

XXVIII International Conference on Neutrino Physics and Astrophysics

平成30年 06月 04日

T2K Status, Results, and Plans

Morgan Wascko

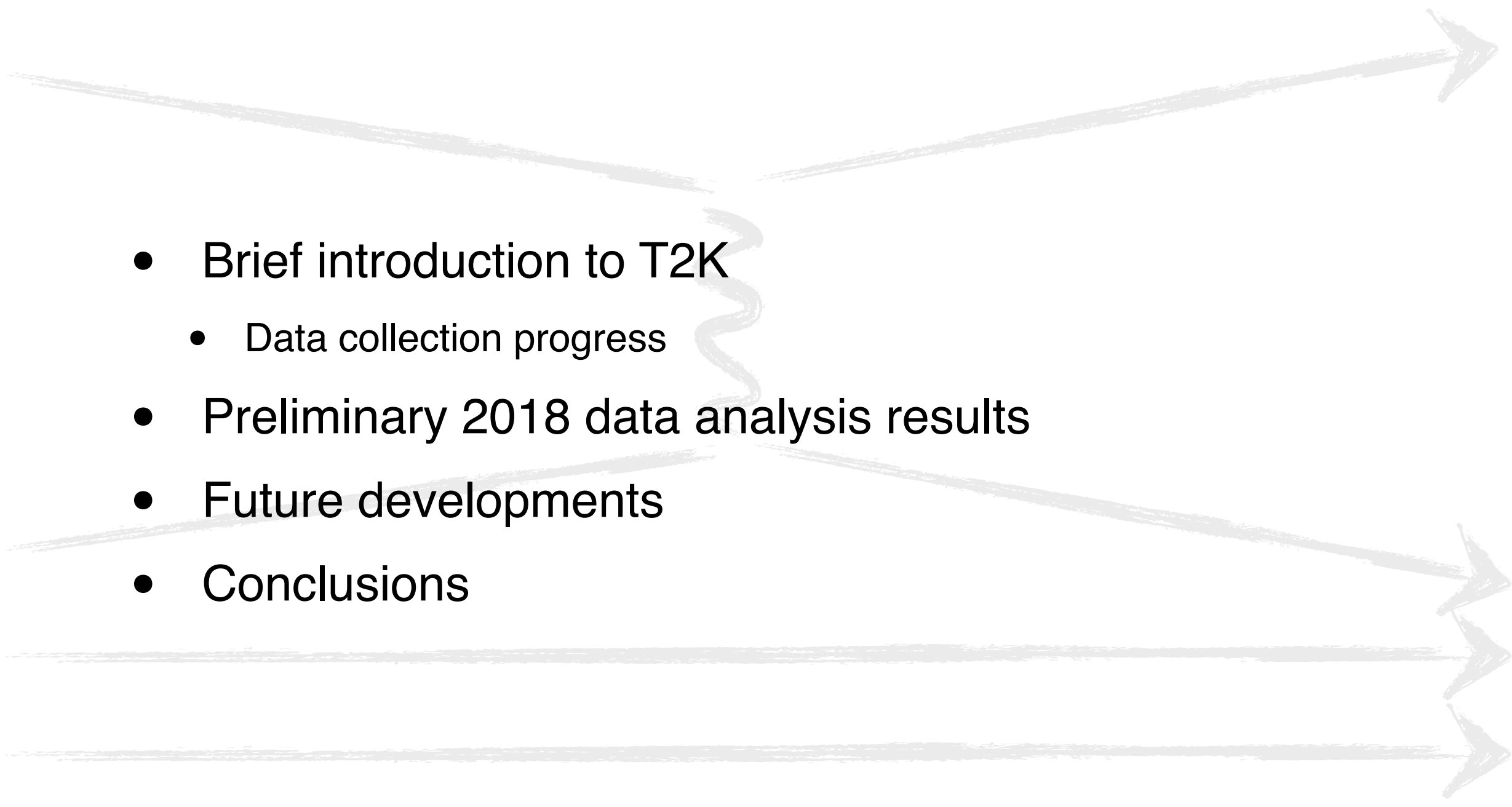
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Imperial College London



on behalf of the T2K Collaboration

Outline

- Brief introduction to T2K
 - Data collection progress
 - Preliminary 2018 data analysis results
 - Future developments
 - Conclusions
- 
- The slide features several decorative elements: a large grey arrow pointing right from the top left, a grey wavy line passing through the list, and three horizontal grey arrows pointing right at the bottom.

Posters on T2K (& related) topics

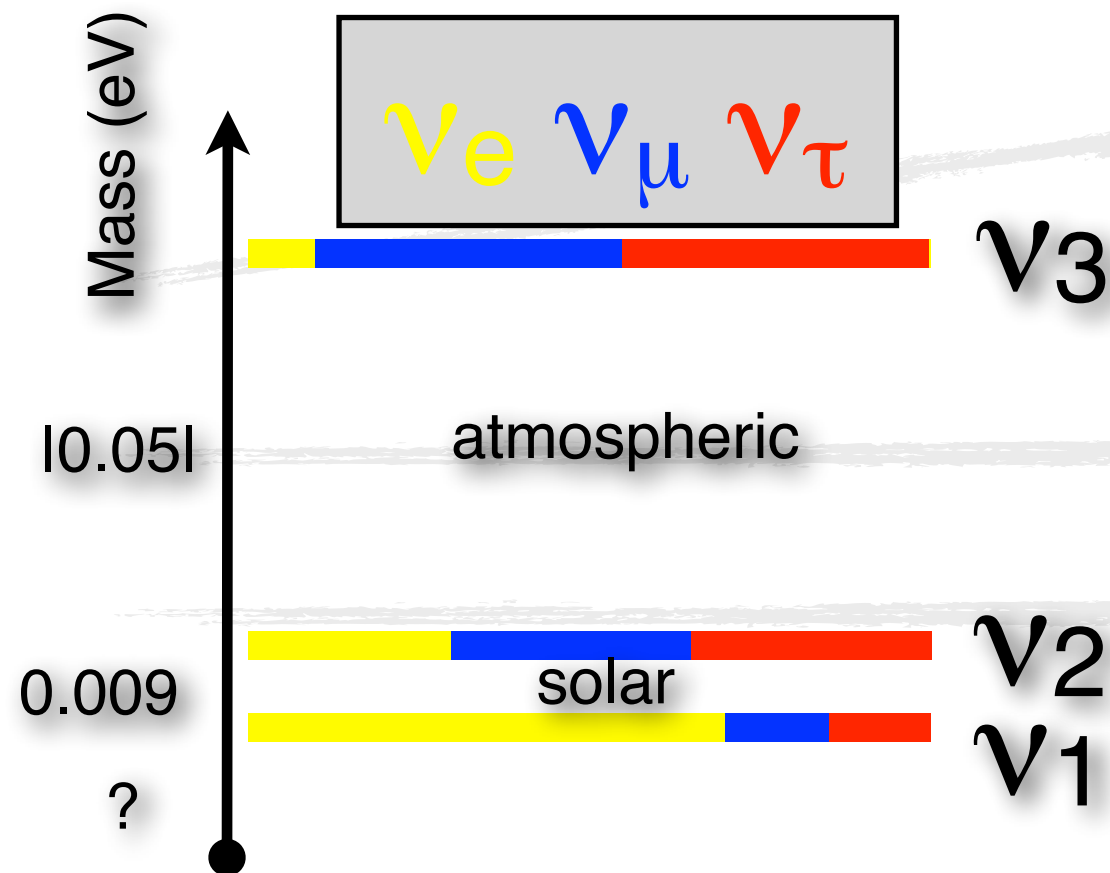
TITLE	NAME		ID	Session
Study of neutrons produced in neutrino interactions with a water target at T2K	Akutsu	Ryousuke	198	Wed
CC ν_μ interactions with at least one π^0 in the final state in the T2K off-axis near detector	Batkiewicz	Marcela	281	Wed
Updated Results for the Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillations from T2K in the 3-flavour Framework	Bench	Francis	277	Wed
The VALOR Neutrino Oscillation Analysis	Bench	Francis	480	Wed
Studying the impact of neutrino cross-section mismodelling on the T2K oscillation analysis	Bienstock	Simon	173	Wed
Measurement of ν_μ CC0 π cross sections on Oxygen and Carbon at the T2K near detector	Buizza Avanzini	Margherita	117	Wed
Characterisation of nuclear effects in muon-neutrino scattering at T2K	Dolan	Stephen	276	Wed
Precise measurement of ν xsec & flux w/ Hybrid Emulsions for ν CPV: NINJA & EMPHATIC	Fukuda	Tsutomu	318	Mon
Neutrino event detection with nuclear emulsion in the NINJA experiment	Hiramoto	Ayami	299	Mon
A muon antineutrino CC π^0 inclusive analysis at the T2K near detector ND280	Izmaylov	Alexandr	358	Wed
Measurement of ν interactions on H ₂ O and CH with 3D-grid detector in by WAGASCI	Kin	Ken'ichi	263	Wed
Current and future measurements of ν_e and $\bar{\nu}_e$ in the T2K off-axis near detector	King	Sophie	381	Wed
Development of a 3D highly granular scintillator neutrino detector for the T2K experiment	Kudenko	Yury	121	Wed
ND280 Upgrade overview and status	Łagoda	Justyna	120	Wed
Search for heavy neutrinos with the near detector ND280 of the T2K experiment	Lamoureux	Mathieu	132	Wed
Towards measuring CC and NC $1\pi^0$ production using photon tagging in the ND280 ECal	Lawe	Matthew	330	Wed
Measuring neutrino oscillations around the second maximum	Litchfield	Phill	445	Wed
Detecting supernova neutrino bursts with SK-Gd prototype: EGADS	Pronost	Guillaume	258	Wed
Pre-Supernova Silicon Burning Neutrinos at Super-Kamiokande	Simpson	Charles	359	Wed
Constraining the T2K Neutrino Flux Prediction with 2009 NA61/SHINE Replica-Target Data	Vladisavljevic	Tomislav	200	Wed
Measuring the ν_μ -0 π cross section on lead at the T2K near detector	Wąchała	Tomasz	148	Wed
Event selection for the measurement of CC $\bar{\nu}_\mu$ 1π production in the T2K near detector	Żarnecki	Grzegorz	245	Wed

Standard neutrino picture

flavour atmospheric accelerator/reactor solar mass

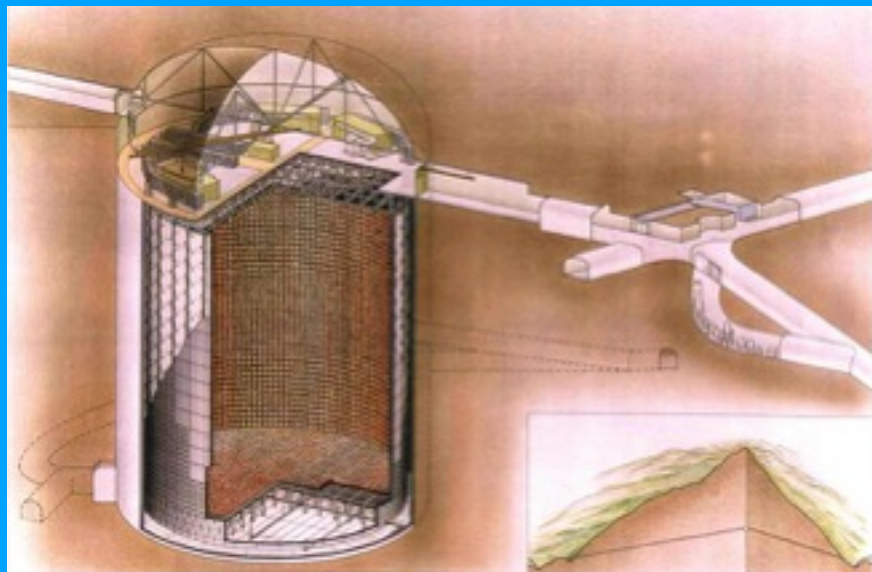
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}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

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



- What is the value of δ_{CP} ??
- What is the mass hierarchy?
- Is PMNS parametrisation correct?
- What is the absolute mass scale?
- Why so small??
- What is the nature of neutrino mass?
 - Dirac or Majorana?

T2K



ICRR, Univ. of Tokyo

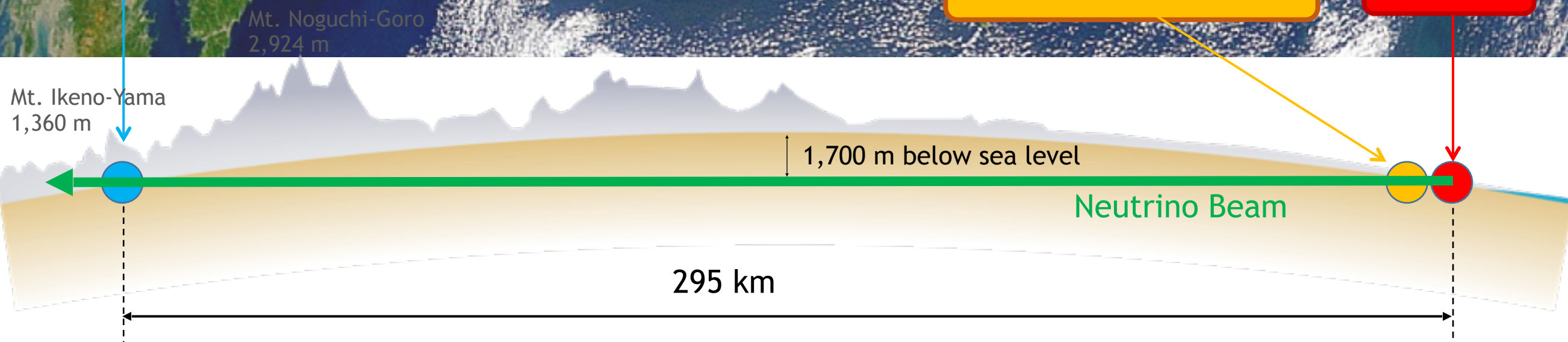


KEK / JAEA

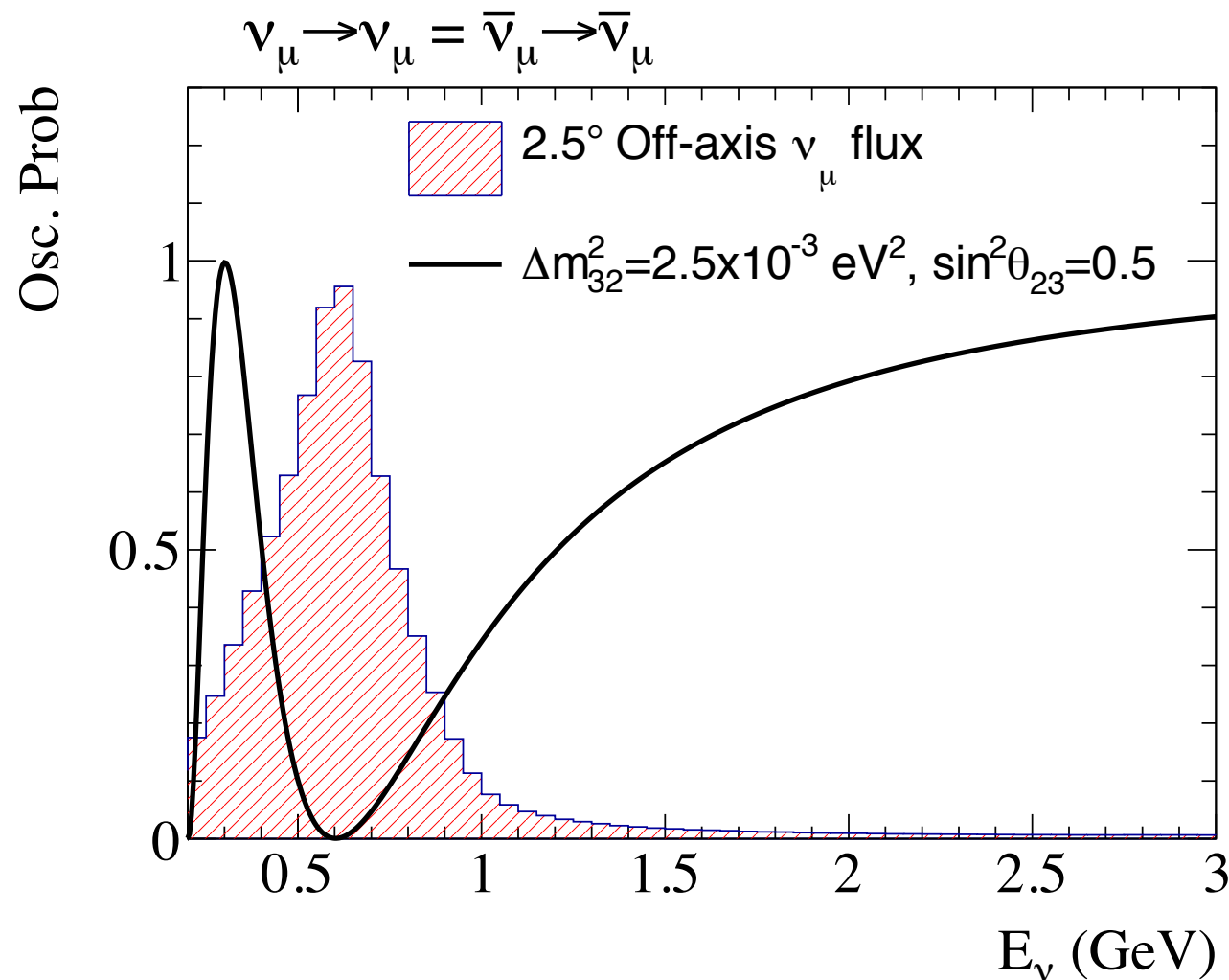
Super-Kamiokande

Near Detectors

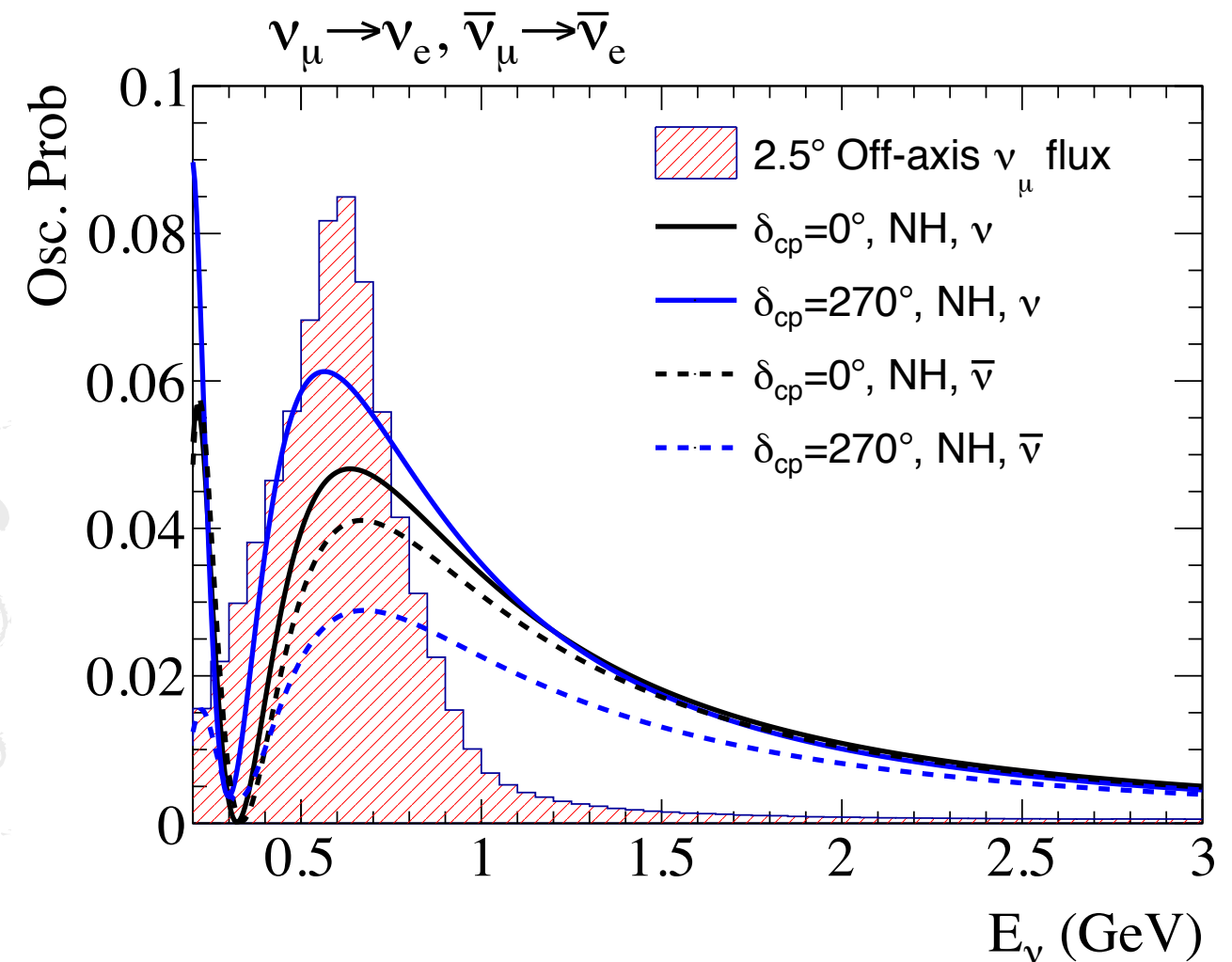
J-PARC



Measuring oscillation params @T2K



- Tests CPT symmetry
- Leading order dependence on $\sin^2 2\theta_{23}$
 - Difficult to distinguish $\theta_{23} > 45^\circ$ from $\theta_{23} < 45^\circ$
- Leading order dependence on $|\Delta m_{32}^2|$
 - Doesn't depend on the sign of the mass splitting (hierarchy)



- Tests CP symmetry
- Leading order dependence on $\sin^2 2\theta_{13}, \sin^2 \theta_{23}$
 - Can separate $\theta_{23} > 45^\circ$ from $\theta_{23} < 45^\circ$
- Sub-leading dependence on $\sin(\delta_{cp})$
 - Can detect CP violation
- Sub-leading dependence on Δm_{32}^2 through matter effect
 - Relatively small in T2K due to baseline

see poster by:
R.P. Litchfield, #445, Wed

The T2K Collaboration (2018)

~500 members, 67 Institutes, 12 countries

Canada

TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France

CEA Saclay
LLR E. Poly.
LPNHE Paris

Germany

Aachen U.

