T2K/HK beam-related physics

2022/12/15, NA61++/SHINE workshop

K.Sakashita(KEK/J-PARC neutrino group)

T2K and Hyper-K experiment

Large size Water Cherenkov detector

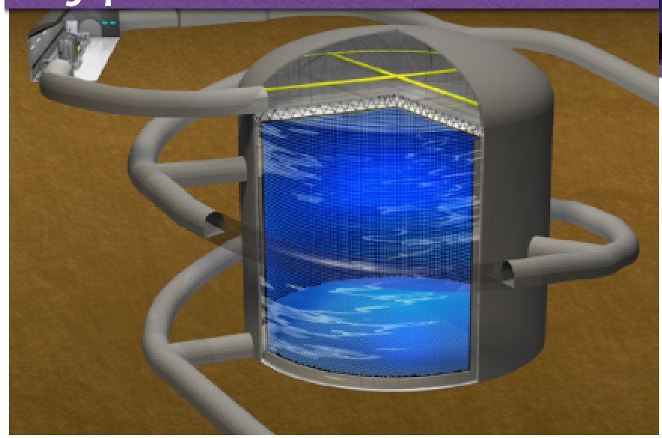
$$Prob.(\nu_\mu \rightarrow \nu_e) \Leftrightarrow Prob.(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

Super-Kamiokande
(ICRR, Univ. Tokyo)

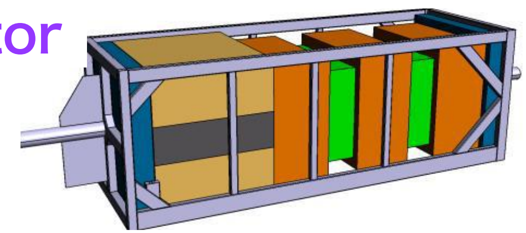
High intense ν beam

J-PARC Main Ring
(KEK-JAEA, Tokai)

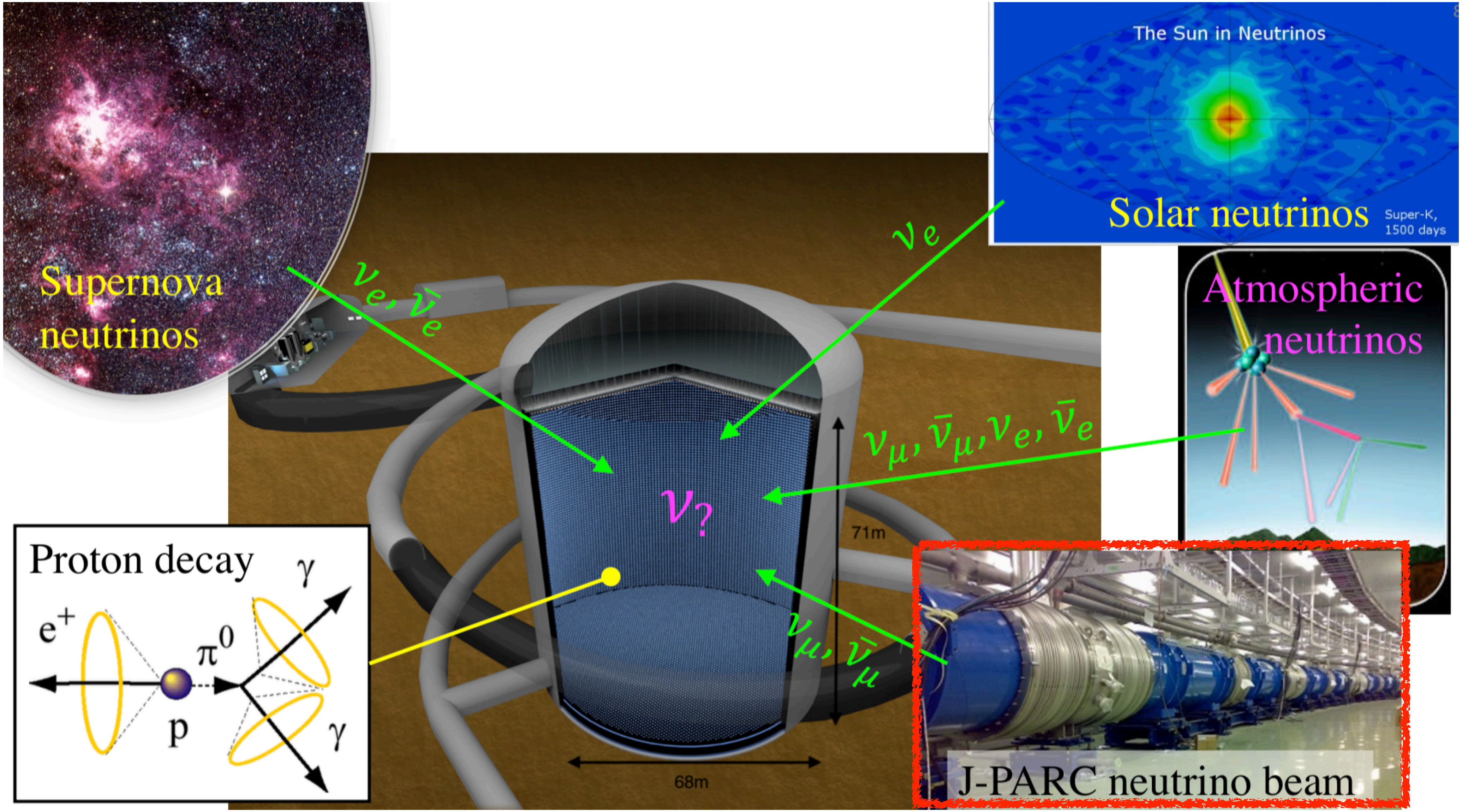
Hyper-Kamiokande



Upgraded ND280 &
Intermediate detector



Broad science questions will be addressed with unprecedented sensitivities

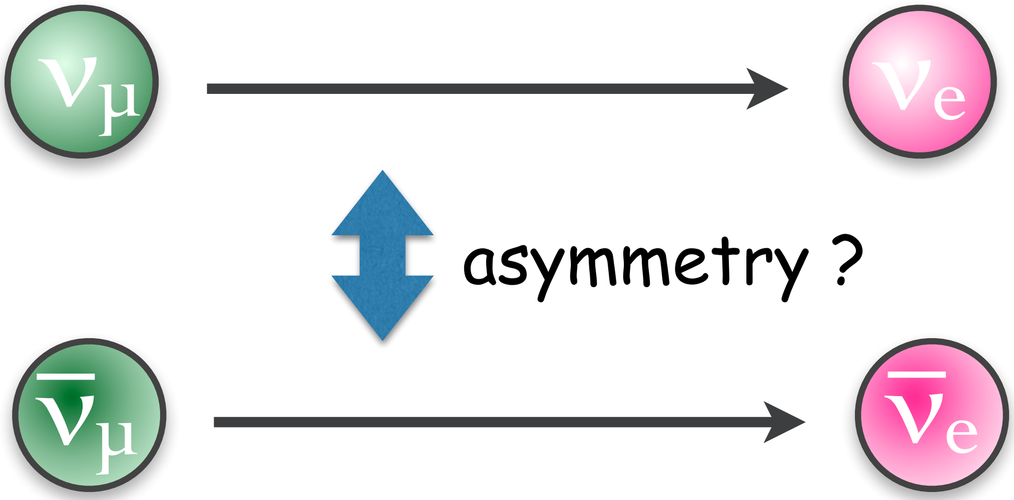


Do neutrinos violate CP symmetry ?

