Latest results and future potential of Japanese long baseline neutrino oscillation experiments

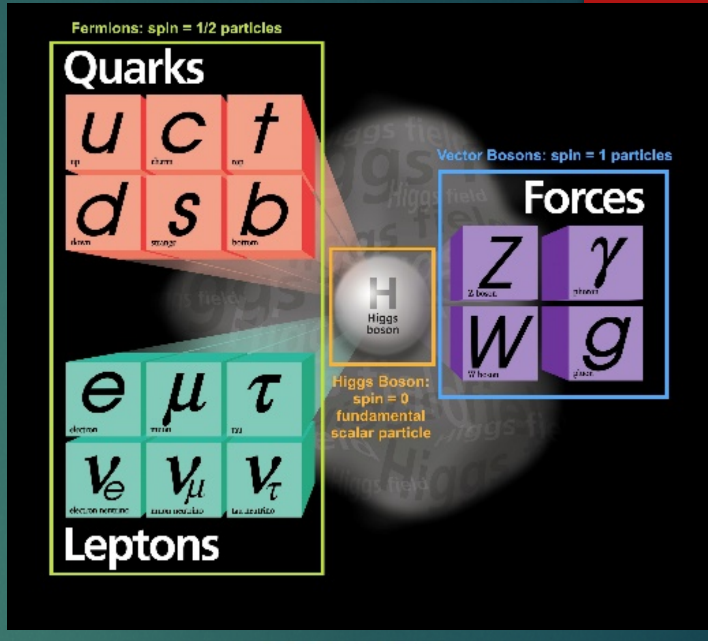
TAKASHI KOBAYASHI

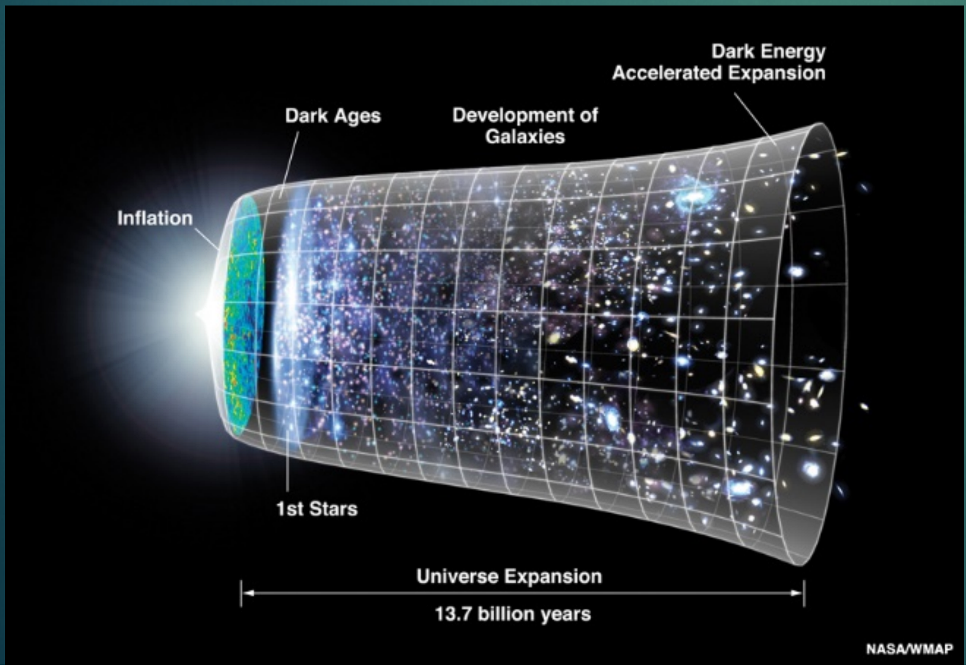
IPNS/KEK, J-PARC

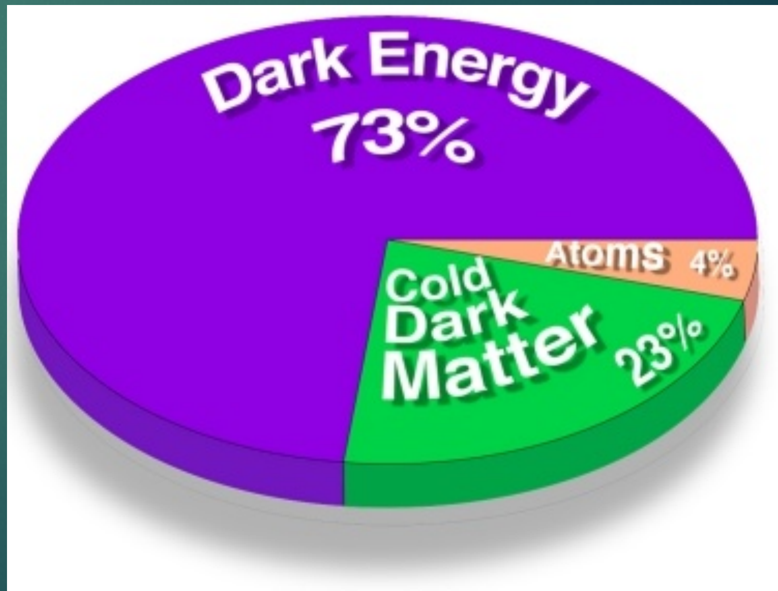
Contents

Fundamental questions in our universe

- Origin/fate of our universe
- Origin of matter
- Origin of mass
- Origin of Dark matter
- Origin of Dark energy

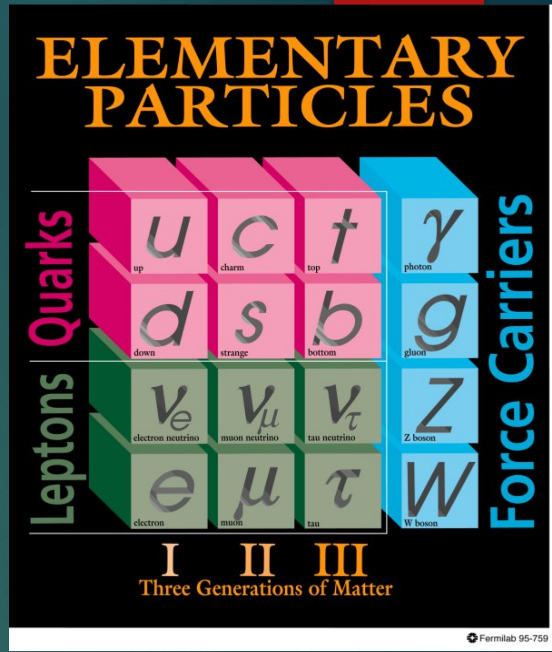


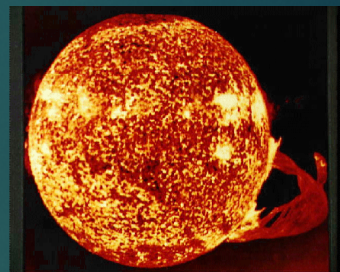




Neutrinos

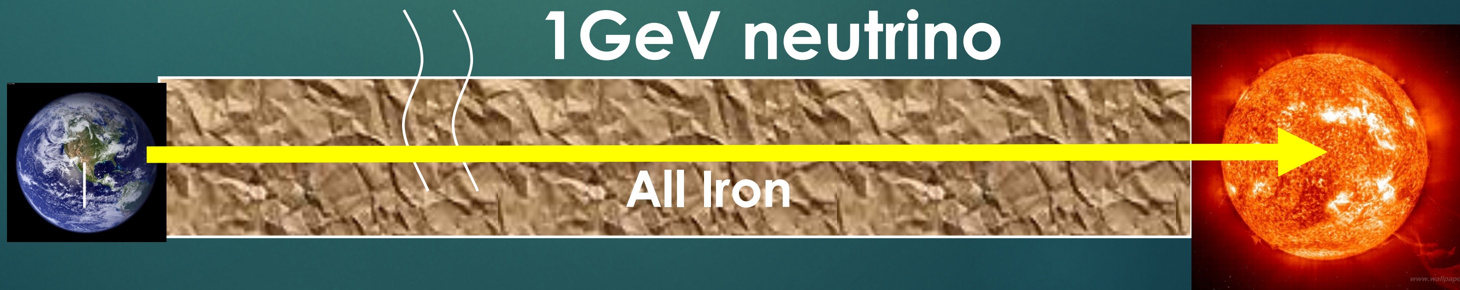
- One of elementary particles in the "Standard Model"
- Extreme nature
  - Extremely light (but precise value unknown)
    - < 1/ 1,000,000 of other lightest particle, Electron
  - Extremely abundant in the Universe
    - 100 million/m^3 "Cosmic ν background"
  - Extremely weak interaction with matter
    - Difficult to detect
- Least known particle
  - Mass
  - Relation between 3 types
  - Particle = Anti-particle?