Italy

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

Japan

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

Poland

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

Russia

INR

Spain

IFAE, Barcelona
IFIC, Valencia
U. Autonoma
Madrid

Switzerland

ETH Zurich
U. Bern
U. Geneva

United Kingdom

Imperial C.
London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway
U.L.
STFC/Daresbury
STFC/RAL
U. Glasgow
U. Liverpool
U. Sheffield
U. Warwick

USA

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

Vietnam

IFIRSE
IOP, VAST

T2K Breakthrough Prize Celebration, 2016



T2K experimental strategy

Search for CPV by comparing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

Intense beam

π, π, π, π, K

protons

oscillation

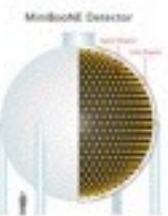
ν, ν, ν, ν

Gigantic detector



$\Phi_\nu(E)$

see A. Marino's talk later today



SciBooNE

see talks by U. Mosel, (& F. Sanchez & D. Ruterbories) later today

$$\Phi_{\nu\text{near}}(E) \cdot \sigma_{\text{near}}(E, Q^2) \cdot \epsilon_{\text{near}}(E) \Leftrightarrow \Phi_{\nu\text{far}}(E, \theta, \Delta m^2, \delta) \cdot \sigma_{\text{far}}(E, Q^2) \cdot \epsilon_{\text{far}}(E)$$

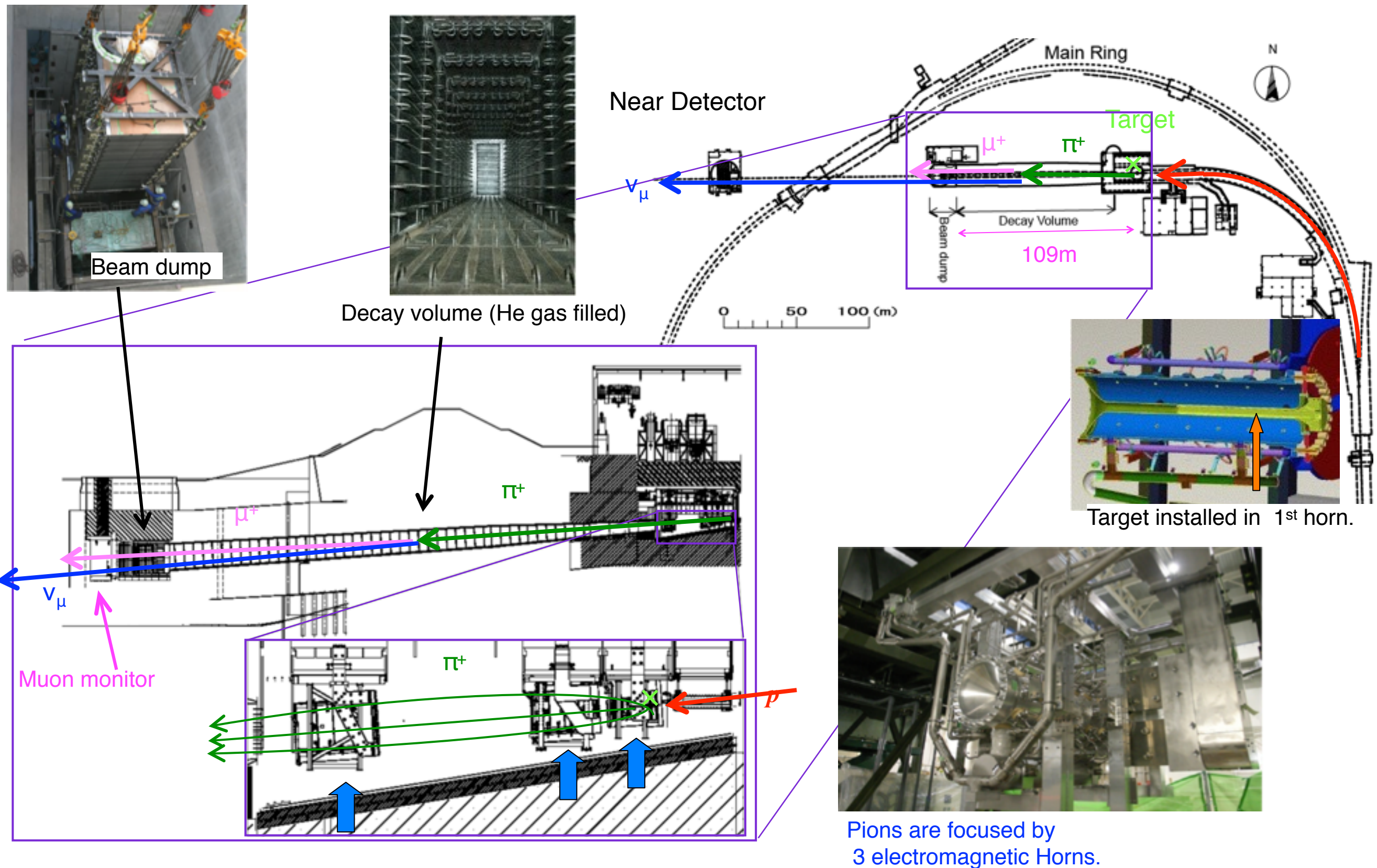
ν

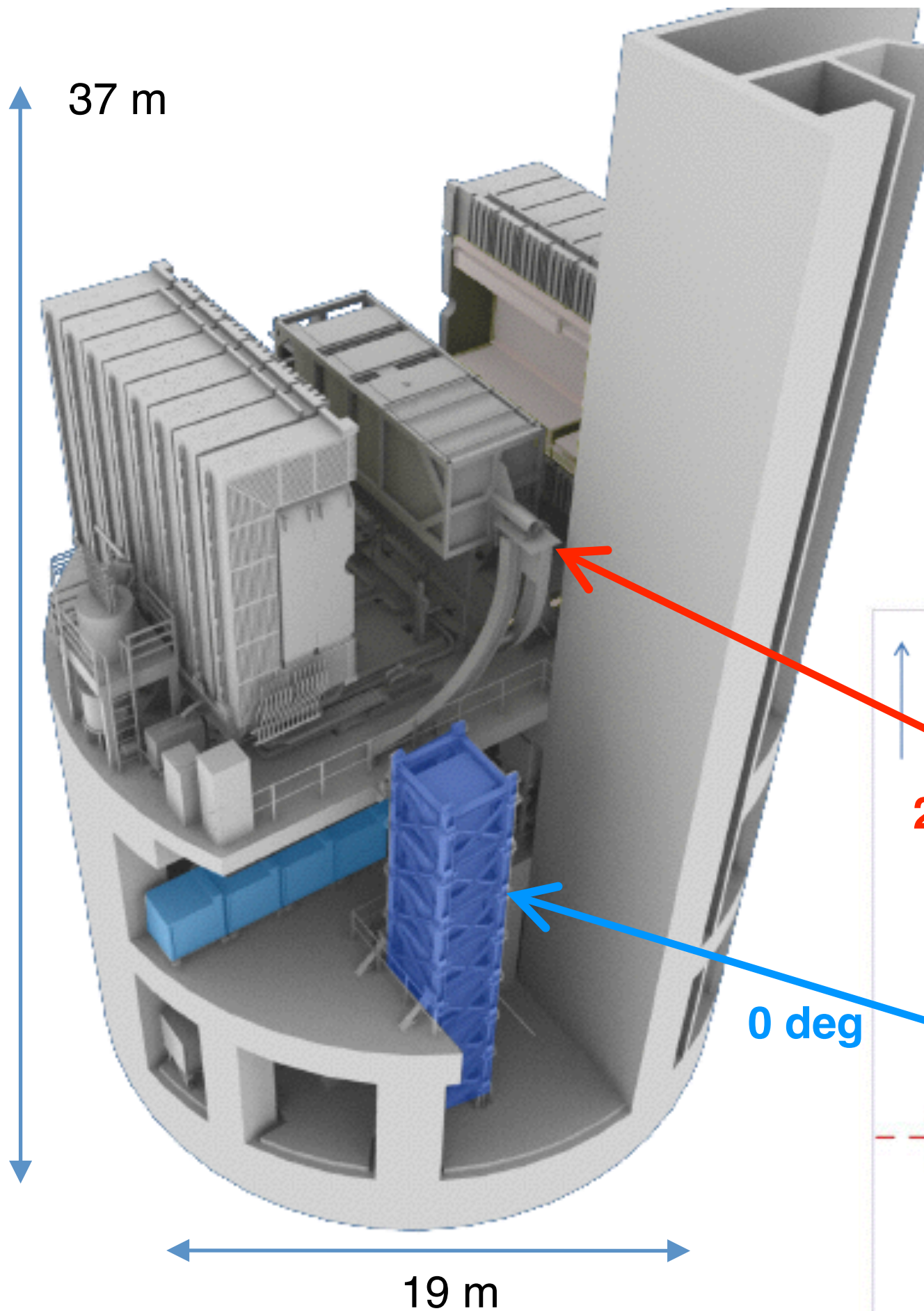
μ

proton

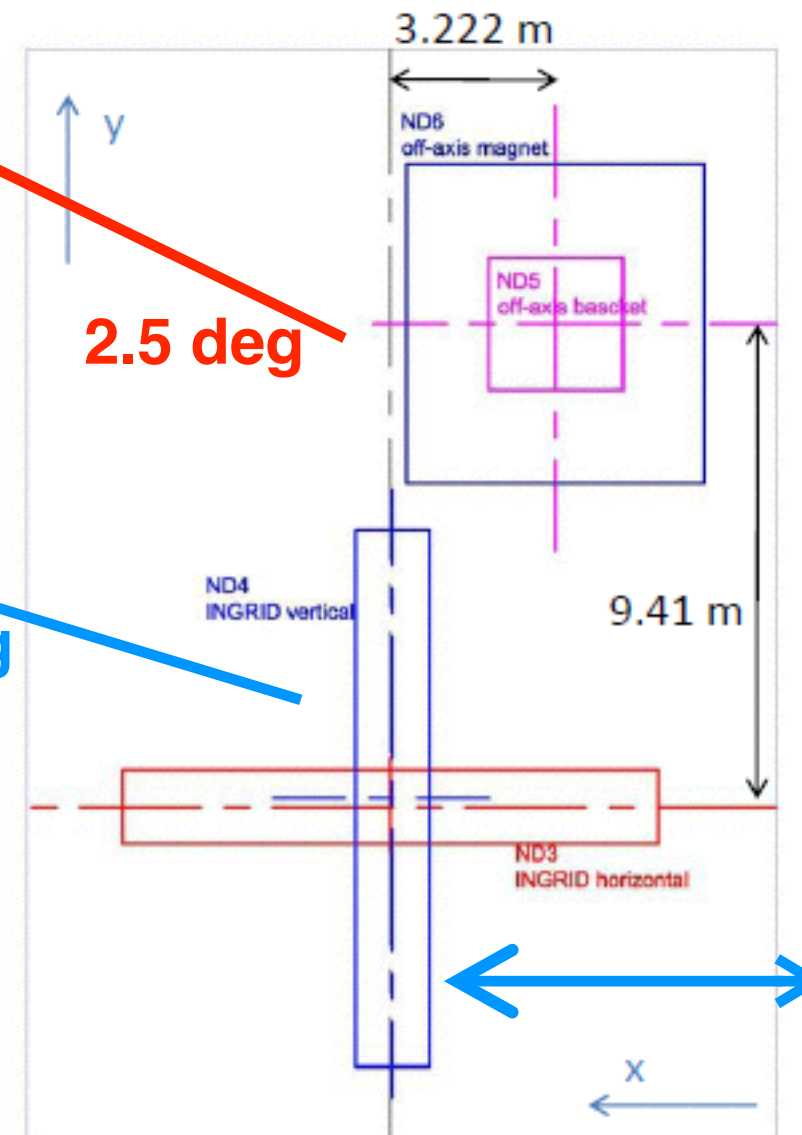
π

J-PARC neutrino beamline overview






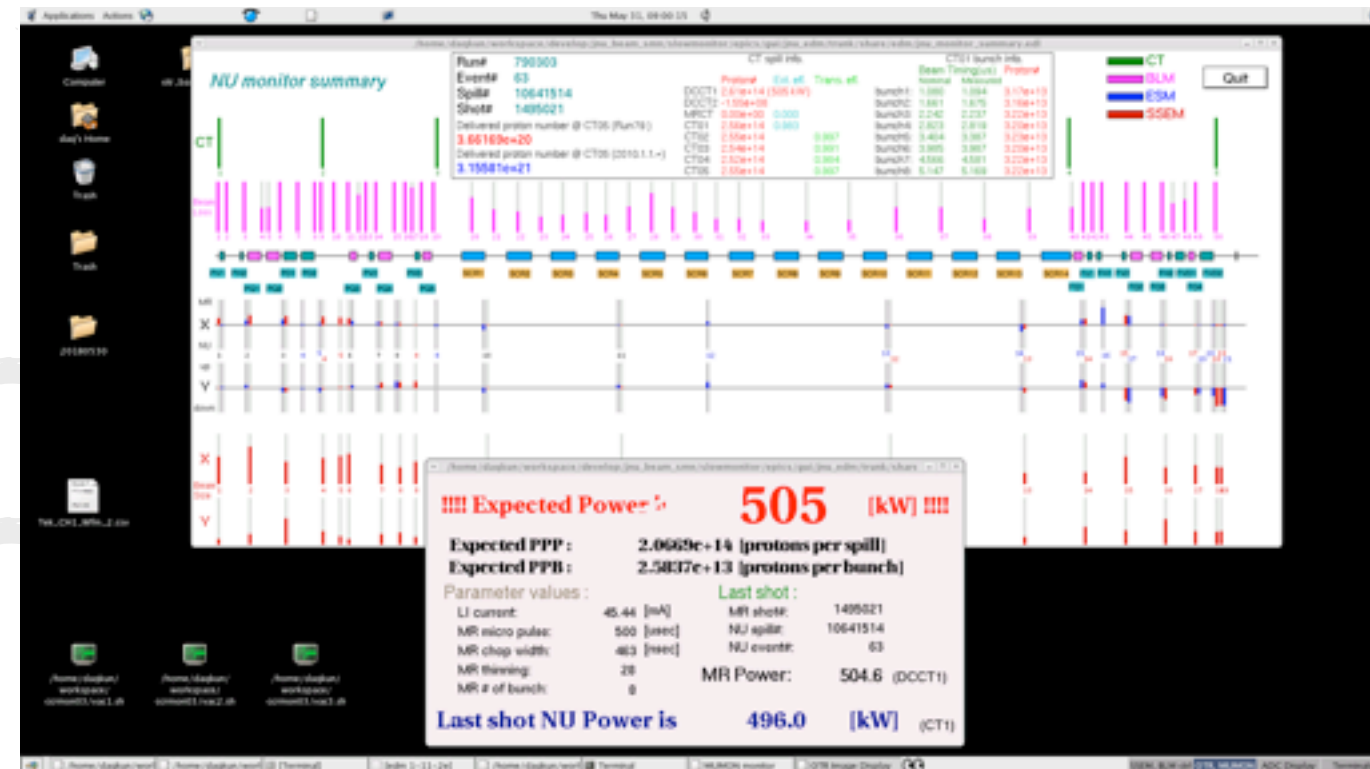
T2K Near Detector pit
houses both the
off-axis (ND280) and
on-axis (**INGRID**)
detectors




Beam delivery & stability

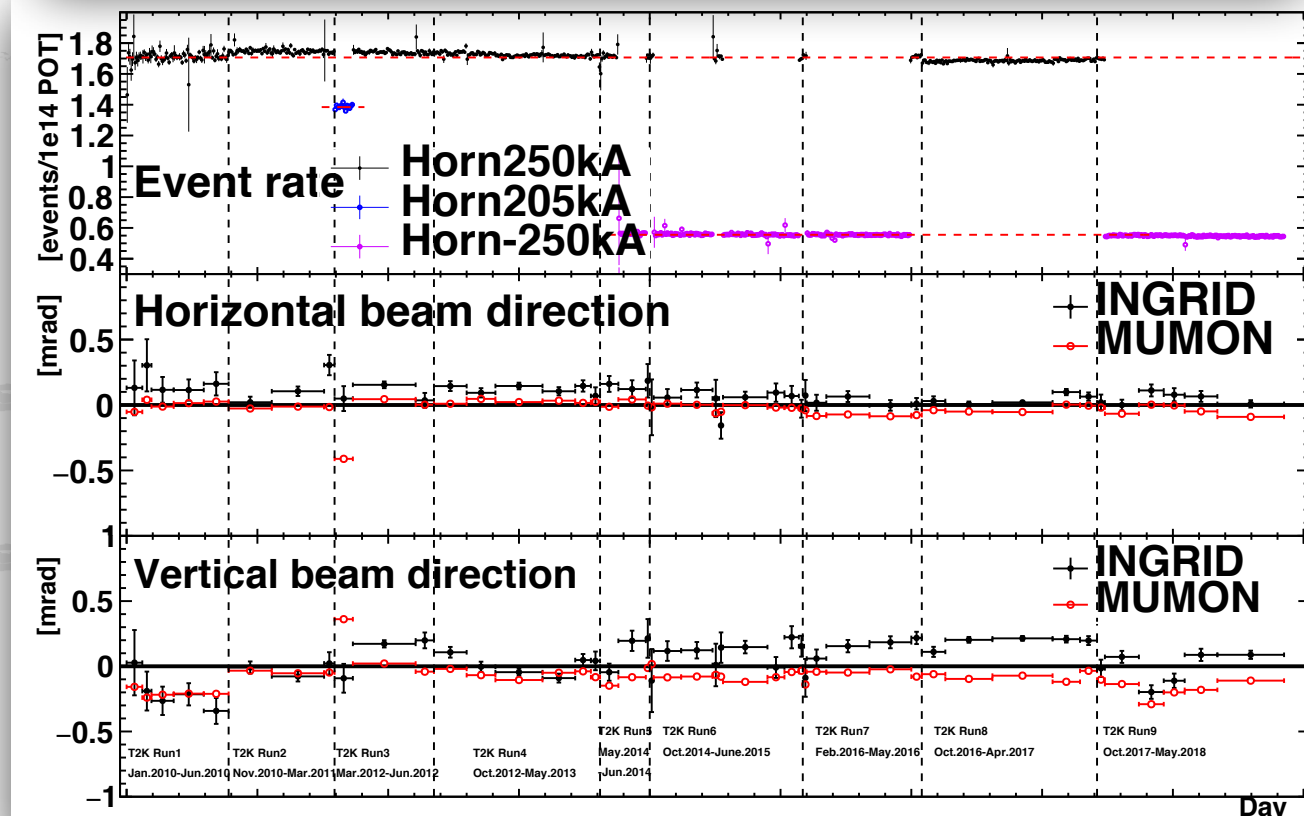
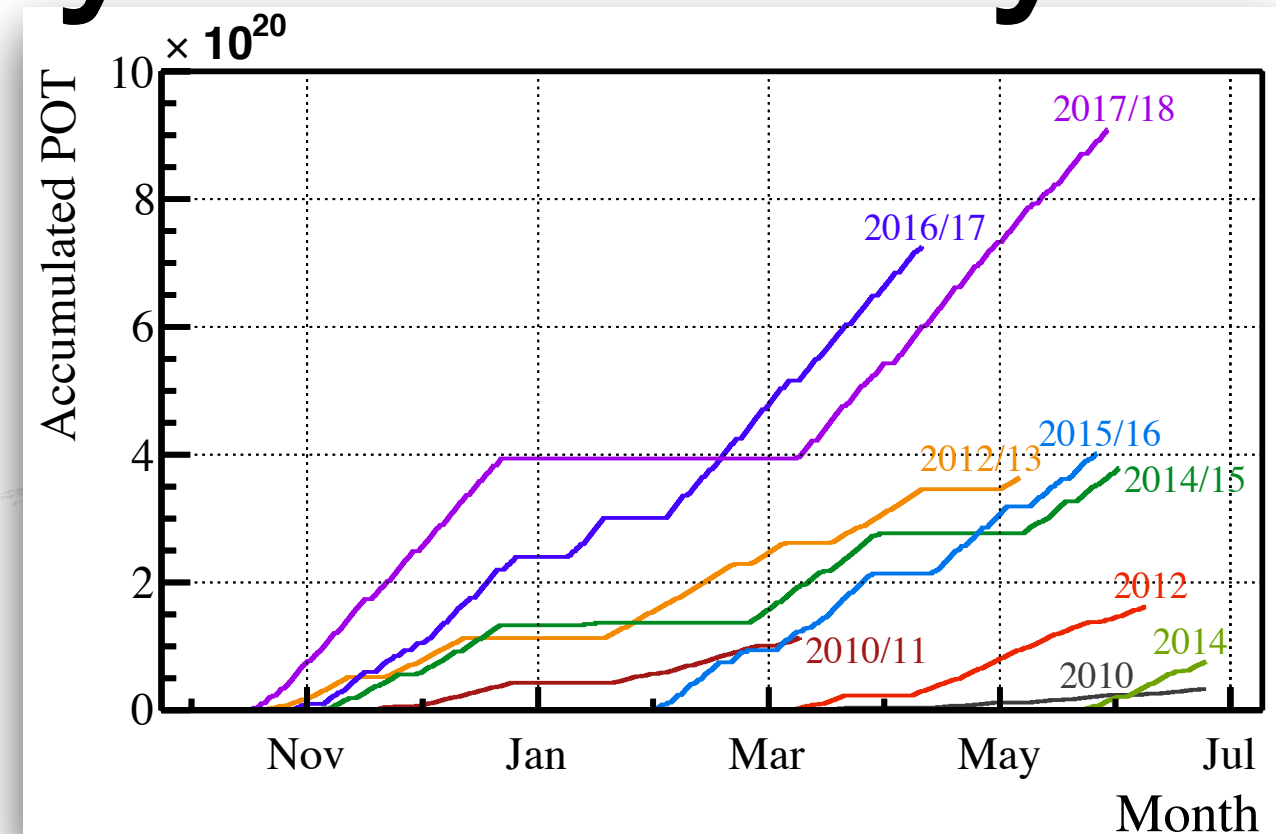
- Milestones this year: 
 - exceeded 3×10^{21} POT;
 - achieved 500 kW beam power!
- Beam delivery summary
 - 3.16×10^{21} POT TOTAL
 - 1.51×10^{21} POT ν -mode (FHC)
 - 1.65×10^{21} POT $\bar{\nu}$ -mode (RHC)
 - Beam operated stably at 485 kW!
 - More than double $\bar{\nu}$ data set in 2017/18!
- Analysis results presented today:
 - 1.49×10^{21} POT ν -mode
 - 1.12×10^{21} POT $\bar{\nu}$ -mode
- Stable neutrino rates and beam direction demonstrated by INGRID and MUMON

MR Run#	79
MR Shot#	853269
	(2018/05/06 01:54:30)
NU Run#	790157
Event#	22809
Spill#	9809738
Deliv. p# (this J-PARC run)	2.10329e+20
Deliv. p# (2010/Jan/1~)	3.00000e+21

