Neutrino Oscillation Studies with T2K and Super-Kamiokande Experiments

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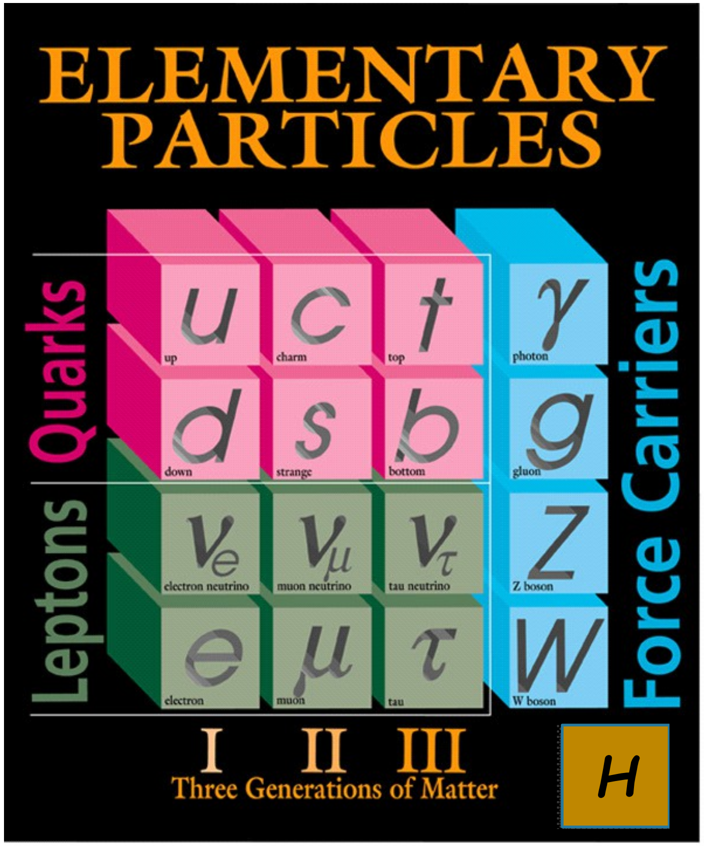
Neutrinos: basic facts

- neutral leptons
  - only weak interactions
    → very low cross-section
    for interactions with matter
  - CC and NC interactions

- exist in 3 flavours
  - measurements of Z^0 width in LEP
  - astrophysical constraints
    → some hints for existence of
    so called “sterile neutrinos”

- assumed to be massless in SM
  - disproved by existence of oscillations

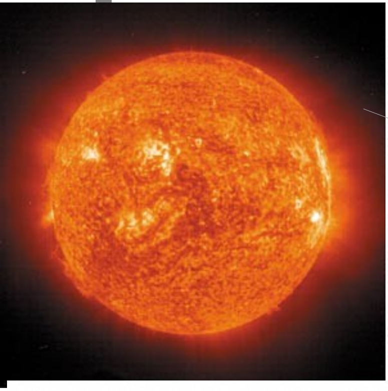
- second most abundant particles in the Universe (after photons)

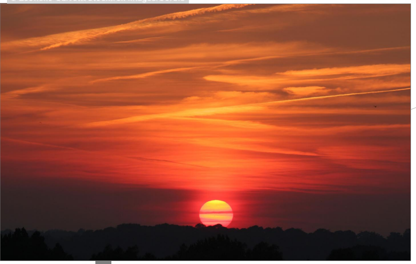


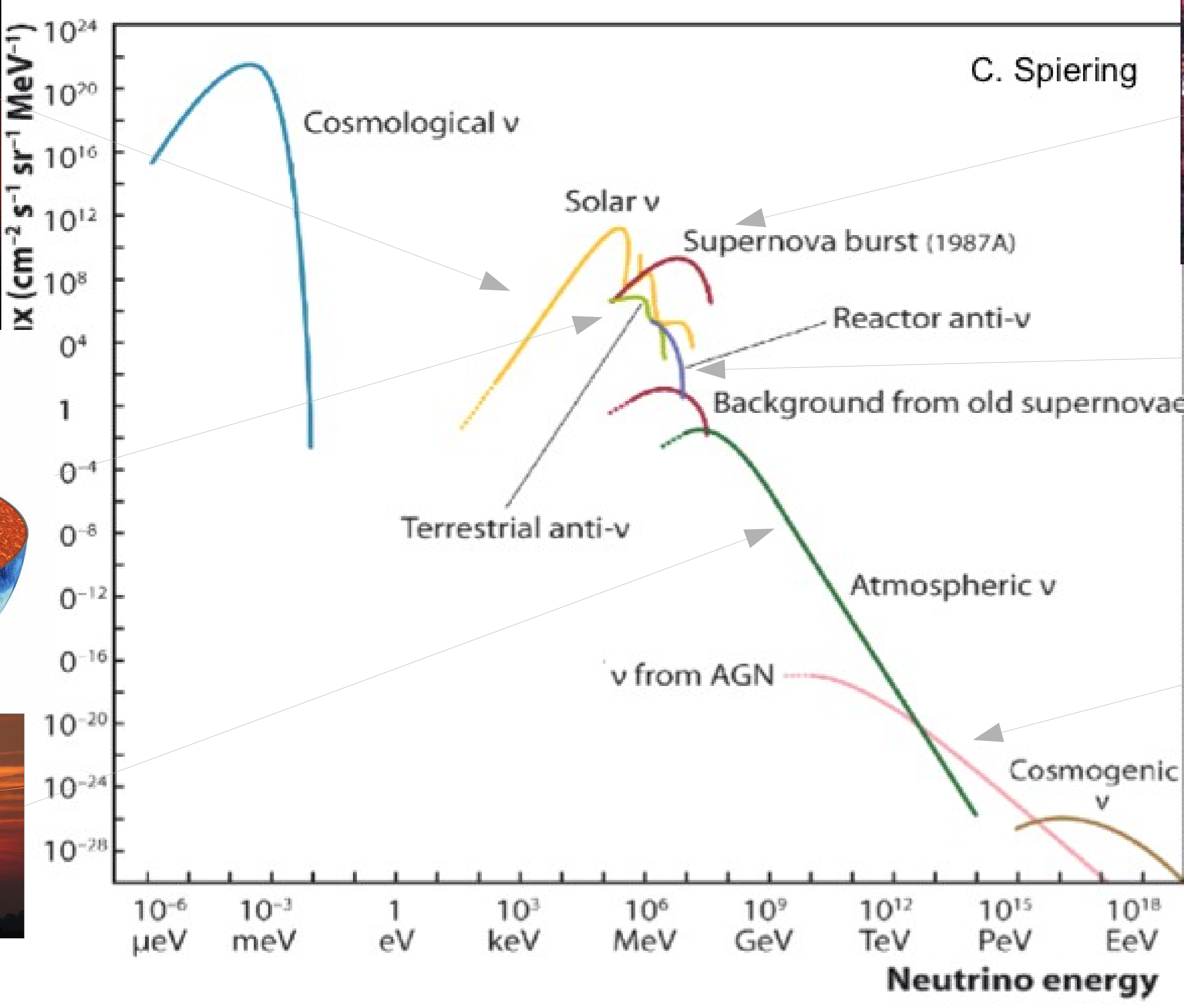
Fermilab 95-759

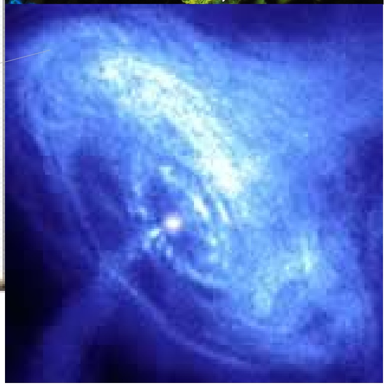
Sources of neutrinos

- many sources, wide spectrum of energies



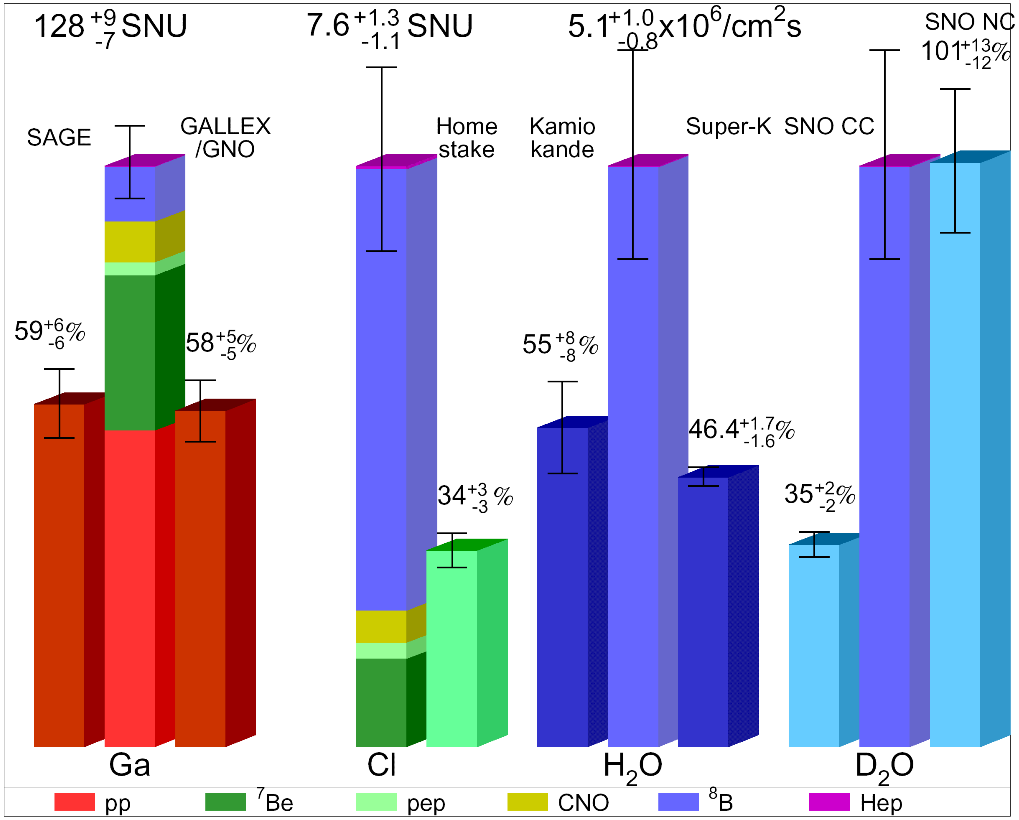




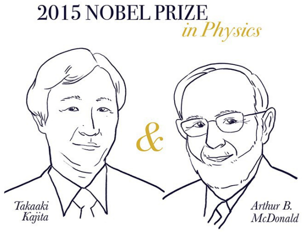


A bit of history

- 1960' : Solar Neutrino Problem: deficit of solar neutrinos wrt to calculations
  - solved in 2001 by SNO
  - (not very good example to explain oscillations)
- 1980' : Atmospheric background to search for proton decays
  - strange angular dependence in muon atmospheric neutrinos observed in KamiokaNDE experiment



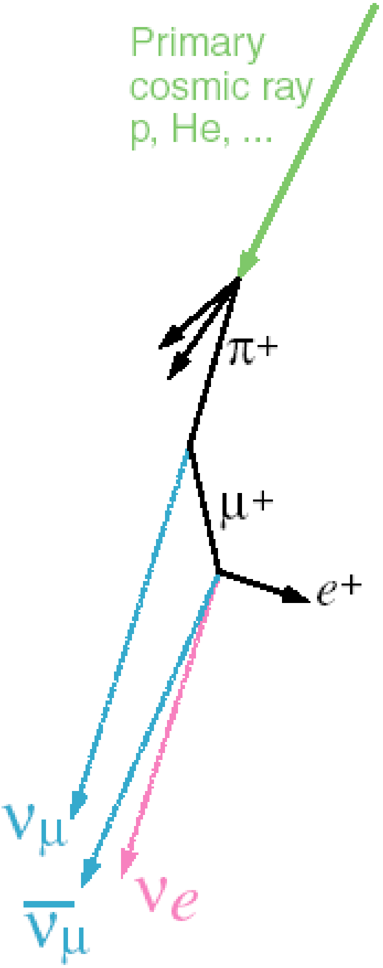
- 1998: Super-Kamiokande confirms existence of neutrino oscillations
- 2015: Nobel prize for T. Kajita (SK) and A. McDonald (SNO)



- 2016: Breakthrough prize for SNO, SK, K2K/T2K, Daya Bay, KamLAND

Atmospheric neutrinos

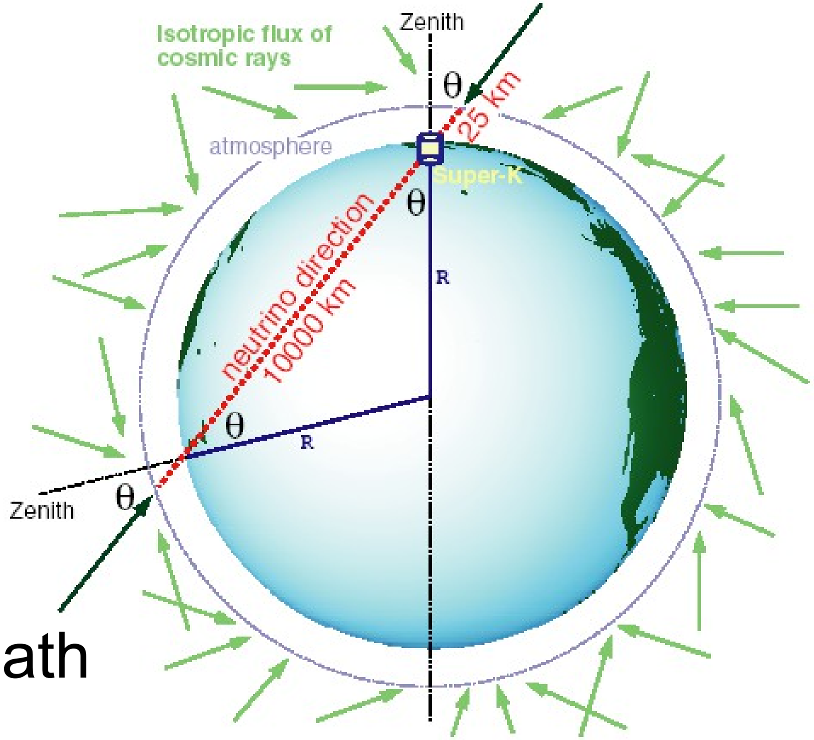
- created in the decays of particles produced by primary cosmic rays in the atmosphere



expectation:
$N\nu_\mu/N\nu_e \sim 2$

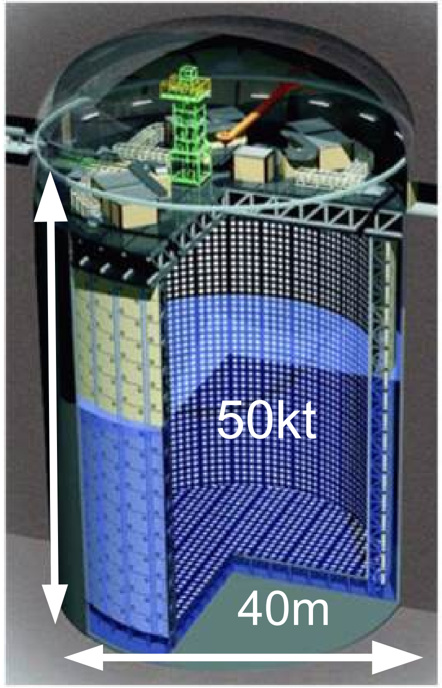
energies ~1 GeV

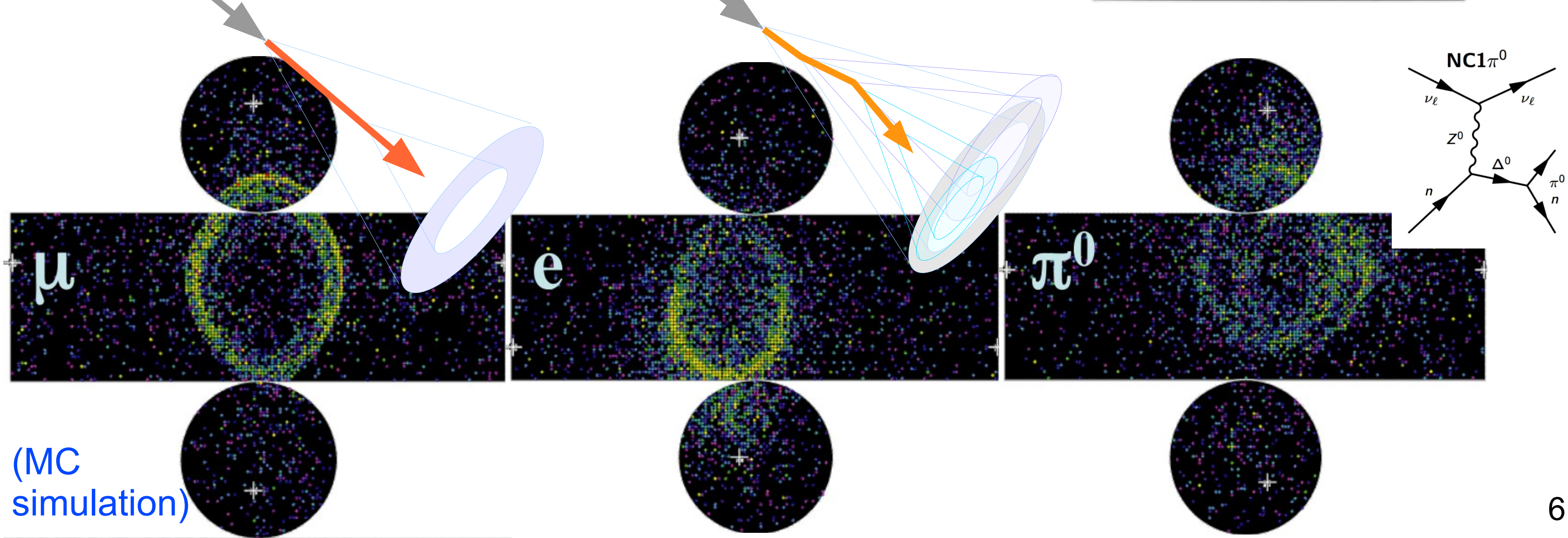
direction → path



Super-Kamiokande detector

- water Cherenkov detector
  - total mass 50 kt, fiducial mass 22.5kt (now +4.7kt)
  - >11000 PMTs in inner and ~2000 in outer detector
- ΔE/E ~10% for 2-body kinematics
- very good μ/e separation
  - muons misidentified as electrons: <1%
- π^0 detection (2 e-like rings)
- no charge identification

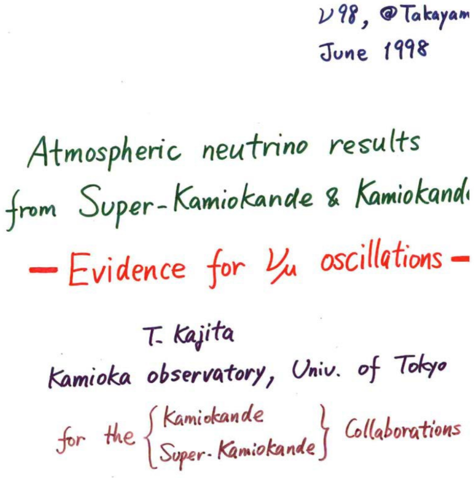




(MC simulation)

SK discovery of oscillations

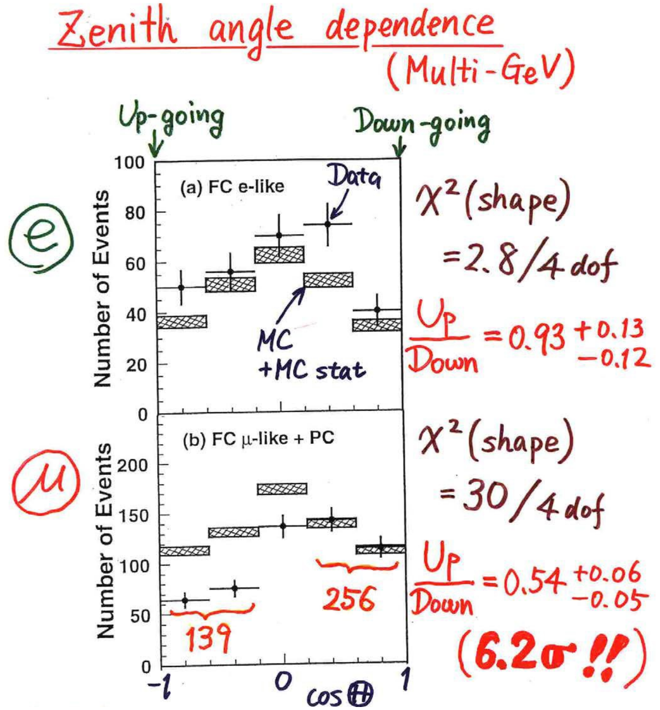
Kajita-san's presentation
at NEUTRINO 98
conference



ν98, @Takayam
June 1998

Atmospheric neutrino results
from Super-Kamiokande & Kamiokand
— Evidence for ν_μ oscillations —

T. Kajita
Kamioka observatory, Univ. of Tokyo
for the {Kamiokande / Super-Kamiokande} Collaborations



Zenith angle dependence
(Multi-GeV)

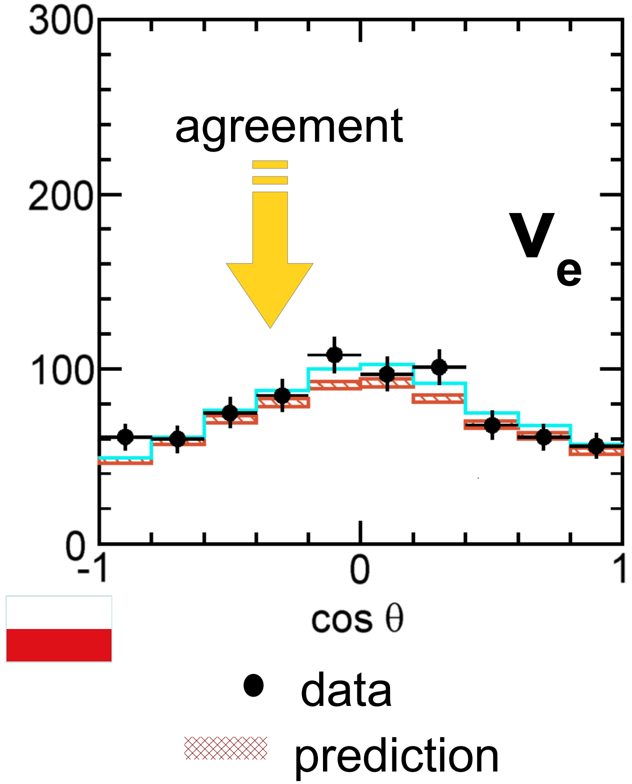
χ^2(shape) = 2.8/4 dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) = 30/4 dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

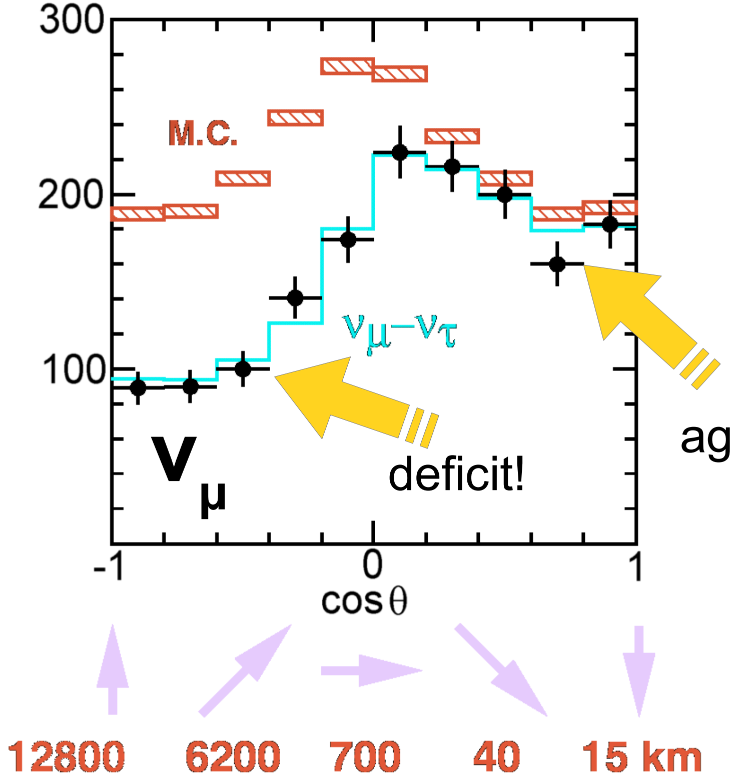
(6.2σ !!)



agreement

● data

▨ prediction



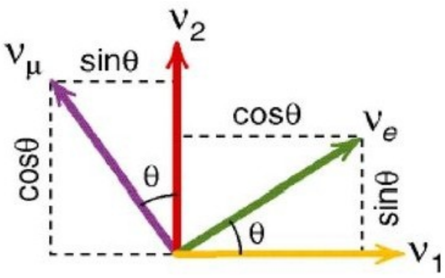
deficit!

agreement

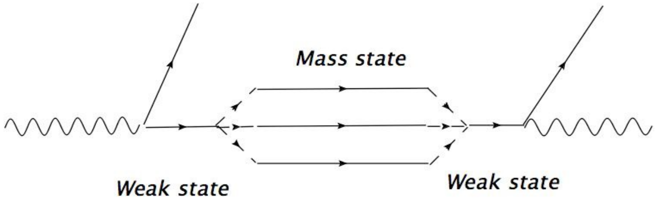
12800 6200 700 40 15 km

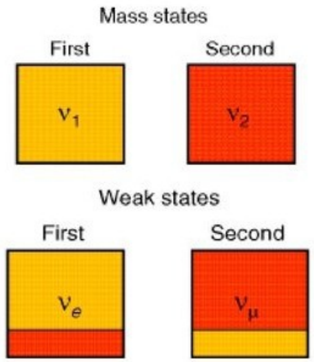
Neutrino oscillations: 2-flavour approximation

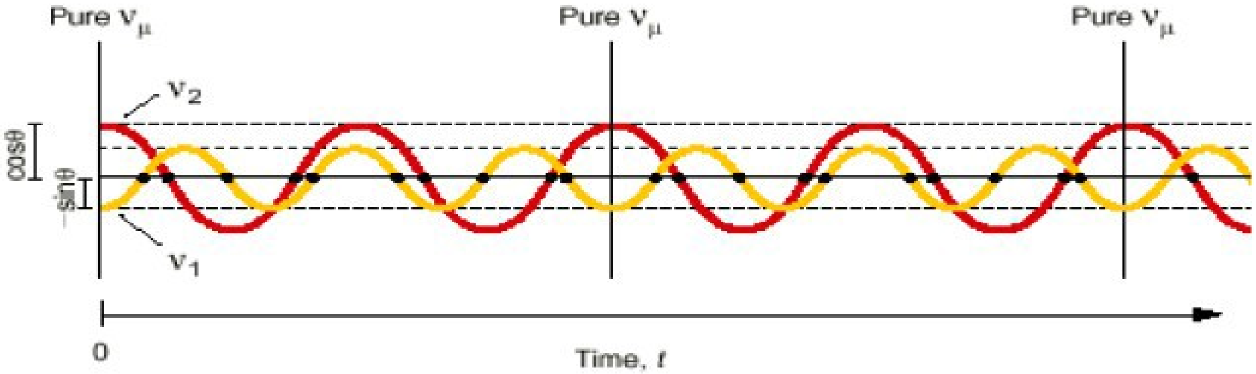
- periodic change of flavour during propagation because
- mass and flavour eigenstates are not identical



$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$







- probability of neutrino to change flavour

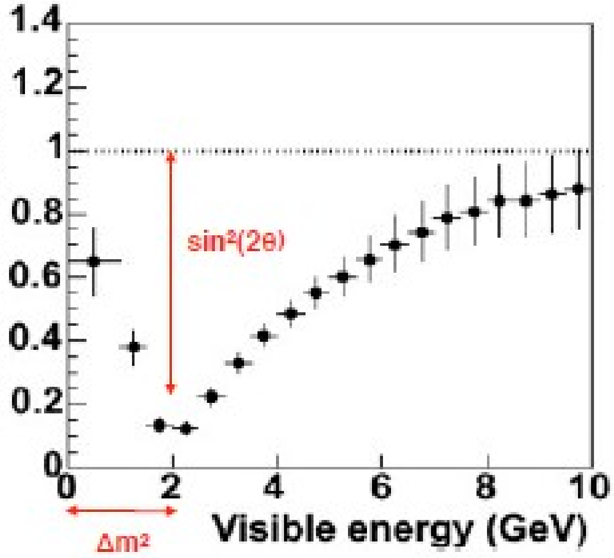
$$P(\nu_\alpha \rightarrow \nu_\beta)=\sin^2(2\theta)\sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

where L is path [km] and E neutrino energy [GeV]

- $\Delta m^2 = m^2_2 - m^2_1$ → if 0 - no oscillations

Appearance and disappearance

- **disappearance**:
  - looking for the same flavour of neutrinos at the production and detection point
  - dip in the **measured/expected ratio** → information on mixing angle and mass splitting
  - CPT conservation requires the same survival probability for neutrinos and antineutrinos



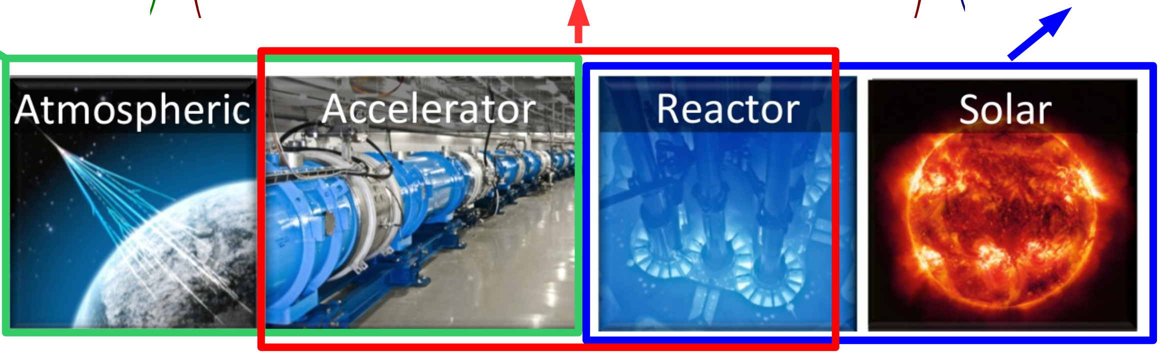
- **appearance**: direct observation of the flavour change
- possible appearance channels for 3 flavours:
  - $\nu_e \rightarrow \nu_{\mu,\tau}$: neutrino energy below threshold for charged lepton production (solar, reactor)
  - $\nu_\mu \rightarrow \nu_\tau$: challenging: large τ lepton mass, small *ct*, discovered 2015
  - $\nu_\mu \rightarrow \nu_e$: subdominant, discovered 2013 (in T2K)
  - ν_τ: no good ν_τ sources

Neutrino oscillations for 3 flavours

- Pontecorvo-Maki-Nakagawa-Sakata matrix
  - parametrized by **3 mixing angles** and CP-violating phase $\boldsymbol{\delta_{CP}}$

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

+ Majorana phases

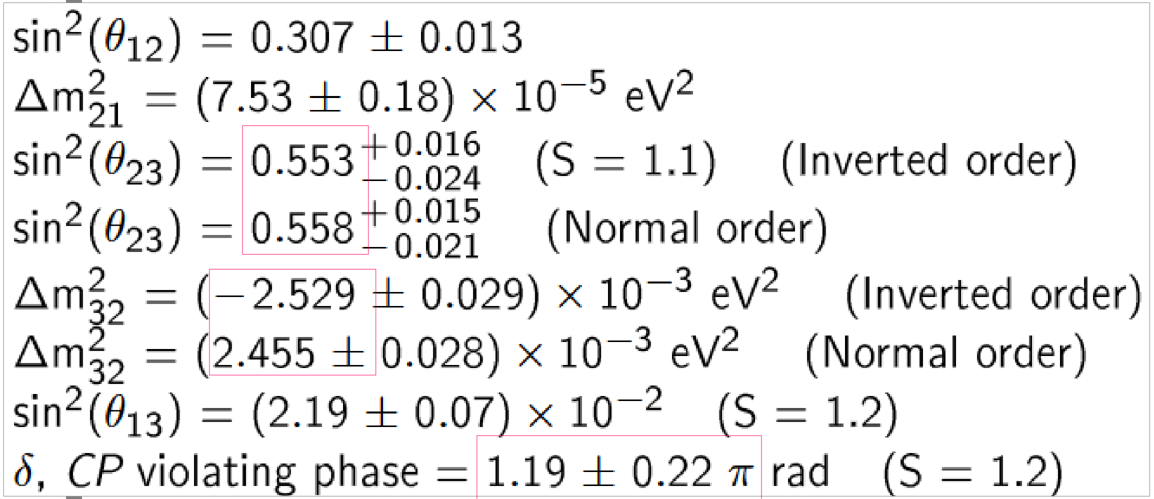


$$P_{\nu_\alpha\rightarrow\nu_\beta}=\delta_{\alpha\beta}-4\sum_{i>j}\Re\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\Delta m^2_{ij}\frac{L}{4E}\pm2\sum_{i>j}\Im\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\Delta m^2_{ij}\frac{L}{4E}$$

- matter effects → presence of electrons modifies propagation of electron component → additional asymmetry not related to CP violation

Current knowledge

- precise measurements test the 3-flavor paradigm



$\sin^2(\theta_{12}) = 0.307 \pm 0.013$

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$

$\sin^2(\theta_{23}) = 0.553^{+0.016}_{-0.024}$ (S = 1.1) (Inverted order)

$\sin^2(\theta_{23}) = 0.558^{+0.015}_{-0.021}$ (Normal order)

$\Delta m^2_{32} = (-2.529 \pm 0.029) \times 10^{-3}\ \mathrm{eV}^2$ (Inverted order)

$\Delta m^2_{32} = (2.455 \pm 0.028) \times 10^{-3}\ \mathrm{eV}^2$ (Normal order)

$\sin^2(\theta_{13}) = (2.19 \pm 0.07) \times 10^{-2}$ (S = 1.2)

δ, CP violating phase $= 1.19 \pm 0.22\ \pi$ rad (S = 1.2)

Phys. Rev. D 110, 030001 (2024)

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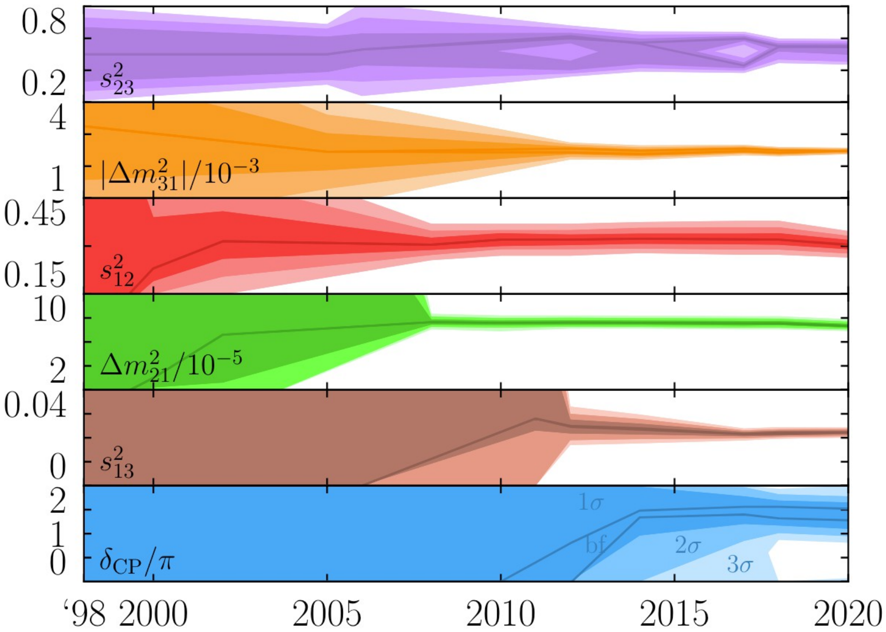
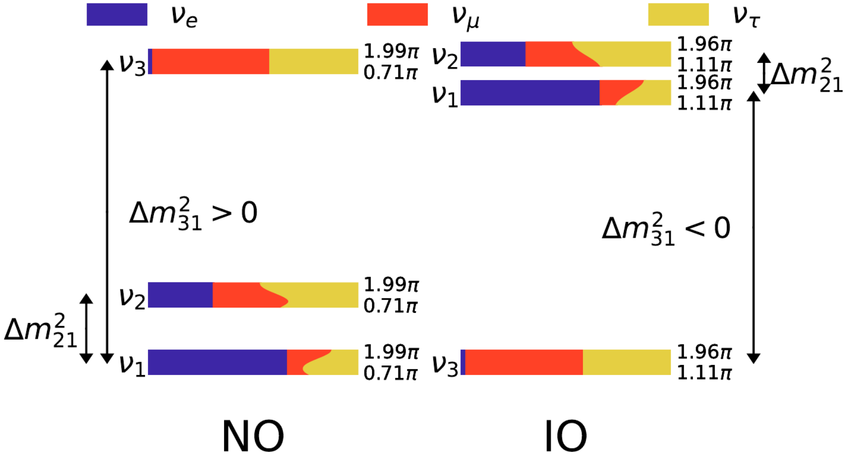
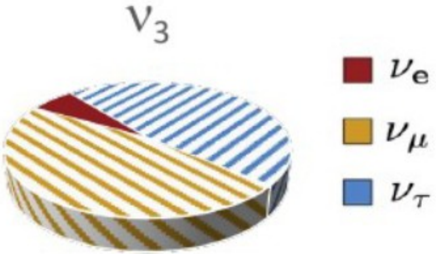


- mass ordering, θ_{23} octant, CP violation ???





