Near Detectors for precision measurements of neutrino oscillation parameters with T2K and Hyper-K

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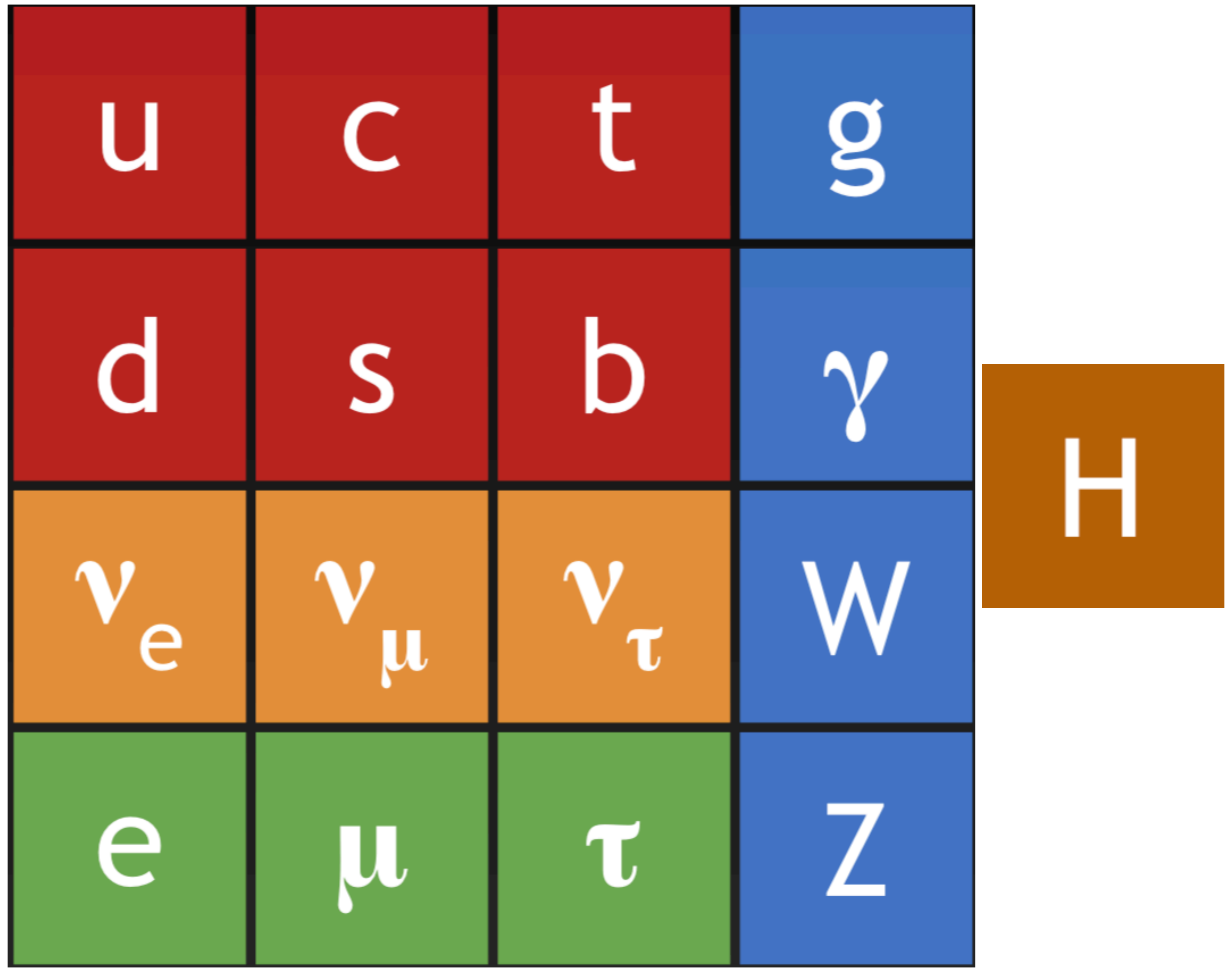
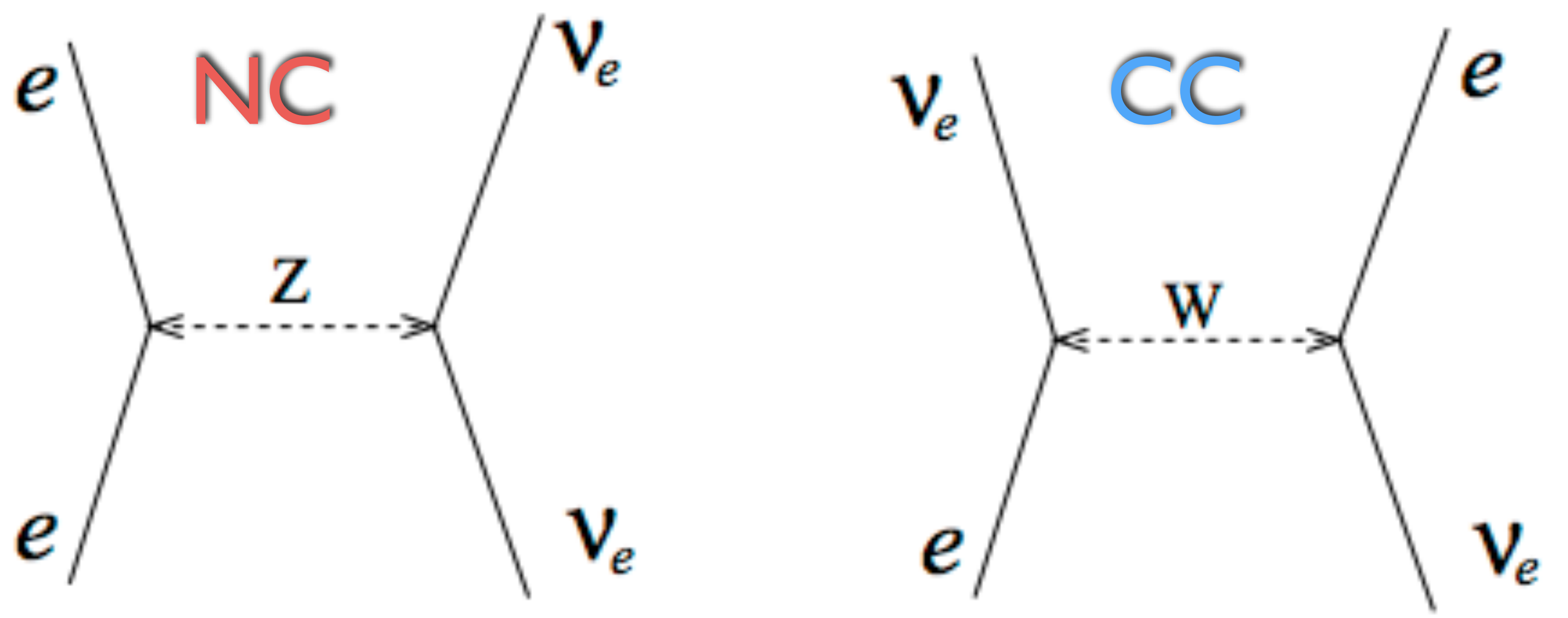
IPHC seminar - 21/03/2024

Neutrinos in the SM



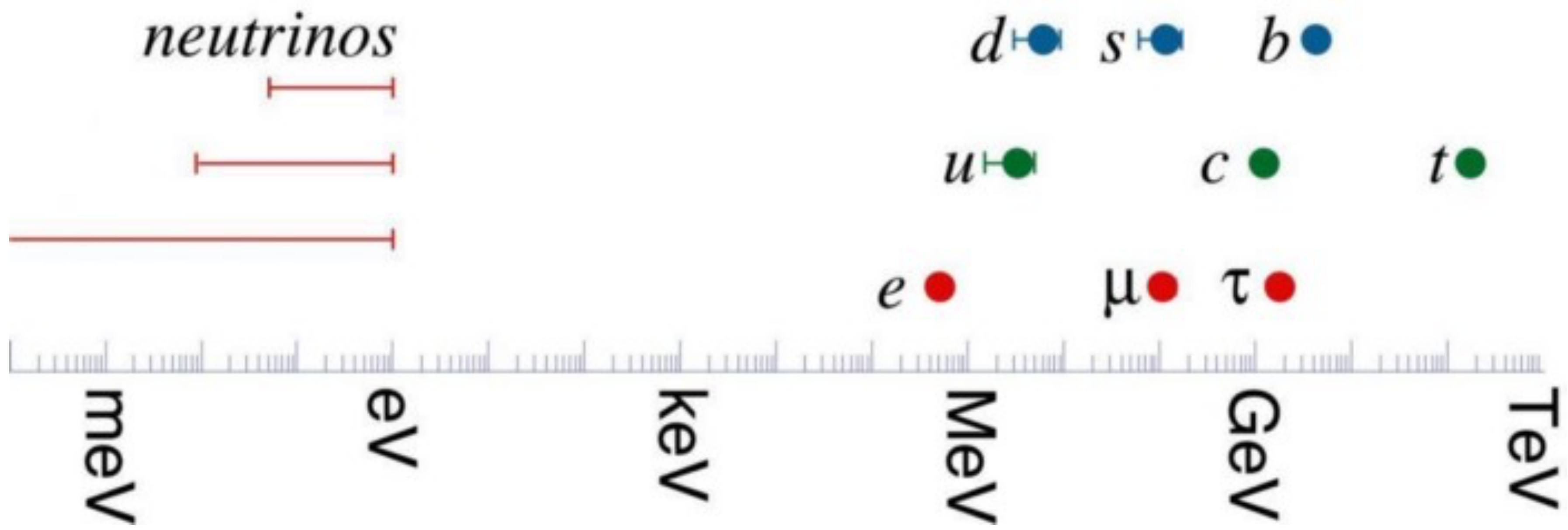
u	c	t	g	
d	s	b	γ	H
ν_e	ν_μ	ν_τ	W	
e	μ	τ	Z	

Neutrinos are standard model particles → neutral cousin of the electron and of the other charged leptons



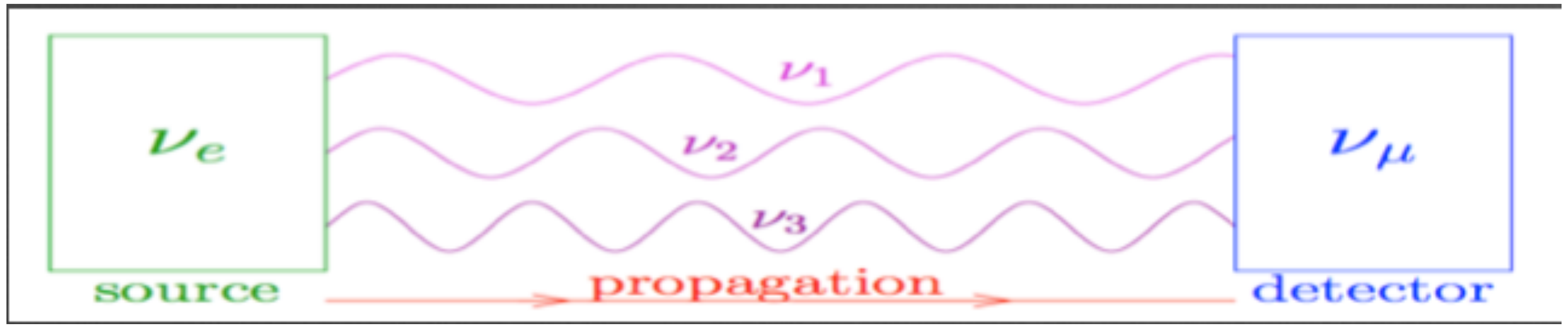
They interact only through weak interactions → Neutral current or Charged current

In the Standard Model neutrinos are massless particles



Neutrino oscillations

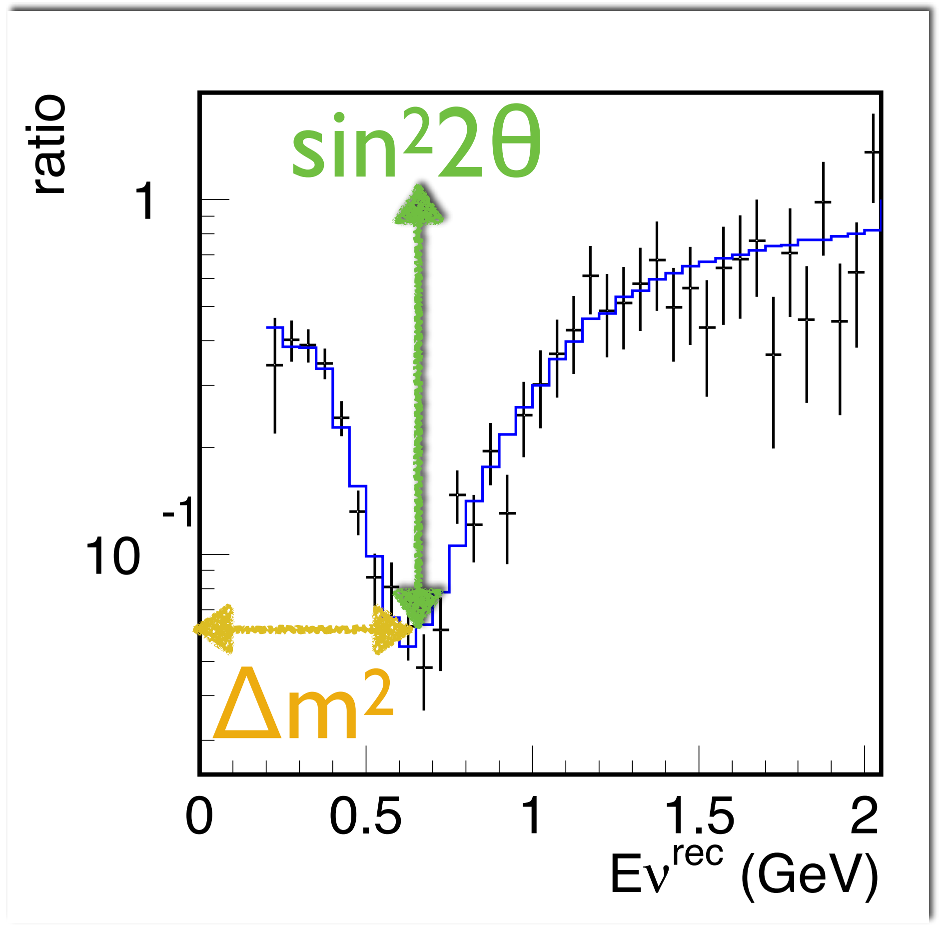
- First introduced by Bruno Pontecorvo in 1957
- Neutrinos are produced in flavor eigenstates (ν_μ, ν_e, ν_τ) that are linear combination of mass eigenstates (ν_1, ν_2, ν_3)
- Neutrino propagate as mass eigenstates
- At the detection a flavor eigenstate is detected → it can be different from the one that was produced



ν_e produced in a mixture of ν_1, ν_2, ν_3

ν_1, ν_2, ν_3 travel at different speed because they have different masses → interference

Different mixture of ν_1, ν_2, ν_3 → ν_μ is detected

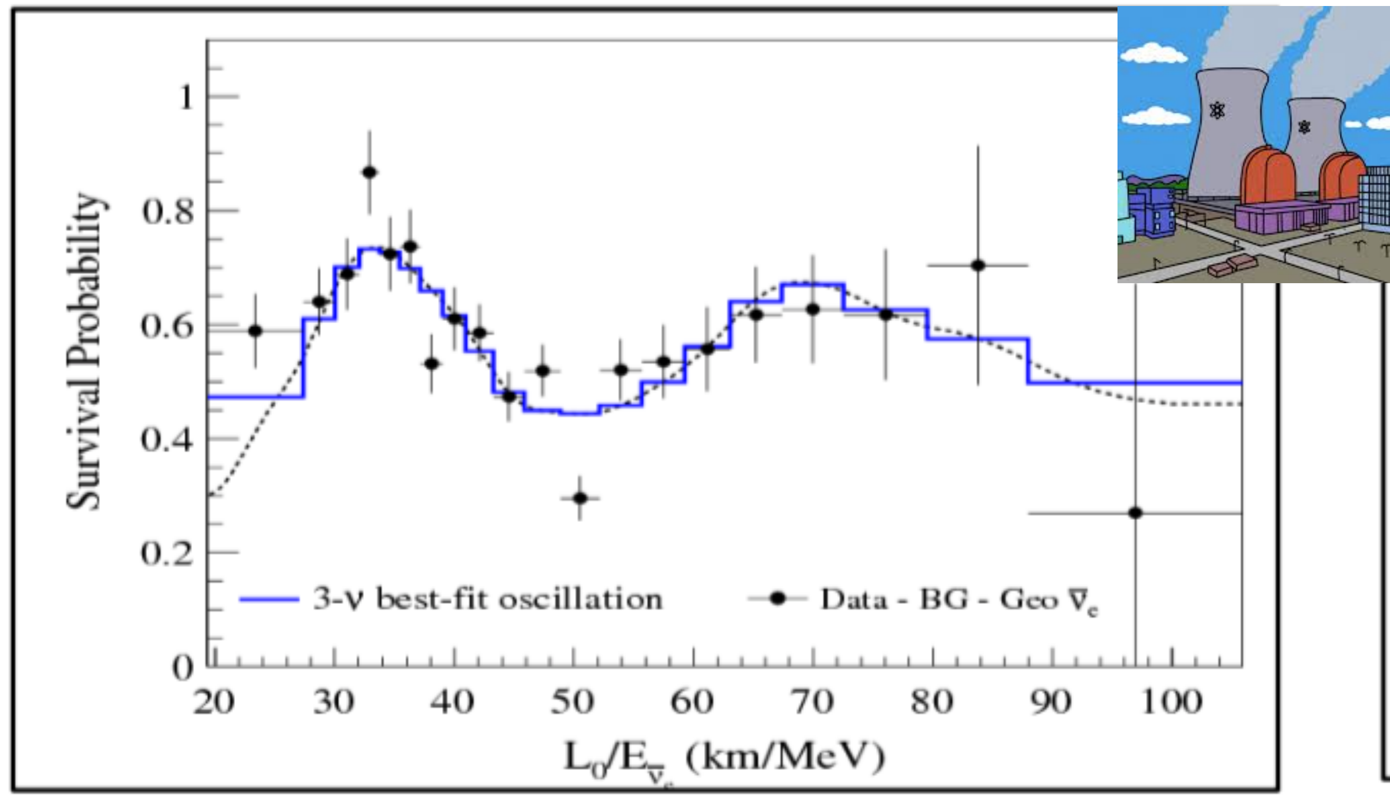


Neutrino oscillation implies massive neutrinos

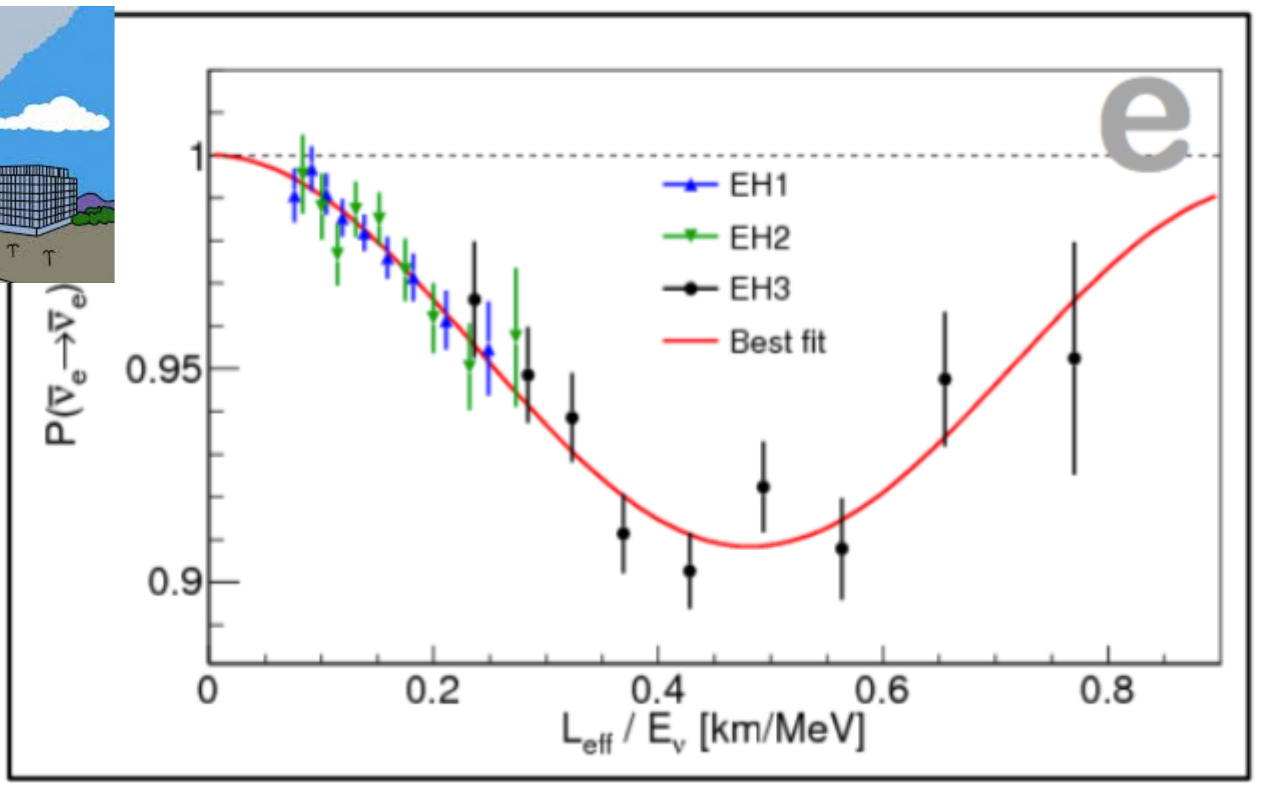
$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2(\Delta m_{12}^2 L/E)$$

Neutrino oscillations

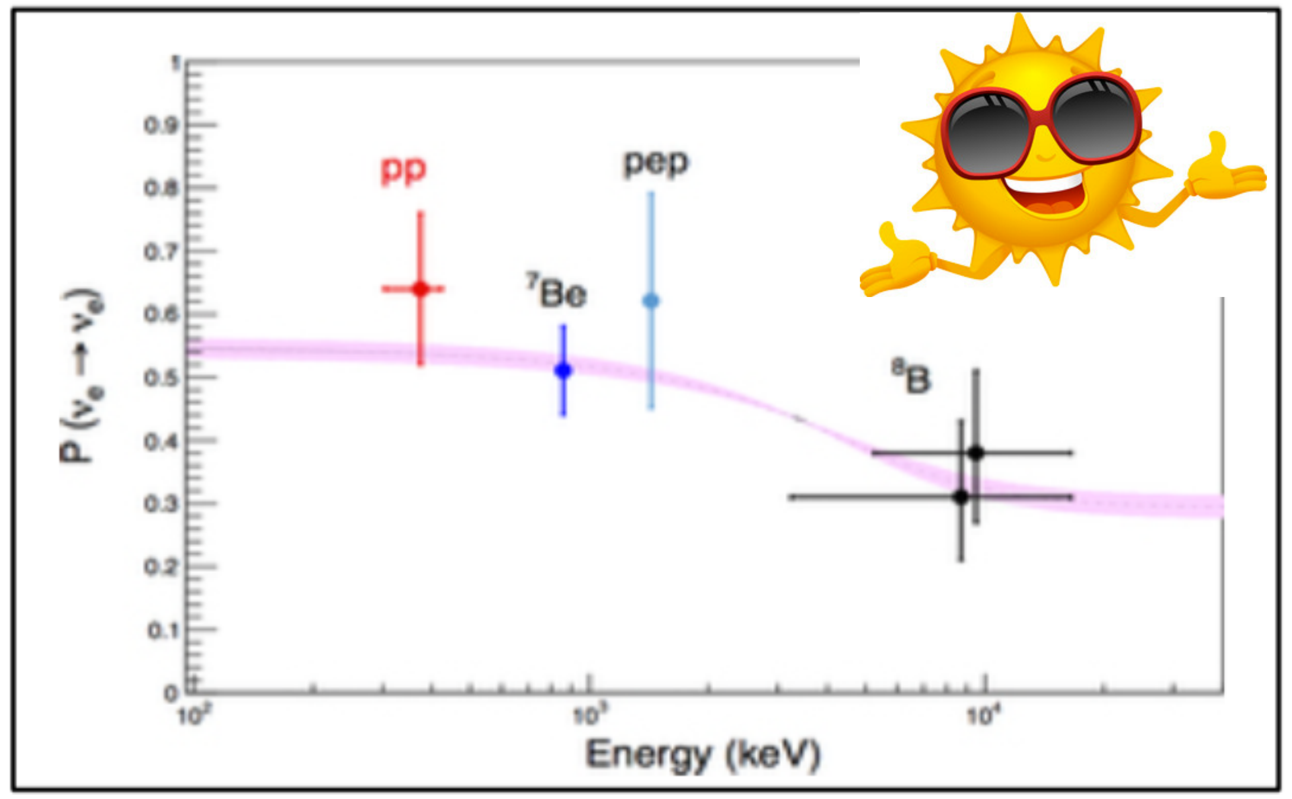
e→e (δm^2 , θ_{12})



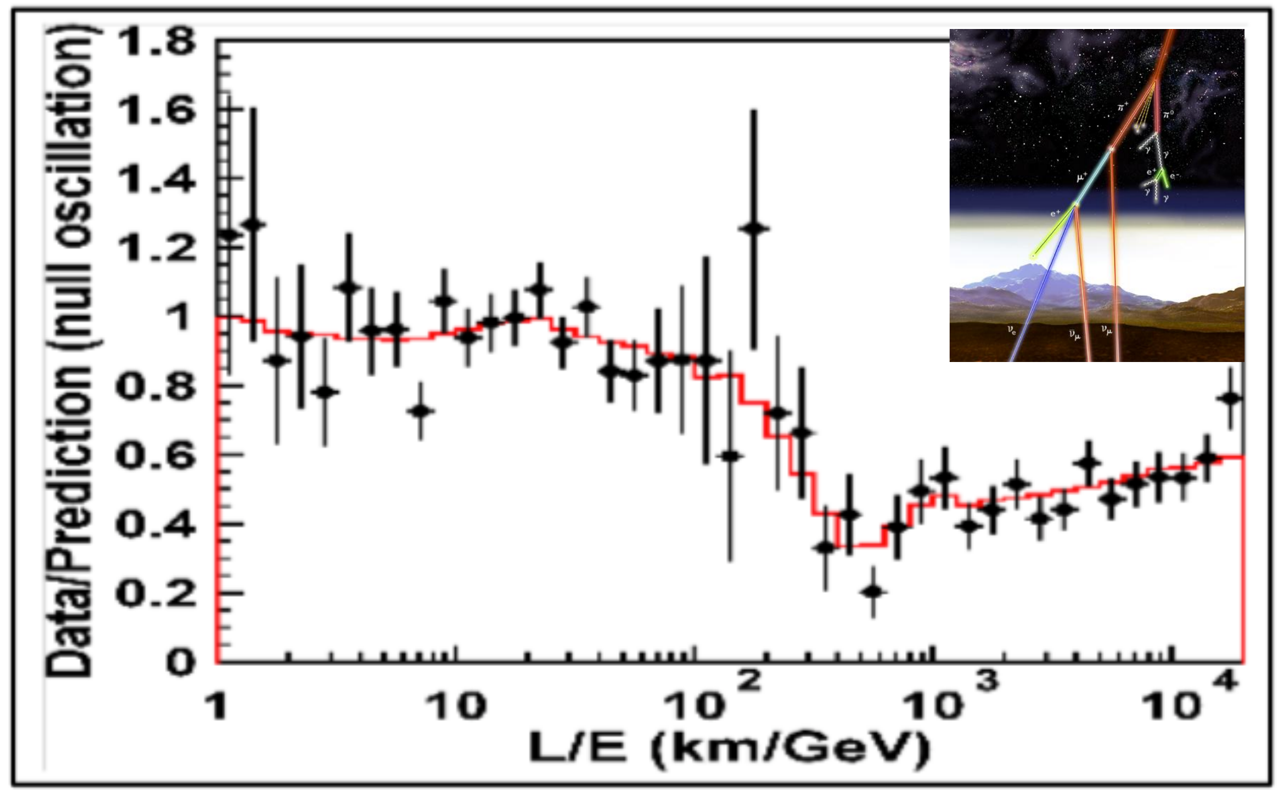
e→e (Δm^2 , θ_{13})



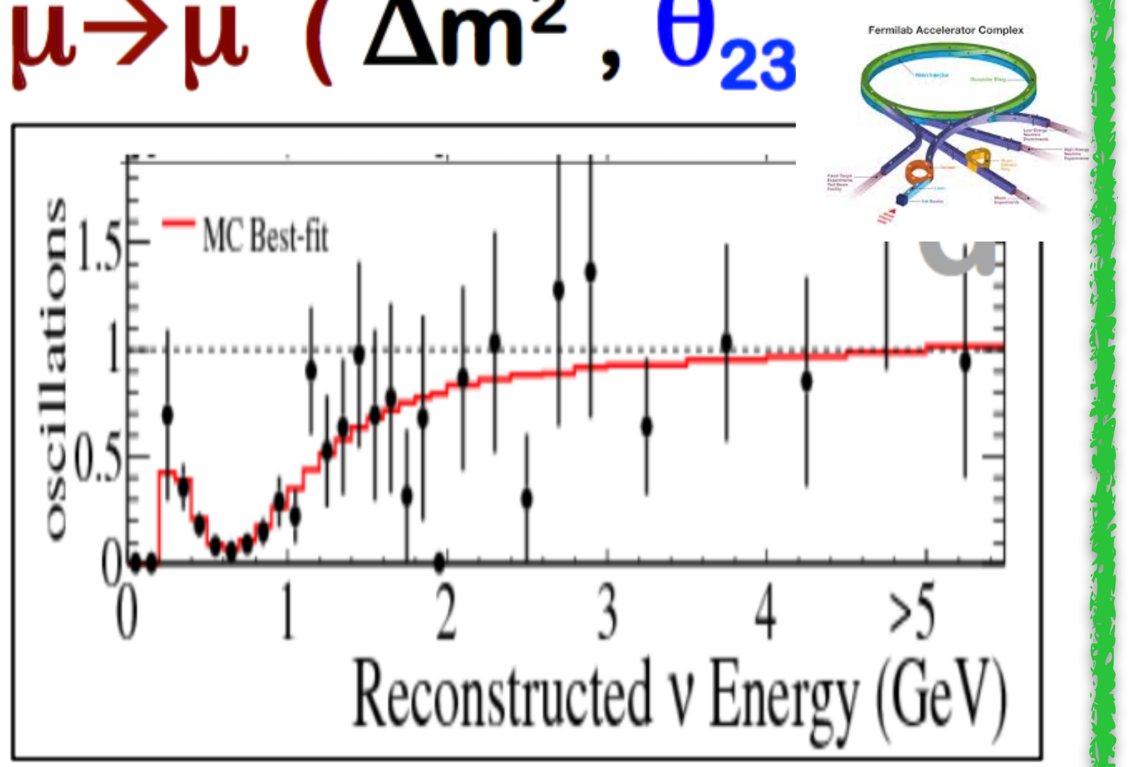
e→e (δm^2 , θ_{12})



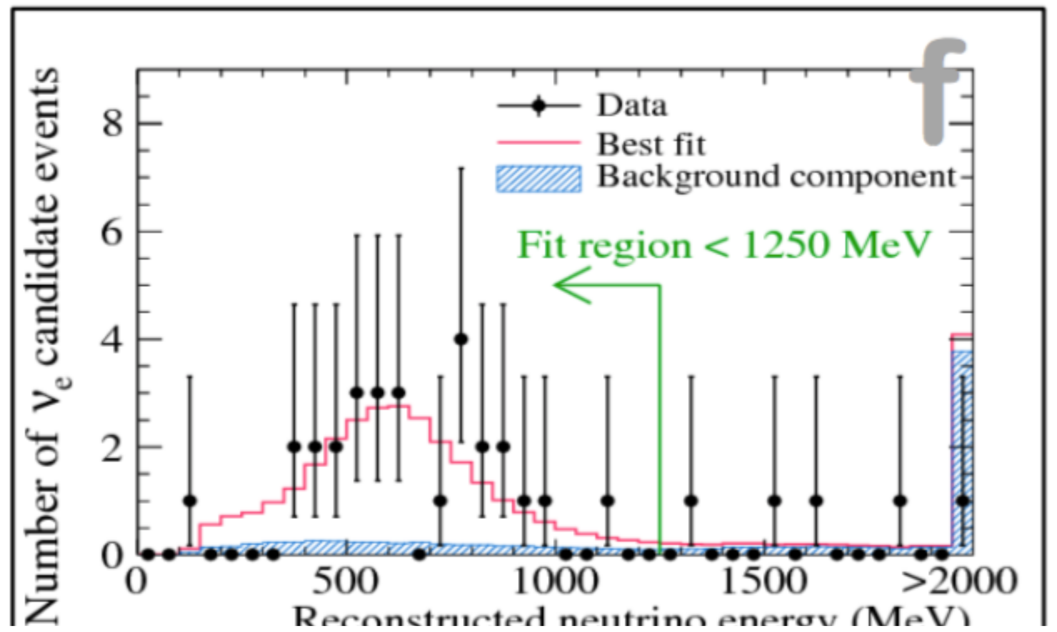
μ→μ (Δm^2 , θ_{23})



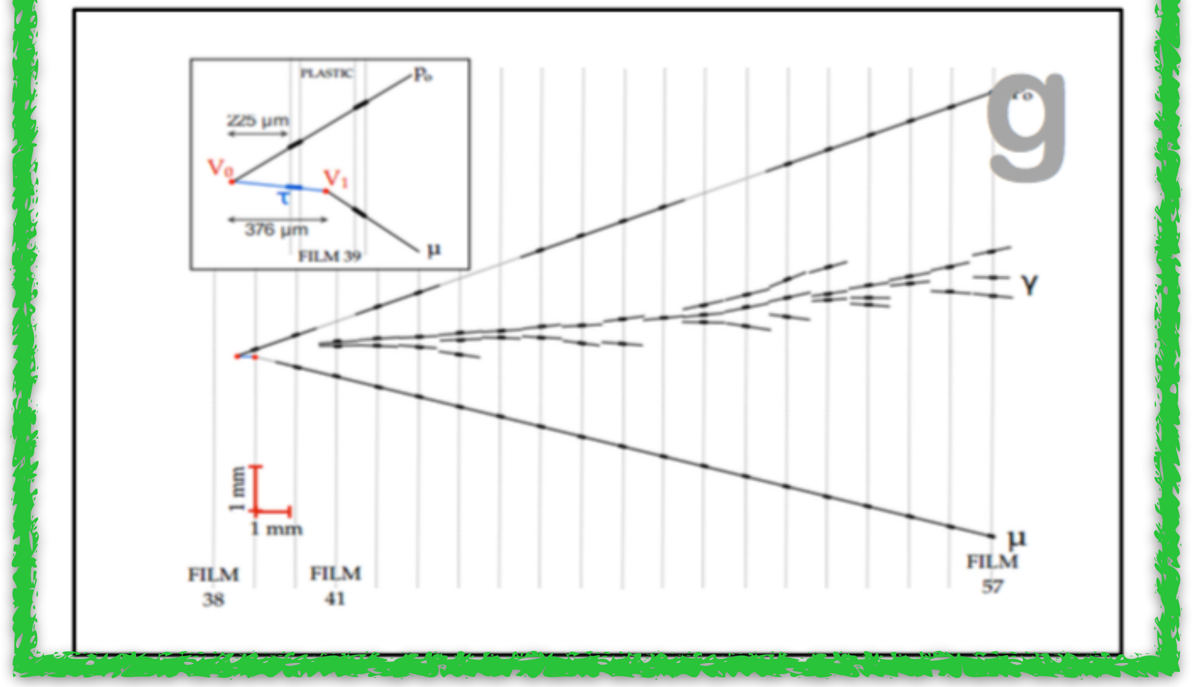
μ→μ (Δm^2 , θ_{23}



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



PMNS matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospherics and LBL
$\theta_{23} \sim 45°$
$|\Delta m^2_{32}| \sim 2.5\text{x}10^{-3}$ eV^2

Reactors
$\theta_{13} \sim 10°$
LBL
θ_{13} and δ_{CP}

Solar and reactors
$\theta_{12} \sim 35°$
$\Delta m^2_{21} \sim 7.5\text{x}10^{-5}$ eV^2

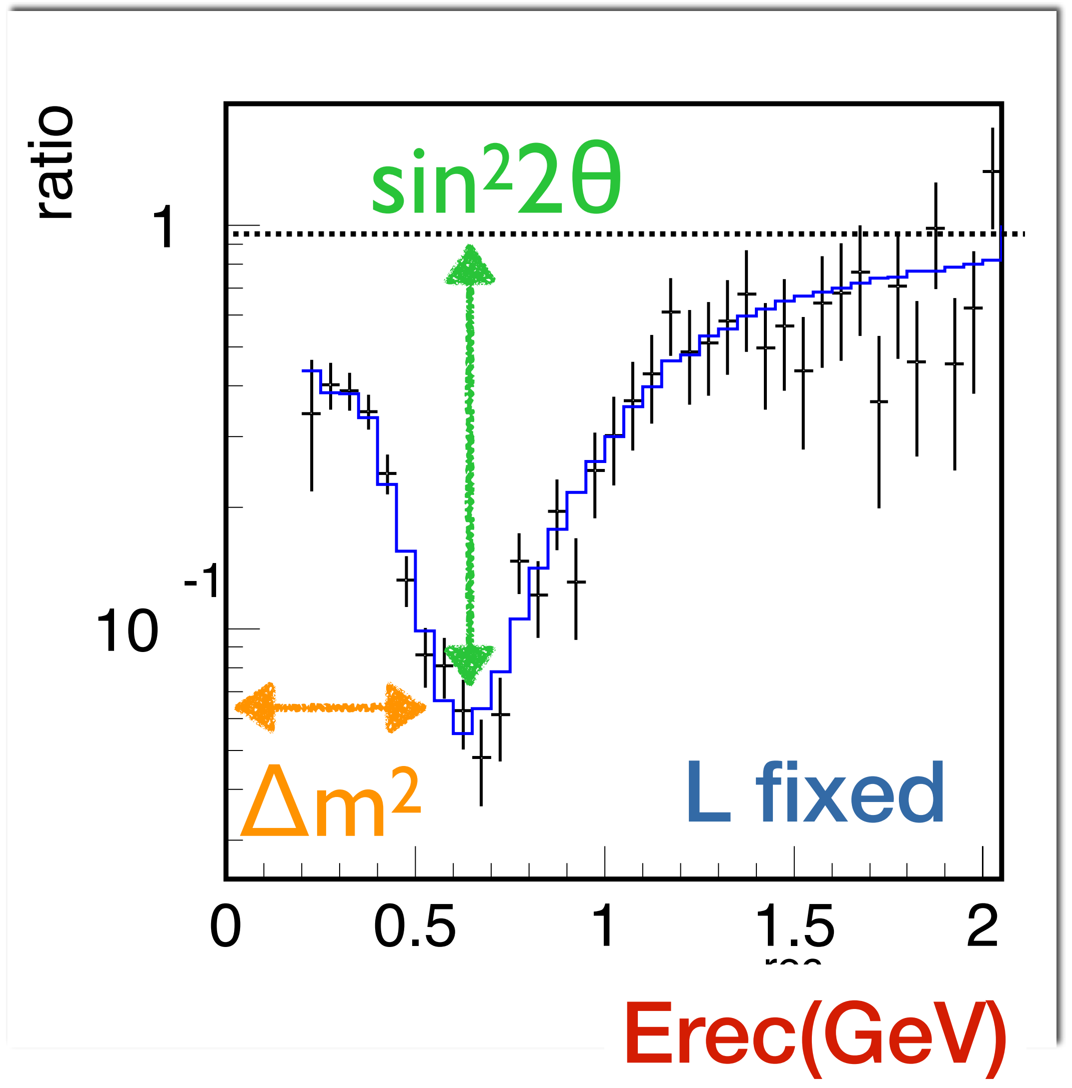
- Long baseline (LBL) experiments sensitive to 5 of the PMNS parameters
  - θ_{23}, $|\Delta m^2_{32}|$ → LBL provides the most precise measurements of these parameters
  - θ_{13} → dominated by reactor experiments
  - δ_{CP} and sign of Δm^2_{32} (normal or inverted ordering) → still unknown and accessible to LBL

Artificial sources of neutrinos

- Oscillations were discovered with solar and and atmospheric neutrinos
- Great sources of neutrinos → they come for free, just need to build a detector
  - Ideal for discoveries (span several ranges of L/E -> Δm^2)
  - Cannot be tuned → not the best sources for precision measurements
- Reactors → reactor spectrum is fixed but the distance can be tuned (KamLAND for θ_{12}, DB/DC/RENO for θ_{13}, Juno for mass ordering)
- Accelerators → can tune energy and distance
  - Well defined L/E → maximize oscillation probability knowing Δm^2
  - Can produce beam of ν_μ and $\bar{\nu}_\mu$

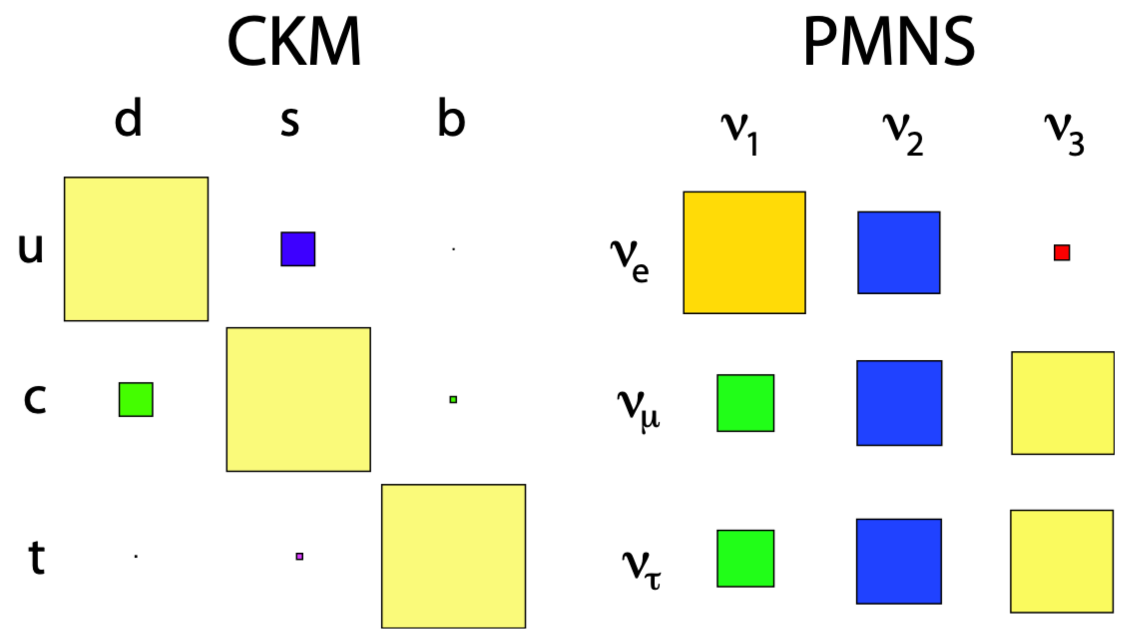
  → 5 oscillation parameters (θ_{23}, θ_{13}, Δm^2_{23}, δ_{CP}, and mass ordering)

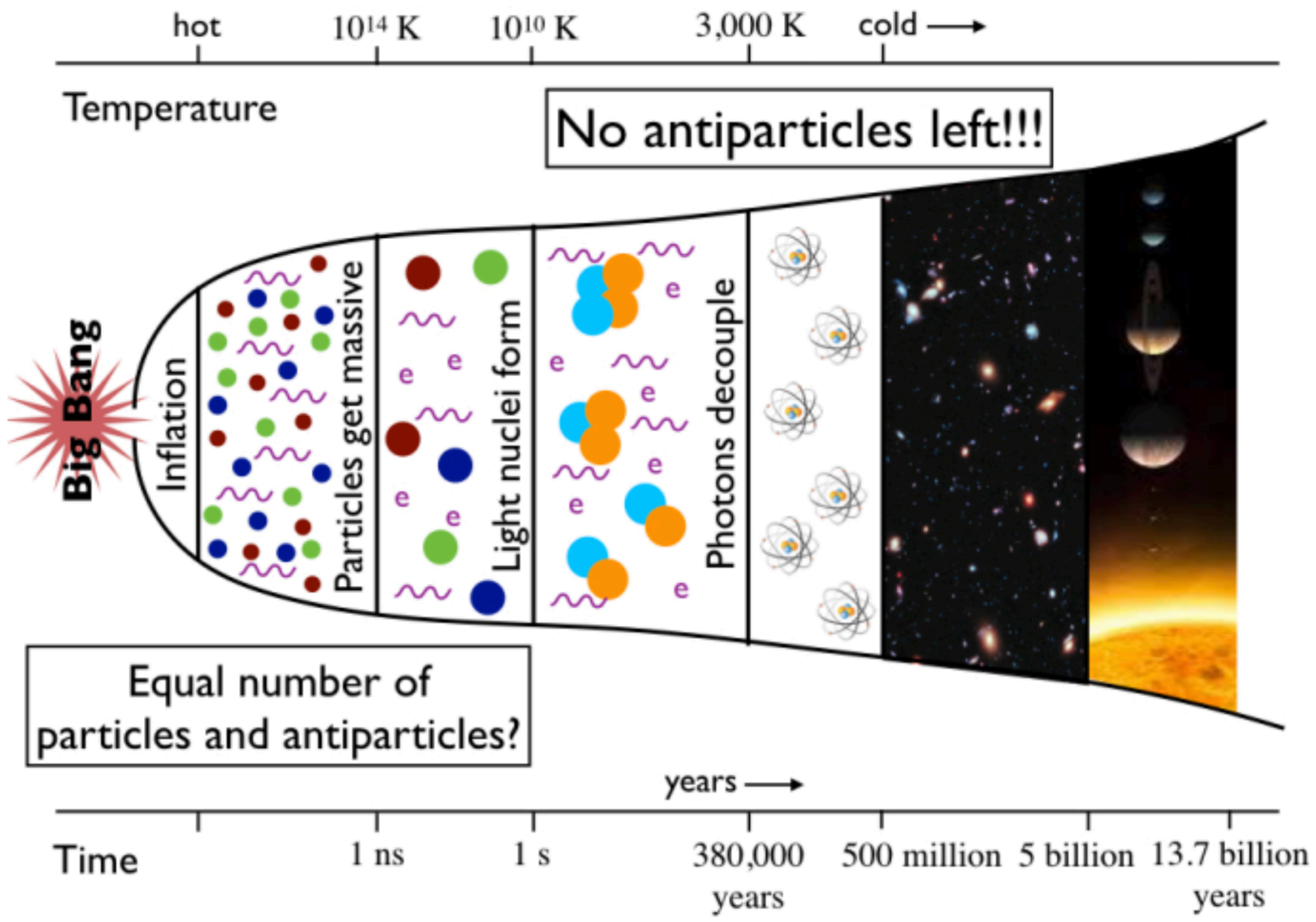
$$P(\nu_\mu \to \nu_\mu) = \sin^2(2\theta)\sin^2(\Delta m^2 L/E)$$

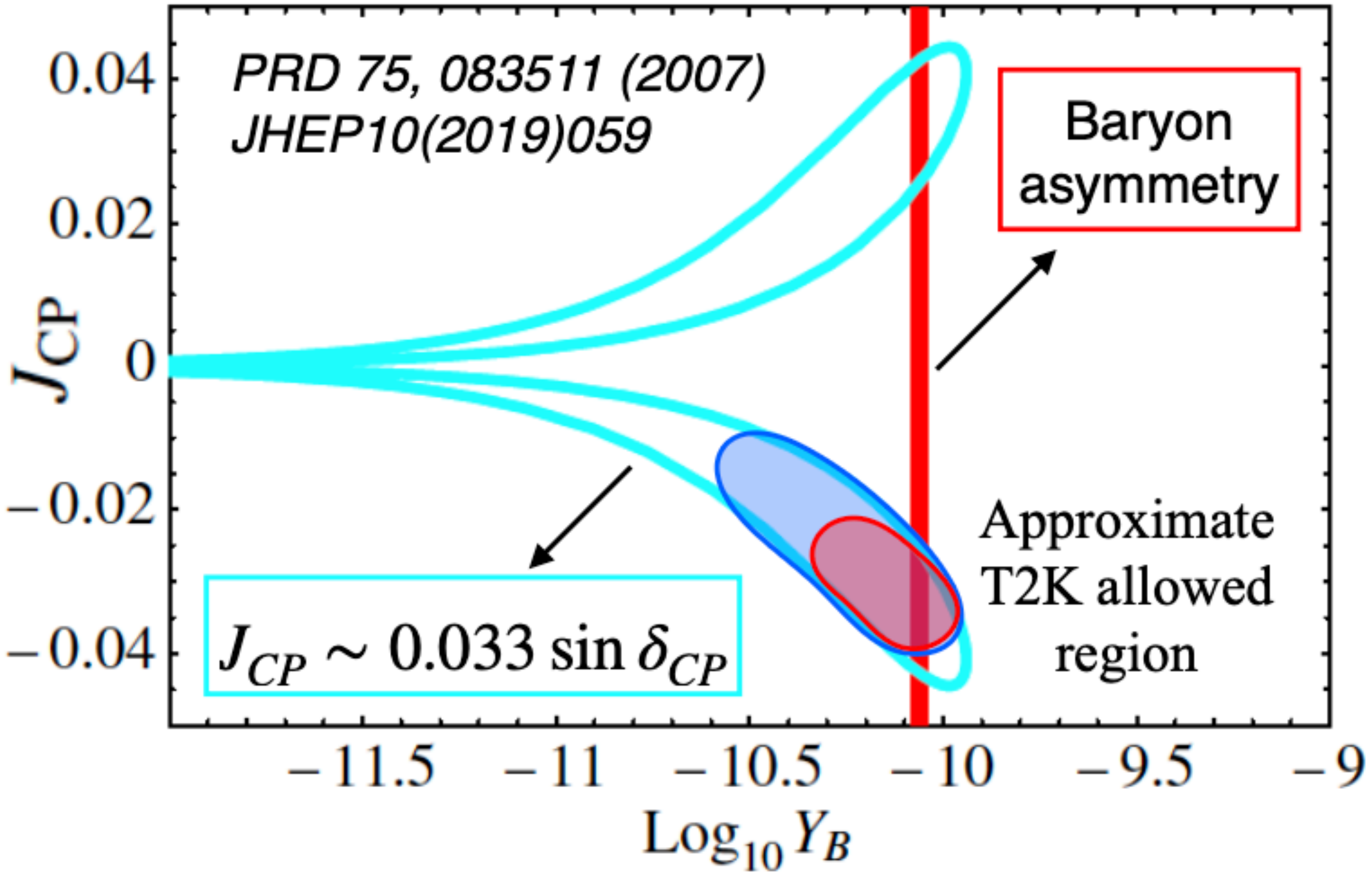


CP violation

- Need to explain the matter-antimatter asymmetry in the Universe
- Which mechanism produced such asymmetry?
- We already observed CP violation in the quark sector but the asymmetry is too small
- Need a different mechanism → CP violation in the leptonic sector → leptogenesis

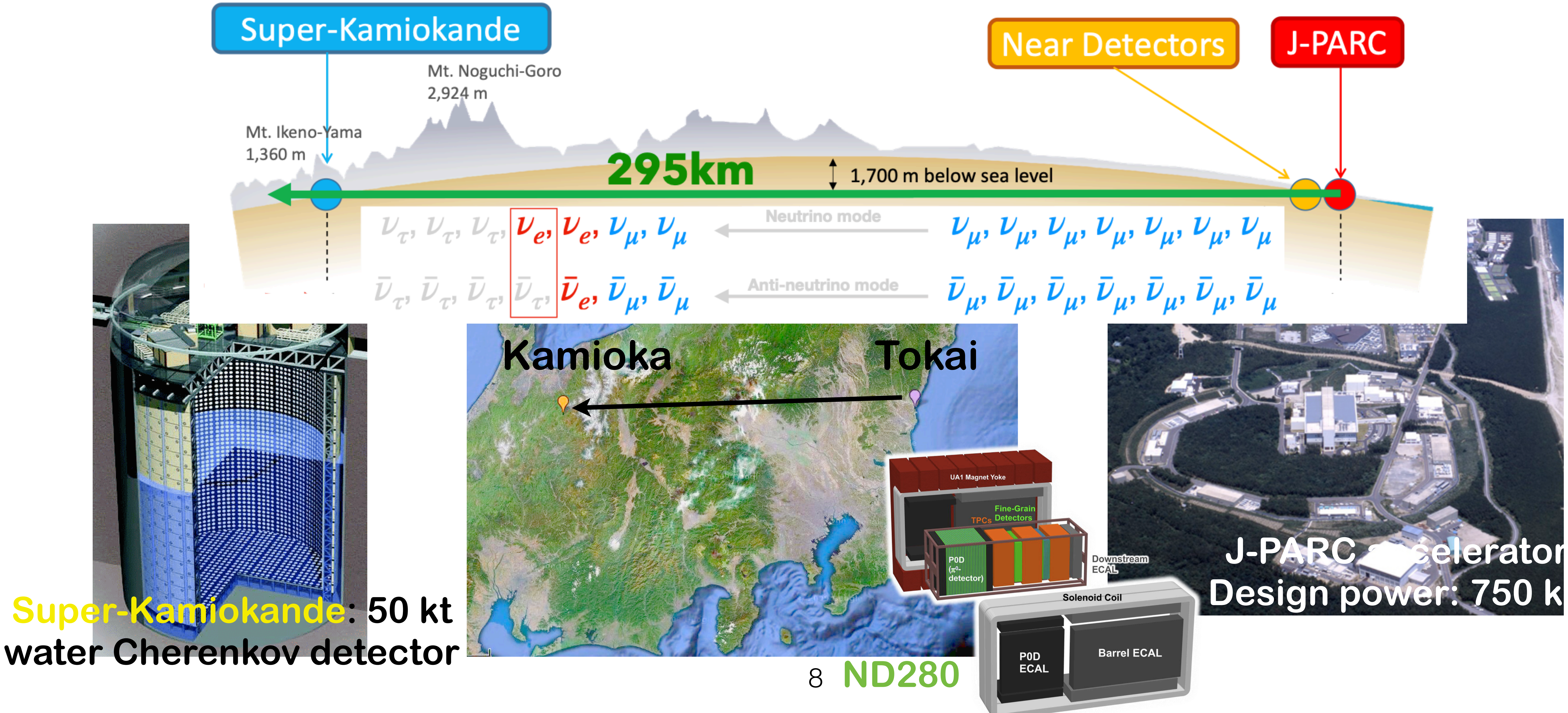






T2K experiment

- High intensity ~600 MeV ν_μ beam at J-PARC (Tokai) → ν or $\bar{\nu}$ mode by changing the horn polarity
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector (Super-Kamiokande)
  - ν_e and $\bar{\nu}_e$ appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ disappearance → θ_{23} and $|\Delta m^2_{32}|$



Super-Kamiokande: 50 kt water Cherenkov detector

ND280

J-PARC accelerator
Design power: 750 k

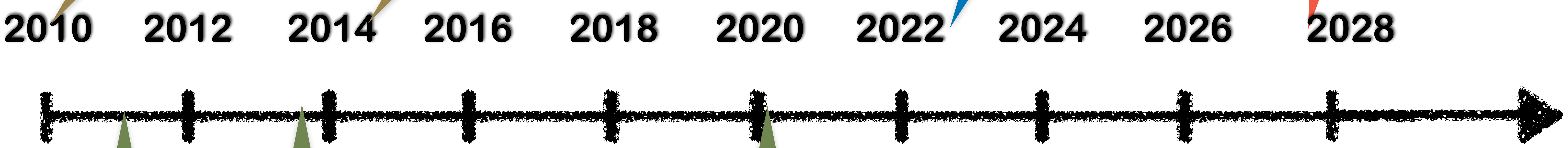
A long journey

T2K starts data taking

Take data in $\bar{\nu}$-mode

ND280 upgrade

Hyper-K



Hints of ν_e appearance ($\theta_{13}\neq0$@2.5σ)

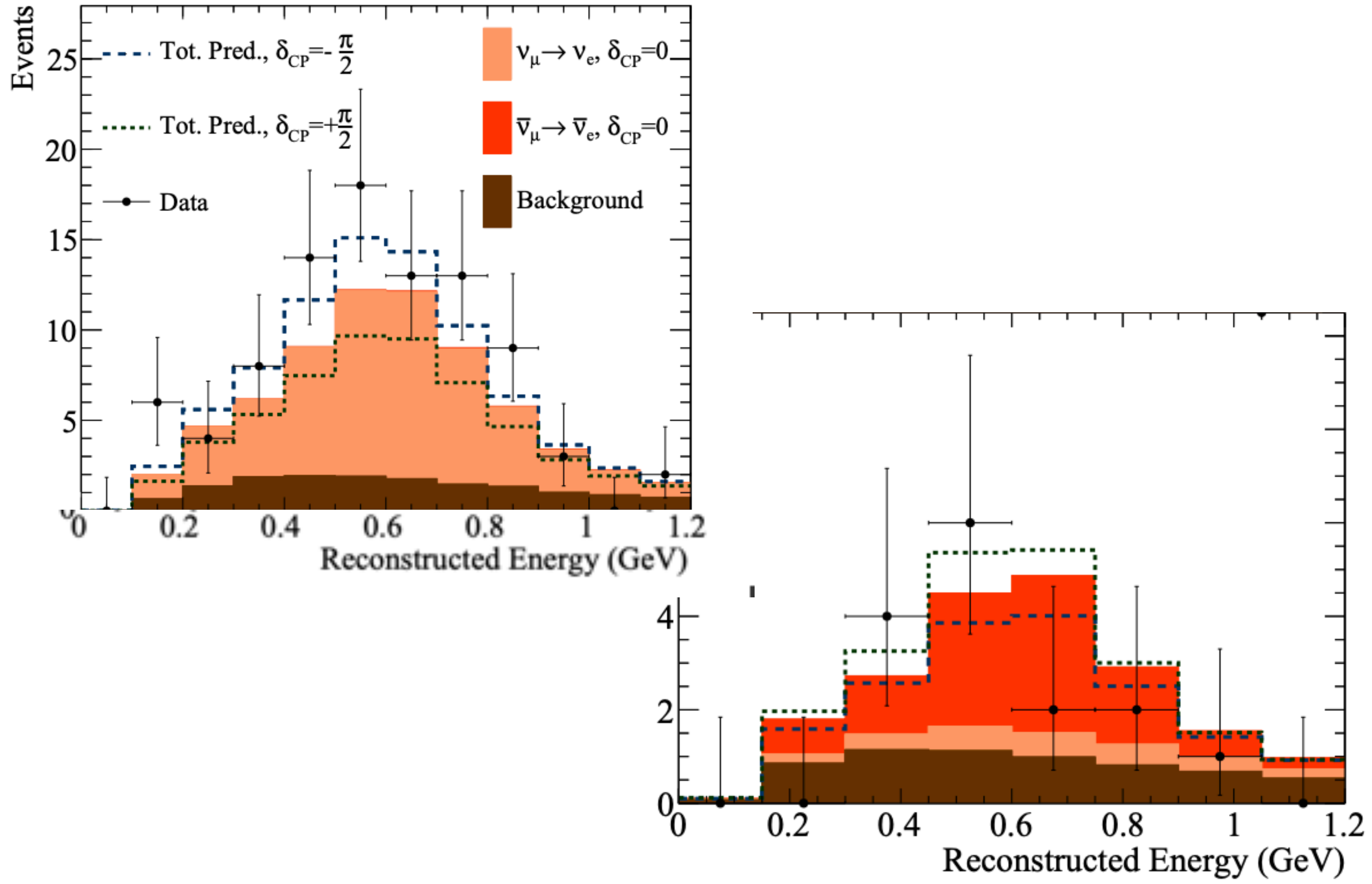
Phys.Rev.Lett. 107 (2011) 041801

Observation of ν_e appearance ($\theta_{13}\neq0$@7.3σ)

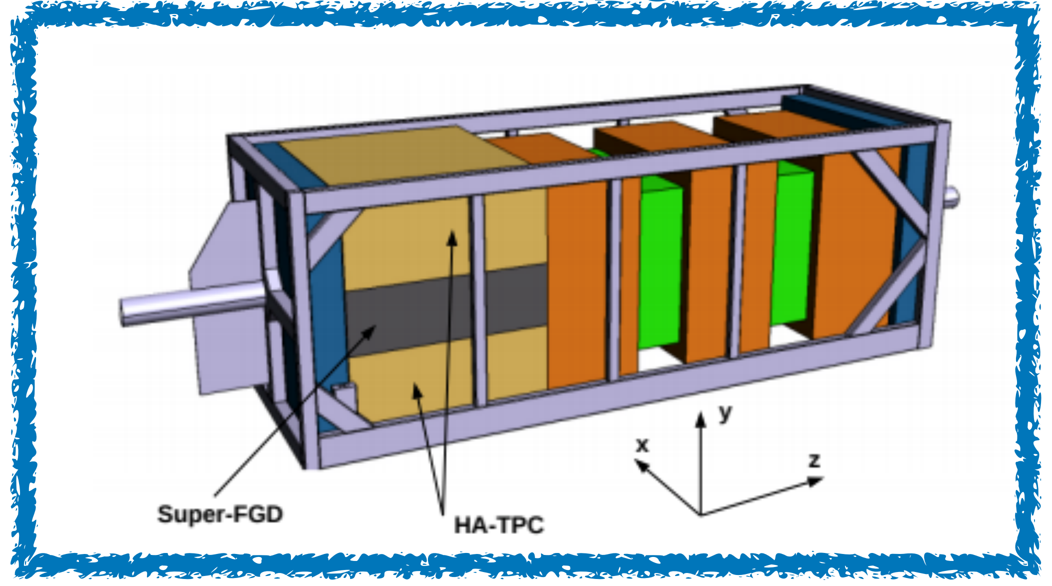
Phys.Rev.Lett. 112 (2014) 061802

Hints of CP violation → $\sin(\delta_{CP})=0$ excluded at 95%

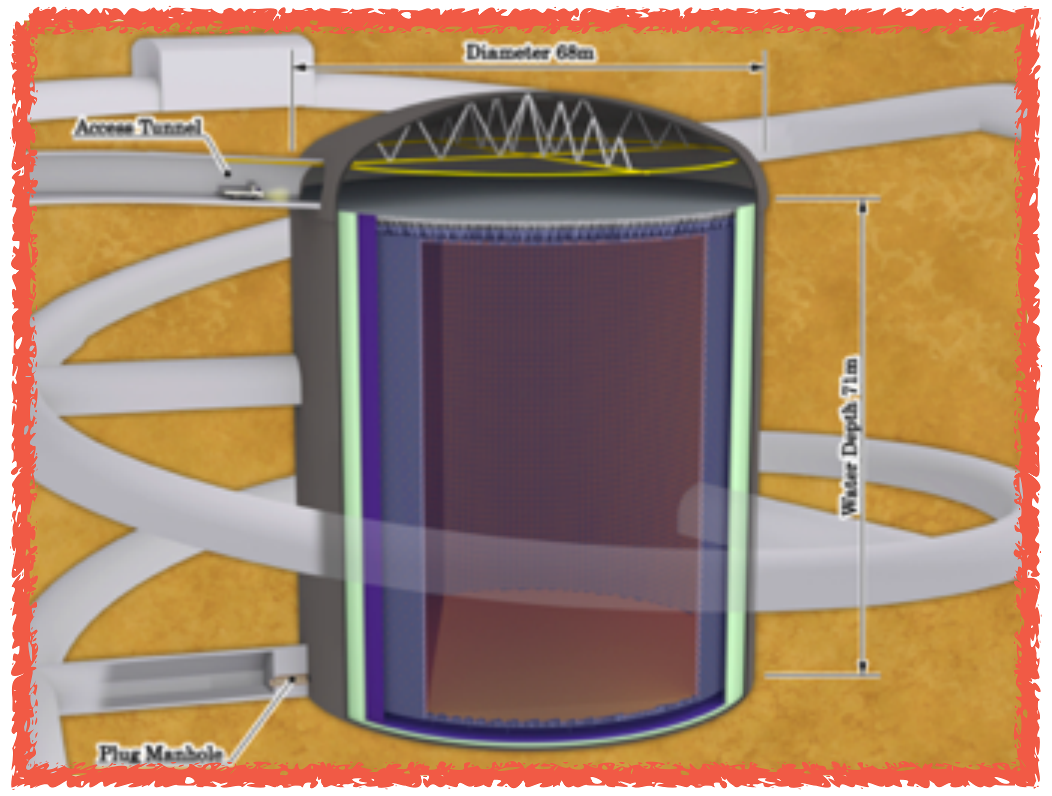
Nature Vol. 580, pp. 339-344



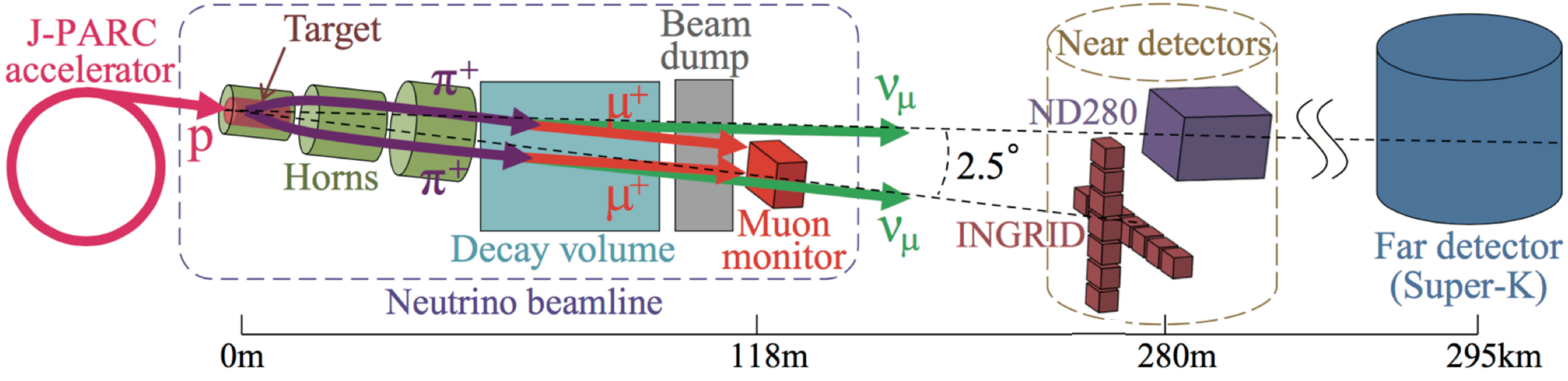
2023: T2K-II + Near Detector Upgrade



2027: Hyper-K (8xSuper-K)

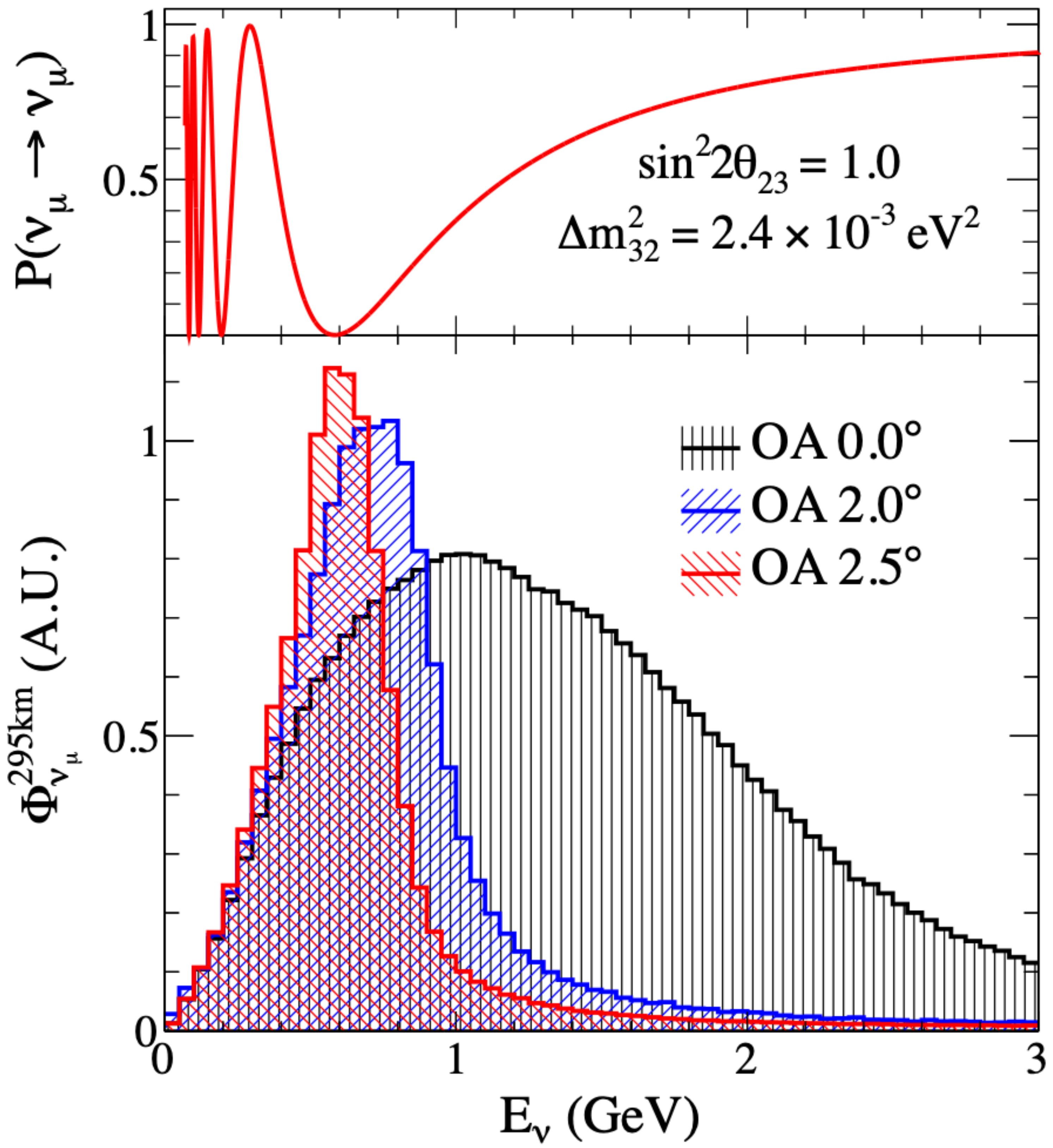


T2K beamline



- 30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target
- p+C interactions producing hadrons (mainly pions and kaons)
- Hadrons are focused and selected in charge by 3 electromagnetic horns
  - If π^+ are focused ν_μ are produced by $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - Changing the horn current we can produce $\bar{\nu}_\mu$ from $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- Off-axis technique → detectors intercept a narrow-band beam at the maximum of the oscillation probability

