TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

T2K and future

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T2K

Weak and mass eigenstates are different: Mixing

$$< \nu_l | \nu_i >= U_{li} : PMNS\ matrix$$
$$l = e, \mu, \tau : weak\ eigenstates$$
$$i = 1, 2, 3\ : mass\ eigenstates$$

Neutrino particle (mass eigenstate) has mixed flavours e/μ/τ (weak eigenstates)!

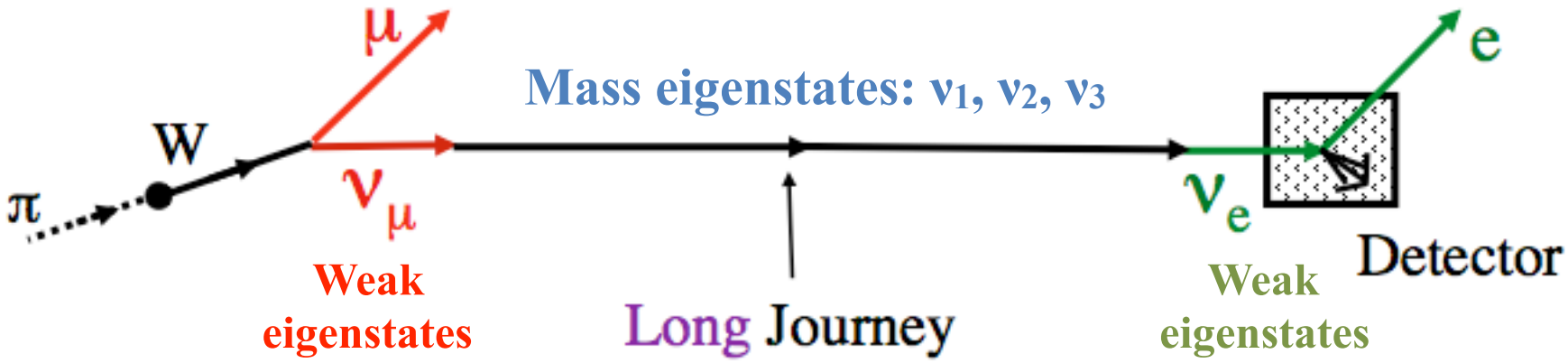
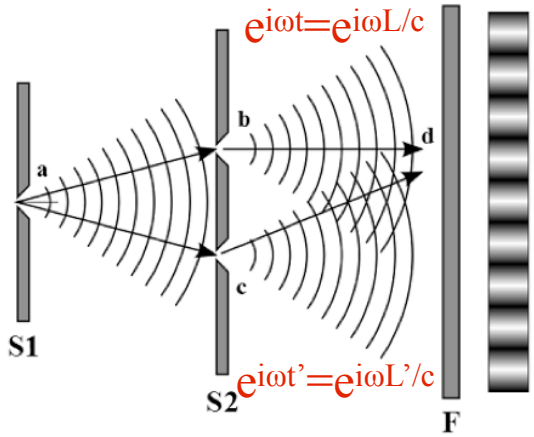
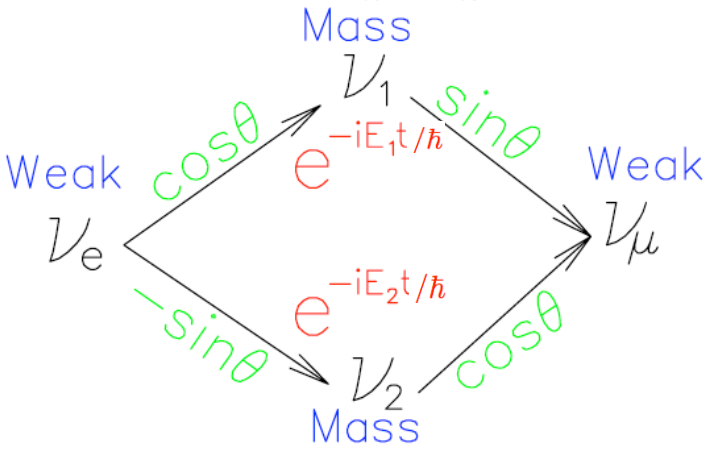


Figure: Boris Kayser

- Quantum mechanical interference:

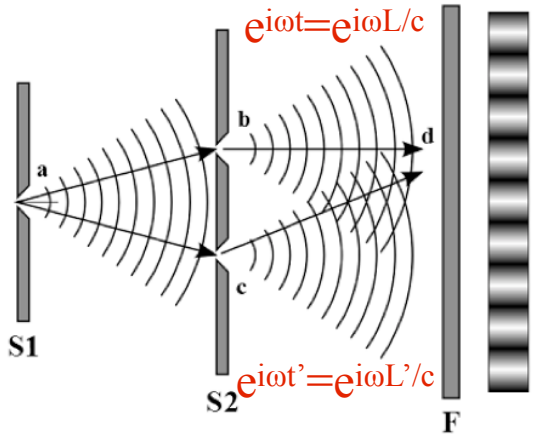


$$\omega t = 2\pi\nu t = \frac{2\pi E}{h} = \frac{E}{\hbar} \quad (\hbar = h/2\pi)$$

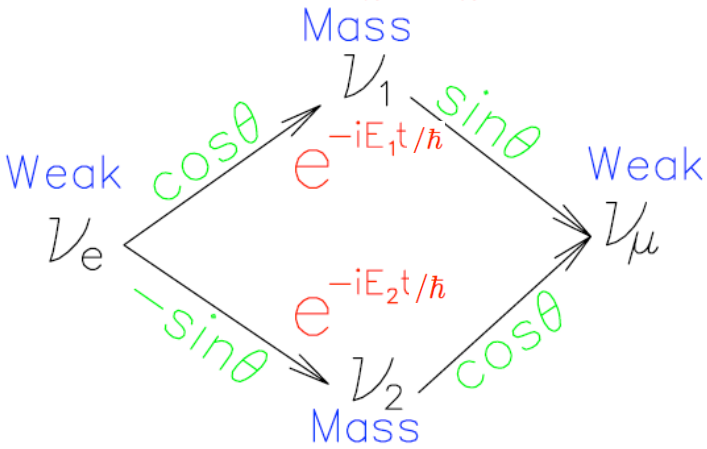


Difference in the masses creates phase difference as neutrino propagates

- Quantum mechanical interference:



$$\omega t = 2\pi\nu t = \frac{2\pi E}{h} = \frac{E}{\hbar} \quad (\hbar = h/2\pi)$$



- Lepton flavour oscillates!

$$\begin{aligned} P_{l\to l'} &= |<\nu_{l'}(t)|\nu_l(t)>|^2 \\ &= |\Sigma_i <\nu_{l'}|\nu_i> e^{-iE_it} <\nu_i|\nu_l>|^2 \\ &= |\Sigma_i U^*_{li} U_{l'i} e^{-im_i^2 L/2E}|^2 \end{aligned}$$

$$\boxed{\begin{aligned} Prob(\nu_e \to \nu_\mu) &= |\sin\theta\cos\theta(e^{\frac{-iE_1t}{\hbar}} - e^{\frac{-iE_2t}{\hbar}})|^2 \\ &= \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2(eV^2)L(km)}{E_\nu(GeV)} \end{aligned}}$$

Δm^2_{23}~2.5×10^{-3} : oscillation max at 300km for 0.6GeV

PMNS matrix

weak eigenstate

Pontecorvo-Maki-Nakagawa-Sakata mass mixing matrix

mass eigenstate

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

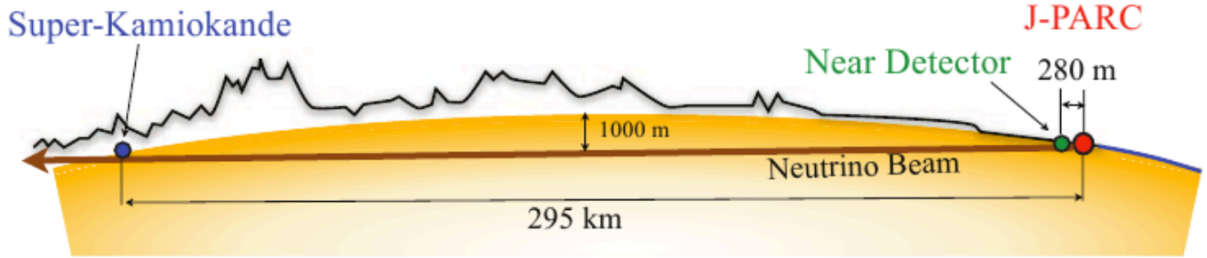
Atm/long-baseline ν

CP violation and θ_{13}

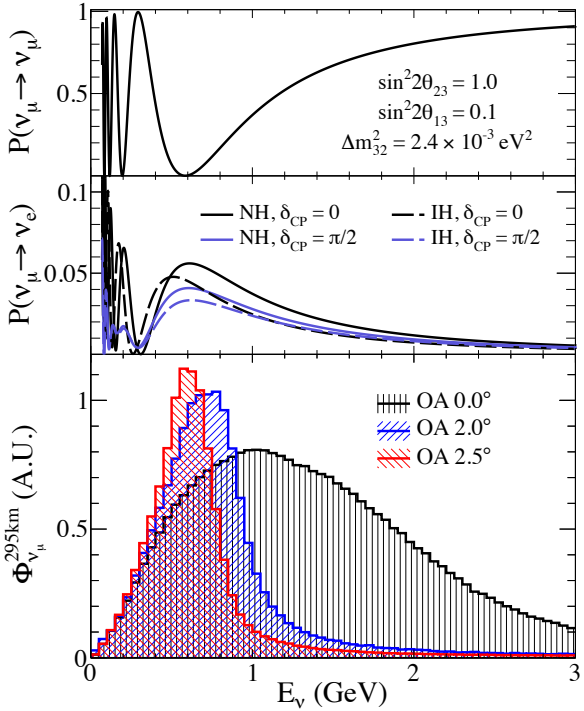
solar/reactor ν

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \cos\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\cos\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

T2K Long Baseline Neutrino Experiment

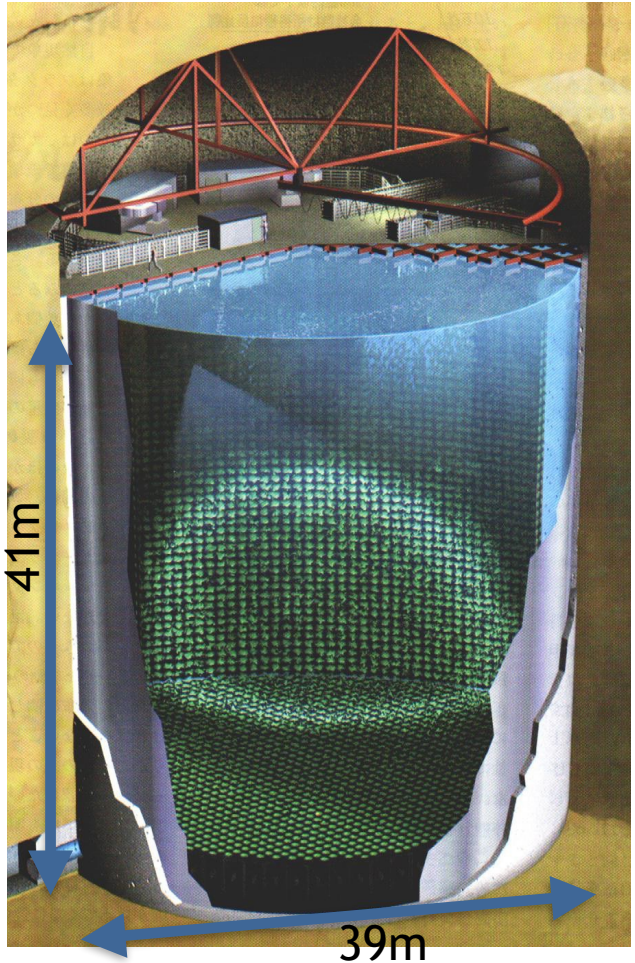


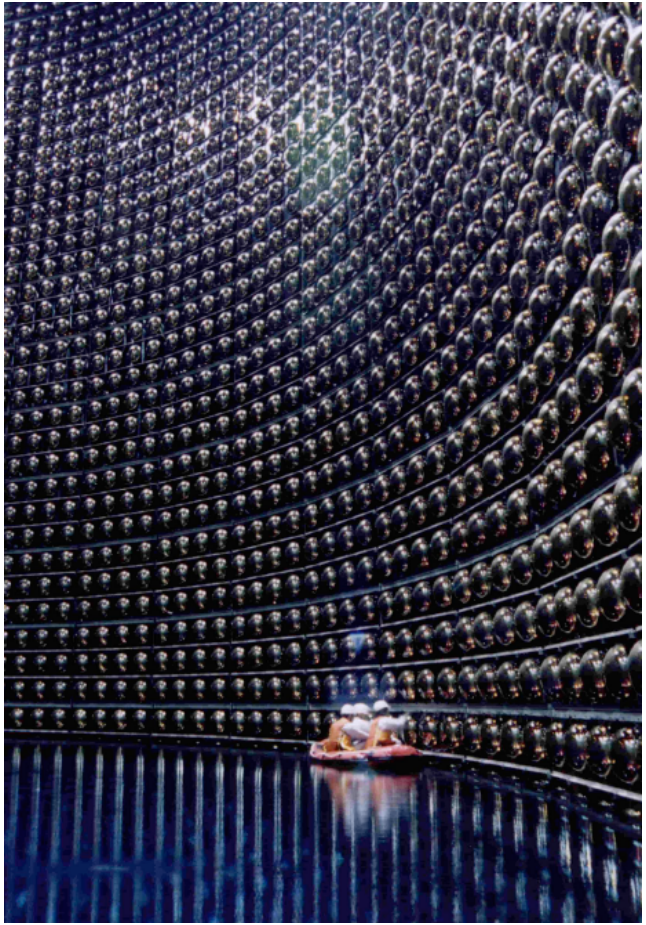
Passage of the muon neutrino beam from J-PARC to Super K



off-axis beam tuned at the oscillation max.

