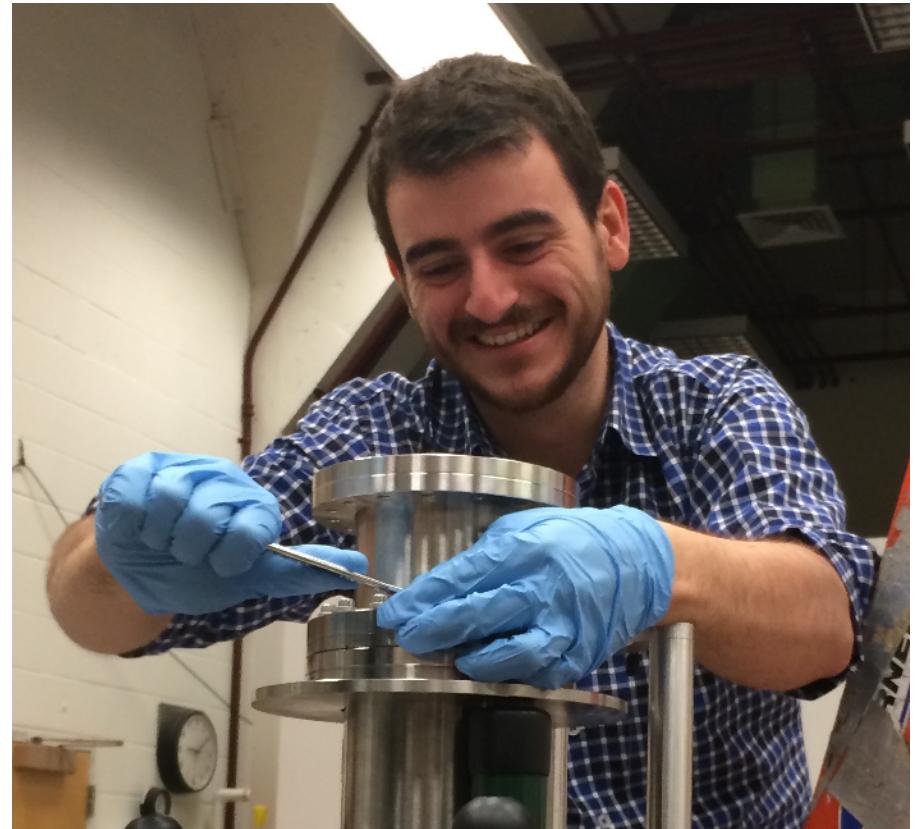




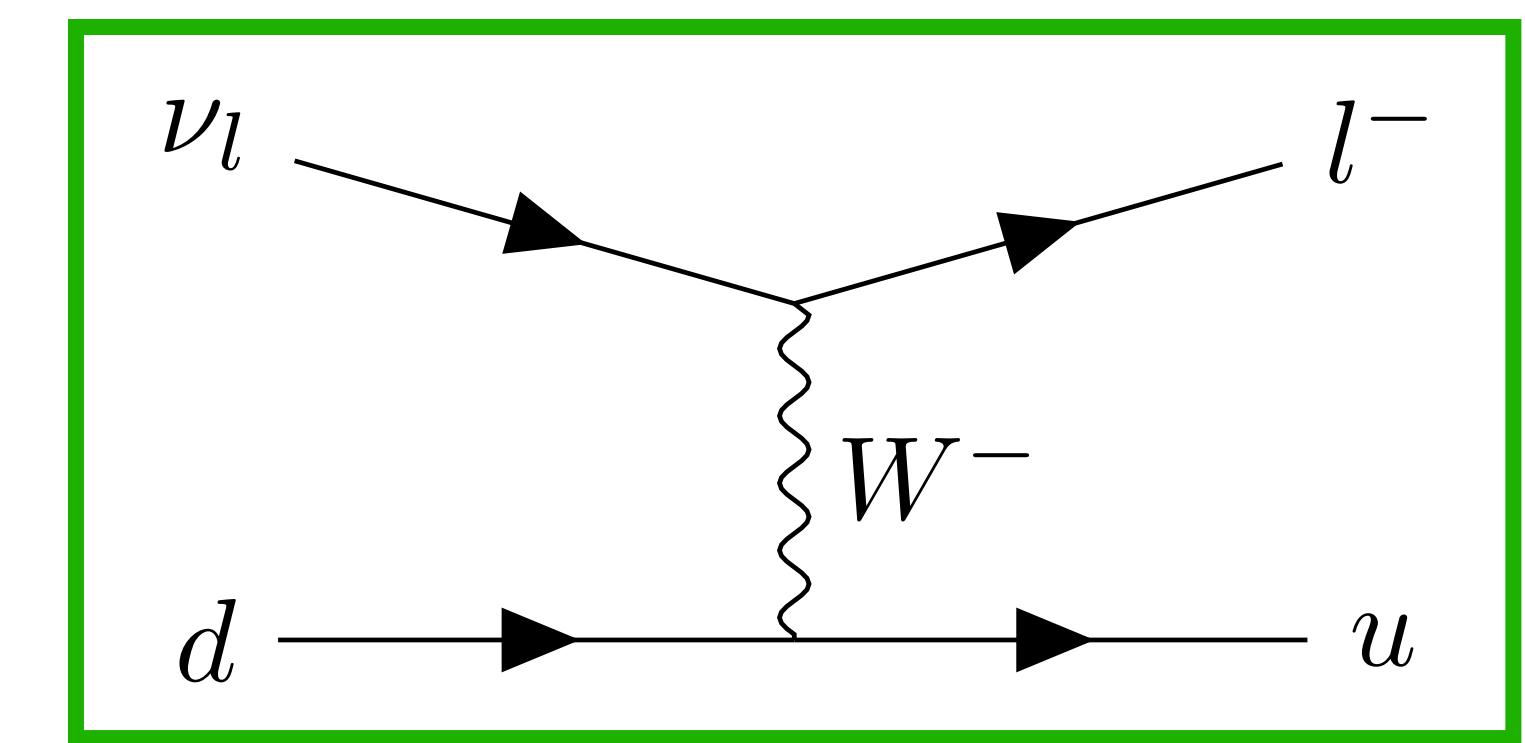
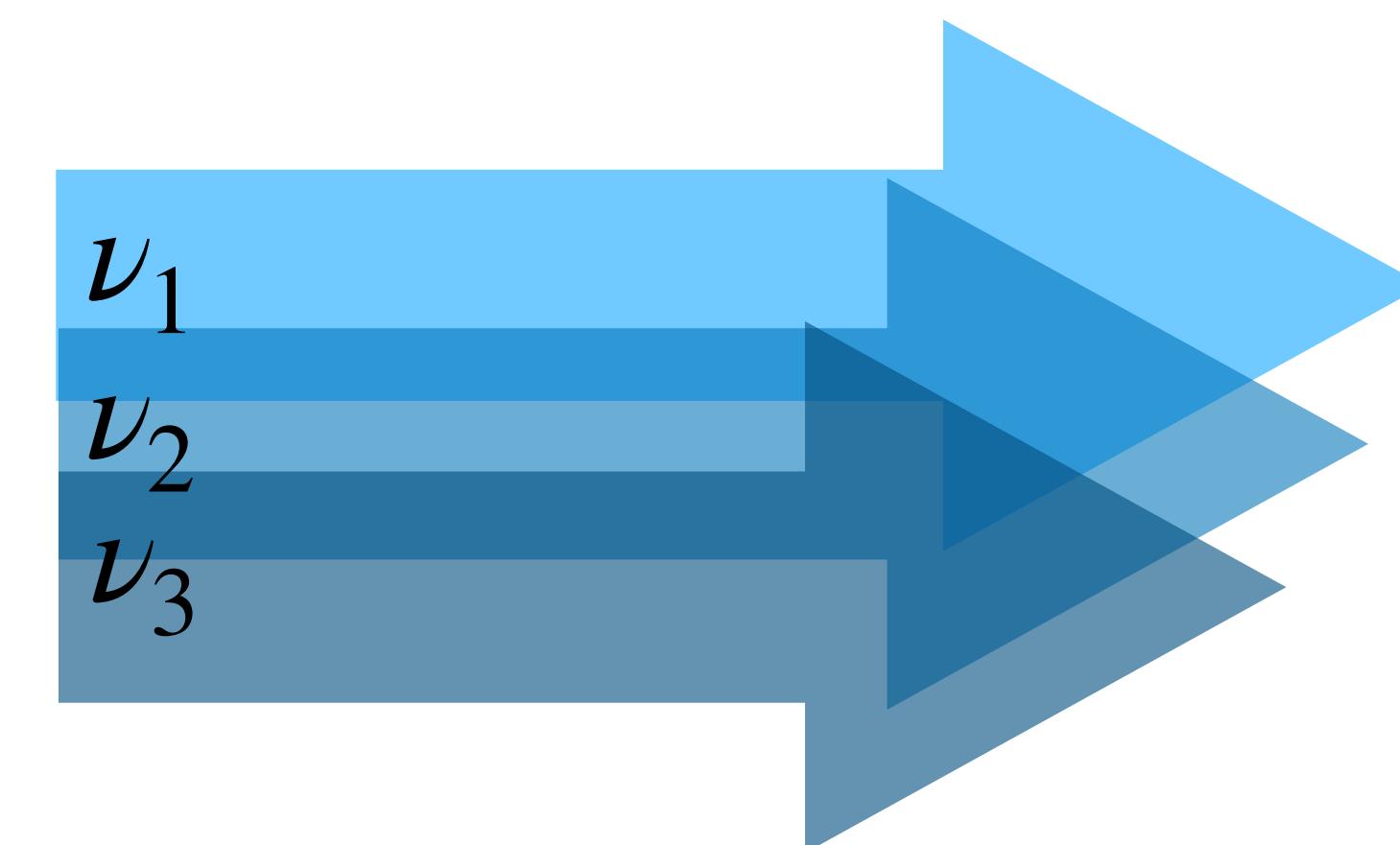
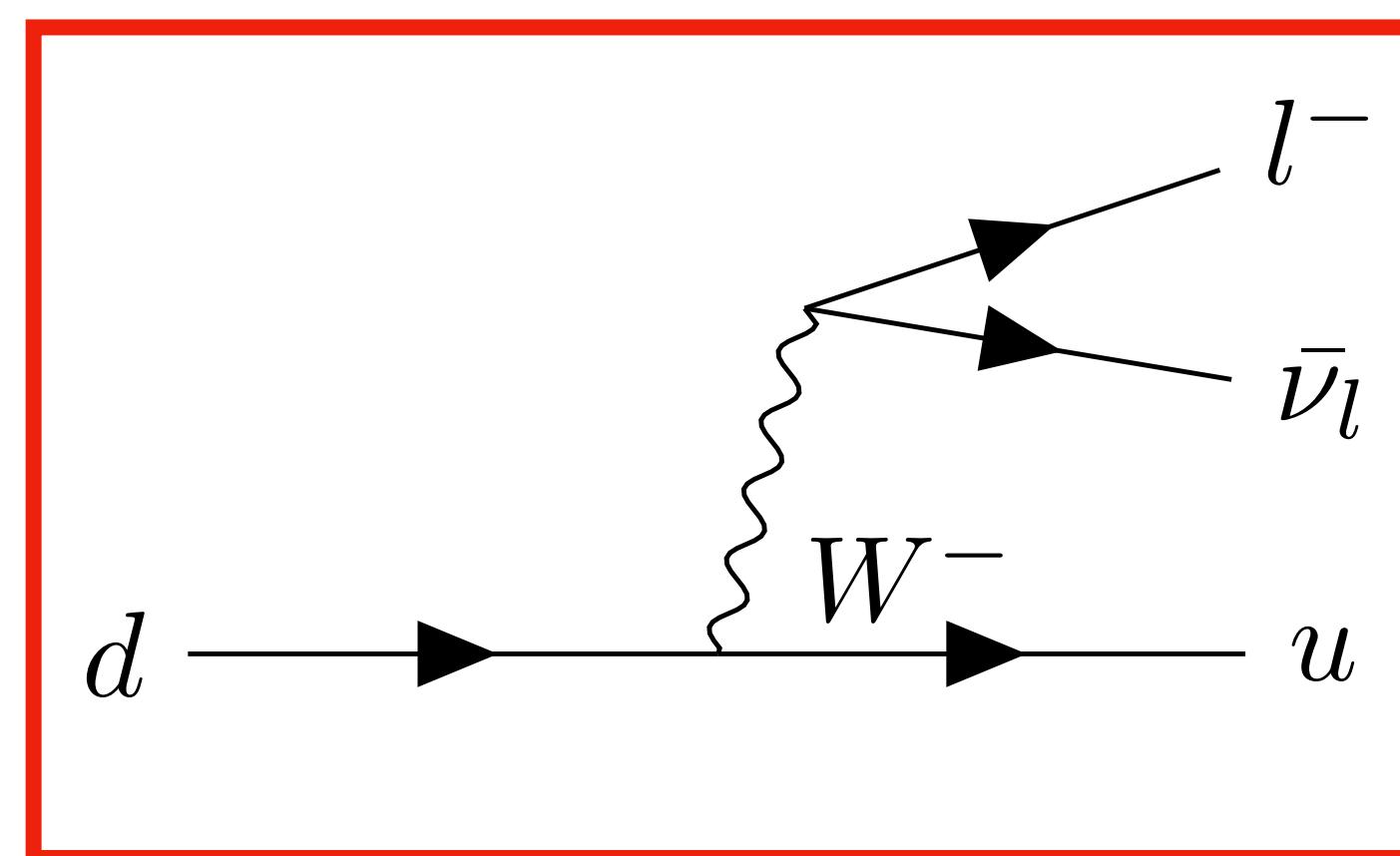
The T2K Experiment: Status, Results and Prospects



Mathieu Guigue for the T2K Collaboration
XIX International Workshop on Neutrino Telescopes
February 22nd 2021

Neutrino weak states: $\nu_e, \nu_\mu, \nu_\tau \rightarrow \text{production}$ and **detection**

Neutrino mass states: $\nu_1, \nu_2, \nu_3 \rightarrow \text{propagation}$



If $(\nu_e, \nu_\mu, \nu_\tau) \neq (\nu_1, \nu_2, \nu_3)$ and non-degenerate masses

\rightarrow Phase difference between mass states during propagation

\rightarrow Different flavor state detected after propagation

Neutrinos mixing matrix

Mass and flavor states mixing: $|\nu_i\rangle = \sum_{\alpha=1}^3 U_{\alpha i} |\nu_\alpha\rangle$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix U is **unitary**

→ 3 angles θ_{ij} with $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$

→ 3 phases: δ_{CP} (Dirac phase) and η_i (Majorana phases)

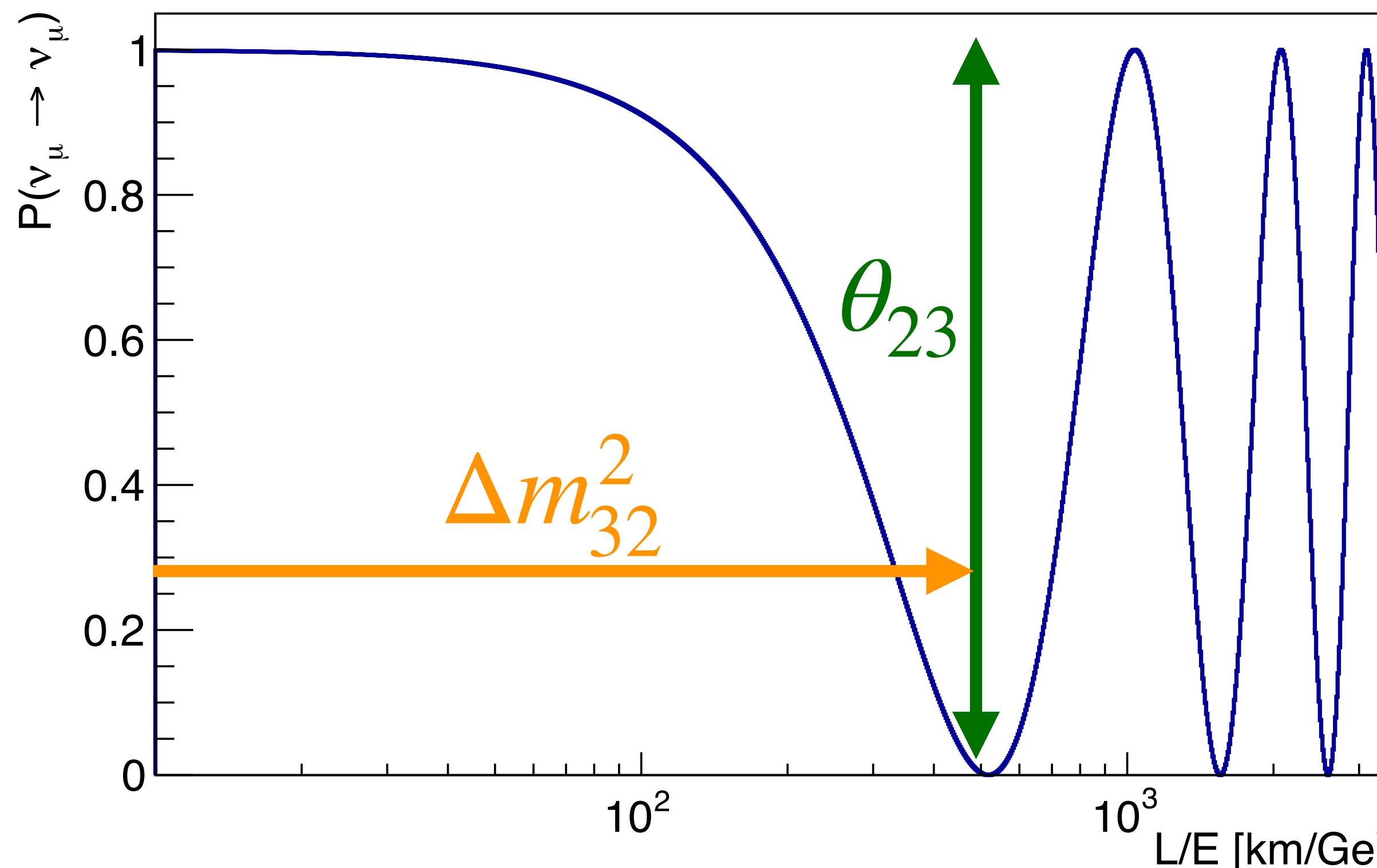
(Majorana phases don't show up in neutrino oscillations)

$\nu_\mu/\bar{\nu}_\mu$ disappearance probability

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum \textcolor{red}{\mathcal{O}_{ij}} \sin^2 \frac{\Delta m_{ij}^2 L}{4E} \pm 2 \sum \textcolor{blue}{\mathcal{U}_{ij}} \sin 2 \frac{\Delta m_{ij}^2 L}{4E}$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

CP-conserving CP-violating



Energy of maximum oscillation:

$$E_{\text{osc}} = \frac{L_{0,ij}^{\text{osc}} |\Delta m_{ij}^2|}{4\pi}$$

Look for surviving muons neutrinos in
muon neutrino beam
For $L_{0,32}^{\text{osc}} = 295$ km, $E_{\text{osc}} \approx 0.6$ GeV

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum \textcolor{red}{\mathcal{O}_{ij}} \sin^2 \frac{\Delta m_{ij}^2 L}{4E} \pm 2 \sum \textcolor{blue}{\mathcal{U}_{ij}} \sin 2 \frac{\Delta m_{ij}^2 L}{4E}$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

CP-conserving

CP-violating

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{13}^2 L}{4E_\nu} \right) + 8 \frac{\Delta m_{21}^2}{\Delta m_{31}^2} J_{CP}^{\max} \sin \left(\frac{\Delta m_{13}^2 L}{4E_\nu} \right) \cos \left(\frac{\Delta m_{13}^2 L}{4E_\nu} \pm \delta_{CP} \right)$$

$$J_{CP}^{\max} = \cos \theta_{12} \sin \theta_{12} \cos \theta_{23} \sin \theta_{23} \cos^2 \theta_{13} \sin \theta_{13}$$

ν or anti- ν

Look for appearing electron neutrinos from muon neutrino beam

- Difference between ν_e and $\bar{\nu}_e$ appearance if $\delta_{CP} \neq 0, \pi$
- CP violation only possible if all parameters are non zero
- The sign of δ_{CP} is related to the sign of Δm_{21}^2 and Δm_{31}^2

Neutrino actually propagating in matter (Earth crust)

- Modifies pattern differently for ν and anti- ν \rightarrow mimics CP violation
- Effect depends on the sign of Δm_{31}^2

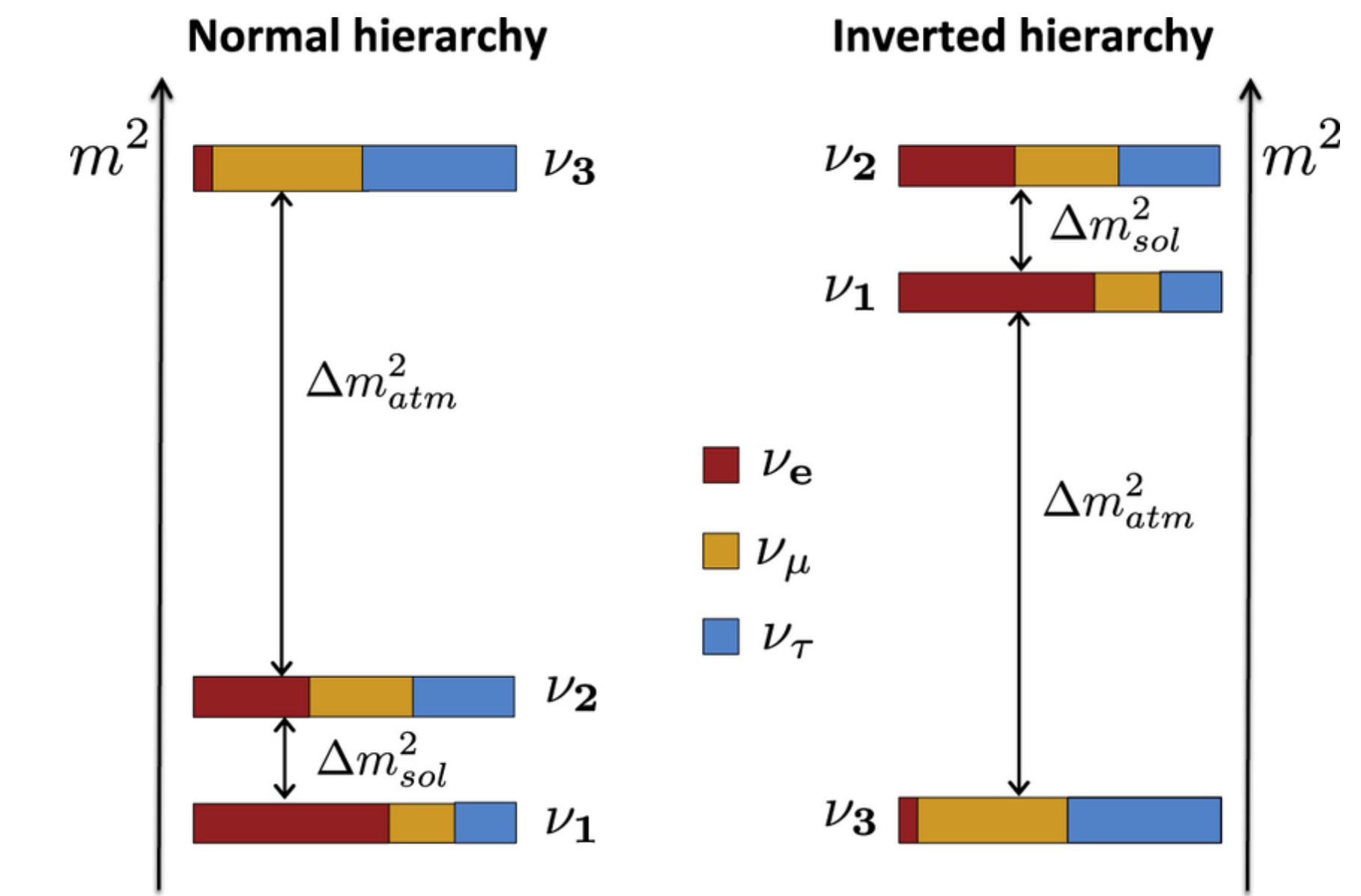
(Some) open questions in neutrino physics

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric and
accelerator Reactor and accelerator Solar and reactor $0\nu\beta\beta$ experiments
 $\theta_{13} \approx 8^\circ$ $\theta_{12} \approx 34^\circ$
 $\theta_{23} \approx 50^\circ$ Accelerator only: $\delta_{CP} = ?$ $\Delta m_{12}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$
 $|\Delta m_{32}^2| \sim 2.5 \times 10^{-3} \text{ eV}^2$

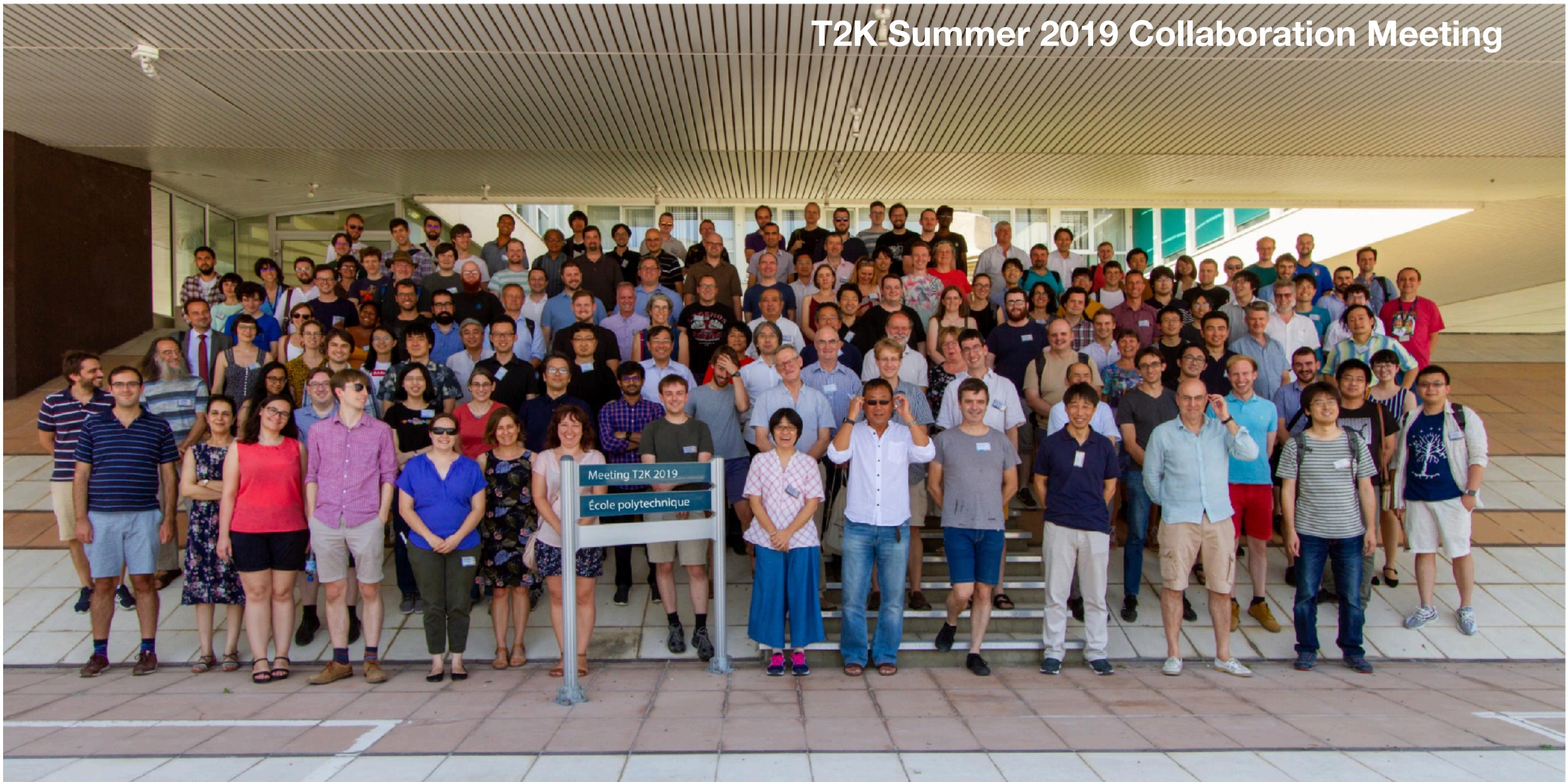
Questions to long-baseline experiments:

- Value of CP violation phase δ_{CP}
- θ_{23} octant
- Mass ordering $\Delta m_{31}^2 \leq 0?$
- Consistency of the whole PMNS framework



