IMPACT ON LONG BASELINE EXPERIMENTS (WITH FOCUS ON THE PROGRAM IN JAPAN)

MARK HARTZ
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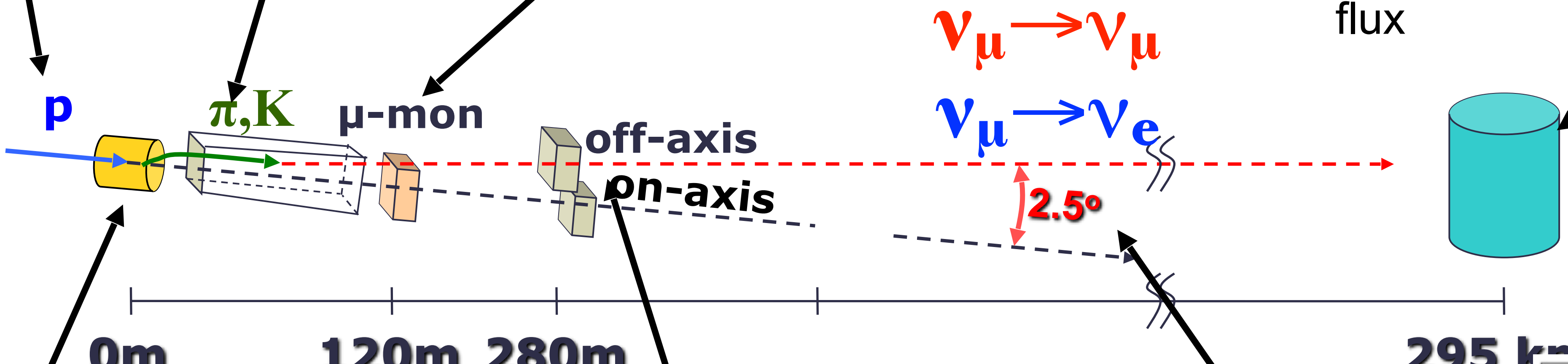
LONG BASELINE ACCELERATOR NEUTRINO EXPERIMENTS

T2K/T2HK Schematic:



30 GeV
proton beam

Decay volume

MUMON measures muons from pion decay

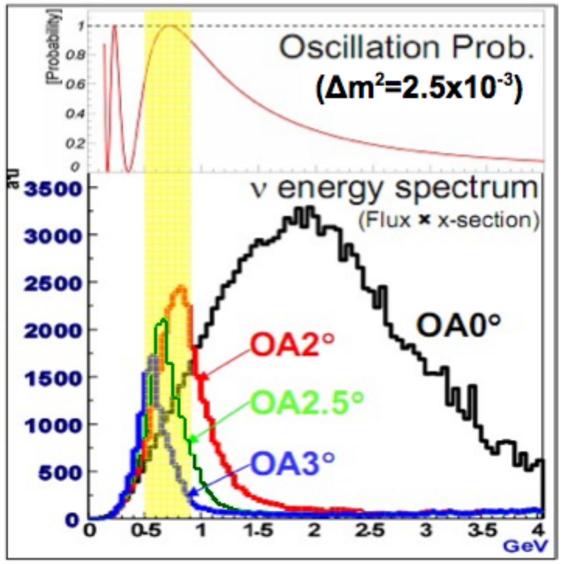
Off-axis **far detector** at 295 km: SK or HK water Cherenkov detector measures oscillated flux

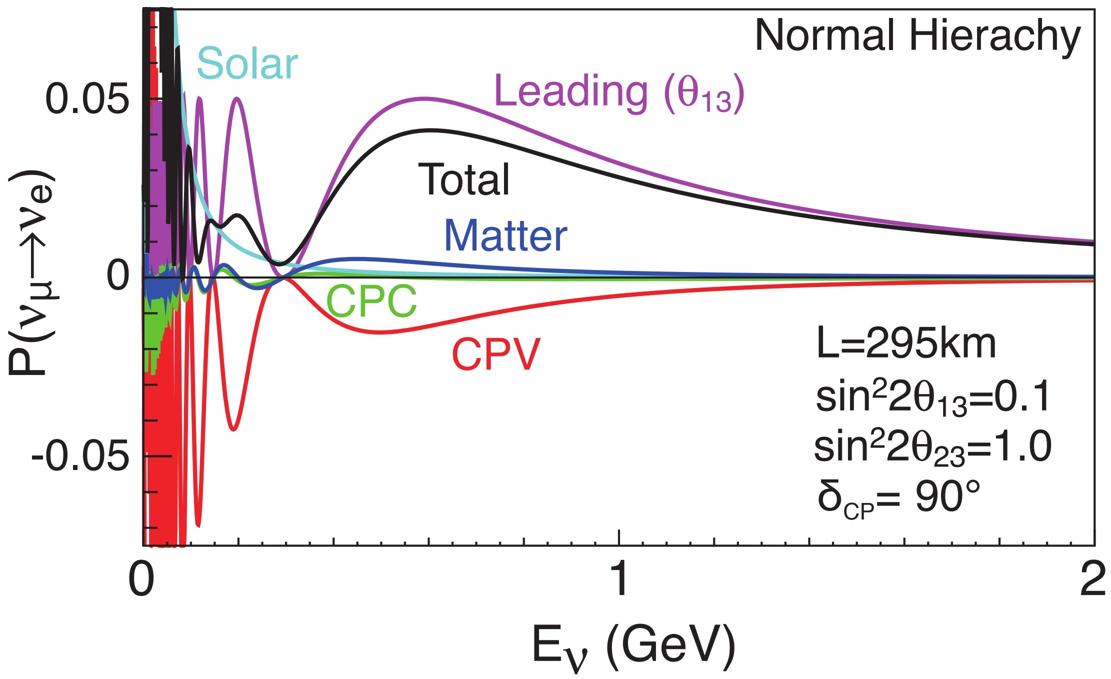
Beam on graphite target

3 magnetic horns focus positively charged hadrons

Off-axis **near detector**: ND280 detector measures spectra for various neutrino interactions

Off-axis = narrow band beam





Primary goal is detection of CP violation

T2K -> T2K-II

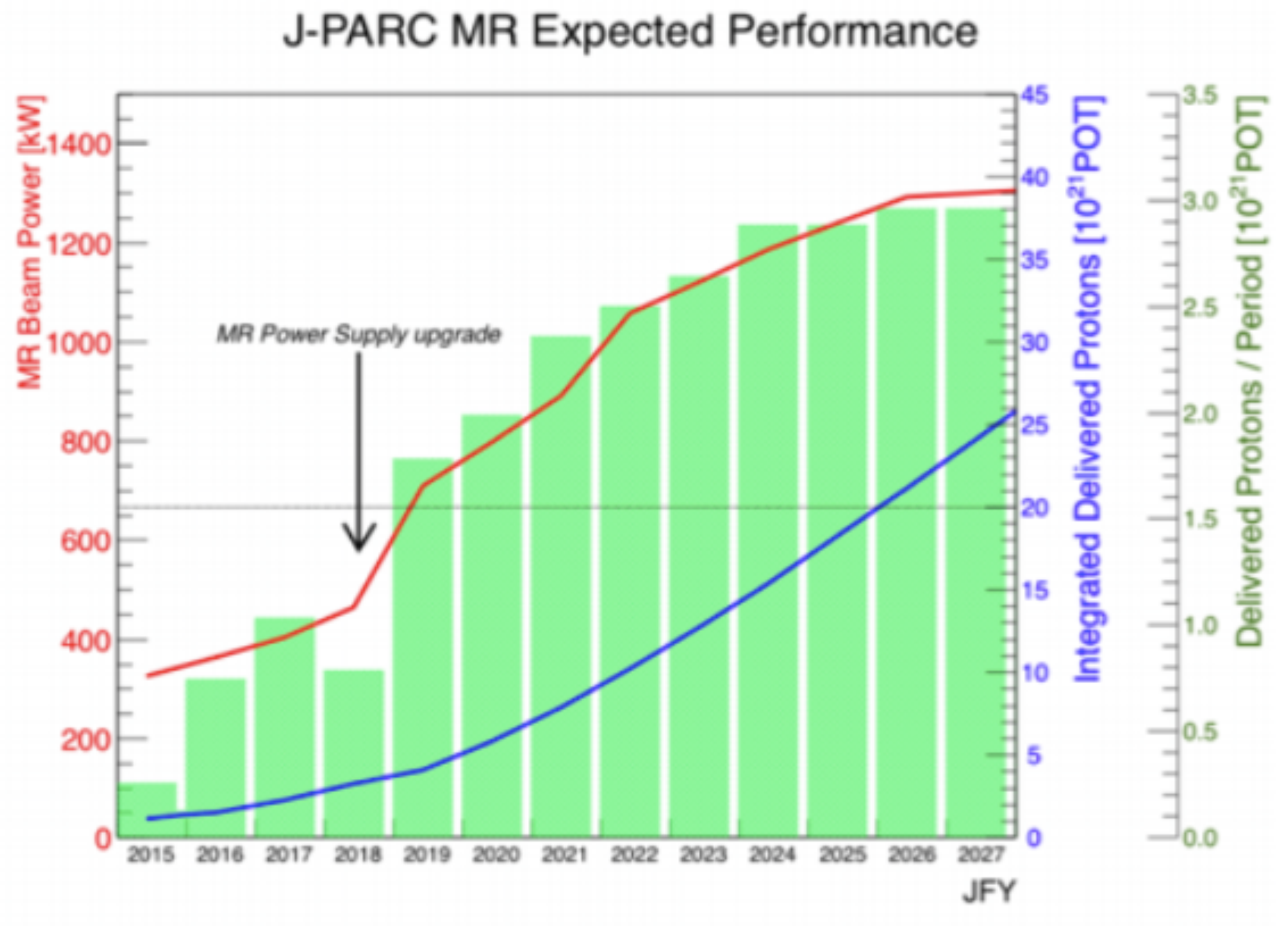
T2K is approved to collect 7.8x10^{21} POT, about 5 times the current data set

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:

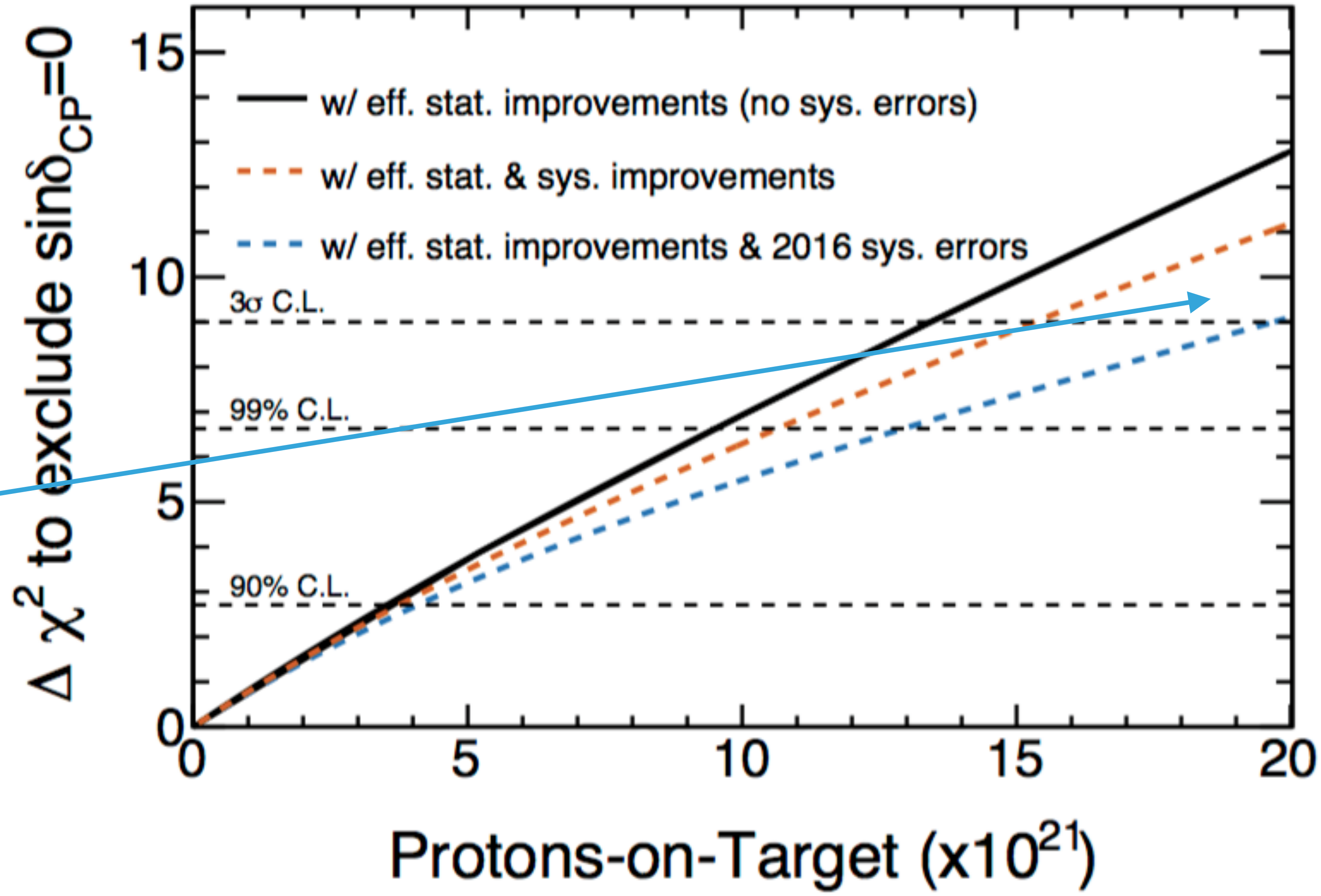
- Operate horns at higher current = more neutrinos
- New multi-ring samples at Super-K
- Expanding the fiducial volume at Super-K
- Reduction of systematic errors



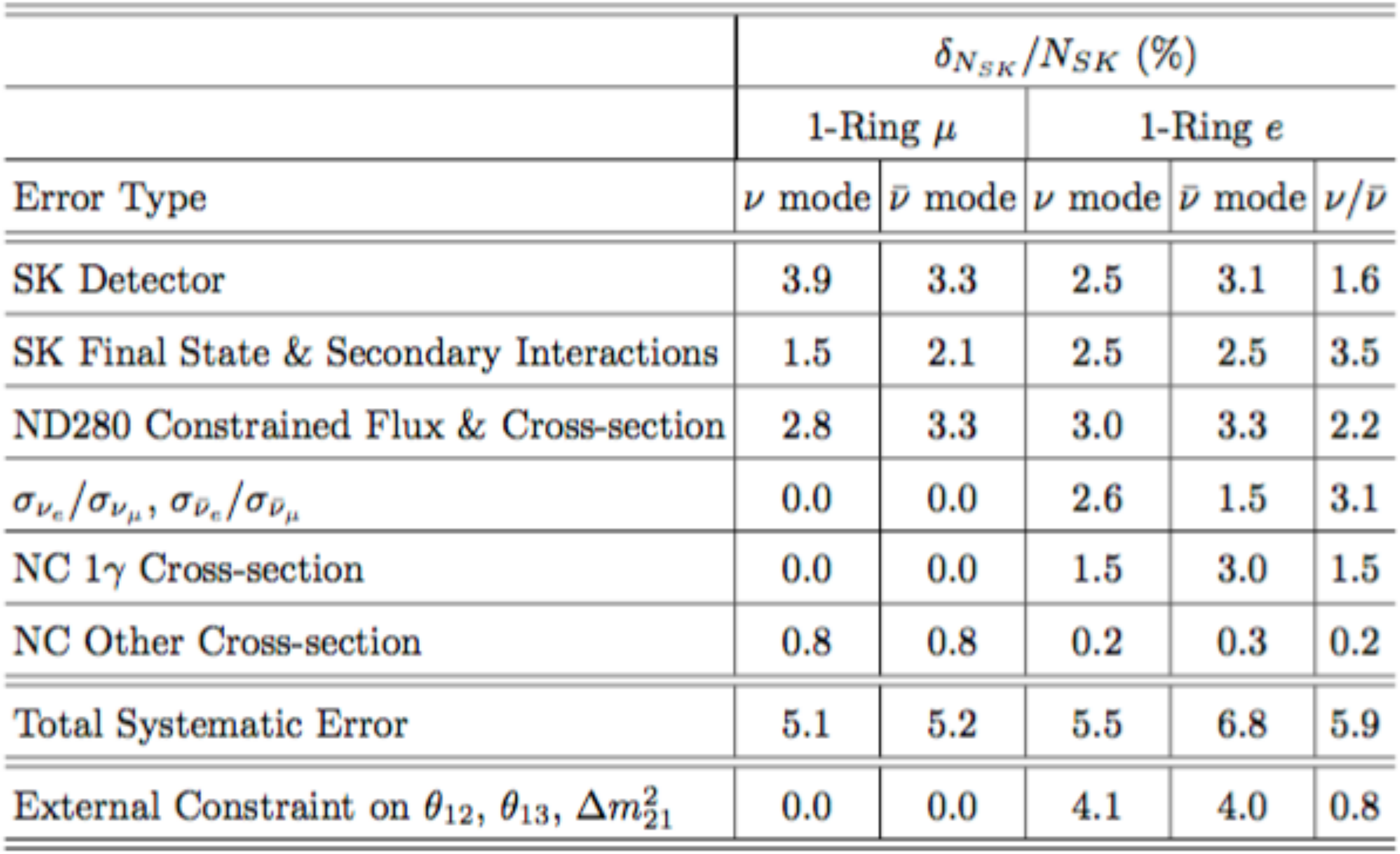
T2K-II SENSITIVITY FOR CP VIOLATION DISCOVERY

