Long baseline ν experiments in Japan: from T2K to Hyper-K

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on behalf of the T2K and HK collaboration

EDSU 2022, Ile de la Réunion

November 8th, 2022

Outline

1. Neutrino oscillations and long baseline experiments
2. The T2K experiment
3. The T2K oscillation analysis
4. Recent T2K oscillation results
5. T2K and neutrino cross section
6. The future of T2K
7. The Hyper-Kamiokande experiment
8. HK sensitivity for neutrino oscillations
9. HK astrophysics program

1. Neutrino oscillations and long baseline experiments

Neutrino Oscillations (known)

Neutrinos are produced as linear combinations of mass/energy eigenstates, described by the PMNS matrix: 3 mixing angles and 1 complex CPV phase.

Atmospheric+LBL | Reactor+LBL | Solar

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

Time evolution: flavour content "oscillates" in L(distance)/E(neutrino).

Can parameterize neutrino oscillations as:

- Two mass differences (Δm_{12}^2 , Δm_{23}^2)
- And the 4 mixing parameters (3 angles and one phase)

Look at Gonzales-Garcia's talk for more details

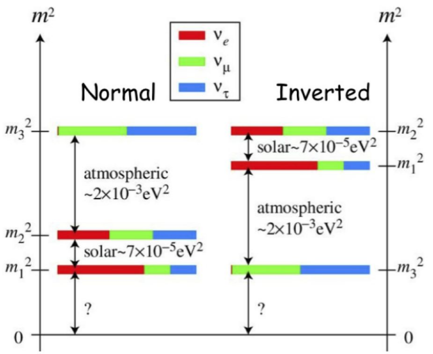
SuperK., T2K, Minos, Nova
θ_{23}(NH)= 42.1°(2%)
$|\Delta m^2_{31}|$= 2.51 x 10^{-3} eV^2 (1%)

Double Chooz, RENO, DayaBay, T2K, NOvA
θ_{13}(NH)= 8.62° (1%)
δ_{CP} ???

Homestake, Sage, Gallex/GNO
SuperK., SNO, Borexino, Kamland
θ_{12} = 33.45 (2%)
Δm^2_{21}= 7.42 x 10^{-5} eV^2 (3%)

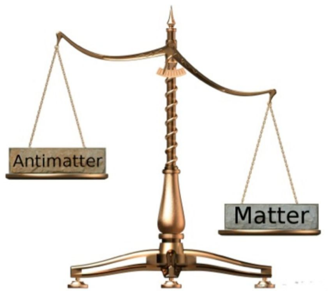
NuFit 5.1 (2021)

Neutrino Oscillations (unknown)



δ_{CP} ?

Mass ordering ?



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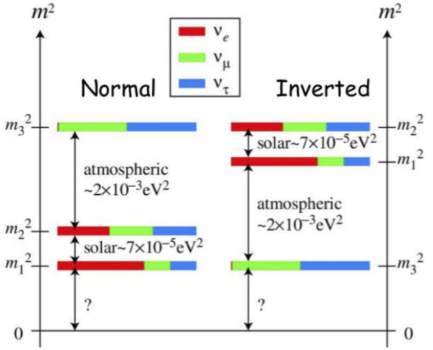
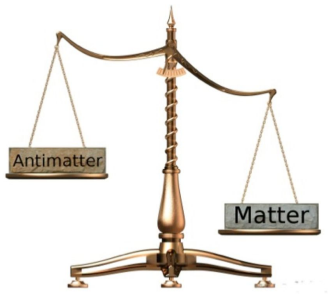
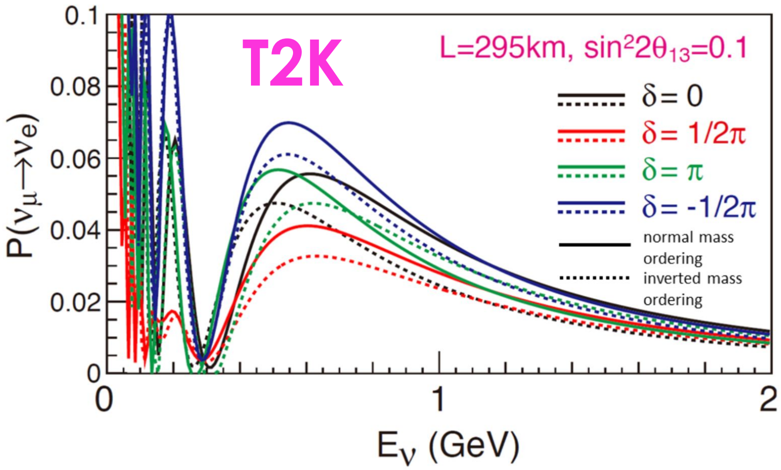


δ_{CP} ?

Mass ordering ?





Oscillation probability depends on δ_{CP}, differently for ν and $\bar{\nu}$ → study of ν vs $\bar{\nu}$ oscillations

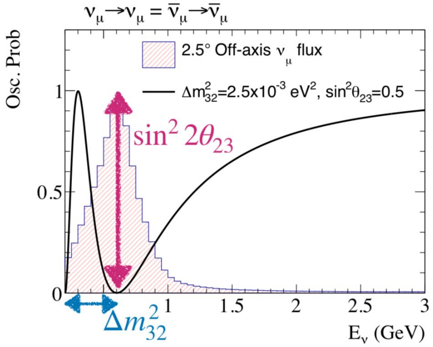
Oscillations perturbed in matter, differently depending on the MO → sensitive to sign of mass splitting

Oscillation measurements with LBL

Long baseline accelerator-based experiments are sensitive to:

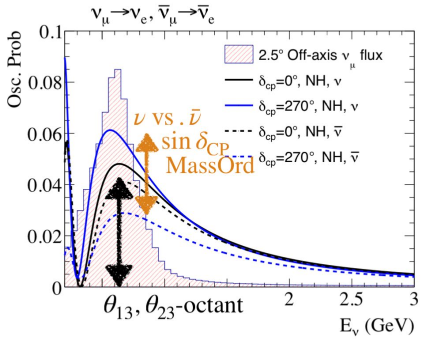
*** Atmospheric parameters (θ_{23}, $|\Delta m^2_{32}|$) through ν_μ disappearance**

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



*** (θ_{13}, δ_{CP}) depends on the $\nu_e/\bar{\nu}_e$ appearance**

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \overset{(-)}{+} O(\sin\delta_{CP})$$



In the case of T2K, $\boldsymbol{\delta_{CP}}$ change the appearance probability by **±30%** while the mass ordering has a ~10% effects

The T2K experiment

T2K "hybrid" collaboration meeting, May 2022

The T2K Collaboration

~528 members, 76 Institutes, 14 countries

Canada
TRIUMF
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

CERN

France
CEA Saclay
LLR E. Poly.
LPNHE Paris

Germany
RWTH Aachen
Universität Mainz

Hungary
Eötvös Loránd U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
Keio U.
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tohoku U.
Tokyo Institute Tech
Tokyo Metropolitan U.
Tokyo U of Science
U. Tokyo
Yokohama National U.
ILANCE

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR
JINR

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid
U.Sevilla

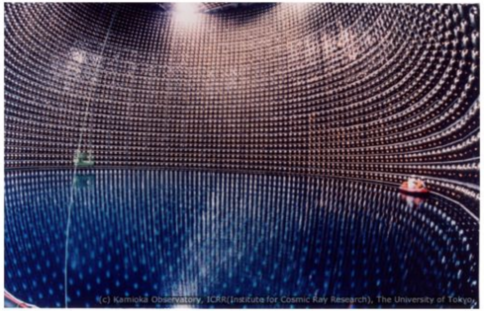
Switzerland
ETH Zurich
U. Bern
U. Geneva

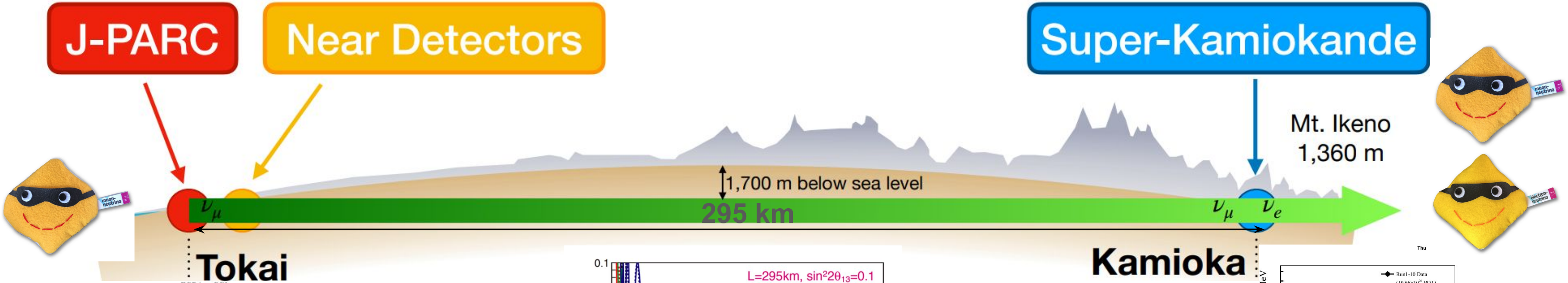
United Kingdom
Imperial C. London
King's College London
Lancaster U.
Oxford U.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Glasgow
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
U. Houston
Louisiana State U.
Michigan S.U.
SLAC
Stony Brook U.
U. C. Irvine
U. Colorado
U.Pennsylvania
U. Pittsburgh
U. Rochester
U. Washington

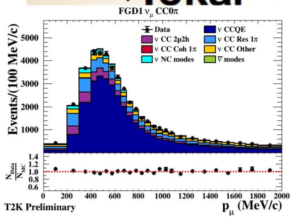
Vietnam
IFIRSE
Hanoi Univ. Science

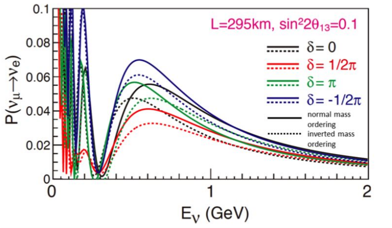
The T2K experiment



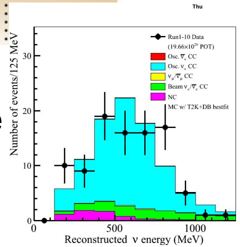


ν_μ beam

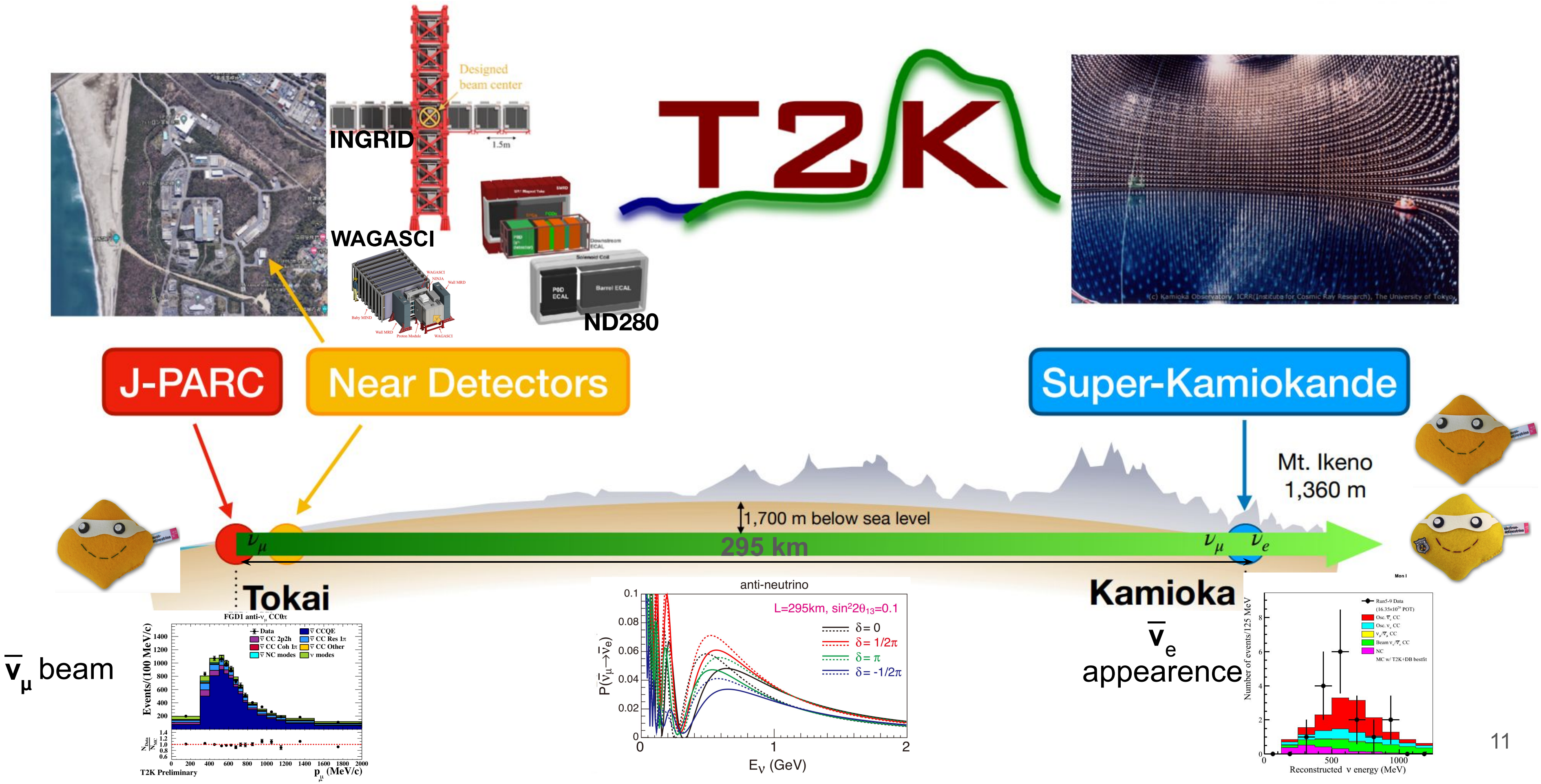




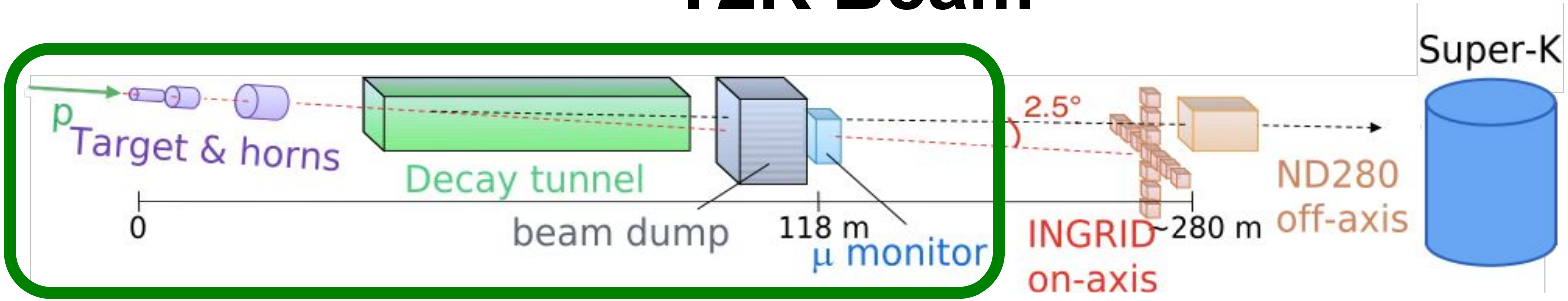
ν_e appearence



The T2K experiment



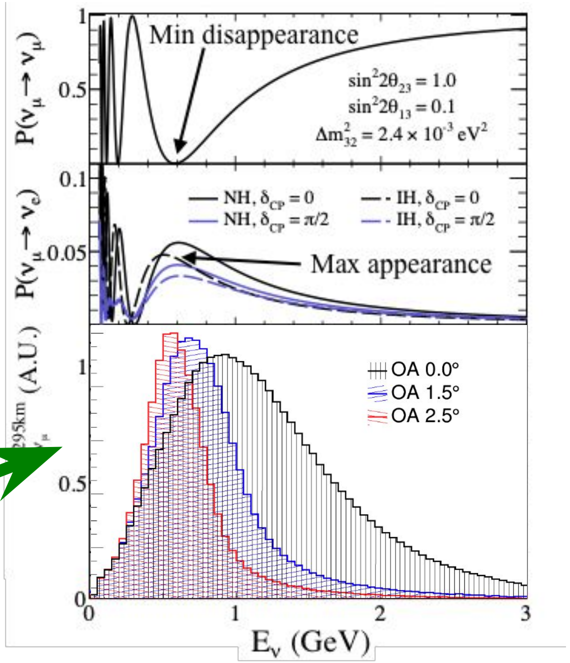
T2K Beam



30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target producing hadrons (mainly pions and kaons)

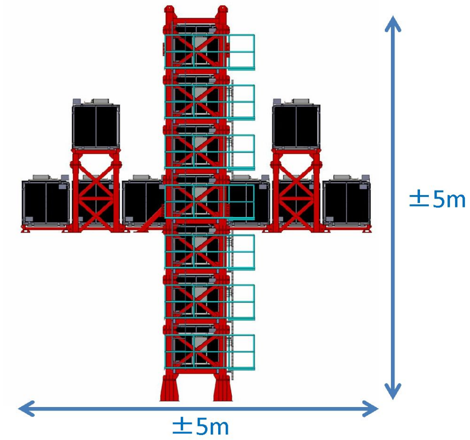
Hadrons are focused and selected in charge by 3 electromagnetic horns: ν_μ **beam created by** π^+ **and** $\bar{\nu}_\mu$ **beam by** π^- **decay**

Detectors 2.5° off the direction of the beam centered around 0.6 GeV. **Off-axis method** reduce high energy tail and maximize oscillation detection probabilities



T2K near detector complex

INGRID, on-axis

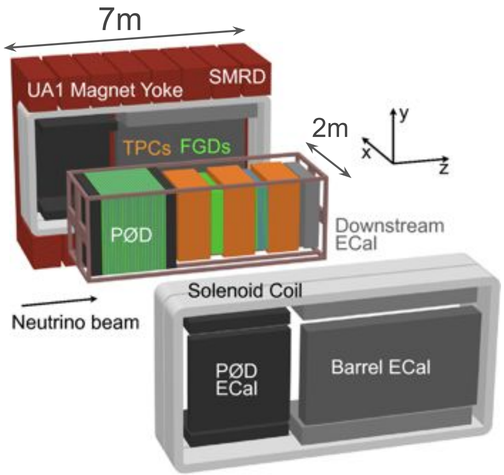


14 **Iron/scintillator** modules

Monitor the beam stability and direction

day-by-day looking at ν ($\overline{\nu}$) interactions + cross section measurements

ND280, 2.5° off-axis



Active **scintillator** (~1.5t) + passive **water** (~0.5t + 2t) targets

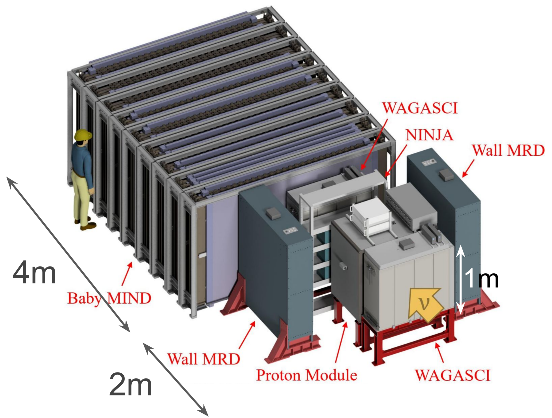
Tracking with 3 **TPC**

Magnetized for charge and momentum measurements

Ecal to distinguish tracks from showers

Used for OA and xsec measurements

WAGASCI, 1.5° off-axis



Recently added (2019)

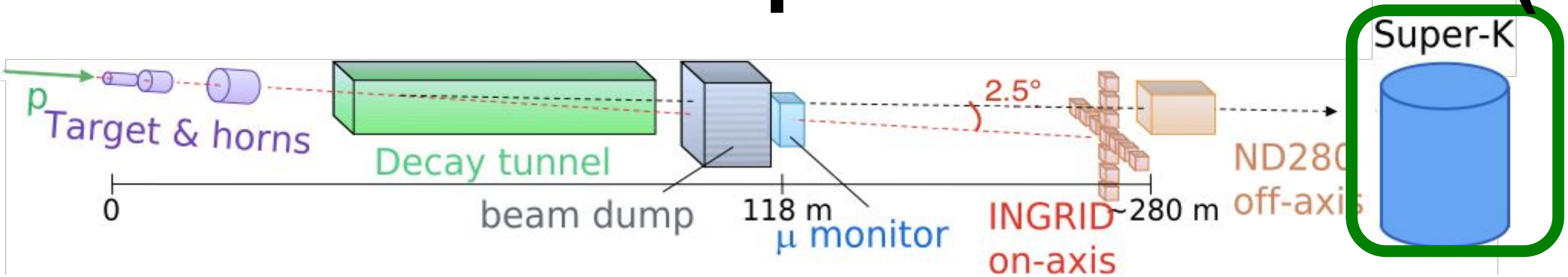
Segmented cubic CH/H_2O (WAGASCI) and SMRD+BabyMIND

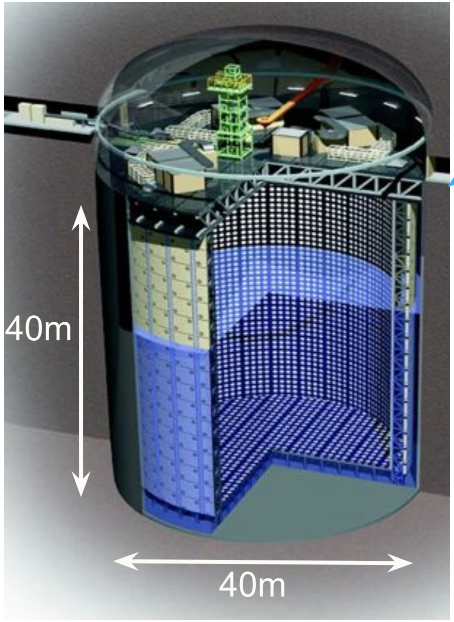
Magnetized detector

Made of **80% of water (~0.5t)**

So far used for xsec meas.