From JPhysG 43 084001

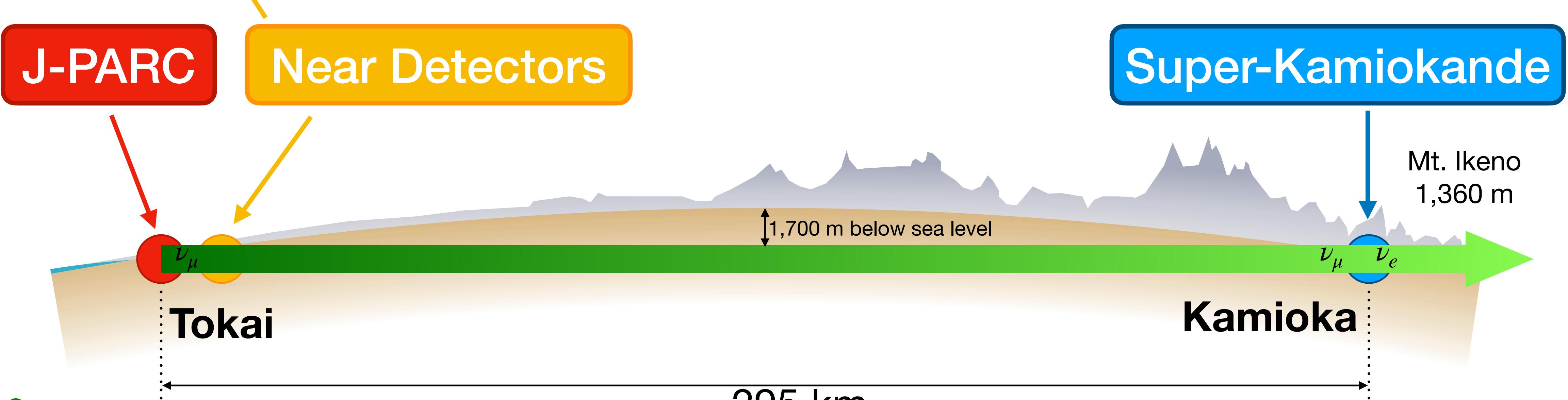
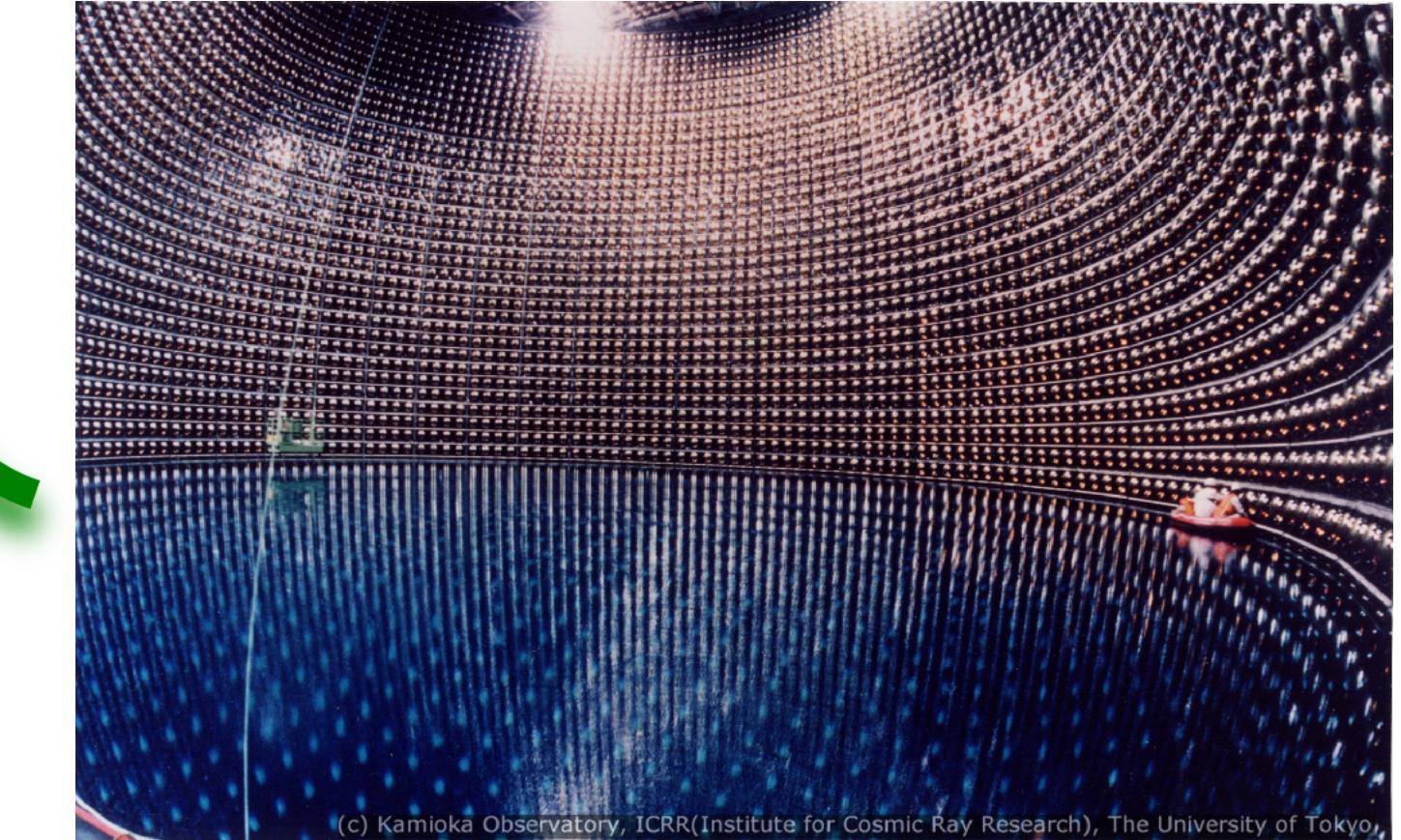
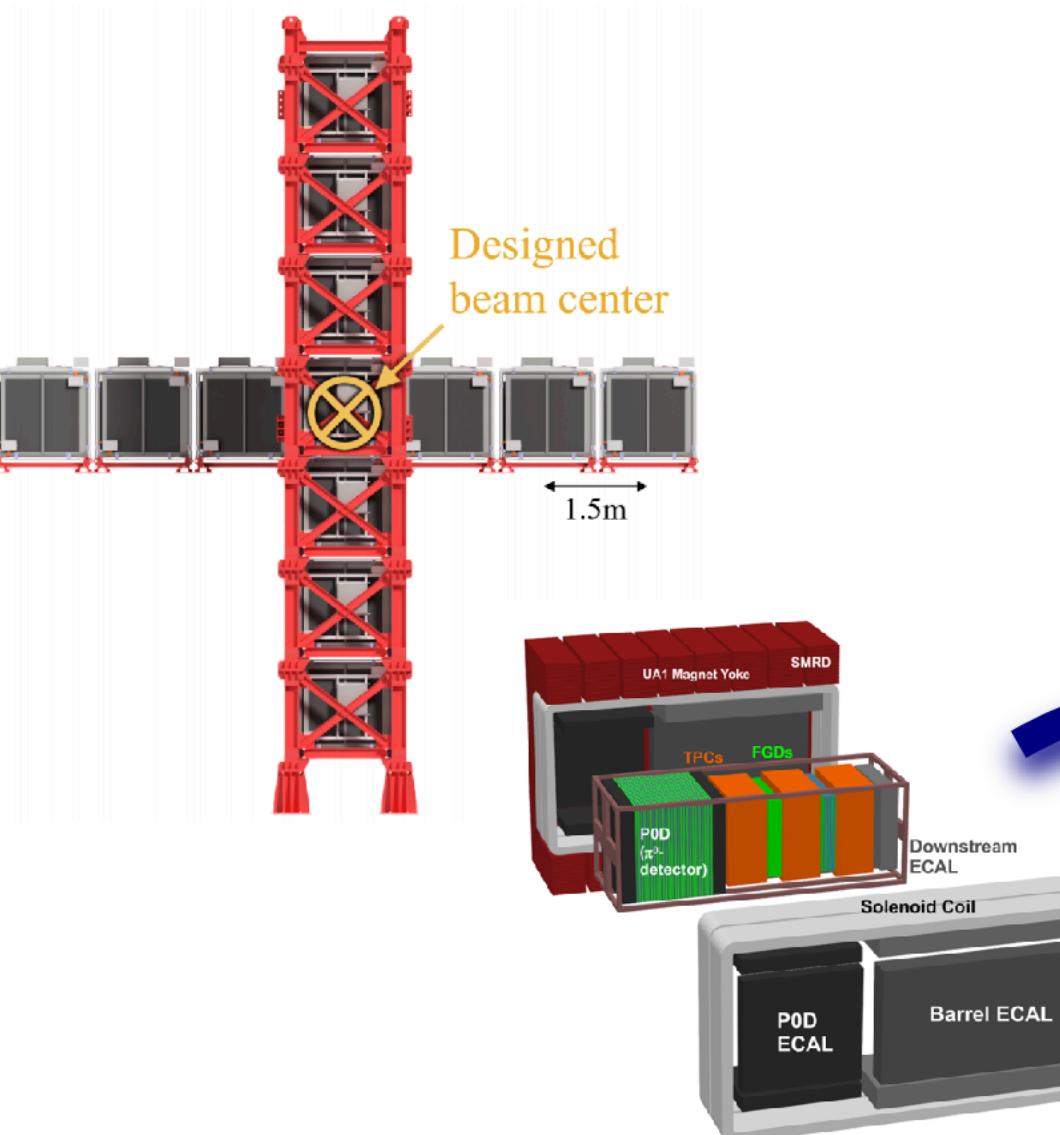
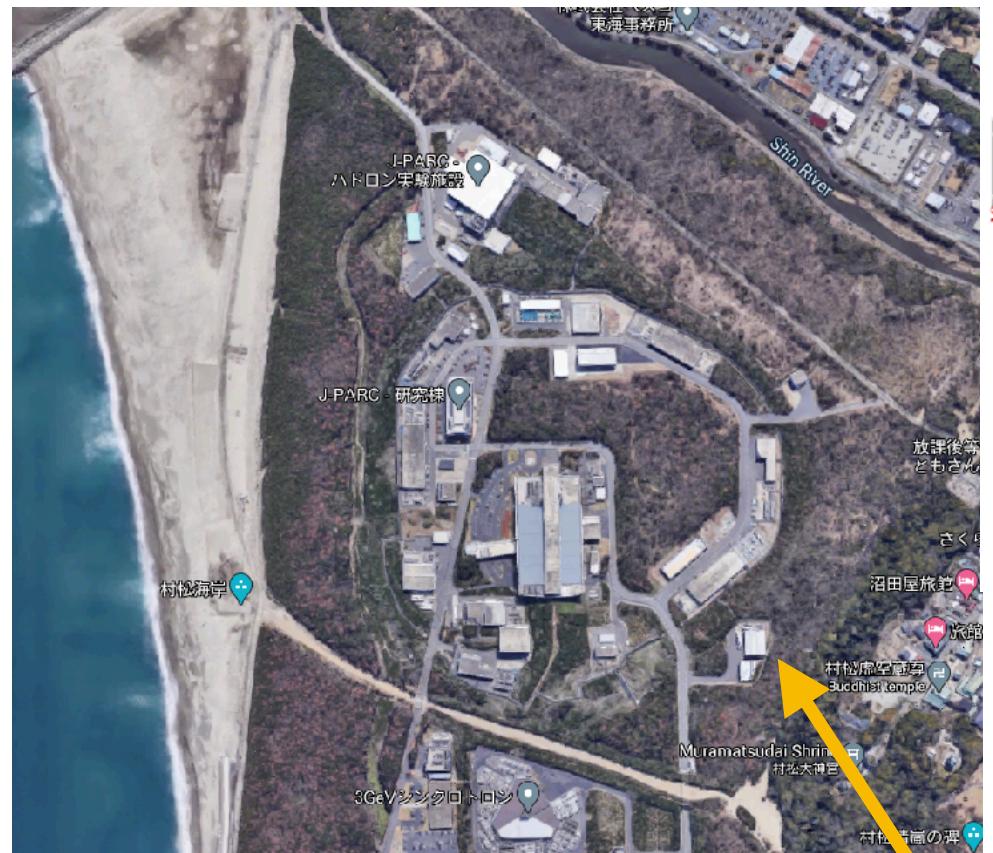
T2K Collaboration



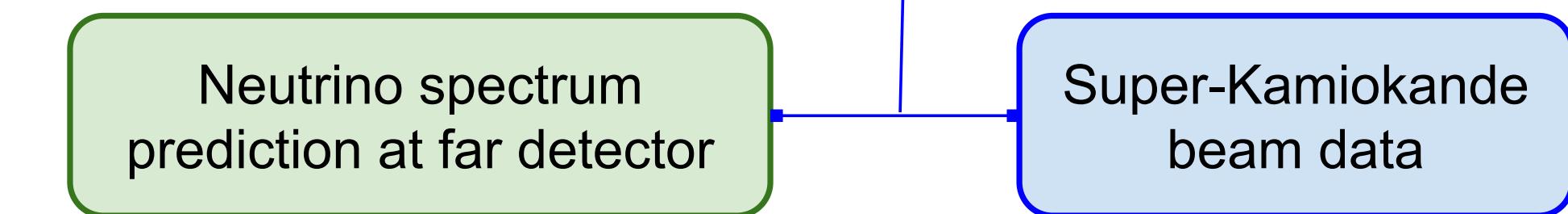
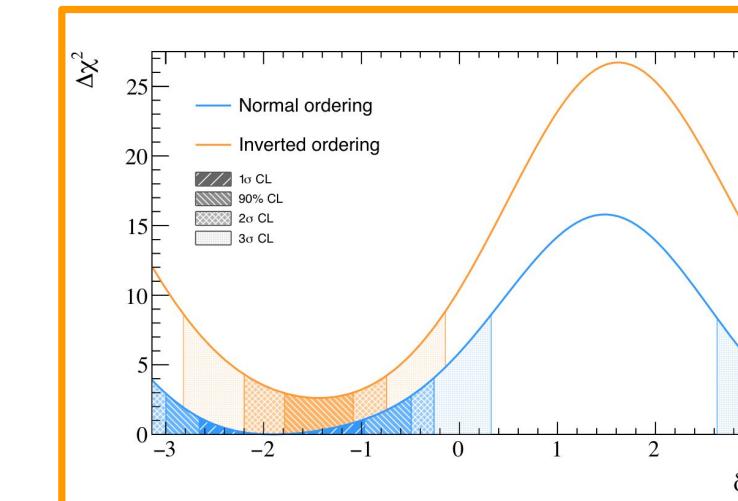
~500 members over 12 countries and 69 institutes



From Tokai To Kamioka

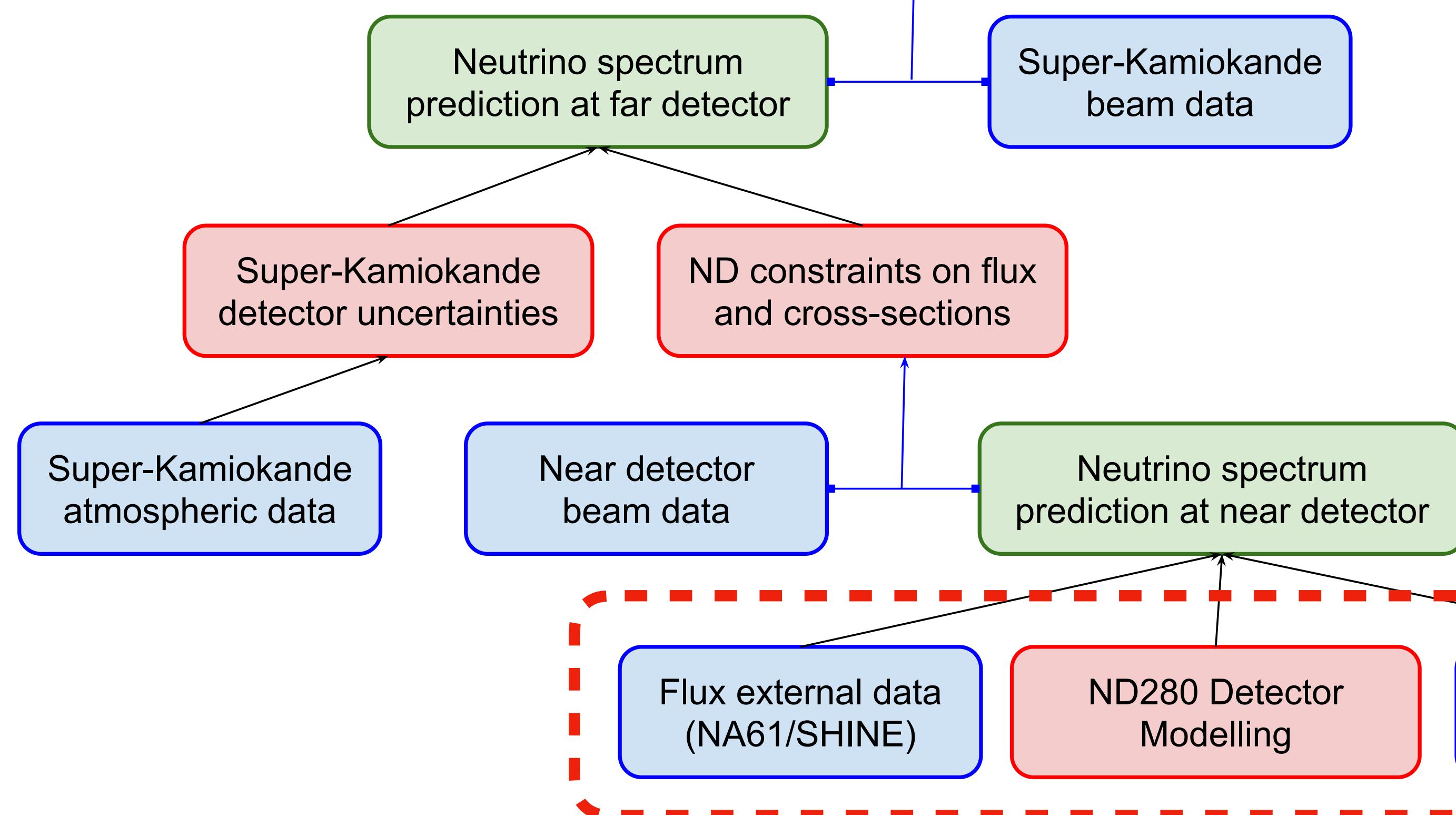
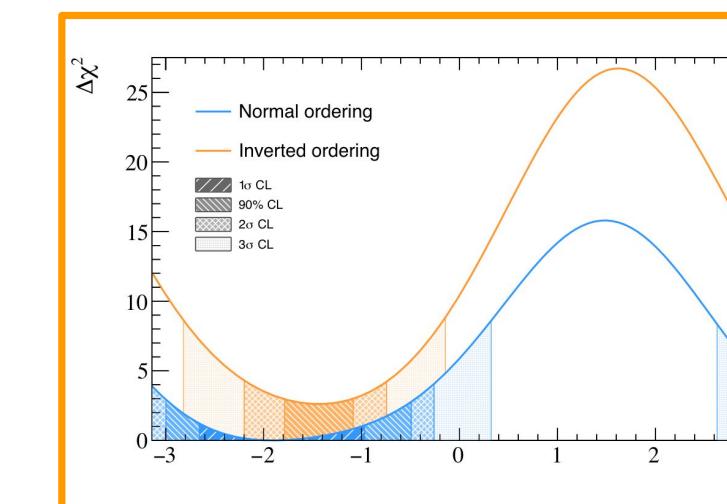


Oscillation analysis strategy

 $\delta_{CP}, \sin^2 \theta_{13}, \Delta m_{32}^2 \dots$ 

Oscillation analysis strategy

$$\delta_{CP}, \sin^2 \theta_{13}, \Delta m_{32}^2 \dots$$



Two analyses:

- ND fit then SK fit
- ND+SK joint fit

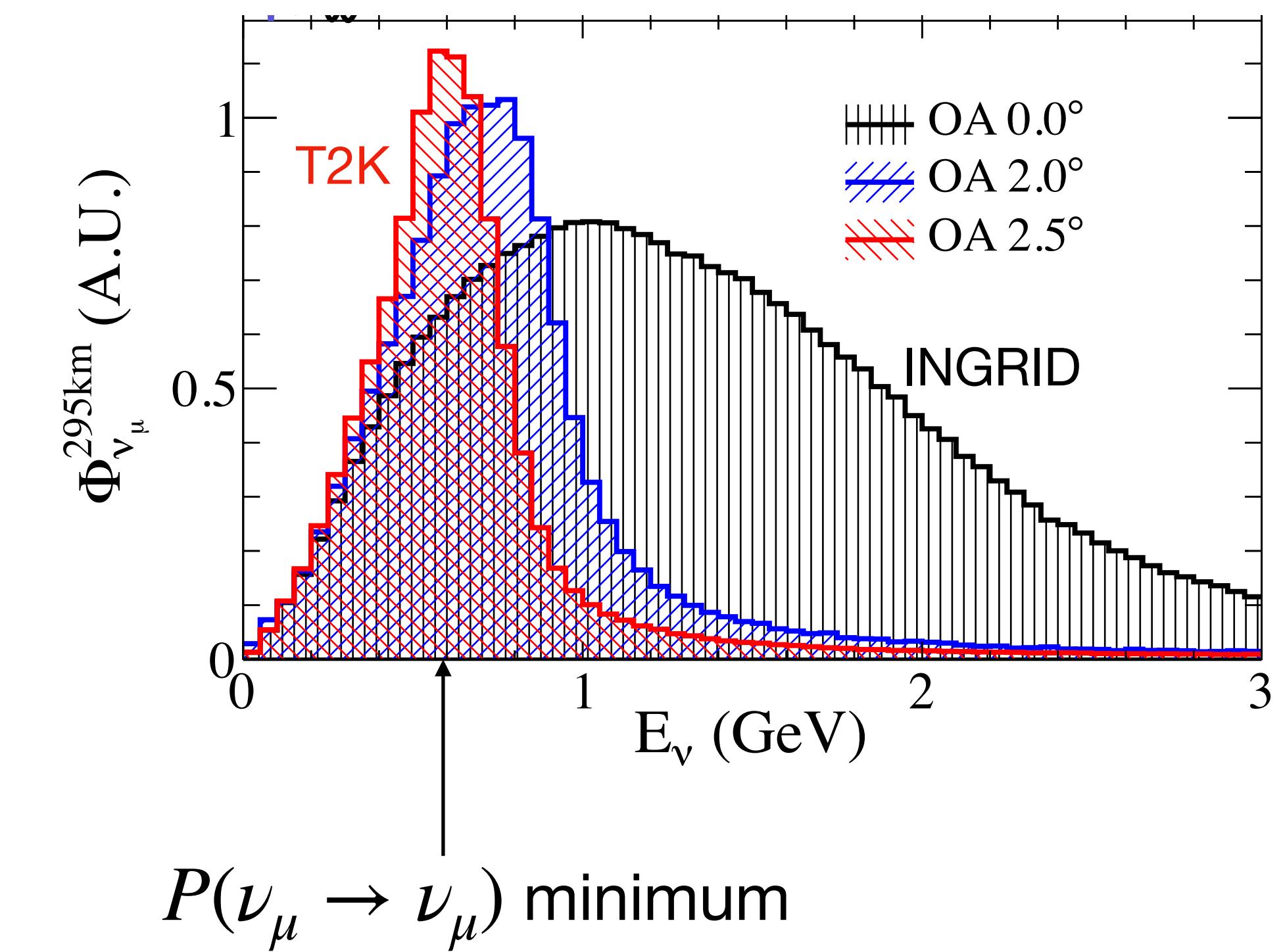
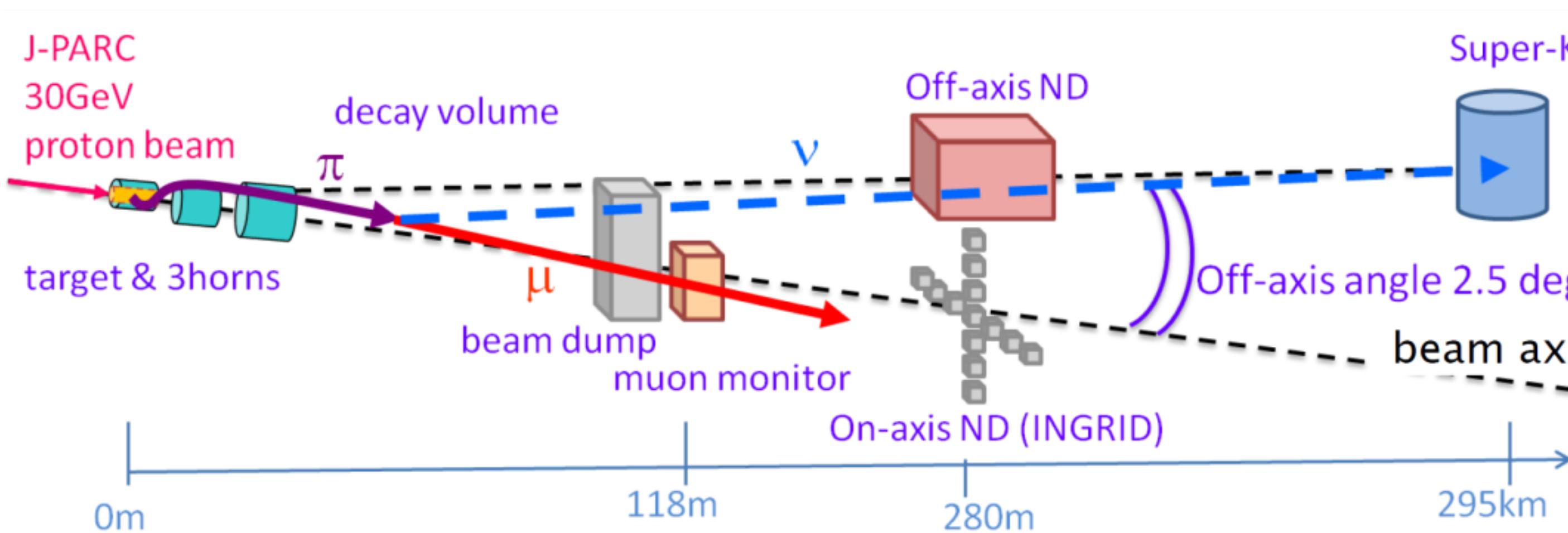
See Joe Walsh's parallel talk

Produced from hadrons generated by Protons On graphite Target (POT)
 at J-PARC decaying into a ~ 100 m long volume

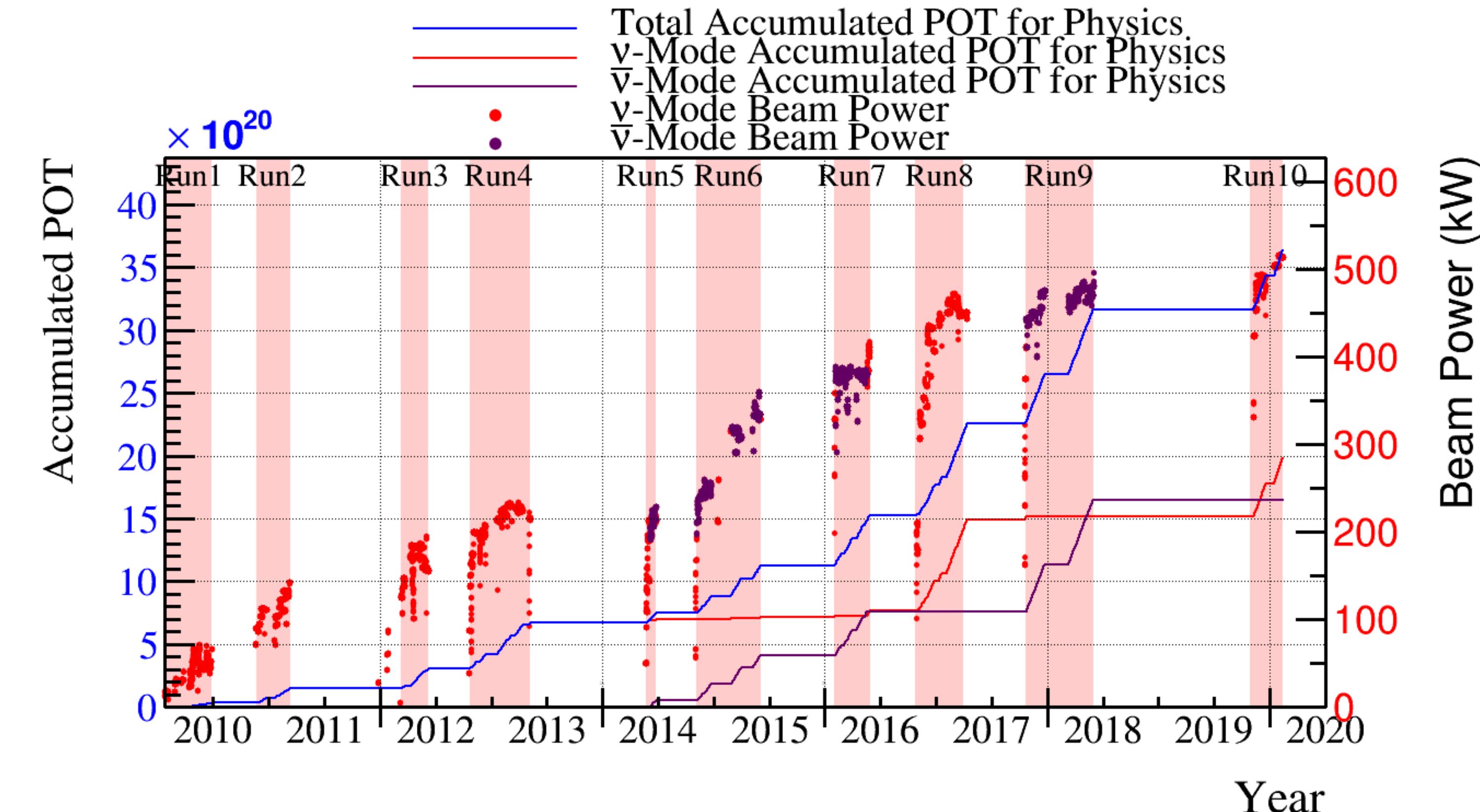
Magnetized “horns” to select hadrons charge \rightarrow enrichment in ν_μ or $\bar{\nu}_\mu$

Muon flux monitoring after beam dump

2.5° off-axis beam for ND and SK



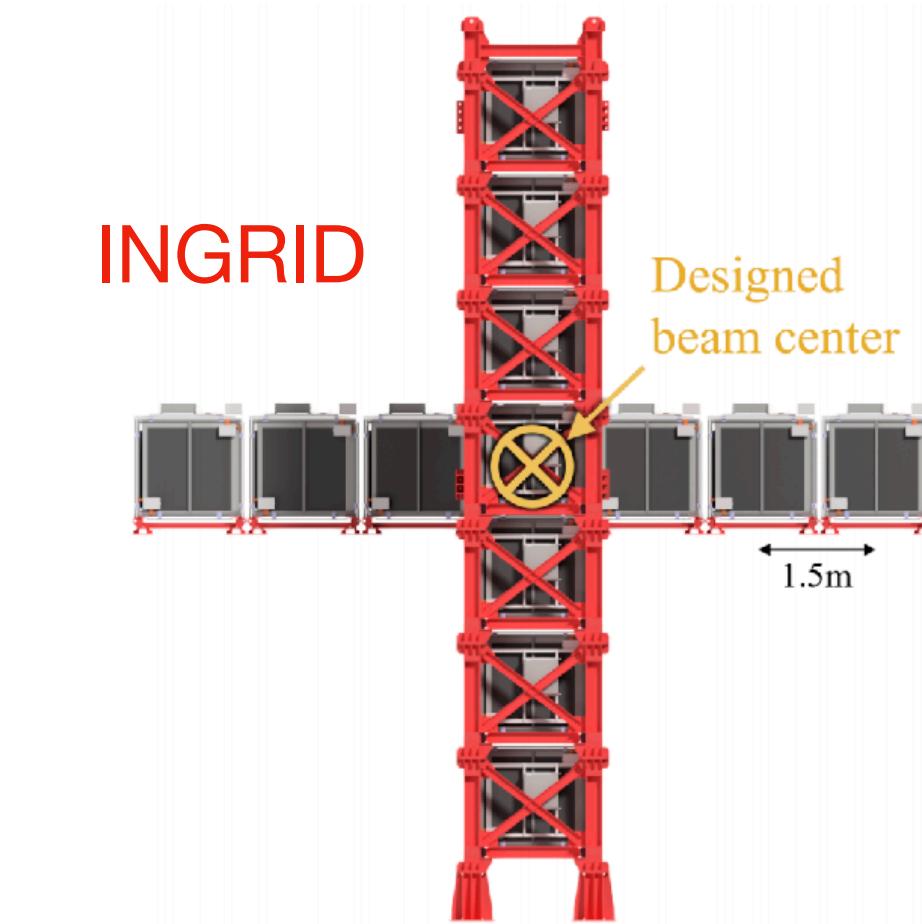
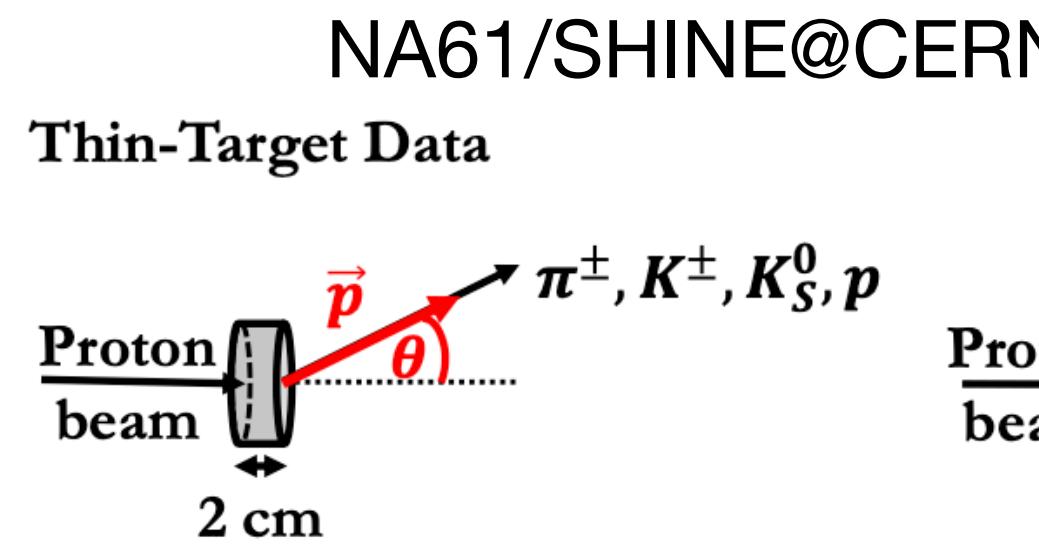
Data taking status



Steady increase in beam power: **515 kW this year**

Run 1-10: 1.97×10^{21} POT in ν mode and 1.63×10^{21} POT in $\bar{\nu}$ mode

Flux constraints



Production of ν in anti- ν mode (**wrong-sign background**)