ν_μ survival probability



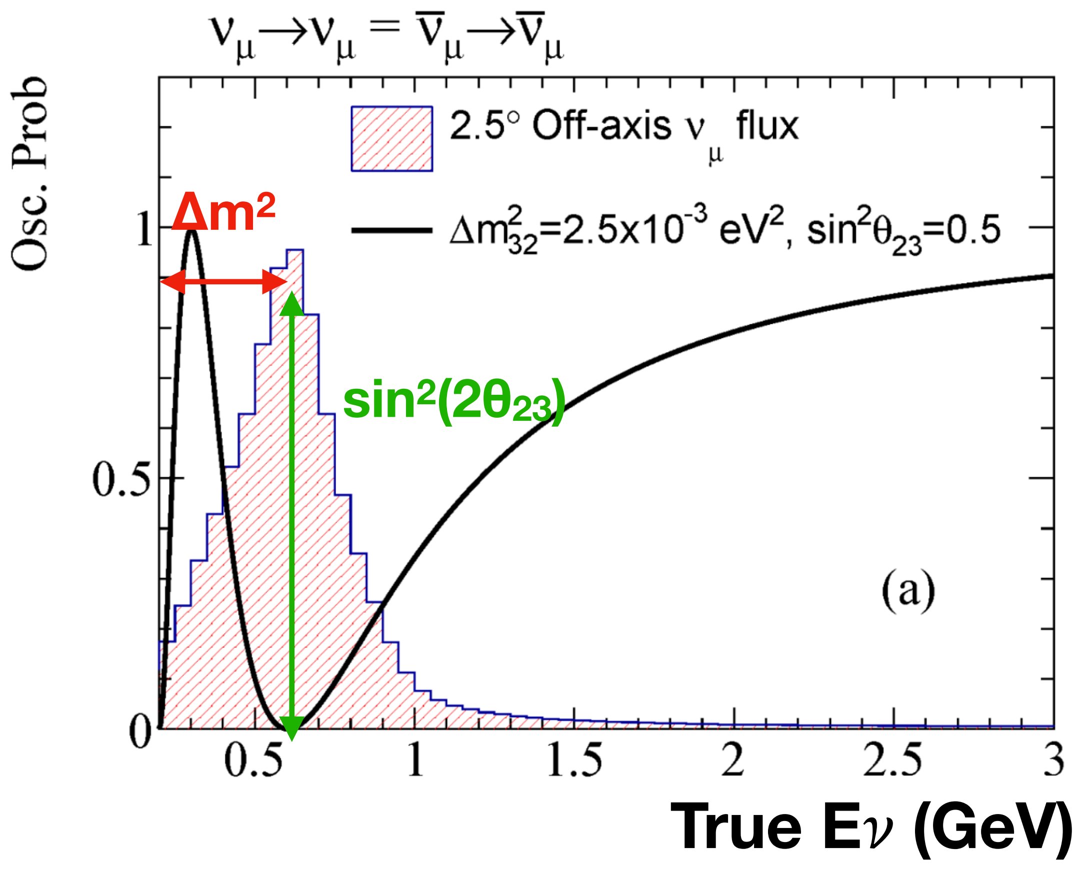
Physics case

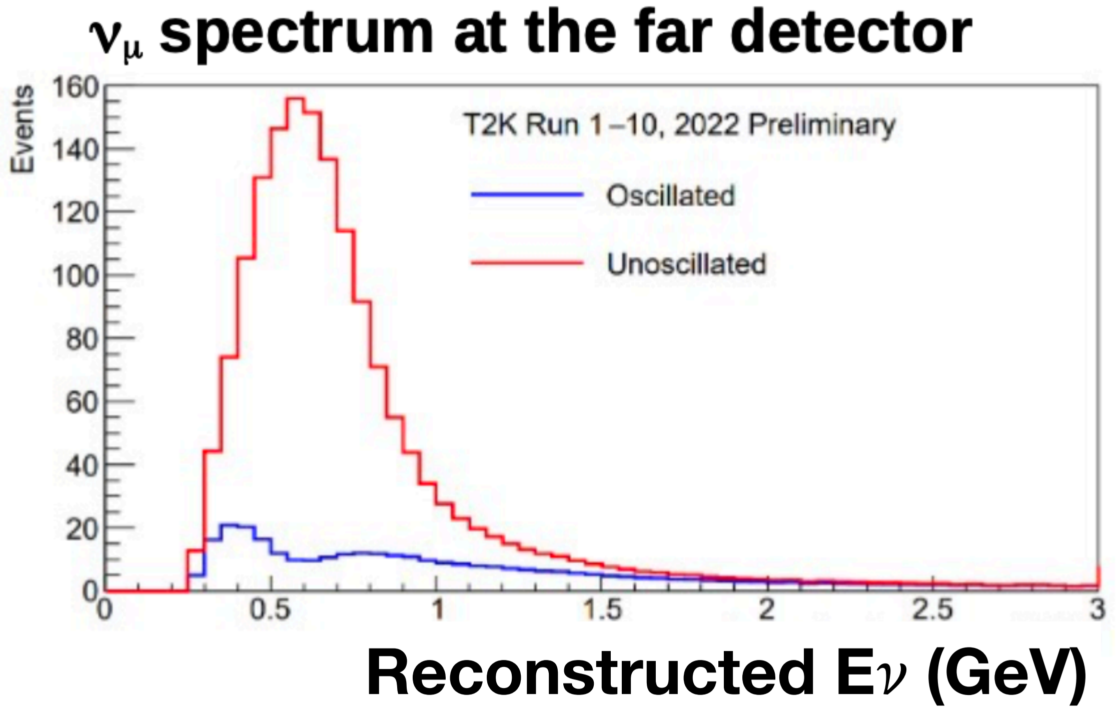
ν_μ and $\bar{\nu}_\mu$ disappearance

$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

Same oscillation probability for ν and $\bar{\nu}$

Sensitive to $|\Delta m^2_{32}|$ and to $\sin^2(2\theta_{23})$ → no sensitivity to mass ordering and δ_{CP}





ν_e and $\bar{\nu}_e$ appearance

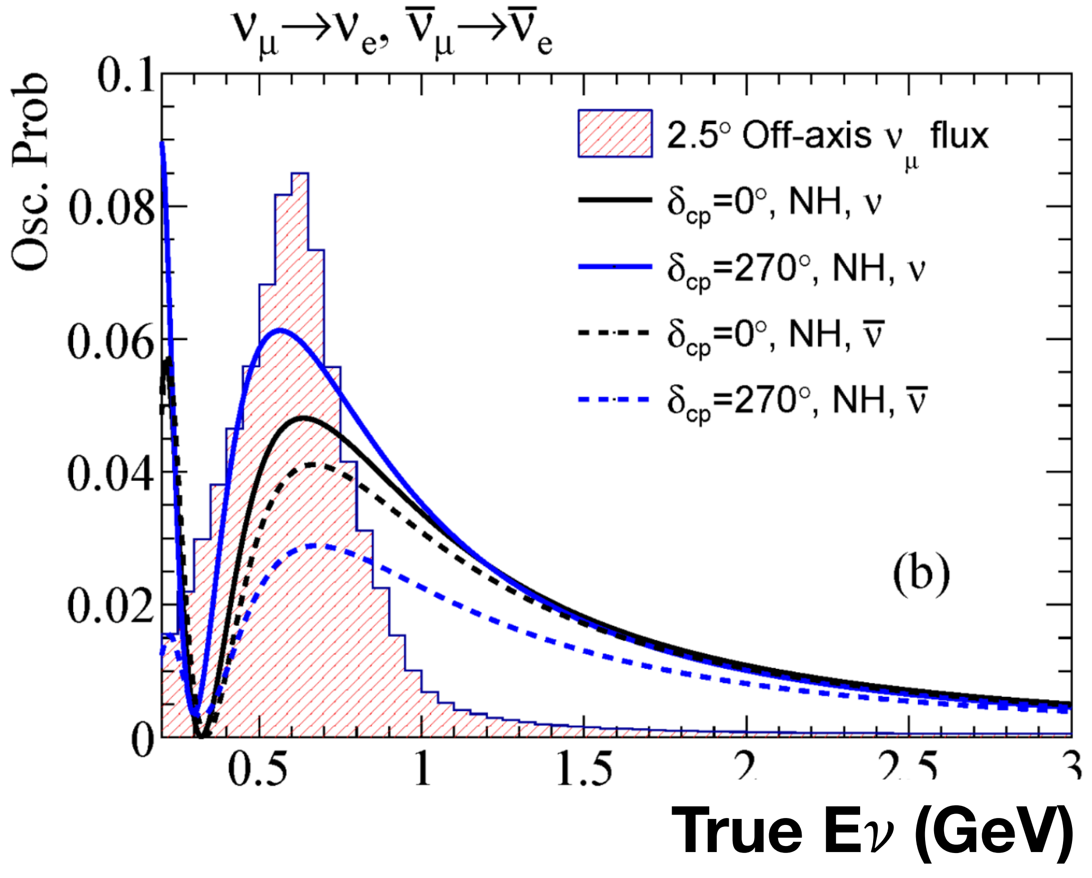
$$P(\overline{\nu_\mu} \to \overline{\nu_e}) \simeq \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta_{31}$$
$$(\mp)\alpha\frac{J_0 \sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}]$$
$$+\alpha\frac{J_0\cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}] + O(\alpha^2)$$

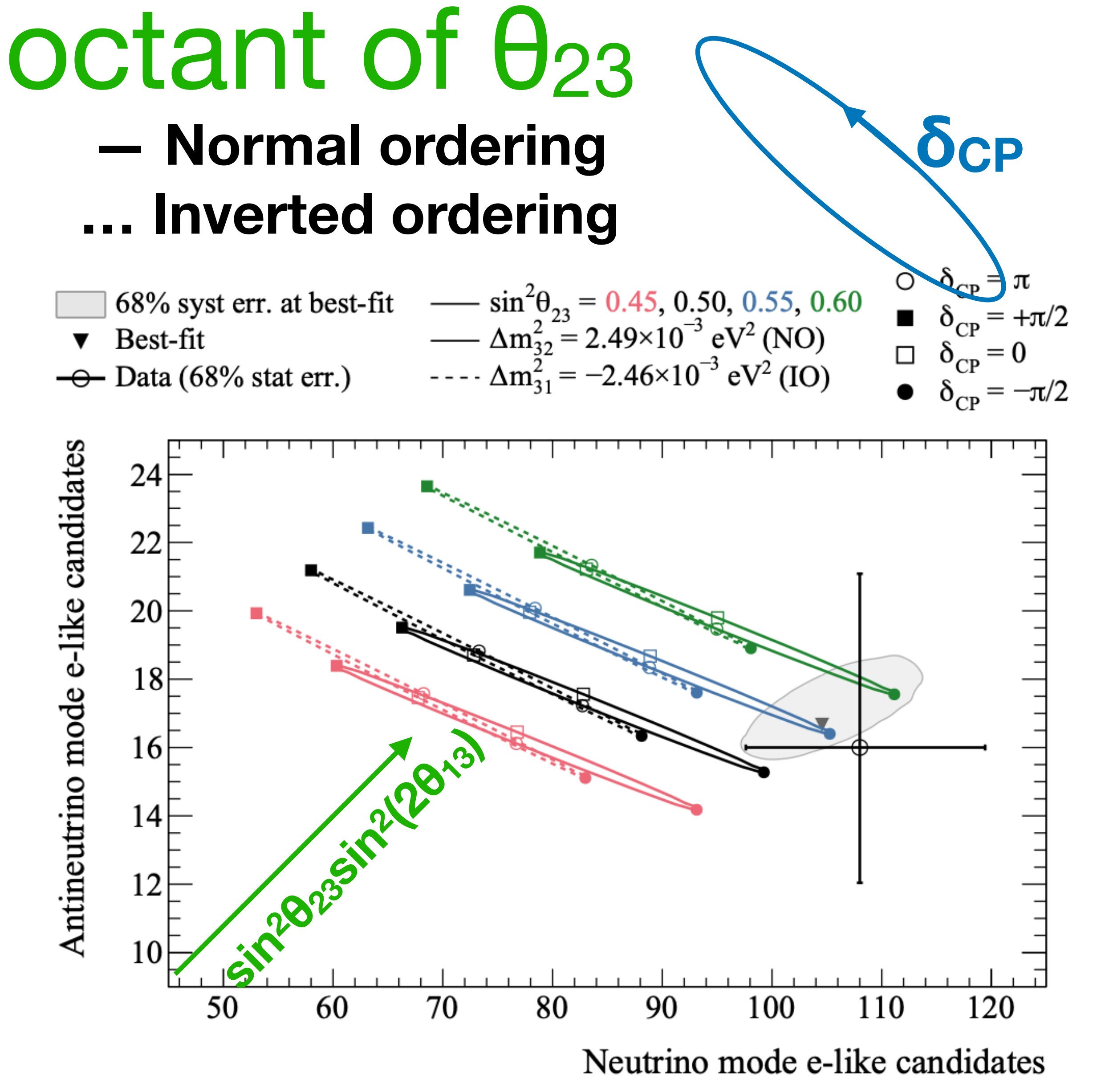
$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30$

$J_0 = \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$

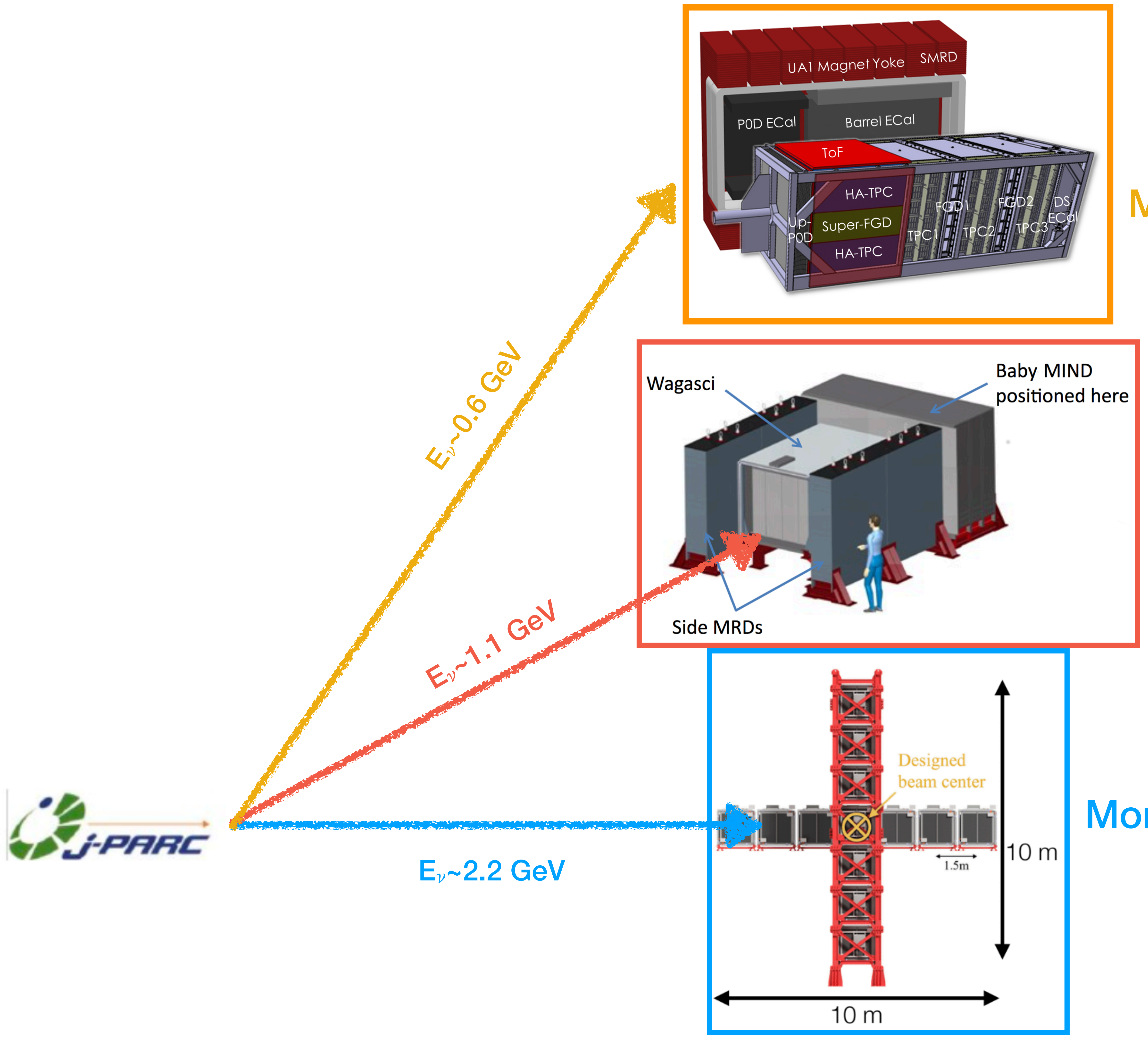
$A = (\mp)2\sqrt{2}G_F n_e E/\Delta m^2_{31}$

Sensitivity to δ_{CP}, to the mass ordering and to the octant of θ_{23}





Near Detector complex



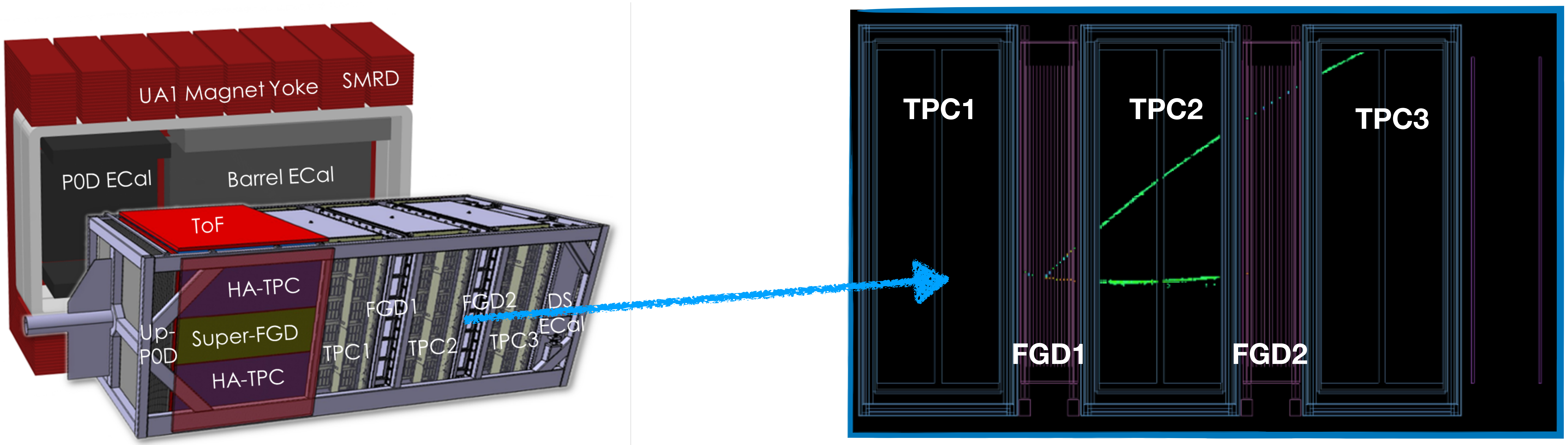
Off-Axis ND280
Constrain systematics in T2K oscillation analyses
Measure neutrino cross-sections
In operation since 2010 and upgraded in 2023

WAGASCI/BabyMIND
Installed in 2019
Cross-sections on water

INGRID: on-axis detector
Monitoring ν beam profile day-by-day
Cross-section measurements
In operation since 2009

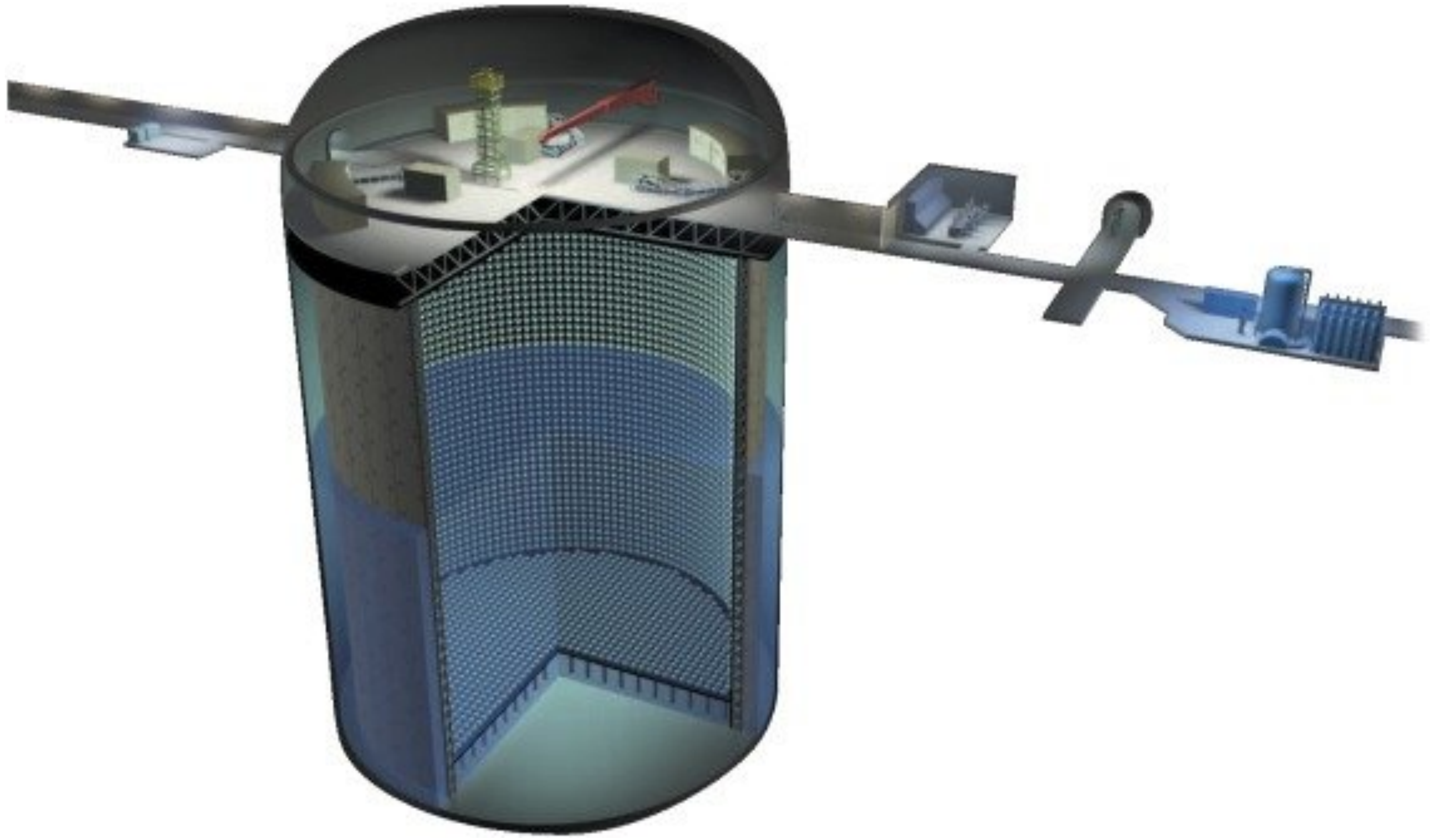
- Near Detector complex at 280 m from the target
- Several detectors installed to monitor the beam, reduce systematic uncertainties in oscillation analyses, and measure ν and $\bar{\nu}$ cross-sections

Off-axis ND280

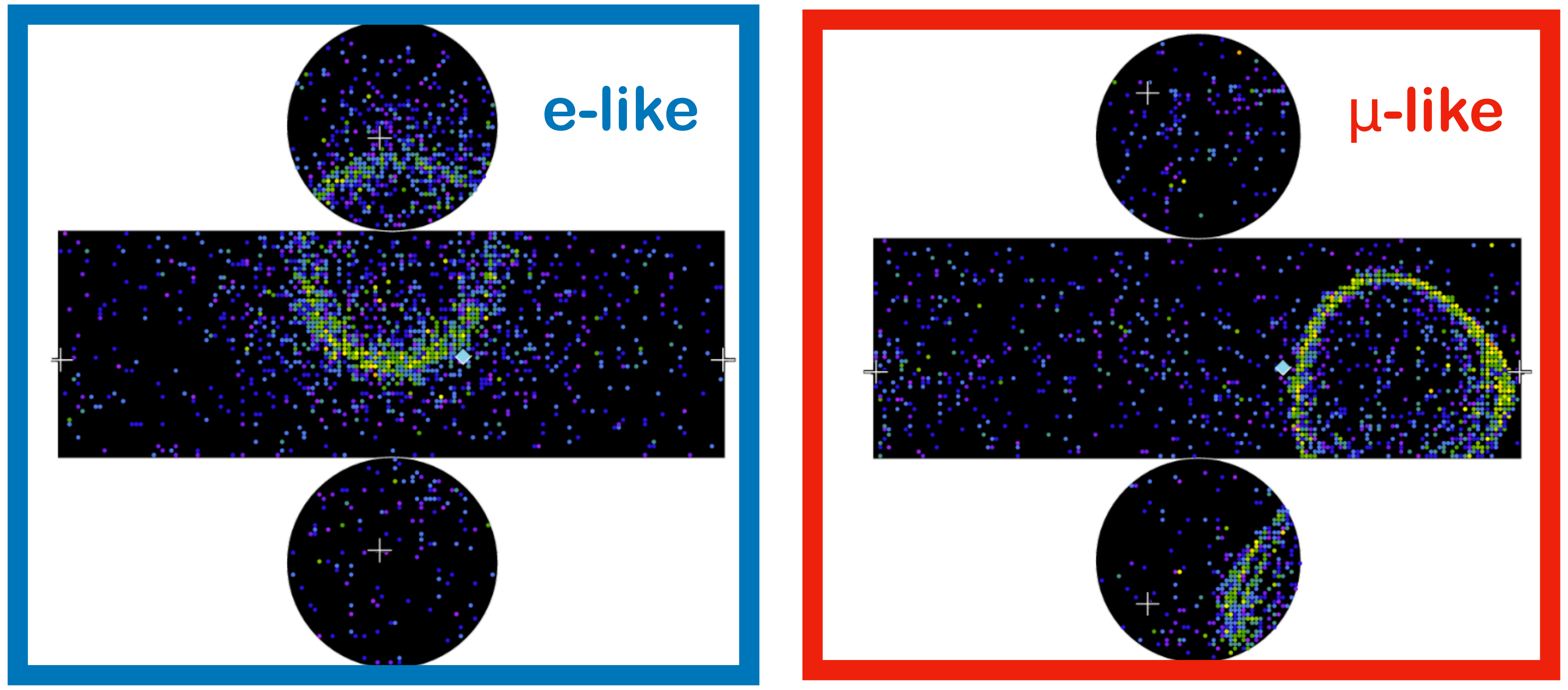


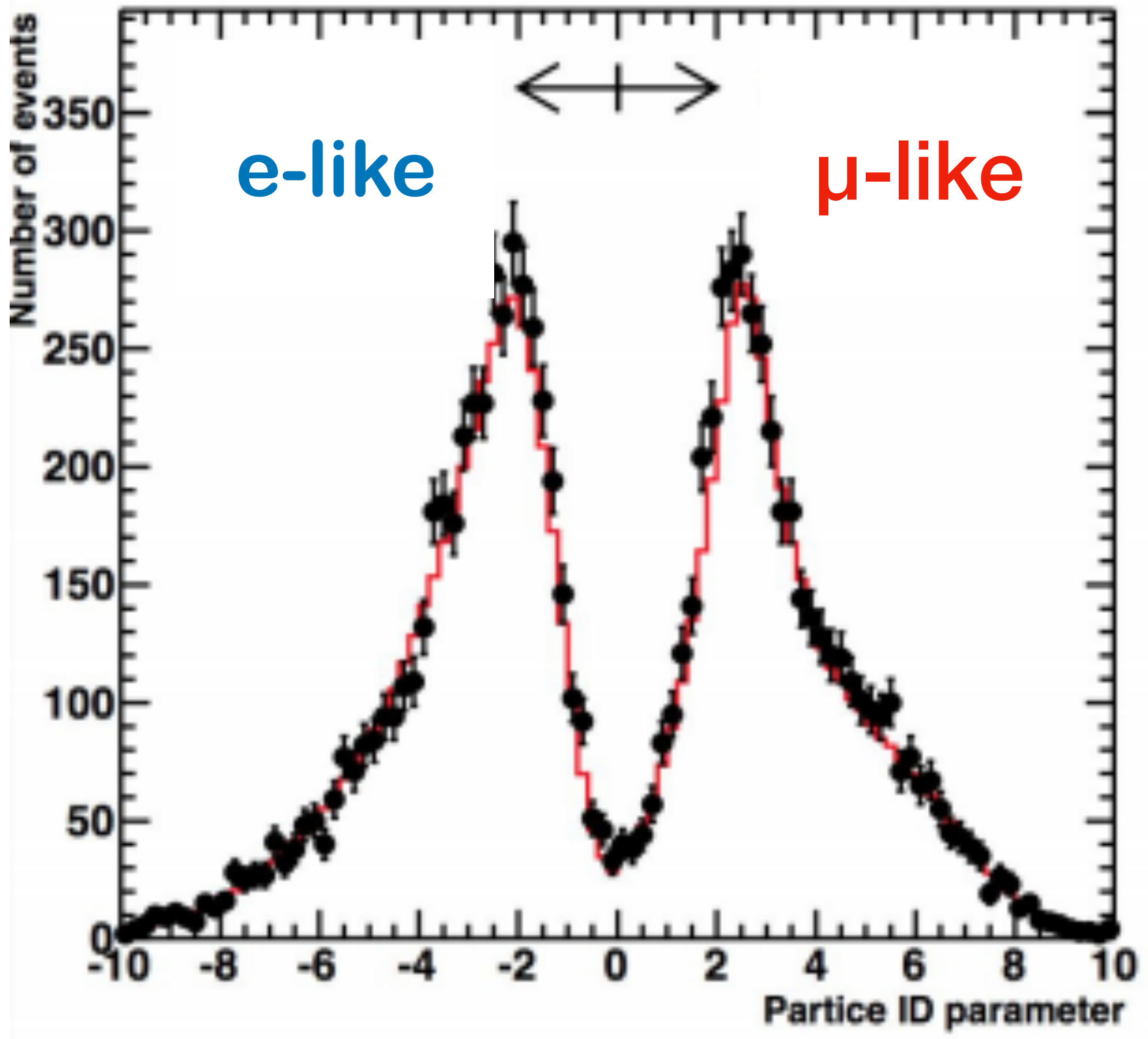
- Measure beam spectrum and flavor composition before the oscillations
- Detector installed inside the UA1/NOMAD magnet (0.2 T)
- An electromagnetic calorimeter to distinguish tracks from showers
- Upgraded in 2023 but for the analyses shown here the original tracker system is used:
  - 2 Fine Grained Detectors (target for ν interactions). FGD1 is pure scintillator, FGD2 has water layers interleaved with scintillator
  - 3 Time Projection Chambers: reconstruct momentum and charge of particles, PID based on measurement of ionization

Super-Kamiokande



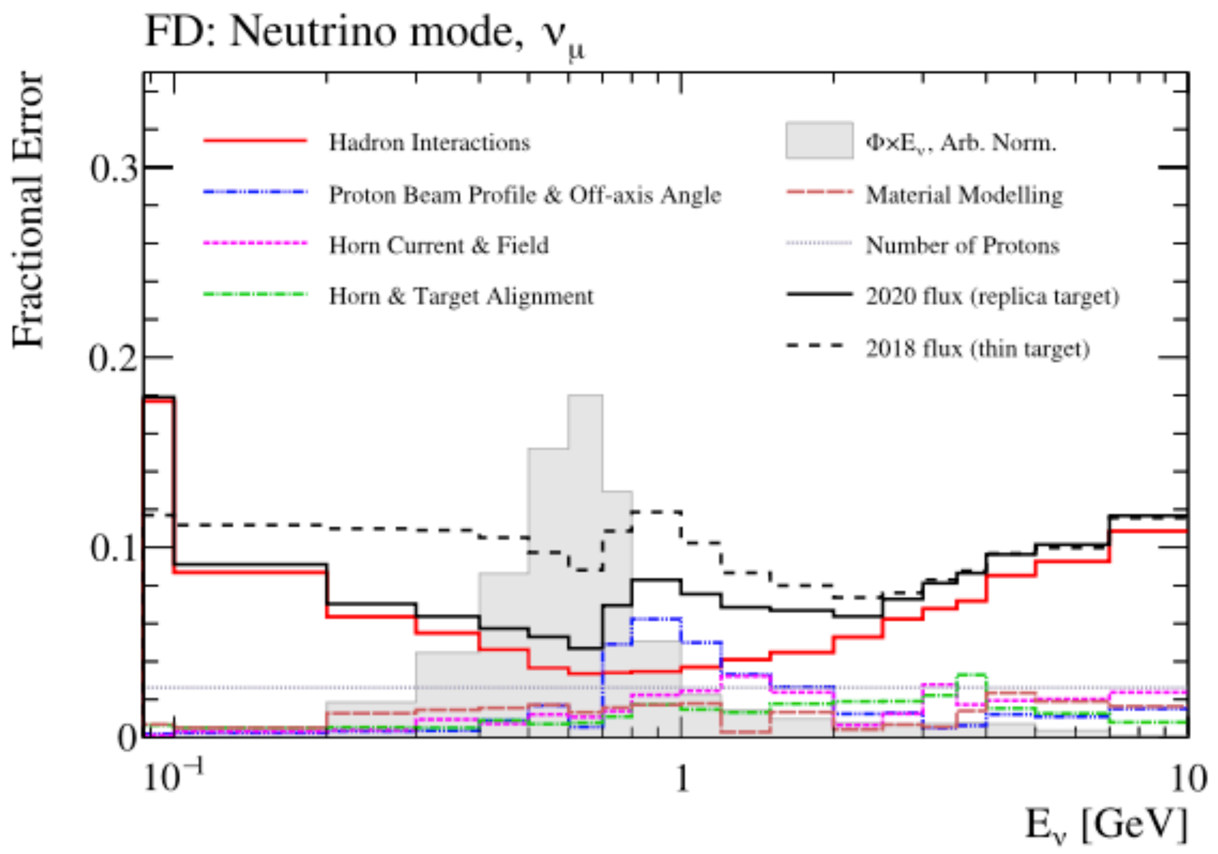
- 50 kton water Cherenkov detector
  - ~11k 20” PMTs for the inner detector, ~2000 8” PMTs for the outer detector, used as veto
- ~1000 meters underground in Kamioka, operated since 1996
- Different shape of Cherenkov ring → distinguish e/μ
- Added 0.03% Gd in 2022 → improve neutron tagging efficiency

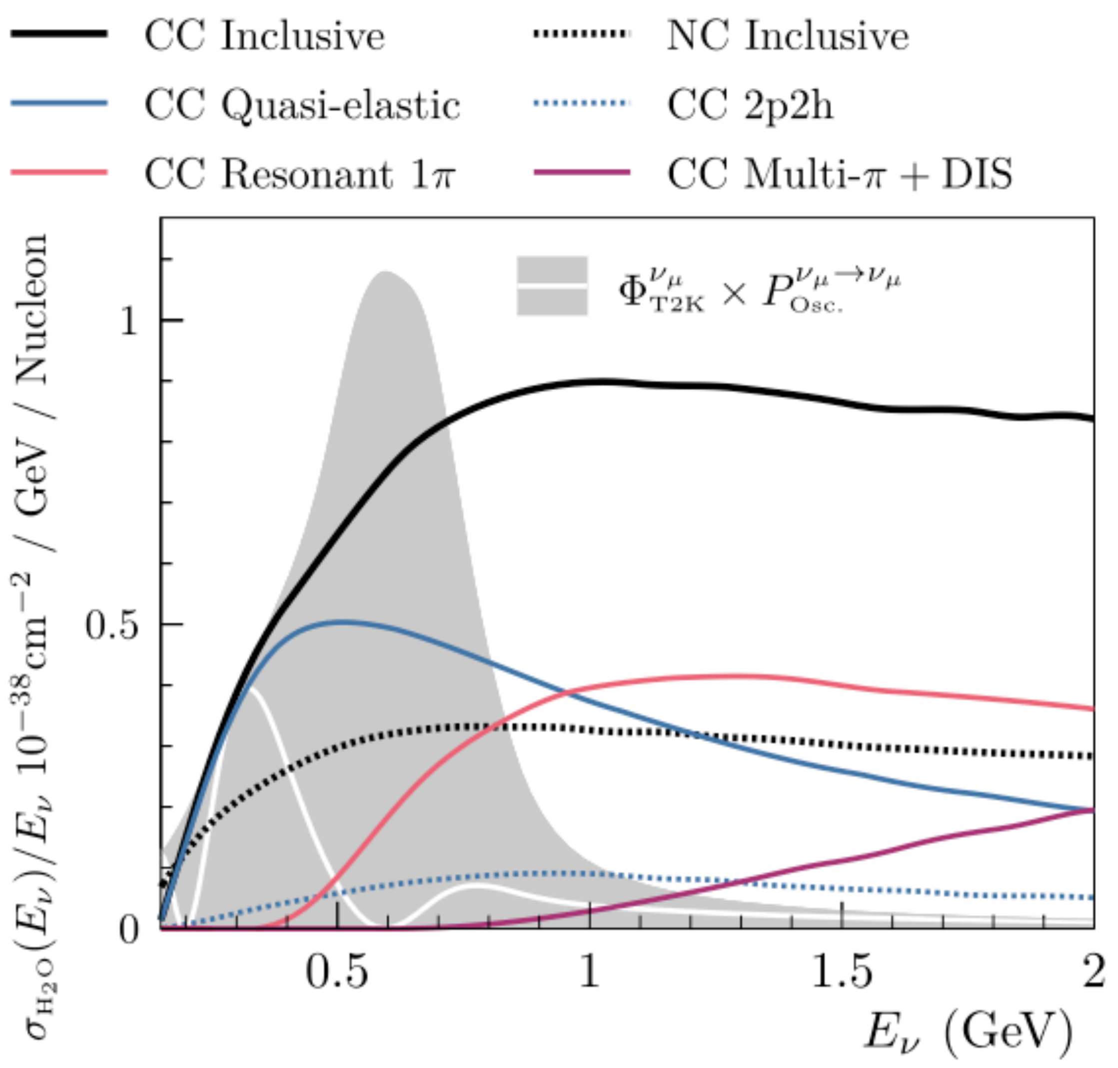


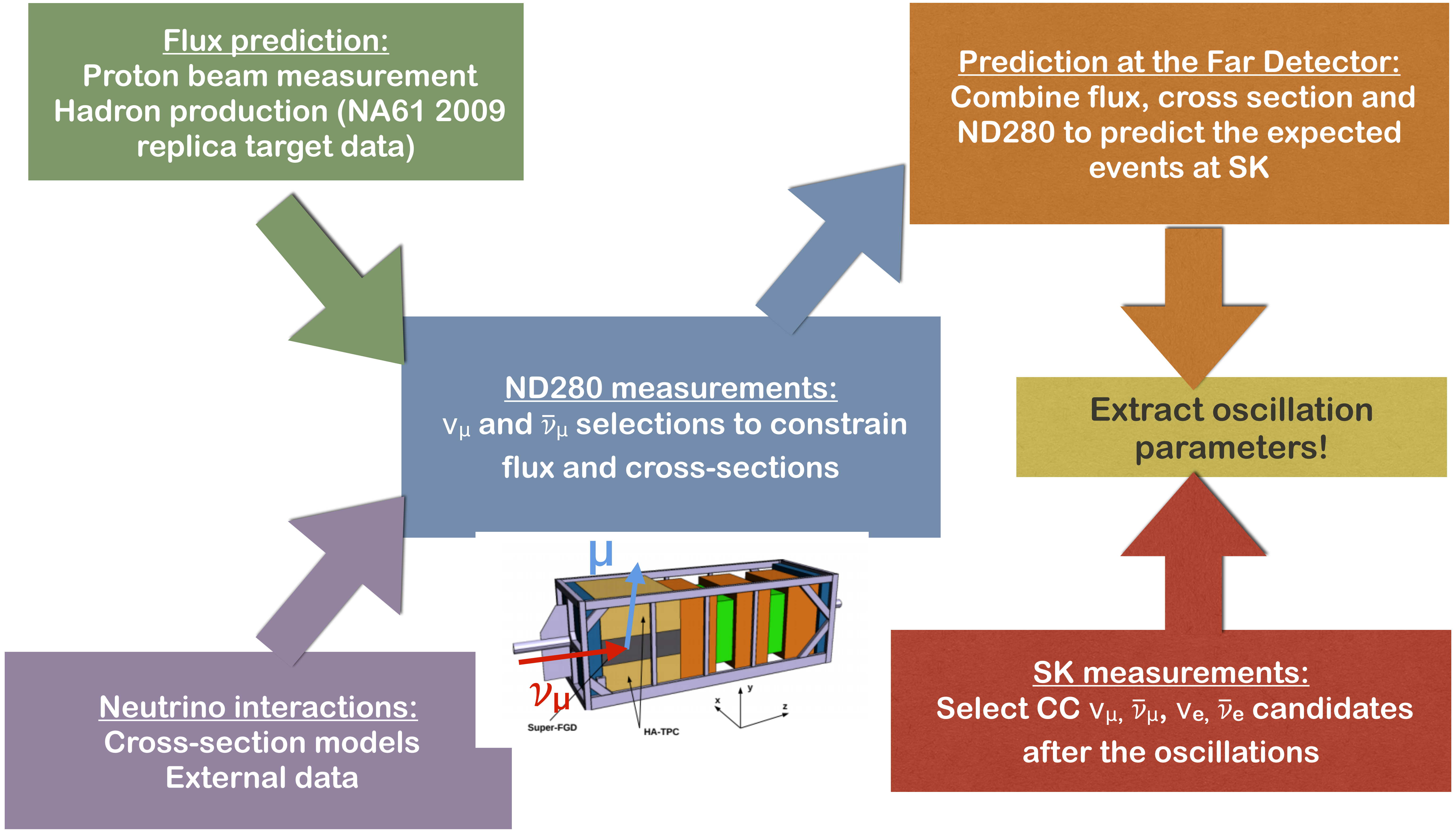


T2K Oscillation analyses

T2K oscillation analysis







Flux prediction:
Proton beam measurement
Hadron production (NA61 2009 replica target data)

Prediction at the Far Detector:
Combine flux, cross section and ND280 to predict the expected events at SK

ND280 measurements:
ν_μ and $\bar{\nu}_\mu$ selections to constrain flux and cross-sections

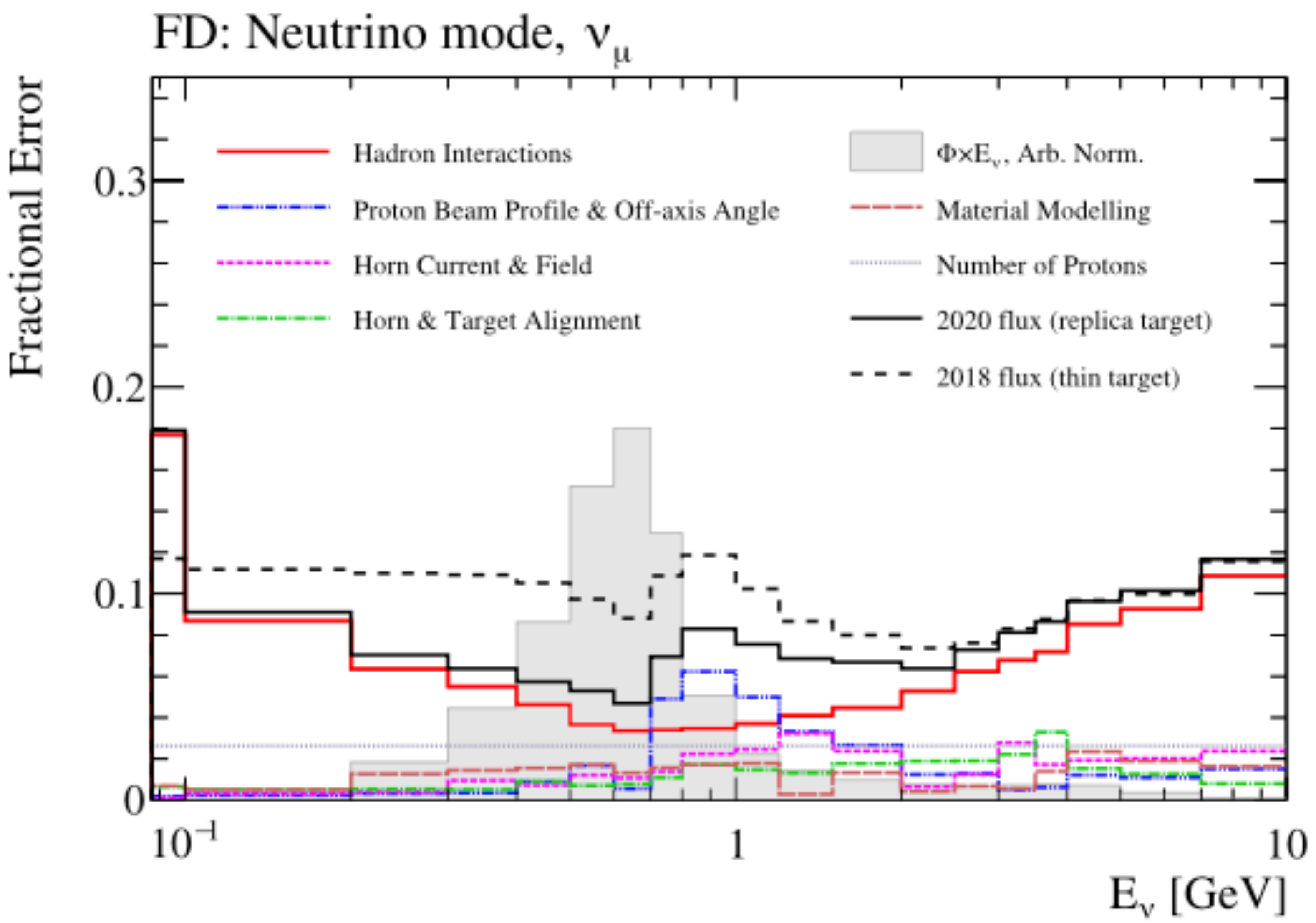
Extract oscillation parameters!

Neutrino interactions:
Cross-section models
External data

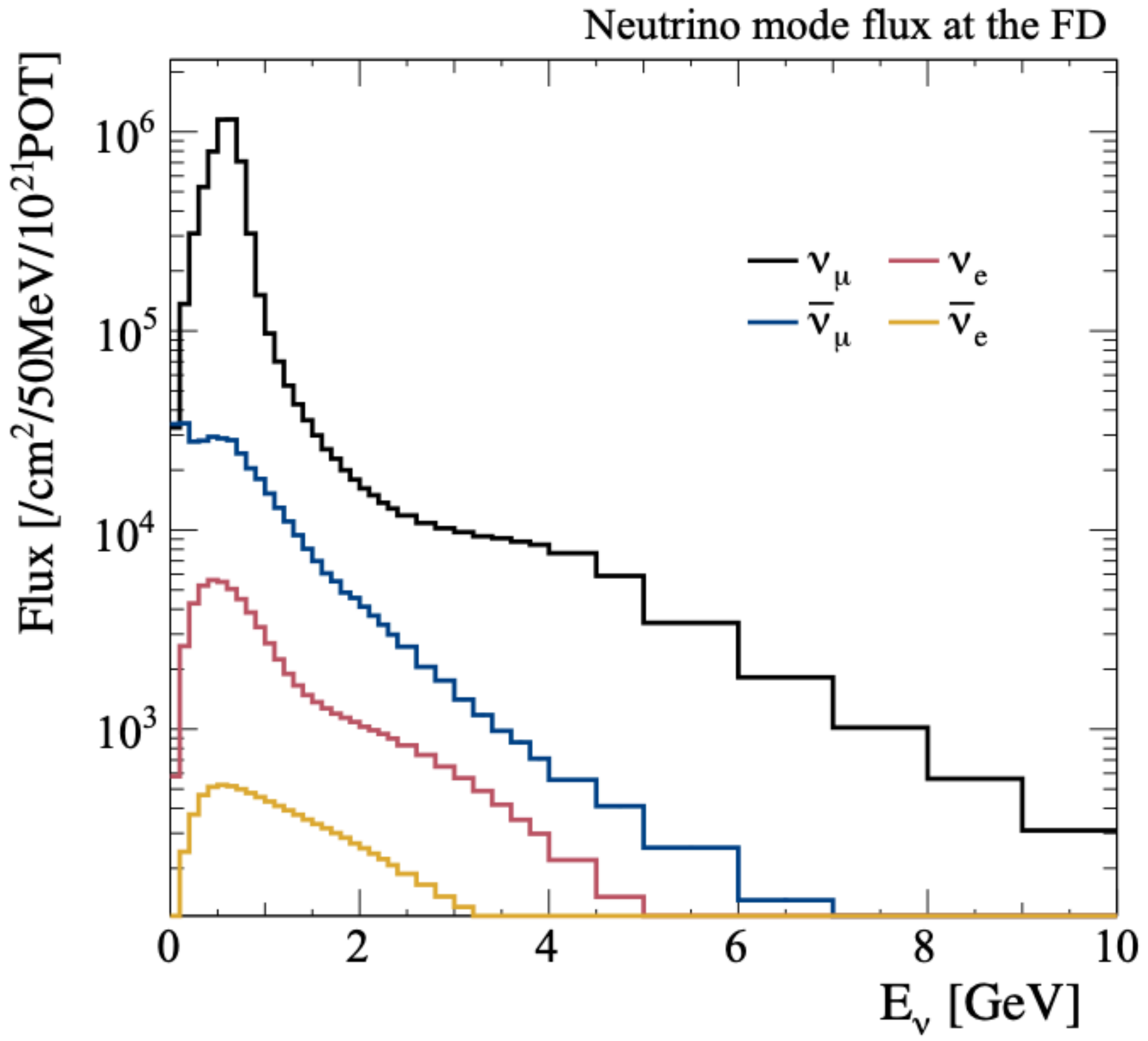
SK measurements:
Select CC ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ candidates after the oscillations

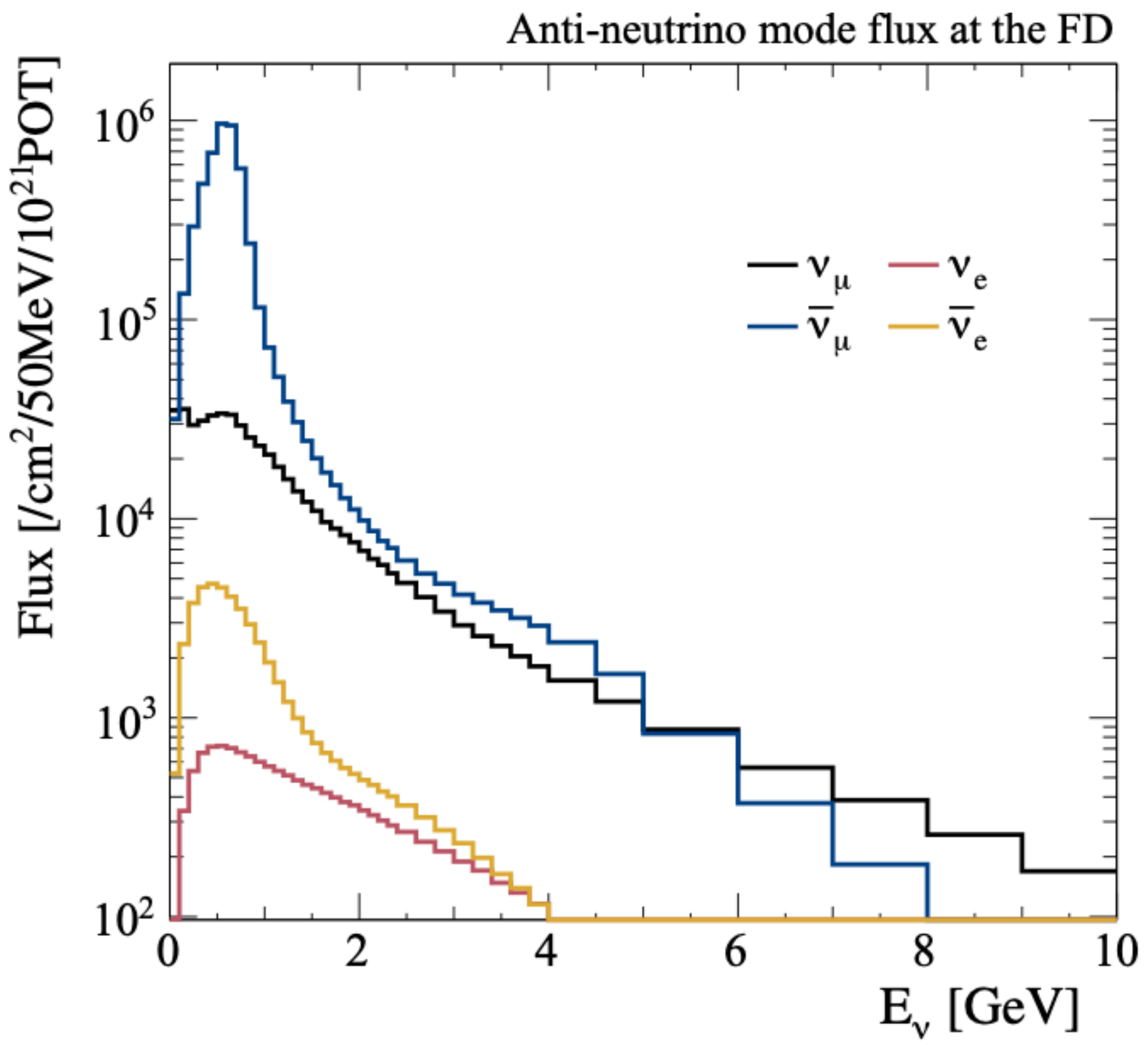
Neutrino flux predictions

- Systematics on ν and $\bar{\nu}$ fluxes dominated by hadron-production cross-sections uncertainties in p-C collisions
- Reduced to ~5% thanks to the data from NA61/SHINE



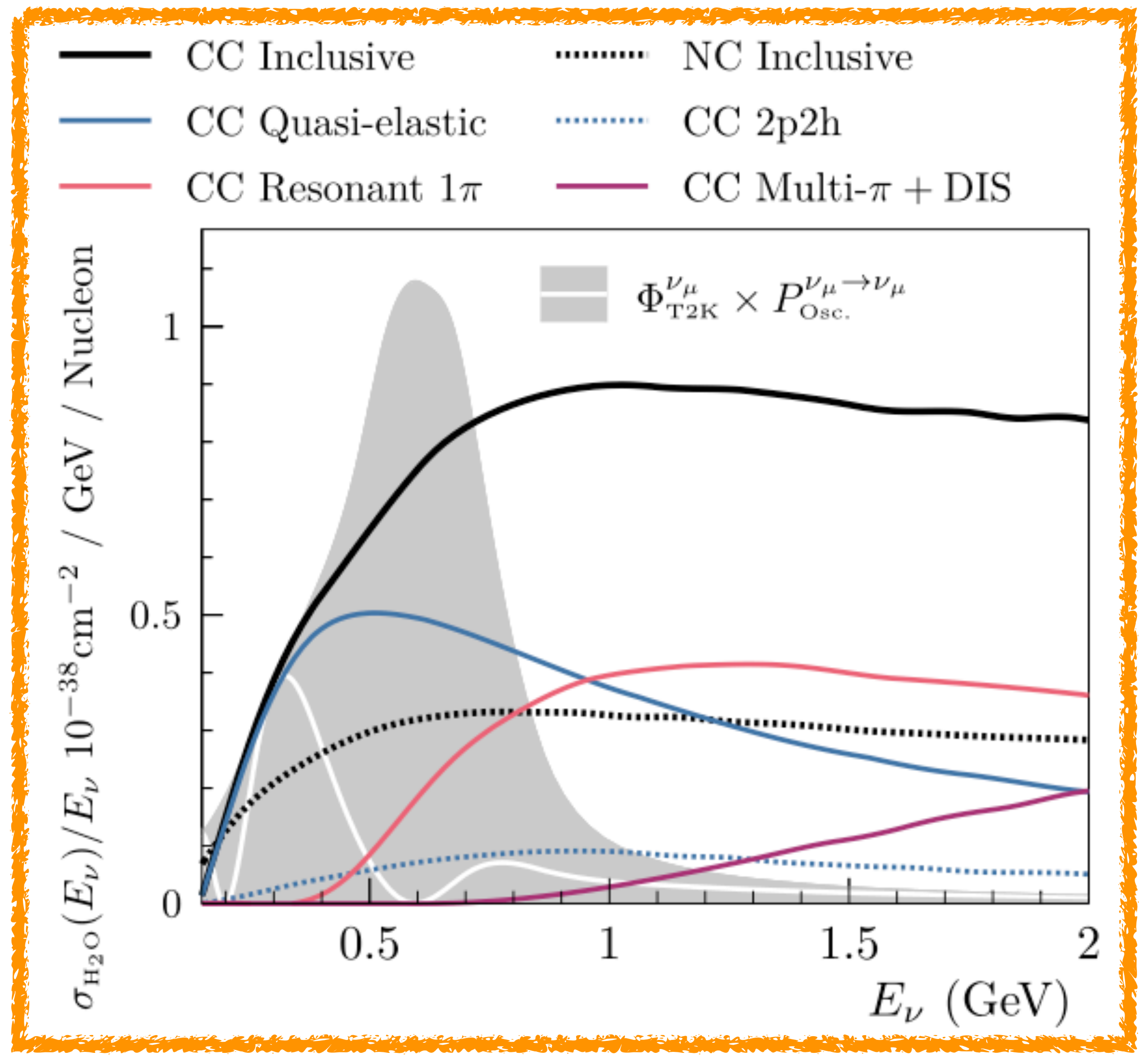
Eur.Phys.J.C 76
(2016) 11, 617
Eur.Phys.J.C 76
(2016) 2, 84





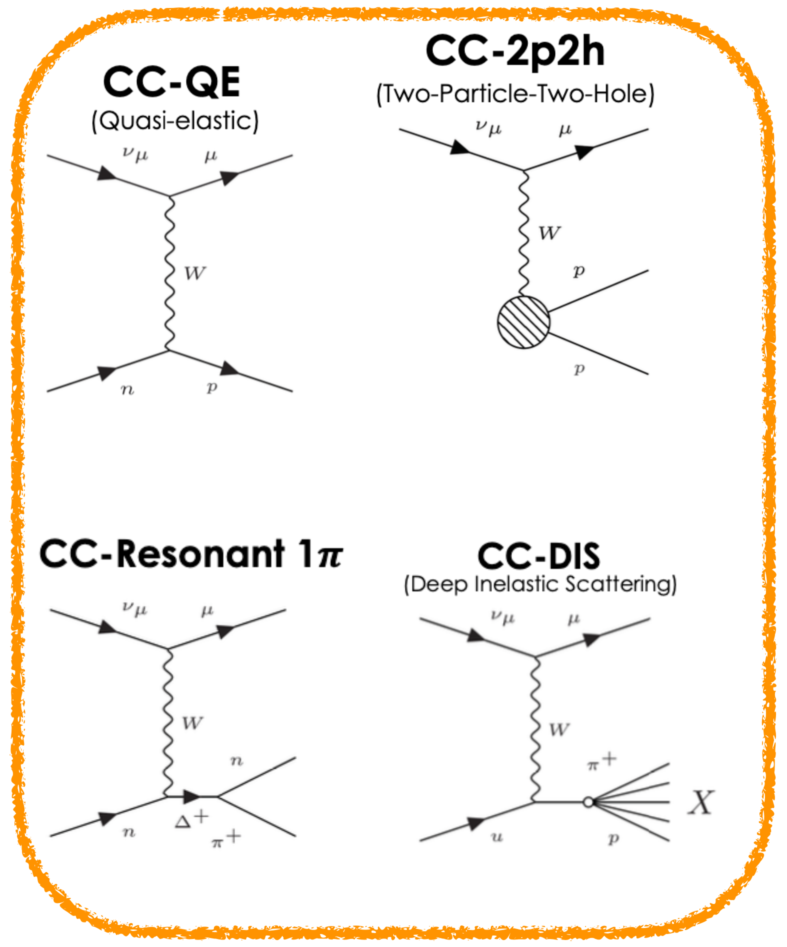
Y. Nagai, Hadron Production Measurements for Determination of Neutrino Flux

ν cross-section model

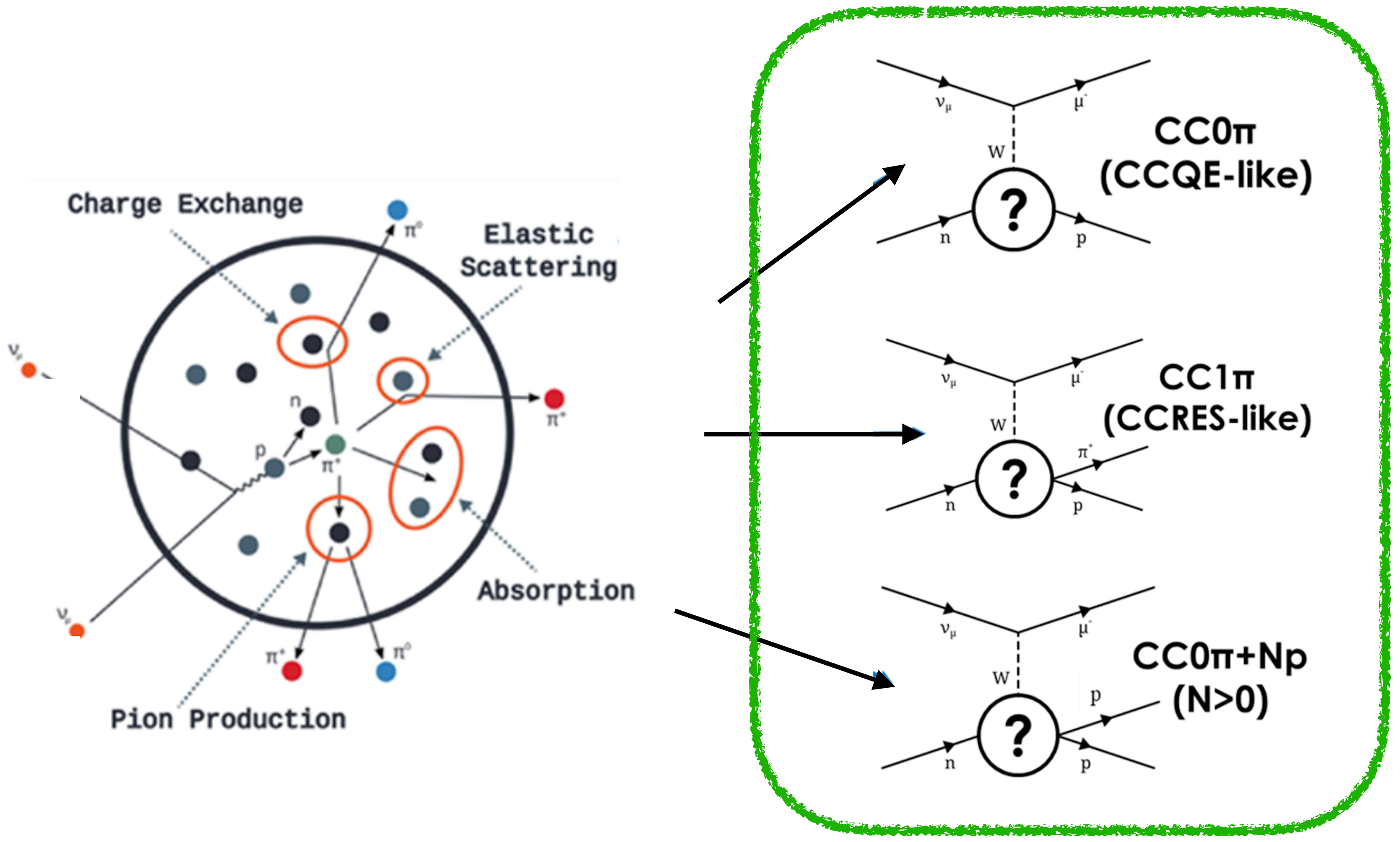


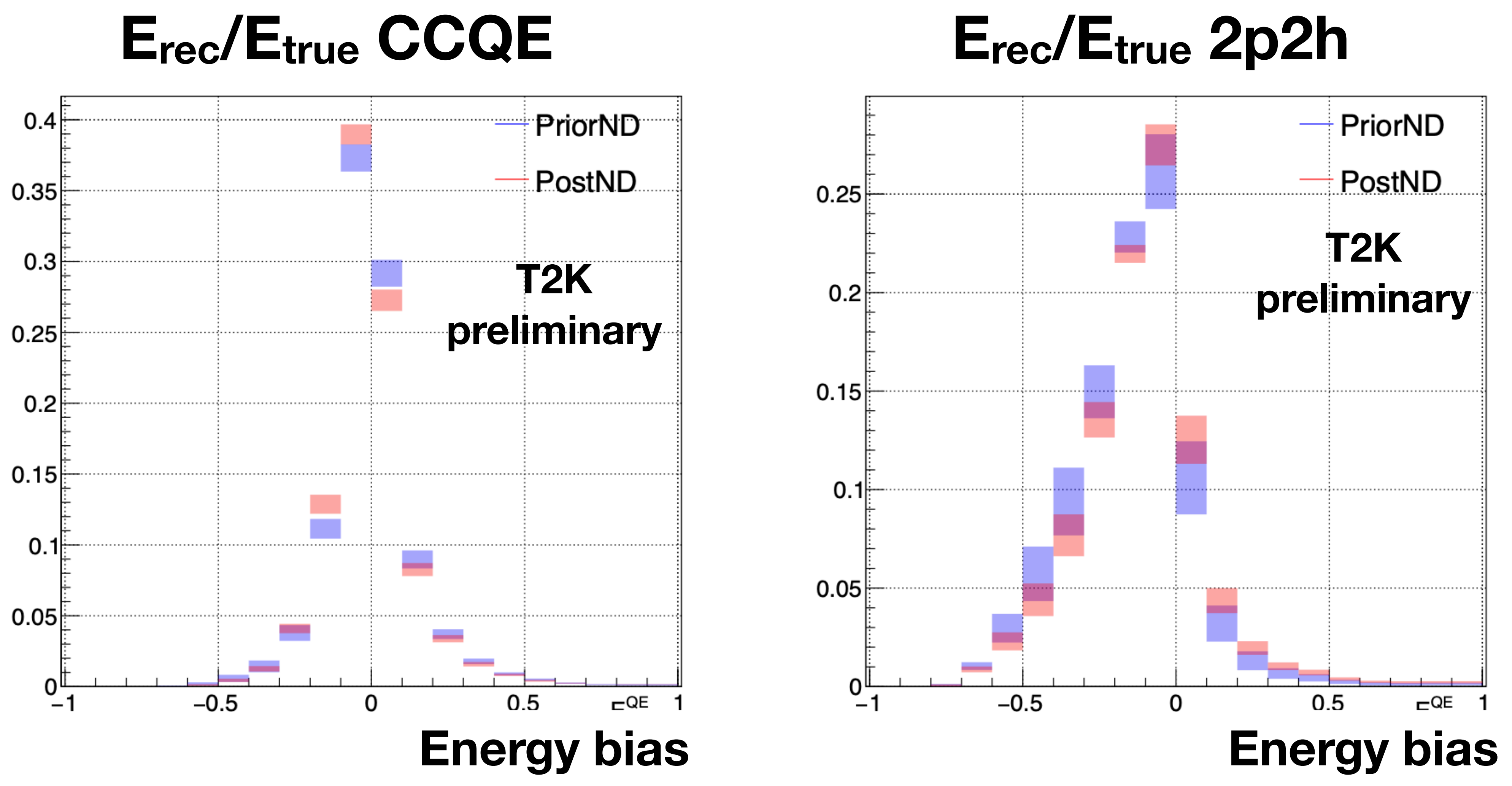
- At T2K energies dominated by CCQE channel
- Significant 2p2h and resonant contributions
- Mis-modeling of these contribution might bias the neutrino energy reconstruction → important to have a correct model with Near detector data