Super-Kamiokande water Cherenkov detector

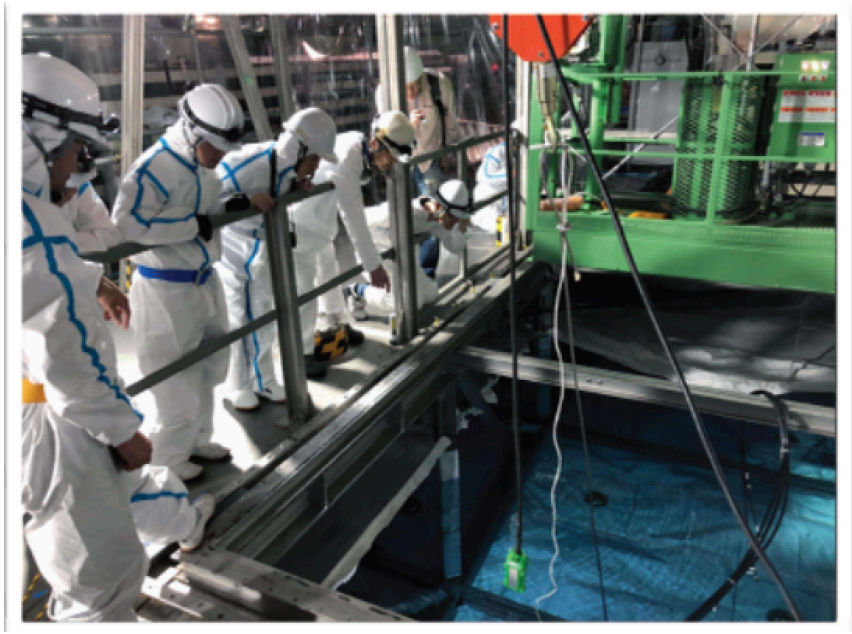




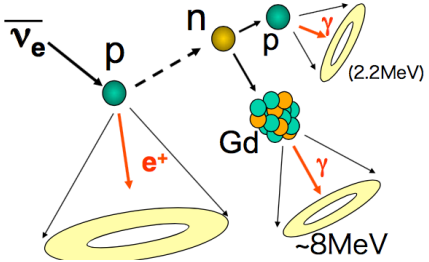
11,146 of 20inch PMTs

Tank is open this summer for preparation of Gd loading

SK tank open for SK-Gd



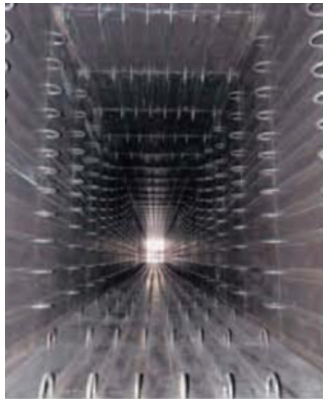
- Anti-neutrino tag
  - Relic supernova neutrinos
  - Sub-GeV atmospheric neutrino direction

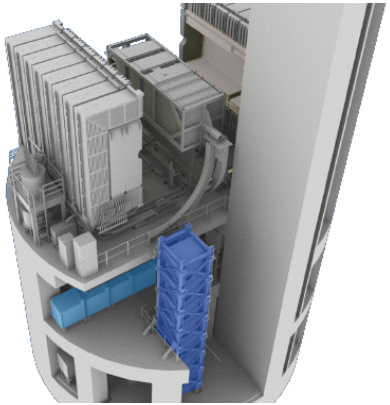


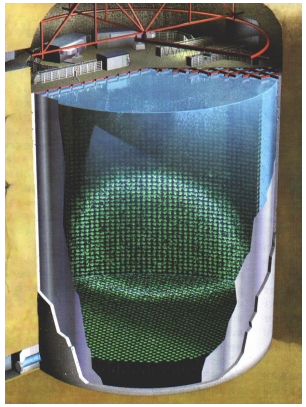
Open for the first time since 2007

UBC undergraduate student and Canadian scientists participate in the work

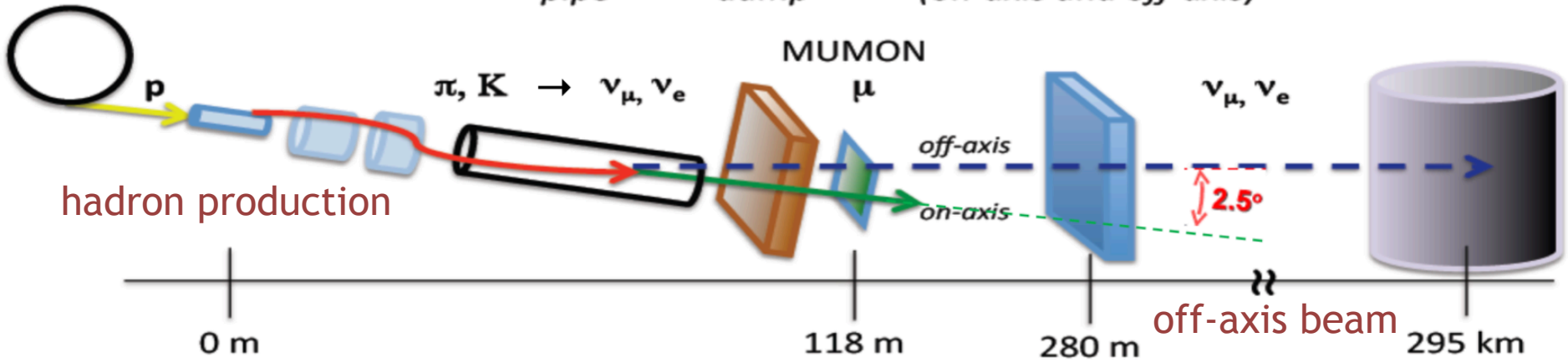
Neutrino production





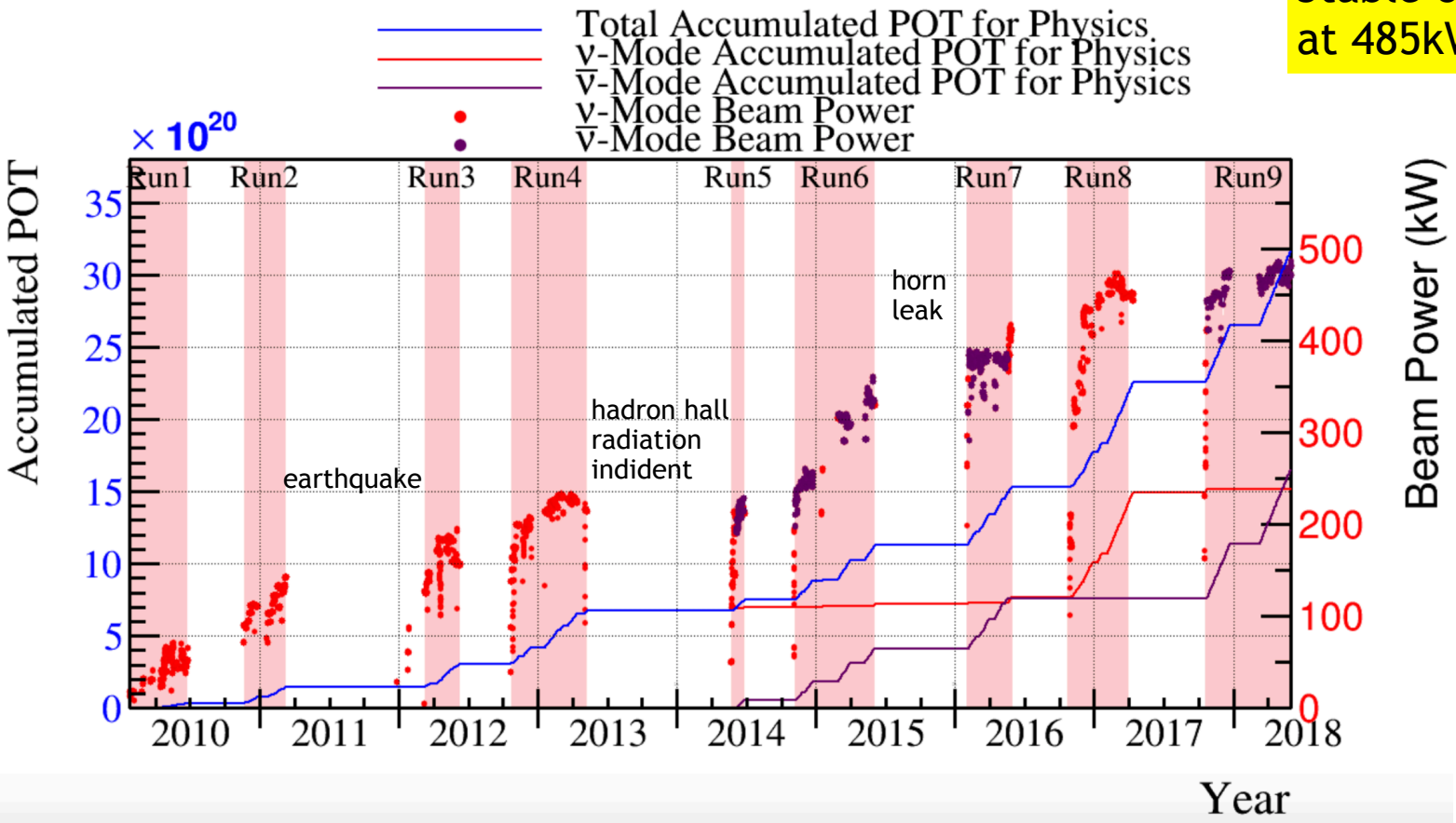


30 GeV PS target horns decay pipe beam dump near detectors (on-axis and off-axis) far detector

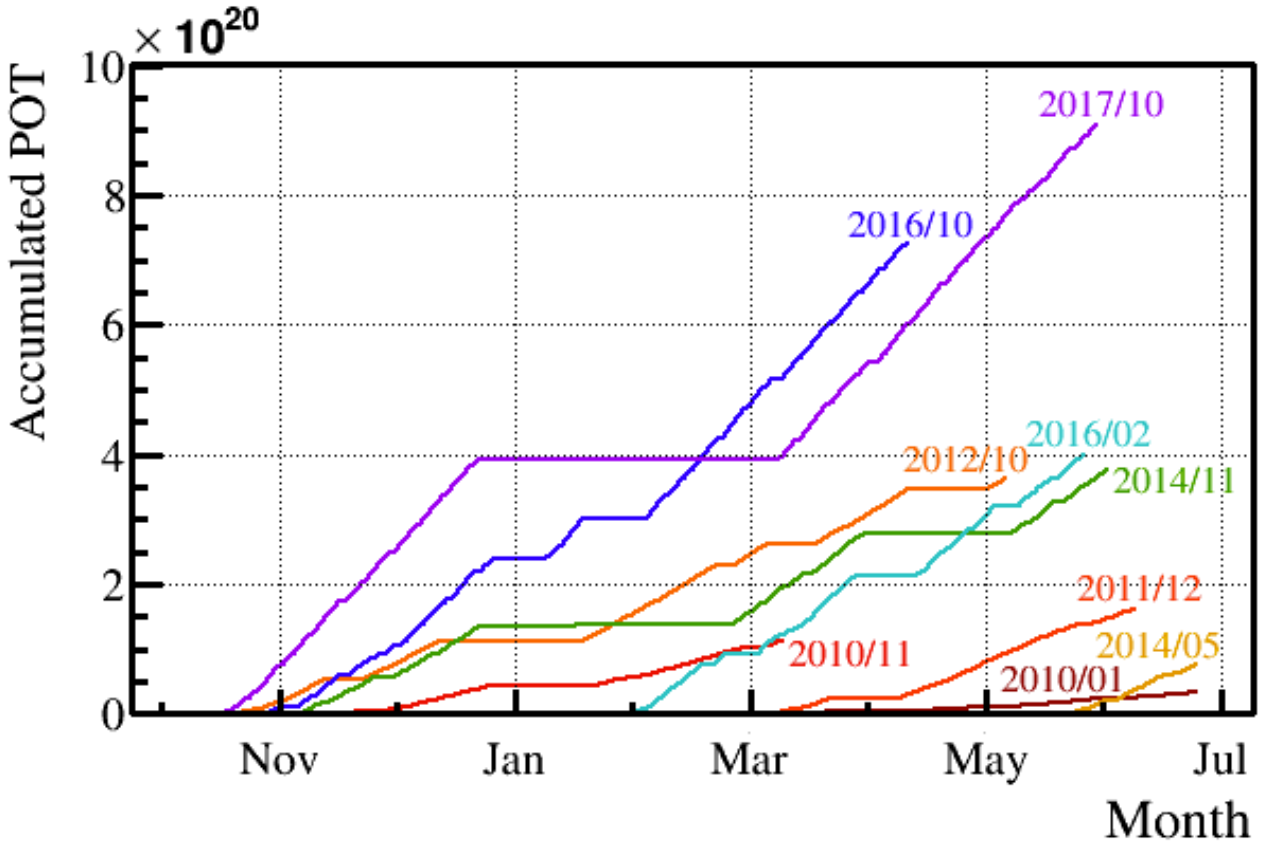


T2K data taking

Stable operation
at 485kW in 2017/18

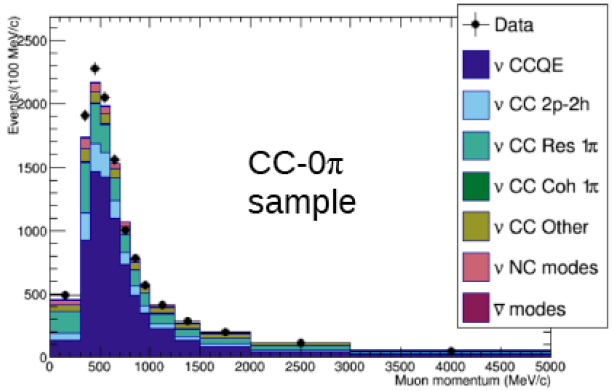


Accumulated proton on target (POT)



