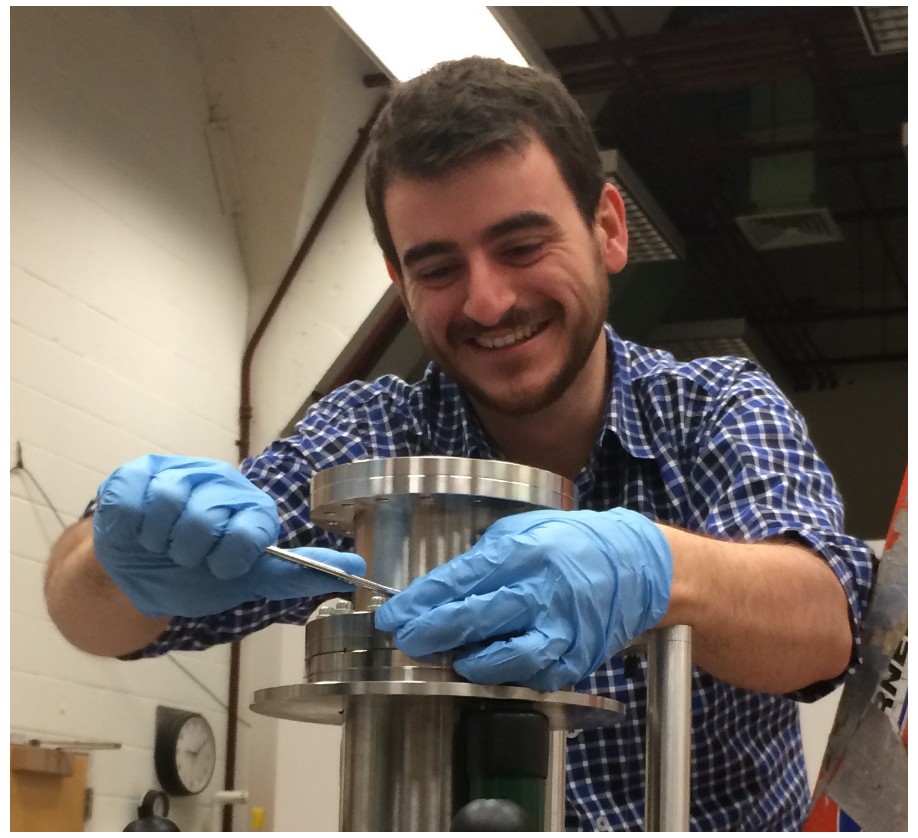
The T2K Experiment: Status, Results and Prospects



Mathieu Guigue for the T2K Collaboration

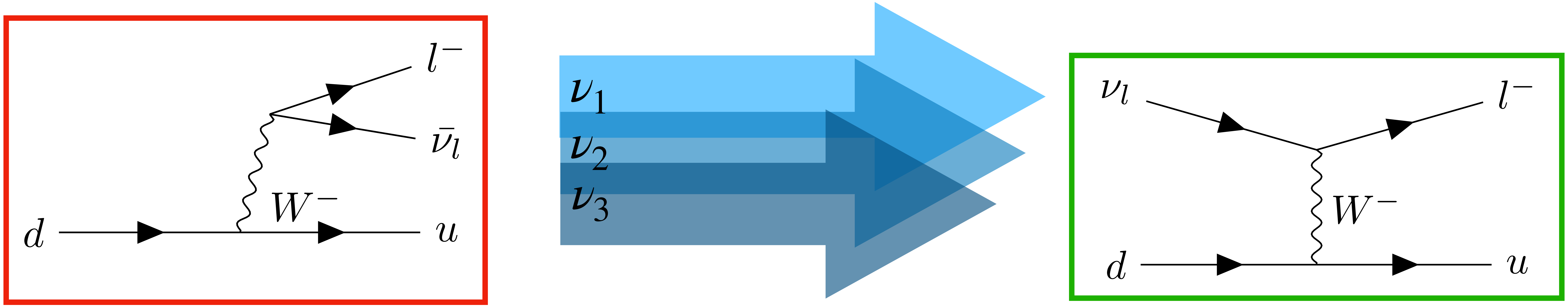
XIX International Workshop on Neutrino Telescopes

February 22nd 2021

Neutrino flavor and masses mixing

Neutrino weak states: $\nu_e,\ \nu_\mu,\ \nu_\tau$ → **production** and **detection**

Neutrino mass states: $\nu_1,\ \nu_2,\ \nu_3$ → **propagation**



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

→ Phase difference between mass states during propagation

→ Different flavor state detected after propagation

Neutrinos mixing matrix

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

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

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)

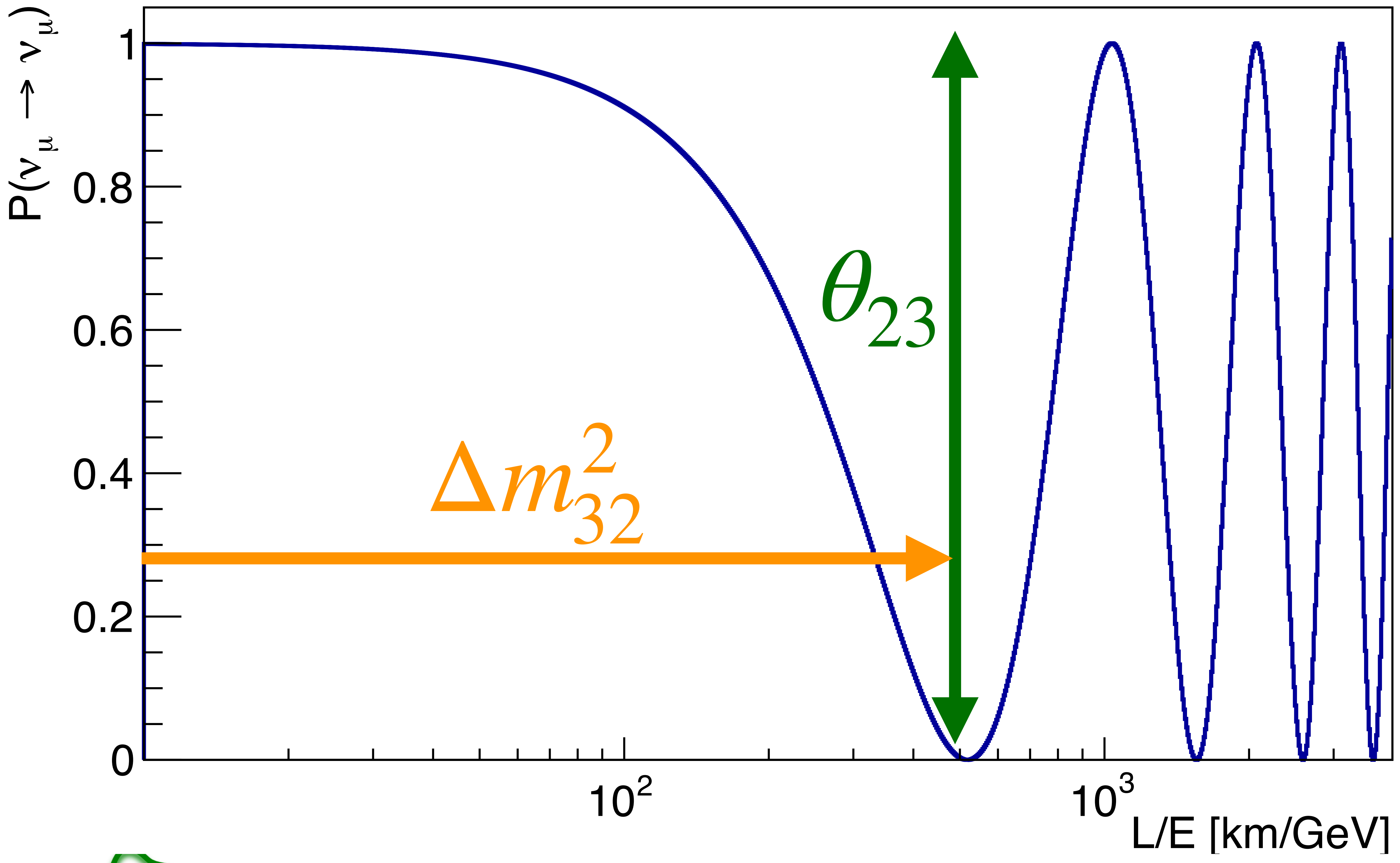
$\nu_\mu/\bar{\nu}_\mu$ disappearance probability

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

CP-conserving

CP-violating

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



Energy of maximum oscillation:

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

Look for surviving muons neutrinos in muon neutrino beam

For $L_{0,32}^{\rm osc} = 295$ km, $E_{\rm osc} \approx 0.6$ GeV

$\nu_\mu \rightarrow \nu_e$ oscillation probability in vacuum

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

CP-conserving — CP-violating

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

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

$$J^{\max}_{\mathrm{CP}} = \cos\theta_{12} \sin\theta_{12} \cos\theta_{23} \sin\theta_{23} \cos^2\theta_{13} \sin\theta_{13}$$

ν or anti-ν

Look for appearing electron neutrinos from muon neutrino beam

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

Neutrino actually propagating in matter (Earth crust)

- Modifies pattern differently for ν and anti-ν → mimics CP violation
- Effect depends on the sign of Δm^2_{31}

(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
$\theta_{23} \approx 50^\circ$
$\left|\Delta m^2_{32}\right| \sim 2.5 \times 10^{-3}\mathrm{eV}^2$

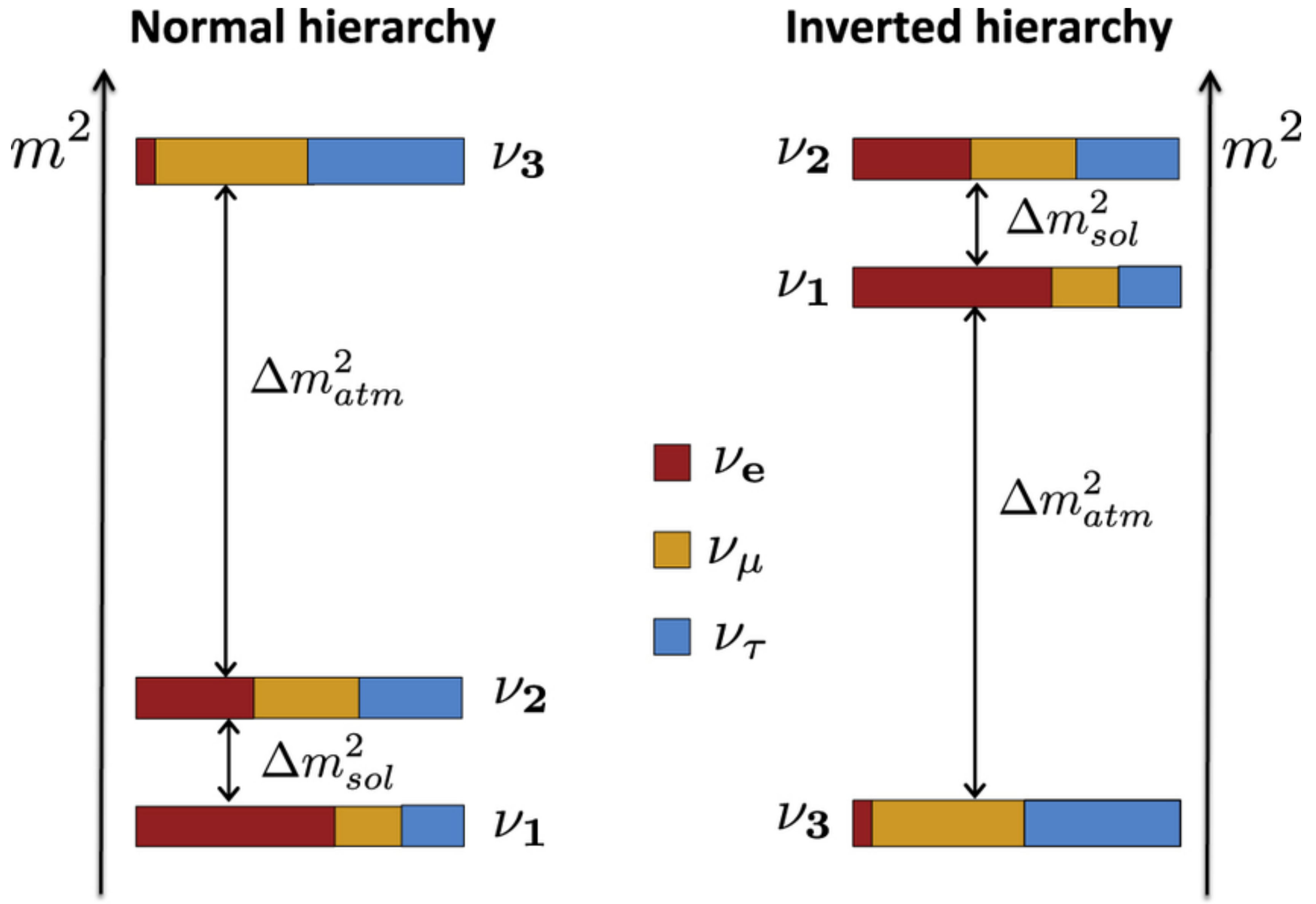
Reactor and accelerator
$\theta_{13} \approx 8^\circ$
Accelerator only: $\delta_{\mathrm{CP}} = ?$

Solar and reactor
$\theta_{12} \approx 34^\circ$
$\Delta m^2_{12} \sim 7.5 \times 10^{-5}\mathrm{eV}^2$

$0\nu\beta\beta$ experiments

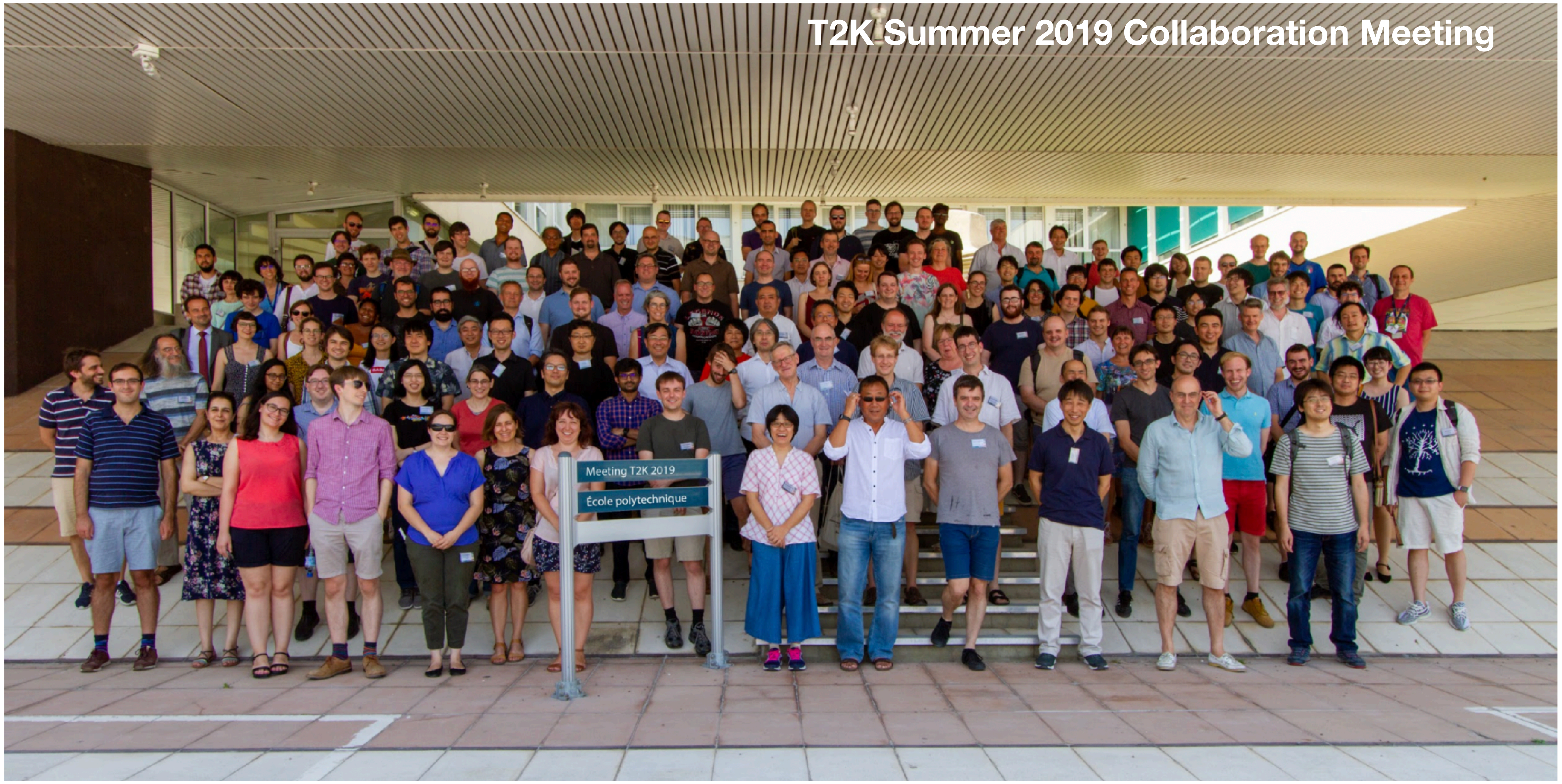
Questions to long-baseline experiments:

