UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Constraint on the matter-antimatter symmetry-violating phase in neutrino oscillations by the T2K experiment

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Outline

- Neutrino Oscillations in a nutshell
- The T2K experiment
- Analysis procedure
- Cross-section analysis
- Results
- Next steps and beyond

Neutrino Oscillations in a nutshell

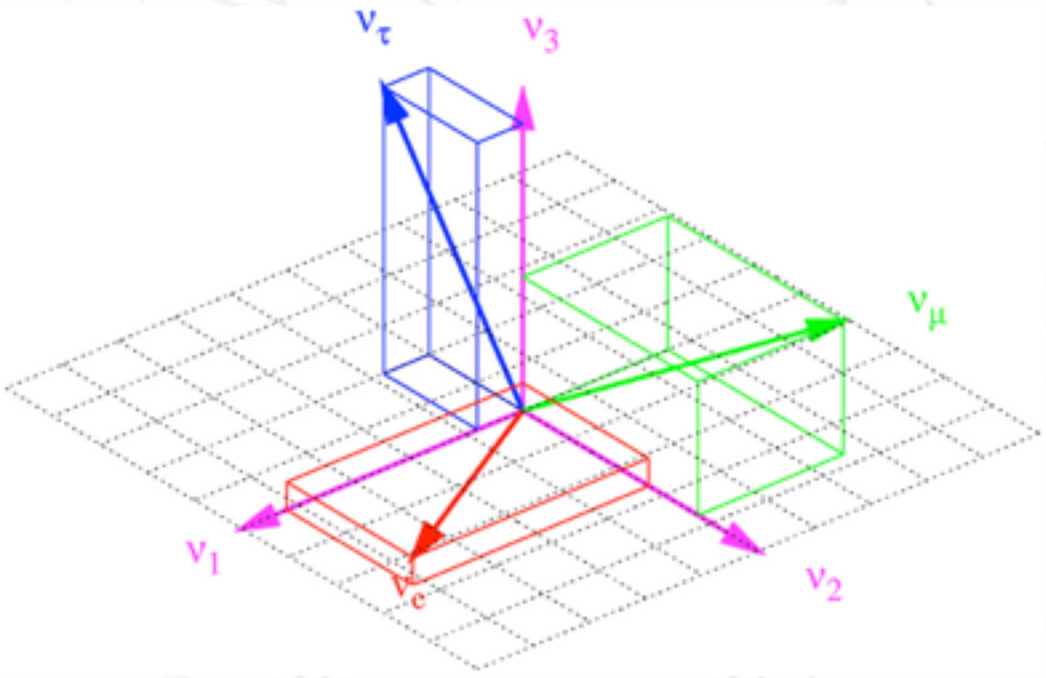
Neutrino oscillations

- Neutrino flavour eigenstates are not the same than the neutrino Lorentz eigenstates.
- Eigenstates are related through a rotation matrix.

Flavour eigenstates	Lorentz eigenstates
$(\nu_e, \nu_\mu, \nu_\tau)$	(ν_1, ν_2, ν_3)
state of the neutrino interactions	states of the neutrino propagation in space

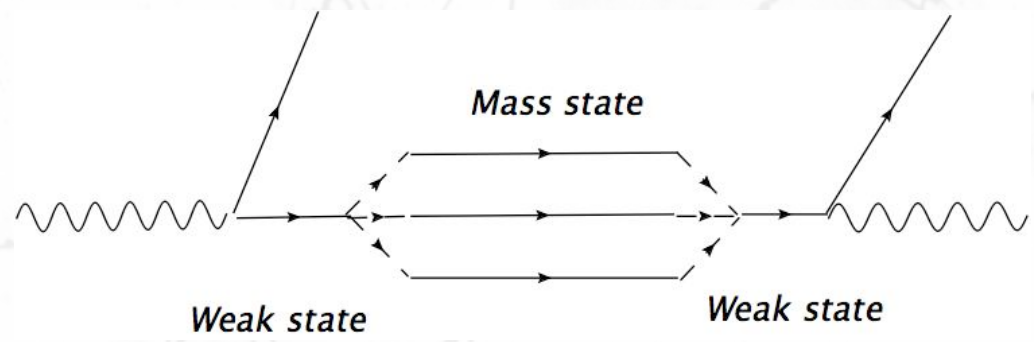
Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

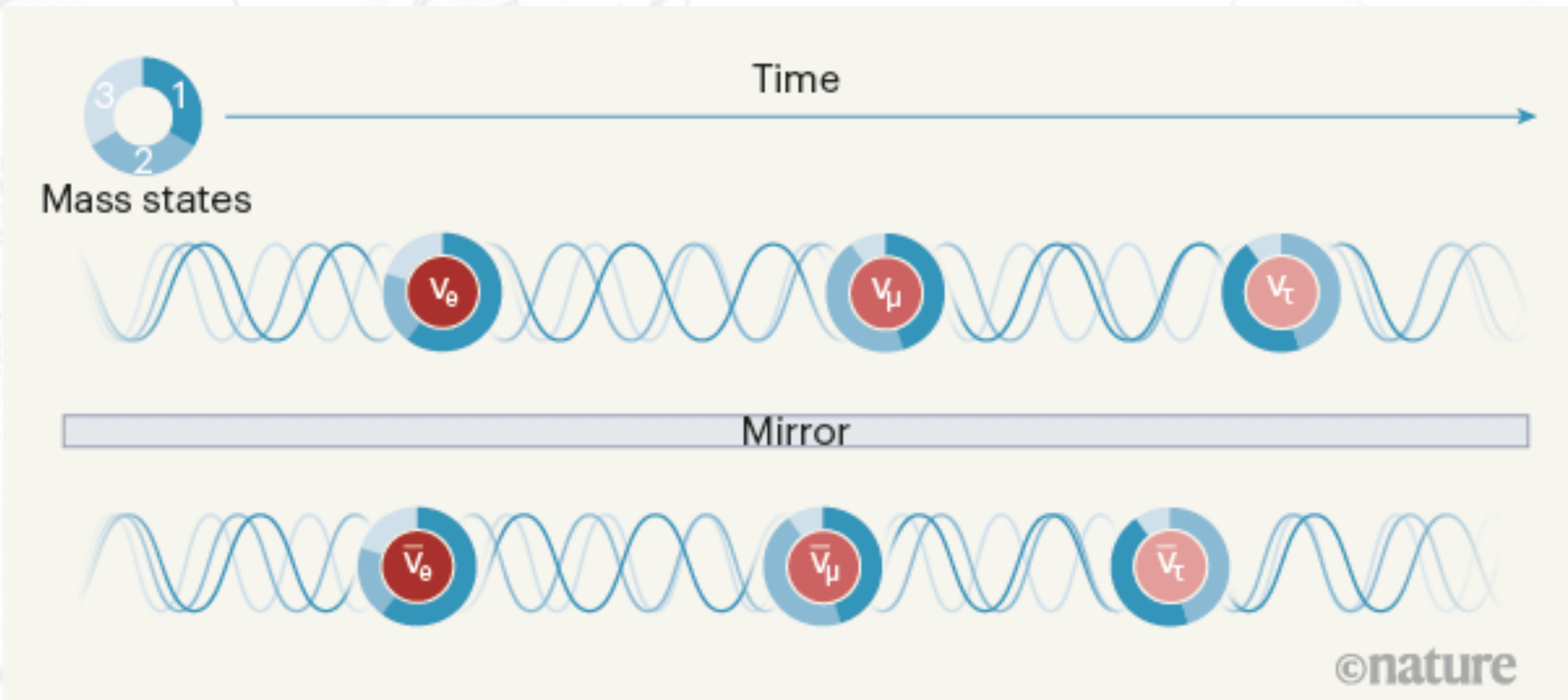
$$\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} = U_{PNMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Neutrino oscillations

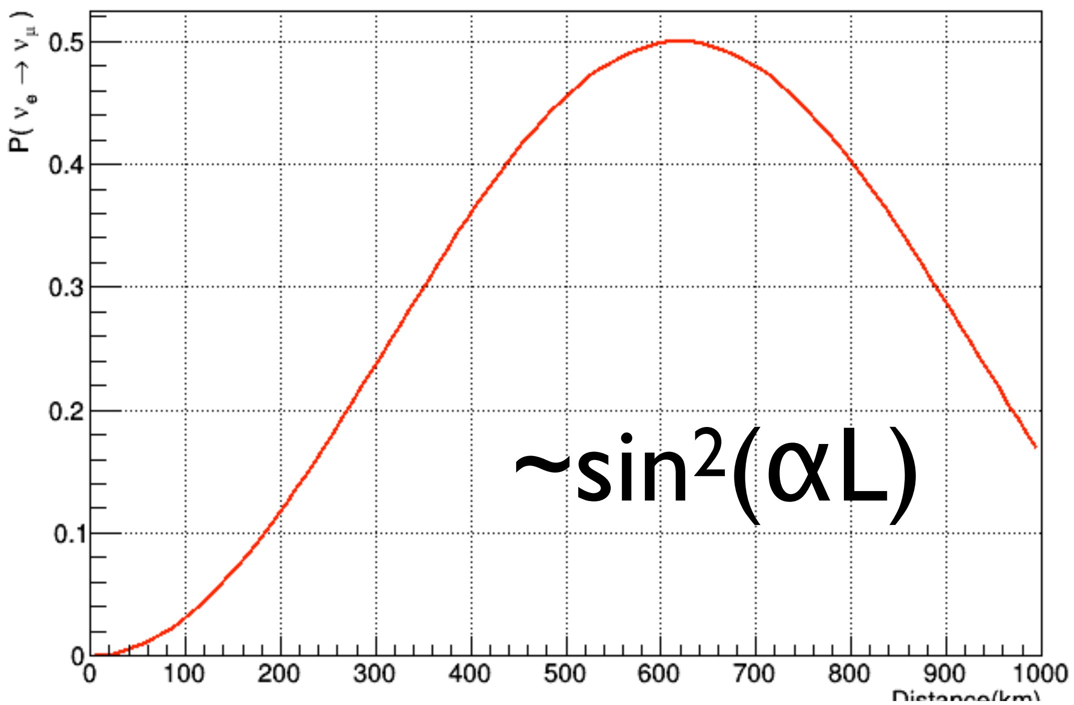
- Neutrinos are produced always as a flavour neutrino (electron, muon, tau) but they propagate in vacuum as mass states (they do no interact)

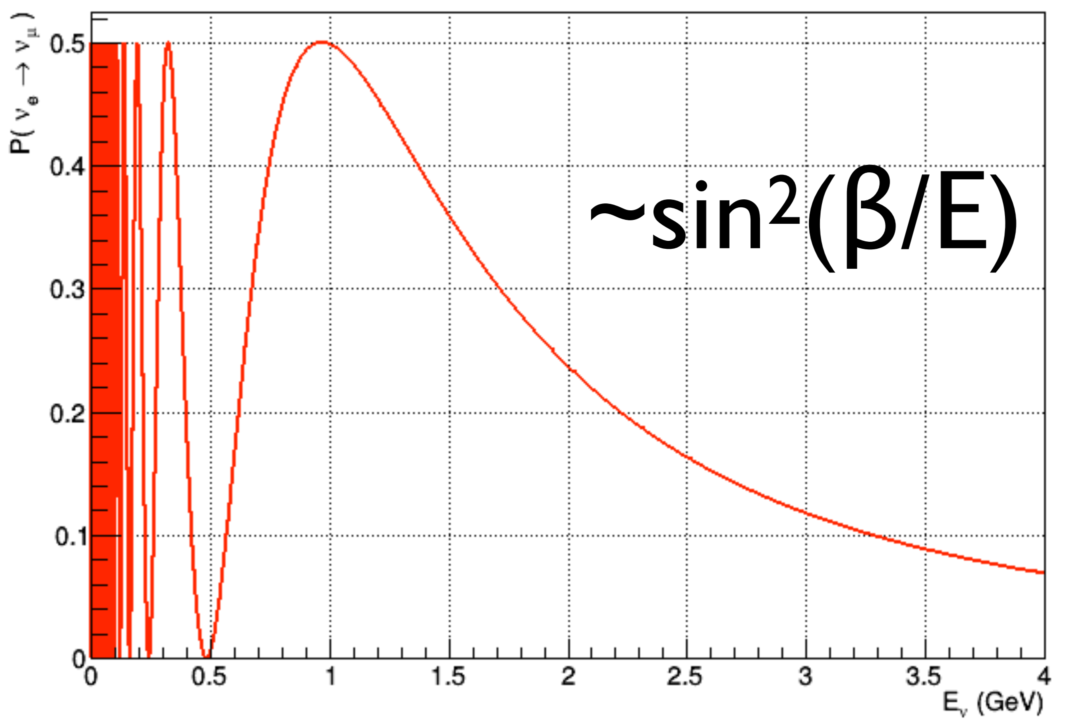




- Neutrinos propagate at different speeds (mass) keeping the coherence, at the interaction point the proportions change and other neutrino flavour might appear.

Oscillations with 2ν





$\theta = \pi/2$

$\Delta m^2 = 2.\text{x}10^{-3}\ eV^2$

Simplified 2ν formula

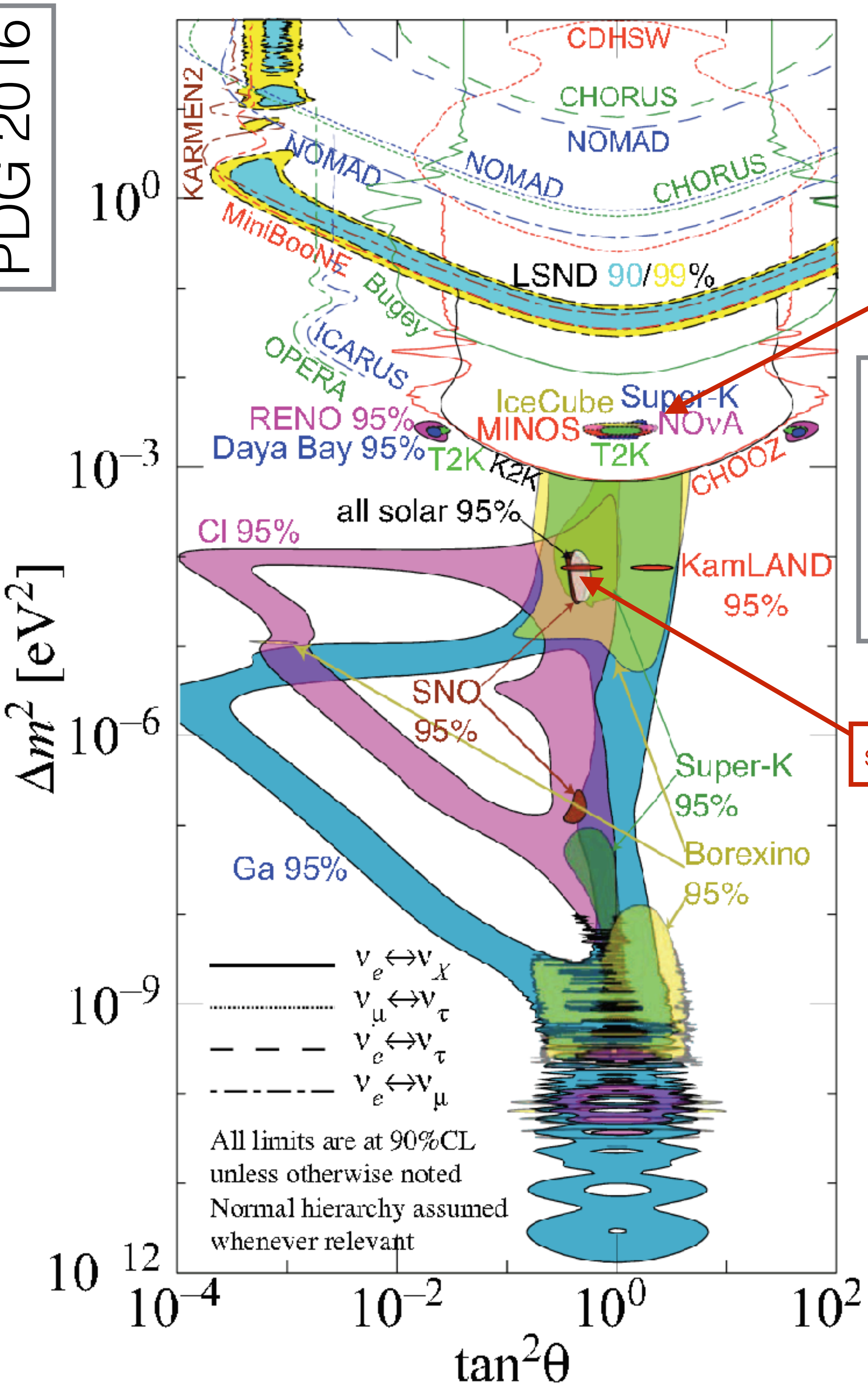
$$|<\nu_\mu|\nu_e;t>|^2 = \sin^2\frac{\theta}{2}\sin^2 1.267\frac{\Delta m^2 L}{E}\frac{GeV}{eV^2 km}$$

Oscillations are seen as change of ν flavour composition as function of: Energy & Distance

$P(\nu_\alpha \to \nu_\beta)$

Oscillation parameters

PDG 2016



atmospheric

solar

PNMS Matrix

$$U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

PDG 2018

Precision	Parameter	best-fit	3σ
~4%	Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.96
~3%	$\Delta m^2_{31(23)}$ [10^{-3} eV ^{2}]	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
~11%	$\sin^2\theta_{12}$	0.297	0.250 – 0.354
~15%	$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
	$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
~7%	$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
	$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
~31%	δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

Most of the parameters measured with <10% precision

θ_{23} is known with 15% precision

Remaining parameters are δ_{CP} and the hierarchy

Mass hierarchy

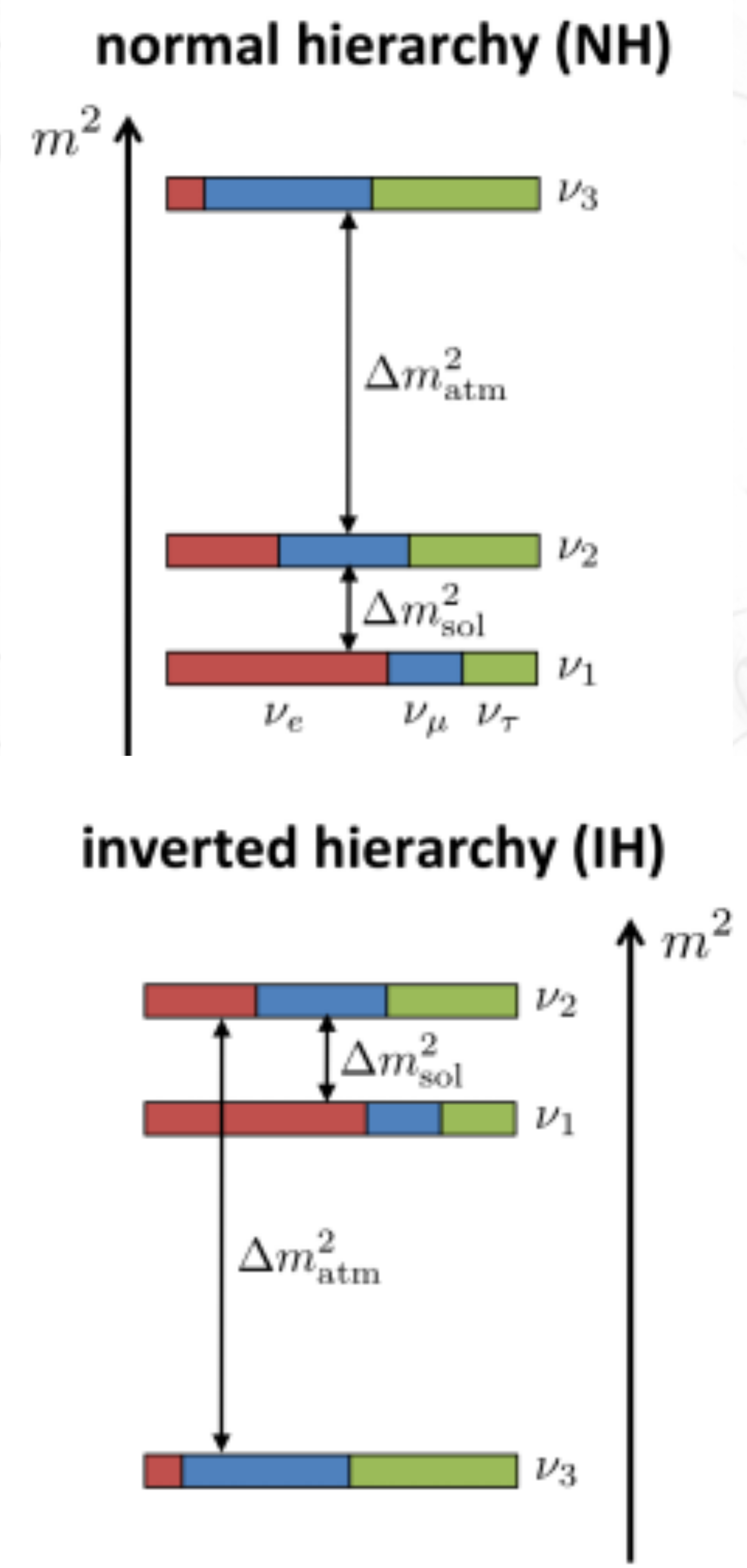
- Oscillations is a quantum interference phenomenon that depends on the (quadratic) mass difference:

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

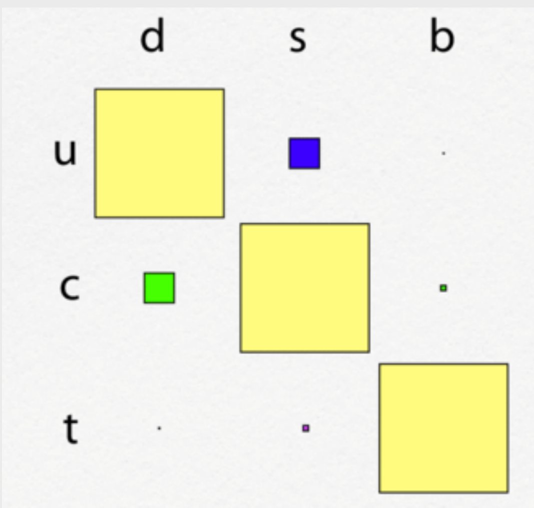
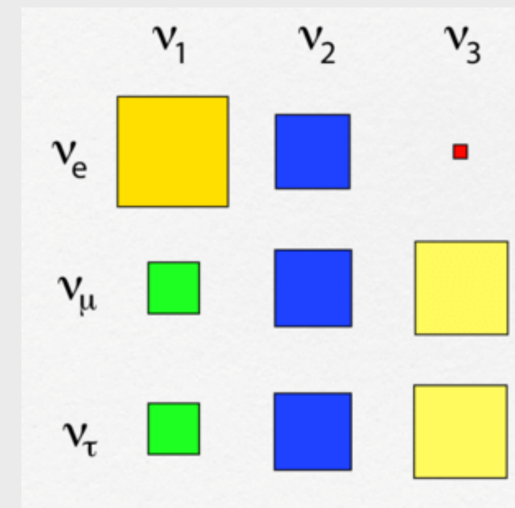
- Due to matter effects in solar neutrinos we know:

$$\Delta m^2_{12} > 0$$

- Hierarchy determines the ordering of the masses. Traditionally:
    - Normal: $m_1 < m_2 < m_3$
    - Inverted: $m_3 < m_1 < m_2$

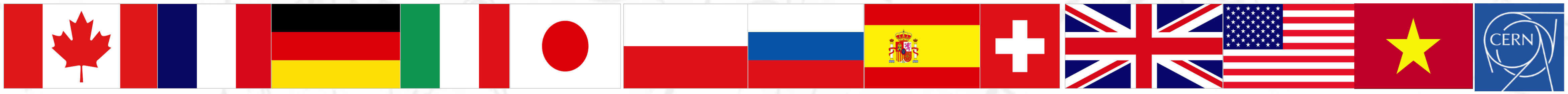


PNMS vs CKM

CKM	PNMS
 Mostly diagonal	Flat"ish" 
$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$ Unitarity is not enforced by construction	$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$ Unitarity enforced by construction following N_ν=3 from LEP

T2K experiment

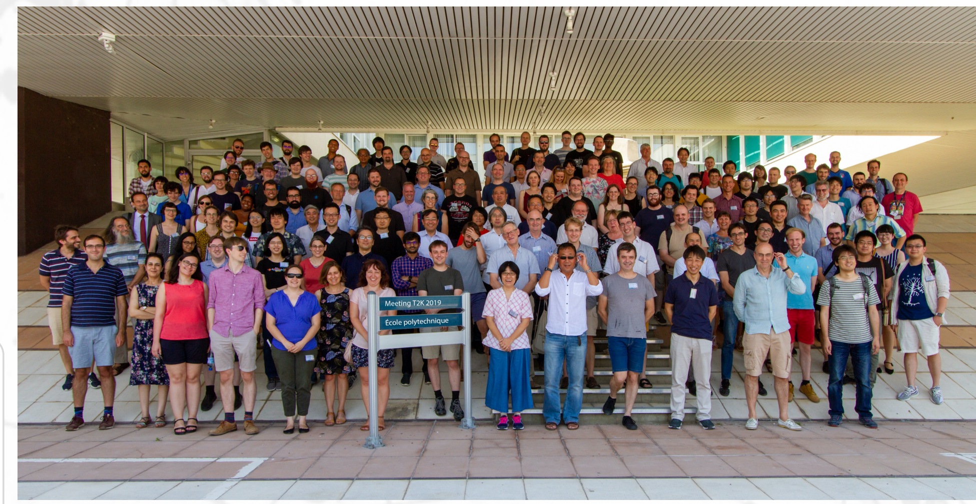
T2K Collaboration



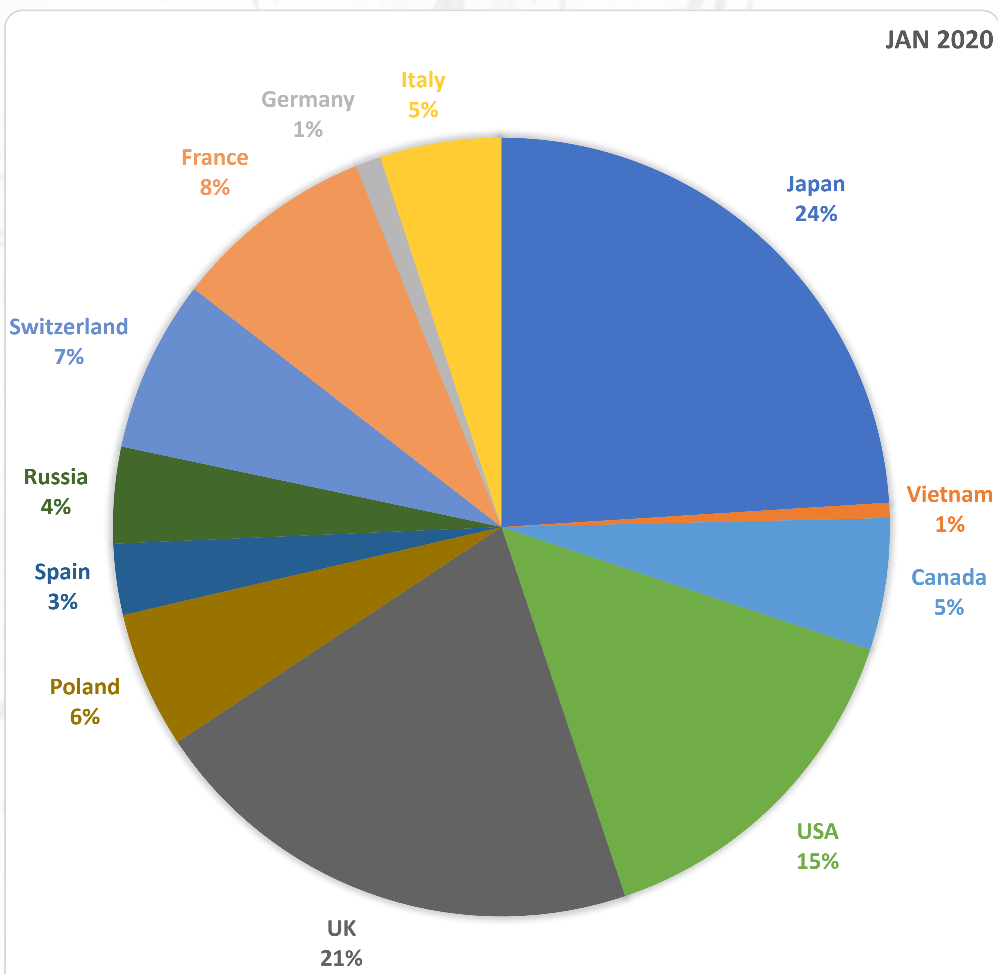
~500 members, 69 Institutes, 12 countries

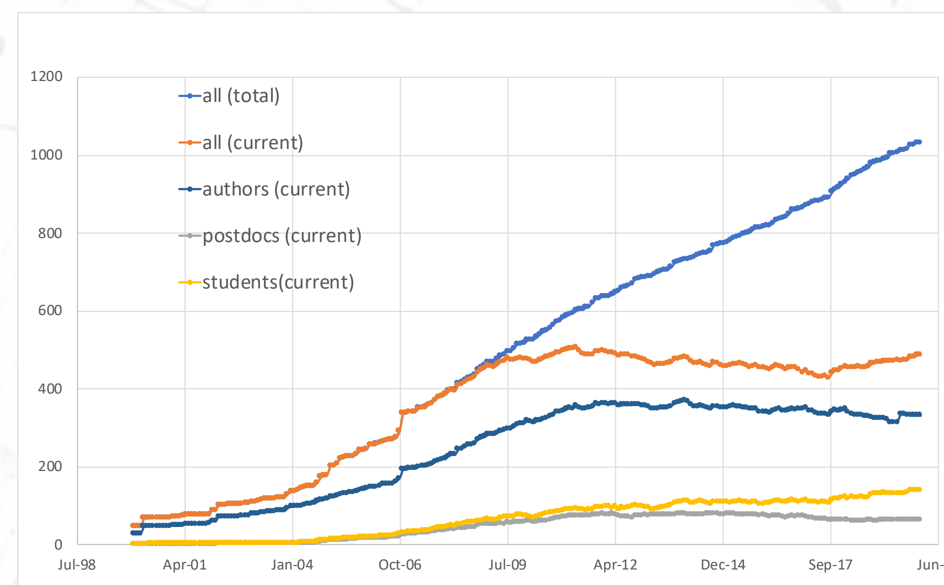
Asia	117
Japan	114
Vietnam	3

Americas	96
Canada	26
USA	70



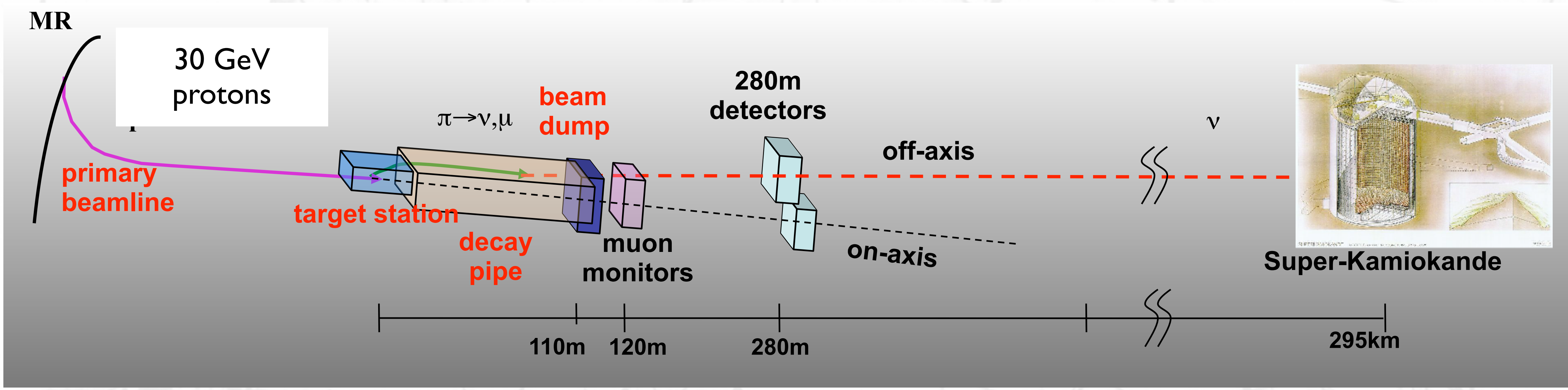
Europe	262
France	40
Germany	5
Italy	24
Poland	27
Russia	19
Spain	14
Switzerland	34
UK	99





Very strong European contribution including CERN

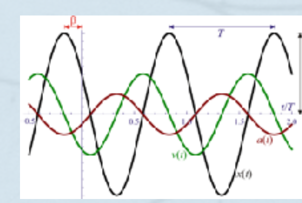
T2K experiment



Neutrinos produced in a particle accelerators or nuclear reactors.

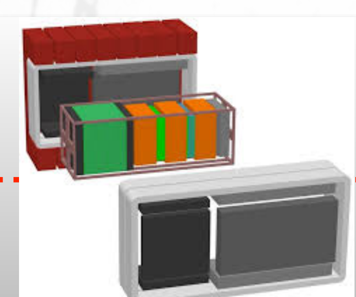
Neutrino flux properties

ν oscillations



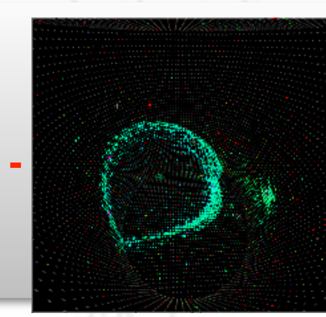
Neutrino flux & flavour

$\nu_\mu,\bar{\nu}_\mu$

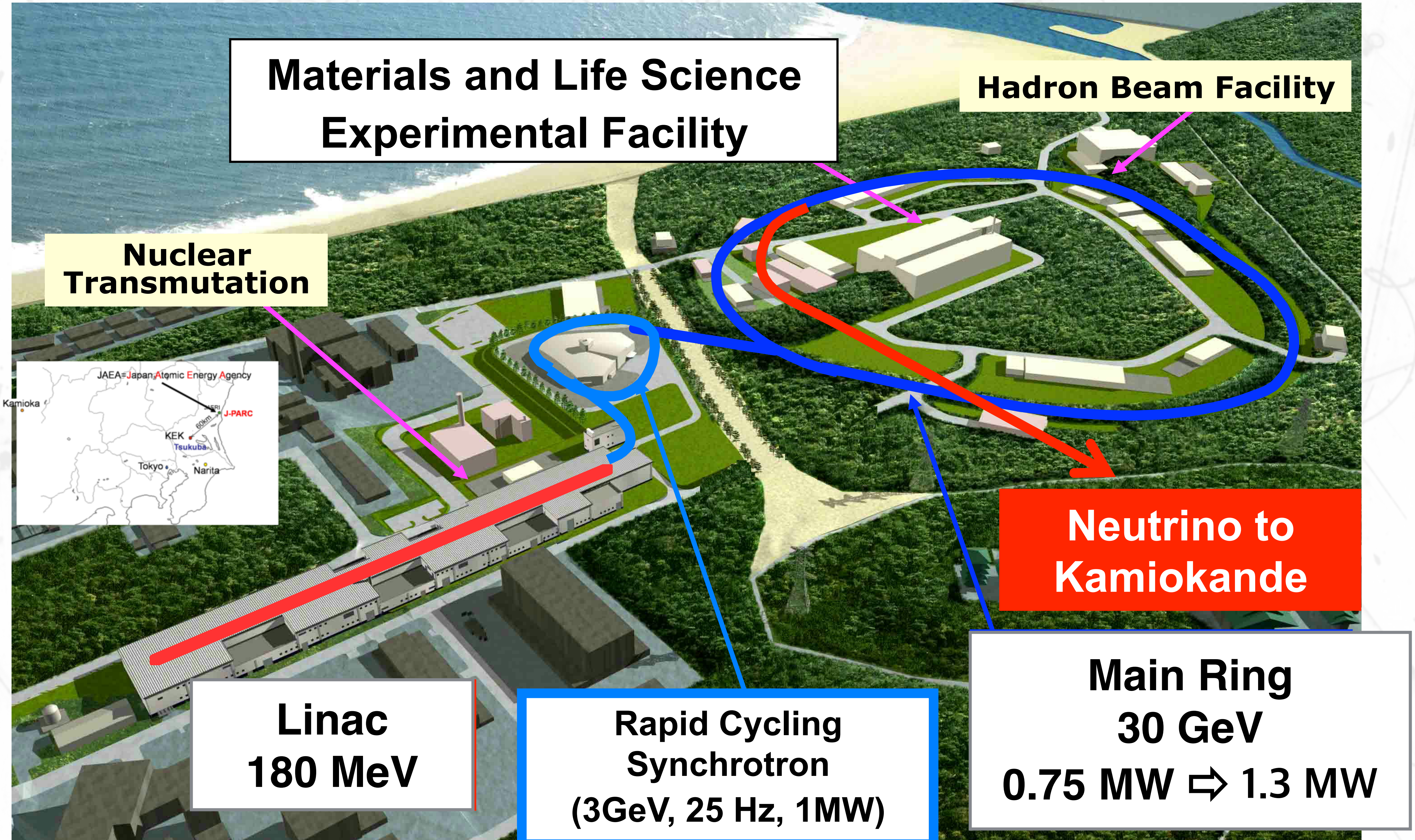


$\nu_e\bar{\nu}_e$

$\nu_\mu\bar{\nu}_\mu$



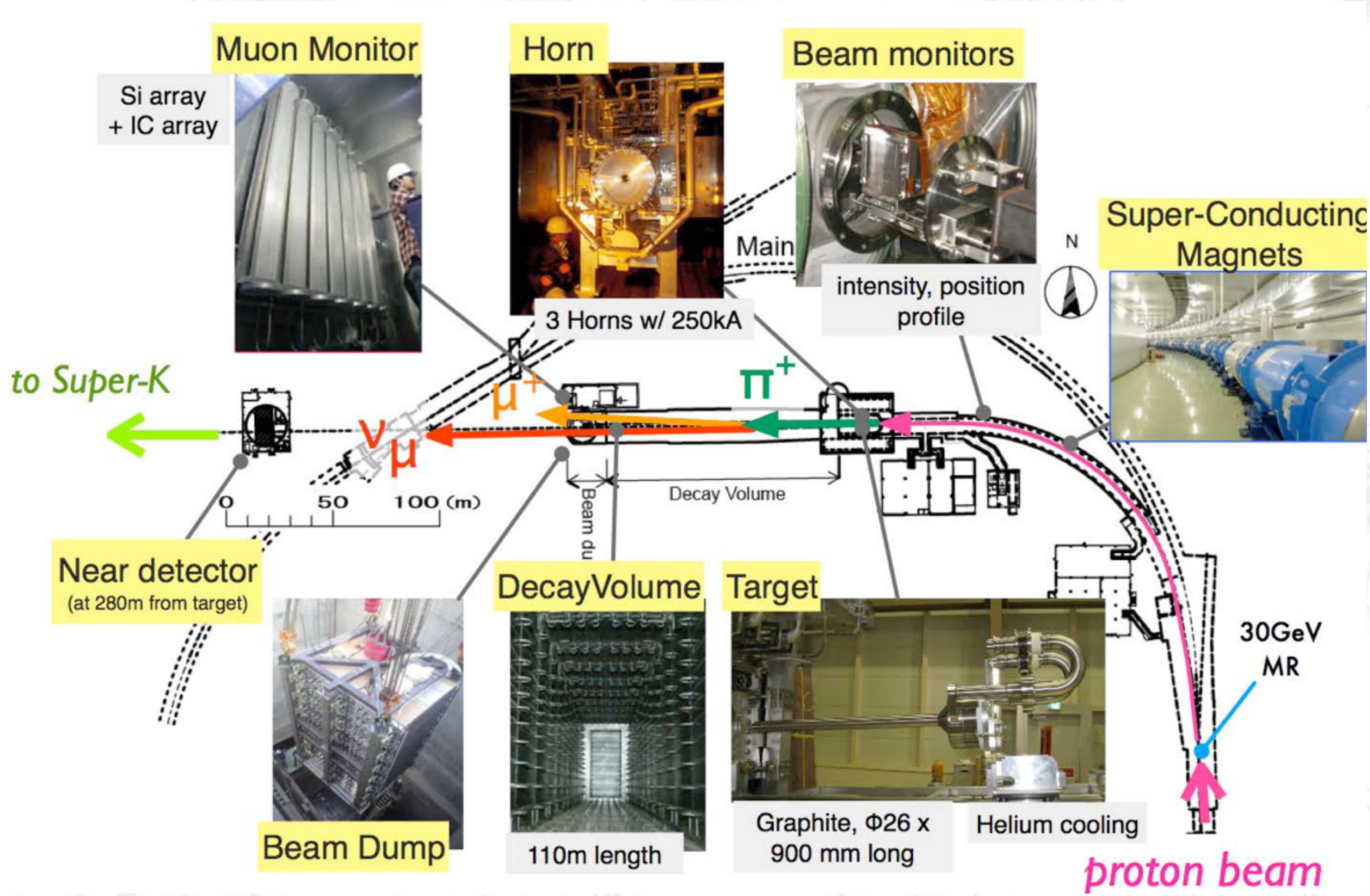
JPARC



J-PARC = Japan Proton Accelerator Research Complex

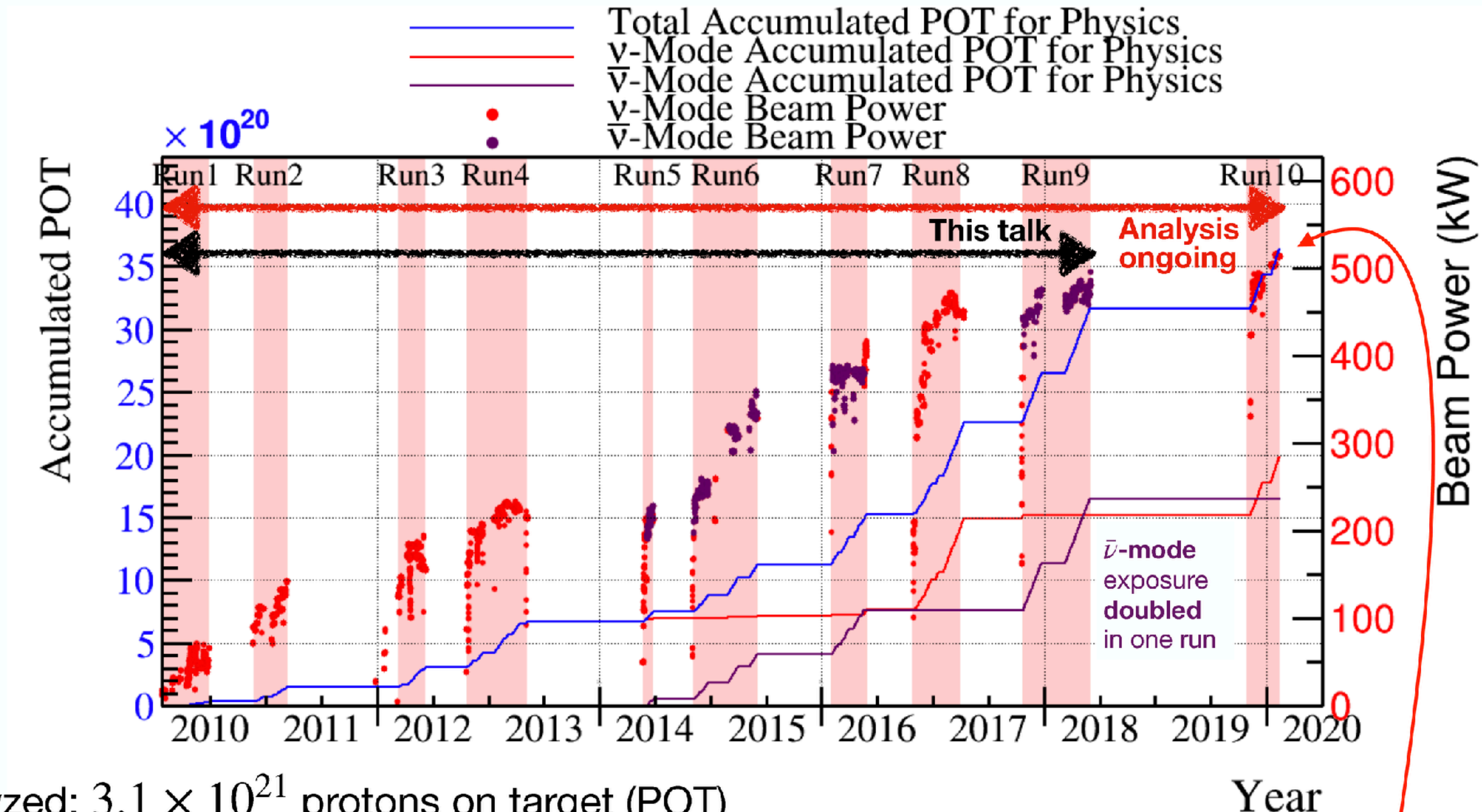
Joint Project between KEK and JAEA

ν beam @ JPARC



Fast extraction with beam pulse every 2 sec.

Data Set



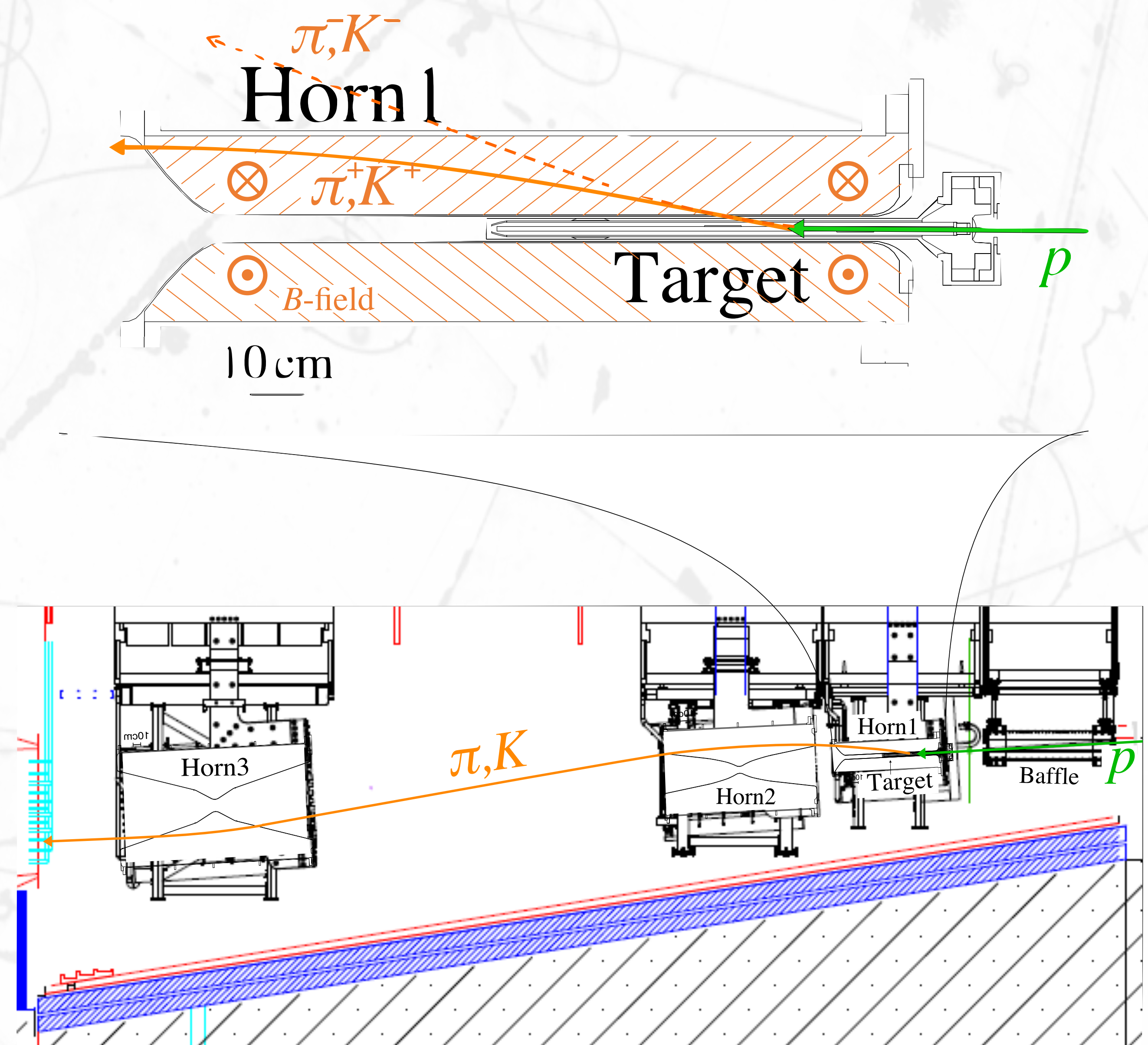
Analyzed: 3.1×10^{21} protons on target (POT)

approx 50% ν - 50% ν̄

515 kW stable operation in 2019
+ 33% of ν-mode for next analysis

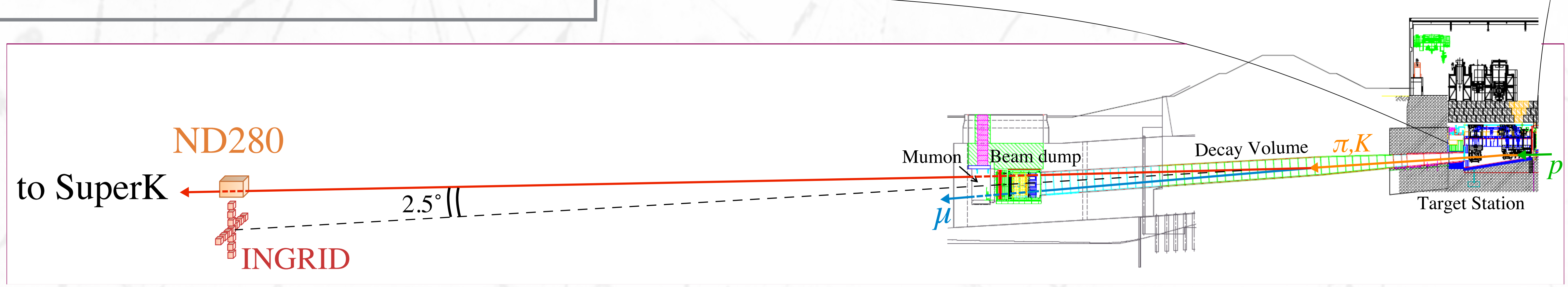
Neutrino beam

- 3 Horns system with 250 kA current sinusoidal ~3ms pulse.
- Forward (neutrino enhanced) and Reversed (anti-neutrino enhanced) modes.
- The beam is slightly tilted towards the earth.