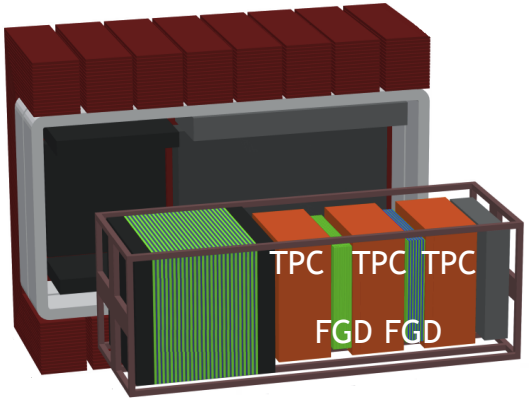
- Total POT till May 2018:
  - 3.16×10^{21} POT
    - ν: 1.51×10^{21}
    - $\bar{\nu}$: 1.65×10^{21}
  - Data analyzed till Dec.2017
    - ν: 1.49×10^{21}
    - $\bar{\nu}$: 1.12×10^{21}

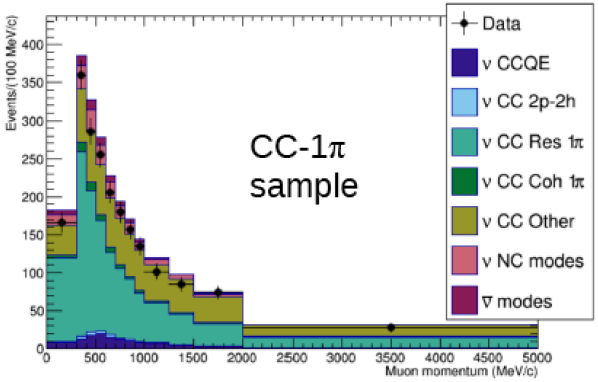
Near detector samples

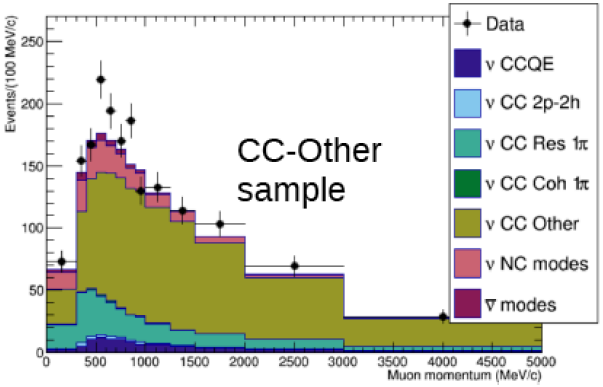


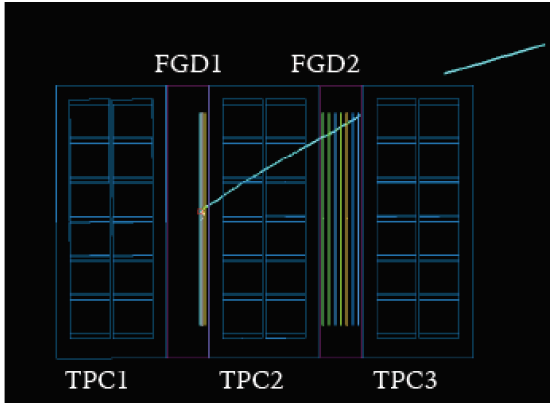
Selection:

- Identify highest momentum muon-like track
- Separate by number of tagged pions

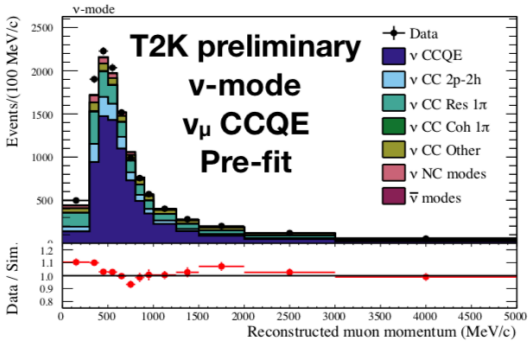


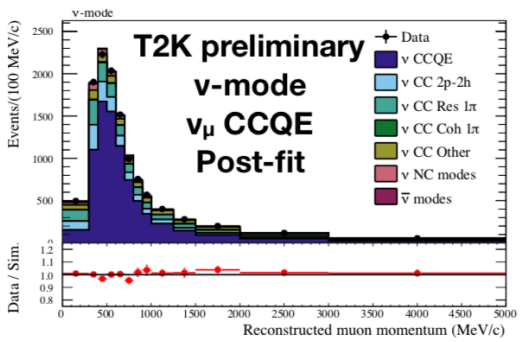




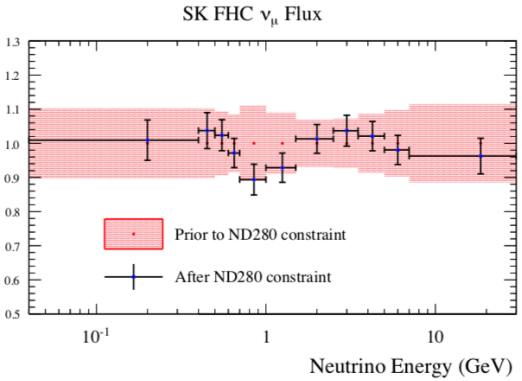


Near detector fit for far detector prediction

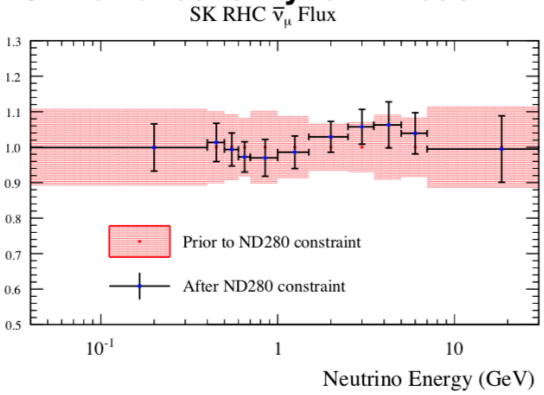




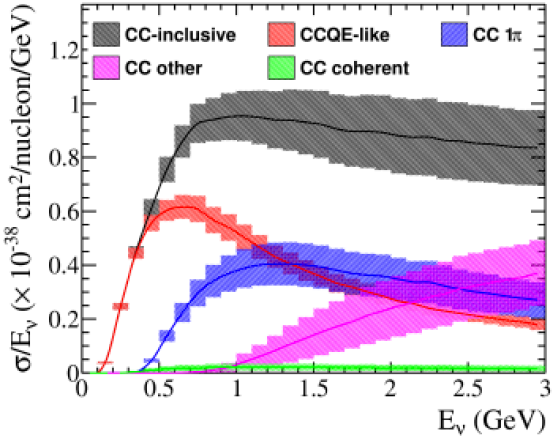
SK flux uncertainty for ν-mode



SK flux uncertainty for ν̄-mode

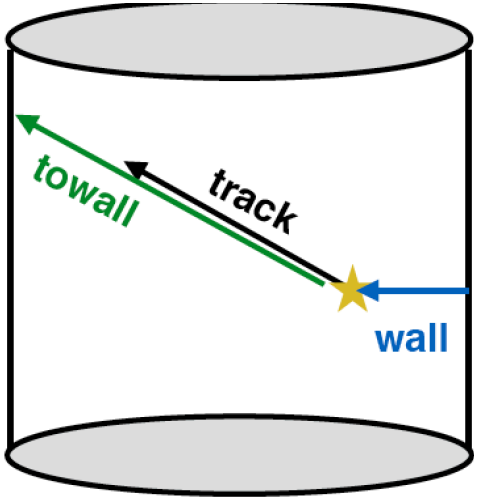


- Likelihood fit to tune the cross section models:
  - CC0π, CC1π, CCOther
- Far detector prediction
  - Covariance matrix (effectively taking ratio)



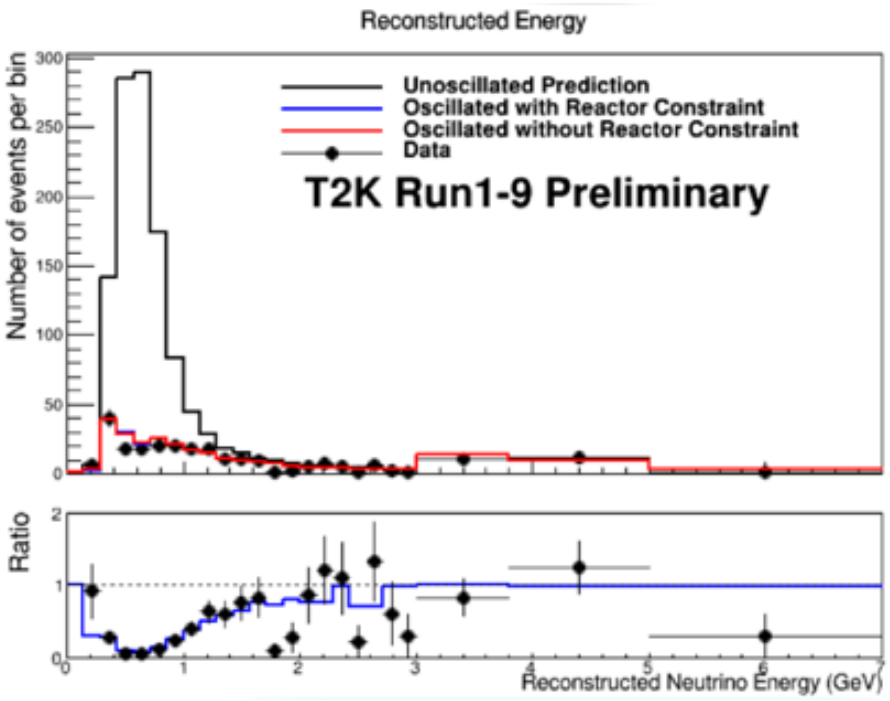
Improvements in far detector (SK) analysis

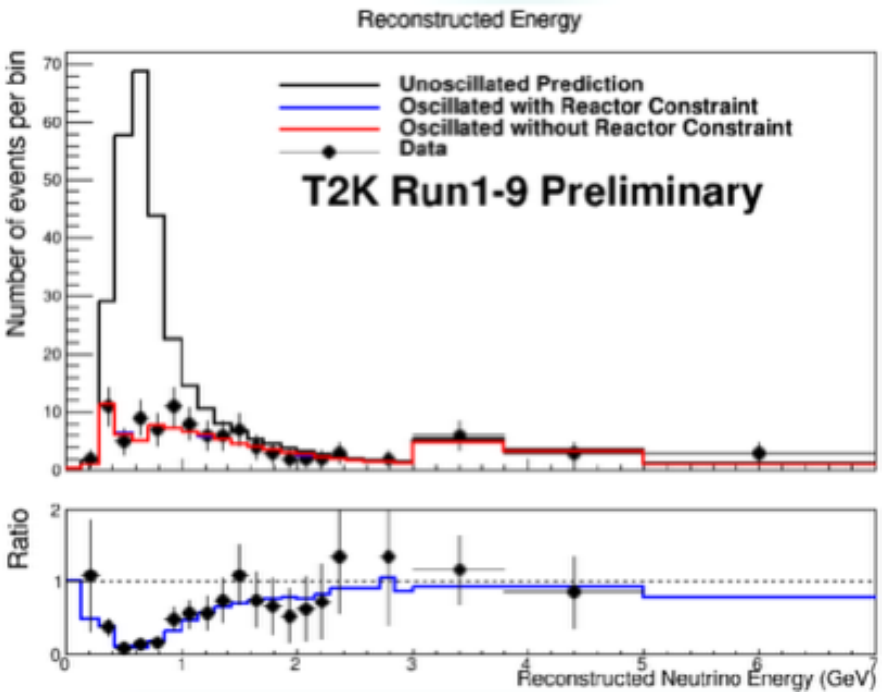
- Expand the fiducial volume by 20%
  - new reconstruction code (fiTQun)
  - with small “wall” but long enough “towall”
- Additional 1 decay electron events (+10%)
  - CC1π with π track below Cherenkov threshold
    - π track visible case to come [S.Berkman (UBC)]



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

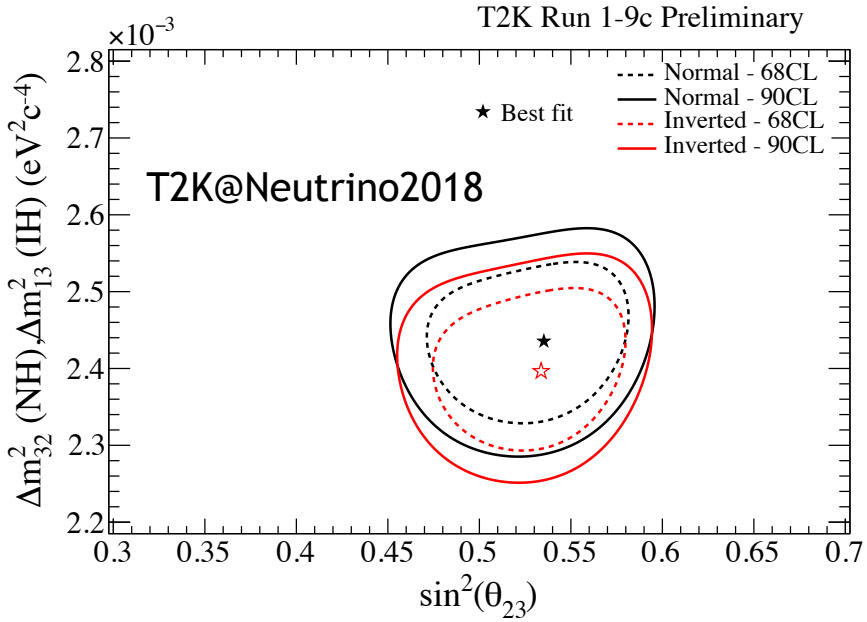
ν_μ disappearance

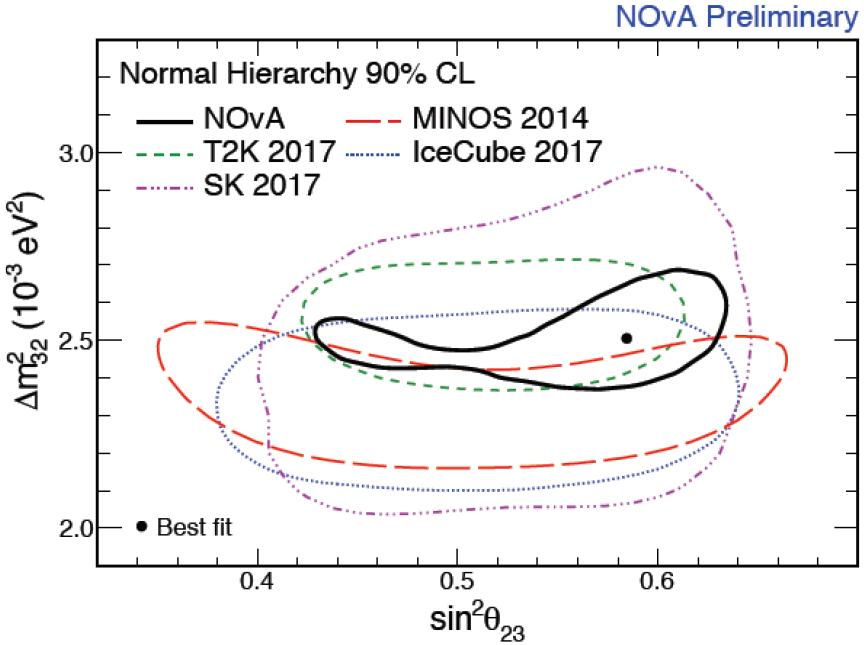




θ_{23} (atmospheric) mixing

- Maximal mixing favoured by T2K
  - Indication of symmetry in PMNS?
- NOvA's new result is consistent but best fit at non-maximal