Generator



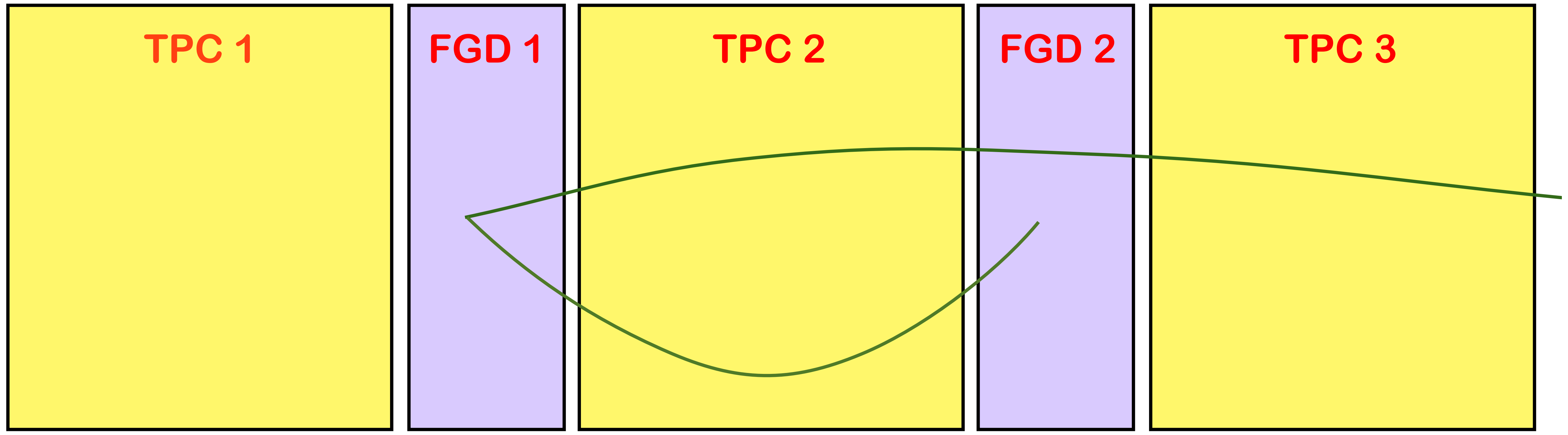
Observables

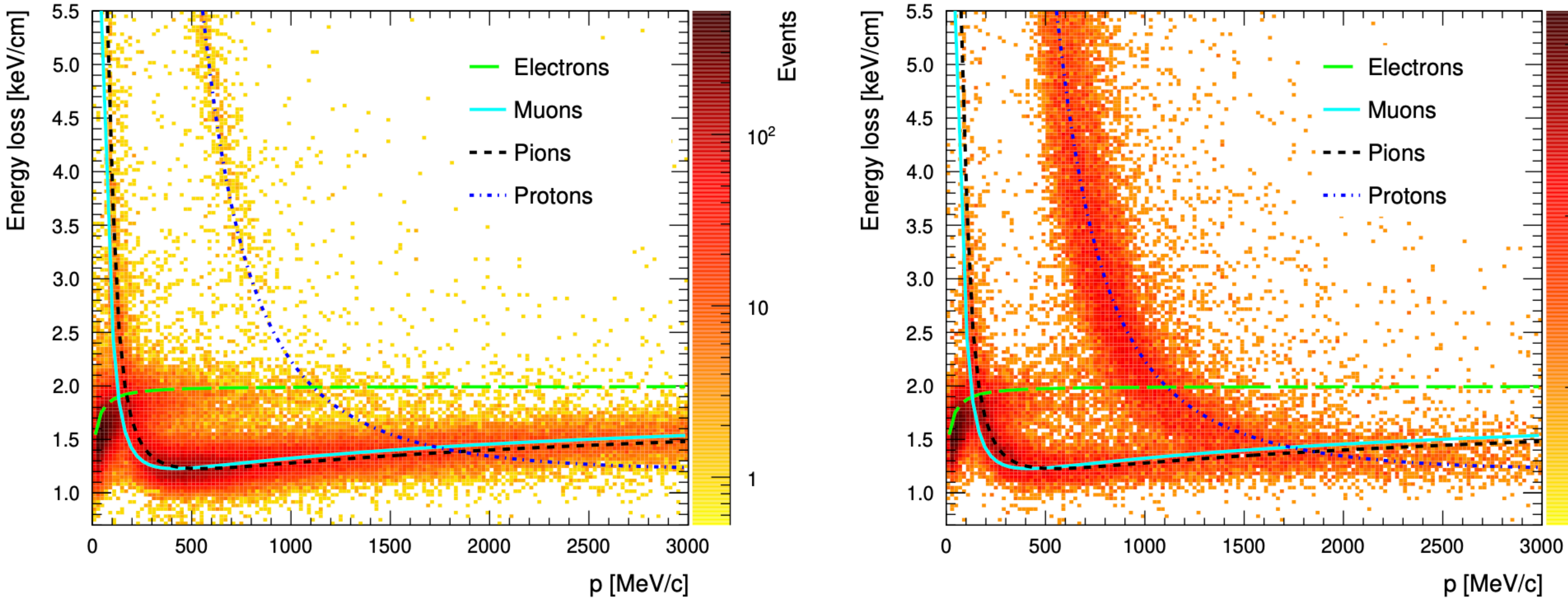


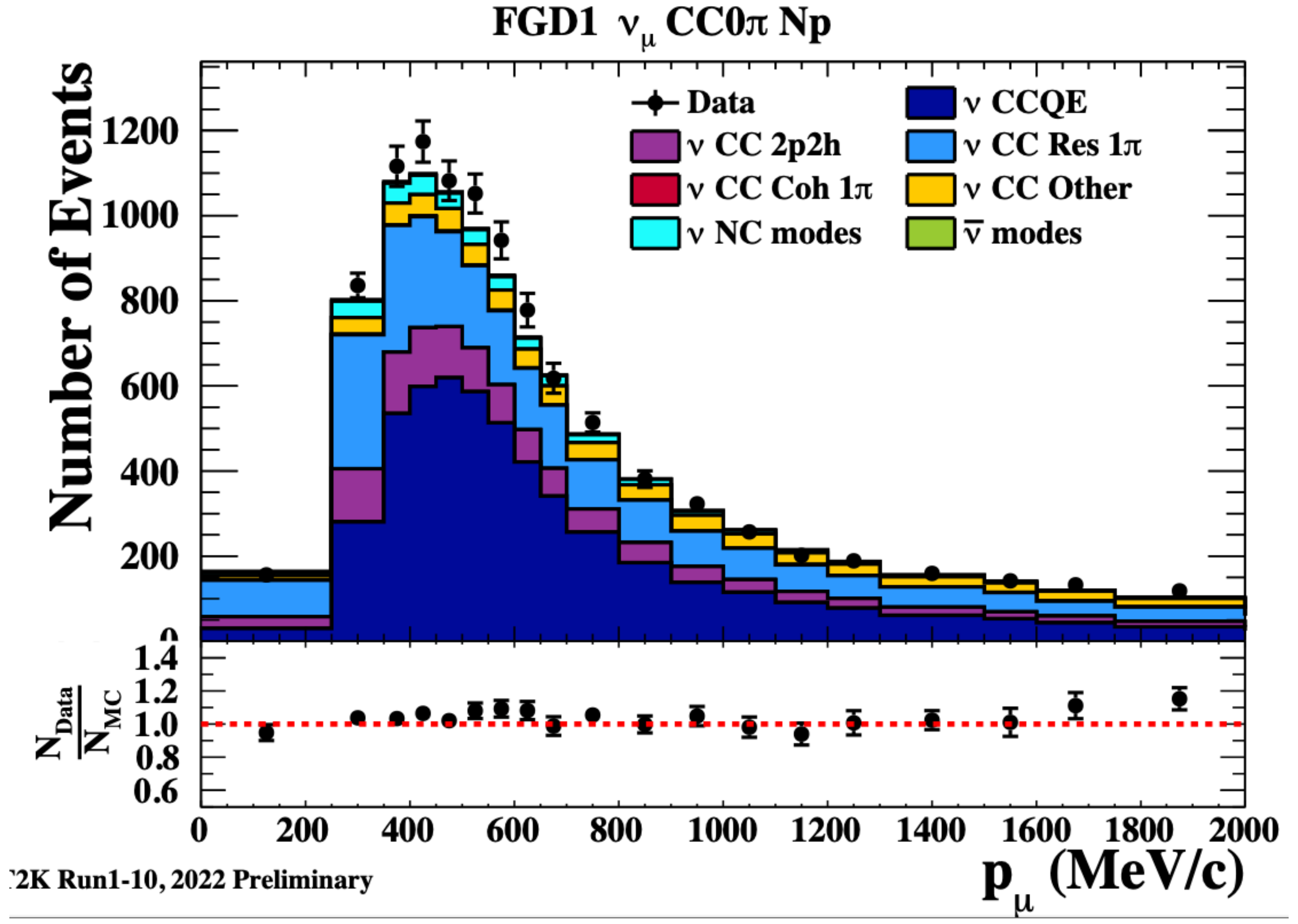


SK 1Rμ sample

ν_μ selections at ND280



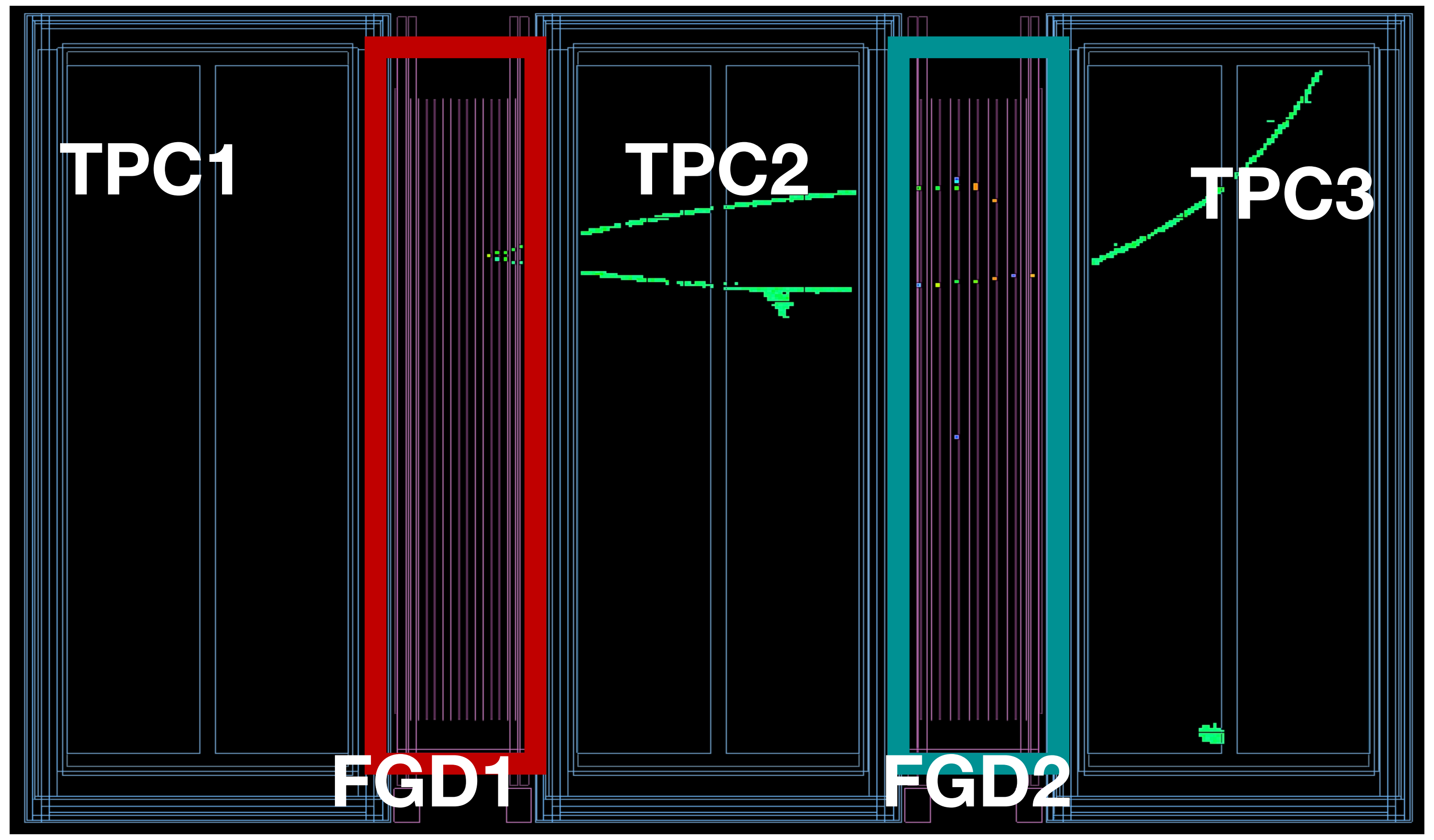




2K Run1-10, 2022 Preliminary

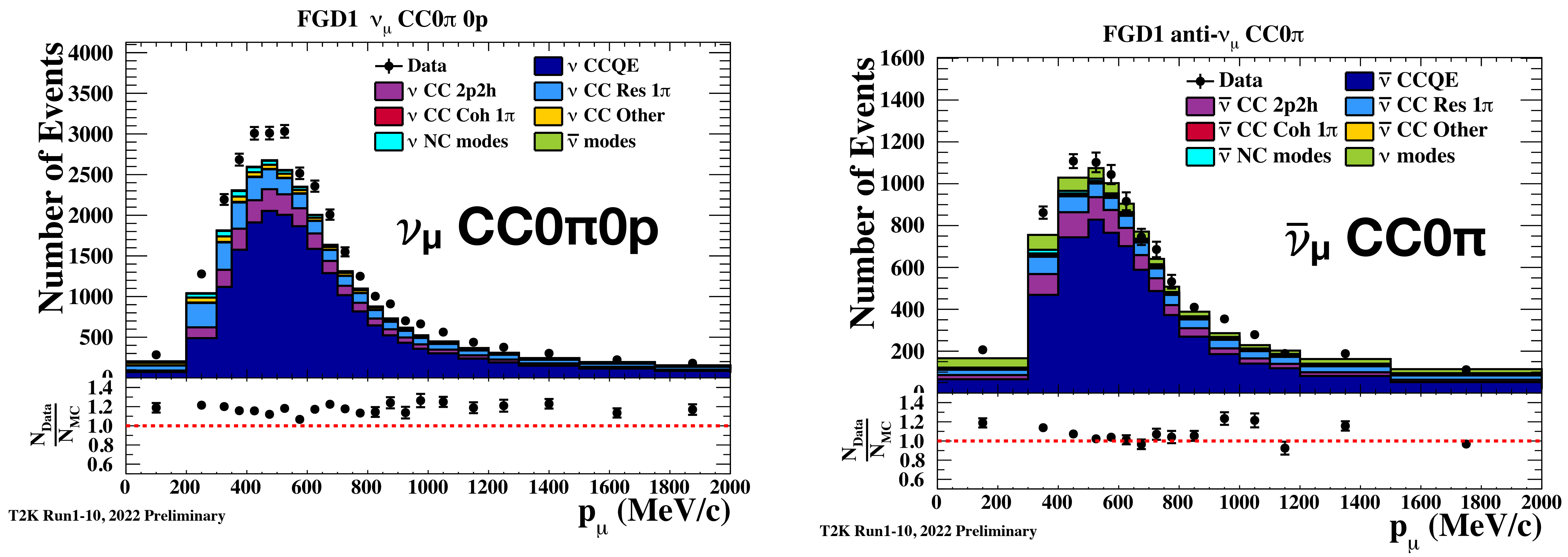
- ND280 is a magnetized detector
- Select neutrino and anti-neutrinos interactions by reconstructing muon charge
  - $\nu_\mu + n \rightarrow \mu^- + p$ while $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
- TPC PID (dE/dx vs P) is also used to select muons
- Reconstruct momentum and angle of the leptons in the TPCs

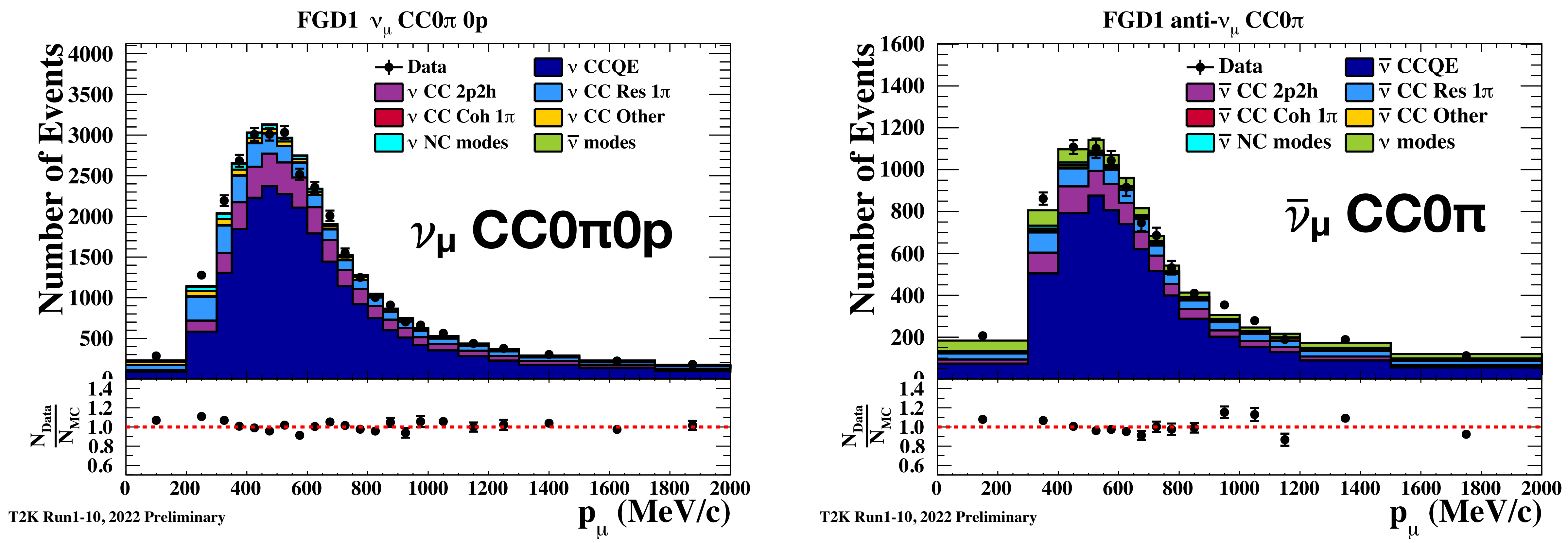
ND280 selections



- ND280 magnetized detector
- Select interactions on CH (FGD1) and CH/Water (FGD2)
- Precise measurement of P_μ and θ_μ with the TPCs
- Distinguish ν from $\bar{\nu}$ interactions thanks to the reconstruction of the charge of the lepton
- Separate samples based on number of reconstructed pions (CC0π, CC1π, CCNπ), protons, photons, etc → 22 samples in total are used in the fit

Before the fit

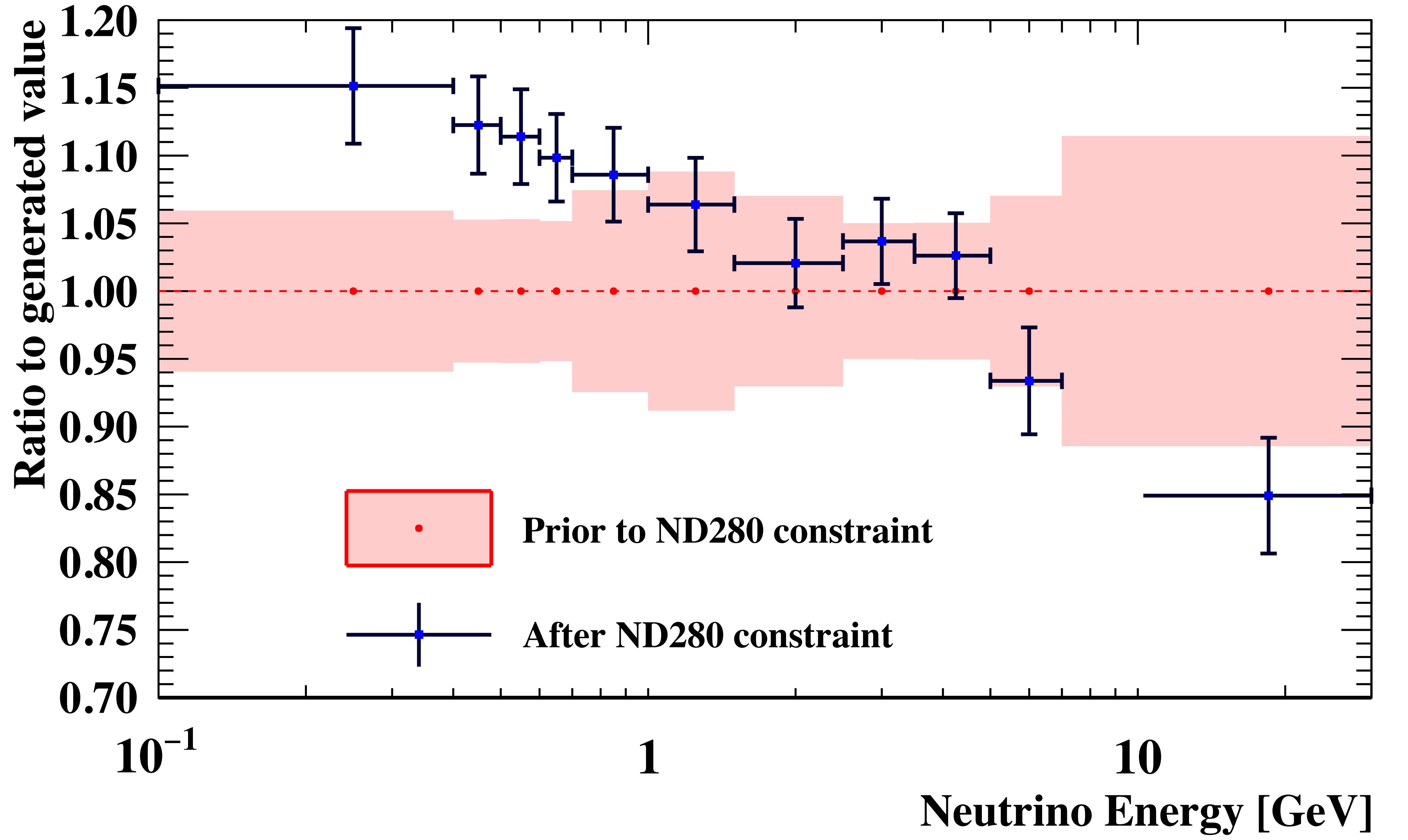




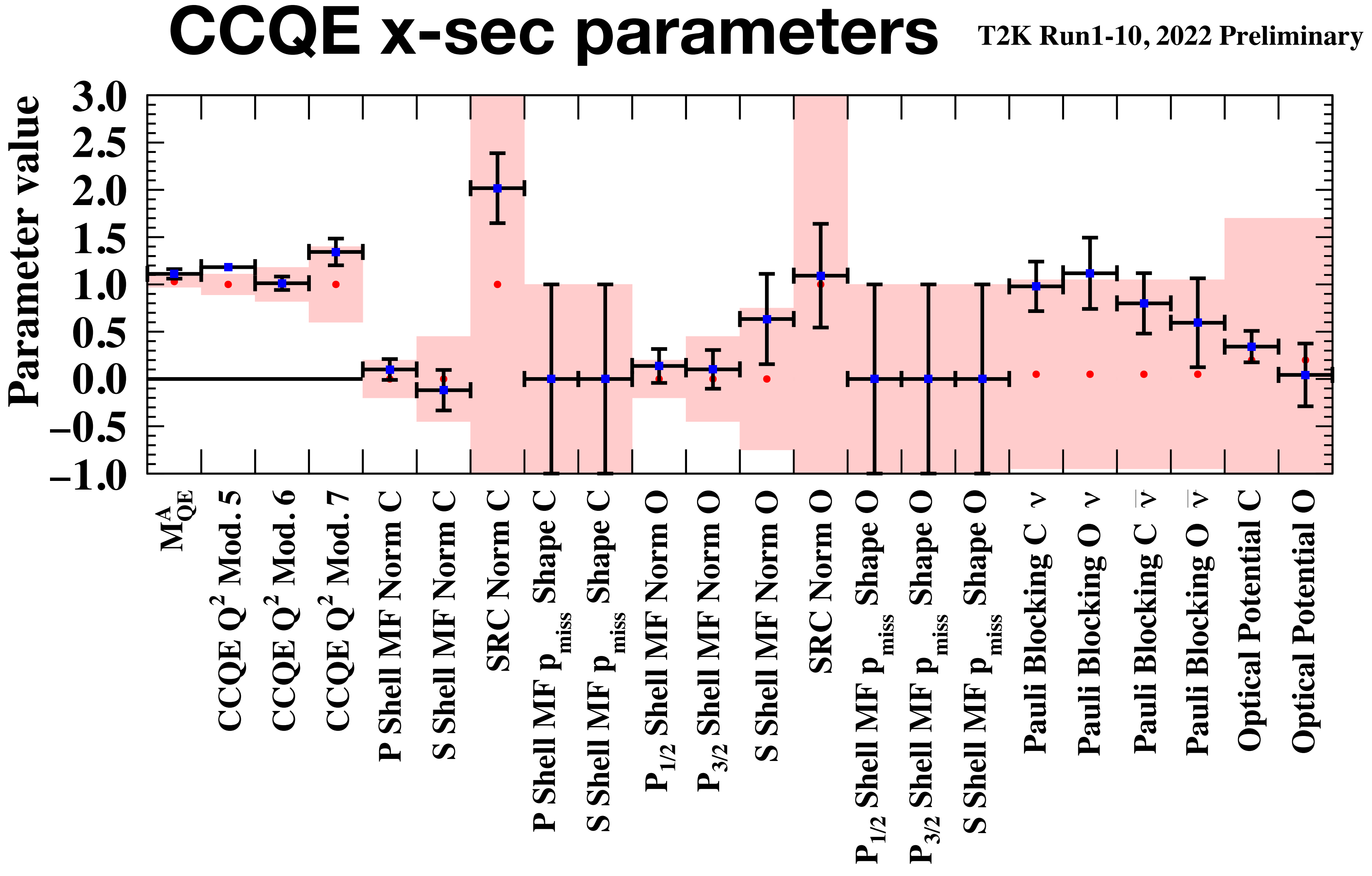
After the ND280 fit
Constraint flux and cross-section model

ND280 fit

ND280 ν-mode flux parameters



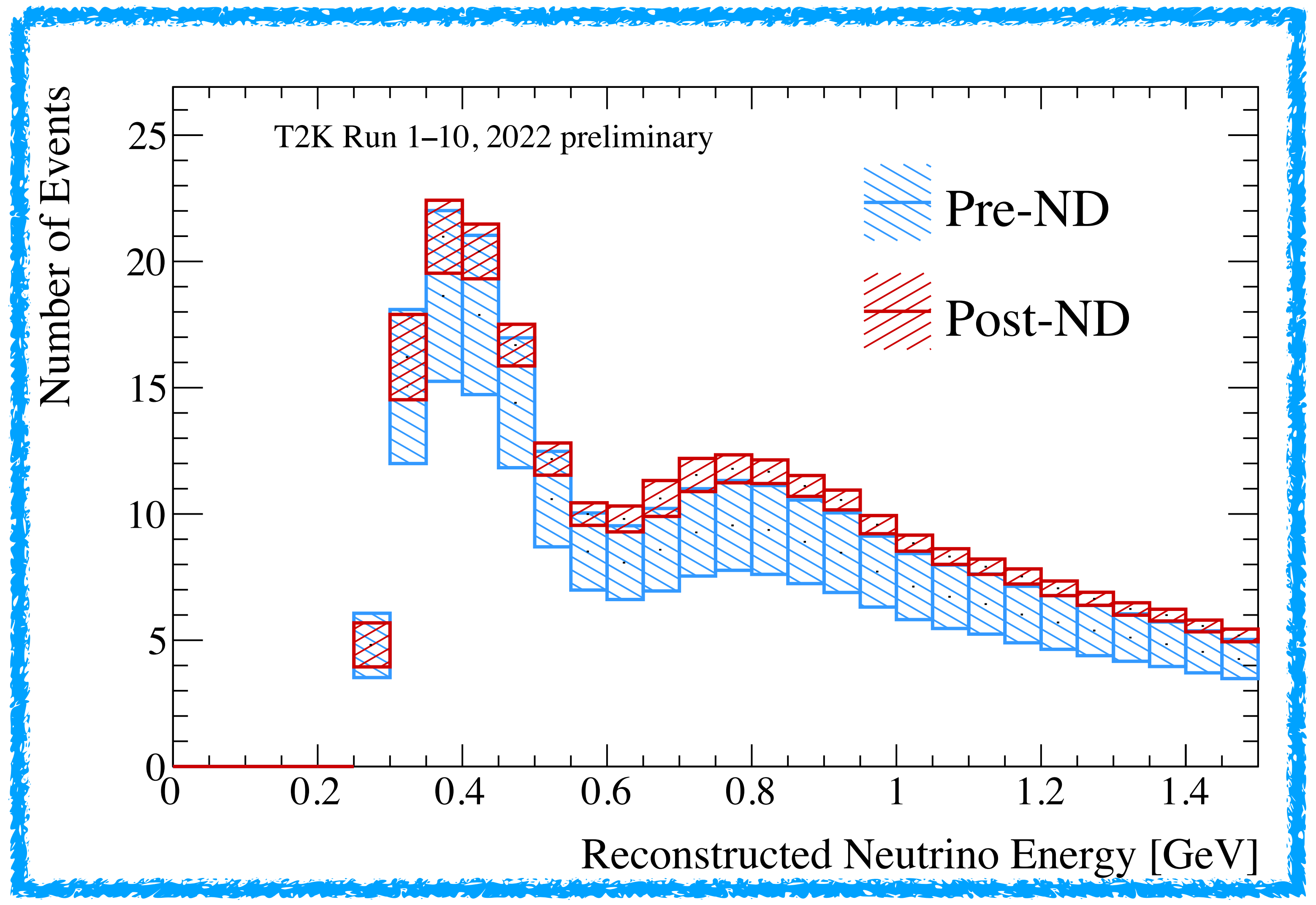
CCQE x-sec parameters



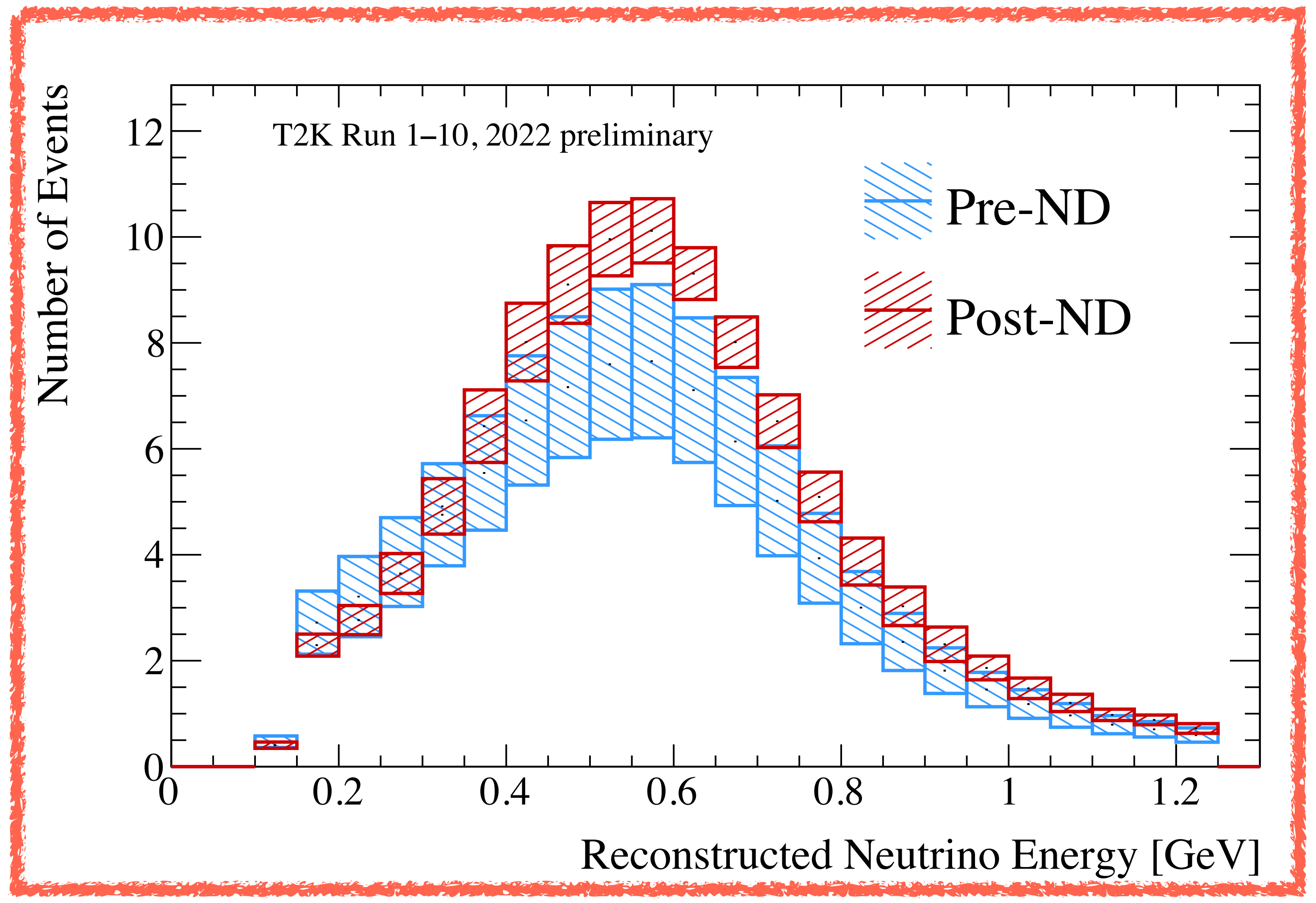
- Tune and reduce uncertainties from flux and cross-section systematics
- Correlate flux and cross-section to predict expected spectra at the Far Detector

Sample	Pre-ND fit	Post-ND fit
ν-mode 1Rμ	16.7%	3.4%
ν-mode 1Re	17.3%	5.2%
ν-mode MR	12.5%	4.9%
ν-mode 1Re+d.e.	20.9%	14.3%
$\bar{\nu}$-mode 1Rμ	14.6%	3.9%
$\bar{\nu}$-mode 1Re	14.4%	5.8%

SK Single ring μ-like sample

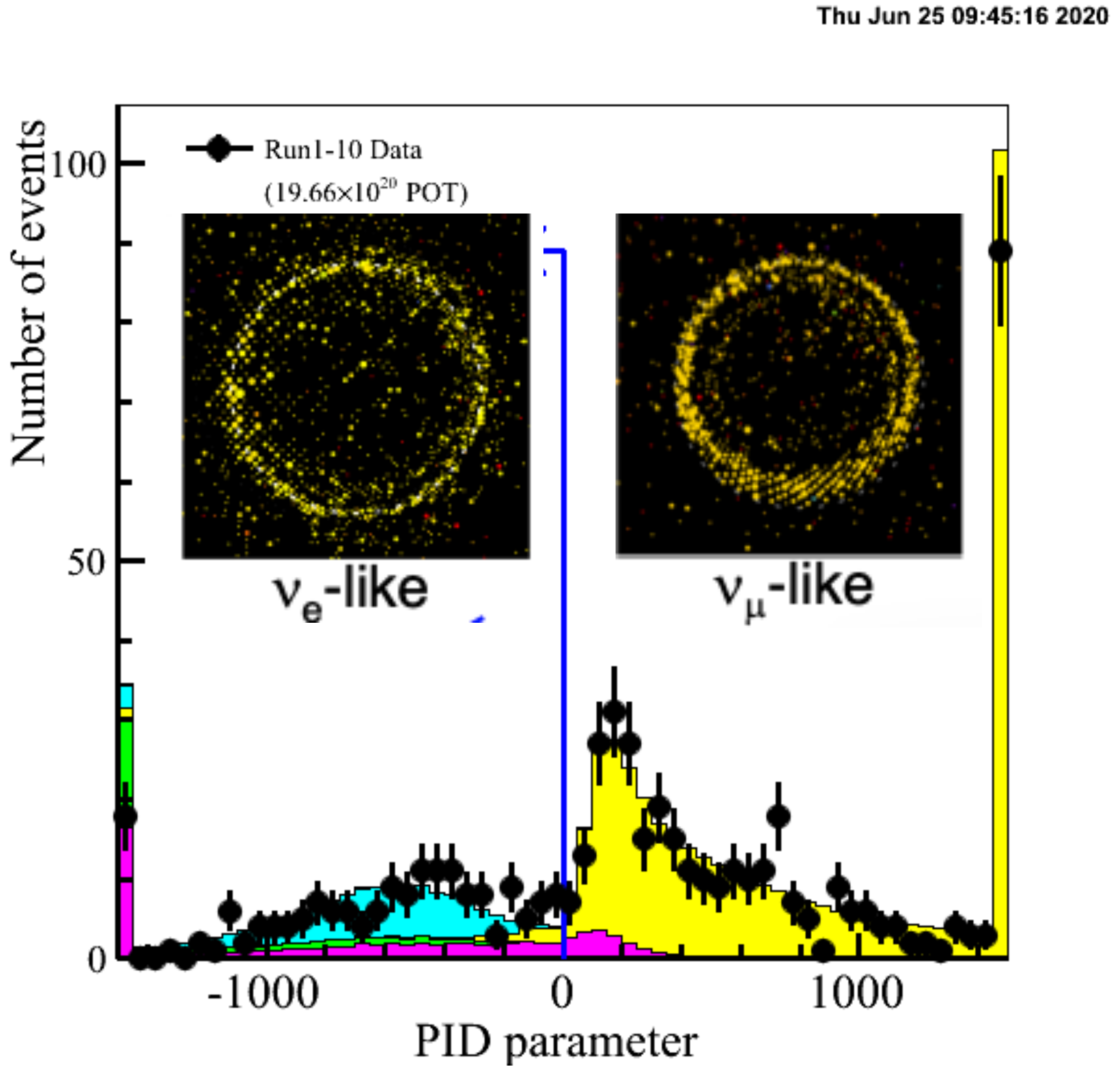


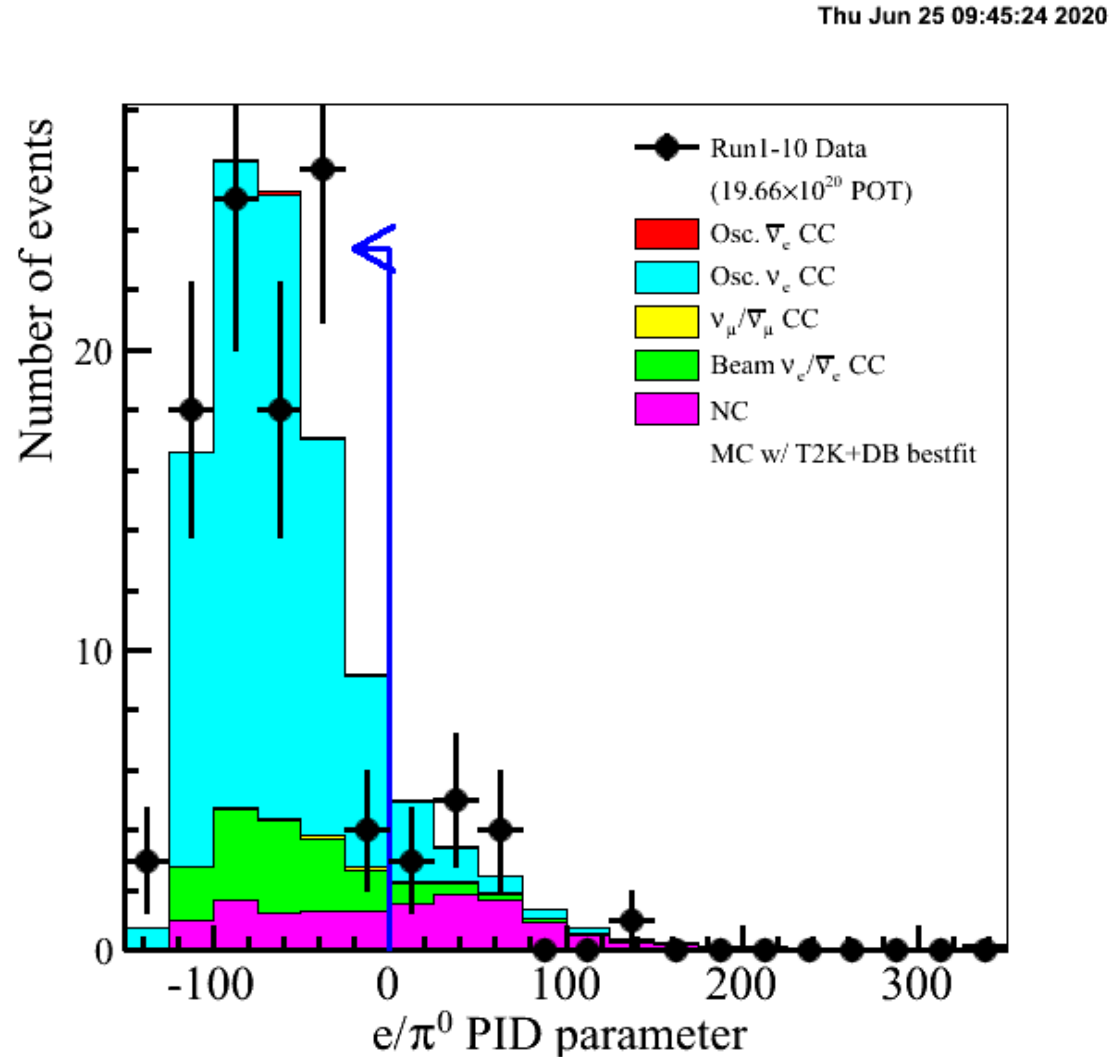
SK single ring e-like sample

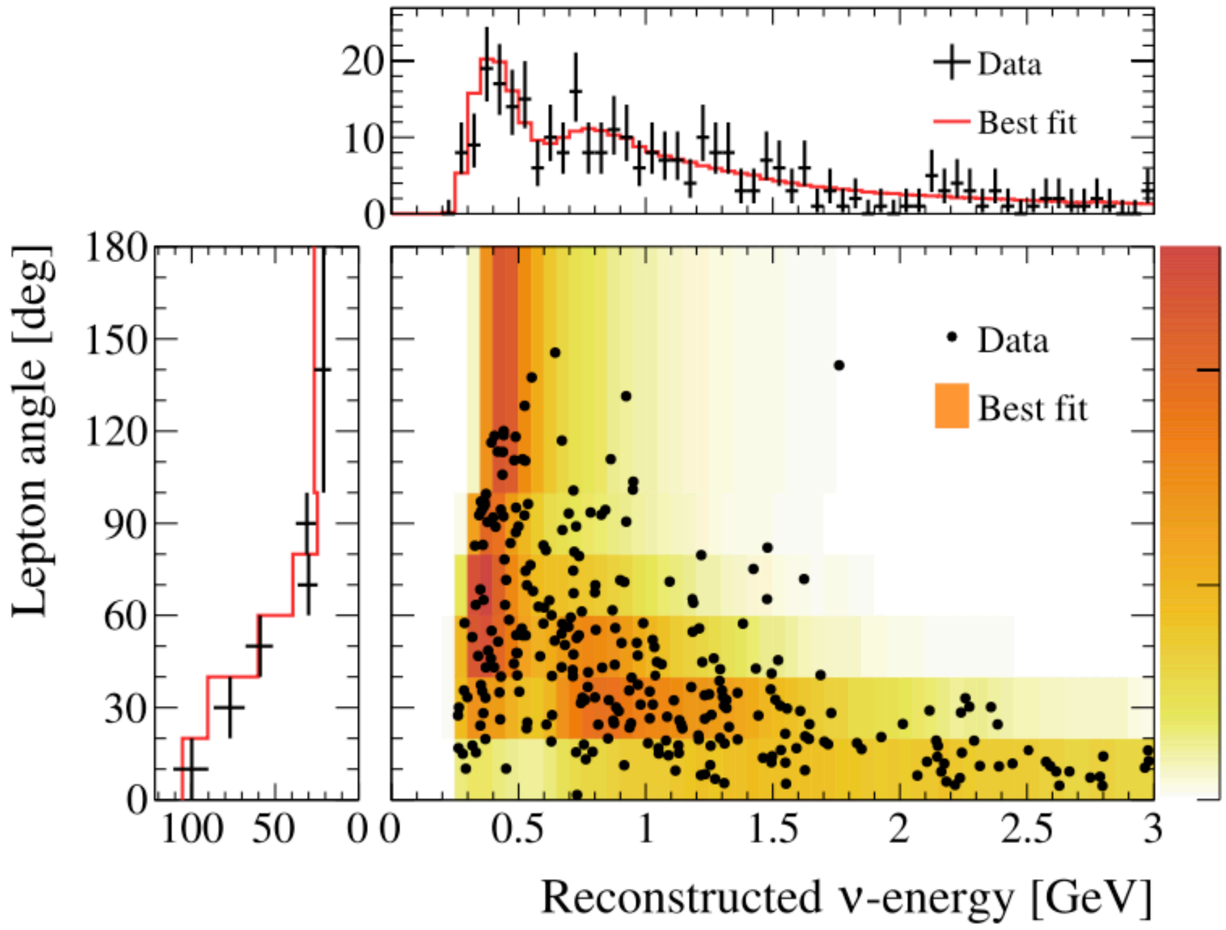


SK selections

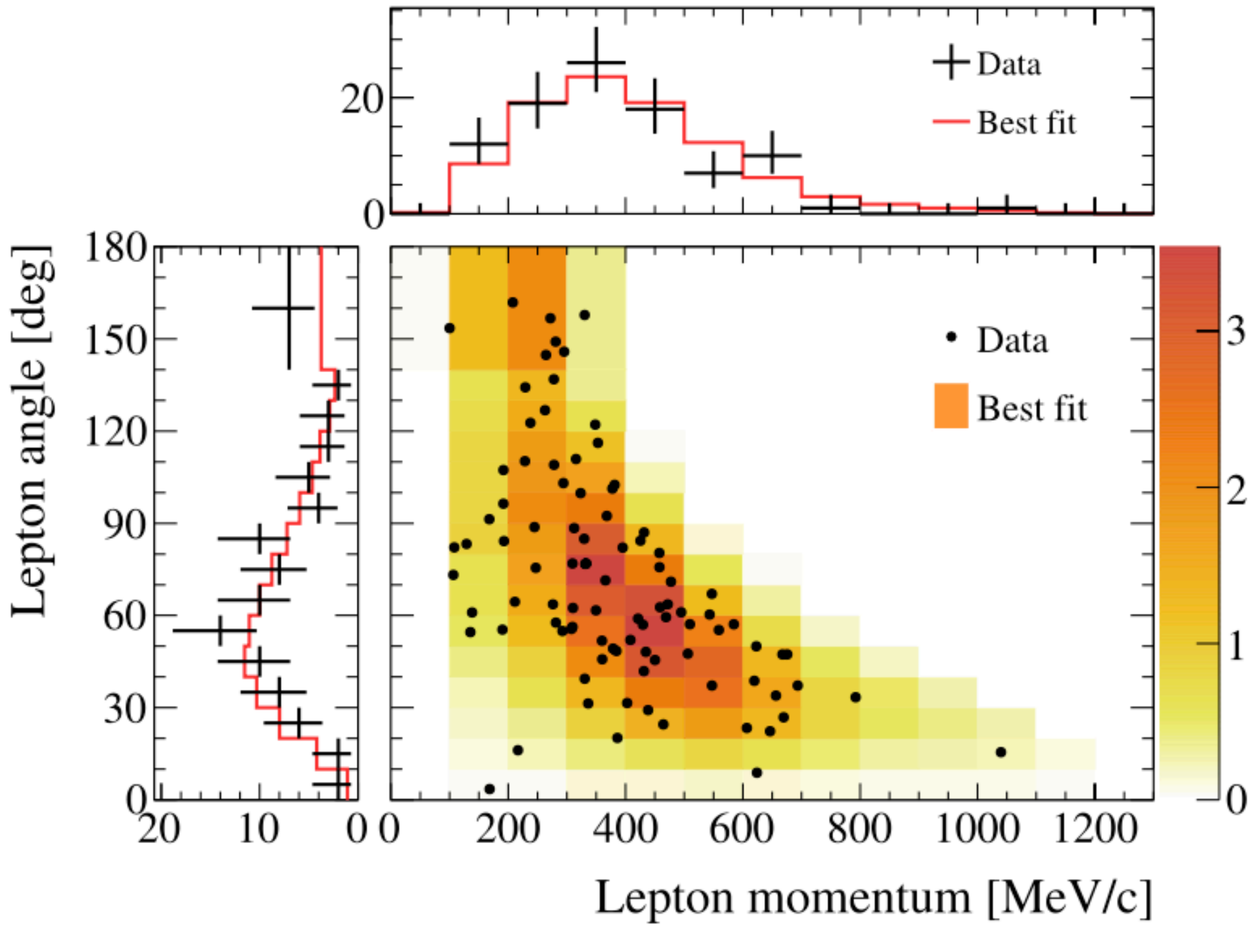
- Single ring (mostly CCQE)
- PID to distinguish e from μ and e from π^0
- Reconstruct momentum and angle of the lepton → neutrino energy through QE formula



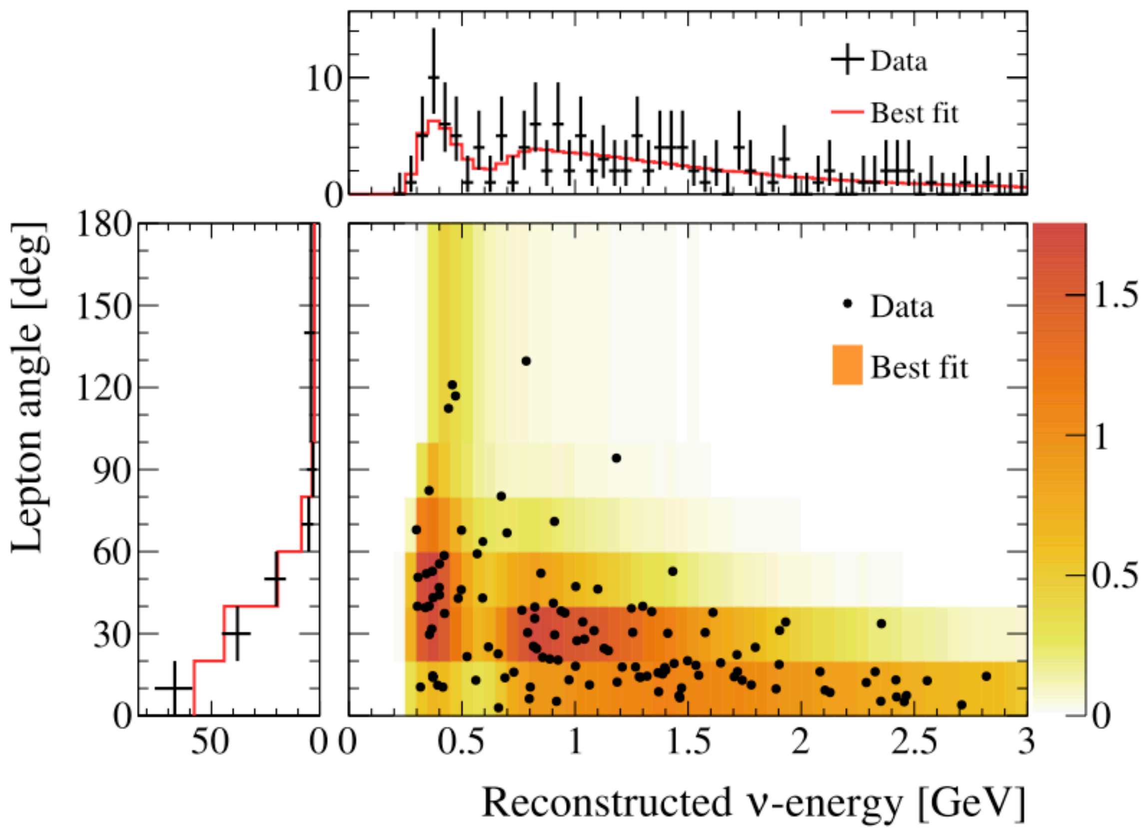




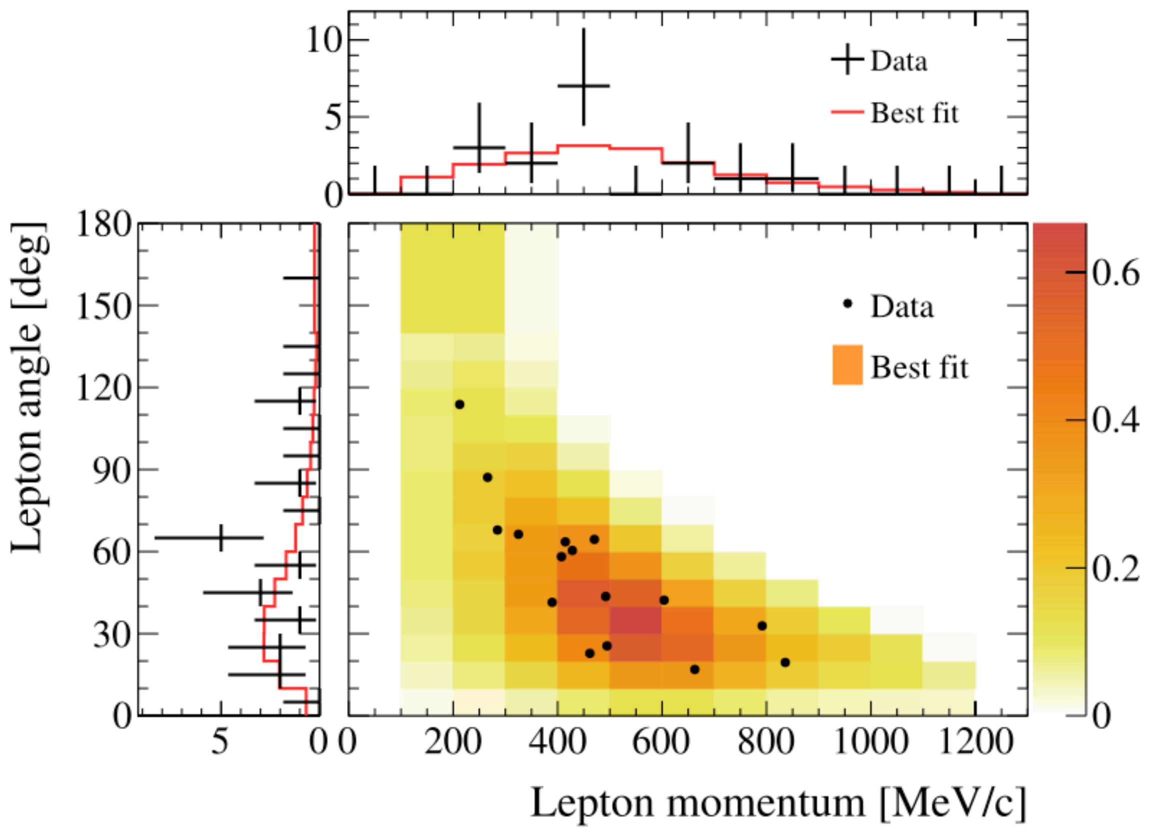
ν-mode 1 Rμ



ν-mode 1 Re



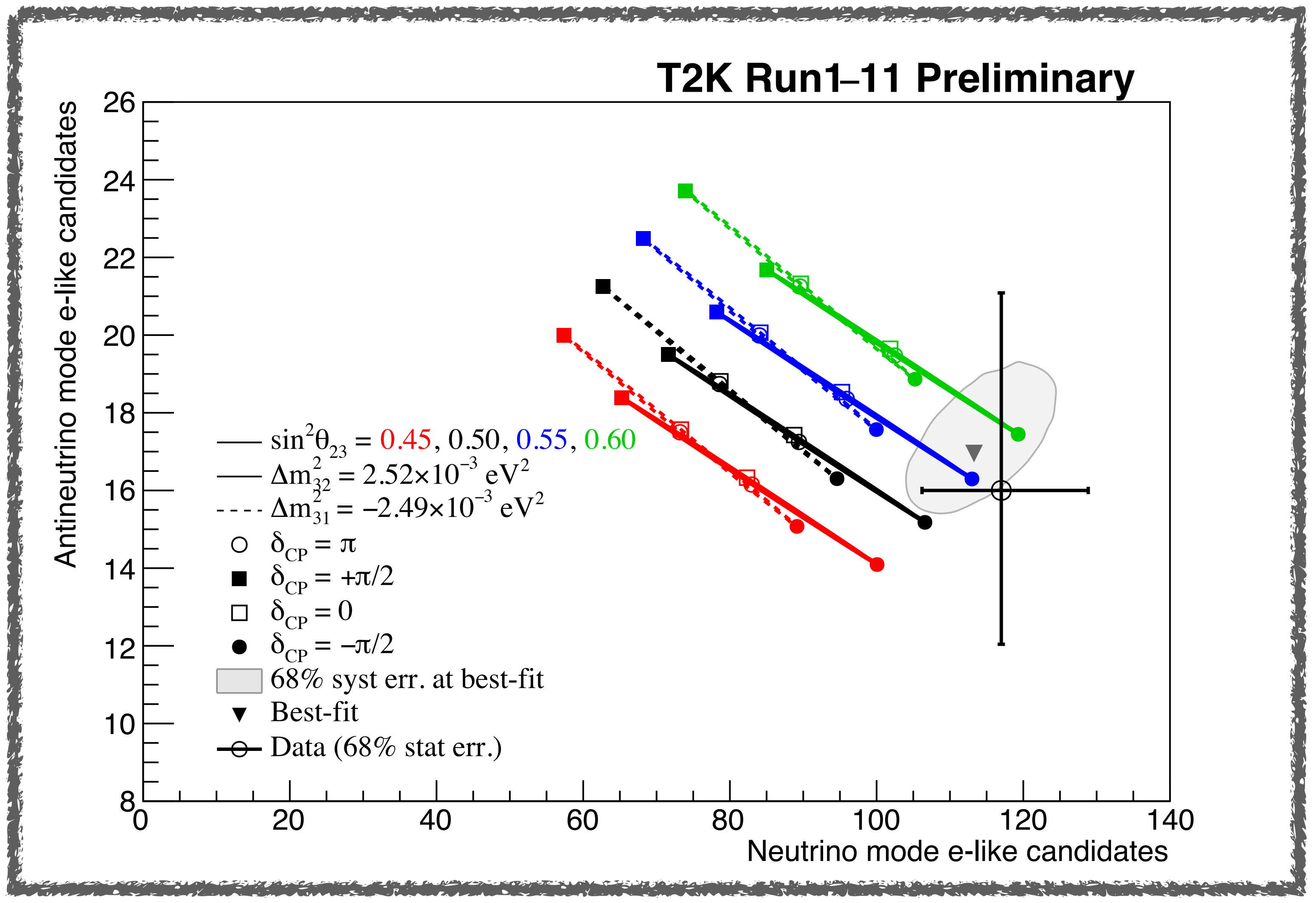
$\bar{\nu}$-mode 1 Rμ



$\bar{\nu}$-mode 1 Re

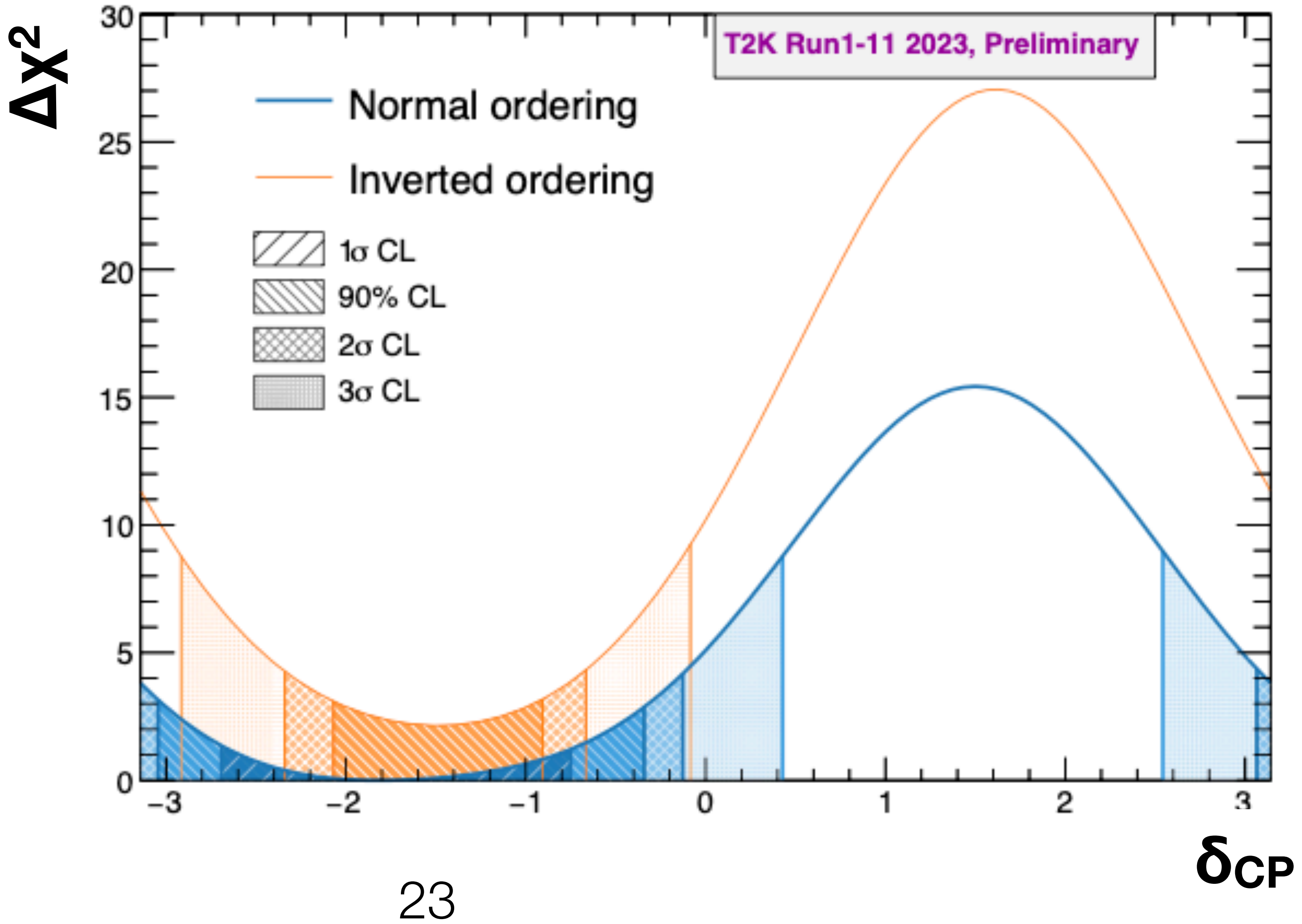
Oscillation analysis results

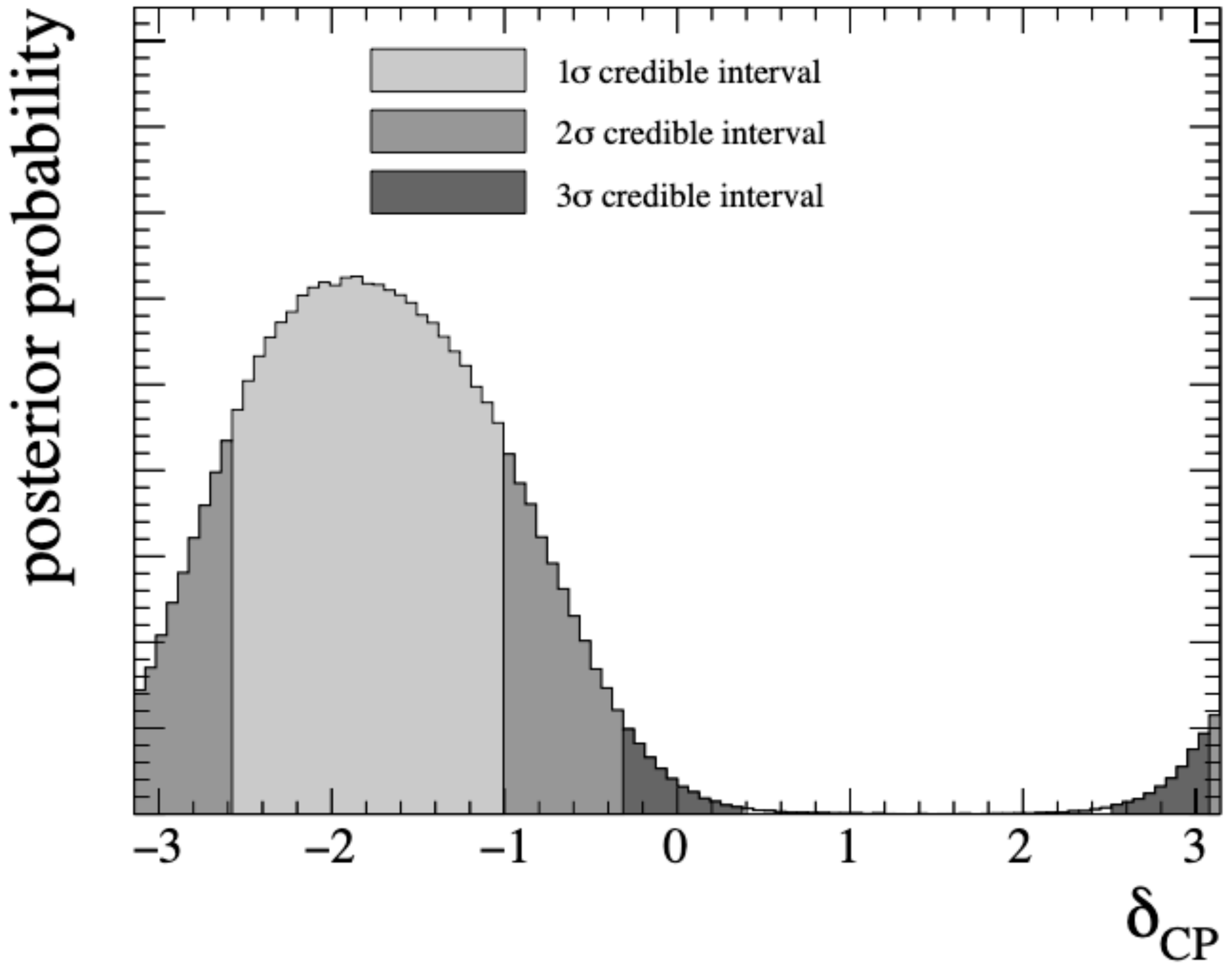
Sample	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Data
ν-mode 1Rμ	417.2	416.3	417.1	418.2	357
ν-mode MR	123.9	123.3	123.9	124.4	140
$\bar{\nu}$-mode 1Rμ	146.6	146.3	146.6	147.0	137
ν-mode 1Re	113.2	95.5	78.3	96.0	102
$\bar{\nu}$-mode 1Re+d.e.	10.0	8.8	7.2	8.4	15
$\bar{\nu}$-mode 1Re	17.6	20.0	22.2	19.7	16



Credible intervals marginalized over both hierarchies

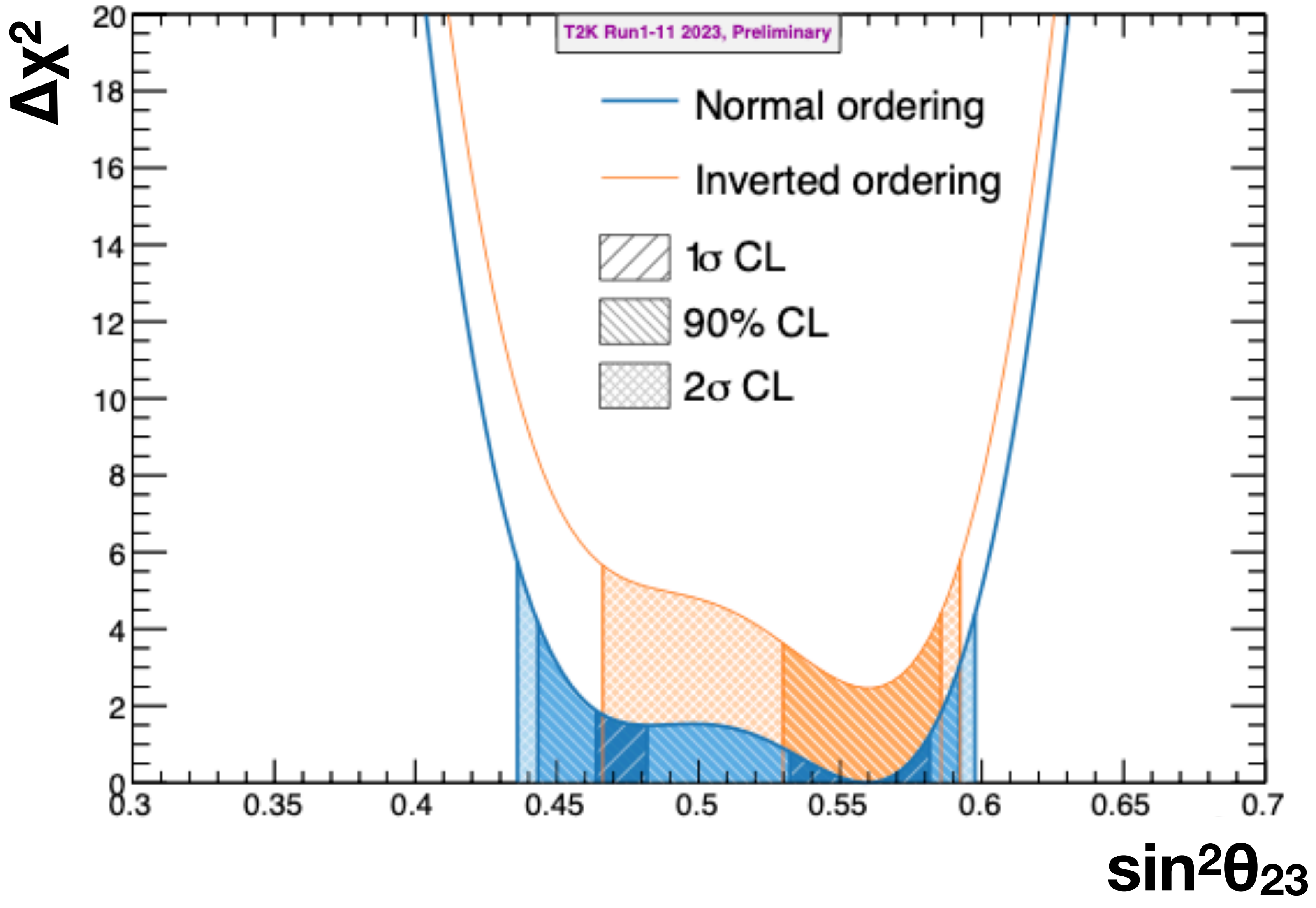
- Preference for δ_{CP}~-π/2 but CP conserving values are within the 2σ interval

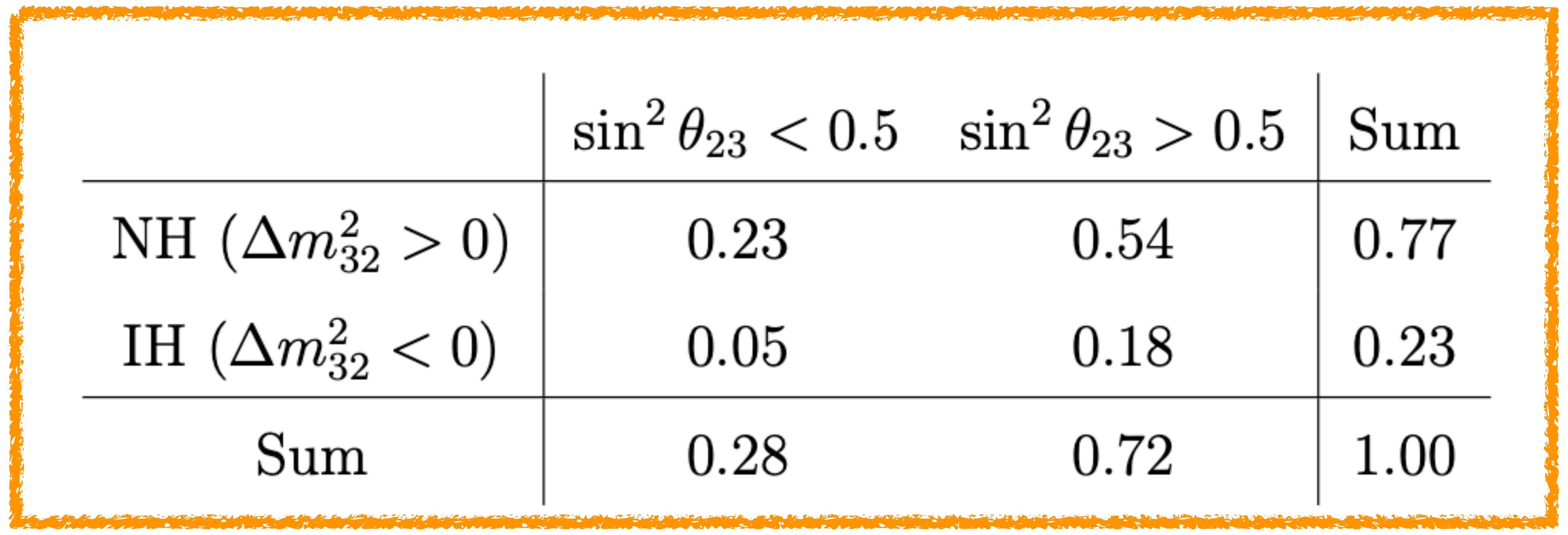




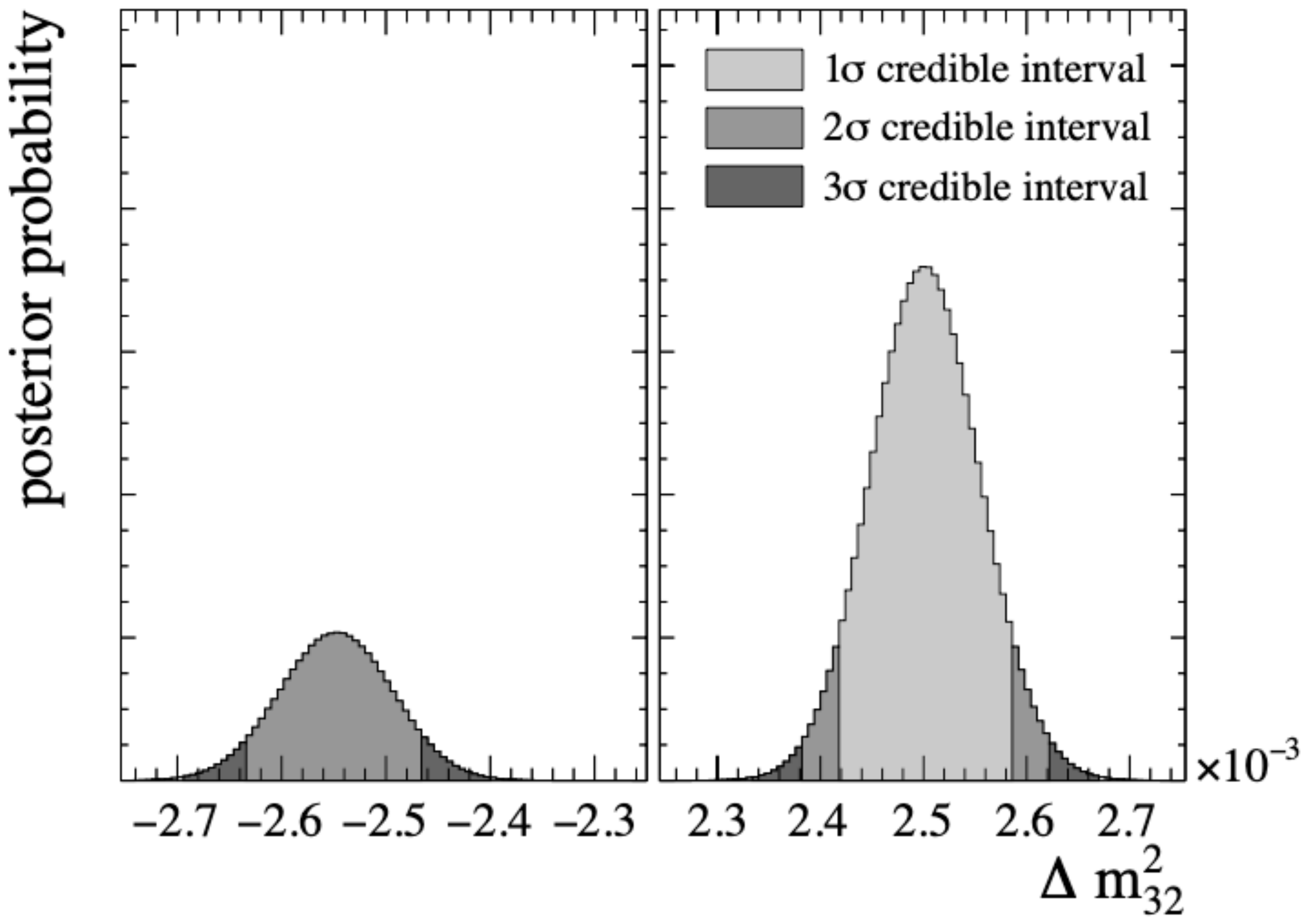
Mass ordering and θ_{23} octant

- Slight preference for normal ordering and upper octant but none of them is significant
  - Bayes factor NO/IO = 3.3
  - Bayes factor (θ_{23}>0.5)/(θ_{23}<0.5) = 2.6



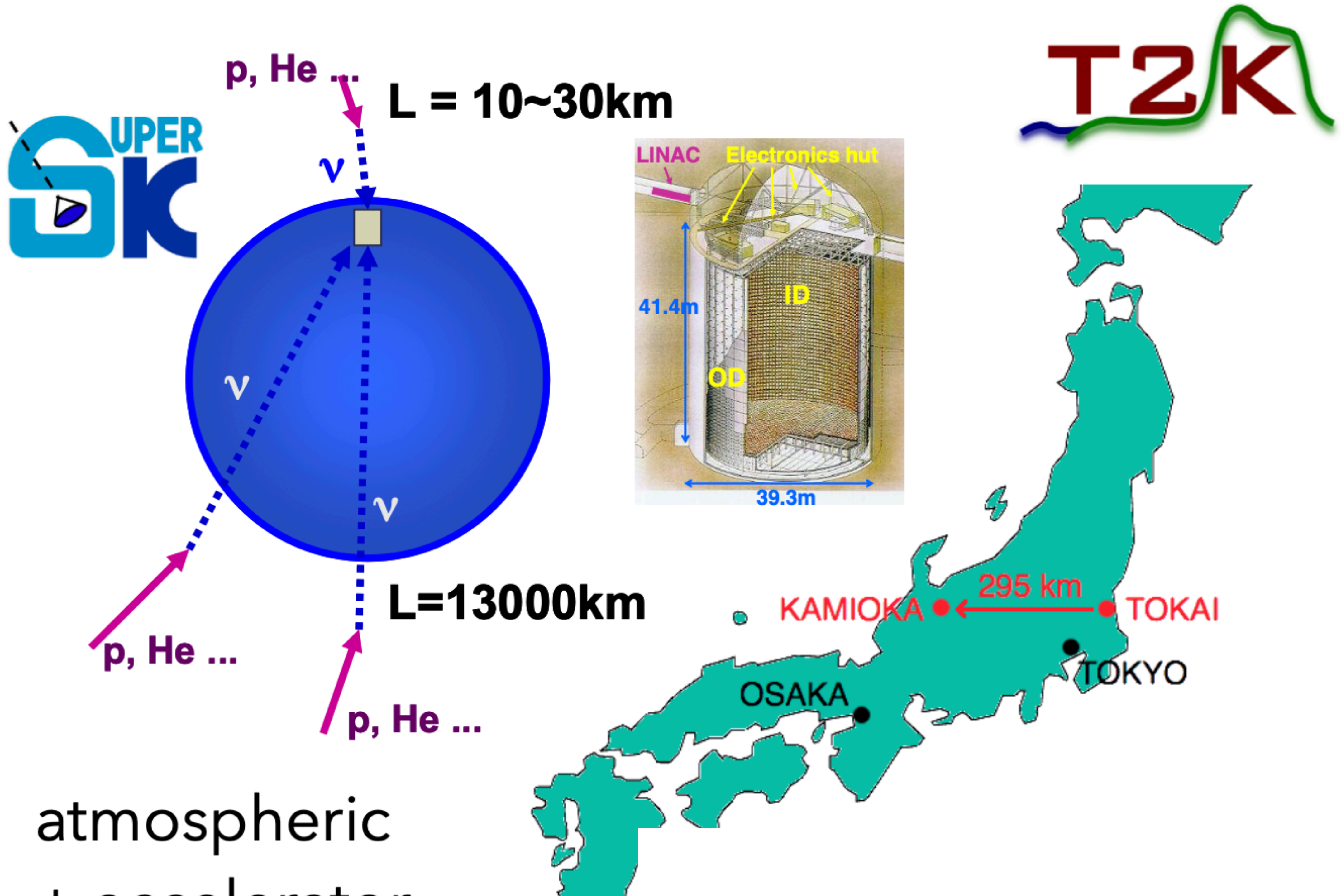


	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.23	0.54	0.77
IH ($\Delta m^2_{32} < 0$)	0.05	0.18	0.23
Sum	0.28	0.72	1.00