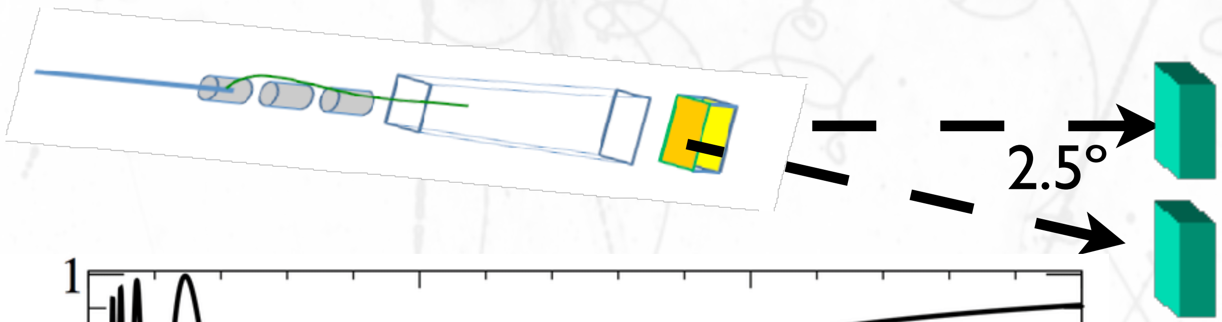


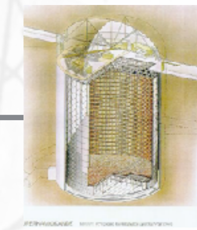
planned upgrade to reach 320kA

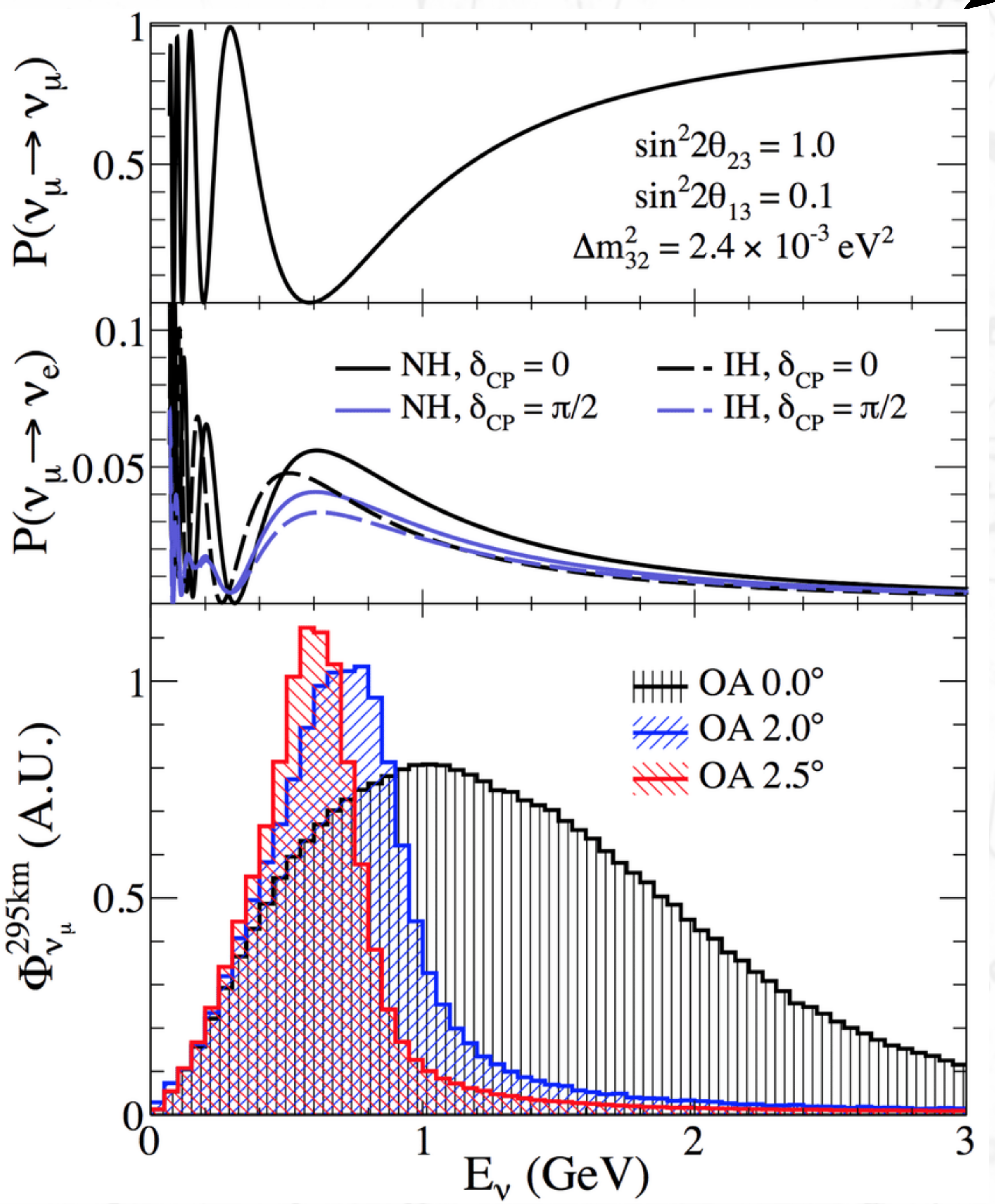
→ +~20% ν flux



Off-axis beam







Off-axis

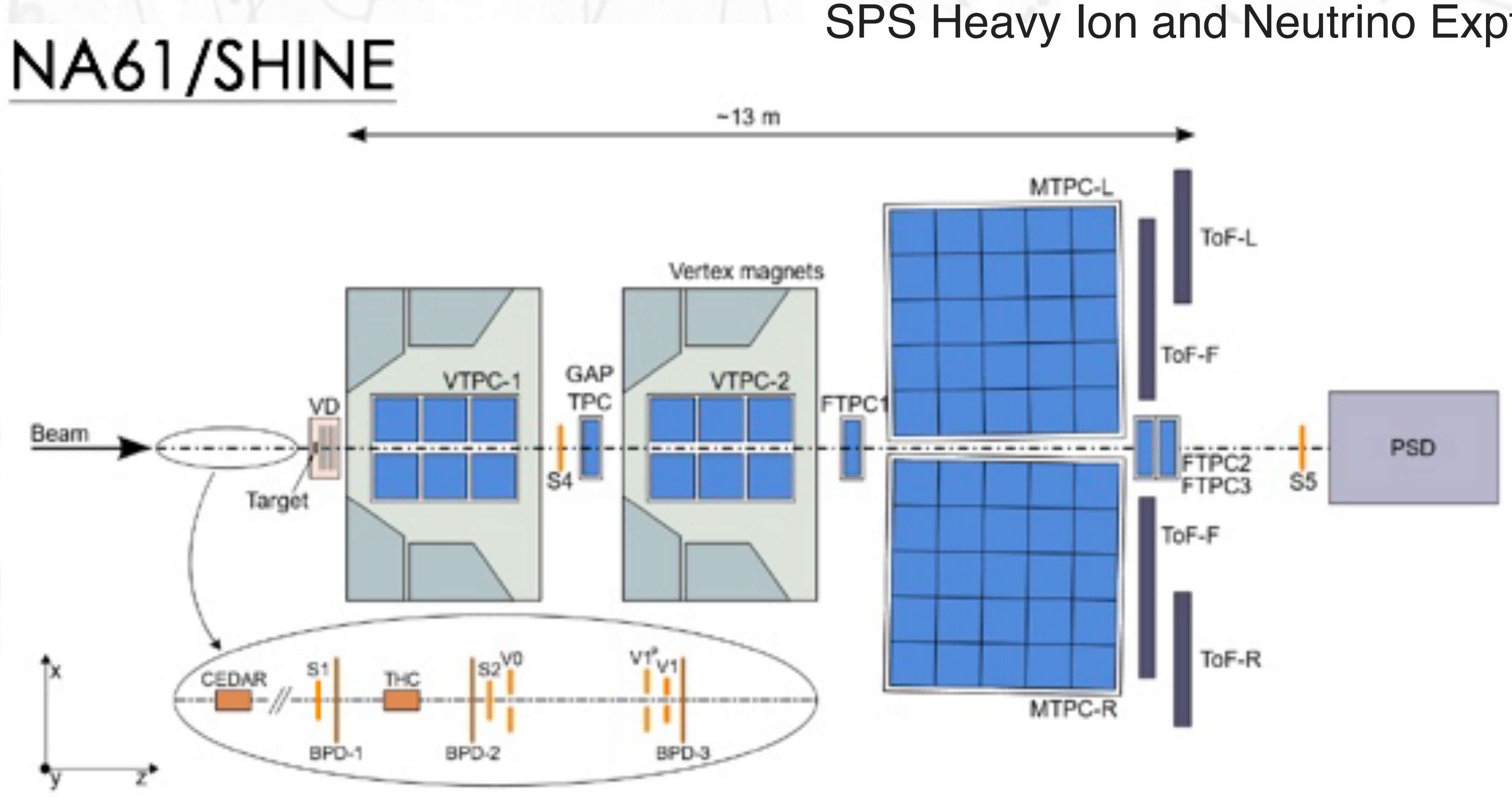
- off-axis optimises the flux at the maximum of the oscillation.
- Only one oscillation maximum can be measured at a fixed distance.
- Narrow beam less dependent on beam uncertainties but more on beam pointing.
- Lower energies achieved.

On-axis

- on-axis optimises the total integrated flux.
- Spectrum with higher neutrino energy (longer oscillation distances)
- If broad enough, more than one oscillation maximum can be measured at a fixed distance.

NA61-SHINE

SPS Heavy Ion and Neutrino Expt (SHINE)

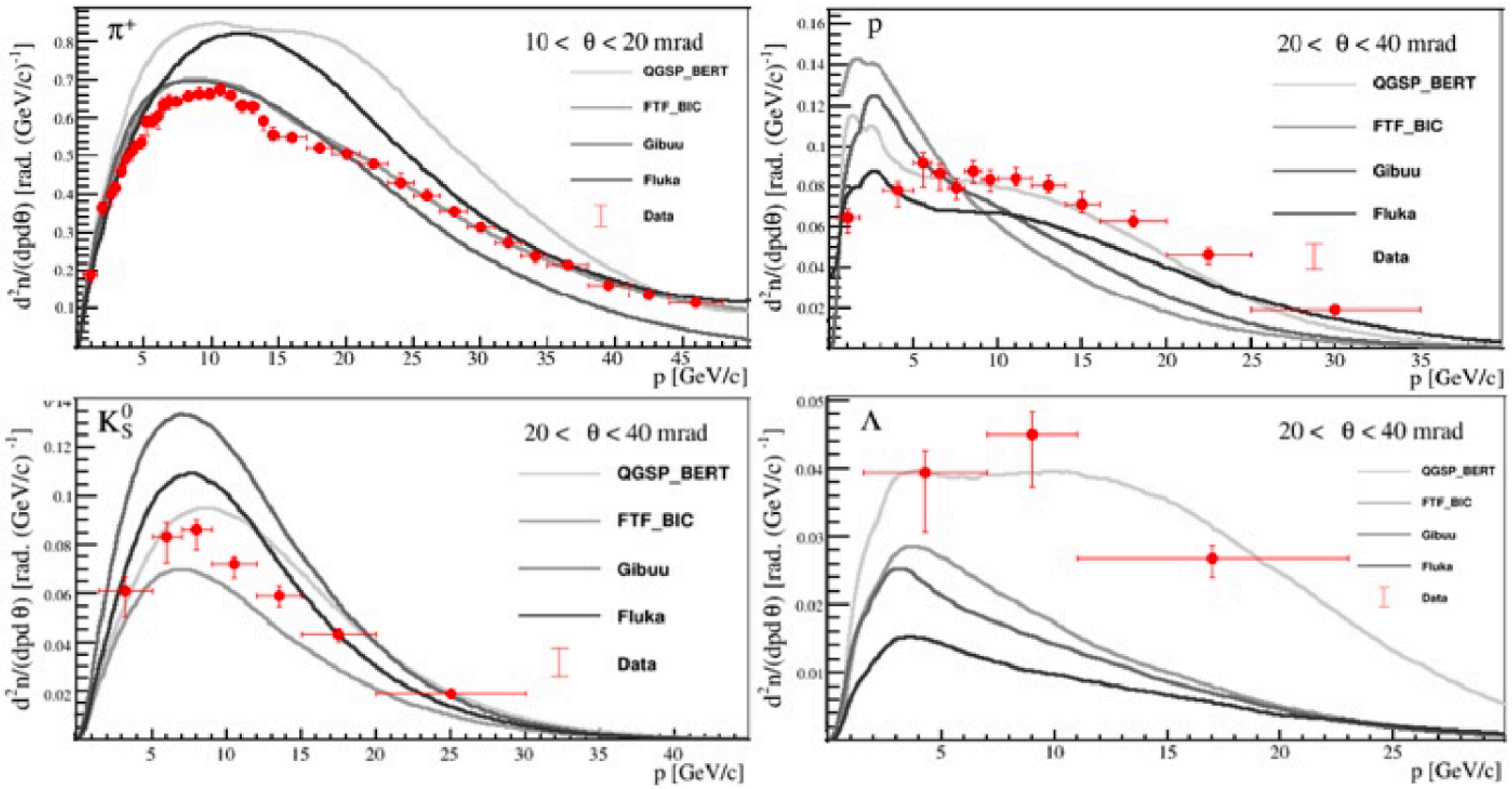


NA61/Shine measures the production of pions and kaons as function of the momentum and angle for protons interacting with carbon.

Hadro production experiments carried in equal conditions to ν beam experiments are critical!

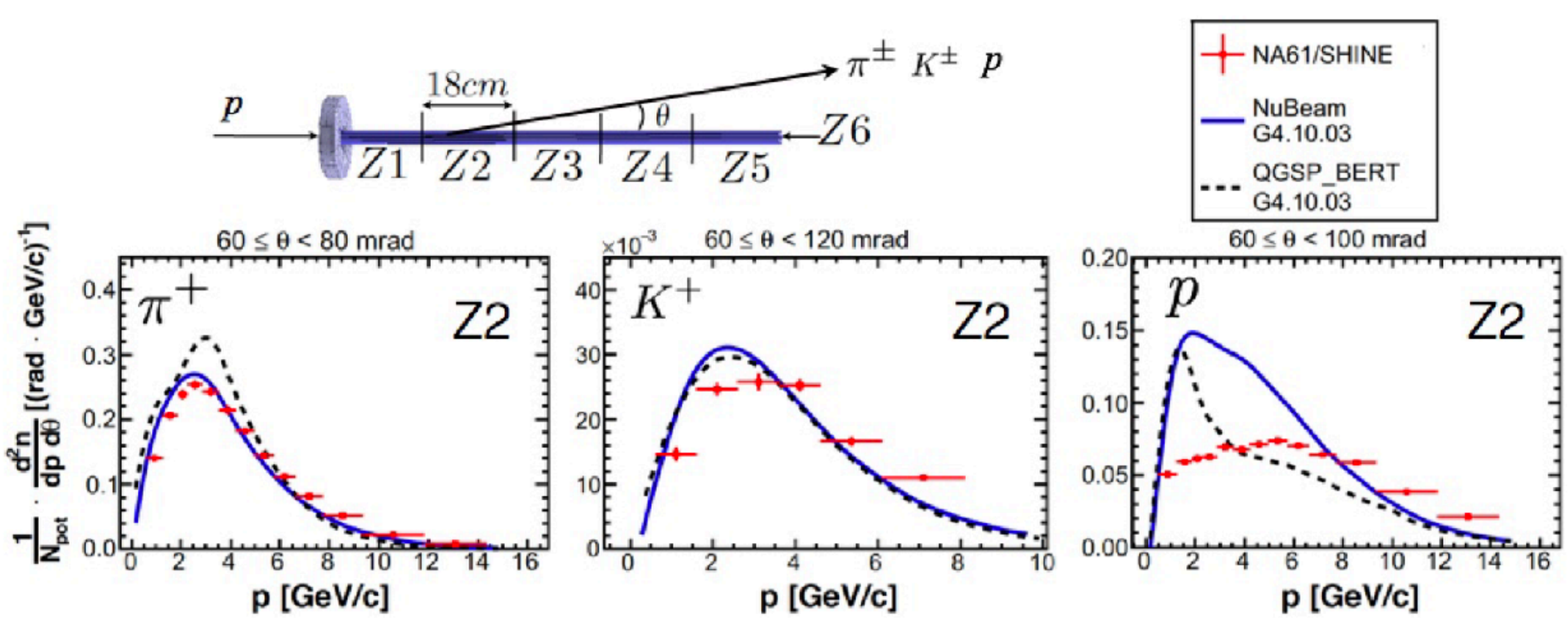
Latest measurements made with exact T2K replica target

NA61-SHINE



Measurement of pions, proton, K and Lambas in a 30 GeV proton-Carbon interactions

Measurement of production with exact replica of the target to account for re-interactions inside the target



Beam monitors

Proton beam monitors are essential for protecting beam-line equipment, as well as for understanding and predicting the **neutrino flux**

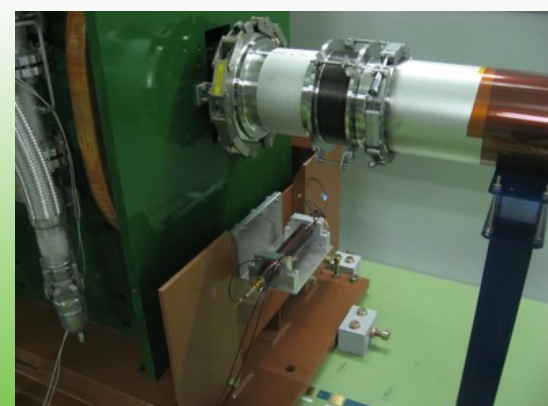
Beam intensity

Current transformers

<2.7% precision

Beam Loss

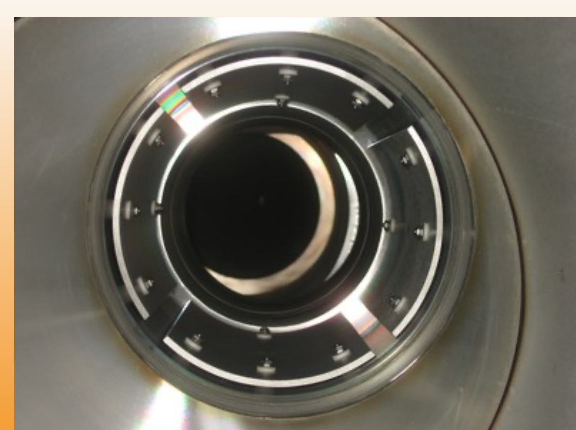
Sensitive down to 16mW loss



Beam position

Electro Static monitors

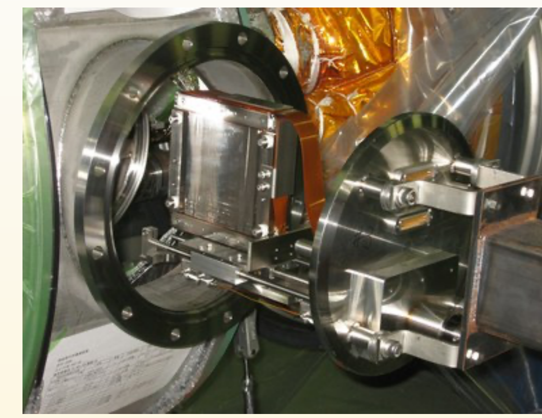
450μm precision



Beam position and profile

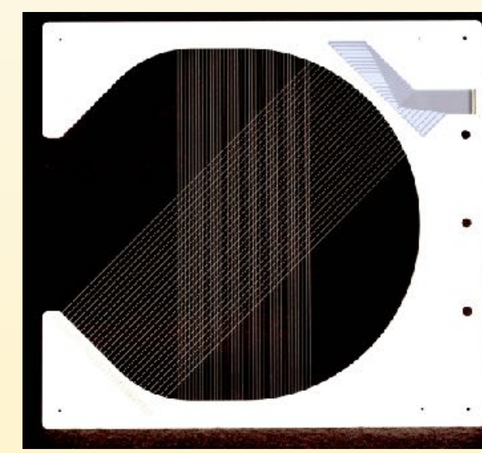
Segmented Secondary Emission Monitors

100μm position
200μm width



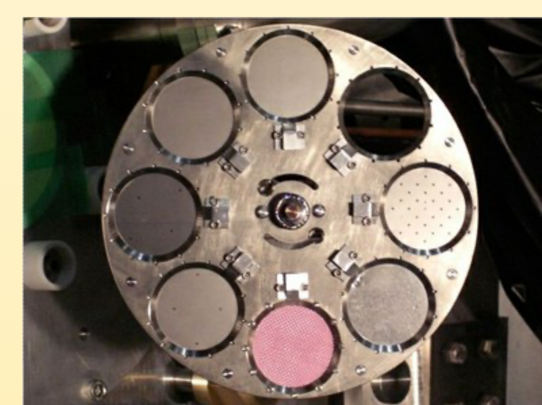
Wire Secondary Emission Monitors

100μm position
200μm width

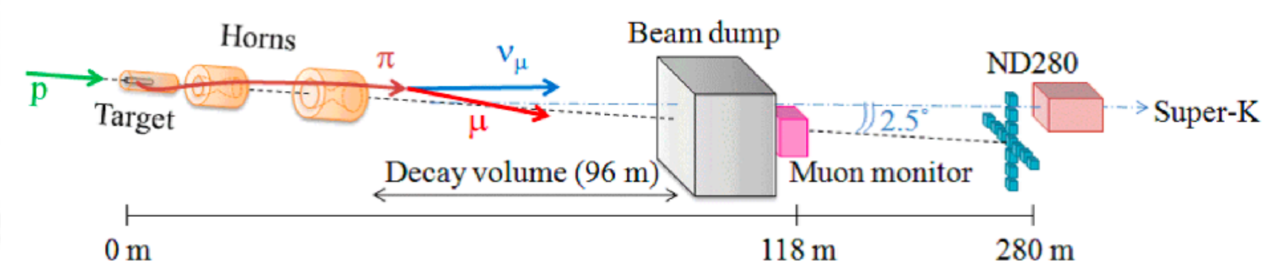


Optical transition radiation

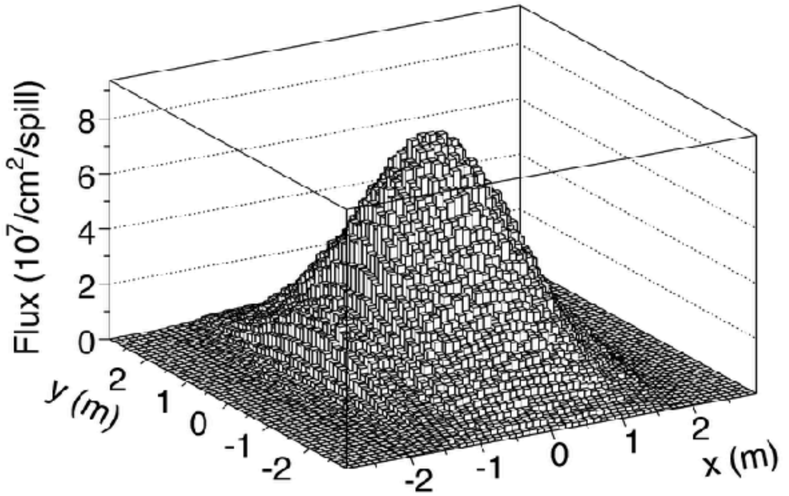
<500μm precision



Muon monitors

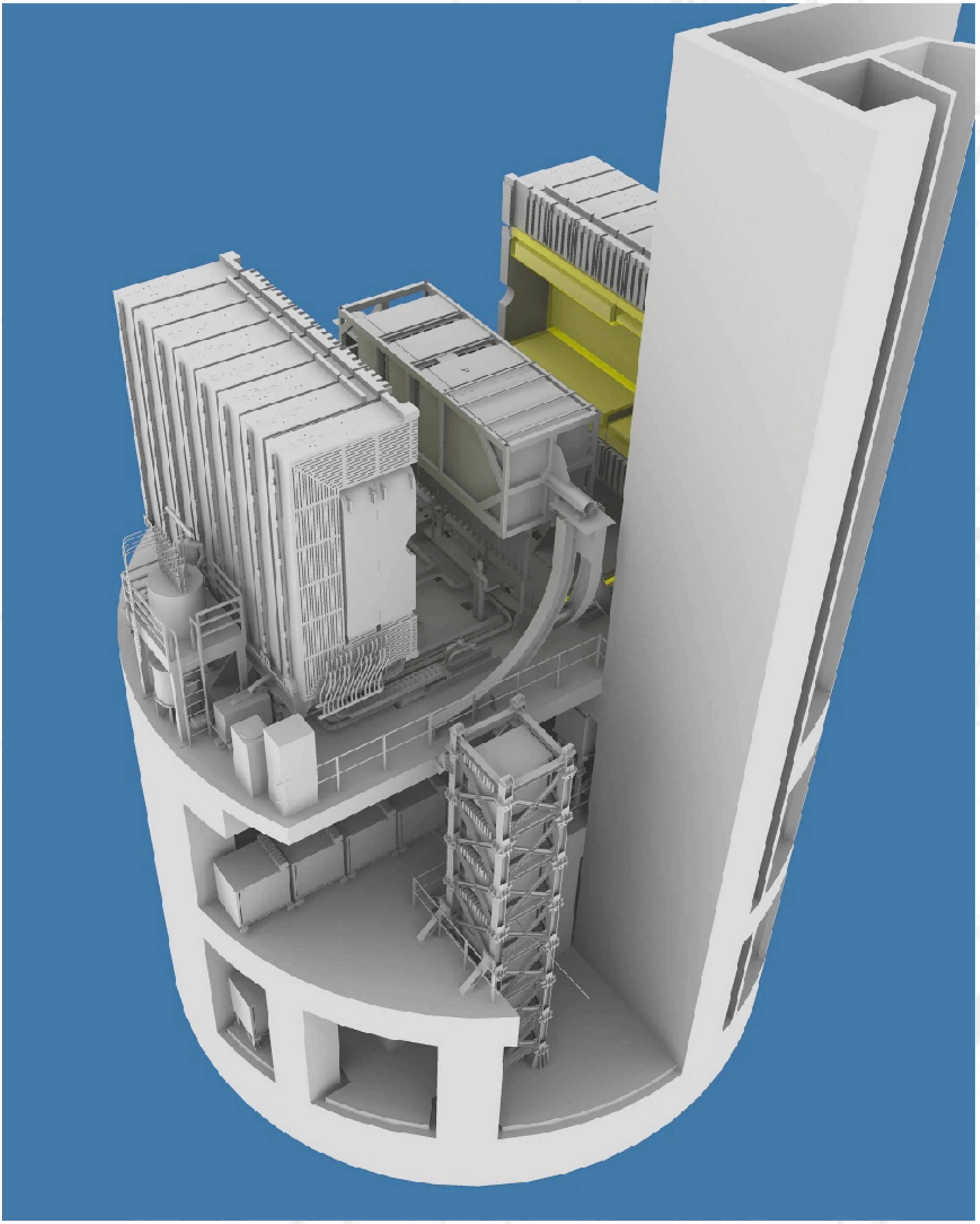


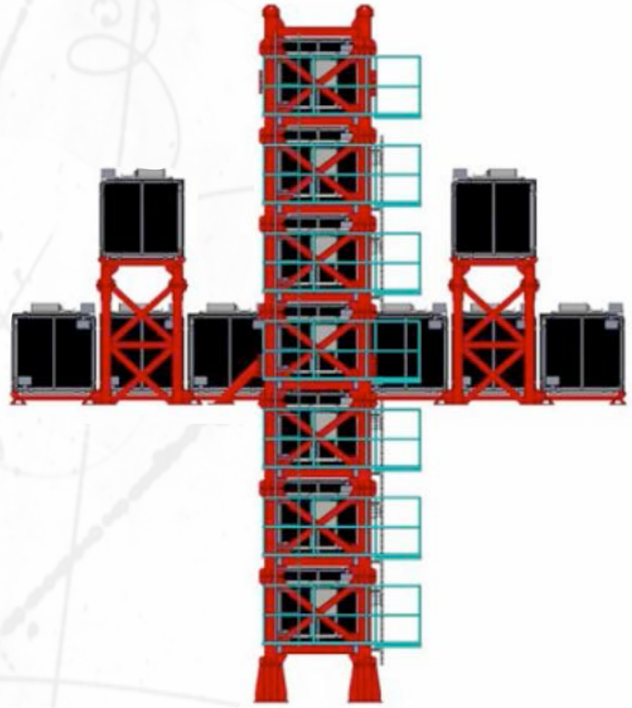
- Monitors the beam direction from the μ produced in π decays.
- Embedded in the beam dump samples the high energy muons.
- ionisation chambers and silicon PIN diodes.
- High irradiation area: ~10^{14} electrons/cm/month at 750 KW.



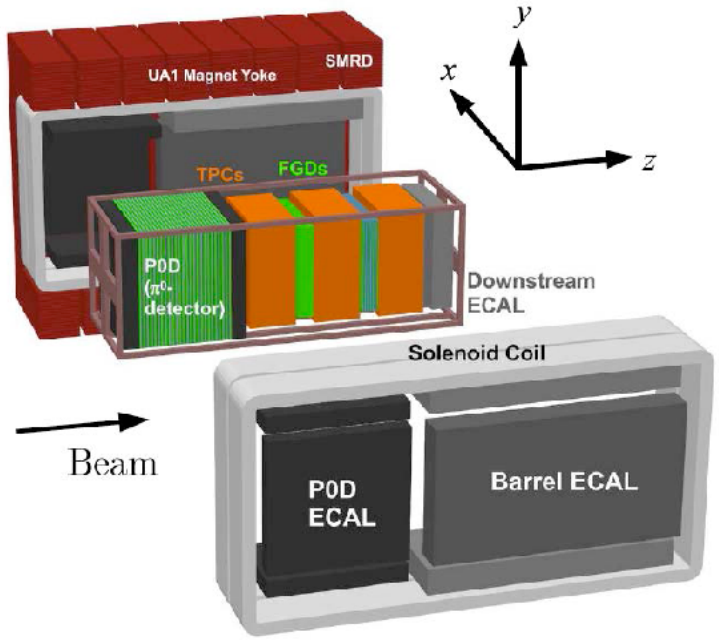
Simulation of fluence

Near Detector Site

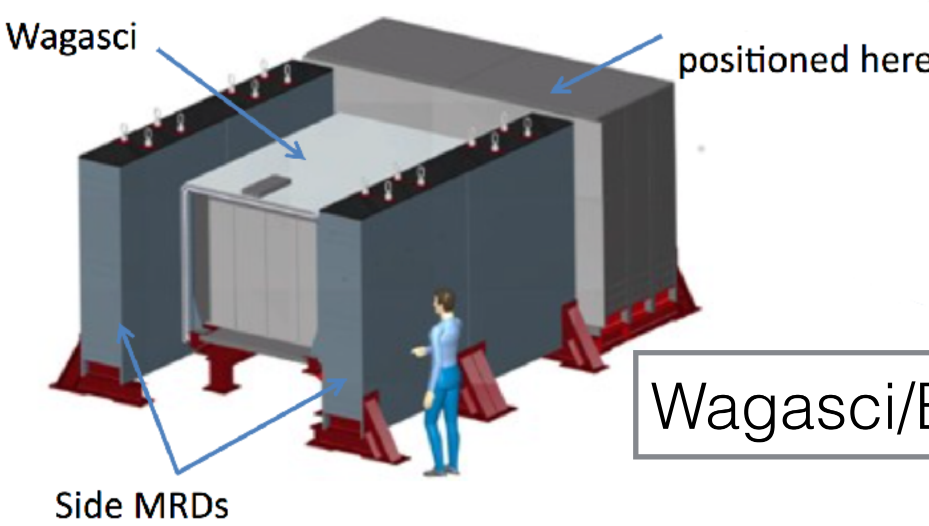




INGRID: On-axis



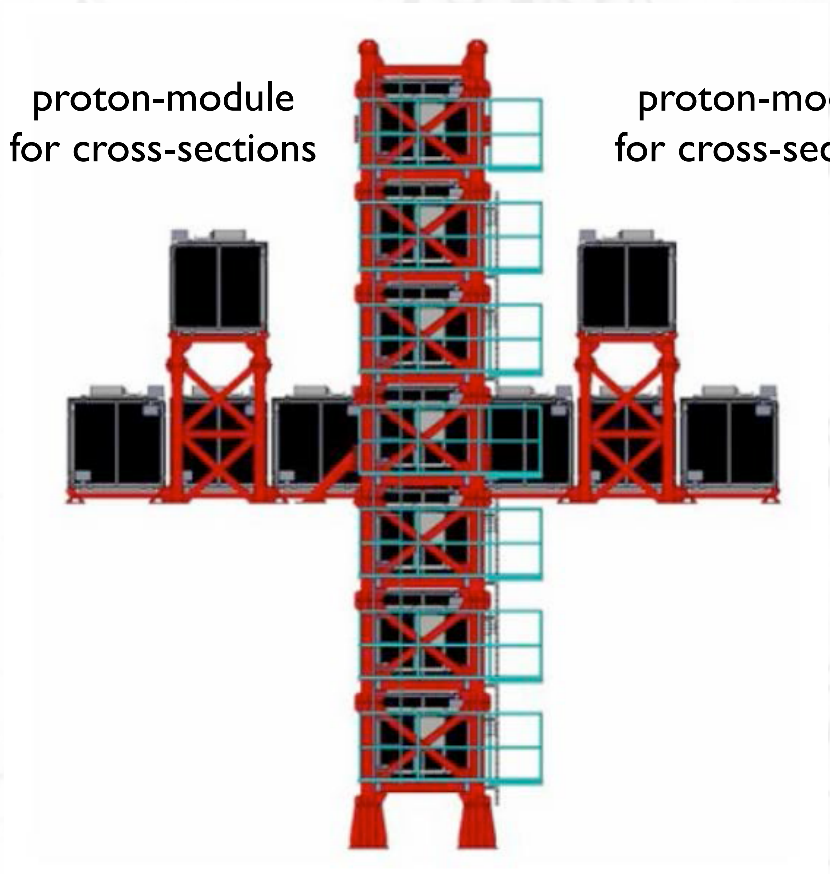
ND280: Off-axis



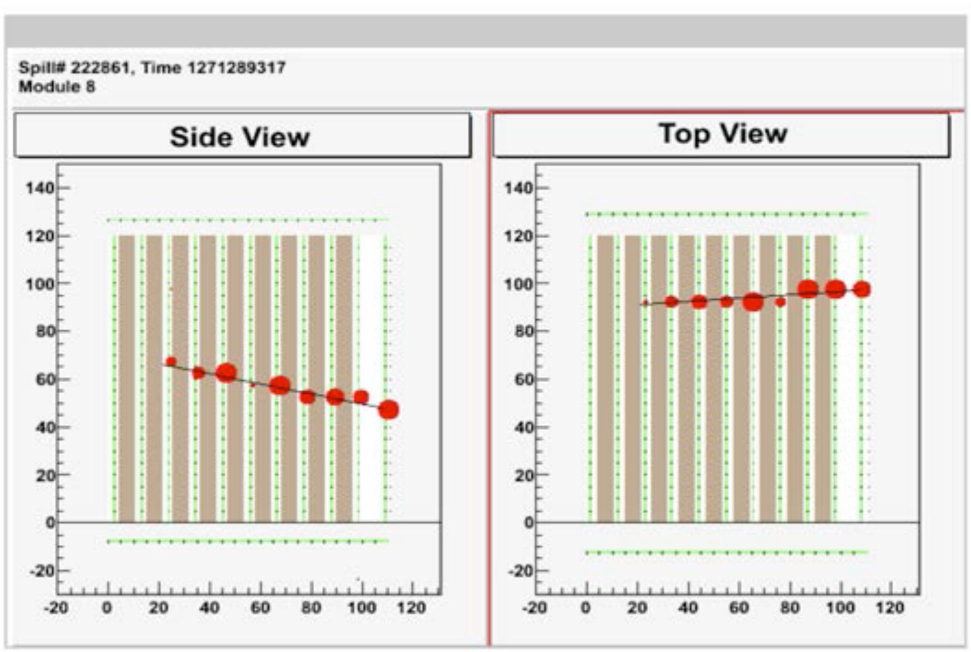
New!

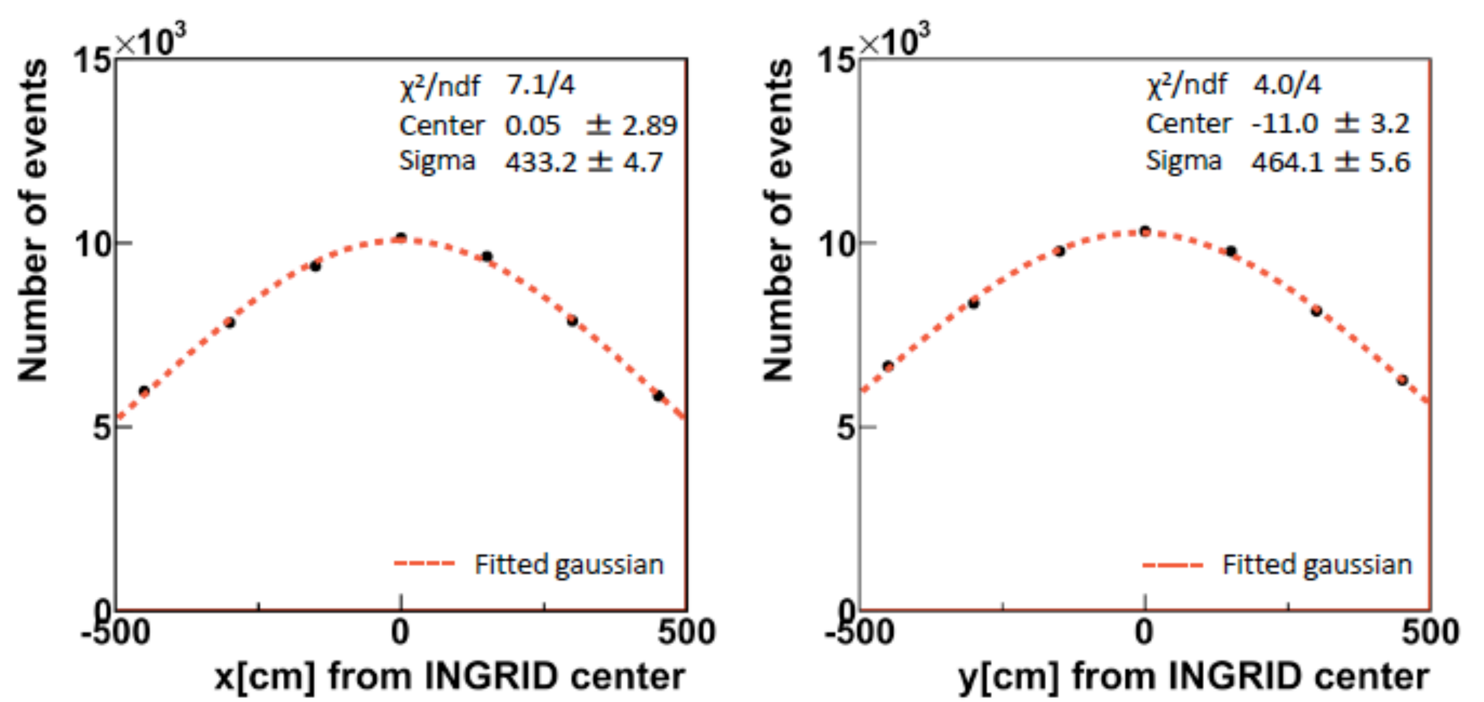
Wagasci/BabyMind: Off-axis

On-Axis ND



- INGRID counts $\nu(\bar{\nu})$ CC events in a cross of 13 identical detectors:
  - total rate monitors beam intensity stability with respect to proton on target counting.
  - The relative event counts between modules monitor the beam direction stability.