The far detector: Super-Kamiokande (SK)



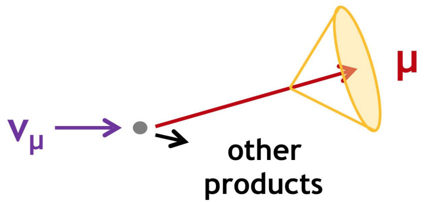


SK is a 50 kton water Cherenkov detector

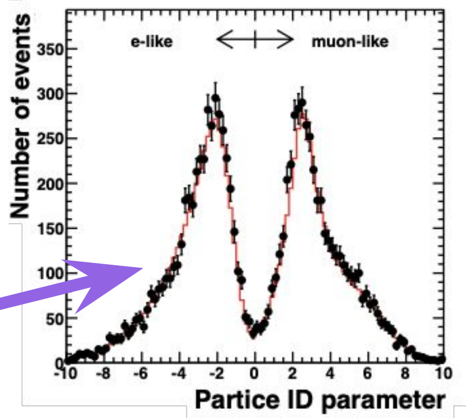
Inner detector ~11000 20 inch PMTs

Outer detector ~2000 8 inch PMTs

Recently loaded with Gadolinium!



Very good μ/e separation
-> distinguish the appearance and the disappearance channels

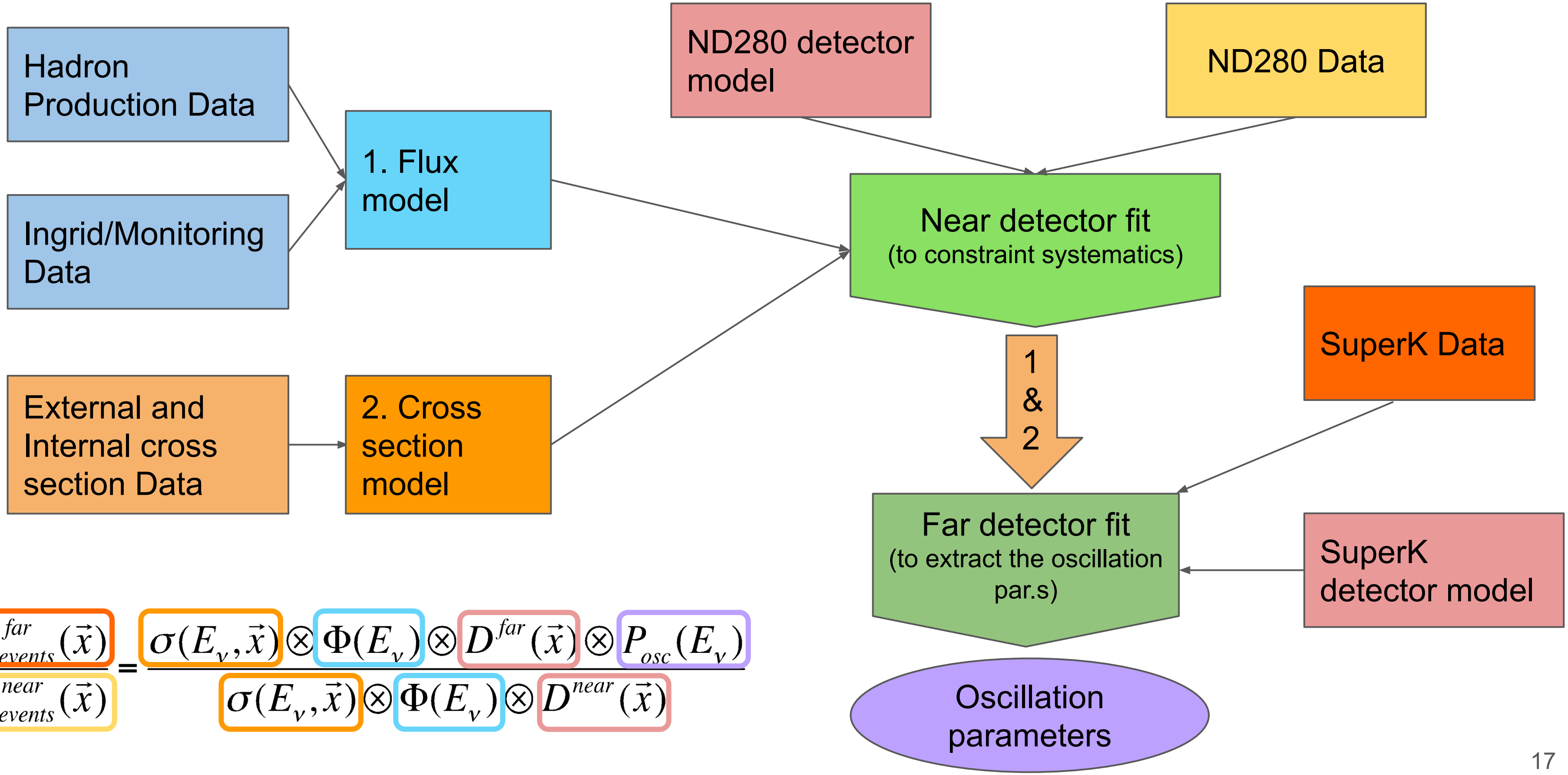


3. T2K oscillation analysis

T2K Oscillation Analysis strategy

$$\frac{N_{events}^{far}(\vec{x})}{N_{events}^{near}(\vec{x})} = \frac{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{near}(\vec{x})}$$

T2K Oscillation Analysis strategy



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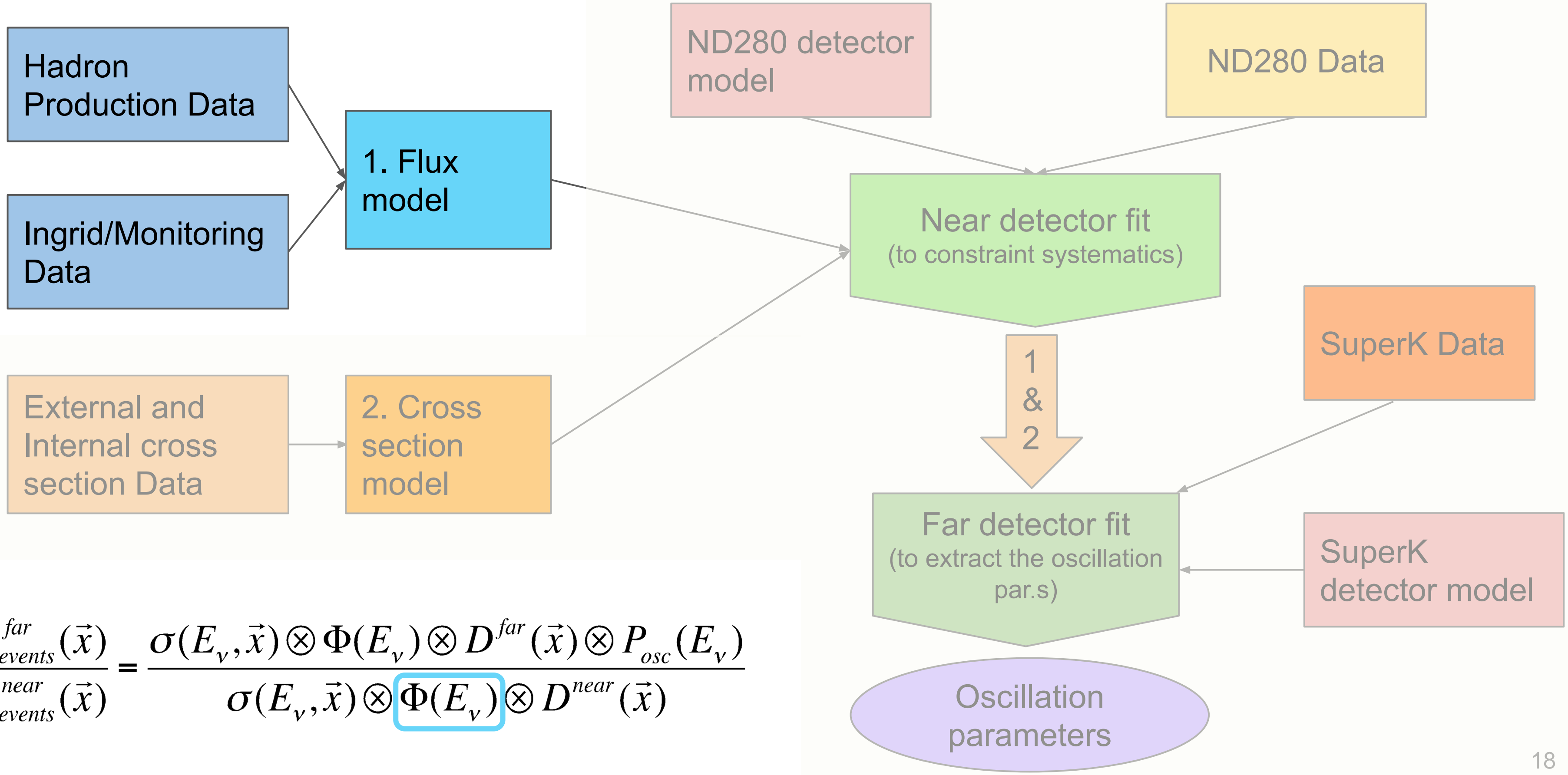
T2K Oscillation Analysis strategy



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T2K flux predictions and uncertainties

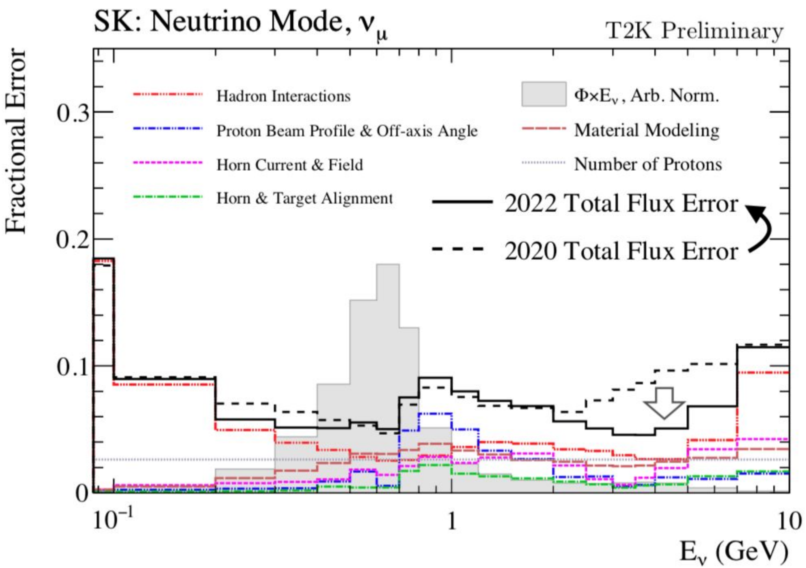


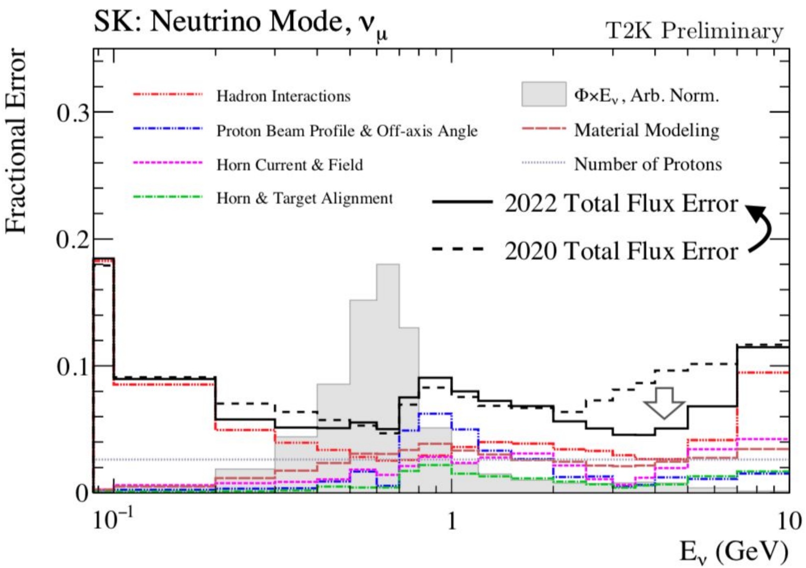
Photo from this summer
(by Eric D. Zimmerman, NA61/SHINE)

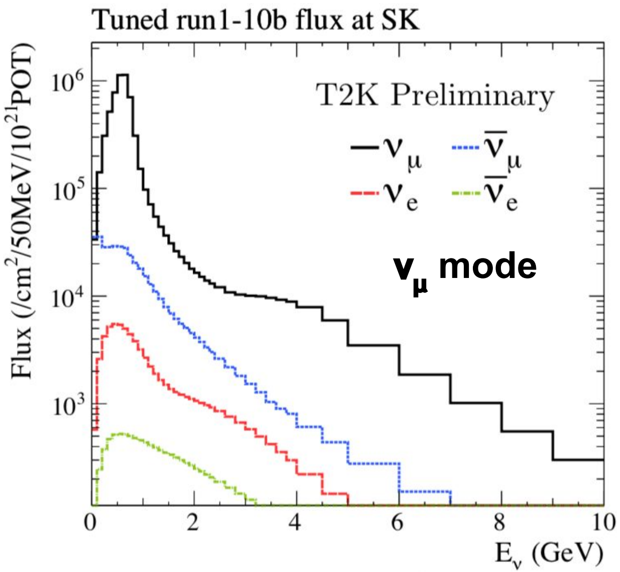
Simulations made with FLUKA and then tuned on external data.

Fluxes known with uncertainties smaller than **5%** in the peak region based on **NA61/SHINE** measurements using the **T2K replica-target**.

Dominant systematics due to the hadron interactions modeling. New measurements ongoing @NA61 → uncertainty reduction expected!

T2K flux predictions and uncertainties





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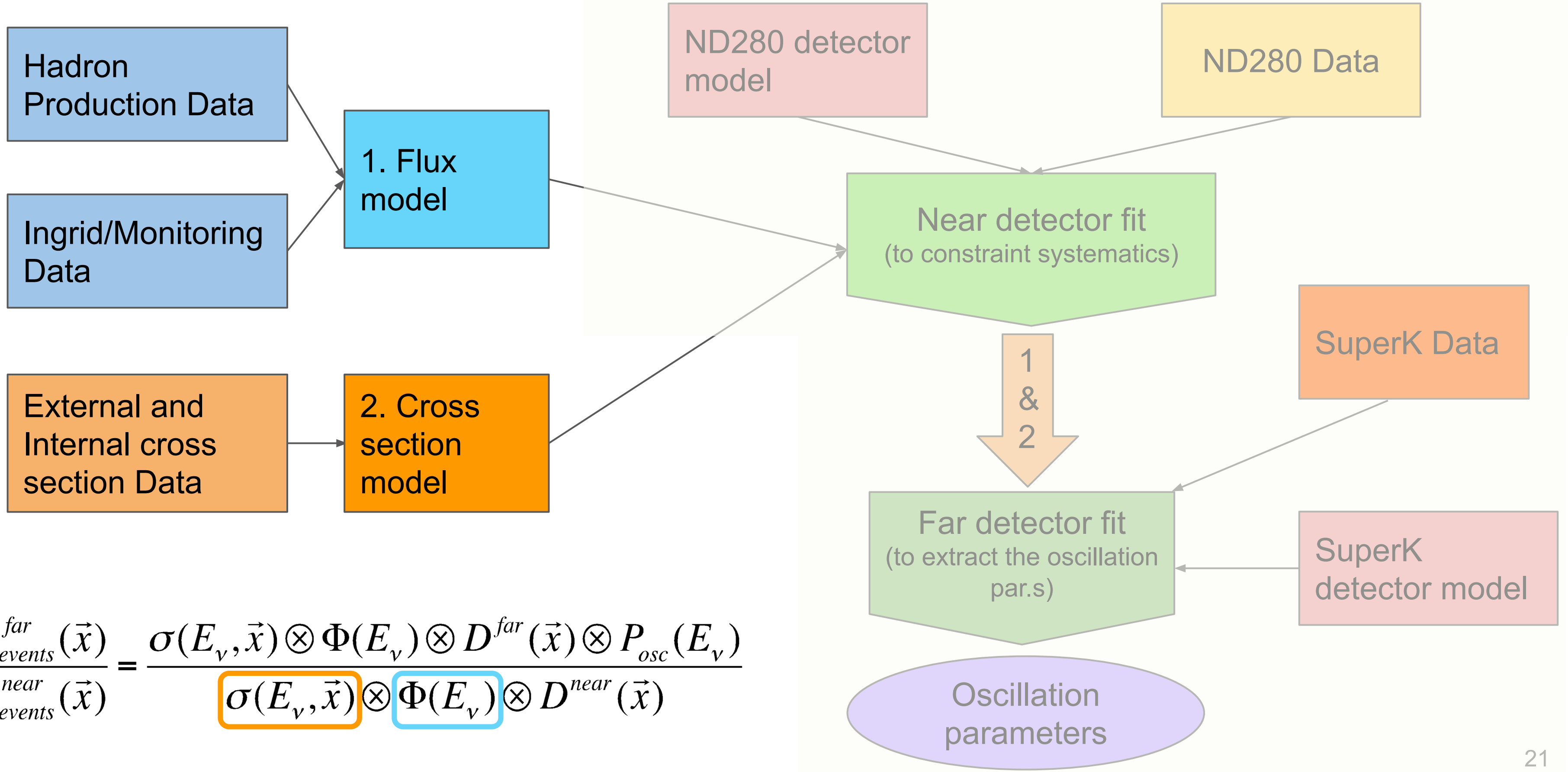
T2K Oscillation Analysis strategy



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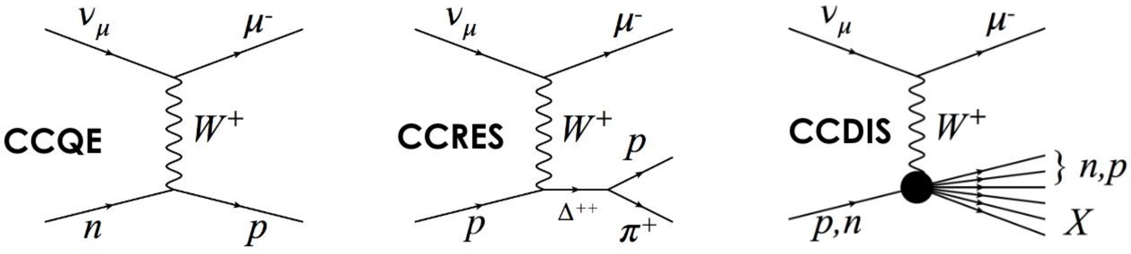
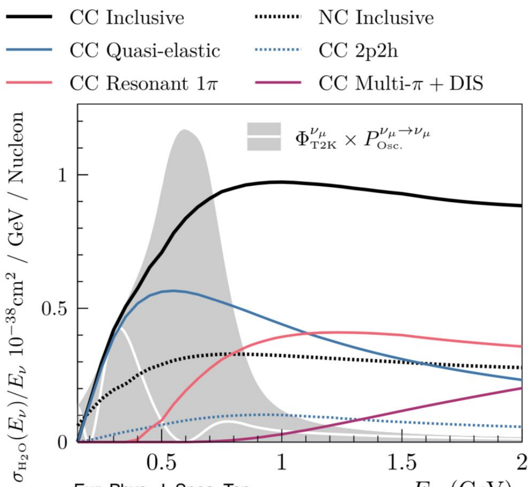
ν interactions predictions and uncertainties

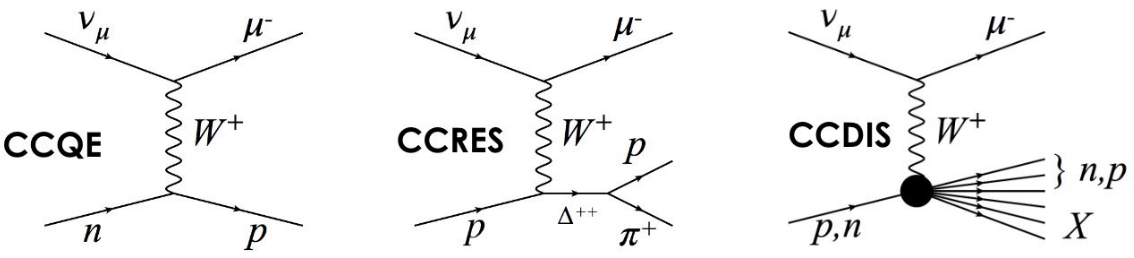


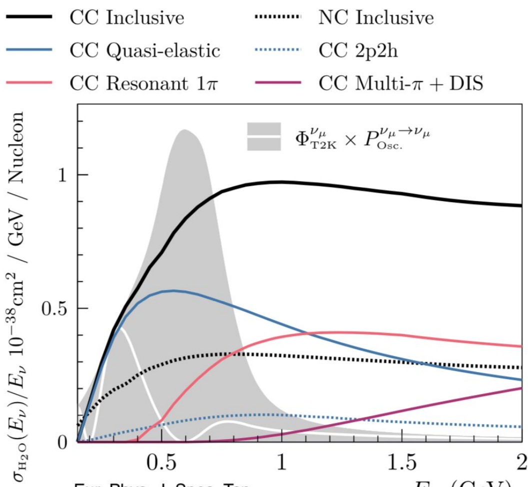


Eur. Phys. J. Spec. Top. (2021) 230:4469–4481

CCQE interactions are the dominant one at T2K energies.
Neutrino energy reconstruction is based on the CCQE assumption.
Ideally we want to select CCQE events, but nuclear effect play an important role

