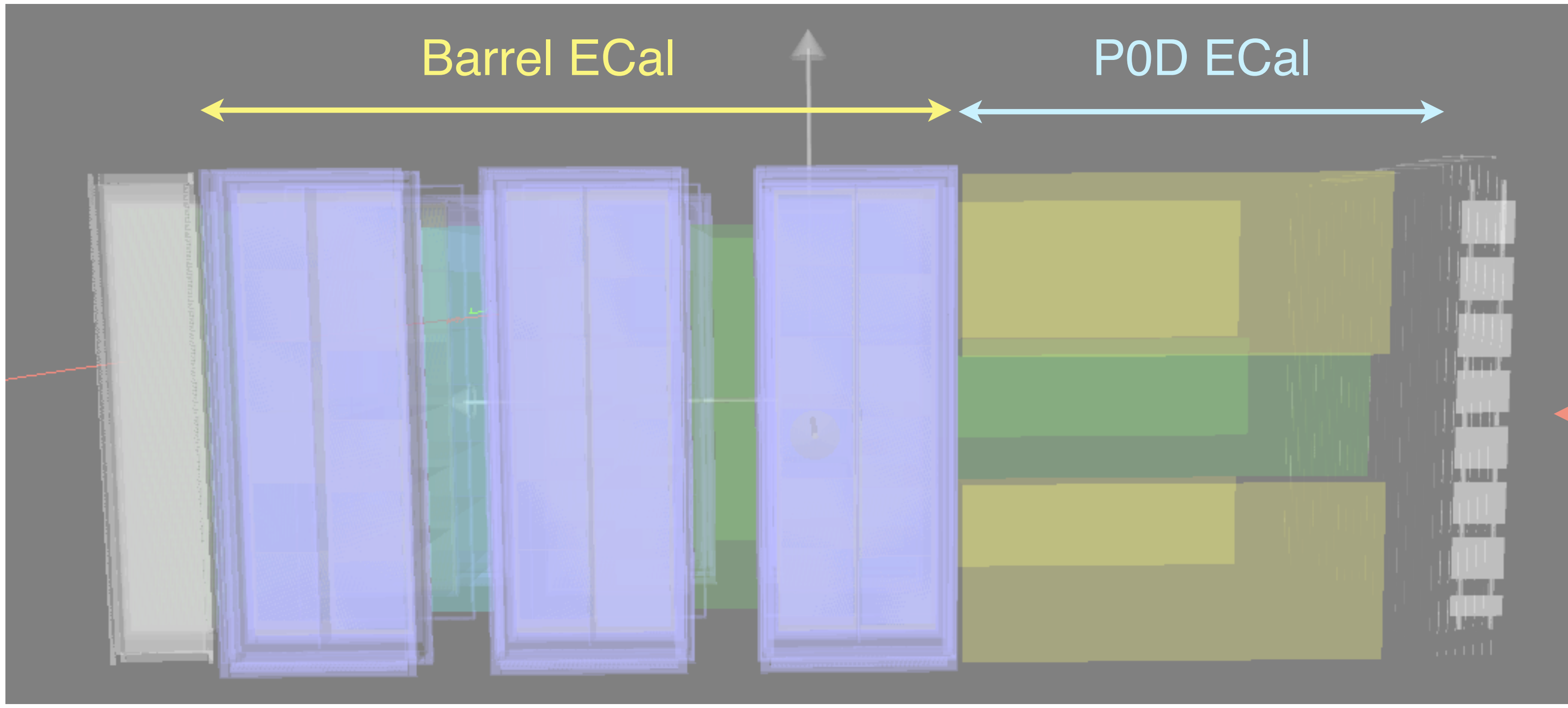
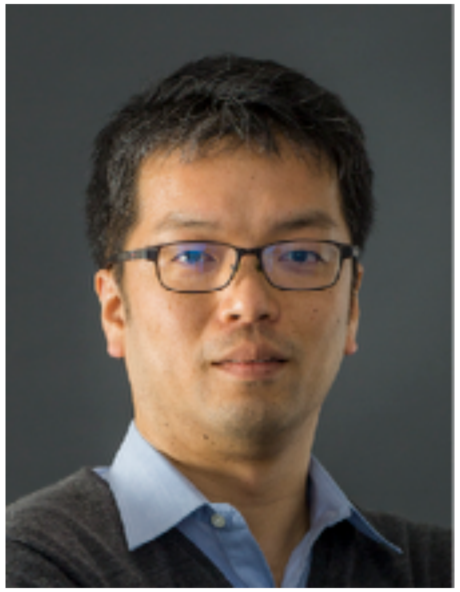
T2K near detector upgrade & Hyper-Kamiokande project





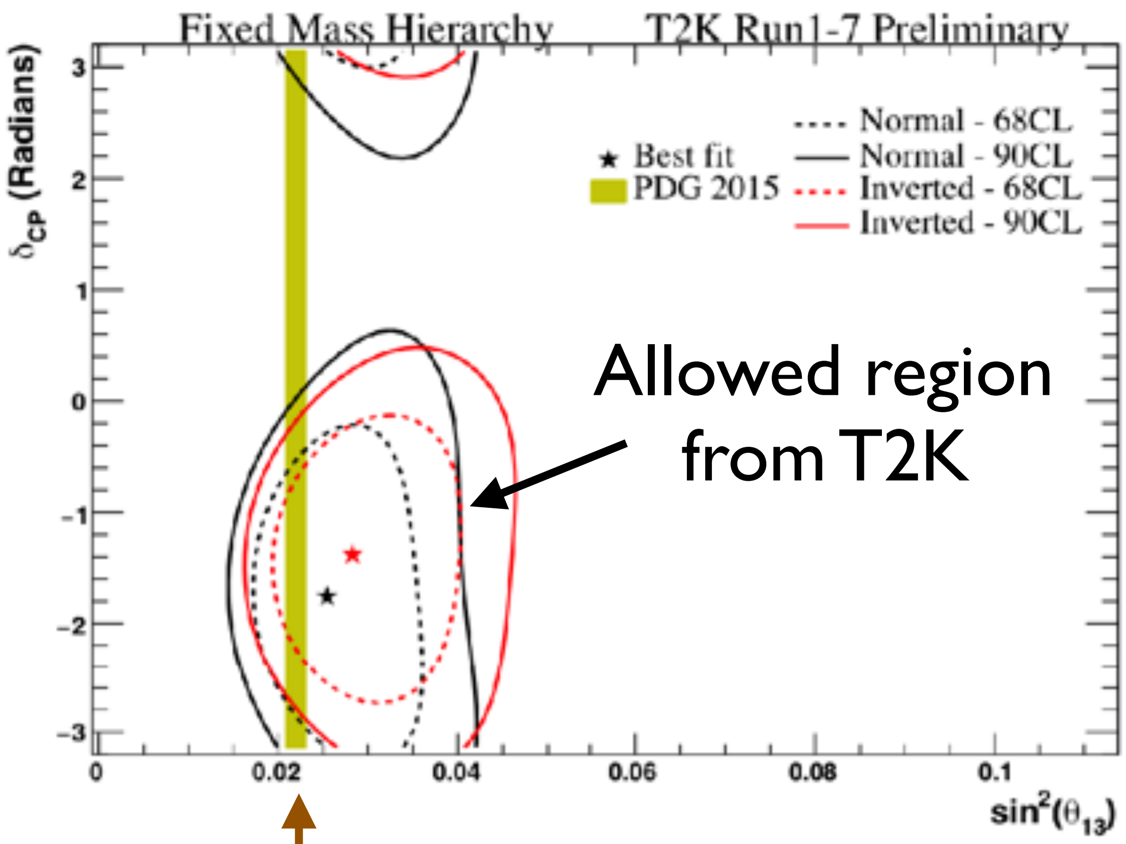
Masashi Yokoyama

Department of Physics, The University of Tokyo

T2K: ND280 upgrade convener & Executive Committee
Hyper-K: Physics Coordinator & Steering Committee

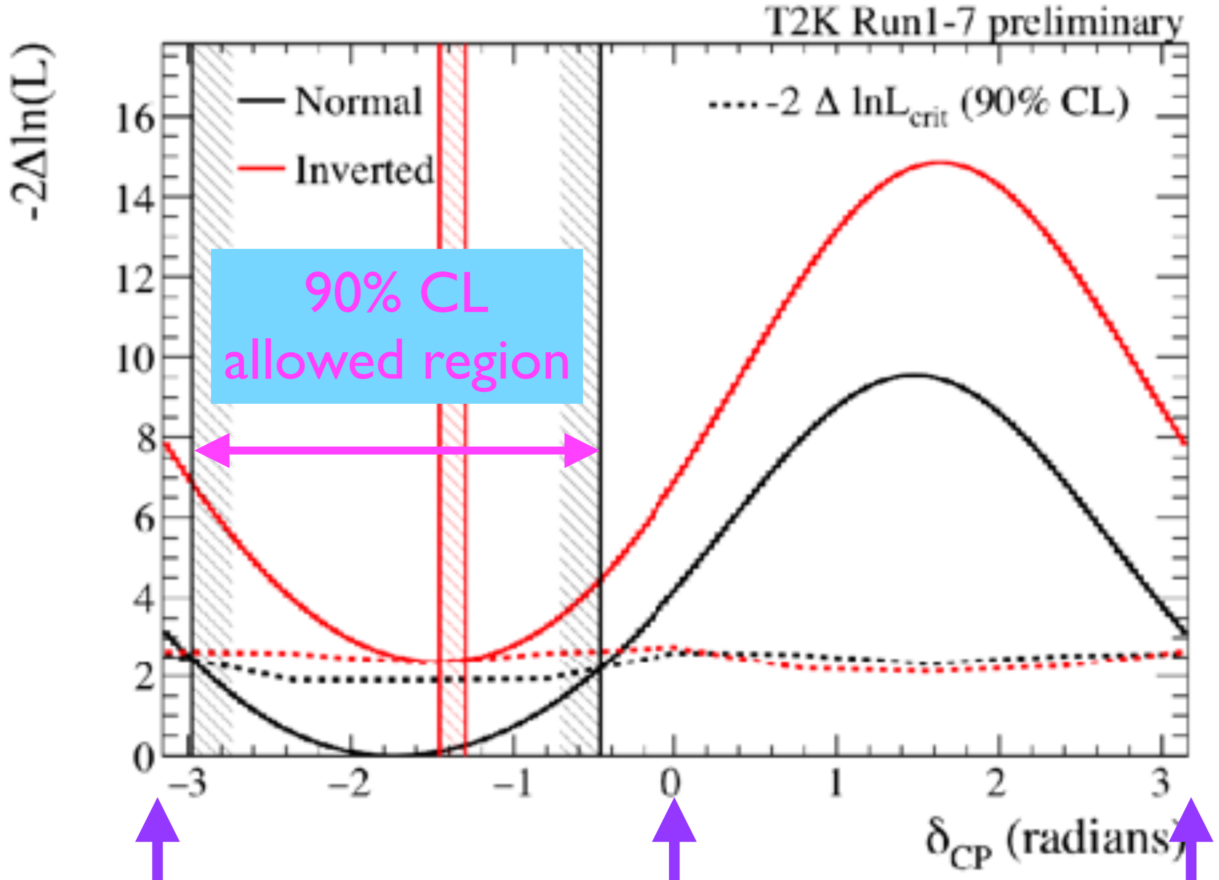
May 15, 2017 @ IoP Bhubaneswar

Breaking results from T2K



Allowed region from T2K

Results from reactor experiments



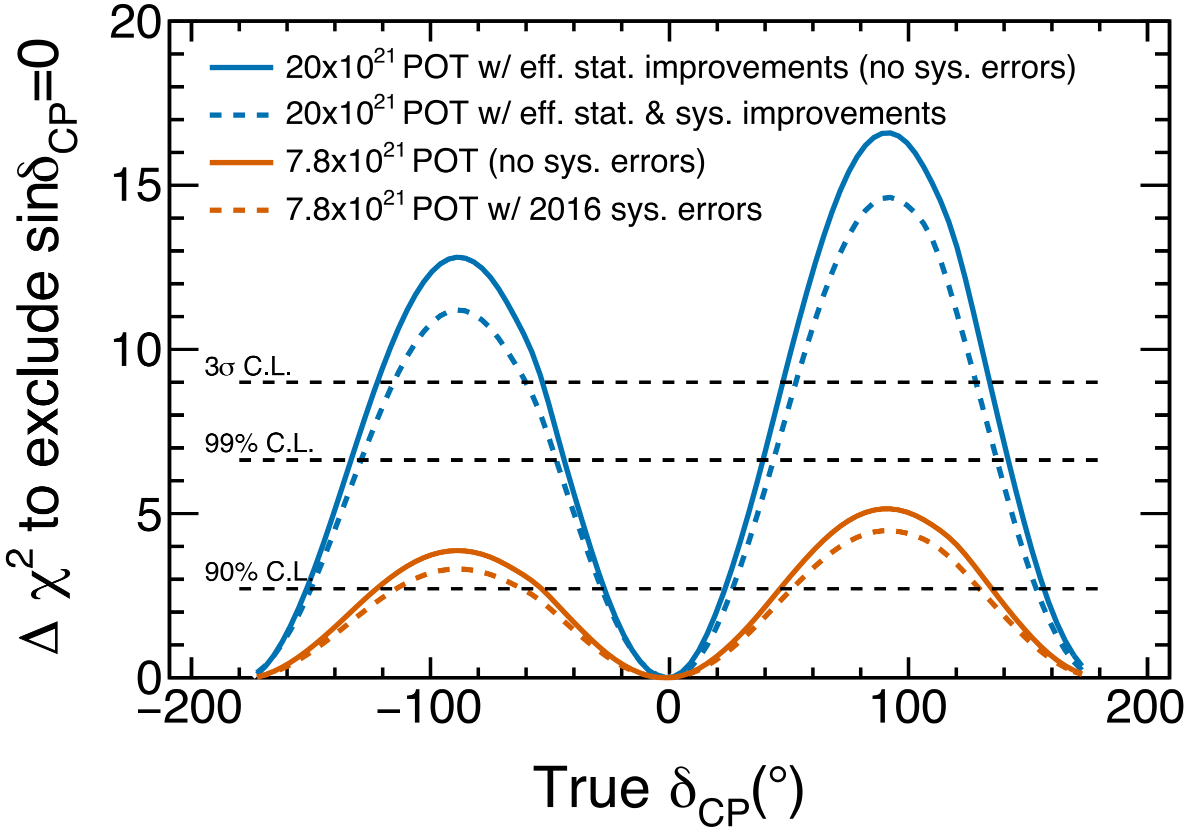
90% CL allowed region

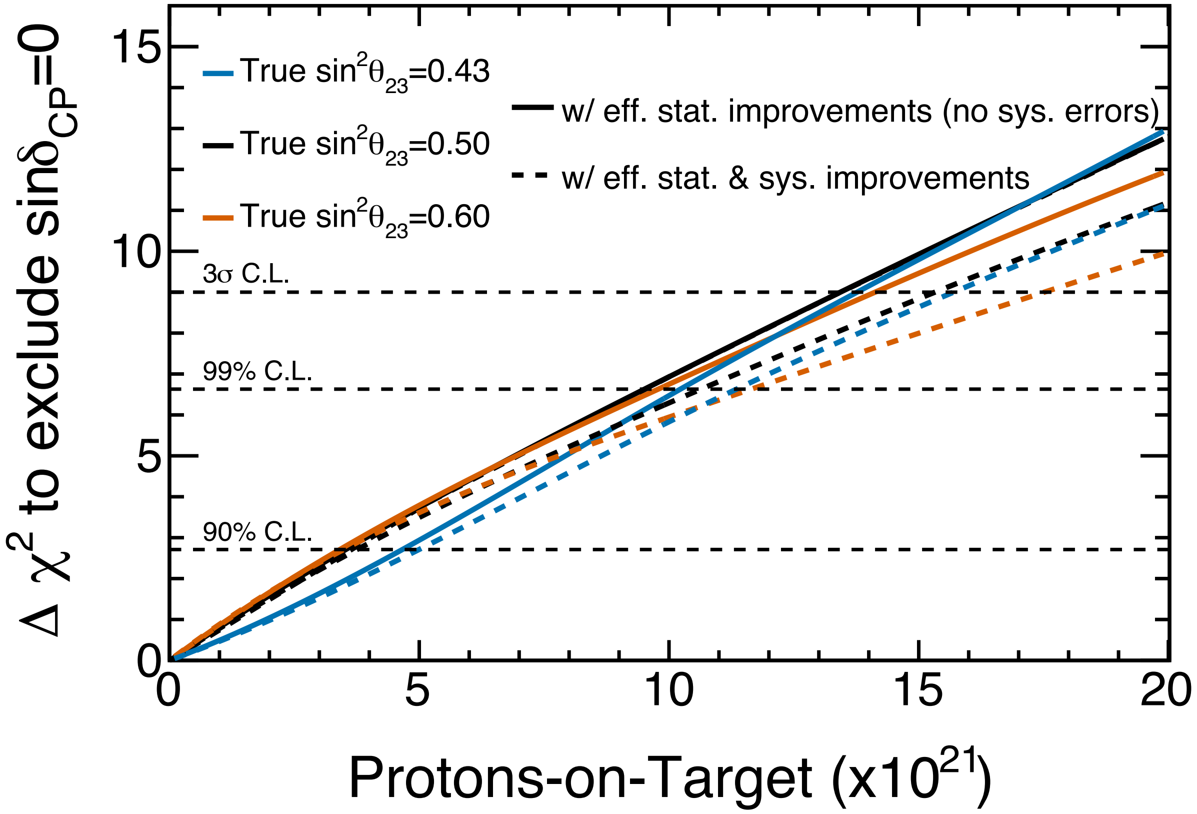
CP conserved points

First ever measurement of leptonic CP asymmetry;
Already hint of possible large CPV!!

T2K-II extension

- Proposal to accumulate 20E21 POT (1/30 g of protons!) by 2025-2026
  - With increased beam power of J-PARC
- >3σ sensitivity for CP violation for favorable paerameters





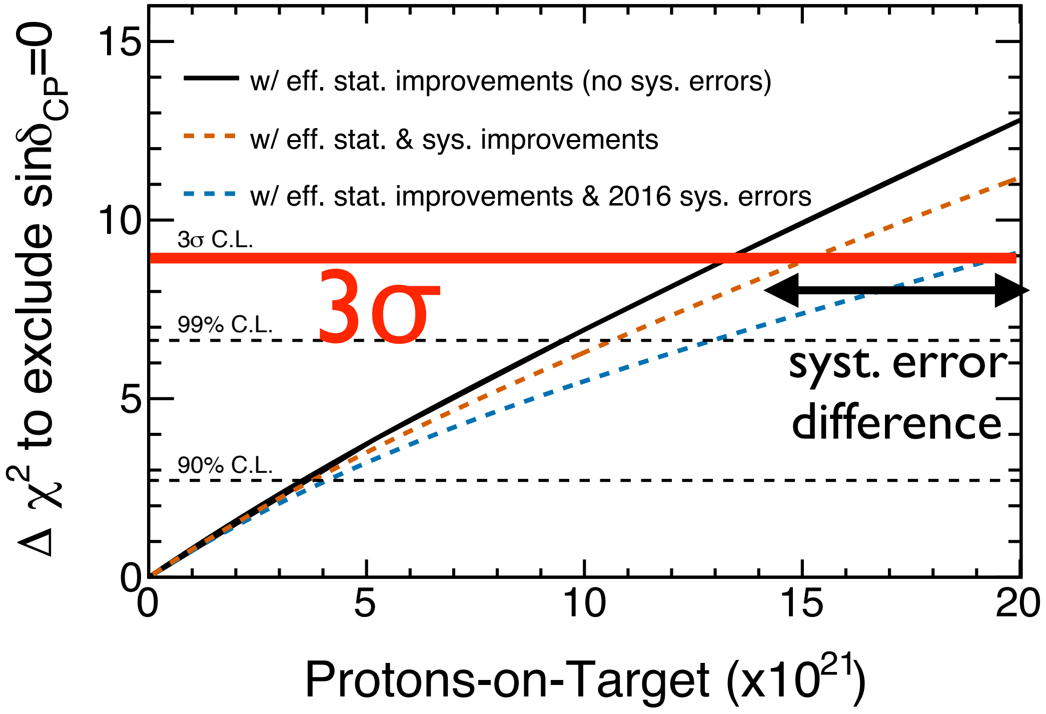
Need for precision

- In the standard framework, expected difference between ν and anti-ν is ~±25% at maximum
- A few % uncertainty is necessary for measurement
  - Large statistics and control of systematics are crucial
    - Statistics → beam power increase, additional samples
    - Systematics → *neutrino interaction*, hadron interaction

Systematic uncertainty of ν_e events at SK (goal at proposal: <10%)

9.9%(2012) →8.8%(2013) → 6.8%(2014) → 5.4%(2016)