Is θ_{23} mixing maximal?
μ-τ symmetry?
Is $\theta_{23} \lesssim 45°$?

matter antimatter

ν_e appearance channel

$$P(\nu_\mu \to \nu_e) = 4 c_{13}^2 \underline{s_{13}^2} s_{23}^2 \sin^2\Delta_{31}$$

dominant term – θ_{13}

$$+8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta_{CP} - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$

CP cons.

$$-8 \boxed{c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \boxed{\sin\delta_{CP}}} \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$

CP violation

$$+4 s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta_{CP}) \sin^2\Delta_{21}$$

solar term

matter effects

$$-8 c_{13}^2 s_{13}^2 s_{23}^2 \frac{aL}{\underline{4E_\nu}} (1-2s_{13}^2) \cos\Delta_{32} \sin\Delta_{31} + 8 c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\underline{\Delta m_{31}^2}} (1-2s_{13}^2) \sin^2\Delta_{31}$$

for $\bar{\nu}$: $\delta_{CP} \to -\delta_{CP}$

$a \to -a$

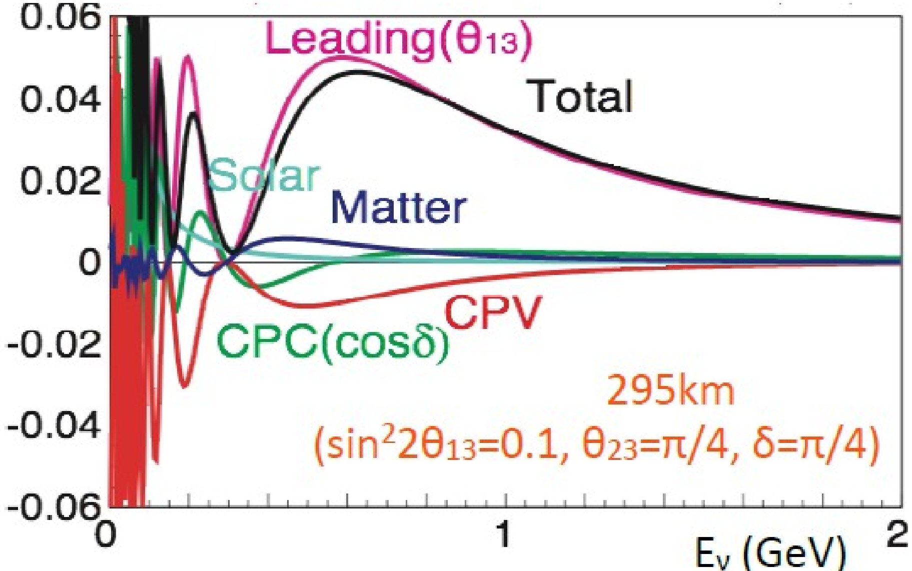
$s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$

$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$

$a = 2\sqrt{2}\, G_F E_\nu n_e$

n_e related to matter density (presence of electrons modifies the mixing)

- Jarlskog invariant ~0.033 $\sin\delta_{CP}$ (for quark sector 3 x 10^{-5})
- channel sensitive to θ_{23} octant
- matter term differs in sign for $\nu/\bar{\nu}$ → sensitive to mass ordering



T2K experiment

- located in Japan
- searches for oscillations in high purity ν_μ beam
- other measurements: cross sections, sterile ν search
- started to take data in 2010, with neutrino and antineutrino beam
- off-axis technique

Near Detectors

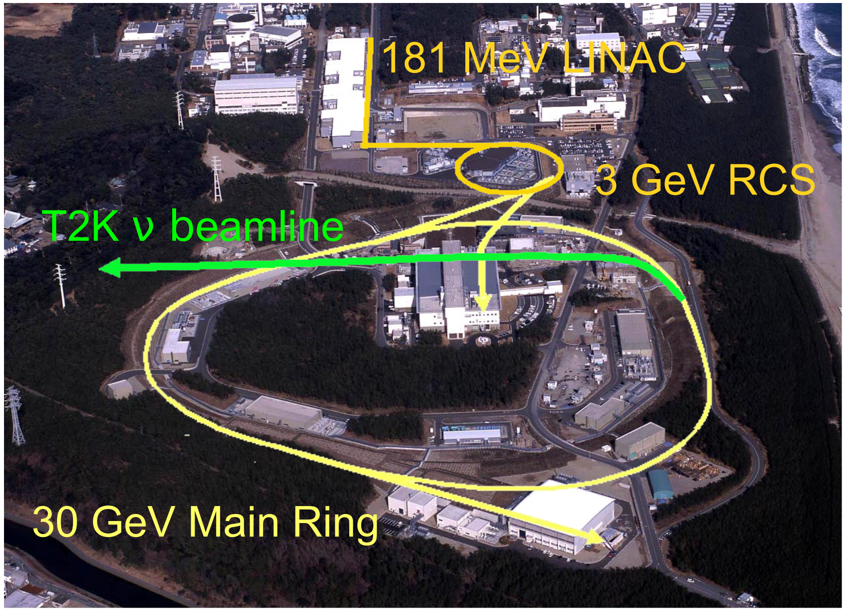
Super-Kamiokande
(ICRR, Univ. Tokyo)

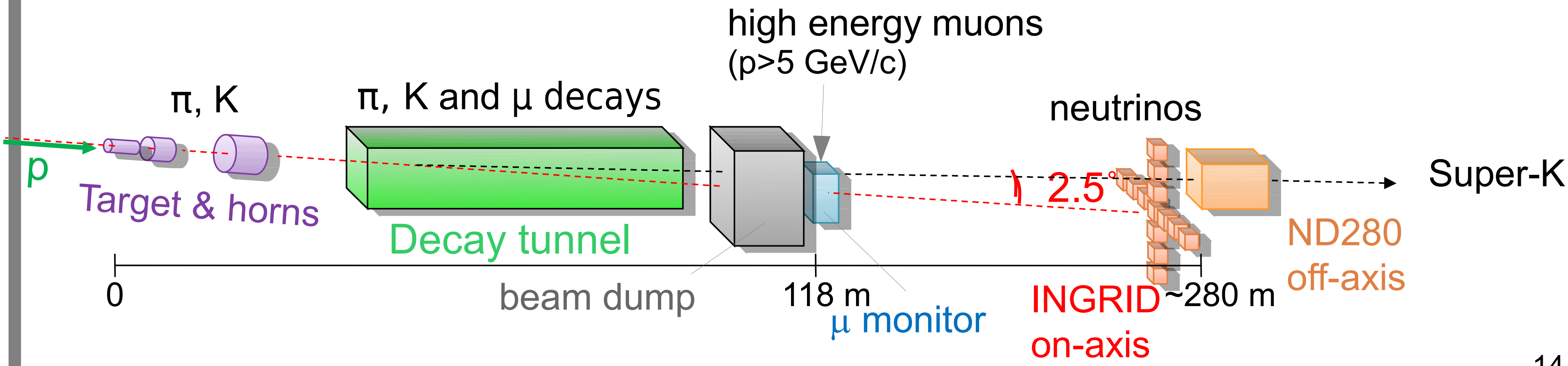
295km

J-PARC Main Ring
(KEK-JAEA, Tokai)

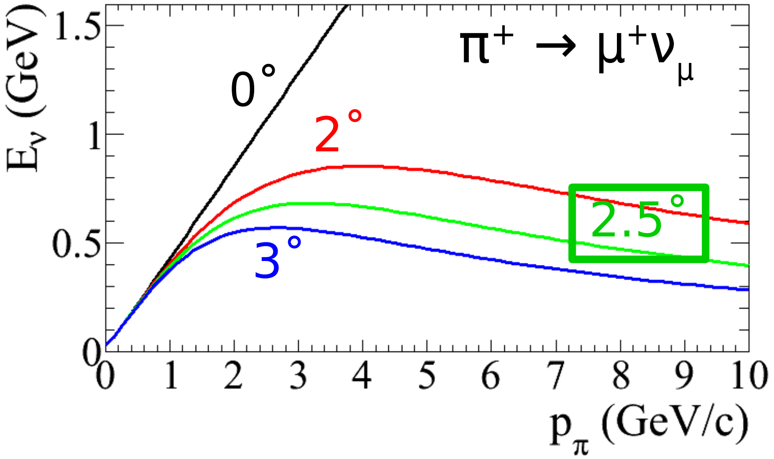
Beam

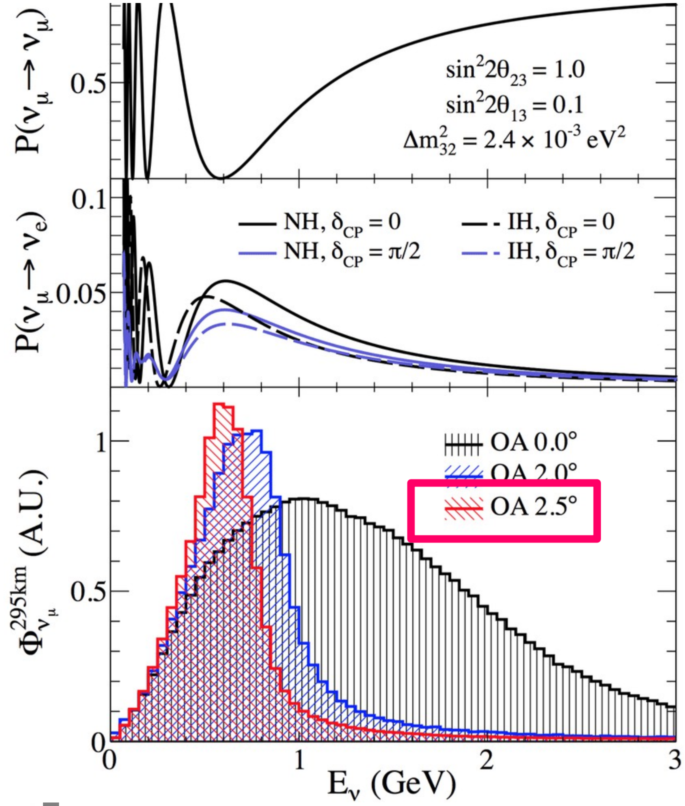
- proton accelerator chain at J-PARC
  - 30 GeV proton beam,
    1.36 s pulse period, 8 bunches
  - power achieved: over 800 kW
  - position, profile and intensity
    of the proton beam monitored
- graphite target, 3 horns focusing positively or negatively charged hadrons
- 96 m decay tunnel, beam dump





Off-axis beam





for angles ≠ 0
the dependence of
E_ν from E_π is
reduced

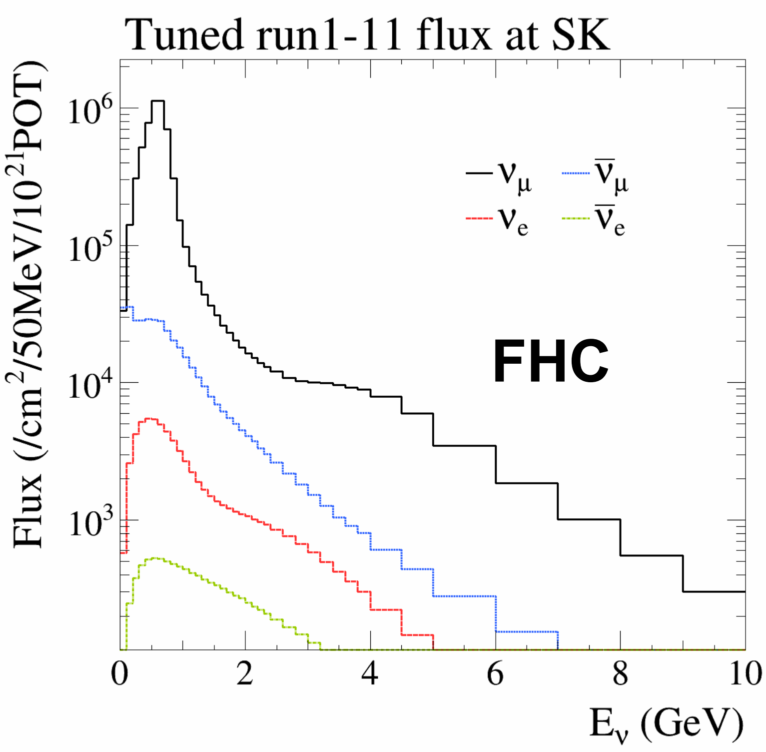
narrow spectrum,
tuned at the first
oscillation maximum

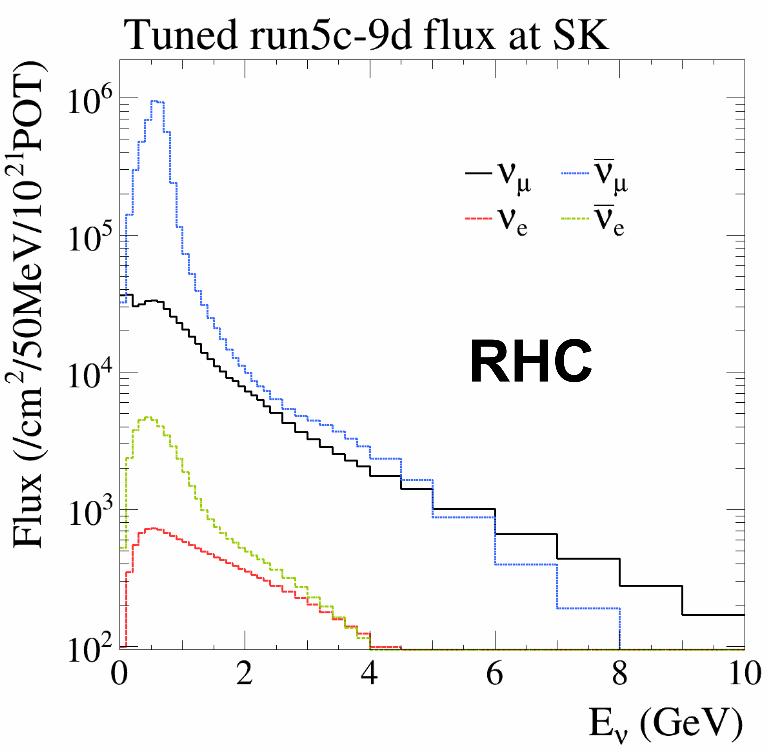
- CC QE sample enhanced
- background from intrinsic ν_e reduced
- background from NC π^0 production reduced

the direction must be precisely controlled
(<1mrad to keep peak energy stable
δE/E ~2% at far detector)

Neutrino fluxes

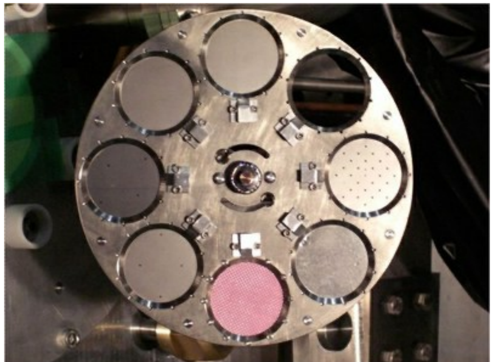
- system of 3 horns with 250 kA current sinusoidal ~3ms pulse.
- Forward Horn Current (FHC)→ neutrino enhanced beam: $\pi^+ \rightarrow \mu^+ \nu_\mu$
- Reversed Horn Current (RHC) → anti-neutrino enhanced beam: $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$
- currently upgraded to 320kA → +~20% ν flux (the data collected with this focusing are not yet used in the analysis)



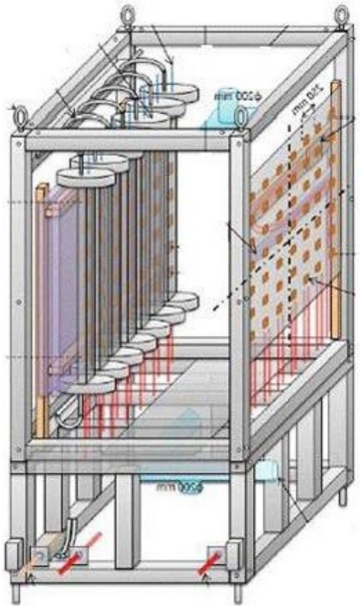


Beam monitoring

- Proton beam monitors
  - essential for protecting beam-line equipment and for understanding and predicting neutrino flux
  - beam intensity (<2.7% precision) and beam loss (sensitive down to 16mW loss)
  - beam position and profile (100μm position, 200μm width)
    - Segmented and Wire Secondary Emission Monitors
    - optical transition radiation

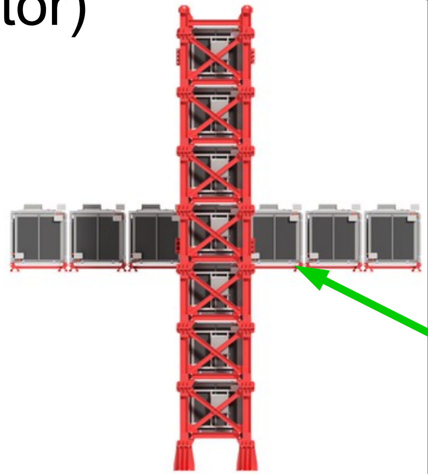


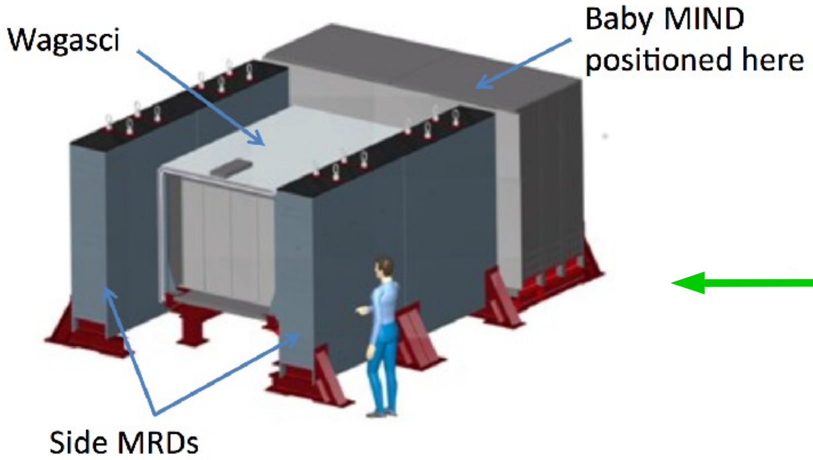
- Muon monitor
  - measures beam direction and intensity on spill-by-spill basis, with high-energy muons from pion decays
  - < 3cm resolution, corresponding to < 0.3 mrad
  - ionization chambers and semiconductor arrays

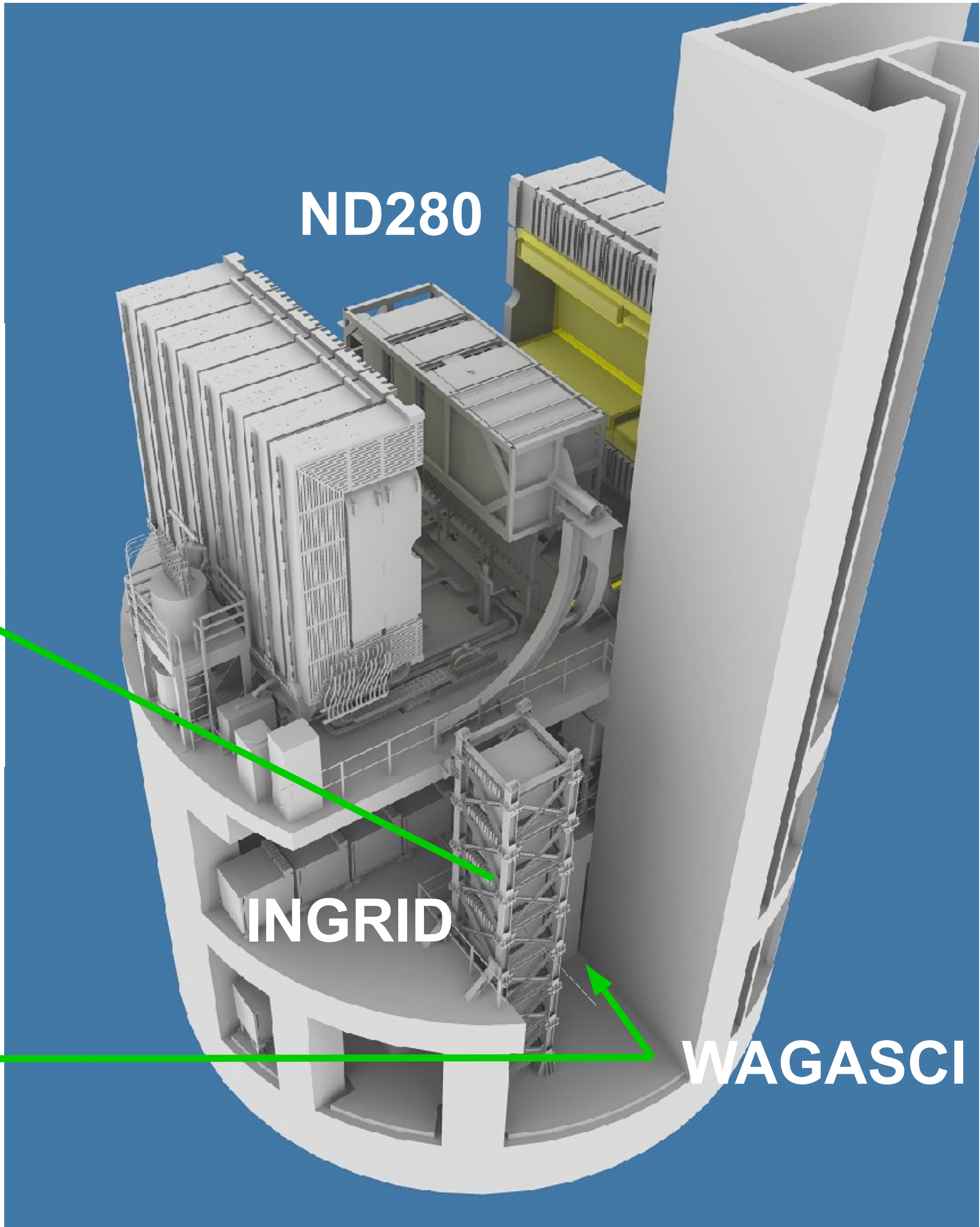


Near detectors

- located at the distance of 280m from the target
  - INGRID (on axis)
  - ND280 (same off axis angle as the Far Detector)
  - WAGASCI (1.5º off-axis)

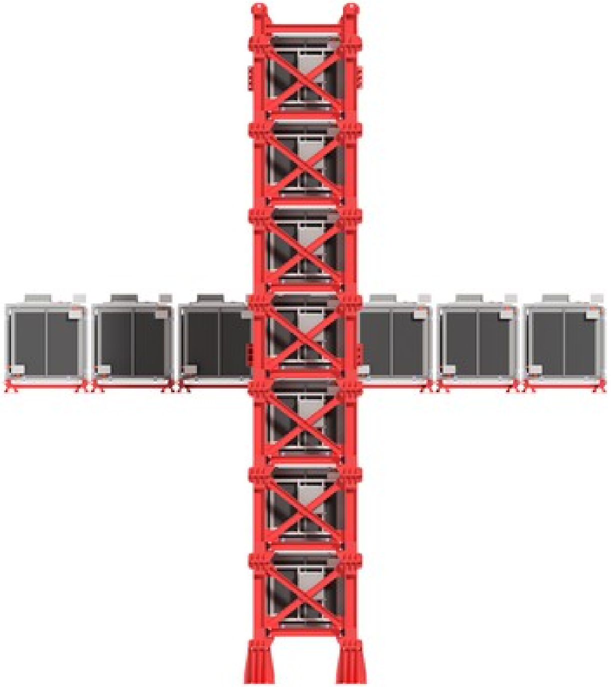


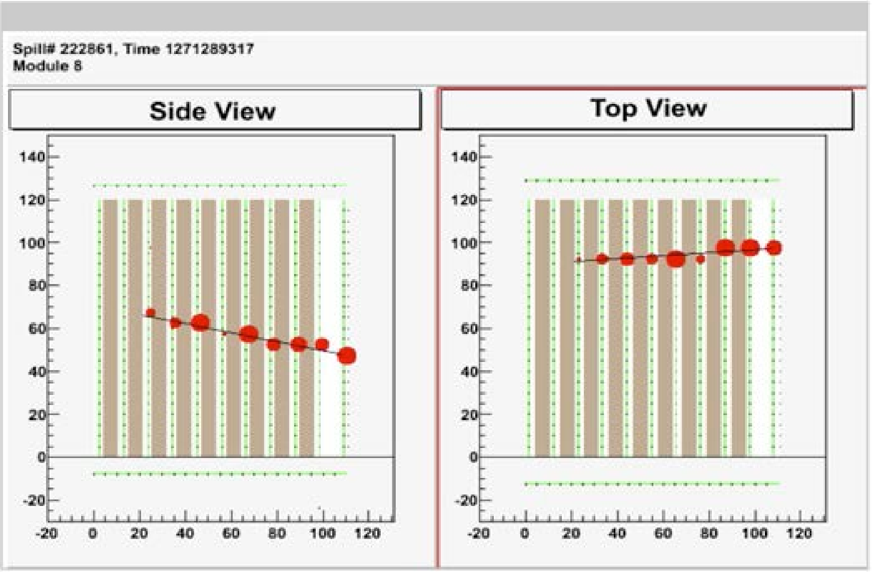




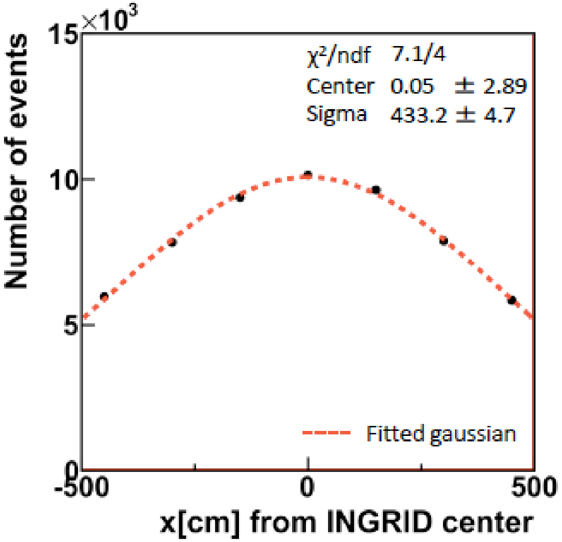
INGRID

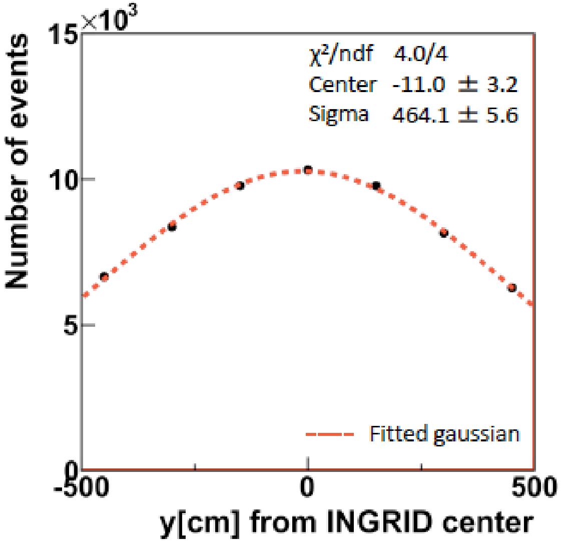
- On-axis Interactive Neutrino GRID (INGRID)
  - 14 identical cubic modules, iron/scintillator sandwich
  - monitors the intensity, profile and direction of the beam with ν interactions
  - relative event counts between modules monitor the beam direction stability.





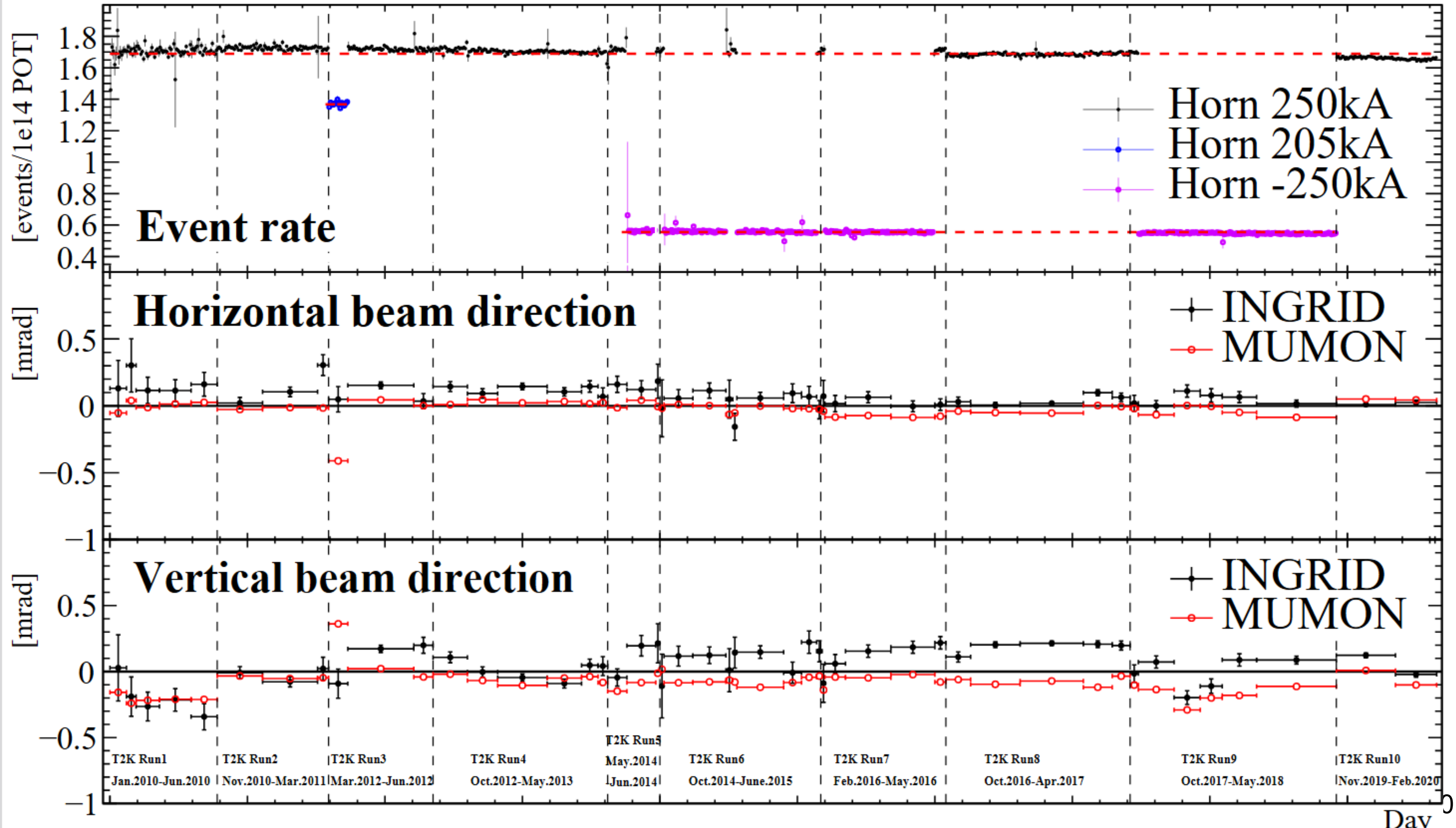
Spill# 222861, Time 1271289317
Module 8





Beam stability (example)

- beam profile and absolute rate stable and consistent with expectations
- targeting efficiency stable at over 99%



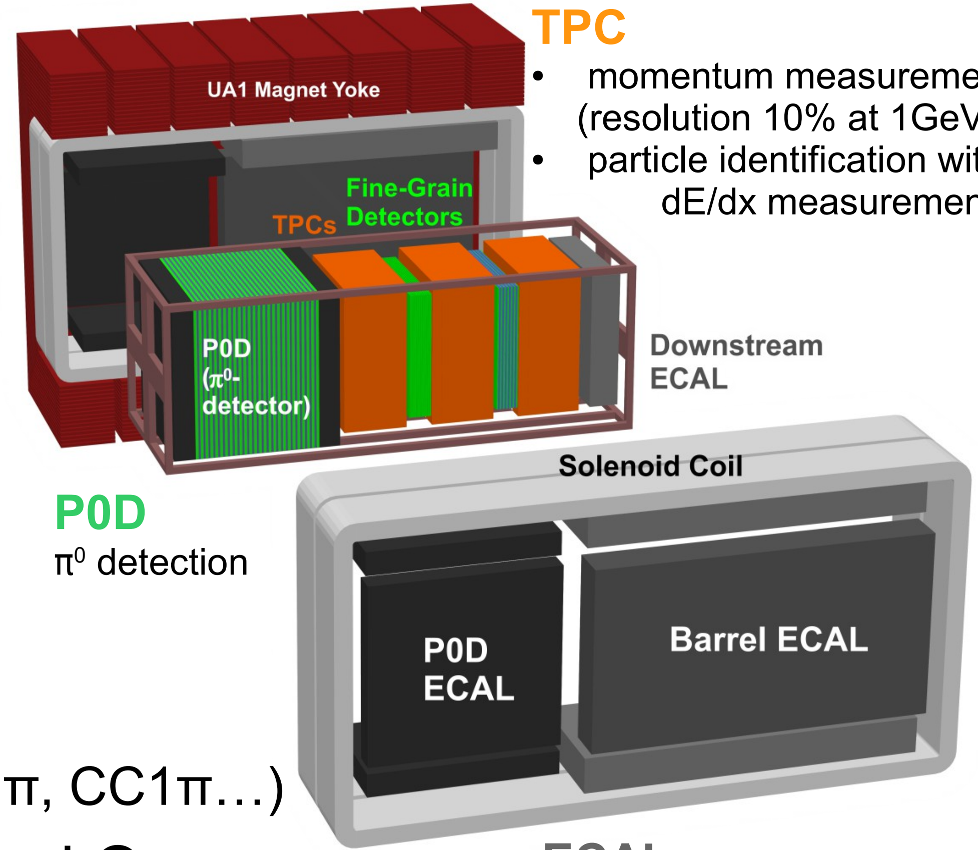
ND280

- ND280 – multi-purpose detector with magnetic field
  - UA1/NOMAD magnet (magnetic field 0.2 T)
- measures the beam before the oscillations
- reconstructs final states to study neutrino interactions and beam properties
  - measures ν interaction rates and flavour → ν_μ and ν_e spectra
- focused on specific background processes to oscillation (NCπ^0, NC1π, CC1π…)
- compare interactions on Carbon and Oxygen (FGD1 and FGD2)
- currently upgraded with a new tracker and TOF (data not yet used in the analysis)

SMRD
improvement of muon identification

FGD
- active target
- recoil protons detection

TPC
- momentum measurement (resolution 10% at 1GeV)
- particle identification with dE/dx measurement