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



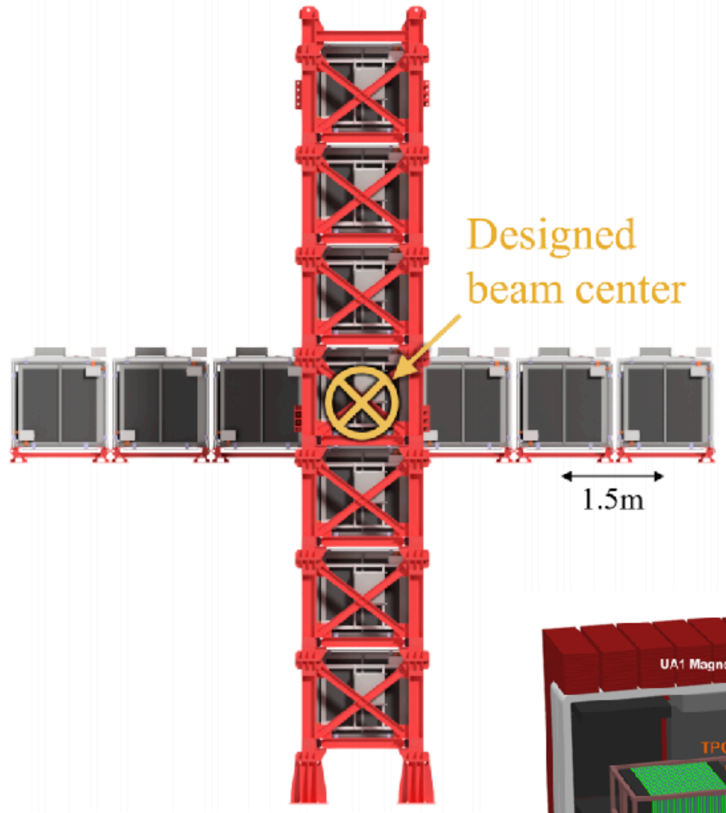
From JPhysG 43 084001

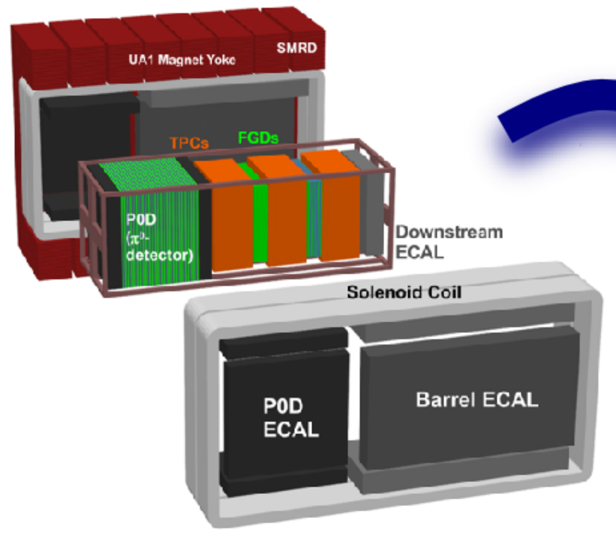
T2K Collaboration

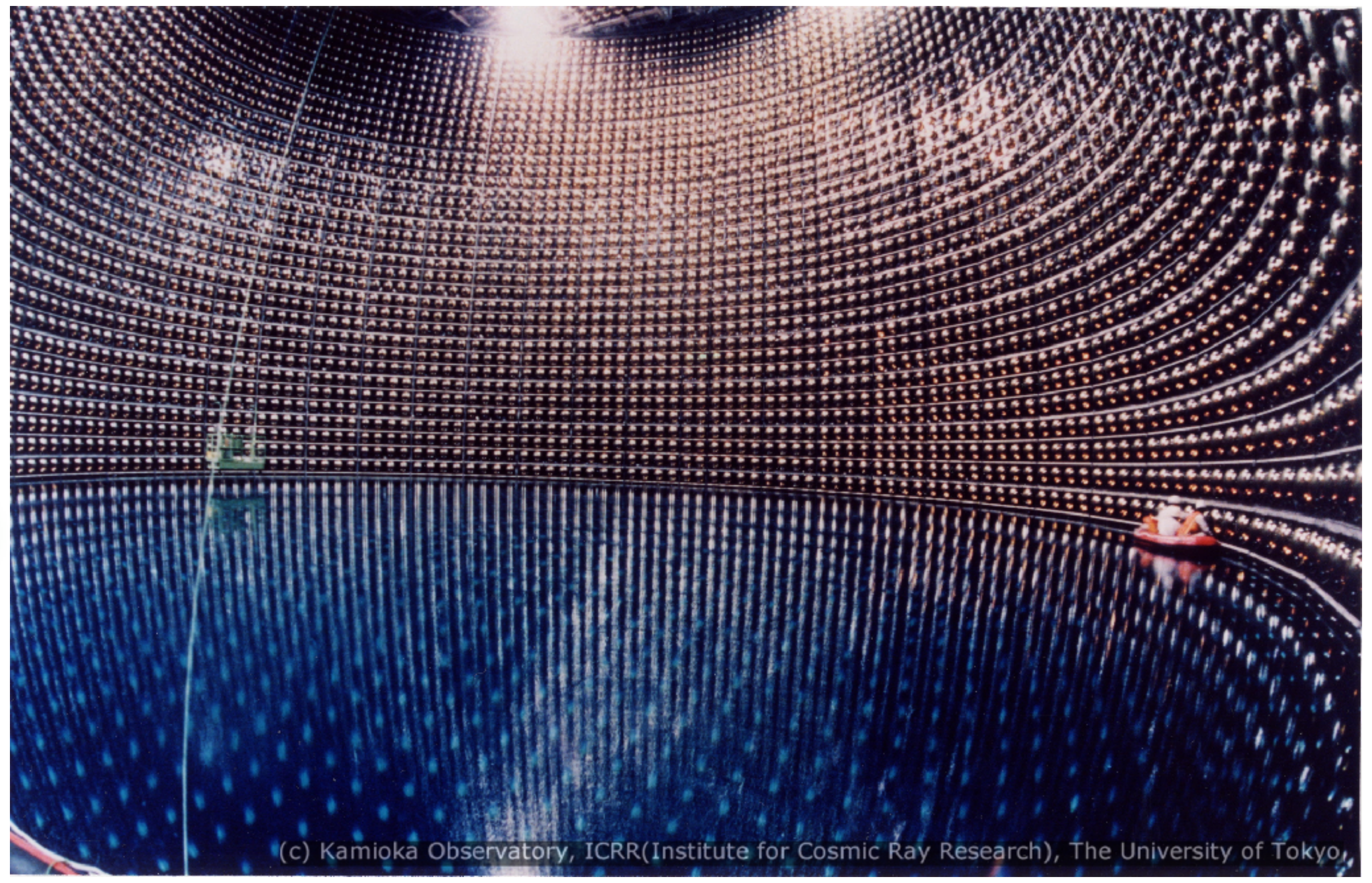


~500 members over 12 countries and 69 institutes

From Tokai To Kamioka



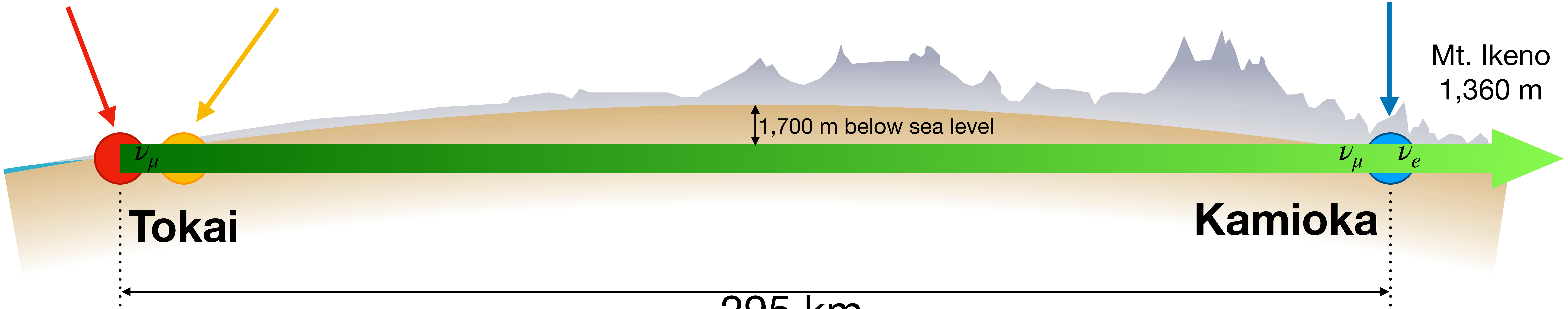




J-PARC

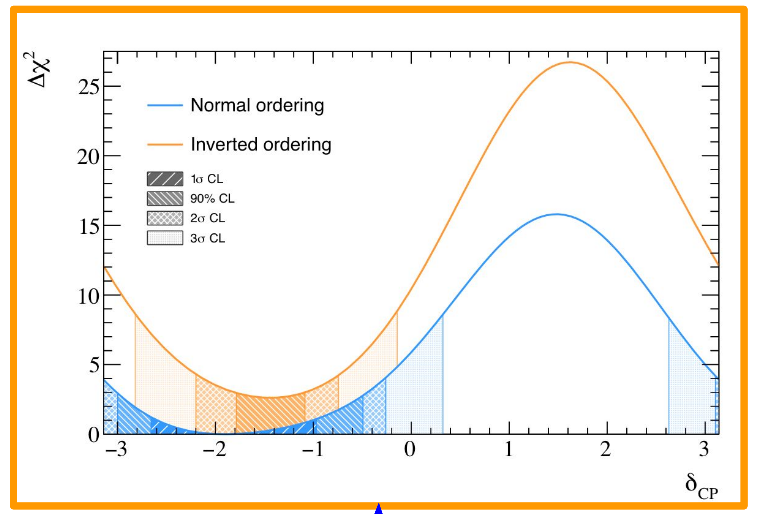
Near Detectors

Super-Kamiokande



Oscillation analysis strategy

$\delta_{CP},\ \sin^2\theta_{13},\ \Delta m^2_{32}\ldots$

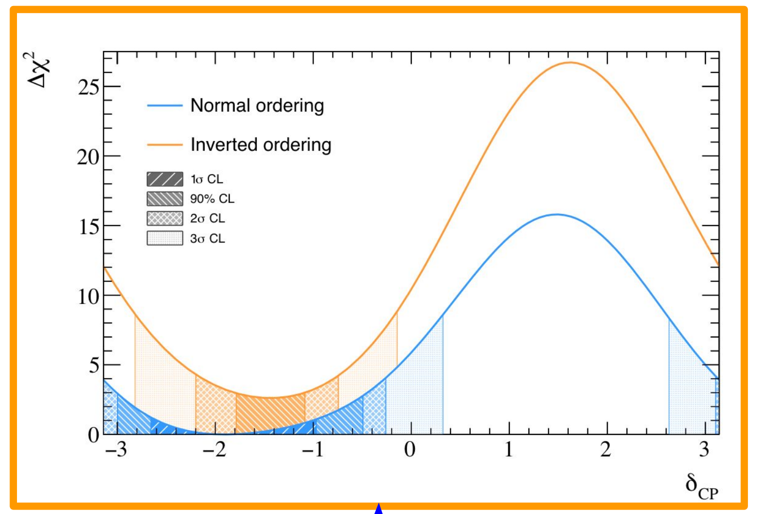


Neutrino spectrum prediction at far detector

Super-Kamiokande beam data

Oscillation analysis strategy

$\delta_{CP}, \ \sin^2\theta_{13}, \ \Delta m^2_{32} \ldots$



Neutrino spectrum prediction at far detector

Super-Kamiokande beam data

Super-Kamiokande detector uncertainties

ND constraints on flux and cross-sections

Super-Kamiokande atmospheric data

Near detector beam data

Neutrino spectrum prediction at near detector

Flux external data (NA61/SHINE)

ND280 Detector Modelling

Cross-sections external data

Two analyses:

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

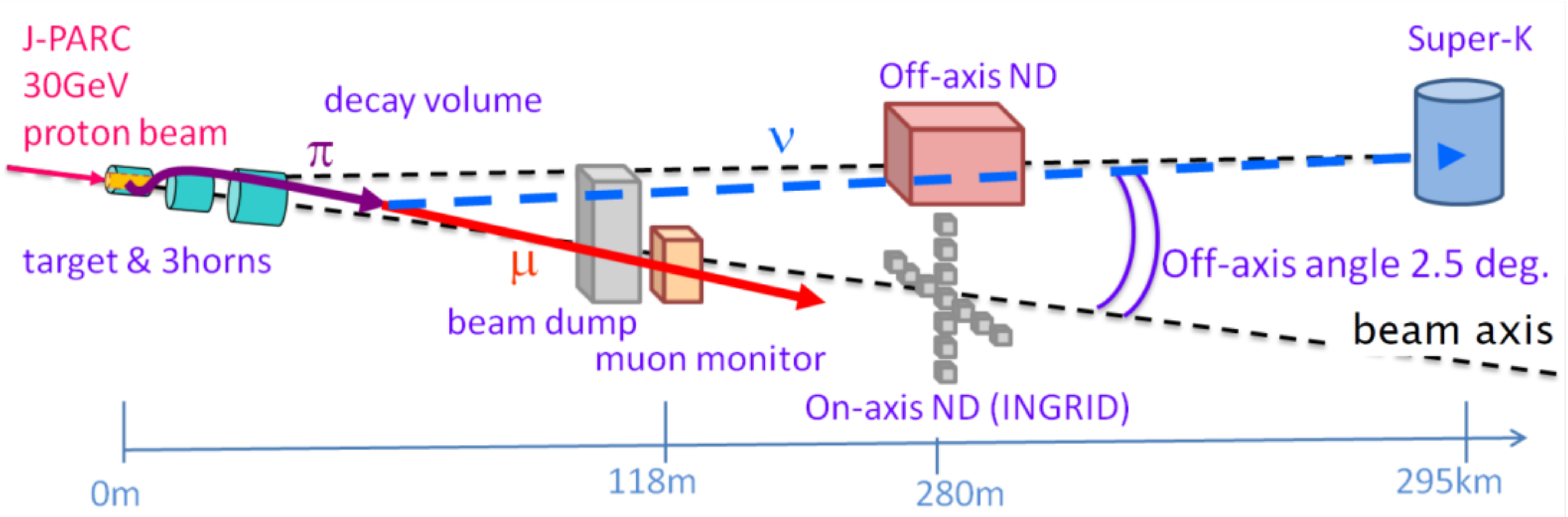
See Joe Walsh's parallel talk

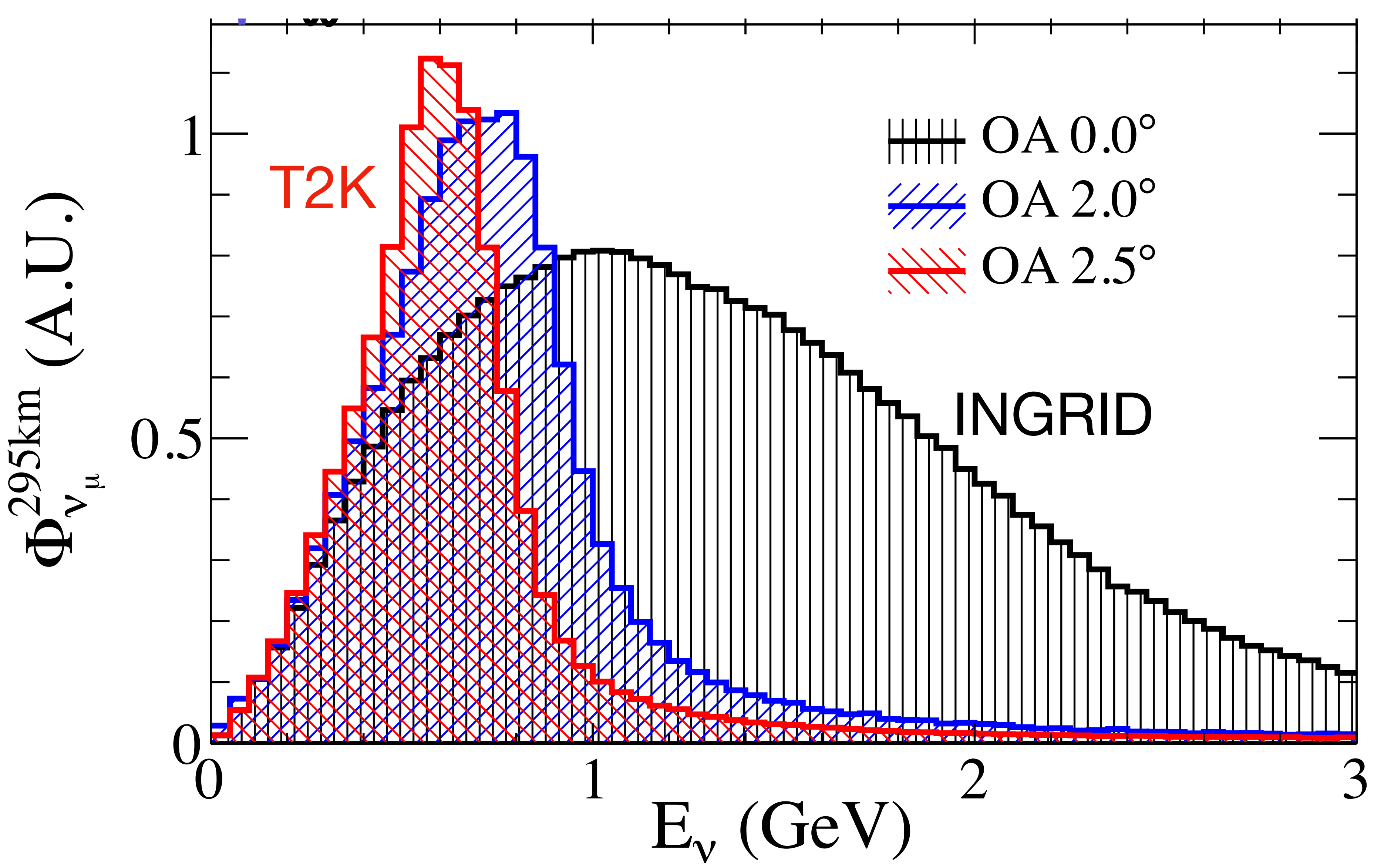
Muon neutrinos production at J-PARC

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

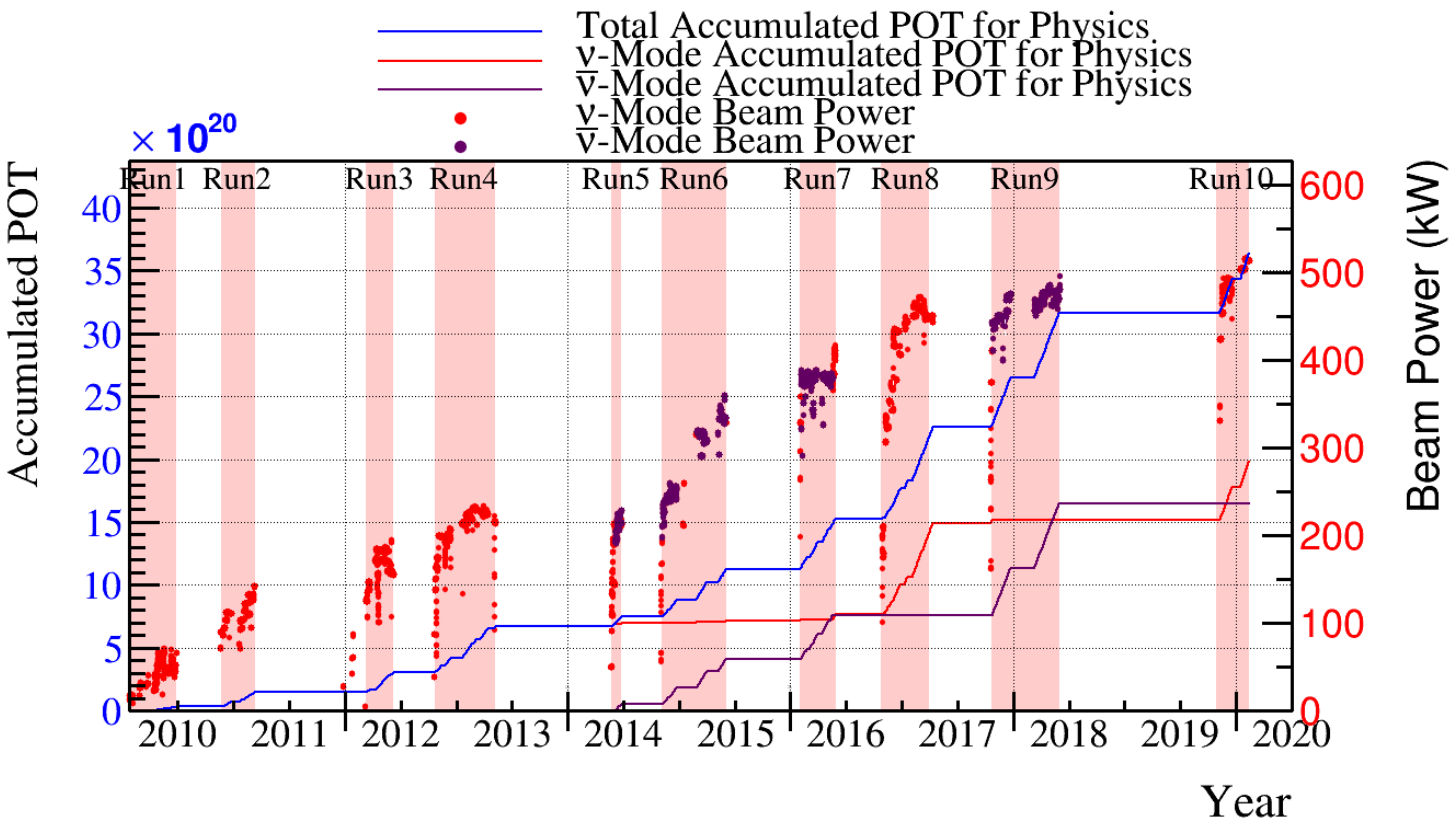
- Magnetized “horns” to select hadrons charge → enrichment in ν_μ or $\bar{\nu}_\mu$
- Muon flux monitoring after beam dump

2.5° off-axis beam for ND and SK





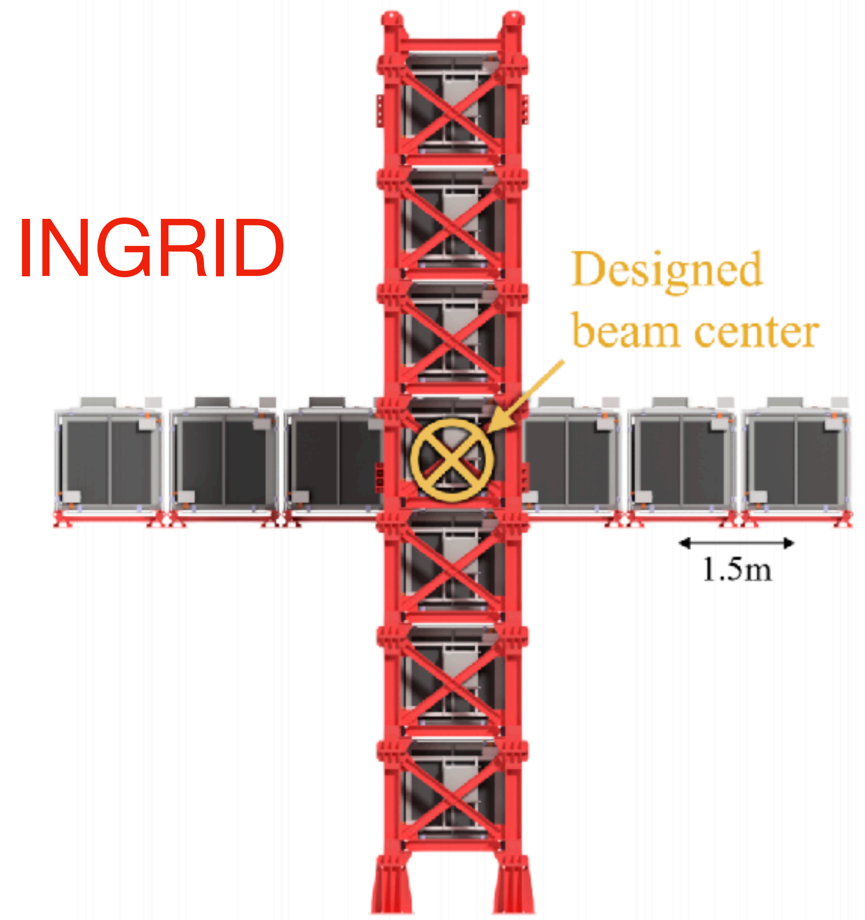
Data taking status



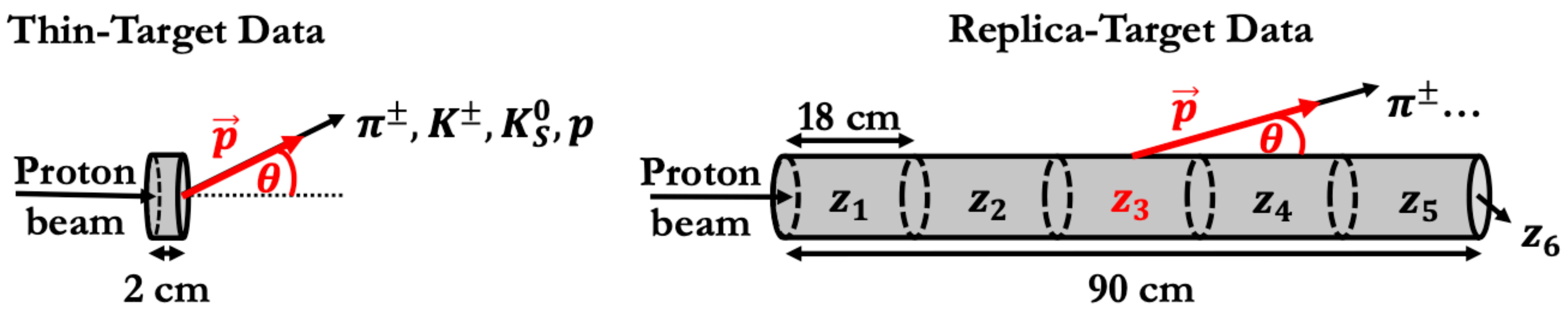
Steady increase in beam power: **515 kW this year**

