NEAR DETECTOR CHALLENGES FOR T2K AND HYPER-K

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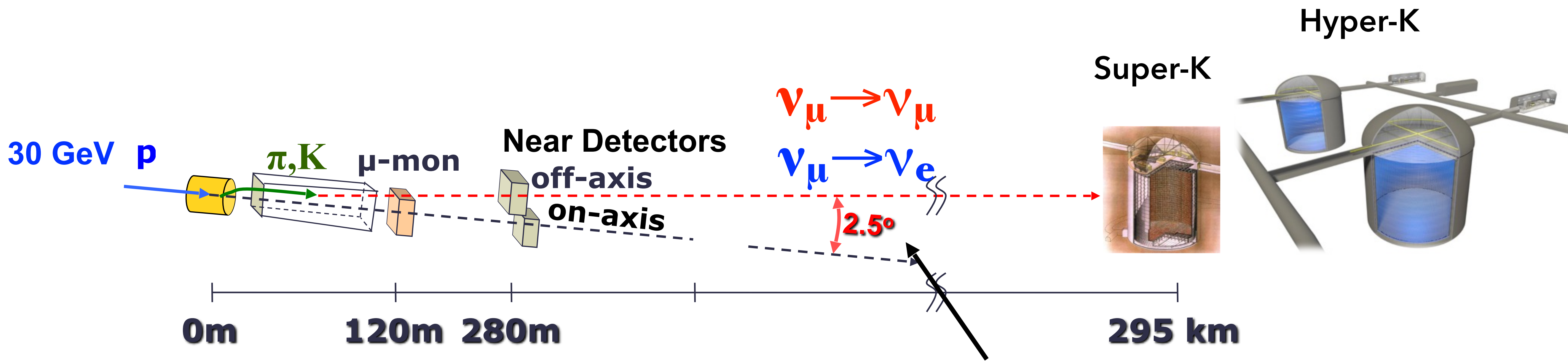
Workshop on Neutrino Near Detectors based on gas TPCs

CERN, Nov. 8-9, 2016

T2K/HYPER-K OVERVIEW



Off-axis = narrow band beam

Key Features:

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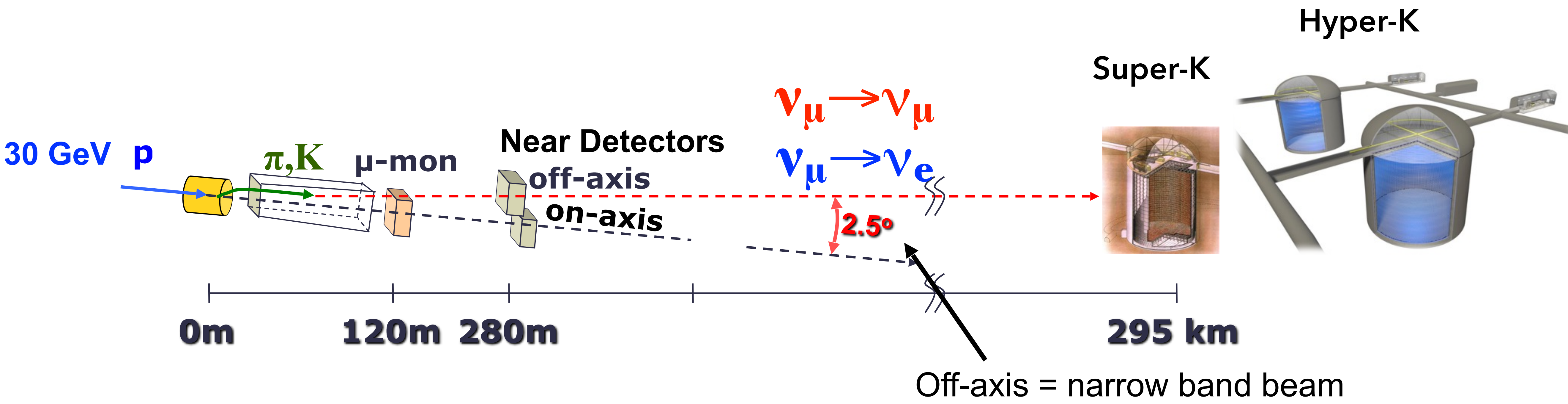

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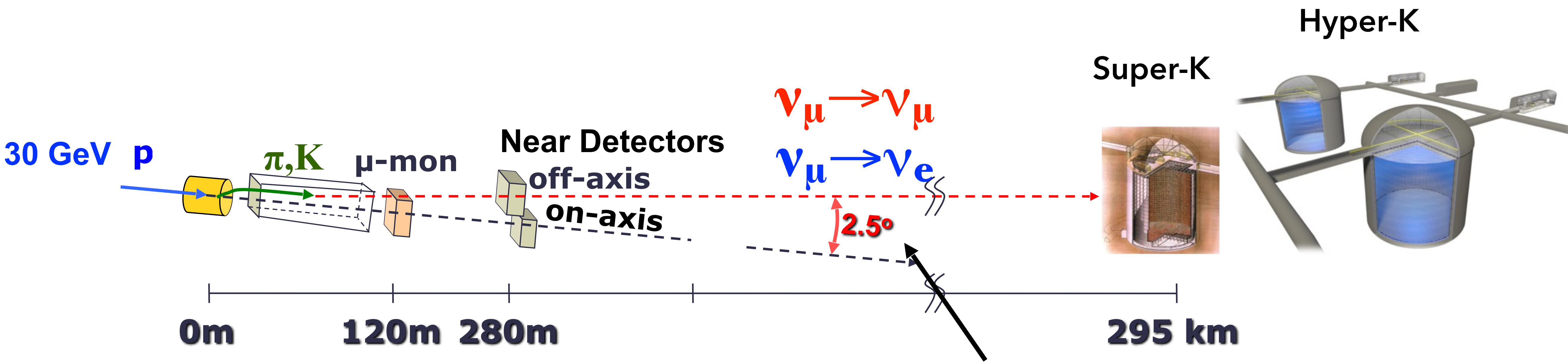

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Off-axis narrow beam with a peak energy at the first oscillation maximum (600 MeV) at 295 km

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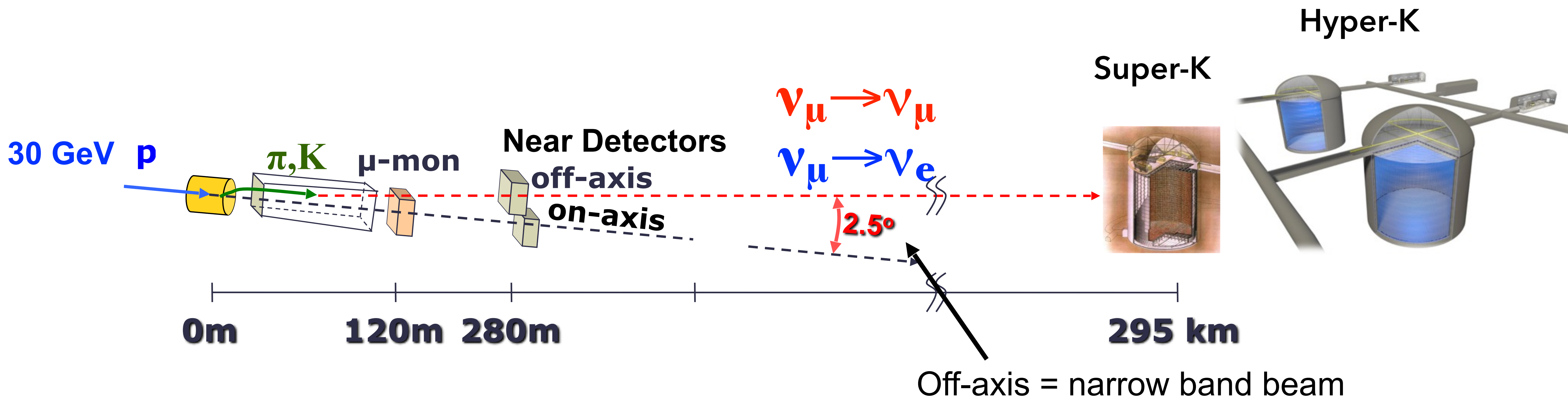

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Near detectors to measure neutrino event rates before oscillations

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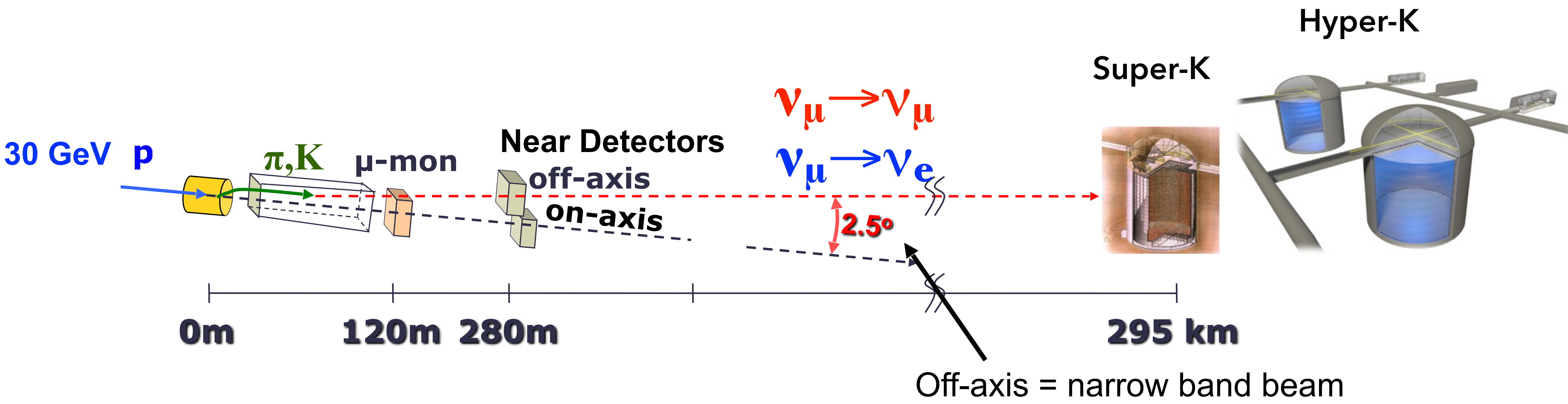

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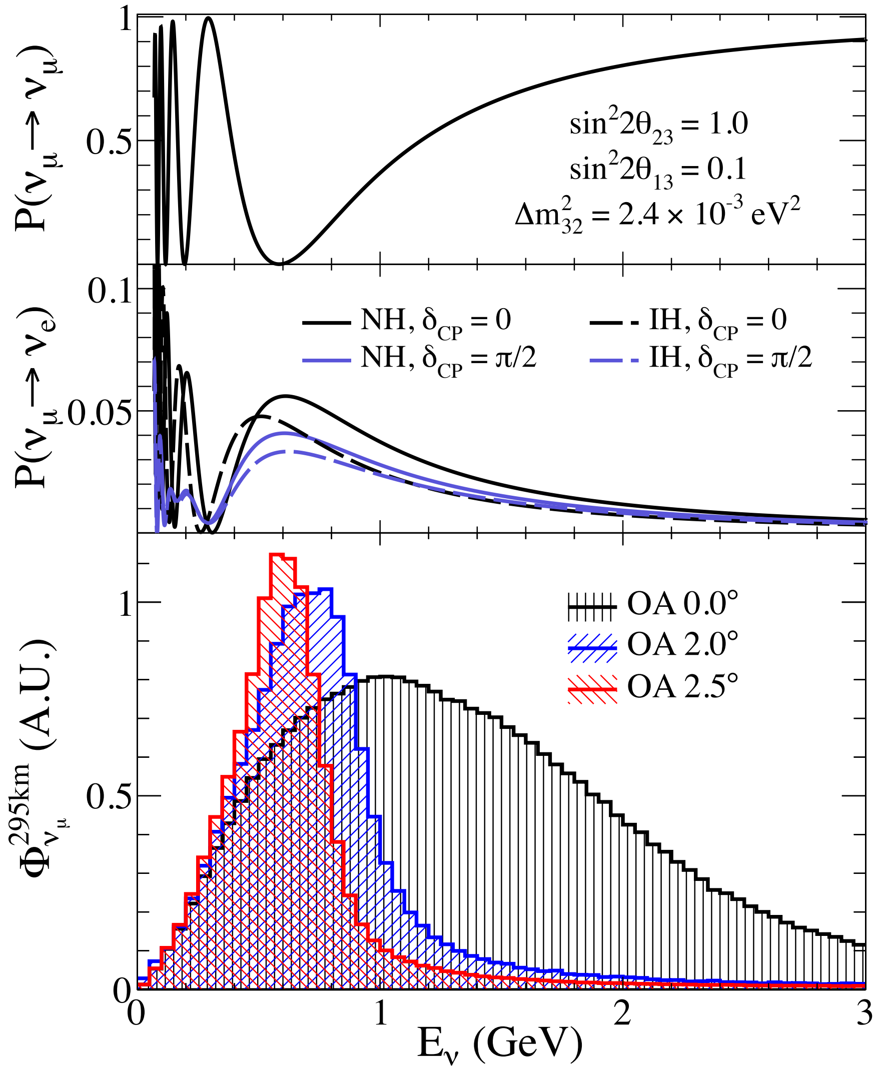
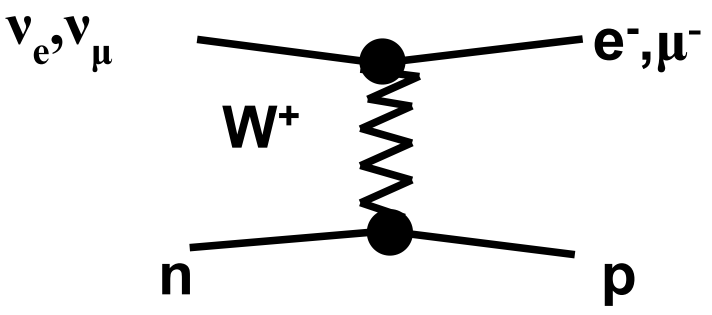
Water Cherenkov far detectors Super-K (T2K) and Hyper-K

BEAM, OSCILLATIONS AND INTERACTIONS

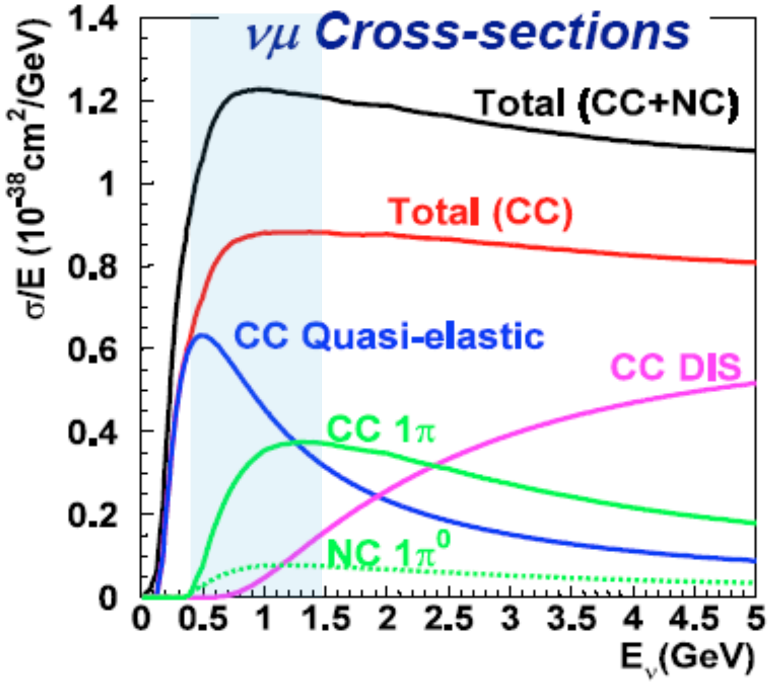
- Off-axis beam = narrow band spectrum peaked at first oscillation maximum



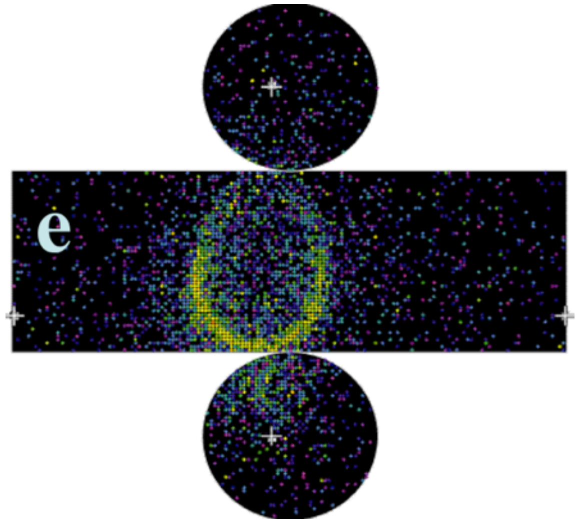
- Predominantly CCQE interactions at the peak energy:



T2K signal at SK

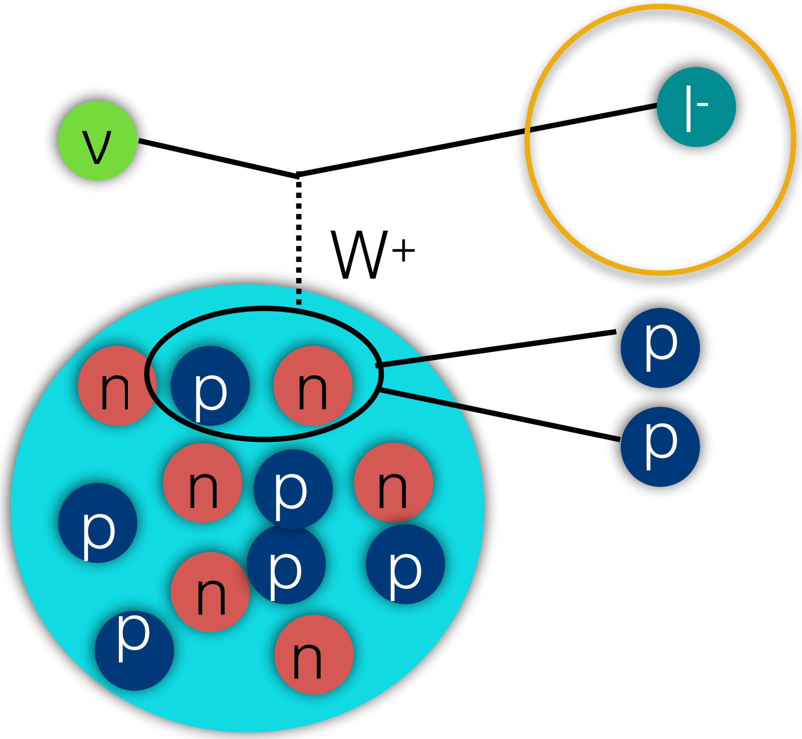


- Signal candidates in water Cherenkov detector are single ring lepton candidates



NON-CCQE INTERACTIONS

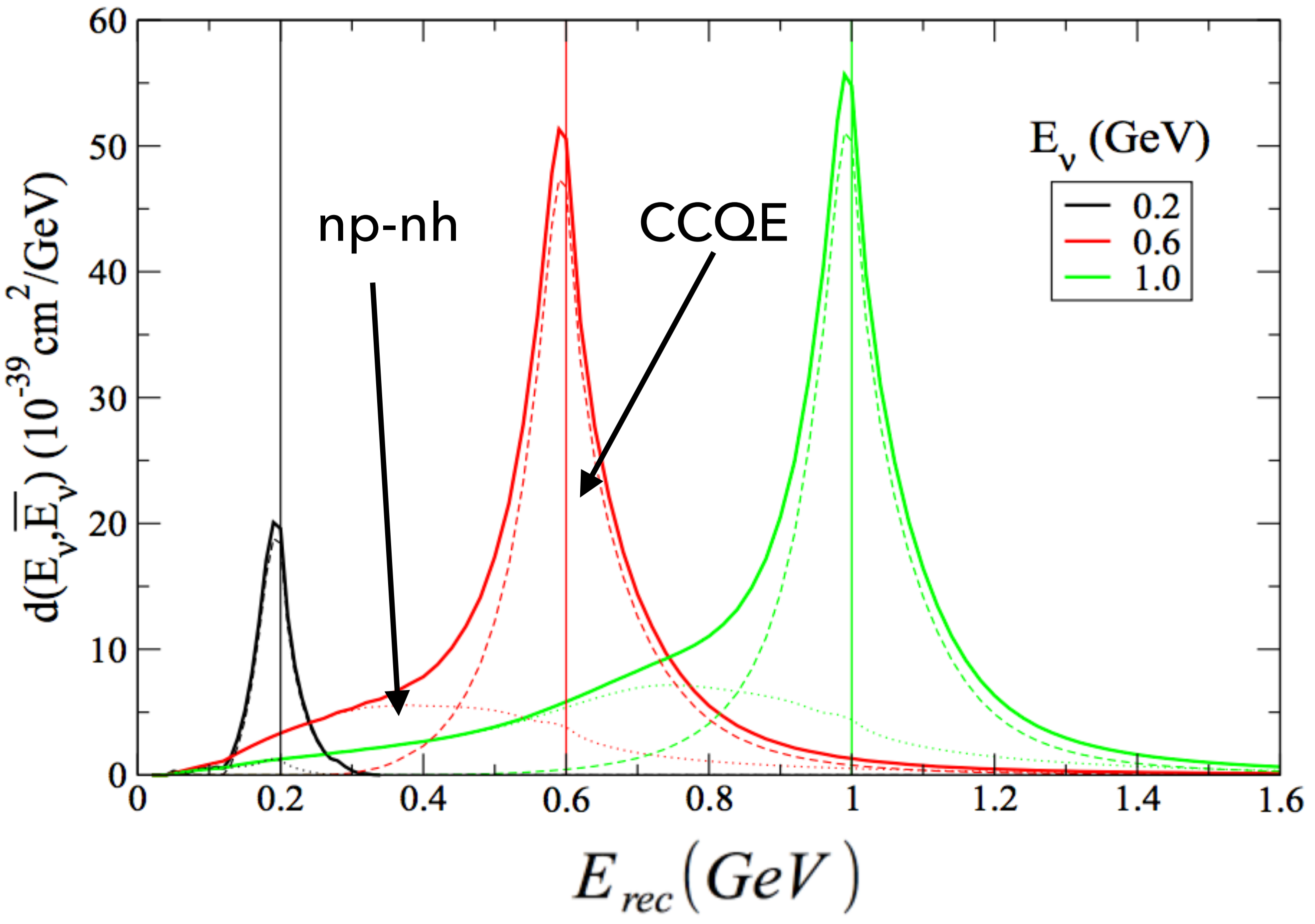
Can have CC interactions where only a lepton candidate is visible, but interaction was not CCQE