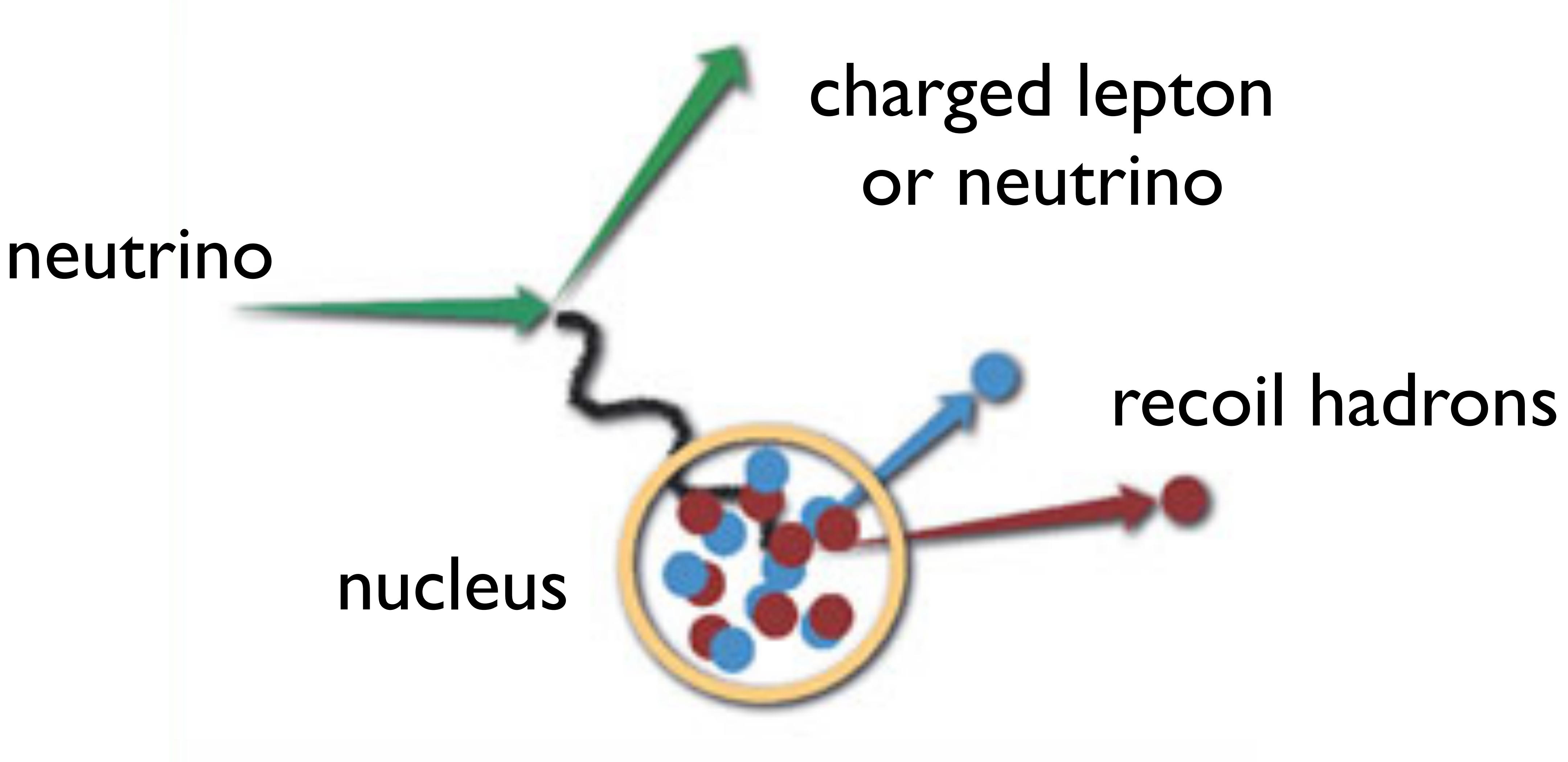
Goal for T2K-II systematics: ~4% in total



3σ

syst. error difference

Neutrino interaction

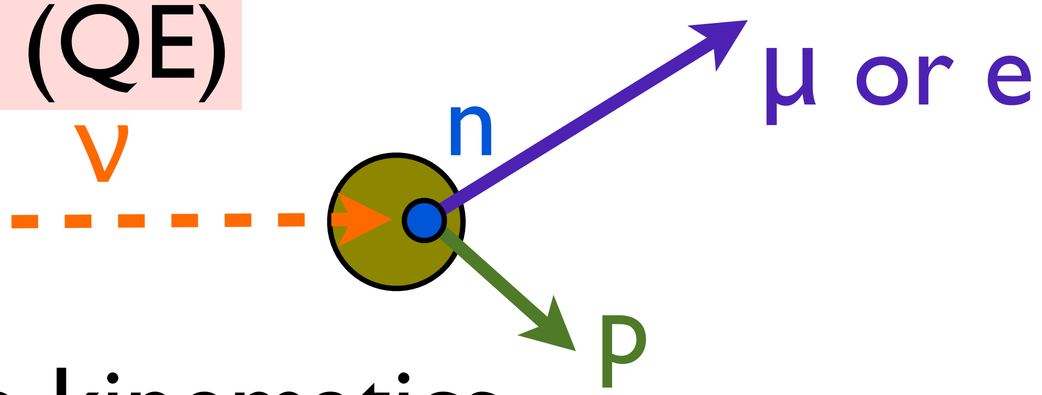


- Properties of neutrinos are derived from measurement of final state particles in interaction with nucleus
- Complicated because of nucleus structure and hadronic interactions
  → source of one of major systematic uncertainties

Neutrino interaction in T2K

Charged current (CC) quasi-elastic (QE)

$\nu + n \rightarrow \mu/e + p$



- Largest cross section in ~<1GeV
- Energy reconstruction with lepton kinematics
  - E_ν reconstructed assuming CCQE in T2K

CC single pion production

$\nu + p(n) \rightarrow \mu/e + n(p) + \pi^\pm$

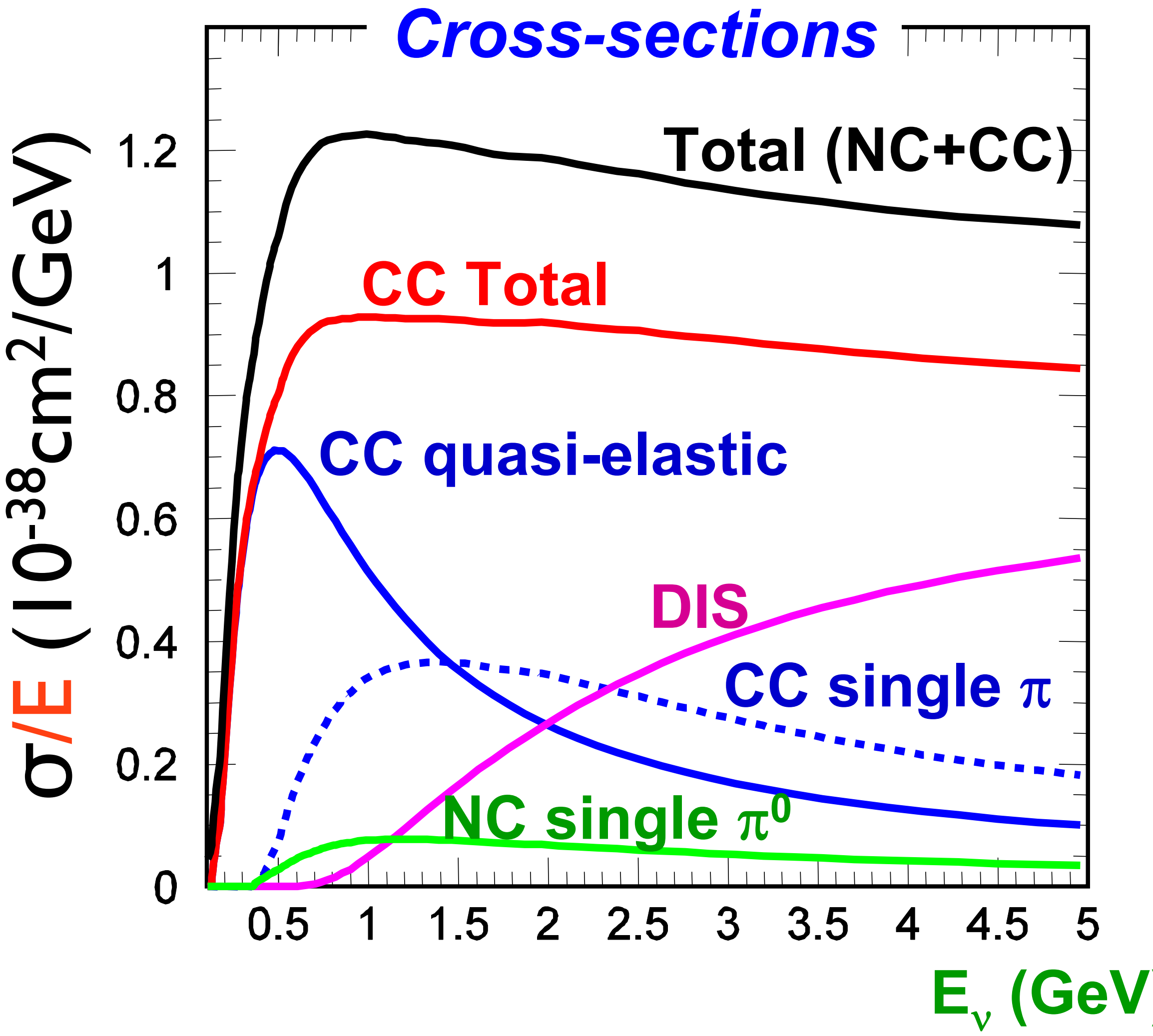
NC single pion production

- π^+: BG in ν_μ disappearance
- π^0: BG in ν_e appearance

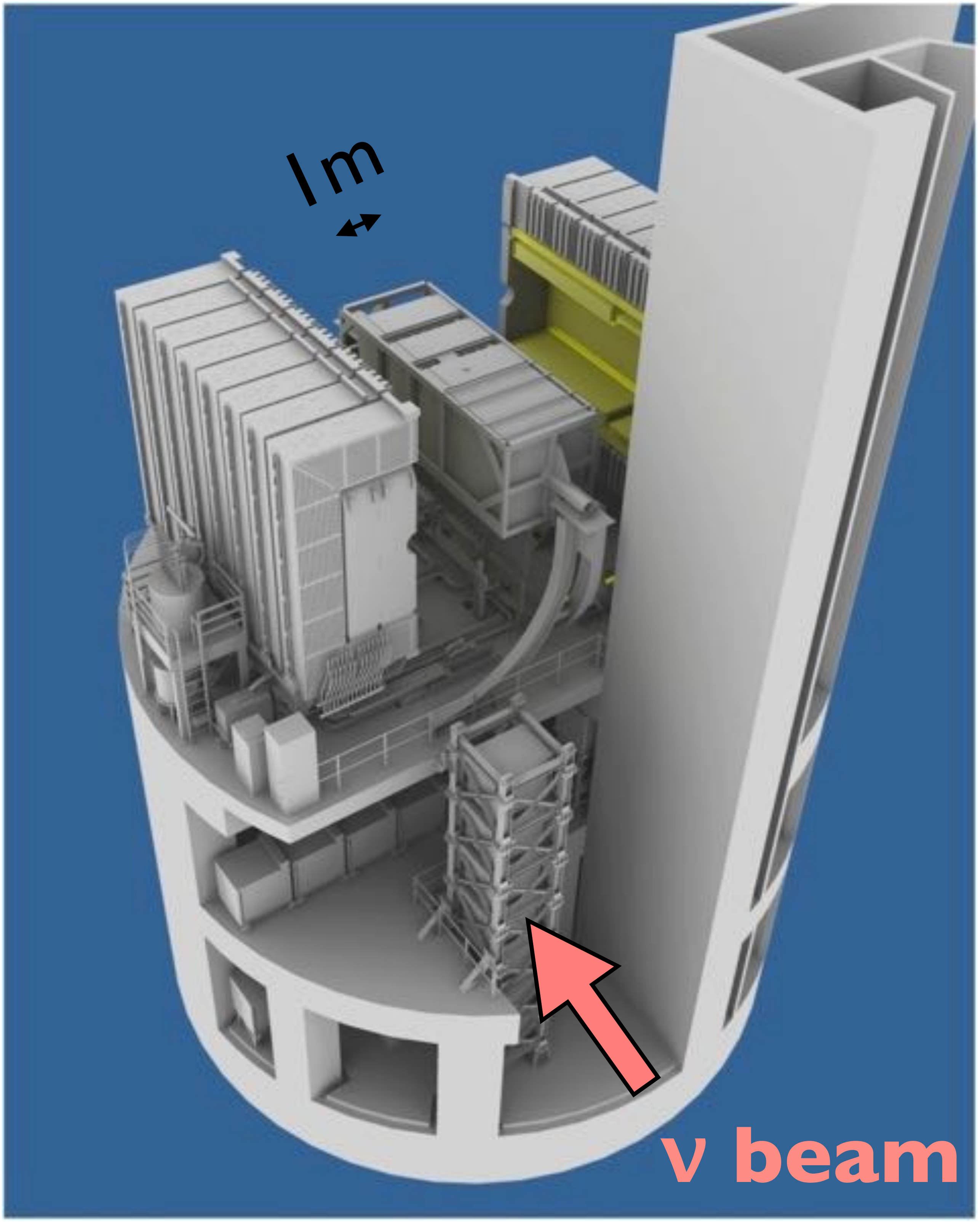
Multi-pion production

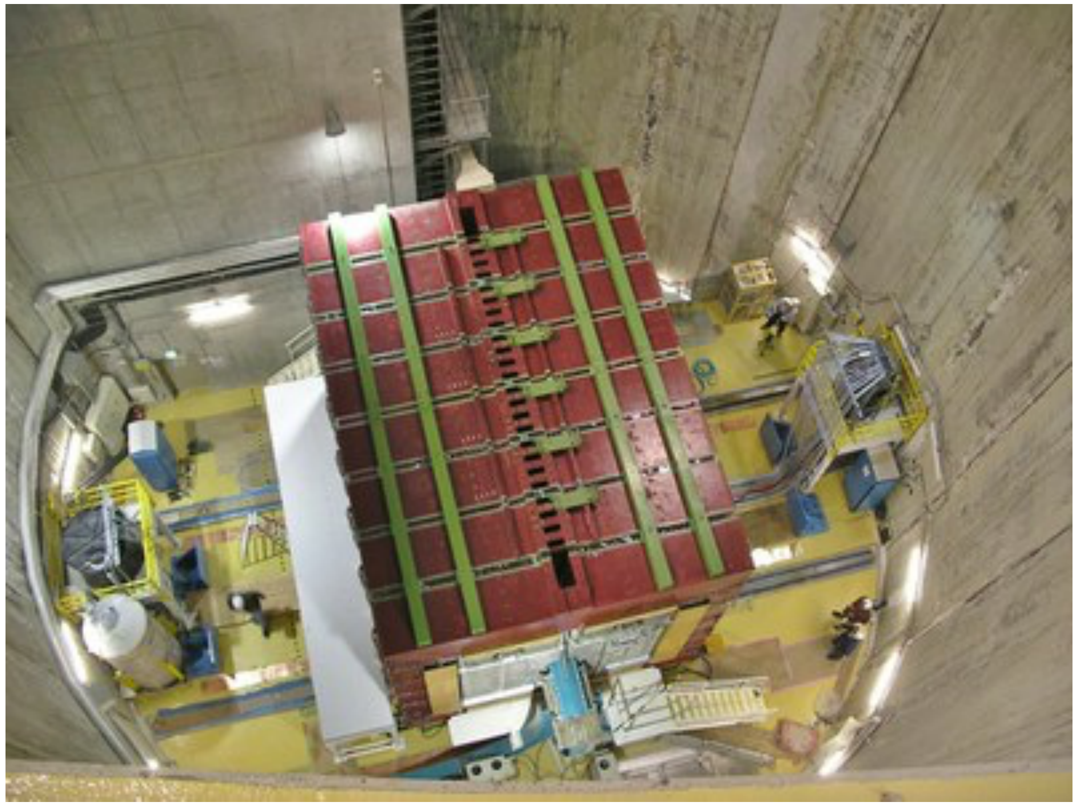
++ Nuclear effects

NEUT MC simulator



“Near” detectors

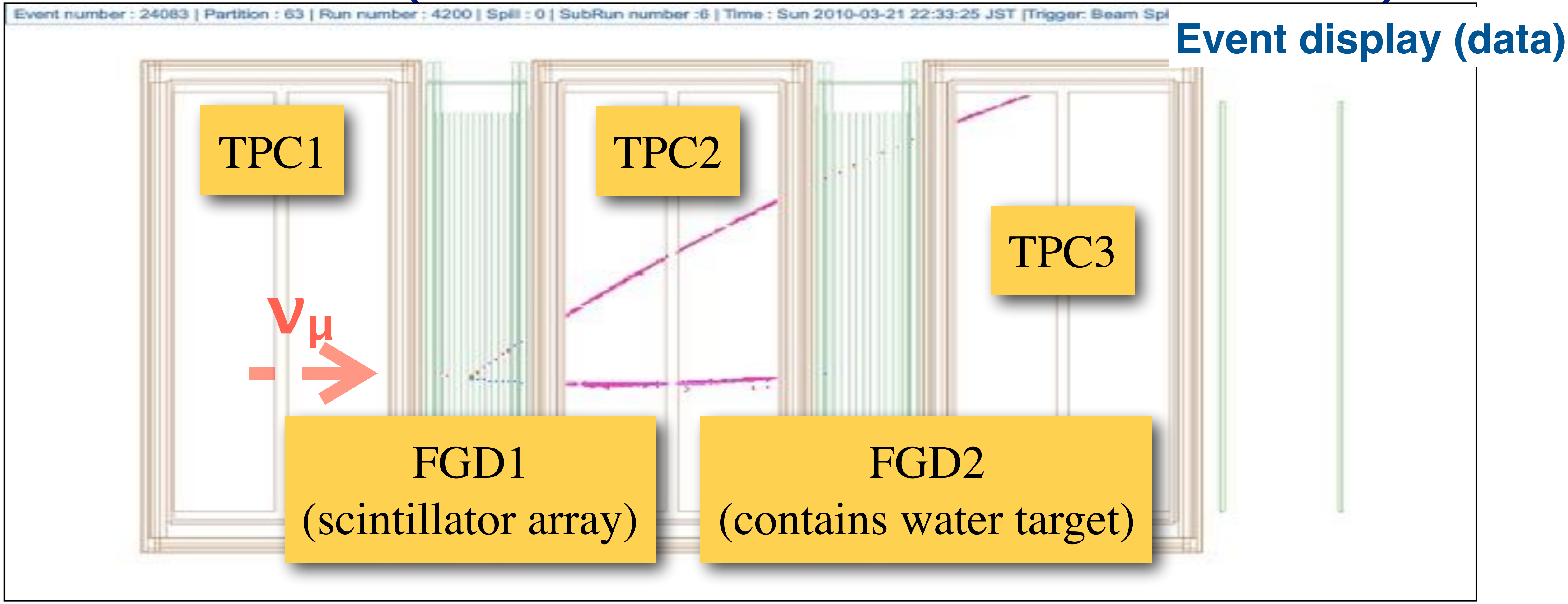




- “Smaller” detectors at J-PARC (~280m downstream) to characterize neutrinos just after production (before neutrino oscillation)
- Reduce systematic errors

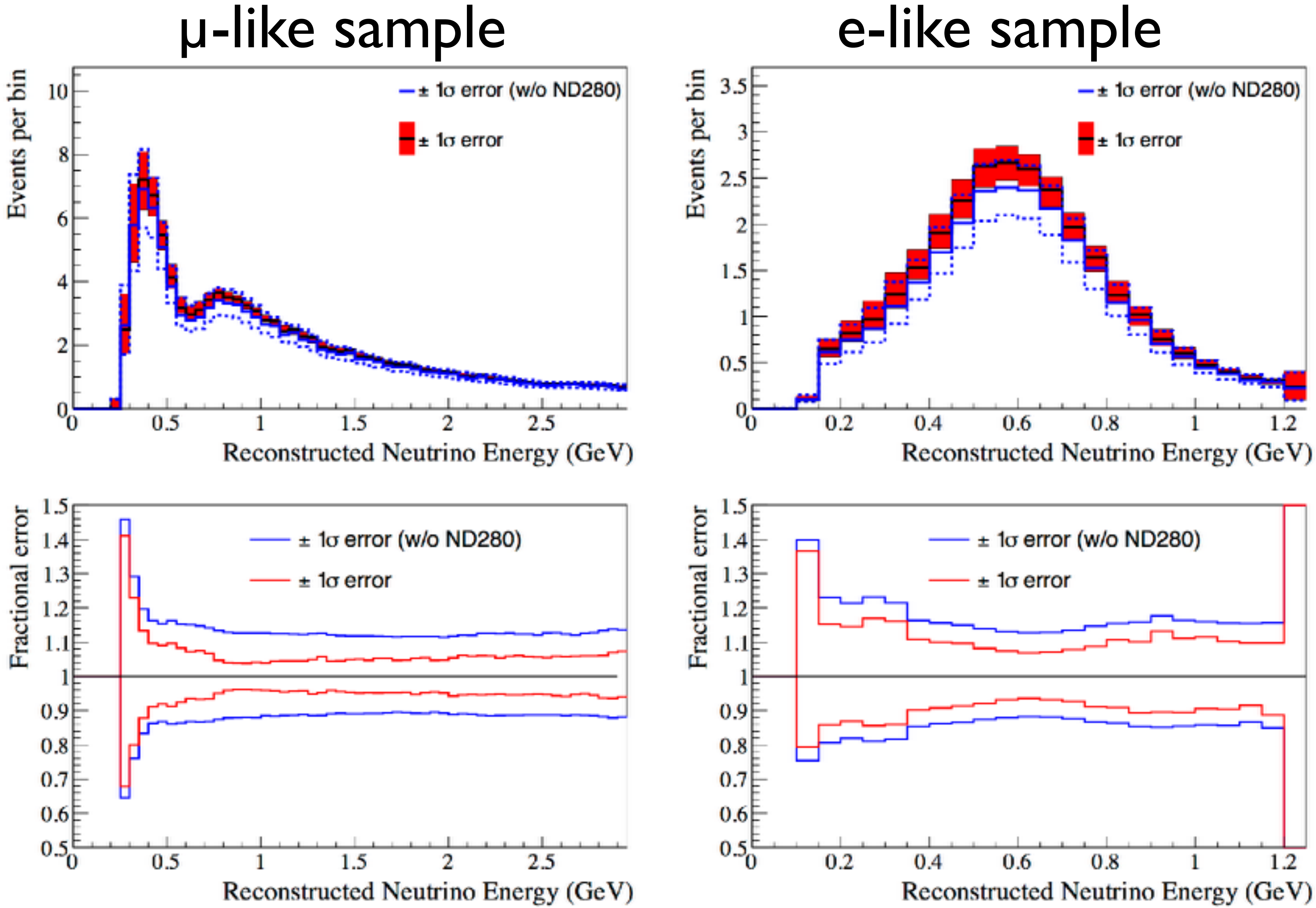

NGD-01-08-50

ND280 (Near Detector at 280m)