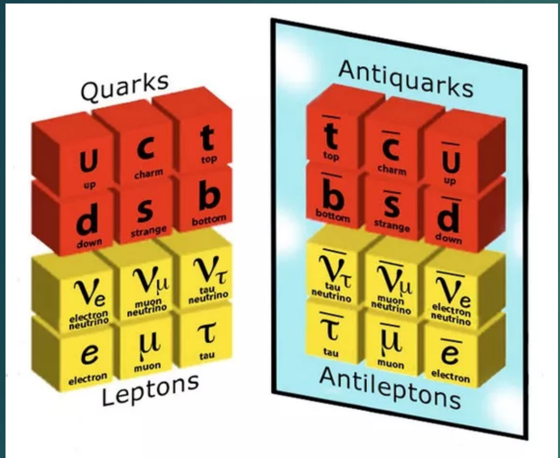


$6x10^{10}/cm^2/s$ on Earth

Unraveling nature of neutrino could provide breakthrough to understand our nature



Toward understanding mystery of matter-dominated universe



- At the beginning of Universe: #particle = #anti-particle
  - Fate should be "Nothing"!!!
- To survive
  - Sakharov's 3 conditions
    - **C and CP violation**
    - Baryon number violation
    - Interactions out of thermal equilibrium
- Known CP violation in quarks cannot account for the present amount of matter
- **CP violation in neutrino (if exist) can give solution!!**

Neutrino oscillation

- Flavor of neutrino changes to other flavor during flight
- Only occur when neutrino has finite mass
- Discovered in 1998 by SuperK → Kajita-san's nobel prize in 2015
- The way of changing depend on mass, (energy/flight distance) of neutrino
- Strong tool to explore neutrino mass and mixing

Mu neutrino

Tau neutrino

"Standard picture" of 3 flavor mixing

Flavor eigenstates — Mass eigenstates

ν_e, ν_μ, ν_τ — m_1, m_2, m_3

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \mathrm{U}_{\mathrm{PMNS}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata Matrix (CKM matrix in lepton sector)

$$\mathrm{U}_{\mathrm{MNS}} = \begin{pmatrix}1 & 0 & 0\\ 0 & +c_{23} & +s_{23}\\ 0 & -s_{23} & +c_{23}\end{pmatrix}\begin{pmatrix}+c_{13} & 0 & +s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & +c_{13}\end{pmatrix}\begin{pmatrix}+c_{12} & +s_{12} & 0\\ -s_{12} & +c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

$c_{ij} = \cos(\theta_{ij}),\quad s_{ij} = \sin(\theta_{ij})$

Atm/Acc — Acc/Reactor — Sol/Reactor

6 independent parameters govern oscillation

θ_{12}, θ_{23}, θ_{13}, δ

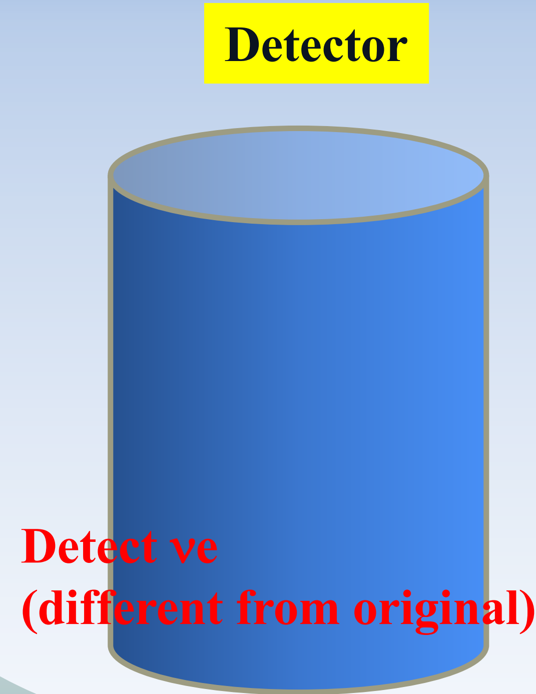
Δm_{12}^2, Δm_{23}^2, Δm_{13}^2

$\Delta m_{ij} = m_i^2 - m_j^2$

Methods (types) of oscillation experiments

Appearance :

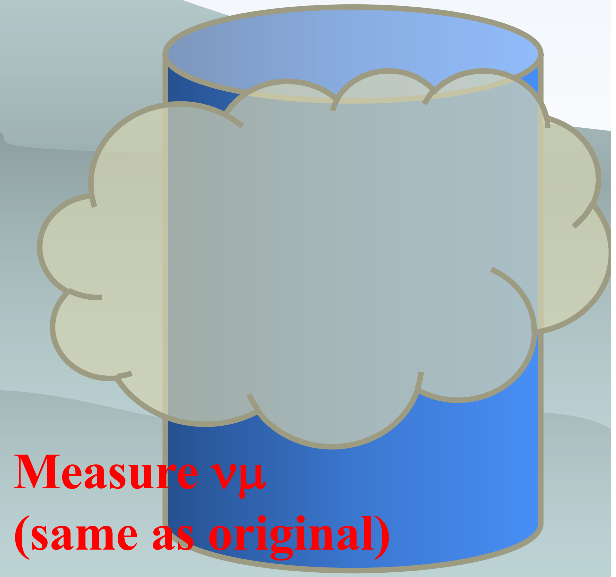
Muon neutrino



Disappearance :

Muon neutrino

Measure behavior of decrease

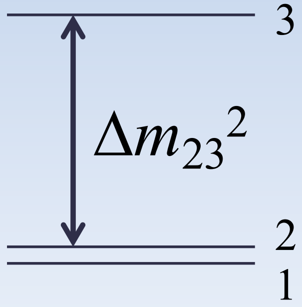


Oscillation probabilities

when $\begin{cases} \Delta m_{12}^2 << \Delta m_{23}^2 \approx \Delta m_{13}^2 \\ E_\nu / L \approx \Delta m_{23}^2 \end{cases}$

contribution from Δm_{12} is small

(No CPV & matter eff. approx.)



ν_μ disappearance (LBL/Atm) → θ_{23} and $\Delta m_{23}{}^2$

$$P_{\mu \to x} \approx 1 - \underbrace{\cos^4 \theta_{13}}_{\sim 1} \cdot \sin^2 2\theta_{23} \cdot \sin^2\left(1.27 \Delta m_{23}^2 L / E_\nu\right)$$

ν_e appearance (LBL/Atm) → θ_{13} and $\Delta m_{13}{}^2$

$$P_{\mu \to e} \approx \underbrace{\sin^2 \theta_{23}}_{\sim 0.5} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(1.27 \Delta m_{13}^2 L / E_\nu\right)$$

ν_e disappearance (Reactor) → Pure θ_{13} and $\Delta m_{13}{}^2$

$$P_{e \to x} \approx 1 - \underbrace{\sin^2 2\theta_{13}}_{\ll 1} \cdot \sin^2\left(1.27 \Delta m_{13}^2 L / E_\nu\right)$$

Present knowledge

$$U_{MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\theta_{12} = 33° \pm 1°$$

$$\theta_{23} = 46° \pm 3°$$ 45° ?

$$\theta_{13} = 8.9° \pm 0.4°$$

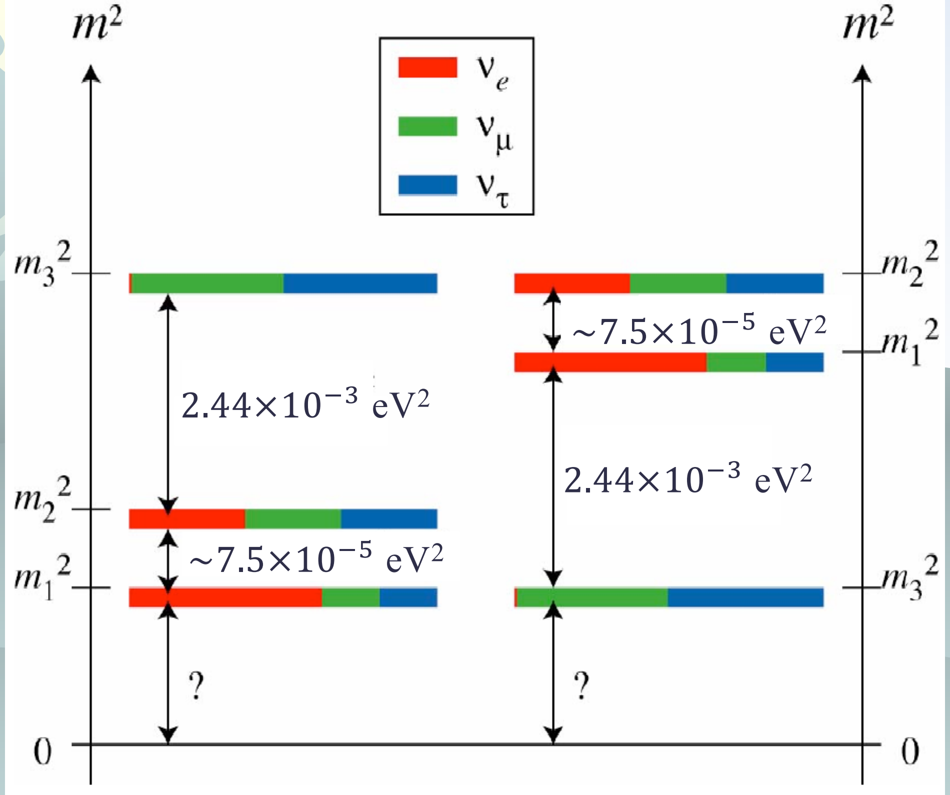
Unknown Mass Ordering

normal: $m_1 < m_2 \ll m_3$

inverted: $m_3 \ll m_1 < m_2$

$\Delta m_{21}^2 = 7.5 \pm 0.2 \times 10^{-5}$ eV²

$|\Delta m_{32}^2| = 2.44 \pm 0.06 \times 10^{-3}$ eV²



δ Unknown

$\nu_\mu \rightarrow \nu_e$ appearance and CPV

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right)$$ **Main**

$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$ CP-odd

$$+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\} \sin^2\frac{\Delta m_{21}^2 L}{4E}$$ Solar

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E}(1 - 2S_{13}^2)$$ **Matter**

$\delta \rightarrow -\delta$, $a \rightarrow -a$ for $\bar{\nu}_\mu \to \bar{\nu}_e$

Matter eff.: $a = 7.56 \times 10^{-5}[\mathrm{eV}^2] \cdot \left(\frac{\rho}{[\mathrm{g/cm}^3]}\right) \cdot \left(\frac{E}{[\mathrm{GeV}]}\right)$

$$A_{CP} \equiv \frac{P - \bar{P}}{P + \bar{P}} \approx \frac{\Delta m_{12}^2 L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

N($_e$) ∝ sin^{2}2 $_{13}$; A_{CP} ∝ $\frac{1}{\sin\ _{13}}$

CP asymmetry as large as ~27% at 1st osc maximum

T2K (Tokai to Kamioka) (2010~)

- High intensity ν_μ beam from J-PARC MR to Super-Kamiokande
- Evidence → Observation of ν_μ → ν_e (2011-2013)
- Goals:
  - Discovery → Precise measurement of ν_e appearance
  - Precise meas. of ν_μ disappearance
  - → Measure CP symmetry, contribution to mass hier. determ.
  - Neutrino interaction cross section meas.

The T2K experiment
The collaboration

~ 500 members, 62 Institutes, 11 countries

Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen

Switzerland
ETH Zurich
U. Bern
U. Geneva

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Metropolitan U.
U. Tokyo
Yokohama National U.