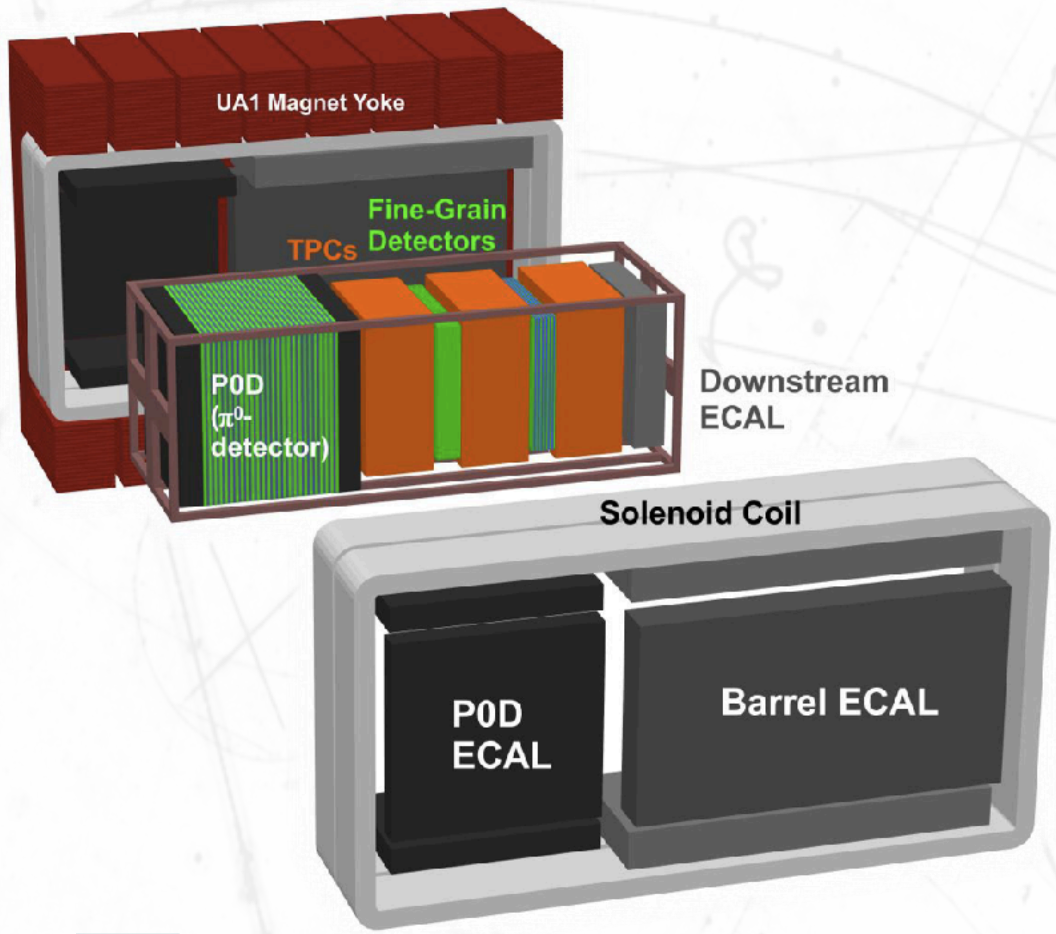


Off-Axis ND

- Same off-axis angle as SuperKamiokande (2.5 degrees)
- Measure ν_μ and ν_e spectrum before the oscillation → TPCs + FGDs
- Measure background processes to oscillation (NCπ^0, NC1π, CC1π…)
- Compare Carbon and Oxygen interactions (FGD2 and P0D)

ND280 installed in ex-UA1 magnet (0.2 T) 3.5x3.6x7.3 m

SMRD (Side Muon Range Detector):
scintillator planes in magnet yokes.
Measure high angle muons



2 FGDs (Fine Grained Detector):
active target mass for the tracker, optimized for p/π separation
Carbon+Water target in FGD2

3 TPCs (Time Projection Chambers):
measure momentum and charge of particles from FGD and P0D, PID capabilities through dE/dx

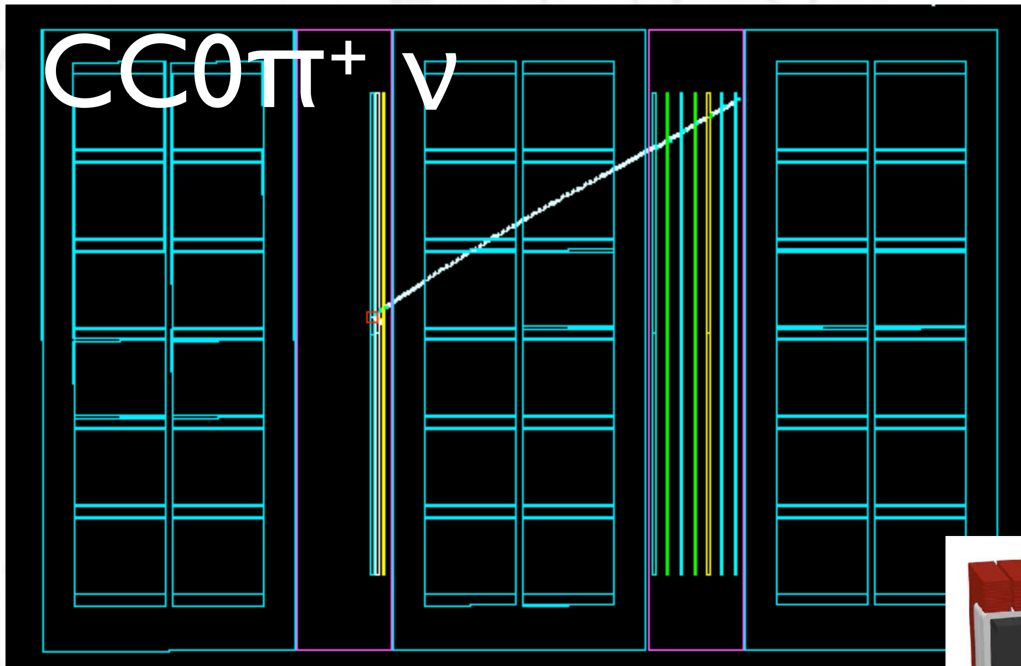
P0D (π0 detector):
scintillator bars interleaved with fillable water target bags and lead and brass sheets.
Optimised for γ detection

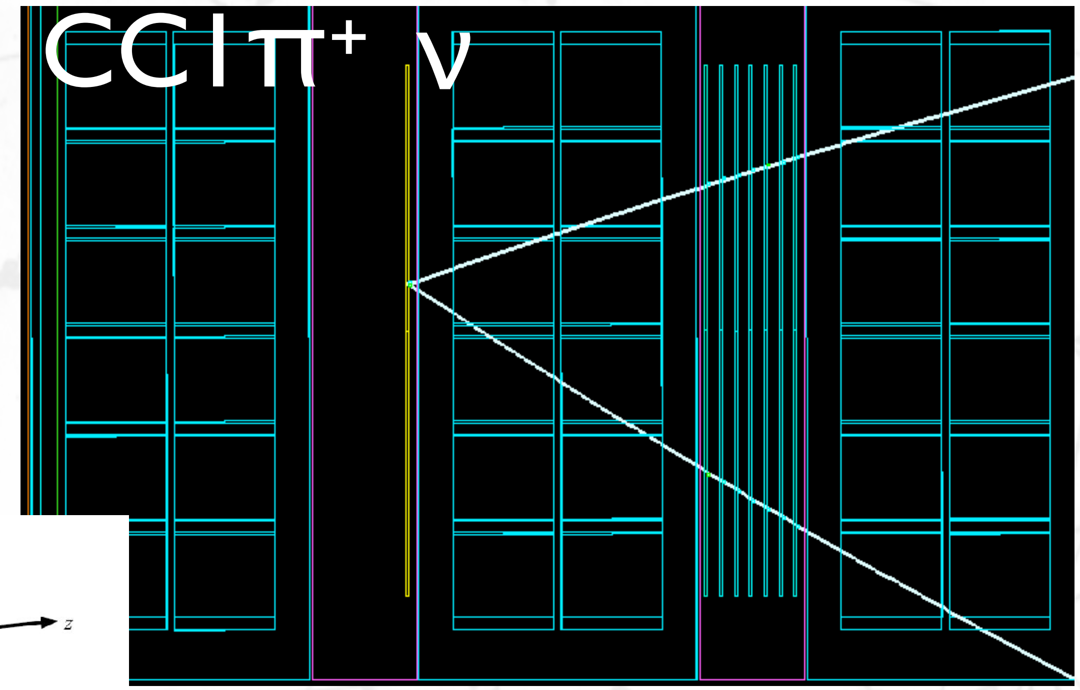
P0D, Barrel and Downstream ECAL:
scintillator planes with radiator to measure EM showers

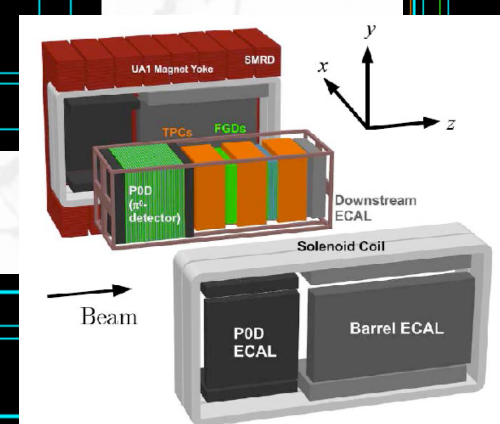
Magnet was granted by CERN

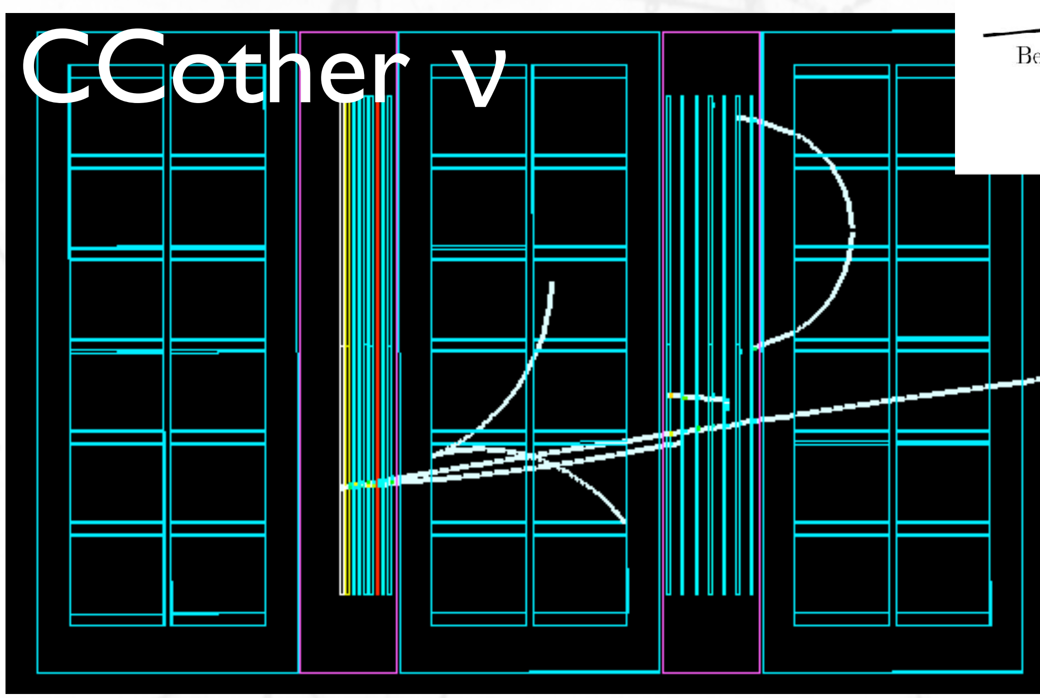
Off-Axis ND

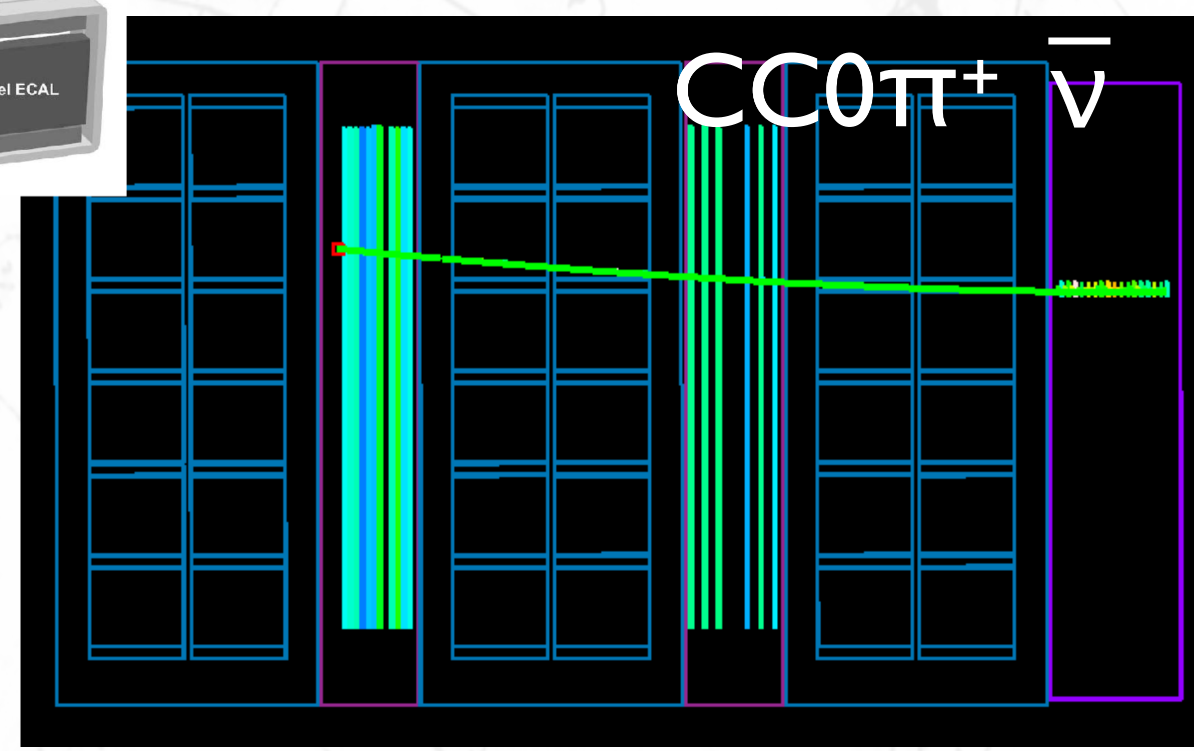
Off-axis ND280 analysis real events







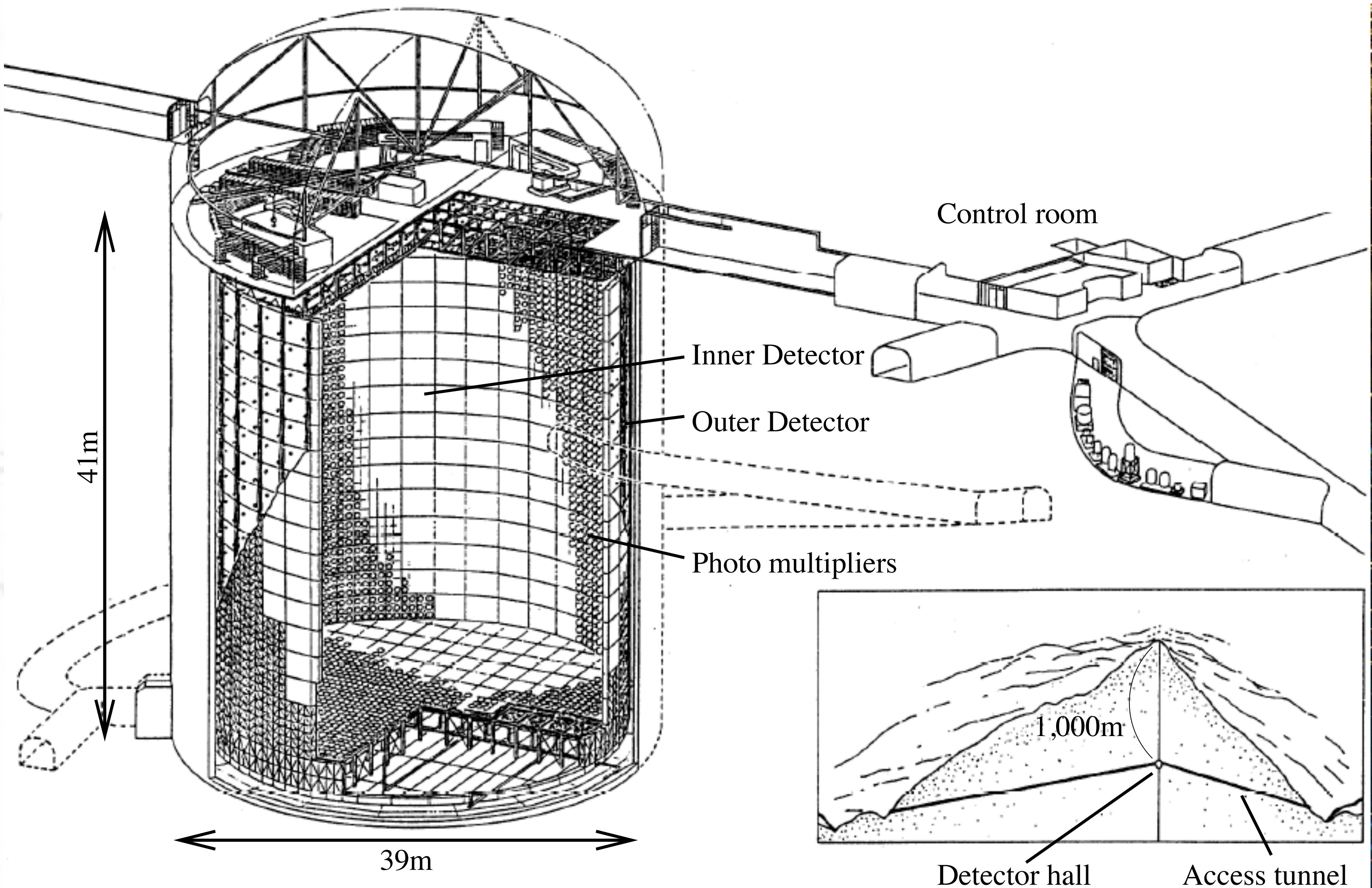


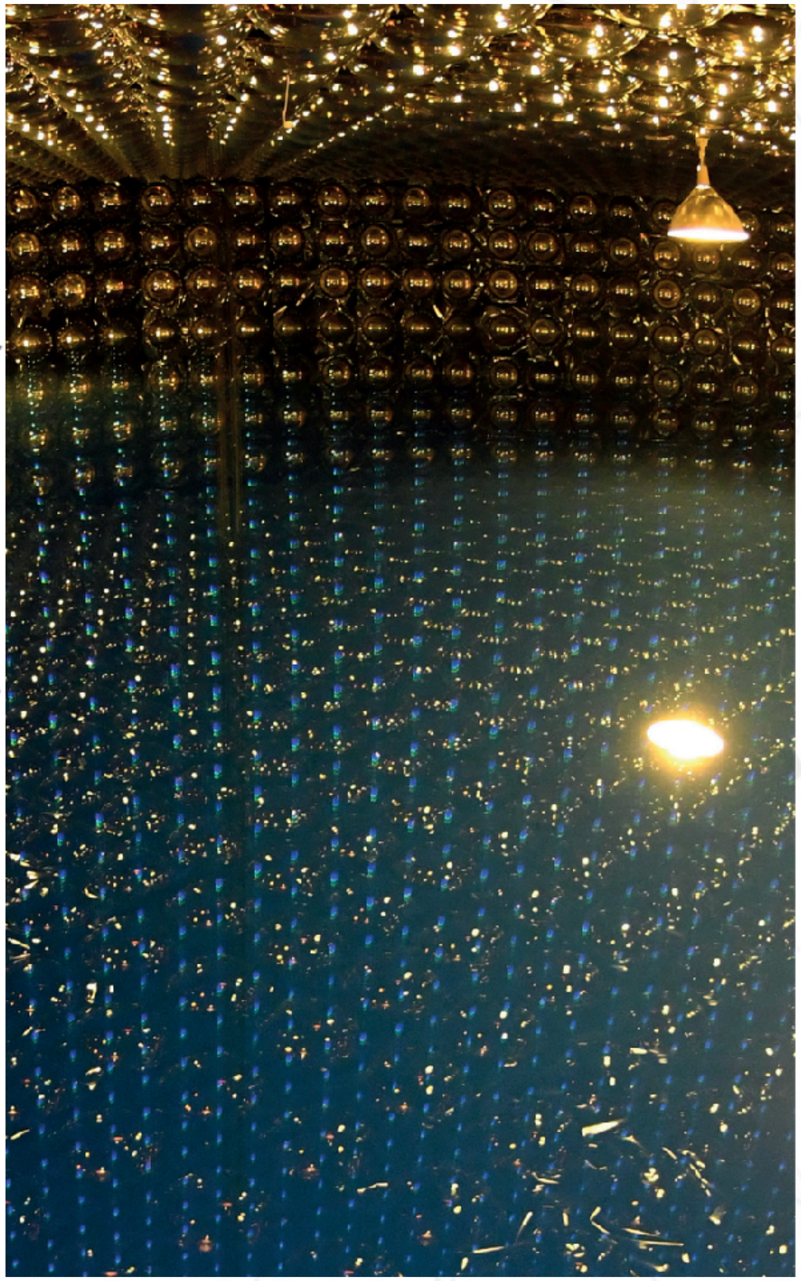


Far detector

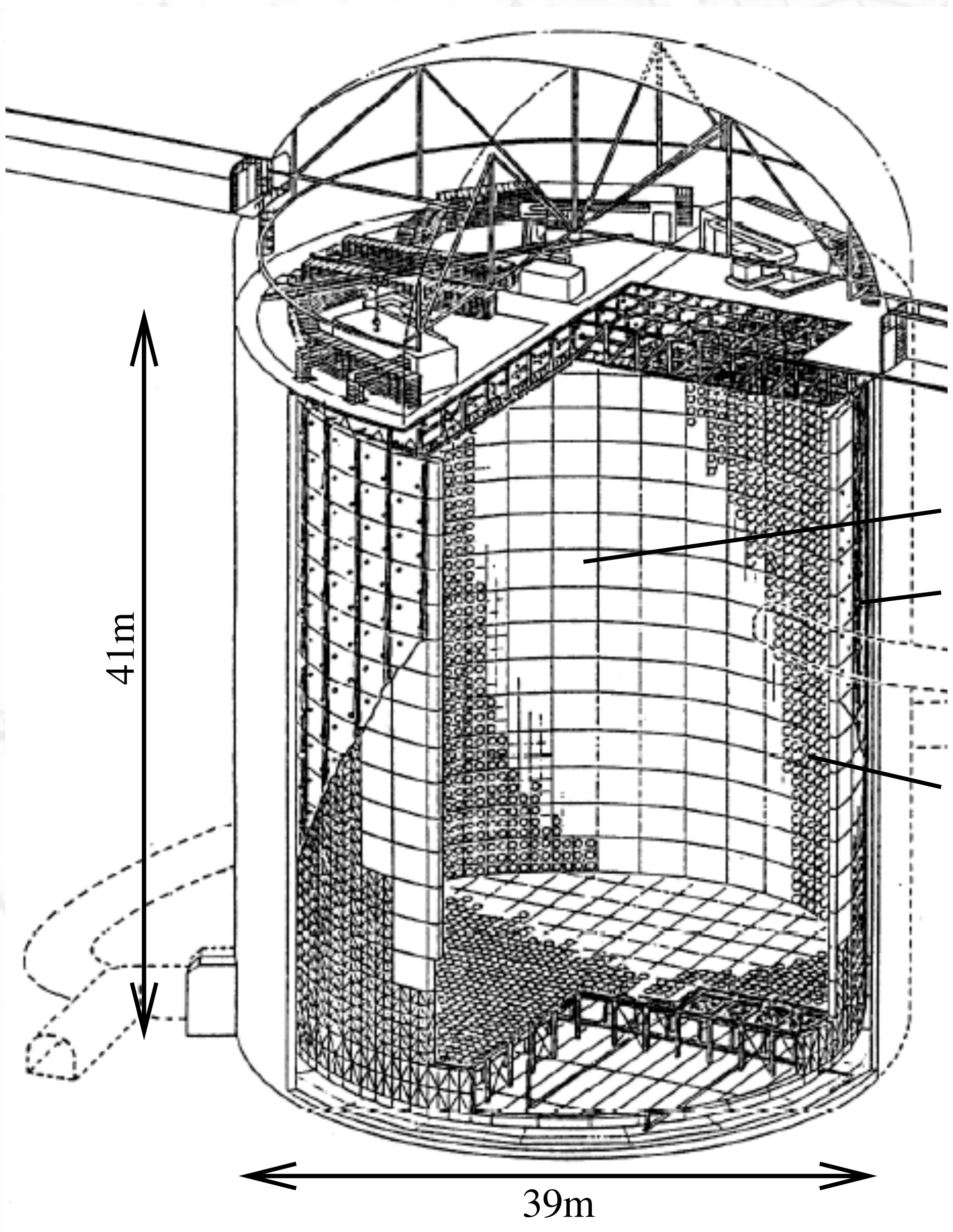
50 kton of ultra-pure water

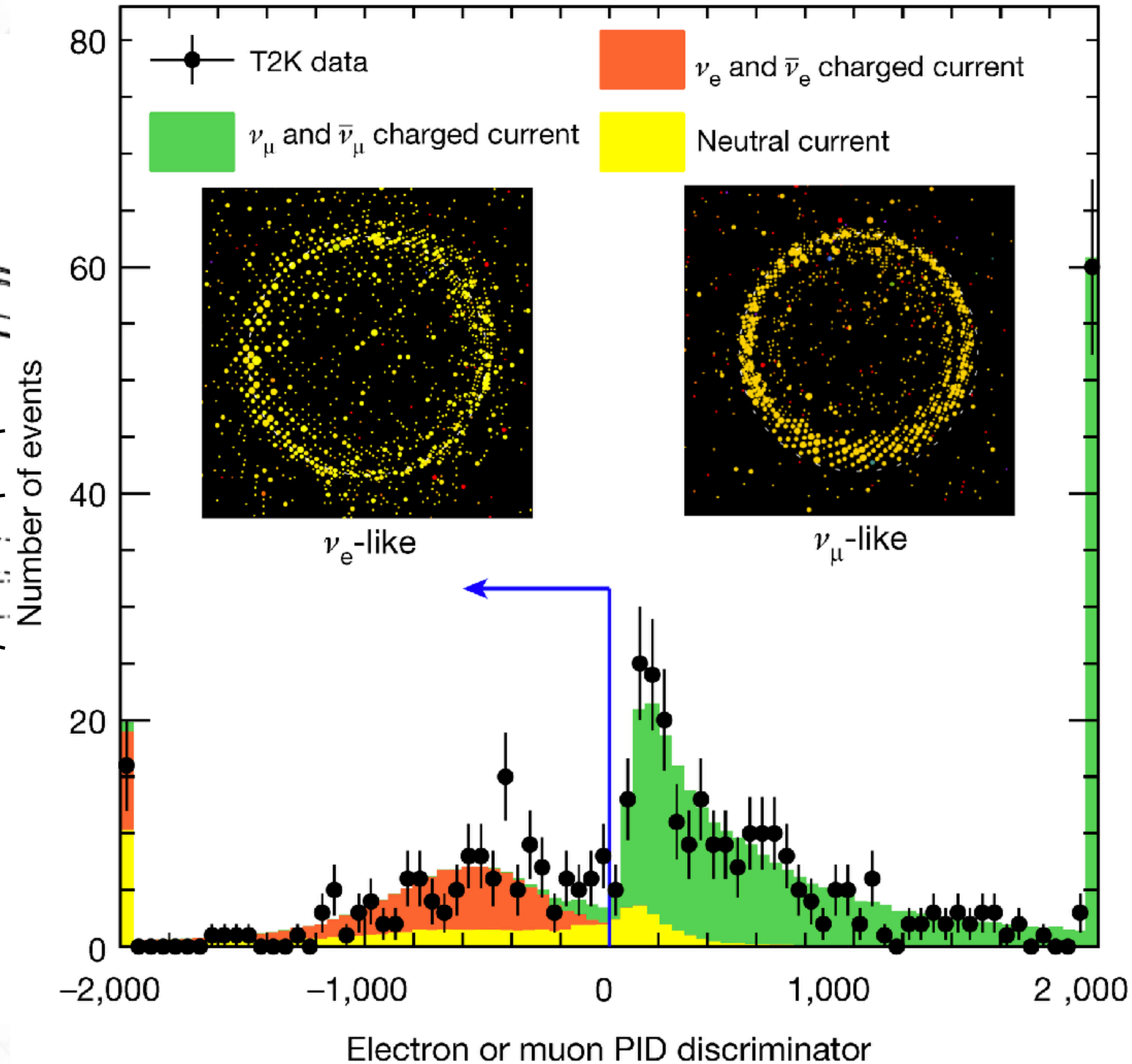
~11000 20” PMT’s





Far detector





Particle identification

Interaction vertex reconstruction

Track Multiplicity

Particle range

Electromagnetic energy reconstruction

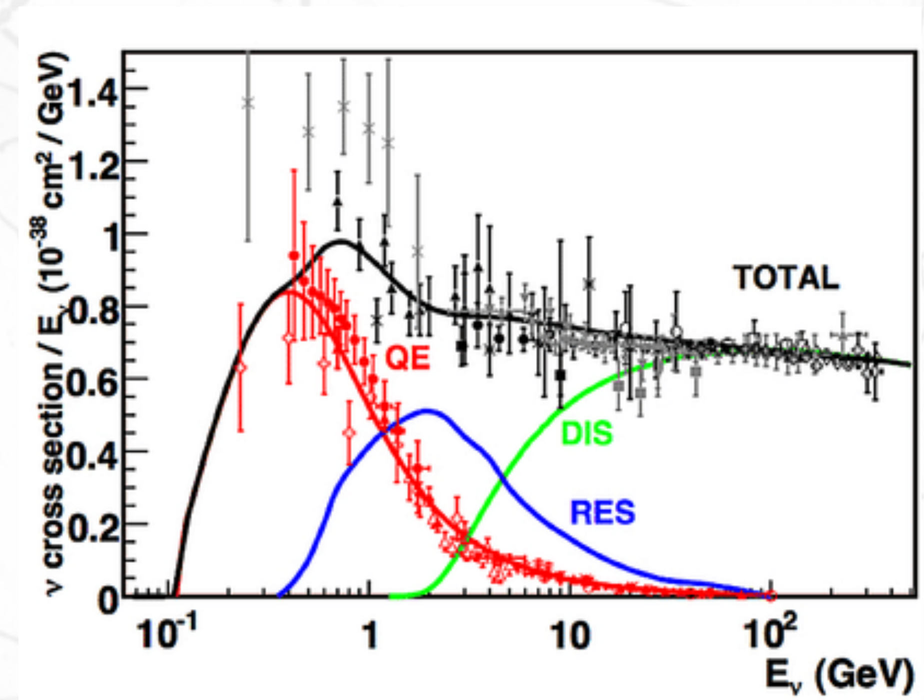
Hadronic interactions

Neutrino-nucleus cross-sections

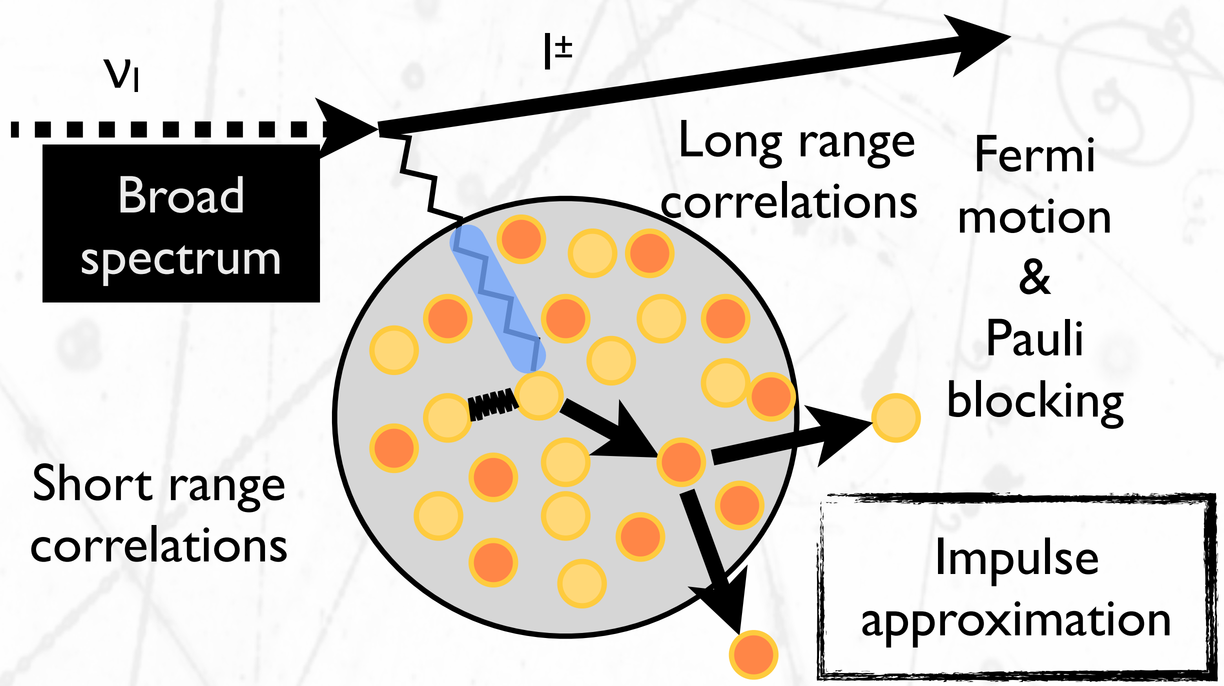
νA cross-sections

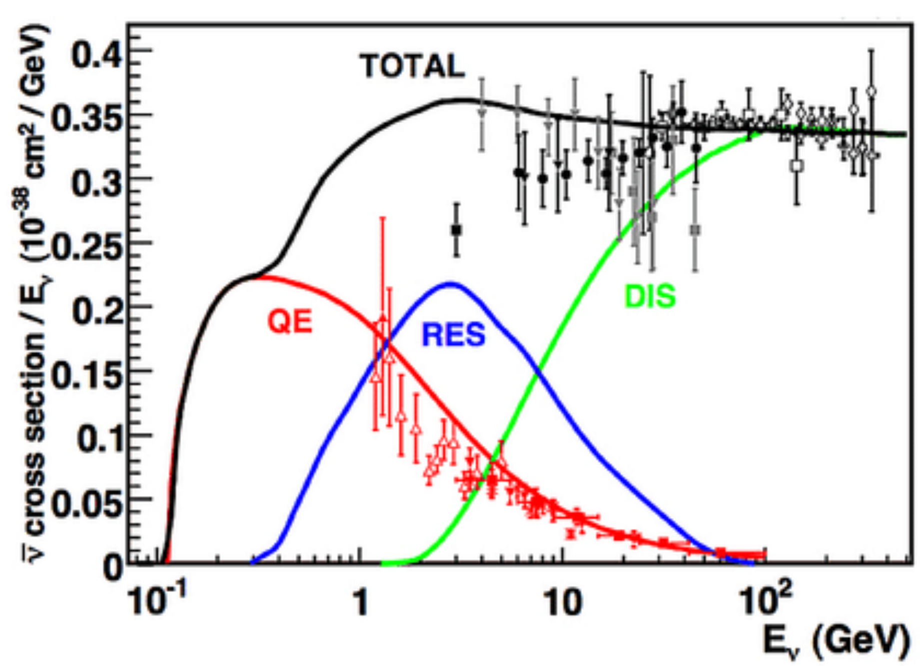
@ the nucleon level !

$CCQE$	$\nu_\mu n \to \mu^- p$
$CC1\pi$	$\nu_\mu p \to \mu^- \Delta^{++} \to \mu^- \pi^+ p$
	$\nu_\mu n \to \mu^- \Delta^{+} \to \mu^- \pi^+ n$
	$\nu_\mu n \to \mu^- \Delta^{+} \to \mu^- \pi^0 p$
$CCN\pi$	$\nu_\mu N \to \mu^- \Delta^{+,++} \to \mu^- N' \pi\pi \ldots$
$CCDis$	$\nu_\mu N \to \mu^- N' \pi, \pi, \ldots$



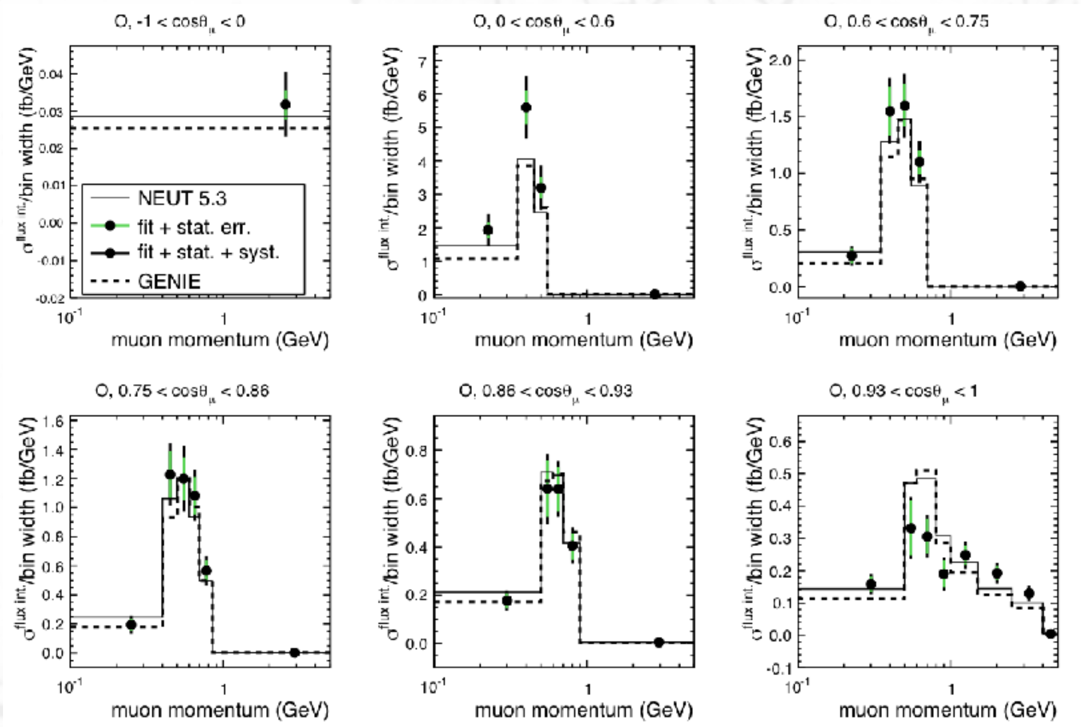
@ the nucleus level !



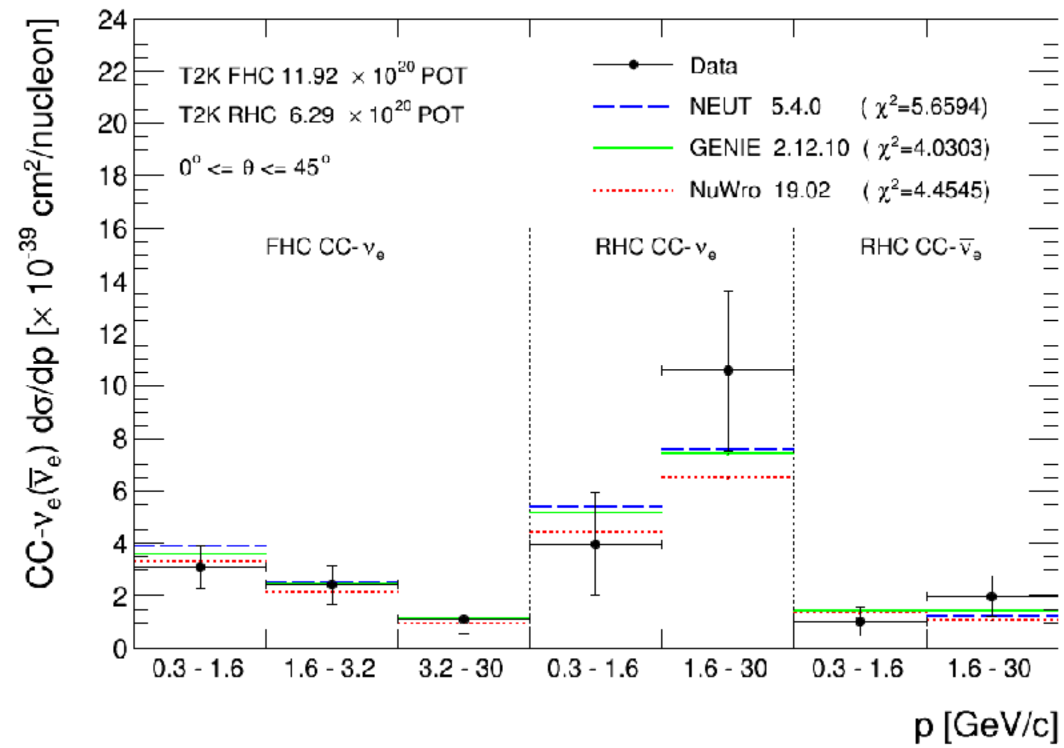


νA cross-sections

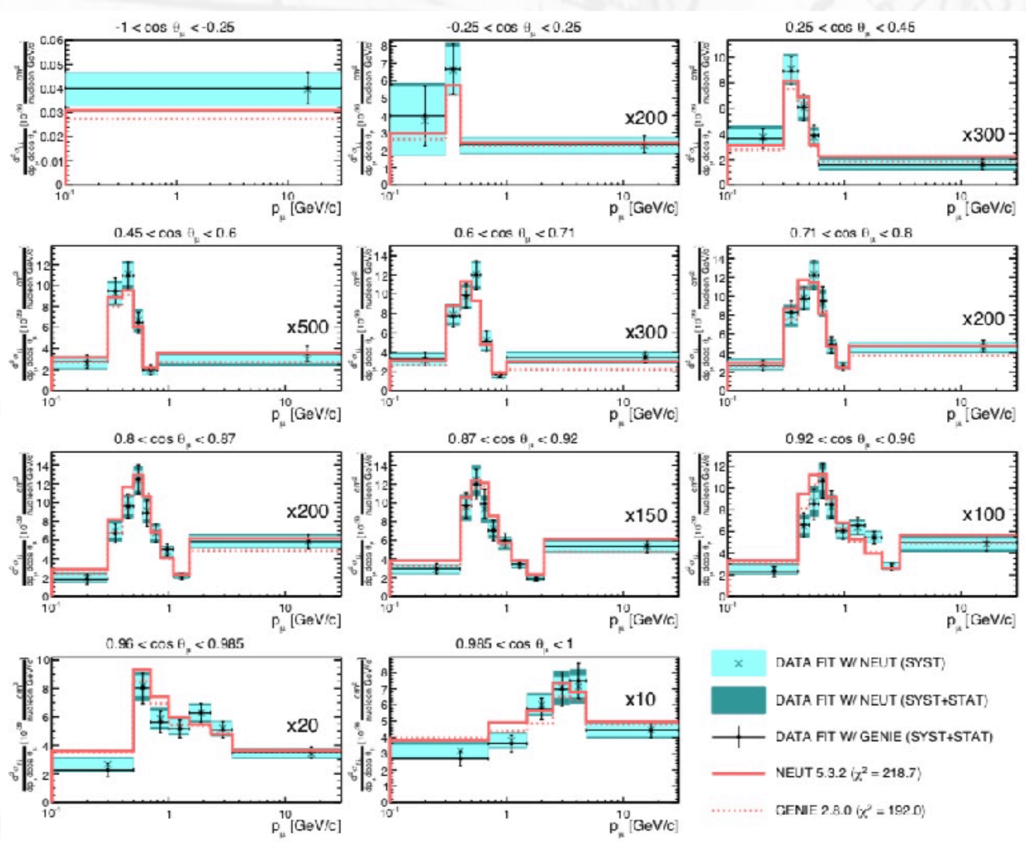
νμ CC0π on Oxygen



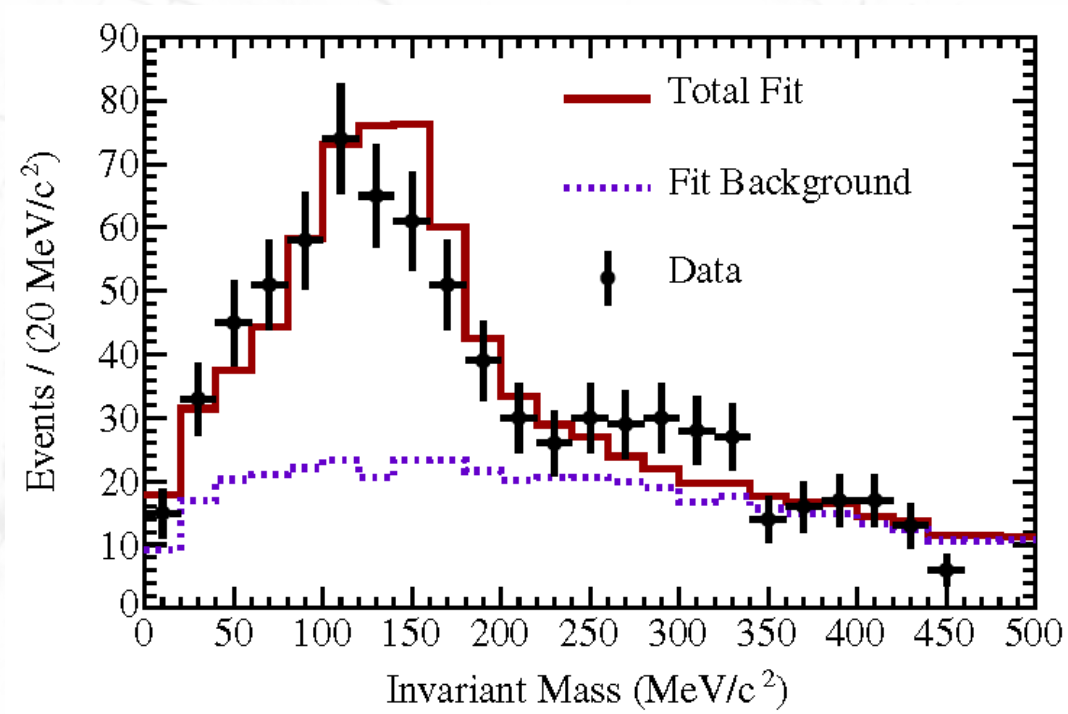
νe CC on Carbon



inclusive νμ CC on C

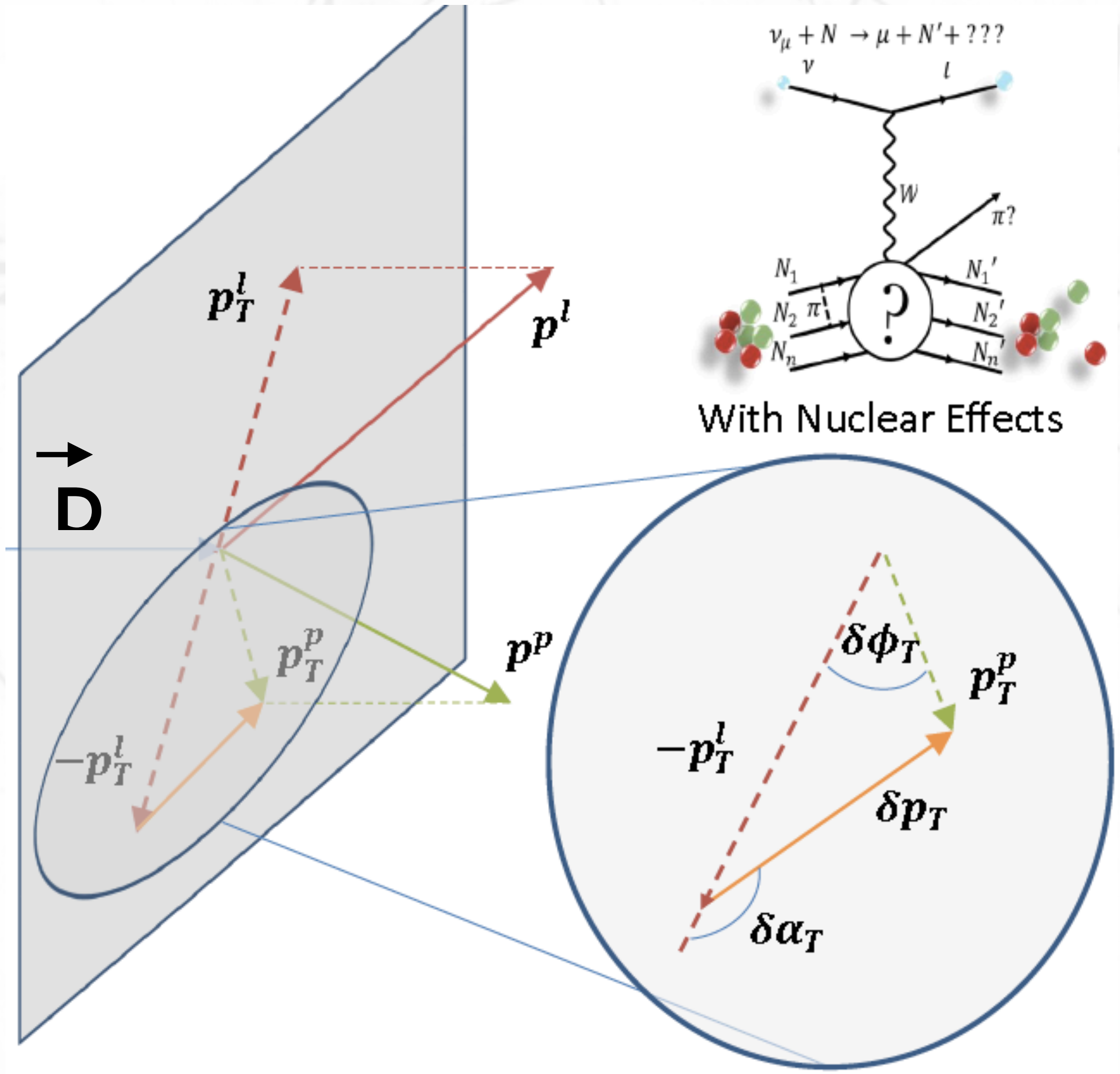


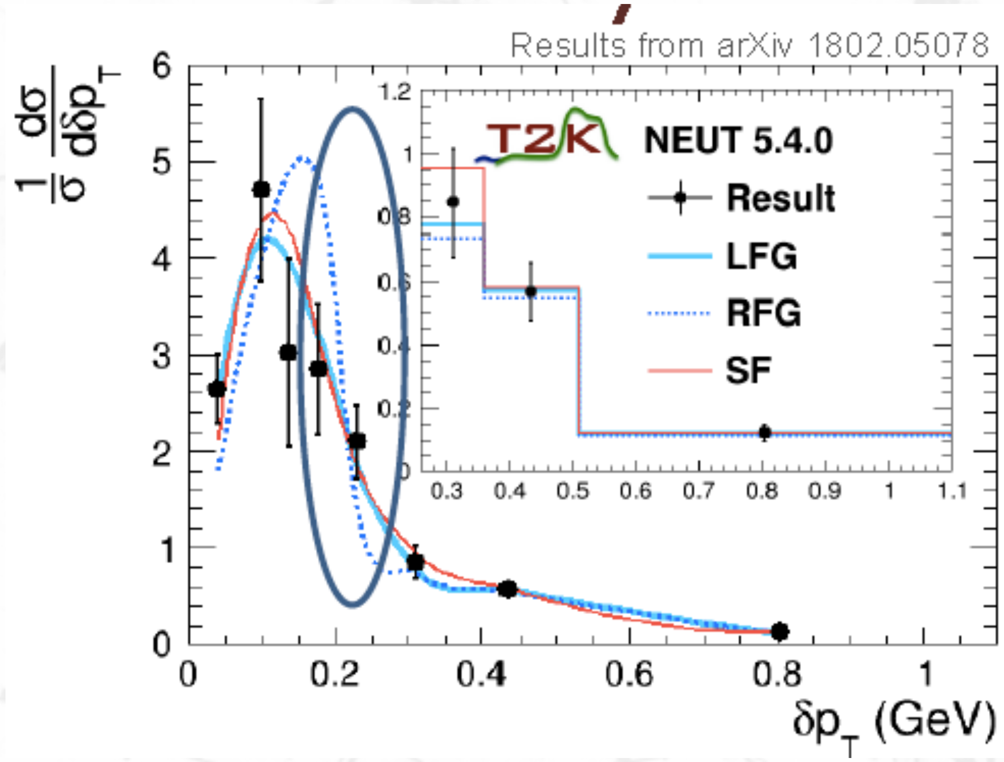
νμ NCπ⁰ on Water

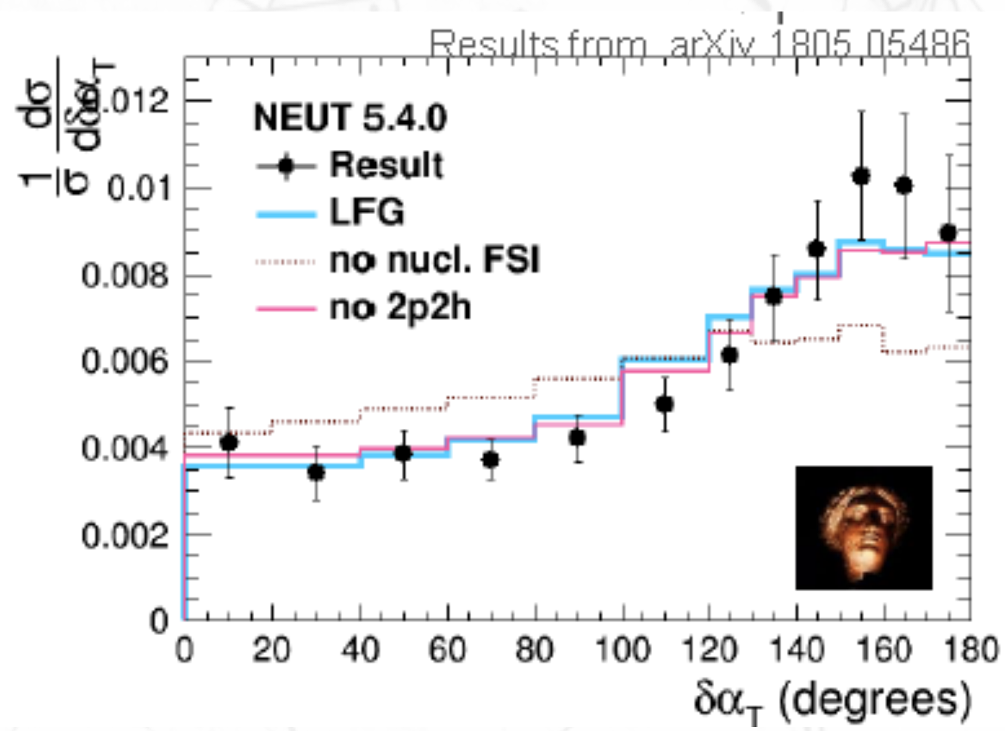


νA cross-sections

Low energy recoil proton allow us to measure transverse momentum imbalance to access nuclear effects: Fermi momentum and re-interactions.