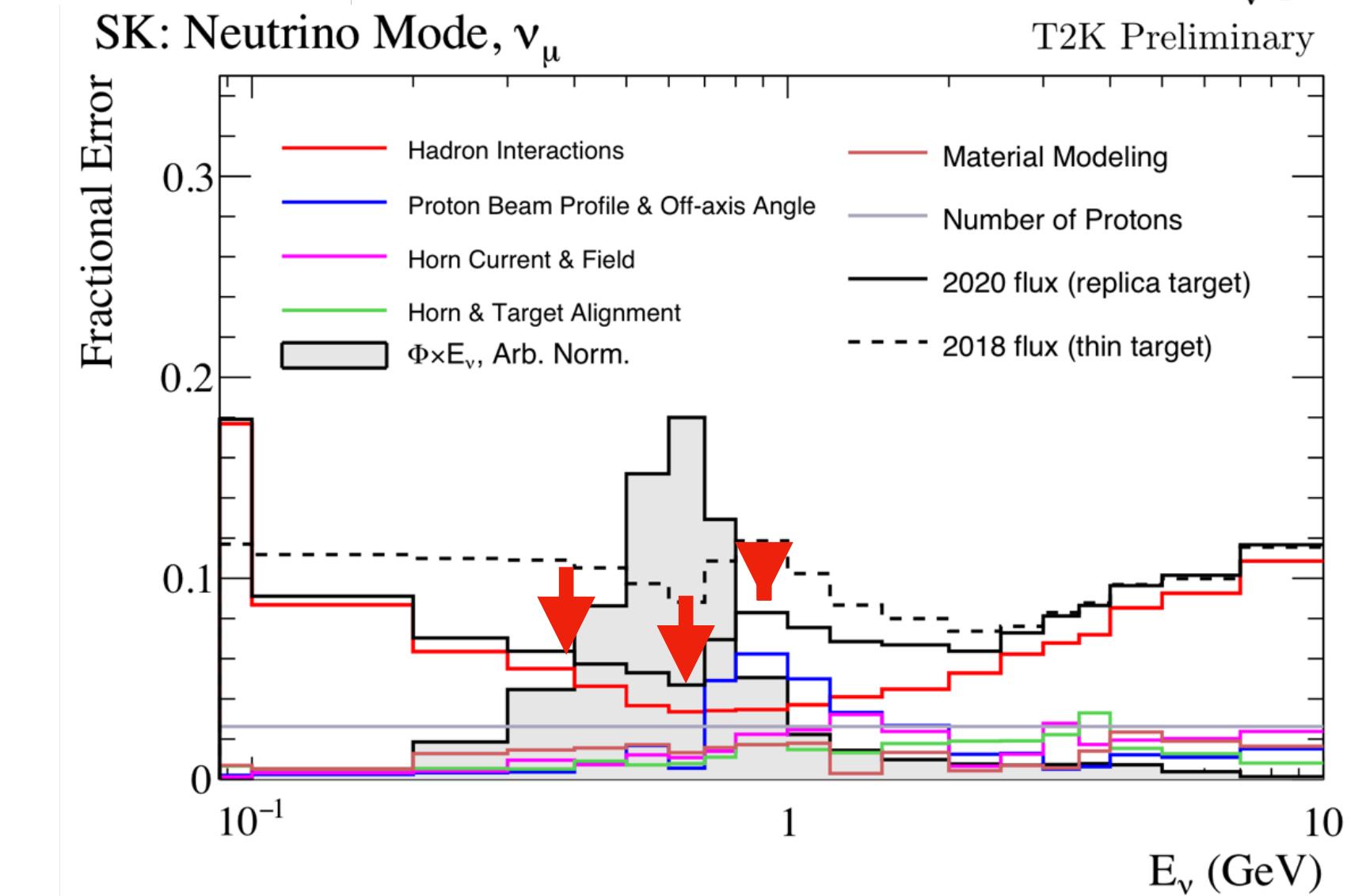
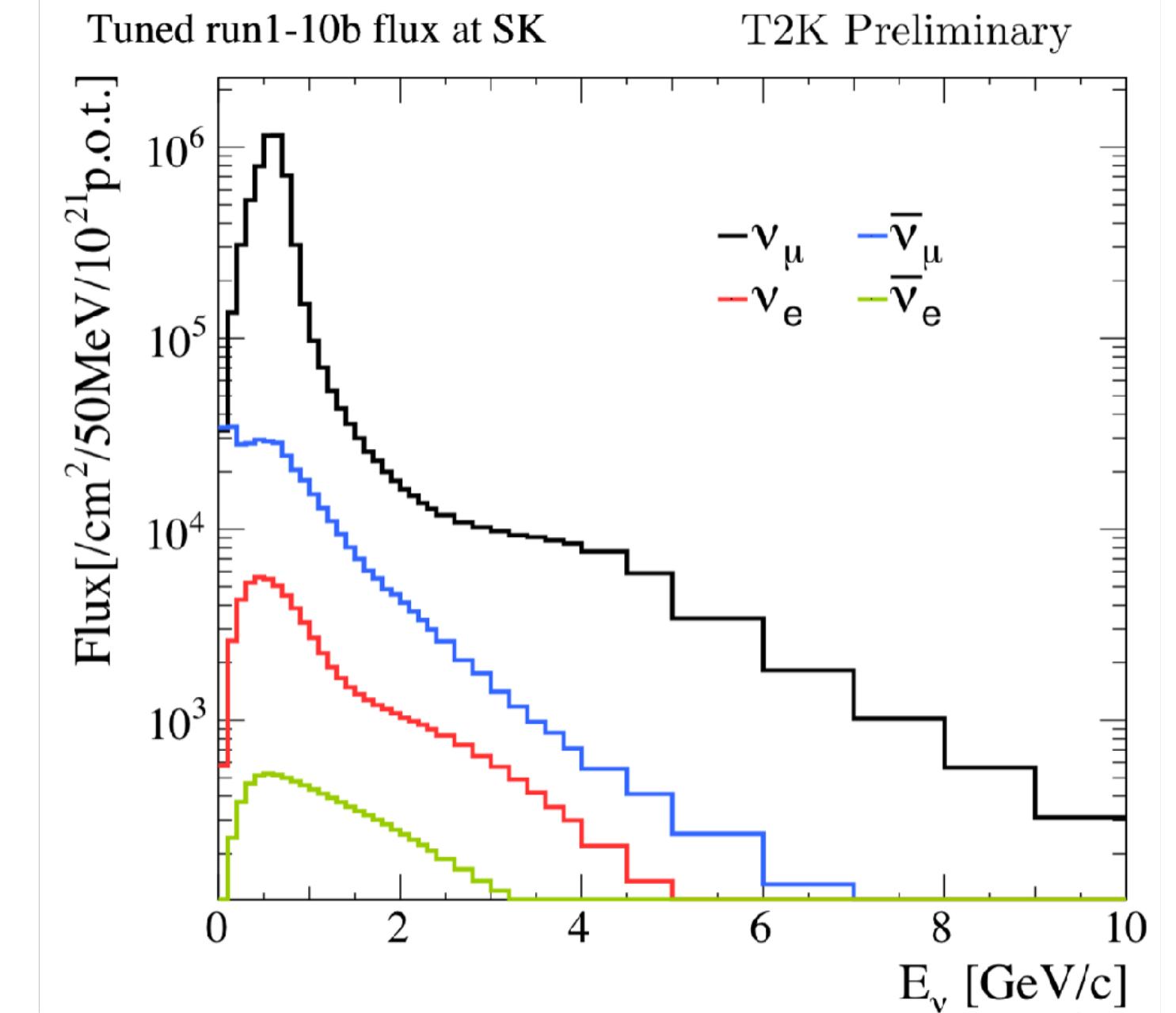
Hadron production simulations by Fluka

Interactions constrained with NA61/SHINE (CERN)

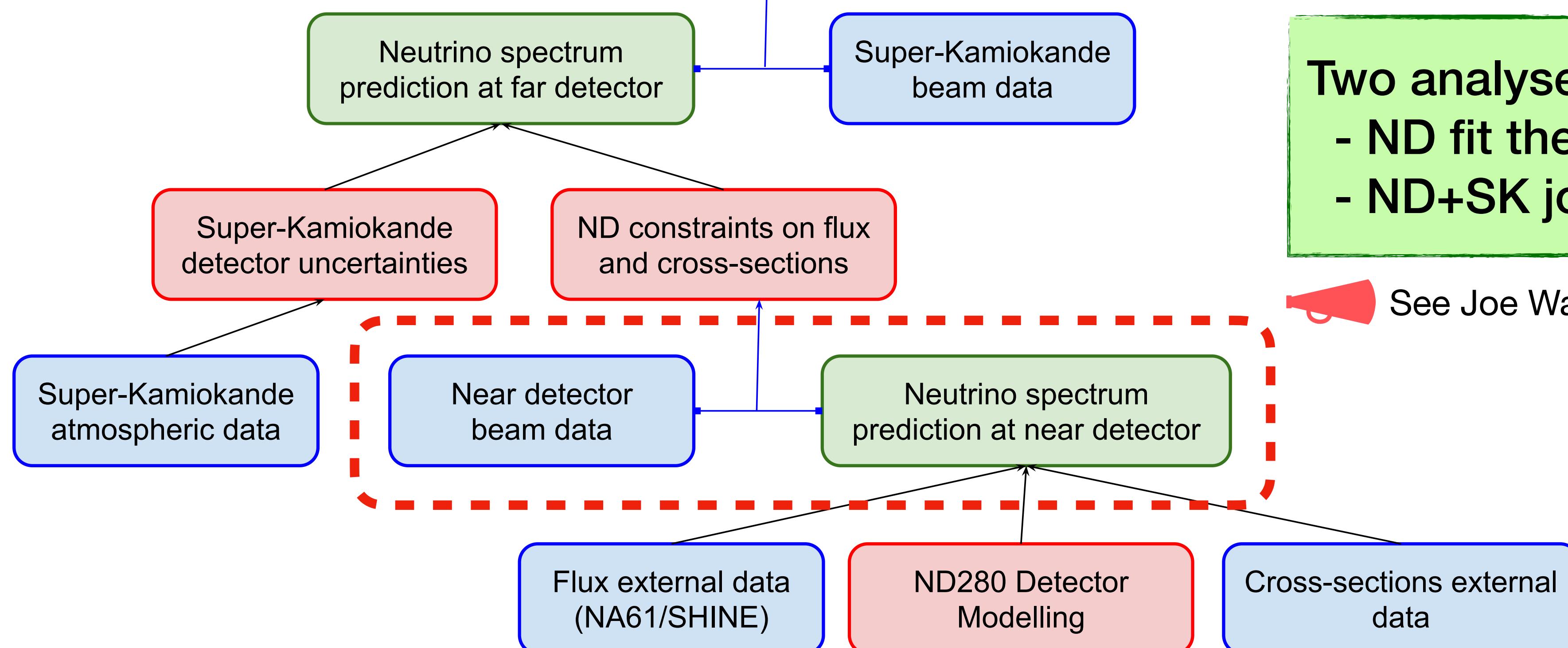
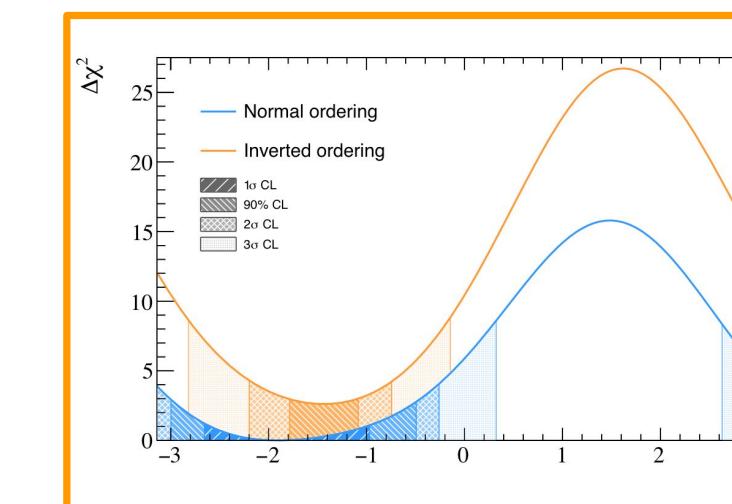
New: T2K graphite replica target

Monitoring of neutrino beam rate and direction by INGRID and MUMON on-axis detectors

Flux uncertainties reduced from 8% to 5%



Oscillation analysis strategy

 $\delta_{\text{CP}}, \sin^2 \theta_{13}, \Delta m_{32}^2 \dots$


Off-axis Near Detector at 280m (ND280)

2.5° off-axis composite detector inside a 0.2 T Magnet:

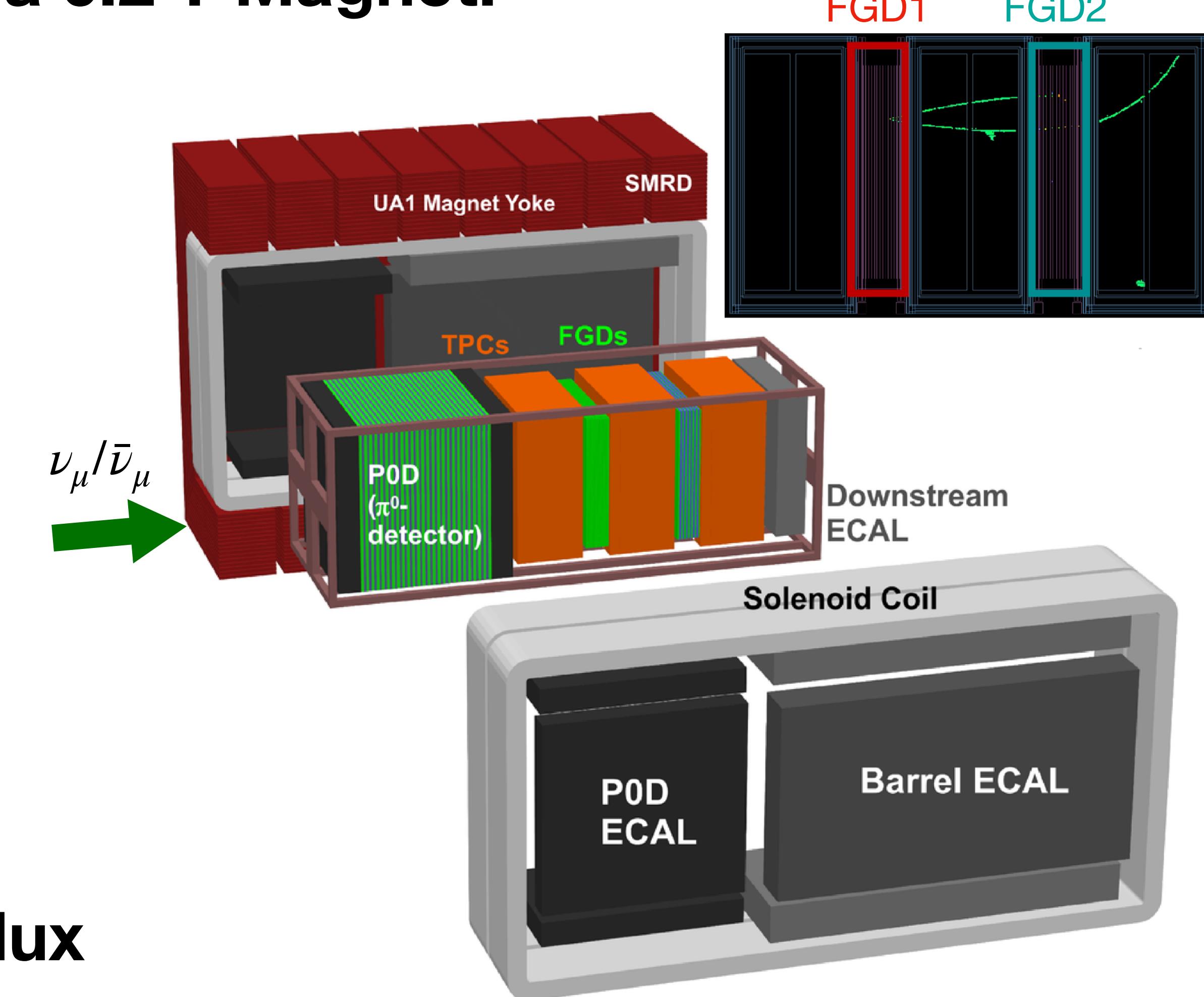
- Two Fine Grained scintillating detectors
FGD1 (CH) and FGD2 ($\text{CH}, \text{H}_2\text{O}$)
- Three Time Projection Chambers (TPCs) between FGDs
- One Upstream π^0 detector
- ECal surrounding inner detectors

FGDs used as neutrino targets

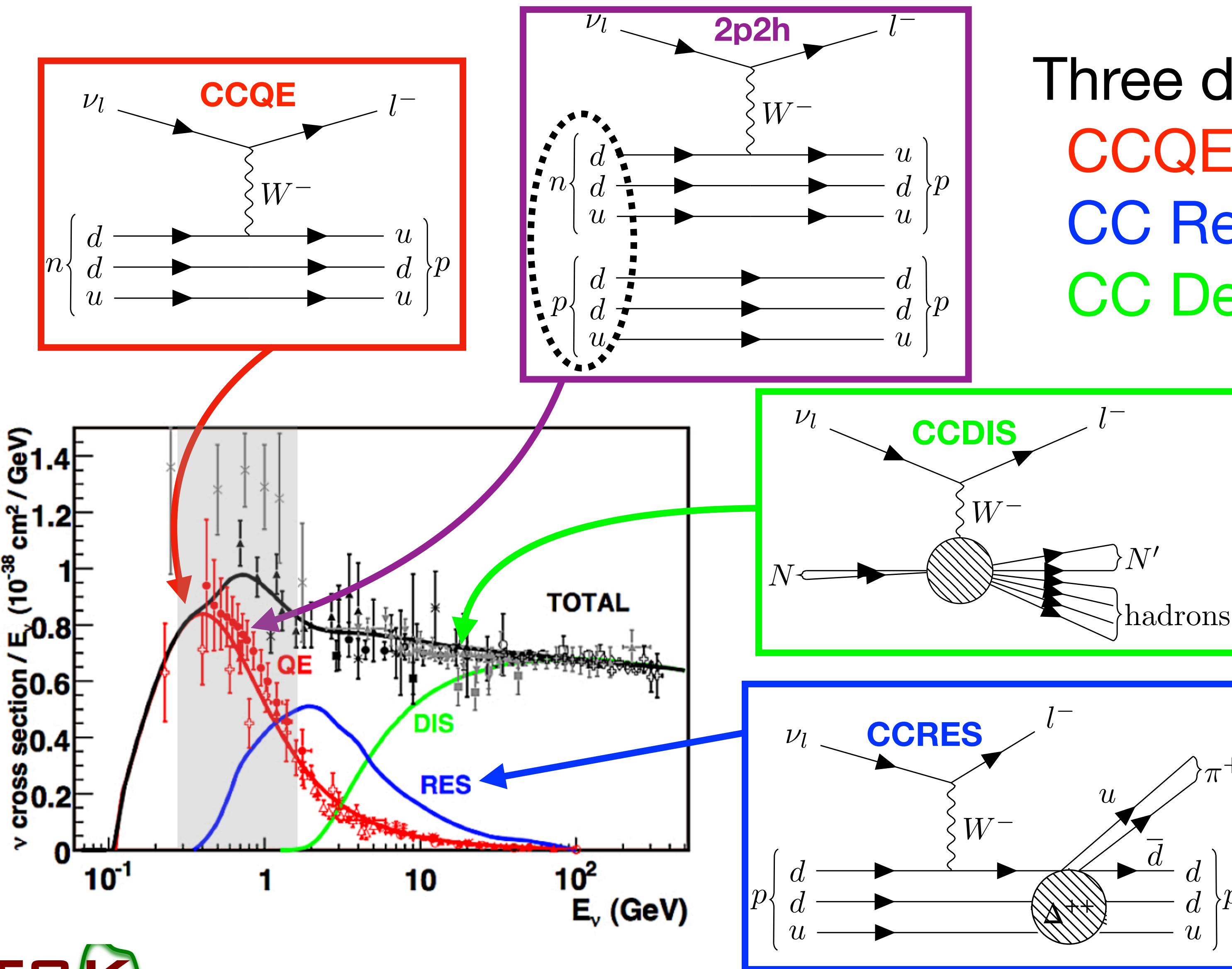
TPC for Particle Identification

Magnetization \rightarrow charge and momentum

\Rightarrow **Constraints on cross-sections and flux uncertainty model**



Neutrino interactions



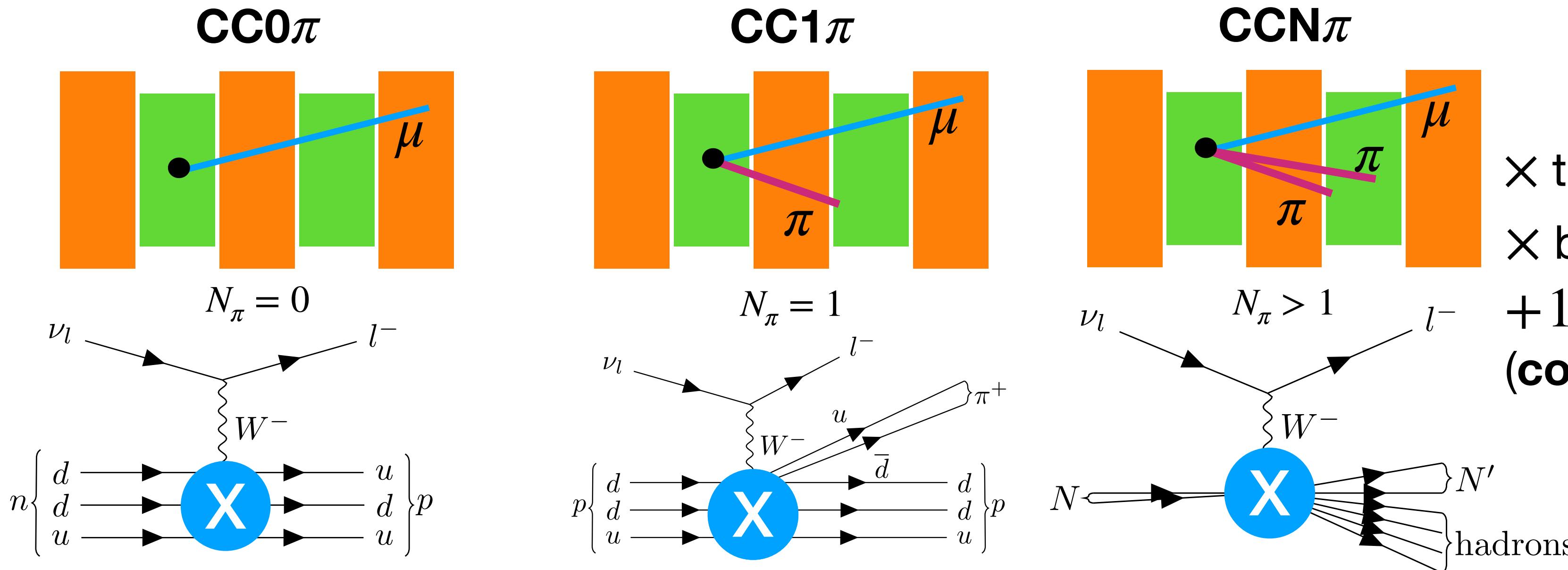
Three dominant interaction channels:

- CCQE (and 2p2h)**
- CC Resonant (RES)**
- CC Deep Inelastic Scattering (DIS)**

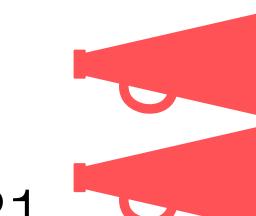
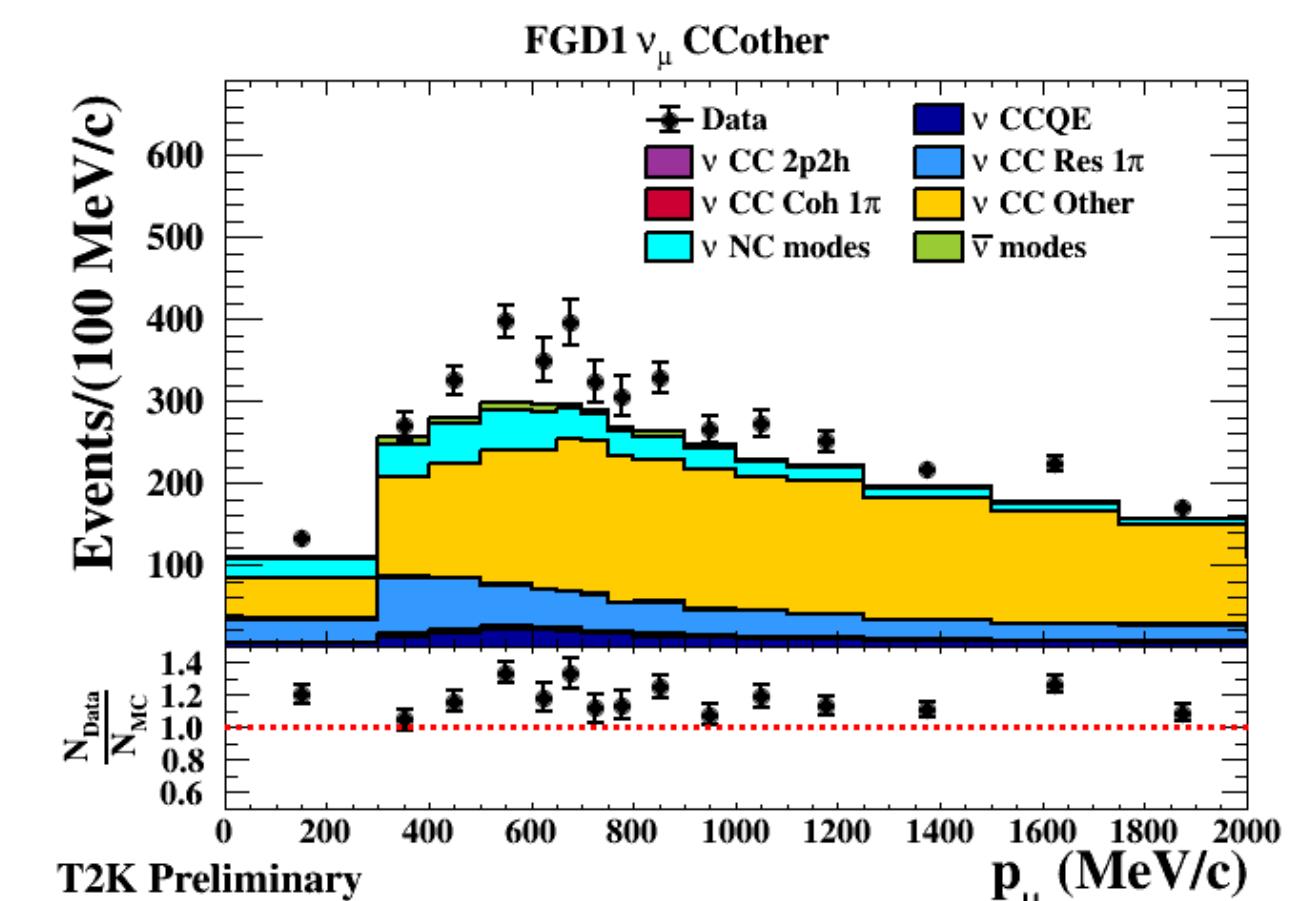
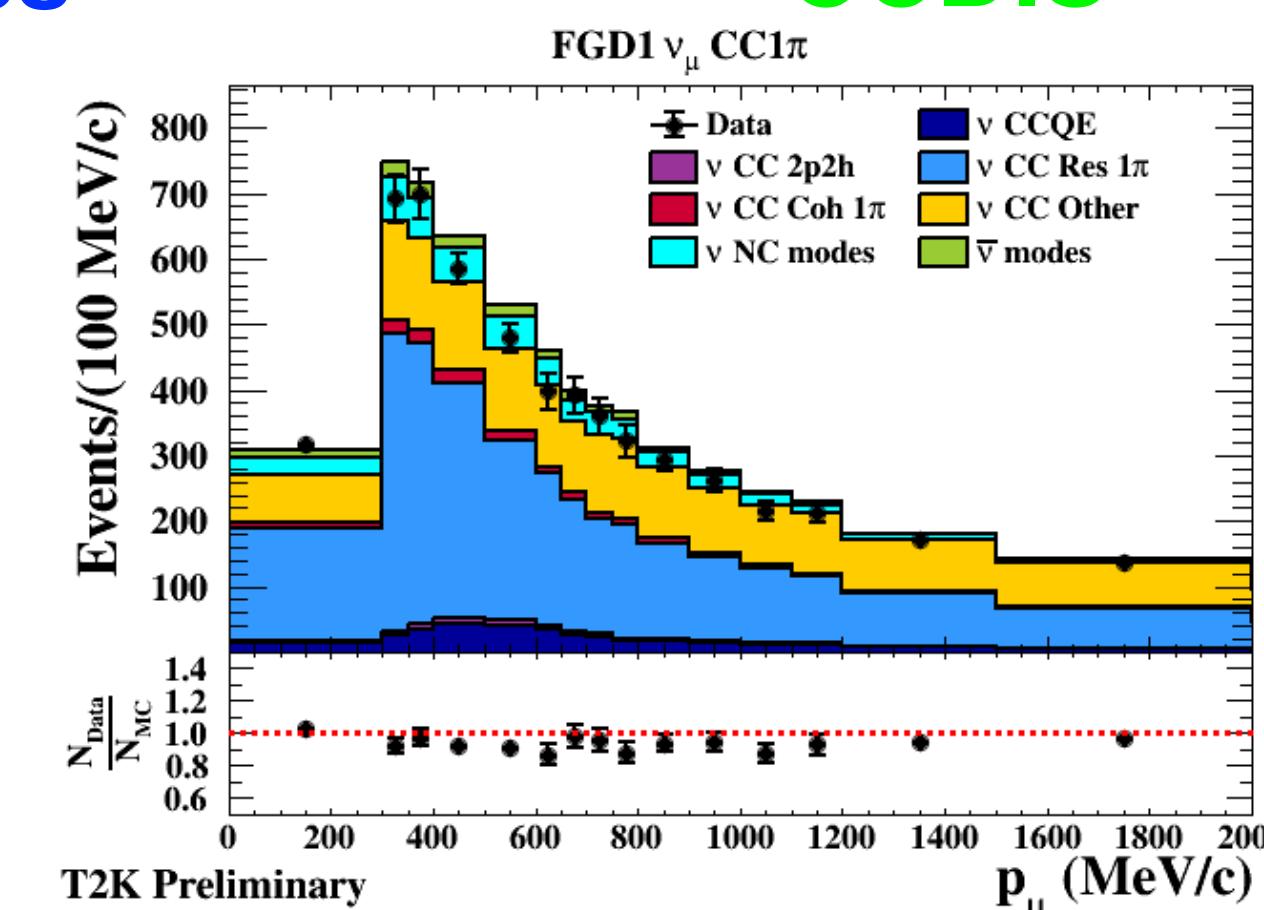
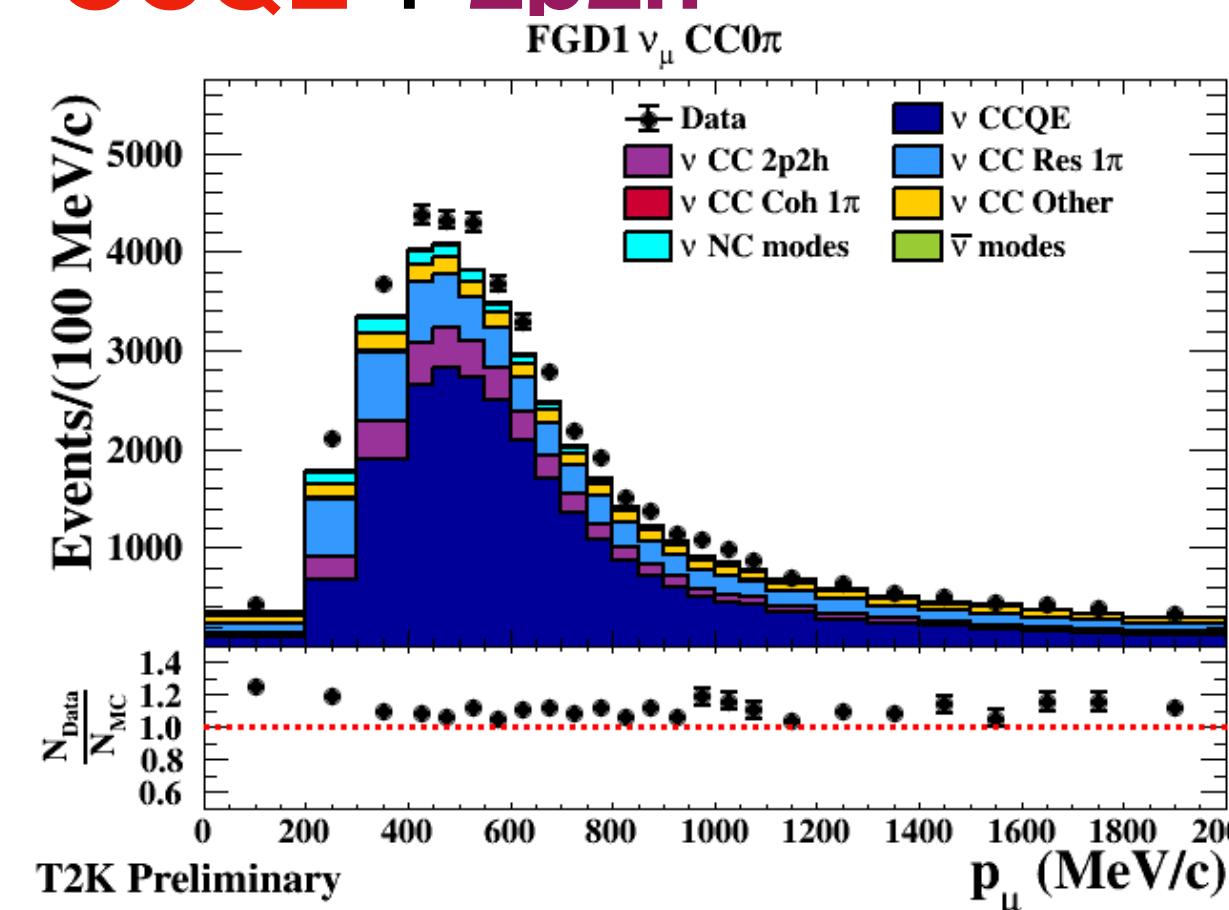
→ Define ND samples enriched in each of the processes using **reconstructed pion multiplicity**

→ Constrain cross-section models for each interaction

ND280 samples



× target detector (FGD1 or FGD2)
 × beam mode (ν or anti- ν)
 + 1 sample ν events in anti- ν beam mode
(constrain wrong-sign background)
= 18 samples



See Joanna Zalipska's parallel talk



See Kamil Skwarczynski's parallel talk

Many interesting problems being tackled in neutrino interactions!

