UNIVERSITÉ
DE GENÈVE
FACULTÉ DES SCIENCES

Recent results on CP violation from T2K

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Université de Genève

Outline

- Neutrino Oscillations in a nutshell
- T2K experiment
- Analysis procedure
- T2K recent results
- Next steps and beyond

Neutrino oscillations

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

Flavour eigenstates

$$(\nu_e, \nu_\mu, \nu_\tau)$$

state of the neutrino interactions

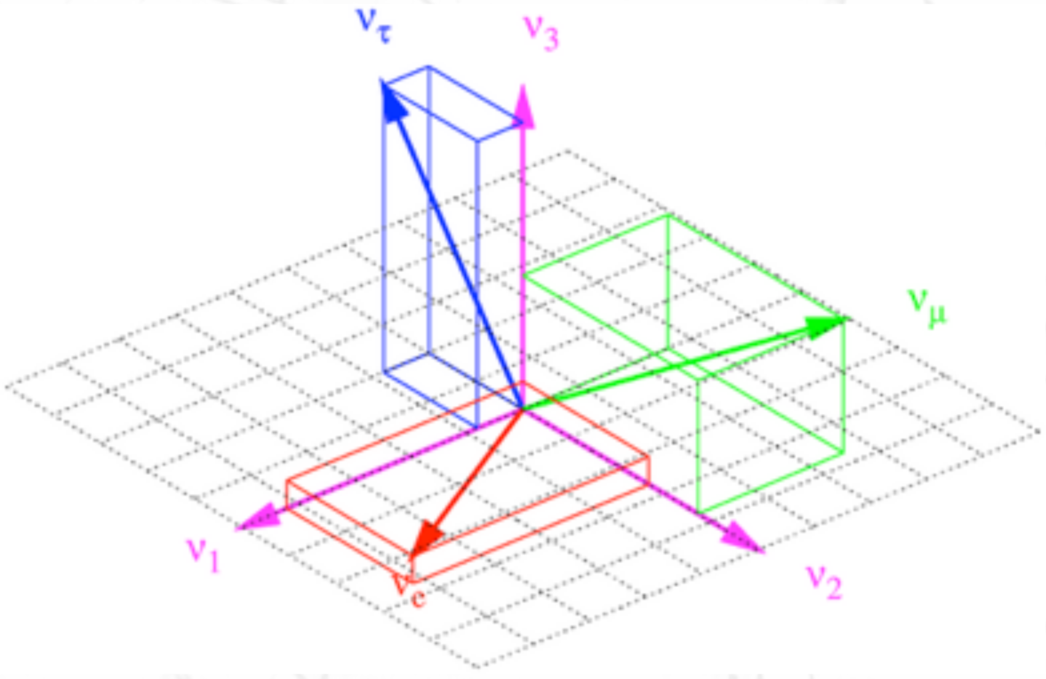
Lorentz eigenstates

$$(\nu_1, \nu_2, \nu_3)$$

states of the neutrino propagation in space

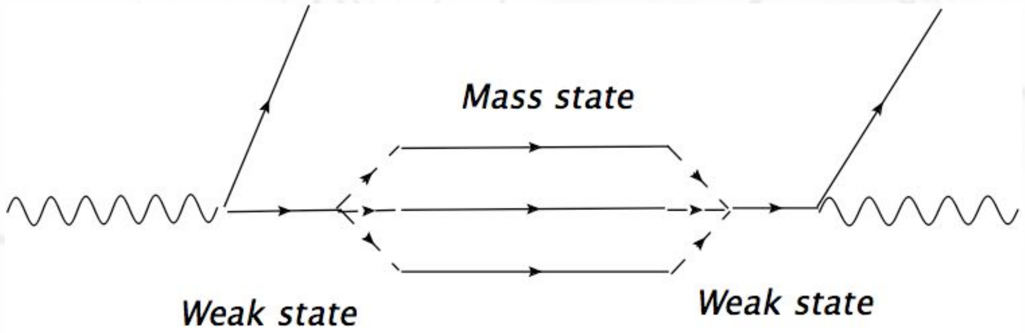
Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

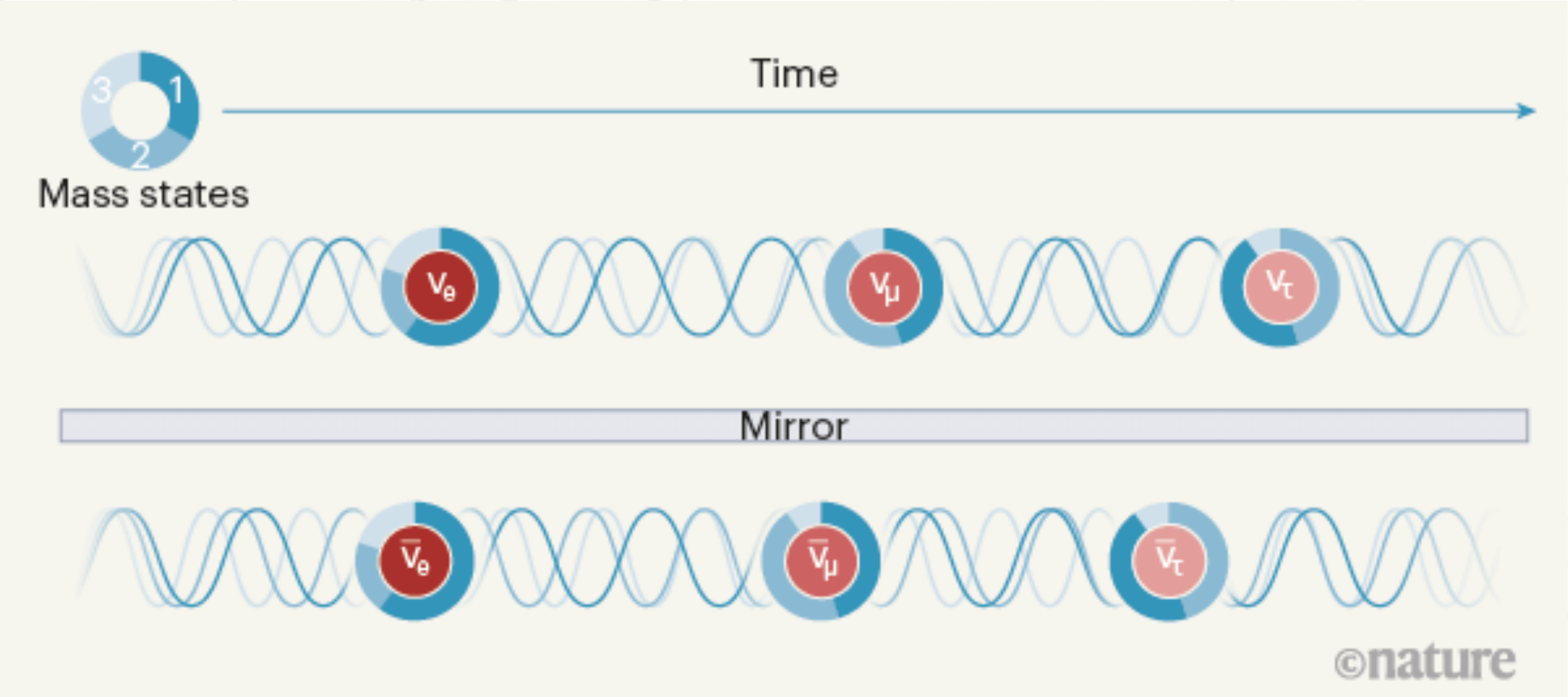
$$\begin{pmatrix}\nu_e & \nu_\mu & \nu_\tau\end{pmatrix} = U_{PNMS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



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)

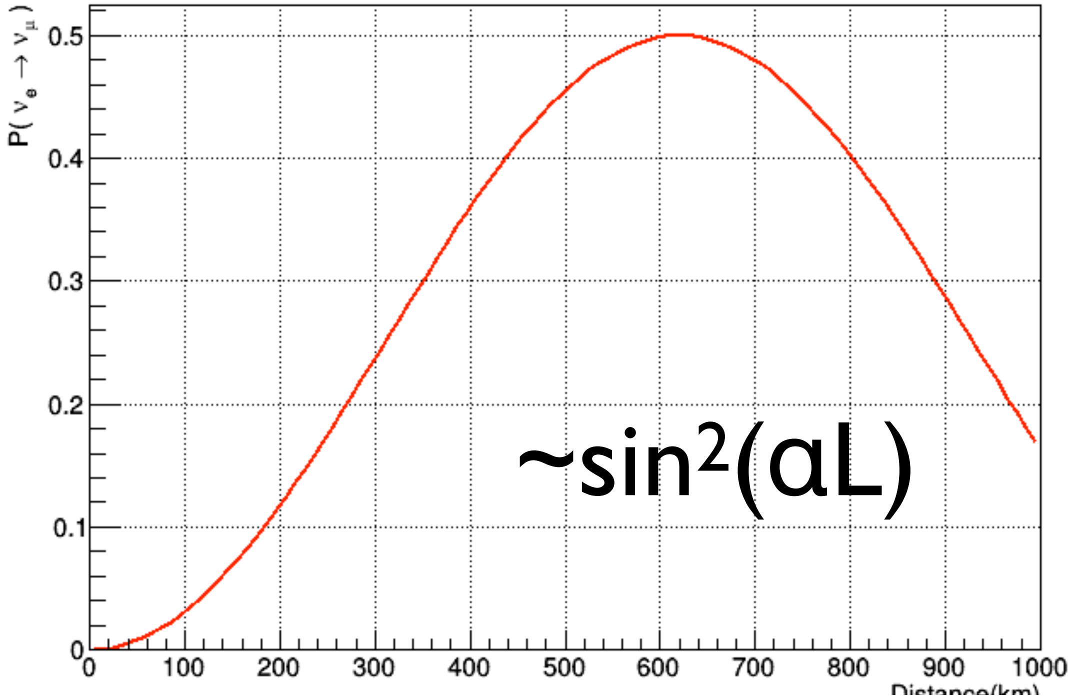




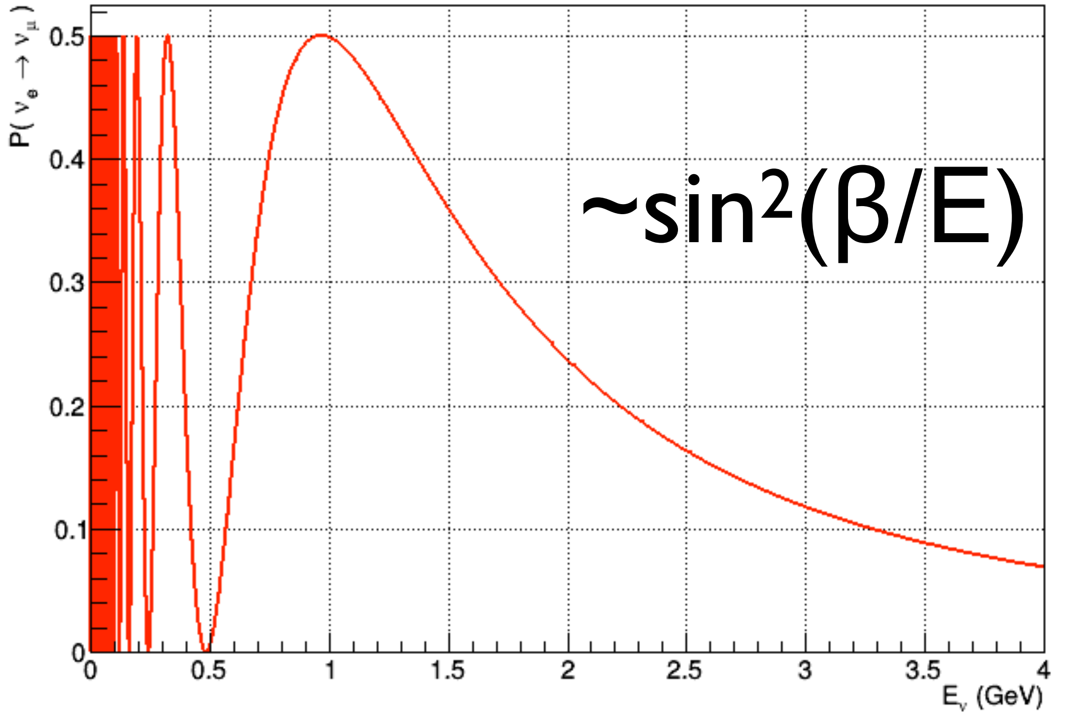
- Neutrinos propagate at different speeds (mass) keeping the coherence, at the interaction point the proportions change and other neutrino flavour might appear.

Oscillations with 2ν

θ = π/2
$\Delta m^2 = 2.\mathrm{x}10^{-3}\ \mathrm{eV}^2$



~sin²(αL)



~sin²(β/E)

Simplified 2ν formula

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

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

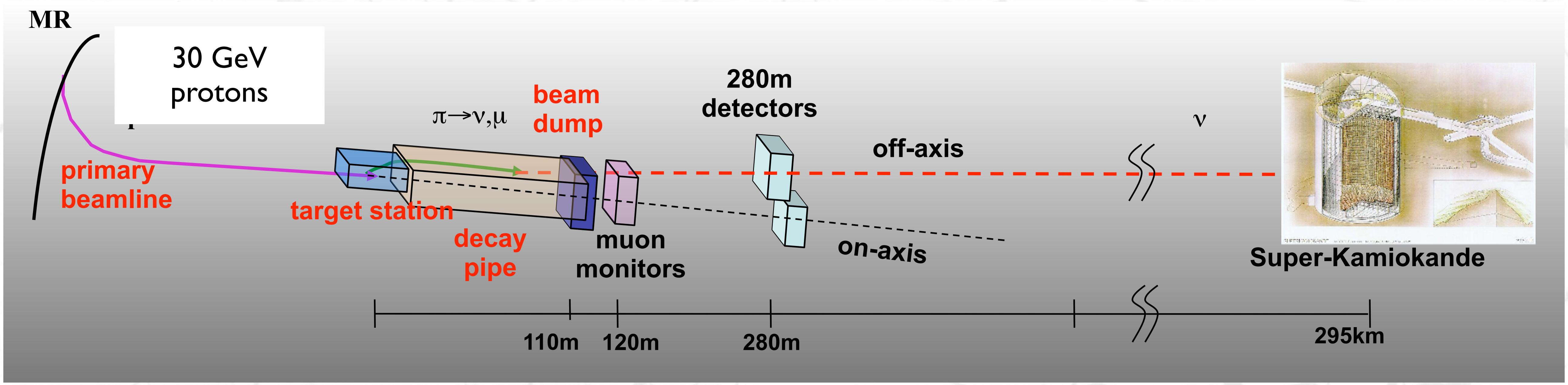
$$P(\nu_\alpha \to \nu_\beta)$$

CP violation

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

CP violation

T2K experiment

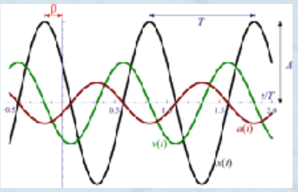


Accelerator neutrinos:

$$pA \to X\pi^+ \to X\mu^+\nu_\mu$$
$$pA \to X\pi^- \to X\mu^-\bar{\nu}_\mu$$

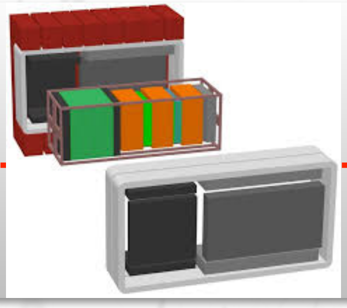
Neutrino flux properties

ν oscillations



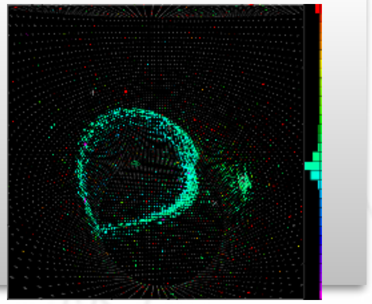
Neutrino flux & flavour

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

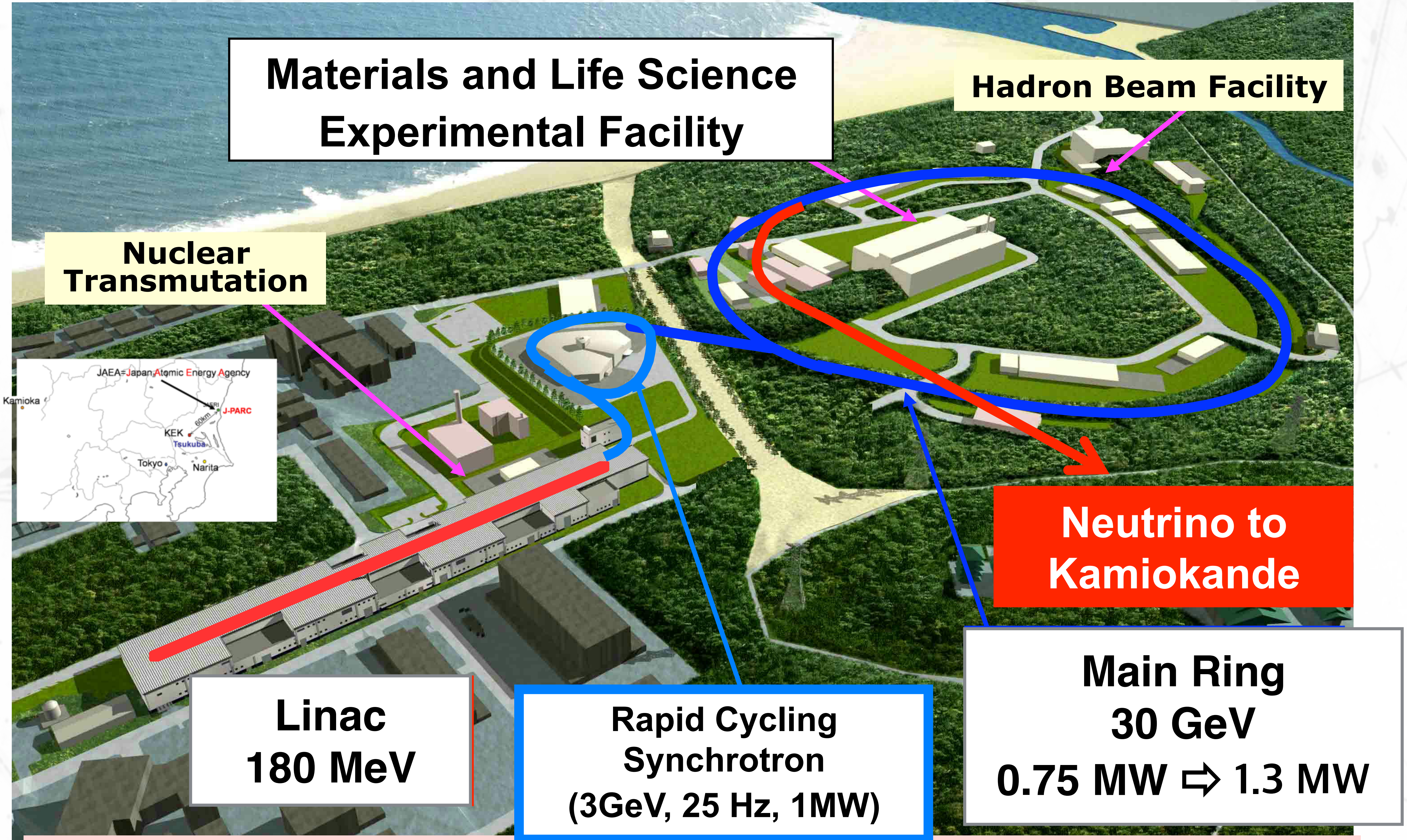


$\nu_e \bar{\nu}_e$

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



JPARC



Materials and Life Science Experimental Facility

Hadron Beam Facility

Nuclear Transmutation

Neutrino to Kamiokande

Linac
180 MeV

Rapid Cycling Synchrotron
(3GeV, 25 Hz, 1MW)

Main Ring
30 GeV
0.75 MW ⇨ 1.3 MW

J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA

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)

