CURRENT ACTIVITIES and FUTURE PLANS of the LPNHE neutrino group

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LPNHE PARIS

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The LPNHE neutrino group

- **The group is composed of**

  (5 permanents) Bernard Andrieu (CR), Claudio Giganti (CR/HDR), **Jacques Dumarchez** (DR), Luca Scotto Lavina (CR), Boris Popov (DR)

  + new MdC SU to start from September 2018

  (1 benevole) Jean-Michel Levy

  (1 PhD student) Simon Bienstock (2015-2018) [STEPUP grant, T2K oscillation analysis]

  - (3 PhD students) Laura Zambelli (2010-2013) [ED grant, analysis of NA61/SHINE data for T2K], Pierre Bartet-Friburg (2013-2016) [CNRS grant, analysis of ND280 data], Matej Pavin (2014-2017) [ILP grant, analysis of NA61/SHINE data for T2K]

- **The group participates in the following experiments:**

  T2K [till 2020] (T2K-II [till 2026])

  NA61/SHINE (for T2K and for FNAL neutrino beams [till 2020], for HK/DUNE > 2021)

  WA105 [2014-2017]

  Recently joined Hyper-K ([2018-])

The LPNHE neutrino group

- **Main research topics:**

  Precise measurement of neutrino and anti-neutrino oscillation parameters and search for CP-violation in the lepton sector

  Measurements of neutrino and anti-neutrino interaction cross sections

  Hadron production measurements for precise predictions of accelerator neutrino fluxes

- **The group had and still has some important responsibilities:**

  T2K Oscillation Analysis convener (CG), T2K Beam Group convener (BP), ND280 Magnet operation, TPC operation, Publication Board members, Speakers Board members, Internal referees, NA61/SHINE analysis coordinator, etc.

- **More than 40 publications during the last 5 years**

- **Awards: Le Prix "La Recherche" Physique (2012) and Breakthrough Prize in Fundamental Physics (2016)**

Neutrino oscillations

"The discovery that neutrinos can convert from one flavour to another and therefore have nonzero masses is a major milestone for elementary particle physics. It represents compelling experimental evidence for the incompleteness of the Standard Model as a description of nature… Neutrino oscillations and the connected issues of the nature of the neutrino, neutrino masses and possible CP violation among leptons are today major research topics in particle physics."

[Scientific Background on the Nobel Prize in Physics 2015]

- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

A neutrino state with a well defined flavour, $|\nu_\alpha\rangle$ with $\alpha = e, \mu$ or τ, can be described in terms of mass eigenstates $|\nu_k\rangle$

$$|\nu_\alpha\rangle = \sum_{k=1}^{3} U^*_{\alpha k} |\nu_k\rangle$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$, and $\delta = \delta_{CP}$ is the CP-violating phase

(neglecting possible Majorana phases)

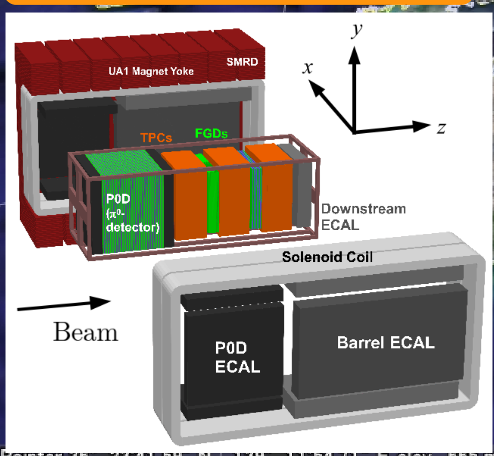
T2K experiment in Japan

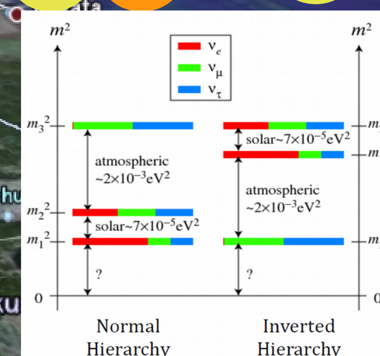
T2K is a long-baseline accelerator neutrino oscillation experiment.

Main goals are to study ν_μ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance, thus to measure the parameters θ_{13}, θ_{23} and δ_{CP}

Super-Kamiokande

ND280+INGRID





J-PARC

Neutrino oscillation probabilities

For neutrino oscillations in vacuum, the flavour change probability is

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{k>j} \mathrm{Re}(U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right) + 2\sum_{k>j} \mathrm{Im}(U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)$$

with $\Delta m^2_{kj} \equiv m^2_k - m^2_j$

Formulae for neutrino oscillation probabilities (relevant for T2K):

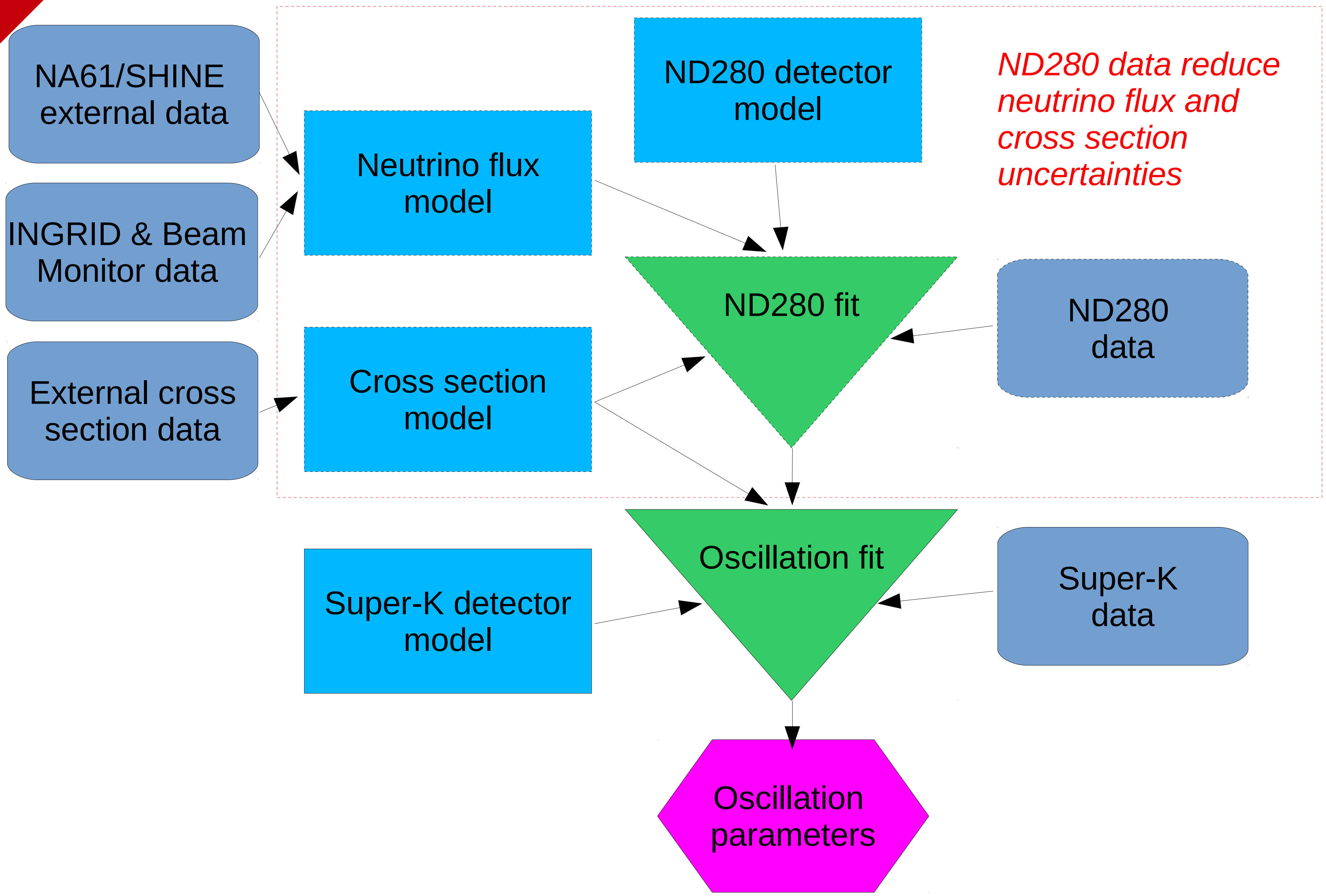
The ν_μ-survival probability for a neutrino with energy E traveling a distance L:

$$\begin{aligned} P(\nu_\mu \to \nu_\mu) = 1 &- 4(s^2_{12}c^2_{23} + s^2_{13}s^2_{23}c^2_{12} + 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta)s^2_{23}c^2_{13}\sin^2\phi_{31} \\ &- 4(c^2_{12}c^2_{23} + s^2_{13}s^2_{23}s^2_{12} - 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta)s^2_{23}c^2_{13}\sin^2\phi_{32} \\ &- 4(s^2_{12}c^2_{23} + s^2_{13}s^2_{23}c^2_{12} + 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta) \\ &\times (c^2_{12}c^2_{23} + s^2_{13}s^2_{23}s^2_{12} - 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta)\sin^2\phi_{21}, \quad \phi_{ij} = \frac{\Delta m^2_{ij} L}{4E} \end{aligned}$$

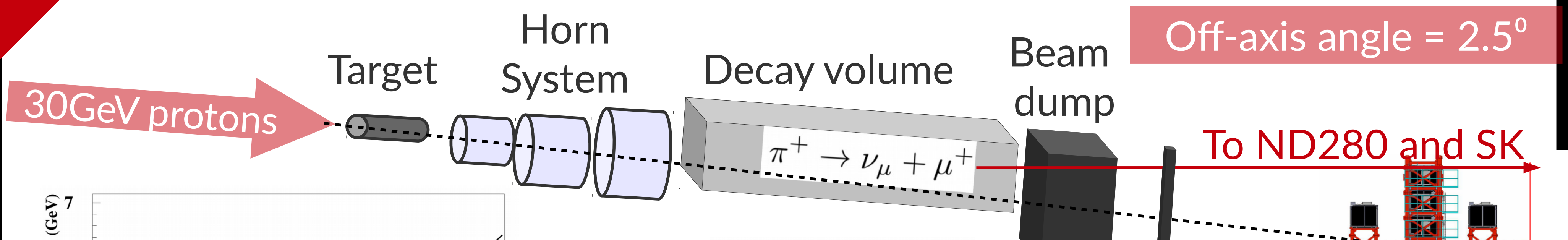
The ν_e-appearance probability (to first-order approximation in matter effects)

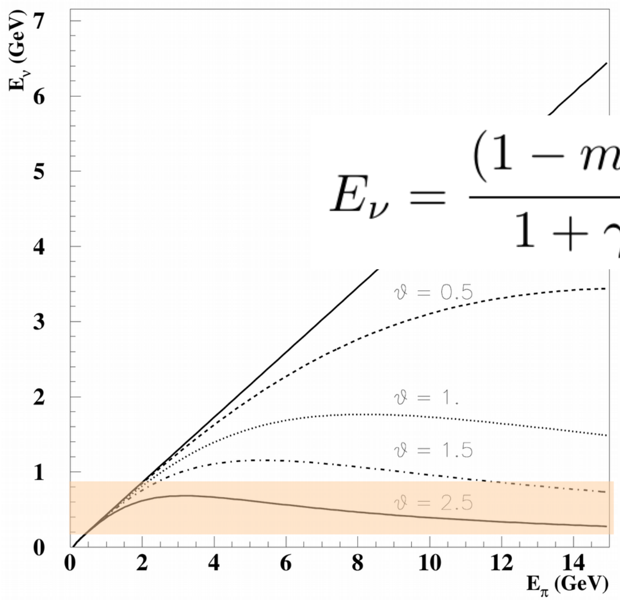
$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4c^2_{13}s^2_{13}s^2_{23}\sin^2\phi_{31}\left(1 + \frac{2a}{\Delta m^2_{31}}(1 - 2s^2_{13})\right) + 8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\phi_{23}\sin\phi_{31}\sin\phi_{21} \\ &- 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\phi_{32}\sin\phi_{31}\sin\phi_{21} \\ &+ 4s^2_{12}c^2_{13}(c^2_{12}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\phi_{21} \\ &- 8c^2_{13}s^2_{13}s^2_{23}(1 - 2s^2_{13})\frac{aL}{4E_\nu}\cos\phi_{32}\sin\phi_{31}. \end{aligned}$$

T2K Analysis strategy

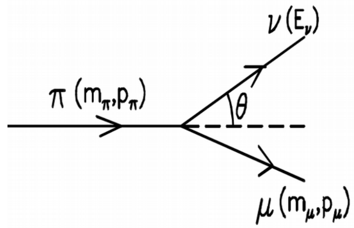


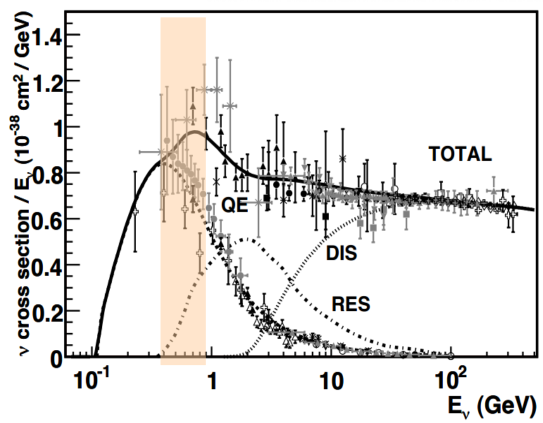
The neutrino beam: Off-axis technique

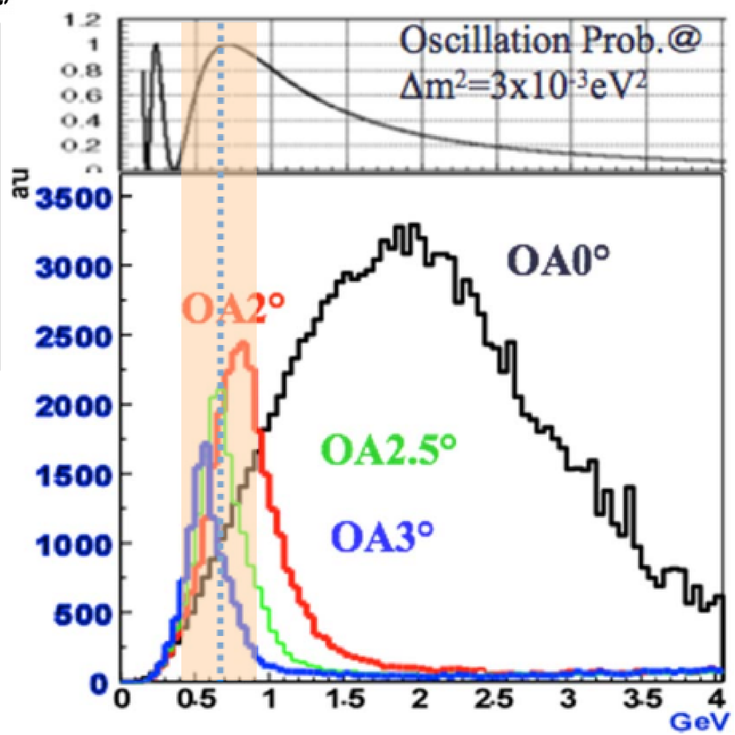




$$E_\nu = \frac{(1 - m_\mu^2/m_\pi^2)E_\pi}{1 + \gamma^2 \tan\theta^2}$$



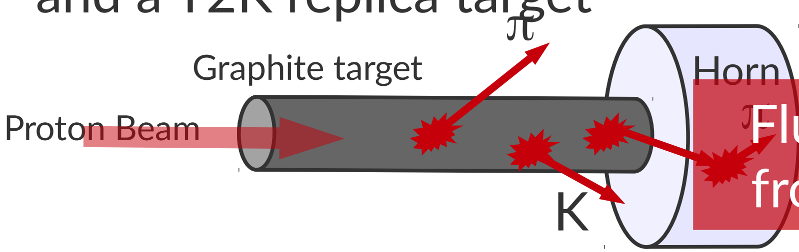




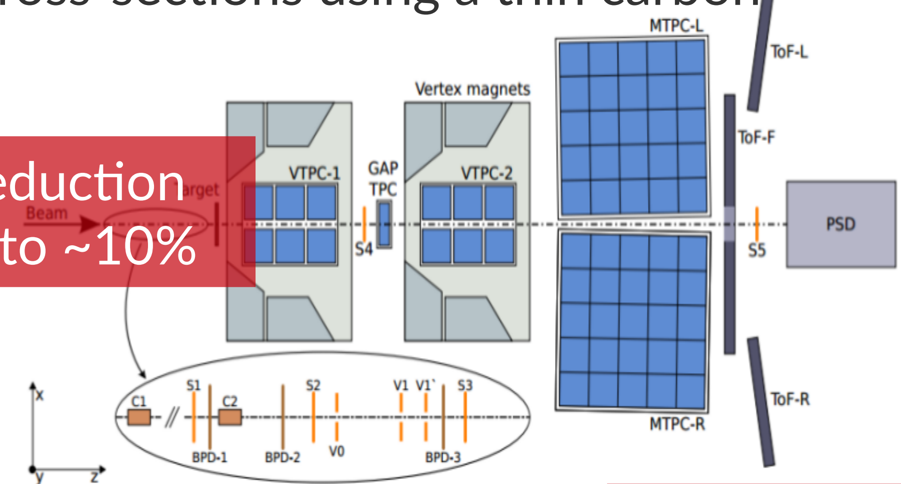
- Enhances neutrino oscillation effects
- Enhances CCQE (ν_μ n → μ- p) interactions
- Reduces background from π^0 production
- Reduces ν_e contamination at the peak

The neutrino beam: flux predictions

- Fluxes are predicted from a data-driven simulation → NA61/SHINE experiment measures hadron production cross-sections using a thin carbon and a T2K replica target

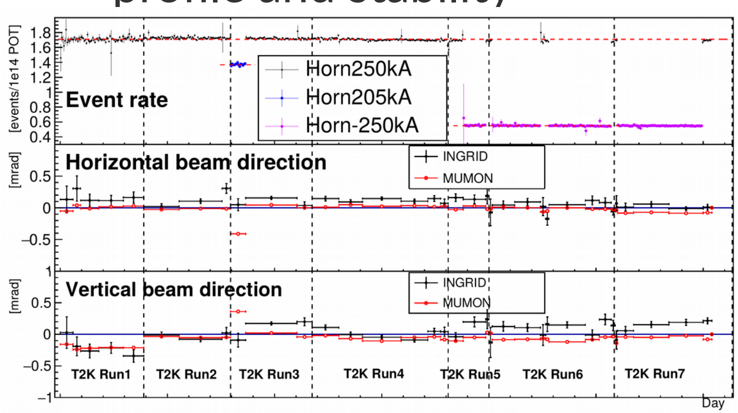


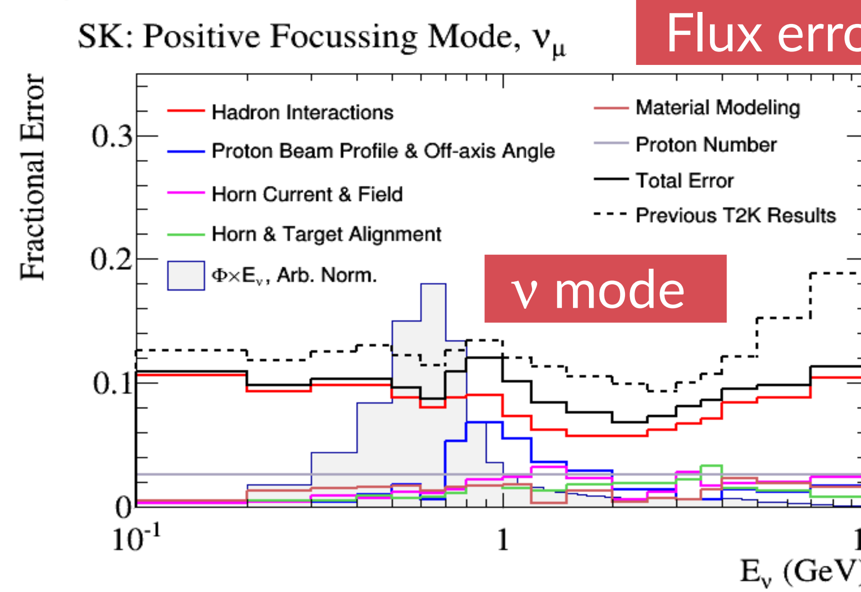
Flux error reduction from ~25% to ~10%



- Beam alignment monitoring provides input to estimations of beam systematics

- INGRID detector provides high-statistics monitoring of the beam intensity, direction, profile and stability





Flux errors

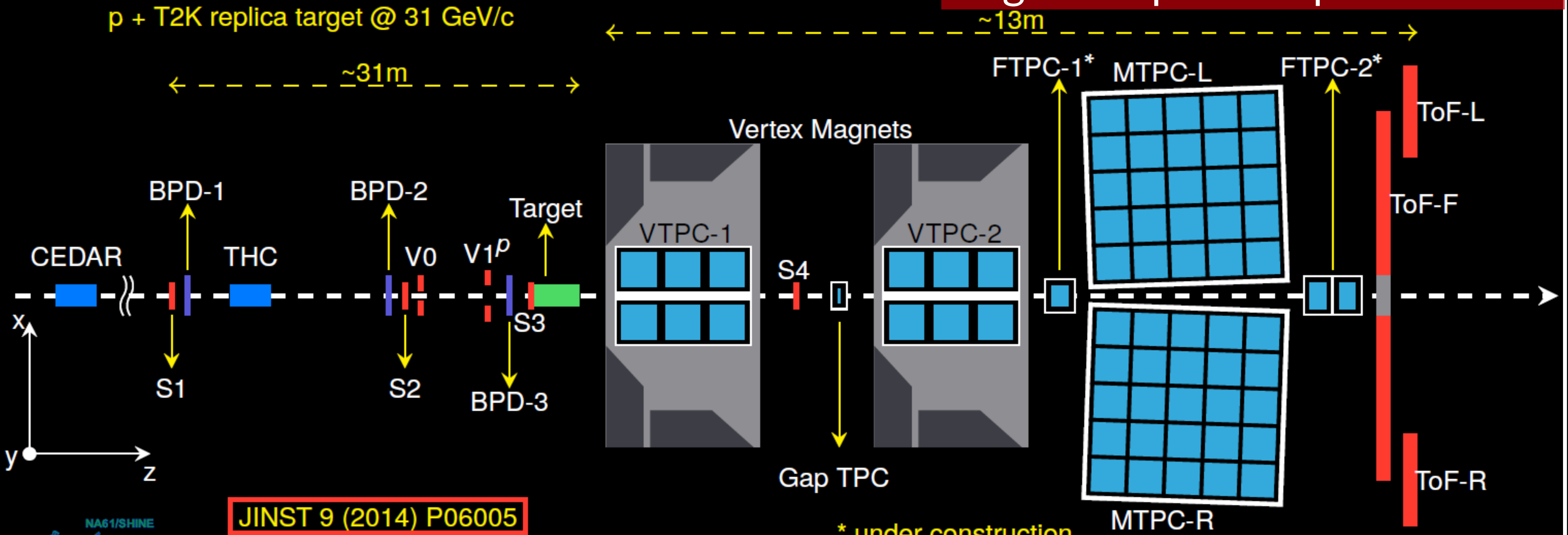
ν mode

Flux errors are further constrained with the ND280 analysis of ν_μ CC events

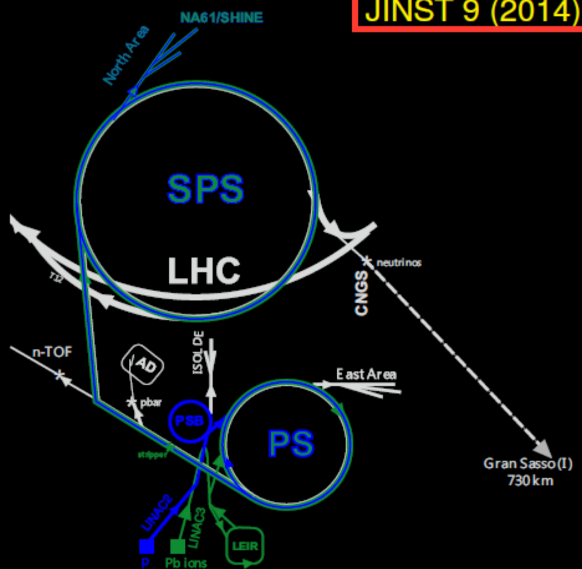
NA61/SHINE experiment @ CERN

- SPS Heavy Ion and Neutrino Experiment

Large-acceptance spectrometer



JINST 9 (2014) P06005



- Search for the critical point of strongly interacting matter (p+p, p+A, A+A)
- Precise hadron production measurements for neutrino flux predictions in T2K and Fermilab neutrino experiments
- More reliable simulations of cosmic-ray air showers

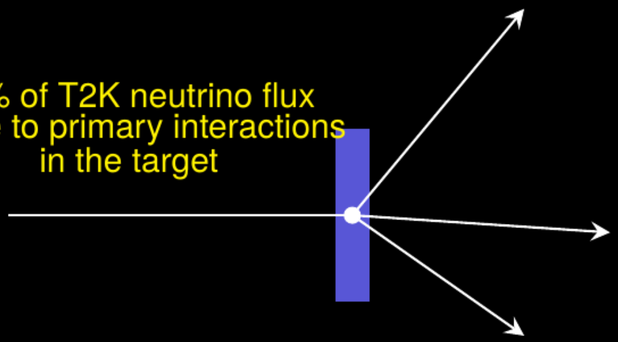
NA61/SHINE for T2K (pC @ 31 GeV/c)

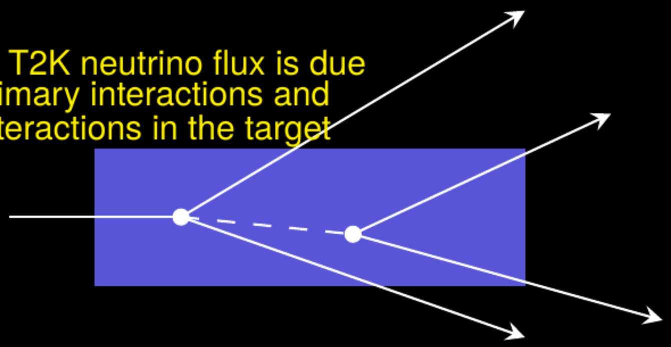
Thin carbon target

- 2.5×2.5 cm^2 , L = 2 cm = 0.04 λ_{int}
- Measurements of production cross section and spectra of $\pi^{\pm}$, $K^{\pm}$, K^0_s, p, Λ L.Zambelli's PhD

T2K replica target

- L = 90 cm = 1.9 λ_{int}, r = 1.3 cm
- Measurement of charged pion spectra exiting the target

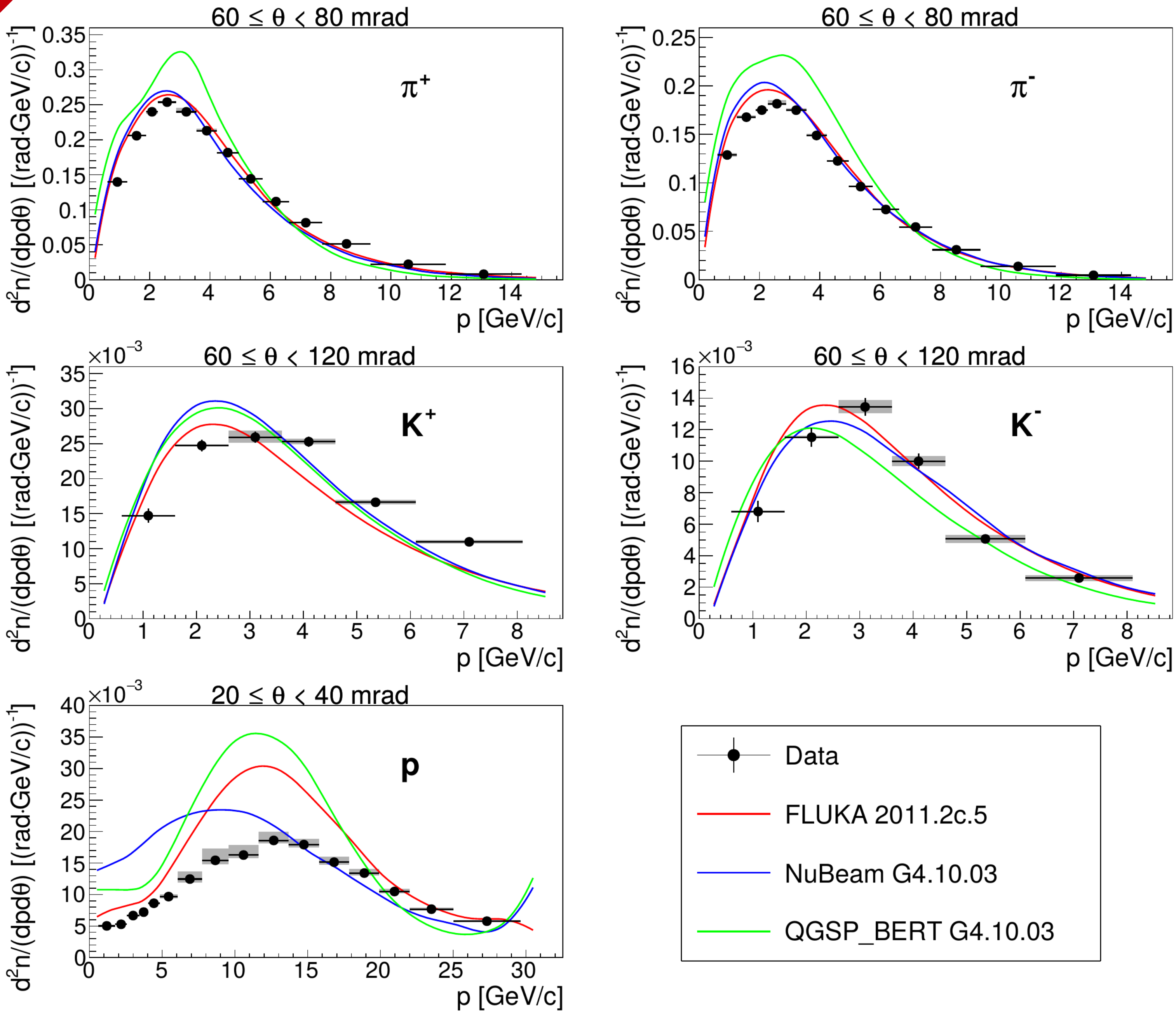




Beam	Target	Year	Triggers [10^6]	Status	Comment
	thin	2007	0.7	published ($\pi^{\pm}$, K^+, K^s_0, Λ)[1,2]	has been used for T2K
protons	replica	2007	0.2	published ($\pi^{\pm}$)[3,4]	proof of principle
at	thin	2009	5.4	published ($\pi^{\pm}$, $K^{\pm}$, p, K^s_0, Λ)[5,6]	being used in T2K
31 GeV/c	replica	2009	2.8	published ($\pi^{\pm}$)[7,8]	being used in T2K
	replica	2010	10.2	analysis finalized (M.Pavin's PhD)	prepared for use in T2K

[1] Phys. Rev. C84, 034604 (2011).
[2] Phys. Rev. C85, 035210 (2012).
[3] Nucl. Instrum. Meth. A701, 99 (2013).
[4] CERN-THESIS-2011-165
[5] CERN-THESIS-2013-290
[6] Eur. Phys. J. C76, no.2, 84 (2016)
[7] CERN-THESIS-2015-103
[8] Eur. Phys. J. C76, no.11, 617 (2016)

NA61/SHINE: T2K replica-target results



Measured hadron yields from second longitudinal (18-cm long) target bin in a selected polar angle interval.