ν interactions predictions and uncertainties





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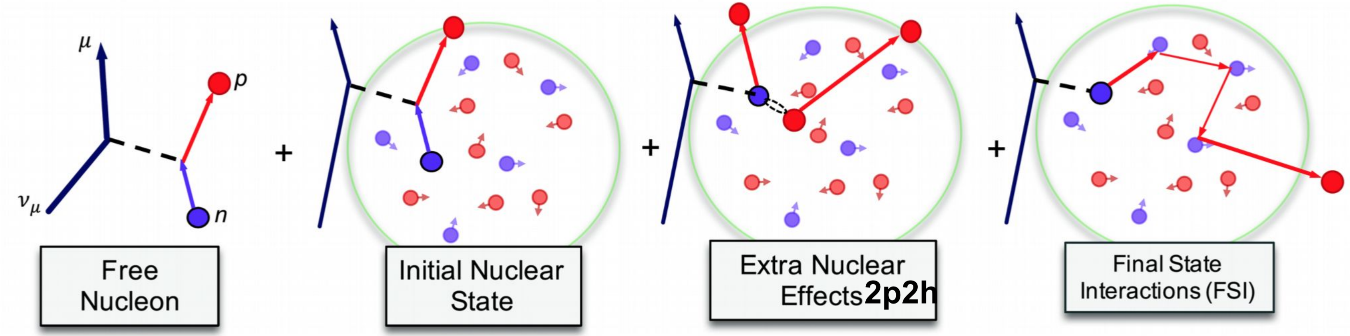
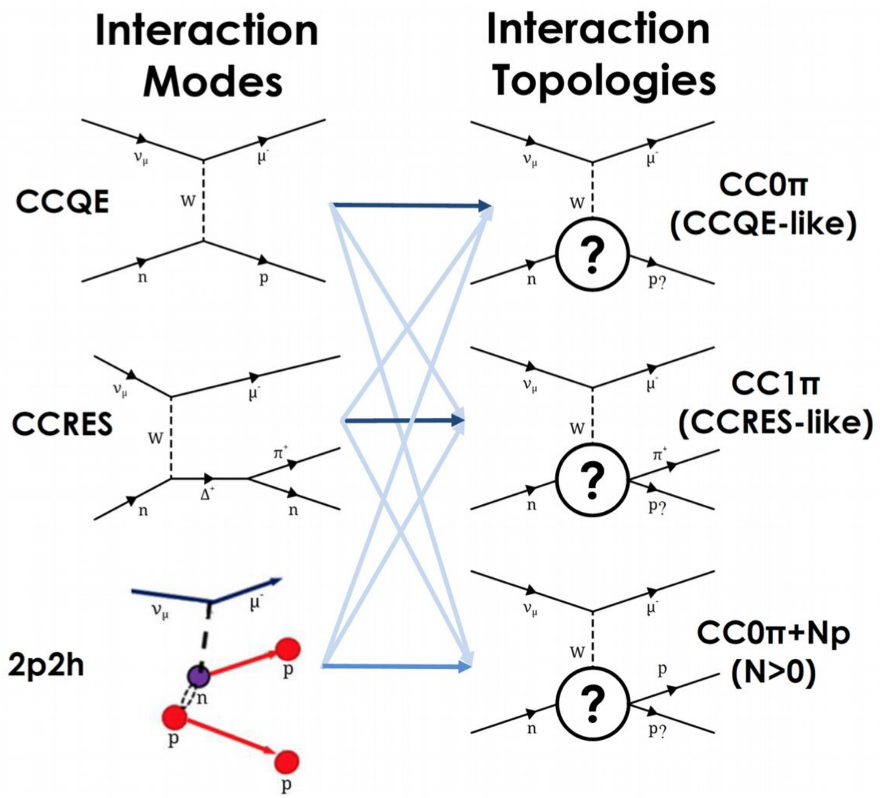


ν interactions predictions and uncertainties



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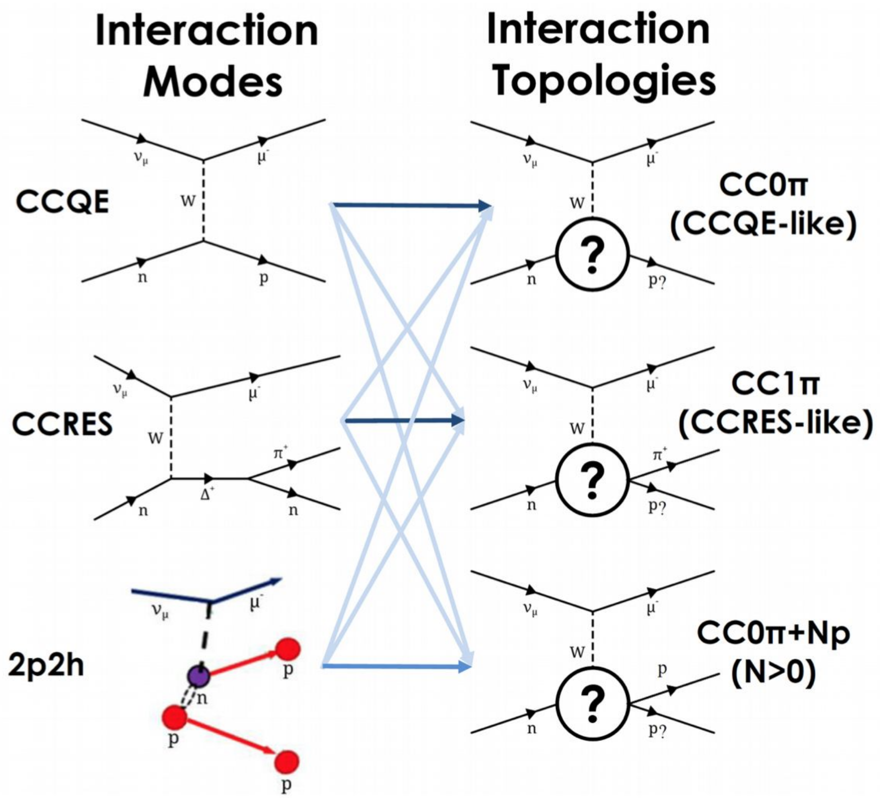
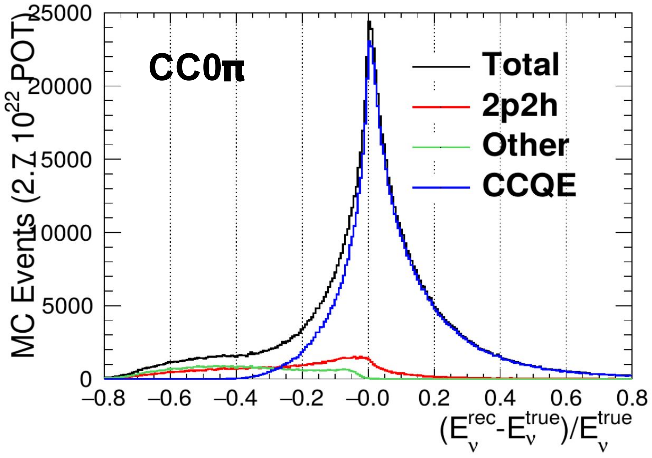
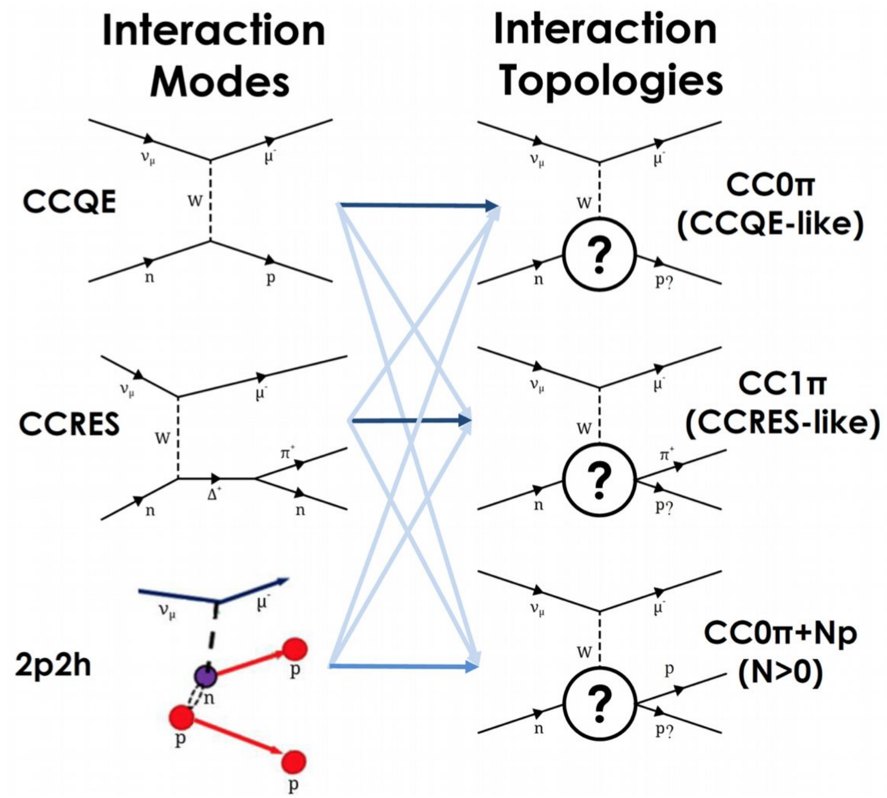
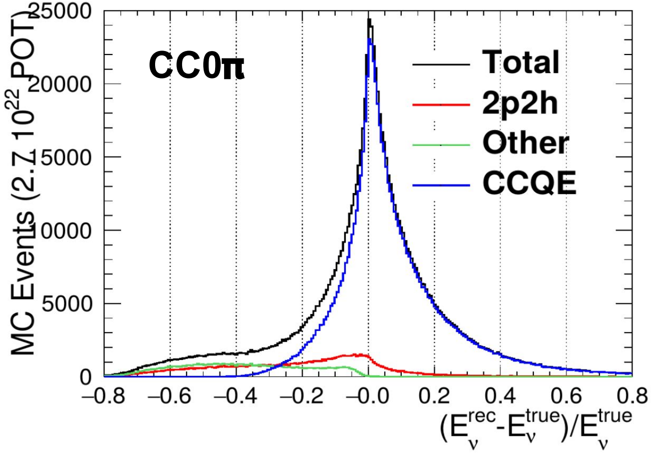




Energy bias introduced by the initial state nucleons and non-CCQE interactions

ν interactions predictions and uncertainties



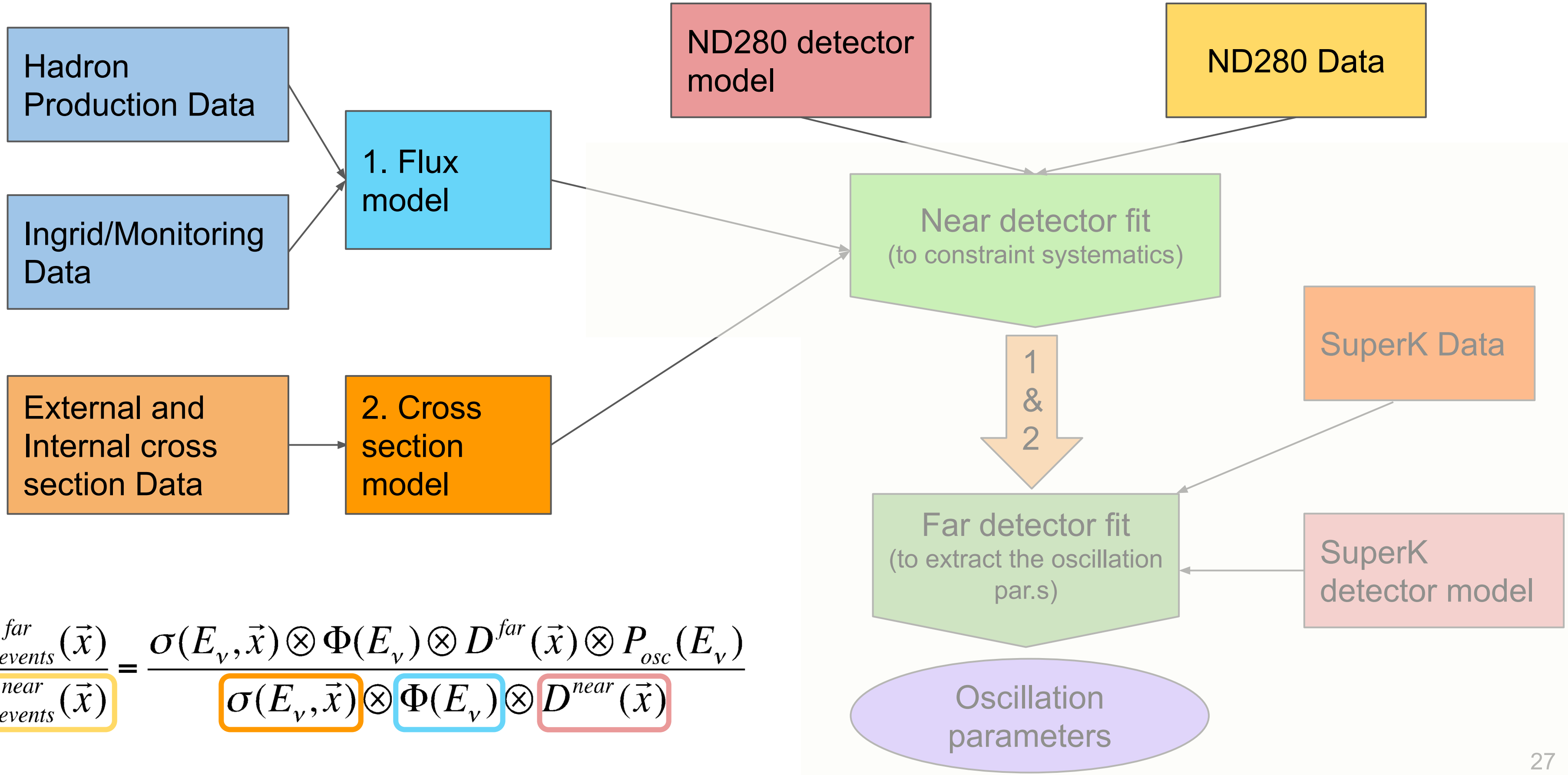


Energy bias introduced by the initial state nucleons and non-CCQE interactions

Interaction models and uncertainties are chosen in order to quantify:

- **the relative CCQE (and other) contributions in the CC0π topology** to know how often we mis-reconstruct E_ν
- **the initial nucleon momentum and energy**, to know how wide our E_ν resolution is
- **the cross section energy and target (O and C) dependence** to extrapolate from the near to the far detector

T2K Oscillation Analysis strategy



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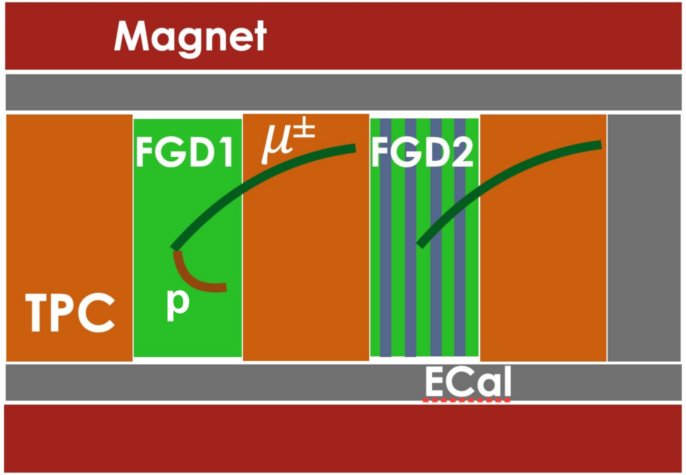
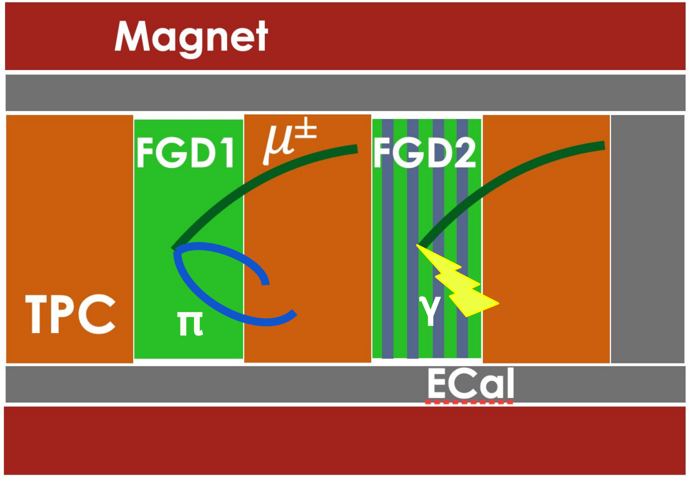
Near detector samples





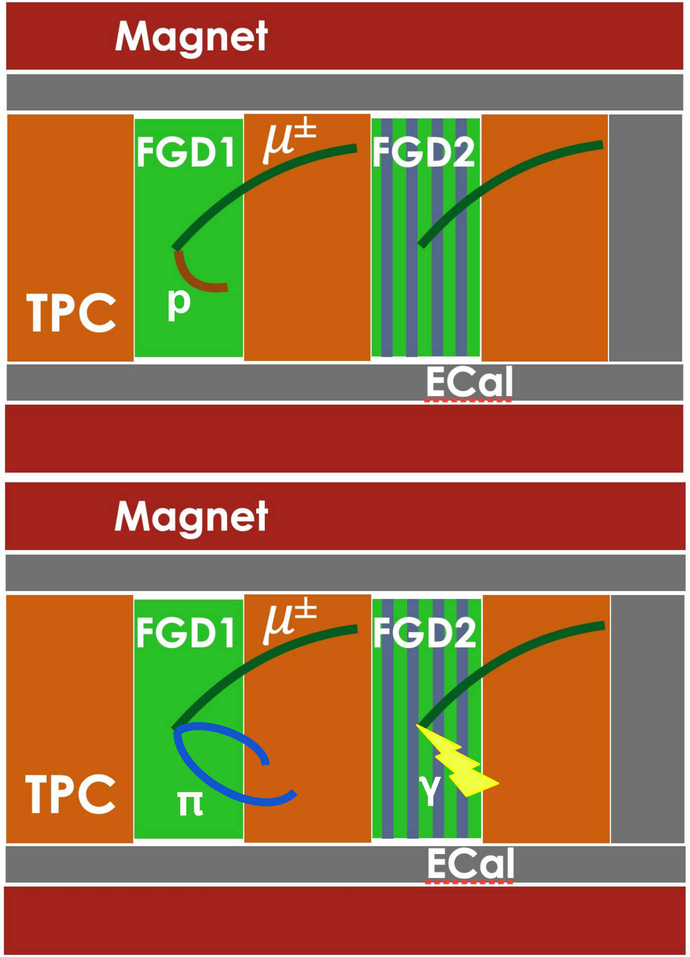
Events with **vertex in FGD1 (C only) or FGD2 (C+O)**

Samples defined depending on the **proton, π and γ multiplicity**

In antineutrino mode, both μ^+ and μ^- selection

In total **22 samples**

Near detector samples



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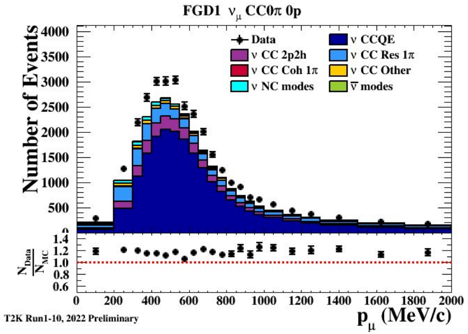
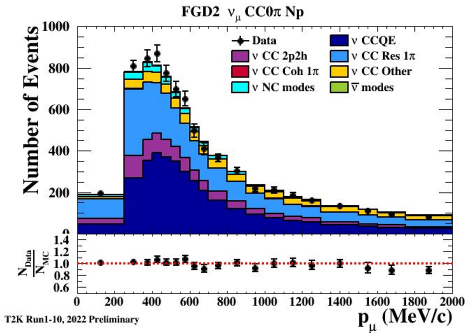
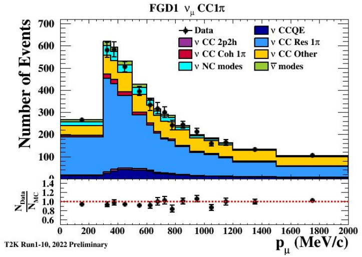
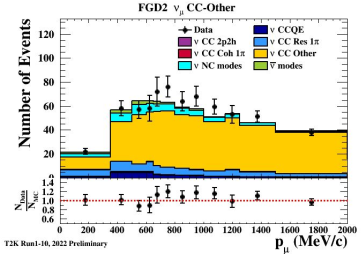
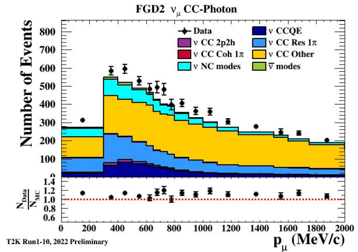