Recent analyses:

- First measurement of transverse kinematic imbalance in CC1 π^+ [02/2021]
- First CC- $\nu_e/\bar{\nu}_e$ inclusive cross-section measurement [10/2020]
- CC0 $\pi\bar{\nu}_\mu$ cross-section measurements on H₂O [07/2020]
- CC0 $\pi\nu_\mu$ cross-sections on H₂O and CH [04/2020]
- CC0 $\pi\nu_\mu/\bar{\nu}_\mu$ cross-sections on C and O [04/2020]
- Combined ν_μ and $\bar{\nu}_\mu$ CC0 π cross-sections measurement [02/2020]
- CC1 π^+ cross-sections on CH [01/2020]



See Ka Ming Tsui's parallel talk



See Grzegorz Żarnecki's parallel talk

Cross-section modeling for ND fit

Improvements in this analysis to modeling of neutrino cross-sections

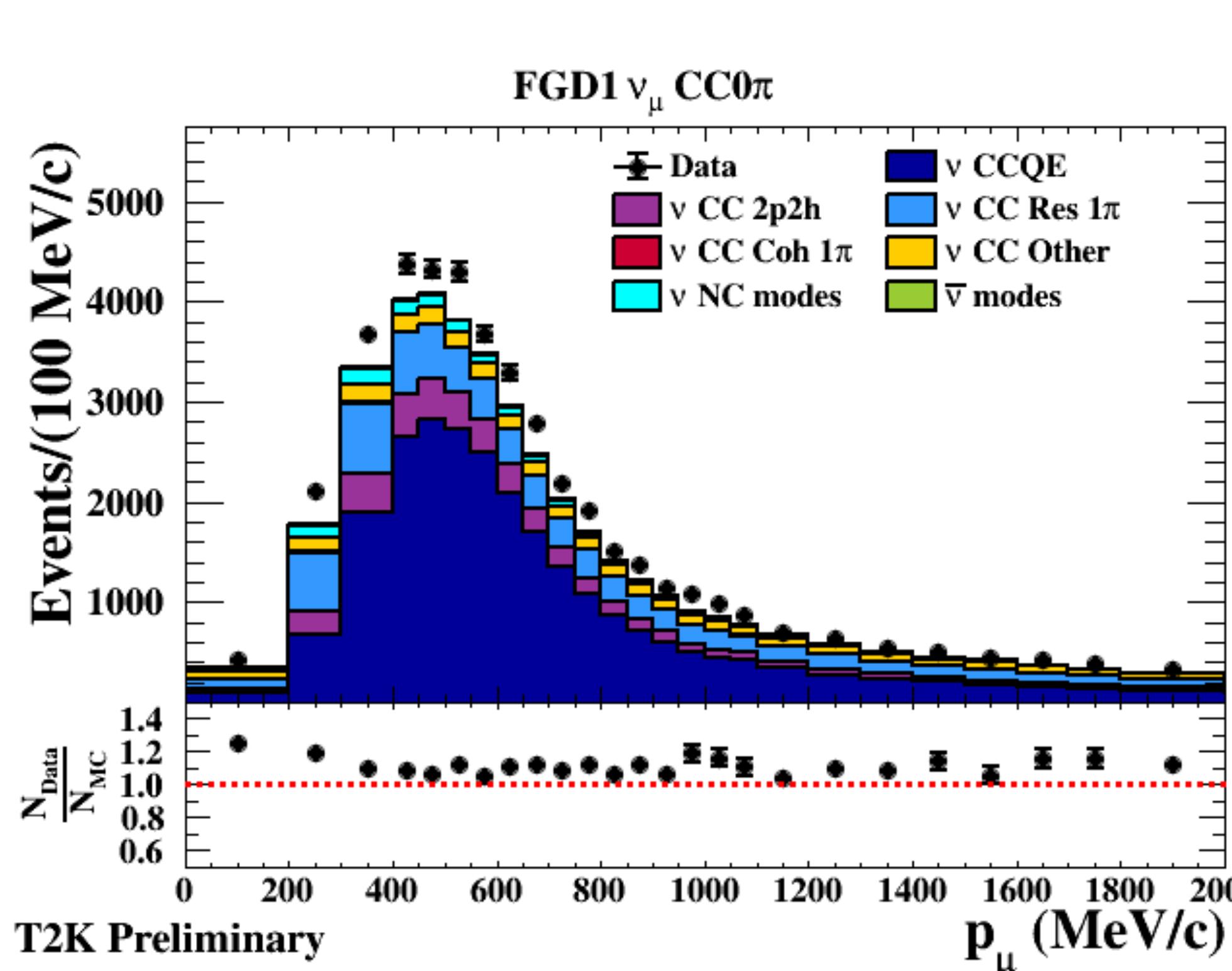
- Tuning of baseline nuclear model (Spectral Function)
- 2p2h modeling: new uncertainty on energy dependence
- Improvements of nucleon-nucleus binding energy (momentum shift)
- Improved parametrization of CCDIS and CCN π models

Near detector fit

Modeling of neutrino cross-sections

Model after fit reproduces well the data (p-value of 0.74)

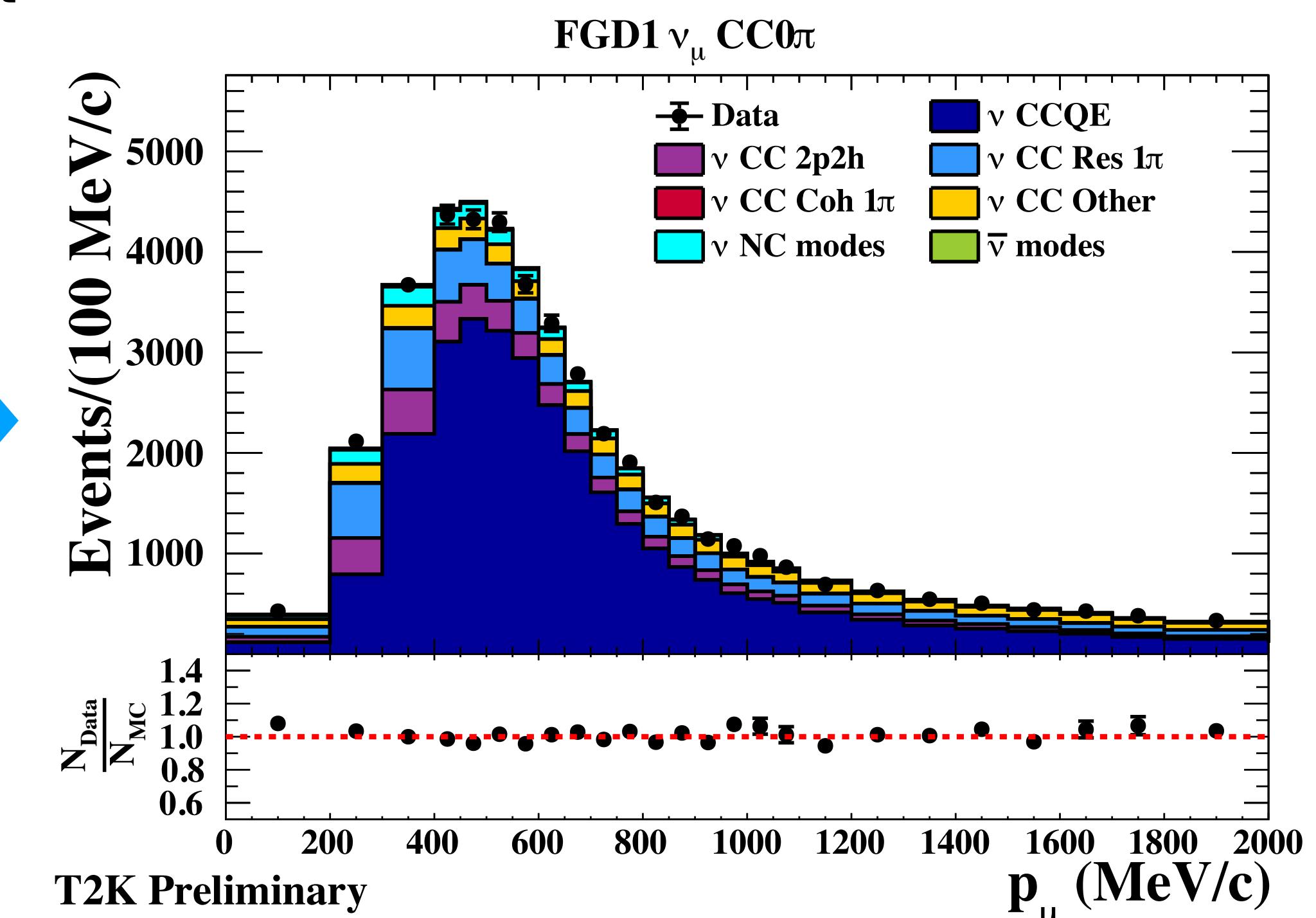
ND280 Run 2-9: 1.15×10^{21} POT in ν and 0.83×10^{21} POT in $\bar{\nu}$



Prefit → Postfit

CC0 π

Fit using
 $p_\mu, \theta_\mu \dots$



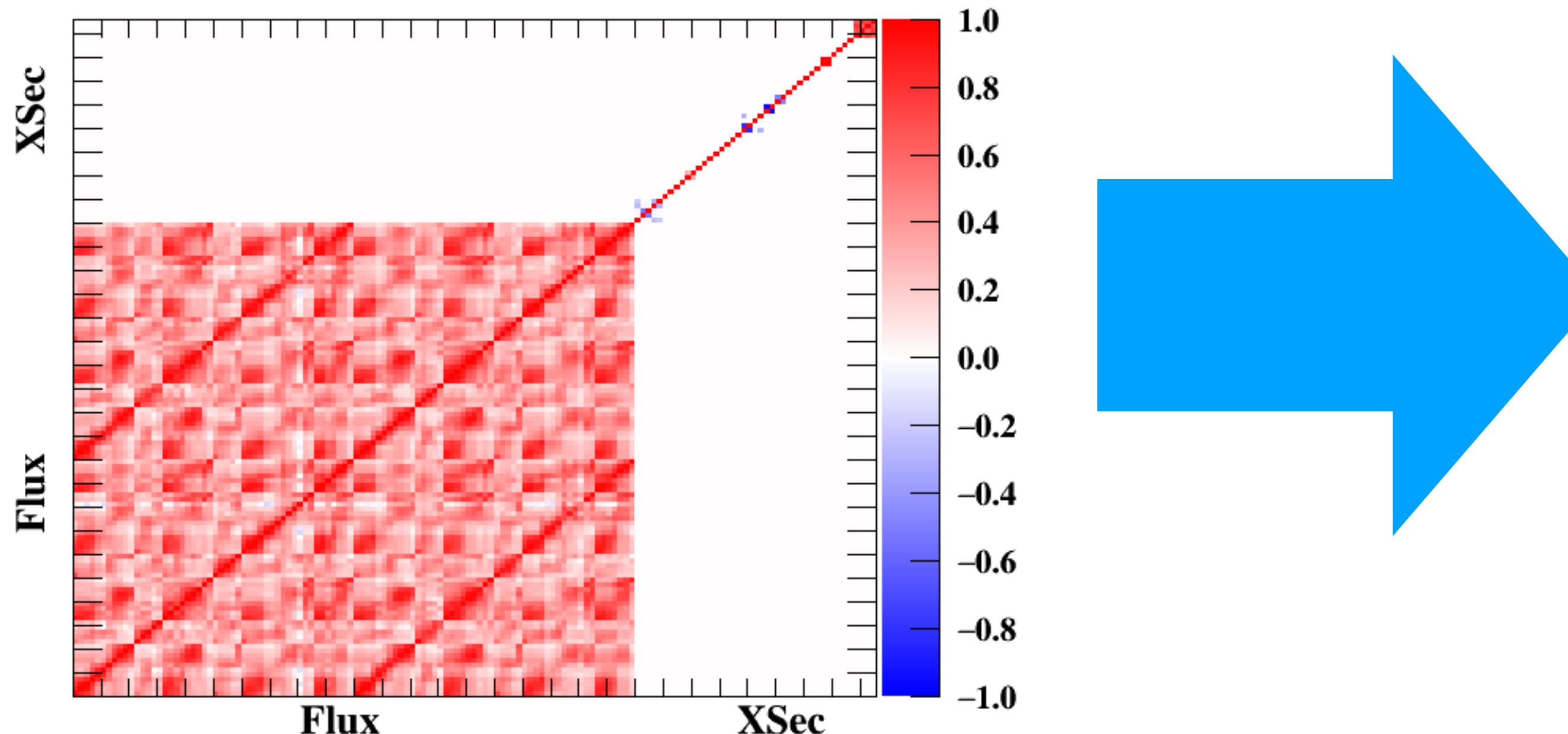
Near detector fit

Modeling of neutrino cross-sections

Model after fit reproduces well the data (p-value of 0.74)

Introduction of anti-correlations between flux and cross-section parameters due to fit

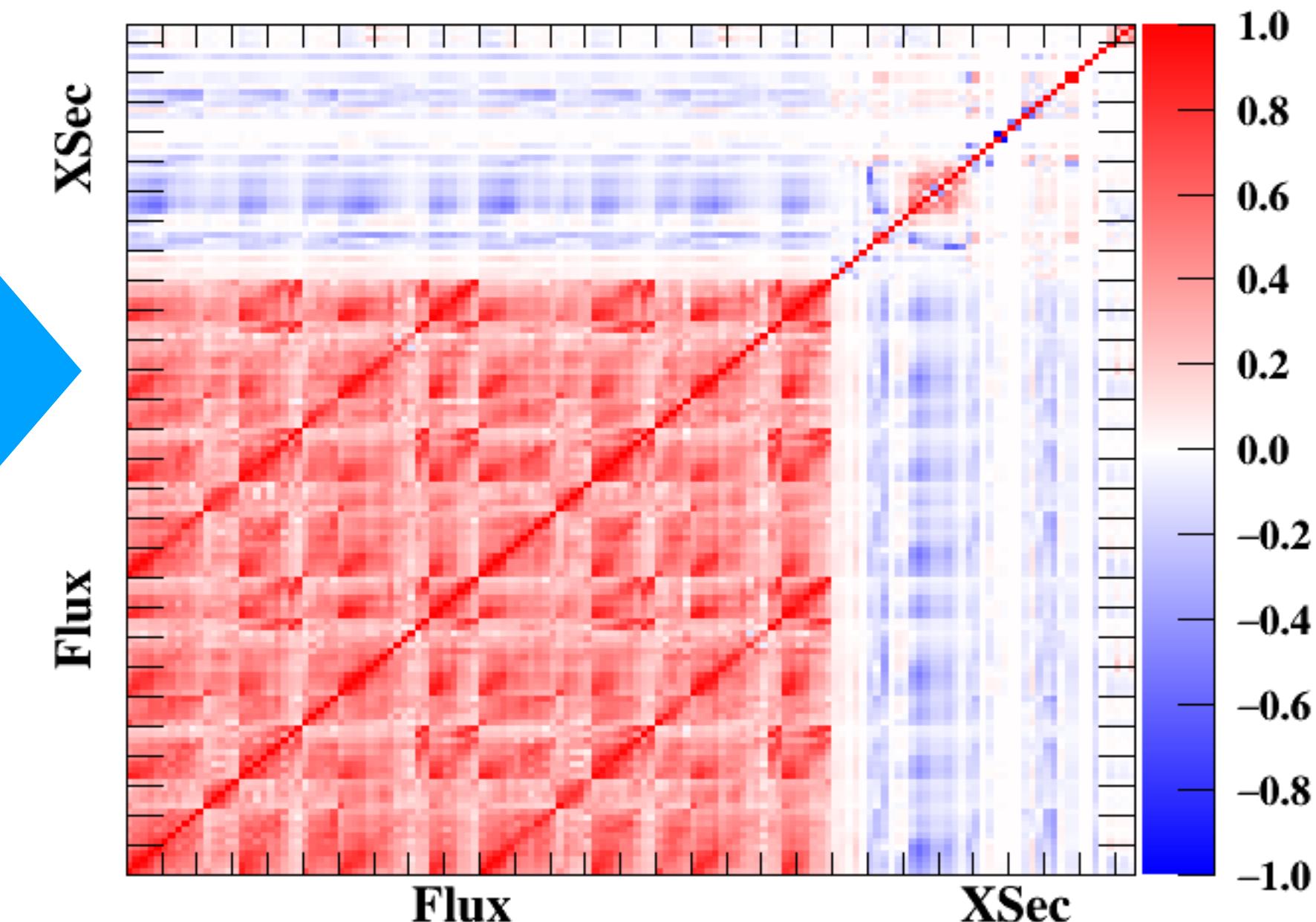
Flux and Xsec Prefit Correlation Matrix



T2K Preliminary



Flux and Xsec Postfit Correlation Matrix



T2K Preliminary

Near detector fit

Modeling of neutrino cross-sections

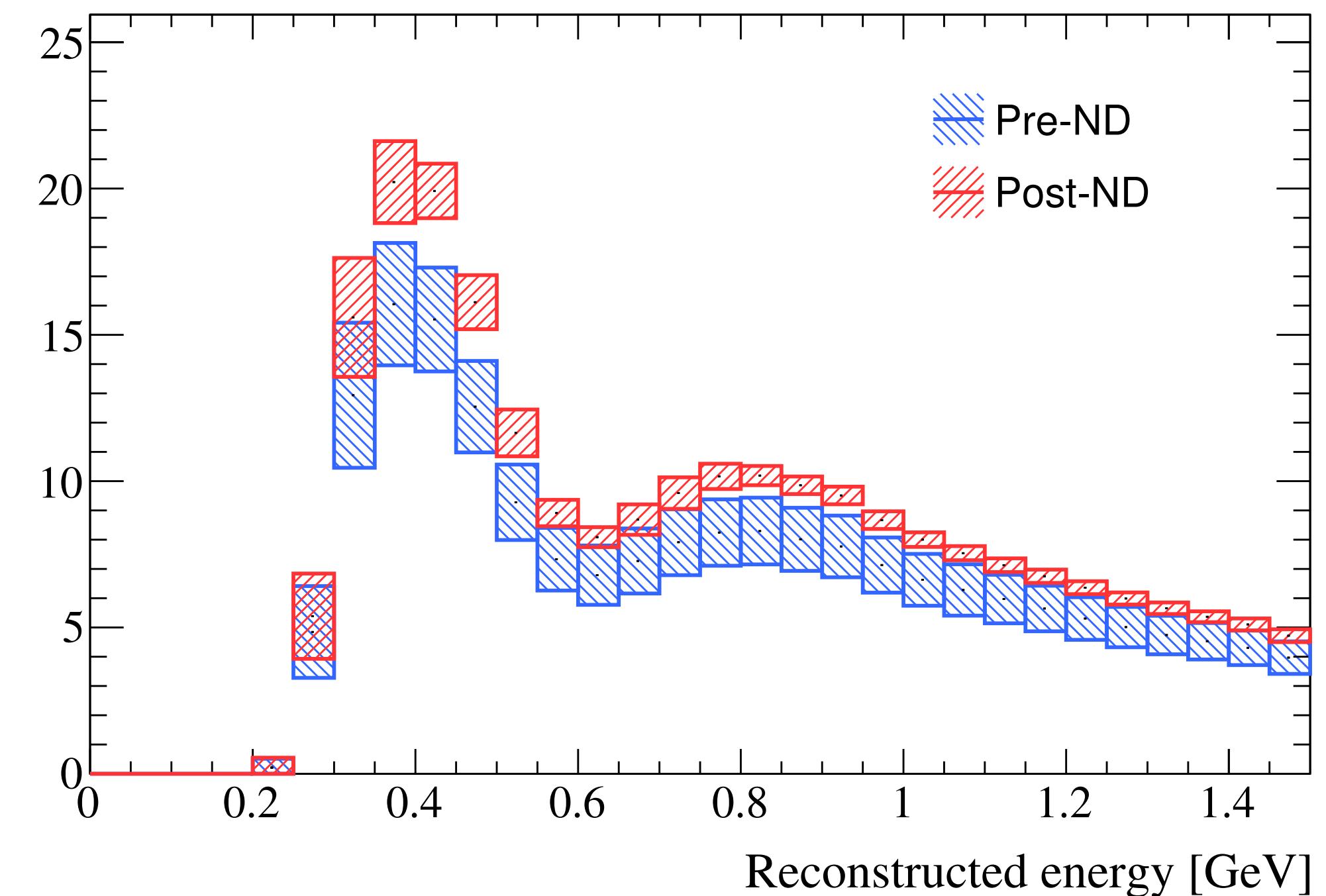
Model after fit reproduces well the data (p-value of 0.74)

Introduction of anti-correlations between flux and cross-section parameters due to fit

→ Spectra prediction at far detector

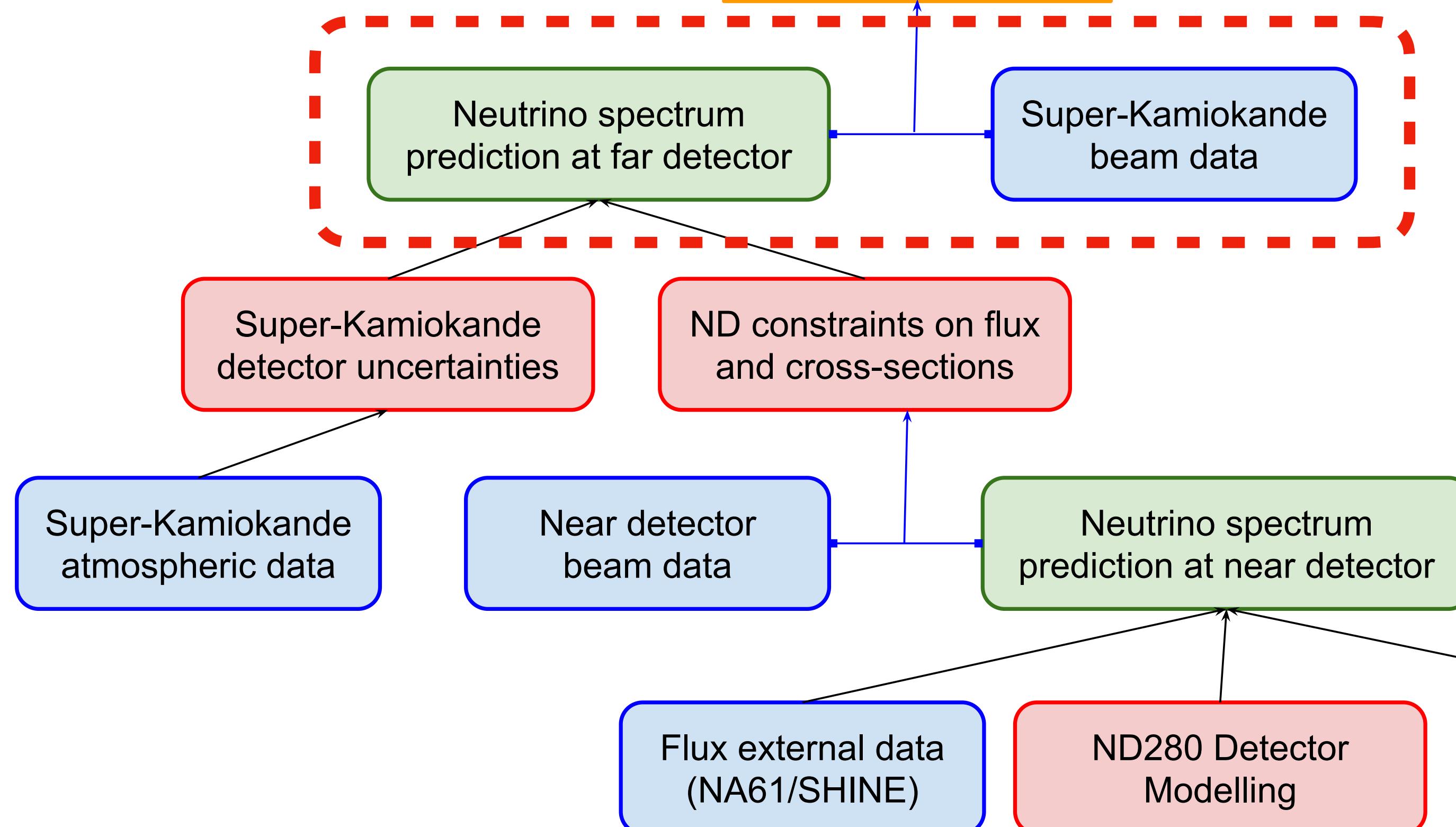
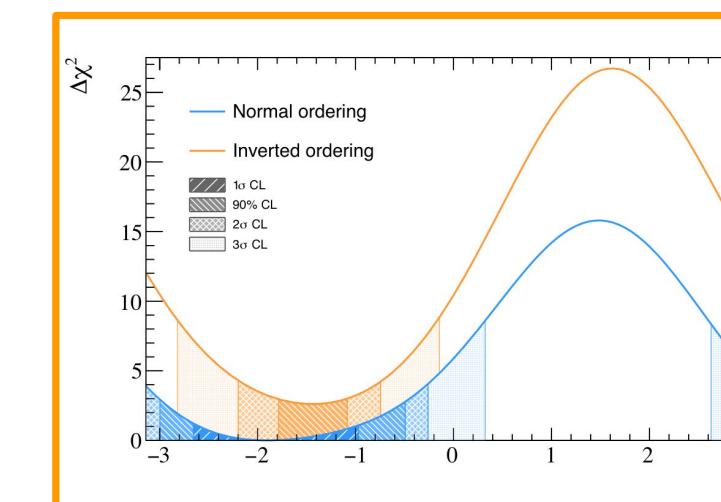
→ **Flux and cross-section uncertainties reduction at SK from ~13% to ~4%**

FHC 1R μ average spectrum with all systematics



Oscillation analysis strategy

$$\delta_{CP}, \sin^2 \theta_{13}, \Delta m_{32}^2 \dots$$

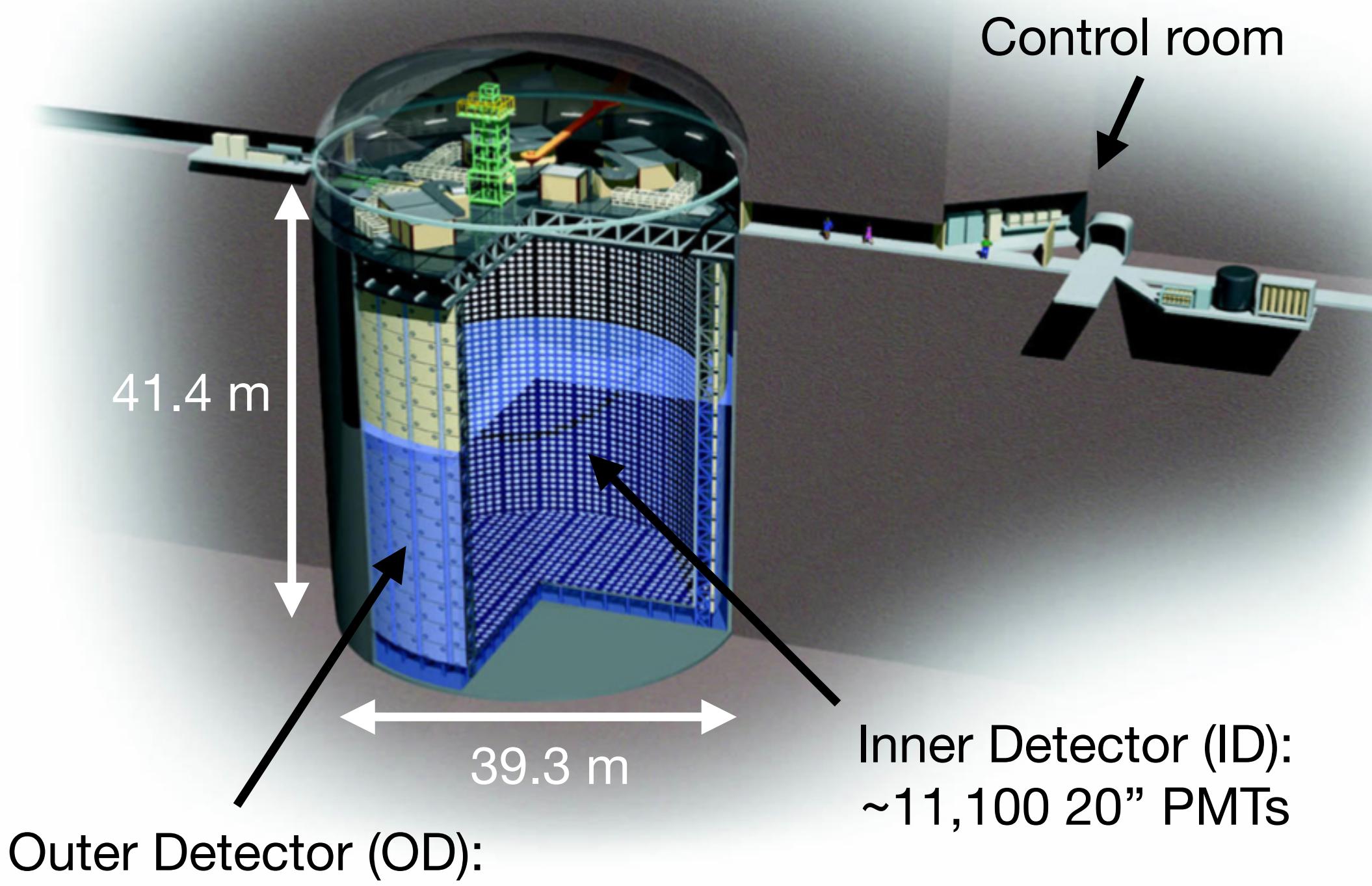


Two analyses:

- ND fit then SK fit
- ND+SK joint fit

See Joe Walsh's parallel talk

Off-axis Far Detector: Super Kamiokande



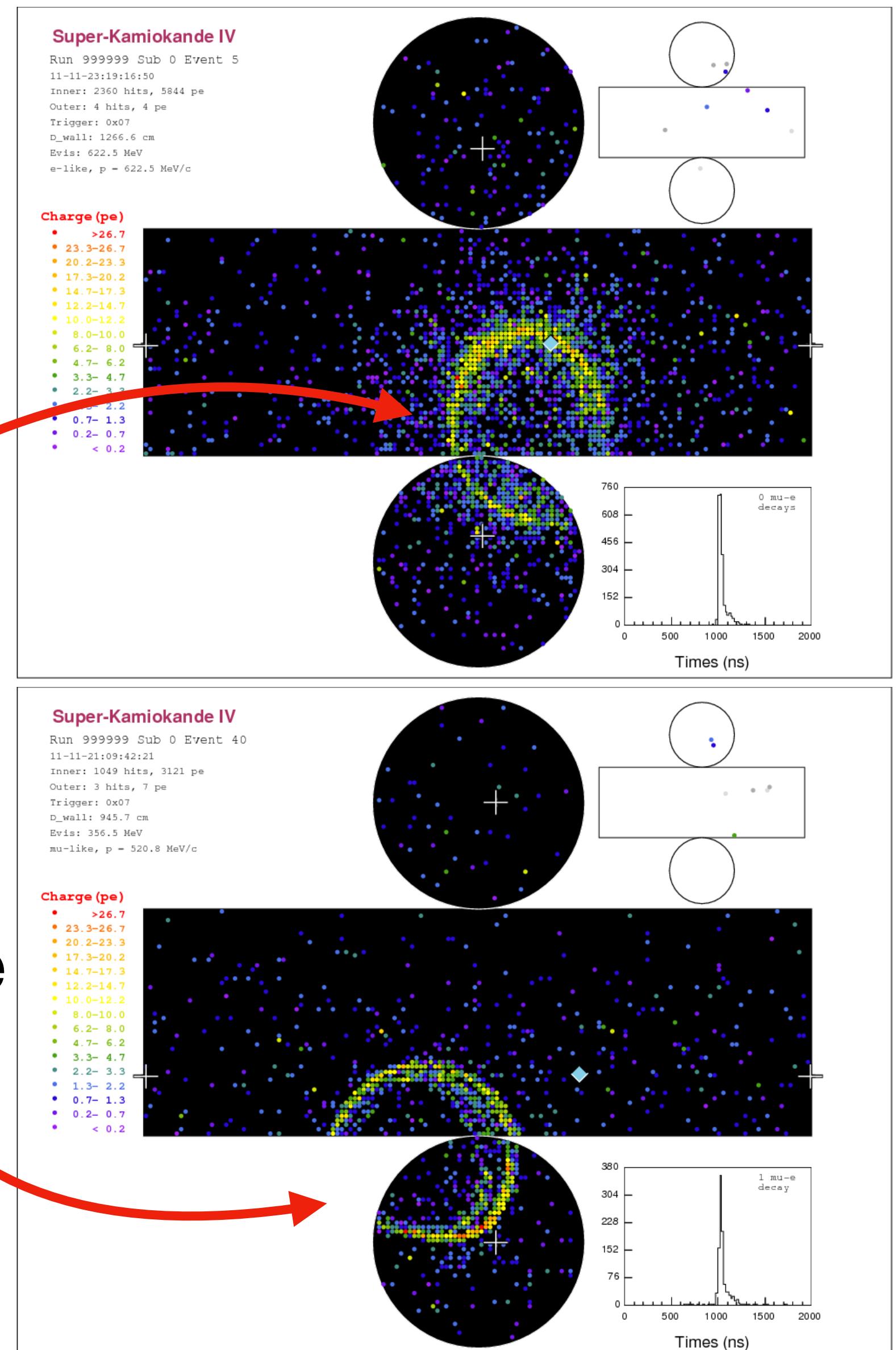
50 kton of purified water
1000 m under Mount Ikeno

e - μ identification et kinematics using Cherenkov ring pattern

No charge identification (contrary to ND280)

Fuzzy $\rightarrow e$ -like

Sharp $\rightarrow \mu$ -like



Super-Kamiokande samples

Selection based on ring counting and shape

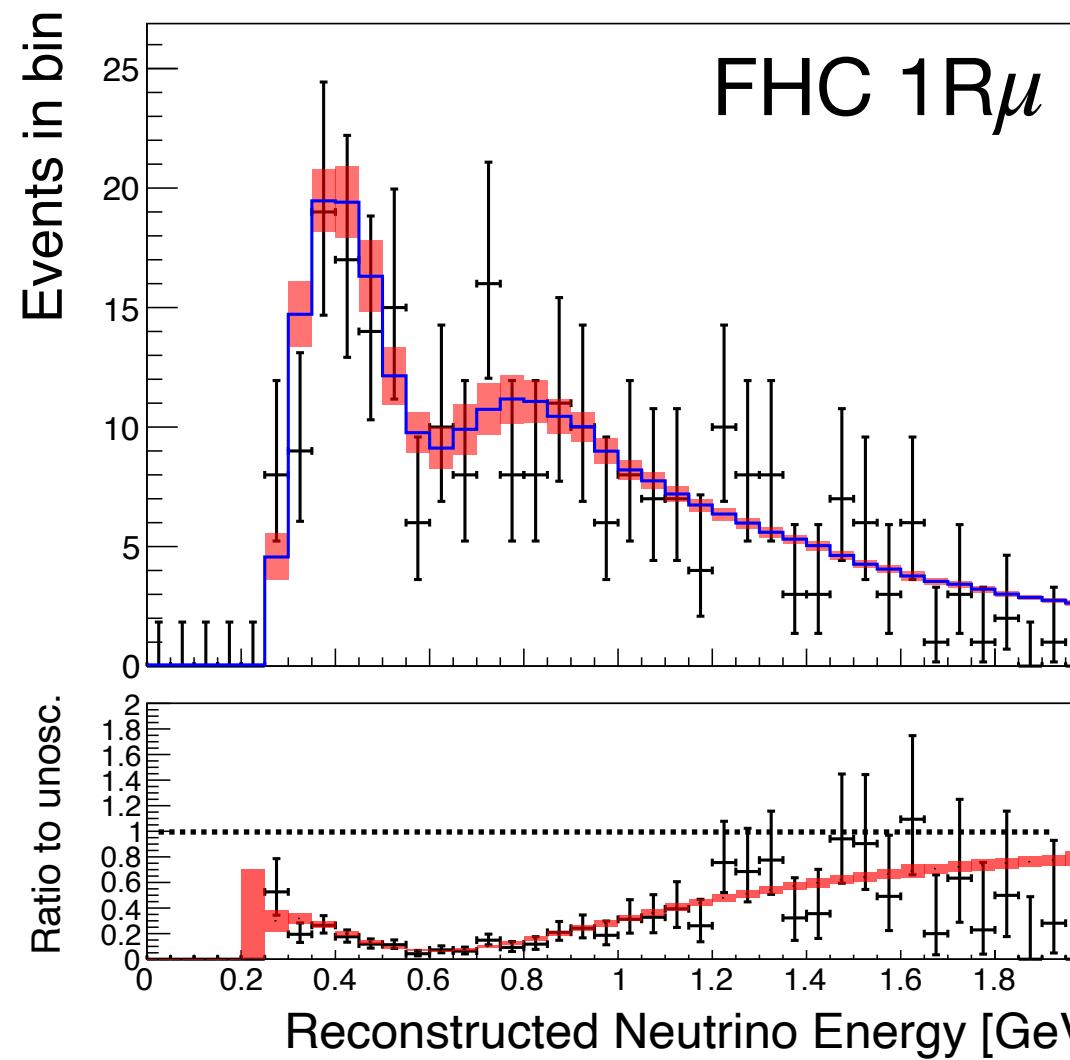
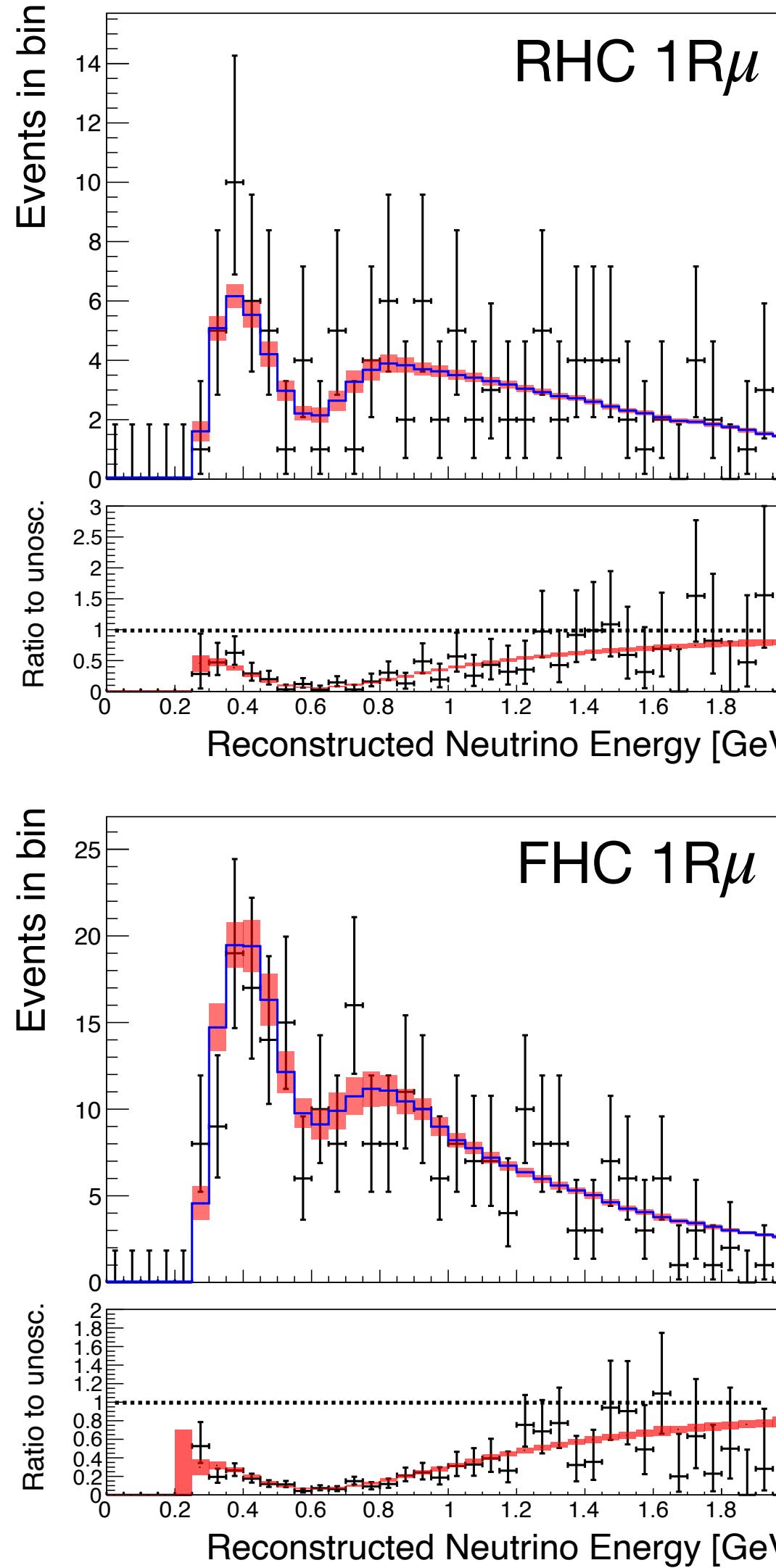
Two samples with 1 μ -like ring (ν mode and anti- ν mode) $\rightarrow \nu_\mu\text{-CC}0\pi$

Two samples with 1 e -like ring (ν mode and anti- ν mode) $\rightarrow \nu_e\text{-CC}0\pi$

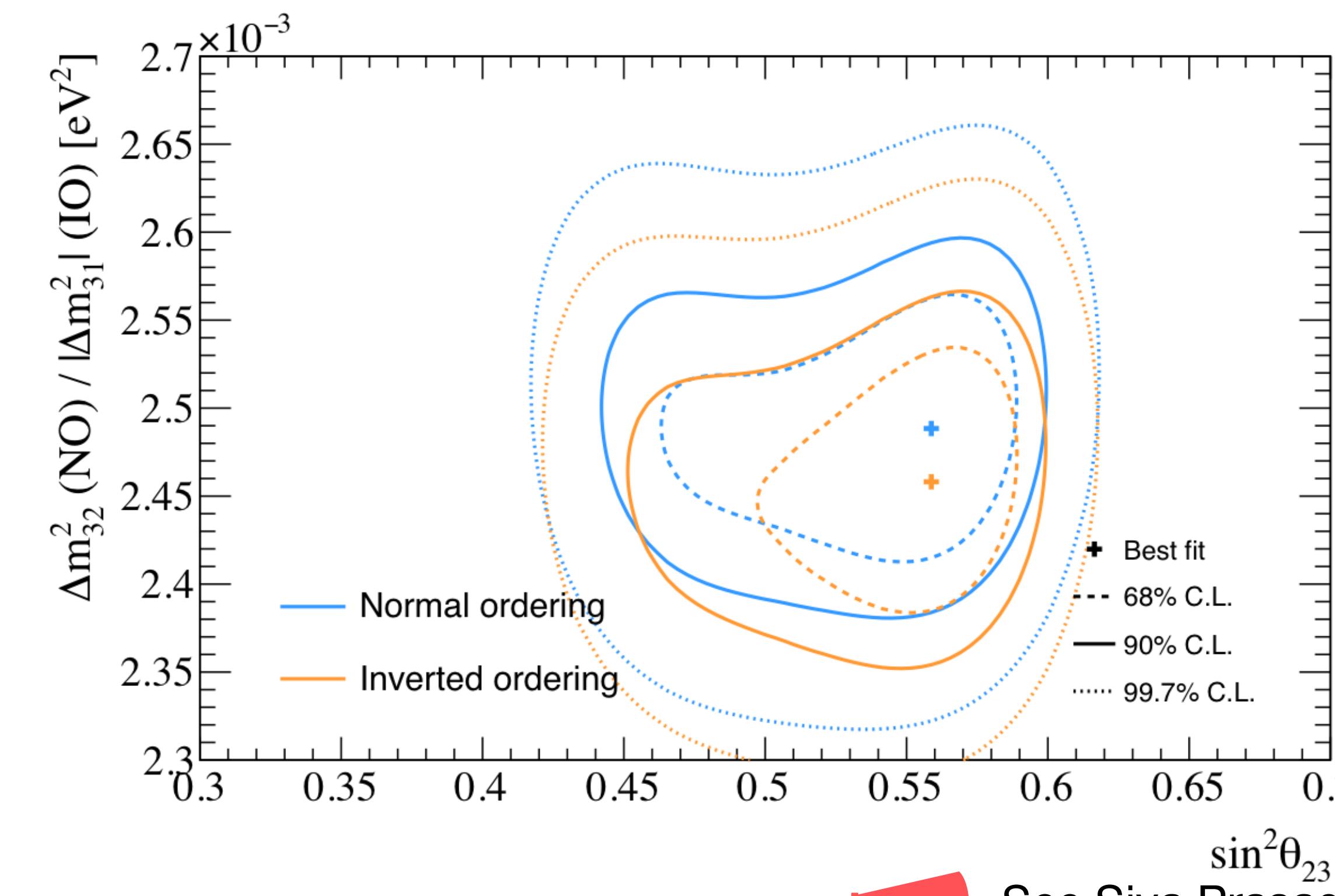
One sample with 1 e -like ring + 1 Michel electron ring $\rightarrow \nu_e\text{-CC}1\pi$

Sample	ν -mode 1R μ	$\bar{\nu}$ -mode 1R μ	ν -mode 1Re	$\bar{\nu}$ -mode 1Re	ν -mode 1Re1de
Number of events	318	137	94	16	14
Total uncertainty (after fit) [%]	3.0	4.0	4.7	5.9	14.3
Total uncertainty (before fit) [%]	11.1	11.3	13.0	12.1	18.7

$\nu_\mu/\bar{\nu}_\mu$ disappearance results



Analysis using five SK Run 1-10 samples
 Upper octant preference (77.1% prob) from ν_e samples
 Normal hierarchy preferred at 80.8%



See Siva Prasad Kasetti's parallel talk

Run 1-9 analysis → [PRD 103 \(1\), L011101](#)

$\nu_e/\bar{\nu}_e$ appearance results

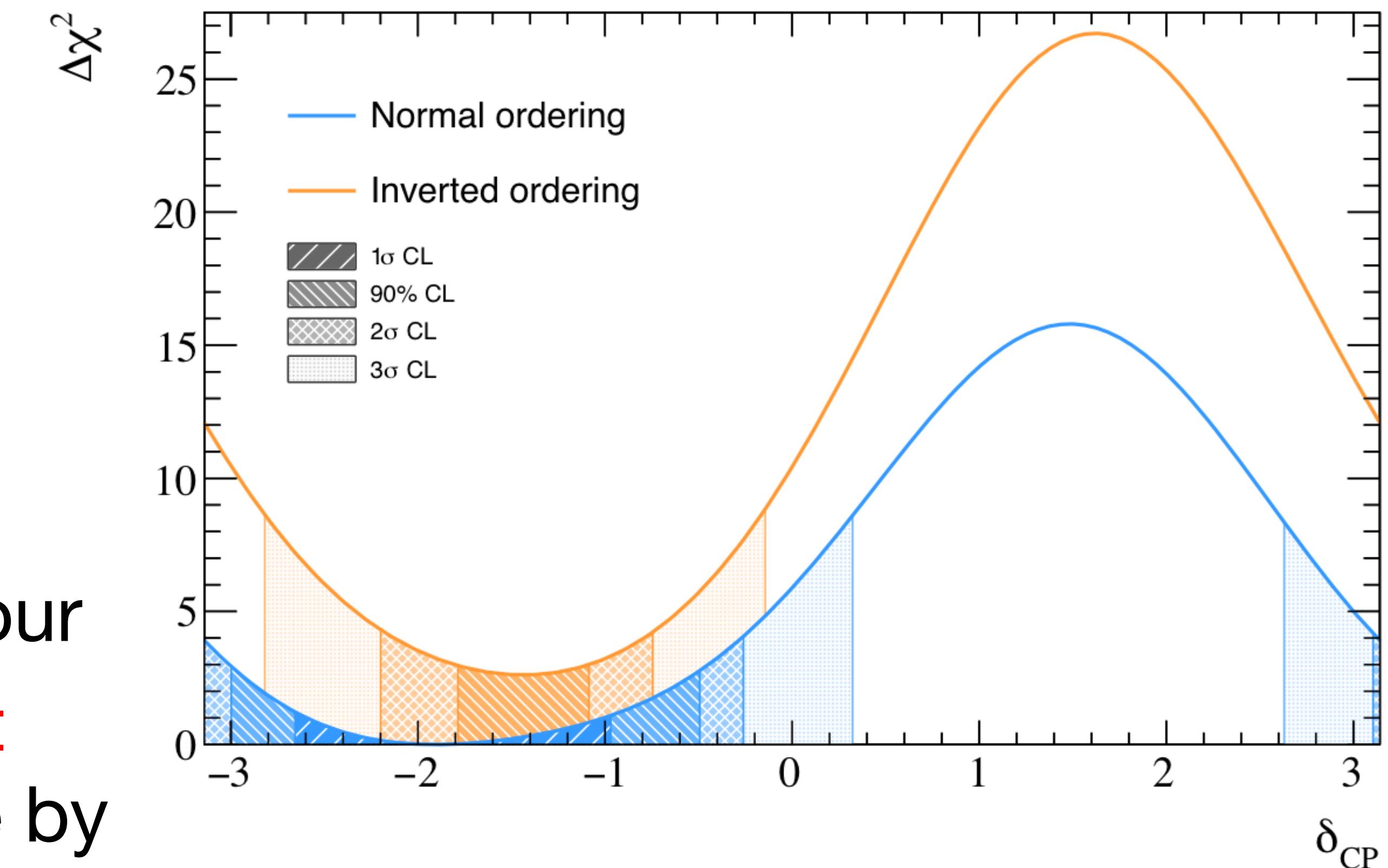
$\delta_{\text{CP}} = -\frac{\pi}{2}$ favored

35% of values excluded at 3σ
 marginalized across hierarchies

CP conservation excluded at 90%

Largest $\Delta\chi^2$ change seen in any of our
 robustness studies would cause **left**
(right) edge of 90% interval to move by
0.073 (0.080)

Feldman-Cousins corrections included

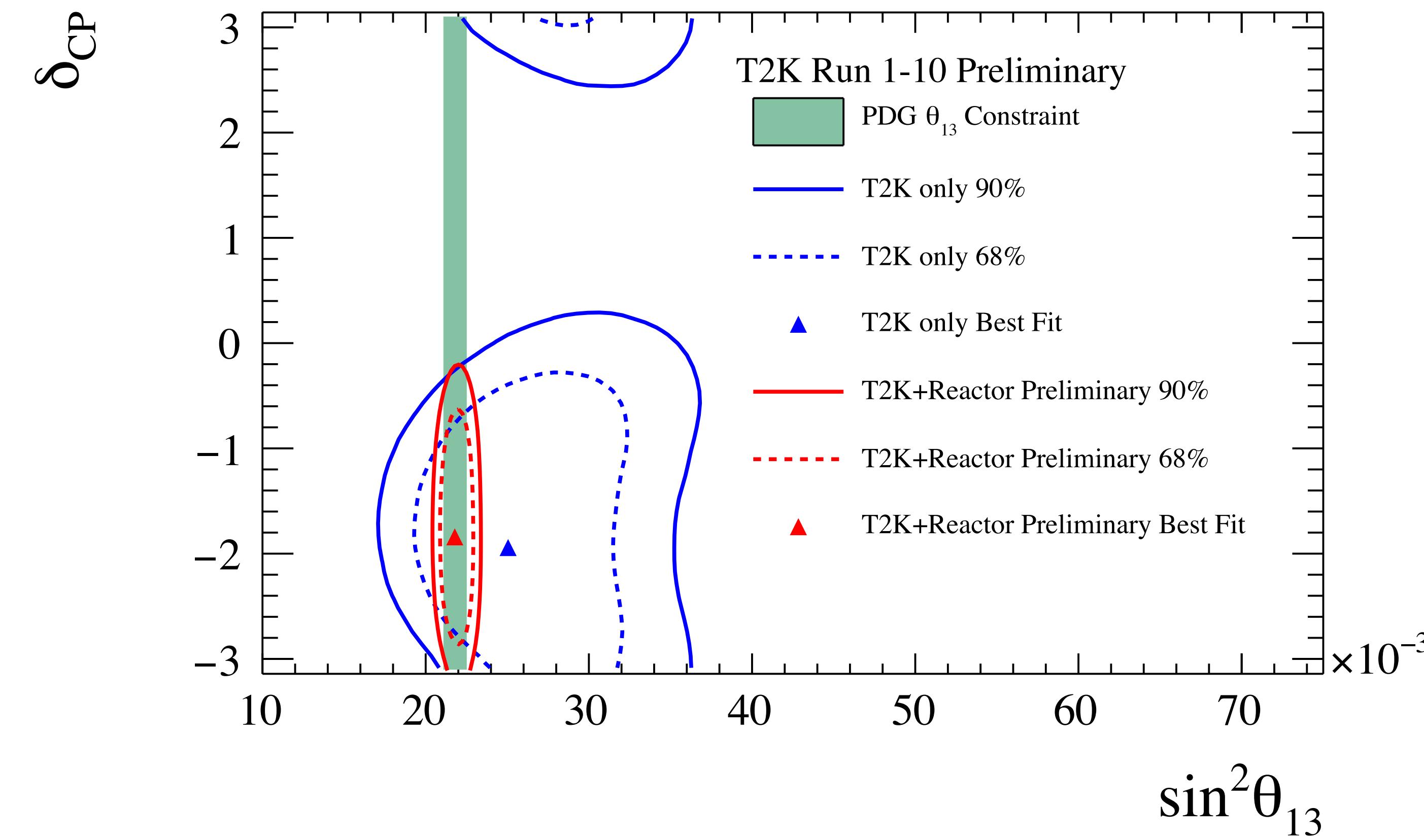


See Joe Walsh's parallel talk

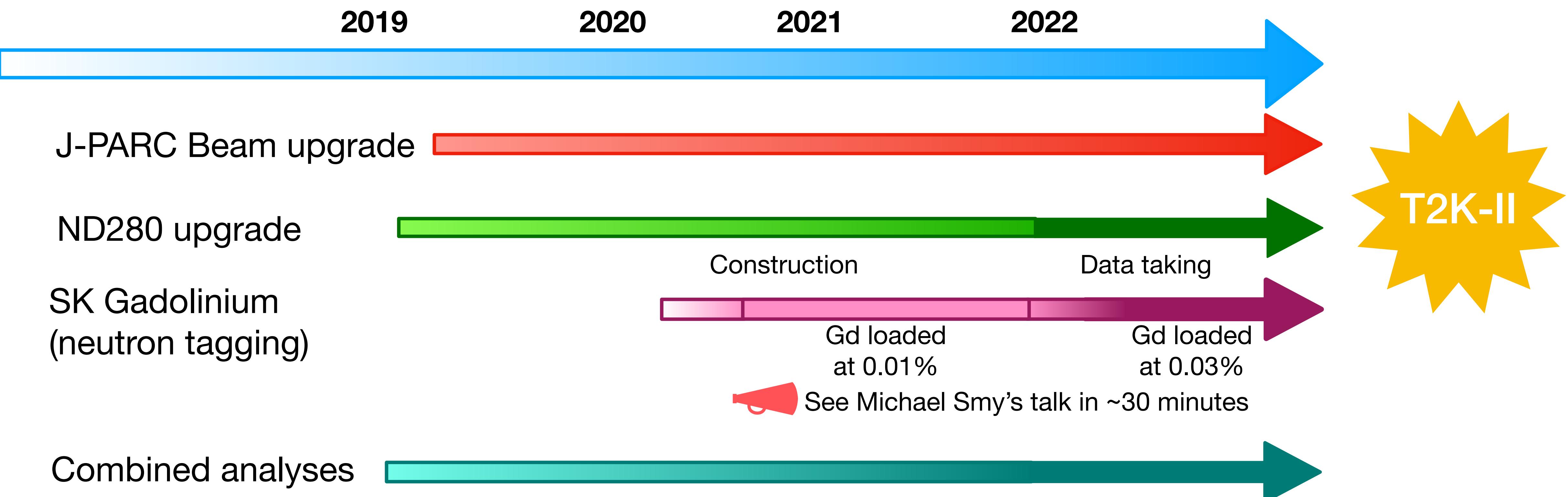
Reactor constraints impact on δ_{CP} vs θ_{13}

Constraints on θ_{13} compatible with PDG2019 at better than 1σ

Using PDG2019 constraint on θ_{13} , better constraint on δ_{CP}



T2K's Bright Future



Combined analyses

Experiments with different neutrino energies have different oscillation patterns (and potentially different systematic uncertainties)

Two on-going combined analyses efforts:

- T2K beam and Super-Kamiokande atmospheric data
 - longer baseline and higher energy neutrino: more sensitive to mass ordering
- T2K and NO ν A beam data
 - systematic uncertainties and longer baseline: more sensitive to mass ordering

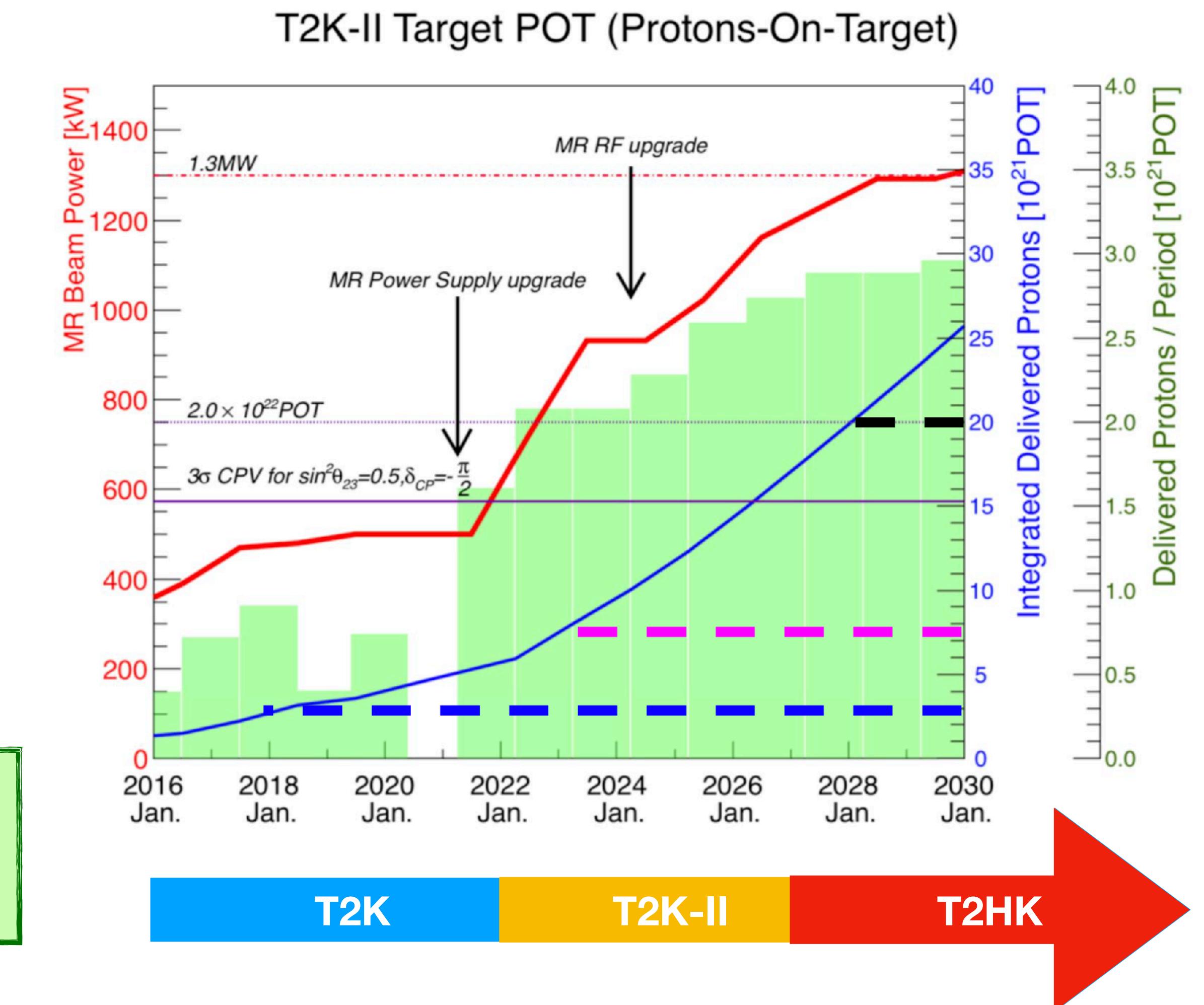


J-PARC beam upgrade

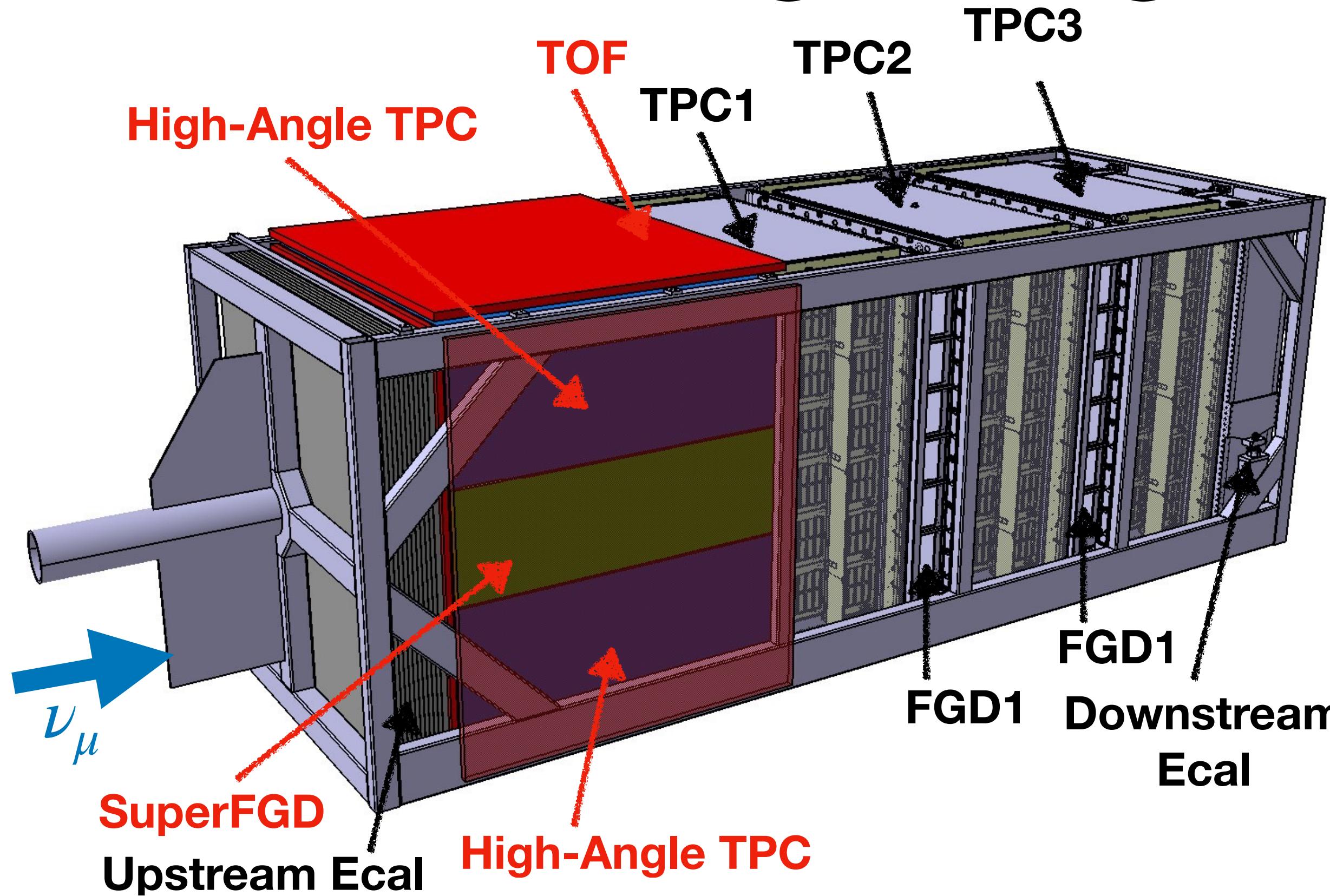
J-PARC main ring upgrades on-going

- 2x more pulse per second
(One pulse every 2.5 s → 1.3 s)
- Increase power from 515 kW to up to 1.3 MW