For a favorable value of $\delta_{cp}=3\pi/2$, can have 3σ sensitivity for CP violation discovery

Reduction of systematic errors is necessary to maximize the probability of a 3σ oscillation discovery

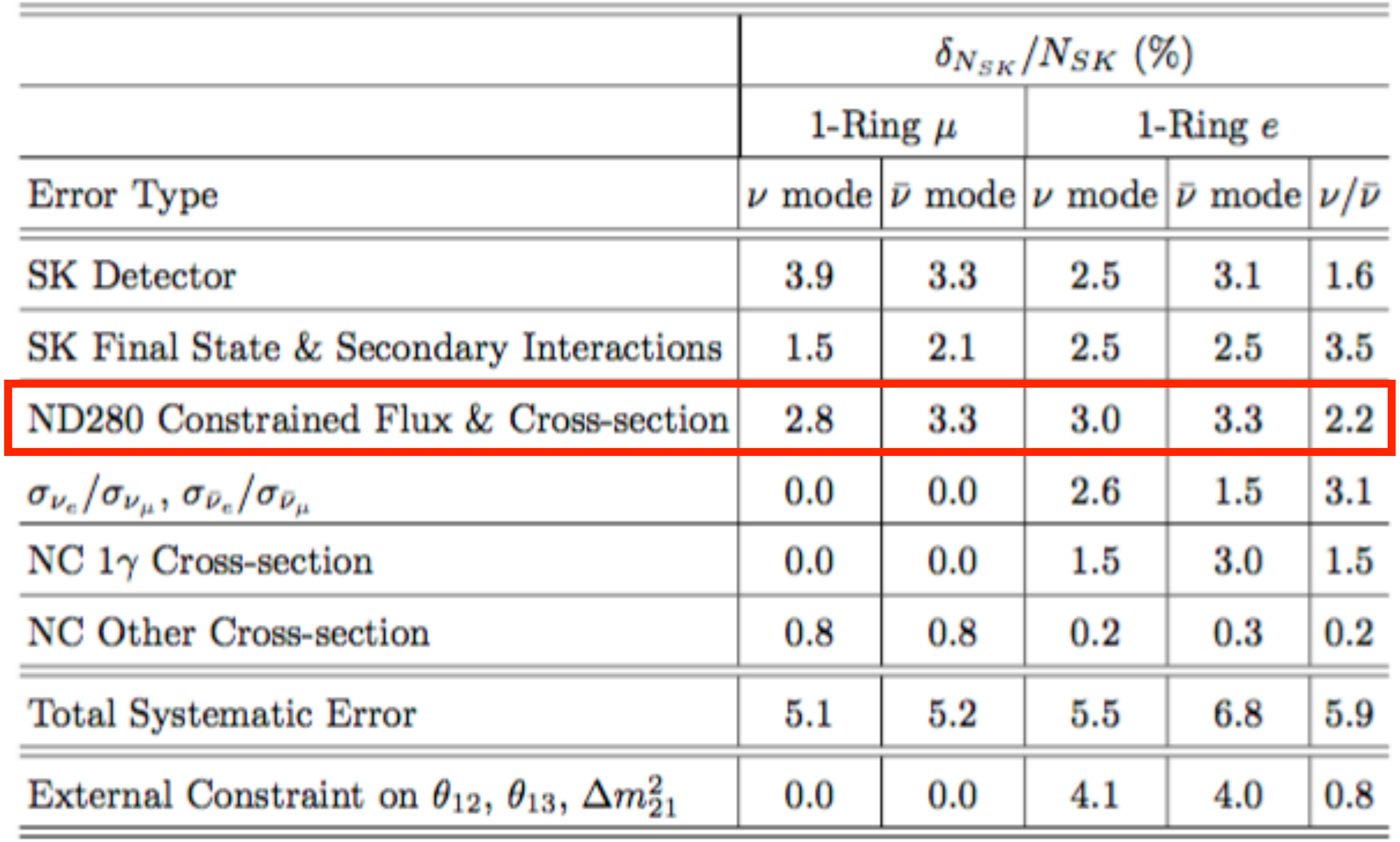


T2K-II SYSTEMATIC ERRORS



	$\delta_{N_{SK}}/N_{SK}$ (%)				
	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

T2K-II SYSTEMATIC ERRORS



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Systematic errors on neutrino flux model enter directly here

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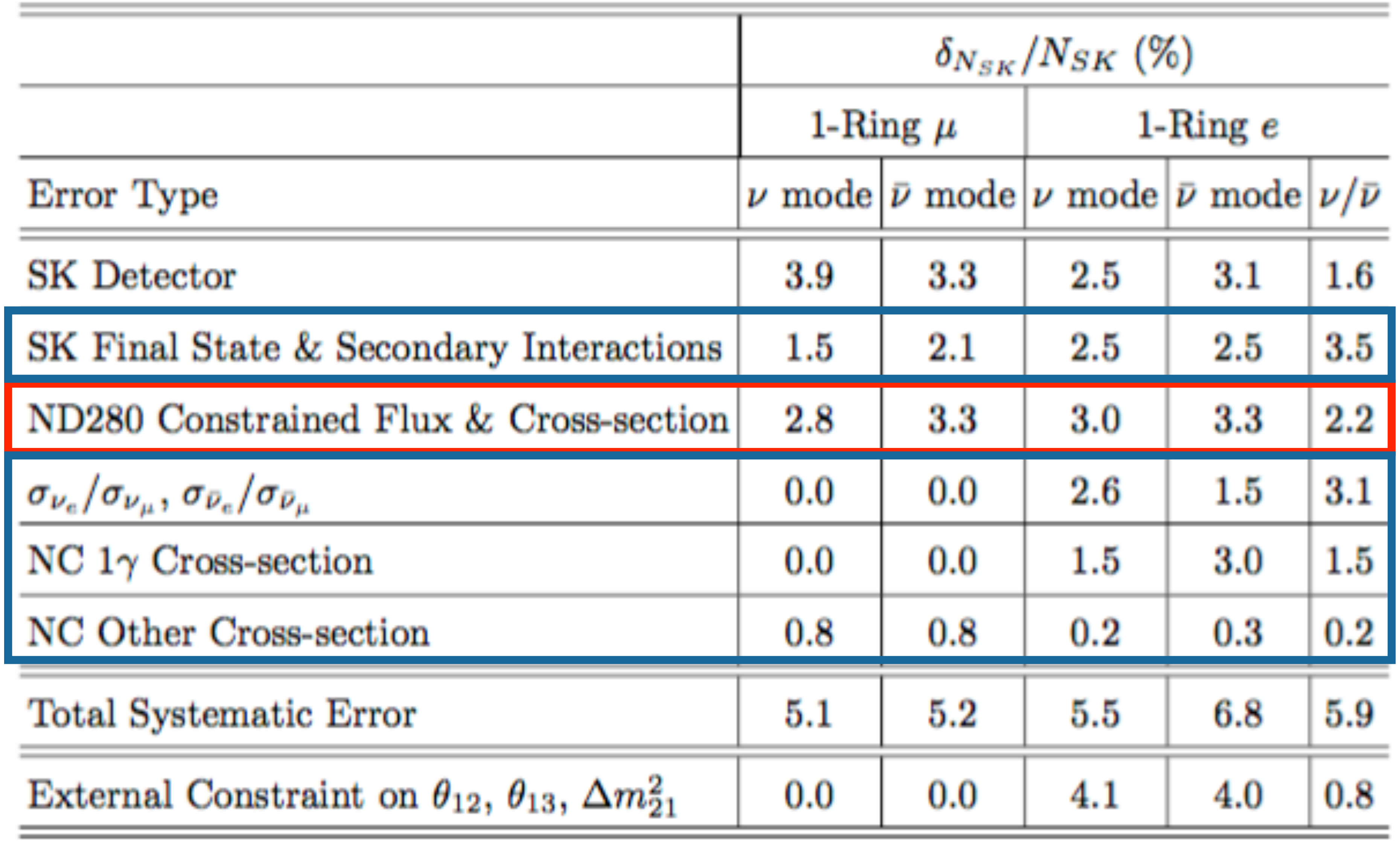

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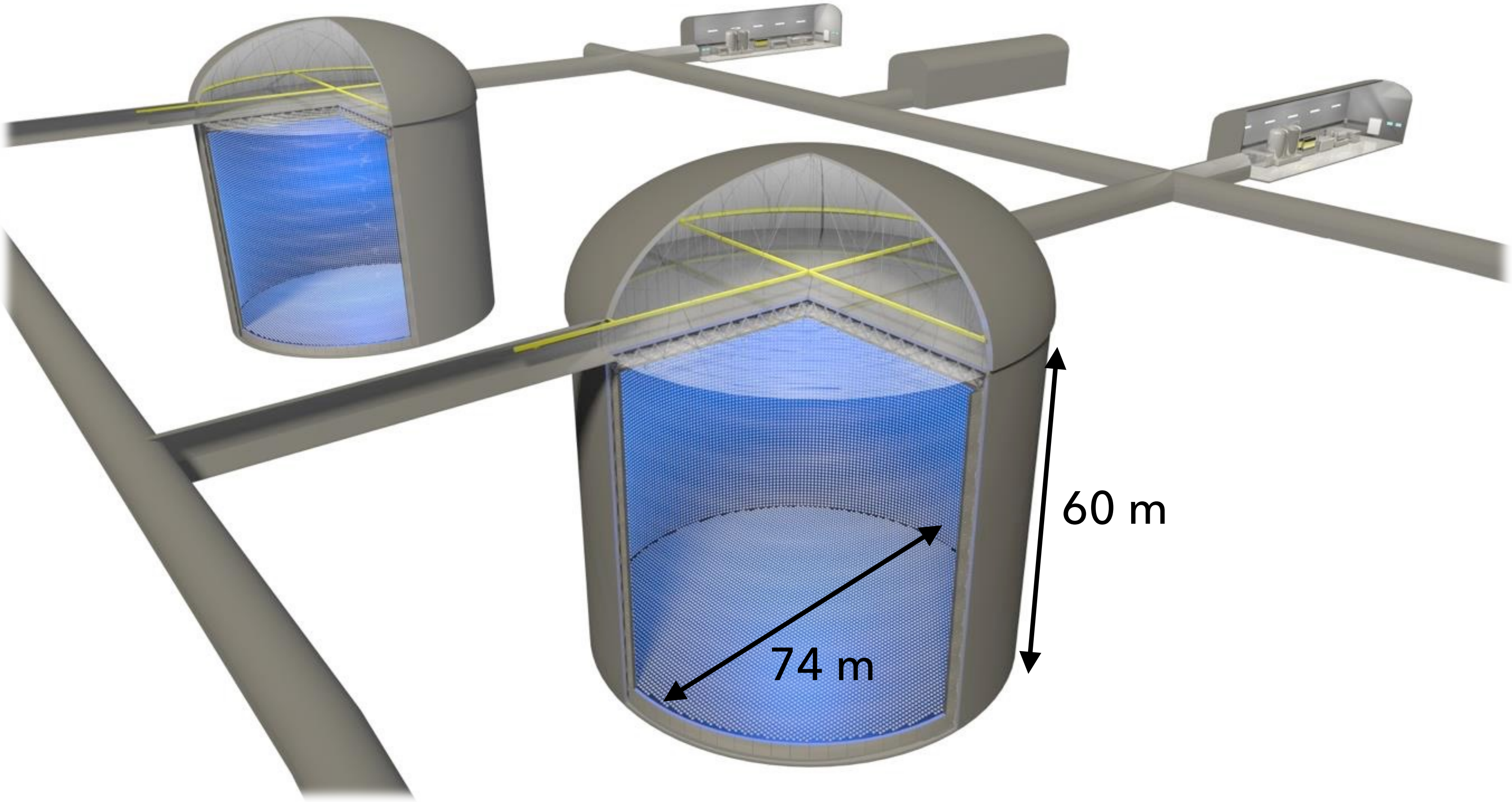
Systematic errors on neutrino flux model enter directly here

Reduced flux systematic errors → better measurement of neutrino-nucleus scattering (see talk by H. Tanaka)

HYPER-K



Hyper-K Tank:

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)

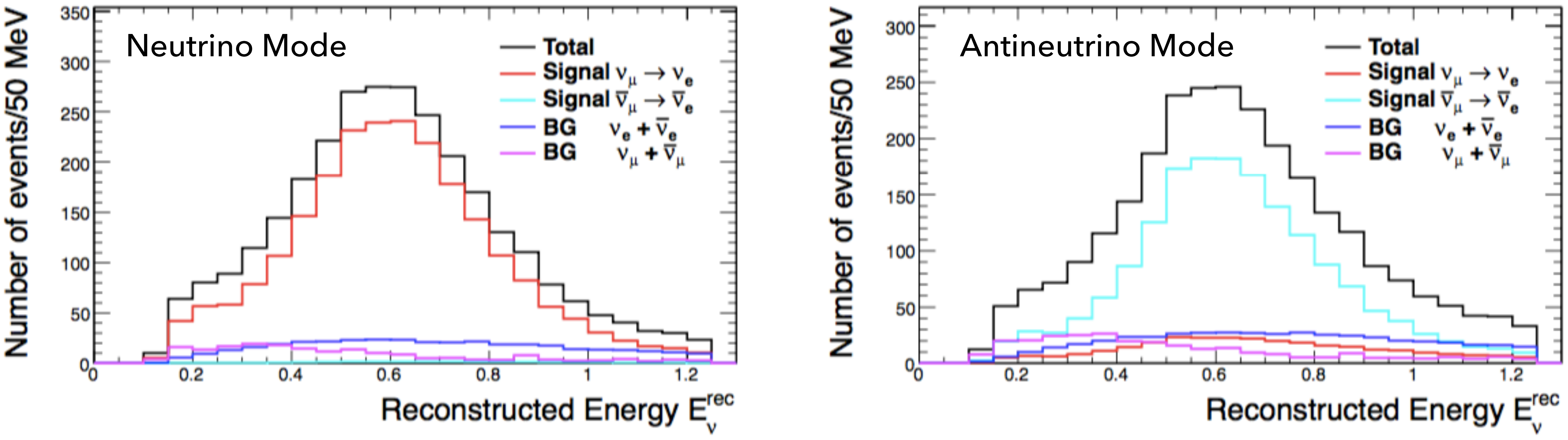
2 Tanks with staging:

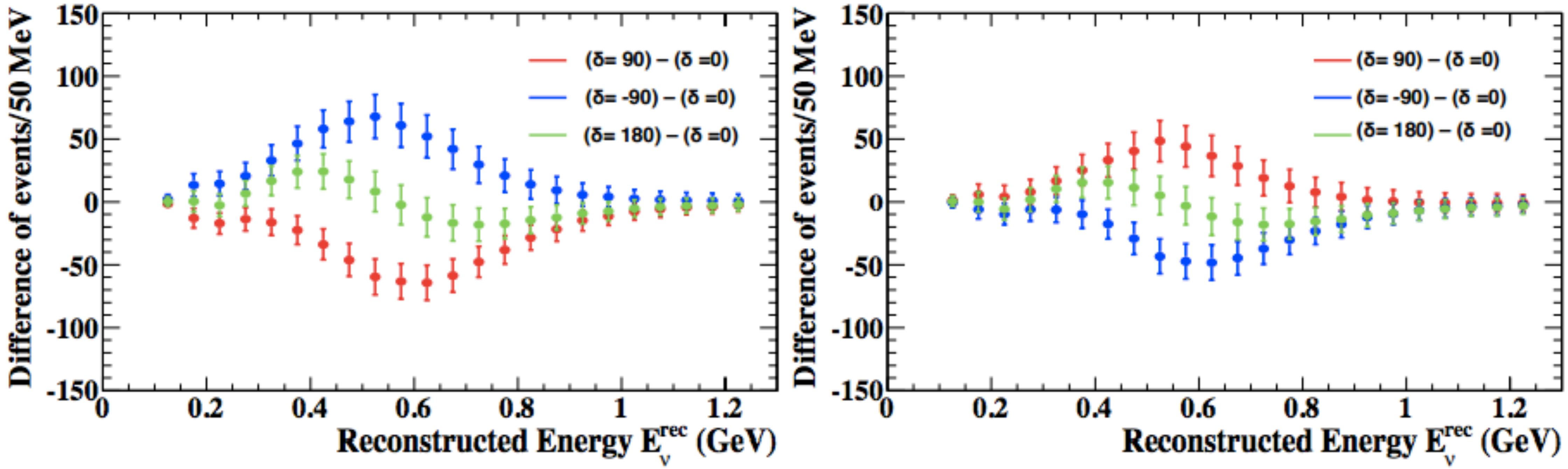
Design was updated from original design of 2 horizontal egg-shaped tanks

Goal of design update: maintain the physics while minimizing cost → Fiducial volume is 2/3 of original while cost is significantly reduced