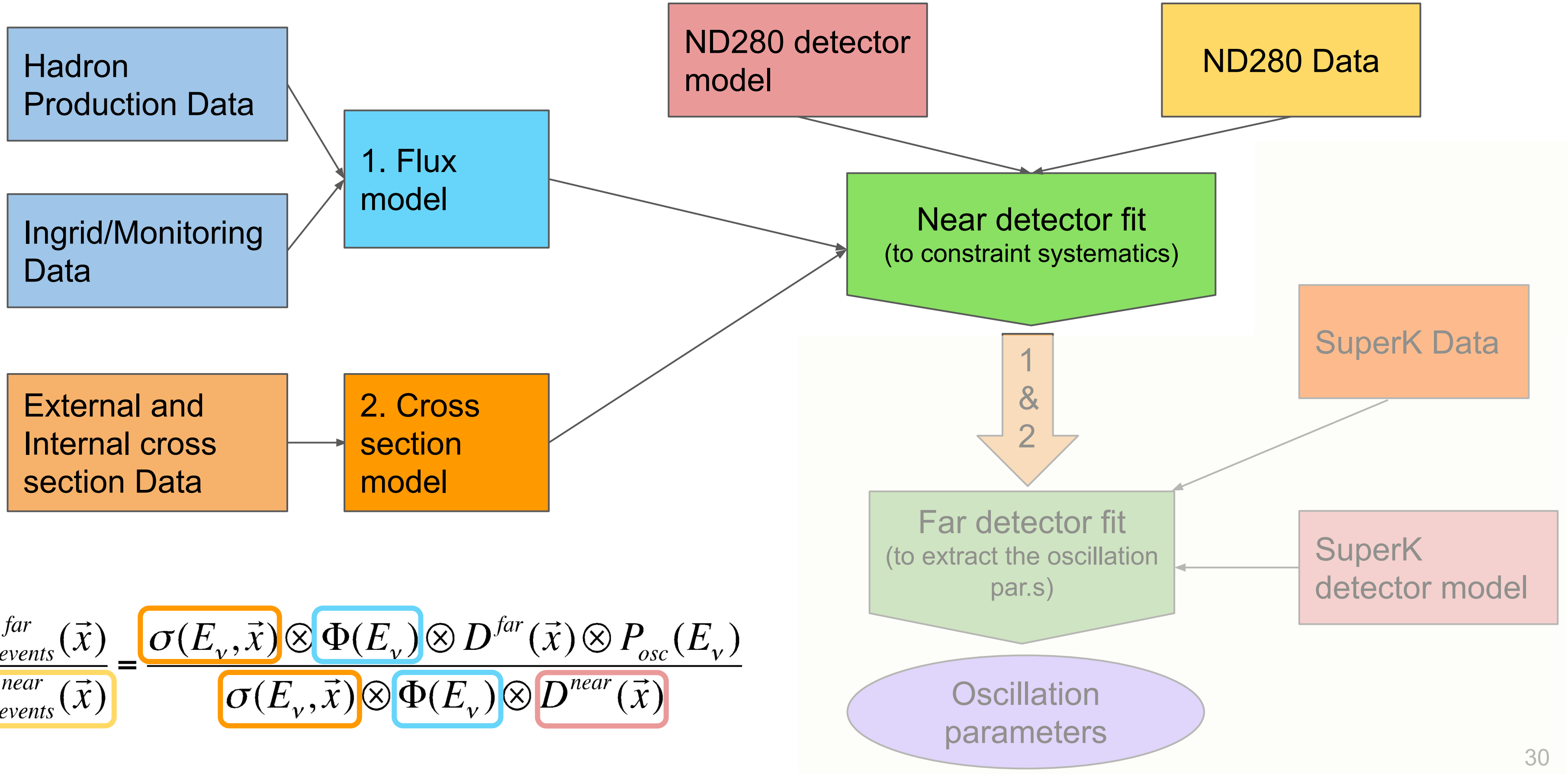






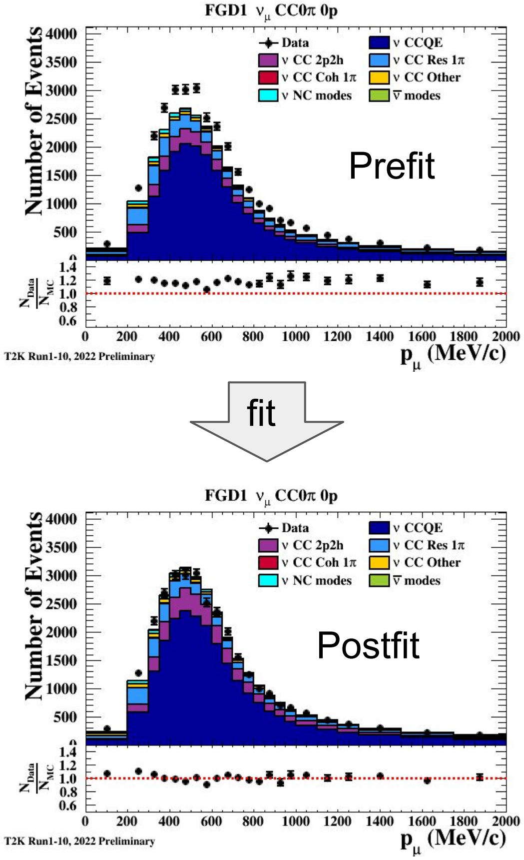
Here some examples for the ν-mode selection

T2K Oscillation Analysis strategy

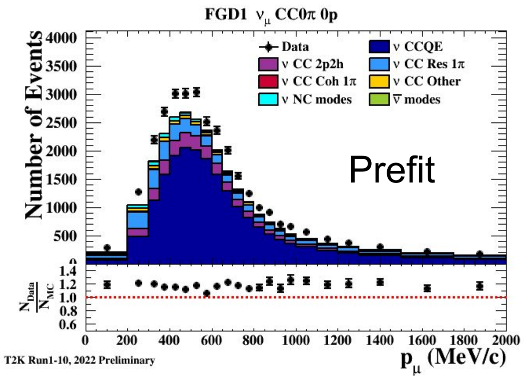


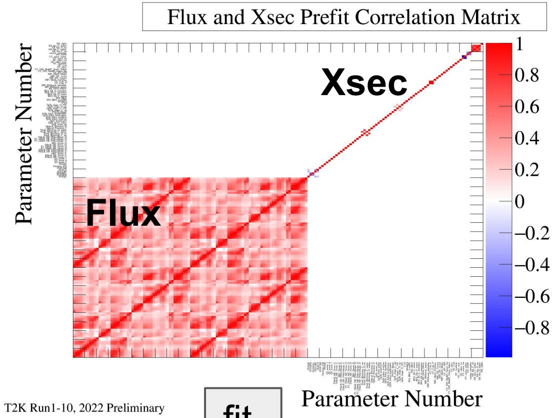
$$\frac{N^{far}_{events}(\vec{x})}{N^{near}_{events}(\vec{x})} = \frac{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{near}(\vec{x})}$$

Near detector fit



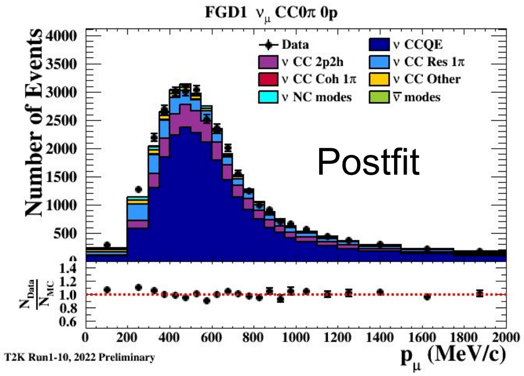
Near detector fit

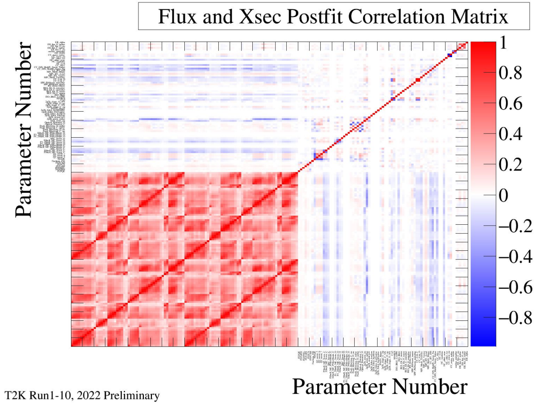




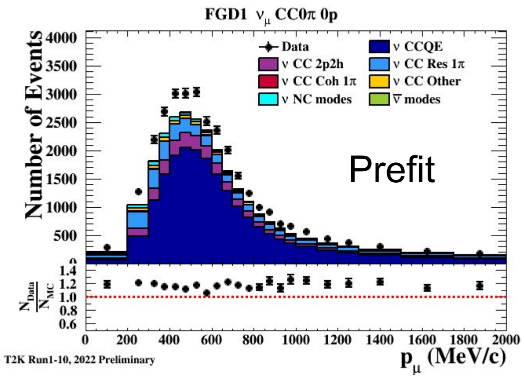
fit

fit

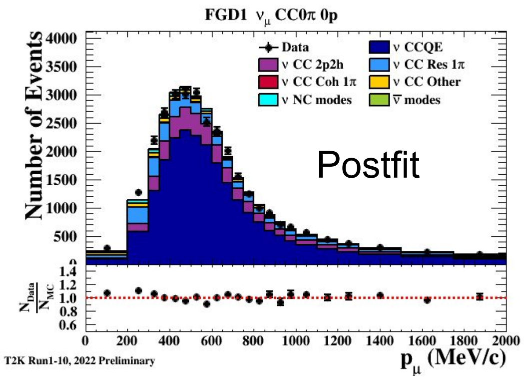


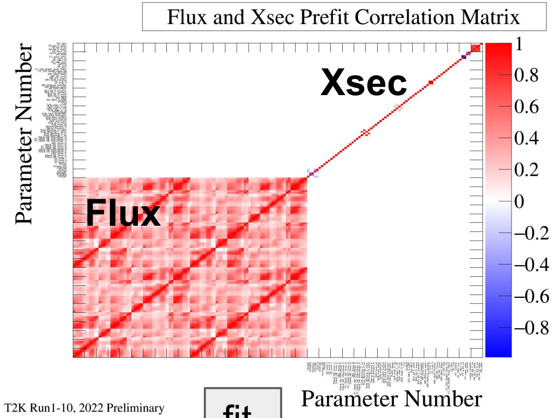


Near detector fit

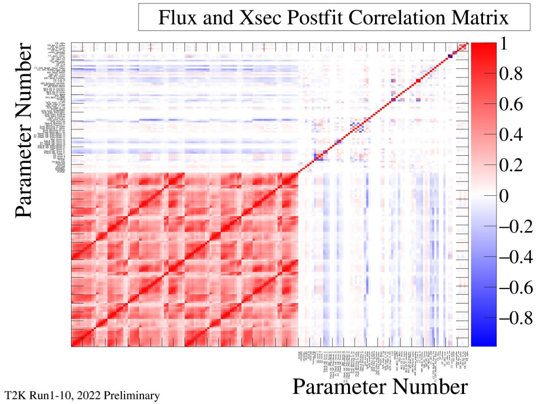


fit



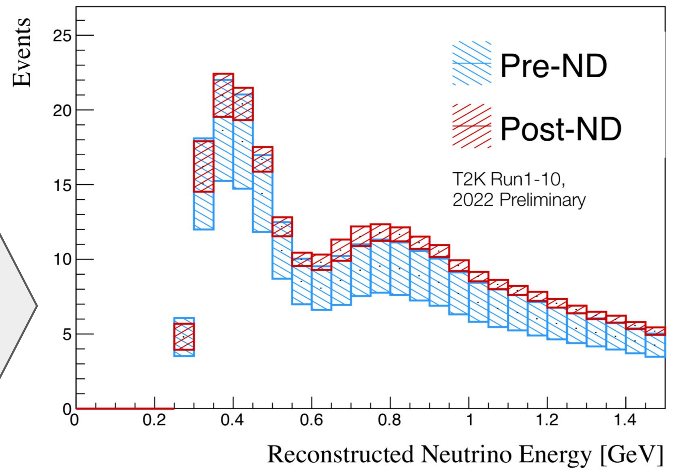


fit



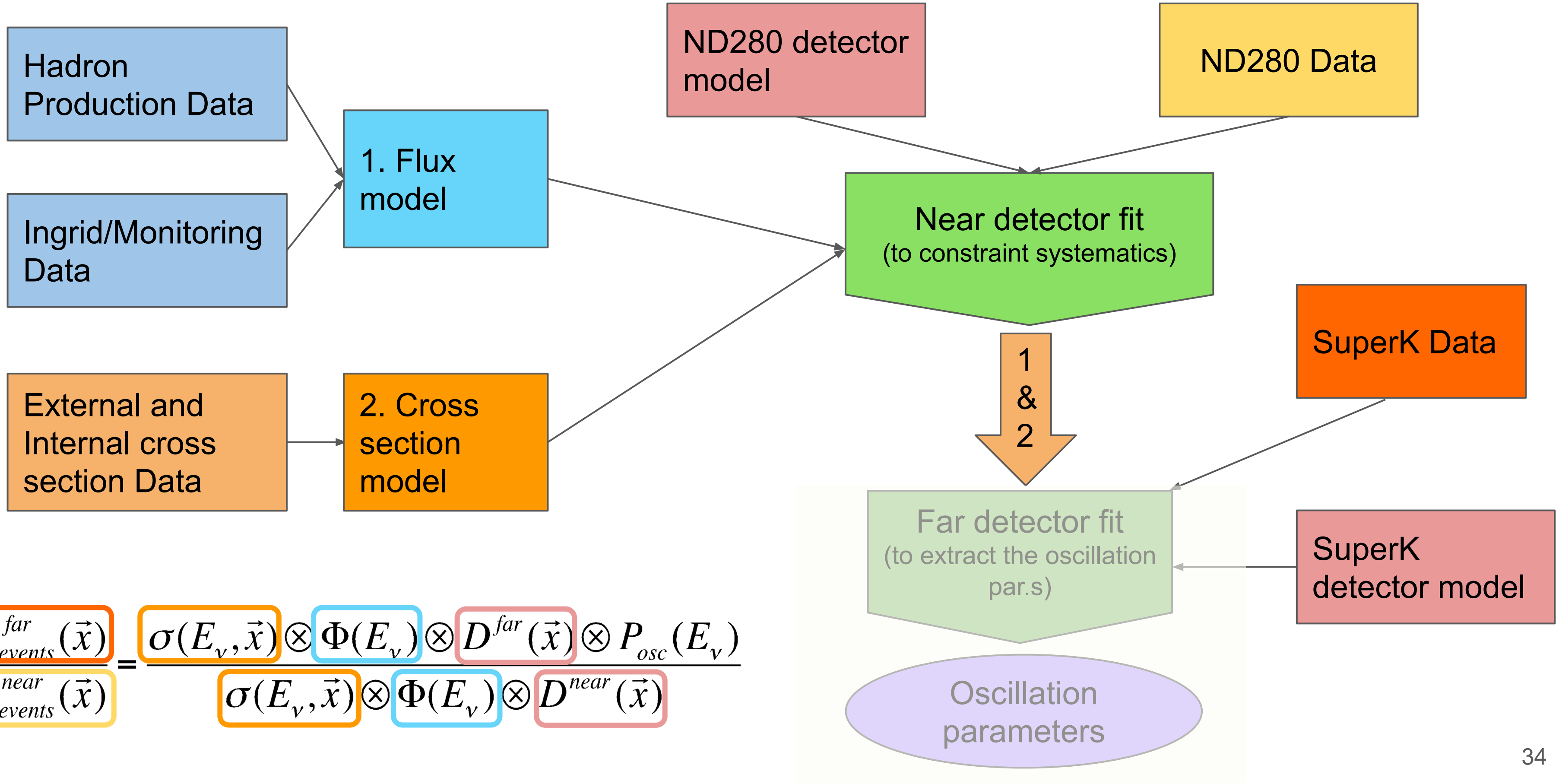
Prediction at Super-Kamiokande

Total syst uncertainty on neutrino mode 1Rμ events at SK



Flux and xsec uncertainties reduced from 17% to 3% thanks to the near detector fit!

T2K Oscillation Analysis strategy



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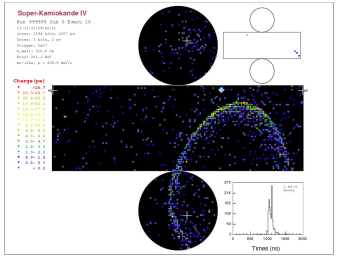
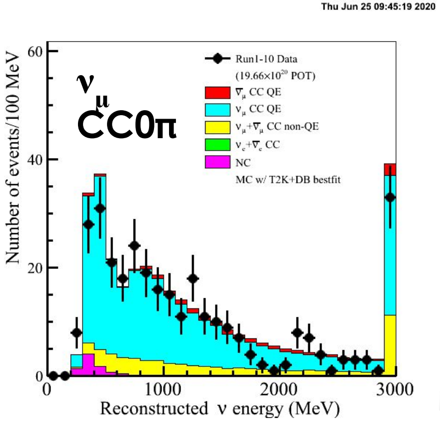
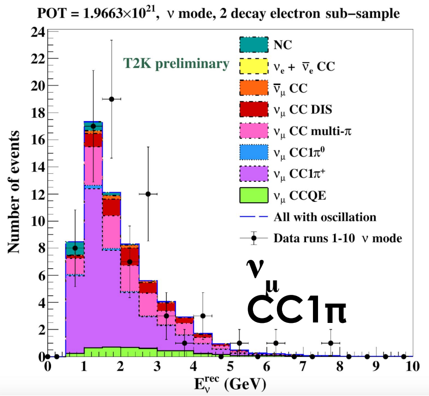
6 samples at the SK