Boost statistical power during T2K-II
Prepare for Hyper-Kamiokande



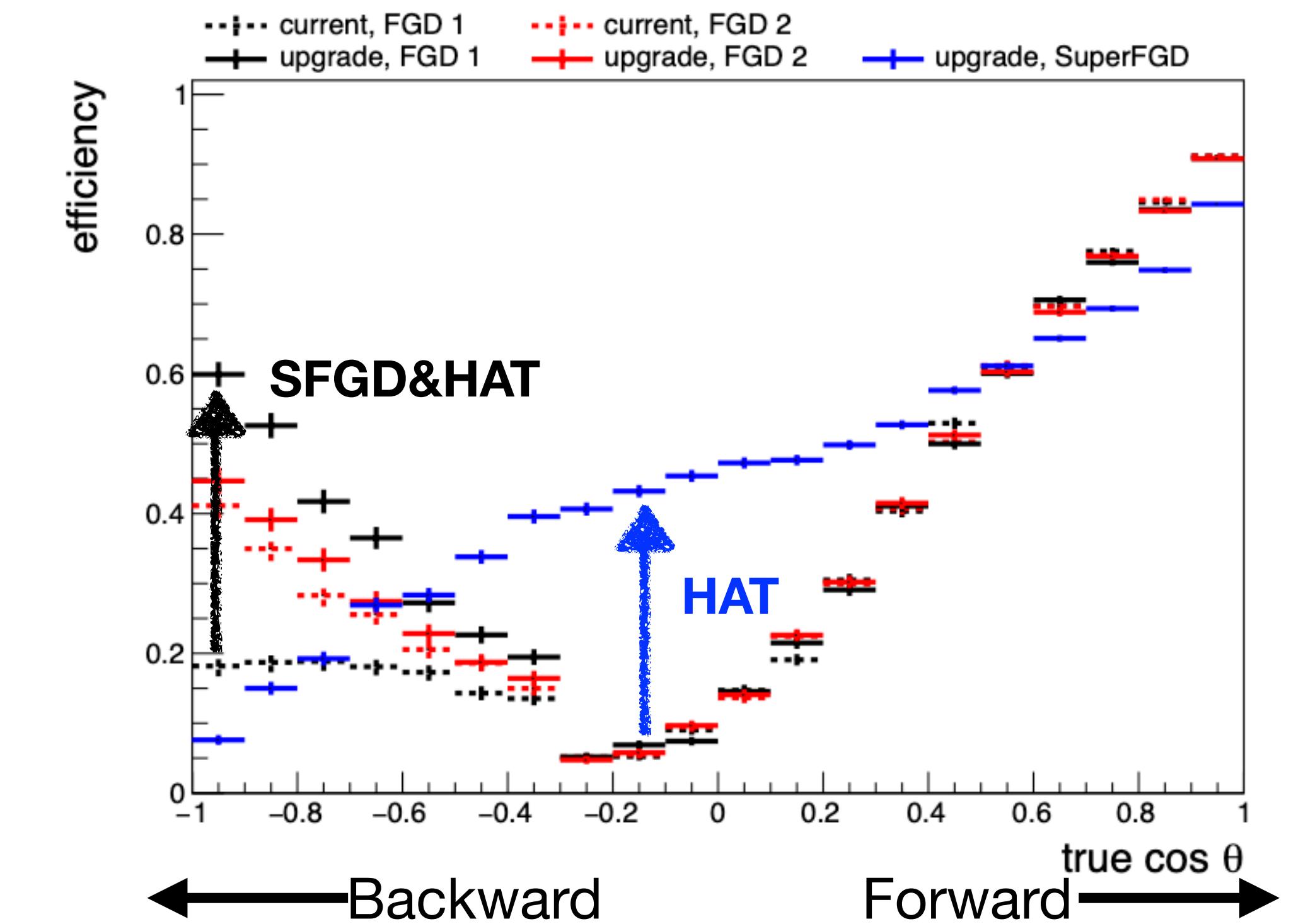
Upgrading the ND280 detector



SuperFGD (SFGD) $2 \cdot 10^6$ 1-cm³ scintillator cubes
 High-Angle TPCs (HATs) with Resistive MicroMegas
 Time-Of-Flight detector (TOF)



See César Jesús-Valls' parallel talk



Improved reconstruction at high and backward angles → better constraints on cross-sections
 Increased target mass → statistical power
 Better vertex reconstruction
 Outgoing proton/neutron reconstruction
 Installation at J-PARC in 2022

Summary and prospects



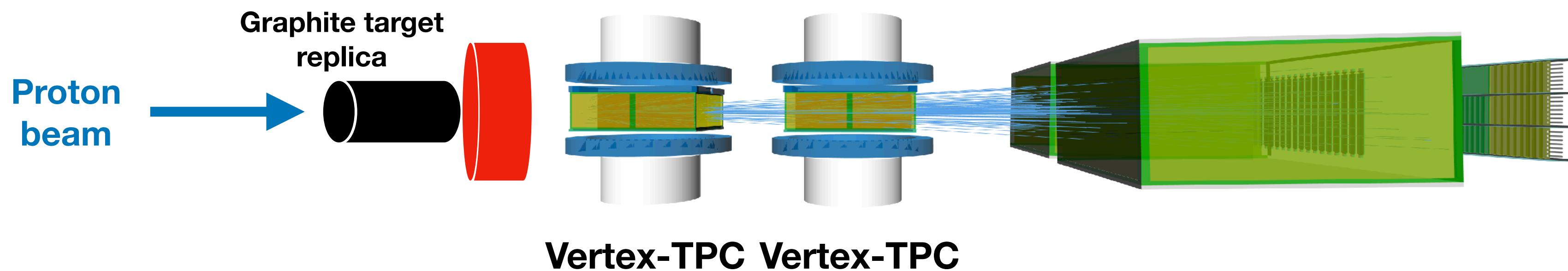
Nezu shrine, Tokyo

Parallel session T2K talks

- Probing nuclear effects in neutrino CC $1\pi^+$ interactions with transverse kinematic imbalance measurement in T2K
Ka Ming Tsui → Fri 19 10:20am
- Towards the cross-section measurement of the ν_μ CC single π -production in the T2K near detector
Grzegorz Żarnecki → Fri 19 11:35am
- Characterizing 2p2h interactions using low momentum protons
Joanna Zalipska → Fri 19 11:45am
- Future neutrino physics using the upgraded ND280 detector of the T2K experiment
César Jesús-Valls → Wed 24 11:00am
- Using proton information to constrain T2K fit
Kamil Skwarczyński → Wed 24 12:20pm
- T2K latest oscillation analysis results and methodology
Joe Walsh → Wed 24 5:50pm
- T2K latest results on muon neutrino and antineutrino disappearance
Siva Prasad Kasetti → Wed 24 6:10pm
- Ageing of the scintillator detectors of the T2K off-axis and on-axis near detectors, ND280 and INGRID
Maria Antonova → Thu 25 12:10pm

Go check them out!

Backup slides

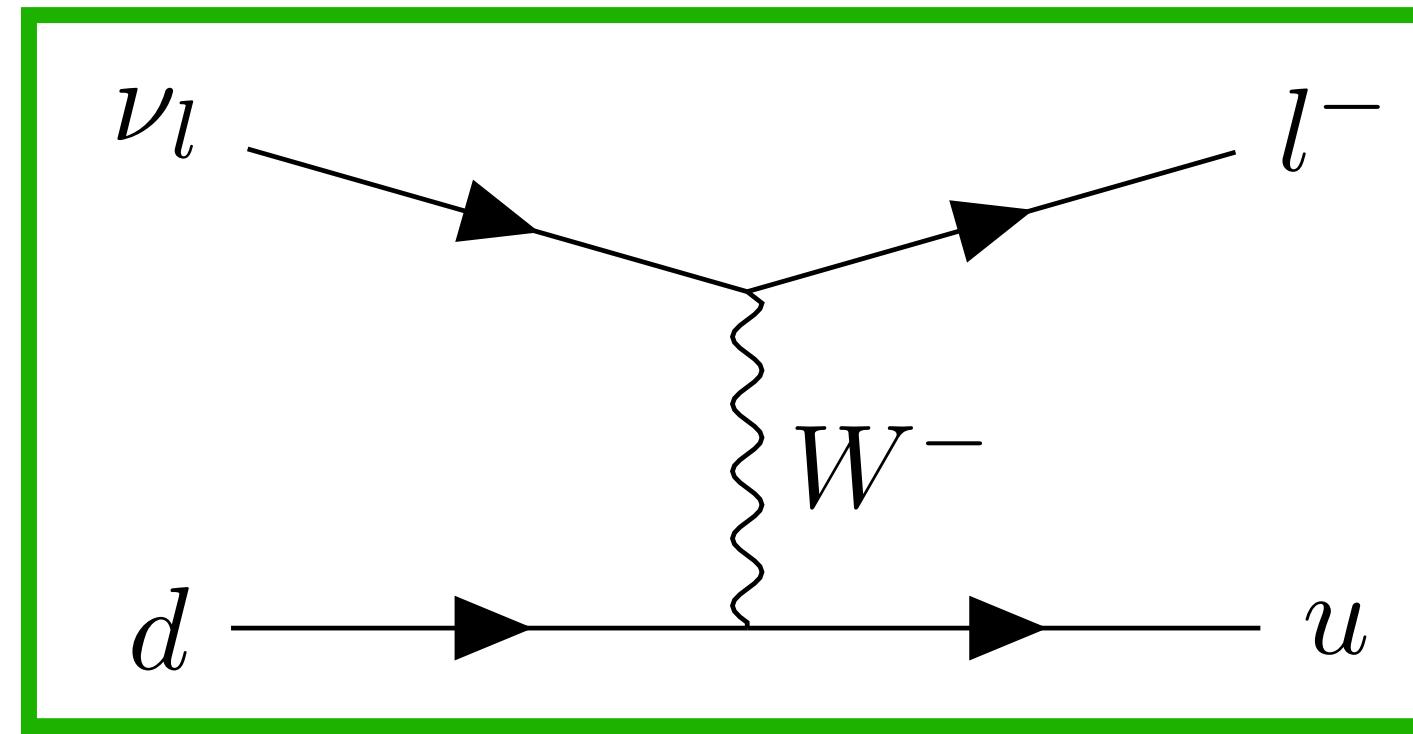


Experiment at CERN

Production of hadrons (pions and kaons) as a function of momentum and angle for protons interacting with carbon target (~T2K)

New: using T2K replica graphite target

Reconstructing neutrino energy

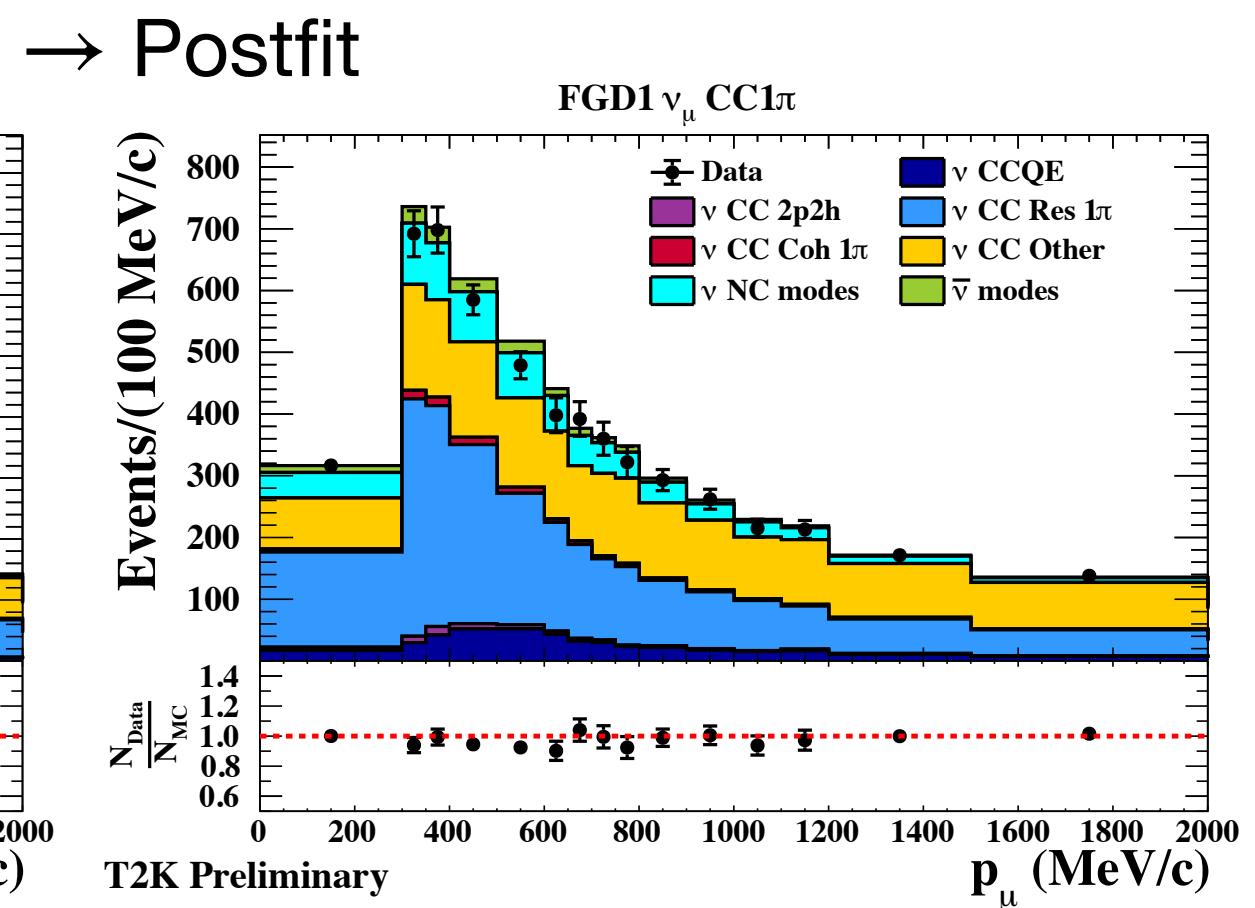
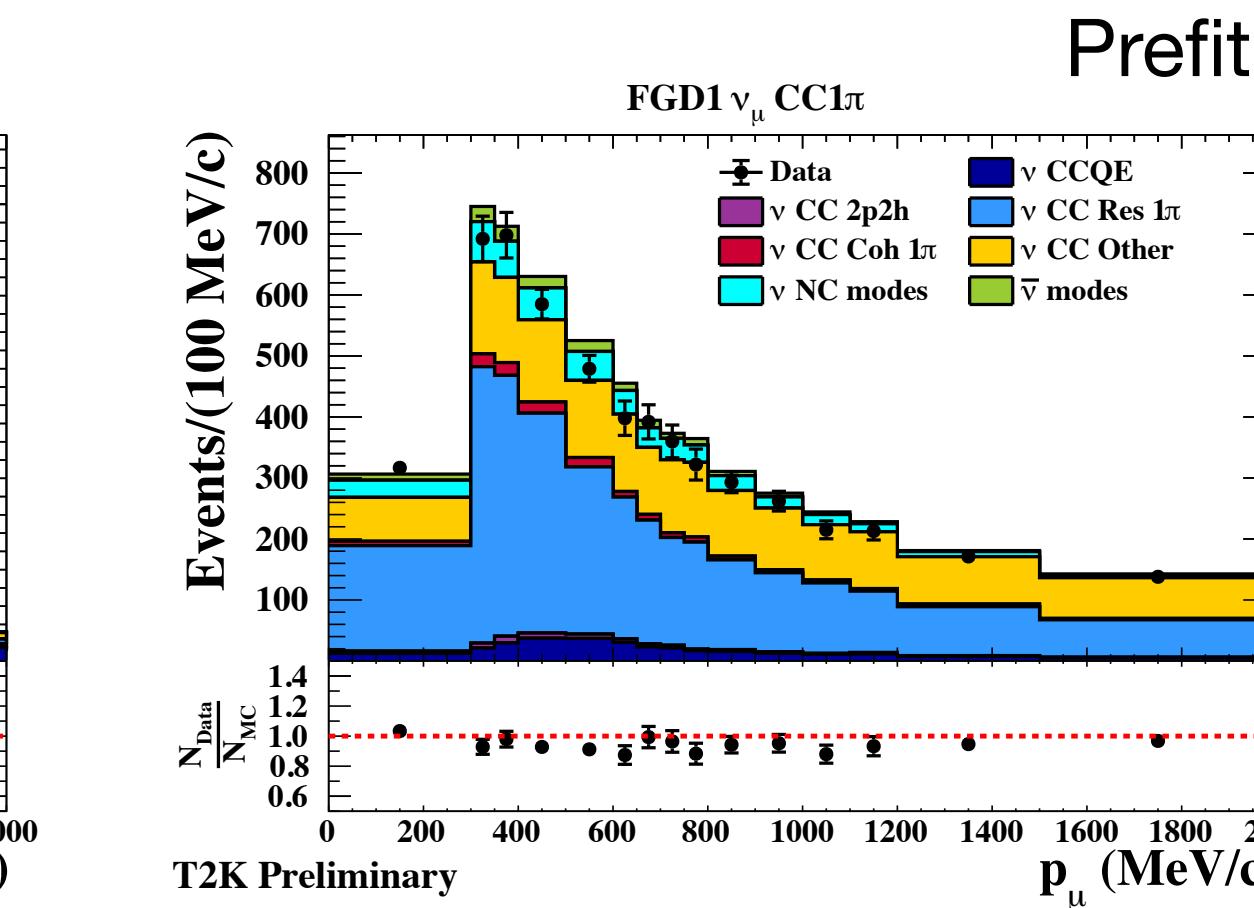
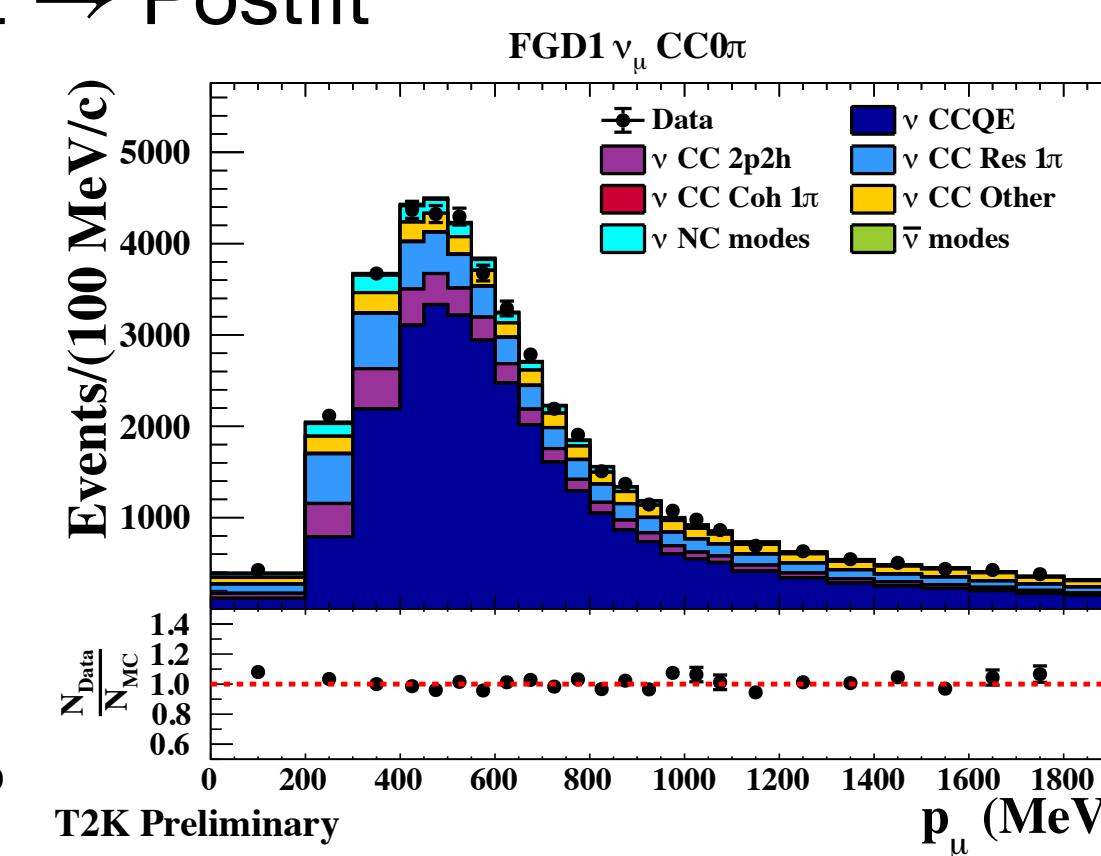
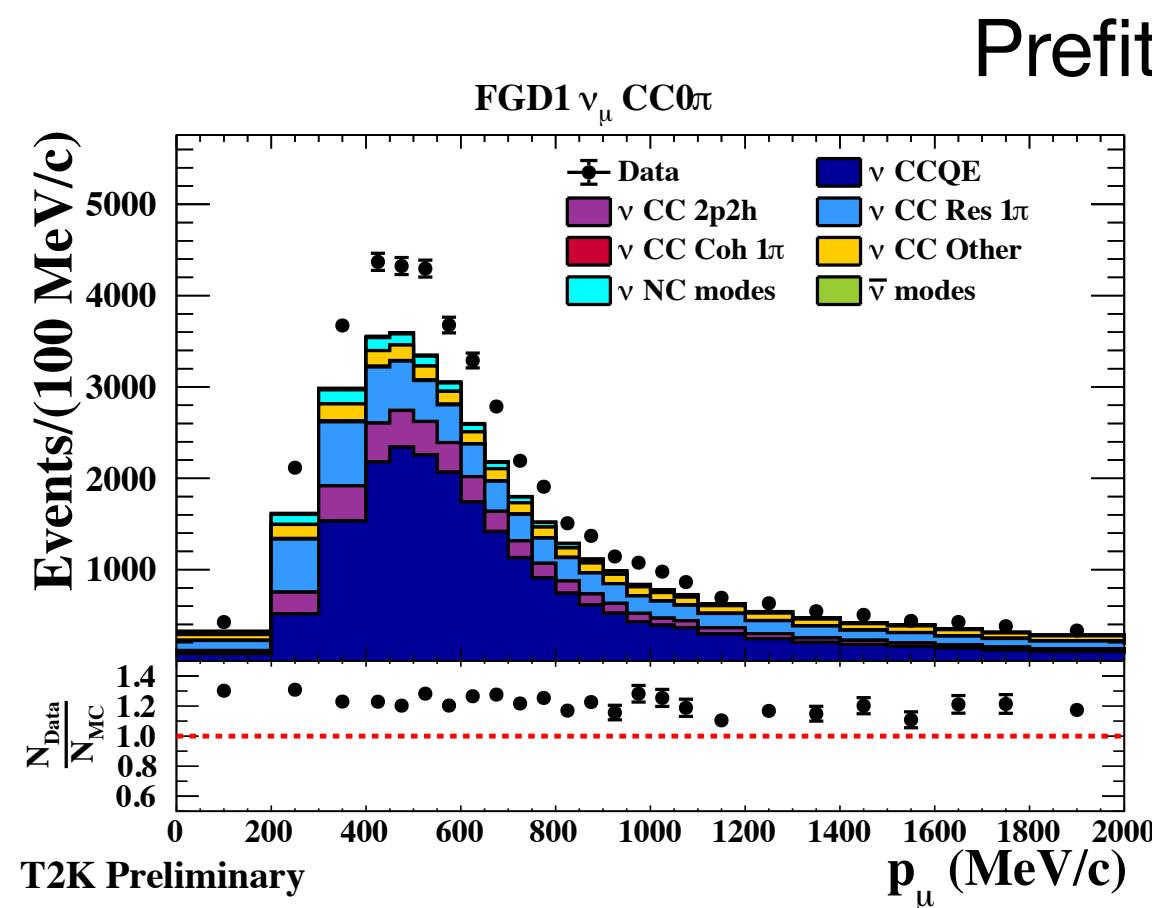
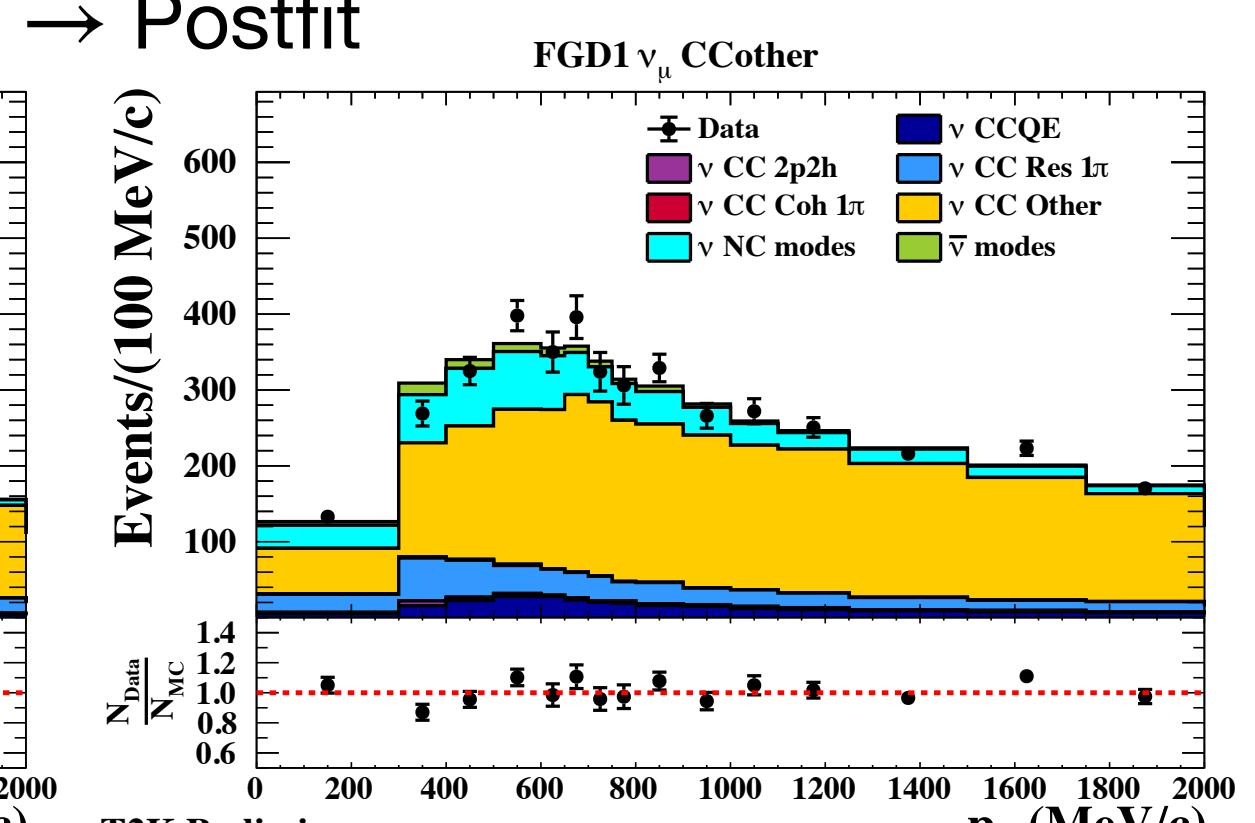
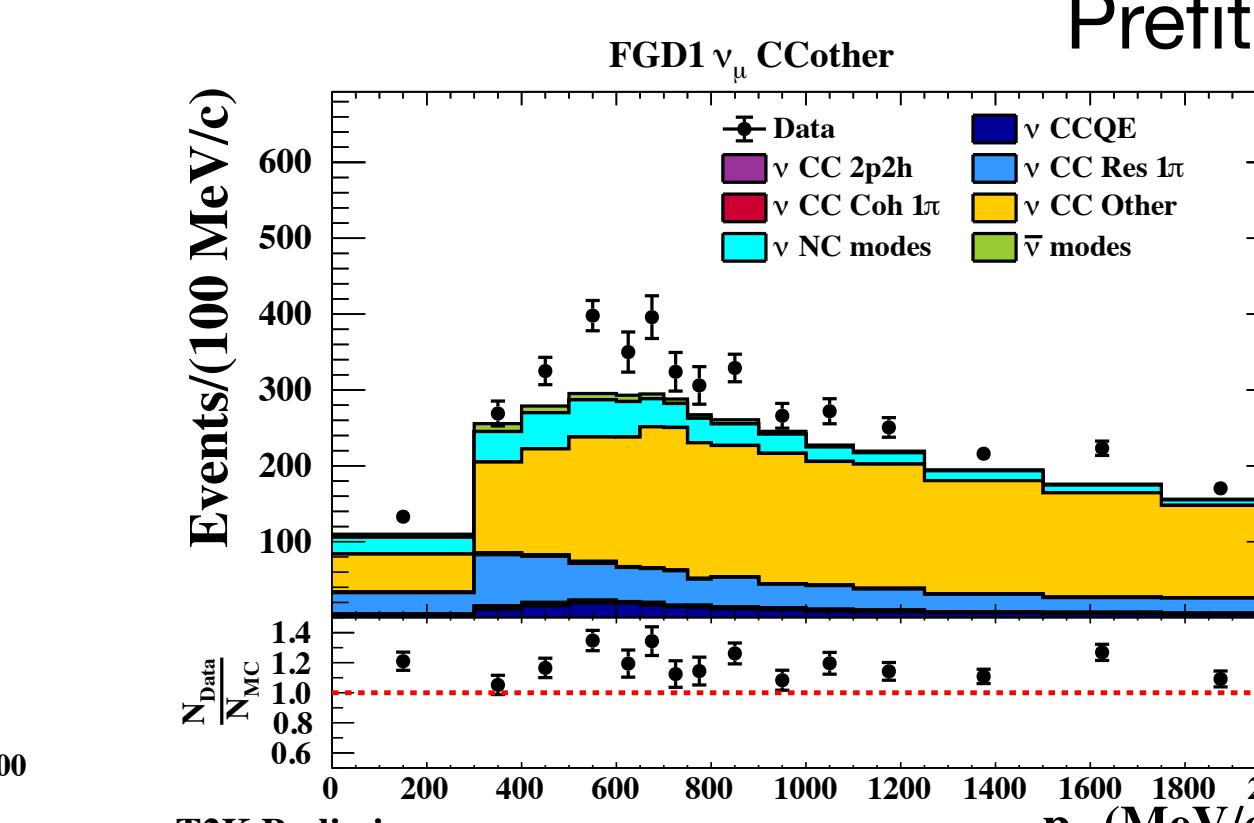
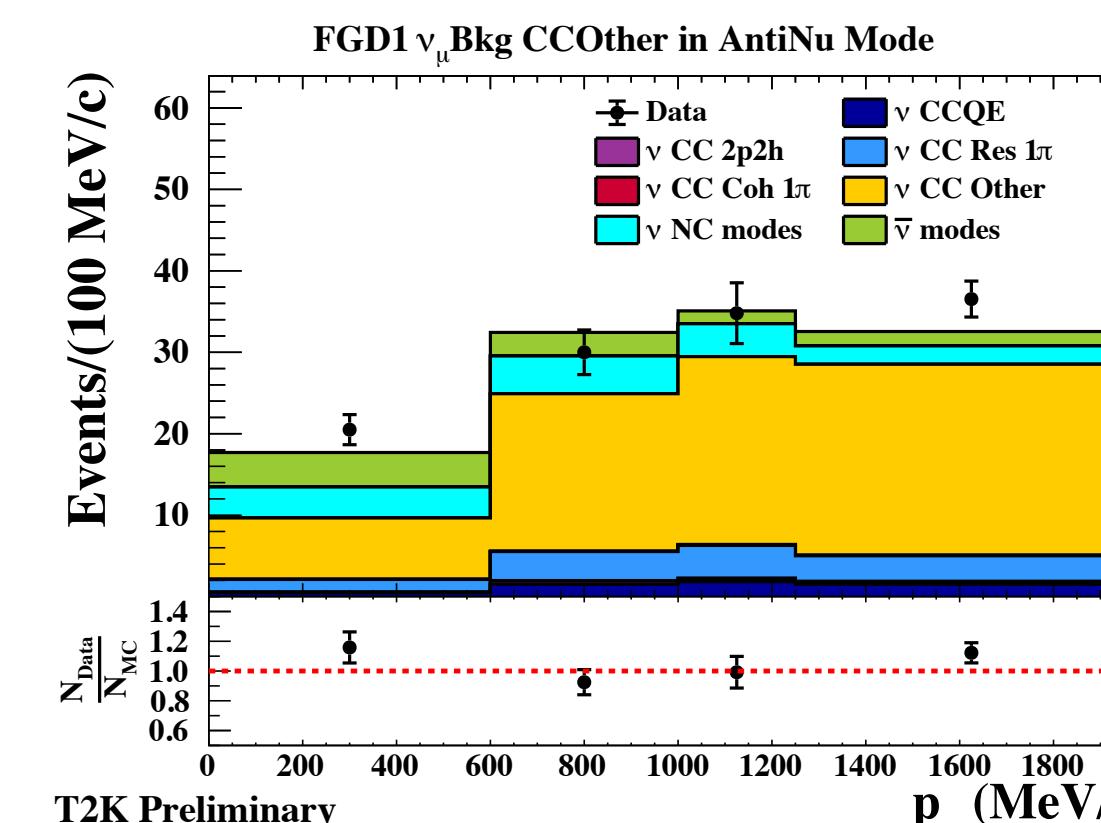
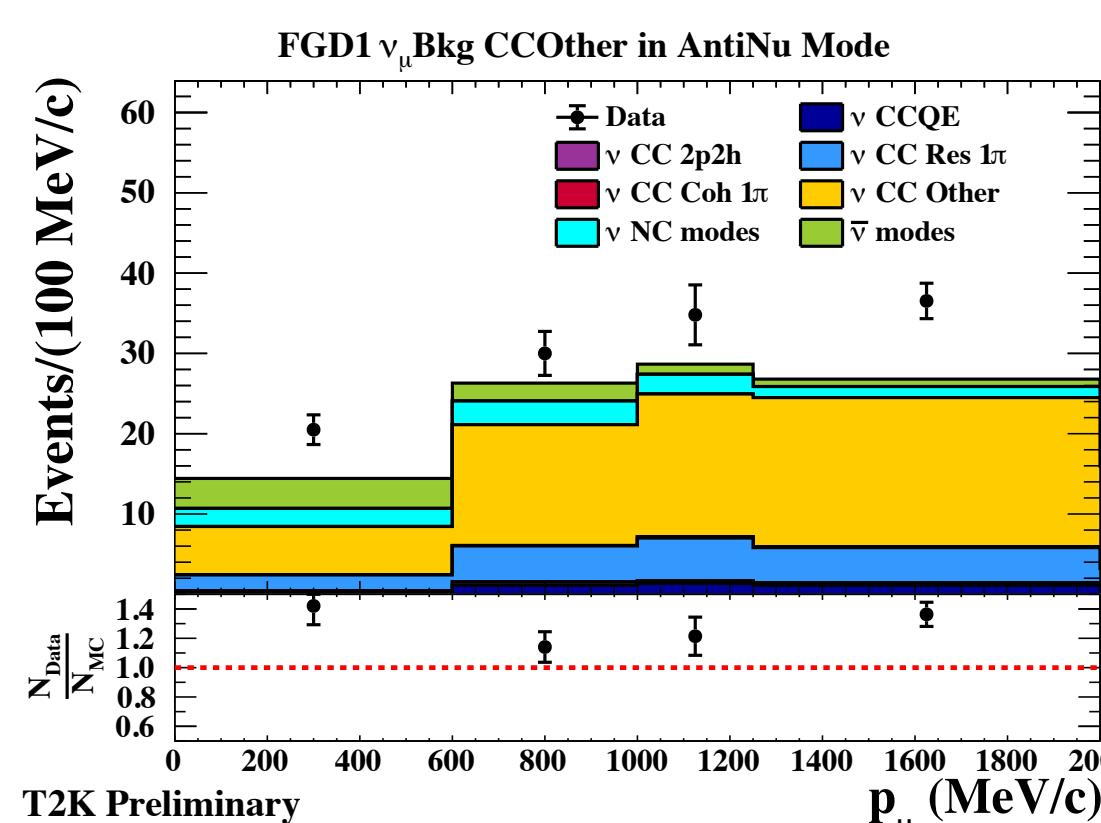


