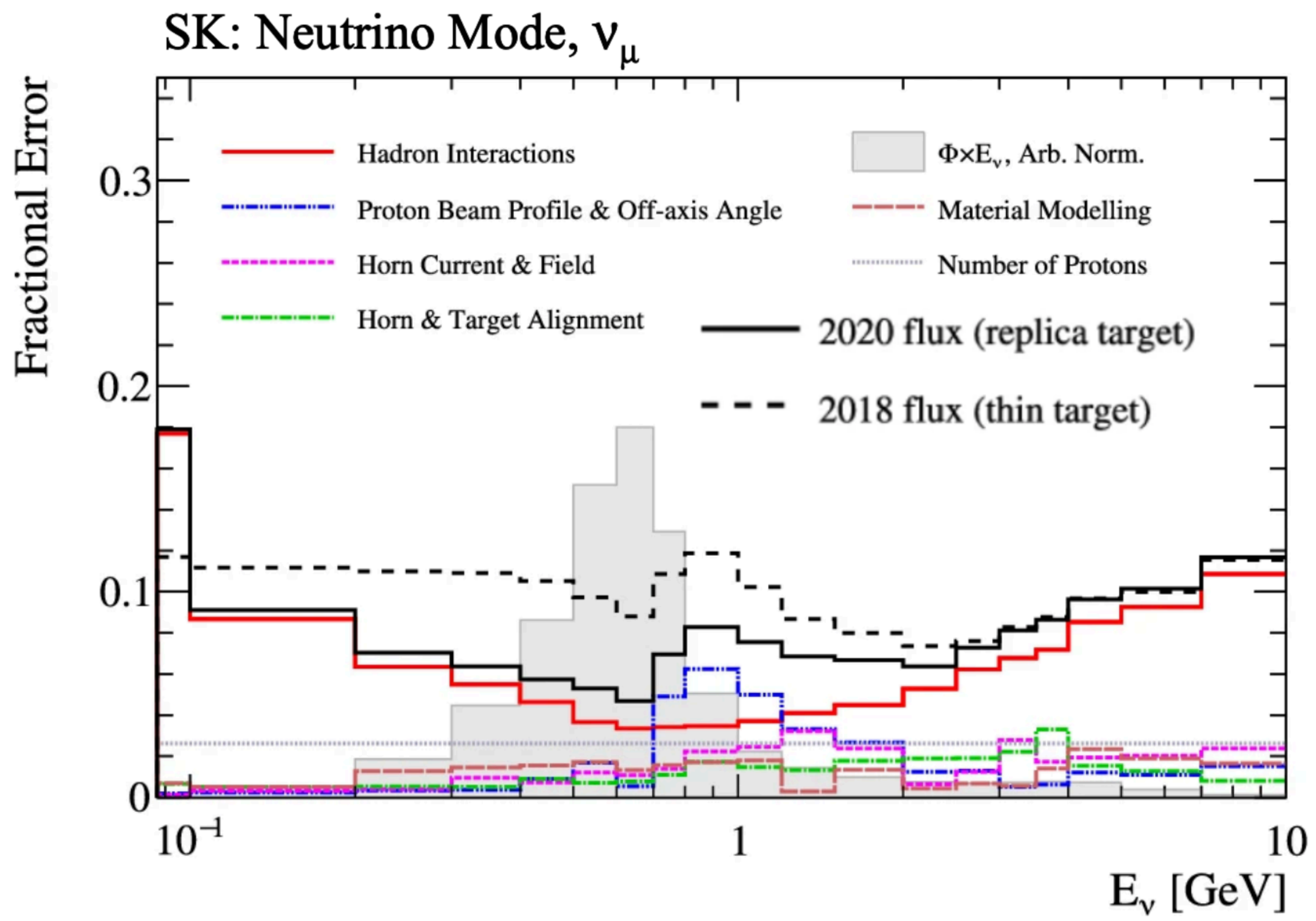
Neutrino flux | Detector efficiency | Neutrino interaction

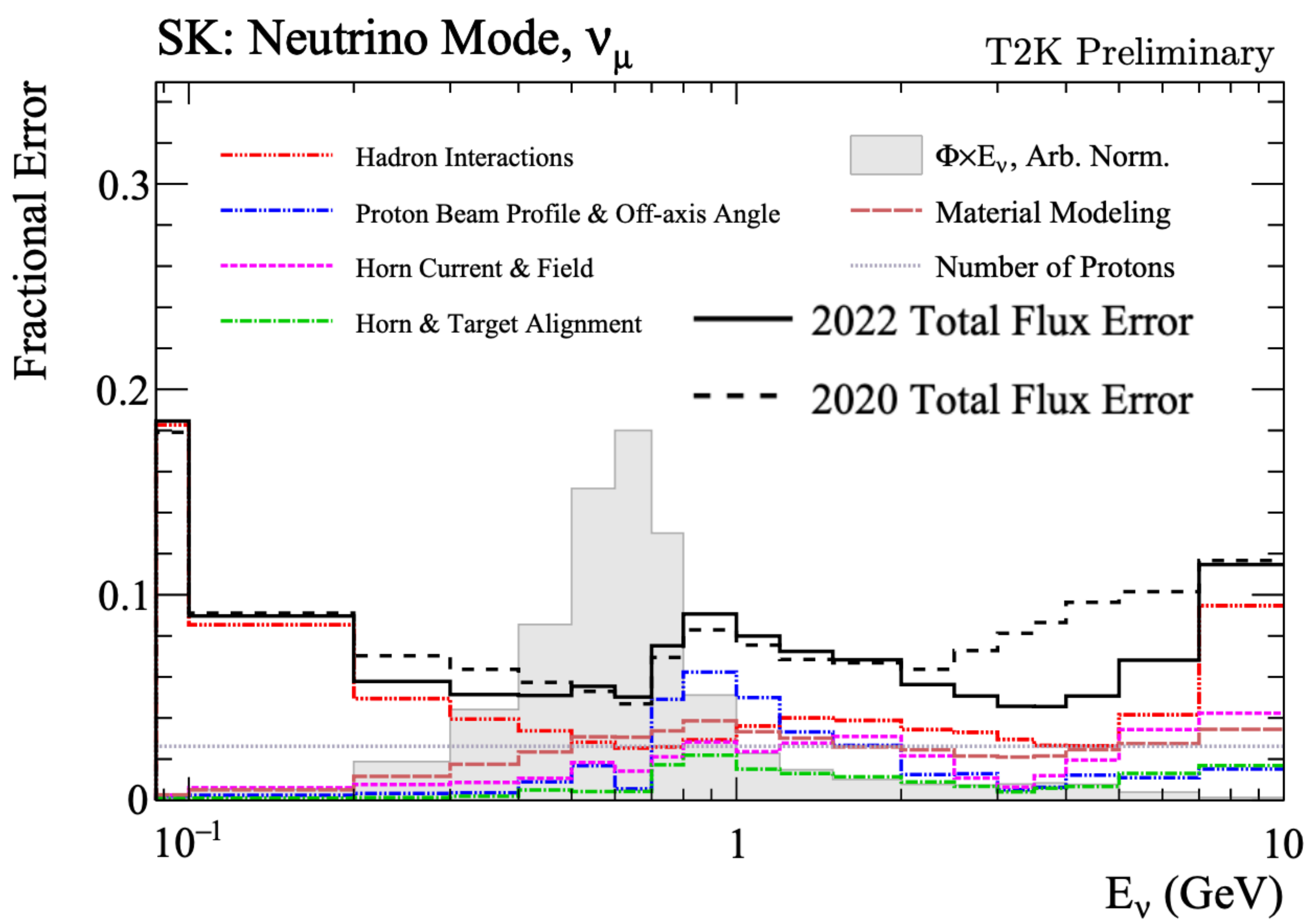
E.g.: uncertainties on 1-Ring ν_μ and ν_e events at Super-K are reduced from ~15% to < 5% with near detector constraints

Neutrino beam

- T2K setup allows switching between neutrino and antineutrino beam modes by changing polarity of focusing horns
- Flux simulation tuned with NA61/SHINE hadron production data
- NA61/SHINE replica target data (**Eur. Phys. J. C 76, 617 (2016)**):
    - Reduce flux uncertainty from ~10% to ~5% around flux peak
    - Include exiting kaons, protons and pions
    - Reduce uncertainties at higher energies
- Further flux fine tuning based on in-situ measurements with beam monitors



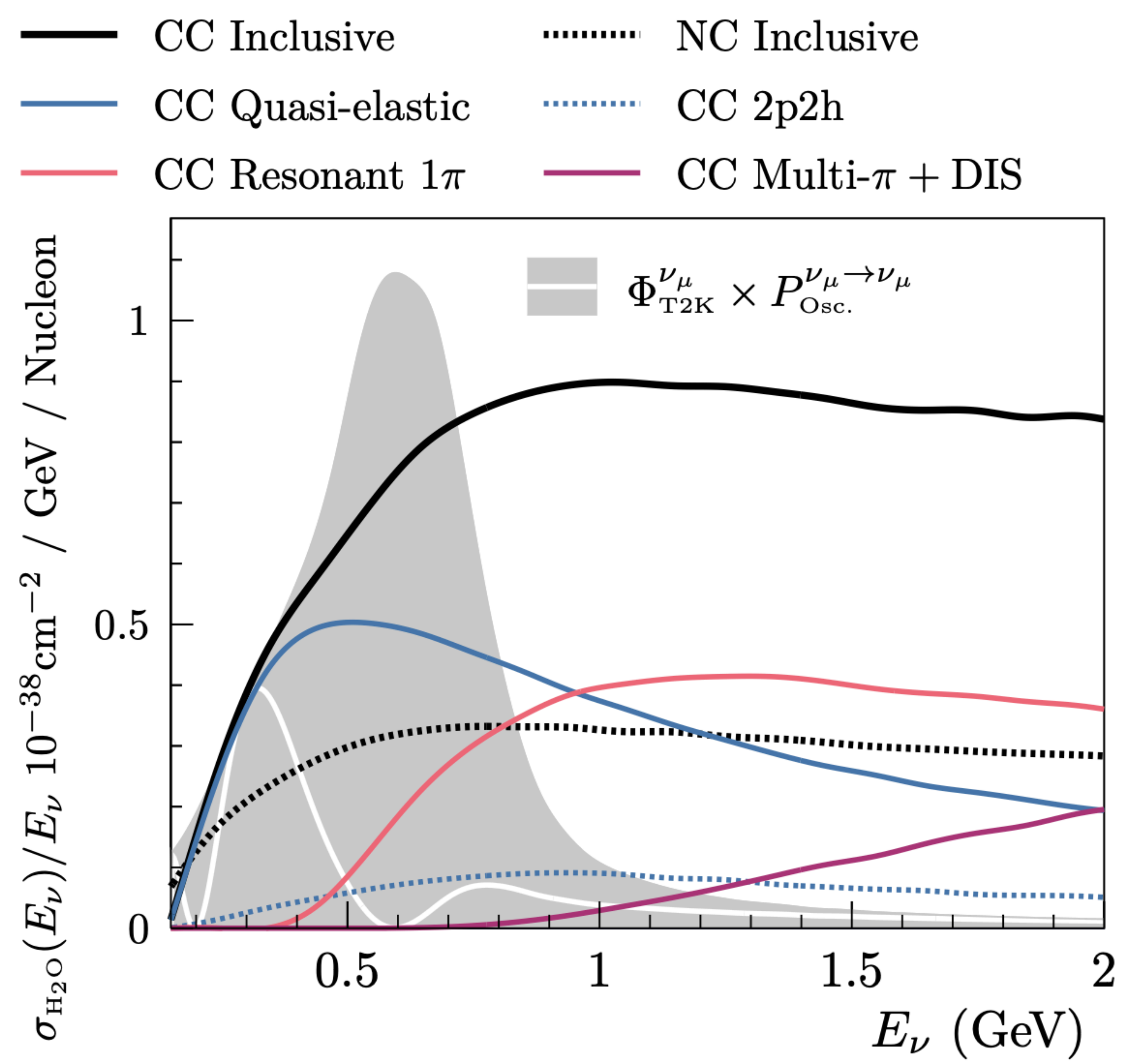




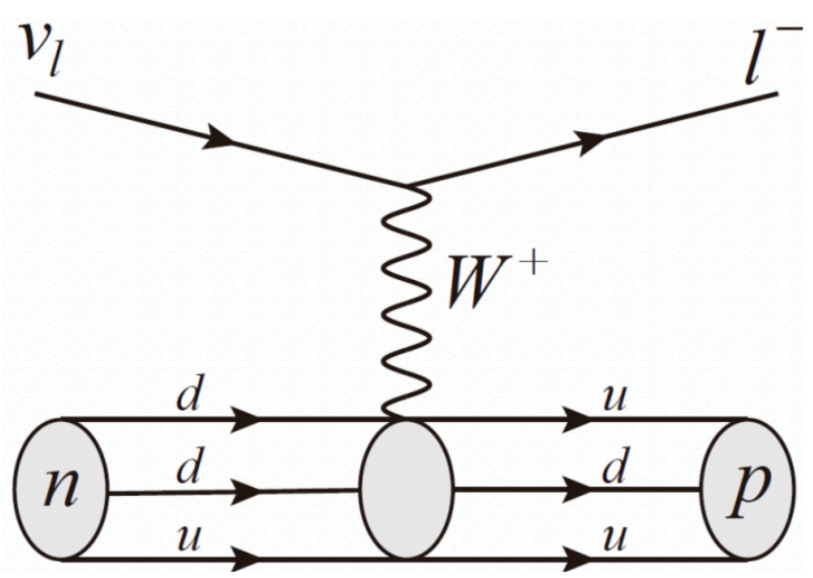
Neutrino interaction model

- **NEUT** to simulate neutrino interactions (**Eur. Phys. J. Spec. Top. 230, 4469–4481 (2021)**)