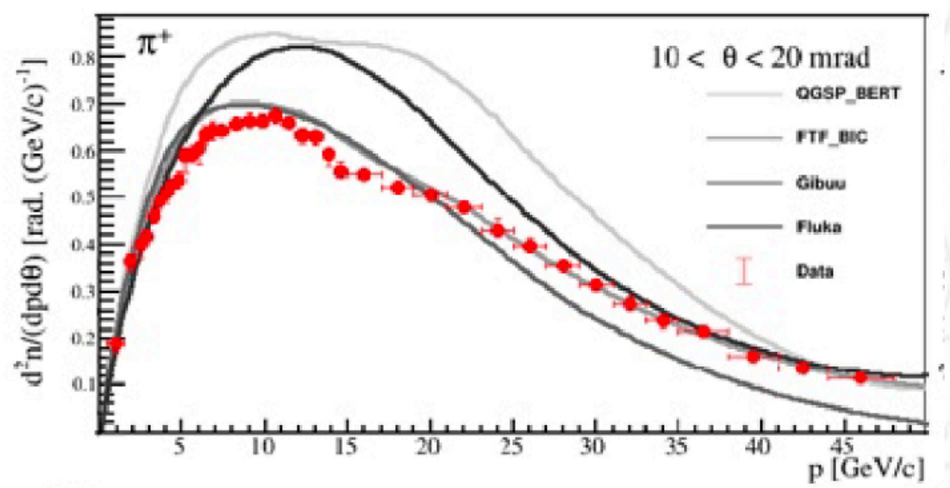


Analysis procedure

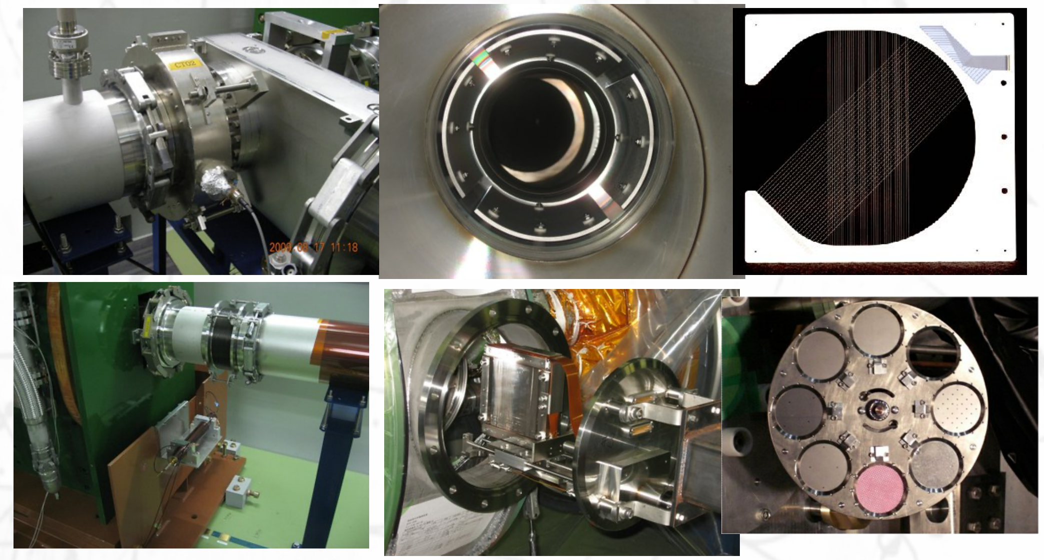
Beam model

Beam model is obtained from a full GEANT simulation of the particle transport reweighed by the NA61 results

Input

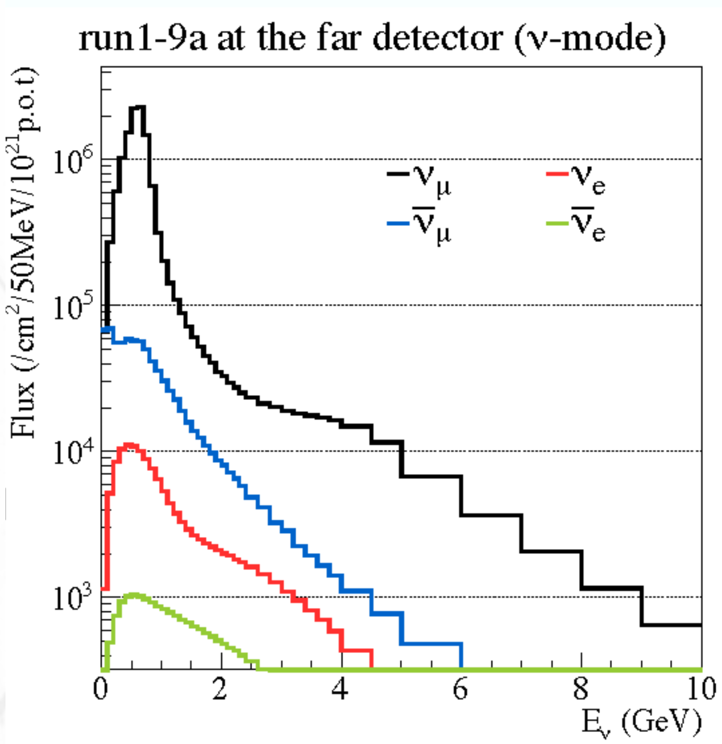


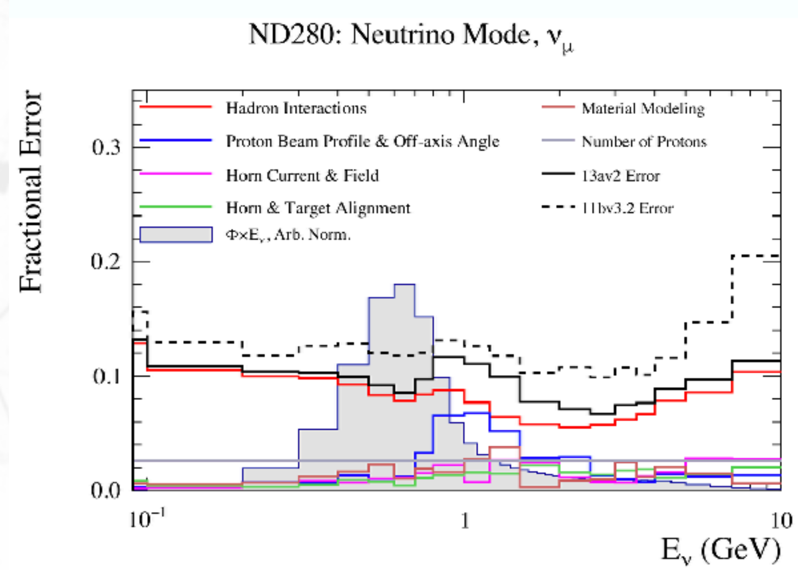
Beam monitors

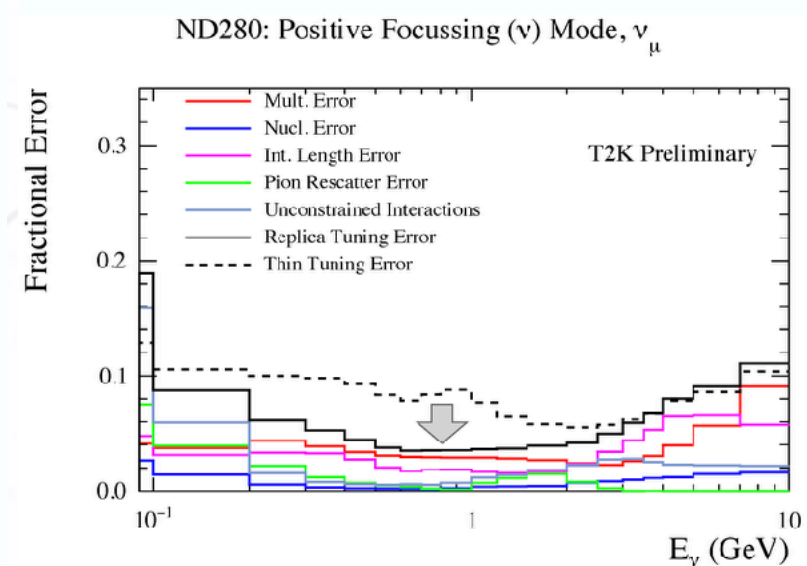


GEANT 3

Output

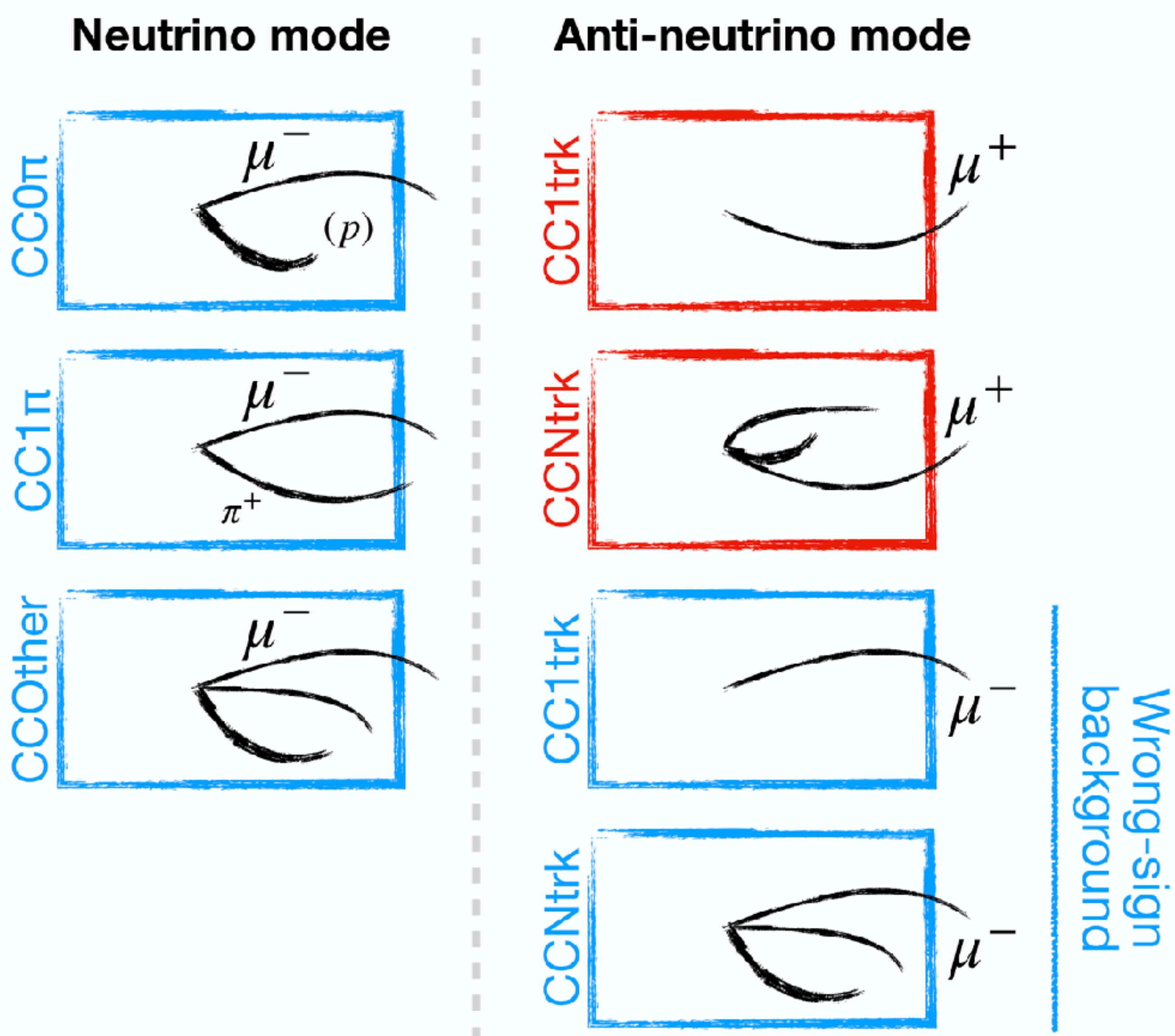






Including error covariance matrix

Near detector data



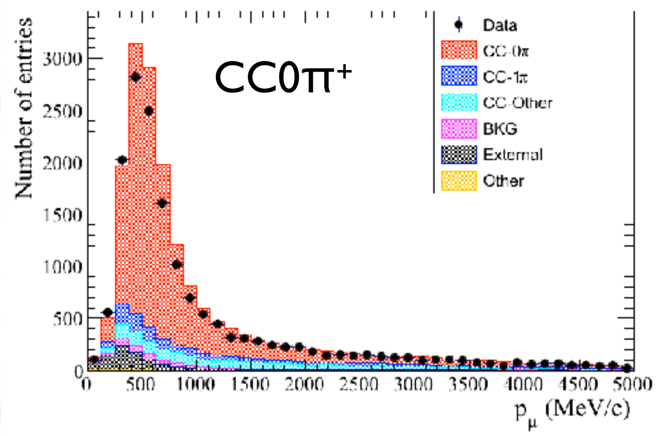
Each sample for two targets FGD1,2 ~ (C,O)

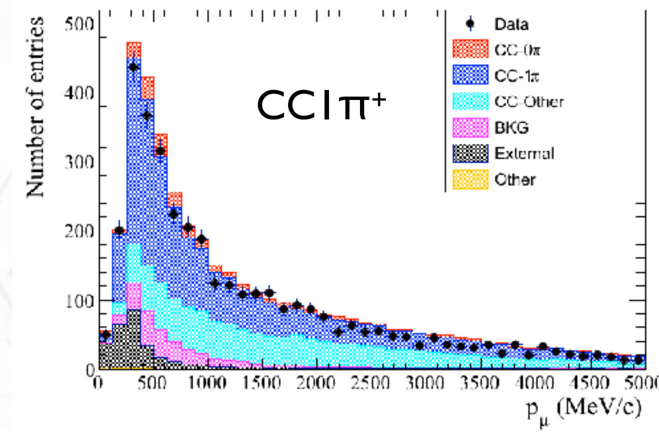
CCOther are CC events with multiple π's, π^0 or π^- candidates

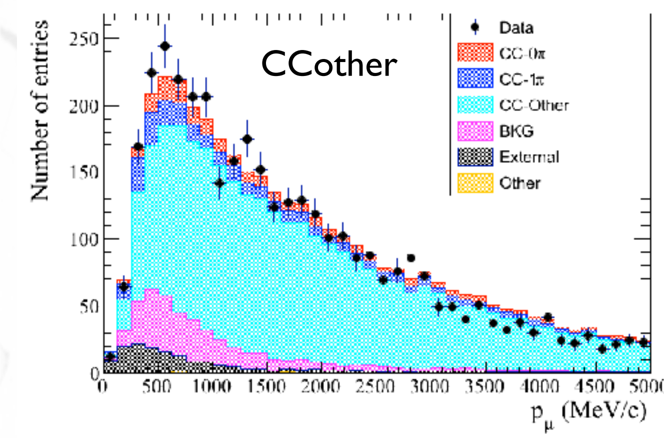
- Analysis of muon kinematics: (p_μ cos θ_μ)
  - E_ν obatined from interaction model in generators.
- Three samples of neutrinos (two for antineutrinos): enriched in
  - CCQE → CC0π
  - CCRes → CC1π
  - CC-DIS → CCOther
- the different samples also have different E_ν dependencies.
- Wrong Sign background:
  - neutrinos in anti-neutrino mode.
- Neutrino interaction in Oxygen from FGD2 data.

Conceptually

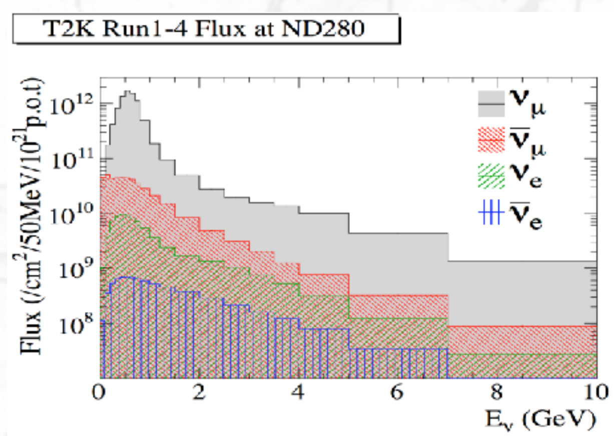
Near detector data





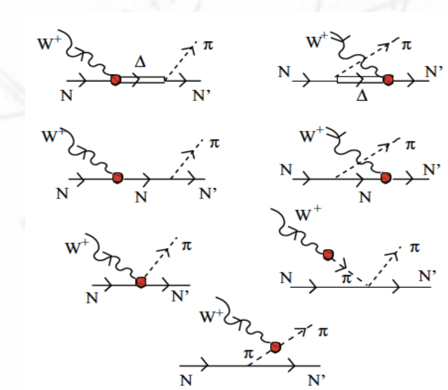


⊕ Hadron production flux prediction Shive + beam monitors

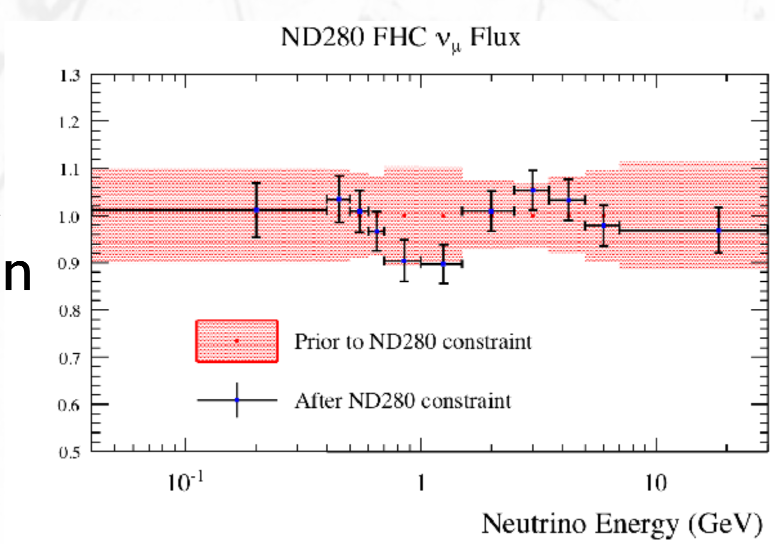


⊕ feed back

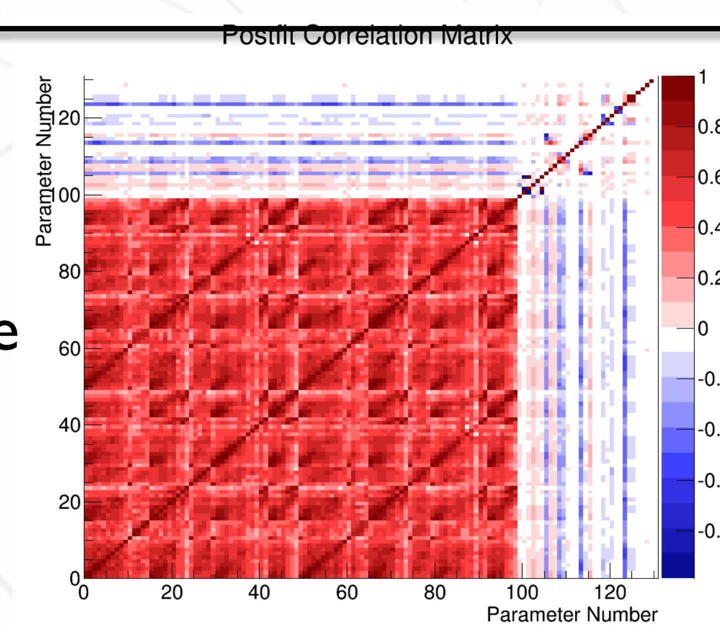
Cross-section model



= Corrected flux and cross-section model



& error covariance matrix



Oscillation fits

$\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ combined analysis within the 3ν oscillation paradigm (PMNS).

Other oscillation parameters from 2018 PDG values.

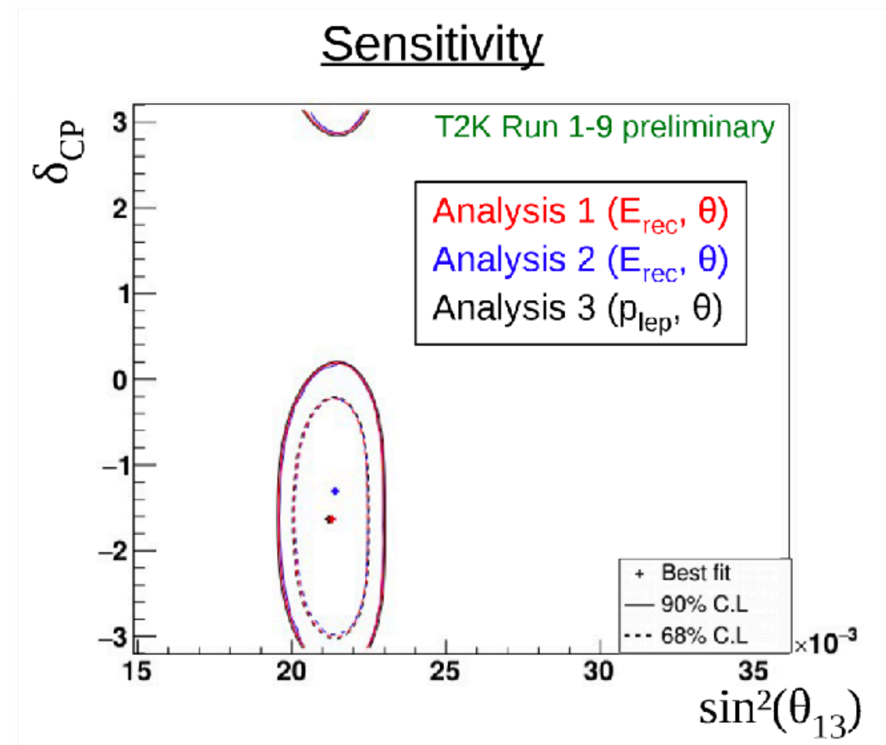
$$-2\ln\lambda(\overline{\delta_{CP}};\boldsymbol{a}) = 2\sum_{i=1}^{N}\left[n_i^{obs}\ln\left(\frac{n_i^{obs}}{n_i^{exp}}\right)+n_i^{exp}-n_i^{obs}\right] +(\boldsymbol{a}-\boldsymbol{a}_0)^T\mathbf{C}^{-1}(\boldsymbol{a}-\boldsymbol{a}_0)$$

Binned likelihood comparing data to MC predictions.

Bins of reconstructed energy from lepton kinematics assuming CCQE two body interactions.

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

ν_e sample also bins in θ_e

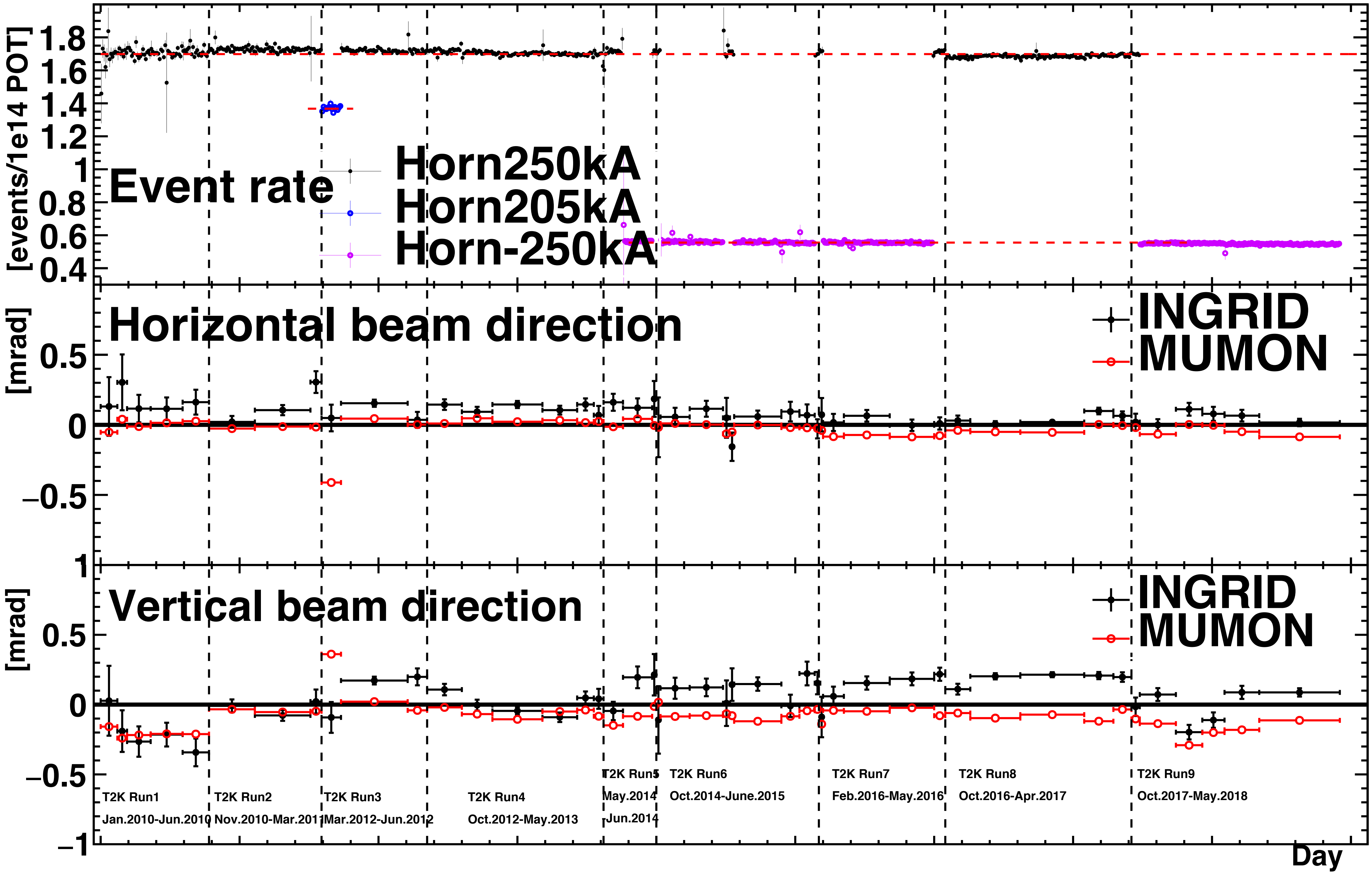


Bayesian Markov Chain MonteCarlo and 2 frequentist approach.

Frequentists confidence intervals (grid search) agree with the Bayesian factors and credible intervals.

T2K results

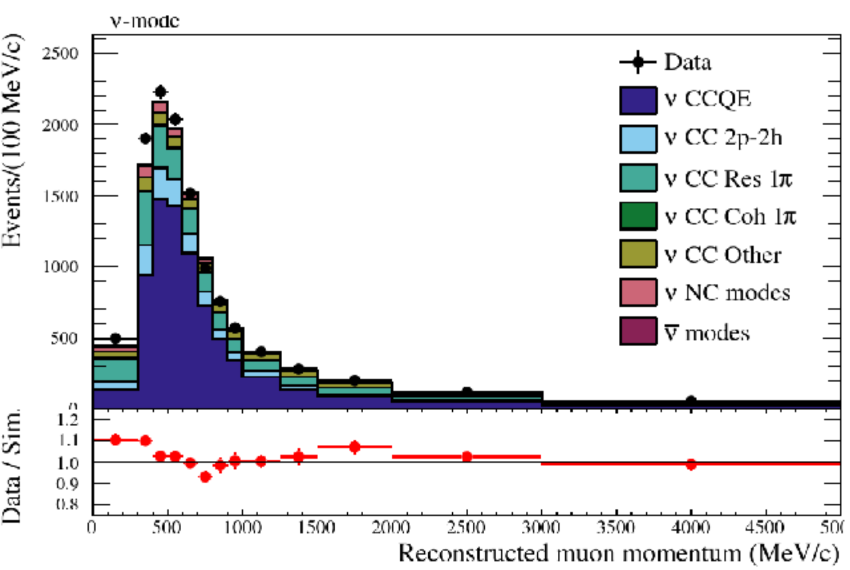
Beam stability

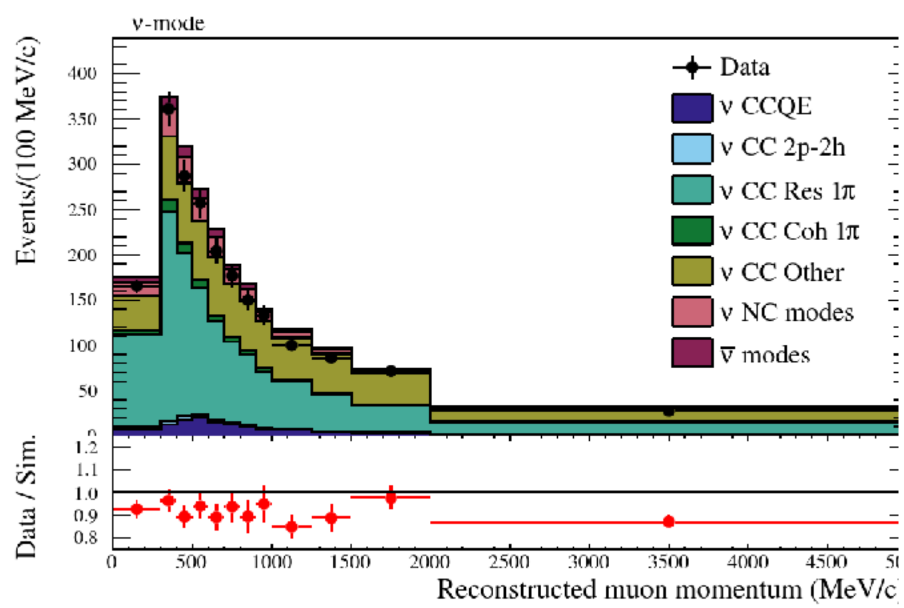


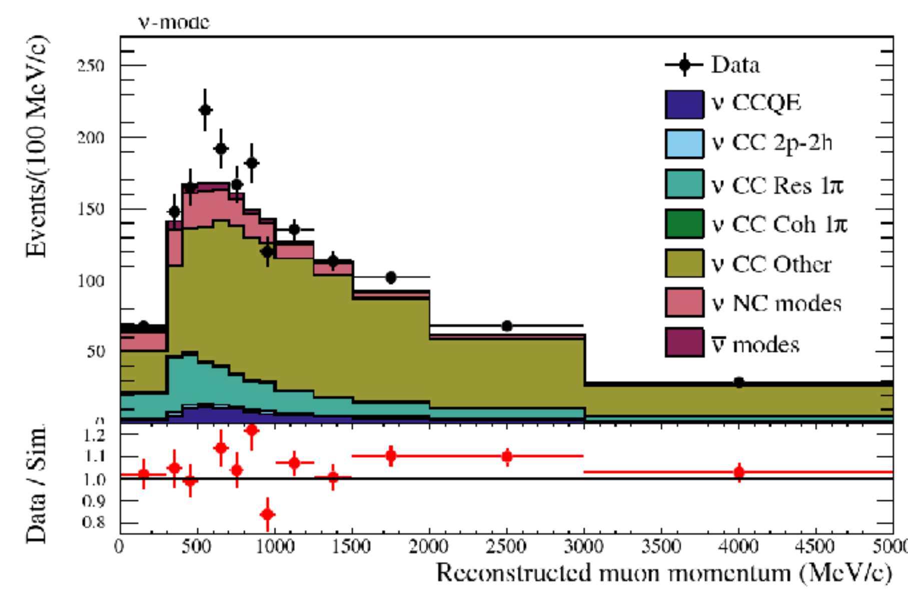
ND input samples

We use 14 different sample in (p_μ, cos θ_μ)

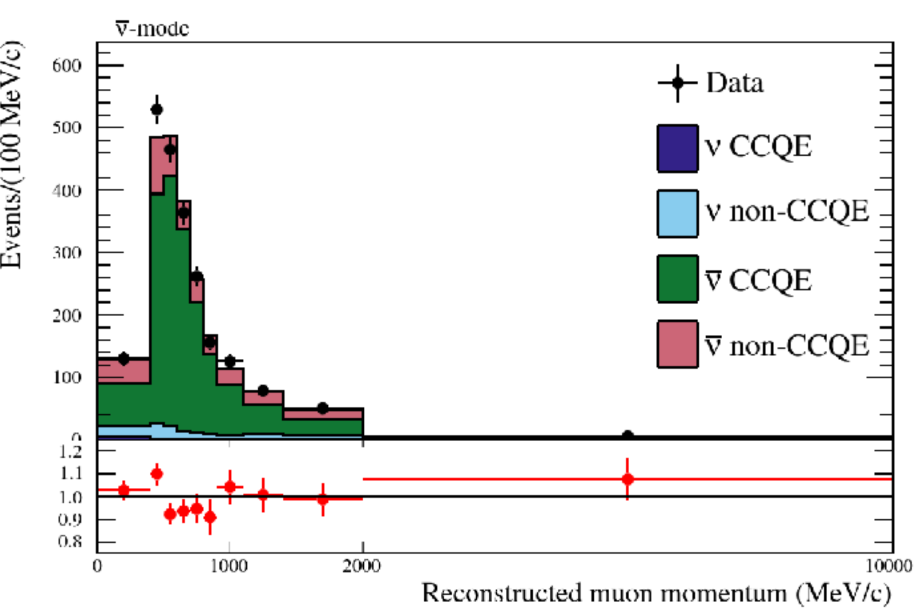
Forward Horn Current

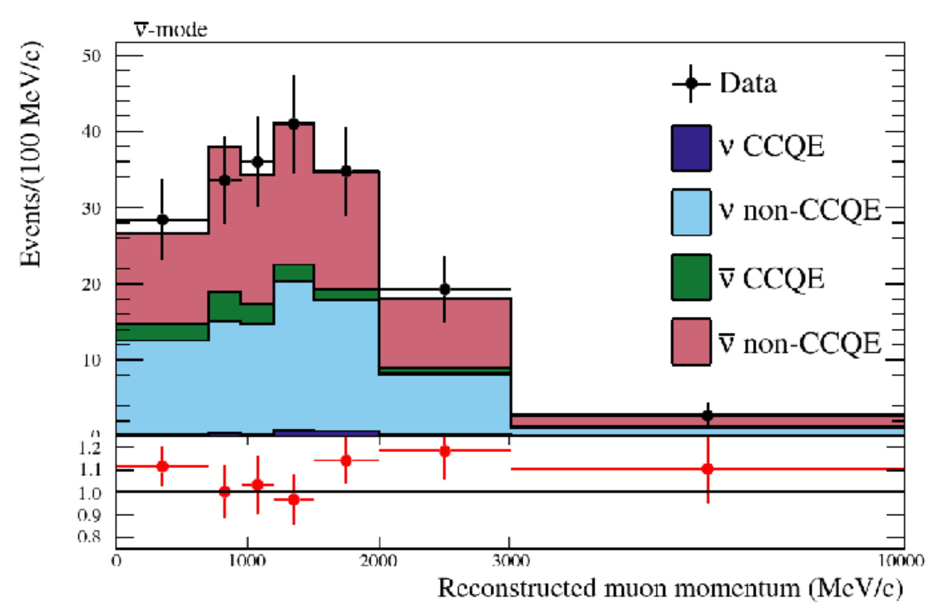




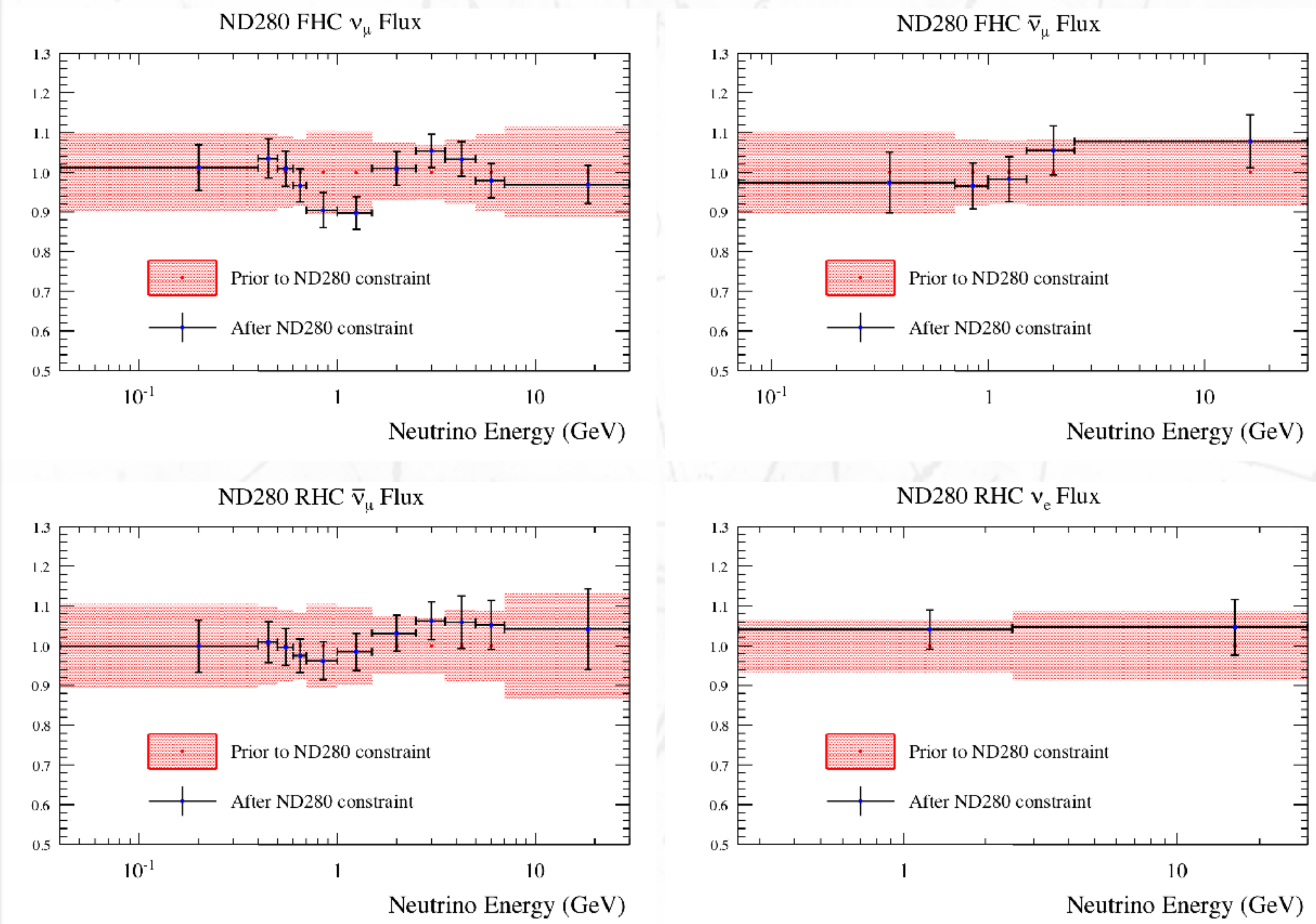


Reversed Horn Current

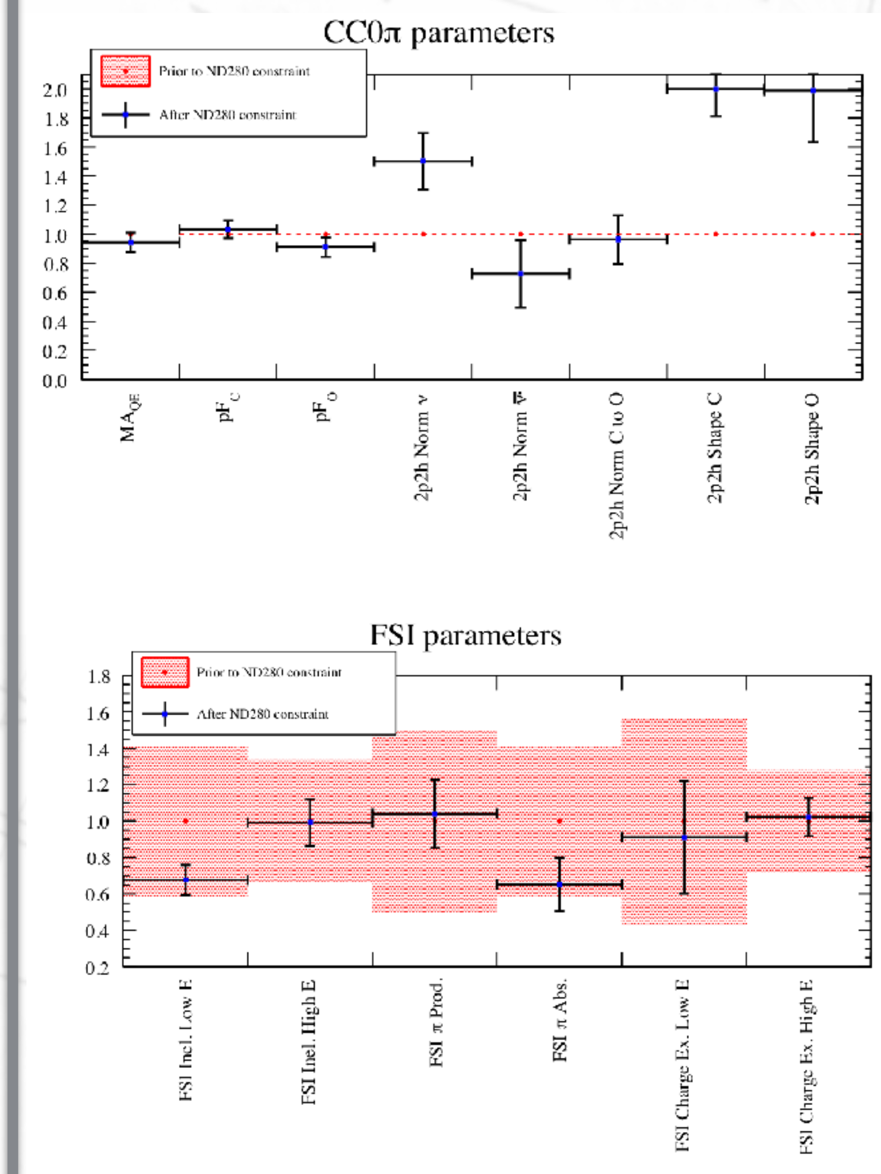




Examples of ND fits

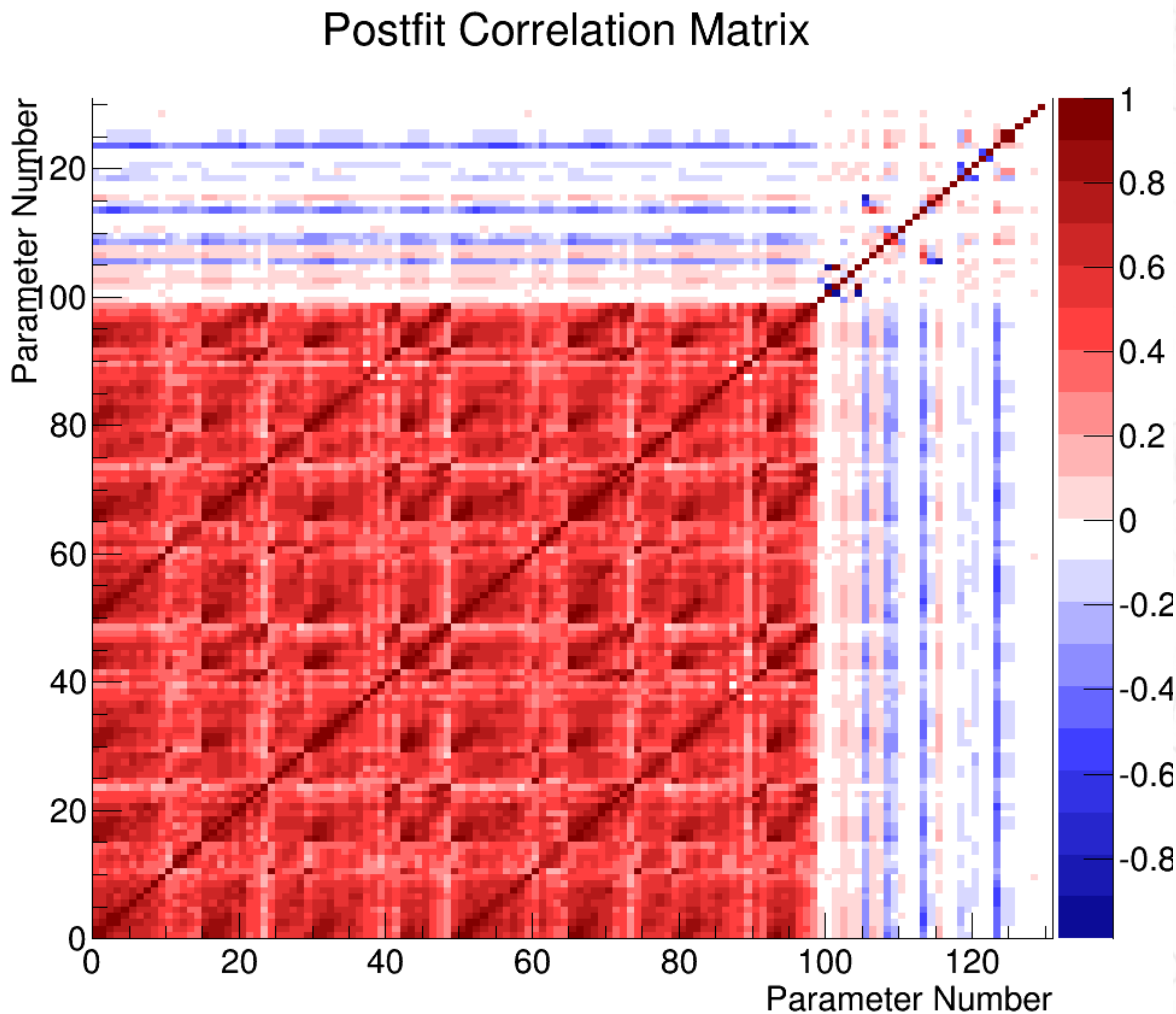


Flux parameters

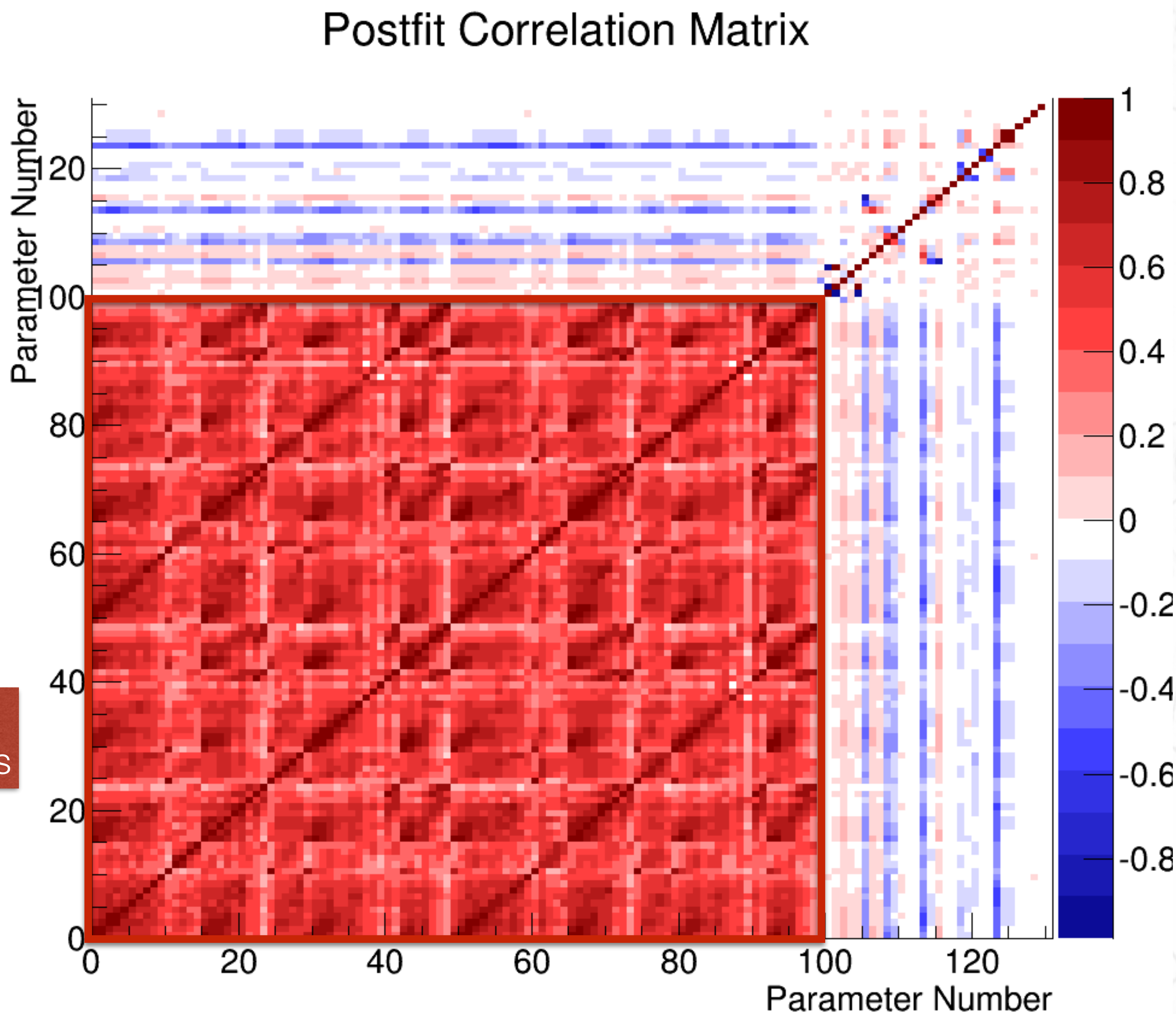


X-section parameters

ND fits

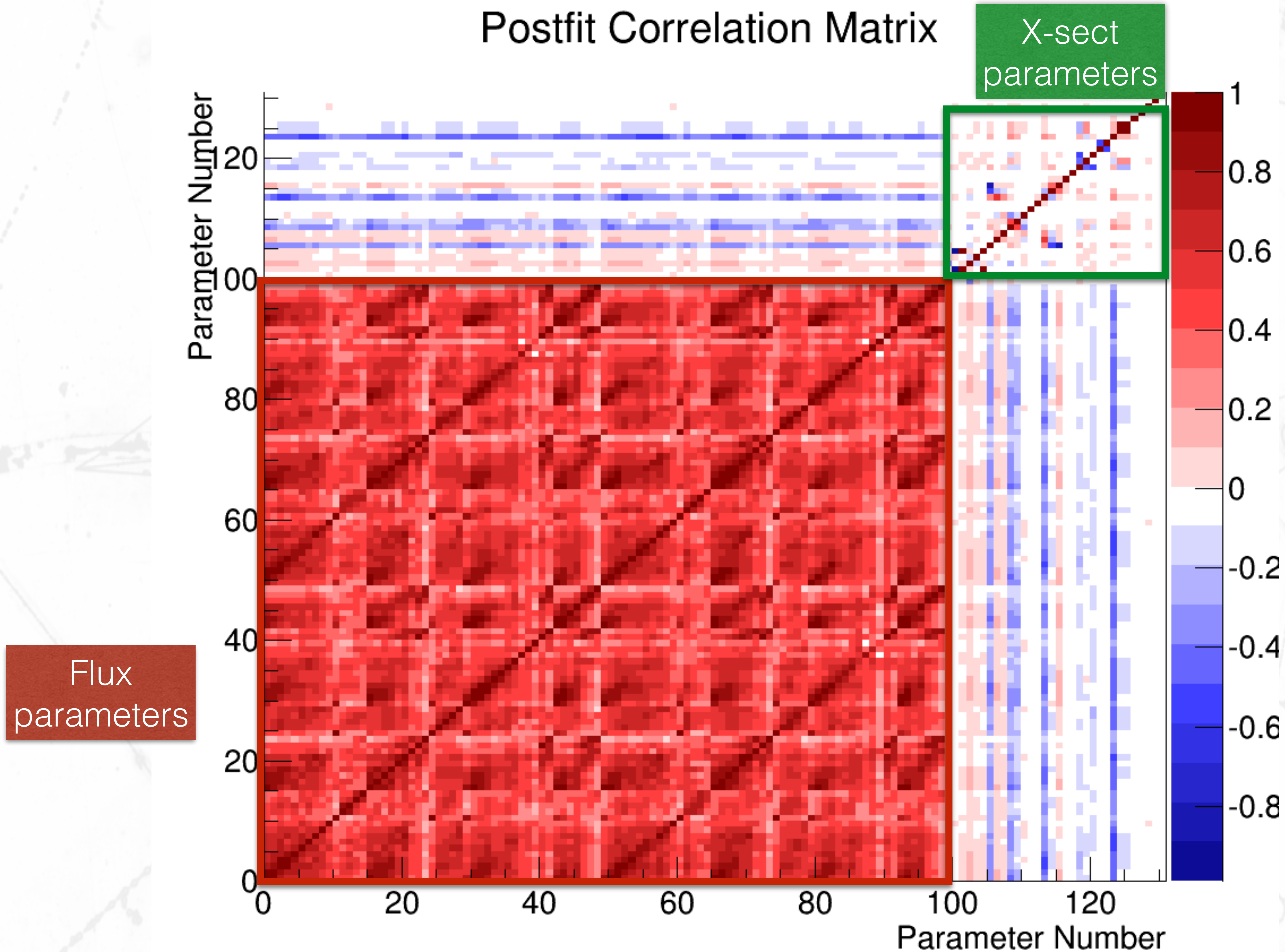

Postfit Correlation Matrix
Parameter Number
Parameter Number
0
20
40
60
80
100
120
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8