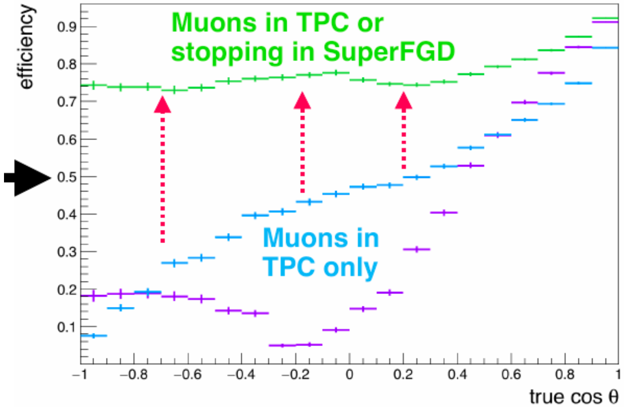


P0D
π^0 detection

ECAL
EM showers

Upgraded ND280

- upgrade finished in spring 2024
- P0D replaced with **SuperFGD** and **High Angle TPCs**, surrounded by **TOF**
- SuperFGD:
  - quasi-3D imaging
  - improved high angle acceptance
  - improved proton detection threshold
  - neutron detection capabilities



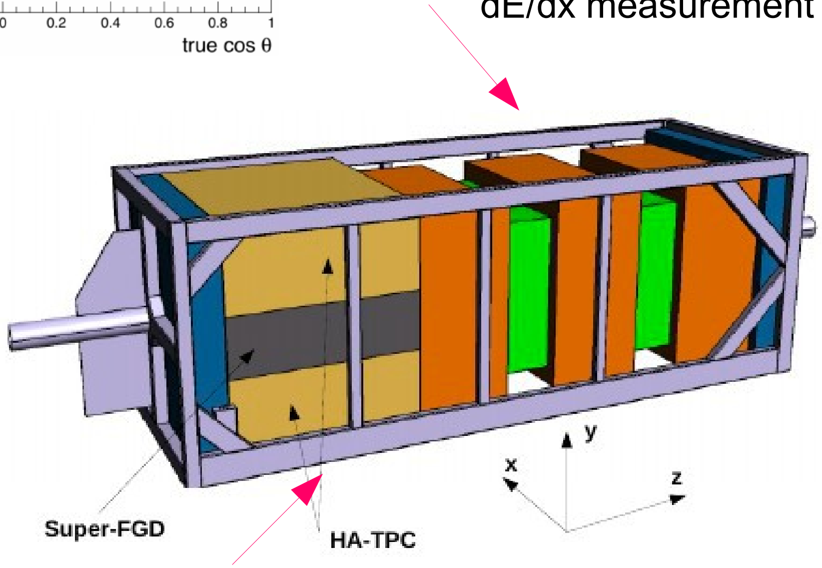
OLD TRACKER

FGD

- active target
- recoil protons detection

TPC

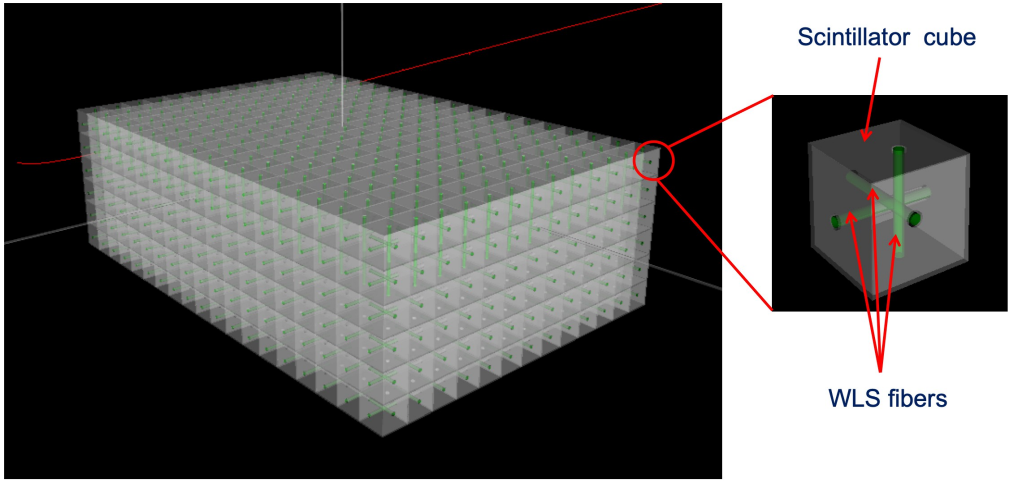
- momentum measurement (resolution 10% at 1GeV)
- particle identification with dE/dx measurement



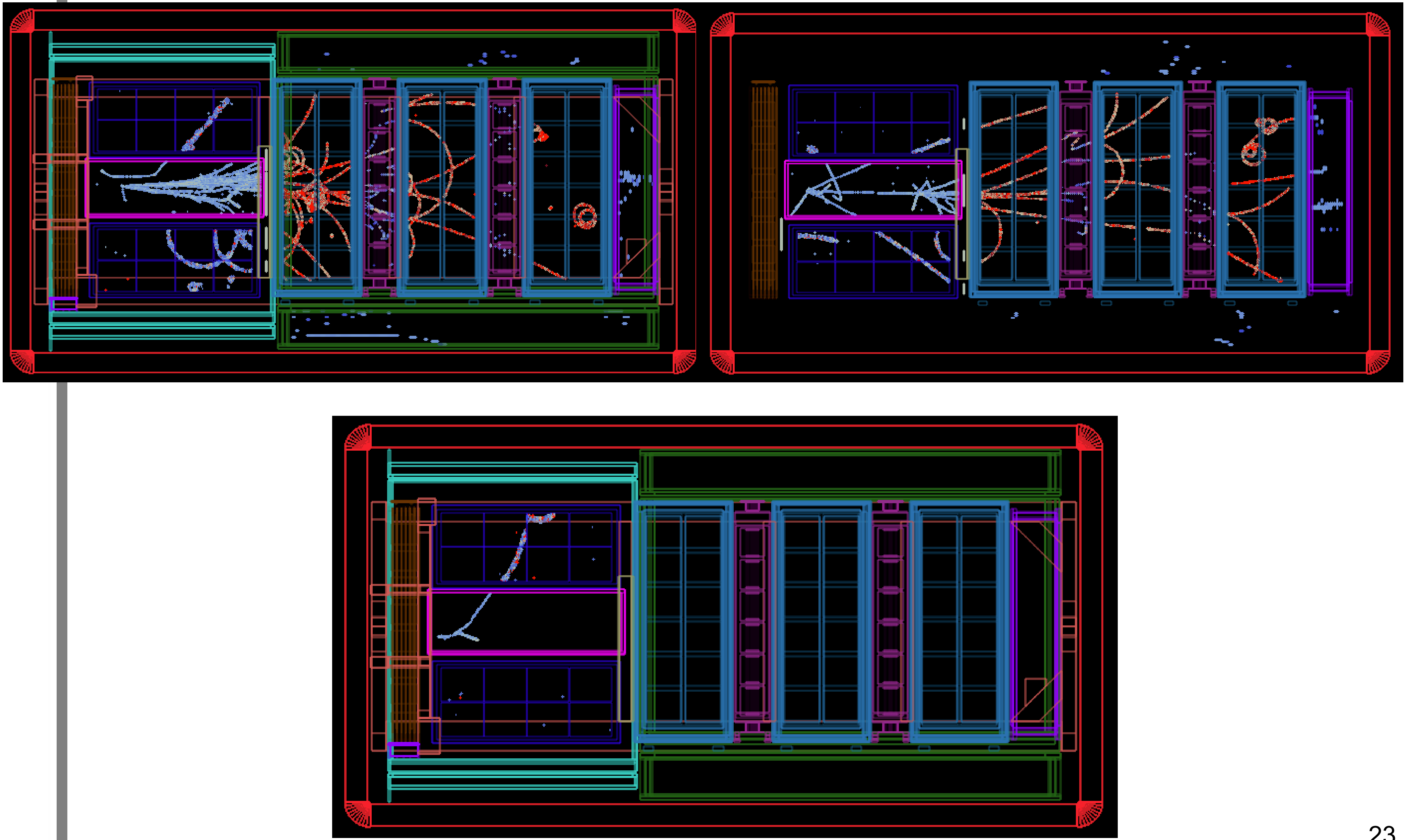
NEW TRACKER

Super-FGD

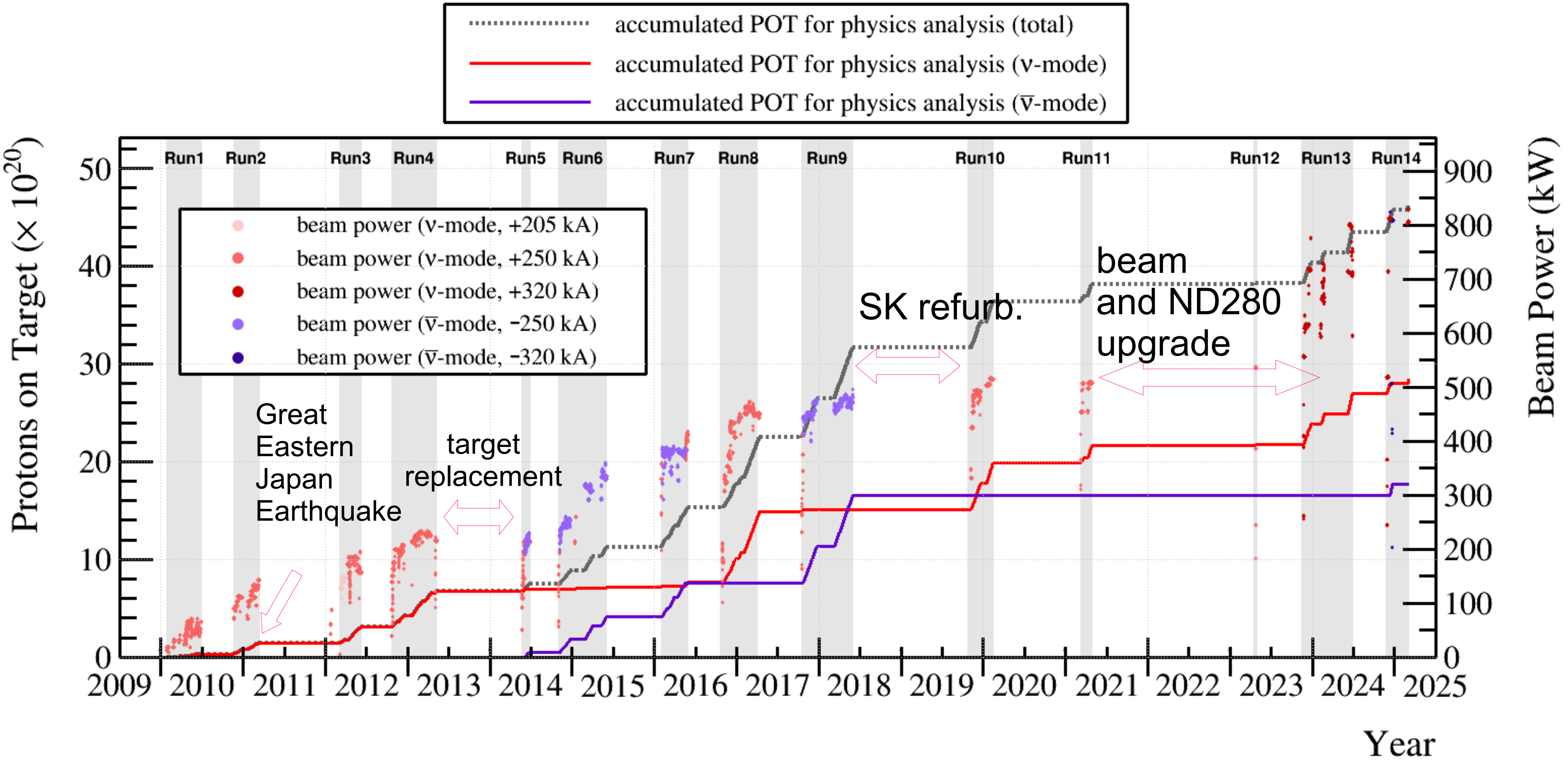
HighAngle TPC



Neutrino events in ND280



Data taking



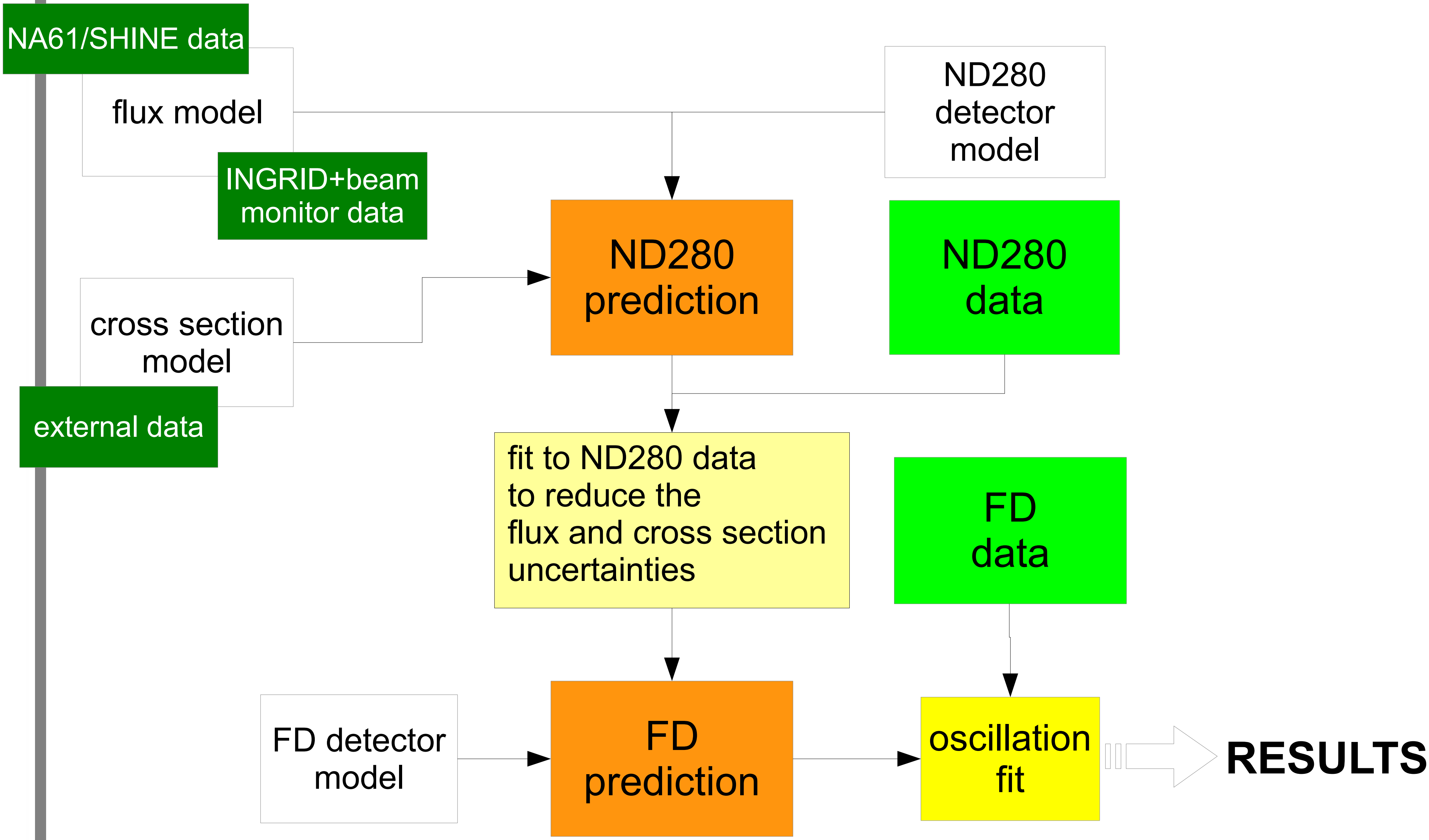
Great Eastern Japan Earthquake

target replacement

SK refurb.

beam and ND280 upgrade

Analysis flow



NA61/SHINE data

flux model

INGRID+beam monitor data

ND280 detector model

cross section model

external data

ND280 prediction

ND280 data

fit to ND280 data to reduce the flux and cross section uncertainties

FD data

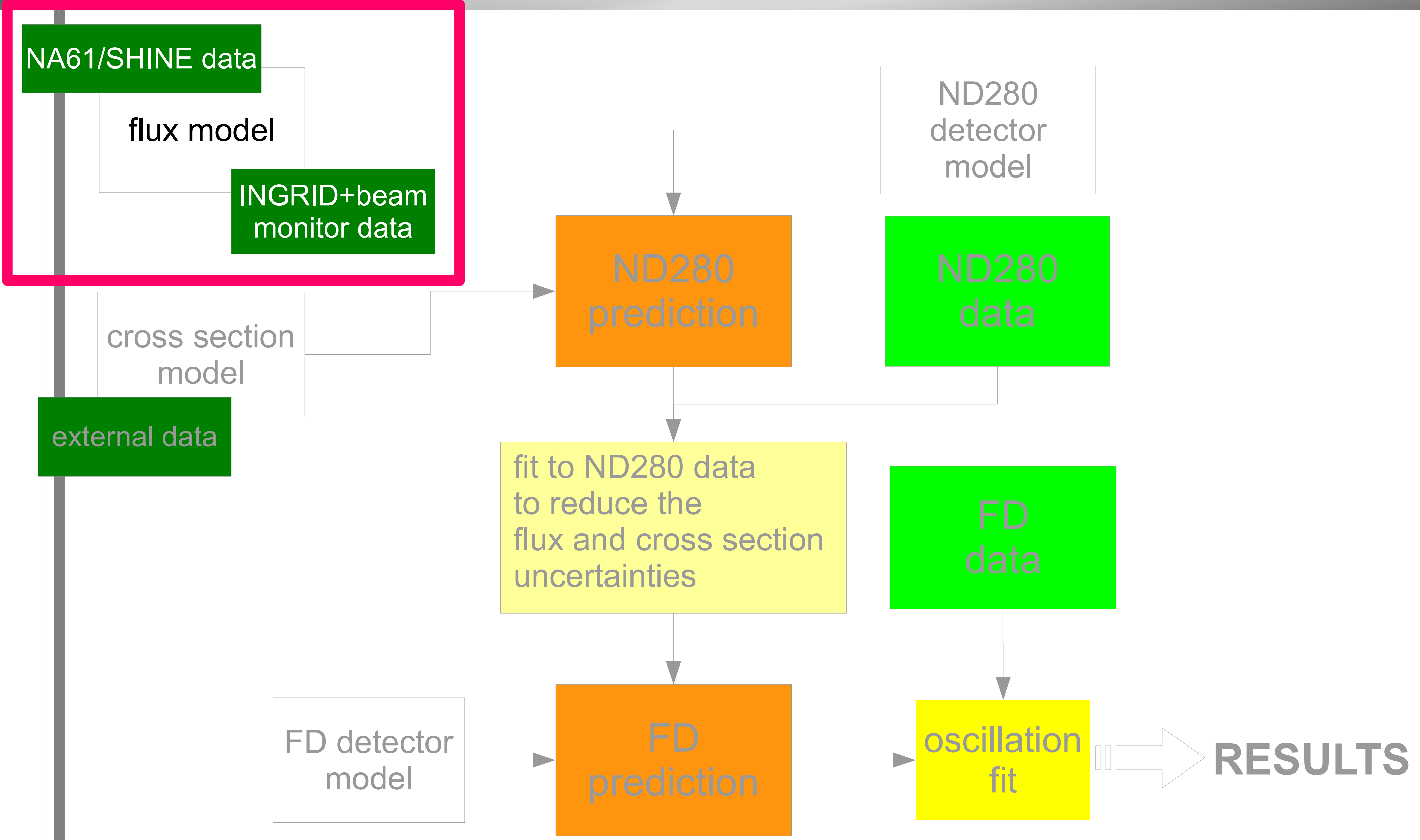
FD detector model

FD prediction

oscillation fit

RESULTS

Analysis flow



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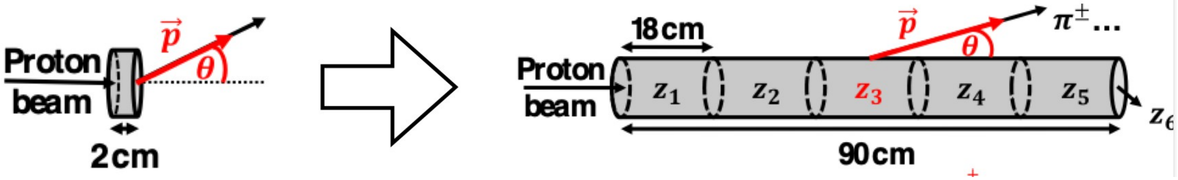
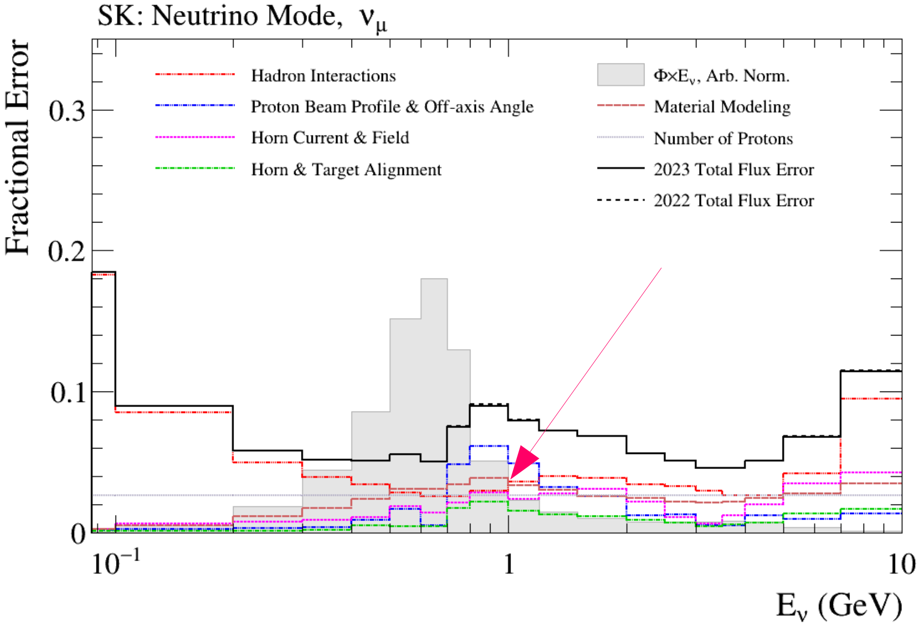
RESULTS

Beam simulation

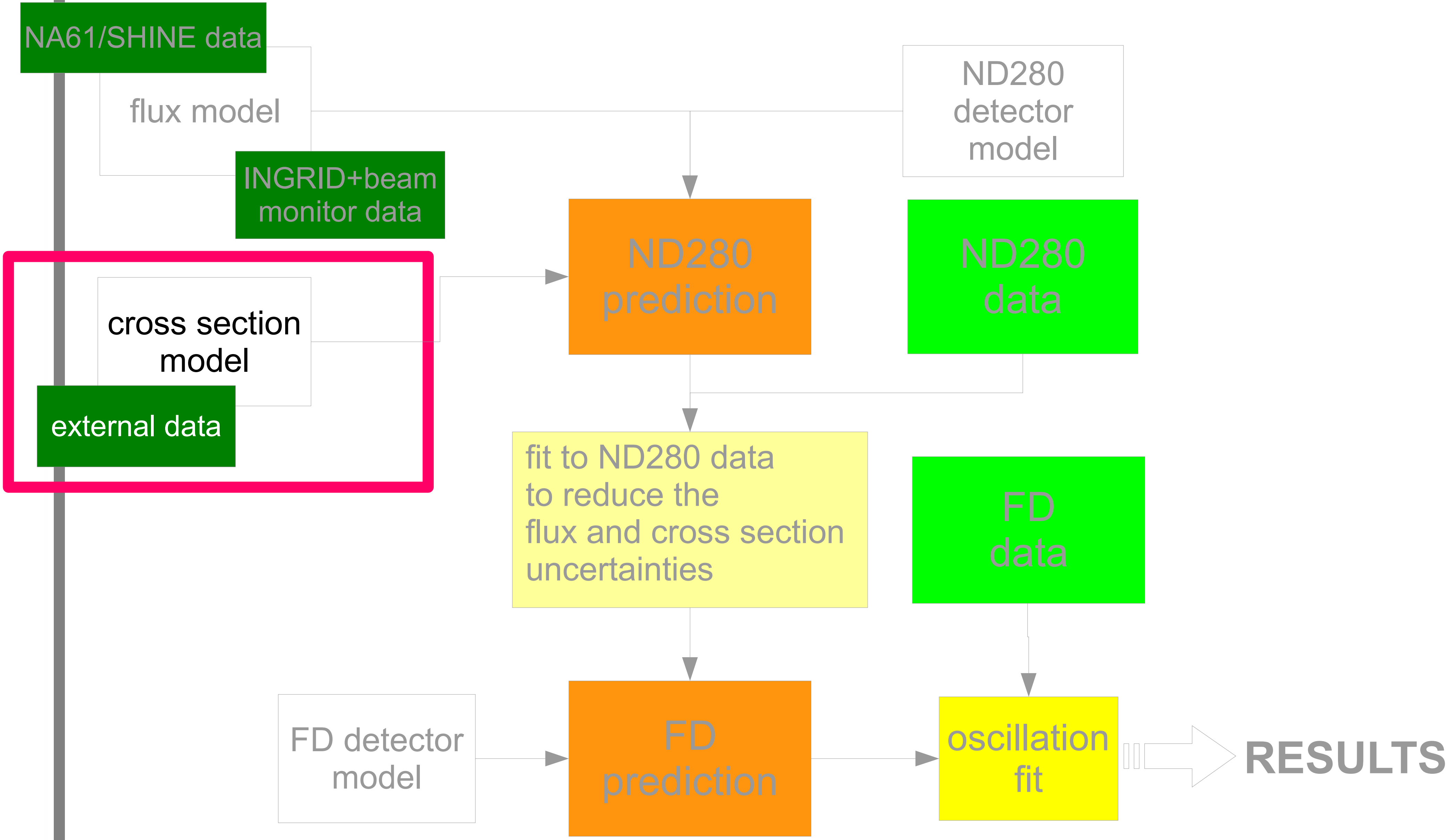
- primary interactions of protons in target simulated with FLUKA (and GEANT 4)
- reweighed to match NA61/SHINE data
  - measurements done with T2K replica target to account for re-interactions inside the target
  - MC spectrum reweighted to match data in momentum, angle and target exit point
  - Flux uncertainties reduced from 8% to 5% in flux peak



- GEANT simulation of the particle transport through horns and decay volume



Analysis flow



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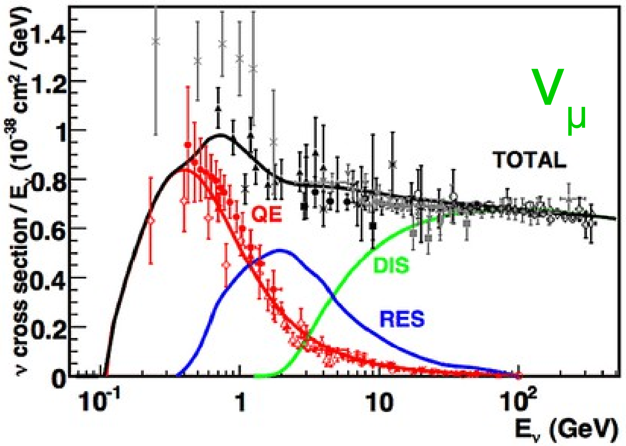
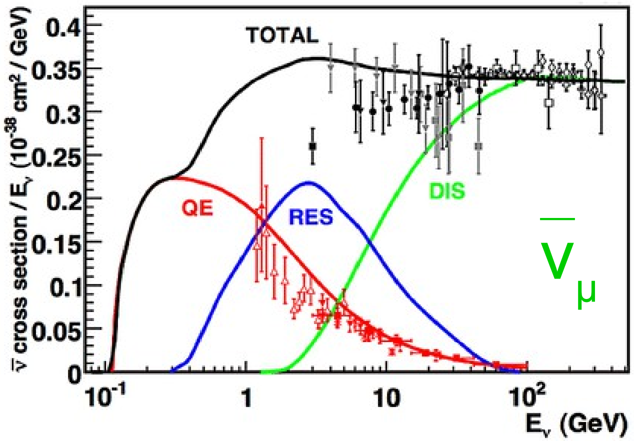
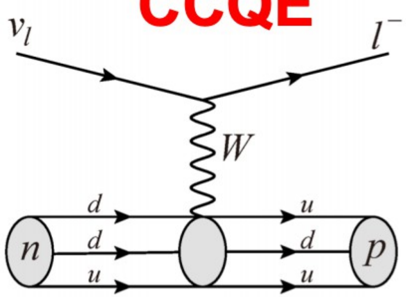
Interactions

- **CC QE** interactions dominate at the energies of T2K
- significant **resonant** contribution

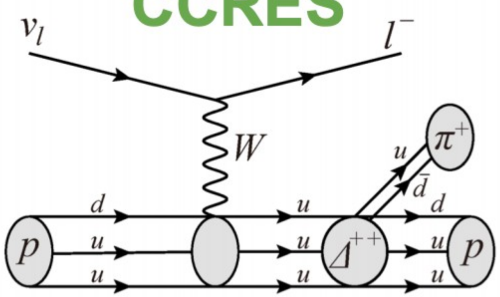




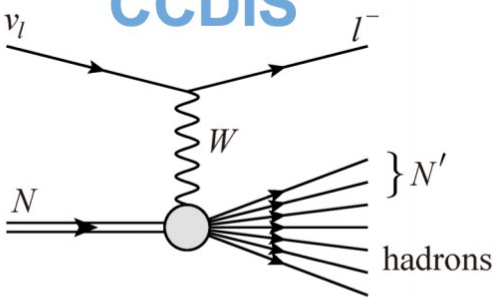
CCQE



CCRES

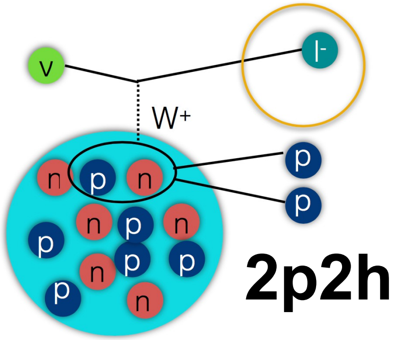


CCDIS



at the nucleus level:

- also multinucleon (2p2h) interactions
- target nucleon initial state – Spectral Function (for QE)
- Final State Interactions (FSI)

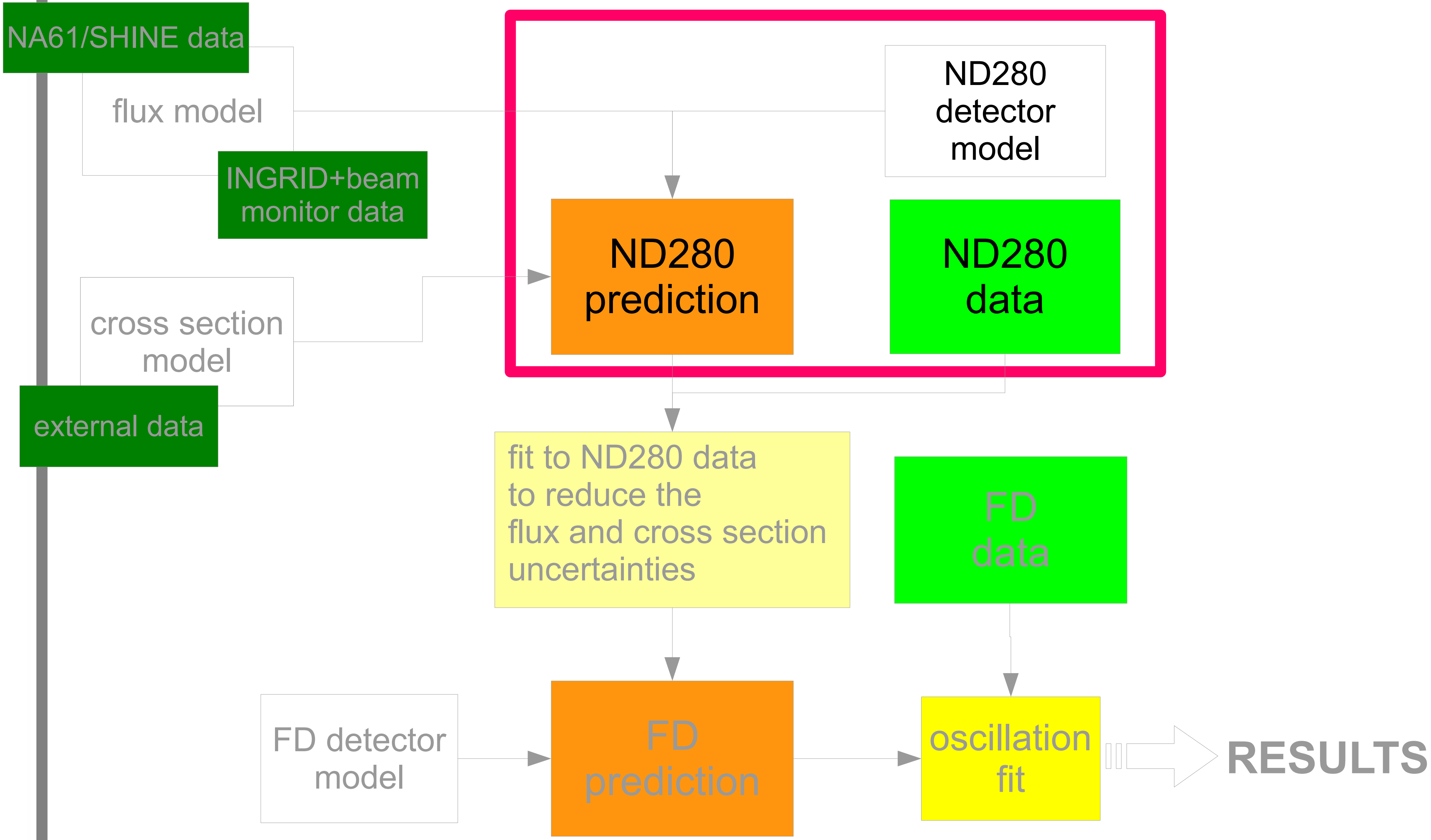


2p2h

- parametrized models - 75 parameters in total
- contribution from Wrocław University theory group

NCBJ

Analysis flow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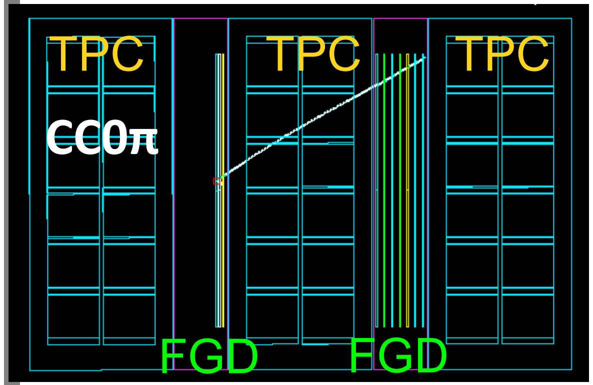
RESULTS

ND280 samples

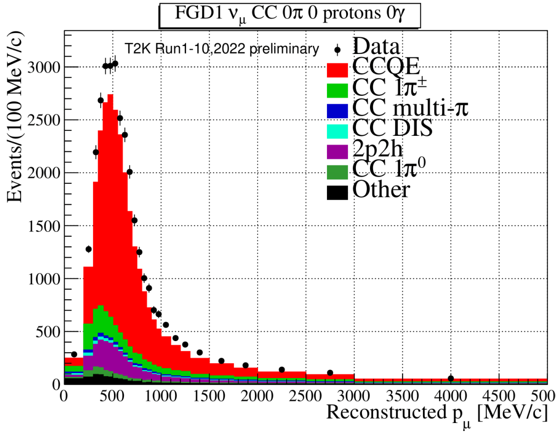
- analysis of ν_μ CC interactions in ND280 to constrain flux and cross section parameters and uncertainties
  - analysis of muon kinematics (p, $\cos\theta$)
  - ν_μ measurement can constrain also ν_e flux
- **(anti)ν_μ CC selection in ND280 tracker for FHC and RHC:** μ^- (μ^+) candidate: highest momentum negative (positive) track
  - starting in FGD FV
  - with long segment in TPC
  - dE/dx compatible with muon hypothesis
- 22 samples in total = sensitivity to different neutrino energy ranges and interactions modes
  - separate samples for **FGD1** and **FGD2** (interactions on CH/Water)
  - **dominant component for FHC and RHC, and for** RHC **also neutrino component of the beam (wrong sign)**
  - **separate multipion samples** ← presence of pions in final state topology