Example is np-nh (multi-nucleon) scattering processes

Can also happen when pion is produced and absorbed

These events have different final state lepton kinematics. If we infer the neutrino energy with CCQE assumption, bias is observed



$$E_\nu^{\rm rec} = \frac{2(m_n - V)E_\ell + m_p^2 - (m_n - V)^2 - m_\ell^2}{2(m_n - V - E_\ell + p_\ell \cos\theta_\ell)}$$

Martini et. al.
Phys.Rev. D87 (2013) 013009

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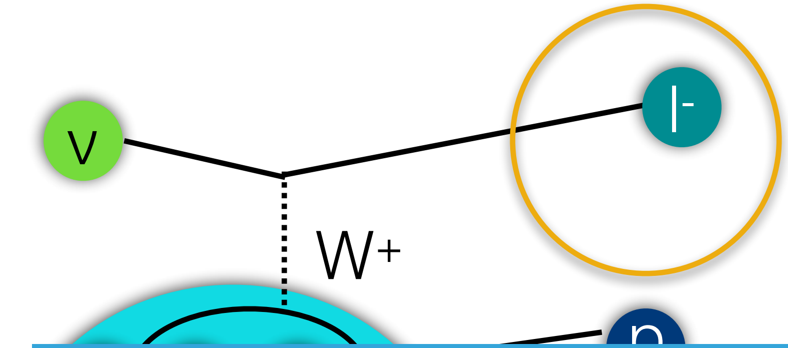

Example is np-nh (multi-nucleon) scattering processes

Can also happen when pion is produced and

Direct measurements or measurements that improve the modeling of non-CCQE interactions are a critical feature of future near detectors

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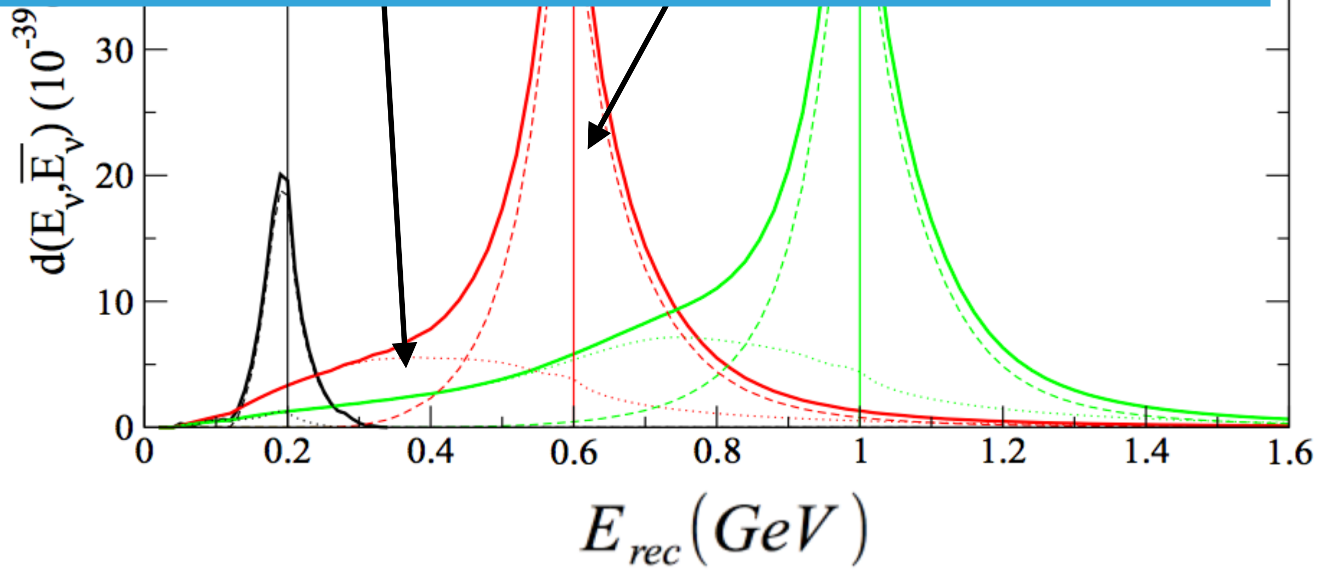

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T2K–II: EXTENDED T2K OPERATION

T2K has received Stage-1 approval from the J-PARC PAC for program to extend operation to 2026: collect 20x10^{21} POT (~3 times original T2K proposal)

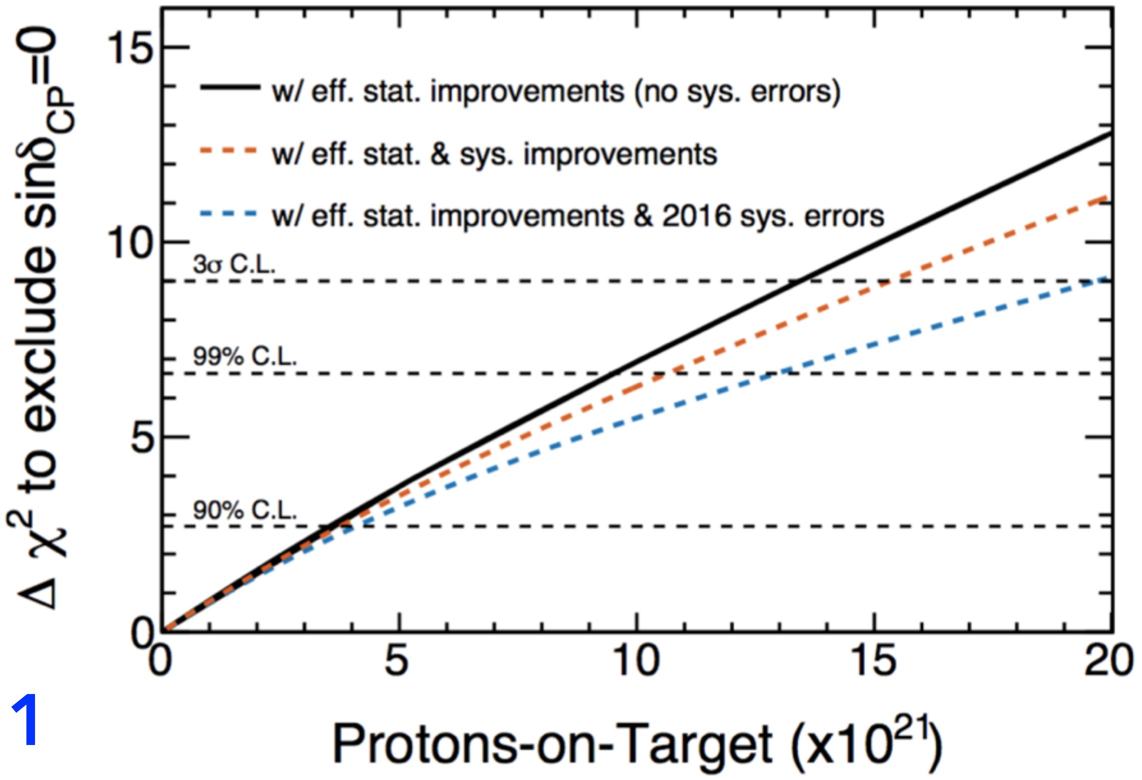
Expect beam power to reach 1.3 MV

	True δ_{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
ν-mode ν_e sample	0	467.6	356.3	4.0	73.3	1.8	32.3
	$-\pi/2$	558.7	448.6	2.8	73.3	1.8	32.3
$\bar{\nu}$-mode $\bar{\nu}_e$ sample	0	133.9	16.7	73.6	29.2	0.4	14.1
	$-\pi/2$	115.8	19.8	52.3	29.2	0.4	14.1

Will collect ~500 electron neutrino and ~125 electron antineutrino candidates

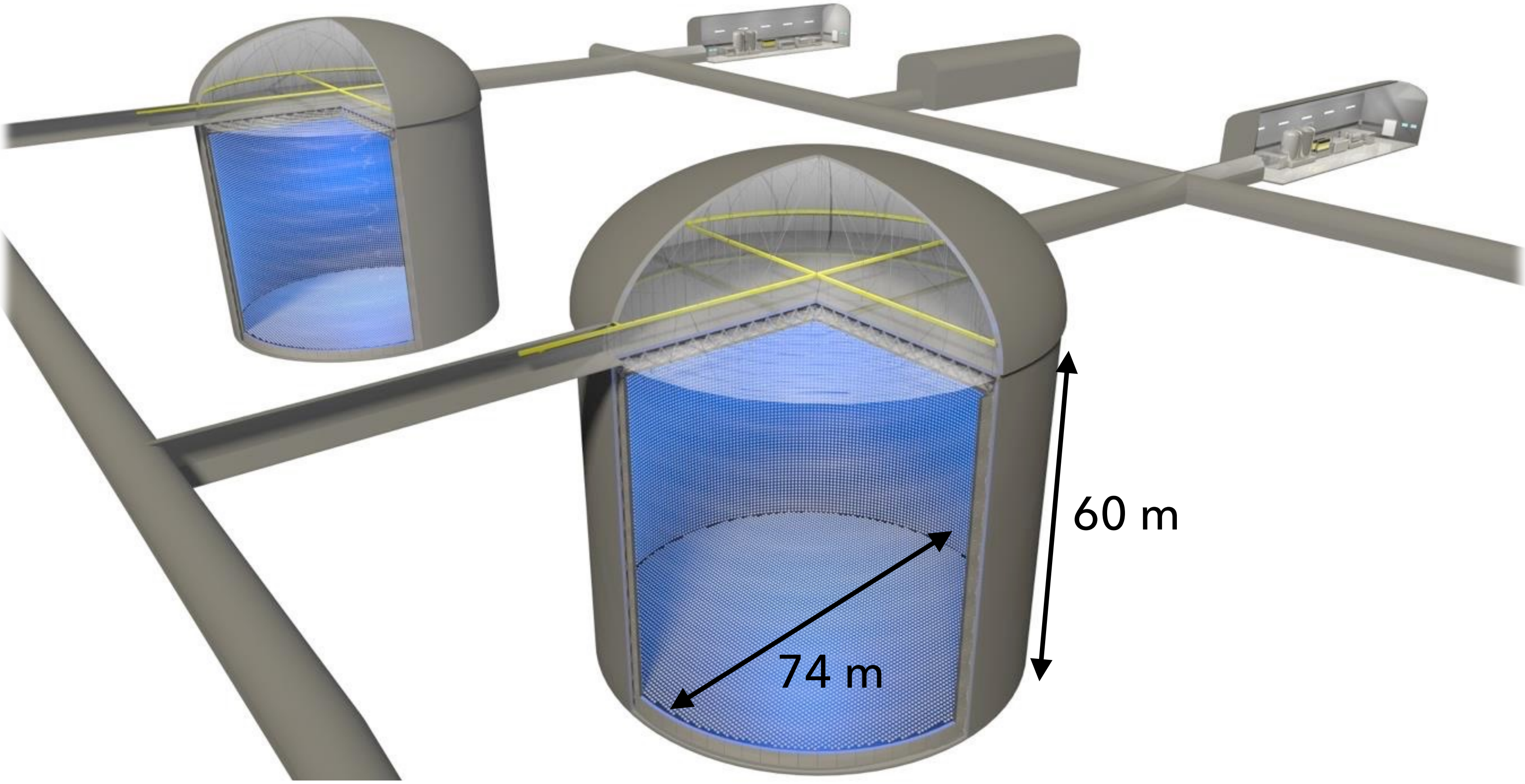
3 sigma CP violation discovery potential for favorable value of $\delta_{cp}=-\pi/2$

Reduction of systematic errors beyond current T2K errors can improve the experimental sensitivity



arXiv:1609.04111

HYPER-K



KEK Preprint 2016-21

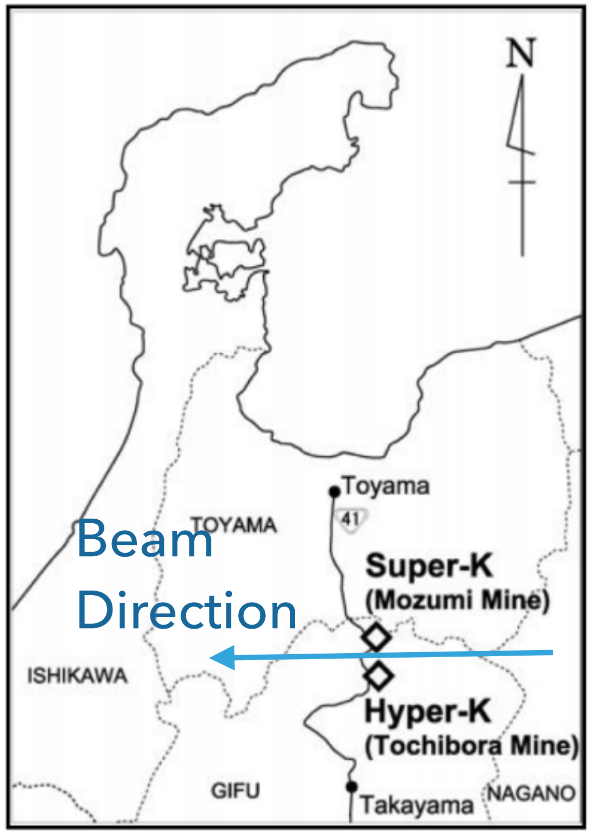
Hyper-K Detector(s):

60 m tall x 74 m diameter

40,000 50cm ϕ PMTs → 40% photo-coverage

260 kton mass (187 kton fiducial volume is ~10x larger than Super-K)

Staged construction of the tanks with the second tank 6 years after first tank



Located south of the J-PARC beam direction. Same off-axis angle as Super-K

Results shown here are for 10 year operation of J-PARC beam with 1.3 MW beam power

CP VIOLATION MEASUREMENT AT HYPER-K

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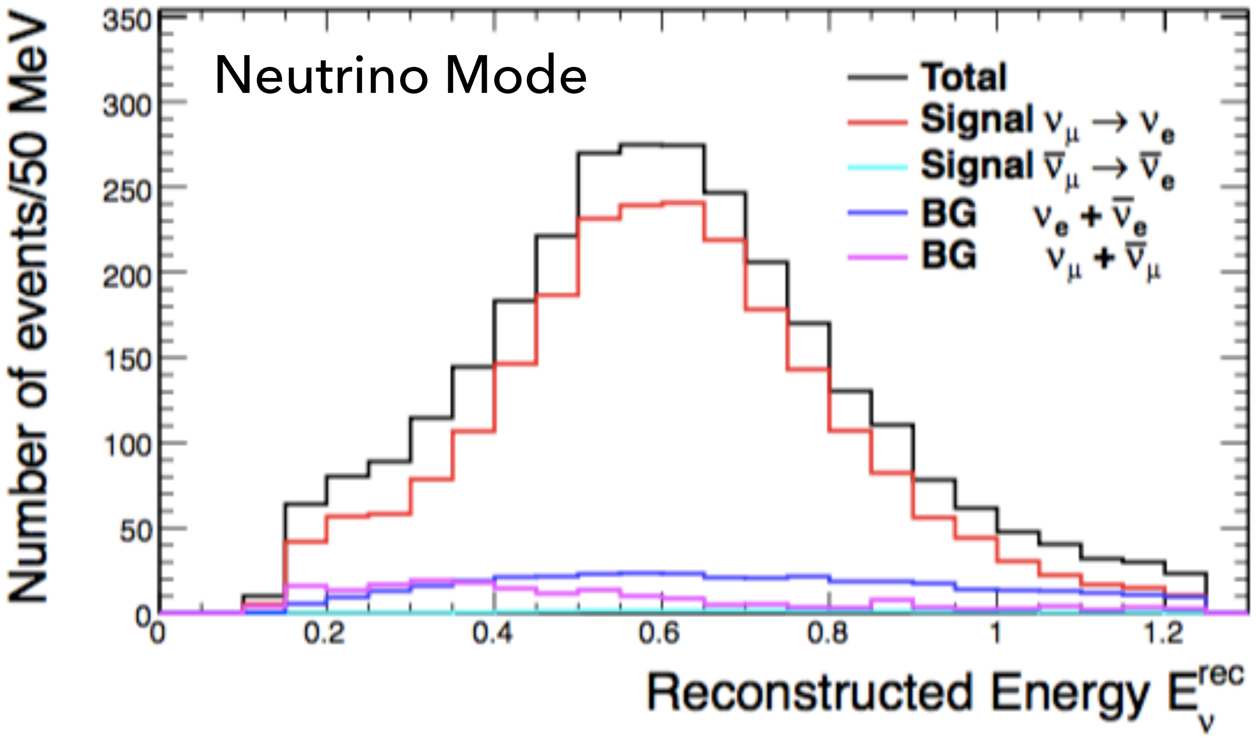