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

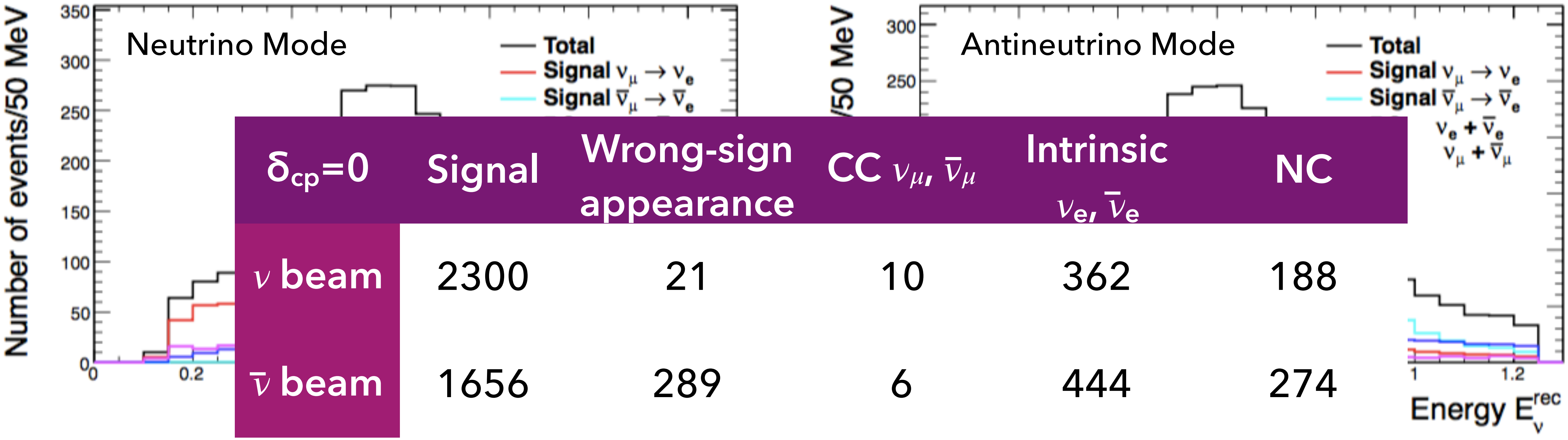
CP VIOLATION MEASUREMENT AT HYPER-K



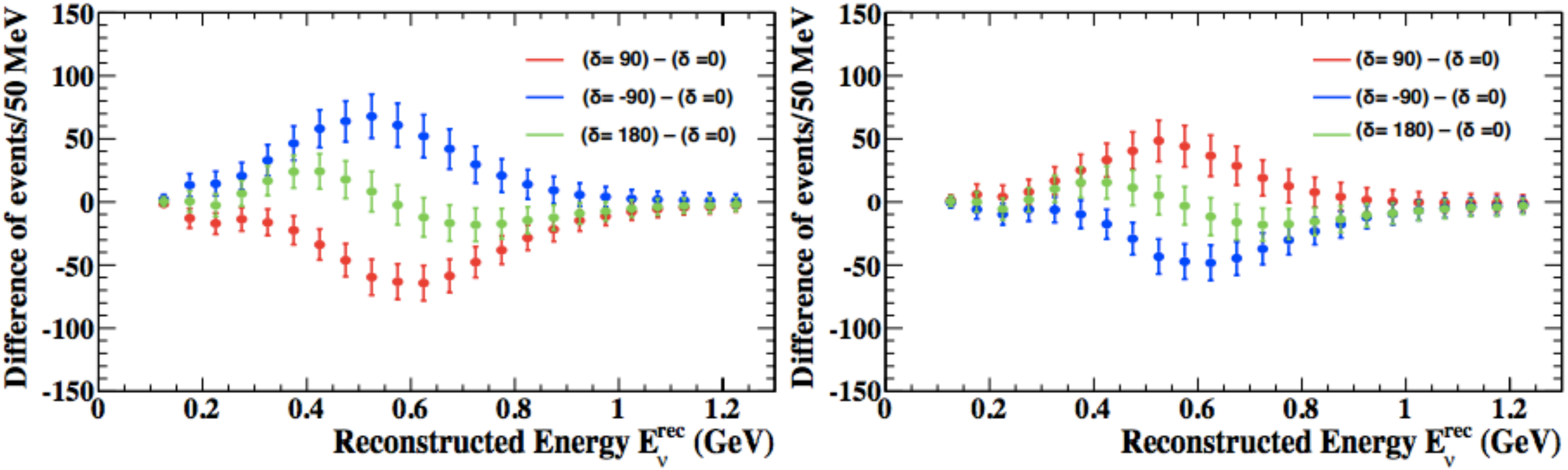


For 187 kton tank, 6 years with 1 tank, 4 years with 2 tanks, 1.3 MW beam power

CP VIOLATION MEASUREMENT AT HYPER-K



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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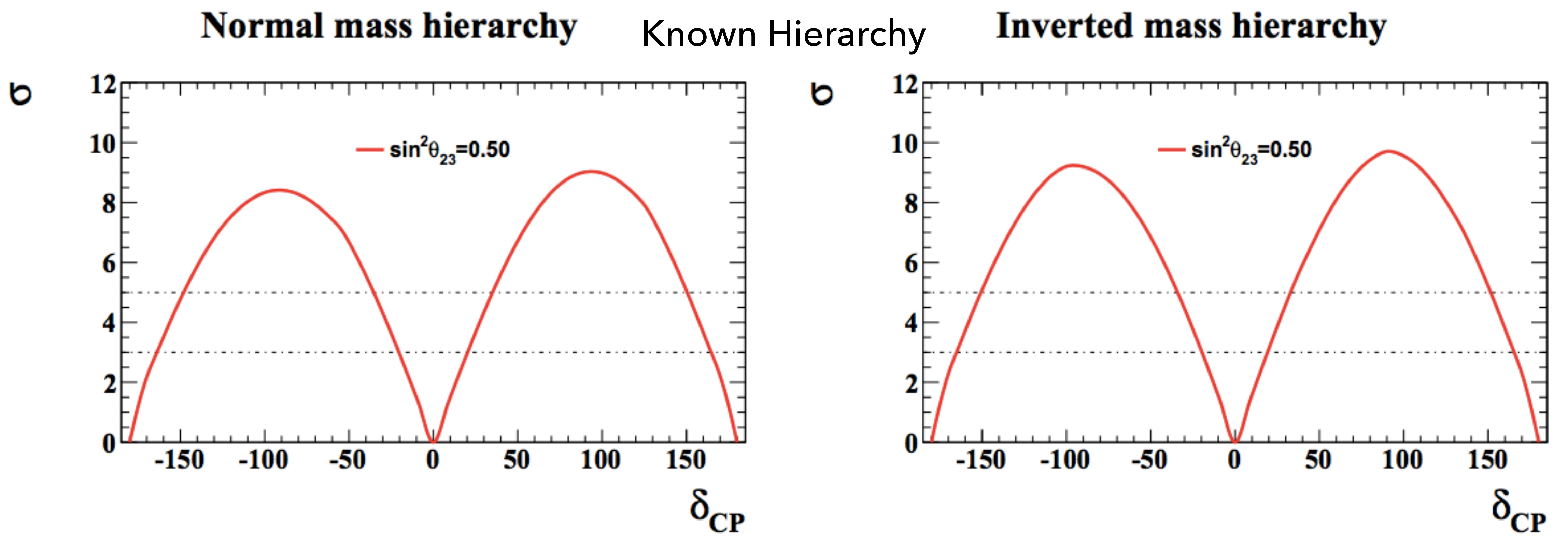
HYPER-K SENSITIVITY AND SYSTEMATIC ERRORS


Known Hierarchy

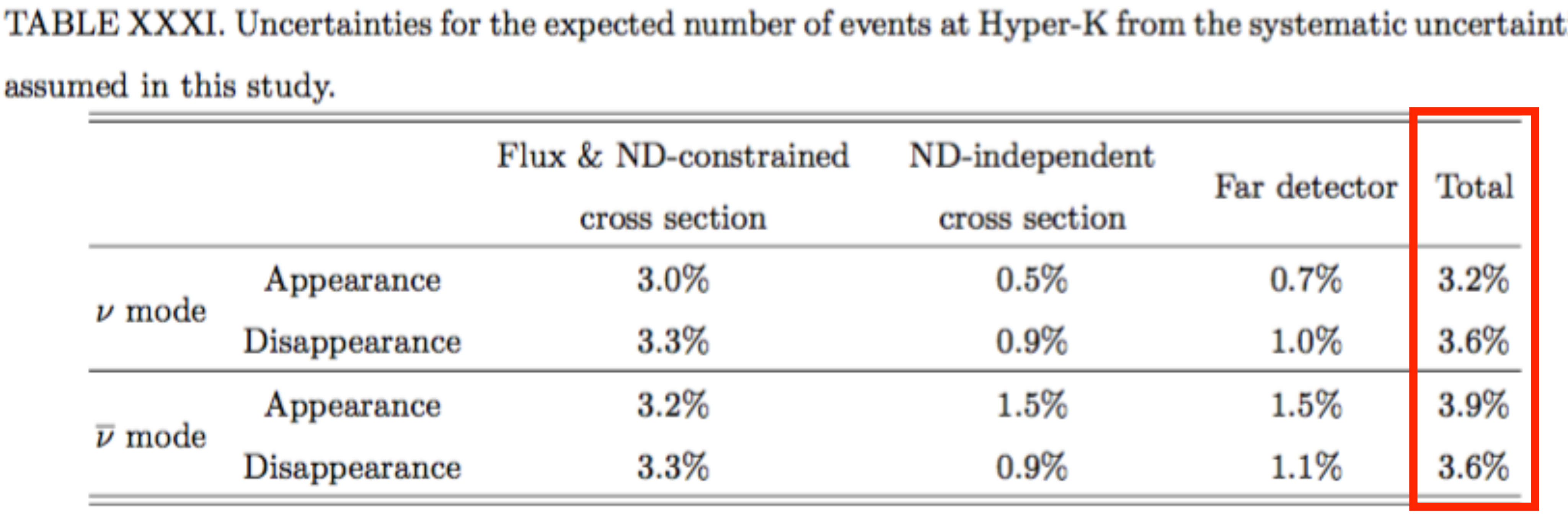


TABLE XXXI. Uncertainties for the expected number of events at Hyper-K from the systematic uncertainties assumed in this study.

		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total
ν mode	Appearance	3.0%	0.5%	0.7%	3.2%
	Disappearance	3.3%	0.9%	1.0%	3.6%
$\bar{\nu}$ mode	Appearance	3.2%	1.5%	1.5%	3.9%
	Disappearance	3.3%	0.9%	1.1%	3.6%

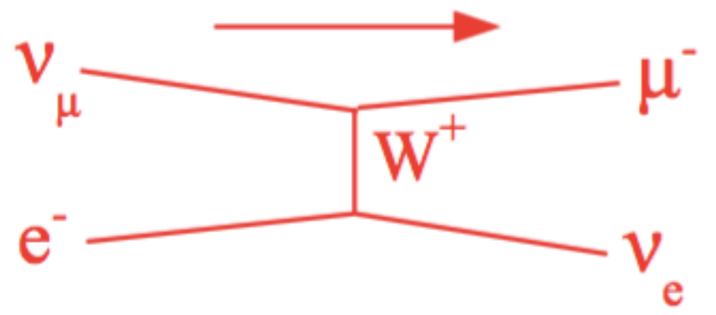
Total systematic error budget for Hyper-K is 3-4%

Sensitivity can be improved with reduction beyond these values

DIRECT MEASUREMENT OF NEUTRINO BEAM

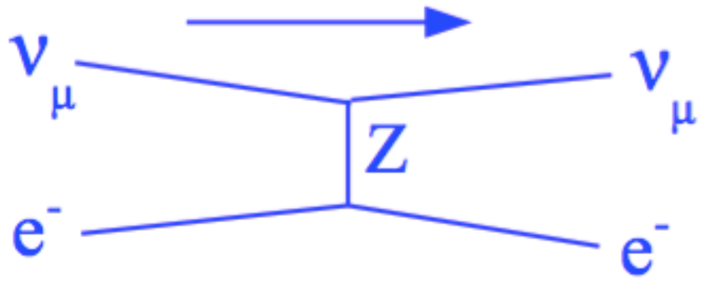
Neutrino-nucleus uncertainties are as large as neutrino flux uncertainties
→ Cannot use neutrino-nucleus interaction measurements to constrain the flux

Need processes with little to no uncertainties on interactions:



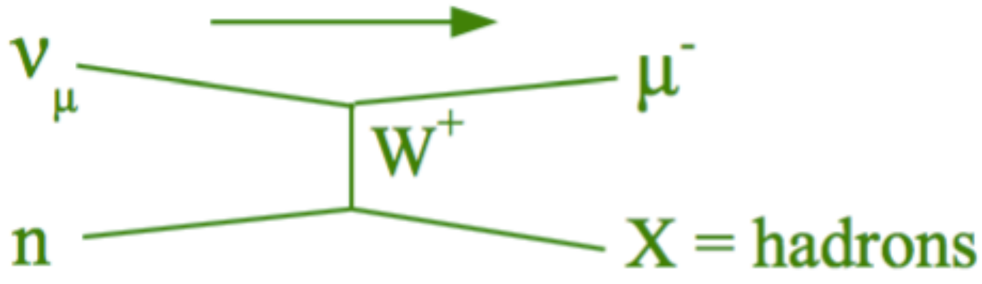
Inverse muon decay:

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

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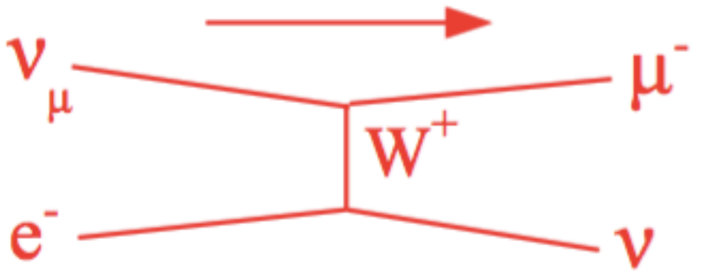
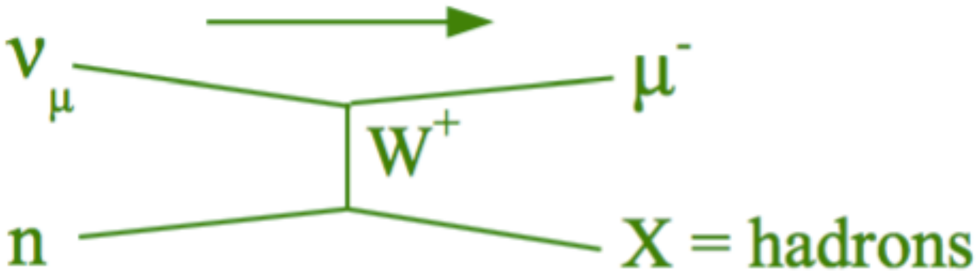


Inverse muon decay:

Threshold is $E_\nu > 12$ GeV

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

WE MUST RELY ON A DATA DRIVEN CALCULATION OF THE NEUTRINO FLUX



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T2K FLUX SIMULATION

Starting point: Proton beam monitors measure the beam trajectory, width, divergence and current

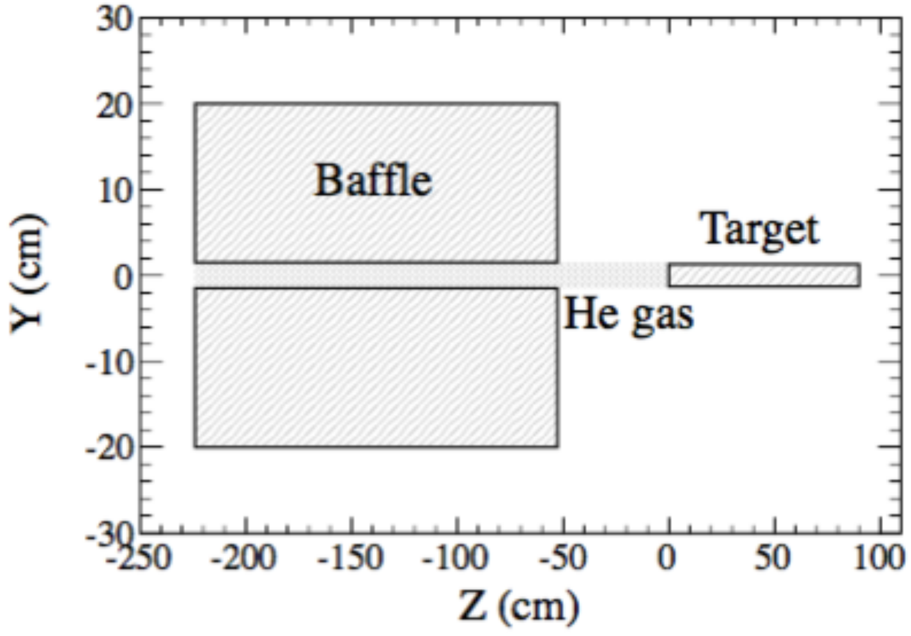


FIG. 14: A two dimensional view of the geometrical set-up in the FLUKA simulation of the baffle and the target.