- Excellent performance as designed
  - Fine Grained Detector (FGD) with carbon and oxygen (water) targets
  - TPC for charge, momentum, and PID
  - Calorimeter coverage
  - Inside UA1 magnet (B=0.2T)
- Weak for high angle and backward tracks
  - When designed, emphasis was on background and forward-going tracks
  - With the large value of θ_{13}, signal becomes more important

Systematic uncertainty for E_ν^{rec} @ SK



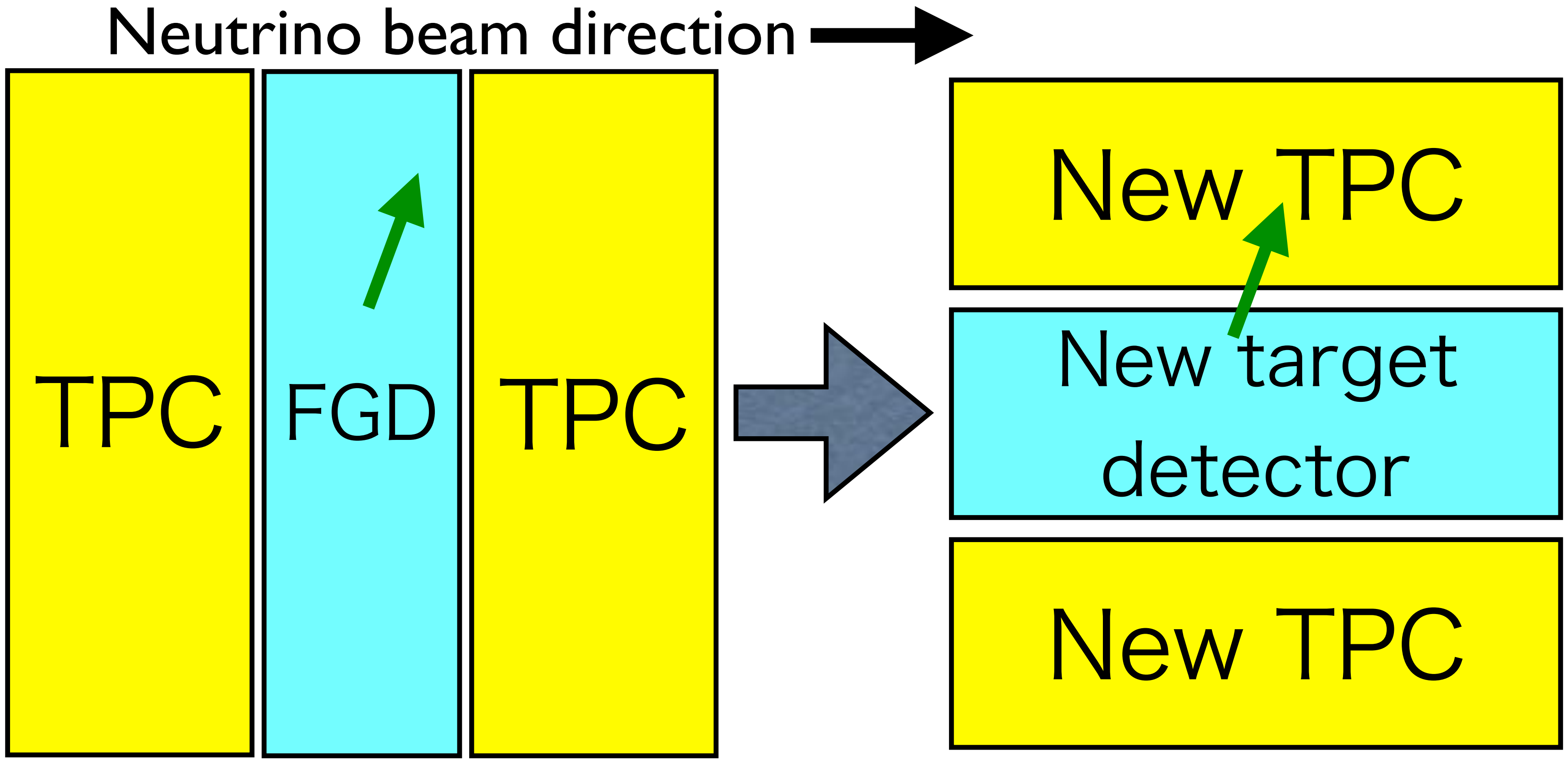
μ-like sample

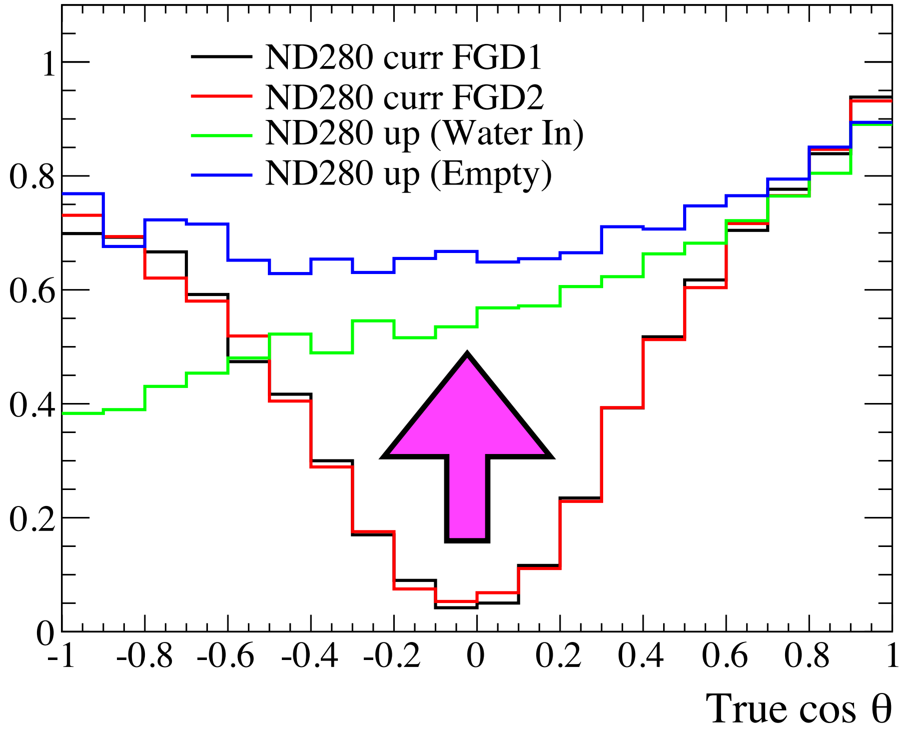
e-like sample

Systematics controlled by near detector data

ND280 upgrade for T2K-II

- Plan to upgrade ND280 in order to reduce systematics
  - Extend angular acceptance with new target detectors and new TPCs
  - Configuration under optimization



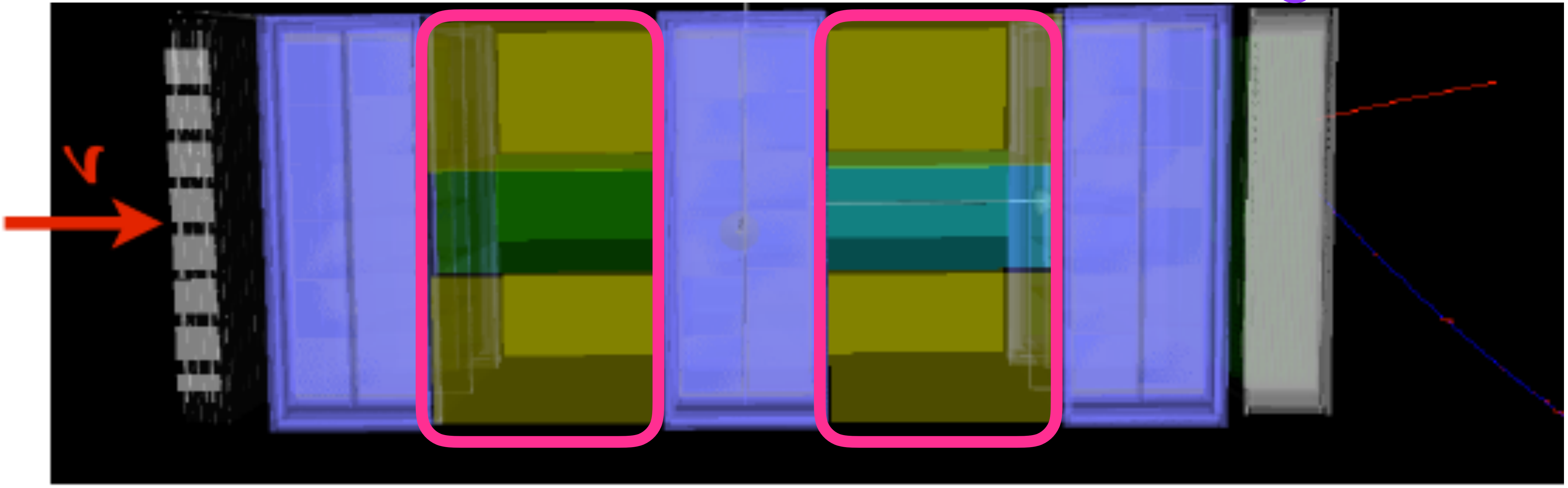


Possible configurations

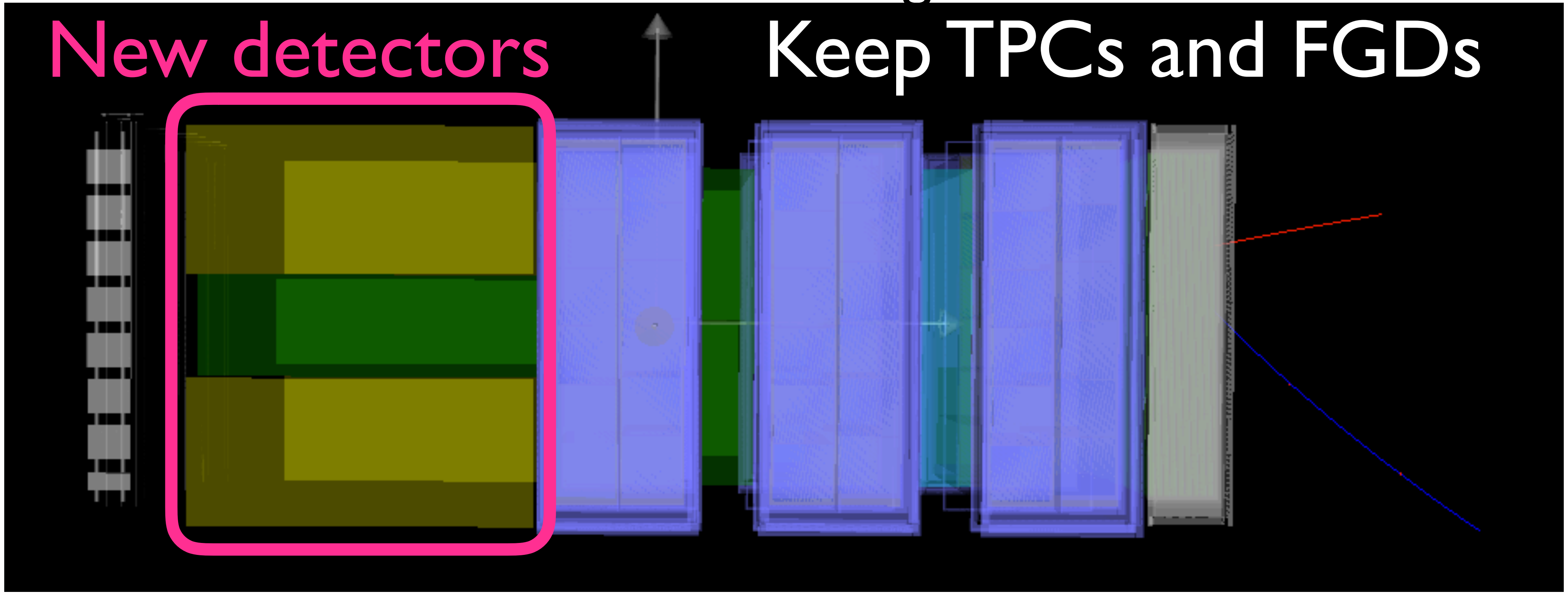
One of *reference* configurations under study

New detectors

Relocate existing TPCs



One of *alternative* configurations



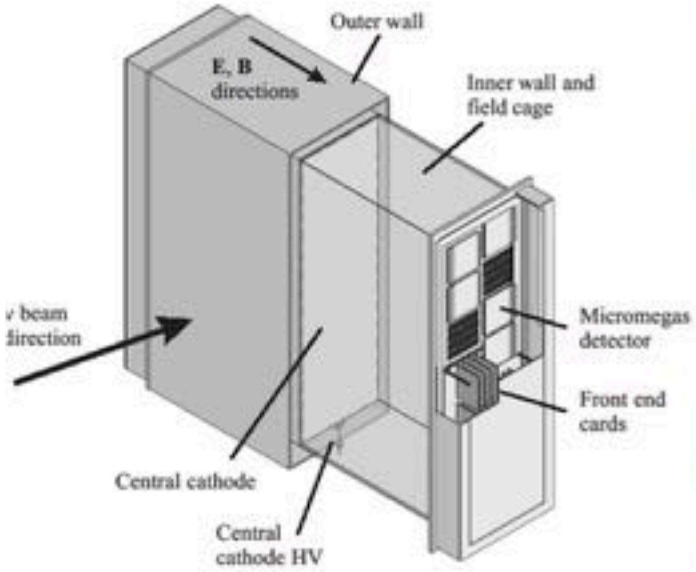
New detectors

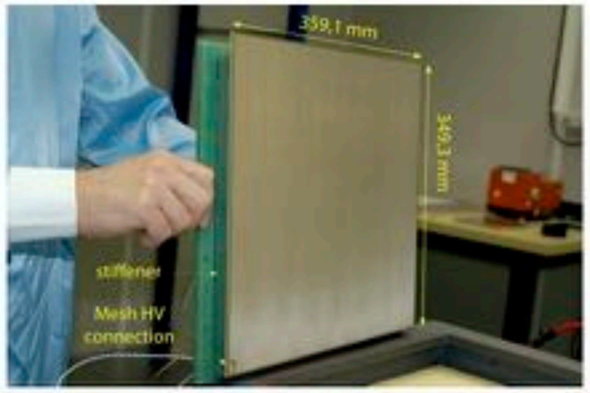
Keep TPCs and FGDs

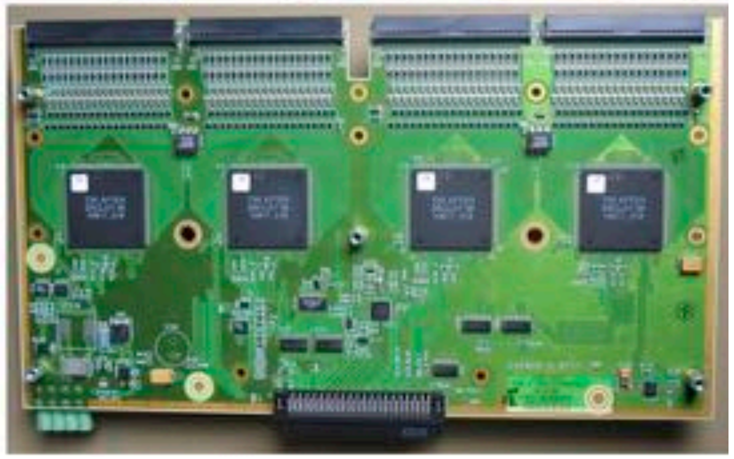
Design study intensively ongoing

TPCs

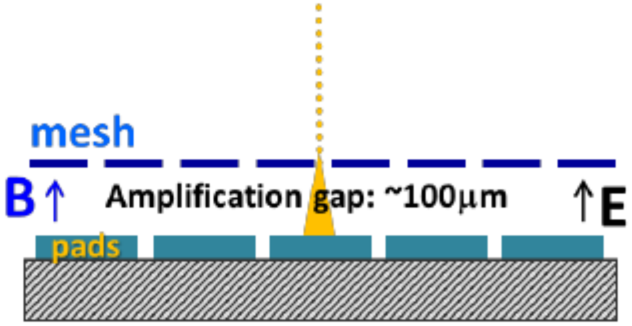
- Requirements similar to existing T2K TPCs

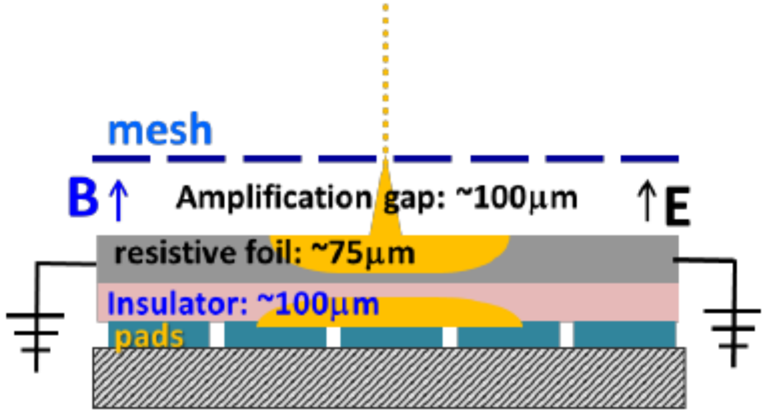






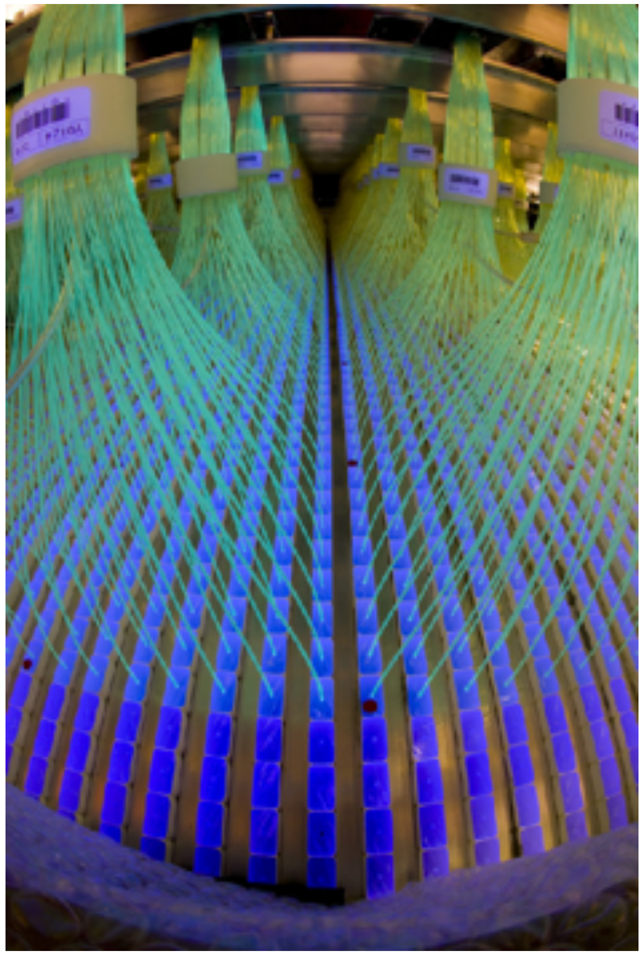
Several possibilities of improvement:
resistive bulk micromegas, thinner field cage, .. to be studied

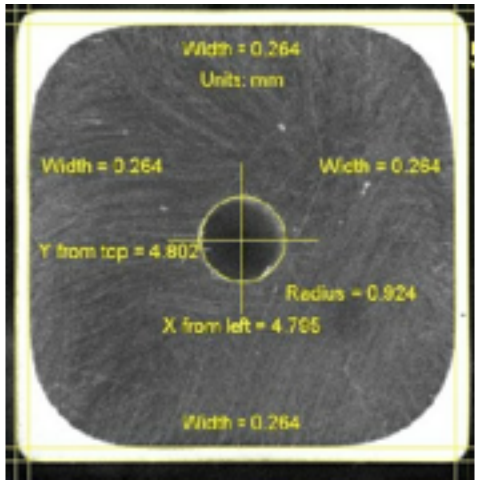


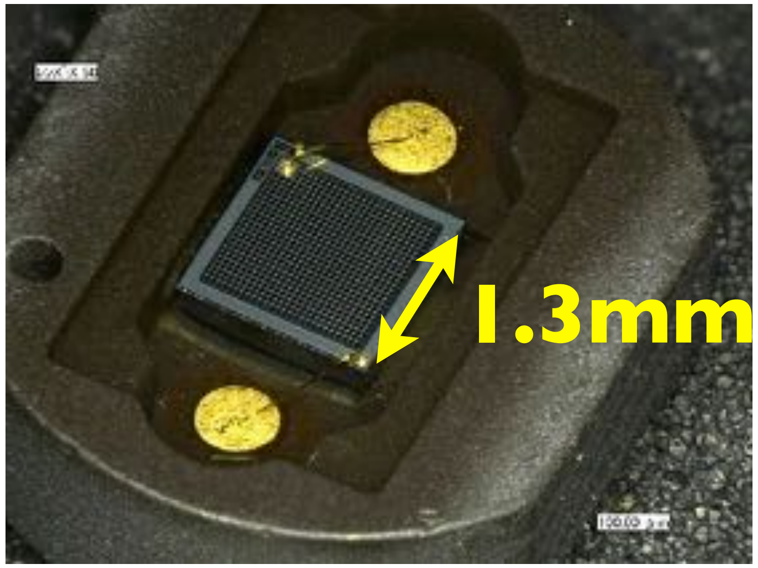


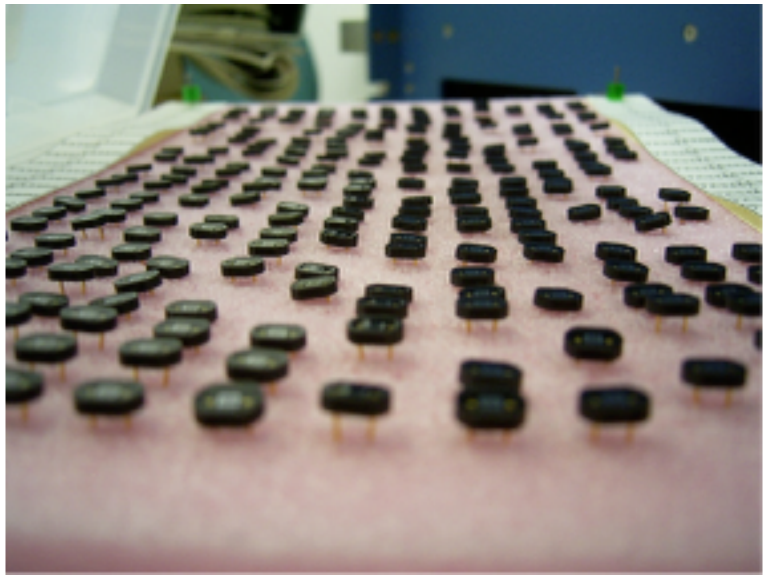
Target detector

- Baseline technology: plastic scintillator + wavelength shifting fiber + MPPC (SiPM)
  - Well established in T2K near detectors
  - New version of MPPCs with better performance, other improvement also to be studied