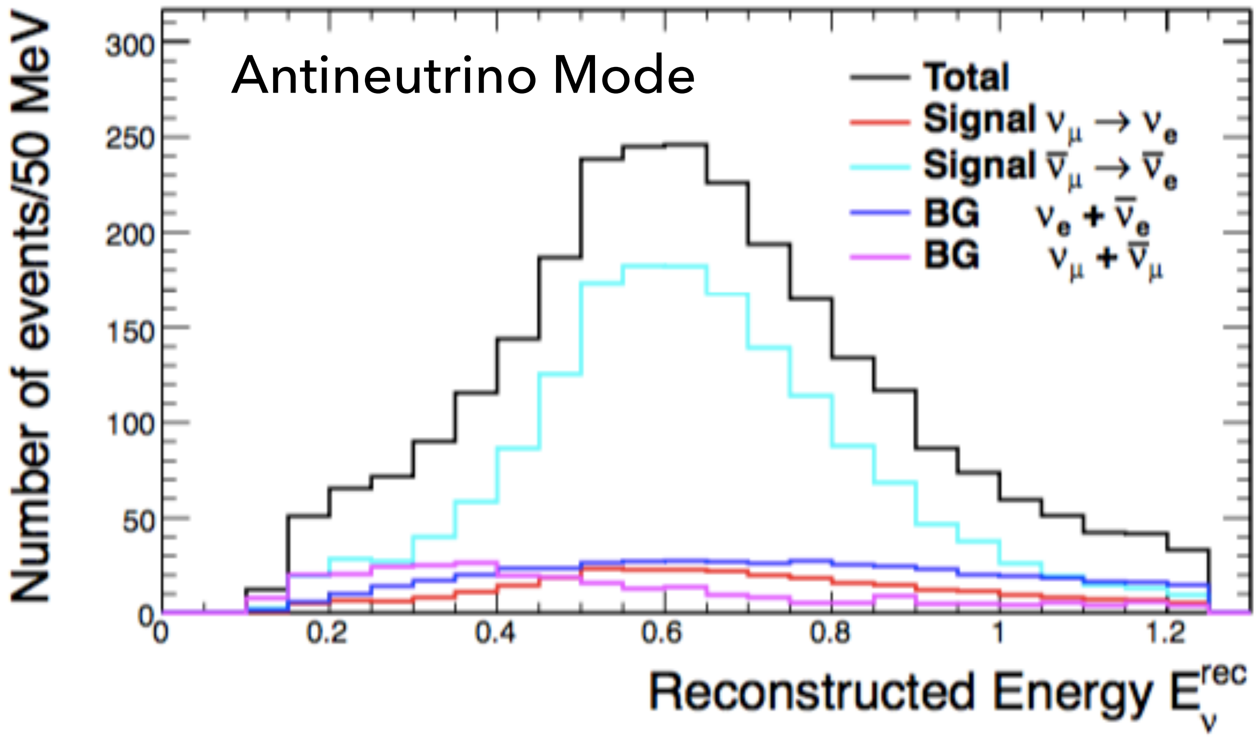

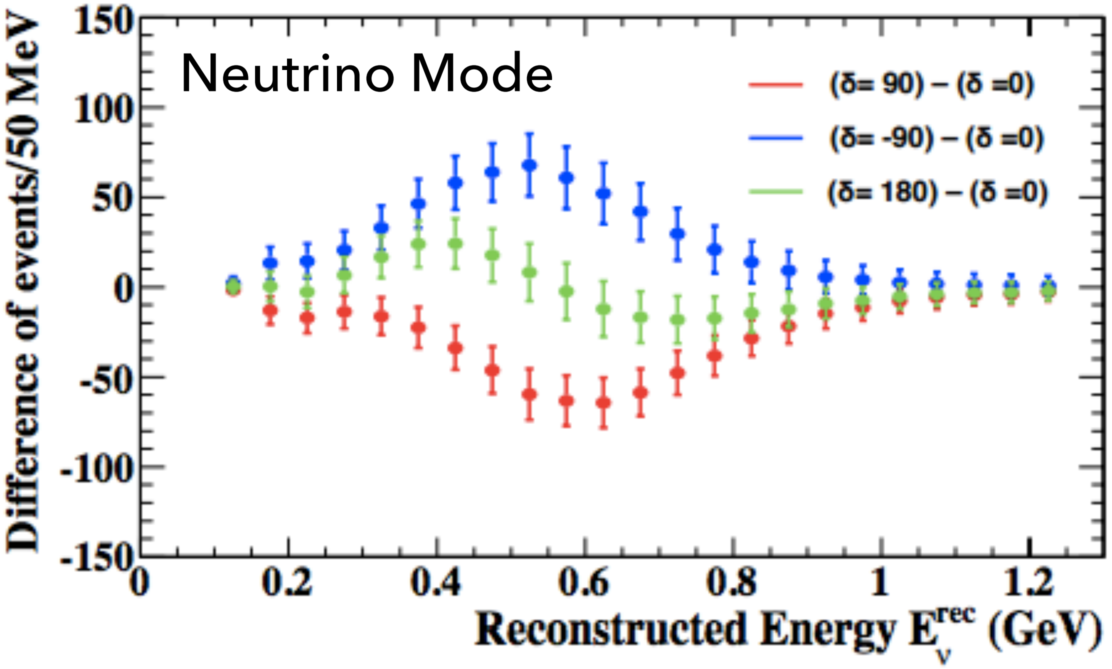

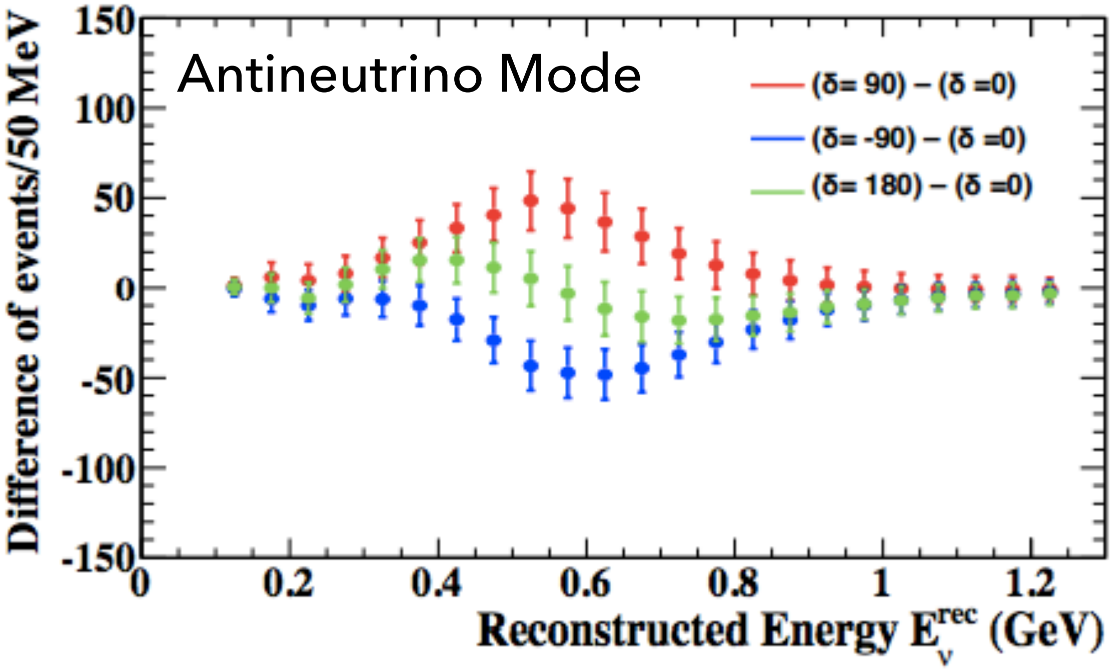

For 187 kton tank, 6 years with 1 tank, 4 years with 2 tanks, 1.3 MW beam power

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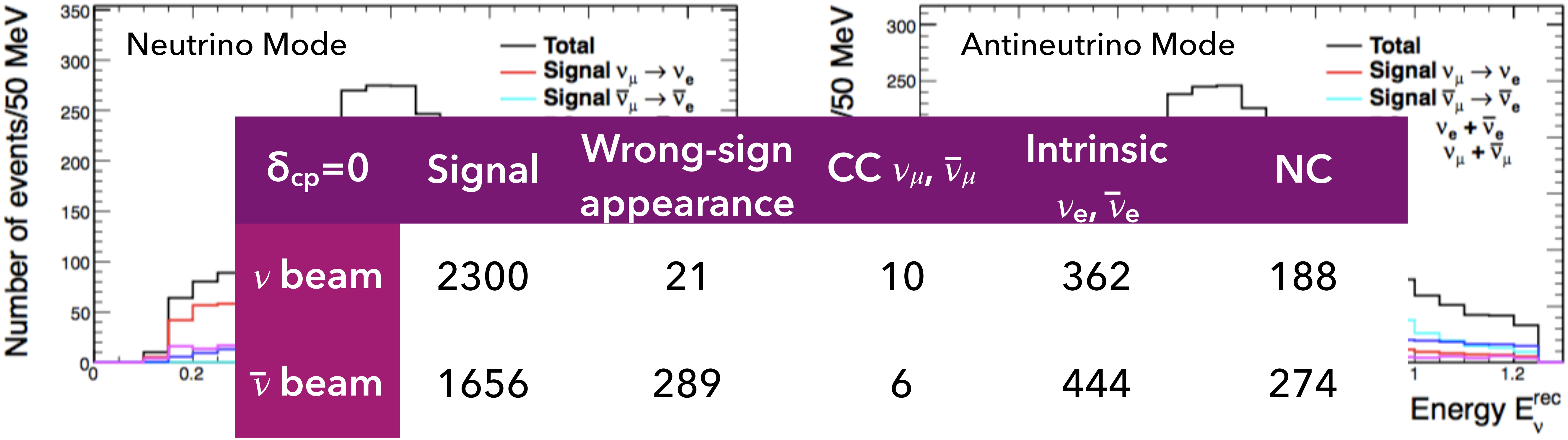
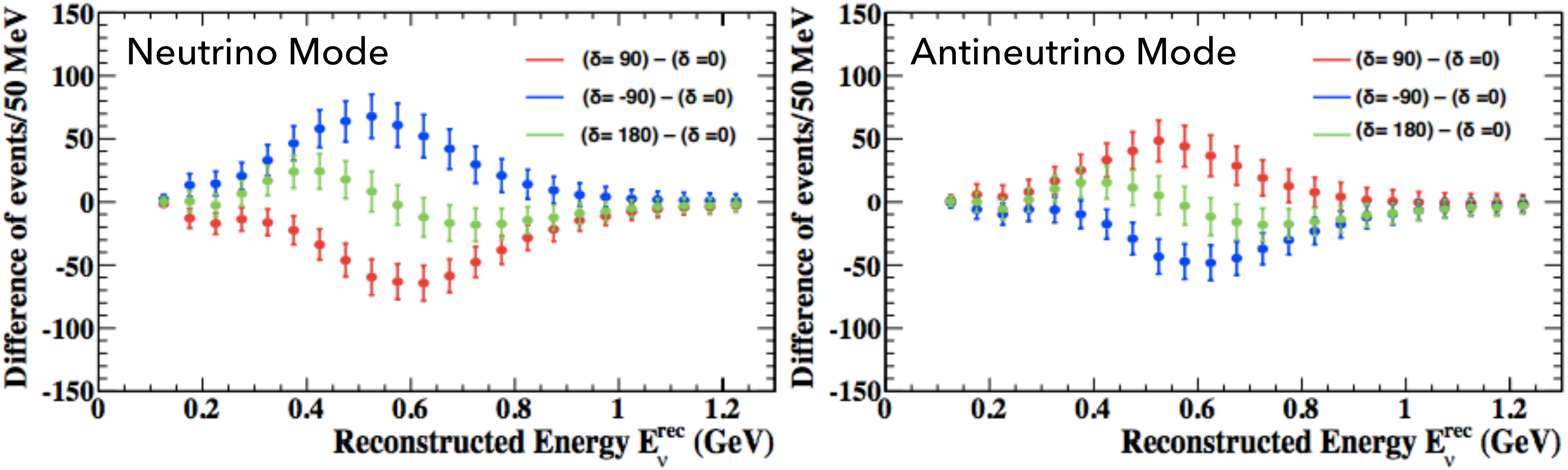


δ_{cp}=0	Signal	Wrong-sign appearance	CC ν_μ, $\bar{\nu}_\mu$	Intrinsic ν_e, $\bar{\nu}_e$	NC
ν beam	2300	21	10	362	188
$\bar{\nu}$ beam	1656	289	6	444	274



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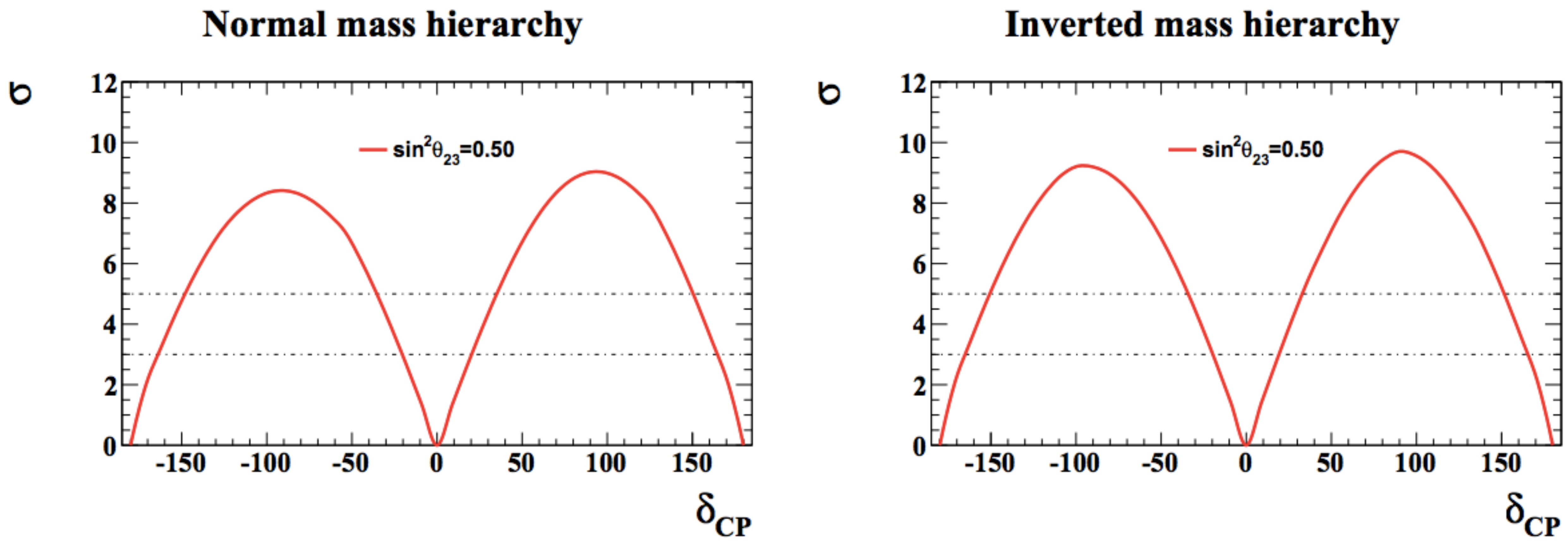
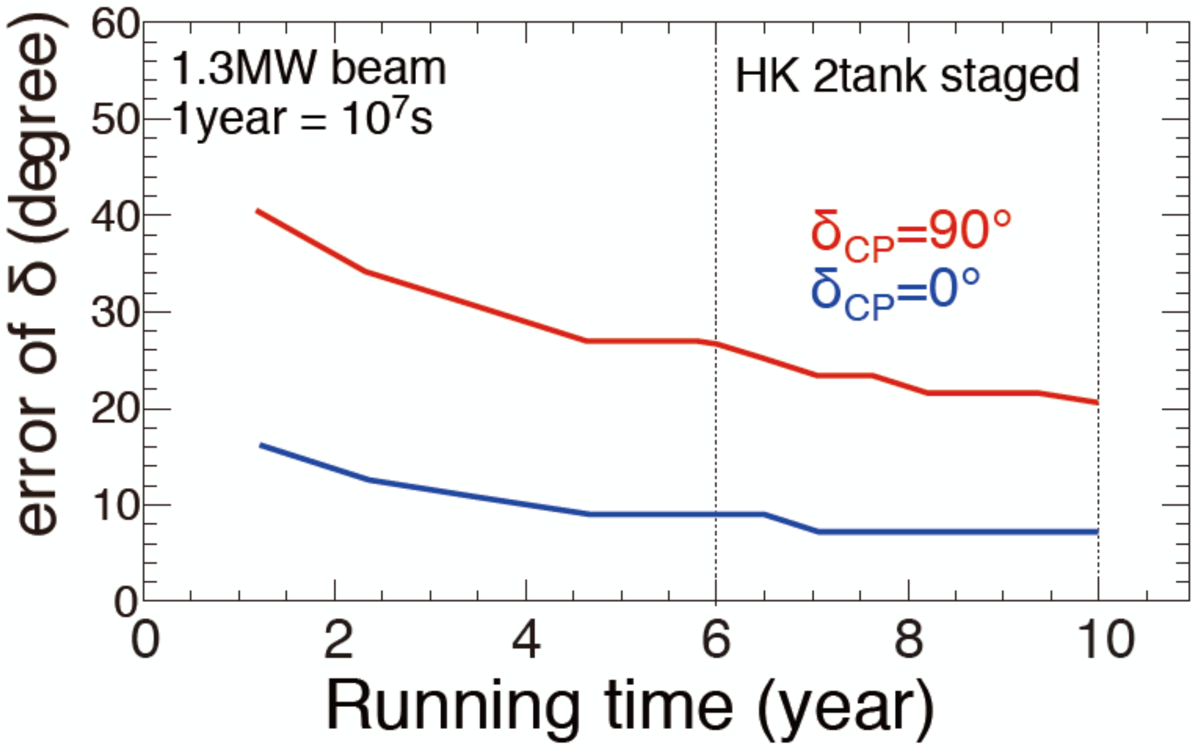
HYPER-K CP SENSITIVITIES



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

21° precision at $\delta_{cp}=90°$

7° precision at $\delta_{cp}=0°$



KEK Preprint 2016-21

NEAR DETECTOR CONSTRAINTS

Event rate dependence at the far detector:

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

Event rate dependence at the near detector:

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Model uncertainties enter extrapolation due to differences in near and far detector rates:

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Different flavor of neutrino flux

Different nuclear target

Different detection efficiency (4π acceptance?)

NEAR DETECTOR CONSTRAINTS

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Goals for near detectors:

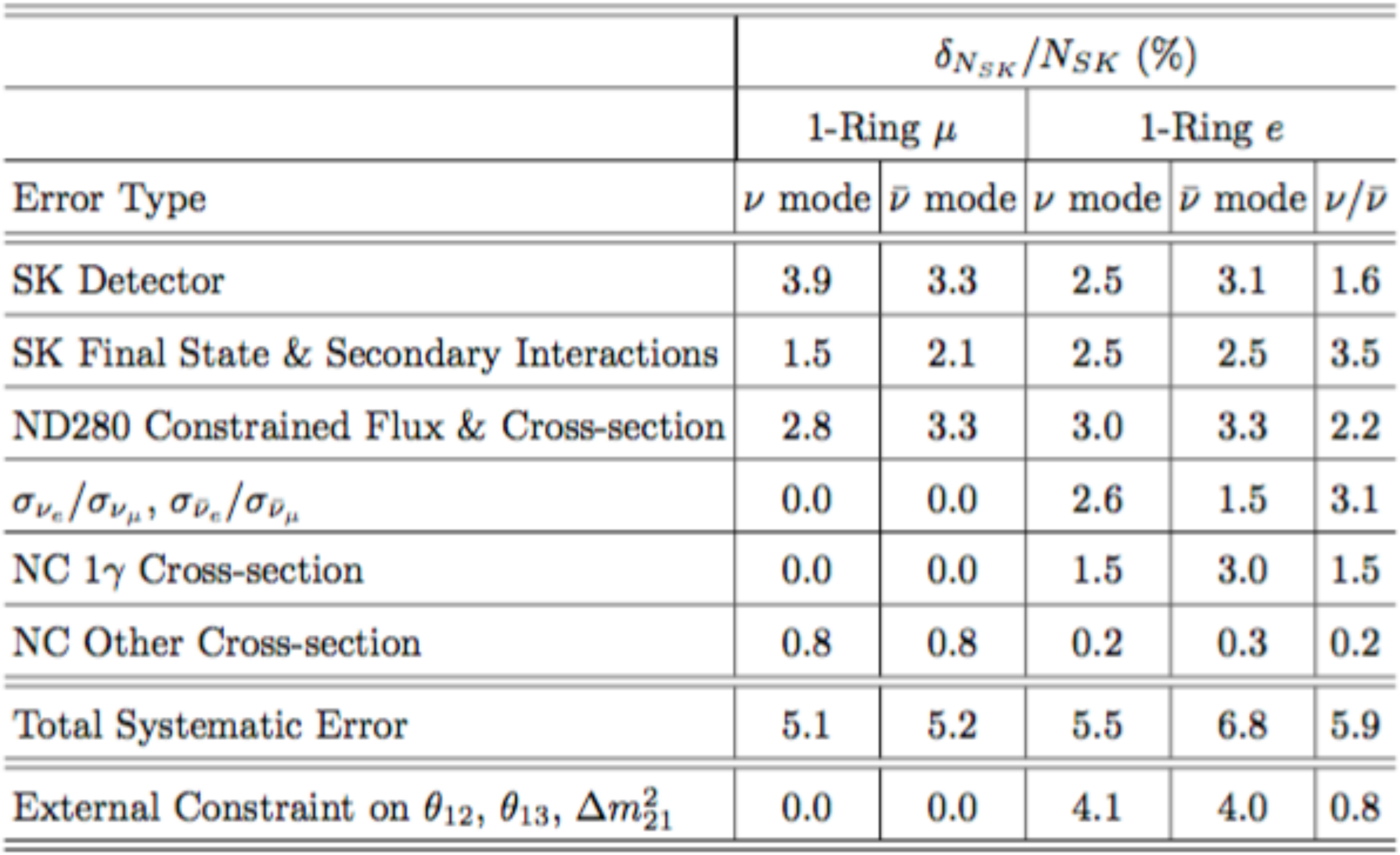
Minimize the differences between near and far detectors
→ Minimize the model dependence in extrapolation

Since differences at near and far detectors will remain, build capable detectors that can make measurements to improve neutrino flux and interaction modeling

Consider supporting measurements for the atmospheric neutrino and nucleon decay physics programs

T2K SYSTEMATIC ERRORS

arXiv:1609.04111



	$\delta_{N_{SK}}/N_{SK}$ (%)				
	1-Ring μ		1-Ring e		
Error Type	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	$\nu/\bar{\nu}$
SK Detector	3.9	3.3	2.5	3.1	1.6
SK Final State & Secondary Interactions	1.5	2.1	2.5	2.5	3.5
ND280 Constrained Flux & Cross-section	2.8	3.3	3.0	3.3	2.2
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.0	0.0	2.6	1.5	3.1
NC 1γ Cross-section	0.0	0.0	1.5	3.0	1.5
NC Other Cross-section	0.8	0.8	0.2	0.3	0.2
Total Systematic Error	5.1	5.2	5.5	6.8	5.9
External Constraint on θ_{12}, θ_{13}, Δm^2_{21}	0.0	0.0	4.1	4.0	0.8

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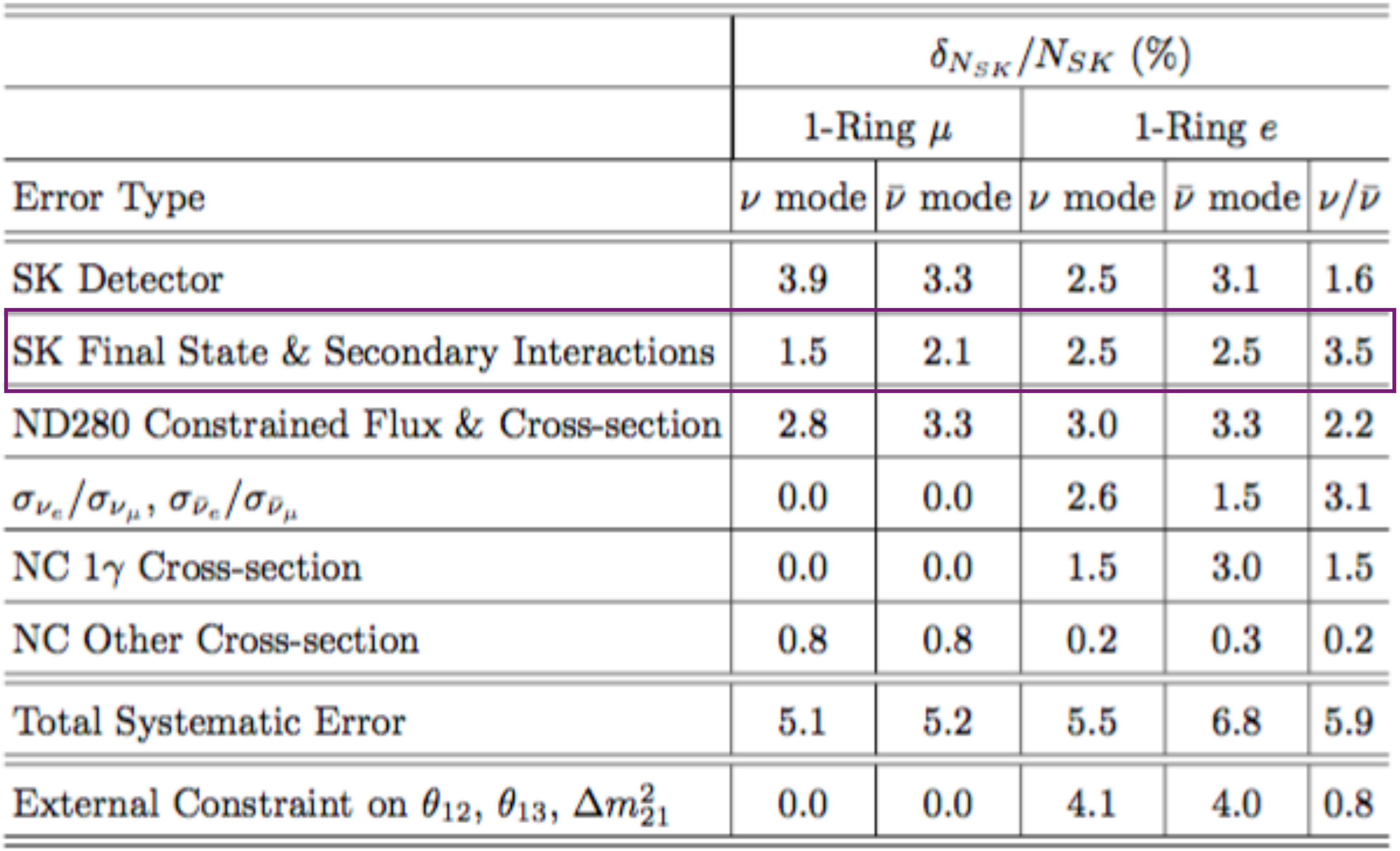

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Events with pion production where the pion is absorbed inside the target nucleus or detector medium