ND fits



Flux parameters

ND fits

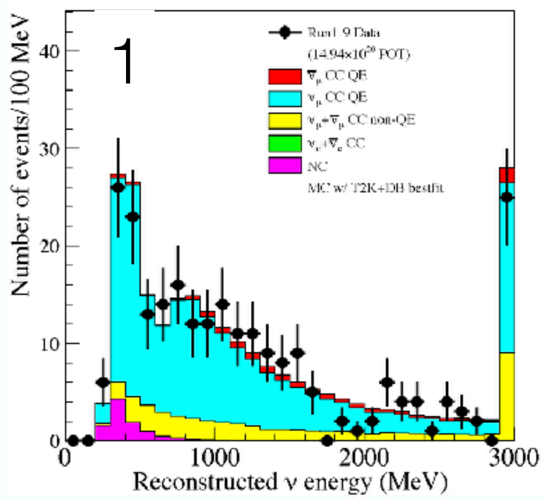


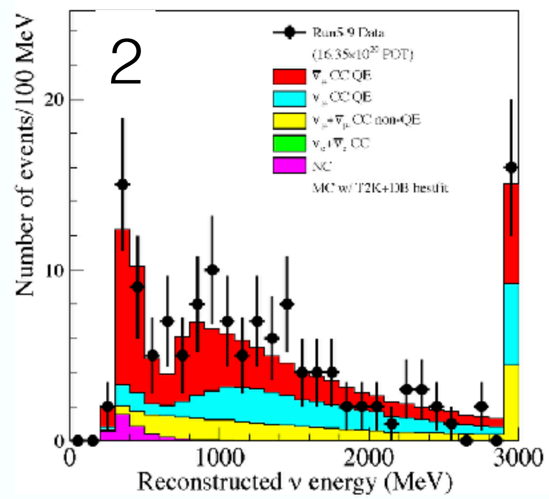
Postfit Correlation Matrix
X-sect parameters
Flux parameters
Parameter Number
Parameter Number
0
20
40
60
80
100
120
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8

SK data

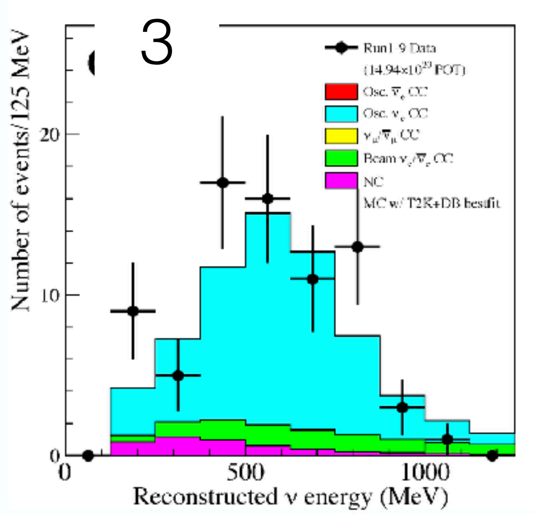
Neutrino mode | Anti-neutrino mode

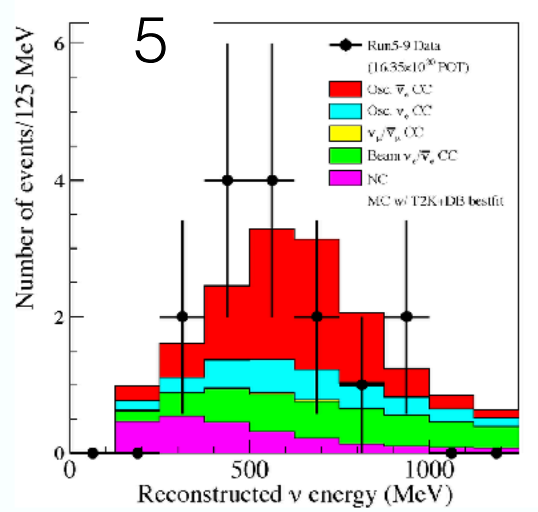
μ-like ring

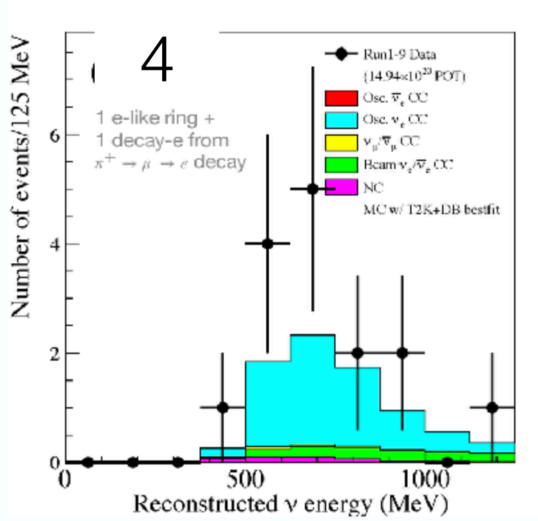




e-like ring



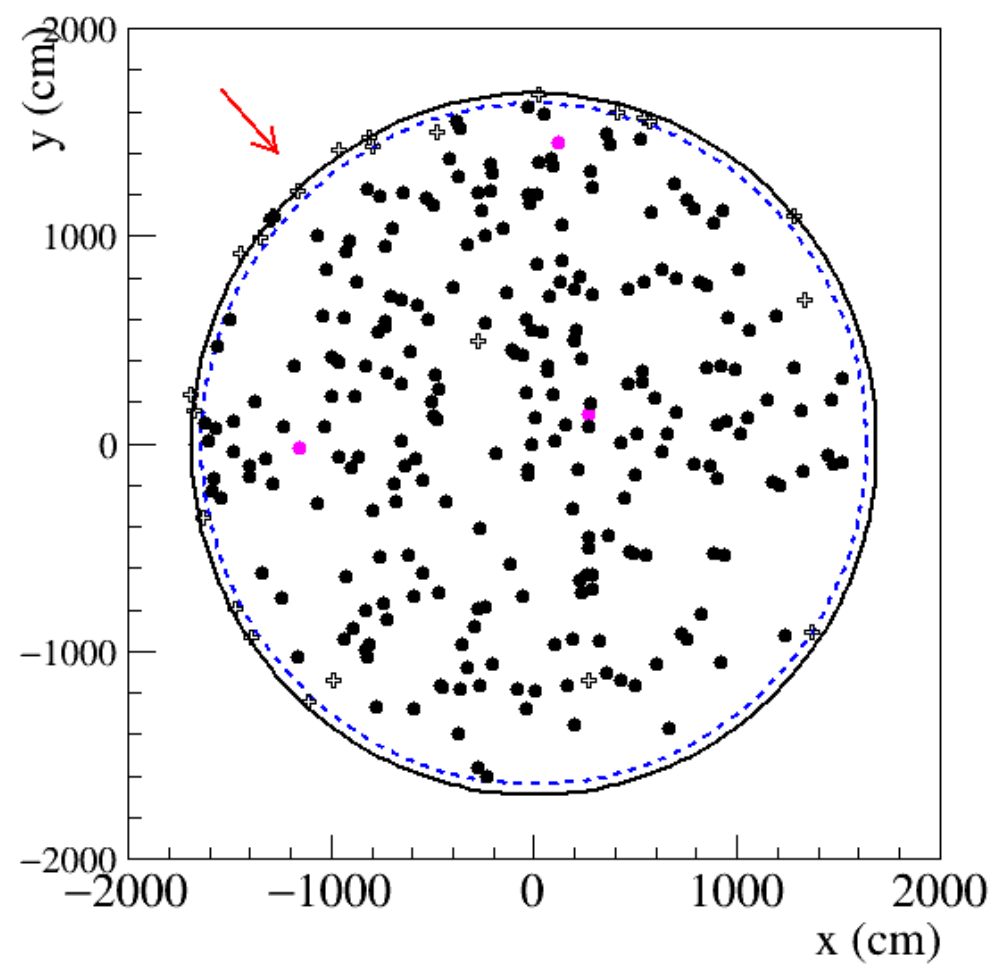




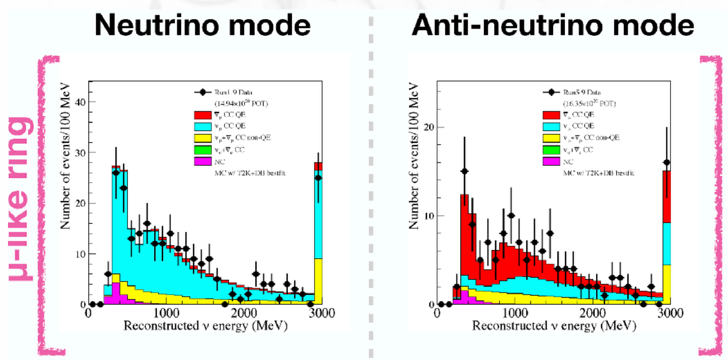
No CC1π sample in anti-neutrino mode because π^- produced in $\bar{\nu}$ interaction are mostly absorbed before decay.

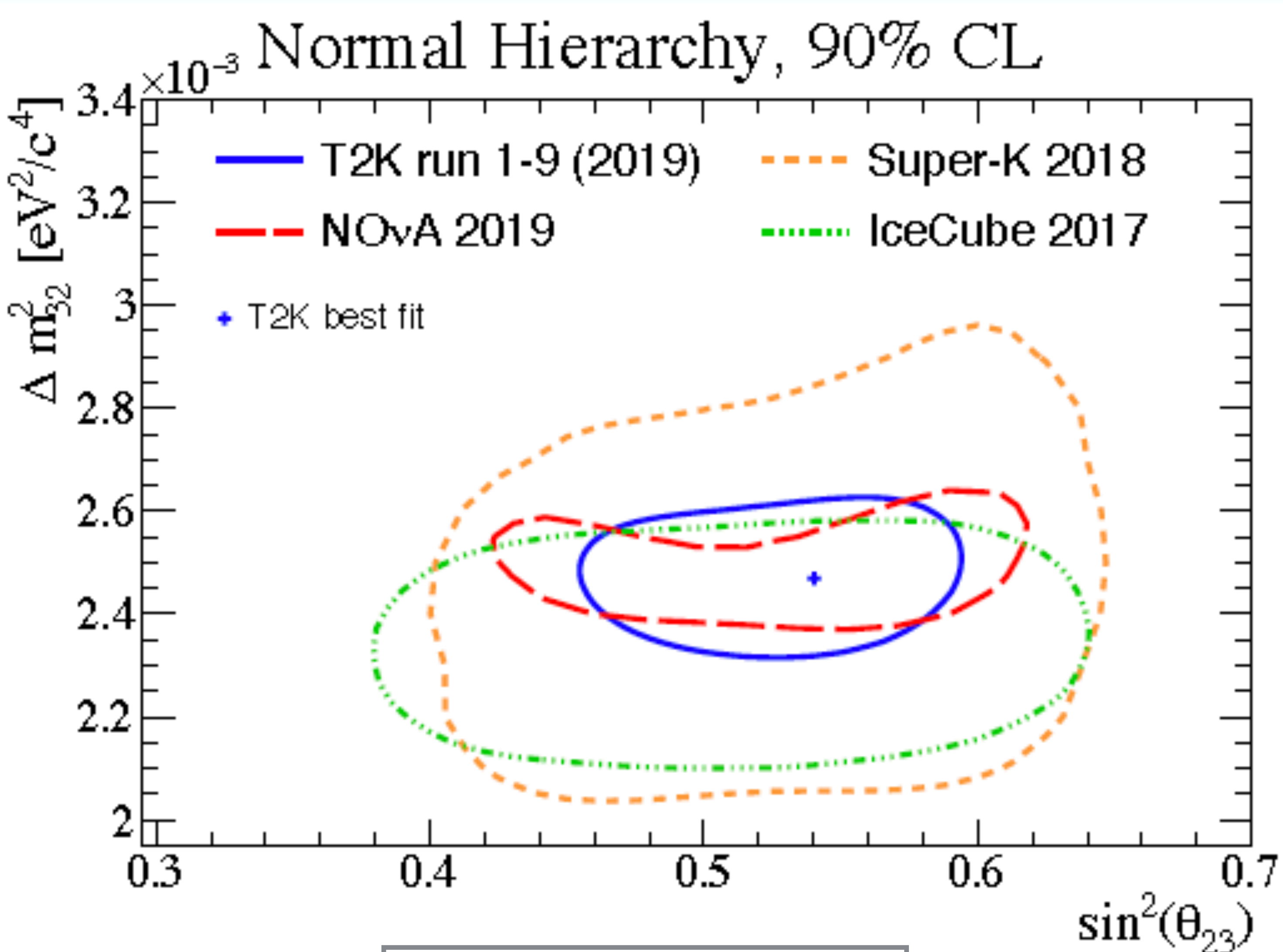
5 SK samples

1. muon candidate, neutrino mode.
2. muon candidate. antineutrino model
3. electron candidates, neutrino mode.
4. electron candidate with a charged pion (Michel electron) neutrino mode.
5. electron candidate, antineutrino mode

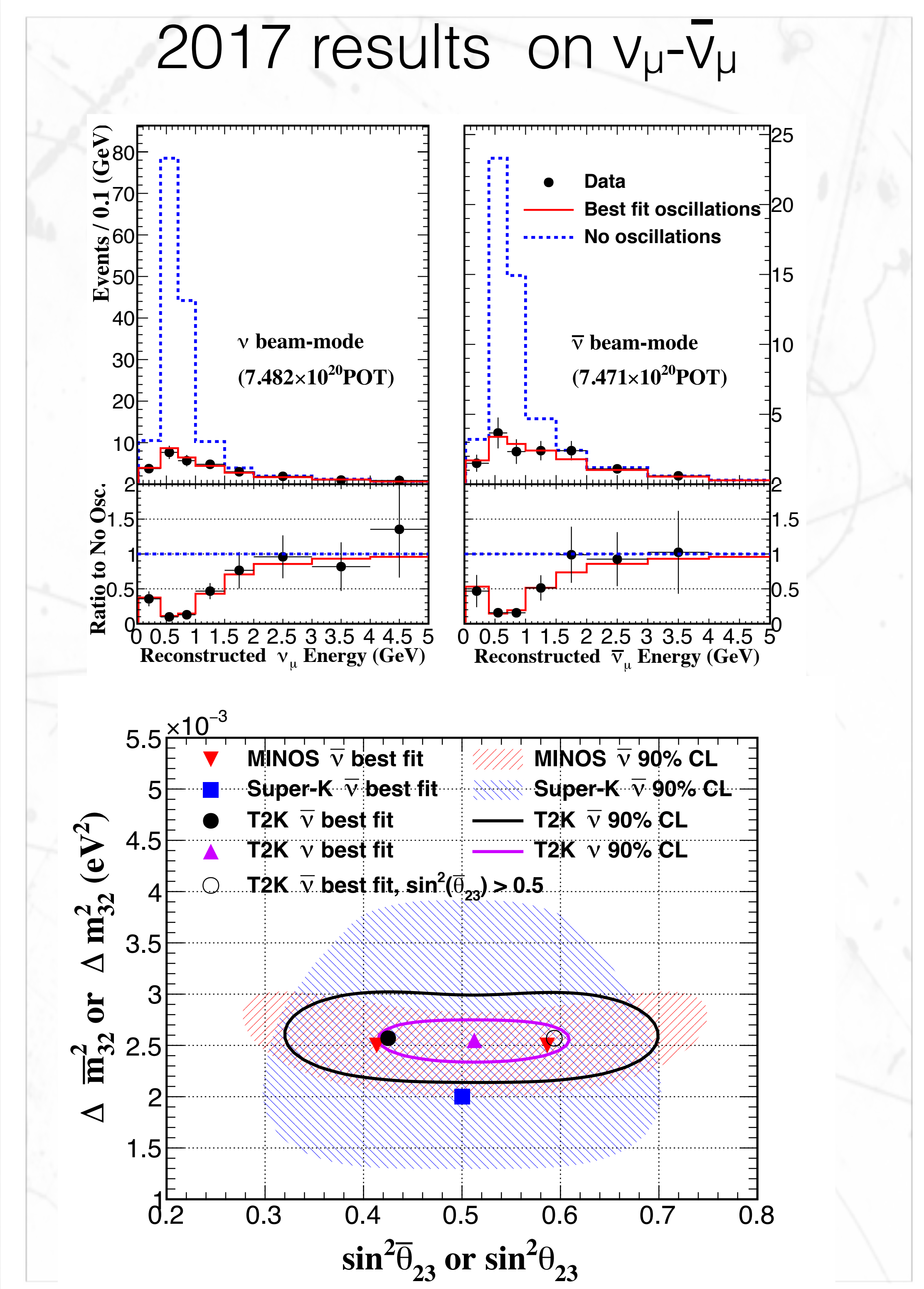


$\overset{(-)}{\nu}_\mu$ disappearance





World leading result

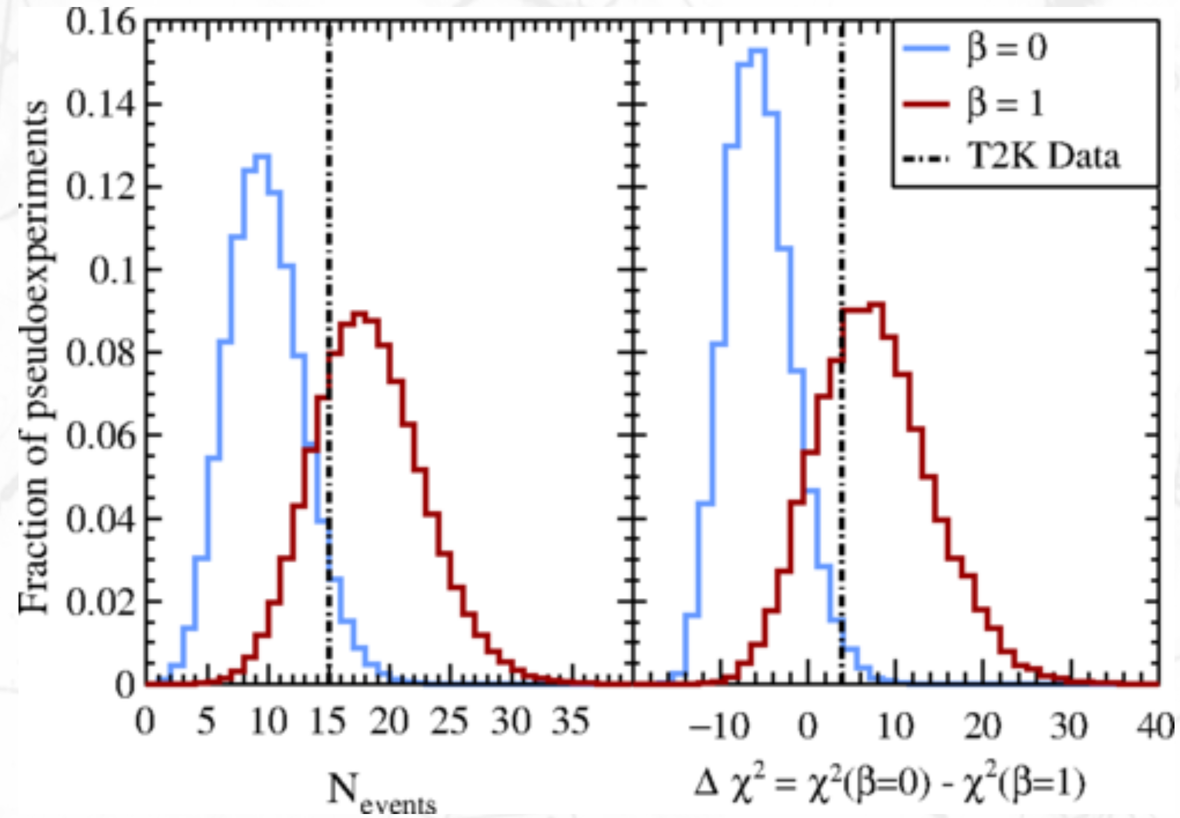


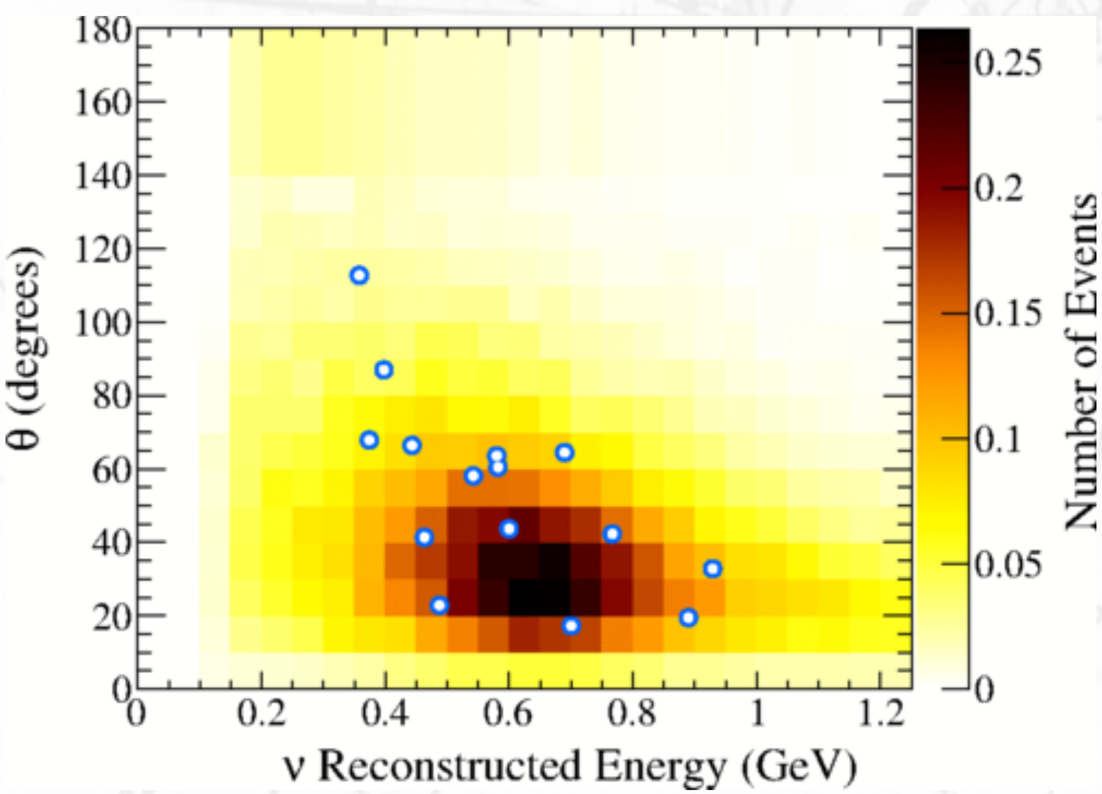
$\bar{\nu}_e$ appearance

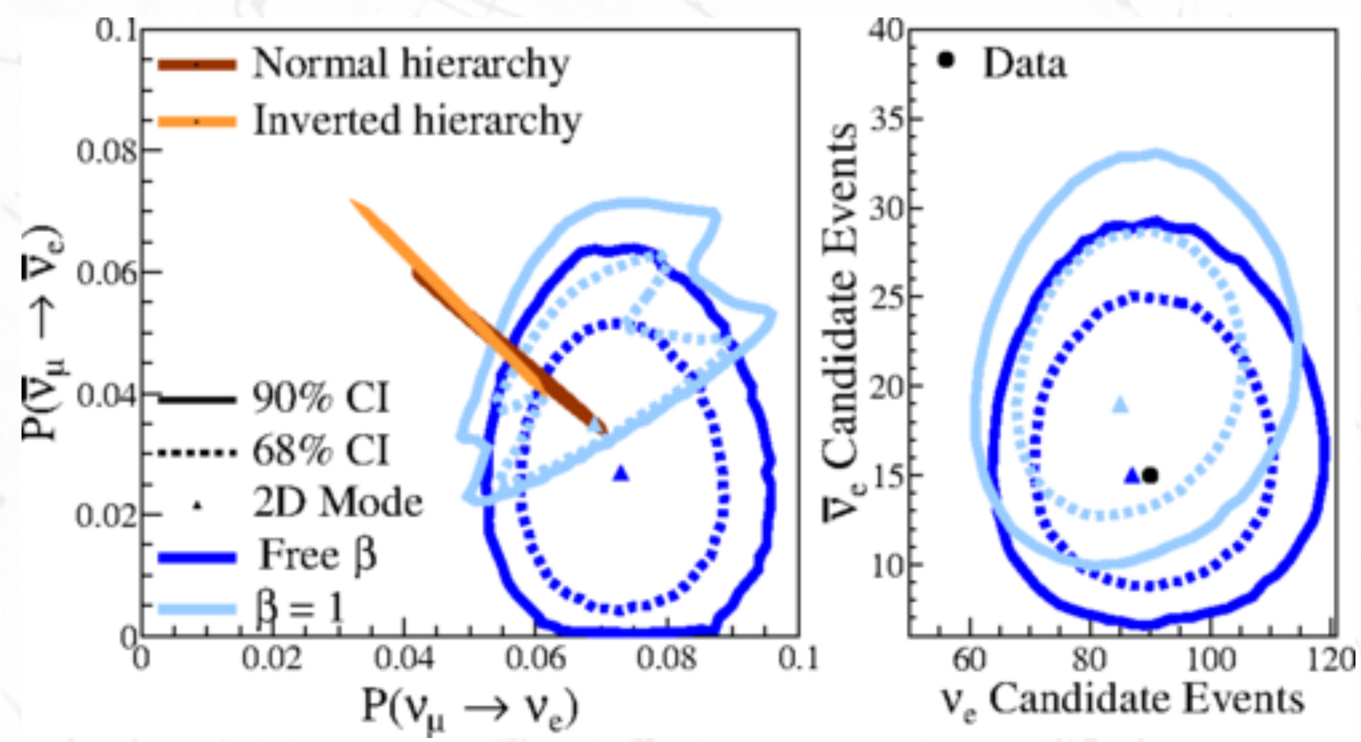
- High background from ν_e.
- strategy is to parametrise the oscillation and measure β

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{\text{PMNS}}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e).$$

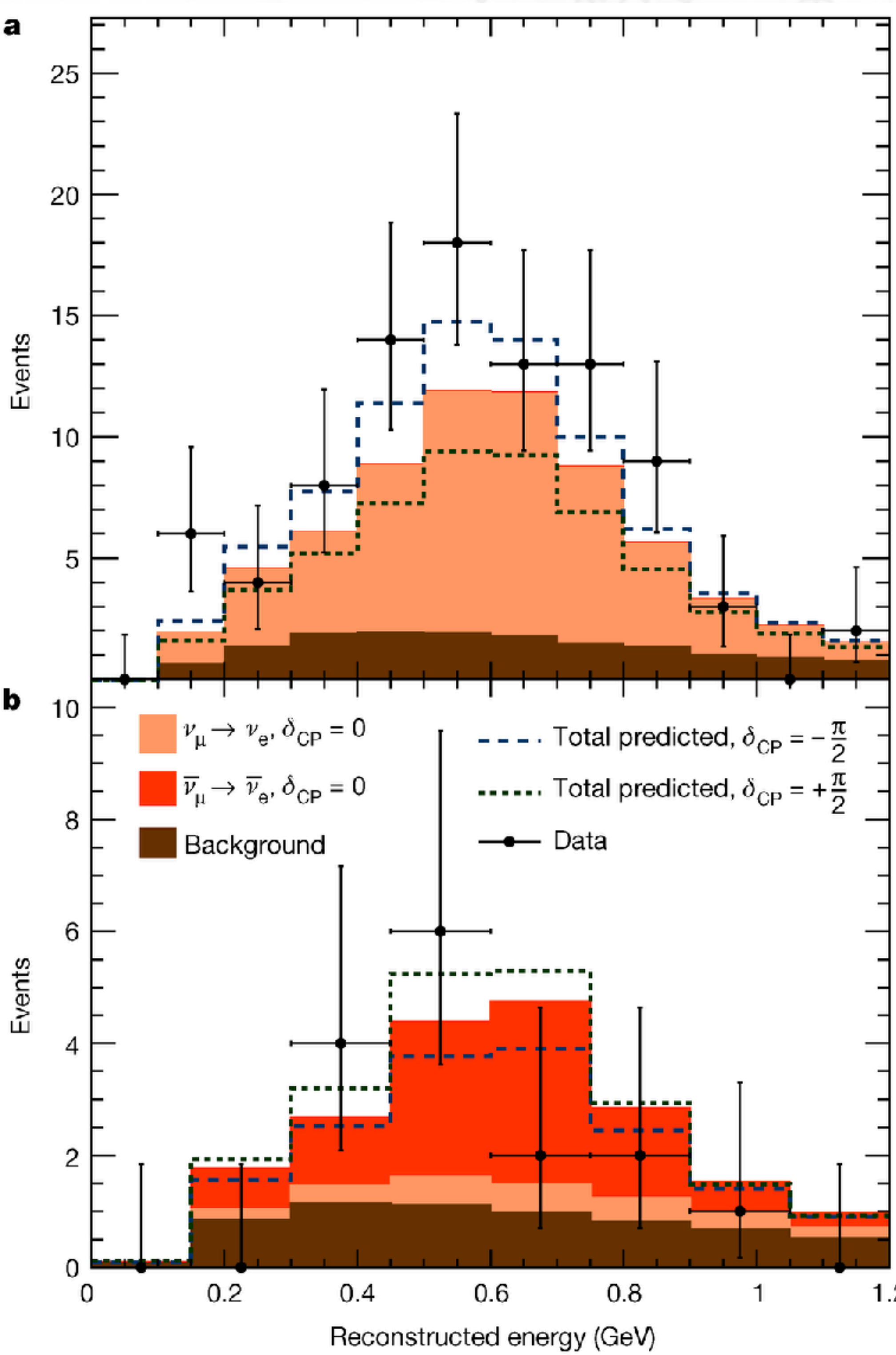
- No $\bar{\nu}_e$ appearance disfavoured to 2.4σ







CP violation phase



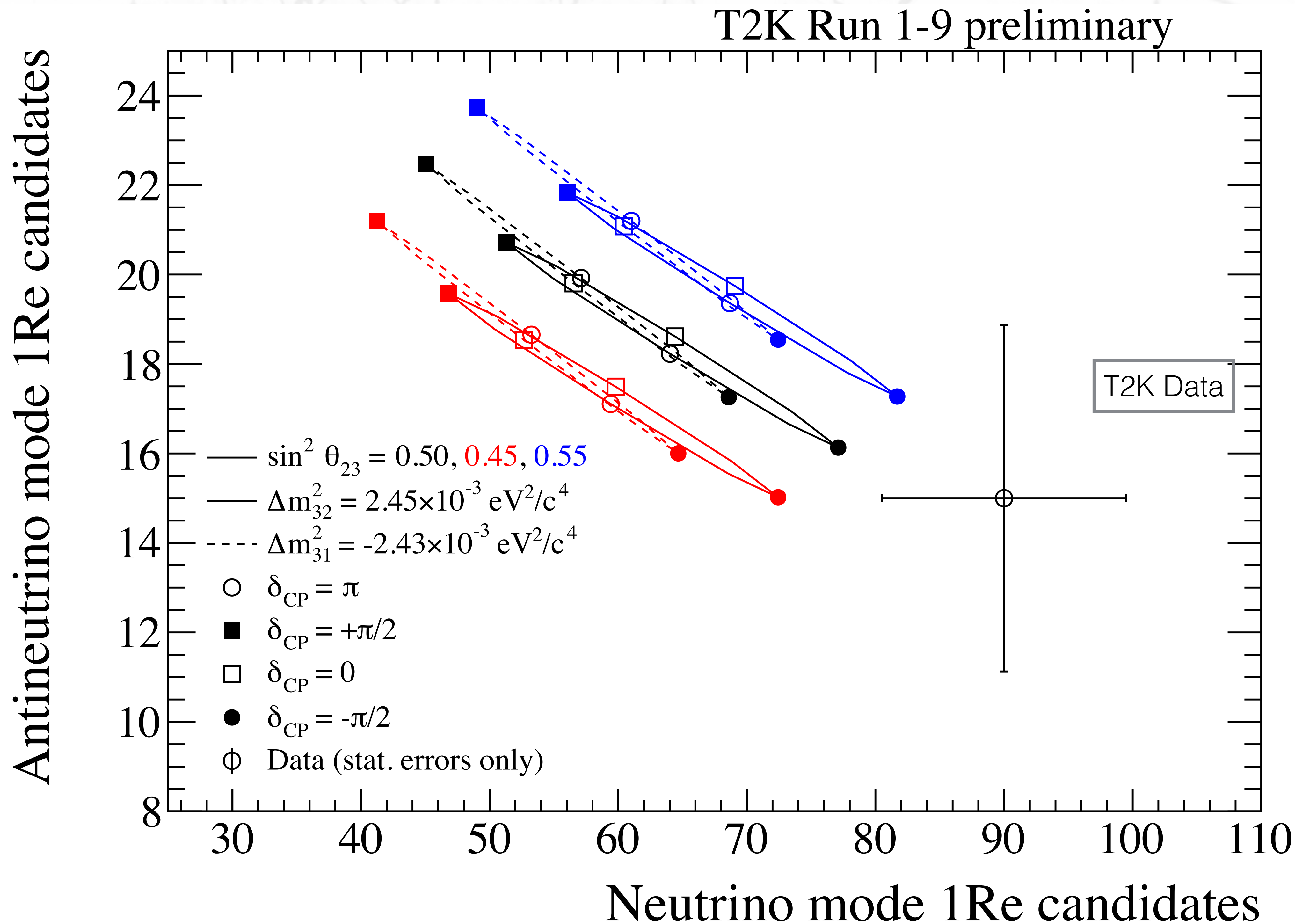
c

	1e0de ν-mode	1e0de $\bar{\nu}$-mode	1e1de ν-mode
$\nu_\mu \to \nu_e$	59.0	3.0	5.4
$\bar{\nu}_\mu \to \bar{\nu}_e$	0.4	7.5	0.0
Background	13.8	6.4	1.5
Total predicted	73.2	16.9	6.9
Systematic uncertainty	8.8%	7.1%	18.4%
Data	75	15	15

$\nu_e/\bar{\nu}_e$ Systematic Uncertainty

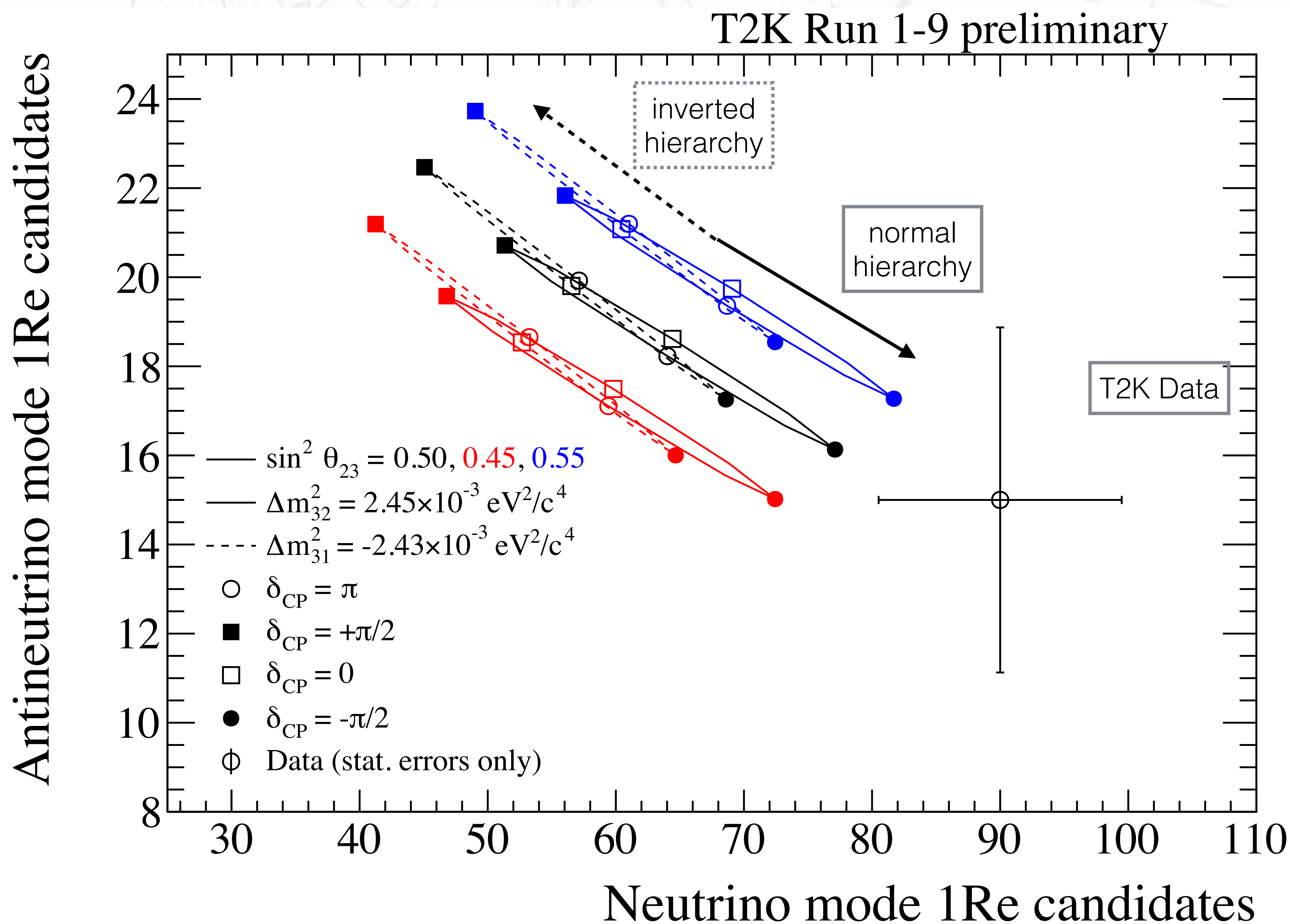
Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%
Super-K Detector Model	1.5 %
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0 %

CP violation phase



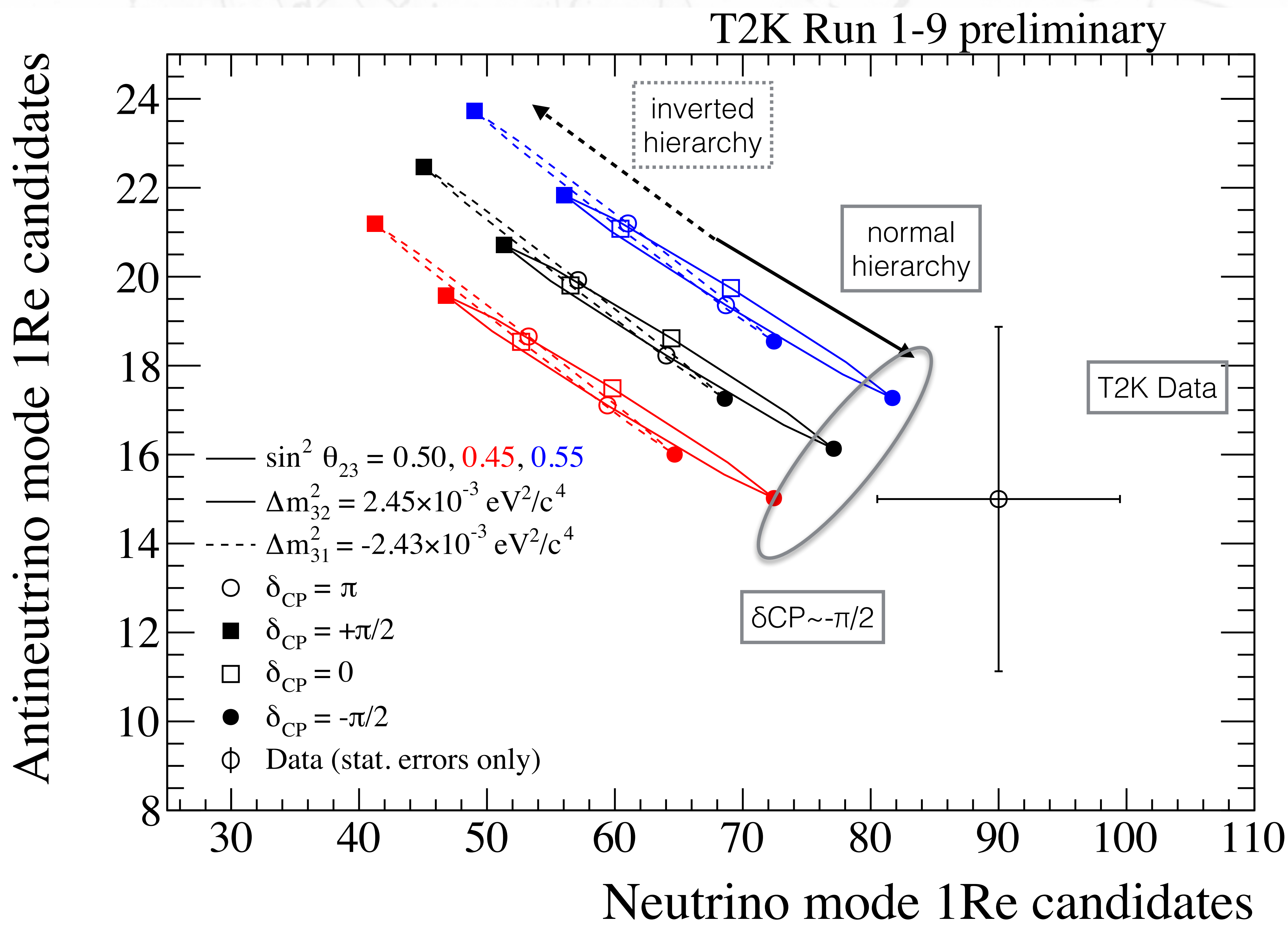
ν energy dependency is not reflected in this plot