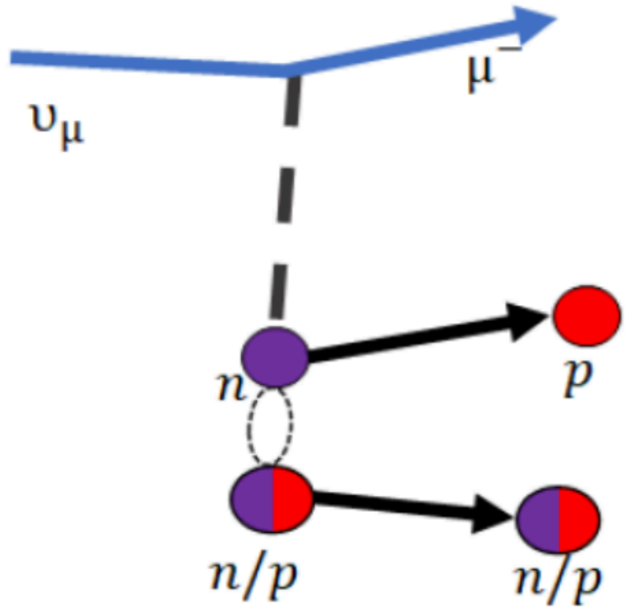
- **Charged Current Quasi Elastic (CCQE)**— dominant reaction for T2K energies:
  - Benhar Spectral Function (SF) model for nuclear structure
  - Include Pauli Blocking
- **2p2h:**
  - Base model: Valencia 2p2h
  - Better description of 2p2h pn/nn pairs contribution
- **Other:**
  - New resonance decay uncertainties
  - New Nucleon Final State Interactions (FSI) uncertainty (**Physical review D 109, 072006 (2024)**)



CCQE



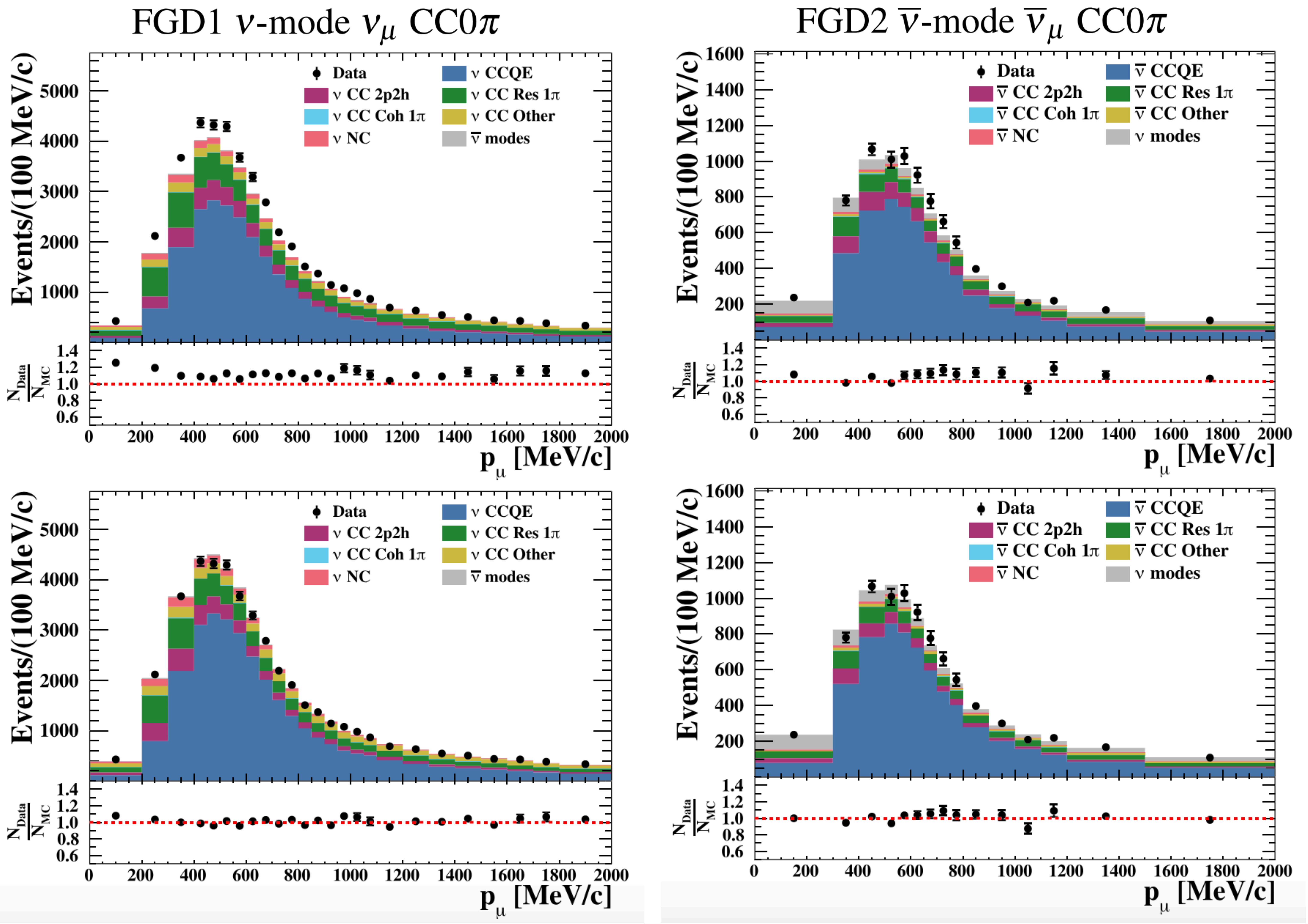
2p2h



ND280 samples: 2022 analysis

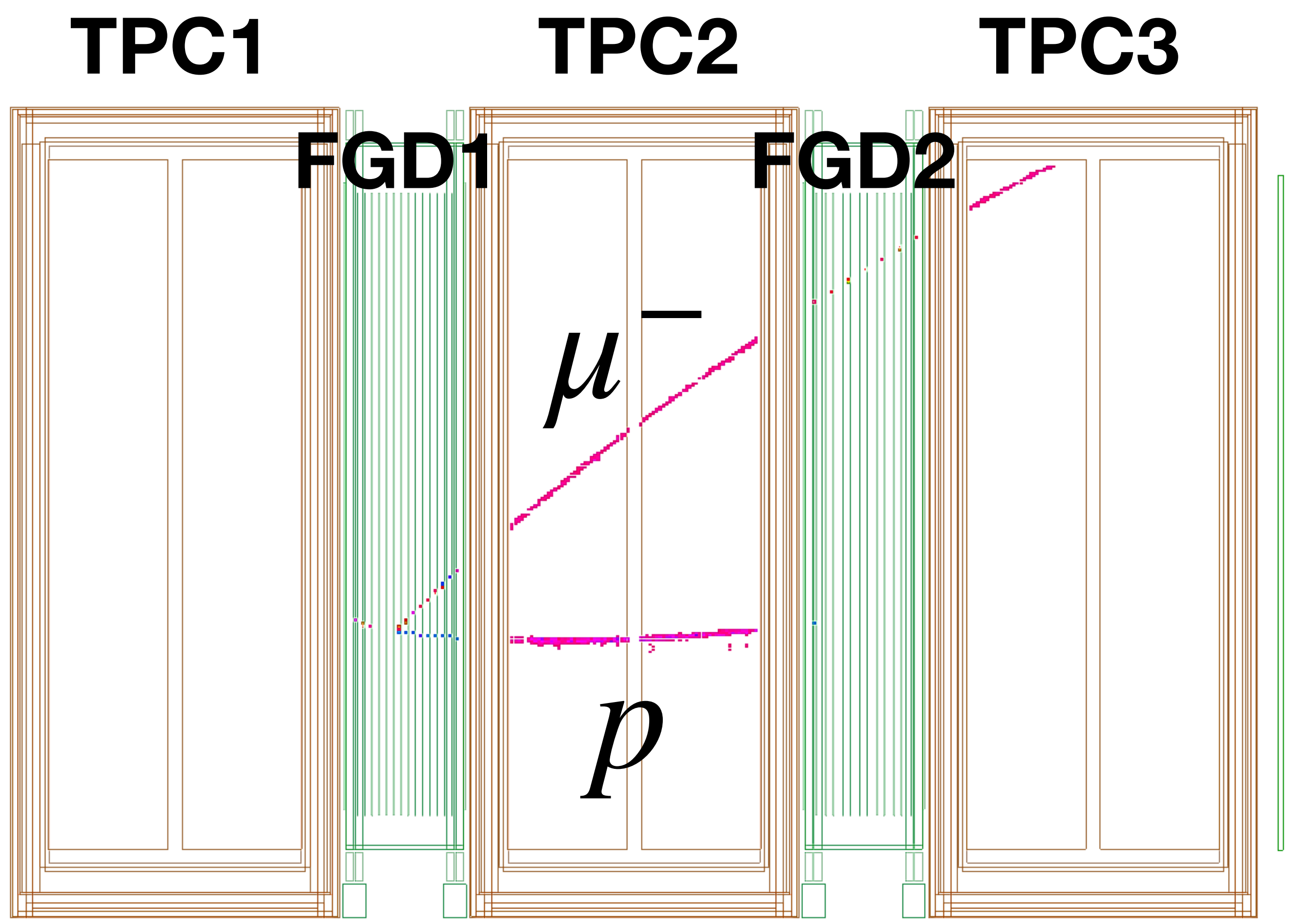
- For **ND280 fit** use samples of muon (anti)neutrino interactions in FGDs enhanced in particular reconstructed topologies. Example: $CC0\pi$, $CC1\pi$ etc

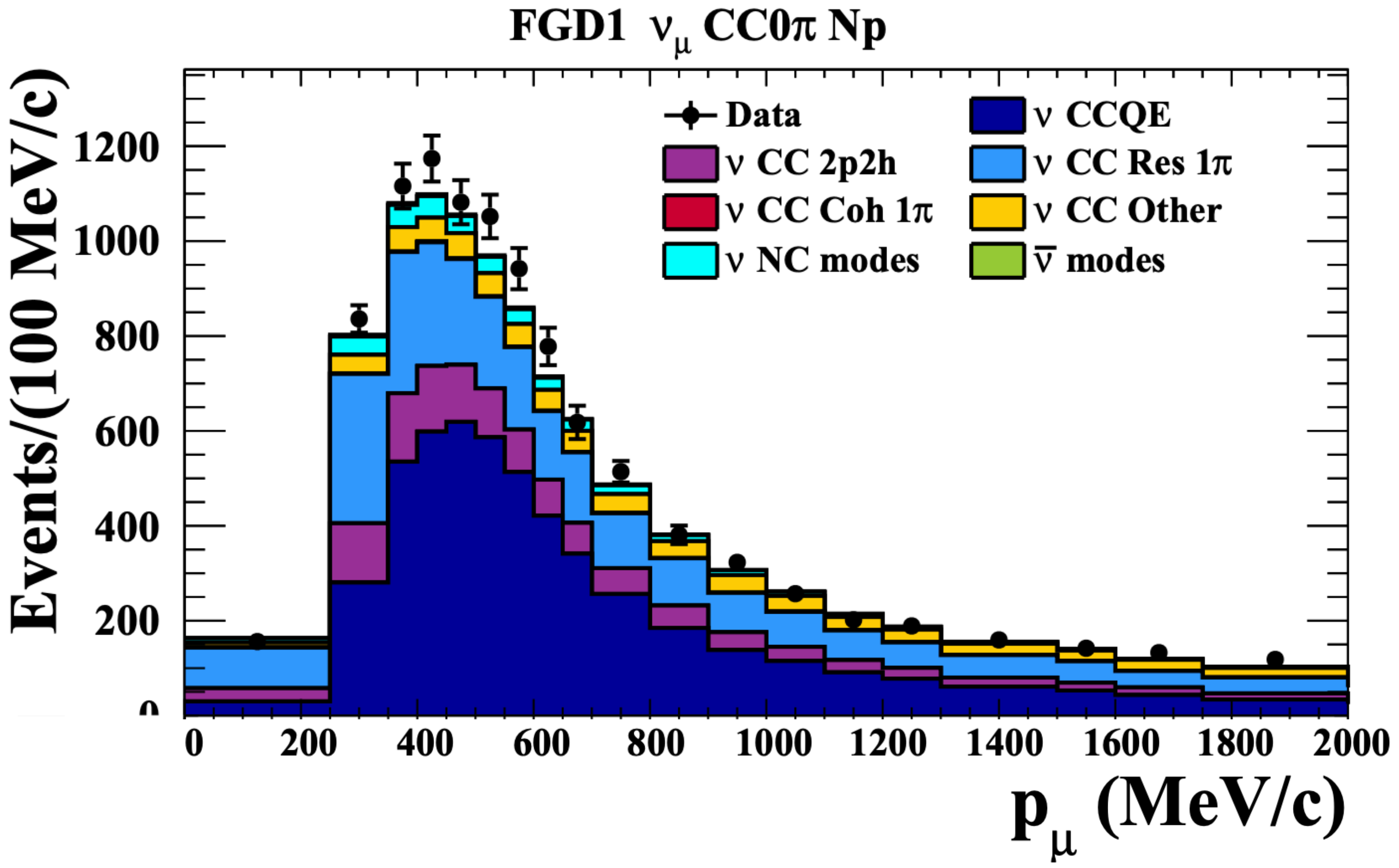
- Fit kinematics distribution to constrain flux and cross-section model parameters