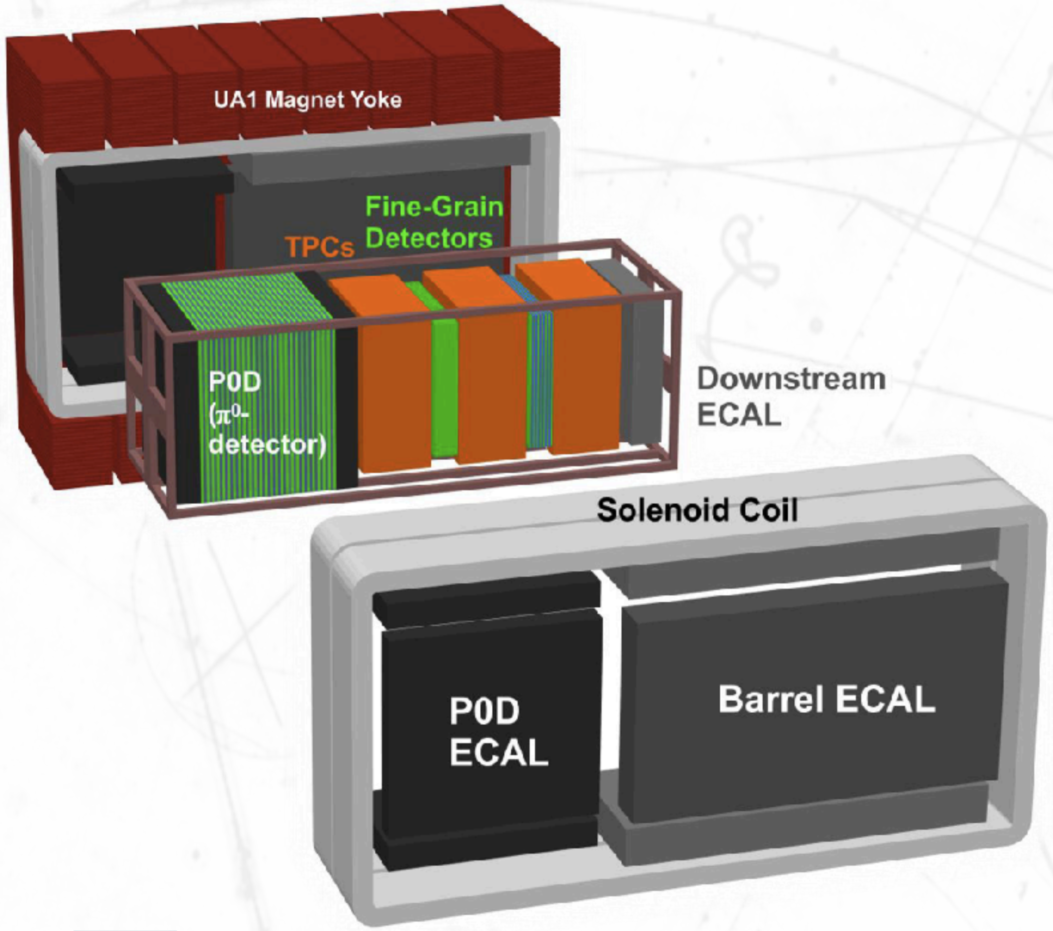
Magnet

Excellent neutrino-antineutrino selection

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

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



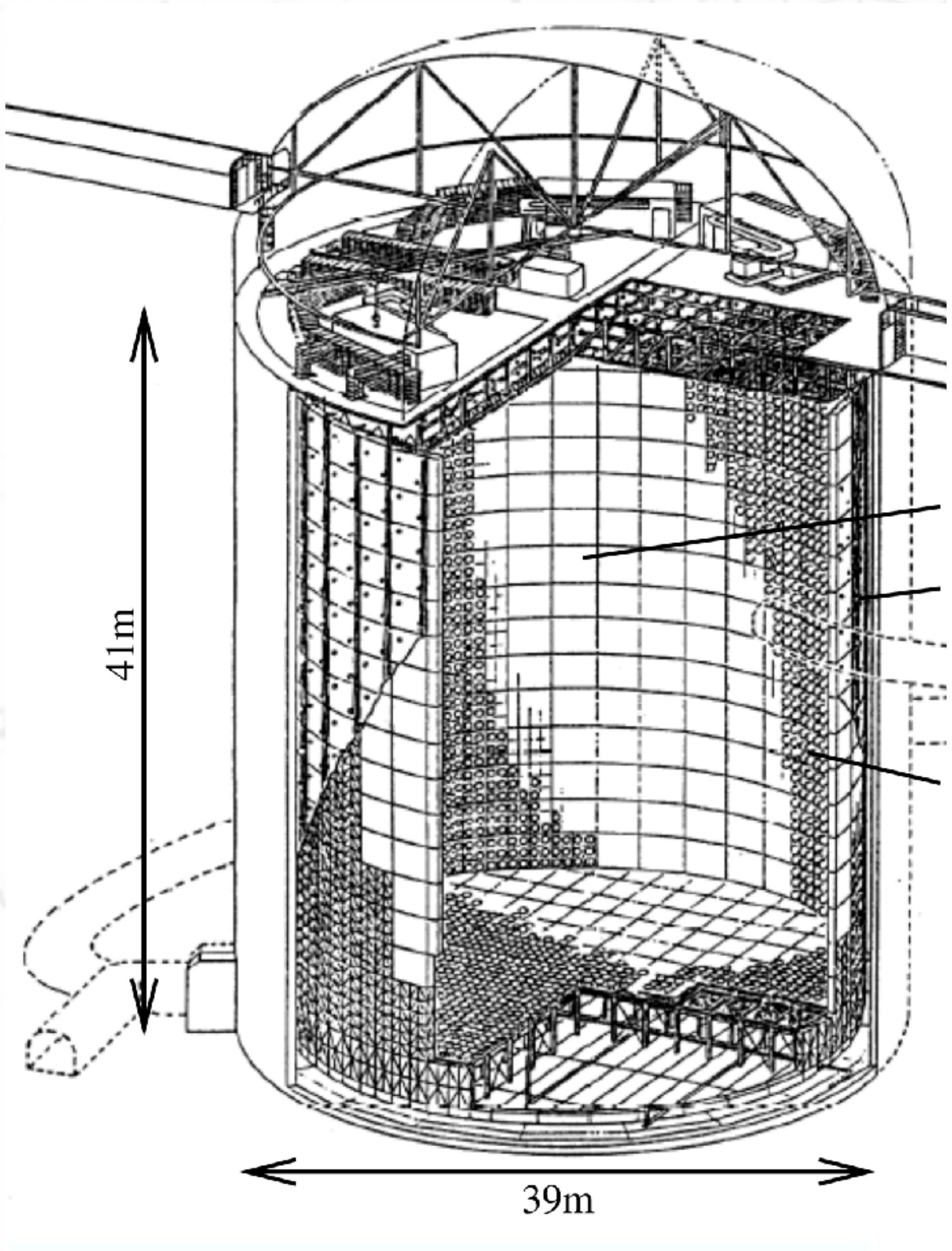
2 FGDs (Fine Grained Detector):
active target mass for the tracker, optimized for p/π separation
Carbon+Water target in FGD2

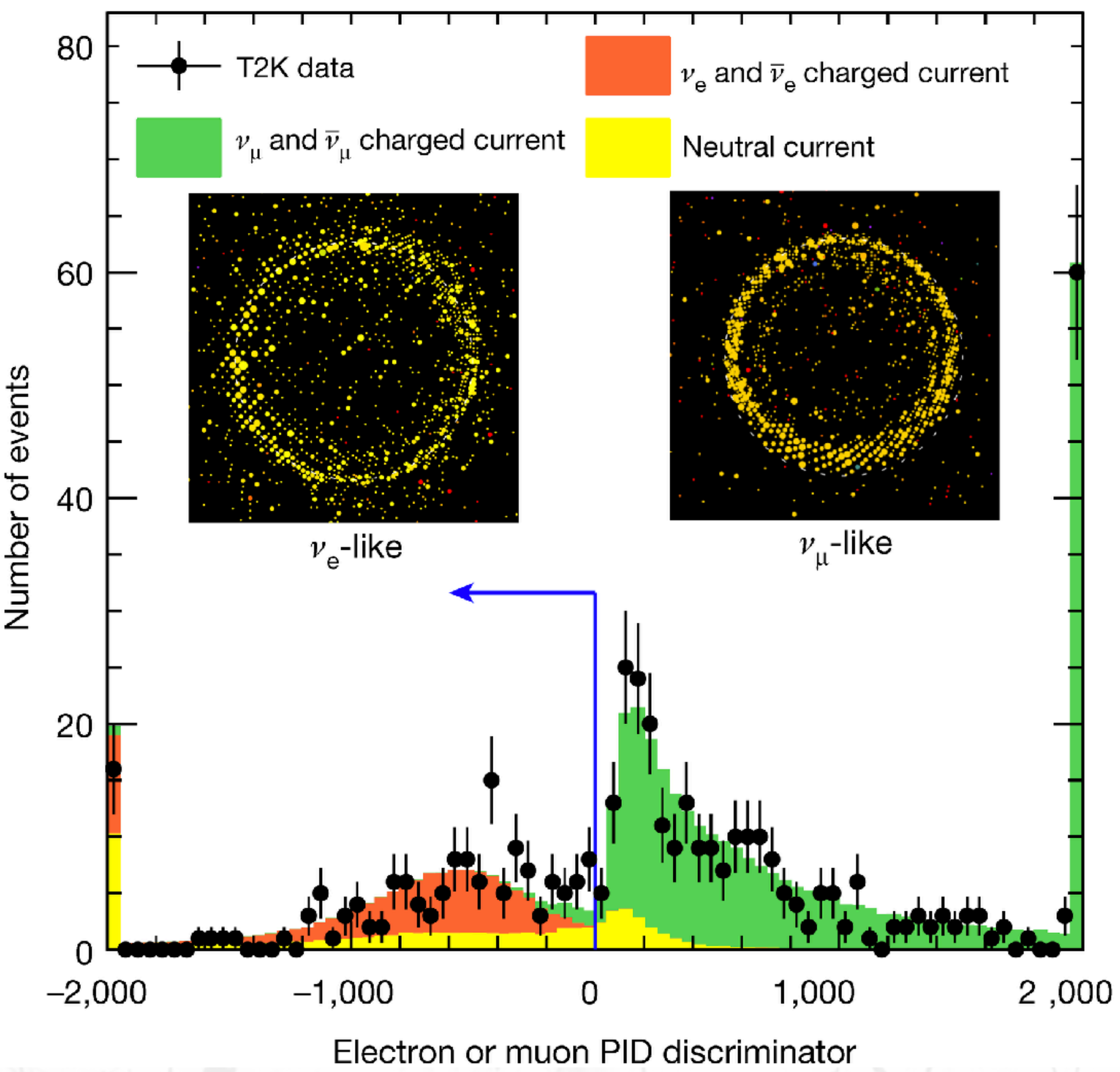
3 TPCs (Time Projection Chambers):
measure momentum and charge of particles from FGD and P0D, PID capabilities through dE/dx

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

Magnet was granted by CERN

Far detector: capabilities





Particle identification

Interaction vertex reconstruction

Track Multiplicity

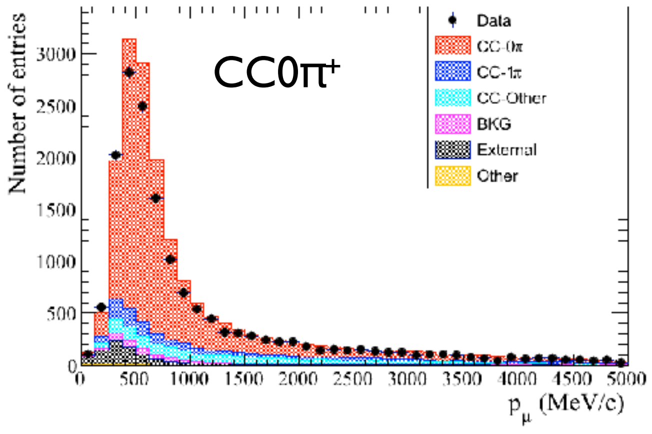
Particle range

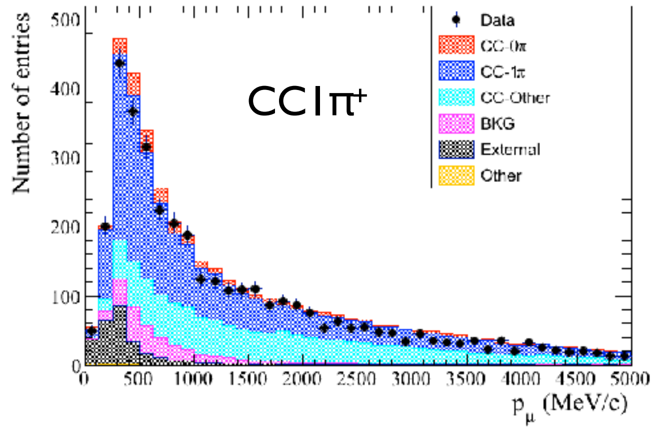
Electromagnetic energy reconstruction

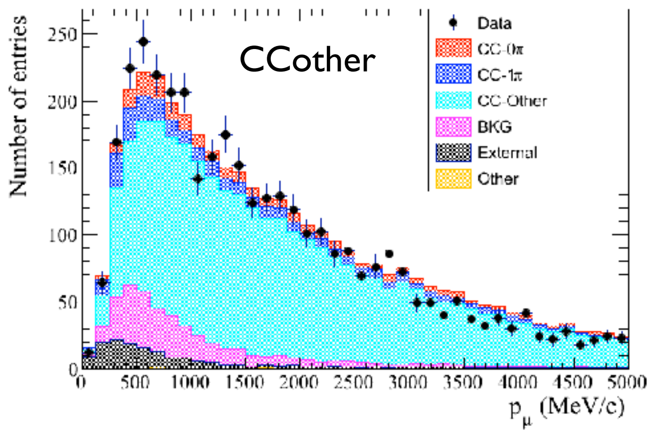
Hadronic interactions

Analysis conceptually

Near detector data

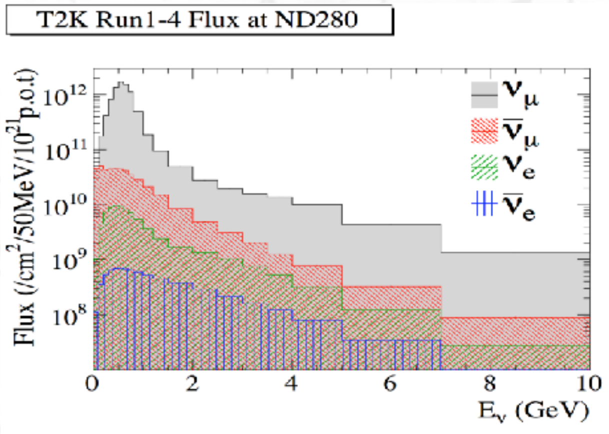






feed back

Hadron production flux prediction Shive + beam monitors



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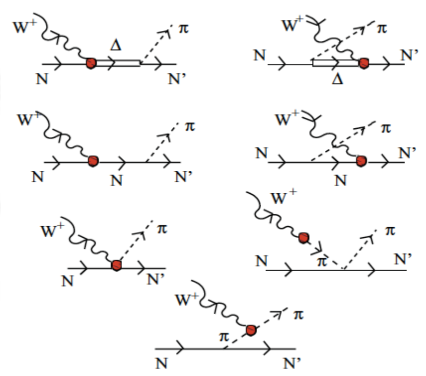
Cross-section model



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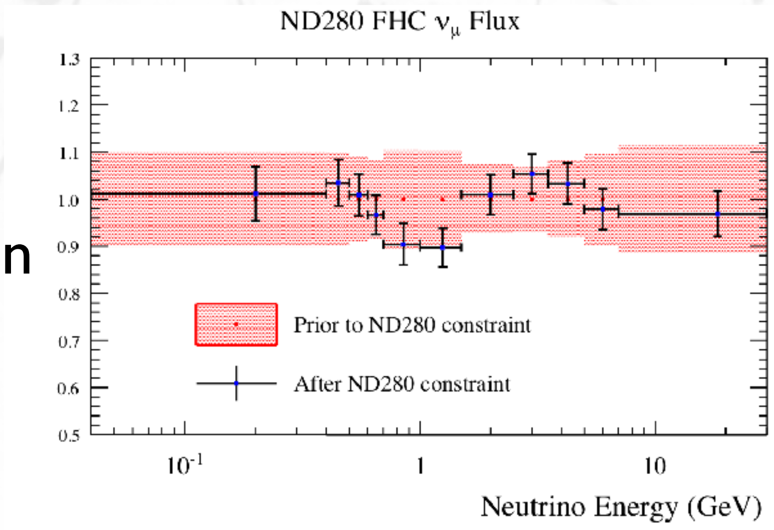
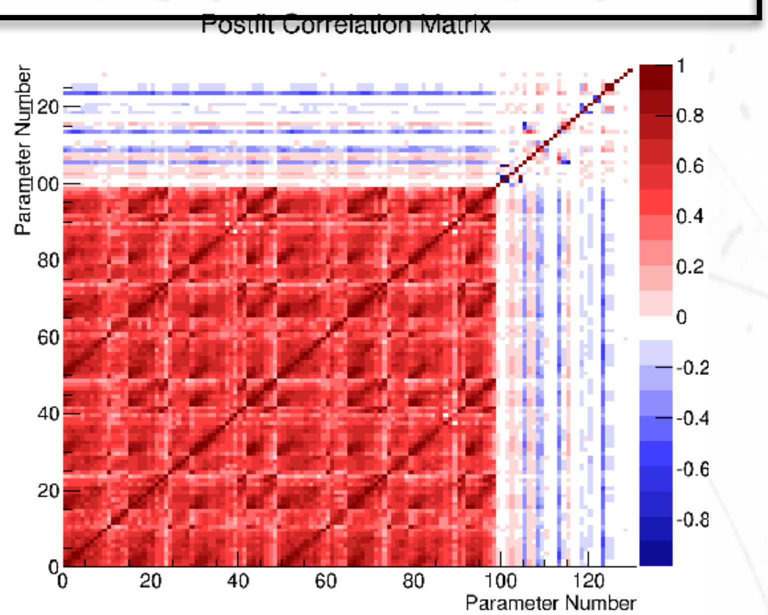
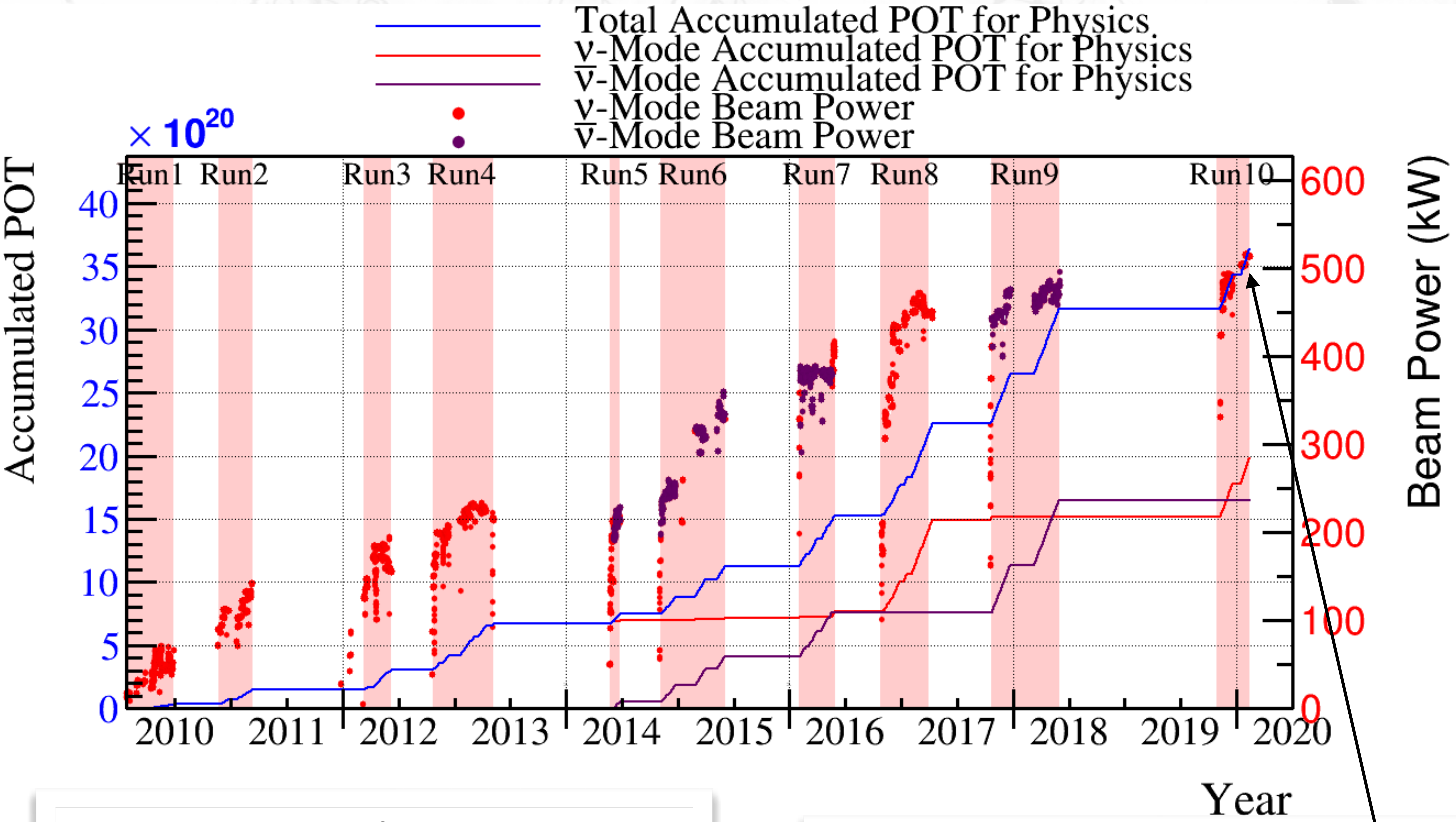
Corrected flux and cross-section model



& error covariance matrix



Data Set

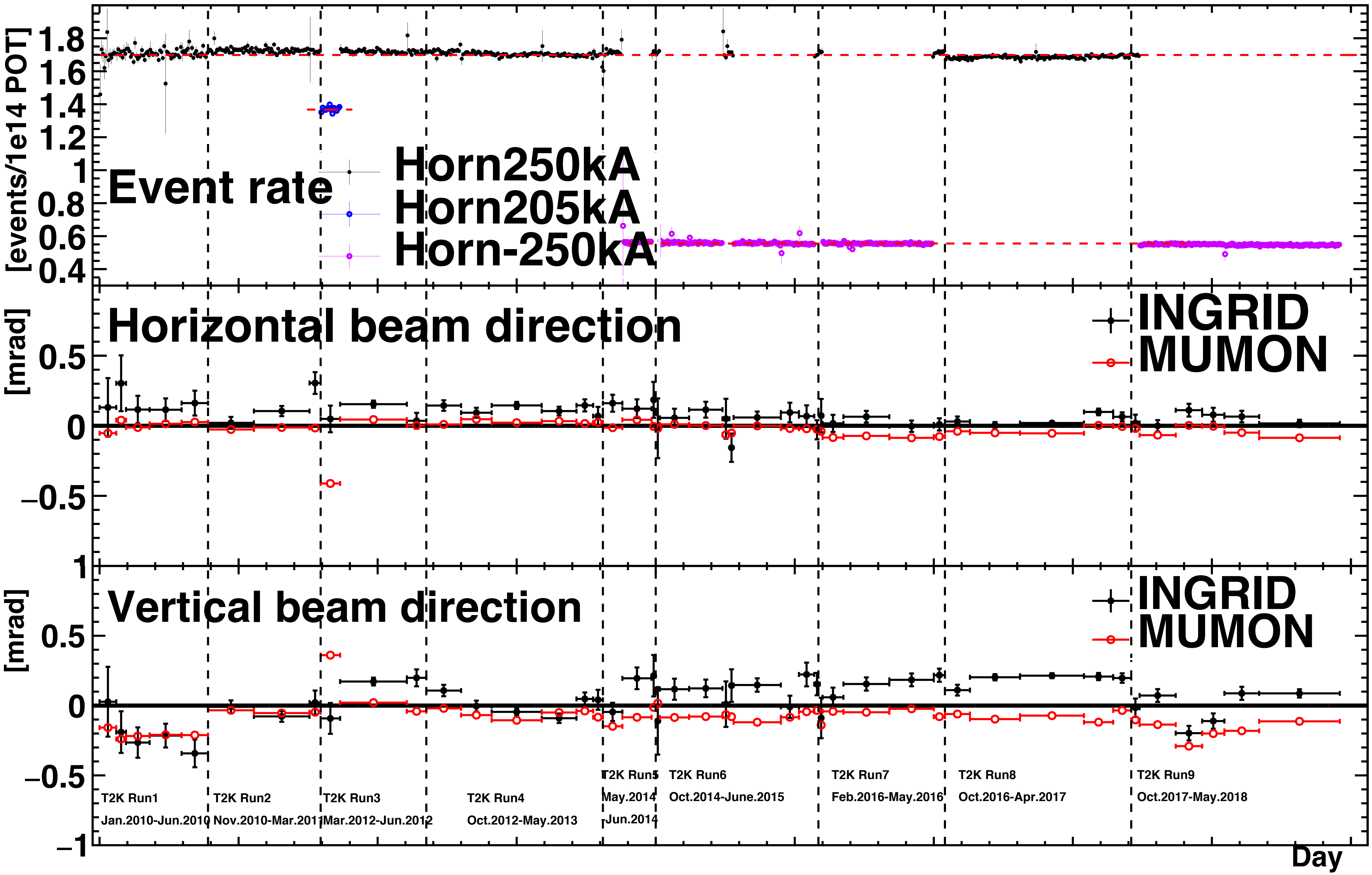


1.97 x 10^{21} POT in ν mode

1.63 x 10^{21} POT in anti-ν mode.