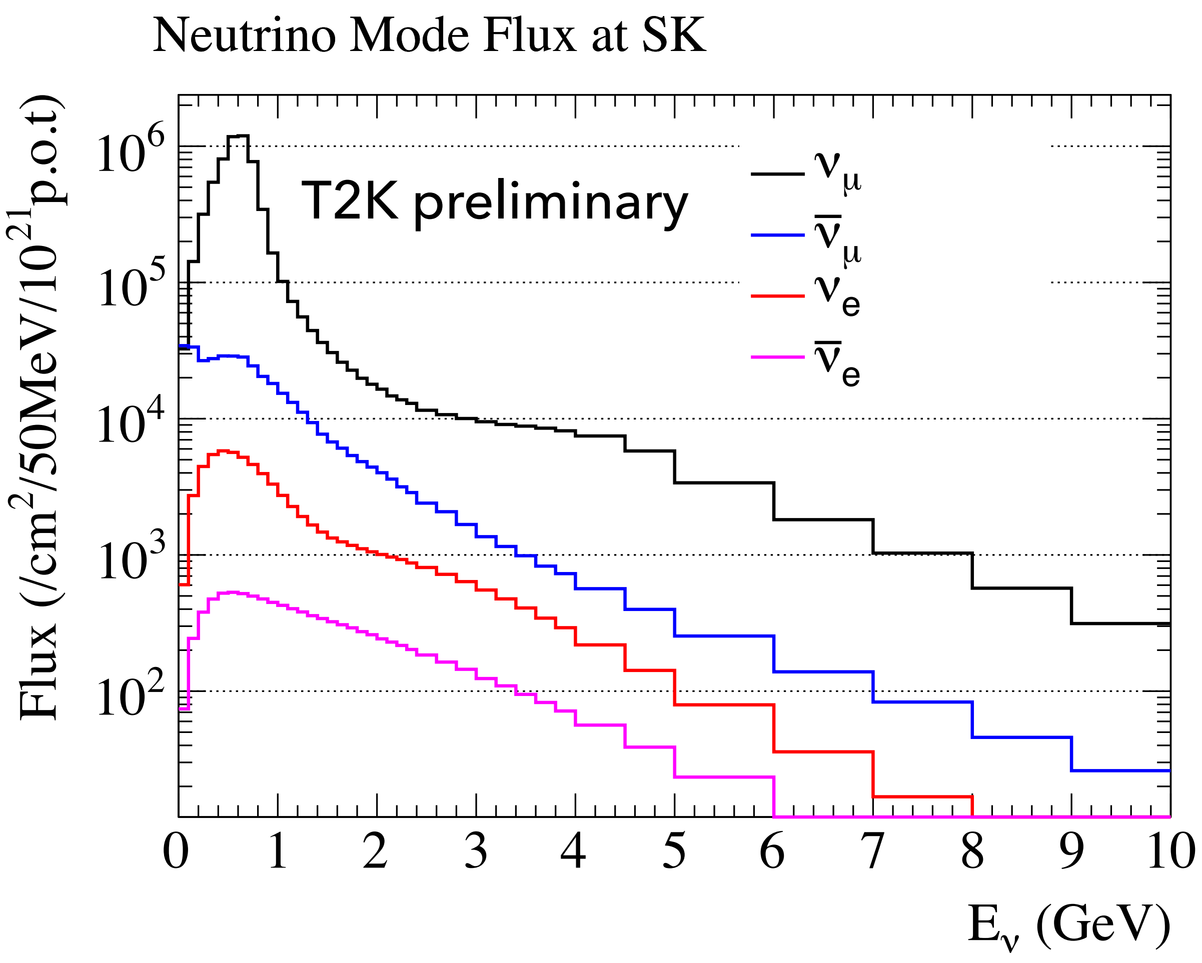
Target simulation: Hadron interactions and particle propagation inside the target are done with a FLUKA2011 based simulation

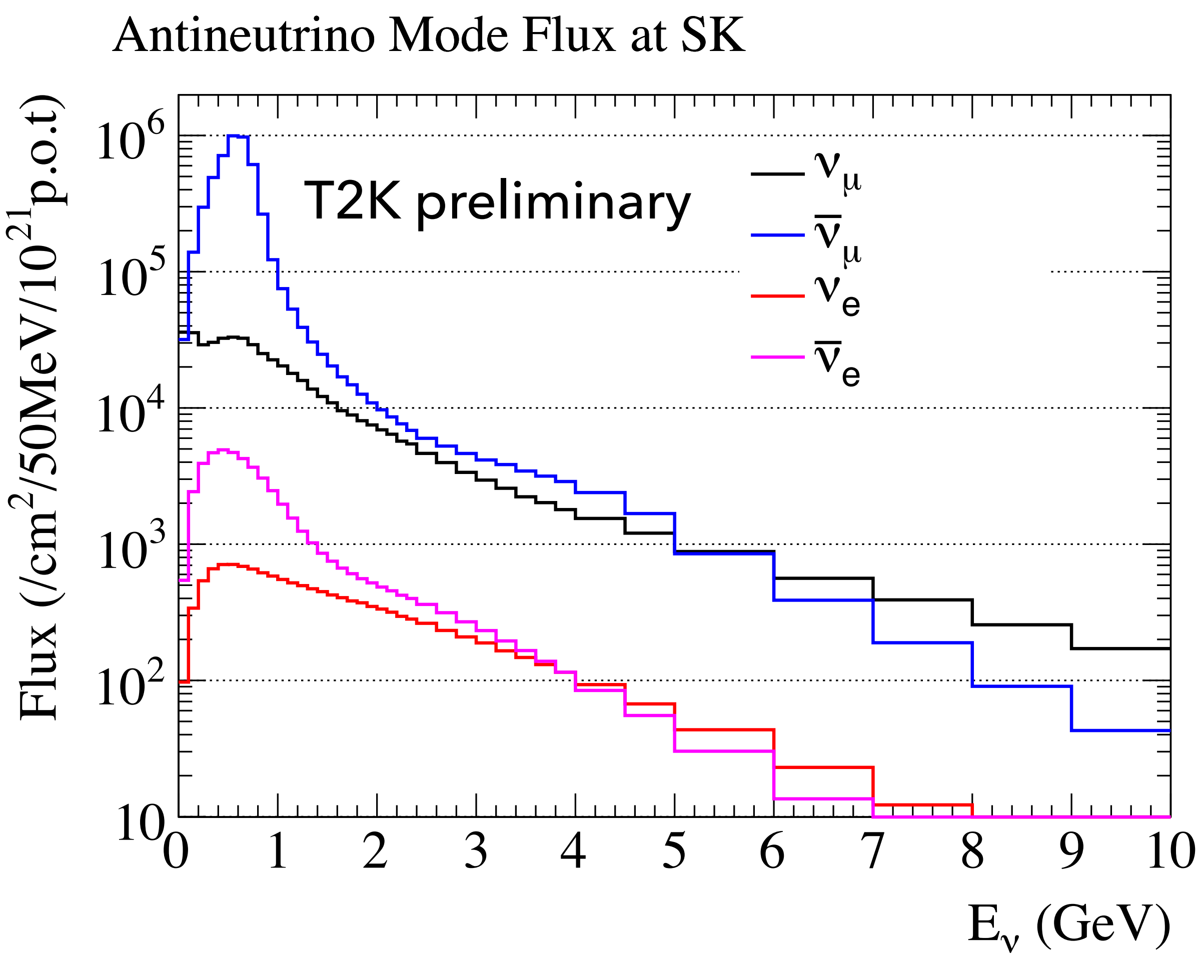
Secondary beam line simulation: Propagation through the secondary beam line including horns and decay volume with GEANT3 (GCALOR) simulation

Hadron interaction: Information from all hadronic interactions are saved and the simulated interactions are tuned using data -> Tuning can modify the prediction by 10% or more

Phys. Rev. D 87, 012001 (2013)

THE T2K FLUX

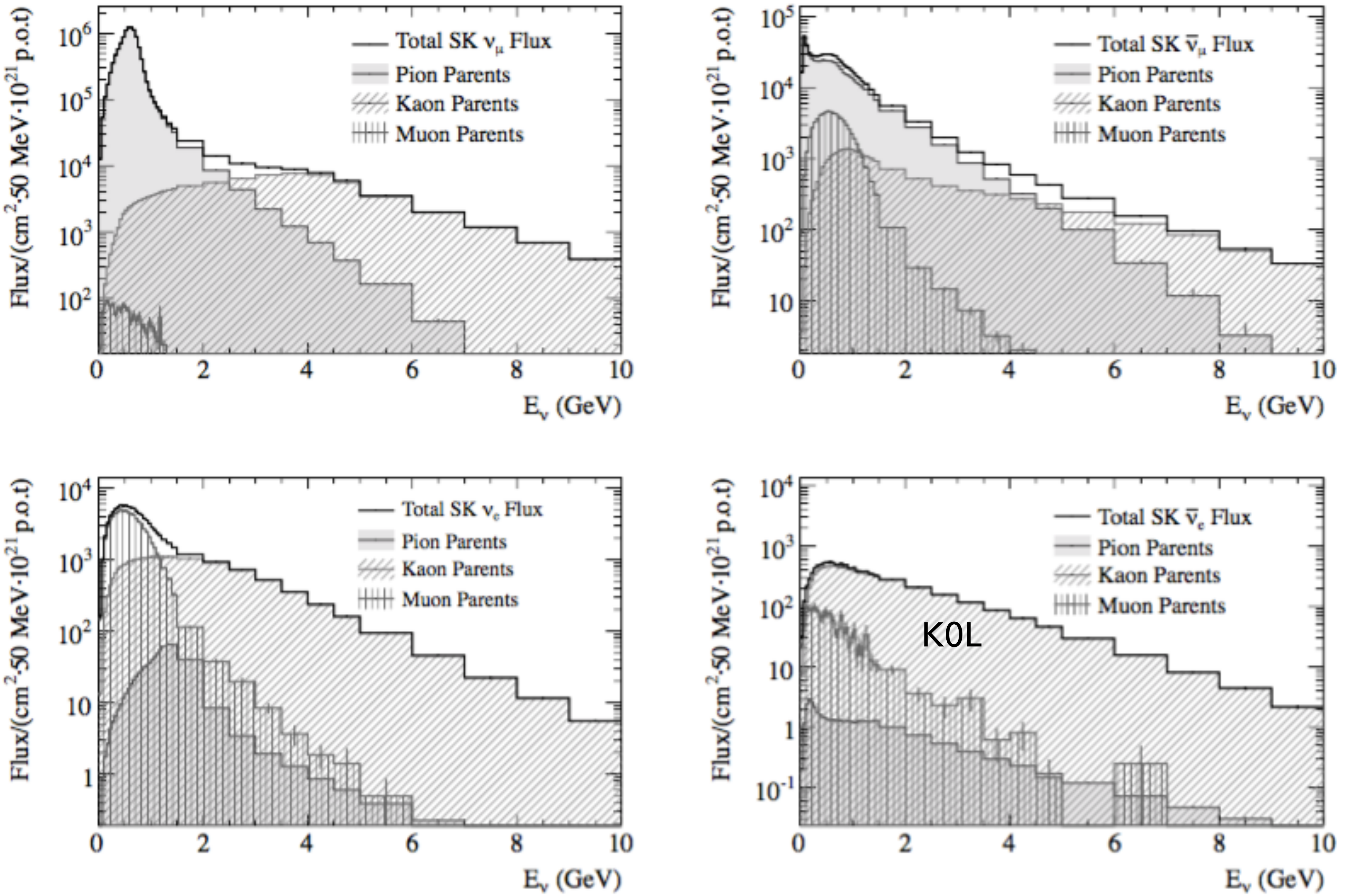

Neutrino Mode Flux at SK


Antineutrino Mode Flux at SK

2.5 degree off-axis fluxes with peak at 600 MeV

Wrong sign flux in antineutrino mode (black left) is further enhanced in by ratio of neutrino/antineutrino interaction cross section

NEUTRINO PARENT PARTICLES

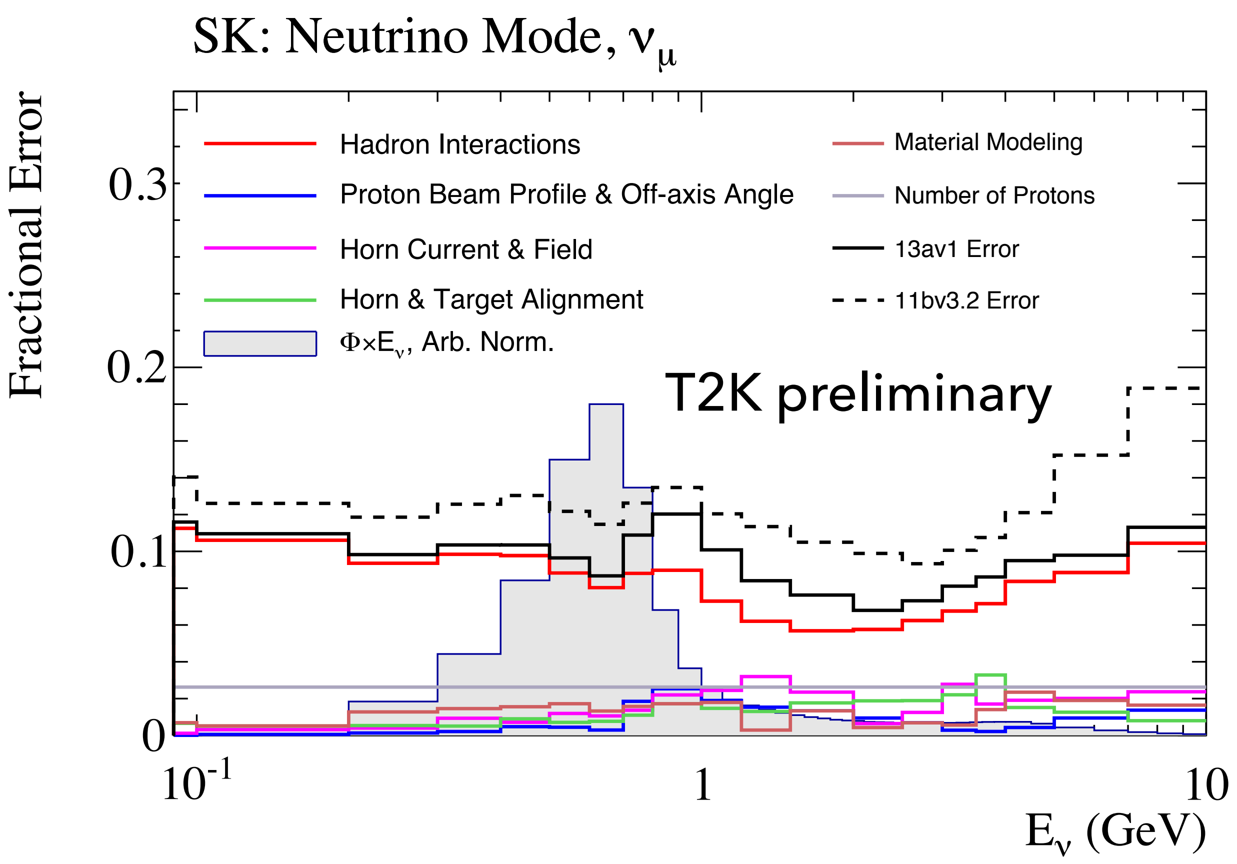


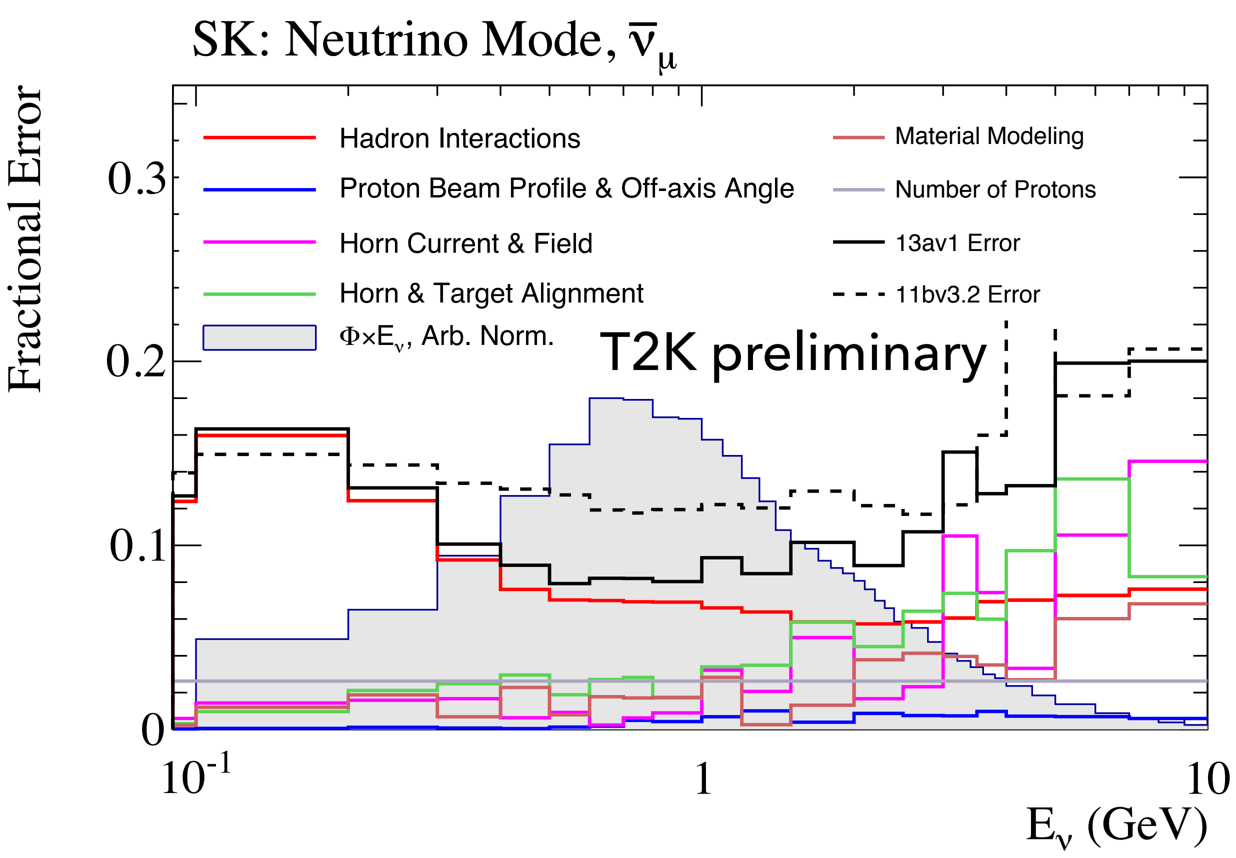
K0L

Electron neutrino flux from muons is related to muon neutrino flux from pions since muons are produced in pion decays