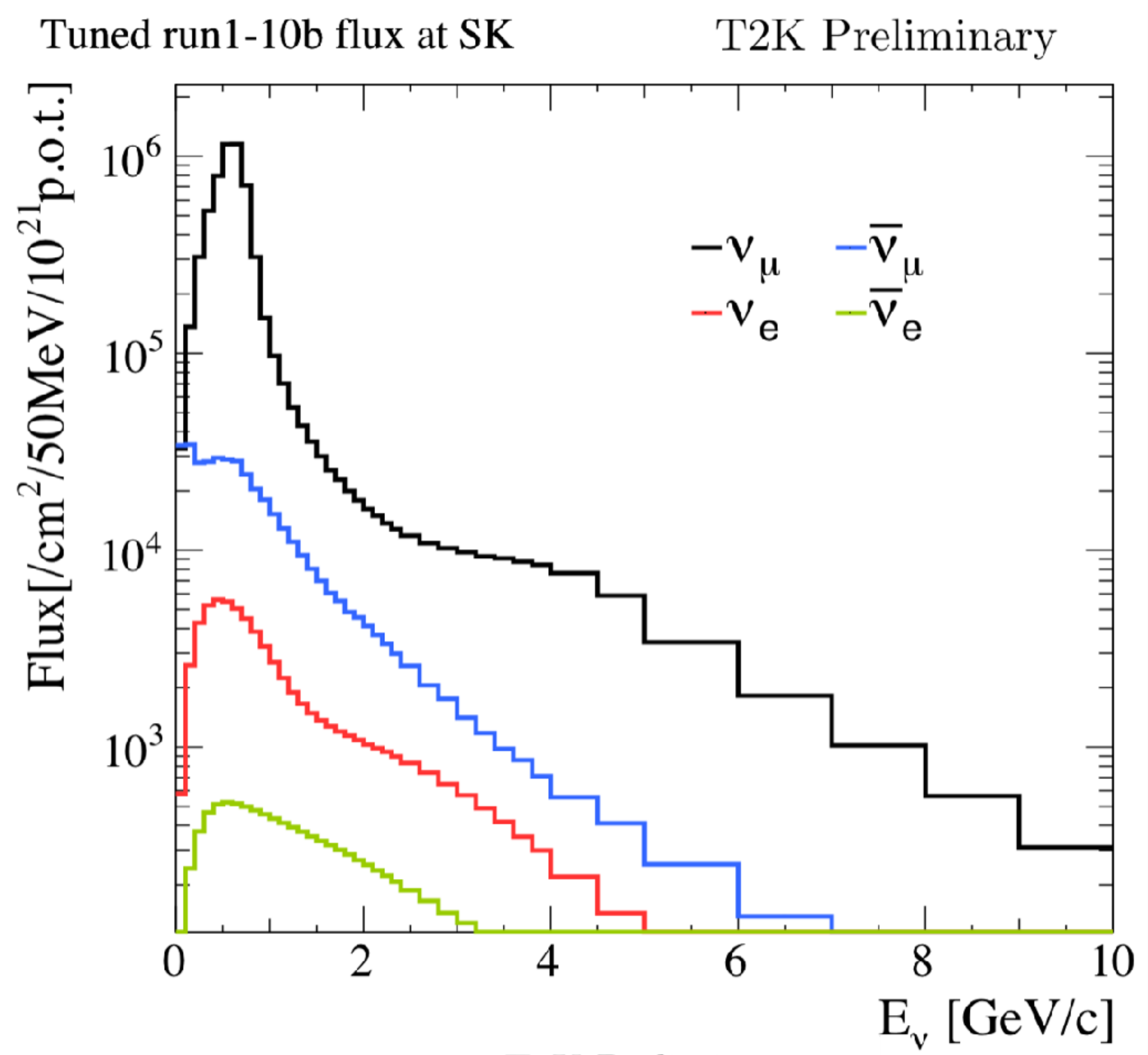
Run 1-10: 1.97×10^{21} POT in ν mode and 1.63×10^{21} POT in $\bar{\nu}$ mode

Flux constraints



NA61/SHINE@CERN

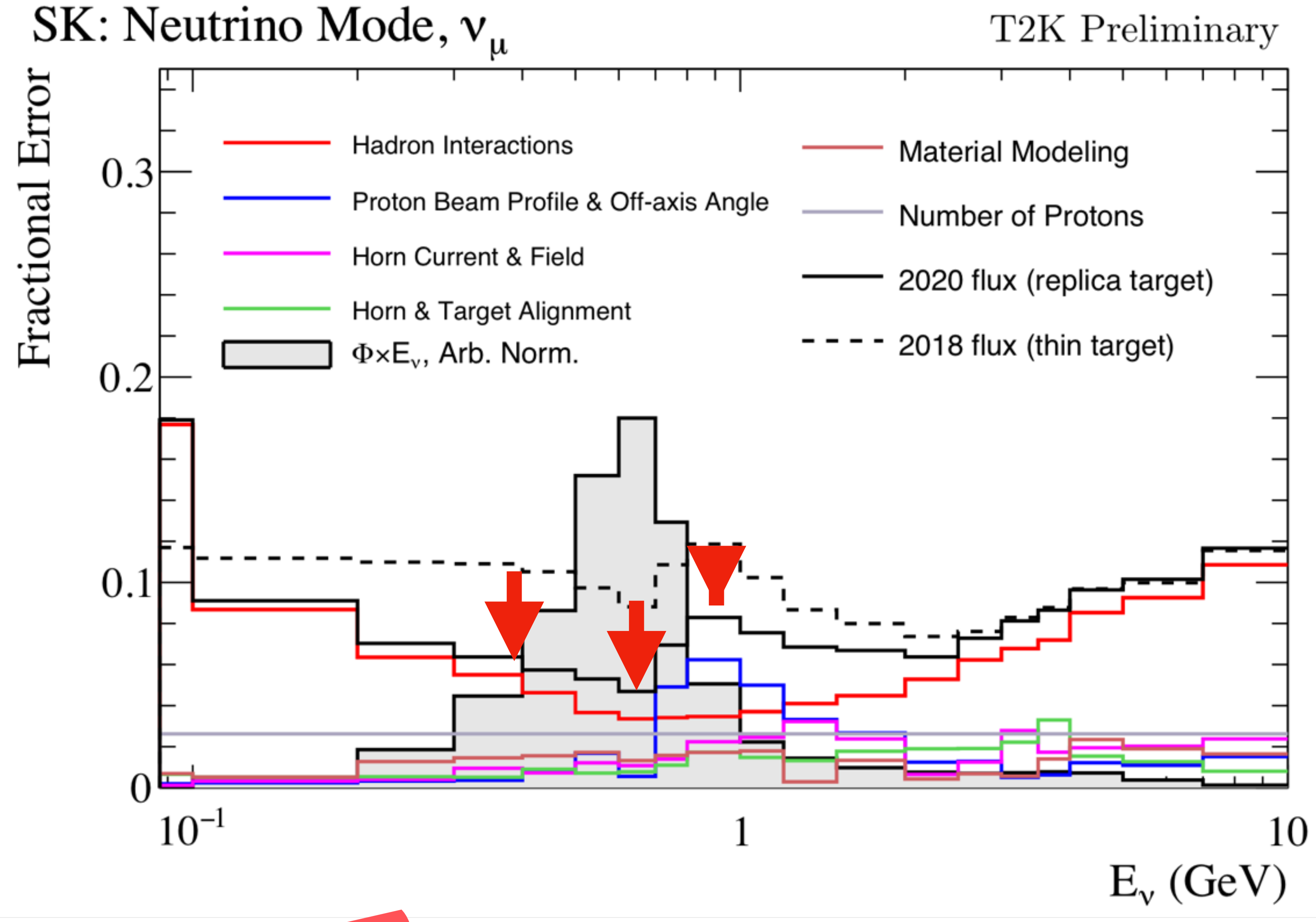




Hadron production simulations by Fluka
Interactions constrained with NA61/SHINE (CERN)
New: T2K graphite replica target

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

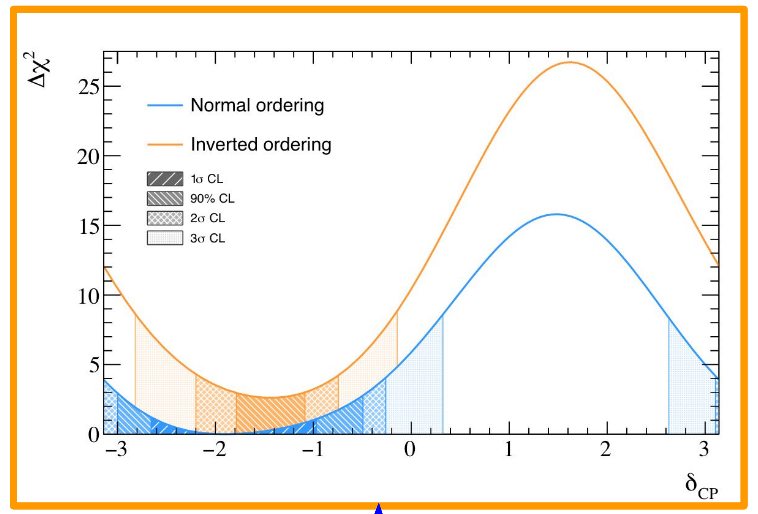
Flux uncertainties reduced from 8% to 5%

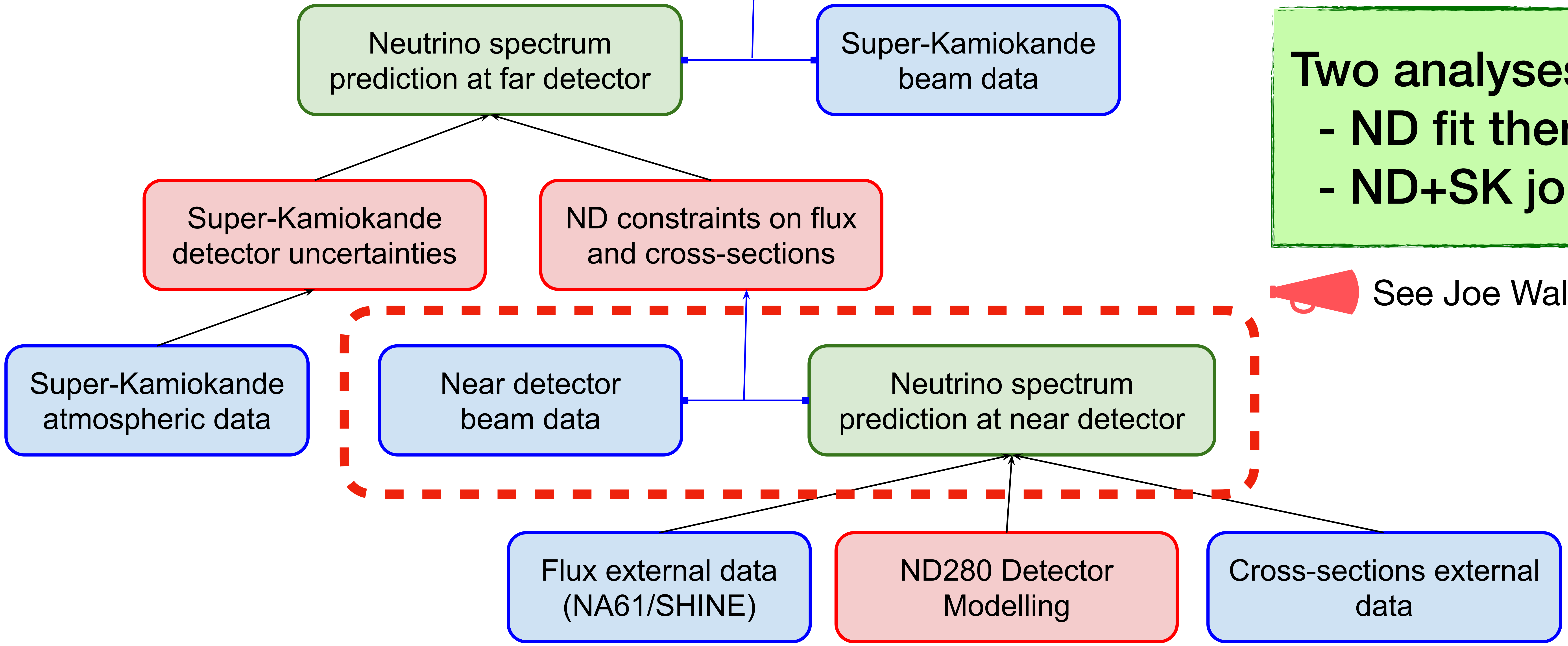


See Maria Antonova 's parallel talk

Oscillation analysis strategy

$\delta_{CP},\ \sin^2\theta_{13},\ \Delta m^2_{32}\ldots$





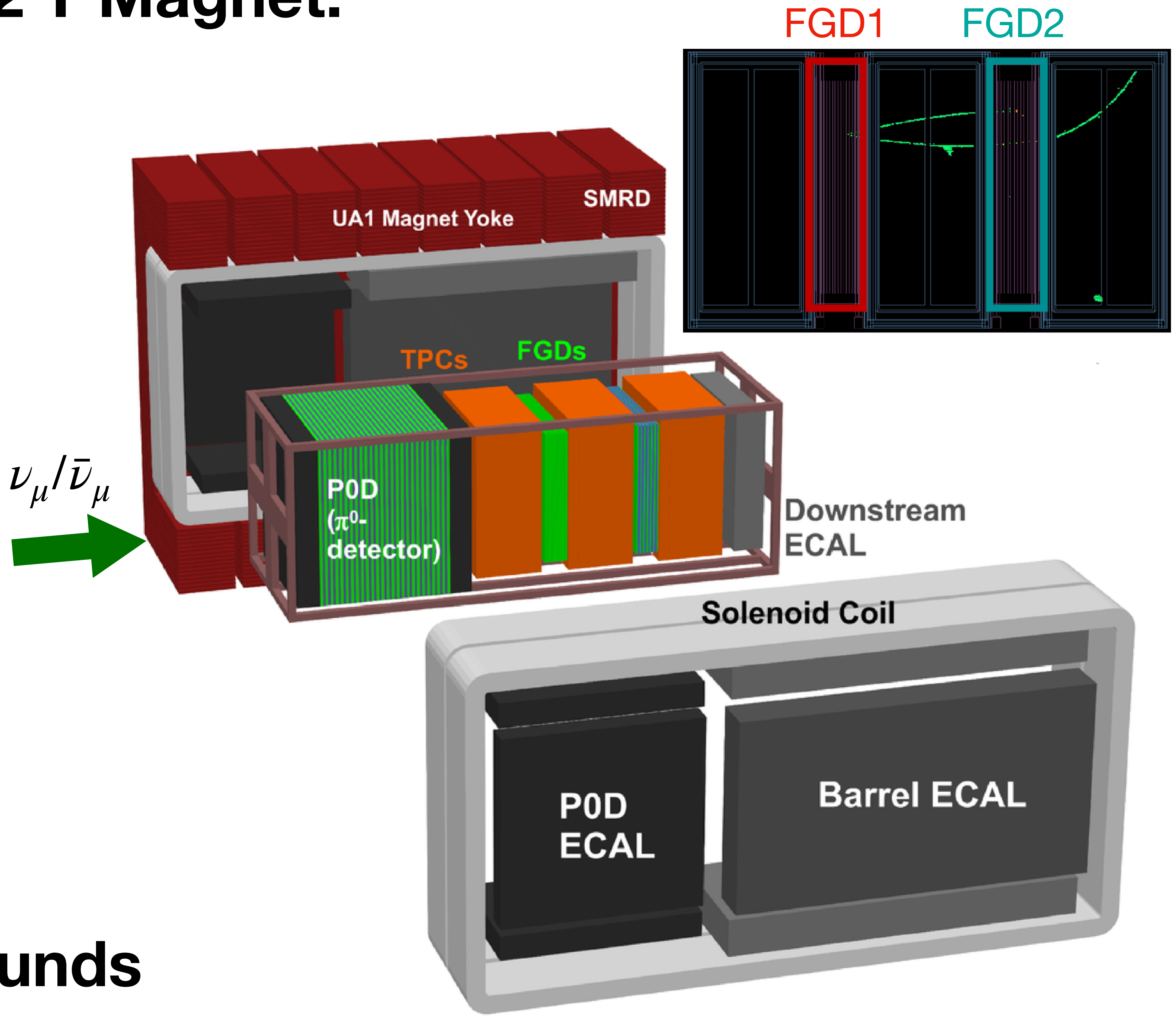
Two analyses:
- **ND fit then SK fit**
- **ND+SK joint fit**

See Joe Walsh's parallel talk

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 (CH,H_2O)
- 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

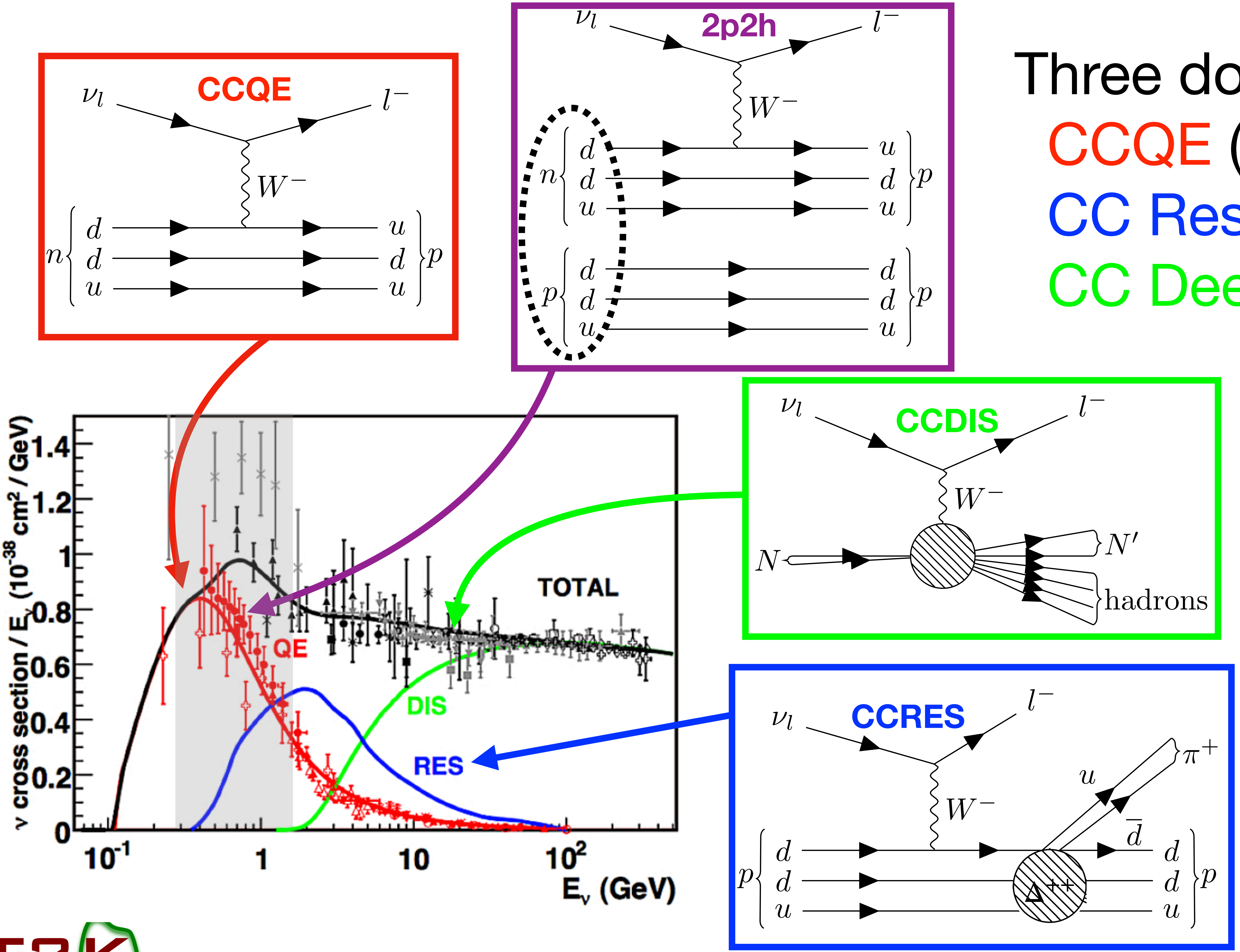
Magnetization → charge and momentum

⇒ Constraints on cross-sections, flux uncertainty model and wrong sign backgrounds

Neutrino interactions

Three dominant interaction channels:

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

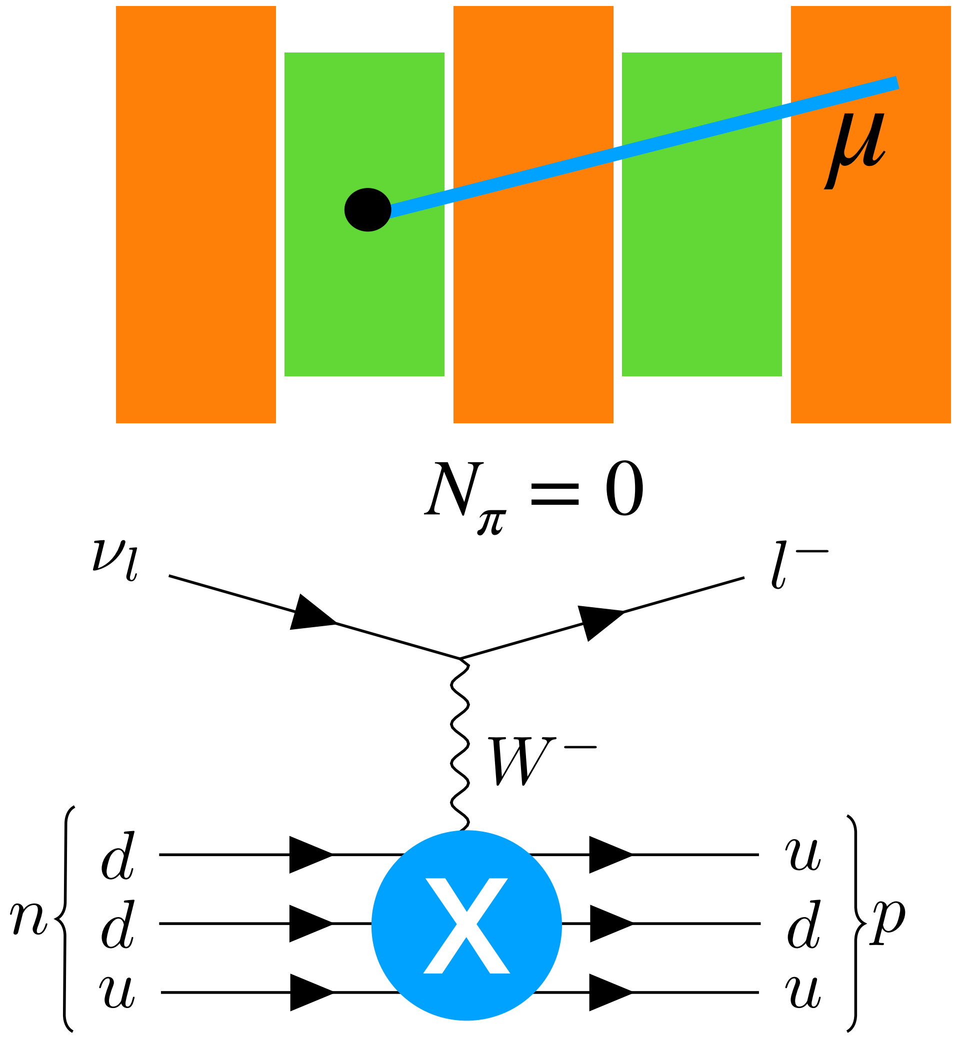


→ Define ND samples enriched in each of the processes using **reconstructed pion multiplicity**