ν_e appearance

SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	
ν mode 1Rμ	268.5	268.2	268.5	268.9	243
$\bar{\nu}$ mode 1Rμ	95.5	95.3	95.5	95.8	102
ν mode 1Re 0 decay-e	73.8	61.6	50.0	62.2	75
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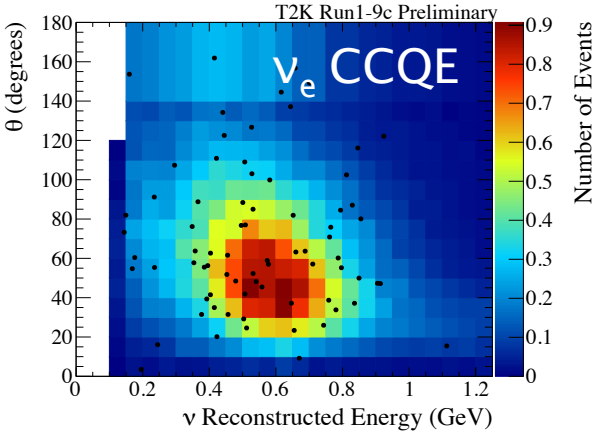
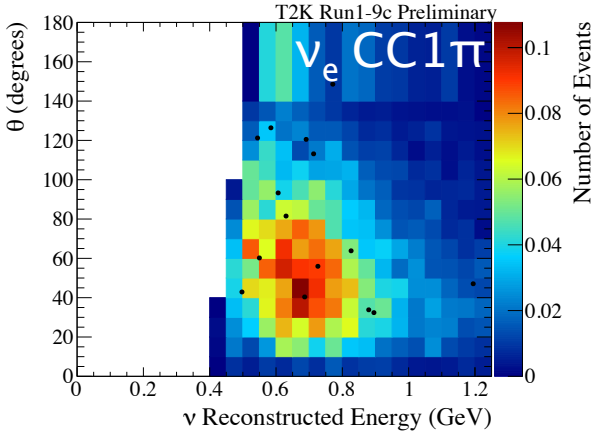
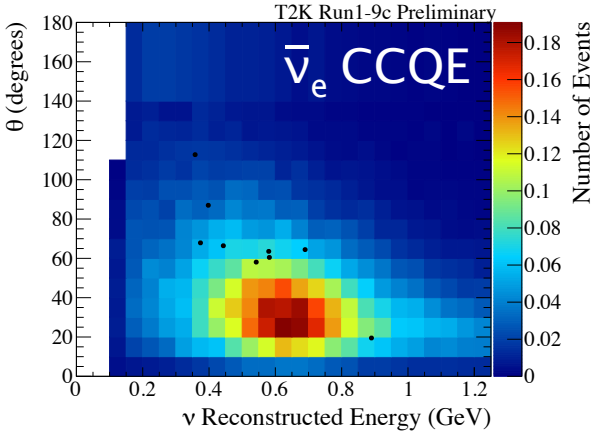
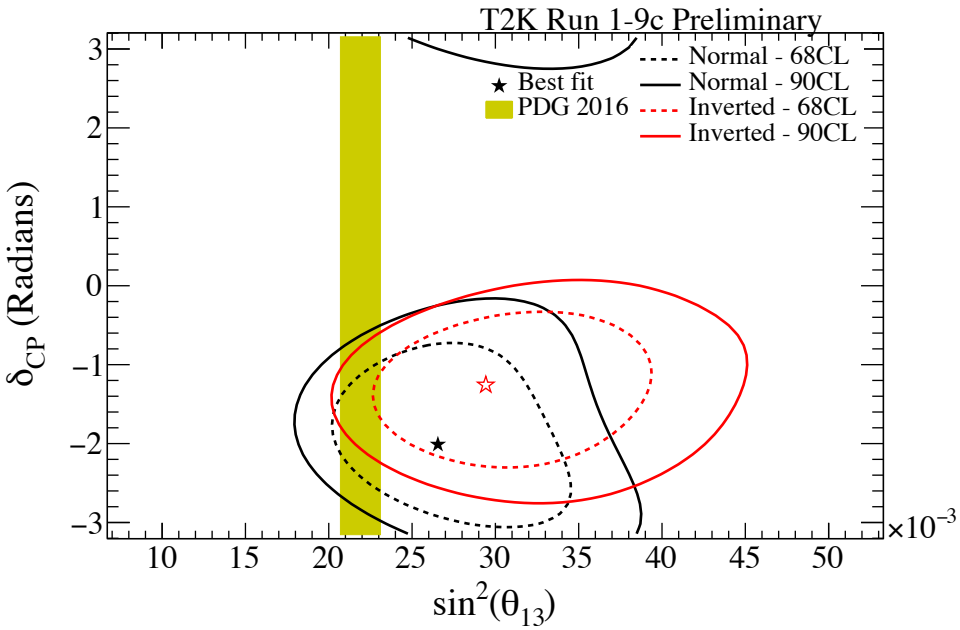


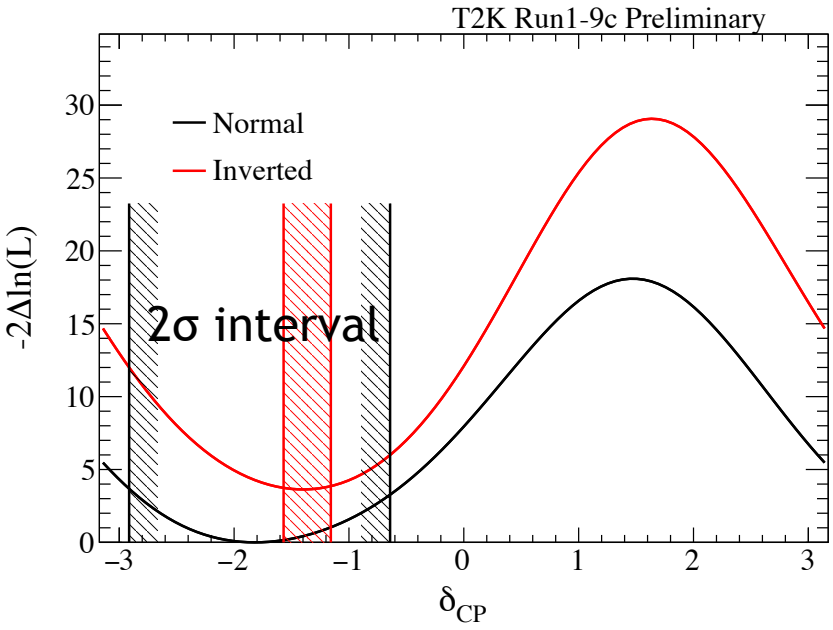




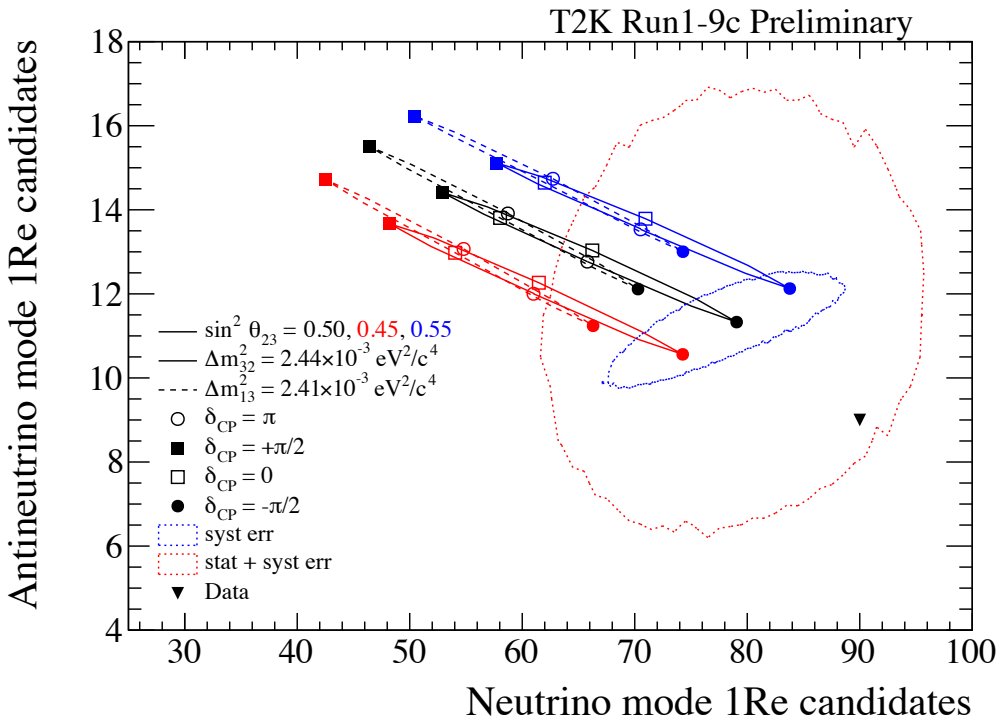
- T2K's θ_{13} consistent with Reactor neutrino result
- Disfavour CP conserving δcp=0,π at 2σ
- Normal hierarchy favoured

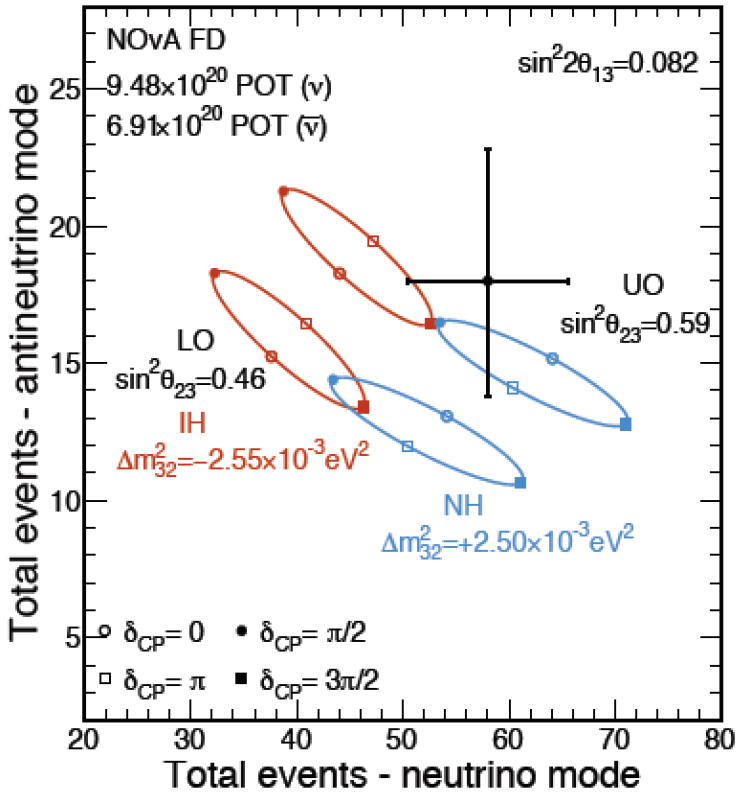
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.204	0.684	0.888
IH ($\Delta m^2_{32} < 0$)	0.023	0.089	0.112
Sum	0.227	0.773	1





Comparison with NOvA



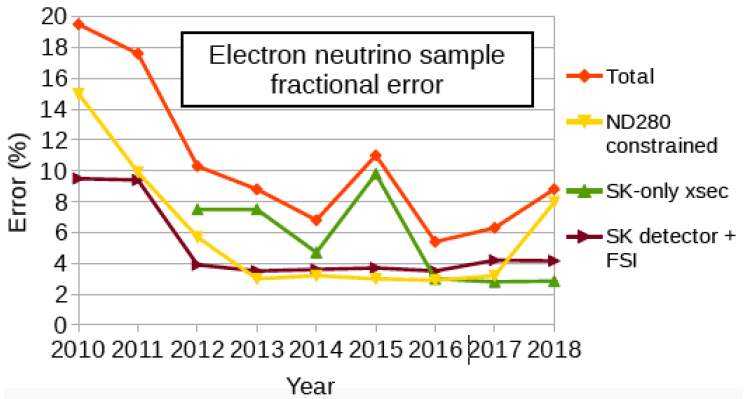


Systematic uncertainties

	1-Ring μ		1-Ring e			
Error source	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	ν mode cc1π	$\bar{\nu}/\nu$ ratio
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
NC1γ	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