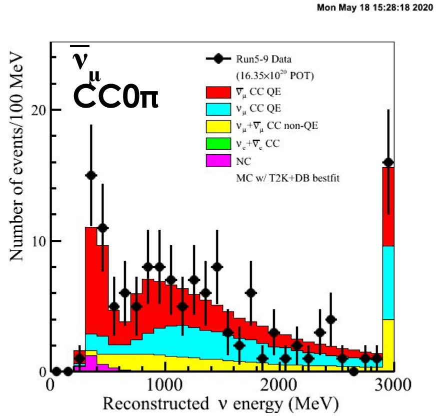
Far detector samples

Disappearance channel

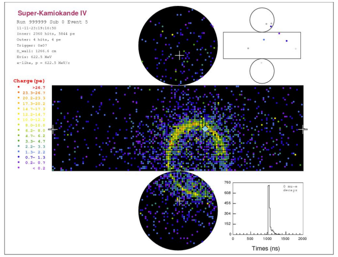


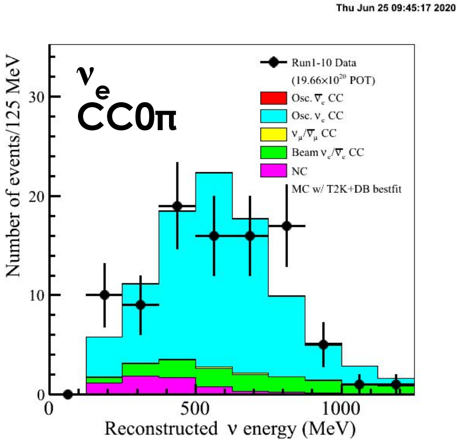


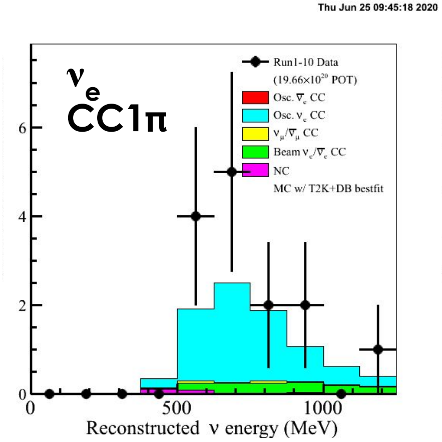


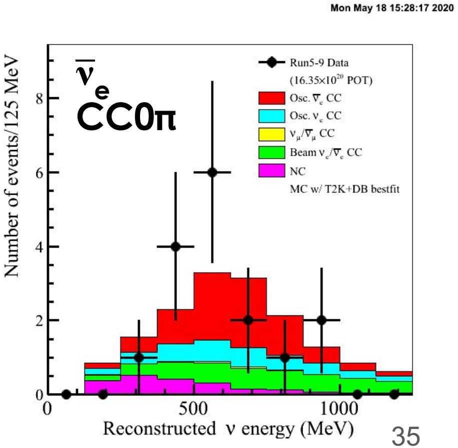


Appearance channel

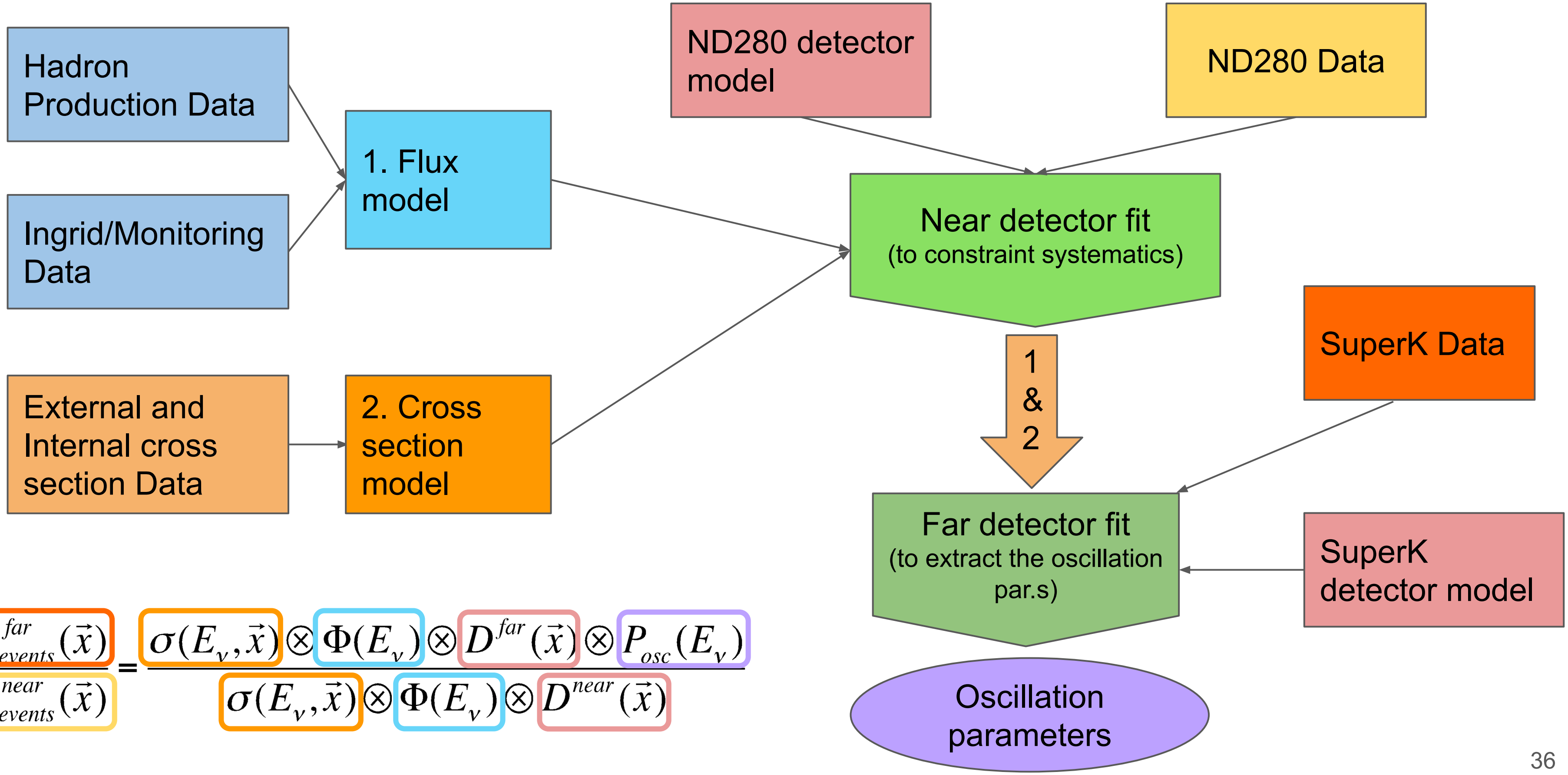








T2K Oscillation Analysis strategy



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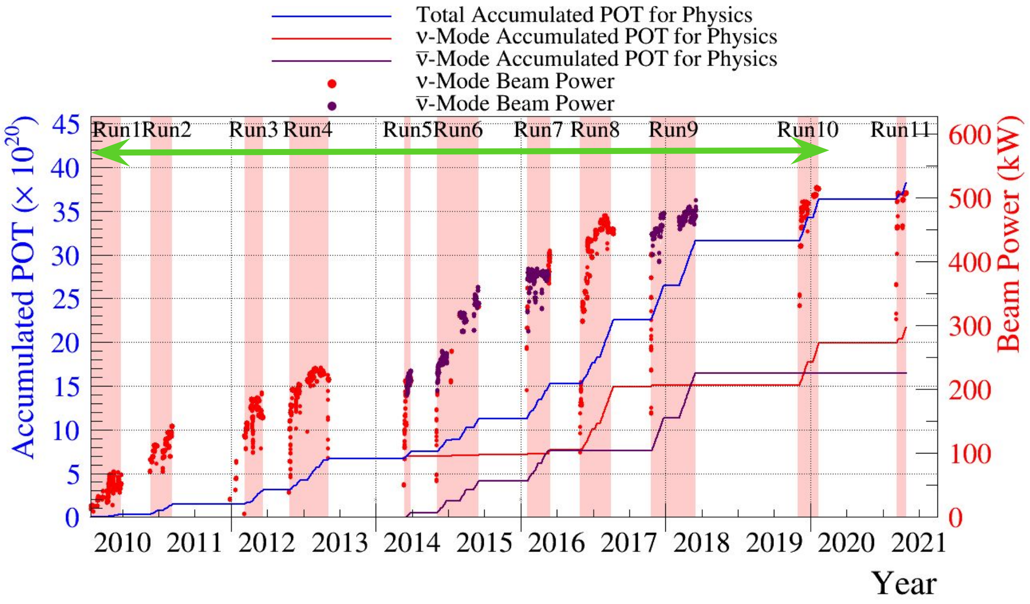
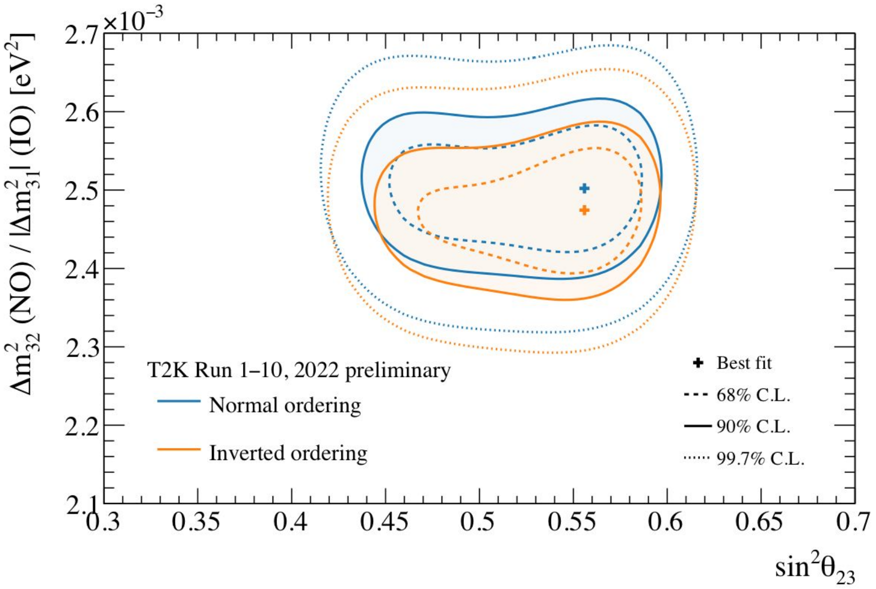
4. T2K oscillation results

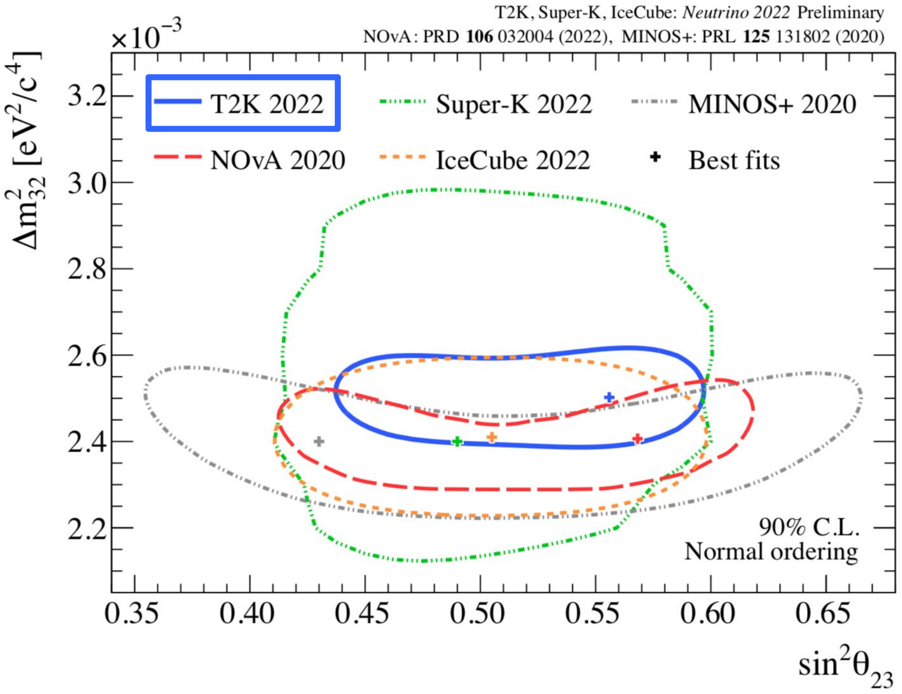
as from OA2022, using 3.6×10^{21} protons on target



Oscillation results as presented at NEUTRINO 2022

Disappearance: atmospheric mixing parameters

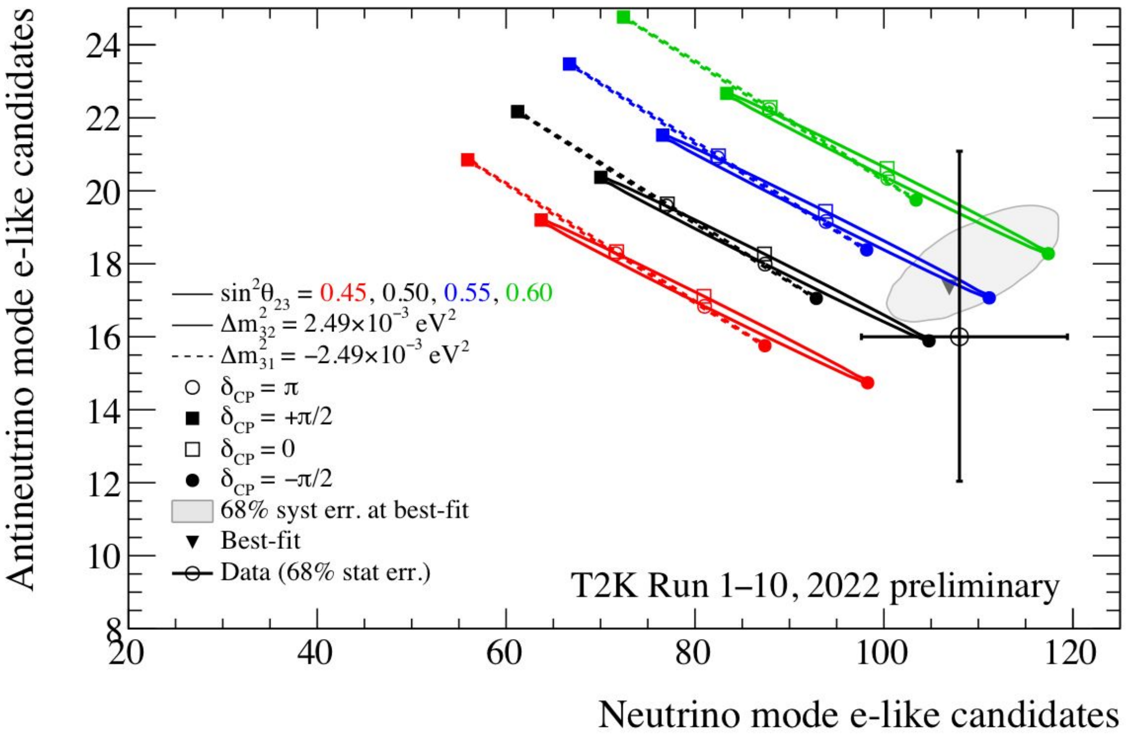




World leading measurement of the atmospheric parameters!

Still compatible with both octants, slightly preferring the upper one

ν_e and $\bar{\nu}_e$ appearance

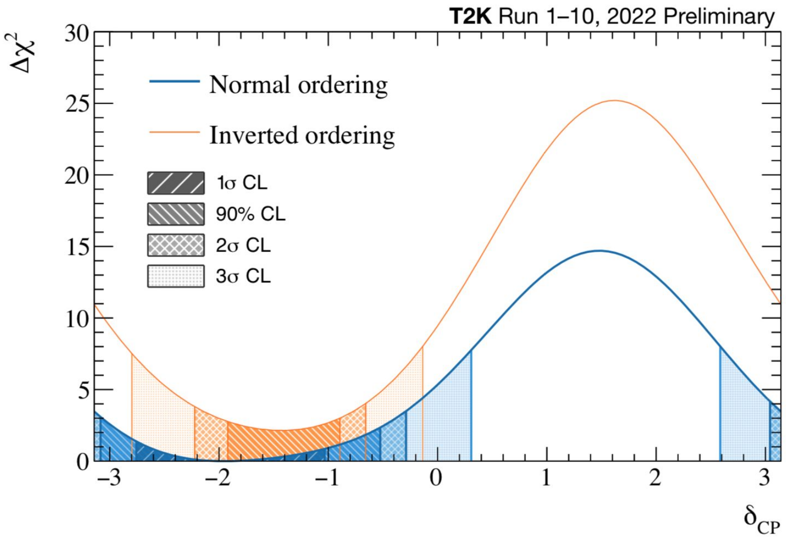


T2K data prefers (near-)maximal CP violation, with $\delta_{CP} \approx -\pi/2$

Slight preference for Normal Ordering

Slight preference for the upper octant for θ_{23}

ν_e and $\bar{\nu}_e$ appearance: δ_{CP}

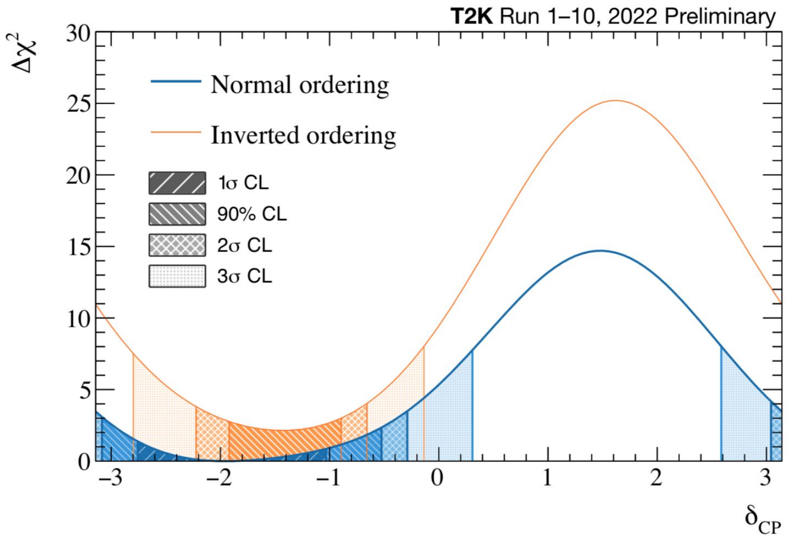


Large region of δ_{CP} values excluded at 3σ

CP conservation excluded at 90%

Preference for Normal Ordering

ν_e and $\bar{\nu}_e$ appearance: δ_{CP}

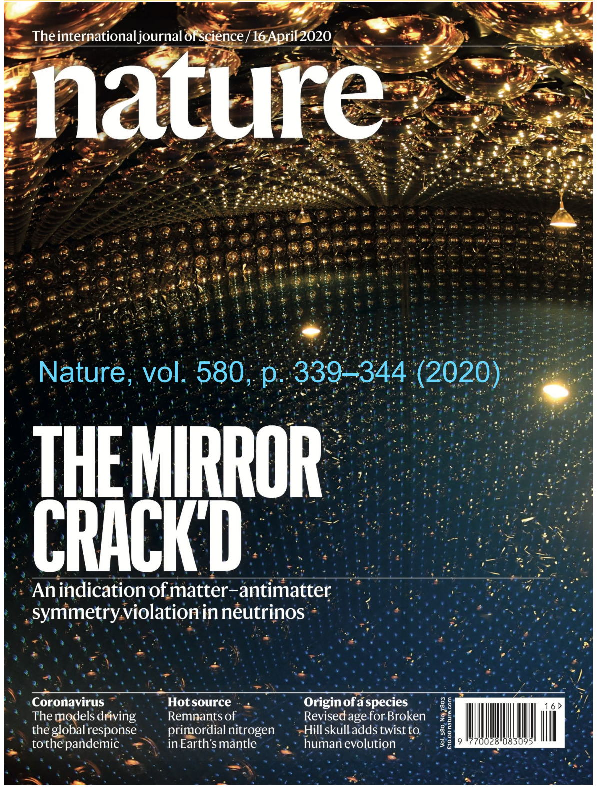


Large region of δ_{CP} values excluded at 3σ

CP conservation excluded at 90%

Preference for Normal Ordering

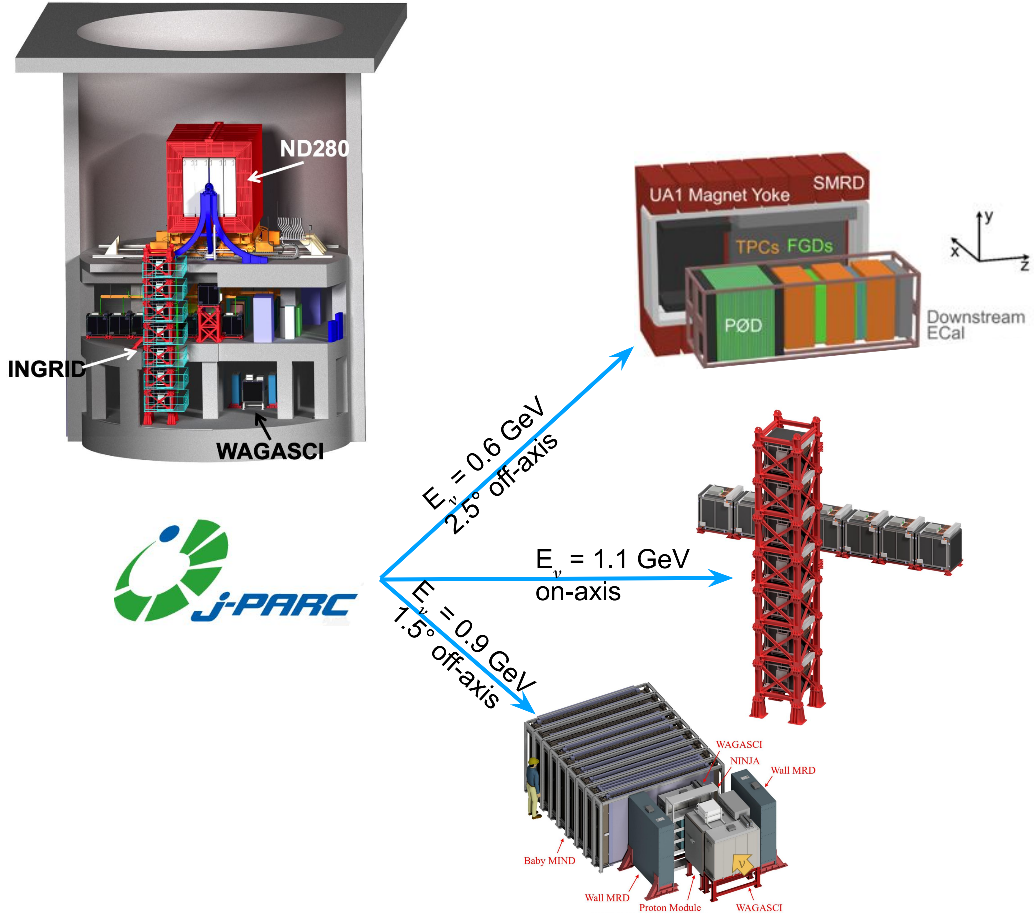
OA2018: for the first time, 3σ intervals for δ_{CP}



Nature, vol. 580, p. 339–344 (2020)

5. T2K and neutrino cross sections

T2K cross section measurements



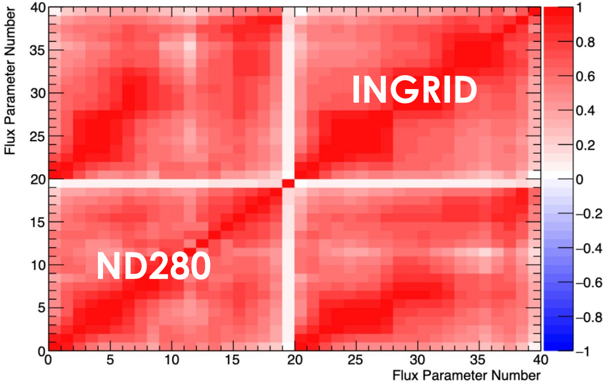
T2K near detector complex allows to measure neutrino cross sections:

- at **different off-axis**, i.e. different energies
- on **different targets**: Carbon, Oxygen, Iron,...
- with **different samples**: ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$
- spanning **different final state topology**
- **limiting model dependence**
- So far **>20 publications**: 6 CC-Inclusive, 3 ν_e, 12 CC0π, 4 CC1π

T2K world-leading experiment also in the xsec field!

First on/off axis cross section measurement

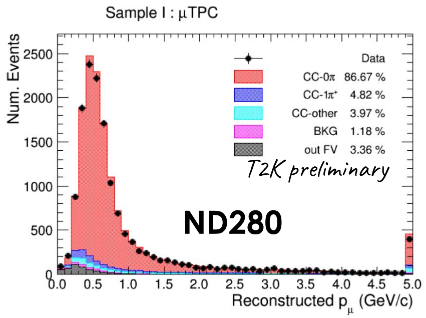
Input flux correlation matrix

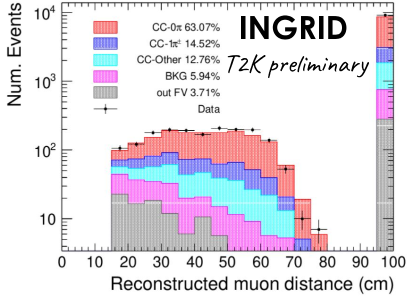


CC0π cross section, the most relevant at T2K energy

Joint on/off axis measurement allows to study the **energy dependence of ν interactions** (same beam but different spectra)

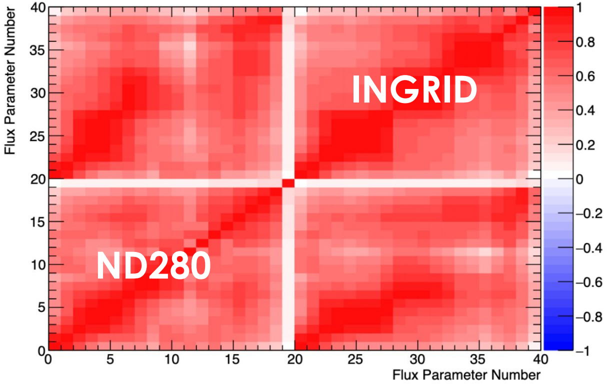
Cross section extracted in 2D as a function of the **muon kinematics**





First on/off axis cross section measurement

Input flux covariance matrix



CC0π cross section, the most relevant at T2K energy

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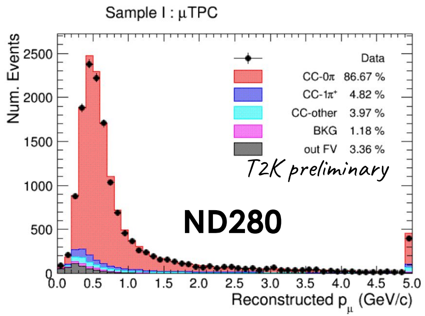
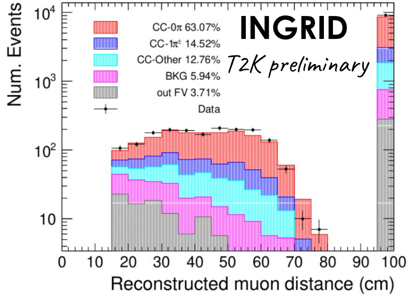
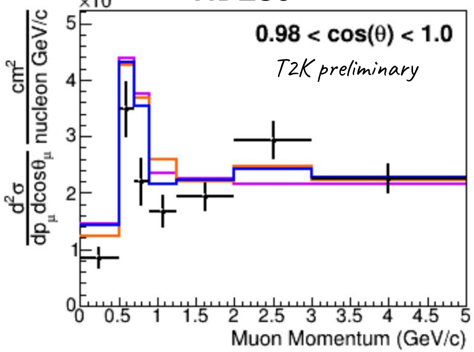
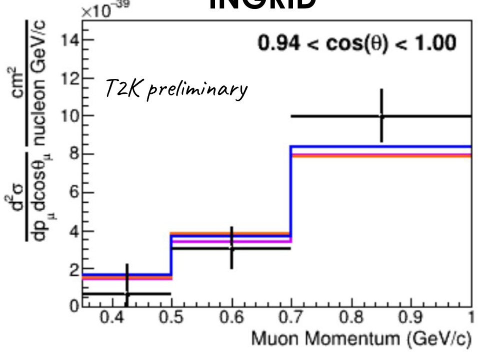


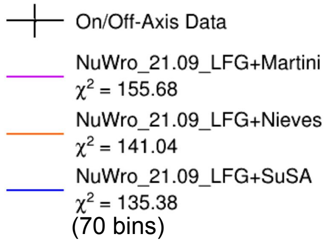


ND280



INGRID





Models struggle in reproducing data

Links to NuInt2022 talks

[latest T2K xsec results]

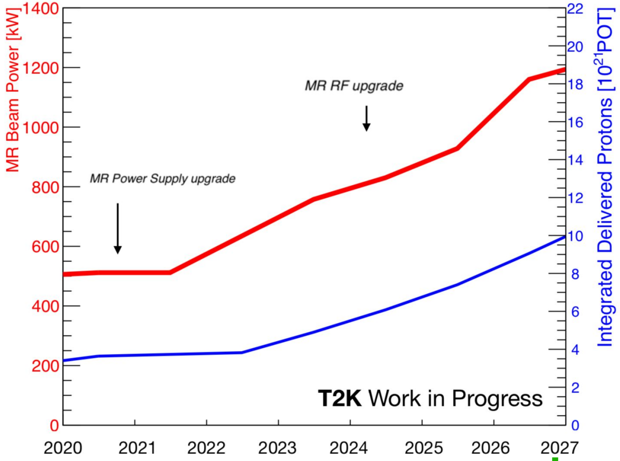
[joint on/off-axis $\nu/\bar{\nu}$]

[CC1π analysis]

6. The future of T2K
(and beginning of HK)

T2K beam upgrade

Remember this when I will talk about HK



HK starts!