CP violation phase



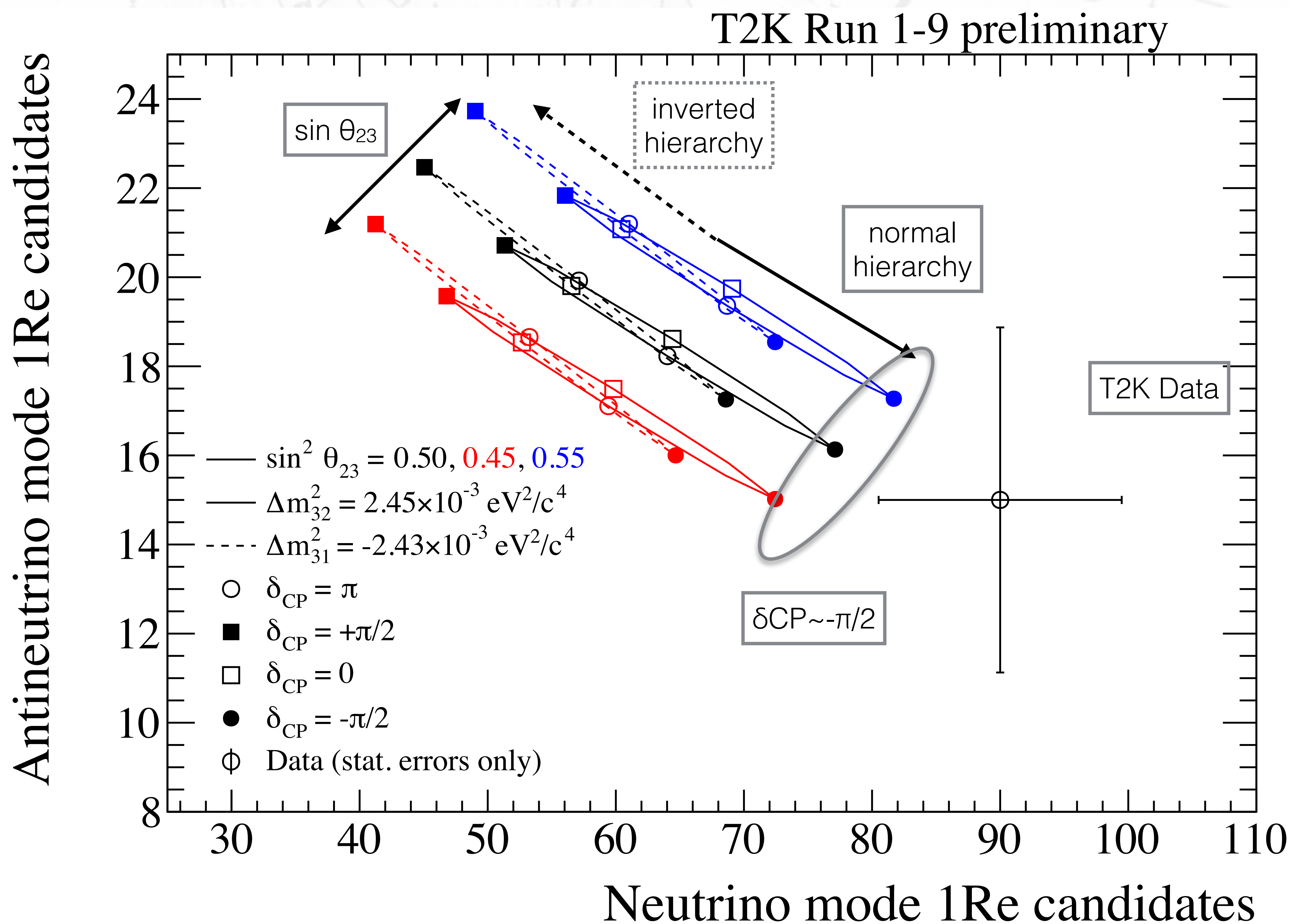
ν energy dependency is not reflected in this plot

CP violation phase

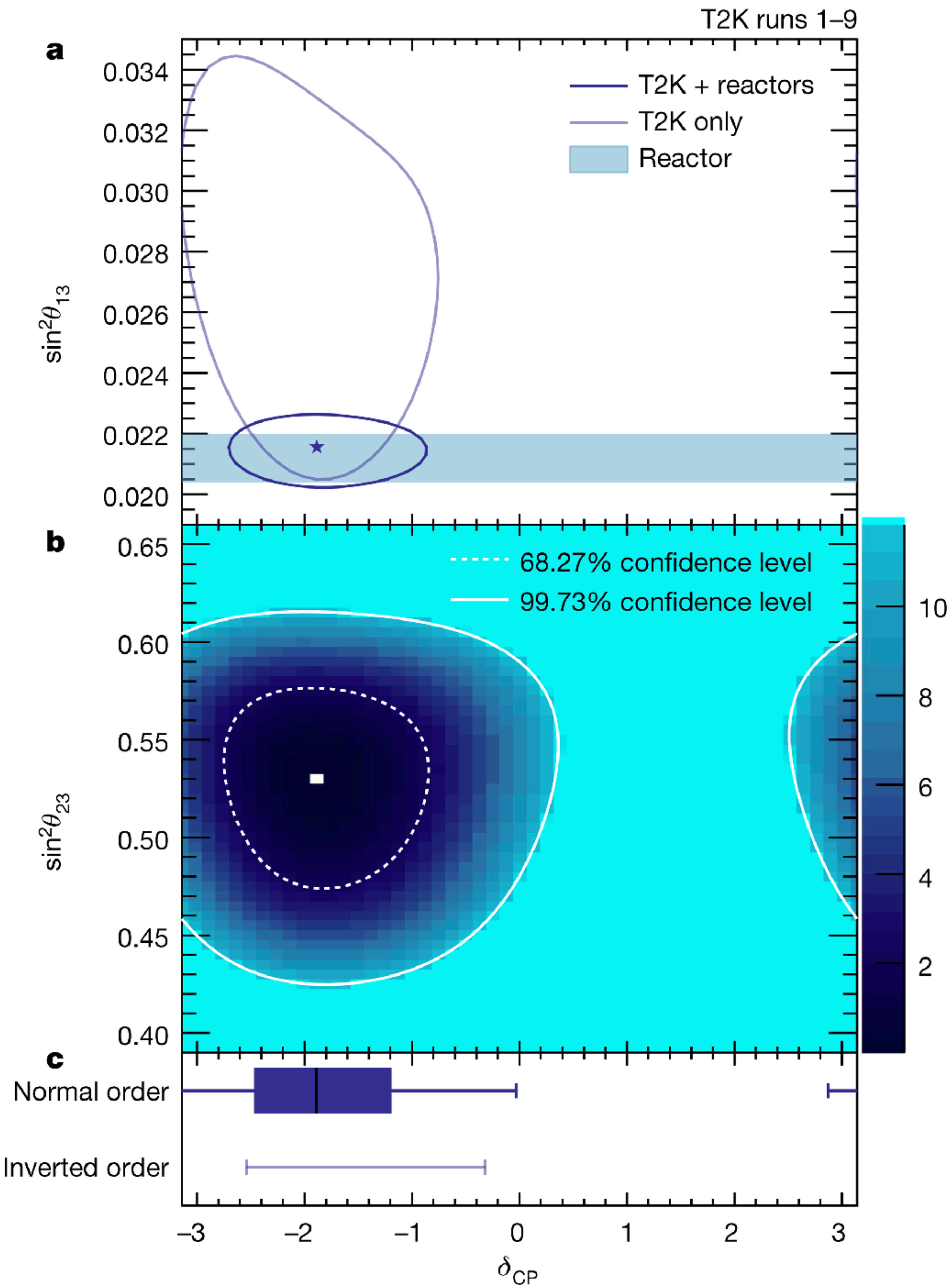


ν energy dependency is not reflected in this plot

CP violation phase



ν energy dependency is not reflected in this plot



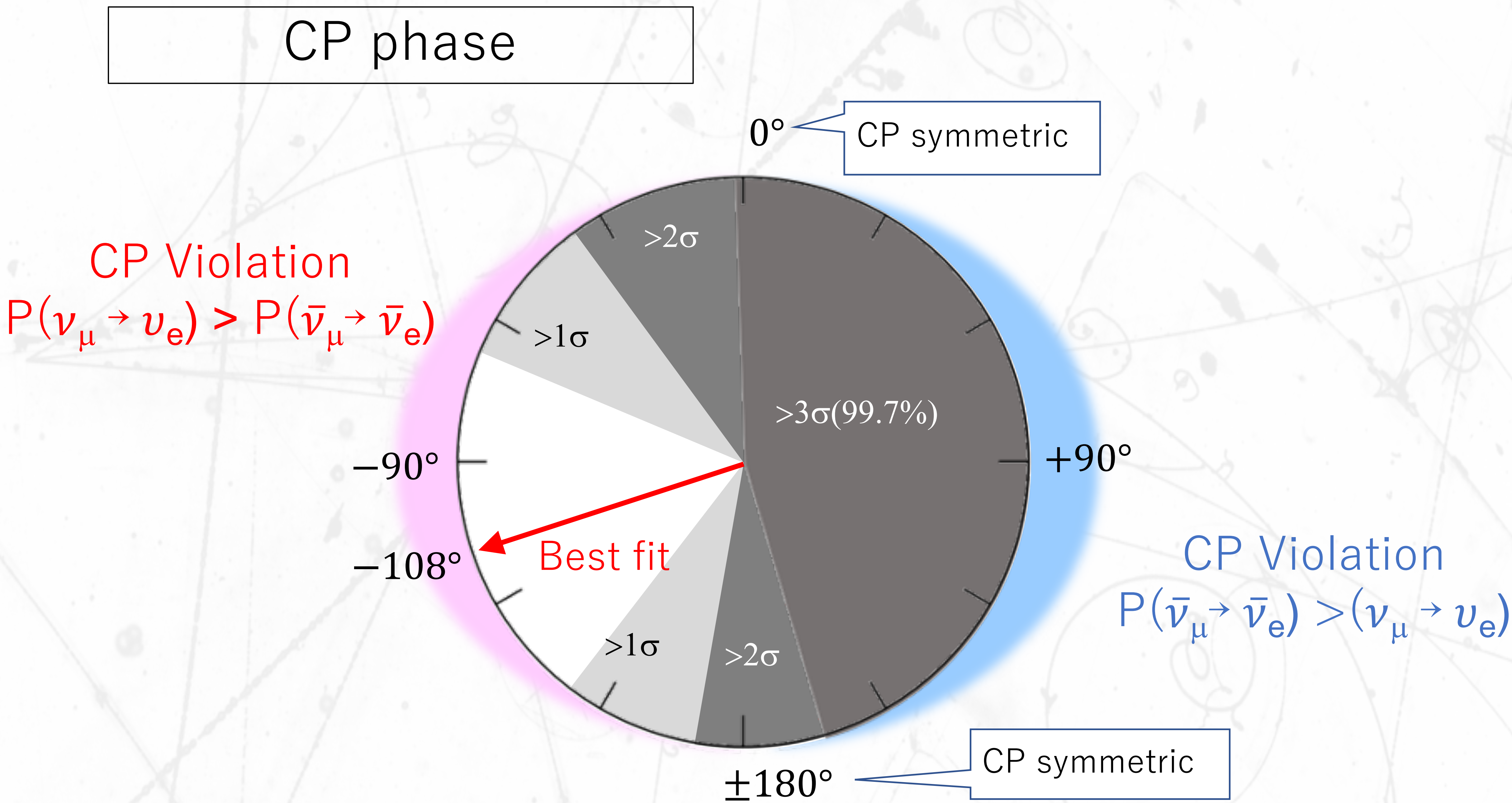
δ_{CP} measurement

Fit uses the value of θ_{13} from reactor experiments

Data also prefers Normal Hierarchy with a posterior probability of 89%

CP violation phase

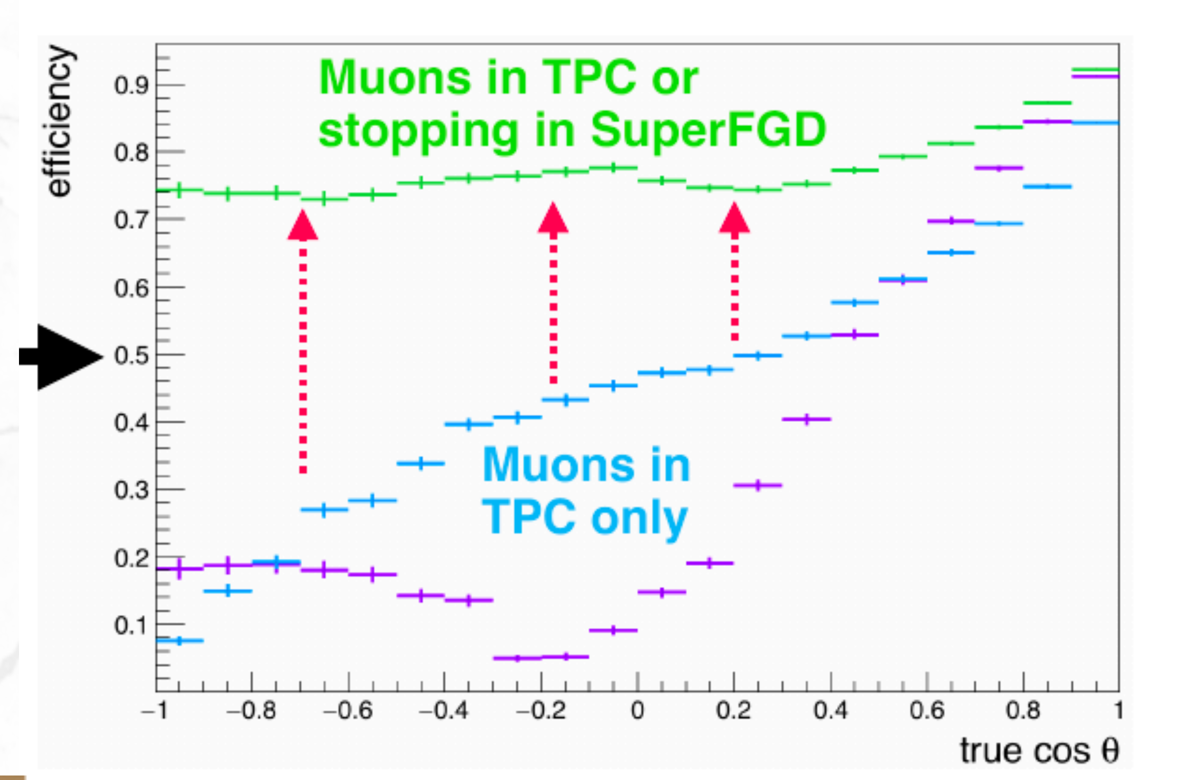
T2K result excludes most of the δ_{CP}>0 values @ 99.7% CL

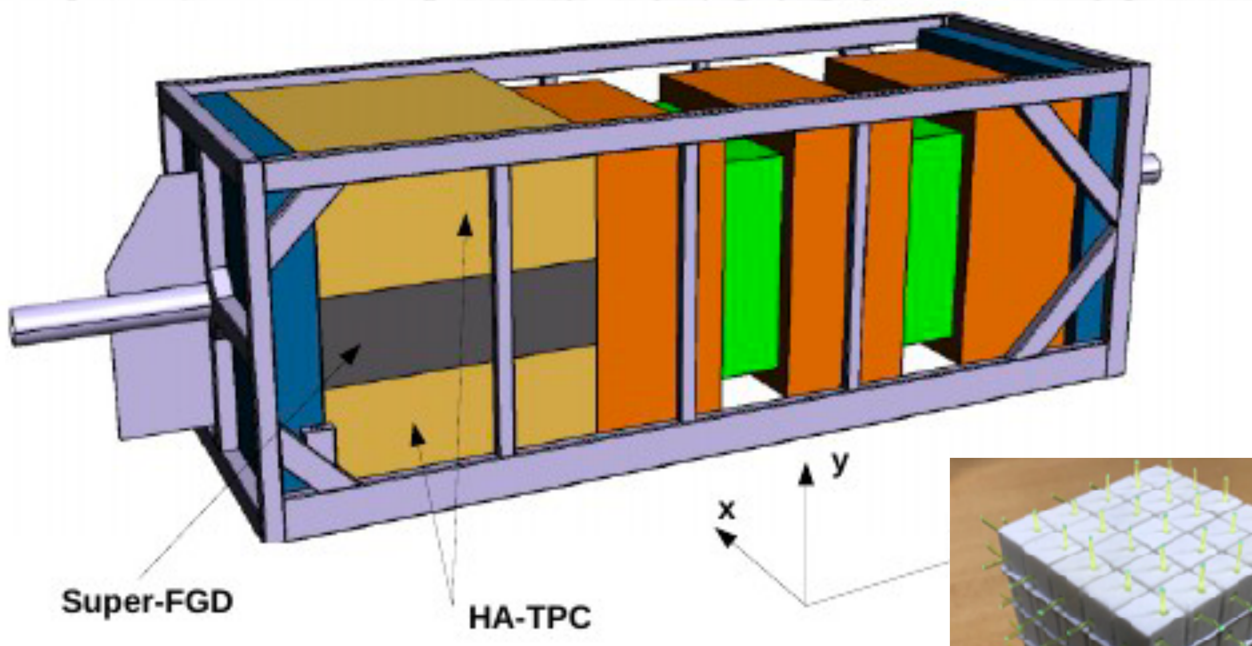


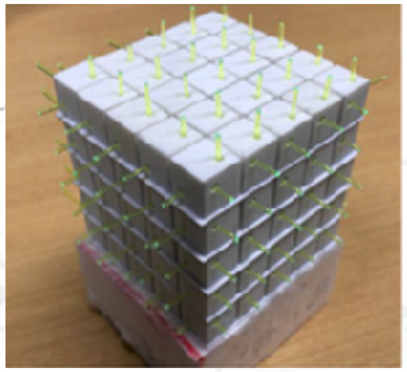
Plot by the T2K Spokes-Person A.Ichikawa

Next steps and beyond

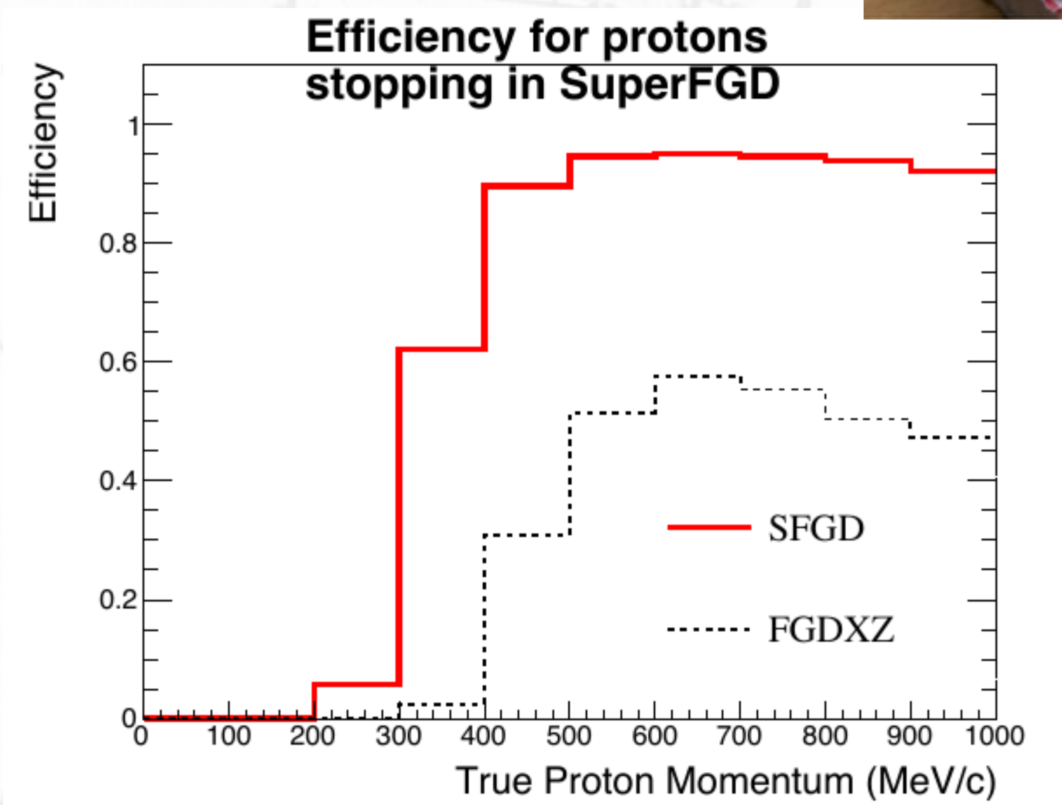
ND280 upgrade







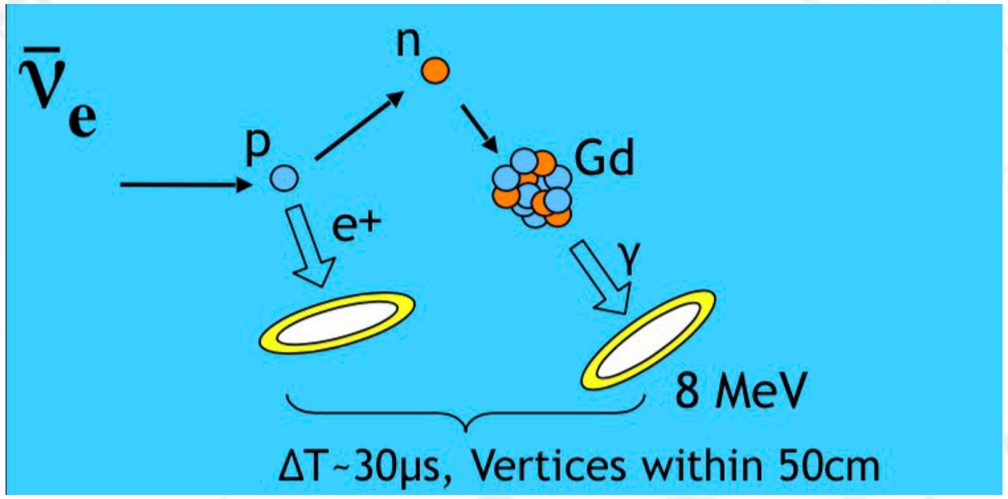
ND280 upgrade goals

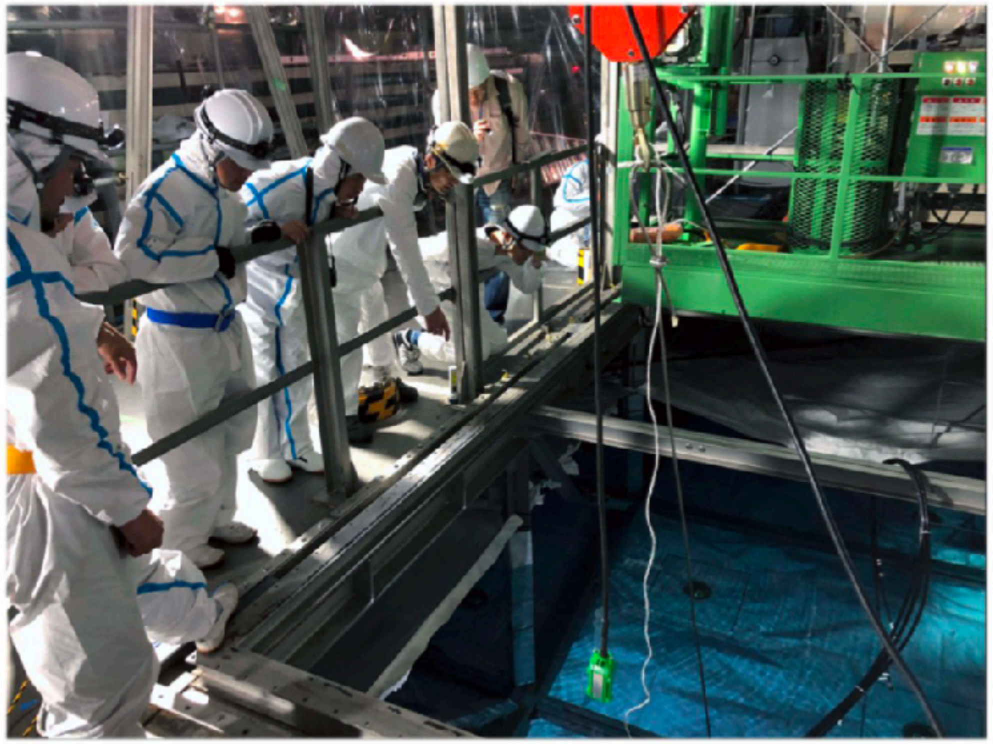


- quasi-3D imaging.
  - Improved target tracking.
  - Improved proton detection threshold.
  - neutron detection capabilities
- Improved high angle acceptance:
  - High Angle TPC's.
- x 2 in statistics for equal p.o.t.
- Time of Flight for background reduction.

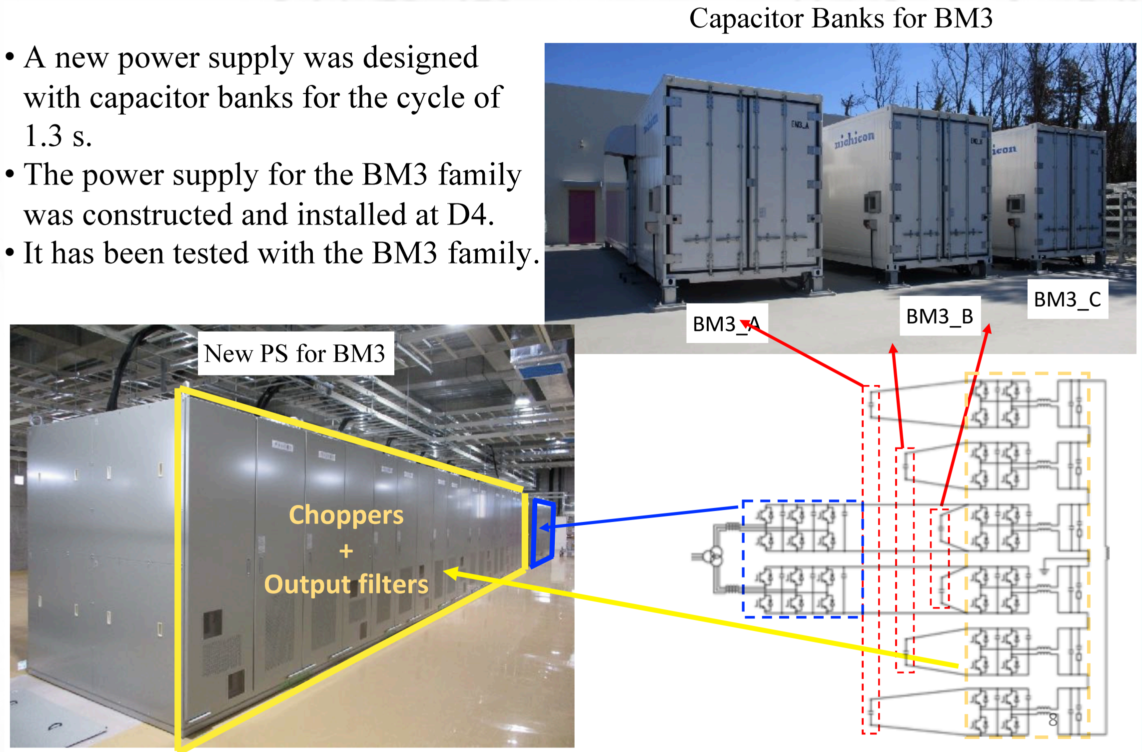
SK Gadolinium

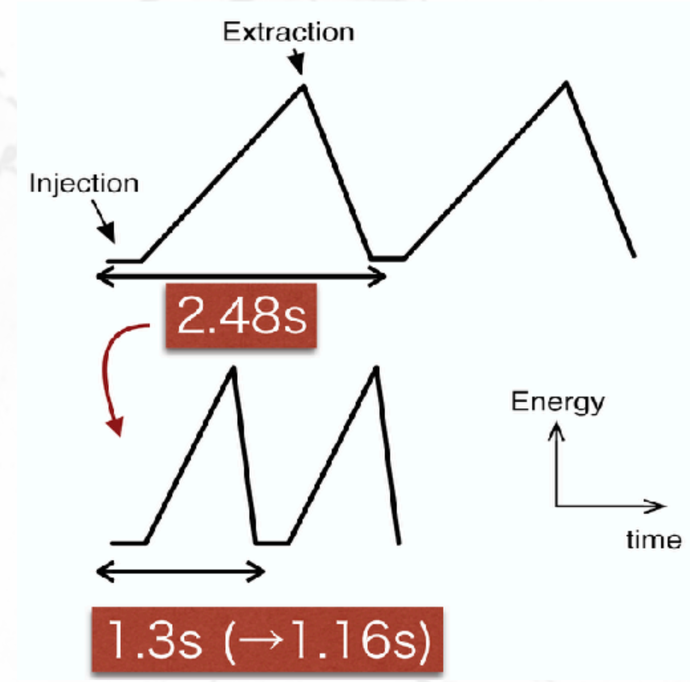
- SK Gadolinium project
  - enhance neutron detection improve low-energy ν_e detection (non-T2K goal).
  - may provide wrong-sign background constraint in $\bar{\nu}_e$
    - more data samples.
- Leak repairs to SK tank finished in 2019.
- Load $Gd_2(SO_4)_3$ in stages up to 0.2%.
- Loading to start in 2020.





Beam upgrade





f_{rep}=0.4 Hz ⊕ PPP = 2.7x10^{14} ⊕ 30 GeV = 515 kW

515 kW stable operation in 2019

MR Power Supply approved

JFY 2020

f_{rep}=0.77 Hz ⊕ PPP = 2.2x10^{14} ⊕ 30 GeV = 810 kW

exp. >800 kW by 2023

RF upgrade and Machine development

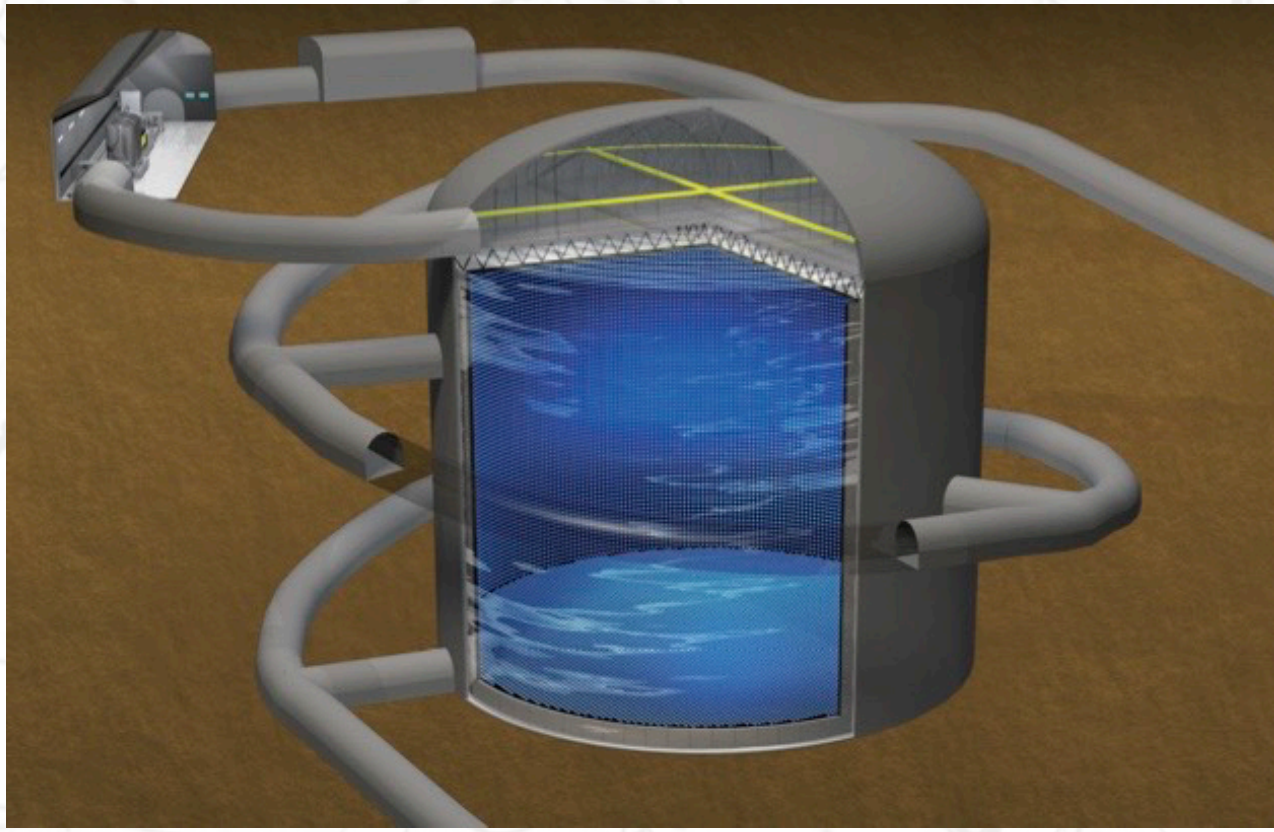
f_{rep}=0.86 Hz ⊕ PPP = 3.2x10^{14} ⊕ 30 GeV = 1.3 MW

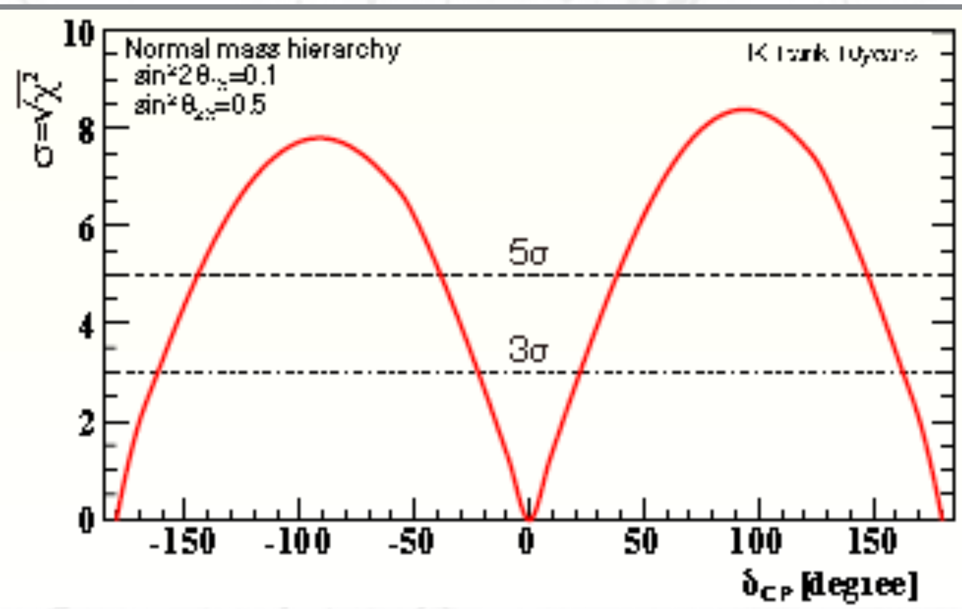
HyperKamiokande

Approved early 2020

- 1000-2000 $\nu_e + \bar{\nu}_e$ events.
    - 115 in T2K
- > 5σ discovery of CP violation.
- Precise measurement of θ_{23}

Same neutrino spectrum as T2K.
Same ND280 as in T2K
T2K results in x-sect and oscillation fosters future HK results.





	SK	HK
Site depth	Mozumi (1000m)	Tochibora (650m)
# PMT	11,129	40,000
Photo-coverage	40 %	40% (x2 QE)
Mass Fiducial mass	50 ktons 22.5 ktons	260 kkons 188 ktons

Conclusions & step forward

- Long Base Line technology is very **mature**.
  - research of years show the requirements for a **precision measurement using this technology.**
  - This includes **hadron production experiments, nuclear theory, beam monitor technology and advanced statistical methods.**
- Closing the **measurement of the PMNS matrix.**
  - Atmospheric angle close to maximal.
  - Rejected $\delta_{CP} > 0$ with 99.7% C.L.
  - Mild preference for normal hierarchy.
- T2K improving **statistical and systematic errors** control:
  - **Upgrade of ND280** for x-section
  - Use of **NA61/SHINE T2K replica-target** measurements will reduce significantly the flux errors.
- And, this is just the beginning:
  - **SK-Gd** may improve the results for antineutrinos.
- T2K measurements paves the road for the approved **HyperKamiokande**!

T2K Collaboration thanks NA61 and CERN for their invaluable contribution to the success of the experiment.


The international journal of science / 16 April 2020
nature
THE MIRROR CRACK'D
An indication of matter–antimatter symmetry violation in neutrinos
Coronavirus
The models driving the global response to the pandemic
Hot source
Remnants of primordial nitrogen in Earth's mantle
Origin of a species
Revised age for Broken Hill skull adds twist to human evolution
Vol. 580, No. 7803
£10.00 nature.com

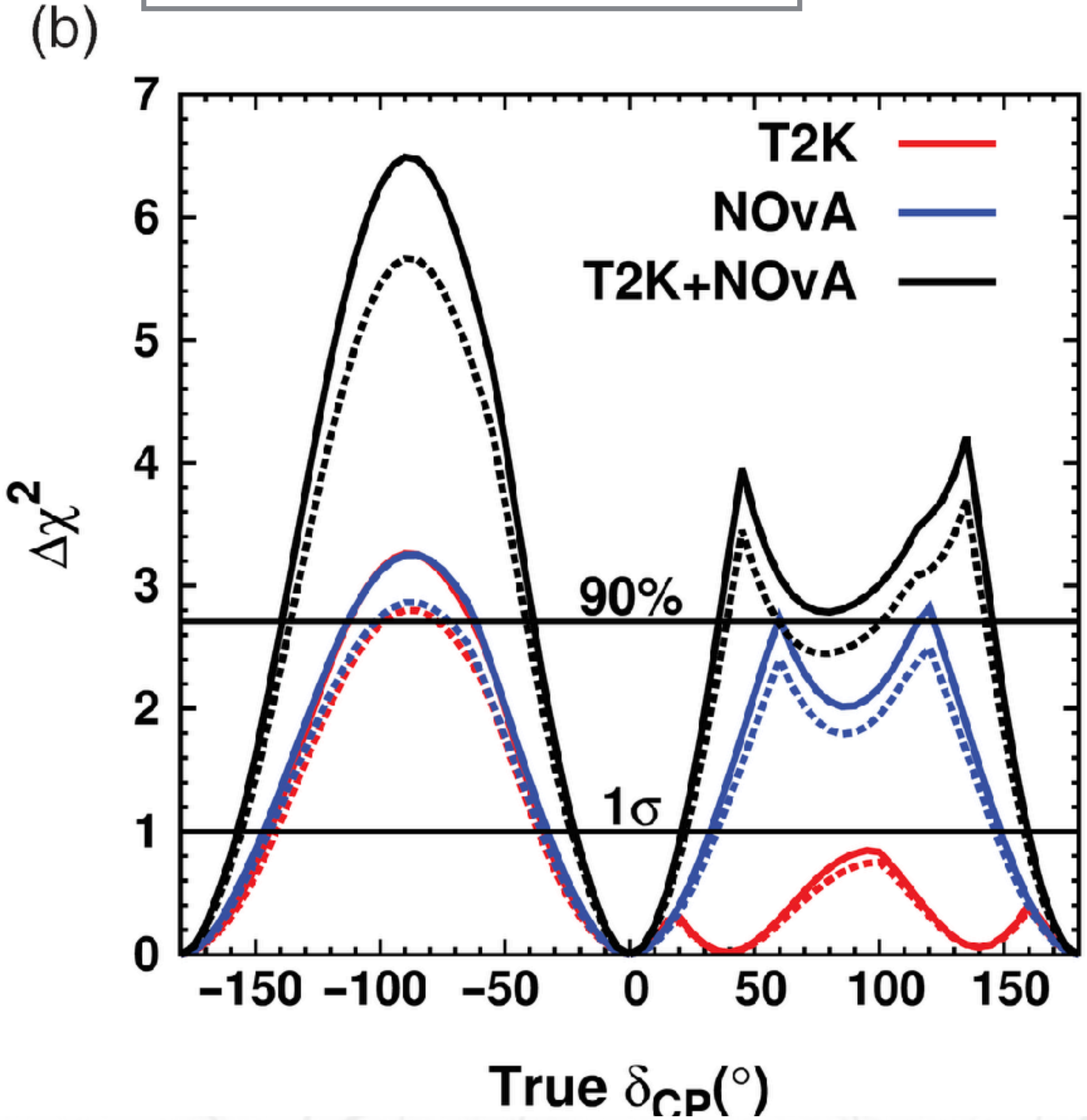
Supporting slides

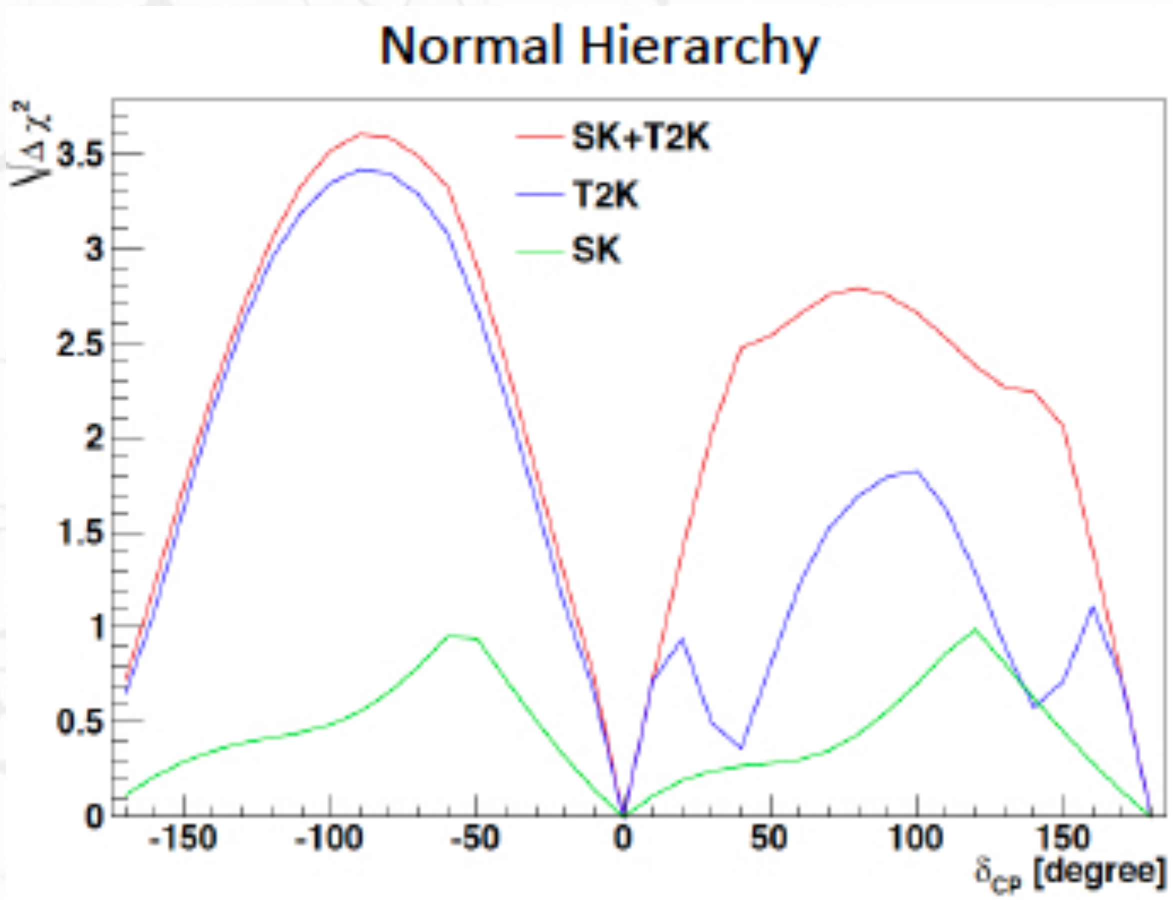
Combined analysis

Sensitivity T2K+Nova

Progress of Theoretical and Experimental Physics, Volume 2015, Issue 4, April 2015, 043C01