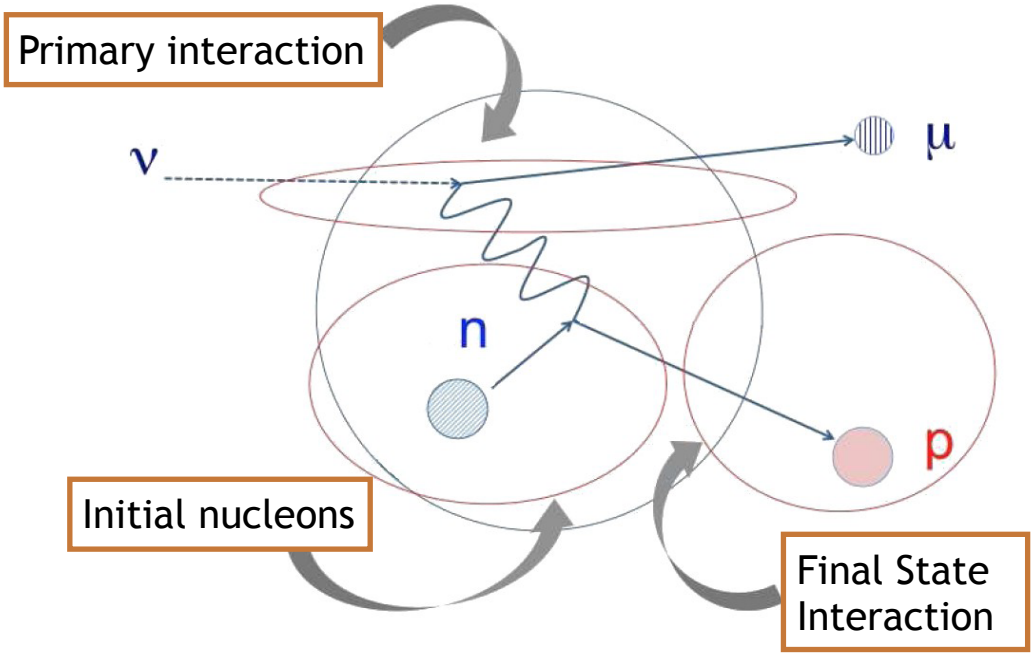
- Taking the ratio with the near detector cancels systematics
  - higher order error remains
- Source of systematics
  - Detector (SK) efficiency
  - Flux
    - near-to-far extrapolation
  - cross section

- Systematics improved but limited
  - cross section systematics is challenging
    - theoretical uncertainties
    - binding energy Eb is introduced this year
- Systematics is significant in the neutrino mode:
  - statistics: 11.5% (75 events)
  - systematics: 8.8% (hope to go back to ~6%)



Challenge in the neutrino cross section

- Primary interaction
  - Nucleon form factor
  - Multi-nucleon effects
- Initial nucleons
  - initial nucleon momentum
    - Random Phase Approximation?
    - Binding energy?
- Final State Interaction
  - nucleon traveling nucleus
    - Cascade model?
      (traveling like real particle)
  - energy-momentum conservation?
- Neutrino challenge
  - initial neutrino energy not known

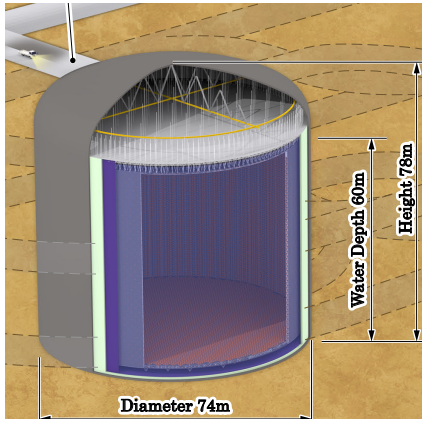


Similar challenge in
electron and pion scatterings

Model tuning at a few% level has limitations

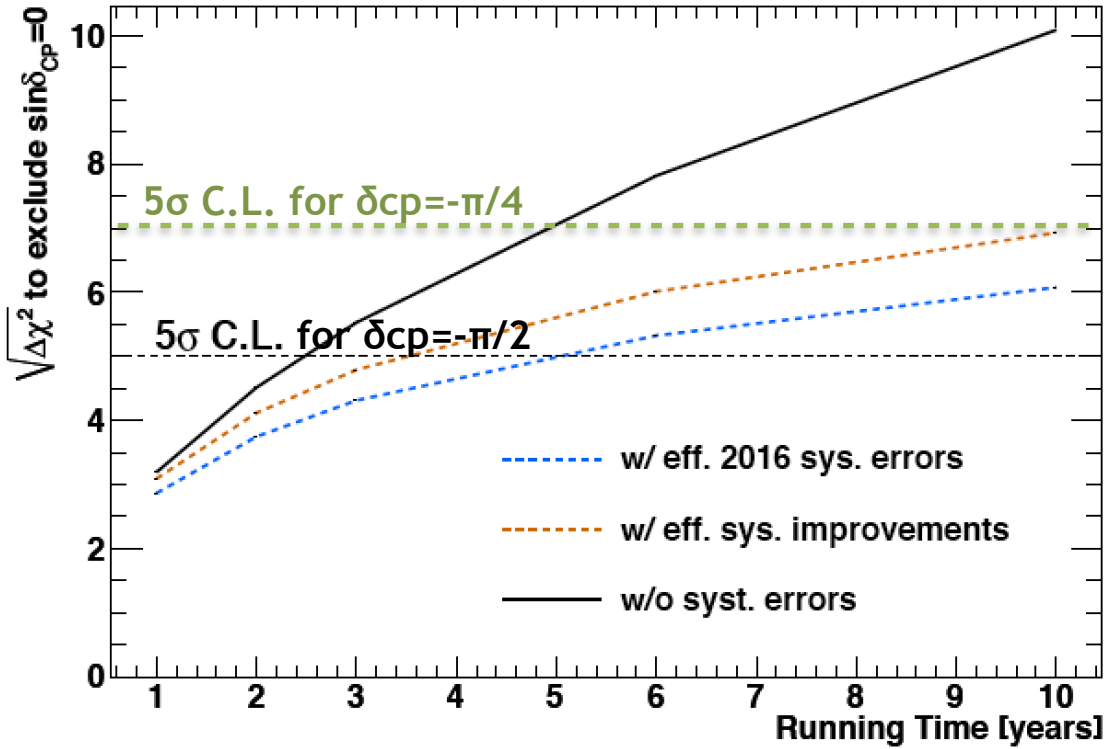
CP violation sensitivity at Hyper-Kamiokande

- HyperK water Cherenkov
  - 187kton fiducial (x8 of SK)
  - 20k-40k photosensors

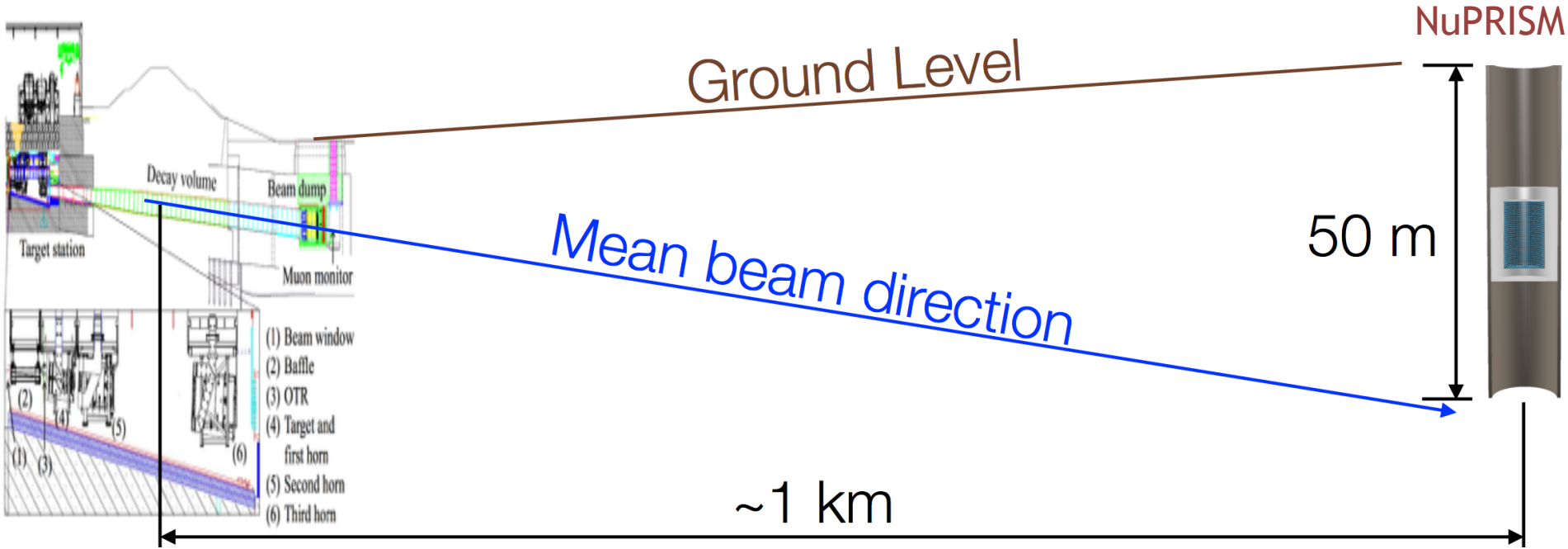


- HyperK CP sensitivity will be limited by systematics
  - Improving systematics will be essential

HK Sensitivity for δcp=-π/2 (maximal CP viol.)



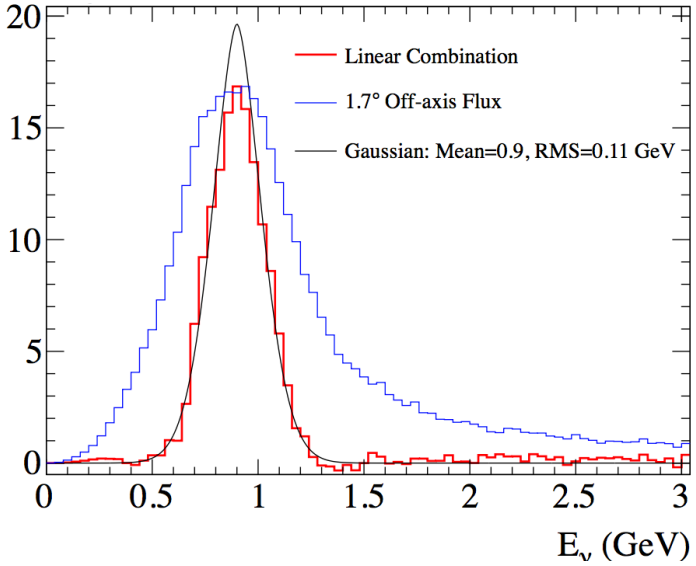
Solving cross section systematics by E61(NUPRISM)

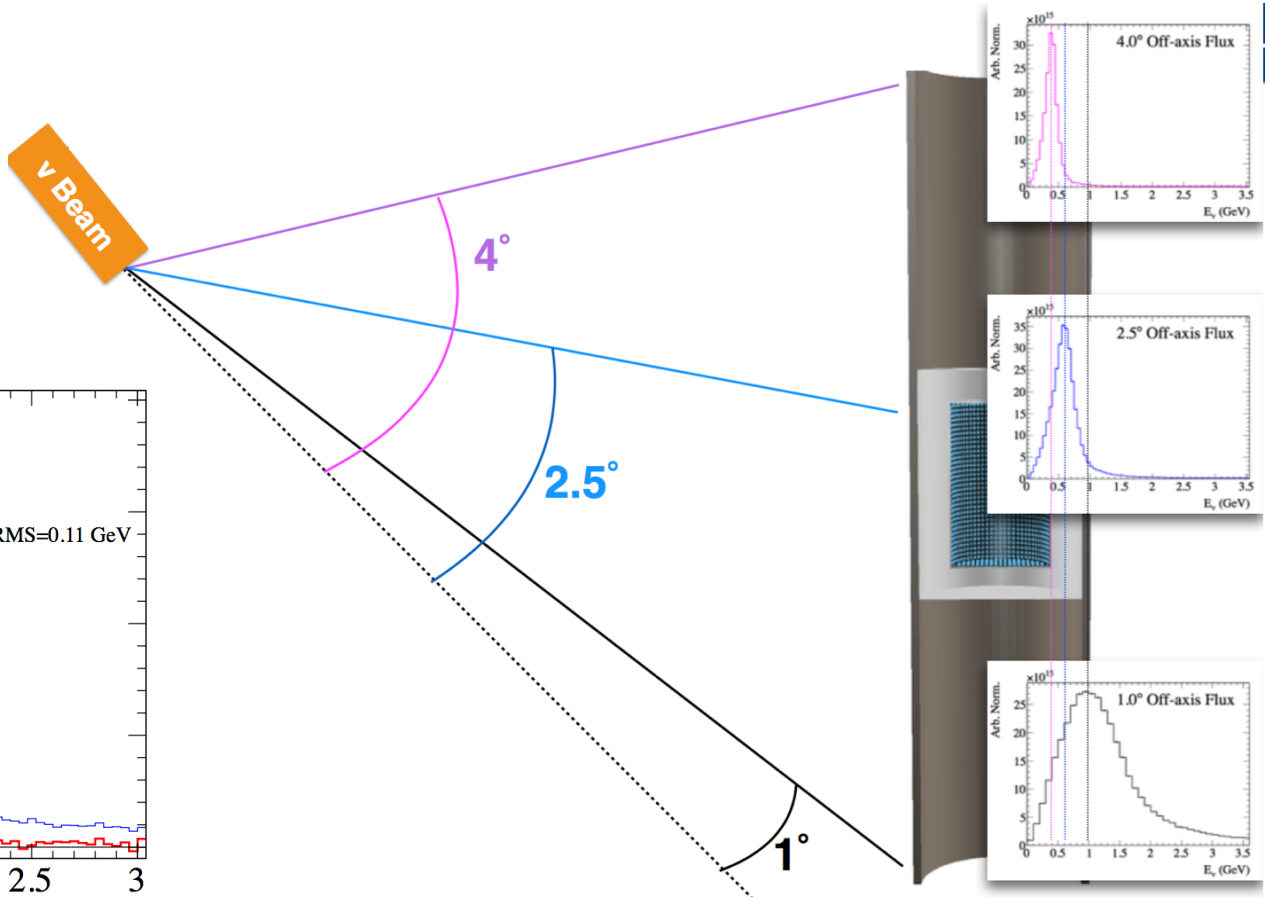


NUPRISM linear combination

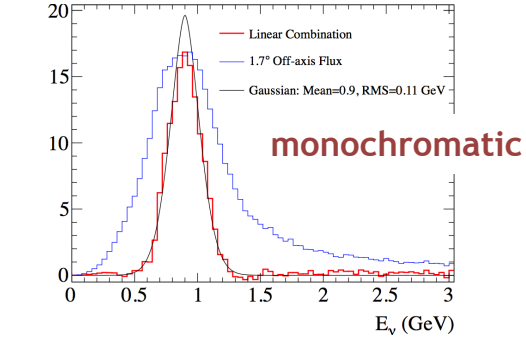
Linear combination of events at different off-axis position:

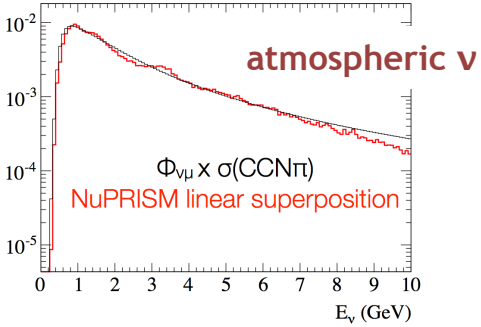
➜ Monochromatic ν beam response

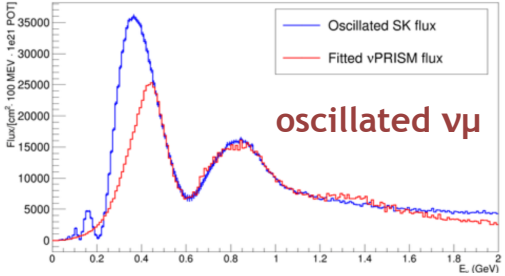


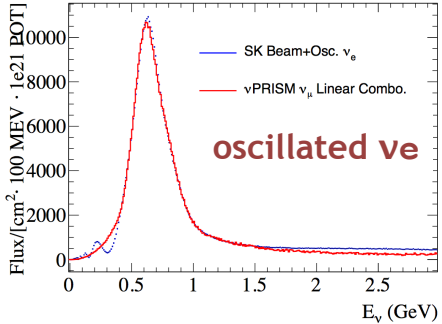


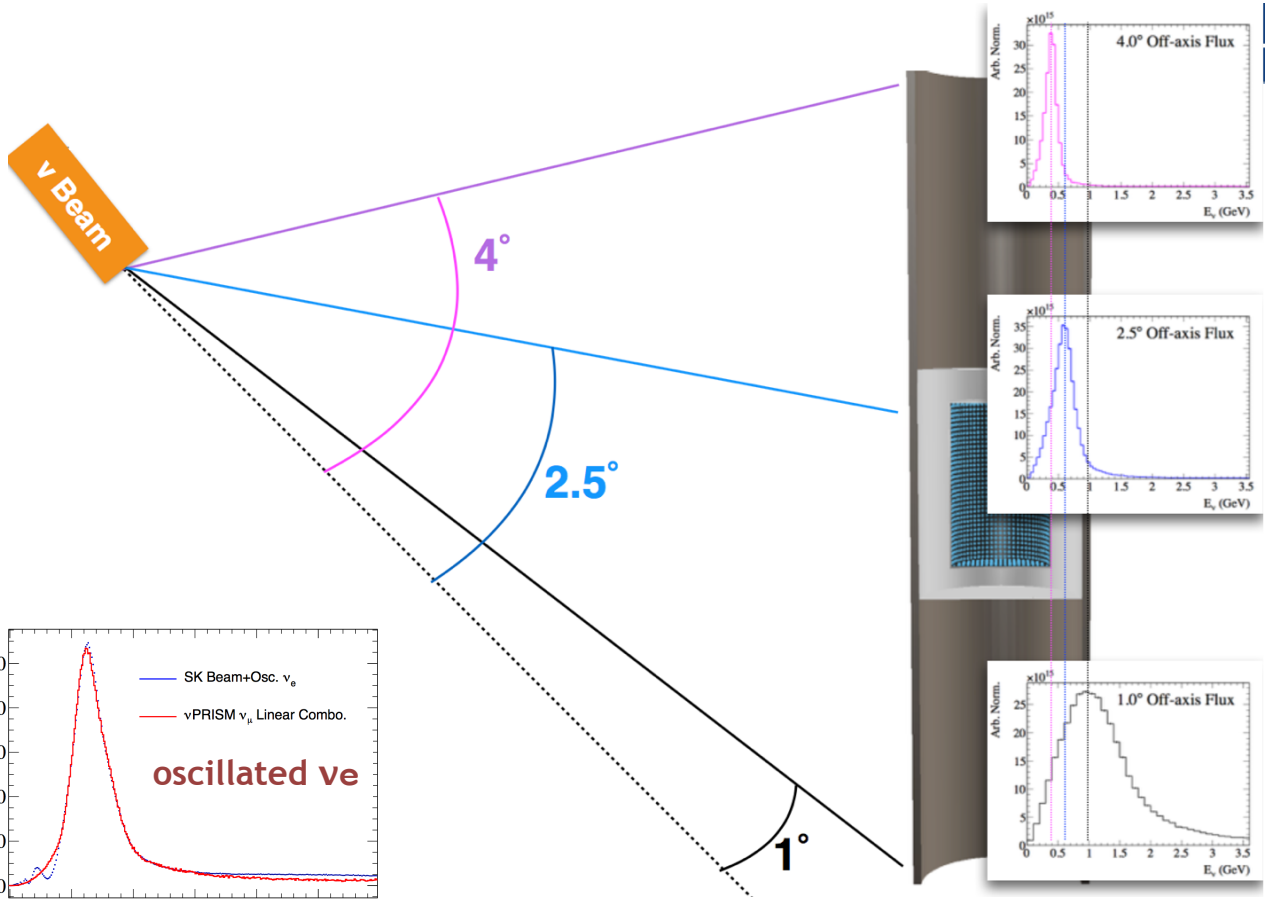
NUPRISM linear combination





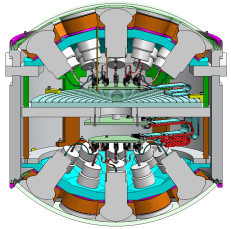


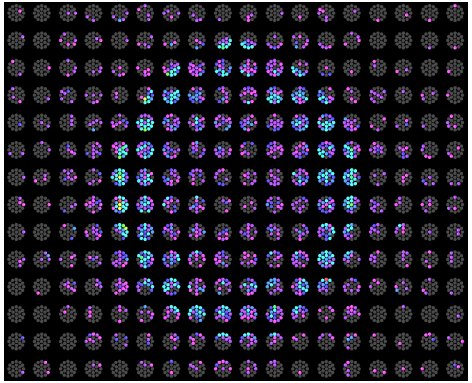


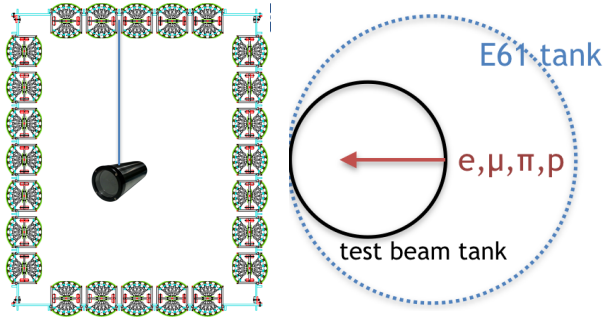


Challenge of E61(NuPRISM) water Cherenkov

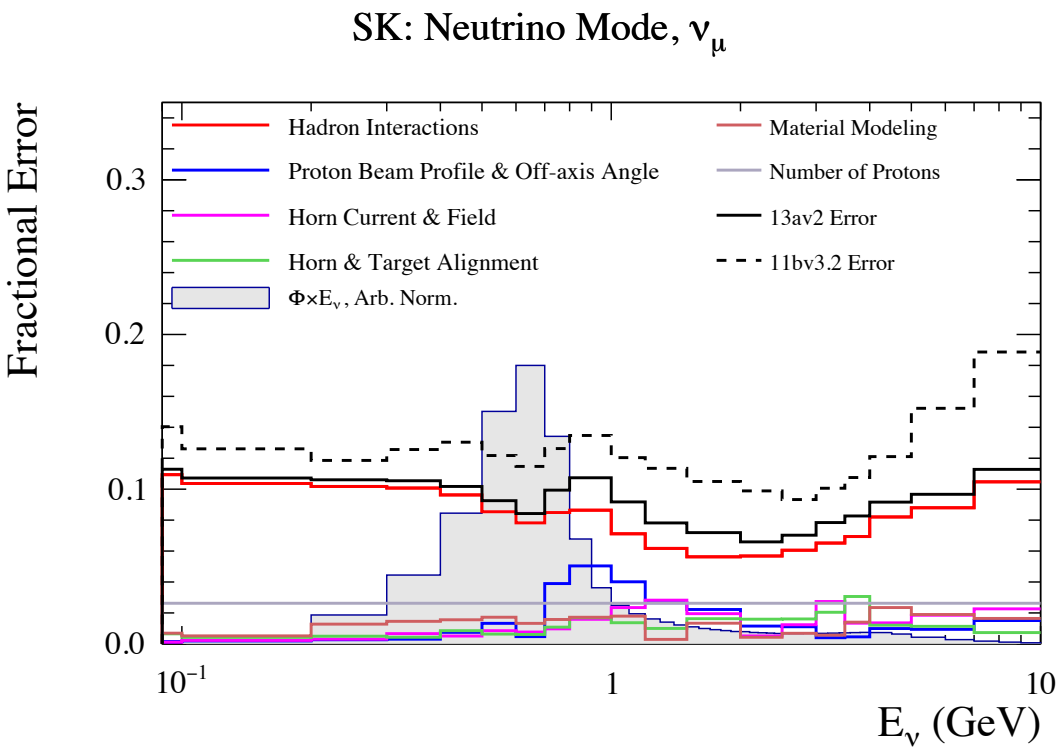
- Precise vertex reconstruction required
  - fiducial error ~1% → 1-2cm in vertex error
    - buoyancy and distortion of the support in water
    - SNO, KamLand, JUNO: ~3cm in vertex error
- Fine granularity
  - multi-PMT with 3-inch PMT's
- Precise in-situ/ex-situ calibration
  - in-situ: photogrammetry (3D reconst. by camera)
    - SNO+ demonstrates 0.5-1cm precision in a pool
  - ex-situ
    - Photosensor test facility : angular response
    - Charged particle beam test of test water Cherenkov
      - vertex, hadronic effect, multi-ring reconstruction





