# T2K, HYPER-K AND NUPRISM: LONG BASELINE NEUTRINOS IN JAPAN

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*Kavli IPMU, the University of Tokyo & TRIUMF*

*TRIUMF Science Week: Particle Physics, Nuclear Physics and Beyond*
*July 13, 2017*

T2K Hyper-Kamiokande νPRISM

# NEUTRINO MIXING & OSCILLATIONS

*Neutrino mass and flavor states mix according to unitary matrix:*

$$U=\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s^{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

*Accessible through neutrino oscillations ($s_{12} = \sin\theta_{12}$, etc.)*

*Majorana phases if neutrinos are Majorana particles*

*$\delta$, $\alpha_{21}$ and $\alpha_{31}$ introduce new sources of CP violation*

*The flavor content of neutrino states oscillate as they traverse matter or vacuum:*

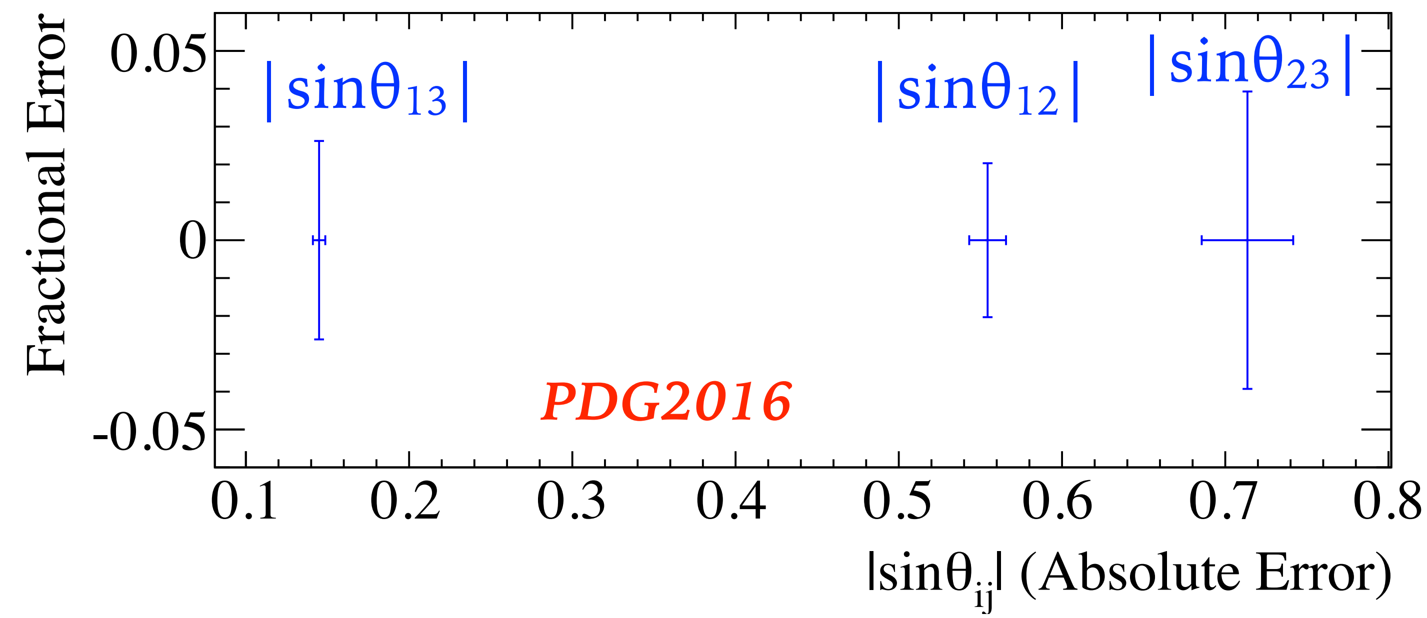
$$P_{\alpha\to\beta}=\delta_{\alpha\beta}-4\sum_{i>j}\mathrm{Re}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\left(\boxed{\frac{\Delta m^2_{ij}L}{4E}}\right)$$
$$+2\sum_{i>j}\mathrm{Im}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin\left(\boxed{\frac{\Delta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

*Dependence on mass squared differences of mass states, distance and energy*

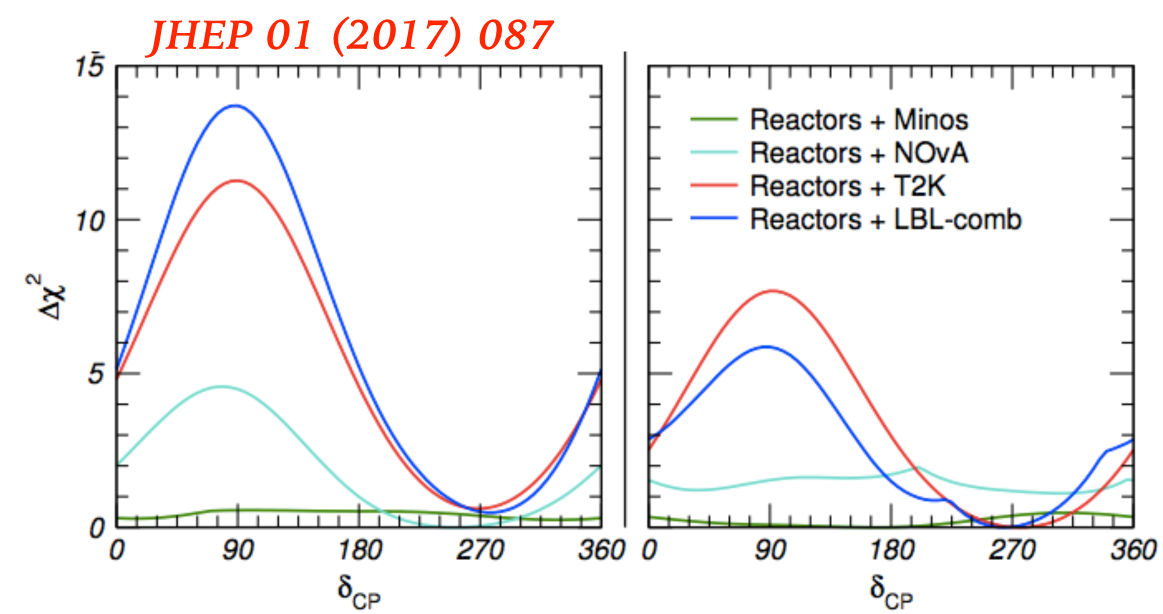
*Oscillations from flavor **α** to **β** in vacuum*

# STATE OF OSCILLATION PARAMETER MEASUREMENTS

- *Three mixing angles measured with <5% precision*




- *Weak global preference for $\delta_{cp}$ near 3π/2 (-π/2) driven by T2K +Reactors+NOvA*




- *Whether the **$m_3$** state is heaviest (normal ordering) or lightest (inverted ordering) is still undetermined*

$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\,\mathrm{eV}^2$$

$$\Delta m^2_{32} = (2.45 \pm 0.05) \times 10^{-3}\,\mathrm{eV}^2$$

or

$$\Delta m^2_{32} = (-2.52 \pm 0.05) \times 10^{-3}\,\mathrm{eV}^2$$

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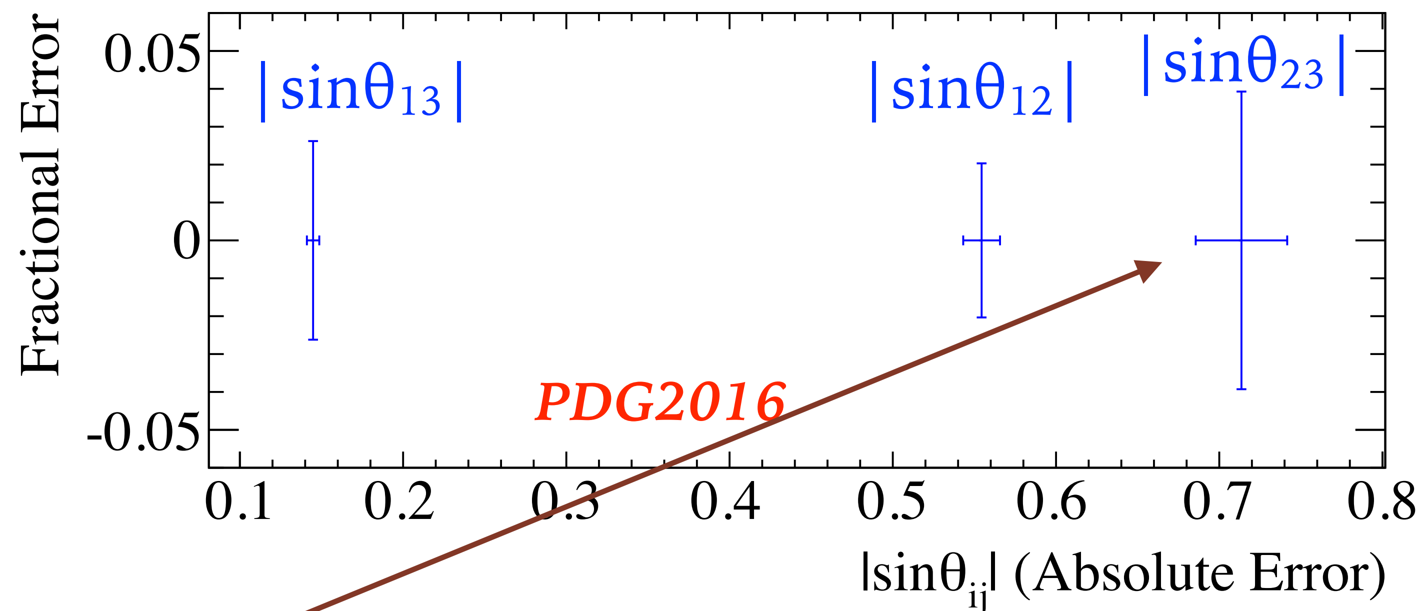
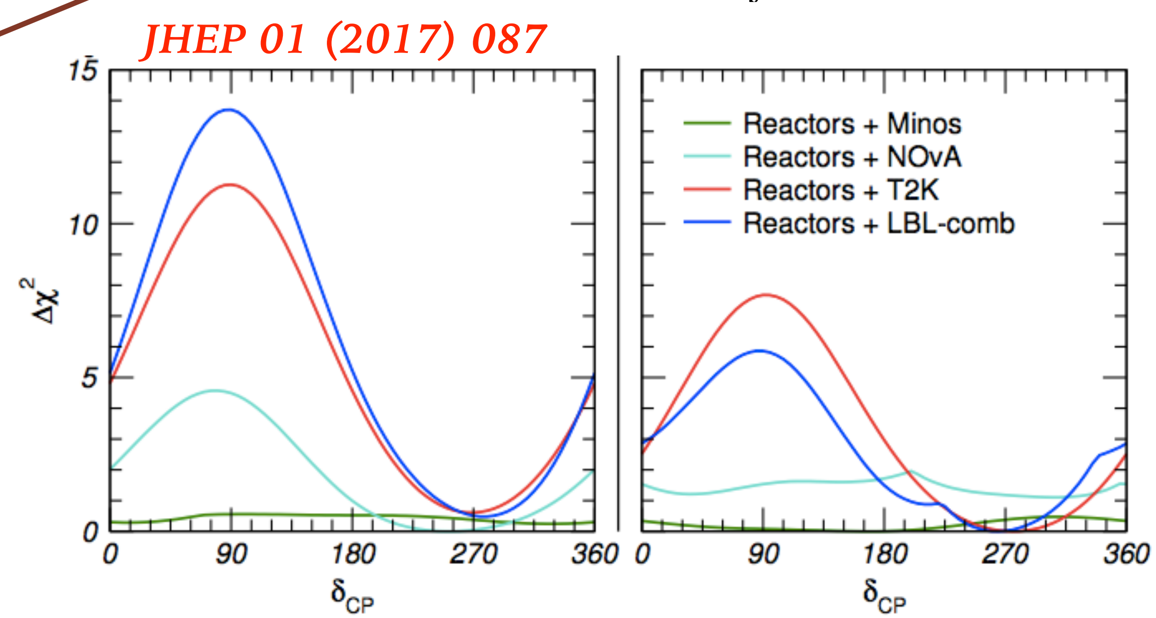



- *Weak g* … *$\delta_{cp}$ near 3π/2 (-* …
  *+React* …

T2K is leading the efforts to measure:
$\sin^2\theta_{23}$
$\delta_{cp}$
$\Delta m^2_{32}$

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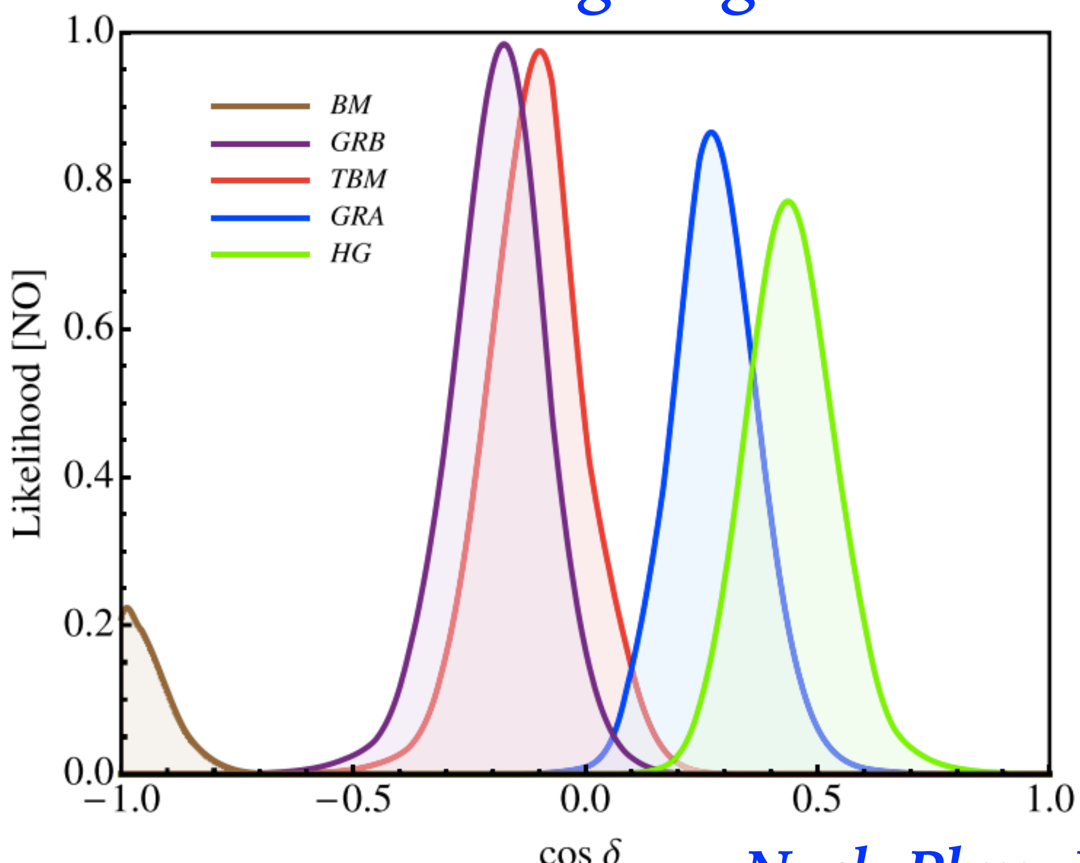
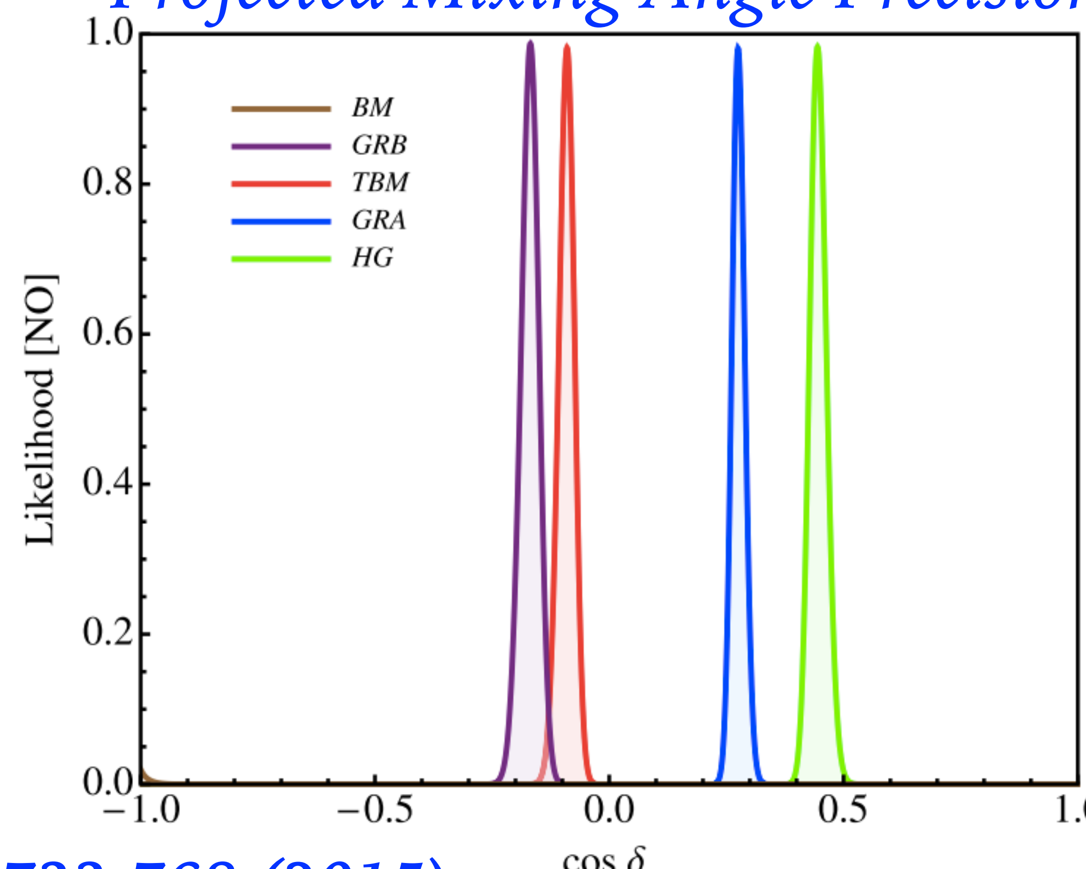
# WHY MEASURE THESE PARAMETERS?

- *Neutrino mixing allows for a* ***new source of CP violation***
  - *CP violation through the Dirac phase may be a sufficient source for* ***leptogenesis***
- *Small neutrino masses indicate new physics at a larger mass scale beyond the standard model*
  - ***Precise values*** *of the mixing parameters may indicate or disfavor models of* ***flavor symmetries***

*Current Mixing Angle Precision*




*Projected Mixing Angle Precision*




***Nucl. Phys. B, Vol. 894, 733-768 (2015)***

# STATUS OF T2K

# THE T2K EXPERIMENT

*ND280 Near Detector*


*Muon (anti)neutrino survival:*

$$P_{\mu\to\mu} = 1 - \left(\boxed{\sin^2 2\theta_{23}} - \sin^2\theta_{23}\cos 2\theta_{23}\sin^2 2\theta_{13}\right)\sin^2\left(\frac{\boxed{\Delta m^2_{32}}L}{4E_\nu}\right) + \ldots$$

*Generate beam of 99% muon (anti)neutrinos*

*Electron (anti)neutrino appearance:*

*Discovery of $\nu_e \to \nu_\mu$ transition*
*Phys.Rev.Lett. 112 (2014) 061802*

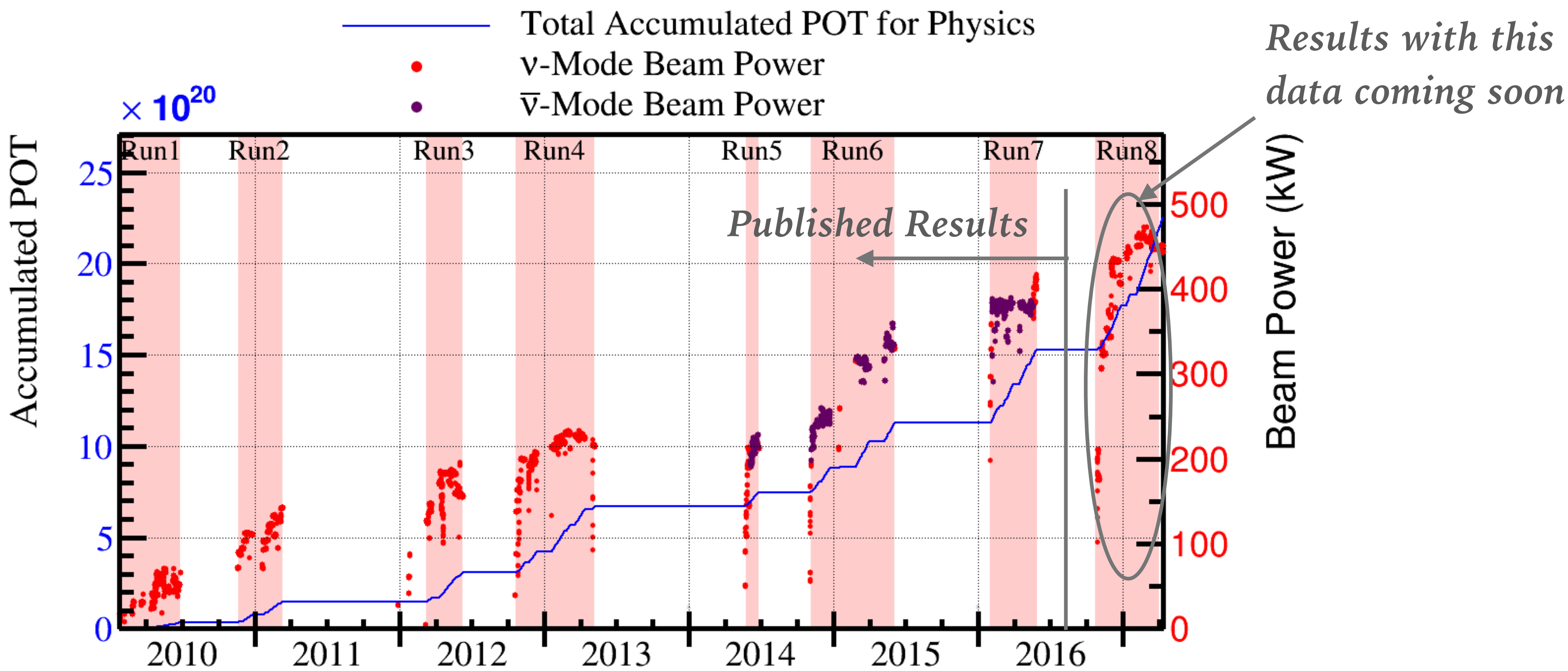
$$P_{\mu\to e} = \boxed{\sin^2\theta_{23}\sin^2 2\theta_{13}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right) \boxed{\mp} \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin^2 2\theta_{13}\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\boxed{\sin\delta_{CP}} + \ldots$$

sign flips for antineutrinos

# 2016 BREAKTHROUGH PRIZE

- *T2K shared the 2016 Breakthrough Prize in Fundamental Physics for the investigation of neutrino oscillations (discovery of electron neutrino appearance)*

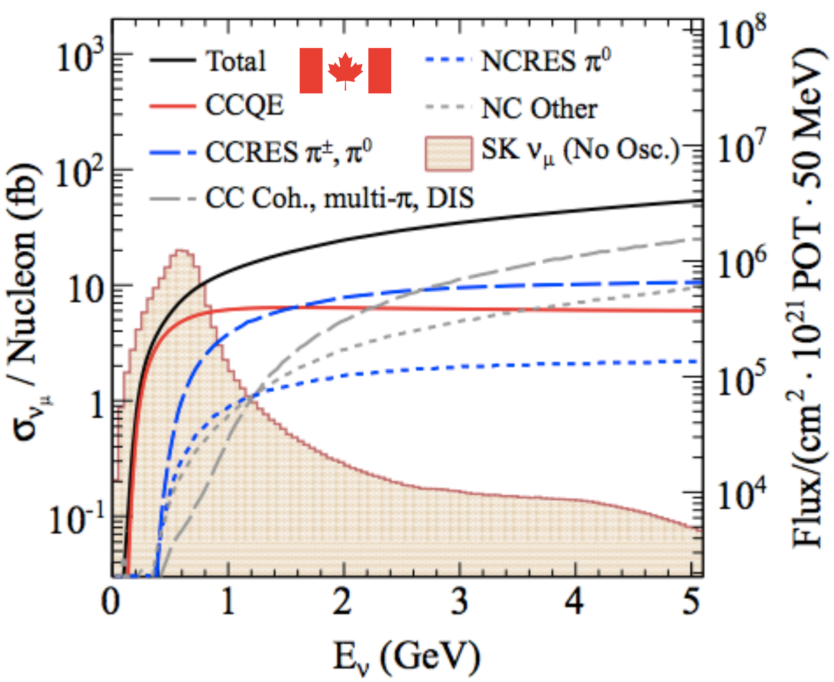
# T2K DATA COLLECTION HISTORY



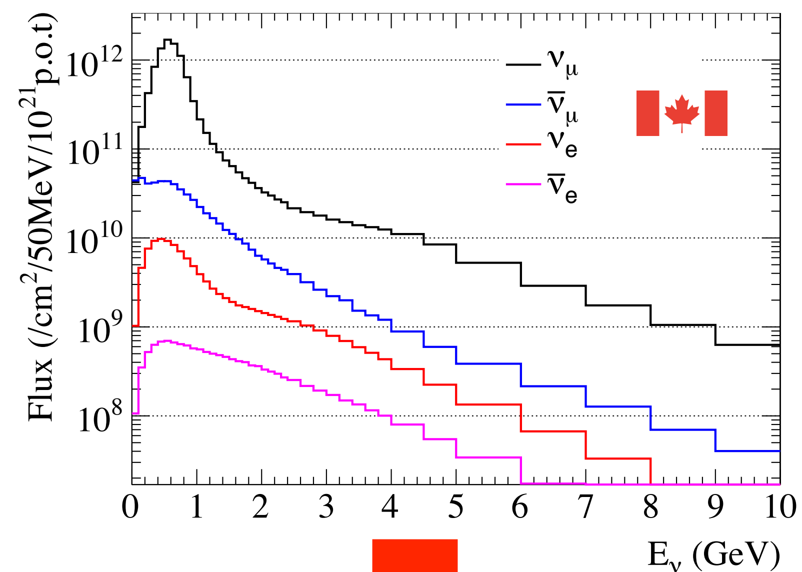

- *T2K has accumulated **14.7e20** protons-on-target (POT) in neutrino mode and **7.6e20** POT in antineutrino mode*
  - ***29% of the approved** T2K POT*
  - *7.5e20 neutrino mode, 7.5e20 antineutrino mode for public results*
  - ***Phys. Rev. Lett. 118 (2017) no.15, 151801 - PRL Editor's Suggestion***
- *Accelerator has achieved stable operation with **460 kW beam power***

# EXTRACTING OSCILLATION PARAMETERS, STEP 1

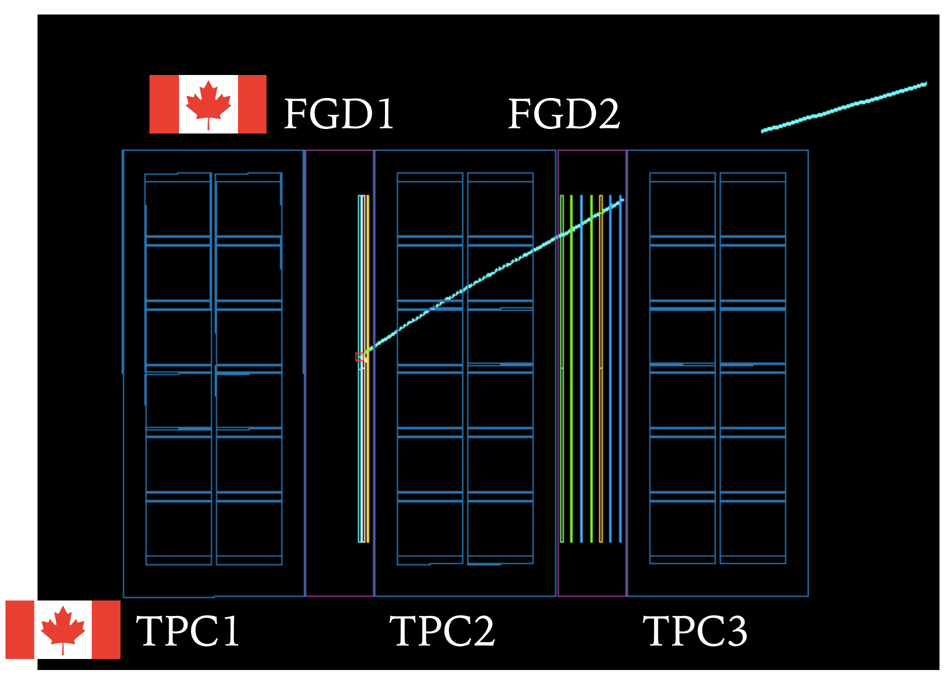
*Neutrino-nucleus Interaction Model*



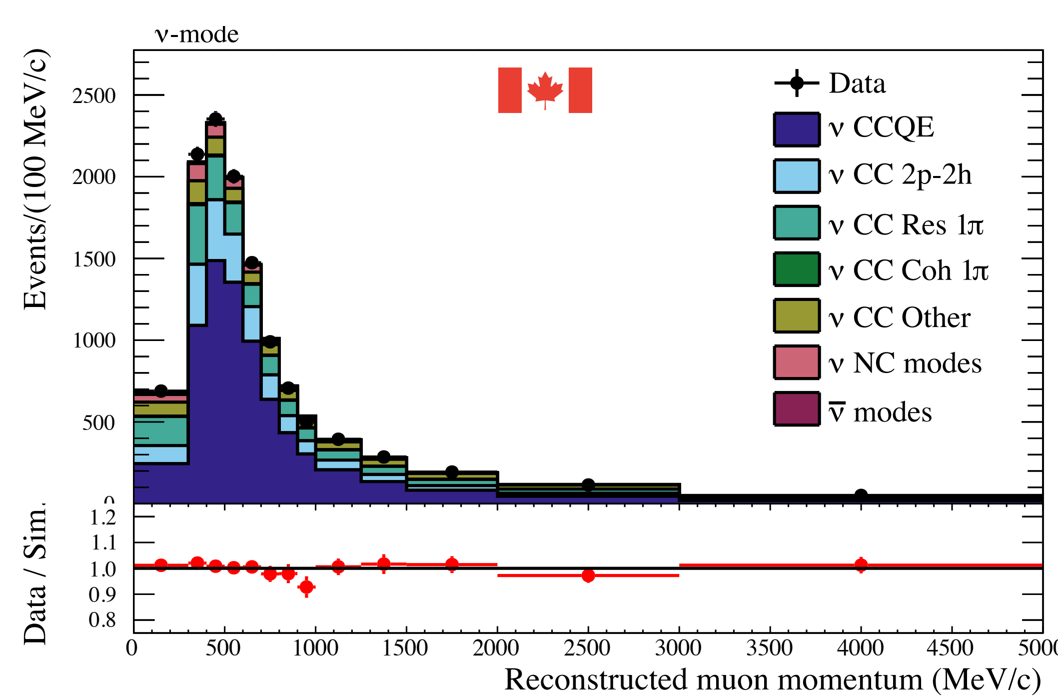

*Neutrino Flux Model*




*ND280 Data*




*Fit to ND280 data constrains neutrino flux and interaction model parameters*



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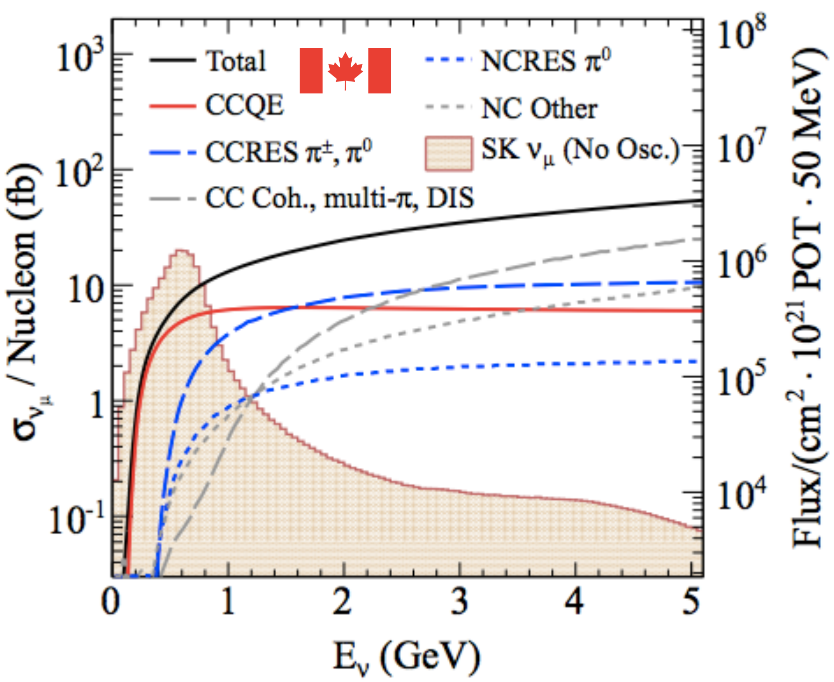