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

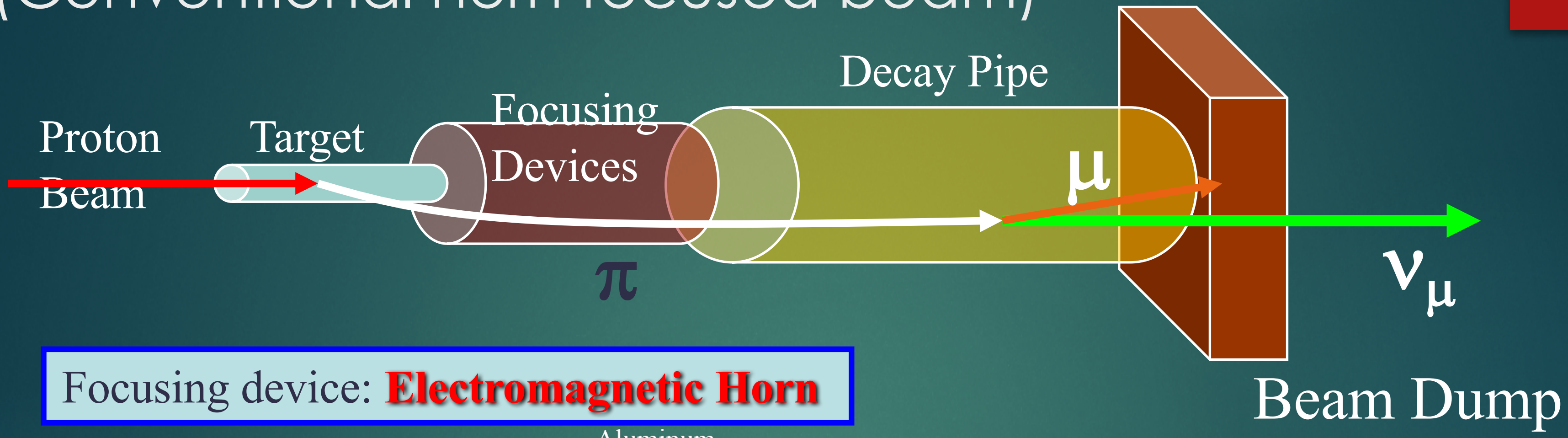
Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR

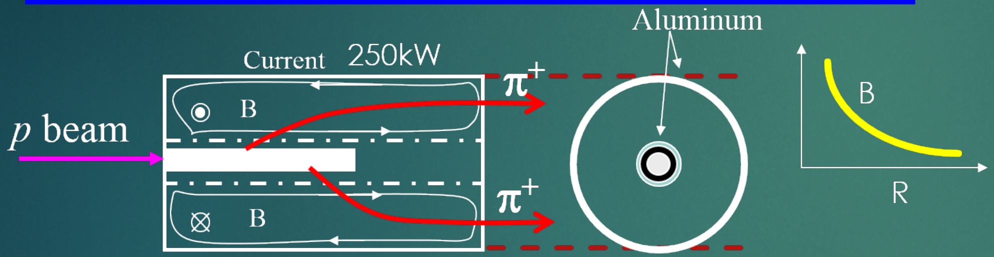
United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

How to make ν_μ beam
(Conventional horn focused beam)



Focusing device: **Electromagnetic Horn**

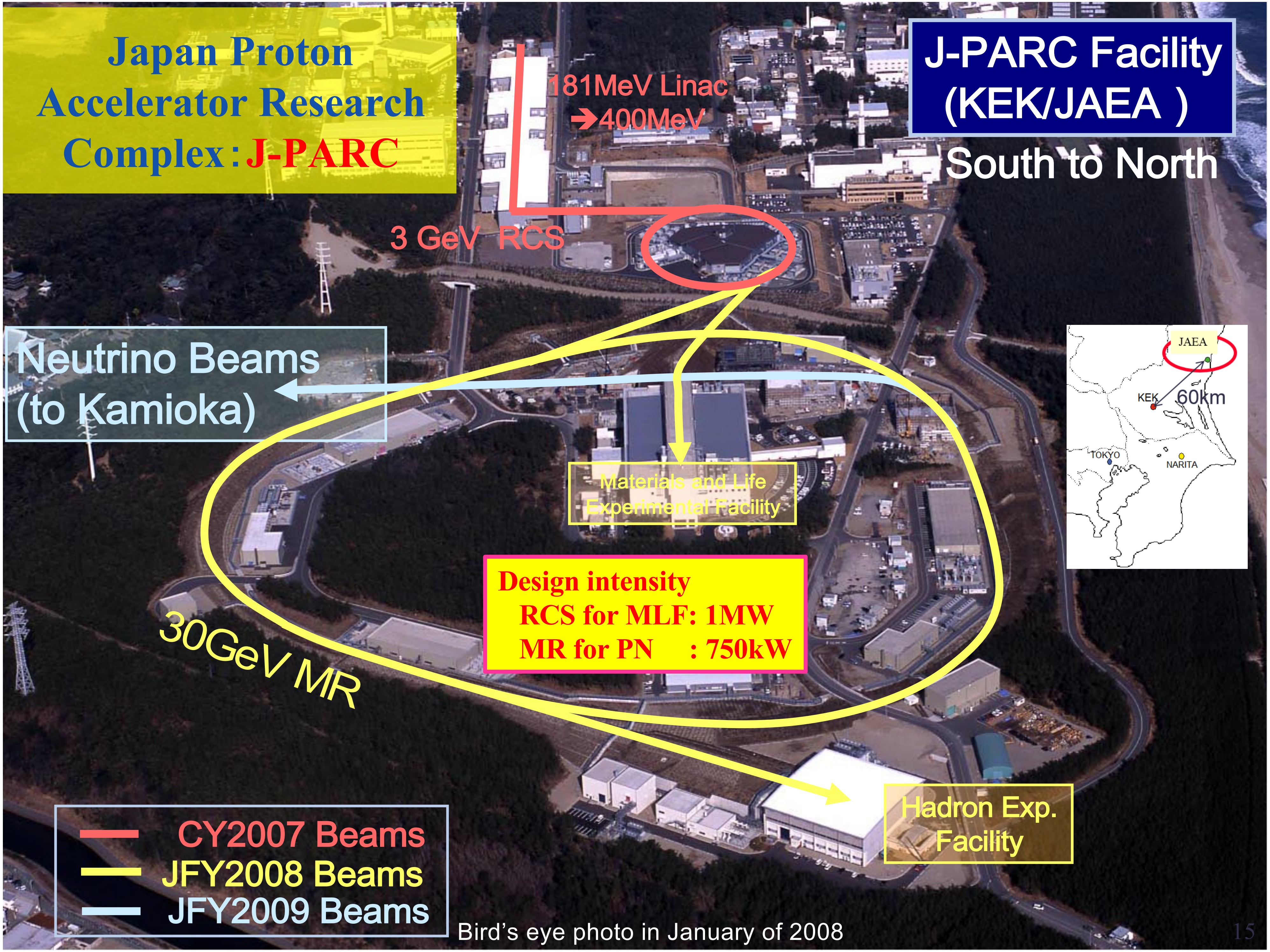


- Pure ν_μ beam (≳99%)
- $\nu_\mu/\bar{\nu}_\mu$ can be switched by flipping polarity of Horns

For high sensitivity/precise experiment

→ More neutrinos

→ Higher proton beam power
x machine operation time
x running efficiency

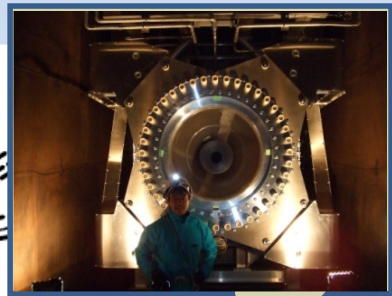


Bird's eye photo in January of 2008

Neutrino facility for T2K at J-PARC

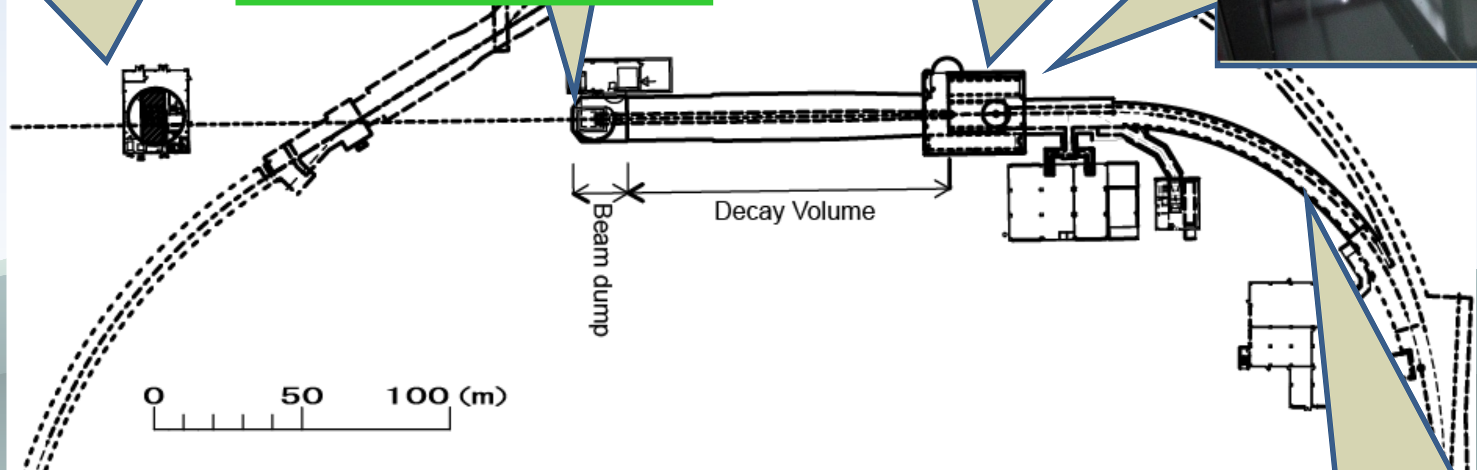
Neutrino monitor bld.