Can bias event rates and energy inference

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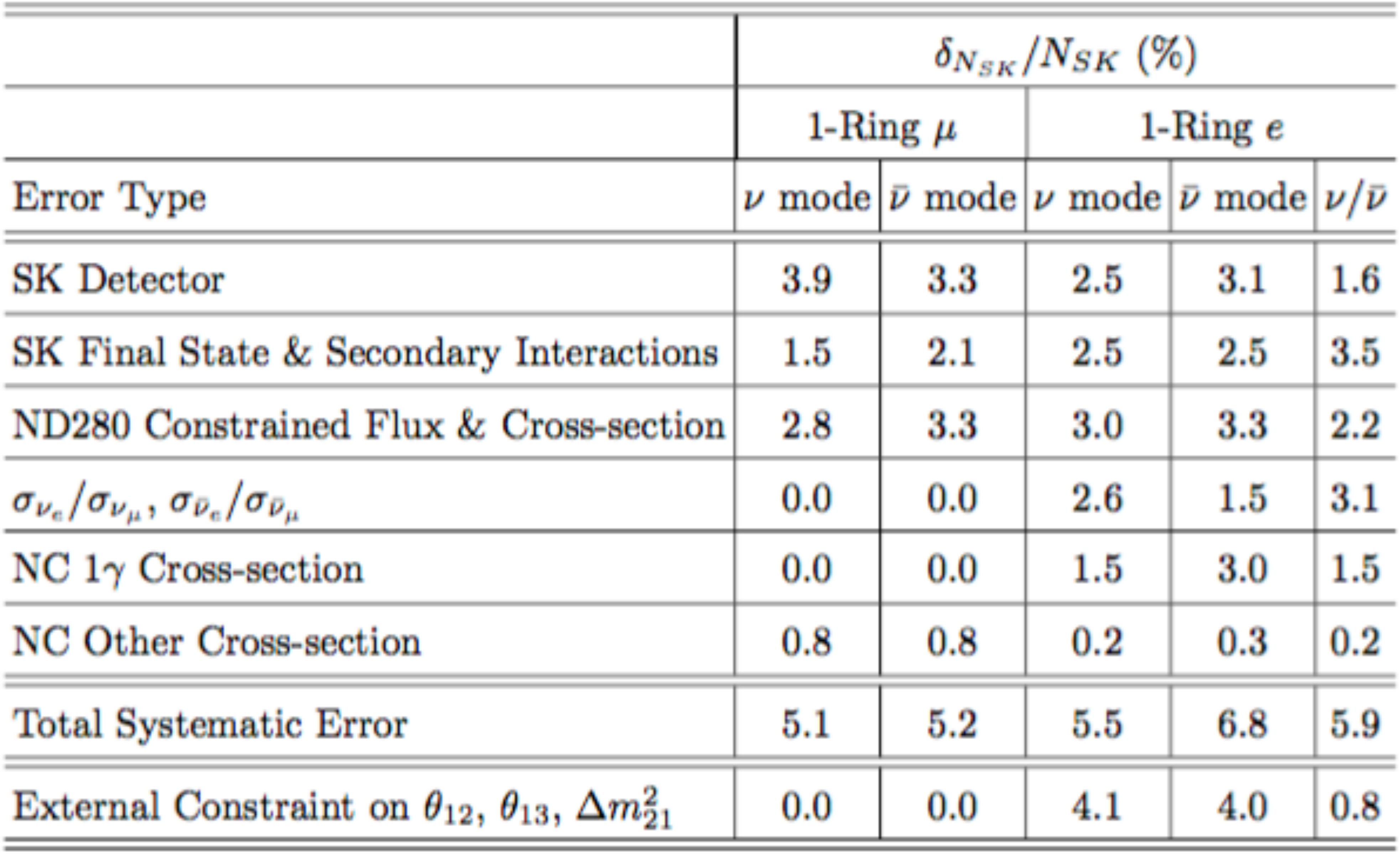

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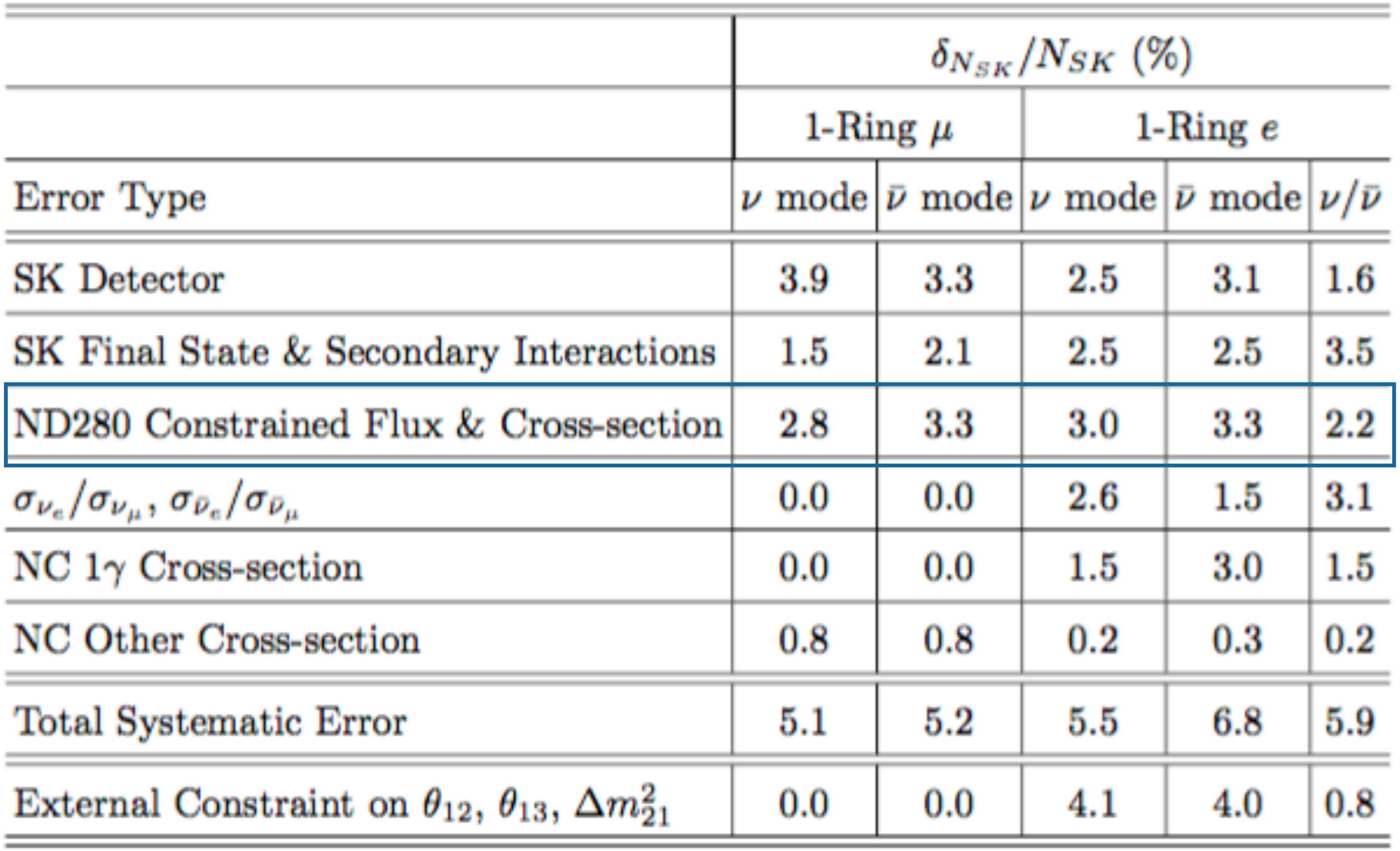

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Uncertainty in extrapolation from near detector

Benefit from improved near/far matching as discussed on previous slide

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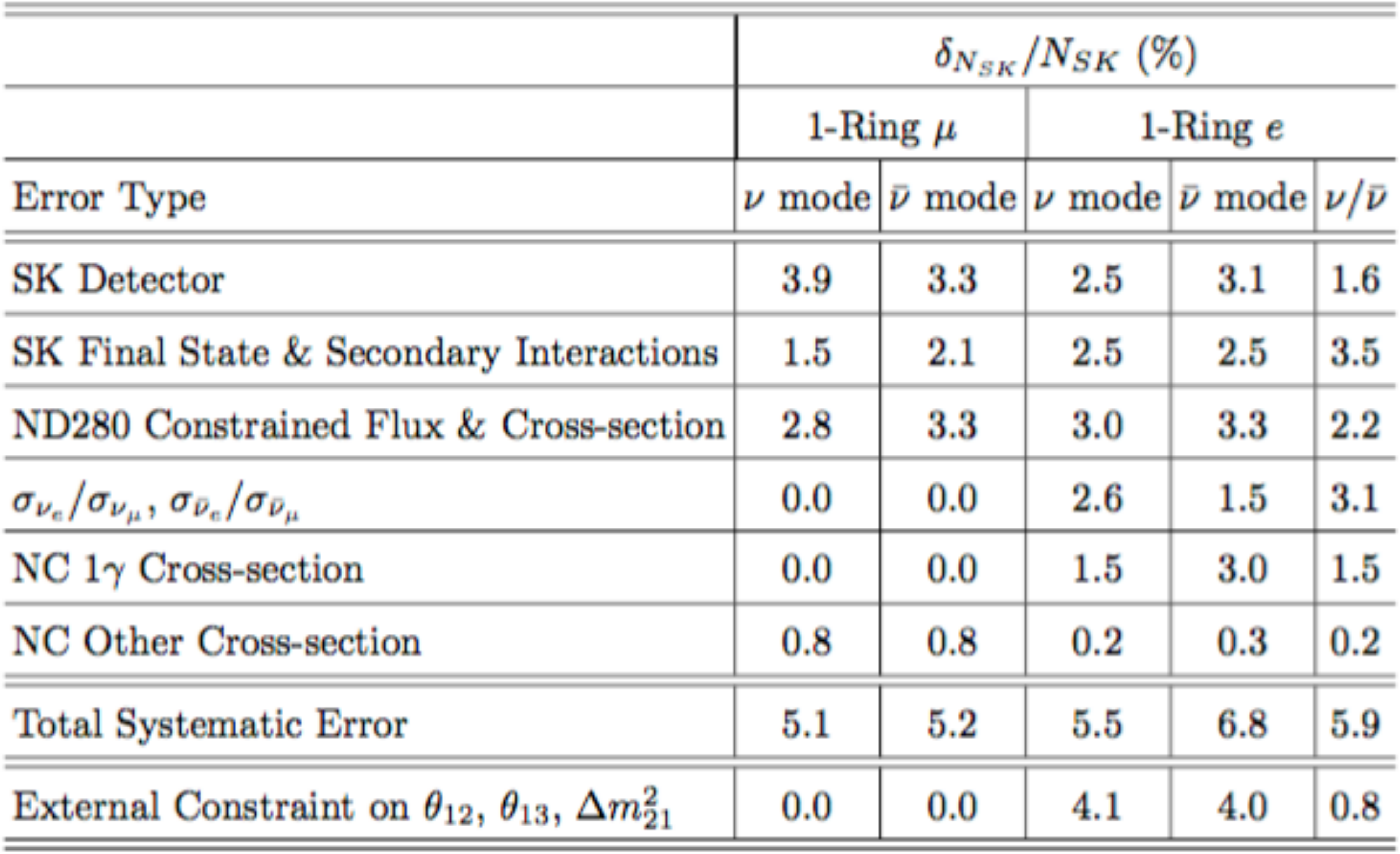

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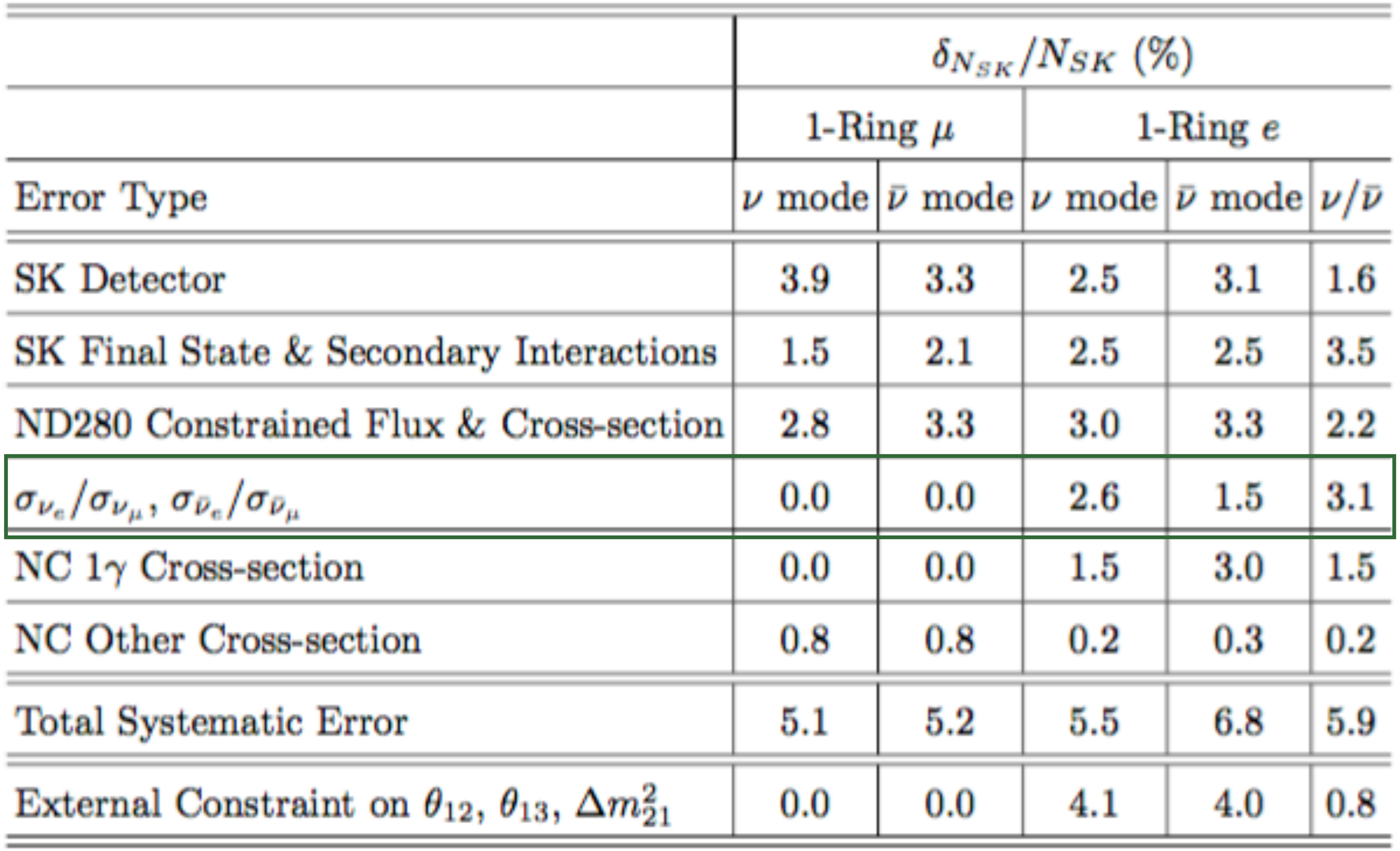

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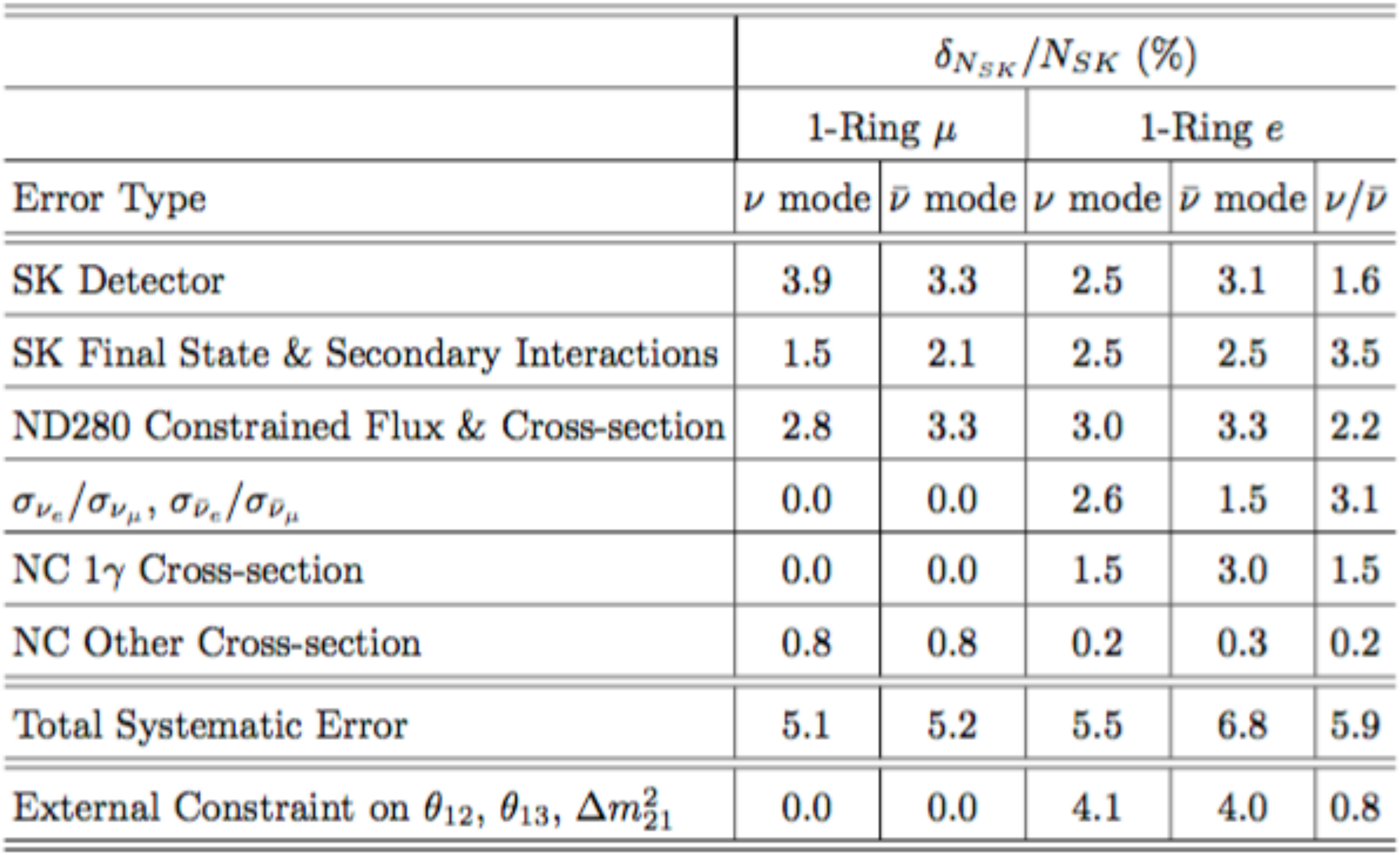
SK Detector	3.9	3.3	2.5	3.1	1.6
SK Final State & Secondary Interactions	1.5	2.1	2.5	2.5	3.5
ND280 Constrained Flux & Cross-section	2.8	3.3	3.0	3.3	2.2
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.0	0.0	2.6	1.5	3.1
NC 1γ Cross-section	0.0	0.0	1.5	3.0	1.5
NC Other Cross-section	0.8	0.8	0.2	0.3	0.2
Total Systematic Error	5.1	5.2	5.5	6.8	5.9
External Constraint on θ_{12}, θ_{13}, Δm^2_{21}	0.0	0.0	4.1	4.0	0.8

Uncertainty on electron (anti)neutrino cross sections

Need to make measurements with <3% precision

T2K SYSTEMATIC ERRORS

arXiv:1609.04111



	$\delta_{N_{SK}}/N_{SK}$ (%)				
	1-Ring μ		1-Ring e		
Error Type	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	$\nu/\bar{\nu}$
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T2K SYSTEMATIC ERRORS

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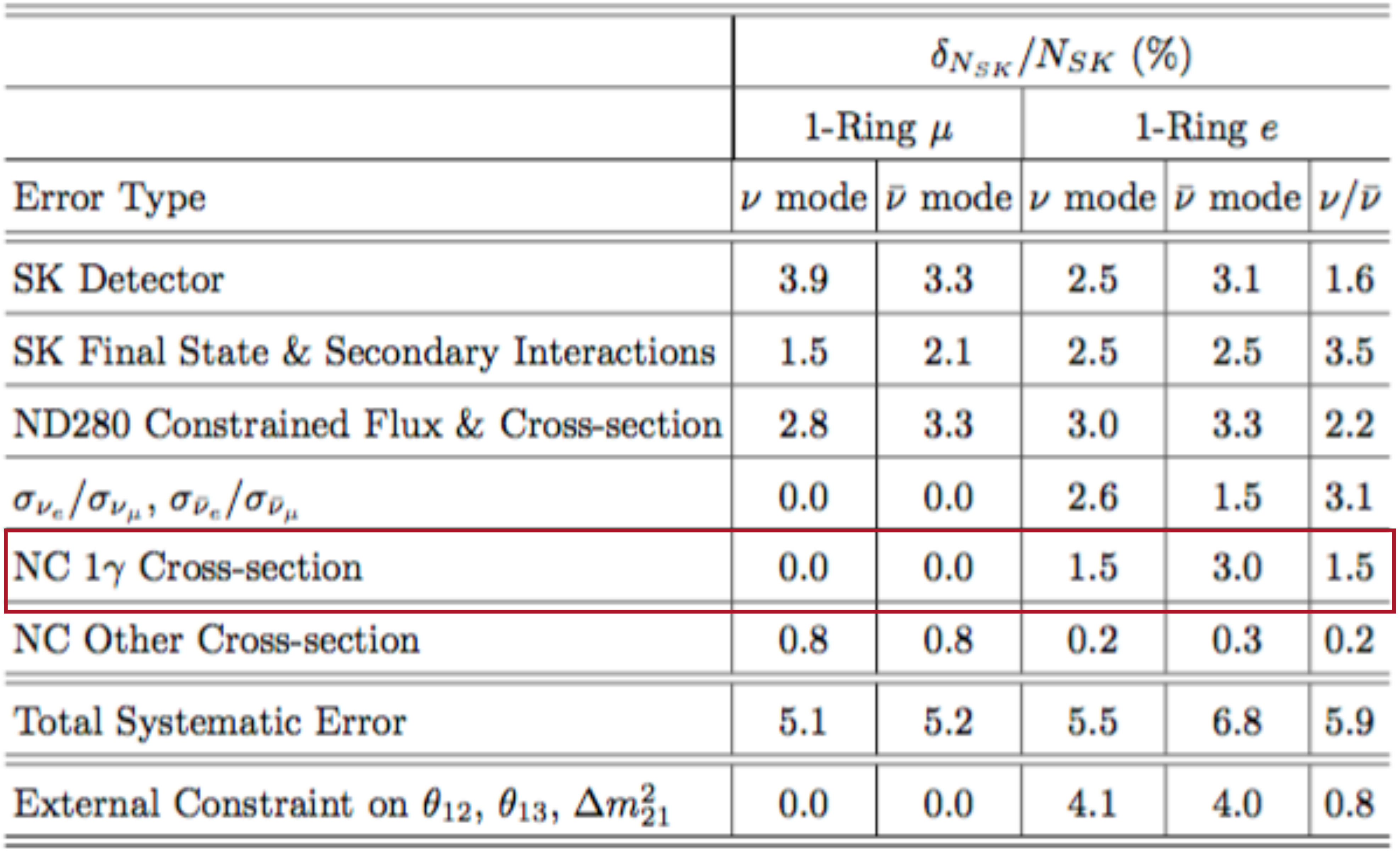