- Detection of final state lepton to get kinematic information and flavor ID
- Determine neutrino energy for studying oscillation pattern
- Assuming quasi-elastic scattering from single bound nucleon (CCQE):

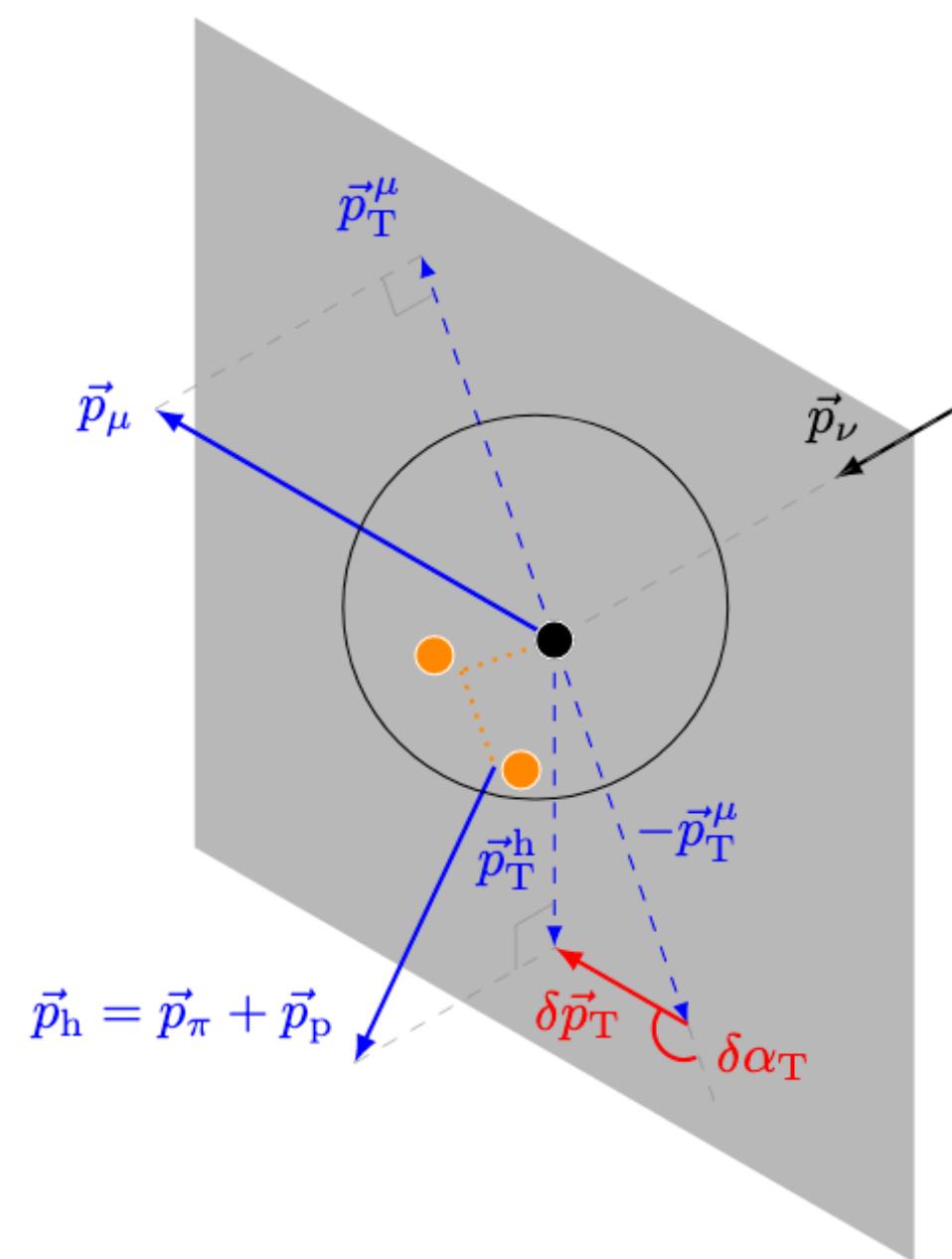
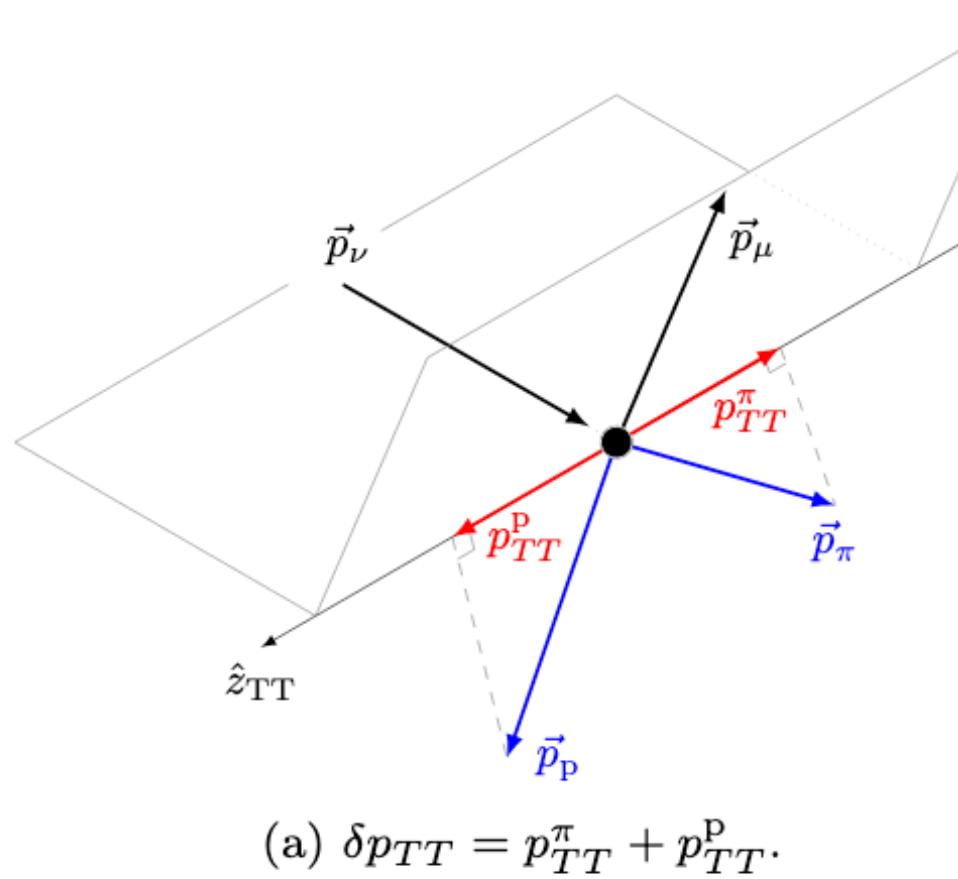
$$E_0^{\text{rec}} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos \theta_l)}$$

Only uses particle masses (m_n , m_p & m_e), lepton kinematics (p_l and $\cos \theta_l$) and nuclear model (E_b)

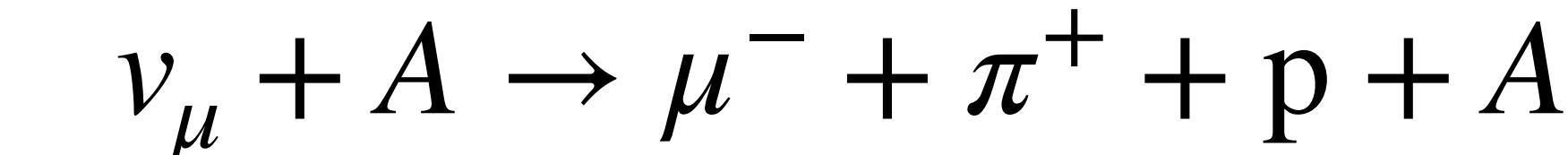
(Some) ND280 samples


CC0 π
CC1 π

CCOther Background
CCN π

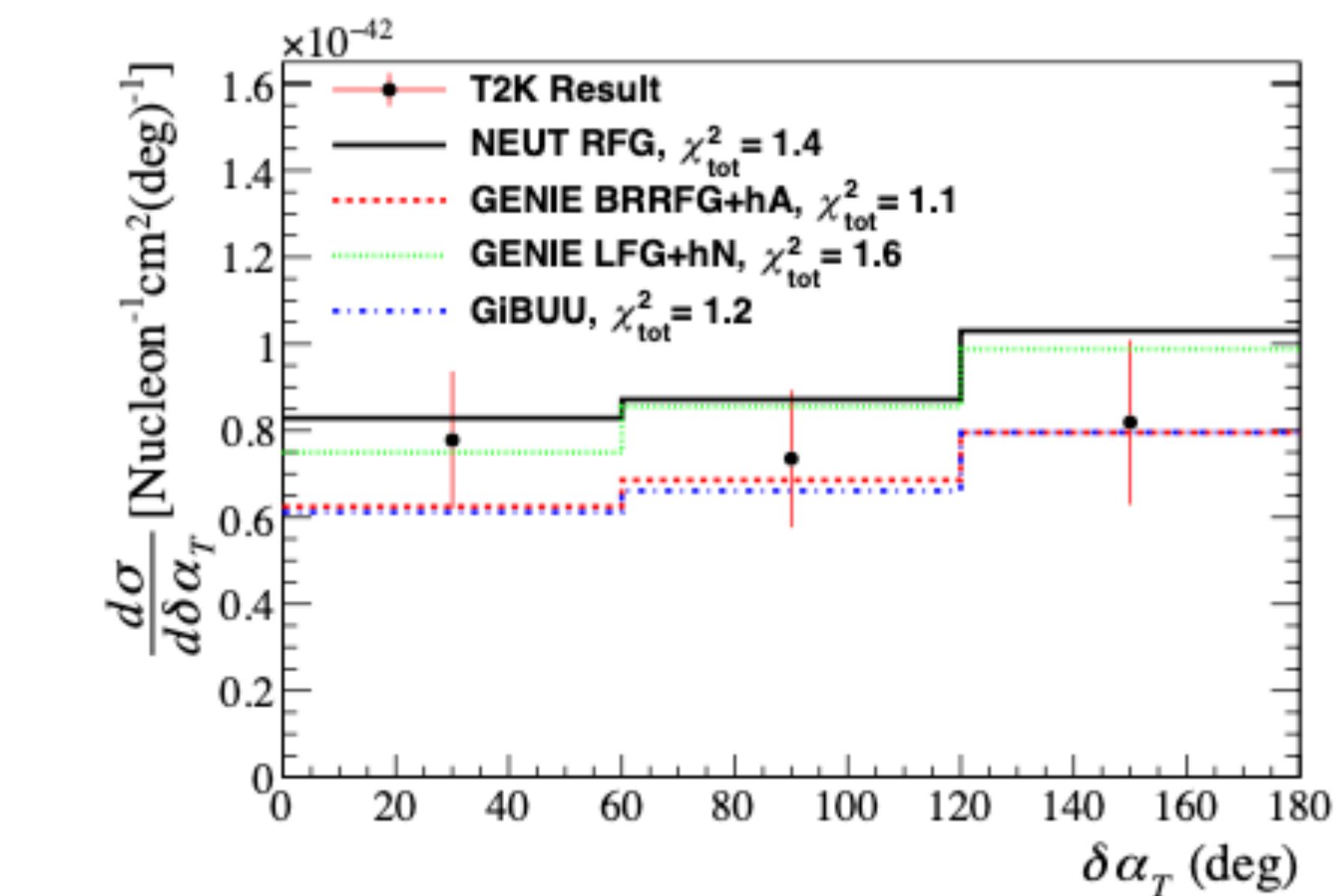
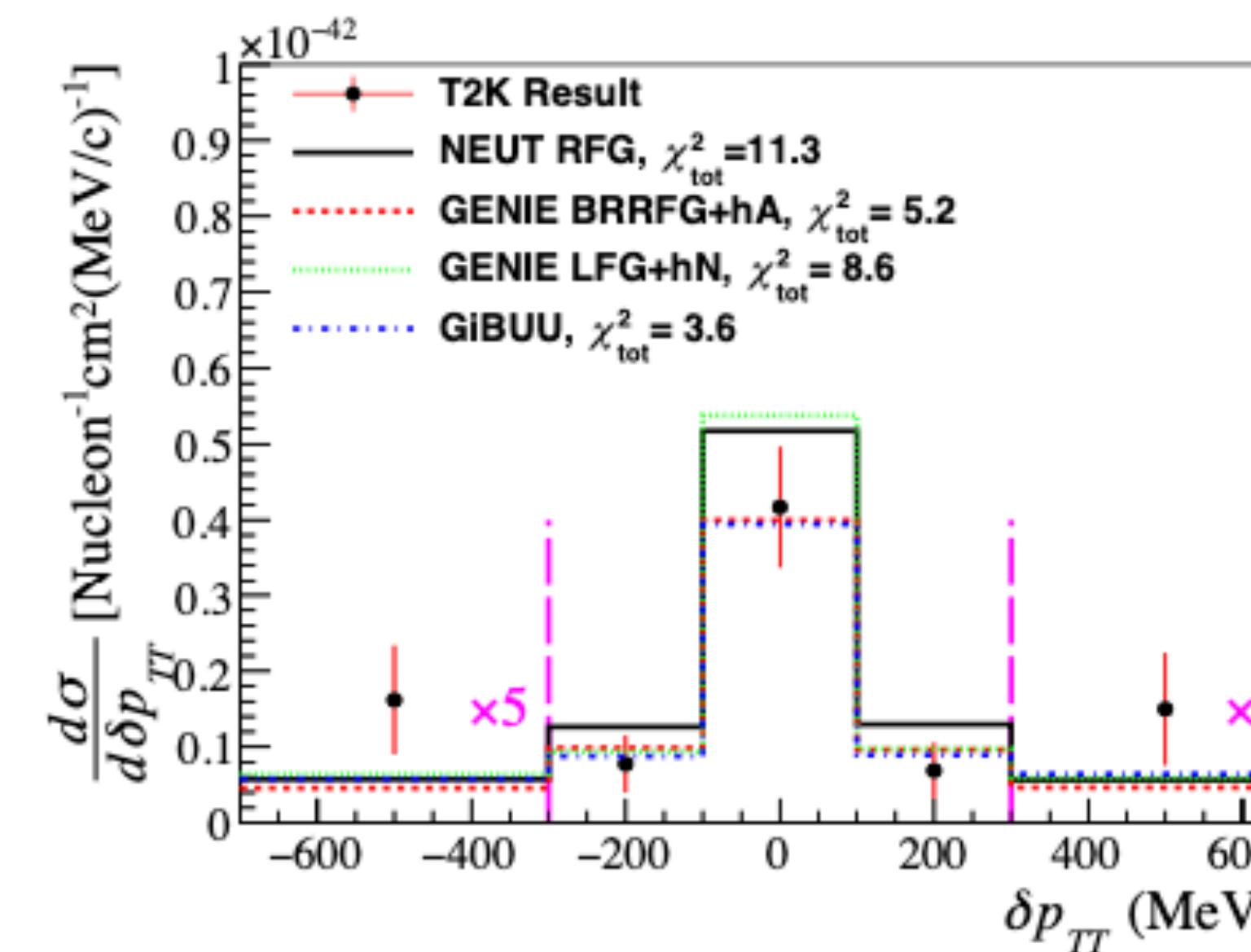
Transverse kinematic imbalance in CC1 π^+



ν_μ CC1 π^+ interaction on nucleus with at least 1 proton in FGD1:



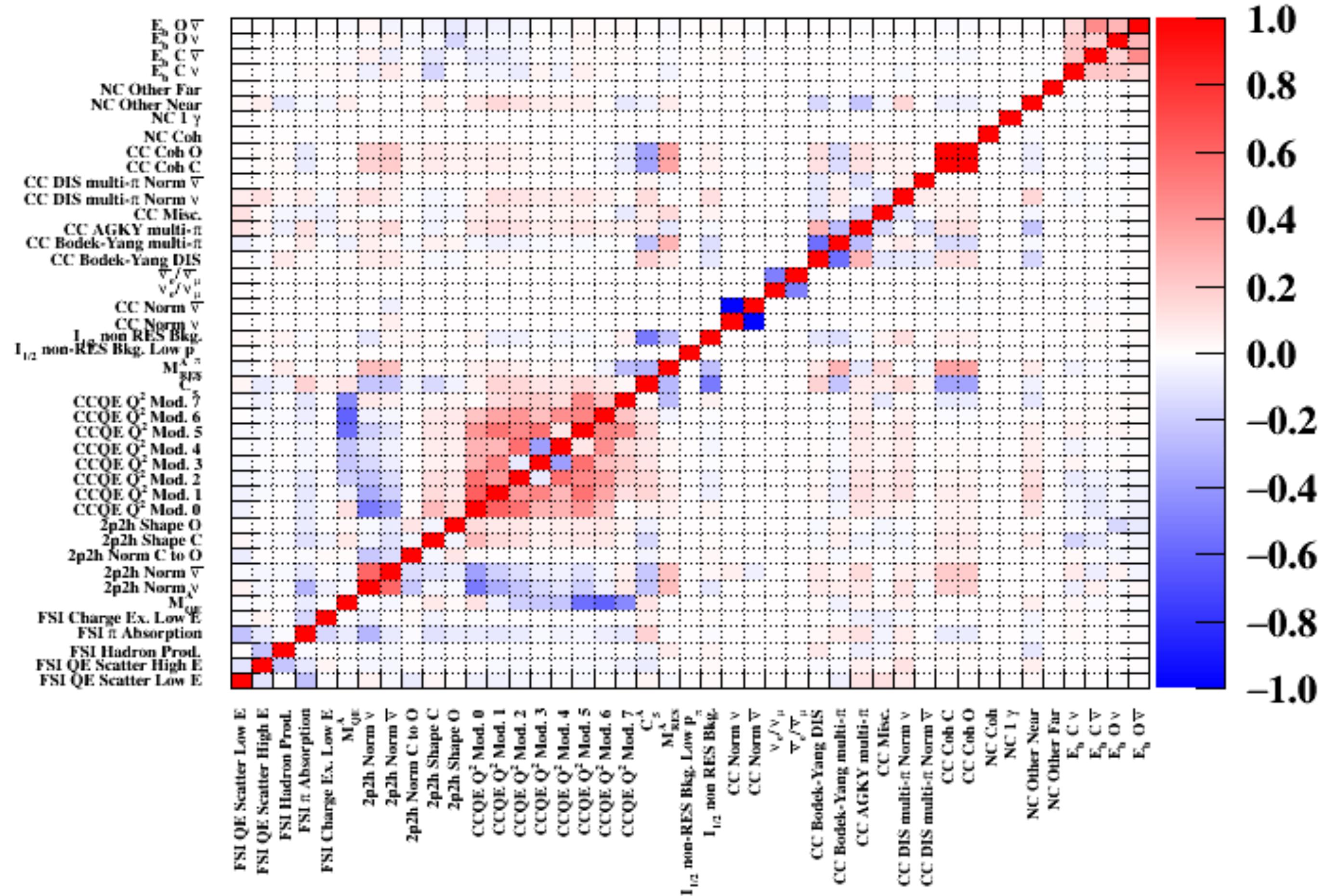
Imbalance kinematic transverse to neutrino direction provide insights on Final State Interactions and nuclear initial state



See Ka Ming Tsui's parallel talk

Cross-section correlation matrix

XSec Correlation Matrix



T2K Preliminary

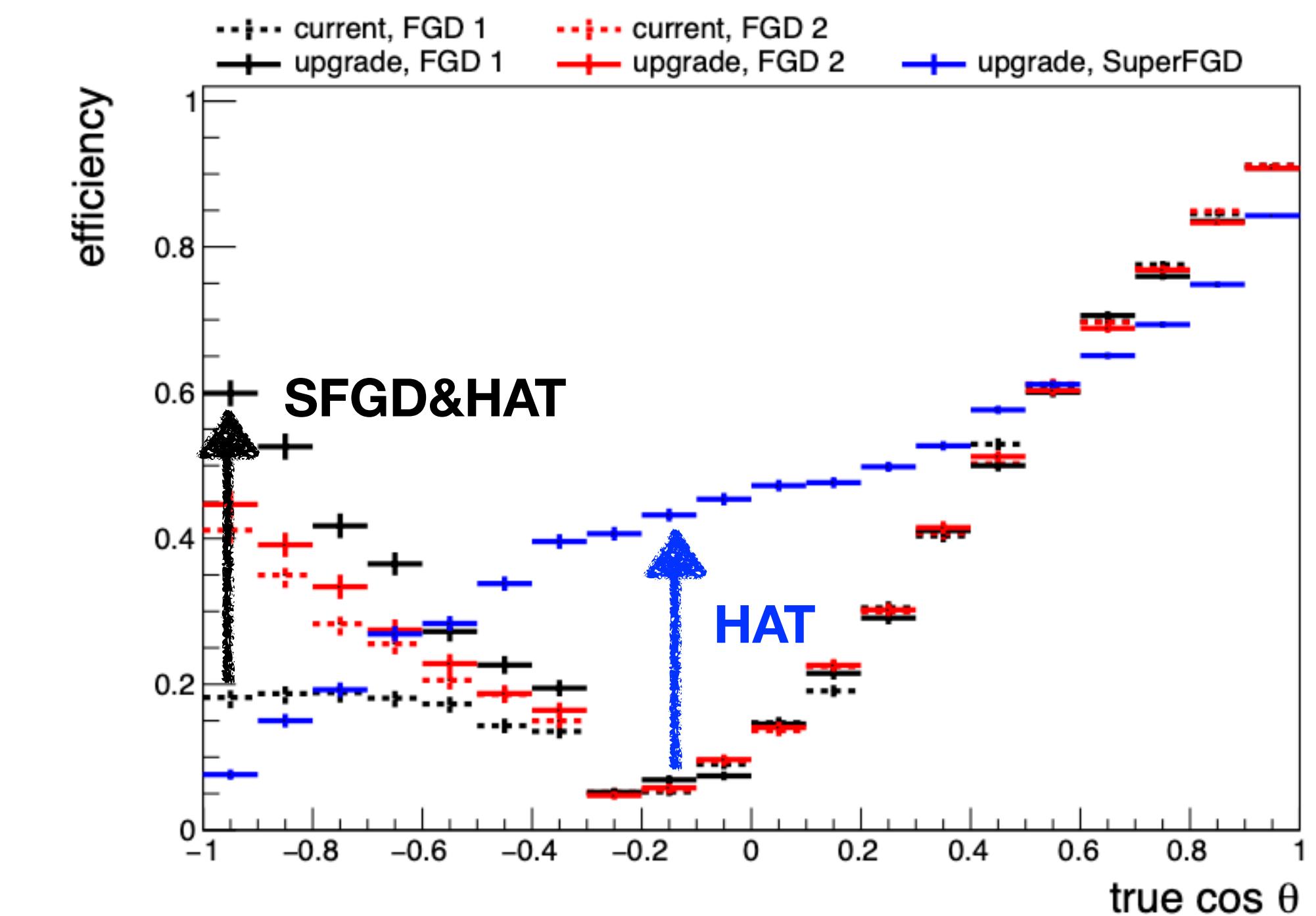
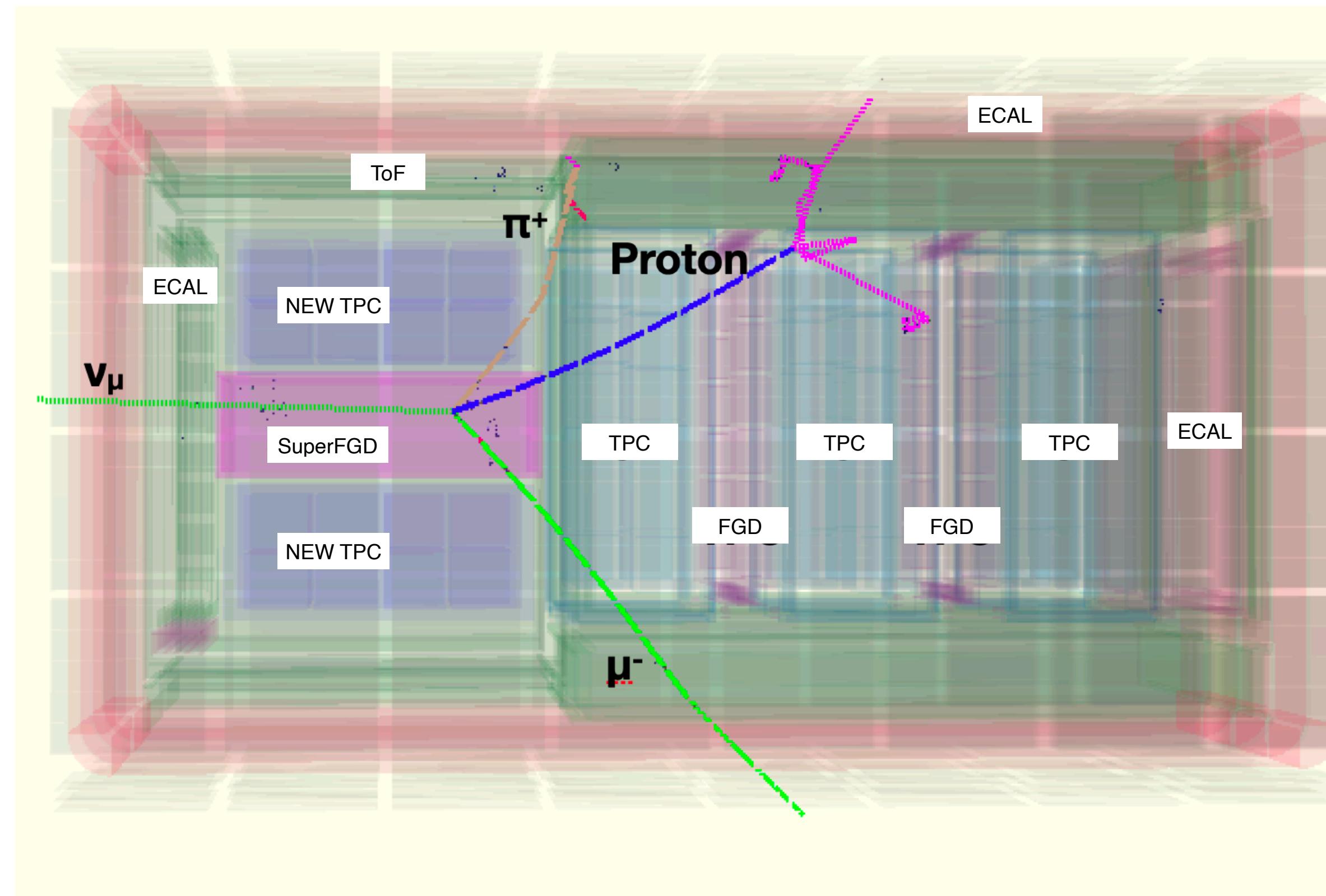
Detector expected performances

ν_μ interactions in FGDs/SuperFGD

Outgoing muon detected by HAT/v-TPC/Ecal

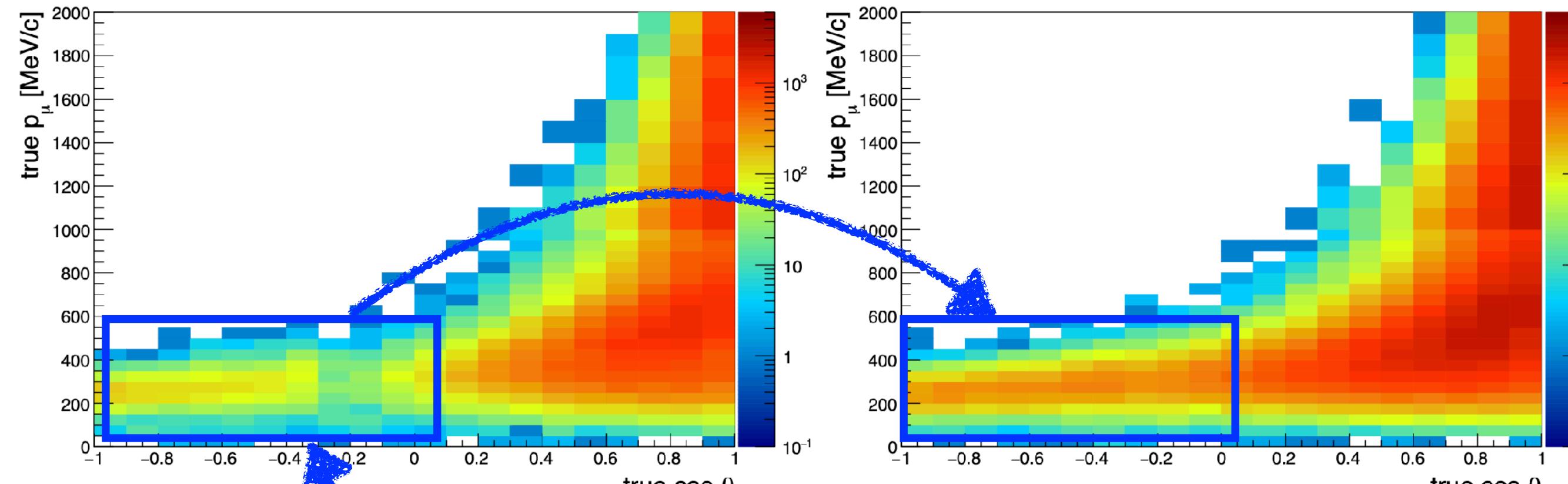
Precise kinematic reconstruction by TPCs