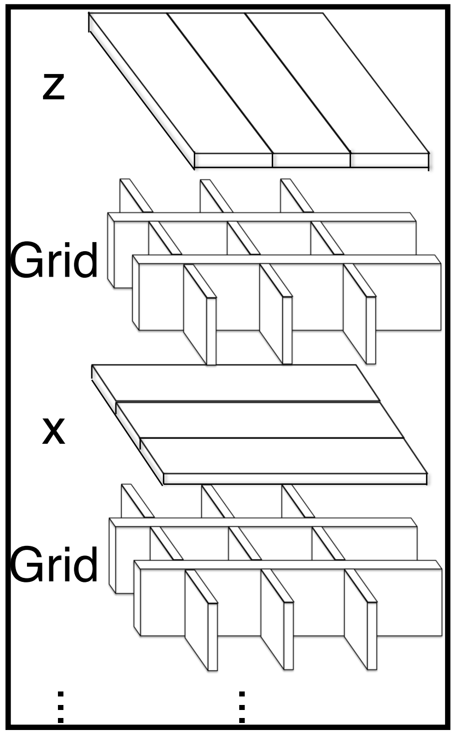




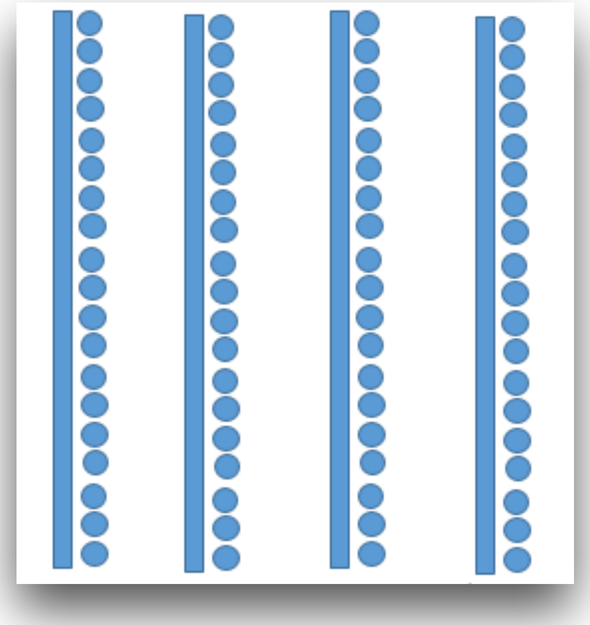
Target detector

- Provide target mass for neutrino interaction
  - Especially important for νe measurement
  - Water target necessary or not?
- Acceptance for large angle tracks
- Reconstruct tracks inside detector
- Background reduction/control for νe measurement

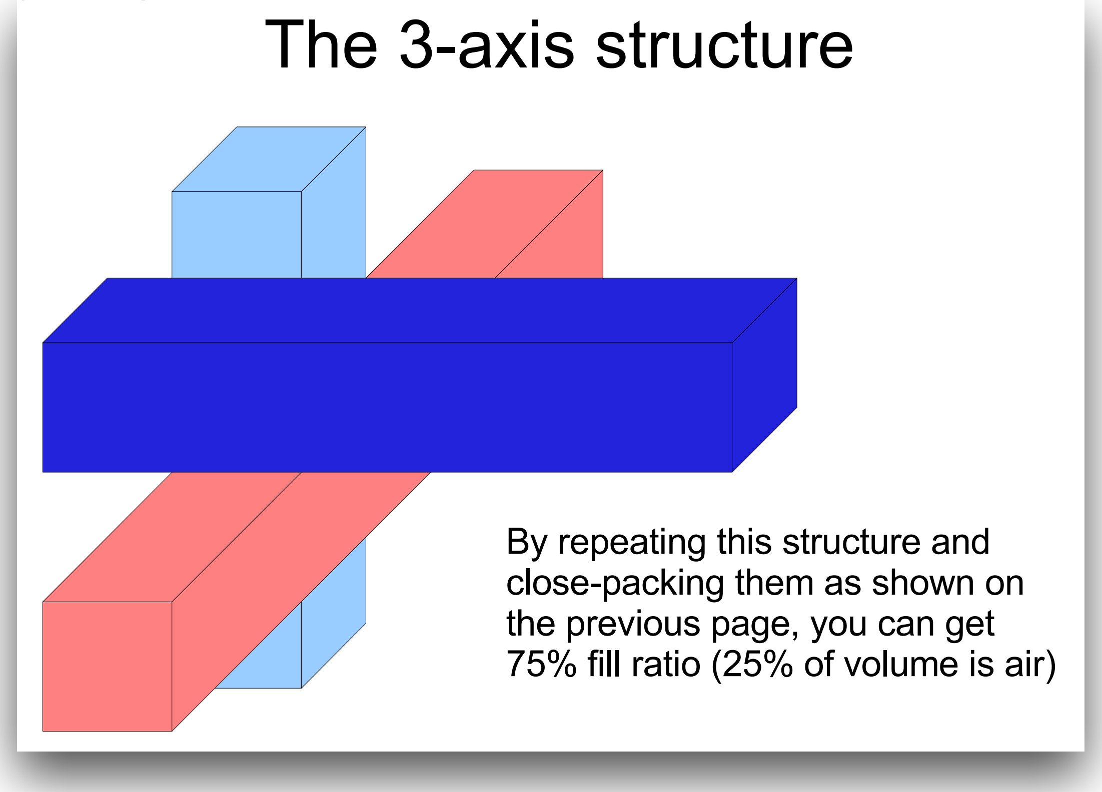
WAGASCI-like



scintillating fiber



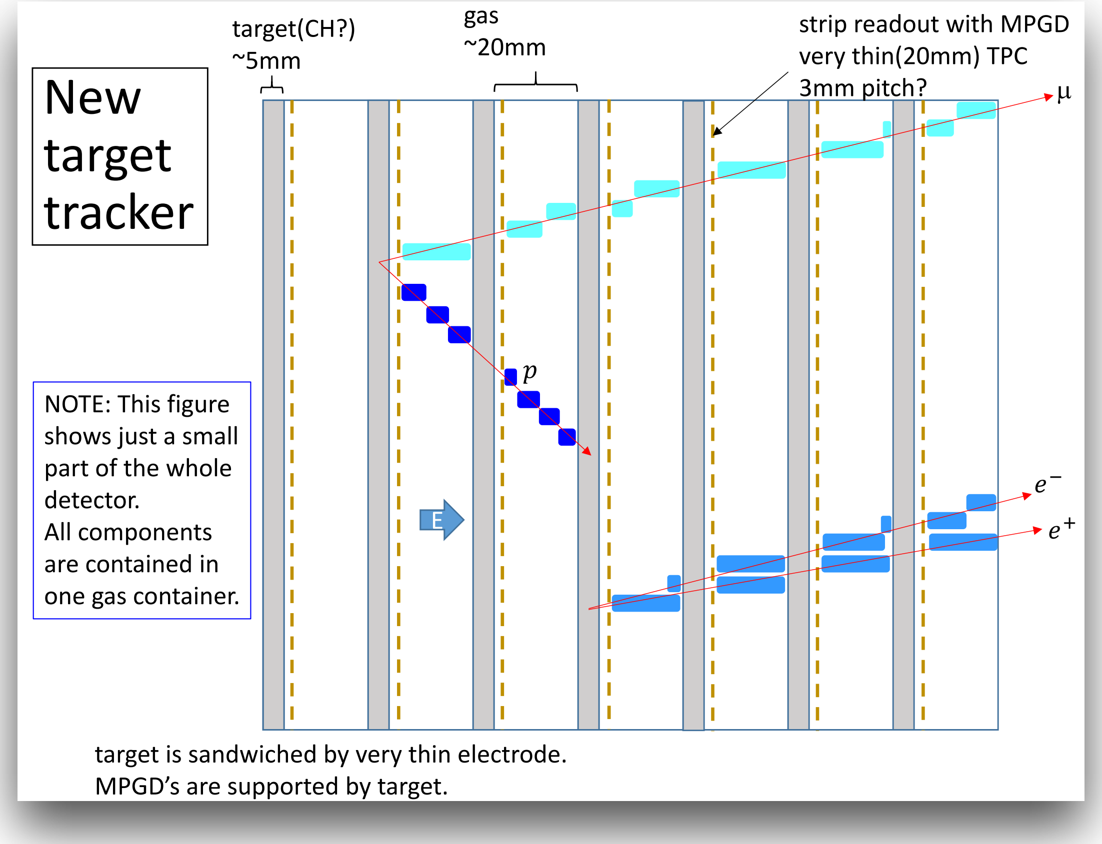
3D-FGD



The 3-axis structure

By repeating this structure and close-packing them as shown on the previous page, you can get 75% fill ratio (25% of volume is air)

gas-based tracker



NOTE: This figure shows just a small part of the whole detector.
All components are contained in one gas container.

target is sandwiched by very thin electrode.
MPGD's are supported by target.

Still several concepts: selection in ~half year

Forming the project

- T2K officially launched ND upgrade project after a few years of internal discussion
- Aim to become also project at CERN Neutrino Platform, submitted Expression of Interest
- Having workshops (open to non-T2K people)
  - 1st/2nd meetings held at CERN
    https://indico.cern.ch/event/568177/ , https://indico.cern.ch/event/613107/
  - 3rd one at J-PARC, *next weekend* (May 20/21)
    https://indico.cern.ch/event/633840/
- In the process of defining Work Packages, design & responsibilities

ND280 upgrade timeline

- 2017: optimization studies, define configuration finalize responsibilities, write proposals
- 2018: Prototype and test, fix detector parameters (granularity etc.)
- 2019-20: Production, integration, system test
- 2021 summer: installation and commissioning

Still in an early stage of project —
new partners are very welcome!

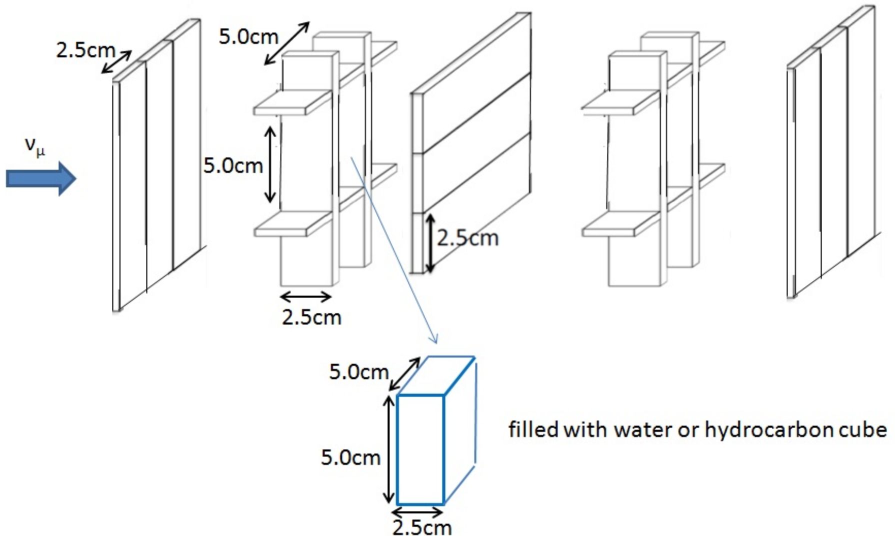
Other R&D activities in J-PARC

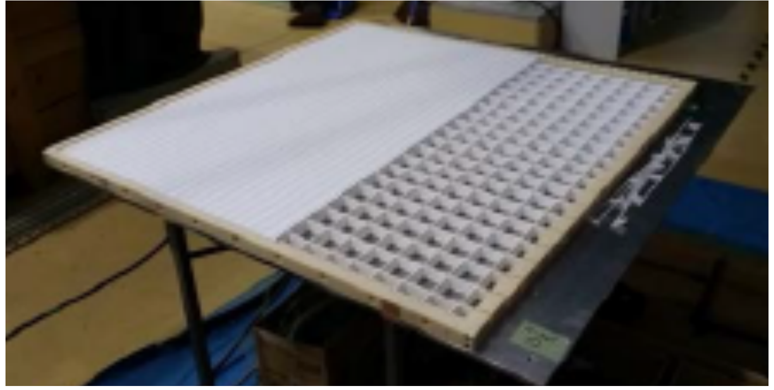
- Many test projects and R&D in J-PARC

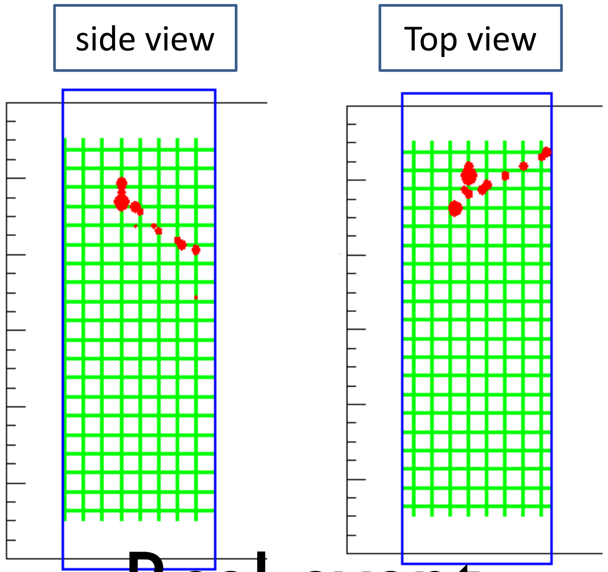
3D grid structure of scintillator for large angle tracking (WAter Grid And SCIntillator, "WAGASCI")

Graduate students leading the project!

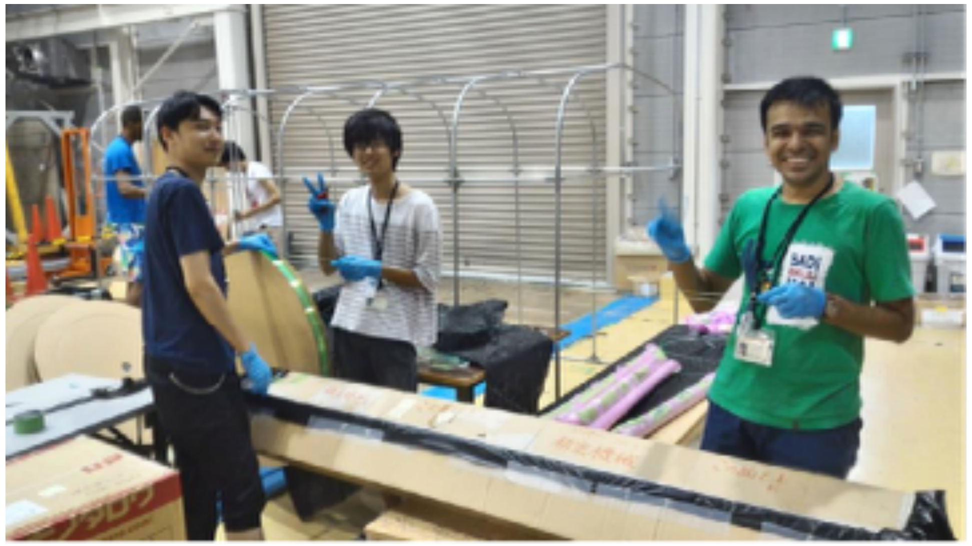
- First test module installed last summer
- More module under construction







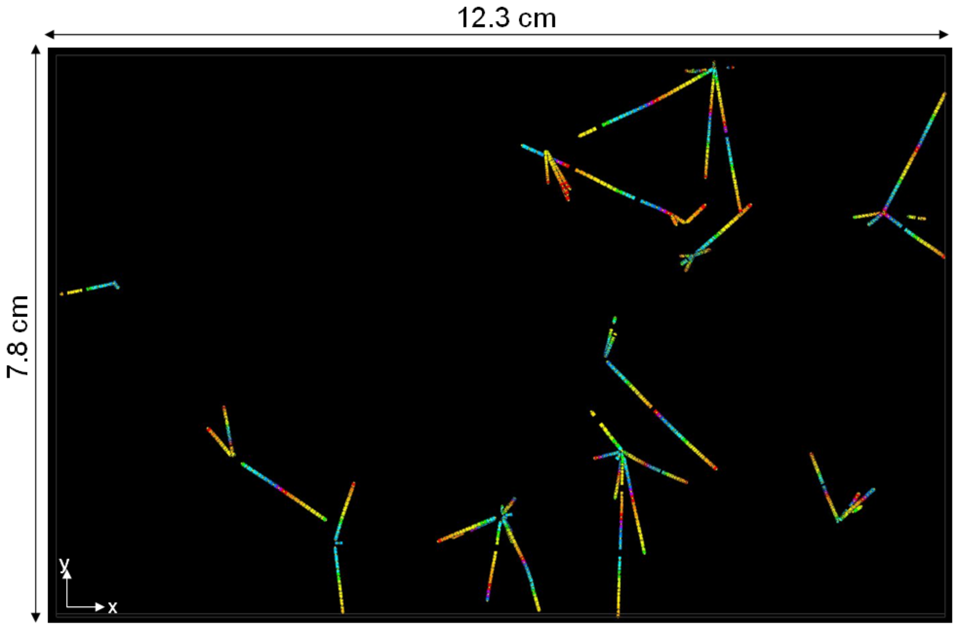
Real event



Jay Vora from IITB worked for construction

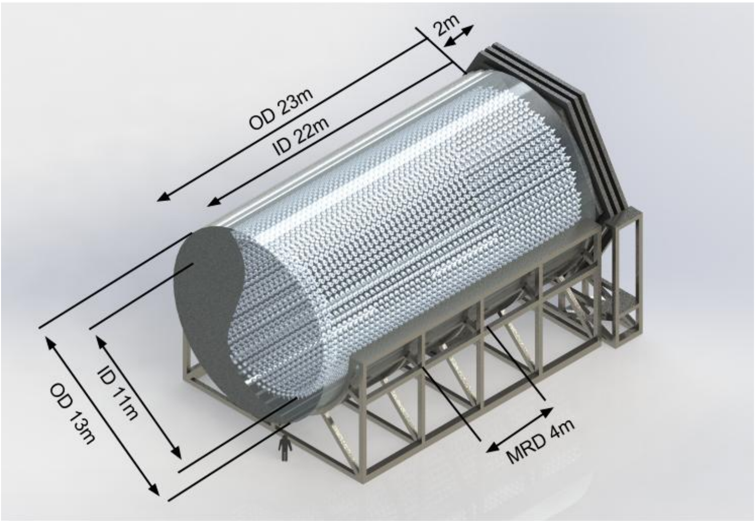
Nuclear emulsion technique (Neutrino Interaction research with Nuclear emulsion and J-parc Accelerator, “NINJA”)

- Excellent (<μm) spatial resolution for ν interaction study
- Data with small module being analyzed
- Staged approach to larger experiment



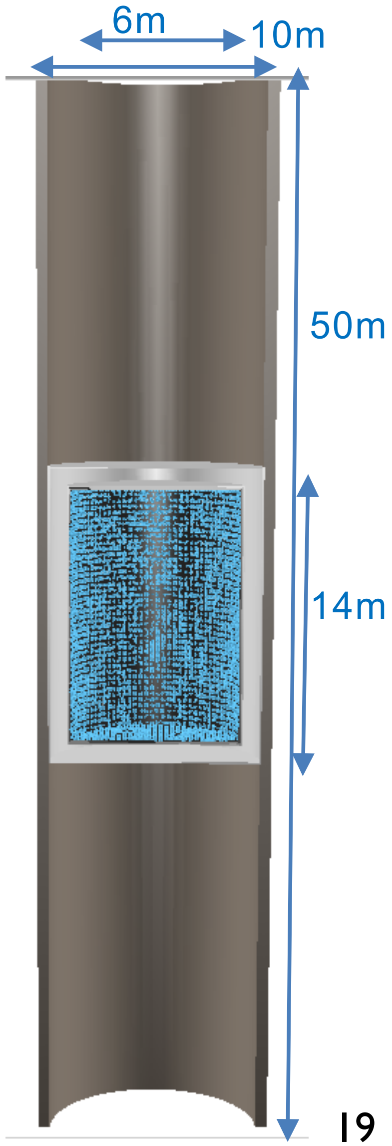
Water Cherenkov Detectors

- Utilize different off-axis angles to sample different energy spectrum (“NuPRISM”)
    - At 1-2km from target
- Also considered as a near detector for Hyper-K, merged with another proposal with Gd loading (“TITUS”)