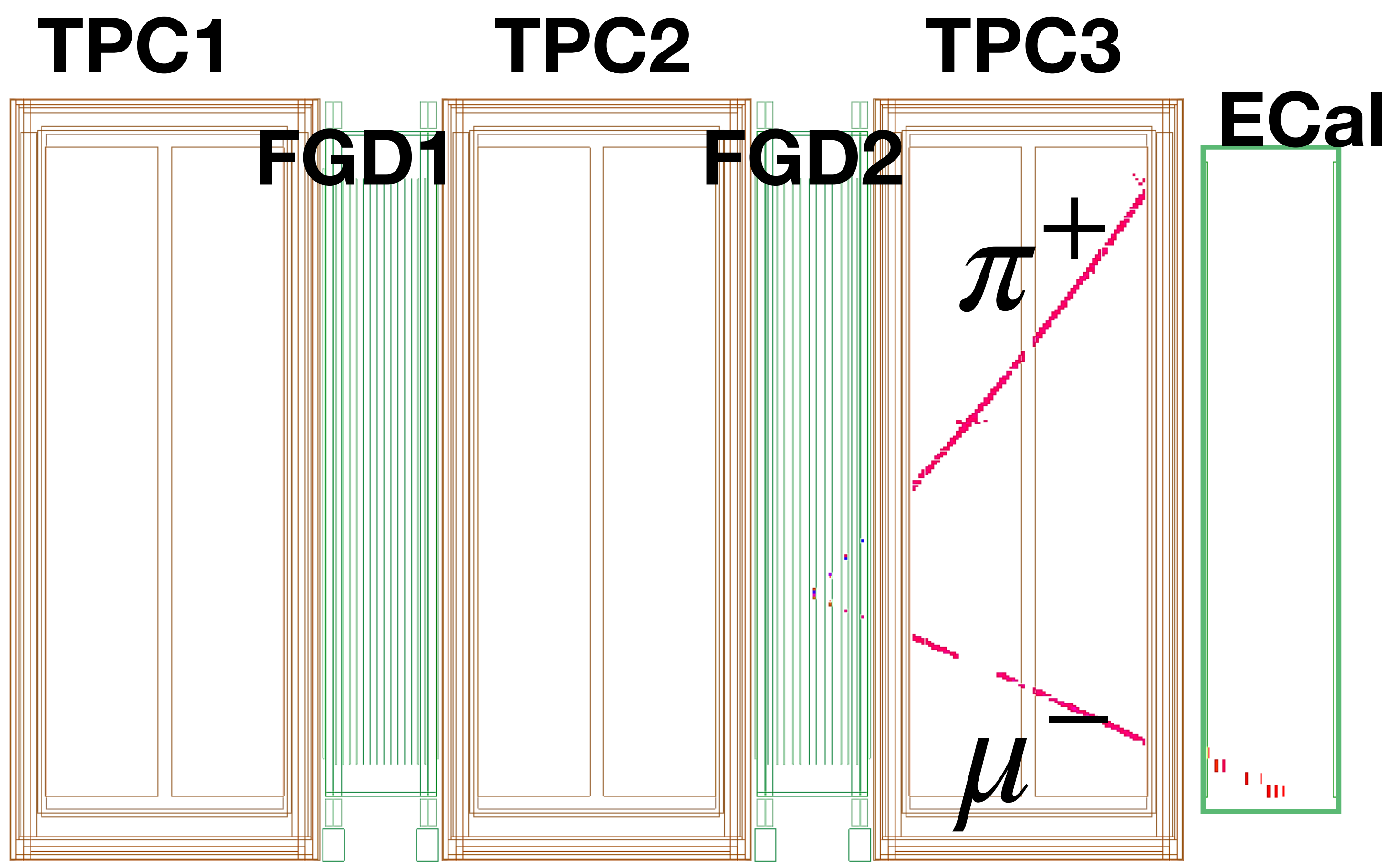
Examples of ND280 samples

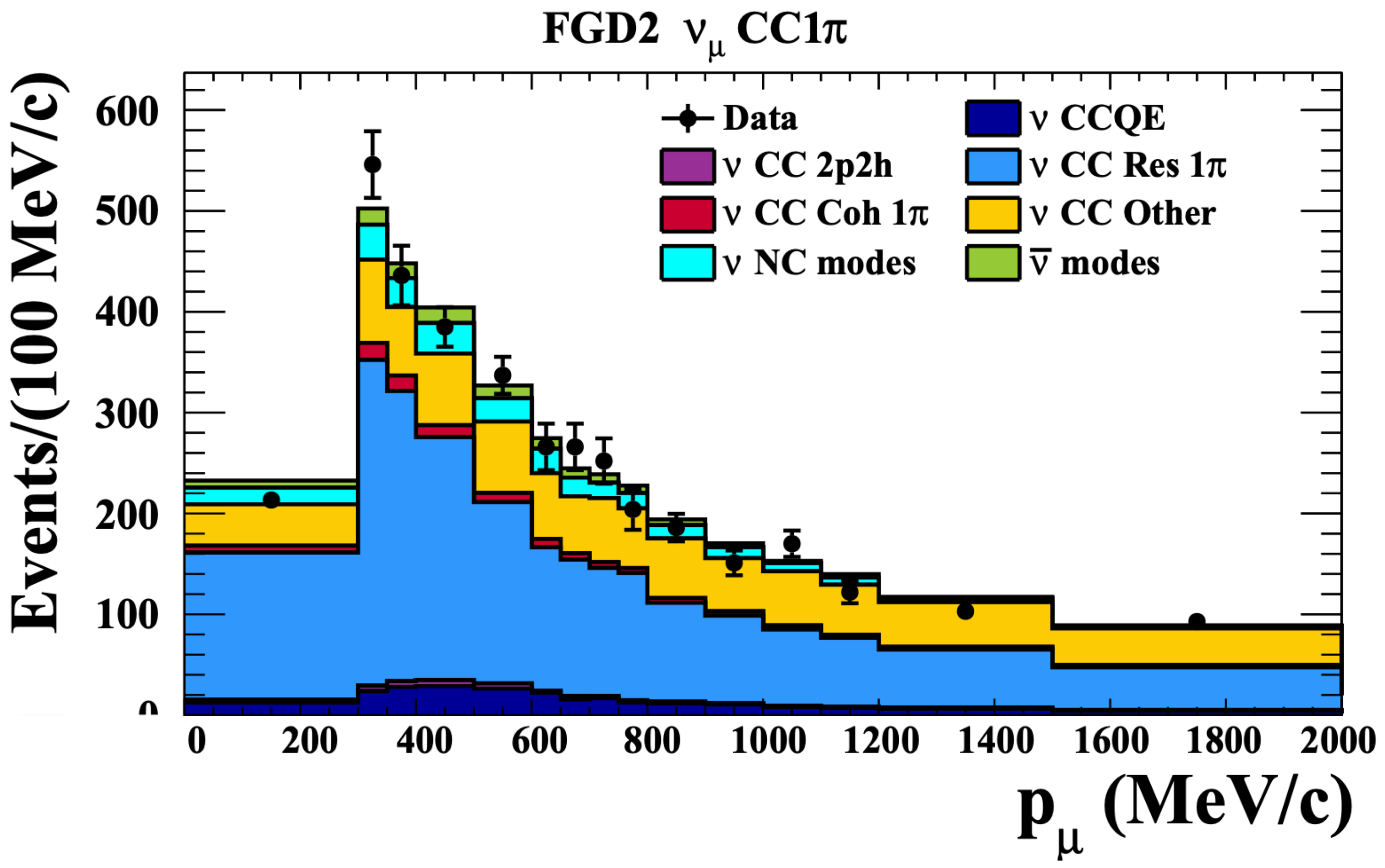
CC0π (1p) in FGD1



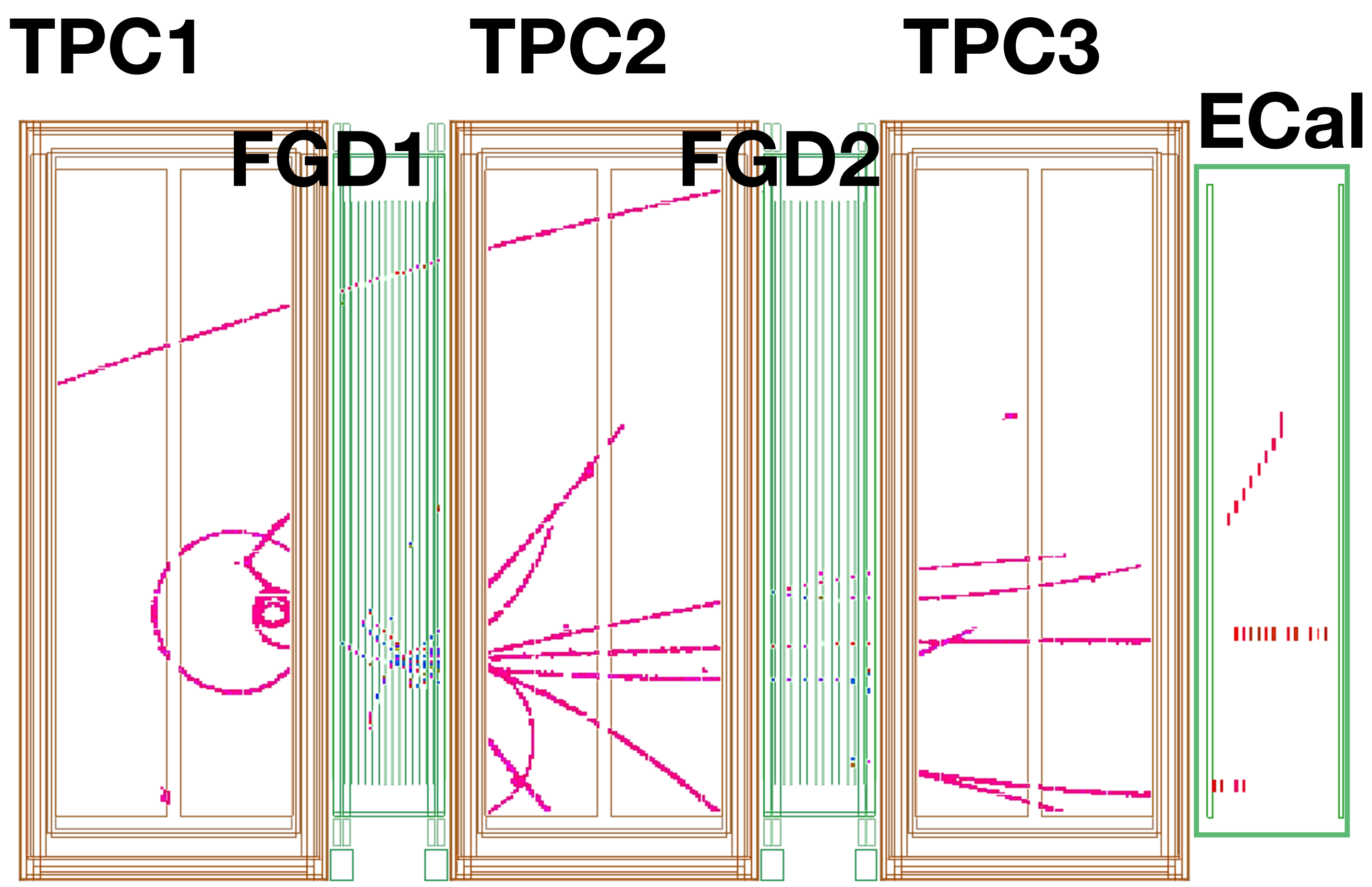


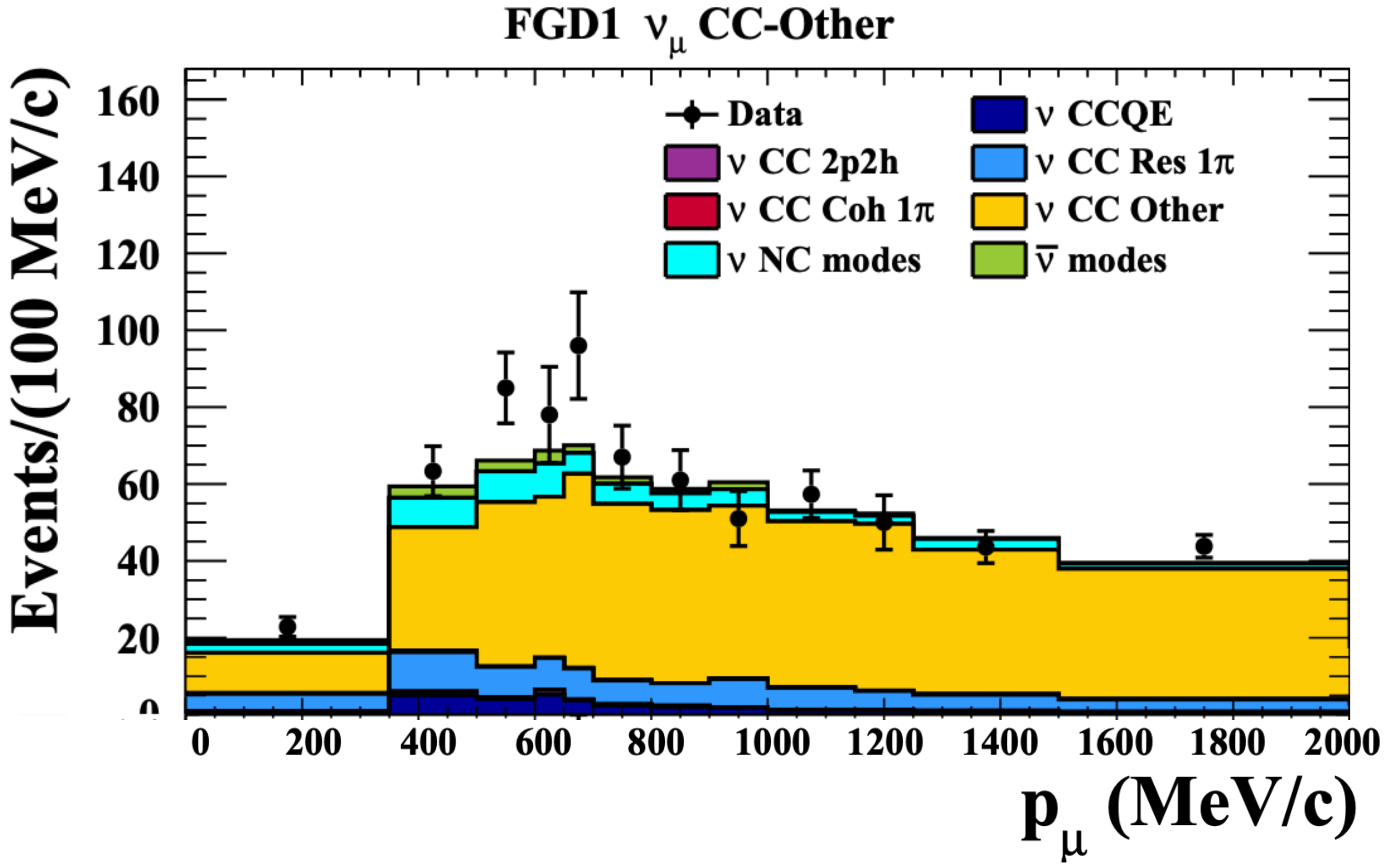
CC1π in FGD2





CC-Other in FGD1





Towards Oscillation Analysis 2024

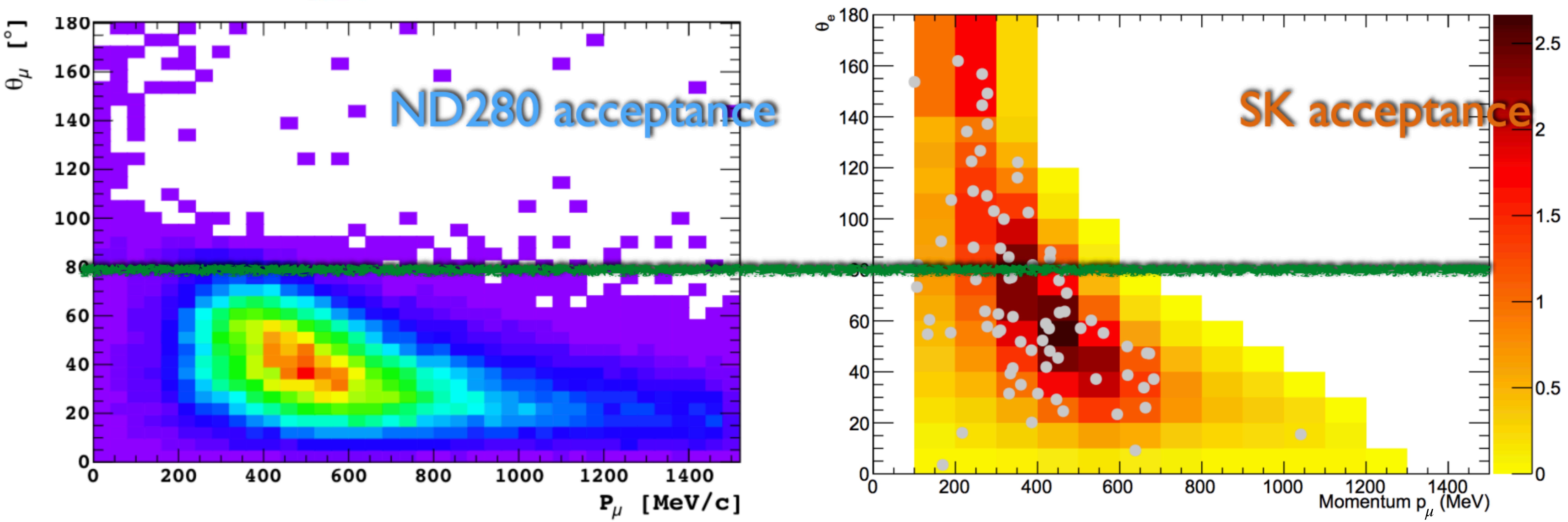
- **Near detector:**
  - Improved particle tracking
  - New parameterisation for detector systematics
  - **"4π" selection in neutrino mode**
  - Updated cross-section systematics model

- **Far detector:**
  - Include data collected in 2021 (first run with Gd (0.01%) in Super-K): +9% statistics in neutrino mode
  - New multi-ring $\nu_e CC1\pi^+$ sample (+60% statistics)