Phys. Rev. D 87, 012001 (2013)

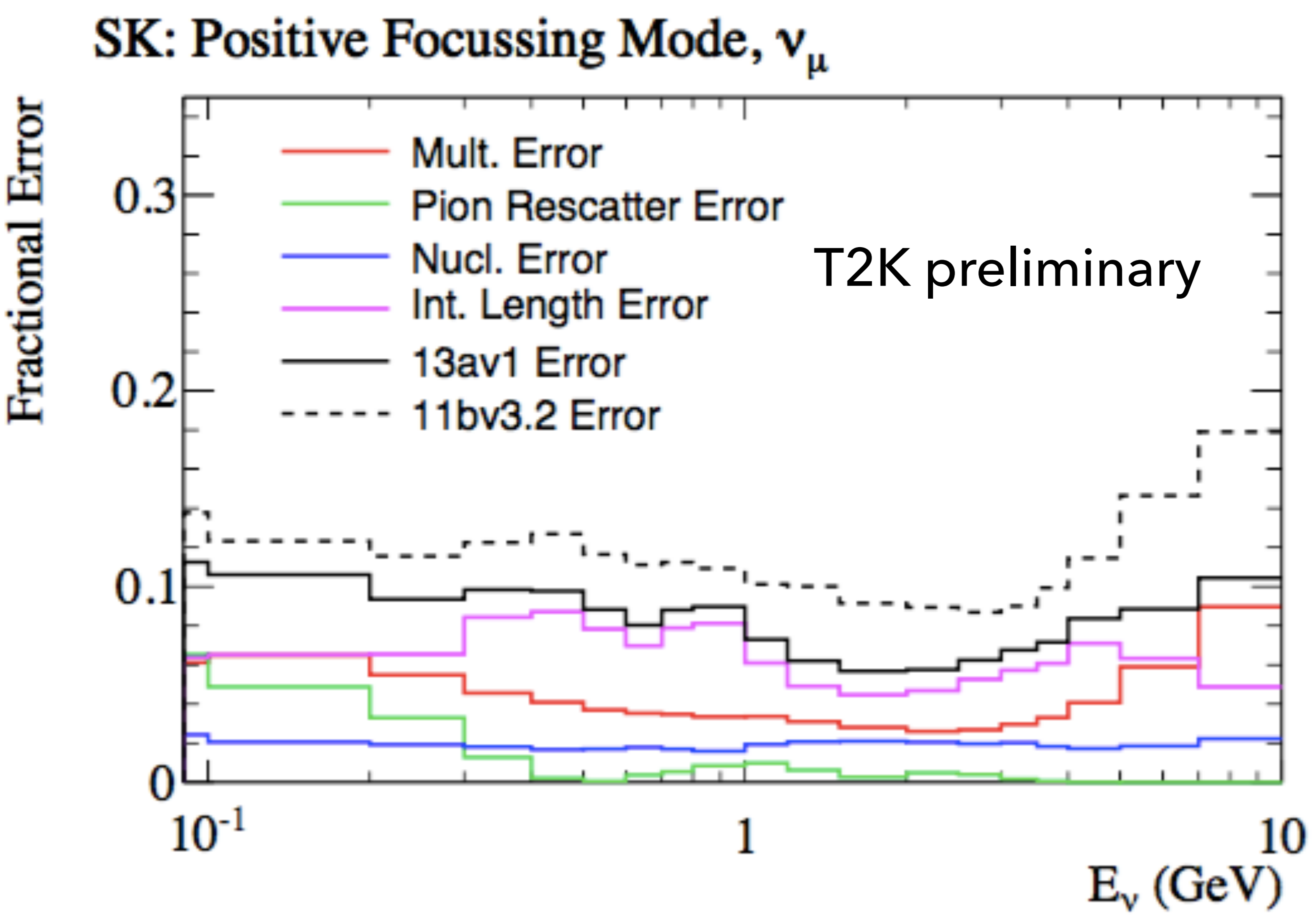
T2K FLUX UNCERTAINTIES

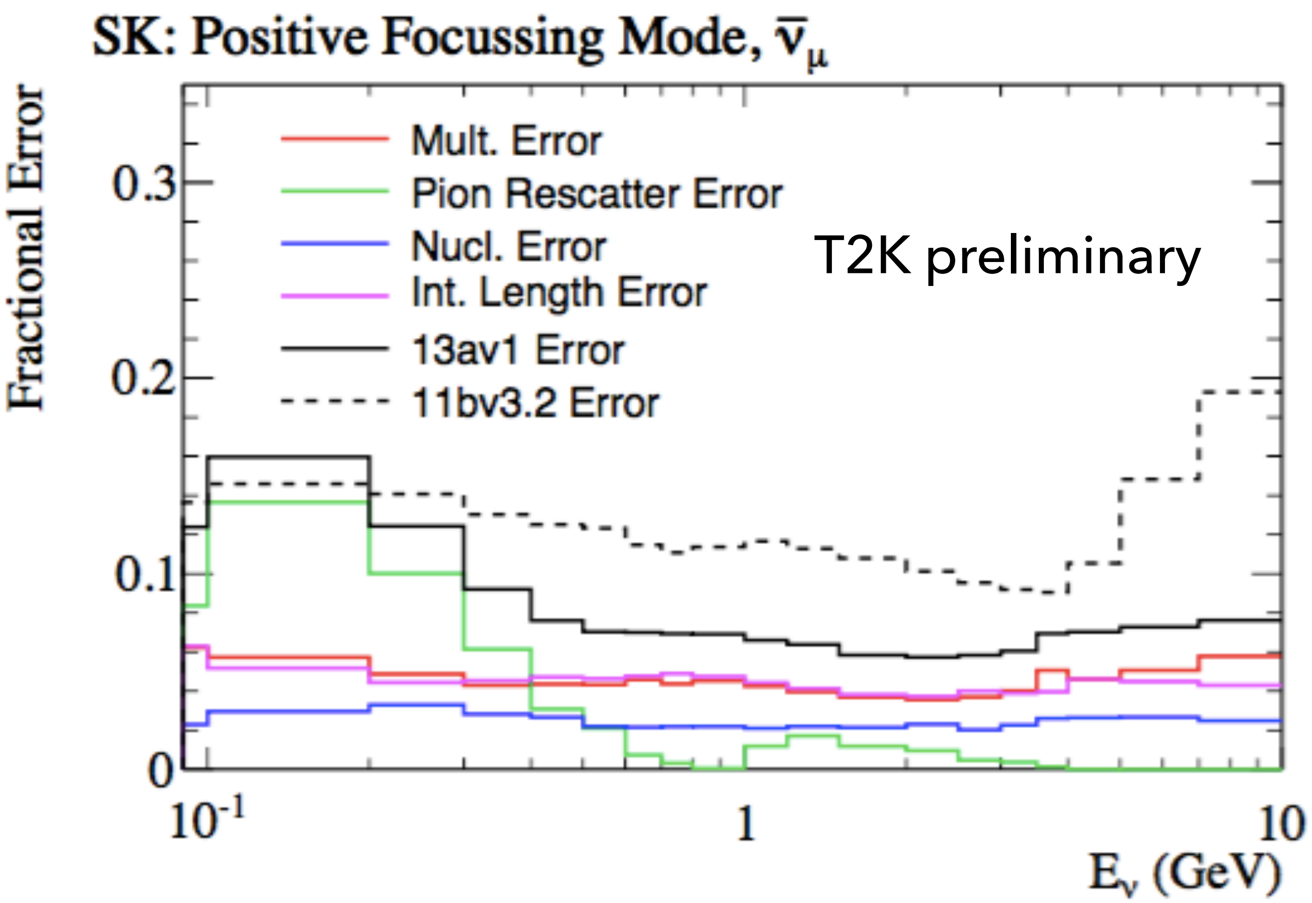

SK: Neutrino Mode, ν_μ


SK: Neutrino Mode, $\bar{\nu}_\mu$

Hadron interaction uncertainties are the dominant errors on the T2K flux estimation

T2K FLUX UNCERTAINTIES


SK: Positive Focussing Mode, ν_μ


SK: Positive Focussing Mode, $\bar{\nu}_\mu$

For right-sign flux, the production cross-section uncertainty (interaction length) is dominant - arising from the model dependent subtraction of the elastic and quasi-elastic cross sections

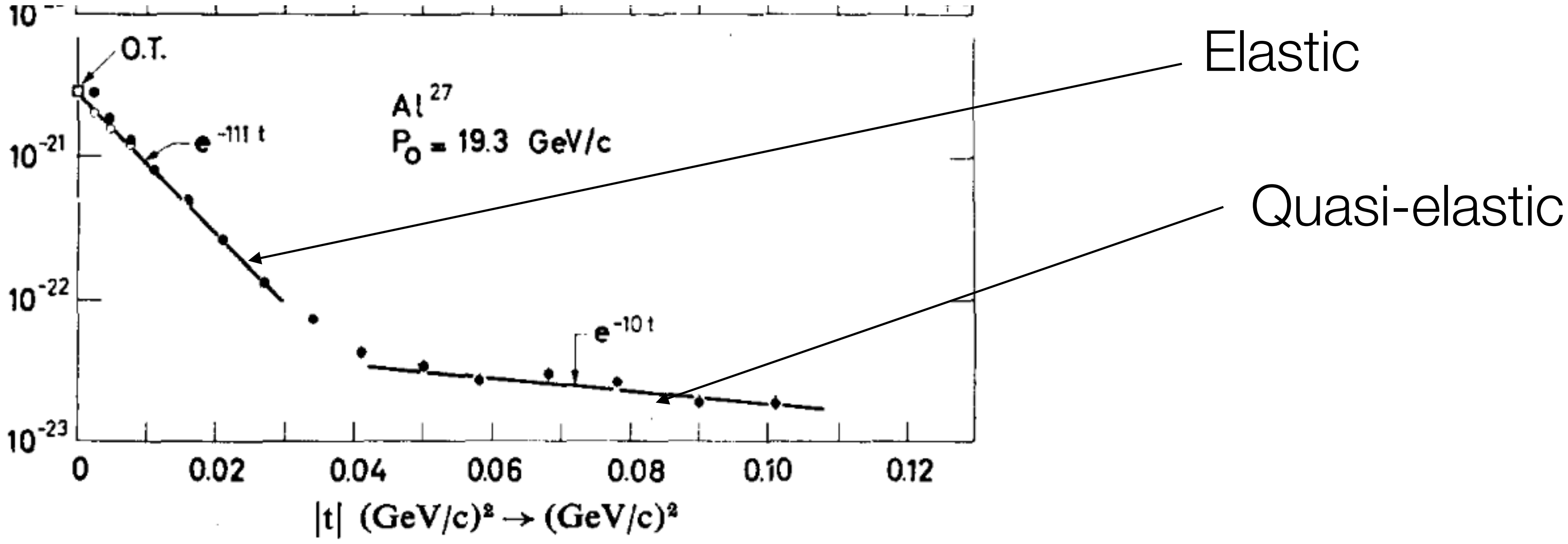
For the wrong-sign flux, the pion re-scattering error becomes dominant at low energy

Difficult error to estimate since there is significant nuclear target and CoM energy scaling applied

ELASTIC/QUASI-ELASTIC CROSS SECTION MEASUREMENT

There are old data sets measuring the contributions to the momentum transfer from elastic and quasi-elastic at ~20 GeV

G. Bellettini et al., Nucl. Phys. 79, 609 (1966)



Elastic

Quasi-elastic

The energy loss is in such scattering is very small, so it should be possible to measure the momentum transfer form the scattering angle

Potential measurement using emulsion with no PID or spectrometer requirement

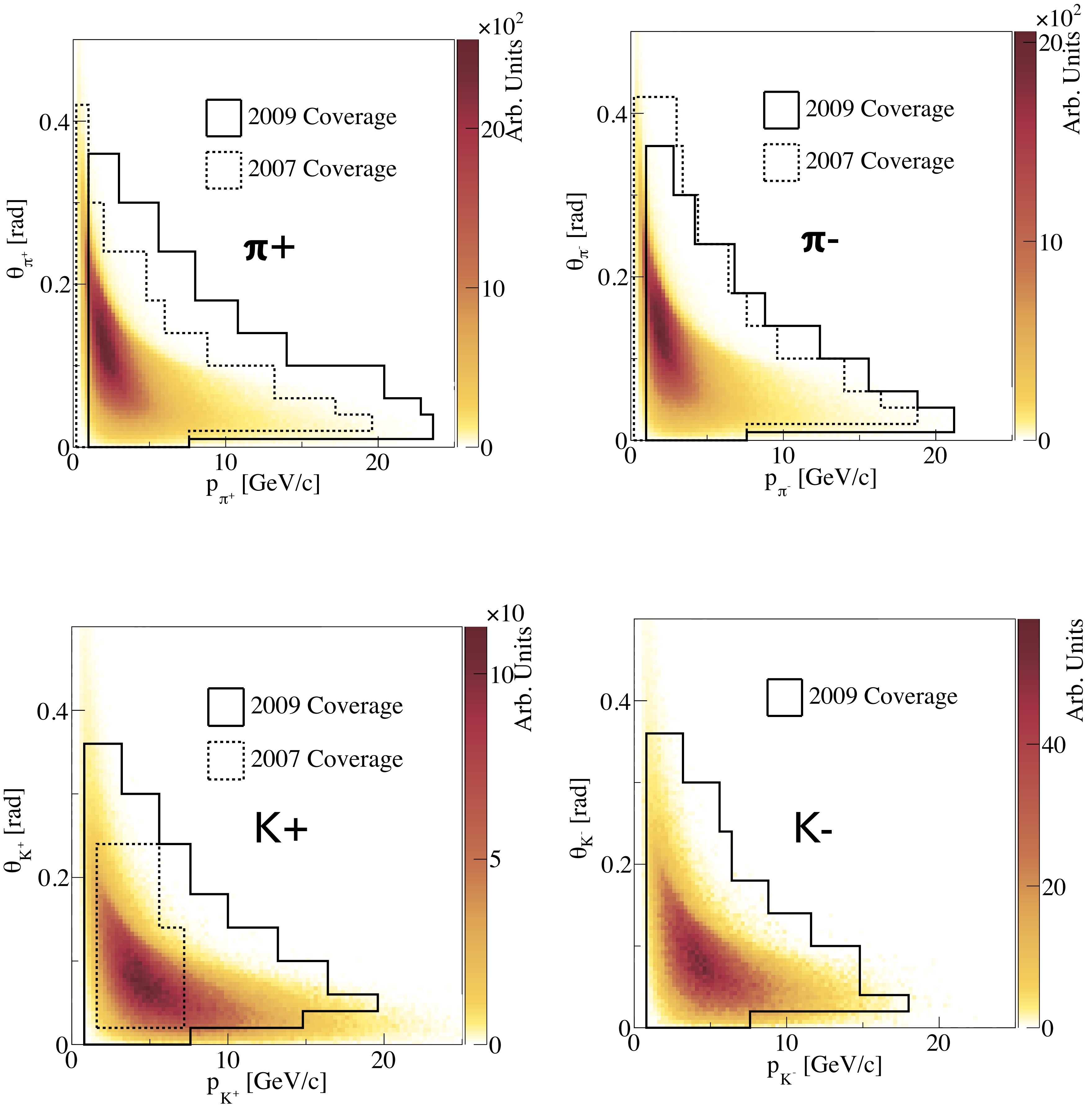
Need scattering angle resolution of better than ~2 mrad

NA61/SHINE COVERAGE

Thin target data from NA61/SHINE covers well the phase space of primary interactions

We currently use the 2009 NA61/SHINE thin target data in our tuning

The European Physical Journal C, 76(2), 1-49 (2016)