Muon monitors



Electromagnetic horn

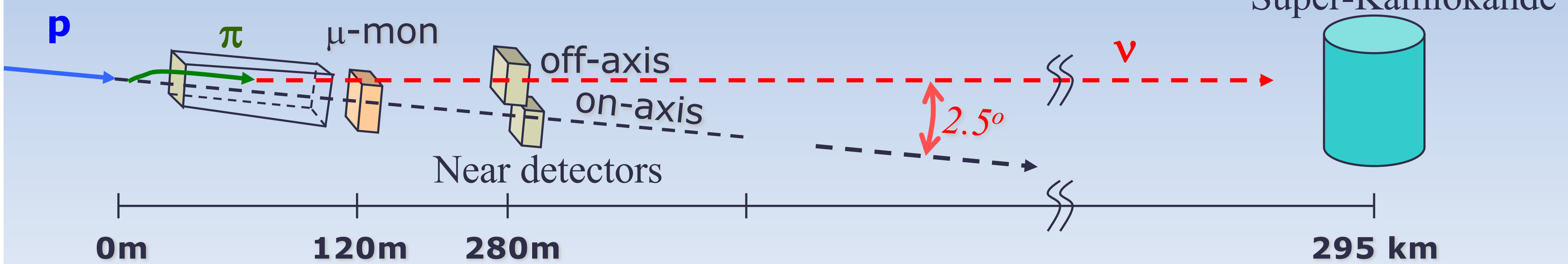
Target



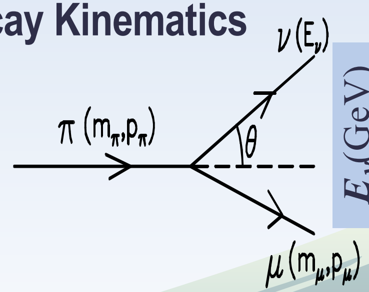
Primary beamline (superconducting

- Fast Extracted (FX) beam from MR @ 30GeV
  - 8 bunches 581ns apart
- Proton beam transport
  - Superconducting combined function magnets
- Graphite target (26mmφx90cm)
- 3 horns @ 250kA
- 117m of decay volume (from target)
- SK direction is given by GPS survey at 2μrad precision

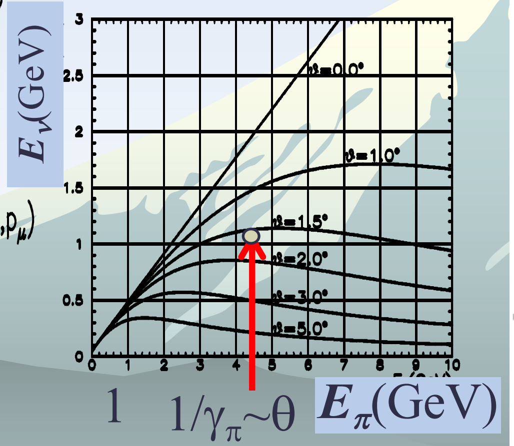
Off-axis beam



Decay Kinematics

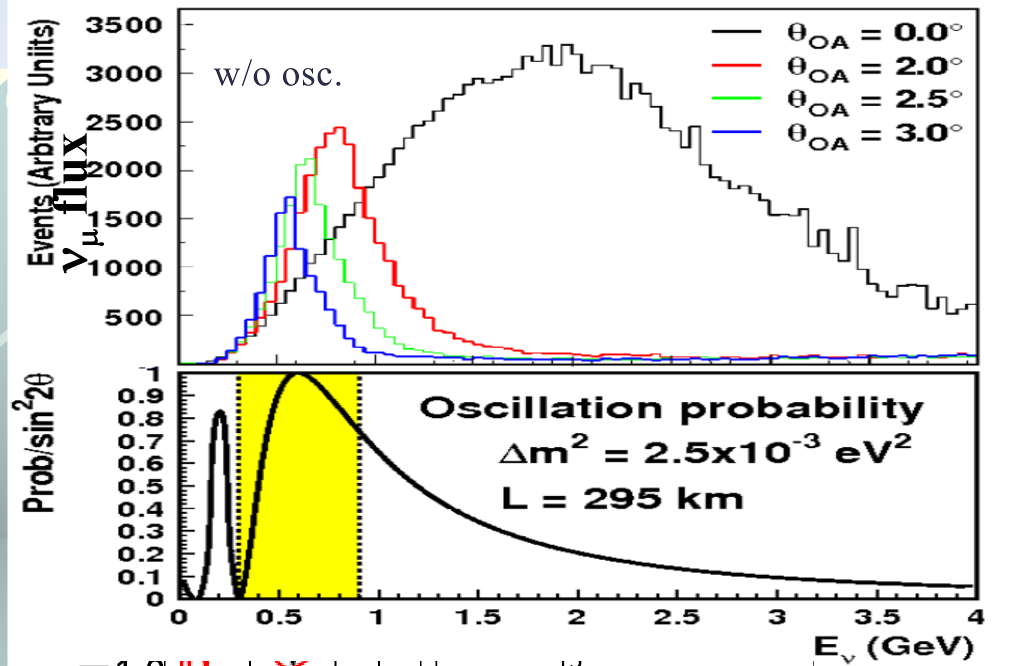


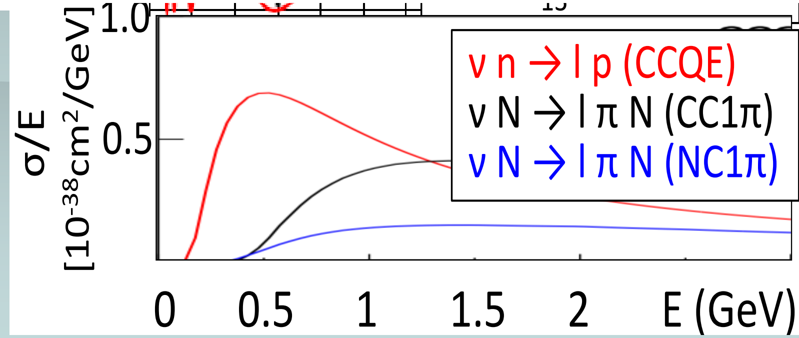
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$



$$E_\nu^{max}[\mathrm{GeV}] \approx \frac{30}{\theta[\mathrm{mrad}]}$$

- **High intensity/narrow band/tunable LE beam**
- **First application for T2K**

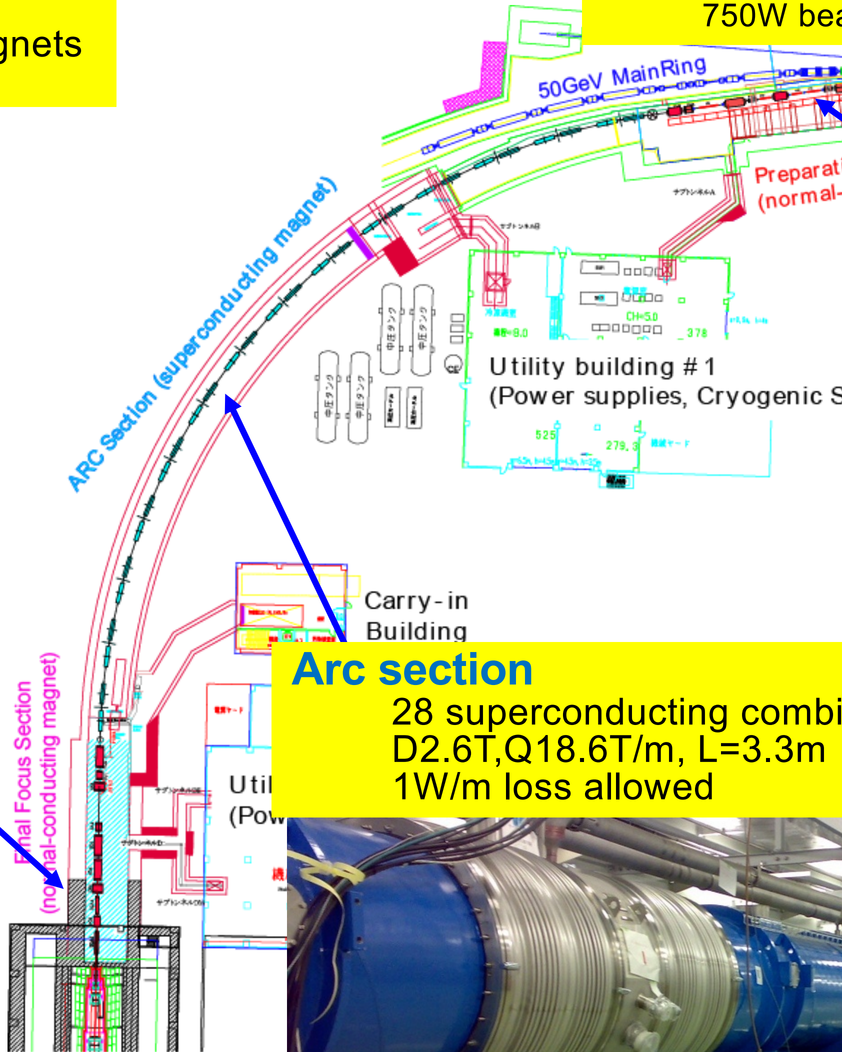




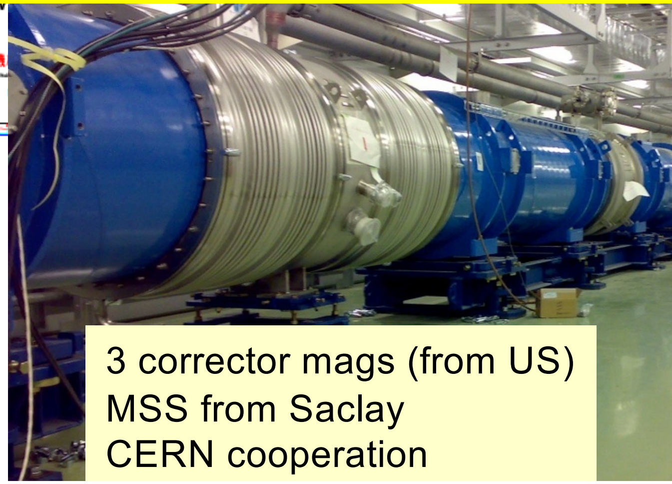
Primary beamline

Final focusing (FF) section
10 normal conducting magnets
250W loss shield

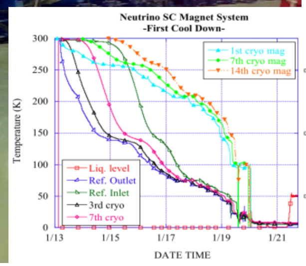
Preparation section
11 normal conducting magnets
750W beam loss shield