  - Updated detector systematics

Introduction of “4π” samples

Previous ND280 analyses mainly focused on forward-going muon tracks

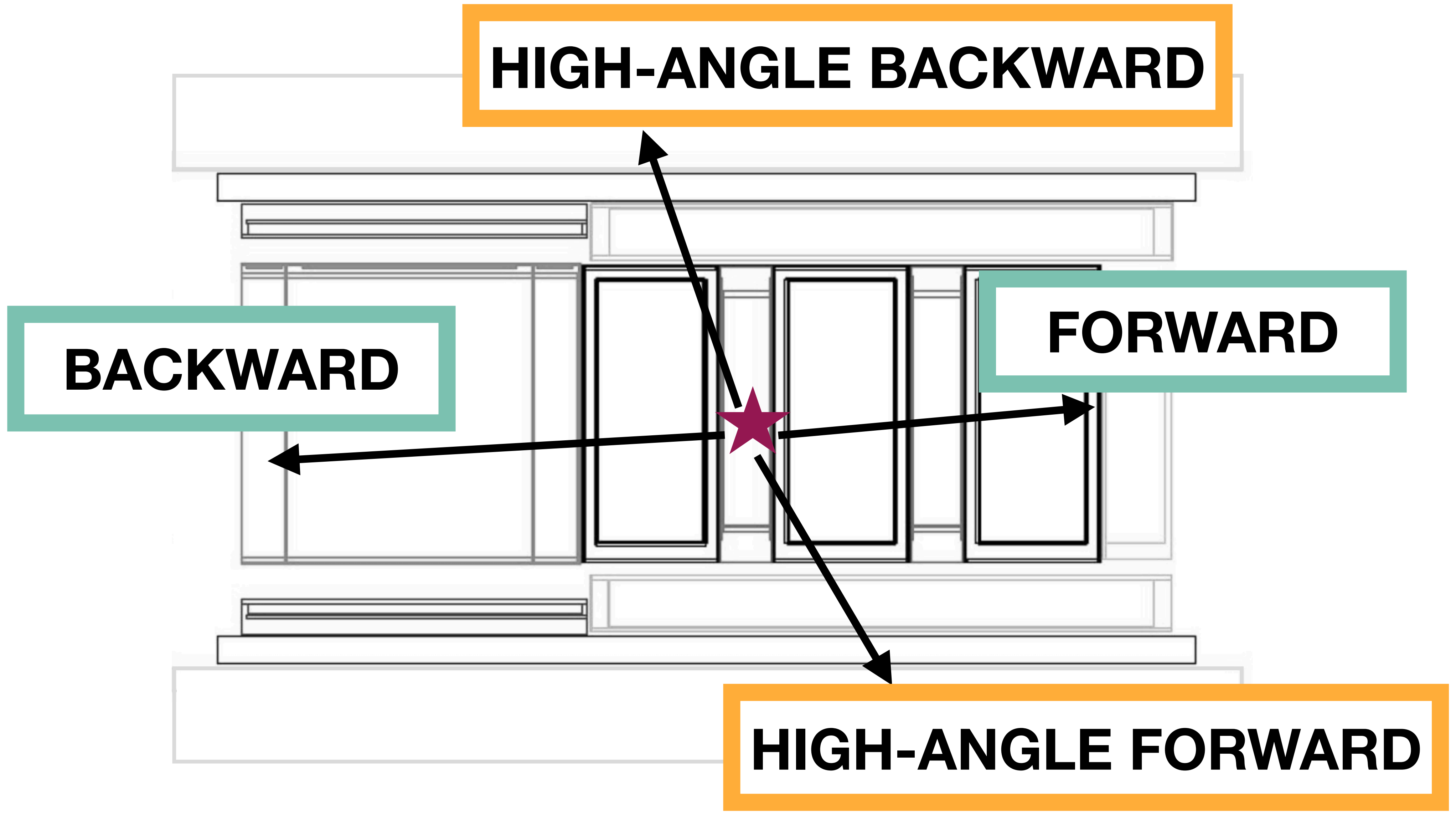
In contrast, the far detector Super-Kamiokande has the full “4π” acceptance due to its geometry



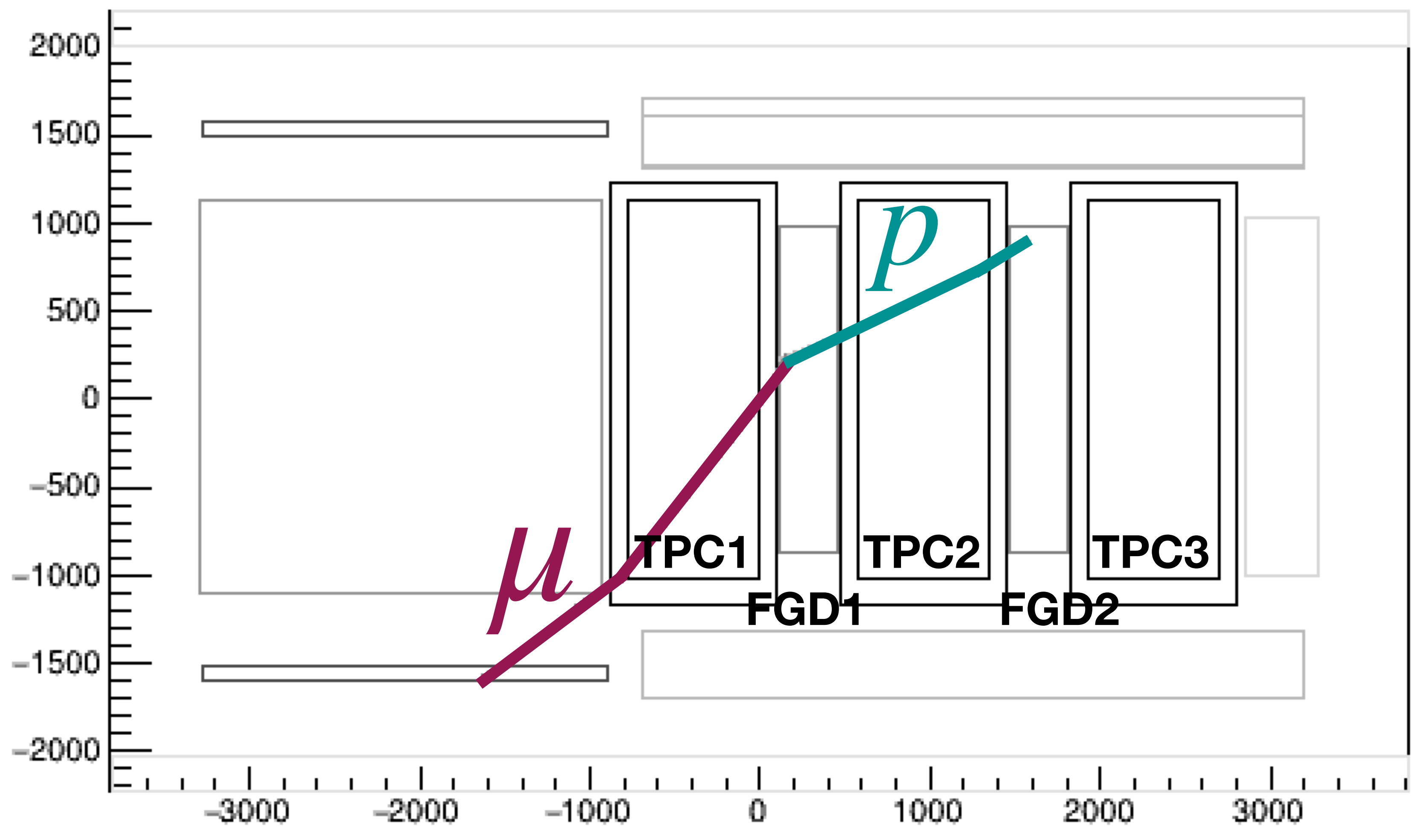
Introduction of "4π" samples

- TOF between ND280 modules can be used to determine **muon direction**:
  - Forward (FWD) or High-angle Forward (HA-FWD)
  - Backward (BWD) or High-angle Backward (HA-BWD)

- **Muon momentum** is reconstructed:
  - FWD, BWD - using curvature in TPC
  - HA-FWD, HA-BWD - using track length in FGD/ECal/SMRD