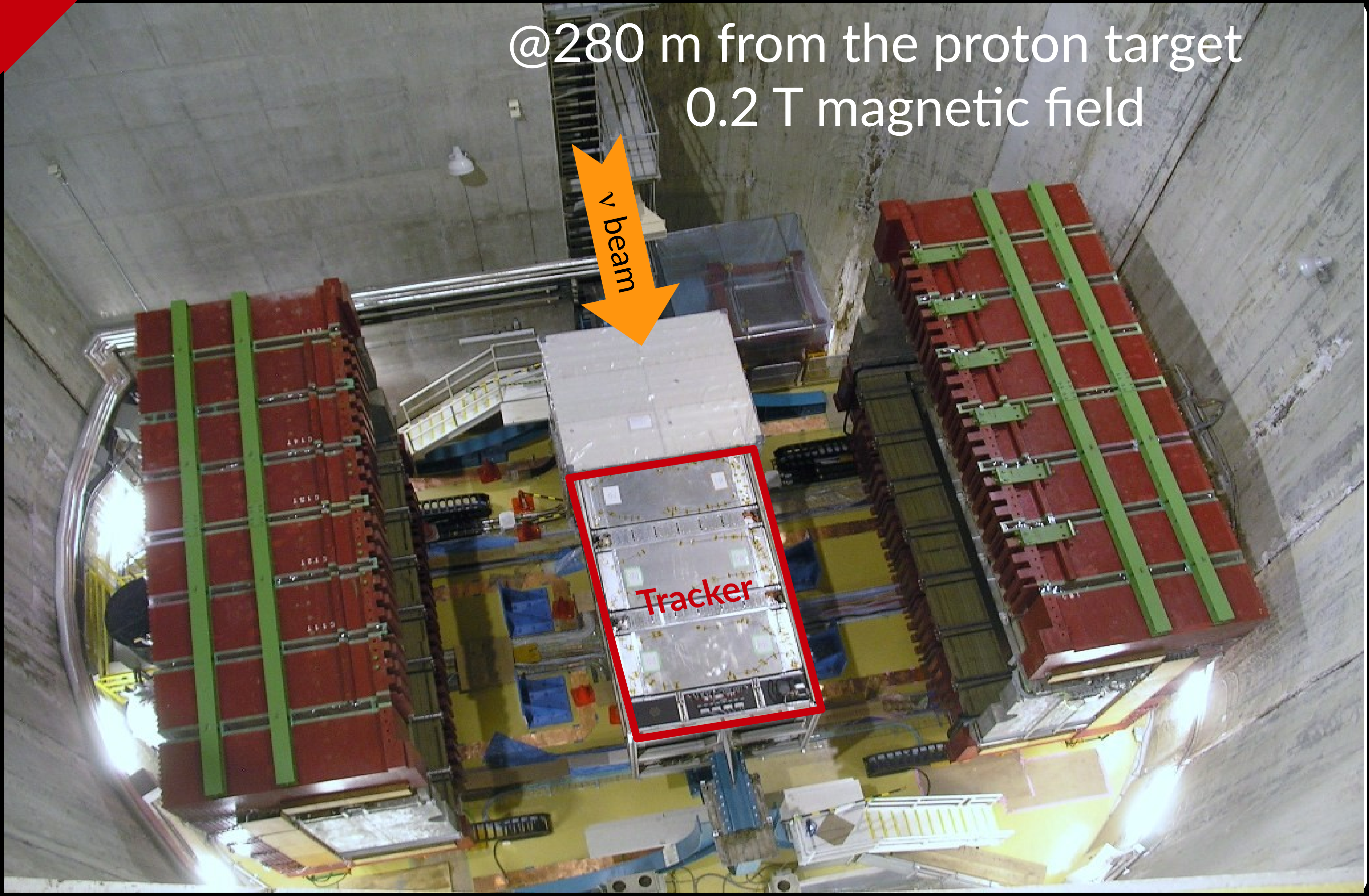
Comparison with model predictions.

These new data are being prepared for publication.

They will be used for further reduction of uncertainties on (anti-)neutrino flux in T2K, see later.

M.Pavin's PhD

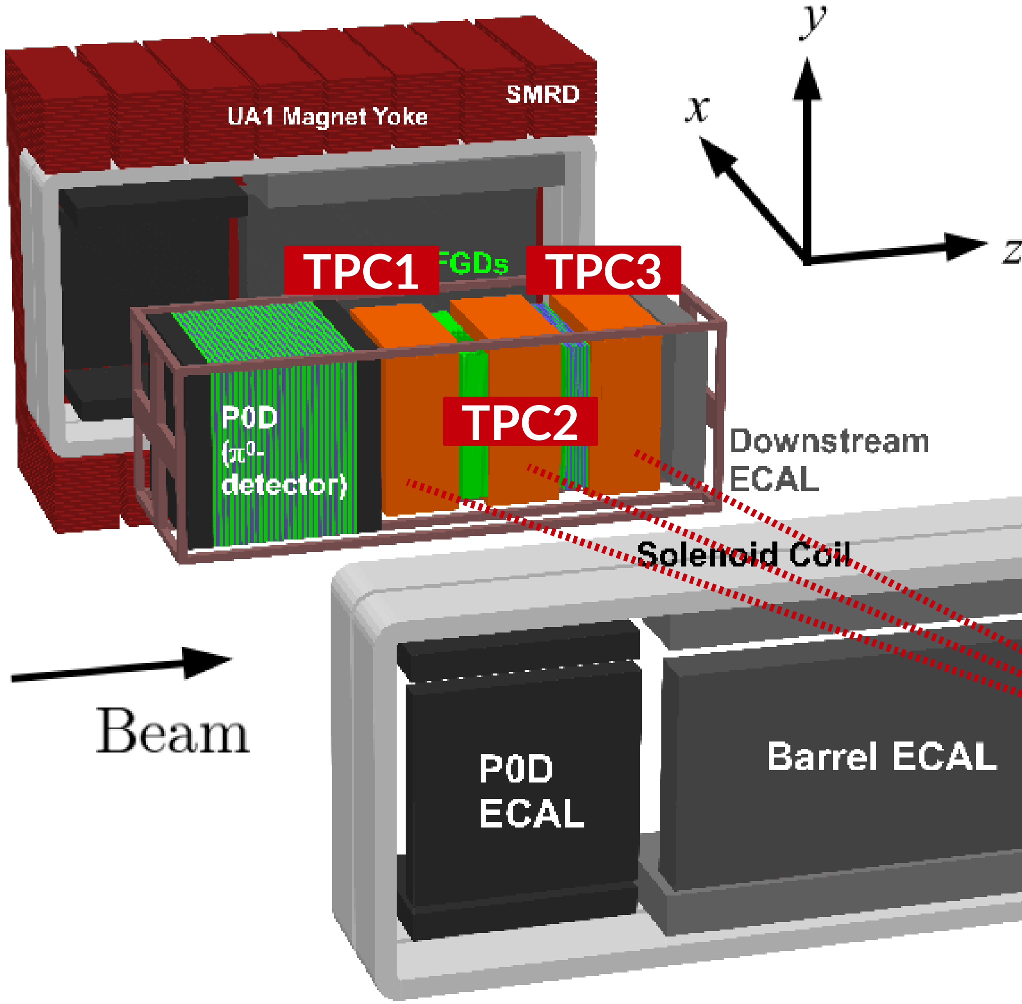
The T2K off-axis near detector: ND280

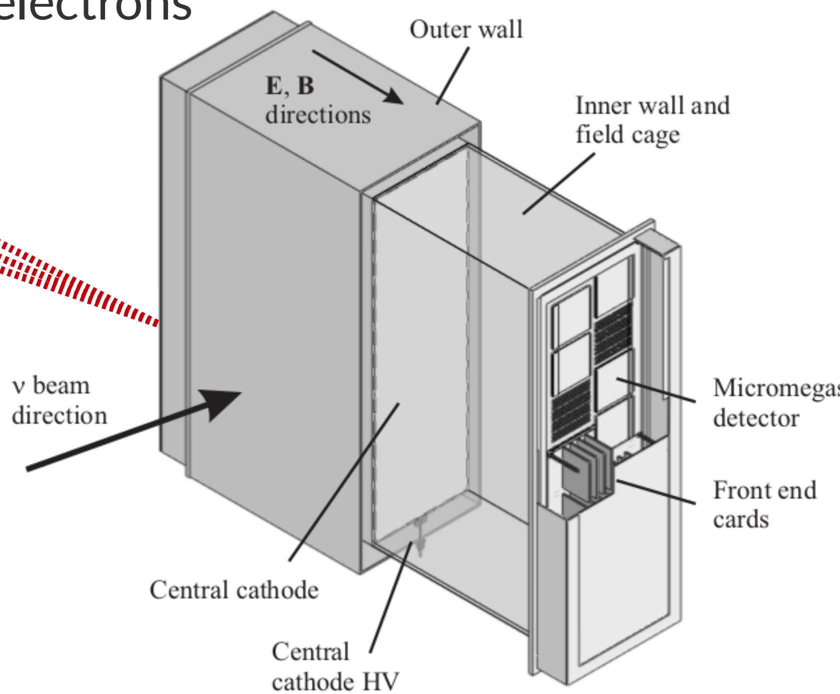


Time Projection Chambers (TPCs)

Argon-based gaseous detectors with good tracking and particle identification

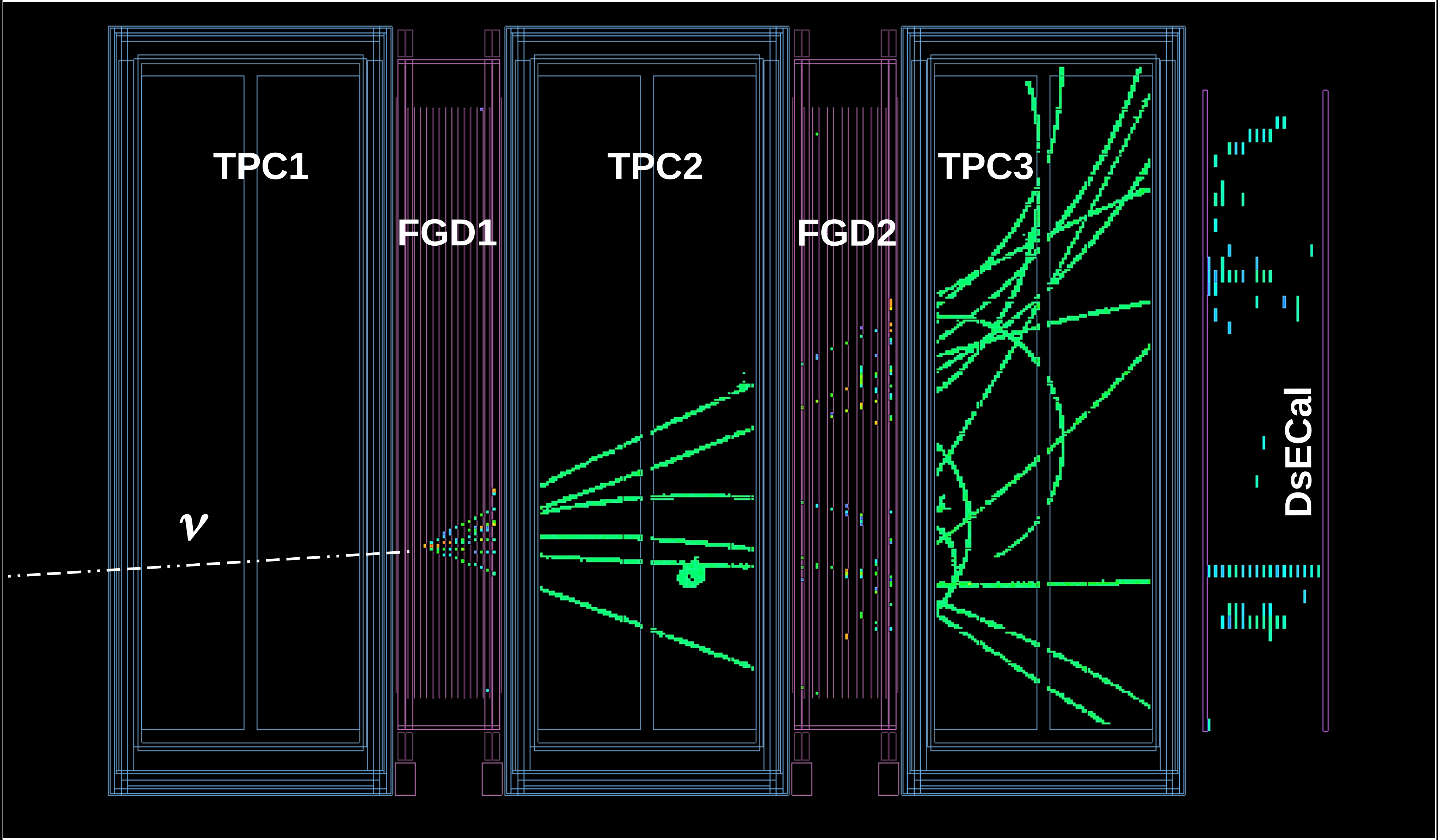
- Measure the momentum (10% resolution at 1 GeV/c) and the sign of charged particles
- Good separation between muons and electrons





LPNHE contributions: magnet and TPCs

ND280 reconstructed (tracker) event

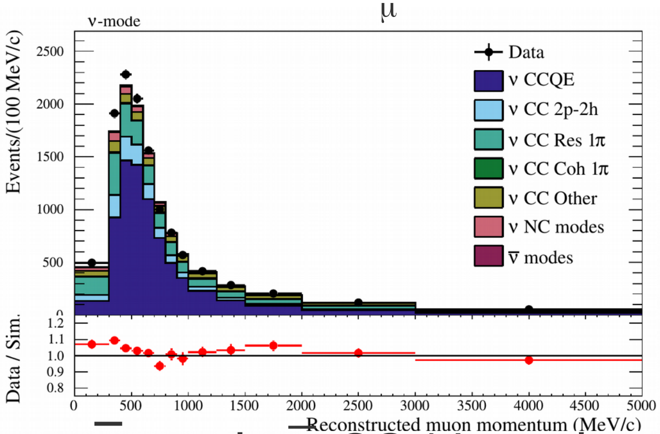


ND280 constraints

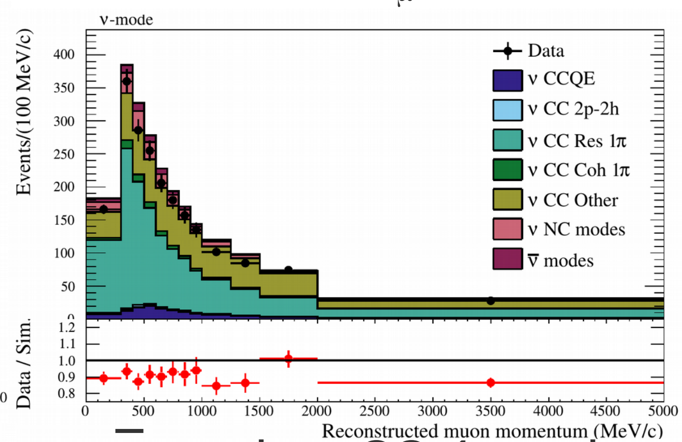
- Several ν_μ CC and $\bar{\nu}_\mu$ CC samples in ν-mode and $\bar{\nu}$-mode are selected according to the event topology
- The simulation is fit to the data to adjust flux and cross-section parameters

ND280 data reduce the uncertainty on the expected number of events at SK (flux x cross-section) from ~25% down to below ~3%

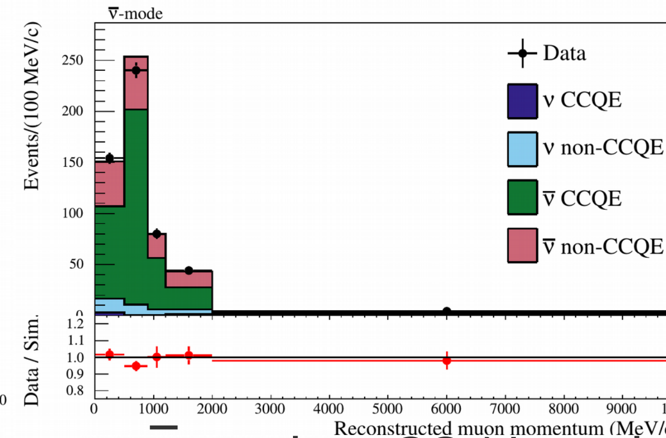
ν-mode ν_μ CC-0π



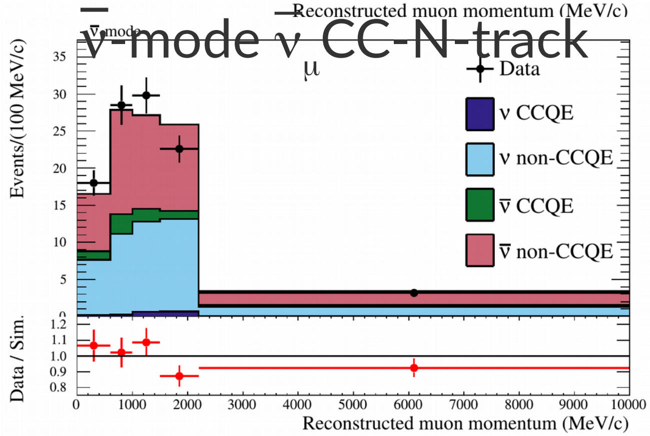
ν-mode ν_μ CC-1π^+



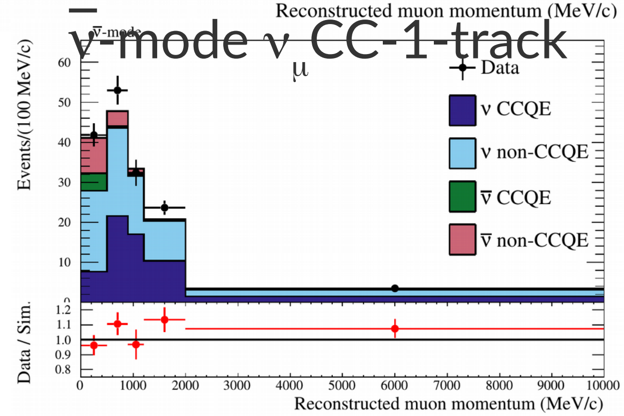
$\bar{\nu}$-mode $\bar{\nu}_\mu$ CC-1-track