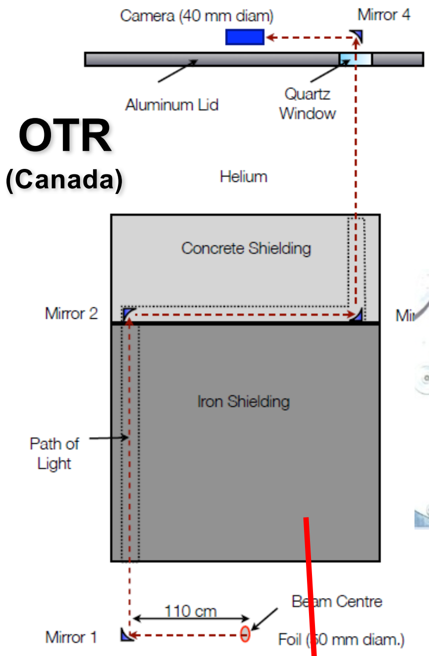
Arc section
28 superconducting combined function magnets
D2.6T,Q18.6T/m, L=3.3m
1W/m loss allowed

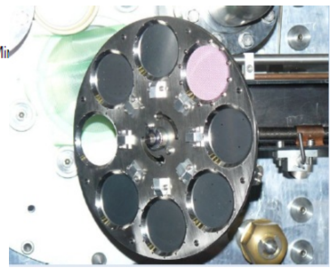


3 corrector mags (from US)
MSS from Saclay
CERN cooperation



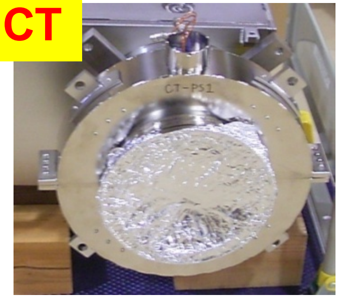
Beam Monitors



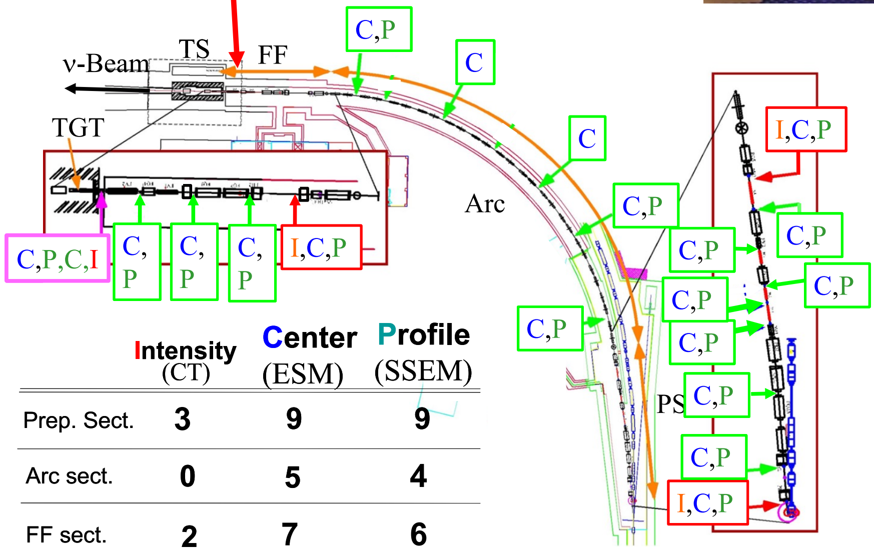


ESM

CT



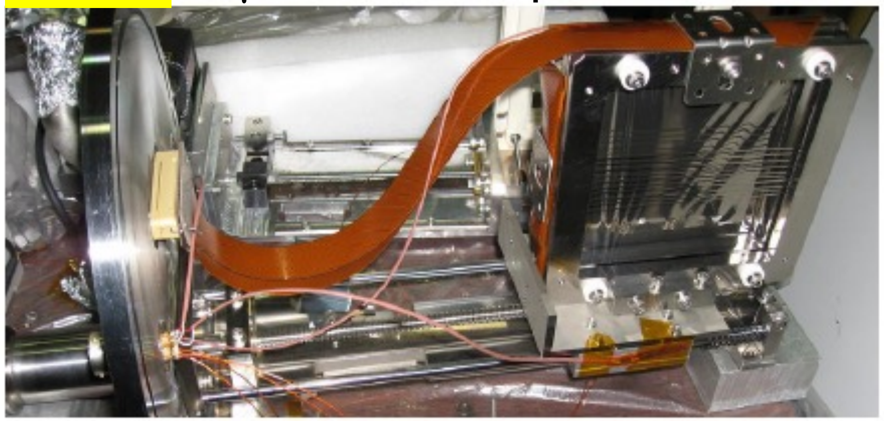
- Position:
  - 21 x Electrostatic monitors
- Profile
  - 19 x Segmented Secondary Emission monitors
- Intensity
  - 5x Current Transformers
- Loss
  - 50 x proportional counters
- Targetting
  - Optical Transition Radiation detector (Canada)
- Elec.: from US/Korea/Jp
- Beam timing: GPS (US)



	Intensity (CT)	Center (ESM)	Profile (SSEM)
Prep. Sect.	3	9	9
Arc sect.	0	5	4
FF sect.	2	7	6

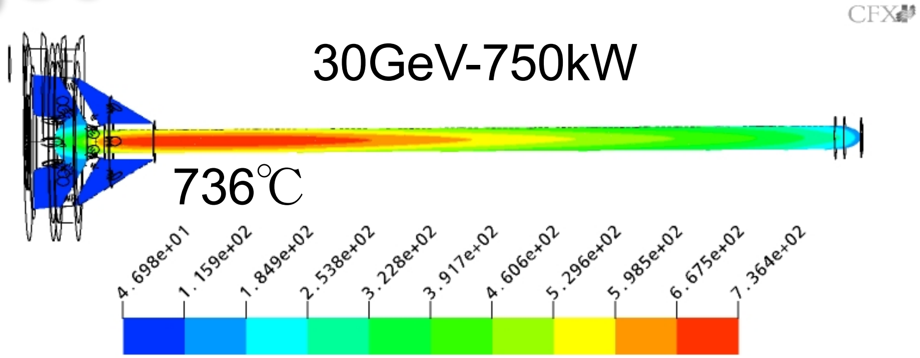
Beam loss monitor will be placed along the beam line.

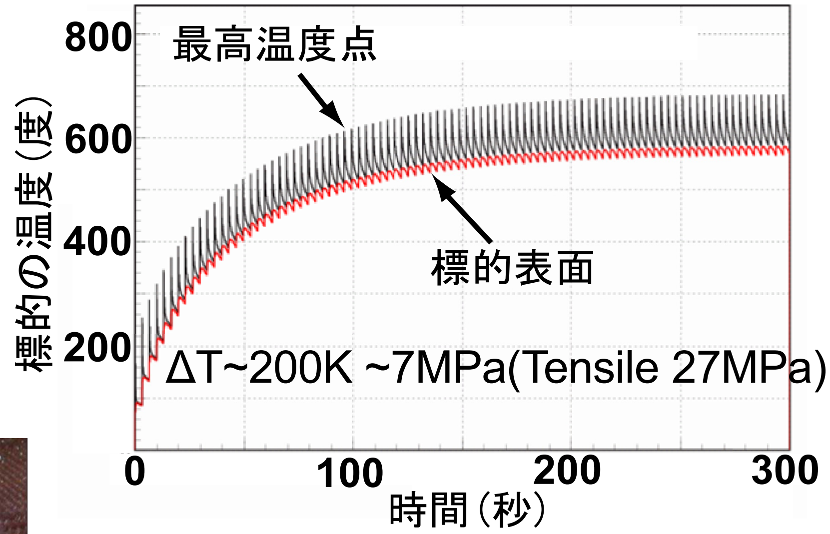
SSEM   5μm[t] Ti foil strips

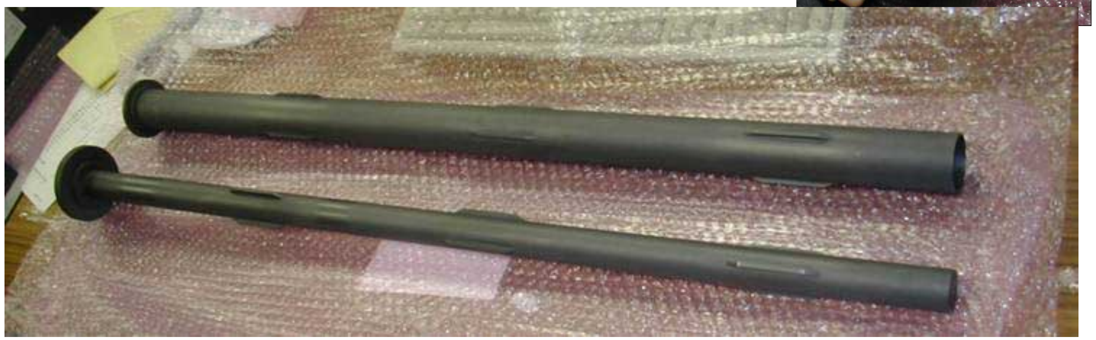


Target

- Isotropic Graphite (IG-430) 1.8g/cm3
- 26mm(D)x900mm(L)
  - 1.9 int len. (70% int.),
- Heat load: 58kJ/spill (~20kW)
- Thermal shock stress (ΔT~200K) ~ 7MPa (< tensile strength 37MPa)
- Forced flow Helium gas cooling in Ti-alloy(Ti-6 A1-4V) container
  - Higher temp = less rad. damage
  - O2 < 100ppm to avoid Oxidization (burn!) → to keep S.F.>2 for 5 yrs
- Remote maintenance
- Design done by KEK/RAL







Electromagnetic horns

- 3 horn system
- 320kA design (now 250kW)
  - 0.7ms for 1st horn
  - 2ms for 2nd/3rd (series)
- Max field: 2.1T
- Al alloy (A6061-T6)
- Heat load ~11kW@1st horn (beam+Joule)
- Water cooled.
- Design max thermal stress: 25MPa (Lorentz+Thermal) (cf. tensile stren. 282MPa)
- Fully remote maintenance