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

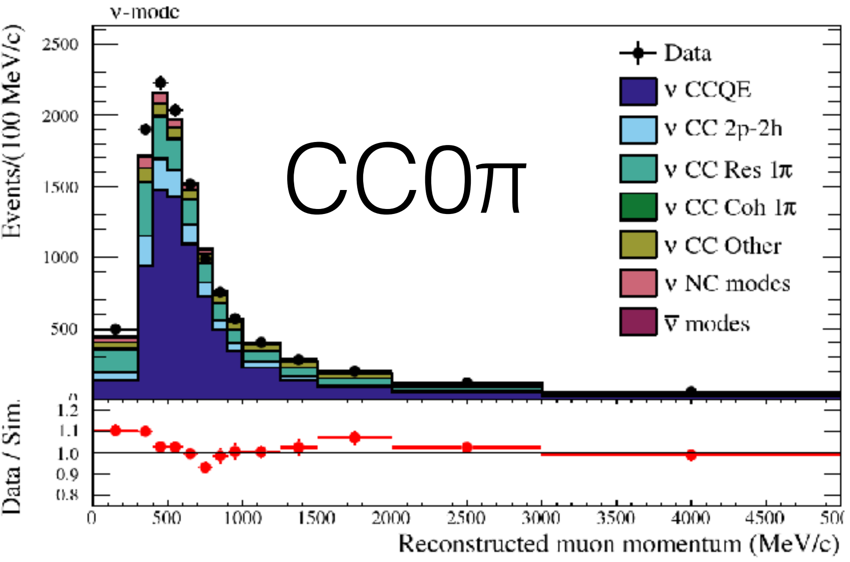
Beam stability

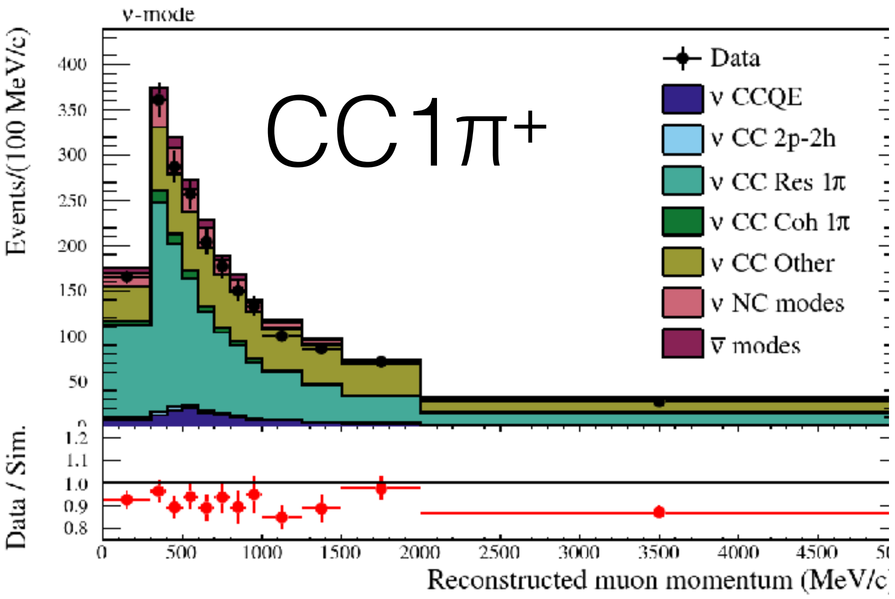


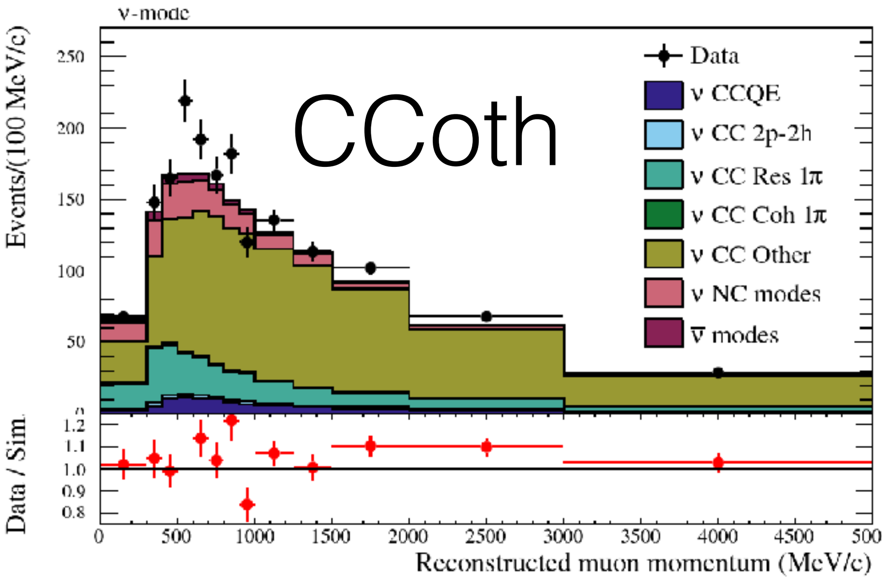
ND input samples

We use 18 different sample in (p_μ, cos θ_μ)

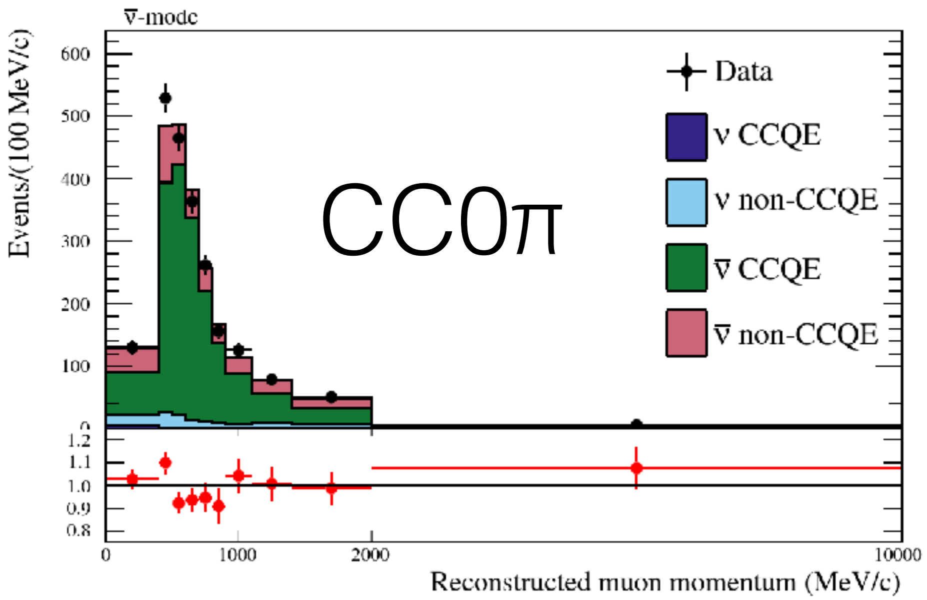
Forward Horn Current



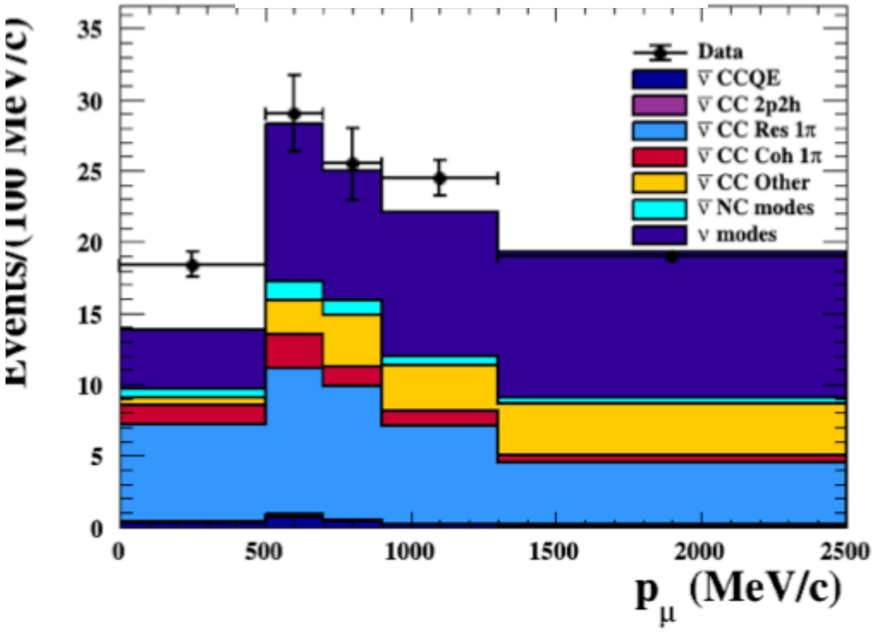




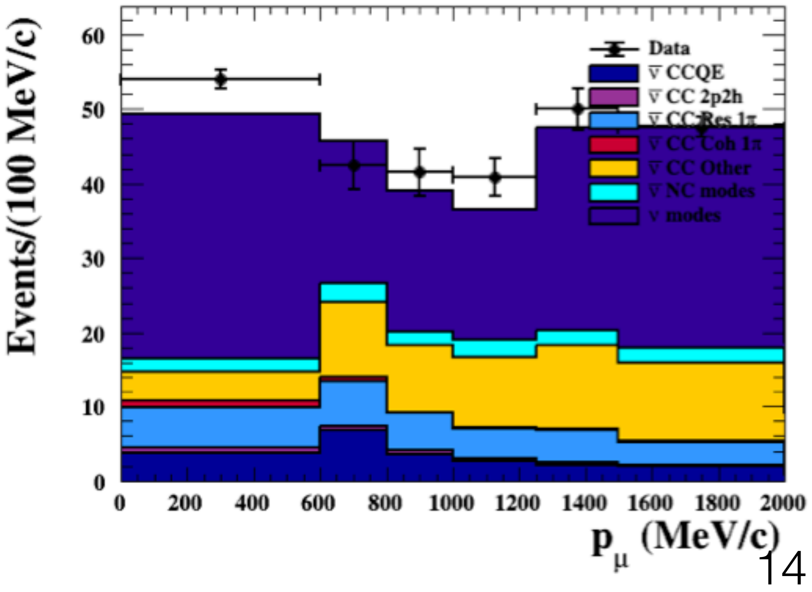
Reversed Horn Current



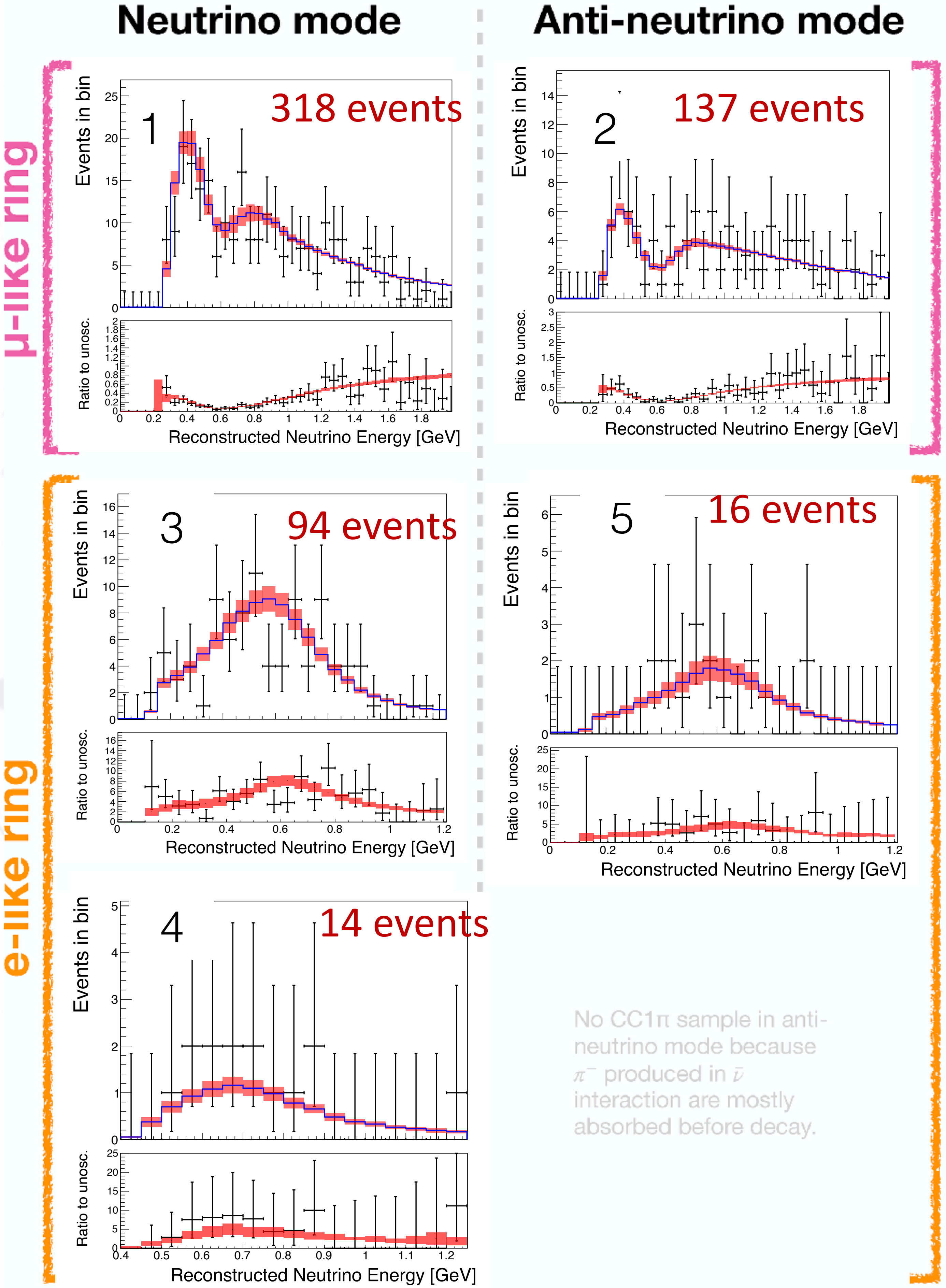
CC1π+



CCOth



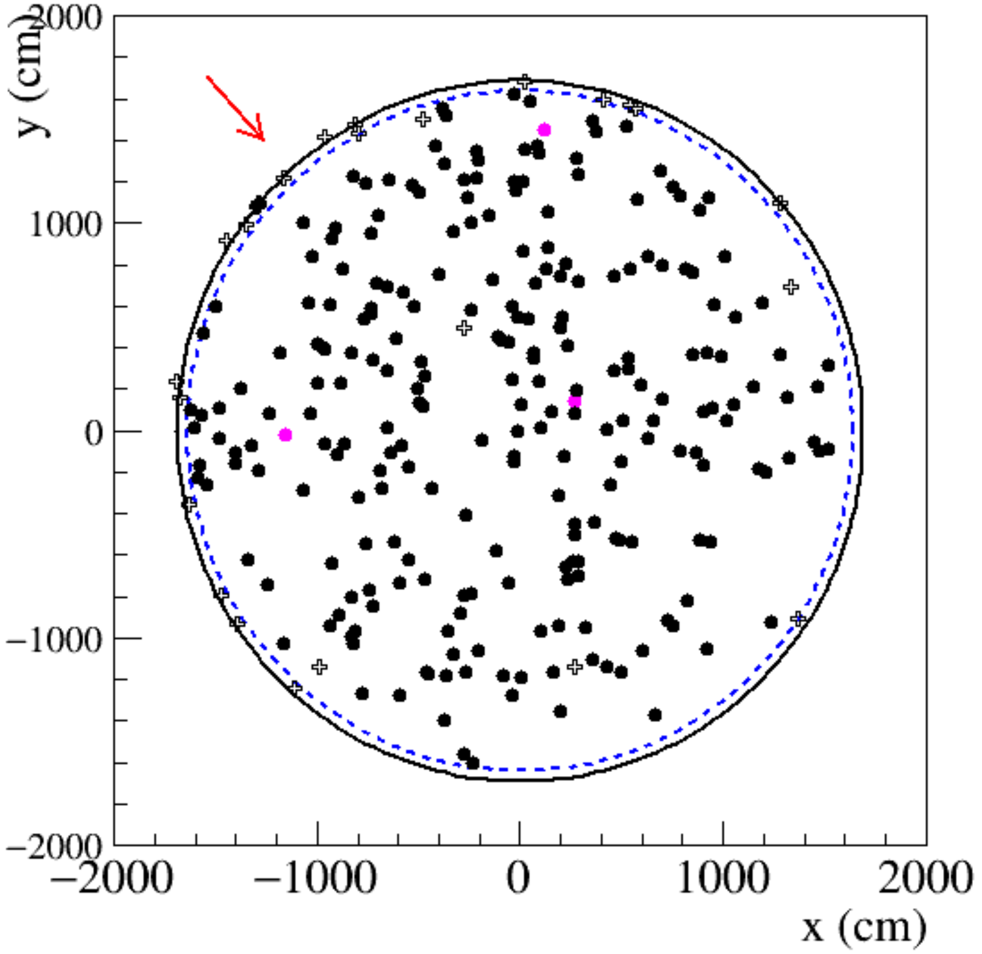
SK data



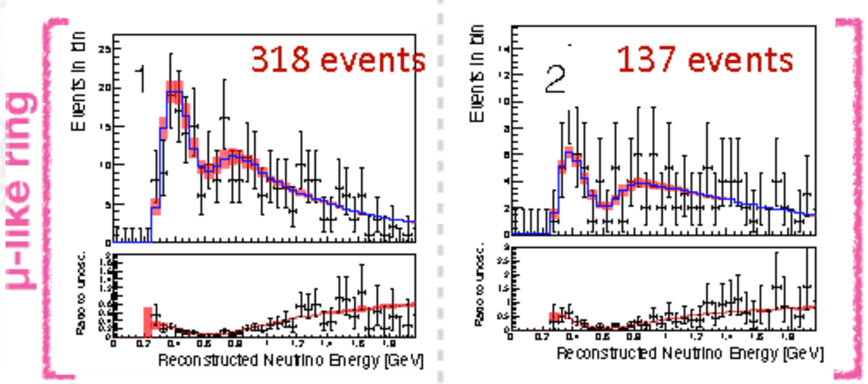
No CC1π sample in anti-neutrino mode because π^- produced in $\bar{\nu}$ interaction are mostly absorbed before decay.