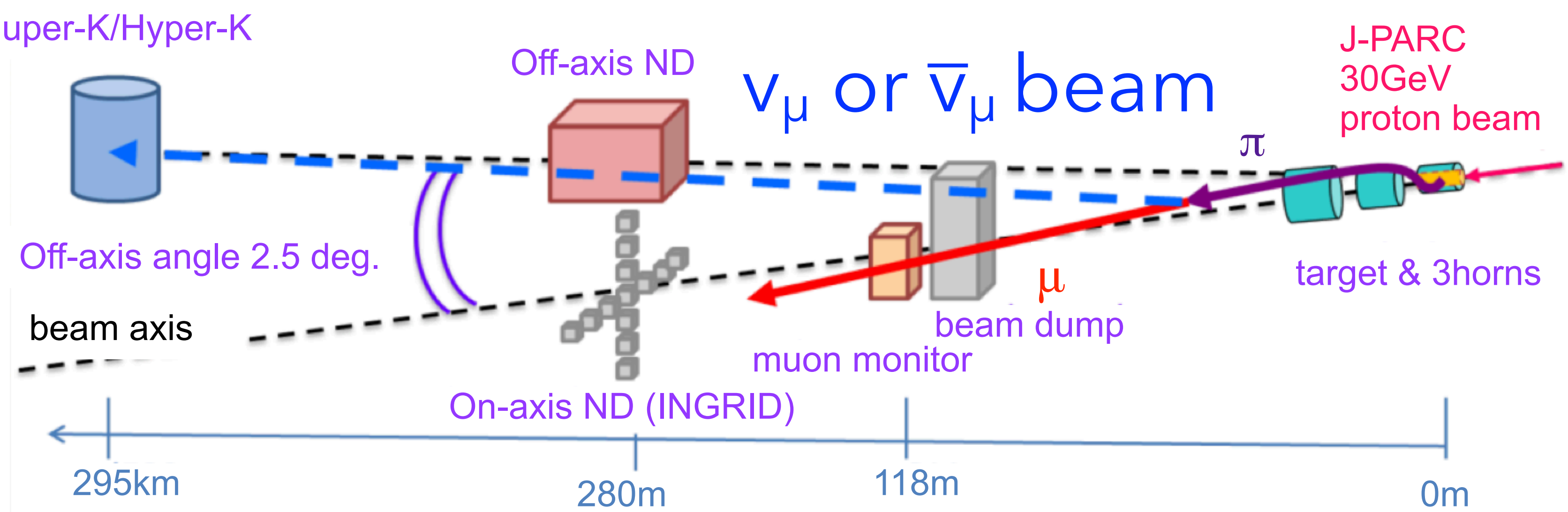
- It is still unknown but the size of CP violation of neutrino could be $O(10^3)$ larger than the quarks

- Neutrino are the possible source of CP violation which can explain the matter-antimatter asymmetry in the universe

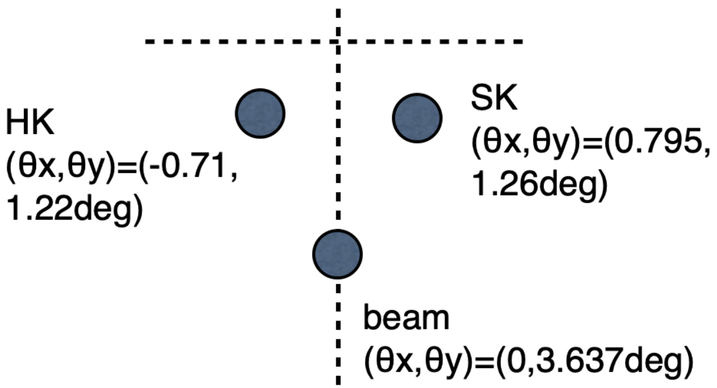
[Nucl. Phys. B774 (2007) 1], [JHEP 03, 034(2019)]
[arXiv:1609.05028. arXiv:1807.06582]