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Error Type	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	$\nu/\bar{\nu}$
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External Constraint on θ_{12}, θ_{13}, Δm^2_{21}	0.0	0.0	4.1	4.0	0.8

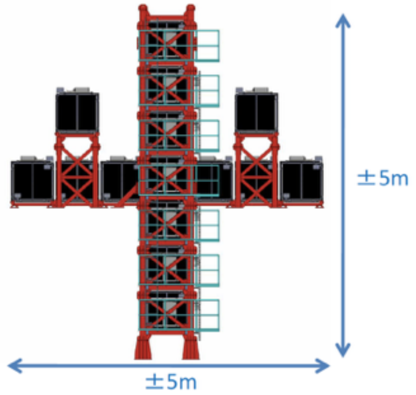
Intrinsic background (also intrinsic electron (anti)neutrinos and other NC modes)

Flux is similar at near and far detector, need similar detection efficiency

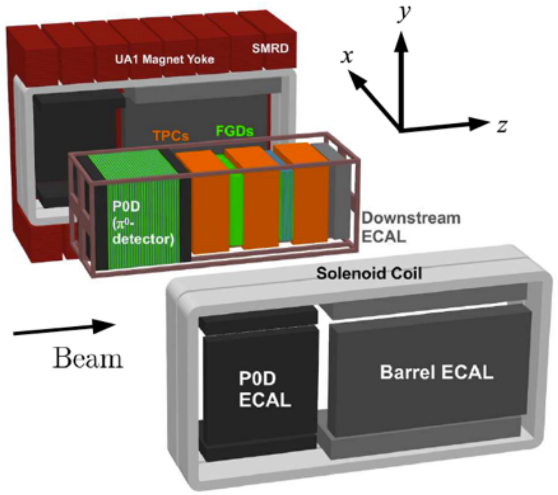
NEAR/INTERMEDIATE DETECTOR STRATEGY FOR HYPER-K

Baseline strategy is to build on the success of the T2K near detector program

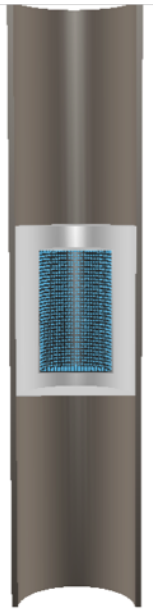
Upgraded(?) INGRID:
- Neutrino event rate monitoring with high statistics
- Precision beam direction measurement



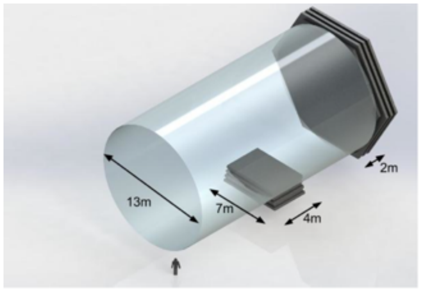
Upgraded ND280:
- Measurement of exclusive hadronic final states+leptonic final states for model building
- Magnetized detector for right-sign/wrong-sign separation



Intermediate Water Cherenkov Detector
- Loaded with Gd for final state neutron detection
- Off-axis spanning to measure energy dependence of interaction rates/final state particle kinematics
- 1-2 km baseline
- Naturally minimizes differences: nuclear target, efficiency and acceptance, unoscillated neutrino spectrum



Merging of NuPRISM and TITUS efforts



HYPER-K SYSTEMATIC ERROR/SENSITIVITY STUDIES (SO FAR)

The evaluation of the systematic error requirements for Hyper-K is onging

Studies for near detector requirements (R. Shah):

- Identify potential sources of systematic errors that may be constrained by near detector measurements
- Evaluate the impact on the CP violation sensitivity for Hyper-K
- Set near detector requirements based on sensitivity impact studies

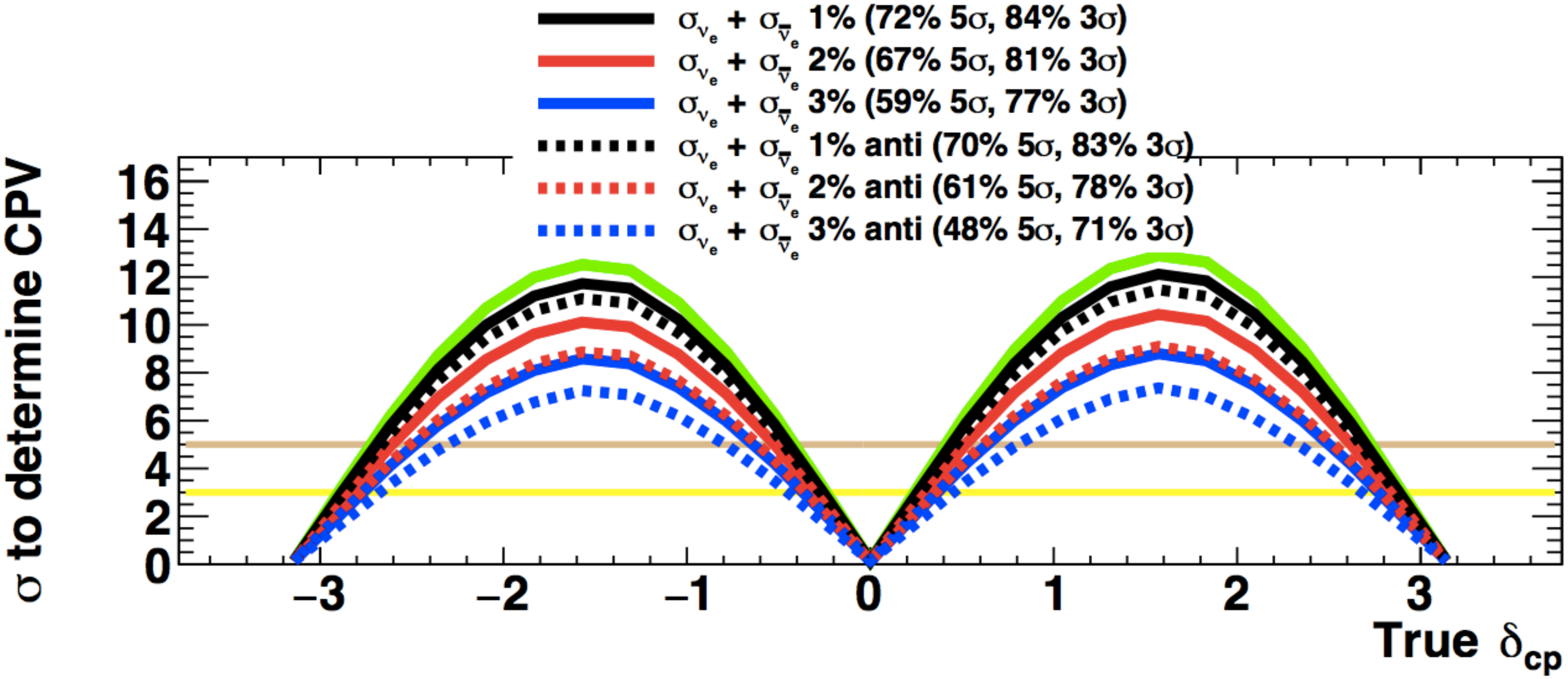
Some additional investigation into spectrum shape uncertainties will be shown here (work-in-progress)

We can’t show a complete picture of the requirements yet, but these studies show some of the important measurements that are needed

ELECTRON NEUTRINO CROSS SECTION UNCERTAINTY

Sensitive to uncertainties on the difference between the muon and electron (anti)neutrino interaction cross sections

Day and McFarland (Phys.Rev. D86 (2012) 053003) made preliminary uncertainty estimates for the single nucleon cross section of ~3% (used by T2K)

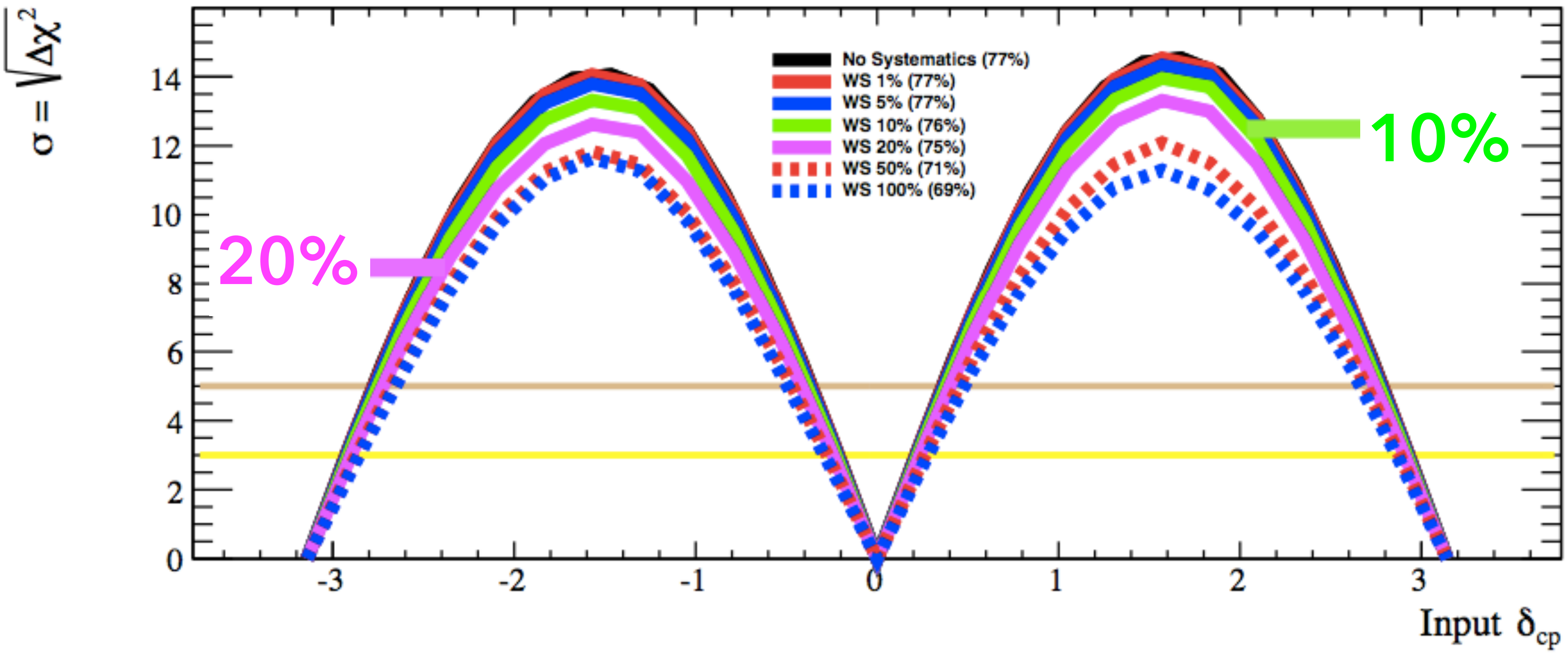


Reduction of this uncertainty from 3% to 2% can have a significant impact on the CP violation discovery sensitivity

2-3% measurements are a real challenge in near detectors since we only have ~0.5% electron neutrinos near the flux peak

WRONG SIGN BACKGROUND UNCERTAINTY

Study the impact of uncertainties on the wrong-sign background (neutrino interactions in antineutrino beam operation mode) to evaluate the importance of a magnetized detector

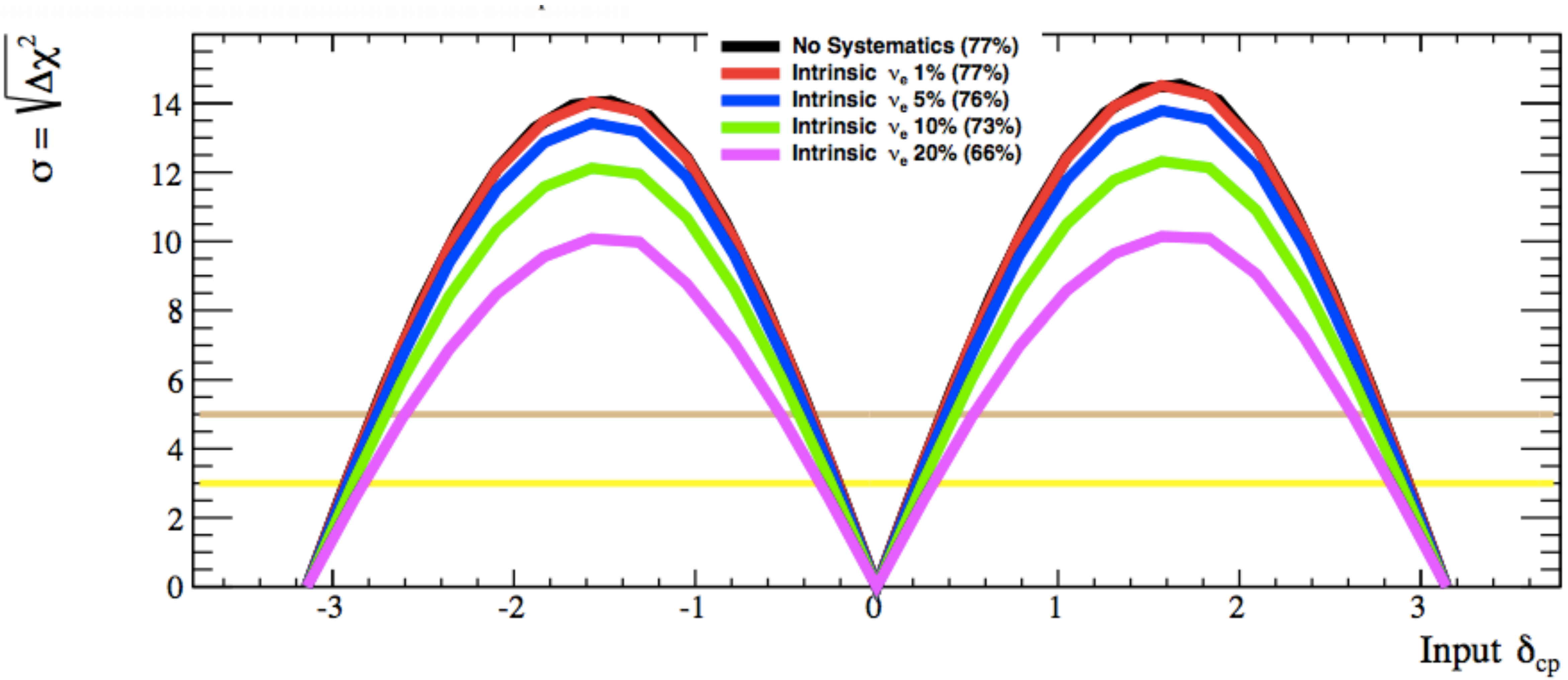


Measuring the wrong-sign background with 5% precision ensures that it does not significantly impact the CP violation discovery sensitivity

Can be done with the upgraded ND280

INTRINSIC ELECTRON NEUTRINO BACKGROUND

The intrinsic electron (anti)neutrino and neutral current backgrounds have a similar parent neutrino flux at the near and far detectors → Can be directly measured



A measurement with 5% precision ensures a minimal impact on the CP violation sensitivity

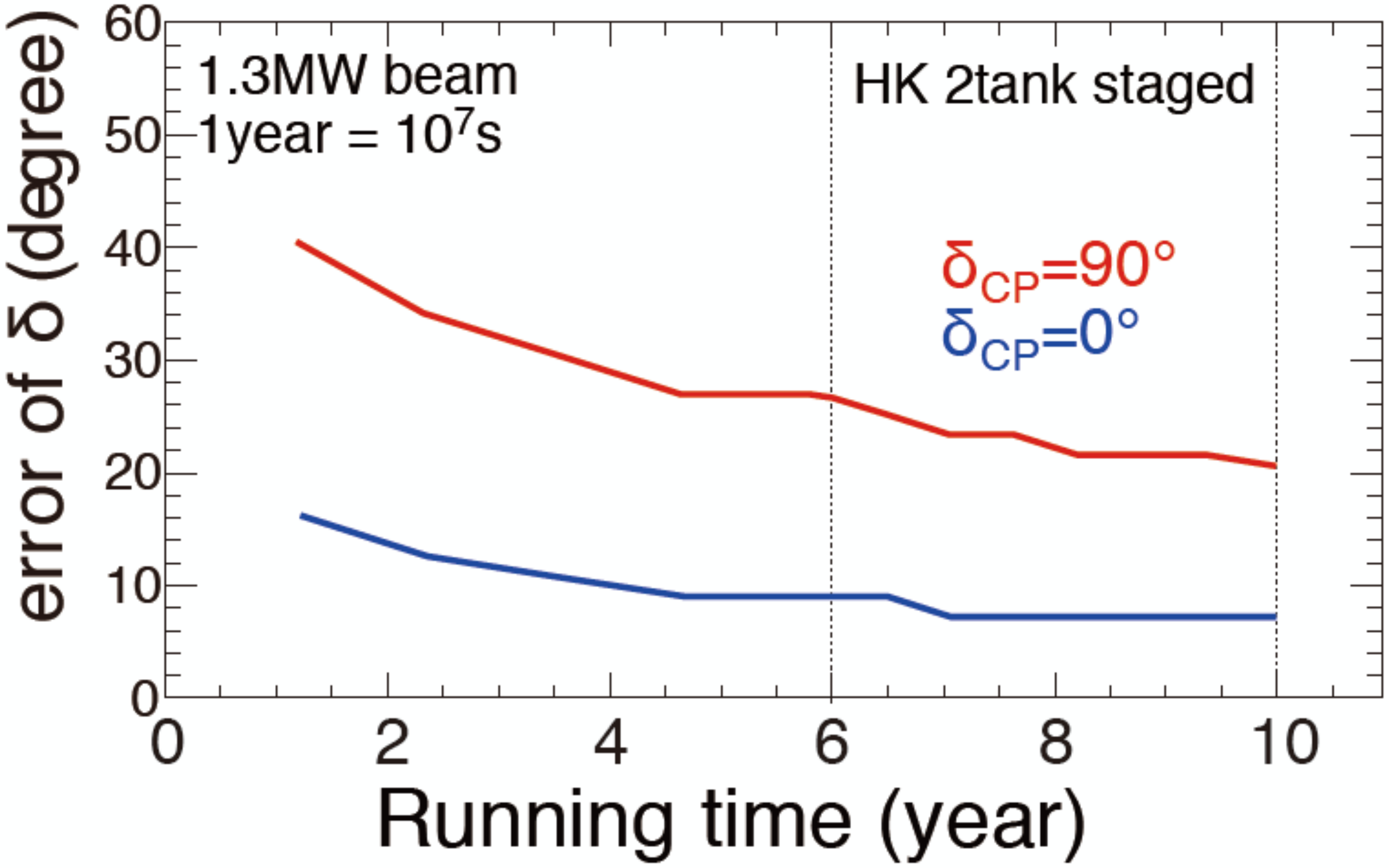
Can be done with an intermediate water Cherenkov detector

SPECTRUM SHAPE UNCERTAINTIES

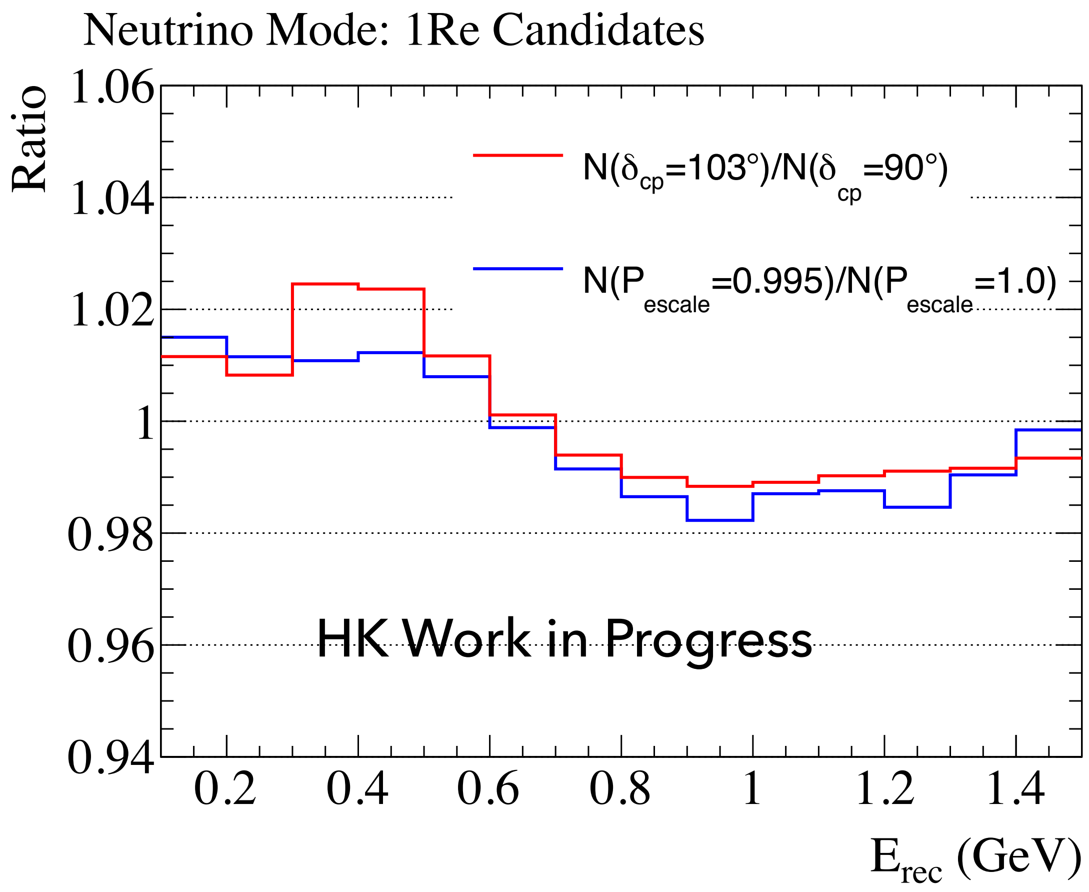
Spectrum shape uncertainties can be important for $|\Delta m^2_{32}|$, $\sin^2\theta_{23}$ and δ_{cp} measurements

