TRIUMF

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

T2K and HyperK

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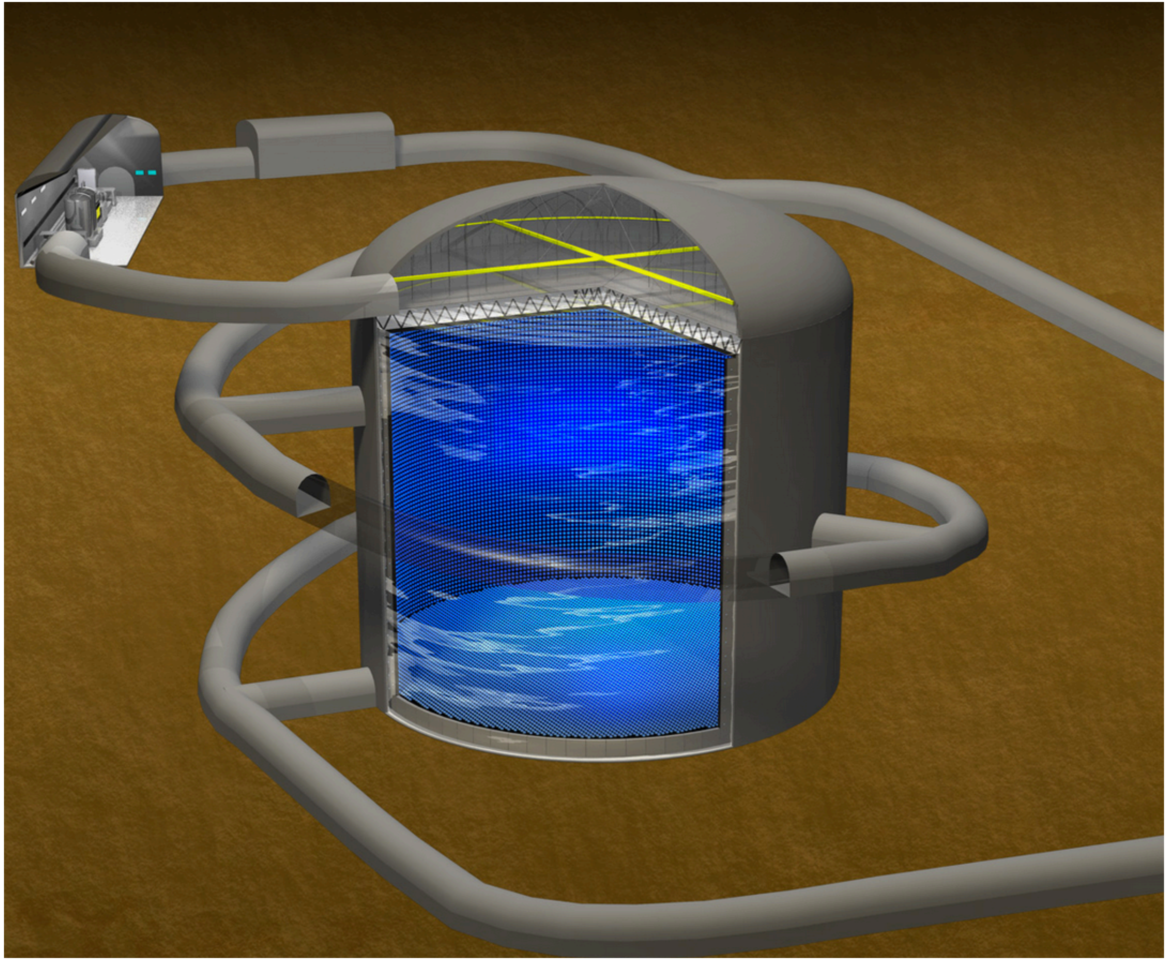
June 15 @ CAP2018 IPP AGM

Hyper-Kamiokande

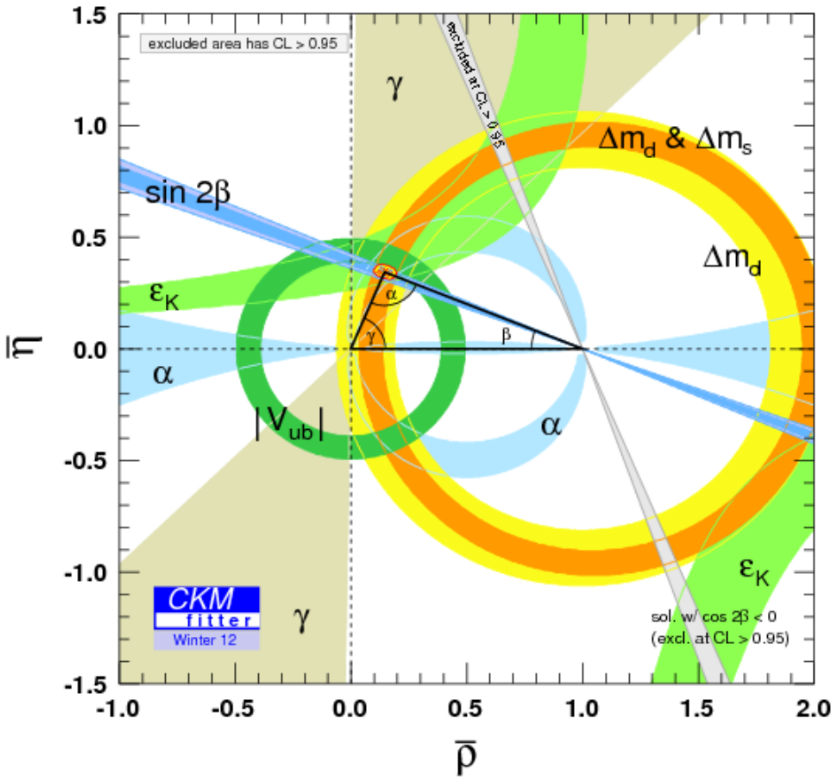


- 187kton (fid.) water Chrenkov
  - 8 times SuperK
- Physics goal
  - precision ν oscillation
    - long baseline
    - atmospheric
  - neutrino astronomy
    - supernova neutrino
    - solar neutrino
  - new physics
    - nucleon decays
    - dark matter
- Funding expected this year
  - baseline built by Japan
  - international contributions
    - enhanced photosensor
    - near detector

Precision measurement of PMNS

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$
(Quarks)

$$V_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$
(Leptons)



- Lepton mixing is large and neutrino masses are small
  - different origin from Higgs Yukawa coupling?
    - see-saw mechanism
  - could explain baryon asymmetry
    - Leptogenesis

Test of PMNS e-μ unitarity triangle

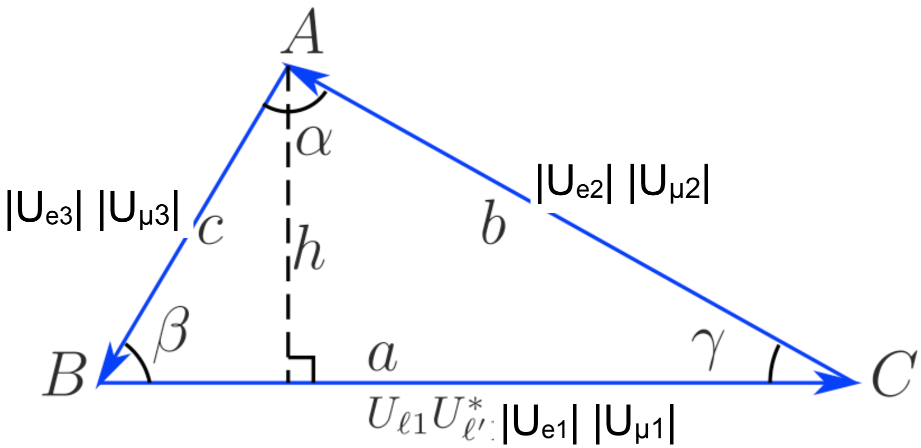
solar, Kamland, reactor, **JUNO**

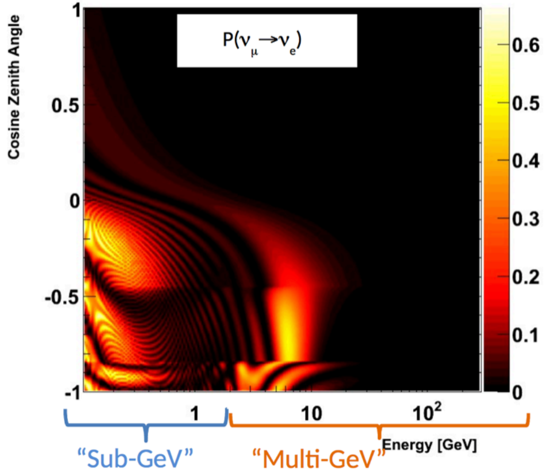
$$|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2 = 1$$

HK atmospheric, long baseline

$$|U_{\mu1}|^2+|U_{\mu2}|^2+|U_{\mu3}|^2 = 1$$

$$U_{e1}U^*_{\mu1}+U_{e2}U^*_{\mu2}+U_{e3}U^*_{\mu3} = 0$$





$$P_{\ell\to\ell'} = 4ab\sin(\Delta_{12}\pm\gamma)\sin\Delta_{12} + 4bc\sin(\Delta_{23}\pm\alpha)\sin\Delta_{23} + 4ac\sin(\Delta_{31}\pm\beta)\sin\Delta_{31}$$

Δ_{13} : $\beta \sim \delta_{cp}$

Δ_{12} : $\gamma \sim \delta_{subGeV\text{-}atm}$

Δ_{23} : $\alpha \sim \delta_{nth\text{-}max}$

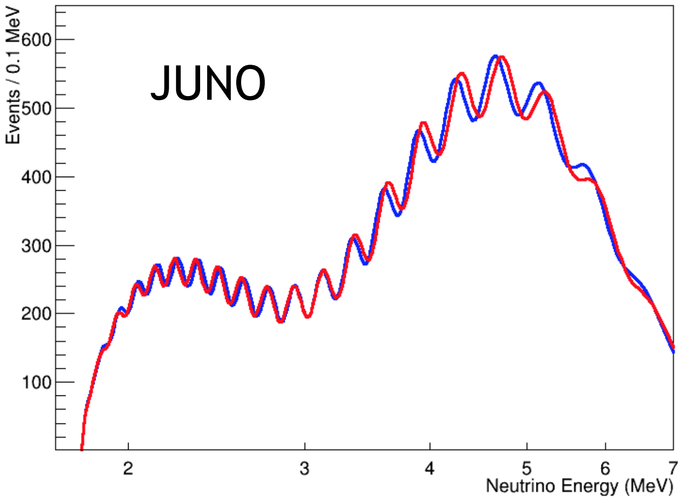
HK long baseline, atmospheric

All sides and angles are in principle accessible

$|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2 = 1$

- Solar neutrino: $|U_{e2}|^2$
  - MSW conversion in the sun: $\nu_e \rightarrow \nu_2$ and detect ν_e
- KamLand: $|U_{e1}|^2|U_{e2}|^2$
  - Reactor ν_e disapp. at Δ_{12} scale
- Reactor θ_{13}: $|U_{e3}|^2$ ($|U_{e1}|^2 + |U_{e2}|^2$)
  - Reactor ν_e disapp. at Δ_{13} scale
- All the parameters are measured:
  - Precision measurement of all $|U_{e1}|^2|U_{e2}|^2$, $|U_{e2}|^2|U_{e3}|^2$, $|U_{e3}|^2|U_{e1}|^2$ expected by JUNO

$$
\begin{aligned}
P_{disapp} &= 1-P_{e\rightarrow e} \\
&= 4|U_{\ell 1}|^2 |U_{\ell 2}|^2 \sin^2\Delta_{12} \\
&\quad + 4|U_{\ell 2}|^2 |U_{\ell 3}|^2 \sin^2\Delta_{23} \\
&\quad + 4|U_{\ell 3}|^2 |U_{\ell 1}|^2 \sin^2\Delta_{31}
\end{aligned}
$$