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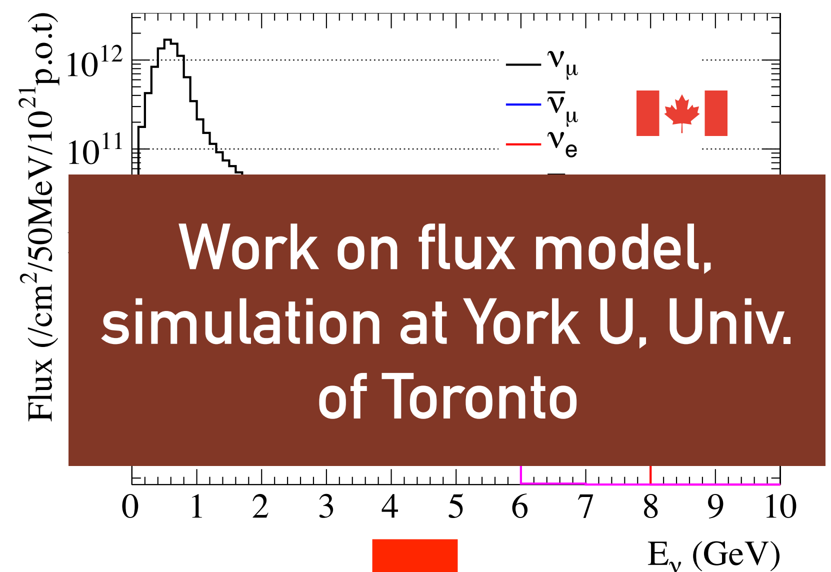


Work on flux model, simulation at York U, Univ. of Toronto

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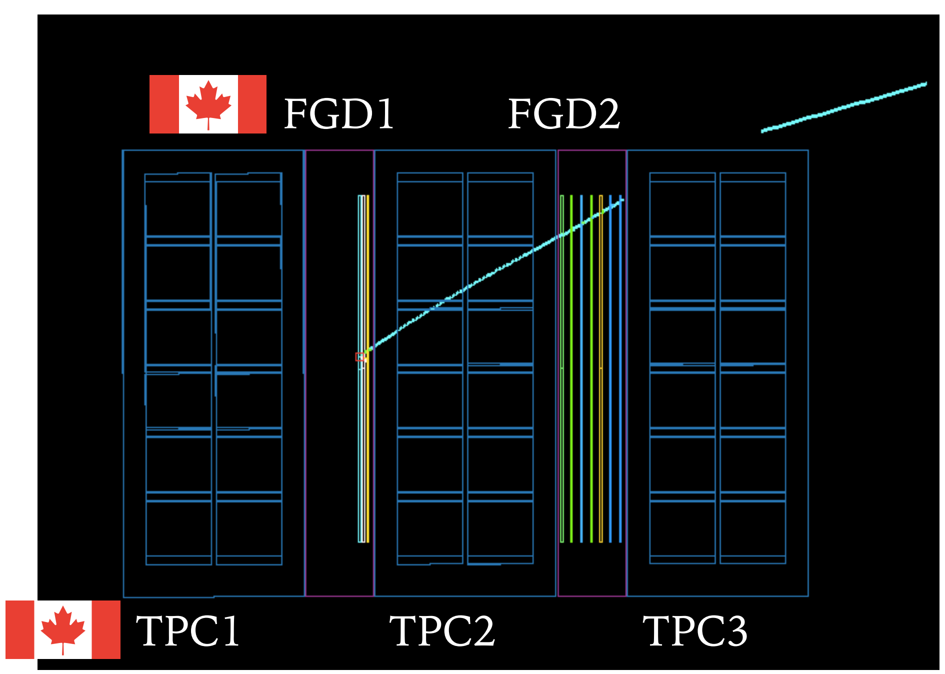


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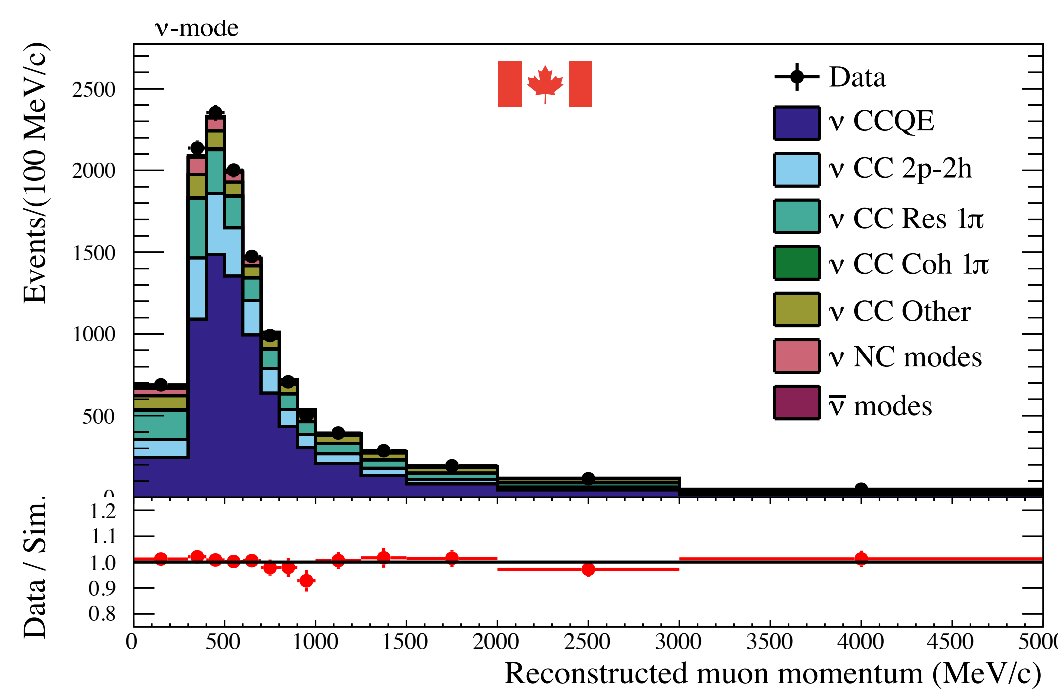

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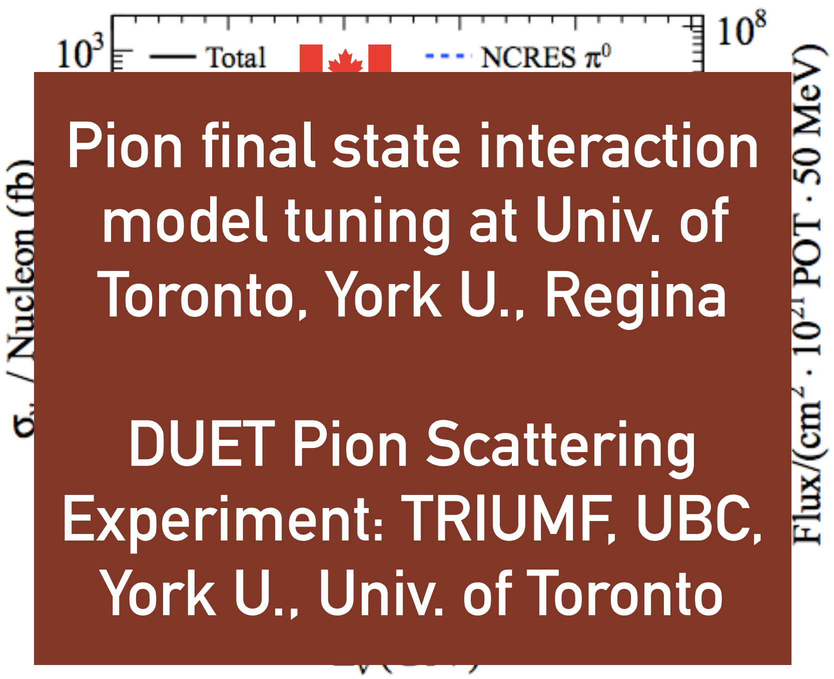


Pion final state interaction model tuning at Univ. of Toronto, York U., Regina

DUET Pion Scattering Experiment: TRIUMF, UBC, York U., Univ. of Toronto

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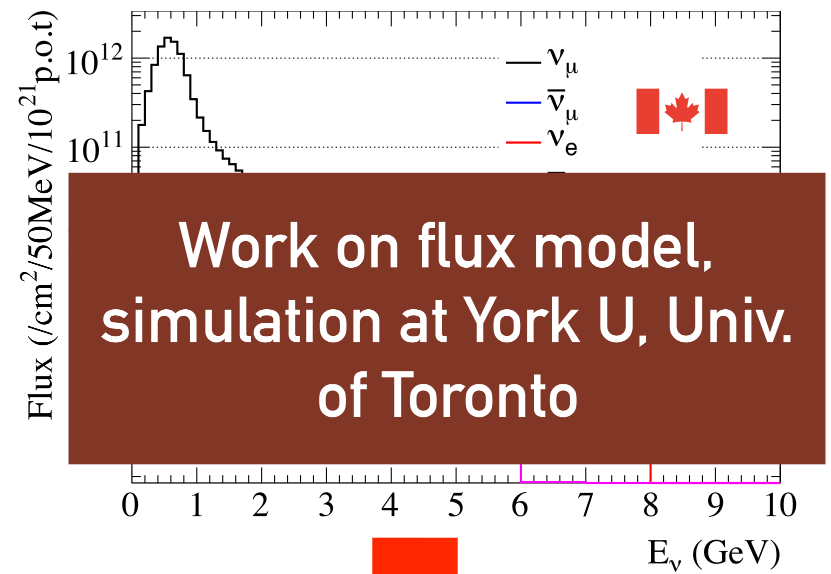


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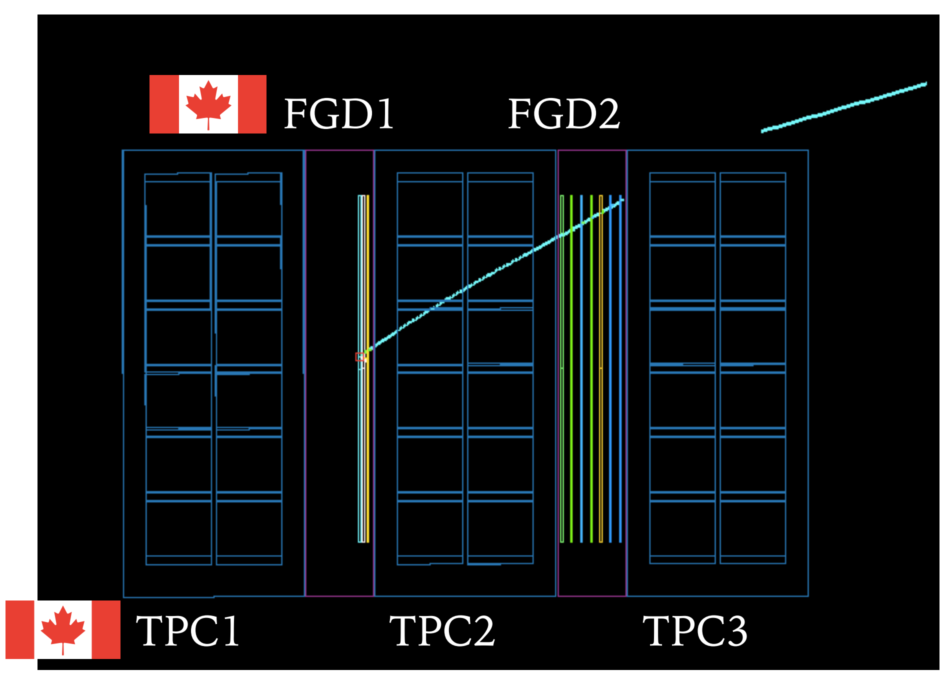


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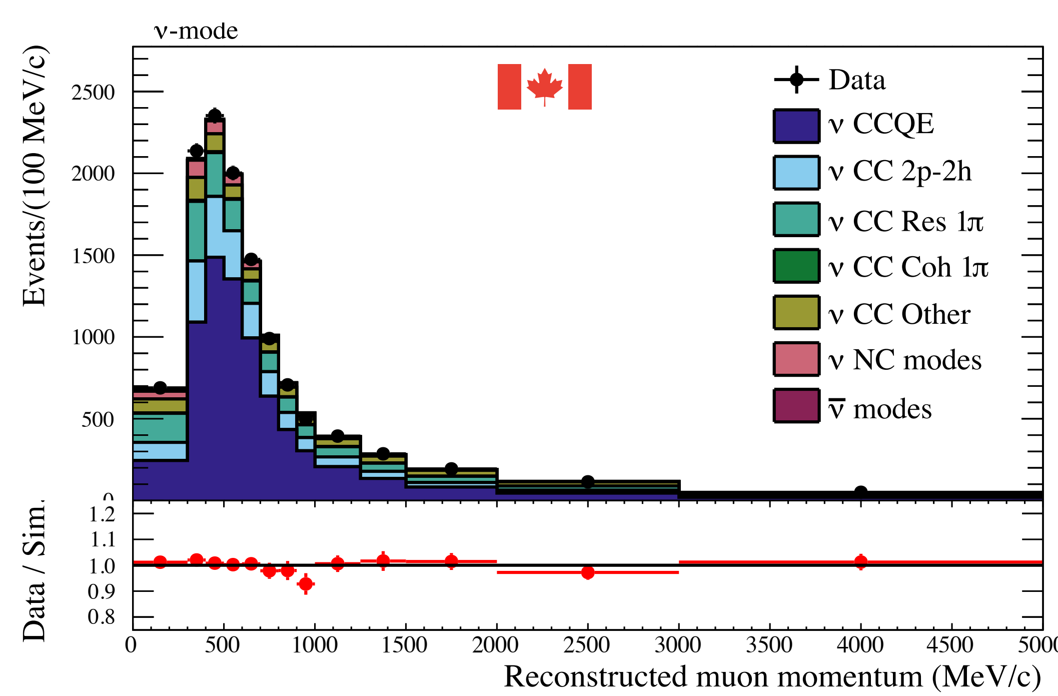

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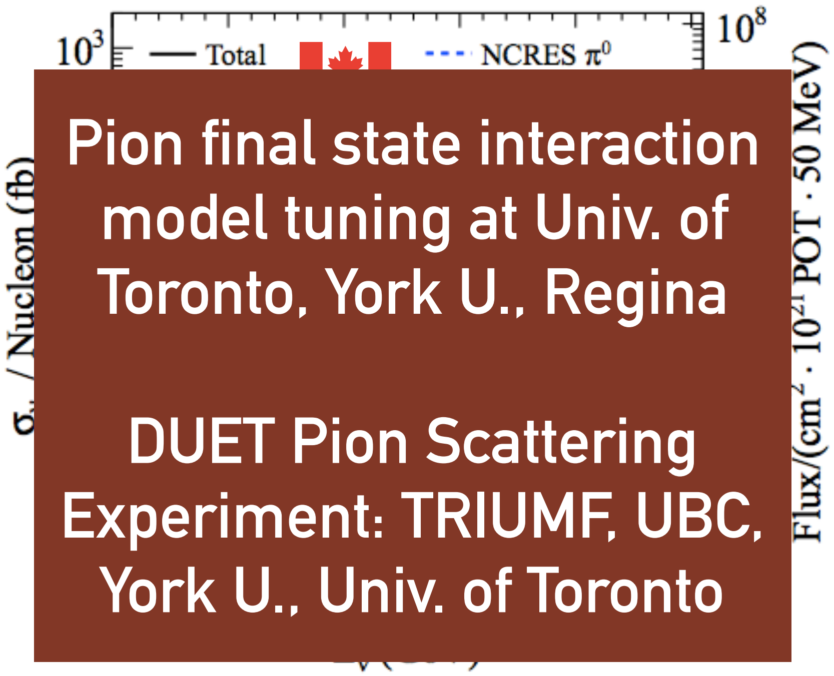


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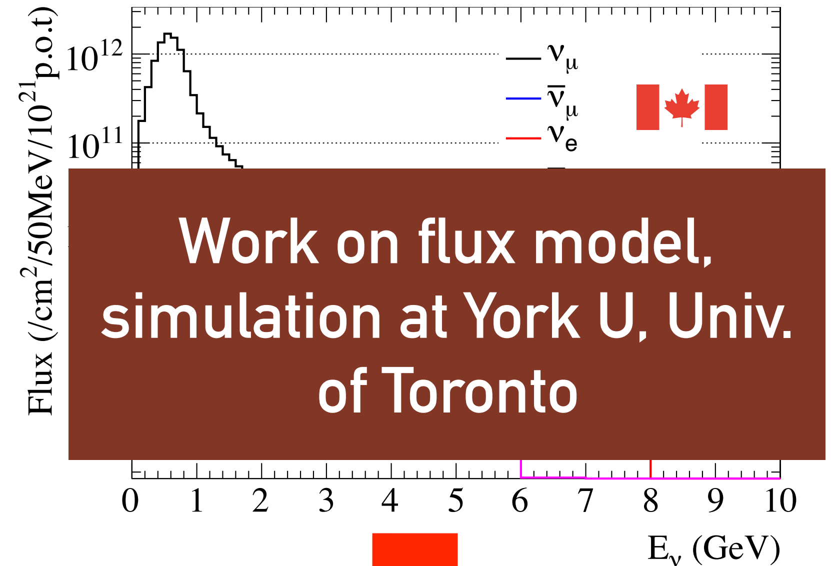


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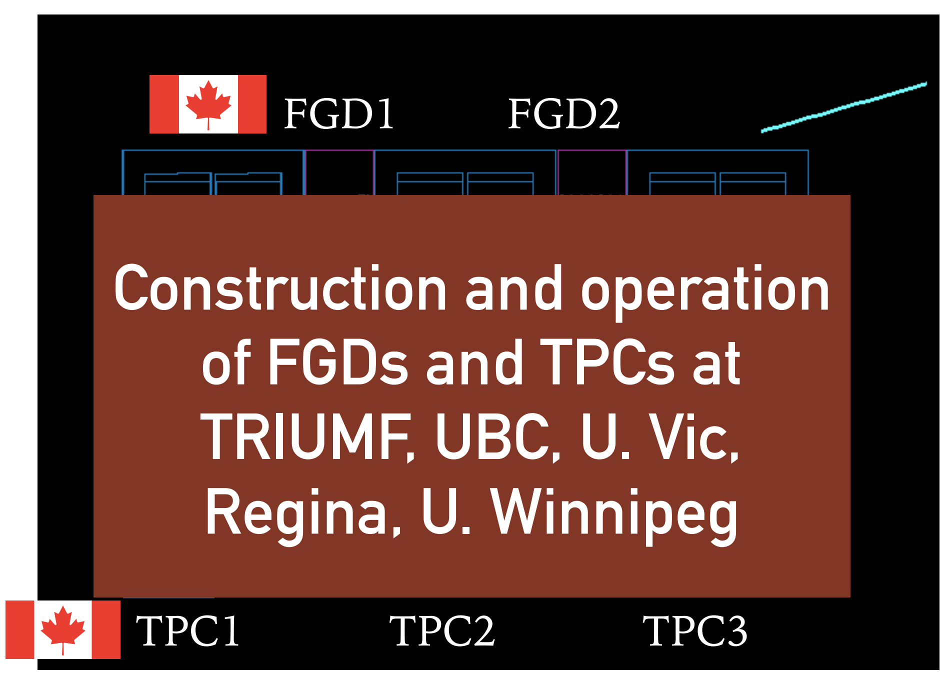


Construction and operation of FGDs and TPCs at TRIUMF, UBC, U. Vic, Regina, U. Winnipeg

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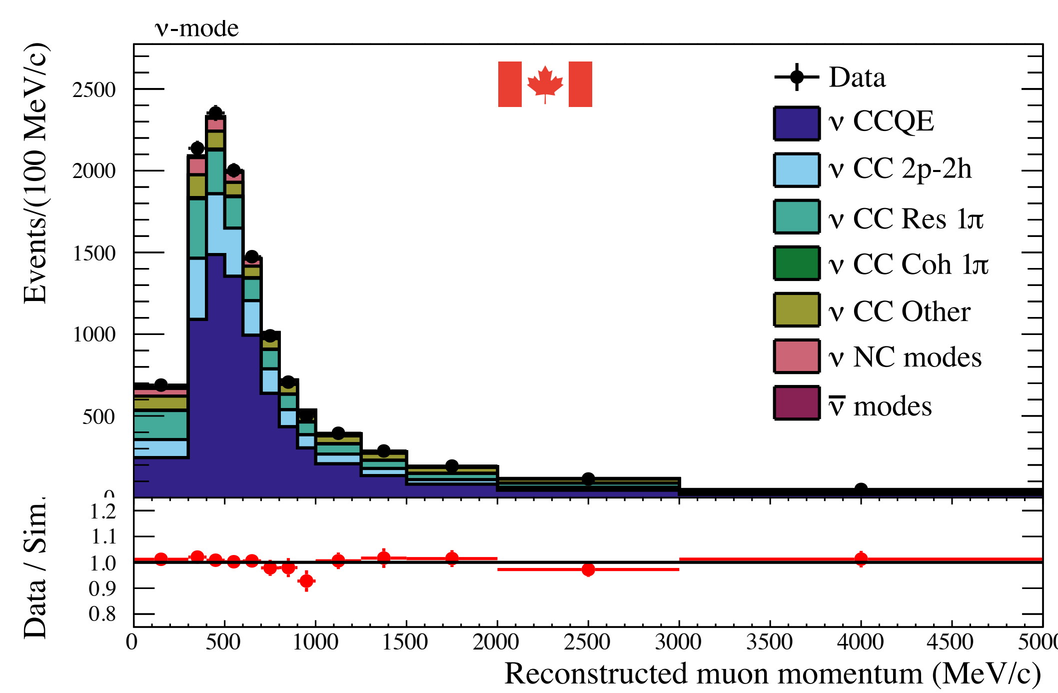

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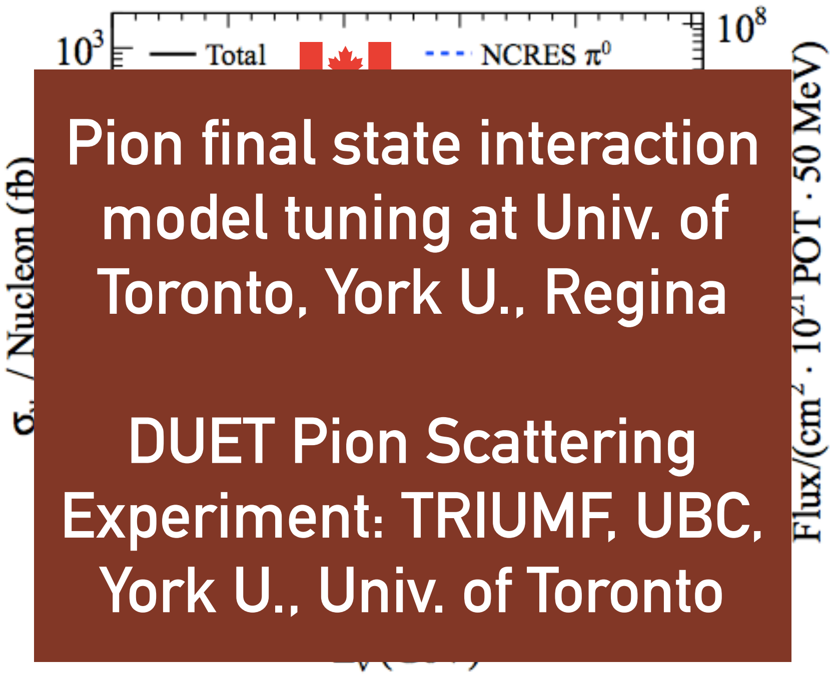


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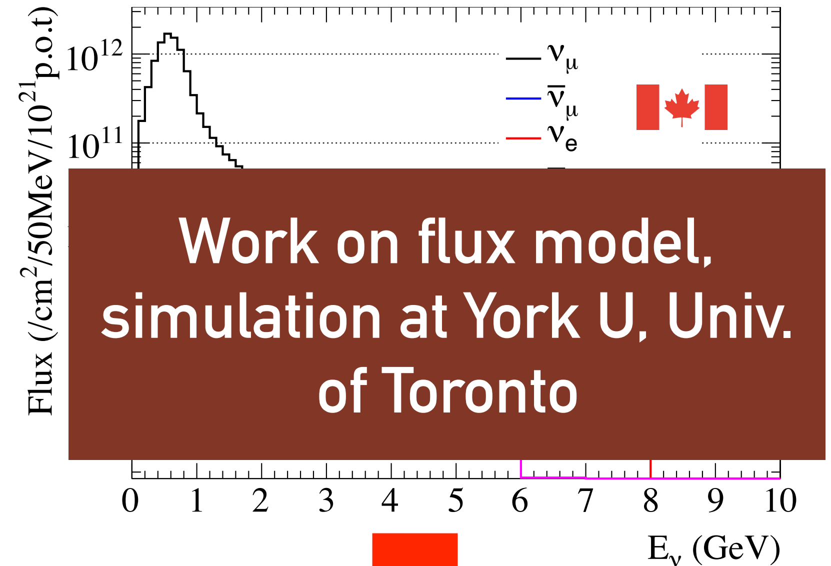


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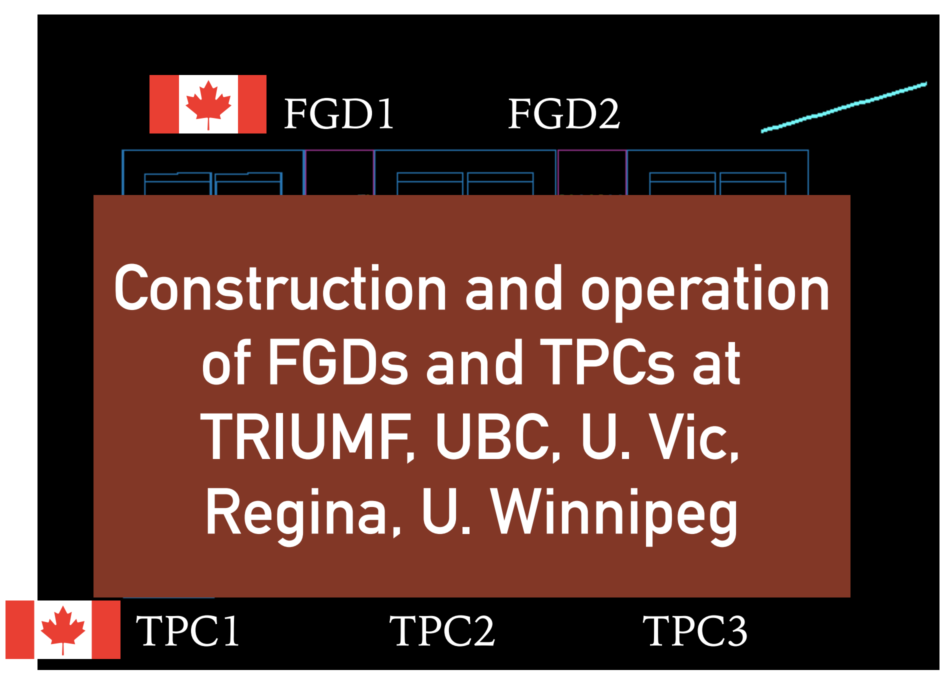


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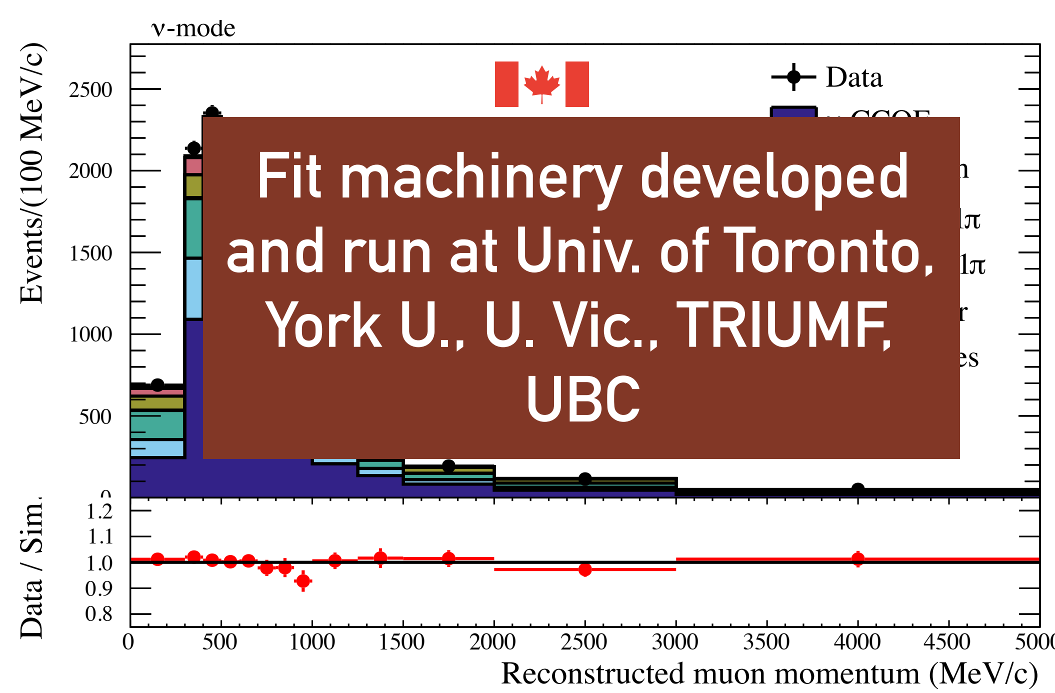



Fit machinery developed and run at Univ. of Toronto, York U., U. Vic., TRIUMF, UBC

# EXTRACTING OSCILLATION PARAMETERS, STEP 2

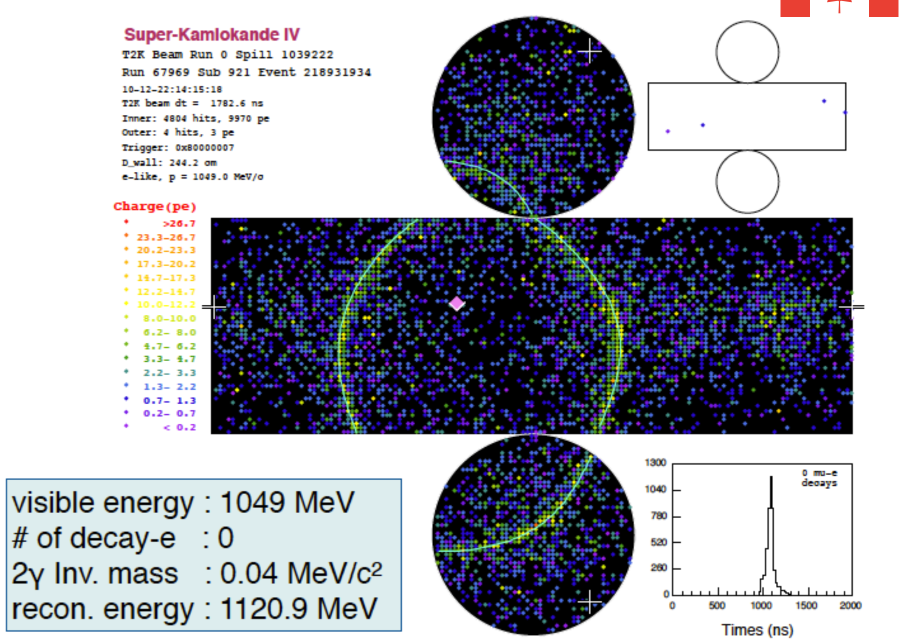
*Prediction at far detector*

*Oscillation Probability*

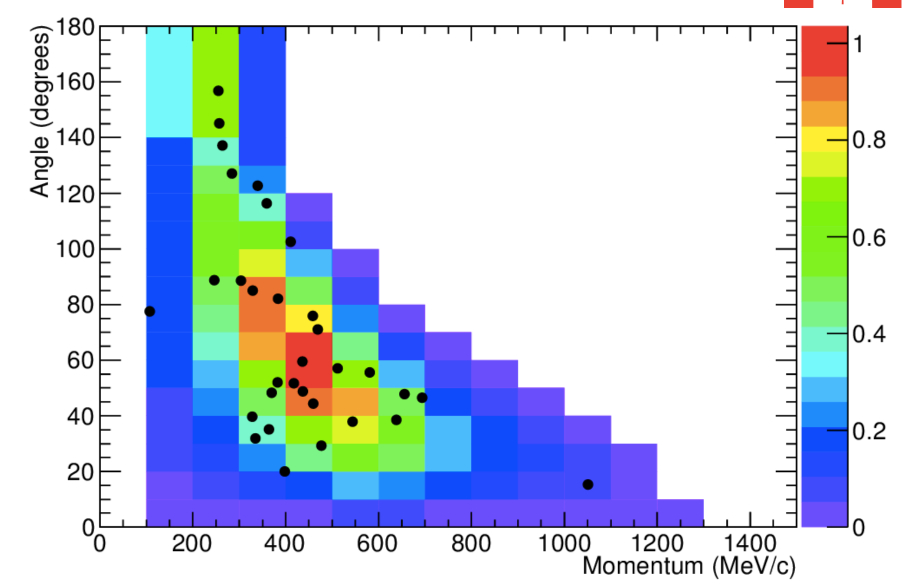
$$N_k(p_k,\theta_k) \propto \sum_i^{E^{true}\text{ bins}} \sum_j^{\text{flavors}} \Phi_j^{far}(E_i^{true})\, P_{\nu_j\rightarrow\nu_k}(E_i^{true})\, \sigma_k^A(E_i^{true}, p_k, \theta_k \ldots)\, \epsilon(p_k,\theta_k \ldots)\, M_{det}$$