→ Constrain cross-section models for each interaction

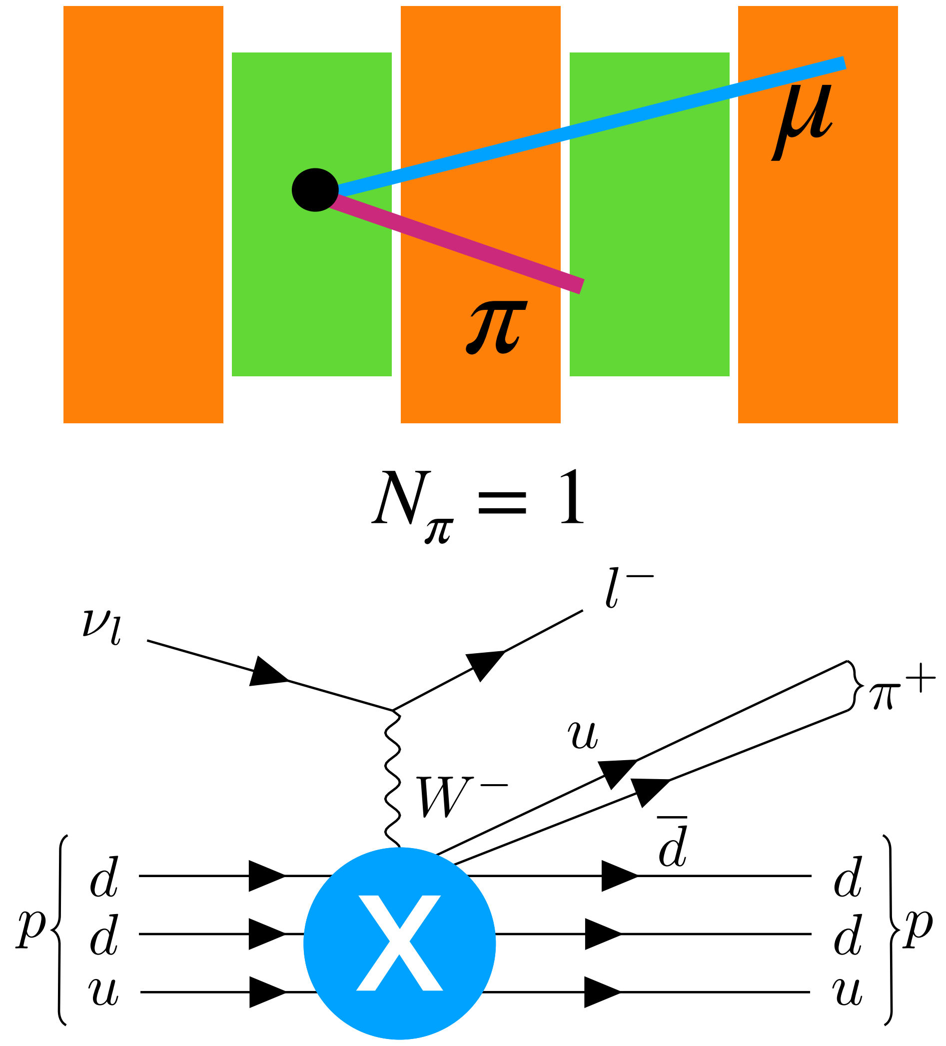
ND280 samples

CC0π



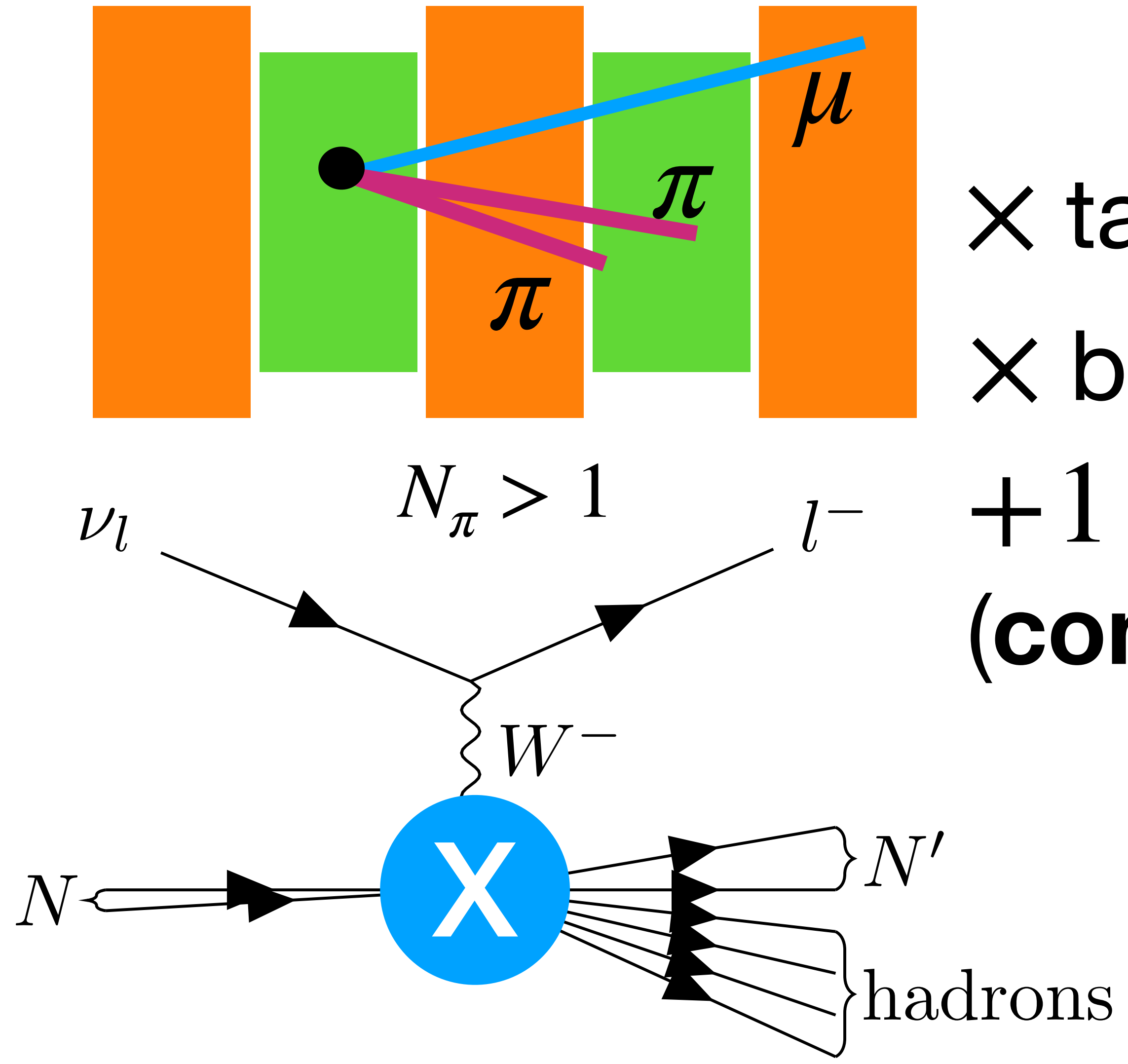
~CCQE + 2p2h

CC1π

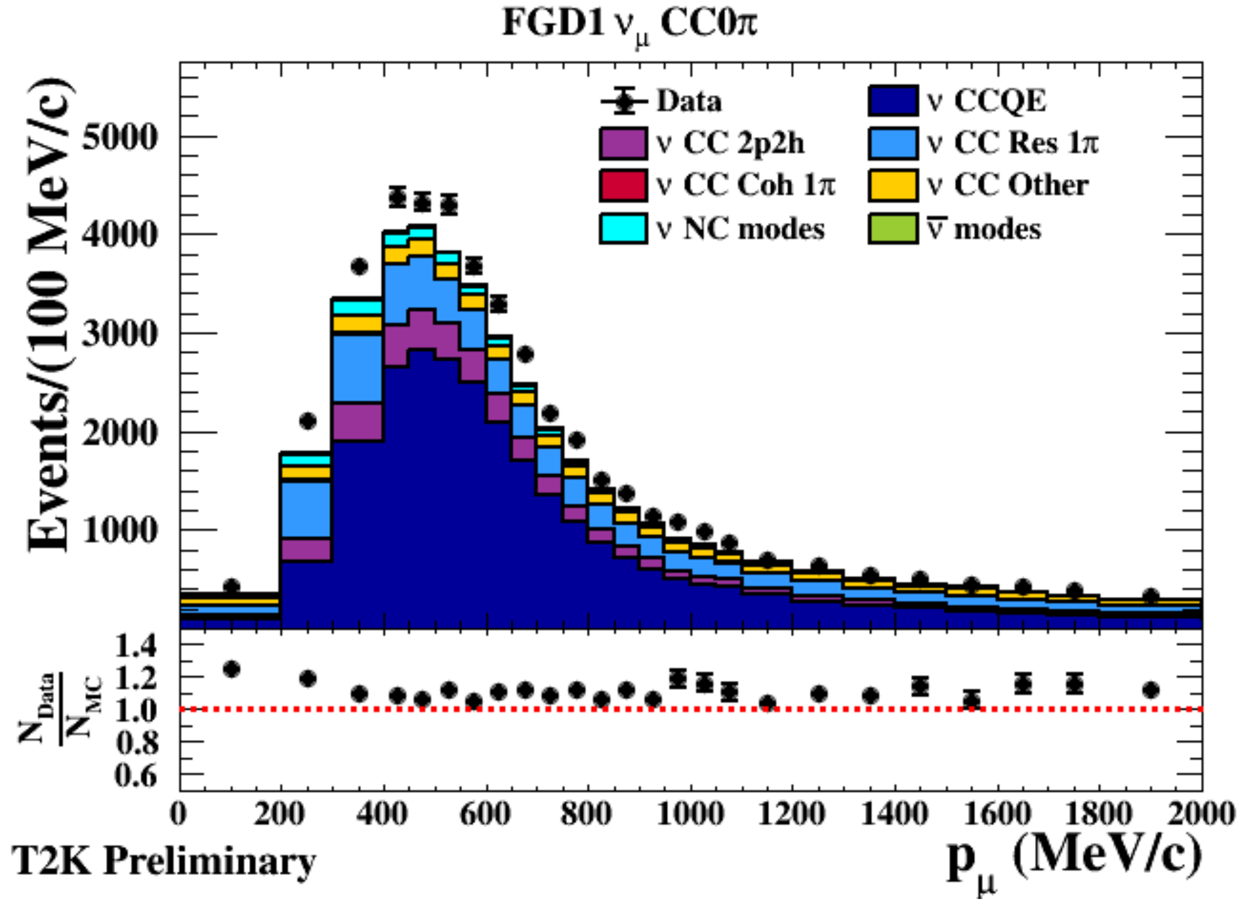


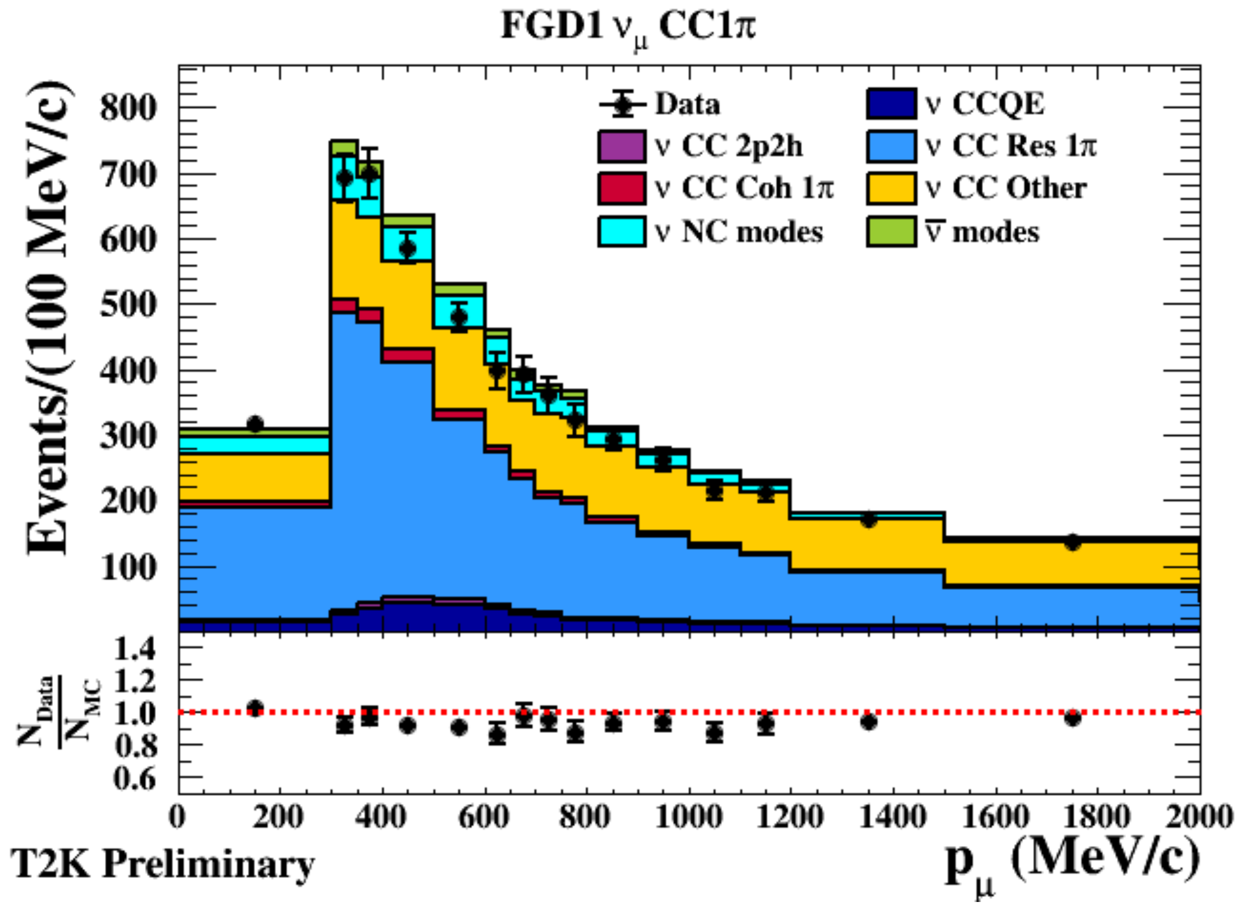
~CCRes

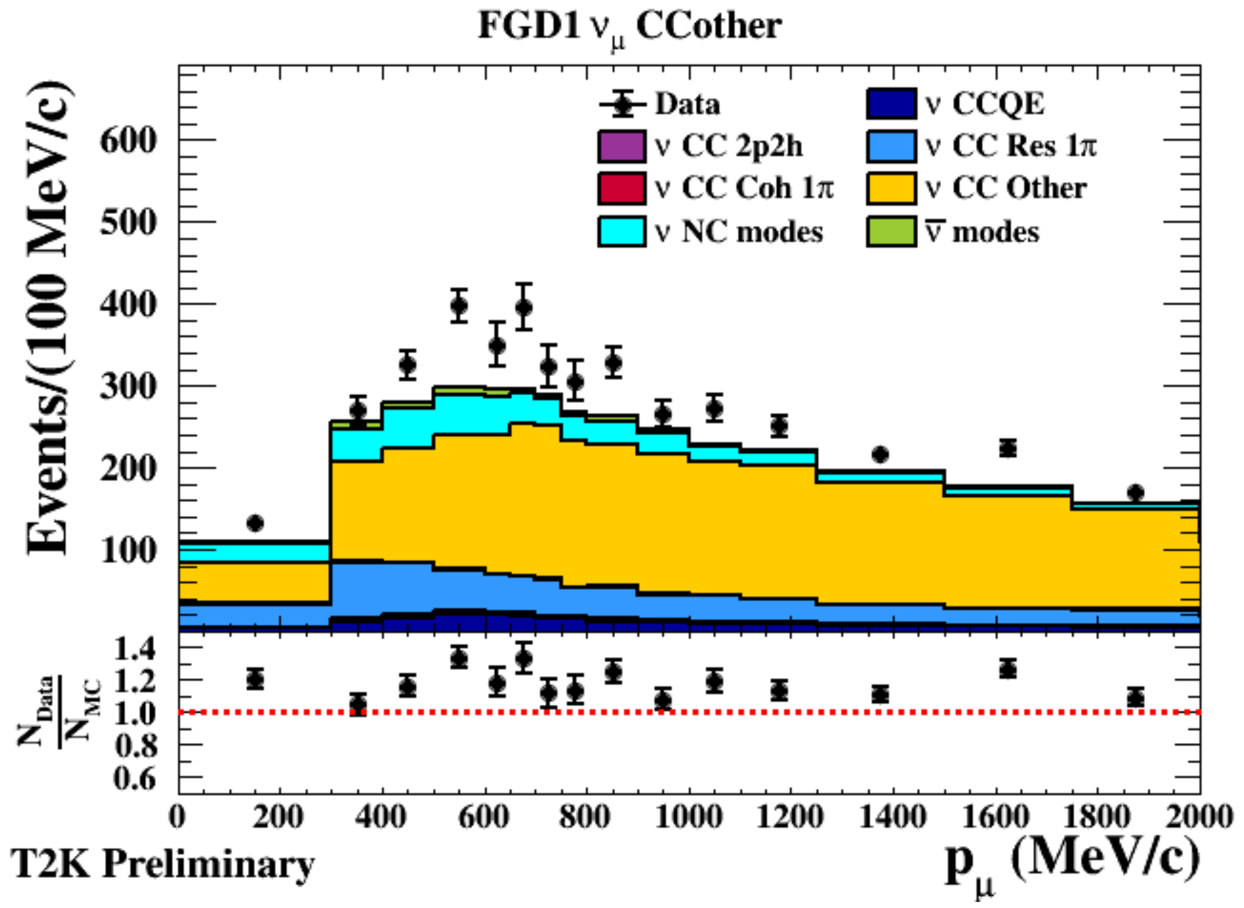
CCNπ



~CCDIS







$\times$ target detector (FGD1 or FGD2)

$\times$ beam mode (ν or anti-ν)

$+1$ sample ν events in anti-ν beam mode **(constrain wrong-sign background)**

= 18 samples

Cross-section using Near Detectors

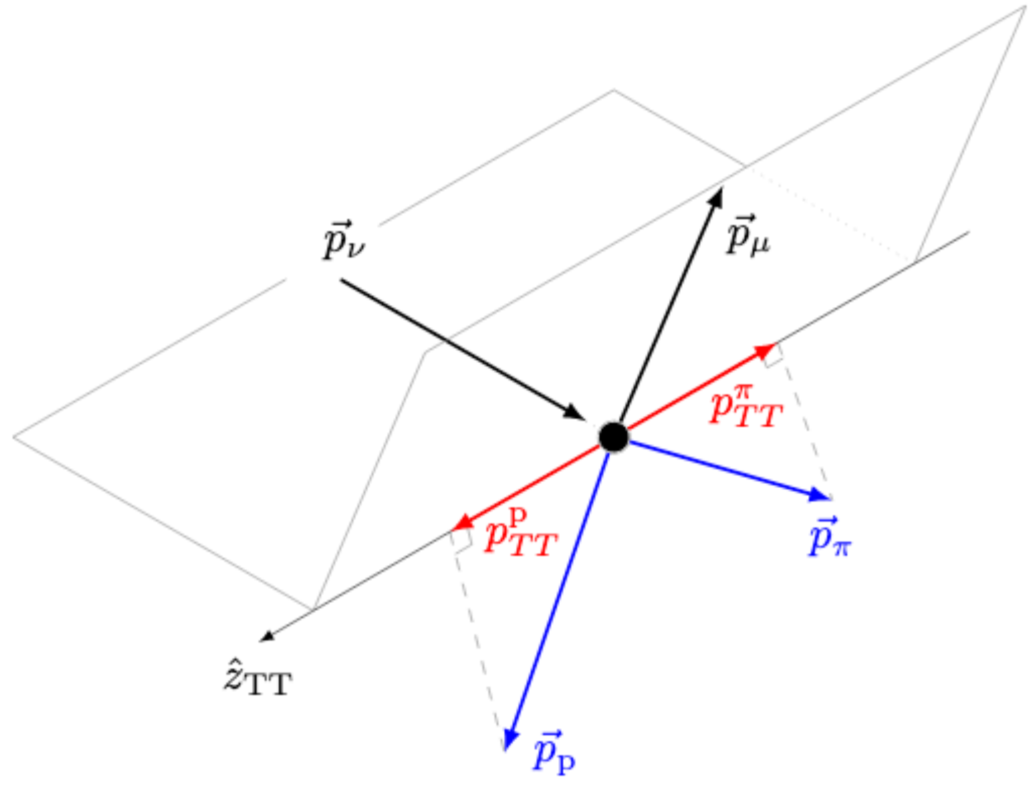
Many interesting problems being tackled in neutrino interactions!