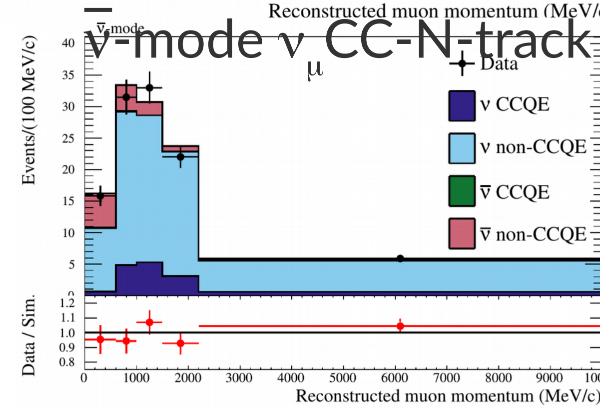
$\bar{\nu}$-mode ν_μ CC-N-track



$\bar{\nu}$-mode ν_μ CC-1-track



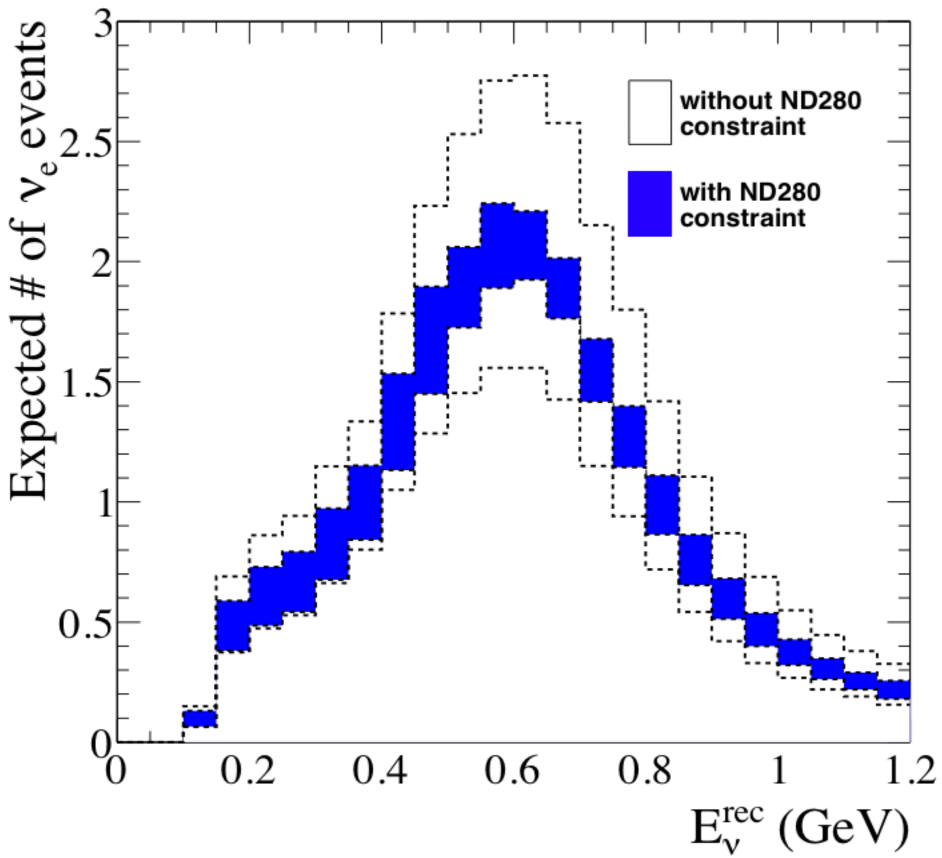
$\bar{\nu}$-mode ν_μ CC-N-track



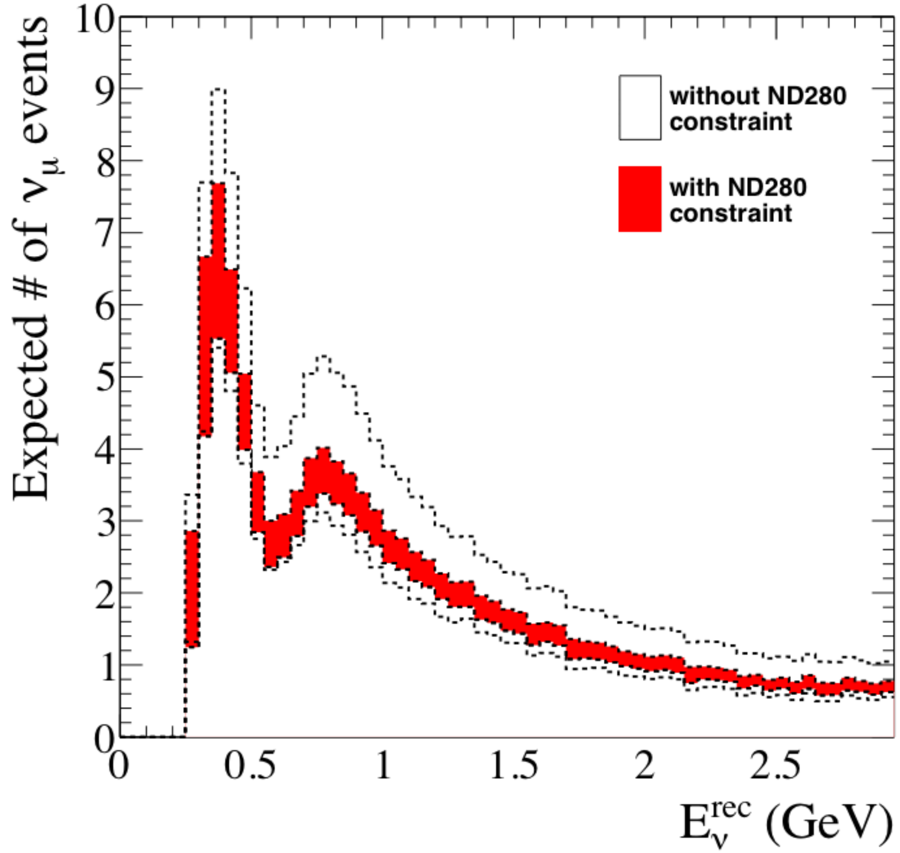
ND280 constraints for Super-K

Examples of error reduction on the expected number of events in Super-K

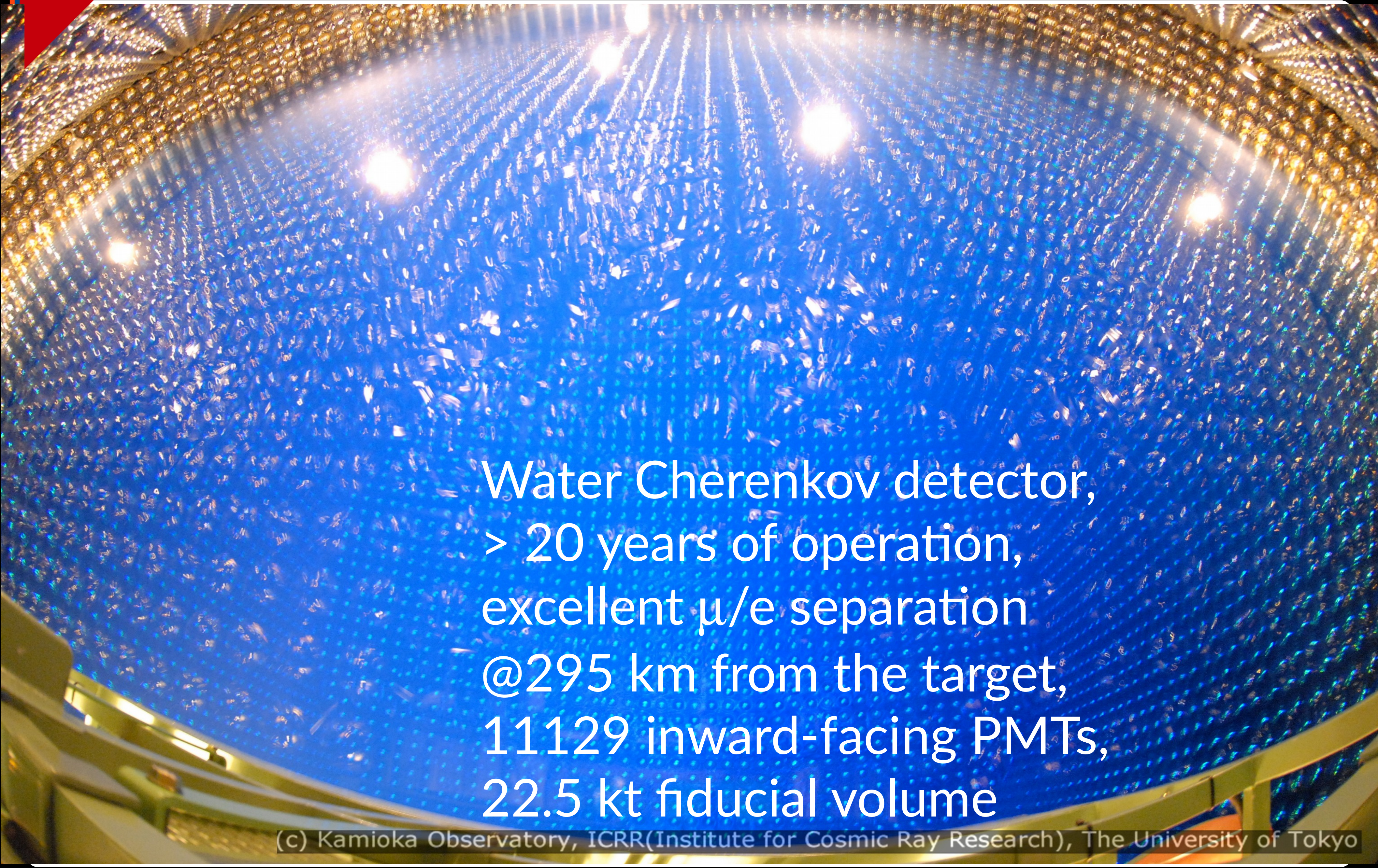
For $\nu_\mu \rightarrow \nu_e$ appearance



For ν_μ disappearance



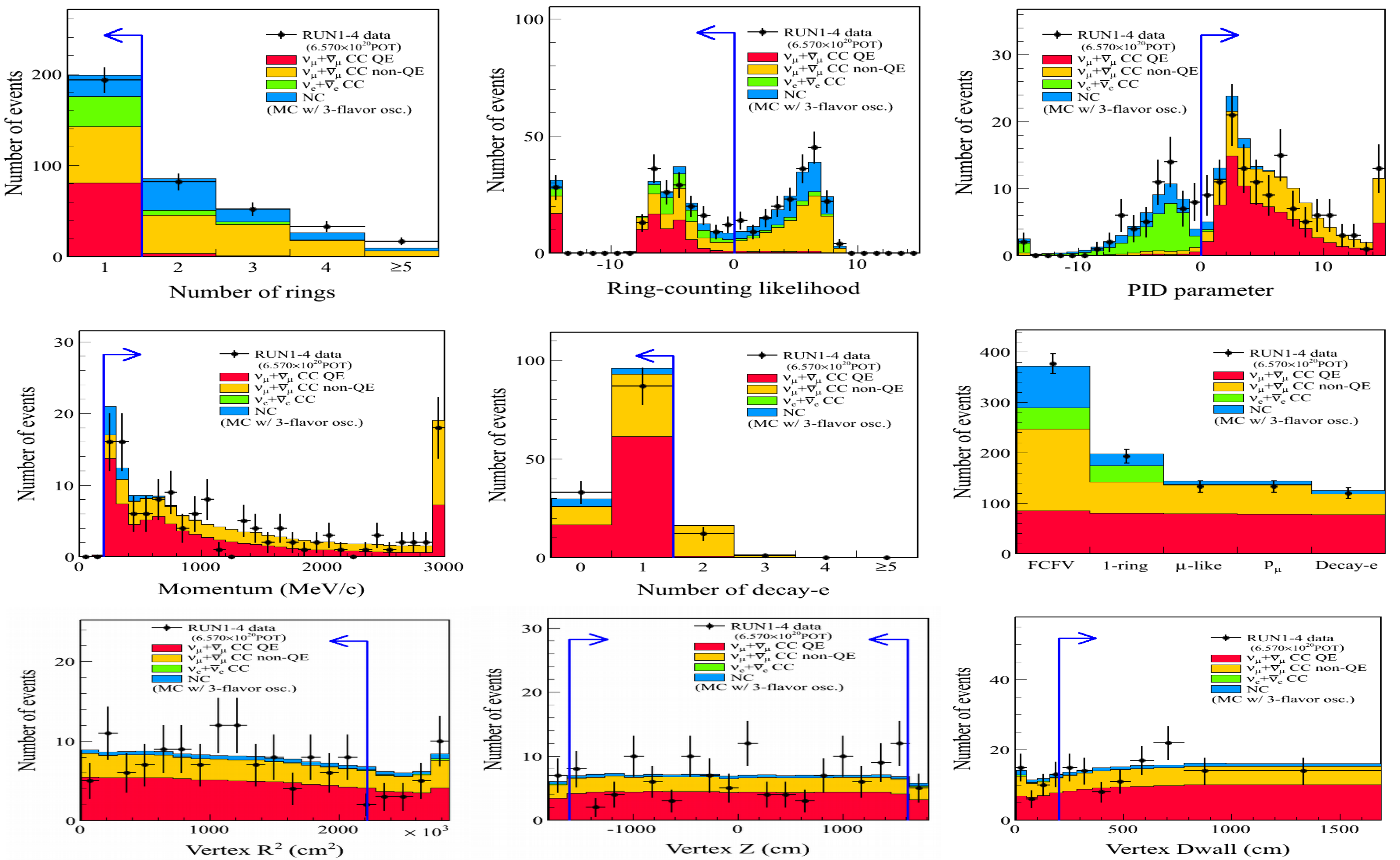
The T2K far detector: Super-K



Water Cherenkov detector,
> 20 years of operation,
excellent μ/e separation
@295 km from the target,
11129 inward-facing PMTs,
22.5 kt fiducial volume

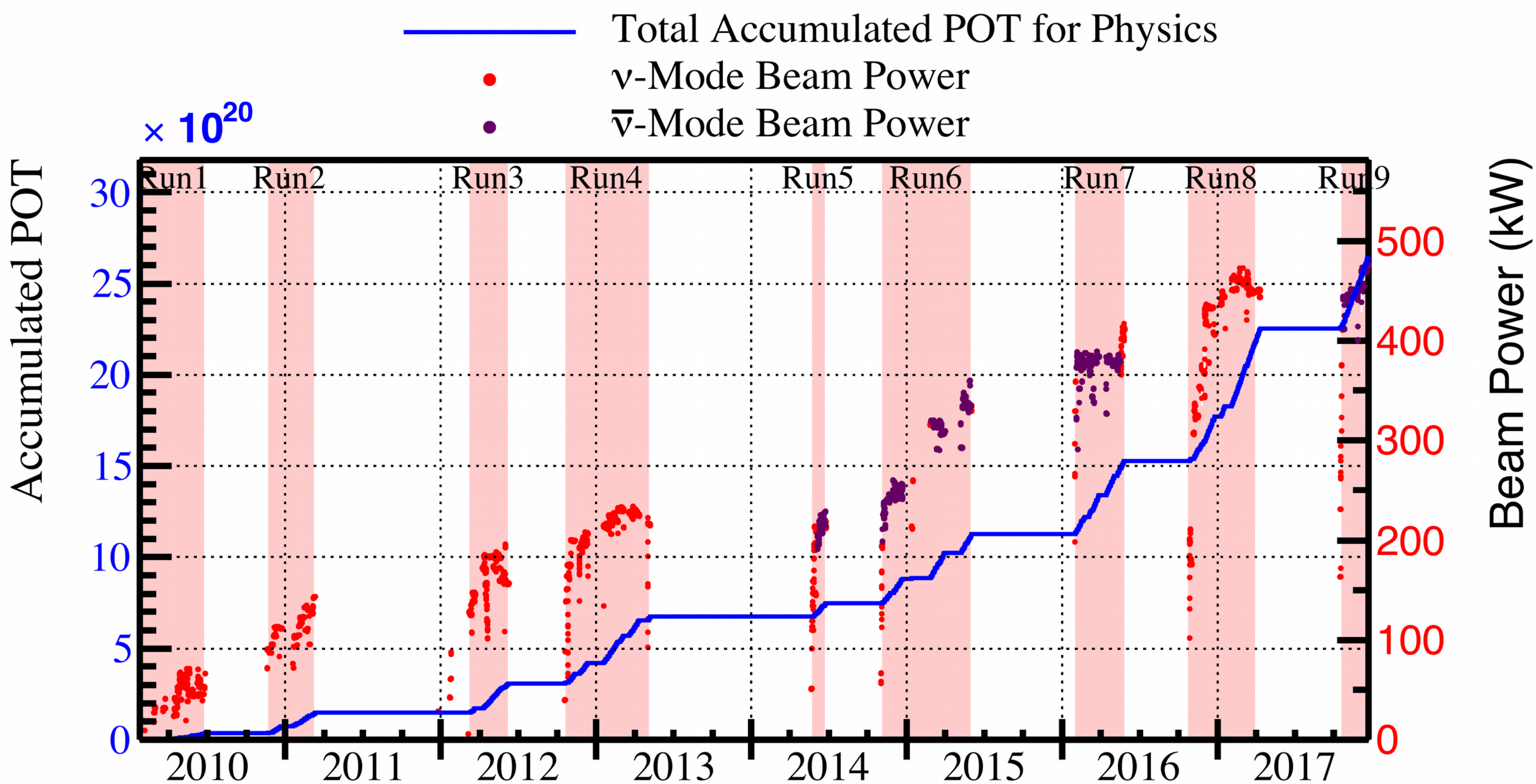
Super-K event selection examples

Detector is well-understood



Collected data (up to end of 2017)

Reached stable operation at 480 kW beam power by now!



23 Jan. 2010 - 22 Dec. 2017

POT total: 2.65×10^{21}

ν-mode 1.51×10^{21} (57.14%)

$\bar{\nu}$-mode 1.14×10^{21} (42.86%)

A selection of recent T2K results

Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam

T2K Collaboration (K. Abe (Tokyo U., ICRR) *et al.*). Jun 2011. 20 pp.

Published in **Phys.Rev.Lett. 107 (2011) 041801**

DOI: 10.1103/PhysRevLett.107.041801

e-Print: **arXiv:1106.2822 [hep-ex] | PDF**

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote

ADS Abstract Service; OSTI Information Bridge Server; Interactions.org article

Detailed record - Cited by 1333 records 1000+ (as of Dec,20 2017)

First T2K physics paper

FUNDAMENTAL PHYSICS BREAKTHROUGH PRIZE

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LAUREATES

2016 BREAKTHROUGH PRIZE in FUNDAMENTAL PHYSICS

Koichiro Nishikawa and the K2K and T2K Collaboration

Affiliation when awarded Breakthrough Prize: KEK: High Energy Accelerator Research Organization

Citation: For the fundamental discovery and exploration of neutrino oscillations, revealing a new frontier beyond, and possibly far beyond, the standard model of particle physics.

Based on 1.43×10^{20} p.o.t.

6 events observed while expected background is 1.5 ± 0.3 (syst)

First indication of $\nu_\mu \rightarrow \nu_e$ appearance and non-zero value of θ_{13} with a significance of 2.5σ

Discovery of $\nu_\mu \rightarrow \nu_e$ appearance

Phys. Rev. Lett. 112 (2014) 061802

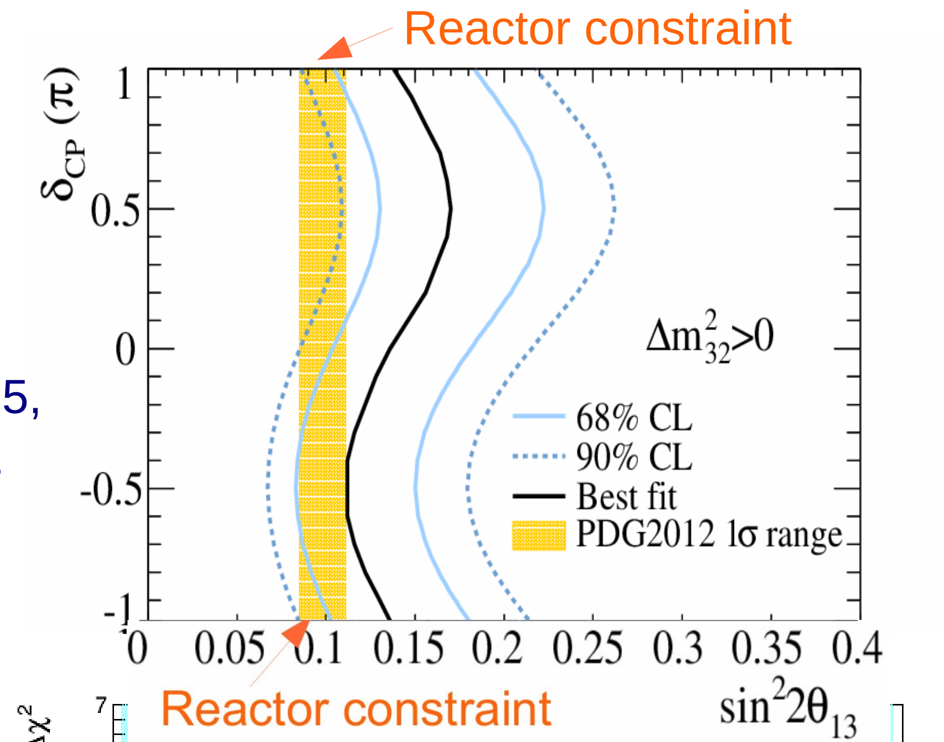
Based on 6.57×10^{20} p.o.t.

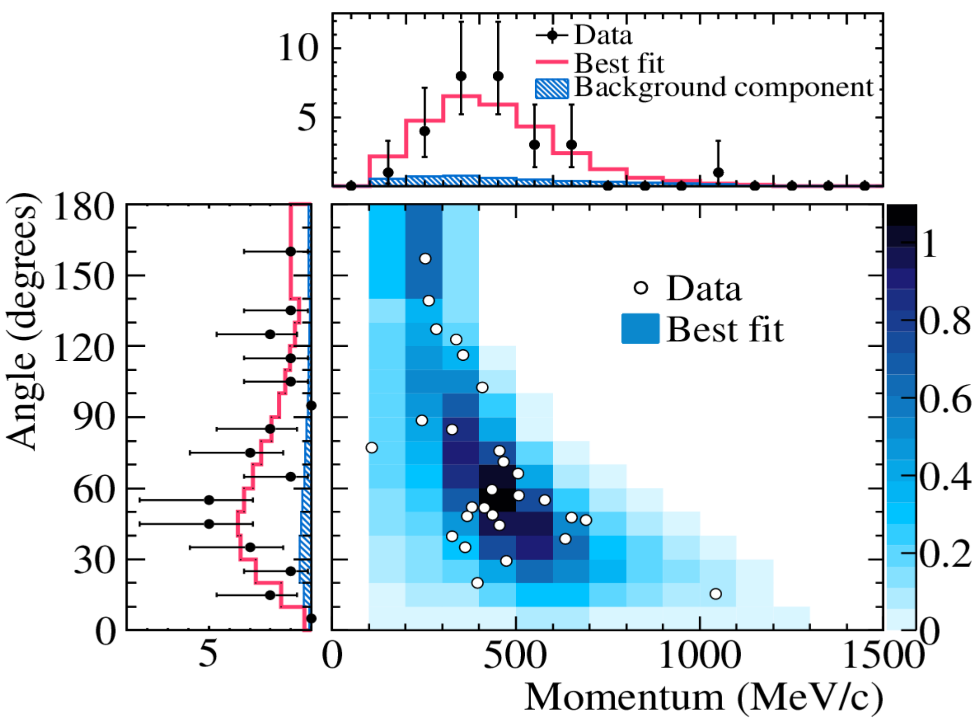
28 events observed while expected background is 4.92 ± 0.55

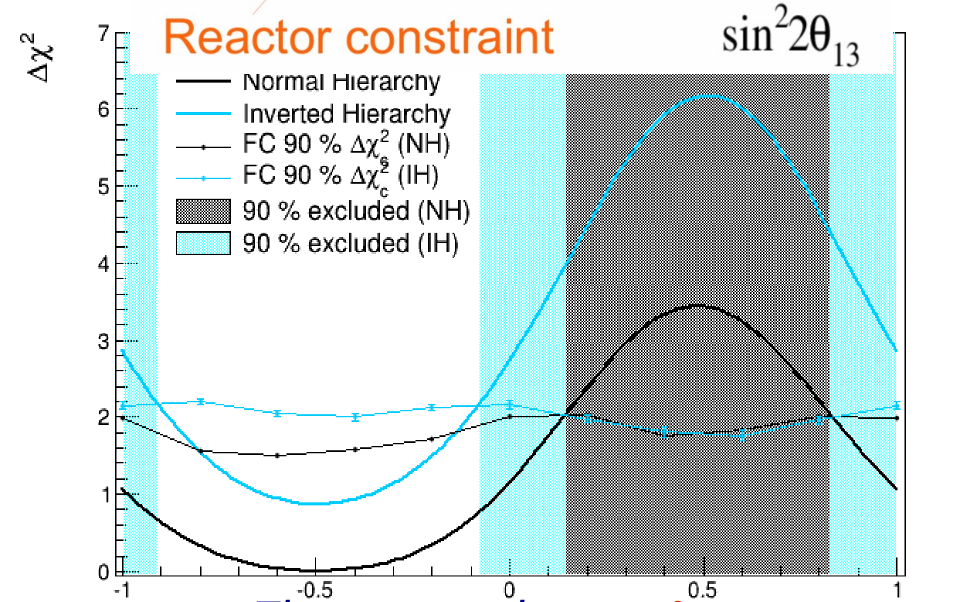
First observation of neutrino appearance with a significance of 7.3σ

Assuming $|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2, $\sin^2\theta_{23}=0.5$, $\delta_{CP}=0$, and $\Delta m^2_{32}>0$ ($\Delta m^2_{32}<0$) a best fit is

$\sin^2 2\theta_{13}=0.140^{+0.038}_{-0.032}$ $(0.170^{+0.045}_{-0.037})$







First constraints on δ_{CP}

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

Phys. Rev. Lett. 116 (2016) 181801

Since 2014 T2K started running in anti-neutrino mode

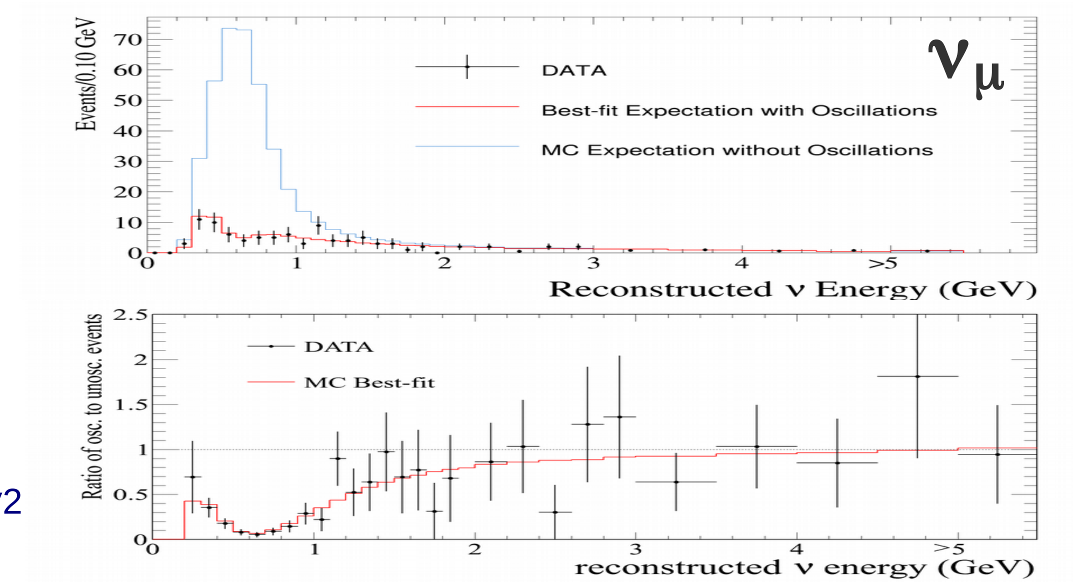
First analysis of $\bar{\nu}_\mu$ disappearance:

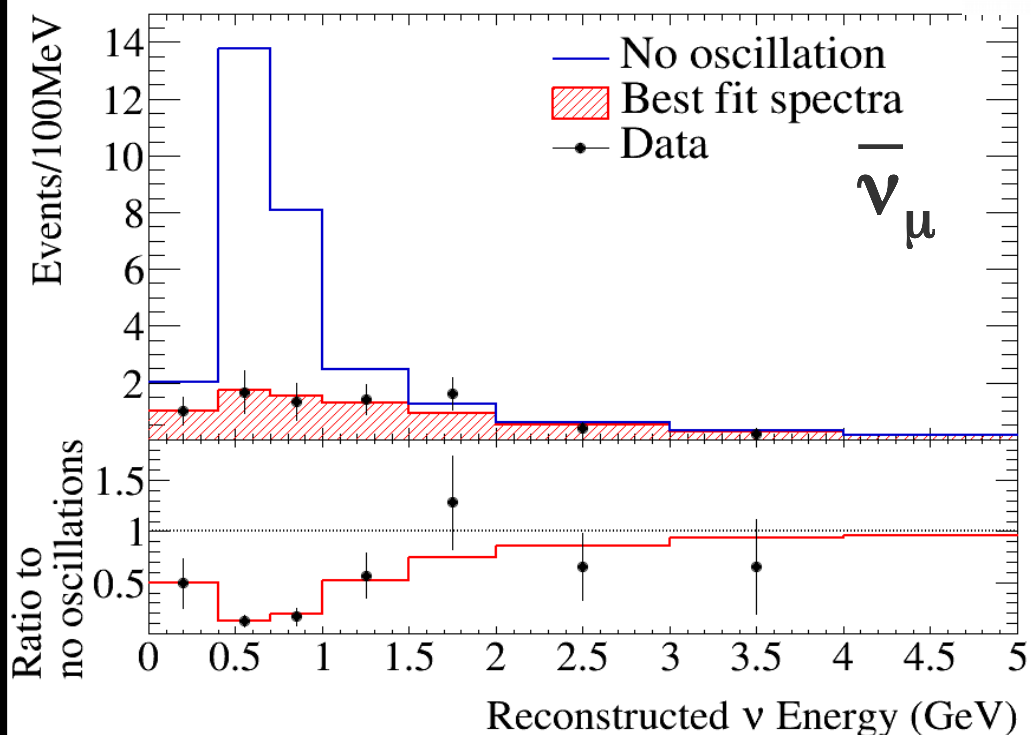
Based on 4.01×10^{20} p.o.t.