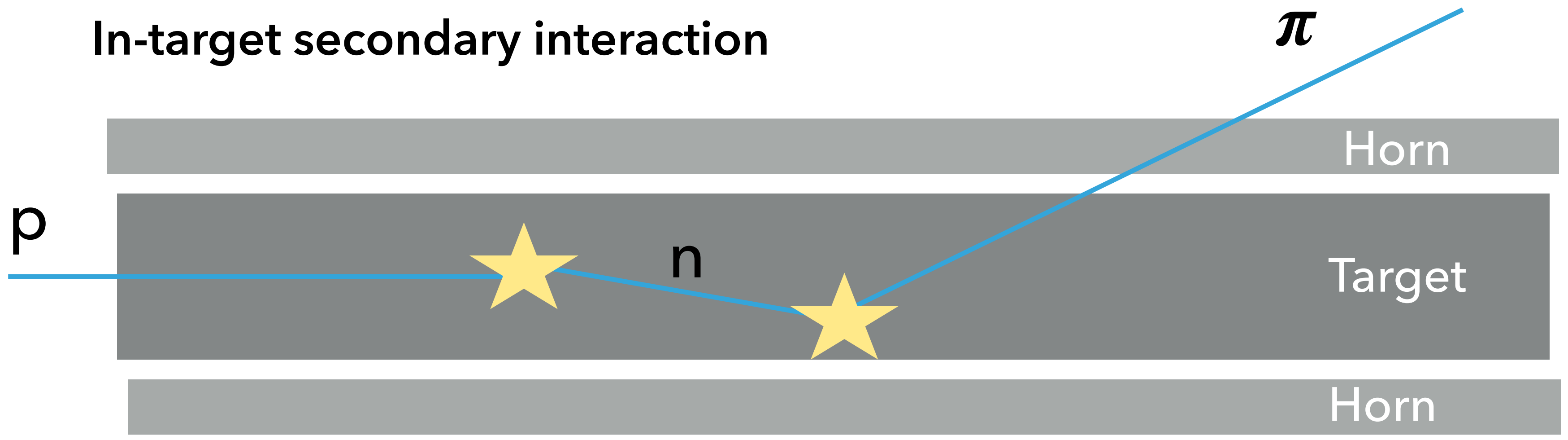


HADRON INTERACTION LOCATIONS

Primary interaction

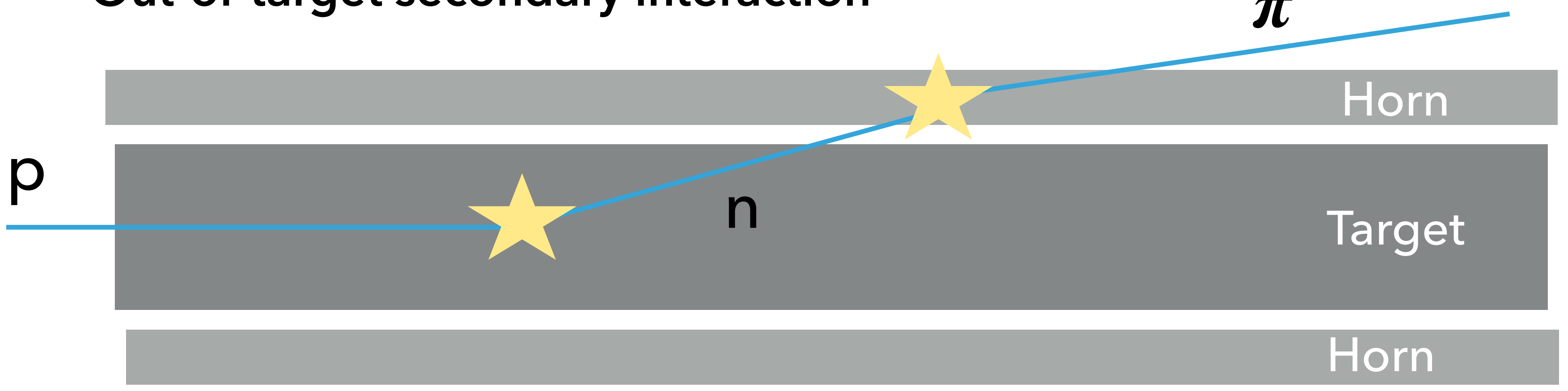
Measured with NA61 thin target data

In-target secondary interaction



Accounted for in NA61 replica target data

Out-of-target secondary interaction



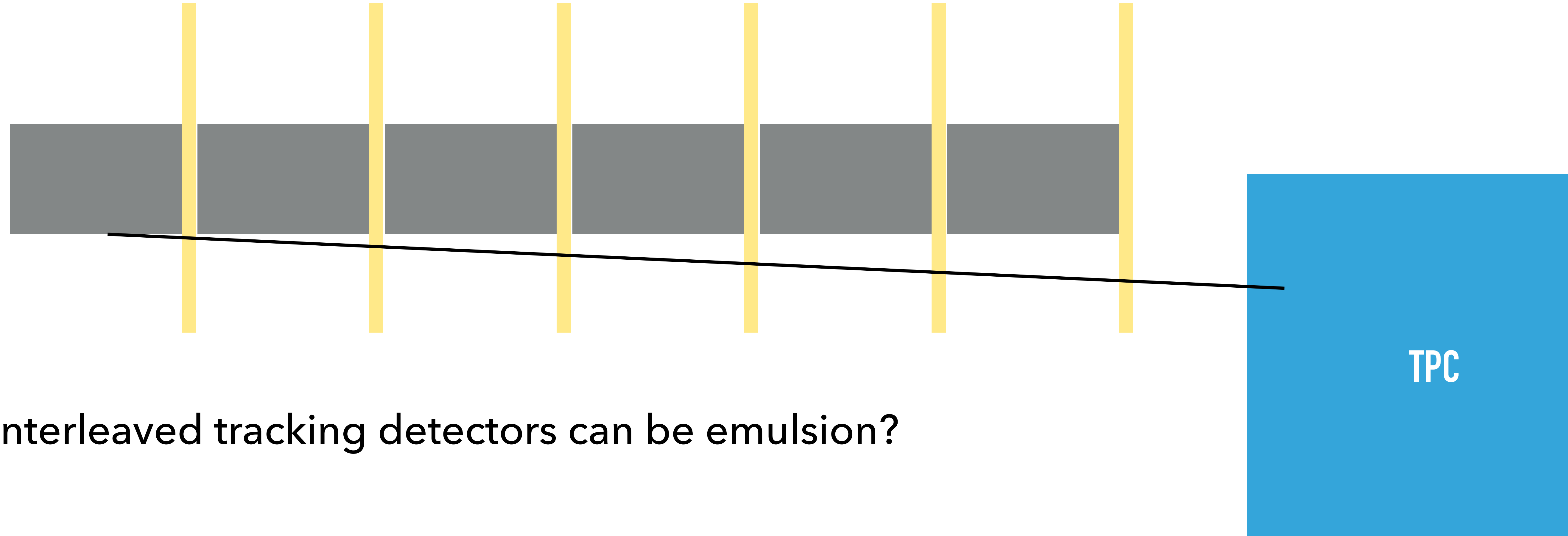
No data from NA61, rely on other measurements (HARP, etc.)

COMMENT ON REPLICA TARGET DATA

T2K is now working on the implementation of replica target data in the flux calculation

As Matej pointed out yesterday, there are some discrepancies in the most upstream bin at small angles that may be due to the resolution of the track extrapolation

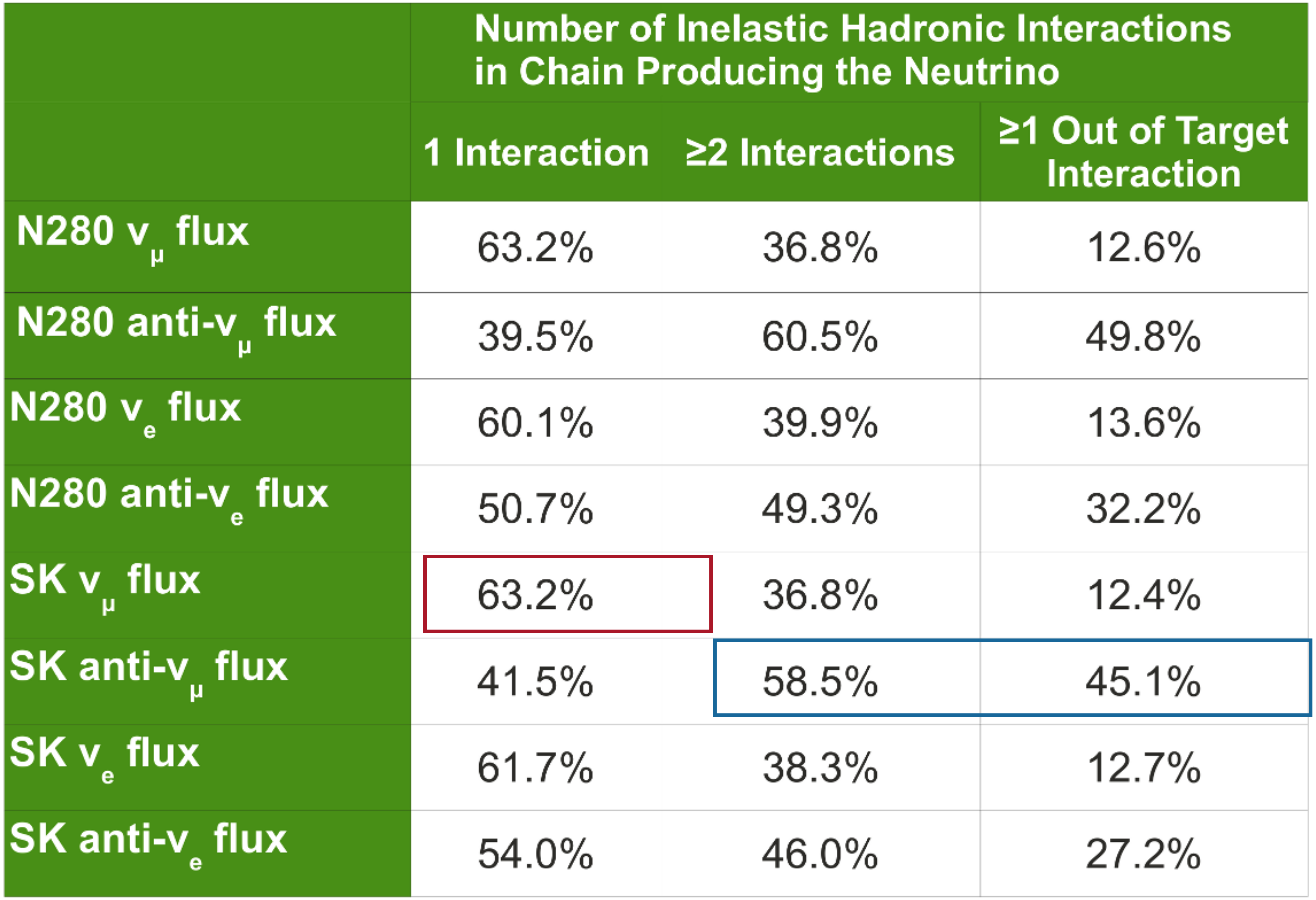
Could benefit from long target measurement with nearby tracking detectors to improve matching between TPC tracks and target surface



Interleaved tracking detectors can be emulsion?

INTERACTION BREAKDOWN IN T2K

Percent of the flux from different hadronic interaction chain configurations

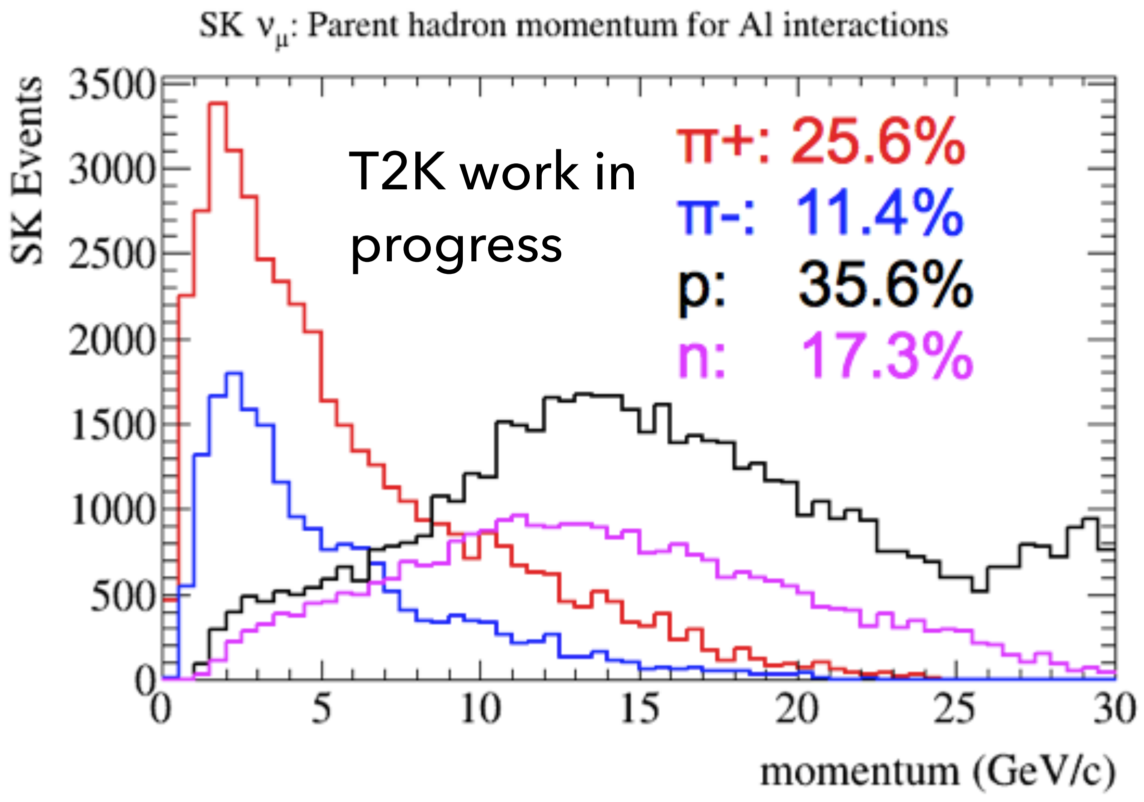


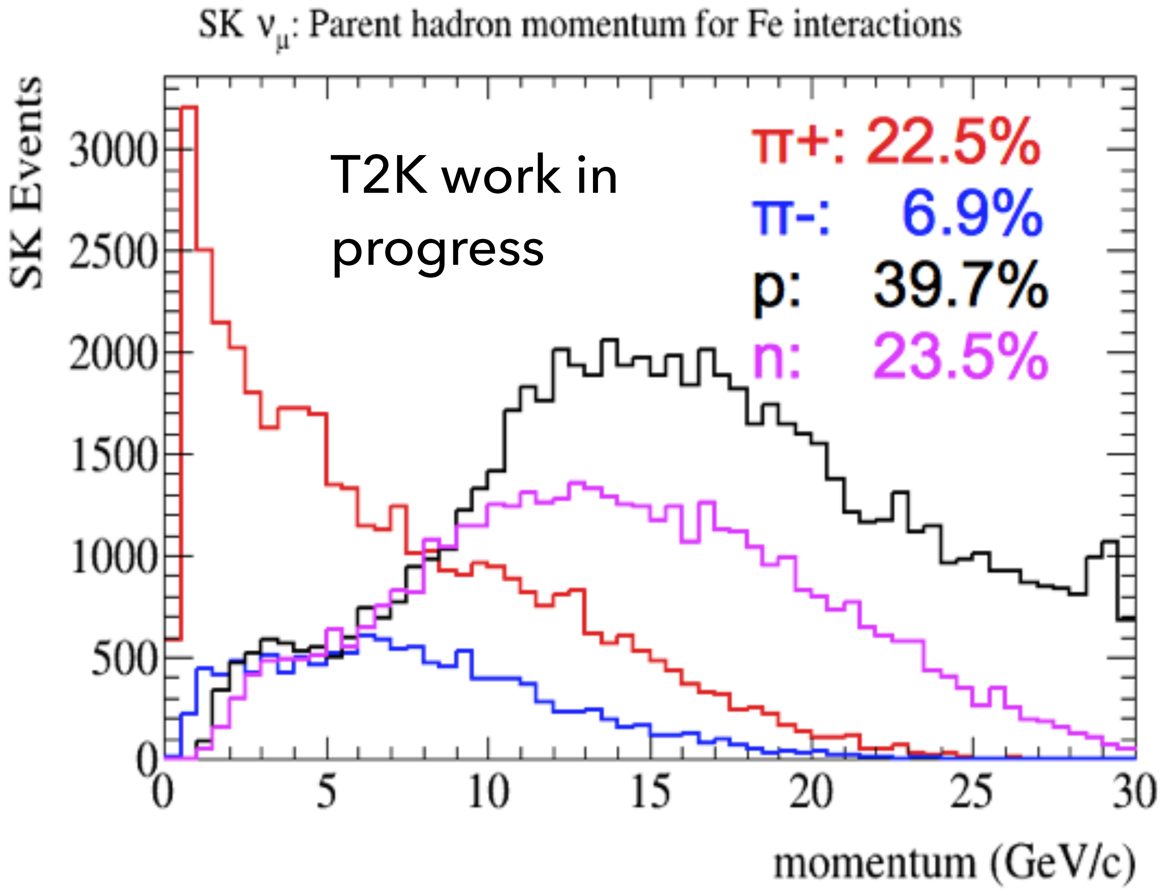
	Number of Inelastic Hadronic Interactions in Chain Producing the Neutrino		
	1 Interaction	≥2 Interactions	≥1 Out of Target Interaction
N280 ν_μ flux	63.2%	36.8%	12.6%
N280 anti-ν_μ flux	39.5%	60.5%	49.8%
N280 ν_e flux	60.1%	39.9%	13.6%
N280 anti-ν_e flux	50.7%	49.3%	32.2%
SK ν_μ flux	63.2%	36.8%	12.4%
SK anti-ν_μ flux	41.5%	58.5%	45.1%
SK ν_e flux	61.7%	38.3%	12.7%
SK anti-ν_e flux	54.0%	46.0%	27.2%

63% of the flux comes from primary proton interactions

Almost half of wrong-sign flux from interactions in horns or decay volume wall

OUT-OF-TARGET INTERACTIONS





Interactions in horns (top) and decay volume walls include protons and pions

Now we tune with existing hadron interaction data and assumptions for target nucleus and center of mass energy scaling