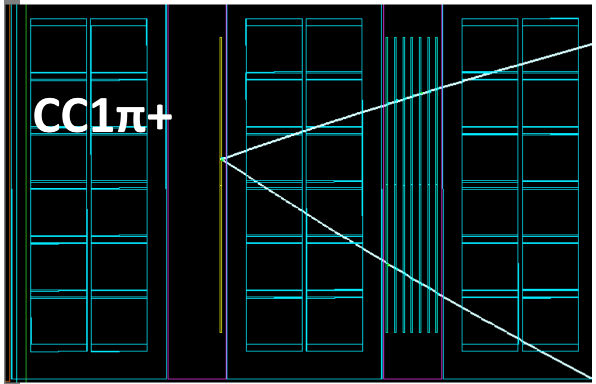
Examples of FGD1 FHC samples



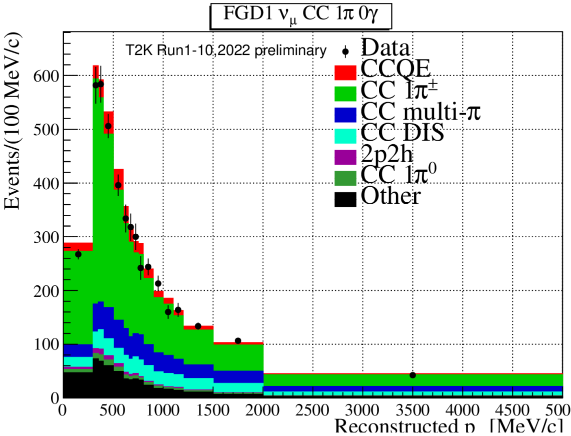
CC 0π – dominated by **CC QE**

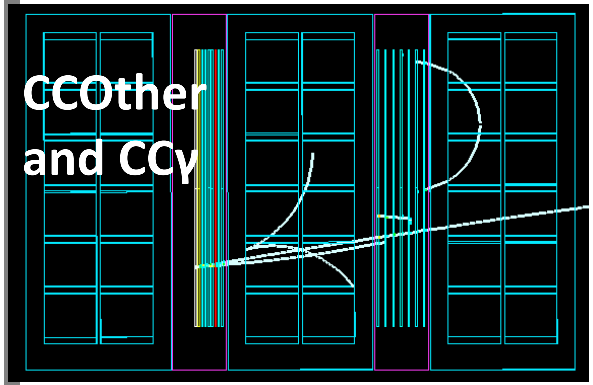
splitted into 0proton and Nproton for FHC



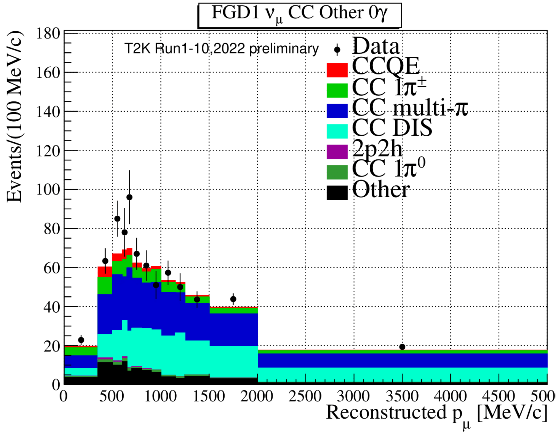


CC $1\pi^+$ – enhanced in **resonant pion production**

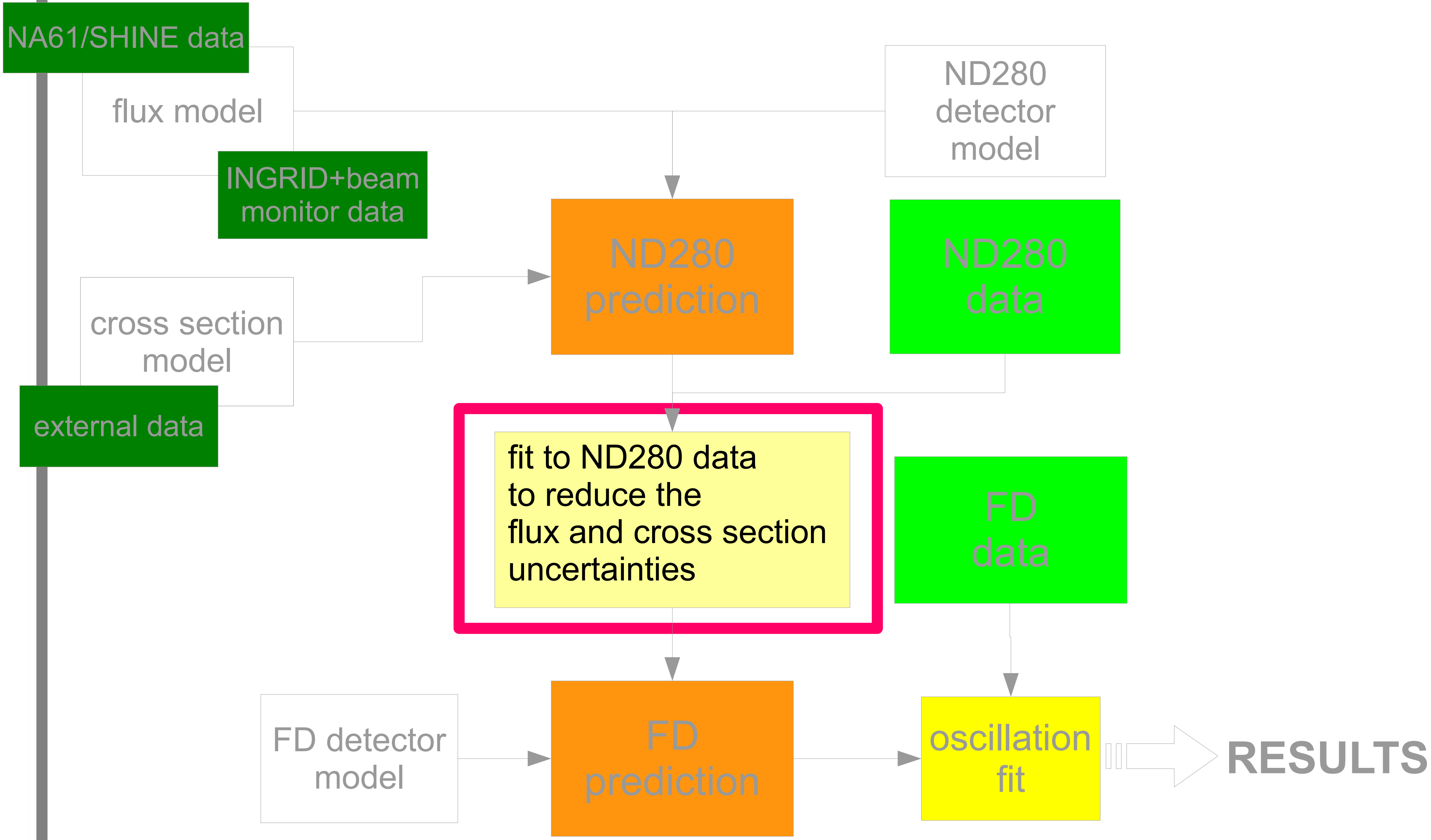




CC Photon and CC Other – mostly **multipion production** and **DIS**



Analysis flow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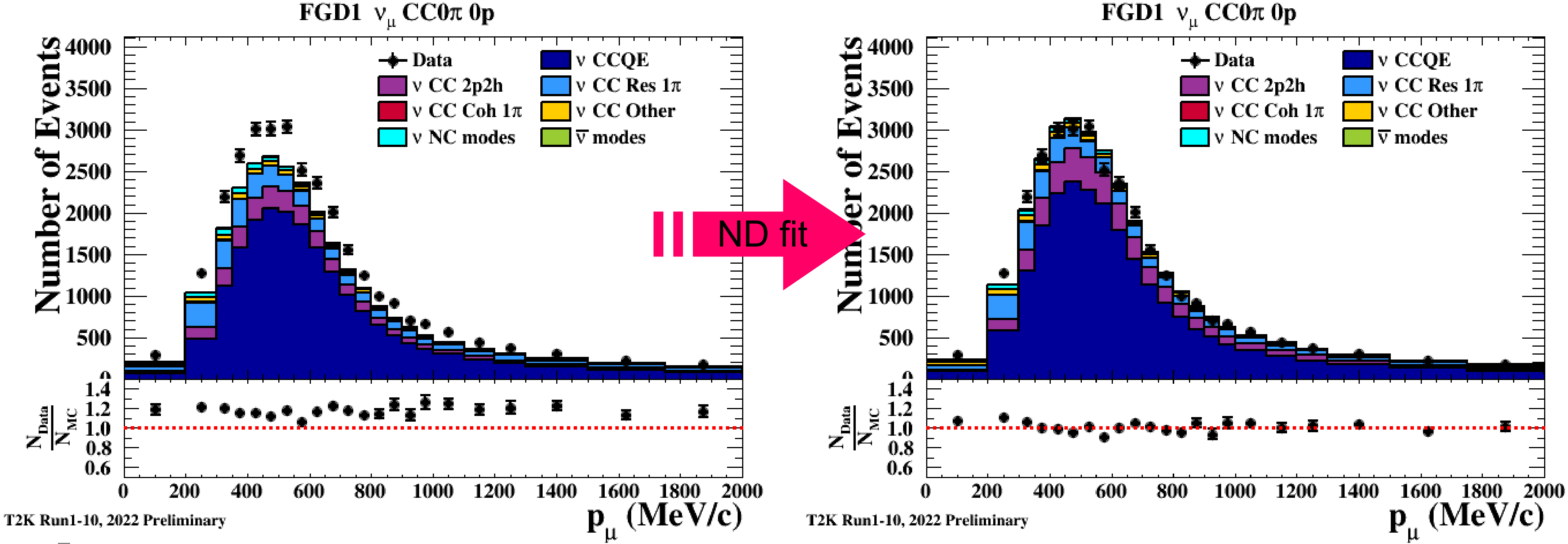
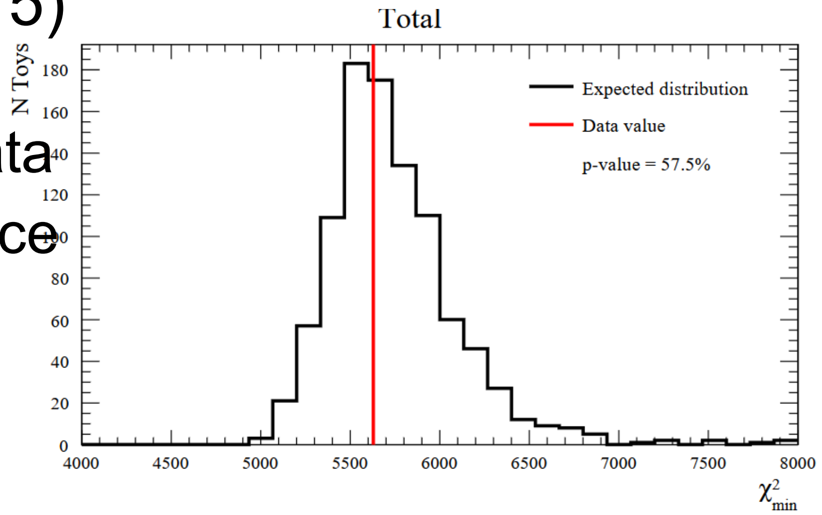
RESULTS

Post-fit



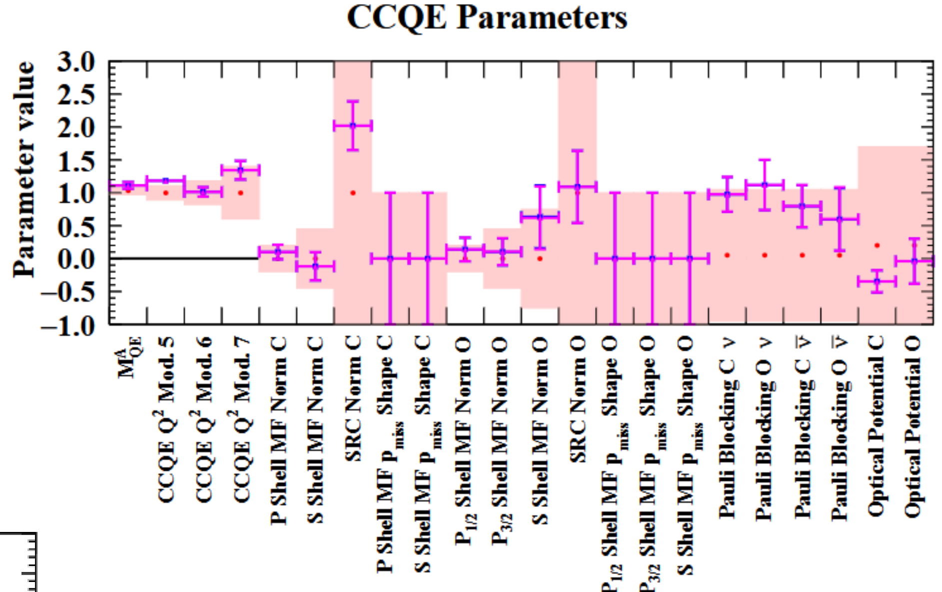
- good fit to data (prior model p-value=0.575)
  - test the model ability to cover the phase space region which best describes the data
  - “toy” data sets thrown from prior covariance and the nominal model is fit to each toy
  - p-value: the fraction of fits with a χ^2_{min} greater than that of the data
  - data is adequately consistent with our input model

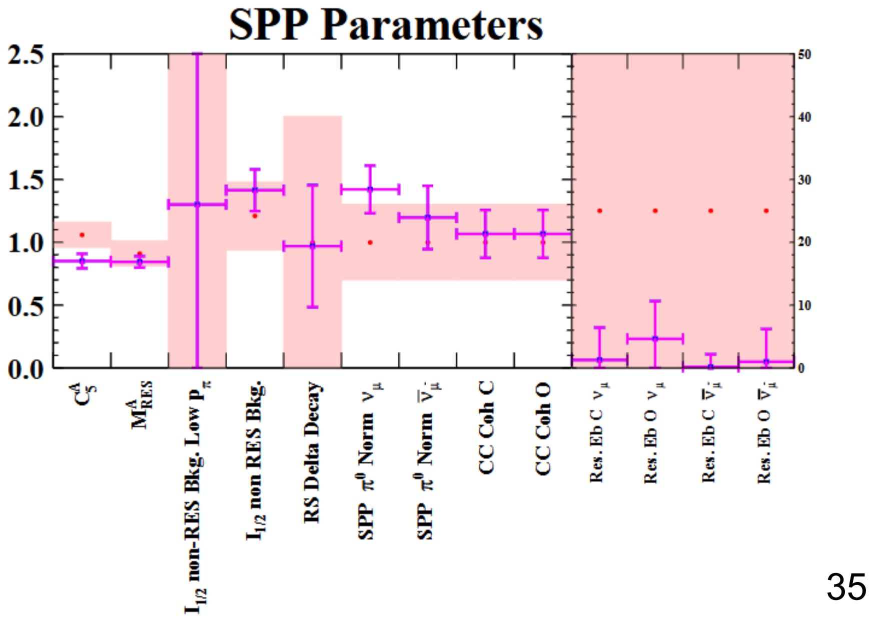


Examples of post-fit parameter values

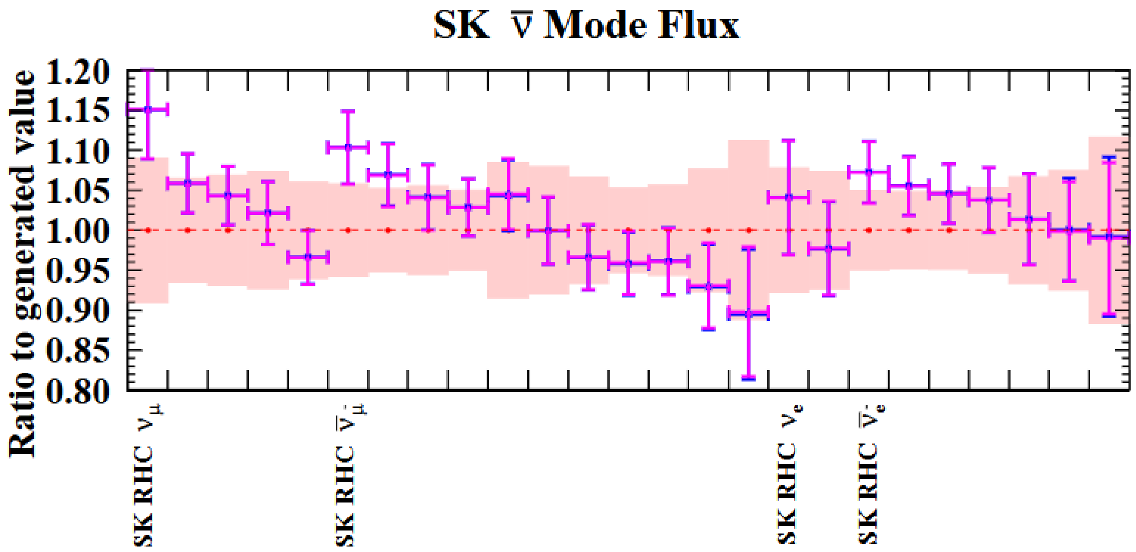
- corrected flux and cross-section model
- significant reduction in parameter uncertainties

Some of cross section parameters

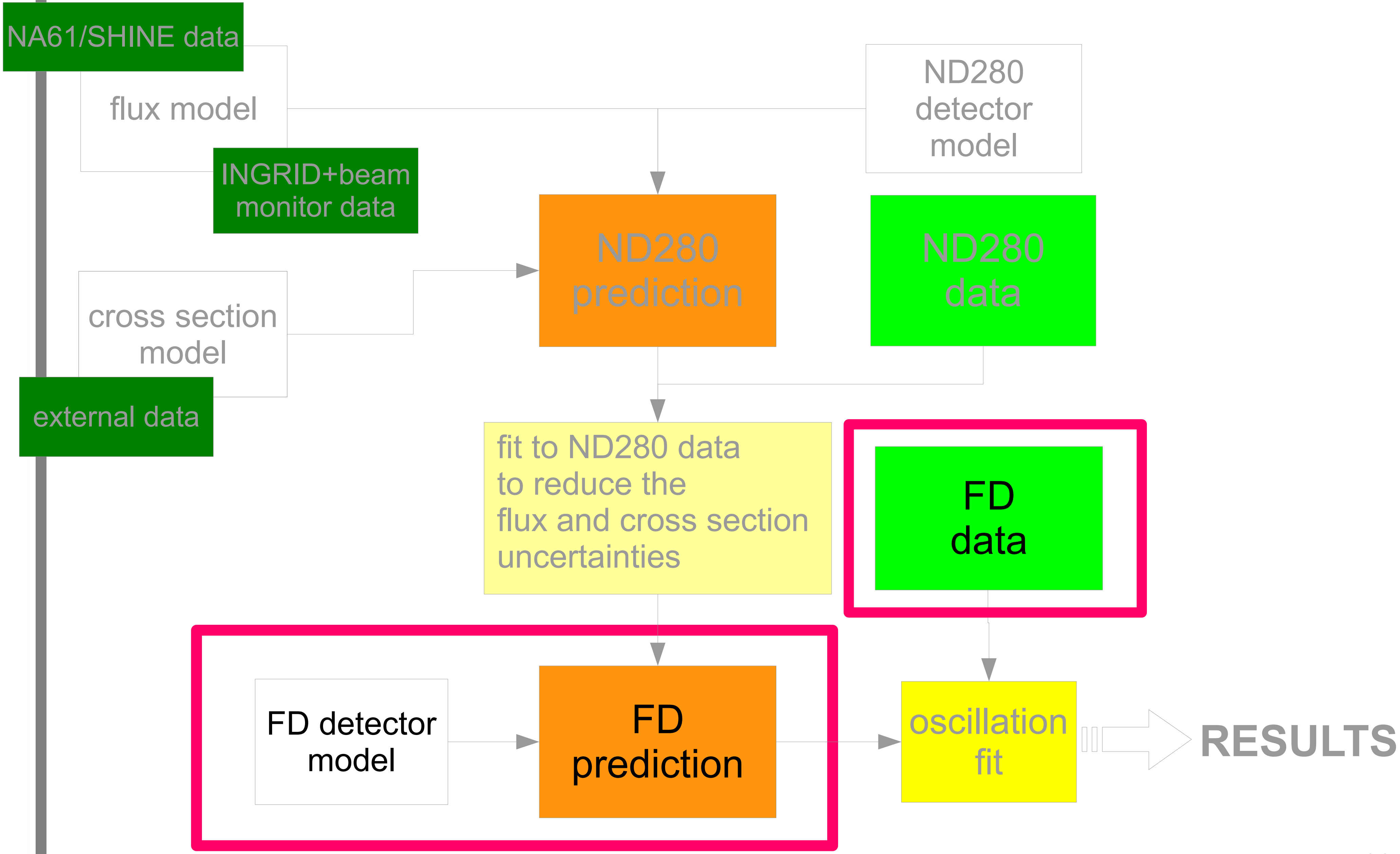




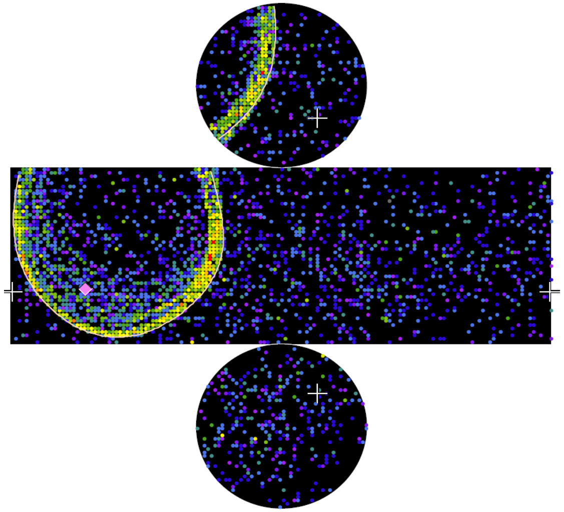
Example of flux parameters



Analysis flow

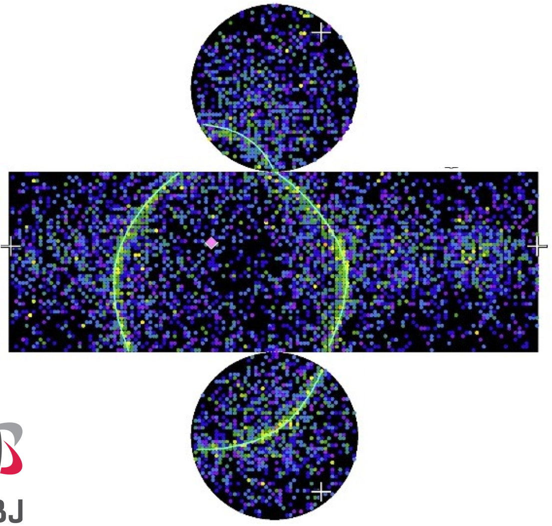


Far Detector Samples



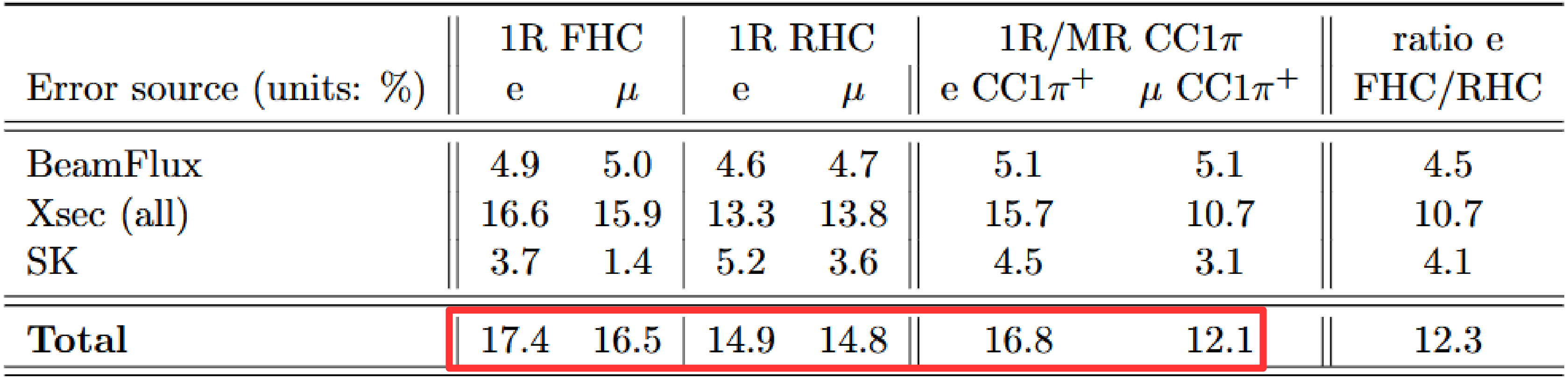
- 5 samples of single ring events
  - muon candidate, FHC
  - muon candidate, RHC
    - μ-like PID
    - $p_\mu > 200$ MeV/c
    - Michel electron 1 or 0
  - electron candidate, FHC
  - electron candidate, RHC
    - e-like PID
    - $p_e > 100$ MeV/c
    - $E_{rec} < 1250$ MeV
    - π^0 rejection
  - electron candidate with a Michel electron from decay of π, FHC
- Multi ring sample: muon candidate with additional Michel electron or second ring from π, FHC

CC 0π



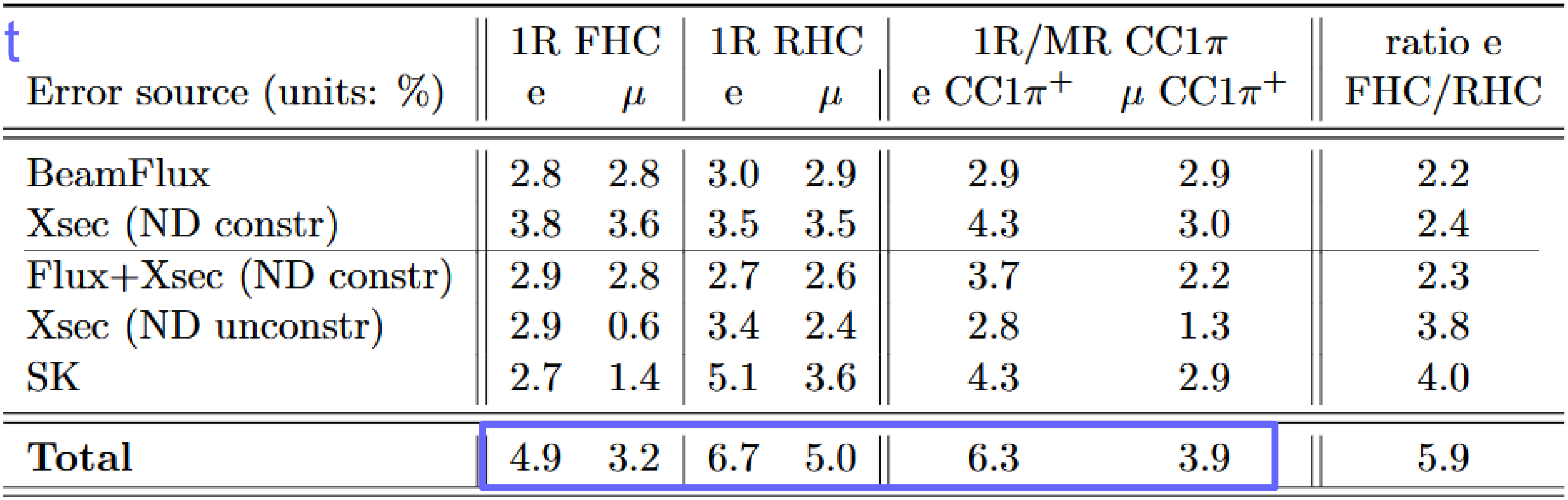
Effect of ND280 fit

Pre fit



Error source (units: %)	1R FHC		1R RHC		1R/MR CC1π		ratio e
	e	μ	e	μ	e CC1π^+	μ CC1π^+	FHC/RHC
BeamFlux	4.9	5.0	4.6	4.7	5.1	5.1	4.5
Xsec (all)	16.6	15.9	13.3	13.8	15.7	10.7	10.7
SK	3.7	1.4	5.2	3.6	4.5	3.1	4.1
Total	17.4	16.5	14.9	14.8	16.8	12.1	12.3

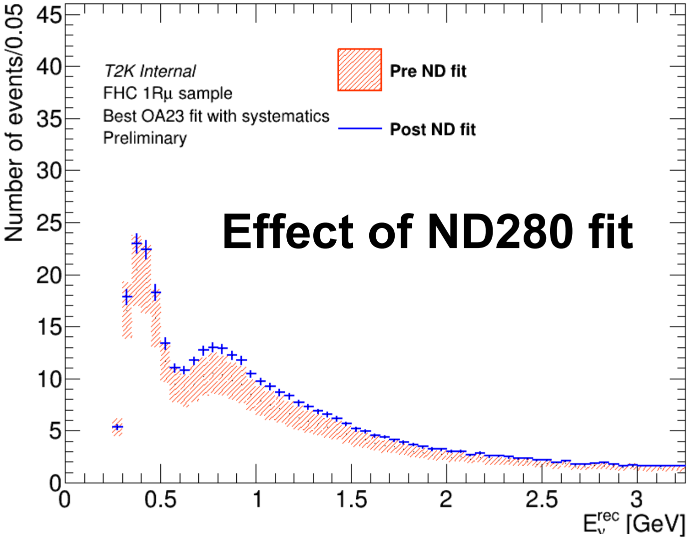
Post fit



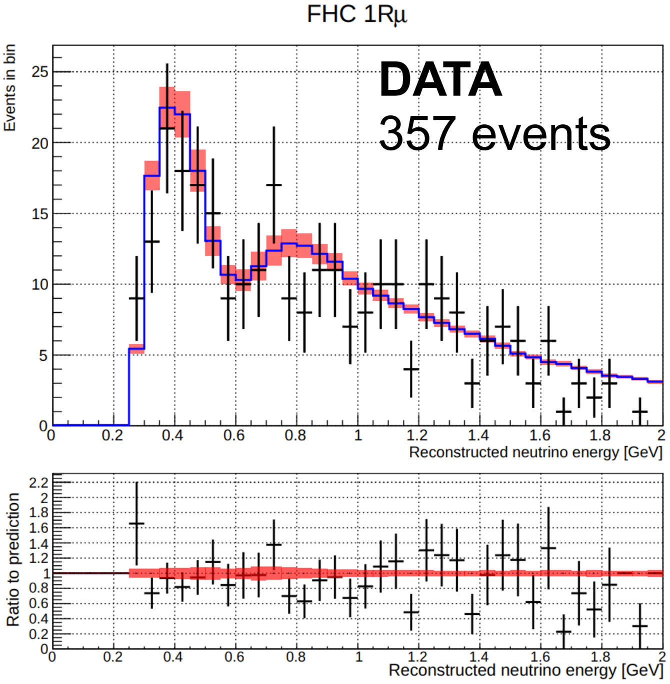
Error source (units: %)	1R FHC		1R RHC		1R/MR CC1π		ratio e
	e	μ	e	μ	e CC1π^+	μ CC1π^+	FHC/RHC
BeamFlux	2.8	2.8	3.0	2.9	2.9	2.9	2.2
Xsec (ND constr)	3.8	3.6	3.5	3.5	4.3	3.0	2.4
Flux+Xsec (ND constr)	2.9	2.8	2.7	2.6	3.7	2.2	2.3
Xsec (ND unconstr)	2.9	0.6	3.4	2.4	2.8	1.3	3.8
SK	2.7	1.4	5.1	3.6	4.3	2.9	4.0
Total	4.9	3.2	6.7	5.0	6.3	3.9	5.9

μ-like samples

FHC 1Rμ



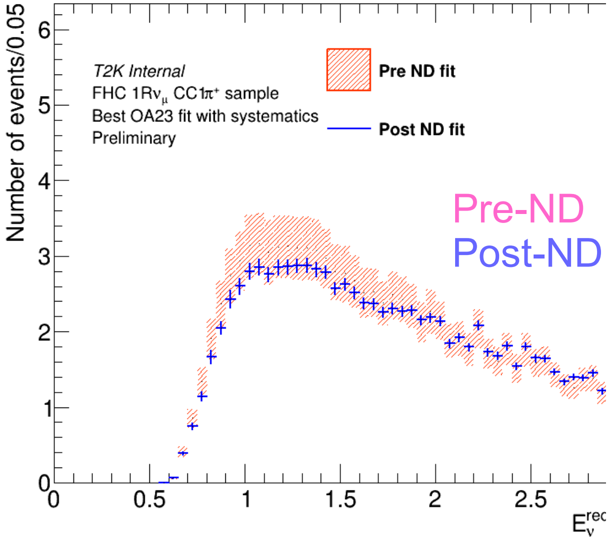
Effect of ND280 fit



DATA

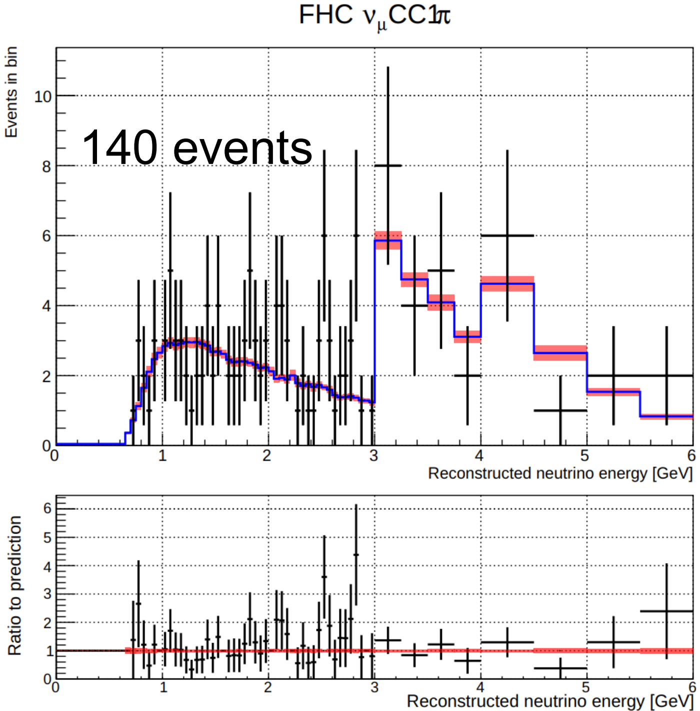
357 events

FHC MR (μ pi)