For next run expected 750 kW

Increase **beam power from ~500 kW to 1.3 MW** via upgrades to main ring power supply and RF (mainly increasing the repeat. rate)

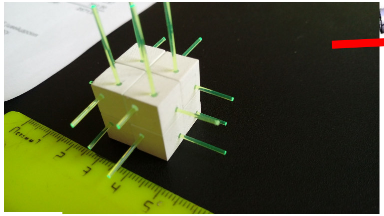
Many upgrades to neutrino beam line (target, beam monitors, ...) ongoing to accept 1.3 MW beam

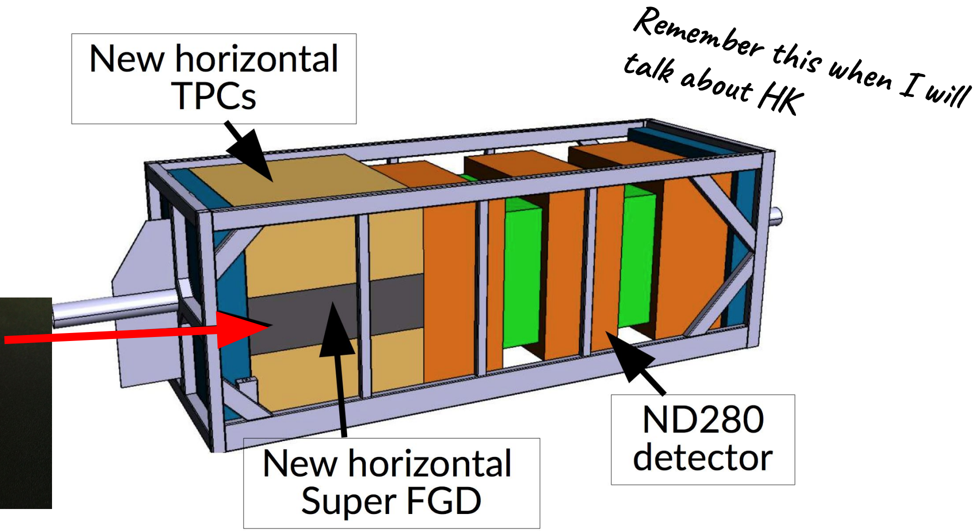
Increase **horn current 250 kA → 320 kA** for ~10% more neutrinos/beam-power and reduced wrong-sign background → Aiming for 320 kA operation in next run (2023)!

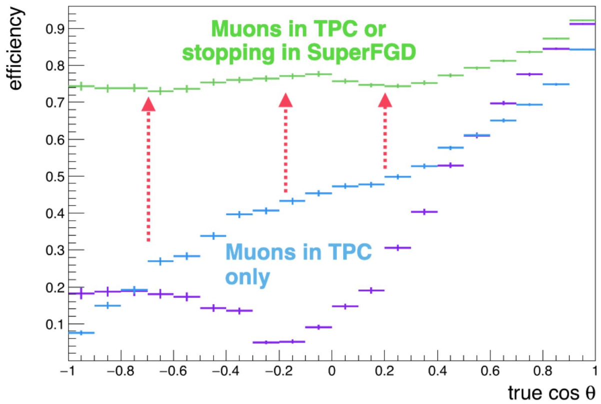
ND280 Upgrade

P0D replaced with a totally active target
SuperFGD: segmented 1cm^3 cubes FGD
Sandwiched by 2 TPCs

2 millions of 1cm^3 cubes.
Optical fibers in 3 directions





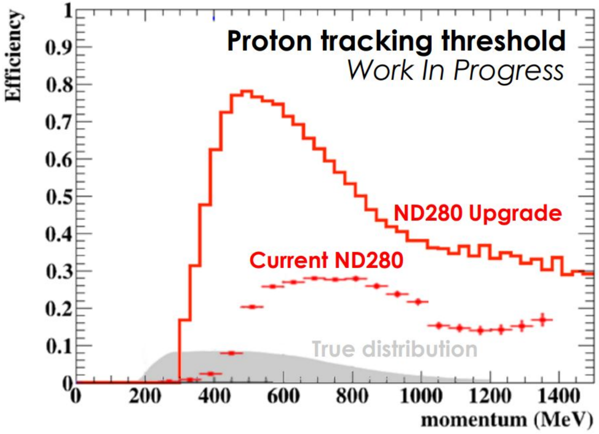


Installation next year!!!!

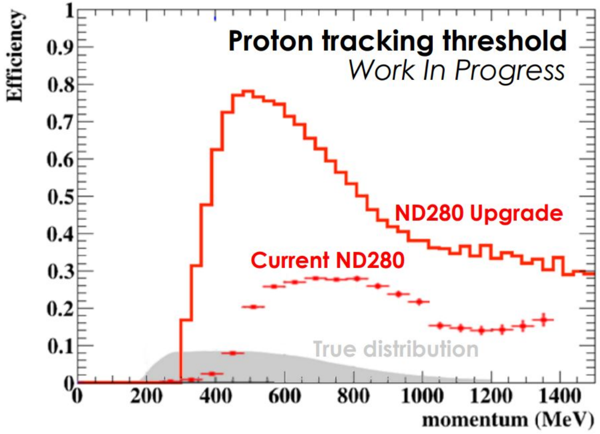
Improve:

- vertex reconstruction
- Acceptance 4π
- Low momentum protons (p_p>300MeV)
- Vertex activity
- Neutron detection
- Expect to reduce systematics @SK by a factor of 30%

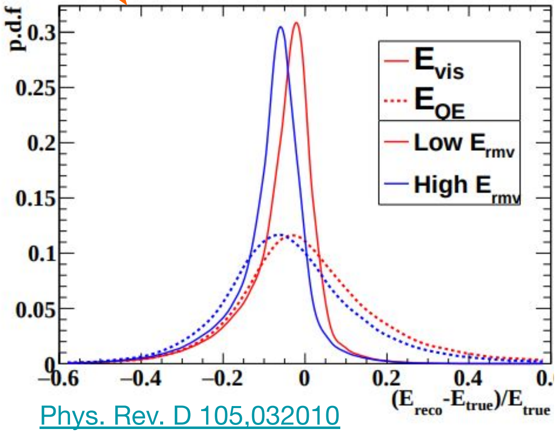
ND280 Upgrade sensitivities up to 2027

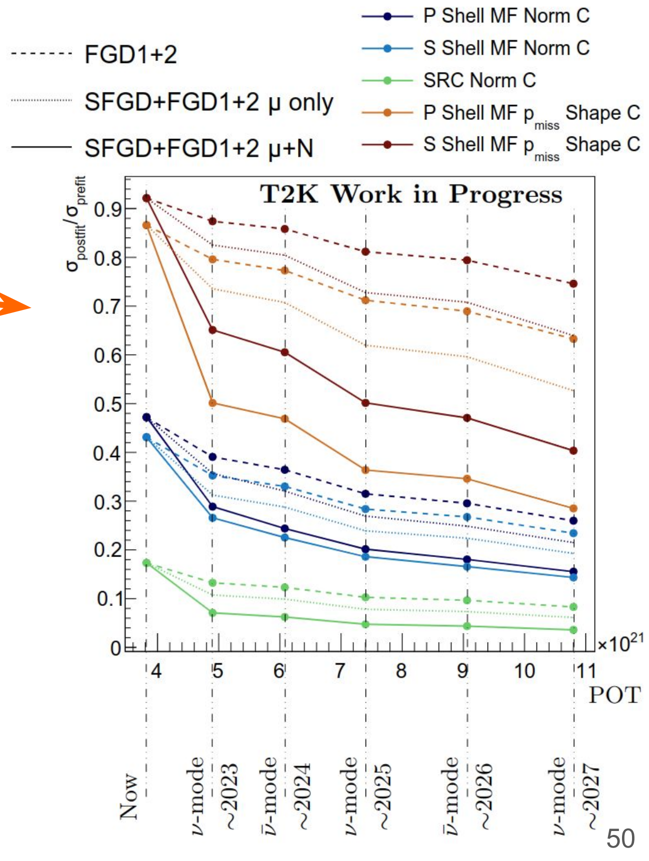


ND280 Upgrade sensitivities up to 2027



possibility to use the proton kinematics info to reconstruct the ν energy and constrain model uncertainties at the ND





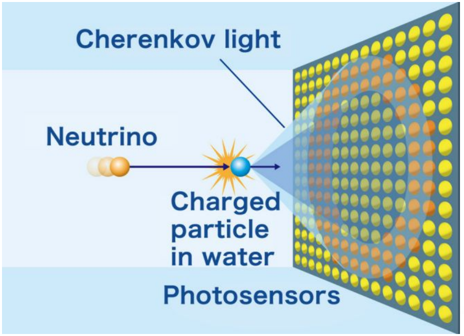
Phys. Rev. D 105,032010

By reducing systematic uncertainties, T2K could exclude CP conservation at 3σ in next years

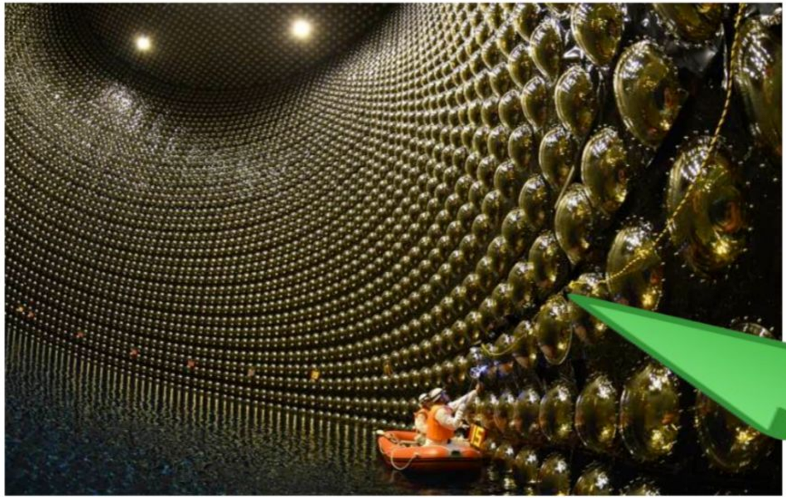
7. The HK experiment

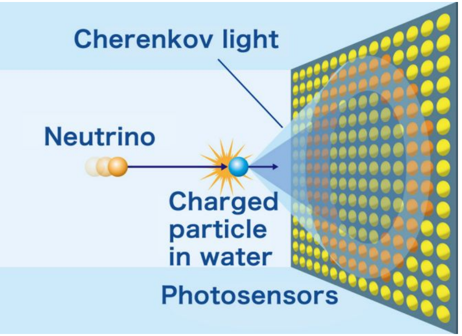
Many inputs from [HK @NOW2022] and [HK @CS-IN2P3]

The Kamiokande series



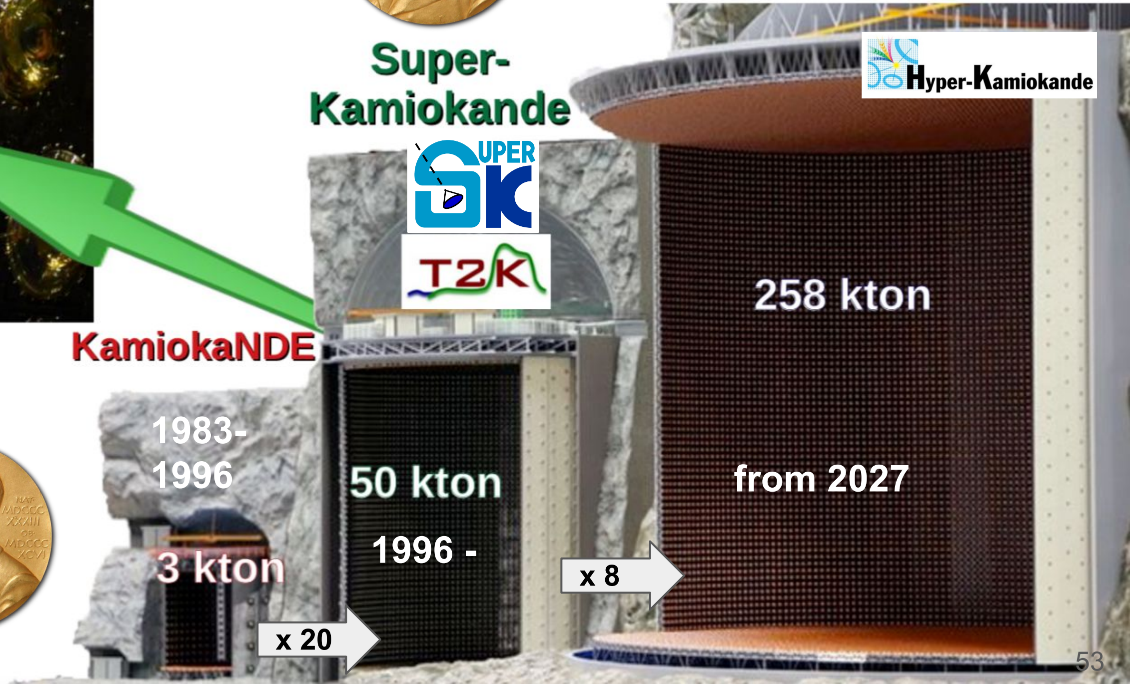
The Kamiokande series



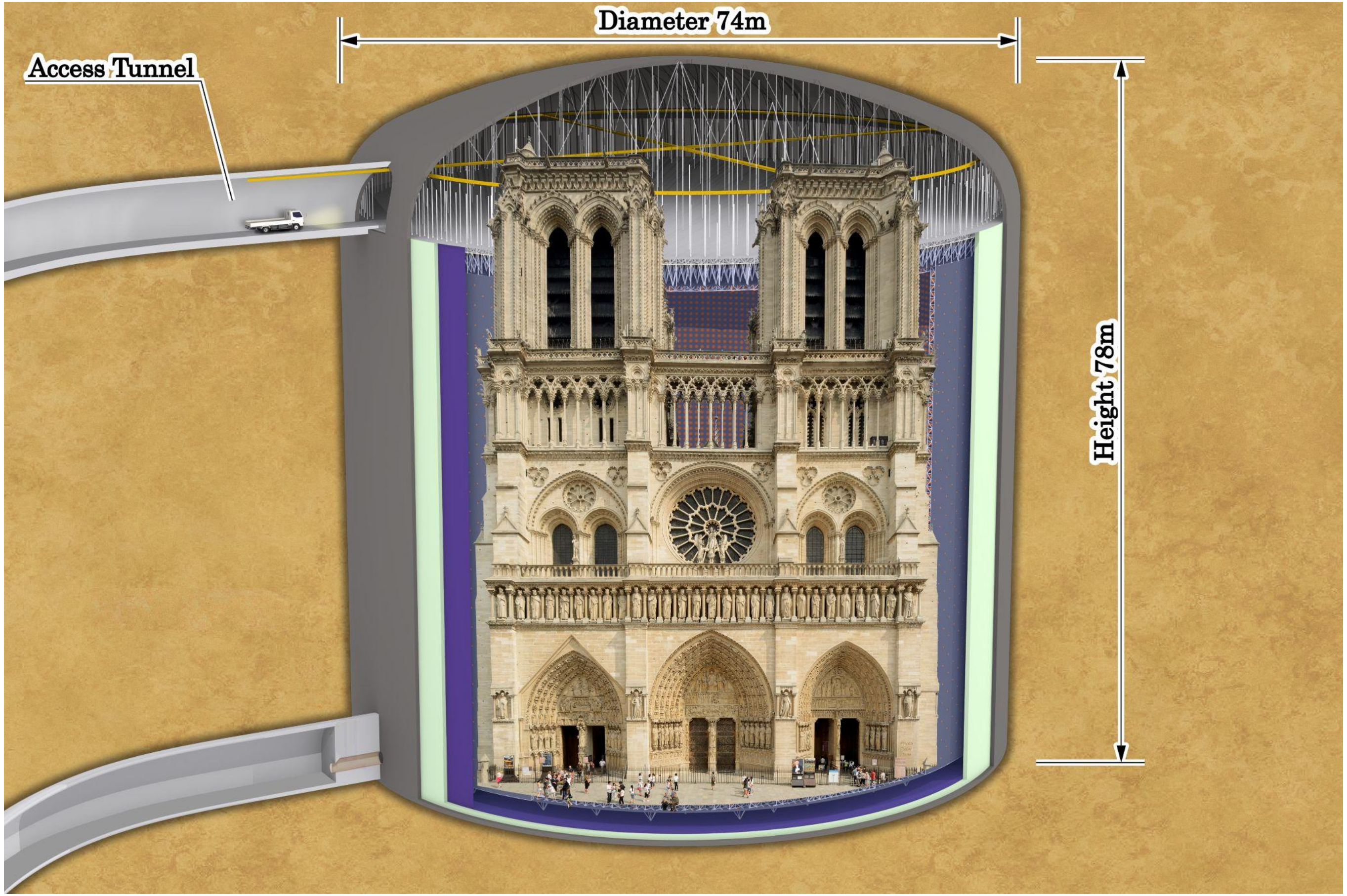


Super-Kamiokande

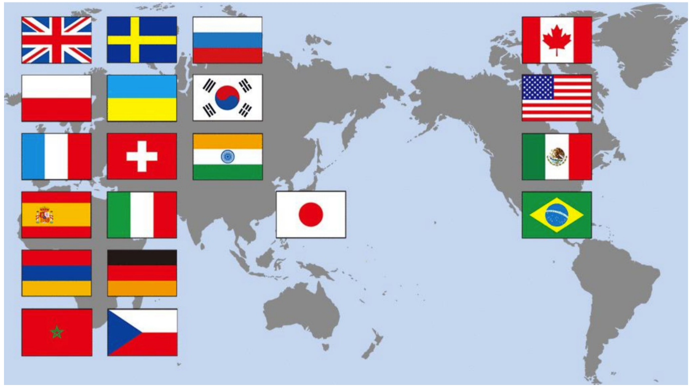
Hyper-Kamiokande



HK w.r.t. French monuments



HK collaboration



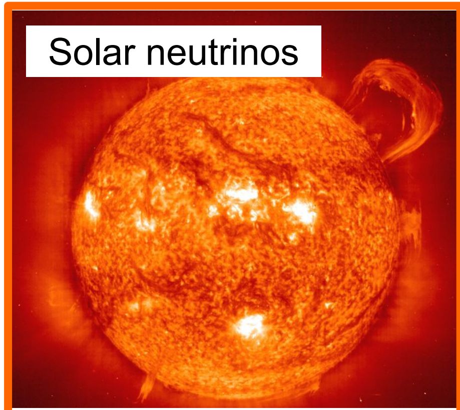
~ 520 members

~ 20 countries

~100 institutes

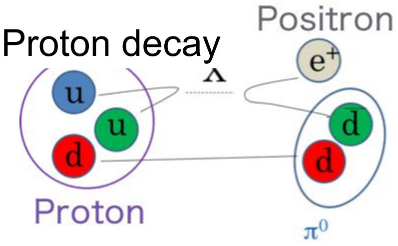
Hyper-Kamiokande physics program

Solar neutrinos



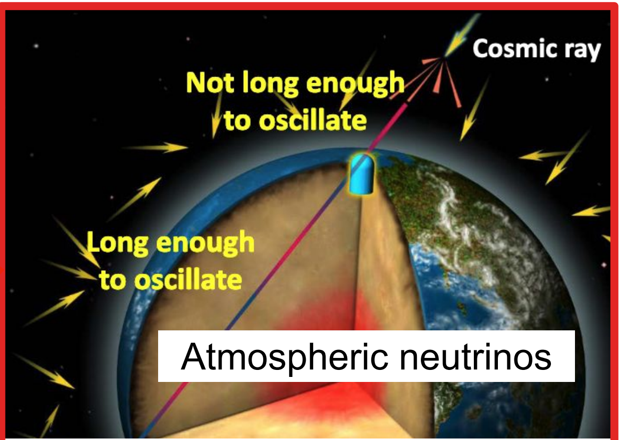
Survival probability up-turn
Solar/reactor tension
hep neutrinos

ν_e



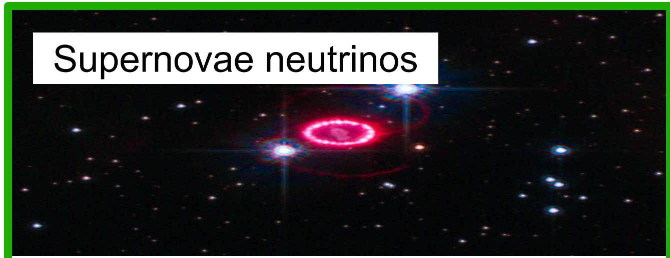
Probe Grand Unification Theories via p-decay

$\nu_e \; \bar{\nu}_e$
$\nu_\mu \; \bar{\nu}_\mu$



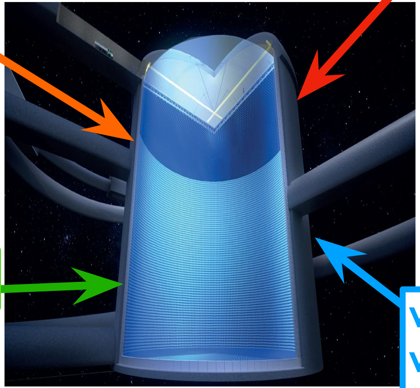
Oscillation affected by matter effects
Sensitive to MO