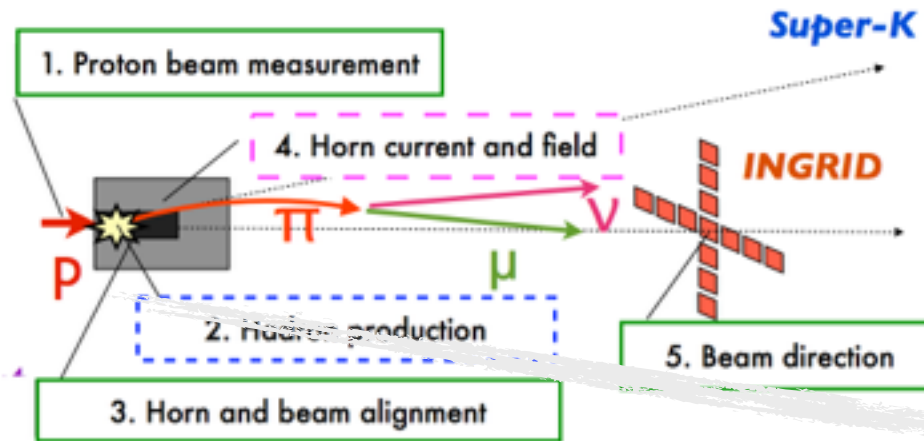


Beam delivery & stability

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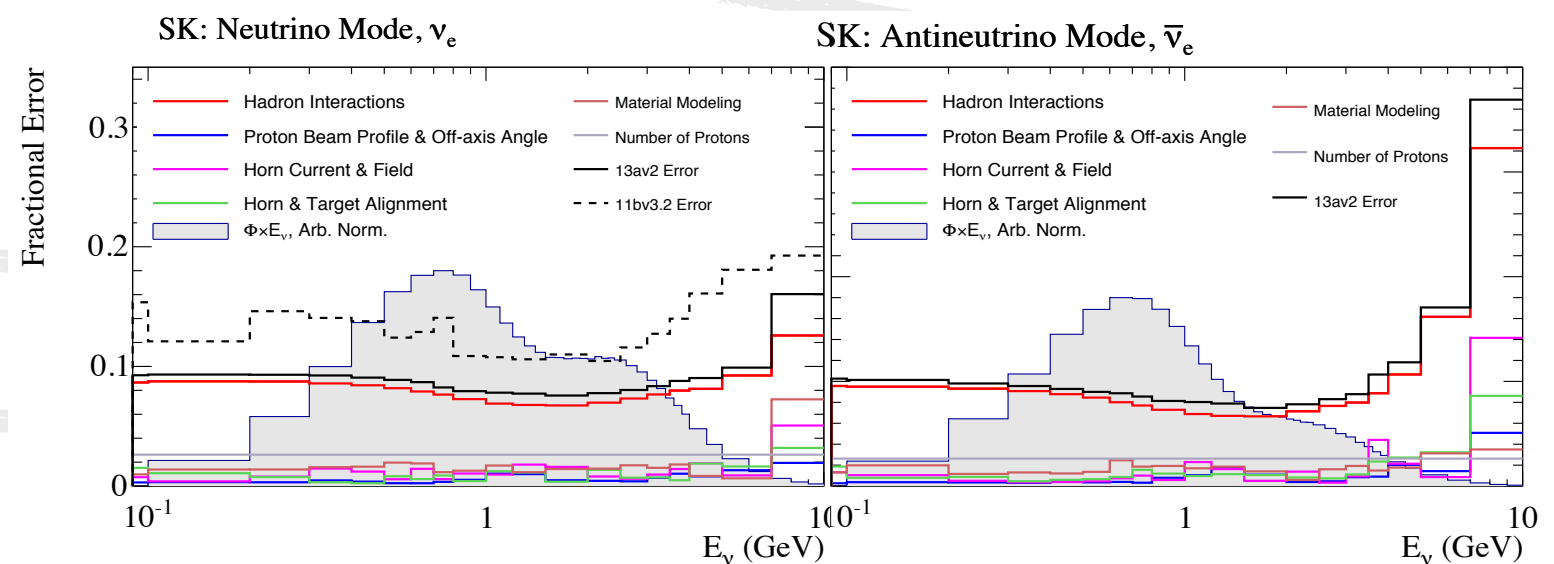
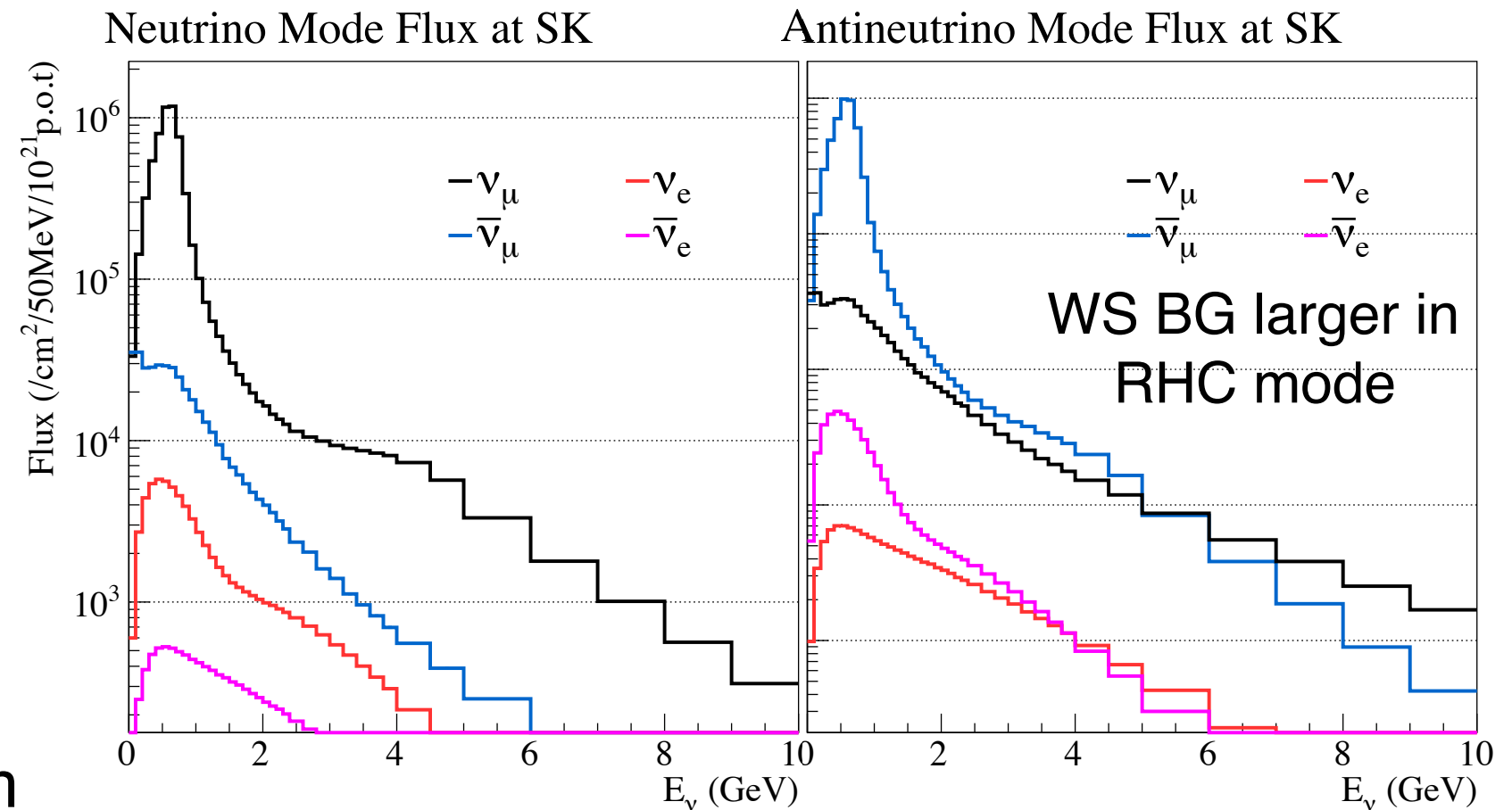
ν Fluxes & Uncertainties



- A priori prediction of flux at Super-K has $\sim 10\%$ uncertainties from 0.1 to 5 GeV
- Tuned with data from CERN NA61/SHINE

see A. Marino's talk later today

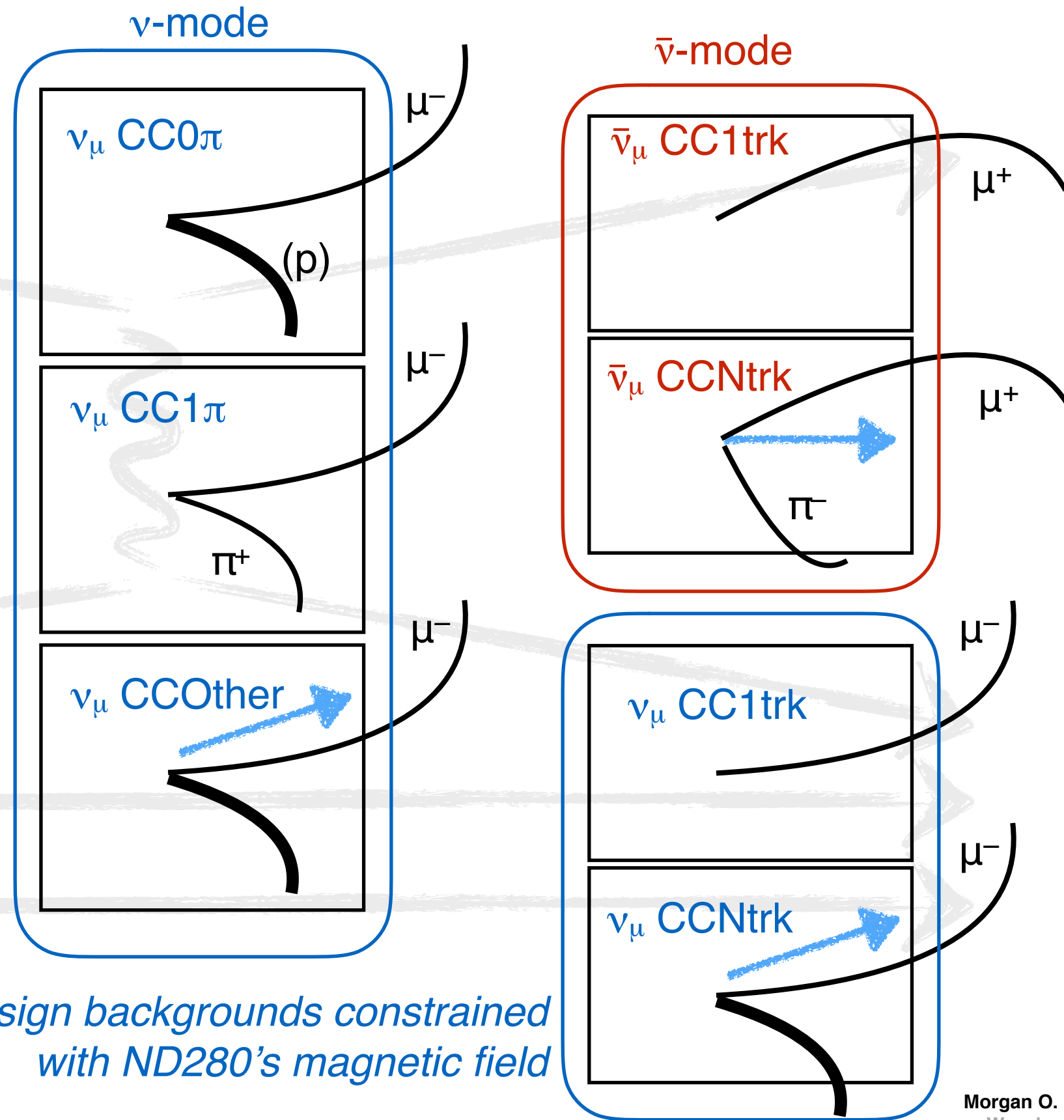
- Near and Far flux shapes are not identical, but highly correlated



see poster by:
T. Vladisavlevic, #200, Wed

ND280 data samples

- 14 total ND280 data samples used by oscillation analysis fit
- ν -mode (FHC)
 - sort by π^+ multiplicity
 - 2 fine-grained detectors (FGDs) (C,O)
 ➔ 6 samples
- $\bar{\nu}$ -mode (RHC)
 - sort by muon charge
 - sort by number of tracks
 - 2 FGDs (C,O)
 ➔ 8 samples



ND280 data fitting

- Parametrise cross section & flux models
 - Constrain by fitting ND280 data
- Result of data fit reduces flux & interaction model uncertainties at SK

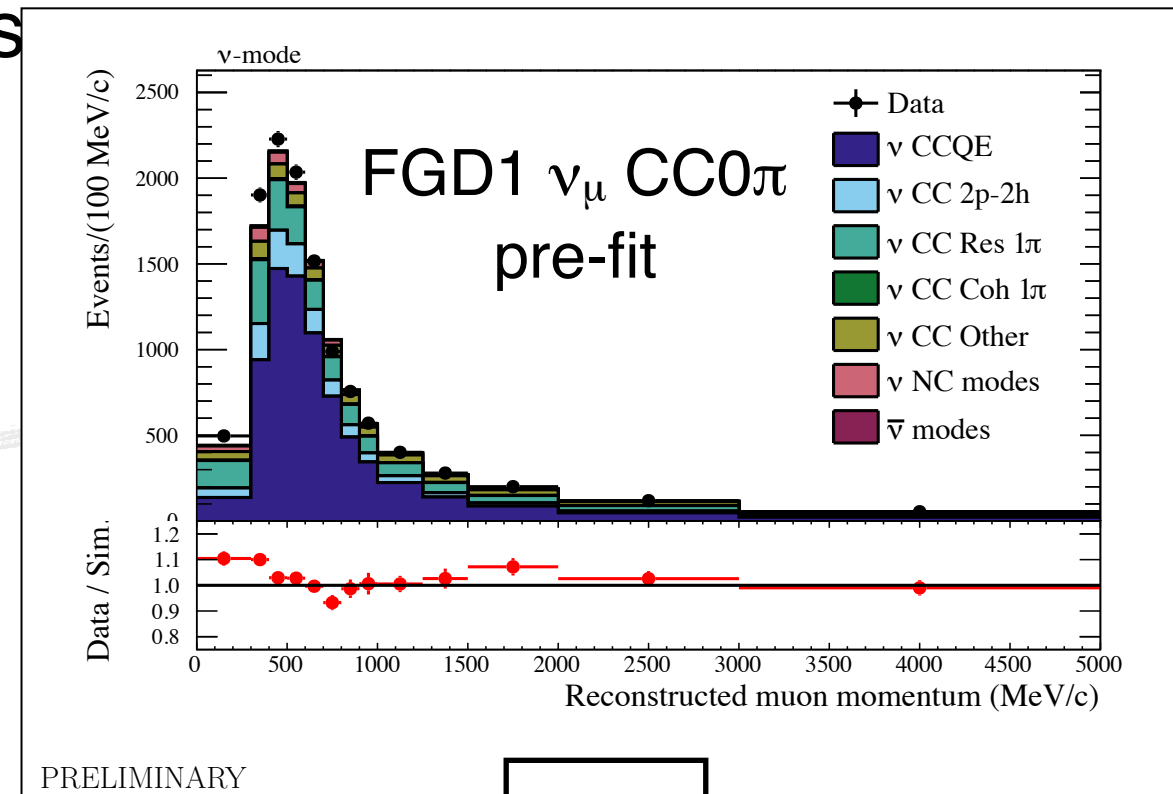
Error source	1-Ring μ		1-Ring e			
	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1 γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87	18.65	5.93

- Also measure ν -nucleus cross sections

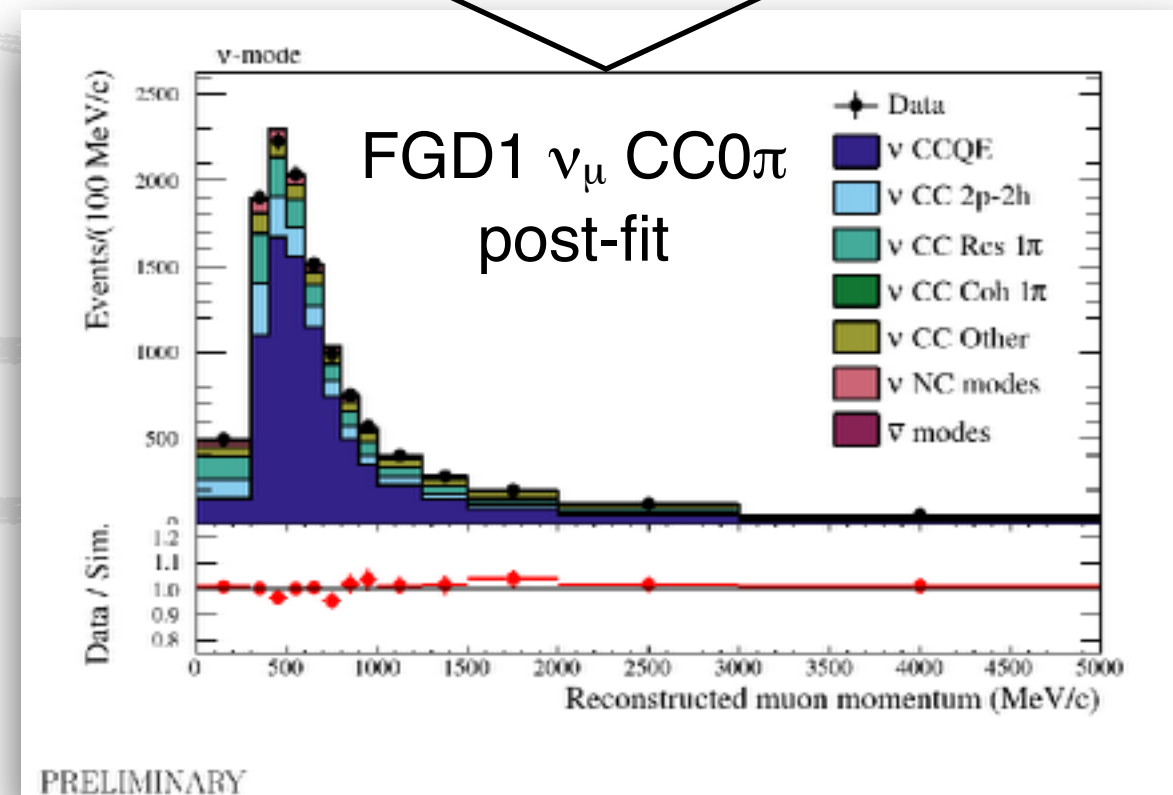
see talk by F. Sanchez later today

see posters by:

M. Batkiewicz, #281, Wed
 M. Buizza Avanzini, #117, Wed
 S. Dolan, #276, Wed
 A. Izmaylov, #358, Wed
 S. King, #381, Wed
 M. Lawe, #330, Wed
 T. Wachała, #148, Wed
 G. Żarnecki, #245, Wed

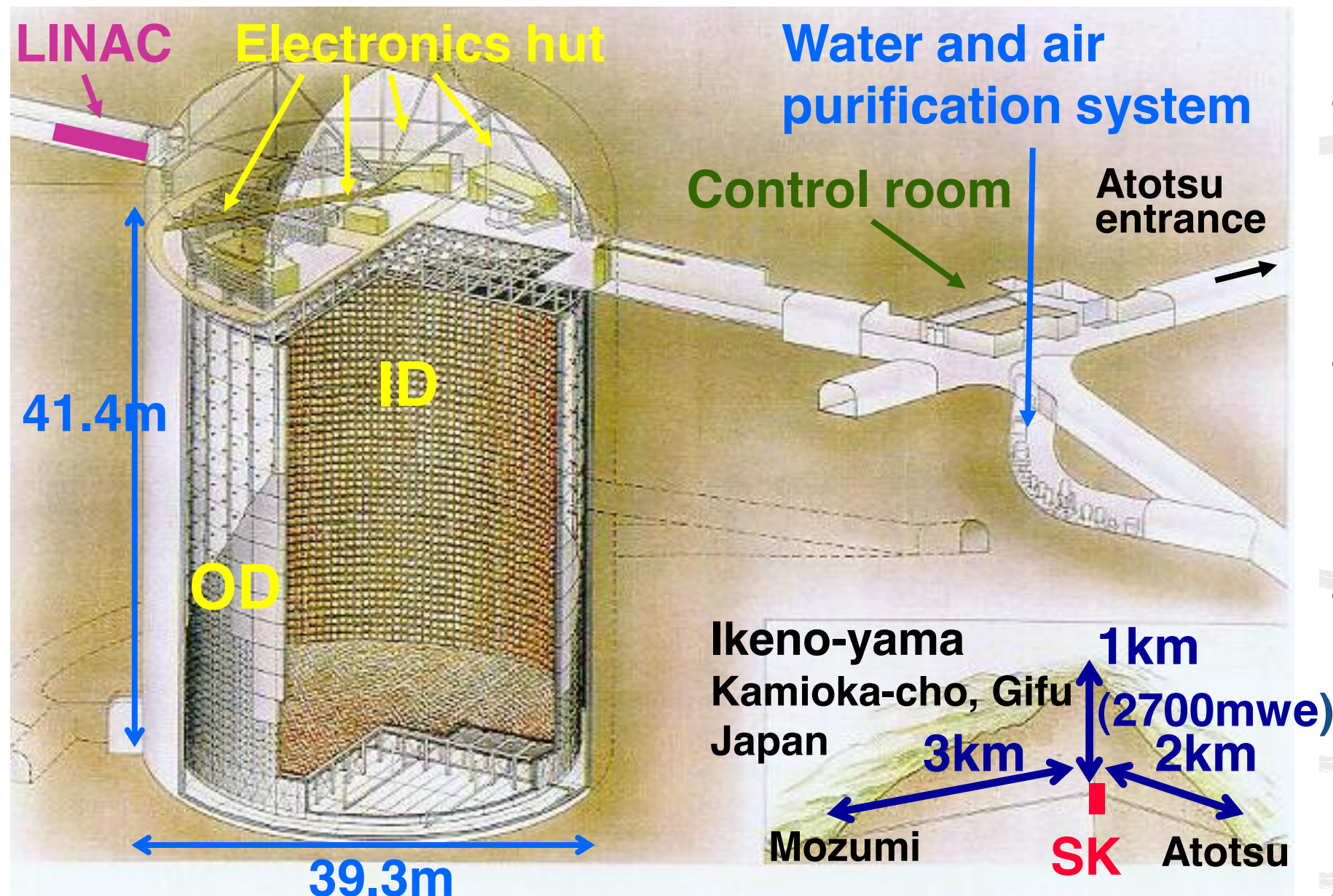


Data fit



Super-K (far) detector

*see talks by Y. Hayato,
M. Ikeda on Tuesday*



- 50 kton water Cherenkov detector
 - **Ultra pure water**
- ~11,000 20" PMT for inner detector (ID) (40% photo coverage)
- ~2,000 outward facing 8" PMT for outer detector (OD) acts as veto region
- Good reconstruction for T2K energy range