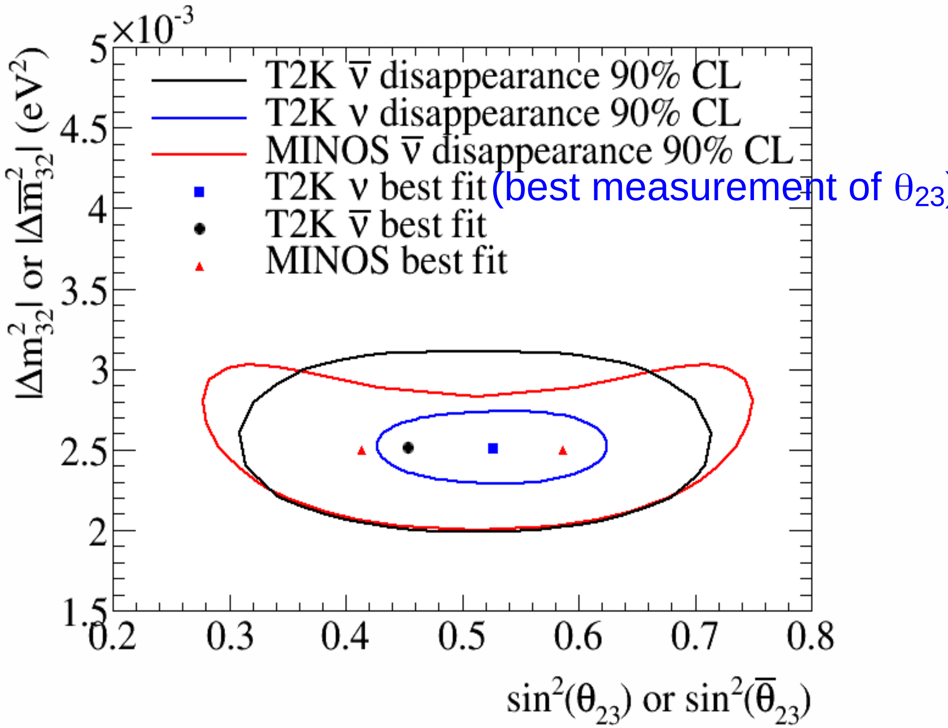
34 events observed

Best-fit:

$\sin^2 \bar{\theta}_{23} = 0.45$, $|\Delta \bar{m}^2_{32}| = 2.51 \times 10^{-3}\ \mathrm{eV}^2$

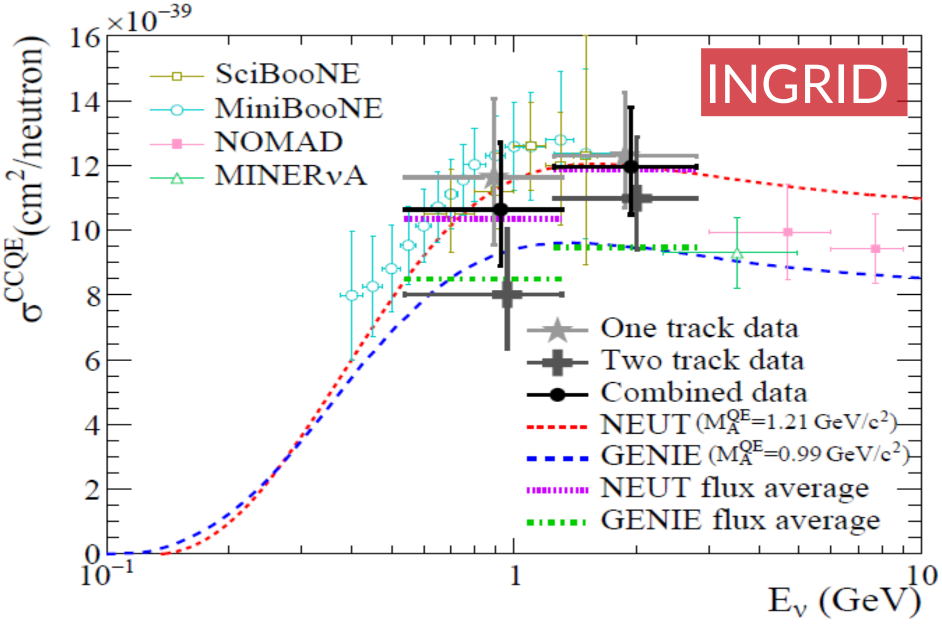


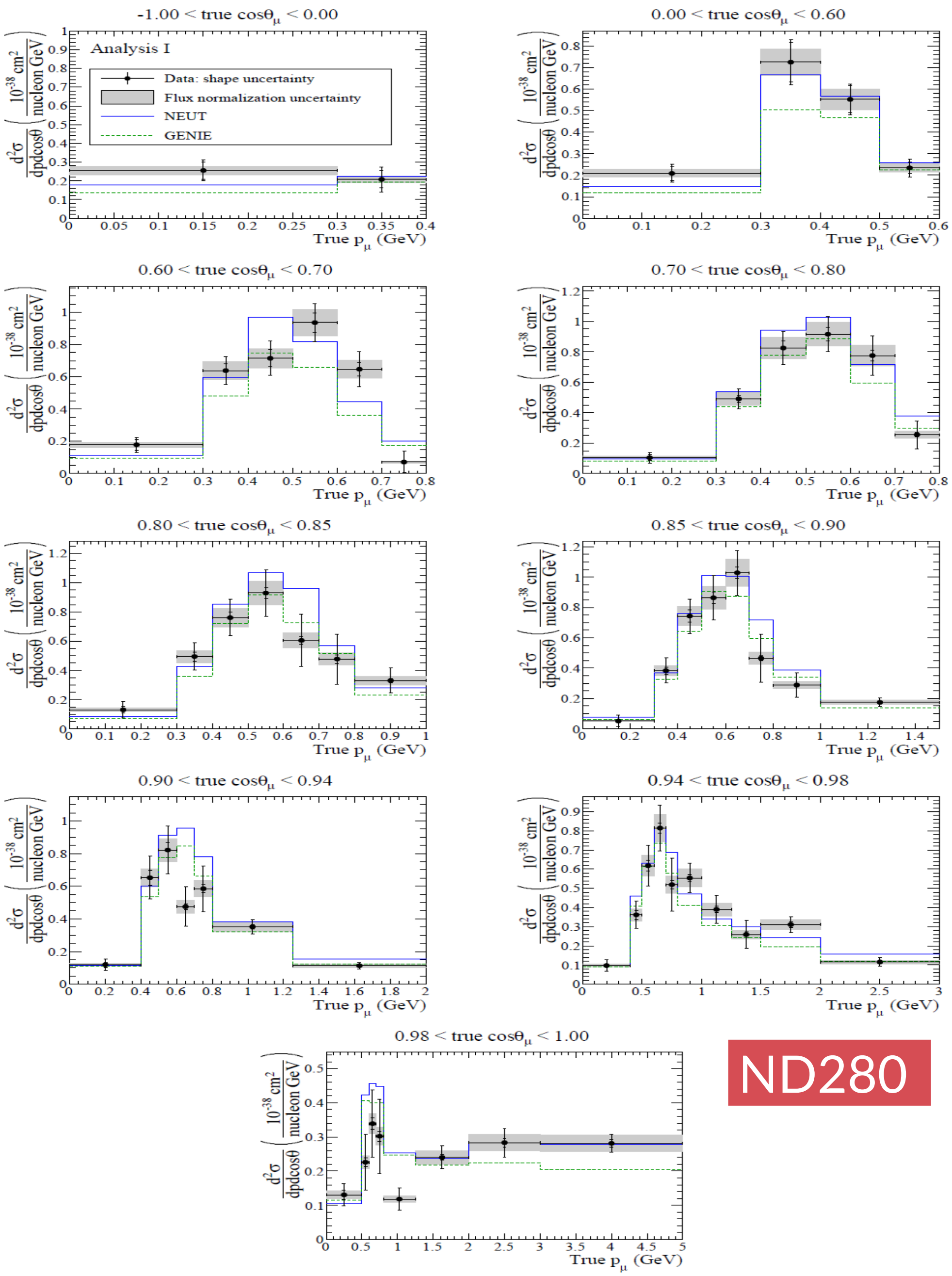




ν cross section measurements in T2K

- Significant efforts within T2K towards better measurements of neutrino cross sections
  - *Crucial for precise determination of oscillation parameters*
- Measurements are performed using ND280, INGRID and SK
- Examples are shown here: *recent results on double differential ν_μ CC interactions on C_8H_8 without pions in the final state* and *ν_μ CCQE cross section on Carbon*





ν cross section measurements in T2K

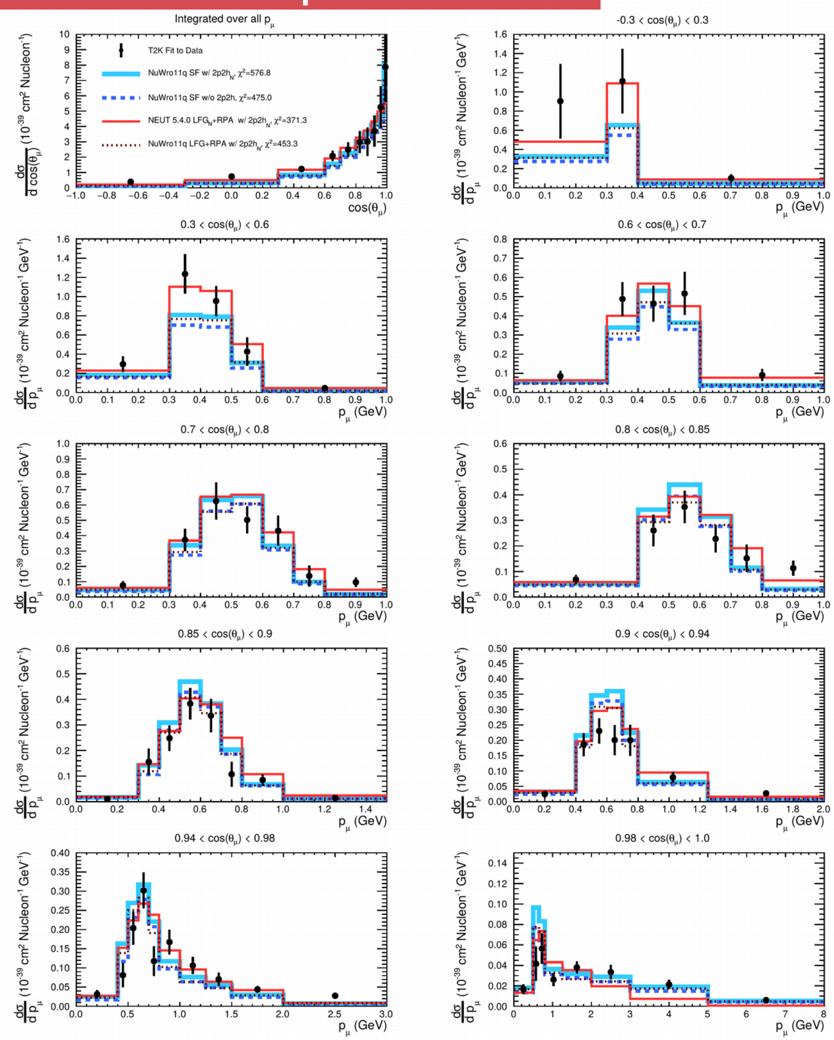
Based on P.Bartet-Friburg's work

Recent measurements from ND280:

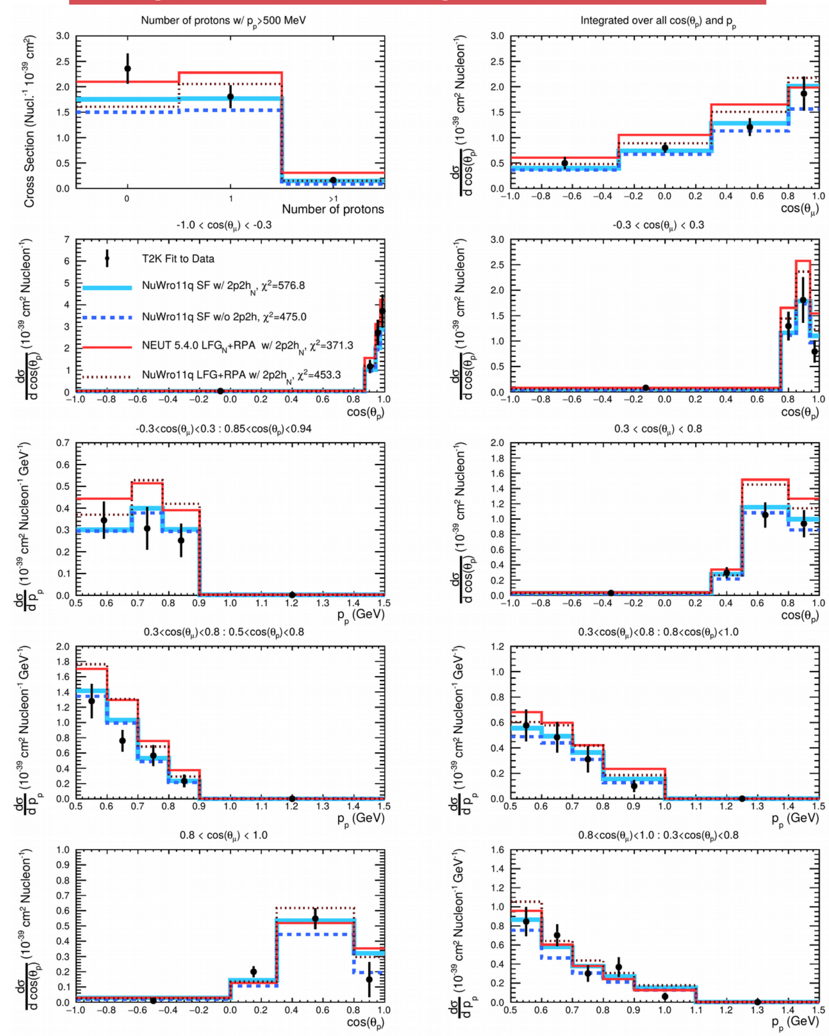
ν_μ CC pionless cross section as a function of muon and proton kinematics (for interactions with 0, 1 and 2 protons)

Important for characterization of nuclear effects in neutrino interactions

no protons with p>500 MeV



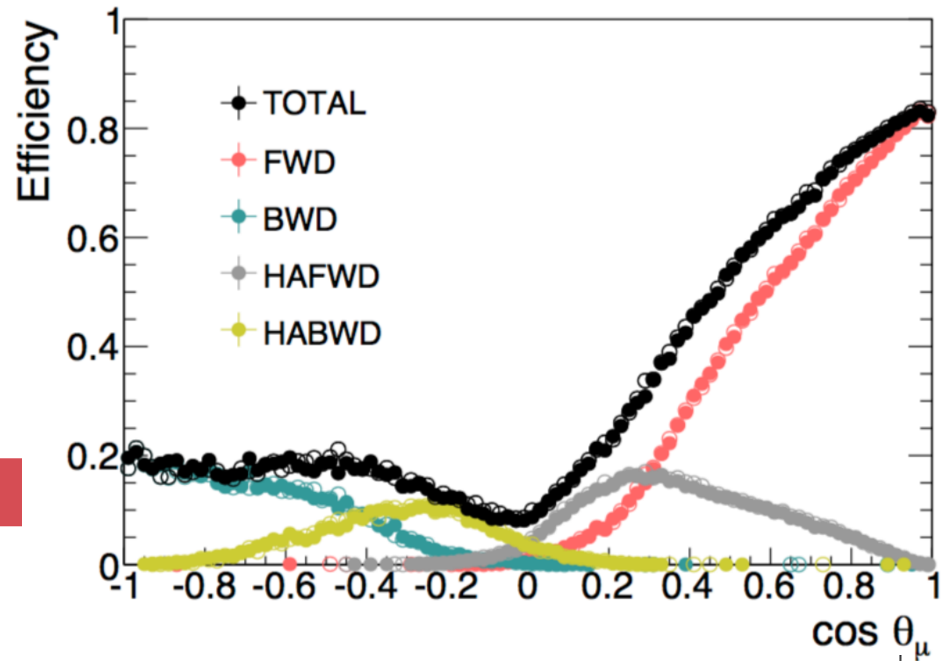
1 proton with p>500 MeV

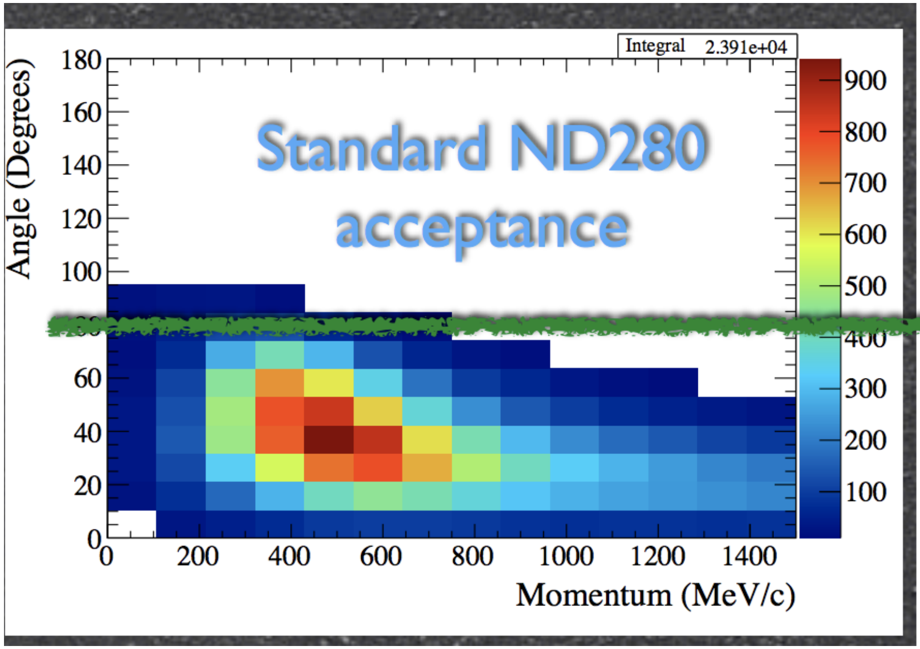


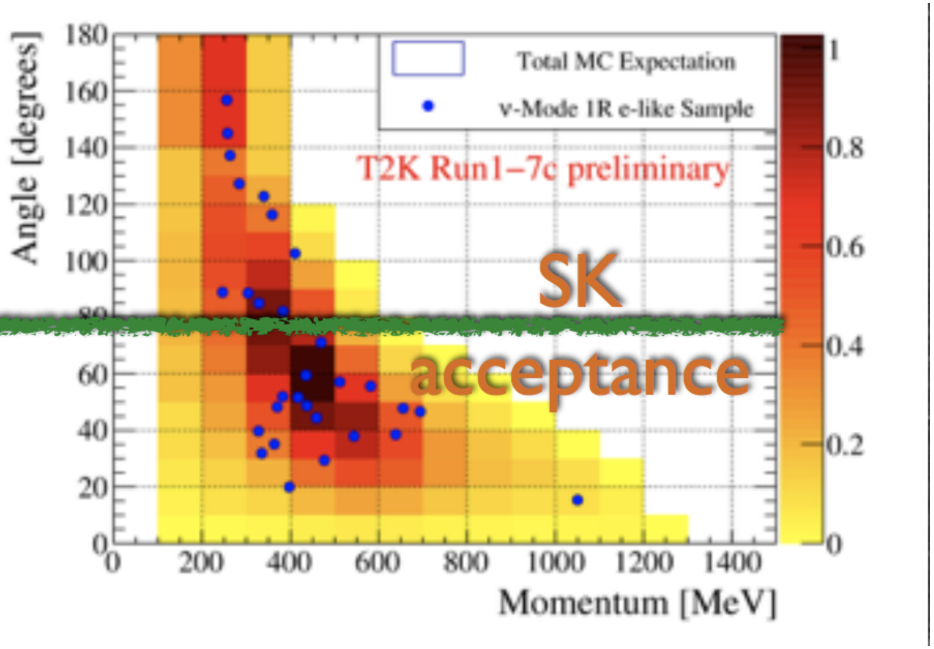
ND280 improved constraints

- The group contributed to the improved selection of ν_μ CC samples
- The efficiency for large-angle and backward-going tracks is improved

P.Bartet-Friburg's PhD







T2K current oscillation analysis: ND

Improved ND280 constraint

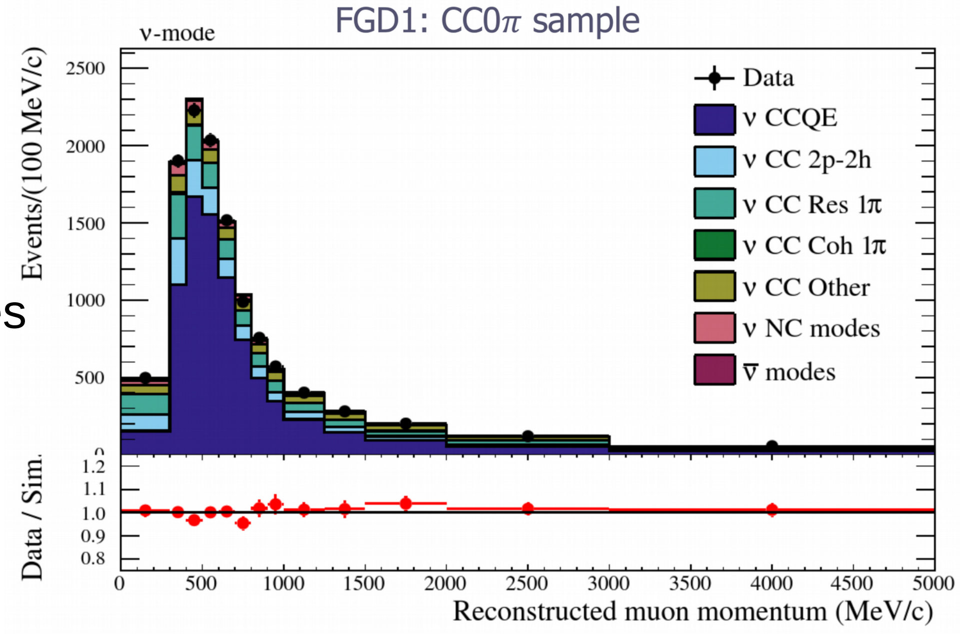
Neutrino flux parameters and neutrino cross section parameters are constrained by using 14 ND280 data samples (6 for ν_μ , 8 for $\bar{\nu}_\mu$)

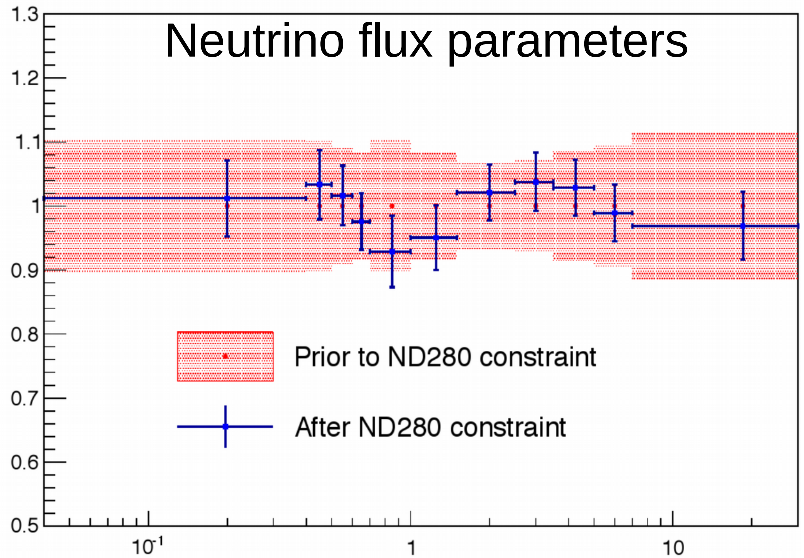
A binned likelihood is maximized to get the central values and the systematic uncertainties

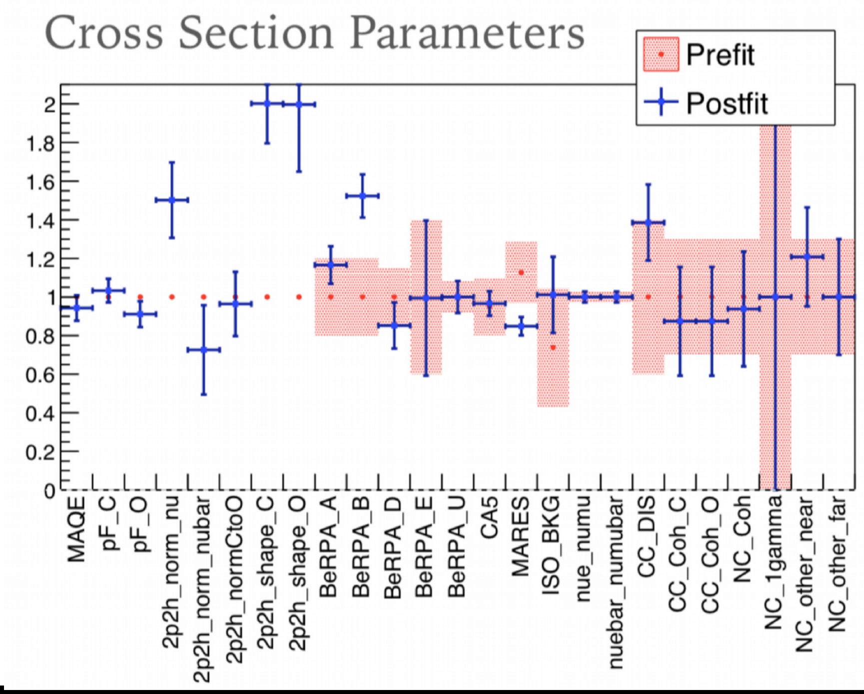
Examples are shown here: *for neutrino flux parameters and for cross section parameters*

Fitted flux parameters are close to their nominal values

The fit enhanced some of the cross section parameters (related to 2p-2h and RPA)







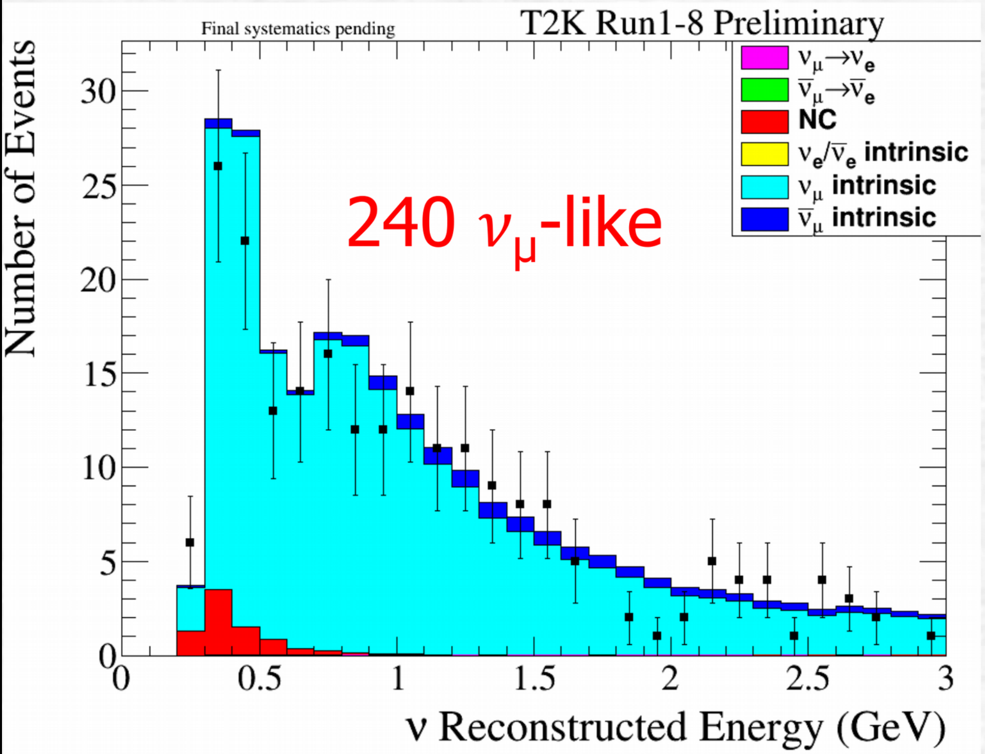
S.Bienstock's PhD

T2K current oscillation analysis: SK

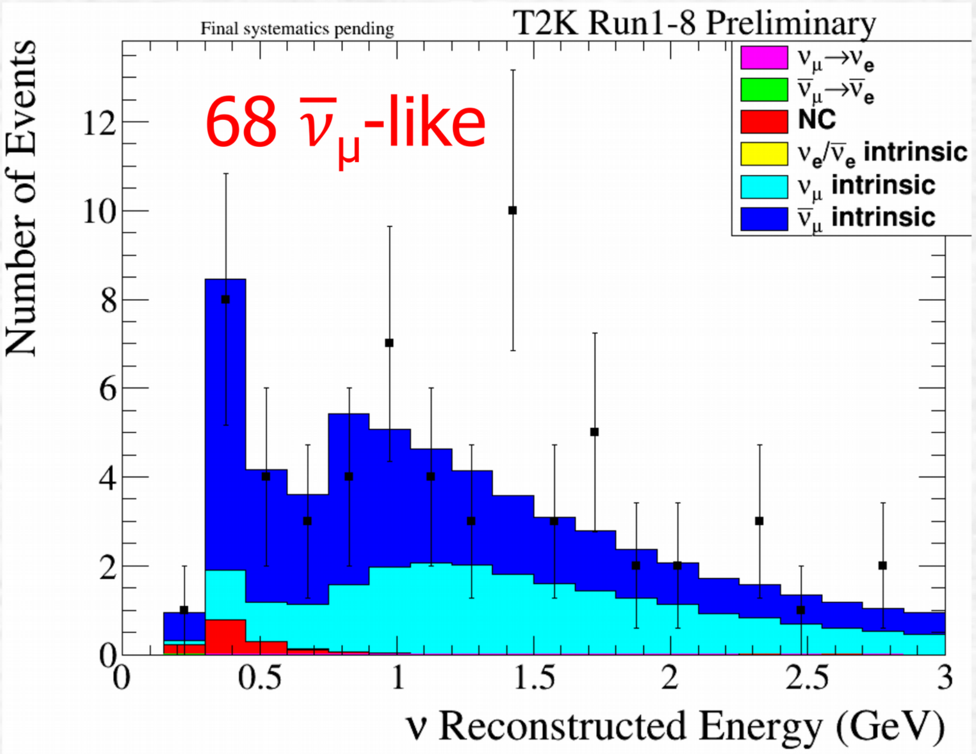
New reconstruction algorithm in Super-K

Re-optimization of the fiducial volume cut:
leads to ~30% increase in effective statistics