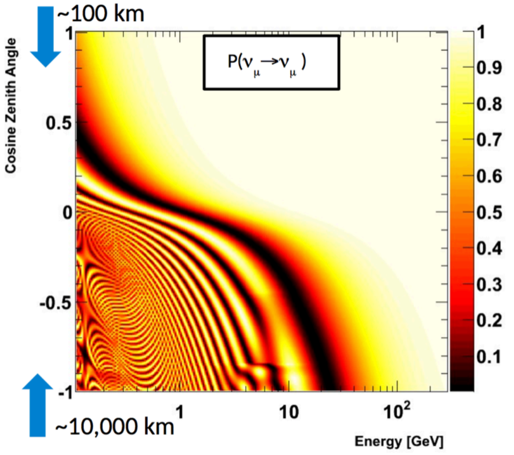


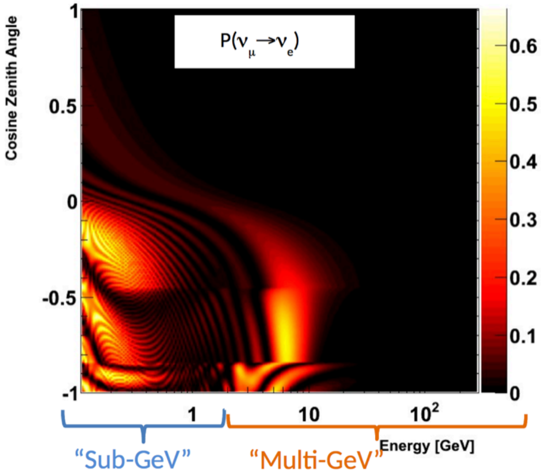
$(\Delta_{13}-\Delta_{23}) \sim 0.03\,\Delta_{23}$ at 1st osci. max

$(\Delta_{13}-\Delta_{23}) \sim 0.3\,\Delta_{23}$ at 10th osci. max

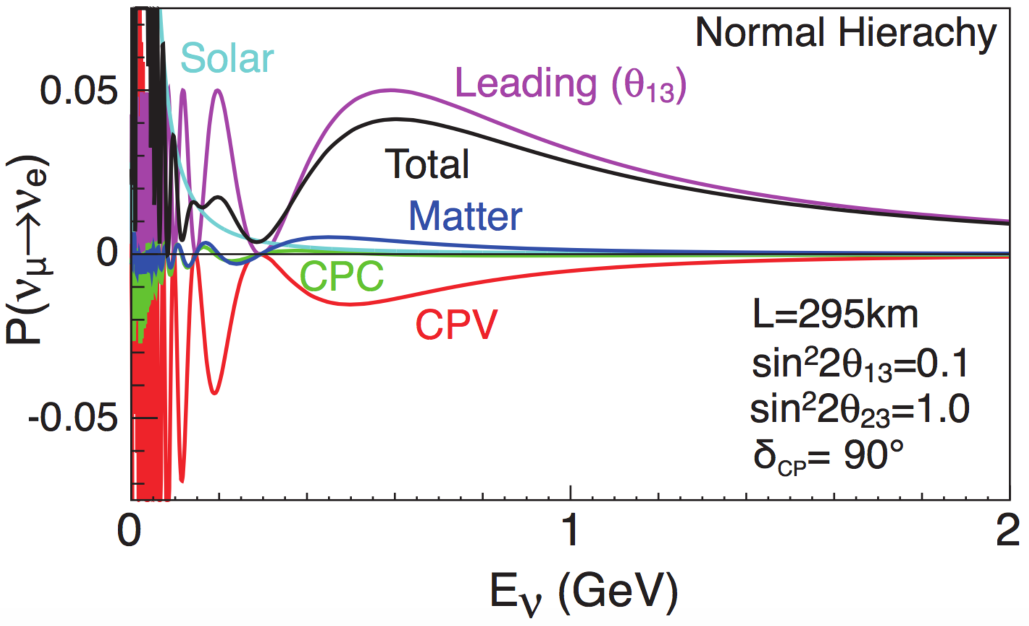
$|U_{\mu 1}|^2+|U_{\mu 2}|^2+|U_{\mu 3}|^2 = 1$

- LBL ν_μ disapp: $|U_{\mu 3}|^2$ ($|U_{\mu 1}|^2$ + $|U_{\mu 2}|^2$)
    - T2K/NOvA/HK/DUNE measure this.
- $\nu_\mu \rightarrow \nu_e$ atm. matter resonance: ($r|U_{\mu 3}|^2$ -1)
    - ν mass hierarchy (~6GeV) [SK,HK]
- Solar scale atm. ν_μ disapp. : $|U_{\mu 1}|^2|U_{\mu 2}|^2$
    - 0.4-0.8GeV up-going atm. ν_μ disapp.
    - anti-ν_μ (neutron tag) has directionality
        - SK-Gd would help this
- 1-3GeV atm. ν_μ disapp.: $|U_{\mu 1}|^2$ / $|U_{\mu 2}|^2$
    - 4-6th oscl. max: phase shift btw Δ_{13}&Δ_{23}
    - T2HKK (Korean detector) can do this as well





CP violation effect for neutrino is large



T2K/HyperK case:

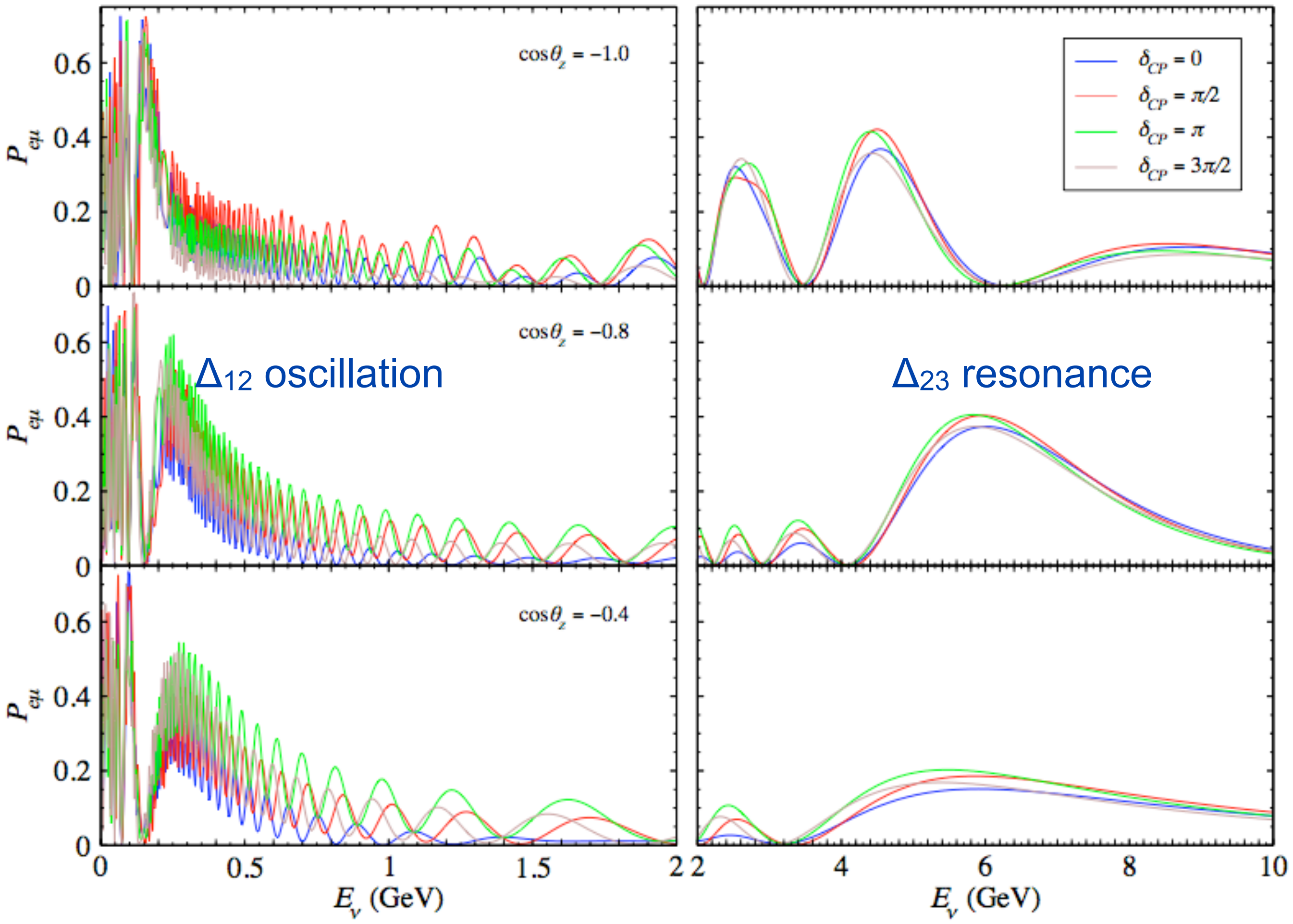
At the peak of E_ν=0.6GeV

$$\frac{Prob(\nu_\mu \to \nu_e) - Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}{Prob(\nu_\mu \to \nu_e) + Prob(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq -0.28 \sin\delta_{CP} + 0.07$$

matter effect

Δ_{23} and Δ_{31} : sensitive to sum of α and β angle contributions

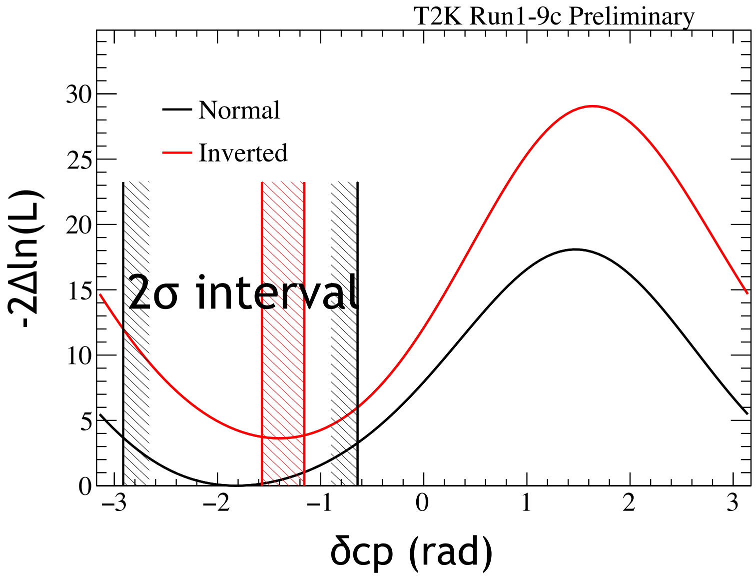
CP violation in atmospheric neutrinos

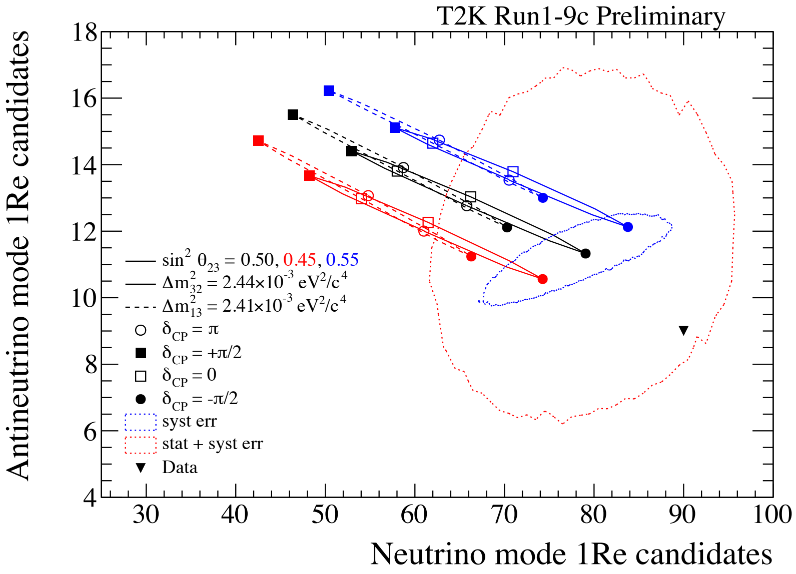


CP effect is not small in particular

+ 1-4GeV
  Δ_{23} : $\alpha \sim \delta_{nth\text{-}max}$
+ sub-GeV
  Δ_{12} : $\gamma \sim \delta_{subGeV\text{-}atm}$