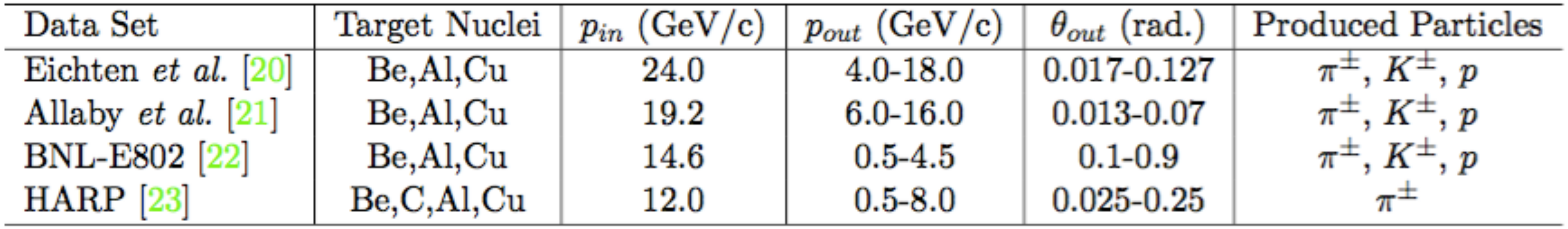
Benefit from new measurements:

p+Al and p+Fe in the 5-30 GeV/c range

π+Al and π+Fe in the 1-15 GeV/c range

SECONDARY INTERACTION TUNING DATA

For proton interactions:



Data Set	Target Nuclei	p_{in} (GeV/c)	p_{out} (GeV/c)	θ_{out} (rad.)	Produced Particles
Eichten *et al.* [20]	Be,Al,Cu	24.0	4.0-18.0	0.017-0.127	$\pi^\pm$, $K^\pm$, p
Allaby *et al.* [21]	Be,Al,Cu	19.2	6.0-16.0	0.013-0.07	$\pi^\pm$, $K^\pm$, p
BNL-E802 [22]	Be,Al,Cu	14.6	0.5-4.5	0.1-0.9	$\pi^\pm$, $K^\pm$, p
HARP [23]	Be,C,Al,Cu	12.0	0.5-8.0	0.025-0.25	$\pi^\pm$

Use HARP data for pion to pion scattering (Nucl.Phys., A821:118–192, 2009)

Estimate scaling to different target nuclei with parameterized fit to existing data:

$$\frac{d^2\sigma}{dp d\theta}(A_1) = \left[\frac{A_1}{A_0}\right]^{\alpha(x_F,p_T)} \frac{d^2\sigma}{dp d\theta}(A_0) \qquad \alpha(x_F,p_T) = P_0 + P_1 x_F + P_2 p_T + P_3 x_F^2 + p_4 p_T^2 + P_5 x_F p_T$$

Estimate scaling to different center of mass energies by assuming invariant cross section is constant when expressed in $x_R = E/E_{max}$ and p_T

SOME LIMITATIONS OF THE DATA

- The dominant systematic uncertainties in HARP are related to particle re-interactions in the TPC field cage
  - New experiments should minimize material between tracking medium and target
- Production measurements by HARP have no data for θ<0.025 rad.
- Allaby et al. and Eichten et al. only measure production out to θ<0.07 rad. and θ<0.127 rad. and >6 GeV/c and 4 GeV/c
- Overlapping data such as E802 and HARP are not fully consistent

Phys.Rev.C80:035208,2009

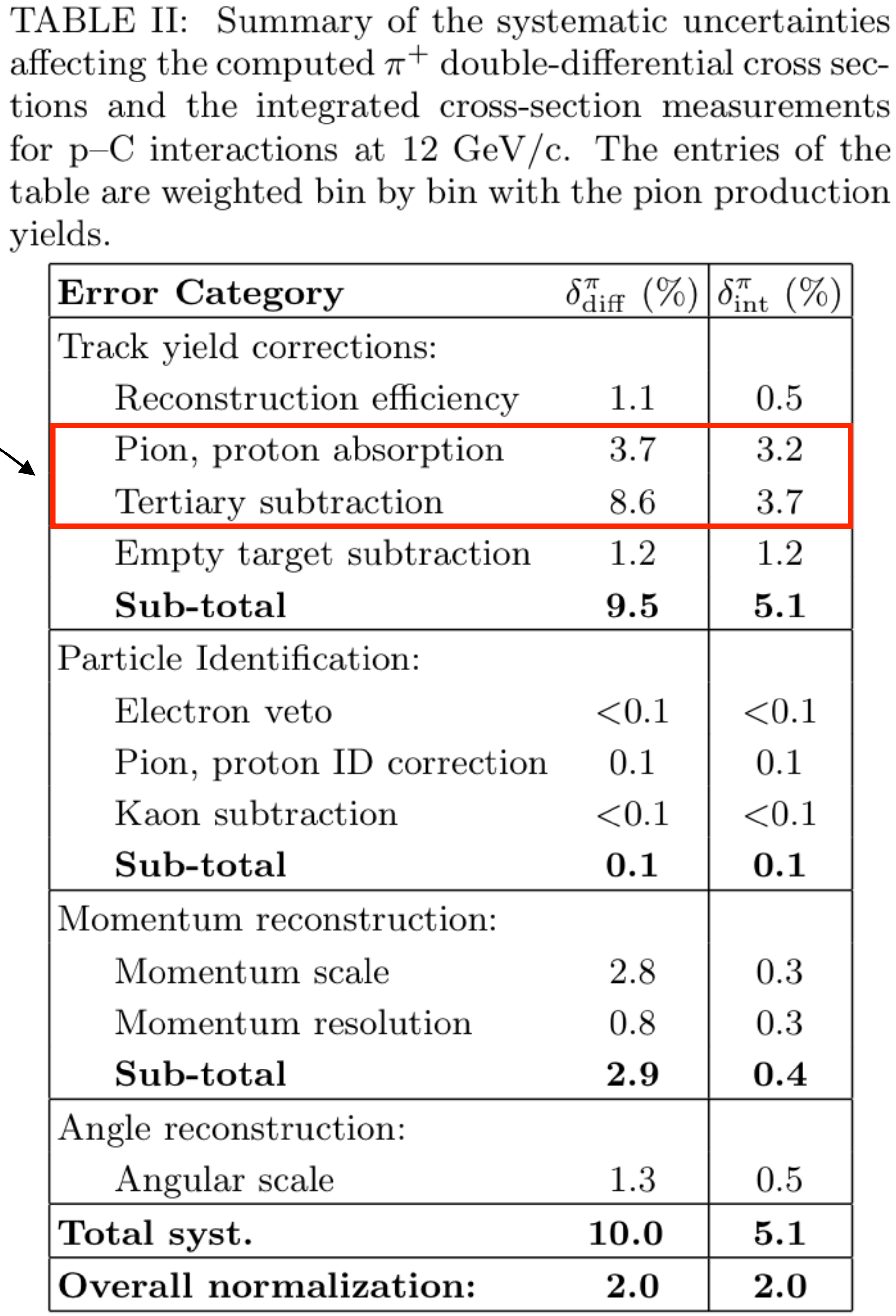


TABLE II: Summary of the systematic uncertainties affecting the computed π^+ double-differential cross sections and the integrated cross-section measurements for p–C interactions at 12 GeV/c. The entries of the table are weighted bin by bin with the pion production yields.

Error Category	$\delta^{\pi}_{\mathrm{diff}}$ (%)	$\delta^{\pi}_{\mathrm{int}}$ (%)
Track yield corrections:		
Reconstruction efficiency	1.1	0.5
Pion, proton absorption	3.7	3.2
Tertiary subtraction	8.6	3.7
Empty target subtraction	1.2	1.2
Sub-total	**9.5**	**5.1**
Particle Identification:		
Electron veto	<0.1	<0.1
Pion, proton ID correction	0.1	0.1
Kaon subtraction	<0.1	<0.1
Sub-total	**0.1**	**0.1**
Momentum reconstruction:		
Momentum scale	2.8	0.3
Momentum resolution	0.8	0.3
Sub-total	**2.9**	**0.4**
Angle reconstruction:		
Angular scale	1.3	0.5
Total syst.	**10.0**	**5.1**
Overall normalization:	**2.0**	**2.0**

COMMENTS SECONDARY AND OUT-OF-TARGET INTERACTIONS

Modeling of secondary and out-of-target interactions are important for precise flux calculations

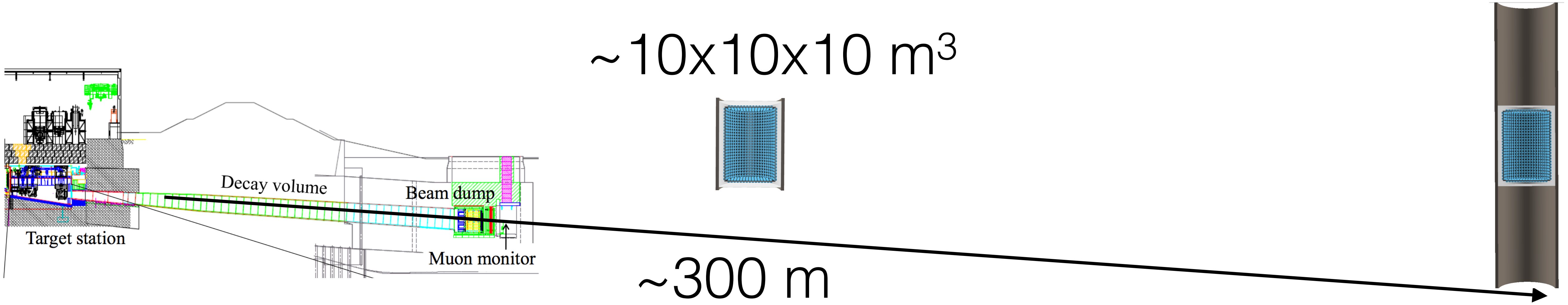
Some data exist, but there are phase space, beam energy and nuclear target limitations

As Matej mentioned, NA61 can take data down to 9 GeV/c, but not below

T2K can benefit from measurements on C, Al and Fe target with pion energies below 9 GeV/c that NA61 cannot access

A compact detector that could be placed in lower energy beam lines at Fermilab or CERN may make these measurements

NUPRISM



~10x10x10 m^3

~300 m baseline

1-2 km baseline

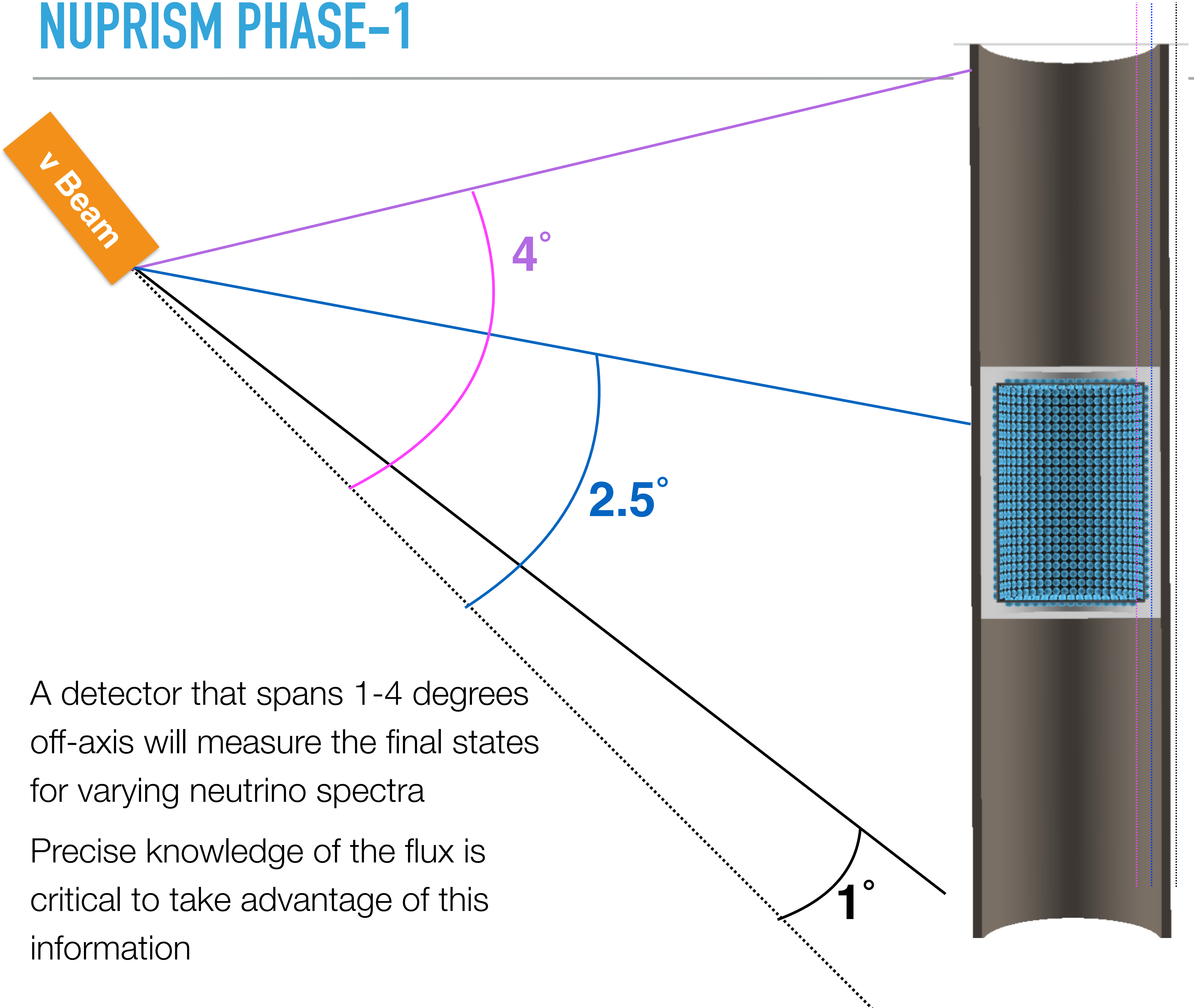
Proposed water ~kton Cherenkov detector in the J-PARC beam (recently received stage-1 status from the J-PARC PAC)

Two phase approach:

Phase-0: Detector on surface at 300 m to prove percent level performance

Phase-1: Movable detector in ~50 m tall pit at ~1 km

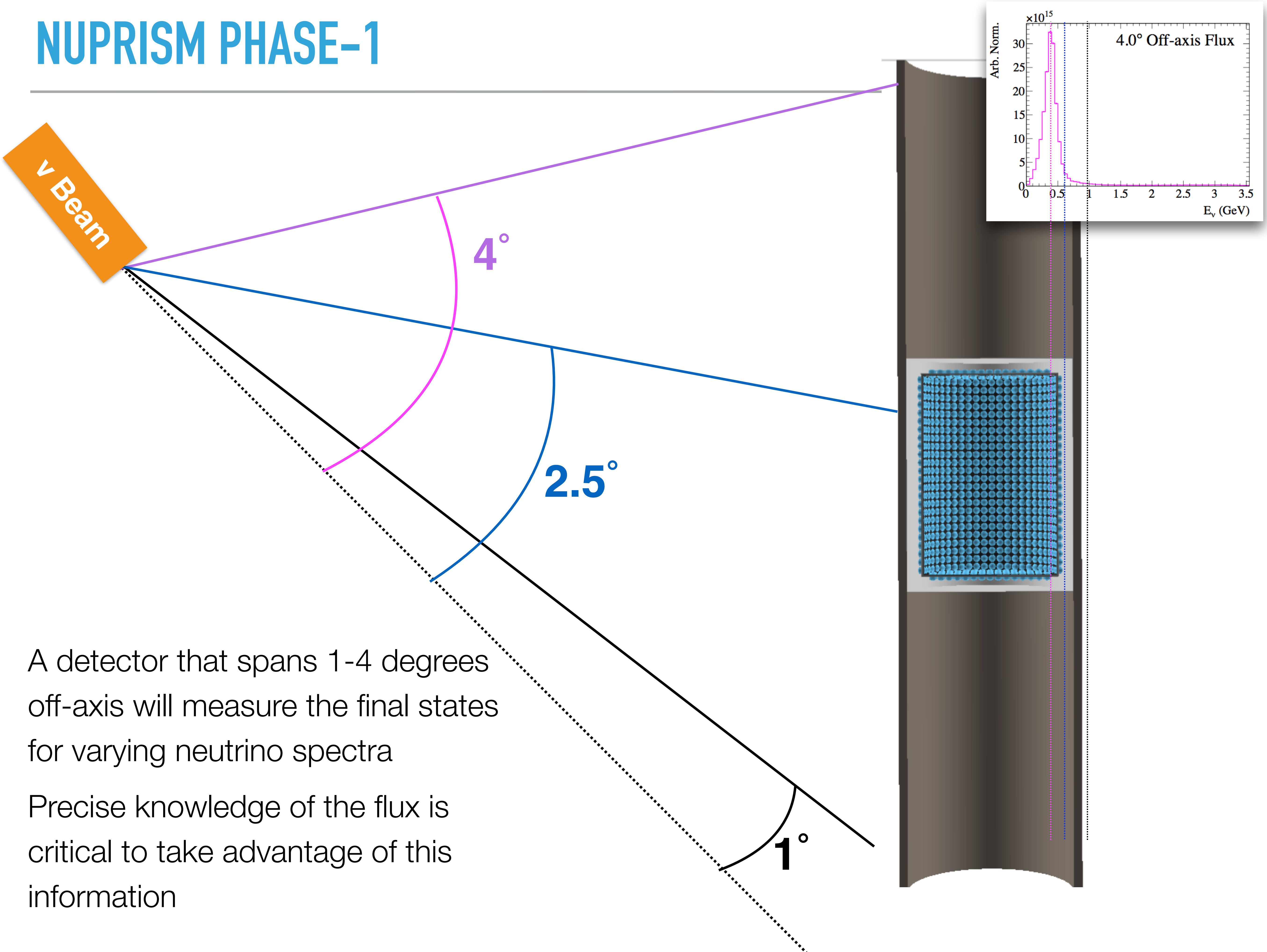
NUPRISM PHASE-1



A detector that spans 1-4 degrees off-axis will measure the final states for varying neutrino spectra