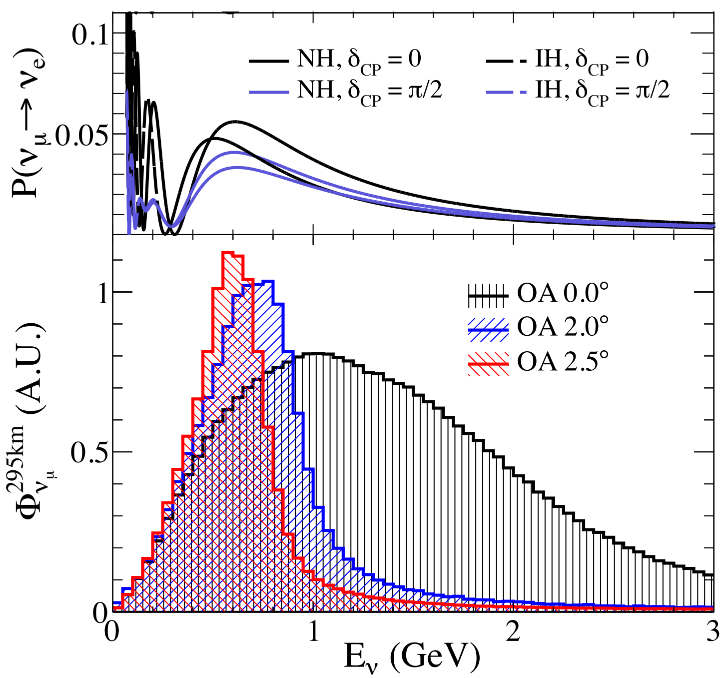


High intense ν_μ beam with off-axis method



J-PARC beam is directed to the same OA(2.5°) for both SK and HK



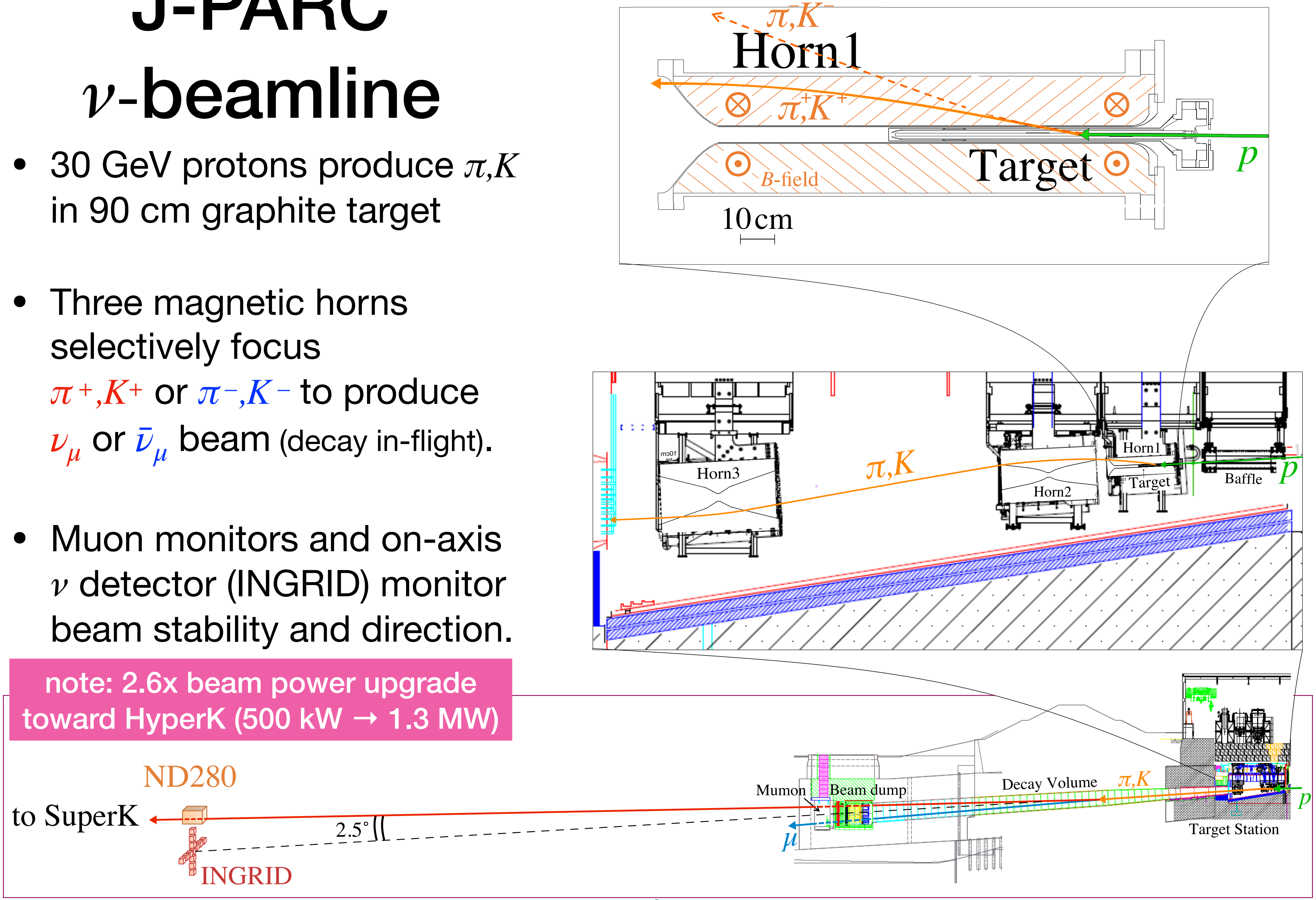


- small ν_e contamination (~1%)
- ν / $\bar{\nu}$ can be switched by flipping horn polarity

J-PARC
ν-beamline

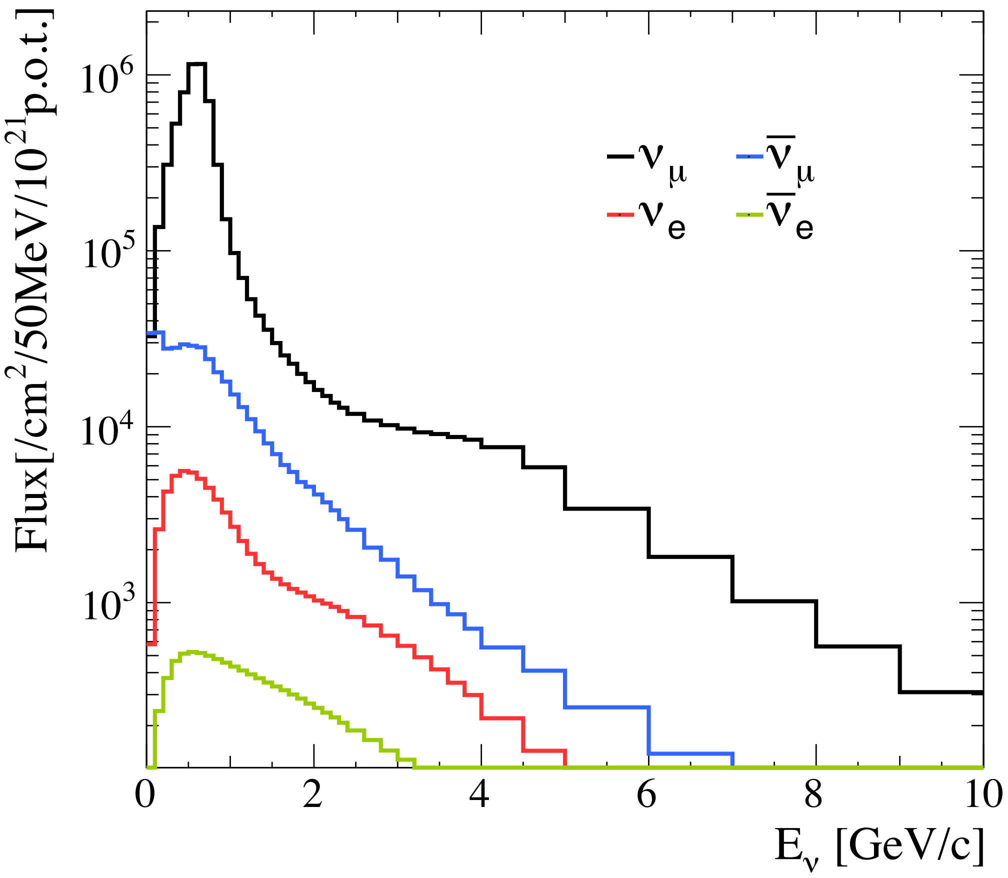
- 30 GeV protons produce π,K in 90 cm graphite target
- Three magnetic horns selectively focus π^+,K^+ or π^-,K^- to produce ν_μ or $\bar{\nu}_\mu$ beam (decay in-flight).
- Muon monitors and on-axis ν detector (INGRID) monitor beam stability and direction.