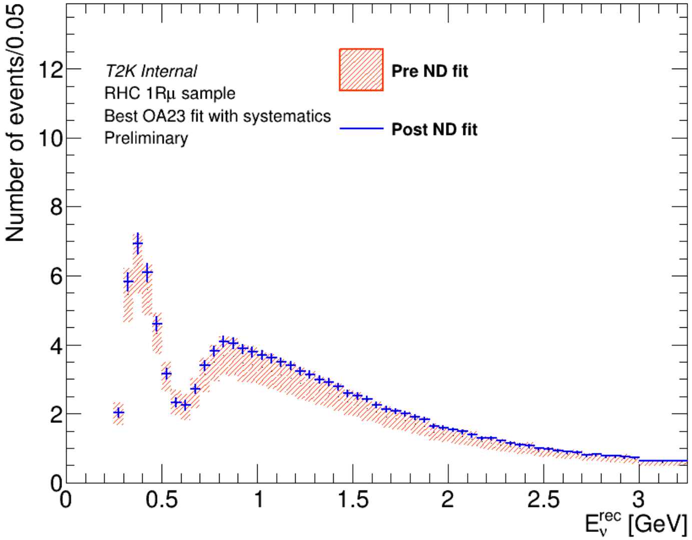
Pre-ND

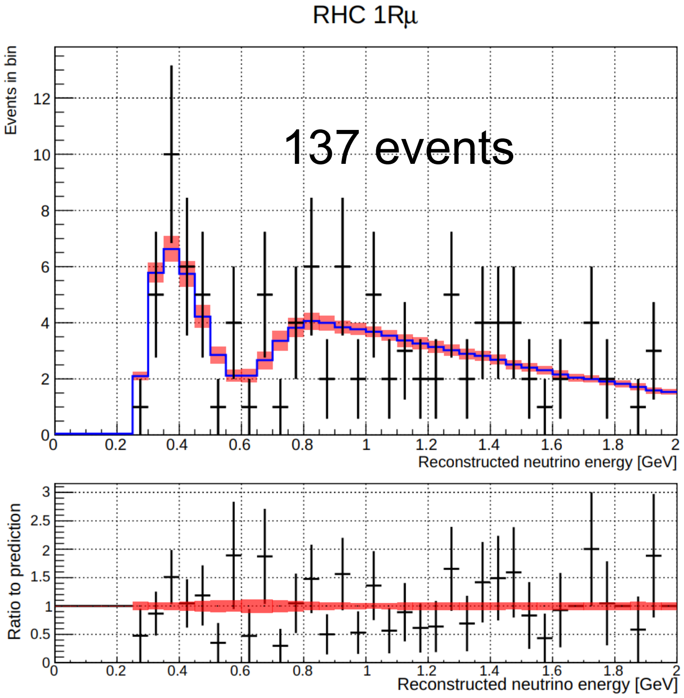
Post-ND



140 events

RHC 1Rμ

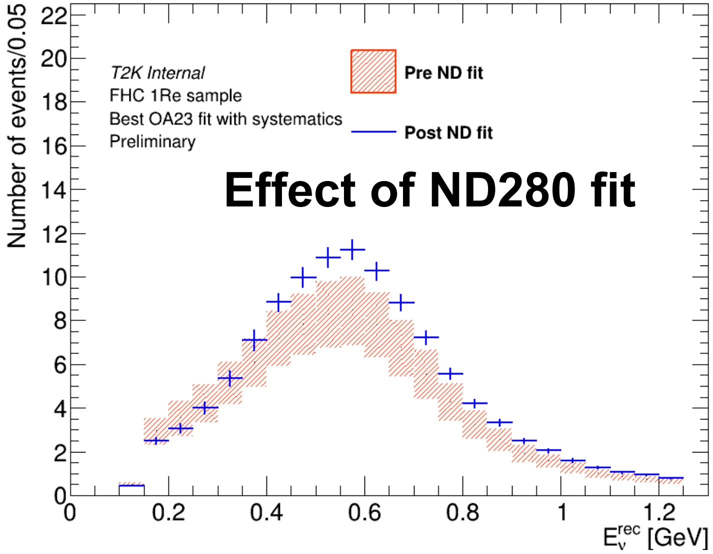




137 events

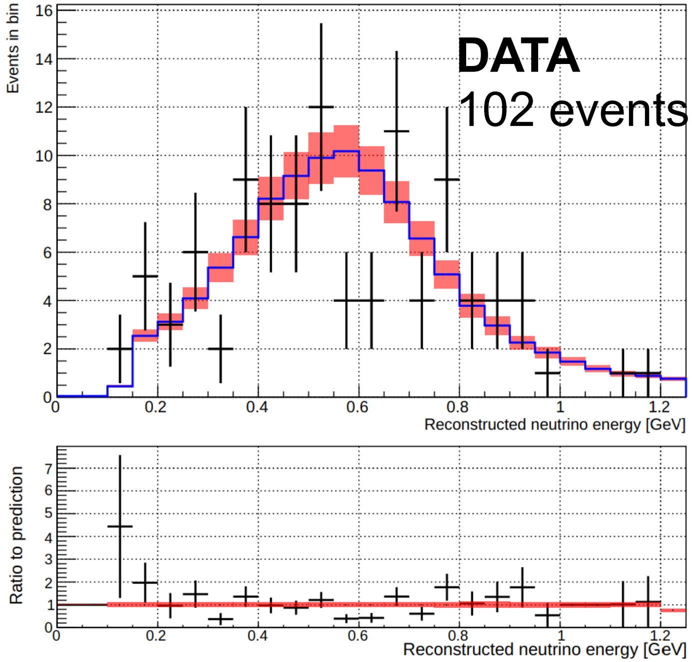
e-like samples

FHC 1Re



Effect of ND280 fit

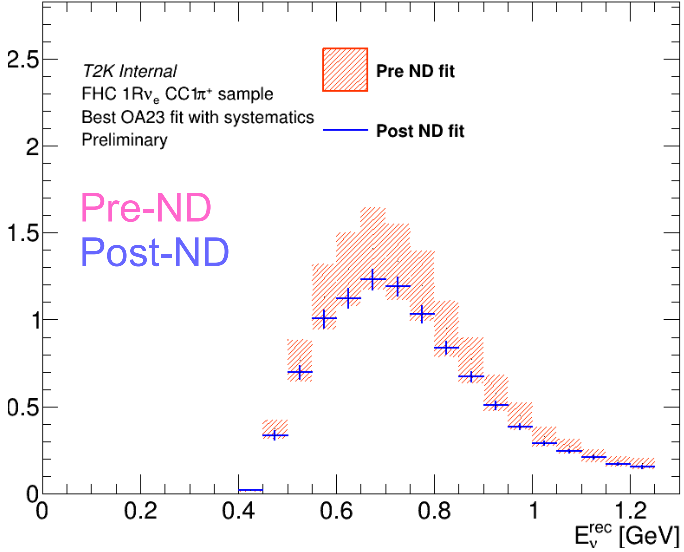
FHC 1Re



DATA

102 events

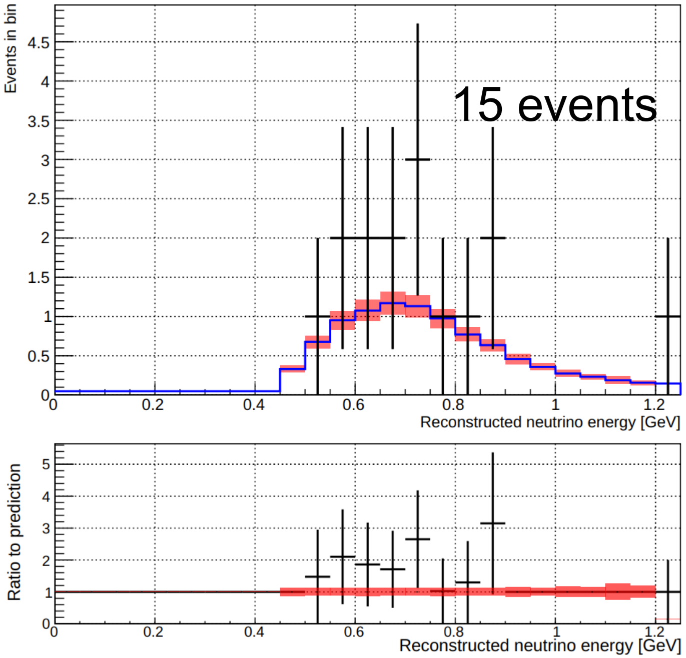
FHC 1Re +pi



Pre-ND

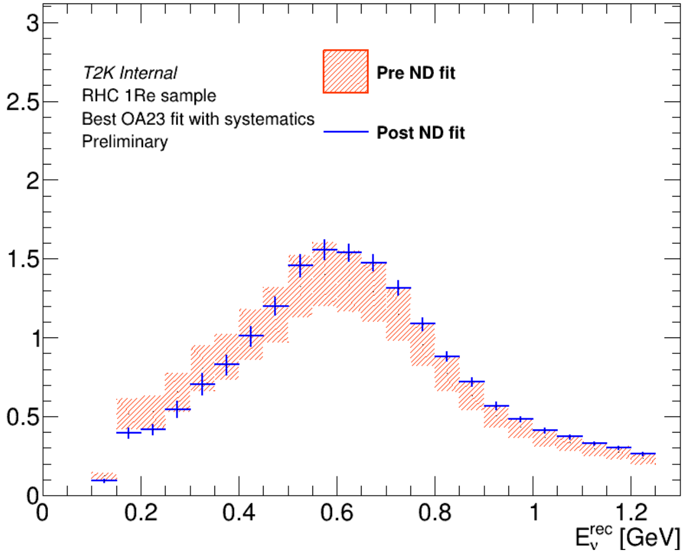
Post-ND

FHC 1Re1d.e

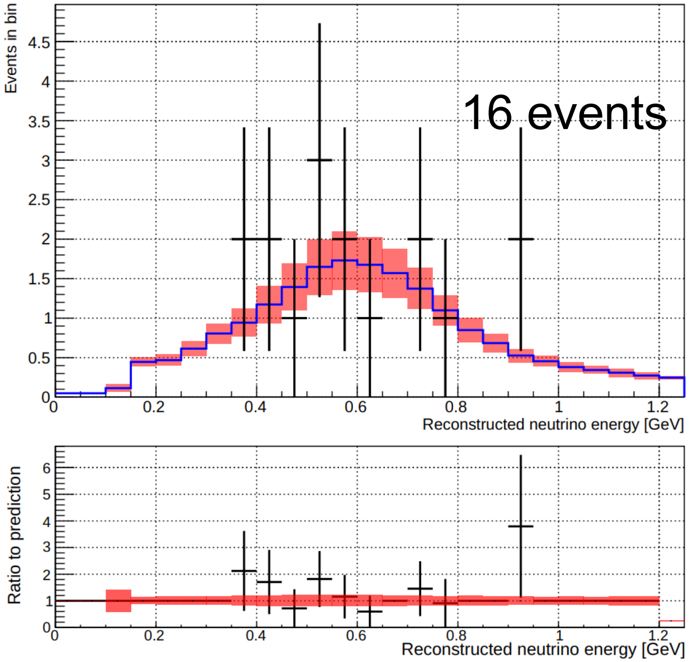


15 events

RHC 1Re

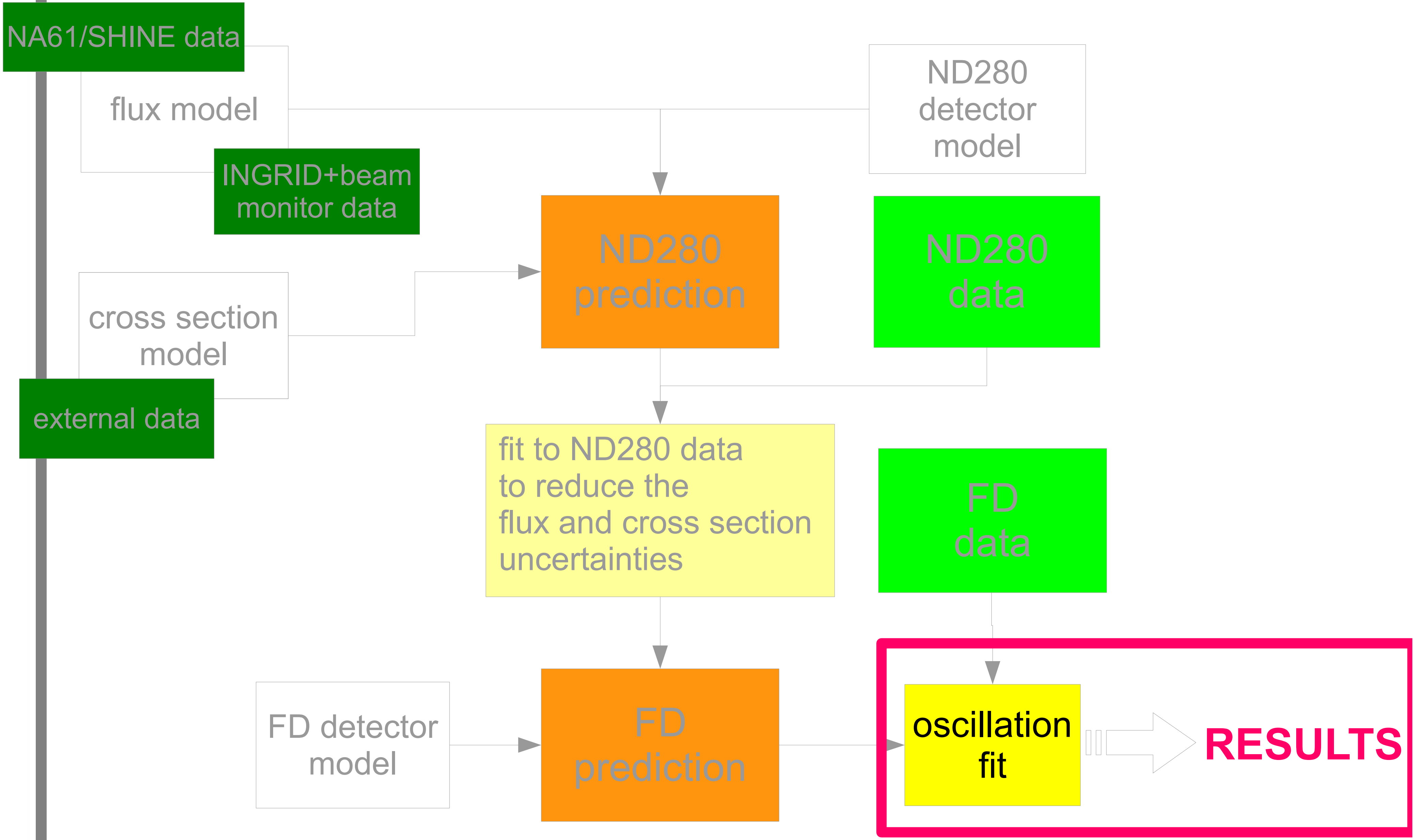


RHC 1Re



16 events

Analysis flow



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RESULTS

Oscillation fits

- $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ combined analysis within the 3ν oscillation paradigm (PMNS)
- several fitter groups with some analysis differences:
  - sequential ND-FD fit ↔ simultaneous ND+FD fit
  - frequentist approach ↔ Bayesian MCMC approach
  - lepton kinematics ↔ reconstructed neutrino energy assuming 2-body interactions

$$E_{rec} = \frac{ME_\mu - m_\mu^2/2}{M - E_\mu + |\vec{p}_\mu| \cos\theta_\mu}$$

- fit for θ_{13}, θ_{23}, Δm^2_{32}, δ_{CP}
  - other oscillation parameters from PDG 2020 values
  - results with T2K data alone and using PDG 2020 constraint on θ_{13} from reactor experiments
- binned likelihood comparing data to MC predictions

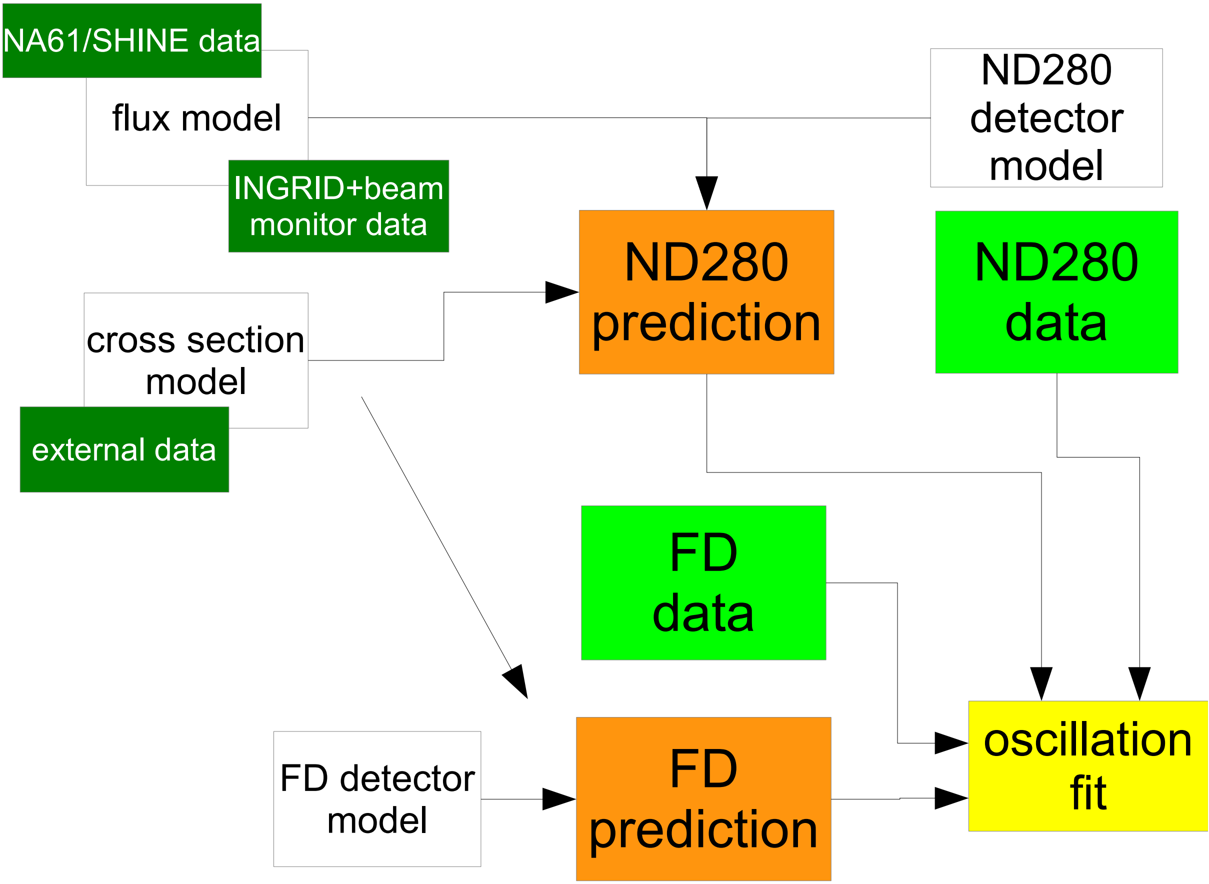
$$-2\ln\lambda(\delta_{CP};\boldsymbol{a}) = 2\sum_{i=1}^{N}\left[n_i^{obs}\ln\left(\frac{n_i^{obs}}{n_i^{\exp}}\right) + n_i^{\exp} - n_i^{obs}\right]$$

nuisance parameters (flux, x-sec, detector)

$$+ (\boldsymbol{a}-\boldsymbol{a}_0)^T \boldsymbol{C}^{-1} (\boldsymbol{a}-\boldsymbol{a}_0)$$

Bayesian analysis

- based on Markov Chain Monte Carlo (MaCh3 package)
  - directed random walk across multi-dimensional parameter space towards lower values of -2LLH (sometimes also in different direction)
  - simultaneous fit of near and far detector samples
  - output: posterior probability distributions of parameters
  - posterior predictive distributions of observables



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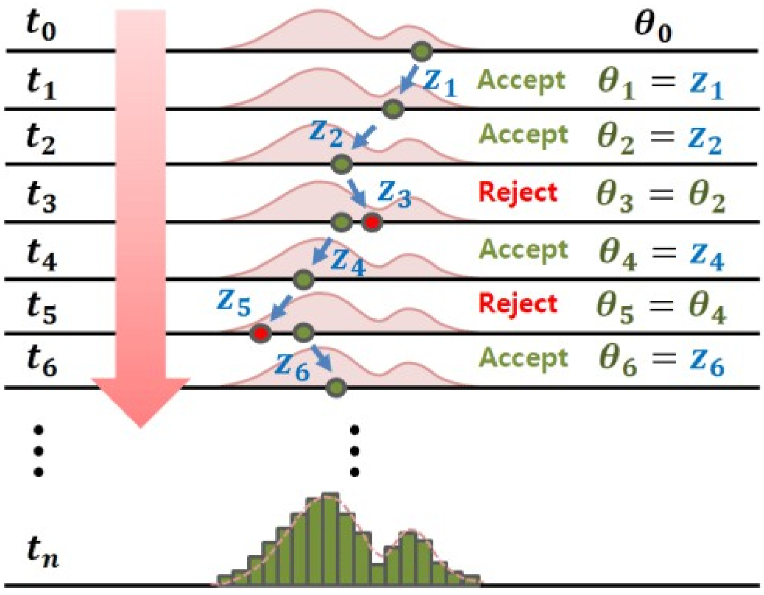
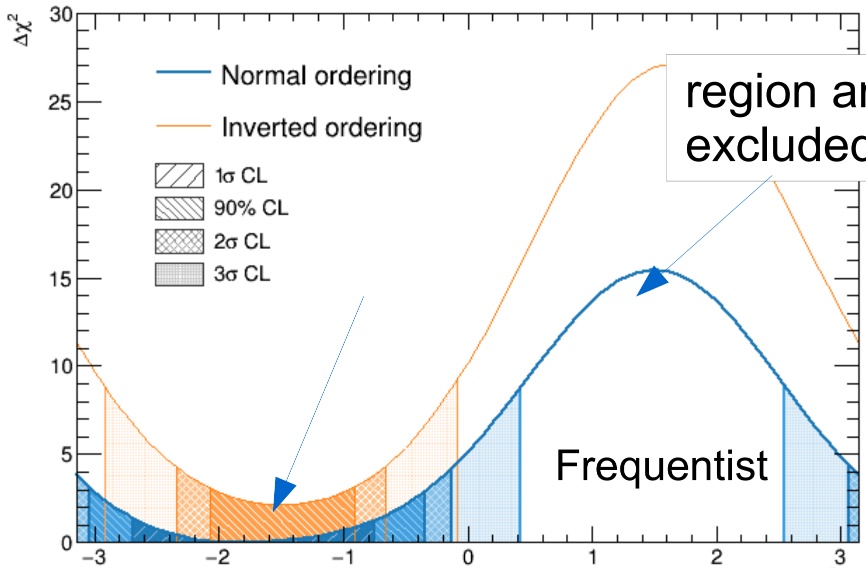


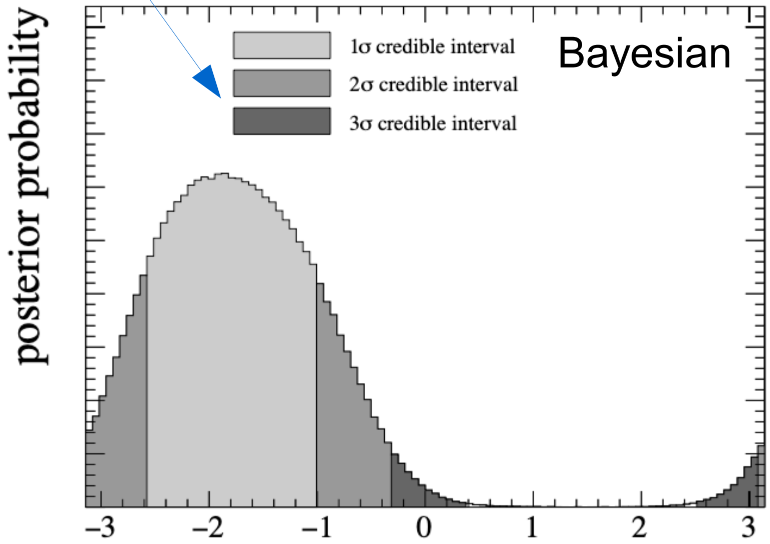
δ_{CP} and Jarlskog invariance



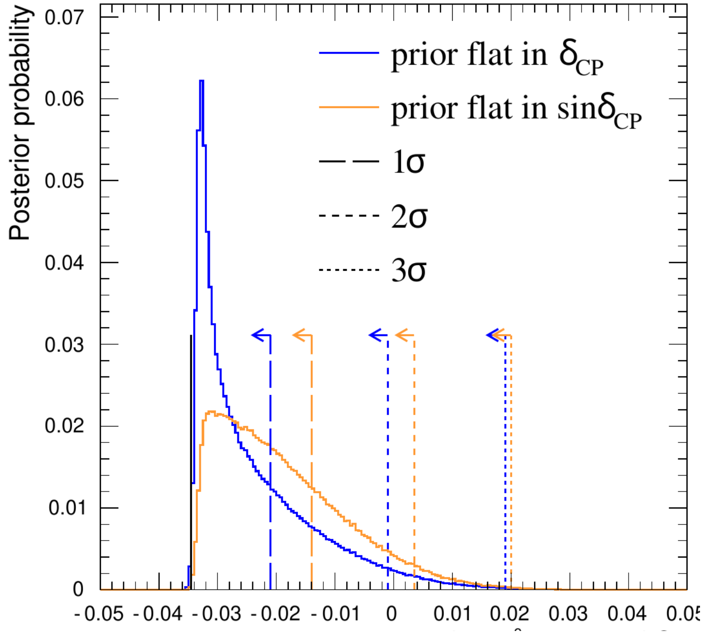
$\boldsymbol{\delta_{CP}}$

region around π/2 excluded at 3σ

CP-conservation (δ_{CP}= 0 or π) excluded at 90% but within 2σ



$\boldsymbol{\delta_{CP}}$



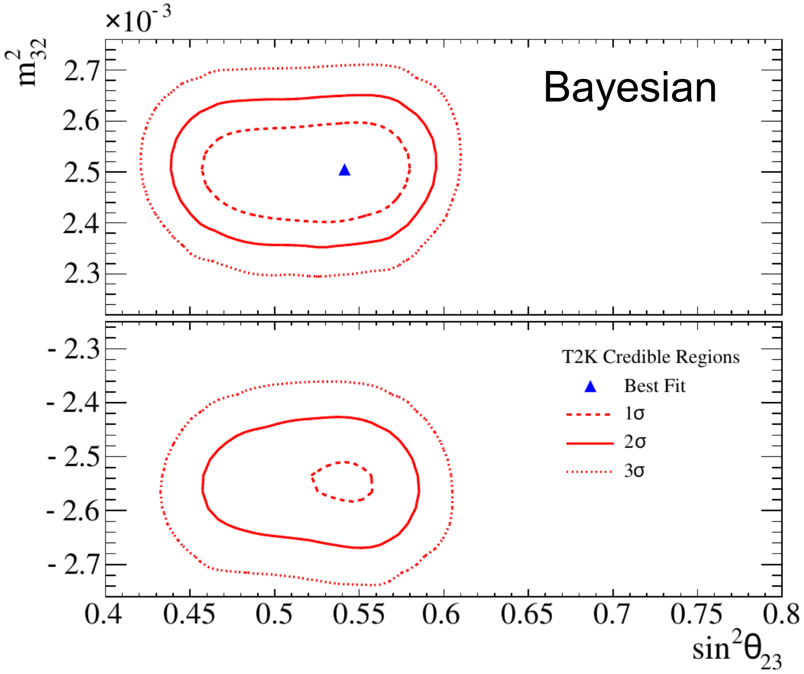
$\boldsymbol{J_{CP}}$

$J_{CP} = s_{13}c^2_{13}s_{12}c_{12}s_{23}c_{23}\ \sin\delta_{CP}$

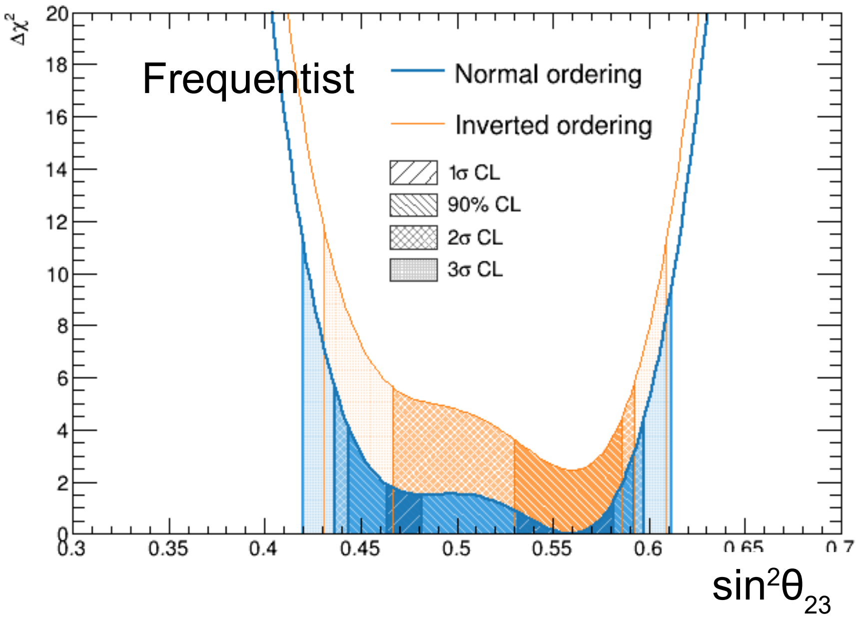
- Independent of PMNS parameterization
- Stable CPV-preference for different priors

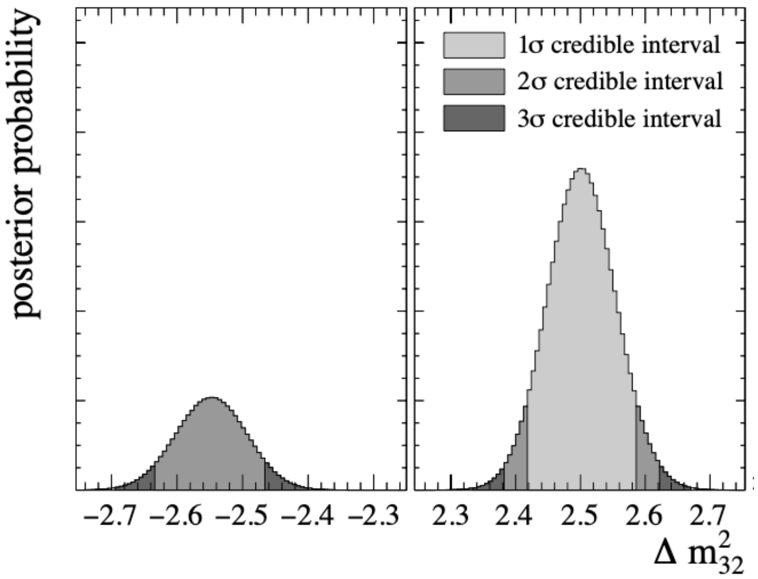
T2K preference for Jarlskog

$\sin^2\theta_{23}$ and $|\Delta m^2_{32}|$



with reactor constraint





Slight preference for normal ordering and upper octant:

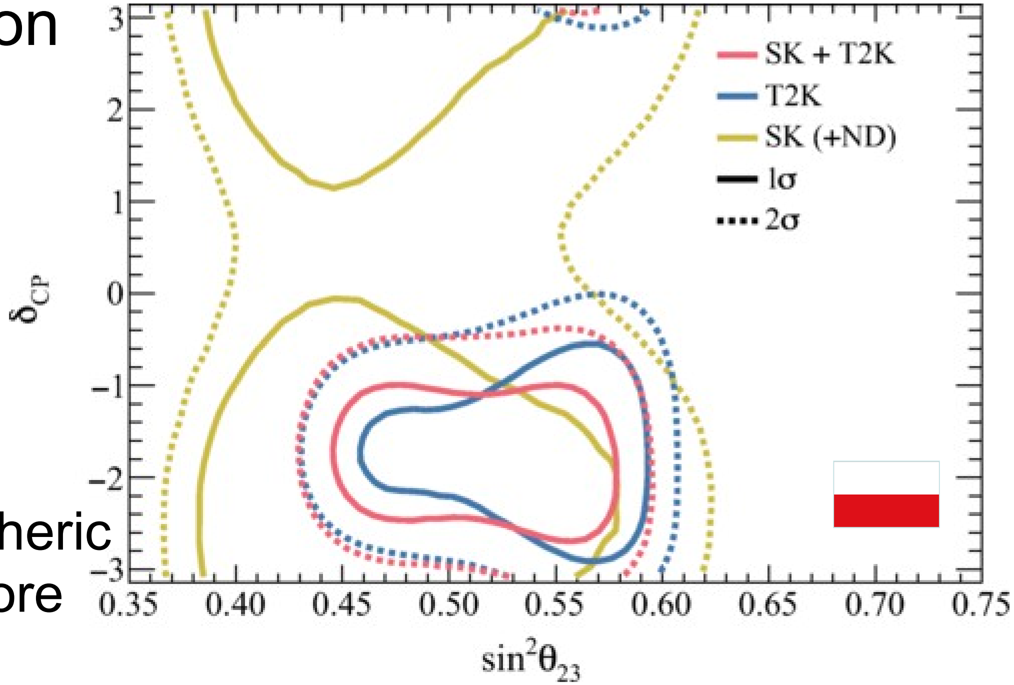
- NO/IO Bayes factor = 3.3
- $(\theta_{23}>0.5)/(\theta_{23}<0.5)$ Bayes factor = 2.6

(barely worth mentioning in Jeffreys' scale)

Δm^2_{32} (NO)/Δm^2_{31} (IO)	$(2.521^{+0.037}_{-0.050})10^{-3}\mathrm{eV}^2/\mathrm{c}^4$	$(-2.486^{+0.043}_{-0.044})10^{-3}\mathrm{eV}^2/\mathrm{c}^4$
$\sin^2(\theta_{23})$	$0.568^{+0.024}_{-0.125}$ (90%)	$0.567^{+0.021}_{-0.048}$ (90%)

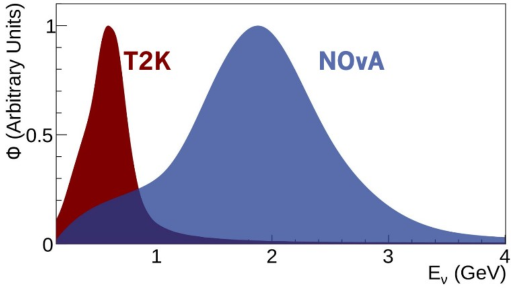
T2K-SK joint fit

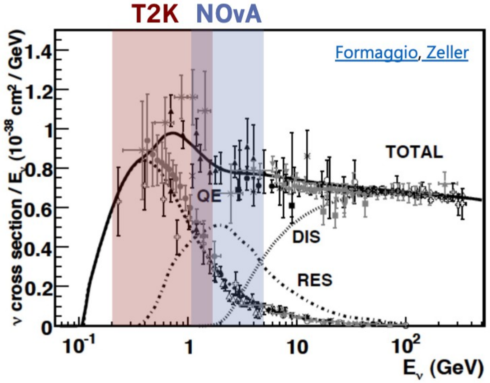
- T2K has good sensitivity to δ_{CP} but mild sensitivity to mass ordering, SK has good constraint on mass ordering but not on δ_{CP}
- common neutrino interaction and detector models have been developed for events from the two experiments with overlapping energies and are found to properly describe both datasets
  - based on SK4 data - 3244 days (2008-2018) of SK4 atmospheric data (PTEP, 5, 053F01, (2019)) and T2K data published in Phys. Rev. D 108, 7, 072011, (2023)
- the combined analysis finds increased preferences for δ_{CP} non conservation (1.9-2.0σ)
- limited preference for the normal ordering with a 1.2σ exclusion of the inverted ordering
- no strong preference for θ_{23} octant
- future updates will include full SK atmospheric statistics (at least 50% more data) and more data from T2K



T2K and NOvA

	T2K	NOvA
baseline	**295** km	**810** km
peak energy	**600** MeV	**2** GeV
CPV effect	32%	22%
Matter effect	9%	29%
Near Detector	multi-purpose (TPC, FGD, ECAL) magnetized	extruded plastic cells filled with liquid scintillator
Far Detector	50 kton Water Cherenkov	14 kton scintillator
reactions	CC QE (also 2p2h, resonant)	mix
e/μ identification	Cherenkov ring shape	convolutional neural network
Neutrino energy reconstruction	2-body formula for QE or resonant interactions	calorimetric