T2K Neutrino2018 result

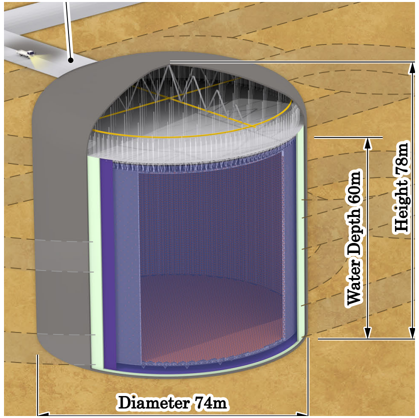




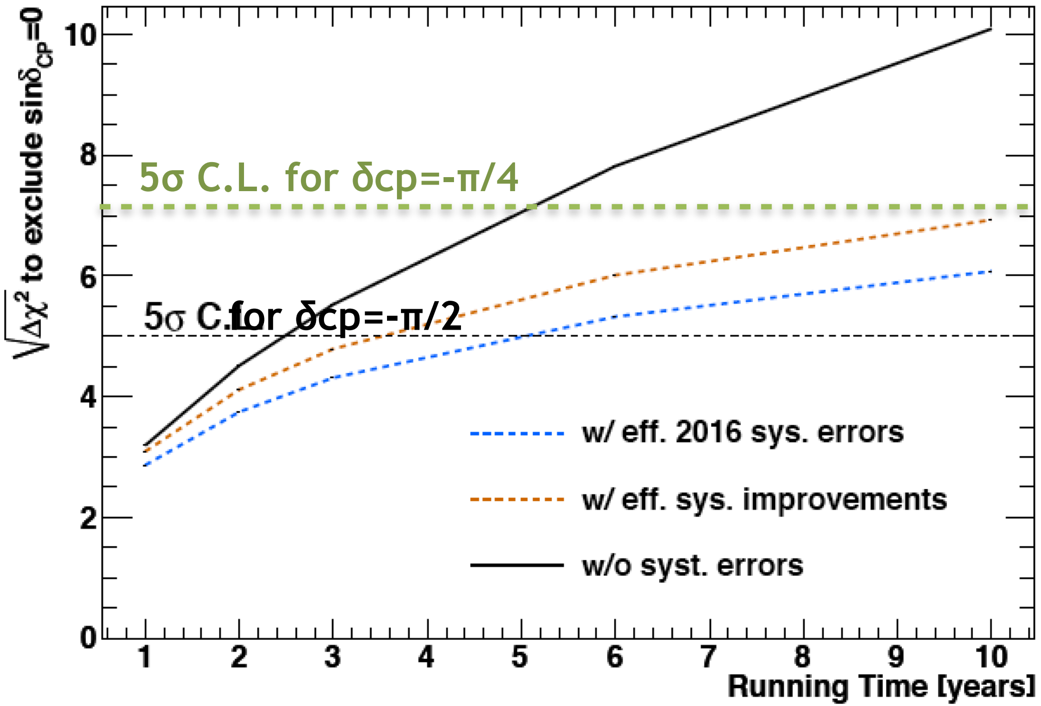
- Based on 90 ν_e and 9 anti-ν_e appearance candidate events
  - CP conserving δcp = 0,π falls out of the 2σ range
- Sounds like we are almost there, but not really…
  - central value is in unphysical region beyond maximal CP: lucky statistical fluctuation
  - **Systematic error** of 8.8%(CCQE neutrino) is significant compared to stat. error of 11.5%

CP violation sensitivity at Hyper-Kamiokande

- HyperK CP sensitivity will be limited by systematics
  - Improving systematics will be essential
- Systematics does not follow gaussian distribution
  - hard to claim signal assuming gaussian errors of 5σ



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

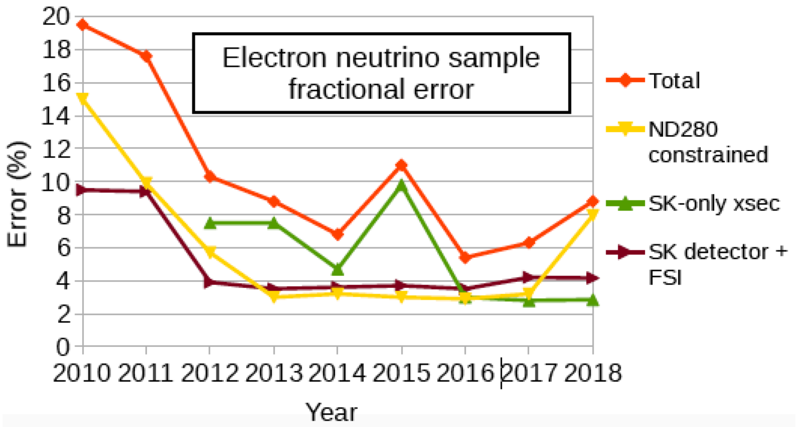


Systematic uncertainties

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

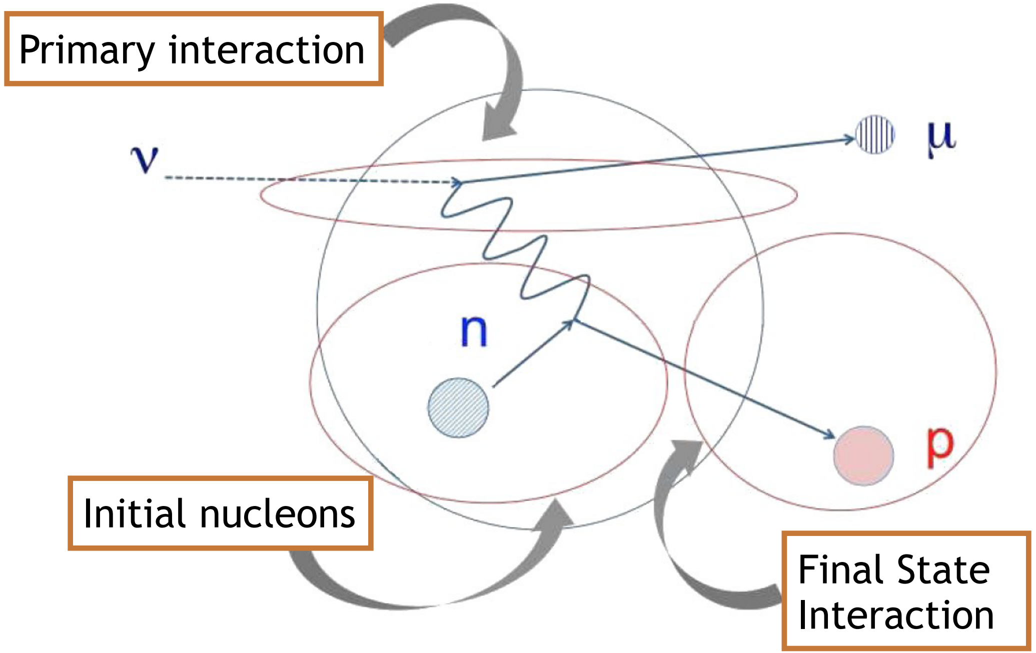
- Taking the ratio with the near detector cancels systematics
  - similar to “side band”
  - limited due to difference in flux shape due to oscillation
- Source of systematics
  - Detector (SK) efficiency
  - Flux
  - cross section

- Systematic uncertainties improved over the years but started to be limited
  - easy to improve ones are already done
  - cross section systematics is challenging
    - theoretical uncertainties
    - binding energy Eb is introduced this year



Challenge in the neutrino cross section

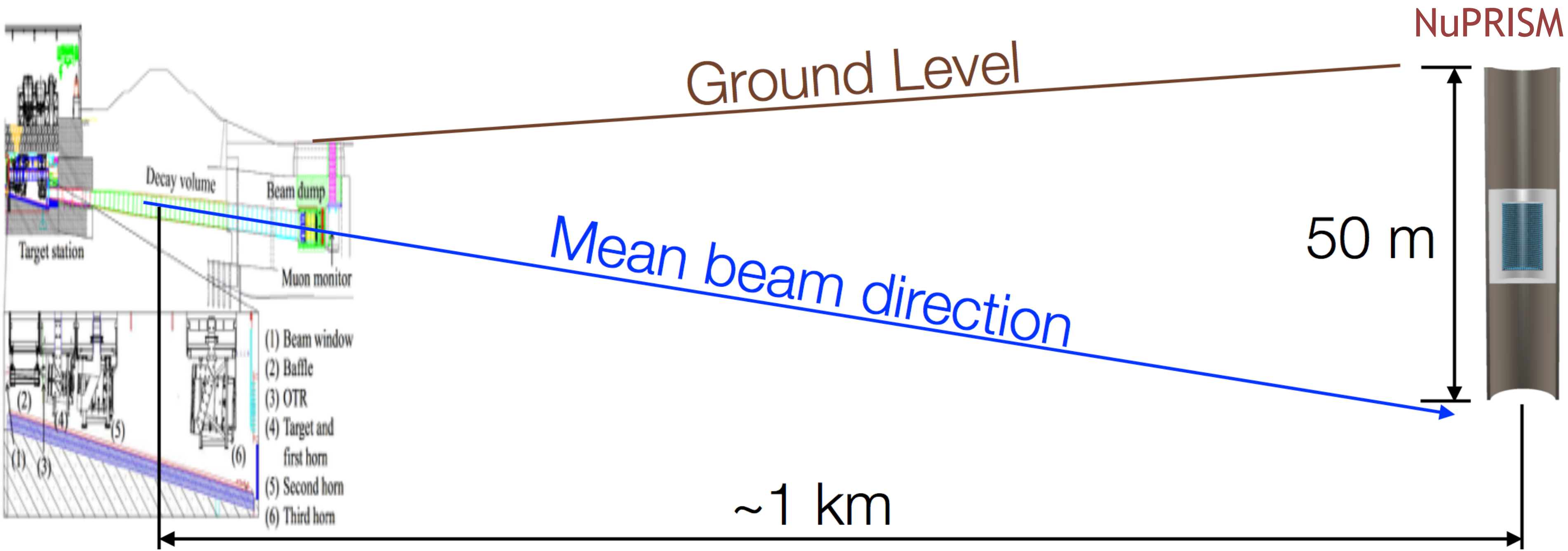
- Primary interaction
  - Nucleon form factor
  - Multi-nucleon effects
- Initial nucleons
  - initial nucleon momentum
    - Random Phase Approximation?
    - Binding energy?
- Final State Interaction
  - nucleon traveling nucleus
    - Cascade model? (traveling like real particle)
  - energy-momentum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



Similar challenge in electron and pion scatterings

Model tuning at a few% level has limitations

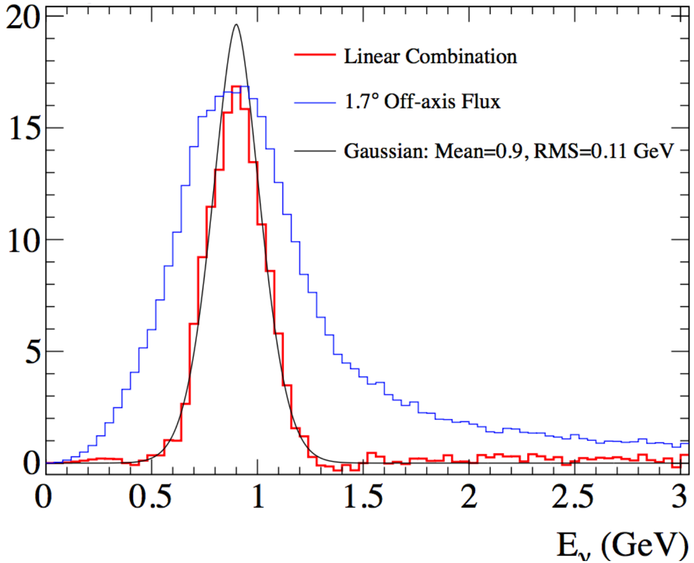
Solving cross section systematics by E61(NUPRISM)

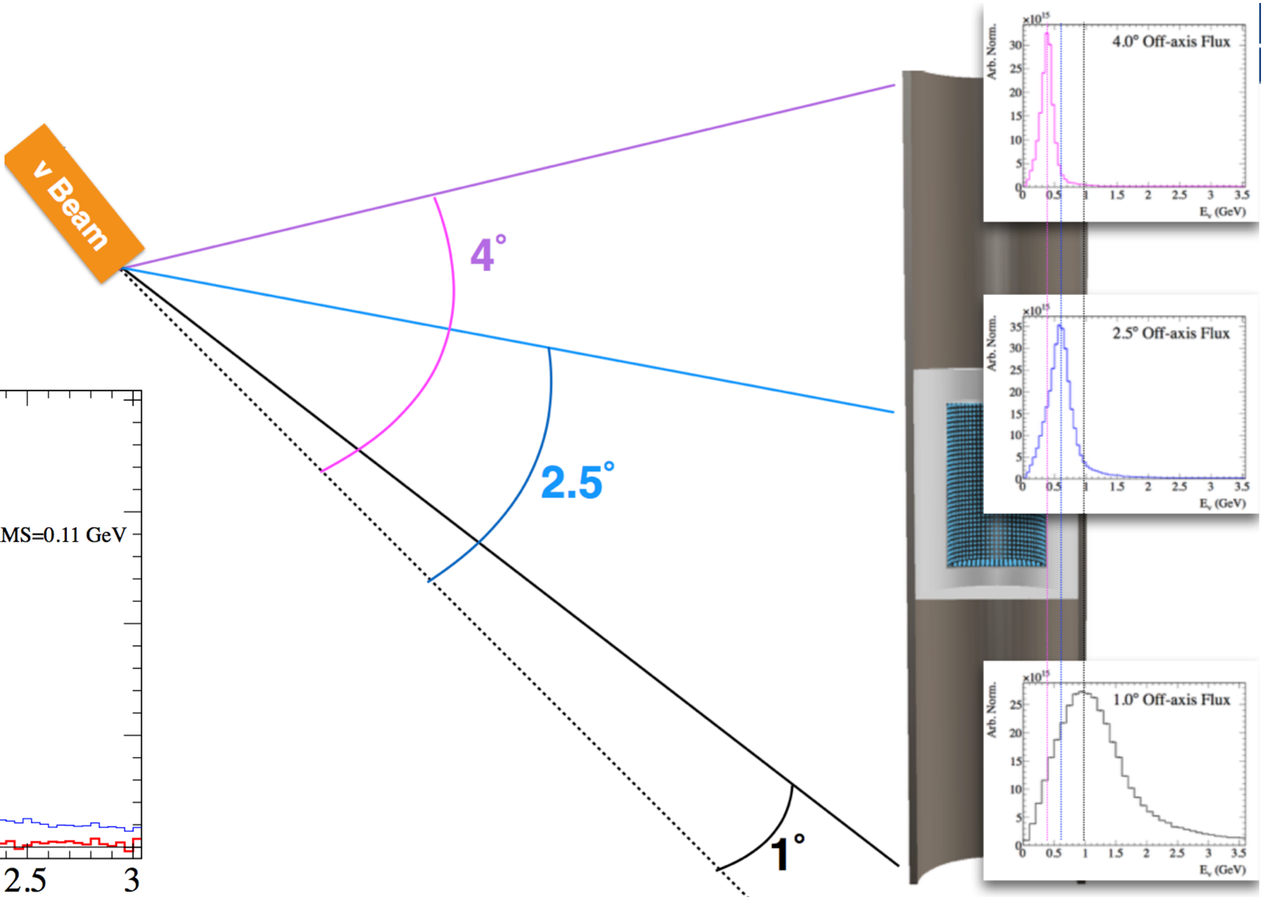


NUPRISM linear combination

Linear combination of events at different off-axis position:

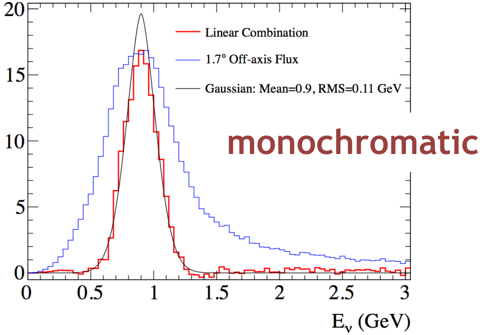
➜ Monochromatic ν beam response

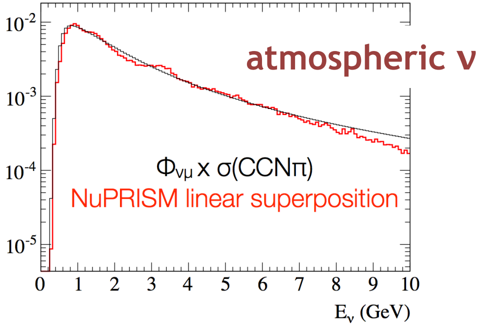


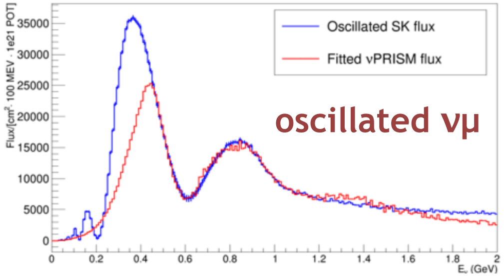


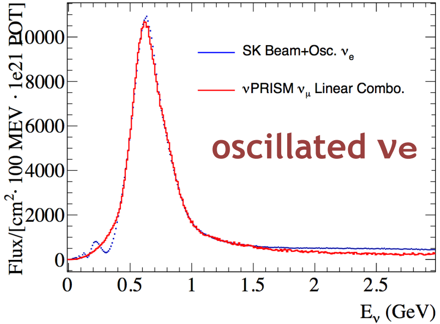
Creating the same shape as far detector

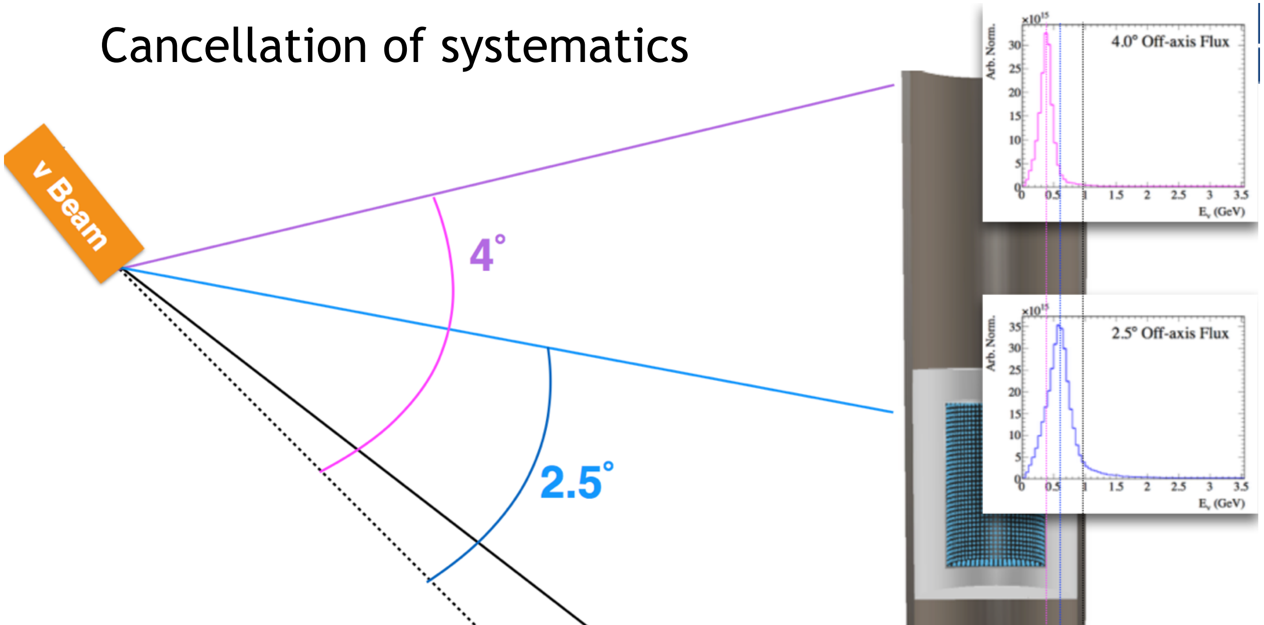
Cancellation of systematics

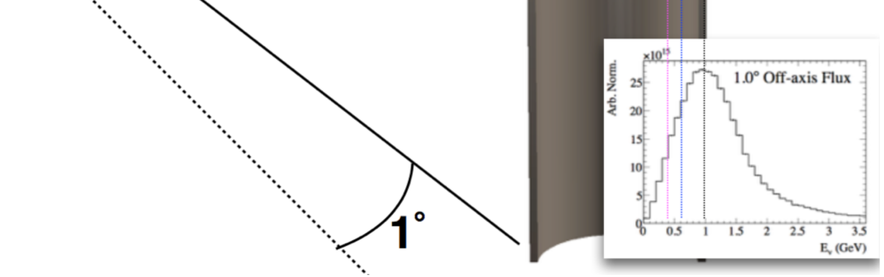






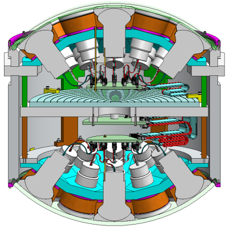


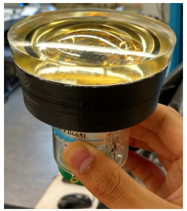


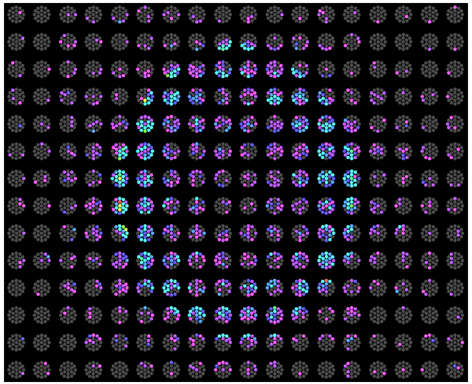


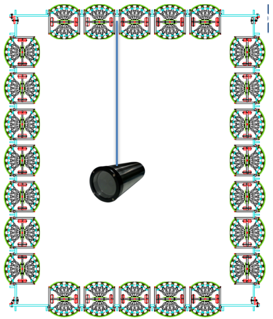
Challenge of E61(NuPRISM) water Cherenkov

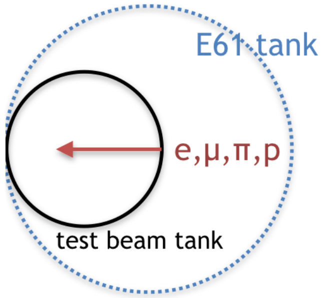
- Precise vertex reconstruction required
  - fiducial error ~1% → 1-2cm in vertex error
    - buoyancy and distortion of the support in water
    - SNO, KamLand, JUNO: ~3cm in vertex error
- Fine granularity
  - multi-PMT with 3-inch PMT's
- Precise in-situ/ex-situ calibration
  - in-situ: photogrammetry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