*Constrained by near detector fit*

*T2K Super-K Data*




*Fit to SK data to extract oscillation parameter intervals*



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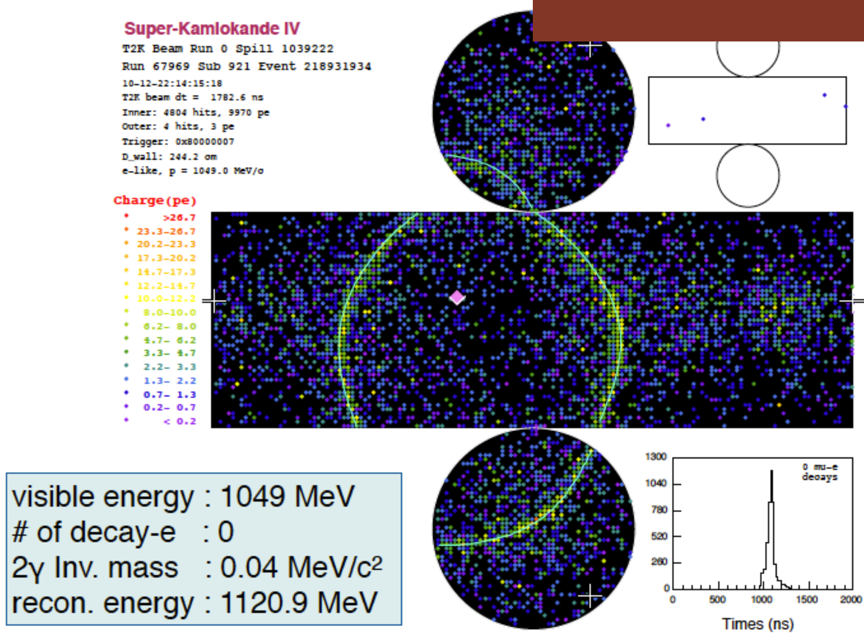
*near detector fit*

Improved event reconstruction and selection developed at UBC, TRIUMF

*T2K Super-K*

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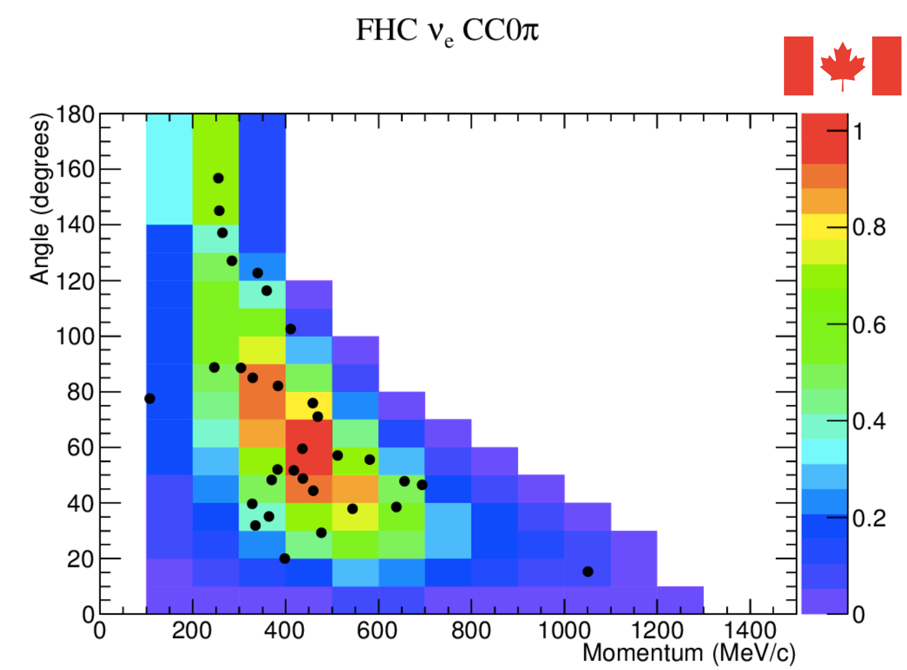

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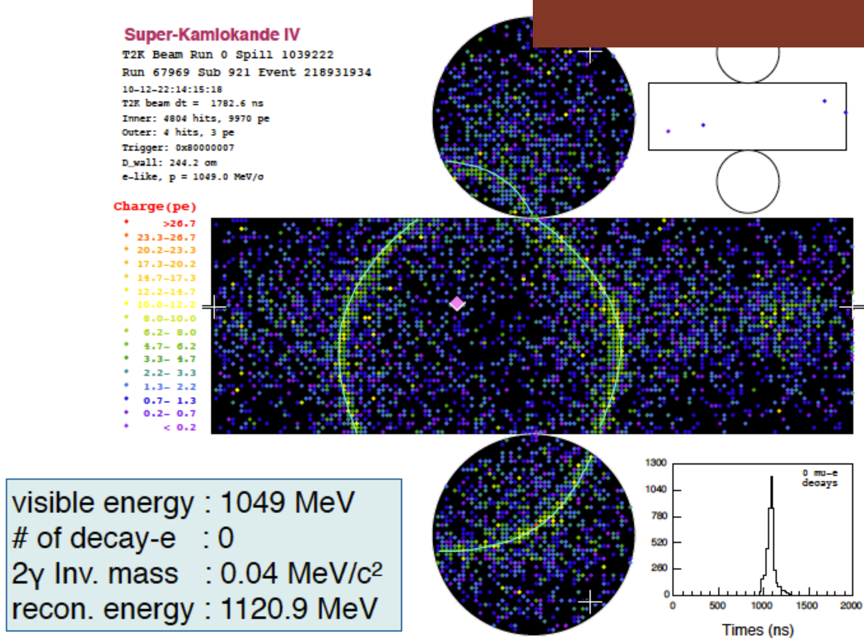
*T2K Super-K...*

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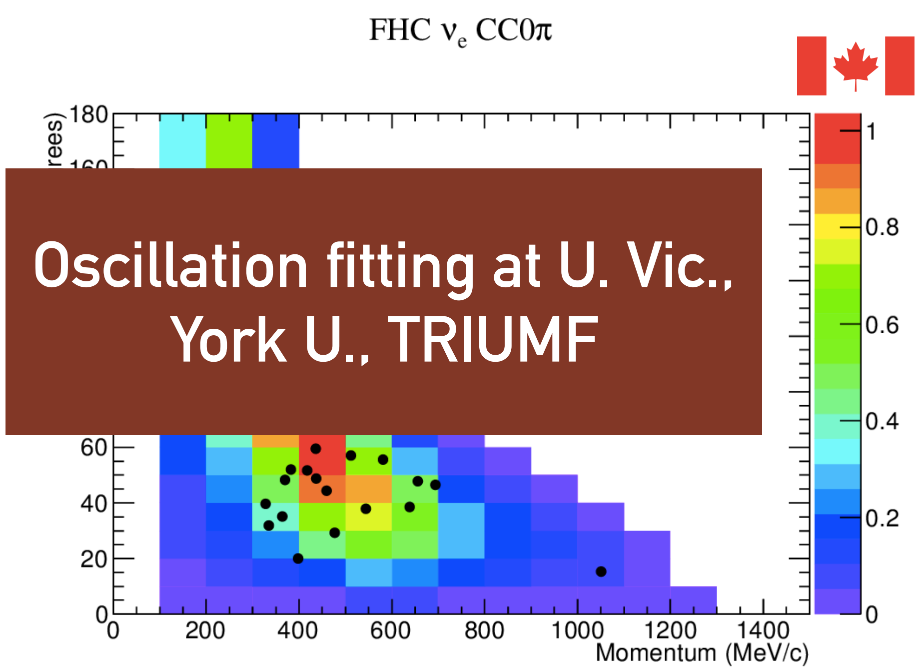
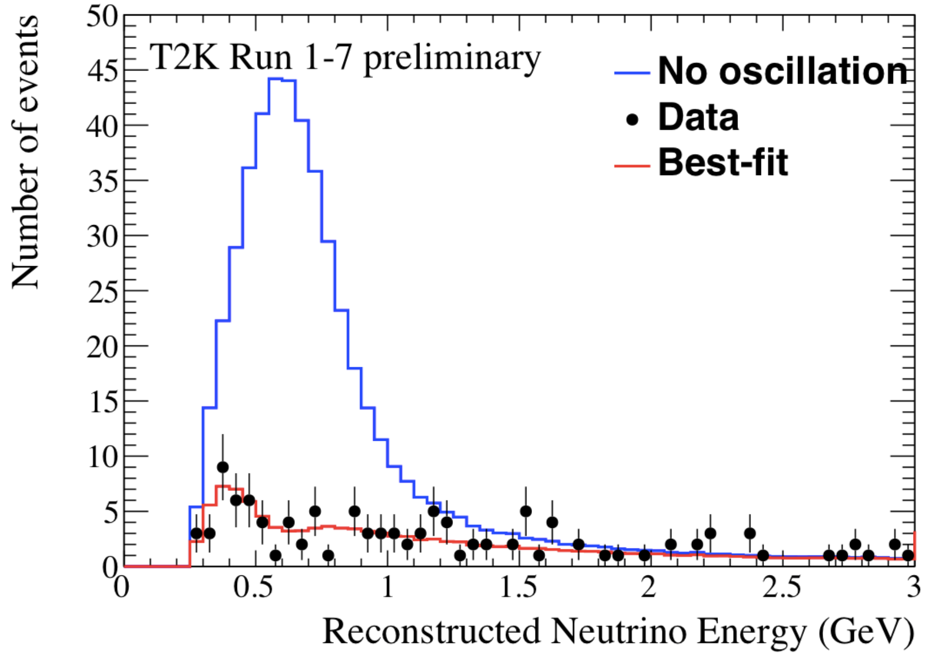


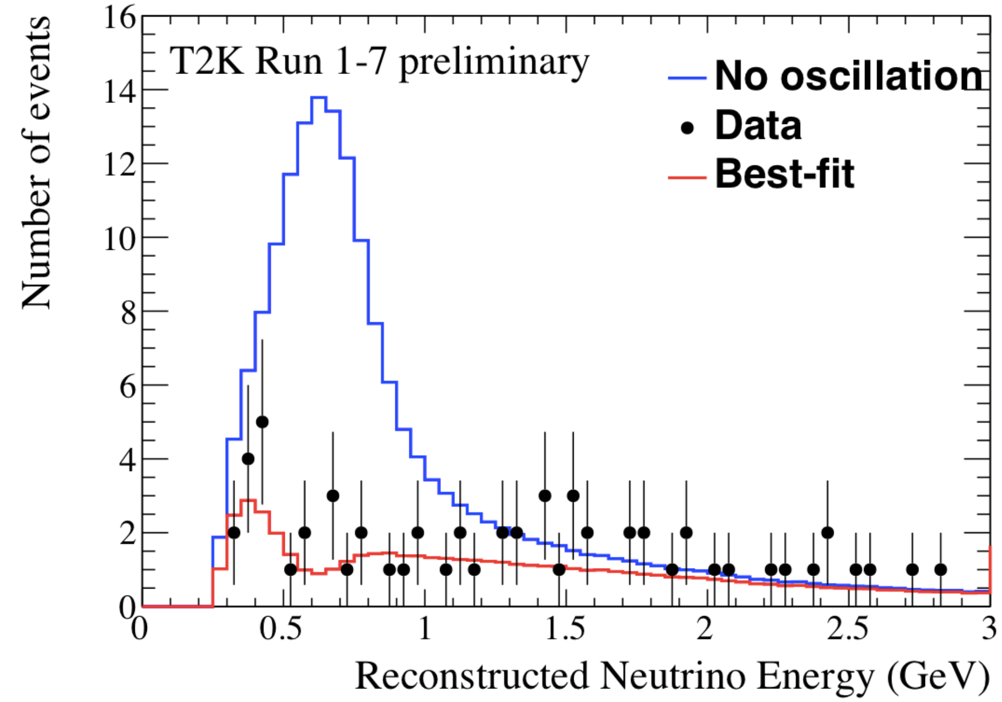

Oscillation fitting at U. Vic., York U., TRIUMF

# T2K DATA

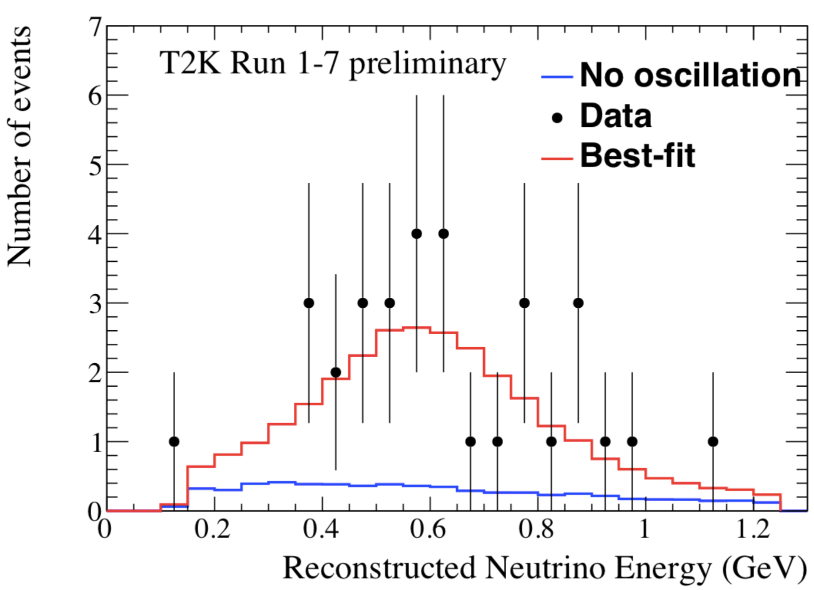
*Muon neutrino candidates*



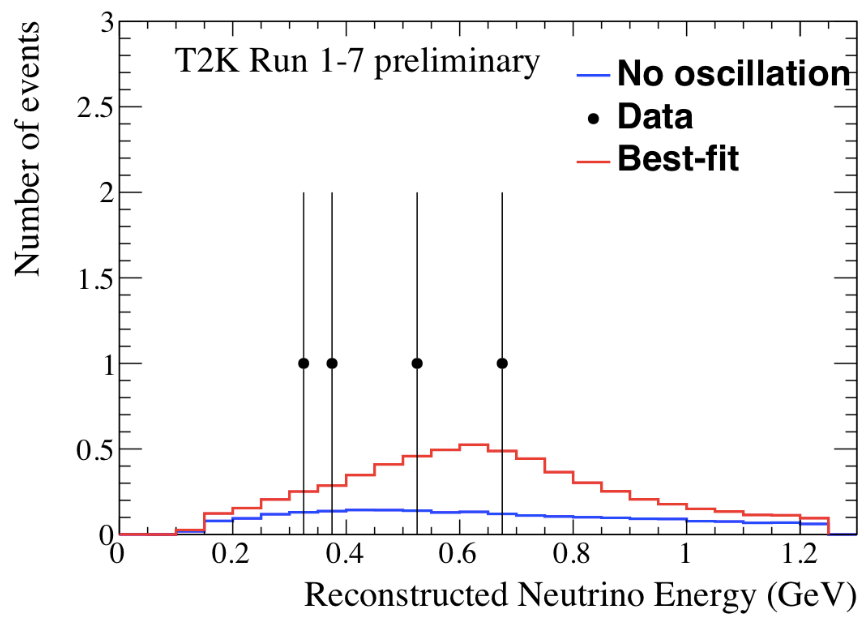

*Muon antineutrino candidates*



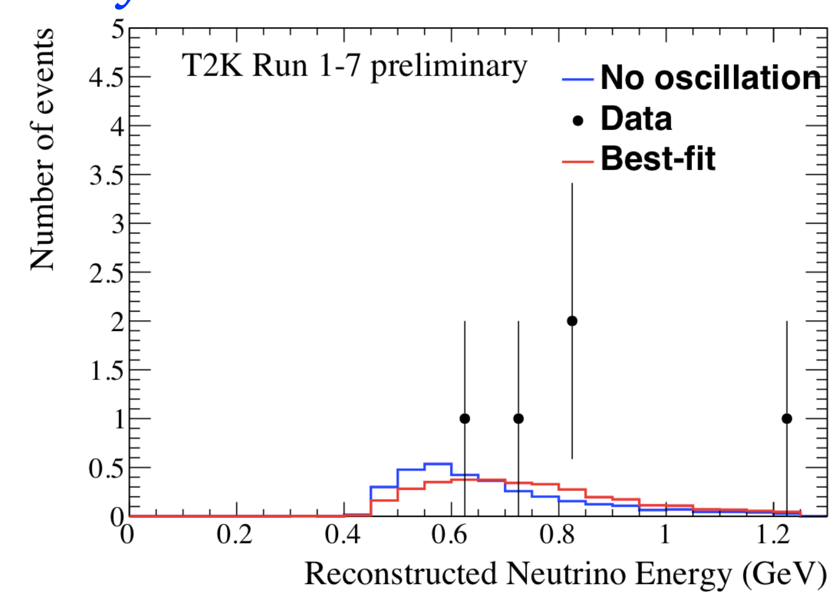

*Electron neutrino candidates*



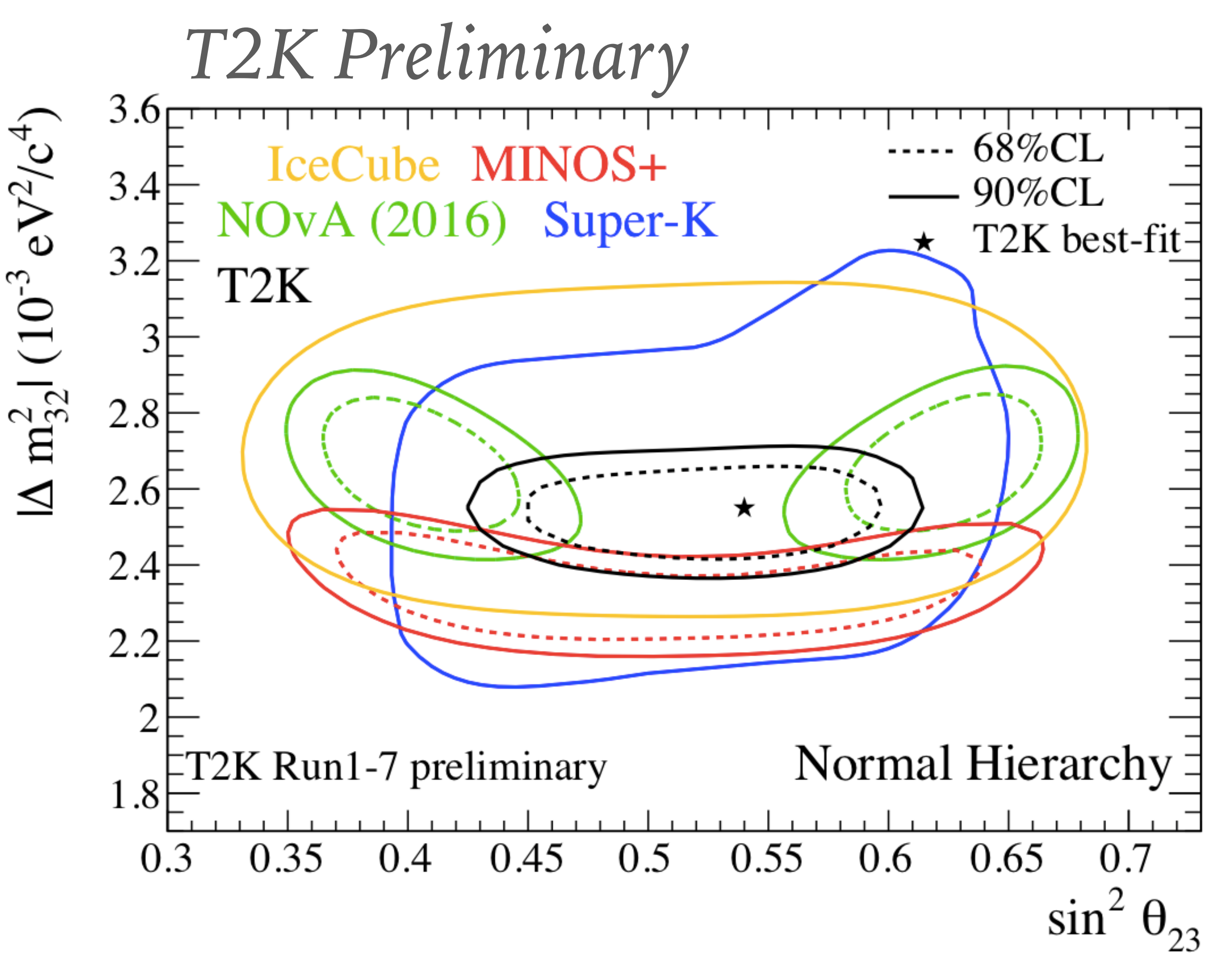

*Electron antineutrino candidates*

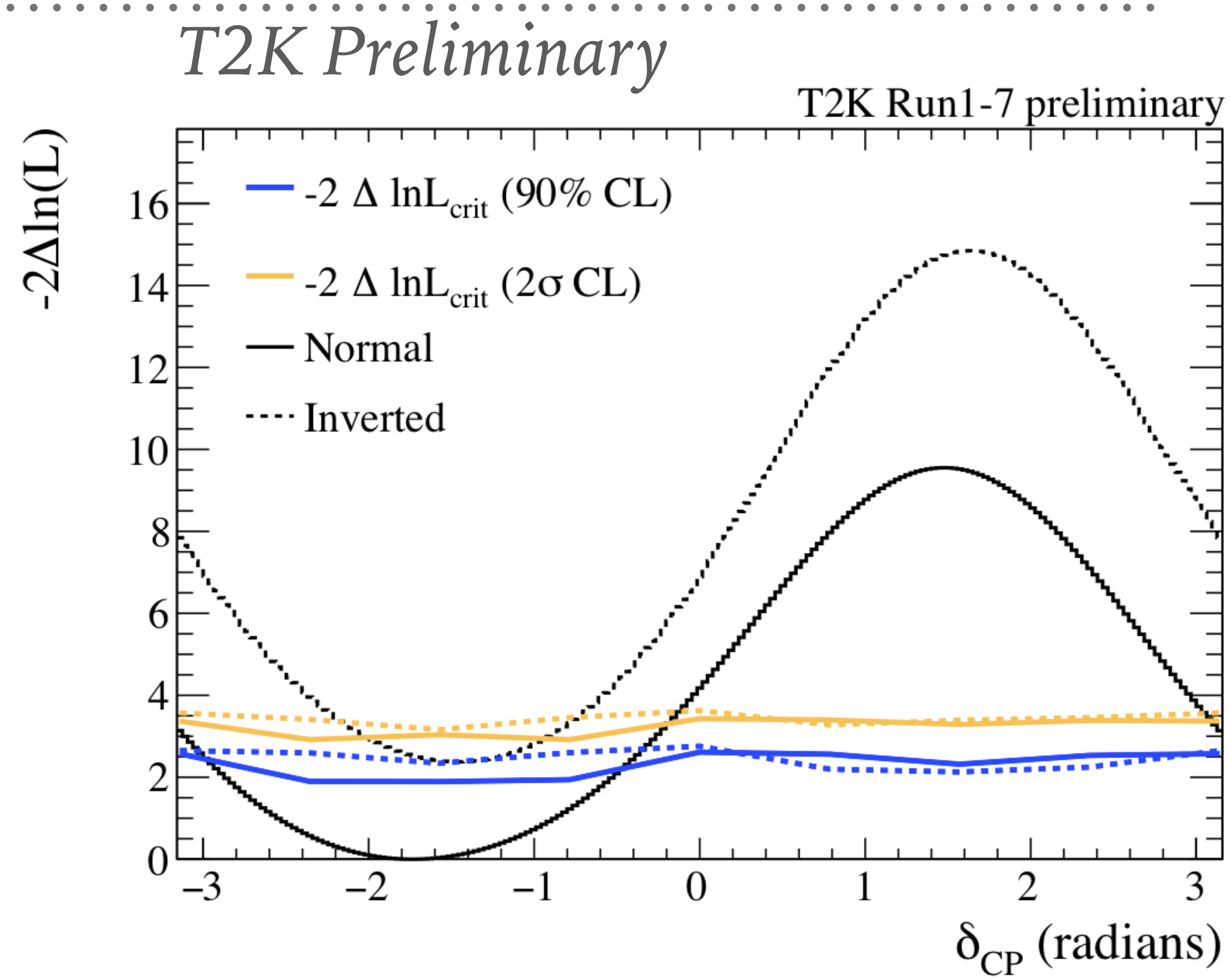



*Electron neutrino candidates - 1 decay electron*



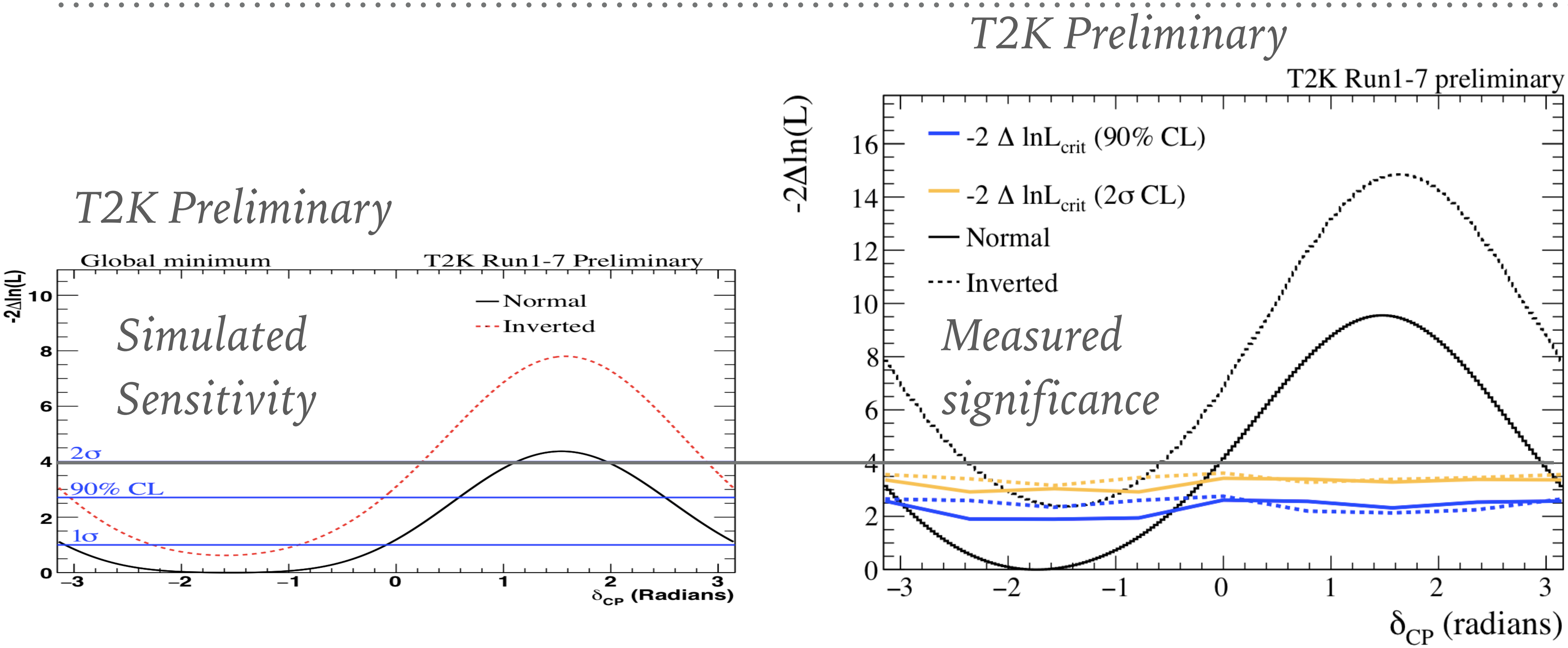
# T2K RESULTS




- *T2K measures $\sin^2\theta_{23}$ consistent with maximal mixing (0.5).*
  - *NOvA prefers non-maximal values*
- *T2K data prefers $\delta_{cp}$ near $-\pi/2$*
  - *CP conserving values (0,π) are weakly disfavored, falling outside of the 90% confidence intervals*

# SENSITIVITY VS. SIGNIFICANCE

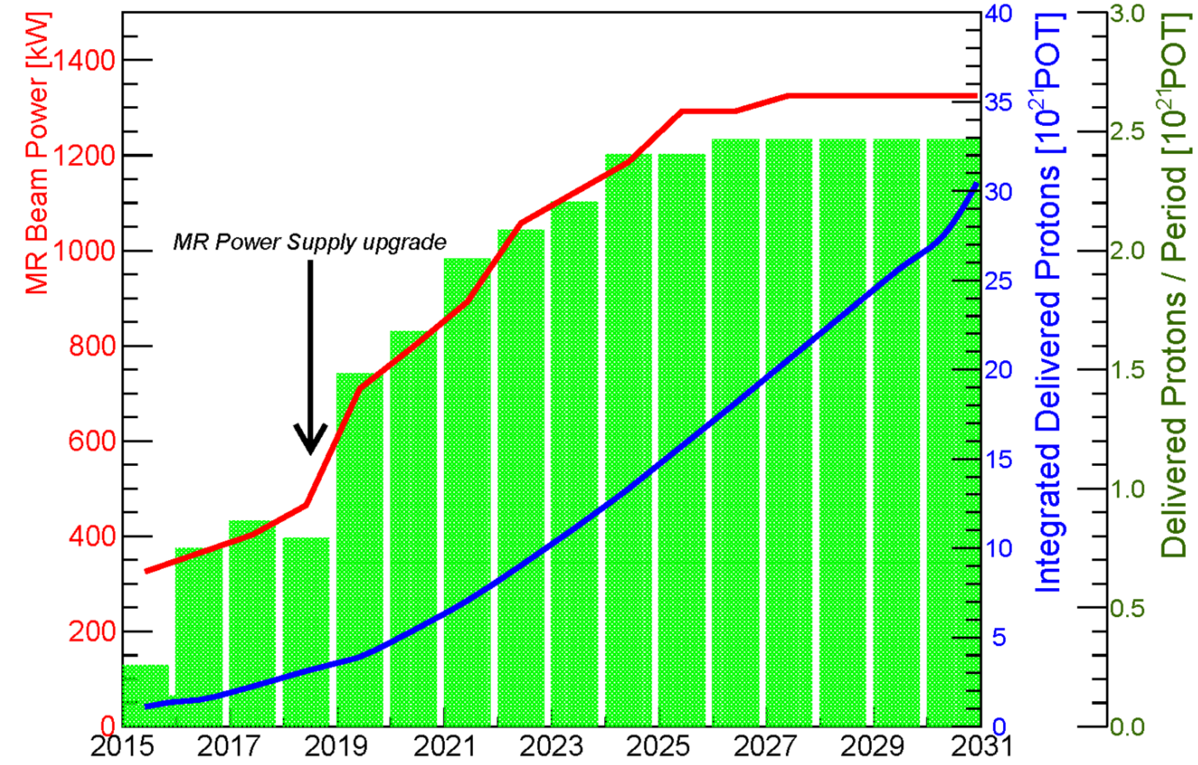



- *The measured significance to disfavor CP conserving values is larger than the simulated sensitivity with an input value of $\delta_{cp}$=-π/2*
- *This is due to a larger than expected number of $\nu_e$ candidates observed in the data*
    - *Assuming it is a statistical fluctuation, significantly more protons on target will need to be accumulated to reach 3σ sensitivity*