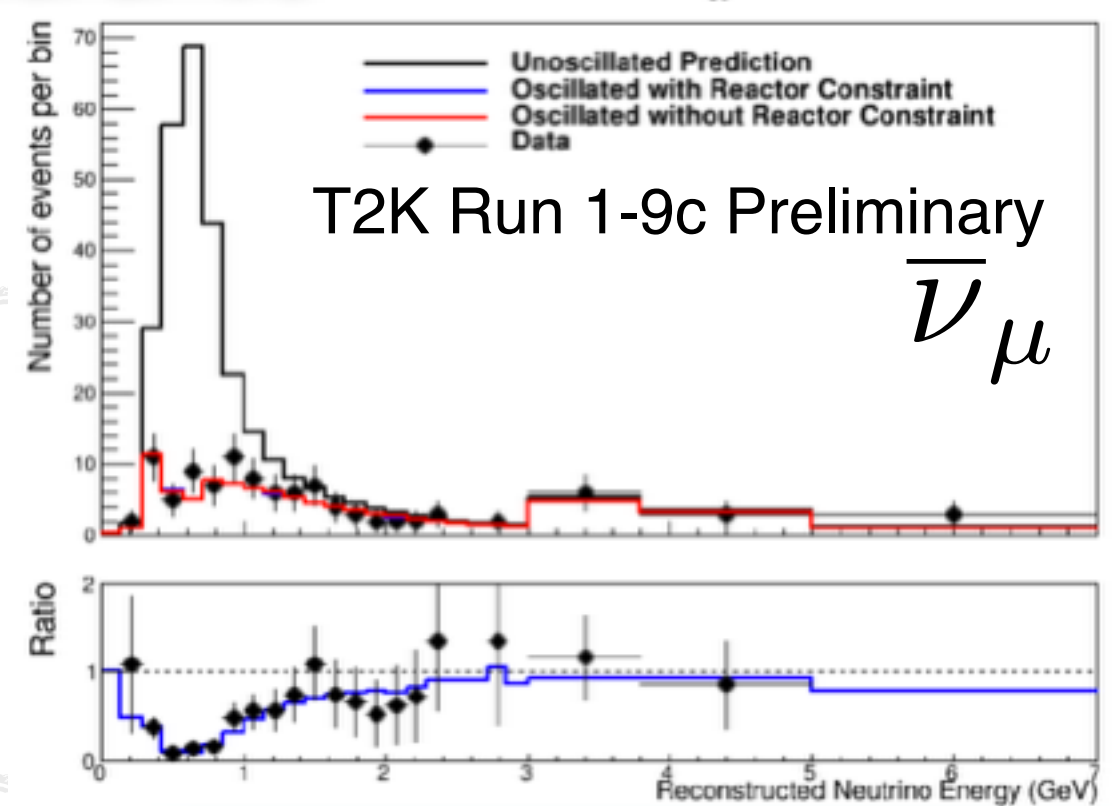
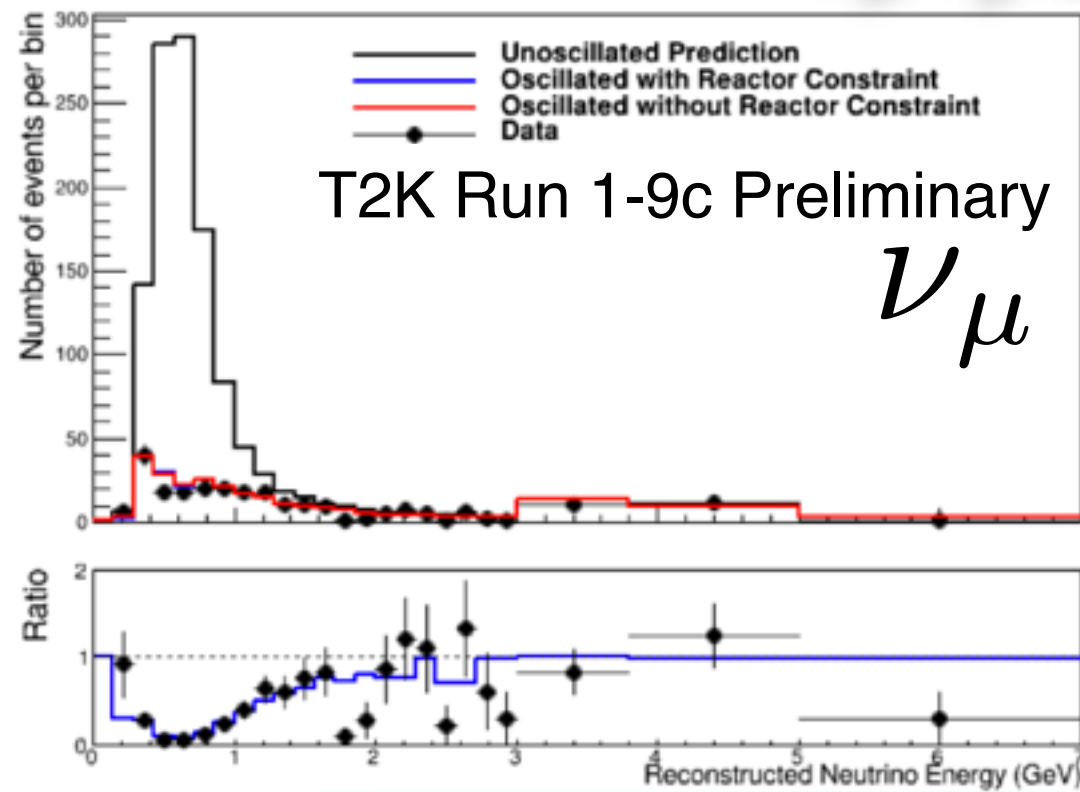
see poster by:
R. Akutsu, #198, Wed

SK data for OA

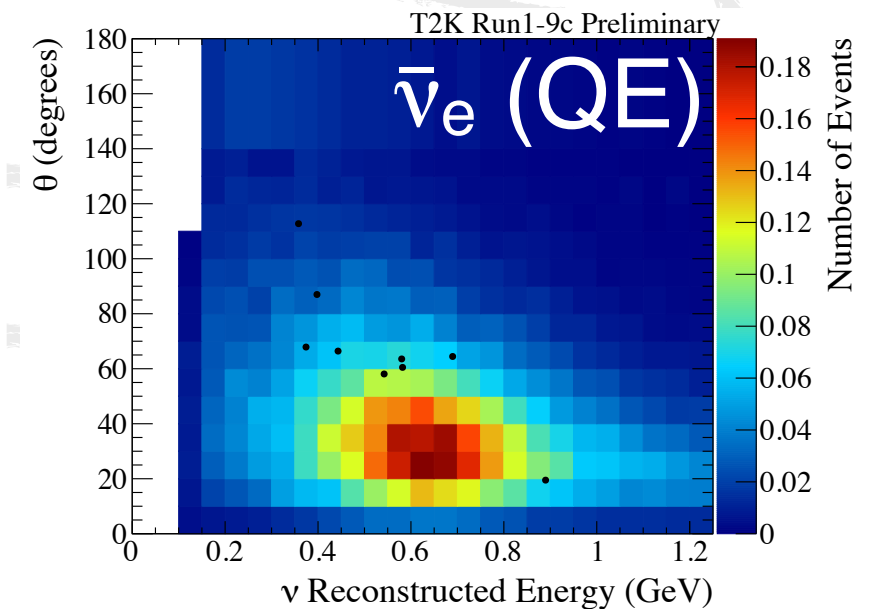
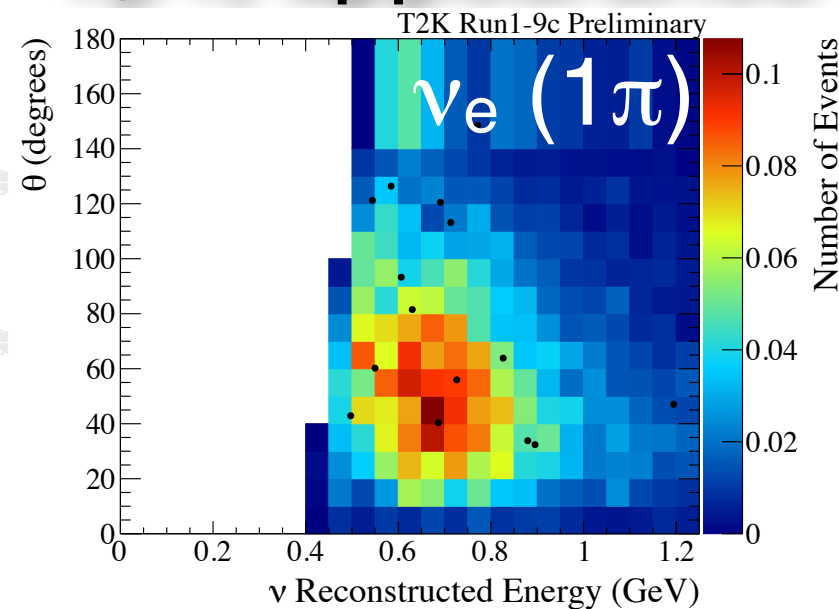
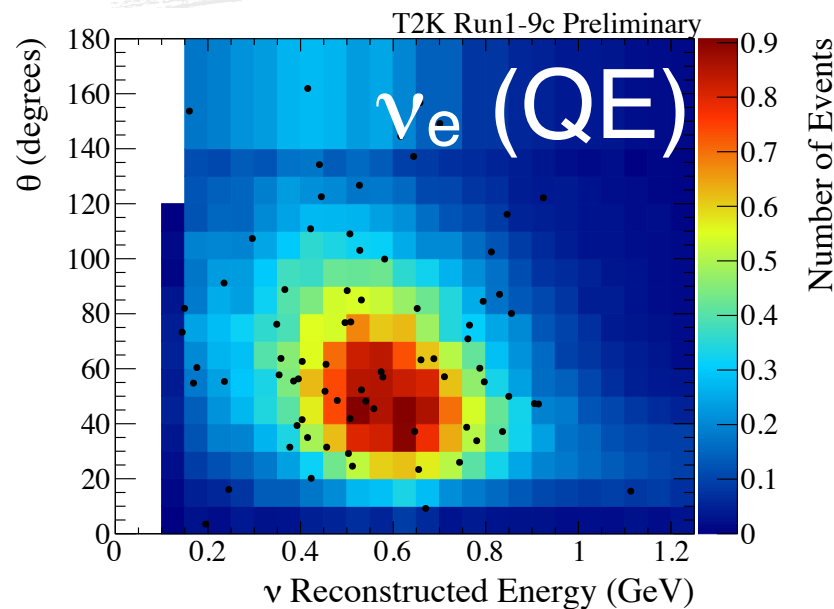
1.49e21 POT

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

1.12e21 POT



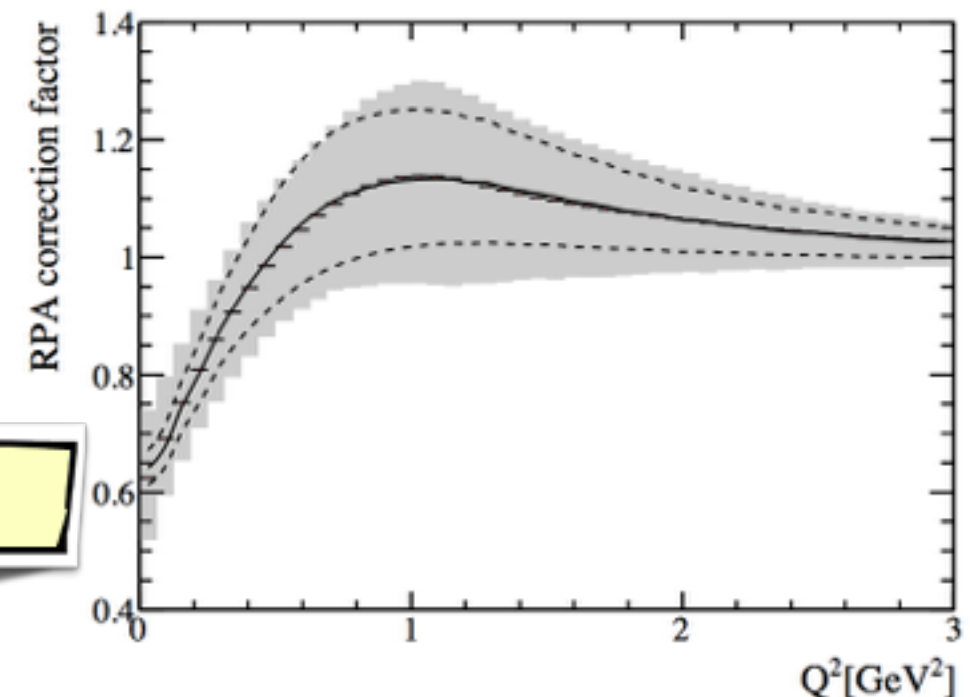
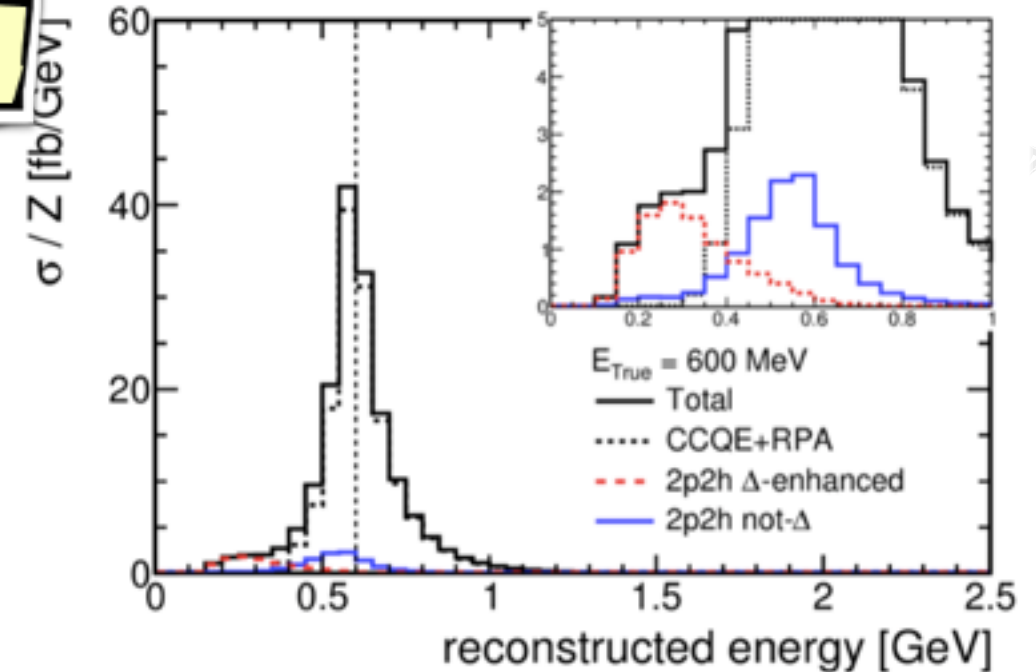
$\nu_e/\bar{\nu}_e$ appearance



Improvements since Neutrino 2016

- Flux model improvements
- Interaction model improvements
 - Pion production model tuning
 - Multinucleon model improvements
 - Improved CCQE model by including effects of long-range correlations (random phase approximation, RPA)
 - New parametrisations of multi-nucleon uncertainties and RPA
- Developed procedure for handling additional systematic errors due to model deficiencies
- SK FV cuts and new data sample

see poster by:
T. Vladisavlevic, #200, Wed

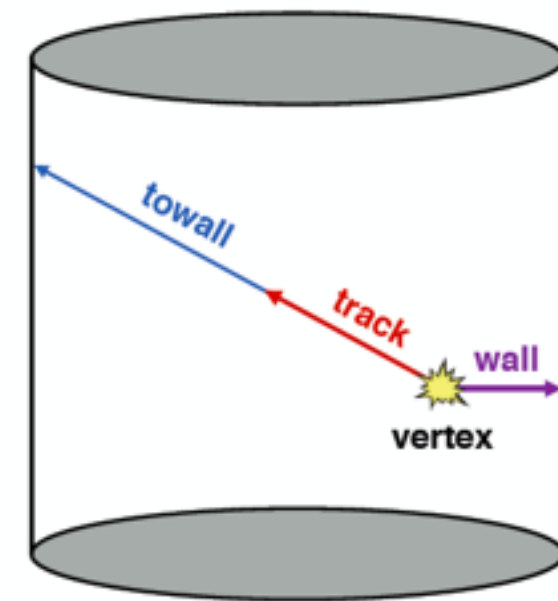
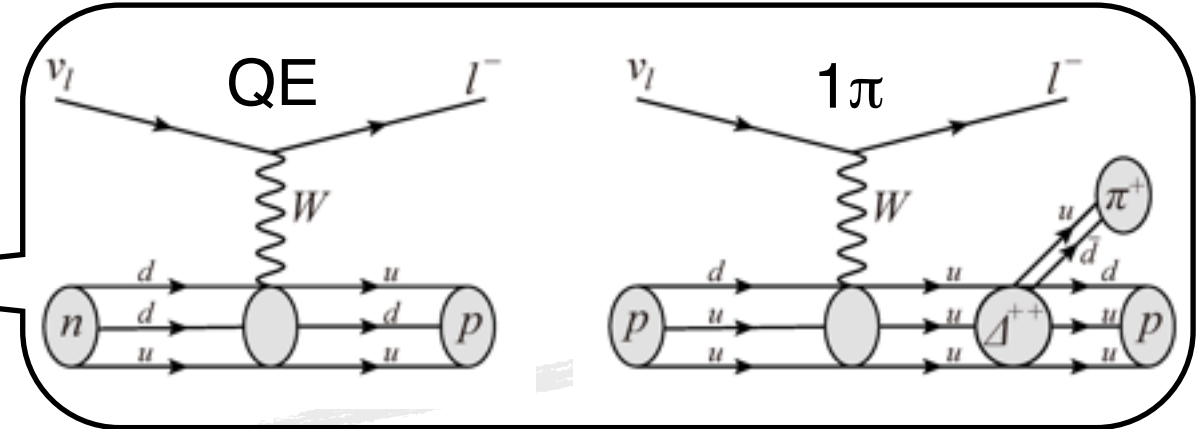


see poster by:
S. Bienstock, #173, Wed

SK FV cuts and new data sample

- Added new SK data sample:
 - ν_e CC1 π in addition to ν_e CCQE
 - Increases statistics $\sim 10\%$
- SK fiducial volume redefined with additional variable
 - previously: **Wall** > 2m
 - now: use **Wall** and **Towall** cuts
 - increases statistics $\sim 15\text{-}20\%$
- Using both improvements, we increase our ν_e efficiency by $\sim 30\%$!

already shown by M. Hartz
<https://www.t2k.org/docs/talk/282>



Sample	Towall Cut	Wall Cut
CCQE 1-Ring e-like FHC	170 cm	80 cm
CCQE 1-Ring μ -like FHC	250 cm	50 cm
CC1 π 1-Ring e-like FHC	270 cm	50 cm
CCQE 1-Ring e-like RHC	170 cm	80 cm
CCQE 1-Ring μ -like RHC	250 cm	50 cm

T2K ν & $\bar{\nu}$ oscillation analyses

- Compare observed rates at SK to predictions under oscillation hypothesis, tuned with observed ND rates

Oscillation Probability *Constrained by near detector fit*

$$N(p_k, \theta_k; \theta_{23}, \Delta m_{32}^2, \delta_{CP} \dots) = \sum_i^{E_\nu \text{ bins}} \sum_j^{\text{flavors}} \boxed{P_{\nu_j \rightarrow \nu_k}(E_{\nu,i}; \theta_{23}, \Delta m_{32}^2, \delta_{CP} \dots)} \boxed{\Phi_j^{\text{far}}(E_{\nu,i}) \sigma_k(E_{\nu,i}, p_k, \theta_k)} \epsilon(p_k, \theta_k) M_{\text{det}}$$

SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$	
FHC 1R $_{\mu}$	268.5	268.2	268.5	268.9	243
RHC 1R $_{\mu}$	95.5	95.3	95.5	95.8	102
FHC 1Re 0 decay-e	73.8	61.6	50.0	62.2	75
FHC 1Re 1 decay-e	6.9	6.0	4.9	5.8	15
RHC 1Re 0 decay-e	11.8	13.4	14.9	13.2	9

- SK event rates are in line with expectations based on oscillation model
 - Of note: 15 events observed in CC1 π ν_e sample, with prediction of 6.9 maximum
 - p-value for up/down fluctuation in 1 of 5 samples is: ~5% (1% with single sample).

see posters by:
F. Bench, #480, Wed
S. Bienstock, #173, Wed

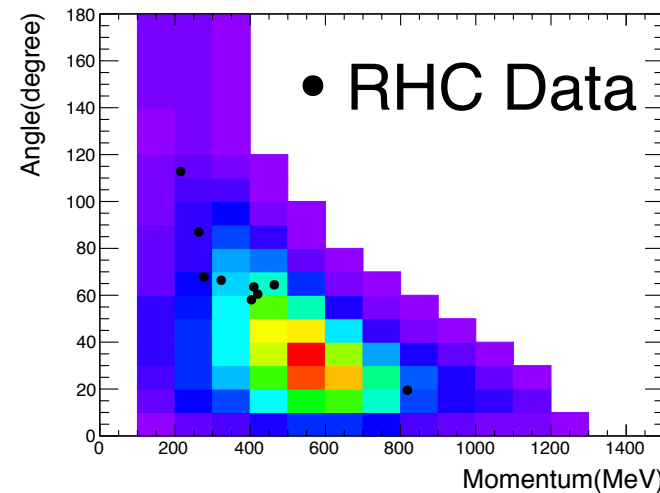
$\bar{\nu}_e$ appearance

- Compare consistency with PMNS $\bar{\nu}_e$ appearance ($\beta = 1$) and no $\bar{\nu}_e$ appearance ($\beta = 0$)
 - if $\beta = 0$ expect 6.5 events
 - if $\beta = 1$ expect 11.8 events
- The data shapes look more consistent with background spectra than $\bar{\nu}_e$ signal spectrum
- Use rate+shape analyses:

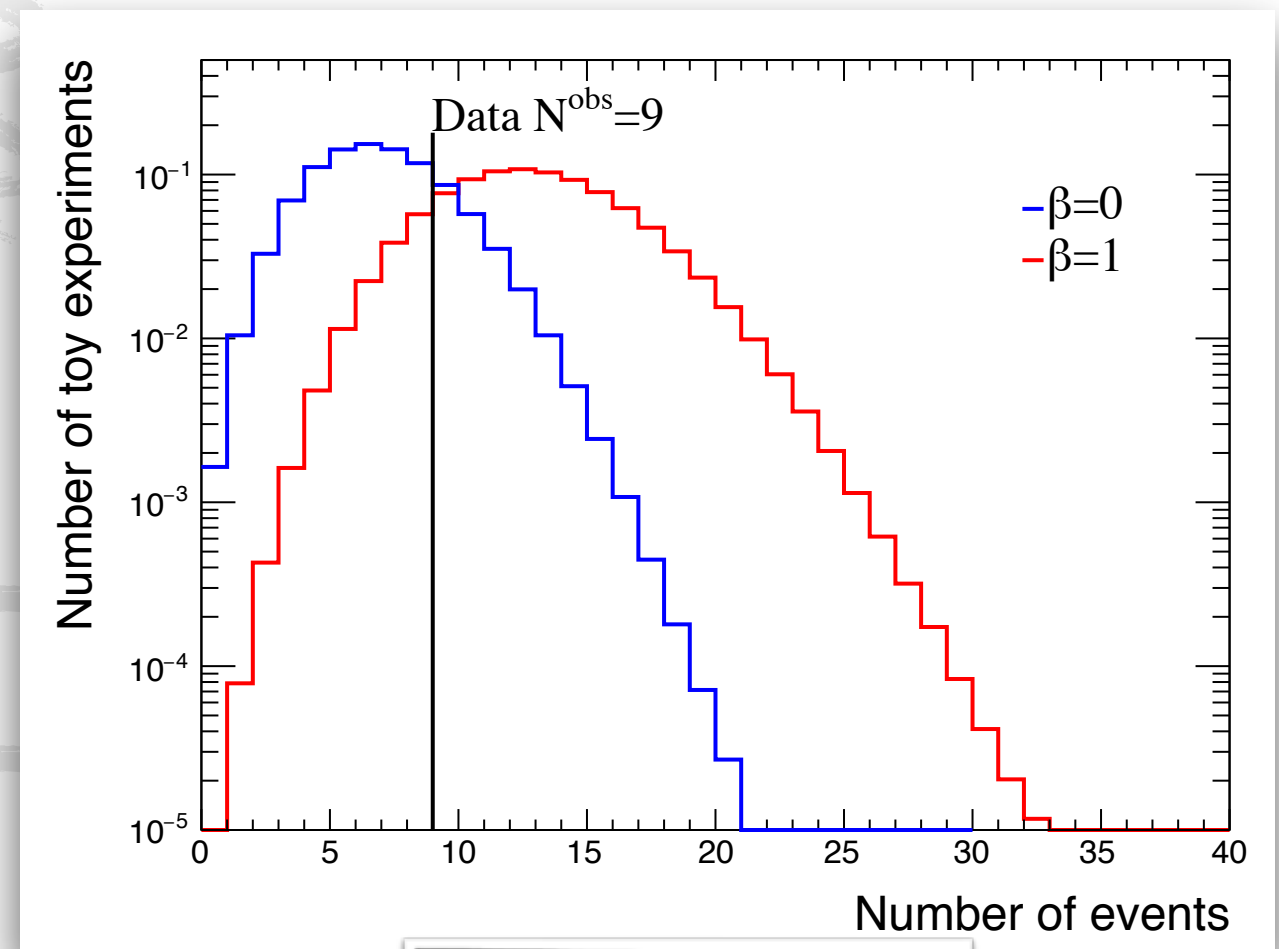
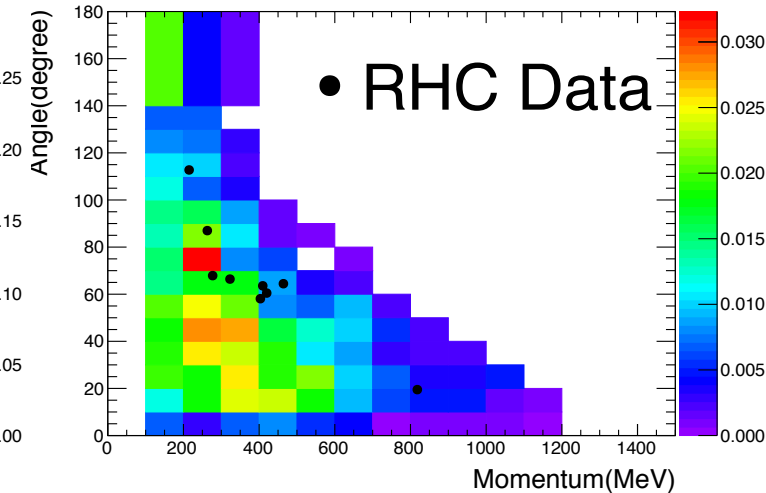
β	HYPOTHESIS	P-VALUE
$\beta=0$	NO appearance	$p=0.233$
$\beta=1$	PMNS appearance	$p=0.0867$

- **No strong statistical conclusion yet**

Shape of $\bar{\nu}_e$ signal

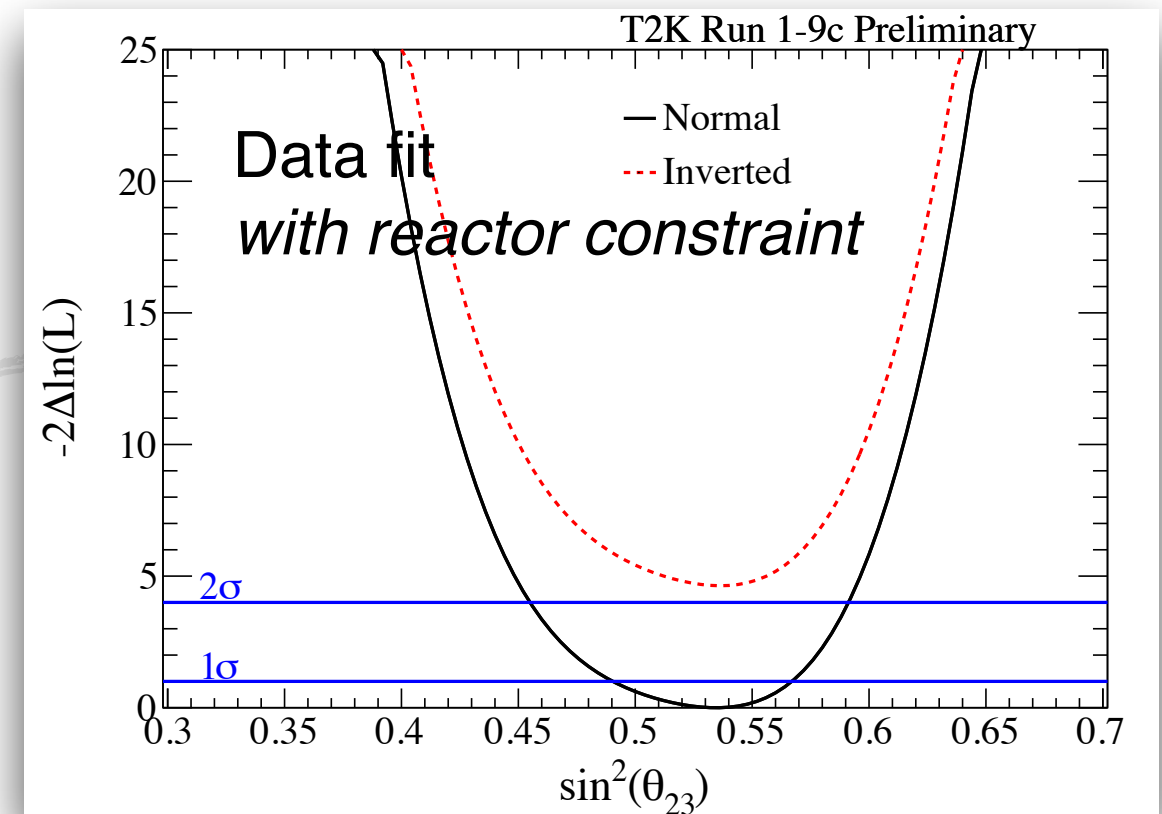
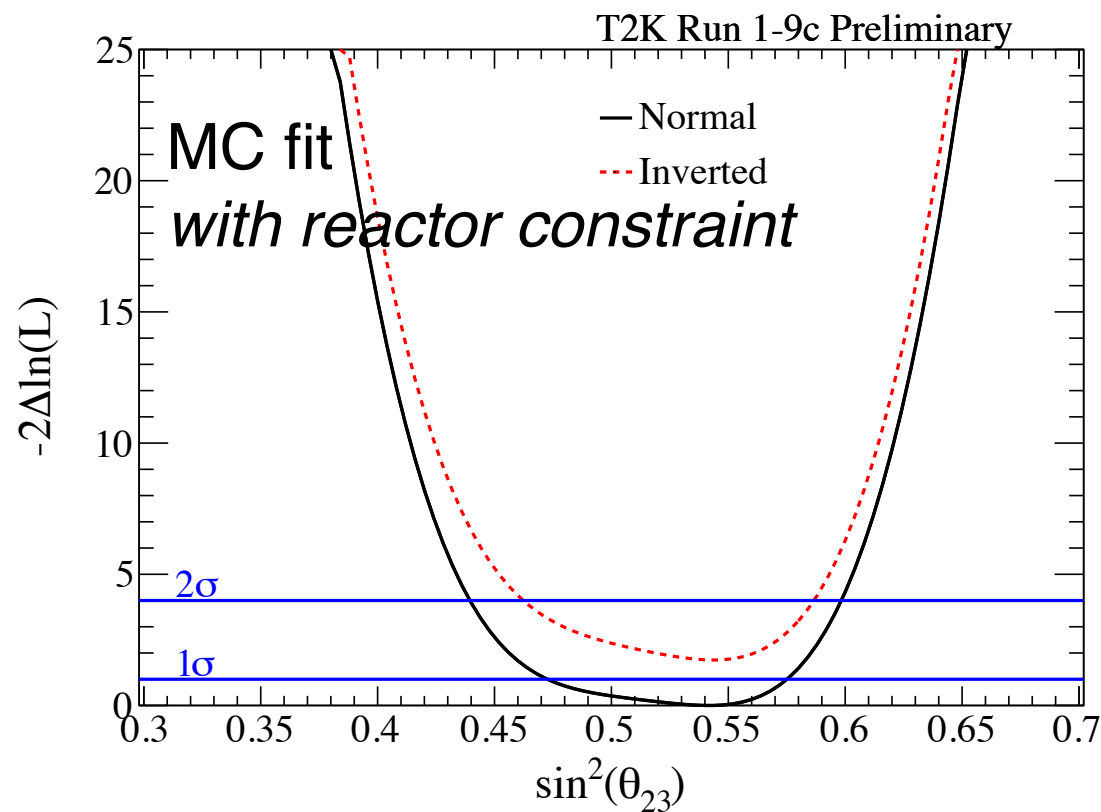


Shape of mis-ID BGs

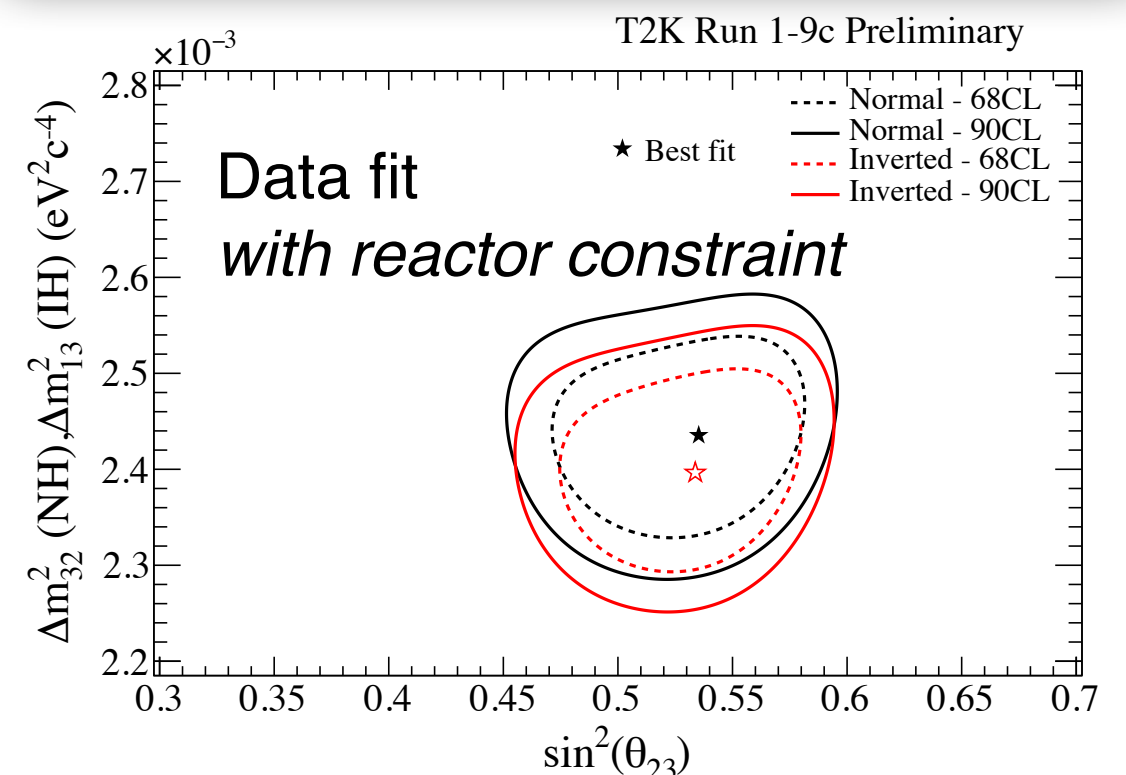


see posters by:
F. Bench, #277, Wed

Atmospheric sector: θ_{23} , $\Delta m^2_{32(1)}$

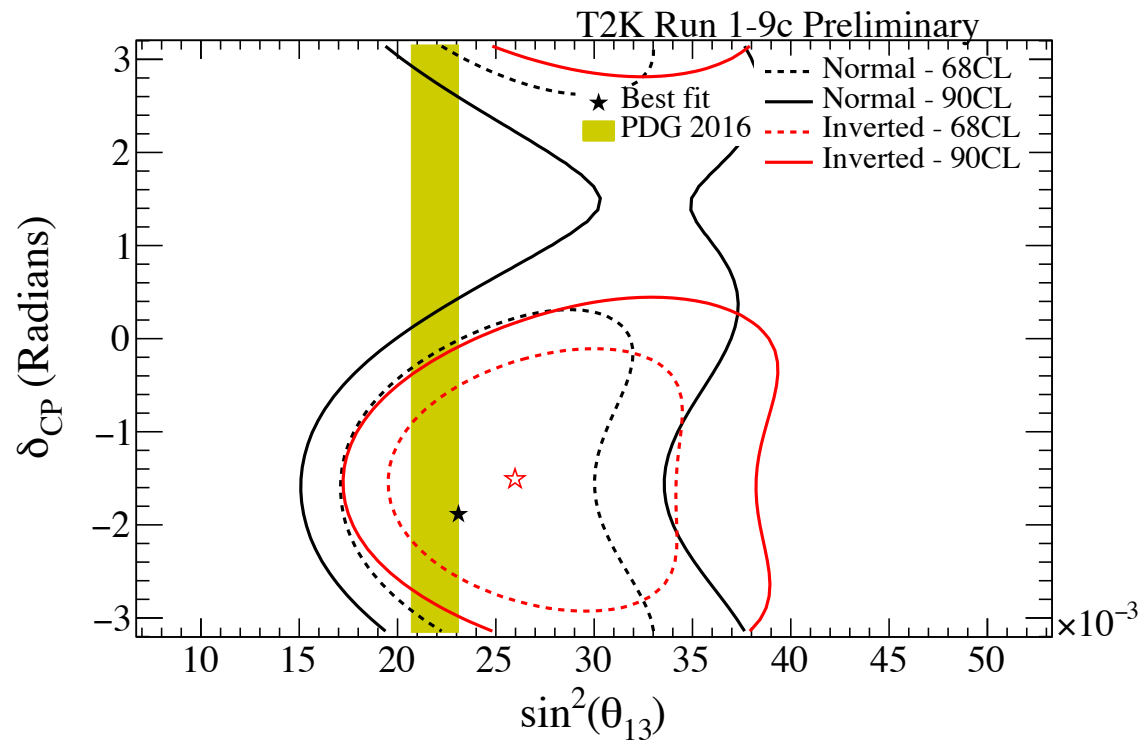


	NH	IH
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$ \Delta m^2 $	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$

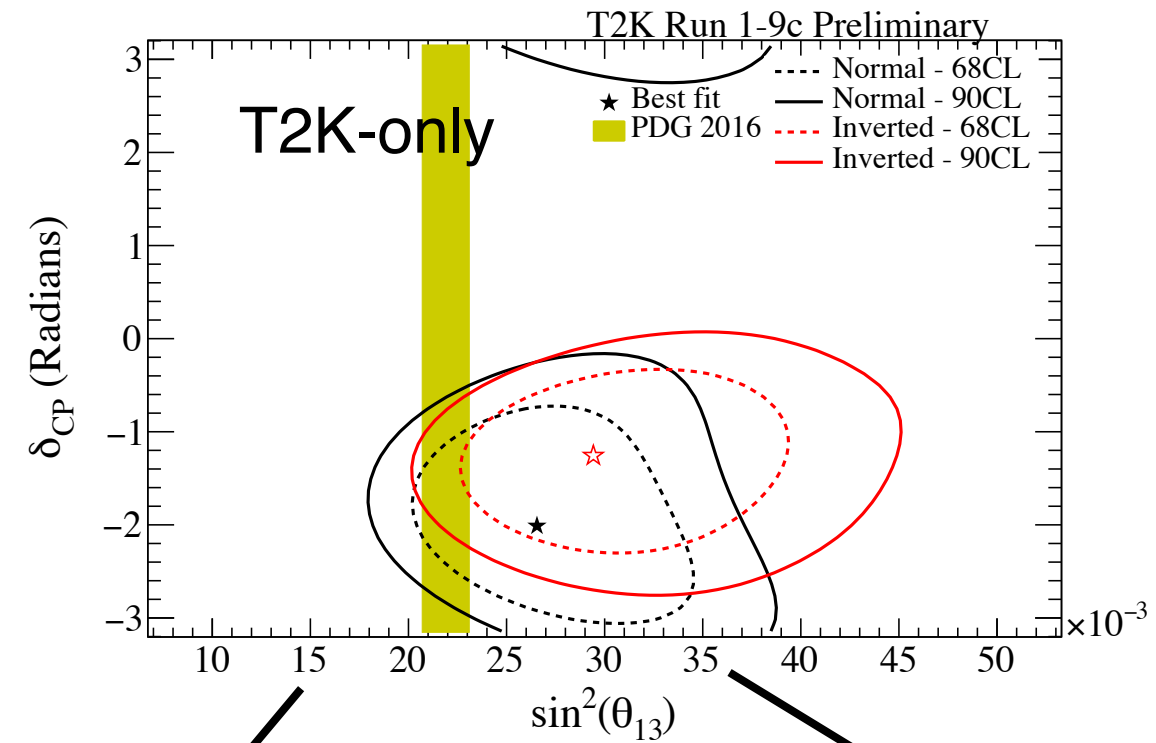


δ_{CP} vs. $\sin^2\theta_{13}$

SENSITIVITY

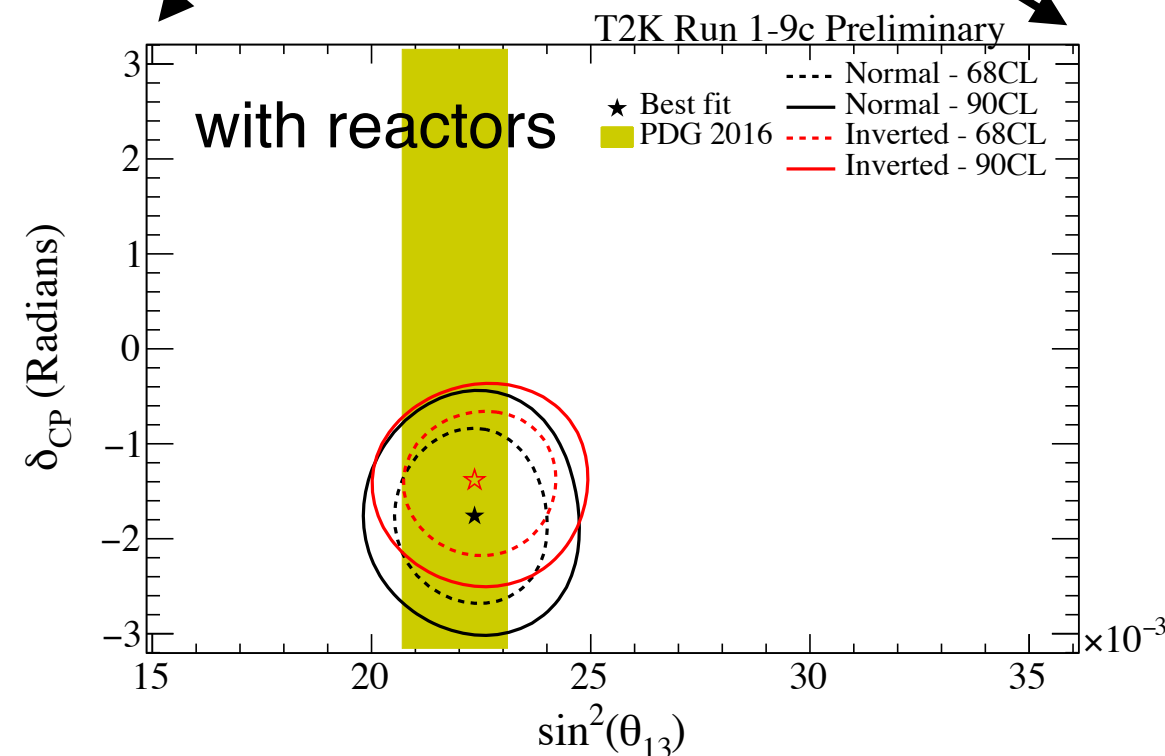


DATA FIT



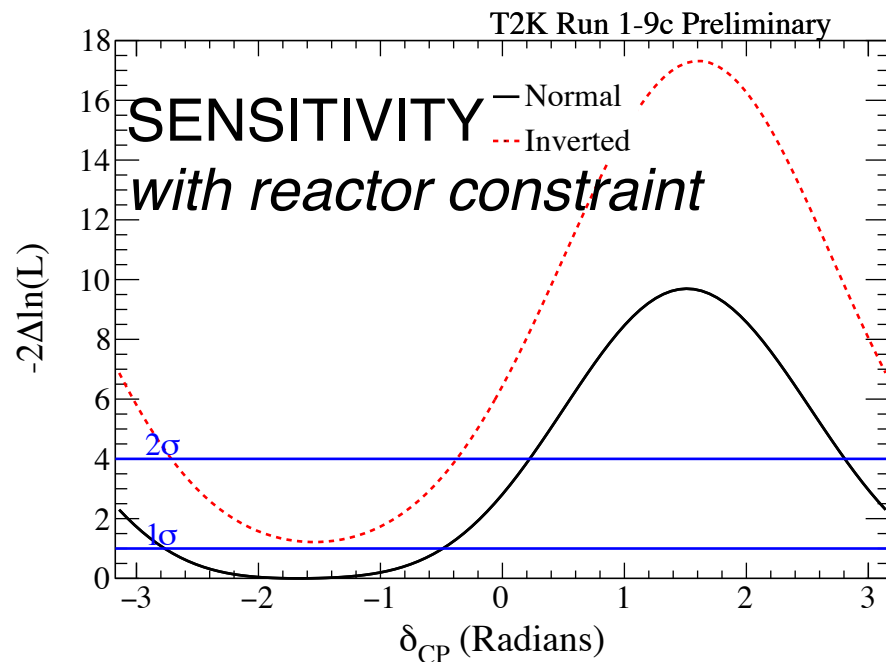
• sensitivity assumptions:

- $\sin^2\theta_{13} = 0.0219$ (2016 PDG)
- $\sin^2\theta_{23} = 0.528$
- NH, $\delta_{CP} = -1.601$
- Data fit stronger than sensitivity

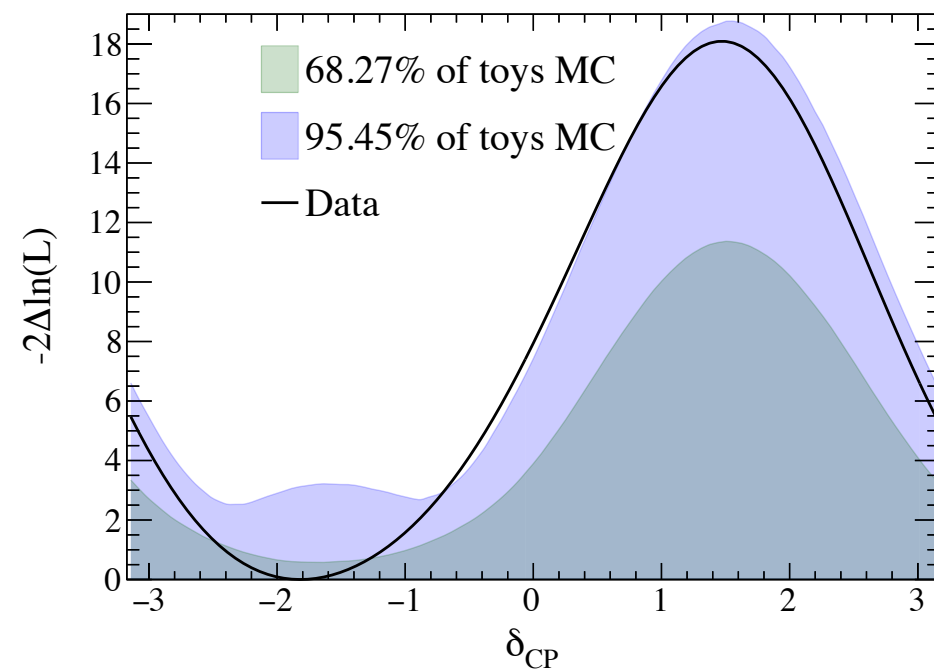
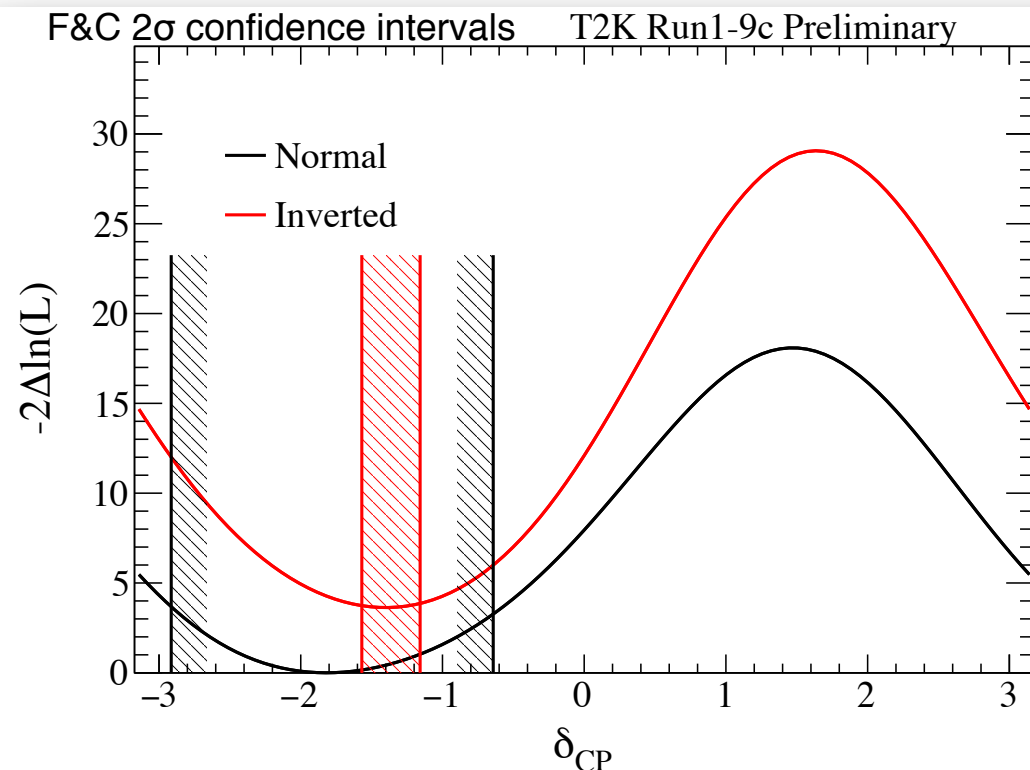


δ_{CP} 1D contours

- CP conserving values outside of 2σ region for both hierarchies
- 19% of toys exclude CP conservation at 2σ CL (both $\delta_{CP}=0$ & $\delta_{CP}=\pi$)



DATA FIT with reactor constraint



δ_{CP}	Hierarchy	90%	2σ
0	NH	0.421	0.288
π	NH	0.388	0.248
0	IH	0.768	0.660
π	IH	0.783	0.685

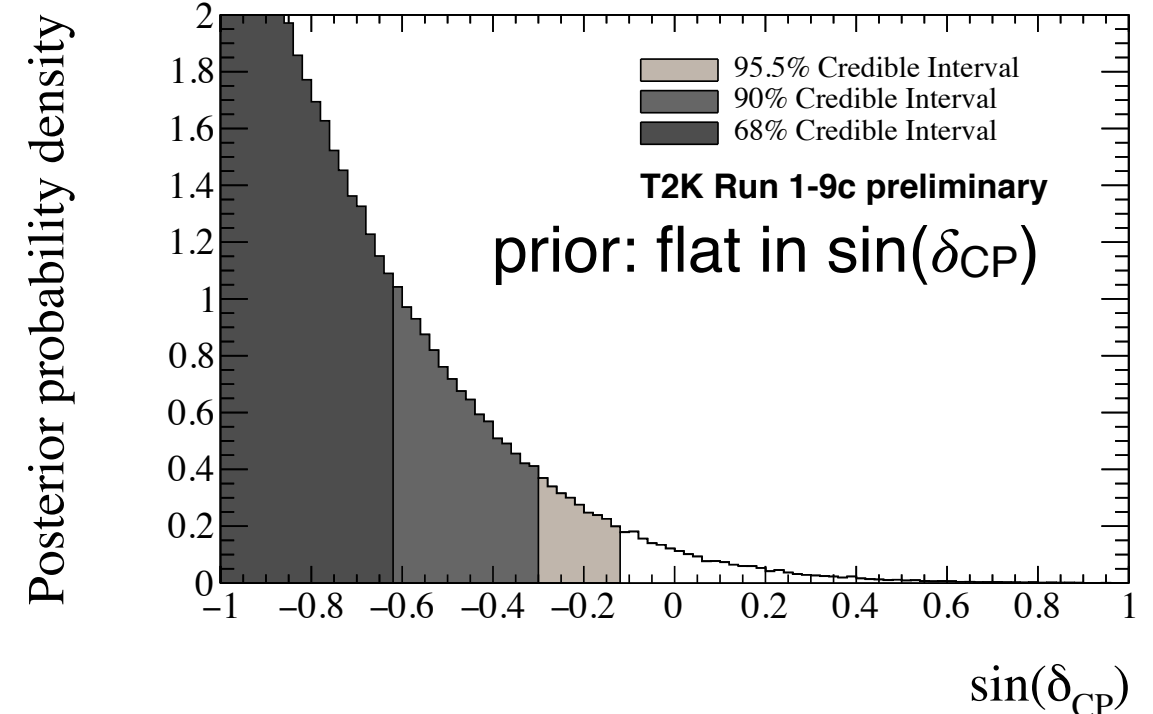
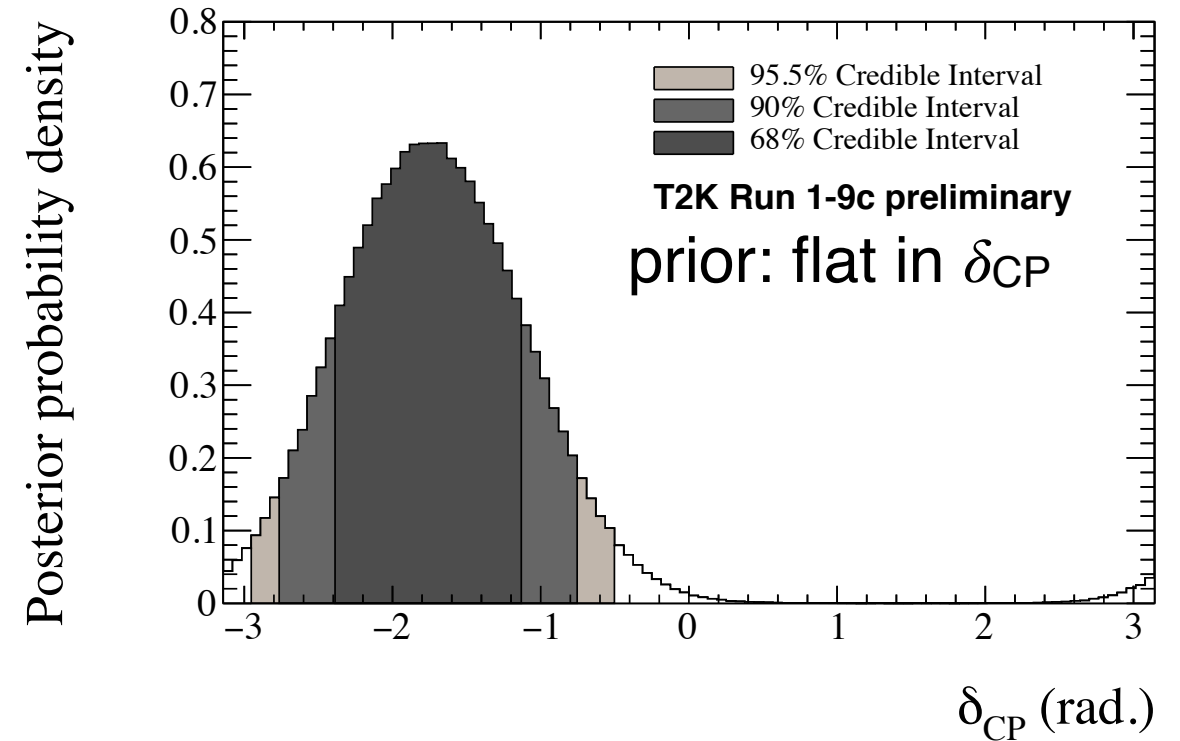
Posterior probabilities

Results from Bayesian analysis

- Prior probability assumption of δ_{CP} does not affect 2σ exclusion of CP conservation

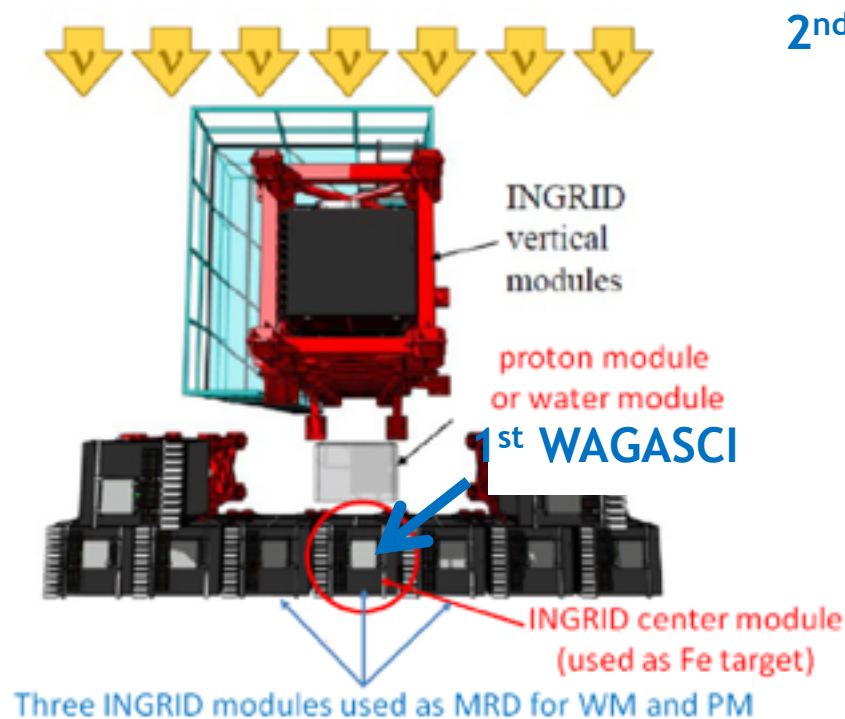
	$\sin^2\theta_{23}\leq 0.5$	$\sin^2\theta_{23}>0.5$	SUM
NH ($\Delta m^2_{32}>0$)	0.204	0.684	0.888
IH ($\Delta m^2_{31}<0$)	0.023	0.089	0.112
SUM	0.227	0.773	1

- Bayes factor for NH/IH is 7.9
- Will explore optimisation of fit variables for future results
- Will add $\sim 50\%$ more RHC data for end of summer result

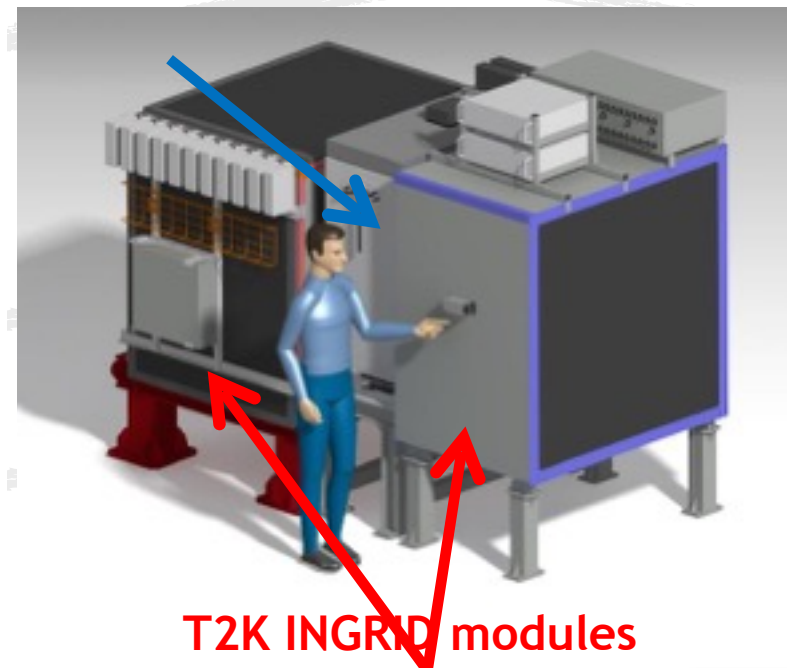


Recent developments

- WAGASCI modules installed in on-axis & off-axis beam positions.
 - On-axis module took neutrino data 2016–2018 as a part of T2K.
 - Off-axis module installed in 2018 by WAGASCI Collaboration.
- Baby MIND Collaboration constructed detector @CERN, installed in T2K ND280 hall.
 - Commissioned with neutrino beam March–May 2018.
- WAGASCI and BabyMIND Collaboration members will join T2K.



2nd WAGASCI

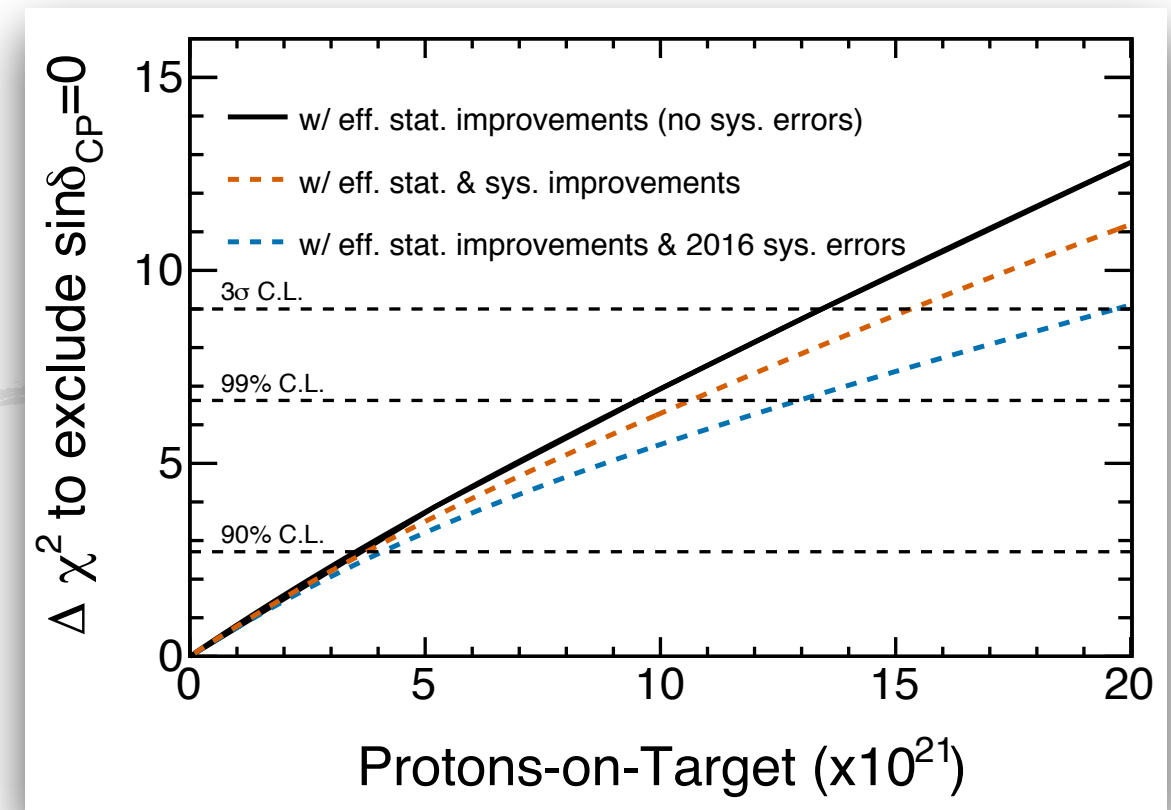
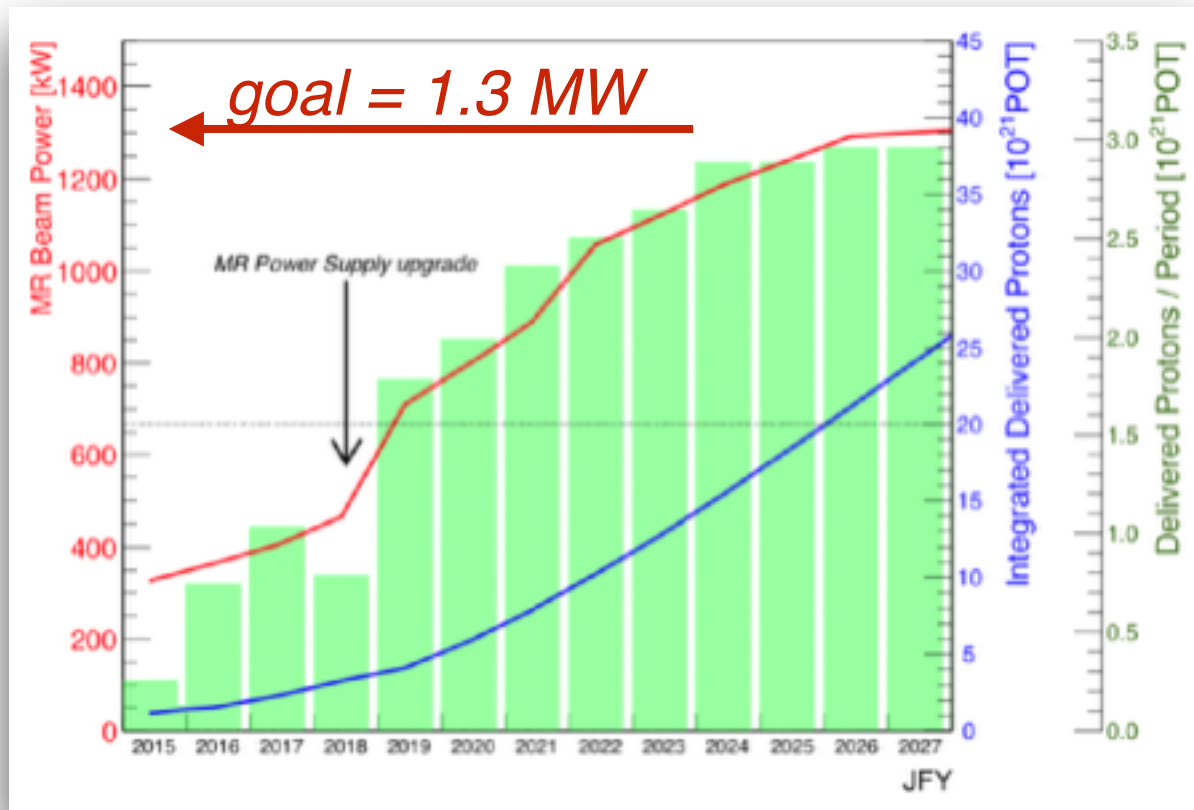


Baby-MIND was installed to T2K ND hall on Feb. 16 2018.



see poster by:
K. Kin, #263, Wed

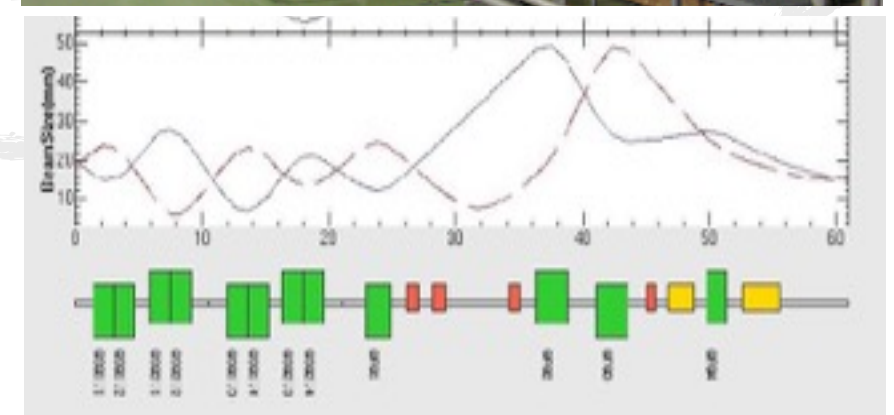
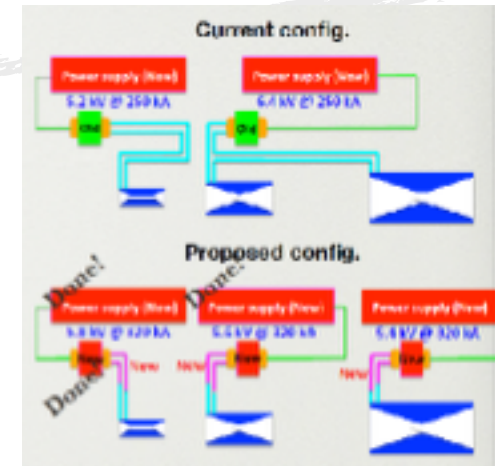
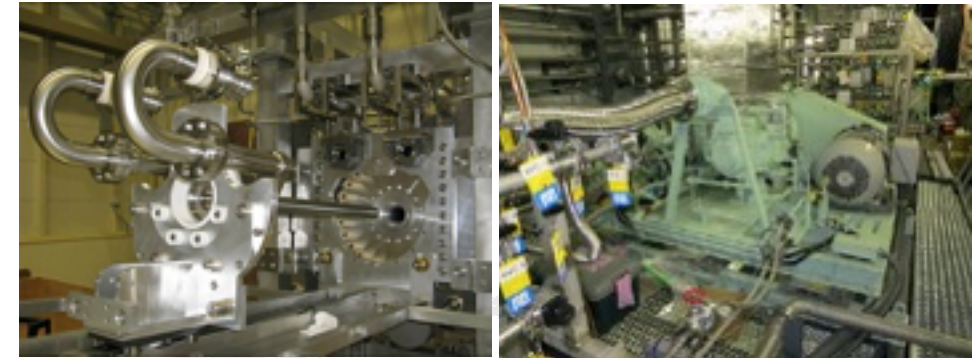
T2K run extension



- T2K's long term goal is the pursuit of CP Violation in the neutrino sector.
- In 2016, T2K phase 2 run extension given Stage-1 status by KEK/J-PARC.
- Proposal to collect 20×10^{21} POT by ~ 2026 ([arXiv:1609.04111 \[hep-ex\]](https://arxiv.org/abs/1609.04111)).
- With 20×10^{21} POT, T2K has up to 3σ (median) CPV sensitivity:
 - Sensitivity improves beyond 3σ with reduced systematic errors.
- T2K initiated Near Detector upgrade project in January 2016.
 - “The T2K ND280 Upgrade Proposal”, submitted to CERN SPSC in Jan. 2018.