Direction and outside-events rejection by TOF



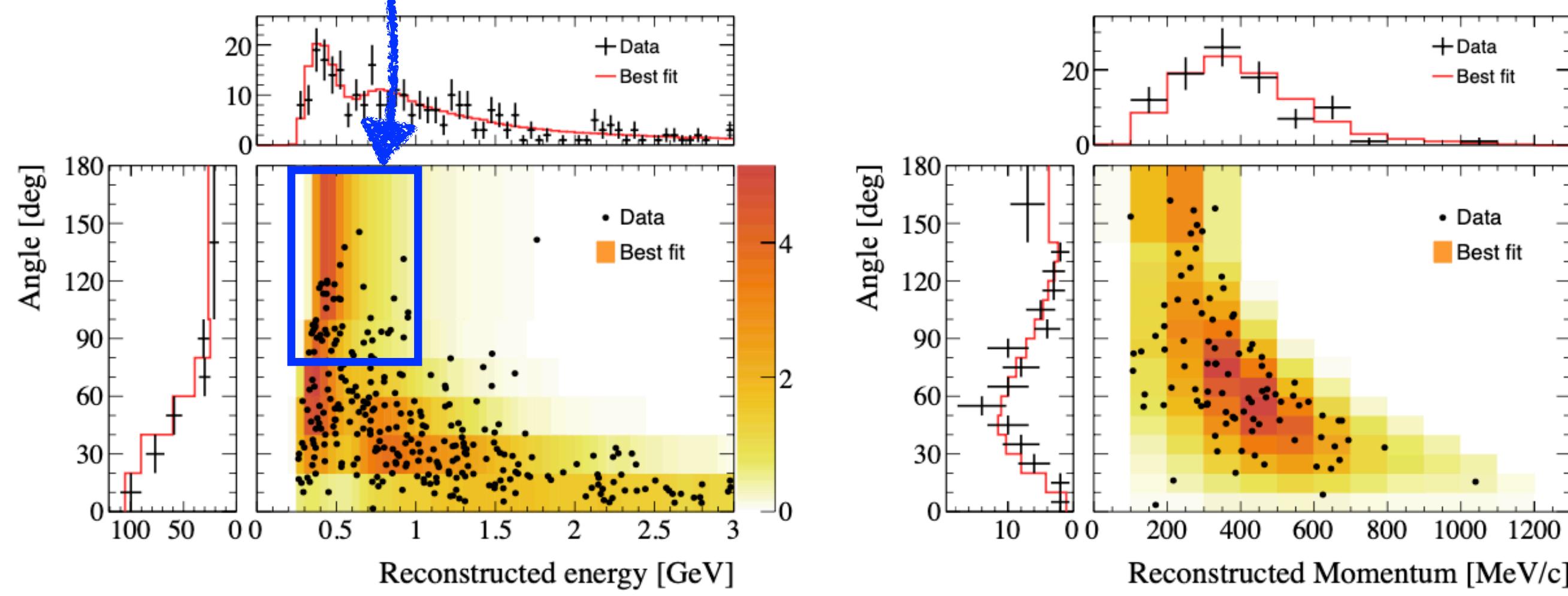
Increased target mass
 Improved selection at high and backward angles
 Better vertex reconstruction
 Outgoing proton/neutron reconstruction

Impact of ND280 upgrade on T2K physics



(a) Current ND280 **ND280 selection**

(b) Upgraded ND280
ND280 Upgrade TDR arXiv:1901.03750



(a) FHC 1R μ

SK selection for OA

(b) FHC 1Re

TN397

Better constraints on cross-sections
 - broader phase-space acceptance
 - increased statistical power

Selection	Current-like	Upgrade-like
ν_μ (ν beam)	100632	$\times 2$ 199605
$\bar{\nu}_\mu$ ($\bar{\nu}$ beam)	32671	60763
ν_μ ($\bar{\nu}$ beam)	16537	29593

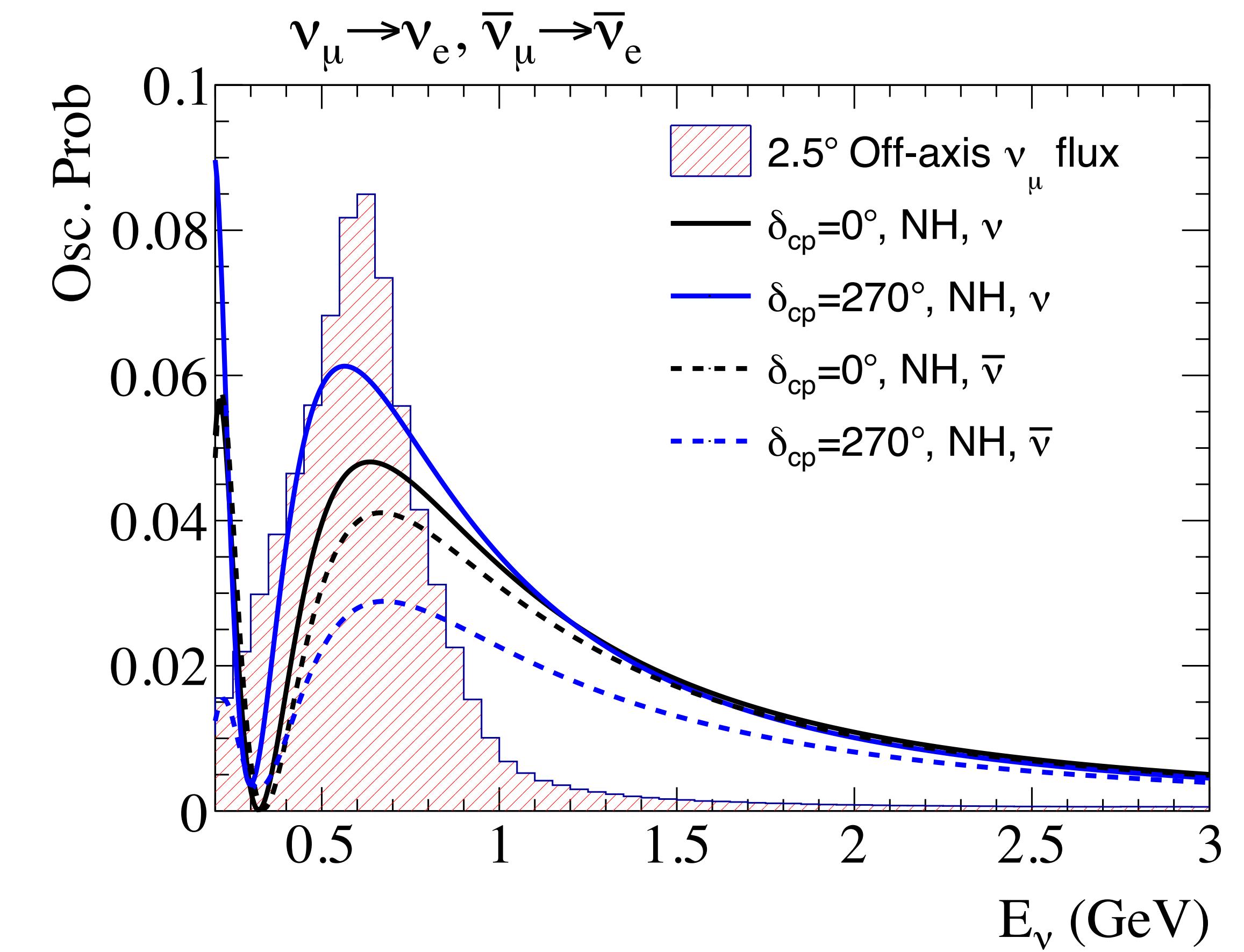
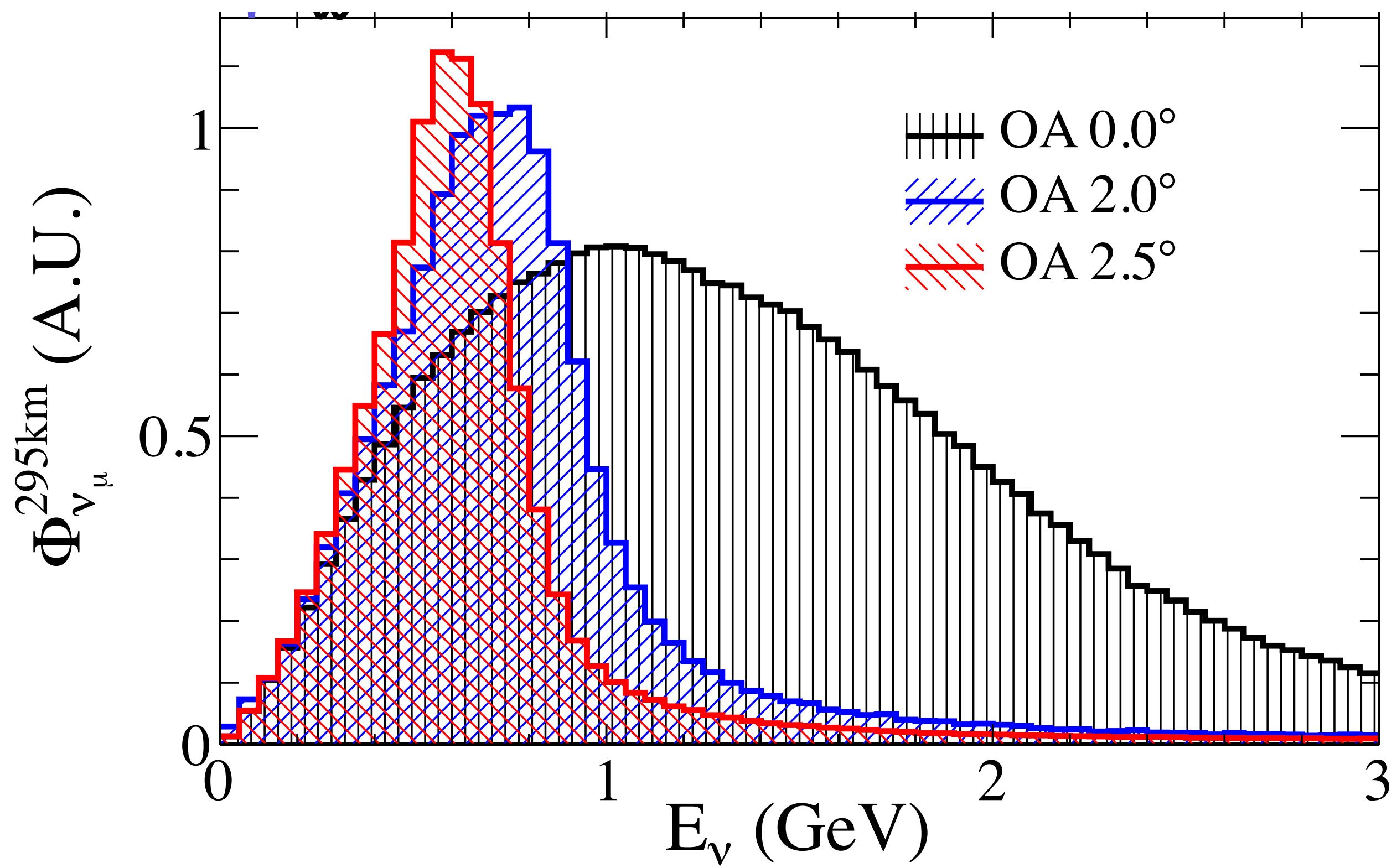
ND280 Upgrade TDR arXiv:1901.03750

@ 10^{21} POT

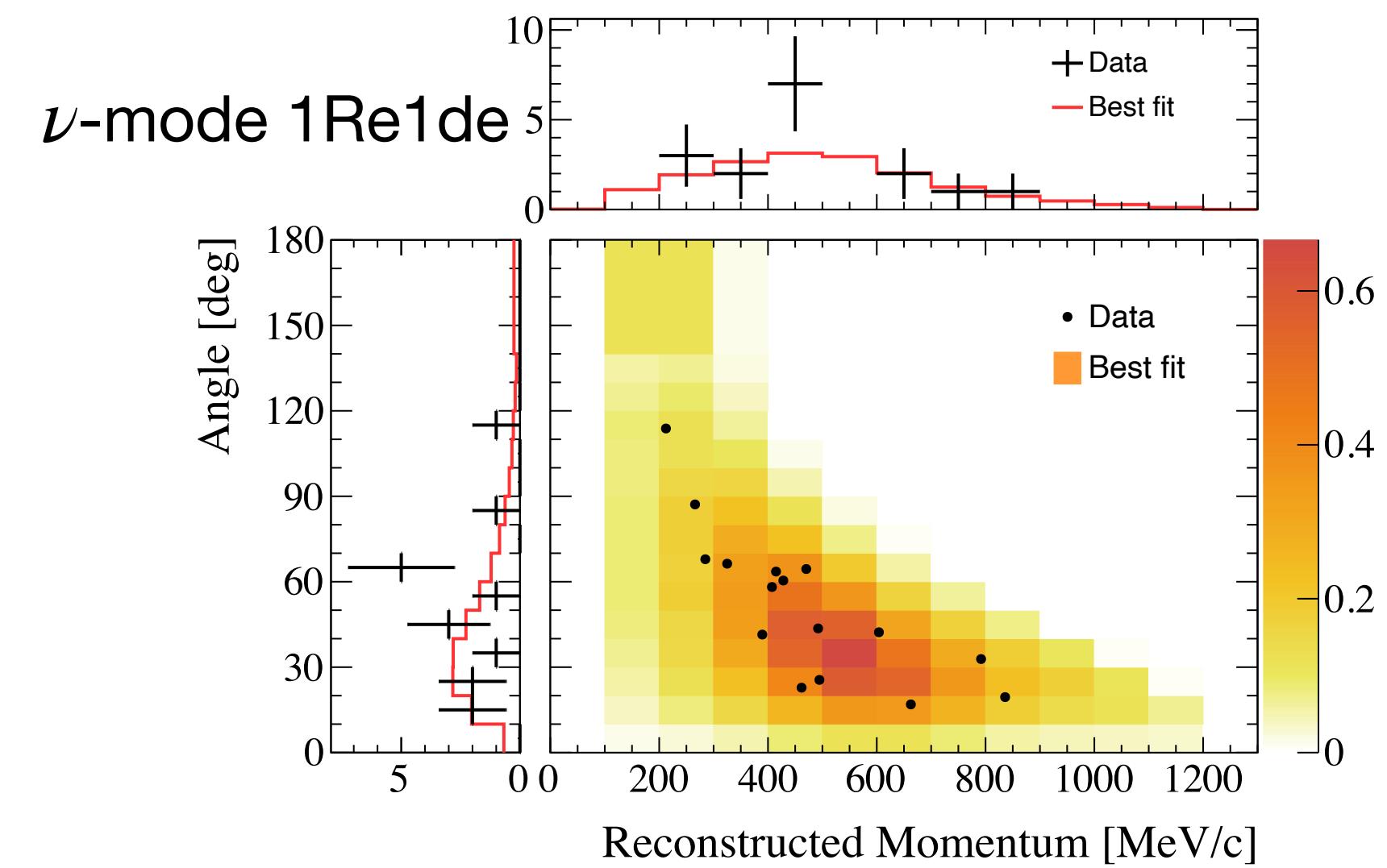
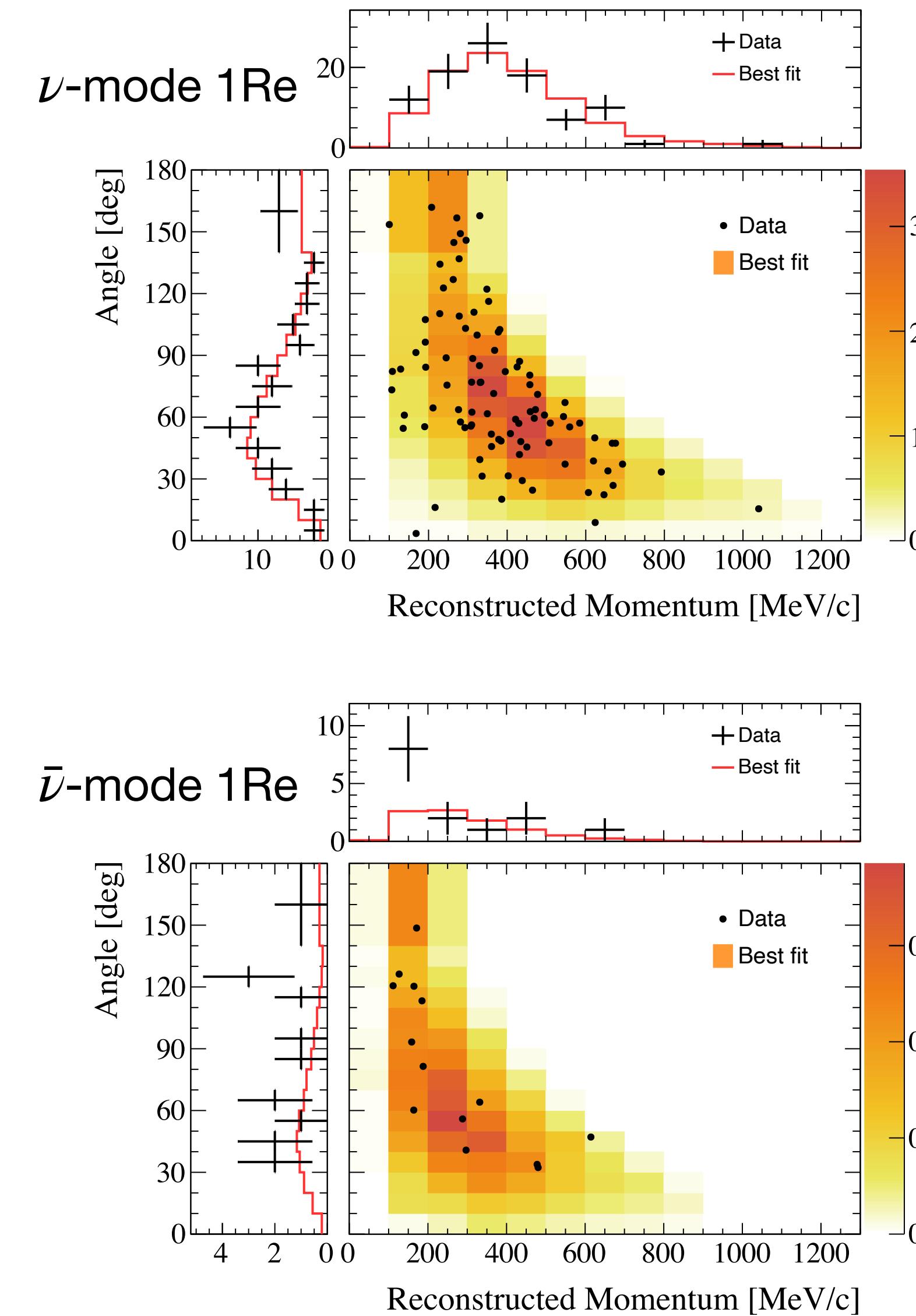
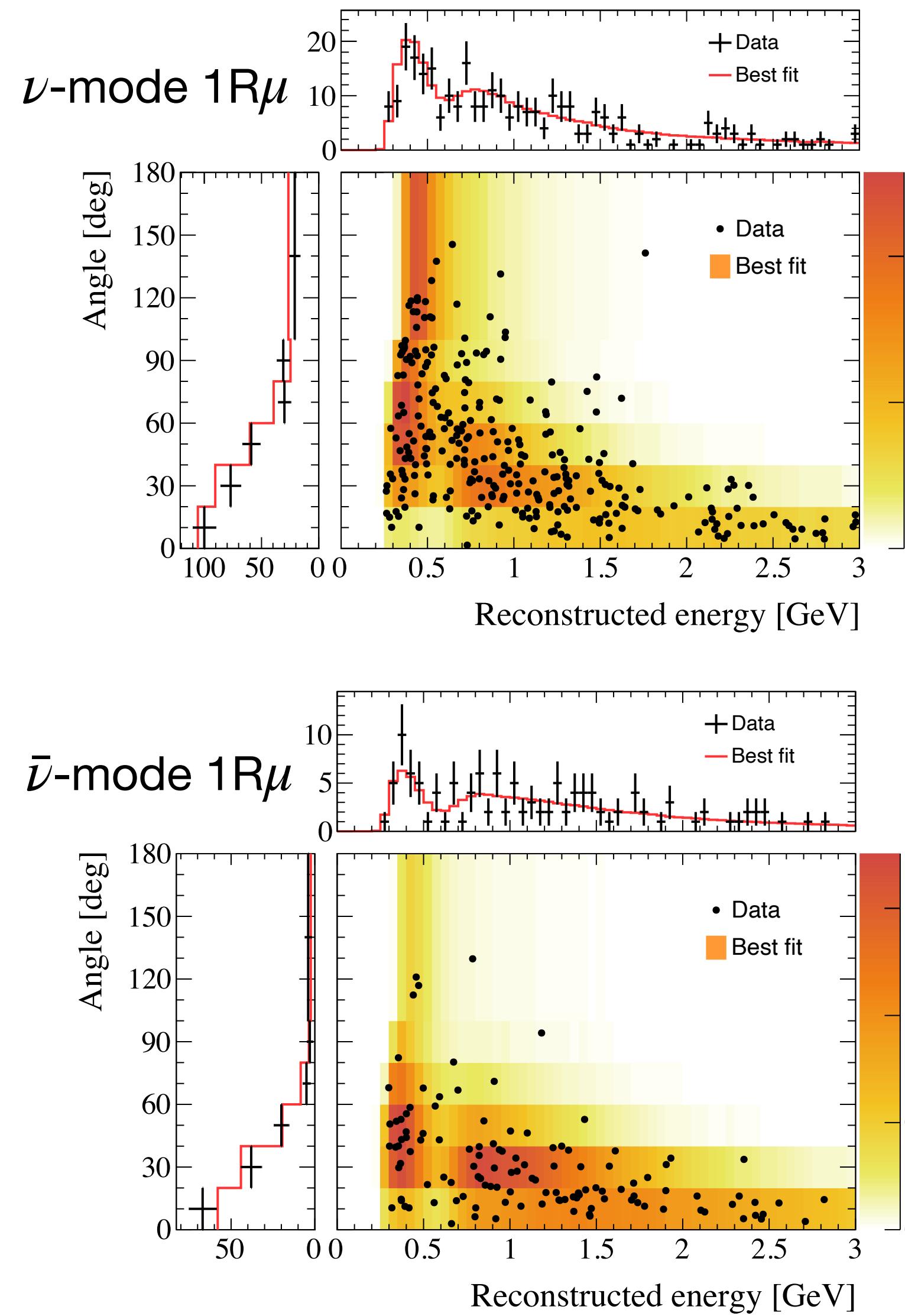


See César Jesús-Valls' parallel talk

Off-axis technique



SK data samples



~Last analysis' best fit

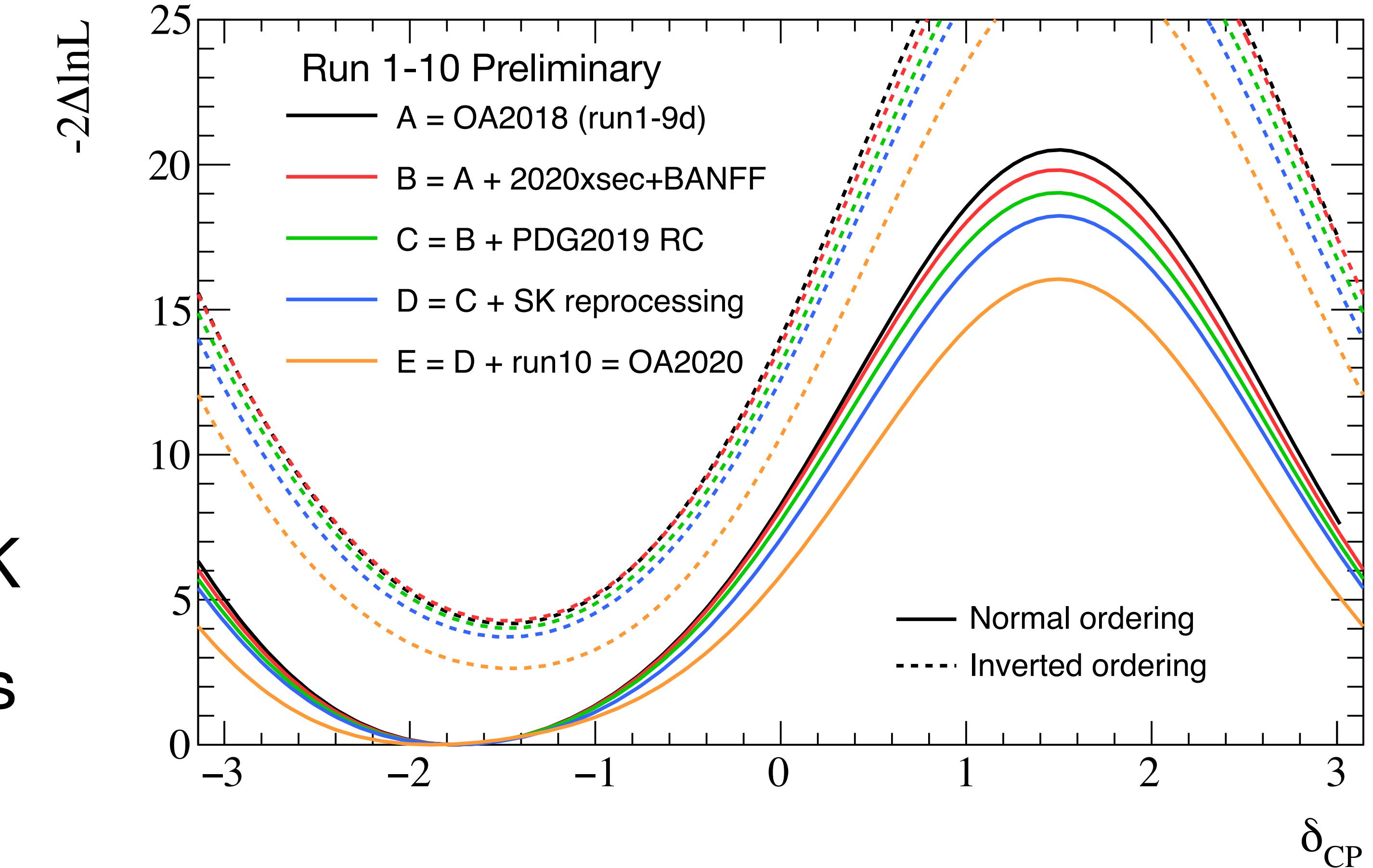
Parameters	A	B	NoCPV	NoMax23	AIO
Δm_{21}^2			7.53×10^{-5} eV ²		
Δm_{32}^2 (NH) / $ \Delta m_{31}^2 $ (IH)			2.509×10^{-3} eV ²		
$\sin^2 \theta_{23}$	0.528	0.45	0.528	0.45	0.528
$\sin^2 \theta_{12}$ ($\sin^2 2\theta_{12}$)			0.307 (0.851)		
$\sin^2 \theta_{13}$ ($\sin^2 2\theta_{13}$)			0.0218 (0.0853)		
δ_{CP}	-1.601	0	0	-1.601	-1.601
Earth matter density			2.6 g/cm^3		
Baseline length			295 km		
Mass hierarchy		Normal		Inverted	

Impact of Run 10 on δ_{CP}

Changes from OA2018 to OA2020 one by one

- B makes analysis changes described above e.g. flux model, xsec model
- C adds update on θ_{13} constraint from PDG2018 to PDG2019
- D adds new calibration for SK that caused some events to migrate in and out of samples
- E adds new run 10 data

→ Largest change in δ_{CP} comes from new data

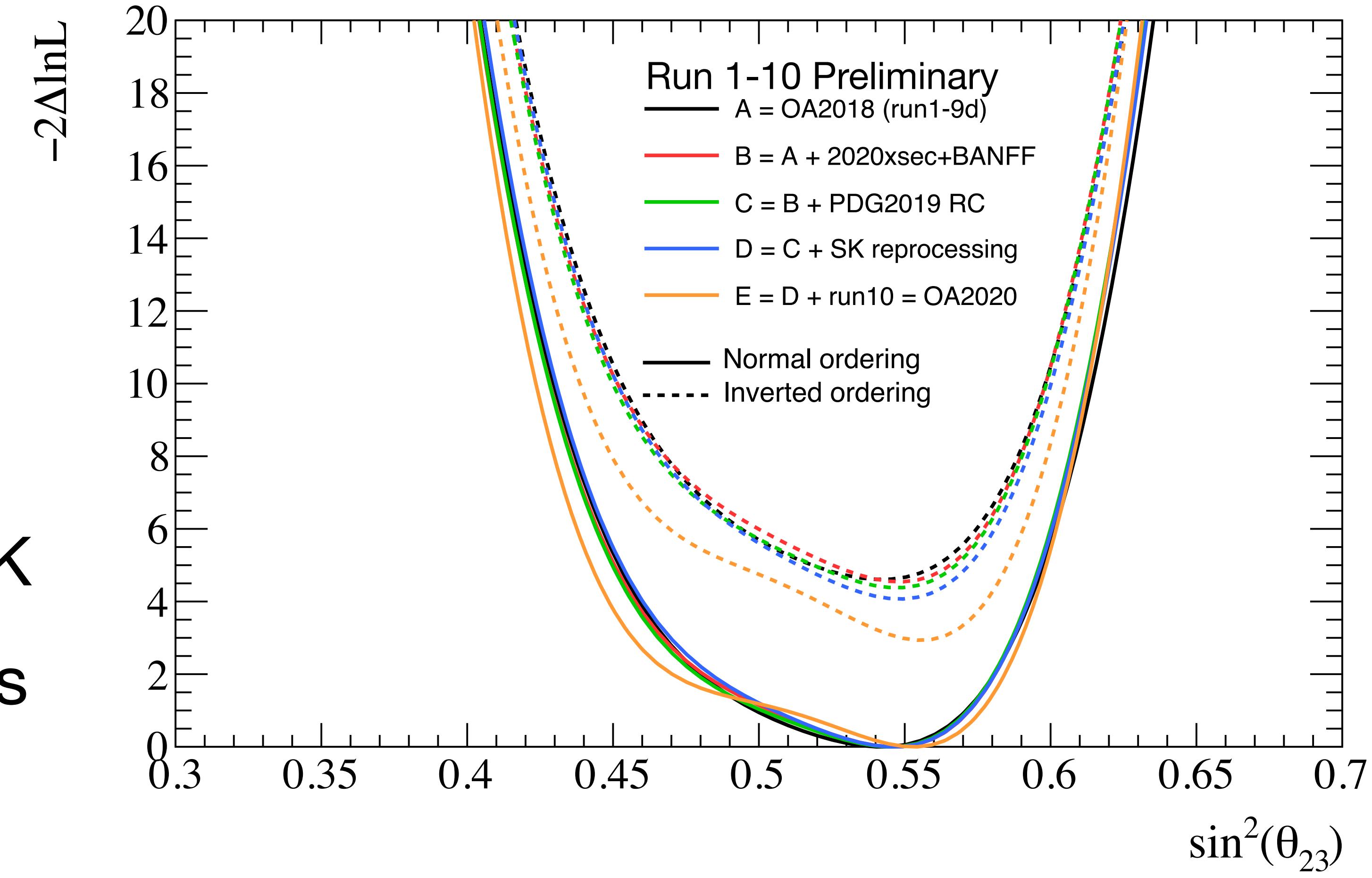


Impact of Run 10 on $\sin^2 \theta_{23}$

Changes from OA2018 to OA2020 one by one

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→ Largest change in $\sin^2 \theta_{23}$ comes from new data



Impact of Run 10 on $\sin^2 \theta_{23} / \Delta m_{32}^2$

Changes from OA2018 to OA2020
one by one

- B makes analysis changes described above e.g. flux model, xsec model
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- D adds new calibration for SK that caused some events to migrate in and out of samples
- E adds new run 10 data

→ Largest change in Δm_{32}^2 comes from xsec model changes

→ Largest change in $\sin^2 \theta_{23}$ comes from new data from run 10