note: 2.6x beam power upgrade toward HyperK (500 kW → 1.3 MW)

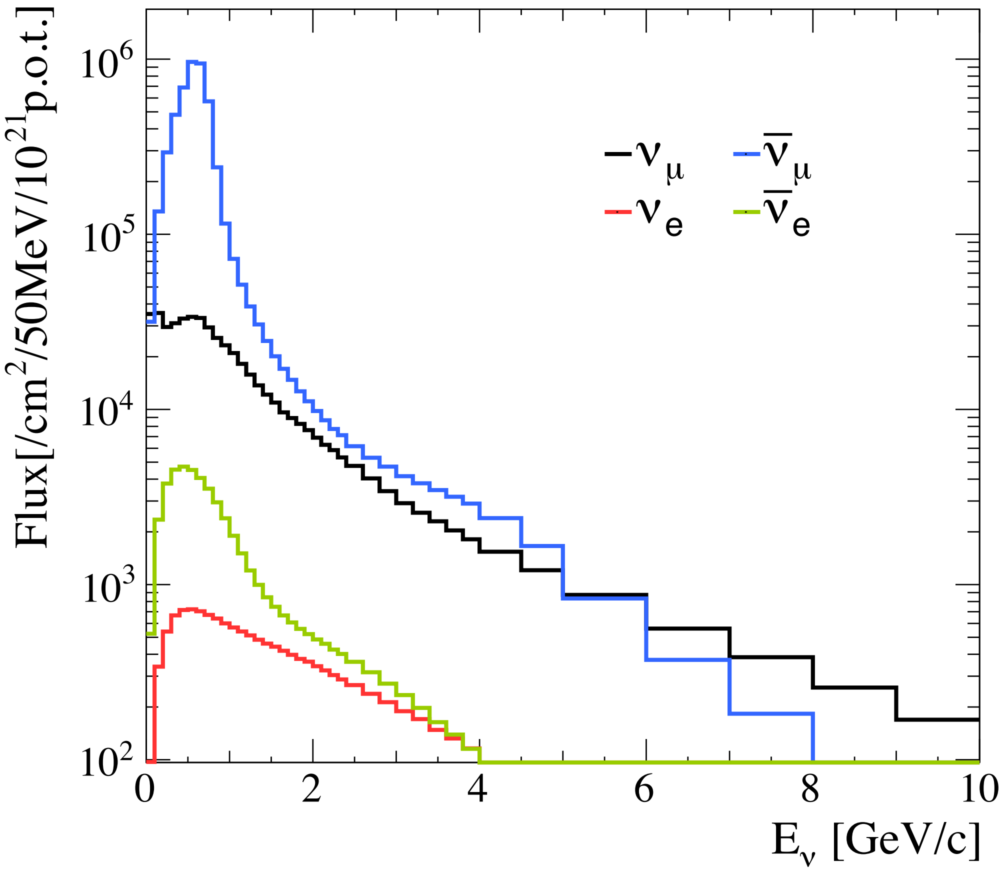


Neutrino flux (prediction)

neutrino-enhanced (FHC)



antineutrino-enhanced (RHC)

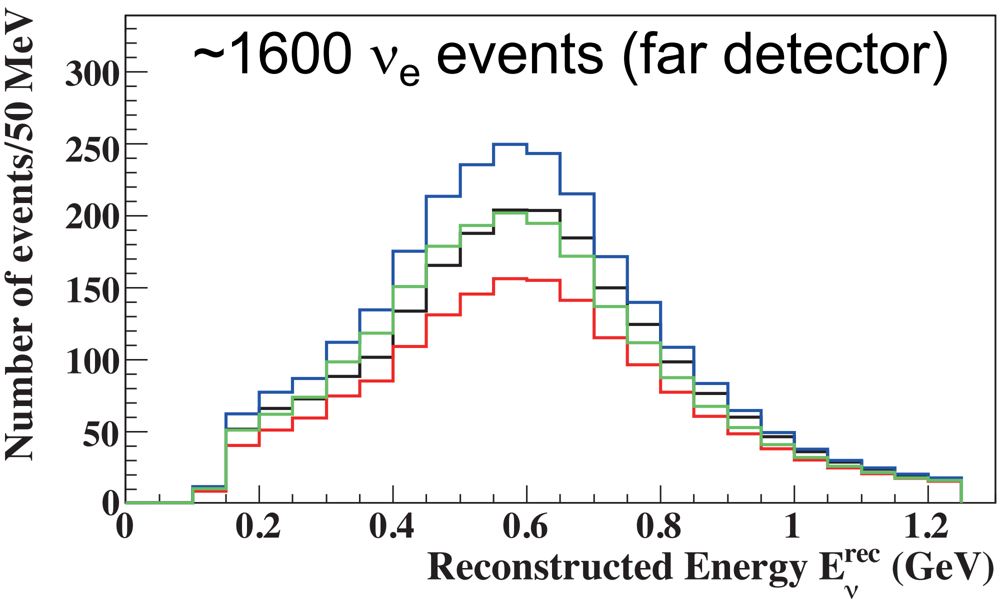


~3% wrong sign (for both FHC and RHC)