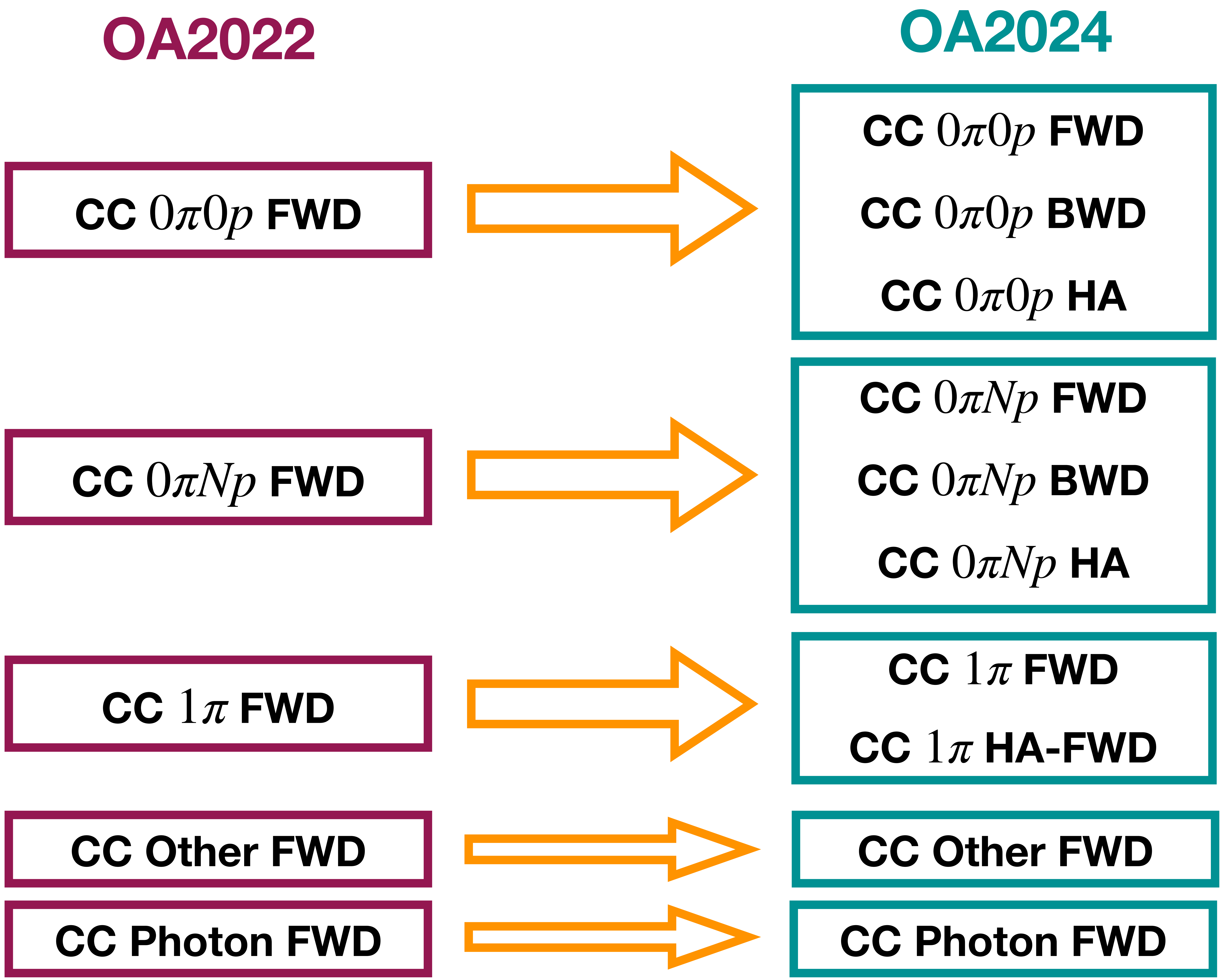


Example of backward-going muon track



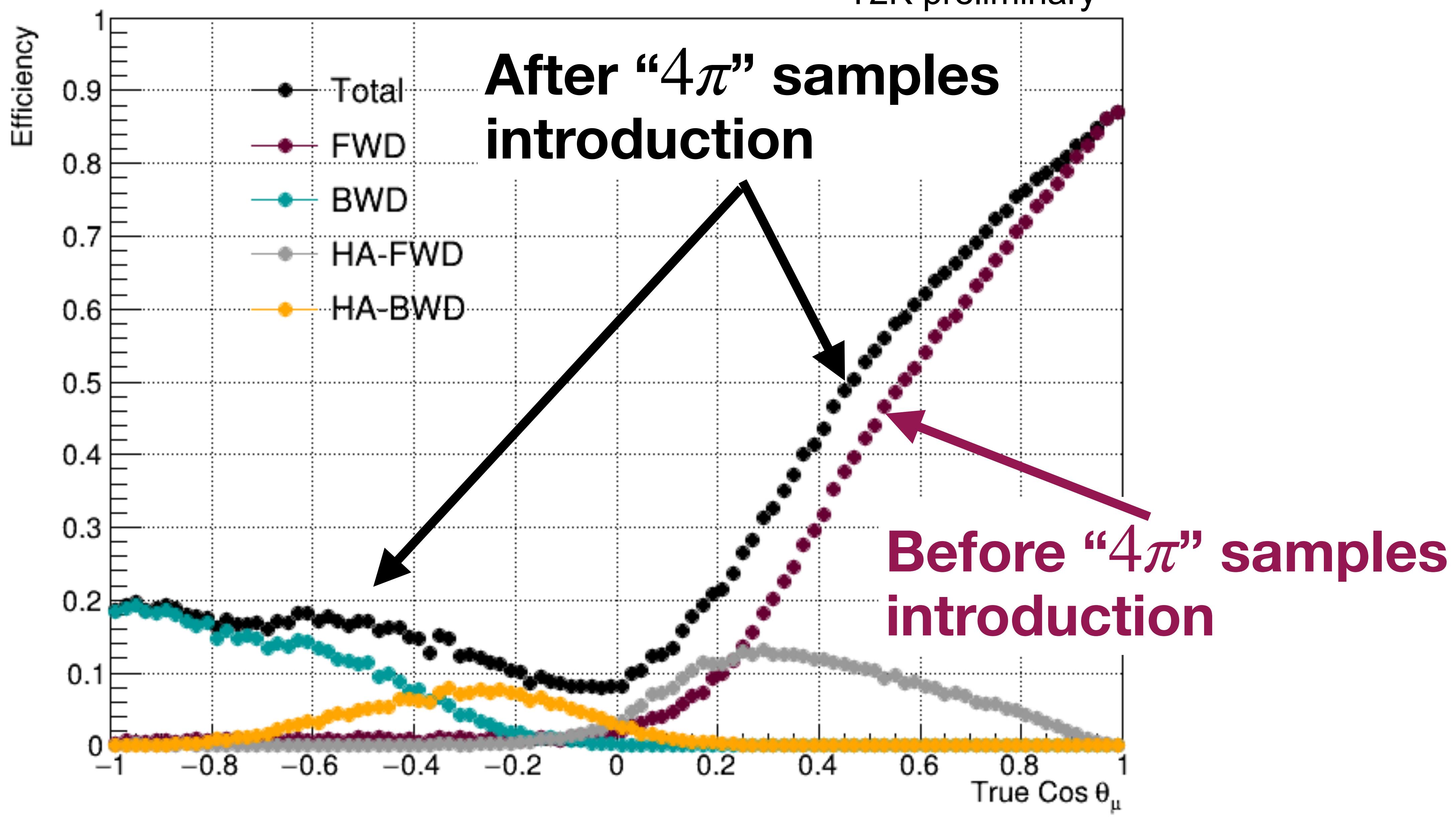
ND280 fit inputs in neutrino mode

1. Select muon candidate
2. Further distribute events into samples according to other tagged products: protons, pions, photons



“4π” selections in neutrino mode

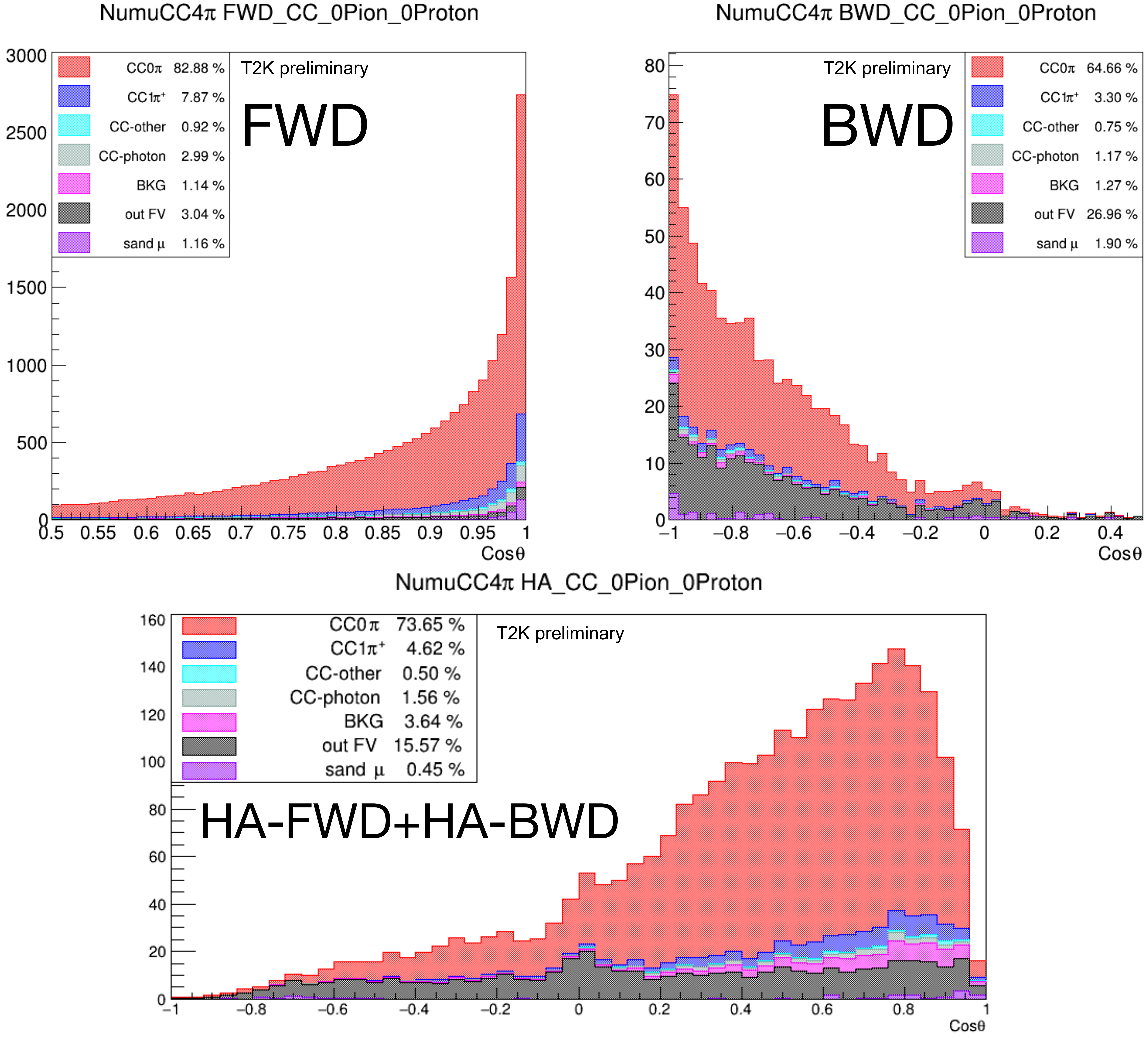
$\nu_\mu CC$ selection efficiency in FGD1



$\cos\theta_\mu$ — cosine between track direction and ν beam

	Average purity for CC, %	
	FGD1	**FGD2**
FWD	92.2	90.3
BWD	79.8	75.0
HA-FWD	89.0	88.5
HA-BWD	78.7	76.1

Example of $\cos\theta$ distributions for different selected samples



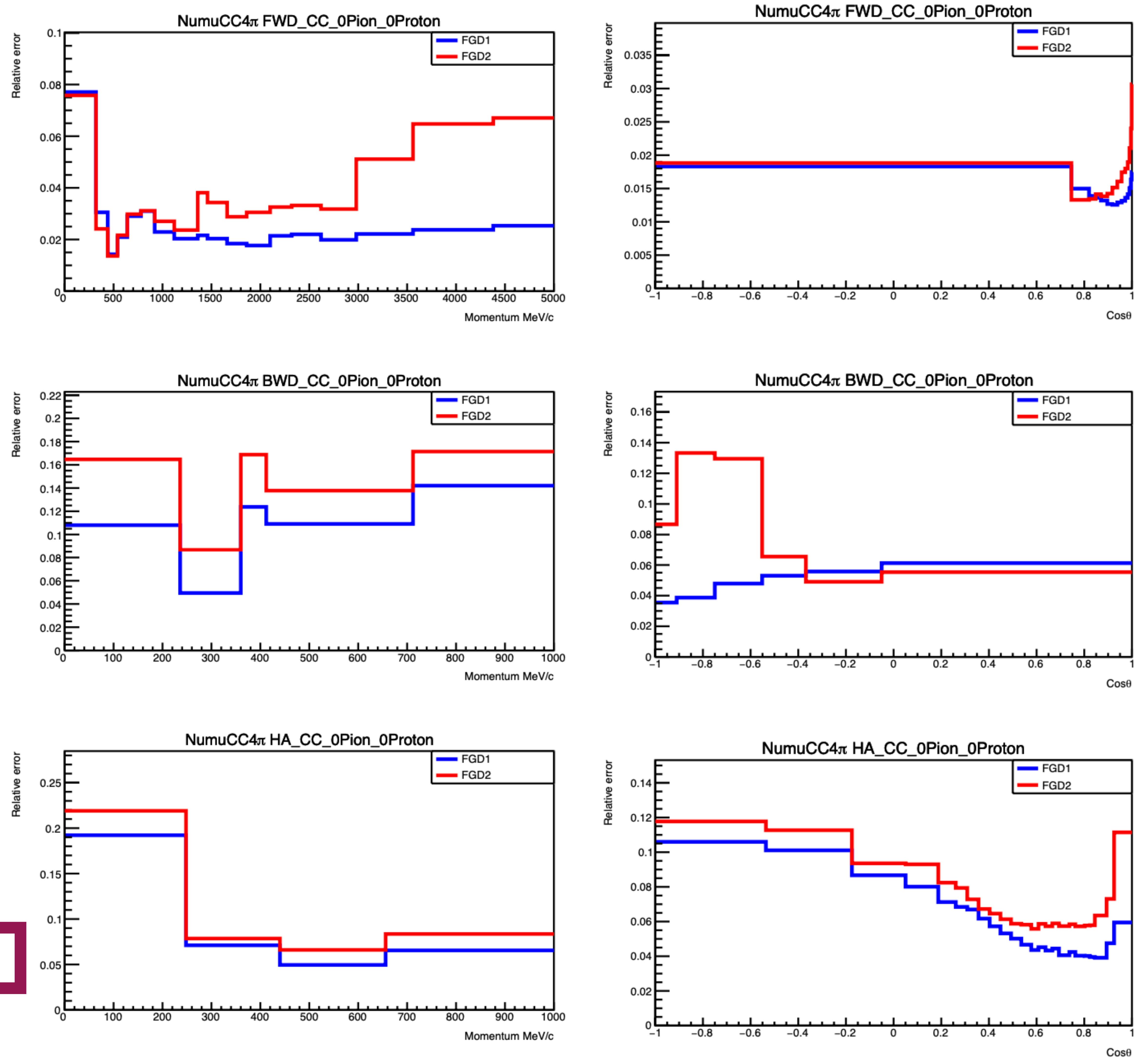
ND280 detector systematic errors

Total systematics: **detector** + cross-section model + flux ~ 10%

29 sources of detector systematics

Systematic error source	CC-0π0p FWD		CC-0π0p BWD		CC-0π0p HA	
	FGD1	FGD2	FGD1	FGD2	FGD1	FGD2
TPC PID	0.3436	0.6731	1.387	1.9316	0.2987	0.7447
FGD PID	0.2717	0.1081	0.1876	0.1138	0.212	0.1141
Momentum resolution	0.0633	0.0523	0.3414	0.183	0.0542	0.0416
Momentum scale	0.0058	0.016	0.311	0.5435	0.0085	0.0149
Range momentum resolution	0	0	0	0	0.0404	0.0433
MomBias from vertex migration	0.0139	0.0276	1.997	2.1151	0.029	0.026
TOF resolution	0.0059	0.002	2.5164	0.4726	1.2319	1.5636
B Field distortion	0.0035	0.0088	0.025	0.0779	0.0076	0.0044
ECal energy resolution	0	0	0	0	3.496	3.6844
ECal energy scale	0	0	0	0	2.7947	2.9748
Charge ID efficiency	0.0063	0.0038	0.0536	0.0044	0	0
TPC cluster efficiency	0.0062	0.0078	0.0126	0	0	0
TPC tracking efficiency	0.3614	0.4755	0.3516	0.3557	0.6219	1.0018
TPC-FGD matching efficiency	0.0723	0.1579	0.0071	0.0040	0.0043	0.0134
FGD hybrid tracking efficiency	0.6365	0.2306	0.6243	0.2573	0.8519	0.4403
Michel electron efficiency	0.1924	0.1752	0.1295	0.1053	0.1584	0.1292
Pile-up	0.4286	0.5037	0.4274	0.5037	0.4283	0.5037
FGF mass	0.6005	0.3845	0.4808	0.2919	0.5586	0.3659
OOFV background	0.4035	0.6866	1.9936	9.0665	1.1823	1.0857
TPC-ECal matching efficiency	0.5735	0.3700	0.8822	0.3114	0.2220	0.2595
TPC-P0D matching efficiency	0	0	0.3715	0.1058	0	0
FGD-ECal matching efficiency	0.0001	0	0	0	1.3793	2.8525
FGD-ECal-SMRD matching	0	0	0	0	0.9271	0.9470
ECal tracking efficiency	0.2885	0.3242	0.4054	0.3818	0.5473	0.5770
ECal PID	0.0460	0.0321	0.0588	0.0755	0.1012	0.1219
ECal photon pile-up	0.7621	0.7621	0.7617	0.7621	0.7621	0.7621
Pion secondary interaction	0.2671	0.2497	0.1328	0.1482	0.2569	0.1823
Proton secondary interaction	0.0022	0.0025	0.0035	0	0.0389	0.0297
Sand muon background	0.0989	0.0804	0.1514	0.0810	0.0344	0.0117
Total detector systematics	1.3458	1.5209	4.0209	10.6167	5.1300	6.1923