Neutrino beam upgrades

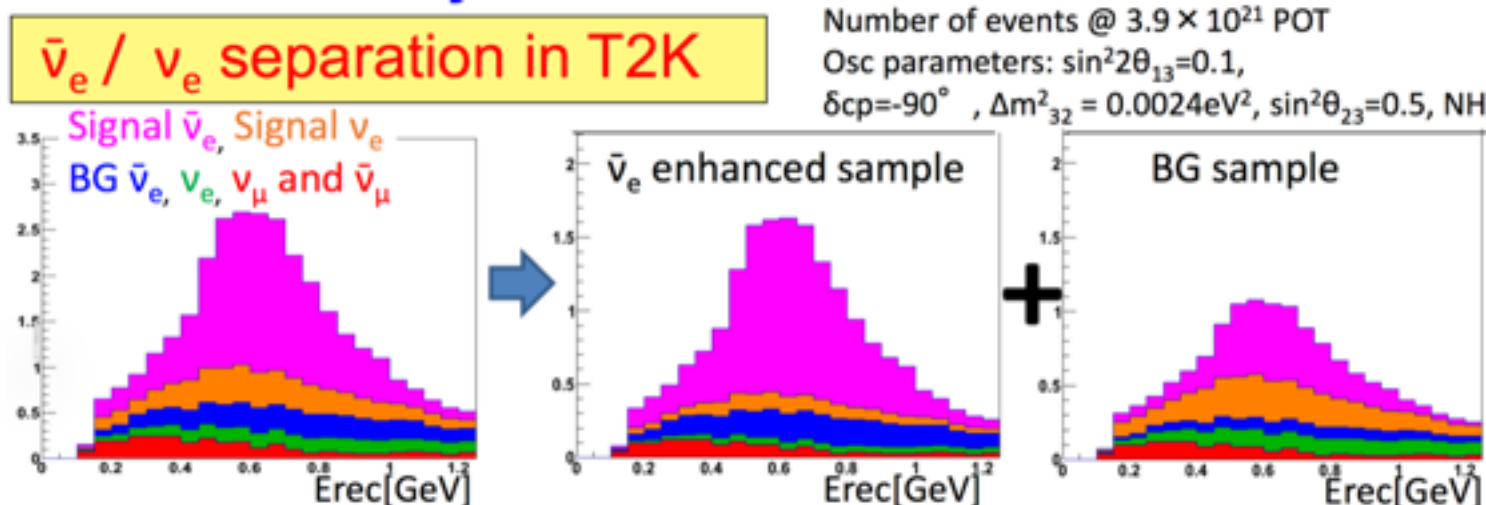
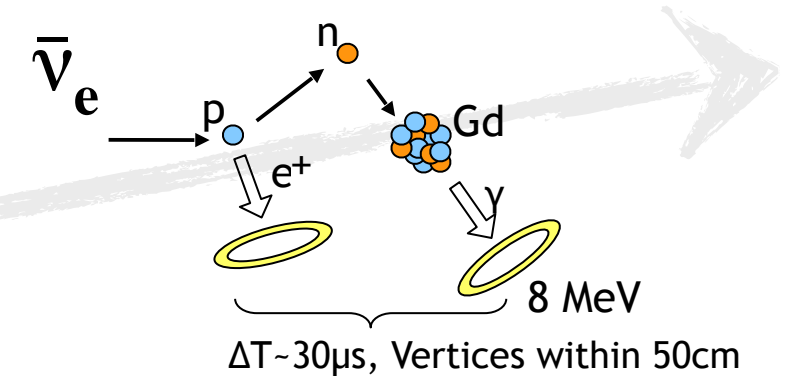
- Main Ring power supply upgrade approved by MEXT
 - MR-PS upgrades will allow 750 kW operation, with eventual upgrades to 1.3 MW
- Beamline upgrades designed to:
 - allow faster beam rep rate (2.2 → 1.3 s)
 - Mitigate beam losses at higher power running conditions
- Improvements needed in:
 - target station
 - horns & horn power supplies
 - remote maintenance
 - apertures in magnet/beam ducts
 - activated water handling
 - many more...
- Aim to complete work when MR-PS upgrade is done
→ **2021**
- TDR has been submitted to KEK-IPNS Director for review in June 2018



Far detector upgrade

- Additional SK data samples under study
 - $\text{CC}1\pi^\pm$ and $\text{NC}\pi^0$, in both FHC and RHC data
- SK-Gd project
 - Initiative to add Gd to SK water
 - enhance neutron detection capability
 - improves low energy antineutrino detection
 - could provide WS BG constraint in T2K $\bar{\nu}$ data
 - Three step timeline
 - T0: repairs to SK tank **ongoing now!**
 - T1: load 0.02% $\text{Gd}_2(\text{SO}_4)_3$, planning ongoing
 - T2: load 0.2% $\text{Gd}_2(\text{SO}_4)_3$, farther future

see M. Ikeda's talk on Tuesday



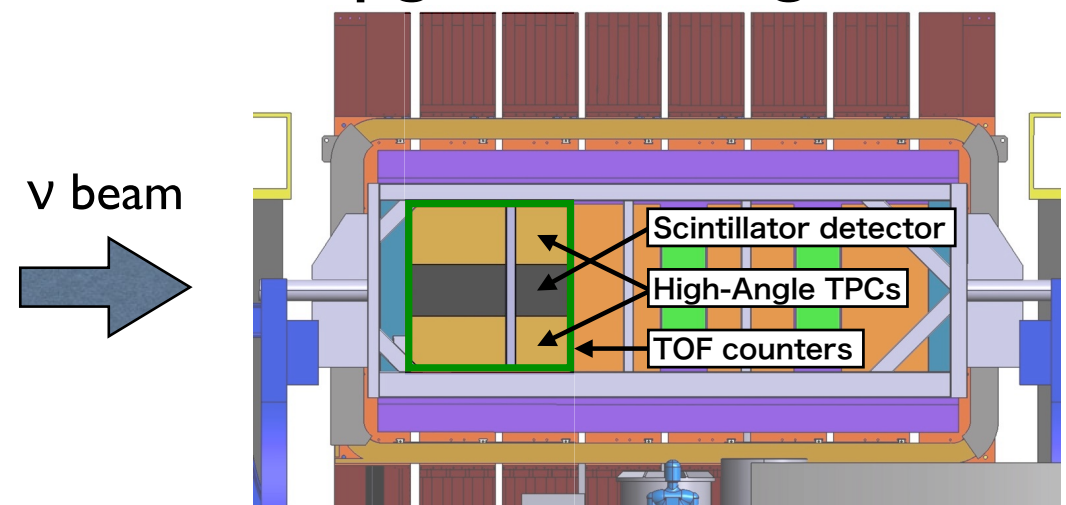
see posters by:
 G. Pronost, #258, Wed
 C. Simpson, #358, Wed

ND280 upgrade

- T2K phase 2 goal: reduce systematics to $\sim 4\%$
- Requirements for upgraded detector:
 - Full polar angle acceptance
 - Fiducial mass of a few tons
 - High efficiency for short tracks
 - Good timing information to determine track direction
- Strong collaboration of experts from Europe (**incl. CERN neutrino group**), Japan, & USA
- Submitted proposal to CERN SPSC
 - supported as a Neutrino Platform project, <http://cds.cern.ch/record/2299599>
 - TDR expected by the end of 2018
- **Aiming for installation in 2021**

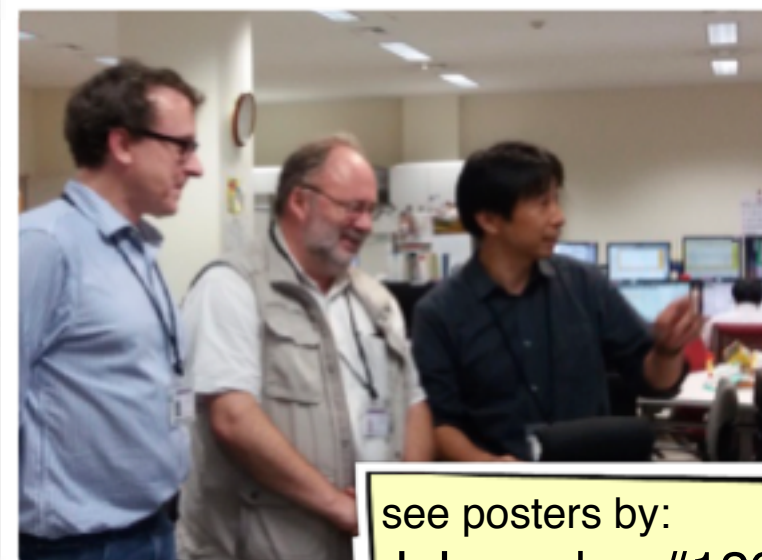
*More information:
F Sanchez's talk later today*

ND280 upgrade configuration



- Replace (most of) P0D with **Scintillator Detector** + **2 High-Angle TPCs** + **TOF**
 - Improve acceptance for large angle tracks
- Keep current “tracker” [2 FGDs + 3 TPCs] (& upstream part of P0D) as well as ECal, magnet & SMRD
 - For keeping continuity and forward acceptance

11



Albert De Roeck
(CERN EP-NU leader)
visiting J-PARC CCR
with T2K
spokespersons

see posters by:
J, Łagoda, #120, Wed
Y. Kudenko, #121, Wed

Working together with NOvA



T2K and NOvA collaborations to produce joint neutrino oscillation analysis

January 30, 2018

The NOvA and T2K Collaborations are working towards the formation of a joint working group to enhance the measurements of neutrino oscillation parameters made by each Collaboration individually. The projected timescale of the NOvA-T2K working group is for production of a full joint neutrino oscillation analysis by 2021.

*Preparing for a joint working group:
three workshops held so far.*

NOvA-T2K Joint Workshop on Neutrino Interaction Uncertainties in Oscillation Measurements

chaired by Tsuyoshi Nakaya (Kyoto), Morgan Wascko (Imperial College London), Peter Shanahan (Fermilab), Mark Messier (Indiana)

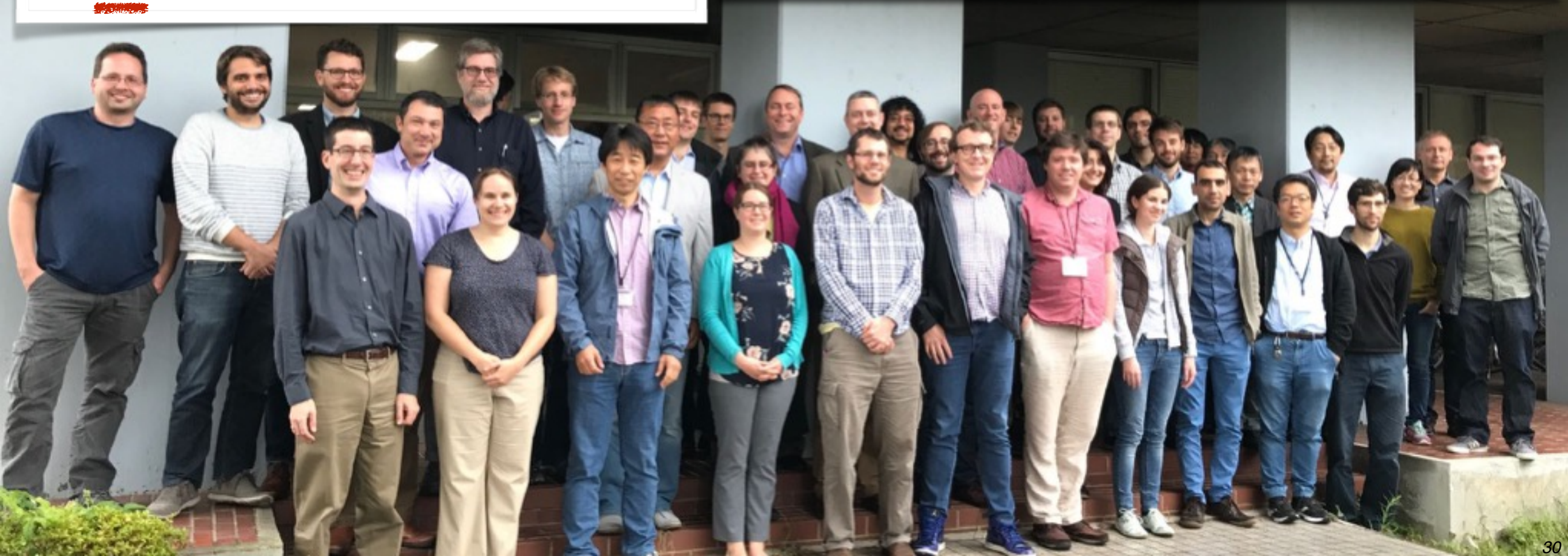
from Sunday, October 15, 2017 at 09:00 to Tuesday, October 17, 2017 at 12:00 (Asia/Tokyo)
at KEK Tokai-1 (Room 116)

2-4 Shirane Shinkutsu, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan

Description Experts from NOvA and T2K collaboration will discuss

- Status and future projections
- Details of our respective cross-section tunes
- Details on underlying correspondence between GENIE and NEUT models
- Details of the oscillation measurements and the role of uncertainties, and starting work to map out cross-section correlations between the two experiments
- Summaries and plans for ongoing work

Material: [Group photo](#) [Slides](#)

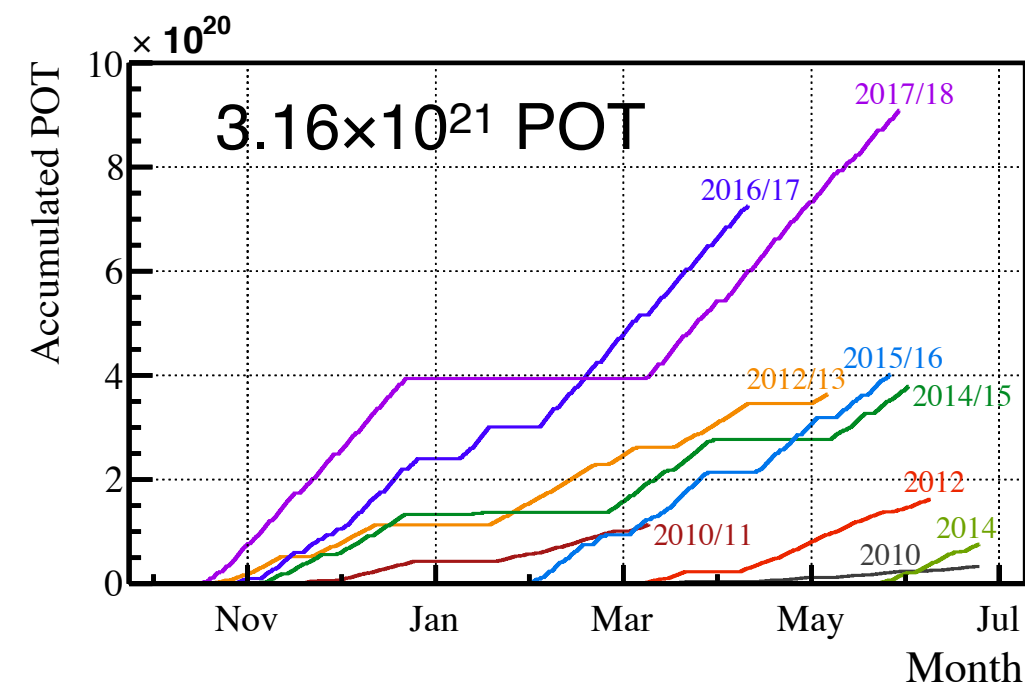


Conclusions

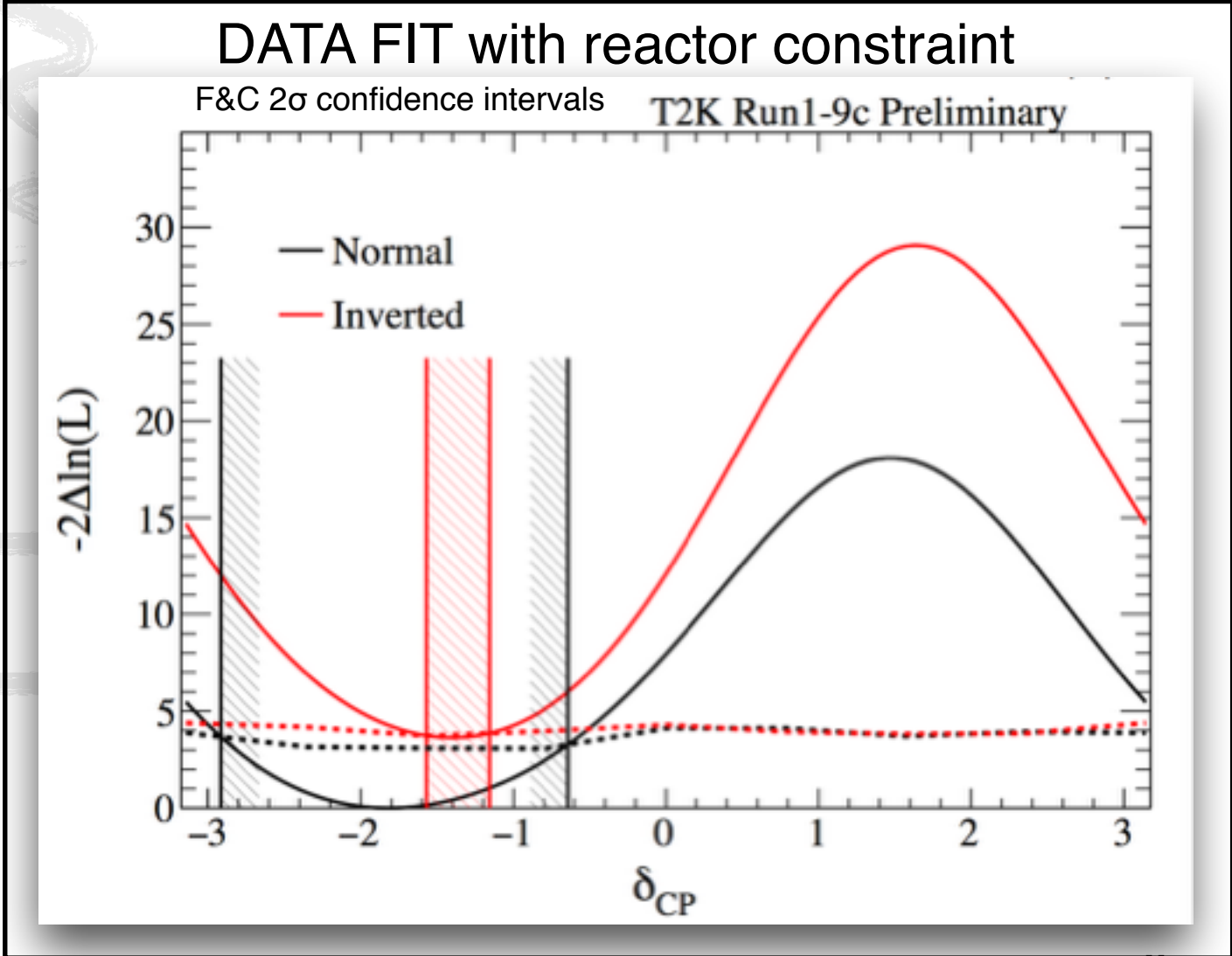
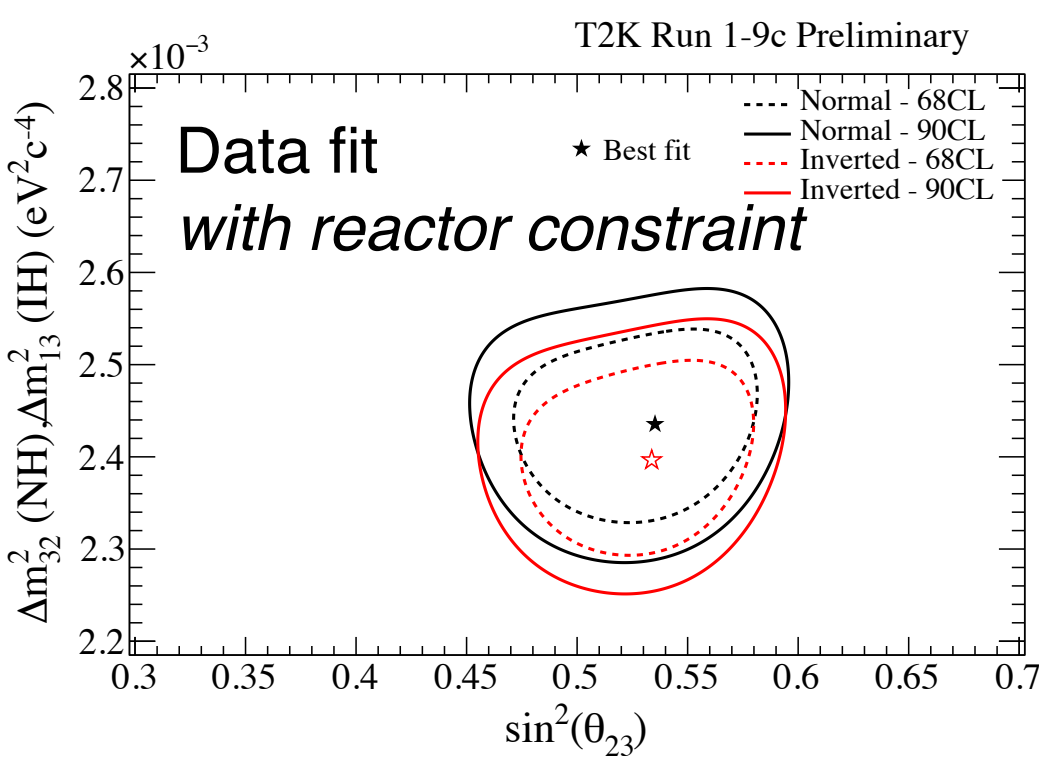
- T2K operated steadily at 485 kW beam power in 2017/18;
 - Collected total of 3.16×10^{21} POT, ~evenly split between FHC and RHC.
- ➡ **More than double the data set shown at Neutrino2016!**
- Analysed 1.49×10^{21} POT in FHC and 1.12×10^{21} POT in RHC:
 - **CP conserving values of δ_{CP} lie outside 2σ region.**
 - **Data show preference for Normal Hierarchy,**
 - Bayes factor for NH/IH is 7.9.
 - Analysis of full data set to be released late summer 2018.
- Upgrades to beam, near and far detectors progressing well:

CPV in neutrino sector is within reach!