TITUS

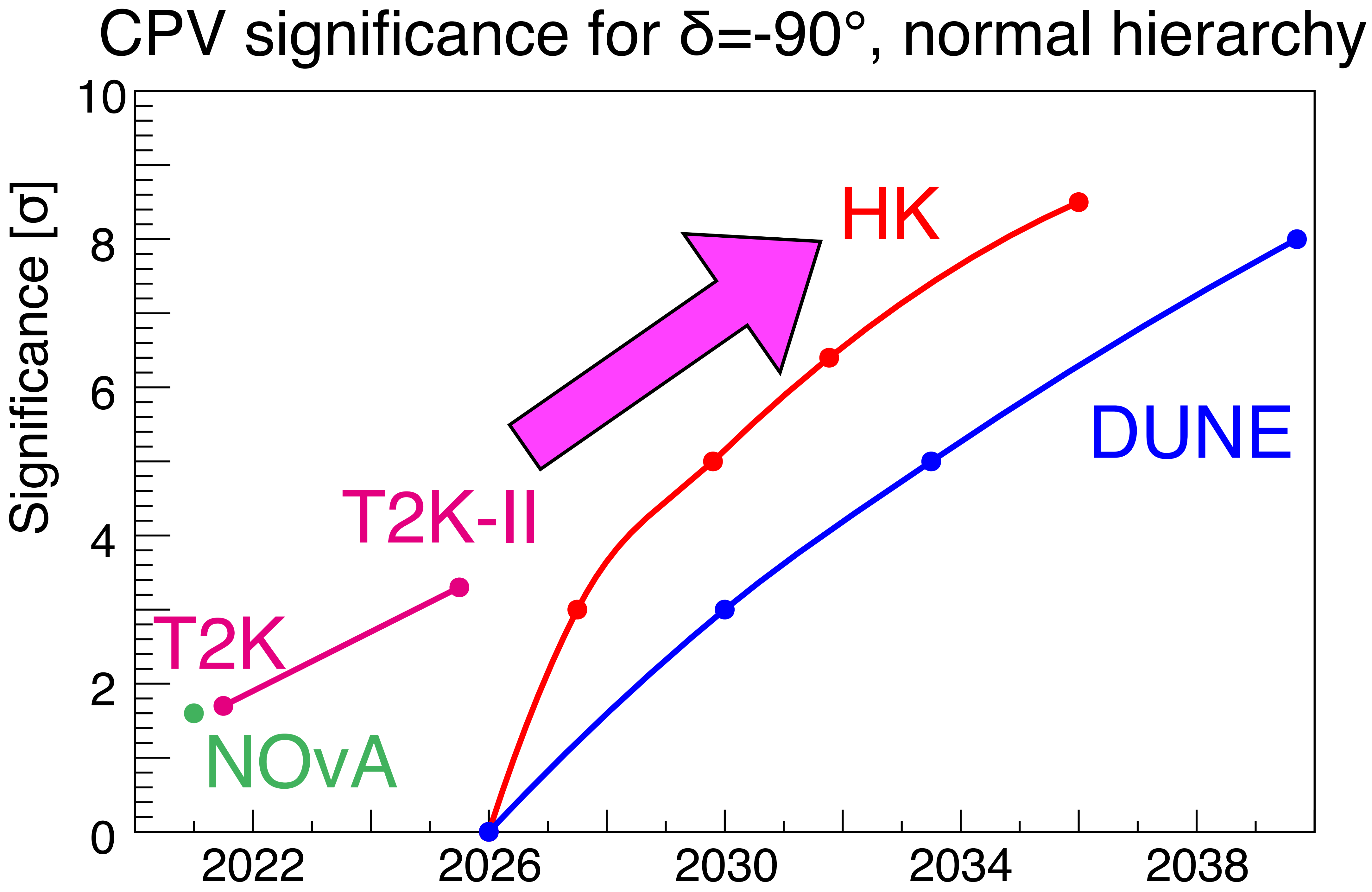
arXiv:1606.08114 [physics.ins-det]



NuPRISM

arXiv:1412.3086 [physics.ins-det]

Opportunities for discovering CPV in lepton sector



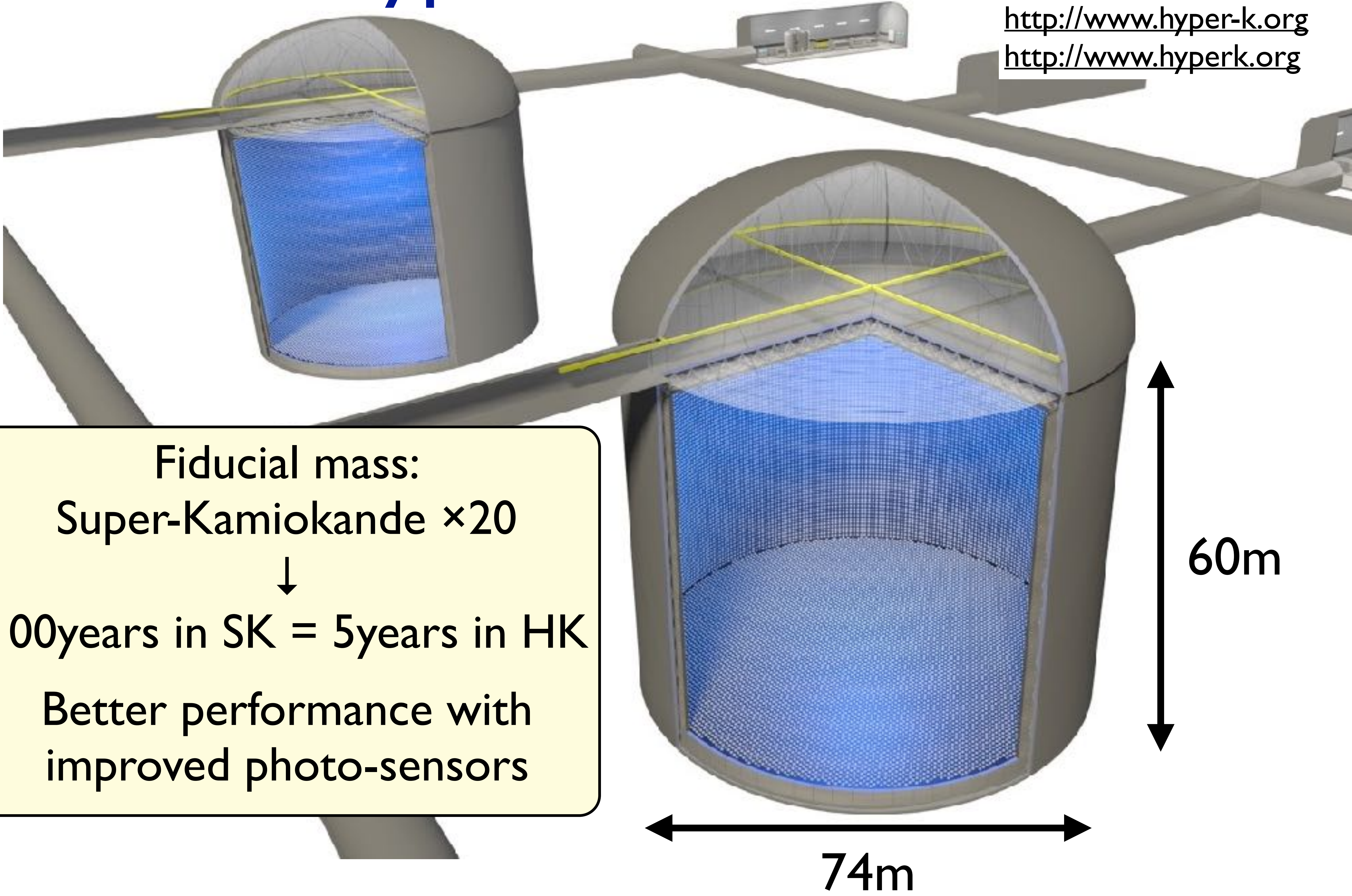
Seamless program of Japan-based experiments

~3σ indication with T2K→T2K-II,

>5σ discovery and measurement with HK

Hyper-Kamiokande

http://www.hyper-k.org
http://www.hyperk.org



Fiducial mass:
Super-Kamiokande ×20
↓
100years in SK = 5years in HK

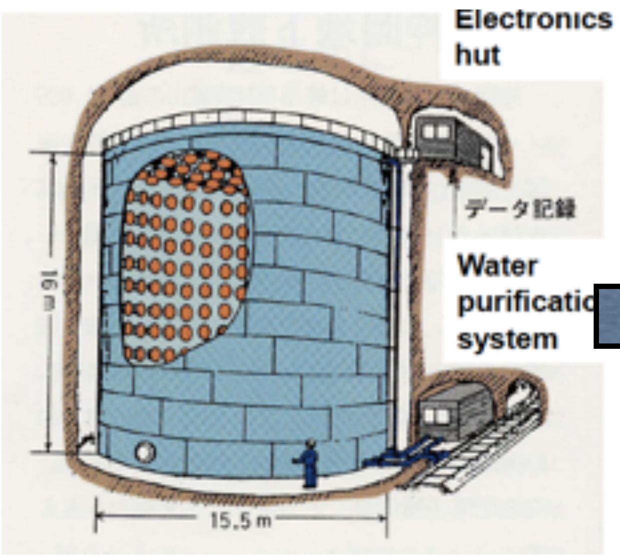
Better performance with
improved photo-sensors

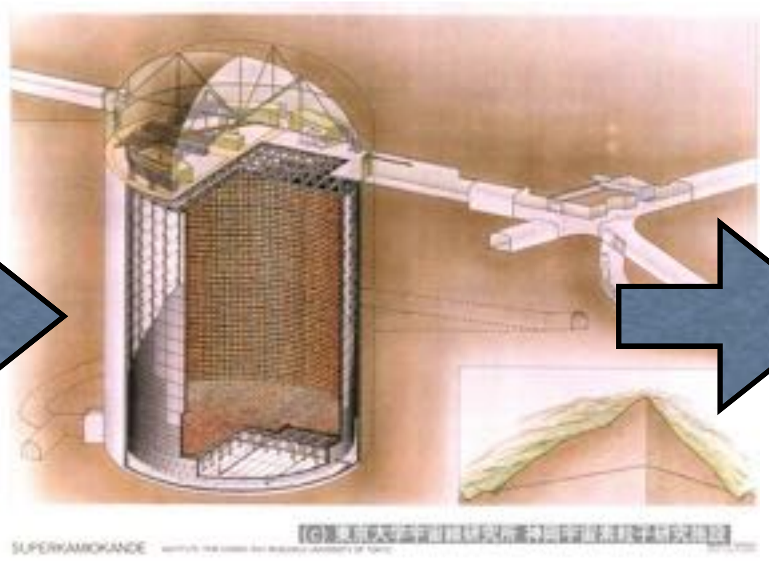
Three generations of K

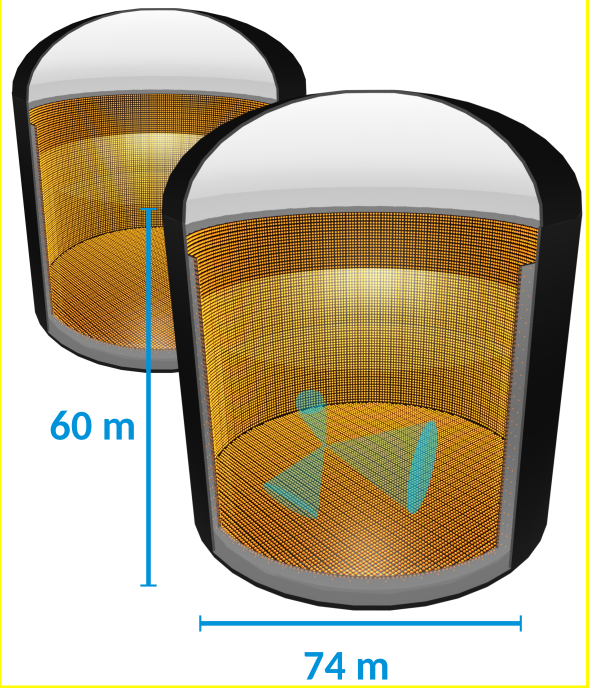
Kamiokande
(1983-1996)

Super-Kamiokande
(1996-)

Hyper-Kamiokande
(202x-)

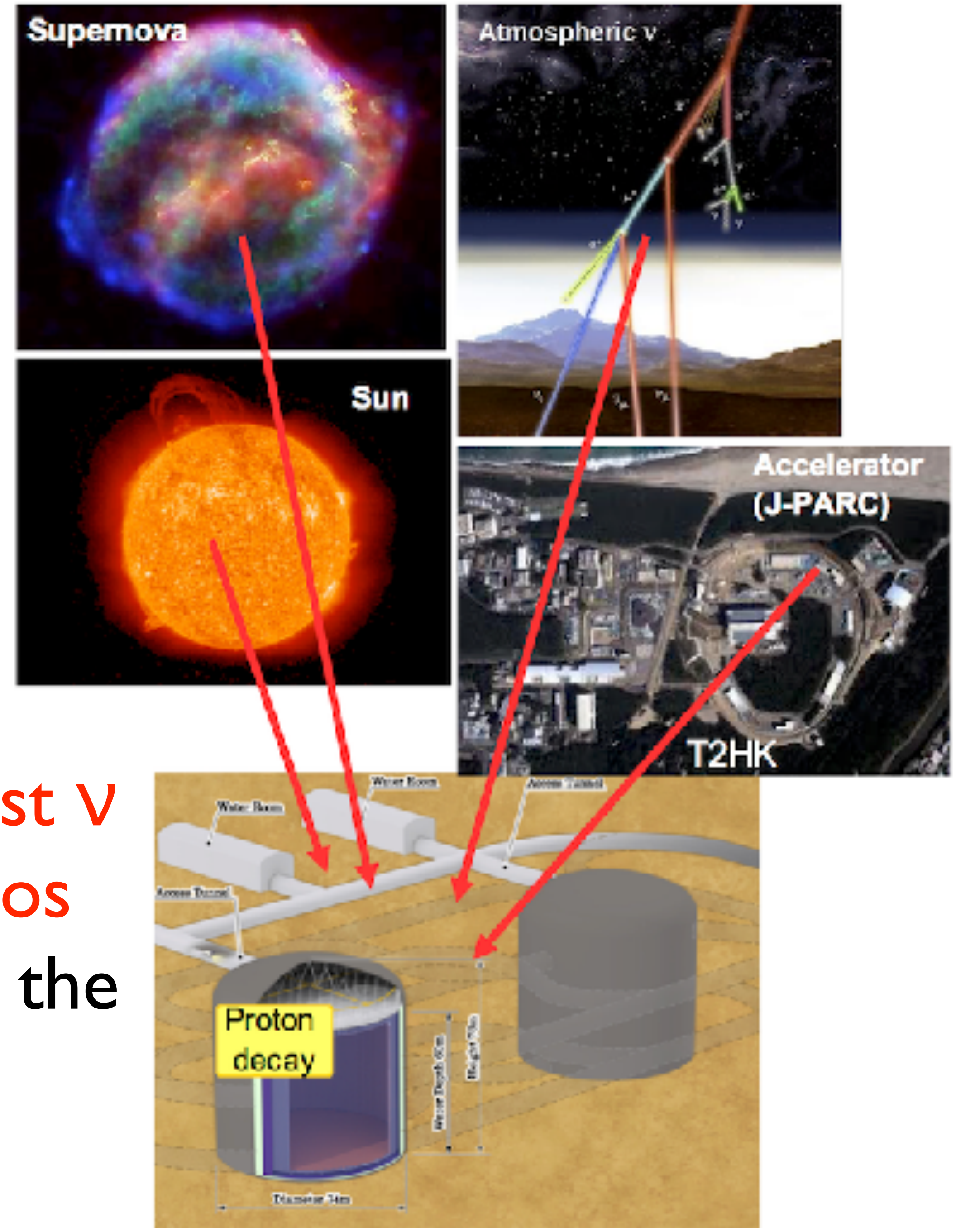




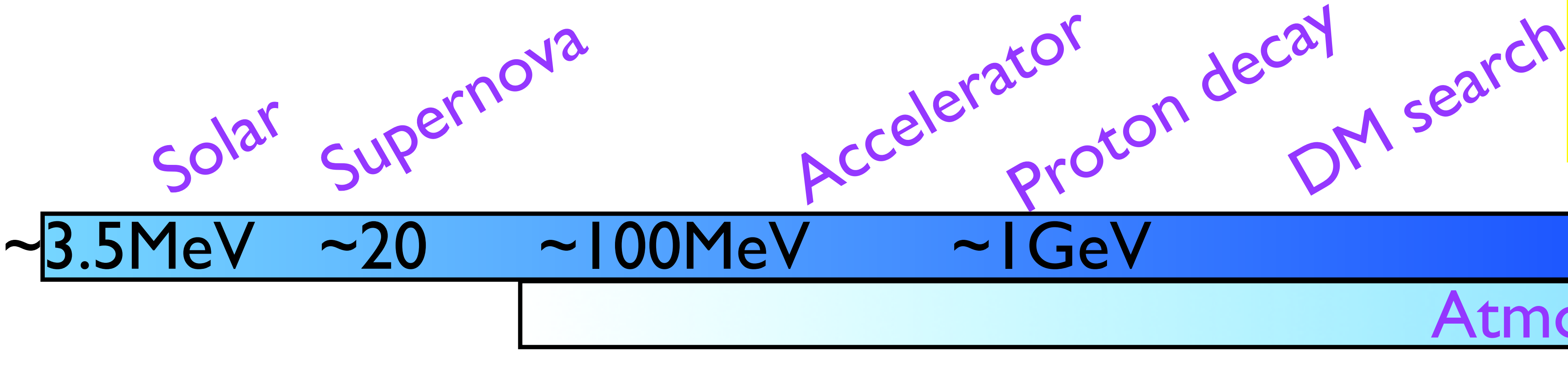


Broad science program with Hyper-K

- Neutrino oscillation physics
  - Comprehensive study with beam and atmospheric neutrinos
- Search for nucleon decay
  - Possible discovery with ~×10 better sensitivity than Super-K
- Neutrino astrophysics
  - Precision measurements of solar ν
  - High statistics measurements of SN burst ν
  - Detection and study of relic SN neutrinos
- Geophysics (neutrinography of interior of the Earth)
- Maybe more (unexpected)



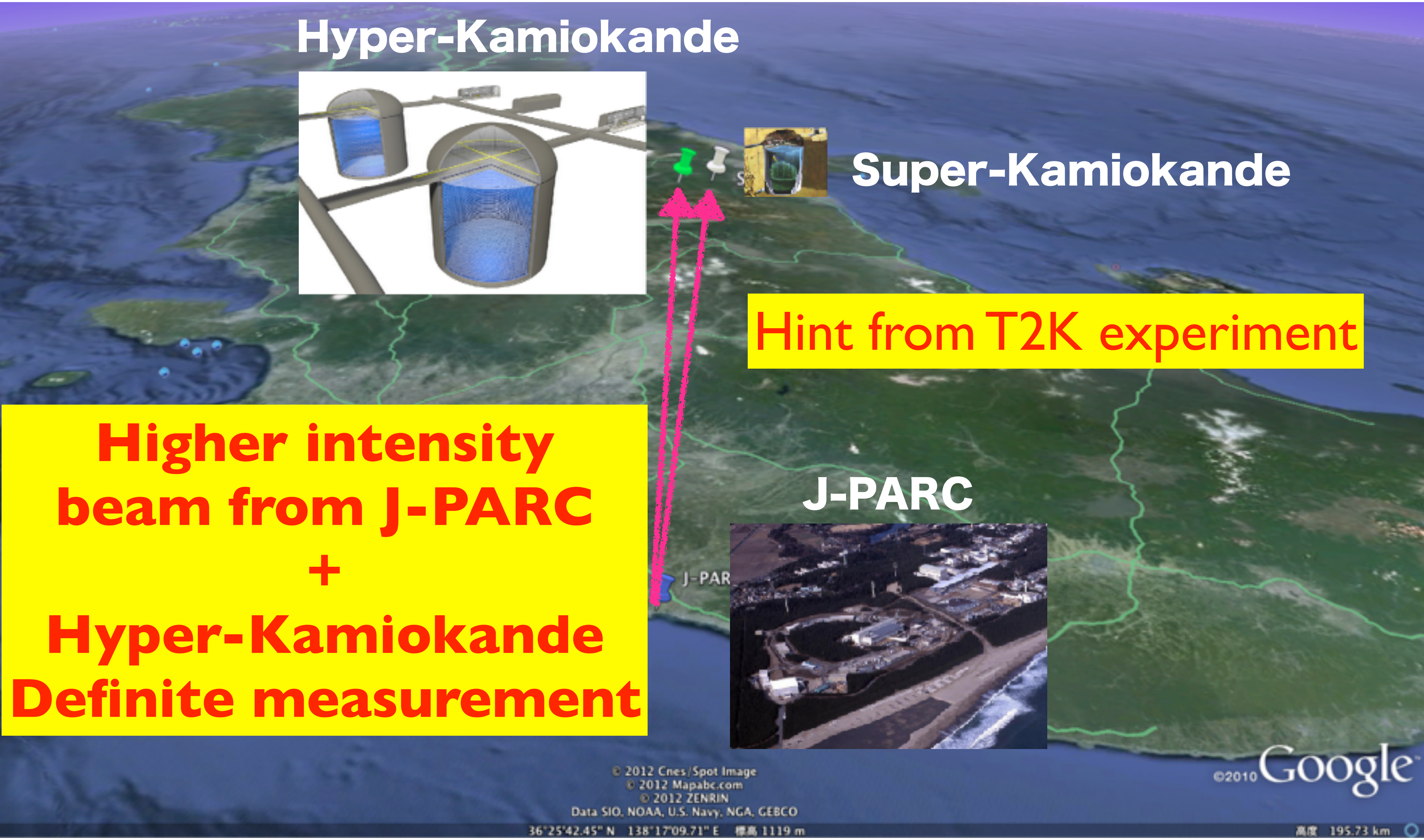
MeV to TeV with a single detector



Well proven, scalable technique

- Feasibility of ~Mton size detector confirmed with various studies over past decade
  - 20 years experience with Super-Kamiokande
- "Ready-for-construction" design developed