Recent analyses:

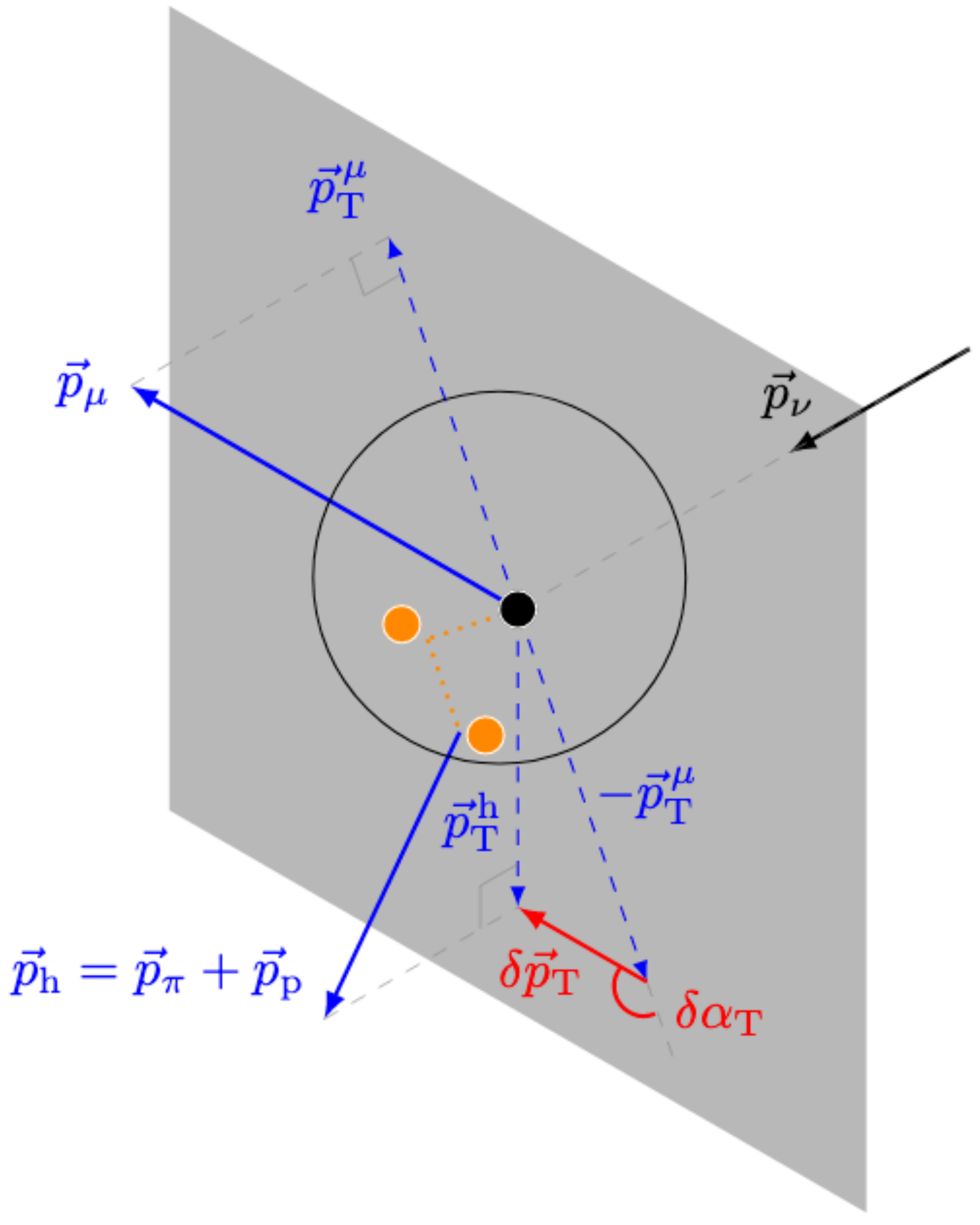
→ First measurement of transverse kinematic imbalance in CC1π^+ [02/2021]

- First CC-$\nu_e/\bar{\nu}_e$ inclusive cross-section measurement [10/2020]
- CC0π $\bar{\nu}_\mu$ cross-section measurements on $\mathrm{H_2O}$ [07/2020]
- CC0π ν_μ cross-sections on $\mathrm{H_2O}$ and CH [04/2020]
- CC0π $\nu_\mu/\bar{\nu}_\mu$cross-sections on C and O [04/2020]
- Combined ν_μ and $\bar{\nu}_\mu$ CC0π cross-sections measurement [02/2020]
- CC1π^+ cross-sections on CH [01/2020]

Transverse kinematic imbalance in CC1π^+



(a) $\delta p_{TT} = p^{\pi}_{TT} + p^{\mathrm{p}}_{TT}$.

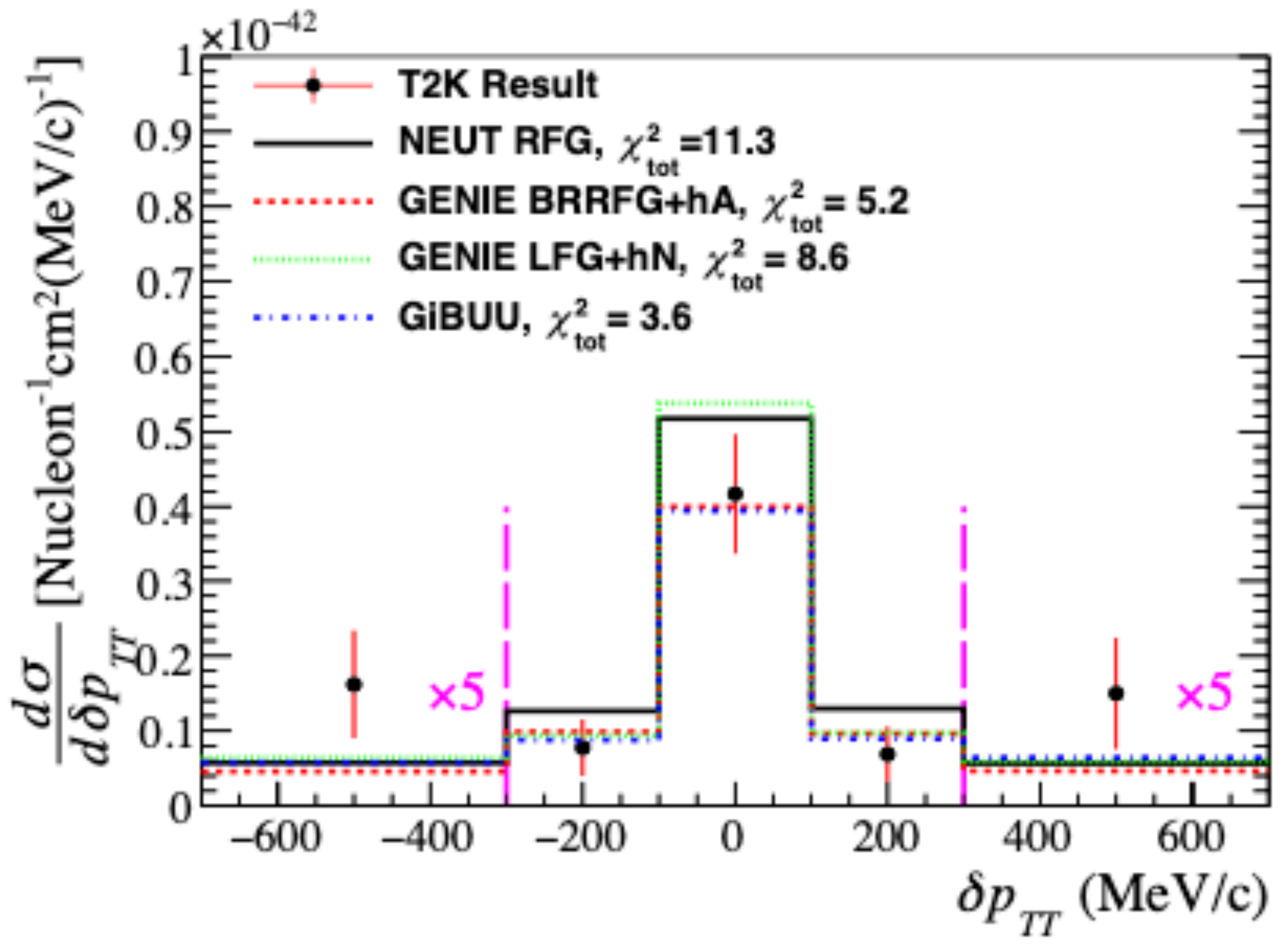


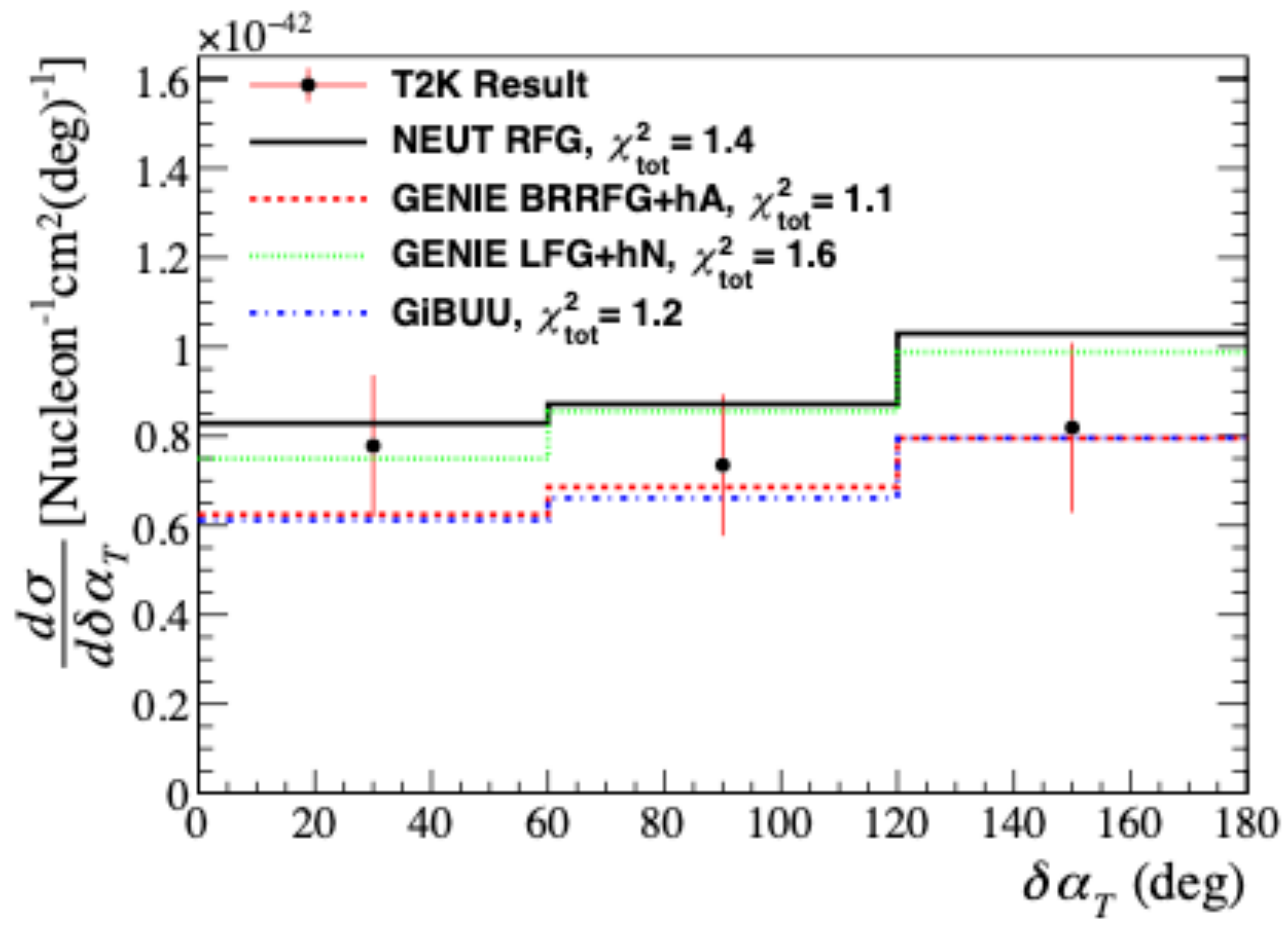
(b) $\delta \vec{p}_T$ and $\delta\alpha_T$.

ν_μ CC1π^+ interaction on nucleus with at least 1 proton in FGD1:

$$\nu_\mu + A \rightarrow \mu^- + \pi^+ + \mathrm{p} + A'$$

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





See Ka Ming Tsui's parallel talk

arXiv:2102.03346

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 CCNπ models

Near detector fit

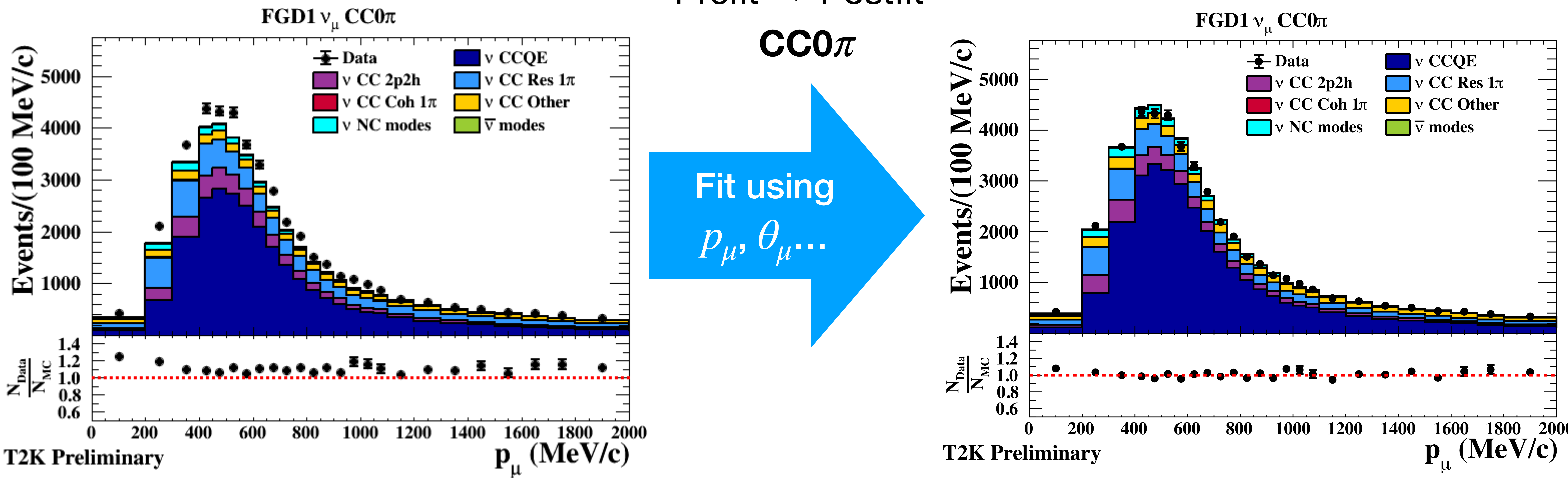
Modeling of neutrino cross-sections

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

CC0π

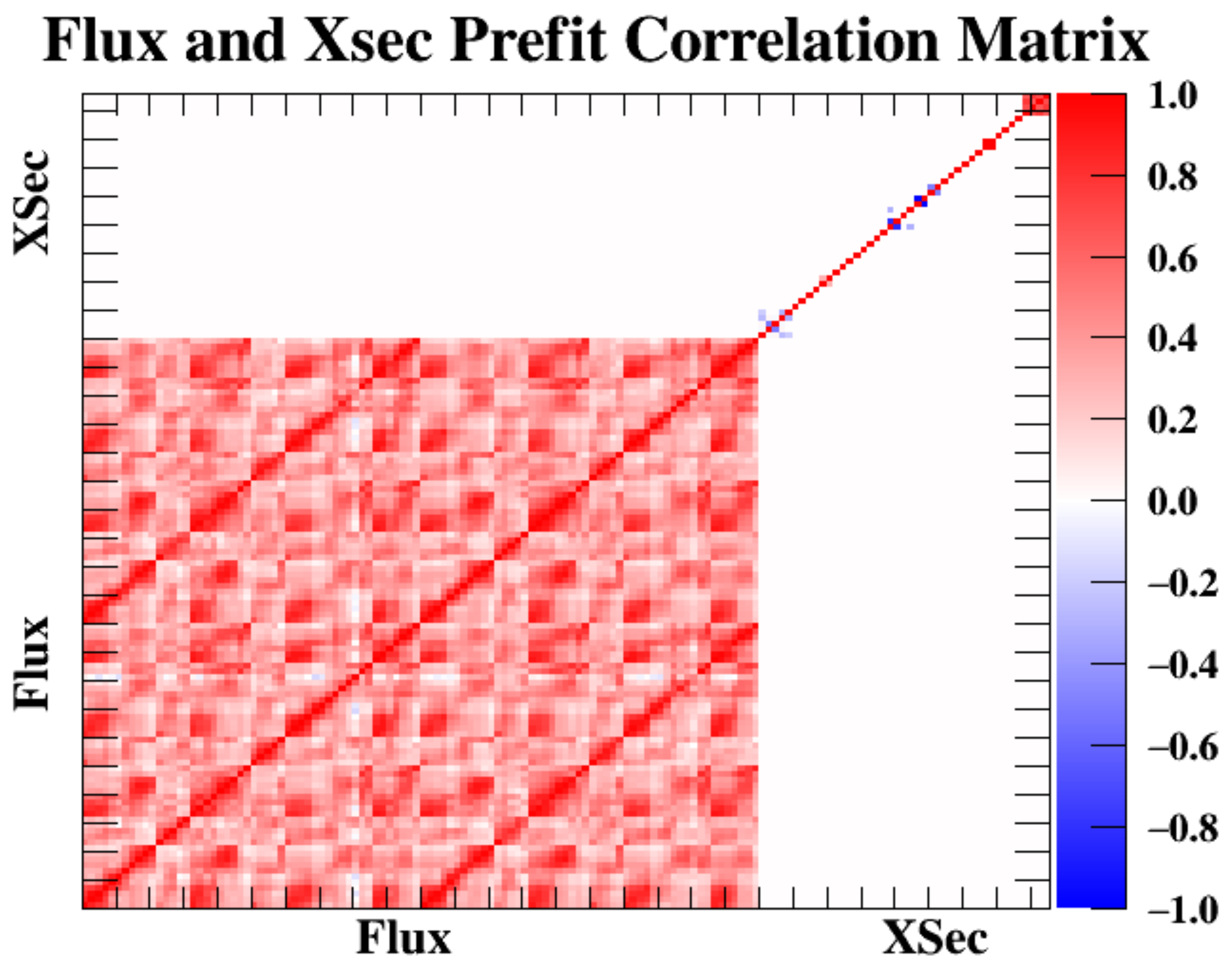


Near detector fit

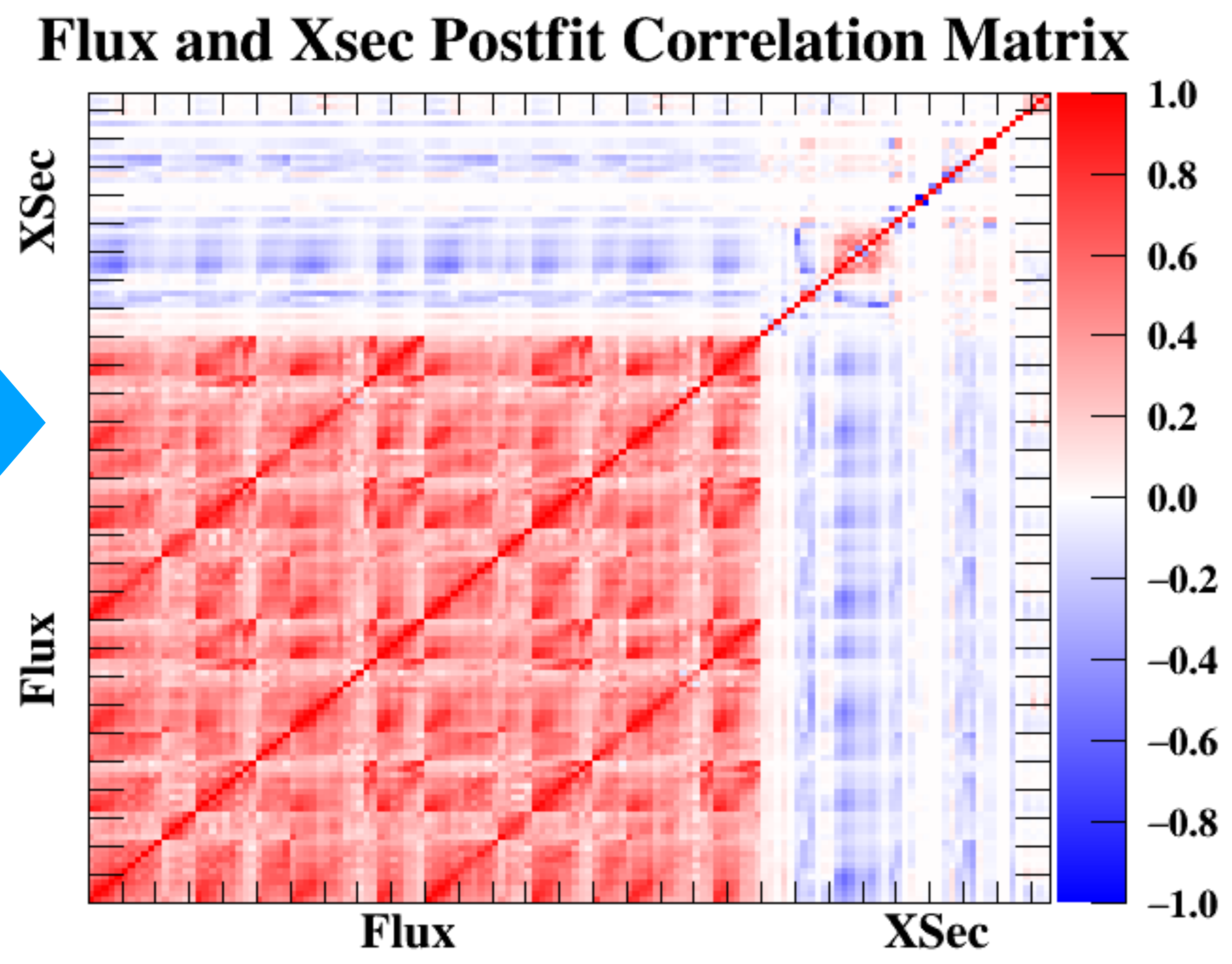
Modeling of neutrino cross-sections

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



T2K Preliminary



T2K Preliminary

Near detector fit

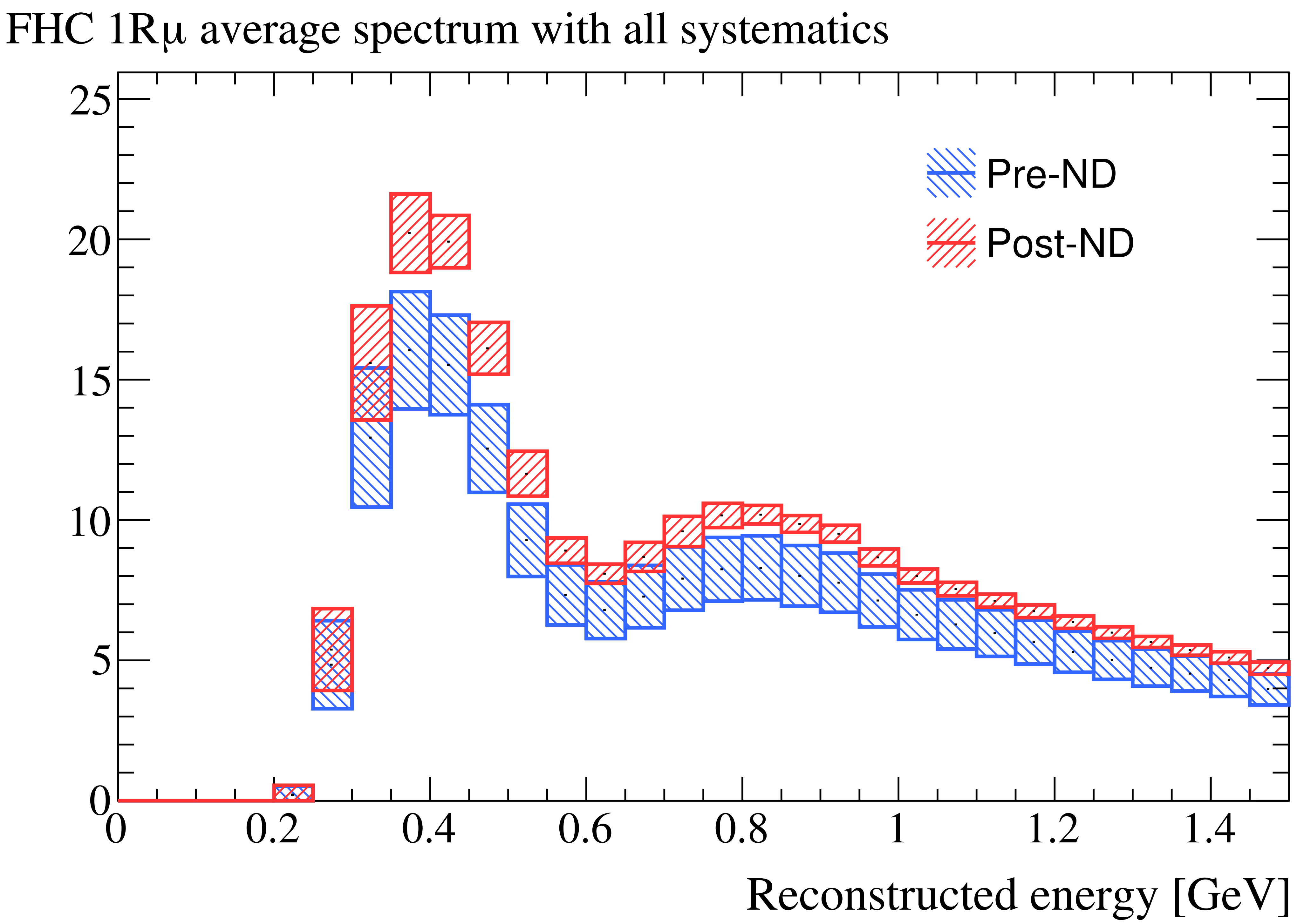
Modeling of neutrino cross-sections

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%**



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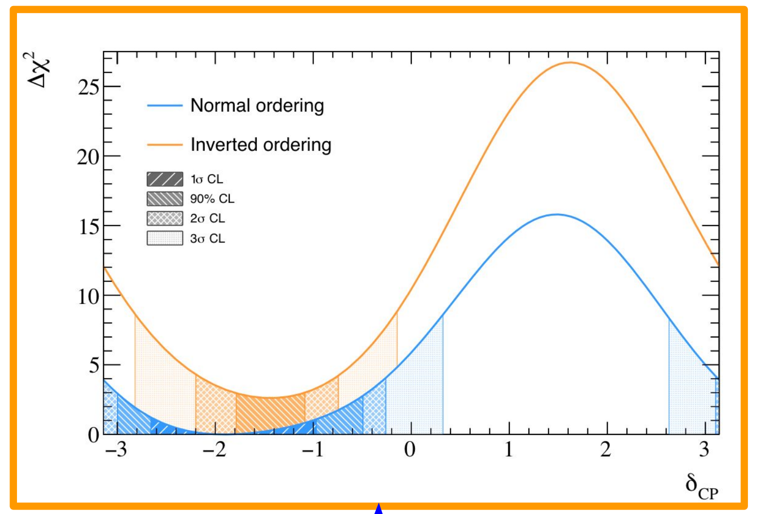
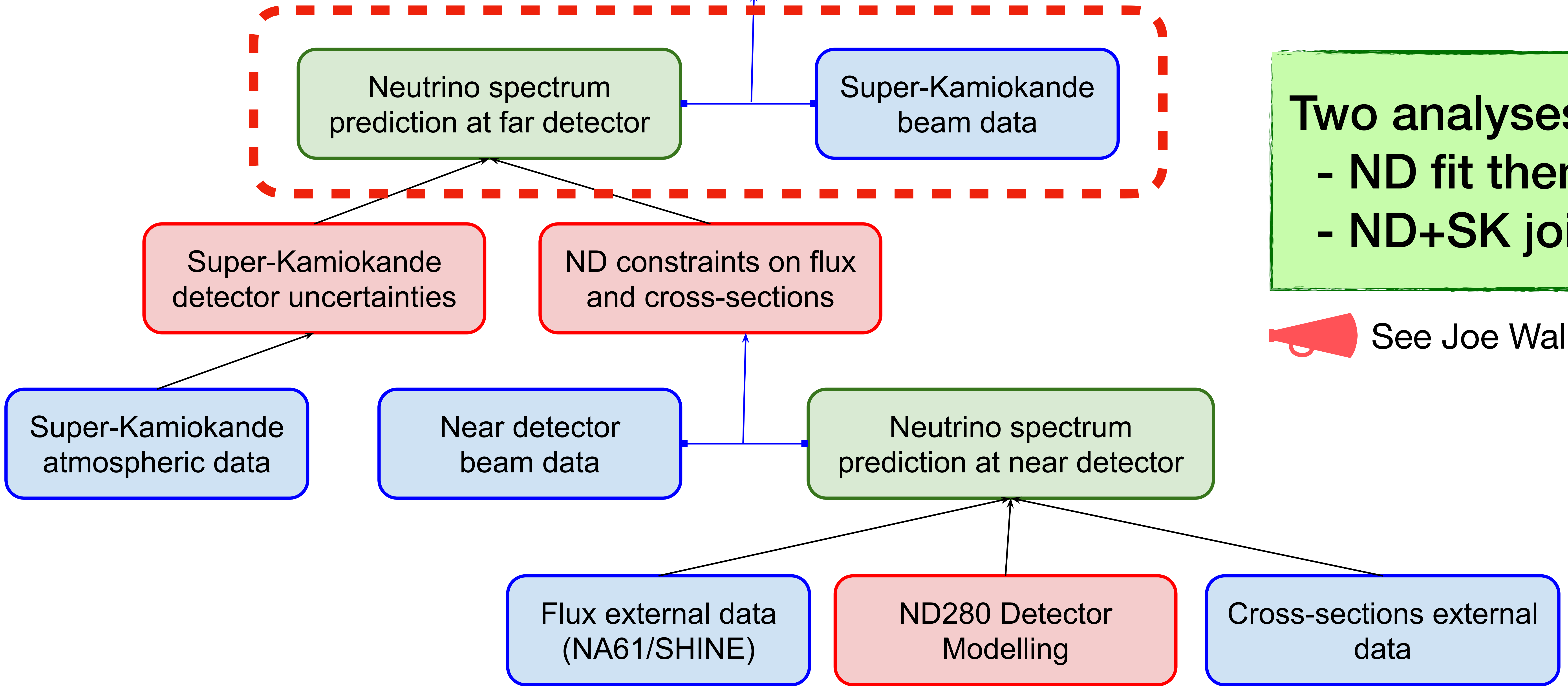
Oscillation analysis strategy

$\delta_{\text{CP}},\ \sin^2\theta_{13},\ \Delta m^2_{32}\ldots$





Two analyses:
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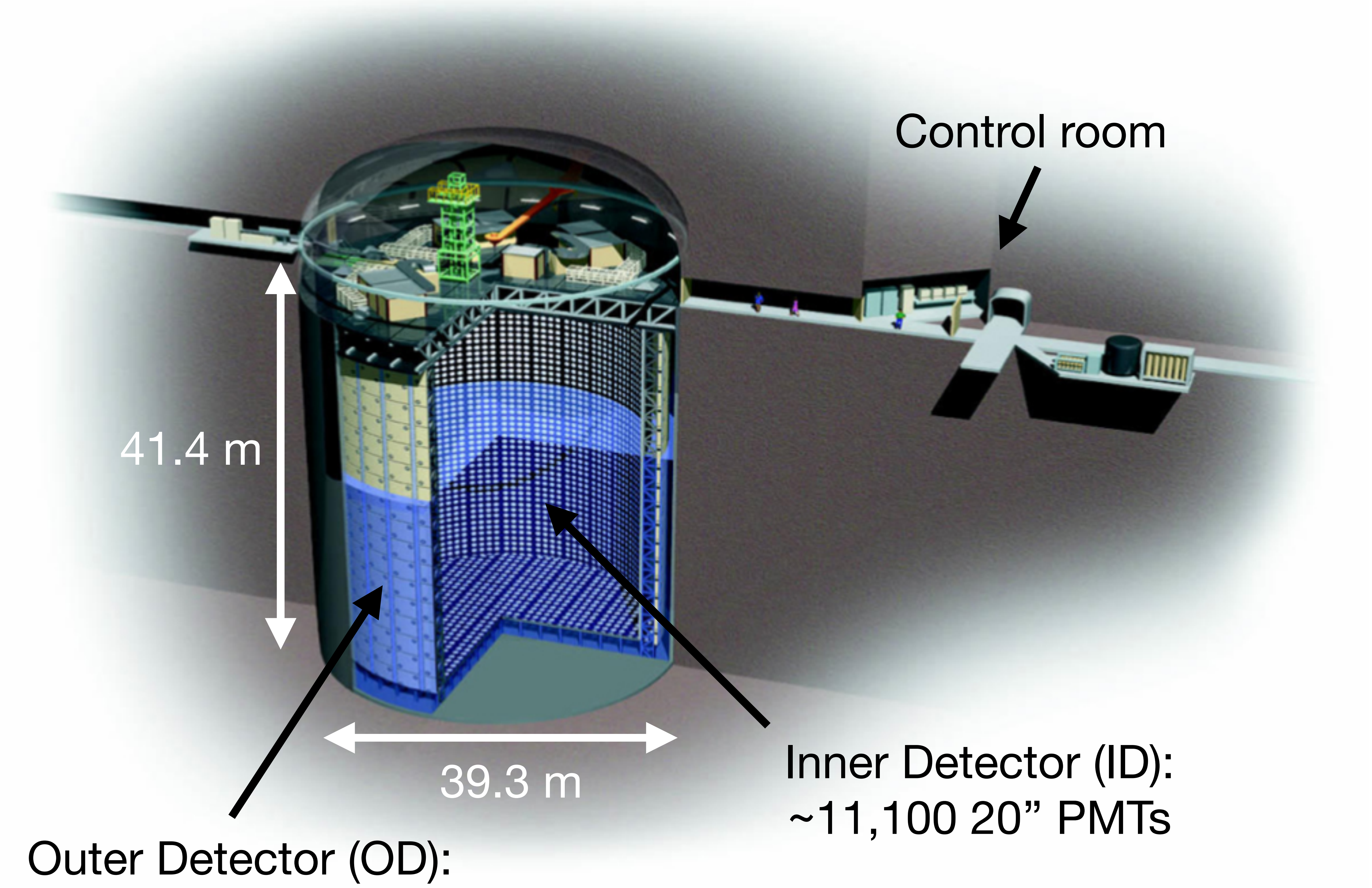
- **ND+SK joint fit**

See Joe Walsh's parallel talk

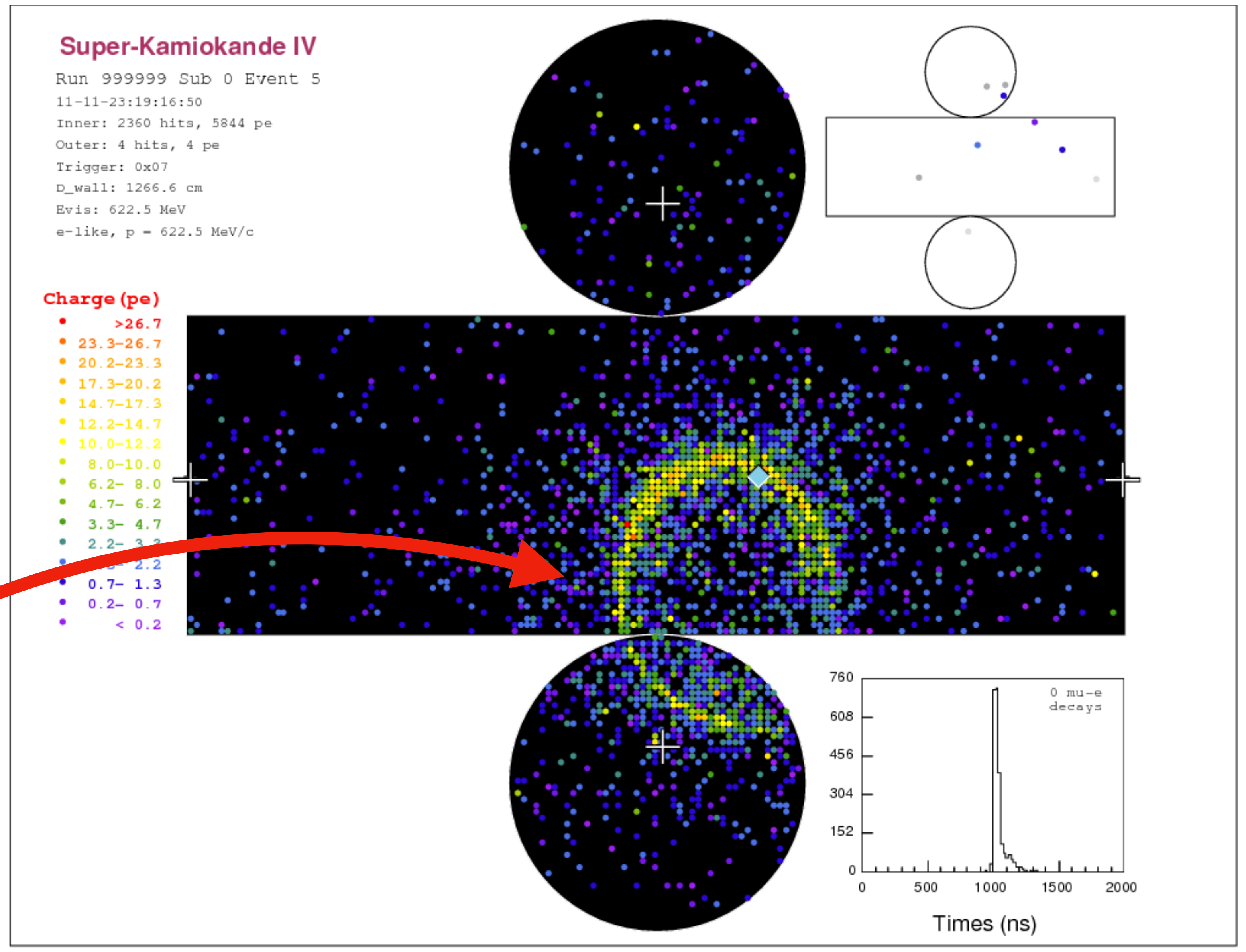
Off-axis Far Detector: Super Kamiokande



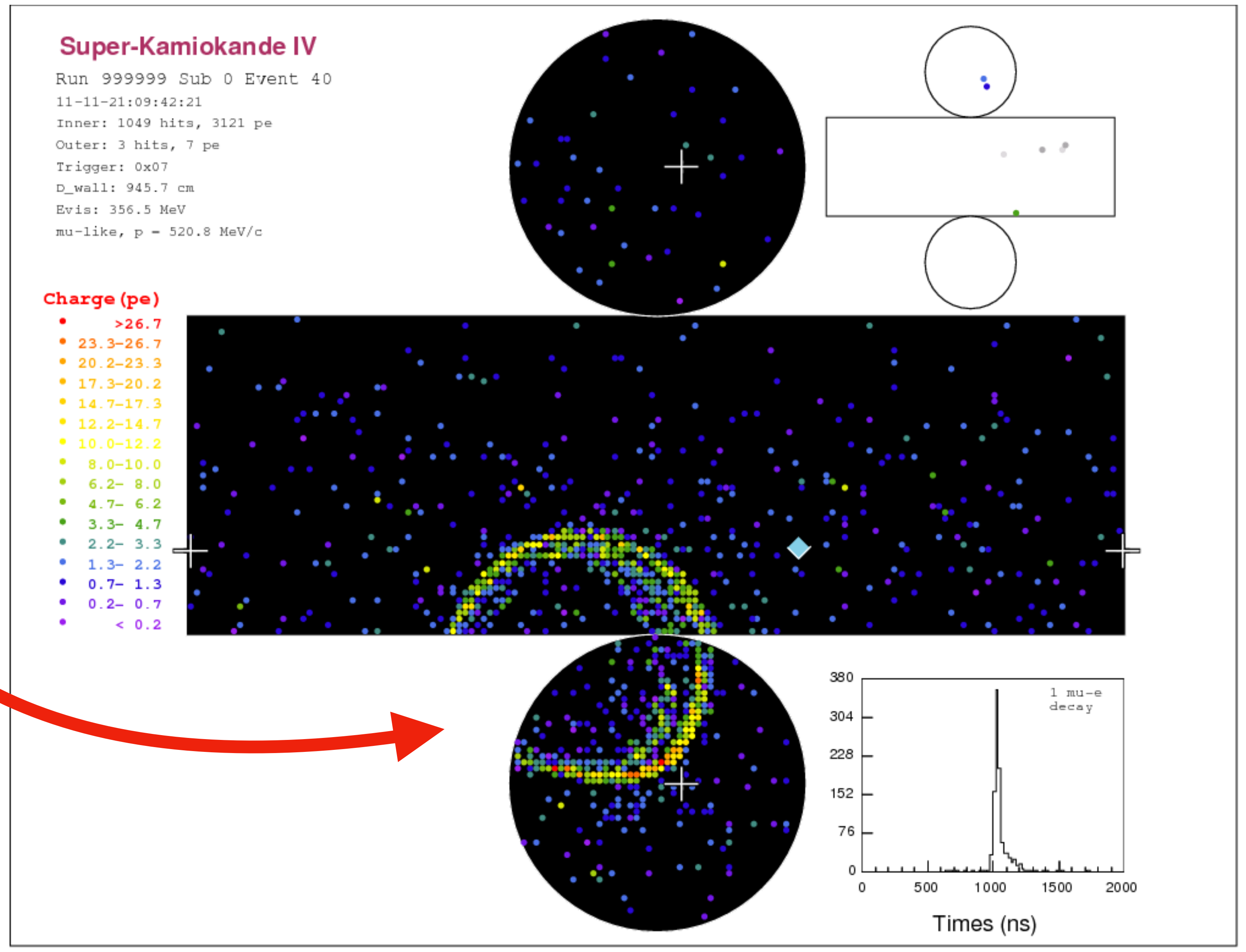
50 kton of purified water

1000 m under Mount Ikeno

Fuzzy → e



Sharp → μ



e-μ identification et kinematics using Cherenkov ring pattern

No charge identification (contrary to ND280)