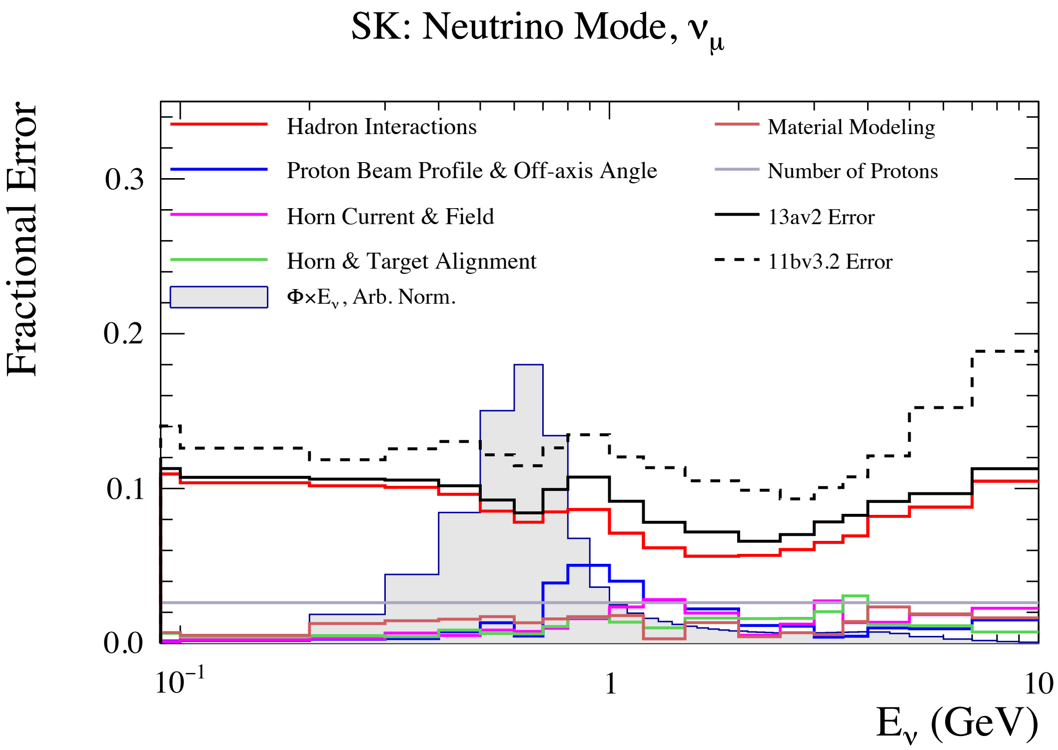






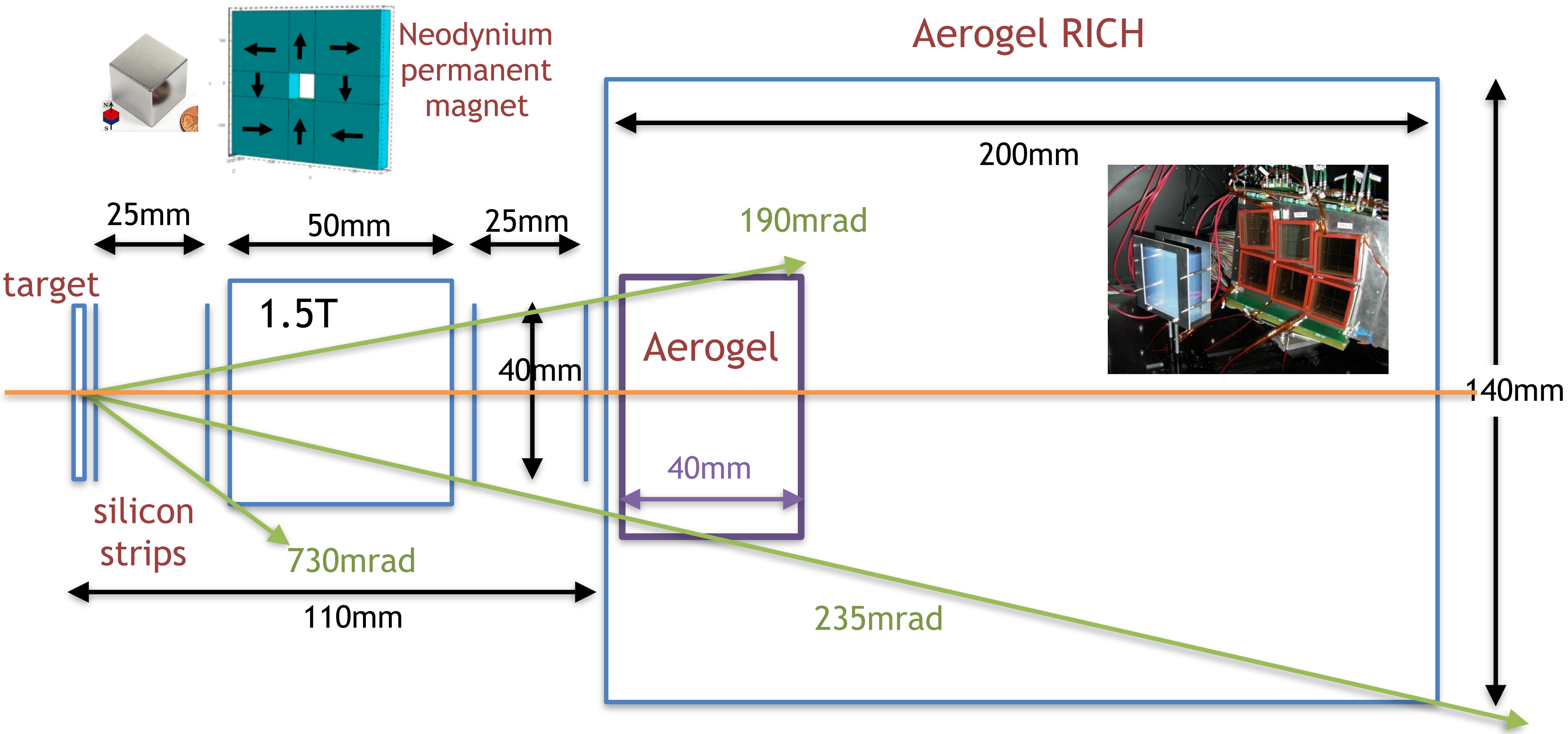


Flux systematics

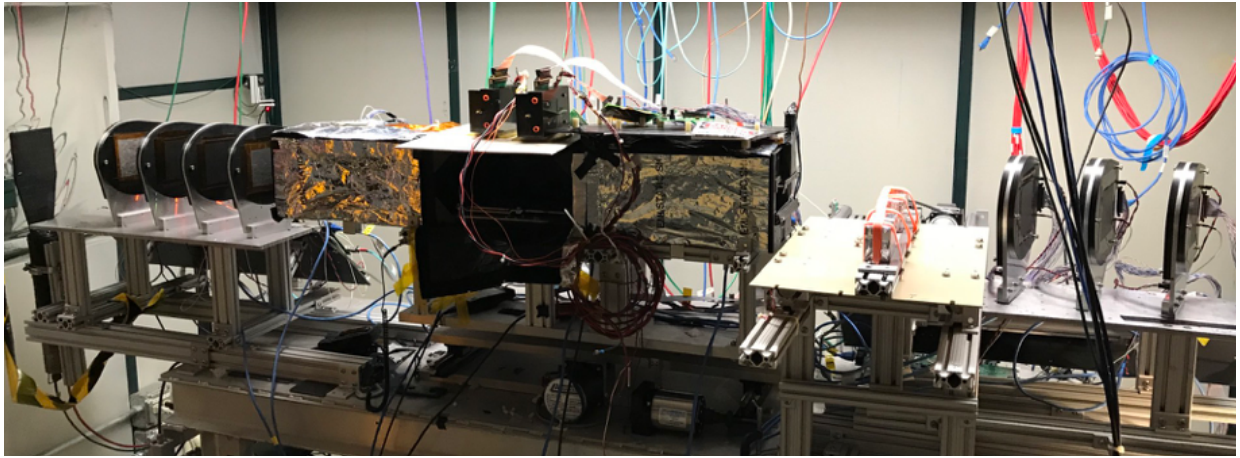


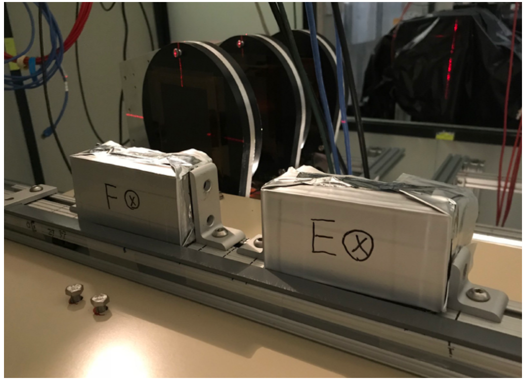
- Dominated by Hadron production error

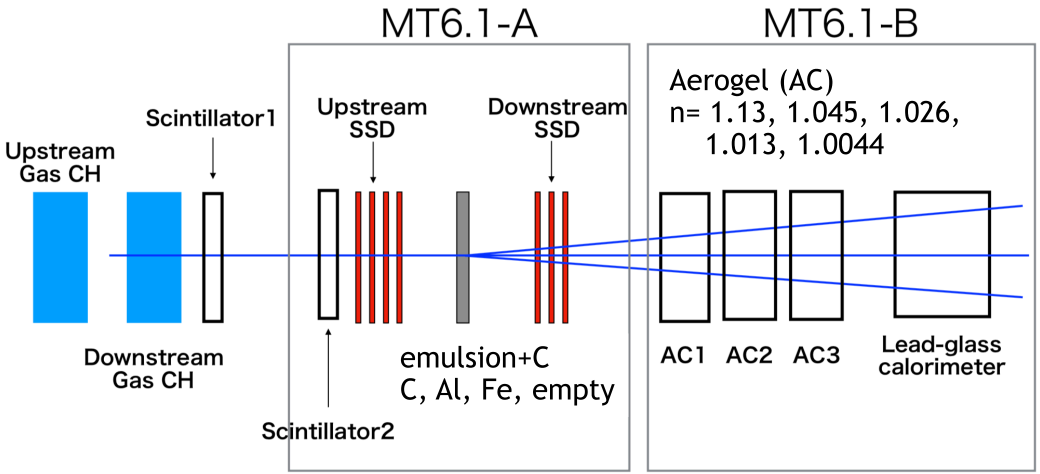
Compact spectrometer

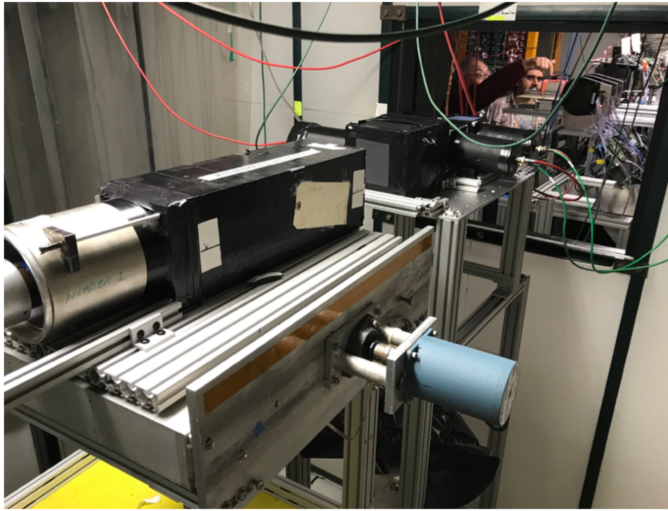


Hadron production experiment in Jan. 2018 @Fermilab

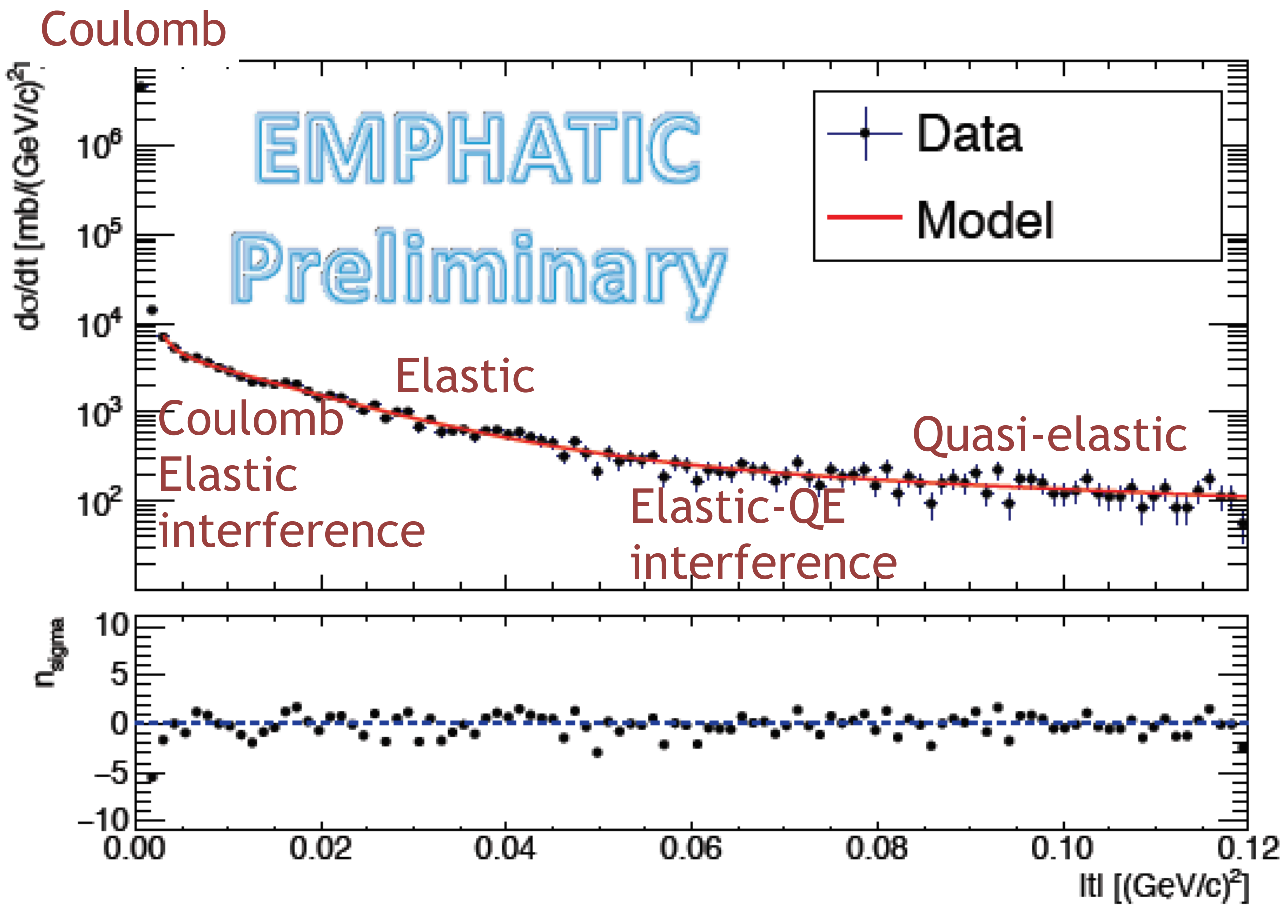






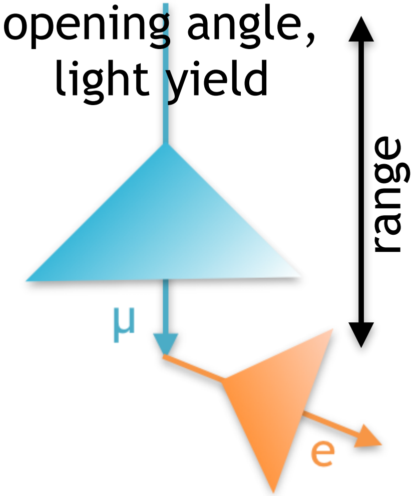


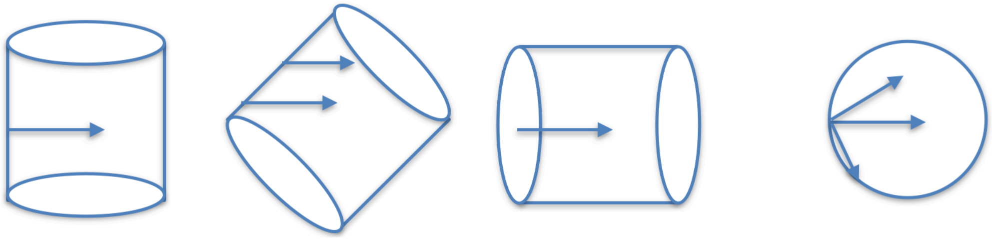
Preliminary result of EMPHATIC



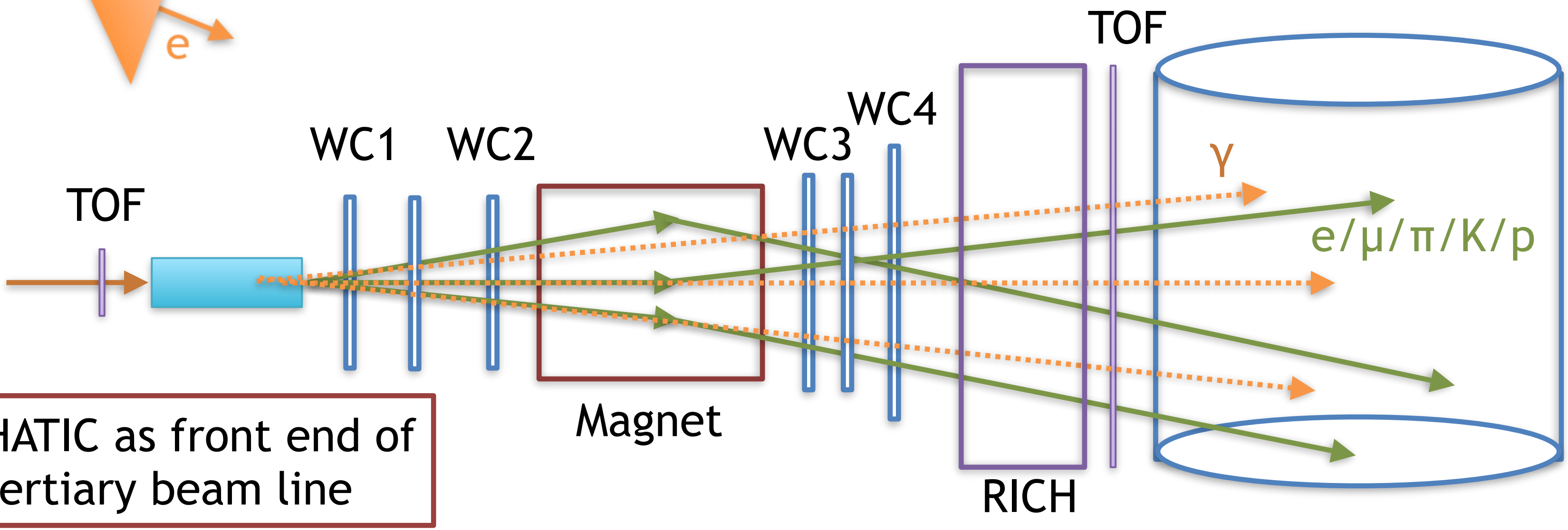
- Confusion in the definition of cross sections
  - e.g. interference terms
  - measure direct information of $t=-Q^2$ distribution for hadron production

EMPHATIC for the water Cherenkov beam test



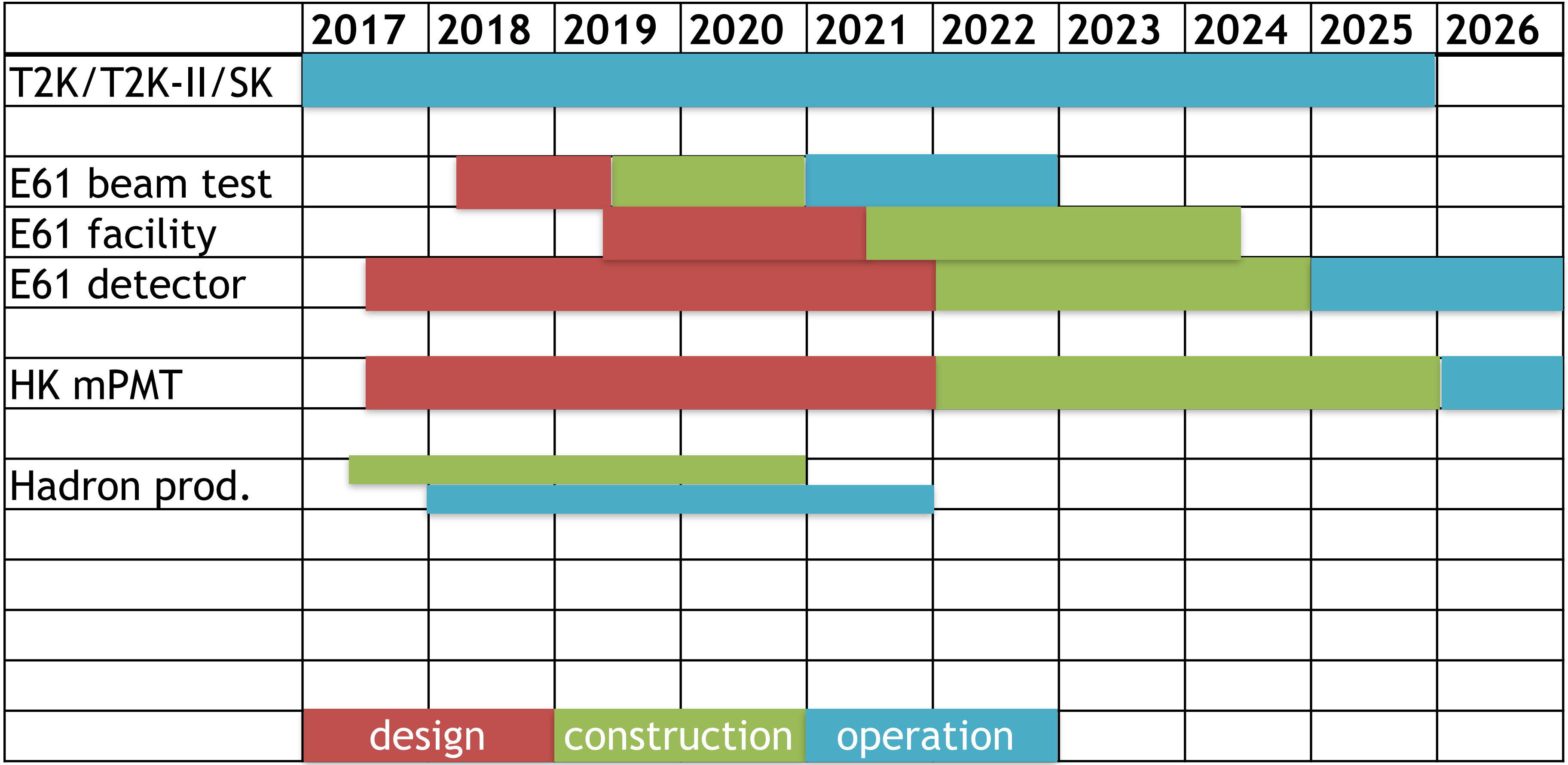


inject beam with various angles



EMPHATIC as front end of the tertiary beam line

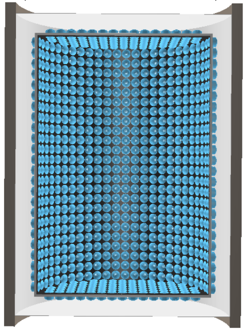
Timelines


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