Joint analyses

- In 2023 we released two joint analyses
- T2K+NOvA combination → in back-up if you are interested don't hesitate to ask!
- T2K+SK combination



atmospheric
+ accelerator

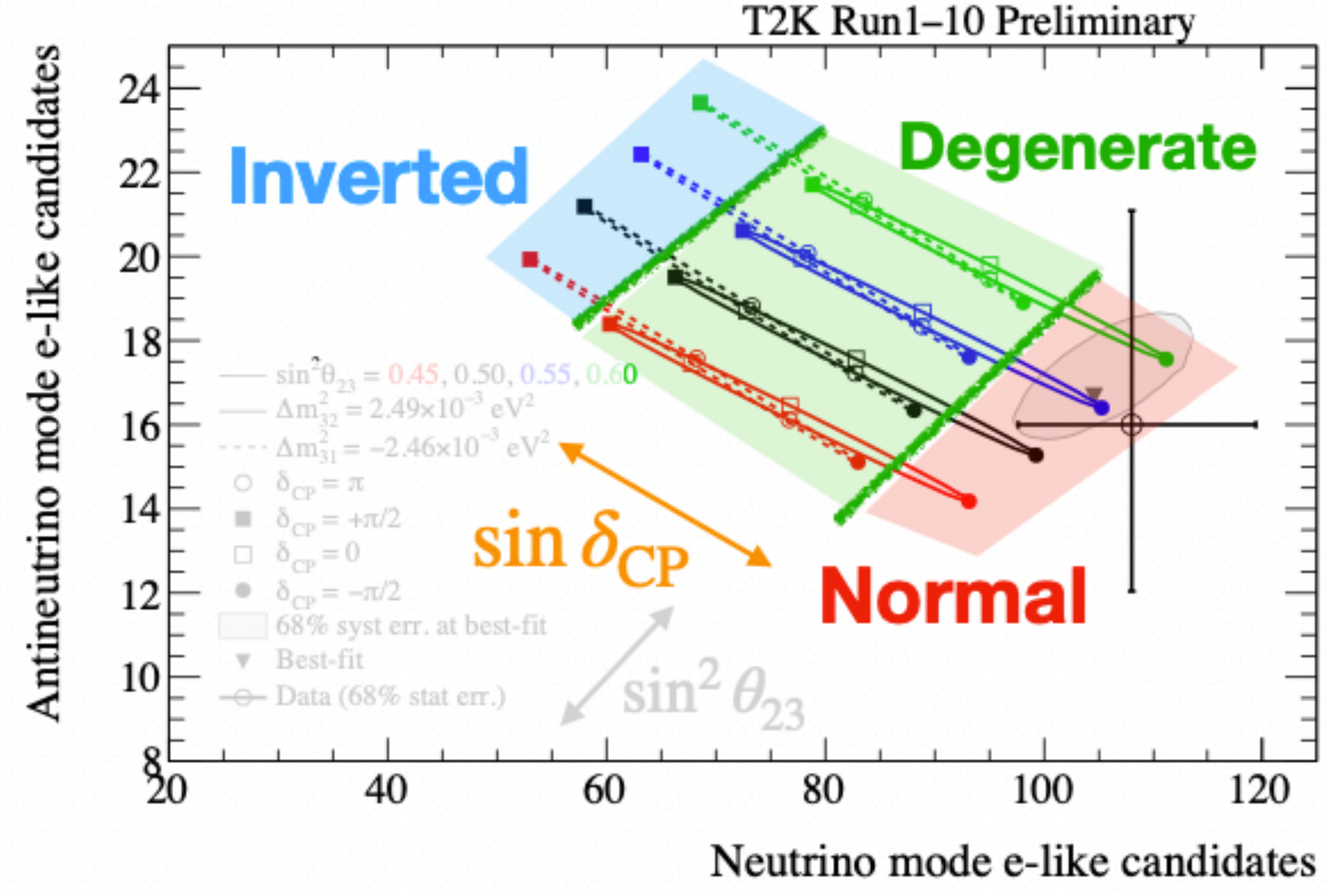
Complementary information

T2K data as in Phys.Rev.D 108 (2023) 7, 072011 - (5 samples) POT: 3.6 x 10^{21}

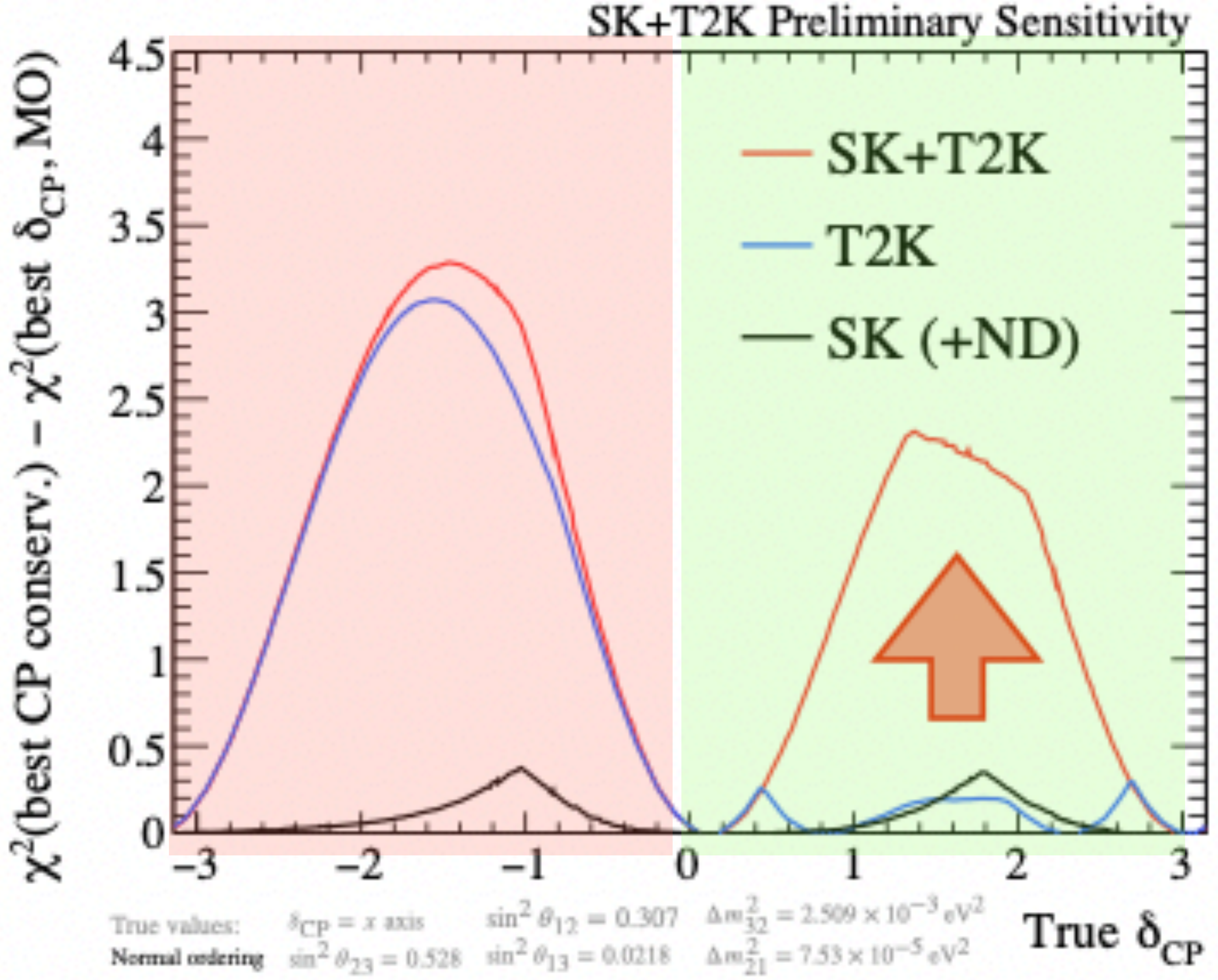
SK-IV data (18 samples) before Gd doping PTEP 2019 (2019) 5, 053F01 - 3244 days (2008-2018)

T2K+SK joint analysis

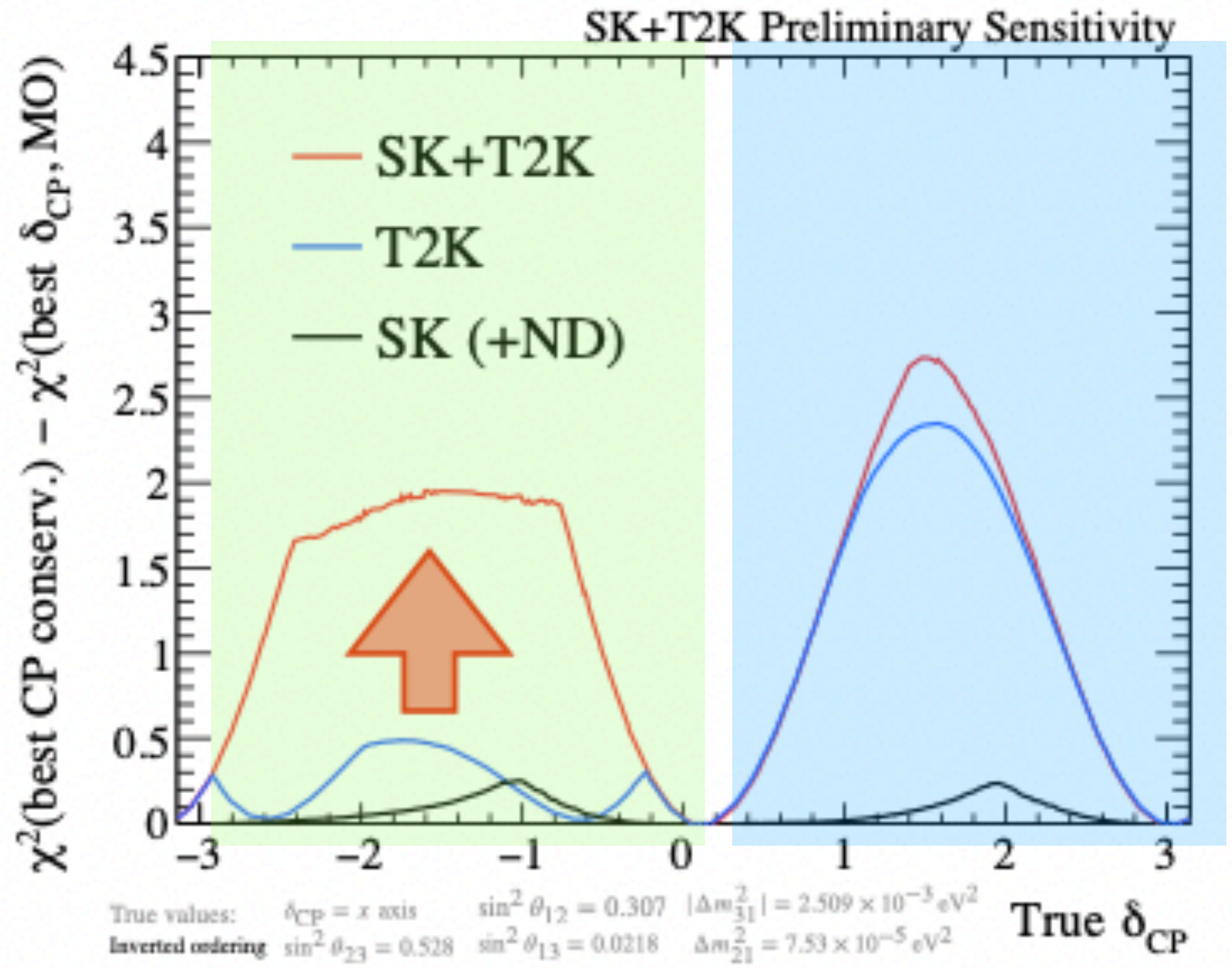
- T2K has good sensitivity to δ_{CP} but mild sensitivity to mass ordering
- SK has good constraint on mass ordering but not on δ_{CP}
- Adding SK atmospheric sample allows to break the degeneracies between the CP violation parameter δ_{CP} and the mass ordering → boost sensitivity to CP



True Normal Ordering



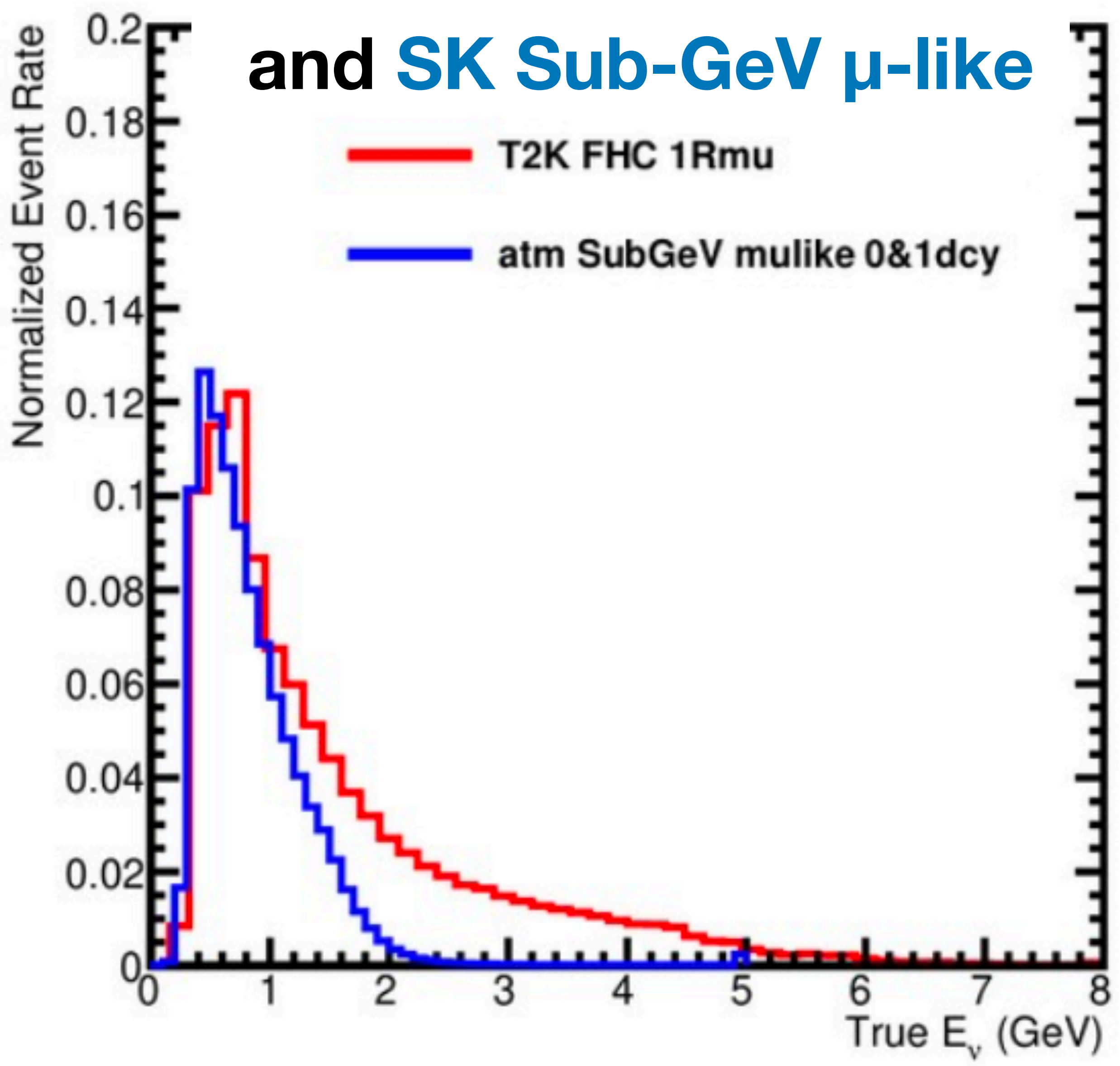
True Inverted Ordering



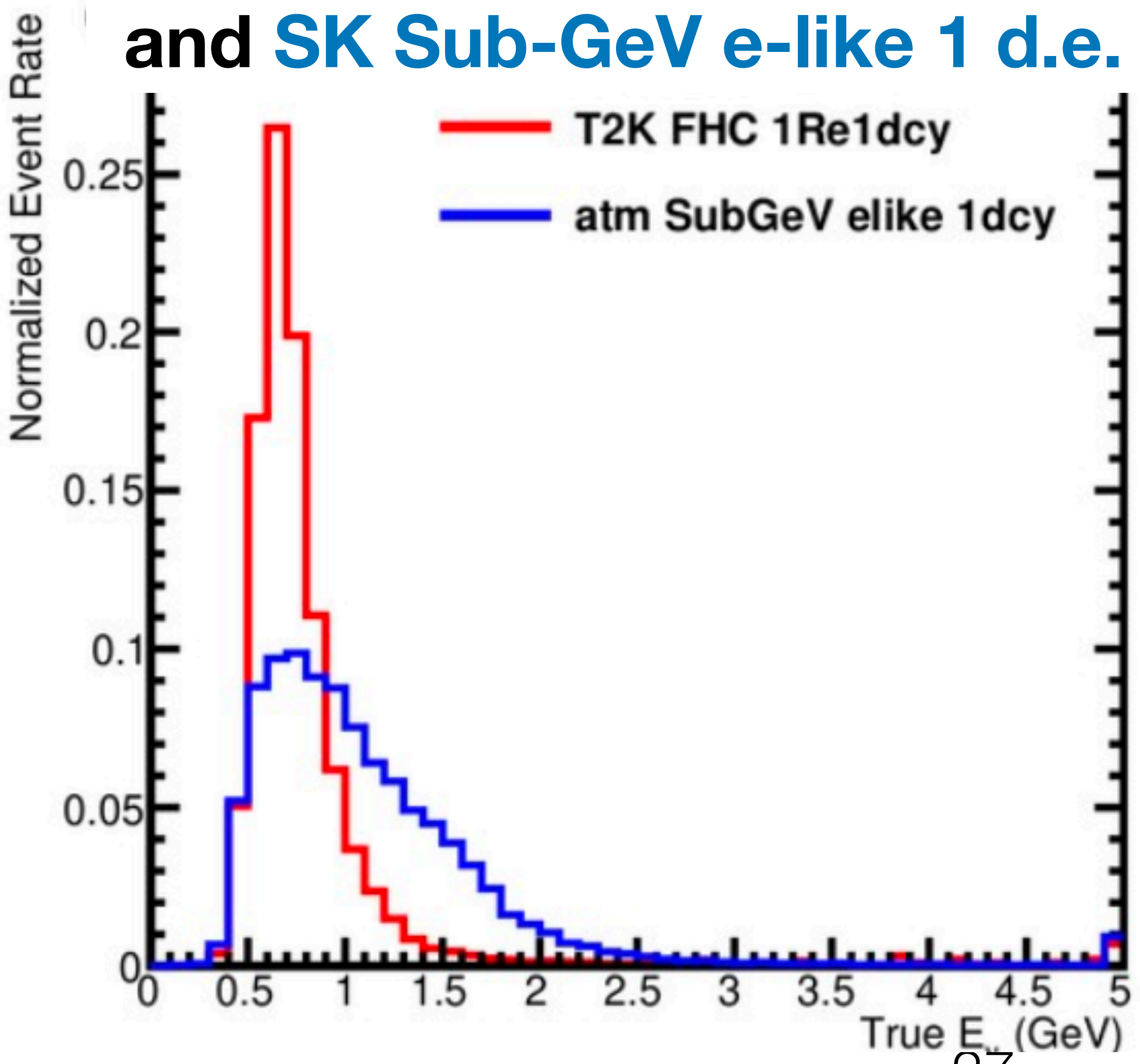
T2K+SK model

- Same far detector → unify model and systematic uncertainties when necessary
  - Evaluate correlations in detector systematics between the T2K beam and SK atmospheric samples
  - Develop unified interaction model for T2K beam and SK low-energy samples covering similar energy region

True Eν T2K 1 Rμ sample and SK Sub-GeV μ-like



True Eν T2K 1 Re+d.e. sample and SK Sub-GeV e-like 1 d.e.



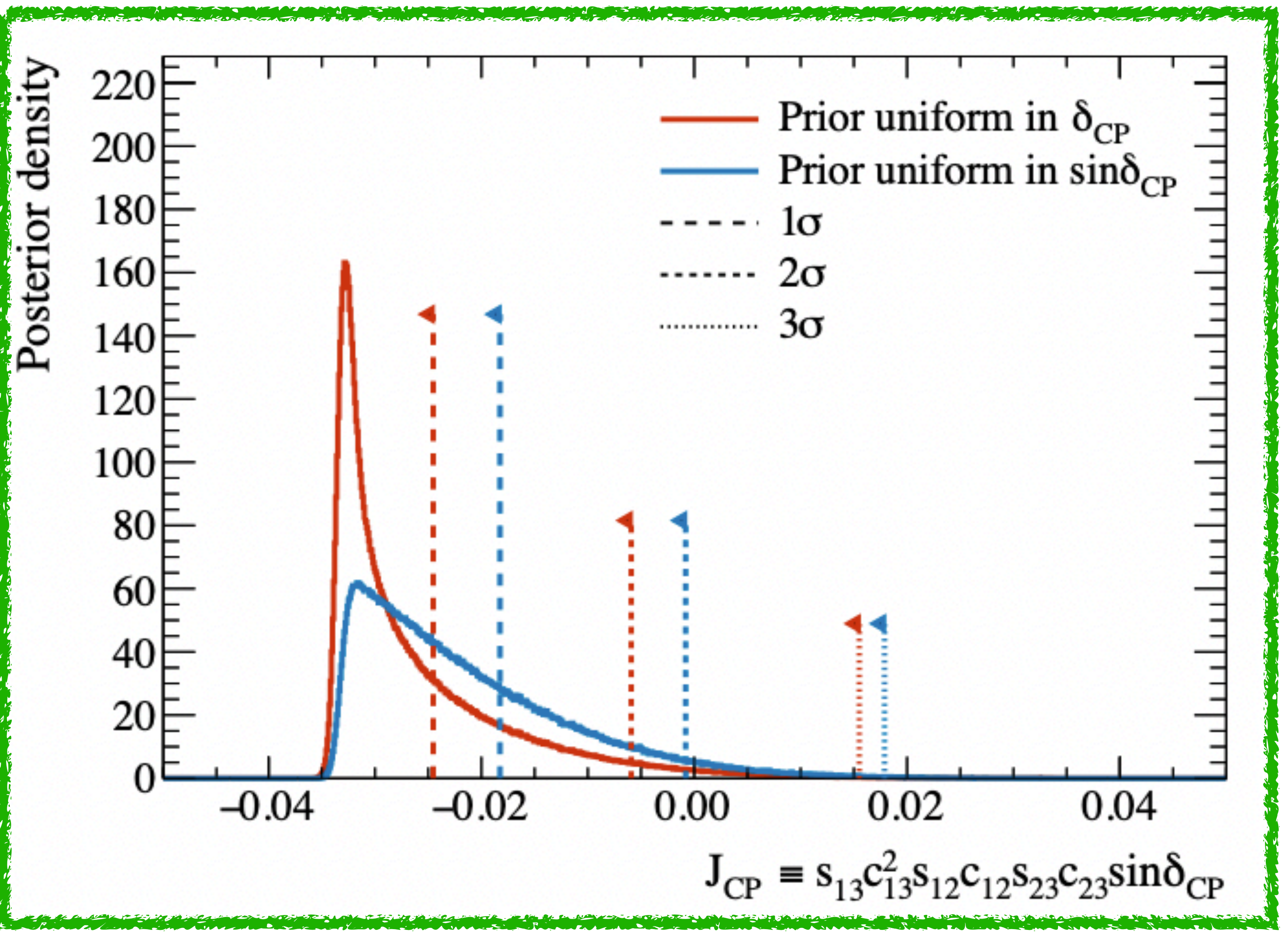
ND280 data used to constraint the cross-section model for SK low-energy samples

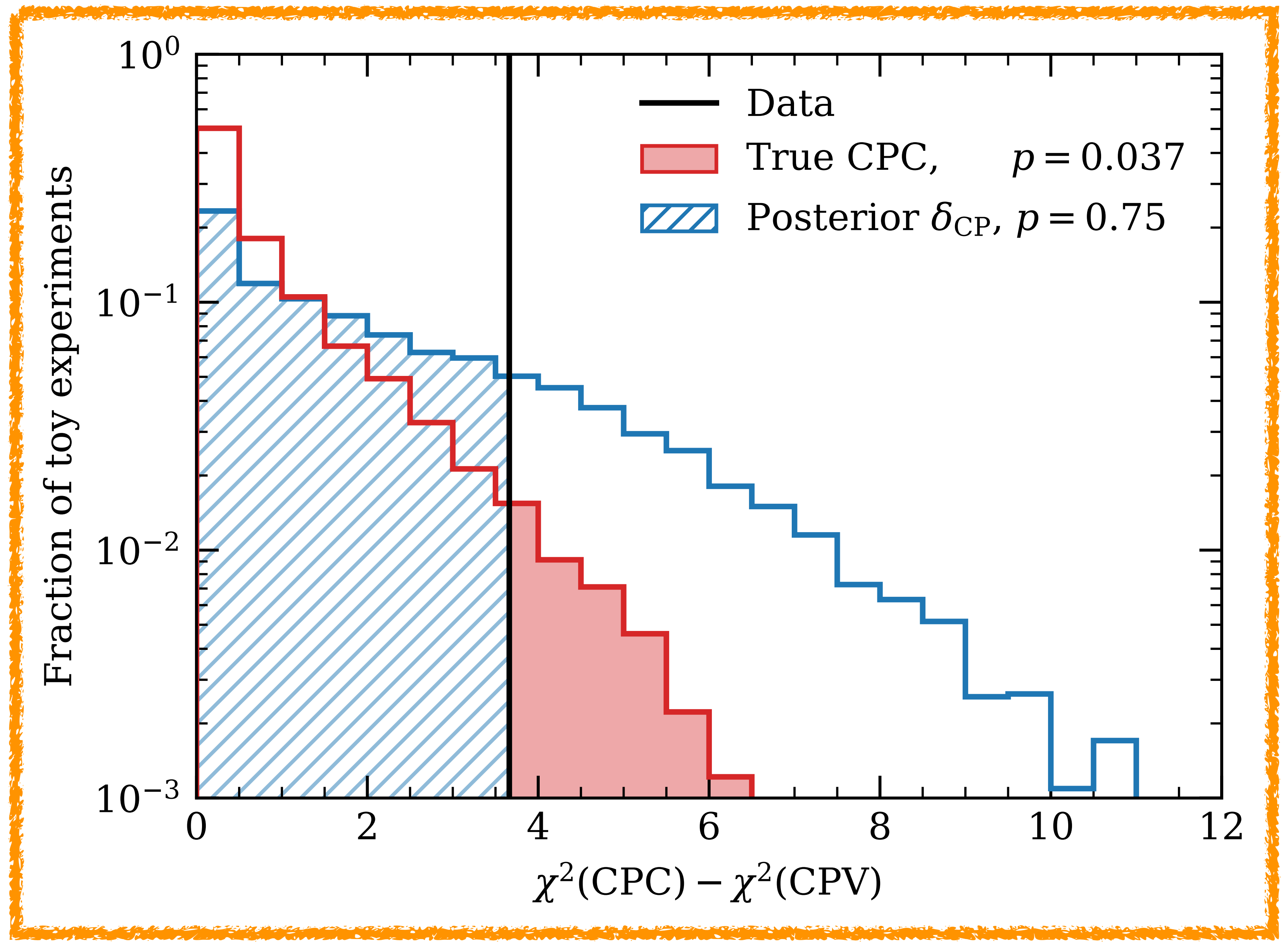
	Low-energy sub-GeV atm + beam	**High-energy** multi-GeV atm
CCQE	T2K model with ND280 constraint, correlated in low-E/highE (except for high-Q^2)	
	high-Q^2 params w/ND280	high-Q^2 params w/o ND
	add ν_e/ν_μ ratio unc. (CRPA)	
2p2h	T2K model w/ND280	SK model (100% error) + T2K-style shape
Resonant	T2K model w/ND280 + new pion momentum dial + NC1π0 uncertainties	SK model for 3 dials common with T2K, use more recent larger T2K priors
DIS	T2K model w/ND280	SK model
ν_τ	SK model (25% norm on top of other syst) for other systematics checked that we have no numerically unstable values	
FSI	T2K model w/ND280	T2K model w/o ND280 should be mostly same as SK model
SI	T2K model, correlated in low-E/high-E only applied to FC and PC for atm, PN not applied to atm	

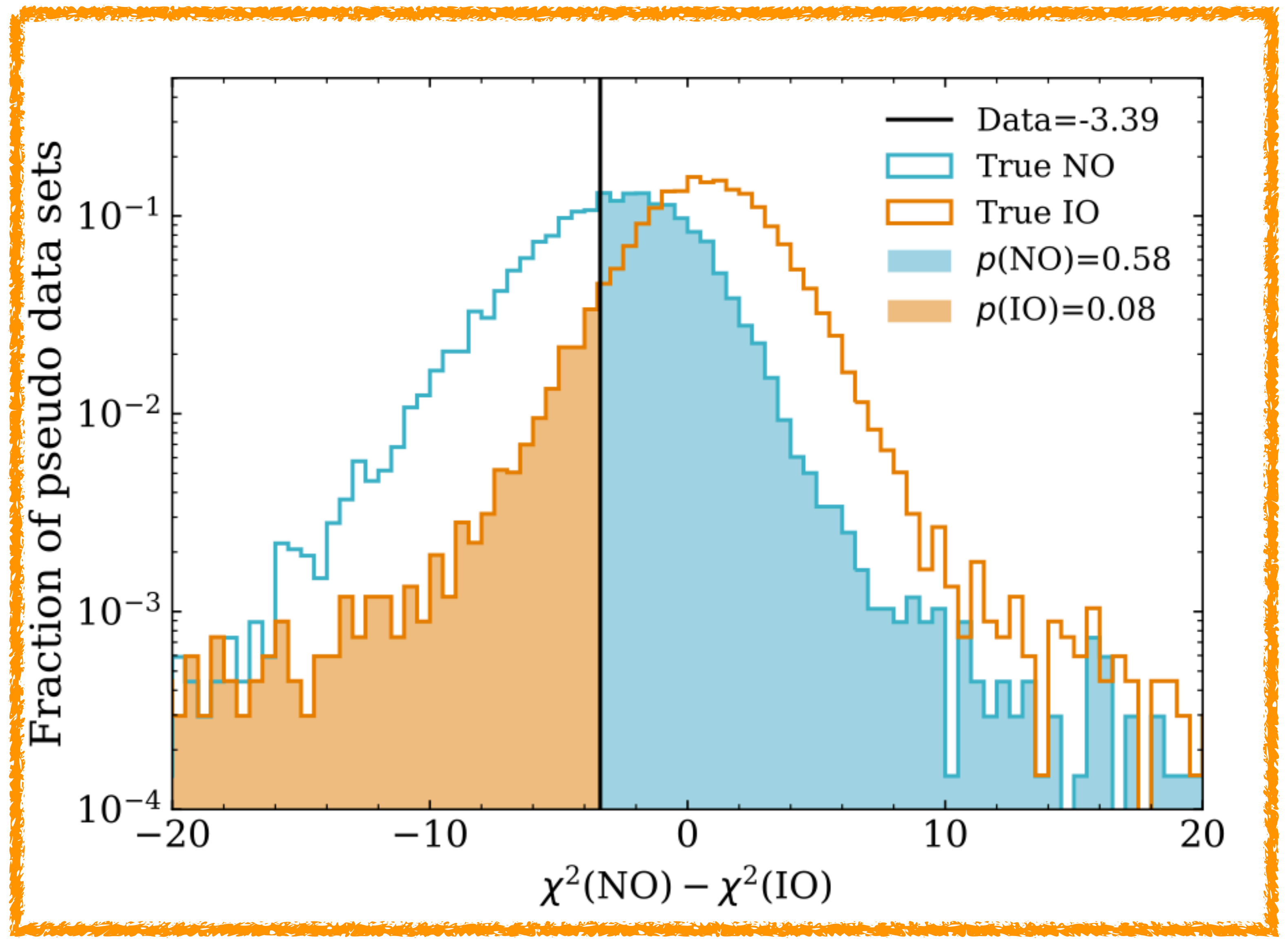
Results

arXiv:2405.12488 accepted on PRL

- Both experiments individually prefer normal ordering and δ_{CP}~-π/2, T2K prefers upper octant, SK prefer lower octant
- We performed Bayesian and Frequentist analyses → frequentist analyses shown today
- The CP-conserving value of the Jarlskog invariant is excluded with a significance between 1.9 and 2 σ
- In the frequentist analysis, p-value for CPC is 0.037 but increase to 0.05 when potential biases due to cross-section mis-modeling are included
- Normal ordering is preferred, p-value for IO 0.08



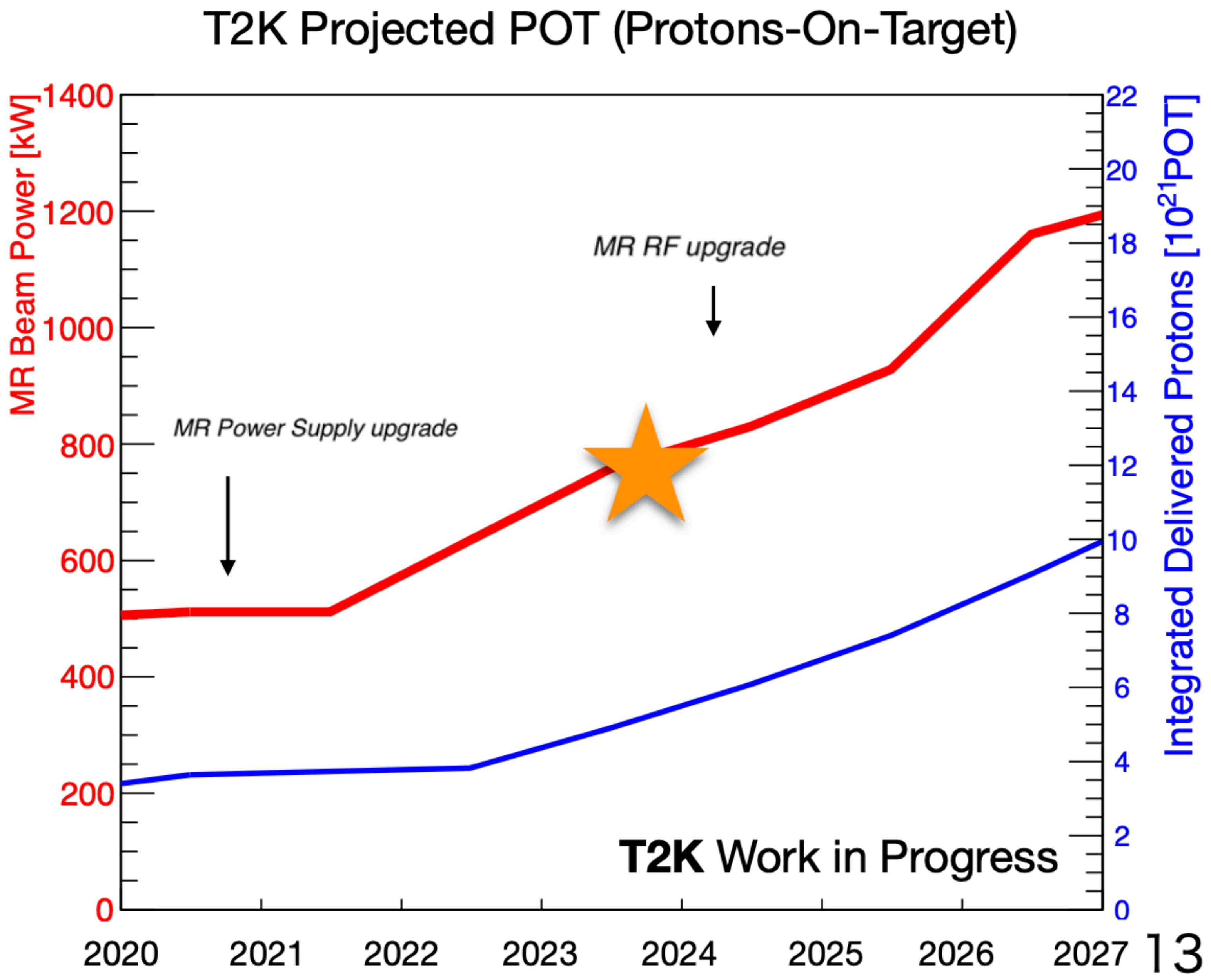


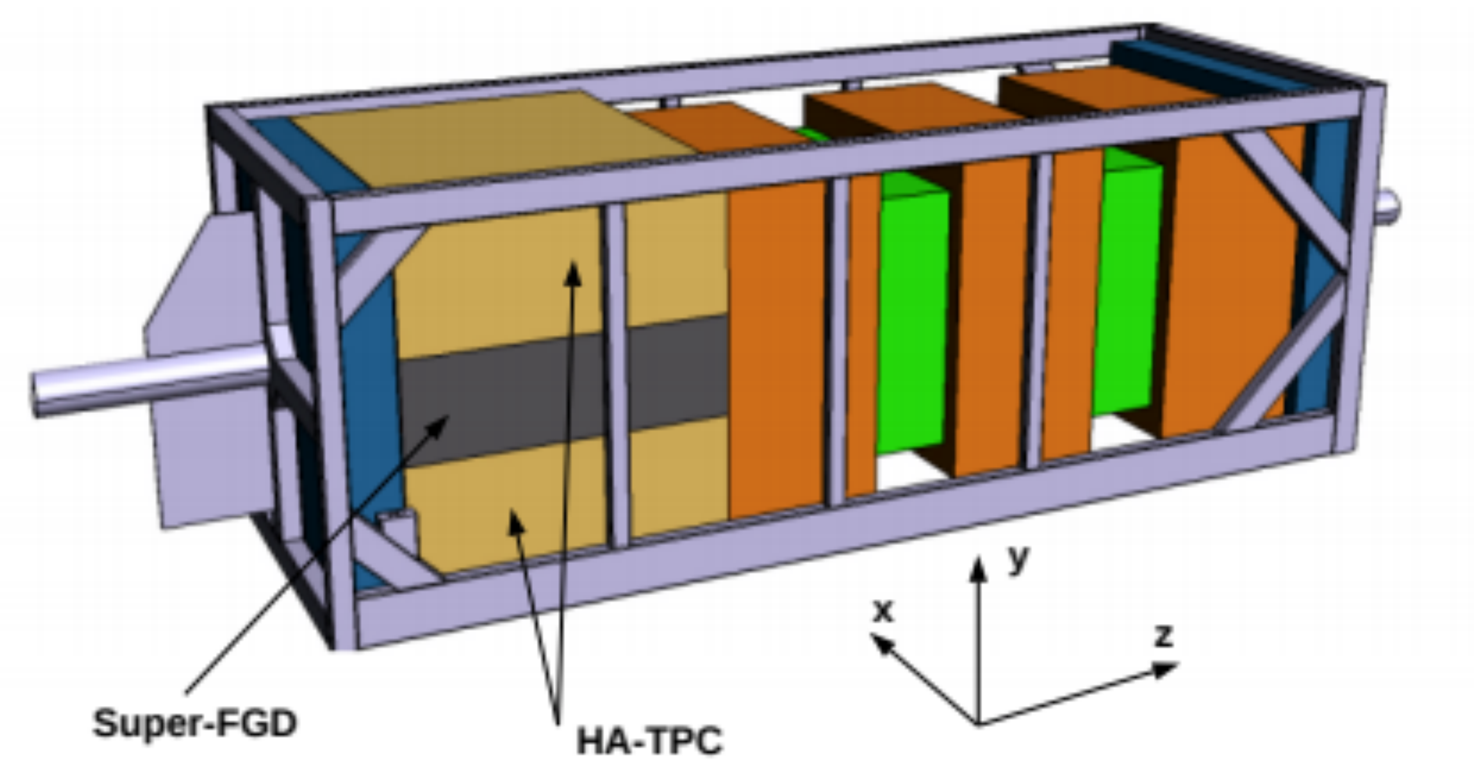


T2K beamline and Near Detector Upgrades

T2K upgrades

- We started to think to this upgrades in ~2018
- Bridge between T2K and Hyper-K coming online in 2027
- Necessary upgrades of the beamline to increase beam power
  - T2K pre-upgrade (500 kW) → Goal is to reach 1.3 MW for HK
  - Near Detector upgrade to reduce systematics uncertainties



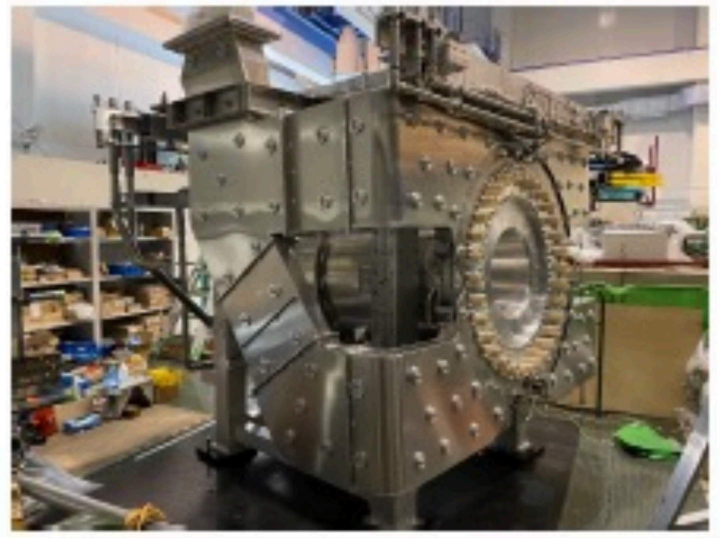


Neutrino beamline upgrades

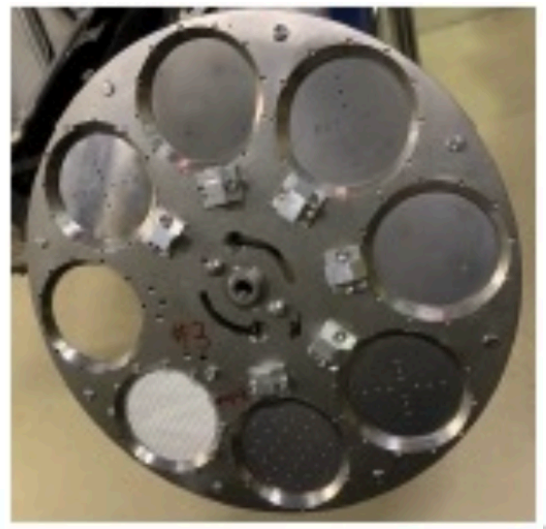
- Replacement of Main Ring power supplies to allow for higher repetition rate from 2.48s to 1.36s
- Several upgrades done on the neutrino beamline to cope with higher beam power
- Horn being operated at 320 kA instead of 250 kA → ~10% increase in the ν flux

New horn PS for 320 kA/1Hz operation

New horns 1 and 2



New OTR

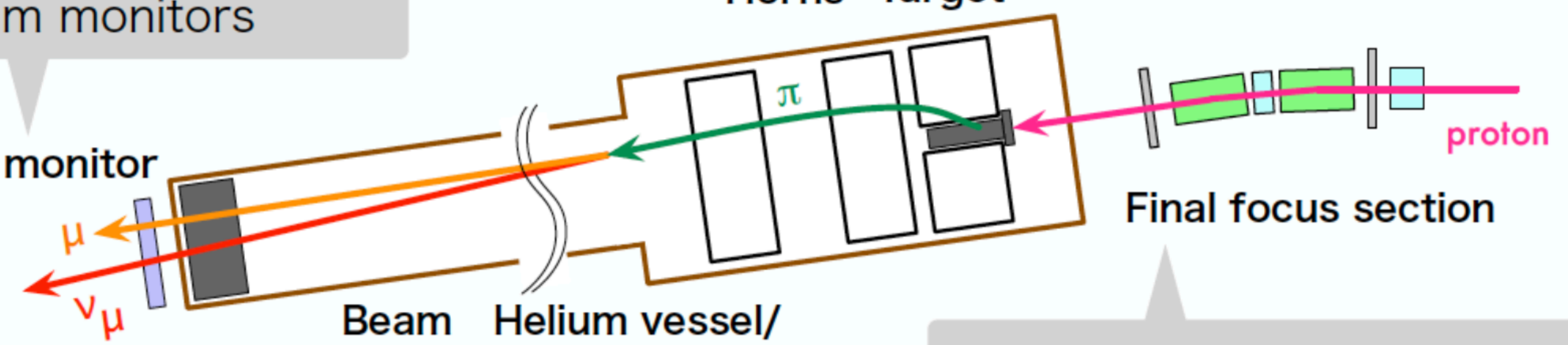


New FVD2 magnet

Increasing cooling capability for the heat generated by beam

Improving performance of beam monitors

Improving performance of beam monitors



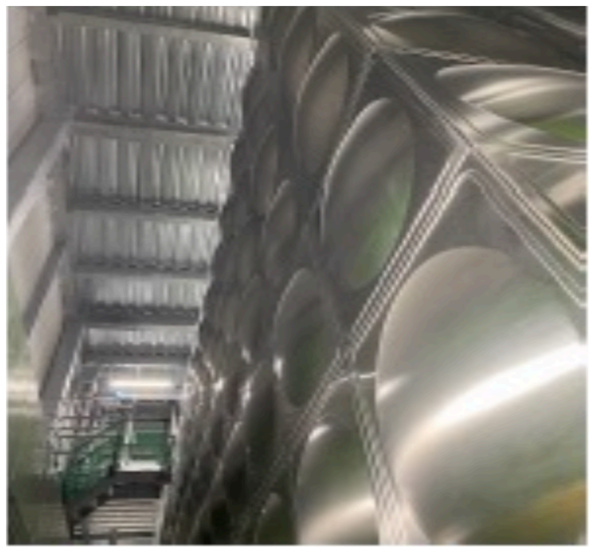
Improving maintainability under higher radio-active environment

Increasing capability of radio-active waste handling

New MUMON Si (Half sensors)

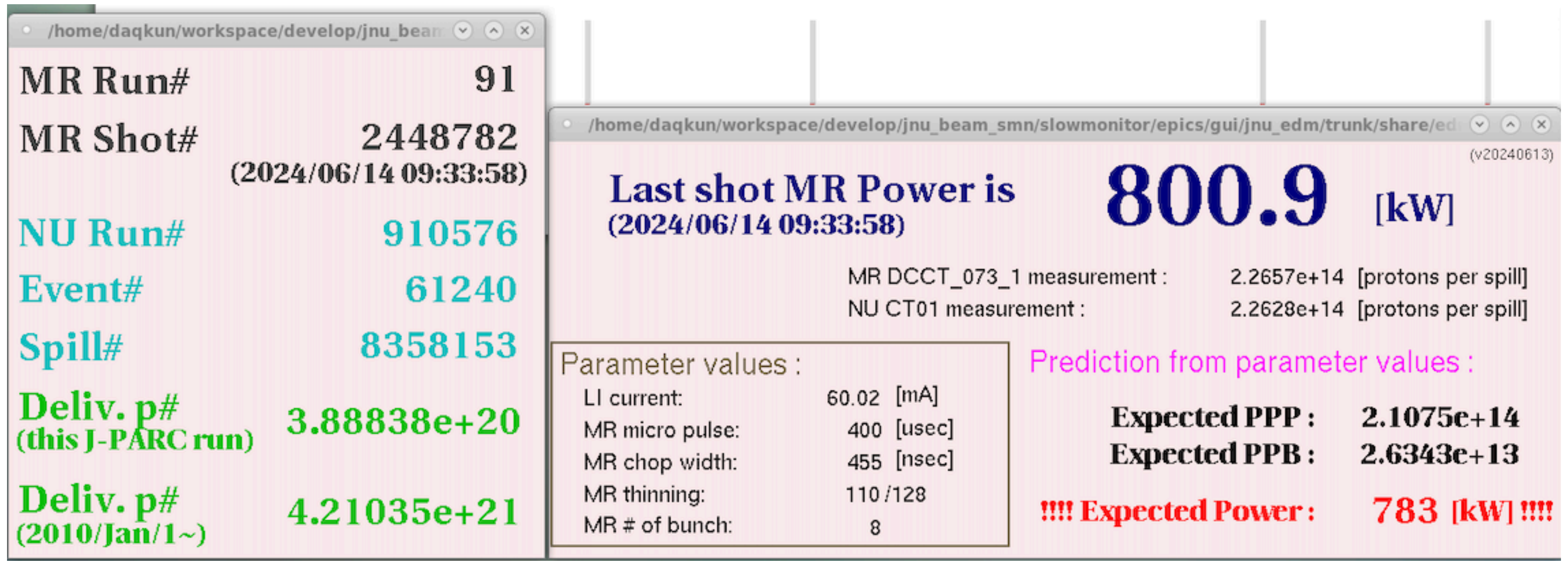
New target

New water tank for radioactive water disposal



New target cooling system

Towards higher beam power


/home/daqkun/workspace/develop/jnu_bean

MR Run#	91
MR Shot#	2448782 (2024/06/14 09:33:58)
NU Run#	910576
Event#	61240
Spill#	8358153
Deliv. p# (this J-PARC run)	3.88838e+20
Deliv. p# (2010/Jan/1~)	4.21035e+21

/home/daqkun/workspace/develop/jnu_beam_smn/slowmonitor/epics/gui/jnu_edm/trunk/share/ed

(v20240613)

Last shot MR Power is (2024/06/14 09:33:58) **800.9** [kW]

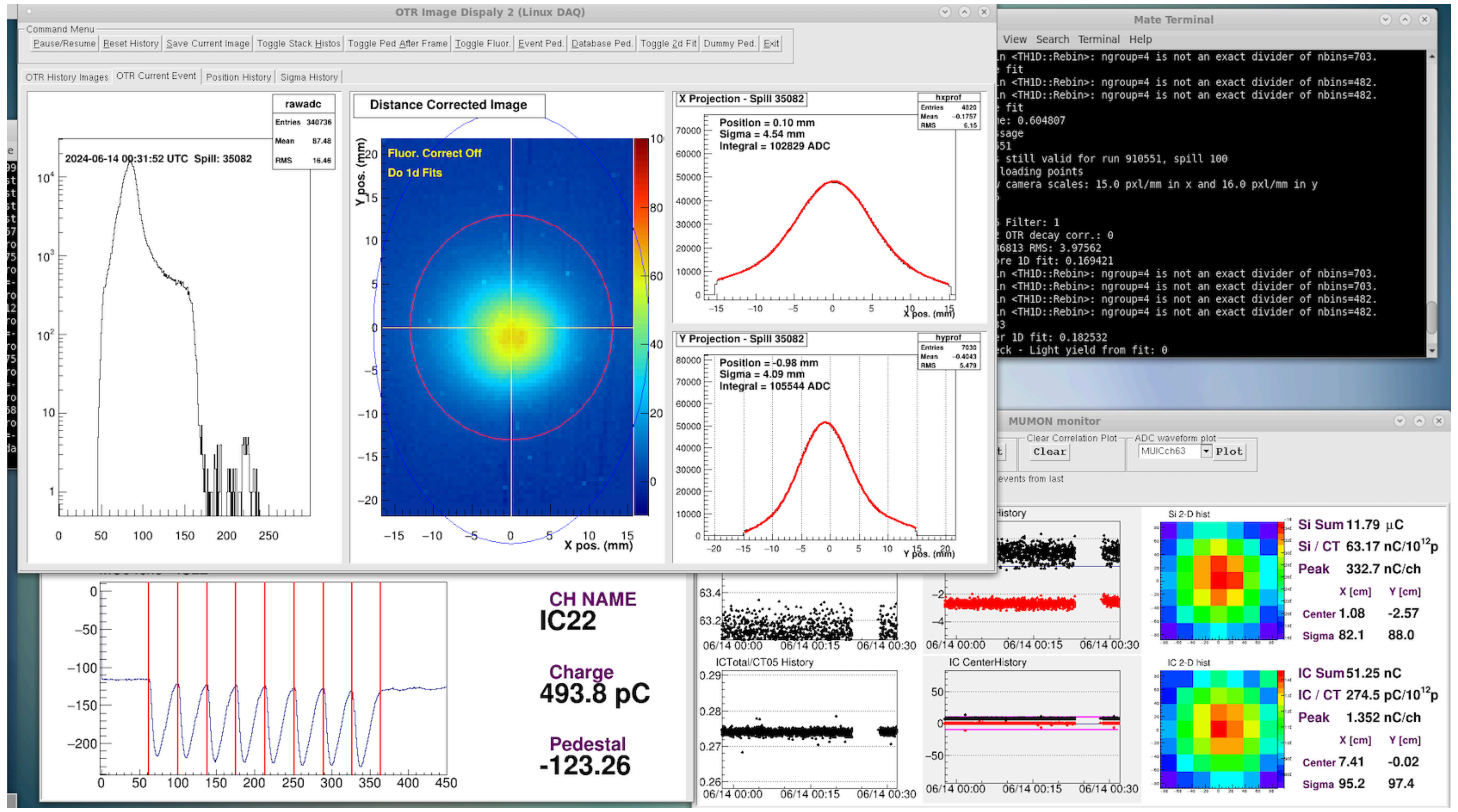
MR DCCT_073_1 measurement : 2.2657e+14 [protons per spill]
NU CT01 measurement : 2.2628e+14 [protons per spill]

Parameter values :

LI current:	60.02	[mA]
MR micro pulse:	400	[usec]
MR chop width:	455	[nsec]
MR thinning:	110 /128	
MR # of bunch:	8	

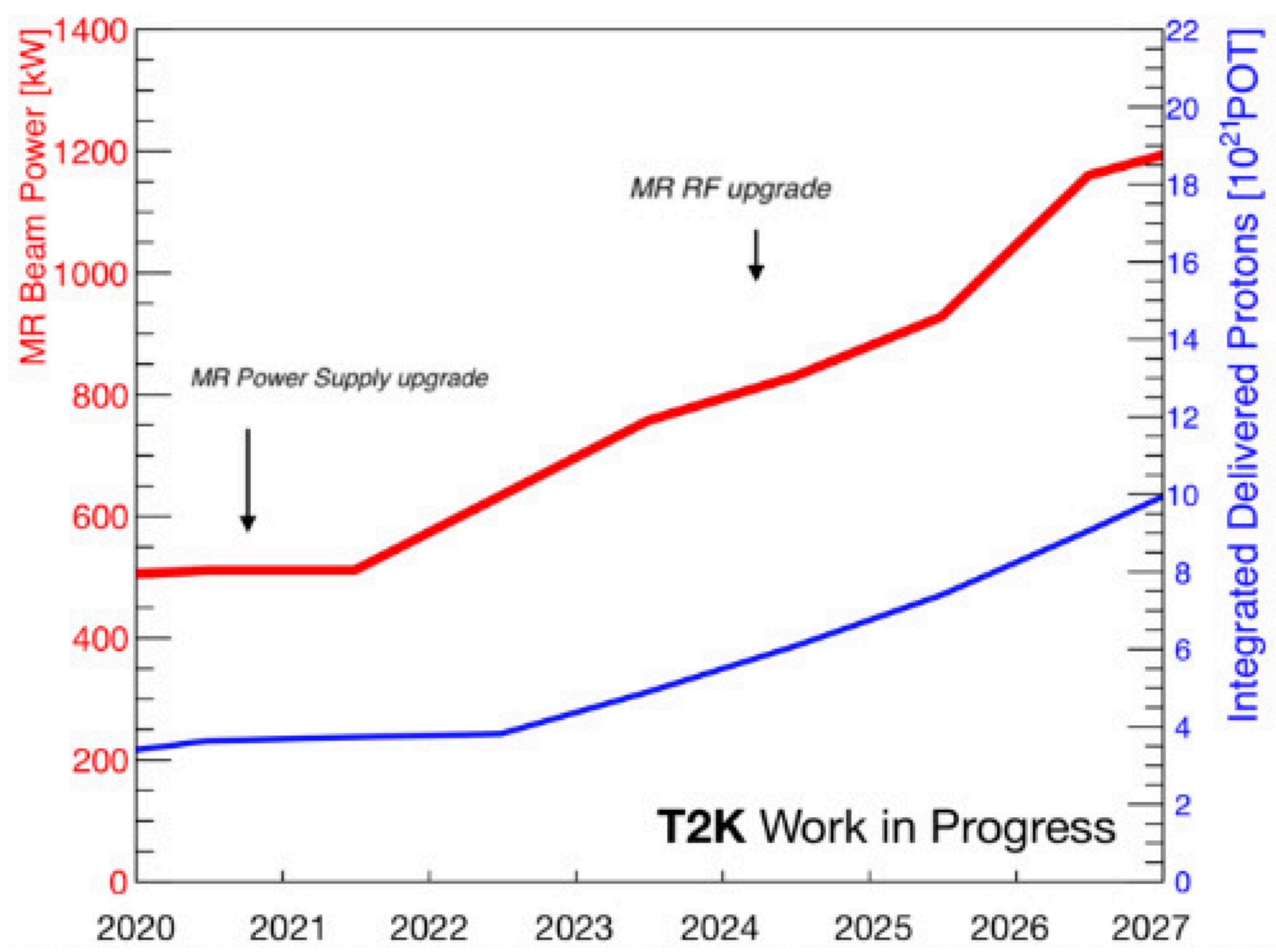
Prediction from parameter values :

Expected PPP : 2.1075e+14
Expected PPB : 2.6343e+13
!!!! Expected Power : 783 [kW] !!!!

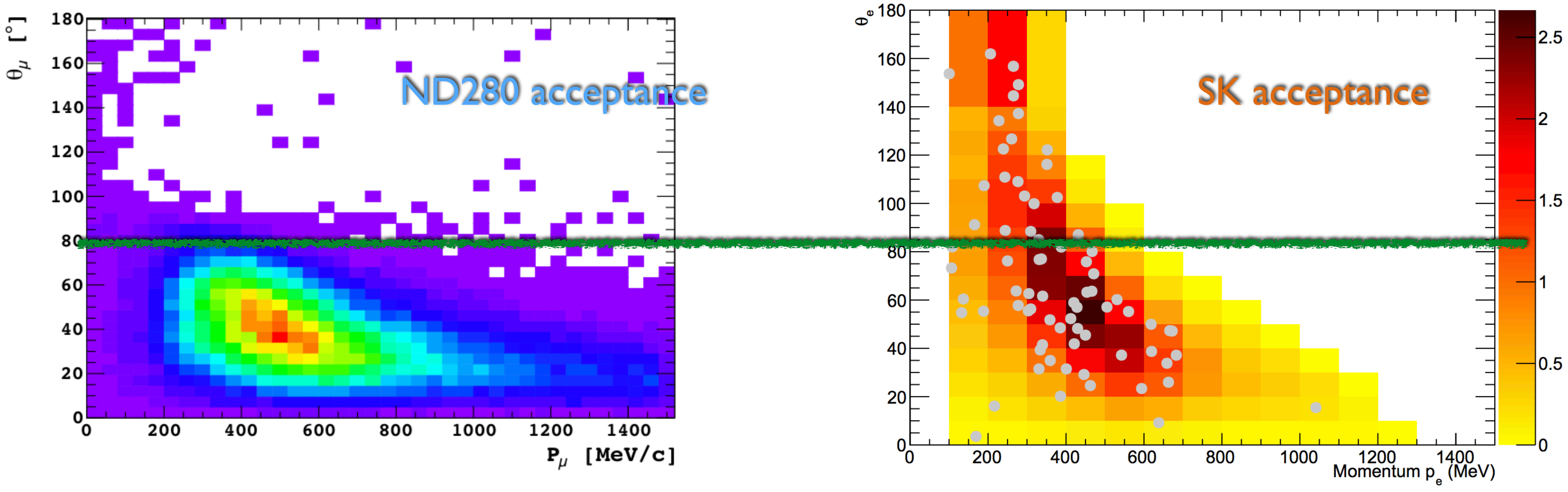


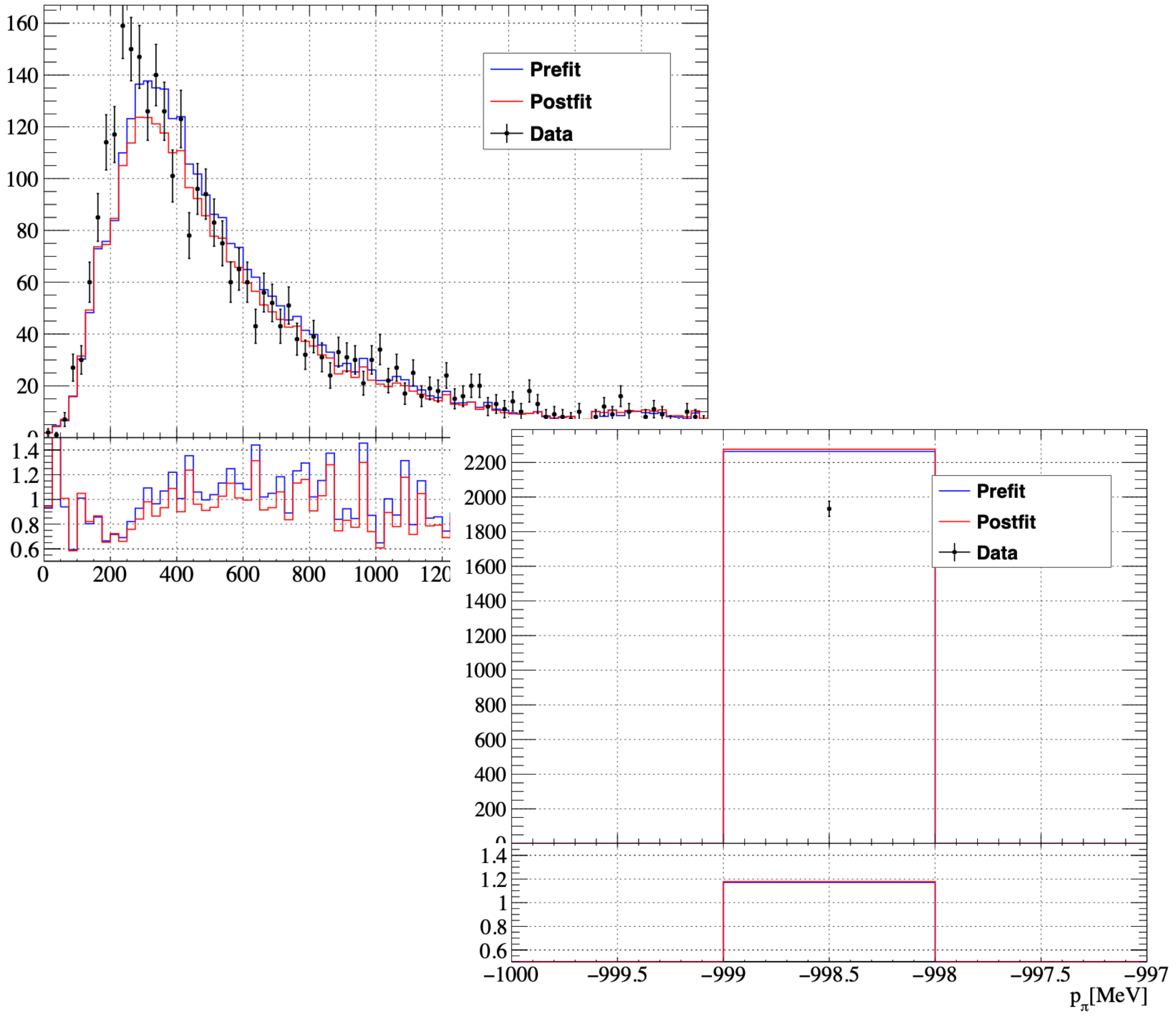
- June 2024 → Beam power increased to 800 kW
- Steady improvements to reach 1.3 MW by 2027 → increase T2K statistics by a factor of 3 by 2027
- Larger statistics → need to reduce systematic uncertainties → ND280 upgrade

T2K Projected POT (Protons-On-Target)



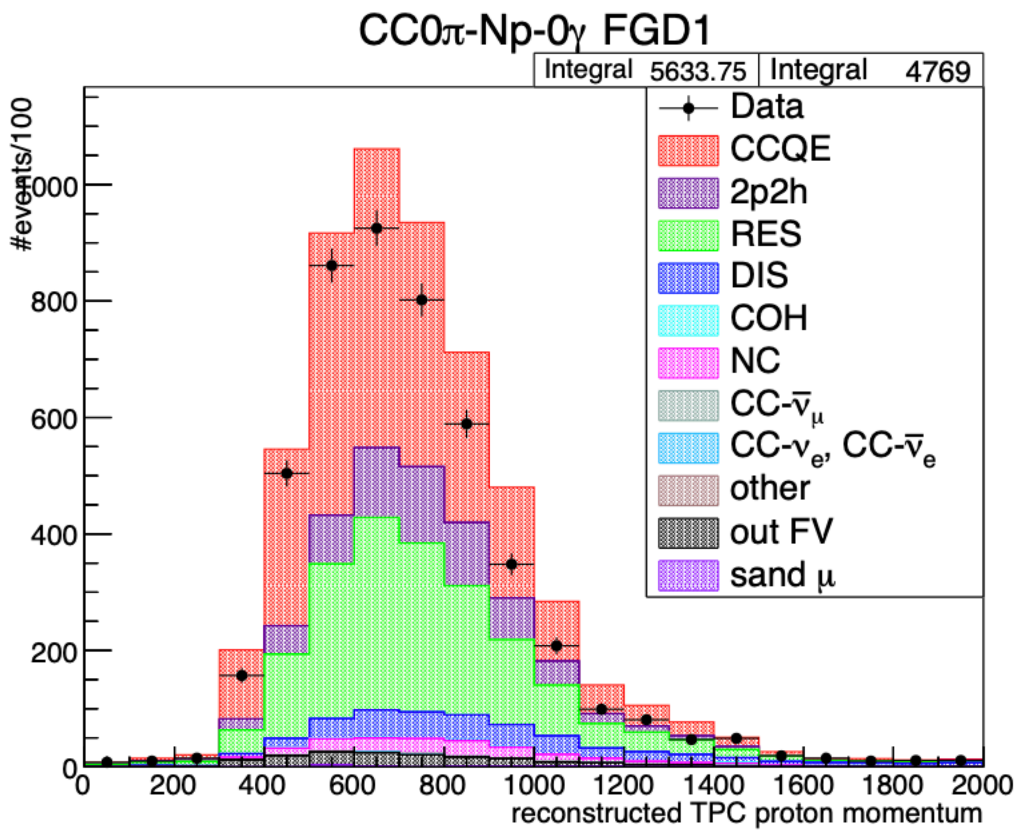
What we can do better?