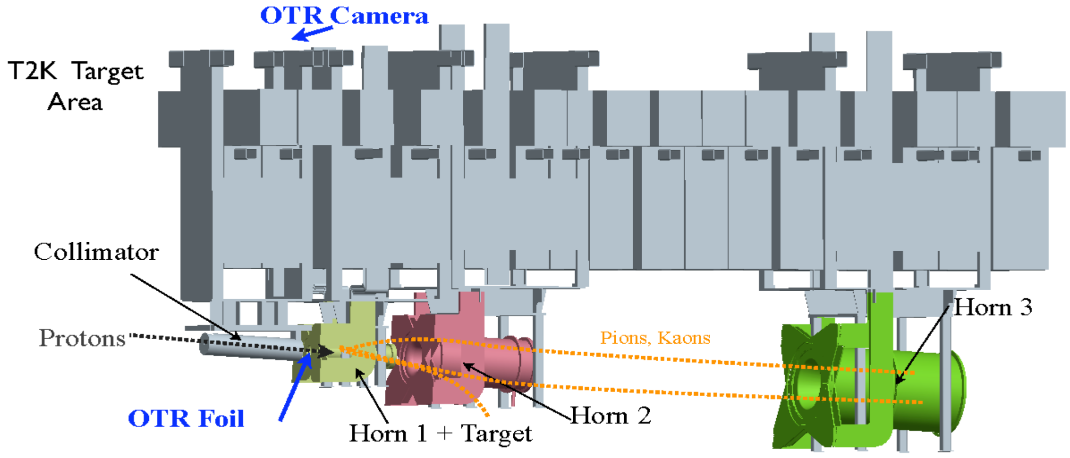
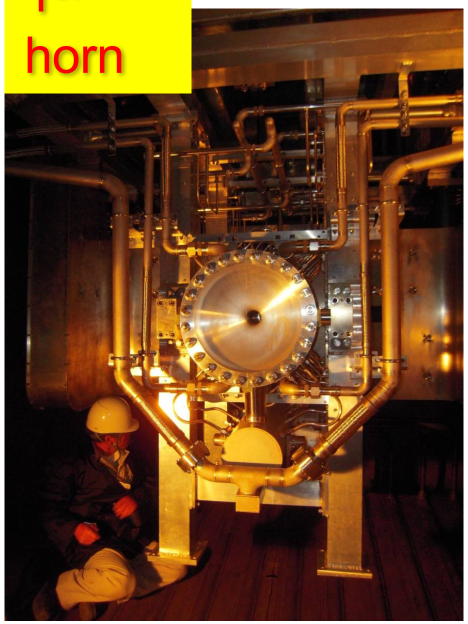


Table 3.8: Heat Load to the horns in unit of kJ/pulse.

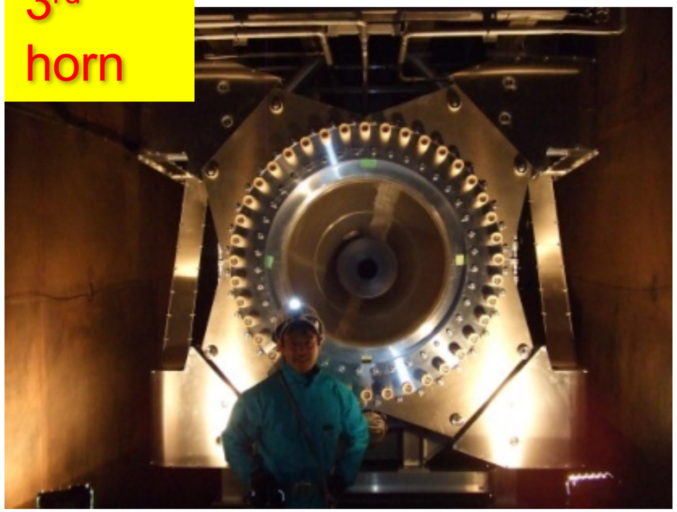
	radiaion		Joel's heat	total
	inner-conductor	outer-conductor		
1st horn	23.6	15.6	3.3	42.5(11kW)
2nd horn	6.7	12.3	3.8	22.8(6.3kW)
3rd horn	2.0	4.0	2.5	8.5(2.4kW)

1st horn

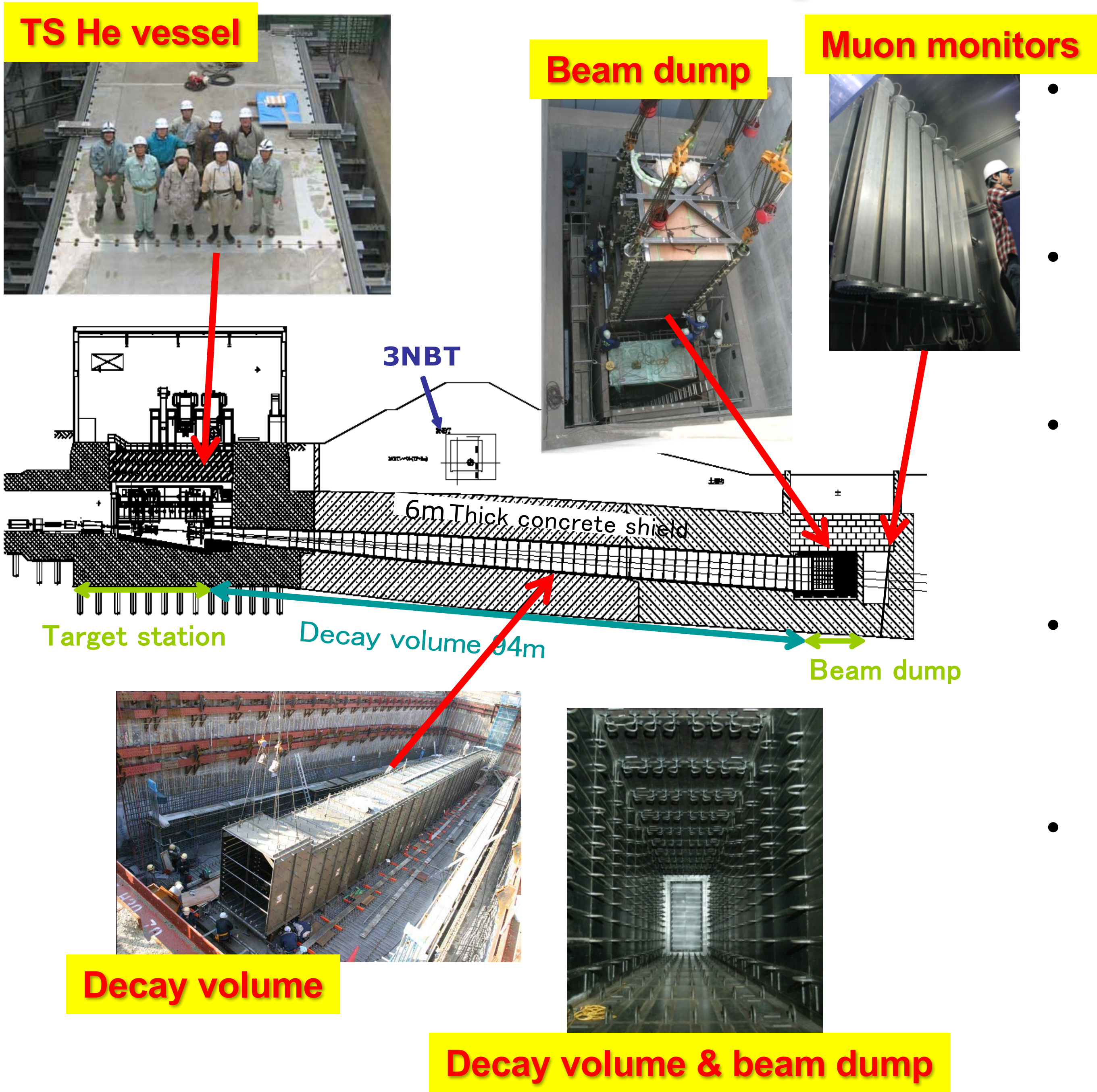


2nd horn (US)