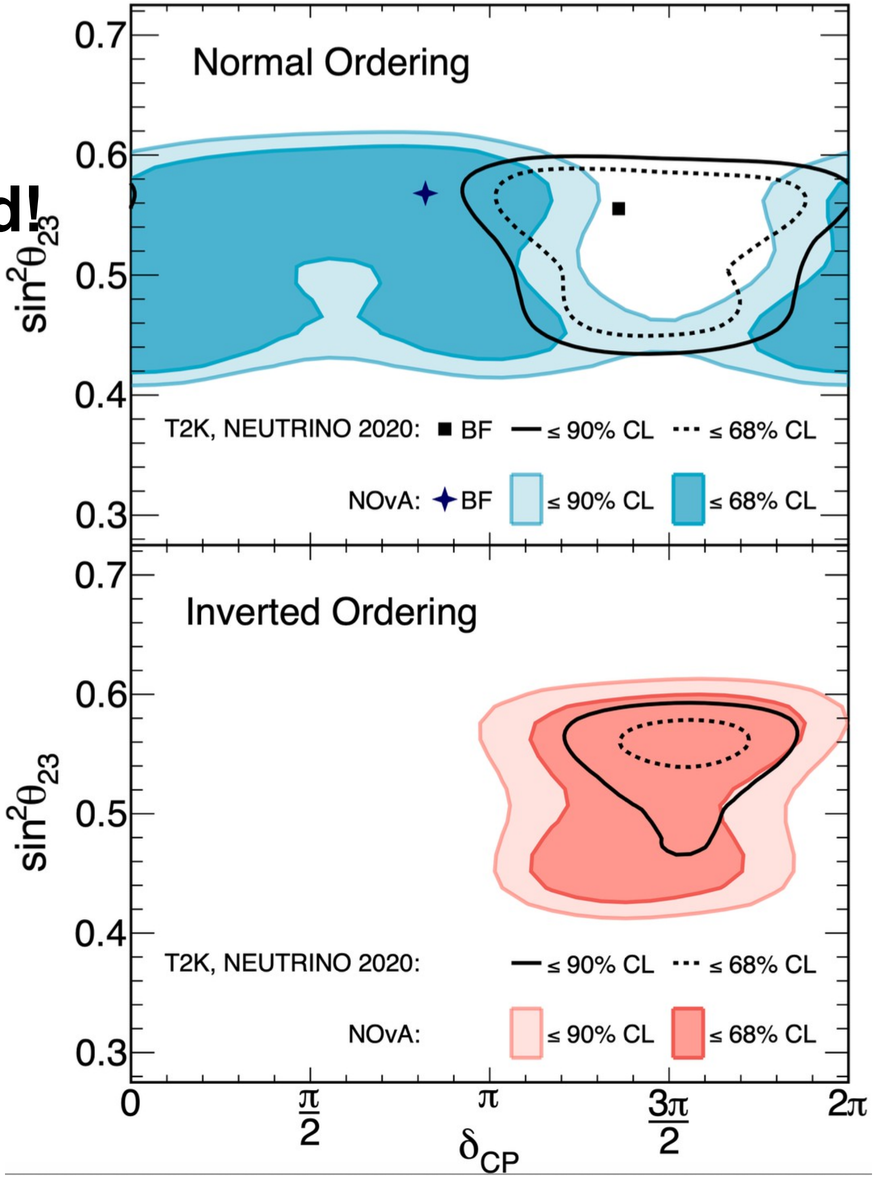




Formaggio, Zeller

T2K vs. NOvA

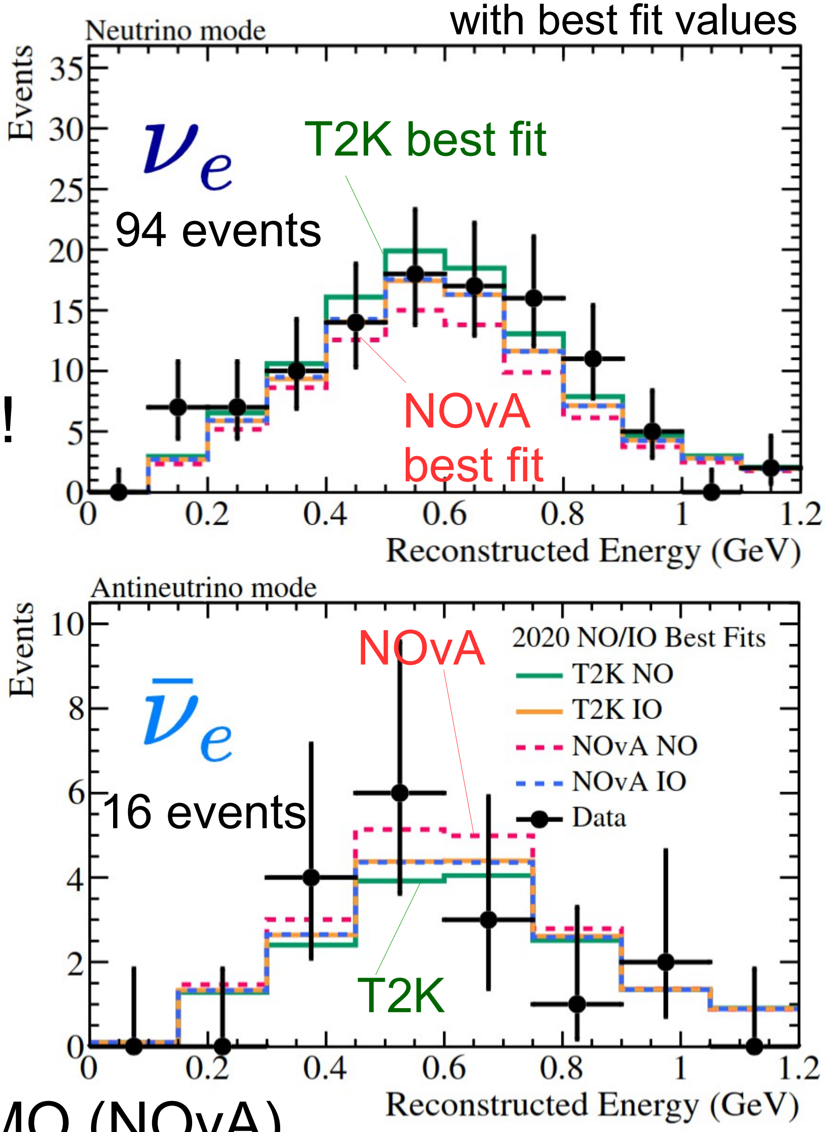
- both show a **weak preference for NO**
- some tension in **δ_{CP}** but remember: current results are **statistically limited!**
  - if IO: consistent preference for the 3π/2 (-π/2) region, small preference for upper octant



T2K vs. NOvA

- both show a **weak preference for NO**
- some tension in δ_{CP} but remember: current results are **statistically limited!**
  - if IO: consistent preference for the 3π/2 (-π/2) region, small preference for upper octant
- **more data needed** in both experiments!
- **joint fit** performed in 2024 (paper in preparation)
- Upgrades in both experiments:
  - NOvA – beam power → 900+ kW
  - T2K – beam power → 1.3 MW, ND280 upgrade, SK-Gd
  - Goal: 3σ sensitivity for CPV (T2K) and MO (NOvA)

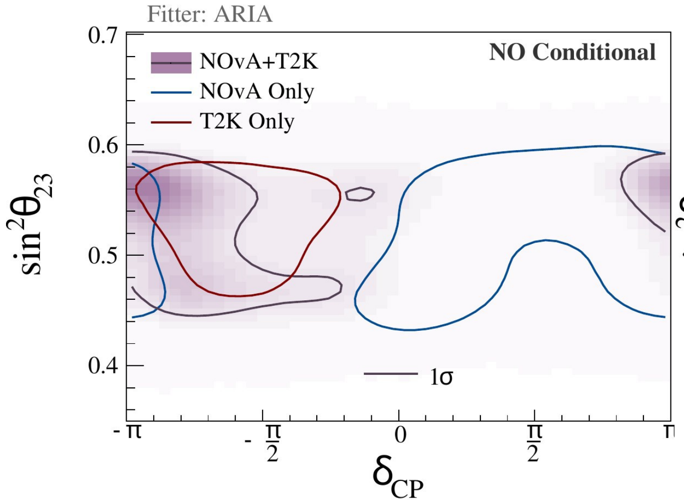
points - T2K data
histograms – predictions
with best fit values

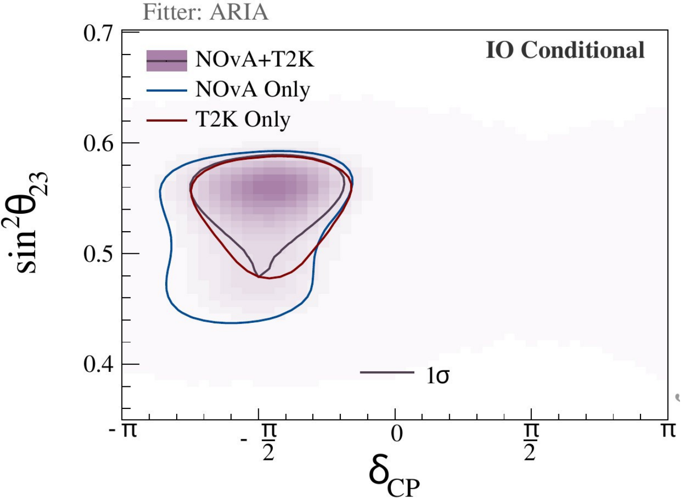


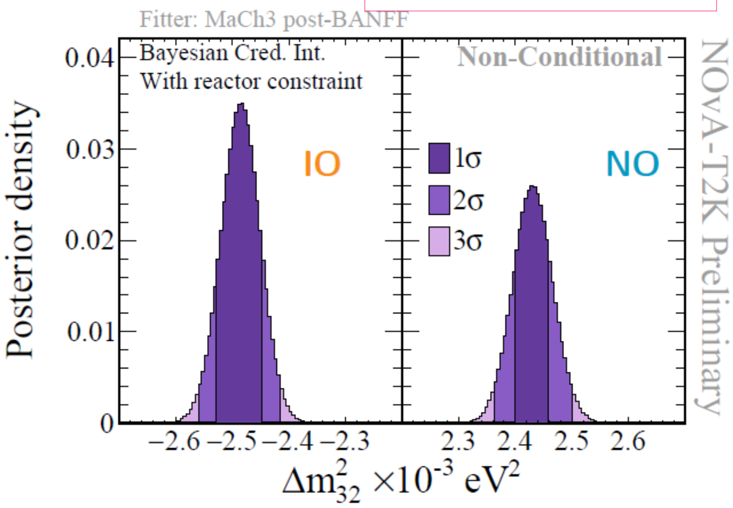
T2K-NOvA joint fit

- opposite to “global fits”, a **full implementation** of
  - consistent statistical inference across the full dimensionality
  - each experiments‘ detailed likelihood, energy reconstruction and detector response
- **in-depth review** of
  - models, systematic uncertainties and their possible correlations
  - different analysis strategies driven by different detector designs
- roughly **doubled statistical power** of individual experiments

Smallest uncertainty in Δm^2_{32} < 2 %

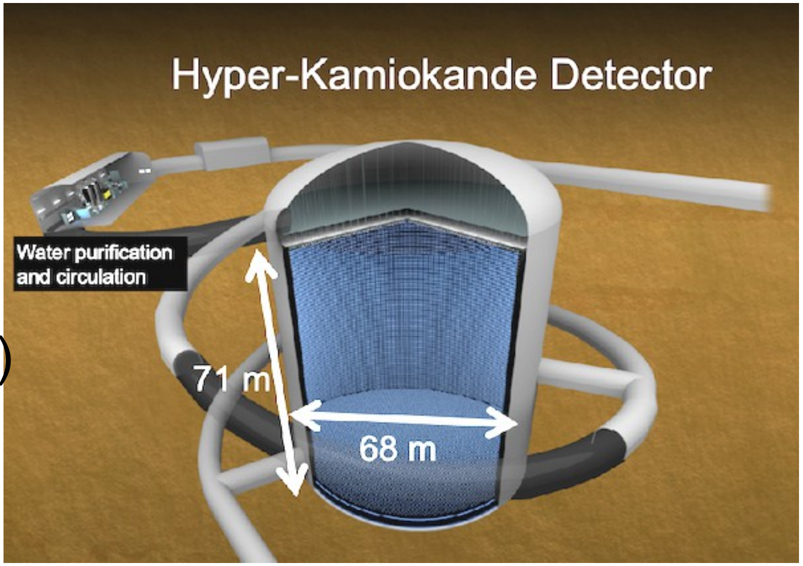






- values of $\boldsymbol{\delta_{CP}}$ ~π/2 disfavoured at >3σ. CP-conserving values of $\boldsymbol{\delta_{CP}}$ (0 and π) excluded at 3σ when IO is assumed
- Bayes factor of **3.6** for upper octant preference (modest) with RC (about 1σ), very weak preference for IO (Bayes factor 1.3)

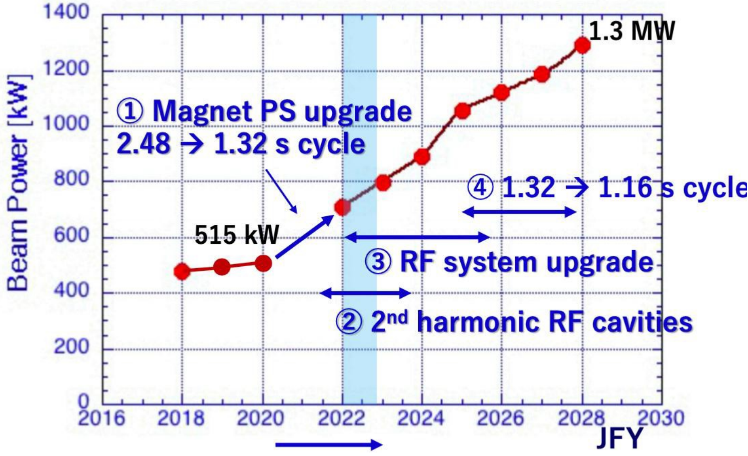
Hyper-Kamiokande

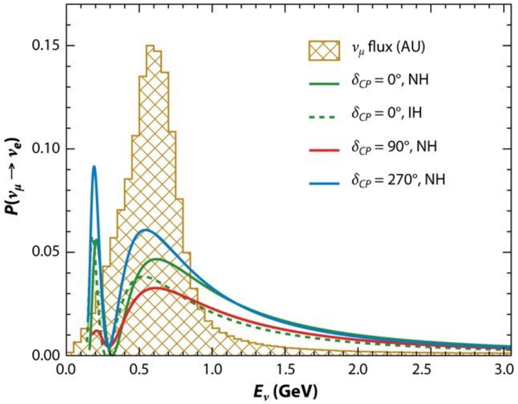


- total mass 258 kt (fiducial mass 186 kt)
  - 8.4 x Super-Kamiokande
  - Inner Detector equipped with:
    - 20 000 20" PMTs (twice better photodetection efficiency, charge and time resolutions) than SK PMTs)
    - 800 multiPMTs (19x3" PMTs to improve the Cherenkov rings reconstructions in the detector corners.)
    - 20% photocoverage
  - Outer Detector: 3600 PMTs mounted on Wave Length Shifter (WLS) plates
  - significant Polish contribution:
    - multiPMTs, elements of underwater electronics
    - electron linear accelerator for calibration NCBJ
    - computing NCBJ
    - development of simulation
    - participation in PMT tests, WCTE tests and installations

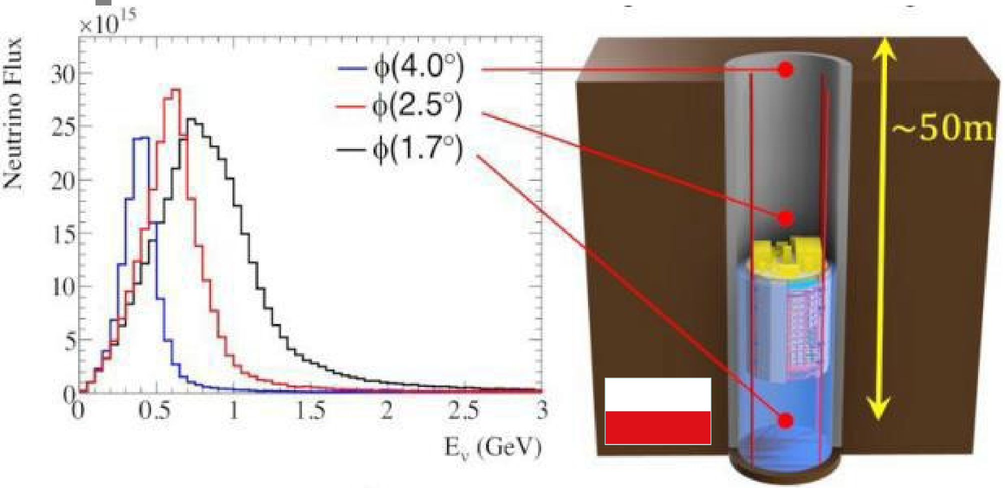
Hyper-K as a long-baseline experiment

- 1.3 MW beam from Tokai, **narrow band** beam and **off-axis** technique as T2K → CC QE events, most events close to oscillation maximum
- **295** km baseline → small matter effect

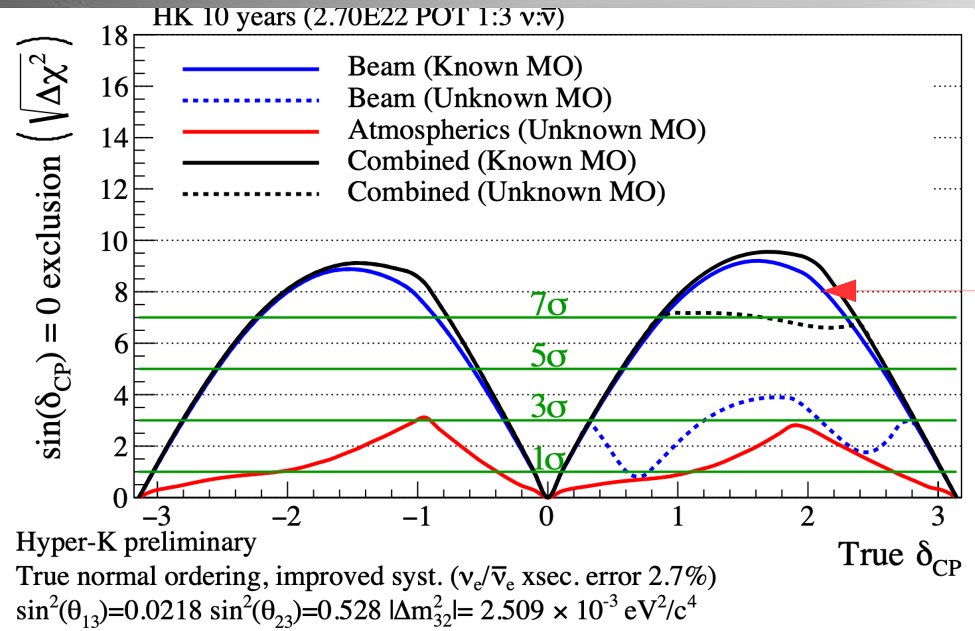


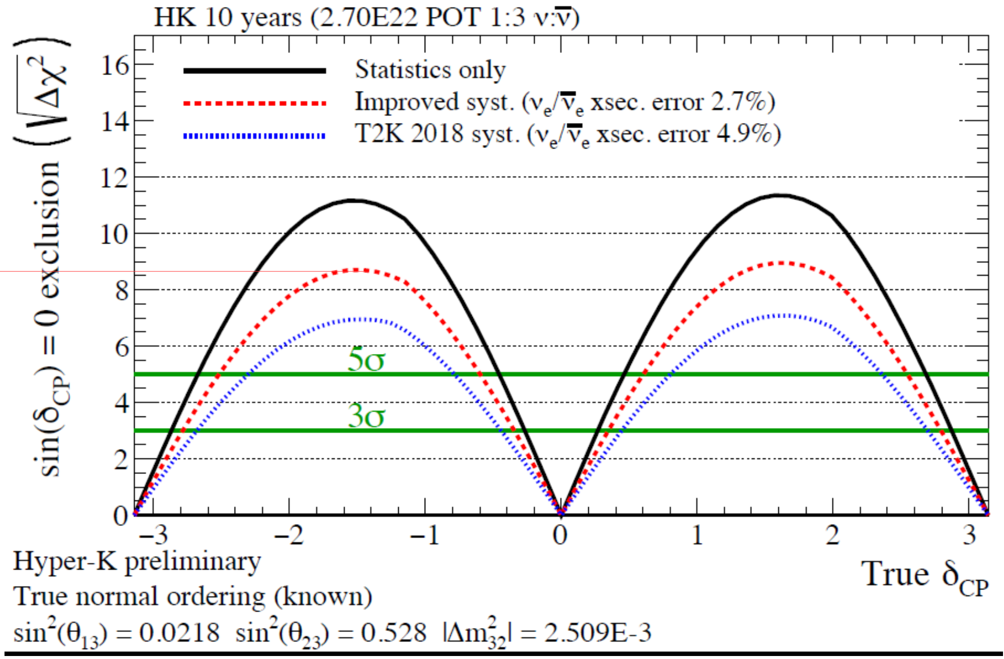


- near detectors: upgraded ND280
- new 1kton scale Water Cherenkov (**IWCD**) with off-axis angle spanning orientation at 830 m from the target
- take ND data in different fluxes → build linear combination to match FD oscillated spectra
- pit excavation will start summer 2025
- prototype beam tests now at CERN



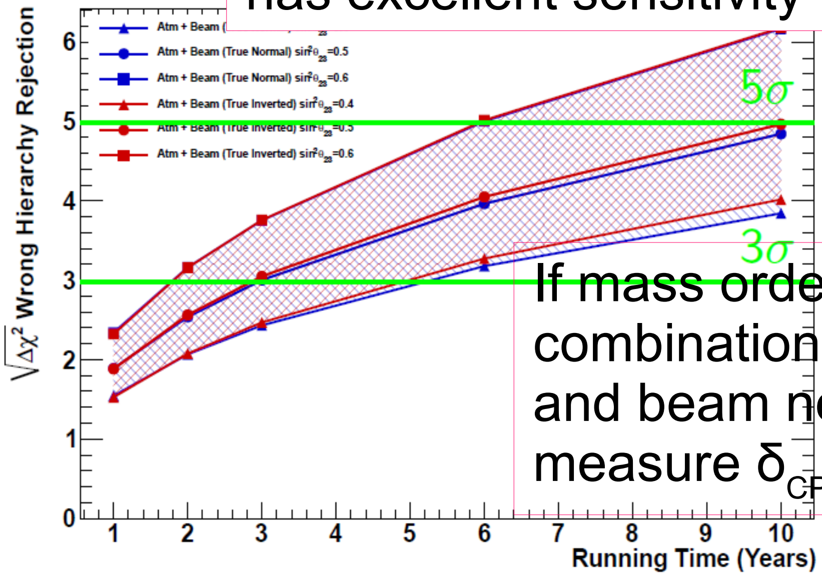
Hyper-K: sensitivities



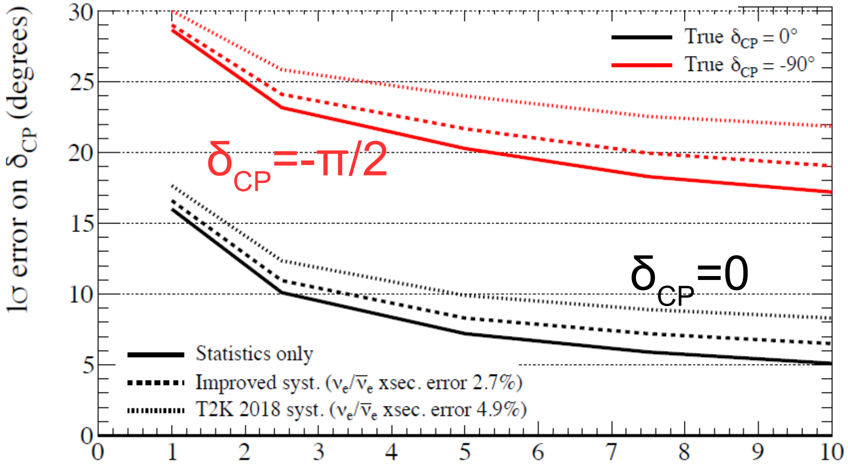


If mass ordering **known**, Hyper-K has excellent sensitivity to CPV

Systematics is crucial!

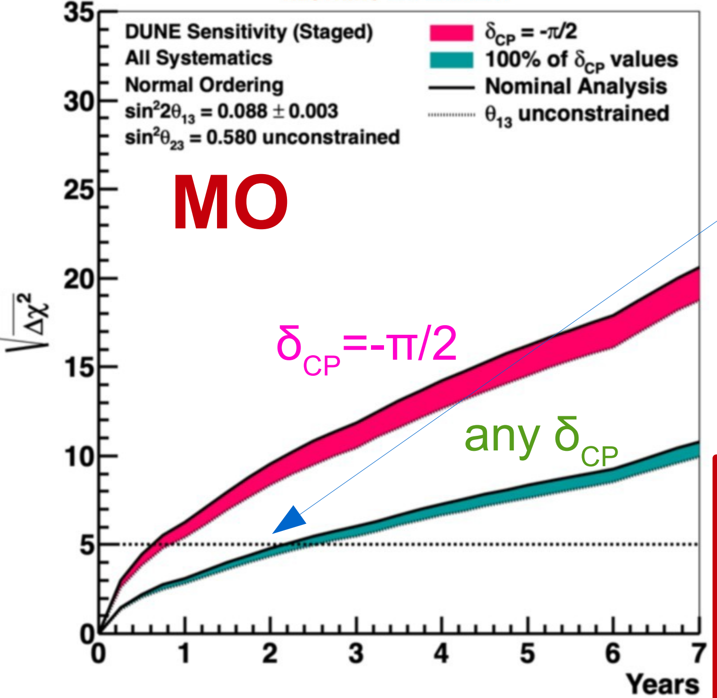


If mass ordering **unknown**, combination of atmospheric and beam neutrinos allow to measure δ_{CP} and MO

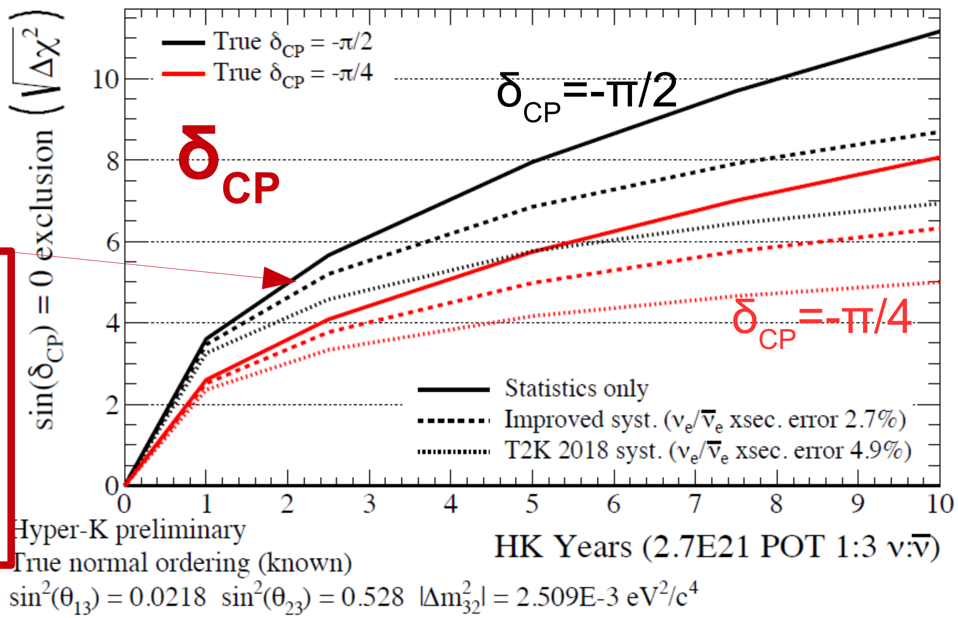


precision of HK δ_{CP} measurement

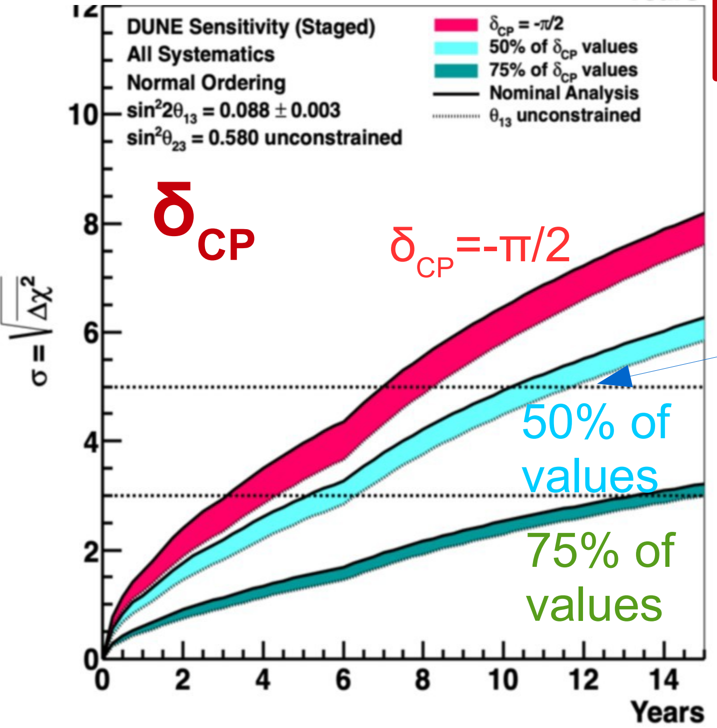
DUNE and Hyper-K



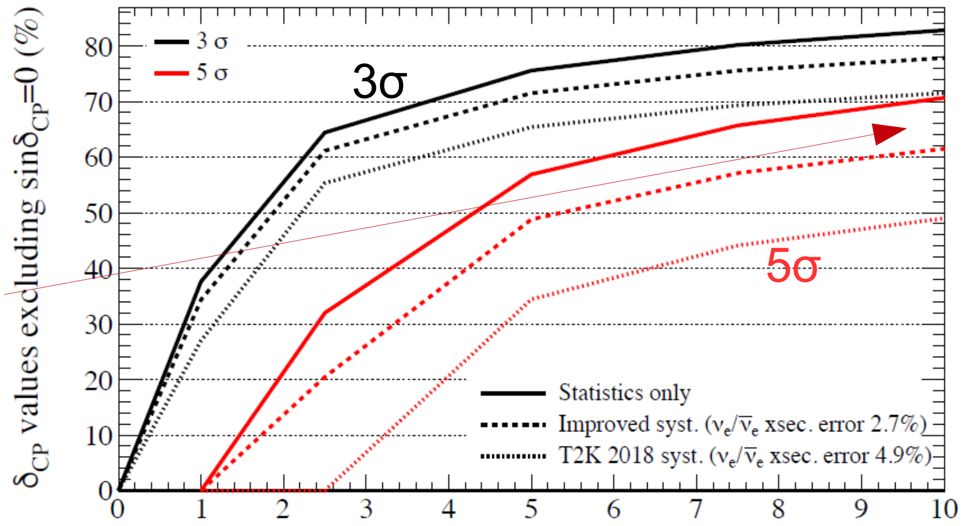
DUNE:
mass ordering
determination
already in phase I



HYPER-K:
if MO known:
2-3y to exclude CP
conservation at 5σ
(for true $\delta_{CP}=-\pi/2$)

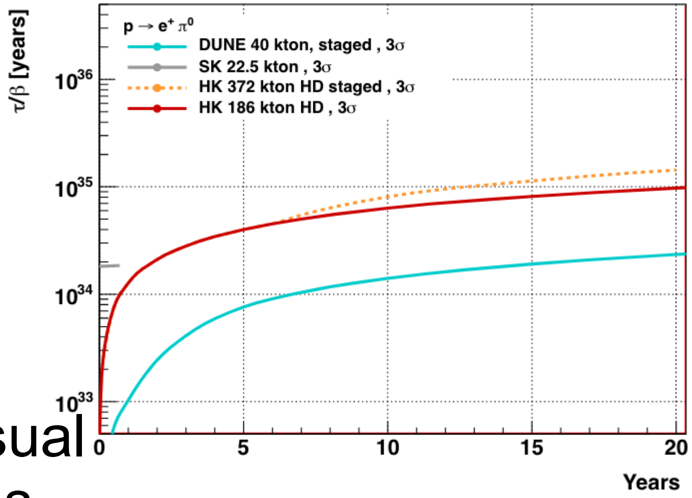


After 10 years
5σ sensitivity for
50% of δ_{CP} values
in DUNE
and 60% in HyperK

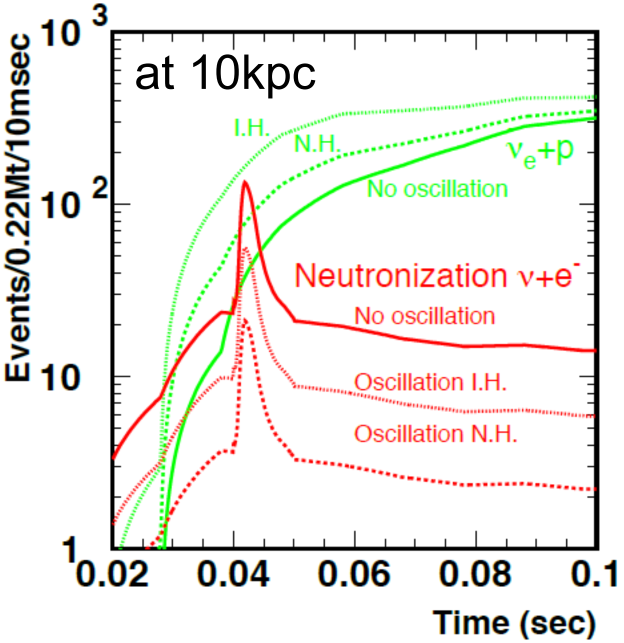


Hyper-K: not only oscillations

- **proton decay**
  - $e^+\pi^0$: 10^{35} years lifetime (3σ)
  - νK^+: 3×10^{34} years lifetime (3σ)



- precise measurements of **solar neutrinos**
  - Δm^2_{21}, day-night asymmetry
  - spectrum shape → allows to distinguish the usual neutrino oscillation scenario from exotic models
- **supernova neutrinos**
  - 54k-90k events expected at 10 kpc burst
  - information on neutrino oscillations and properties (mass, mass hierarchy) as well as core-collapse supernova models
  - early warning for telescopes



- **relic supernova neutrinos**
  - ~4 events expected/year
  - first measurement may be done by SK-Gd but Hyper-K may measure the spectrum

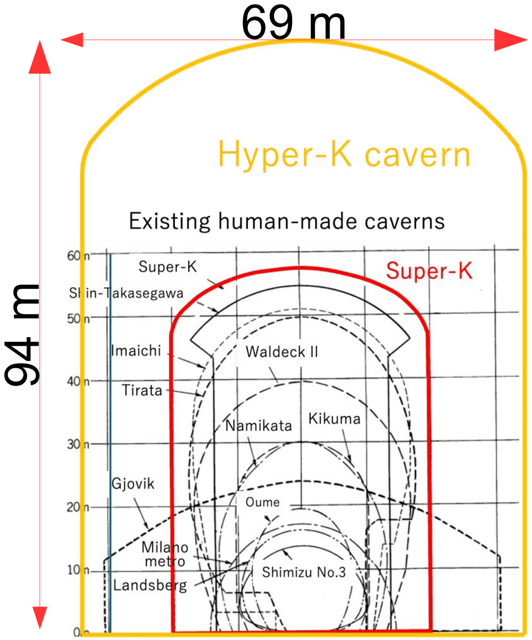
Hyper-K status

- Main cavern: the largest ever human-built cavern
- PMTs production and testing 🇵🇱
- multiPMTs production and testing 🇵🇱


>10,000 delivered

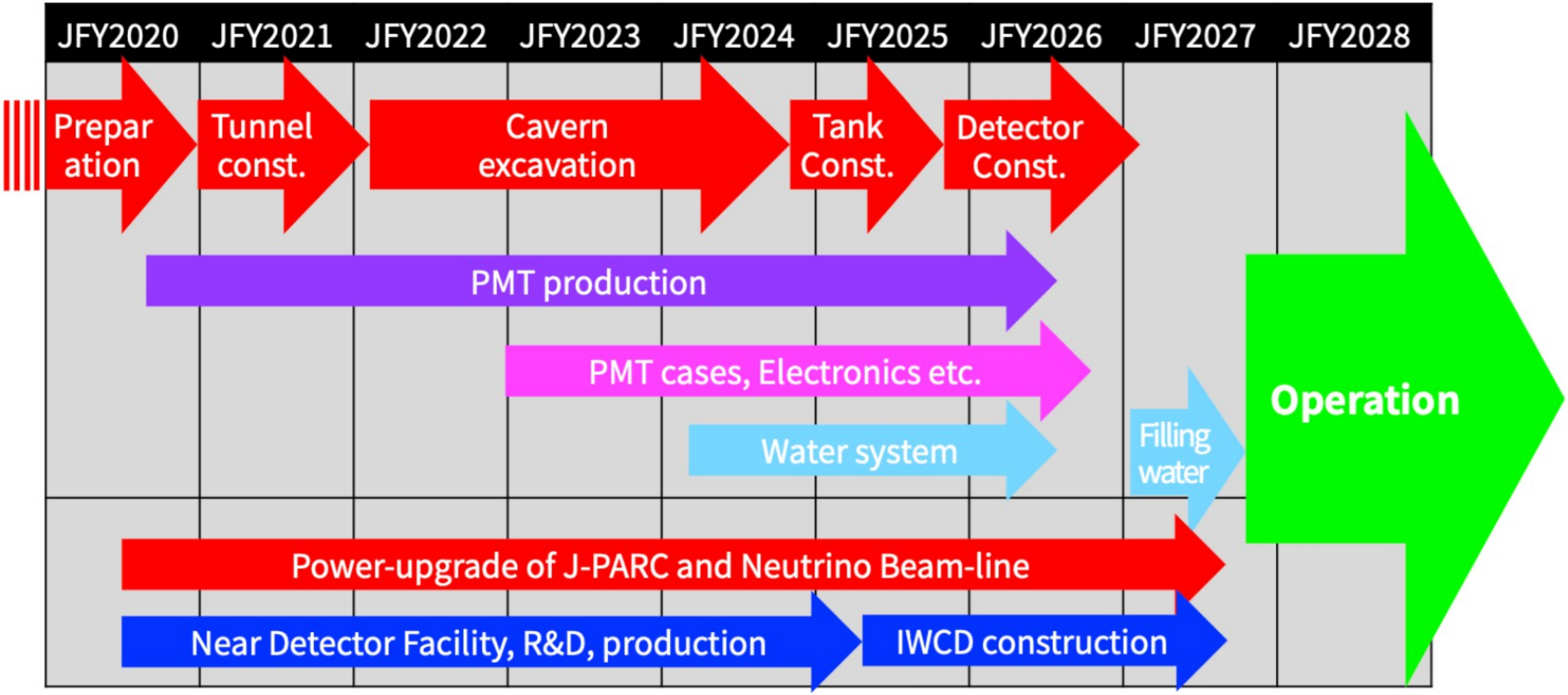

Main cavern: 12 out of 19 horizontal layers completed


【2023/07/13】 Cavern for water purification system (~1/2 of Super-K)



Schedule of Hyper-K

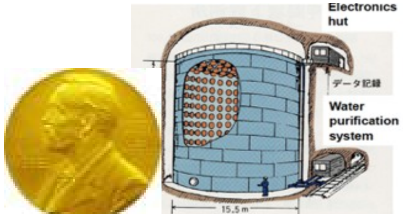
- Construction phase extended by 6 months – changes of the structure of the detector top.
- May 2027: start of the water filling
- December 2027: start of the detector operation



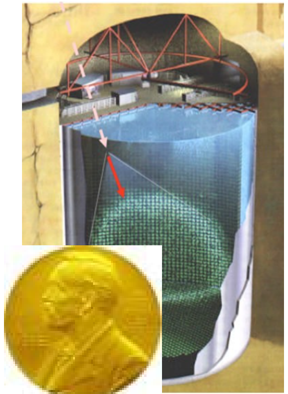
Summary

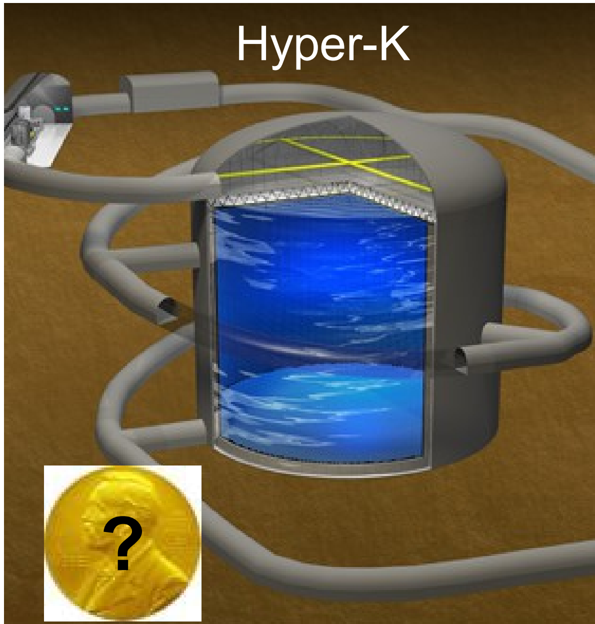
- over 25 years after the discovery of neutrino oscillations we are in the era of precise measurements
- few % precision on most parameters
  - controlling the systematics becoming crucial!
- T2K provides world-leading precision on θ_{23} and CP Violation
  - best precision on $|\Delta m^2_{32}|$ from T2K-NOvA joint fit
- rich T2K cross-section measurements program for the near future (using upgraded facilities)
- Hyper-Kamiokande construction progressing
  - expected to start taking data before 2030
- very exciting neutrino physics possibilities ahead of us!