Neutrino mode (14.7×10^{20} POT)



Antineutrino mode (7.6×10^{20} POT)



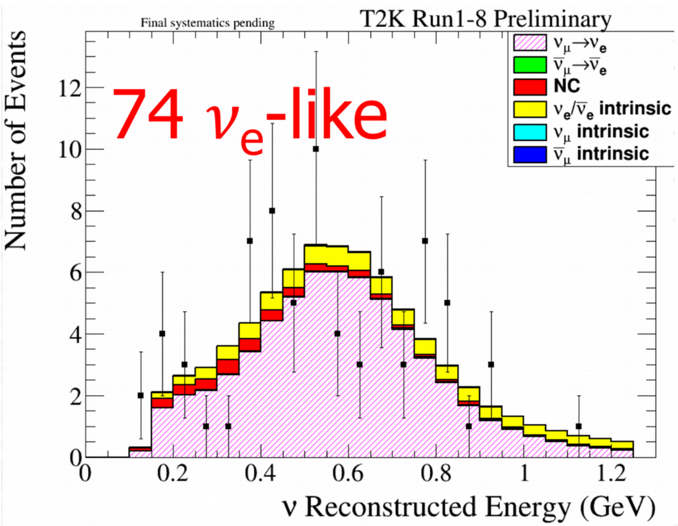
Data ν_μ-like	Expected			
	$\delta = -\pi/2$	$\delta = 0$	$\delta = \pi/2$	$\delta = \pi$
240	267.8	267.4	267.7	268.2

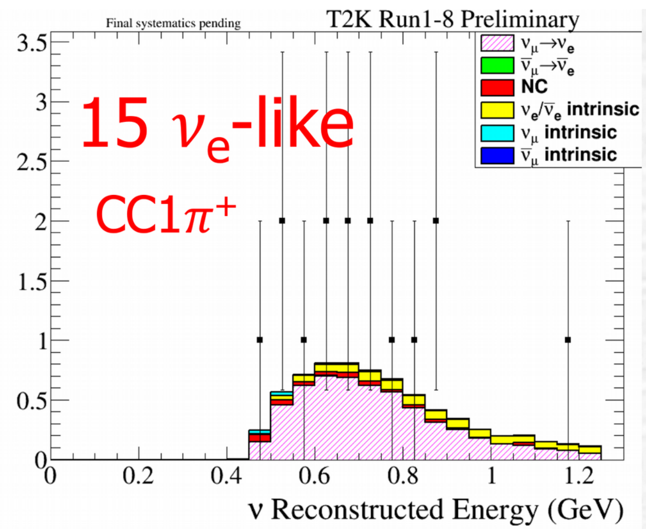
Data $\bar{\nu}_\mu$-like	Expected			
	$\delta = -\pi/2$	$\delta = 0$	$\delta = \pi/2$	$\delta = \pi$
68	63.1	62.9	63.1	63.1

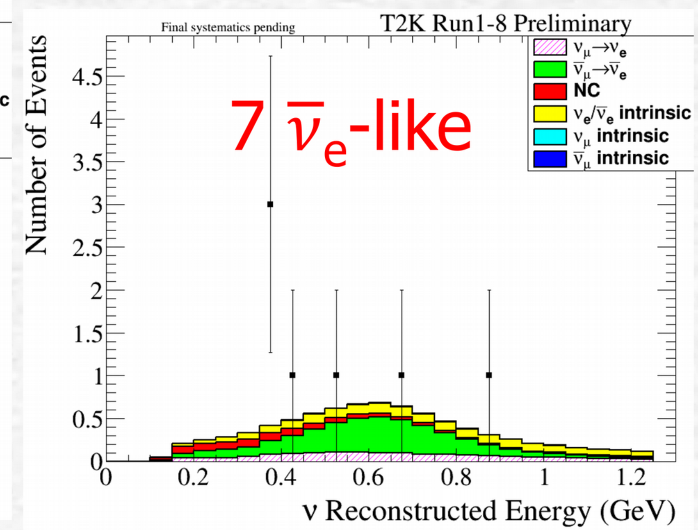
T2K current oscillation analysis: SK

New reconstruction algorithm in Super-K

Re-optimization of the fiducial volume cut:
leads to ~30% increase in effective statistics







Neutrino mode (14.7x10^{20} POT)

Data ν_e-like	Expected			
	δ = -π/2	δ = 0	δ = π/2	δ = π
74	73.5	61.5	49.9	62.0

CC1π^+ sample in **neutrino** mode:
1 e-like ring + 1 decay electron

Data ν_e-like CC1π^+	Expected			
	δ = -π/2	δ = 0	δ = π/2	δ = π
15	6.9	6.0	4.9	5.8

Antineutrino mode (7.6x10^{20} POT)

Data $\bar{\nu}_e$-like	Expected			
	δ = -π/2	δ = 0	δ = π/2	δ = π
7	7.9	9.0	10.0	8.9

T2K analysis: systematic errors (%)

Current systematic uncertainties (in %) on the number of events in Super-K

To be further improved with on-going and future efforts...

	1-Ring **μ-like**		1-Ring **e-like**			
Error source	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π^+	ν-/$\bar{\nu}$-modes
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI + SI + PN	2.20	1.98	3.01	2.31	11.43	1.57
Flux+Cross sect. con ND280	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.08	2.59	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.98	0.18
Total Systematic error	4.40	3.76	6.10	6.51	20.94	4.77

FSI = Final State Interaction
SI = Secondary interactions
PN = Photo-nuclear interactions
NC = Neutral Current

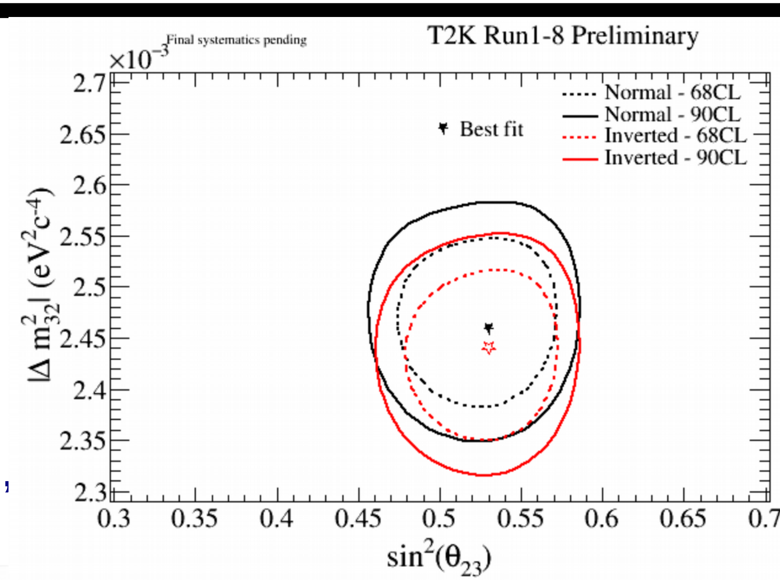
Total error is in 4-7% range (except for ν-mode CC1π sample)

T2K: joint fit of ν + $\bar{\nu}$ data

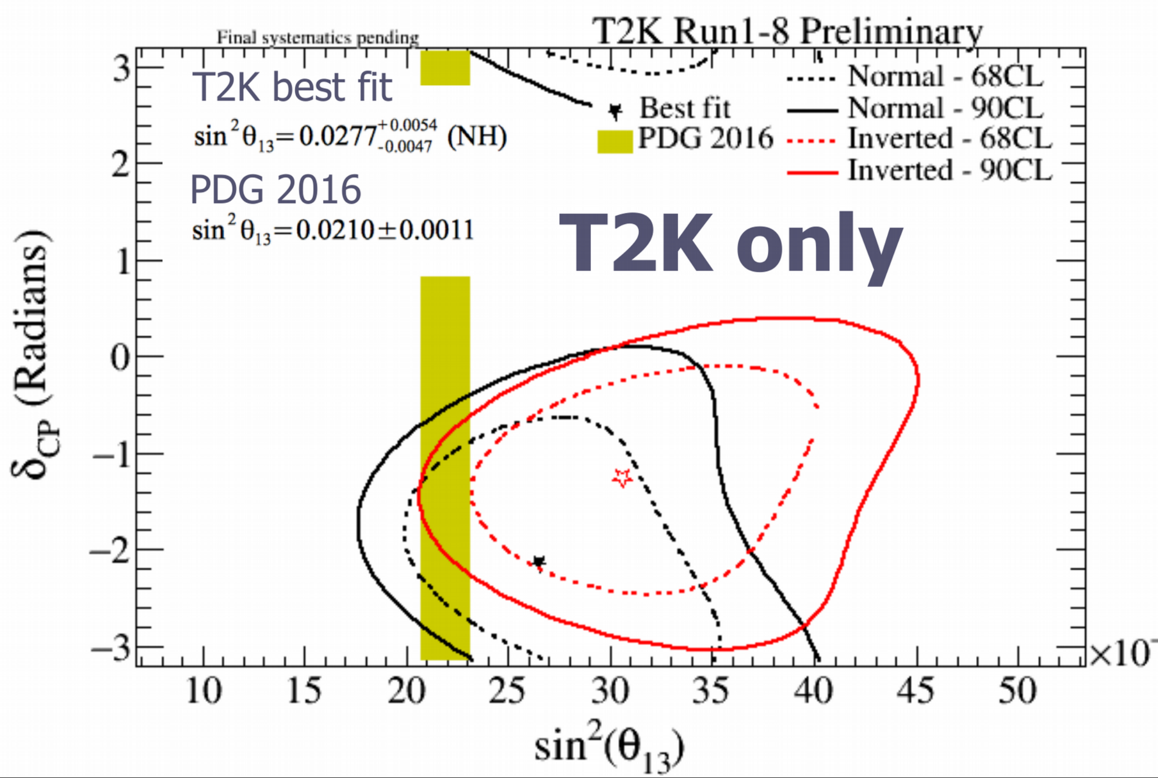
Joint fit of 5 SK data samples in ν and $\bar{\nu}$ mode

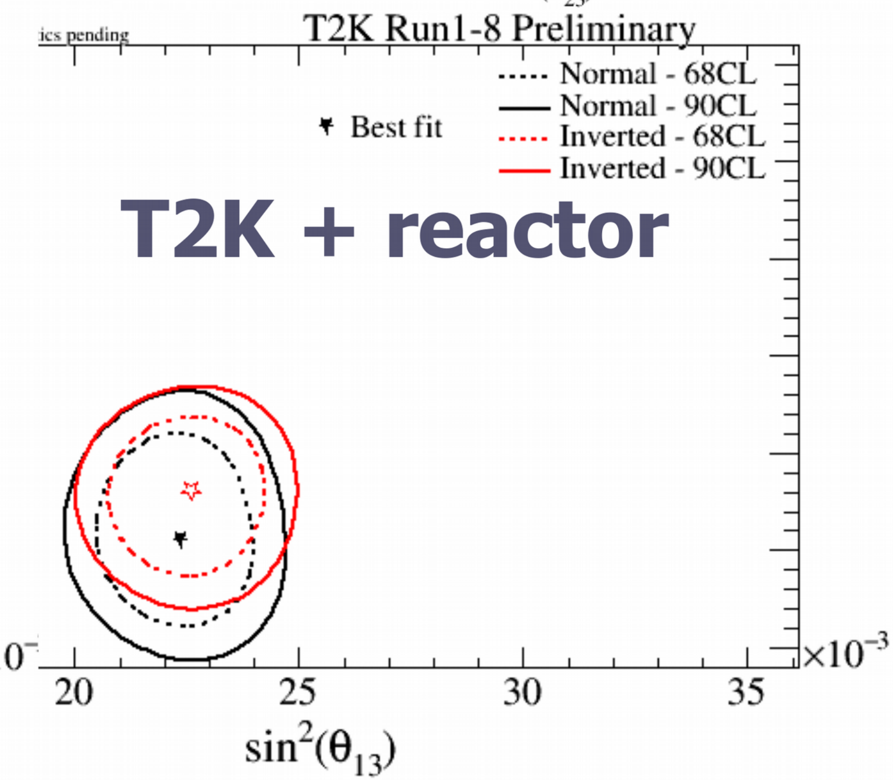
Final systematics pending

{$|\Delta m^2|$, $\sin^2\theta_{23}$}: fit the normal and inverted hierarchy separately, θ_{13} is reactor-constrained



{$\sin^2\theta_{13}$, δ_{CP}}: T2K-only fit (without reactor constraint) gives θ_{13} value compatible with reactor measurements, δ_{CP} close to $-\pi/2$ is preferred





T2K joint fit of $\nu + \bar{\nu}$ data: δ_{CP} result

Joint fit of 5 SK data samples in ν and $\bar{\nu}$ mode

Final systematics pending

$\{\sin^2\theta_{13}, \delta_{CP}\}$: T2K fit (with reactor constraint)

clear preference for δ_{CP} around $-\pi/2$

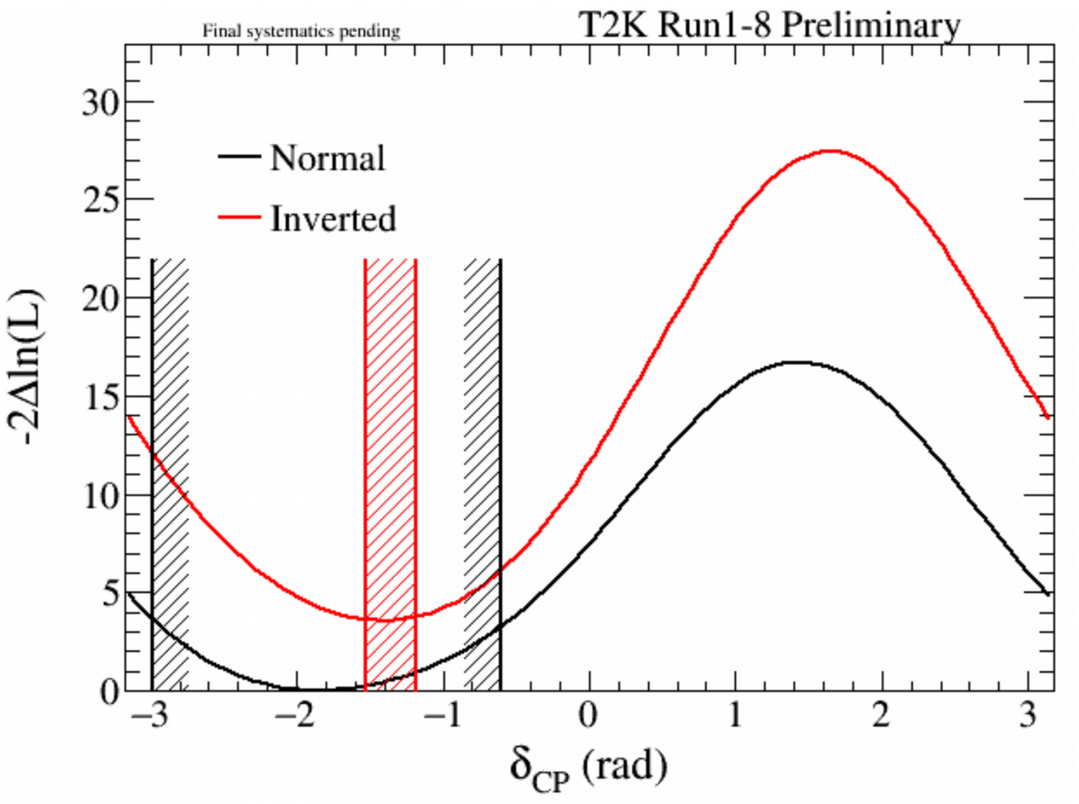
Best fit point: -1.83 radians with Normal mass ordering

2σ C.L. intervals:

Normal Ordering [-2.98; -0.60] radians

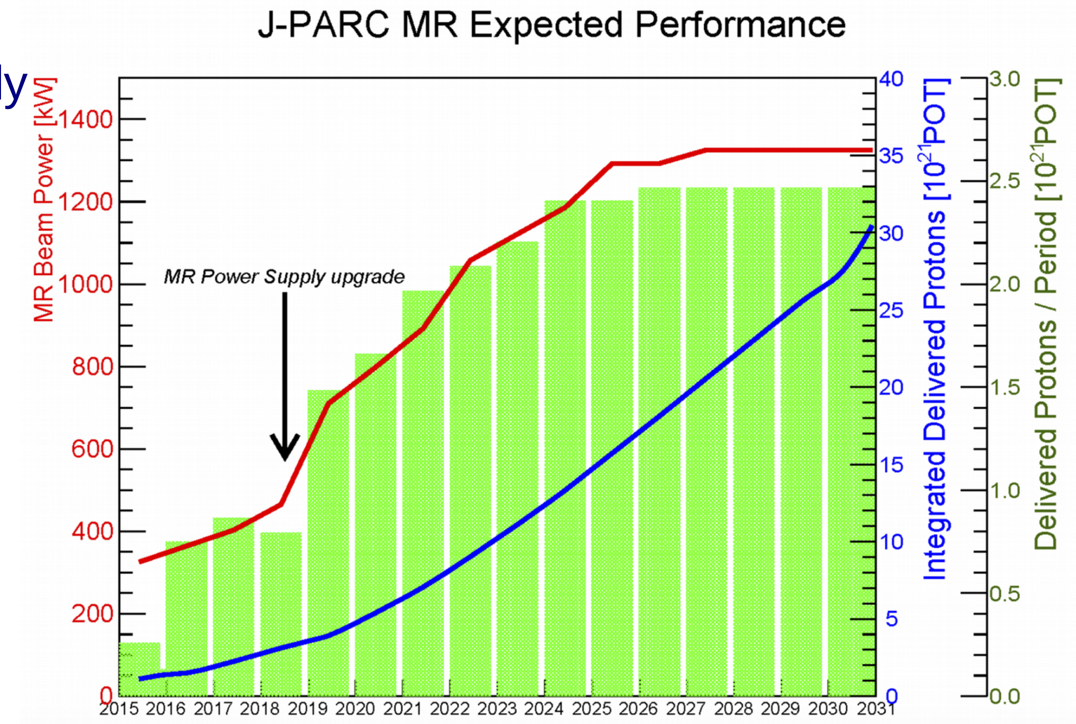
Inverted Ordering [-1.54; -1.19] radians

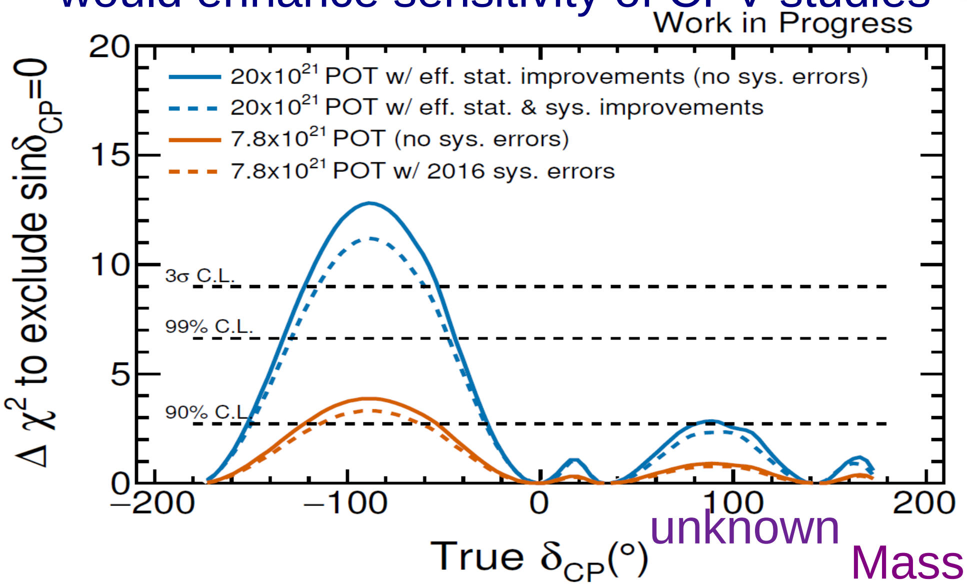
CP conserving values $0,\pi$ both fall outside of the 2σ C.L. intervals



Future plans : T2K Phase II proposal

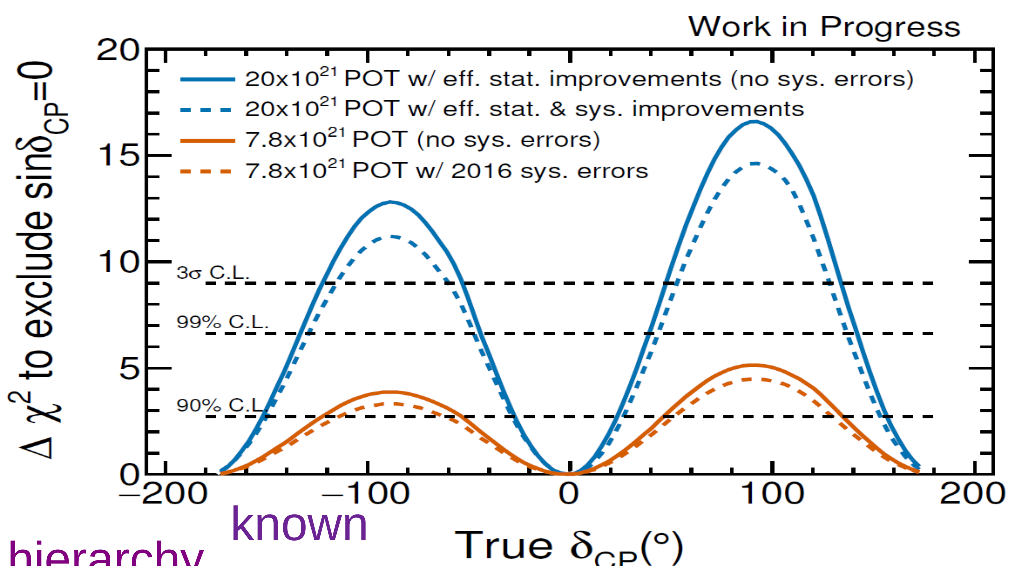
- Approved T2K statistics (7.8×10^{21} p.o.t.) can be accumulated by JFY2020. Recently reached 3.0×10^{21} p.o.t.
- Next generation long-baseline neutrino experiments (Hyper-K and DUNE) are expected to start around 2026
- T2K Phase II, if extended to 2026, could collect about 20×10^{21} p.o.t.
- Neutrino beamline upgrade and analysis improvements (SK fiducial volume to add new event samples) could effectively add about 50% of statistics
- Reduction of systematic uncertainties would enhance sensitivity of CPV studies





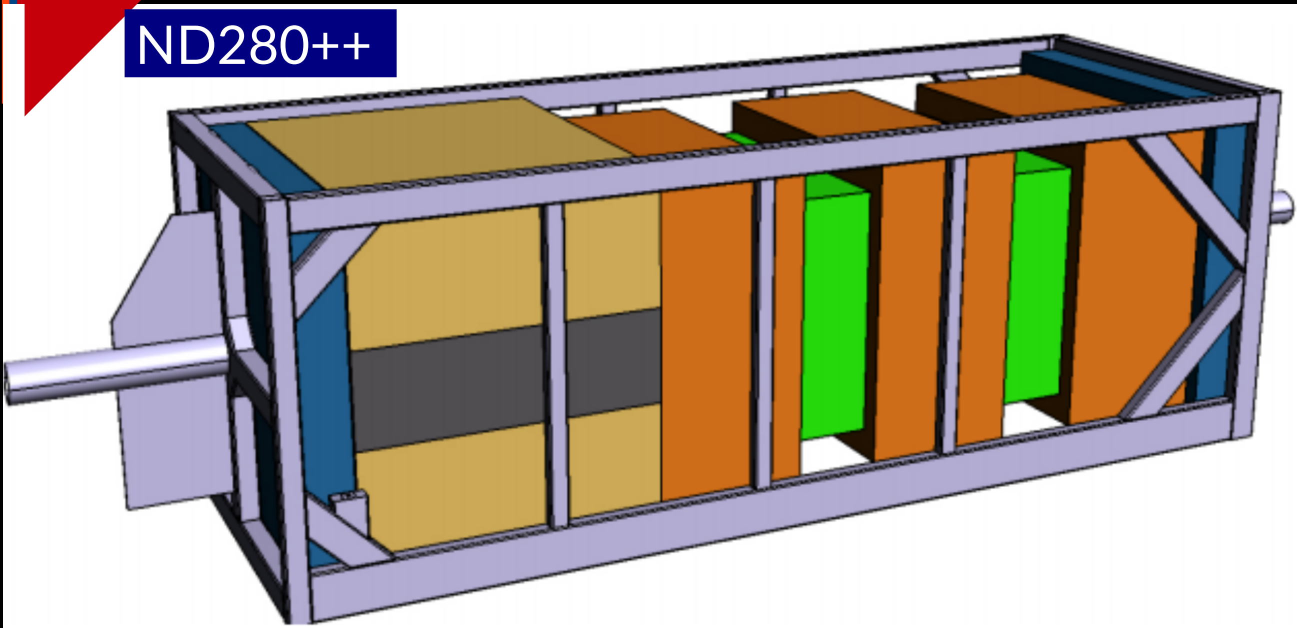
unknown

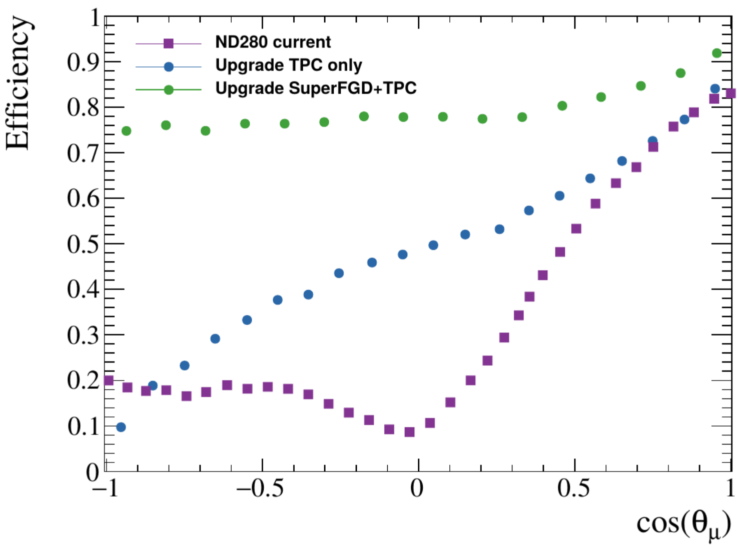
Mass hierarchy



known

ND280 upgrade





Given a large statistics to be collected by T2K-II, systematics needs to be reduced down to 2-3%. Thus, upgraded ND280++ to be installed in 2021 to avoid major limitations of the current detector: reduced angular acceptance and reconstruction of low-momentum hadrons.