Supernovae neutrinos



Core-collapse SNν: constrain SN profile models
Diffuse SuperNova ν background

ν



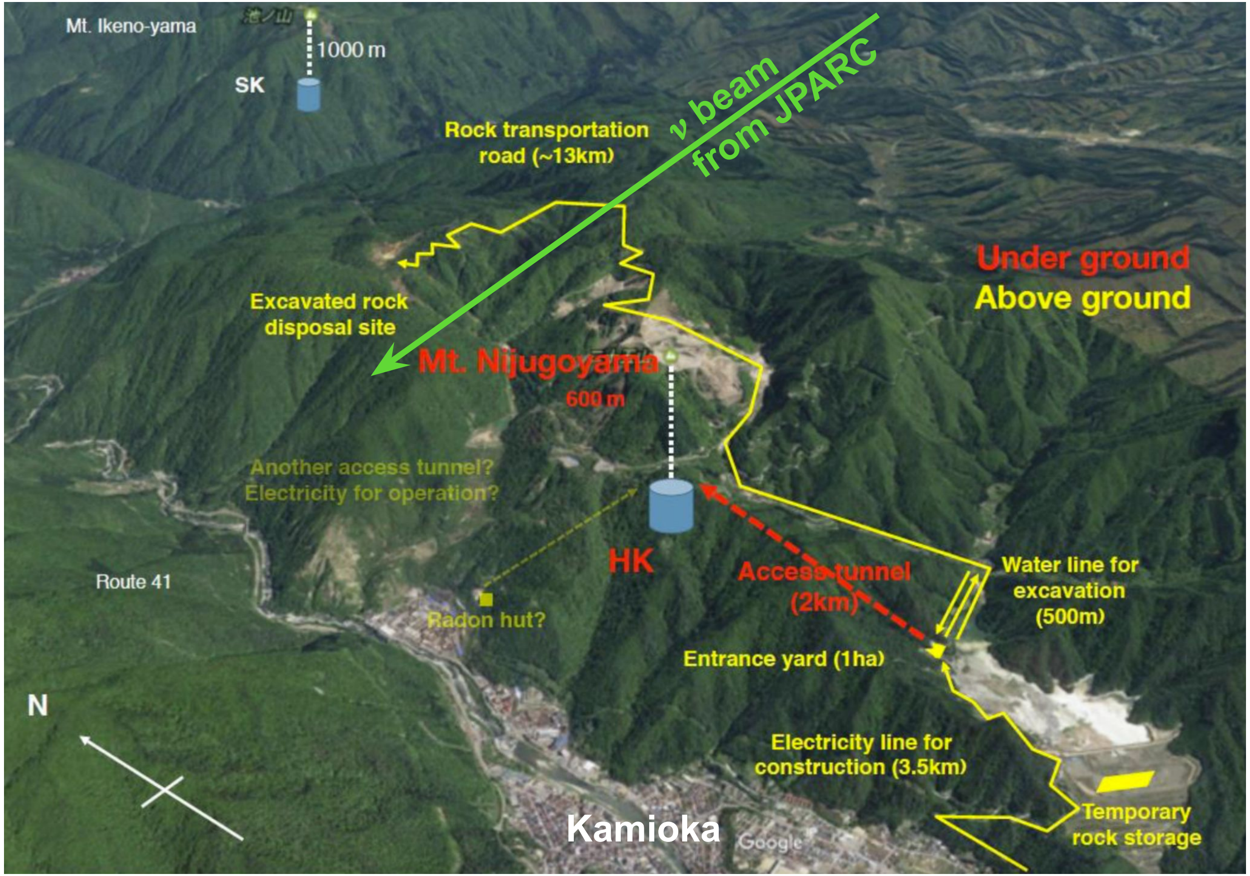
The future and bigger synthesis of T2K and SK physics

$\nu_e \; \bar{\nu}_e$
$\nu_\mu \; \bar{\nu}_\mu$

Observe CP violation for leptons at 5σ
Precise measurement of δ_{CP}

J-PARC accelerator neutrinos

Hyper-Kamiokande location



Very close to SK

Smaller rock overburden

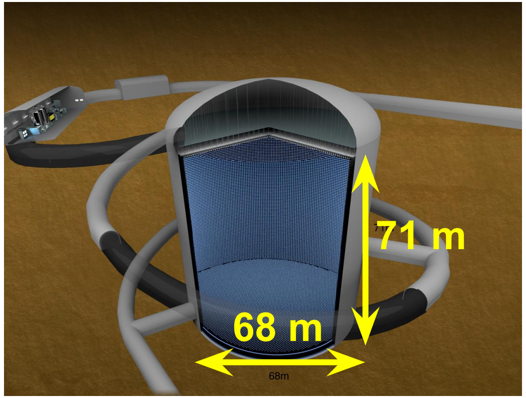
For accelerator ν physics, same 2.5° off-axis as T2K

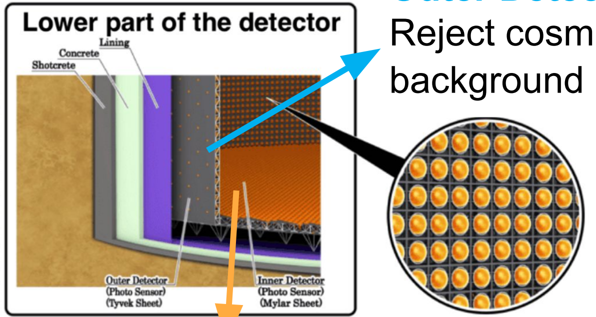
⇒ same oscillation patterns and overall analysis strategy

NEW

Hyper-Kamiokande far detector

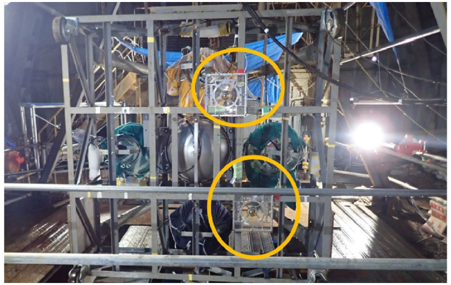
Water Cherenkov detector





Outer Detector (OD)

Reject cosmic ray muons to constrain the external background (~8000 3-inch PMTs + WLS plates)



Inner Detector (ID)

Cherenkov light from neutrino interaction

20000 20-inch Box and Line Dynode **ID PMTs**

2.6 ns timing resolution

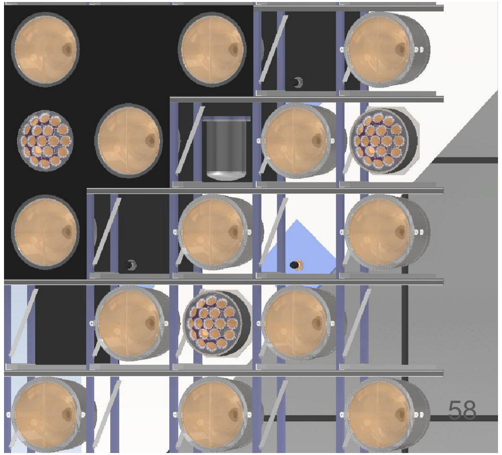
2 times SK PMT efficiency

Additional mPMTs: 19 3-inch PMTs + electronics inside single pressure vessel

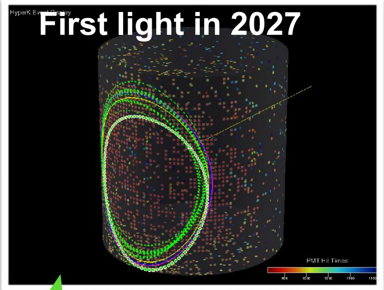
Directional information of arrival photons

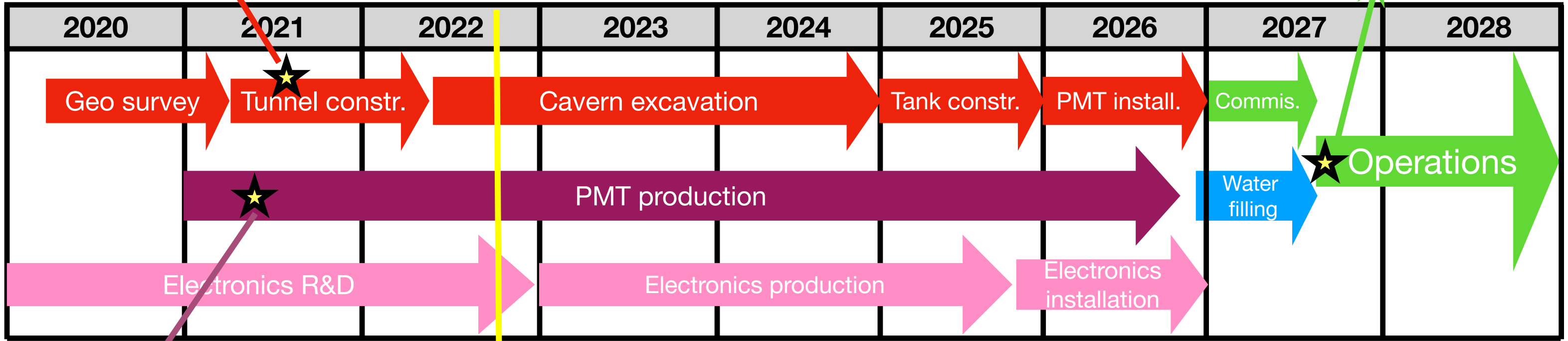
Accurate photon counting

Excellent timing resolution



HK schedule



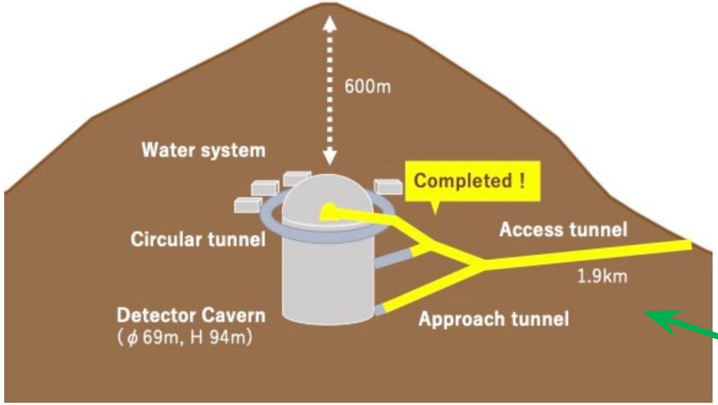


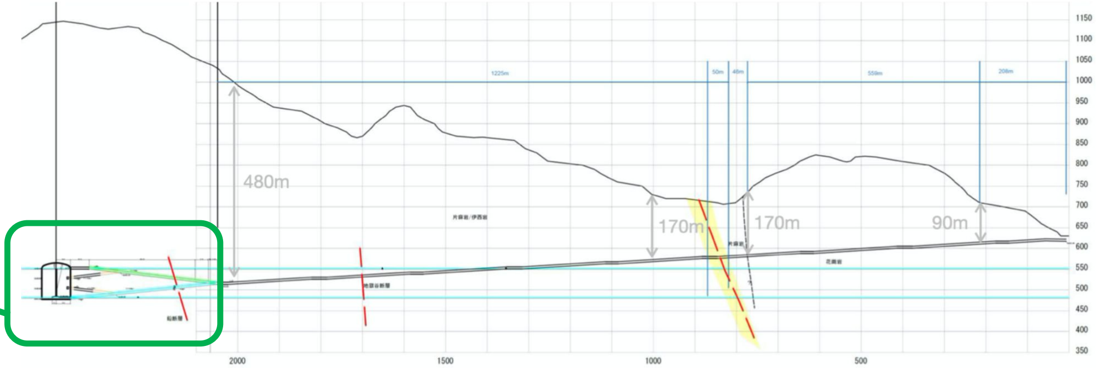
HK approved by MEXT in early 2020

Expected to start data taking in 2027

So far, no delay seen

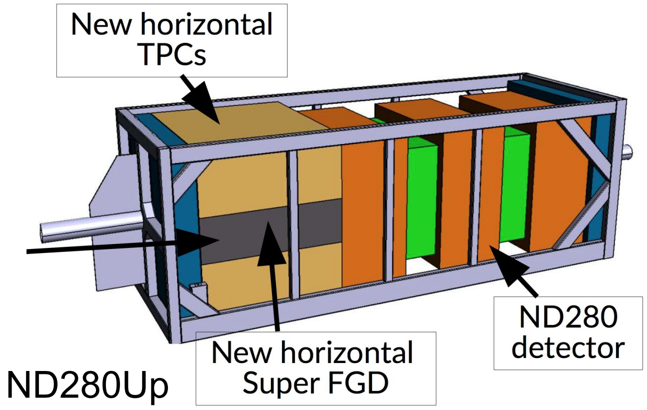
HK construction status

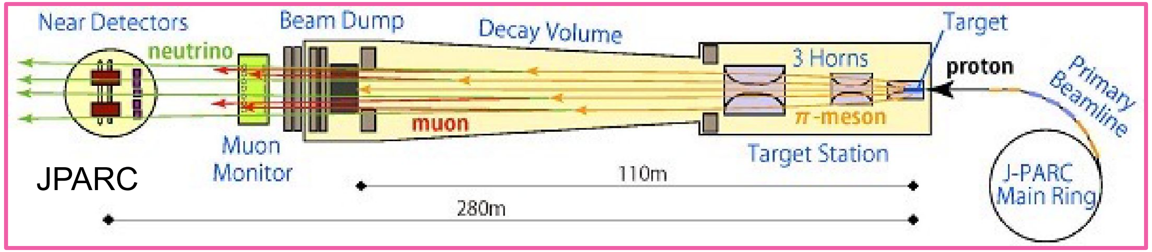




Tokai to HK: heritage from T2K

T2K is upgrading its beam and near detector. In use starting from next year!





By 2027, well characterized new beam and near detector

⇒ Systematics uncertainties under control from the beginning of HK

Tokai to HK: novelties, the IWCD

NEW

IWCD: Intermediate Water Cherenkov Detector

Needed to reach final HK goal for systematics uncertainties

Located at ~ 1km from JPARC.

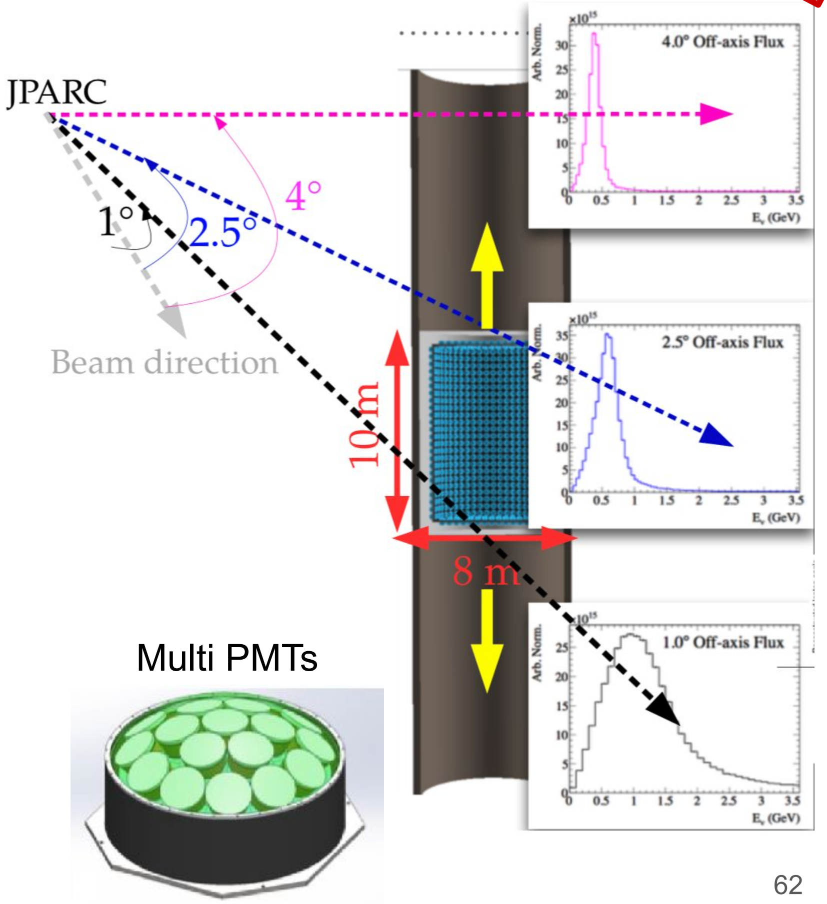
Tall vertical shaft that can span beam from 1° to 4° off-axis

Measure ν interactions on Water

Linear combination techniques

High stats. sample of ν_e and anti-ν_e interactions

⇒ with ND280Upgrade, **expected to reduce the uncertainties on appearance channels of about 50%** w.r.t. T2K (as needed by HK precision measurements)

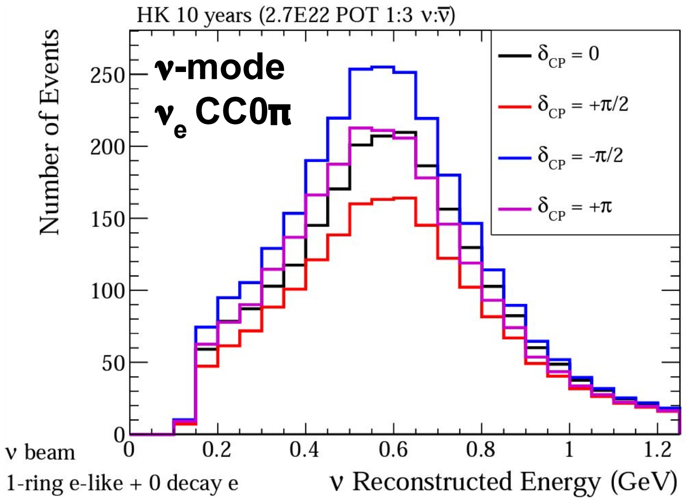


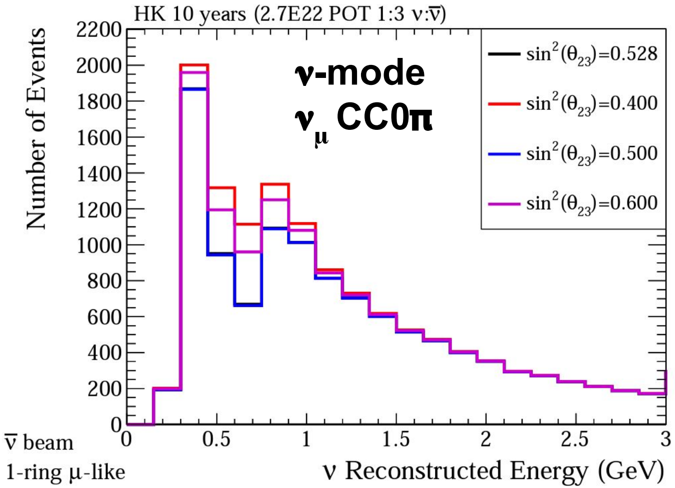
Multi PMTs

8. HK sensitivity to oscillation parameters

Appearance/disappearance channels in HK

Assuming 10 years of data taking (2.7×10^{22} POT), $\nu:\bar{\nu}$ = 1:3 beam mode, Normal Hierarchy, $\sin^2\theta_{13} = 0.0218$



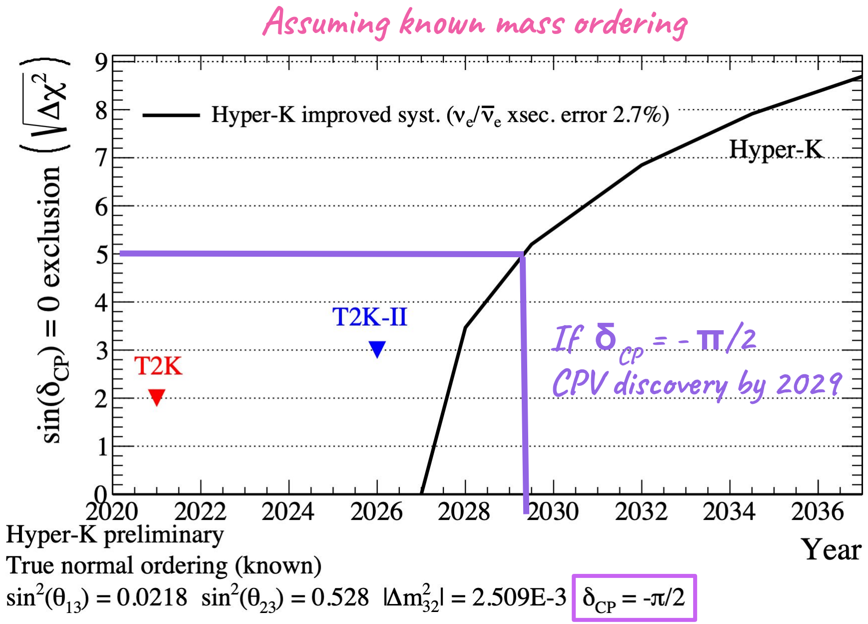


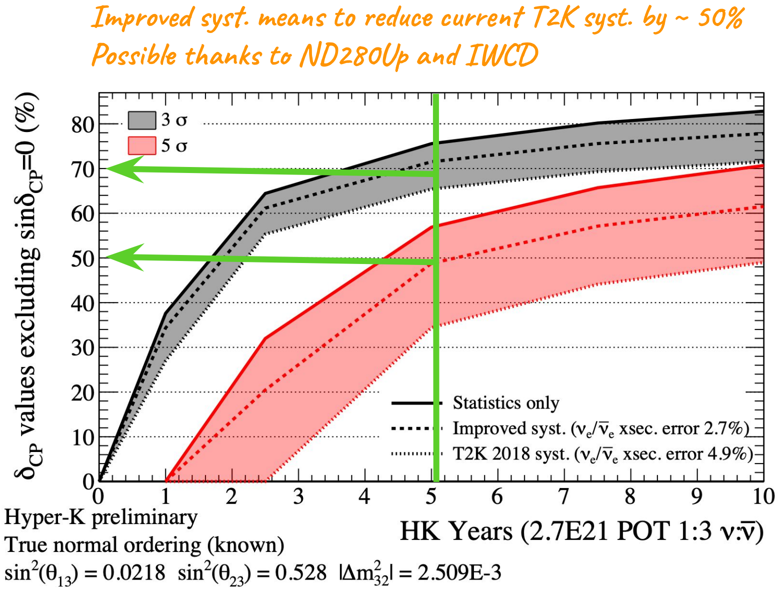
Appearance for $\delta_{CP} = -\pi/2$	**ν-mode** ν_e **CC0π**	**ν-mode** ν_e **CC1π**	**νbar-mode** ν_e **CC0π**
$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$	2253	207	797

Disappearance for $\delta_{CP} = 0$	**ν-mode** ν_μ **CC0π**	**νbar-mode** ν_μ **CC0π**
$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$	8584	7688

Numbers here w/o background contribution

Fast CP-violation discovery



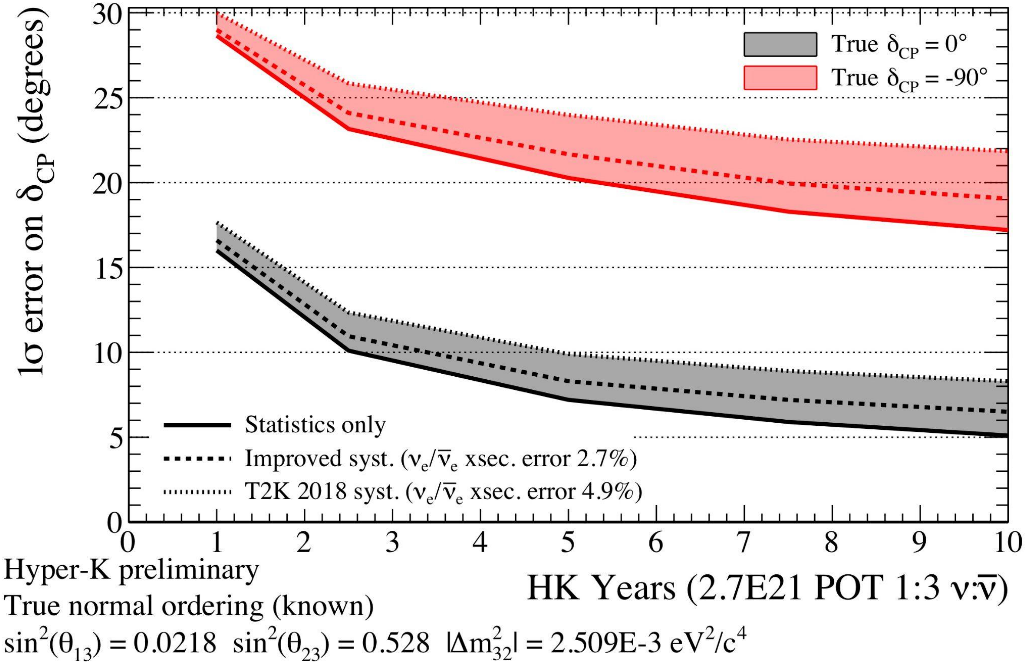


If $\delta_{CP}=-\pi/2$ (as suggested by T2K), **CP violation discovered in 2 years** !!!