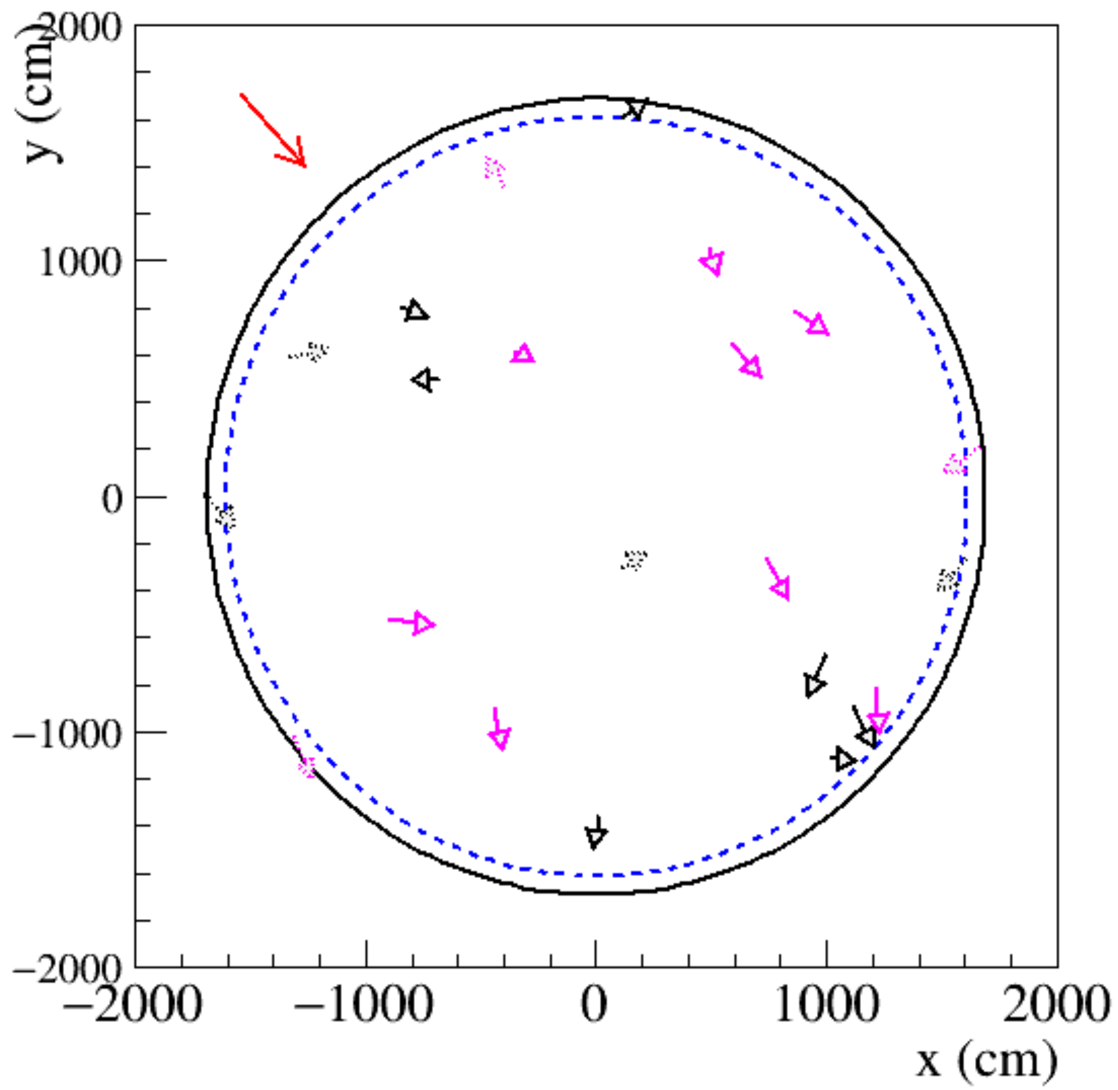
Sensitivity T2K+SK

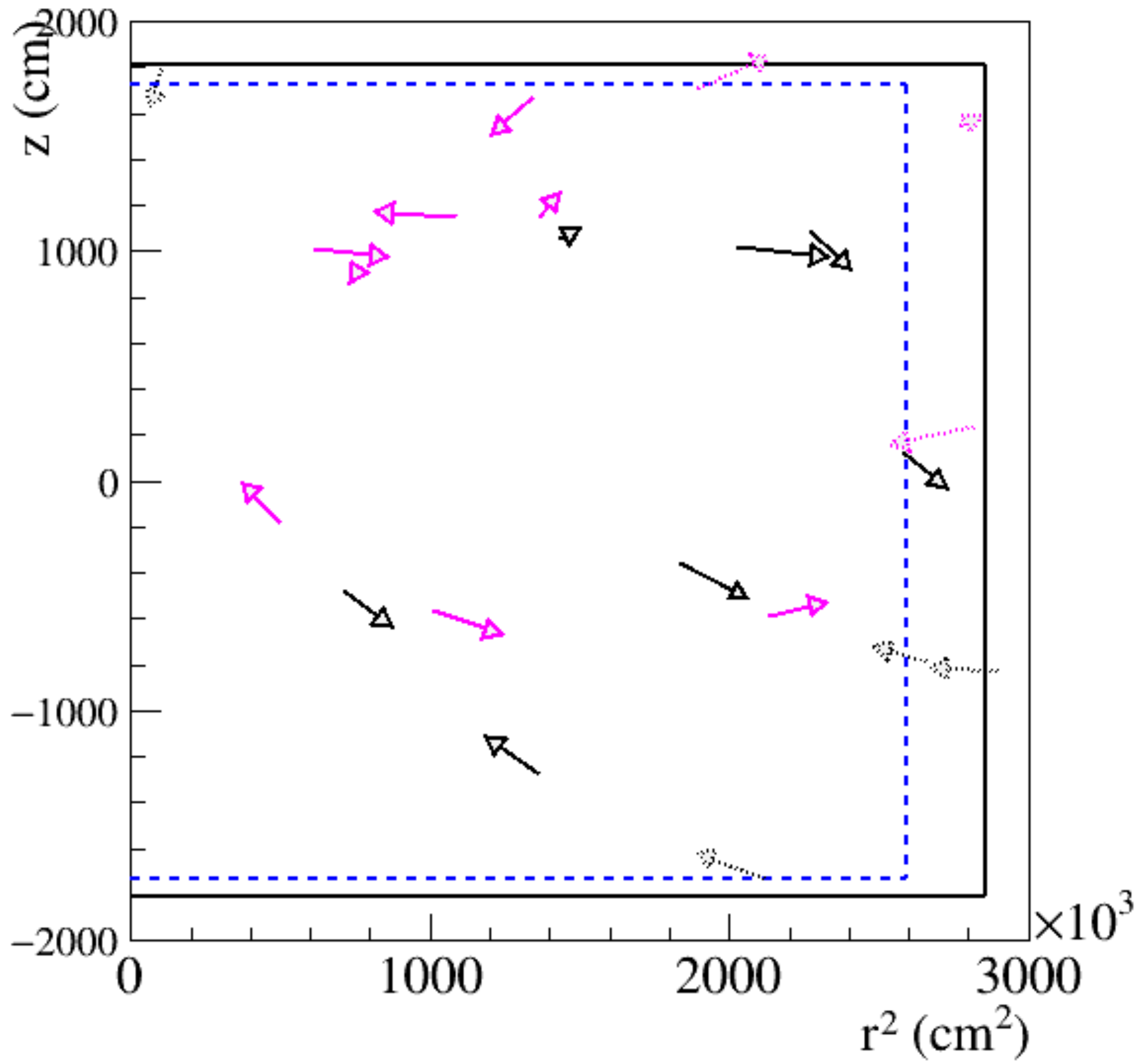


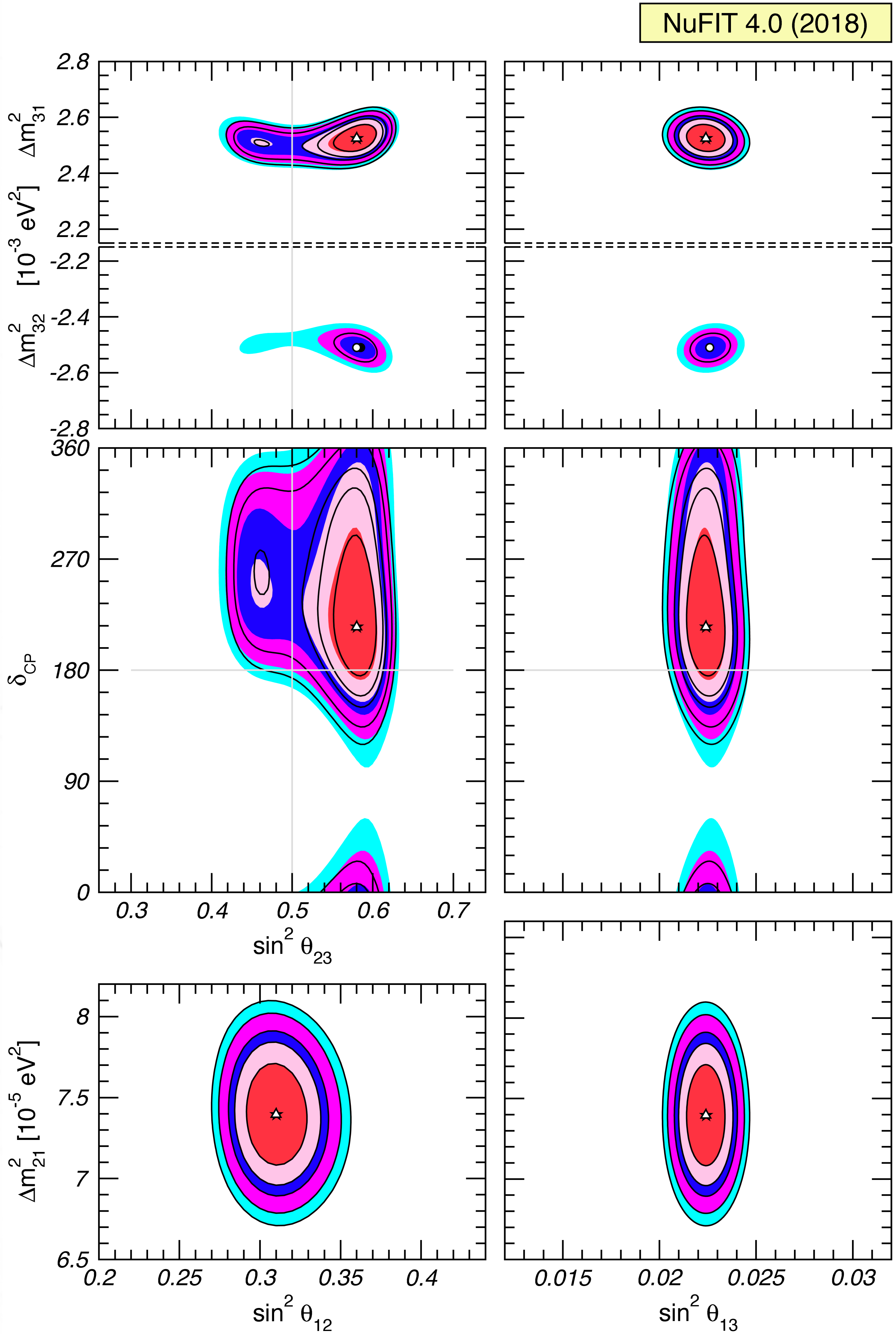


T2K formed working groups with Nova and SK to provide combined oscillation analyses

$\bar{\nu}_e$ vertex distribution





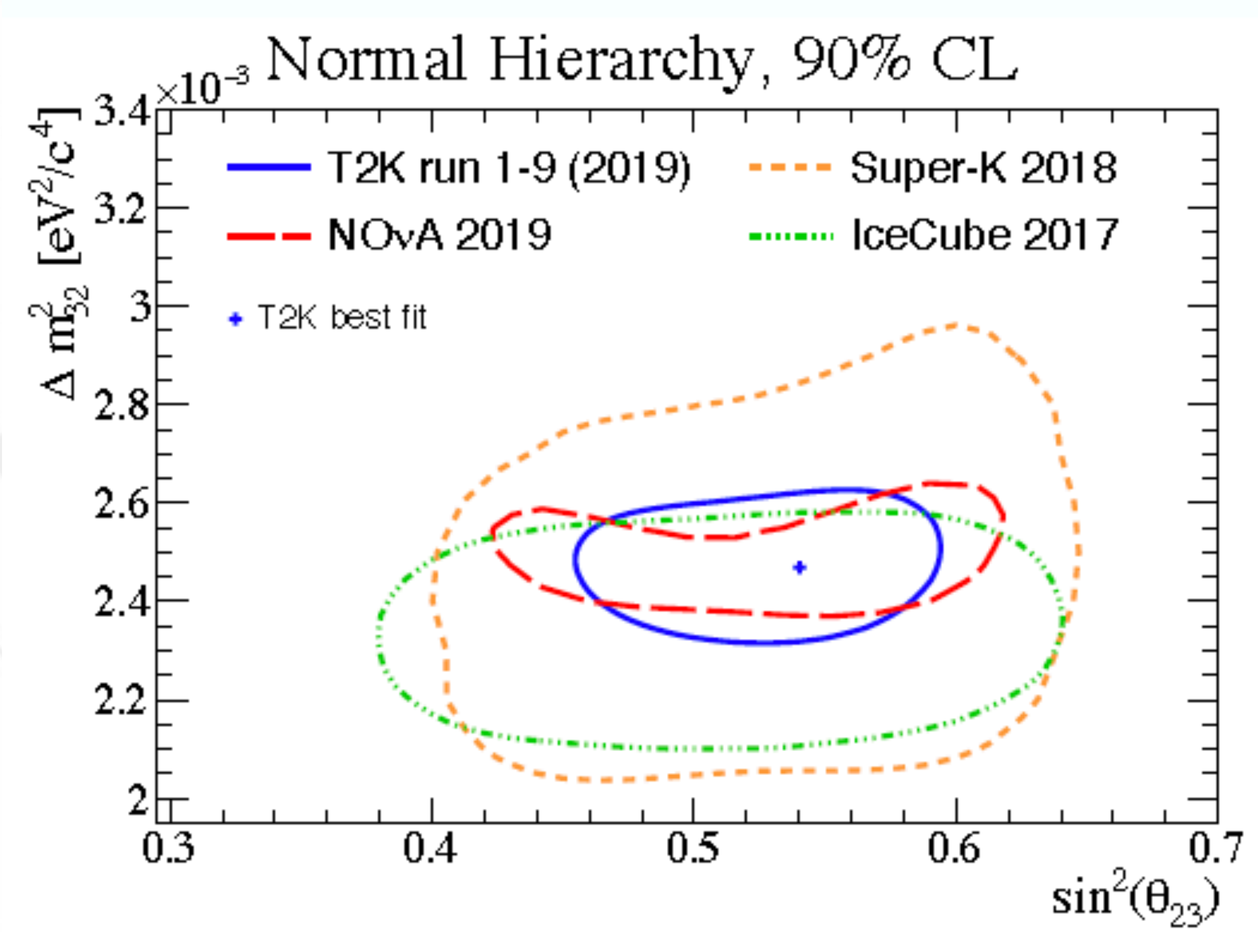


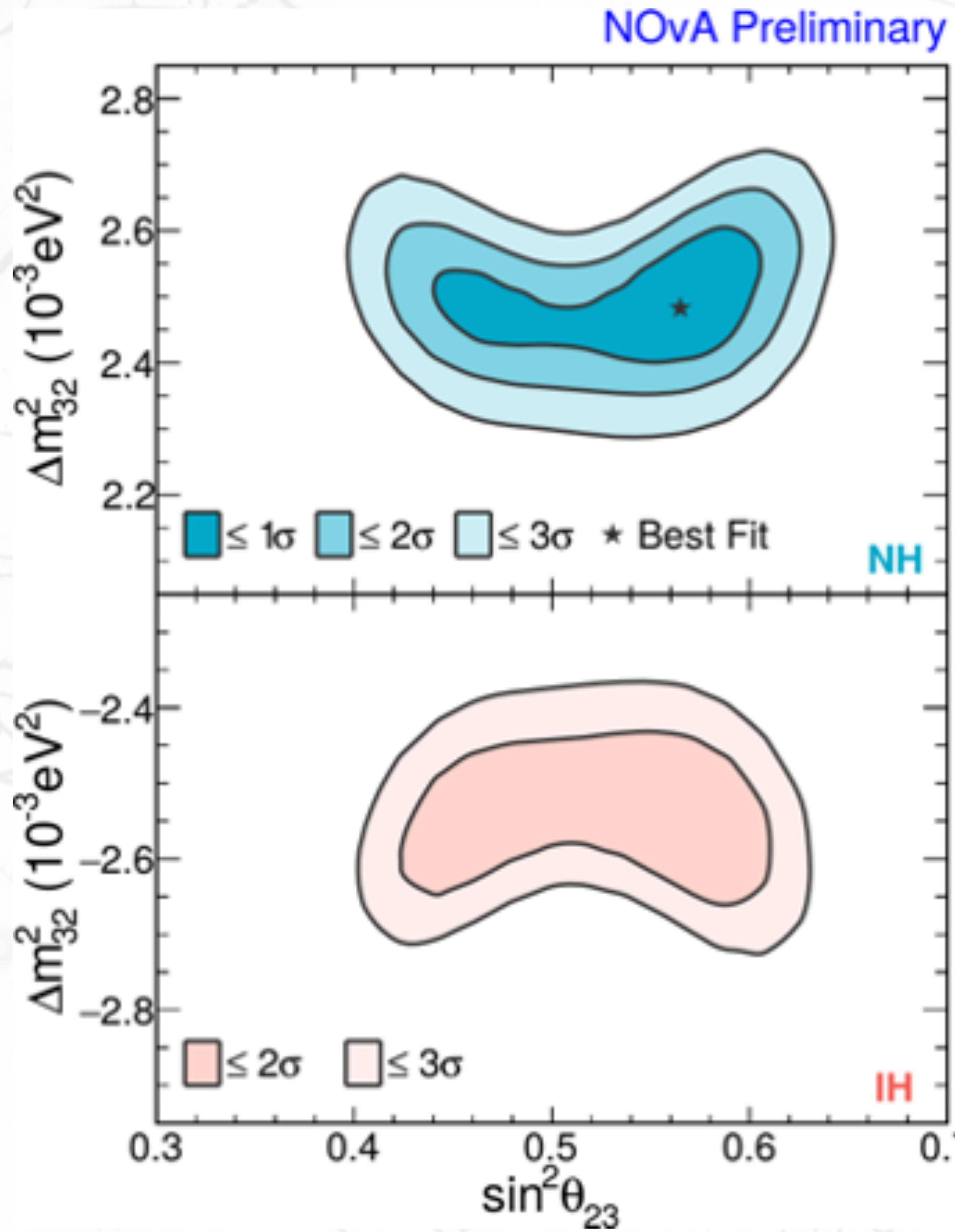
T2K

arXiv:1811.05487v1

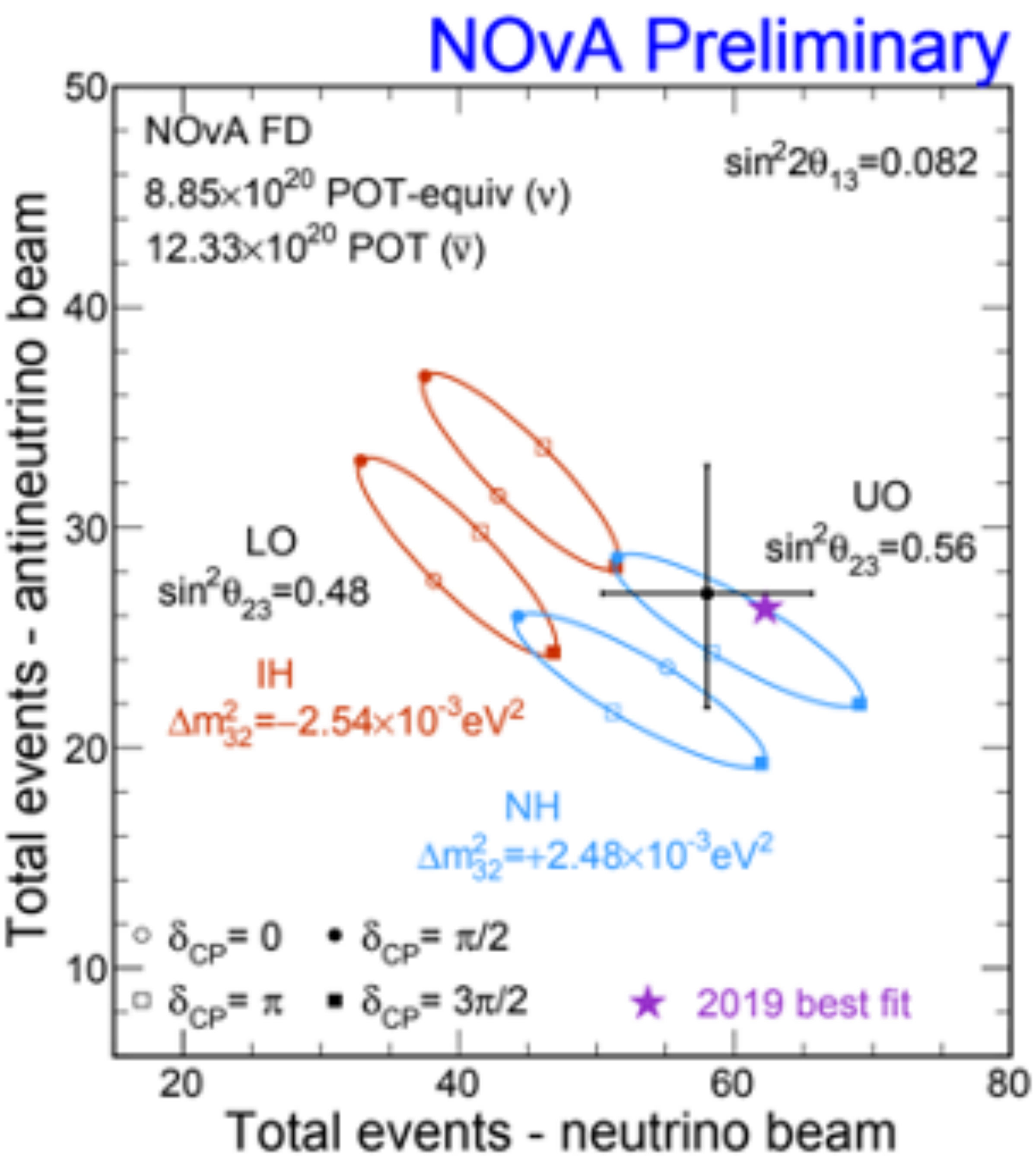
Global Fits

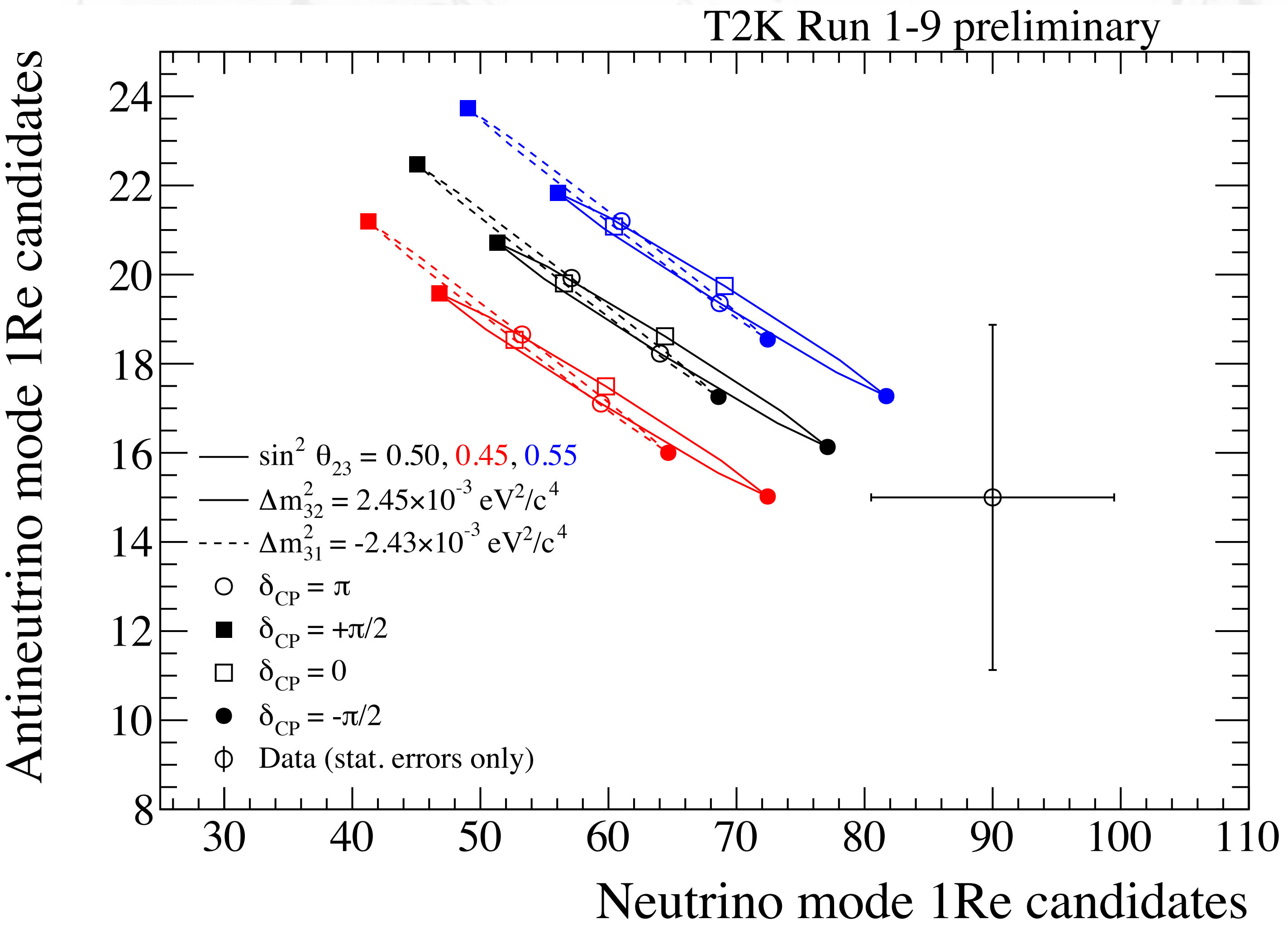
Nova vs T2K results



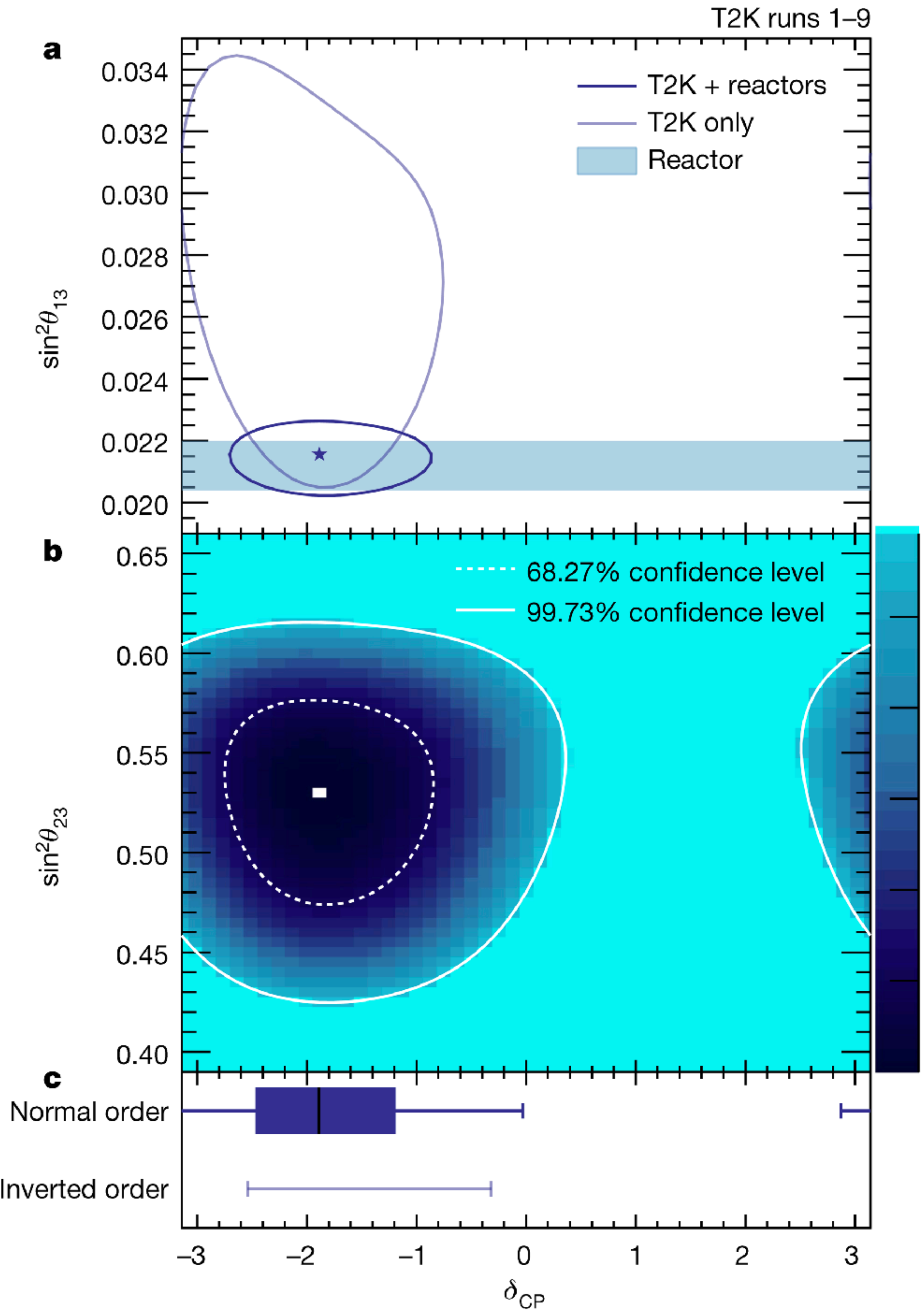


Nova results

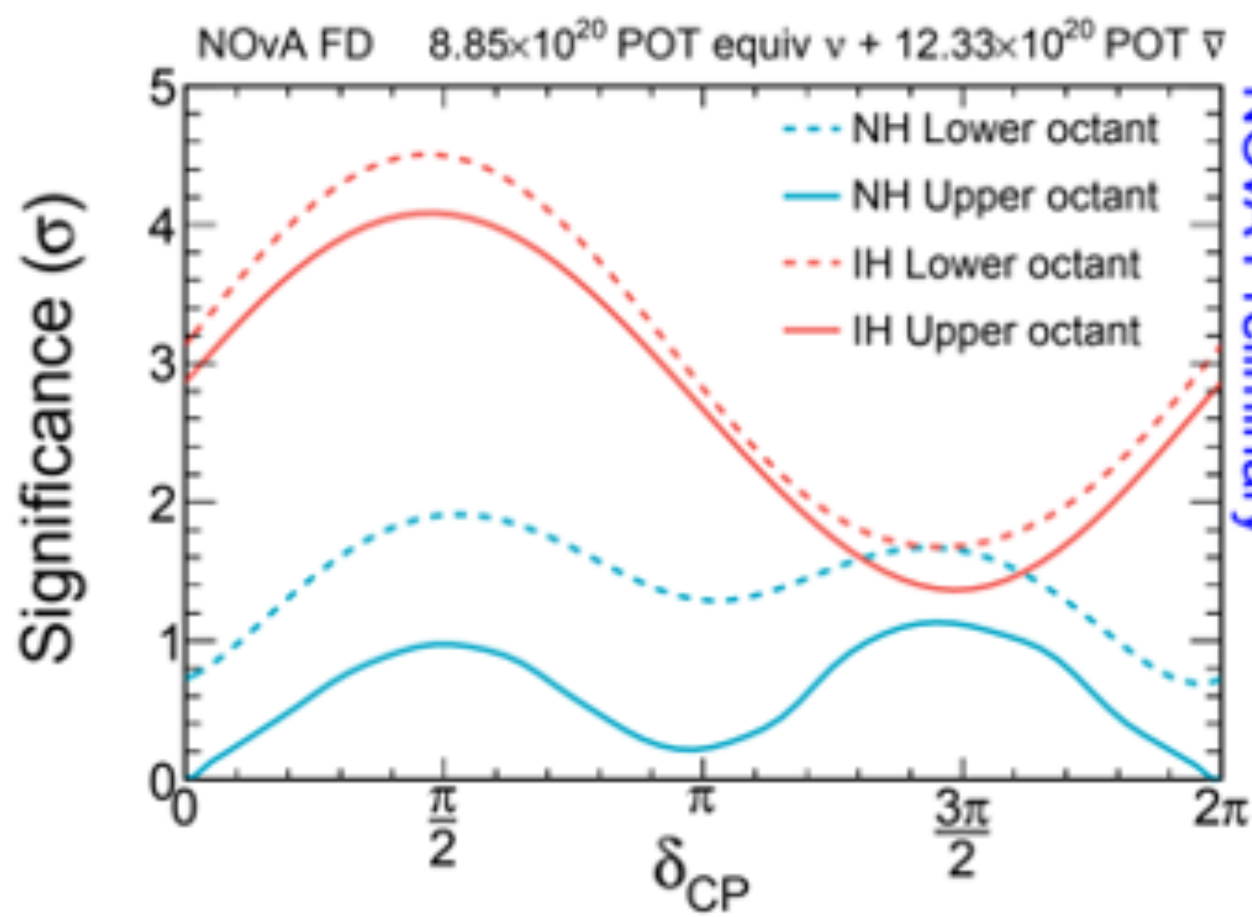




T2K vs Nova



T2K runs 1–9
a
T2K + reactors
T2K only
Reactor
$\sin^2\theta_{13}$
0.034
0.032
0.030
0.028
0.026
0.024
0.022
0.020
b
68.27% confidence level
99.73% confidence level
$\sin^2\theta_{23}$
0.65
0.60
0.55
0.50
0.45
0.40
10
8
6
4
2
c
Normal order
Inverted order
−3
−2
−1
0
1
2
3
δ_{CP}



NOvA FD 8.85×10^{20} POT equiv ν + 12.33×10^{20} POT $\bar{\nu}$
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
NOvA Preliminary
Significance (σ)
δ_{CP}
0
$\frac{\pi}{2}$
π
$\frac{3\pi}{2}$
2π

Approx oscillation formulae

T2K

Appearance

$$P(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \times \left(1 \pm \frac{2a}{\Delta m_{31}^2}(1-s_{13}^2)\right)$$ Leading term

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

$$\mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\Delta_{32}\sin\Delta_{31}\frac{aL}{4E}(1-2s_{13}^2)$$ Matter effect

$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Violating

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

ν vs. $\bar{\nu}$ sign change

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ $\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$ $a = 2\sqrt{2}G_F n_e E$

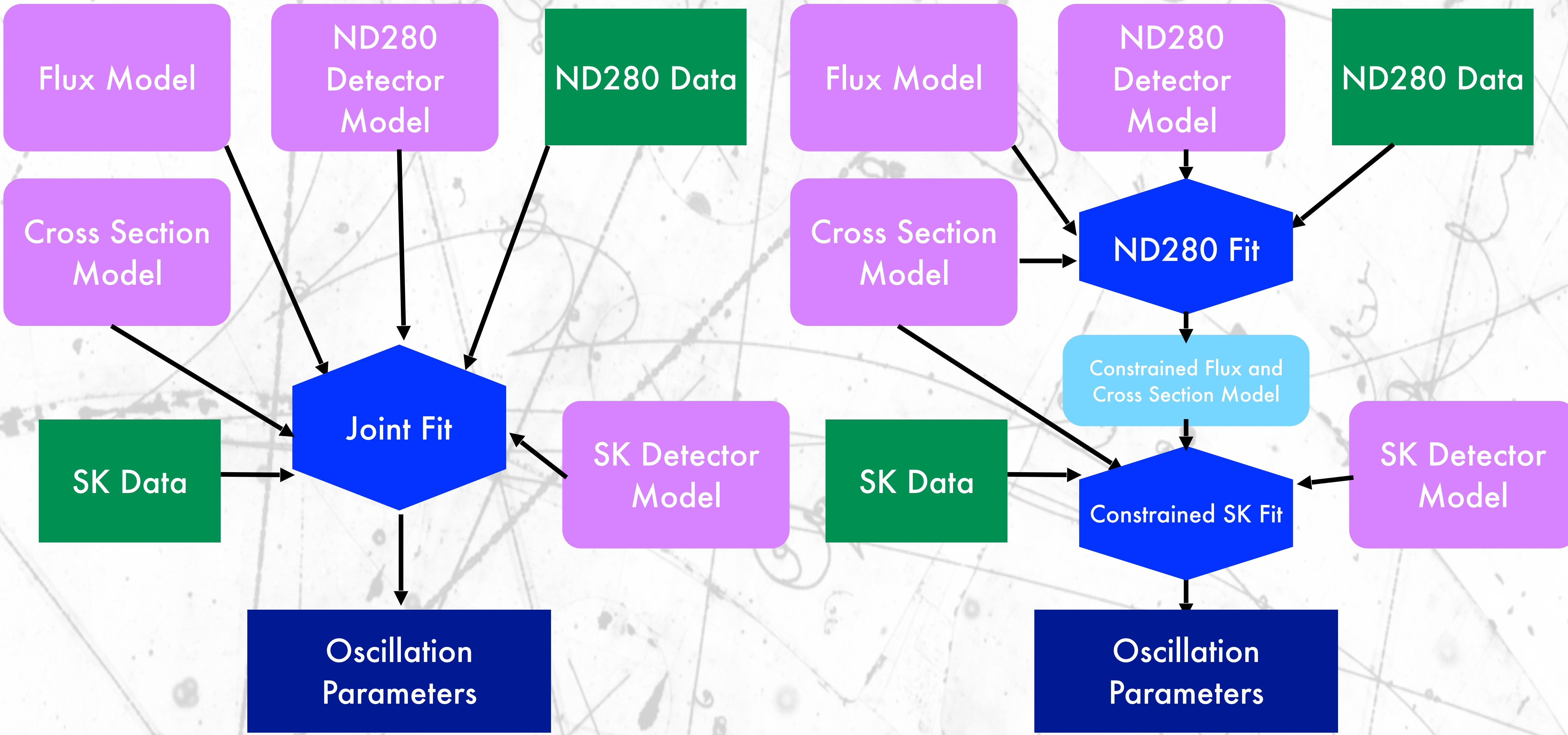
Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - (\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\cdot\sin^2\theta_{23})\cdot\sin^2\frac{\Delta m_{32}^2 \cdot L}{4E_\nu}$$

Statistical methods

	Analysis 1	Analysis 2	Analysis 3
Kinematic variables for 1Re sample at SK	Erec-θ	p_e-θ	Erec-θ
Likelihood	Binned Poisson Likelihood Ratio	Binned Poisson Likelihood Ratio	Binned Poisson Likelihood Ratio
Likelihood Optimization	Markov Chain Monte Carlo	Gradient descent and grid scan	Gradient descent and grid scan
Contours/limits produced	Bayesian Credible Intervals	Frequentist Confidence Intervals with Feldman-Cousins (credible intervals supplemental)	Frequentist Confidence Intervals with Feldman-Cousins
Mass Hierarchy Analysis	Bayes factor from fraction of MCMC points in each hierarchy	Bayes factor from likelihood integration	Frequentist p-value from generated PDF
Near Detector Information	Simultaneous joint fit	Constraint Matrix	Constraint Matrix
Systematics Handling	Simultaneous fit then marginalization	Marginalization during fit	Marginalization during fit

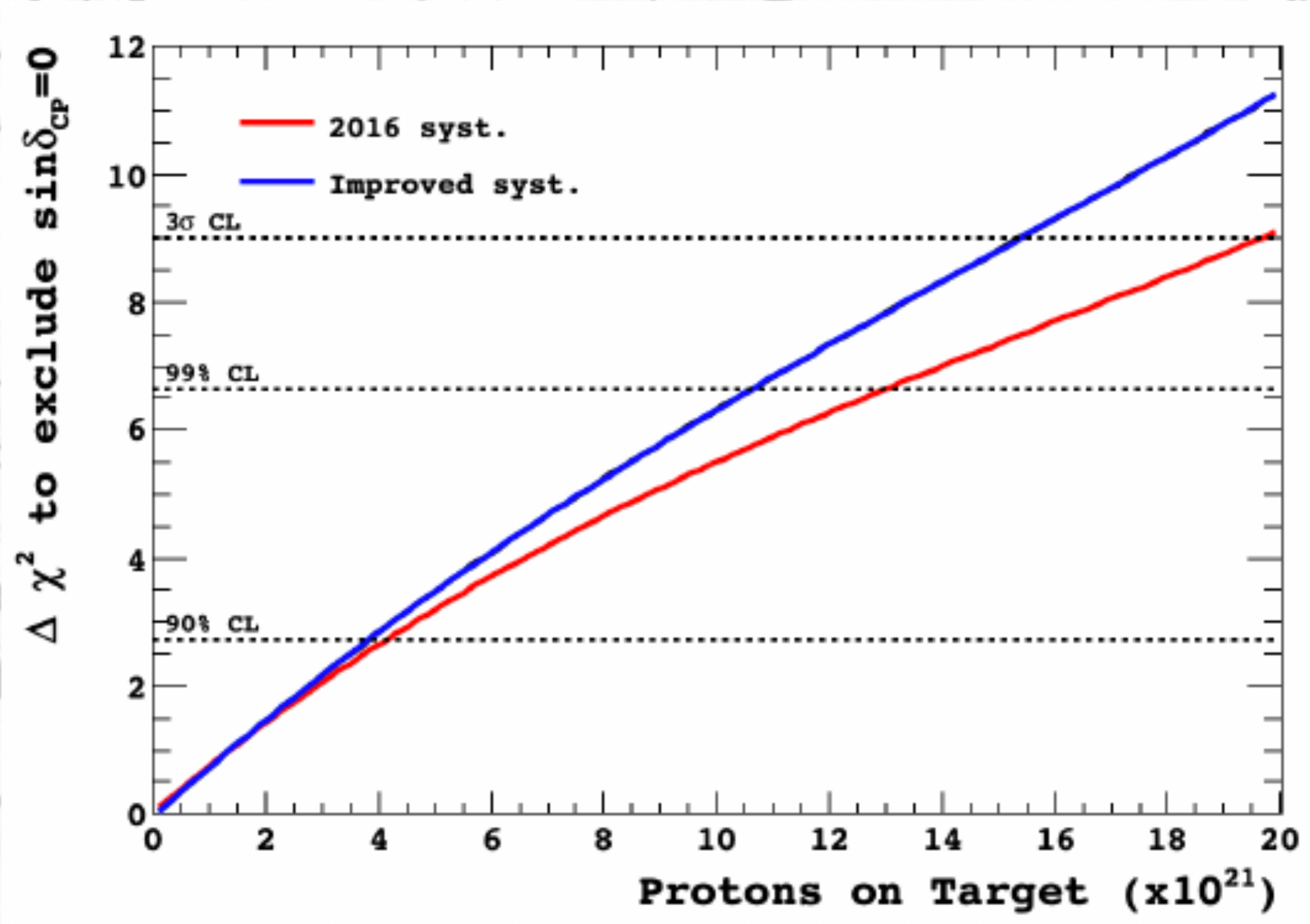
Statistical methods



Joint Fit **Separate ND and SK Fits**

T2K: impact of ND

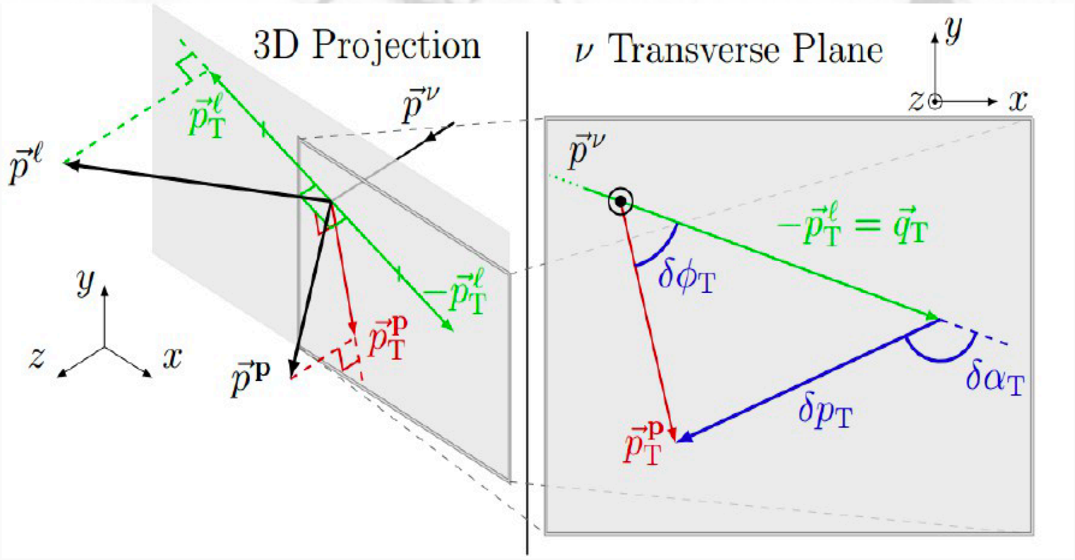
- Why is this so important?:
  - Main systematics are from the **beam modelling** (improved with hadro-production experiments) and **x-section modelling.**



- T2K has still **significant x-section** systematic errors.
- T2K measurements are important for **HK**, **Dune**, **Nova** and **atmospheric neutrino oscillations.**

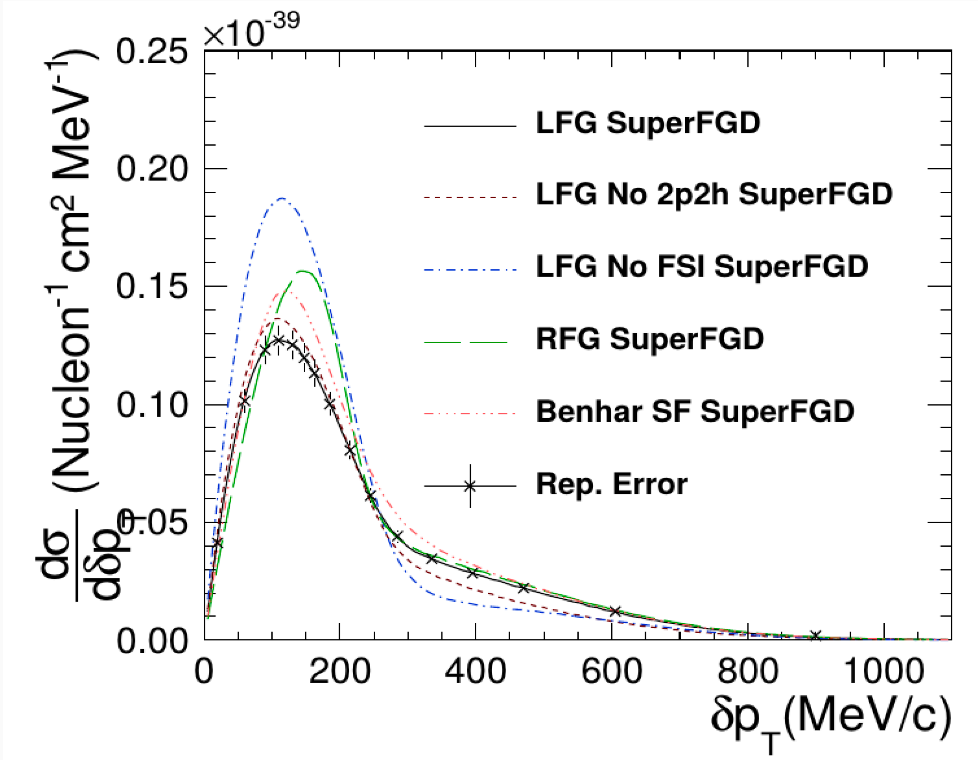
ND280 upgrade

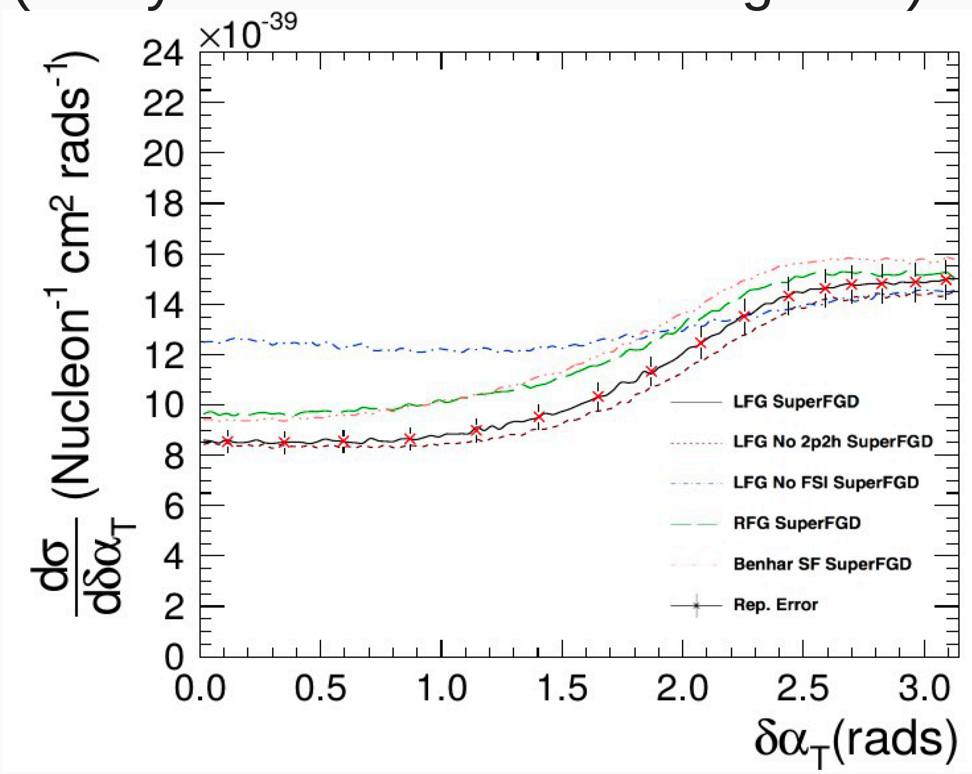
How to use this proton information:
“Single Transverse Variables” and beyond!
→ measurements of Fermi momentum, binding energy, 2p2h...



$\delta\alpha_T$ shape is highly sensitive to proton FSI
→ allows to constrain it to ~1% : **not anymore an issue to use protons in the ND fit for the oscillation analysis!**
(today 30% from e-scattering data)

δp_T is a direct measurement of Fermi momentum: shape measurement <10% precision in each bin with 8×10^{21} POT





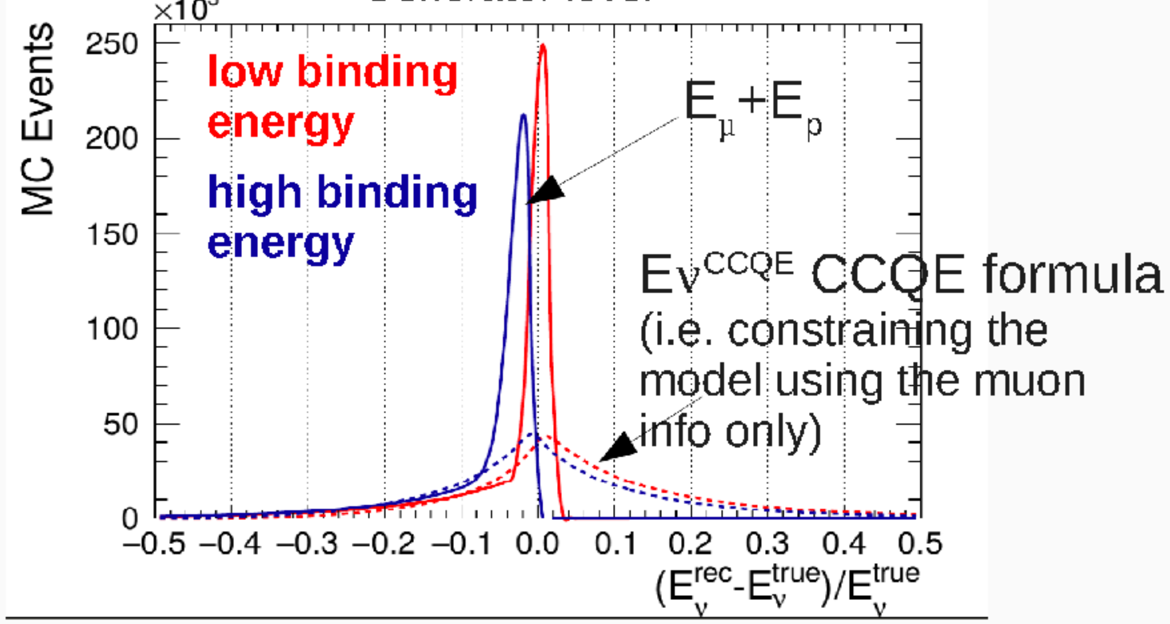
ND280 upgrade

T2K

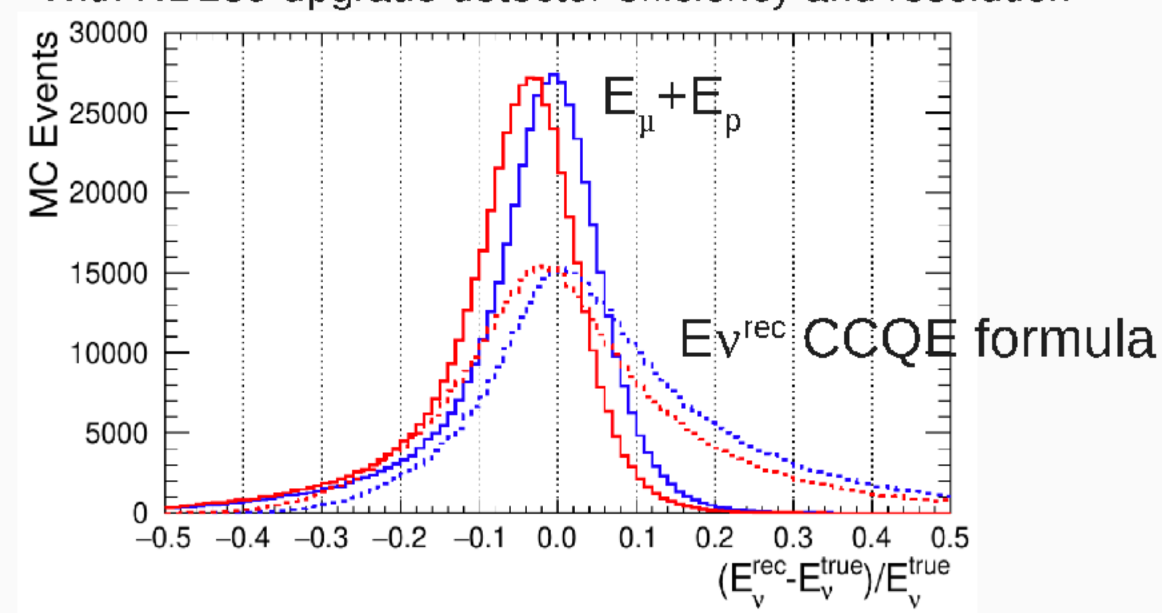
Another variable: total energy

- The $E\nu^{rec}$ CCQE formula does not include information on the outgoing proton → $E\mu$+Ep is a much better estimator of the true neutrino energy

Generator level



With ND280-upgrade detector efficiency and resolution



Smearing of $E\nu^{rec}$ is dominated by Fermi momentum,

smearing of $E\mu$+Ep is dominated by flux (and detector effects)

→ **$E\mu$+Ep is a much more robust estimator of true $E\nu$ and of binding energy**

- **This is just the appetizer! We are starting investigating possible other variables and combinations → a lot of new sensitivity**

A good example of the 'iterative' process: new detector + *DATA* → new ways of doing analysis / looking at our systematics → improvements of oscillation analysis!