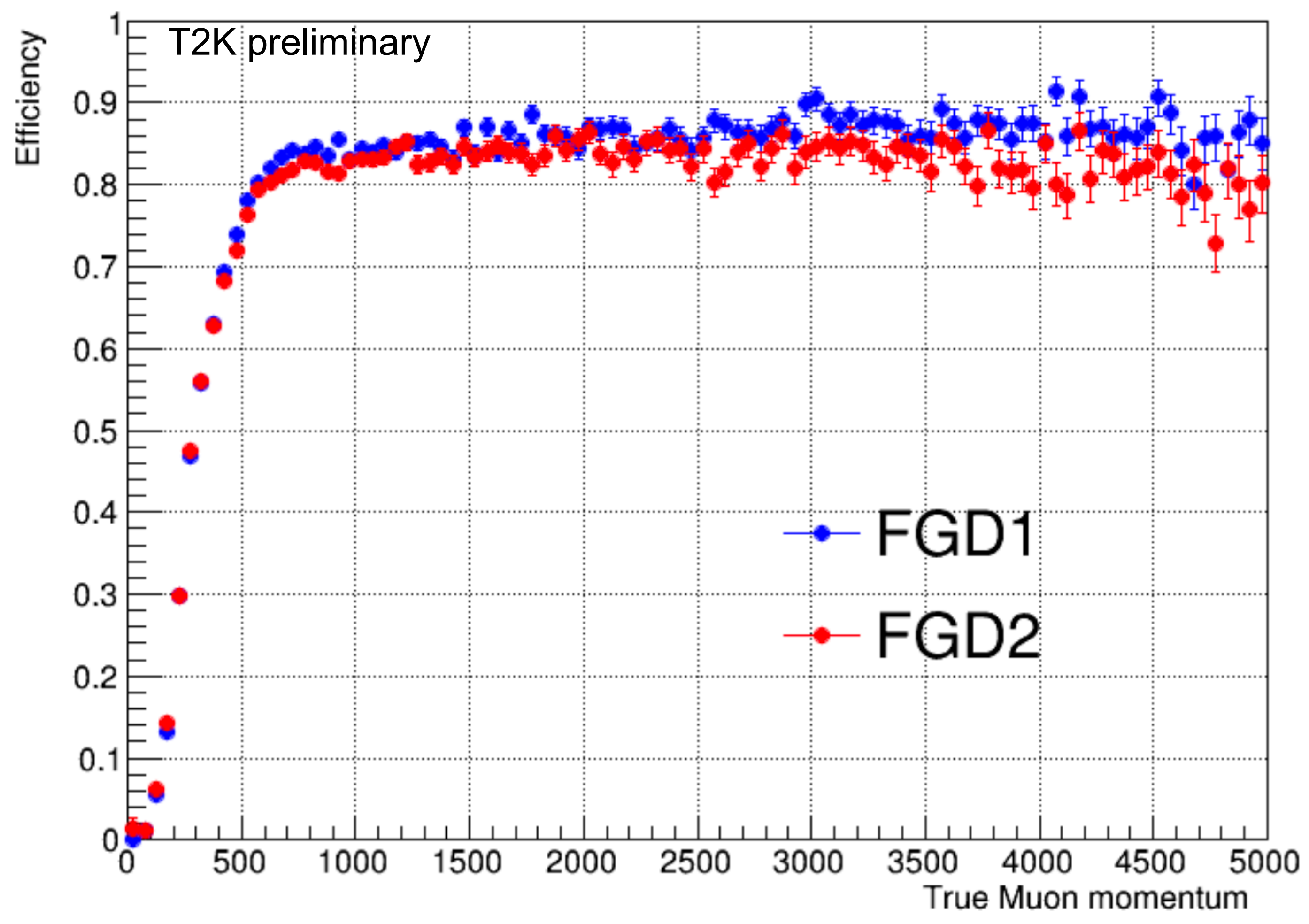
Total detector systematic depending on bin of momentum/cosθ

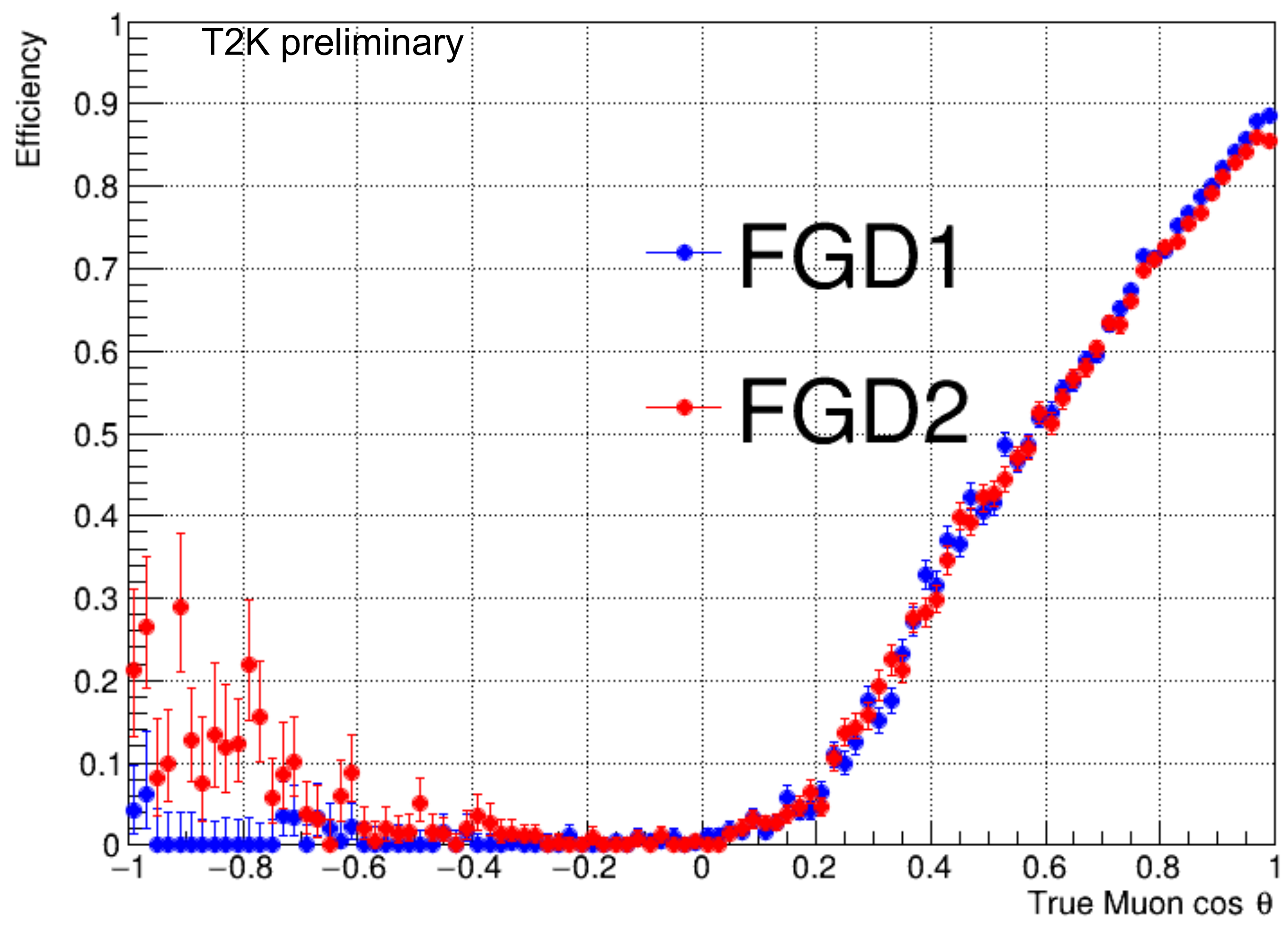


Samples in antineutrino mode

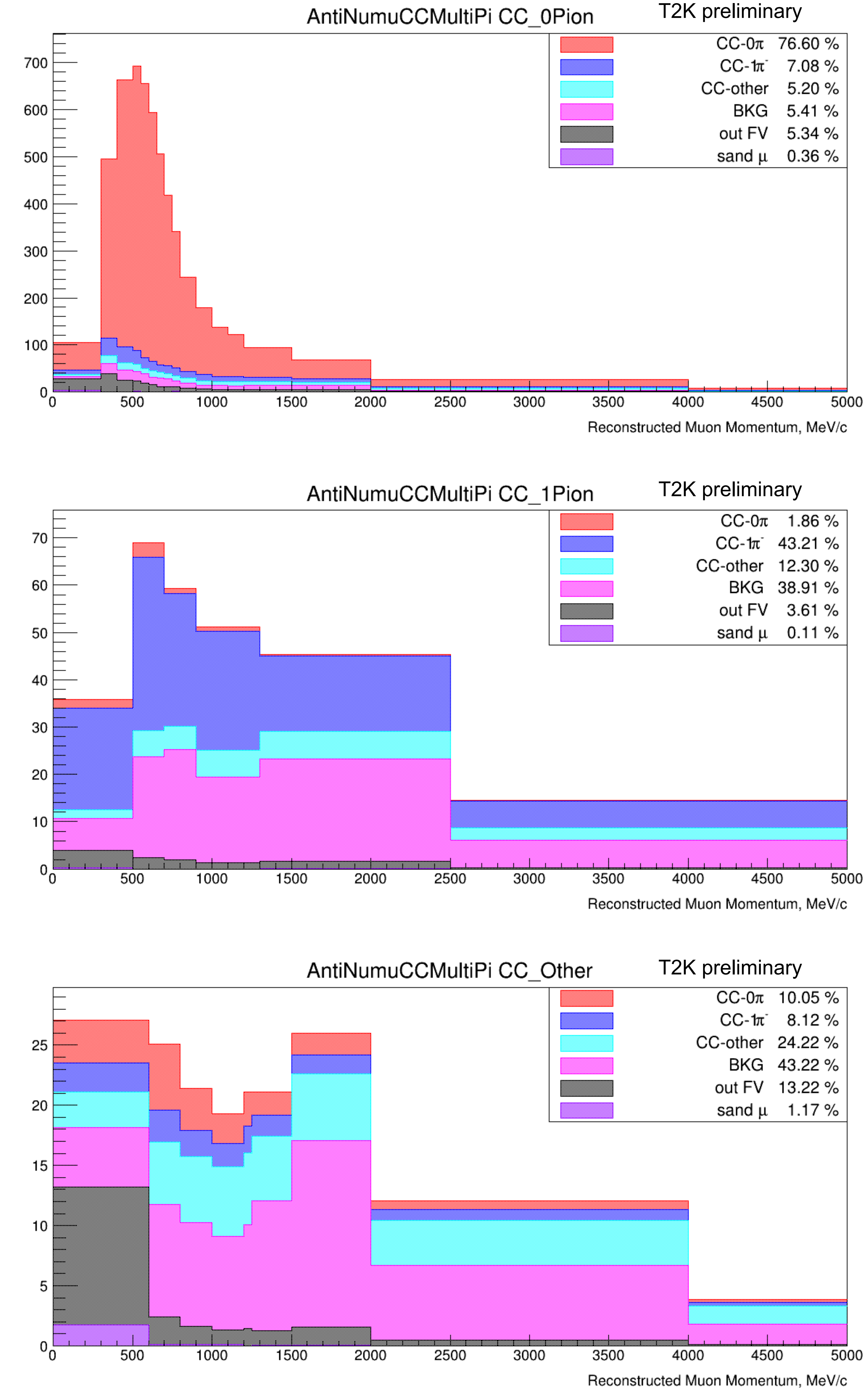
- No "4π" samples for OA2024 due to less statistics → mainly forward-going tracks
- Samples for ND280 fit: $CC0\pi$, $CC1\pi$, CC-Other
- Background contamination from neutrino interactions → constrain with a dedicated selection
- Total detector systematic error up to 4.5% (CC-Other FGD2)