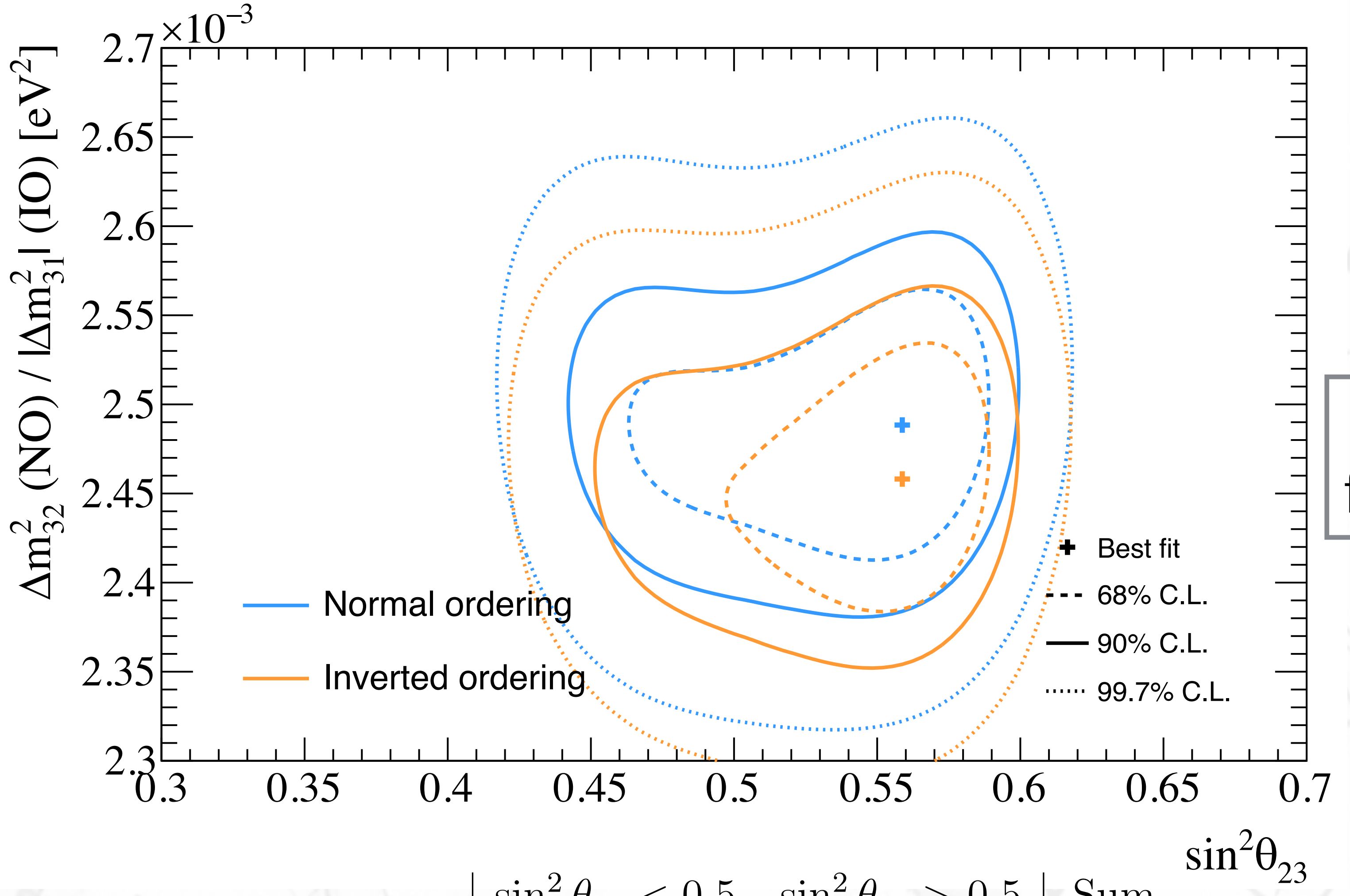
5 SK samples

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





Slight preference for non-maximal θ23

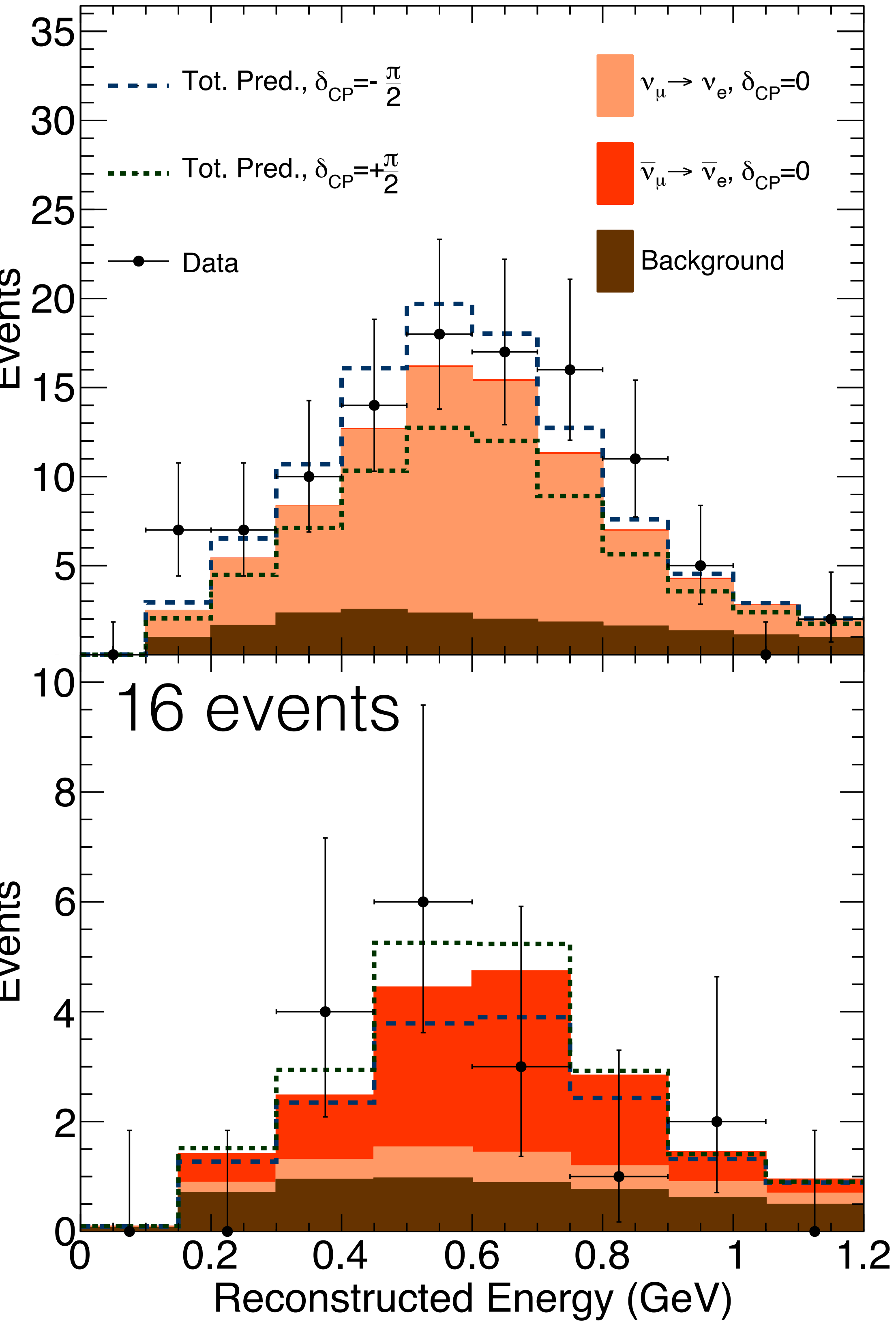
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IH ($\Delta m^2_{32} < 0$)	0.034	0.158	0.192
Sum	0.229	0.771	1.000

Normal hierarchy

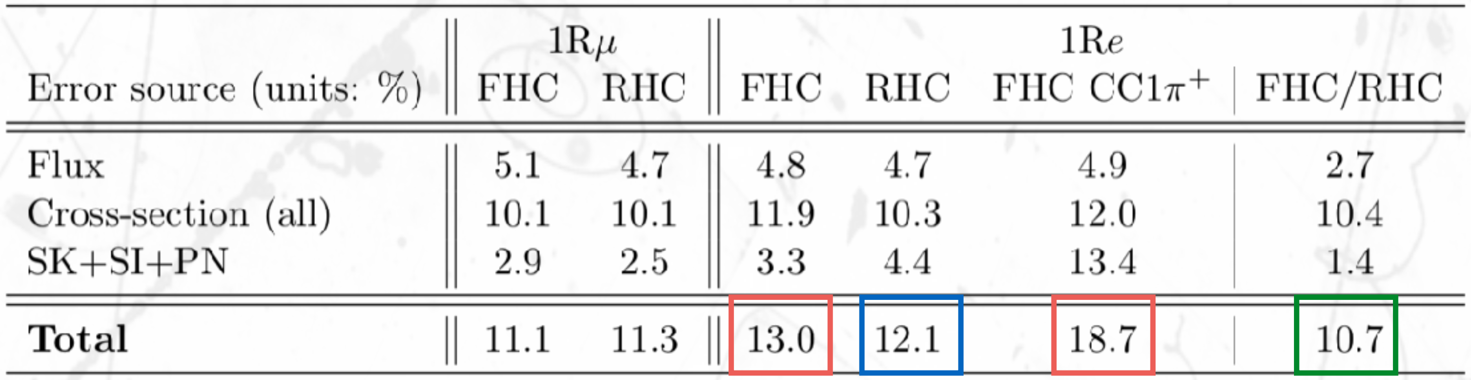
Second octant

ν_e samples

108 events

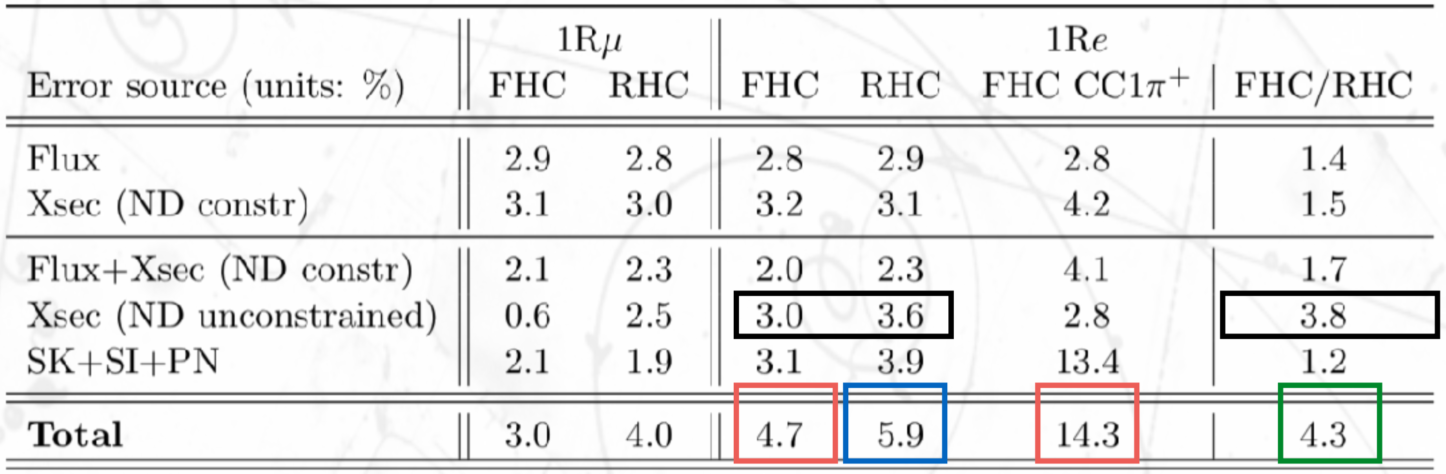


Before ND280 fit



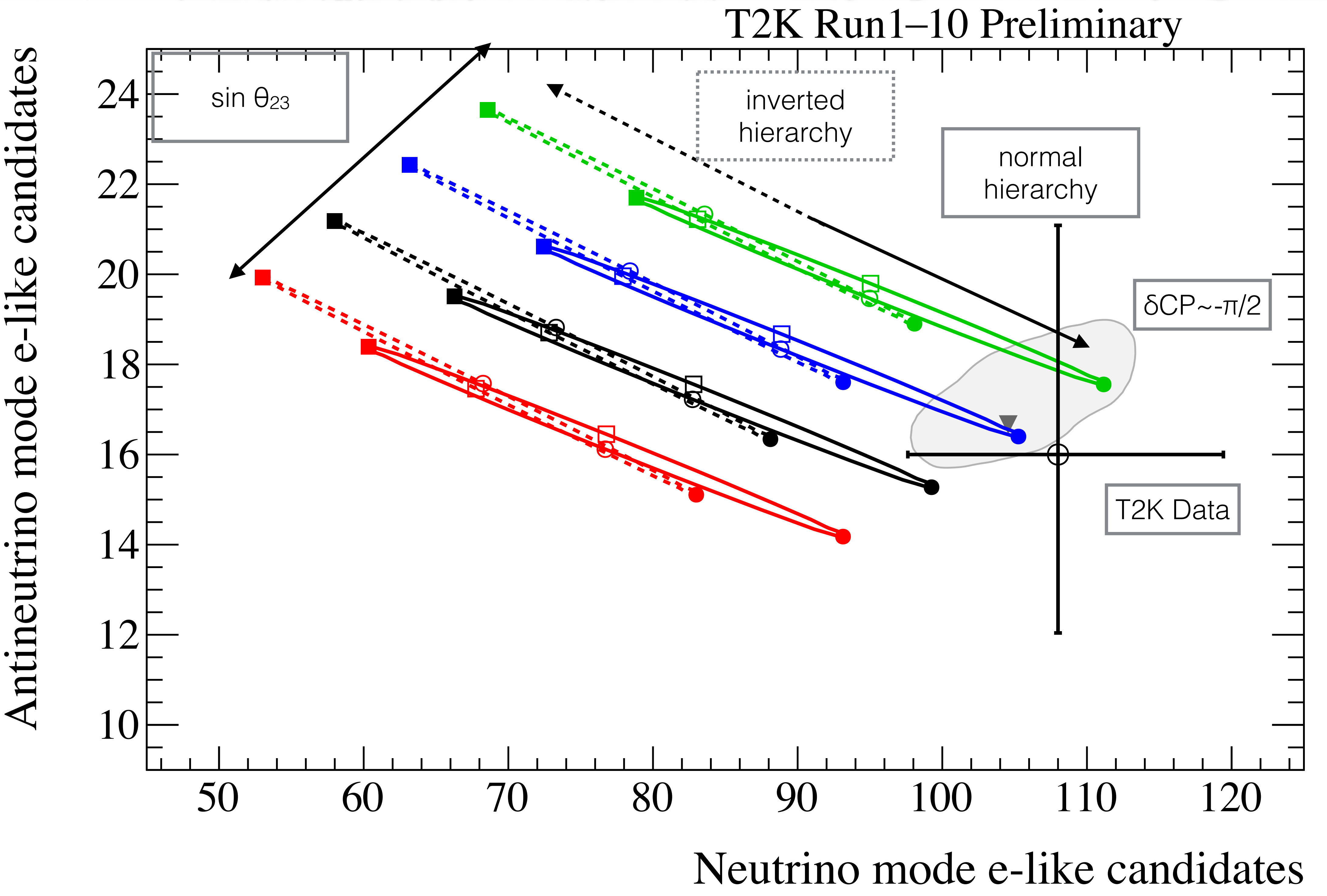
Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
Flux	5.1	4.7	4.8	4.7	4.9	2.7
Cross-section (all)	10.1	10.1	11.9	10.3	12.0	10.4
SK+SI+PN	2.9	2.5	3.3	4.4	13.4	1.4
Total	11.1	11.3	13.0	12.1	18.7	10.7

After ND280 fit



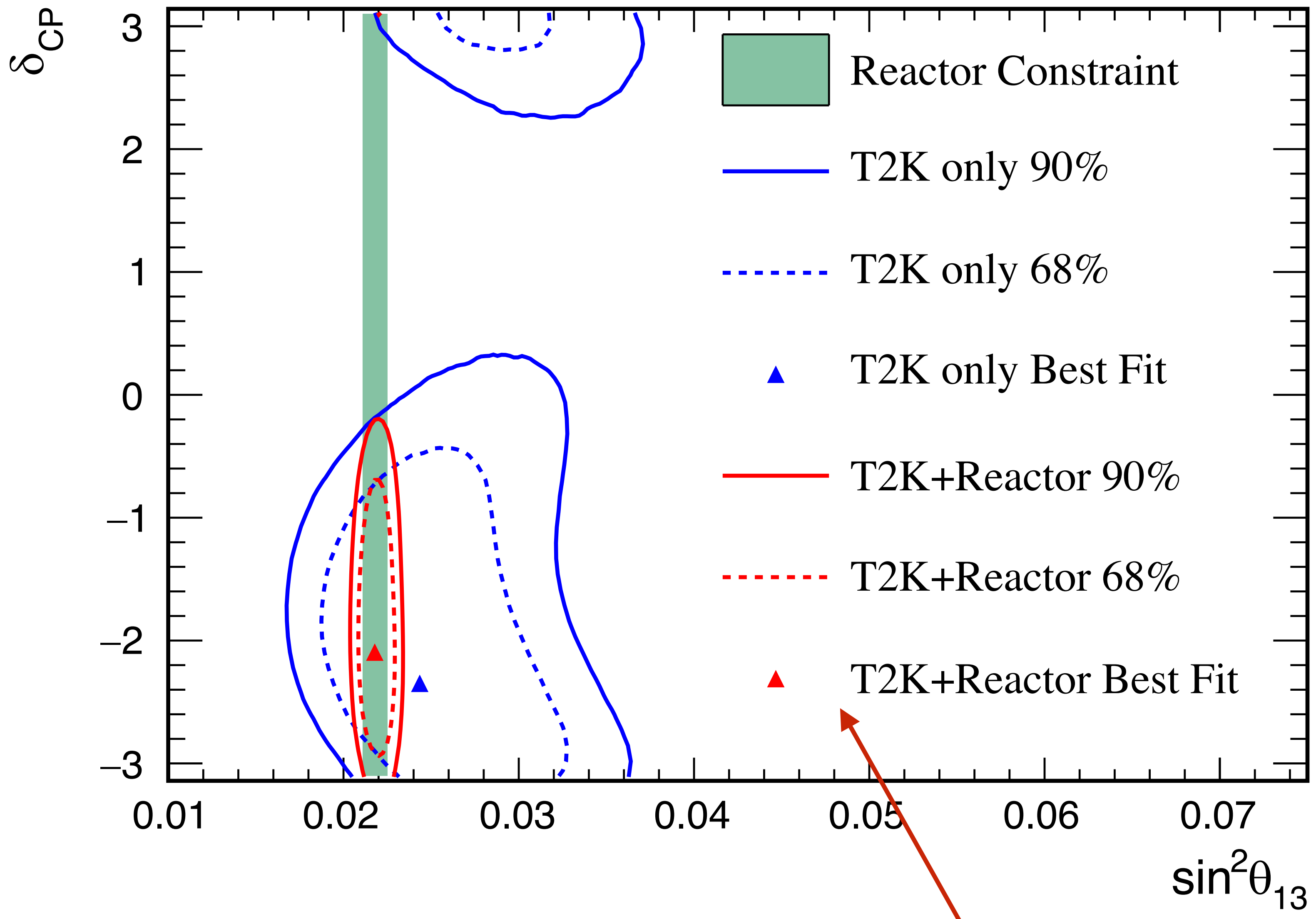
Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

CP violation phase



ν energy dependency is not reflected in this plot

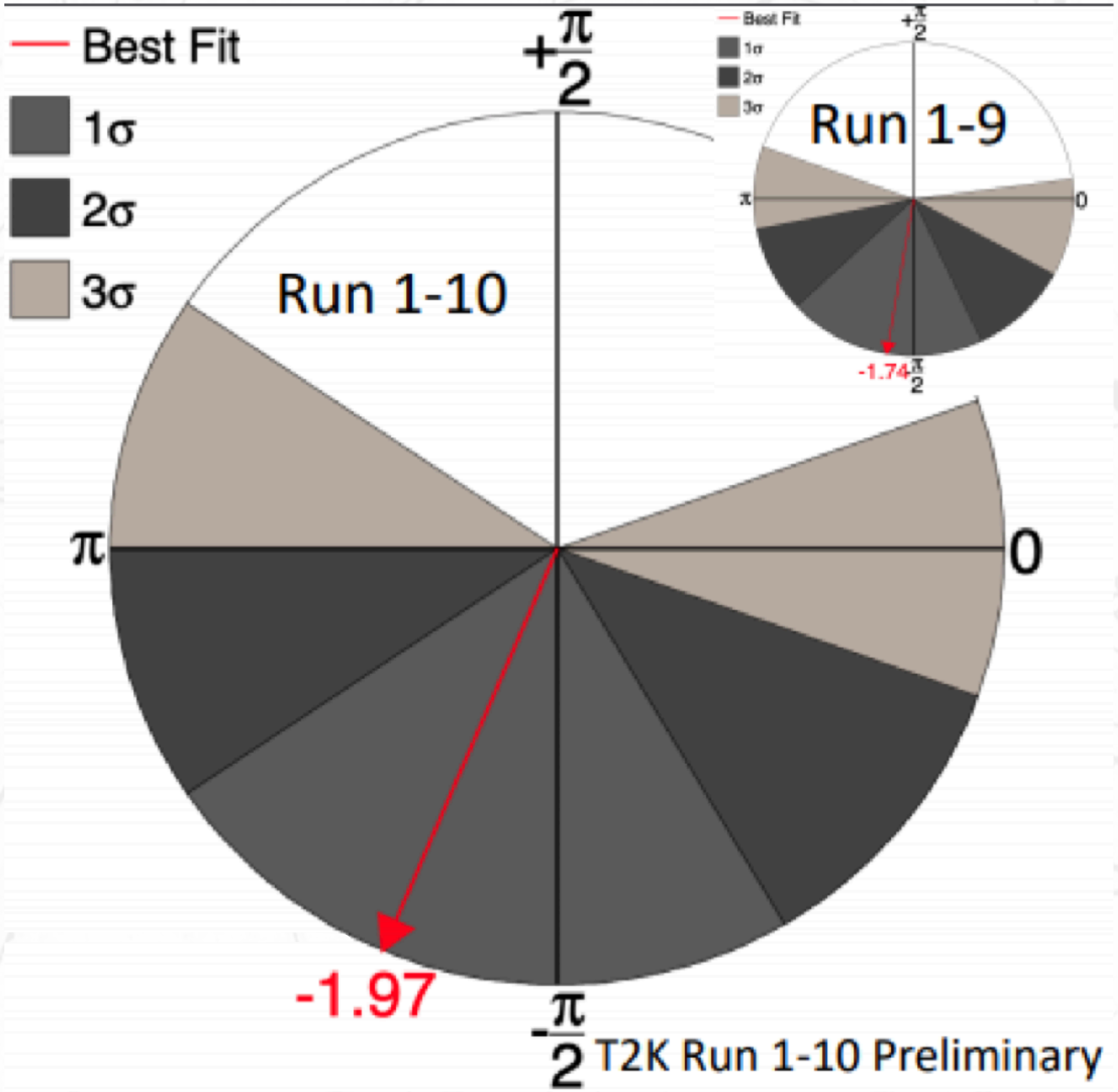
δ_{CP} measurement



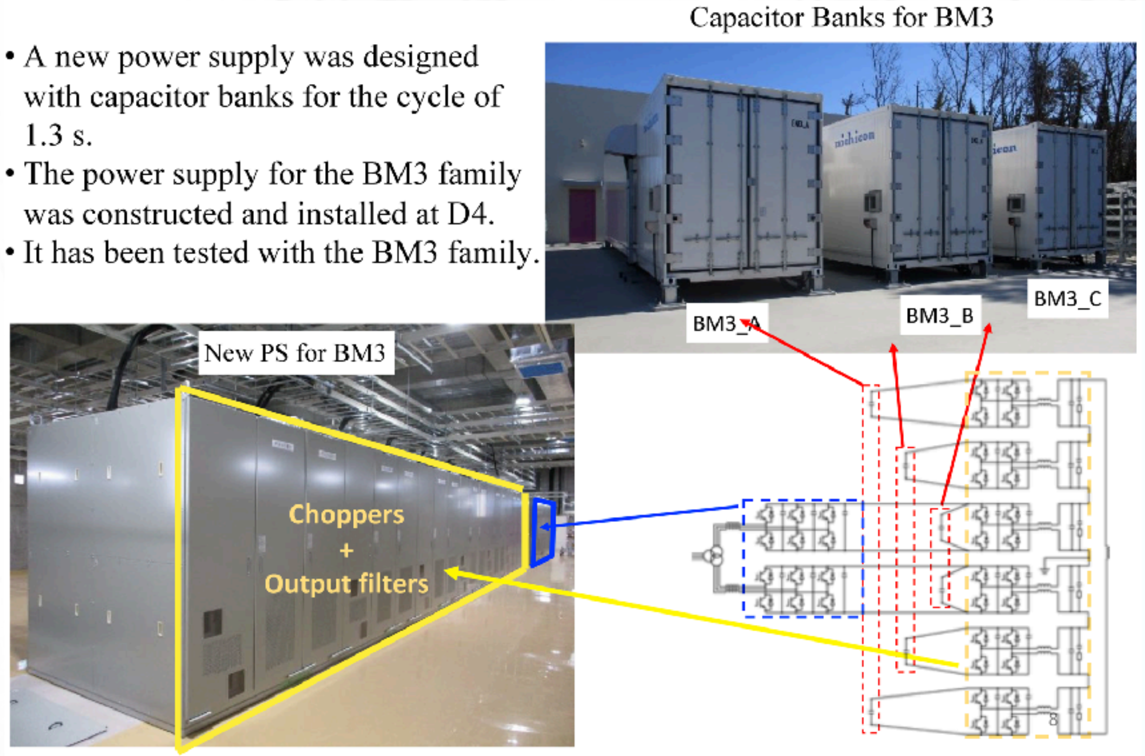
Fit uses the value of θ_{13} from reactor experiments