# THE FUTURE

# T2K–II: EXTENDED T2K OPERATION

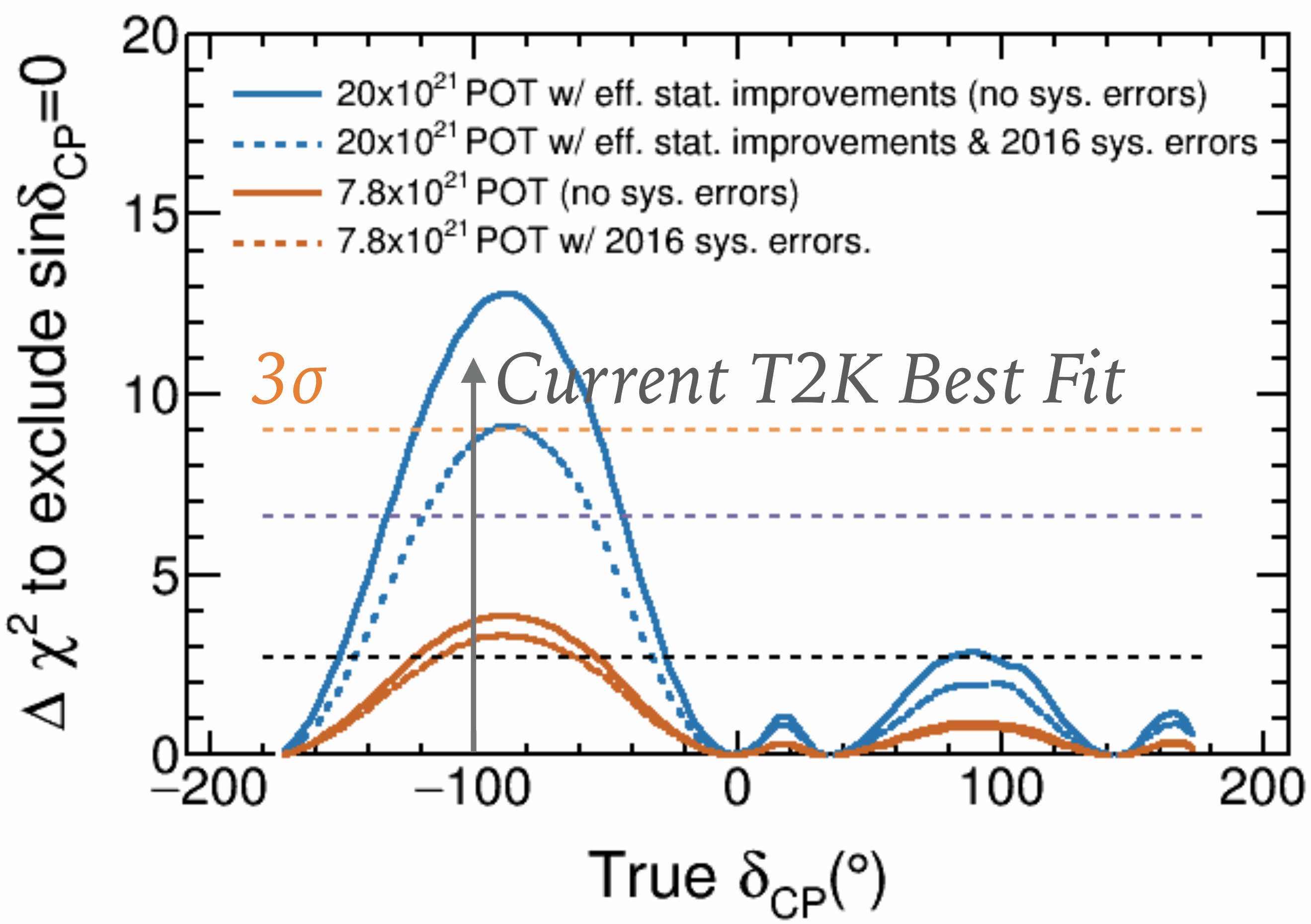
- *T2K originally approved for 7.8e21 POT*
- *Proposal to extend T2K operation to 2026 and collect 20.0e21 POT*
- *Implement analysis and operation improvements to achieve another 50% improvement in experimental sensitivity*

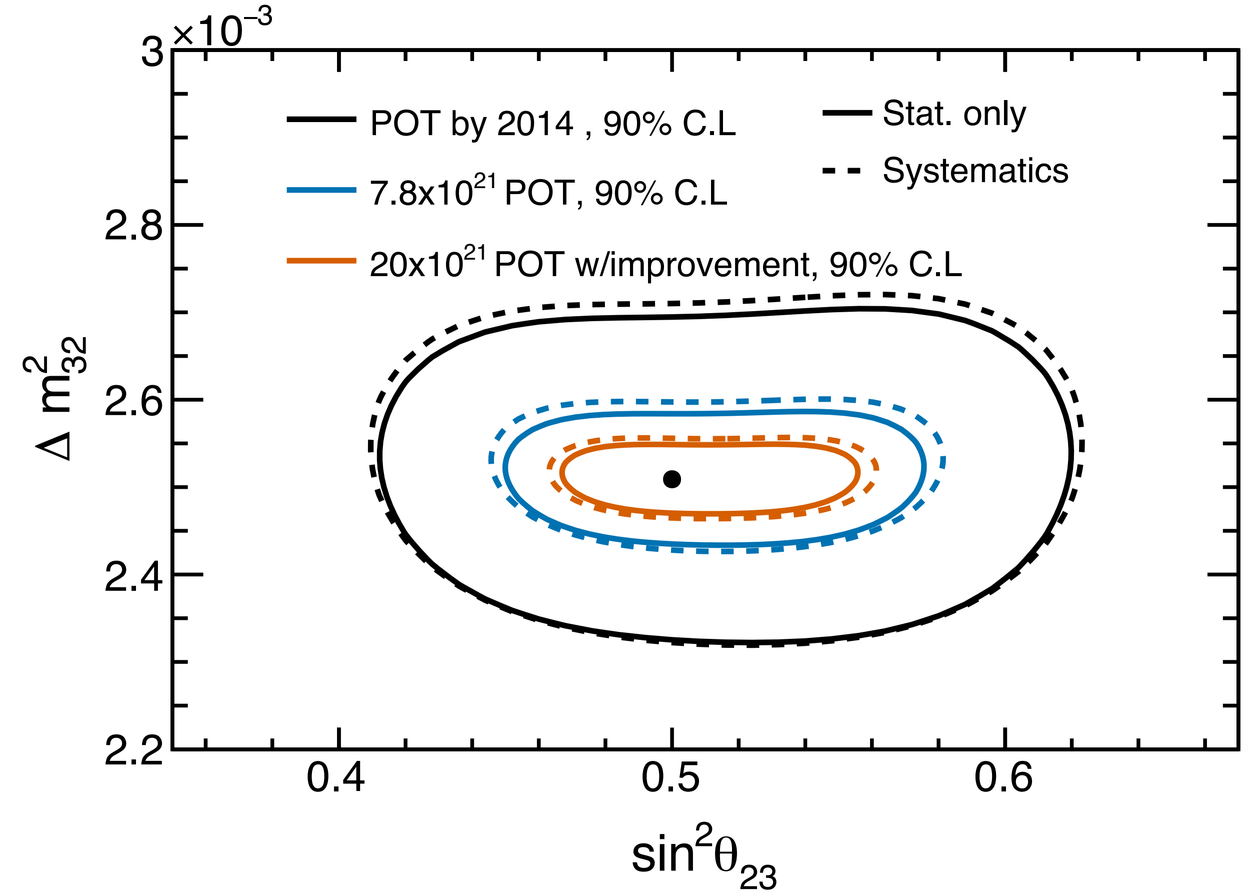



- *J-PARC will upgrade the Main Ring magnet power supplies to achieve 1 Hz operation*
  - *Projected ultimate beam power of 1.3 MW*

| | True $\delta_{CP}$ | Total | Signal $\nu_\mu \to \nu_e$ | Signal $\bar{\nu}_\mu \to \bar{\nu}_e$ | Beam CC $\nu_e + \bar{\nu}_e$ | Beam CC $\nu_\mu + \bar{\nu}_\mu$ | NC |
|---|---|---|---|---|---|---|---|
| $\nu$-mode | 0 | 454.6 | 346.3 | 3.8 | 72.2 | 1.8 | 30.5 |
| $\nu_e$ sample | $-\pi/2$ | 545.6 | 438.5 | 2.7 | 72.2 | 1.8 | 30.5 |
| $\bar{\nu}$-mode | 0 | 129.2 | 16.1 | 71.0 | 28.4 | 0.4 | 13.3 |
| $\bar{\nu}_e$ sample | $-\pi/2$ | 111.8 | 19.2 | 50.5 | 28.4 | 0.4 | 13.3 |

# T2K-II SENSITIVITY



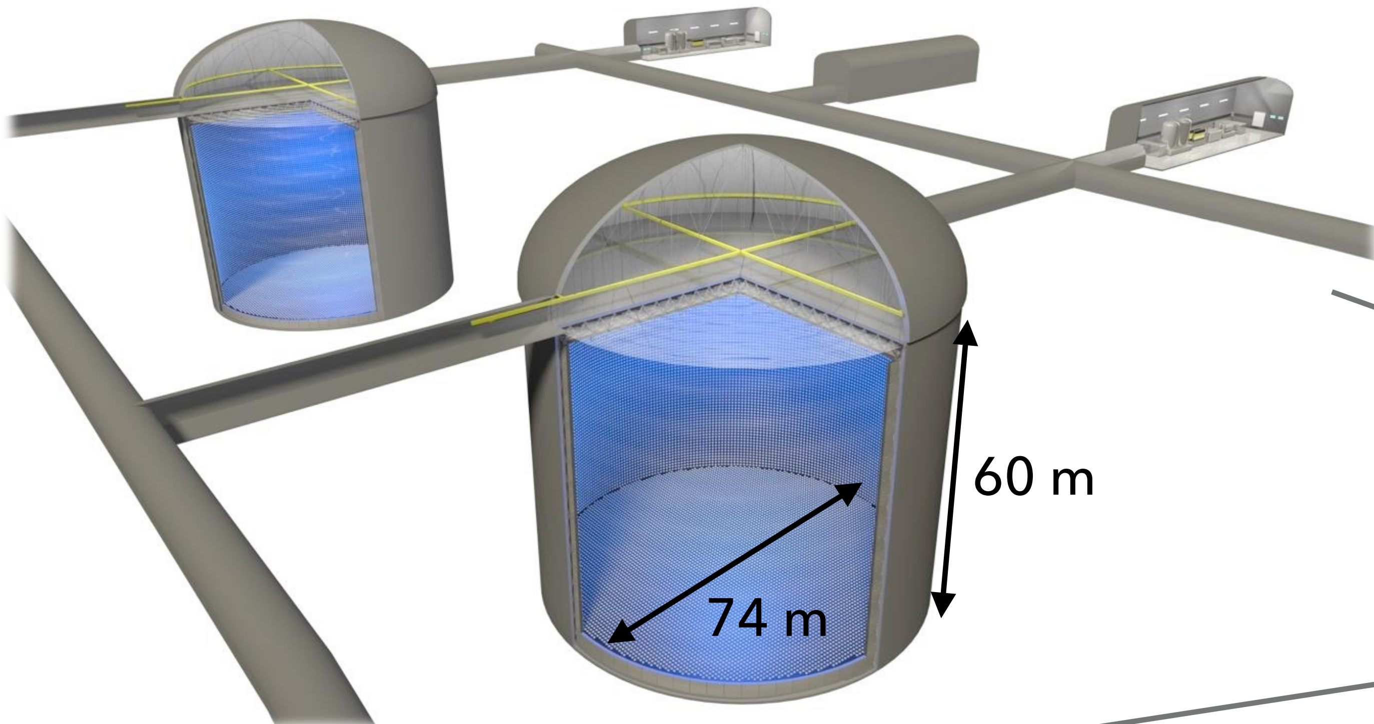



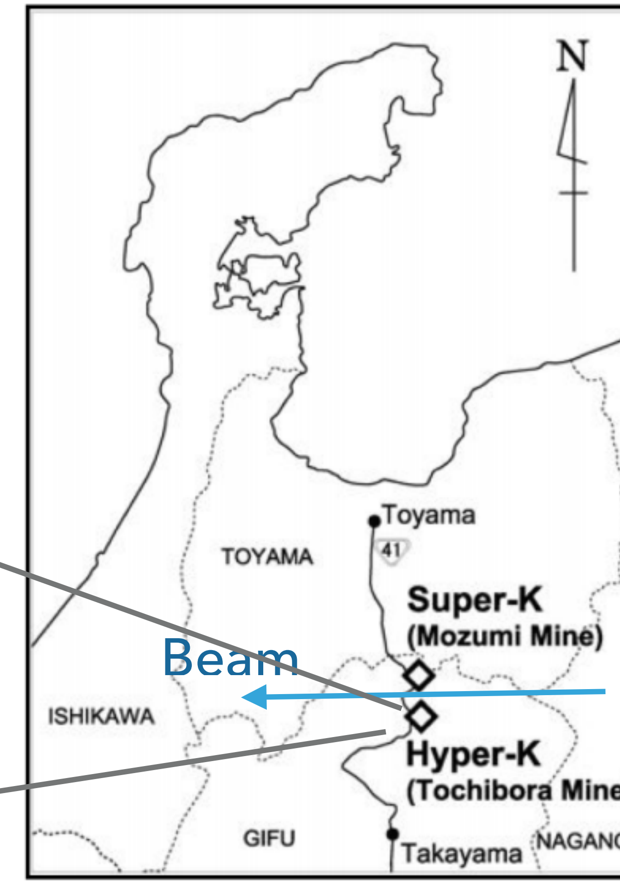

- *If $\delta_{cp}$ is near current best fit, potential for a 3σ discovery of CP violation in T2K-II*
    - *The size of systematic errors has a large impact on the experimental sensitivity (dashed vs. solid lines)*
- *Significant reduction of $\sin^2\theta_{23}$ and $\Delta m^2_{32}$ intervals*
    - *Potential critical cross section modeling uncertainties for this measurement*

# HYPER-K (MORE STATISTICS!)

# HYPER-K

## A new more massive water Cherenkov detector




<u>Hyper-K Detector:</u>

60 m tall x 74 m diameter tank

2 tanks with a staging approach (second tank 6 years later)

40,000 50cm $\phi$ PMTs → 40% photo-coverage

260 kton mass (187 kton fiducial volume is ~8x larger than Super-K)

<u>Hyper-K Physics:</u>

Long baseline neutrinos

Atmospheric neutrinos

Nucleon decay searches

Supernova neutrinos

Solar neutrinos

# HYPER-K EVENT RATES & SPECTRA

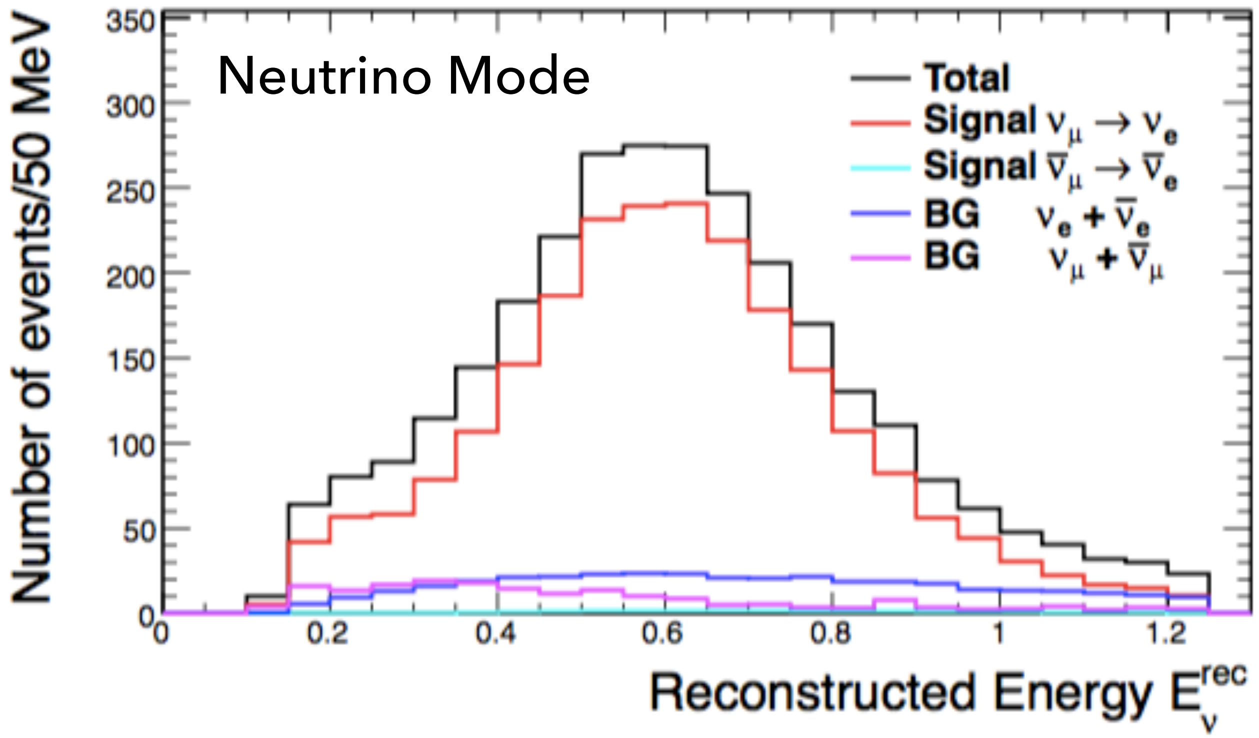
*Electron (anti)neutrino candidates*

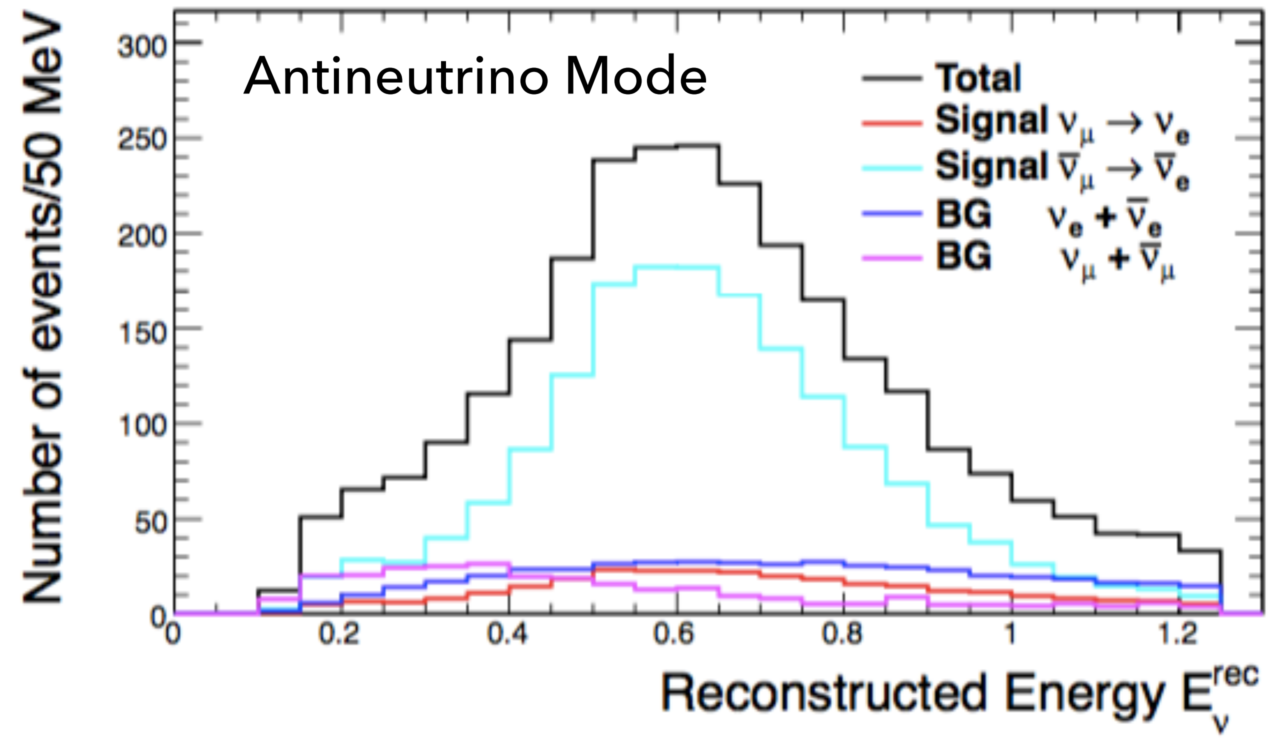
| $\delta_{cp}$=0 | Signal | Wrong-sign appearance | CC $\nu_\mu$, $\bar{\nu}_\mu$ | Intrinsic $\nu_e$, $\bar{\nu}_e$ | NC |
|---|---|---|---|---|---|
| $\nu$ beam | 2300 | 21 | 10 | 362 | 188 |
| $\bar{\nu}$ beam | 1656 | 289 | 6 | 444 | 274 |

*Muon (anti)neutrino candidates*

| | CCQE | CC non-QE | NC | Total |
|---|---|---|---|---|
| $\nu$ beam | 8947 | 4444 | 672 | 14110 |
| $\bar{\nu}$ beam | 12317 | 6040 | 844 | 19214 |

# HYPER-K EVENT RATES & SPECTRA

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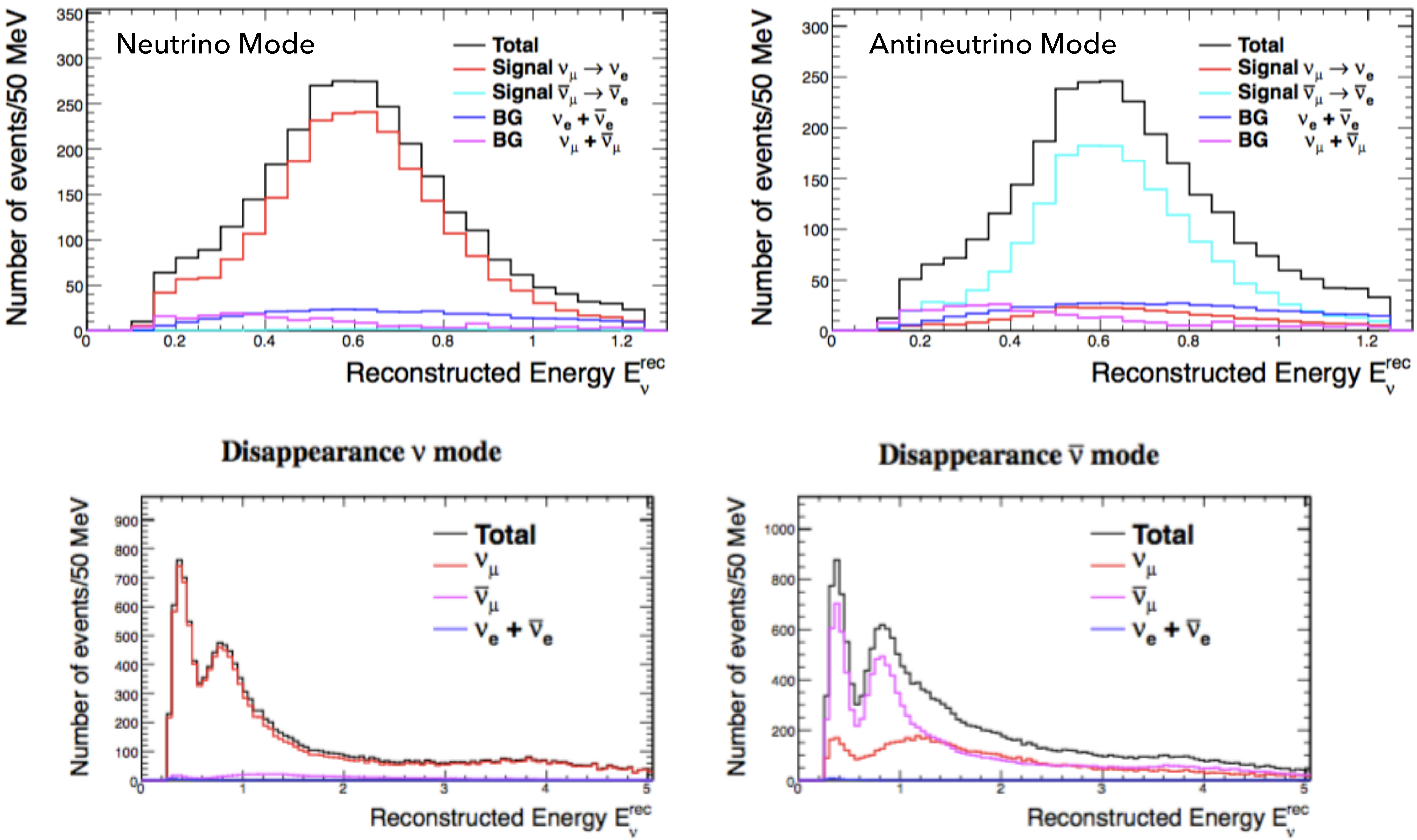
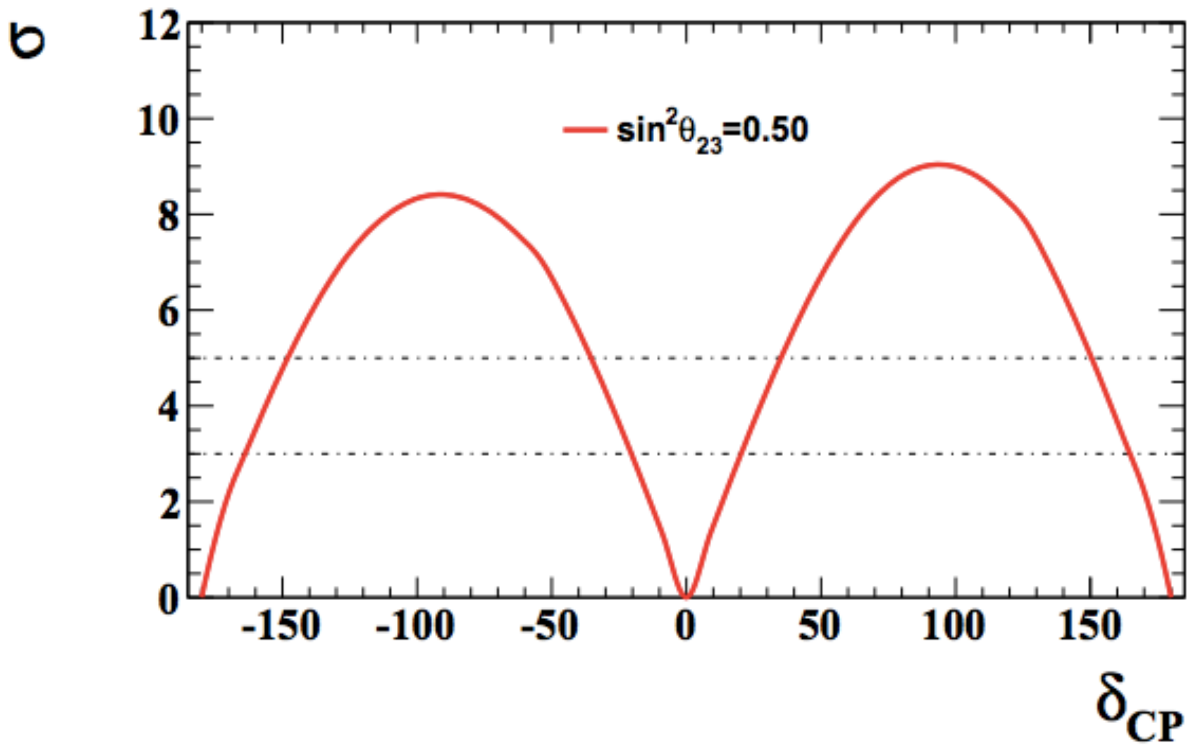
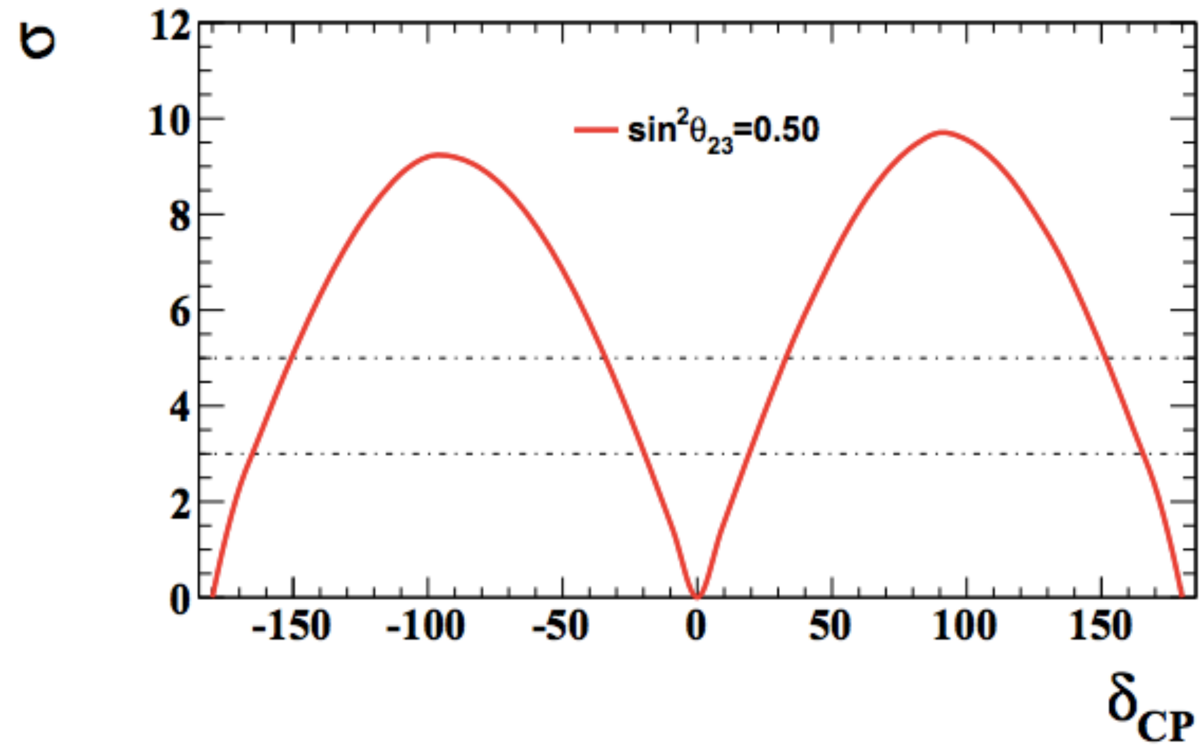