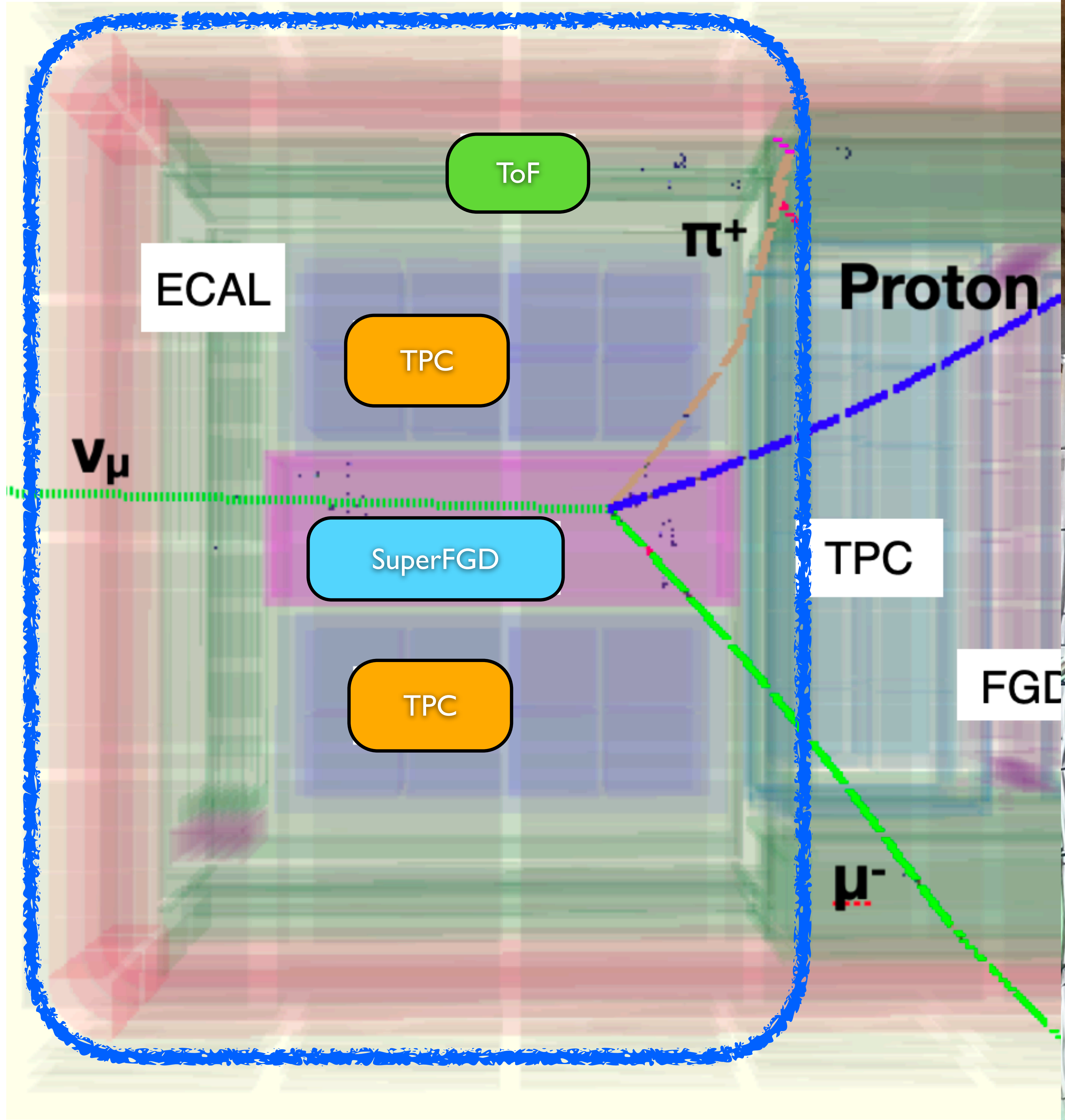


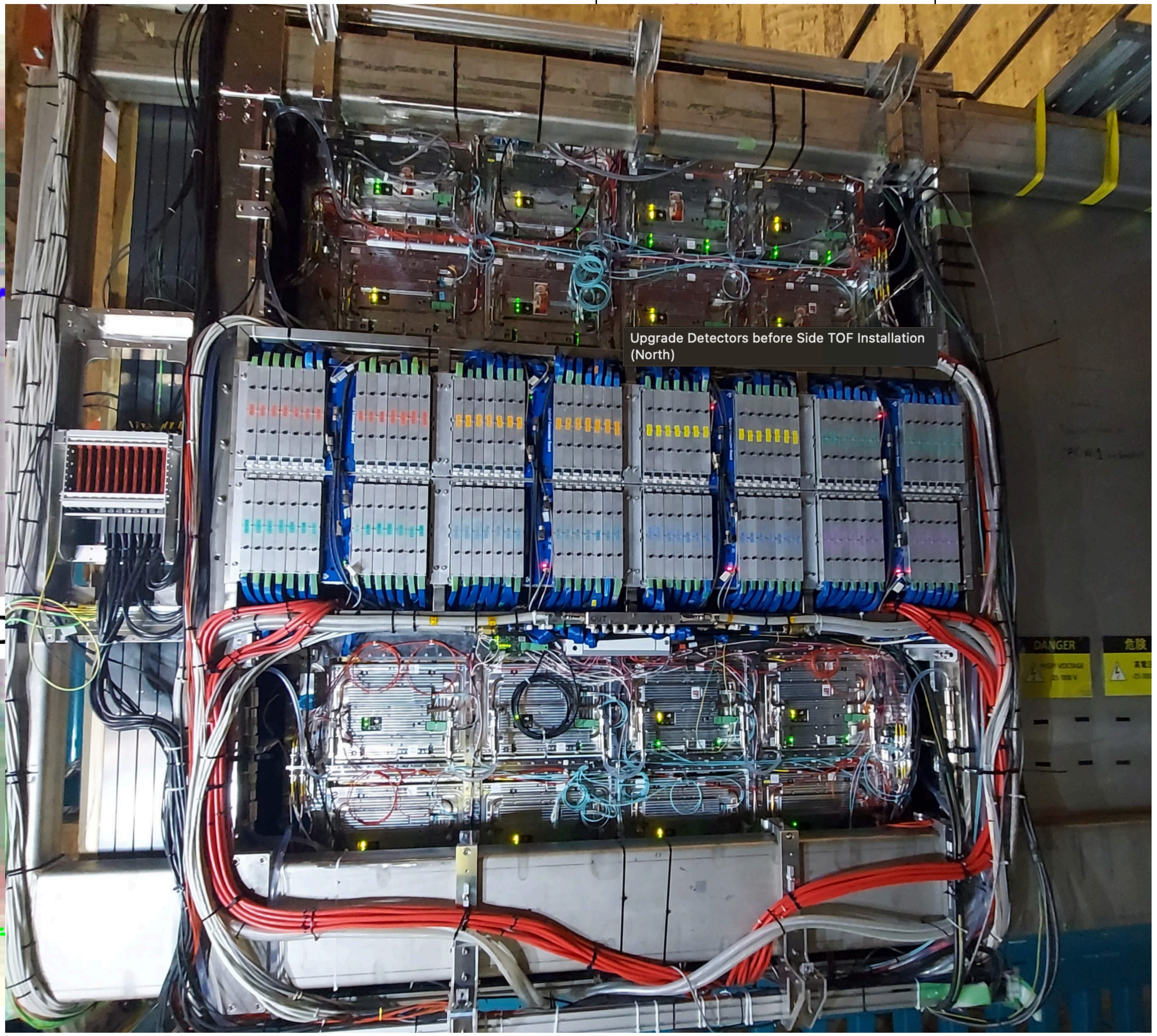
- Improve angular acceptance ν

- But also better reconstruction and usage of the hadronic part of the interactions!
  - Currently samples are selected according to their topology (0π, 1π, 1p, Nπ, …) but the kinematic of the hadrons is not used in any way in the constraint on flux and x-sec systematics → plenty of additional information to be exploited
  - This is due to both, a low efficiency from ND280 to reconstruct hadrons and the diffucties in modeling the x-sec systematics for the hadronic part
    - With the upgrade we plan to improve the efficiency to reconstruct hadronic part



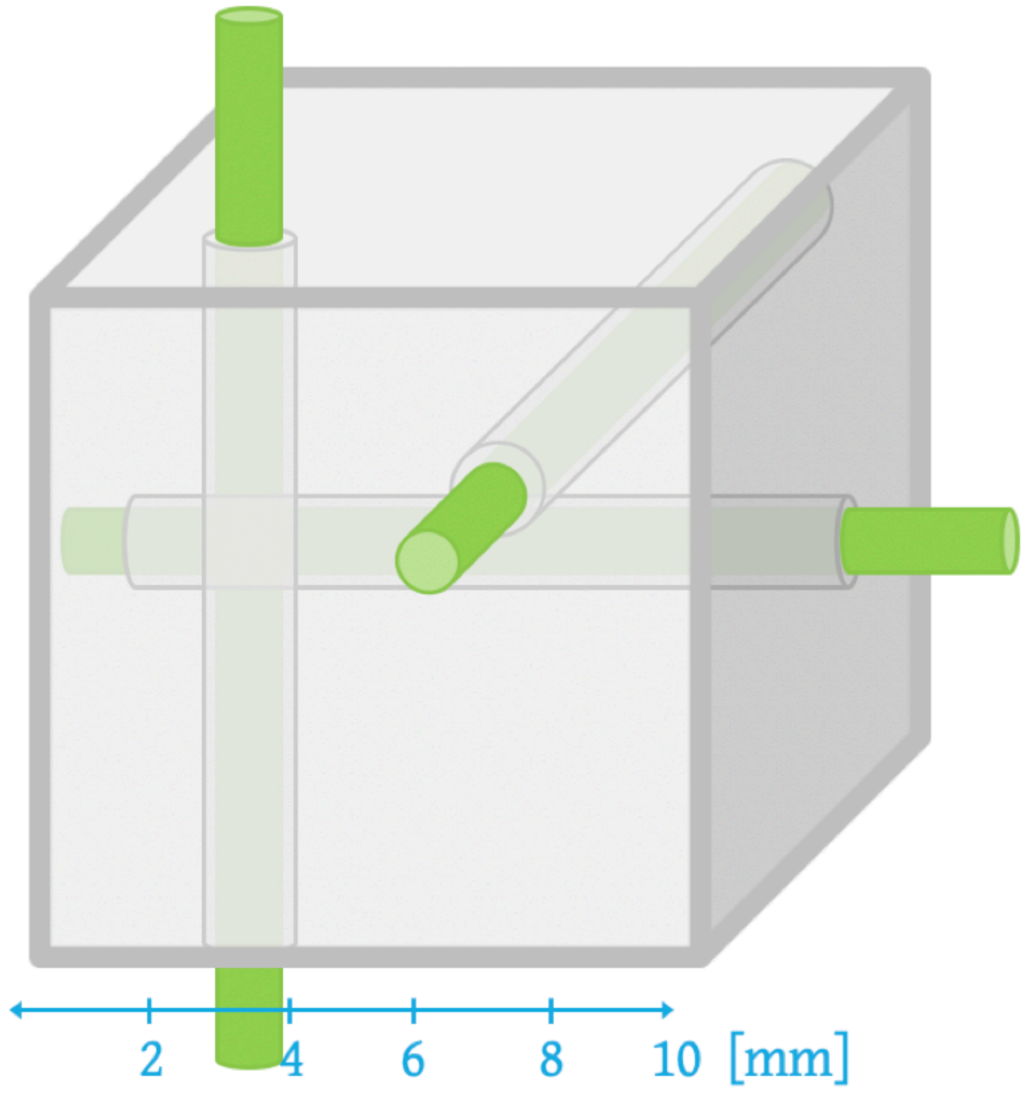
The Near Detector upgrade





Replace part of the P0D detector (measured NC π^0 production) with a new scintillator target (SuperFGD), two TPCs and a ToF detector

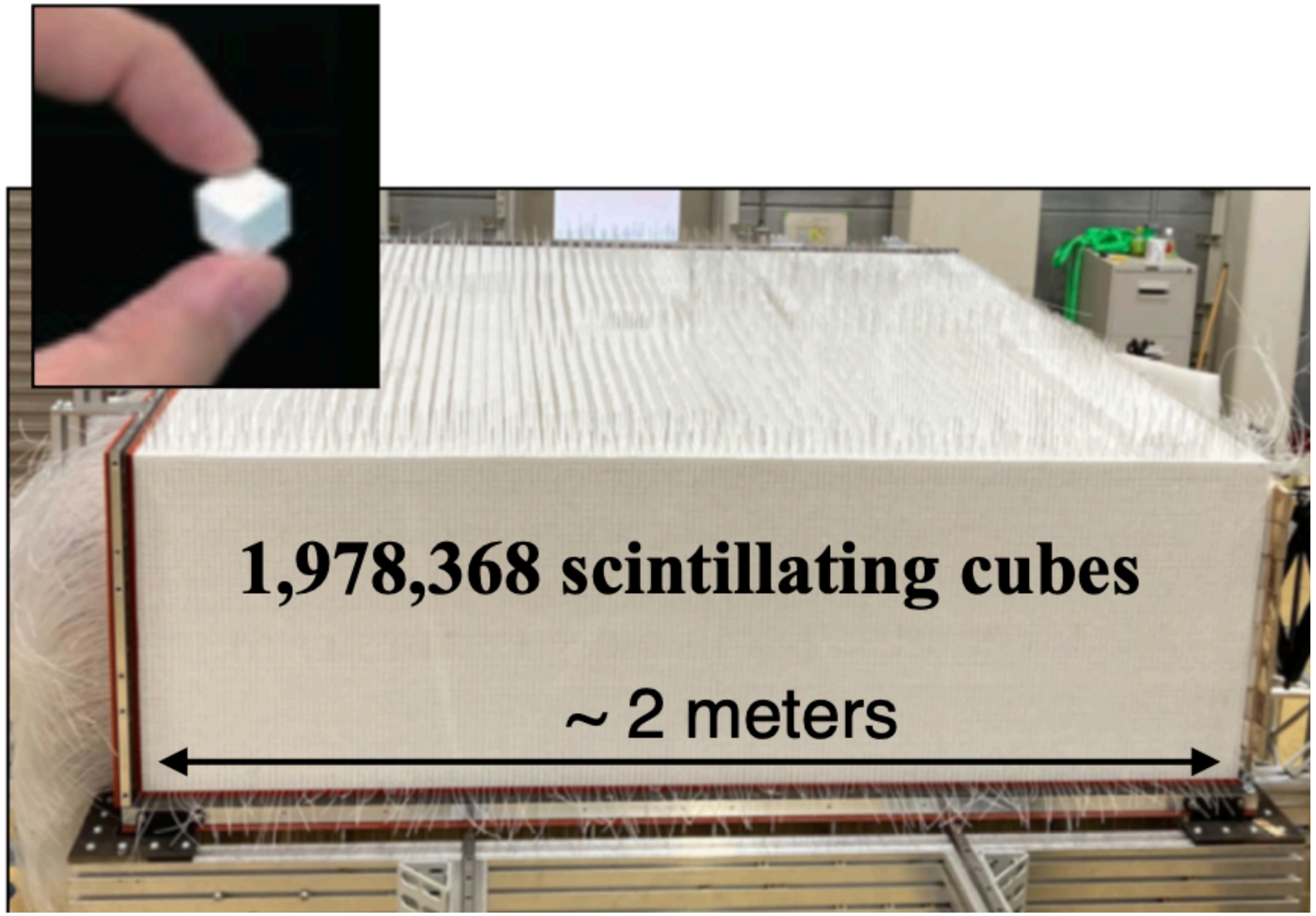
Super-FGD



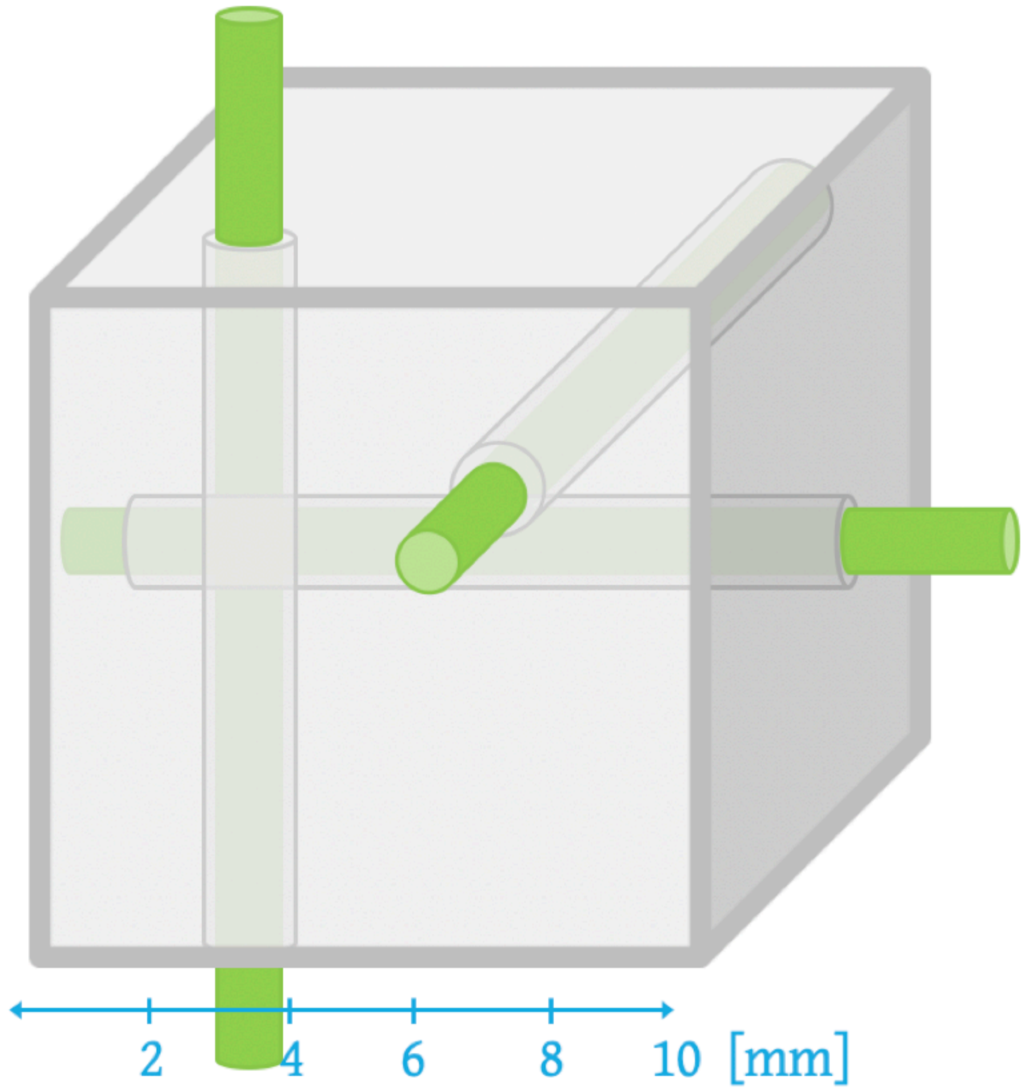
- 2 millions plastic scintillator cubes made of polystyrene and doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP.

- Each cube is optically independent

- Cubes production was done at UNIPLAST (Russia)

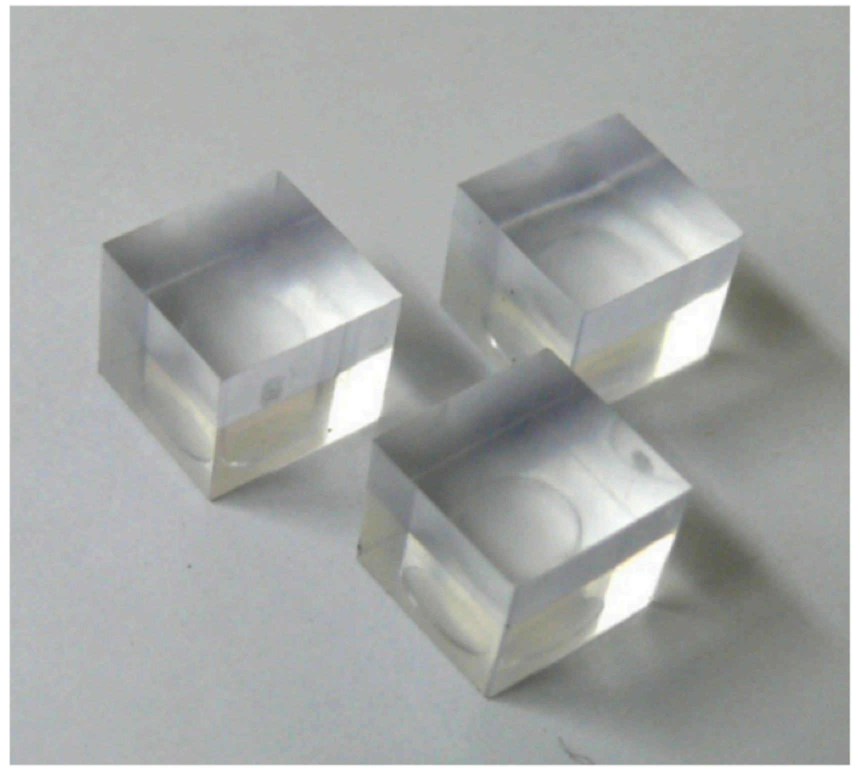


Super-FGD

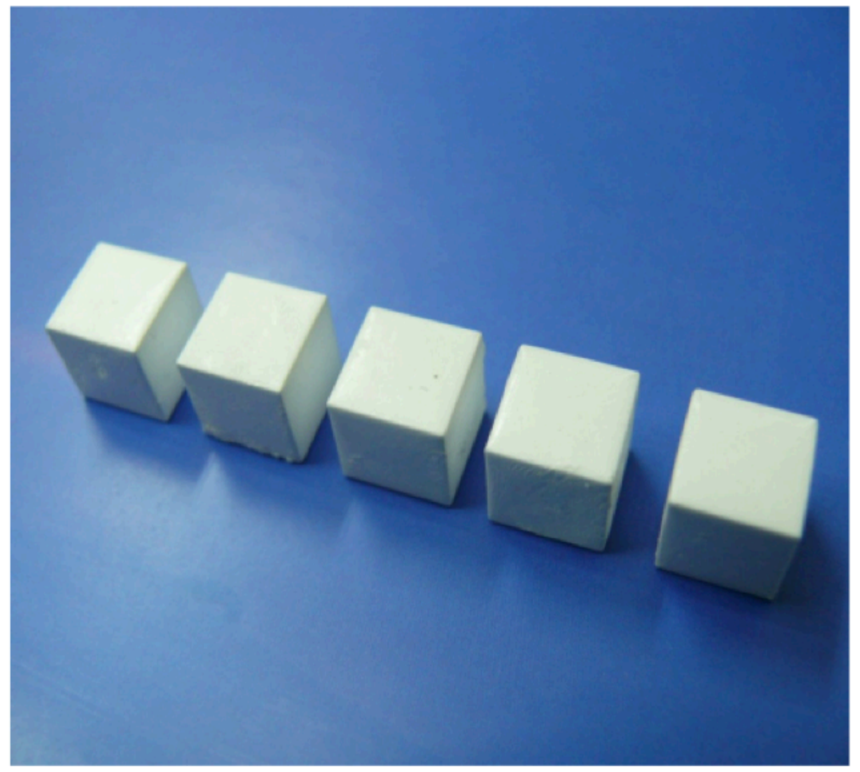


- 2 millions plastic scintillator cubes made of polystyrene and doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP.
- Each cube is optically independent
- Cubes production was done at UNIPLAST (Russia)

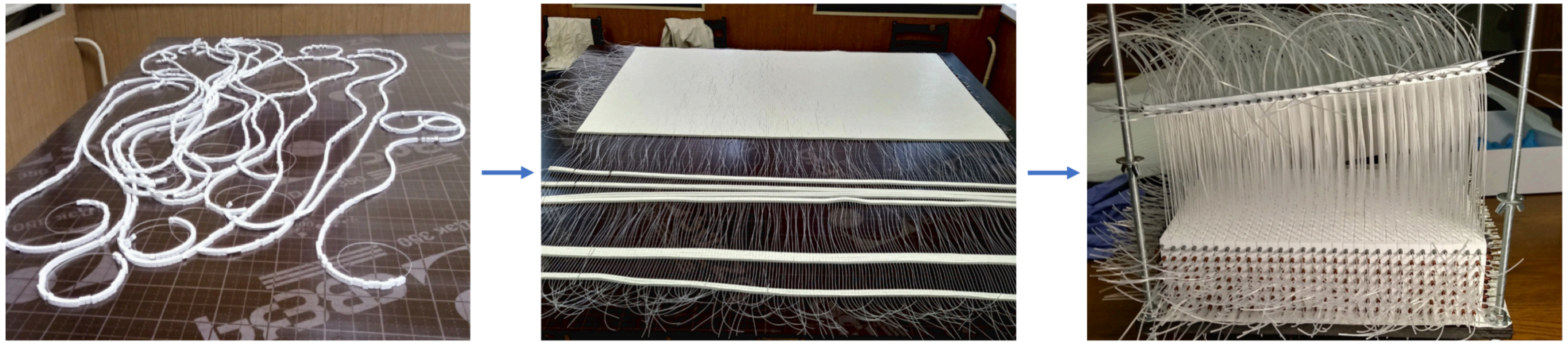
Produce cubes by injection molding



Etched in a chemical to deposit a reflective layer



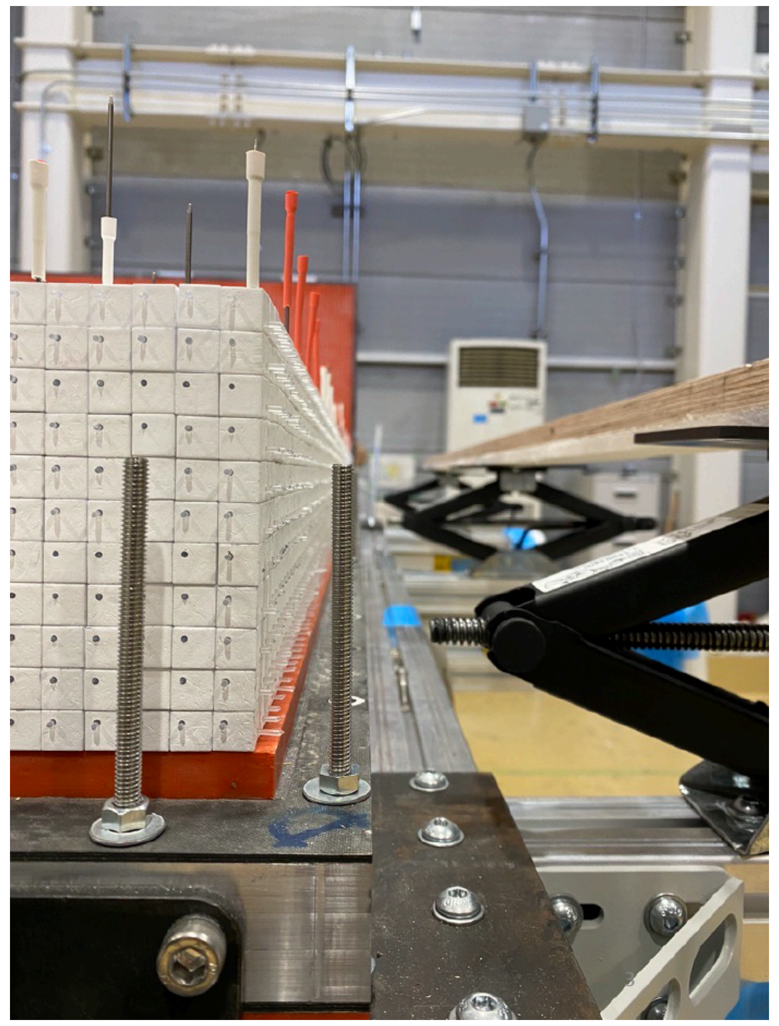
3 orthogonal holes are drilled



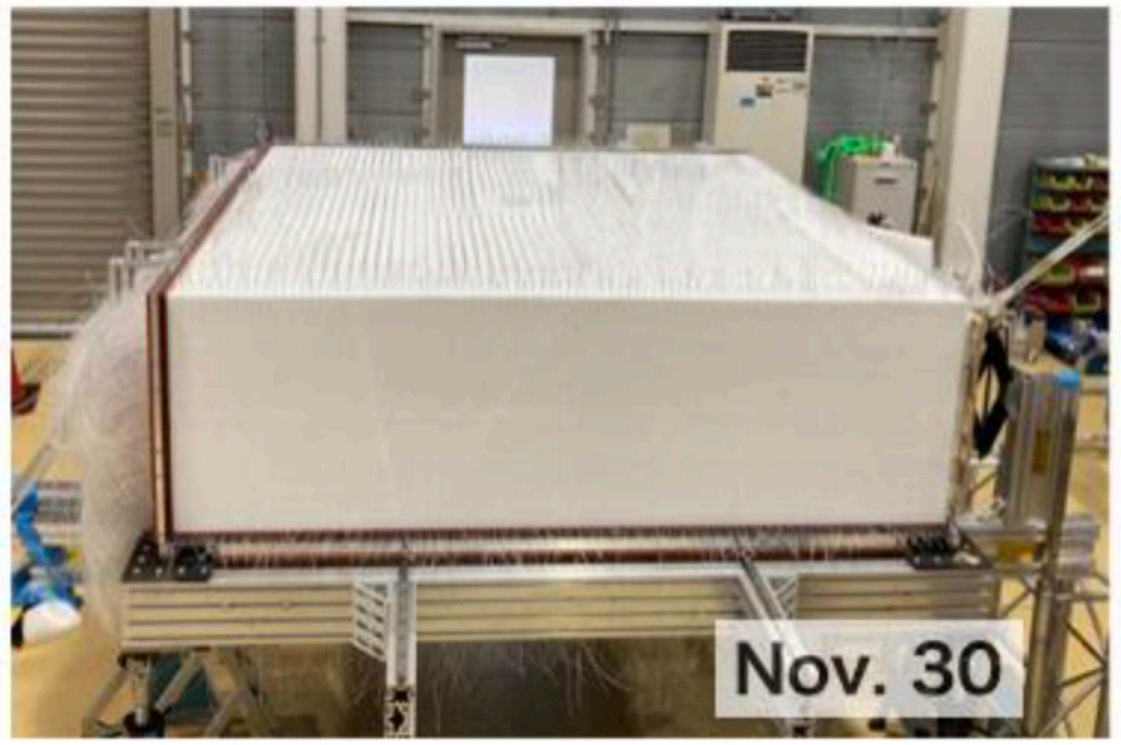
Assembled in 56 X-Y layers with fishing lines before shipment to Japan

SuperFGD assembly at J-PARC

First cube layer assembly



Stop panels removed

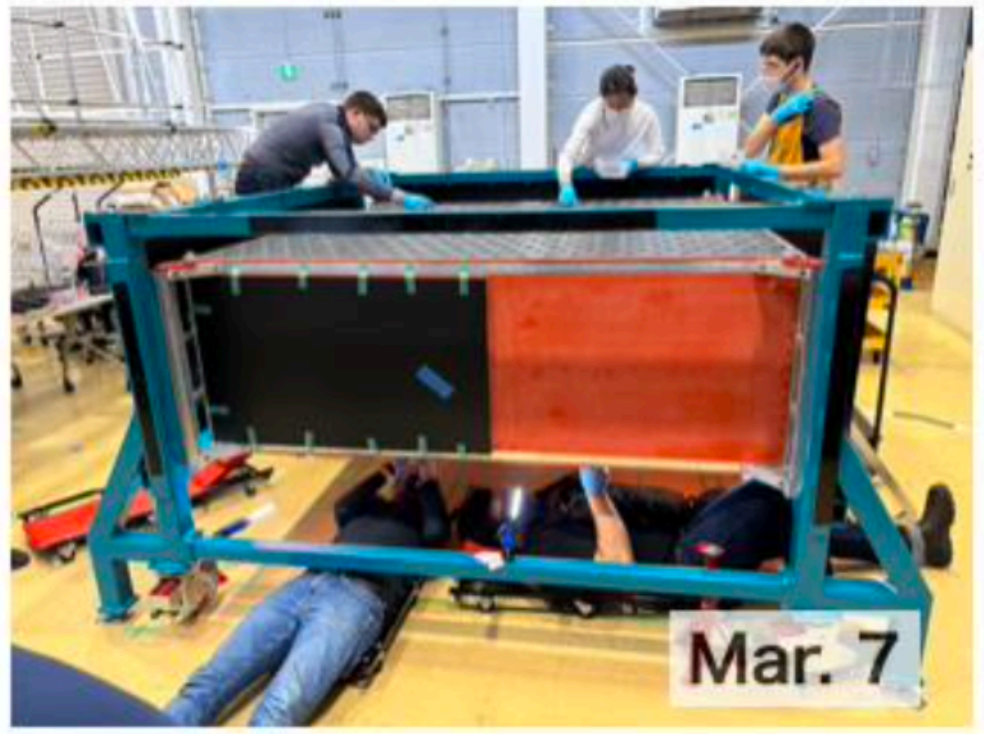


Box closure

Horizontal fibers assembly

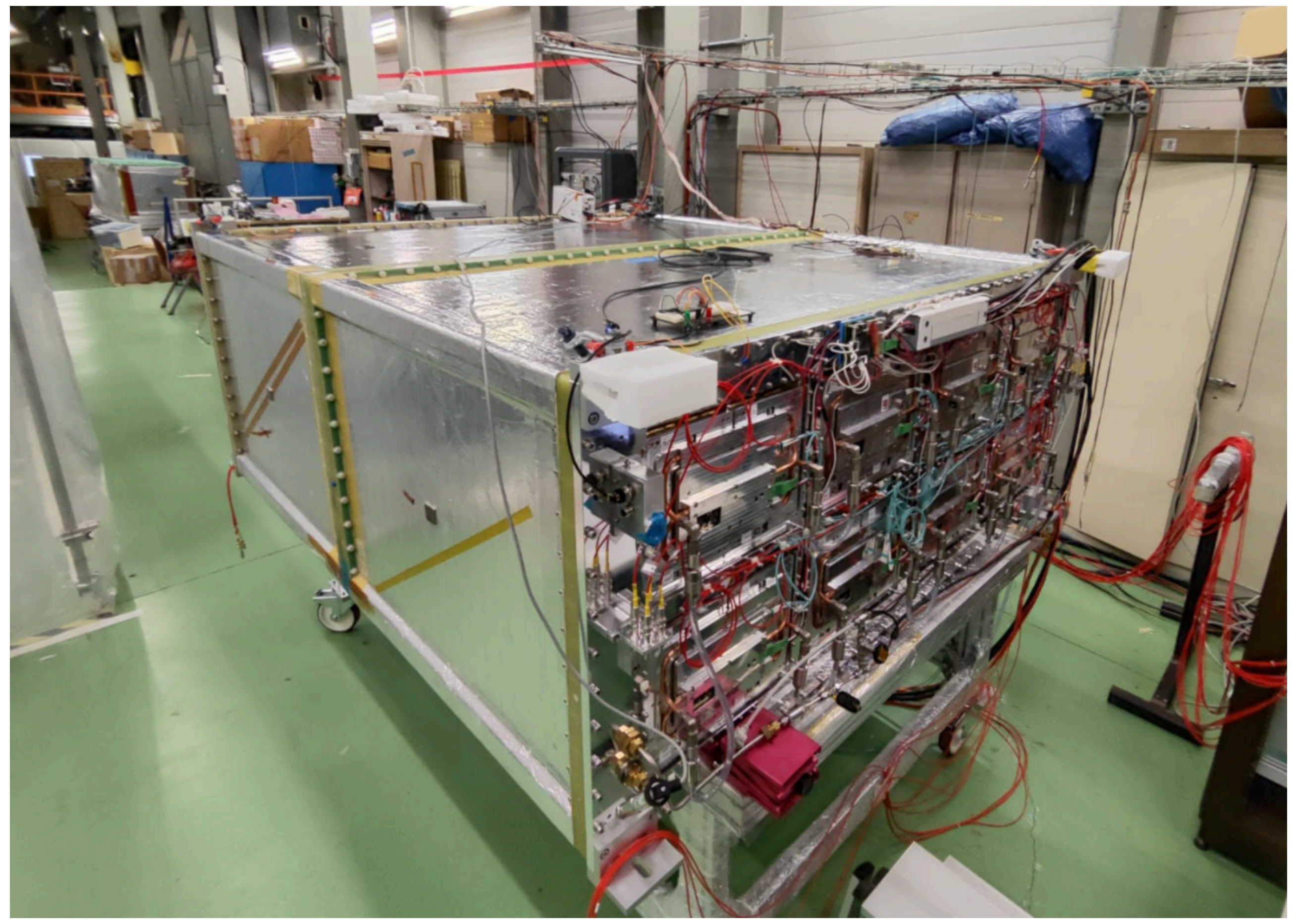
Vertical fibers assembly

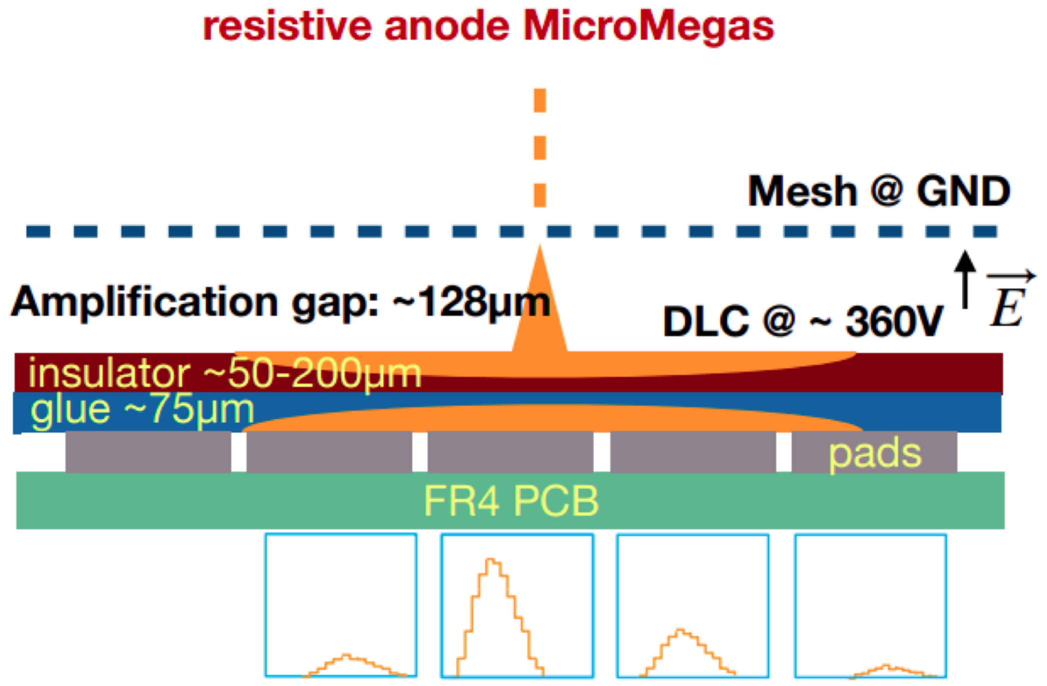
Top MPPCs assembly



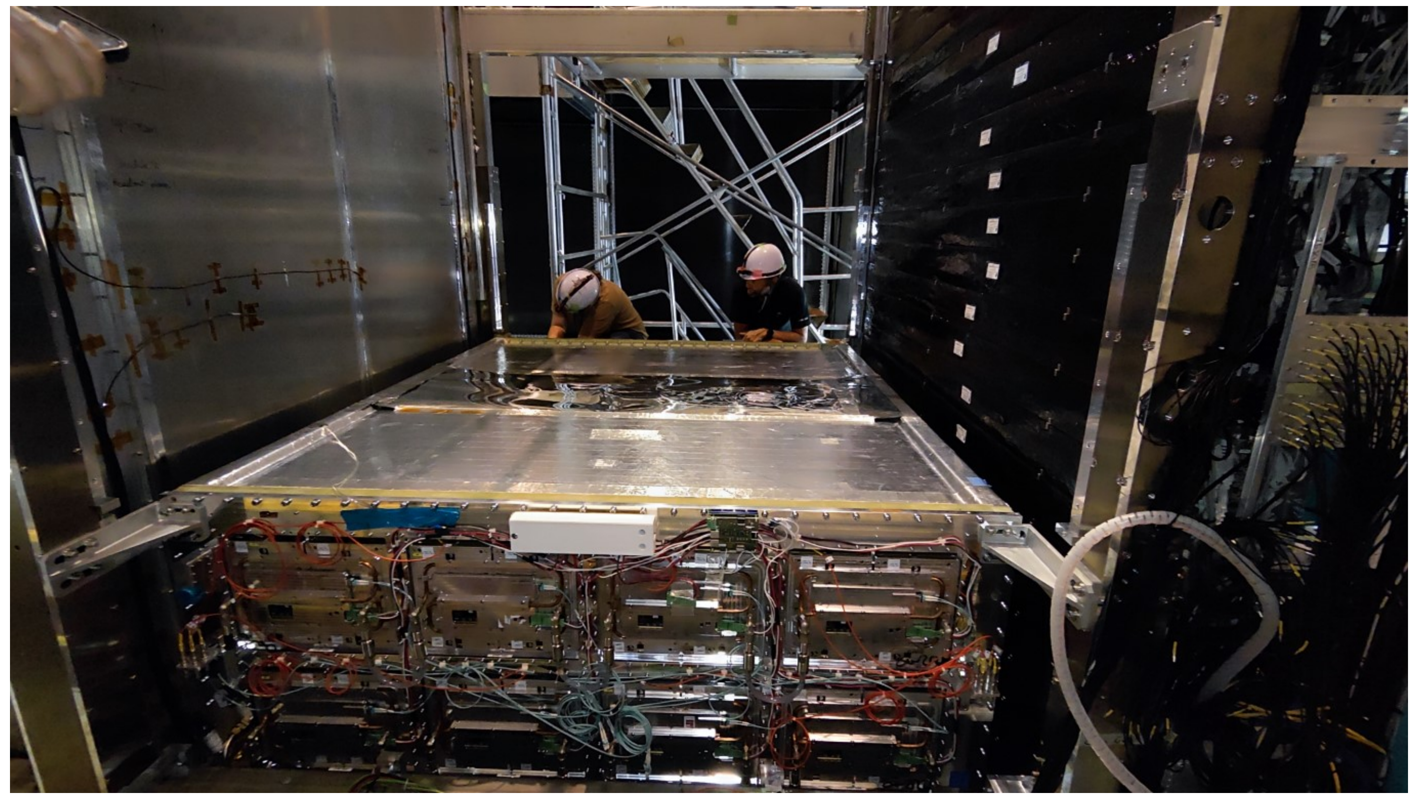
Light barrier/cables asse

High-Angle TPCs

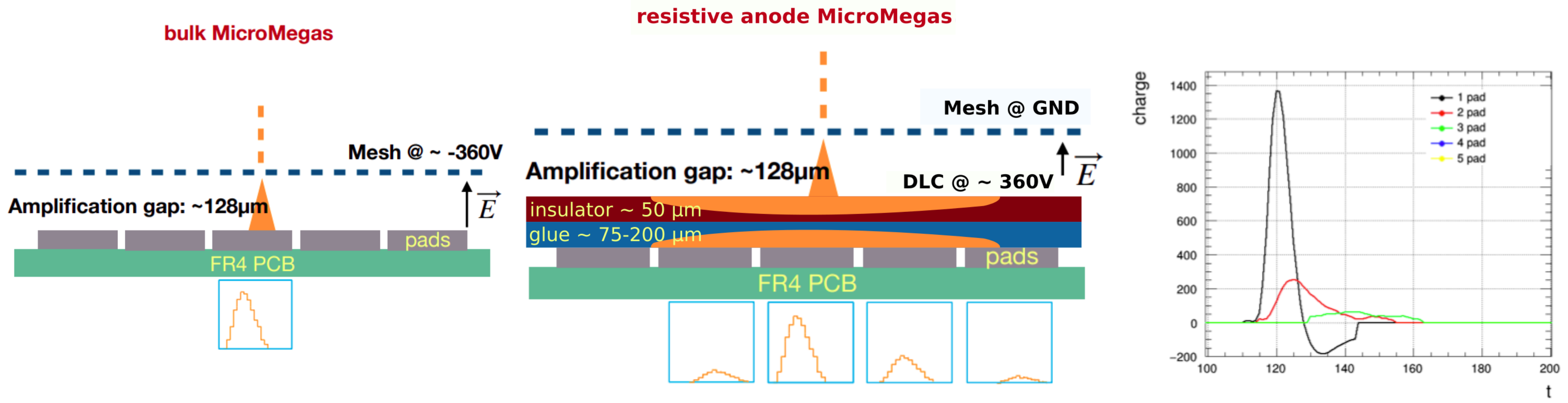




- Reconstruct leptons emitted at high angle with respect to the beam
- TPC instrumented with resistive MicroMegas modules
- Chambers have been assembled and tested at CERN before shipment



HATPC performances

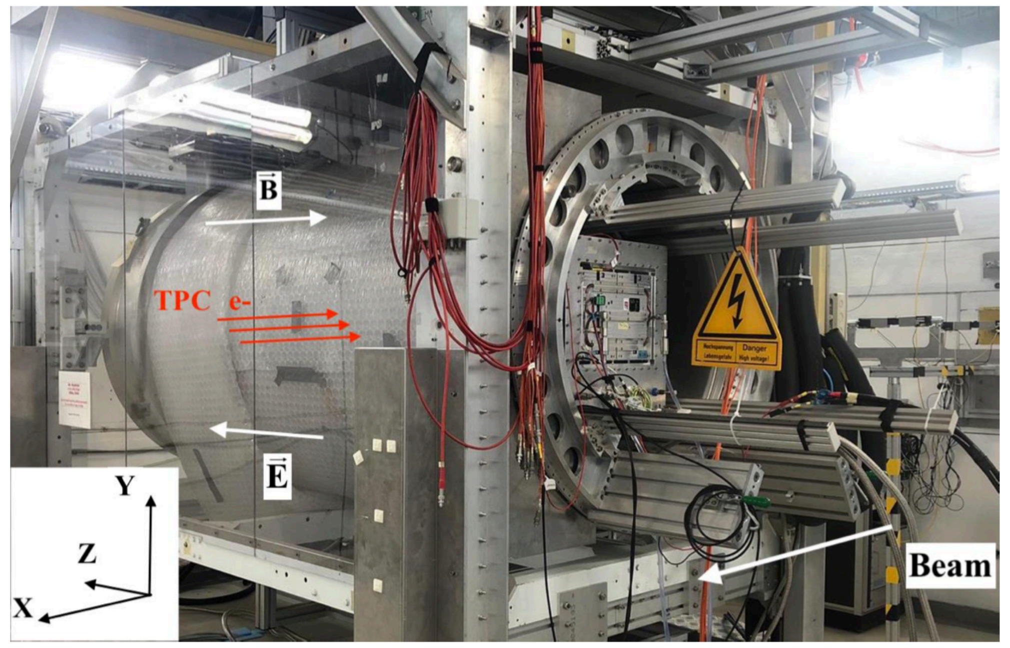


$$\rho(r,t) = \frac{RC}{2t}\exp\left[-\frac{r^2 RC}{4t}\right]$$

R- surface resistivity
C- capacitance/unit area

Gaussian spreading as a function of time with :

$$\sigma_r = \sqrt{\frac{2t}{RC}} \quad \begin{cases} t \approx shaping\ time\ (few\ 100\ ns) \\ RC_{[ns/mm^2]} = \frac{180\ R_{[M\Omega/\blacksquare]}}{d_{[\mu m]}/175} \end{cases}$$



- 3 test beam campaigns to characterise ERAM detectors
- Spatial resolution between 200 and 600 µm (w.r.t. 600 to 1000 for vertical TPCs)
- dE/dx resolution below 10%

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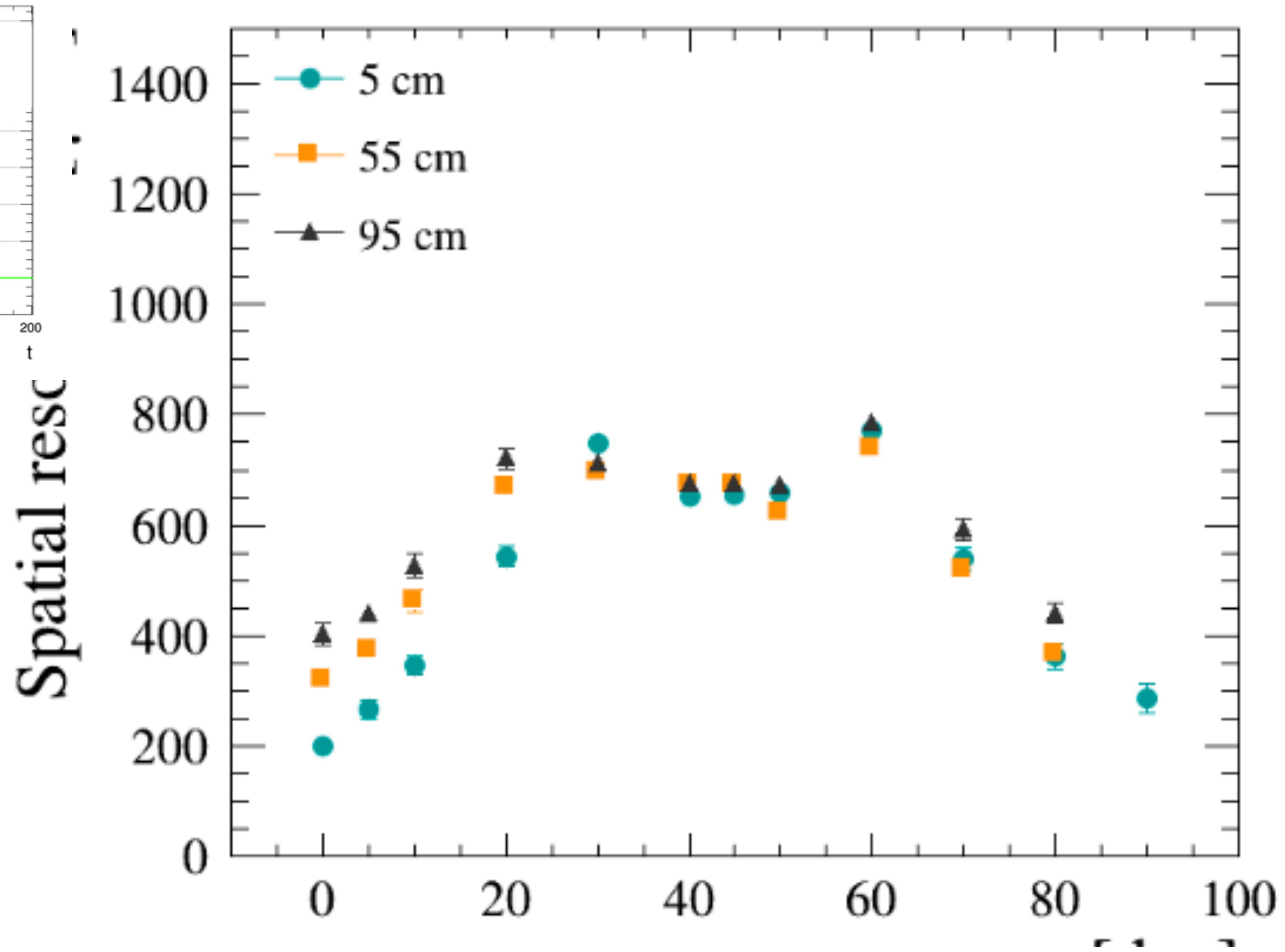
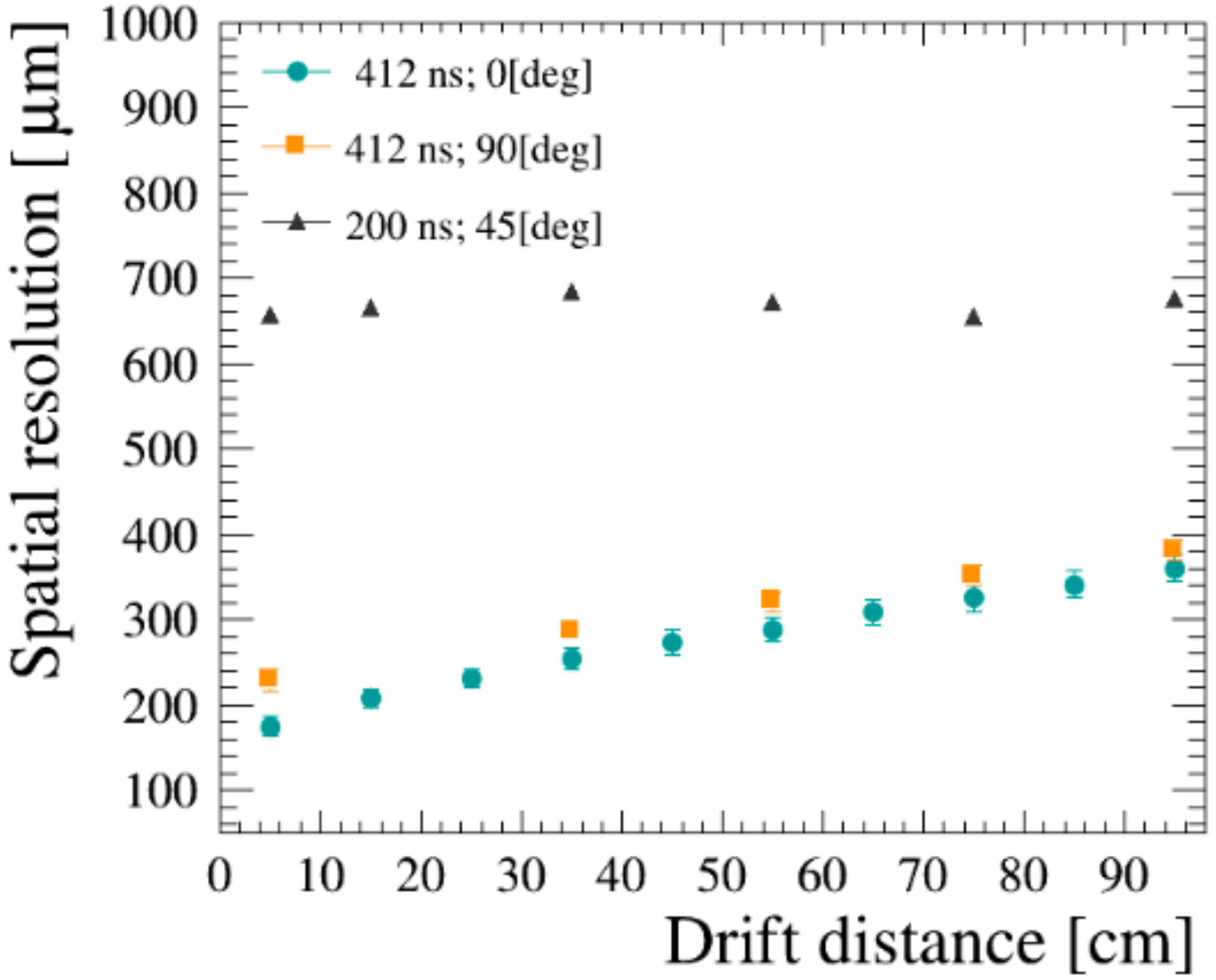
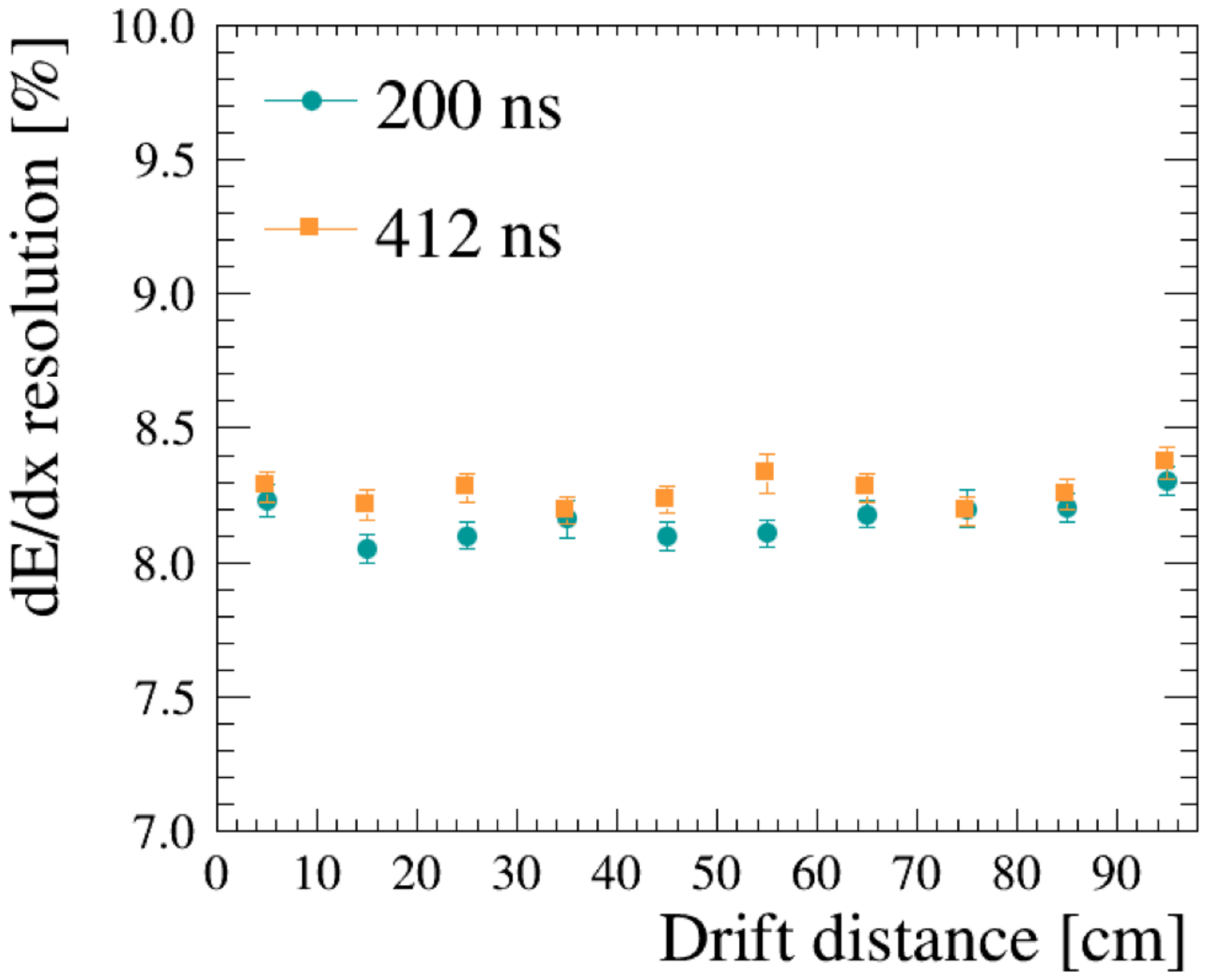
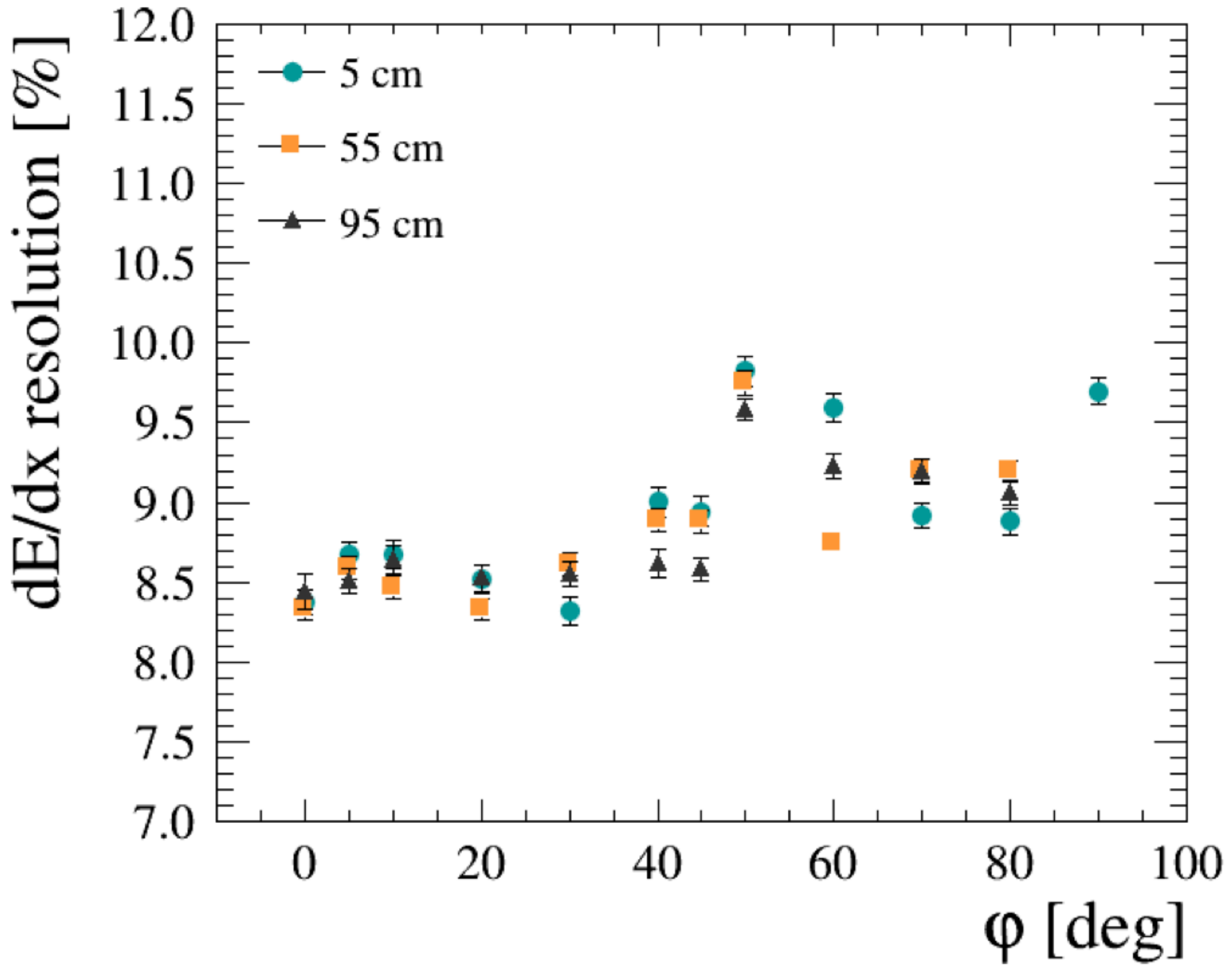
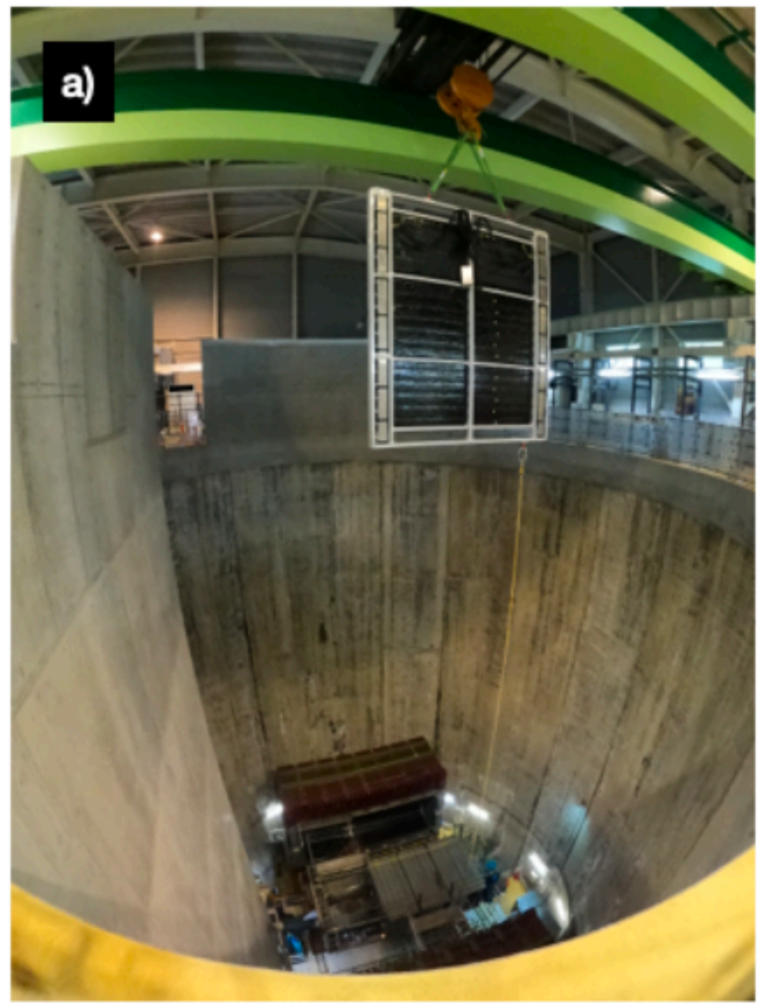


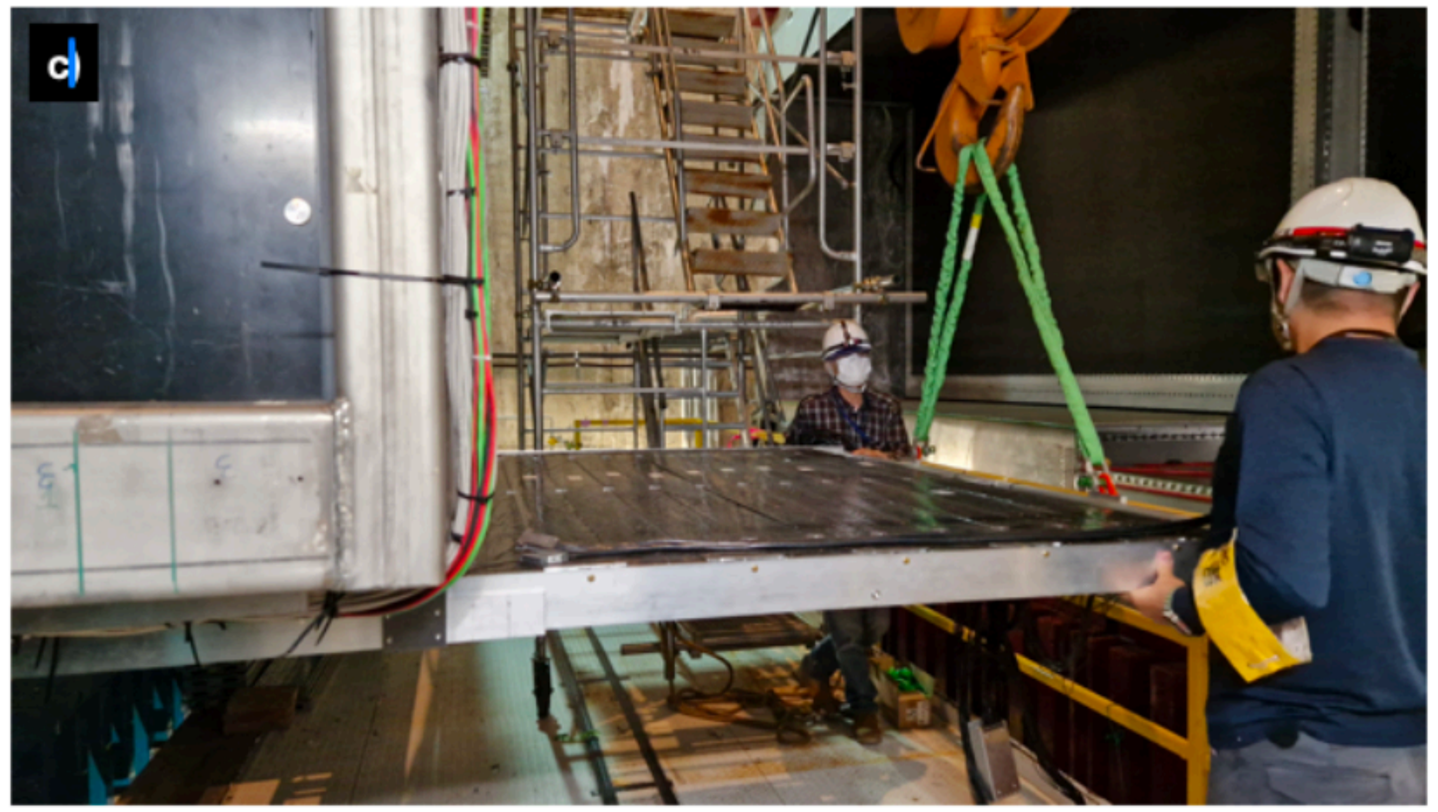




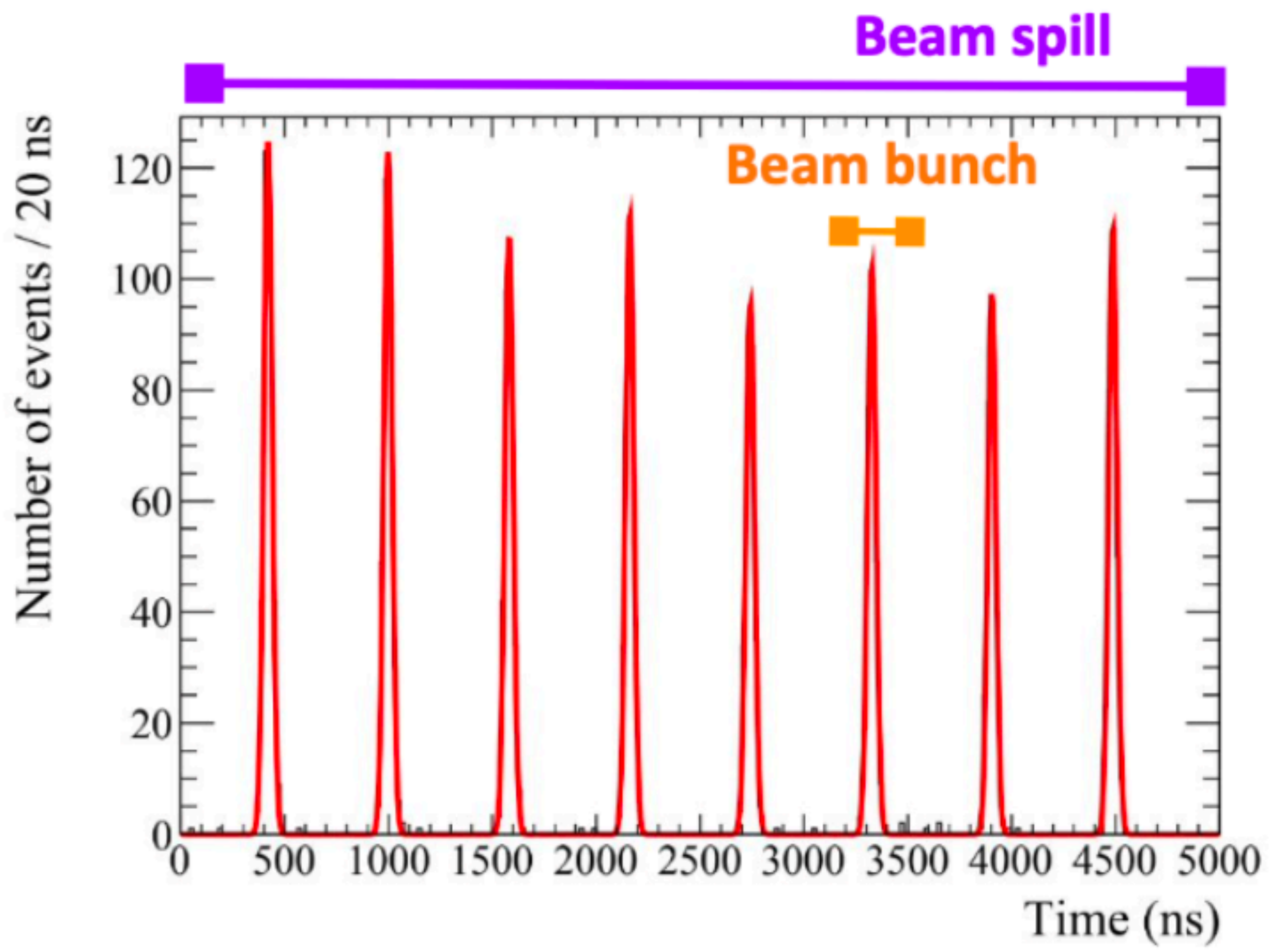


Time-Of-Flight

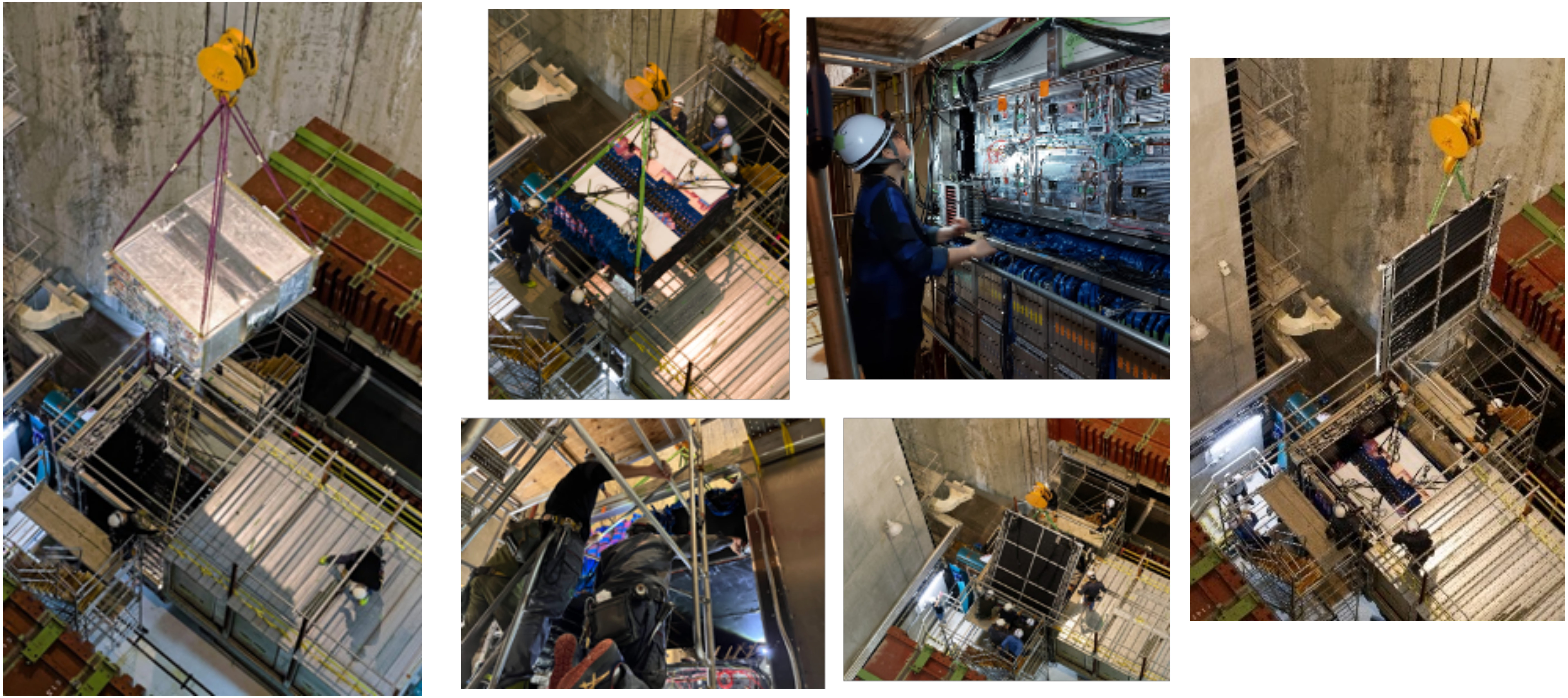




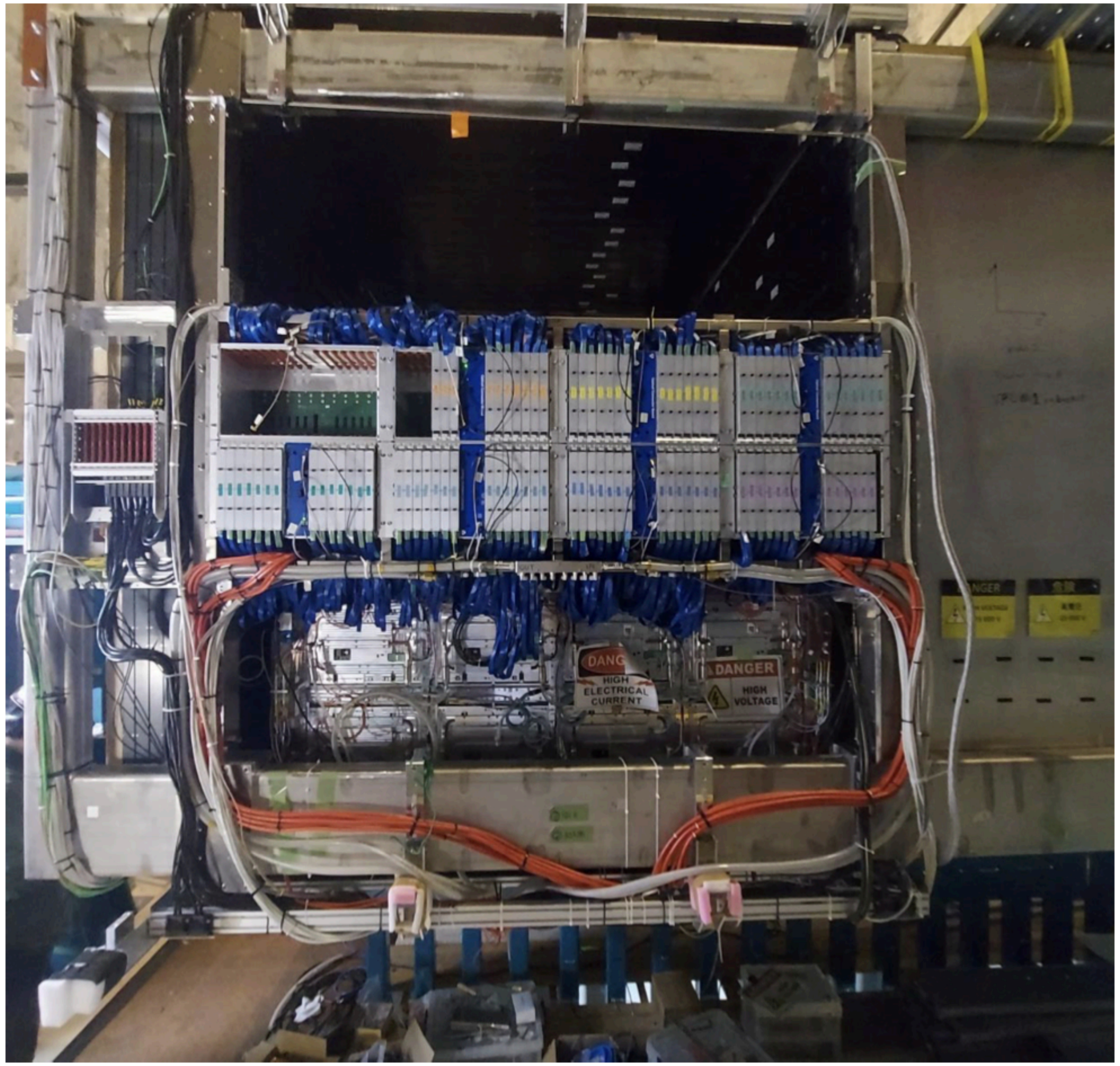
- Reconstruct track direction to reject tracks entering the new tracker region
- All 6 TOF modules assembled and tested at CERN and shipped to J-PARC
- Time resolution ~ 150 ps observed during tests at CERN
- 8 bunches neutrino beam structure clearly visible