CP violation phase

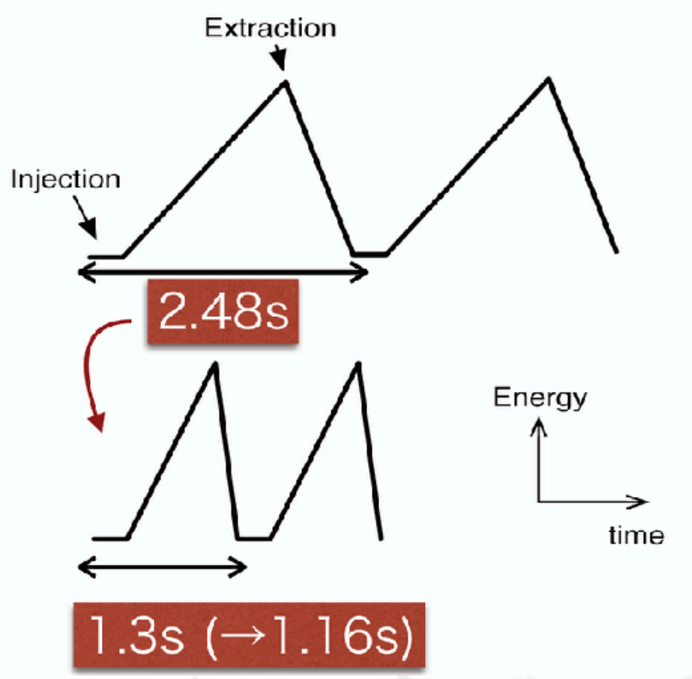
T2K result excludes most of the $\delta_{CP}>0$ values @ 99.7% CL



More stat: Beam upgrade



- A new power supply was designed with capacitor banks for the cycle of 1.3 s.
- The power supply for the BM3 family was constructed and installed at D4.
- It has been tested with the BM3 family.



f_{rep}=0.4 Hz ⊕ PPP = 2.7×10^{14} ⊕ 30 GeV = 515 kW

515 kW stable operation in 2019

MR Power Supply approved

JFY 2020

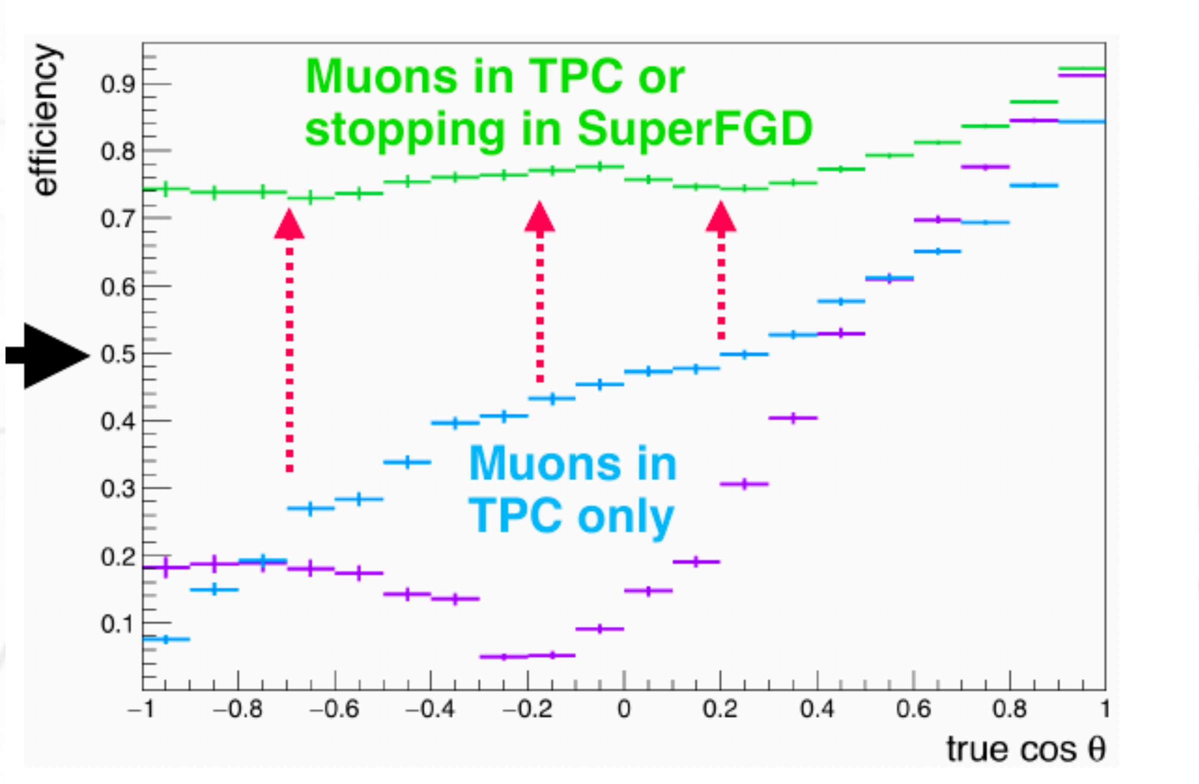
f_{rep}=0.77 Hz ⊕ PPP = 2.2×10^{14} ⊕ 30 GeV = 810 kW

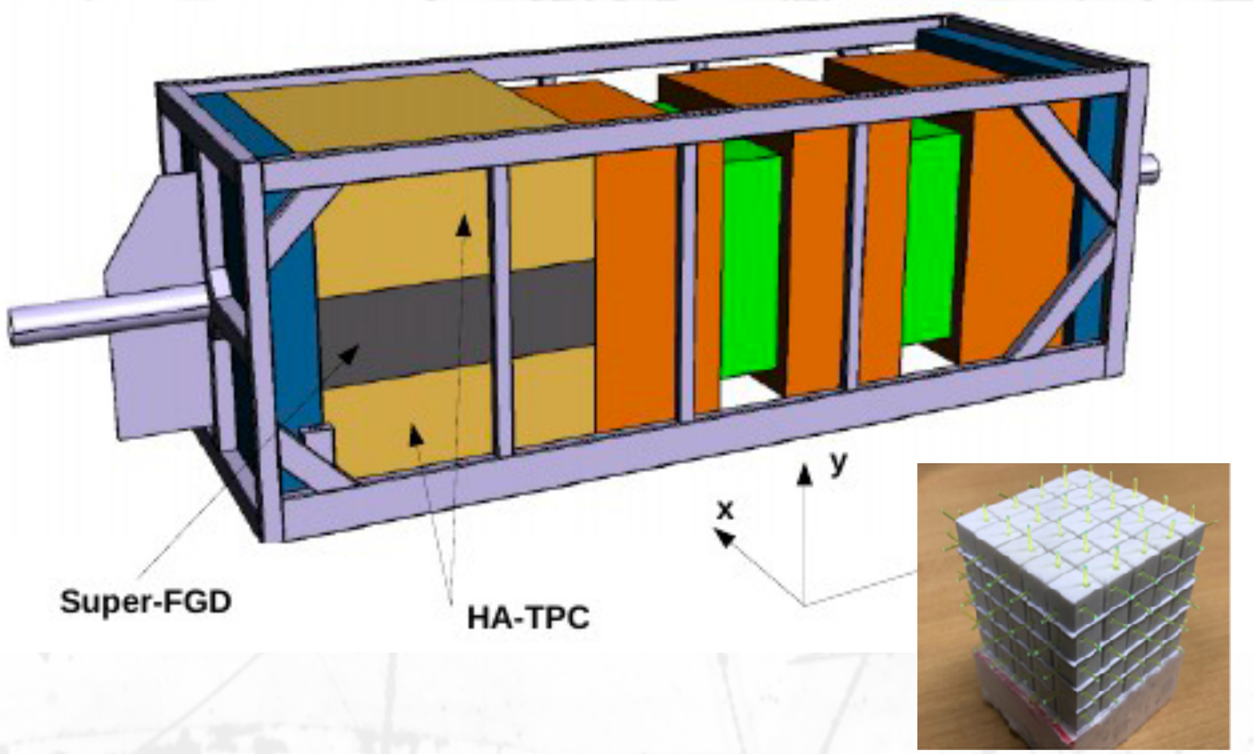
exp. >800 kW by 2023

RF upgrade and Machine development

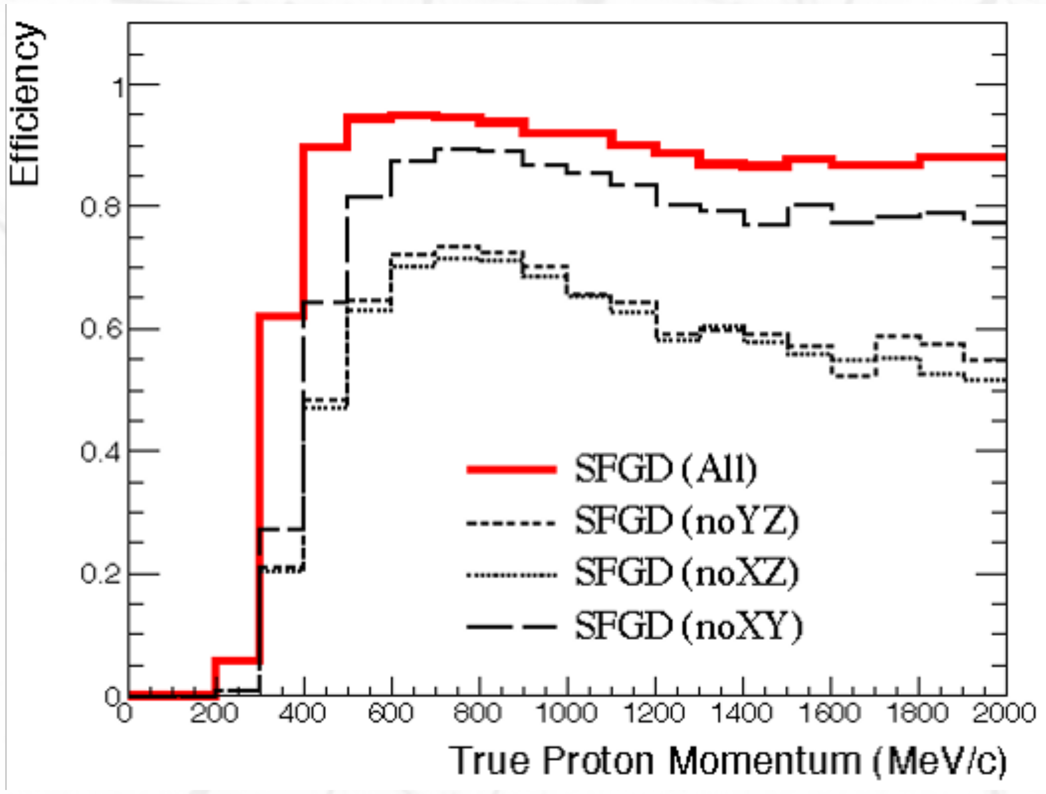
f_{rep}=0.86 Hz ⊕ PPP = 3.2×10^{14} ⊕ 30 GeV = 1.3 MW

Lower systematics: 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.
- Access to neutrons in final state (LANL test beam).

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

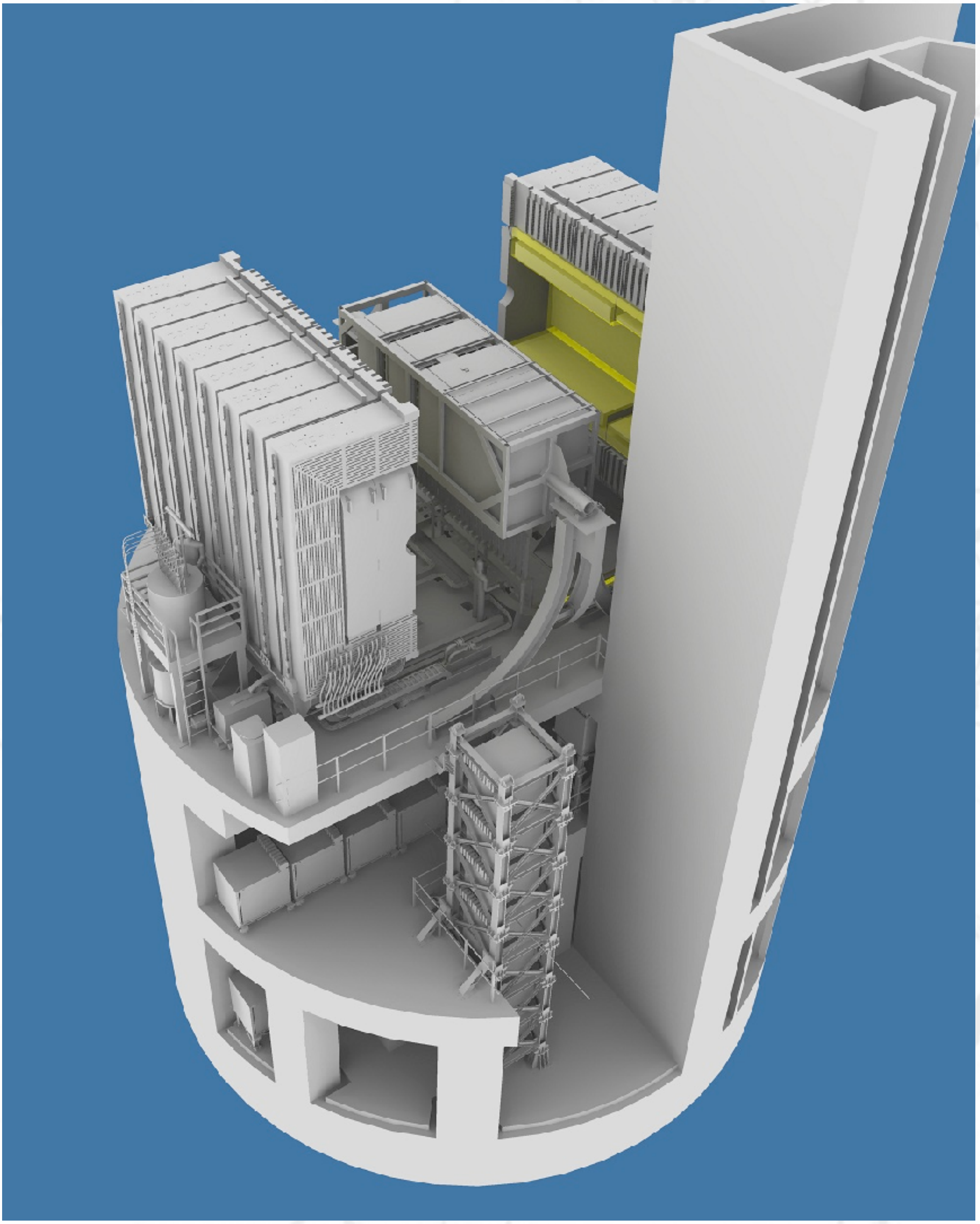
Hot source Remnants of primordial nitrogen in Earth's mantle

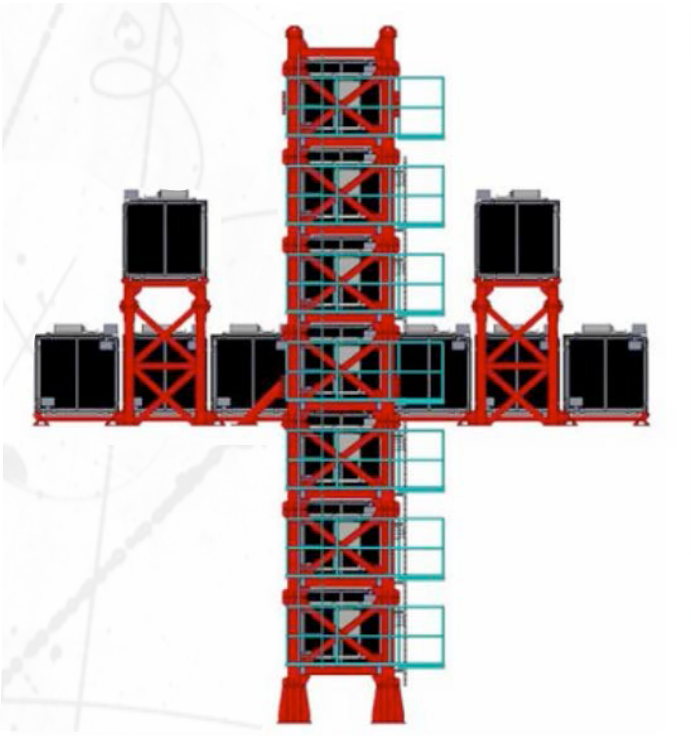
Origin of a species Revised age for Broken Hill skull adds twist to human evolution

Last meeting pre-covid in Ecole Polytechnique (Paris)

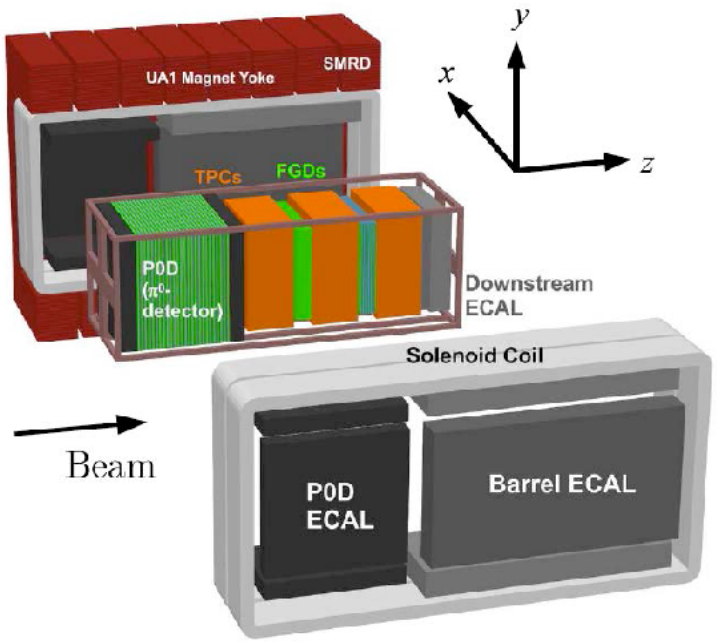
Supporting slides

Near Detector Site

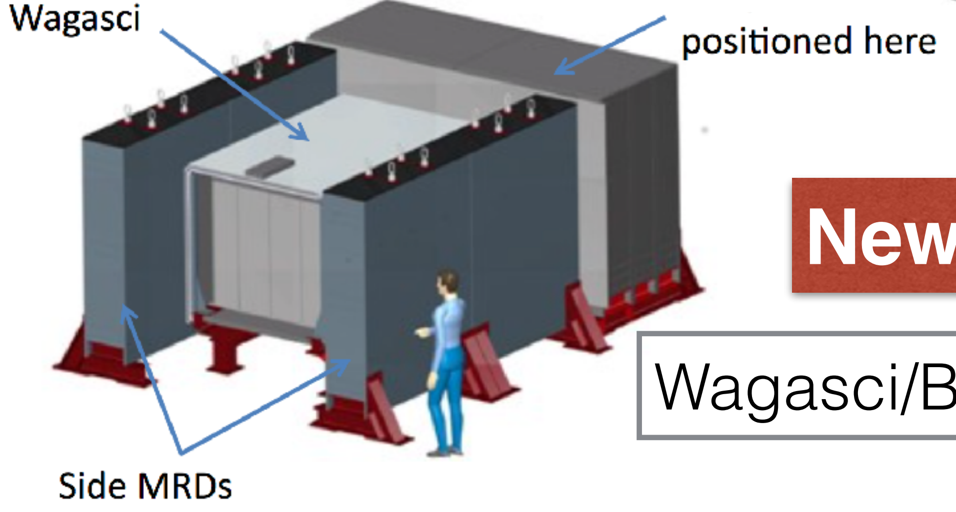




INGRID: On-axis



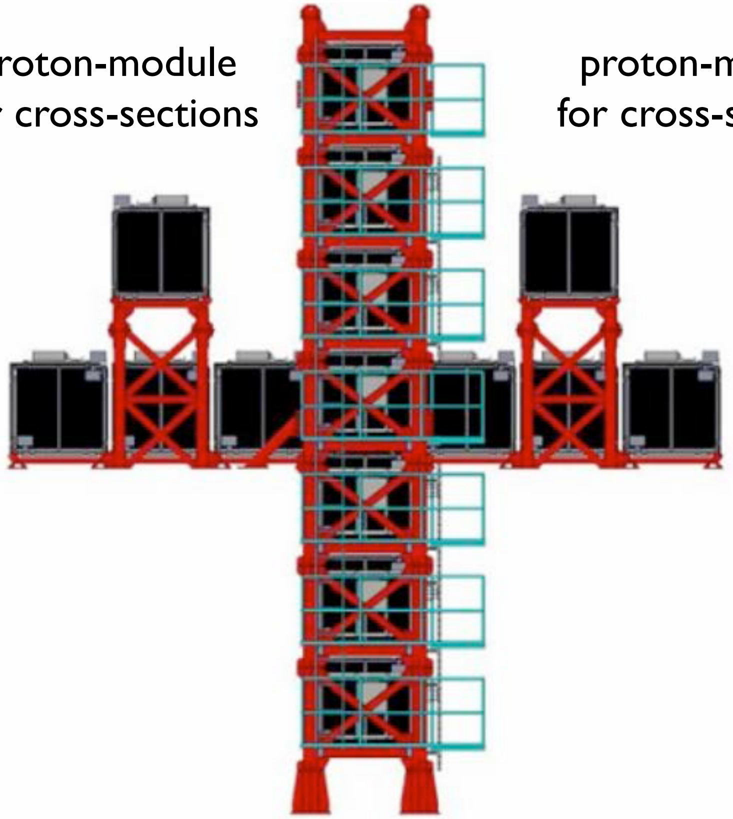
ND280: Off-axis



New in 2019!