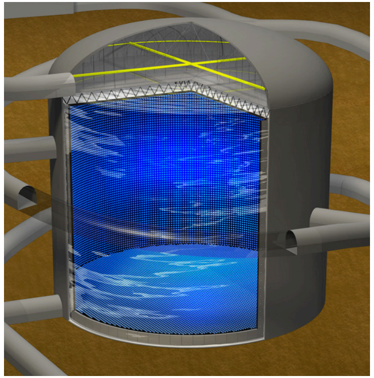
Summary and future vision

- Building up neutrino physics community similar to what was achieved in the quark sector (ε'/ε and B-factories)
  - Two leading projects: HyperK (Japan) and DUNE (US)
  - Study of systematic uncertainty is the main driver for success
- Nuclear/hadronic effects are the main systematics
  - NuPRISM (and DUNE-Prism) provides the solution
    - Serious challenges in achieving 1-2% level in detector systematics
      - Photogrammetry (3D reconstruction with digital camera) developed for SNO+
      - Precise calibration at the photosensor test facility (PTF) at TRIUMF
- Experimental programs to address the challenge of systematics
  - E61(NuPRISM) to cancel the cross section systematics
  - Flux (long baseline, atmospheric): EMPHATIC hadron production exp.
  - Detector: E61(NuPRISM) beam test, Photosensor Test Facility
- Exciting future is ahead in neutrino physics
  - Excellent prospect for HyperK funding in 2018

E61 (NuPRISM)