Precise knowledge of the flux is critical to take advantage of this information

NUPRISM PHASE-1



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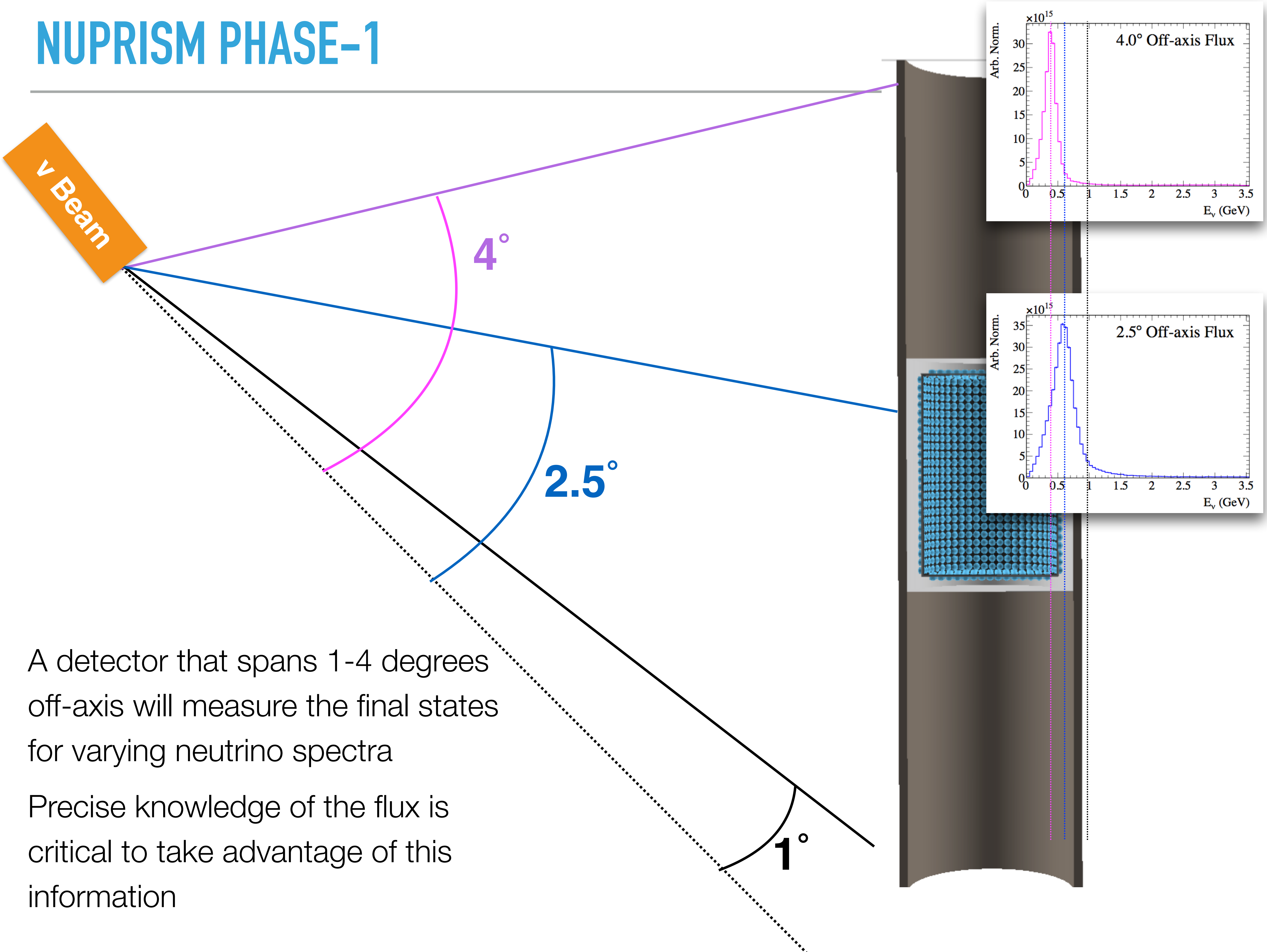
NUPRISM PHASE-1



A detector that spans 1-4 degrees off-axis will measure the final states for varying neutrino spectra

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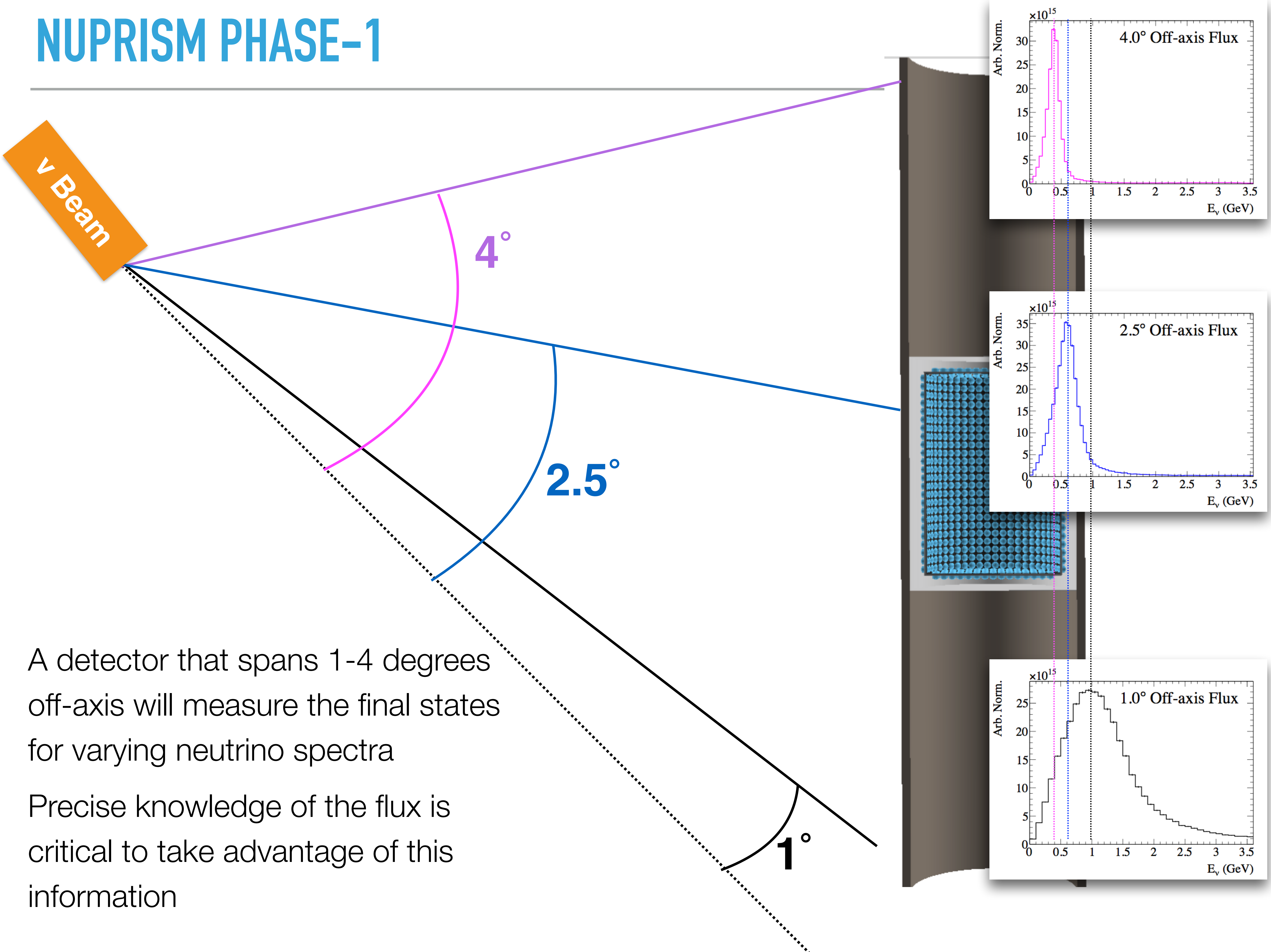
NUPRISM PHASE-1



A detector that spans 1-4 degrees off-axis will measure the final states for varying neutrino spectra

Precise knowledge of the flux is critical to take advantage of this information

ELECTRON NEUTRINO/MUON NEUTRINO RATIO

CP violation detection is done with the modes: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

In near detectors, we make precise measurements of ν_μ and $\bar{\nu}_\mu$ interactions

No precise measurement of electron (anti)neutrino measurements around 1 GeV

Actually need measurements of the ratio $\sigma_{\nu_e}/\sigma_{\nu_\mu}$

In NuPRISM, we take advantage of the fact that the intrinsic electron (anti)neutrino content of the beam increases with off-axis angle (two vs. three body decays)

NUPRISM ELECTRON NEUTRINOS

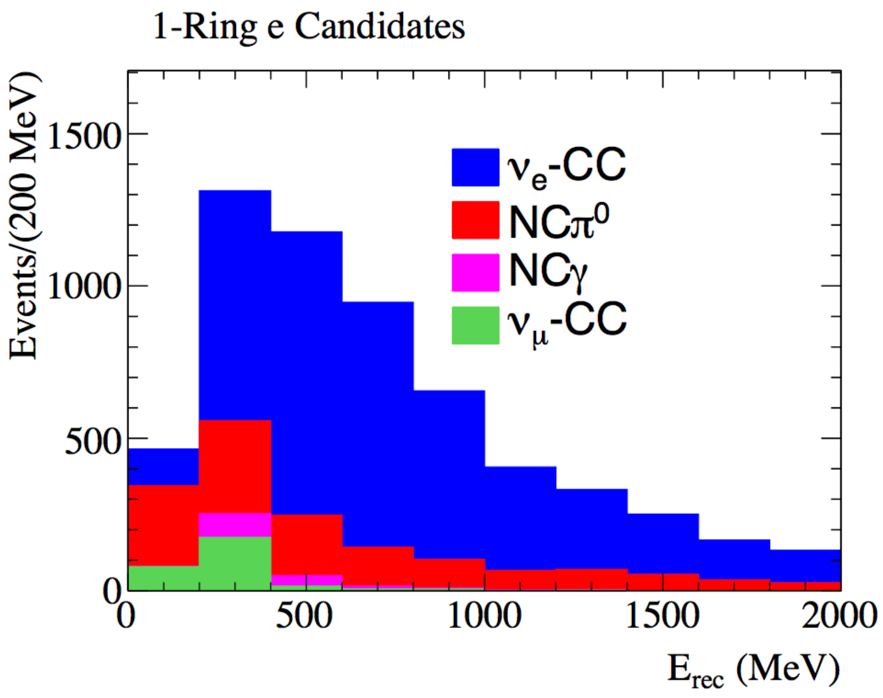


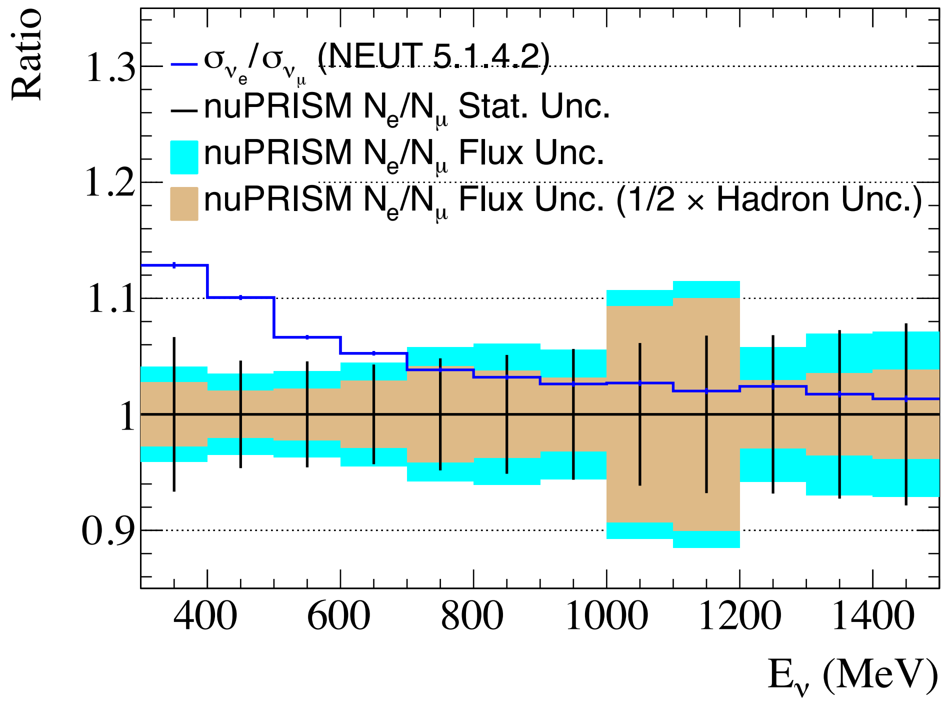
FIG. 24. Selected 1R*e* candidates in the 2.5-4.0° off-axis range for NuPRISM.

4.5e21 POT exposure

3500 candidate events with 71% signal purity

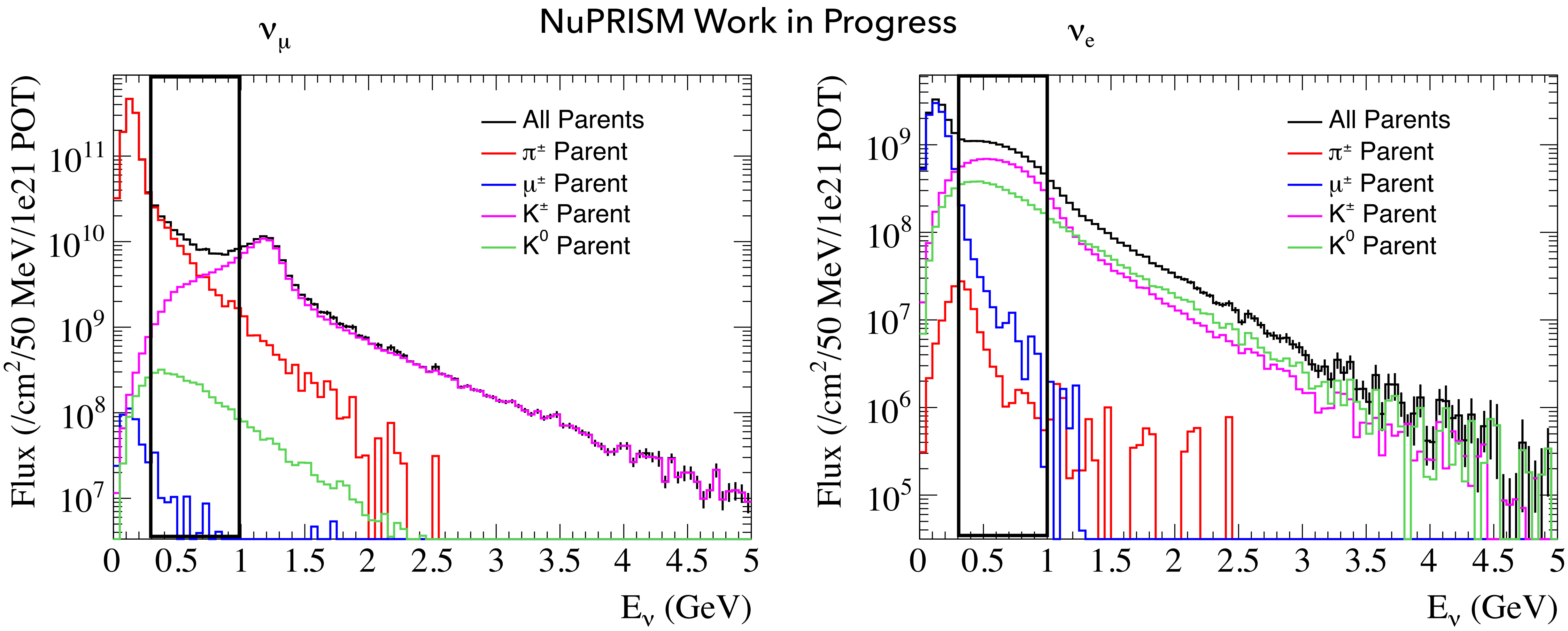
Aiming for ~3% precision on ν_e/ν_μ cross section ratio

Errors on the ν_e/ν_μ flux ratio can be improved with a 50% reduction on the hadron interaction uncertainties



ELECTRON NEUTRINOS AT PHASE-0

The phase-0 detector will be located on the surface at an off-axis angle of 6-12 degrees



In the energy range of interest, electron neutrinos come from K+ and K0L parents

Muon neutrinos come from pi+ and K+ parents

Expect significant uncertainties on the flux ratio (calculation in progress)

May need more precise measurements of the relative pi±, K± and K0L production

CONCLUSION

- Long baseline experiments that will search for CP violation, determine the mass hierarchy and make precision oscillation parameter measurements will need percent level precision
- A precise calculation of the neutrino flux is necessary for oscillation measurements and neutrino-nucleus scattering measurements
- The uncertainties on the modeling of hadron interactions in the flux calculation are dominant
- NA61/SHINE data addresses a majority of the interactions that need to be modeled
  - Improvements to the replica target measurements are desired
  - Measurements of secondary processes below 9 GeV/c are not accessible
  - The measurement of elastic and quasi-elastic cross sections can allow for a model independent extraction of the production cross section
- NuPRISM measurements can also benefit from more precise knowledge of the hadron production data
- Emulsion and a compact emulsion spectrometer may contribute to the necessary program of measurements