3rd horn



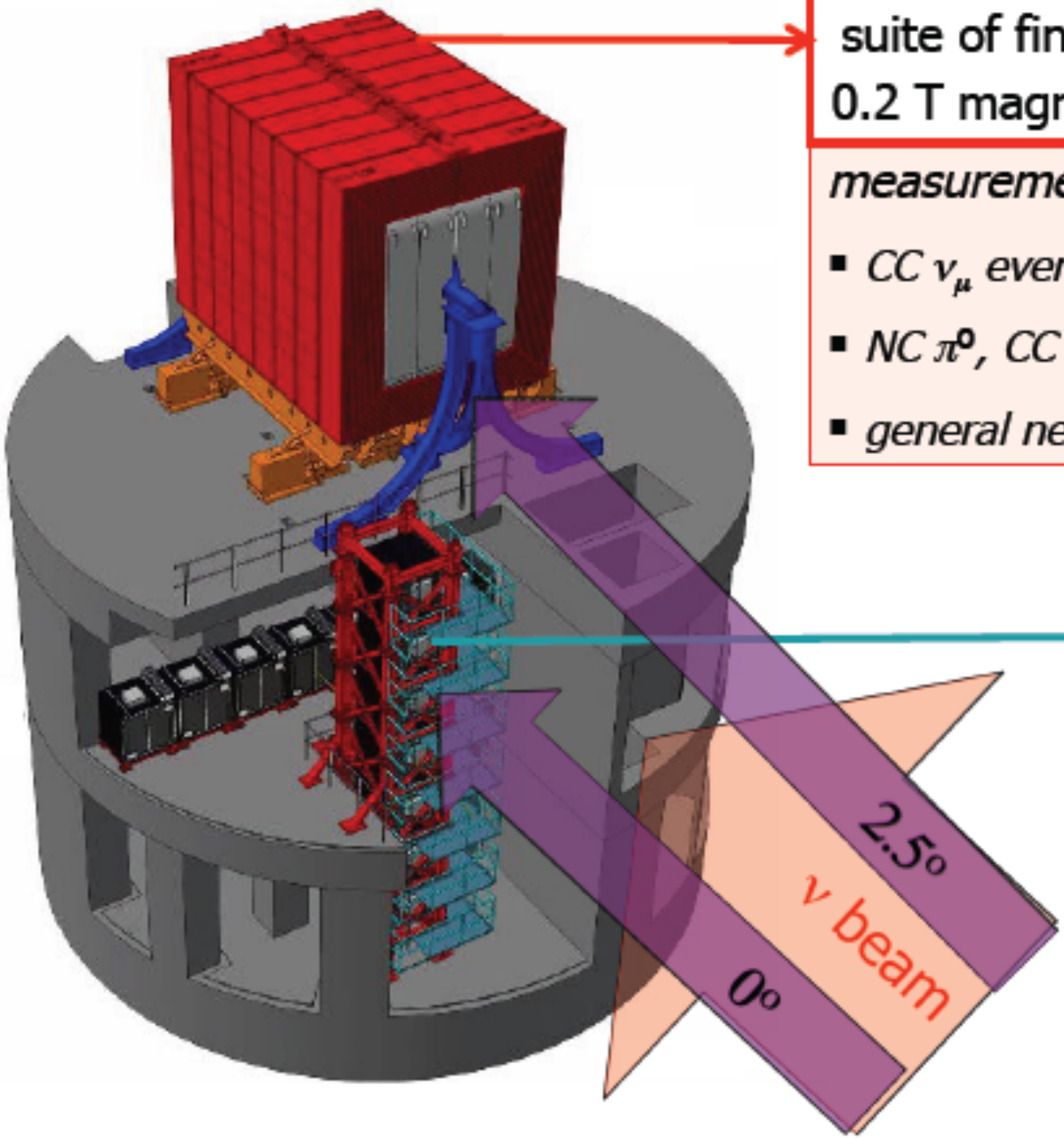
Secondary beamline



- Heat load (@750kW)
  - TS ~300kW
  - DV ~150kW
  - BD ~240kW
- Whole volume filled w/ He gas (~1000m^3)
  - Reduce NOx & ^{3}H
  - Reduce pion abs.
- All inner surfaces water cooled
  - Concrete upto ~100deg
  - Periodically waste with dilution (obey law)
- Beam dump
  - Graphite blocks
  - Water-pipe casted Al block attached to both side
  - Upto 3MW beam
- Muon monitor
  - 5GeV thresh.
  - Ionization chamber & Si
  - 7x7 grid each
  - Monitor dir/int spill-by-spill
  - Emulsion

Near detectors

ND280



Off-Axis (ND280)
suite of fine grain detectors/tracker in 0.2 T magnetic field (UA1/NOMAD magnet)

measurements of

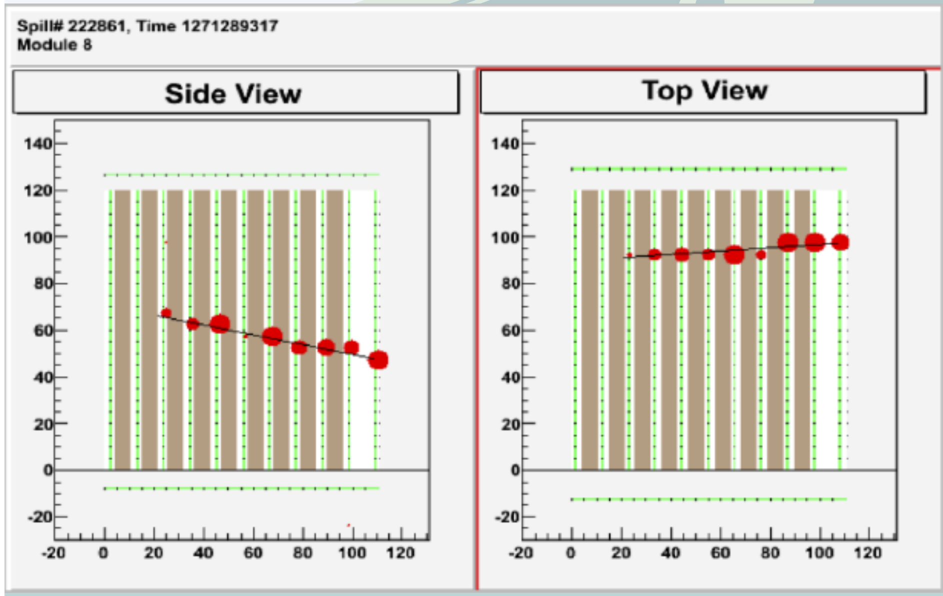
- *CC ν_μ events* (normalization, E_ν-spectrum)
- *NC π^0, CC ν_e events* (backgrounds to ν_e appearance)
- *general neutrino interaction properties*

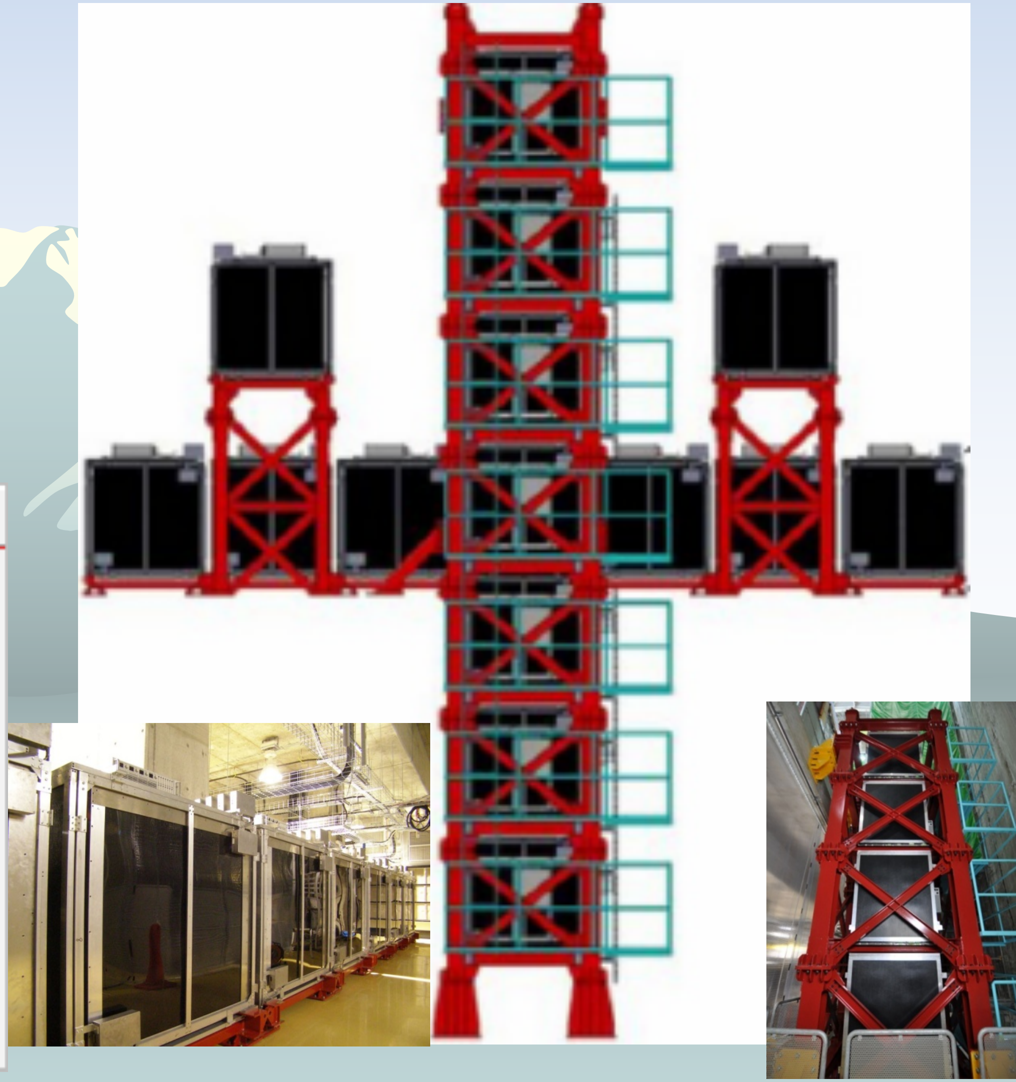
On-axis (INGRID)
scintillator-iron detectors

measurement of beam direction and profile

On-axis INGRID detector

- Placed on beam axis at 280m from target
- Iron plates + Scintillator bar tracker
- Measure neutrino interaction rate & beam profile
  - Monitor beam intensity & direction