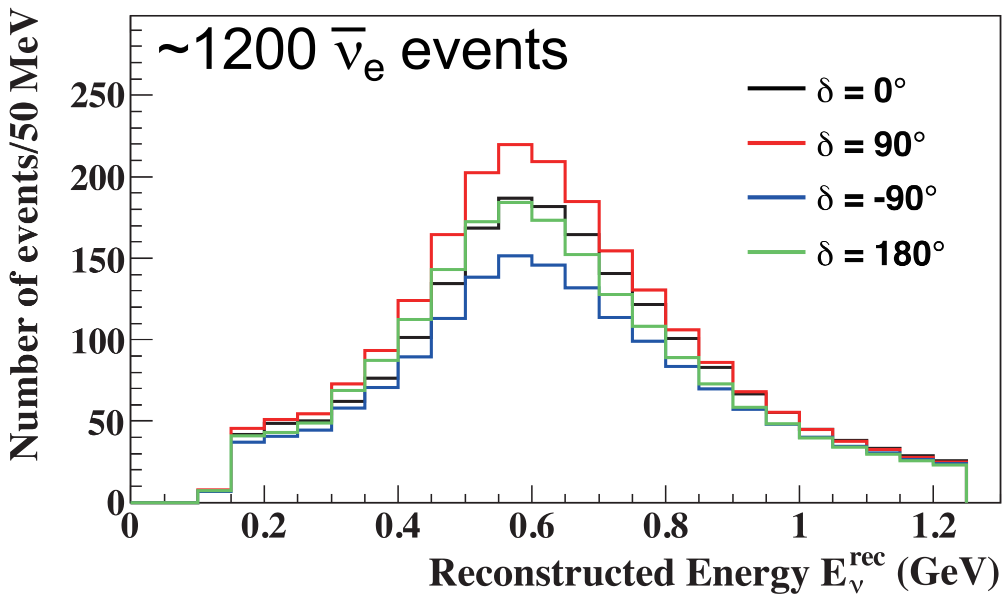
CPV search at Hyper-K

with 190kton Fiducial volume, **1.3MW** x 6cycles/year x 10years

Neutrino mode: appearance



Antineutrino mode: appearance

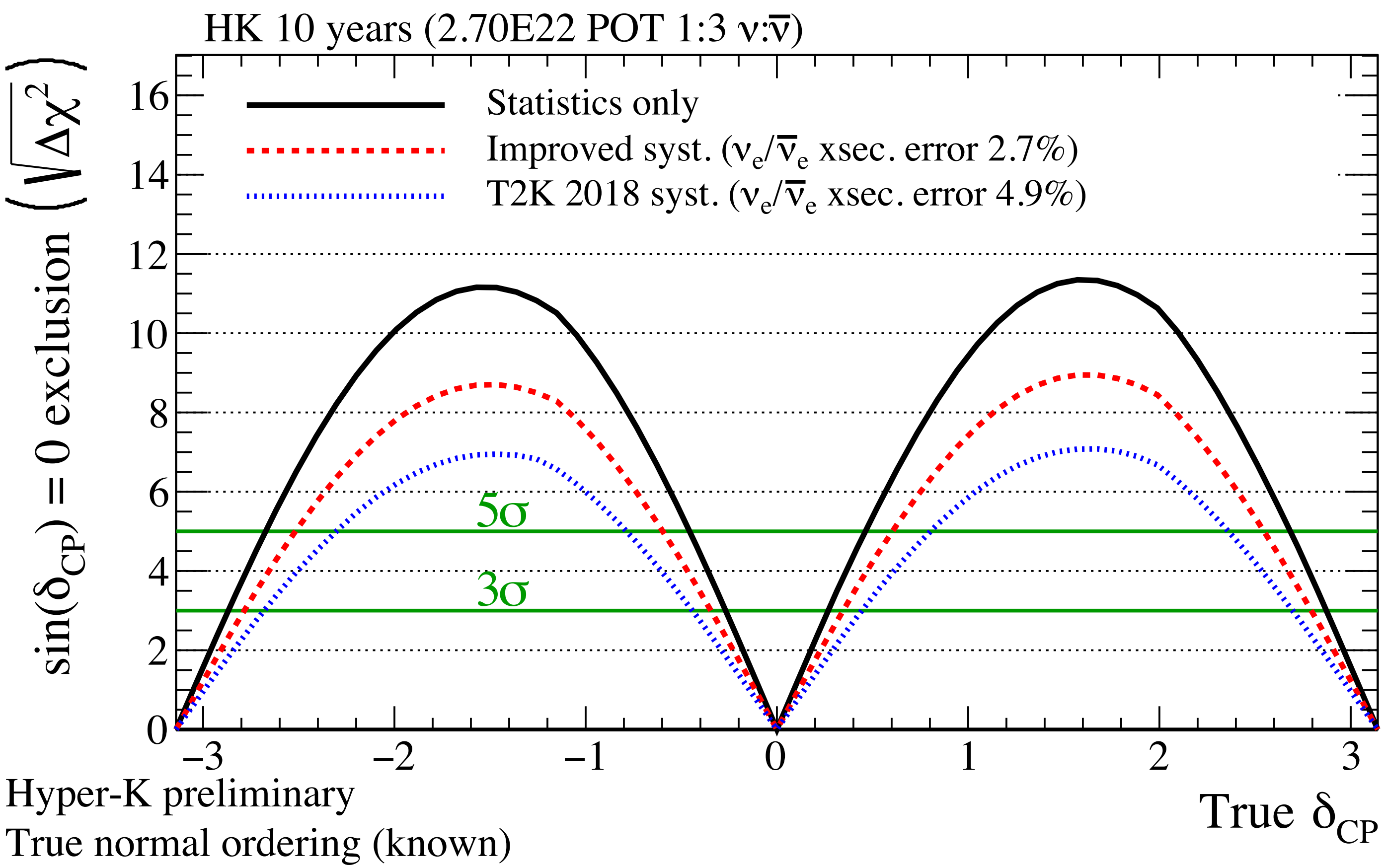


Expected number of ν_e appearance signal and background

	Appearance signal	Wrong sign signal	Beam ν_e background	NC background	Total	T2K-II	T2K(2020)
Neutrino mode	1600	20	260	130	**2010**	*468*	*108*
Antineutrino mode	1200	200	320	200	**1920**	*134*	*16*

Sensitivity to $\sin\delta_{CP} \neq 0$

- **Reduction of systematic error has a large impact to the sensitivity**
- ~8σ for δ_{CP}= - π/2 (favored by T2K)
- Good opportunity to make discovery of CP violation in neutrino sector at >5σ (~60% fraction of δ_{CP} values w/ 10years data taking)

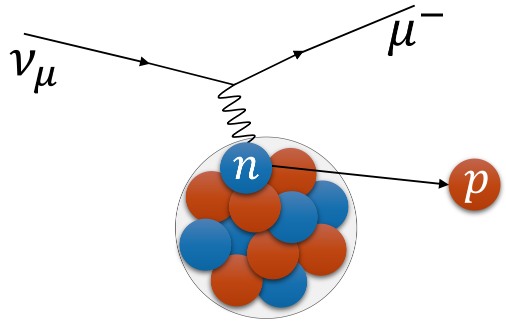


Hyper-K preliminary
True normal ordering (known)
$\sin^2(\theta_{13}) = 0.0218$ $\sin^2(\theta_{23}) = 0.528$ $|\Delta m^2_{32}| = 2.509\text{E-}3$

Systematic error

- # of events
  ~[neutrino flux] x [cross section] x [det. efficiency]