# HYPER-K CPV SENSITIVITIES

Normal mass hierarchy



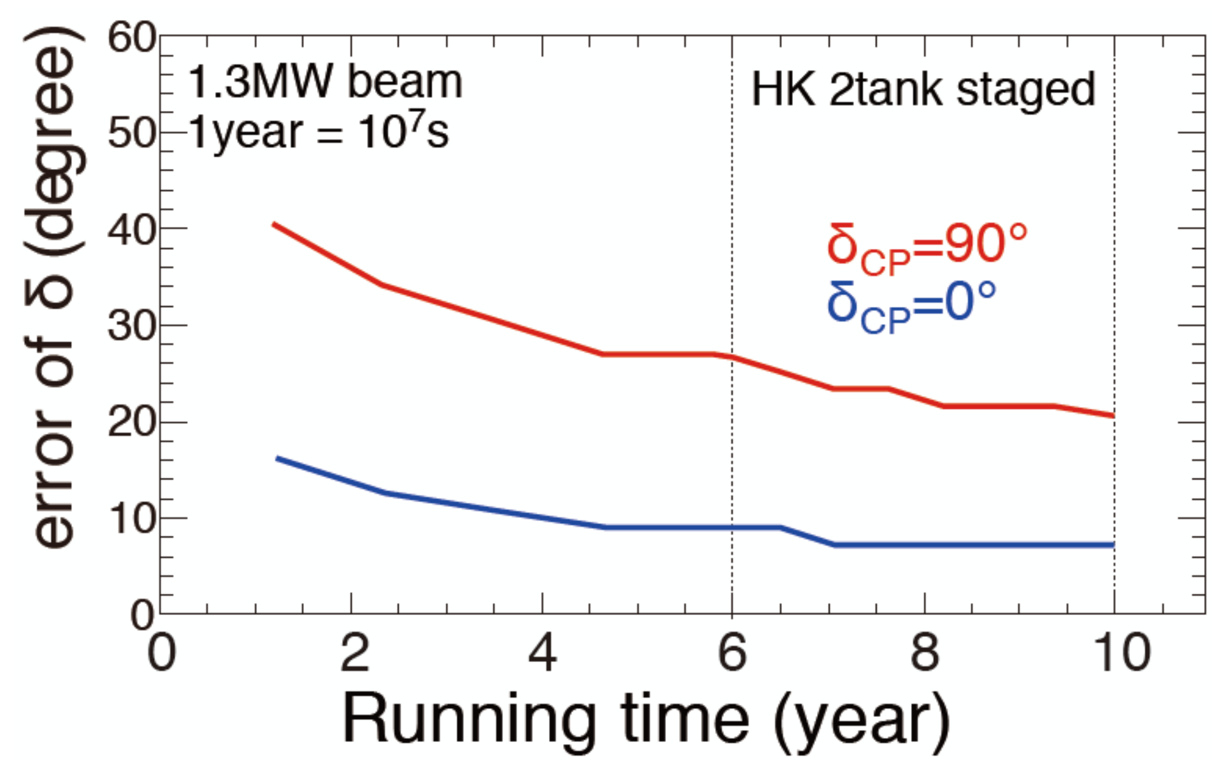

Inverted mass hierarchy



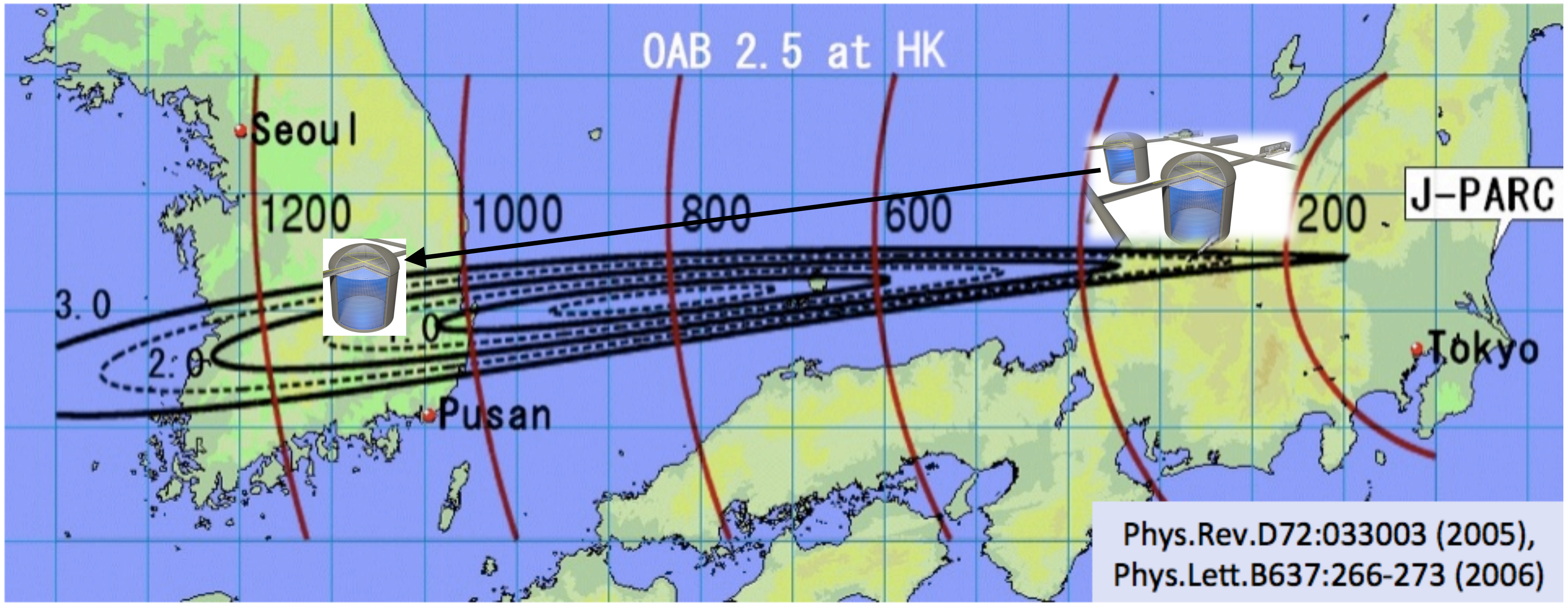

**Exclusion of $\sin(\delta_{cp})=0$ at 3σ for 78% of $\delta_{cp}$ values at 5σ for 62%**

21° precision at $\delta_{cp}=90°$

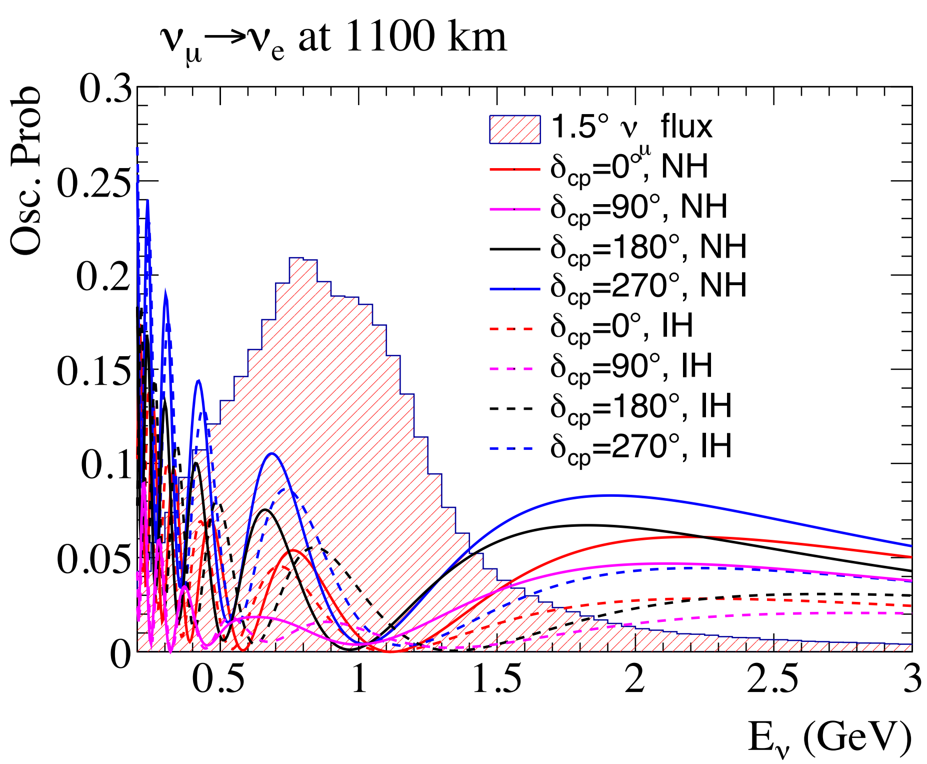
7° precision at $\delta_{cp}=0°$



# HYPER-K WITH SECOND DETECTOR IN KOREA

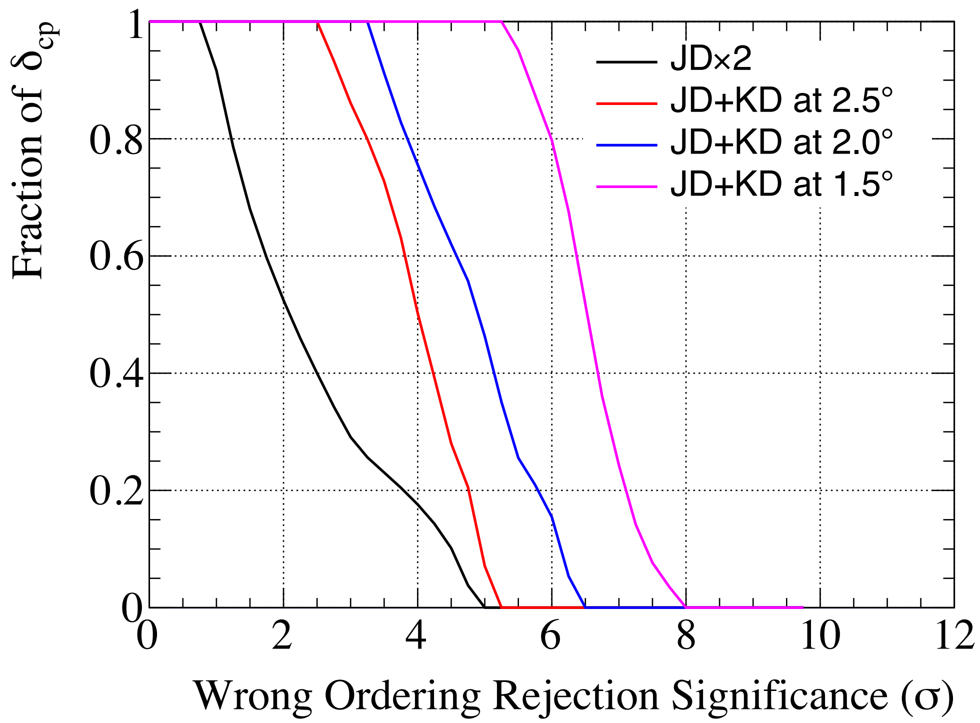


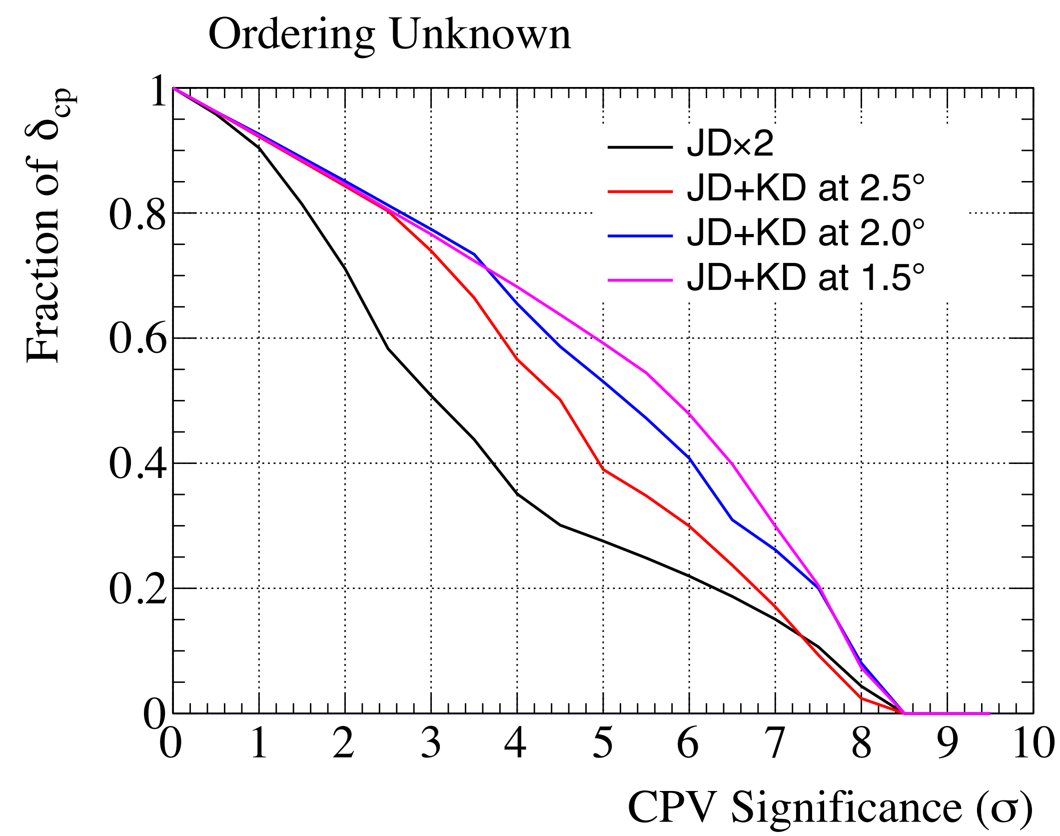

- *Internal efforts in Hyper-K to develop option to build second tank in Korea*
- *TRIUMF, Univ. of Toronto working with Korean collaborators on physics sensitivities*



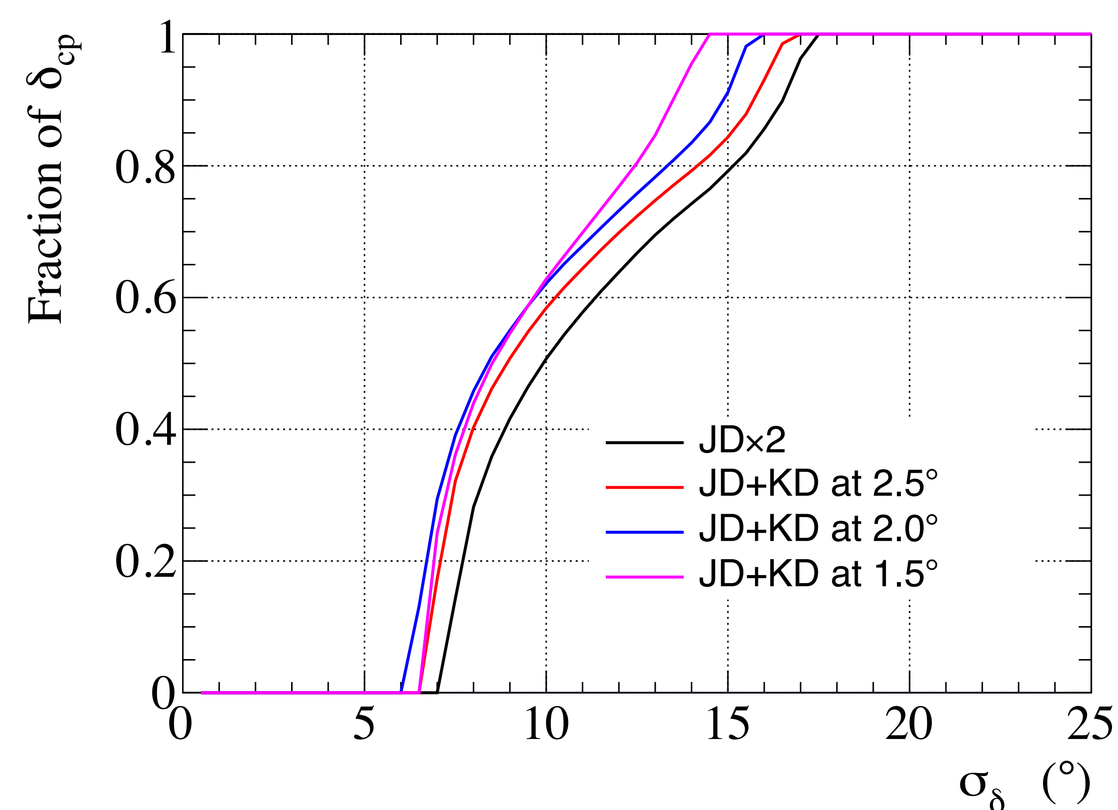

- *Probe the second (first and third) oscillation maxima*
- *Smaller statistics at longer baseline, but larger CP violation effect*
  - *Less sensitive to systematic errors*
- *Larger matter effect to probe the mass ordering*

# SENSITIVITIES WITH KOREAN DETECTOR




- *More sensitivity to mass ordering*
- *CP violation discovery for more true values of $\delta_{cp}$*
- *Better precision on the measurement of $\delta_{cp}$*



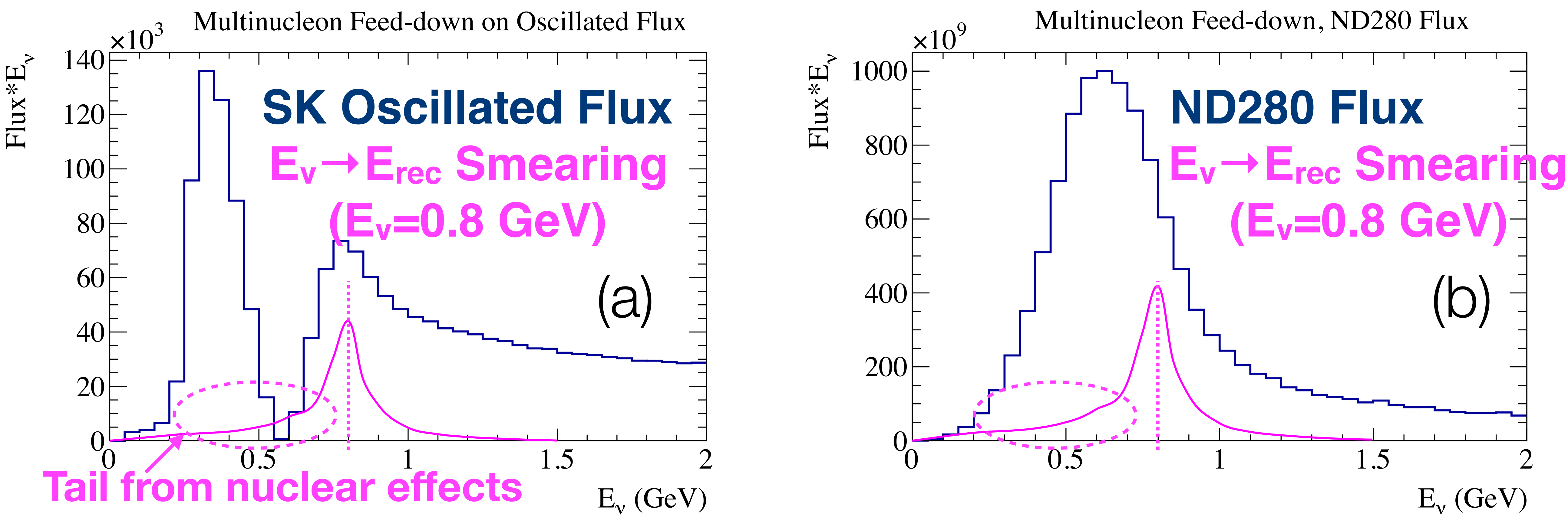
# SYSTEMATIC ERRORS FOR T2K-II AND HYPER-K

Current T2K systematic errors

| Systematic Error Type | 1Re Neutrino Mode | 1Re Antineutrino Mode |
|---|---|---|
| Far Detector Model | 2.39% | 3.09% |
| Final State/Secondary Interactions | 2.50% | 2.46% |
| Extrapolation from Near Detector | 2.88% | 3.22% |
| $\nu_e$(bar)/$\nu_\mu$(bar) | 2.65% | 1.50% |
| NC1$\gamma$ | 1.44% | 2.95% |
| Other | 0.16% | 0.33% |
| Total | 5.42% | 6.09% |

- *Current T2K systematic errors are at the ~6% level*
- *Need reduction to <5% for T2K-II and <3% for Hyper-K*
- *Need to avoid "unknown unknowns" particularly in cross section modeling*
  - ***Modeling neutrino-nucleus scattering at ~1 GeV is a challenging nuclear physics problem!***

# ENERGY RECONSTRUCTION



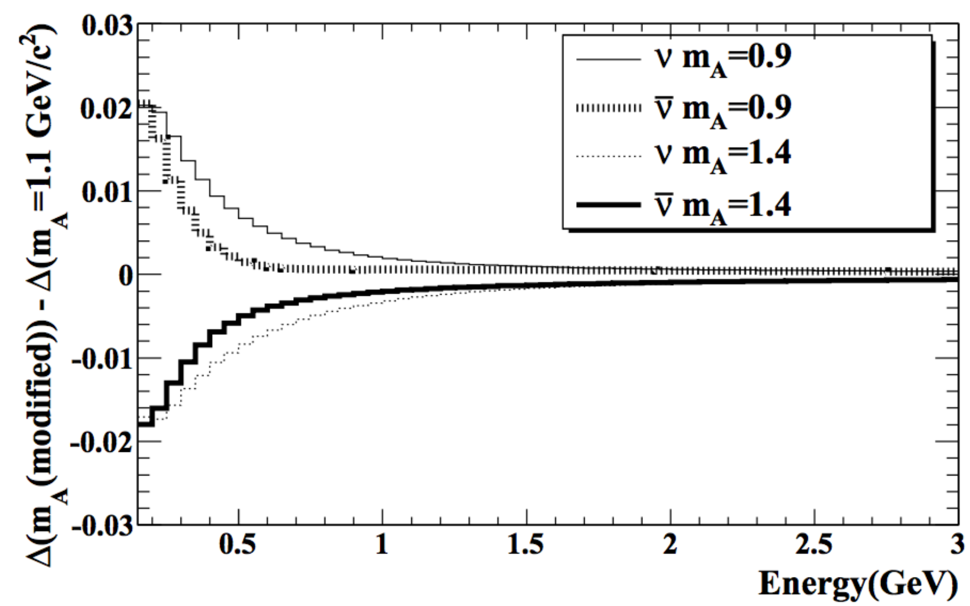

- *Observed spectra are smeared by nuclear effects - populate tails in particular*
- *Different fluxes in near and far detector*
  - *Impact of nuclear effects on the far detector observed spectrum cannot be directly measured in the near detector*

# ELECTRON NEUTRINO CROSS SECTION

- *Observe mostly muon (anti)neutrino interactions in near detector*
- *CP violation is observed on electron (anti)neutrino interactions in far detector*
- *Sensitive to systematic errors on* $\sigma_{\nu_e}/\sigma_{\nu_\mu}, \sigma_{\overline{\nu}_e}/\sigma_{\overline{\nu}_\mu}$

- *Uncertainties can arise from:*
  - *Form factor uncertainties in cross section terms that depend on lepton mass*
  - *Phase nuclear effects combined with phase space differences due to mass*
  - *Radiative corrections (should be calculable)*

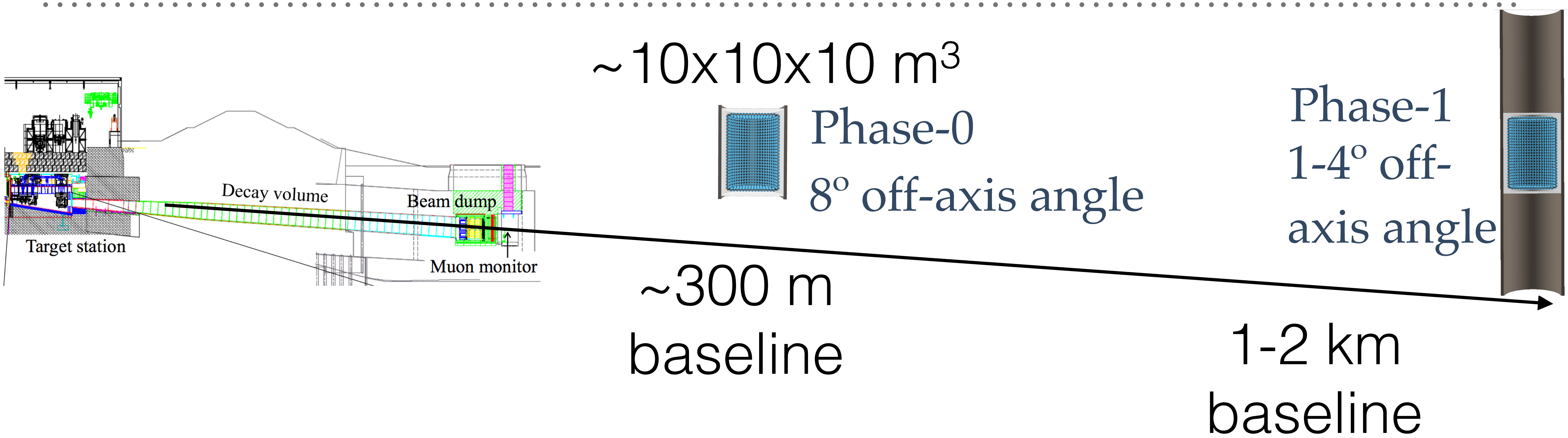
**Phys.Rev. D86 (2012) 053003**




*Uncertainty on relative cross section due to axial form factor uncertainty.*

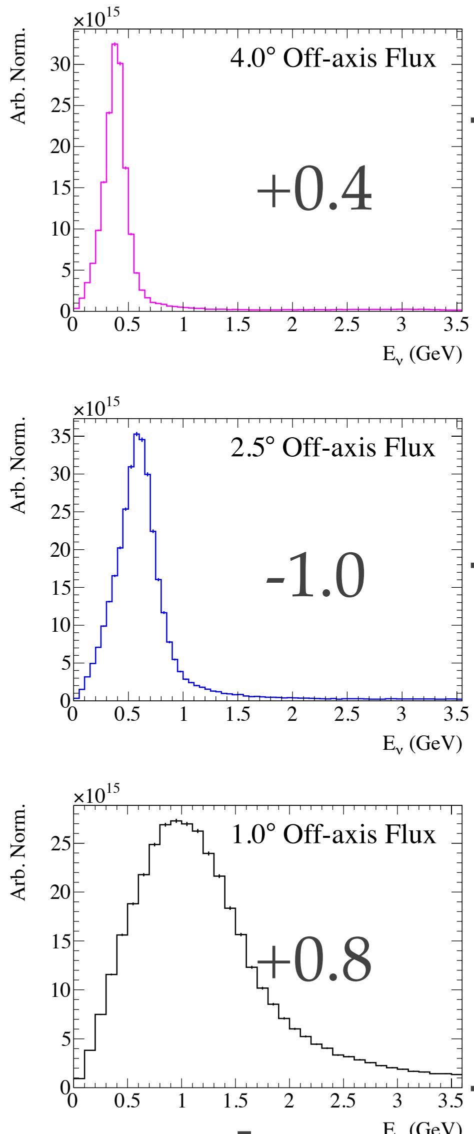
# NUPRISM (E61)

# THE E61 (NUPRISM) EXPERIMENT

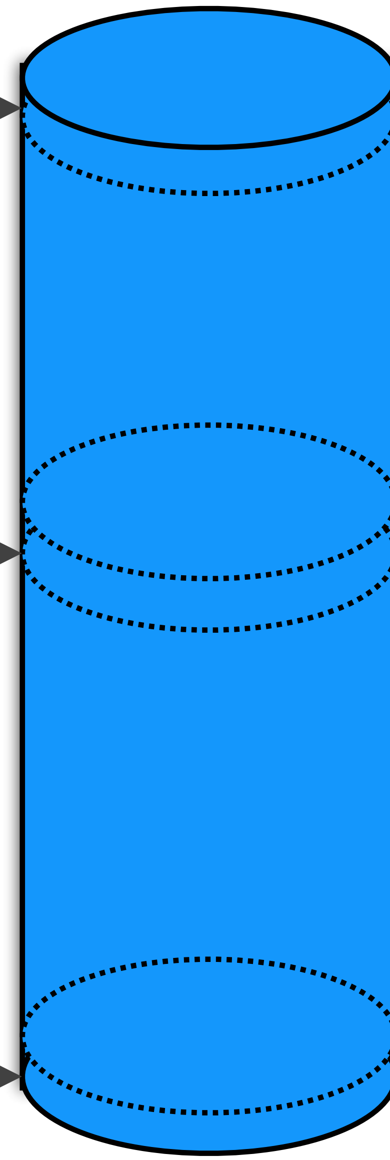



- ***E61 (NuPRISM)** - proposed kiloton scale water Cherenkov detector were position can be moved to make measurements at different off-axis angles*
  - *Address critical neutrino-nucleus scattering uncertainties for T2K & Hyper-K*
- *Staged approach*
  - *Phase-0: stationary detector near existing T2K near detectors*
  - *Phase-1: detector at ~1 km from neutrino source, movable to 1-4° off-axis*
- *Have received stage 1 approval from the J-PARC PAC*
- *Have recently merged with alternative WC detector proposal called TITUS*

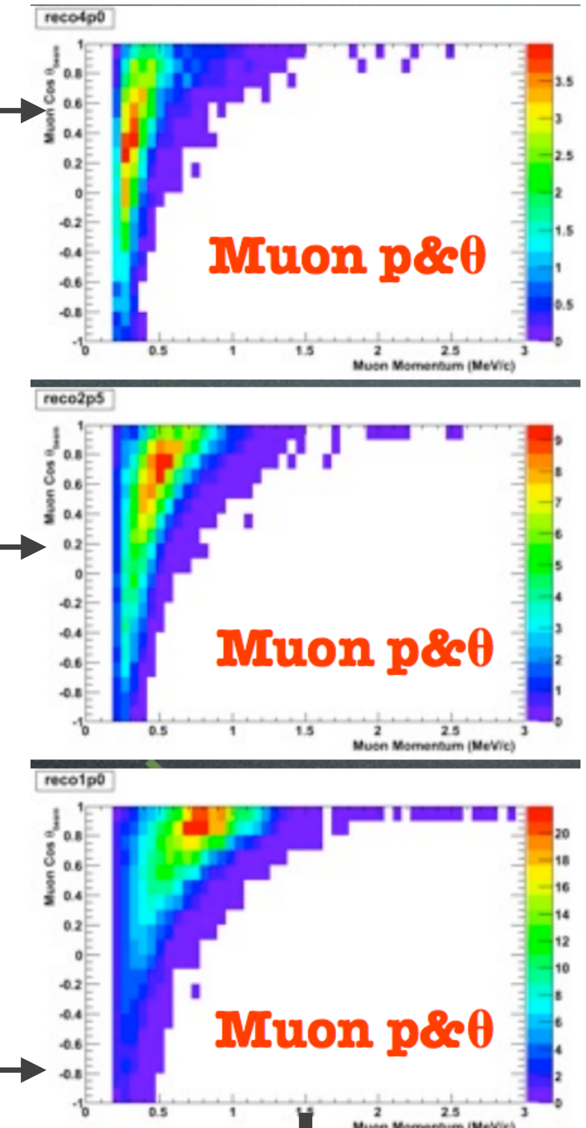
# ADVANTAGE OF MULTIPLE OFF-AXIS ANGLE MEASUREMENTS

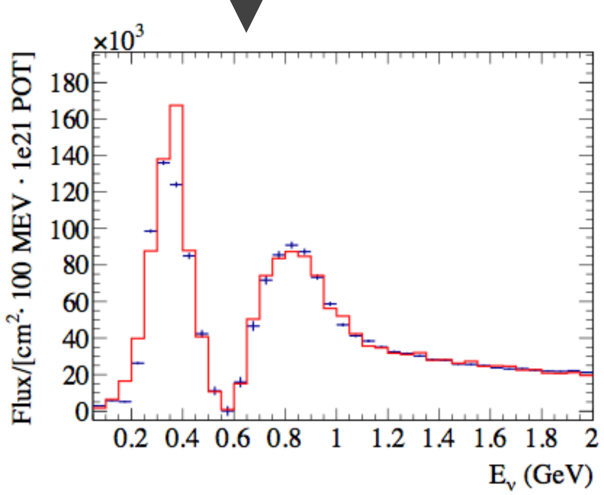



Spectra at at each off-axis bin

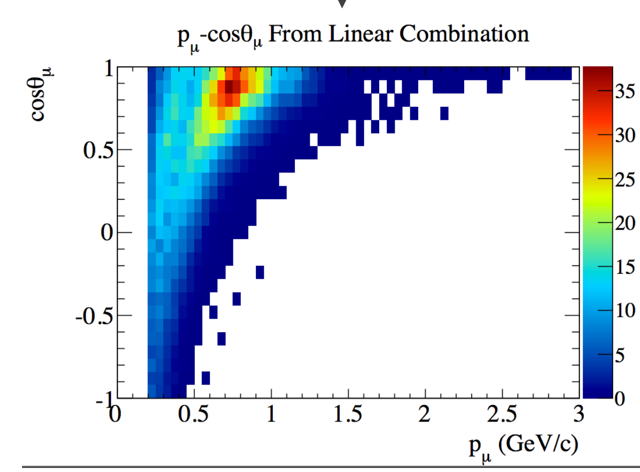


Observed muon kinematic distributions




Linear combinations reproduce the oscillated flux, and predict muon kinematic distributions for the oscillated flux



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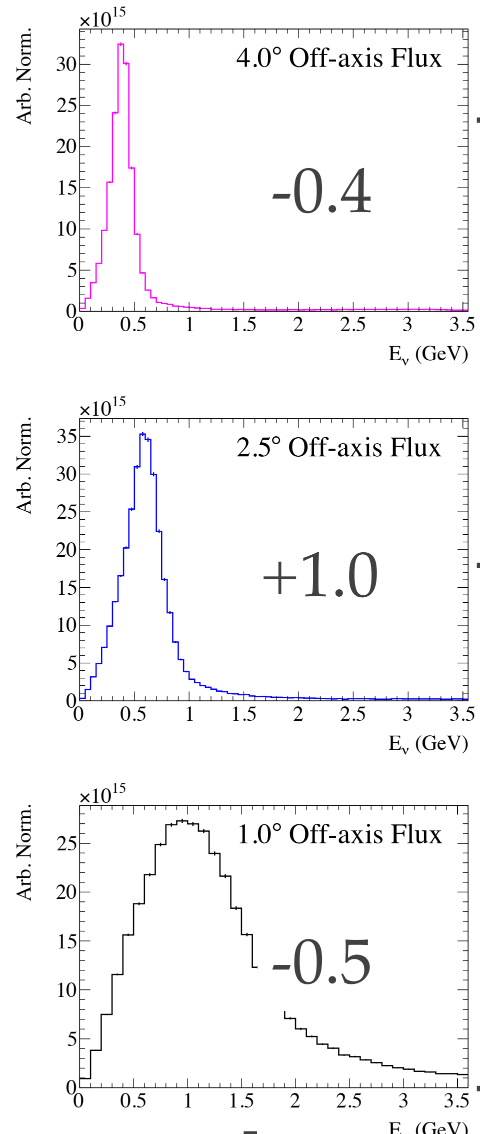
# ADVANTAGE OF MULTIPLE OFF-AXIS ANGLE MEASUREMENTS