LPNHE group contributions:

Optimization of the new detector configuration leading to the ND280++ design;

Participation in the construction of the new High-Angle TPCs (development and production of readout electronics – Front-End Cards; mechanical suspension system; new DAQ).

The ND280 upgrade project is an important part of the T2HK experiment!

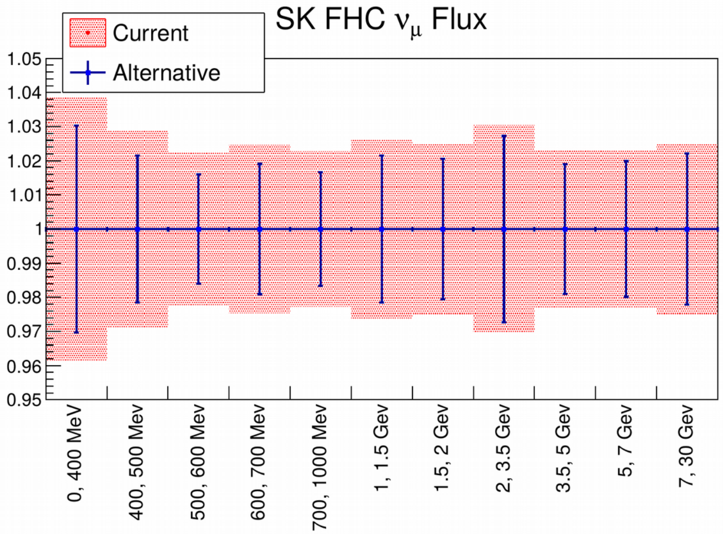
T2K-II

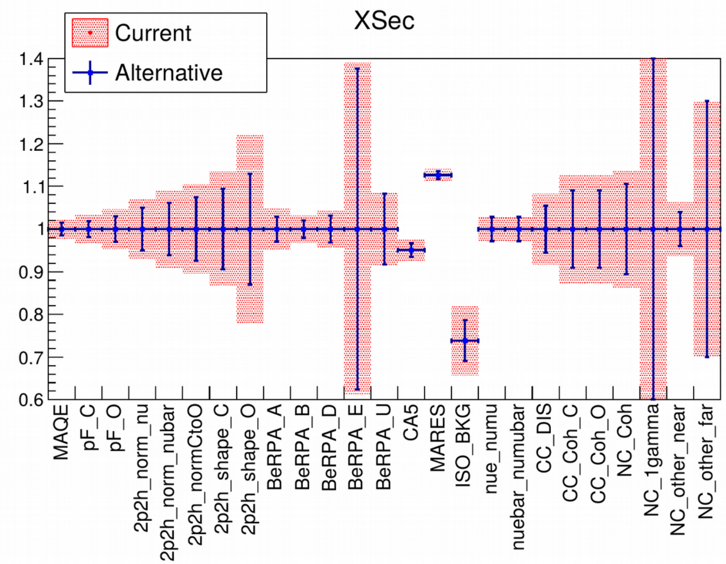
ND280 upgrade (physics motivation)

Sensitivity studies (using the same framework as current T2K analysis) are undergoing in order to assess the impact of upgrade on oscillation and physics analysis.

Parameters	Expected improvement on uncertainties
SK flux	$\sim 20\%$
FSI	$\sim 45\%$
CCQE/2p2h	$\sim 25 - 40\%$
Other (Q^2-dependent)	$\sim 25\%$

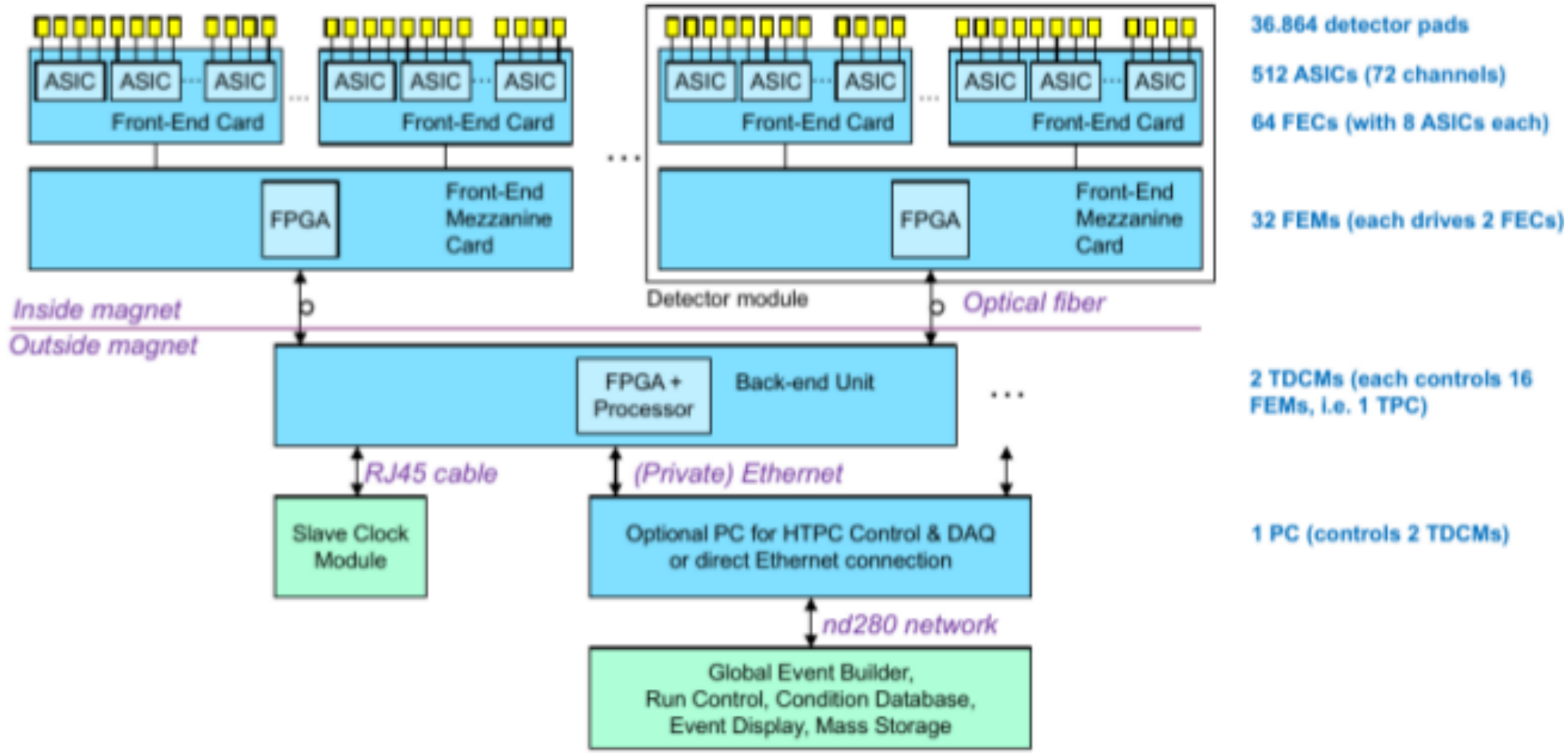
Results obtained with 8×10^{21} POT





T2K-II

ND280 upgrade (lab's resources)

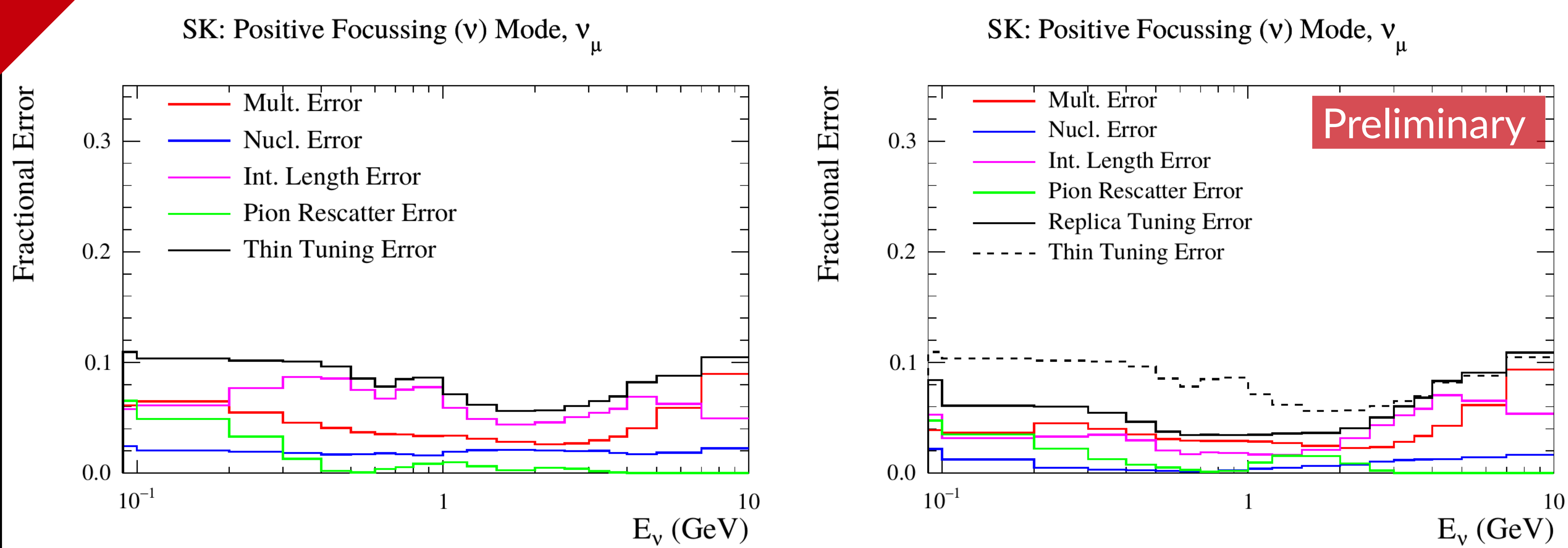


The following manpower has already been allocated by the LPNHE directorate

- electronics engineers to work on TPC FECs (J.-M.Parraud, F.Toussenel)

- mechanical engineers to work on FEC mechanics and cooling (Y.Orain) and on detector integration (W.Ceria)

NA61/SHINE beyond 2020



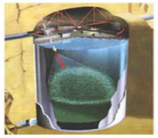
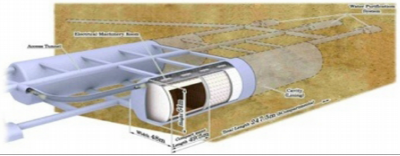
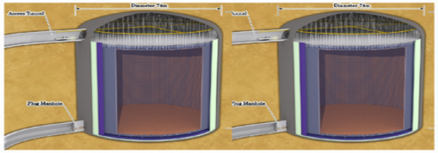
The usage of replica-target NA61/SHINE would allow for further improvement in T2K (anti-)neutrino flux uncertainty (down to ~5%). Even better knowledge is desired for T2K-II and Hyper-K. New measurements are planned for DUNE and Hyper-K after the CERN LS2 (see, CERN-SPSC-2018-008):

- improved measurements with T2K replica target, considering alternative target material – Super-Sialon ($Si_3N_4Al_2O_3$);
- with additional tracking detectors surrounding the long target;
- hadron production with low momentum beam (<12 GeV/c).

NA61++

More distant future: Hyper-K

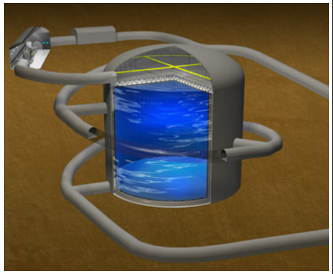
arXiv:1109.3262, arXiv:1412.4673, PTEP 2015 (2015) 053C02
Submitted to Science Council of Japan by T. Kajita on March 31, 2016
... with a different configuration with respect to published papers

	Super-K (SK)	Letter-of-Intent 2011 (LOI)	2 Tanks w/ High Photodetector density (2HD)
			
Total Volume (Fiducial Volume)	0.05Mton (0.022Mt)	1Mt (0.56Mt)	0.52Mt (0.38Mt)
Dimension	39mΦ × 42m (H)	48 (W) × 54 (H) × 250 (L) m³ ×2	74mΦ × 60m(H) ×2
ID #of Photo-sensors (coverage)	11k (Super-K PMT) (40%)	99k (Super-K PMT) (20%)	80k (B&L) (40%)
Single-photon detection efficiency	12%	12%	24%
Photon-yield	1	0.5	2
single-photon timing resolution	~2nsec	~2nsec	1nsec
Beam power		0.75 MW	1.3 MW

New version of Hyper-K TDR (arxiv:1805.04163) was released on May,9 2018

More distant future: Hyper-K

	KAM	SK	HK-1TankHD
Depth	1,000 m	1,000 m	650 m
Dimensions of water tank			
diameter	15.6 m ϕ	39 m ϕ	74 m ϕ
height	16 m	42 m	60 m
Total volume	4.5 kton	50 kton	258 kton
Fiducial volume	0.68 kton	22.5 kton	187 kton
Outer detector thickness	$\sim$ 1.5 m	$\sim$ 2 m	1 $\sim$ 2 m
Number of PMTs			
inner detector (ID)	948 (50 cm ϕ)	11,129 (50 cm ϕ)	40,000 (50 cm ϕ)
outer detector (OD)	123 (50 cm ϕ)	1,885 (20 cm ϕ)	6,700 (20 cm ϕ)
Photo-sensitive coverage	20%	40%	40%
Single-photon detection efficiency of ID PMT	unknown	12%	24%
Single-photon timing resolution of ID PMT	$\sim$ 4 nsec	2-3 nsec	1 nsec



New version of Hyper-K TDR (arxiv:1805.04163) was released on May,9 2018

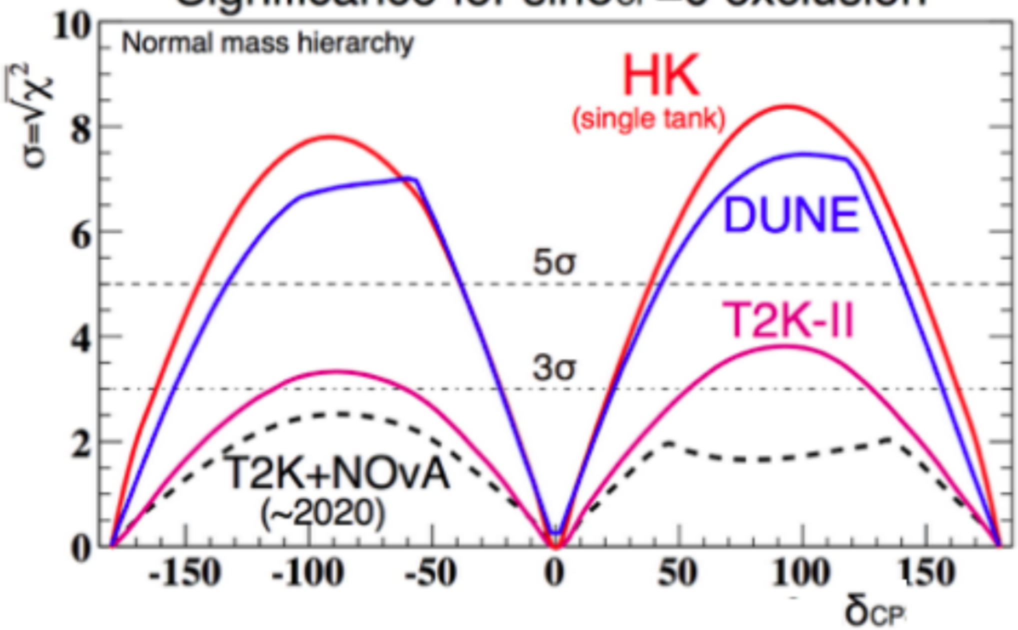
More distant future: Hyper-K

We consider the Hyper-Kamiokande experiment as the most attractive option to pursue our scientific activities:

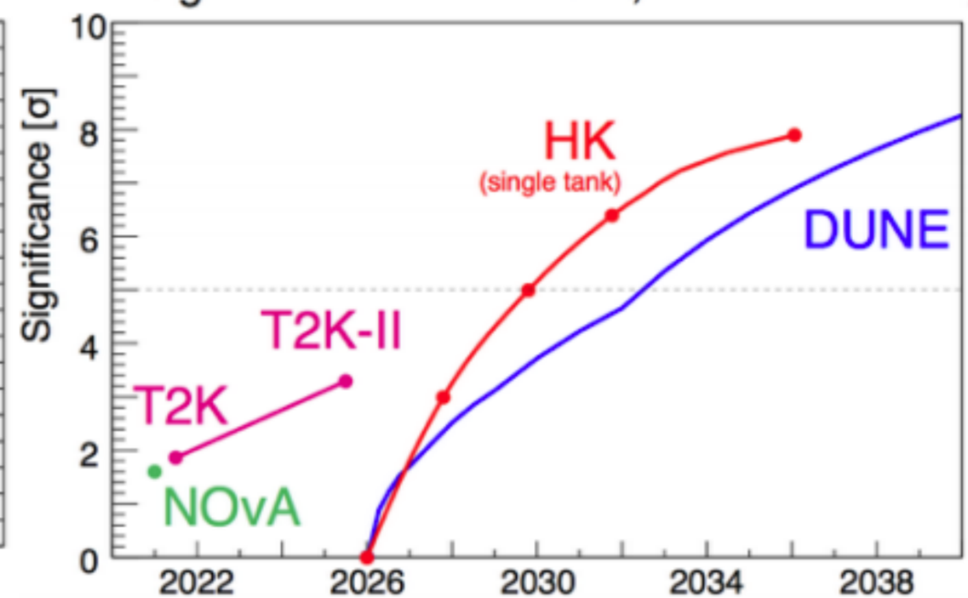
- Already proven water Cherenkov technique
- Large detector size sensitive to rare events (proton decays, supernovae neutrinos)
- Our past, on-going and future contributions to T2K/T2K-II are important investments
- Full participation in Hyper-K will open a possibility to enlarge the group experience by studying solar, atmospheric and supernovae neutrinos and by performing a combined analysis with accelerator (anti-)neutrinos.

Possible hardware contributions are being investigated (underwater multi-PMT tests / APC; electronics for PMT readout based on a chip developed by the Omega lab?)

Significance for $\sin\delta_{CP}=0$ exclusion



CPV significance for $\delta_{CP}=-90°$, normal hierarchy



Participation in T2K and T2K-II allows to work towards Hyper-K

Summary and conclusions (1)

Very successful participation in the **T2K** experiment.

The data samples analysed by T2K so far correspond to

- 14.7×10^{20} protons on target in neutrino mode
- 7.6×10^{20} protons on target in anti-neutrino mode

while the total approved exposure is 7.8×10^{21} p.o.t.

T2K reported first observation of neutrino appearance ($\nu_\mu \rightarrow \nu_e$)

Muon anti-neutrino disappearance results are consistent with our world-leading ν_μ disappearance measurements.

T2K is currently taking more anti-neutrino data to establish electron anti-neutrino appearance and to further constrain δ_{CP}.

Crucial contributions to oscillation analysis (S. Bienstock PhD).

Plan to contribute to future **joint T2K+SK** and **T2K+SK+NOvA** analyses.

Proposal for **T2K-II** (with a goal of 20×10^{21} p.o.t.) is formulated to reach more than 3σ significance for large CP violation.

We are contributing to these efforts.

Summary and conclusions (2)

Made significant contributions to the **NA61/SHINE** experiment.
The analysis of data samples collected for T2K (with a thin carbon target and a replica of the T2K target) allowed to reach <10% uncertainty on (anti-)neutrino fluxes

Important hadron production results recently published

The recently finalised analysis of the ultimate 2010 Replica Target data (Matej Pavin's PhD) could allow to further reduce the T2K flux uncertaities down to ~5%. Paper in preparation.

Given the success of the 'NA61/SHINE for T2K' program, similar measurements are now being performed for **Fermilab neutrino beams**.
Program of **future measurements beyond 2020** is formulated
We are contributing to these efforts.

Summary and conclusions (3)

We are now on the road towards future long-baseline neutrino experiments with a clear goal to study CP violation in the lepton sector.

During 2014-2017 the group has been involved in the **WA105** R&D project for **DUNE.**

We concentrated our efforts on the software development for double-phase LAr TPC in a generic **LArSoft** framework.

This activity will not be pursued given the choice to participate in the Hyper-Kamiokande project.

Summary and conclusions (4)

We are now on the road towards future long-baseline neutrino experiments with a clear goal to study CP violation in the lepton sector.

In September,2017 the group has chosen to participate in the **Hyper-K project**

This is a natural continuation of our involvement in the Japanese neutrino program

Our contributions to the ND280 upgrade project are crucial for both T2K-II and T2HK experiments

Exact hardware contributions to HK are still to be defined in collaboration with LLR and CEA groups

45

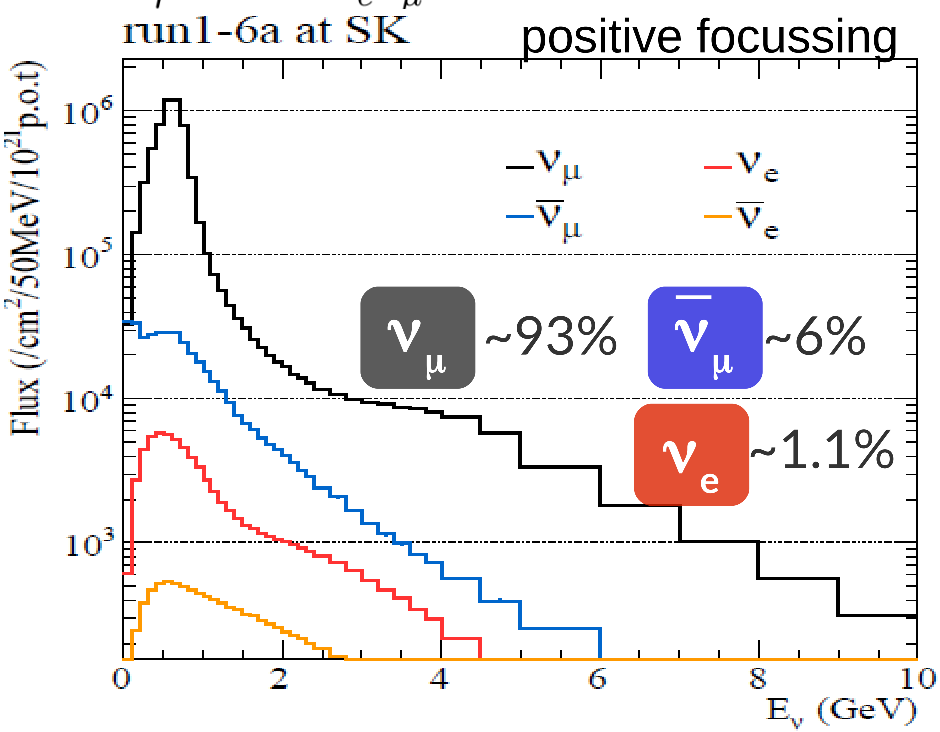
Backup

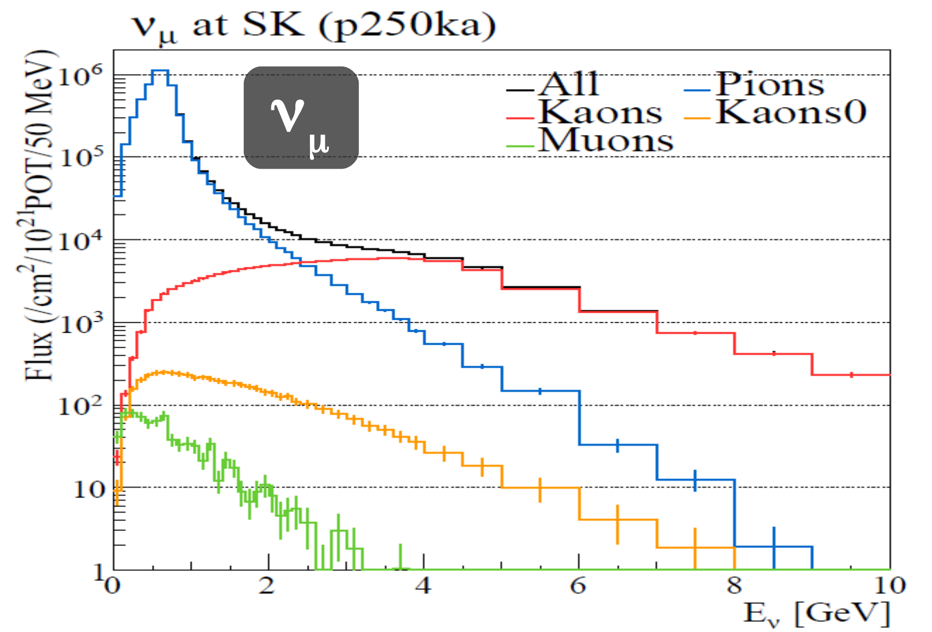
T2K neutrino beam composition

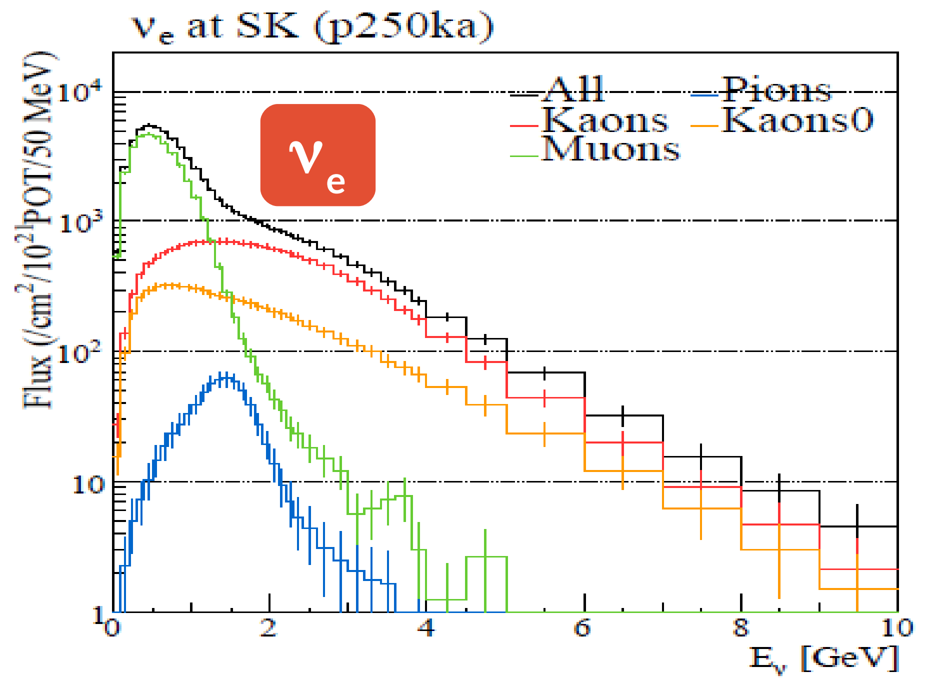
Flux prediction (Beam MC)

Particle (GeV)	Decay channel	Branching ratio (%)
π^+	$\rightarrow \mu^+\nu_\mu$	99.9877
	$\rightarrow e^+\nu_e$	1.23×10^{-4}
K^+	$\rightarrow \mu^+\nu_\mu$	63.55
	$\rightarrow \pi^0\mu^+\nu_\mu$	3.353
	$\rightarrow \pi^0 e^+\nu_e$	5.07
K_L^0	$\rightarrow \pi^-\mu^+\nu_\mu$	27.04
	$\rightarrow \pi^- e^+\nu_e$	40.55