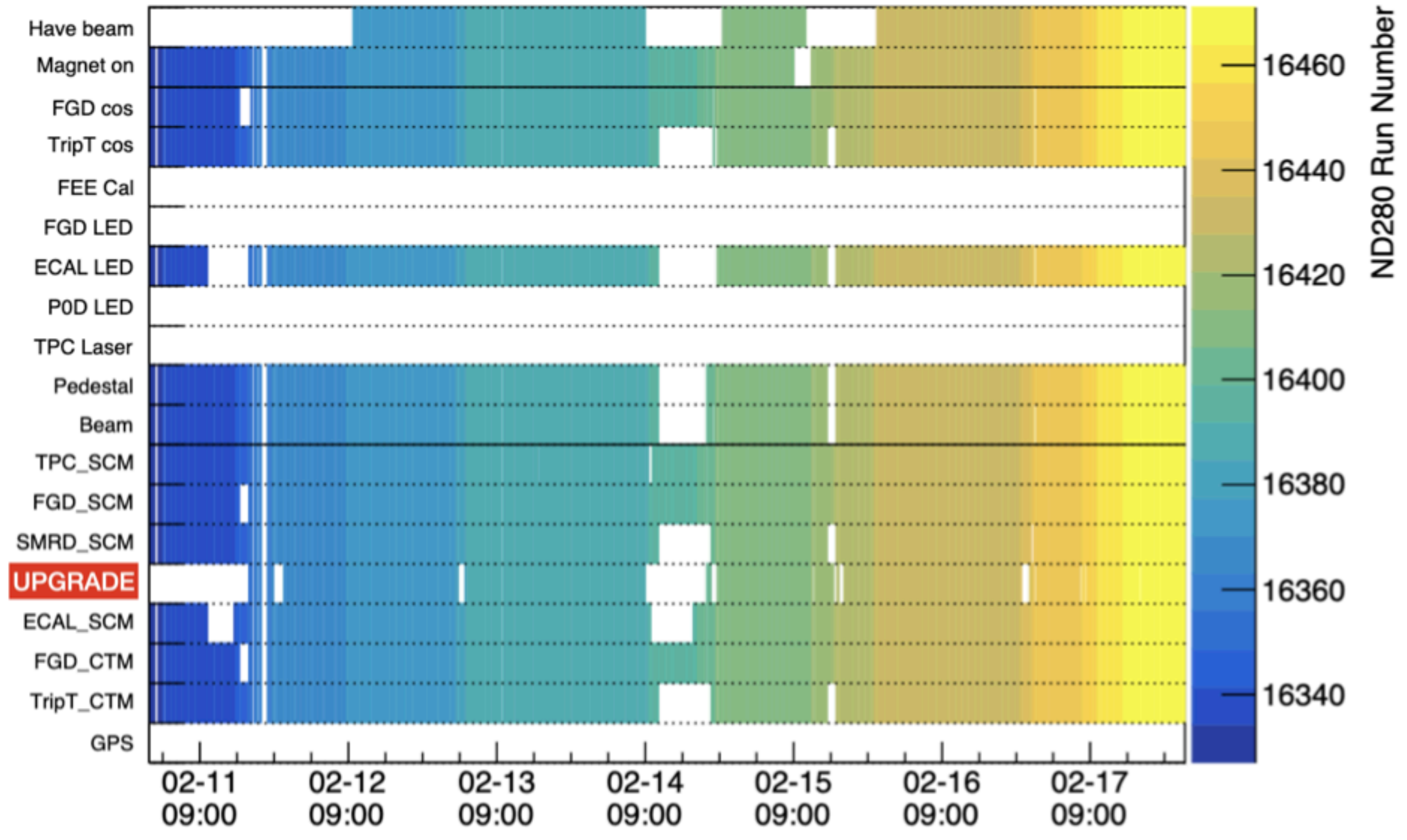


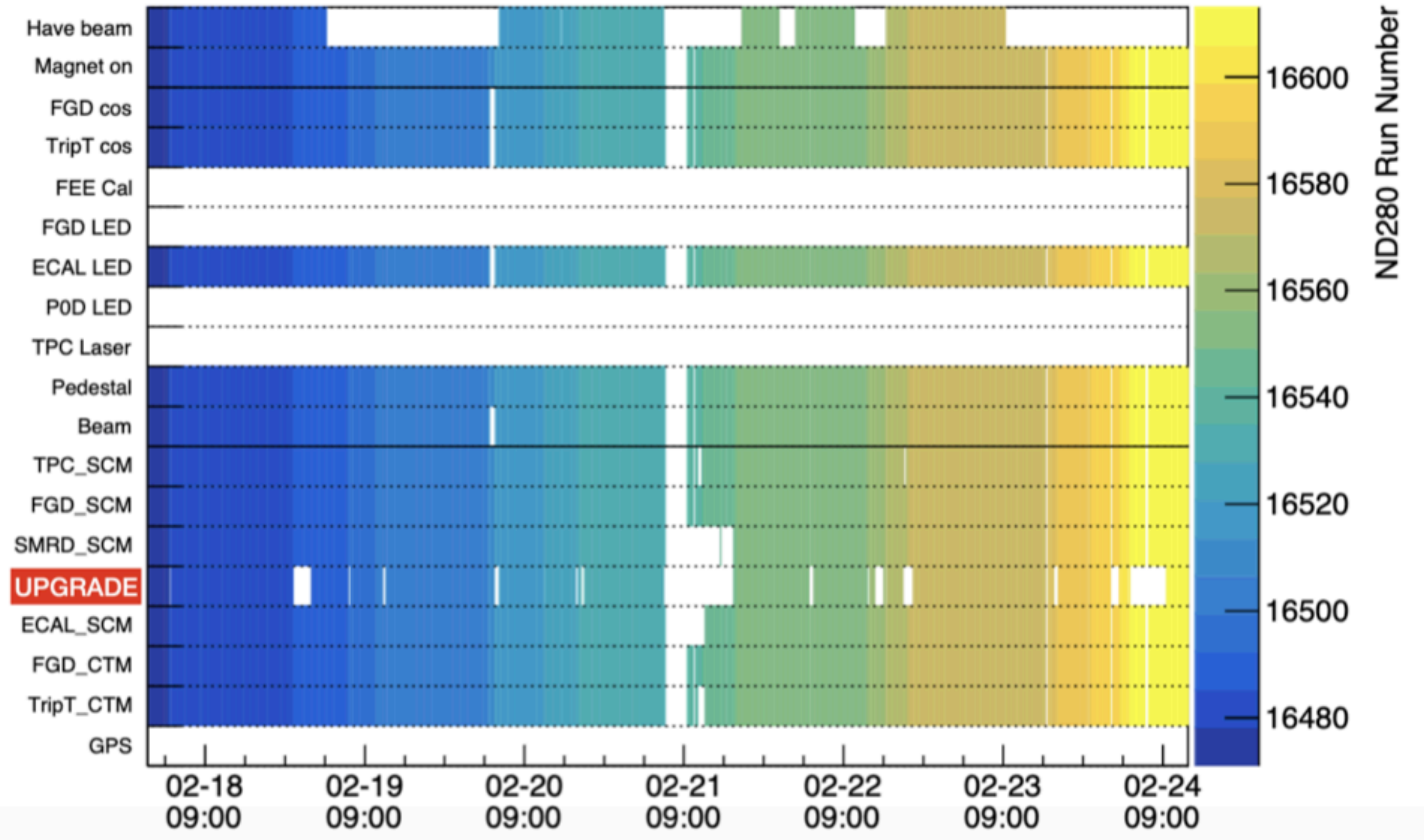
Installation at J-PARC



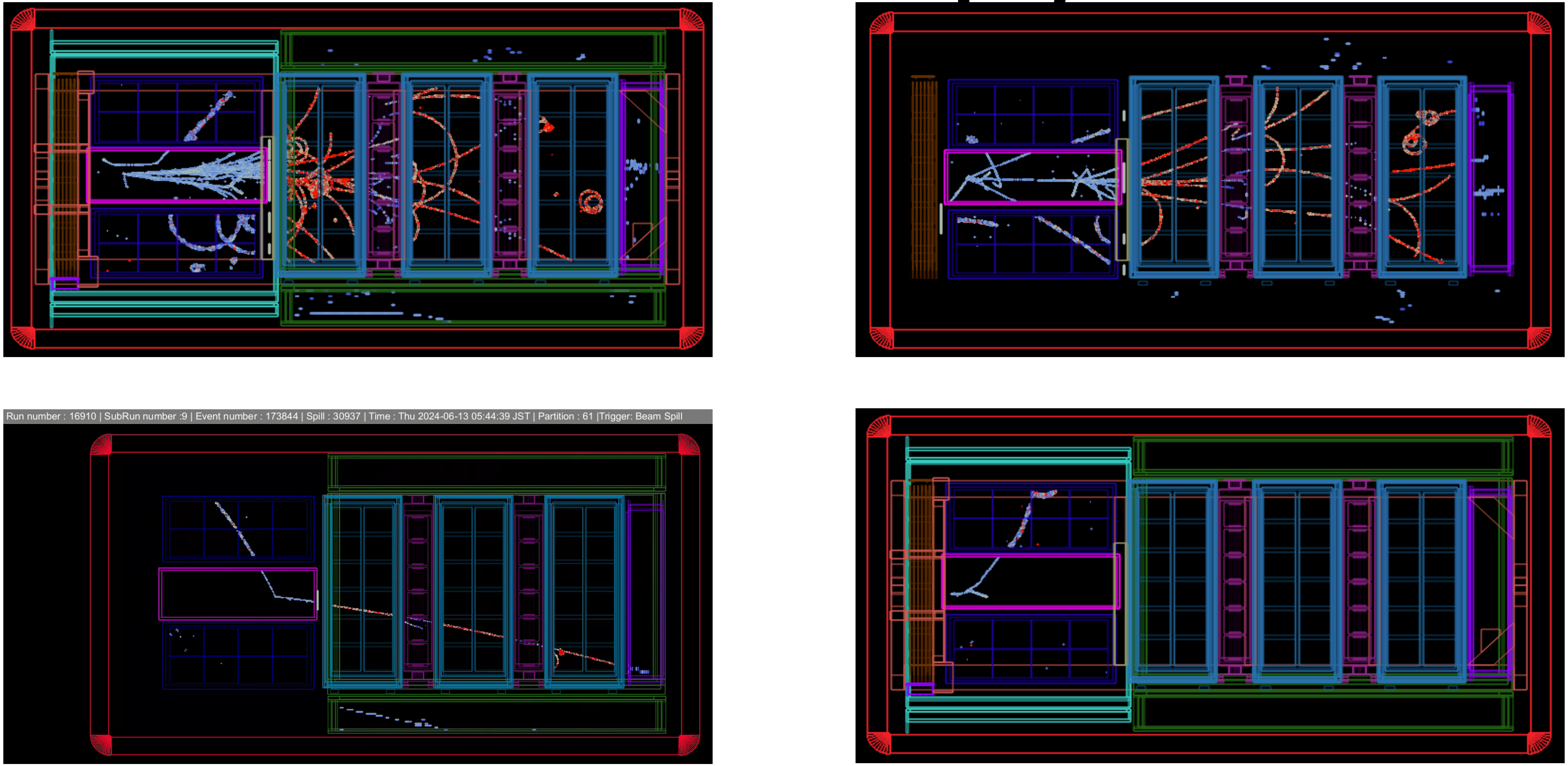
Detectors installed and taking data



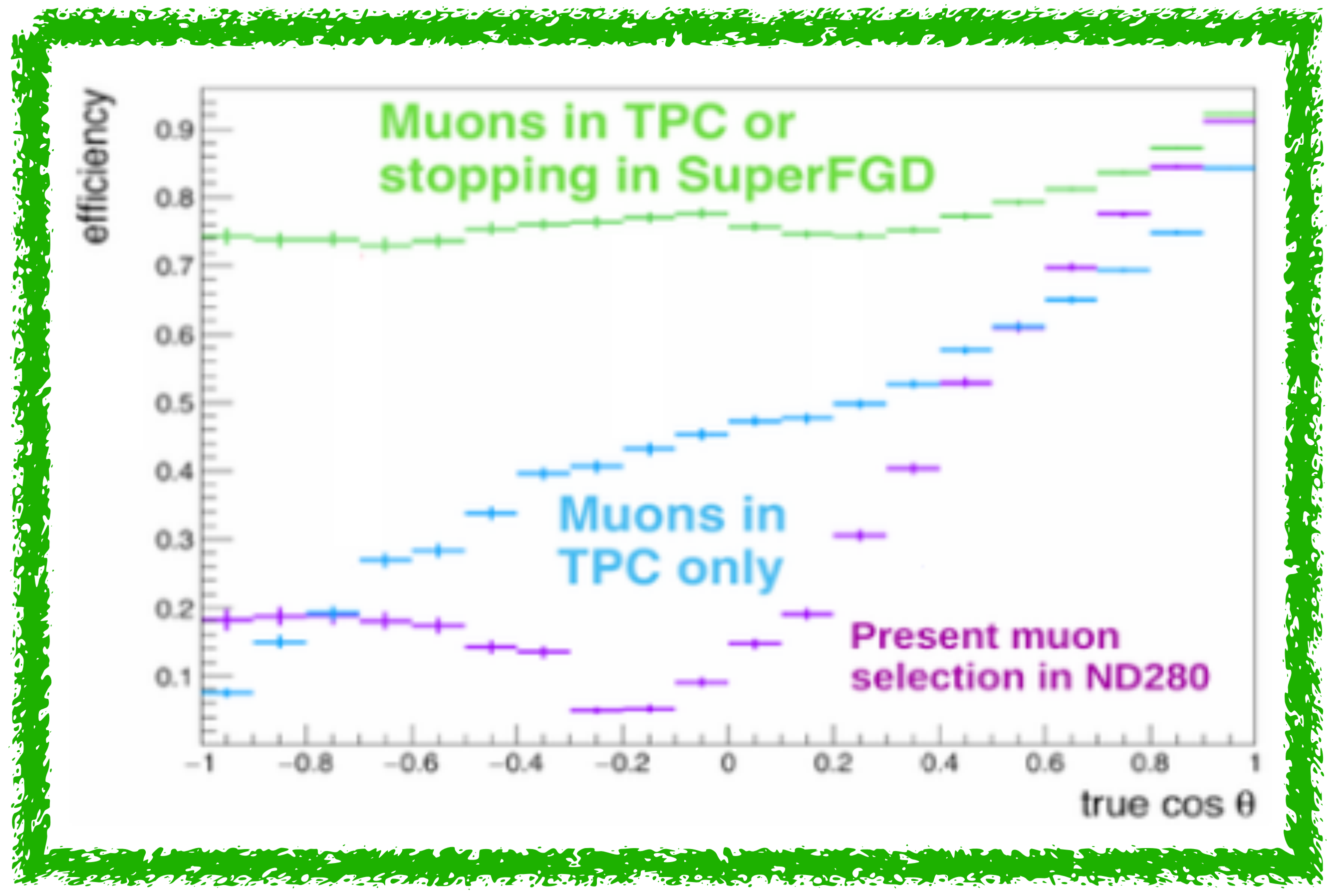


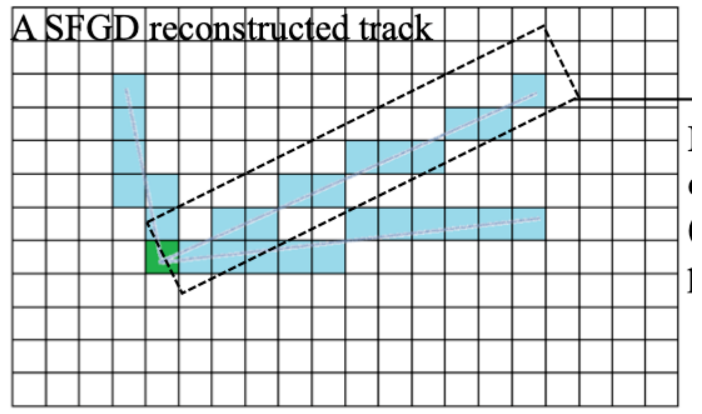


June 2024: Full upgrade

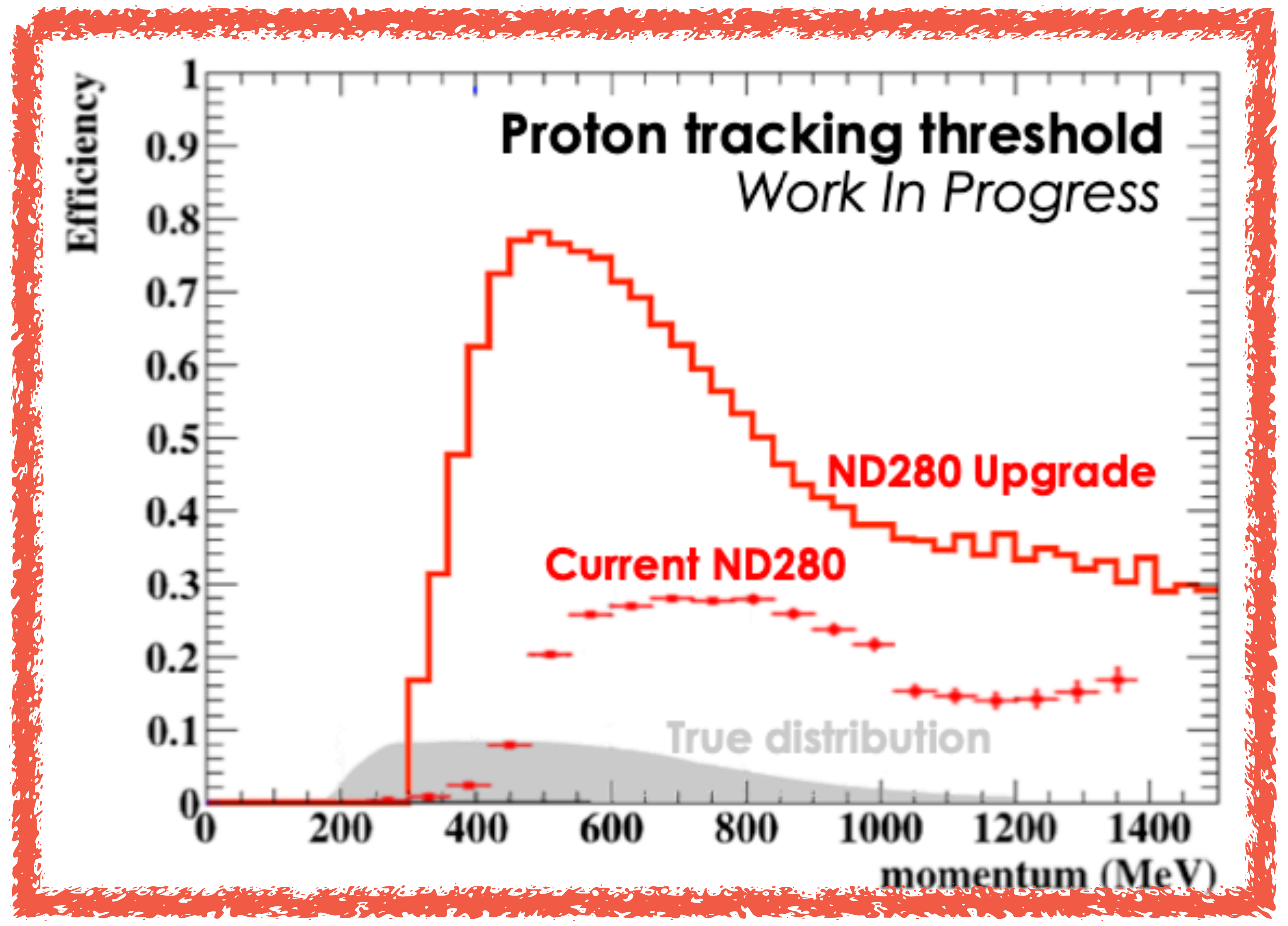


ND280 Upgrade improvements

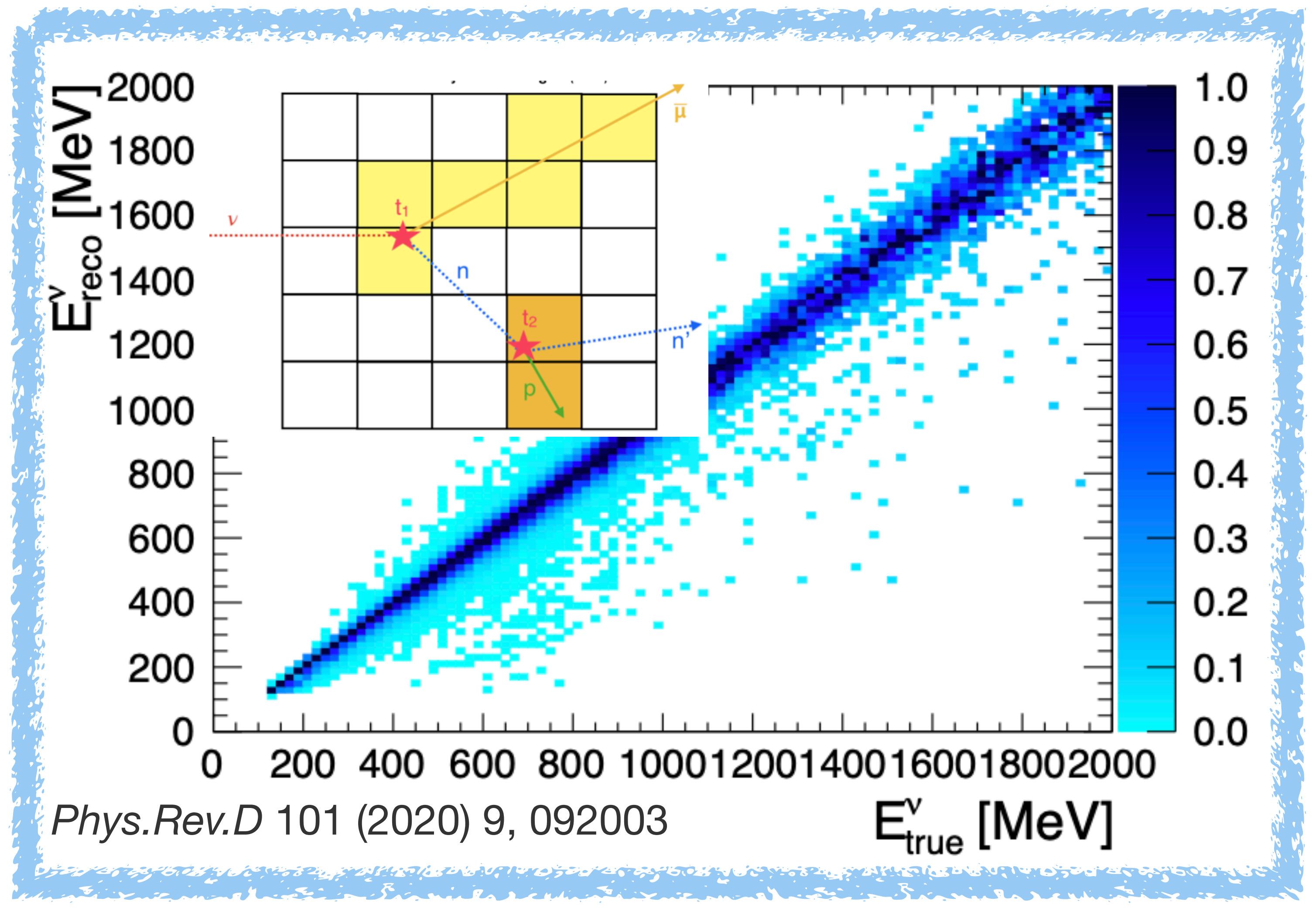




Protons → threshold down to 300 MeV/c
(>500/c MeV with current ND280)



- High-Angle TPCs allow to reconstruct muons at any angle with respect to beam
- Super-FGD allow to fully reconstruct in 3D the tracks issued by ν interactions → lower threshold and excellent resolution to reconstruct protons at any angle
    - Improved PID performances thanks to the high granularity and light yield
- Neutrons will also be reconstructed by using time of flight between vertex of $\bar{\nu}$ interaction and the neutron re-interaction in the detector



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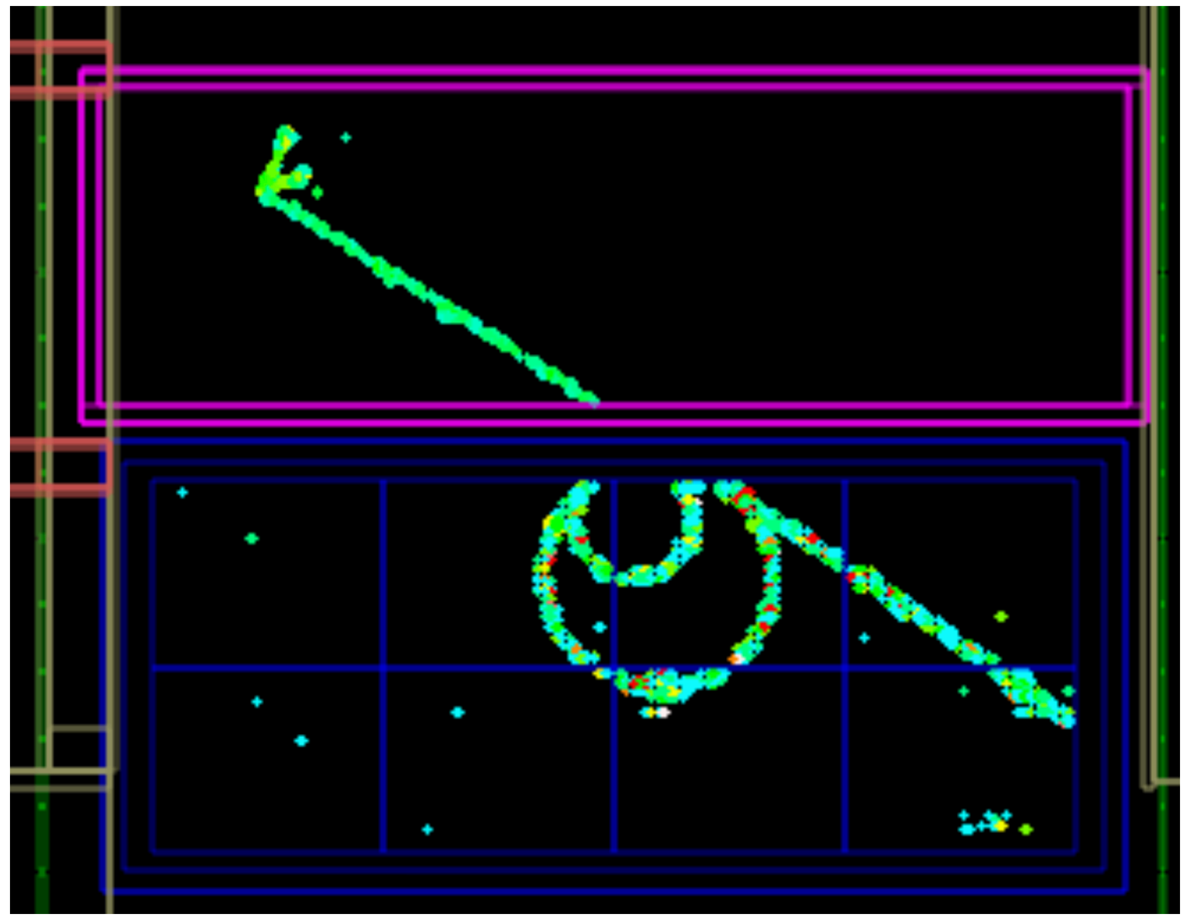
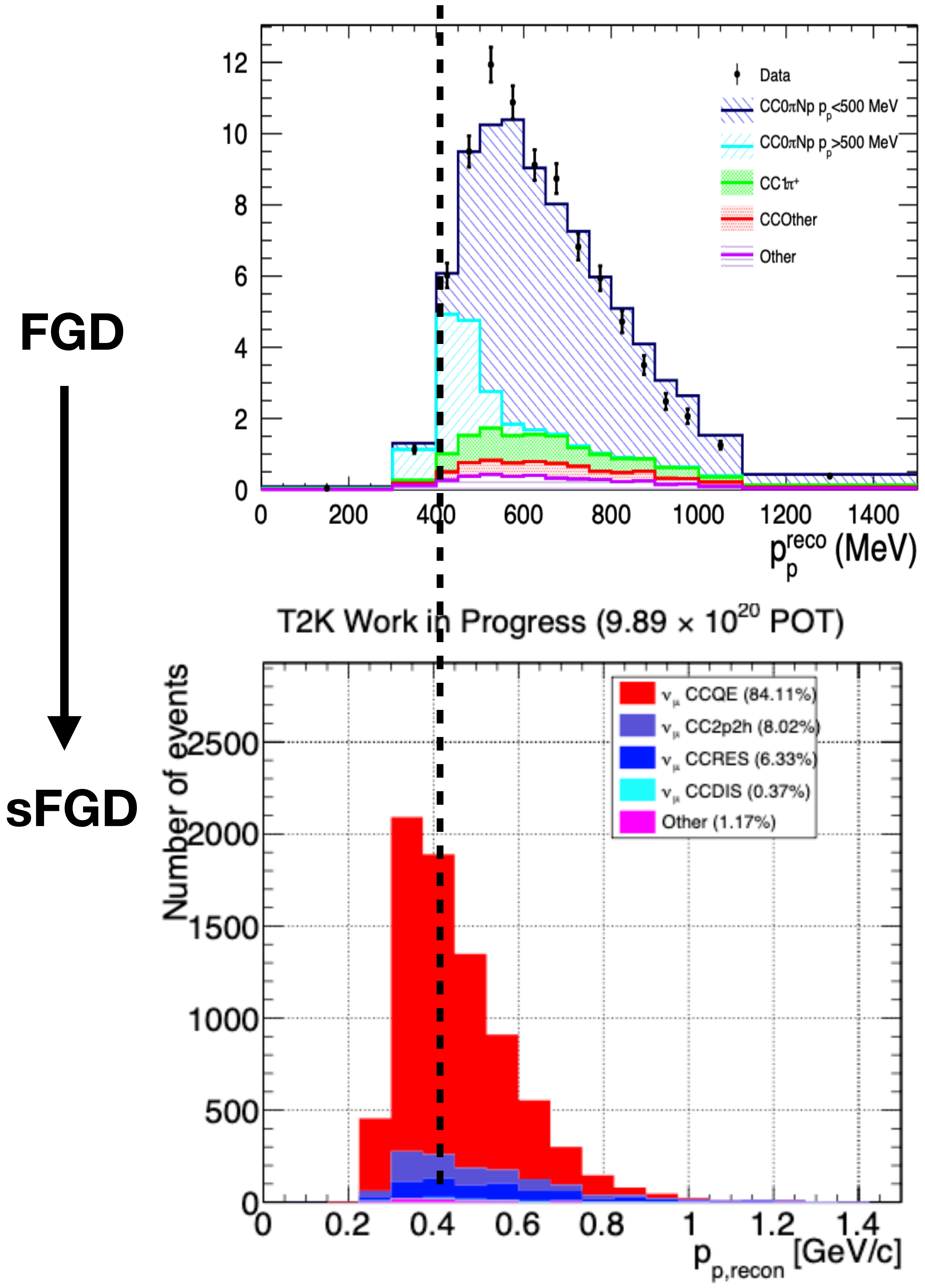
Expected performances ν_μ

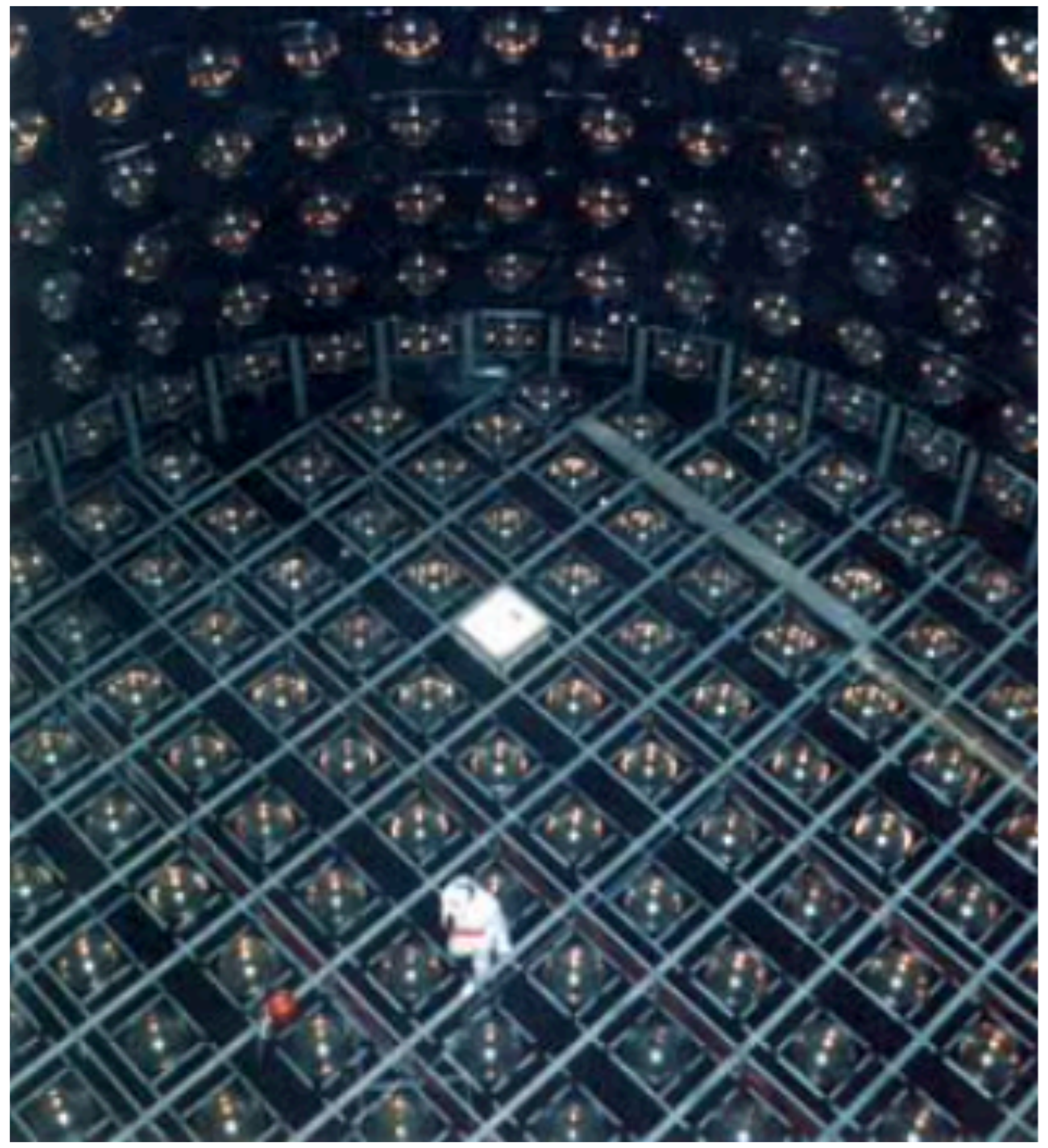
- First physics run with full upgrade currently on-going
- Expect to select 20k ν_μ CC0π interactions in the super-FGD for 1 month of beam
- ~ half of them with a reconstructed proton





Towards Hyper-Kamiokande

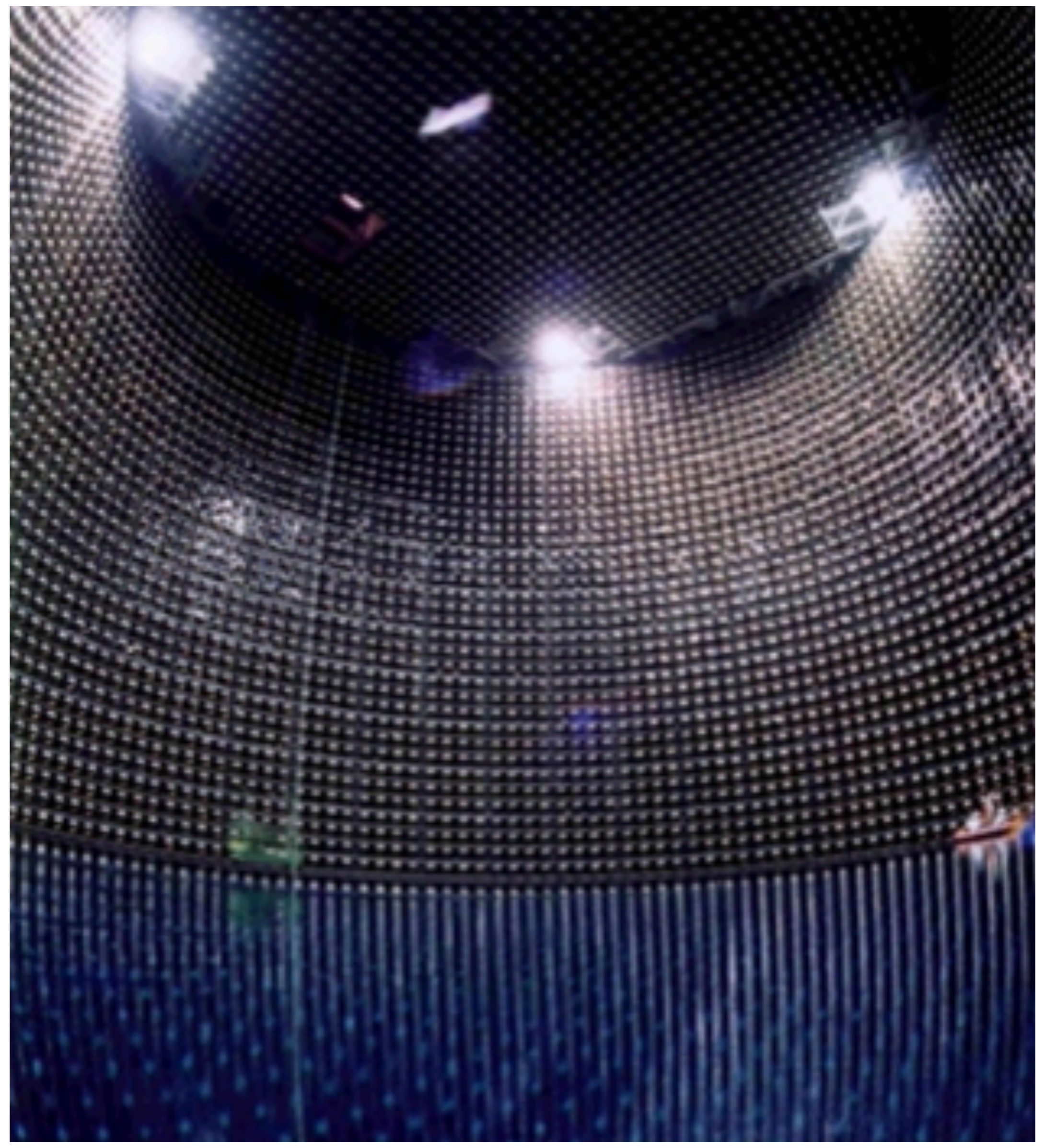
Water Cherenkov Detectors



Kamiokande
(1983-1996)

- Atmospheric and solar ν anomaly
- Supernova 1987A

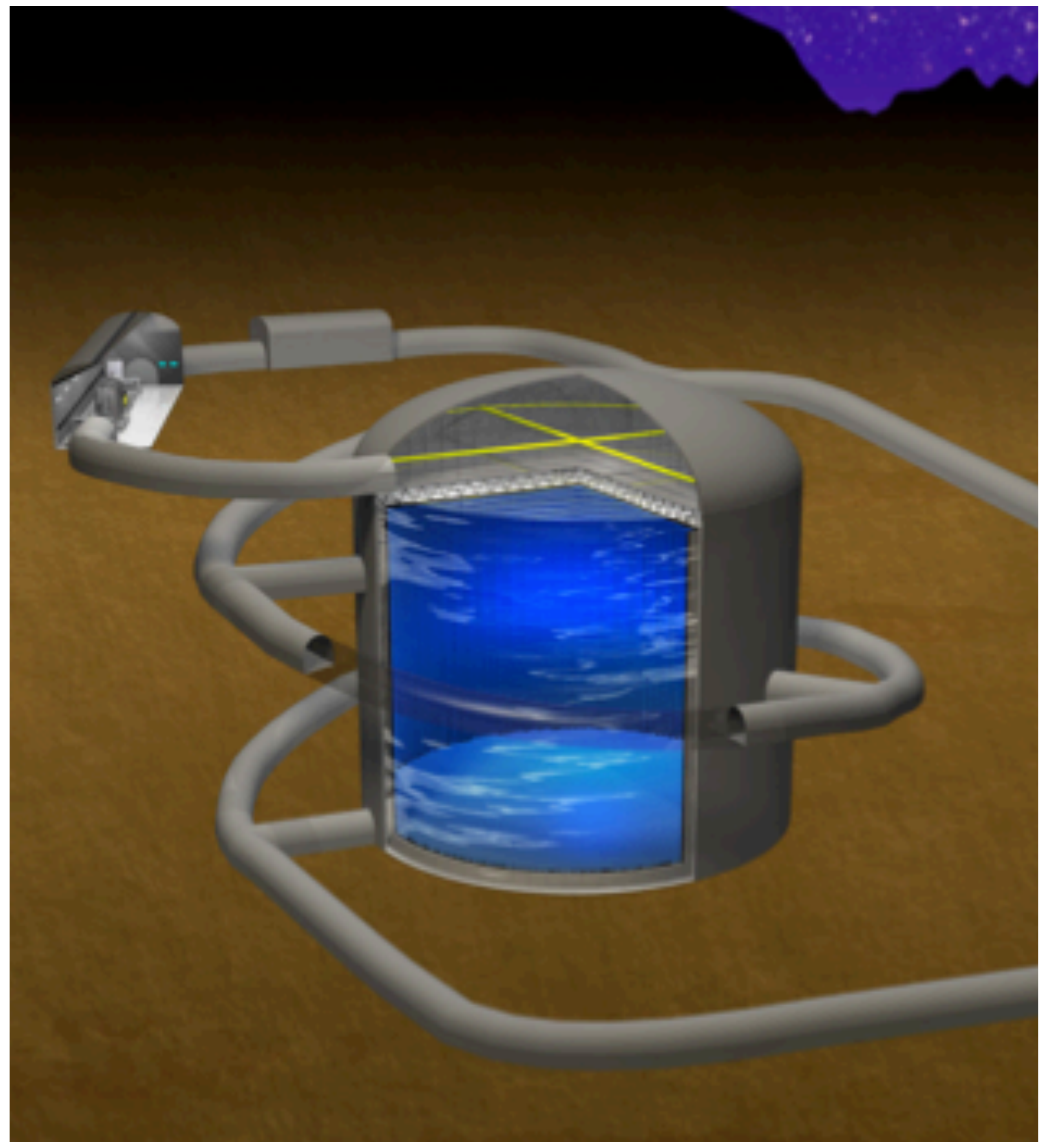
2002



Super-Kamiokande
(1996-ongoing)

- World best limit on proton decay
- Discovery of ν oscillations
- Measurement of oscillations (atm/solar/LBL)

2015



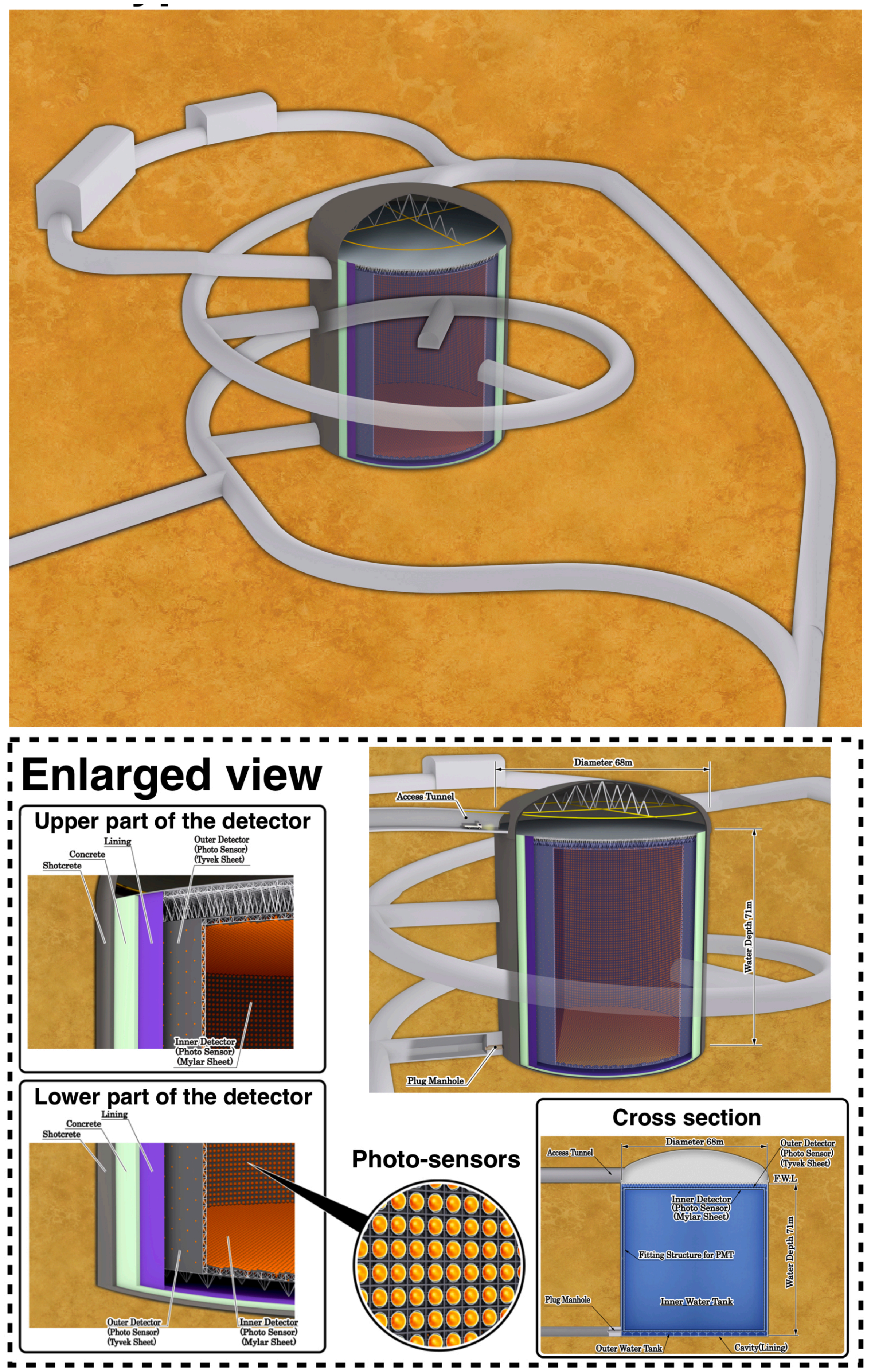
Hyper-Kamiokande
(Start in 2027)

- Extended search of proton decay
- Search for CPV in leptonic sector
- Neutrino astrophysics

203?

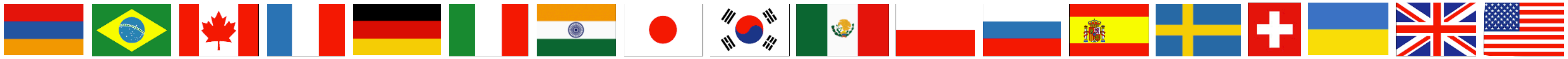
Hyper-Kamiokande

- Extremely well established Water Cherenkov technology
  - 190 kton FV (SK 22.5), instrumented with up to 40k PMTs
- HK will be the most sensitive observatory for rare events (proton decay, SN neutrinos, …)
- Search for CP violation in lepton sector
  - Upgrade of J-PARC neutrino beam (1.3 MW)
  - Near and Intermediate detector complex
- Construction started in April 2020 → start operation in 2027



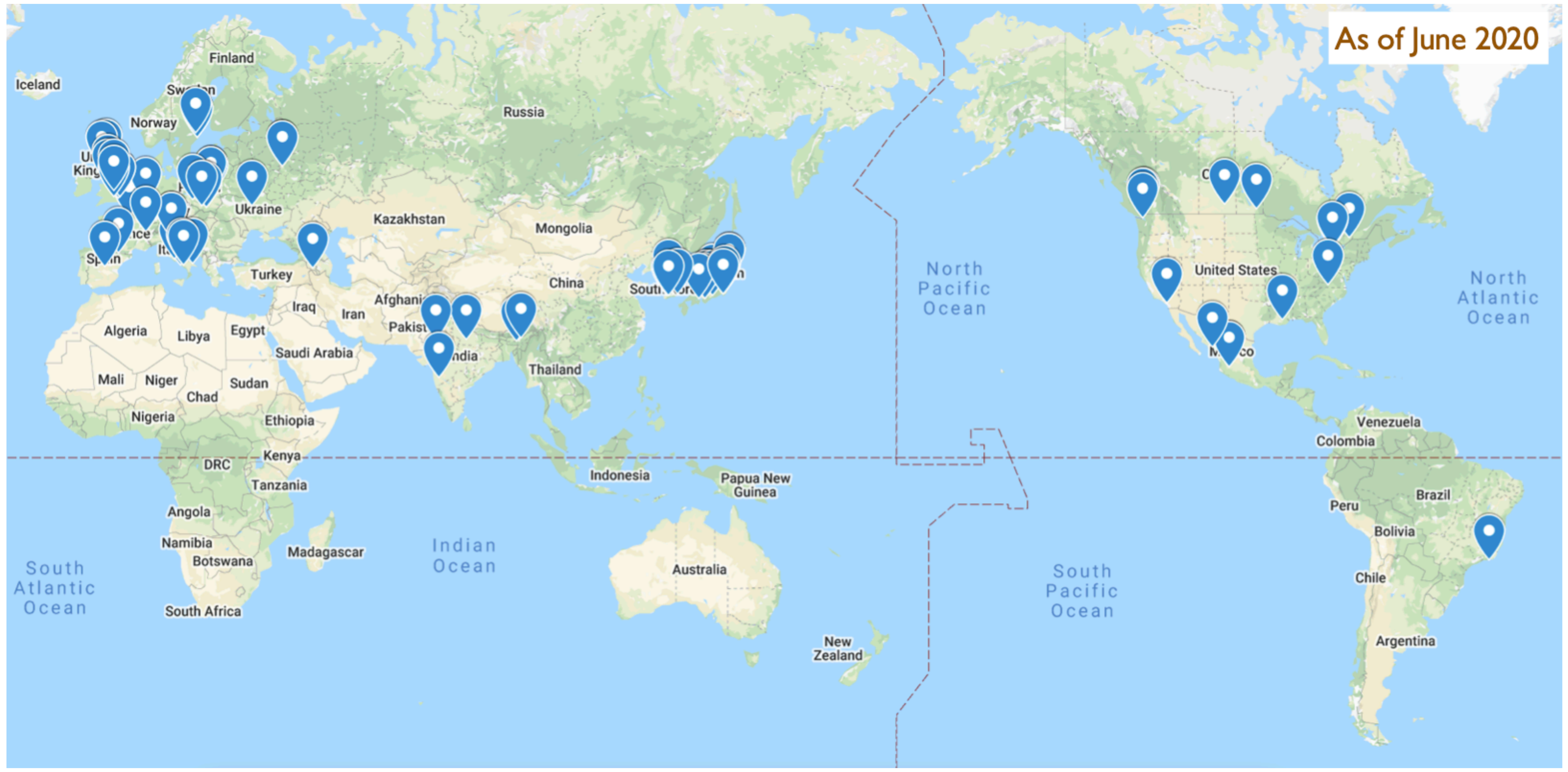
Excavation reached center of cavern dome in July

Hyper-Kamiokande collaboration

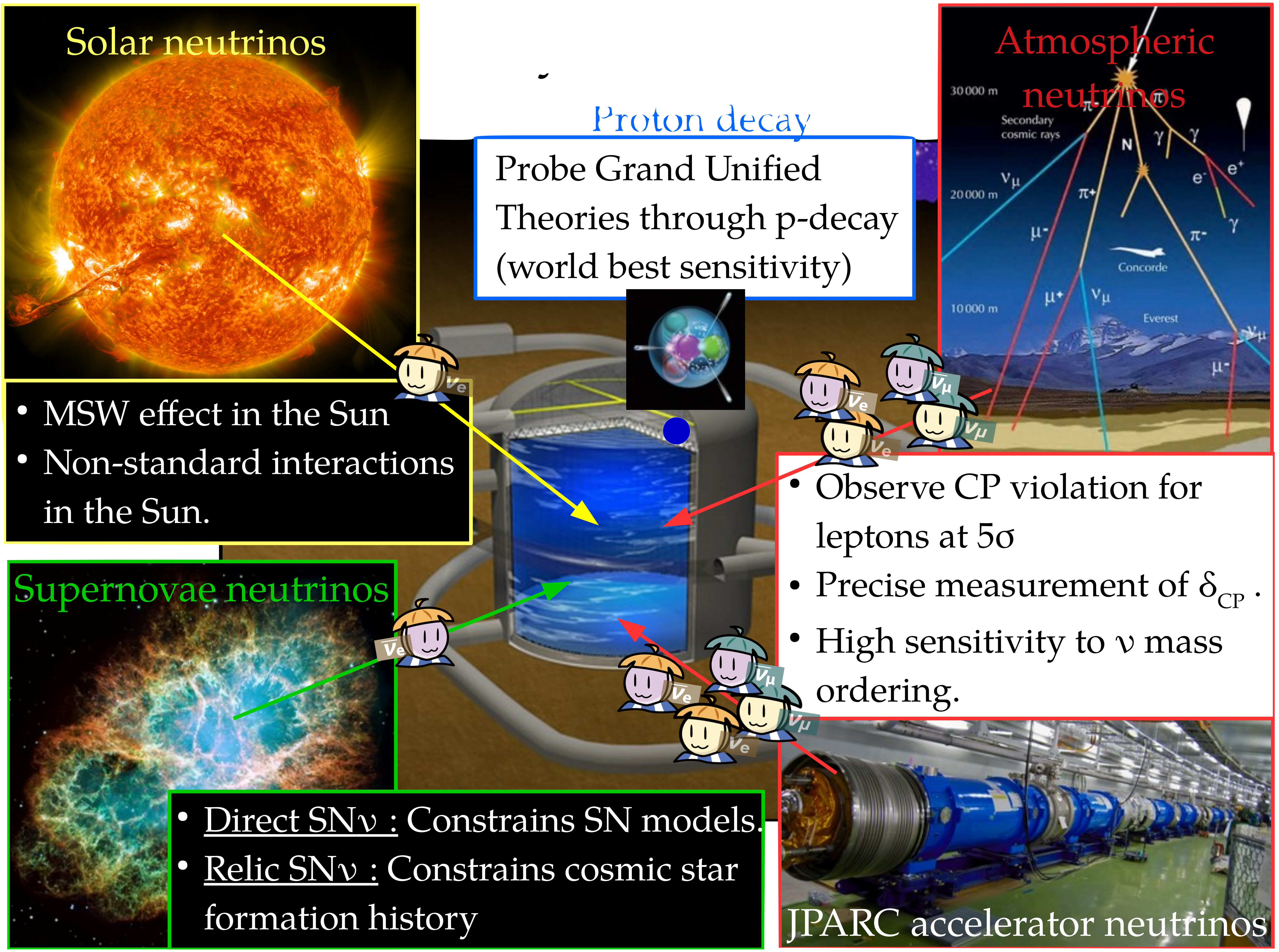


18 countries, 82 institutes, ~390 people

Hyper-Kamiokande


As of June 2020

Physics case



Solar neutrinos

- MSW effect in the Sun
- Non-standard interactions in the Sun.

Proton decay

Probe Grand Unified Theories through p-decay (world best sensitivity)

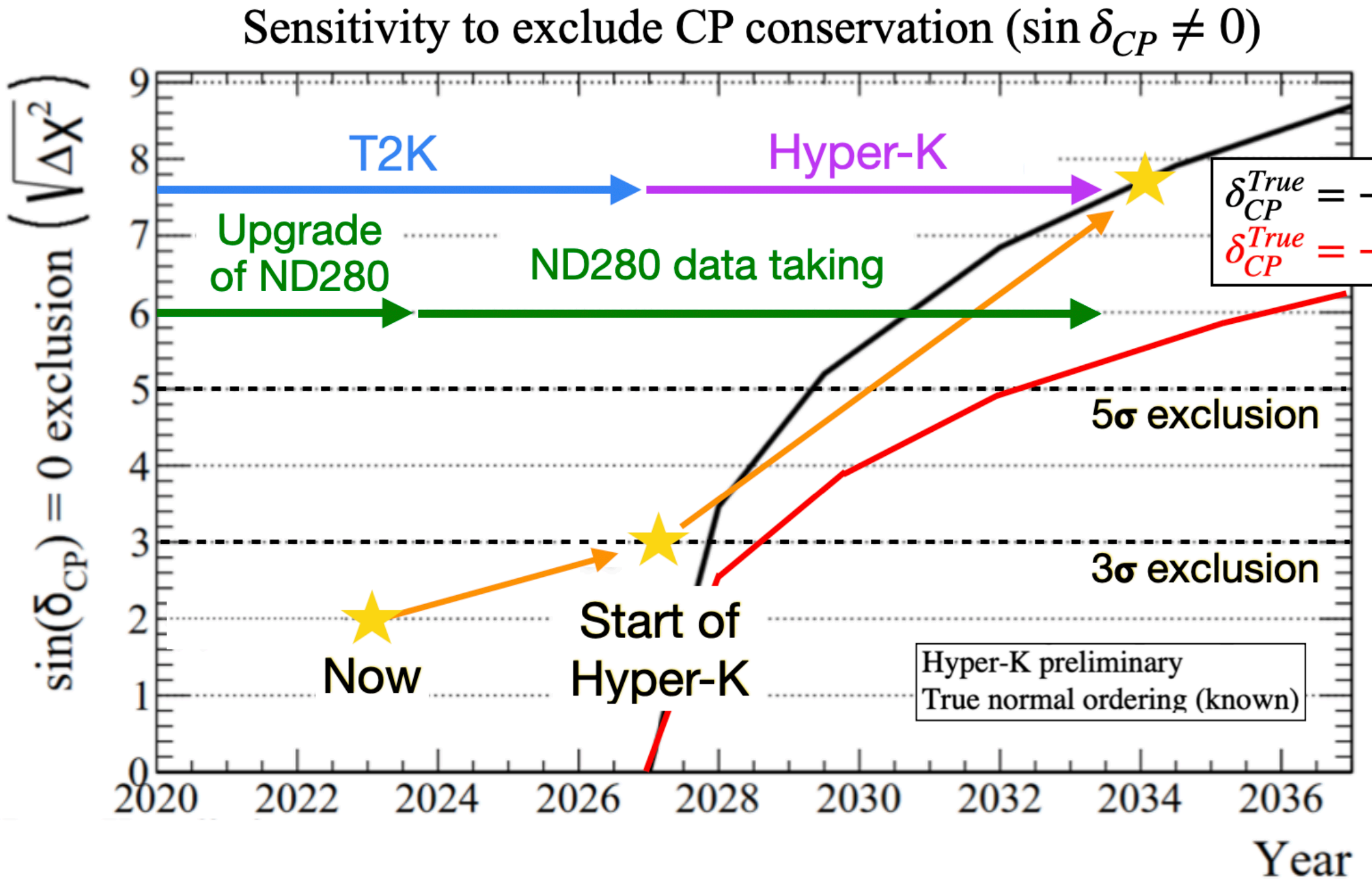
Atmospheric neutrinos

- Observe CP violation for leptons at 5σ
- Precise measurement of δ_{CP} .
- High sensitivity to ν mass ordering.

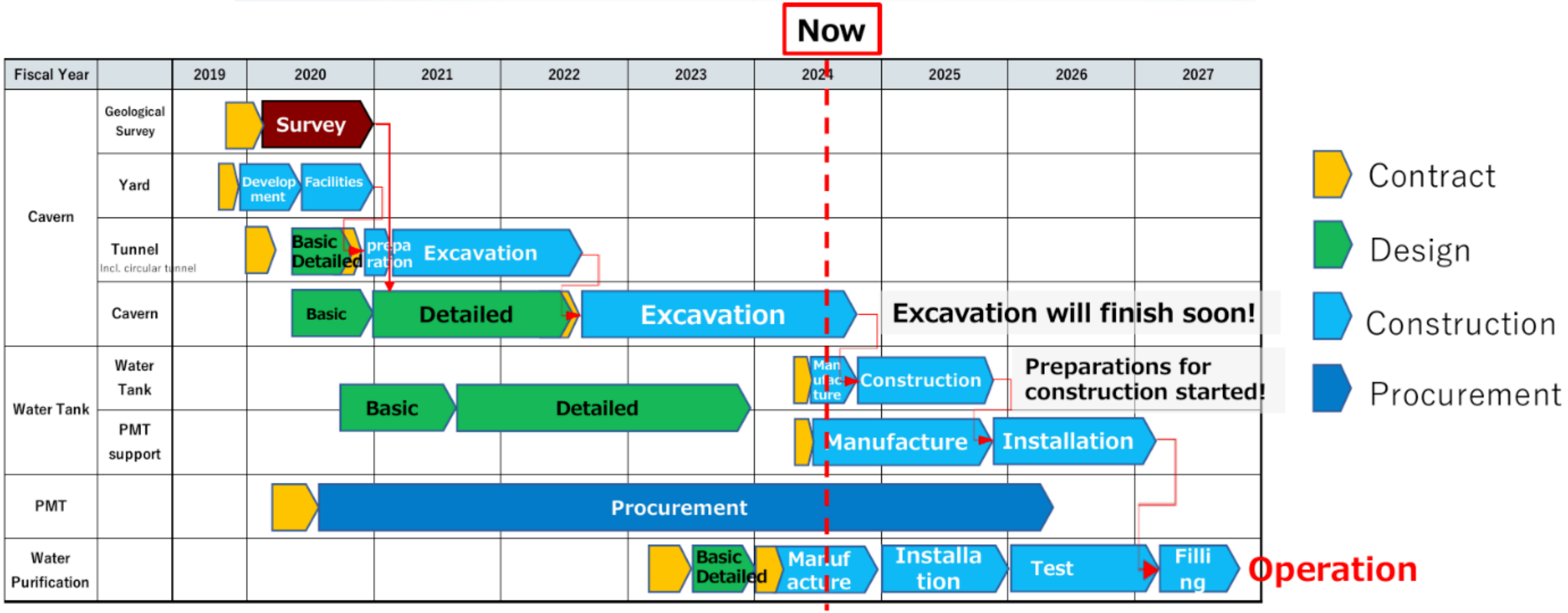
Supernovae neutrinos

- Direct SNν : Constrains SN models.
- Relic SNν : Constrains cosmic star formation history

JPARC accelerator neutrinos


Sensitivity to exclude CP conservation ($\sin \delta_{CP} \neq 0$)

HK schedule



Now

Excavation will finish soon!

Preparations for construction started!

Operation

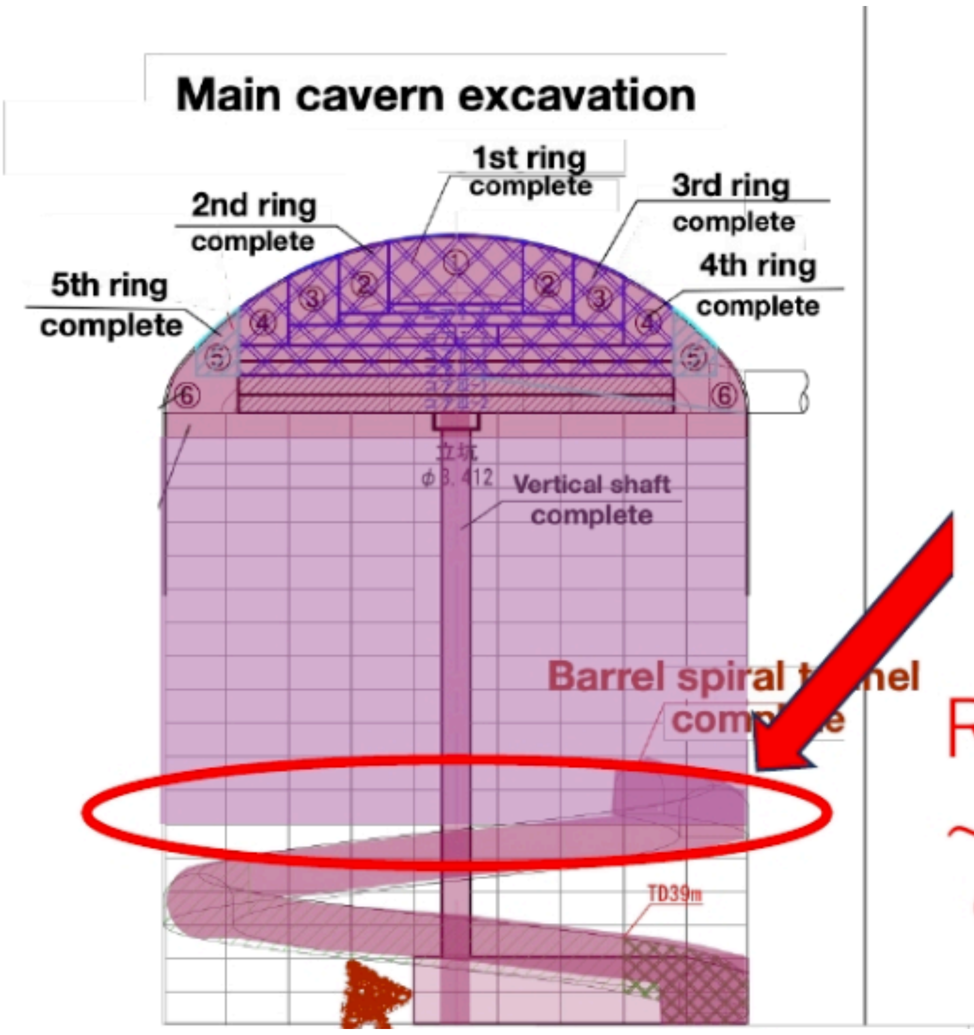
This schedule was proposed to the funding agency, MEXT, in June and approved in August.

Start operation in December 2027!

HK construction status

Excavating world largest human-made cavern

Oct. 3, 2023 Completion of the dome (dia. 69 m, height 21 m, ~1 Super-K)



Excavation of the 13^{th} bench

Remaining ~**2** SK tanks

(~30 m^3/hr average)

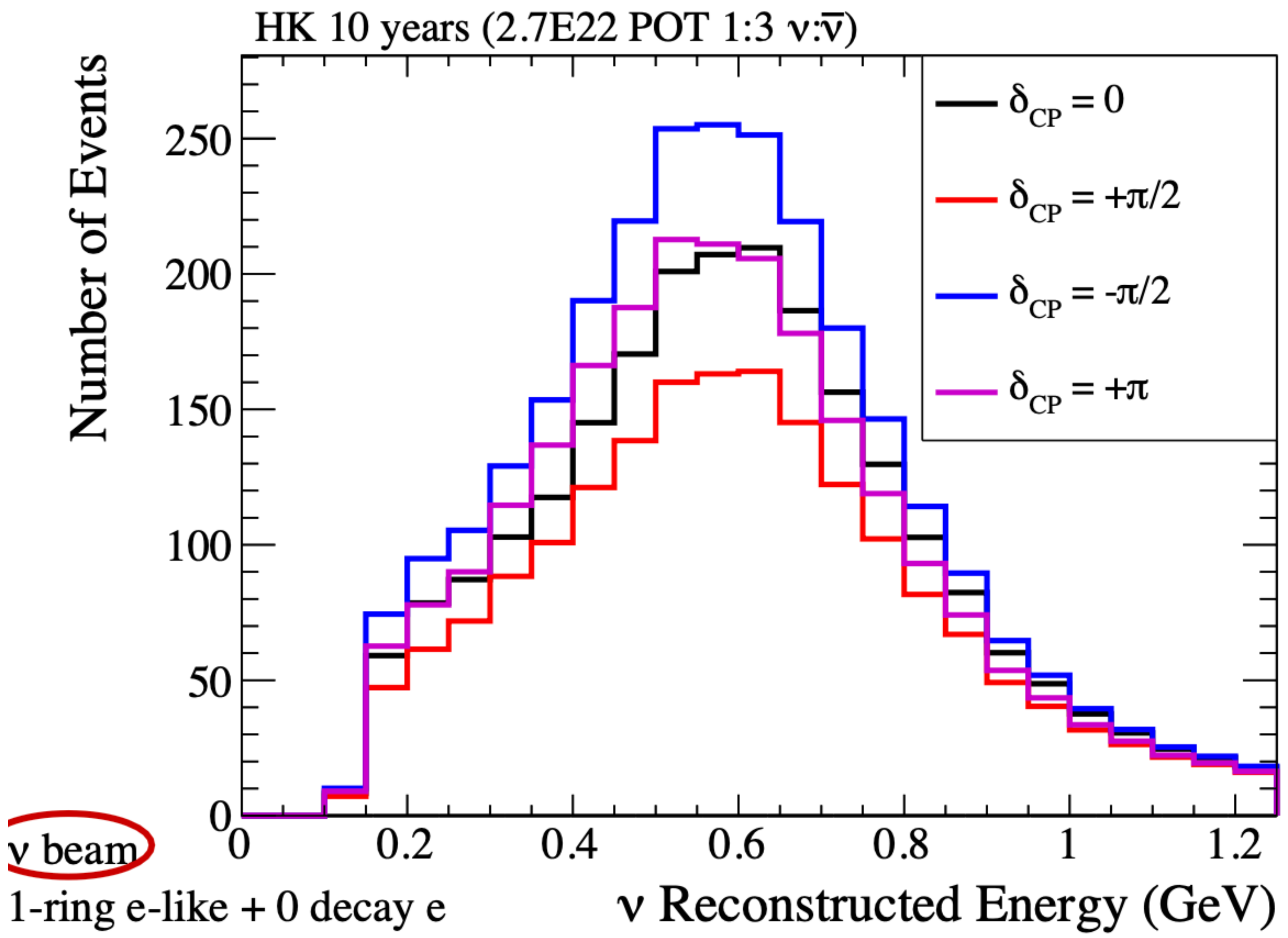
PMT production ongoing, >10,000 delivered.
Screening both at Hamamatsu and Kamioka

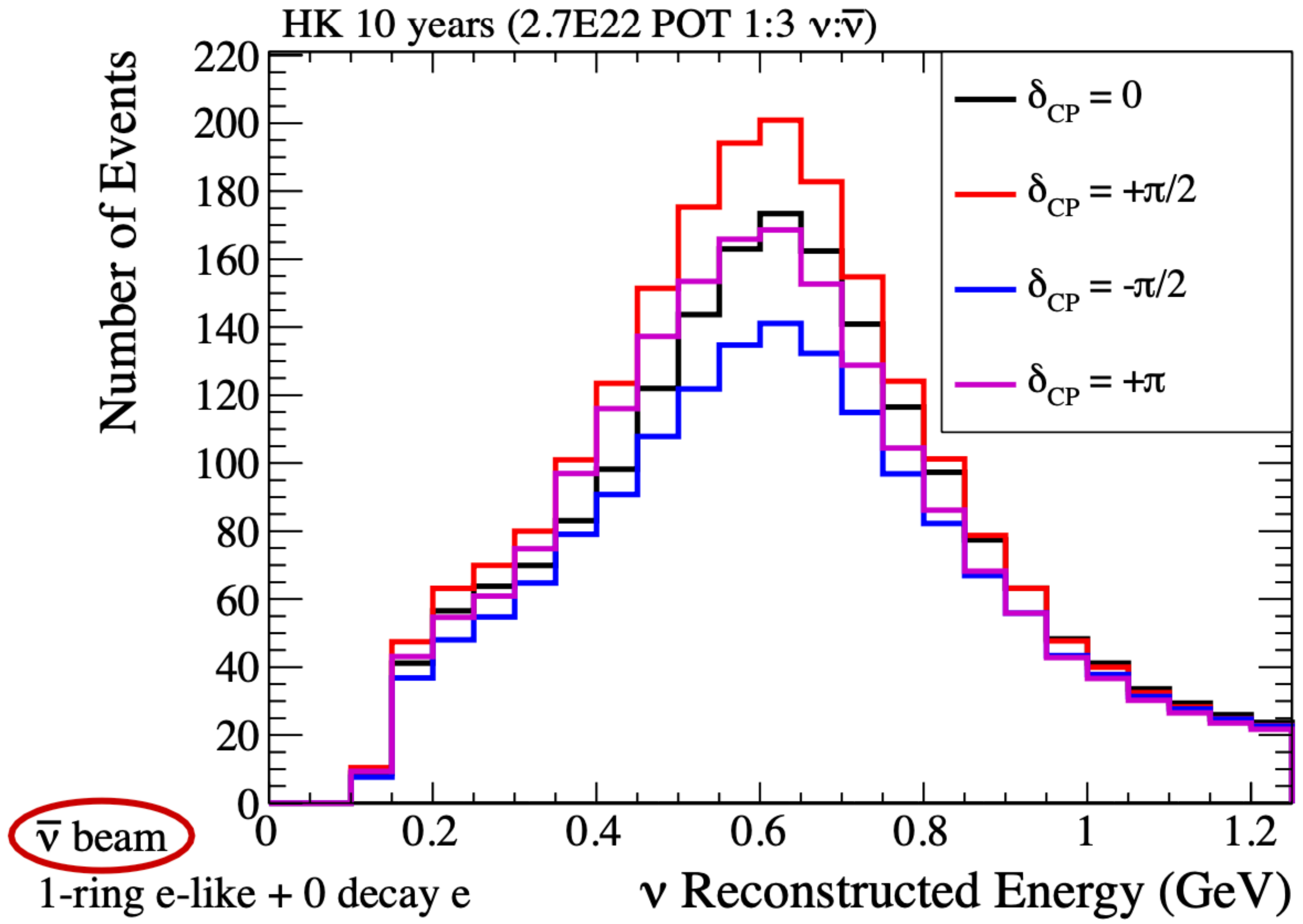
Excavation of the HK cavern will be completed by the end of this year!