Wagasci/BabyMind: Off-axis

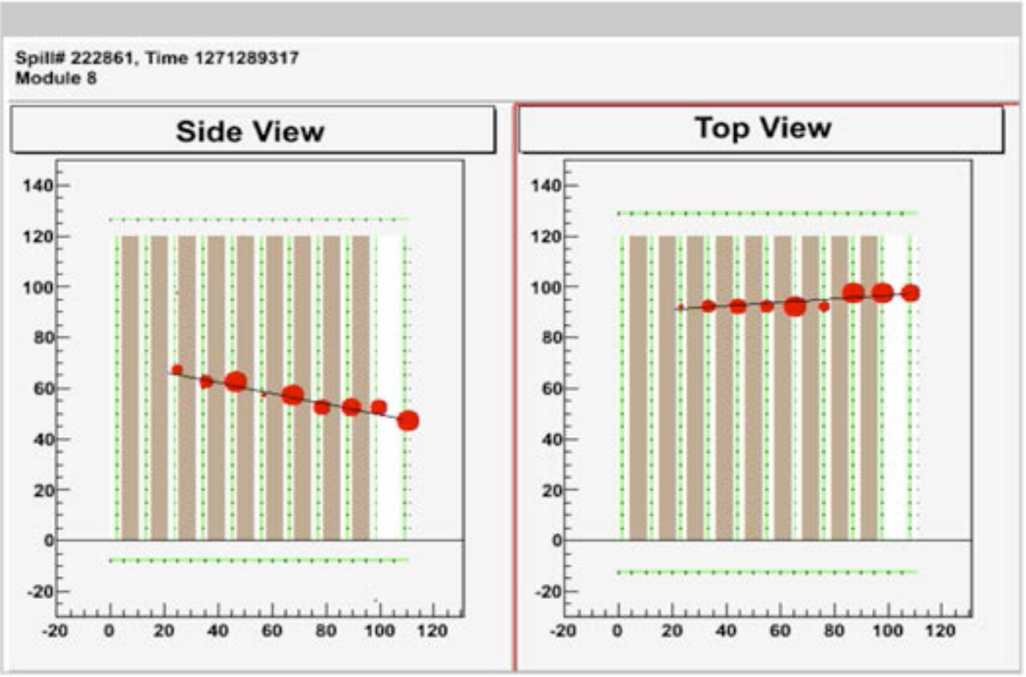
On-Axis ND



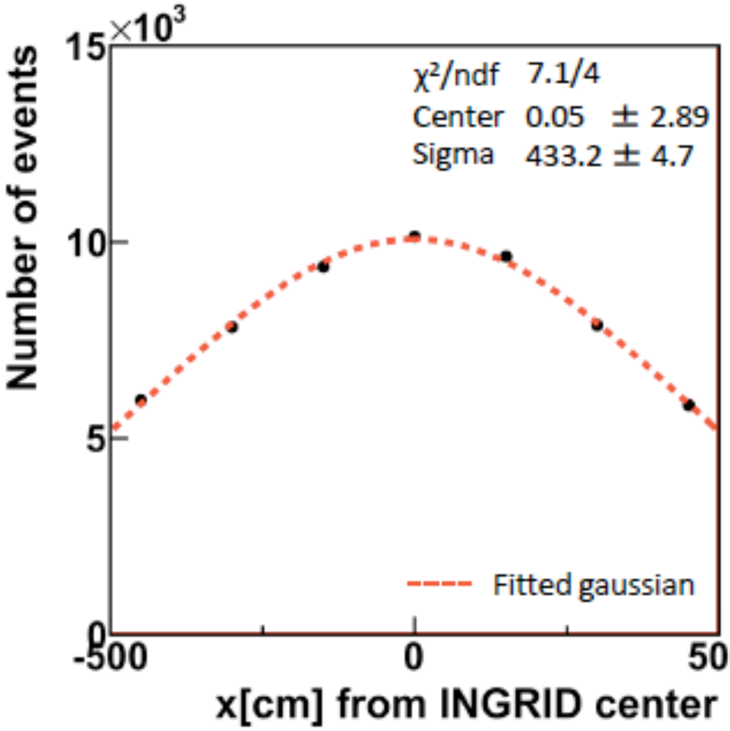
proton-module for cross-sections

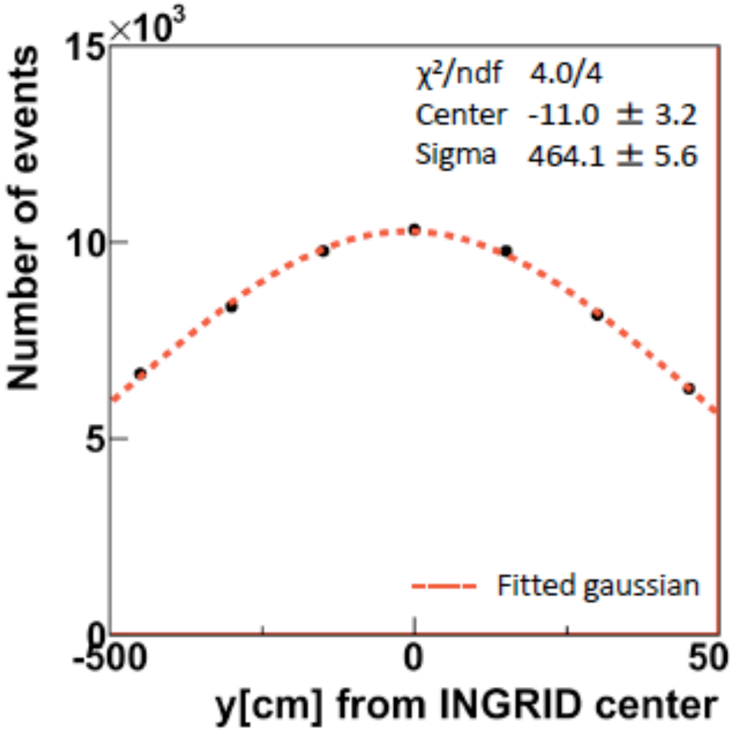
proton-module for cross-sections

- 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.

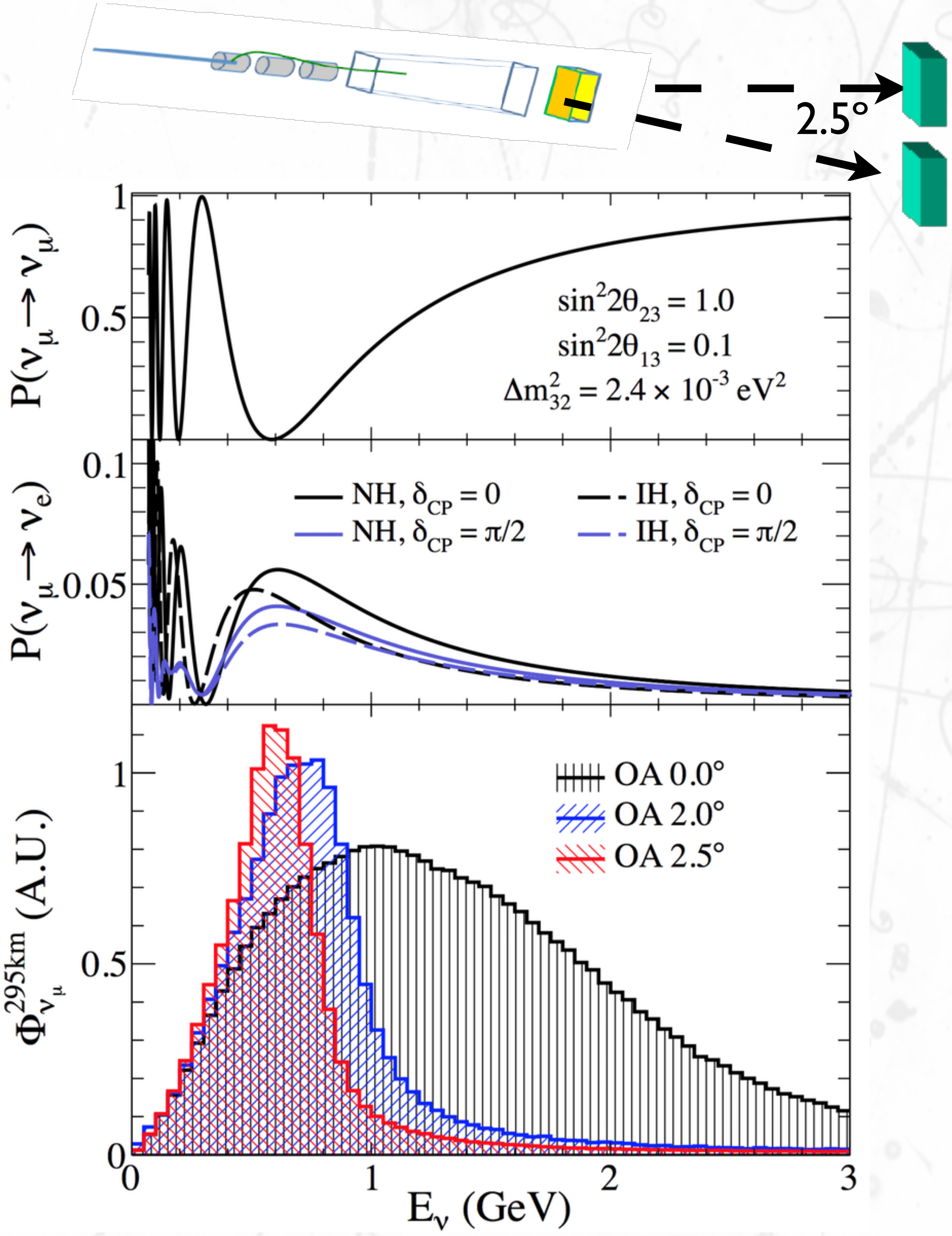


Spill# 222861, Time 1271289317
Module 8





Off-axis beam



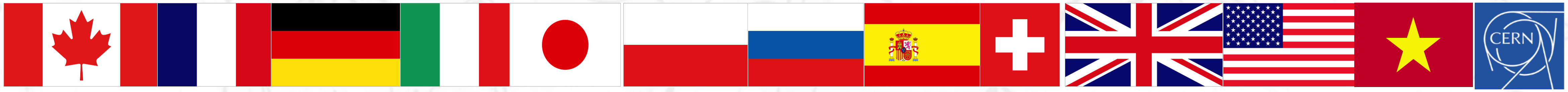
Off-axis

- 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.

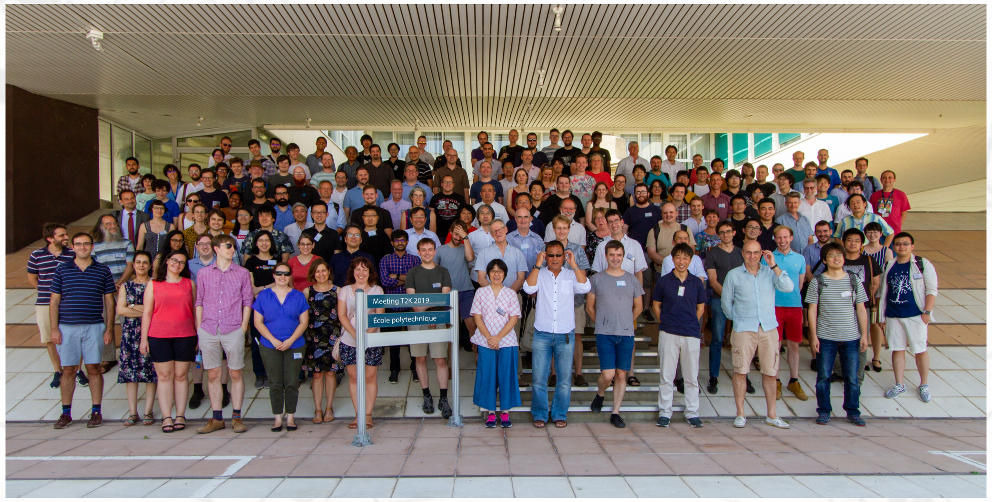
T2K Collaboration

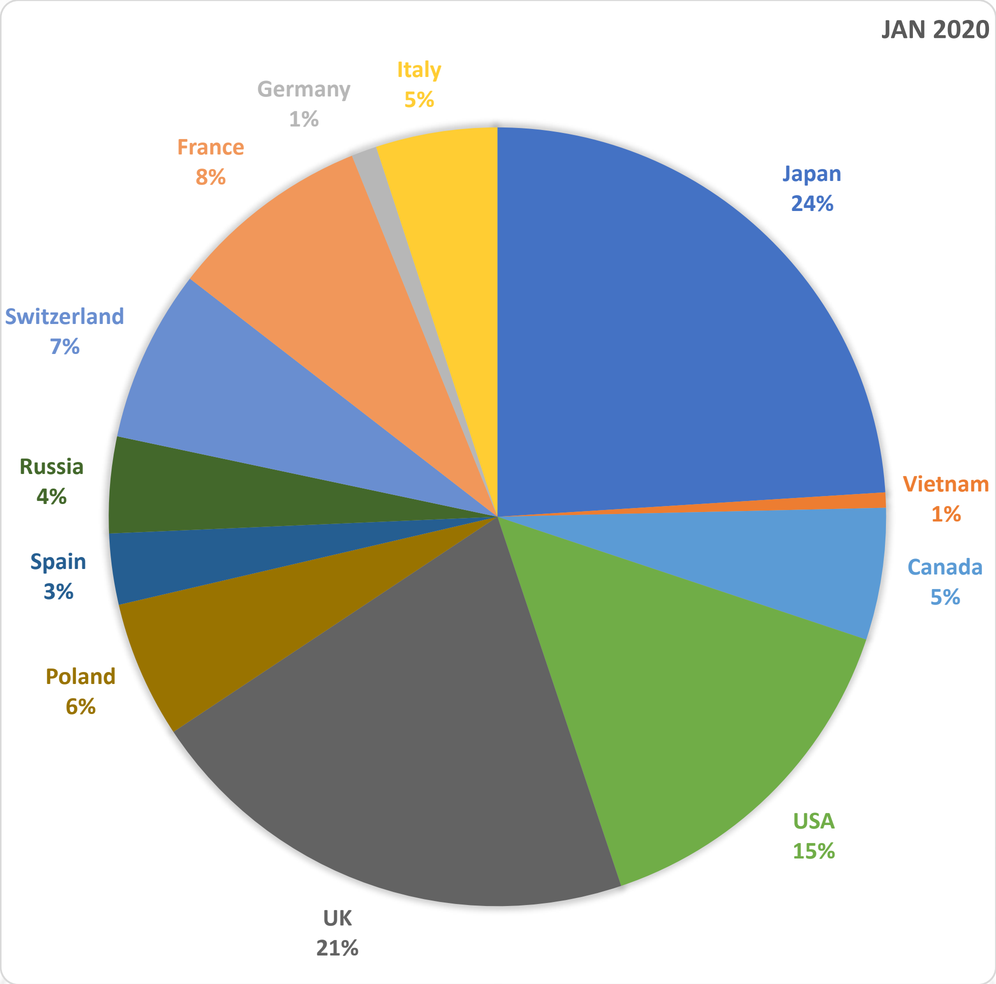


~500 members, 69 Institutes, 12 countries

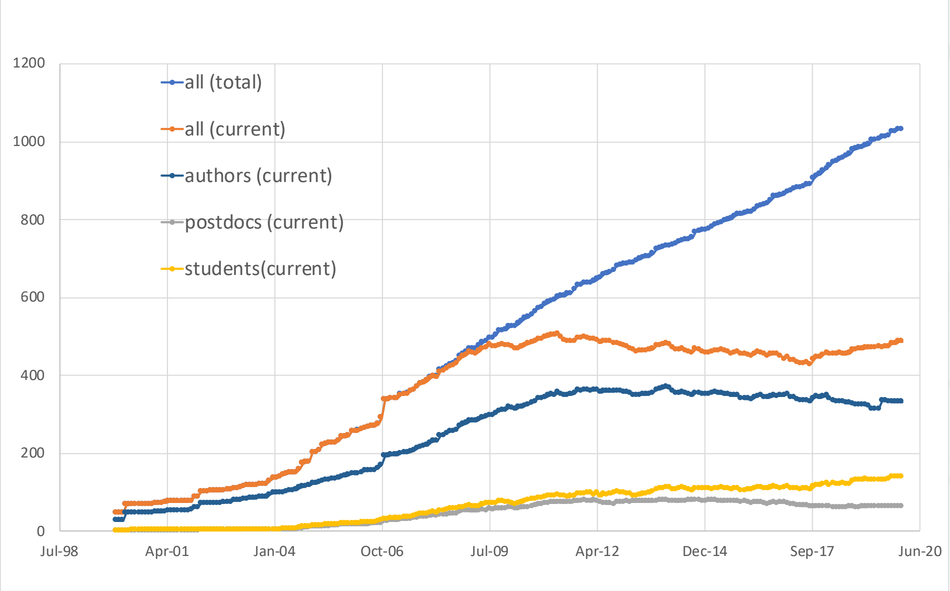
Asia	117
Japan	114
Vietnam	3

Americas	96
Canada	26
USA	70





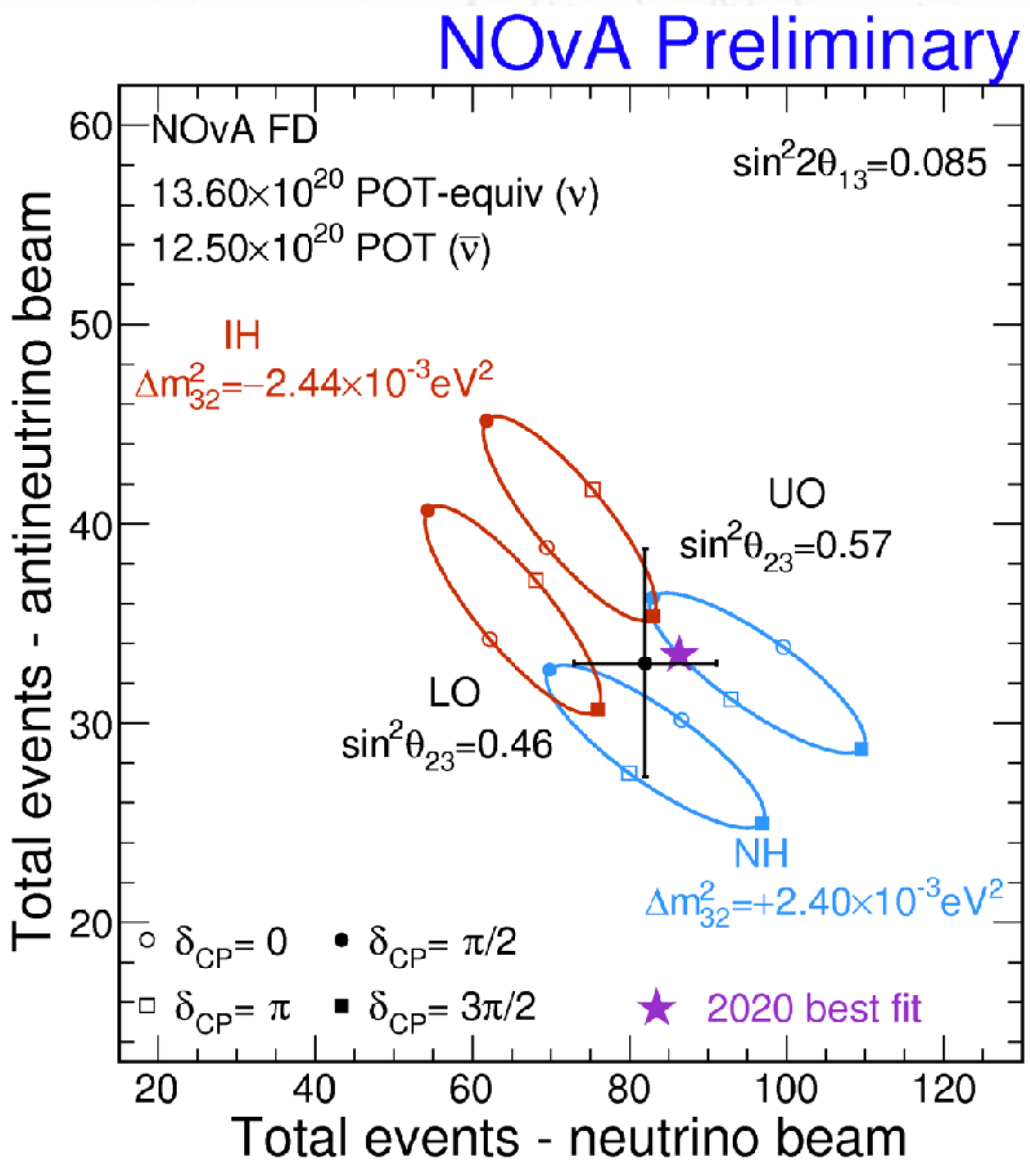
Europe	262
France	40
Germany	5
Italy	24
Poland	27
Russia	19
Spain	14
Switzerland	34
UK	99