- Major error sources are "flux" and "cross section"

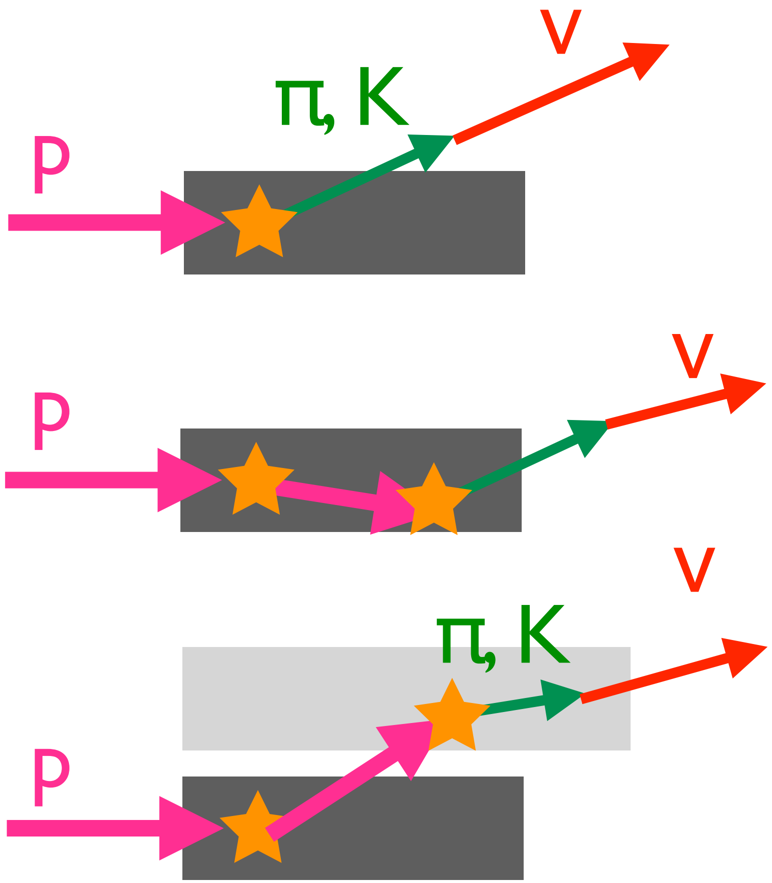


- For both, improvement flux error is critical
  - cross section error is constrained by near detector measurements
  - in particular, understanding of **wrong sign** component is important for CPV

Breakdown of hadron interaction

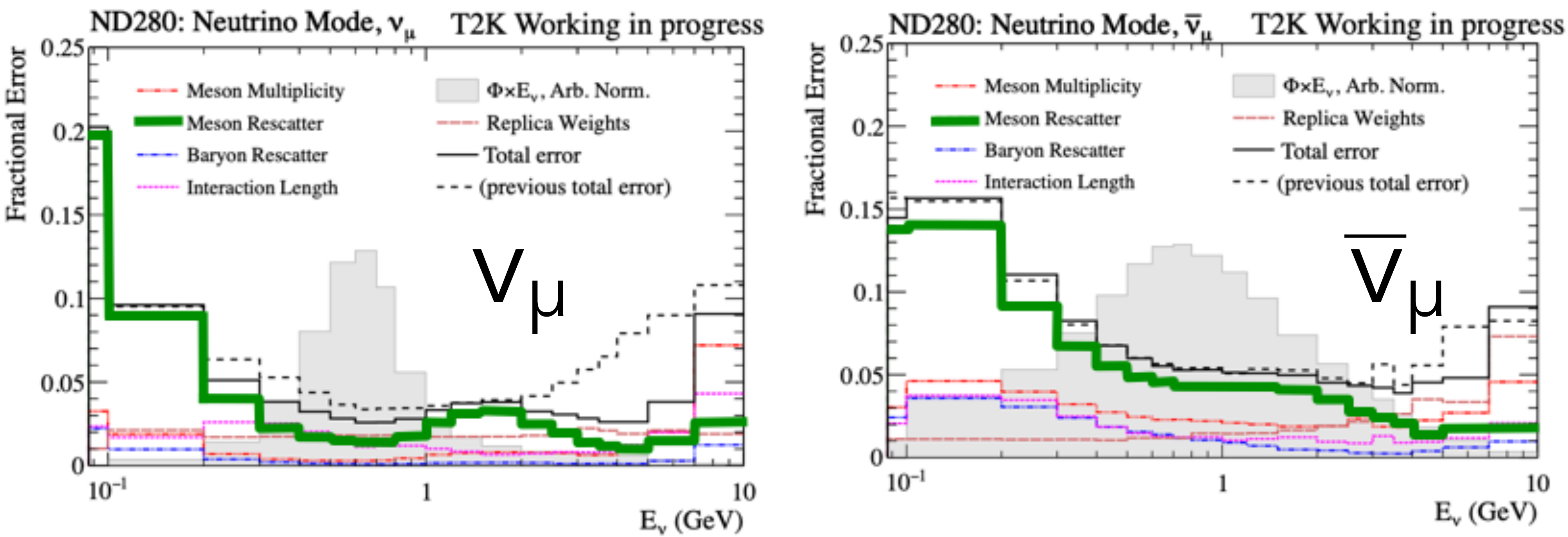
- Percentage of T2K FD flux to in-target or out of target interaction

	in-target primary int.	other than the in-target primary int. (out of target int.)
ν_μ	63.2%	36.8% (12.4%)
$\bar{\nu}_\mu$	41.5%	58.5% (45.1%)
ν_e	61.7%	38.3% (12.7%)
$\bar{\nu}_e$	54.0%	46.0% (27.2%)



- Breakdown of hadron production error

Thanks to NA61/SHINE data, current error is ~5%(10%) for right (wrong) sign flux but still largest error source for the flux



meson scattering outside the target which not covered by HARP data

Flux-weighted fractions of "unconstrained interactions"

SK, Neutrino mode

	→ Carbon	→ Aluminum	→ Iron	→ Titanium	→ Helium	→ Water	→ Other
$\pi^+ \to$	6.93	8.33	6.44	2.19	1.97	11.95	0.44
$\pi^- \to$	3.47	3.66	4.82	0.56	0.21	2.59	0.41
$K^0 \to$	2.94	2.10	1.05	0.15	0.03	0.48	0.08
$K^+ \to$	2.67	2.99	0.75	0.18	0.06	0.85	0.08
$K^- \to$	0.66	0.73	0.25	0.04	0.01	0.14	0.03
$n \to$	2.15	1.22	1.12	0.06	0.77	3.33	0.33
$p \to$	2.70	0.77	0.49	0.05	5.14	6.97	0.26
$\bar{p} \to$	0.12	0.18	0.05	0.01	0.00	0.04	0.00
$\Lambda \to$	1.65	0.66	0.06	0.07	0.00	0.23	0.00
$\Sigma \to$	0.54	0.12	0.02	0.02	0.00	0.04	0.00
$\bar{n} \to$	0.16	0.25	0.08	0.02	0.00	0.07	0.00

largest contributions:

Channel	Flux-weighted fraction [%]
$\pi^+ \to$ Water	11.95
$\pi^+ \to$ Aluminum	8.33
$p \to$ Water	6.97
$\pi^+ \to$ Carbon	6.93
$\pi^+ \to$ Iron	6.44
$p \to$ Helium	5.14
$\pi^- \to$ Iron	4.82
$\pi^- \to$ Aluminum	3.66
$\pi^- \to$ Carbon	3.47
$n \to$ Water	3.33
Other	38.96

SK, Anti-neutrino mode

	→ Carbon	→ Aluminum	→ Iron	→ Titanium	→ Helium	→ Water	→ Other
$\pi^+ \to$	5.00	5.22	6.82	0.86	0.32	2.80	0.49
$\pi^- \to$	5.34	6.64	5.58	1.73	1.56	9.37	0.43
$K^0 \to$	2.86	2.03	1.14	0.14	0.03	0.43	0.09
$K^+ \to$	1.98	1.84	0.93	0.11	0.02	0.33	0.10
$K^- \to$	1.05	1.48	0.26	0.09	0.03	0.41	0.03
$n \to$	3.55	1.22	1.18	0.06	0.82	4.49	0.35
$p \to$	2.66	0.72	0.58	0.04	4.47	4.22	0.37
$\bar{p} \to$	0.16	0.26	0.07	0.02	0.01	0.07	0.00
$\Lambda \to$	3.79	0.92	0.07	0.11	0.00	0.36	0.00
$\Sigma \to$	1.11	0.16	0.02	0.02	0.00	0.06	0.00
$\bar{n} \to$	0.14	0.22	0.08	0.01	0.01	0.05	0.01

largest contributions:

Channel	Flux-weighted fraction [%]
$\pi^- \to$ Water	9.37
$\pi^+ \to$ Iron	6.82
$\pi^- \to$ Aluminum	6.64
$\pi^- \to$ Iron	5.58
$\pi^- \to$ Carbon	5.34
$\pi^+ \to$ Aluminum	5.22
$\pi^+ \to$ Carbon	5.00
$n \to$ Water	4.49
$p \to$ Helium	4.47
$p \to$ Water	4.22
Other	42.85

pion scattering in C,Al,Fe and water should be measured

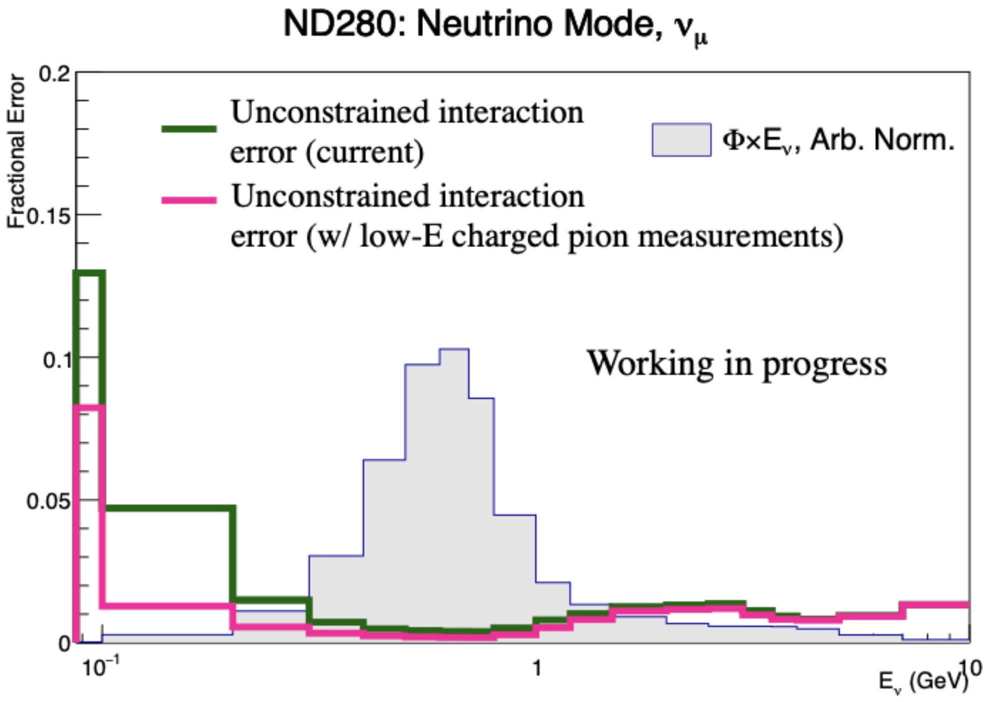
Plan of low momentum beam measurements

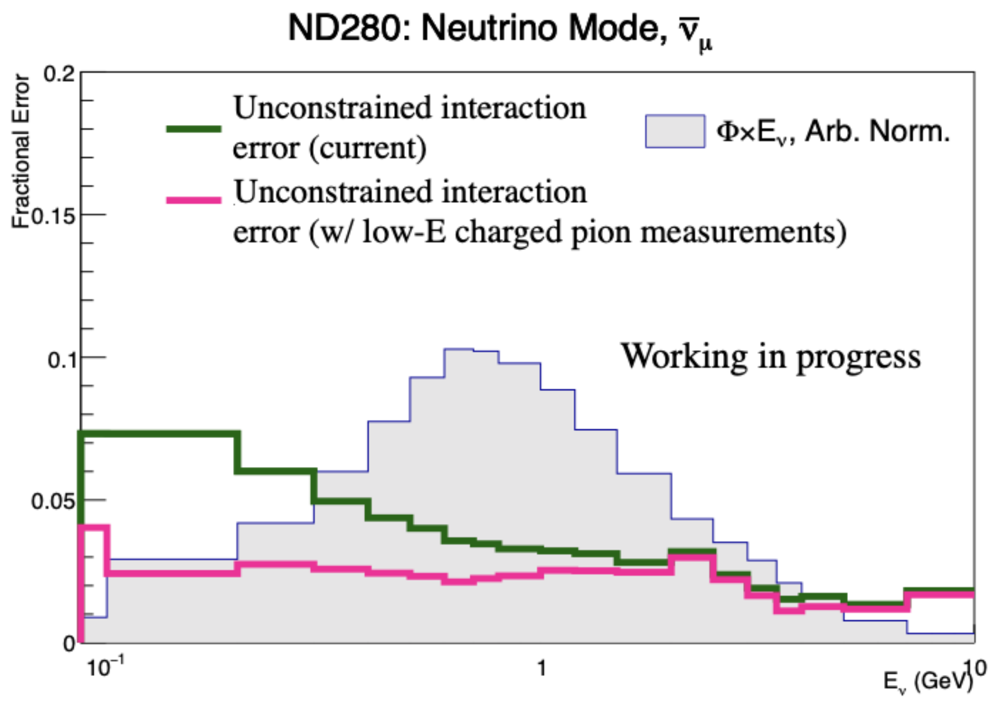
We will propose the following measurements