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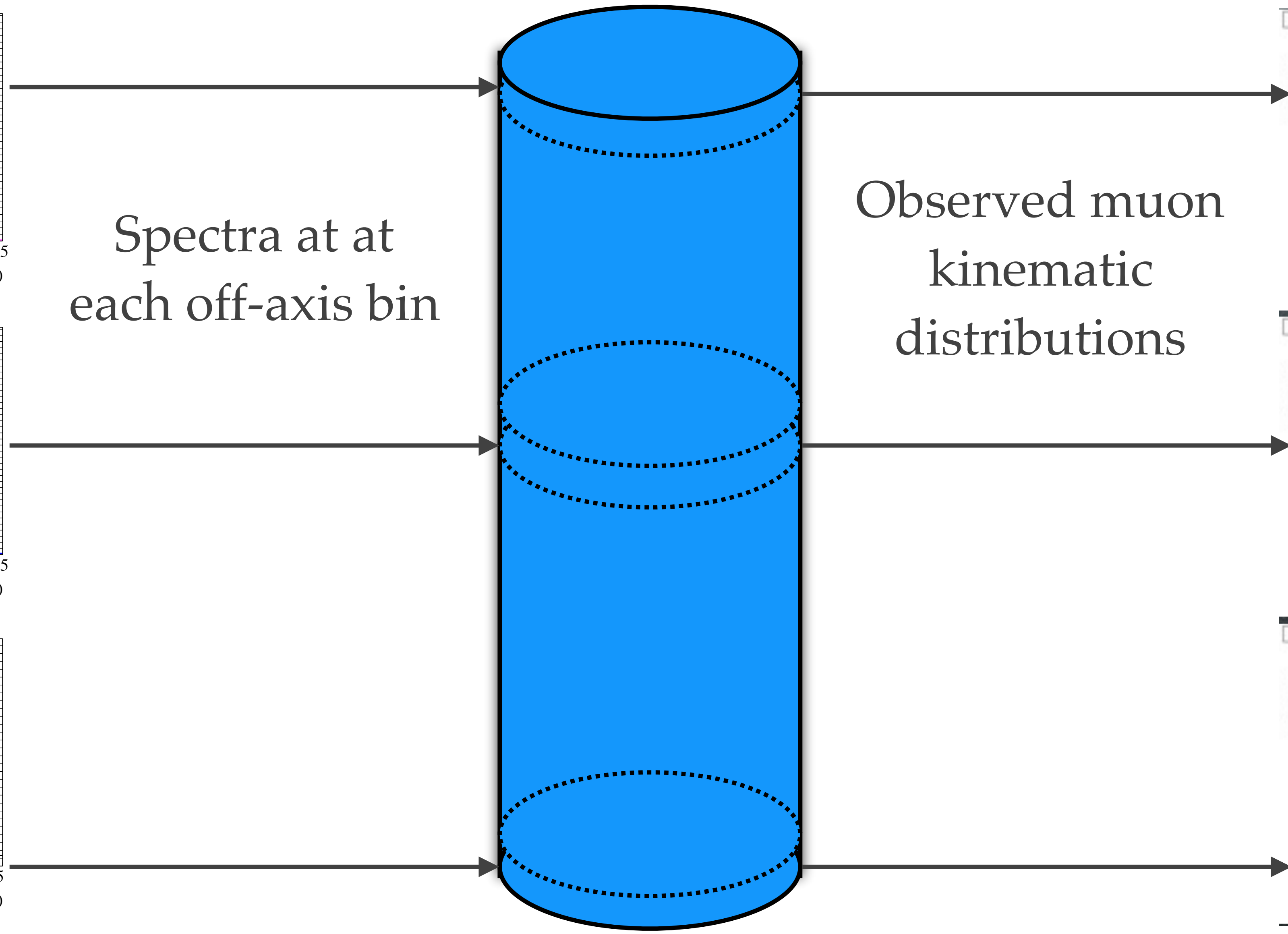

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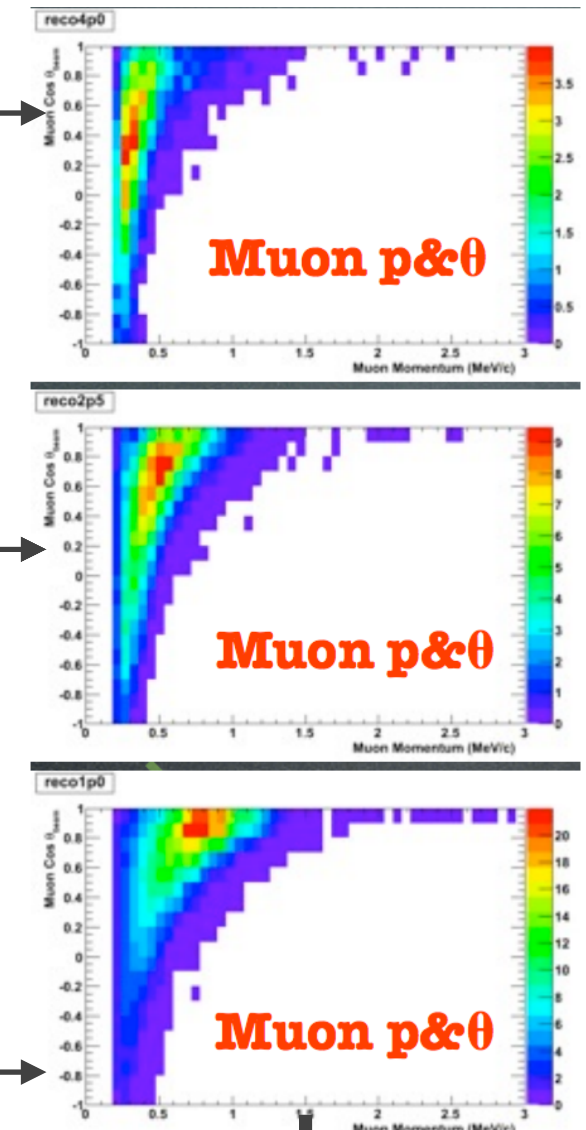


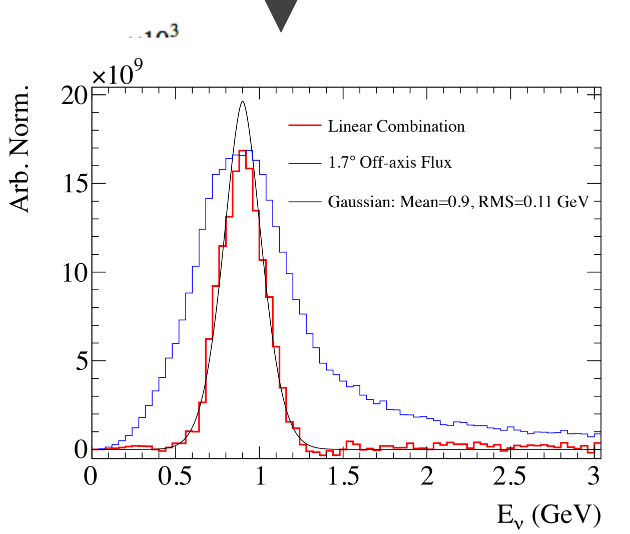


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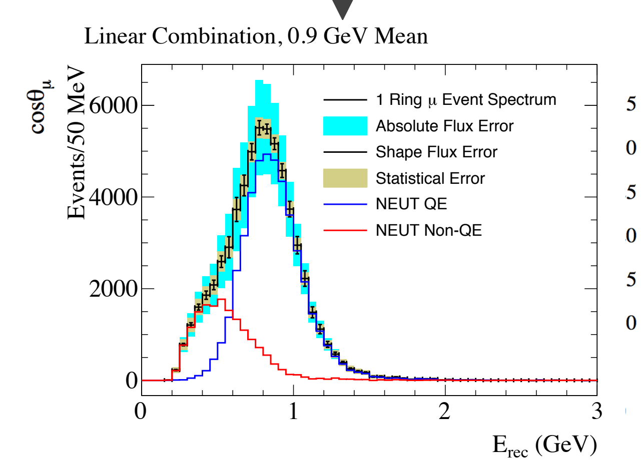
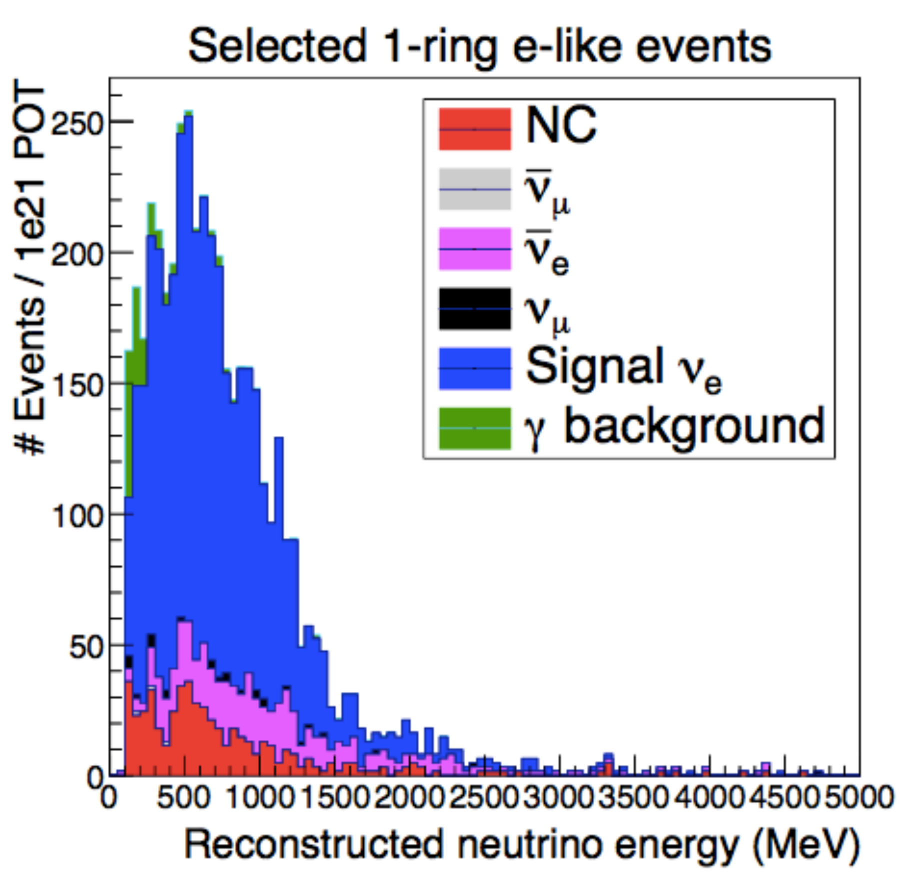


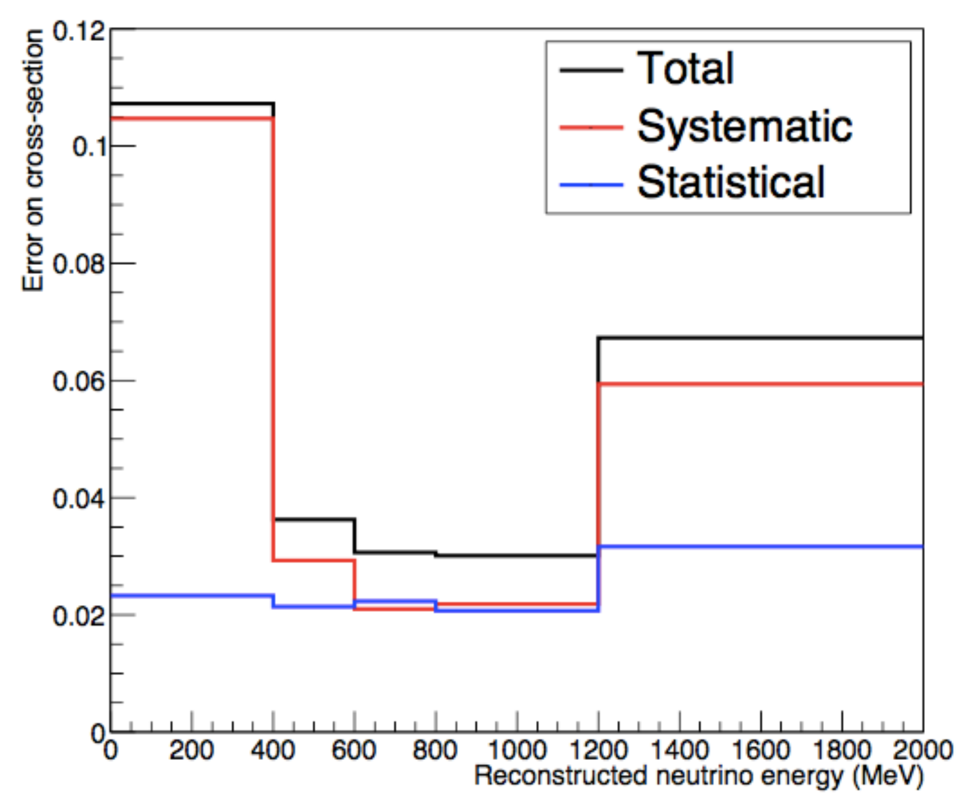
# ELECTRON NEUTRINO CROSS SECTION MEASUREMENT

- *Beam contains contamination of electron (anti)neutrinos from muon and three-body kaon decays*
- *Fraction of $\nu_e$ increases further off-axis*
- *Phase-0: measurement of* $\sigma_{\nu_e}/\sigma_{\nu_\mu}$
- *Phase-1: measurement of* $\sigma_{\nu_e}/\sigma_{\nu_\mu}, \sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$

*High purity $\nu_e$ in Phase-0*

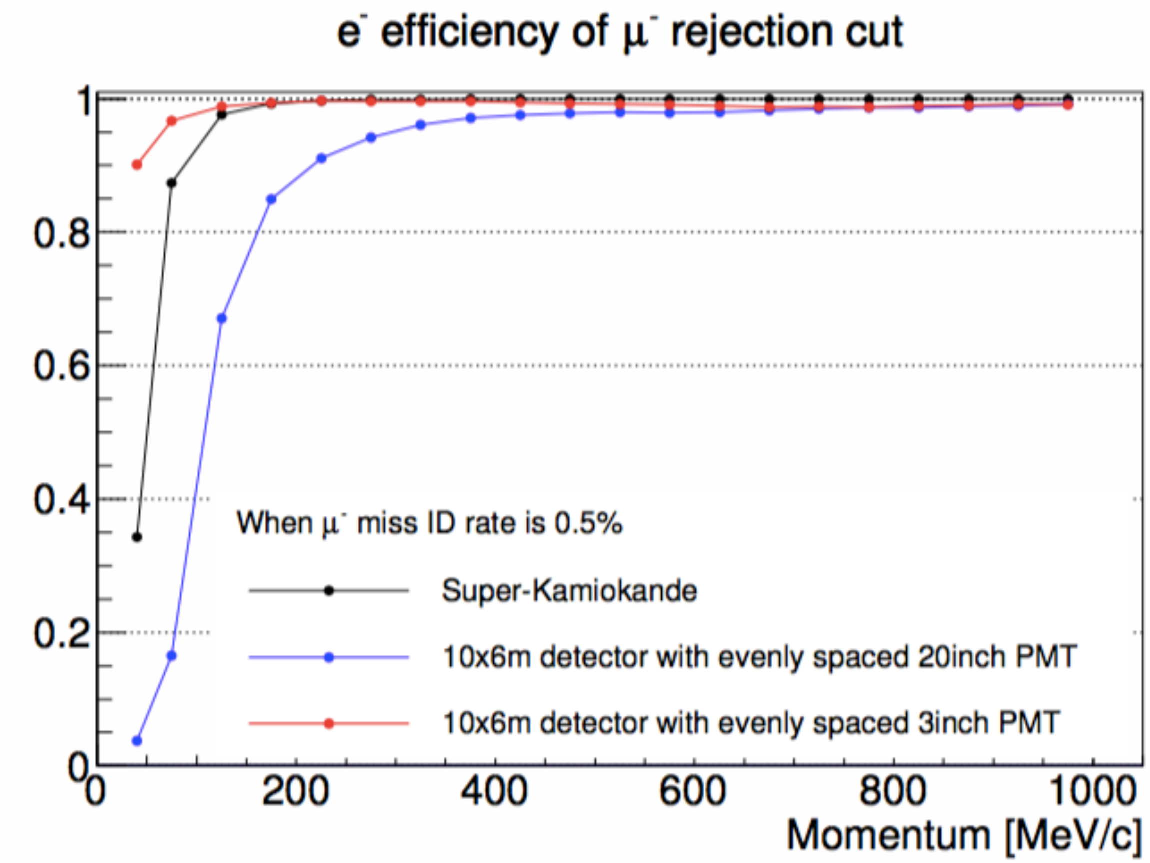


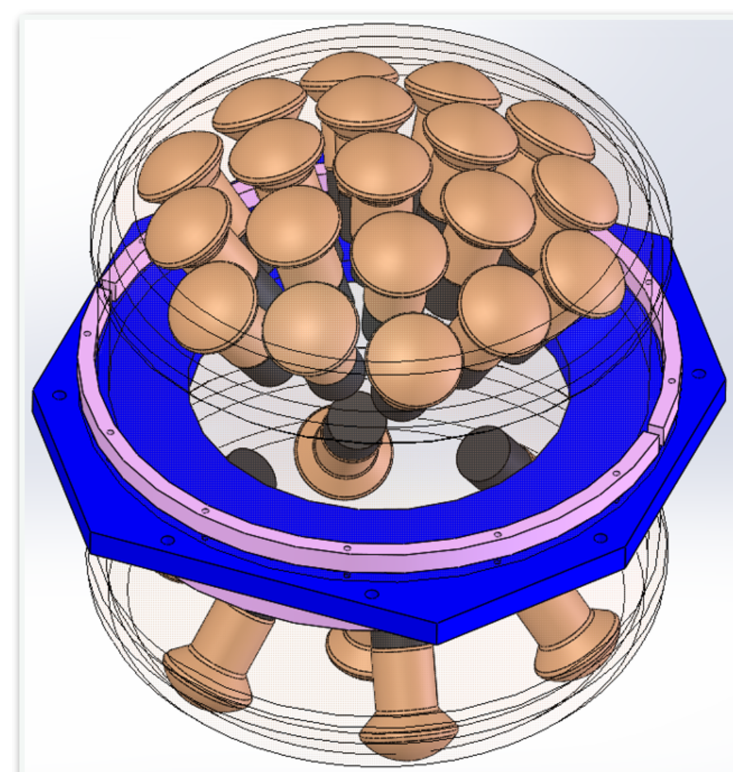

*<3% systematic error on cross section ratio measurement between 400 MeV and 1200 MeV (region of interest)*



# MULTI-PMT PHOTODETECTORS

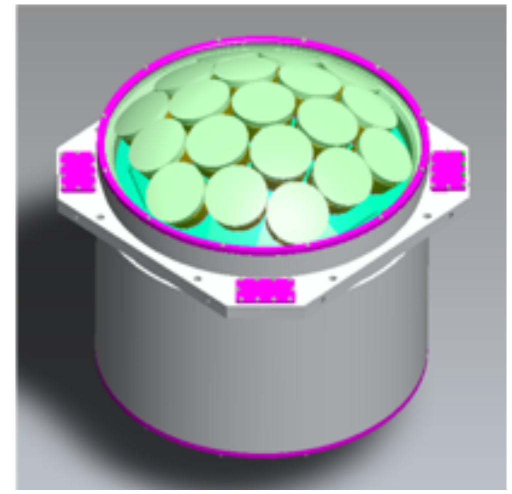
- *E61 requires smaller PMTs (finer granularity) than SK/HK due to the smaller detector size*
- *With 3-inch diameter PMTs, can maintain the performance*
- *Other advantages:*
  - *Cost per photocathode area is competitive with larger area PMTs*
  - *Improved timing resolution has been achieved*
- *Pursue a modular multi-PMT design*
  - *Pressure vessel with acrylic window*
    - *Operation at high pressure = potential photodetector for Hyper-K*
  - *Place readout electronics and high voltage inside vessel*

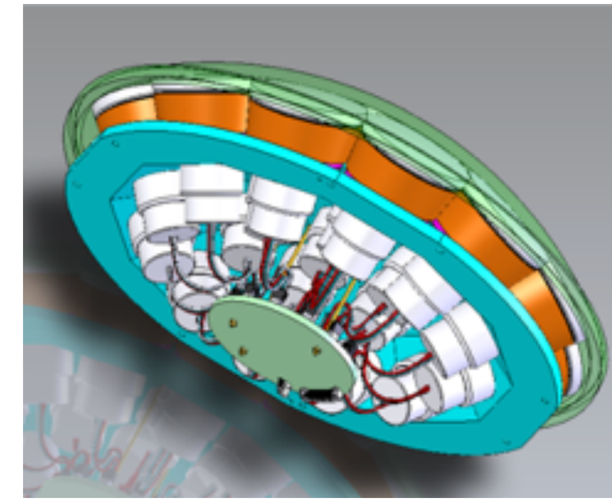


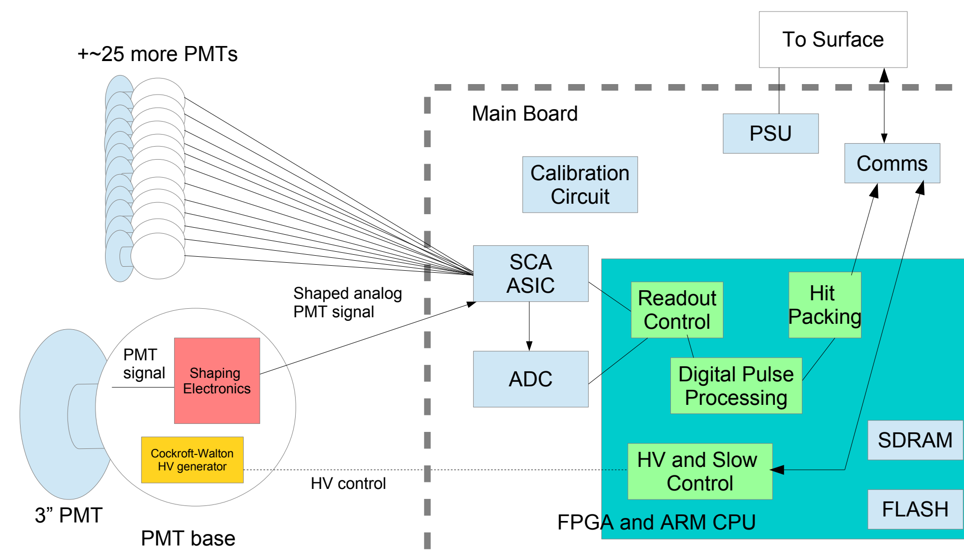
# MULTI-PMT DEVELOPMENT

- *mPMT module design at TRIUMF, Univ. of Toronto, York U.*
  - *Combination of acrylic window with aluminum tube for pressure vessel*

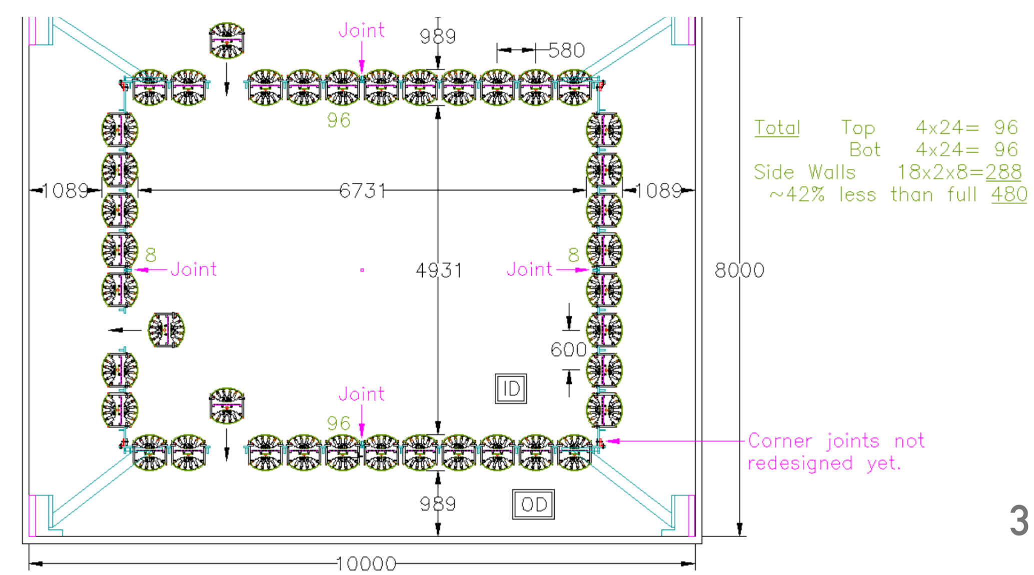




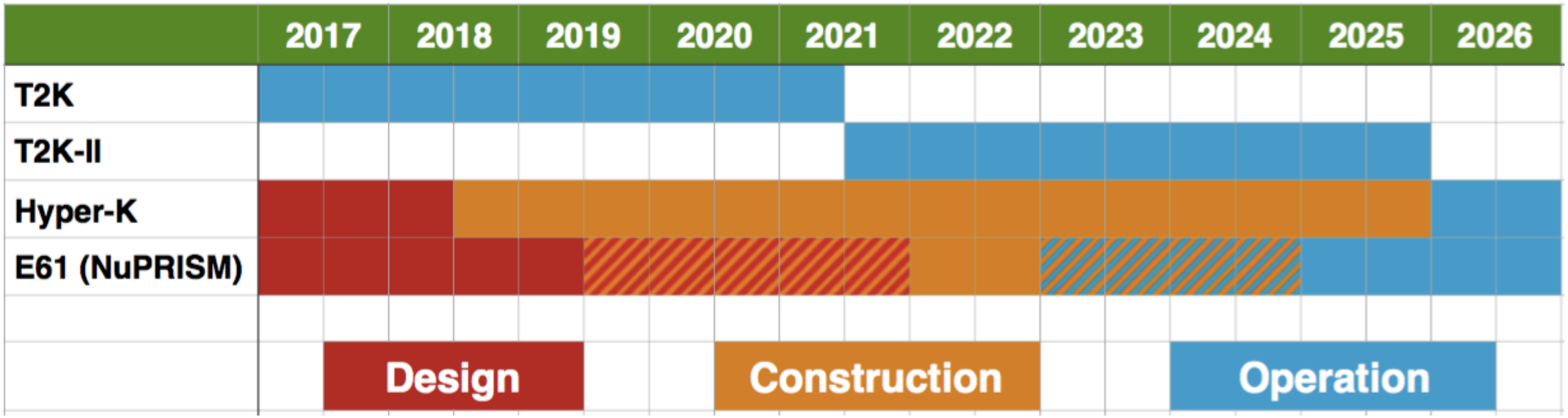
- *mPMT readout electronics development at TRIUMF*
  - *SCA, FADC, time over threshold solutions being considered*




- *mPMT support structure being developed at TRIUMF*



# TIMELINE



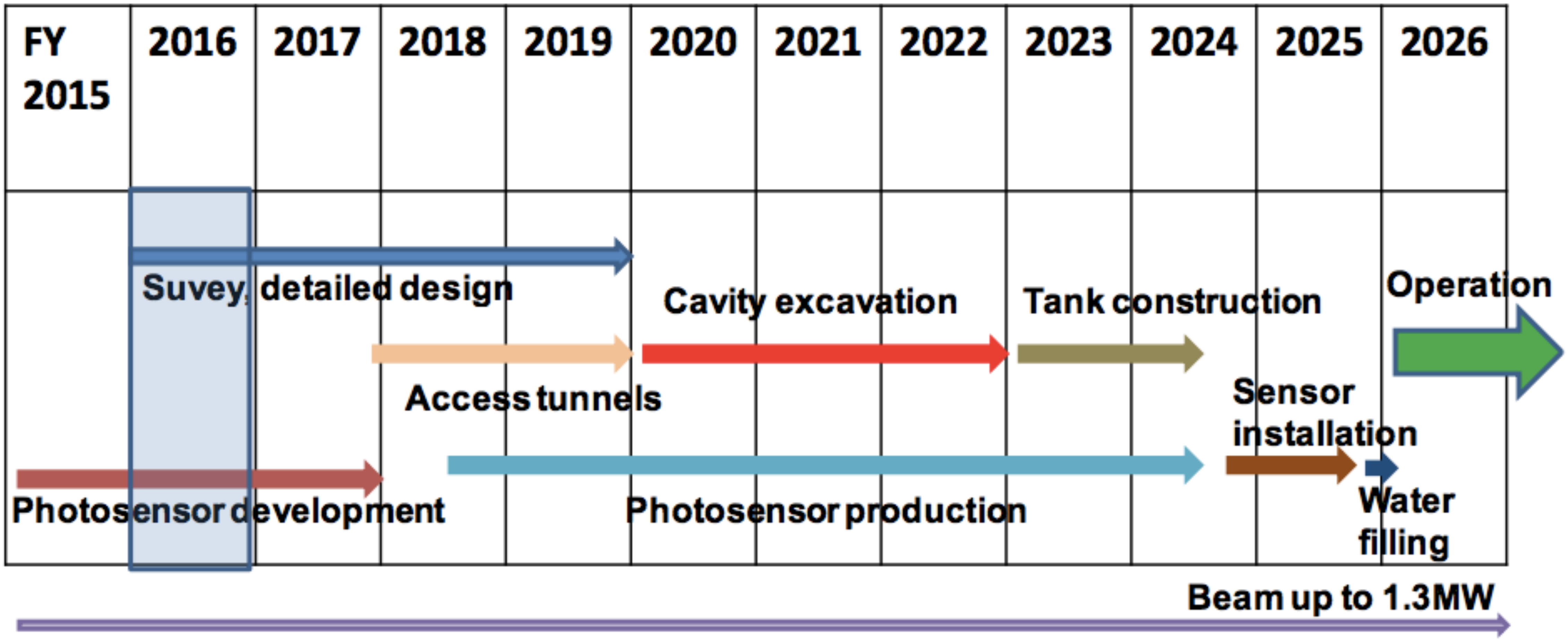

- *T2K-II extension through 2025*
- *Hyper-K coming online in 2026*
- *E61 aims to start taking data before the Hyper-K program to ensure systematic errors are under control for prompt Hyper-K results*

# SUMMARY

- *T2K is making work leading measurements of neutrino oscillations*
    - *Canada making critical contributions to all parts of the experiment*
- *Long-term program for CP violation discovery and precision oscillation parameter measurements*
    - *T2K-II -> Hyper-K*
- *E61 (NuPRISM) will address critical systematic uncertainties in neutrino-nucleus interaction modeling*
- *Exciting program for long baseline neutrinos in Japan with significant physics and technical challenges, potential for high profile discoveries and measurements!*

# THANK YOU

# HYPER-K SCHEDULE

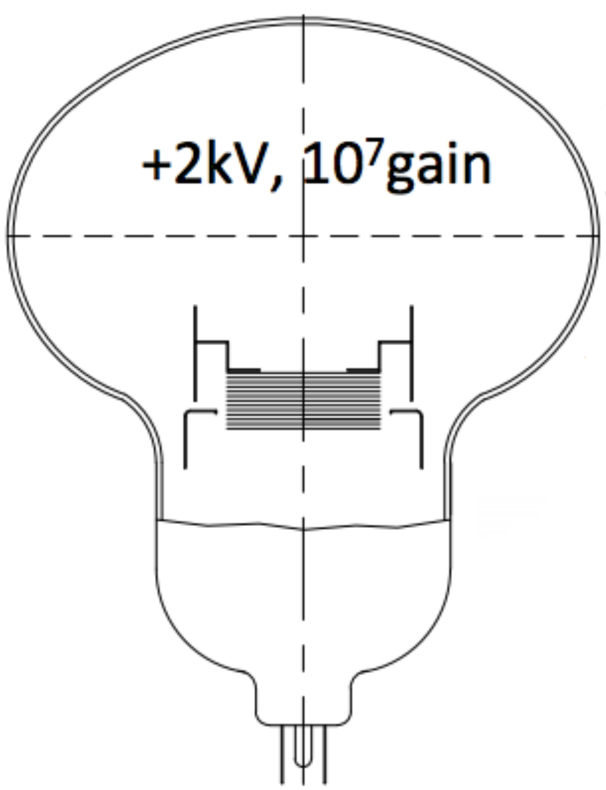



2018-2025: Photo-sensor production and Hyper-K construction

Physics starts from 2026 with 1.3 MW neutrino beam

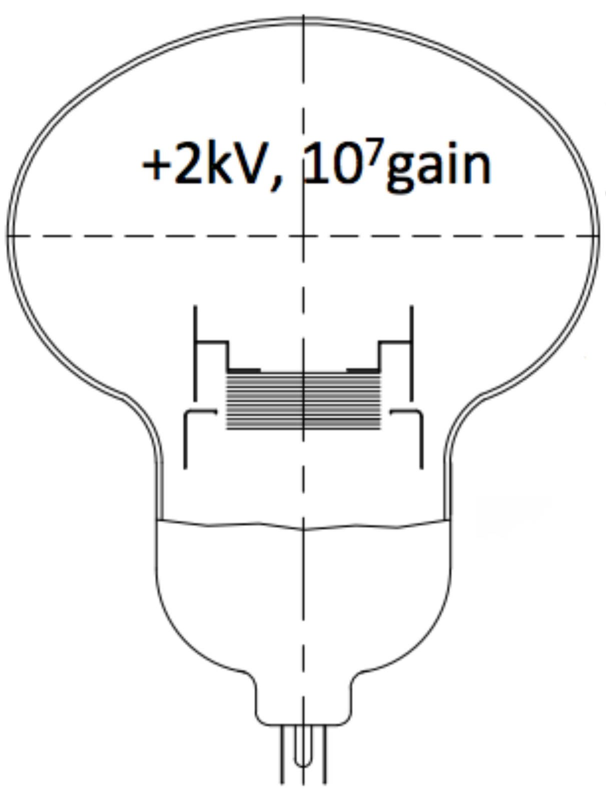
Second tank starts operation 6 years after the first tank