ND280 upgrade

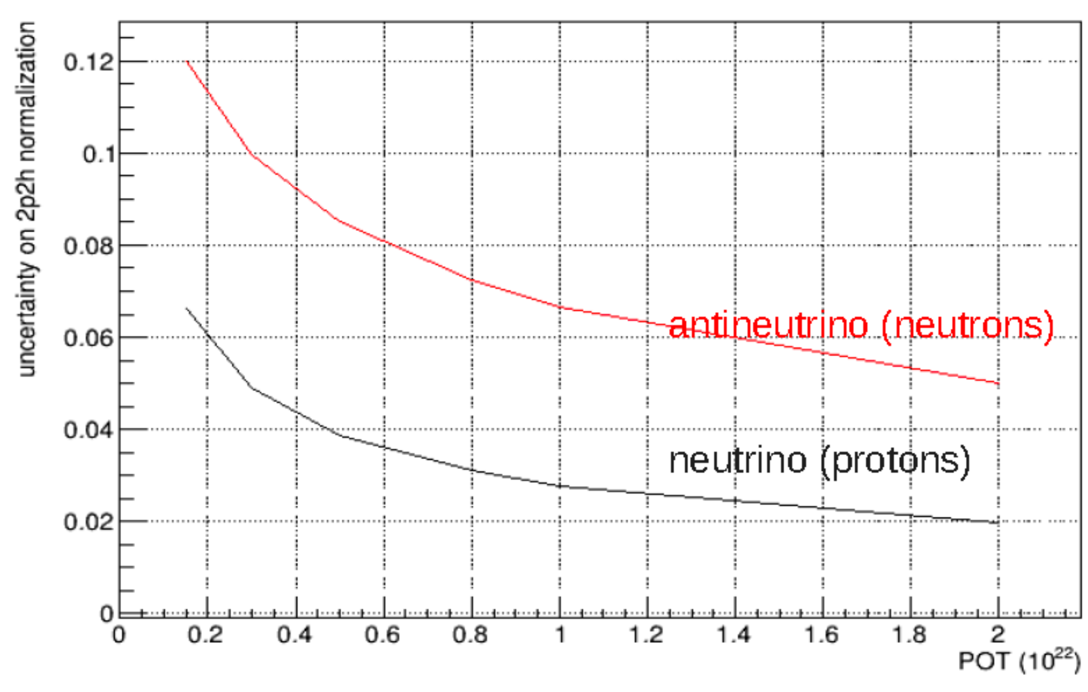
SuperFGD: neutrons

- The superFGD can detect neutrons with ~60% efficiency

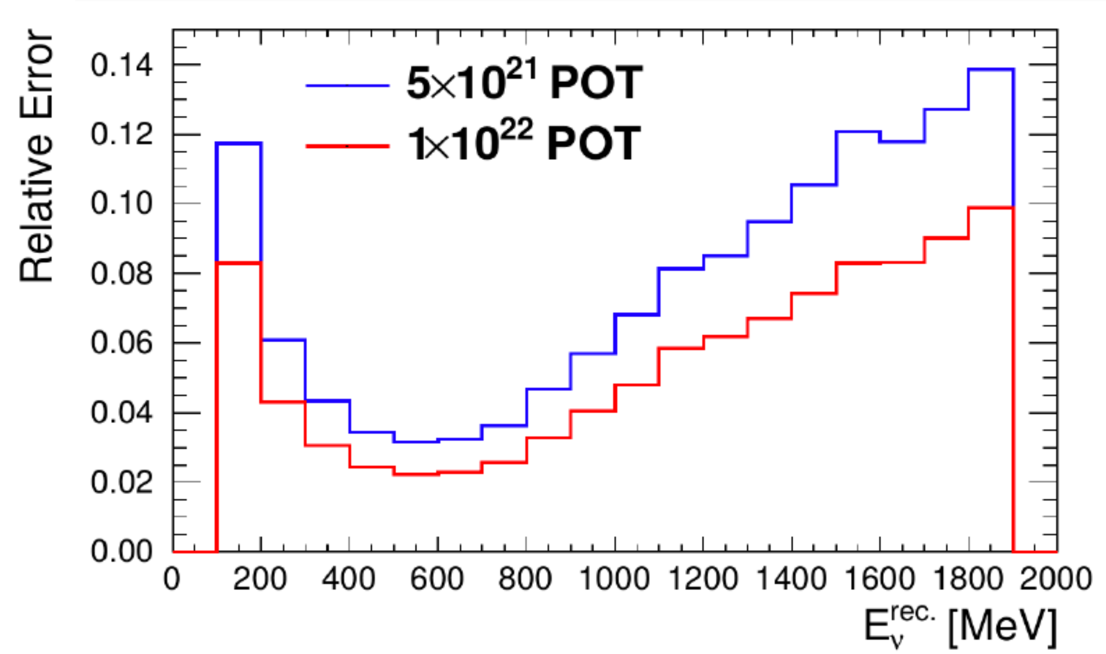
- If the path is long enough (>50 cm) also neutron energy is measured with resolution 15-30%
(to be calibrated with neutron test-beam at LosAlamos)

- The background can be rejected by reducing the fiducial volume (no reliable simulation available yet)

The same analyses shown for protons can be repeated for neutrons.
Example of fitting single transverse variables

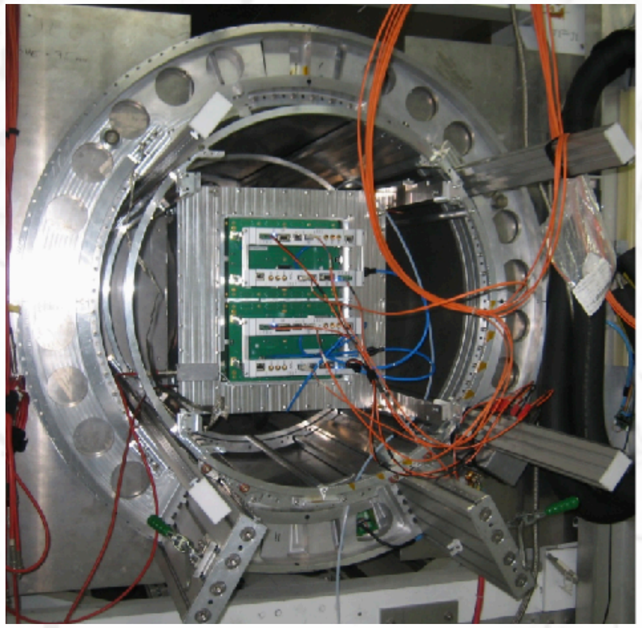


A lot of interesting physics with neutron tagging (e.g. DSNB, increased atm MH sensitivity)
→ e.g. neutron multiplicity as a function of neutrino energy

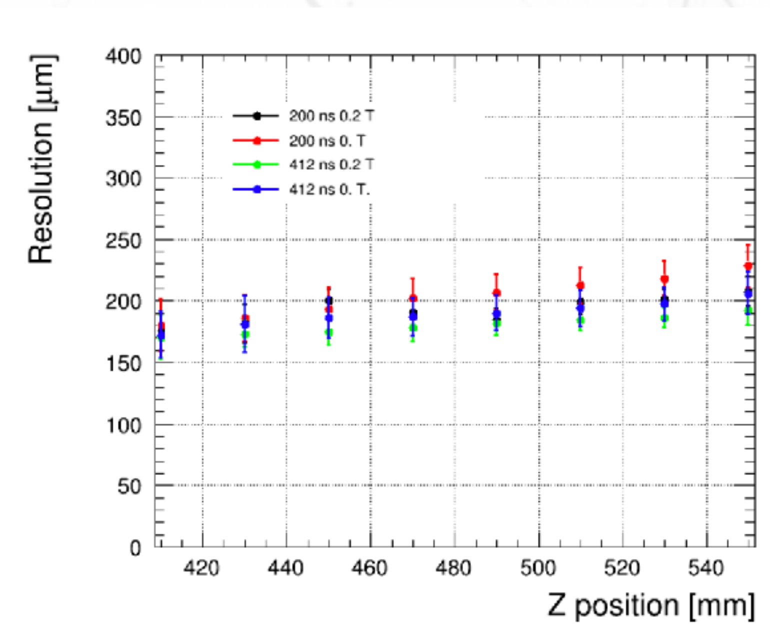


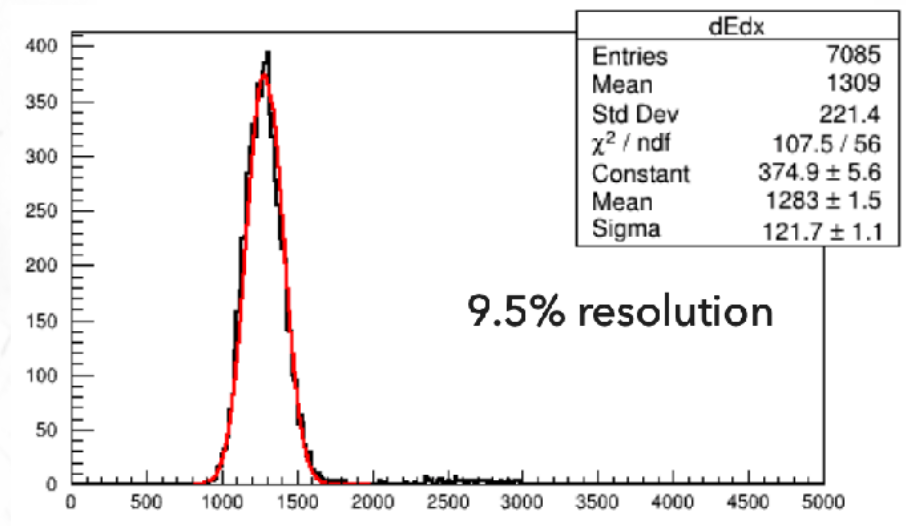
HA-TPC

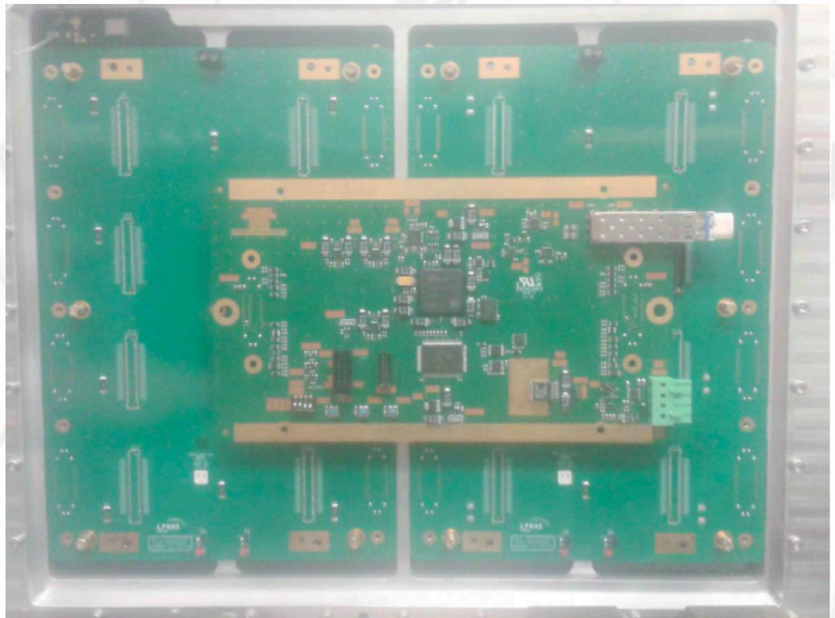
@DESY



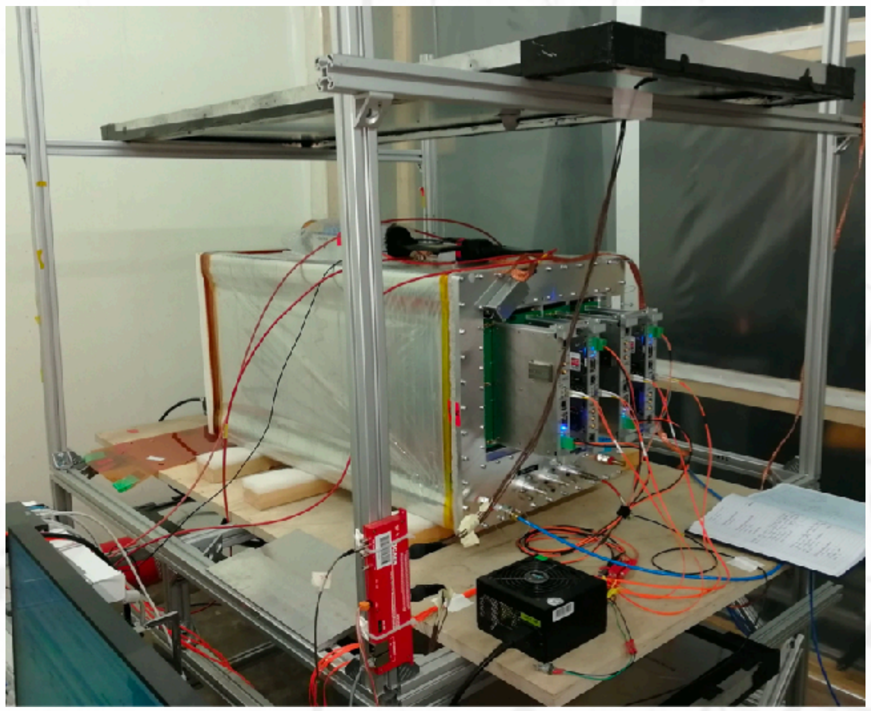
- Test Beam with Resistive MicroMegas at DESY in June 2019
  - 4 GeV electrons, analysis on-going
  - Excellent spatial resolution (~200 μm for horizontal tracks) and dE/dx resolution
- HA-TPC electronics:
  - First Front-End mezzanine (FEM) prototype has been tested
  - First Front-End-Card (FEC) will be delivered in Jan 2020

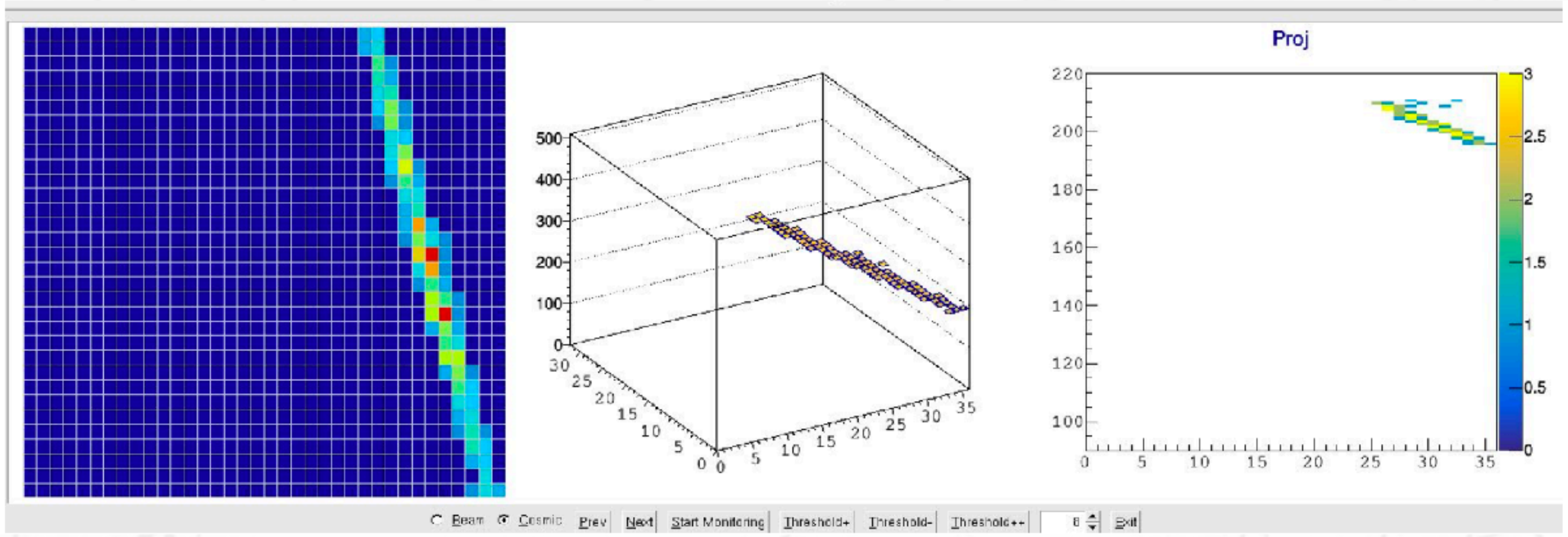


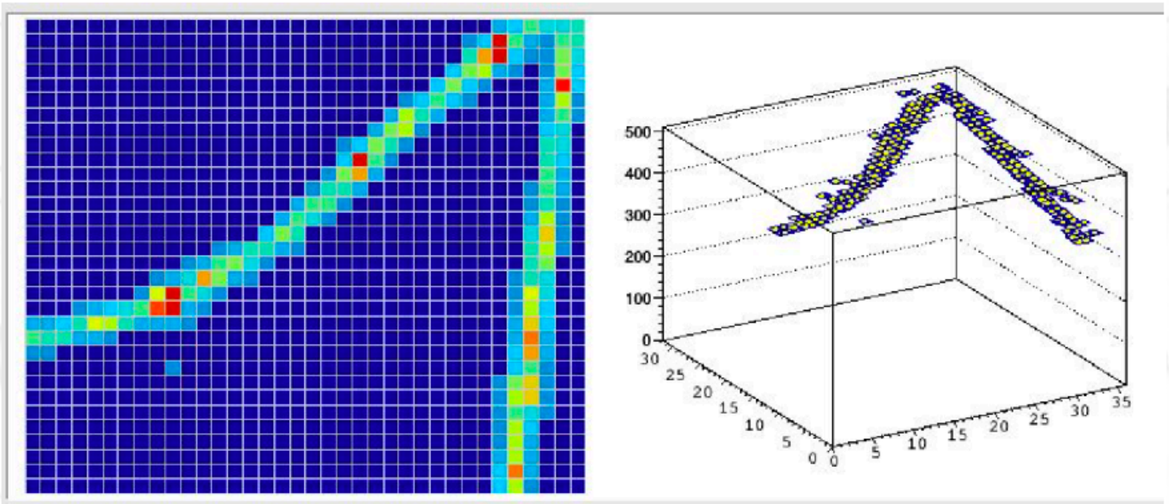




HA-TPC prototype @ CERN





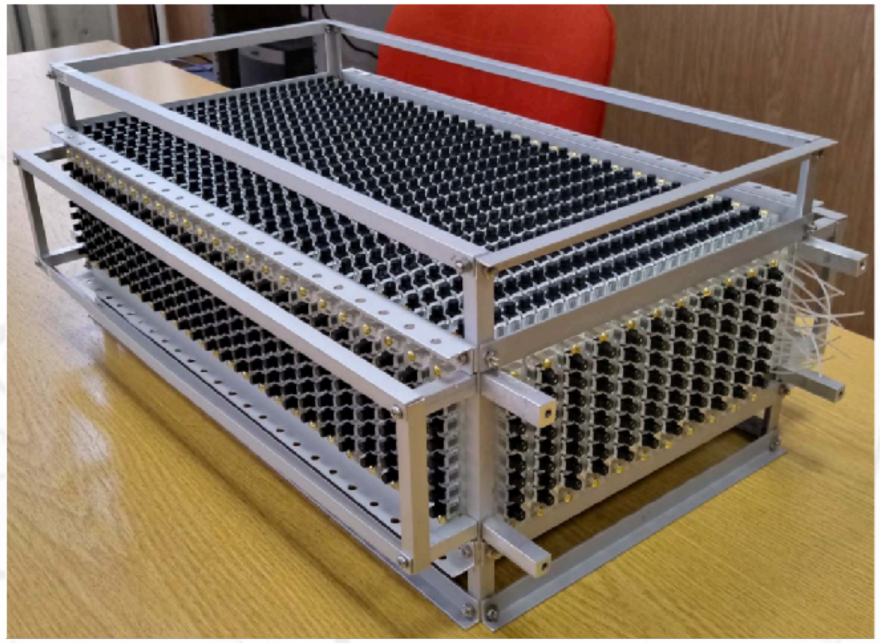


- Stable operation at 18 kV
- 2nd prototype to improve gas leak rate expected in Feb 2020
- First TPC field cage expected in June
    - External review committee for the TPC field cage design has been formed → expect 1st meeting in January

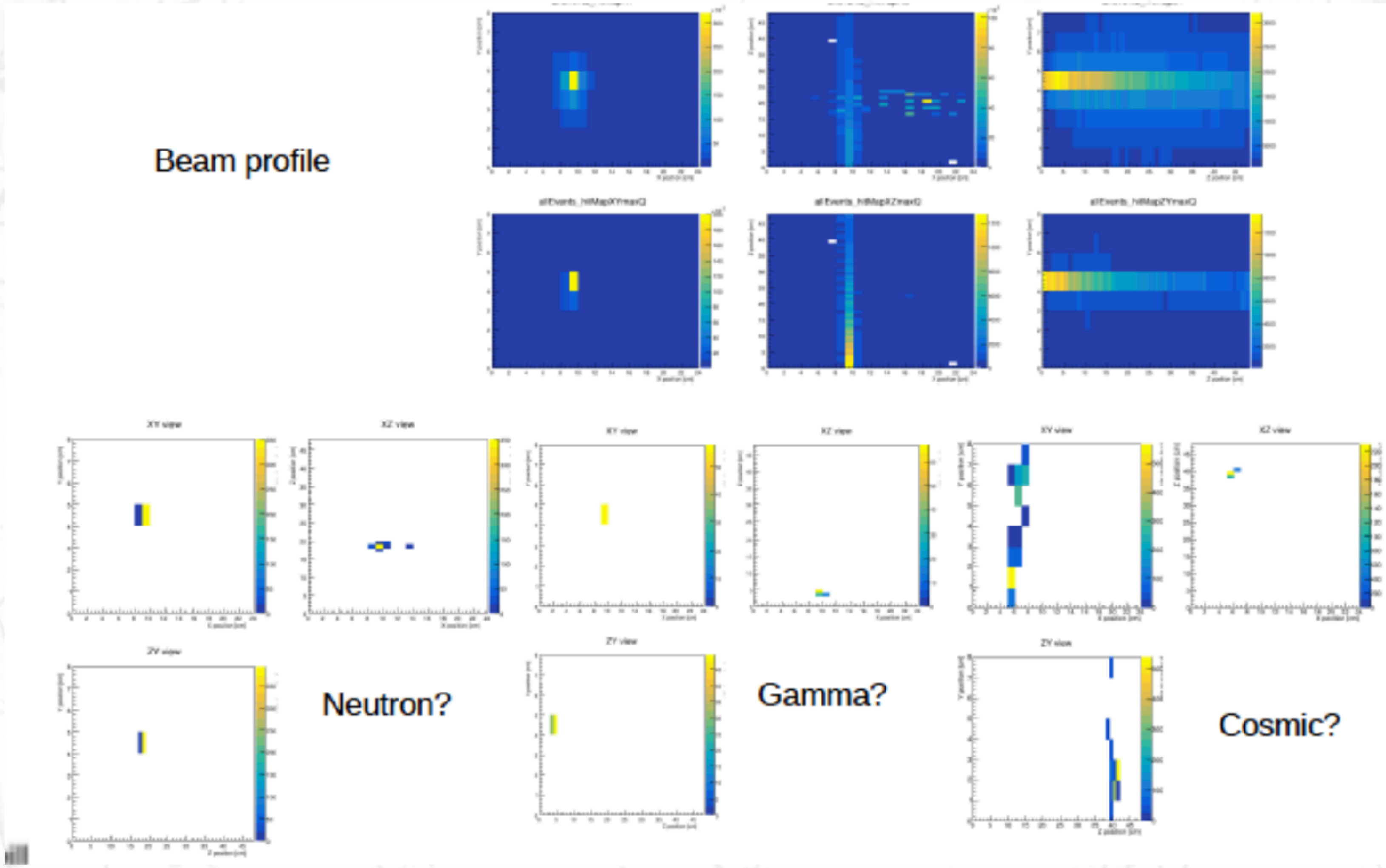
Super-FGD

- Assembly with Fishing Line at INR ➝
  - 27 full size (192 x 184 cubes) x-y layers assembled
  - 56 z layers (15 x 192 cubes) ➝ corresponding to the full height of the Super-FGD
  - All cubes will be produced by Jan 2021
  - Review to discuss feasibility of assembly method organized by T2K ➝ Fishing-Line method has been chosen as primary option for the assembly
  - Design of the Super-FGD electronics is on-going ➝ all CITIROC chips have been bought

Super-FGD prototype neutron tests at LANL

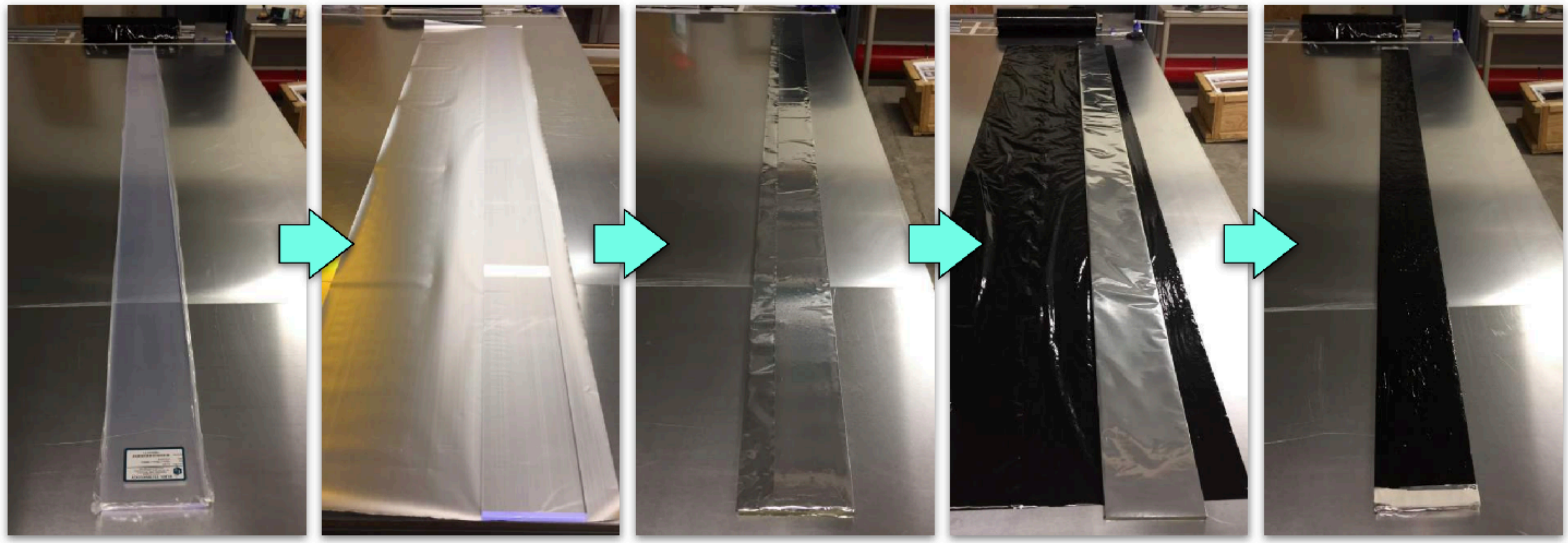


- Data taking in December
- Neutron beam profile clearly visible
- Analysis of the data is on-going



Time Of Flight

- Start assemblying scintillator bars
- Most of the components already received
- First ToF module assembled



3 layers of Al foil + 6 layers of black stretch film

- ## Mock-up basket

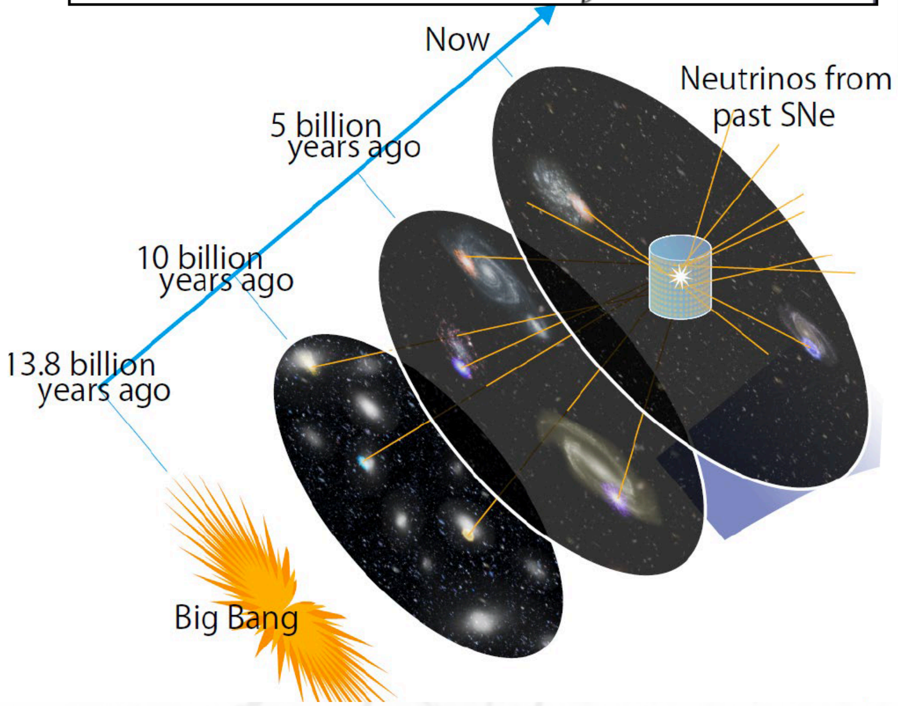
- The 6 ToF modules will be installed into the “mini basket” that has been delivered to CERN
  - Mock-up of the upstream part of the real ND280 basket
  - It will be used to test integration of the different sub-detectors

SK-Gd

Diffused Supernova Neutrino Backgrounds

- Neutrinos produced from the past SN bursts and diffused in the current universe.
  - ~ a few SN explosions every second → $O(10^{18})$ SNe so far in this universe
  - Can study history of SN bursts with neutrinos

$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\max}} R_{SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

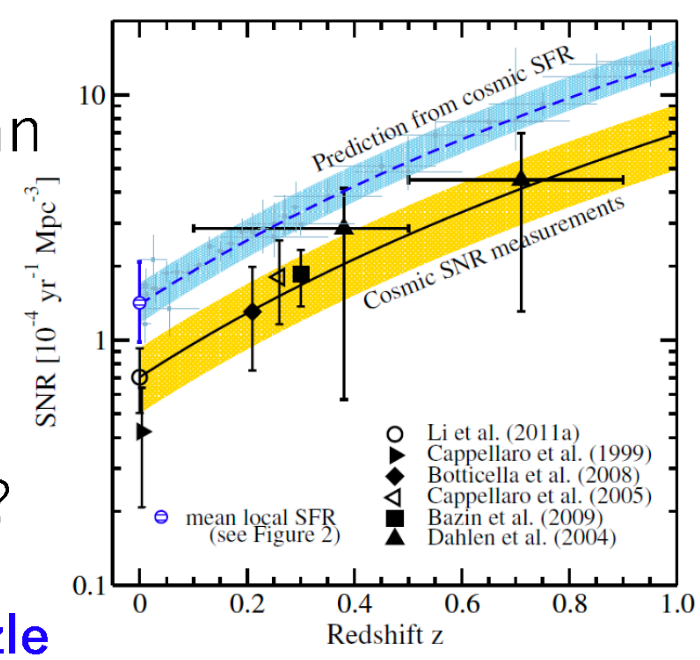


SN rate problem

- Observed SN burst rate lower than prediction from cosmic star formation rate
  - Invisible dim supernova?
  - Black-hole formation?
  - Something blocking optical light?

DSNB signal could resolve the puzzle

H. Horiuchi et al, Astrophys. J. **738**, 154 (2011)



SK-Gd

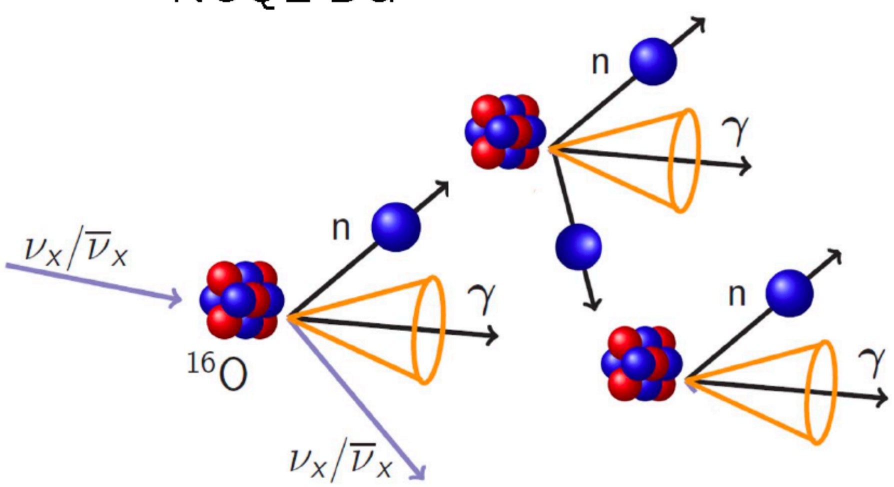
NCQE measurements with T2K

- Another important data:
  Neutron multiplicity

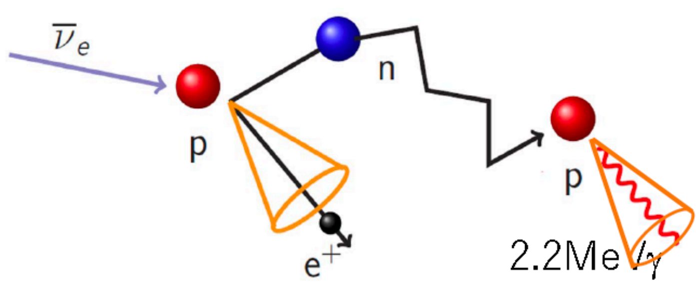
Multiple neutrons produced through hadronic final-state interactions (FSI) in nuclei, and secondary interactions (SI) in the detector medium

➡ Key to reduce NCQE BG

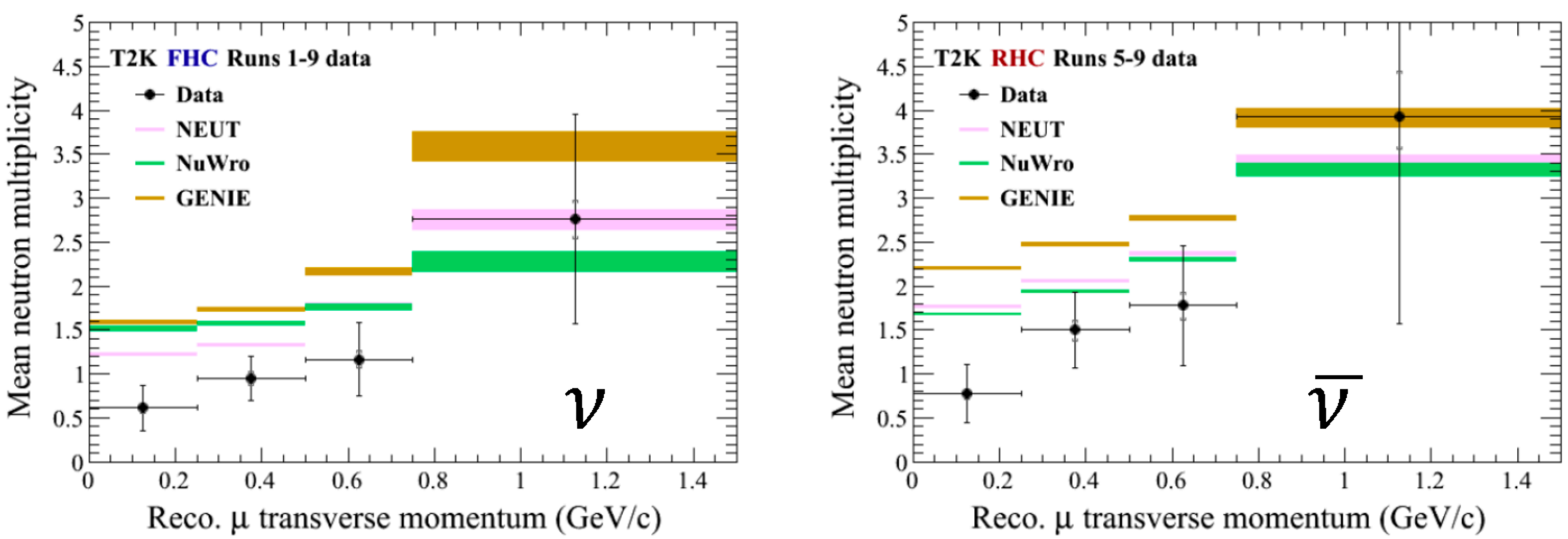
NCQE BG



DSNB



Measured mean neutron multiplicity (CC) and MC predictions

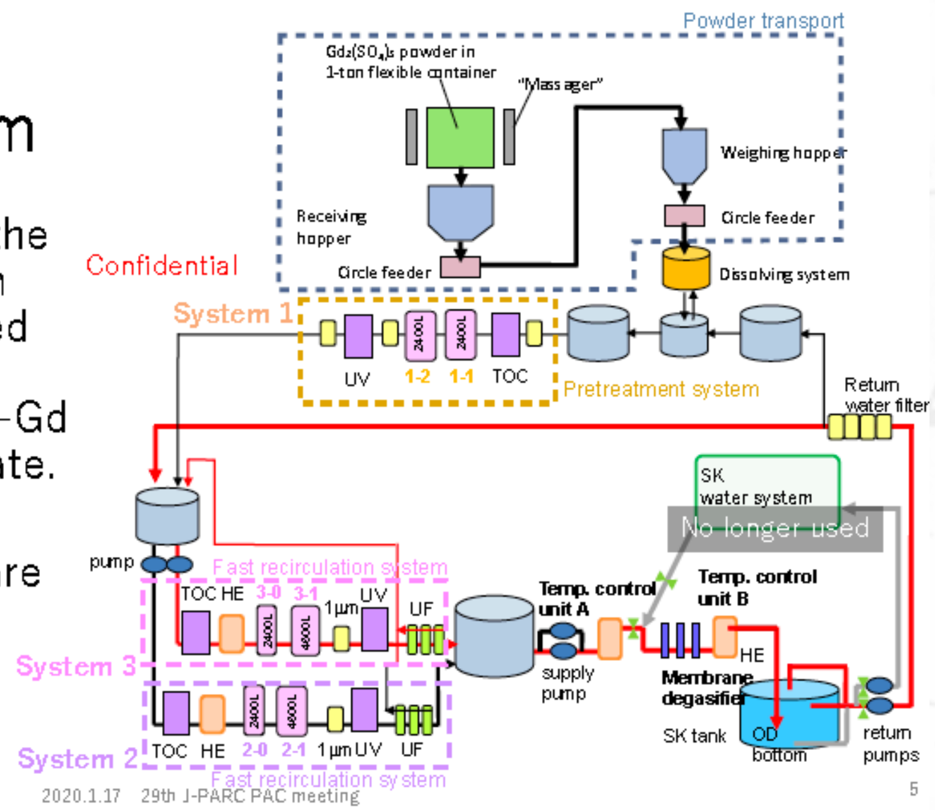


Large discrepancy causes ~44% systematic error for NCQE BG estimation

SK-Gd

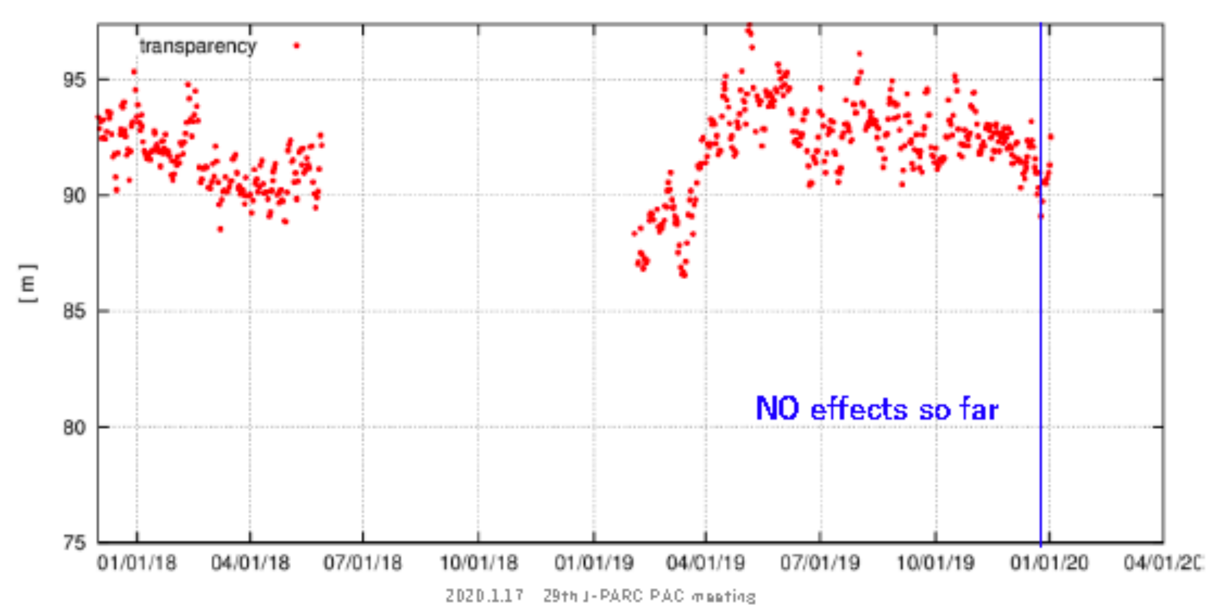
Migration of the water system

- Since Dec. 24, 2019, the SK pure water system has been disconnected from the recirculation loop and the new SK-Gd is in use with 60t/h rate.
- Specially developed resins for $Gd_2(SO_4)_3$ are under final test.
- Full 120t/h power is under preparation

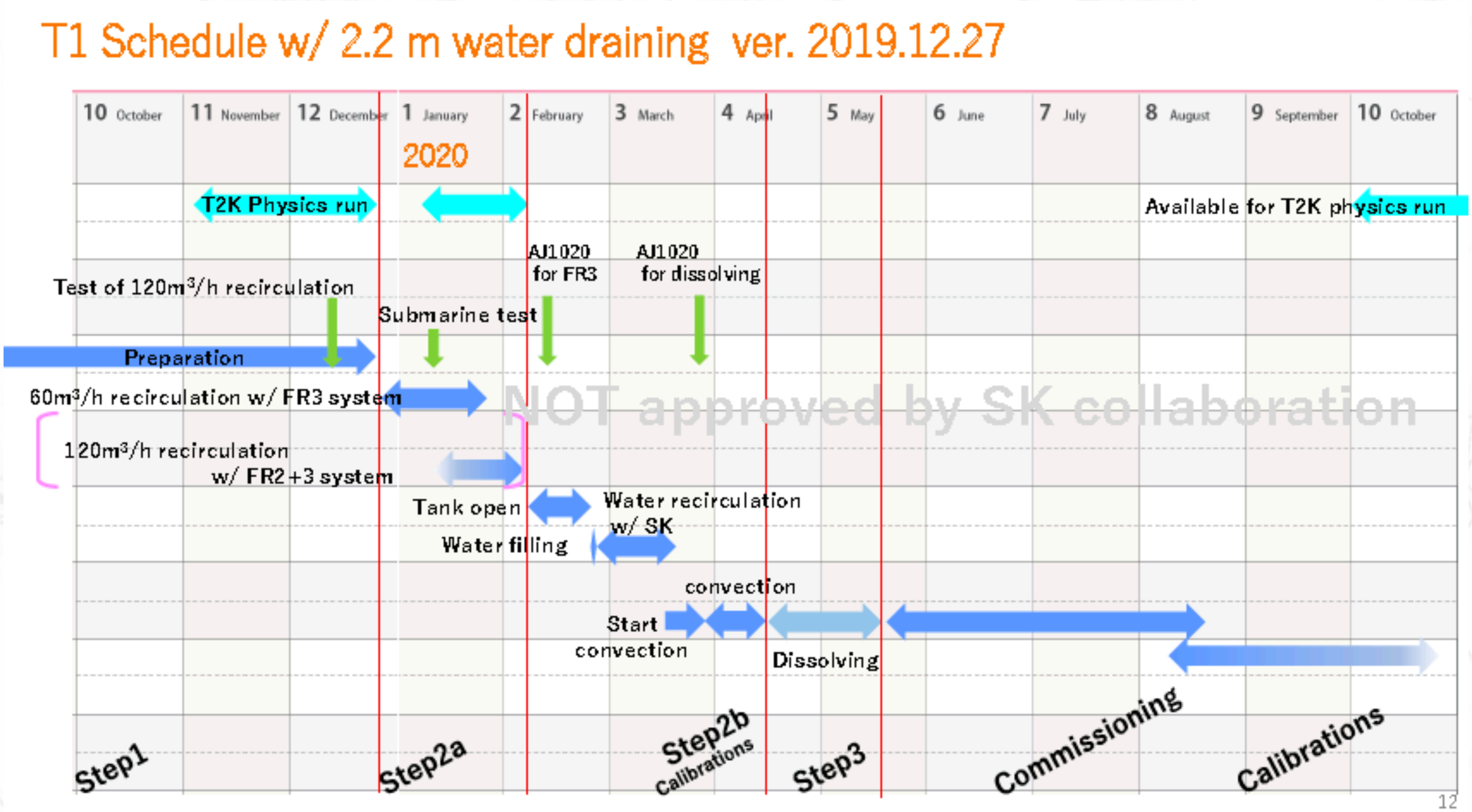


The water transparency

- After 2 weeks of SK-Gd water system operation



SK-Gd



First attempt to dissolve Gd salt stopped because of COVID-19