Long baseline experiment



Hyper-Kamiokande

Super-Kamiokande

Hint from T2K experiment

J-PARC

Higher intensity beam from J-PARC
+
Hyper-Kamiokande
Definite measurement

Closing in on the origin of matter in Universe

Strength of HK long-baseline program

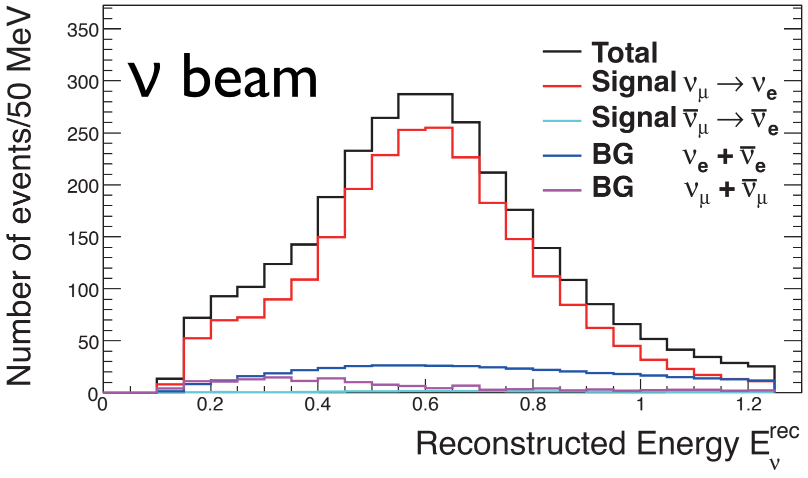
- Best sensitivity for CP measurement
  - Relatively short baseline (~300km): less matter effect
  - Off axis beam at 1st oscillation maximum
- Large statistics with good S/N
  - ~2000 appearance signal events expected
  - S/N~10 at appearance peak
- Performance proven with real data
  - Building on experience from T2K/Super-K
  - Further improvement expected with T2K/T2K-II

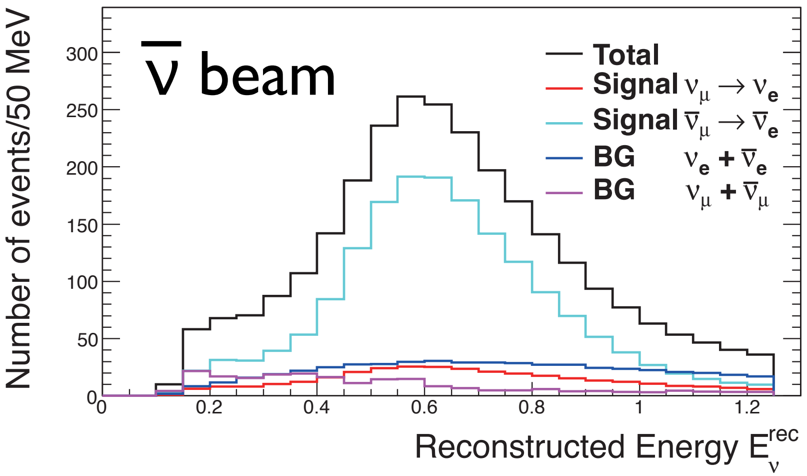
Expected events

1.3MW, 10×10^7sec, $\nu:\bar{\nu}=1.3$

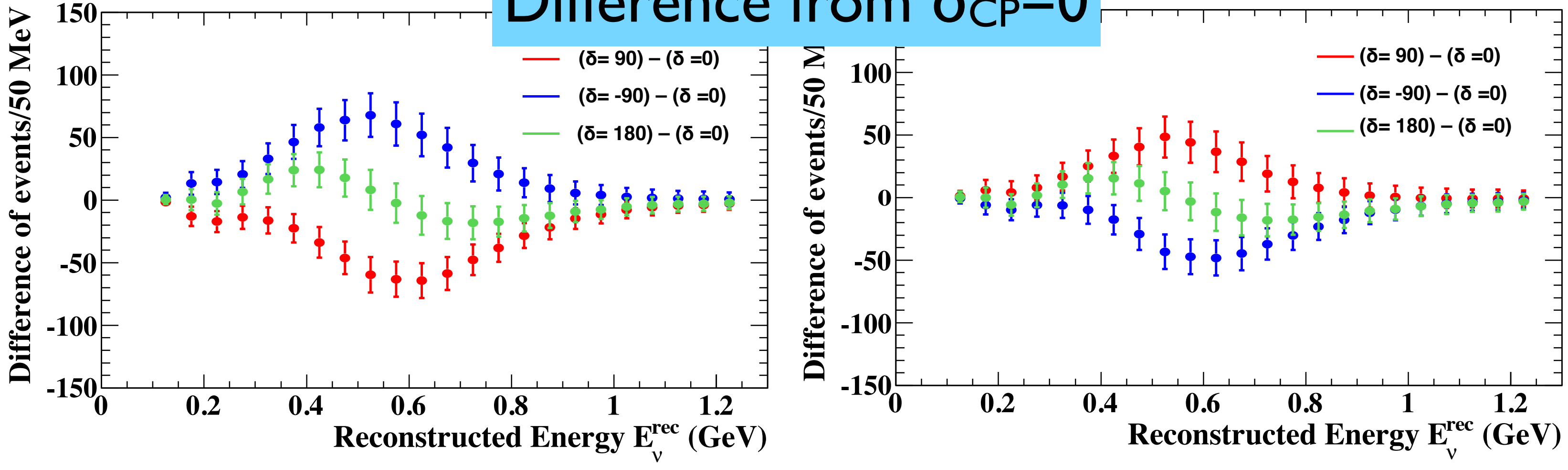
ν_e candidates

Using fiTQun for π^0 rejection





for δ=0	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν beam	2,300	21	10	362	188
$\bar{\nu}$ beam	1,656	289	6	444	274


Difference from δ_{CP}=0

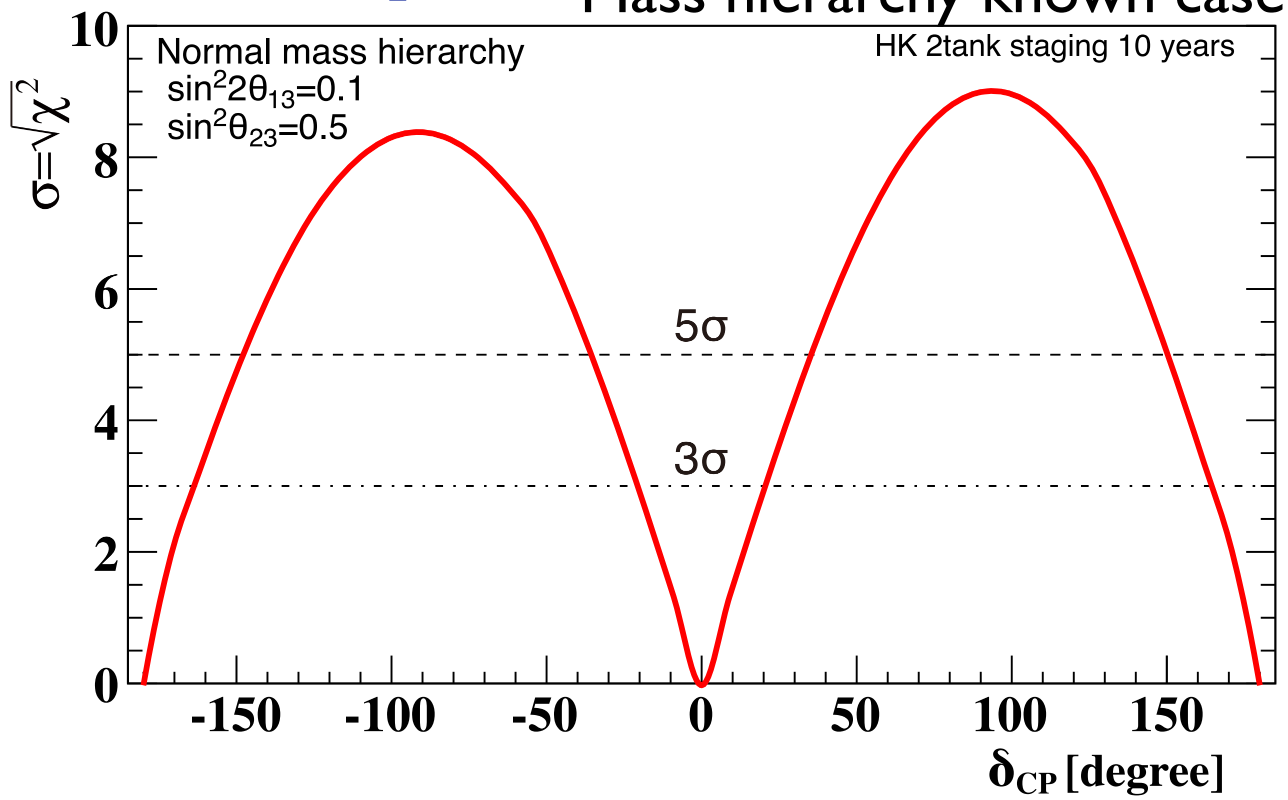
δ=0 and 180° can be distinguished using shape information

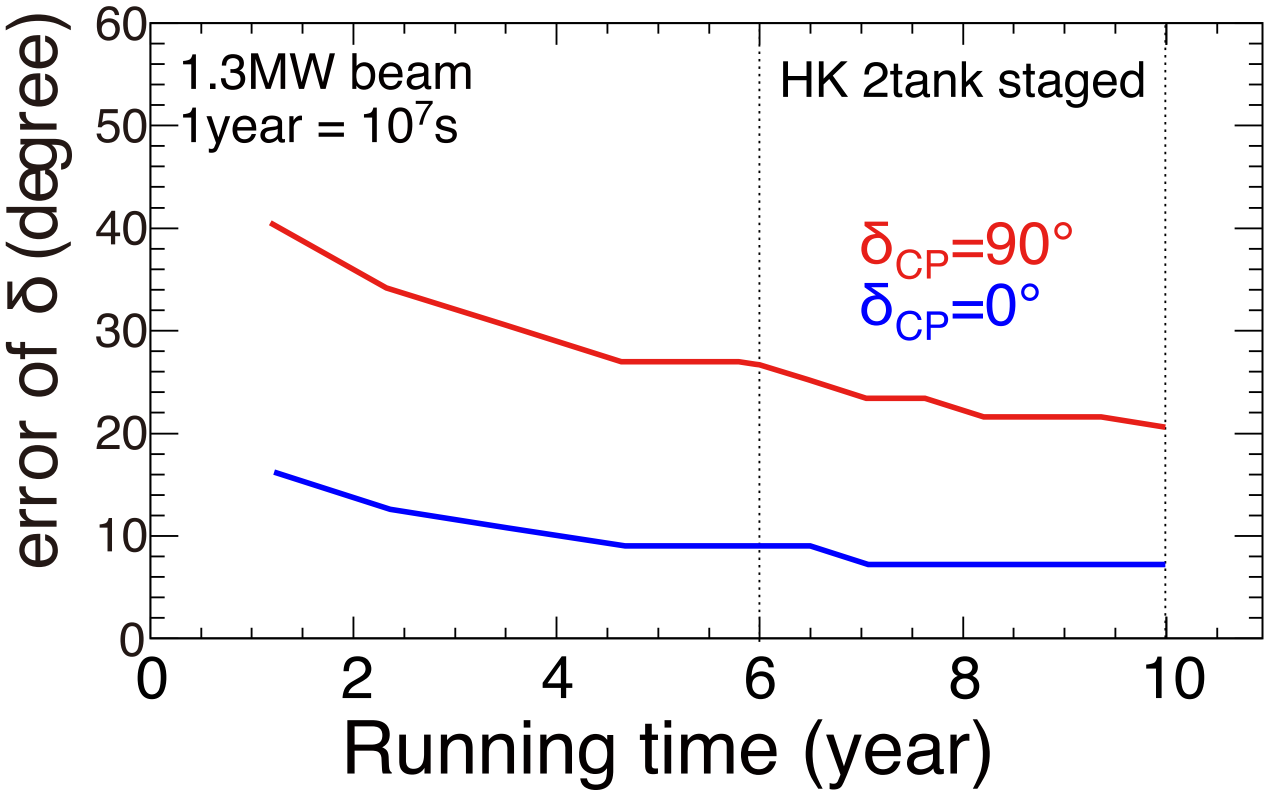
CPV sensitivity

- Exclusion of sinδ_{CP}=0
  - >8σ(6σ) for δ=-90°(-45°)
  - ~80% coverage of δ parameter space with >3σ
- From discovery to δ_{CP} measurement:
  - ~7° precision possible

sinδ=0 exclusion		error	
>3σ	>5σ	δ=0°	δ=90°
78%	62%	7.2°	21°

Mass hierarchy known case





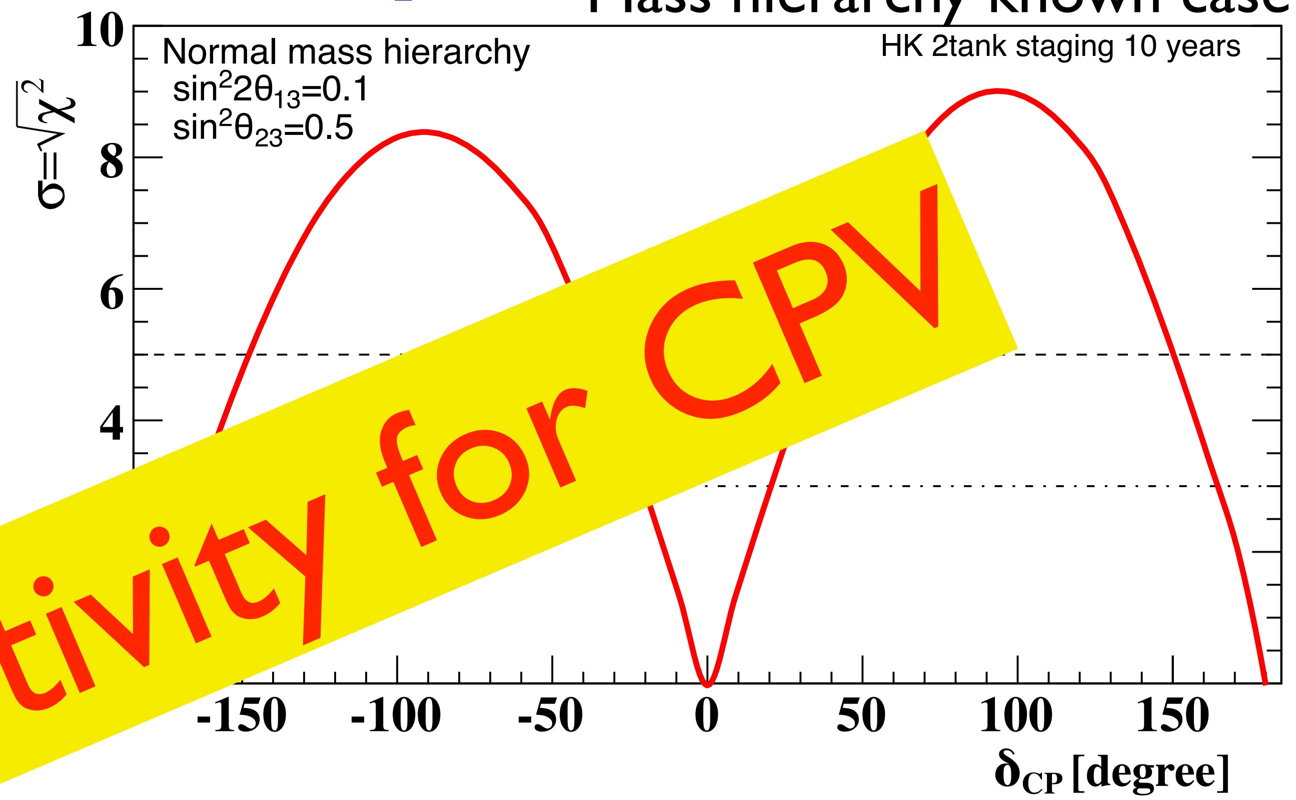
CPV sensitivity

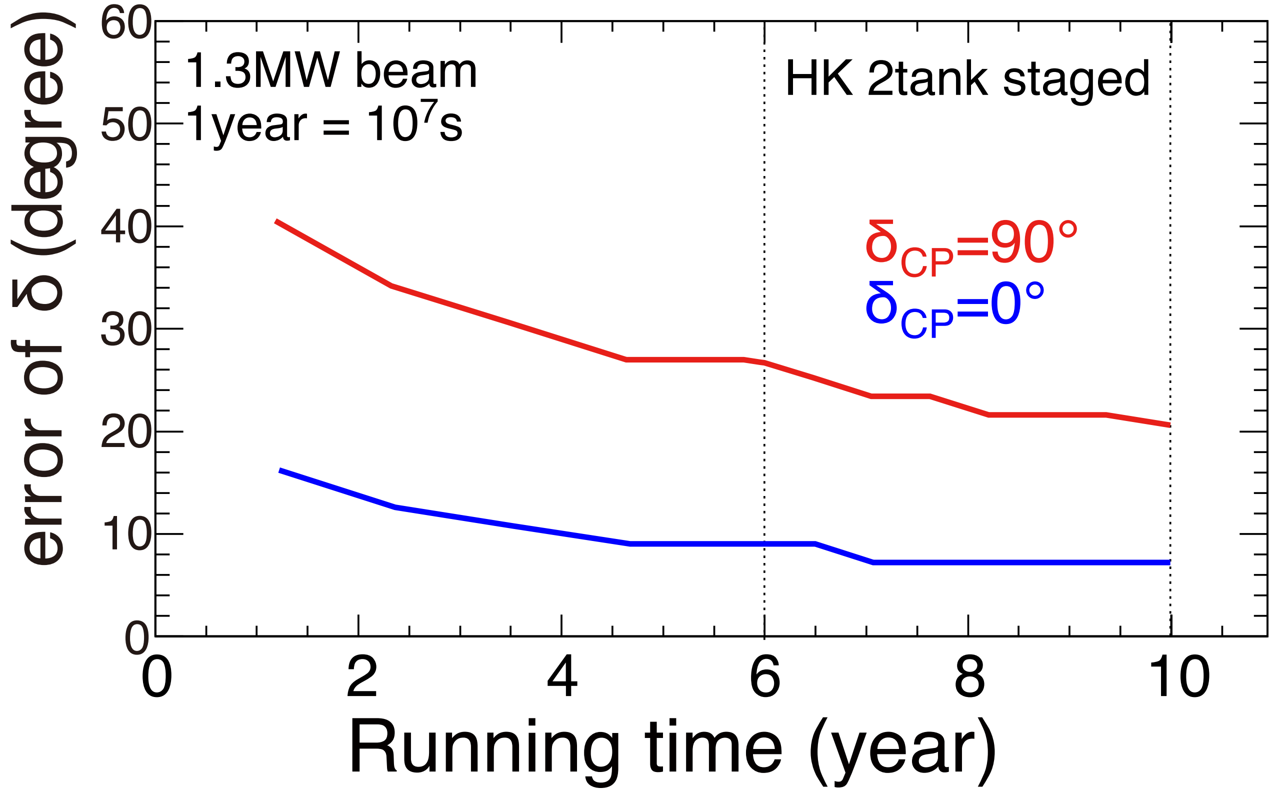
- Exclusion of sinδ_{CP}=0
  - >8σ(6σ) for δ=-90°(-45°)
  - ~80% coverage of δ parameter space with >3σ
- From discovery to δ_{CP} measure
  - ~7° ssible

Excellent sensitivity for CPV

sinδ=0 e usion		error	
>3σ	>5σ	δ=0°	δ=90°
78%	62%	7.2°	21°

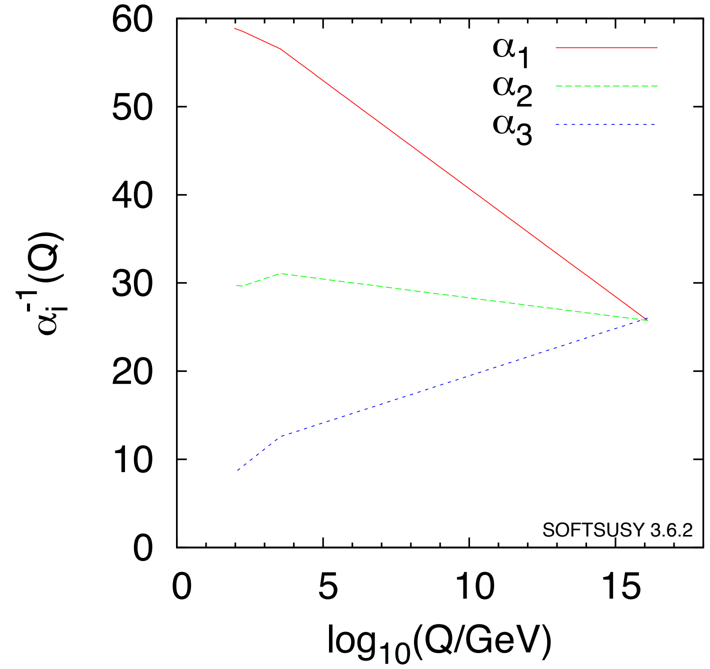
Mass hierarchy known case



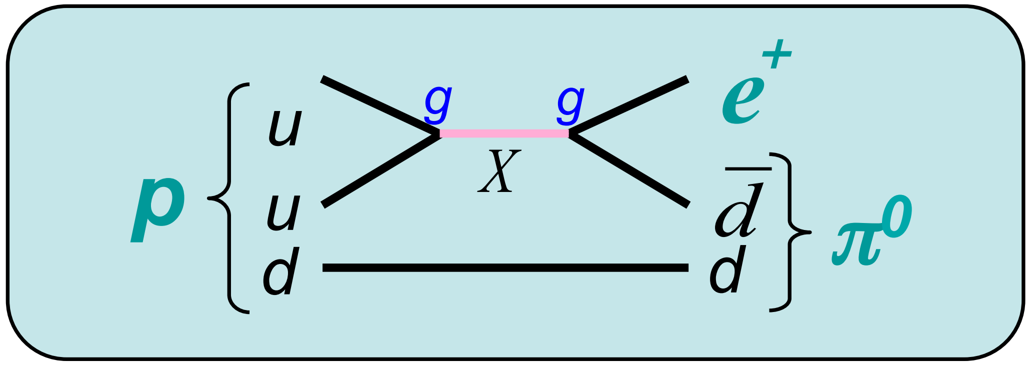


Proton decay searches

- Only way to directly probe Grand Unified Theory which unifies interactions at very high energy
- Two major modes predicted by many models