$\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$



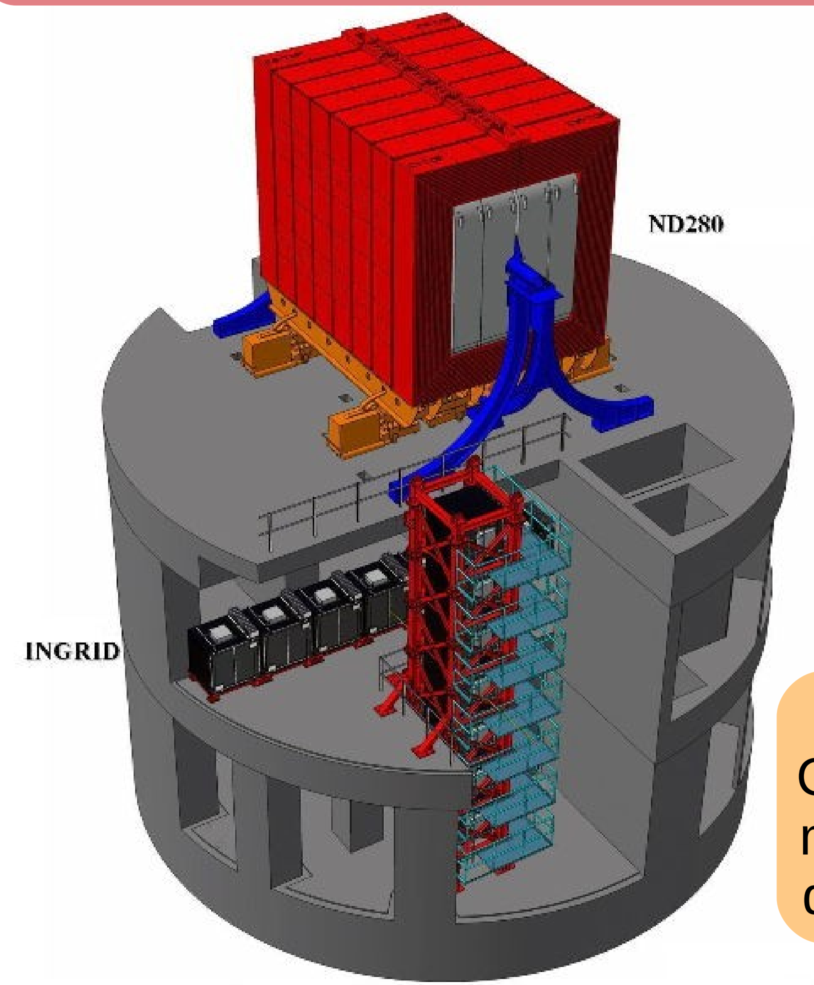


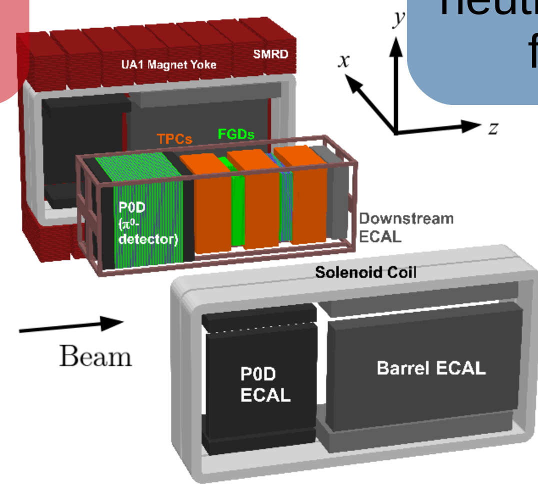


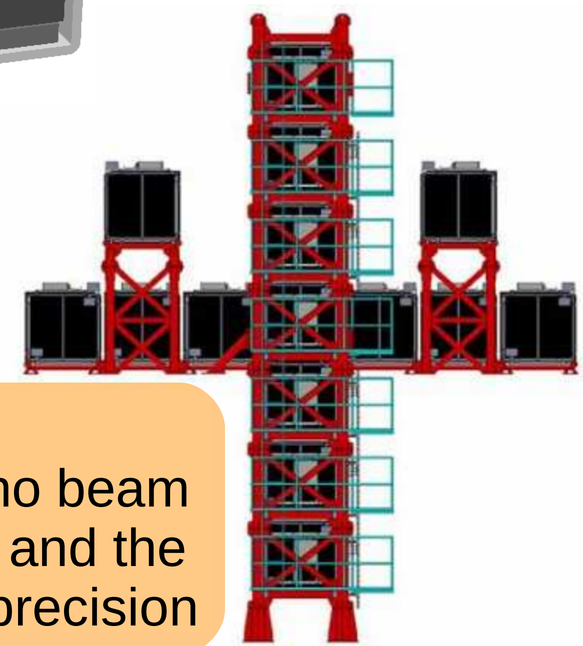
The near detectors

Neutrino monitors at 280 meters from the source → Studies neutrino fluxes *BEFORE* the oscillations

ND280
Characterize the off-axis neutrino beam composition in function of the energy



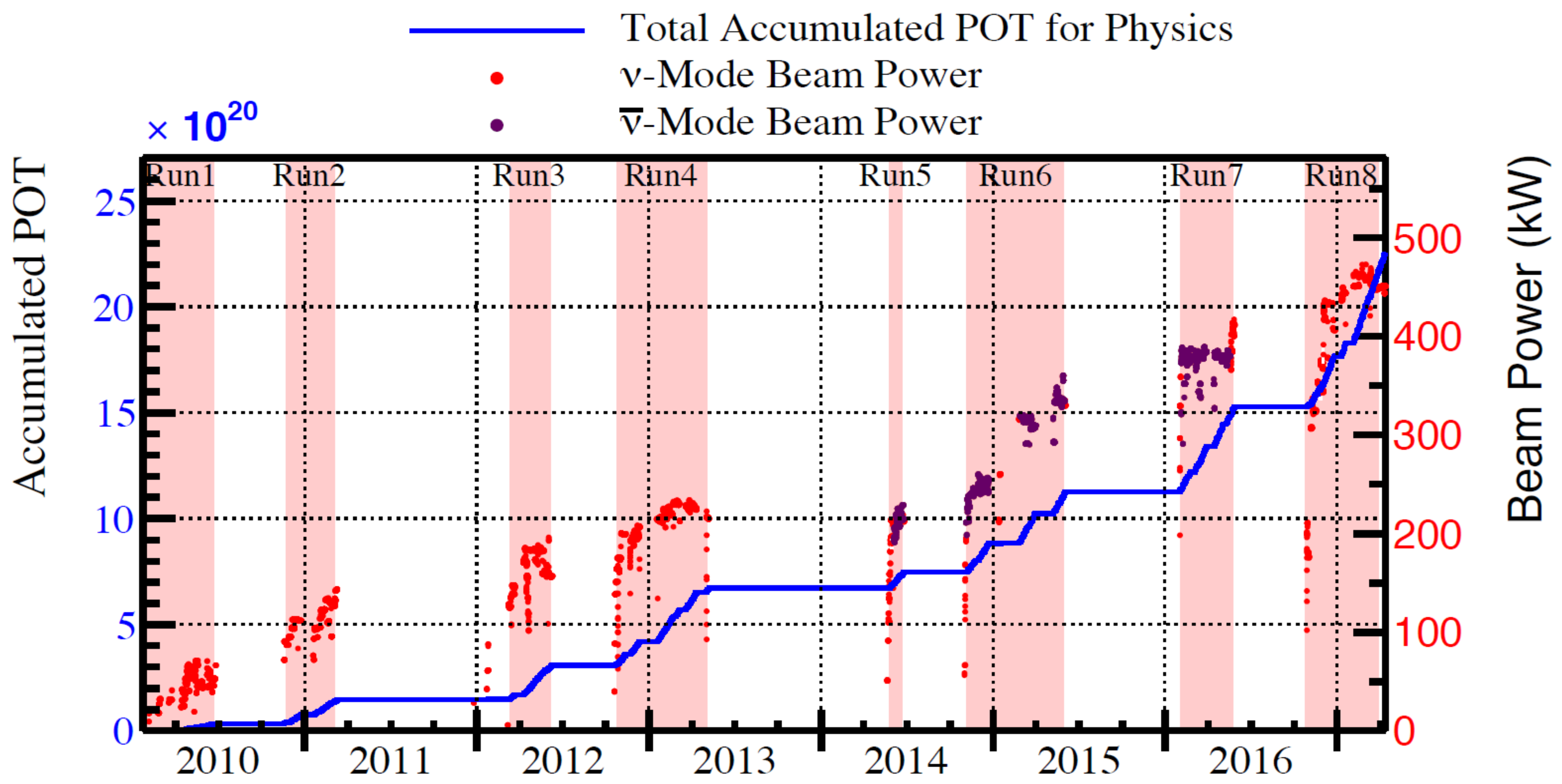




INGRID
Characterize the neutrino beam measuring the intensity and the direction with 0.4mrad precision

Collected data (up to Run9)

Reached stable operation at 470 kW beam power by now!



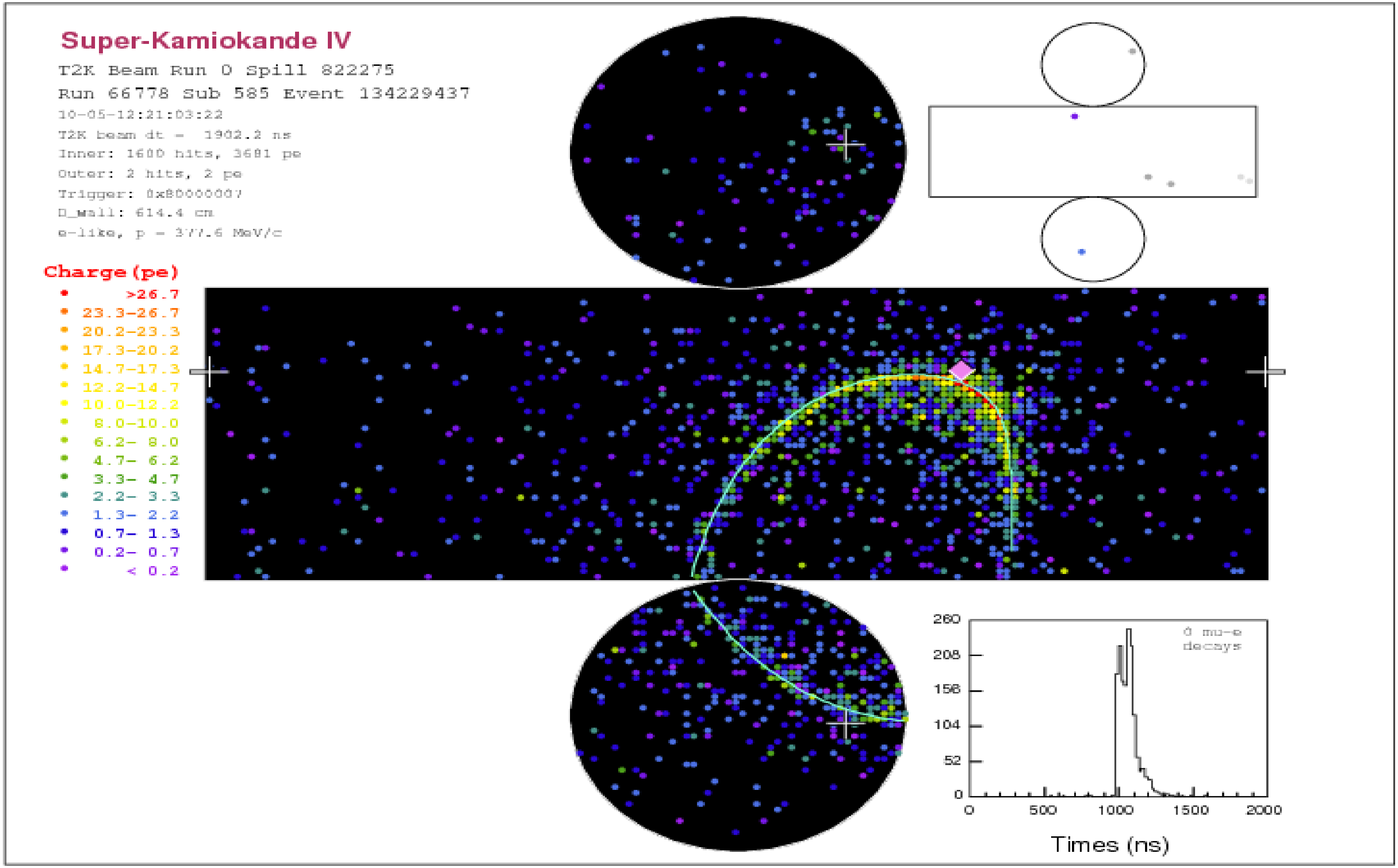
23 January 2010 – 12 April 2017

Total POT: 22.54 x 10^{20}

ν mode POT: 14.93 x 10^{20} (66.2%)

ν̄ mode POT: 7.62 x 10^{20} (33.8%)

Events in Super-K (ν_e candidate)



Discovery of $\nu_\mu \rightarrow \nu_e$ appearance

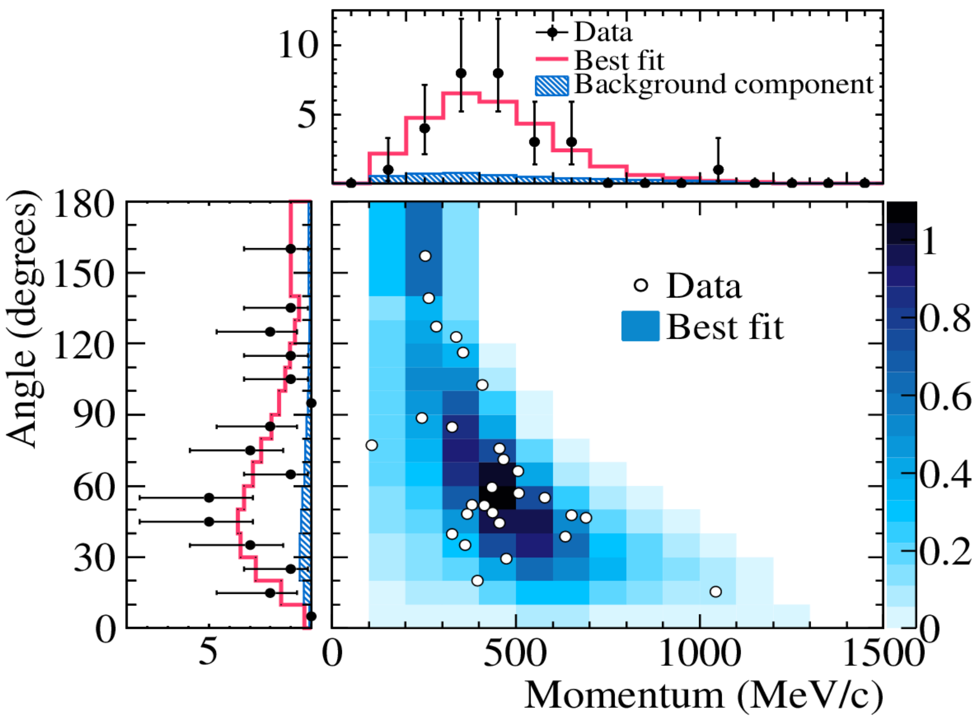
Phys. Rev. Lett. 112, 061802 (2014)

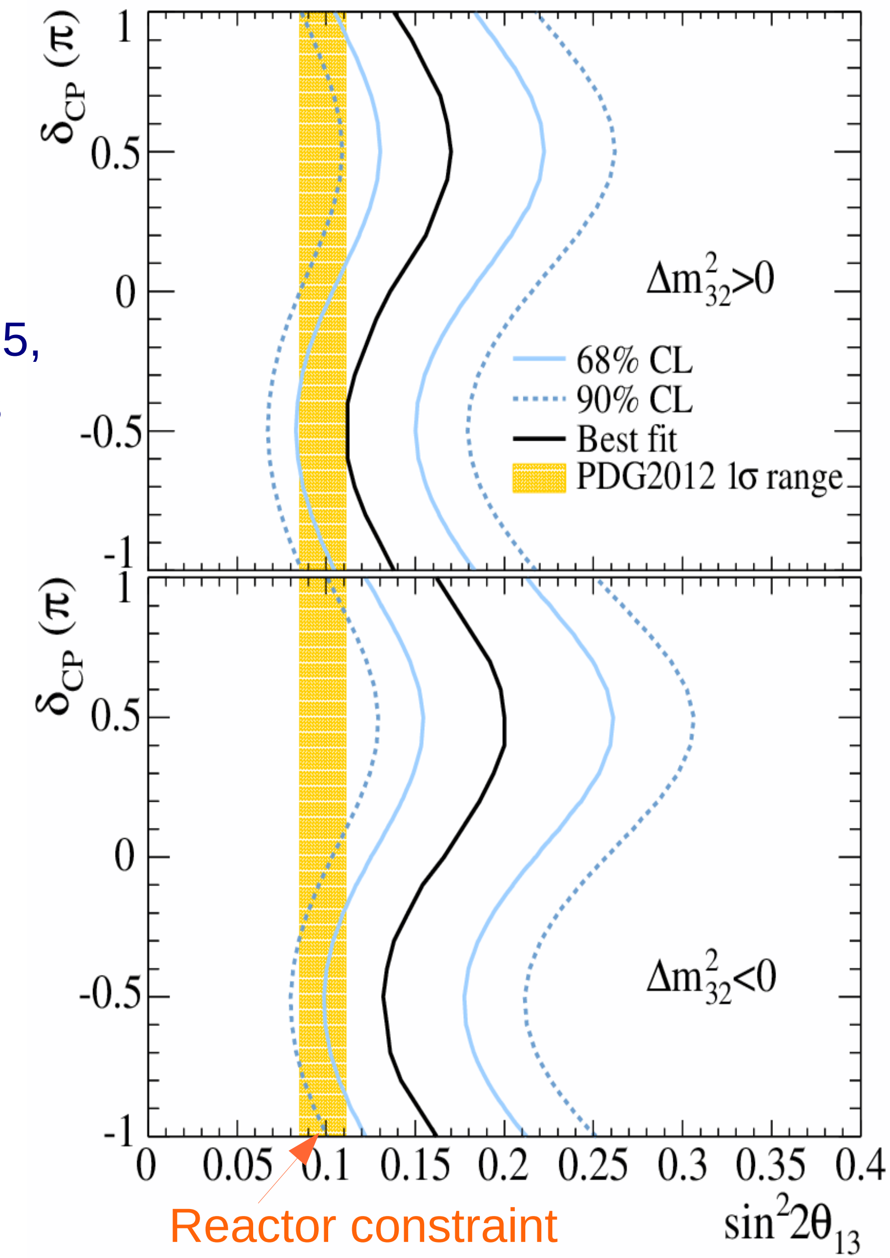
Based on $6.57\text{x}10^{20}$ p.o.t.

28 events observed while expected background is 4.92 ± 0.55

First observation of neutrino appearance with a significance of 7.3σ

Assuming $|\Delta m^2_{32}|=2.4\text{x}10^{-3}$ eV^2, $\sin^2\theta_{23}=0.5$, $\delta_{CP}=0$, and $\Delta m^2_{32}>0$ ($\Delta m^2_{32}<0$) a best fit is $\sin^2 2\theta_{13}=0.140^{+0.038}_{-0.032}$ $(0.170^{+0.045}_{-0.037})$





Precise measurement of ν_μ disappearance

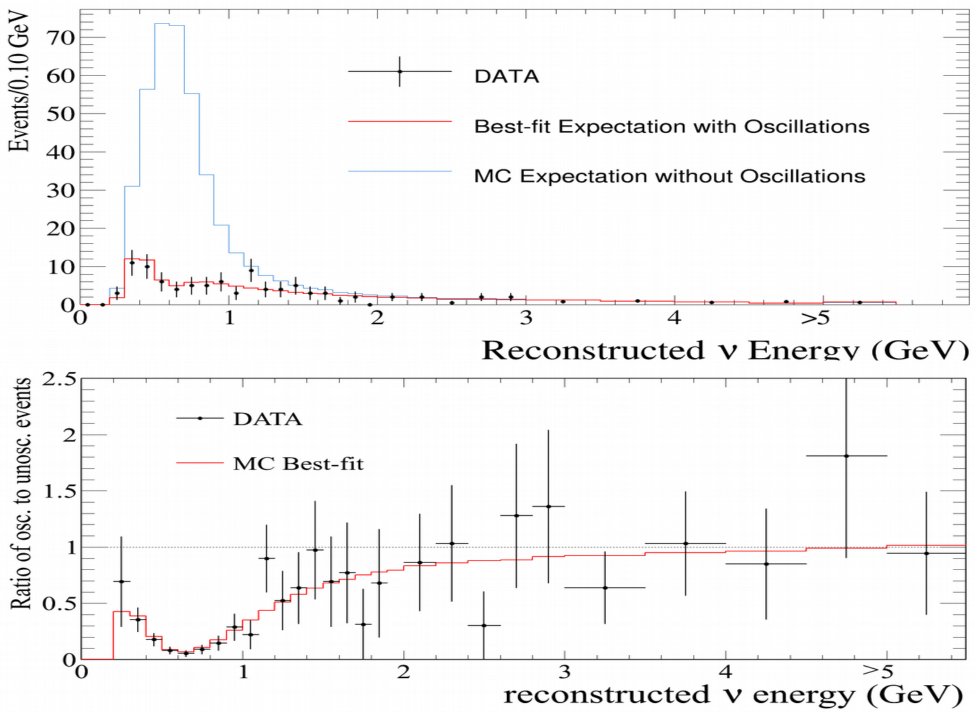
Phys. Rev. Lett. 112, 181801 (2014)

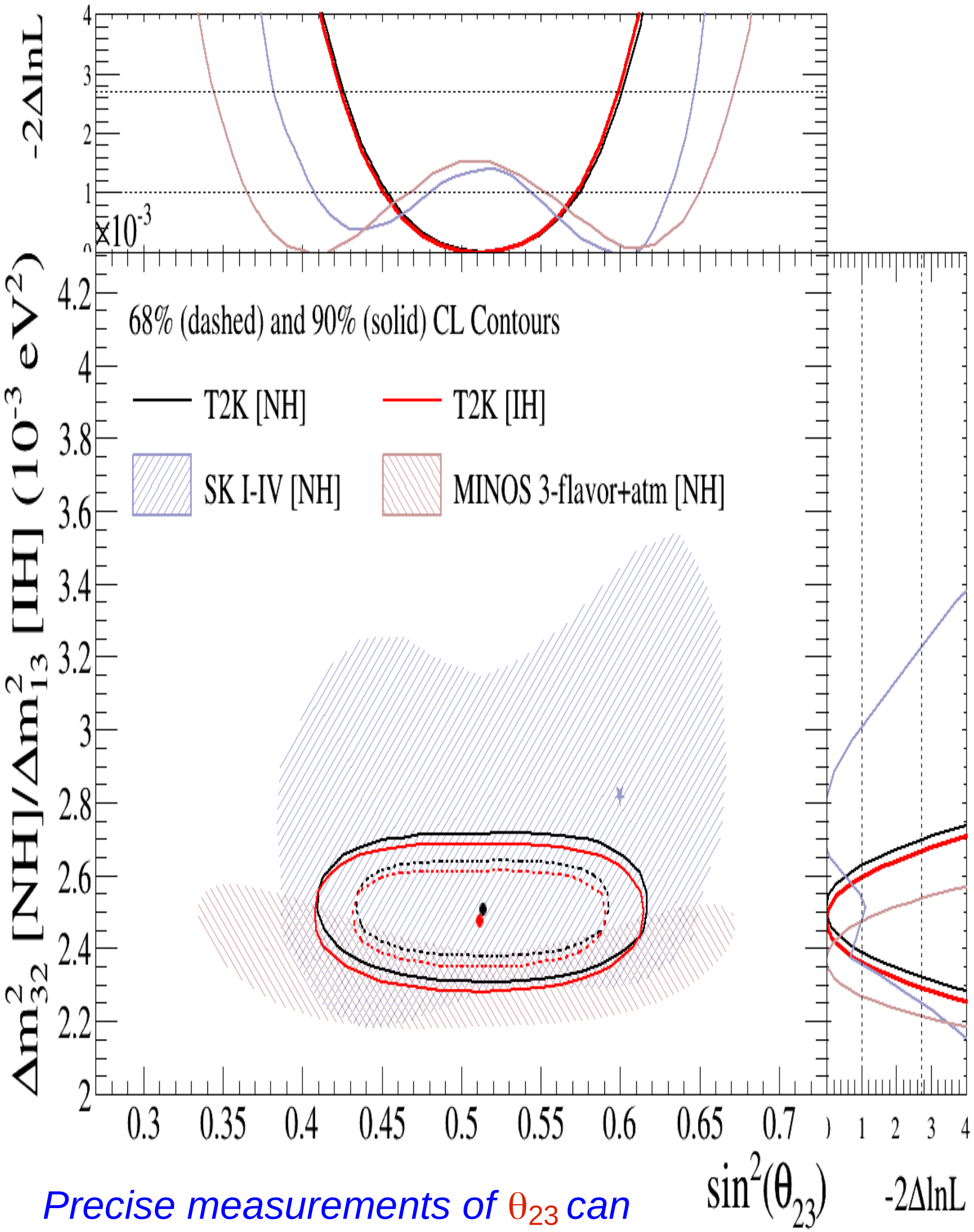
Based on 6.57×10^{20} p.o.t.

120 events observed while expectation without oscillations is 446 ± 22.5

World best measurement of θ_{23}

The 68% C.L. on $\sin^2\theta_{23}$ is $0.514^{+0.055}_{-0.056}$ (0.511±0.055) assuming normal (inverted) mass hierarchy. $\Delta m^2_{32}=(2.51\pm0.10)\times10^{-3}$ eV^2 $\Delta m^2_{13}=(2.48\pm0.10)\times10^{-3}$ eV^2 for normal (inverted) MH.