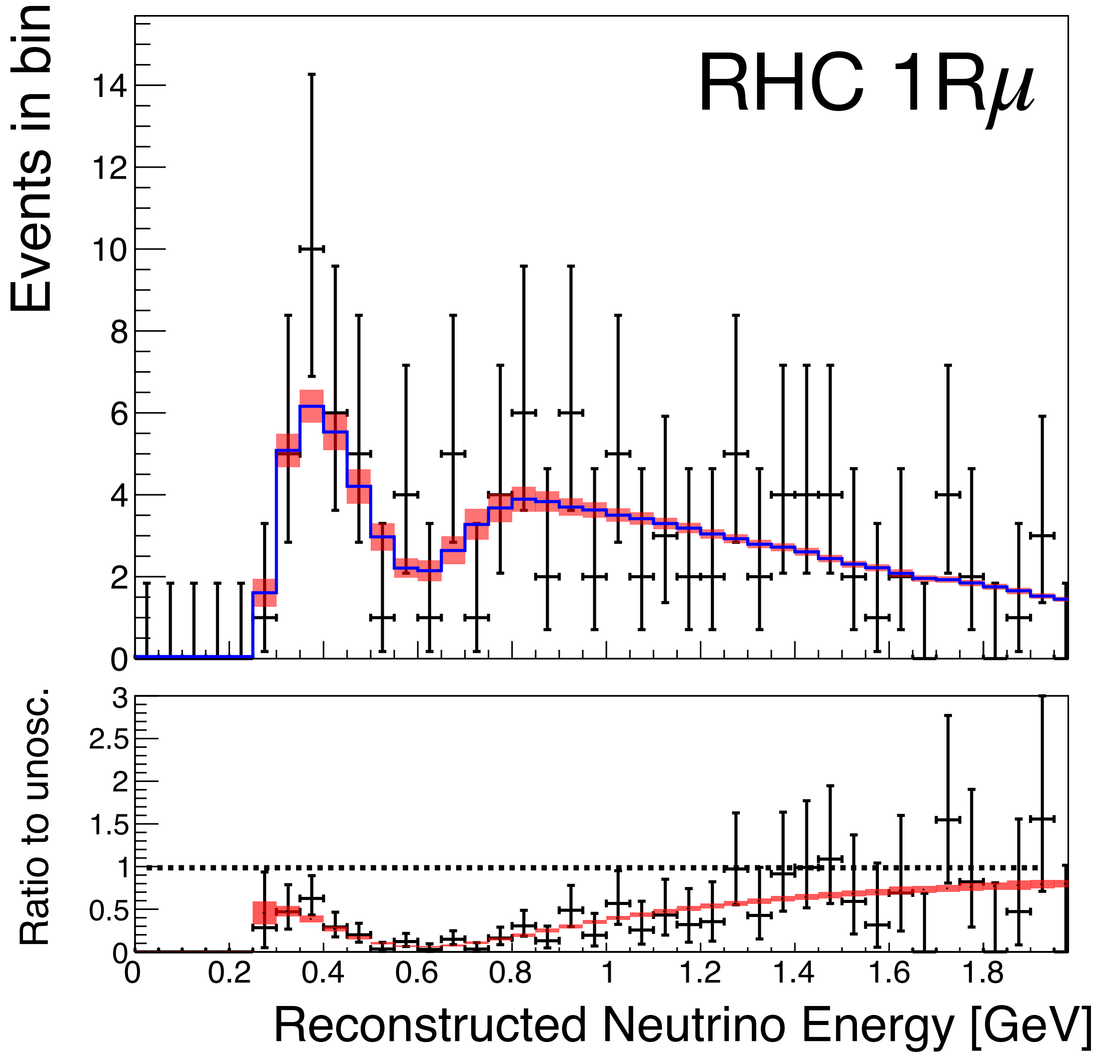
Super-Kamiokande samples

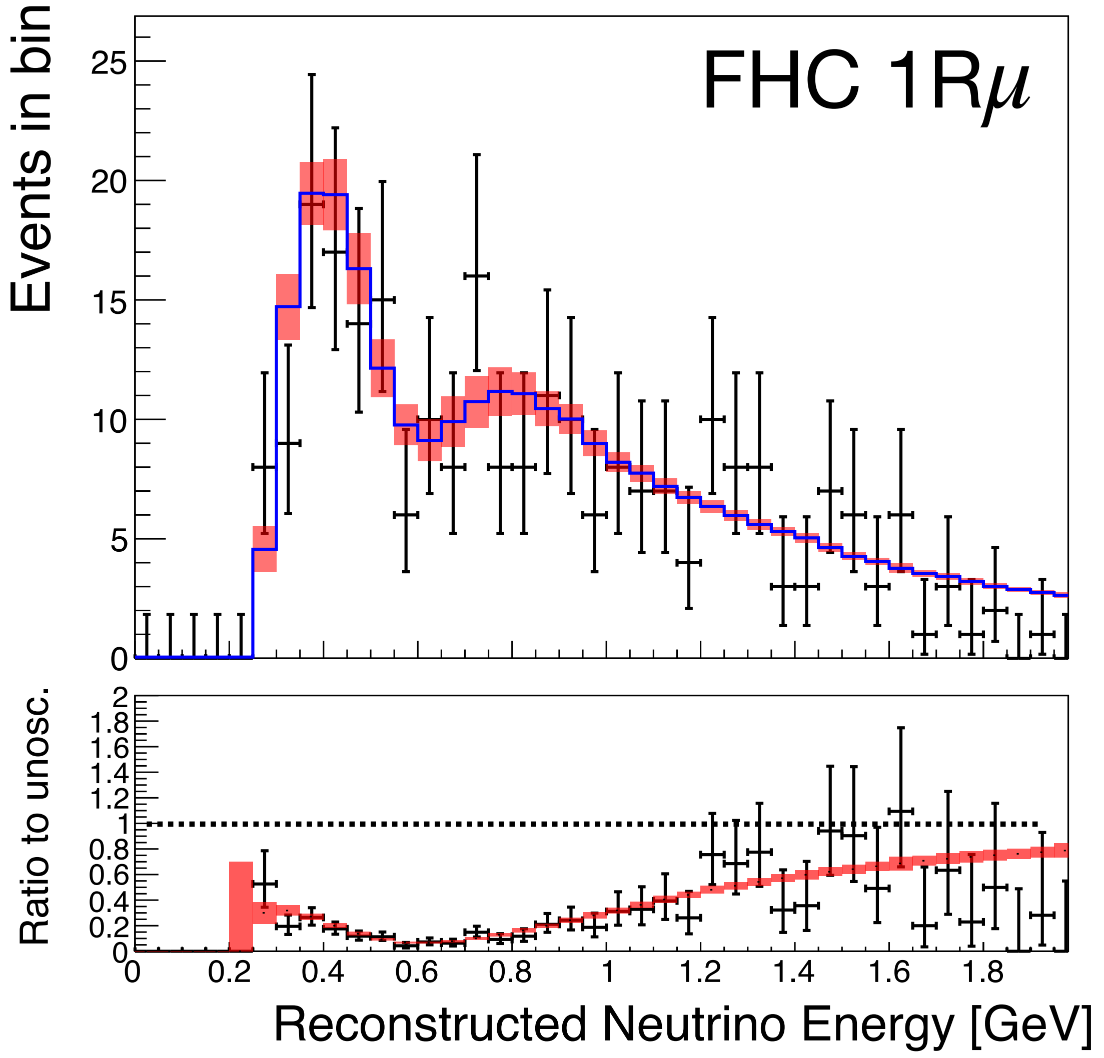
Selection based on ring counting and shape

- Two samples with 1 μ-like ring (ν mode and anti-ν mode) → ν_μ-CC0π
- Two samples with 1 e-like ring (ν mode and anti-ν mode) → ν_e-CC0π
- One sample with 1 e-like ring + 1 Michel electron ring → ν_e-CC1π

Sample	ν-mode 1Rμ	$\bar{\nu}$-mode 1Rμ	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

Disappearance results

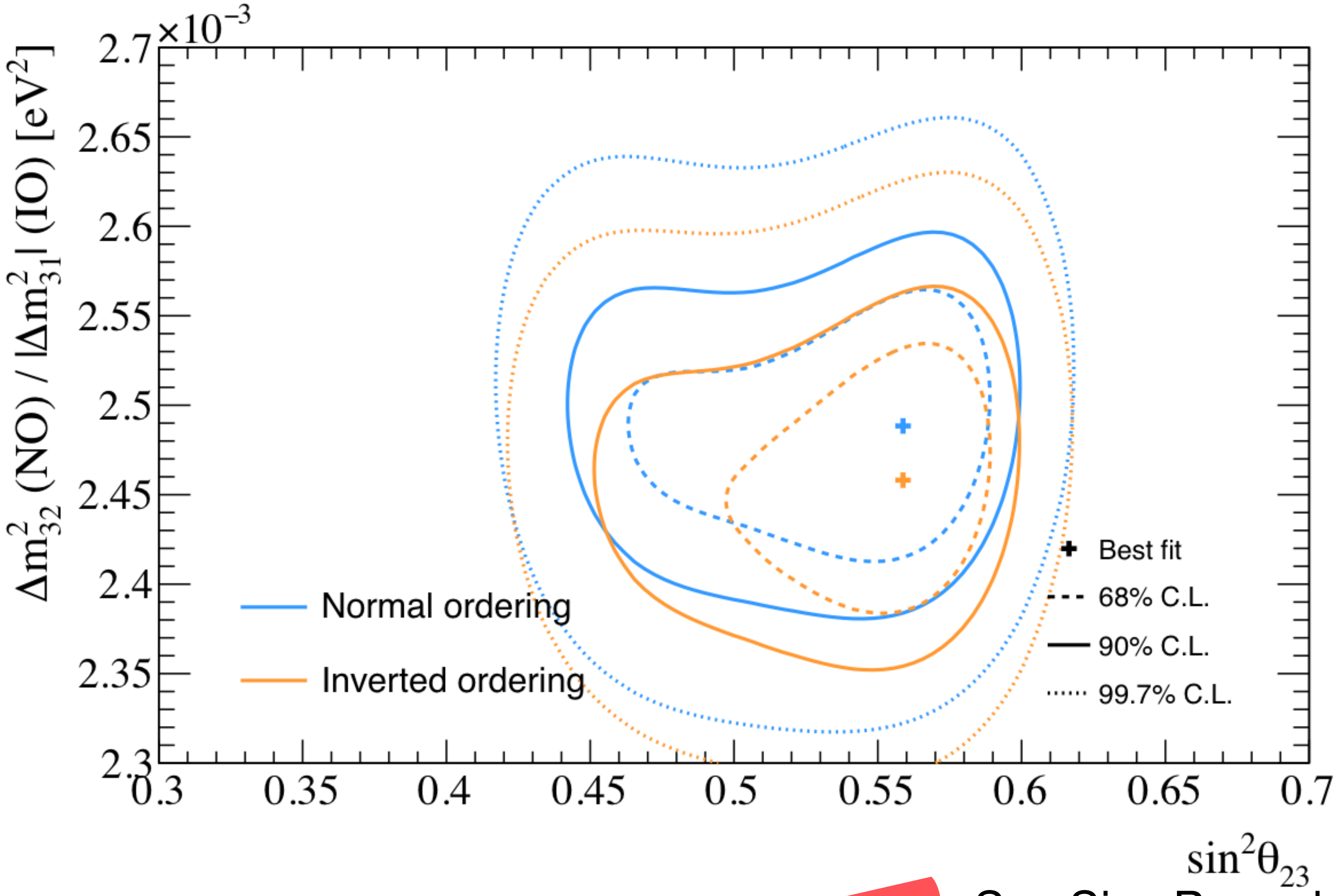




Analysis using five SK Run 1-10 samples

Upper octant preference (77.1% prob) from ν_e samples

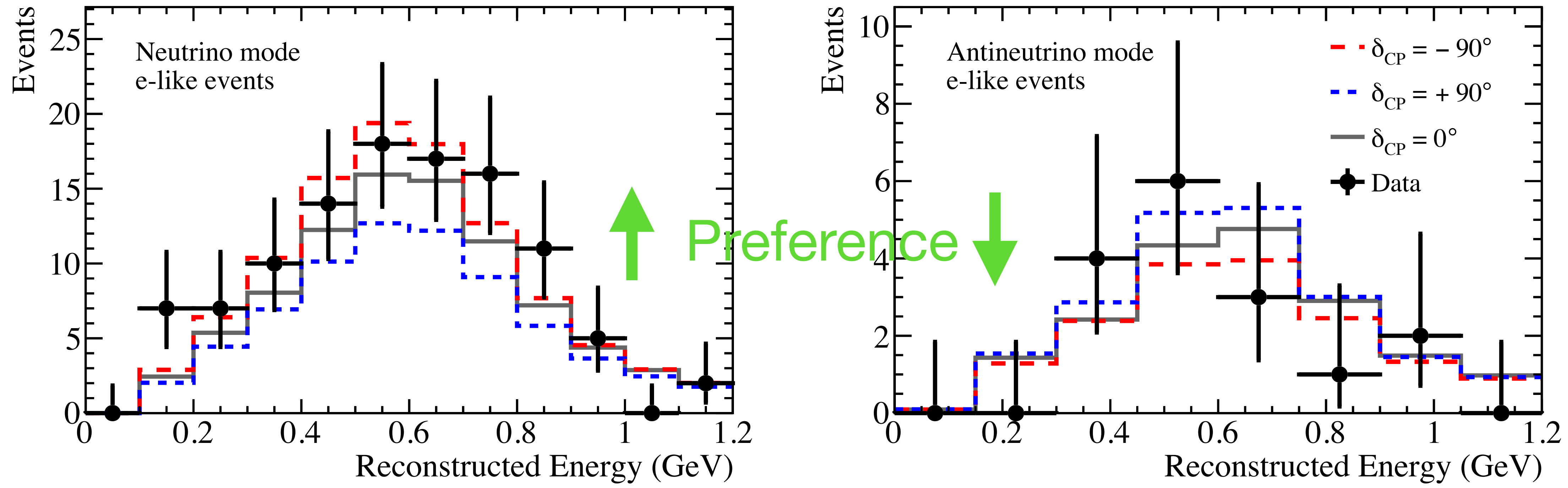
Normal hierarchy preferred at 80.8%

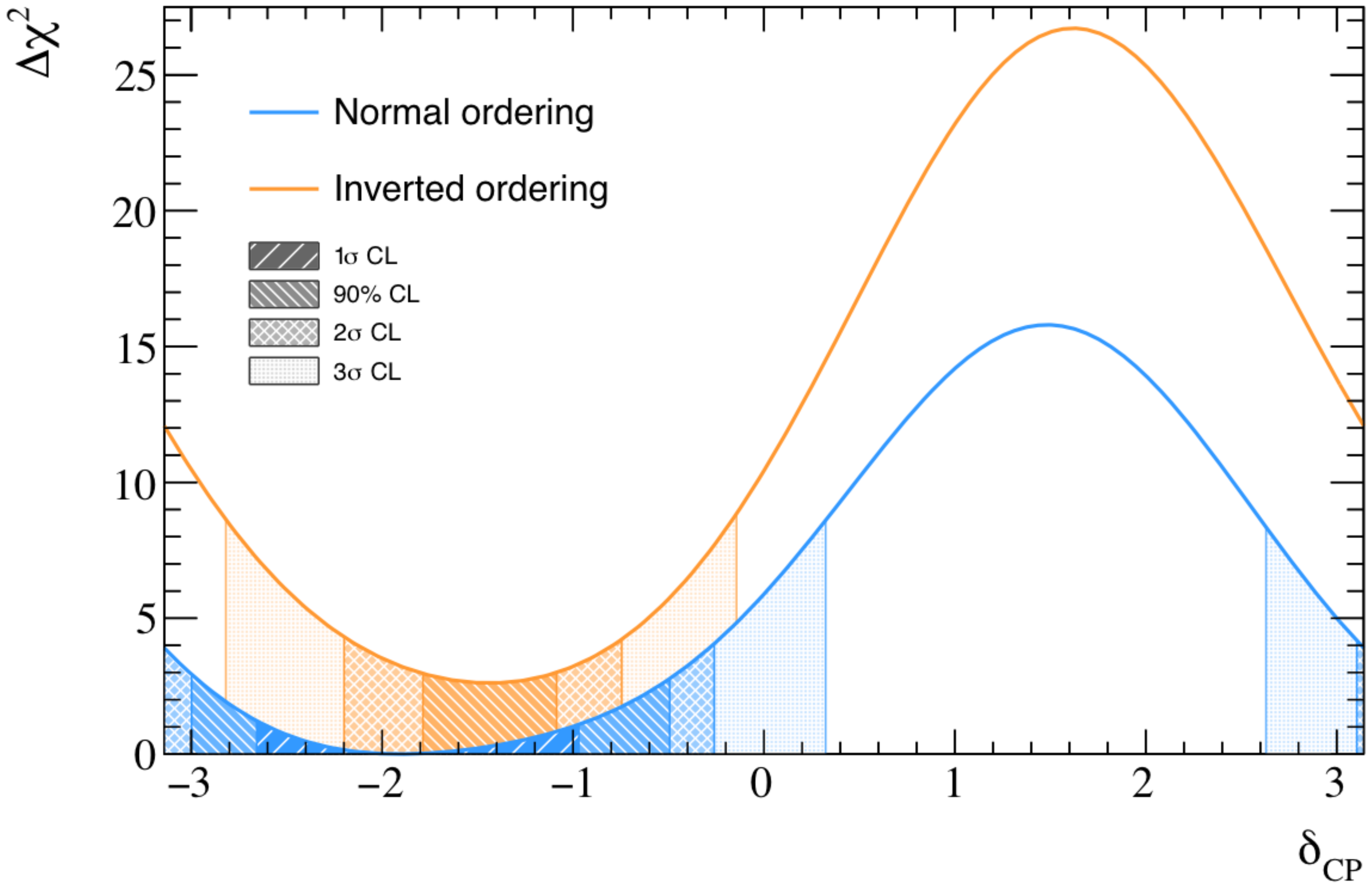


See Siva Prasad Kasetti's parallel talk

Run 1-9 analysis → PRD 103 (1), L011101

Appearance results



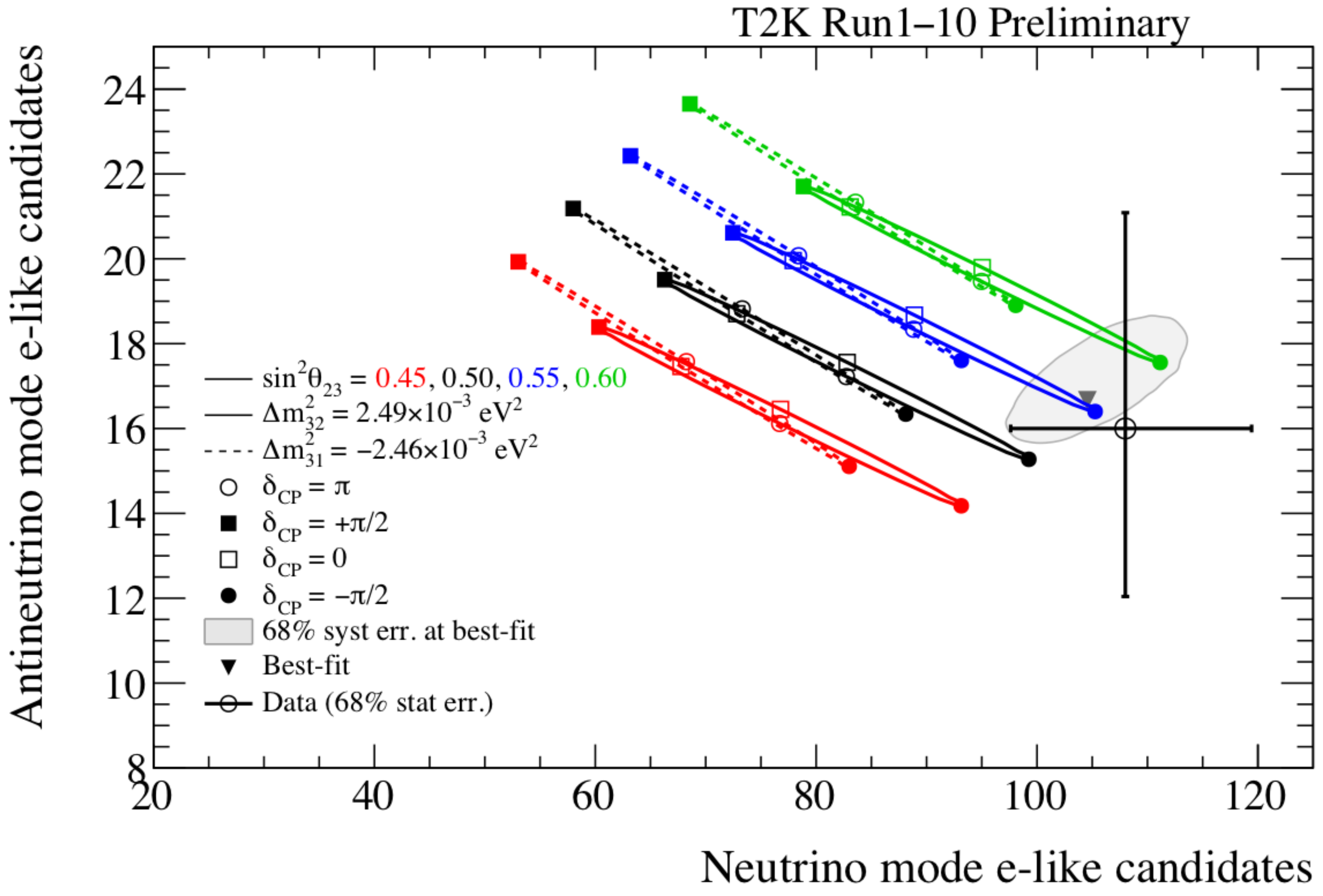


35% of values excluded at 3σ marginalized across hierarchies

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

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)