T2K Neutrino2018 highlights



	$\sin^2\theta_{23}\leq 0.5$	$\sin^2\theta_{23}>0.5$	SUM
NH ($\Delta m^2_{32}>0$)	0.204	0.684	0.888
IH ($\Delta m^2_{31}<0$)	0.023	0.089	0.112
SUM	0.227	0.773	1





**Thank you for your
attention!**
ご清聴ありがとうございました

SK events: 2016 to 2018

Neutrino2016

	OBS.	EXP. (NH, $\sin^2\Theta_{23}=0.528$, NH)			
		$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$
ν_μ	125	127.9	127.6	127.8	128.1
ν_e	32	27.0	22.7	18.5	22.7
$\bar{\nu}_\mu$	66	64.4	64.3	64.4	64.6
$\bar{\nu}_e$	4	6.0	6.9	7.7	6.8

SAMPLE	2016	2018
ν_μ	125	243
ν_e QE	32	75
$\nu_e 1\pi$	N/A	15
$\bar{\nu}_\mu$	66	102
$\bar{\nu}_e$	4	9

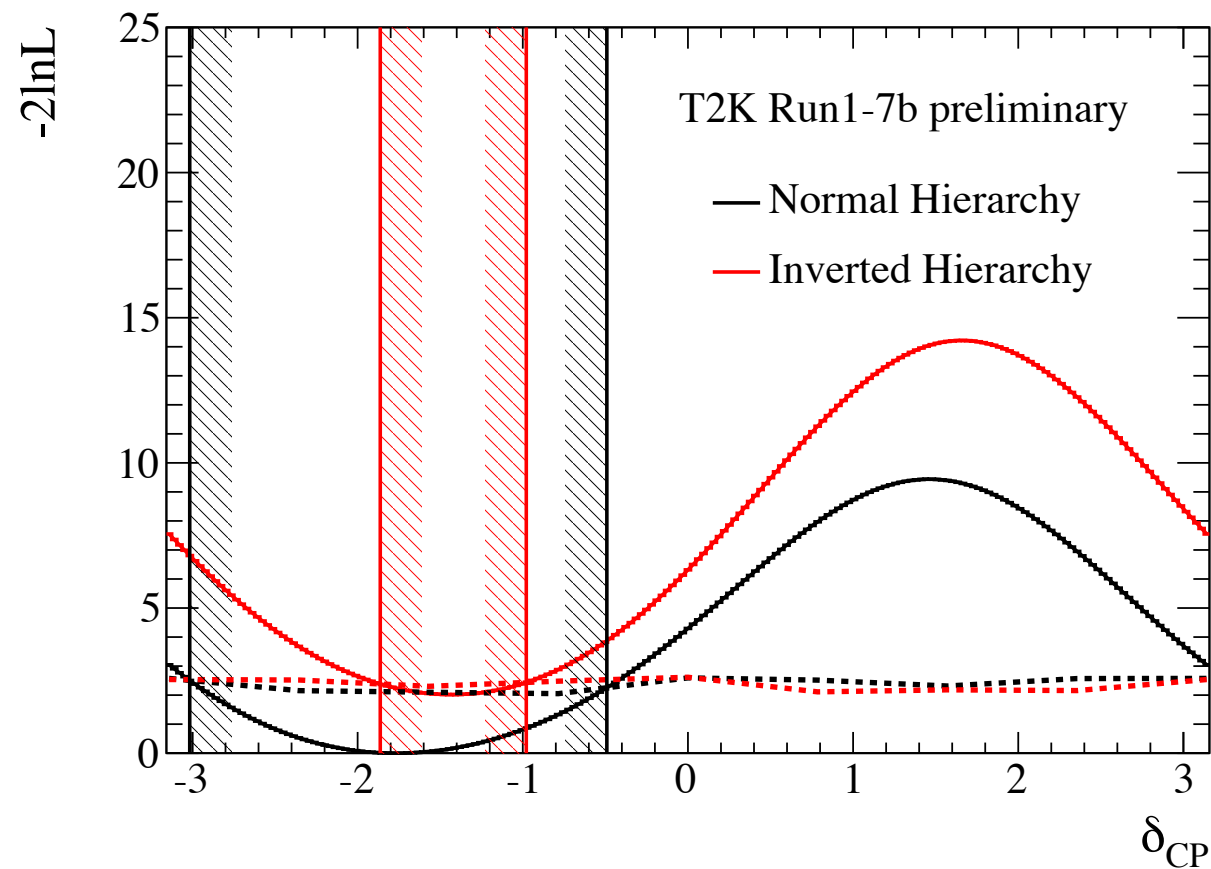
Neutrino2018

SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	
FHC 1R μ	268.5	268.2	268.5	268.9	243
FHC 1Re 0 decay-e	73.8	61.6	50.0	62.2	75
FHC 1Re 1 decay-e	6.9	6.0	4.9	5.8	15
RHC 1R μ	95.5	95.3	95.5	95.8	102
RHC 1Re 0 decay-e	11.8	13.4	14.9	13.2	9

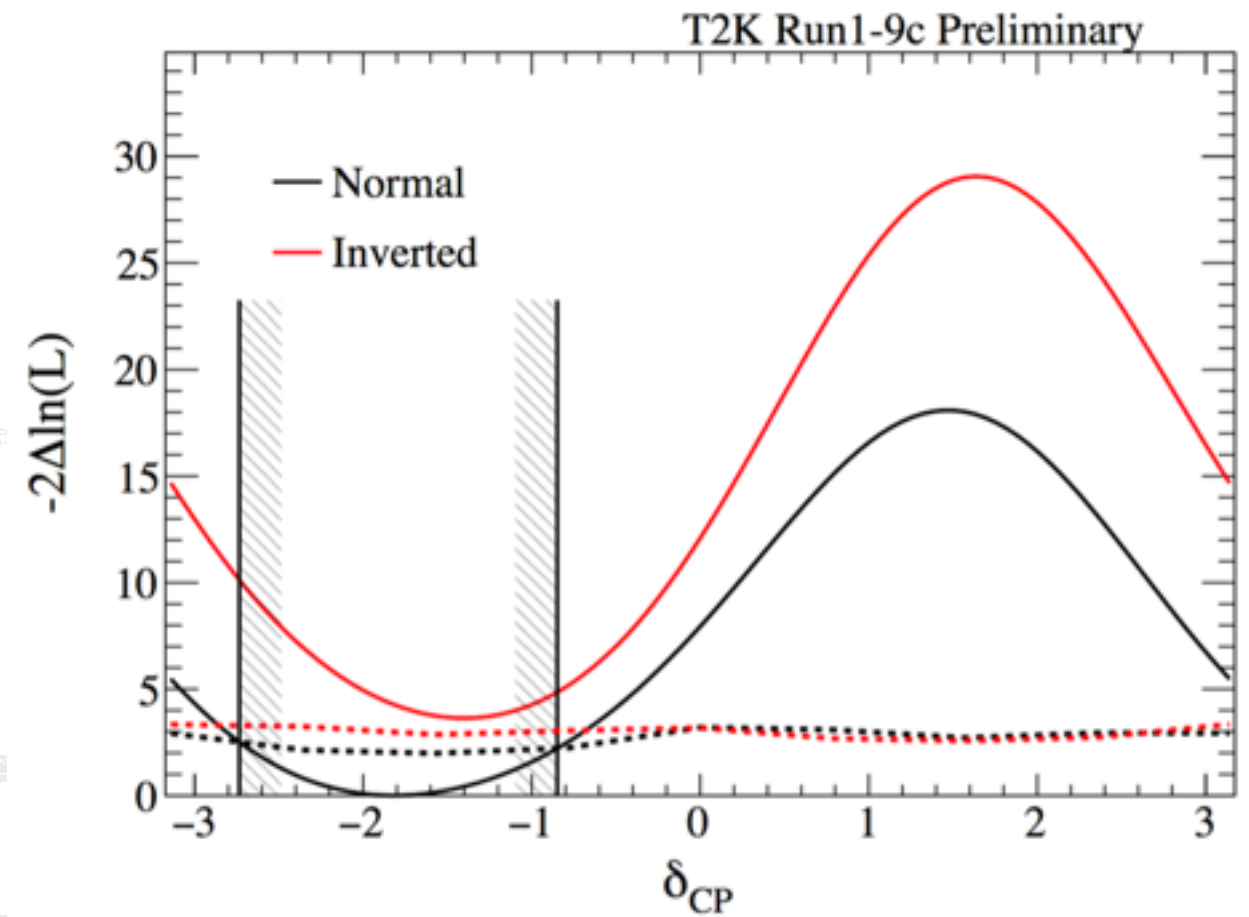
CP exclusion: 2016 to 2018

DATA FIT with reactor constraint

Feldman & Cousin **90% confidence intervals**

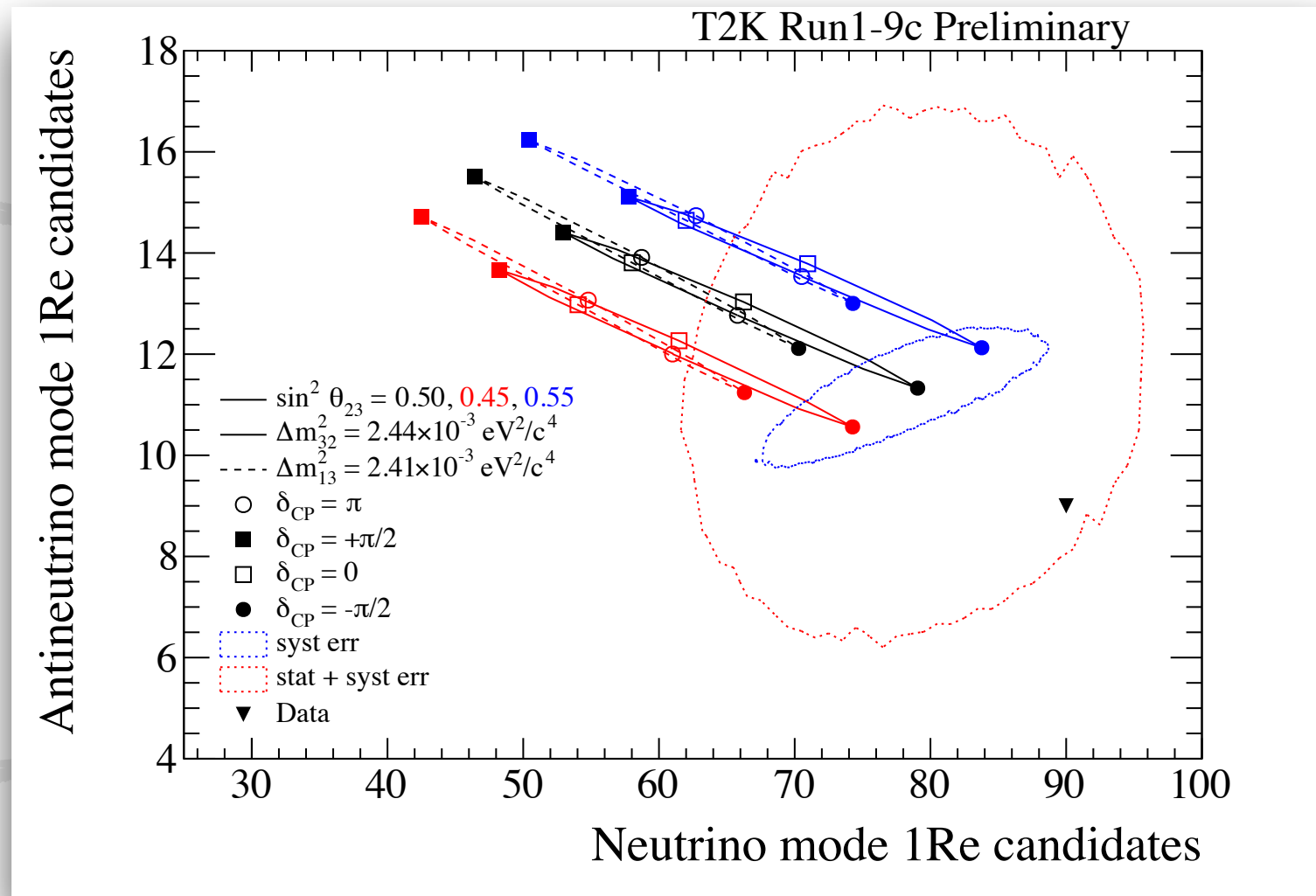


Neutrino2016



Neutrino2018

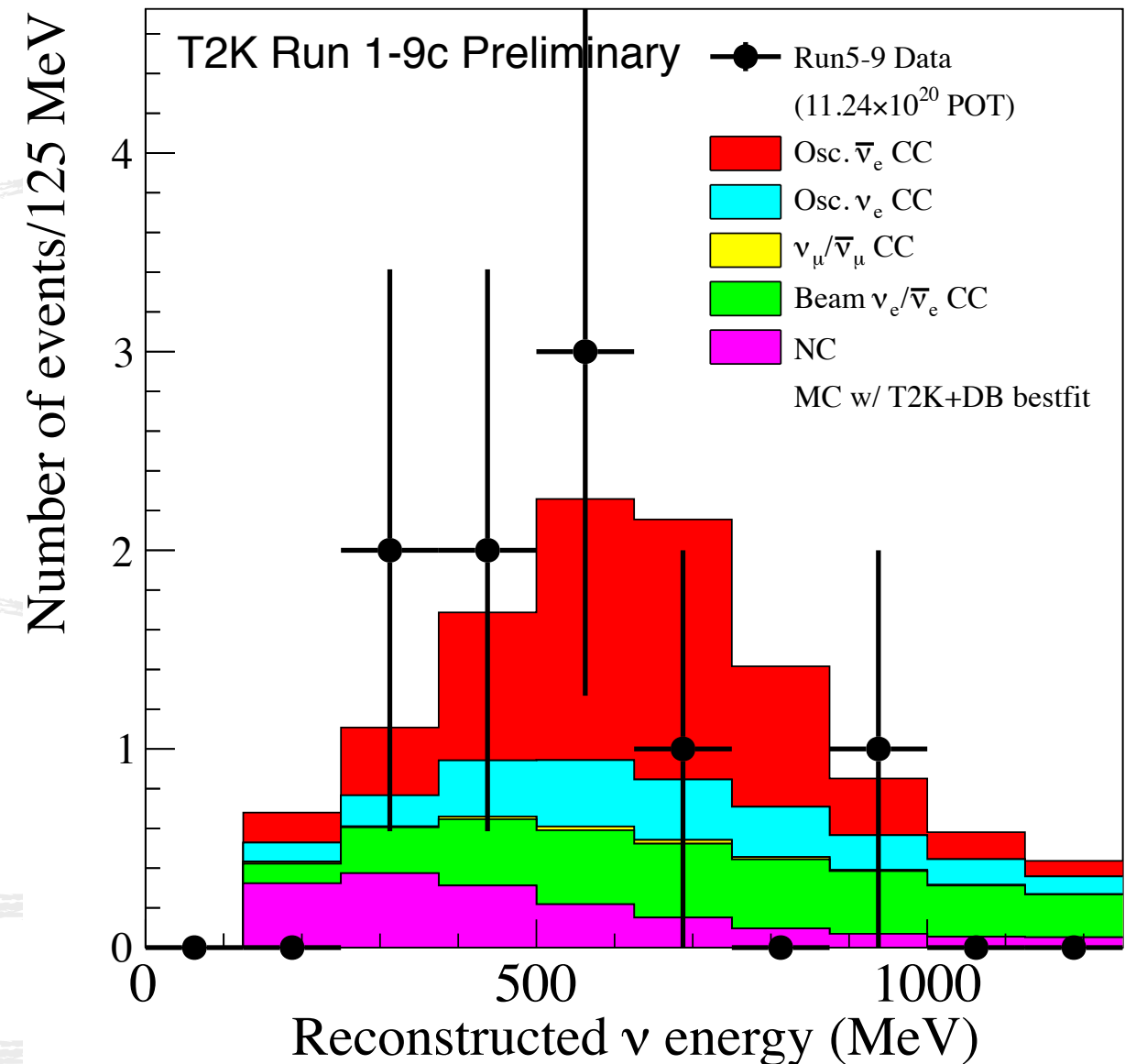
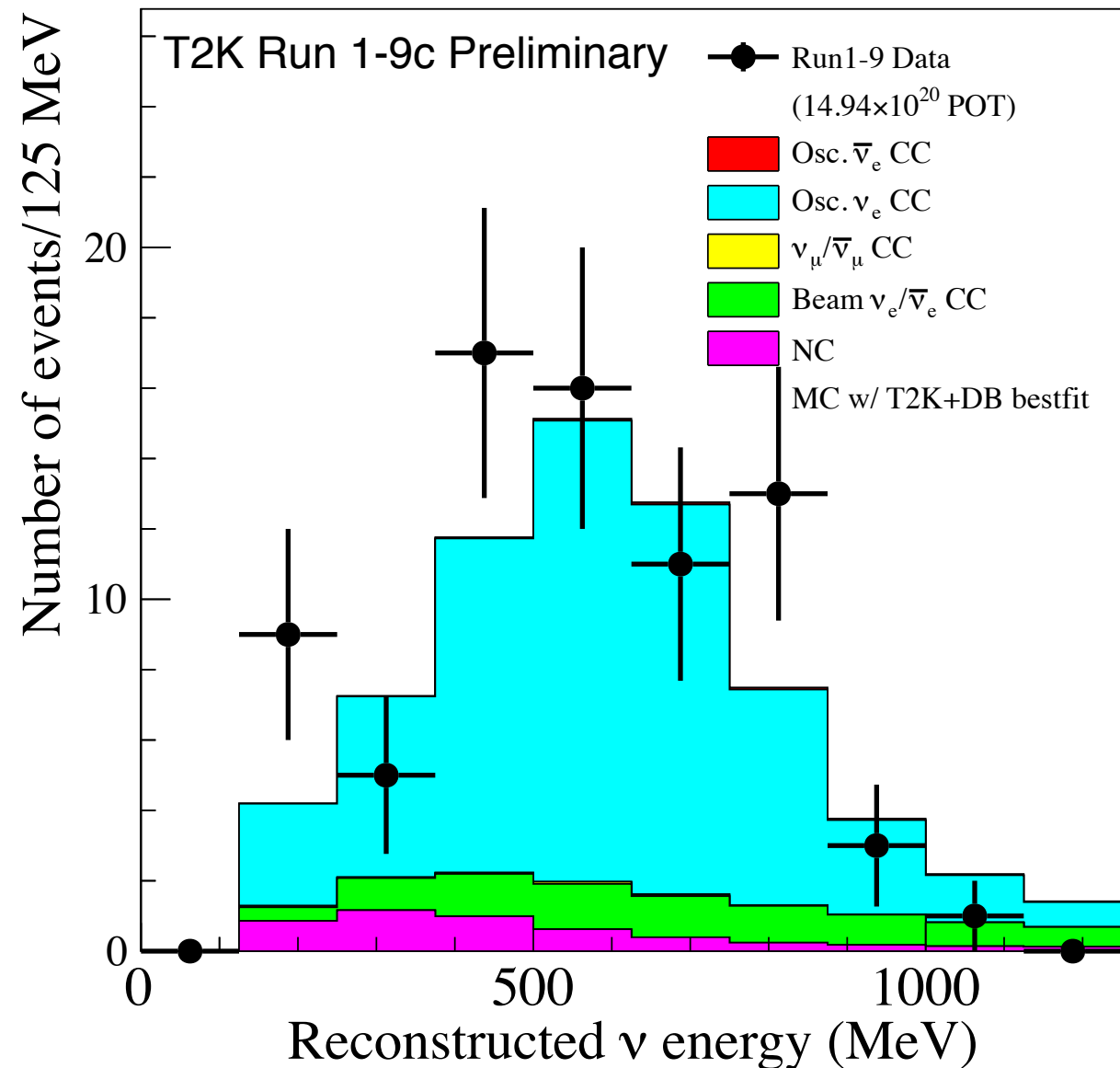
Bi-event plot



Predictions generated for best-fit values of oscillation parameters for different values of δ_{CP} , $\sin^2 \theta_{23}$ and mass hierarchy.

Errors are shown for the case of $\delta_{CP} = -\pi/2$ and $\sin^2 \theta_{23} = 0.5$ in normal hierarchy, with the reactor constraint.

SK e-like events



SK e-like events