Independently from T2K inputs, **HK can exclude CP conservation for a large range of possible δ_{CP} values**: in 5y, 50% of true δ_{CP} can be excluded at 5σ, assuming improved syst. errors.

Precision measurement of δ_{CP}

Assuming known mass ordering



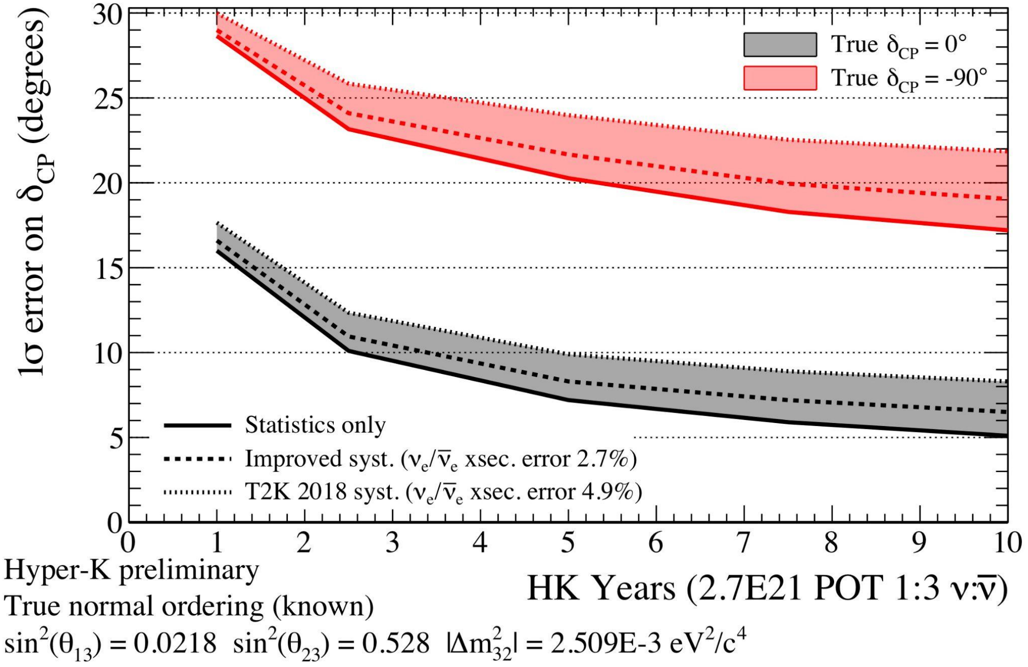
Precise measurement of δ_{CP} will help to discriminate among matter-antimatter models

→ **HK will precisely measure δ_{CP}**

In 10y precision will be ~ 20° if $\delta_{CP} = -\pi/2$ and ~7° if $\delta_{CP} = 0$ (assuming improved systematics)

Precision measurement of δ_{CP}

Assuming known mass ordering



Precise measurement of δ_{CP} will help to discriminate among matter-antimatter models

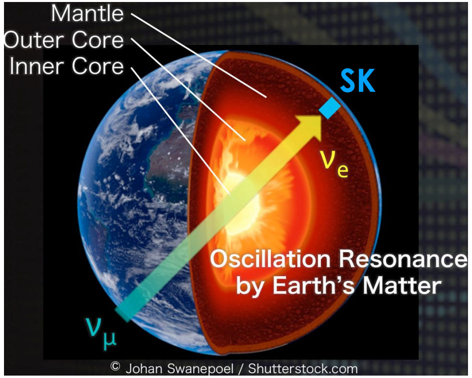
→ **HK will precisely measure δ_{CP}**
In 10y precision will be ~ 20° if $\delta_{CP} = -\pi/2$ and ~7° if $\delta_{CP} = 0$ (assuming improved systematics)

Many experiments (T2K/SK, NOvA, ORCA and JUNO) currently working to determine MO…
but if the MO is not known by 2027?

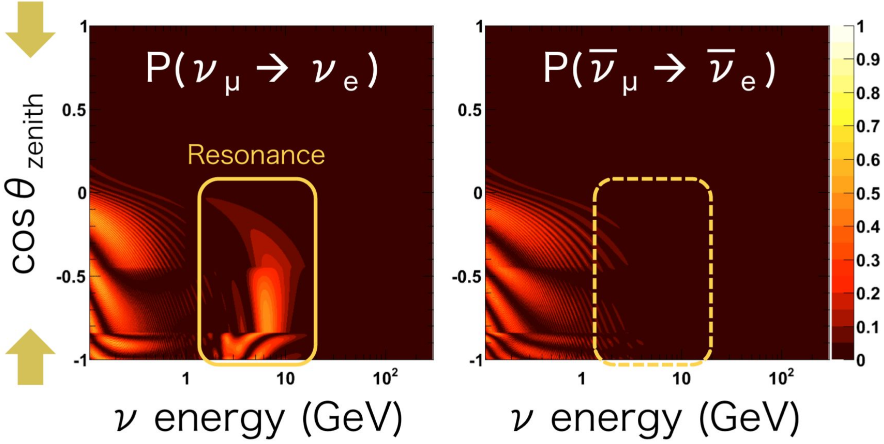
MO and atmospheric neutrinos

Ongoing joint SK-T2K analysis
→ very same concept

Hyper-Kamiokande will measure oscillation of atmospheric neutrinos
Baseline of atmospheric neutrino beam spans from 12km up to 13k km



Normal Hierarchy case



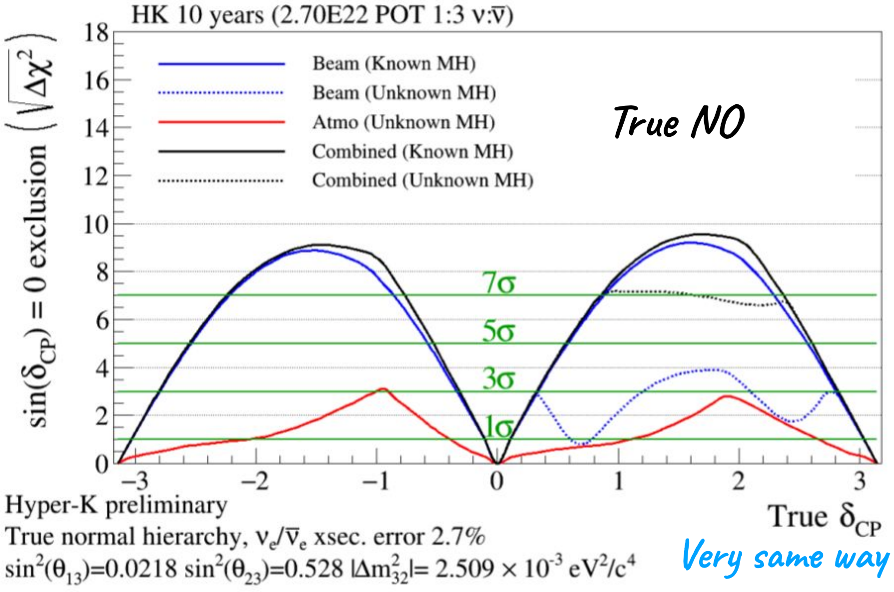
Matter effects in the Earth can be huge (resonance effect) thus making **HK sensitive to the mass ordering** via atmospheric neutrinos

Sensitivity to δ_{CP} is instead limited → opposite situation w.r.t. accelerator neutrinos

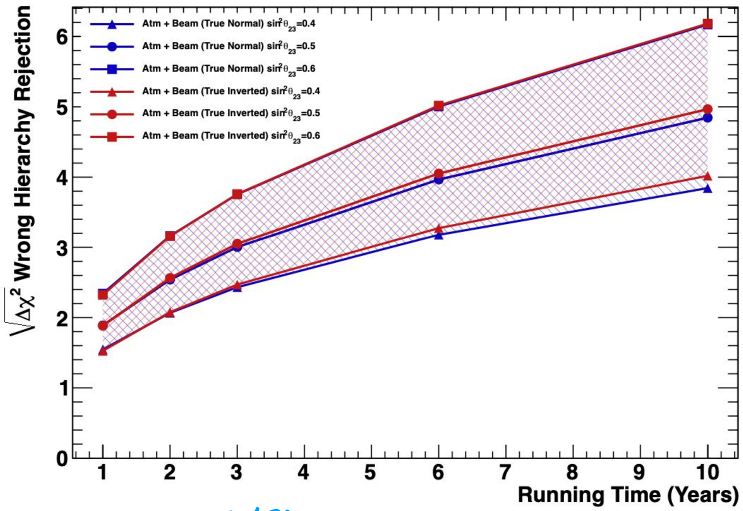
Since the used detector is the same, **combining atmospheric and accelerator neutrino samples is a way to enhance the sensitivity on both MO and δ_{CP}**

Joint accelerator/atmospheric analysis: δ_{CP} and MO sensitivity

Assuming UNKNOWN mass ordering



MO sensitivity



Very same way as the current joint T2K/SK analysis

By combining beam and atmospheric neutrinos HK can achieve 5σ sensitivity to CPV regardless the true mass ordering

HK can determine MO after 6-10 years via atmospheric ν

9. HK astrophysics program

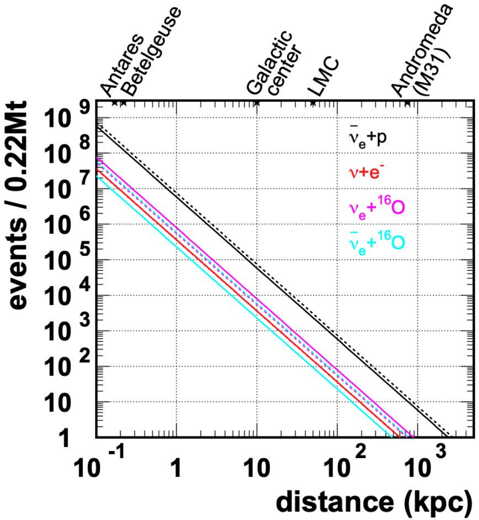
Core-collapse supernova neutrinos

Increase by ~10 in stat sensitivity w.r.t. SK

- SN1987A type ~2500 events
- Galactic center: ~50000+ events

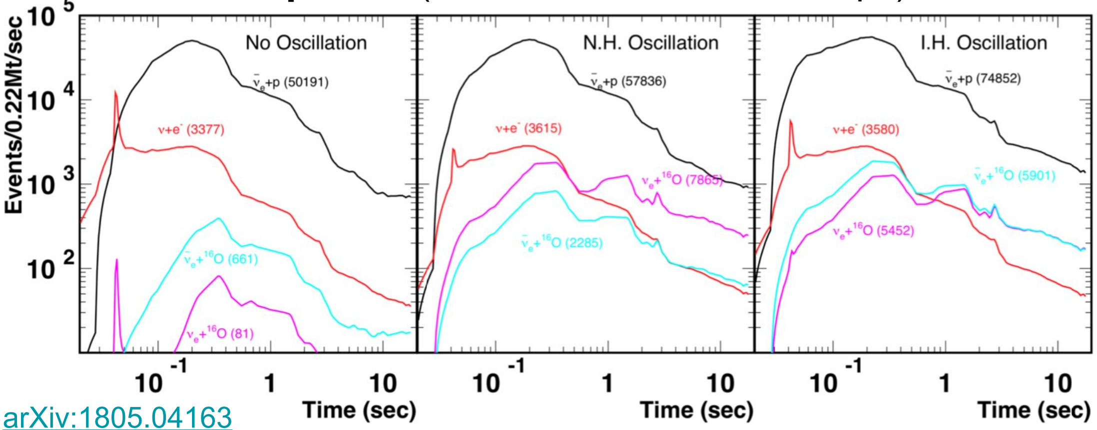
Direction (1°@10kpc) → triangulation

SN ν expected every 3 years in HK!
(if HK is sensitive up to 4 Mpc)

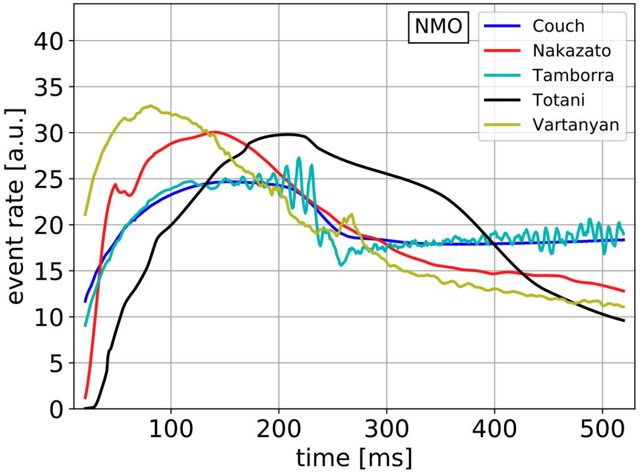


Time profile: collapse models → **Model discrimination**

Time profile (Livermore simulation, 10kpc)



arXiv:1805.04163



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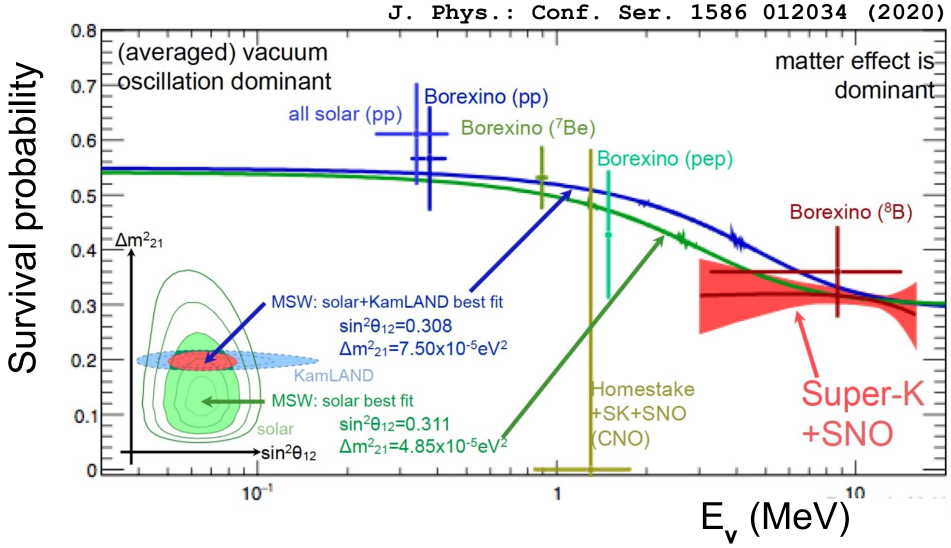
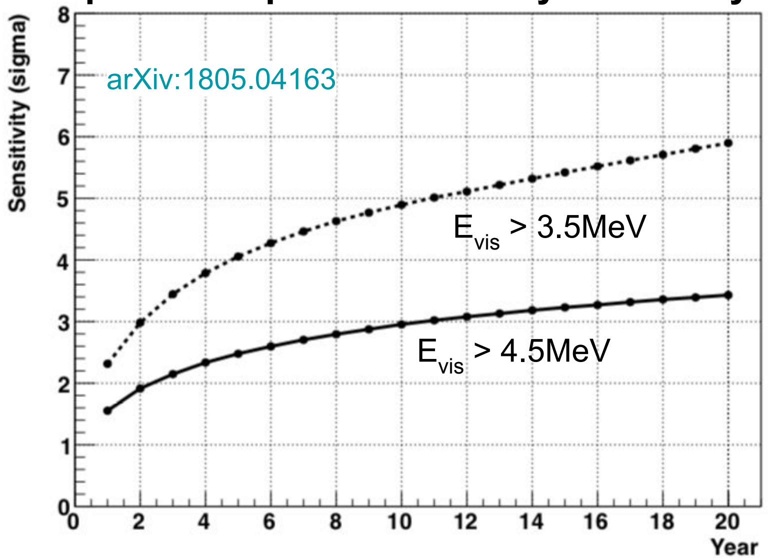
Solar neutrinos

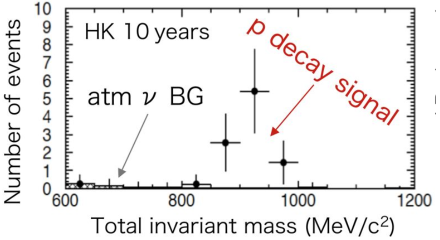


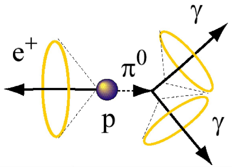


Upturn region to be better explored. So far, SK deviates from standard upturn scenario > 2σ. Displacement of the upturn can be explained by: Statistical fluctuation? Light sterile neutrino? Non Standard Interaction in the dense Sun?

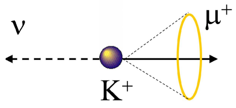
Also, **1.5σ tension between solar and reactor experiments on Δm^2_{12}.** More precise results expected with HK (separation ~5σ). If tension confirmed: new physics?

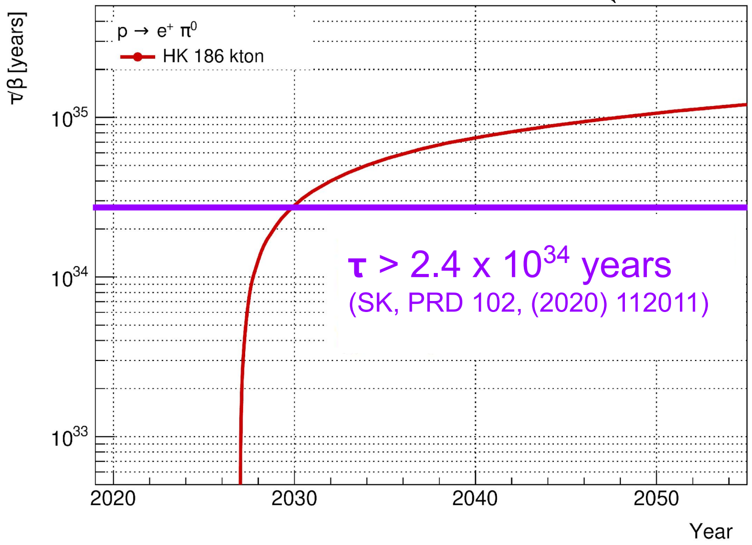
Proton decay

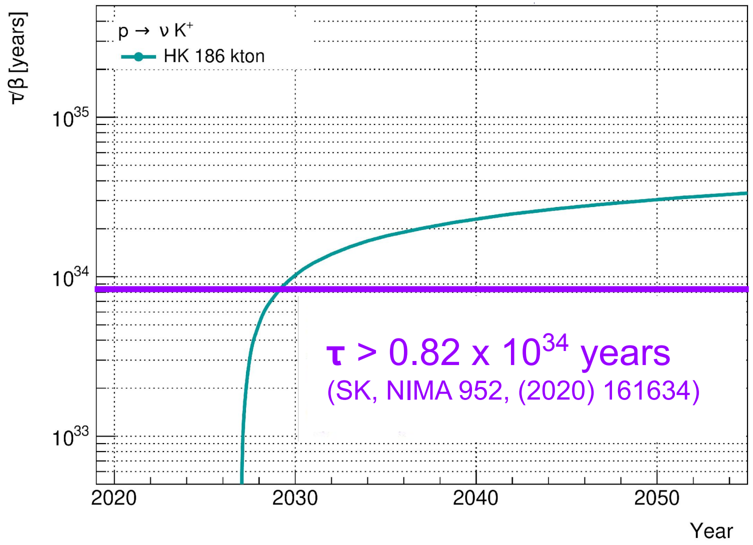




Motivated by Grand-Unification Theories







HK will have the best limit on **p** → $\mathbf{e^+\pi^0}$ → about 1 order of magnitude better than current SK limit

Thanks to its huge mass, HK also sensitive to channels with invisible particles (**p** → **ν** $\mathbf{K^+}$)

HK is sensitive to bound and free proton decay (H_2O)

Summary and conclusions

- ★ **T2K is a leading neutrino oscillation experiment**
- ★ So far, best measurement of atmospheric parameters
- ★ **Hints toward CP violation**
- ★ We are approaching a precision era in neutrino oscillation measurement
- ★ T2K is working on near detector and beam upgrade → inputs to HK
- ★ In parallel, HK construction has started
- ★ **Amazing HK physics potential: from neutrino oscillations to astrophysics**
- ★ **A very exciting decade is starting… stay tuned!!**