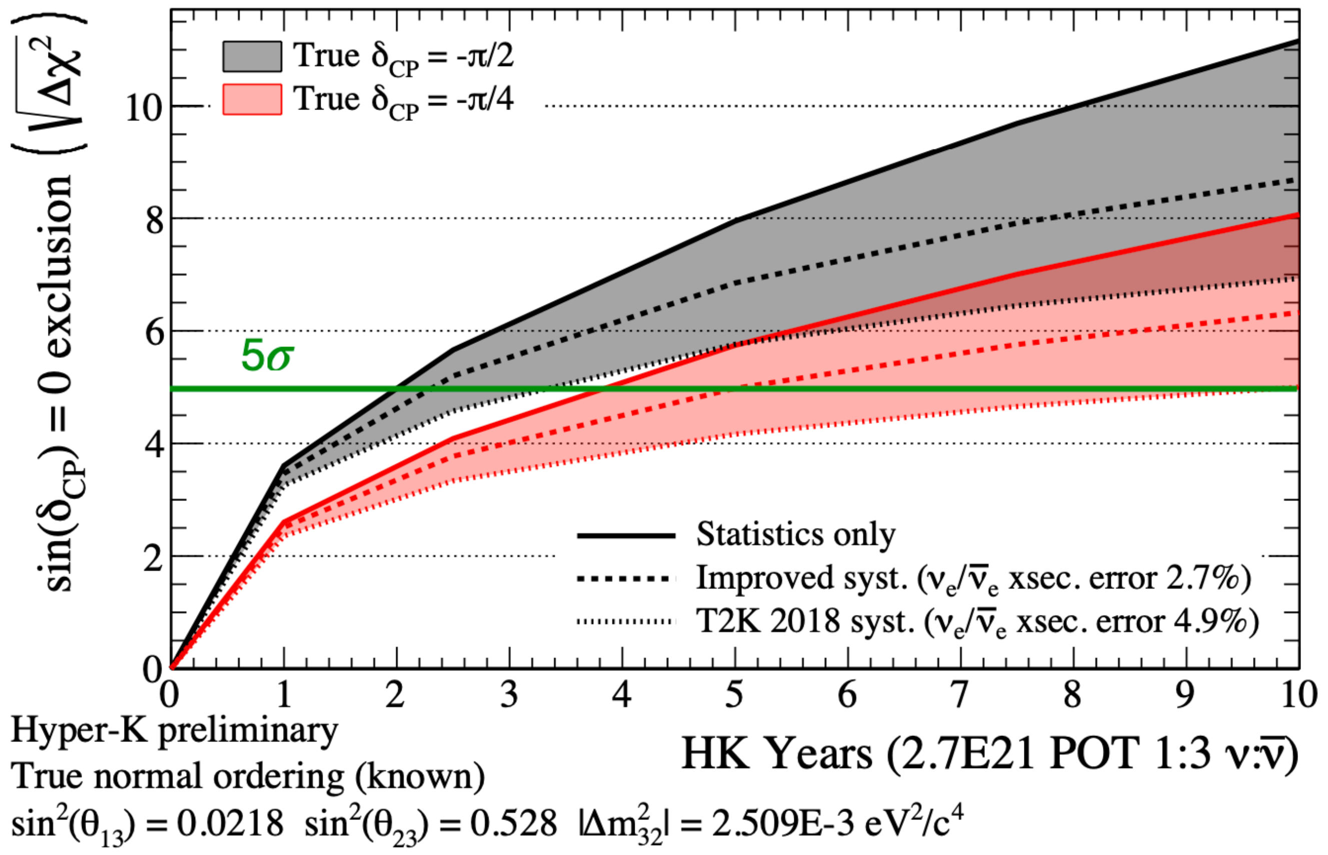
- Excavation on-going → expect to complete by the end of the year
- 20” PMTs being produced by Hamamatsu
- Assembly of the electronics modules on-going at CERN (next slide)
- Goal to start HK operation in 2027

LBL physics at HK

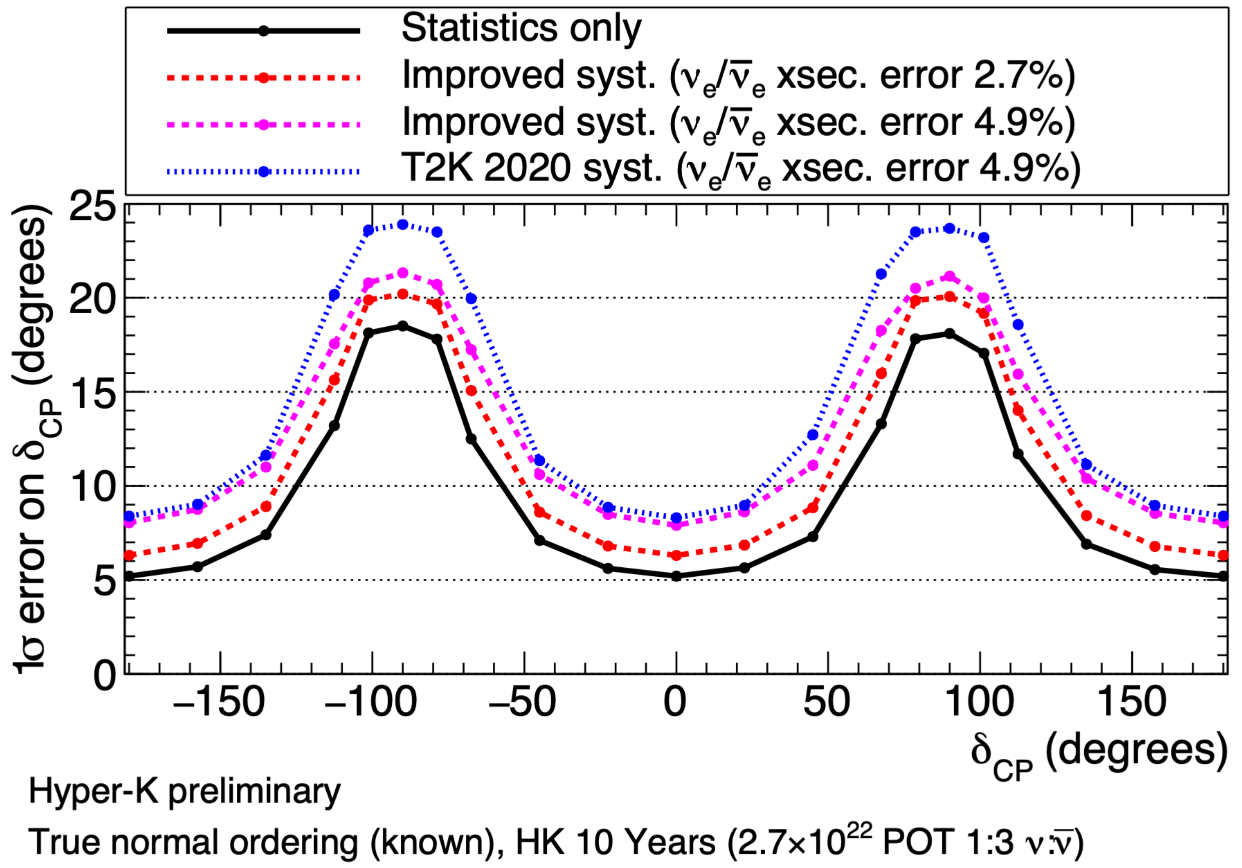
- ~2000 ν_e and 2000 $\bar{\nu}_e$ interactions selected at HK after 10 years of data taking → to be compared with ~100 ν_e and ~20 $\bar{\nu}_e$ in T2K
- Also ~20000 ν_μ and $\bar{\nu}_\mu$ interactions will be selected
- Plan to re-use ND280 to constraint flux and x-sec systematics
    - Intermediate Water Cherenkov detector will be built for HK → only sensitive to lepton kinematics + off-axis spanning
    - Do we need more from ND280? → ND280++







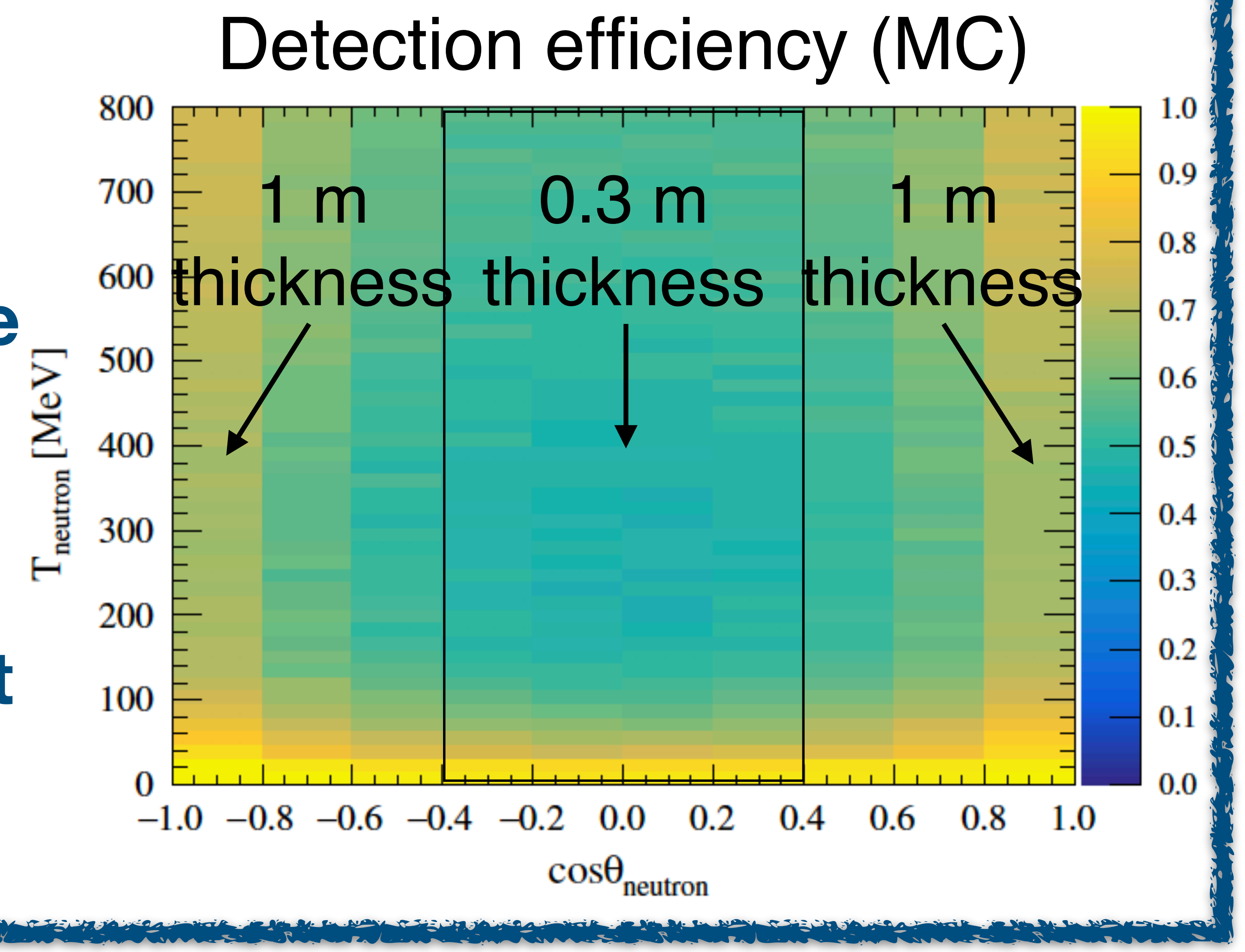
ND280 challenges for HK

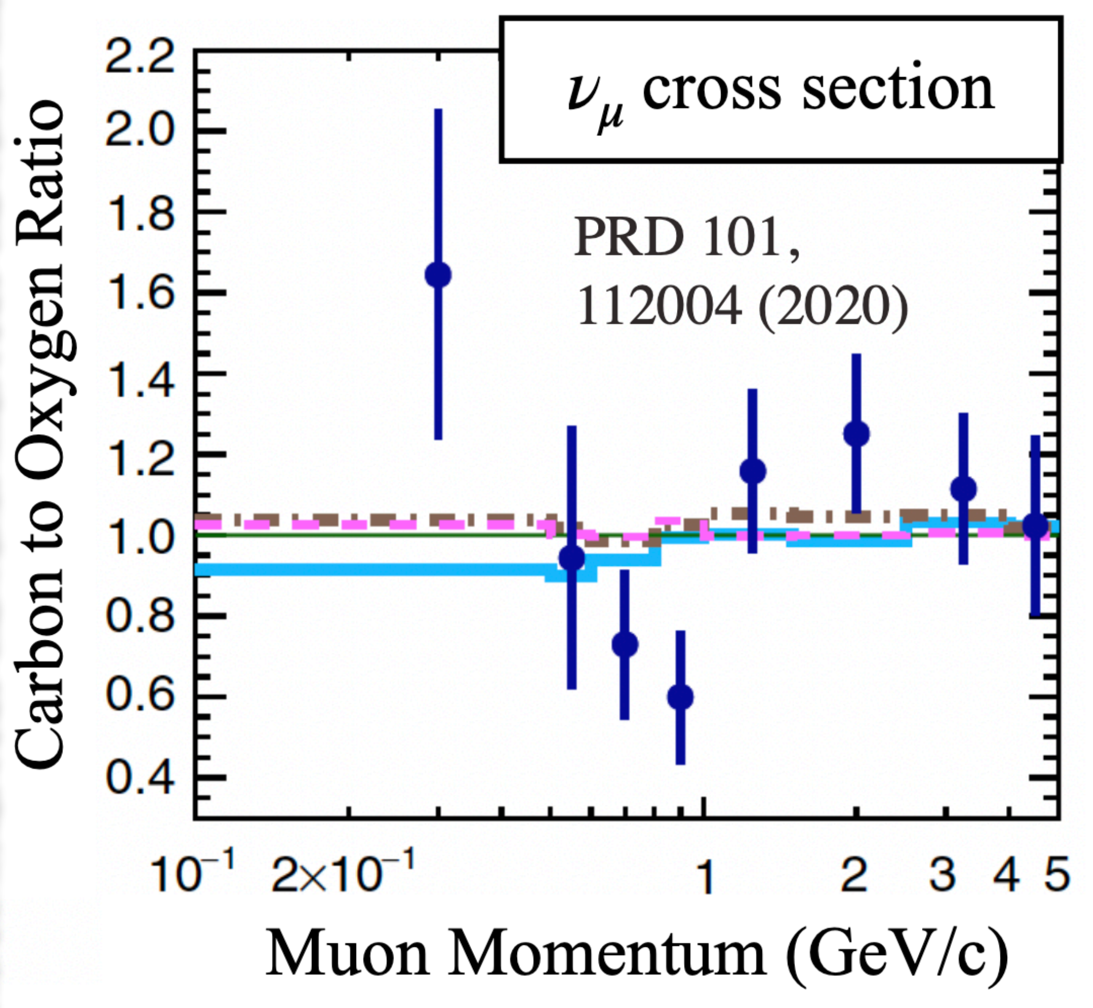


Ultimate precision measurement of δ_{CP} dominated by ν_e/ $\bar{\nu}_e$ uncertainties

→ measure them with higher statistics at the Near Detector

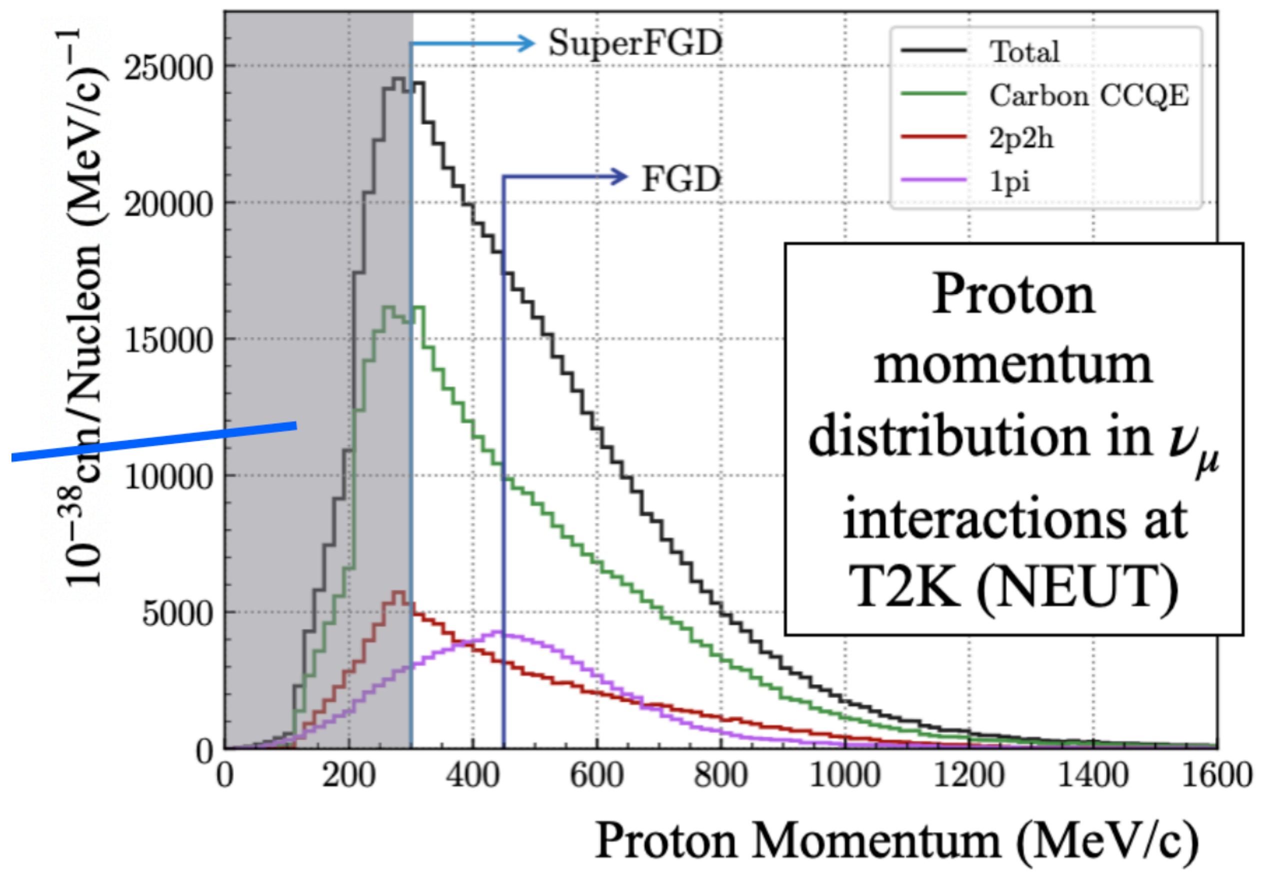
For $\bar{\nu}$ interactions it is crucial to measure neutron kinematics
→ many neutrons escape from sFGD
→ build larger target





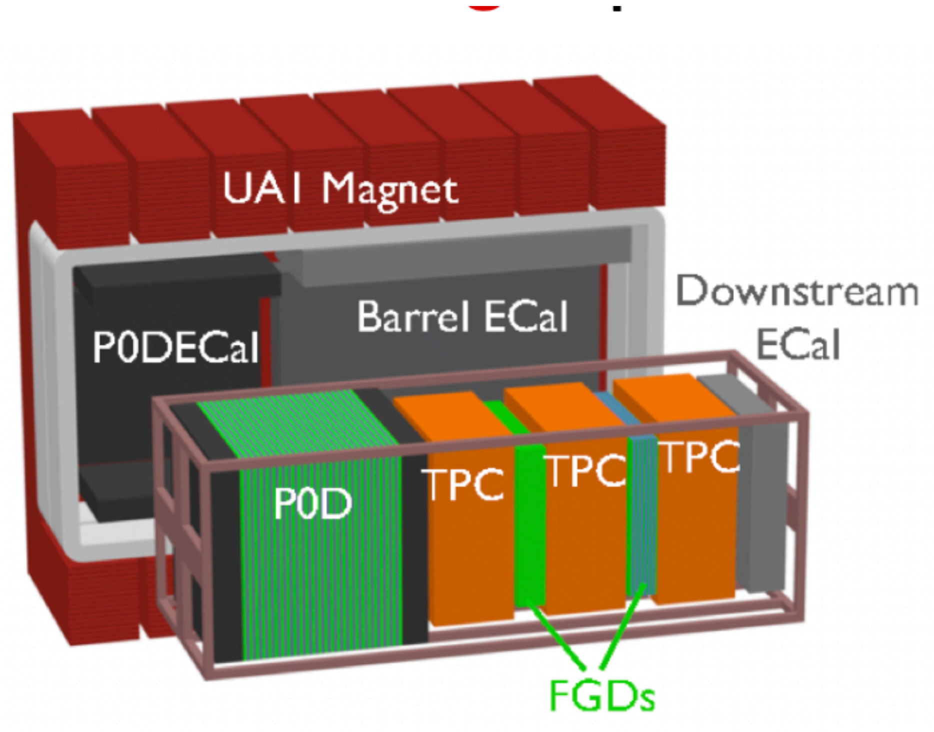
Scaling of cross-section model from Carbon (ND280) to Oxygen (SK/HK) also bring some additional uncertainties → add Water in ND280

For short protons tracks sFGD granularity is not enough and we still miss ~half of the protons → build target with larger granularity

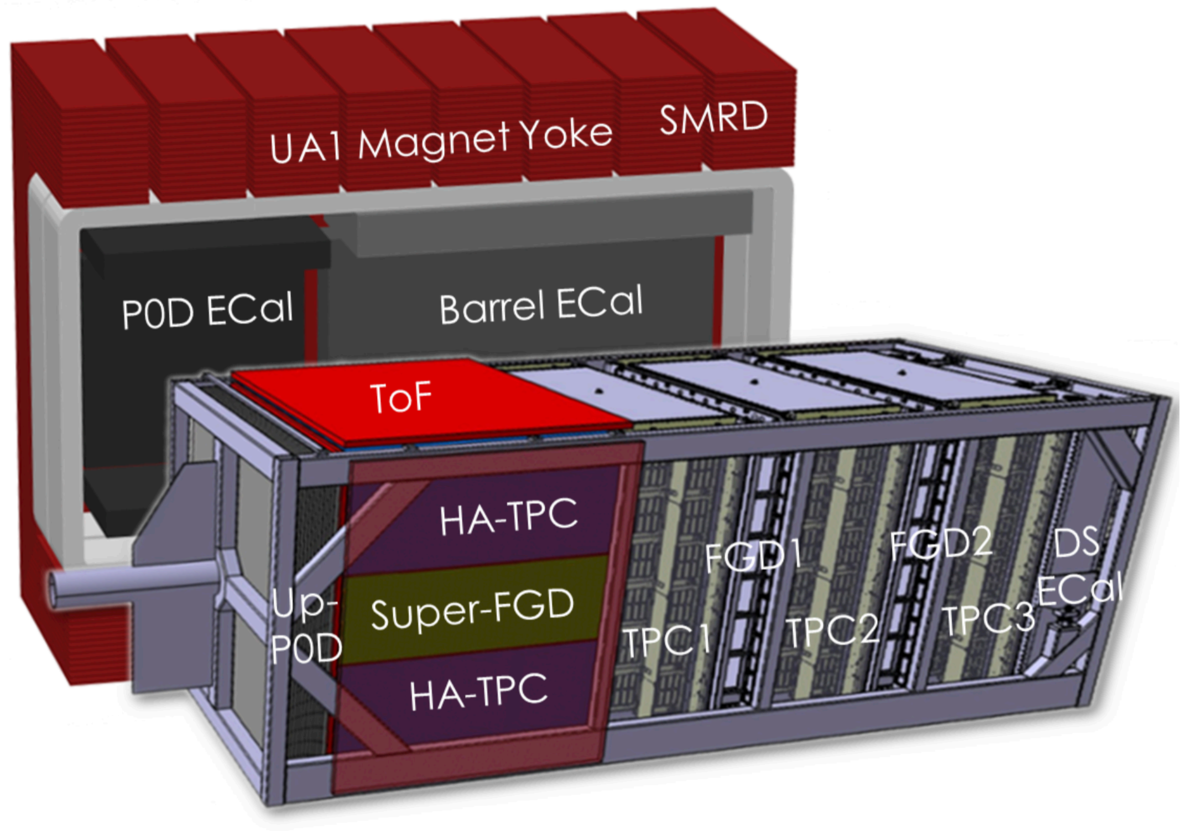


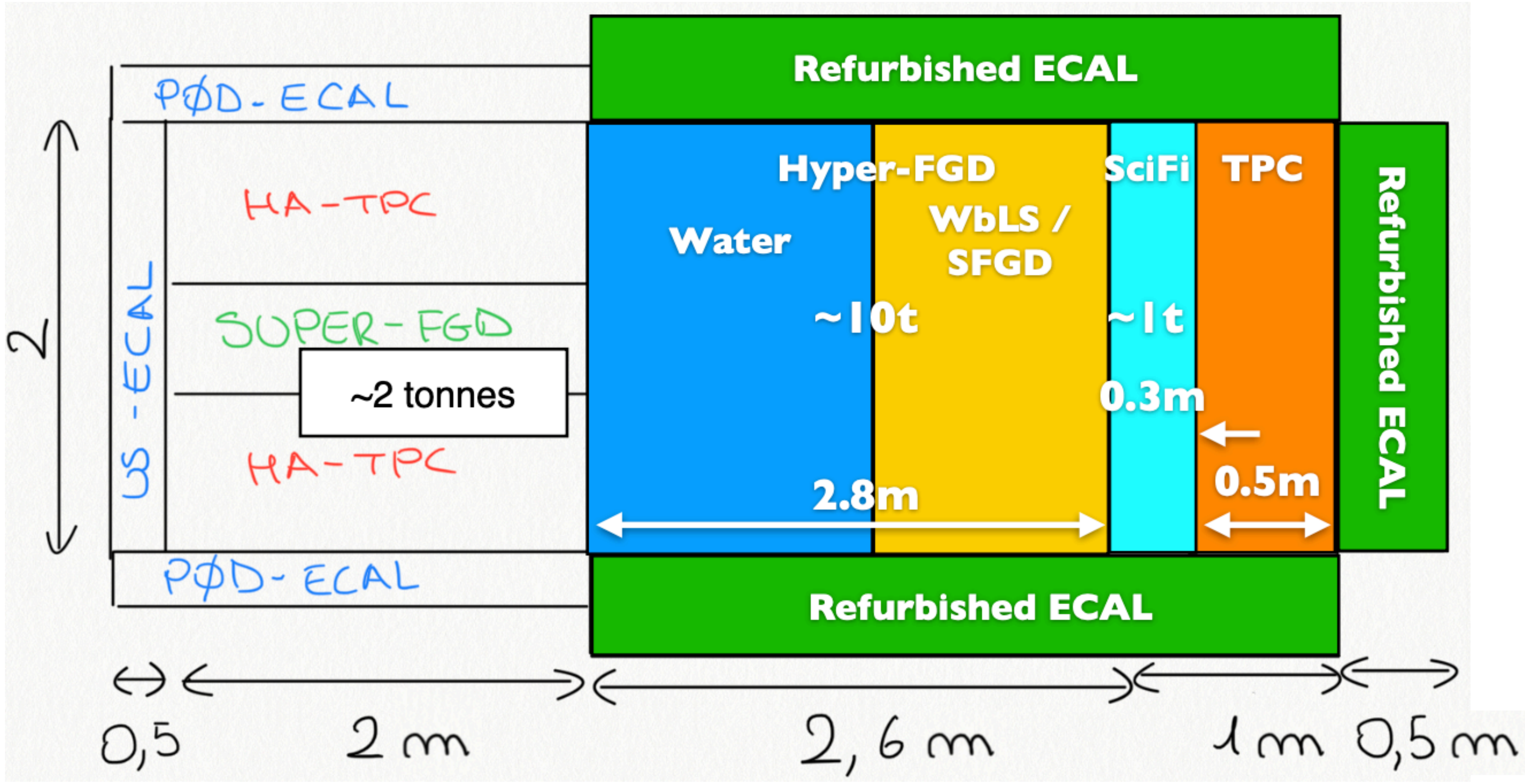
ND280++

- Still profit of ND280 magnetised detector to distinguish ν from $\bar{\nu}$
- Modular detector → can be upgraded in steps
- Recently upgraded with a new 2t high granularity target (Super-FGD)
- A second upgrade will be done during HK to replace the tracker region → ~10 ton available for new ideas!
- Active R&D is on-going



Old ND280

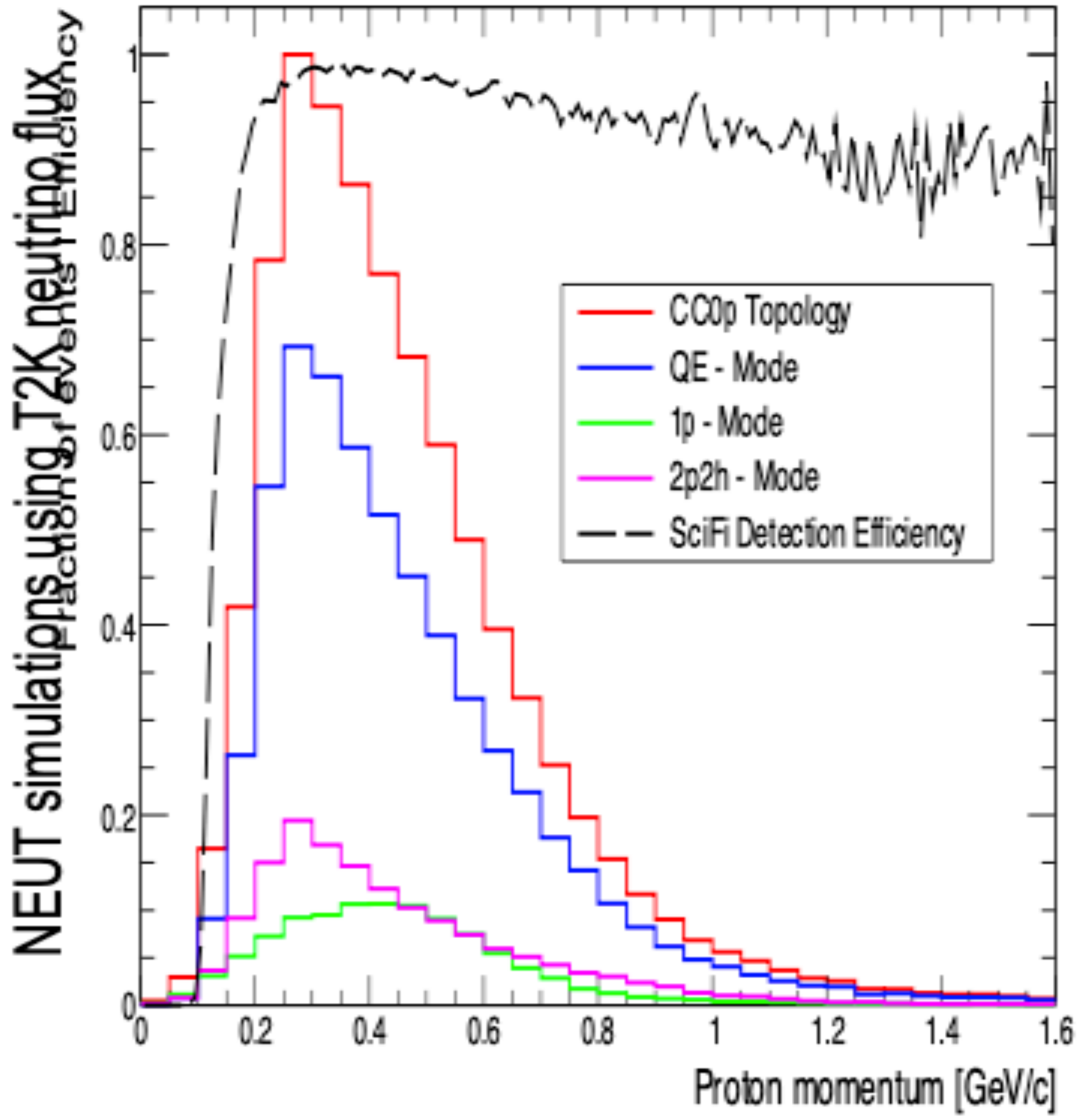


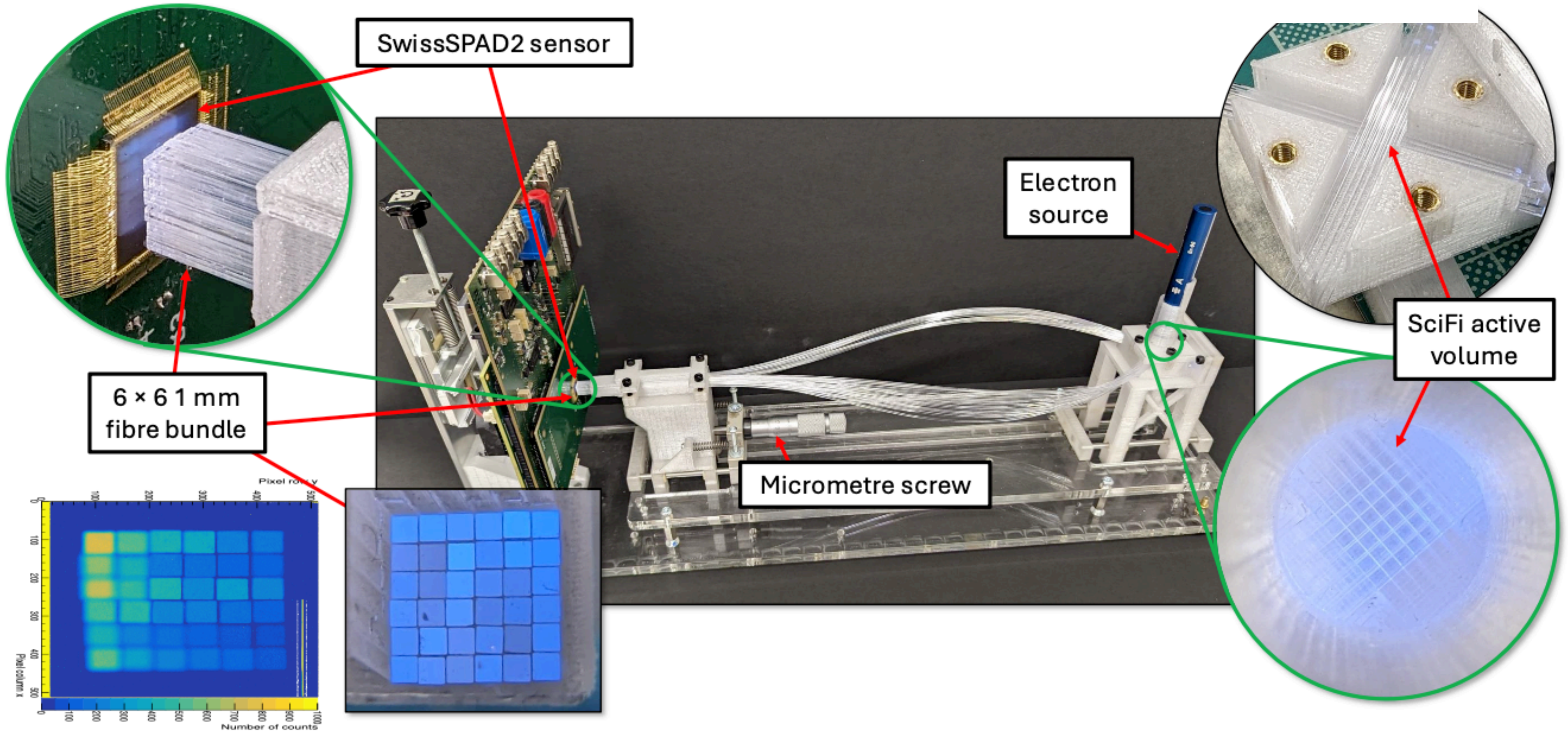


Scintillating-Fibers

- Scintillating-Fibers detector would allow to reduce proton reconstruction threshold to ~ 100 MeV/c → sensitive to all protons emitted in ν interactions!

- Two main challenges:
  - Assemble >100 kg of 0.2 mm diameter fibers
  - State-of-the-art SciFi detectors are read out with SiPM → huge number of channels!

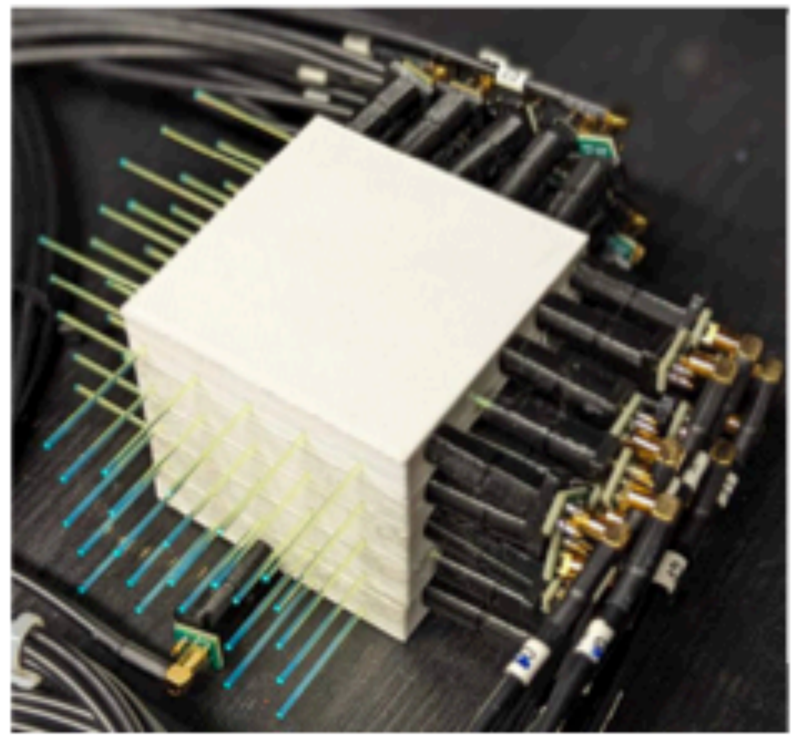


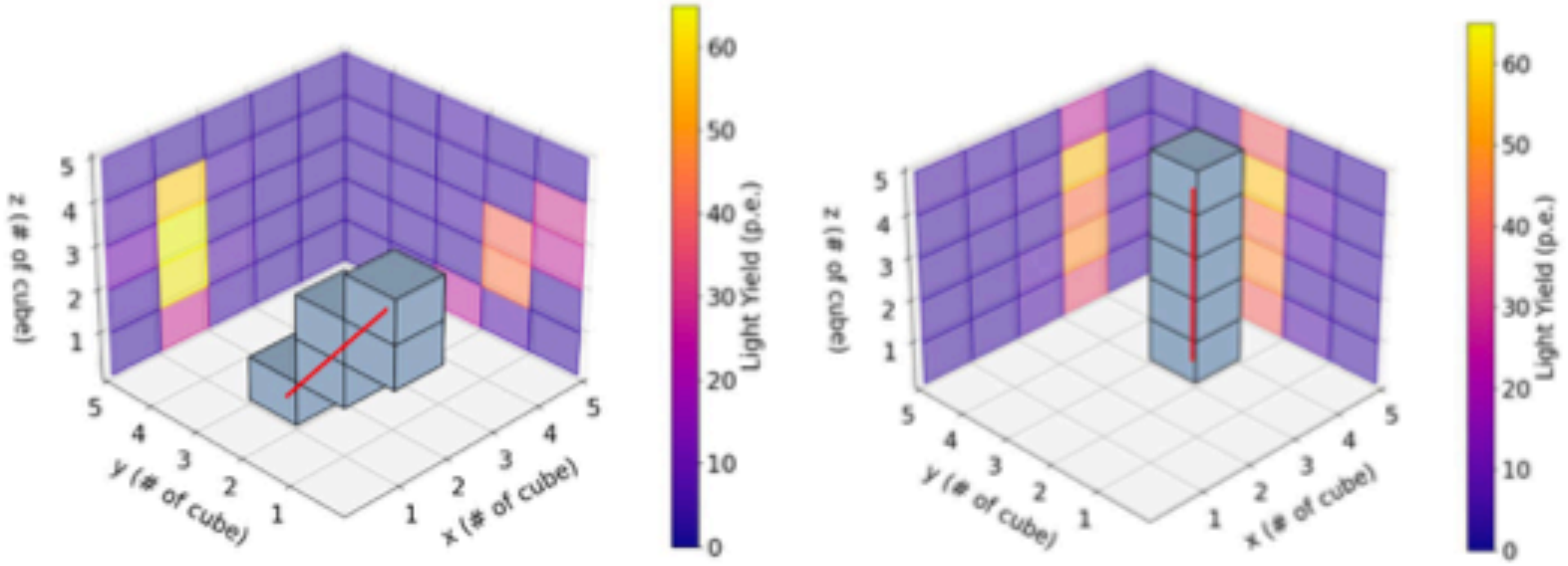


3D printed Super-FGD-like detector

- Active R&D for 3D printed cubes → successfully produced 5x5 cube

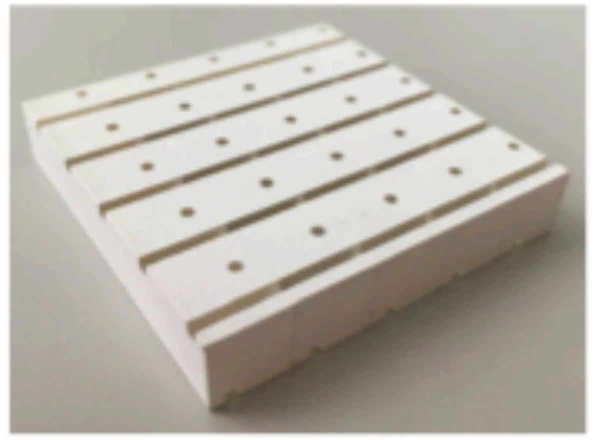
3DET, arXiv:2312.04672





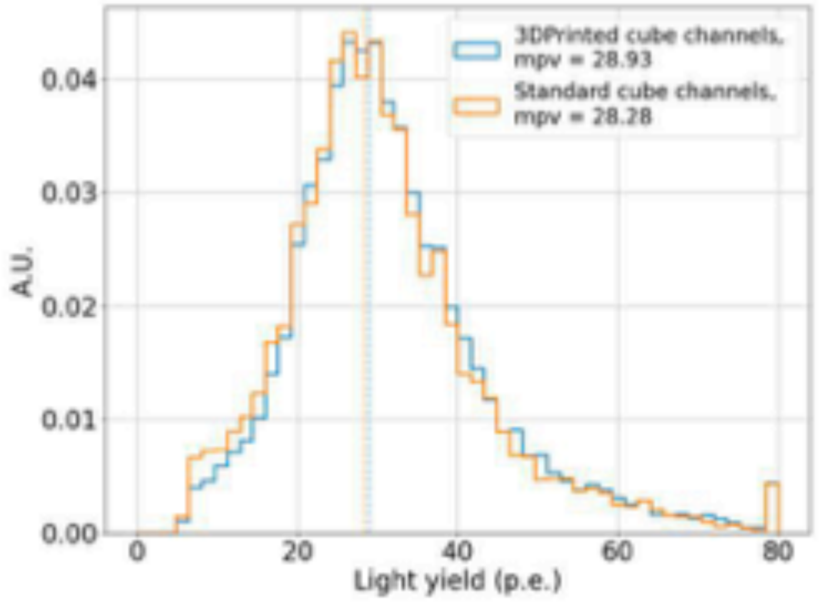
- WLS fibers readout by SiPM on one side
  - Hamamatsu S13360-1325CS with PDE ~ 25%
- CAEN FEB 5702 (FERS, CITIROC ASIC

First ever 3D printed scintillator-based particle detector capable of tracking and calorimetry

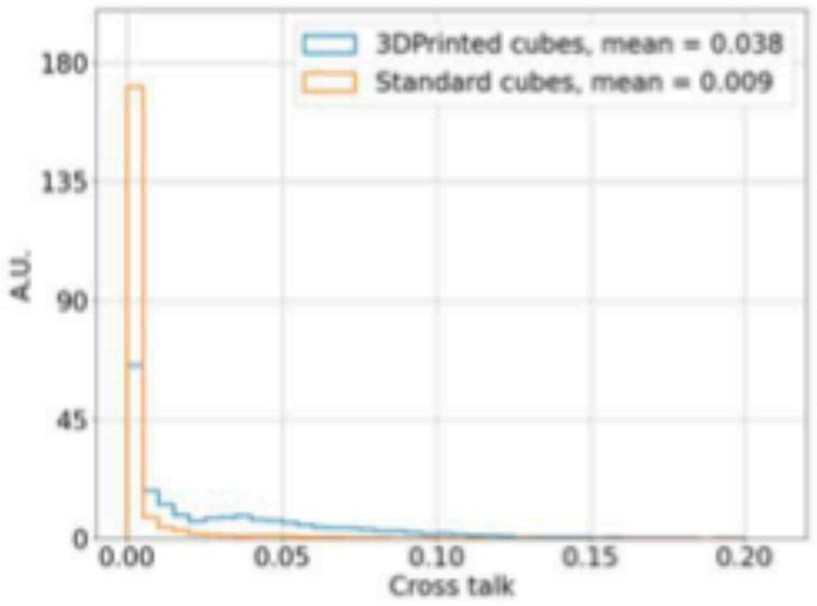


Compared with standard scintillator cubes layer

JINST 16 (2021) 12, P12010

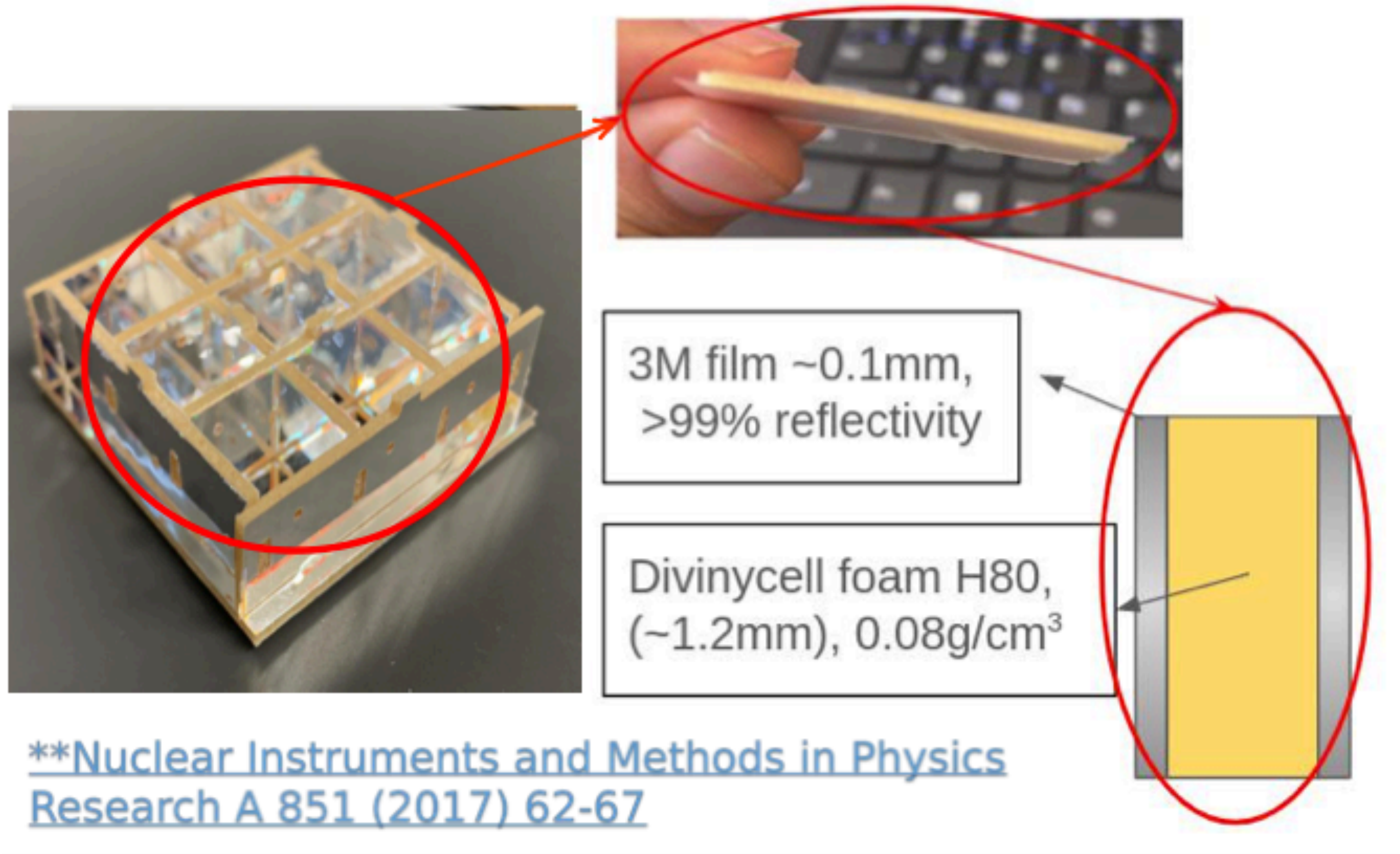


Single channel: ~ 28 pe/cm MIP



Crosstalk ~ 4%

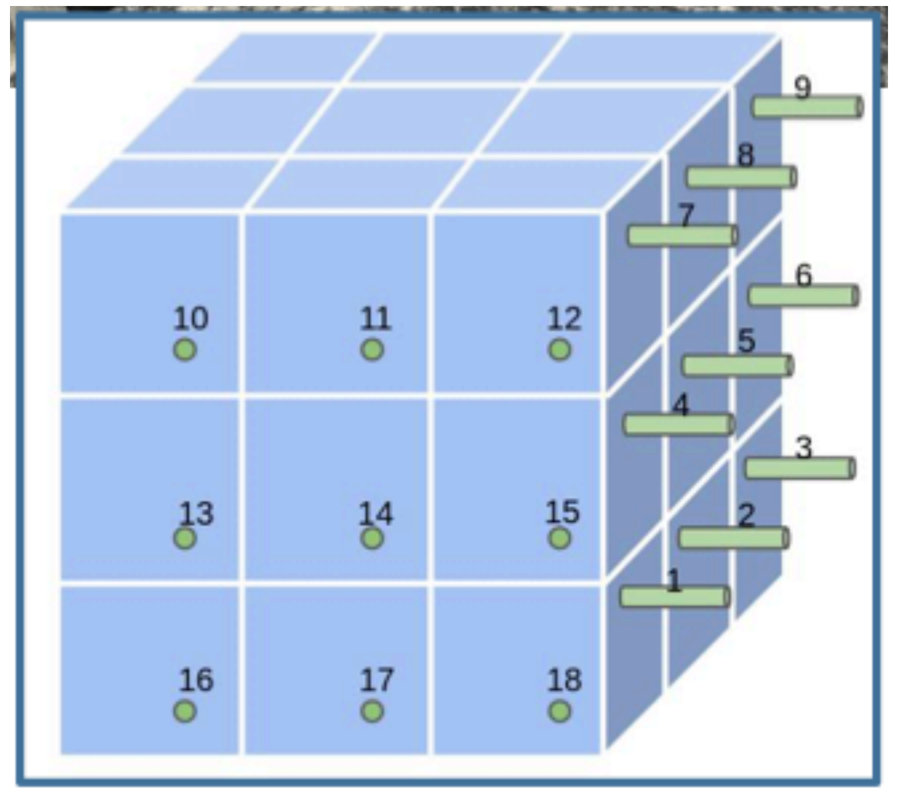
Water-Based Liquid Scintillator



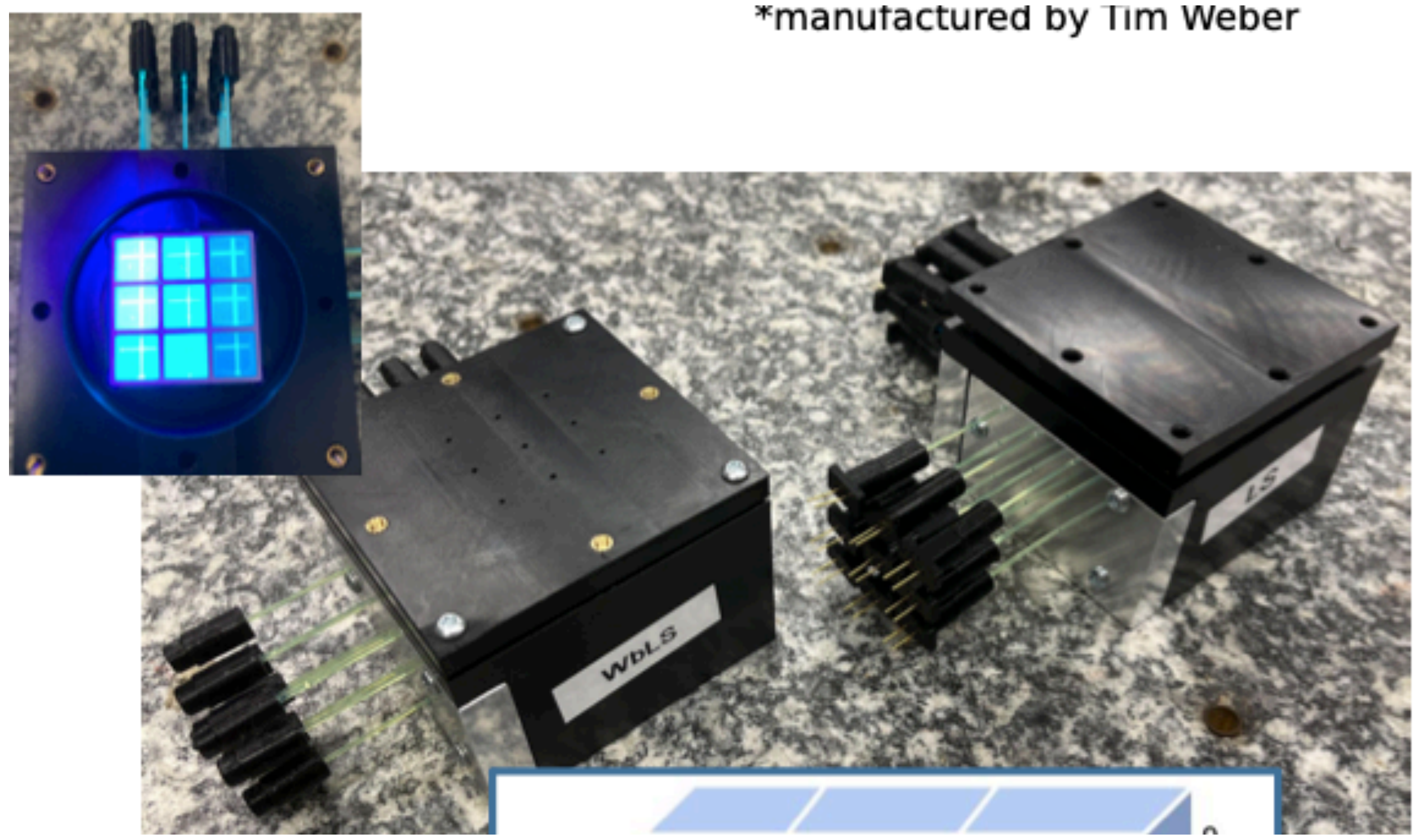
3M film ~0.1mm, >99% reflectivity

Divinycell foam H80, (~1.2mm), 0.08g/cm^3

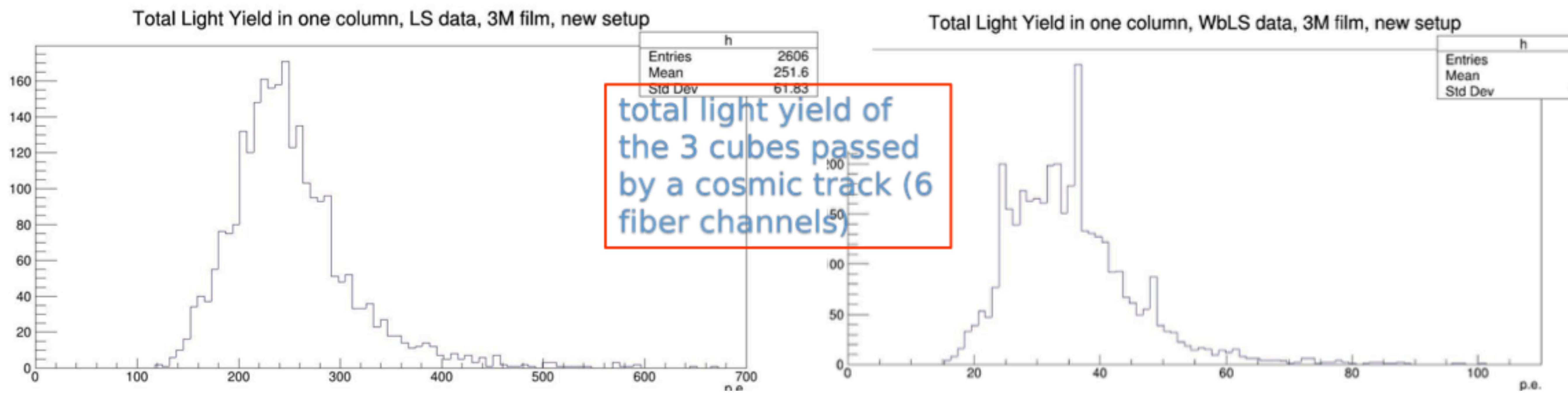
**Nuclear Instruments and Methods in Physics Research A 851 (2017) 62-67



*manufactured by Tim Weber

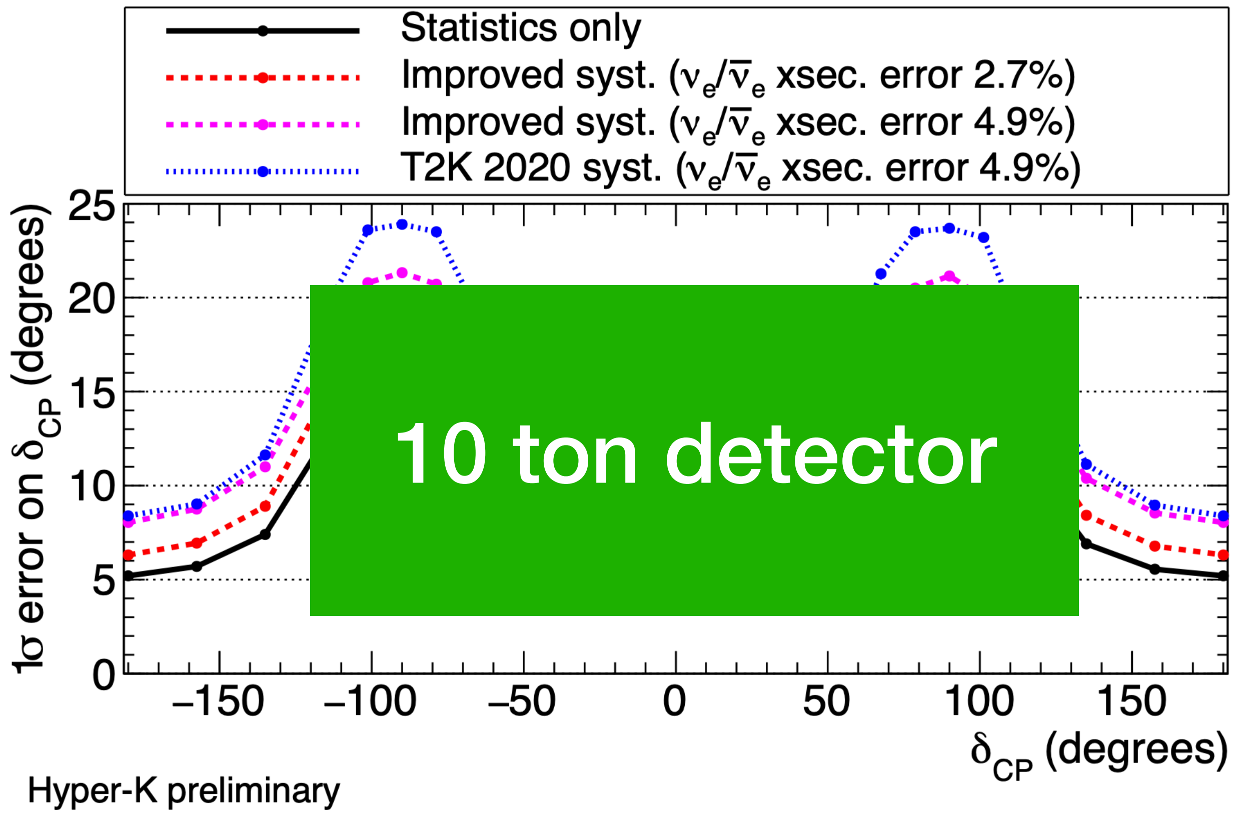


- Similar design as the sFGD with high granularity and cubes-like structure
- Filled with Water-Based LS to measure neutrino interactions on water
- Goal is to keep Water/Carbon ration > 0.9
- PRCI LPNHE/ETHZ funded in 2025 to pursue this R&D on WbLS



total light yield of the 3 cubes passed by a cosmic track (6 fiber channels)

ND280 challenges for HK



10 ton detector

Hyper-K preliminary

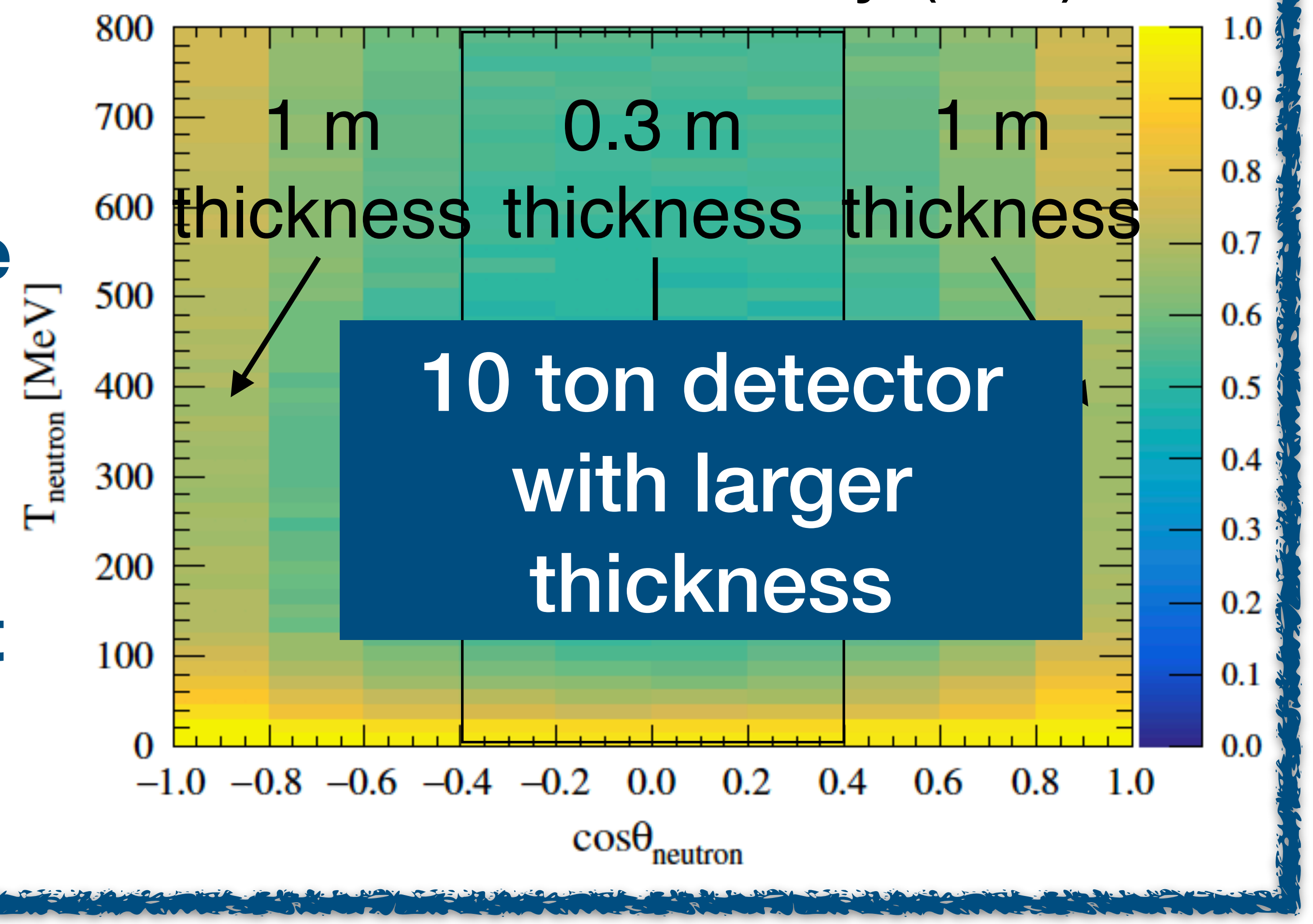
True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)

Ultimate precision measurement of δ_{CP} dominated by ν_e/ $\bar{\nu}_e$ uncertainties

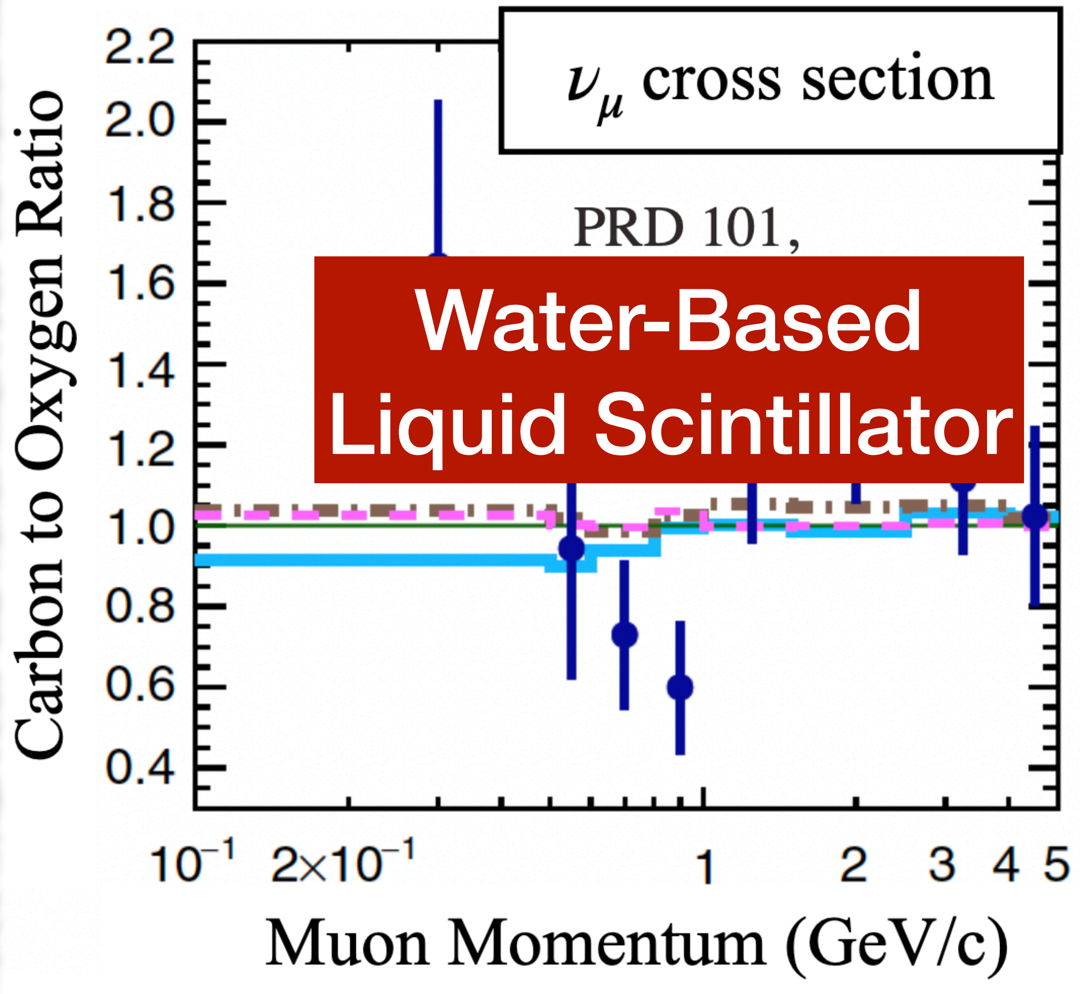
→ measure them with higher statistics at the Near Detector

For $\bar{\nu}$ interactions it is crucial to measure neutron kinematics → many neutrons escape from sFGD → build larger target

Detection efficiency (MC)



10 ton detector with larger thickness

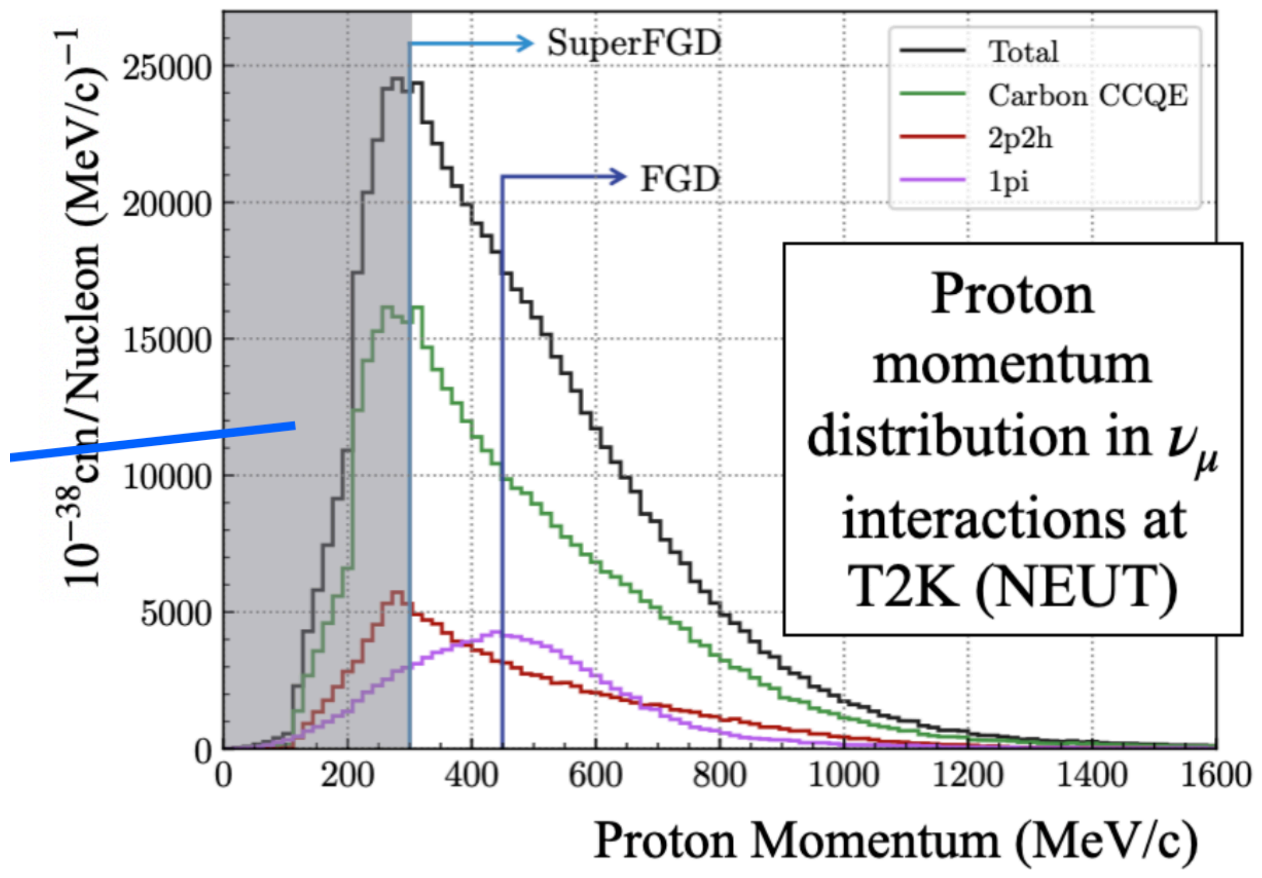


Water-Based Liquid Scintillator

Scaling of cross-section model from Carbon (ND280) to Oxygen (SK/HK) also bring some additional uncertainties → add Water in ND280