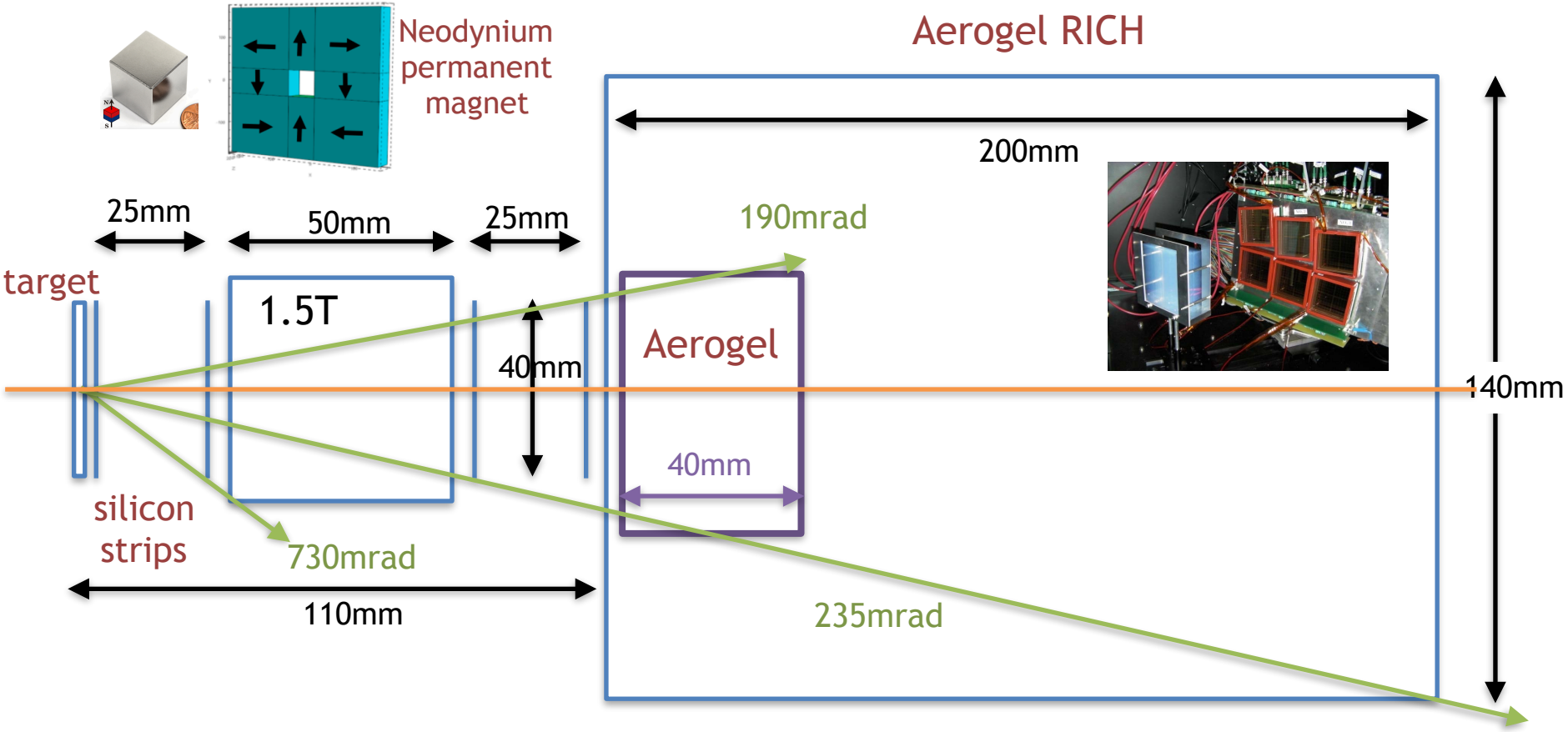


Flux systematics

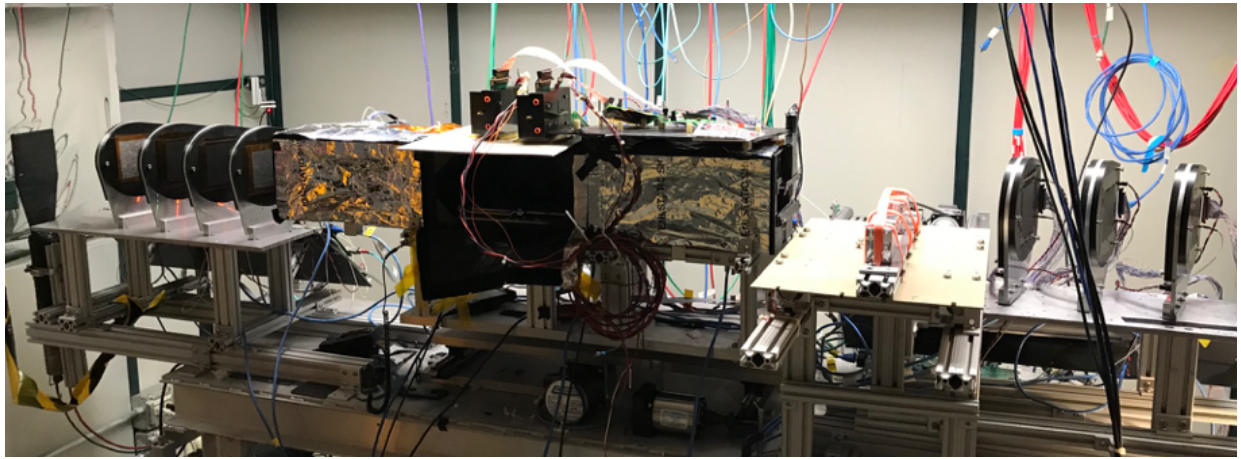


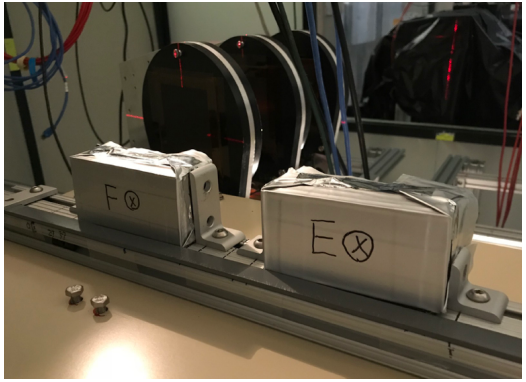
- Dominated by Hadron production error

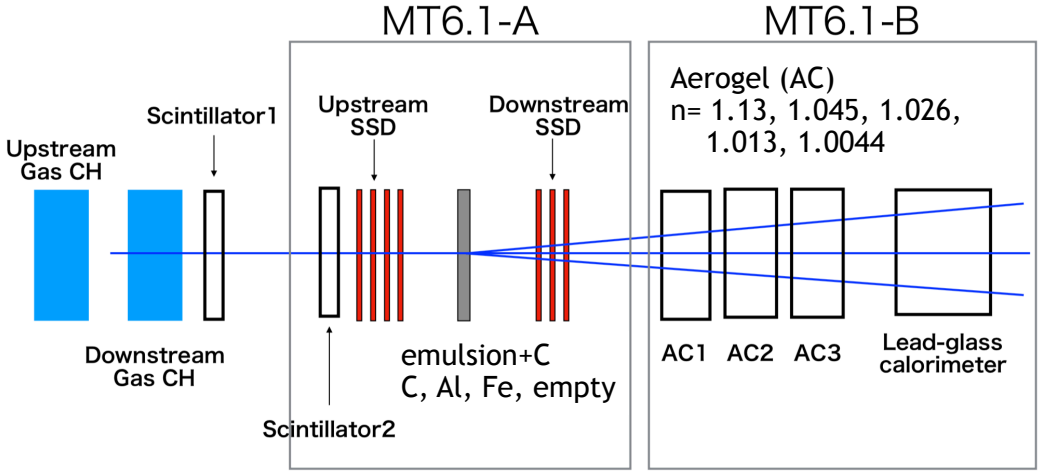
Compact spectrometer (EMPHATIC)

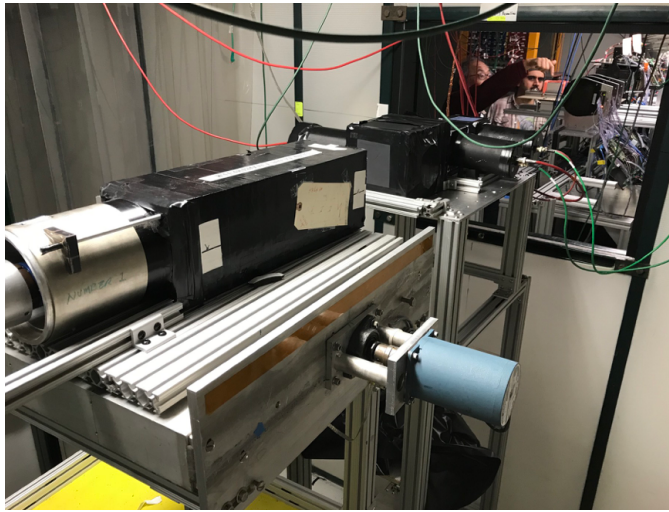


Hadron production experiment in Jan. 2018 at Fermilab

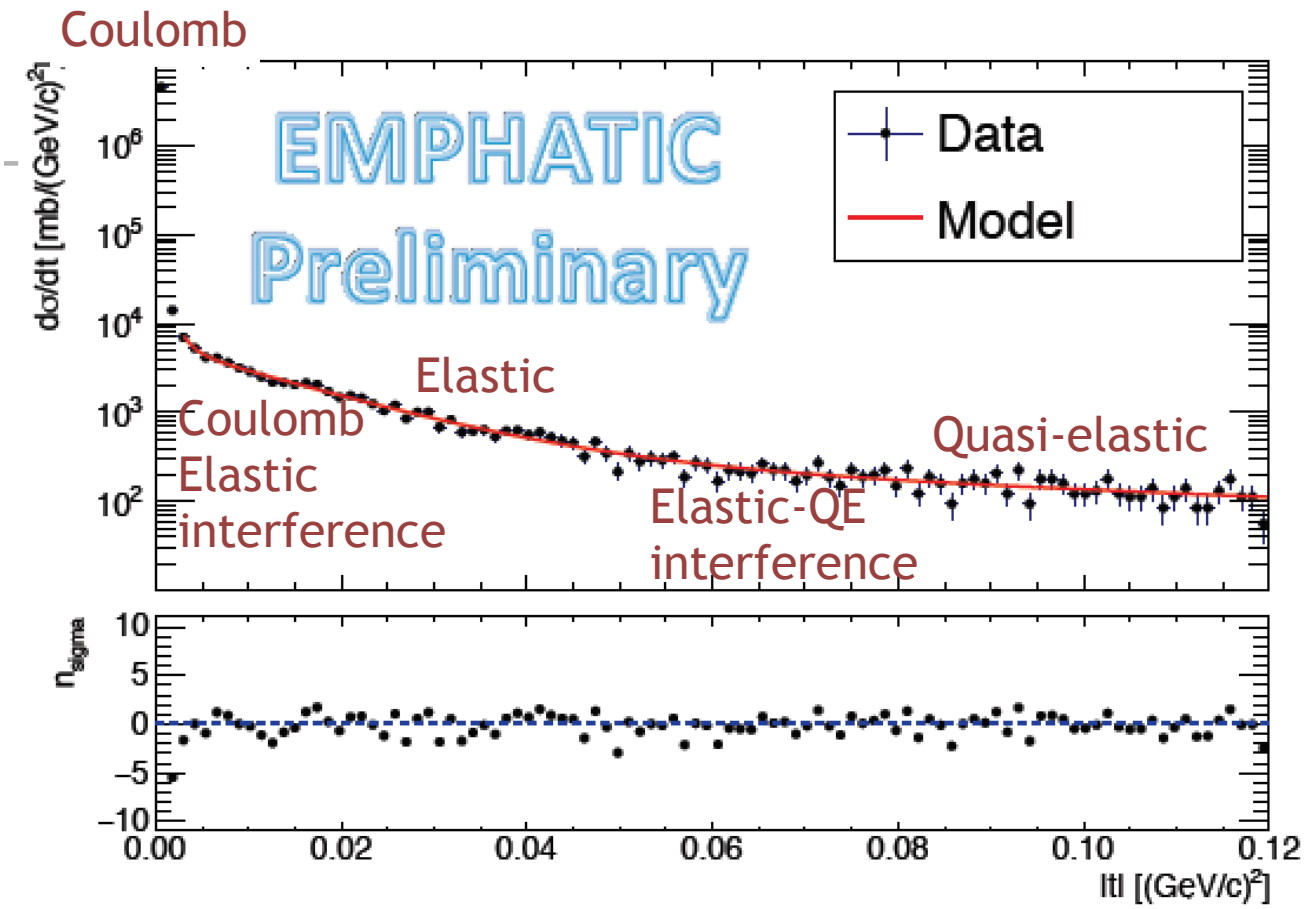






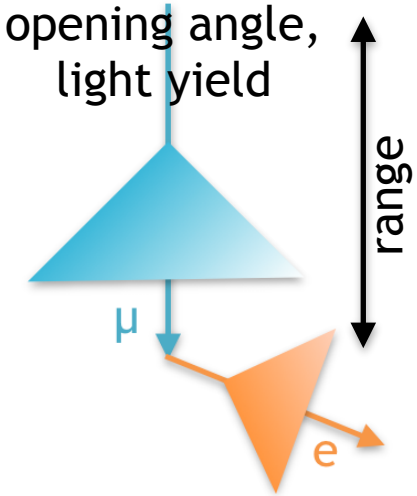


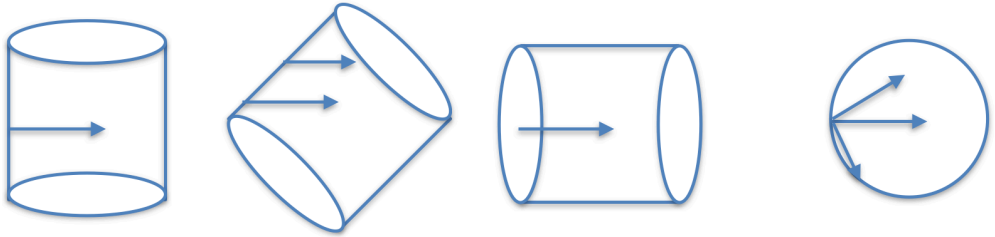
Preliminary result of EMPHATIC



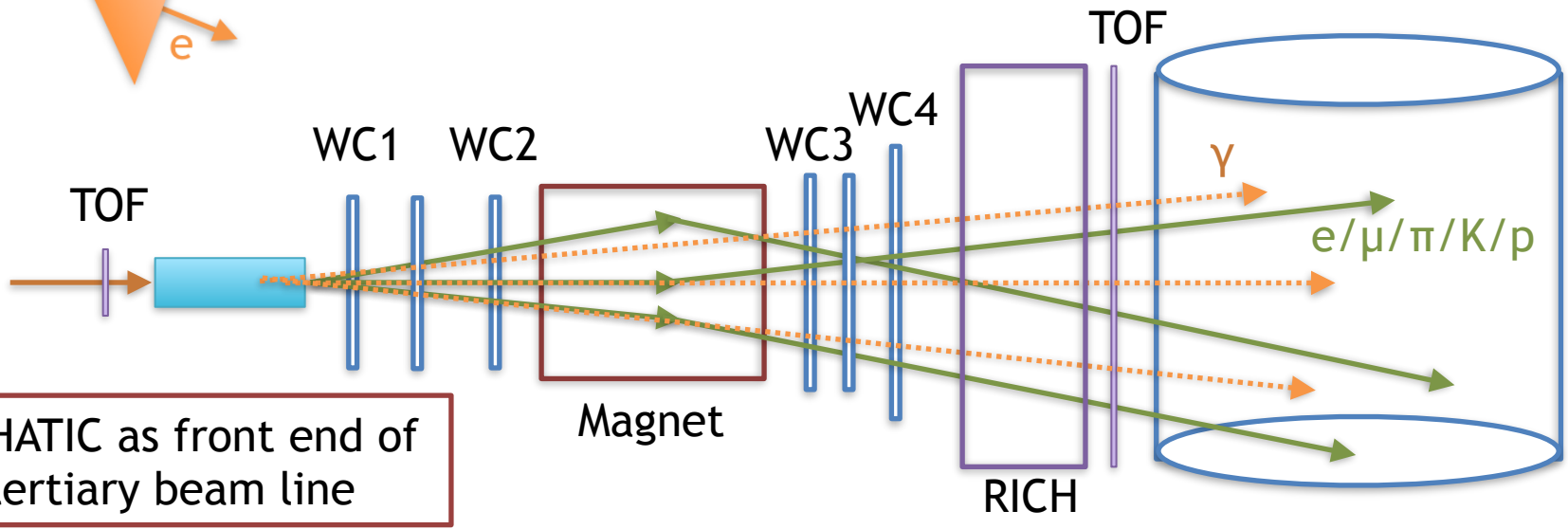
- Confusion in the definition of cross sections
  - e.g. interference terms
  - measure direct information of $t=-Q^2$ distribution for hadron production
- Khalid Gameil's talk in this session