w/ 2cm thin target

- π^+ and π^- beam with 2 GeV/c for Al and Fe targets,
- π^+ and π^- beam with 8 GeV/c for Al, Fe and C targets

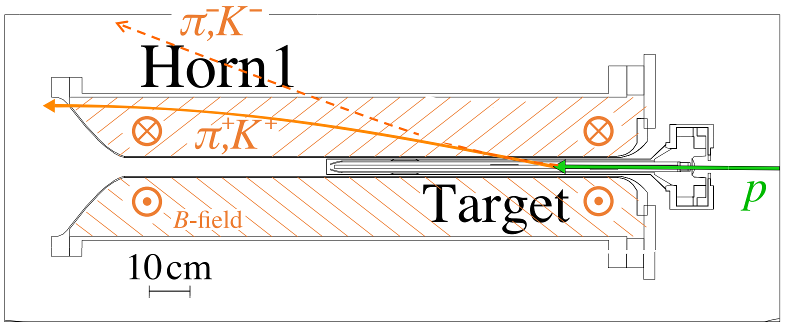
Expected improvements



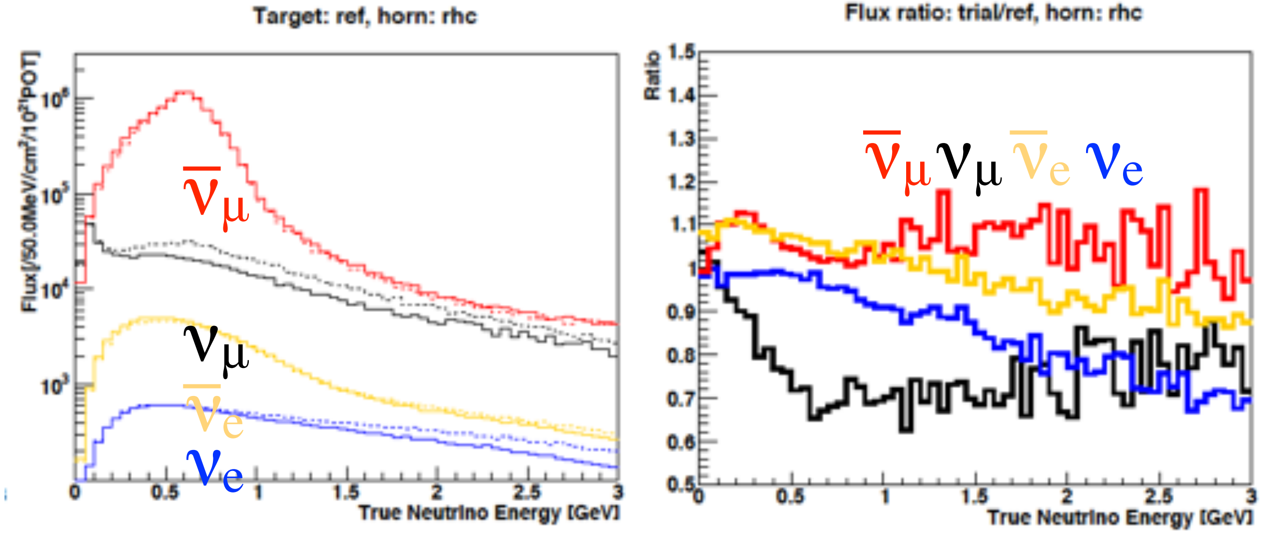


We can improve the flux error less than 5%

Idea to upgrade target to reduce wrong sign

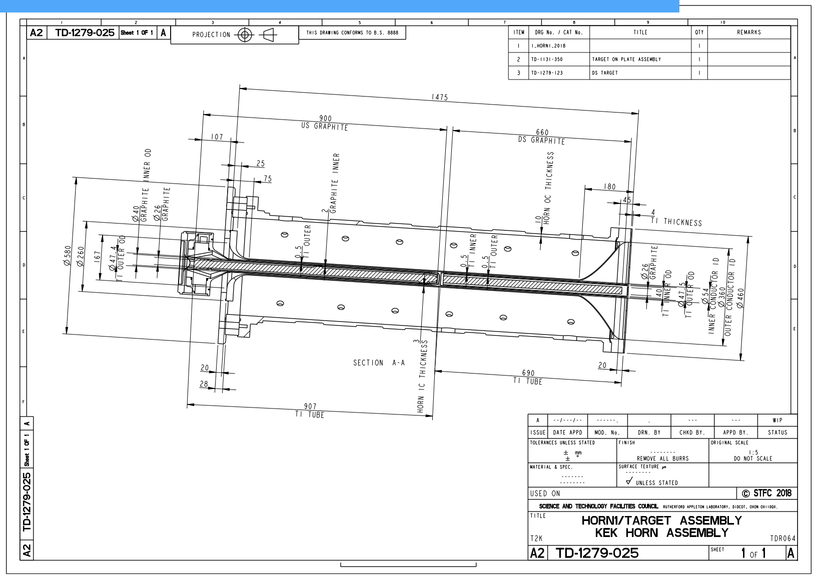


C φ=13mm, L=1500mm Horn = 320kA RHC



Flux MC studies by T.Nakadaira(KEK), J.Nugent(Glasgow)

One of ideas is long target.



→ see more detailed studies on a talk by L.Machado(Glasgow) on Saturday

Plan to propose new measurements for the new HK target after LS3

- Thanks to Chris Densham, Eric Harvey-Fisherden and Mike Fitton

Summary

- Improvement of flux uncertainty is still essential for T2K and Hyper-K experiments toward discovery of neutrino CPV
- We plan to study low-momentum interactions in order to improve the wrong-sign flux uncertainty
- Also, new idea of neutrino production target to suppress wrong-sign flux
    - new hadron production measurement is necessary !