KamiokaNDE



Super-K



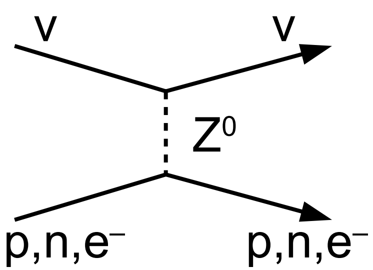


BACKUP

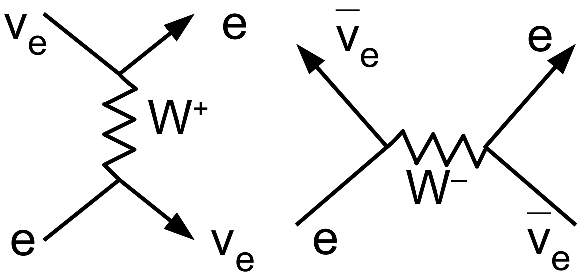
Matter effects (MSW effect)

- solar neutrinos are produced in dense matter of the Sun and propagation in matter is affected by the presence of **electrons**

same for ν_e, ν_μ, ν_τ



only for ν_e

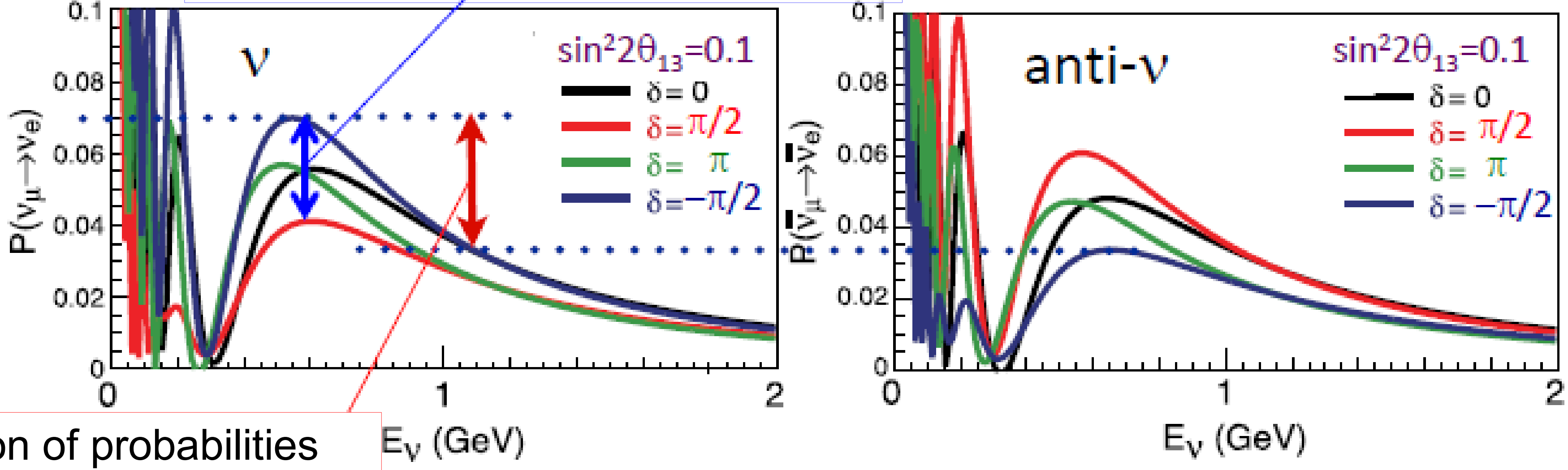


- energy levels of propagating eigenstates are altered for **ν_e component** (different interaction potentials in kinetic part of the hamiltonian)
  - effective mass changed: ν_e raised, $\bar{\nu}_e$ lowered
  - sensitivity to $\Delta m^2 \sim 10^{-5}$ eV^2, while oscillations in vacuum to 10^{-10} eV^2 for energies of solar neutrinos
- resonant enhancement occurs for particular energies
  - depending on electron density and Δm^2
- matter effects are **sensitive** to mass ordering

ν_e appearance

- discovered by T2K in 2013
  - probability depends on θ_{13}, θ_{23} – and δ_{CP}

appearance probability for neutrinos



comparison of probabilities
for netrinos and antineutrinos

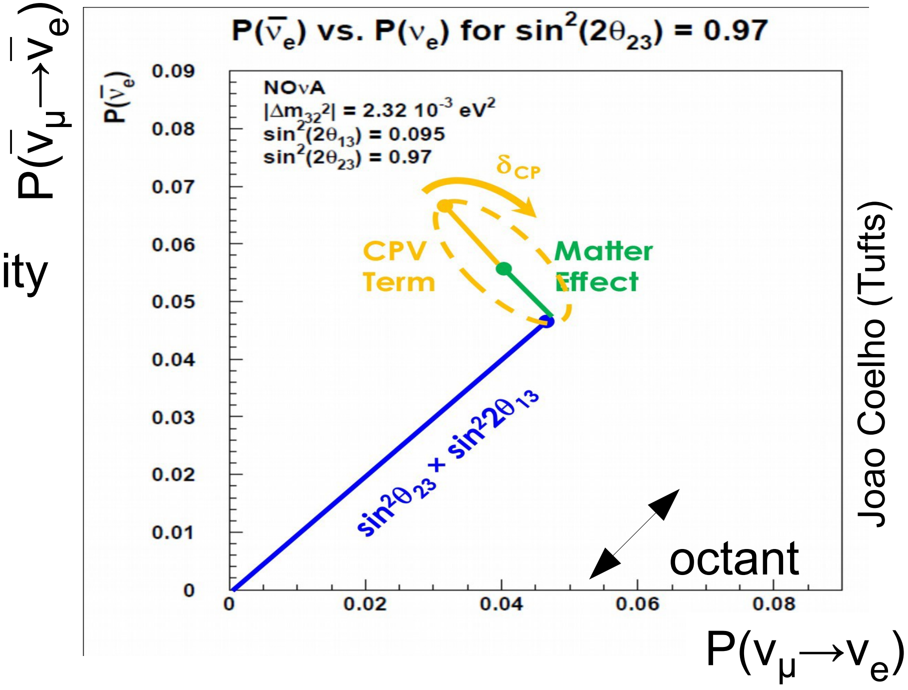
  - due to matter effect different probabilities for ν and $\bar{\nu}$ even if CP is not violated
  - parameter degeneracies to disentagle: effects from mass hierarchy, CP violation, octant of θ_{23} – more effects to study
  - combination of experiment with different baseline increase sensitivity

Biprobability plots

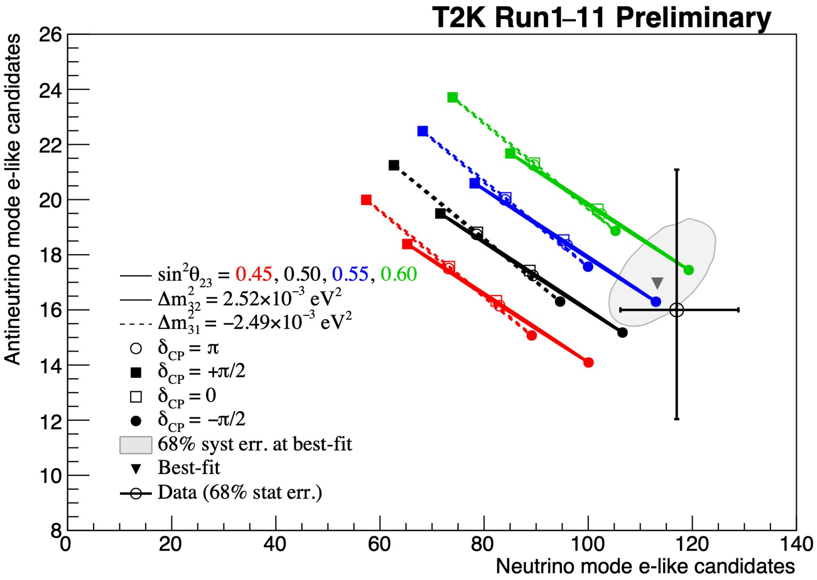
- comparisong of ν_e and $\bar{\nu}_e$ appearance
  - different probabilities for ν and $\bar{\nu}$ even if CP is not violated – due to matter effects
  - parameter degeneracies to disentagle: effects from mass hierarchy, CP violation, octant of θ_{23} – more effects to study
  - combination of experiment with different baseline increase sensitivity: T2K and NOvA, HK and DUNE

biprobability plot

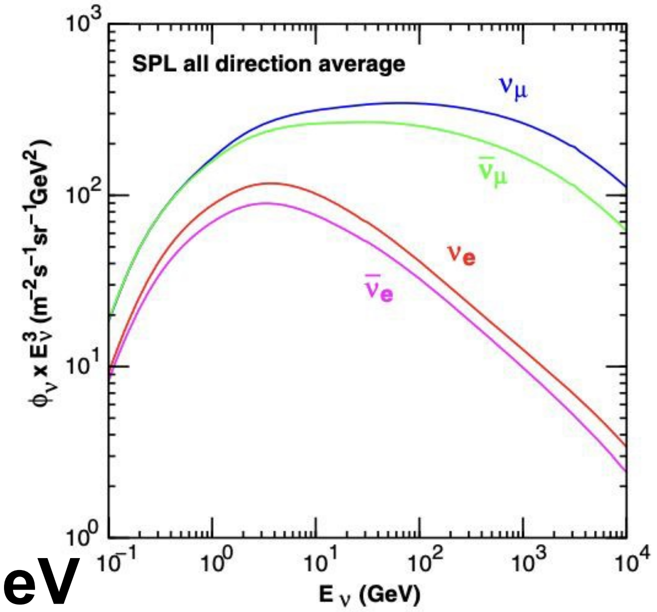
excellent resolution needed



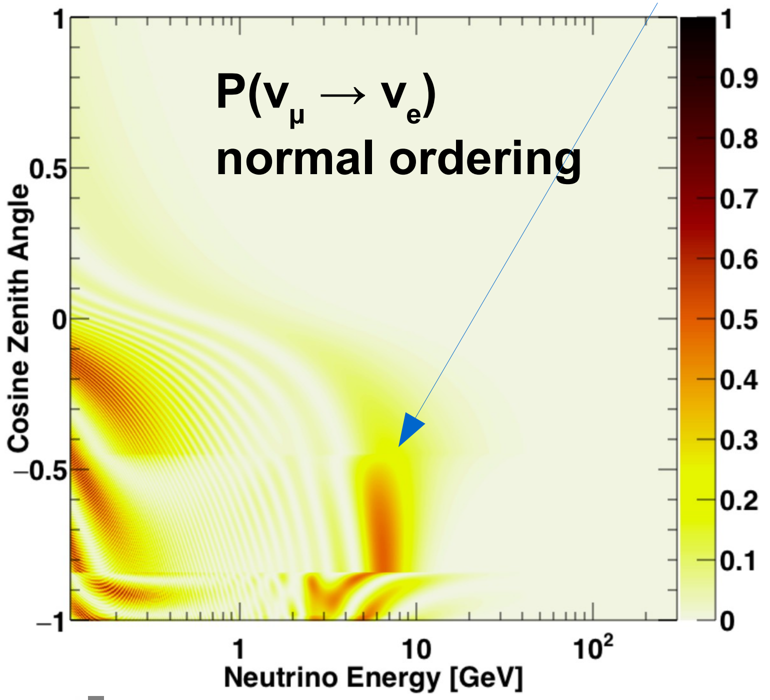
Joao Coelho (Tufts)

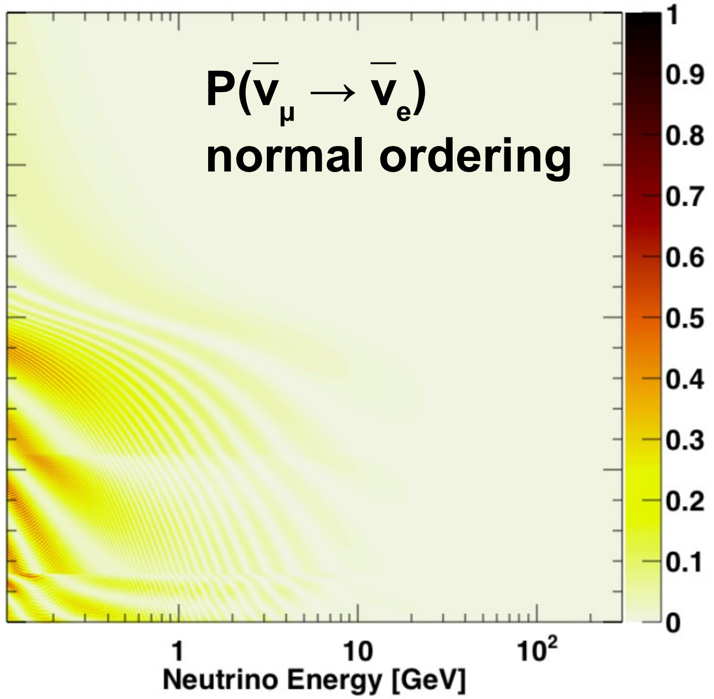


Atmospheric neutrinos

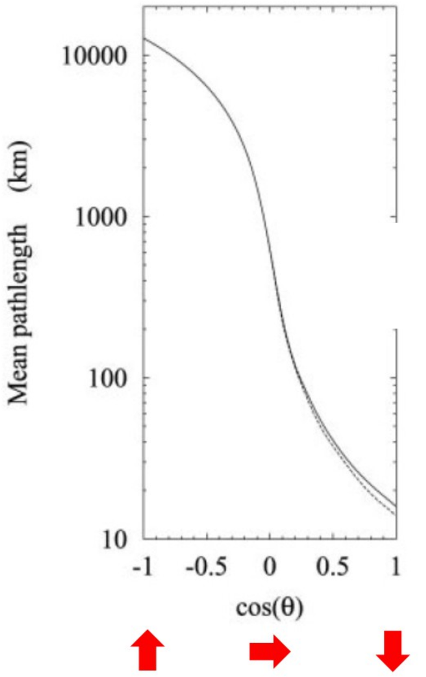


- wide range of energies and baselines
  - baseline determined from direction
- sensitive to θ_{23}, Δm^2_{32}, mass ordering
- mass ordering can be determined using **6-12 GeV** neutrinos thanks to matter effect in the Earth's core
  - for normal (inverted) ordering oscillations enhanced for (anti)neutrinos

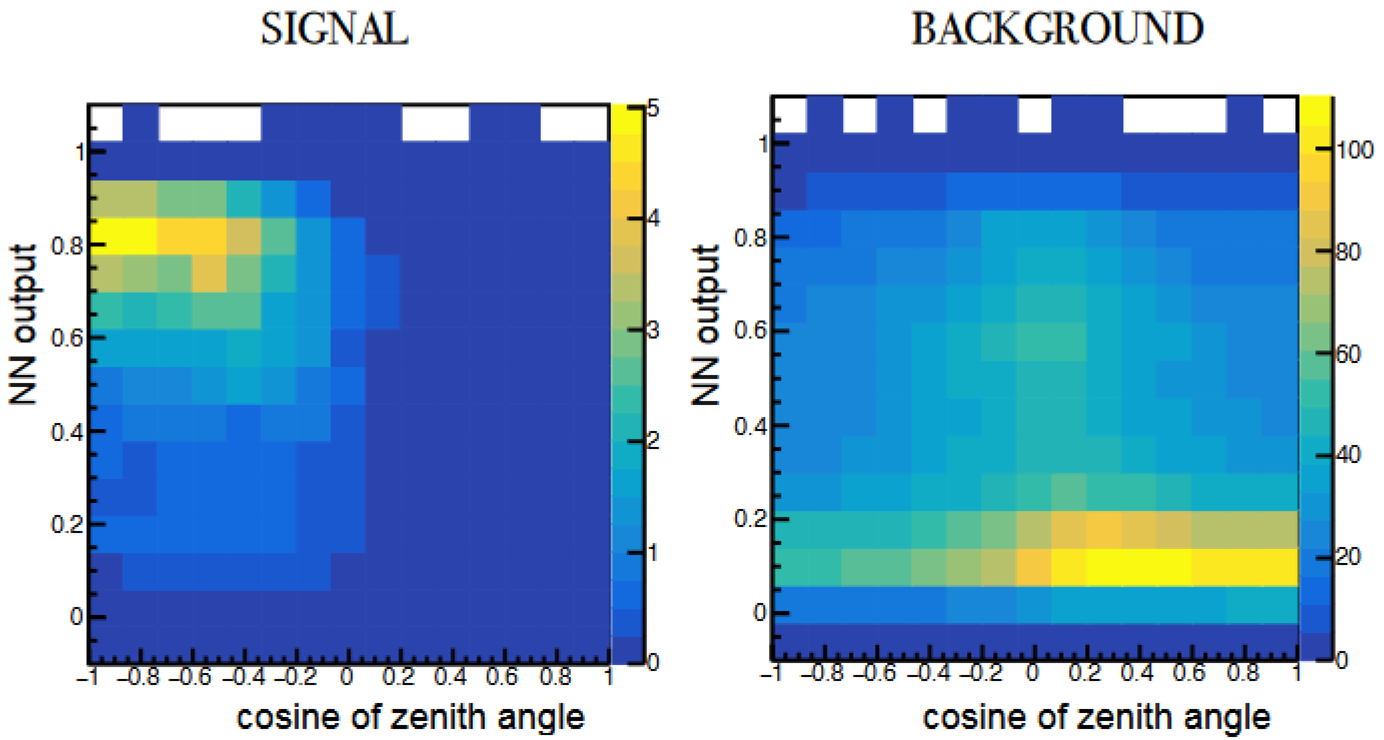

$P(\nu_\mu \rightarrow \nu_e)$
normal ordering


$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
normal ordering

Atmospheric neutrinos travel
15 km to 13000 km.

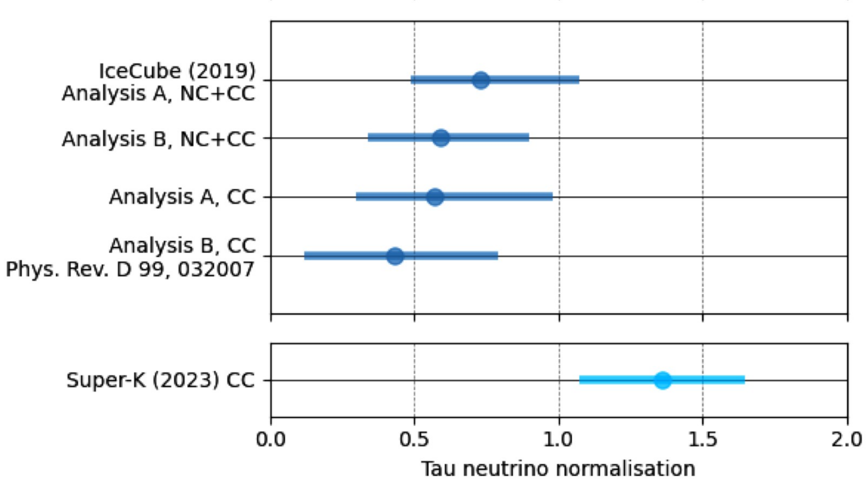


Tau neutrino appearance



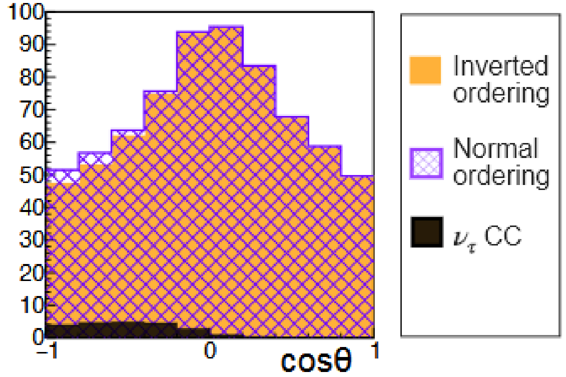
7 input variables to the neural network

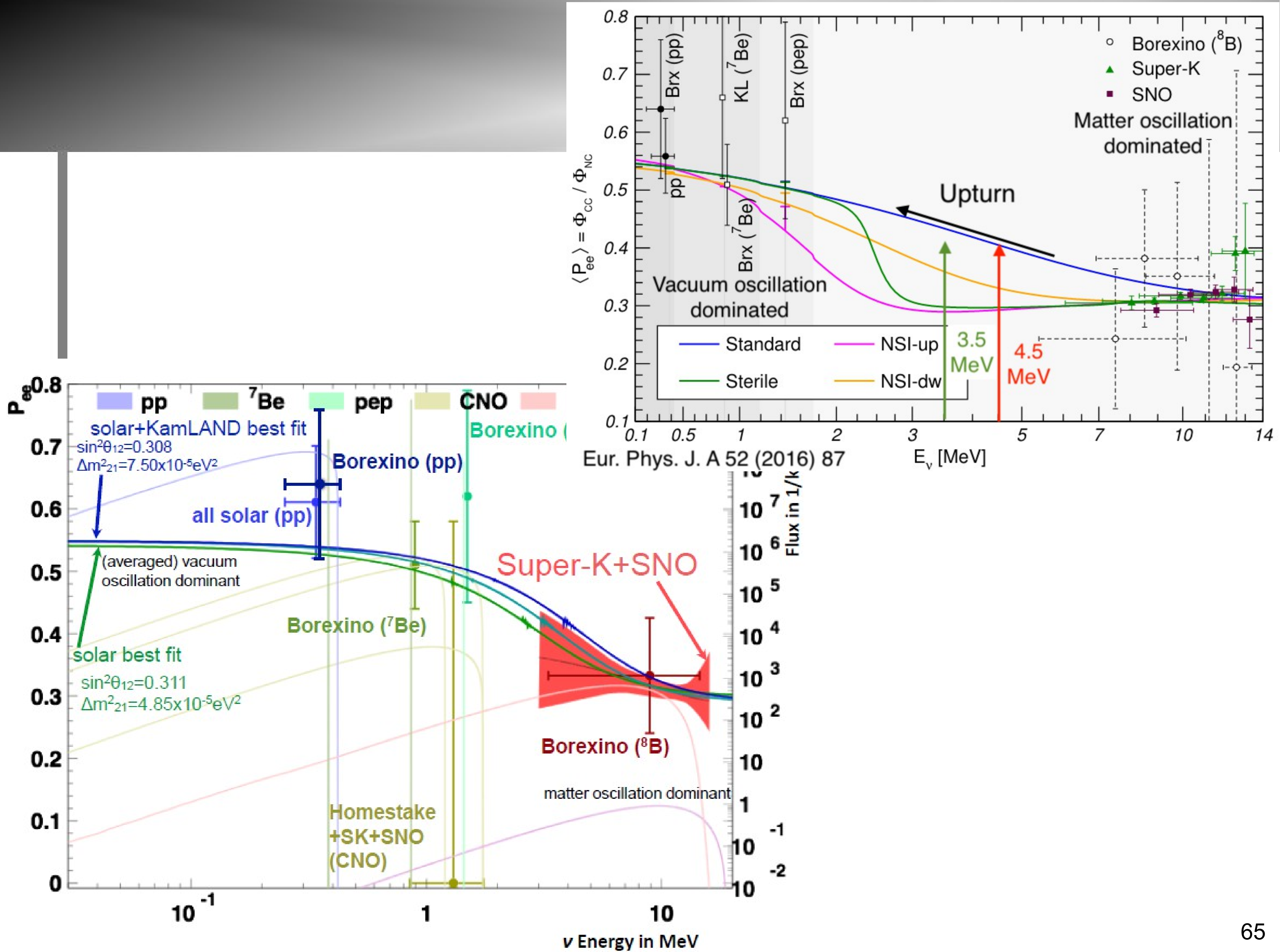
- $\alpha_{\text{fitted}} = 1.36 +/- 0.29$ under normal ordering.
- 428+/-92 observed ν_τ CC events.



EVENT RATES FOR AN ν_e SAMPLE AT SUPER-K

ν_e-like events that produce multiple Cherenkov rings and visible energy $E_{vis} > 1.33$ GeV selected by a BDT





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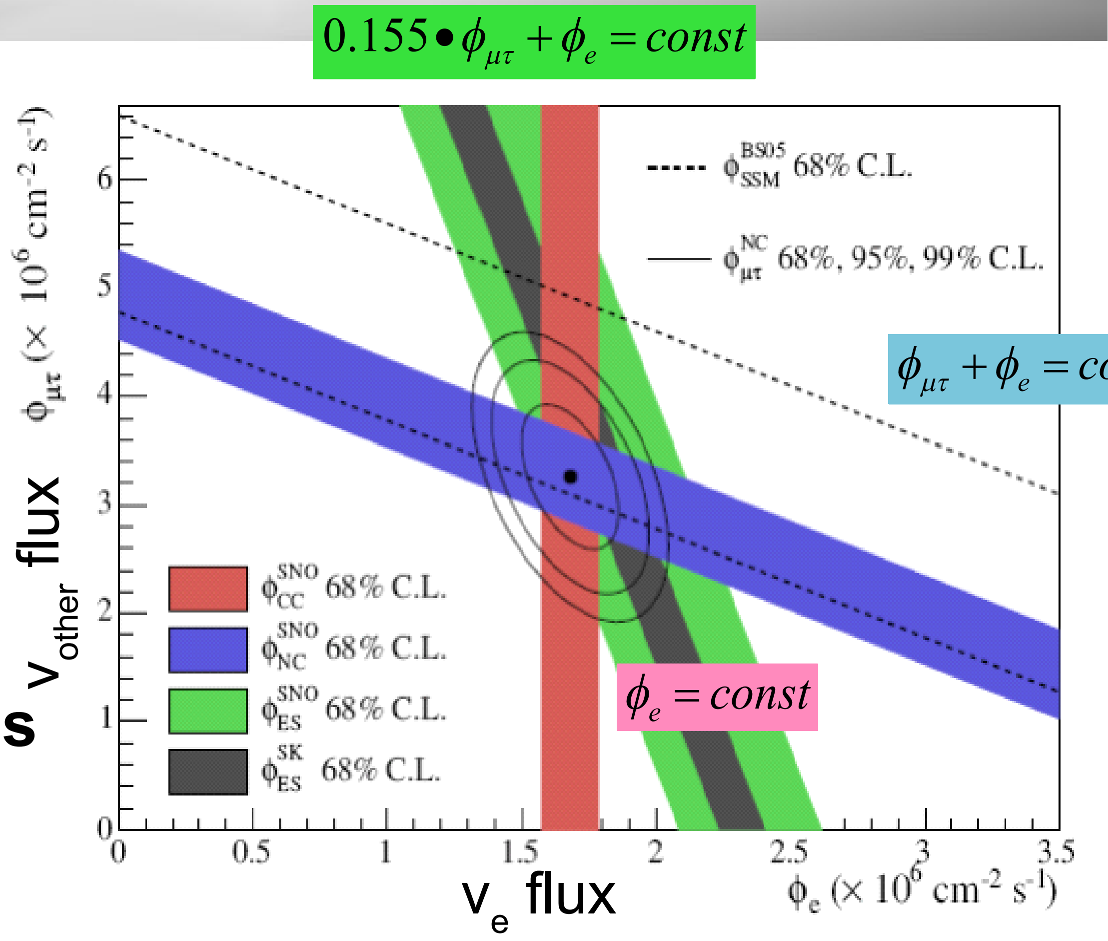
Solar mystery solved by SNO

1. CC ν_e + d → 2p + e
2. ES ν_x + e → ν_x + e
3. NC ν_x + d → ν_x + p + n

- results for ν_e confirm
  the deficit observed before
- but
  results from all channels
  show **presence of neutrinos other than ν_e**
- explanation more complicated than for atmospheric neutrinos and is related to “MSW effect” due to the matter density in core of the Sun



$$\Phi_{CC} = 1.68 \pm 0.06^{+0.08}_{-0.09} \times 10^6\, cm^{-2} s^{-1}$$

$$\Phi_{NC} = 4.94 \pm 0.21^{+0.38}_{-0.34} \times 10^6\, cm^{-2} s^{-1}$$

$$\Phi_{ES} = 2.35 \pm 0.22 \pm 0.15 \times 10^6\, cm^{-2} s^{-1}$$

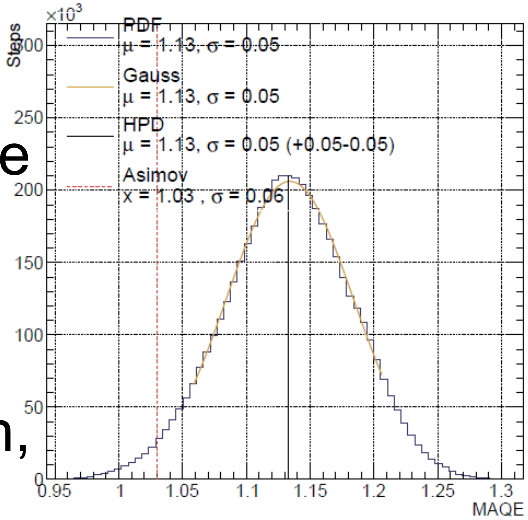
prediction: $5.05^{+1.0}_{-0.8}$

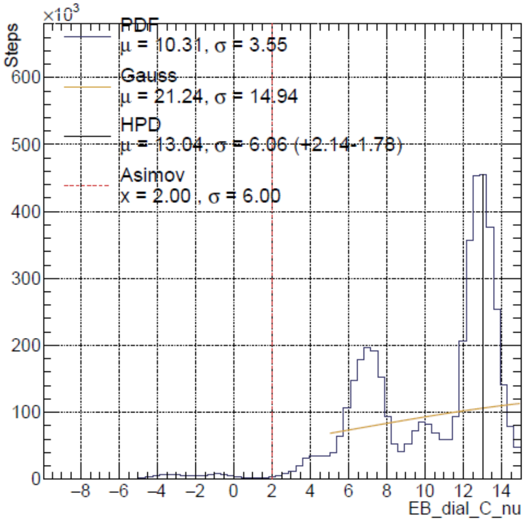
Markov Chain Monte Carlo

- proposal: proposed step leading to state $X(\theta_0)$ can be expressed as $X(\theta_0) = X(\theta) + rand\_proposal(\theta)$ (vector of random numbers drawn from Gaussian distribution, correlated throws)
- acceptance probability of the next step:
  - Metropolis-Hastings algorithm allows to fully explore the space

$$A(\vec{\theta}', \vec{\theta}) = min\left(1, \frac{\mathcal{L}(\vec{\theta}')}{\mathcal{L}(\vec{\theta})}\right) = min\left(1, e^{log\mathcal{L}(\vec{\theta}') - log\mathcal{L}(\vec{\theta})}\right).$$

  - step always accepted if MC better represents the data
  - if the chain remains in the same state, the state contributes to the posterior distribution
  - MCMC aims to find the posterior probability distribution, not just the maximum of the distribution