EMPHATIC for the water Cherenkov beam test



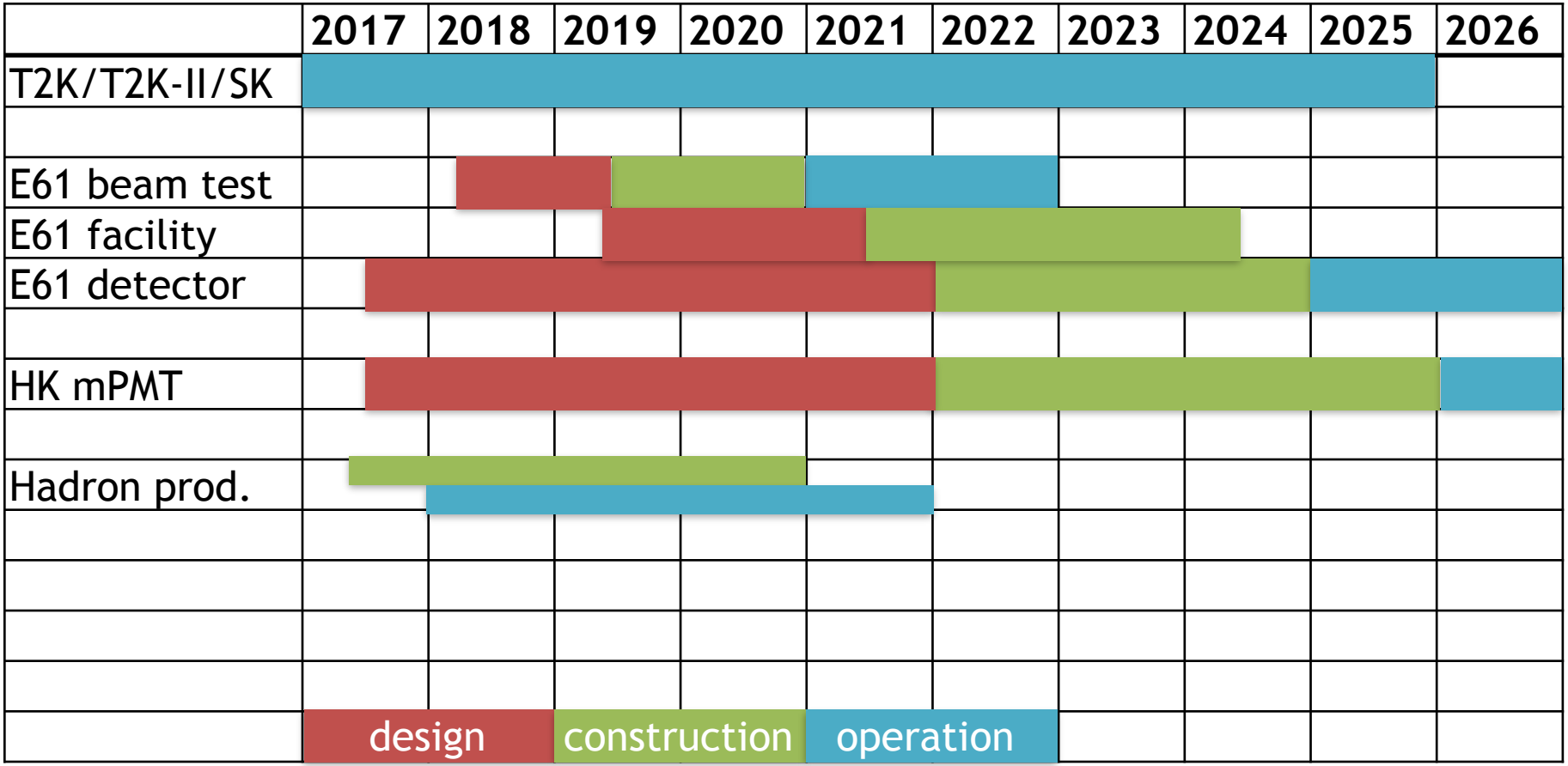


inject beam with various angles



EMPHATIC as front end of the tertiary beam line

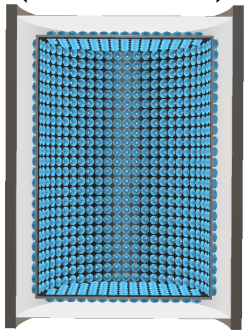
Timelines


2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
T2K/T2K-II/SK
E61 beam test
E61 facility
E61 detector
HK mPMT
Hadron prod.
design
construction
operation

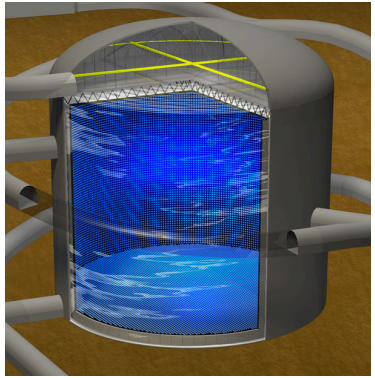
Summary

- T2K experiment had successful data taking till May 2018
  - Stable operation with the proton intensity of 485kW
- Latest result up to December 2017 data
  - Normal mass hierarchy is preferred (posterior prob.=89%)
  - CP conserving $\delta cp=0,\pi$ are disfavoured at 2σ level
    - However, the results are started to be limited by systematics
- New studies to address systematic uncertainties
  - Cross section: E61(NuPRISM)
  - Flux: EMPHATIC hadron production experiment at Fermilab
  - Detector systematics: Water Cherenkov (E61) test at Fermilab
- Excellent prospect for HyperK funding in 2018

E61 (NuPRISM)

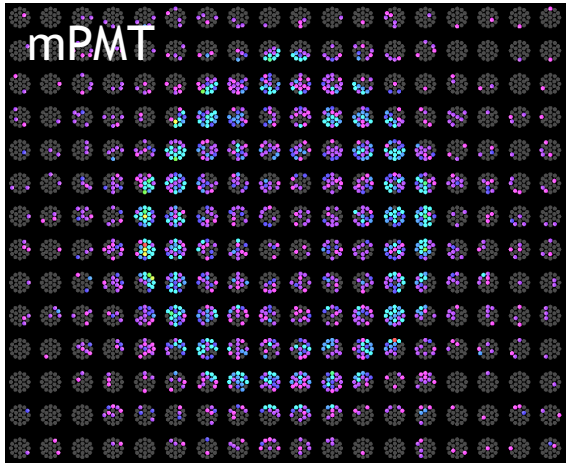


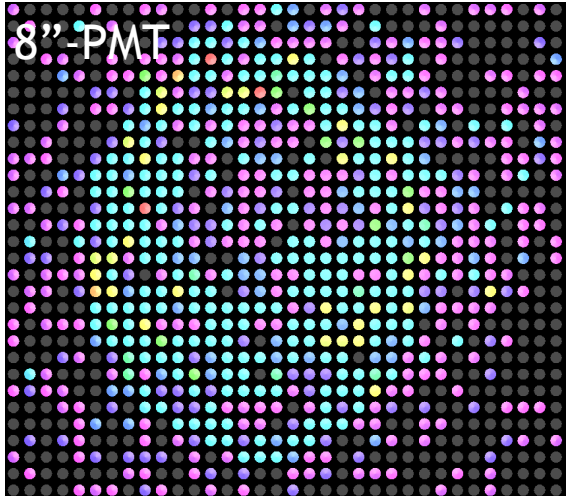
HyperK



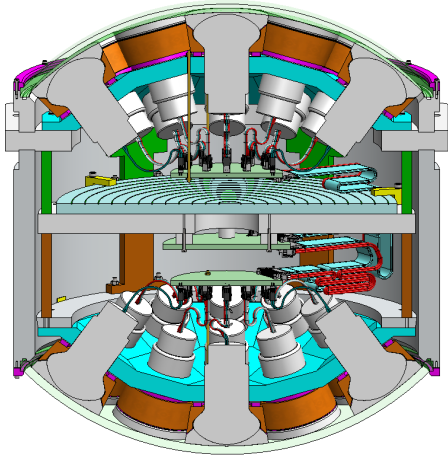
Backup

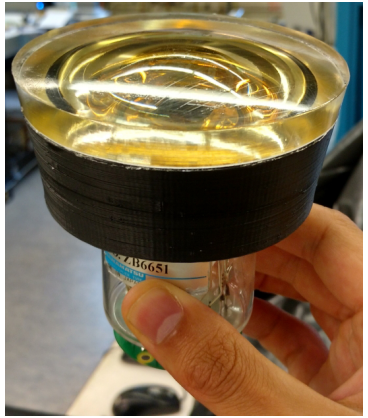
multi-PMT development for E61(NuPRISM) and HyperK





- multi-PMT (mPMT)
  - 19 of 3” PMT’s in a vessel
    - economical 3” PMT’s
- mPMT for E61(NuPRISM)
  - finer granularity for small WC
    - better than 8”
- mPMT for HyperK
  - multi-ring reconstruction
    - CC1π, mass hierarchy
  - angular sensitivity
    - accidental reduction for low E
  - provide calibration standard



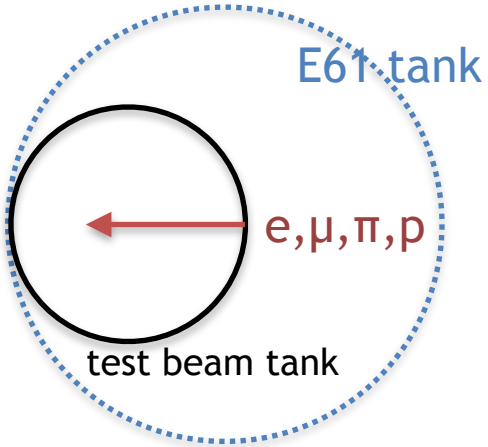


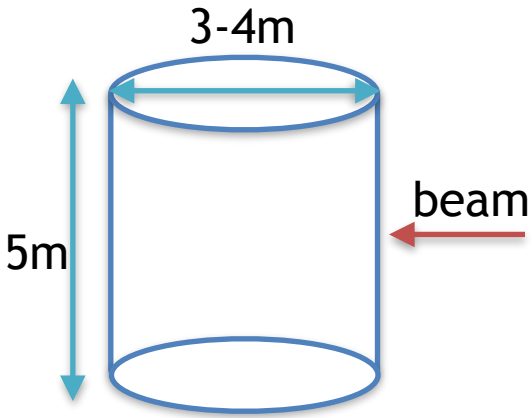
Camera calibration for E61 beam test

- Fiducial calibration limited by the position calibration of PMT's
  - buoyancy on PMT's
  - distortion of the structure
- SNO+ uses six camera's on the wall
  - 1 cm accuracy in a swimming pool
  - Nicon D5000 (12M pixel)
    - much better resolution possible now
    - water resistant camera available
      - SubC (Newfoundland company)
- 3D reconstruction tools available
  - camera positions and angles are fit
    - no need for precise camera position

NuPRISM (E61) prototype beam test for detection efficiency

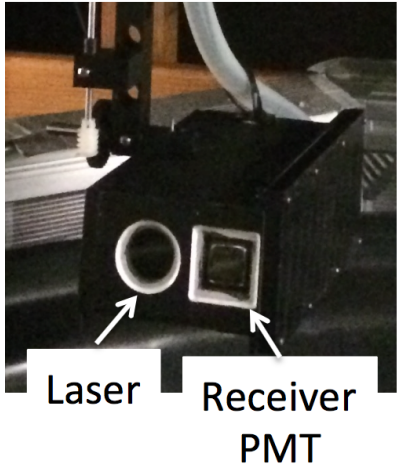
- Water tank for e, μ, π, K, p beam test
  - Fermilab test beam
    - 200MeV/c to 120GeV
  - 3m diameter tank
    - Simulate particles starting at the centre of NuPRISM
    - μ up to 700MeV/c stop inside
    - 8.3 radiation length: fully contain EM shower
- Experimental goal
  - Establish the detector calibration
    - fiducial volume at ~1% → 1-2cm in vertex systematics
    - energy scale at ~1%
  - Response of water Cherenkov to hadrons: π, K, p
  - Immediate impact on T2K and SK analyses
    - multi-ring event reconstruction

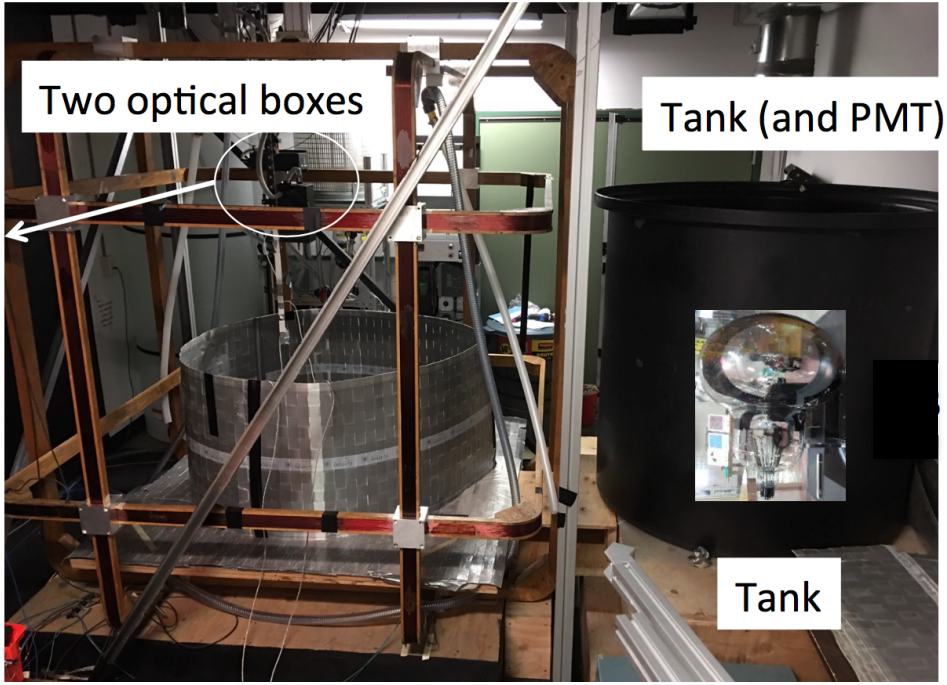


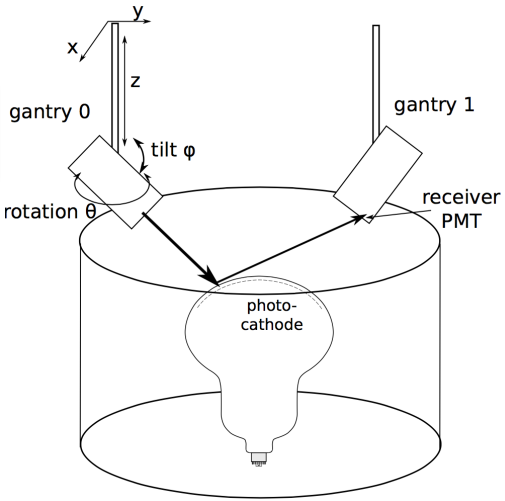


PTF setup

- Robotic arms with laser and PMT
  - laser light with polarization
  - monitor PMT
  - magnetometer
- Magnetic shielding
  - compensation coil, Giron shield







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