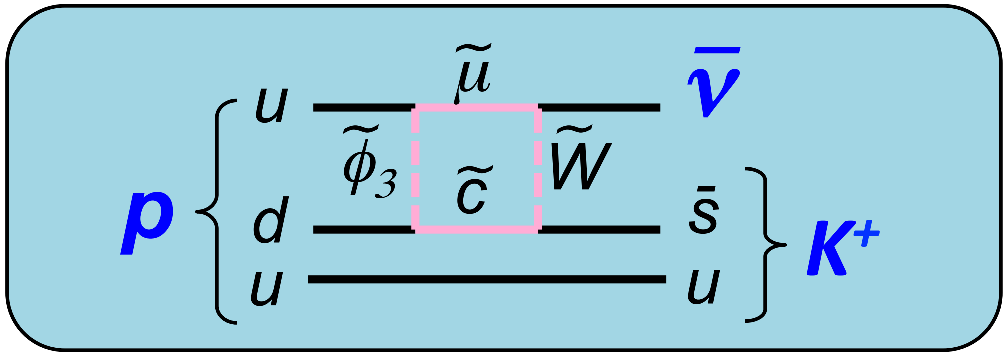
Mediated by gauge bosons



$p \rightarrow e^+\pi^0$

$$\Gamma(p \rightarrow e^+\pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

SUSY mediated



$p \rightarrow \nu K^+$

$$\Gamma(p \rightarrow \bar{\nu} K^+) \sim \frac{\tan^2\beta \times m_p^5}{M_{\tilde{q}}^2 \times M_3^2}$$

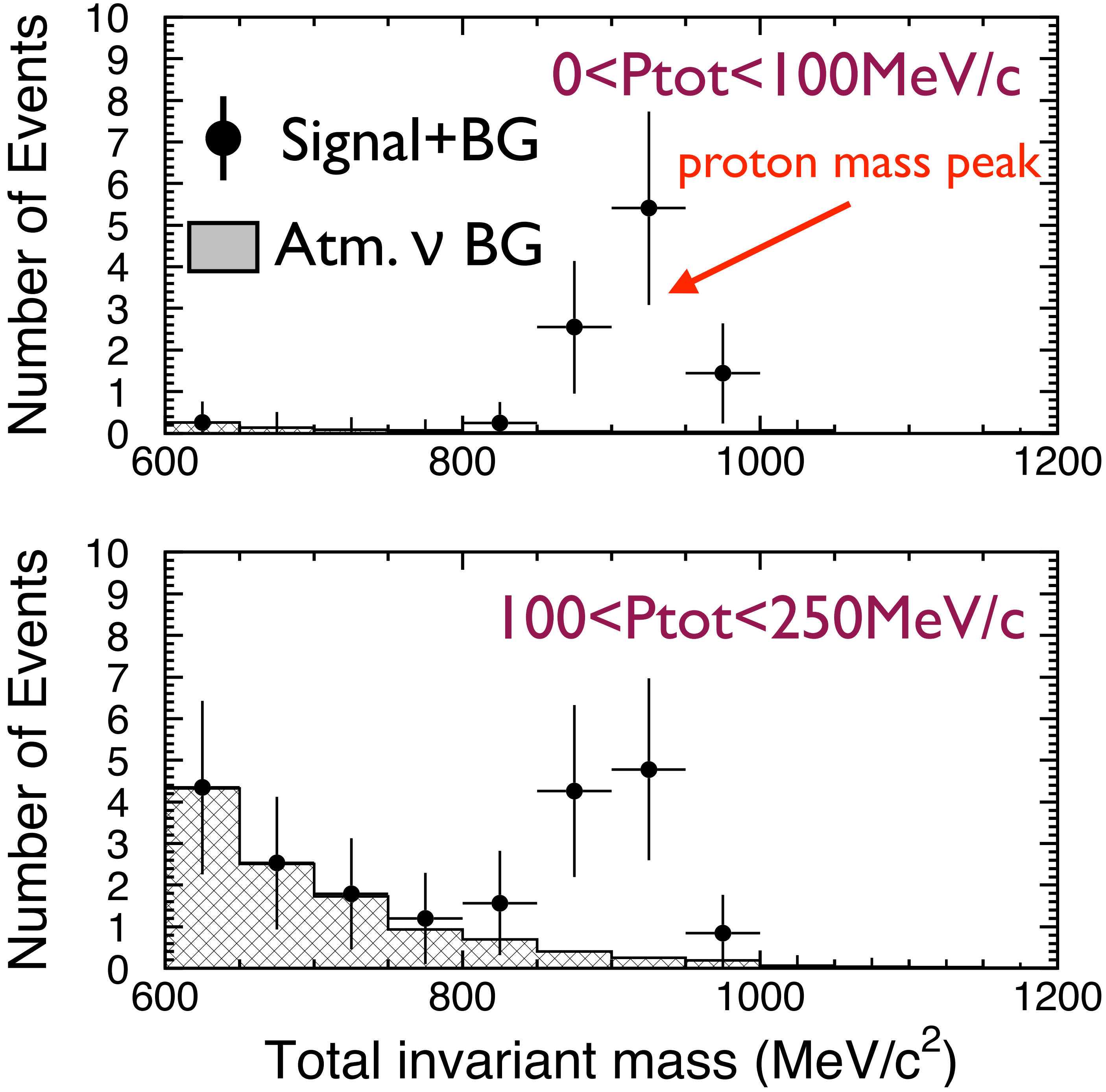
- Need broad searches including other possible modes

$p \rightarrow e^{+}\pi^{0}$

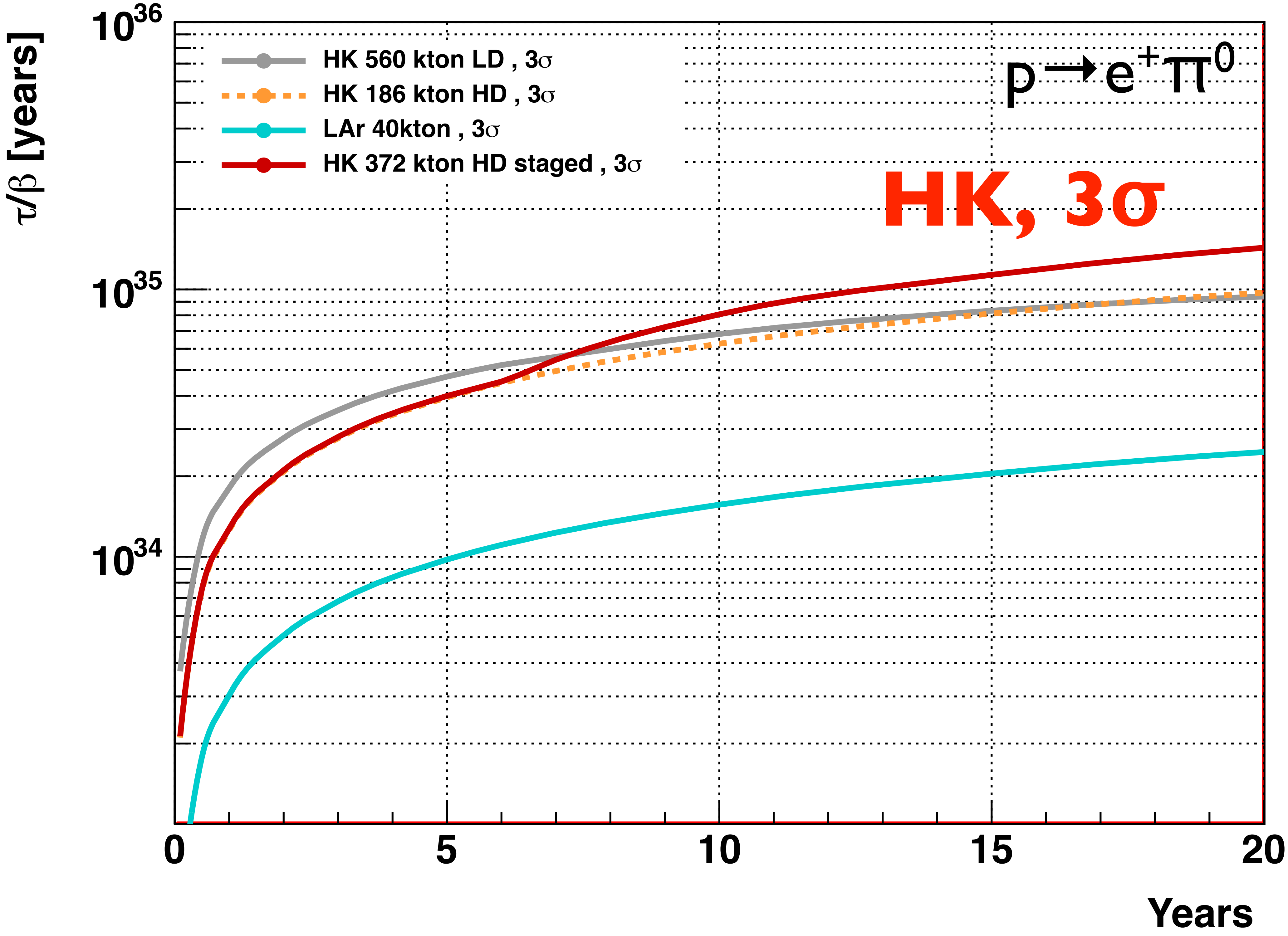
- Can be fully reconstructed
  - Kinematic selection
  - $M_{tot} \sim m_p$, $p_{tot} \sim 0$
- Clear signal can be seen for lifetime above the current limit
- Negligible background in the free proton enhanced region
  - Atm. ν BG suppression by neutron tagging (thanks to higher photon yield)

For $\tau p/Br = 1.7 \times 10^{34}$ years

HK 10 years MC

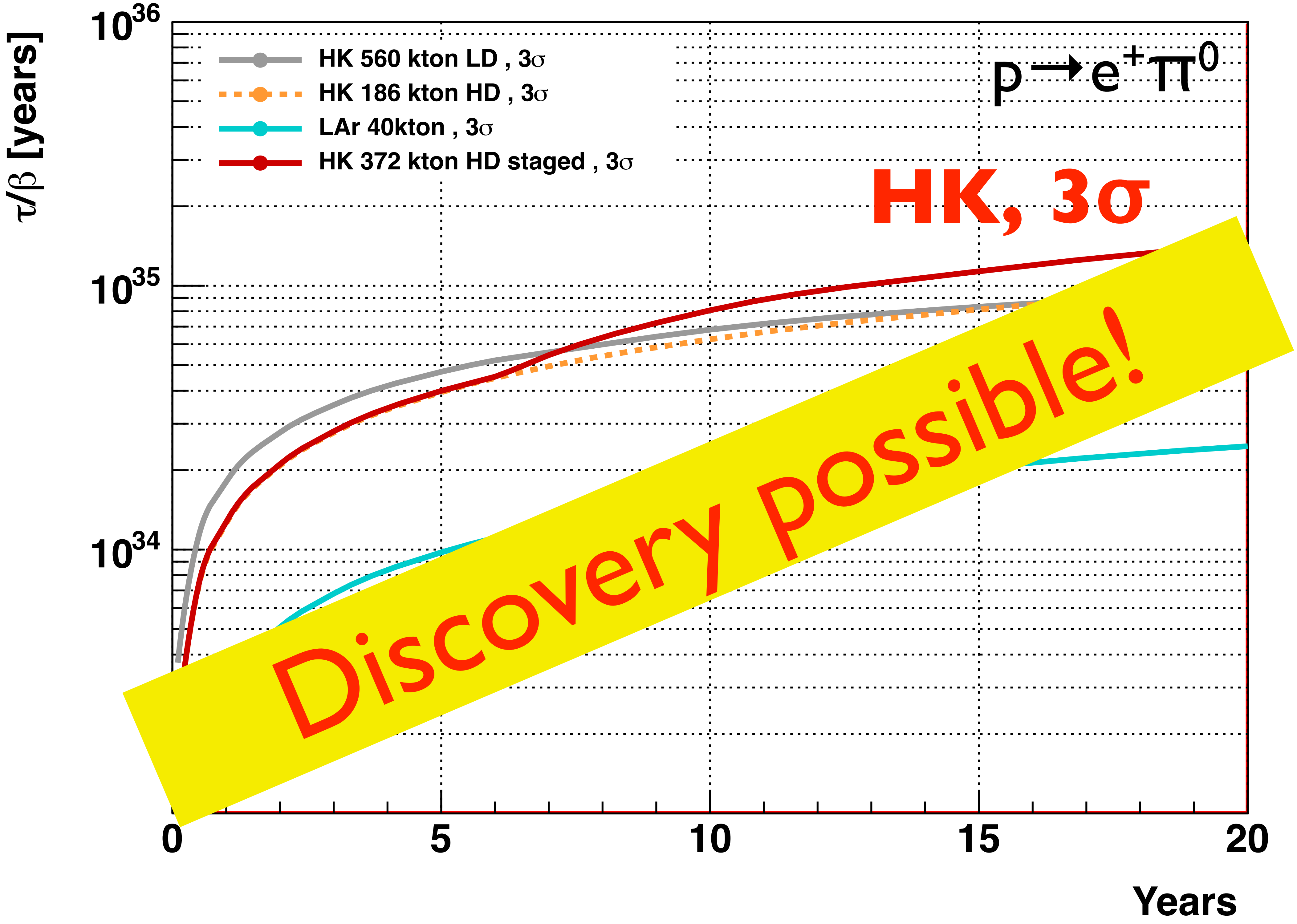


$p \rightarrow e^+\pi^0$ sensitivity



3σ discovery potential will reach ~10^{35} years!

$p \rightarrow e^{+}\pi^{0}$ sensitivity



3σ discovery potential will reach ~10^{35} years!

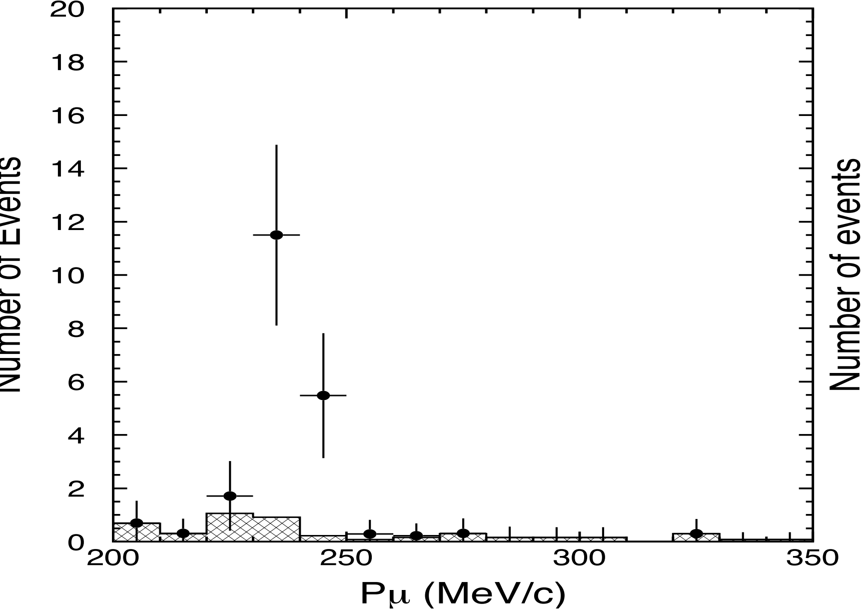
$p \to \bar{\nu} K^+$ sensitivity

- Clear signal can be seen for lifetime beyond the current limit

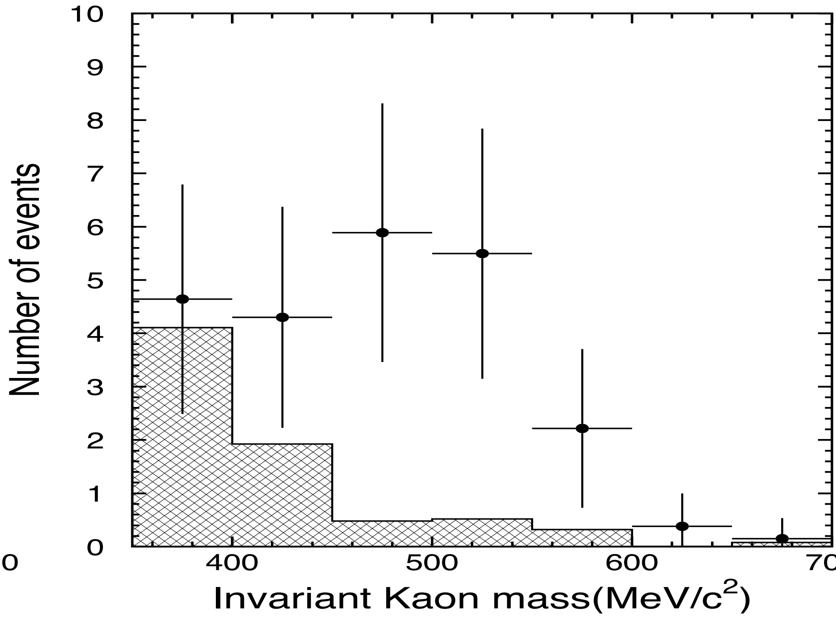
For $\tau_p/Br = 6.6\times10^{33}$ years