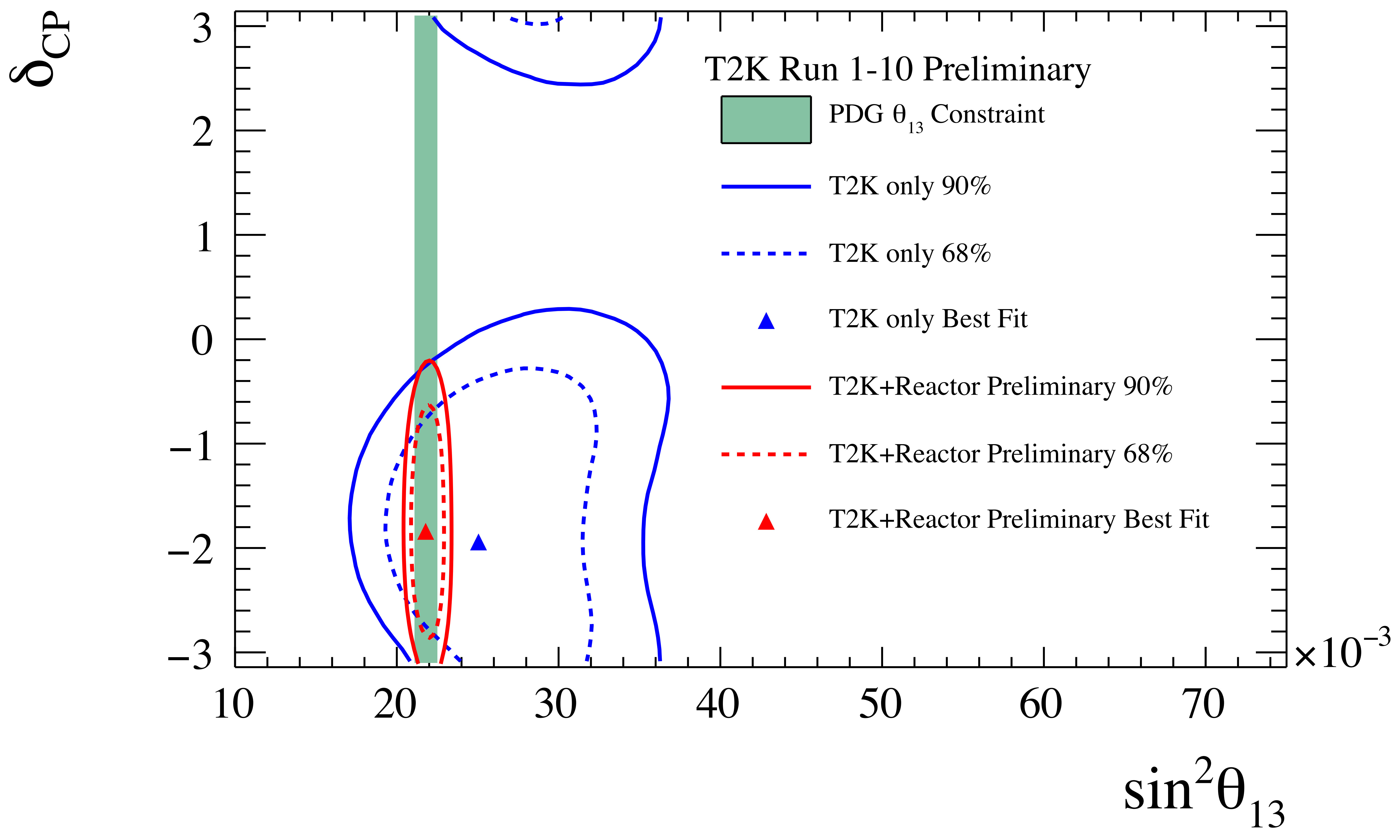


See Joe Walsh's parallel talk

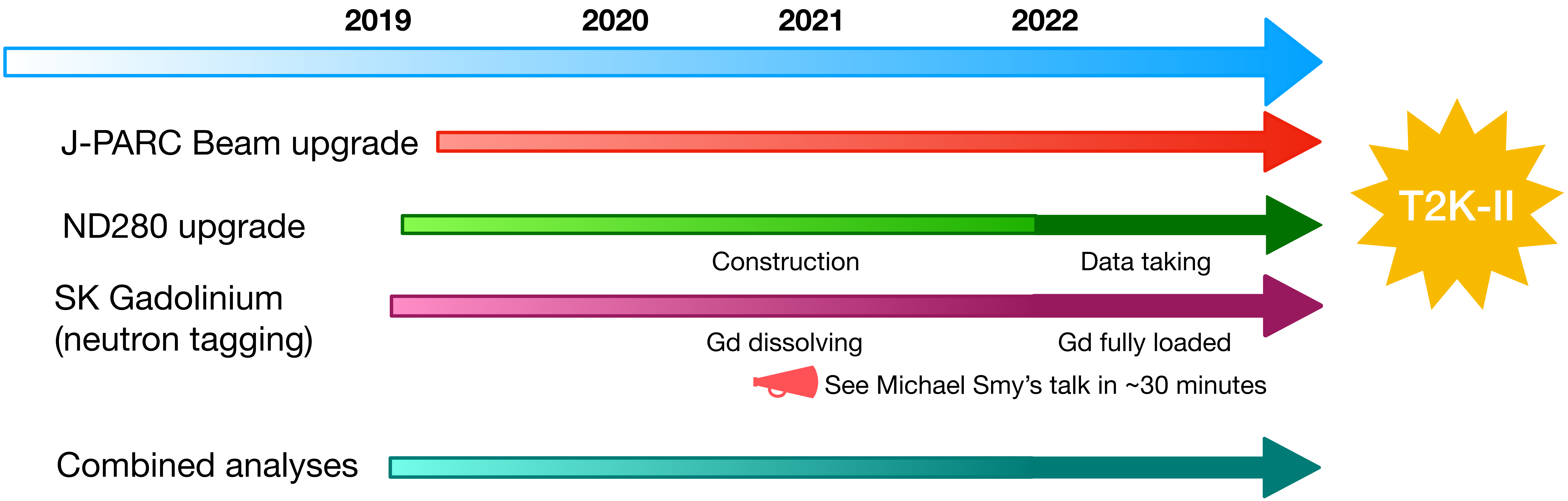
Reactor constraints impact on δ_{CP} vs θ_{13}

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 NOνA beam data

  → systematic uncertainties and longer baseline: more sensitive to mass ordering

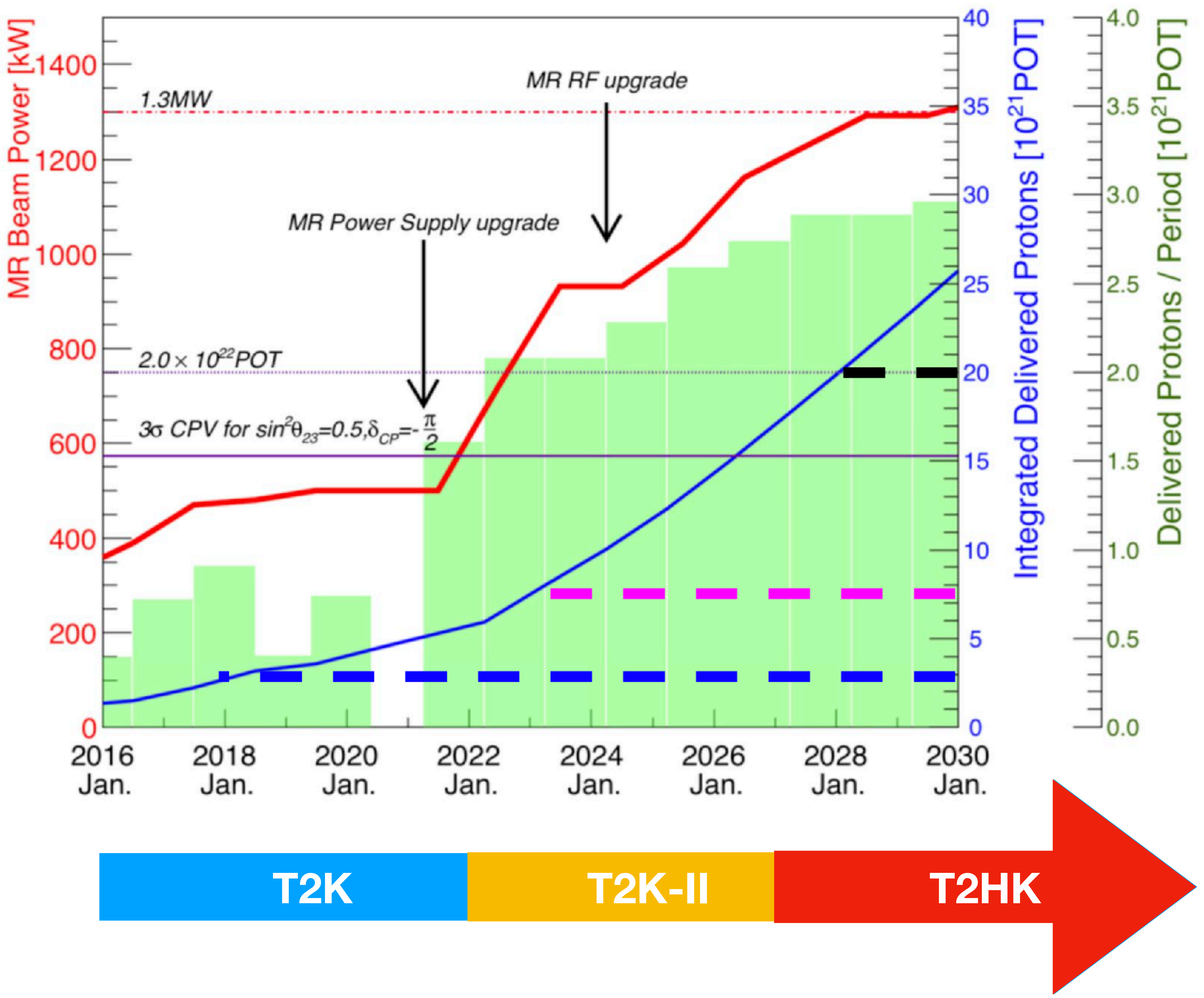
J-PARC beam upgrade

J-PARC main ring upgrades on-going

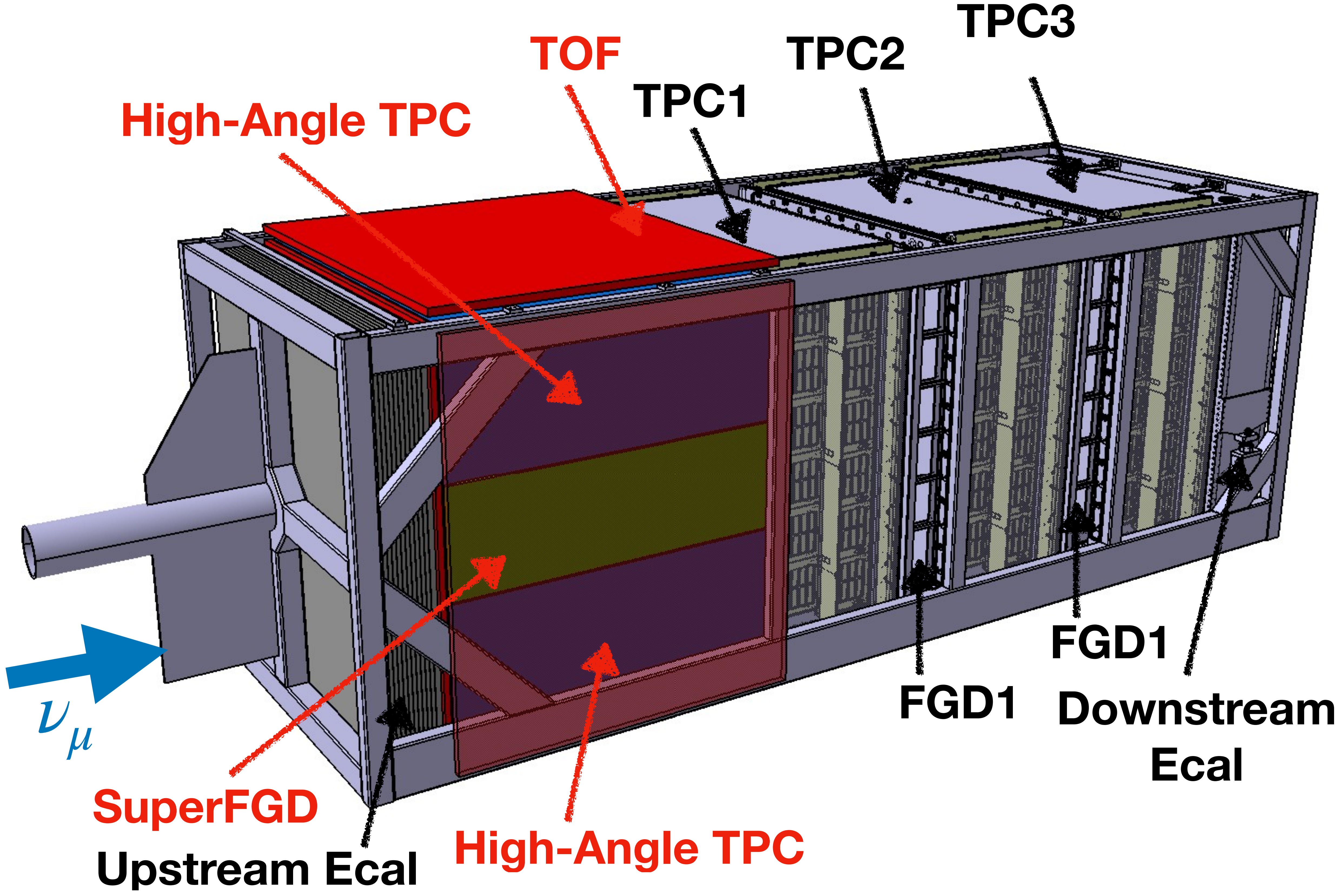
- 2x more pulse per second
(One pulse every 1.3 seconds)

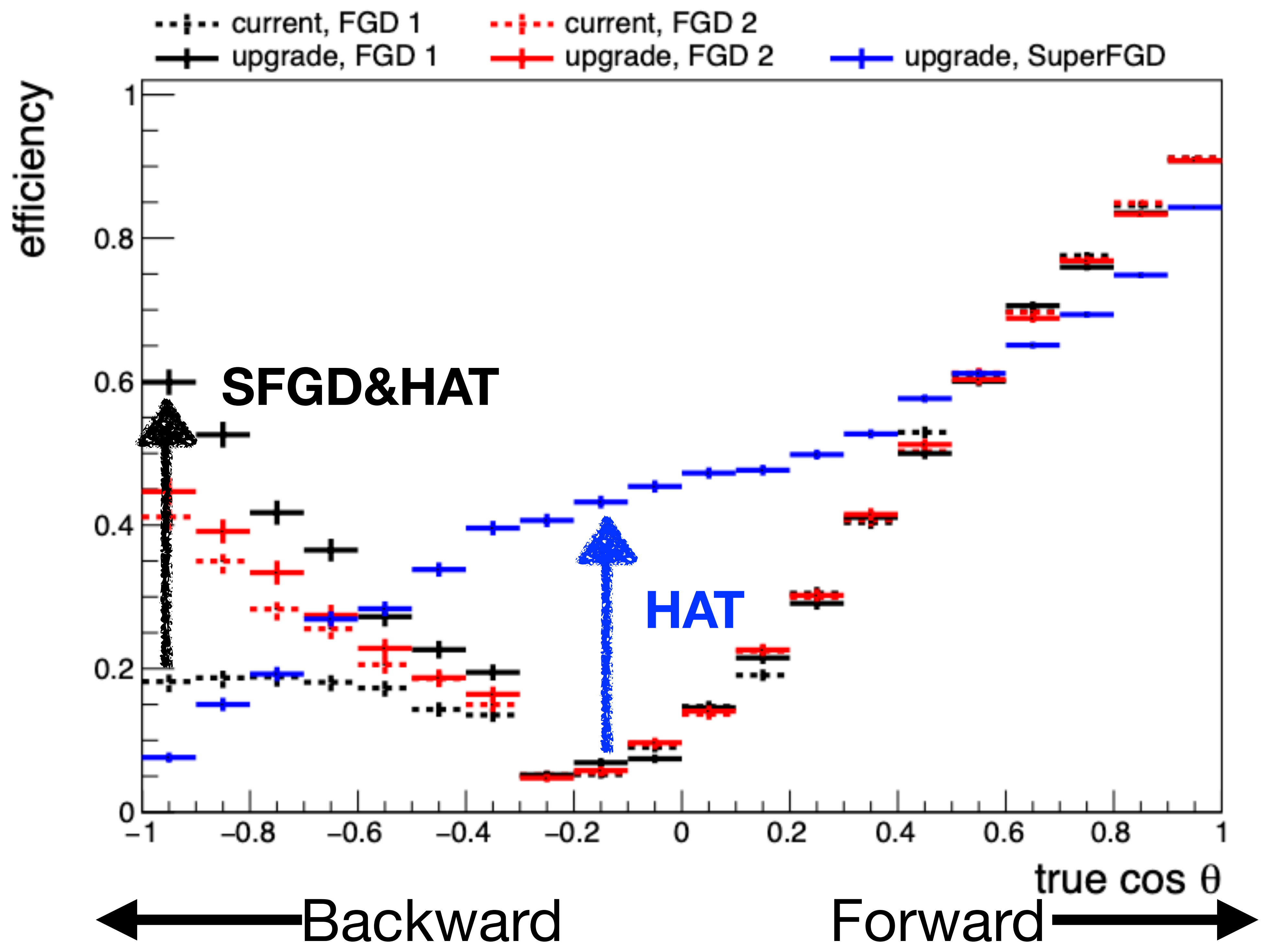
- Increase power from 515 kW
to up to 1.3 MW

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



ND280 Upgraded detector

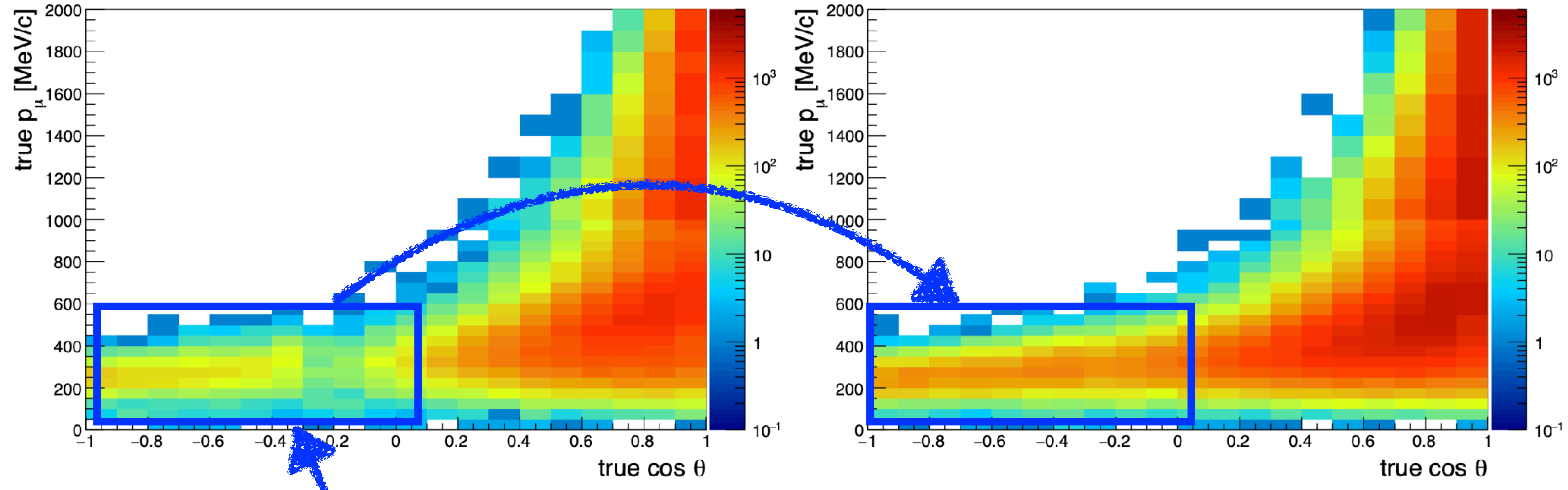




SuperFGD (SFGD) $2 \cdot 10^6$ 1-cm³ scintillator cubes
High-Angle TPCs (HATs) with Resistive MicroMegas
Time-Of-Flight detector (TOF)

- Increased target mass
- Improved reconstruction at high and backward angles
- Better vertex reconstruction
- Outgoing proton/neutron reconstruction
- Installation at J-PARC in 2022

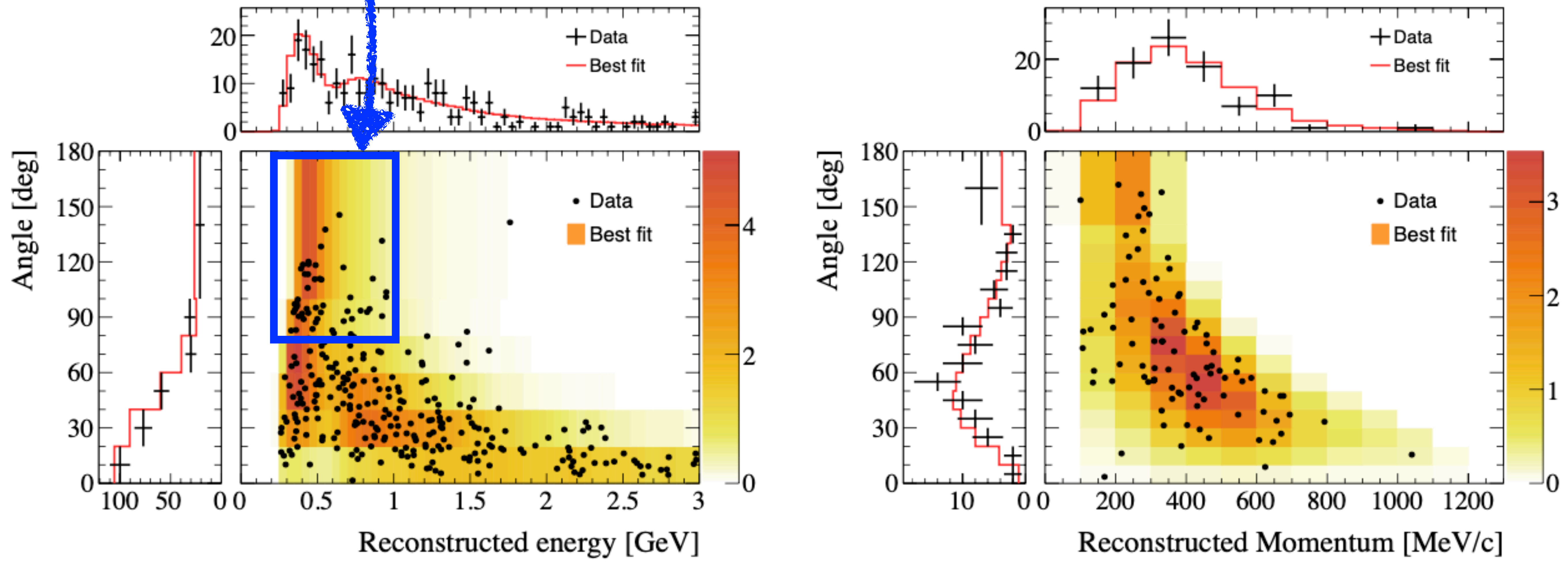
Impact on T2K physics



(a) Current ND280 **ND280 selection** (b) Upgraded ND280

ND280 Upgrade TDR arXiv:1901.03750

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



(a) FHC 1Rμ **SK selection for OA** (b) FHC 1Re **TN397**

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

x2

ND280 Upgrade TDR arXiv:1901.03750 @10^{21} POT

See César Jesùs-Valls' parallel talk

Summary and prospects

Parallel session T2K talks

- Probing nuclear effects in neutrino CC1π^+ interactions with transverse kinematic imbalance measurement in T2K

  Ka Ming Tsui → Fri 19 10:20am
- Future neutrino physics using the upgraded ND280 detector of the T2K experiment

  César Jesús-Valls → Wed 24 11:00 am
- T2K latest oscillation analysis results and methodology

  Joe Walsh → Wed 24 5:50 pm
- T2K latest results on muon neutrino and antineutrino disappearance

  Siva Prasad Kasetti → Wed 24 6:10 pm
- 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!