# HYPER-K PHOTODETECTORS


Super-K PMT

# HYPER-K PHOTODETECTORS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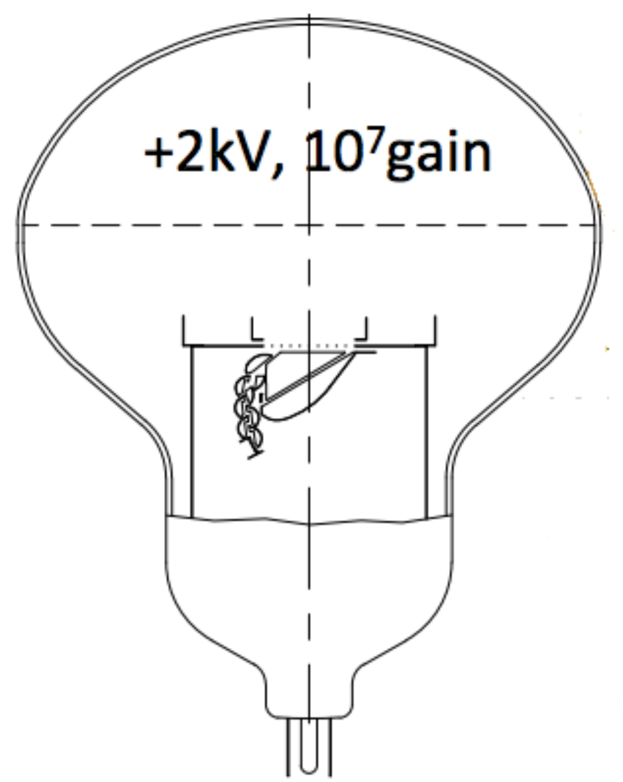



HQE Box&Line

# HYPER-K PHOTODETECTORS

**50 cm Box&Line PMT**

**R12860-HQE** (Box&Line dynode)

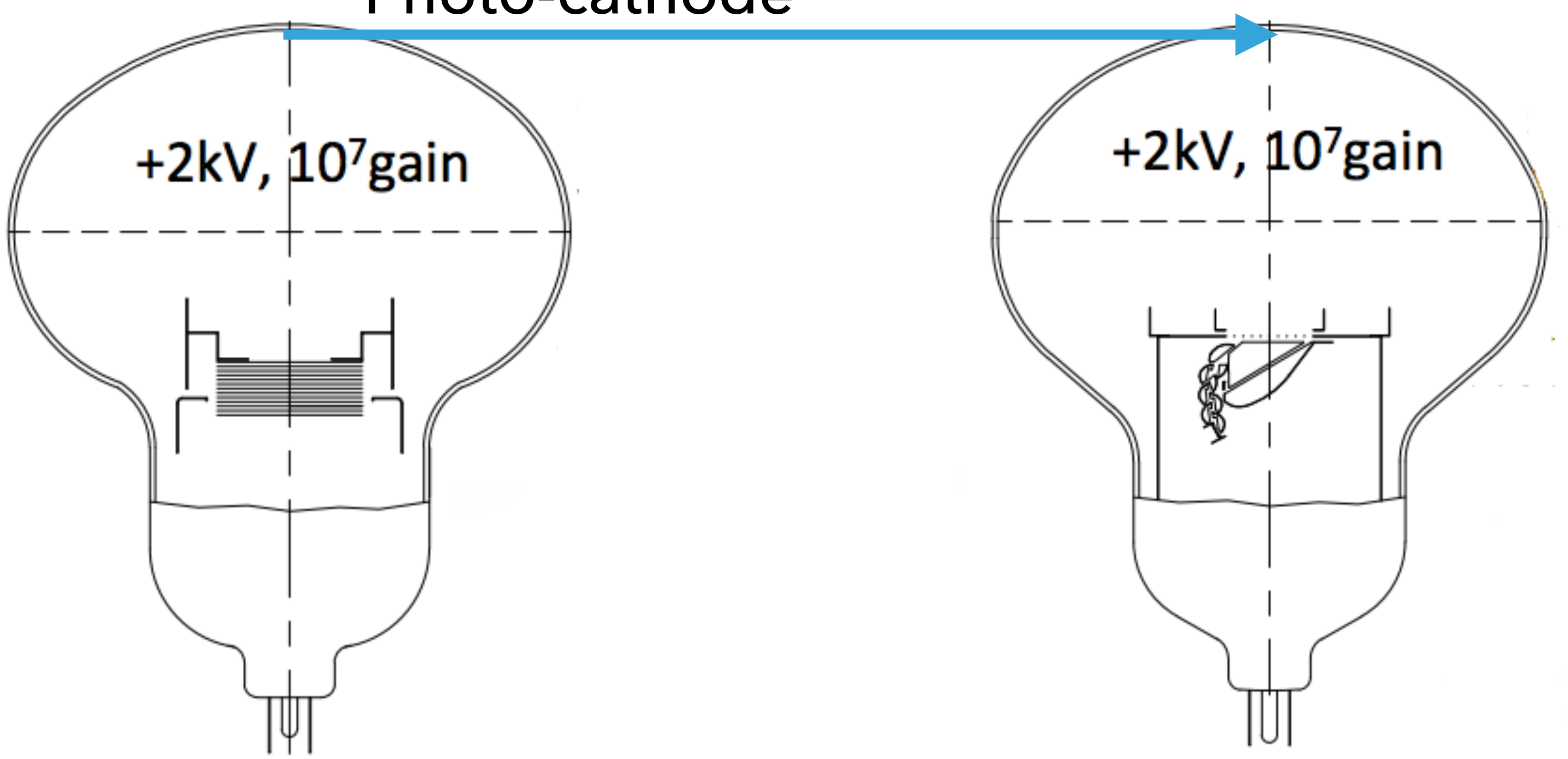
***Developed***
→ Photo-detector in Hyper-K baseline design

**50 cm Hybrid Photo-Detector (HPD)**

**R12850-HQE** (Avalanche diode)

***Under development***
→ Possible further improvement of Hyper-K

High Quantum Efficiency Photo-cathode

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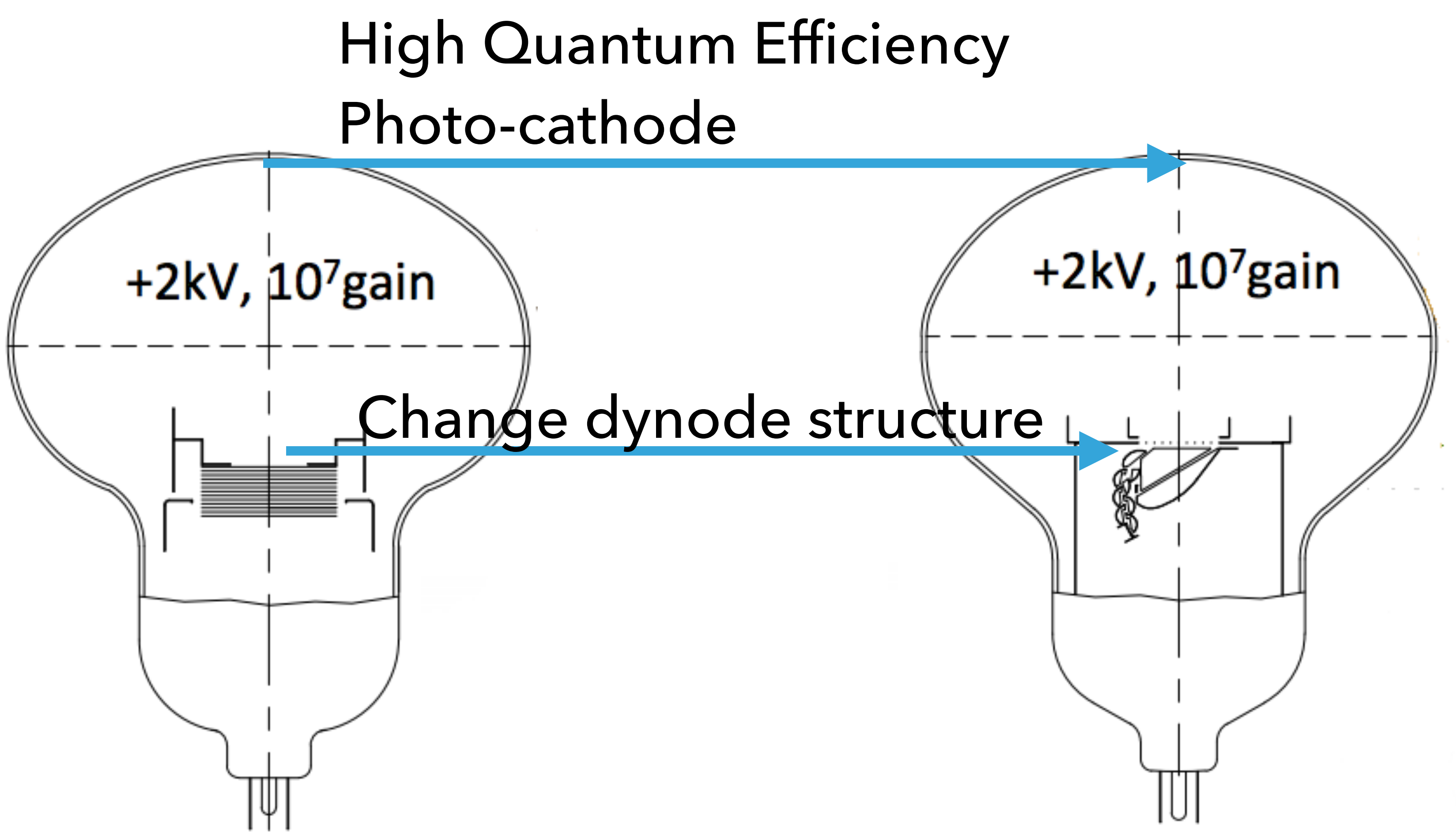


Super-K PMT          HQE Box&Line

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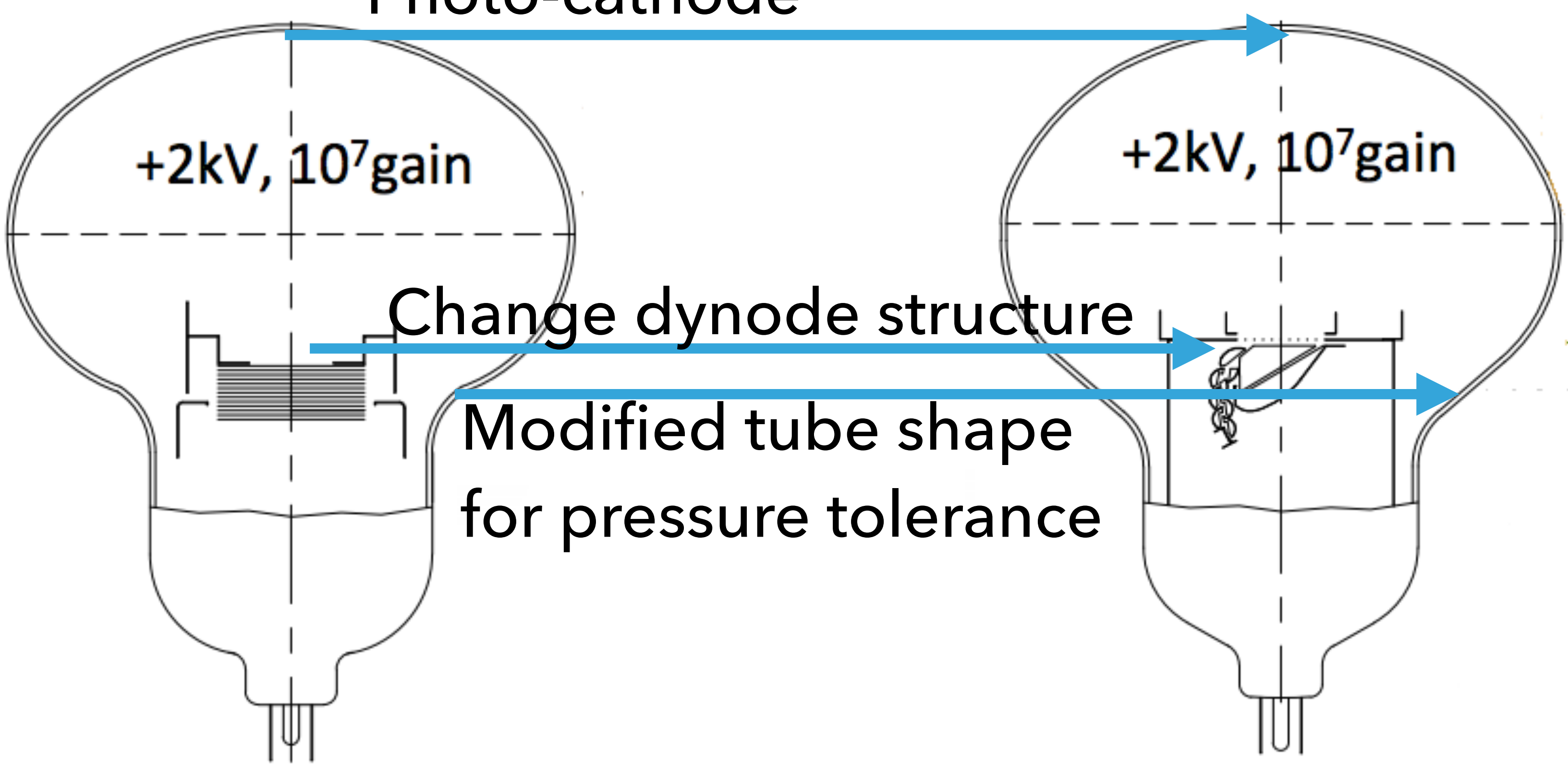


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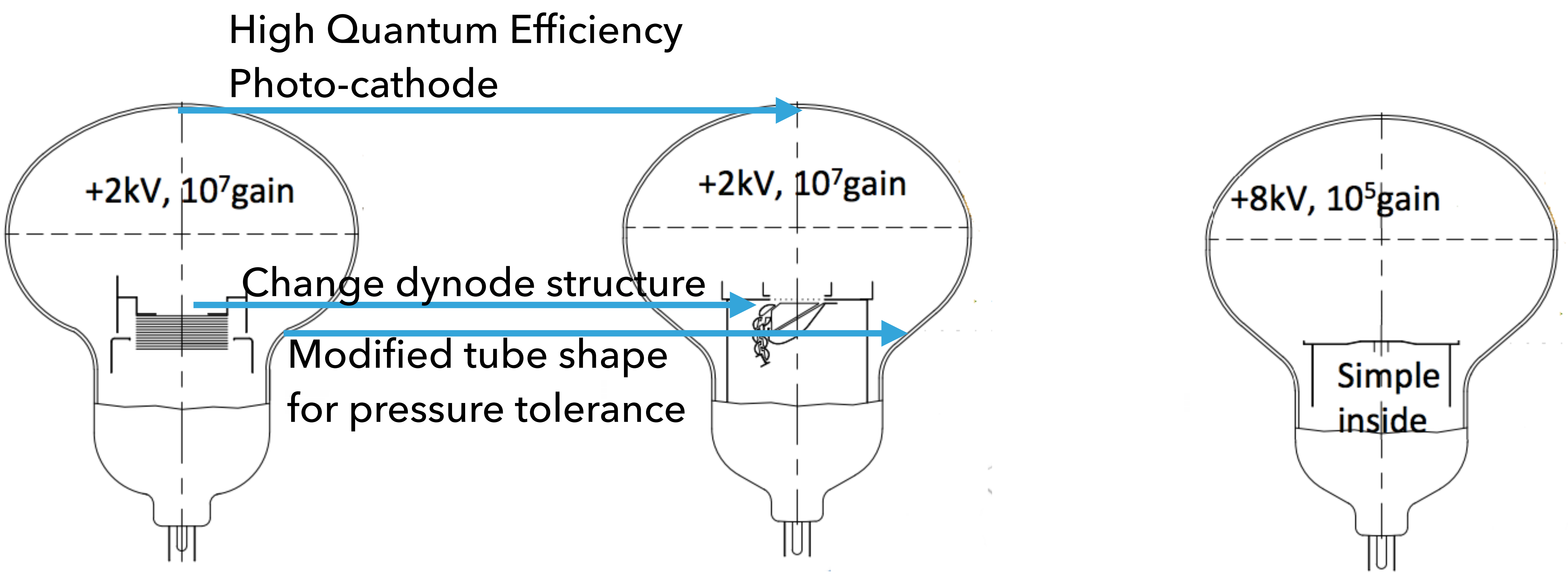


Super-K PMT

HQE Box&Line

HQE HPD

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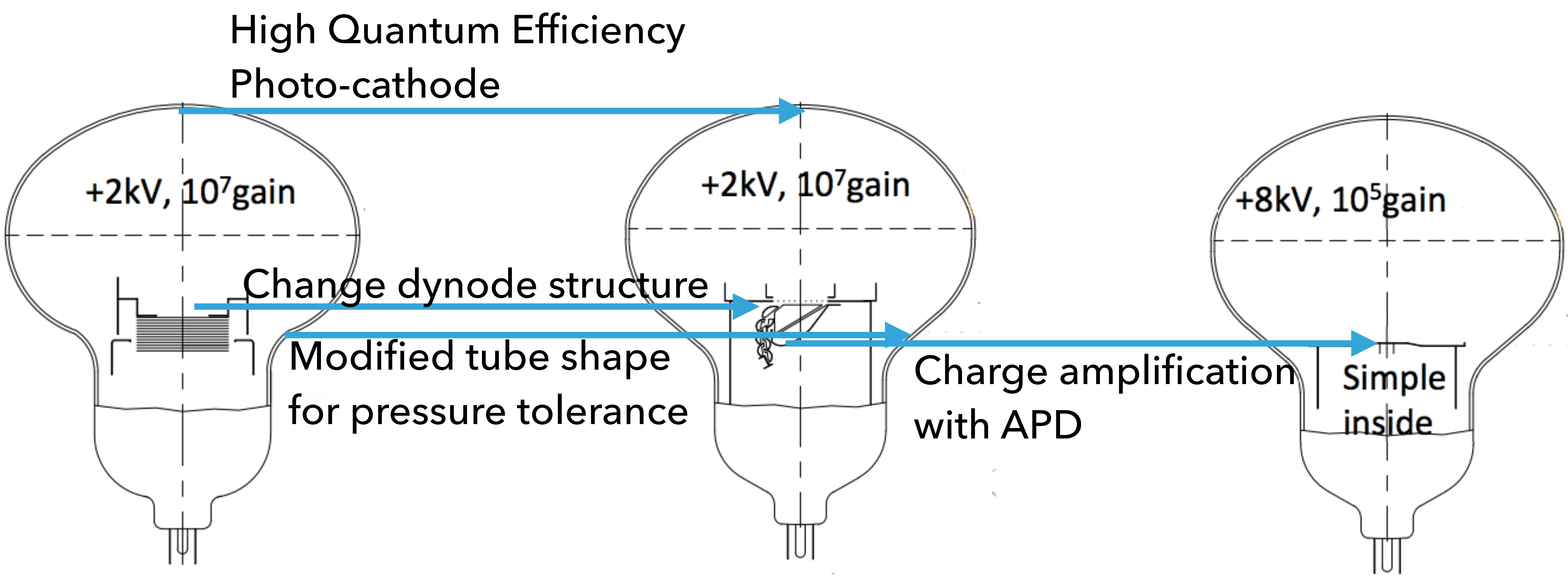
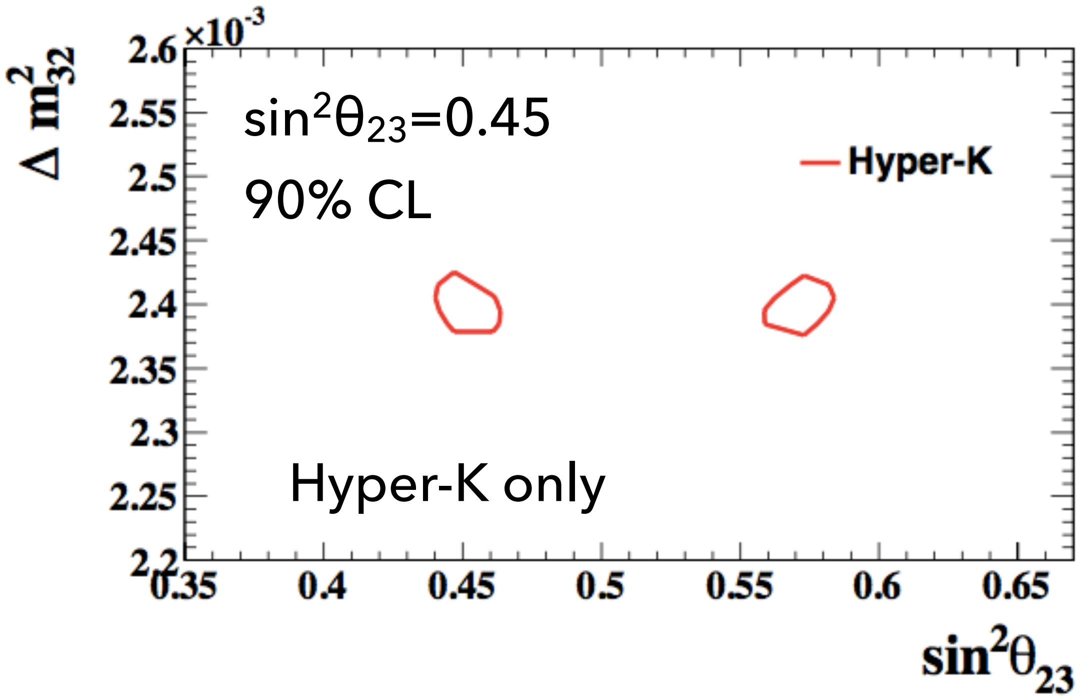
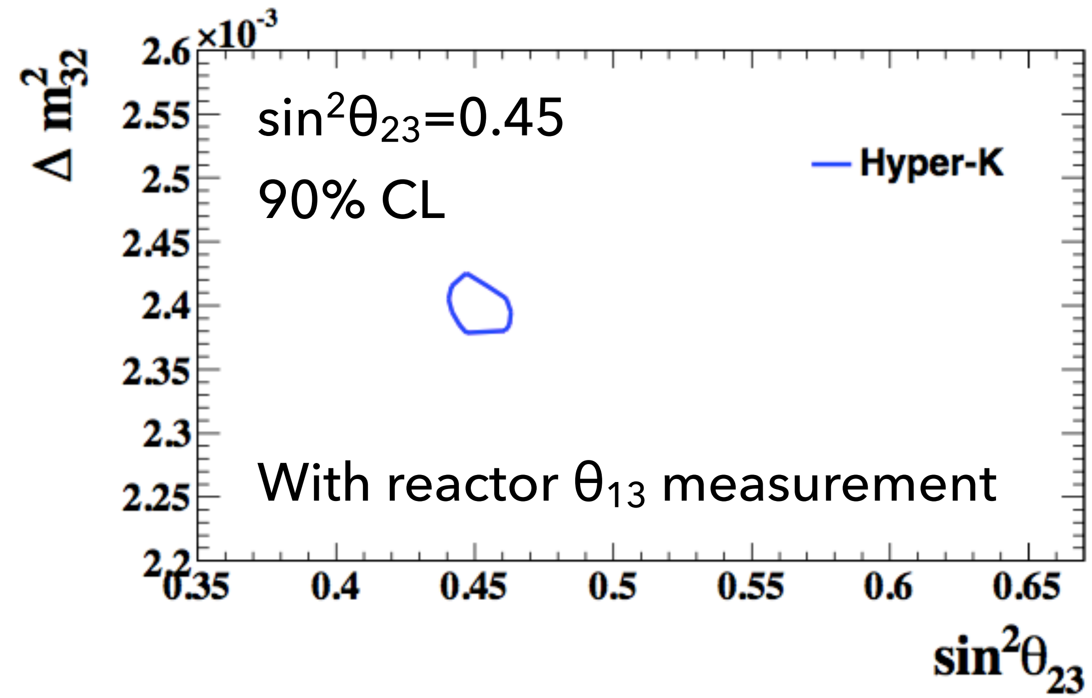



Super-K PMT | HQE Box&Line | HQE HPD

# ATMOSPHERIC PARAMETERS IN HYPER-K

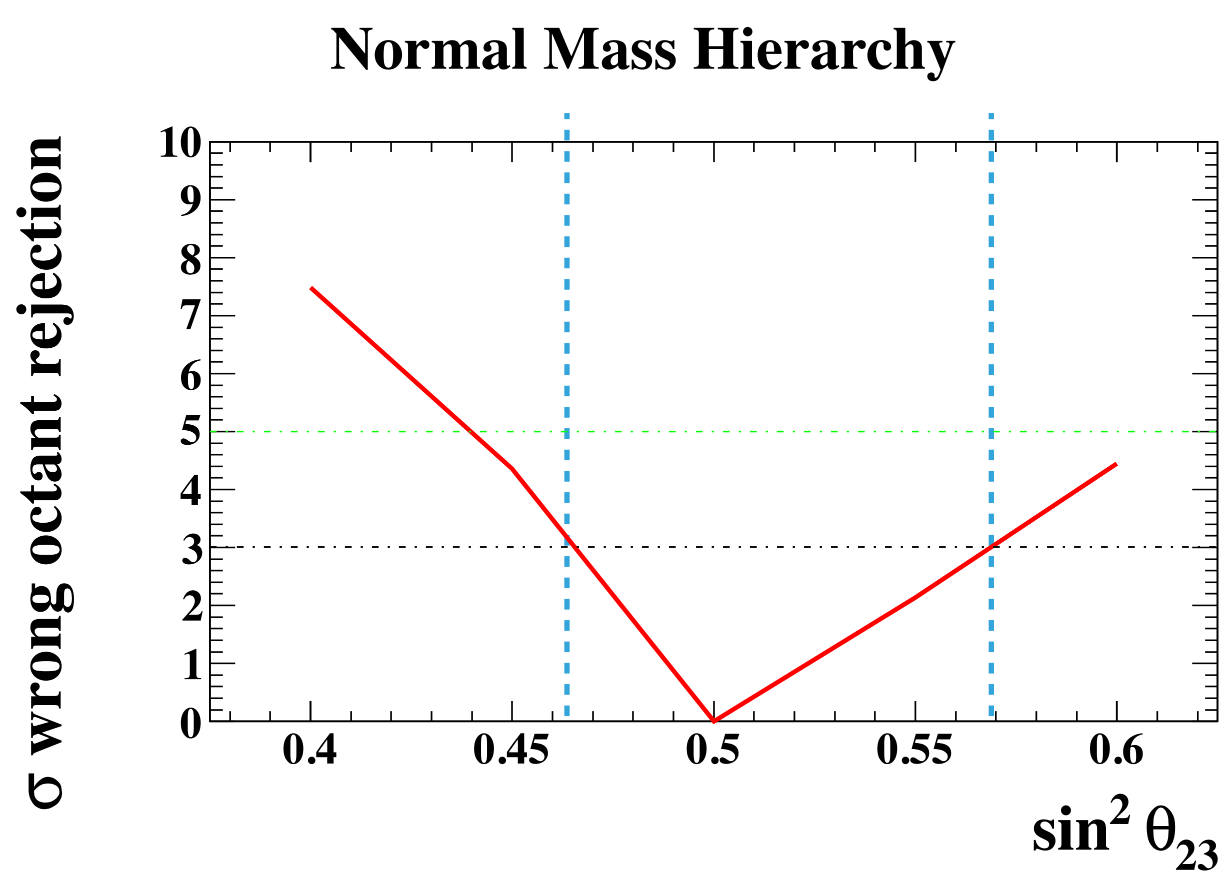


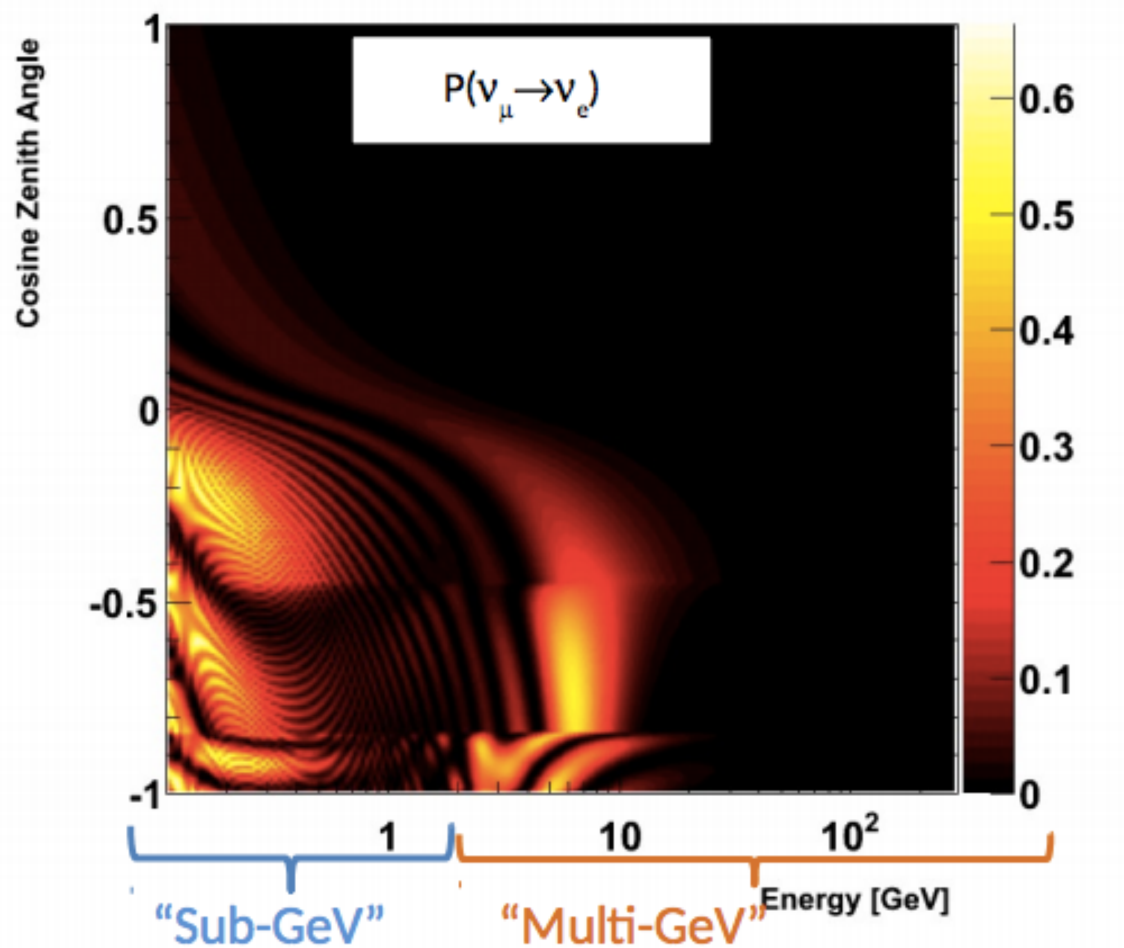

0.6% uncertainty on $\Delta m^2_{32}$

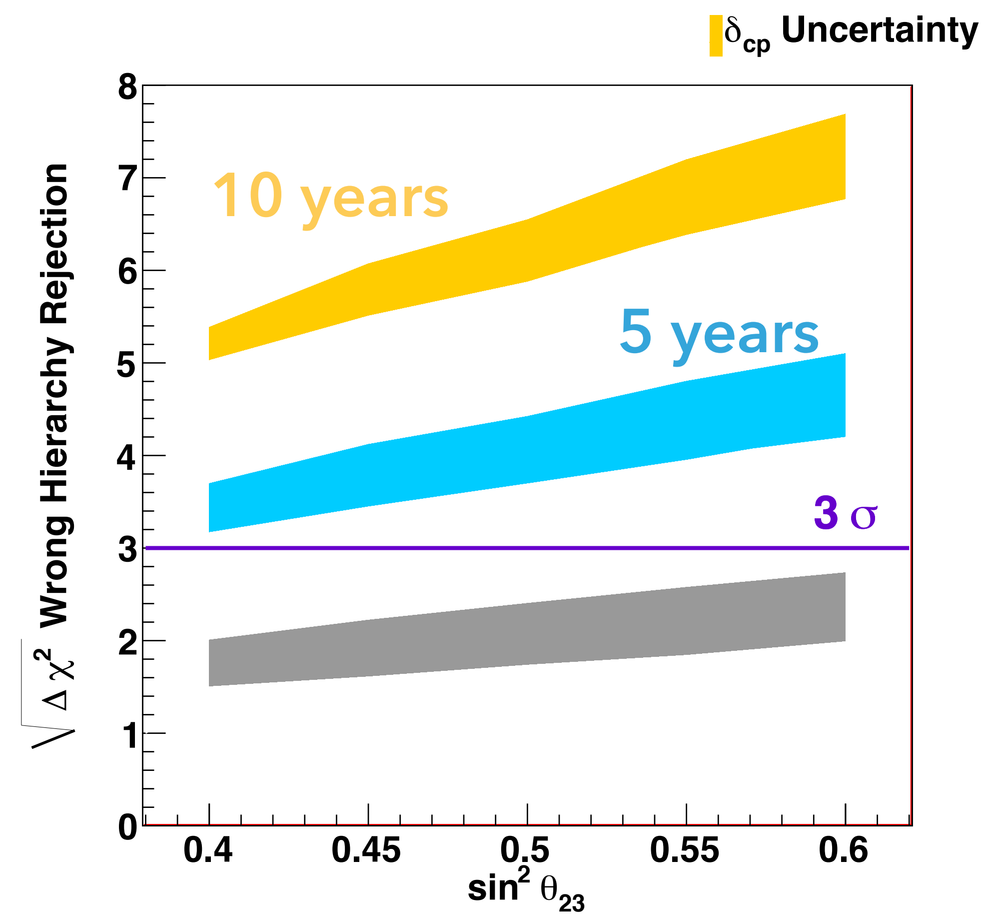
Error on $\sin^2\theta_{23}$ of 0.015 (at 0.5), 0.006 (at 0.45)