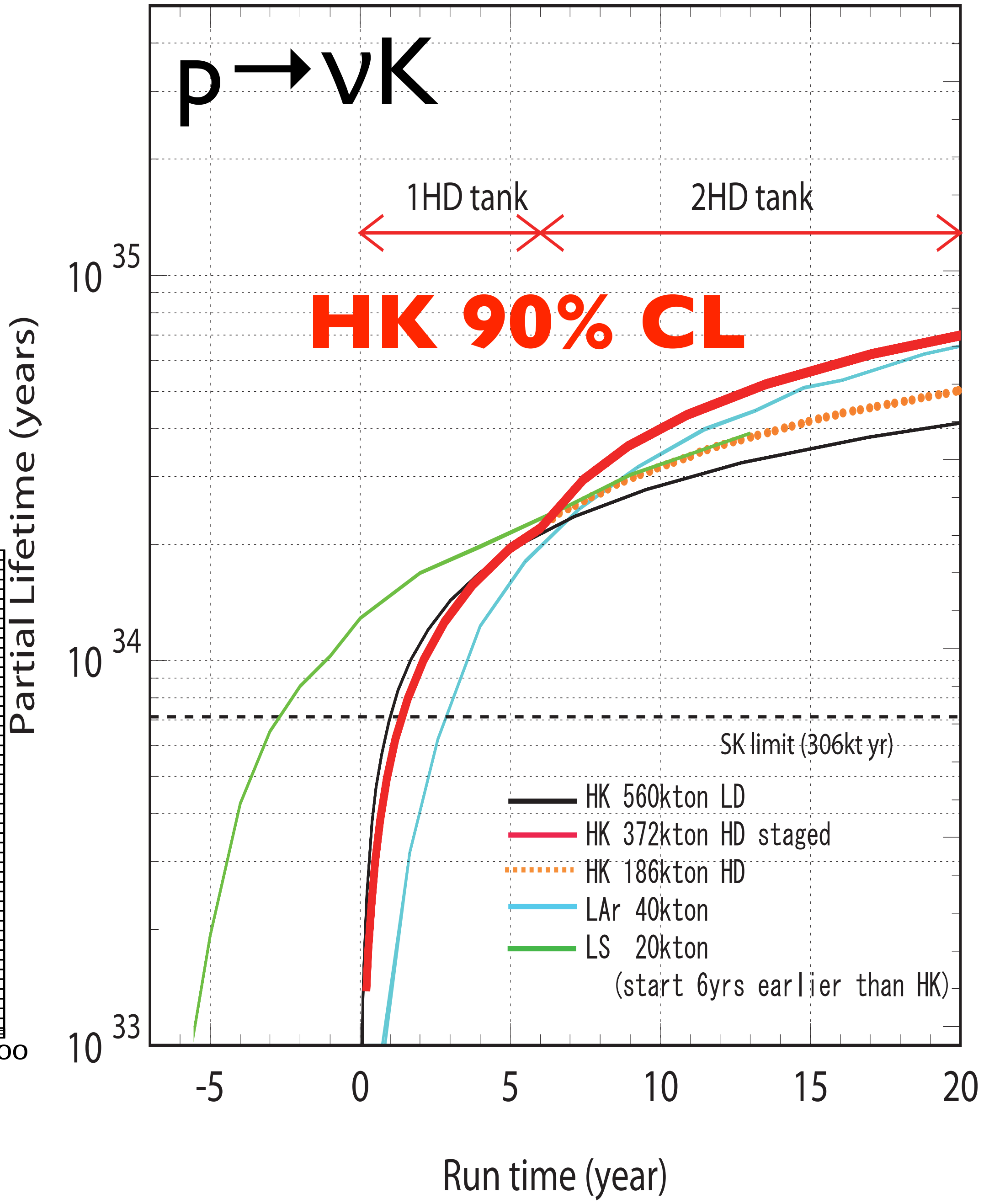
HK 10 years MC

P_μ for $K \to \mu\nu$



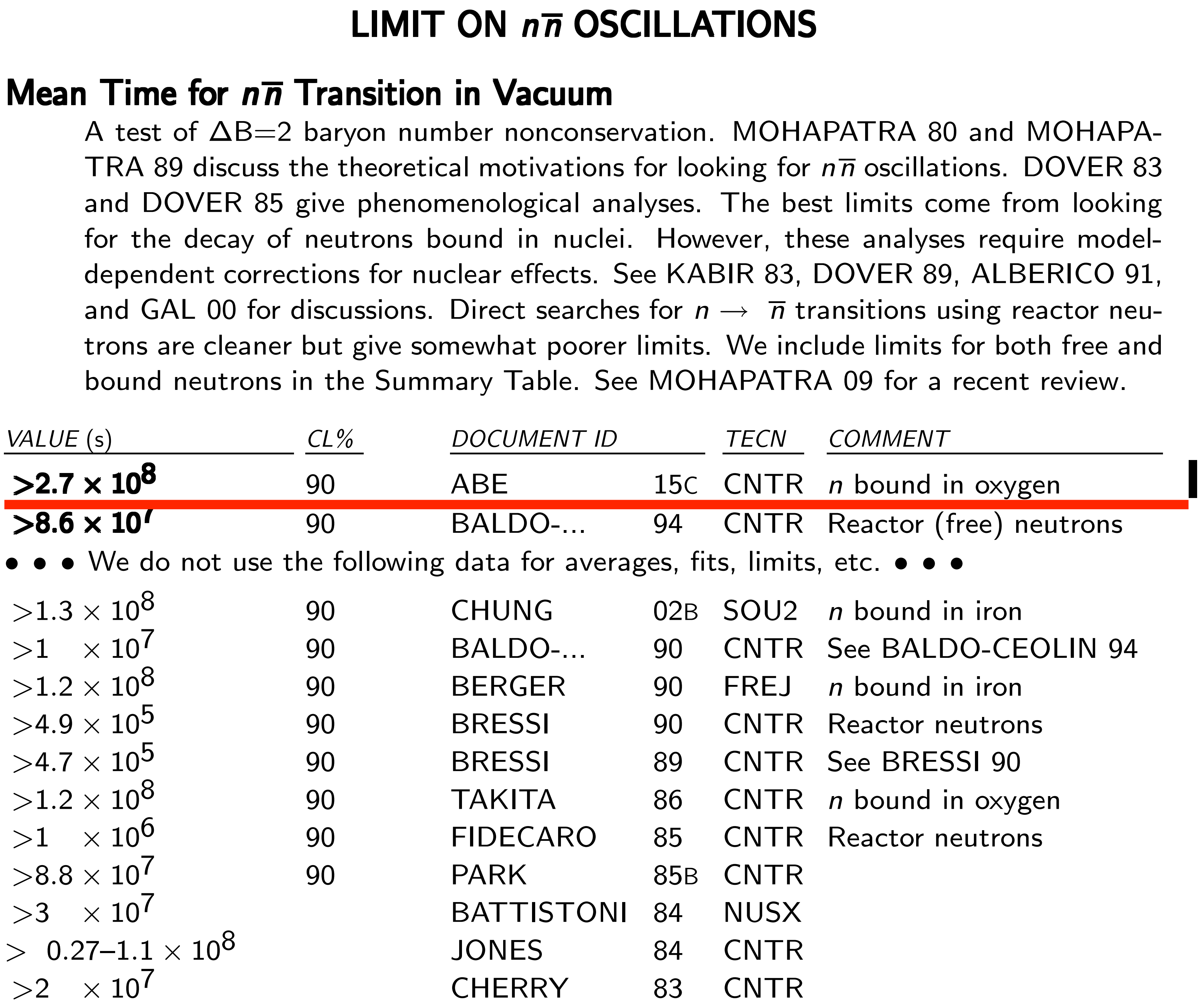
$K \to \pi\pi$





In 10 years, 3σ discovery sensitivity 2.5×10^{34} years

(Answering to earlier question)



LIMIT ON $n\overline{n}$ OSCILLATIONS

Mean Time for $n\overline{n}$ Transition in Vacuum

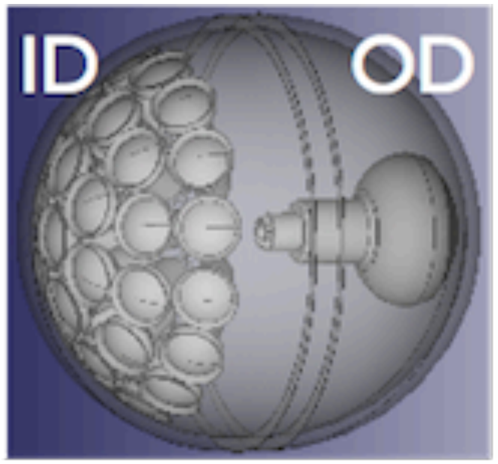
A test of $\Delta B=2$ baryon number nonconservation. MOHAPATRA 80 and MOHAPATRA 89 discuss the theoretical motivations for looking for $n\overline{n}$ oscillations. DOVER 83 and DOVER 85 give phenomenological analyses. The best limits come from looking for the decay of neutrons bound in nuclei. However, these analyses require model-dependent corrections for nuclear effects. See KABIR 83, DOVER 89, ALBERICO 91, and GAL 00 for discussions. Direct searches for $n \to \overline{n}$ transitions using reactor neutrons are cleaner but give somewhat poorer limits. We include limits for both free and bound neutrons in the Summary Table. See MOHAPATRA 09 for a recent review.

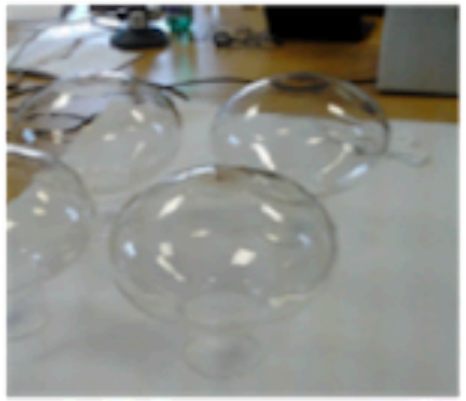
VALUE (s)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$>2.7 \times 10^8$	90	ABE	15C	CNTR	*n* bound in oxygen
$>8.6 \times 10^7$	90	BALDO-...	94	CNTR	Reactor (free) neutrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>1.3 \times 10^8$	90	CHUNG	02B	SOU2	*n* bound in iron
$>1 \times 10^7$	90	BALDO-...	90	CNTR	See BALDO-CEOLIN 94
$>1.2 \times 10^8$	90	BERGER	90	FREJ	*n* bound in iron
$>4.9 \times 10^5$	90	BRESSI	90	CNTR	Reactor neutrons
$>4.7 \times 10^5$	90	BRESSI	89	CNTR	See BRESSI 90
$>1.2 \times 10^8$	90	TAKITA	86	CNTR	*n* bound in oxygen
$>1 \times 10^6$	90	FIDECARO	85	CNTR	Reactor neutrons
$>8.8 \times 10^7$	90	PARK	85B	CNTR	
$>3 \times 10^7$		BATTISTONI	84	NUSX	
$>$ 0.27–1.1 $\times 10^8$		JONES	84	CNTR	
$>2 \times 10^7$		CHERRY	83	CNTR	

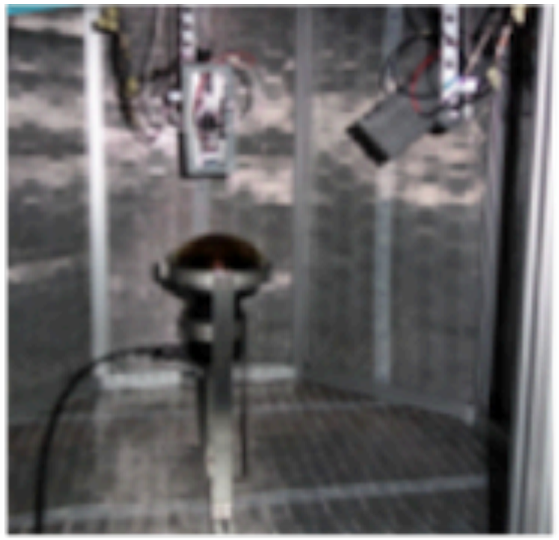
Super-Kamiokande gives the best limit for n-nbar oscillation

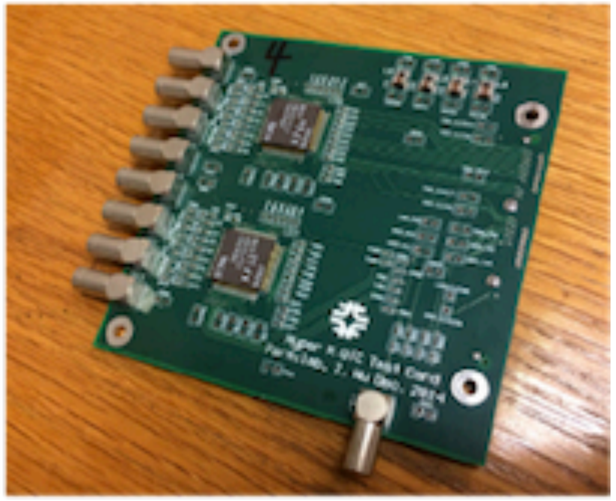
International R&D ongoing

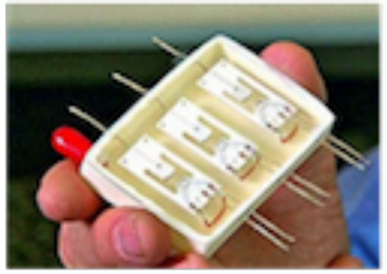
- Intense R&D work over the world
  - Photo-sensor, calibration, electronics, DAQ, software, physics sensitivity studies…



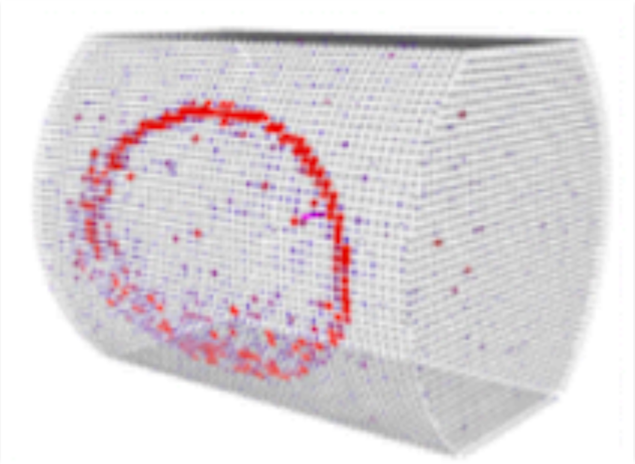




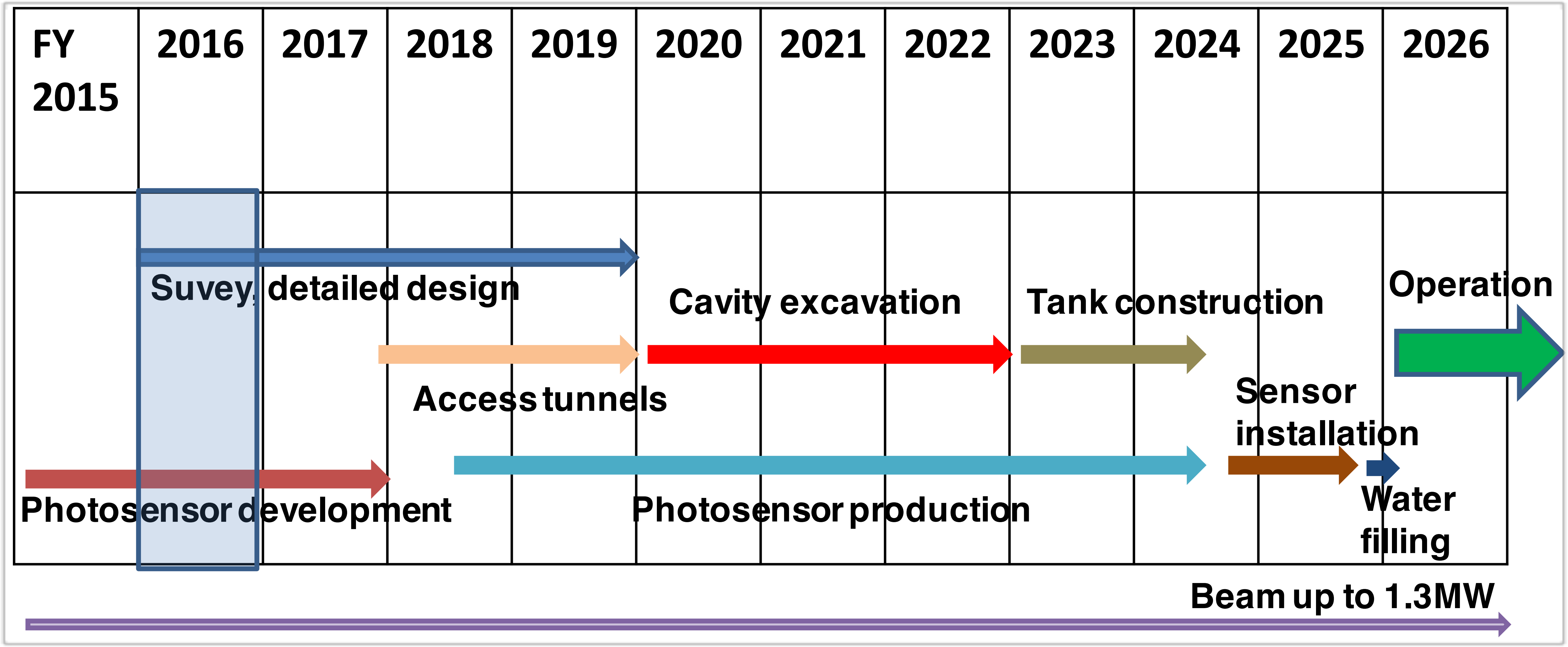




IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 40, NO. 9, SEPTEMBER 2012



Hyper-K construction timeline



FY 2015

2016

2017

2018

2019

2020

2021

2022

2023

2024

2025

2026

Suvey, detailed design

Cavity excavation

Tank construction

Operation

Access tunnels

Sensor installation

Photosensor development

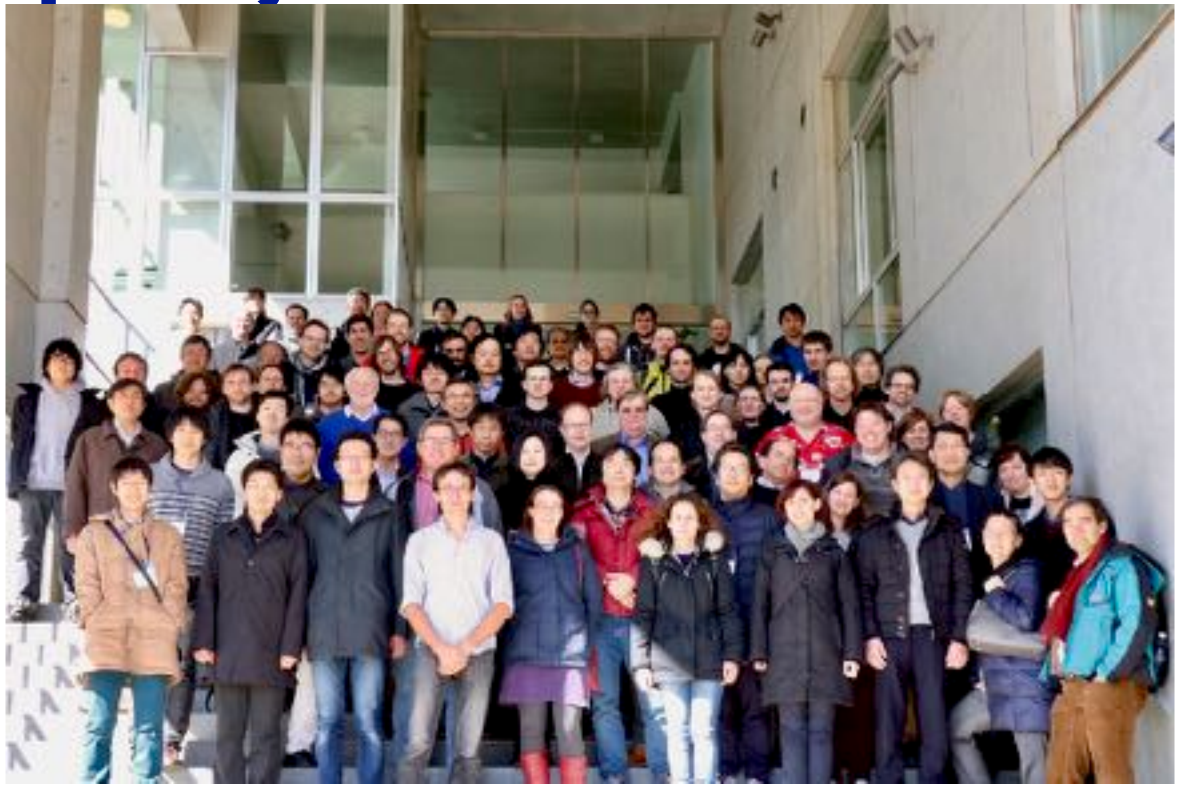
Photosensor production

Water filling

Beam up to 1.3MW

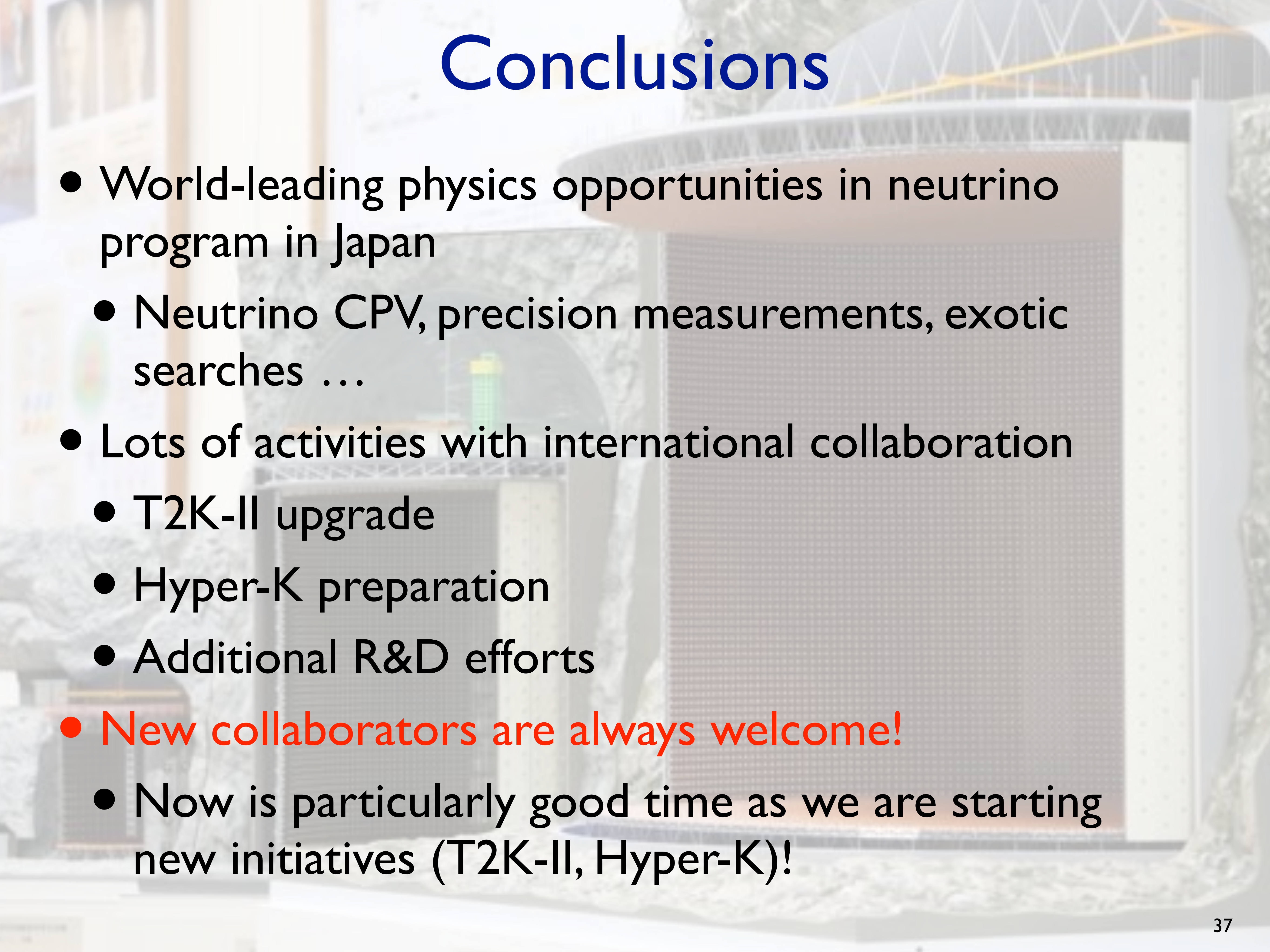
- Assuming construction funding from 2018
- The 1st detector construction in 2018~2025
  - Cavern excavation: ~5 years
  - Tank (liner, photosensors) construction: ~3 years
  - Water filling: 0.5 years

Hyper-Kamiokande project status



- International Proto-Collaboration formed in 2015
  - Currently ~300 members from 15 countries
- Selected as one of 28 highest priority projects among all science projects by Science Council of Japan
- Set as highest priority future projects by ICRR and KEK
- Budget request for construction under preparation by U.Tokyo
  - Formation of new institution,

Conclusions



- World-leading physics opportunities in neutrino program in Japan
  - Neutrino CPV, precision measurements, exotic searches …
- Lots of activities with international collaboration
  - T2K-II upgrade
  - Hyper-K preparation
  - Additional R&D efforts
- New collaborators are always welcome!
  - Now is particularly good time as we are starting new initiatives (T2K-II, Hyper-K)!