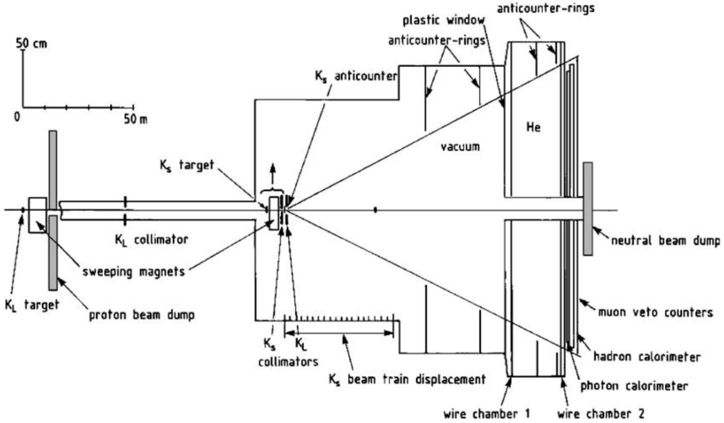
HyperK

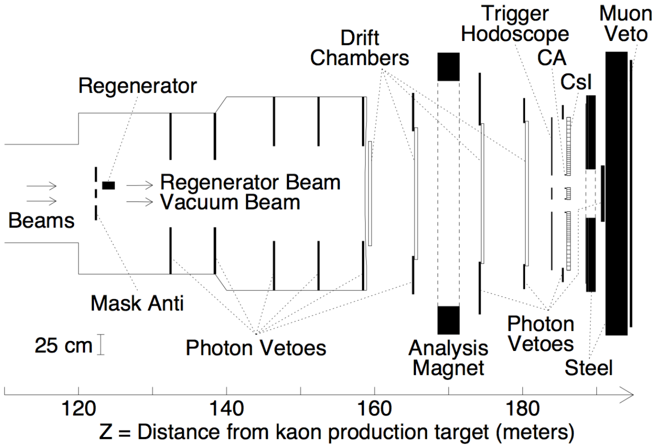


Backup slides

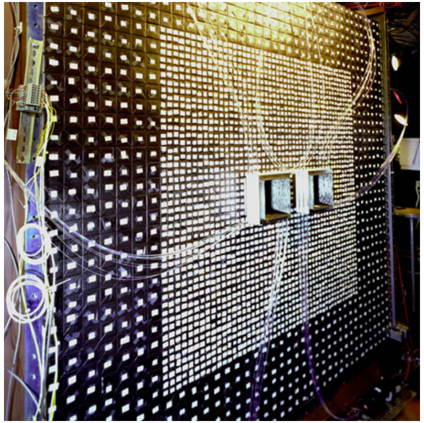
History of precision measurement: ε'/ε

- Dual beam



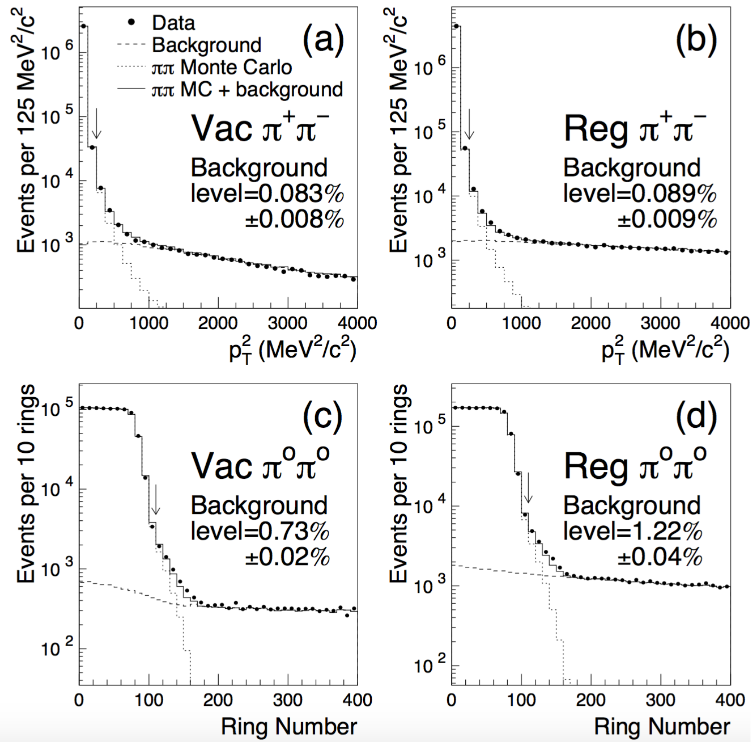


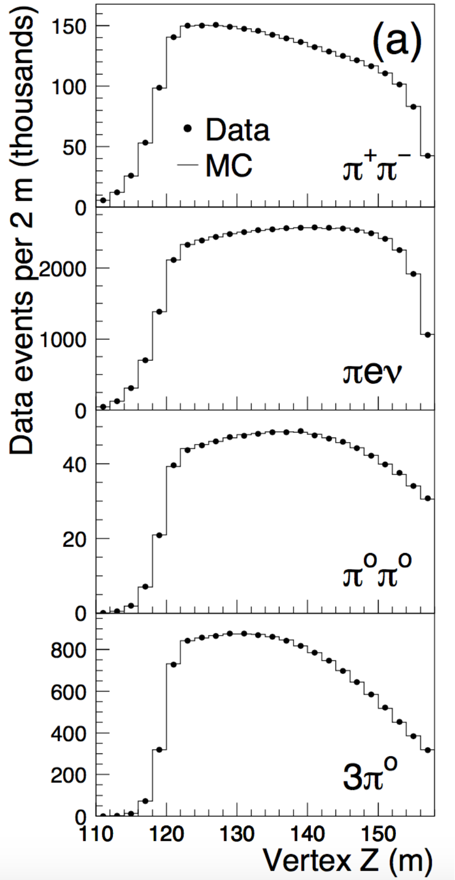
- precision calorimetry
  - fine grained with good resolution
    - Pure CsI (KTeV)
    - Liq. Kr (NA48)



Innovation in data analysis for ε'/ε

- High statistics data/MC comparison
  - High throughput data and Ntuple got available
    - bump up in test of systematics needed
    - 'Deep learning' would also demand innovation for its test
  - blind analysis also became important
- created a vibrant community
  - many excellent physicists from this





Double ratio to cancel systematic uncertainties

- Cancellation of systematic uncertainties

$$Re(\epsilon'/\epsilon) \sim \frac{1}{3} \times \frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-) - \Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-) + \Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}$$

  - Beam normalization: K_L or K_S
  - Decay modes: $\pi^+\pi^-$ or $\pi^0\pi^0$

- Double ratio in neutrino `CP` measurement

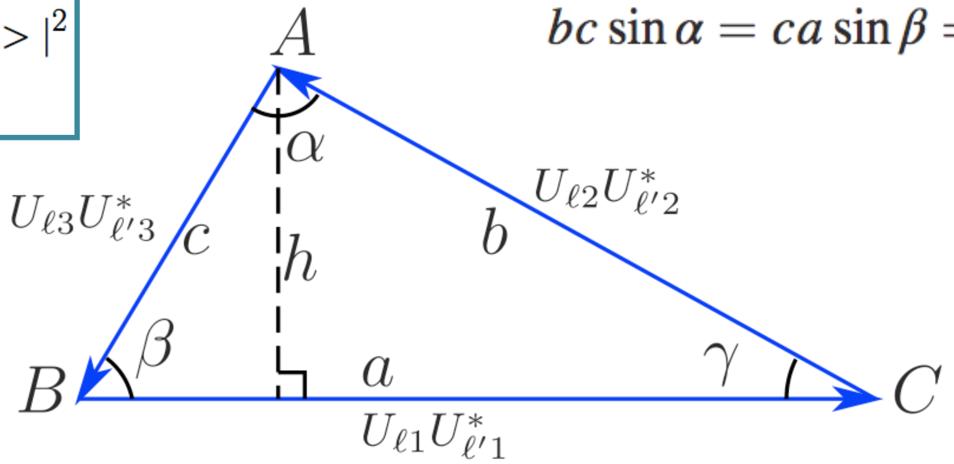
$$\frac{\Phi_{far}(\nu_e)/\Phi_{near}(\nu_\mu) - \Phi_{far}(\bar{\nu}_e)/\Phi_{near}(\bar{\nu}_\mu)}{\Phi_{far}(\nu_e)/\Phi_{near}(\nu_\mu) + \Phi_{far}(\bar{\nu}_e)/\Phi_{near}(\bar{\nu}_\mu)} \simeq \frac{-16 J_{CP} \sin\Delta_{21} + 16 c_{13}^2 s_{13}^2 s_{23}^2 a/\Delta m_{31}^2}{8 c_{13}^2 s_{13}^2 s_{23}^2}$$

$$\simeq -0.28 \sin\delta_{CP} + (0.07, 0.17, 0.3)\ [T2K, NO\nu A, DUNE]$$ at osc. max

  - Beam normalization: $\Phi_{far}\sigma_{far}/\Phi_{near}\sigma_{near}$
  - Particle types: `ν or ν-bar`

Leptonic Unitarity Triangle (PRD89(2014)073002)

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



$$bc\sin\alpha = ca\sin\beta = ab\sin\gamma = J.$$

$a=|U_{\ell 1}|\ |U_{\ell' 1}|$
$b=|U_{\ell 2}|\ |U_{\ell' 2}|$
$c=|U_{\ell 3}|\ |U_{\ell' 3}|$

Appearance

$$P_{\ell\to\ell'} = 4ab\sin(\Delta_{12}\pm\gamma)\sin\Delta_{12} + 4bc\sin(\Delta_{23}\pm\alpha)\sin\Delta_{23} + 4ac\sin(\Delta_{31}\pm\beta)\sin\Delta_{31}$$

α, β, γ measurement

$\Delta_{12}=\Delta m^2_{12}L/4E$
$\Delta_{23}=\Delta m^2_{23}L/4E$
$\Delta_{31}=\Delta m^2_{31}L/4E$

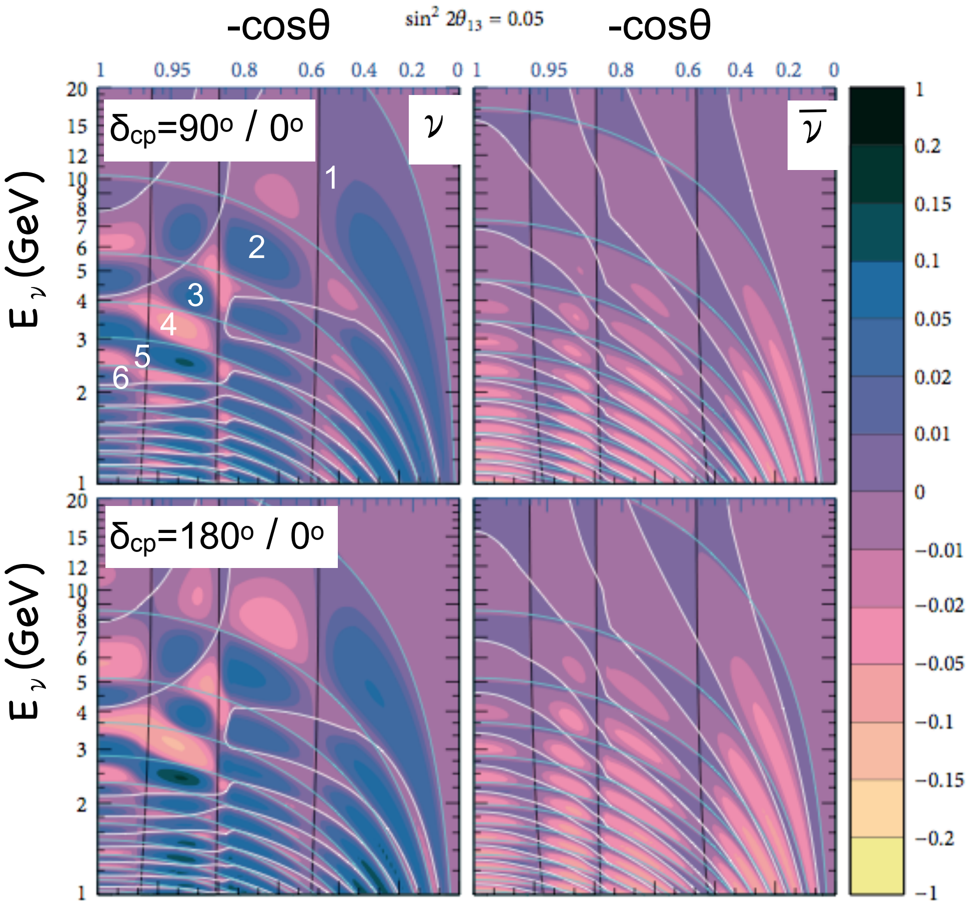
Disappearance

$$P_{disapp} = 1-P_{\ell\to\ell} = 4|U_{\ell 1}|^2\,|U_{\ell 2}|^2\sin^2\Delta_{12} + 4|U_{\ell 2}|^2\,|U_{\ell 3}|^2\sin^2\Delta_{23} + 4|U_{\ell 3}|^2\,|U_{\ell 1}|^2\sin^2\Delta_{31}$$

$|U_{\ell 1}|$, $|U_{\ell 2}|$, $|U_{\ell 3}|$ (a,b,c) measurement

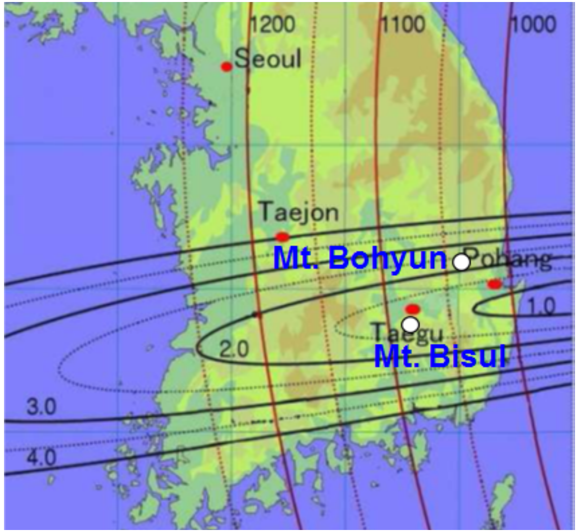
ΔP_{CP} oscillogram of atmospheric neutrinos

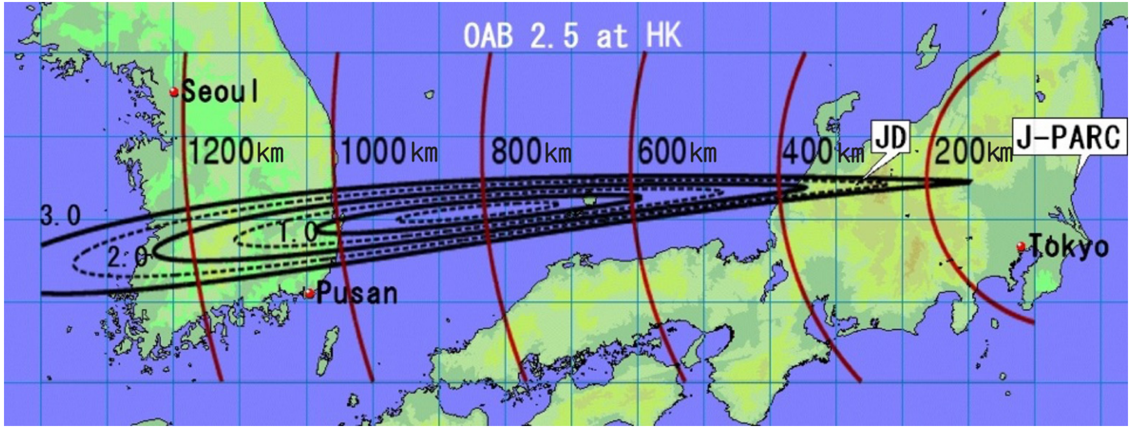
CP effect:
E~1-4GeV
cosθ~0.9
(4-15th
Δ_{32} max)