I will focus on δ_{cp} here (the impact for the atmospheric parameters is well documented in the literature: Phys.Rev. D92 (073014), Phys.Rev. D92 (091301),)

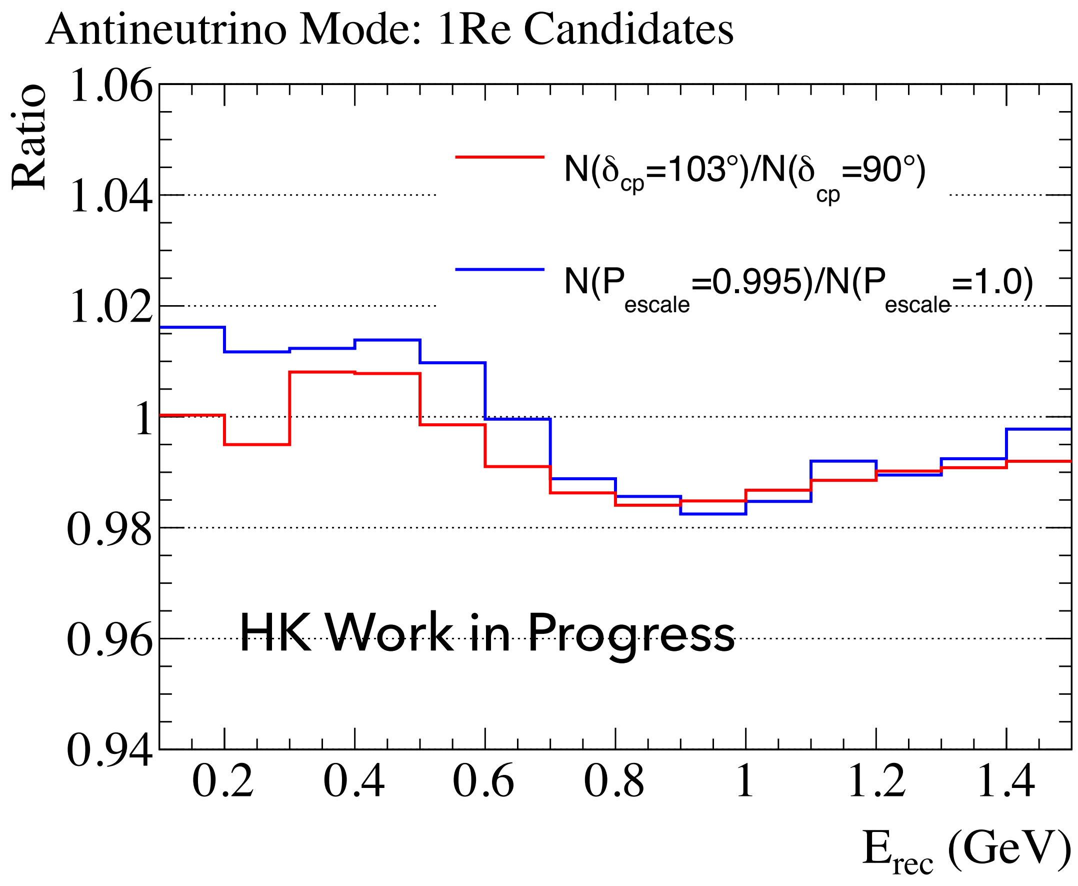
The precision for the δ_{cp} measurement is worse near maximal CP violation because it relies on the $\cos\delta_{cp}$ interference term



SPECTRUM SHAPE UNCERTAINTY, CP PHASE PRECISION



Neutrino Mode: 1Re Candidates



Antineutrino Mode: 1Re Candidates

A 13 degree shift in δ_{cp} near maximal CP violation is roughly equivalent to a 0.5% change in the energy scale

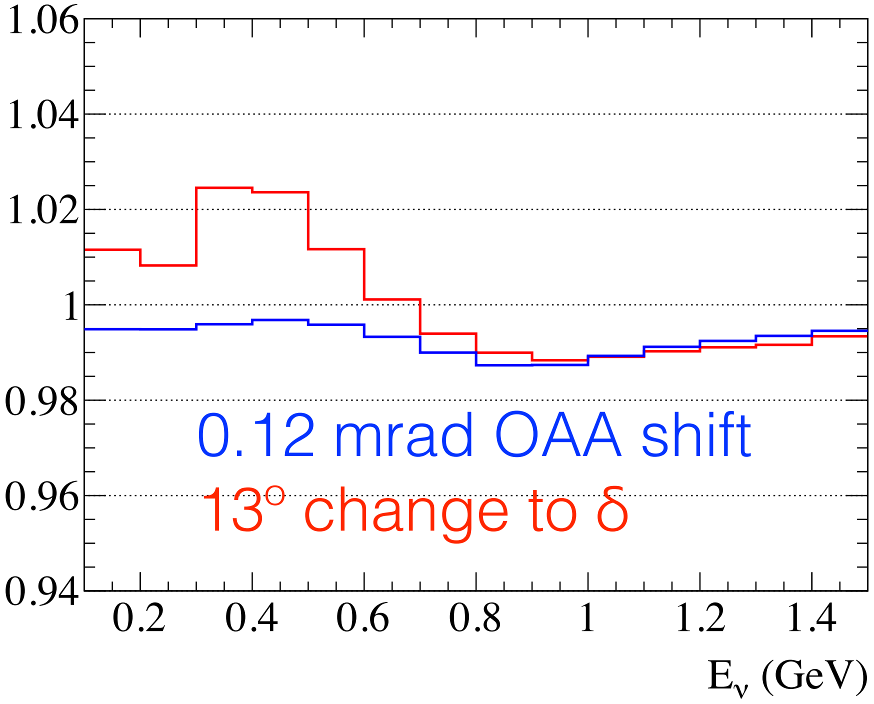
Systematic sources that can shift the peak reconstructed energy:

- **Beam direction**
- **Effective binding energy in the nuclear model**
- **Modeling of non-CCQE interactions**
- Modeling of far detector

Should be addressed with near detector measurements

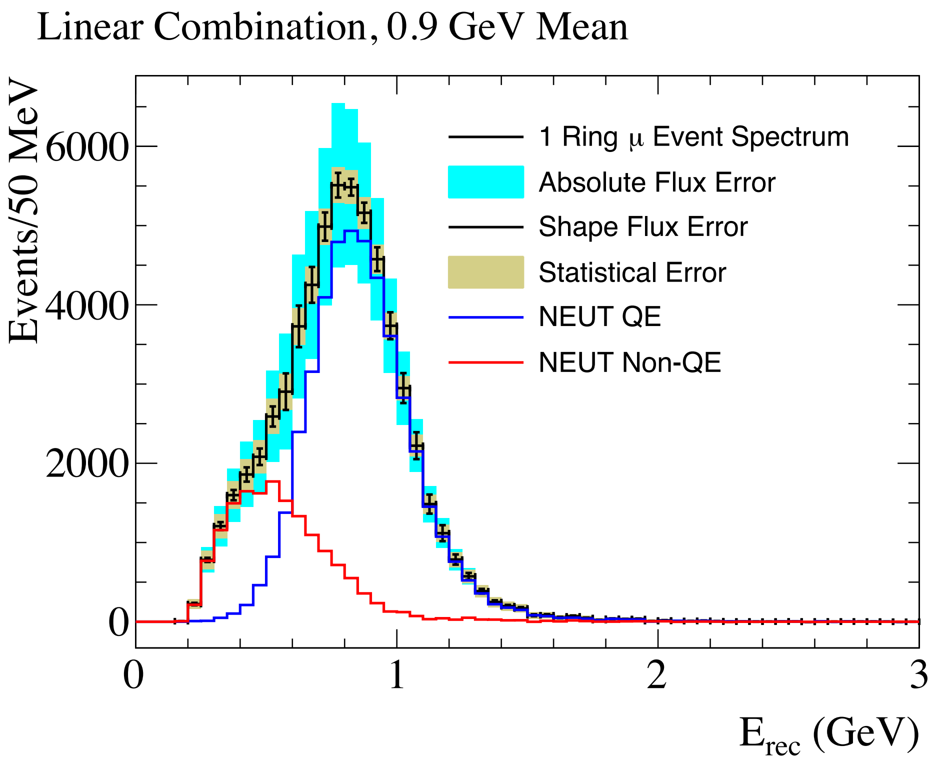
NEAR DETECTOR CONSTRAINTS ON SPECTRUM SHAPE

Beam direction measured by INGRID
- Current uncertainty in neutrino mode is 0.12 mrad
- Spectrum distortion is smaller at low energy, but similar at high energy



Need studies of the near detectors to constraint the peak energy (combined constraint on beam direction and effective binding energy)

The feed-down effect from non-CCQE interactions may be directly measured with the off-axis spanning intermediate water Cherenkov detector
- Sufficient energy scale precision?



Can also be constrained by hadronic final state measurements in upgraded ND
- Build better models
- Calorimetric energy reconstruction

PLAN FOR HYPER-K STUDIES

1. Develop a unified framework for generating Monte Carlo and applying systematic variations for detectors being considered for T2K ND upgrades and Hyper-K

2. Develop a consistent framework for evaluating the ability of detectors to:

    a. Constrain model parameters

    b. Reject or choose models

    c. Directly predict expected observables at the far detector

3. Building on studies presented here, identify the critical model uncertainties and evaluate the proposed detector technologies to address these uncertainties

4. Update the near/intermediate detector requirements and refine designs or explore new detectors where necessary

THANK YOU

OSCILLATION PROBABILITIES

Muon (anti)neutrino survival: $P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\boxed{\theta_{23}} \sin^2 \frac{\boxed{\Delta m^2_{32}} L}{4 E_\nu}$

Electron (anti)neutrino appearance:

$$\begin{aligned}
P(\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)) \approx{} & \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - (+)aL)}{(\Delta_{31} - (+)aL)^2} \Delta^2_{31} \\
& + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \cos\theta_{13} \frac{\sin(\Delta_{31} - (+)aL)}{(\Delta_{31} - (+)aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \cos(\Delta_{32}) \cos\delta \\
& - (+)\sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \cos\theta_{13} \frac{\sin(\Delta_{31} - (+)aL)}{(\Delta_{31} - (+)aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \sin(\Delta_{32}) \sin\delta \\
& + \cos^2\theta_{13} \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta^2_{21}.
\end{aligned}$$

$$\Delta_{31} = \frac{\Delta m^2_{31} L}{4E} \quad \Delta_{21} = \frac{\Delta m^2_{21} L}{4E} \quad a = G_F N_e / \sqrt{2}$$

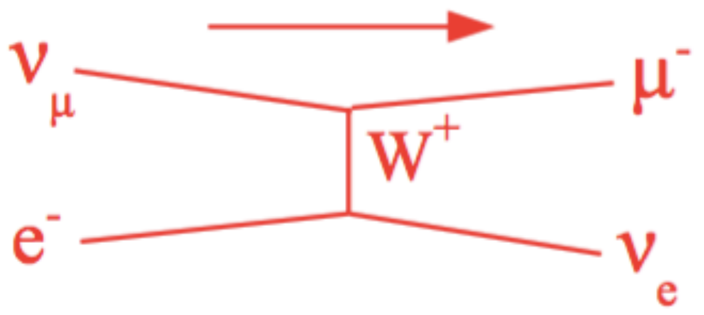
Sensitivity to:

- Leading term: $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, $|\Delta m^2_{32}|$
- Interference terms: $\cos\delta$ (shape distortion) and $\sin\delta$ (neutrino/antineutrino asymmetry)
- Matter effect: sign of Δm^2_{32}

DIRECT MEASUREMENT OF NEUTRINO BEAM

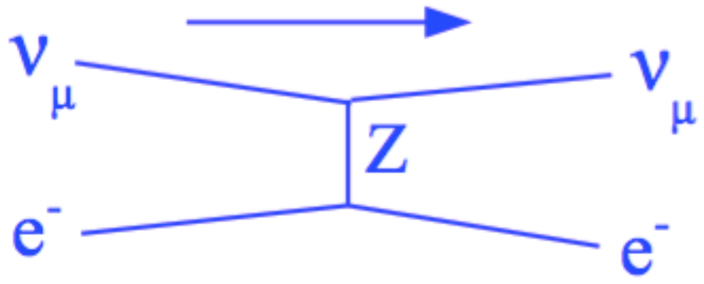
Neutrino-nucleus uncertainties are as large as neutrino flux uncertainties
→ Cannot use neutrino-nucleus interaction measurements to constrain the flux

Need processes with little to no uncertainties on interactions:



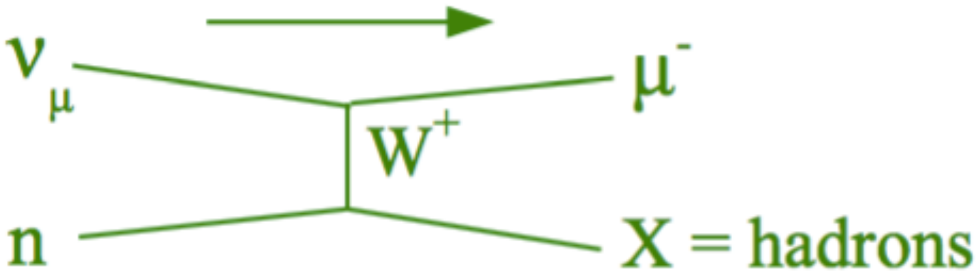
Inverse muon decay:

Threshold is E_ν>12 GeV



Neutrino-electron scattering:

Cross section is too small for <1 GeV J-PARC beam to collect sufficient statistics



Low ν method: cross section is constant with neutrino energy when recoil energy goes to 0

Can measure the neutrino spectrum shape

Works best at energies >1 GeV

DIRECT MEASUREMENT OF NEUTRINO BEAM

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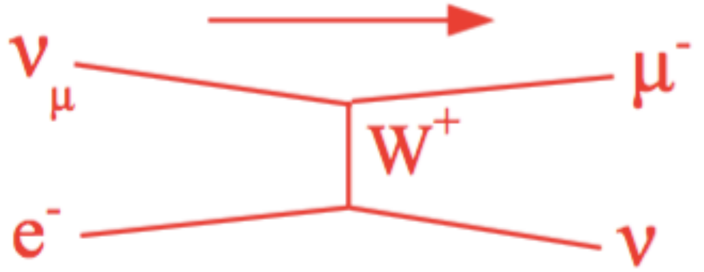
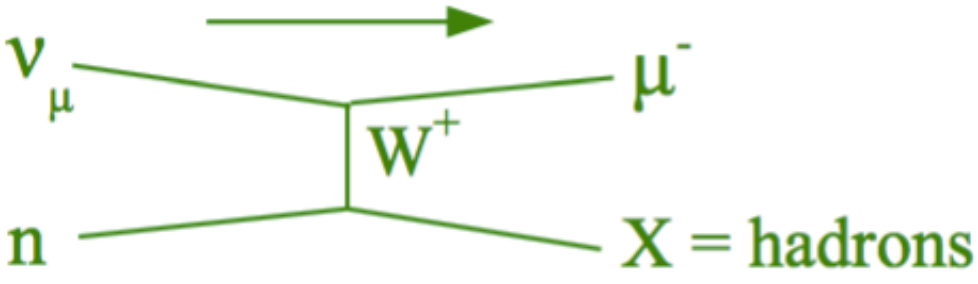


Inverse muon decay:

Threshold is E_ν>12 GeV

NONE OF THESE ARE APPLICABLE TO THE J-PARC NEUTRINO BEAM

ANY NOVEL IDEAS?



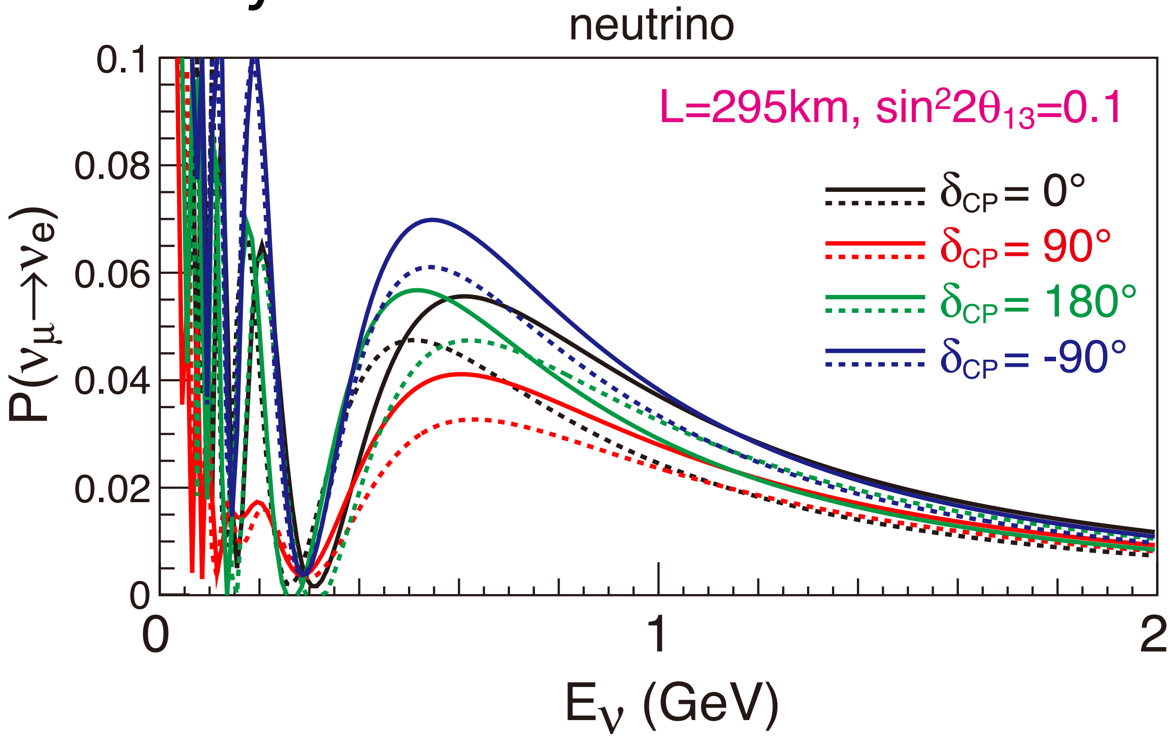
Low ν method: cross section is constant with neutrino energy when recoil energy goes to 0

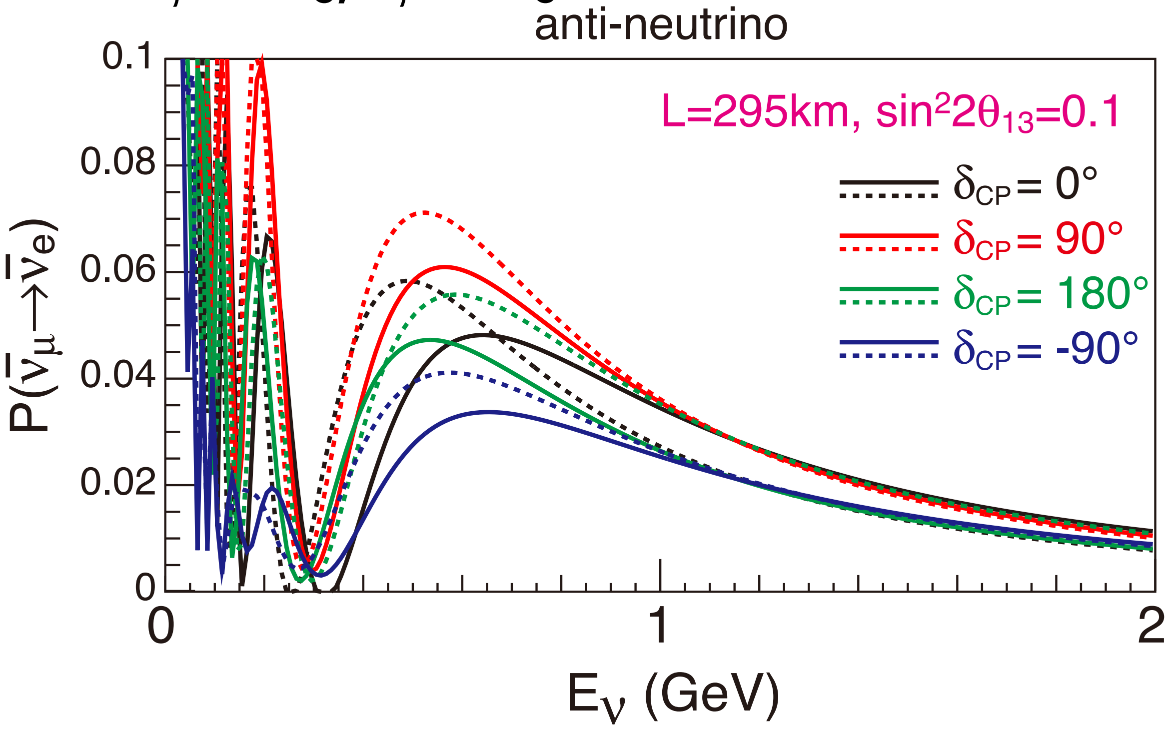
Can measure the neutrino spectrum shape

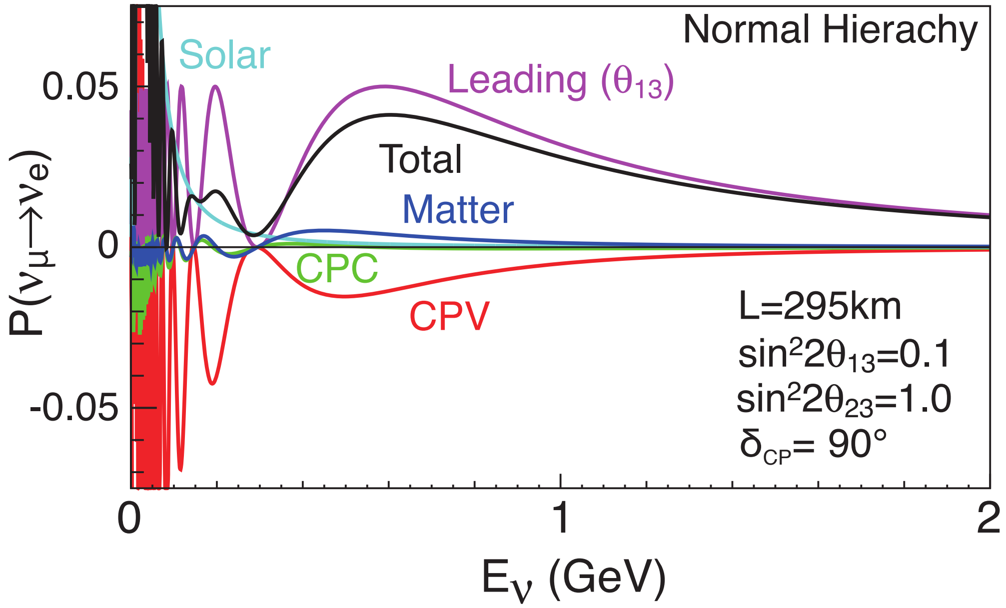
Works best at energies >1 GeV

HYPER-K LONG BASELINE PHYSICS

Primary Goal: Detection of CP violation in the $\nu_\mu \rightarrow \nu_e$, $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ channels