Precise measurements of θ_{23} can constrain models of neutrino mass generation

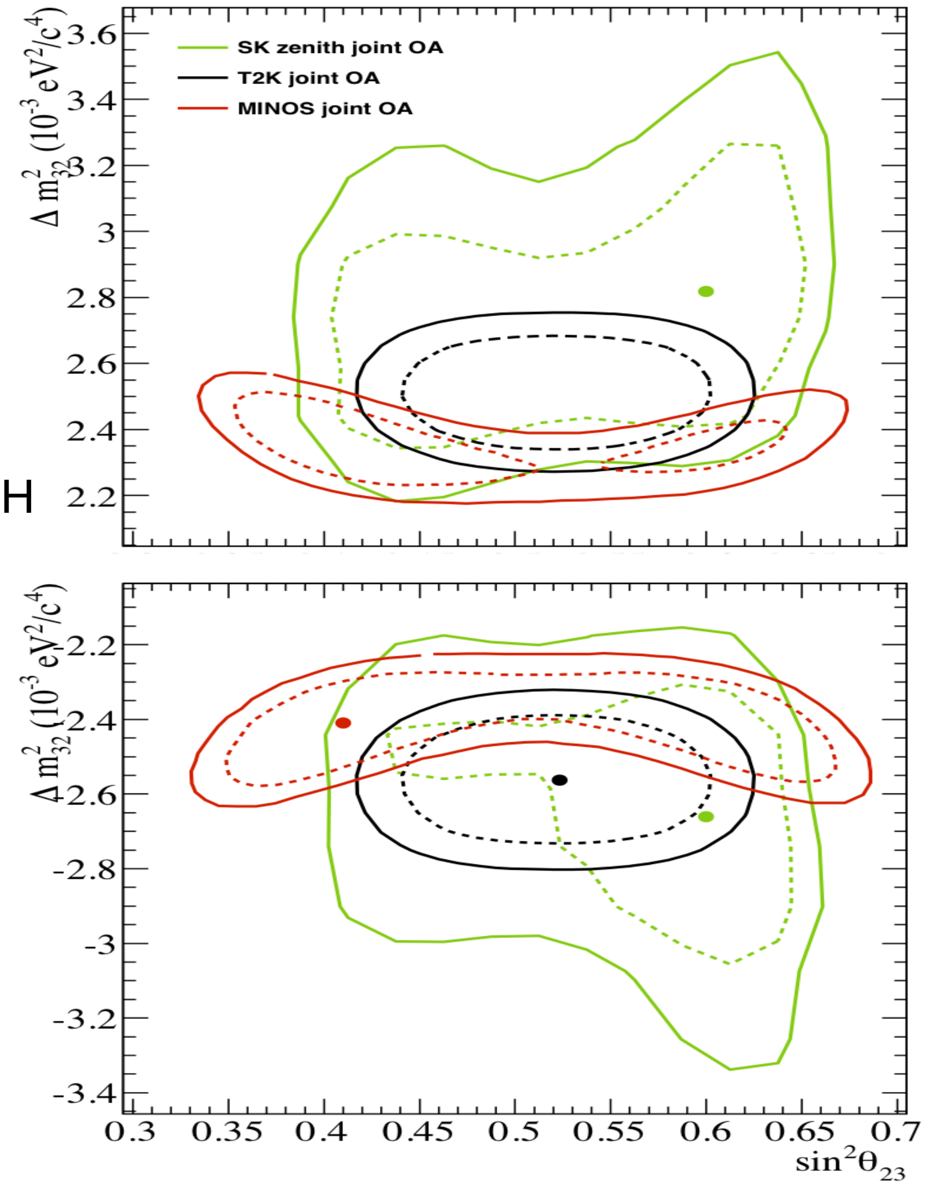
Combined appearance & disappearance

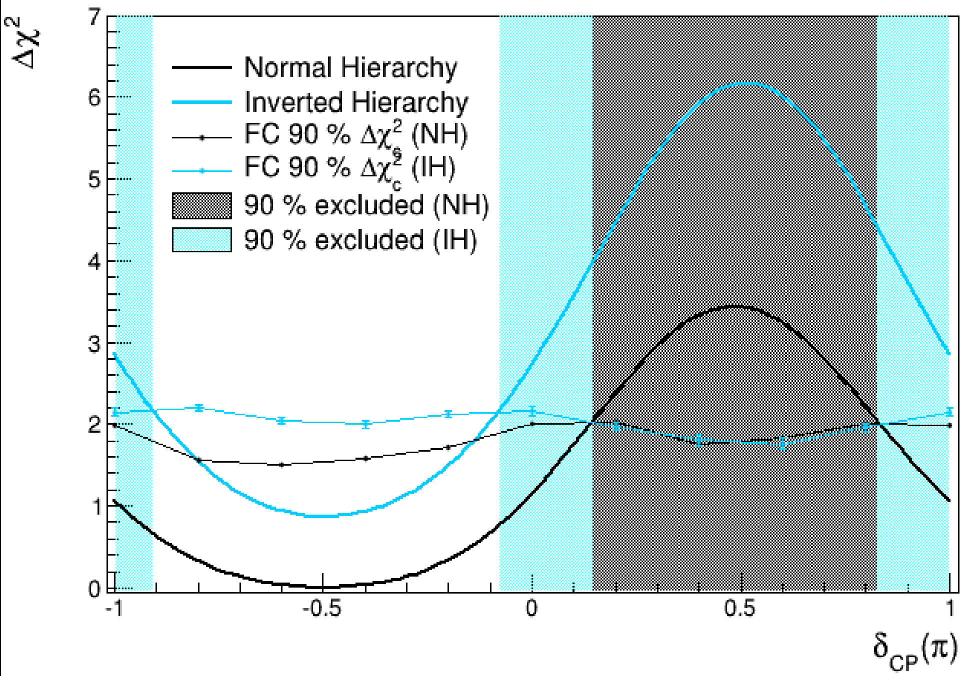
Phys. Rev. D 91, 072010 (2015)

Based on 6.57x10^{20} p.o.t.

Combined analysis of ν_e appearance and ν_μ disappearance to estimate the four oscillation parameters - $|\Delta m^2|$, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, δ_{CP}, and the mass hierarchy (MH).

At 90% C.L. including reactor results we exclude the region δ_{CP}=[0.15,0.83]π (δ_{CP}=[-0.08,1.09]π) for normal (inverted) MH



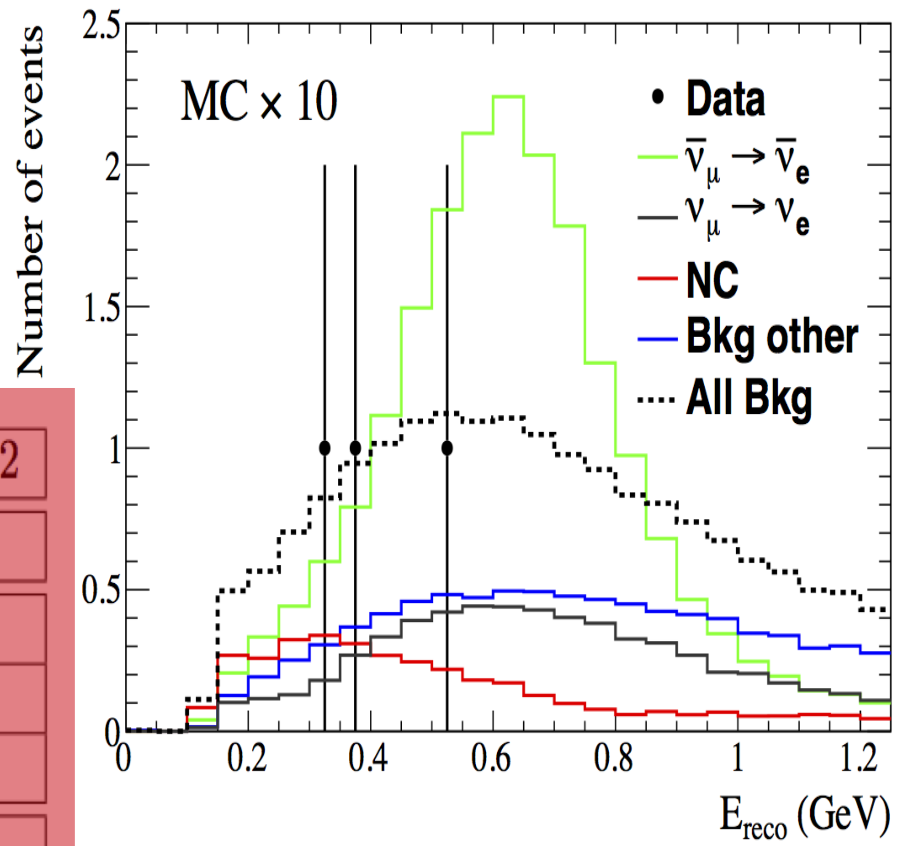


53 Study of $\bar{\nu}_e$ appearance

Too low statistics for $\bar{\nu}_e$ appearance:
with 4.01x10^{20} p.o.t. 3 events observed

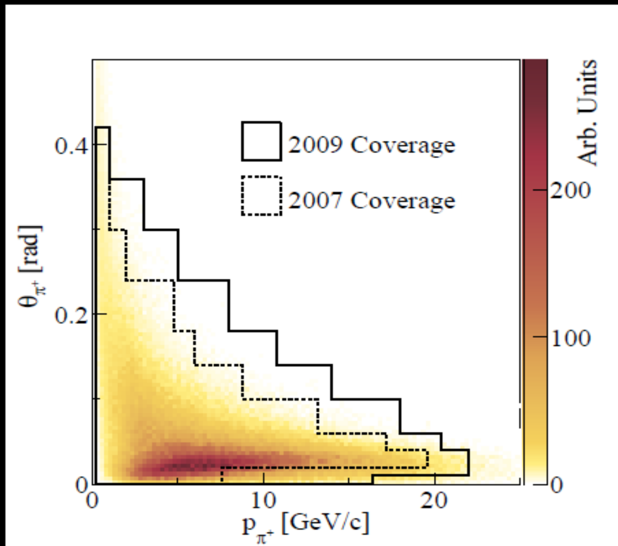
Additional collected data are under analysis

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Sig $\bar{\nu}_\mu \to \bar{\nu}_e$	1.961	2.636	3.288
Bkg $\nu_\mu \to \nu_e$	0.592	0.505	0.389
Bkg NC	0.349	0.349	0.349
Bkg other	0.826	0.826	0.826
Total	3.729	4.315	4.851

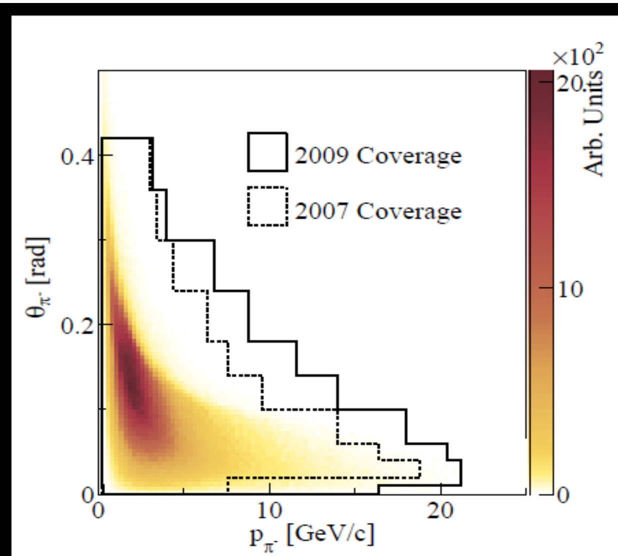


Parameter(s)	Treatment	Nominal value
$\sin^2\theta_{23}$	marginalized	0.528
$\sin^2\theta_{13}$	marginalized	0.025
$\sin^2\theta_{12}$	fixed	0.306
$\lvert\Delta m^2_{32}\rvert$ (NH) / $\lvert\Delta m^2_{31}\rvert$ (IH)	marginalized	2.509×10^{-3} eV^2/c^4
Δm^2_{21}	fixed	7.5×10^{-5} eV^2/c^4
δ_{CP}	marginalized	-1.601
Mass Hierarchy	marginalized	NH

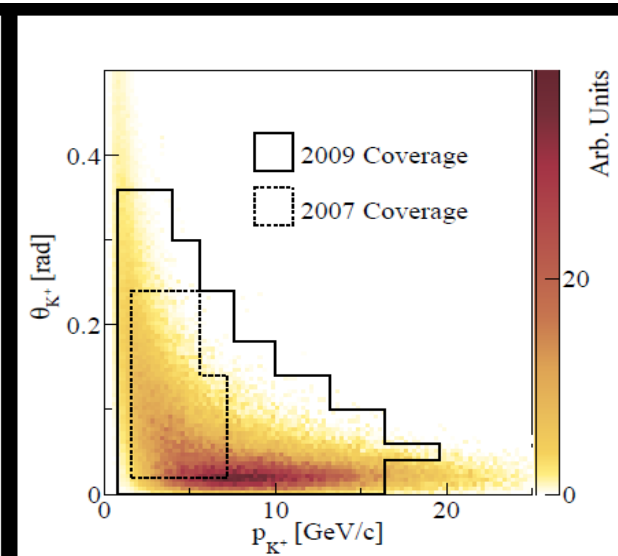
NA61/SHINE coverage for T2K ($\bar{\nu}$ mode)



(g) π^+

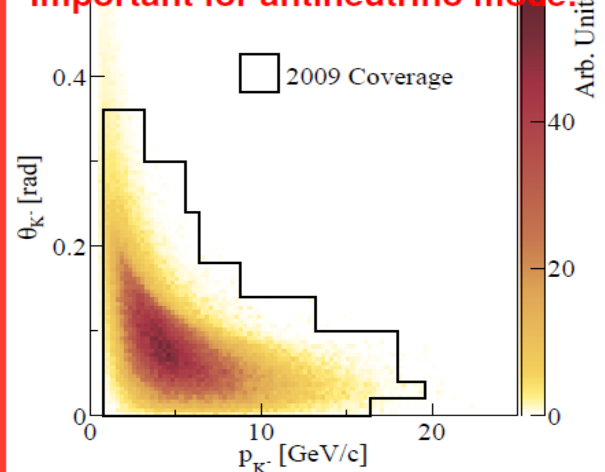


(h) π^-

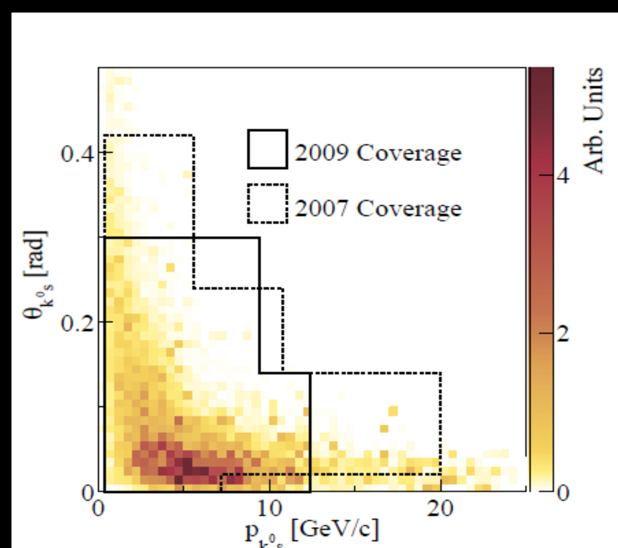


(i) K^+

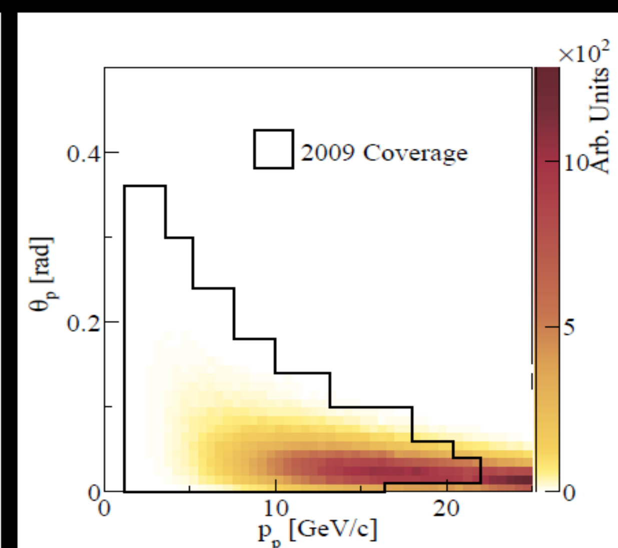
First measurements of K^- spectra. Important for antineutrino mode.



(j) K^-

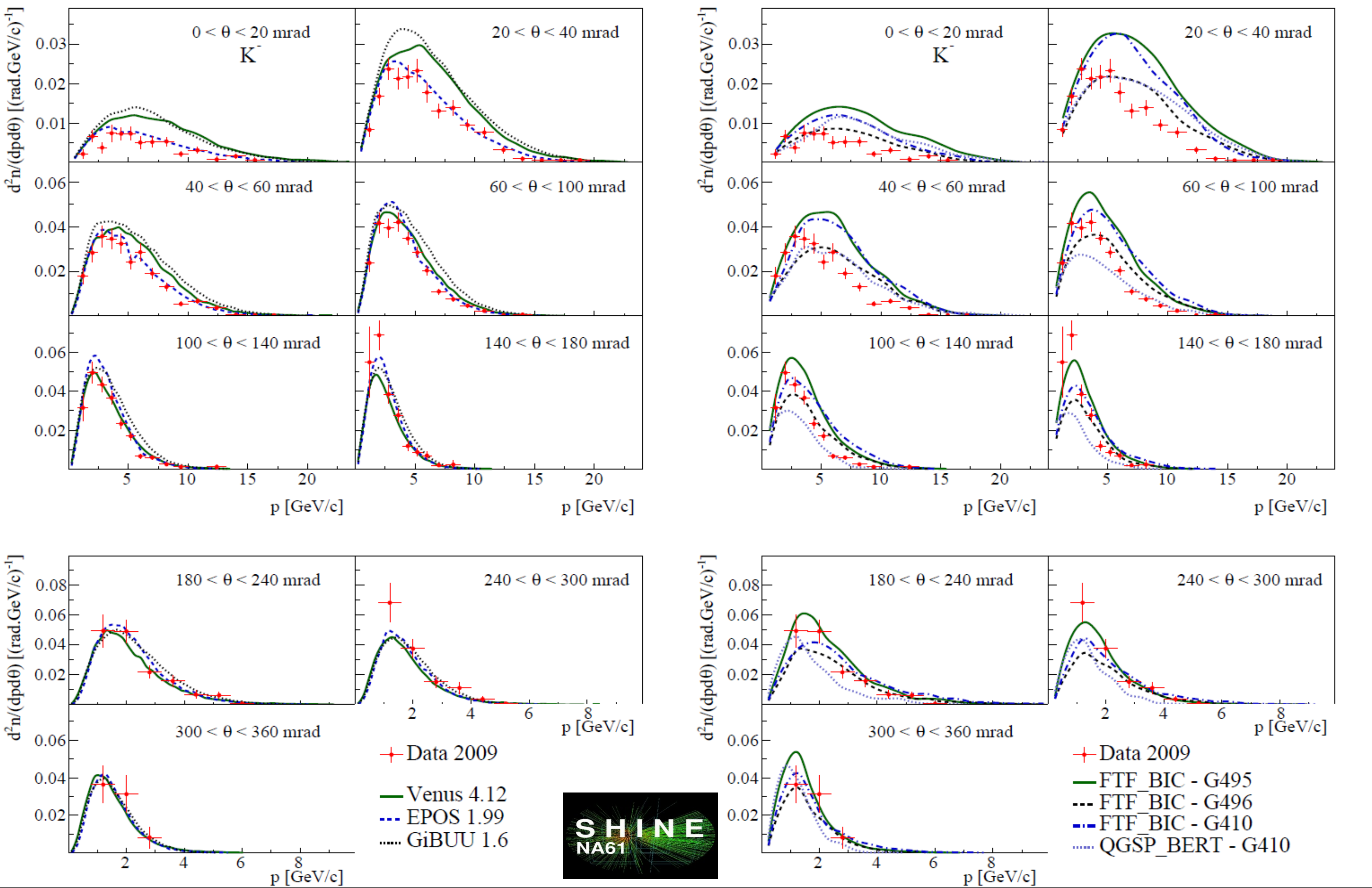


(k) K^0_S



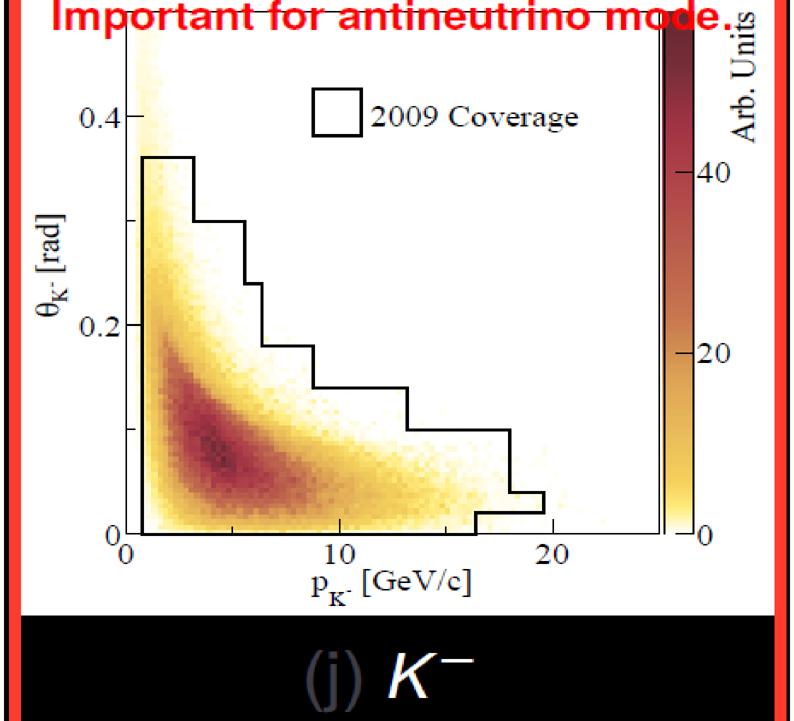
(l) proton

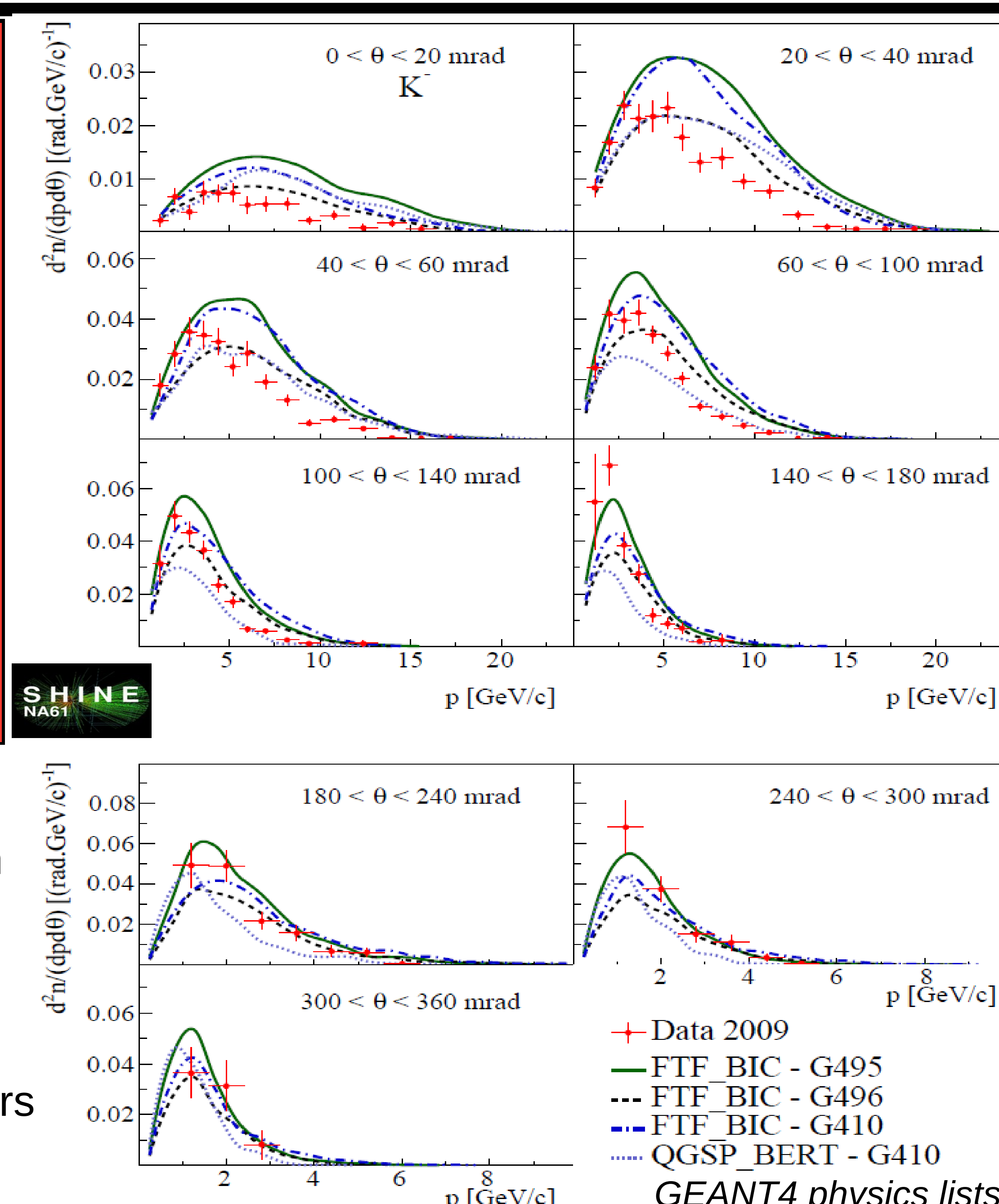
Comparison of K- spectra with models



Comparison of K- spectra with models

First measurements of K^- spectra. Important for antineutrino mode.



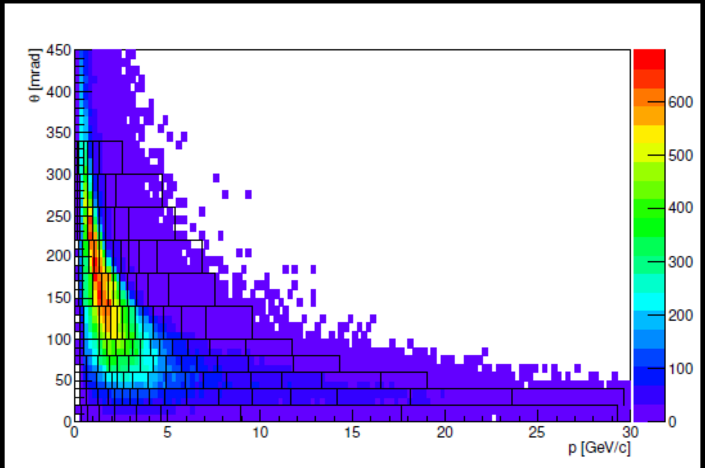


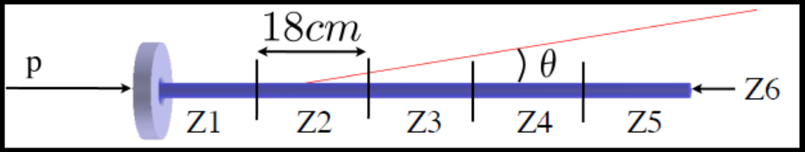
A similar program of hadron production measurements is now approved for Fermilab neutrino beams (including DUNE)

Data-taking plans for the 3 coming years

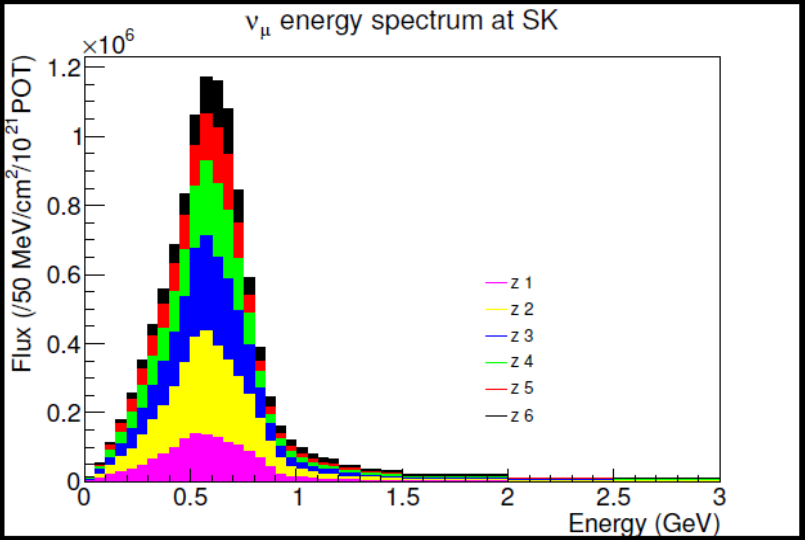
p+RT @ 31 GeV/c analysis

- $tof - dE/dx$ and h^- analysis
- Vertex position is not required $\rightarrow$ TPC tracks are extrapolated towards the target surface
- Phase space: momentum p, polar angle θ and position along the target surface z
- Shape of the spectra depends on the track position $\rightarrow$ 5 longitudinal bins + downstream target face





- z bin contribution to the ν_μ flux at SK



Systematic uncertainties

- Backward track extrapolation (up to 10% for small θ)
- Other contributions: less than 5%