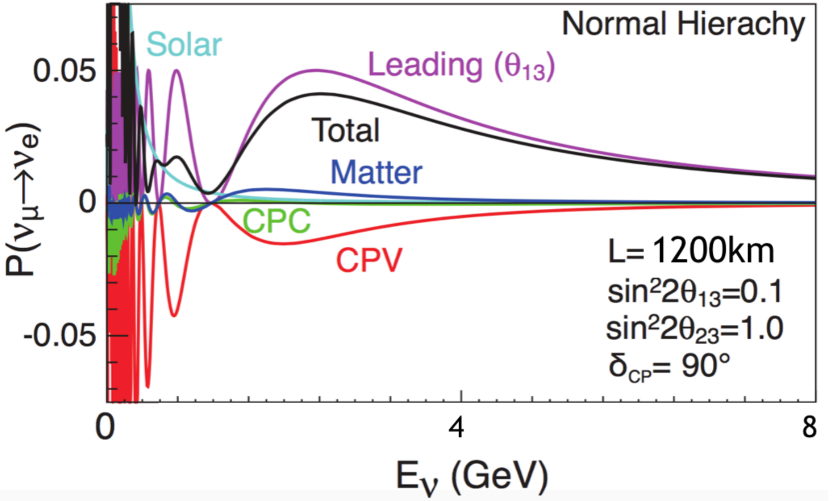
Neutrino/anti-neutrino flux to be understood:
pi+/pi- production ratio

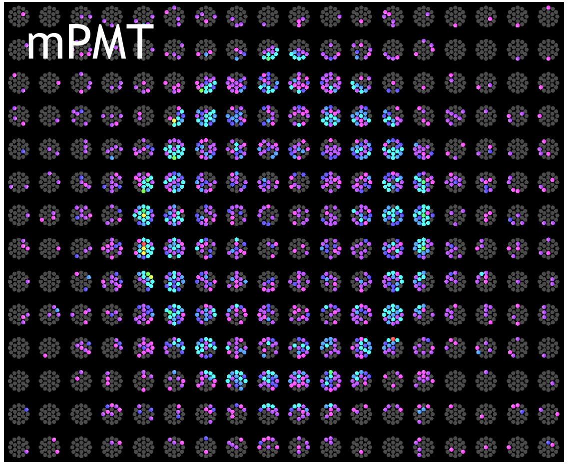
2nd oscillation maximum experiment: T2HKK

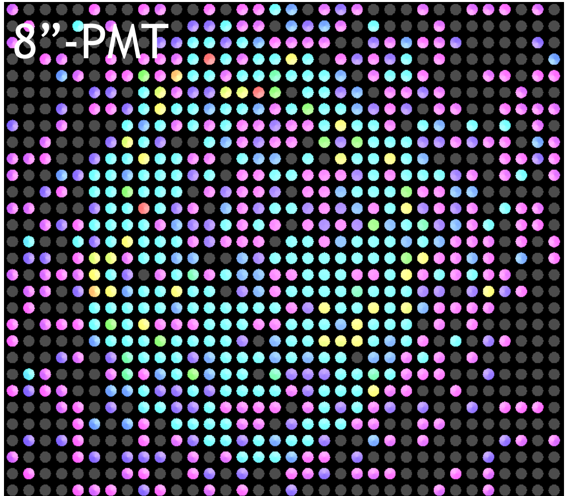




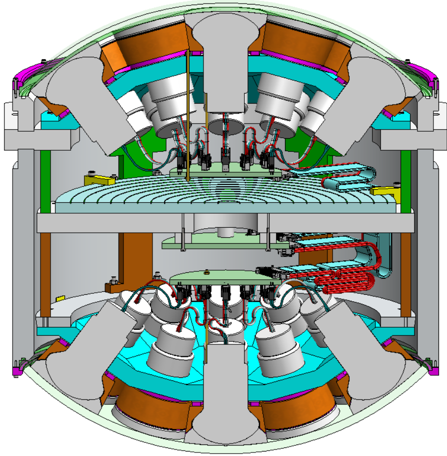
- CP violation is enhanced by x3 at the 2nd oscillation max
  - similar sensitivity for a same detector
  - **impact of systematics is smaller**
- Site study (Mt.Bohyun and Mt.Bisul) on going
  - strong support from the Korean science community

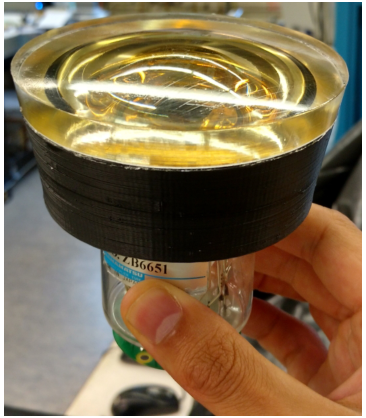






- multi-PMT (mPMT)
  - 19 of 3" PMT's in a vessel
    - economical 3" PMT's
- mPMT for E61(NuPRISM)
  - finer granularity for small WC
    - better than 8"
- mPMT for HyperK
  - multi-ring reconstruction
    - CC1π, mass hierarchy
  - angular sensitivity
    - accidental reduction for low E
  - provide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

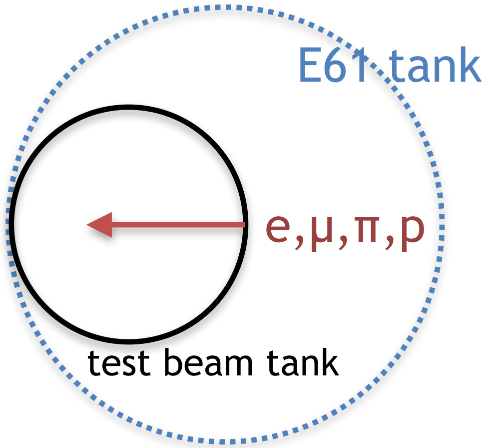


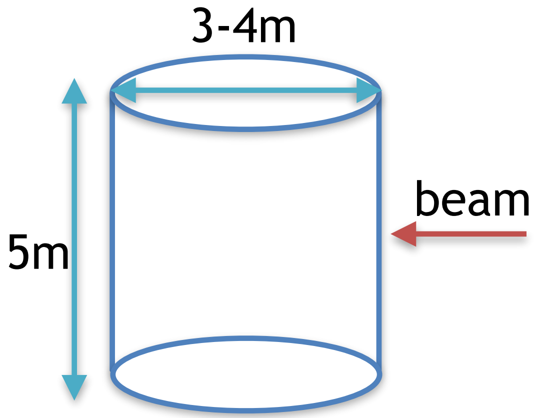


- Fiducial calibration limited by the position calibration of PMT's
  - buoyancy on PMT's
  - distortion of the structure
- SNO+ uses six camera's on the wall
  - 1 cm accuracy in a swimming pool
  - Nicon D5000 (12M pixel)
    - much better resolution possible now
    - water resistant camera available
      - 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

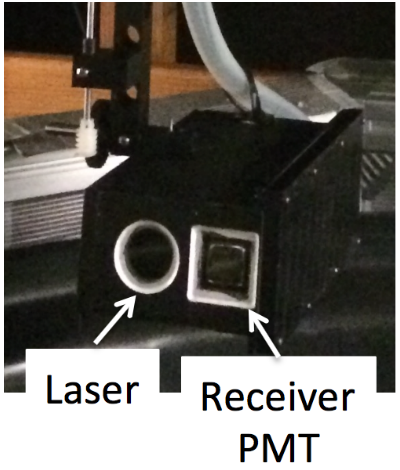


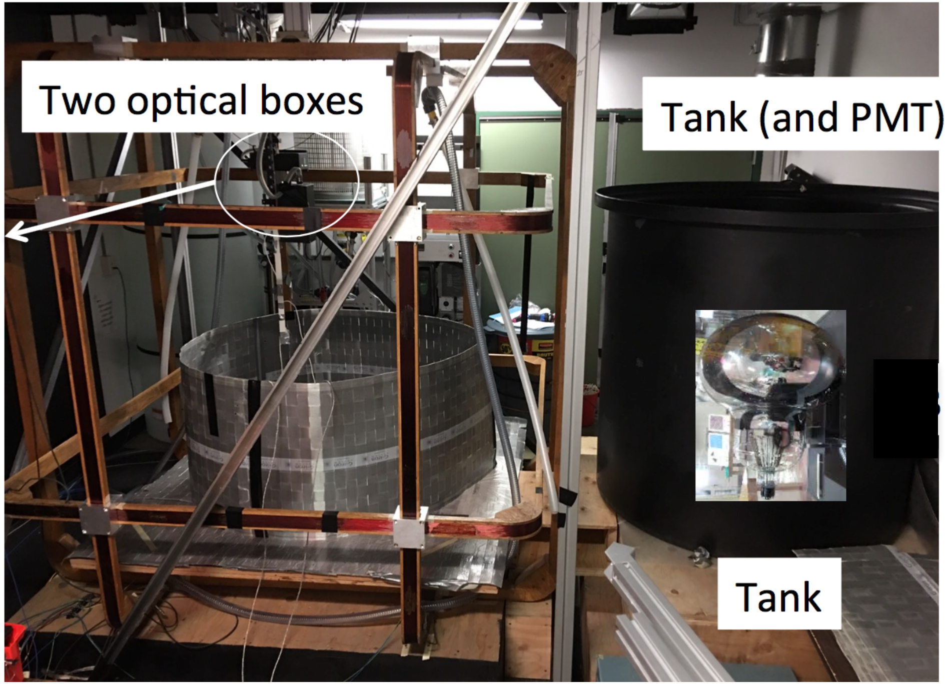


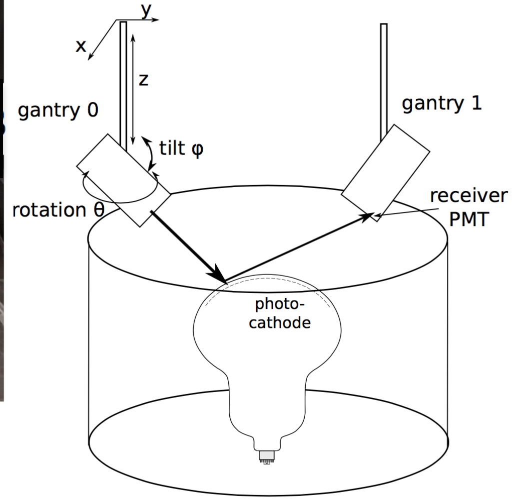
PTF setup

- Robotic arms with laser and PMT
  - laser light with polarization
  - monitor PMT
  - magnetometer

- Magnetic shielding
  - compensation coil, Giron shield

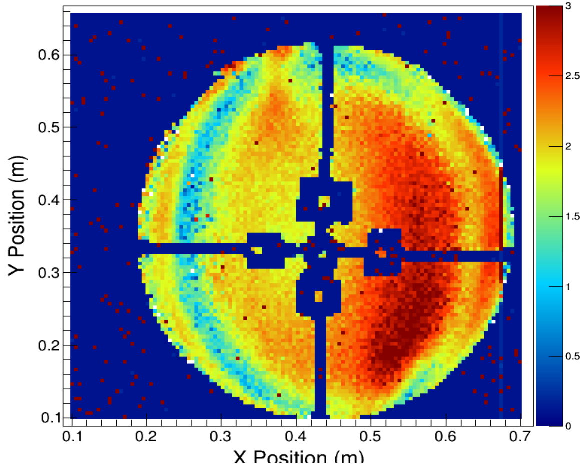




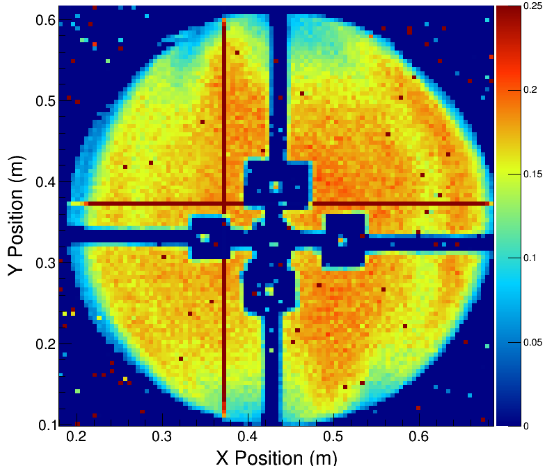


Position dependence (vertical scan)

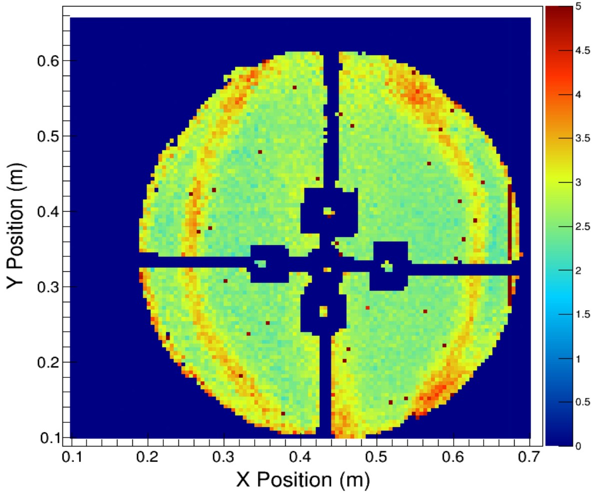
Single PE Gain



Relative Efficiency



Transit time spread (TTS)



Transit time (relative)