At 295 km baseline, the CPV effect dominates over the matter effect

Precision measurement of the θ_{23}, Δm^2_{32}, δ_{cp} and θ_{13} parameters

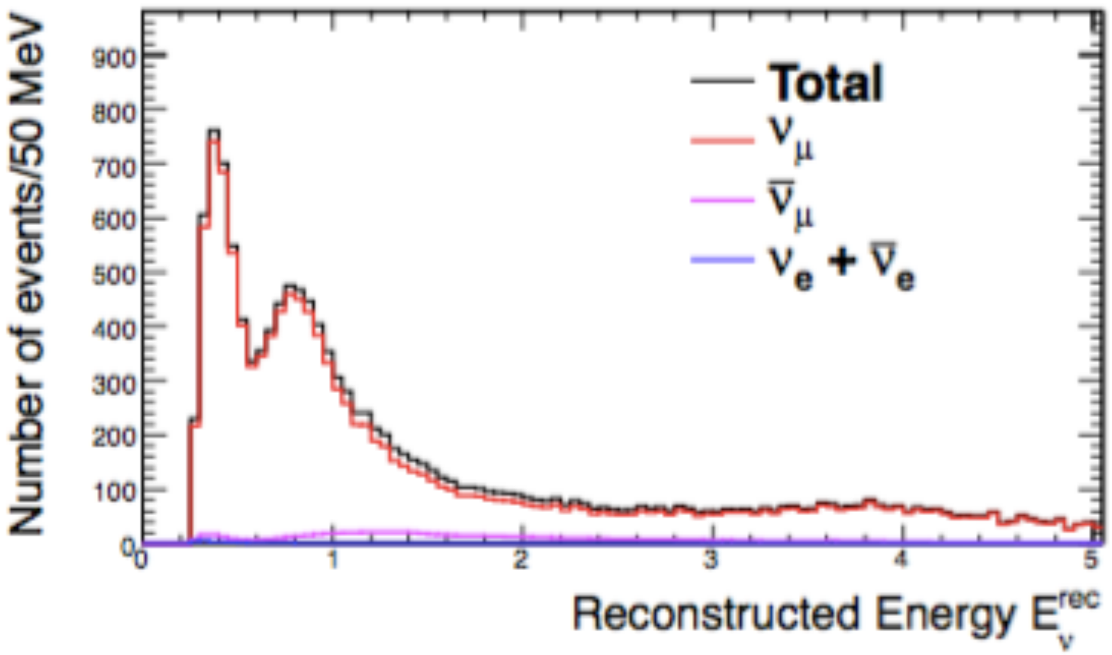
10 years operation with 1.3 MW beam from J-PARC, 3:1 $\overline{\nu}$ to ν ratio

DISAPPEARANCE MODE EVENT RATES

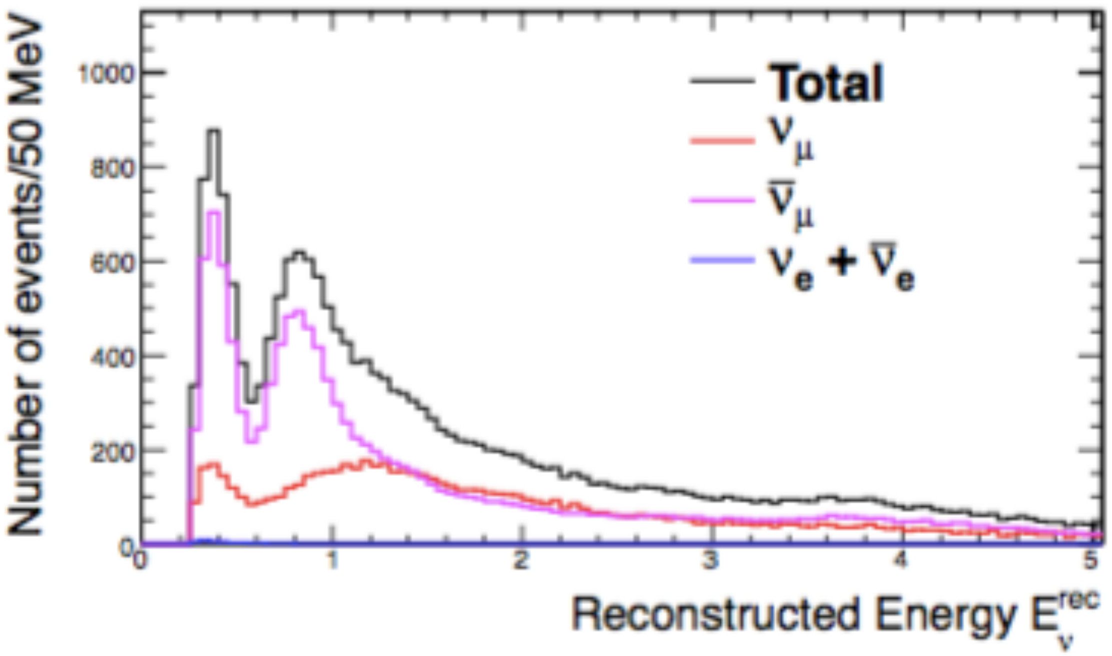
Use kinematic energy reconstruction

$$E_\nu^{\mathrm{rec}} = \frac{2(m_n - V)E_\ell + m_p^2 - (m_n - V)^2 - m_\ell^2}{2(m_n - V - E_\ell + p_\ell \cos\theta_\ell)}$$

Disappearance ν mode

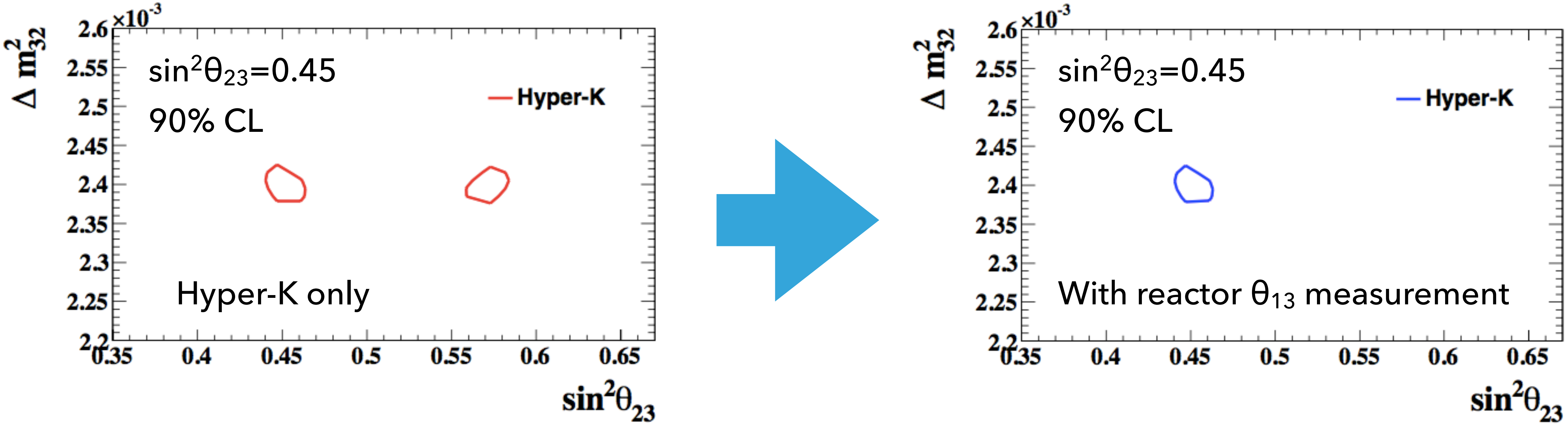


Disappearance $\bar{\nu}$ mode



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

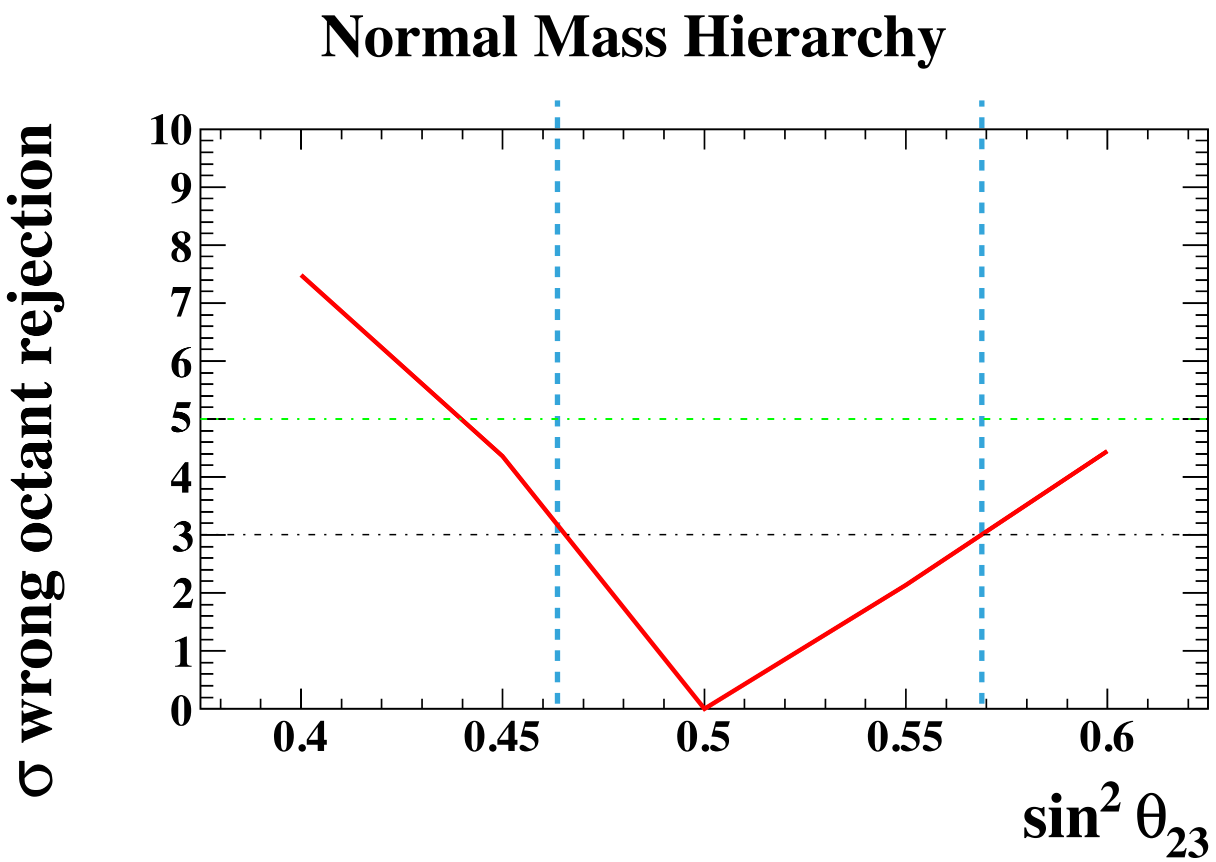
ATMOSPHERIC PARAMETER DETERMINATION



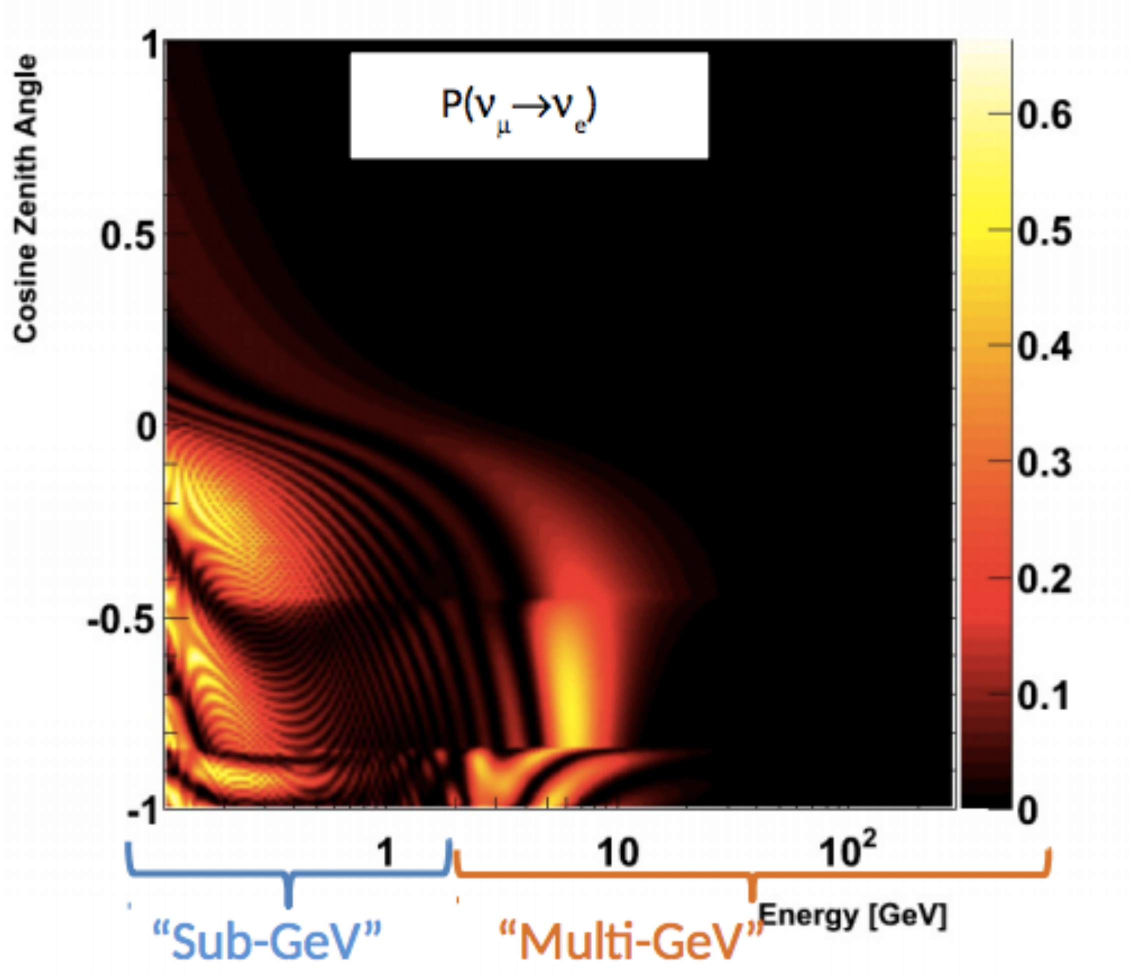
0.6% uncertainty on Δm^2_{32}

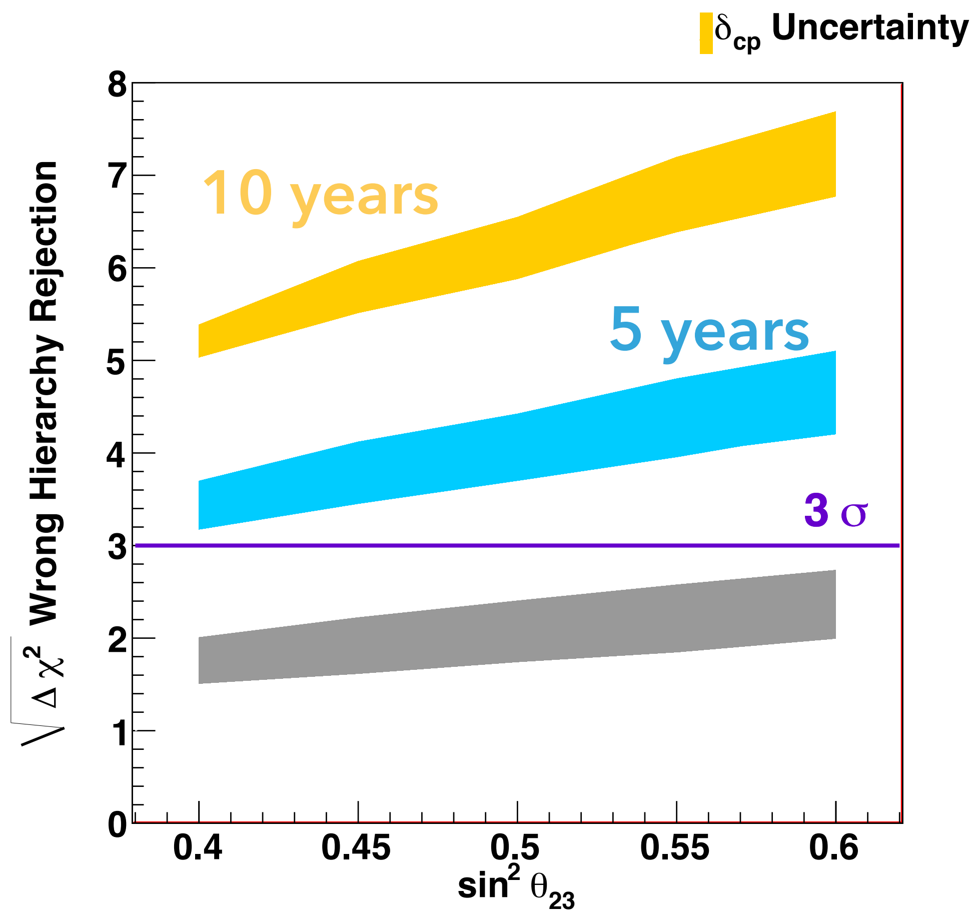
Error on $\sin^2\theta_{23}$ of 0.015 (at 0.5), 0.006 (at 0.45)

Rejection of the wrong octant for non-maximal mixing values of θ_{23}



ATMOSPHERIC NEUTRINOS - MASS HIERARCHY



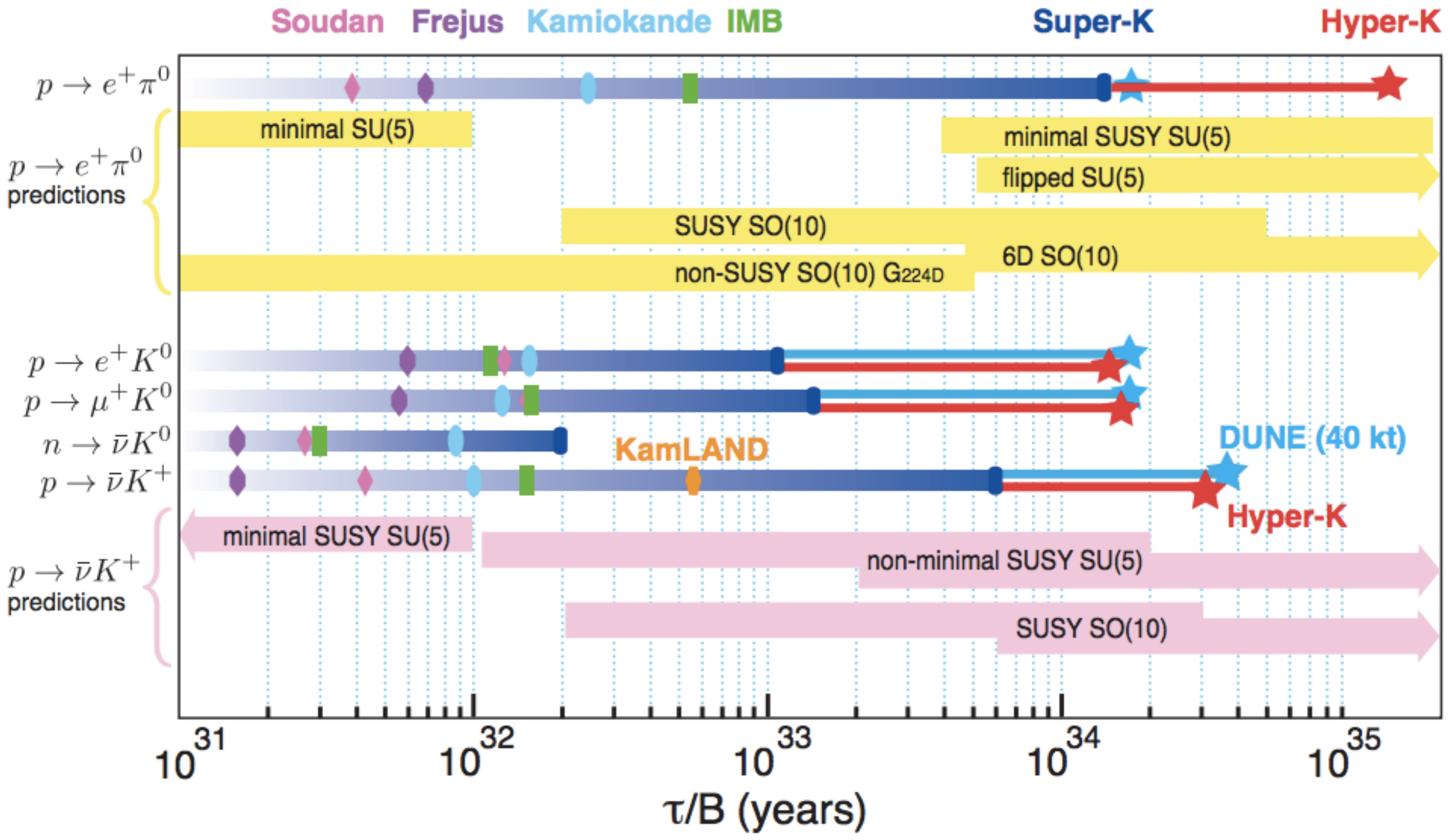


Hyper-K has sensitivity to the mass hierarchy through the atmospheric neutrinos (parametric resonance in the multi-GeV region)