Rejection of the wrong octant for non-maximal mixing values of $\theta_{23}$



# ATMOSPHERIC NEUTRINOS IN HYPER-K



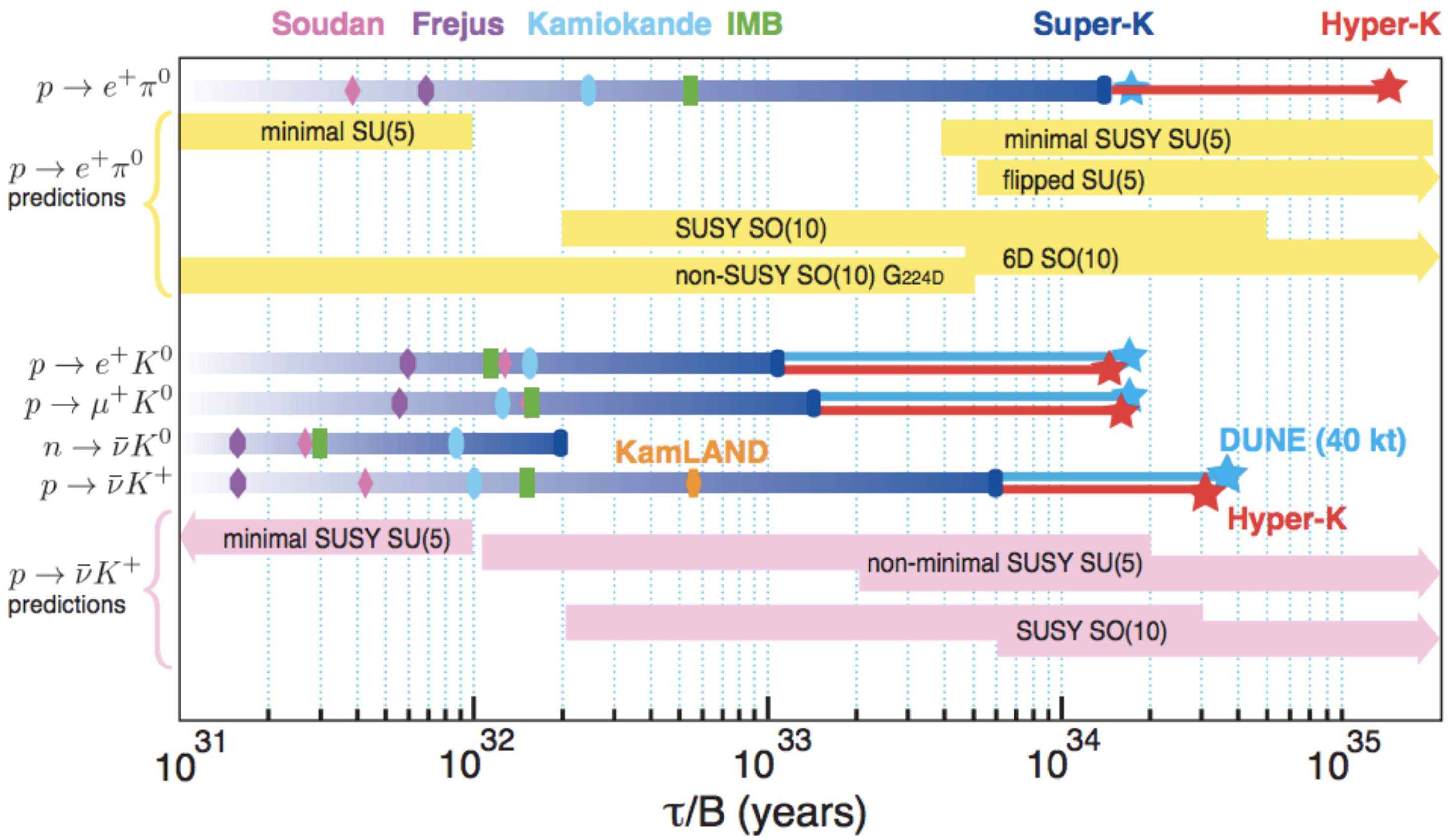




Hyper-K has sensitivity to the mass hierarchy through the atmospheric neutrinos (parametric resonance in the multi-GeV region)

Sensitivity is further improved in combination of accelerator and atmospheric neutrinos

Can determine the hierarchy at >3σ after 5 years, >5σ after 10 years

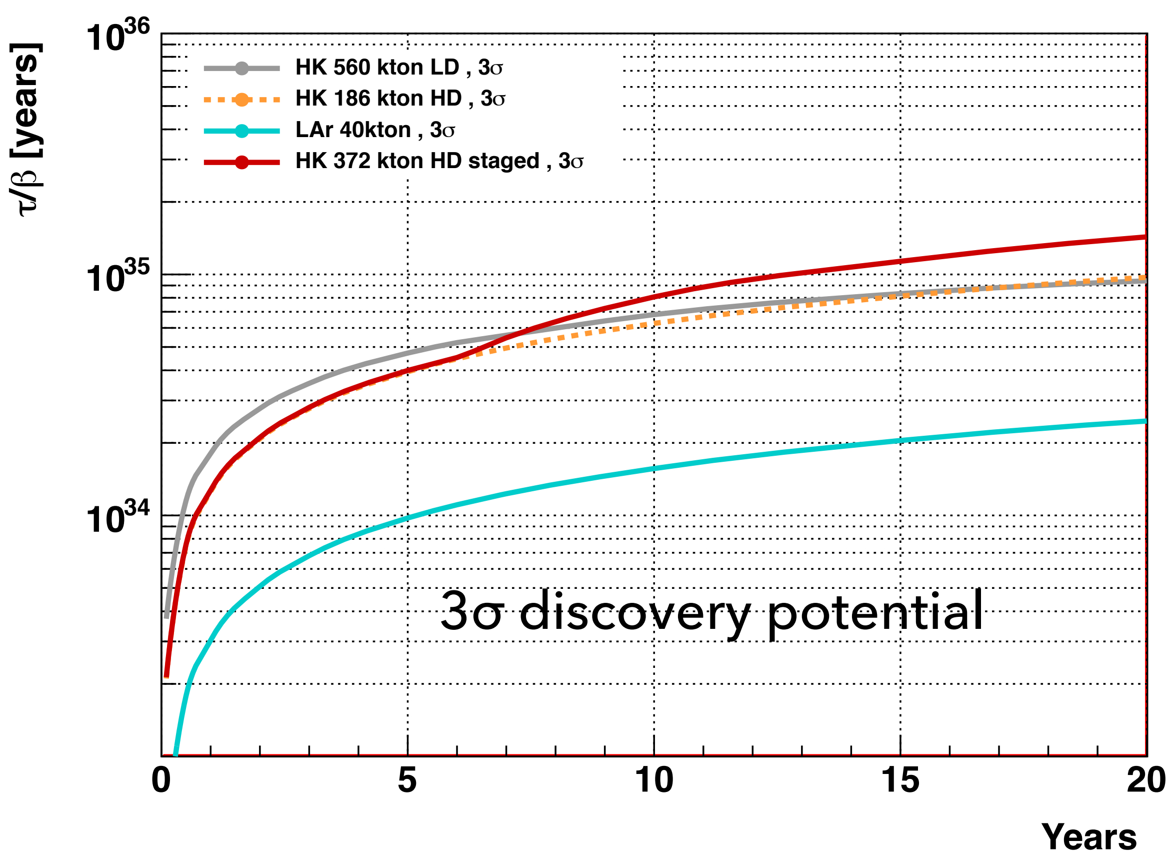
# NUCLEON DECAY IN HYPER-K




1 order of magnitude sensitivity improvements

Leading measurement in $e\pi^0$ mode

Competitive with DUNE in the kaon modes




With smaller tank/high photo-detector density, can achieve same performance as larger tank

Detection of neutron capture on H to reject atmospheric backgrounds

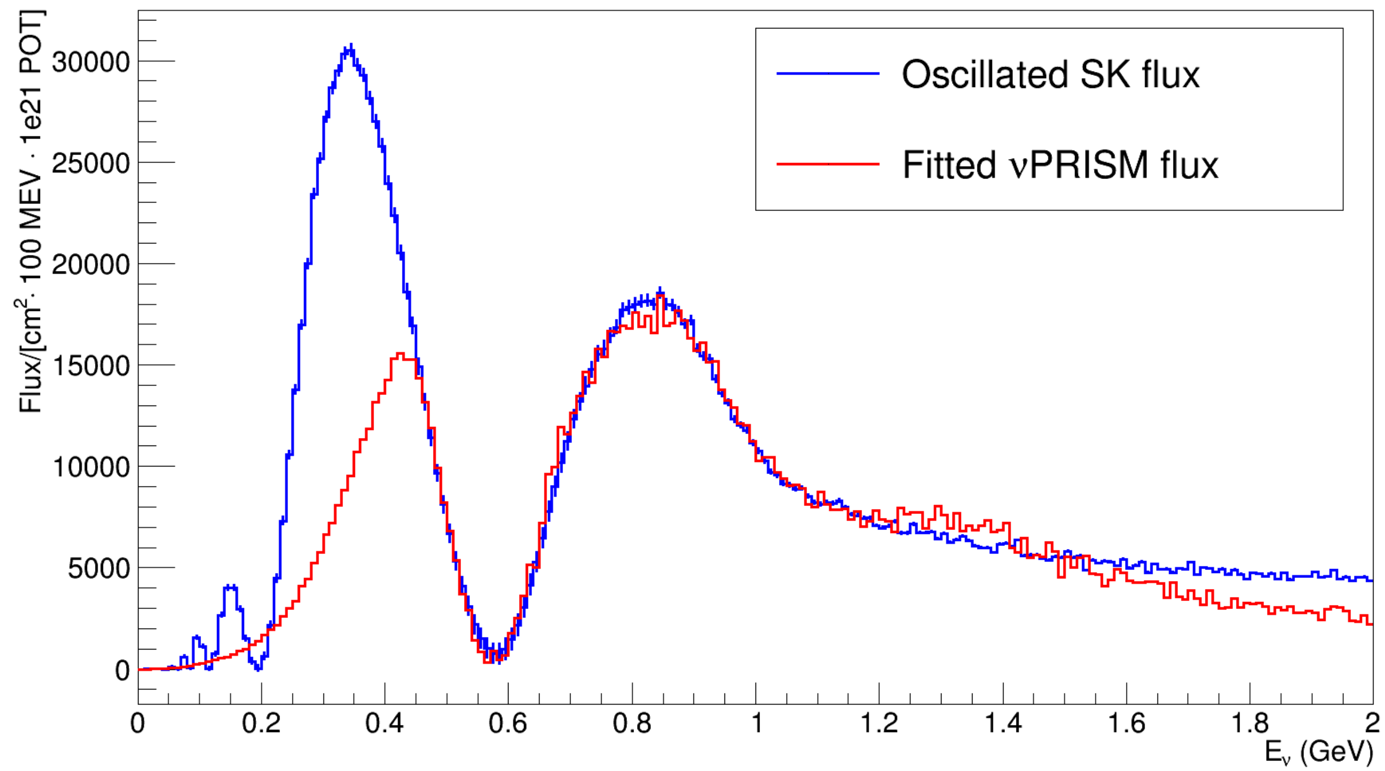
Possible due to PMT efficiency improvements

# T2K DATA

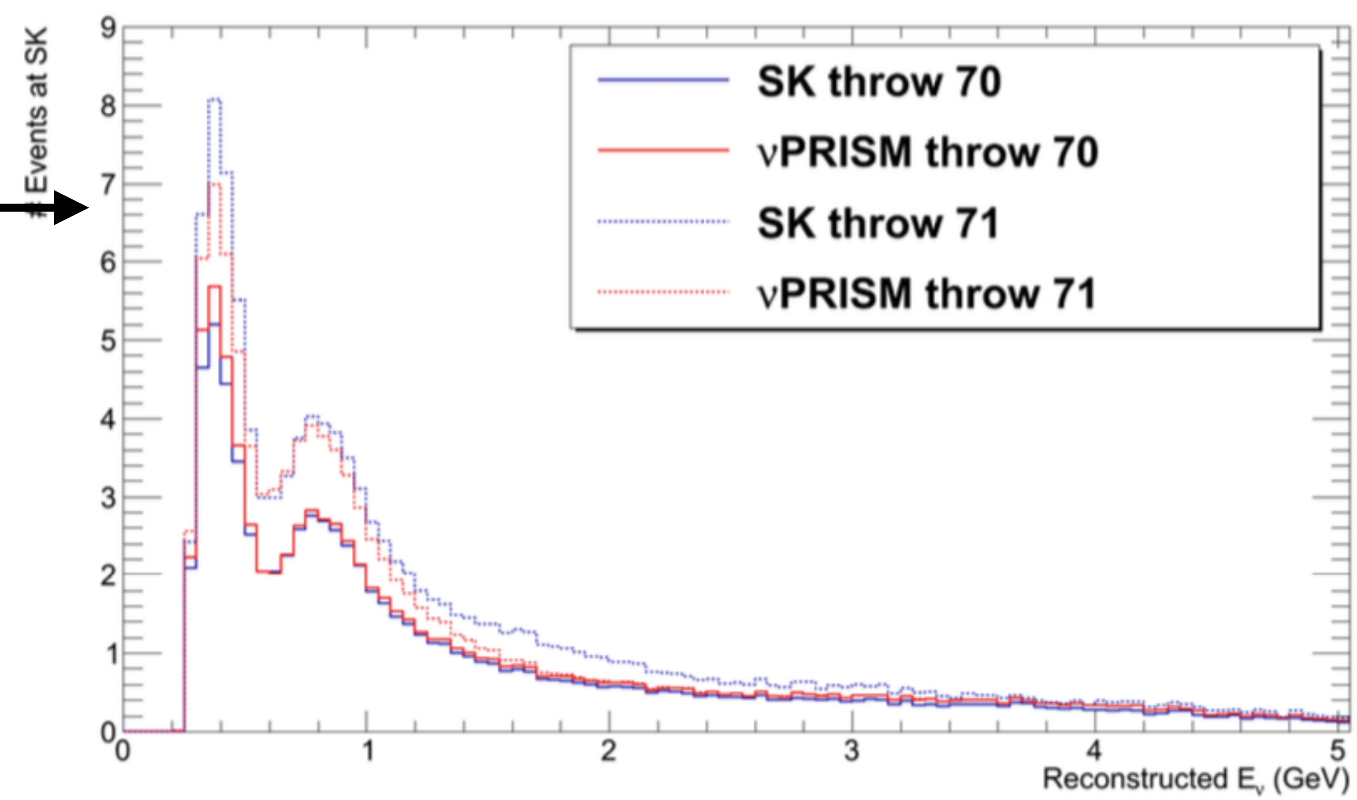
| Beam mode | Sample | $\delta_{CP} = -1.601$ | $\delta_{CP} = 0$ | Exp. Not Osc | Observed |
|---|---|---|---|---|---|
| neutrino | $\mu$-like | 135.815 | 135.459 | 521.777 | 135 |
| neutrino | $e$-like | 28.687 | 24.170 | 6.147 | 32 |
| antineutrino | $\mu$-like | 64.205 | 64.059 | 184.837 | 66 |
| antineutrino | $e$-like | 6.004 | 6.902 | 2.335 | 4 |
| neutrino | CC1$\pi^+$-like | 3.126 | 2.744 | 3.258 | 5 |

# NUPRISM DISAPPEARANCE SPECTRUM

- Linear combination of off-axis fluxes reproduces the far detector spectrum with oscillation hypothesis applied

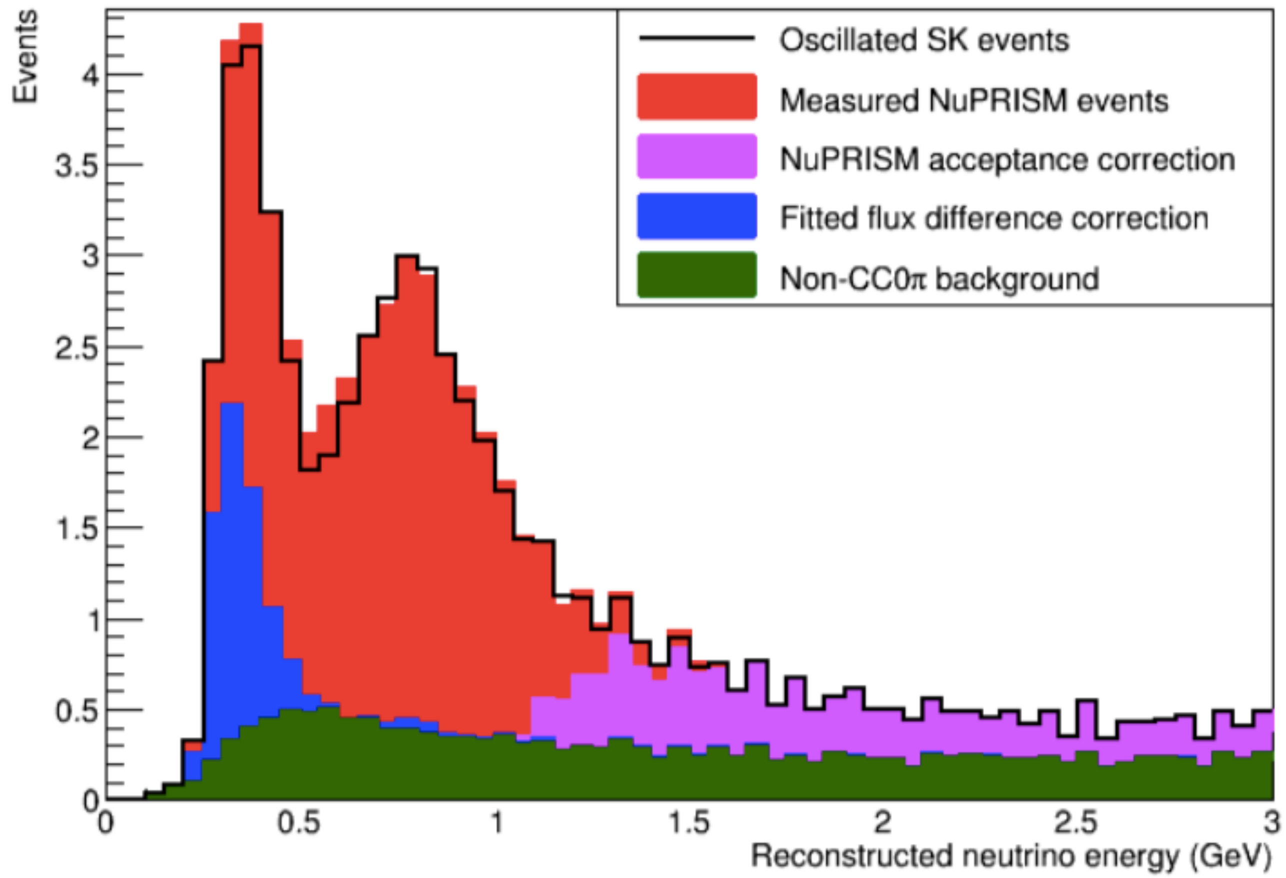


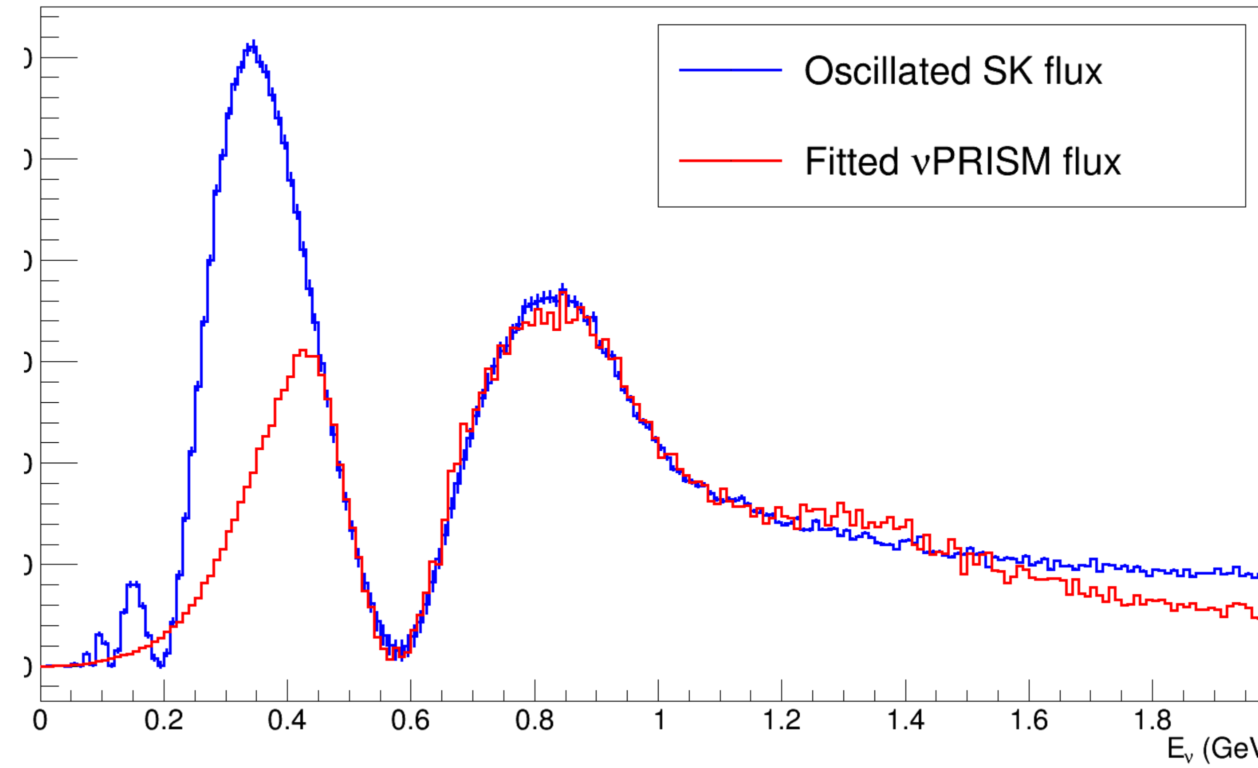

- The linear combination of off-axis measurements are used to predict the reconstructed energy distribution at the far detector

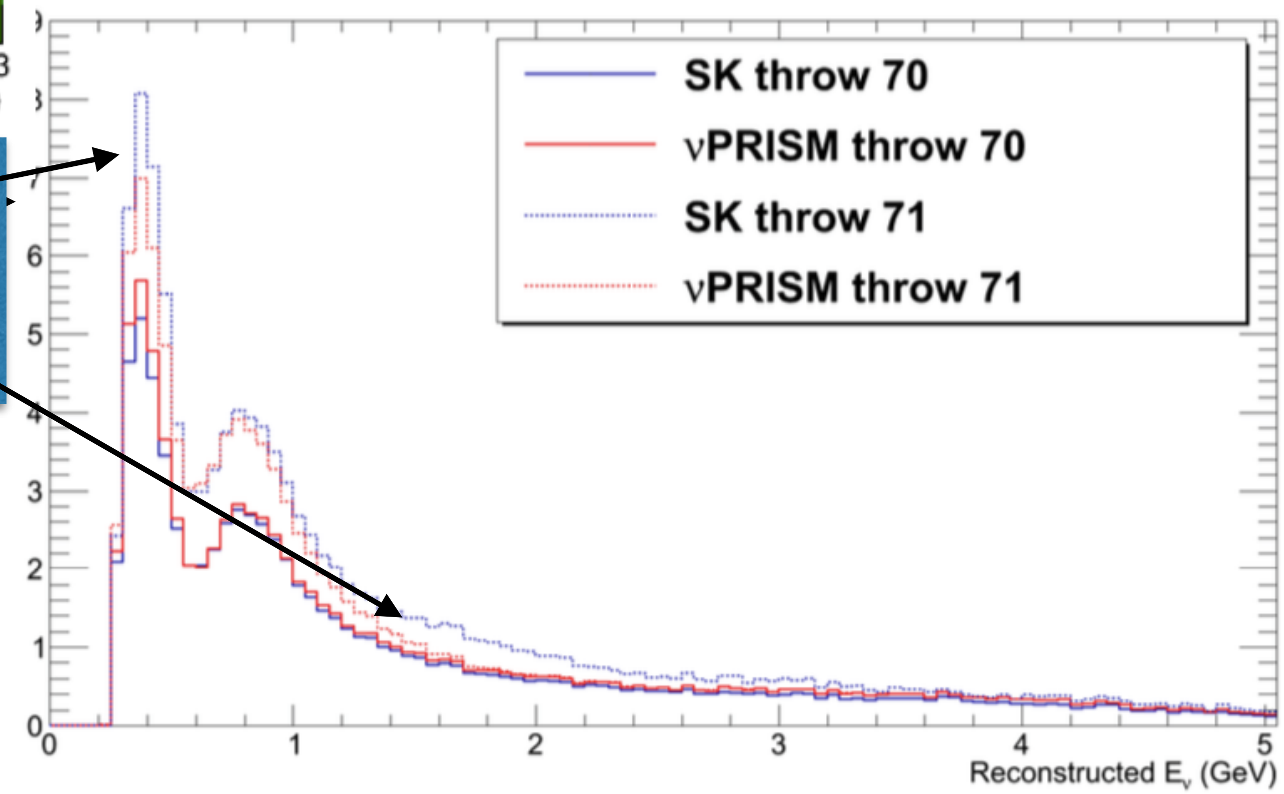



- The **4%** systematic error estimated using the T2K ND280 detector is **reduced to 1% with NuPRISM**

# NUPRISM DISAPPEARANCE SPECTRUM



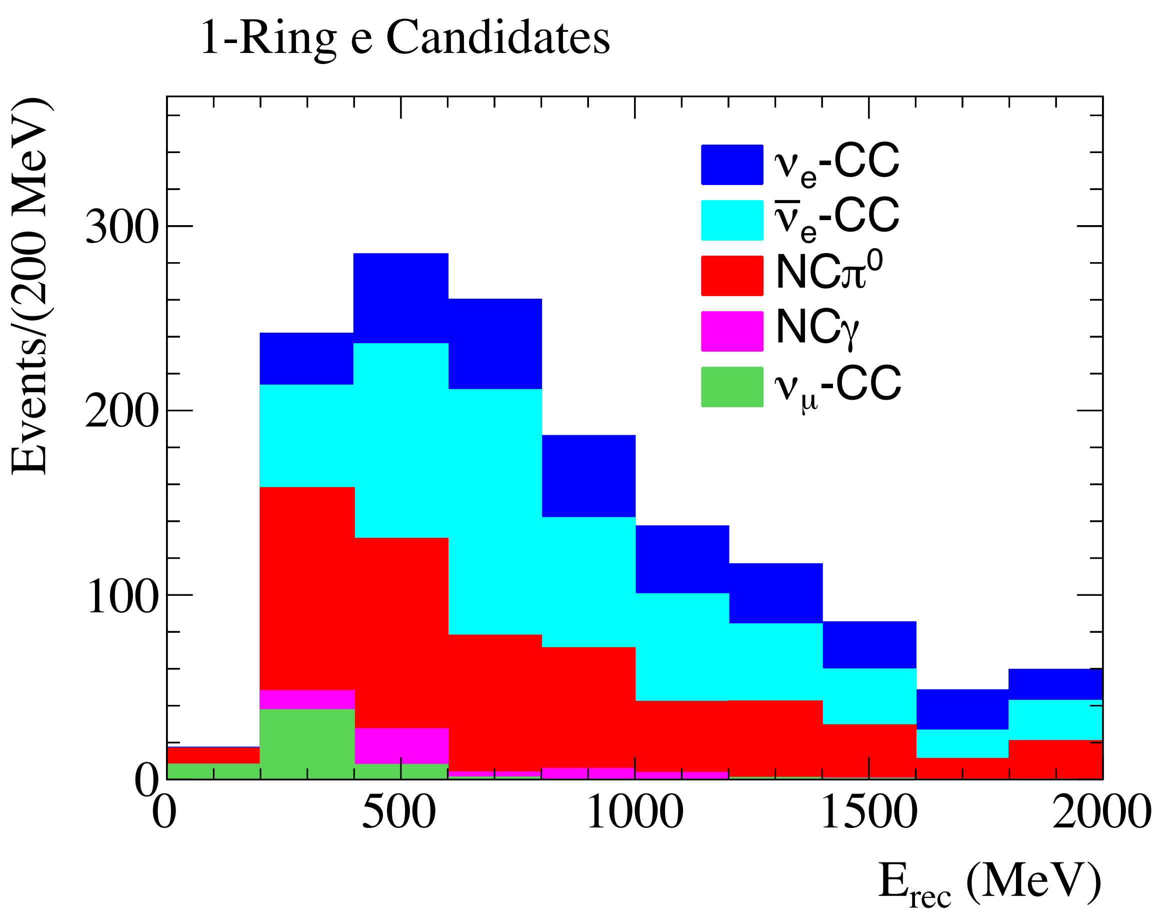




at t

Variations at away from oscillation minimum due to flux and acceptance corrections

- The **4%** systematic error estimated using the T2K ND280 detector is **reduced to 1% with NuPRISM**

# ELECTRON ANTINEUTRINOS IN PHASE-1

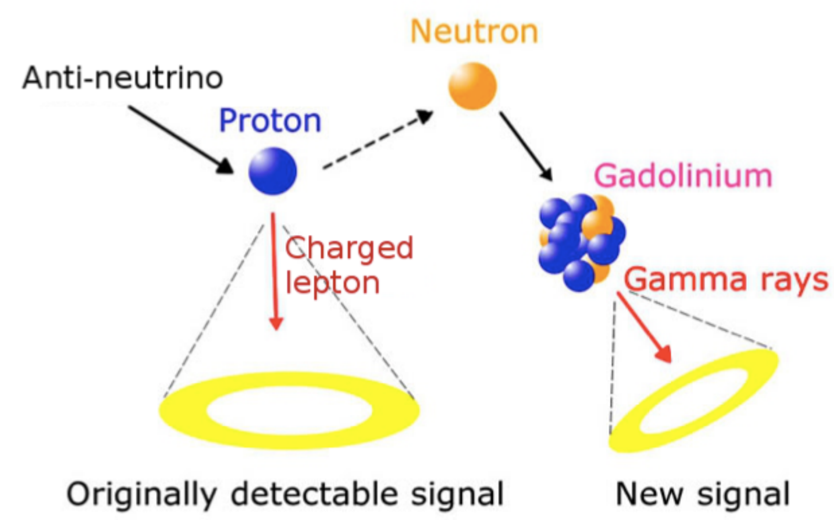



- At 2.5 degrees off-axis, the electron antineutrino rate is twice the electron neutrino rate
- NC background reduction can significantly improve the sample purity

| | Events | Signal % | Wrong-Sign % | Bgnd. % |
|---|---|---|---|---|
| 2.5 | 1128 | 37.5 | 18.4 | 44.1 |

# NEUTRON MEASUREMENTS

- Super-K will be loaded with $Gd_2(SO_4)_3$ to increase neutron detection efficiency to ~90%




- Potential benefits to high energy physics program:
    - Rejection of atmospheric backgrounds to proton decay
    - Statistical separation of neutrinos and antineutrinos in atmospheric and accelerator samples
    - Another probe of the hadronic final states in neutrino-nucleus interactions

**To use the additional information from the neutron detection, measurements of the neutron production in a intermediate/near detector are important**