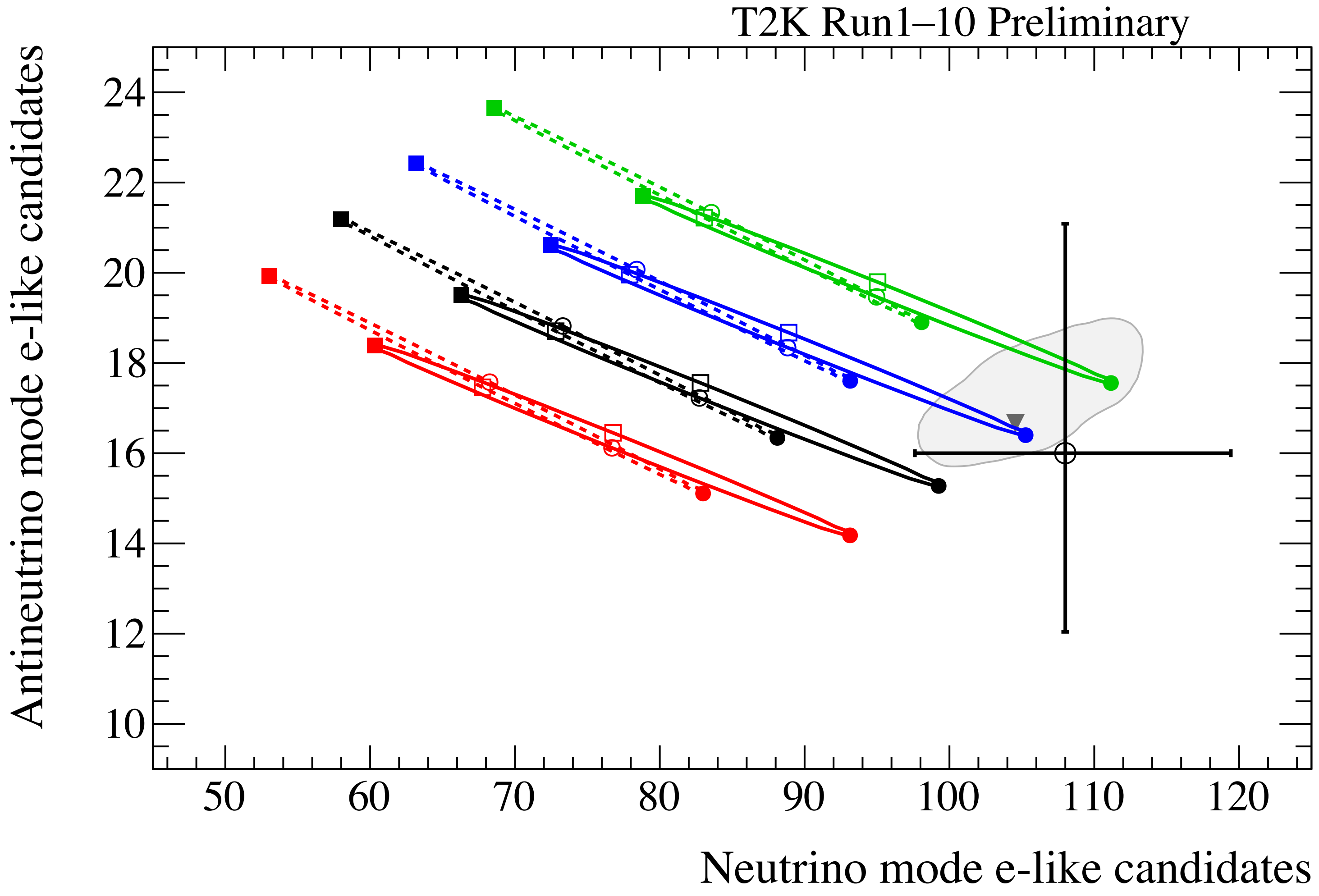


Very strong European contribution including CERN

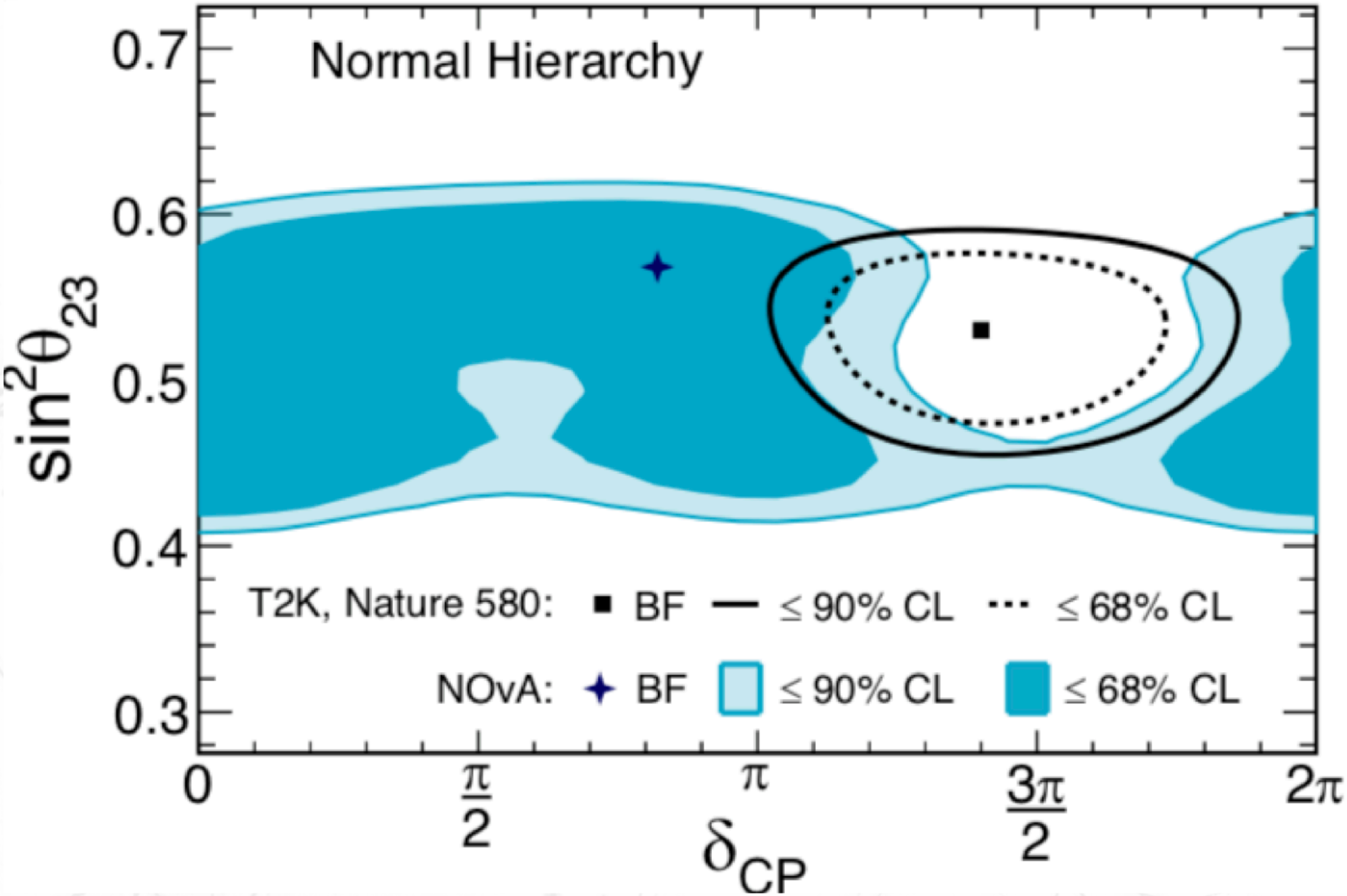
Operated since 2009

Nova results





T2K vs Nova

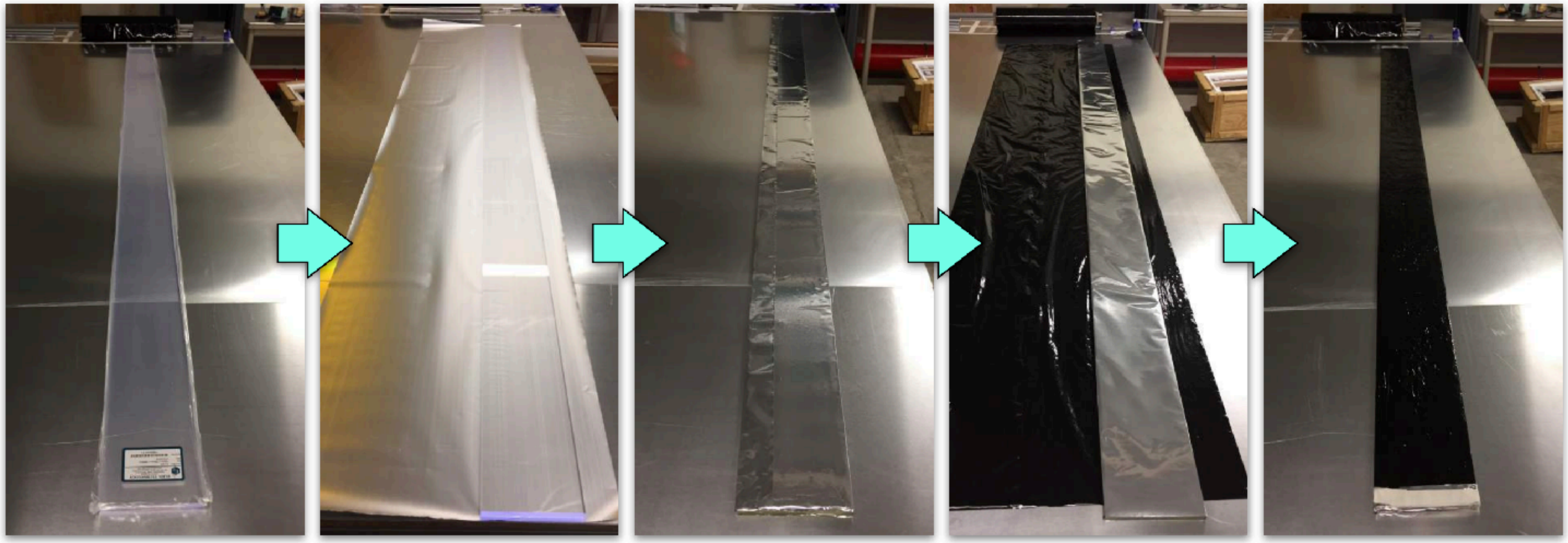

Normal Hierarchy
$\sin^2\theta_{23}$
0.3
0.4
0.5
0.6
0.7
δ_{CP}
0
$\frac{\pi}{2}$
π
$\frac{3\pi}{2}$
2π
T2K, Nature 580: ■ BF — ≤ 90% CL ··· ≤ 68% CL
NOvA: ✦ BF ≤ 90% CL ≤ 68% CL

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

Time Of Flight

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

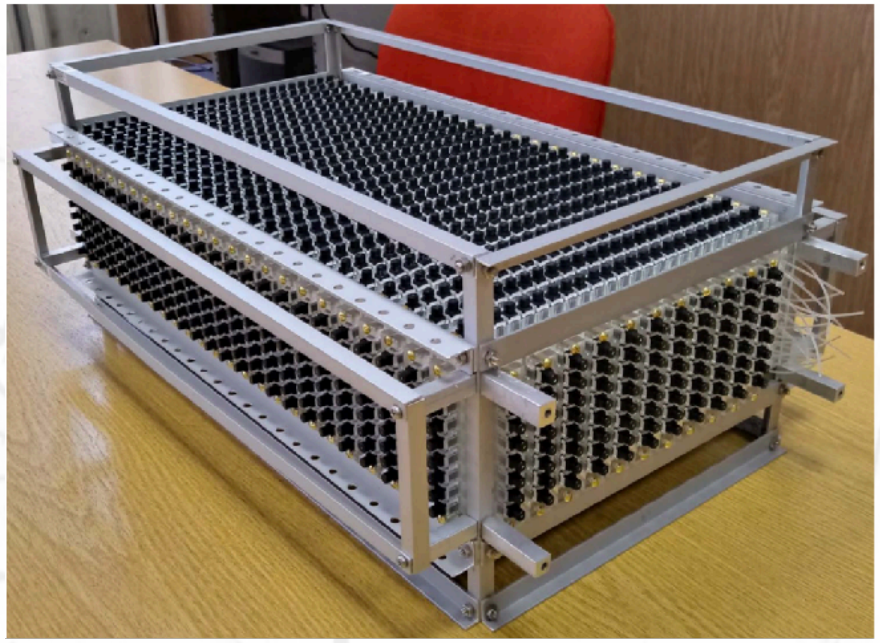


3 layers of Al foil + 6 layers of black stretch film

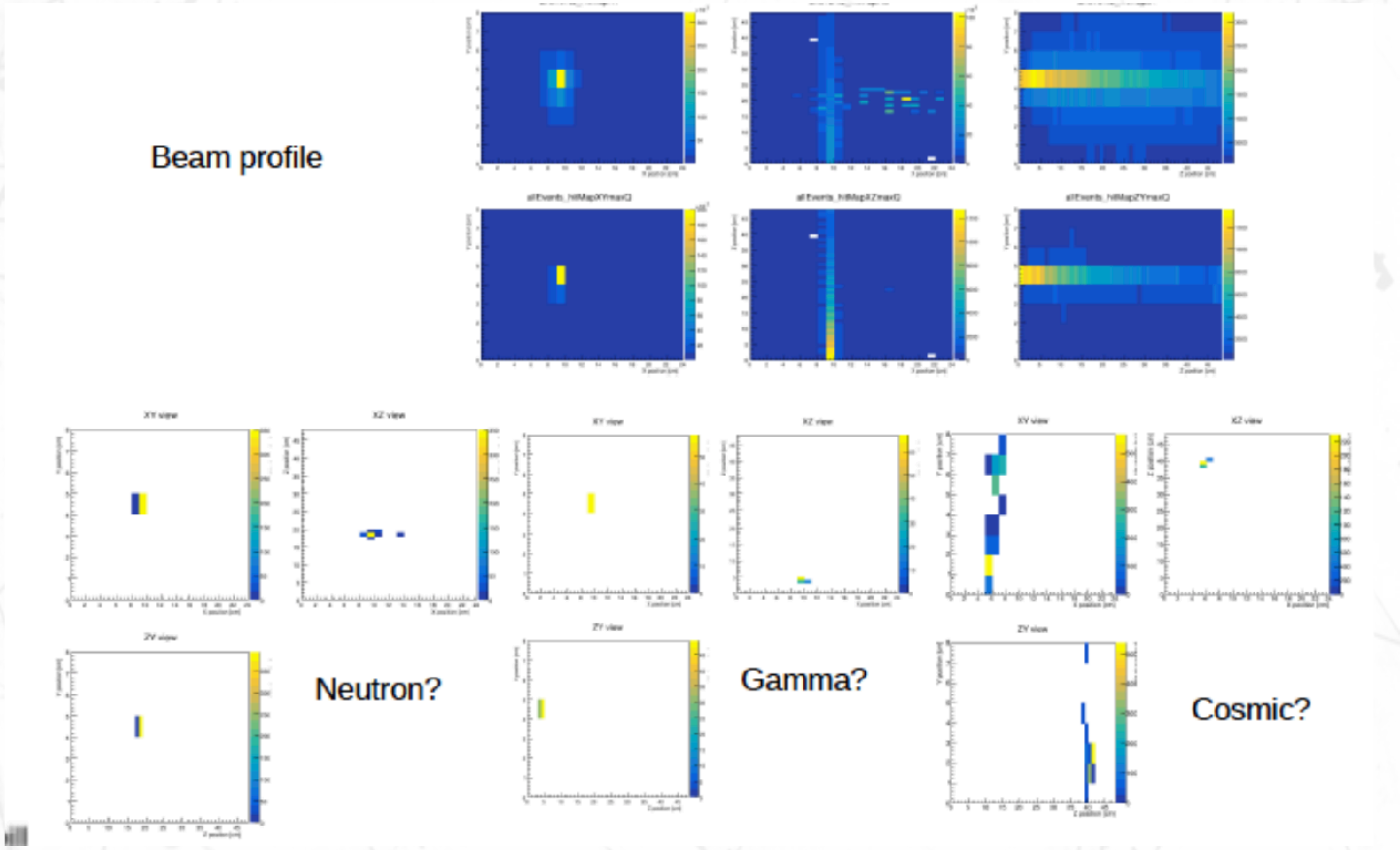
- Mock-up basket

- 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

Super-FGD prototype neutron tests at LANL



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



LBL analysis

- Since the neutrino energy is not monochromatic:
  - we need to determine event by event the energy of the neutrino.
- This estimation is not perfect and the cross-section does not cancels out in the ratio.

$$\frac{N^{far}_{evts}(\vec{\theta}^{reco}_{\nu})}{N^{near}_{evts}(\vec{\theta}^{reco}_{\nu})} = \frac{\int \sigma(E_\nu)\phi^{far}(E_\nu)P_{far}(\vec{\theta}^{reco}_{\nu}|E_\nu)P_{osc}(E_\nu)dE_\nu + Back_{far}(\vec{\theta}^{reco})}{\int \sigma(E_\nu)\phi^{near}(E_\nu)P_{near}(\vec{\theta}^{reco}_{\nu}|E_\nu)dE_\nu + Back_{near}(\vec{\theta}^{reco})}$$

- The neutrino oscillations introduce differences in the flux spectrum and the ratio does not cancel the cross-sections.

$\phi^{far}(E_\nu) \neq \phi^{near}(E_\nu)$ Near and far fluxes are different

$\sigma(E_\nu)$ Cross-section neutrino nucleus are not well known.

$P_{near,far}(\vec{\theta}^{reco}_{\nu}|E_\nu)$ Neutrino energy depended observables depend on cross-section models.

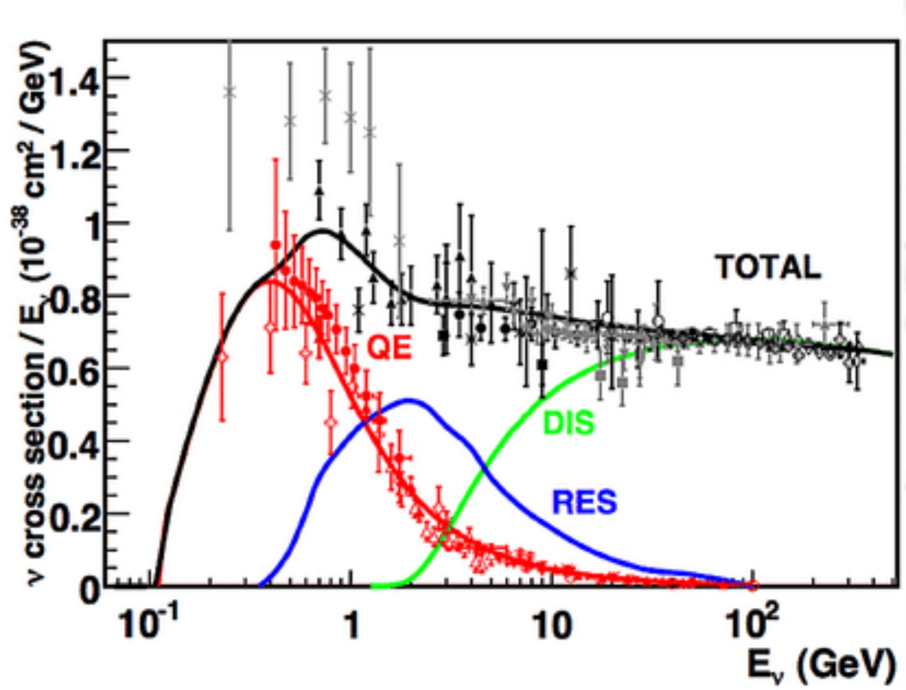
$Back_{near,far}(\vec{\theta}^{reco}_{\nu})$ Background prediction depends on cross-section models.

vA cross-sections

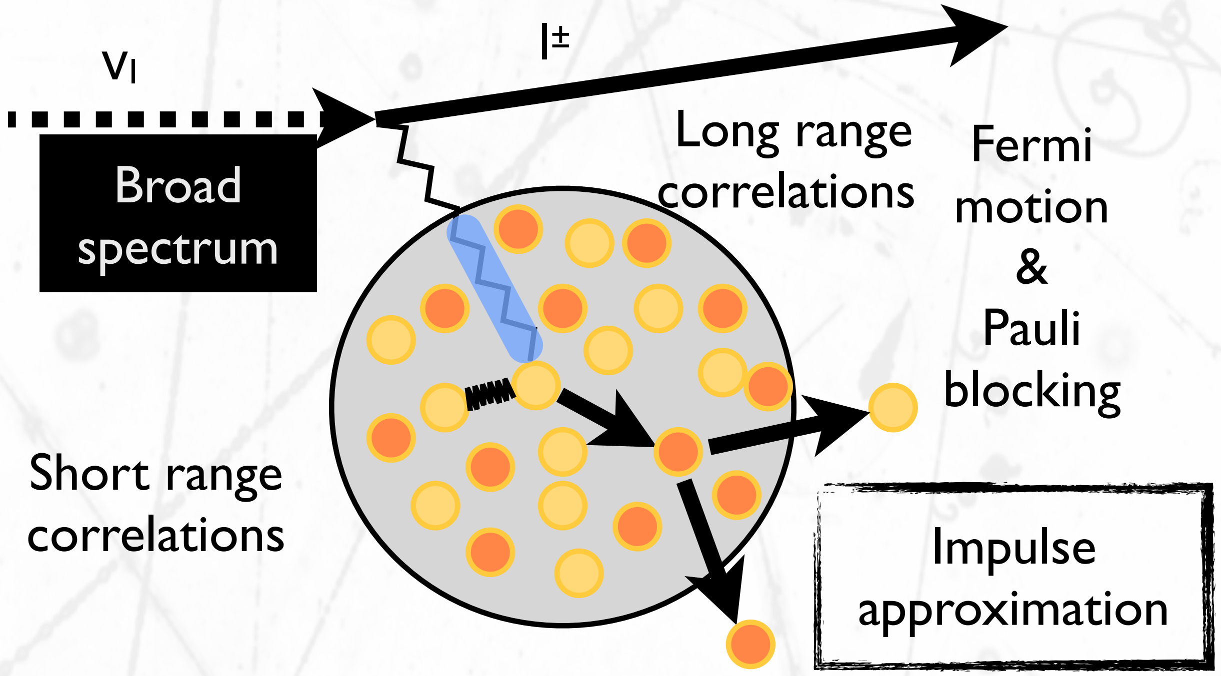
Describing $P_{far}(\vec{\theta}_\nu^{reco}|E_\nu)$

@ the nucleon level !

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



@ the nucleus level !