Sensitivity is further improved in combination of accelerator and atmospheric neutrinos

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

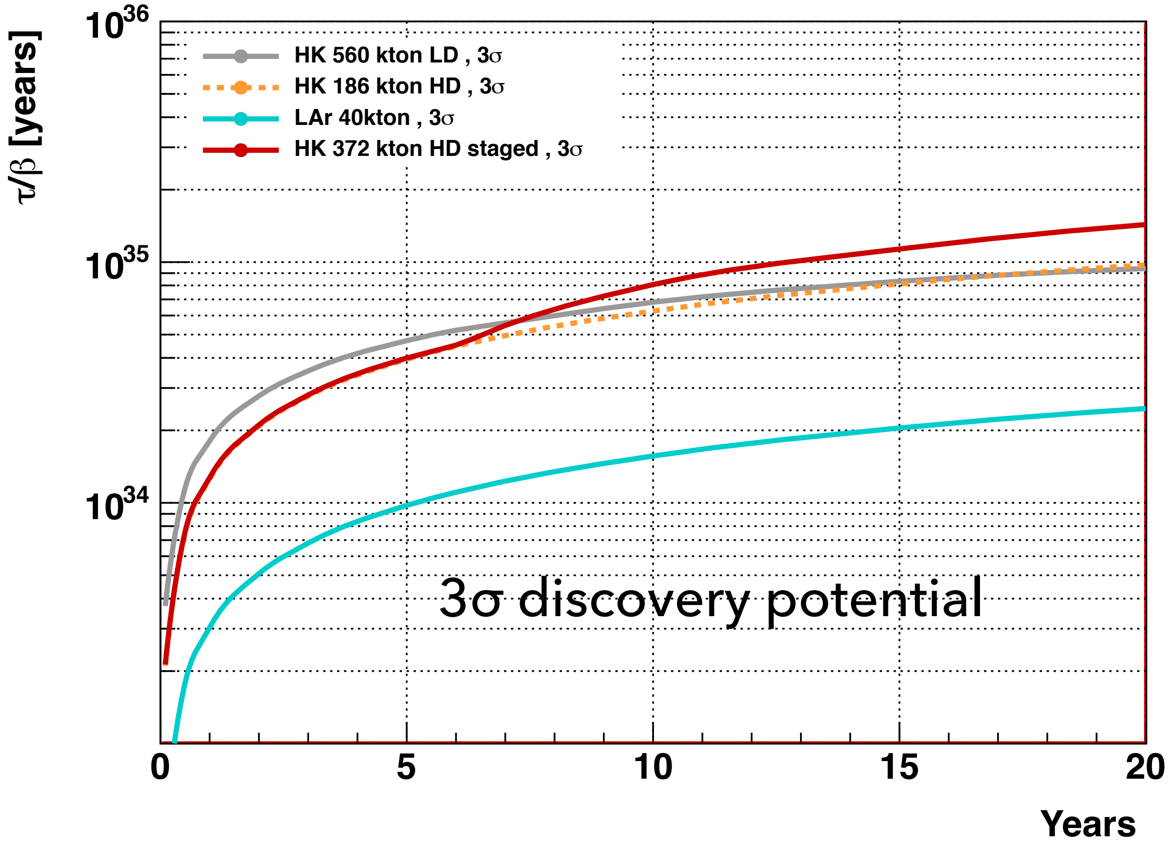
HYPER-K NUCLEON DECAY



1 order of magnitude sensitivity improvements

Leading measurement in eπ^0 mode

Competitive with DUNE in the kaon modes



3σ discovery potential

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 -> T2K-II

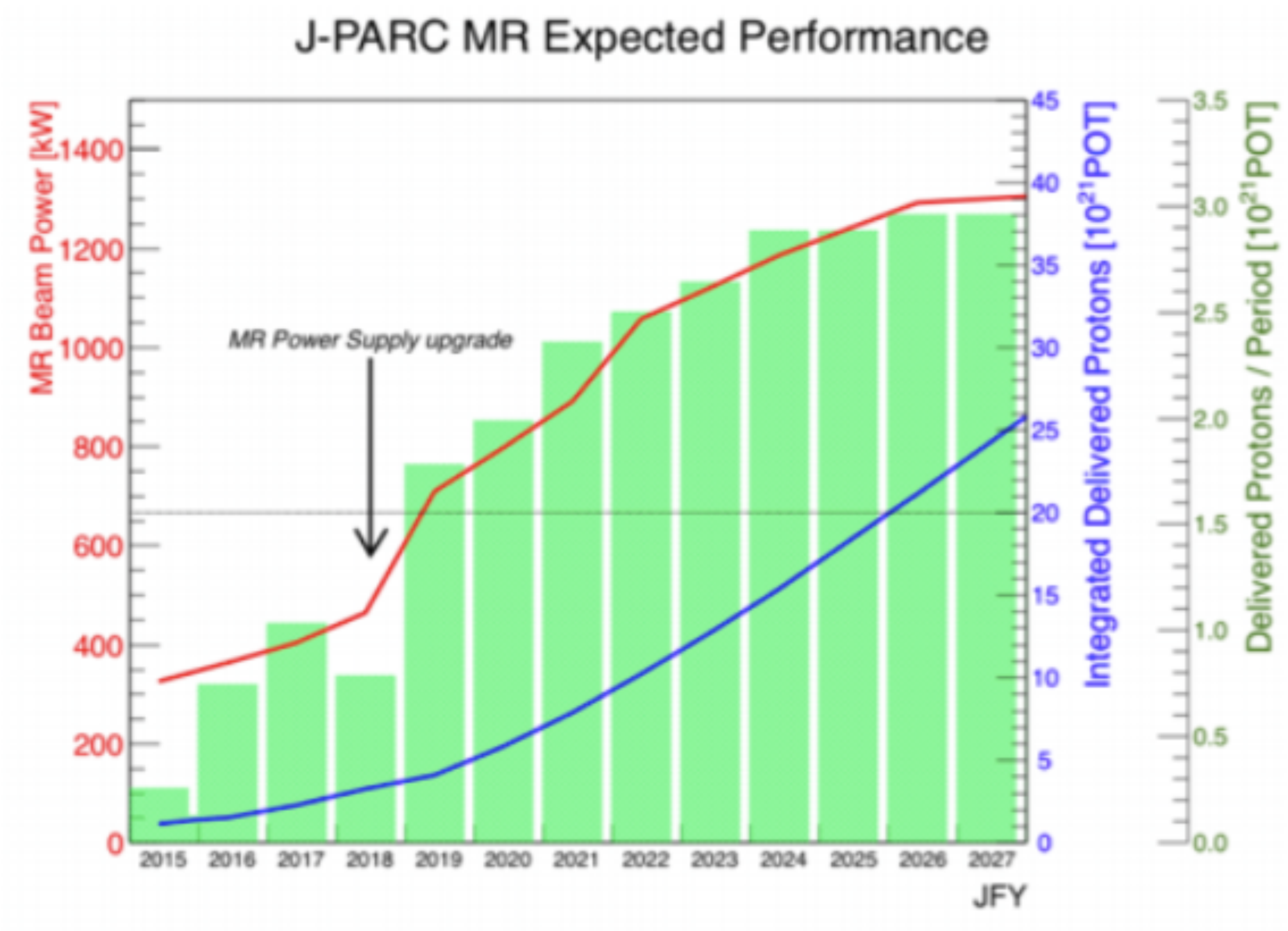
T2K is approved to collect 7.8x10^{21} POT, about 5 times the current data set

T2K has submitted a proposal to extend operation to 2026 and collect 20x10^{21} POT

Main ring power supply upgrade in 2018 will allow for ~1 MW beam

T2K will improves its experimental sensitivity:

- Operate horns at higher current = more neutrinos
- New multi-ring samples at Super-K
- Expanding the fiducial volume at Super-K
- Reduction of systematic errors



ELECTRON NEUTRINO CROSS SECTION MEASUREMENT

Beam ν_e fraction increases with off-axis angle

Off-axis angle (º)	ν_e Flux 0.3-0.9 GeV	ν_μ Flux 0.3-5.0 GeV	Ratio ν_e/ν_μ
2.5	1.24E+15	2.46E+17	0.507%
3.0	1.14E+15	1.90E+17	0.600%
3.5	1.00E+15	1.47E+17	0.679%
4.0	8.65E+14	1.14E+17	0.760%

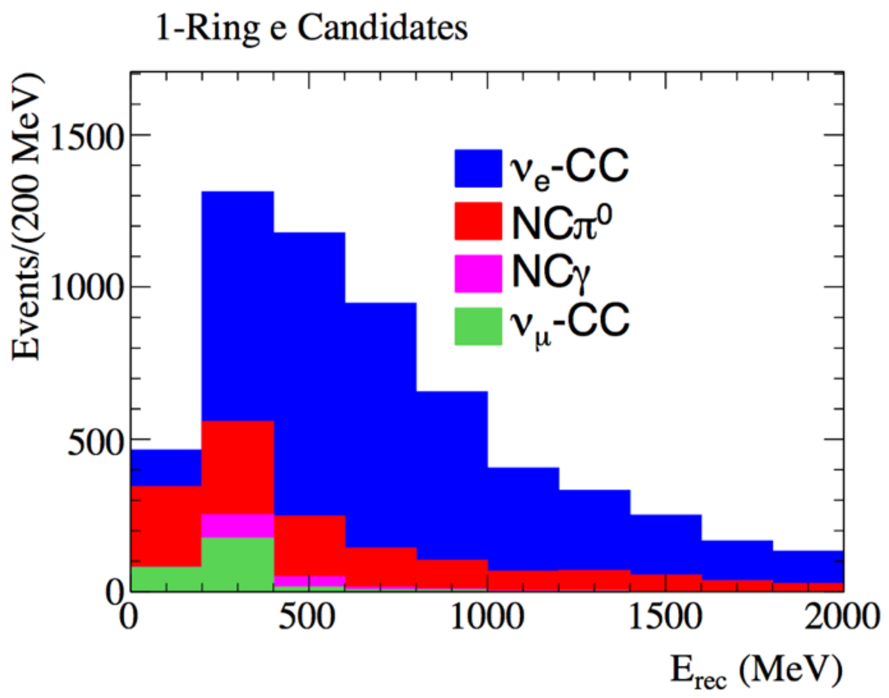


FIG. 24. Selected 1R*e* candidates in the 2.5-4.0° off-axis range for NuPRISM.

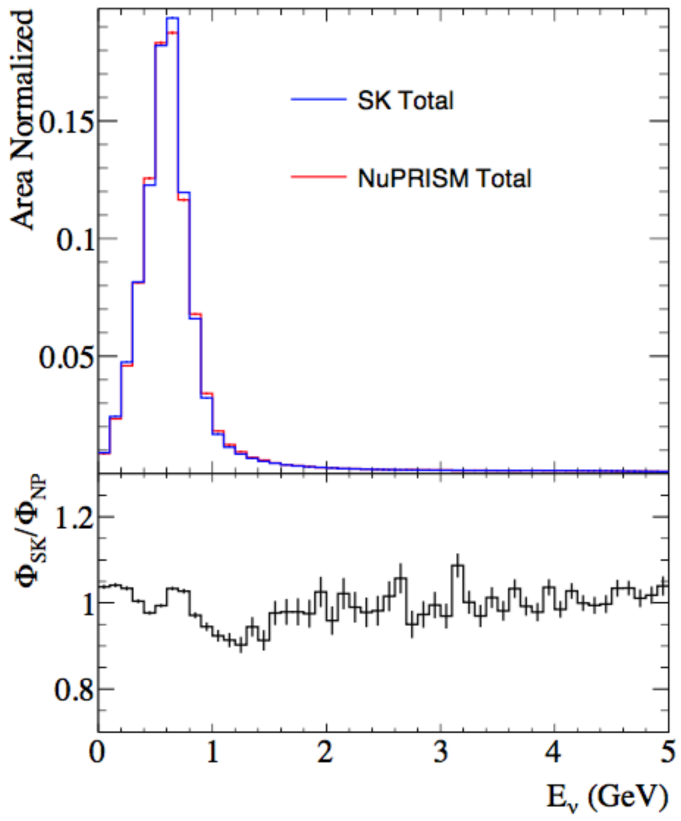
1.5e21 POT exposure at each off-axis position

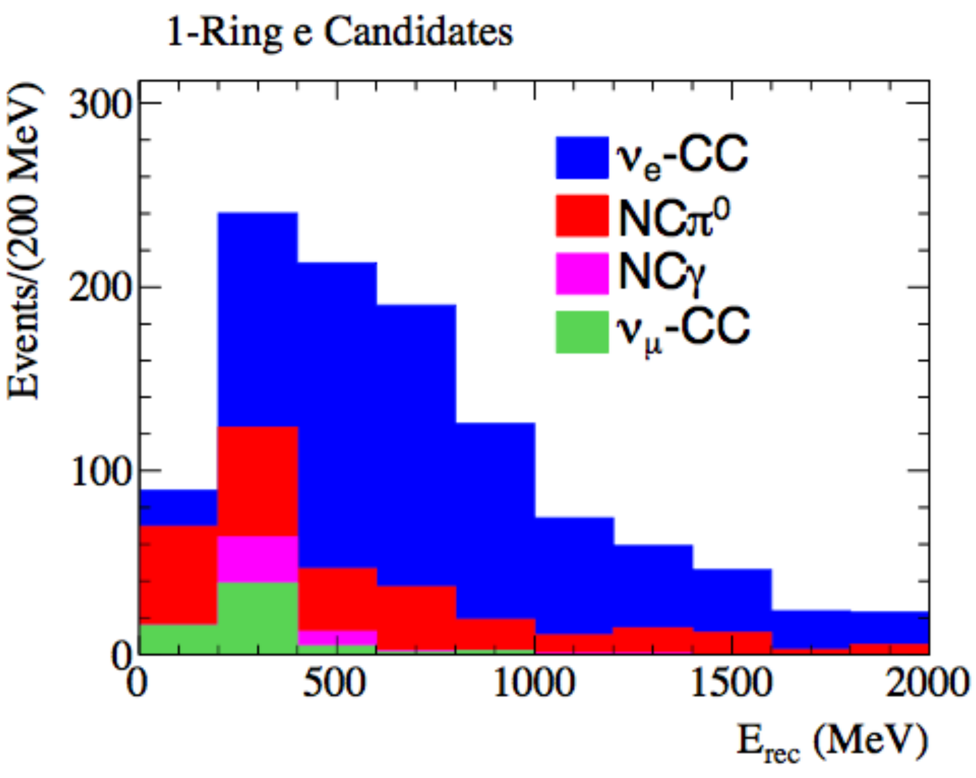
3500 candidate events with 71% signal purity

Aiming for ~3% precision on ν_e/ν_μ cross section ratio

INTRINSIC BACKGROUND MEASUREMENT

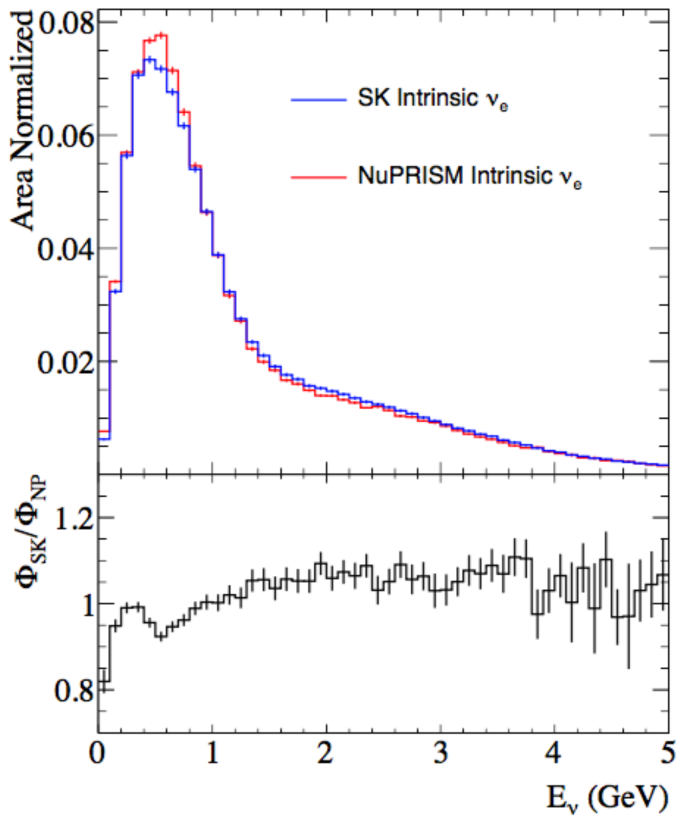
- Total neutrino and intrinsic ν_e and fluxes are nearly identical in the intermediate and far detectors
- Can measure the intrinsic+NC background directly in the intermediate detector





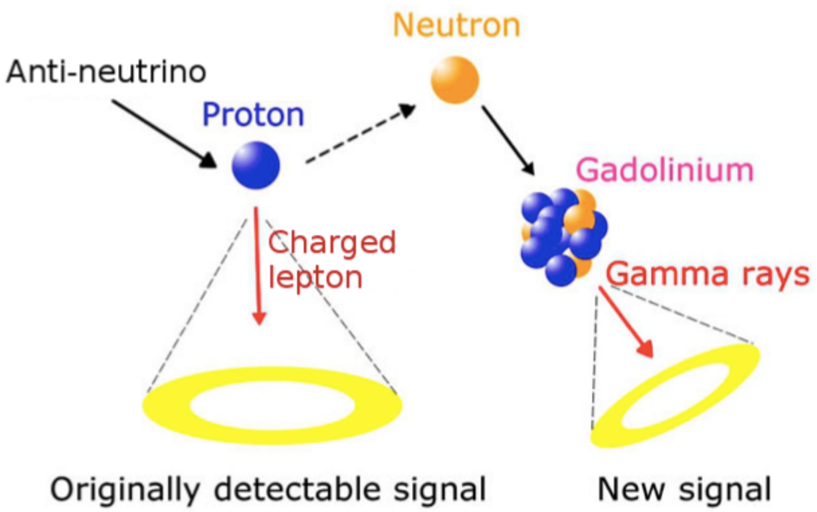
300 ton ID x 1.5e21 POT

3% statistical precision can be achieved



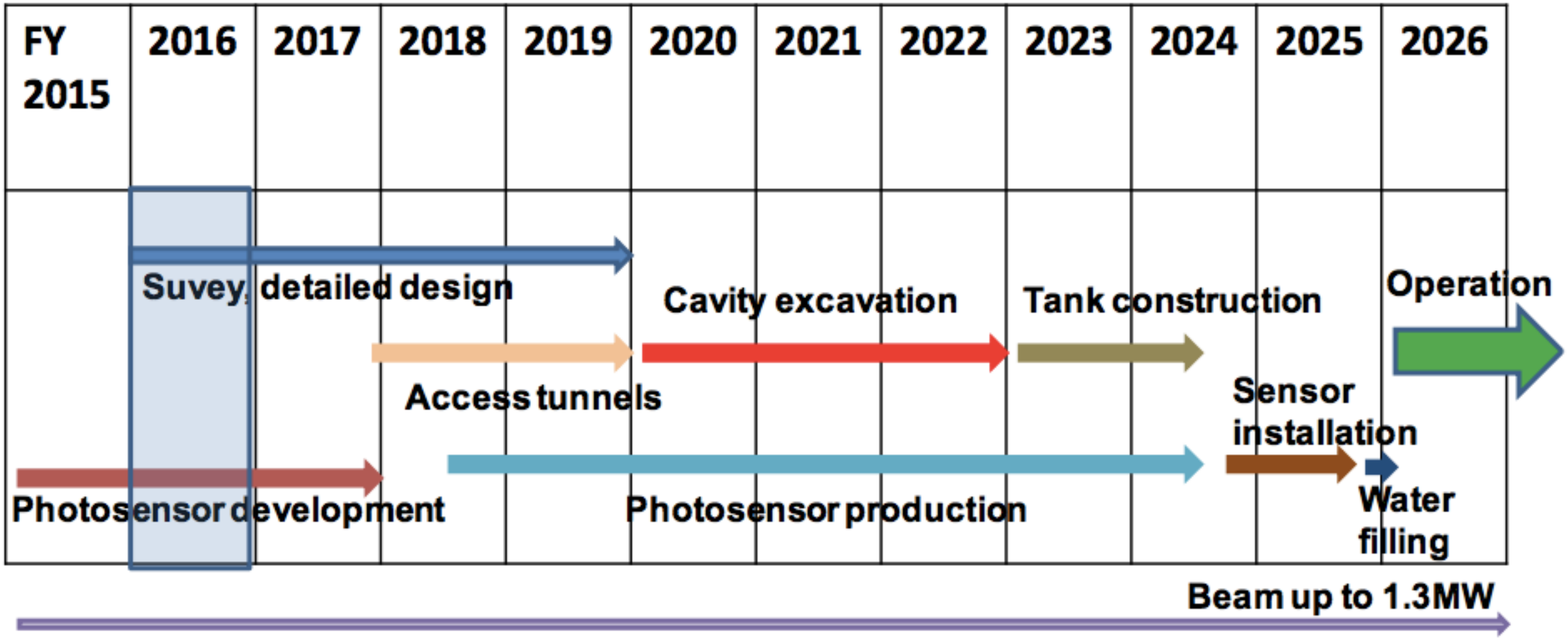
MEASUREMENTS WITH GADOLINIUM LOADING

- 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

HYPER-K TIMELINE



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