$\bar{\nu}_\mu CC$ selection efficiency depending on momentum/cosθ





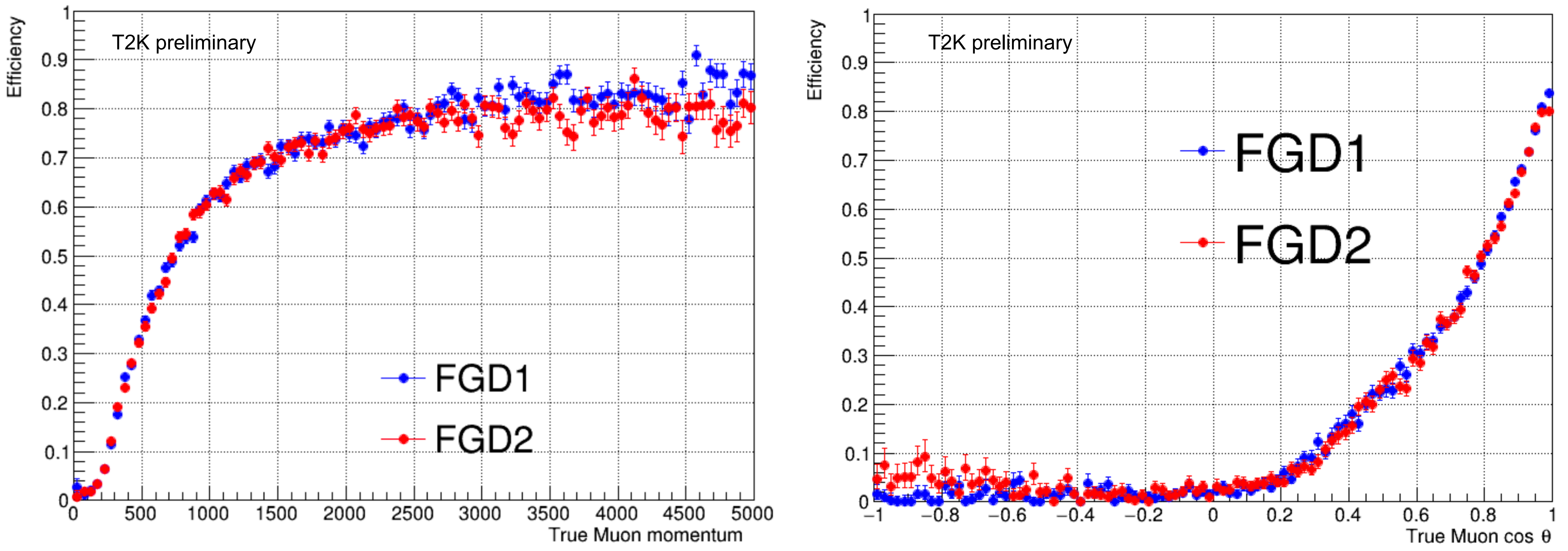
Reconstructed (anti)muon momentum in FGD1

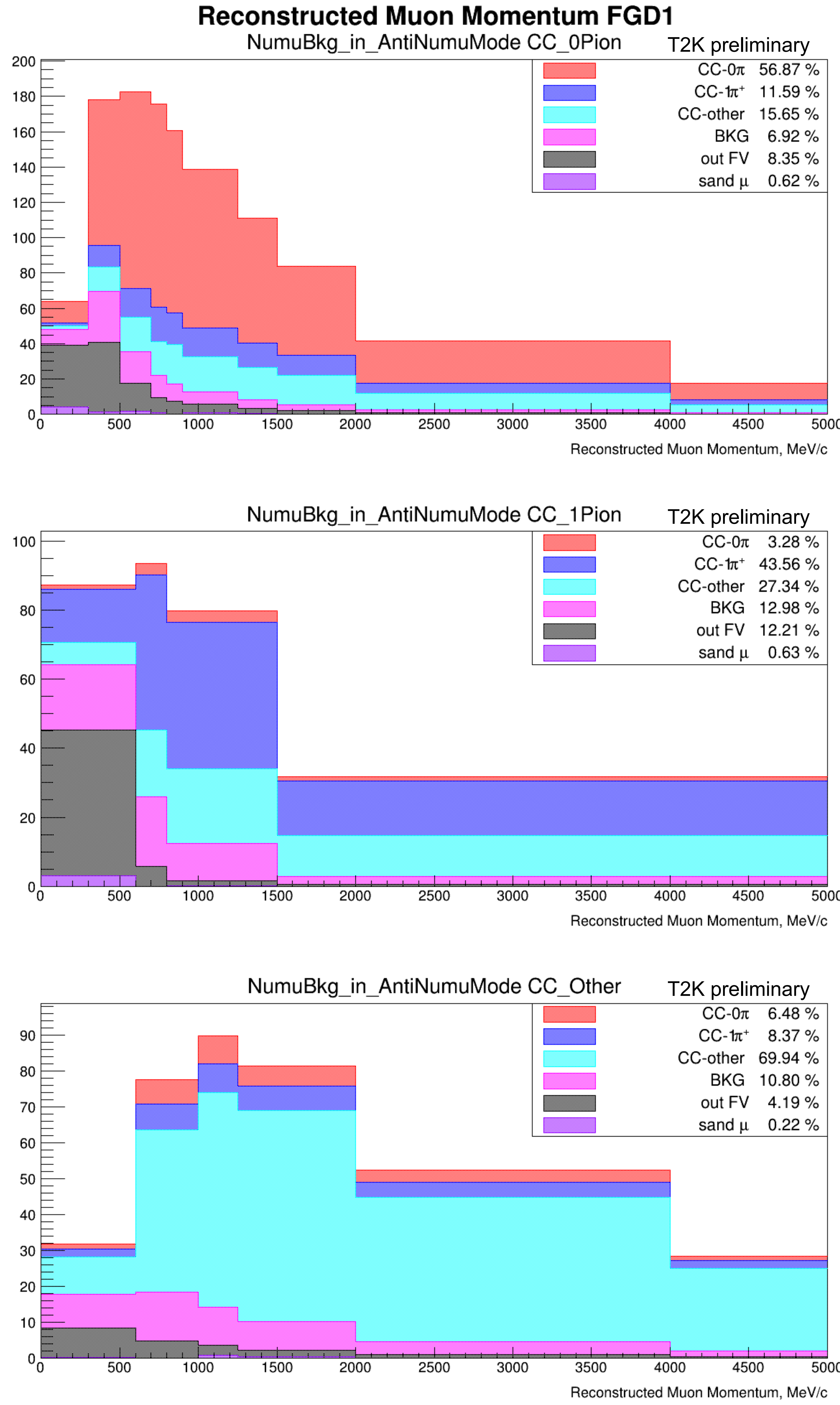


Neutrino background in antineutrino mode

- Same samples as for the antineutrino selection: $CC0\pi$, $CC1\pi$, CC Other
- Tagged μ^-candidate instead of μ^+
- Total detector systematic error up to 2.3% (CC Other FGD1)

$\nu_\mu CC$ selection efficiency depending on momentum/cosθ





Summary

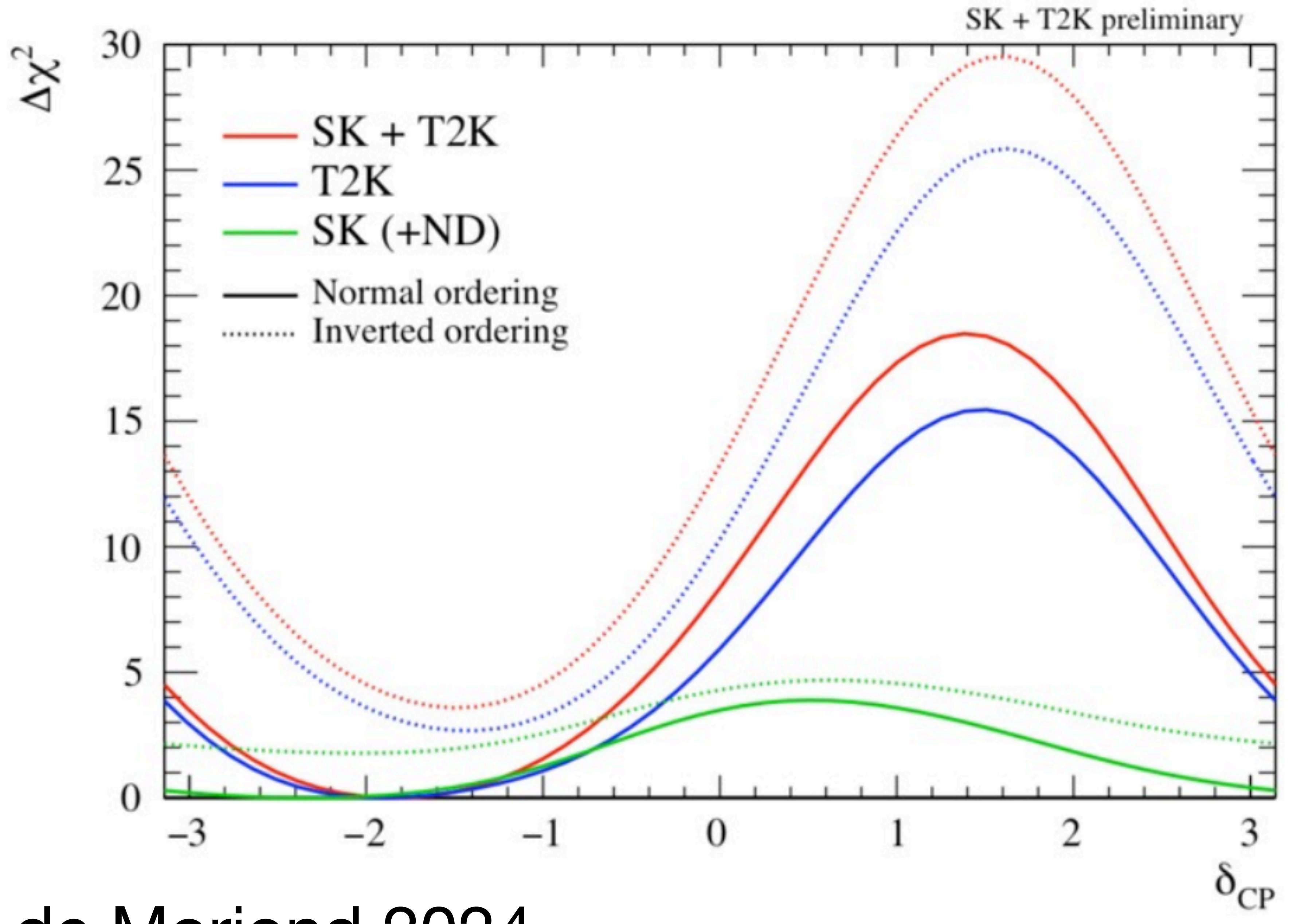
- T2K experiment leads the field of neutrino oscillation studies with accelerators:
  - CP conservation excluded at 90% CL
  - Leading measurements of “atmospheric” parameters
- Now collecting data with upgraded neutrino beam and renewed near detector ND280
- **New T2K oscillation analysis result** being prepared for Neutrino 2024
- Among other updates T2K OA2024 largely based on ND280 samples with increased phase-space acceptance:
  - Make ND280 acceptance closer to Super-K
  - Include topologies with large momentum transfers
  - Increase ND280 statistics by 15%
  - Preparatory step for a move from **ND280** to **ND280 Upgrade**

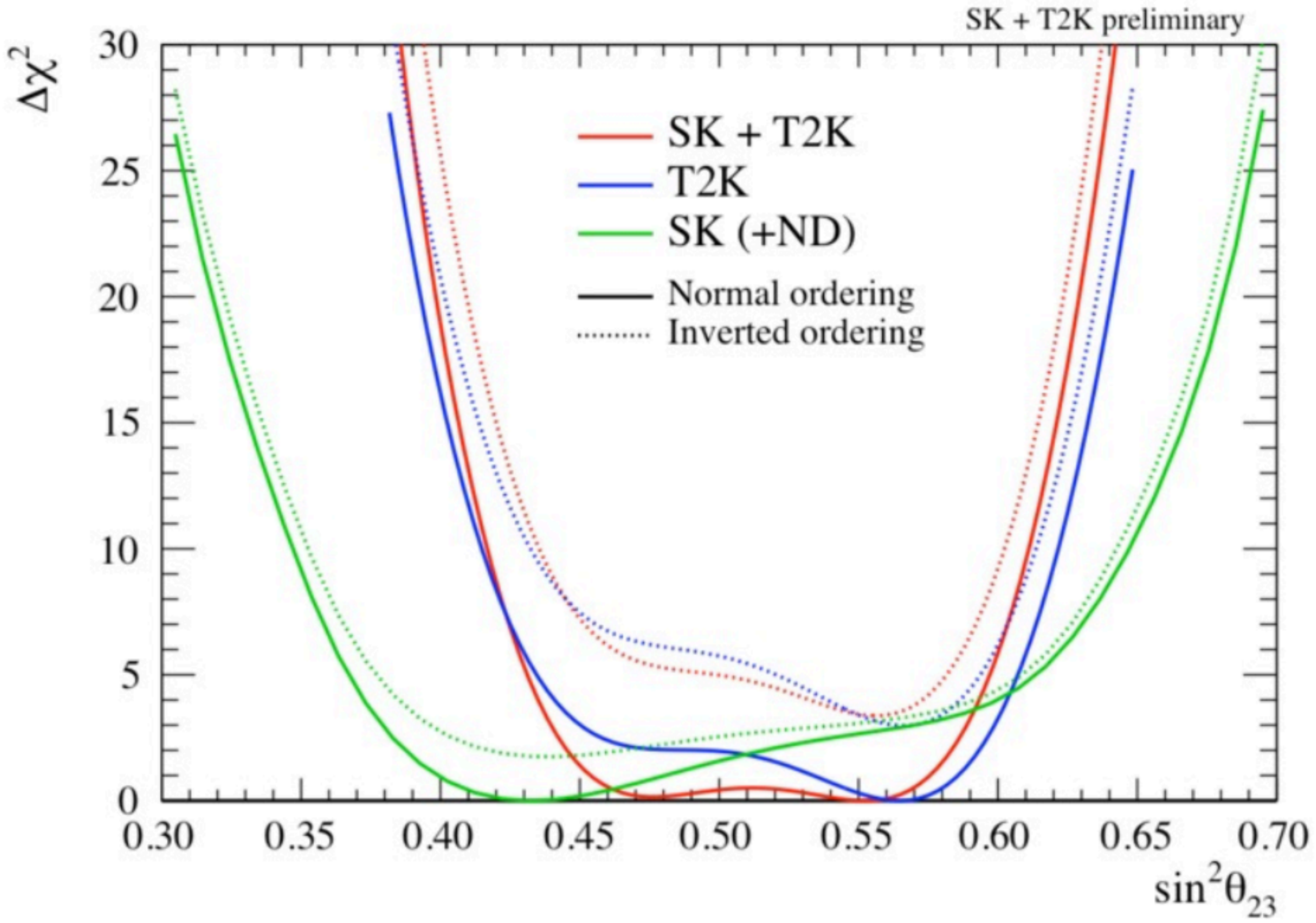
Backup

T2K+SK joint analysis

- Opposite octant preference cancellation (esp. NH)
- NO preference increases slightly
- Main differences are in δ_{CP} and $\sin^2\theta_{23}$