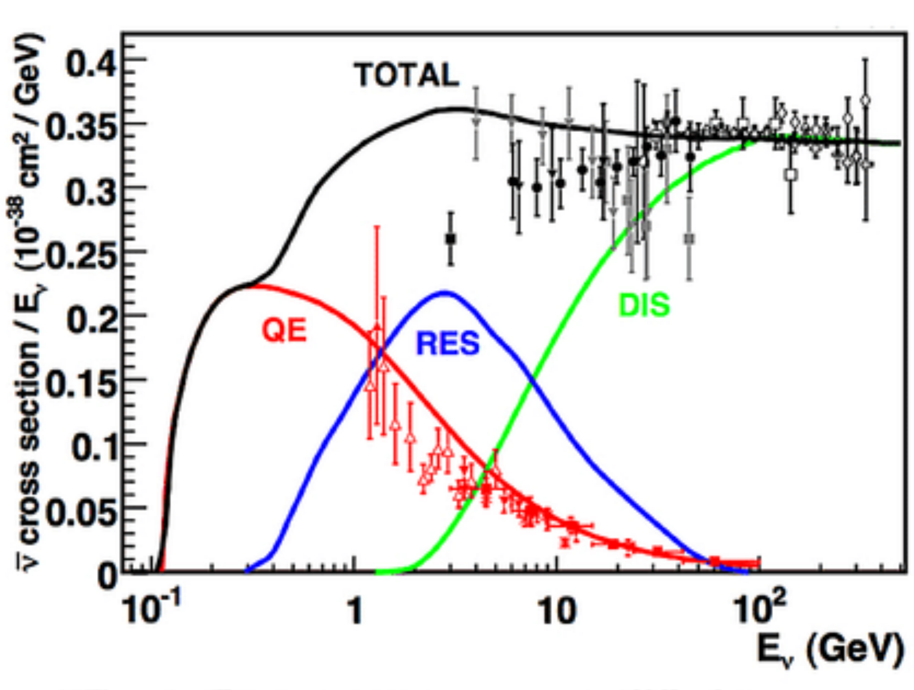
Broad spectrum

Long range correlations

Fermi motion & Pauli blocking

Short range correlations

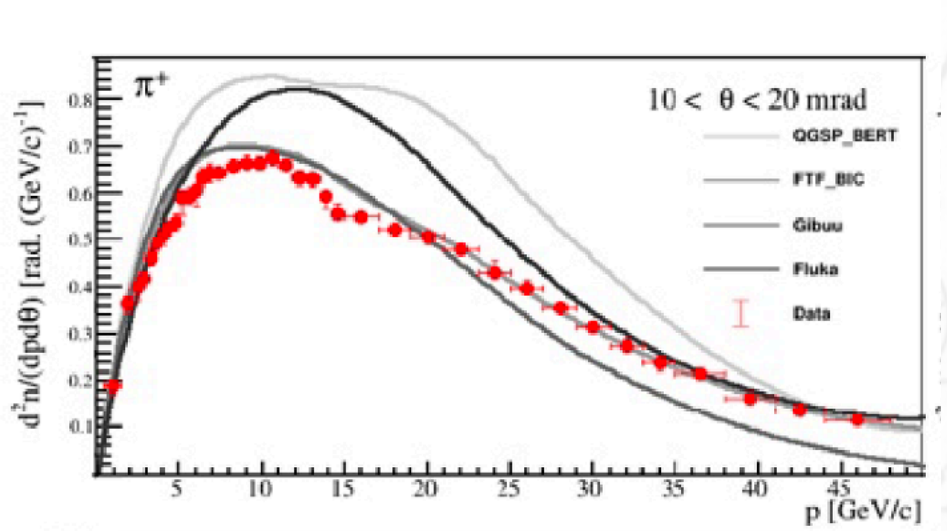
Impulse approximation



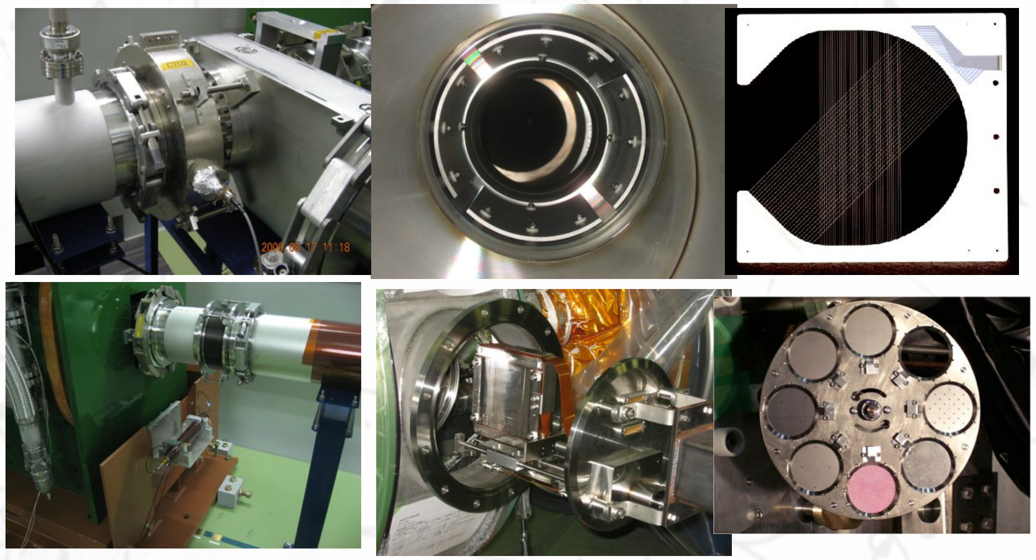
Beam model

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

Input

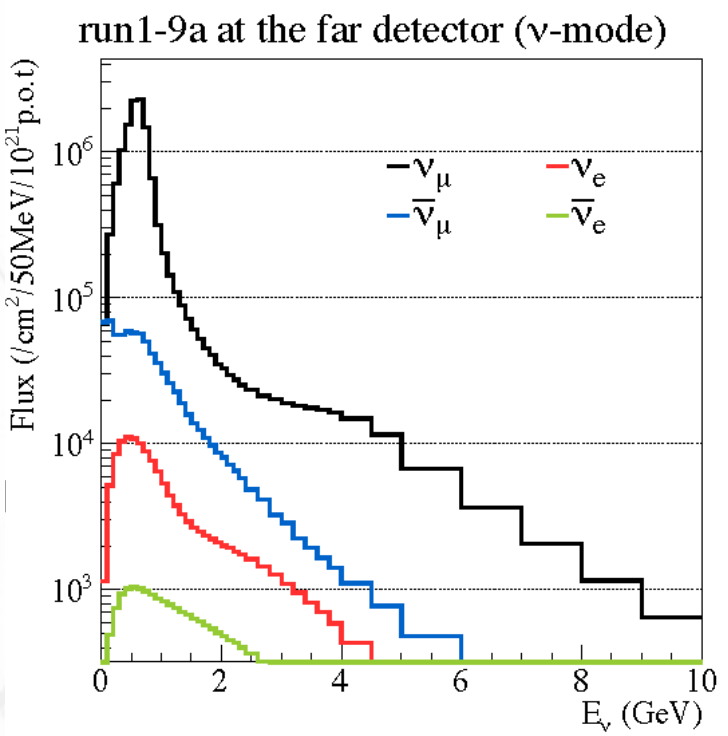


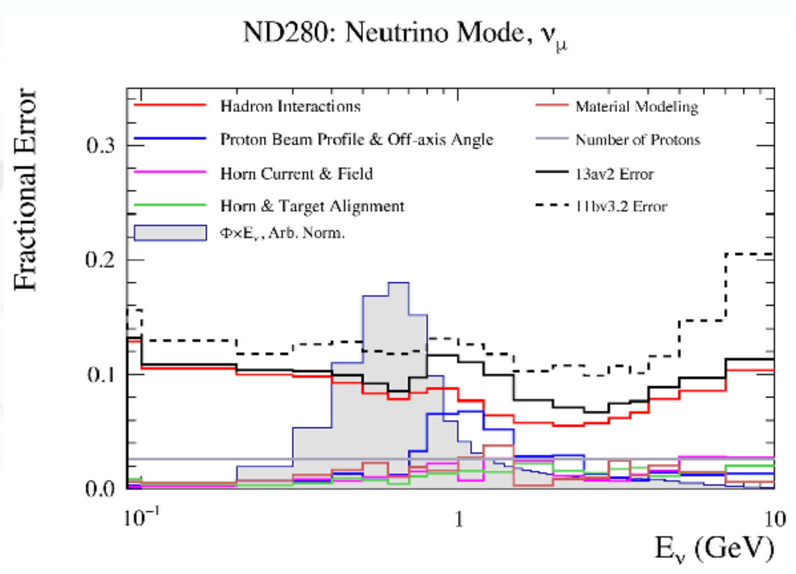
Beam monitors

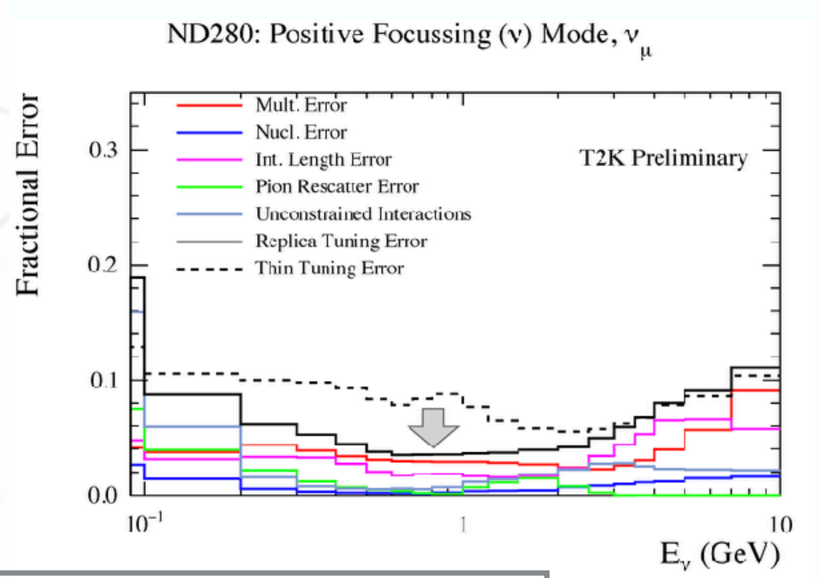


GEANT 3

Output



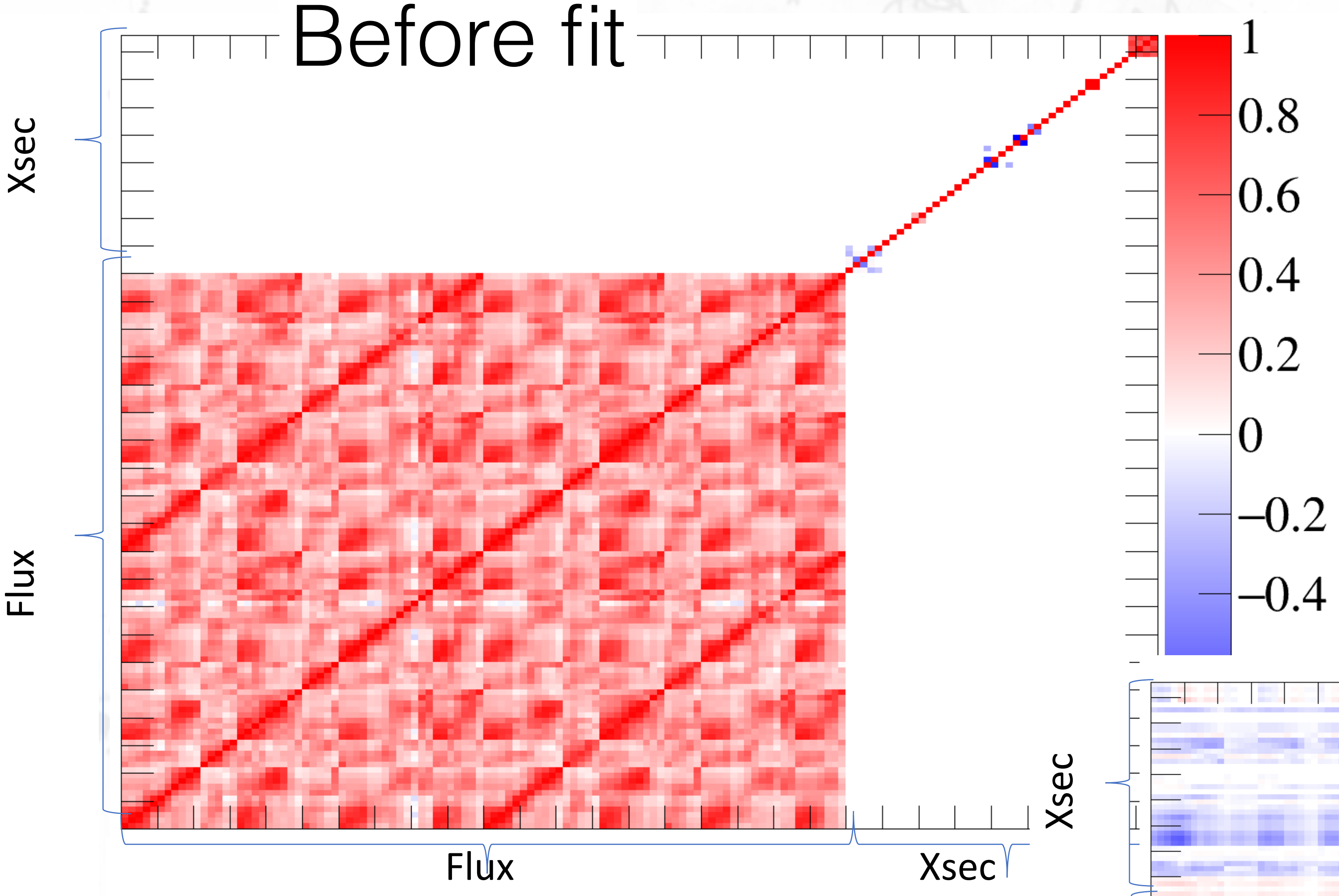




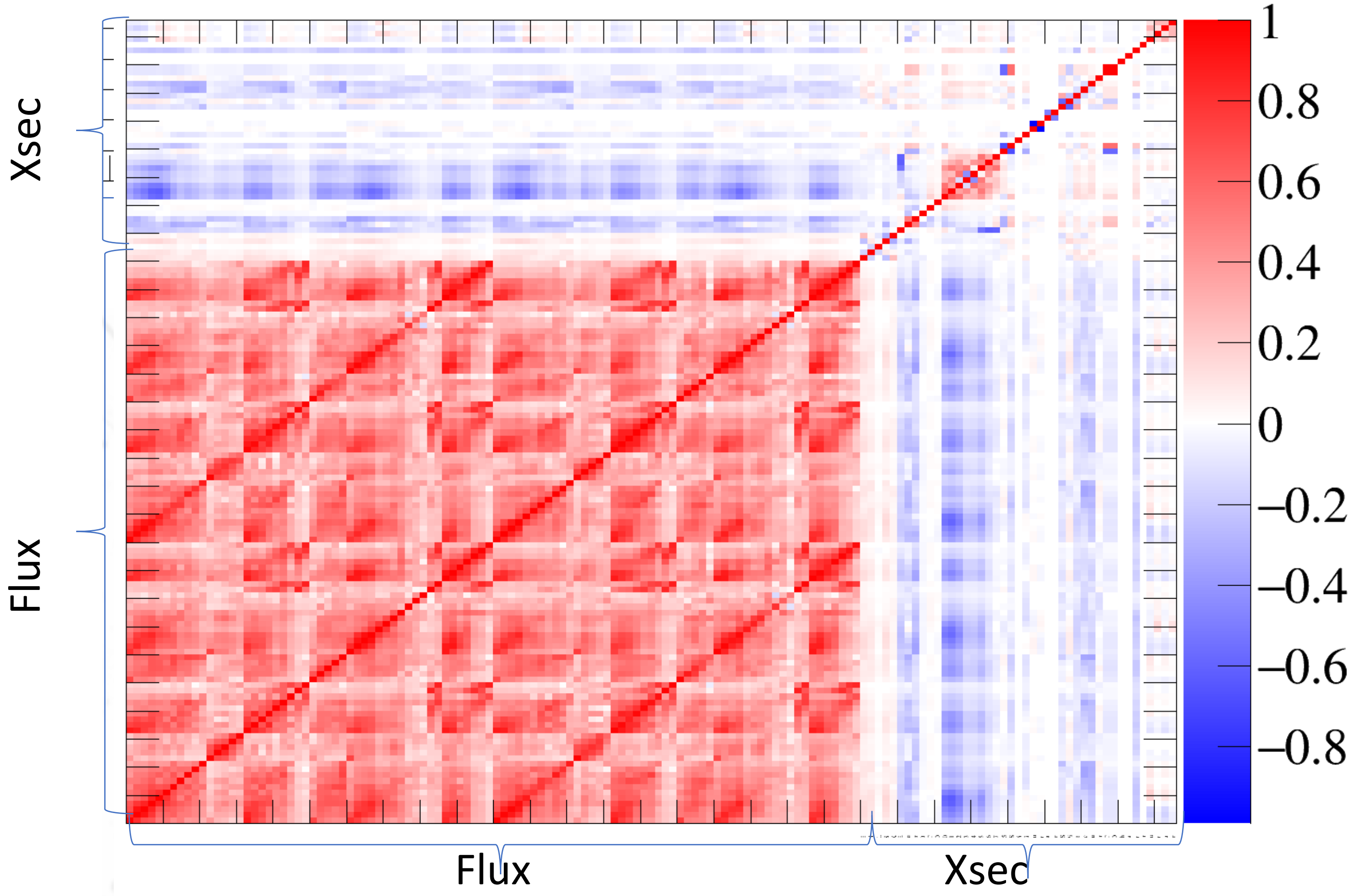
Including error covariance matrix

Correlation matrix

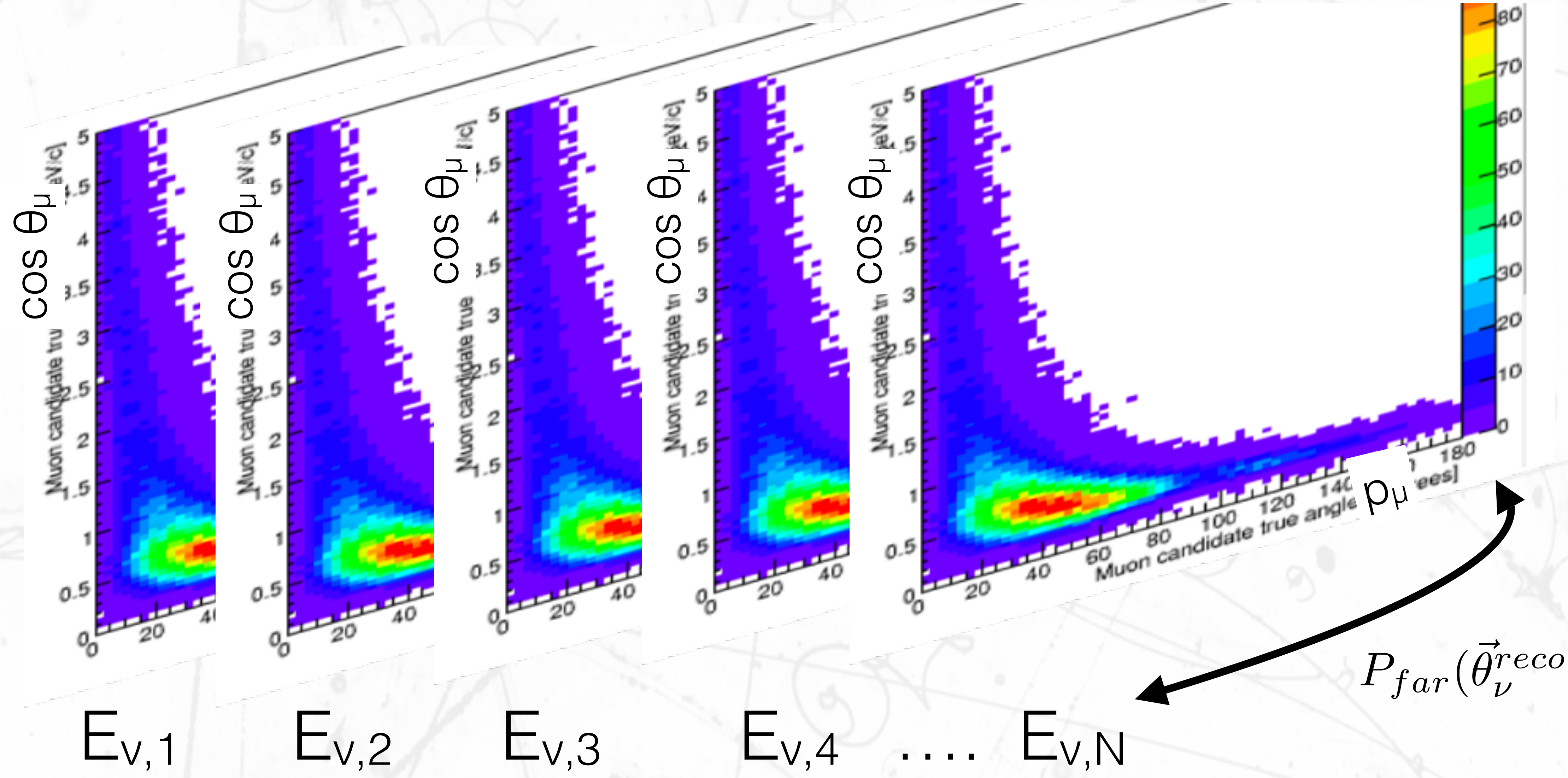
Before fit



After fit



T2K approach



$$\frac{N^{far}_{evts}(\vec{\theta}_\nu^{reco})}{N^{near}_{evts}(\vec{\theta}_\nu^{reco})} = \frac{\int \sigma(E_\nu)\phi^{far}(E_\nu)P_{far}(\vec{\theta}_\nu^{reco}|E_\nu)P_{osc}(E_\nu)dE_\nu + Back_{far}(\vec{\theta}^{reco})}{\int \sigma(E_\nu)\phi^{near}(E_\nu)P_{near}(\vec{\theta}_\nu^{reco}|E_\nu)dE_\nu + Back_{near}(\vec{\theta}^{reco})}$$

$P_{far}(\vec{\theta}_\nu^{reco}|E_\nu)$ is given by νA models

To some level all experiments do the same.