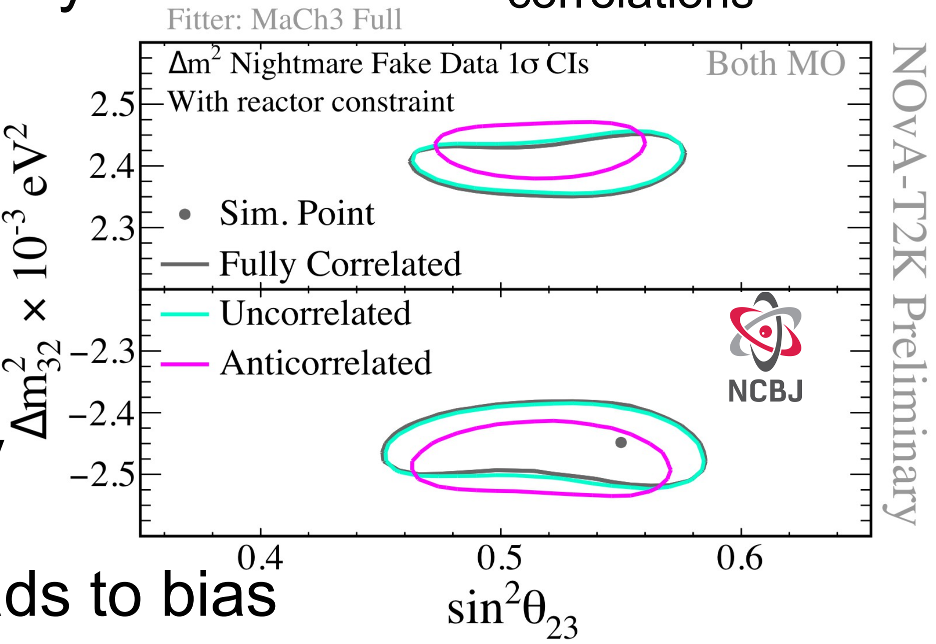




T2K-NOvA joint fit: Checks on impact of correlations in interaction models

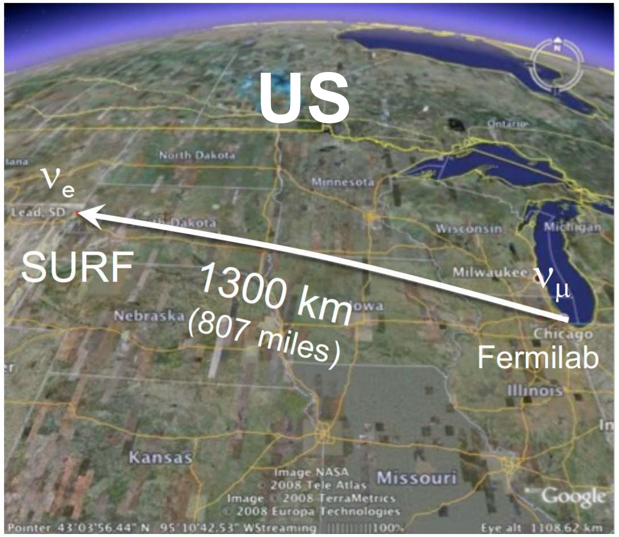
- Strategy to study parameters and their inter-experimental correlations with a significant impact on the parameters of interest δ_{CP}, $\sin^2\theta_{23}$, Δm^2_{32}
- **Fully correlating ν_μ/ν_e and $\bar{\nu}_\mu/\bar{\nu}_e$ cross-section uncertainties, treatment is identical (large δ_{CP} impact)**
- Otherwise, no direct mapping of the systematic parameters between the experiments
- Fabricated, simulated and studied a fully correlated bias for Δm^2_{32} or $\sin^2\theta_{23}$
- Impact of correlations merits further investigation for future analyses with increased statistics
- Given current (2020) statistics, the overall sensitivity gains from correctly correlating systematics would be small, while incorrectly correlating leads to bias

One example of a study to assess the importance of inter-experimental correlations

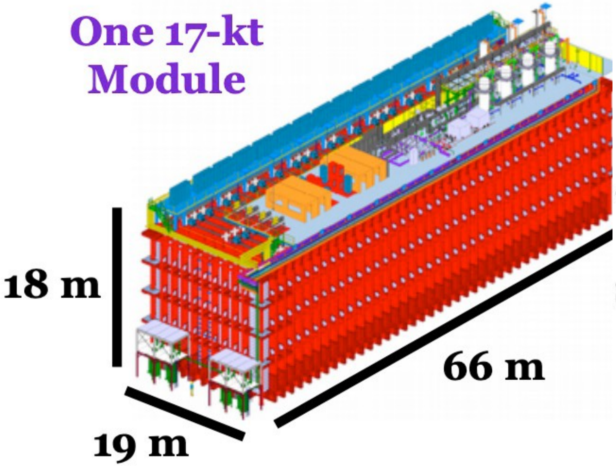


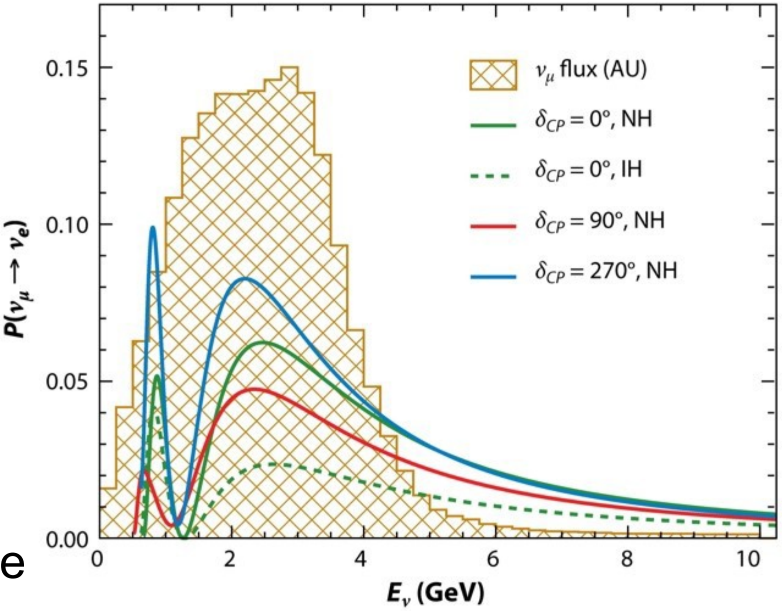
DUNE

- **very long** baseline → large mass effects, removing of degeneracy
- **broad band** beam → covering full oscillation period
- large **LAr** detectors → imaging and calorimetry
- movable and on-axis near detectors to constrain systematic uncertainties



- phase 1: 1.2MW beam, 2x17kt (2x10kt fiducial mass) Far Detector modules
- phase 2: two mor modules, >2MW beam, ND upgrades



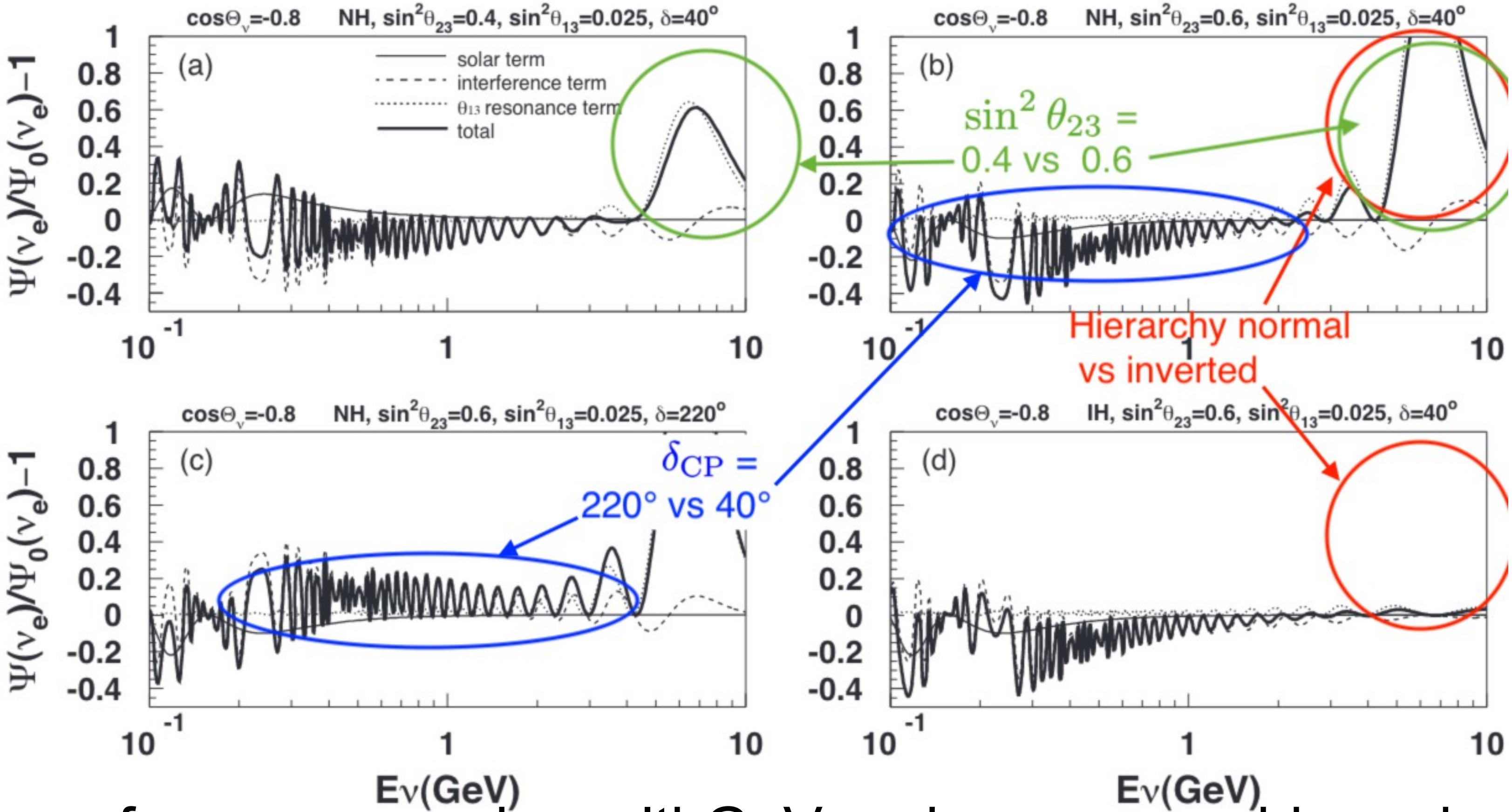


Far site excavation 75% complete, civil construction to be completed in 2024, detector construction underway

Atmospheric neutrinos in Hyper-K

- flux of electron neutrinos – affected by matter effects

ν_e flux relative to no oscillations



$\sin^2\theta_{23}$ = 0.4 vs 0.6

Hierarchy normal vs inverted

δ_{CP} = 220° vs 40°

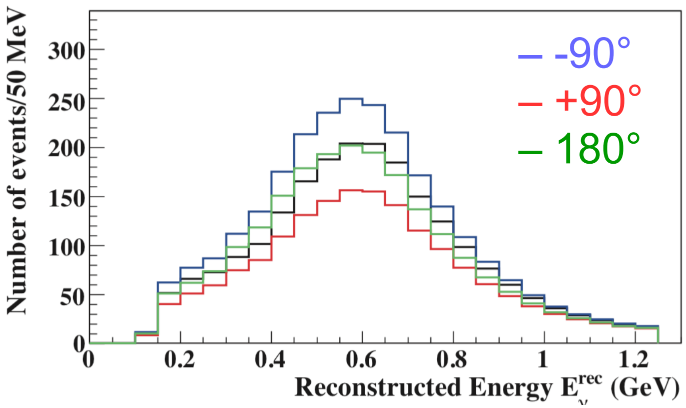
- presence of a resonance in multi-GeV region → mass hierarchy
- magnitude of the resonance → θ_{23} octant
- scale and direction of the effect at 1 GeV → δ_{CP}

HK: Expected numbers of beam events

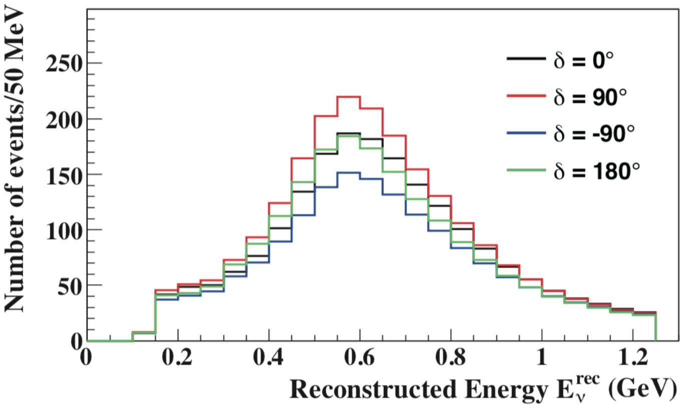
- 10 years exposure
  - $2.7 \cdot 10^{22}$ POT
  - $\nu:\bar{\nu}$ data taking 1:3
- ν_e appearance
  - shape information can be used to distinguish different values of δ_{CP}
- ν_μ disappearance

$\delta_{CP} = 0$	right-sign $\nu_\mu \rightarrow \nu_e$ CC	wrong sign $\nu_\mu \rightarrow \nu_e$ CC	ν_μ, $\bar{\nu}_\mu$ CC	intrinsic beam ν_e	NC
ν beam	**1643**	15	7	259	134
$\bar{\nu}$ beam	**1183**	206	4	317	196

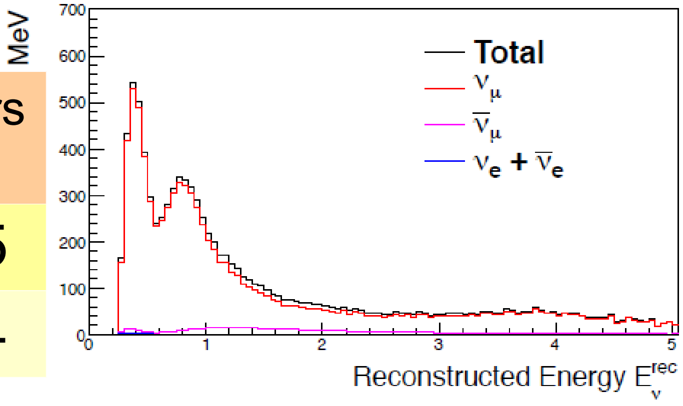
Neutrino mode: appearance



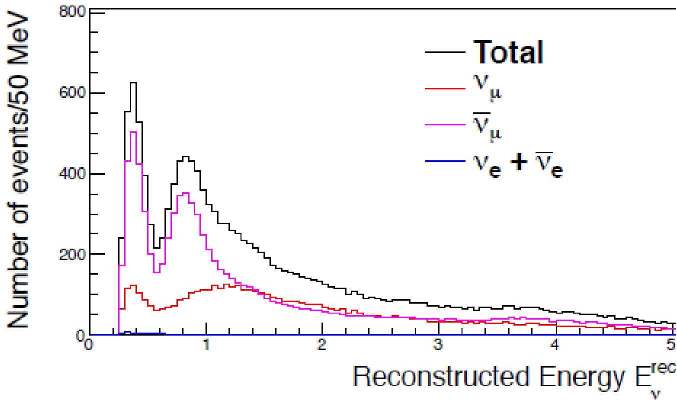
Antineutrino mode: appearance



Disappearance ν mode



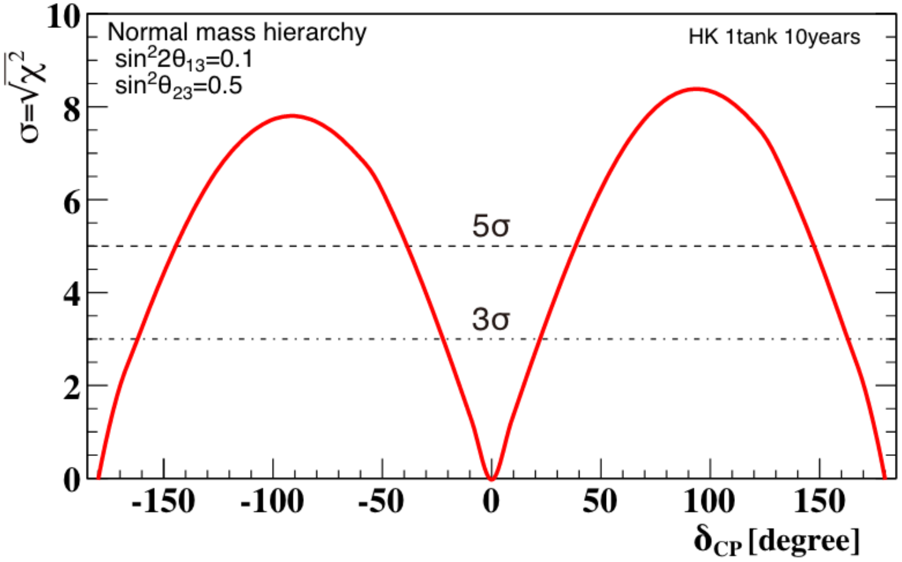
Disappearance $\bar{\nu}$ mode

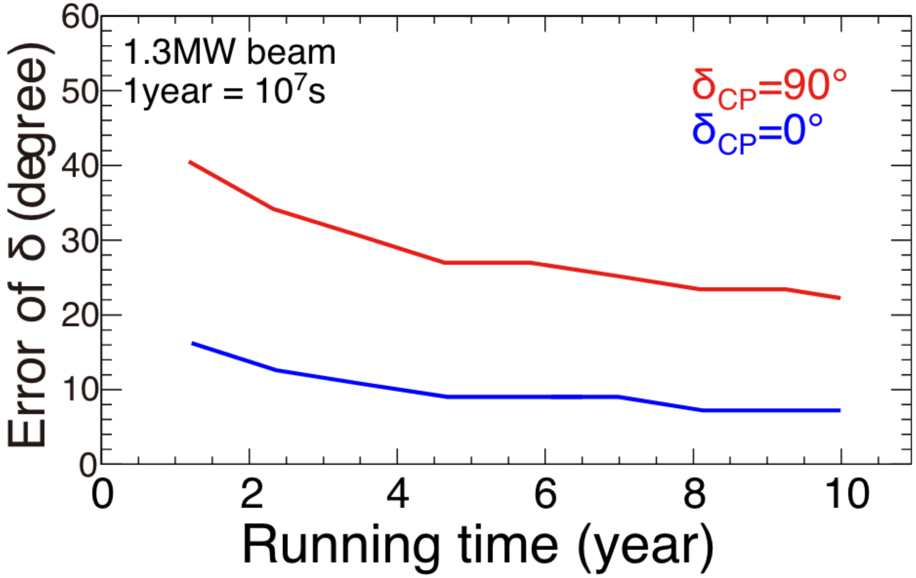


	$\nu_\mu + \bar{\nu}_\mu$ CCQE	ν_μ CC nonQE	others
ν beam	**6391**	3175	515
$\bar{\nu}$ beam	**8798**	4315	614

HK: CPV sensitivity

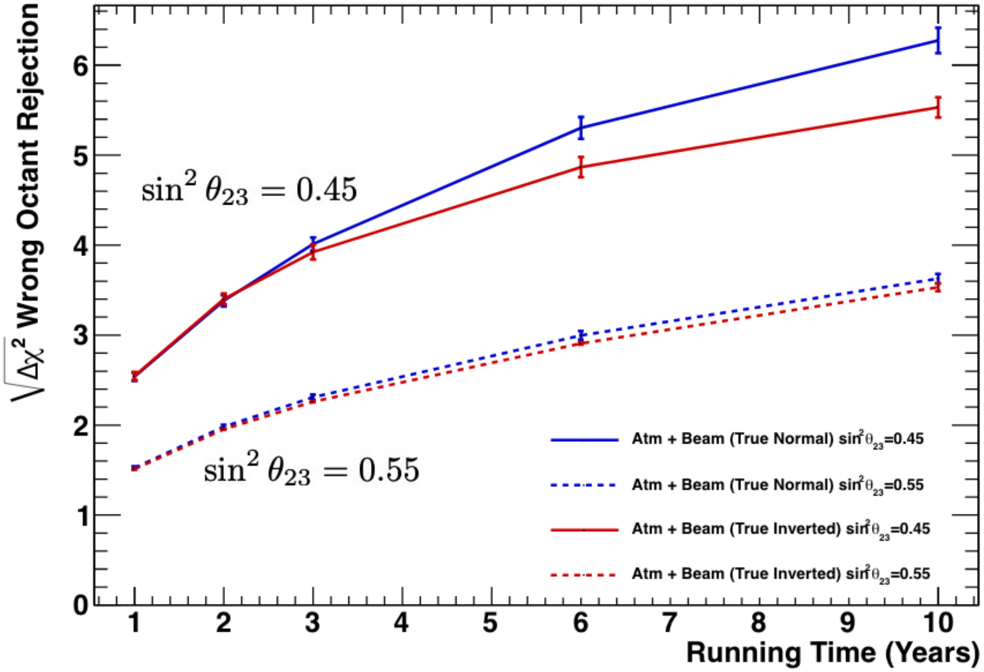
- exclusion of sinδ_{CP} = 0 with
  - ~8σ if true δ_{CP} = ±90°
  - > 5σ for 57% of δ_{CP} values
  - > 3σ for 76% of δ_{CP} values
- δ_{CP} resolution
  - 23° precision at δ_{CP} = ±90°
  - 7.2° precision at δ_{CP} = 0° or 180°
- combination with atmospheric data enhances the sensitivity



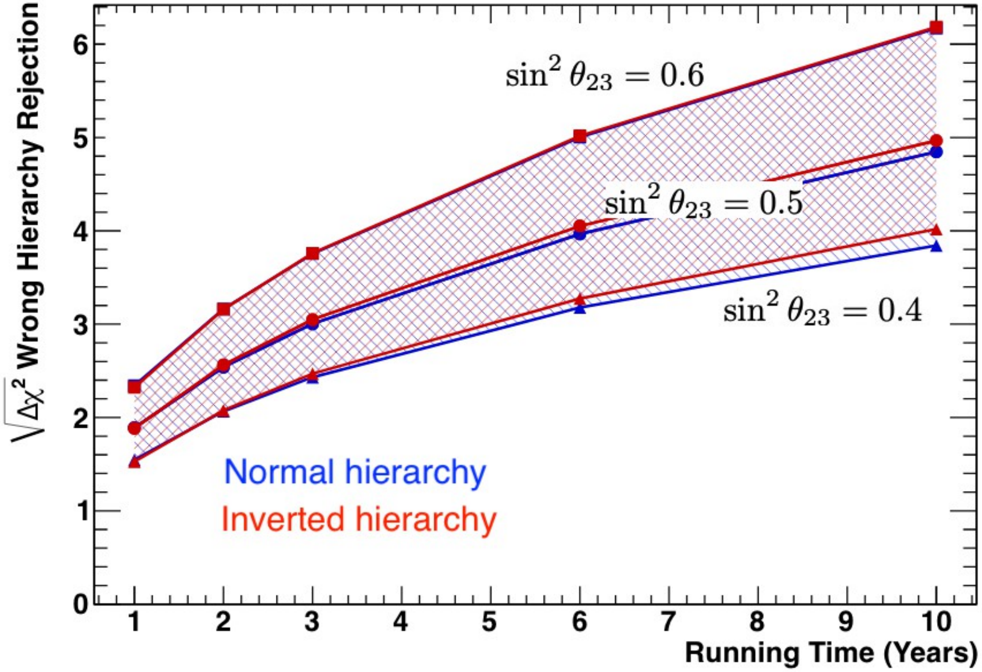


HK: Atmospheric+beam neutrinos

- improved performance for octant determination
- 3σ ability to reject the incorrect mass hierarchy after 5 years



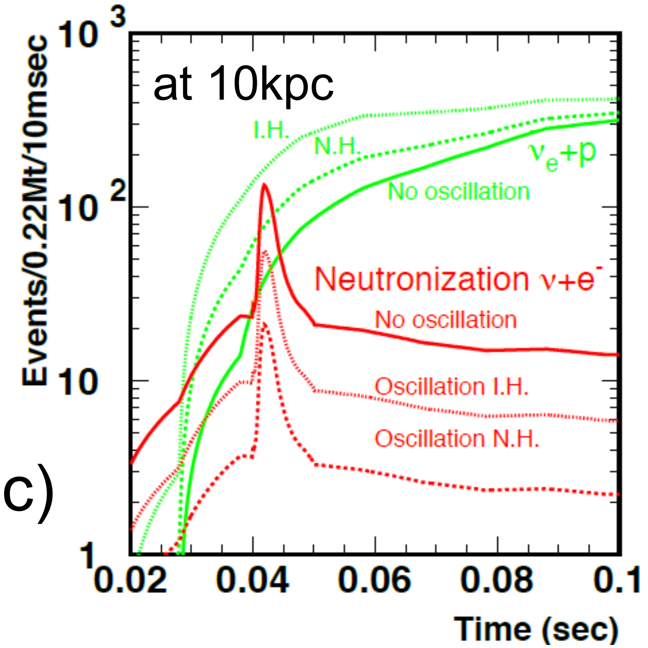
wrong octant rejection
3σ for $|\theta_{23} – 45°| \geq 2.3°$



wrong hierarchy
rejection

HK: Supernova burst neutrinos

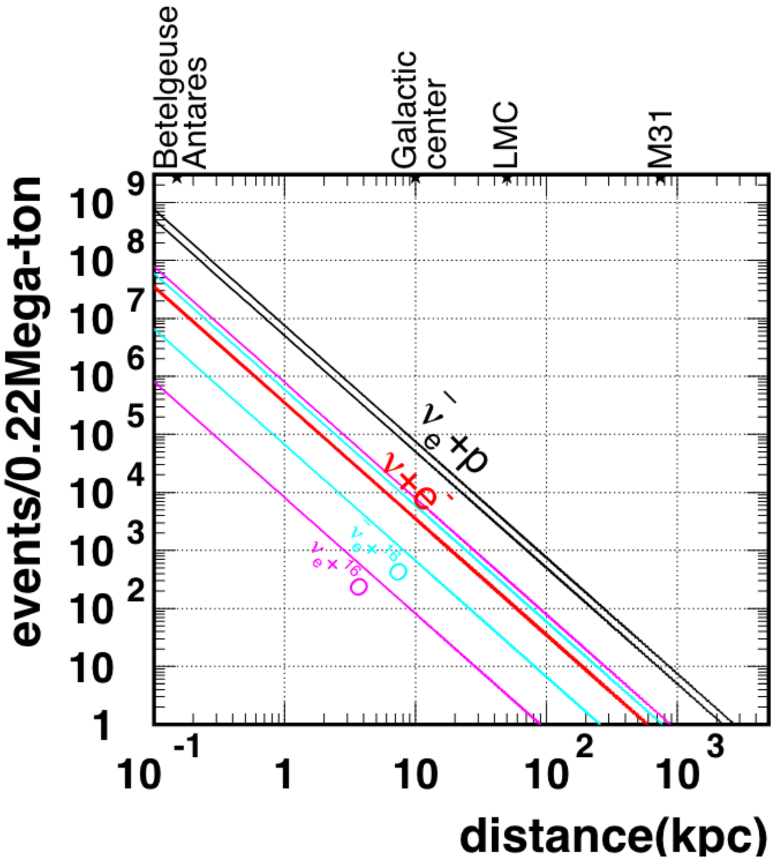
- ν_e from neutronization peak – elastic scattering on electrons (directional information, accuracy 1-1.3° expected for supernova at 10kpc)
- $\bar{\nu}_e$ from cooling phase – inverse beta decay



expectations:

50-80k events (10kpc)

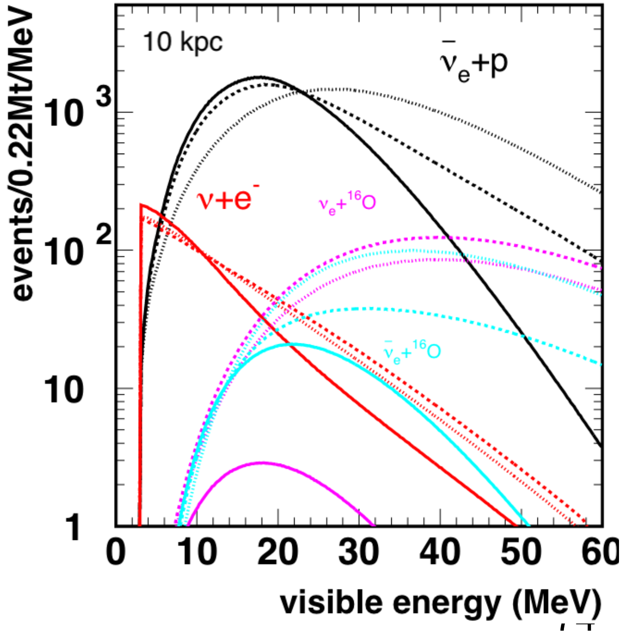
2-3k (SN1987a)



information on

- neutrino oscillations and properties (mass, mass hierarchy)
- core-collapse supernova models

Early warning for telescopes

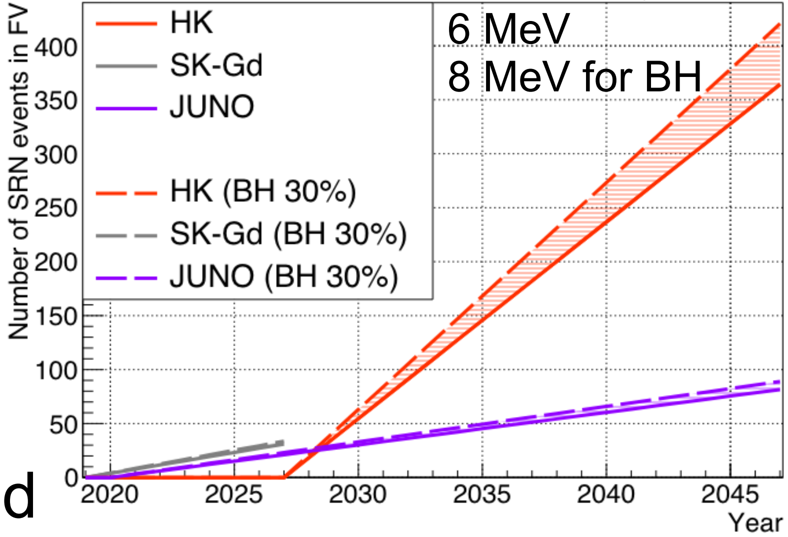


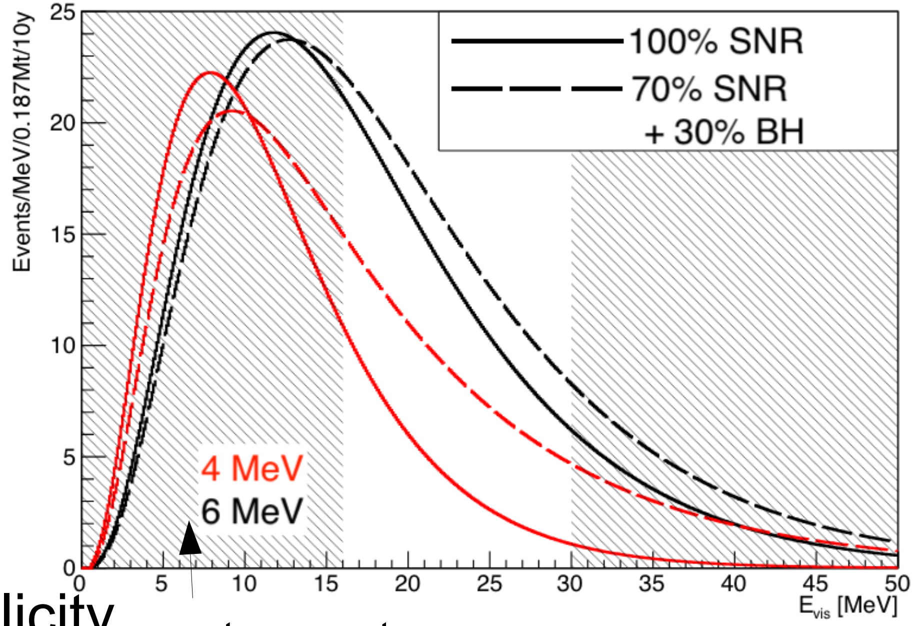
HK: Supernova relic neutrinos

or diffuse supernova neutrino background

- expected flux few tens/cm^2/sec
- search limited by background:
  - spallation for low energies
  - atmospheric neutrinos for high energies
- first measurement may be done by SK-Gd
- Hyper-K may measure the spectrum
- different search window (~16-30 MeV),
  - complementary to SK-Gd searches (10-20 MeV)
  - contribution of extraordinary supernova bursts (like black hole formation, BH): provides information on the star formation history and metallicity

expected inverse beta decay events

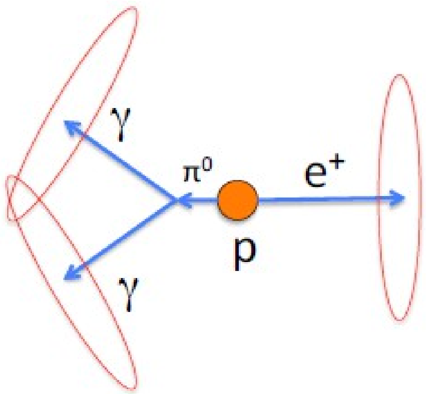




ν temperature
8 MeV for BH formation

HK: Search for p→$e^+\pi^0$ decay

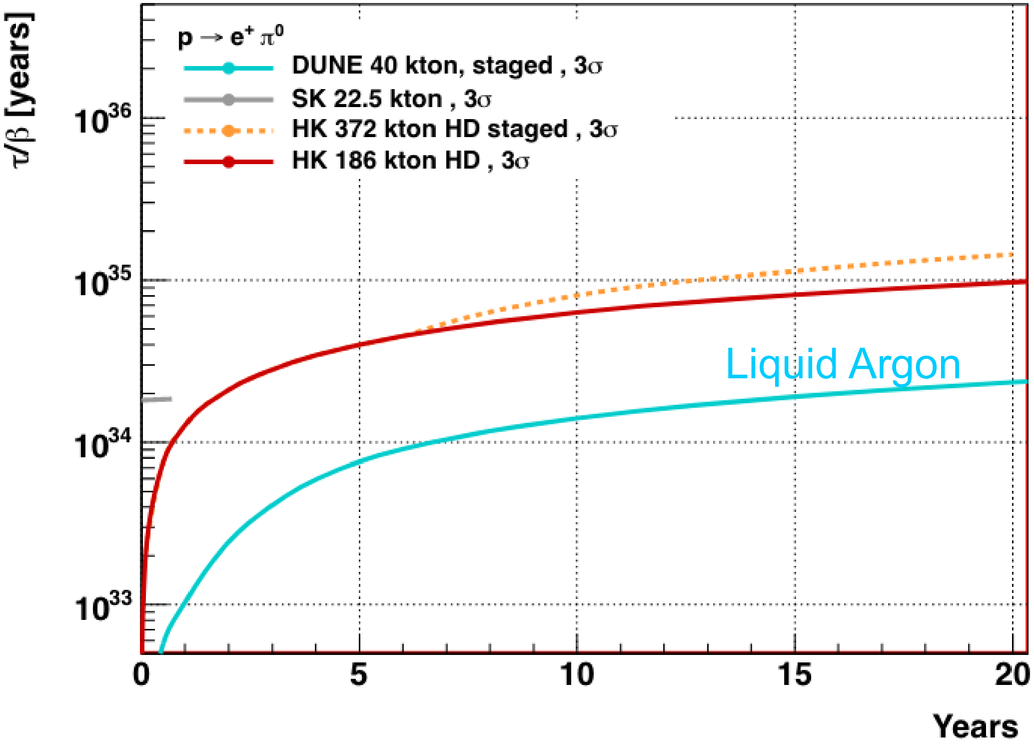
- decay mode p →$e^+\pi^0$ is favoured by many GUTs



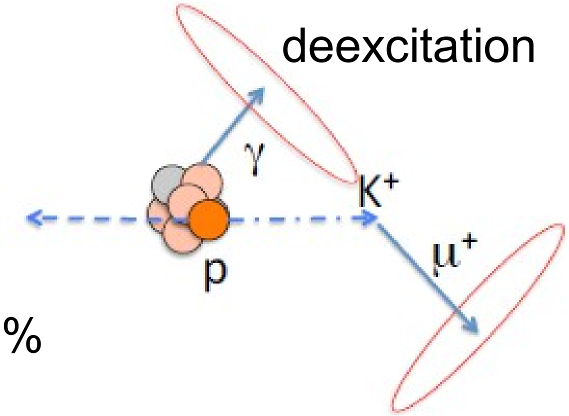
e^+ and photons are detected as e-like rings → final state is fully reconstructed (practically background free)

- analysis similar as in SK but with neutron tagging (veto) thanks to improved PMTs
  - neutron capture in water n(p,d)γ (2.2 MeV)
  - efficient tagging of prompt γ from residual nuclei deexcitation
  - ~50% reduction of atmospheric background

3σ discovery potential reaching t ~ 10^{35} yrs



HK: Search for p→$\bar{\nu}K^+$ decay



- favored by SUSY GUTs
- kaon not visible in Water Cherenkov detector: reconstructed from decay products
  - monochromatic muon (236 MeV) +prompt deex. photon (6.3 MeV)
  - excess in muon spectrum

  $K^+ \to \mu^+\nu$, BR 64%

  - or search for $K^+ \to \pi^0\pi^+$ decay (BR 21%) p = 205 MeV/c (slightly above the threshold)

Partial lifetimes limits (90% C.L., 10 y exposure)

- $7.8 \cdot 10^{34}$ years for $p \to e^+\pi^0$

  $3.24 \cdot 10^{34}$ years for $p \to \bar{\nu}K^+$
- basically one order of magnitude improvement for many other nodes

3σ discovery potential