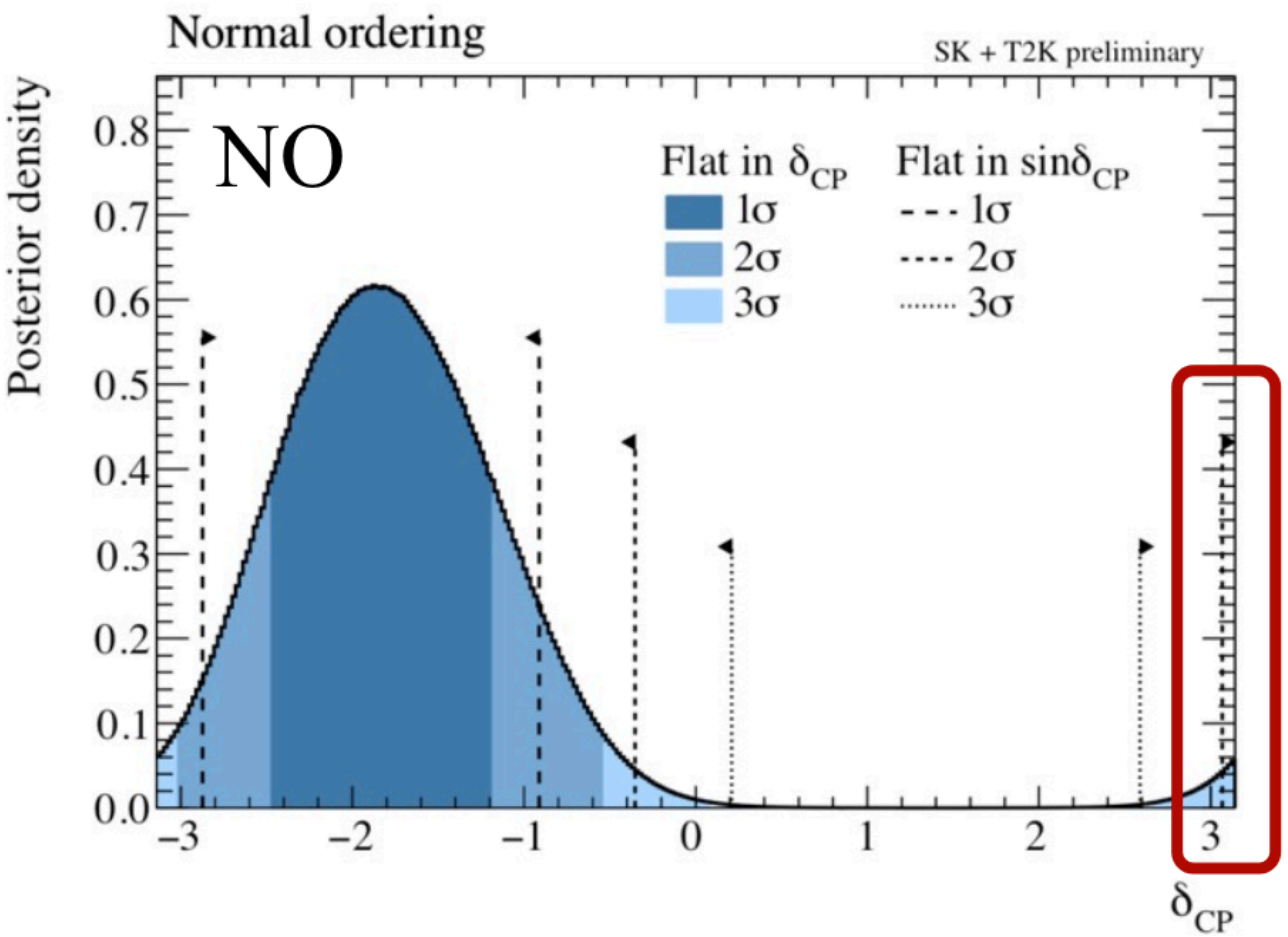
T2K+SK posterior		$\theta_{23} < \frac{\pi}{2}$ 0.39	$\theta_{23} > \frac{\pi}{2}$ 0.61
$\Delta m^2 > 0$	0.90	0.37	0.53
$\Delta m^2 < 0$	0.10	0.02	0.08





* Recontres de Moriond 2024

T2K+SK joint analysis



We usually highlight the most conservative conclusion.

For some combinations of prior, MO, and parameterisation: **the CPC conserving point $\delta = \pi$ is still included within 2σ.**

- Plus larger than expected effects in $CC1\pi^+$ systematic study.

- **Frequentist analysis will also be in the paper (soon) but this only gets around the prior dependence, and is otherwise pretty consistent.**

* Recontres de Moriond 2024

Improvements in particle tracking

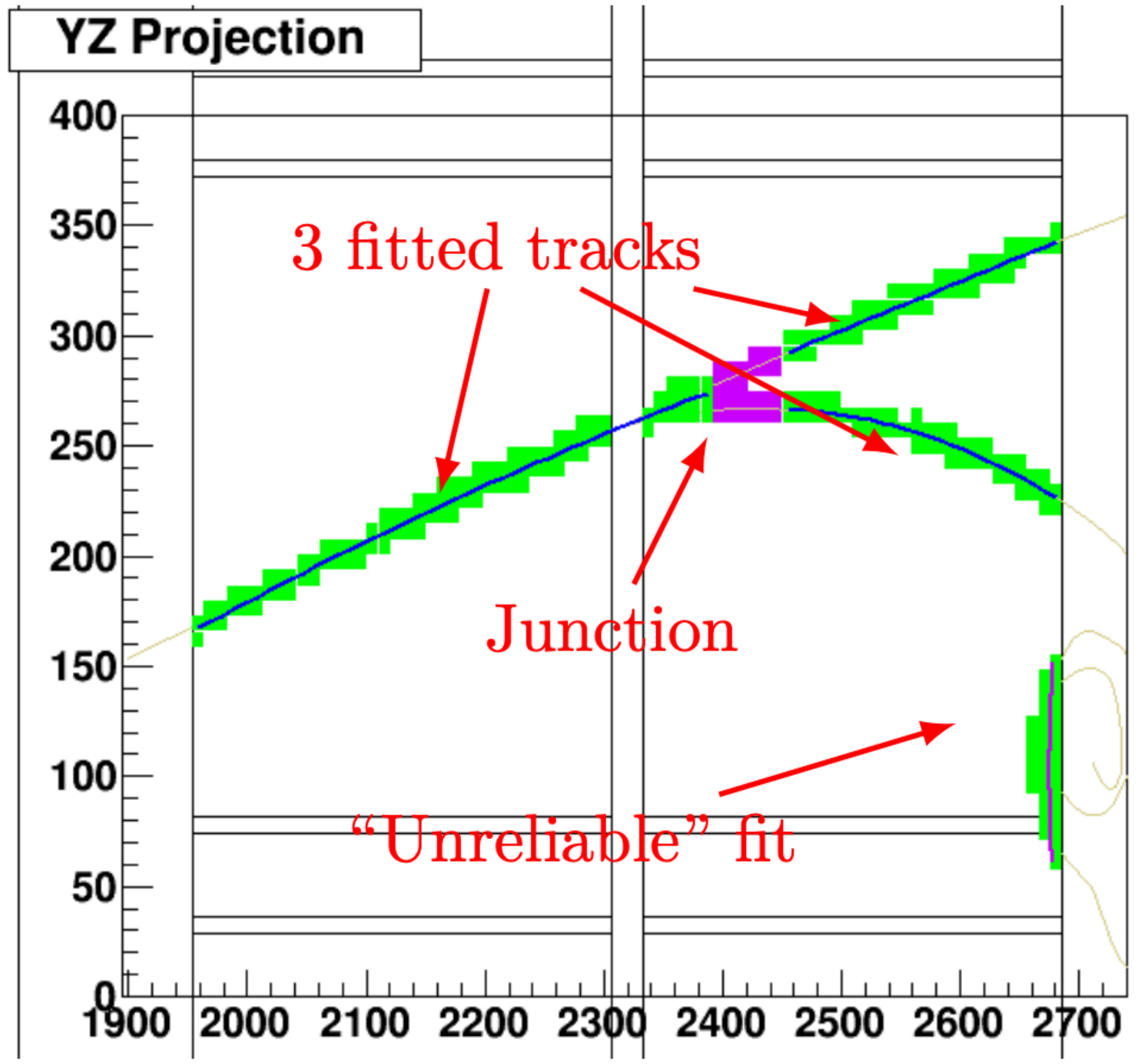
✳ **New algorithm in TPC — TREx:**
- New pattern recognition algorithm
- 3D reconstruction with no preferential direction
- Vertexing in TPCs

✳ **FGD:**
- Electron hypothesis in FGD Particle identification, overall updated FGD PID

✳ **P0D**
- Recover short tracks in downstream P0D with TPC based filtering
- Improve high-angle tracking (short in Z objects)

✳ **ECal**
- Few hits clusters → tag low-energy EM activity
- Improved TPC-ECal matching, filter individual ECal hits to recover TPC-ECal objects with few hits in ECals

Through-going muon emitting a δ-ray inside the TPC. TREx identifies three tracks instead of two and connect them using a Junction



T2K results

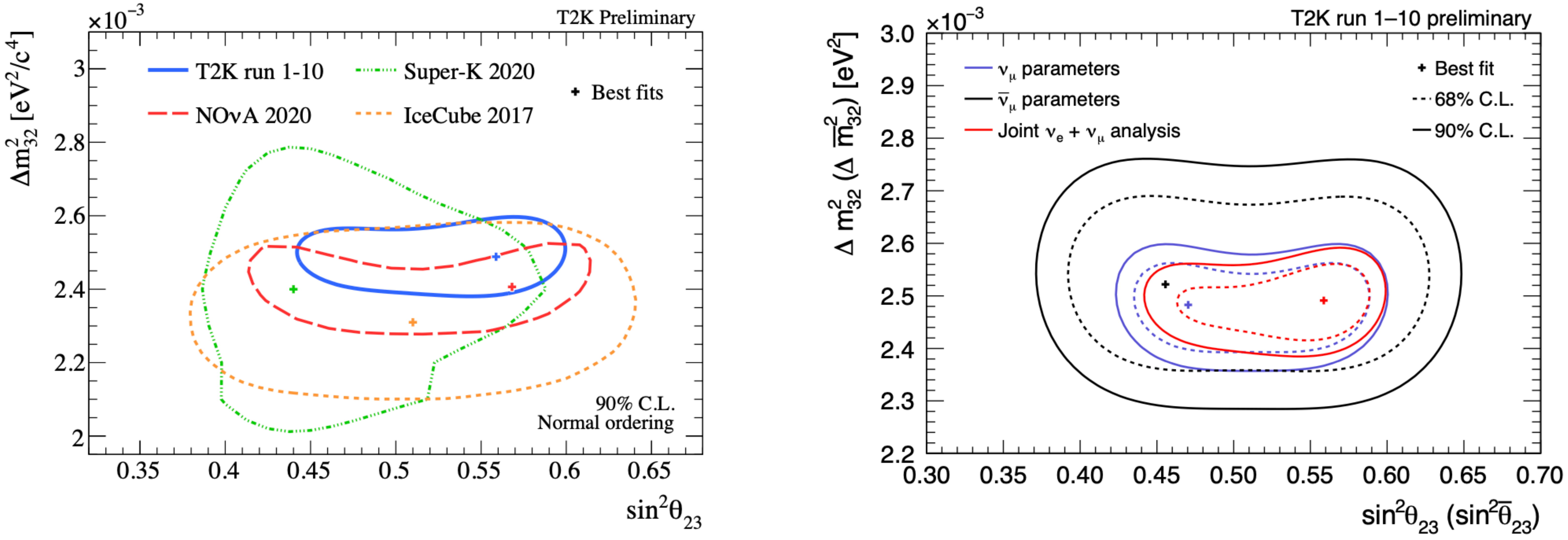


Figure 1 – *Left:* Constraints on atmospheric oscillation parameters and comparison with NOνA,[17] SuperK,[18] and IceCube.[19] *Right:* Constraints from an alternative fit of μ-like samples where the atmospheric parameters for neutrinos ($\sin^2\theta_{23}, \Delta m^2_{32}$) and antineutrinos ($\sin^2\bar{\theta}_{23}, \Delta\bar{m}^2_{32}$) are decoupled from each other. The joint $\nu_e + \nu_\mu$ analysis contours from the left figure are also shown for comparison.

Table 2.2: Oscillation parameters values with and without the reactor constrain obtained in the frequentist analysis from the data fit [77].

Parameter	With reactor constraint		Without reactor constraint	
	Normal ordering	Inverted ordering	Normal ordering	Inverted ordering
δ_{CP} (rad.)	$-1.97^{+0.97}_{-0.62}$	$-1.44^{+0.56}_{-0.59}$	$-2.22^{+1.25}_{-0.81}$	$-1.29^{+0.72}_{-0.83}$
$\sin^2\theta_{13}/10^{-3}$	—	—	$28.0^{+2.8}_{-6.5}$	$31.0^{+3.0}_{-6.9}$
$\sin^2\theta_{23}$	$0.561^{+0.019}_{-0.038}$	$0.563^{+0.017}_{-0.032}$	$0.467^{+0.106}_{-0.018}$	$0.466^{+0.103}_{-0.019}$
$\Delta m^2_{32}/10^{-3}$ (eV^2)	$2.494^{+0.041}_{-0.058}$	—	$2.495^{+0.041}_{-0.058}$	—
$\lvert\Delta m^2_{31}\rvert/10^{-3}$ (eV^2)	—	$2.463^{+0.042}_{-0.056}$	—	$2.463^{+0.043}_{-0.055}$