For short protons tracks sFGD [illegible] protons → build target with larger granularity

Scintillating Fibers ~ 100 MeV/c threshold



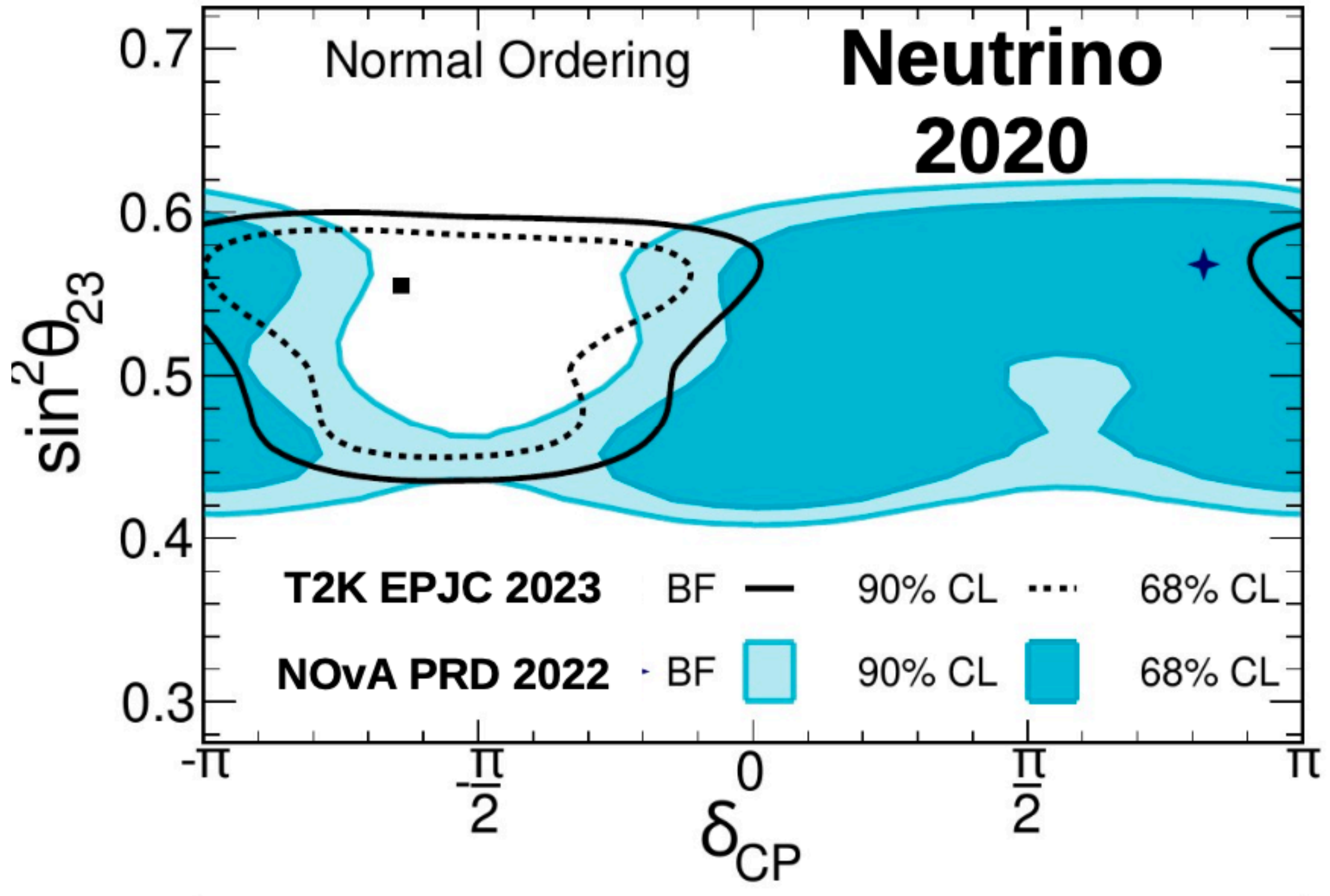
Conclusions

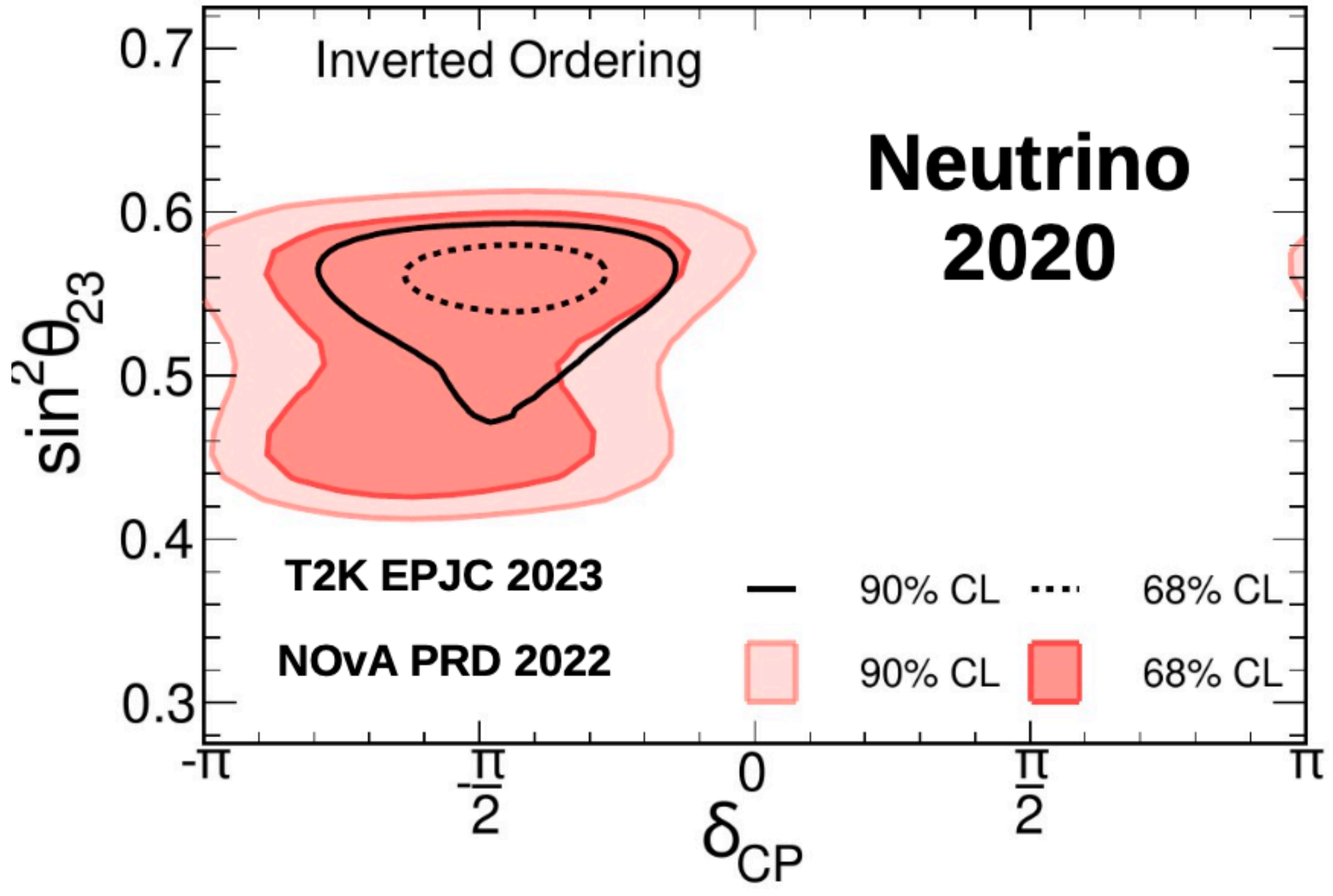
- Neutrino physics is an extremely active field of research
- The japanese programme will lead this quest for the next ~15 years → T2K → Hyper-K
- Hyper-K construction is proceeding on-schedule and first data are expected in December 2027
  - IN2P3 contributions to the Far Detector have been defined
- To pursue this programme measurements with a powerful Near Detector are critical
  - T2K recently upgraded its near detector ND280 → first data have been collected
  - R&D for further upgrades to be done for Hyper-K are starting → goal is to start taking data with ND280++ in 2032

Back-up

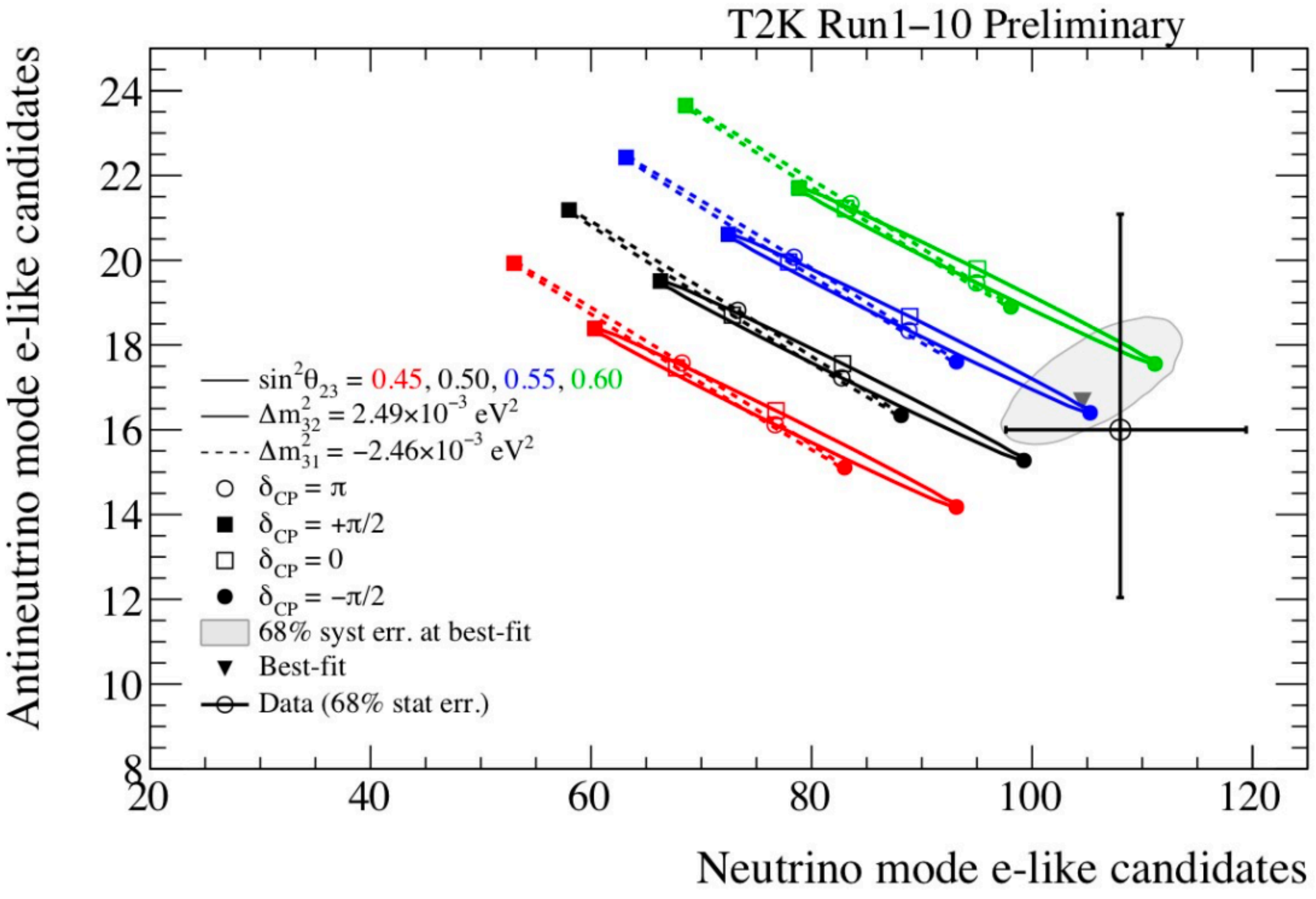
T2K/NOvA joint analysis

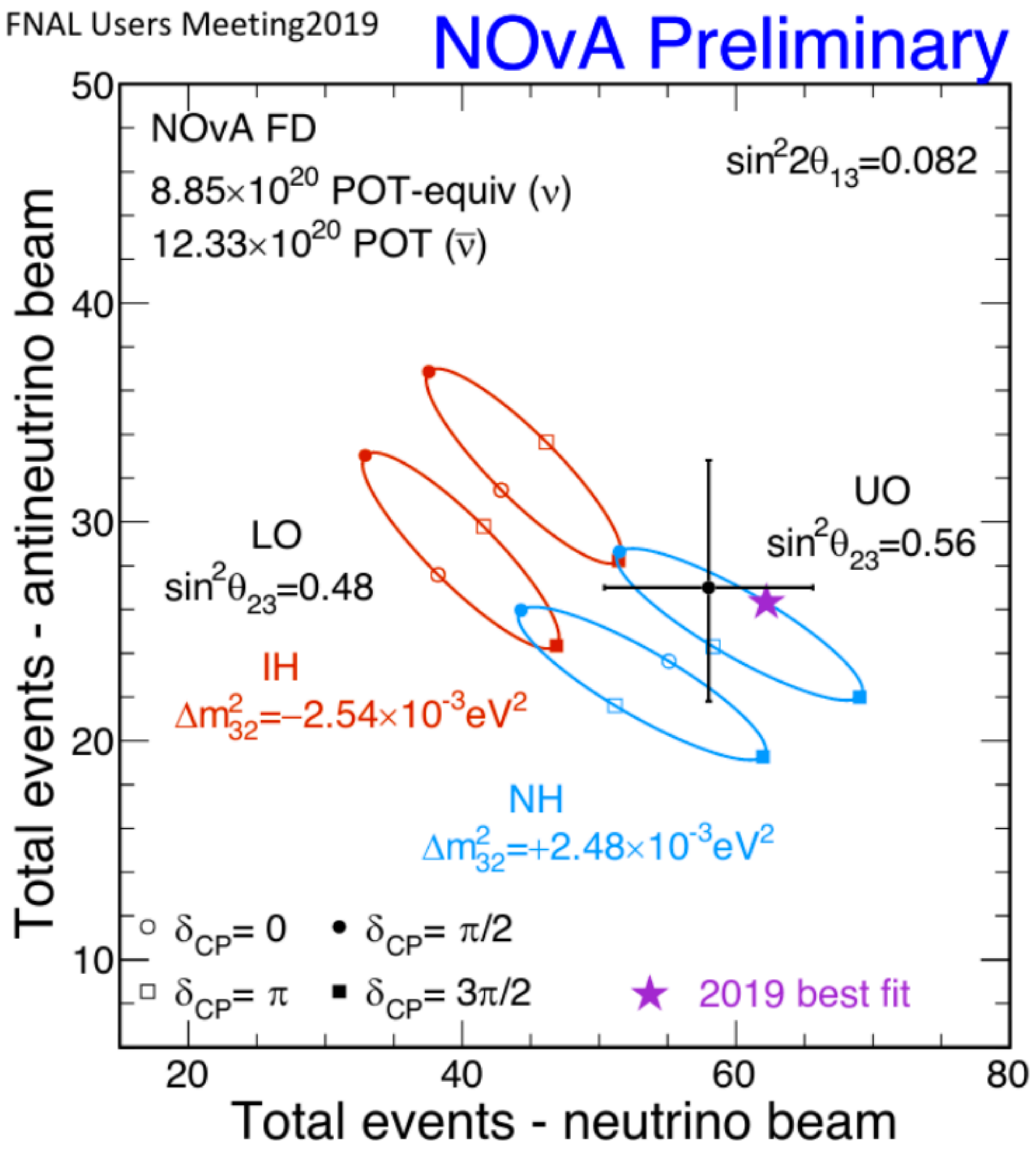
- Profit of different baselines to lift degeneracies of each experiment
  - Full implementation of the likelihood of each experiment and consistent statistical treatment
  - Review of models, systematic uncertainties, possible correlations and of the different analysis approaches





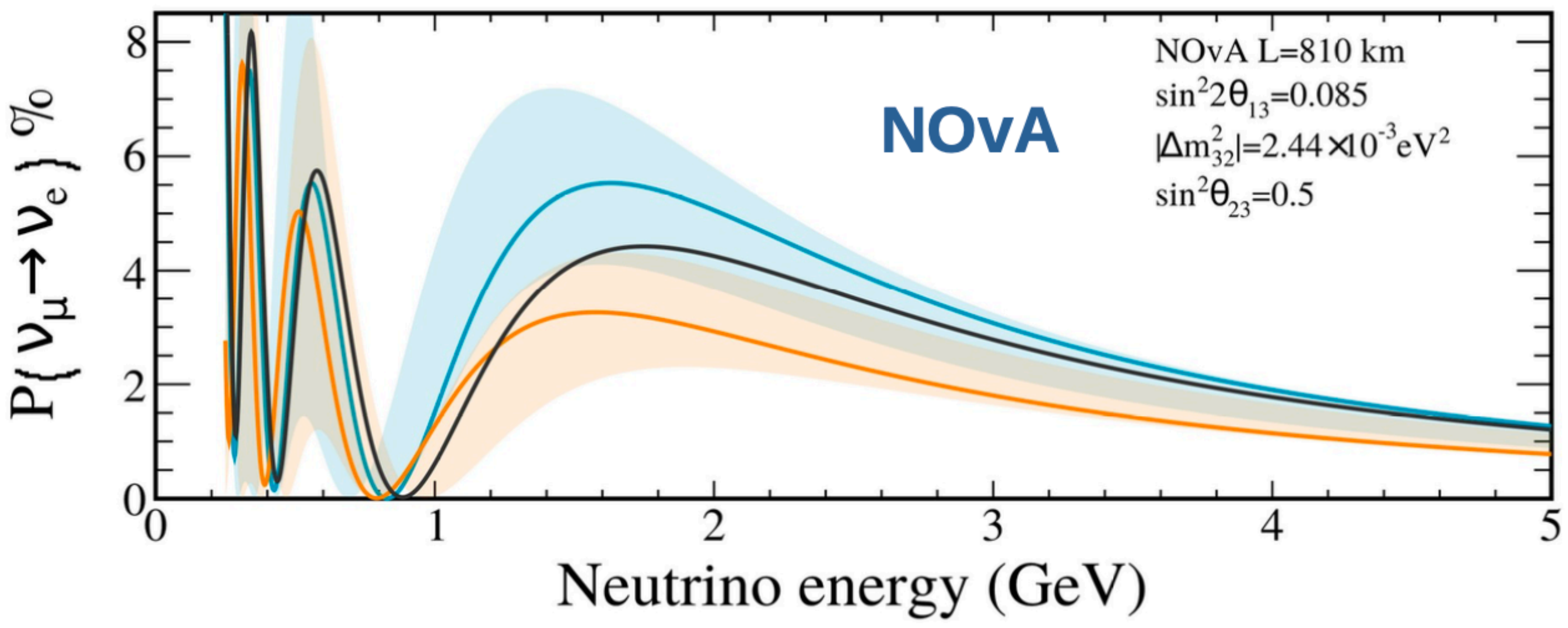
What about δ_{CP} ?

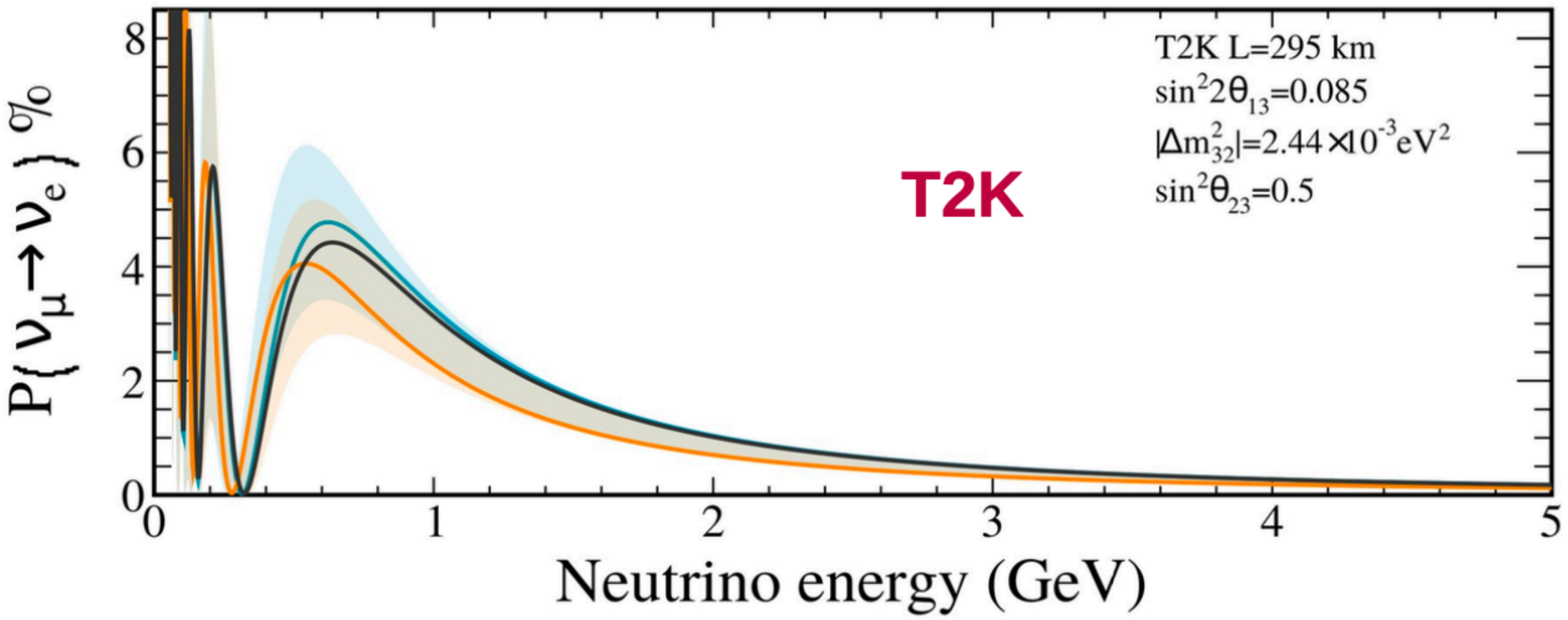




Baseline difference

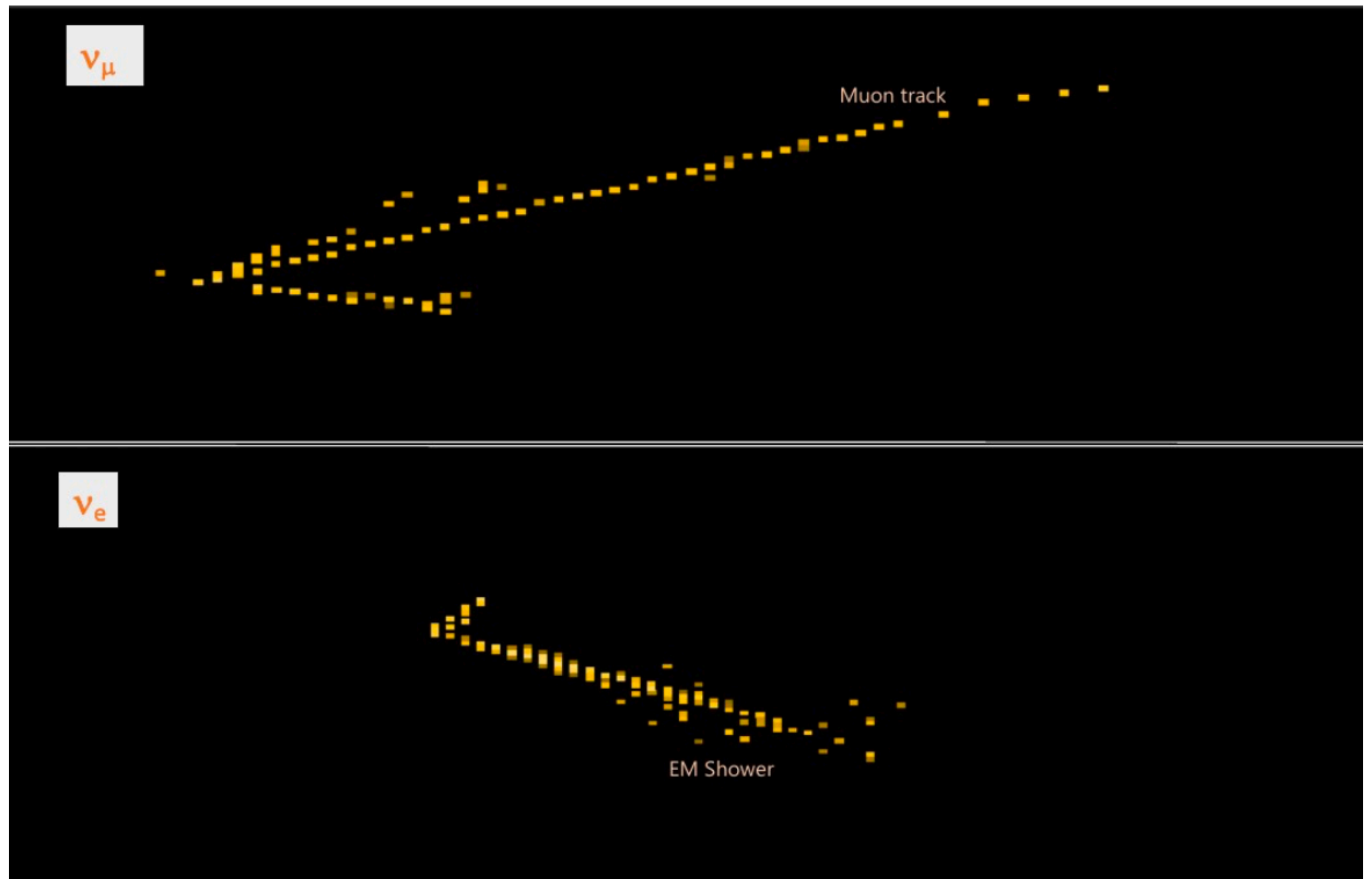
- The koint analysis allows to exploit the possibility of breaking degeneracies thanks to the different baselines
- Matter effect proportional to baseline and neutrino energy
- NOvA has a longer baseline than T2K → larger matter effects
- In T2K larger impact of δ_{CP}

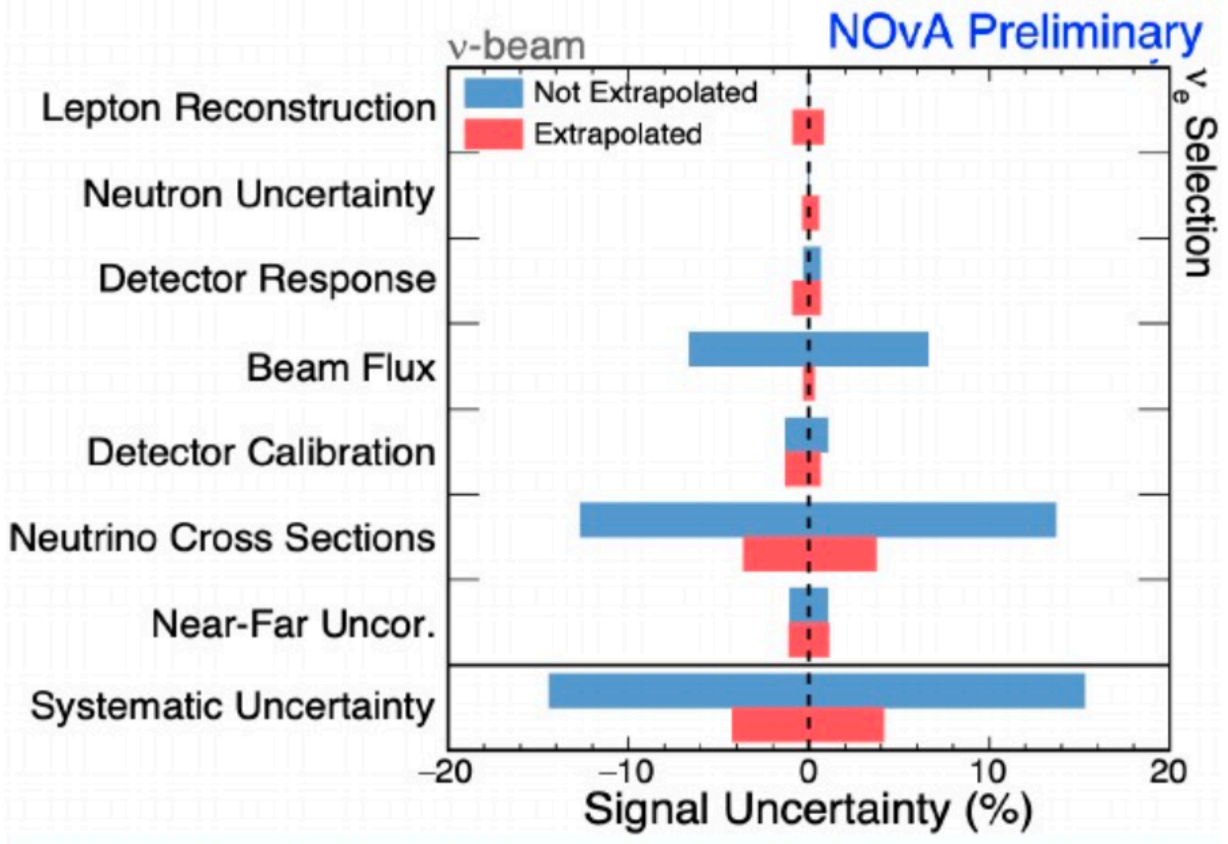




NOvA strategy

- Functionally identical Near and Far detectors → both segmented liquid scintillator detectors
  - Significant cancellations in the uncertainties
  - Model and systematics parameters enter as uncertainties on the far/near ratio
- PID done thanks to calorimetric energy estimation
- Neutrino energy reconstructed from a combination of leptonic and hadronic component





Correlations

Flux Model

- Different energies
- Different tuning to external data
  - thin target vs thick target data
- Enters the analysis differently

☐ No significant correlations between the experiments

Detector Model

- Different detector models
- Different selections
  - inclusive vs exclusive outgoing pions
- Different energy reconstruction
  - calorimetric vs lepton kinematics

☐ No significant correlations between the experiments

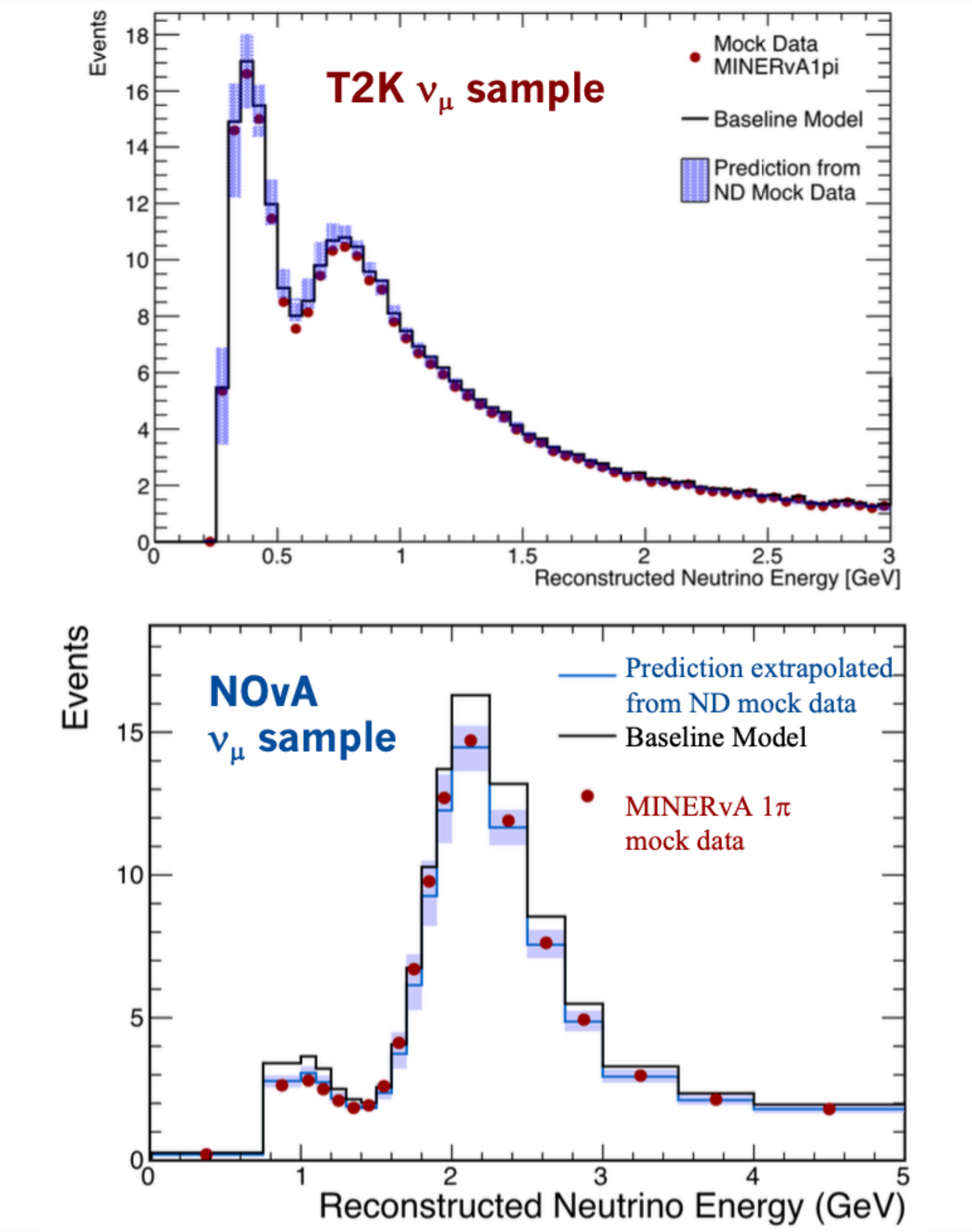
Cross Section Model

- As the underlying physics is fundamentally the same, we expect correlations
- Different neutrino interaction models
  - optimized for different energy ranges
- Systematics are designed for individual models and analysis strategies

☐ Investigate the impact of models and correlations on the joint analysis

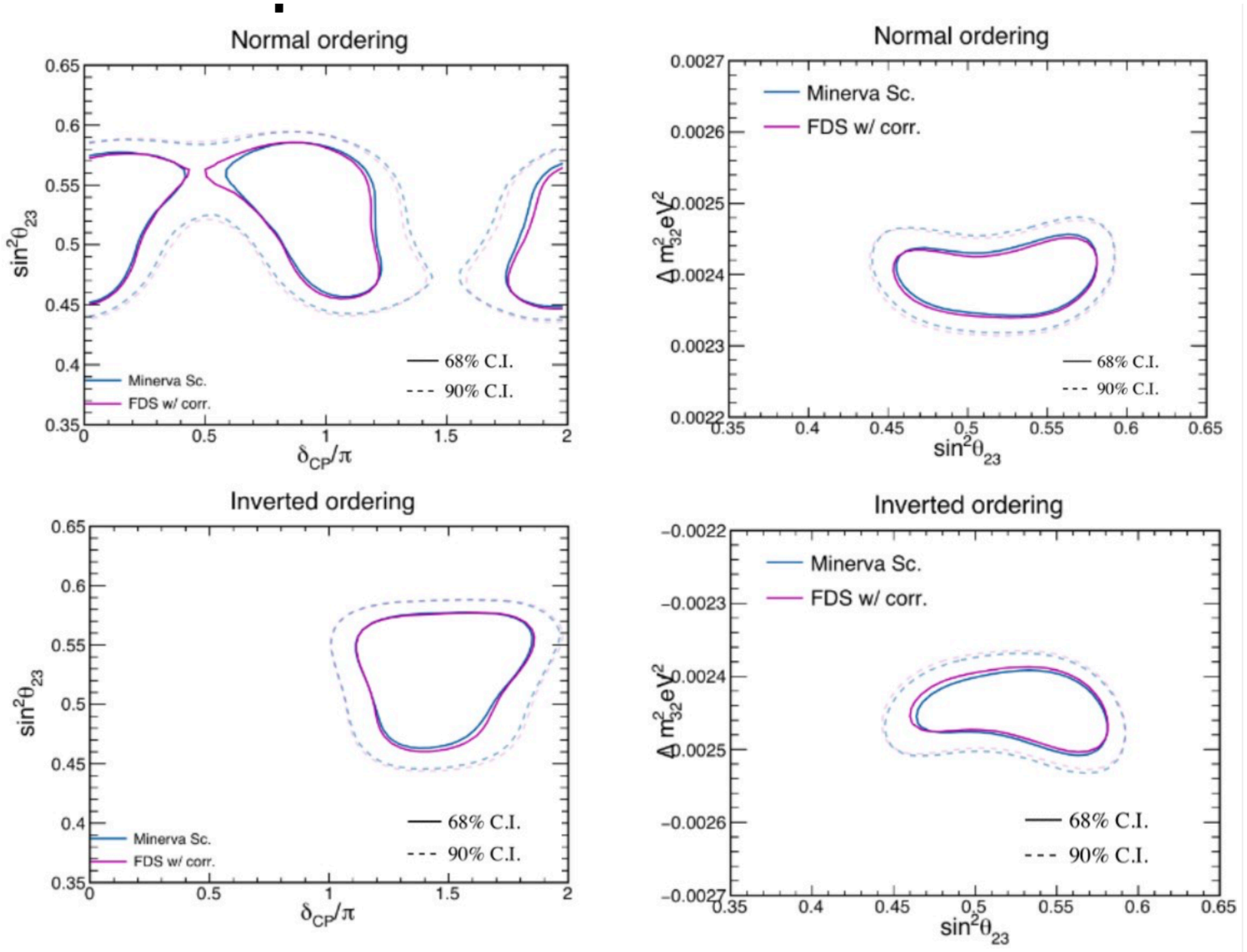
Impact of alternate models

- Strategy used in T2K to address possible deficiencies in our cross-section model
- Produce simulated data at Near and Far detector using an alternative x-sec model and then do the oscillation fit
- Check for possible biases in oscillation parameters → if there are no (small) biases the analysis is robust with respect to the investigated model change



Impact of alternate models

- Strategy used by T2K since many years
- Produce simulated data at Near and Far detector using an alternative x-sec model and then do the oscillation fit
- Check for possible biases in oscillation parameters → if there are no (small) biases the analysis is robust with respect to the investigated model change

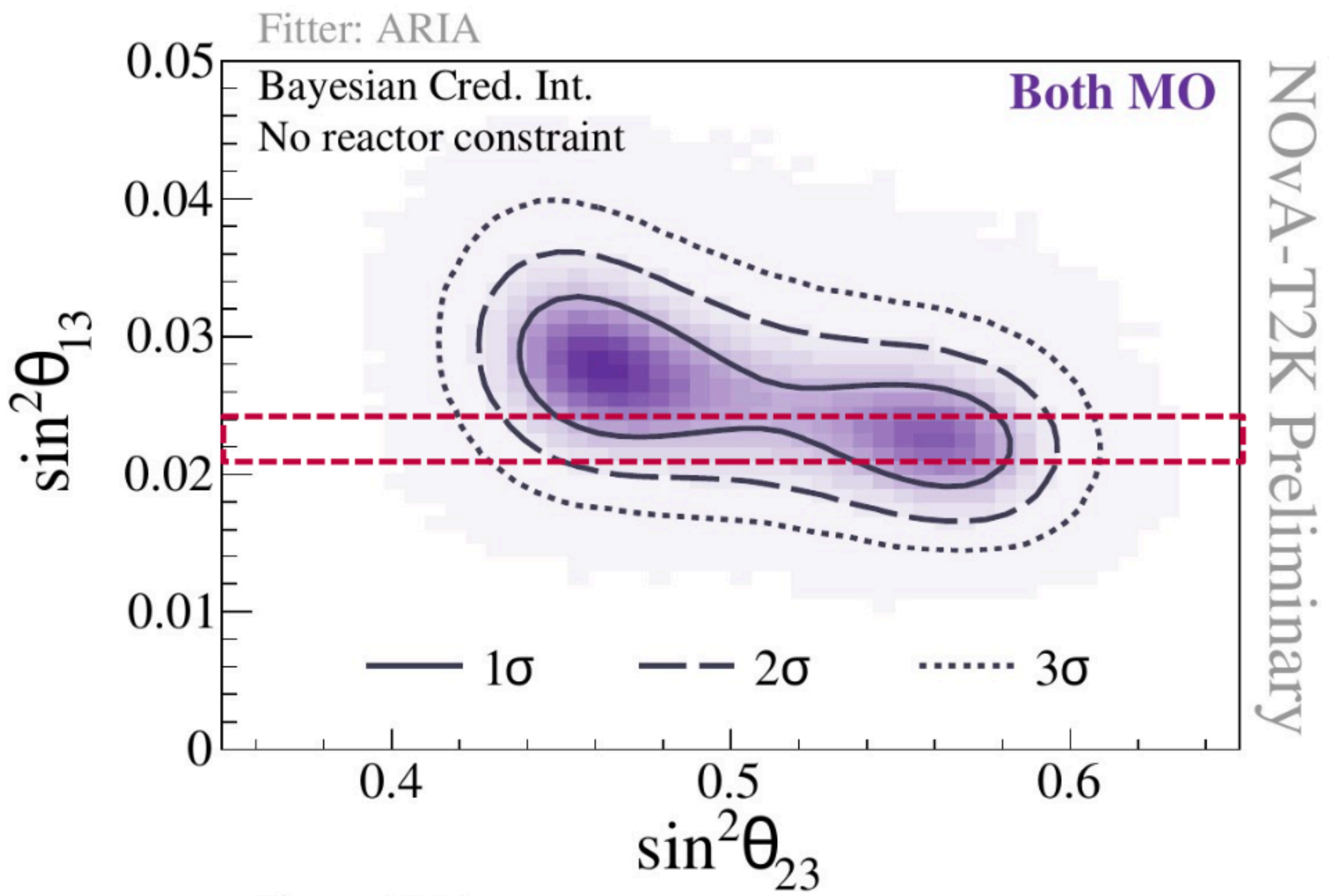


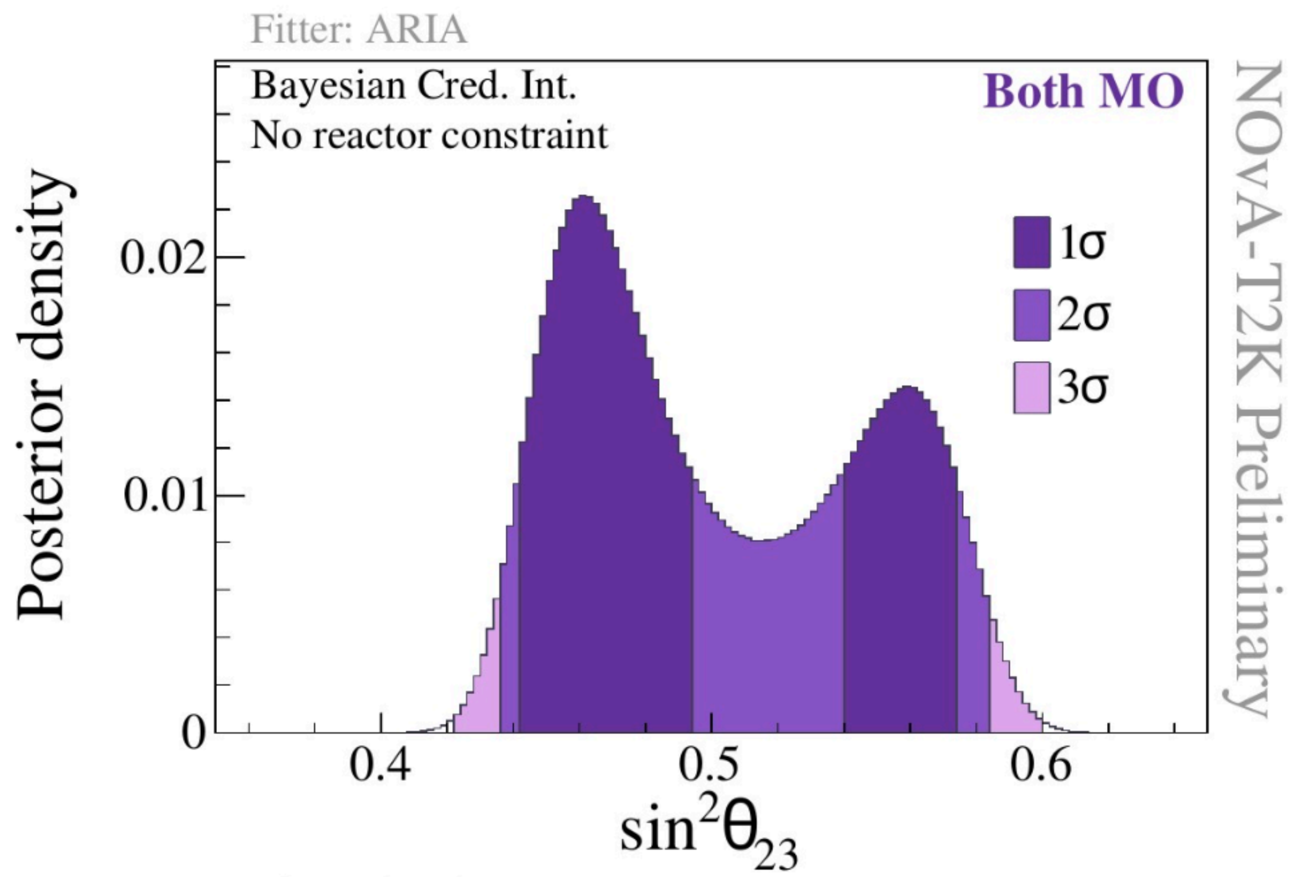
Results : $\sin^2(\theta_{23})$ and $\sin^2(\theta_{13})$

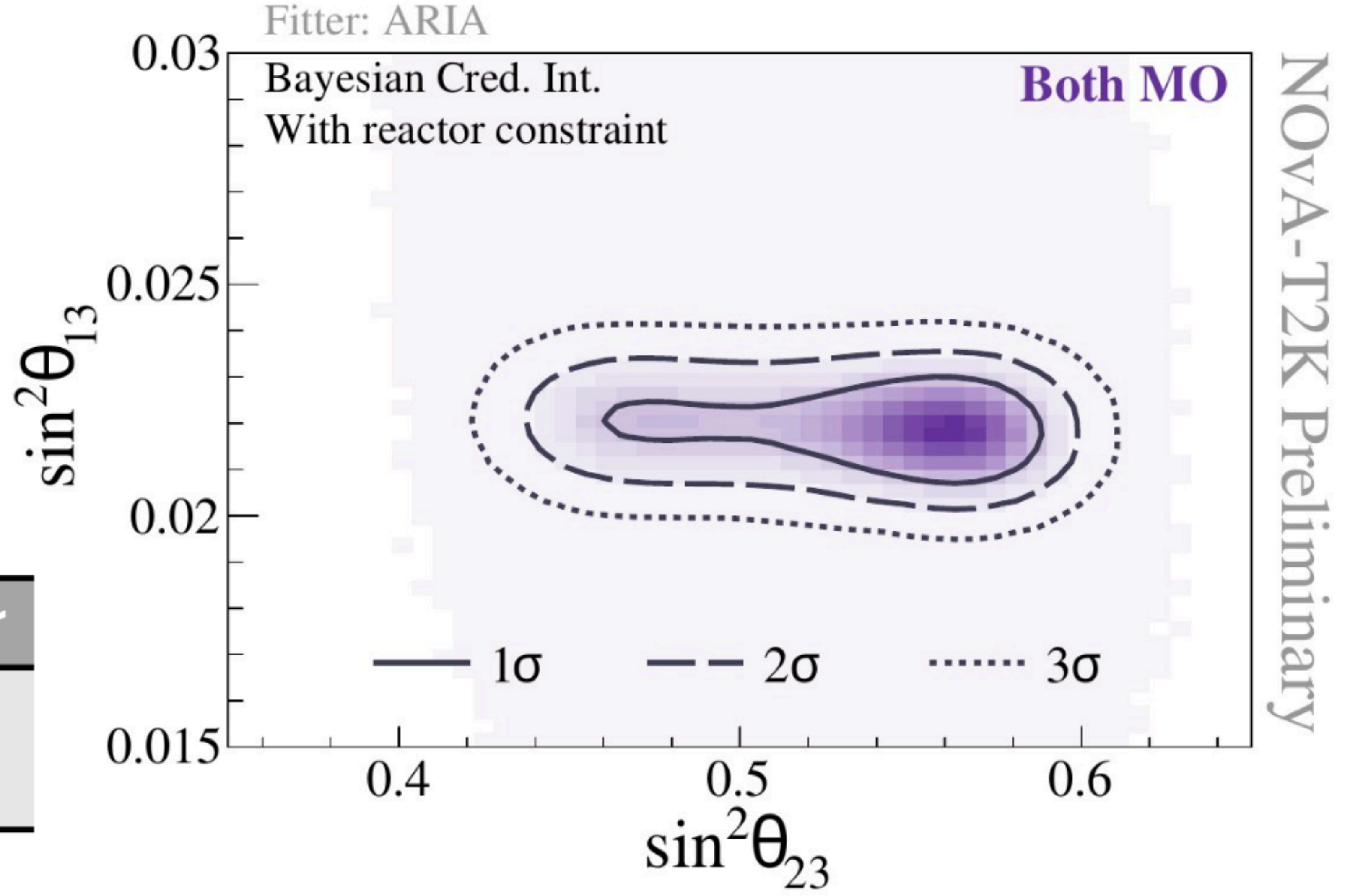
- Degeneracies between θ23 and θ13 → lifted thanks to the precise measurement of θ13 from reactors

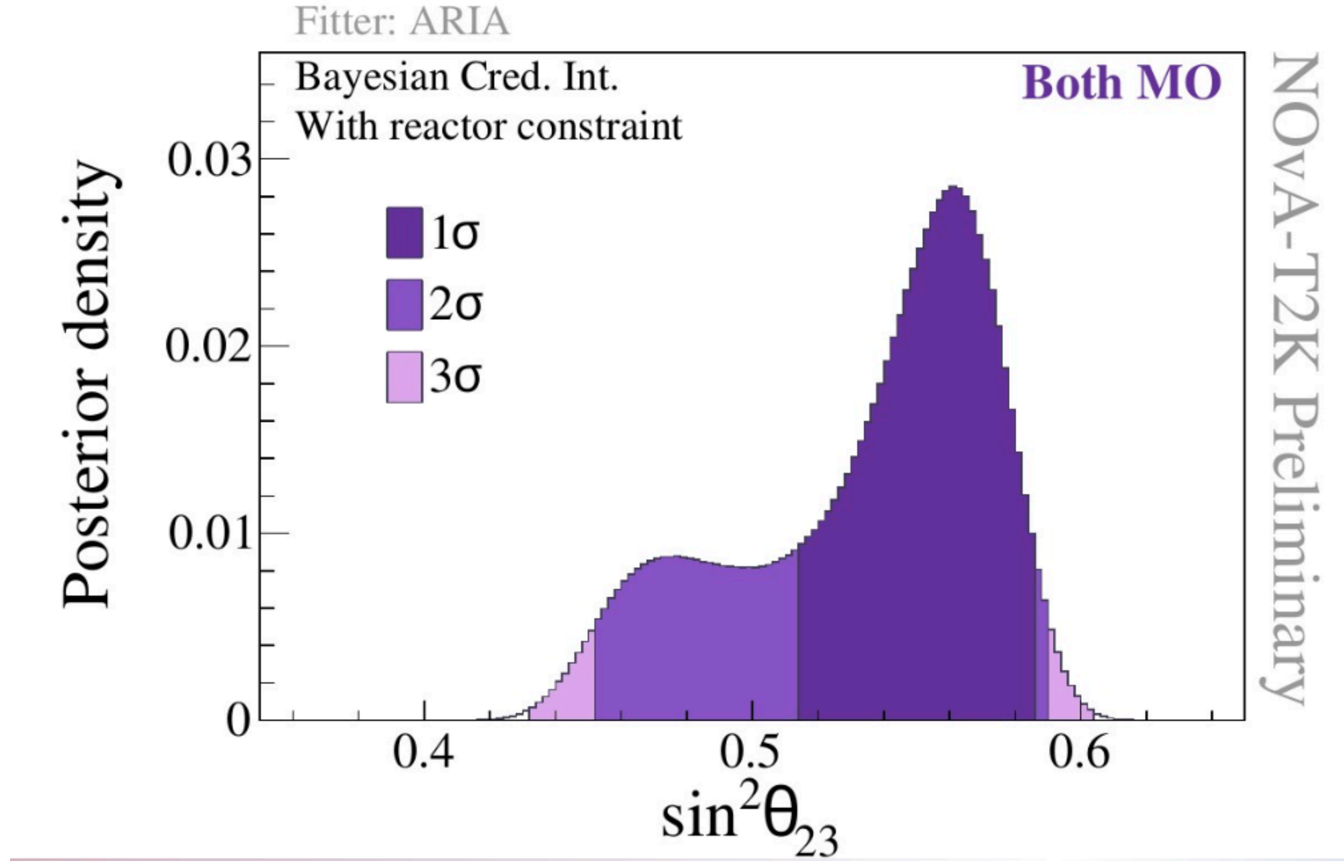
- Adding reactor constraint flip the octant from the (very) modest preference for lower octant to a modest preference for upper octant

	NOvA - T2K w/o reactor	NOvA – T2K – w/ reactor
Bayes factor	**1.17** Lower Octant/Upper Octant ~54% : ~46% posterior	**3.59** Upper Octant/Lower Octant ~78% : 22% posterior



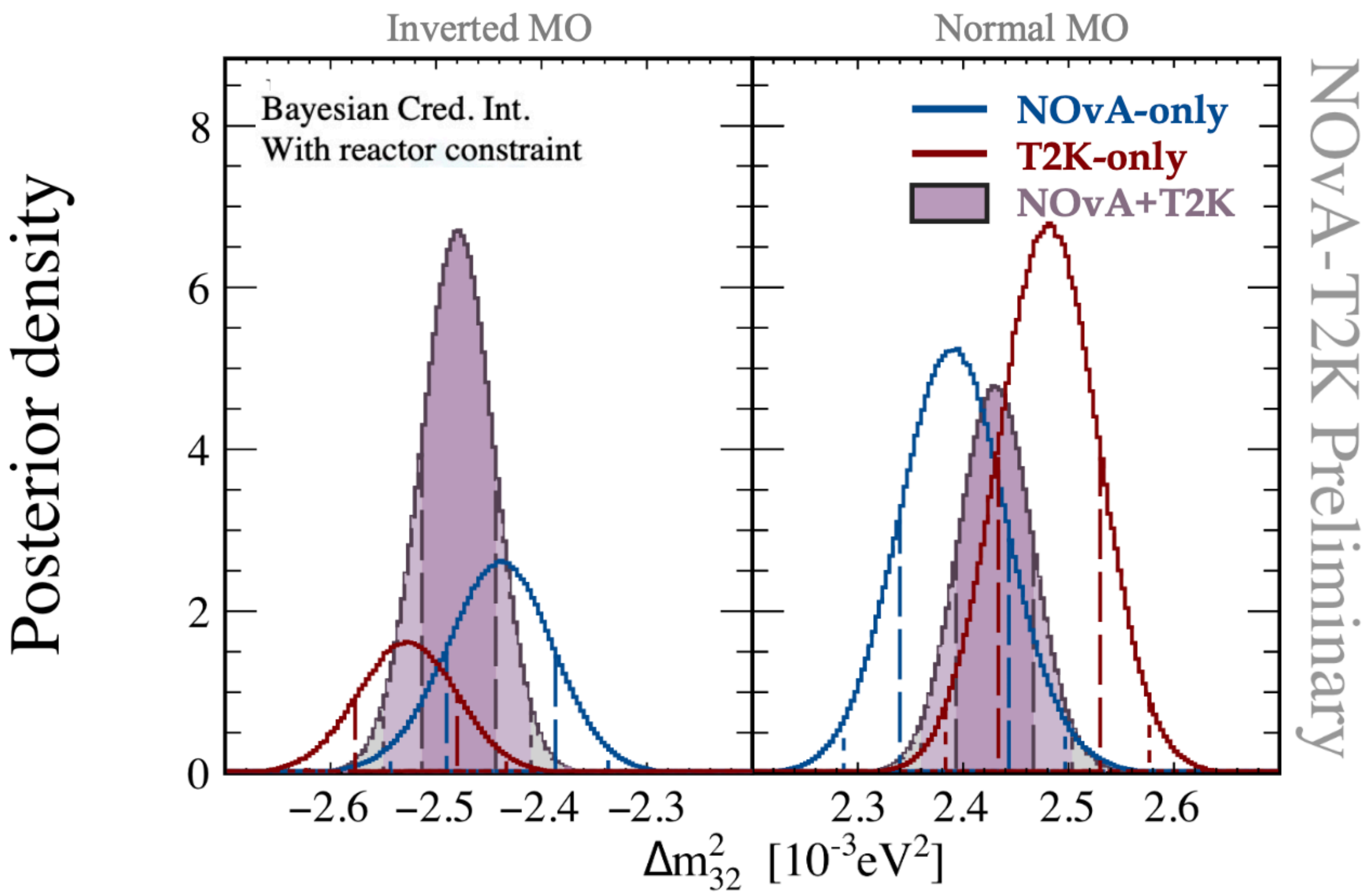




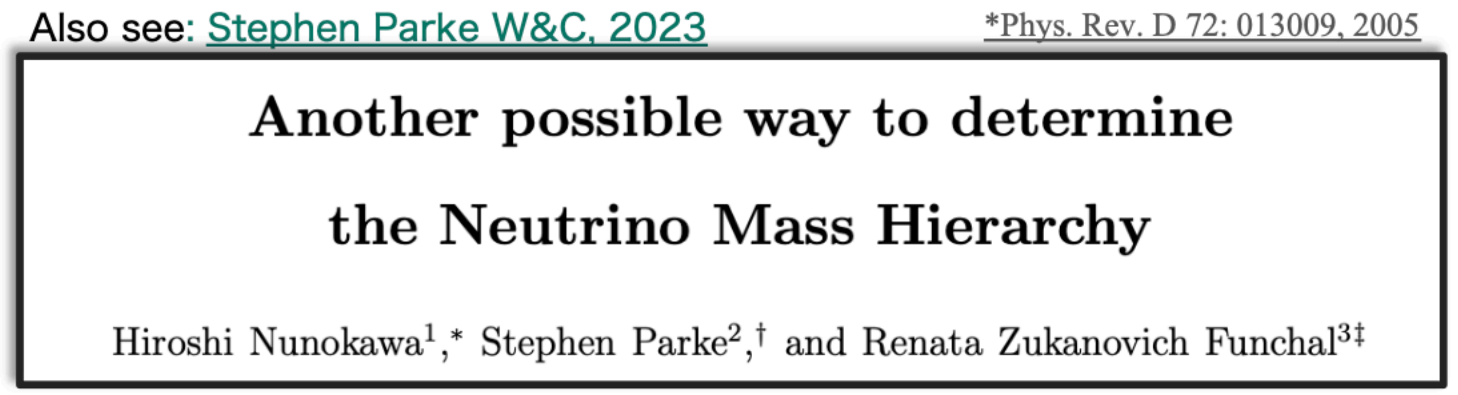


Results : Δm^2_{23}

- When taken alone both, T2K and NOvA prefer normal ordering but combining them is basically a flip-coin with very mild preference for inverted ordering
- But what about reactor measurement of Δm2?



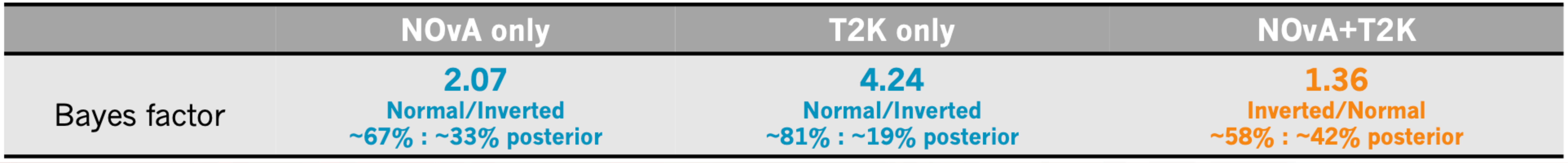
Also see: Stephen Parke W&C, 2023



*Phys. Rev. D 72: 013009, 2005

Another possible way to determine the Neutrino Mass Hierarchy

Hiroshi Nunokawa[1],* Stephen Parke[2],† and Renata Zukanovich Funchal[3]‡



	NOvA only	T2K only	NOvA+T2K
Bayes factor	2.07 Normal/Inverted ~67% : ~33% posterior	4.24 Normal/Inverted ~81% : ~19% posterior	1.36 Inverted/Normal ~58% : ~42% posterior

Mass ordering

ee : reactor disappearance channel → Daya Bay*
μμ : long-baseline disappearance channel → NOvA+T2K

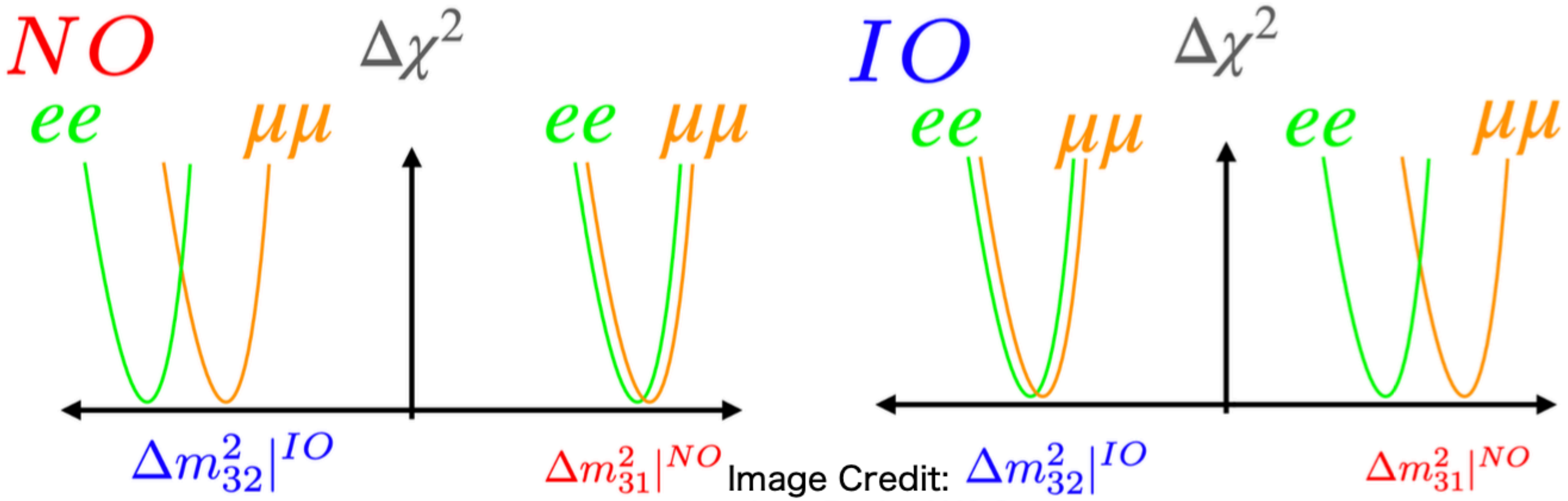
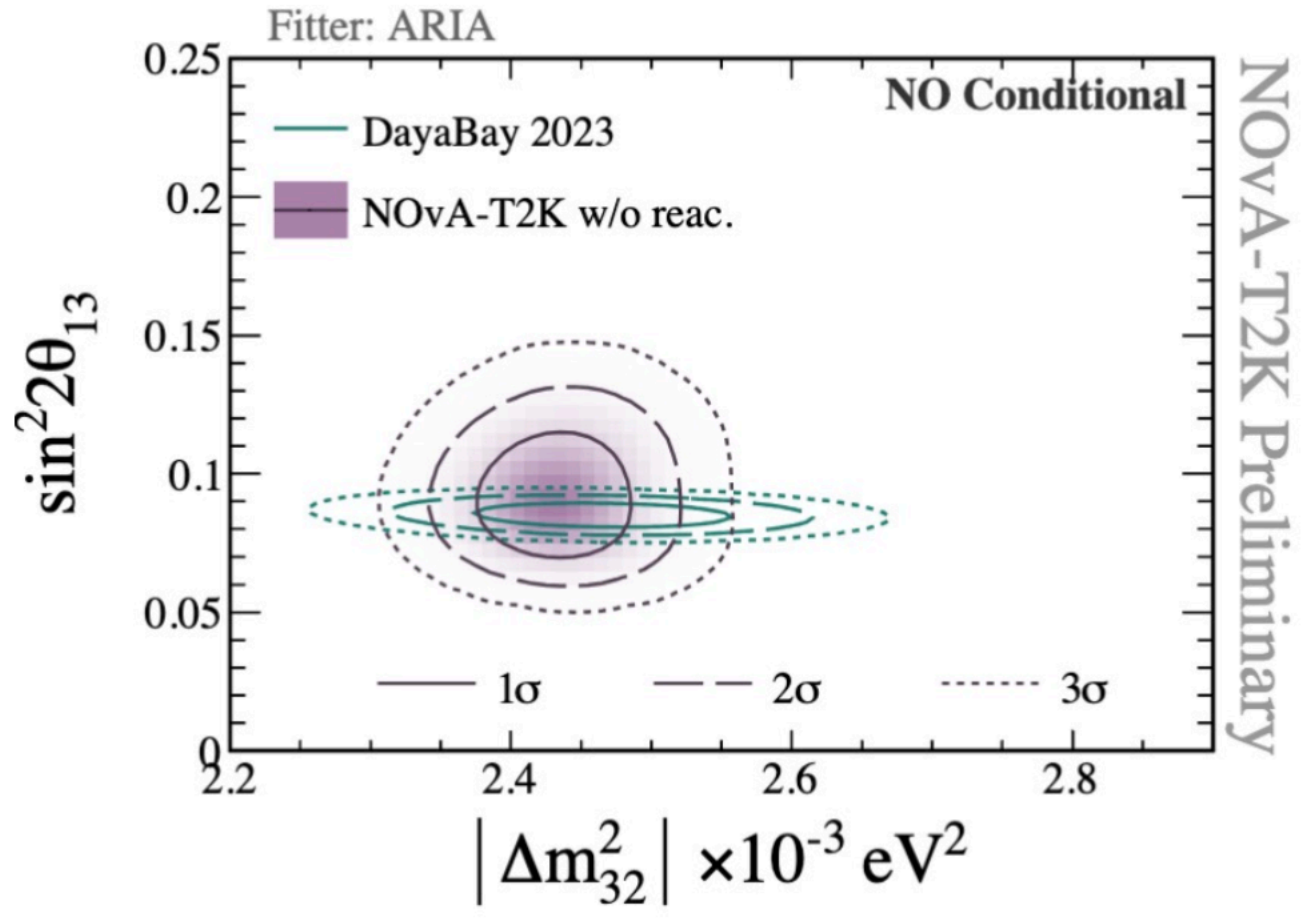
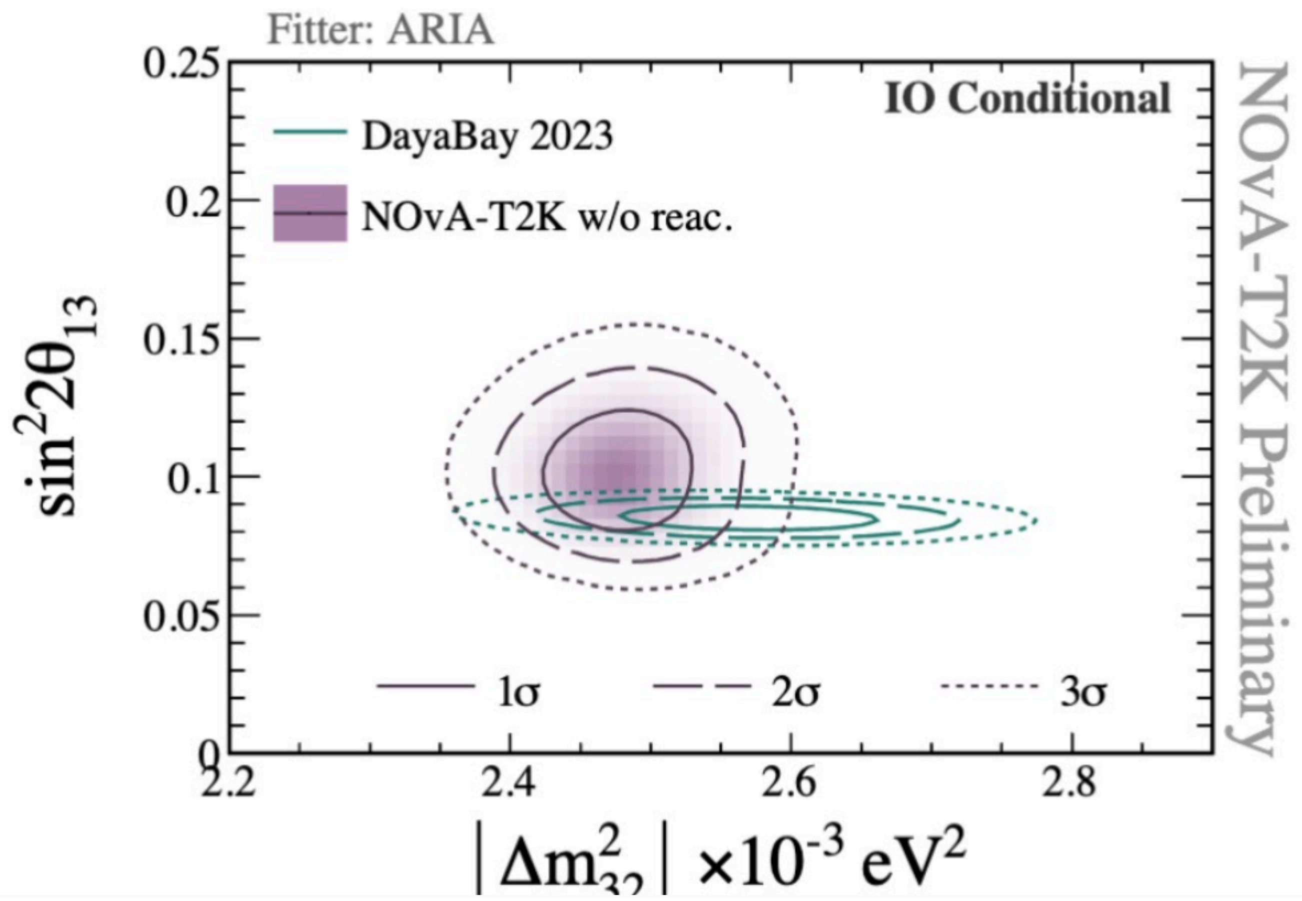


Image Credit:





	NOvA - T2K w/o reactor	NOvA – T2K – 1D Daya Bay	NOvA - T2K - 2D Daya Bay
Bayes factor	**2.47** Inverted/Normal ~71% : ~29% posterior	**1.34** Inverted/Normal ~57% : ~43% posterior	**1.44** Normal/Inverted ~59% : ~41% posterior

- Looking at the true mass ordering reactor and LBL measurement of Δm2 is consistent but it would be off by ~3% in the wrong ordering
- Daya Bay ~2.4% uncertainty on Δm2
- NOvA and T2K have both ~2% → 1.5% when combined
- Including Daya Bay measureement of Δm2 flip again the preference to Normal ordering
- T2K/NOvA joint analysis show no preference for either ordering
- Precision on Δm2 is critical for establishing the mass ordering in combination with JUNO → more tests on-going to test possible impacts of additional alternate models

Measurement of δ_{CP}

- Both mass ordering → higher posterior density around $\delta_{CP}=-\pi/2$
- Normal ordering: wider range of values with higher density close to ±π
- Inverted ordering: enhanced preference for $\delta_{CP}=-\pi/2$
    - If IO is true, CP conservation excluded at 3σ