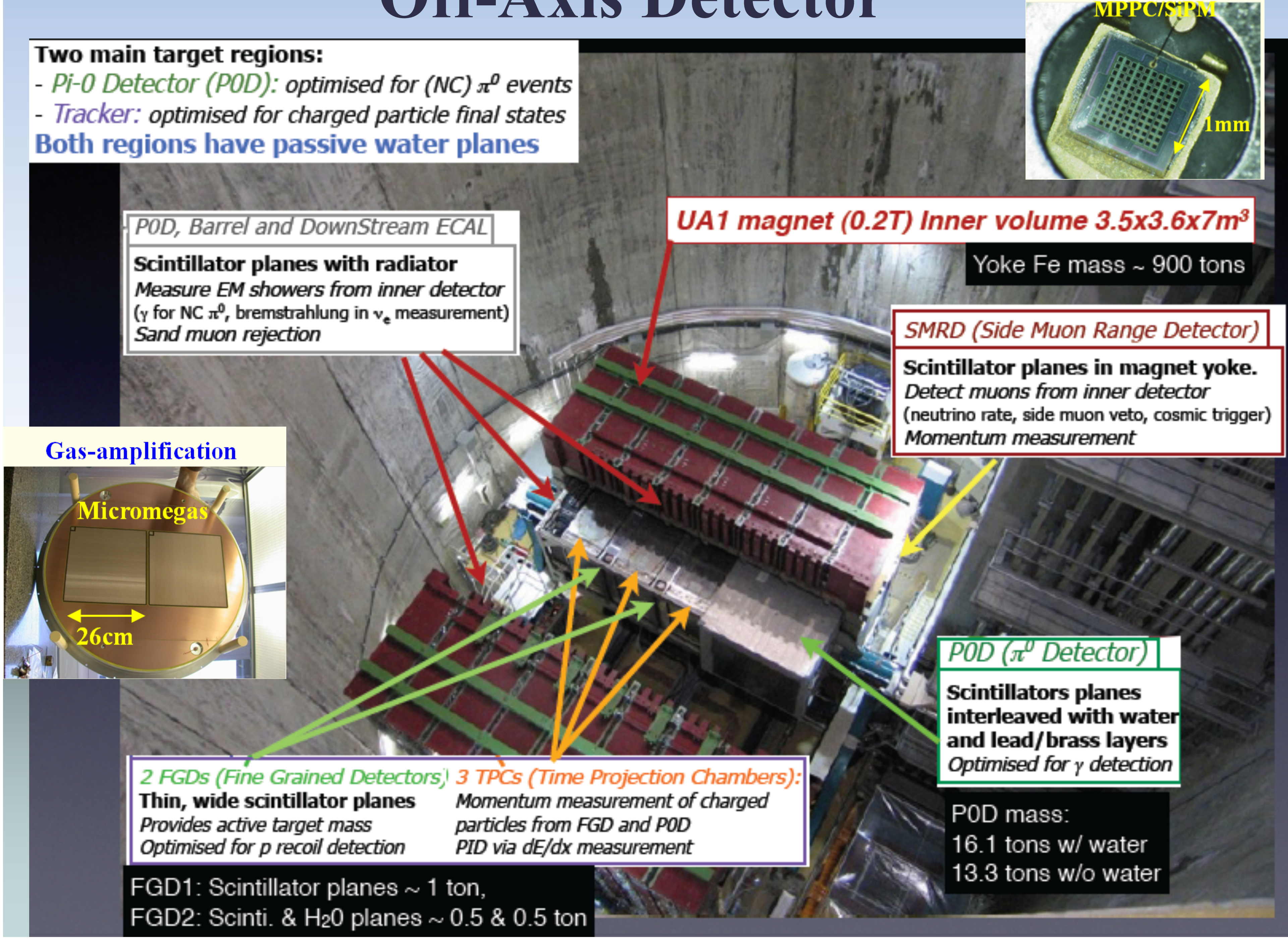




Off-Axis Detector

Two main target regions:
- *Pi-0 Detector (P0D): optimised for (NC) π^0 events*
- *Tracker: optimised for charged particle final states*

Both regions have passive water planes



P0D, Barrel and DownStream ECAL

Scintillator planes with radiator
Measure EM showers from inner detector
(γ for NC π^0, bremstrahlung in ν_e measurement)
Sand muon rejection

UA1 magnet (0.2T) Inner volume 3.5x3.6x7m^3

Yoke Fe mass ~ 900 tons

SMRD (Side Muon Range Detector)

Scintillator planes in magnet yoke.
Detect muons from inner detector
(neutrino rate, side muon veto, cosmic trigger)
Momentum measurement

P0D (π^0 Detector)

Scintillators planes interleaved with water and lead/brass layers
Optimised for γ detection

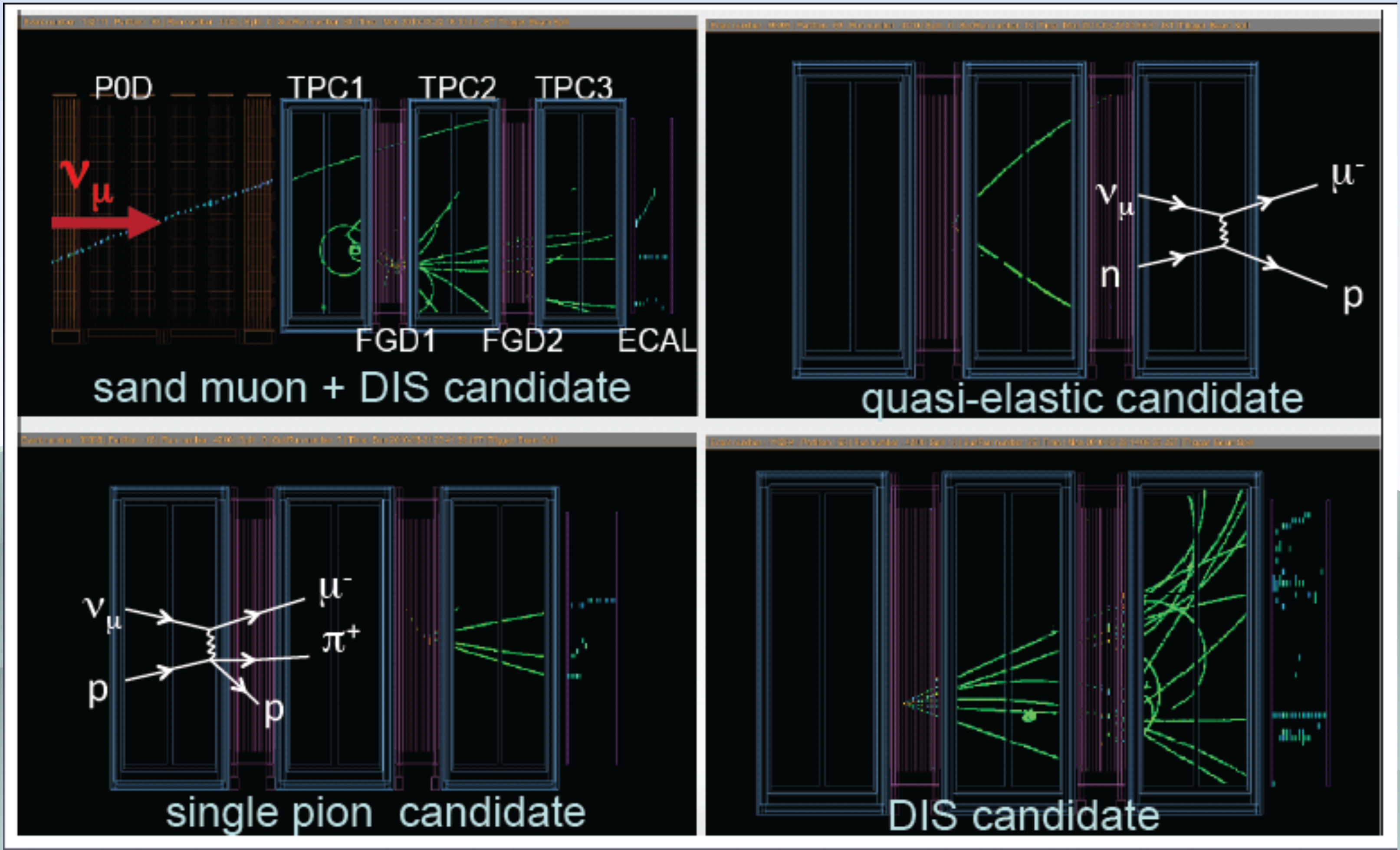
P0D mass:
16.1 tons w/ water
13.3 tons w/o water

2 FGDs (Fine Grained Detectors)
Thin, wide scintillator planes
Provides active target mass
Optimised for p recoil detection

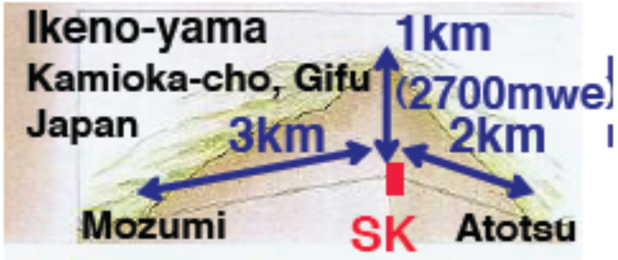
3 TPCs (Time Projection Chambers):
Momentum measurement of charged particles from FGD and P0D
PID via dE/dx measurement

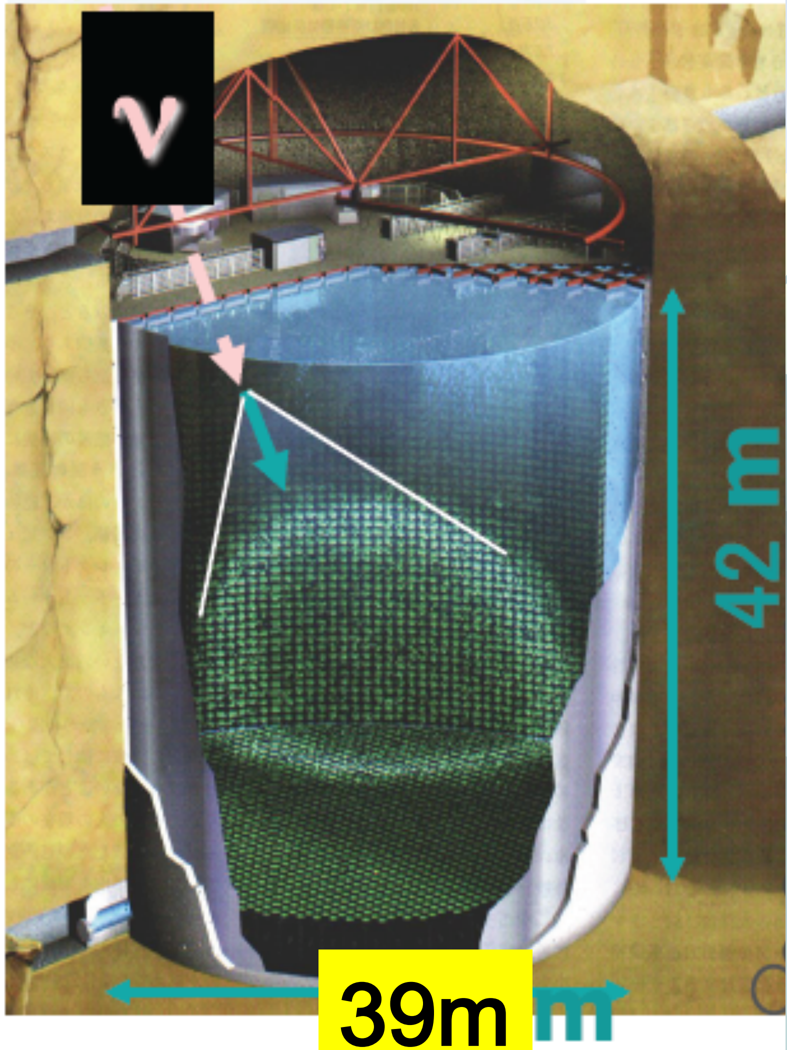
FGD1: Scintillator planes ~ 1 ton,
FGD2: Scinti. & H_20 planes ~ 0.5 & 0.5 ton

ND280 off-axis event gallery

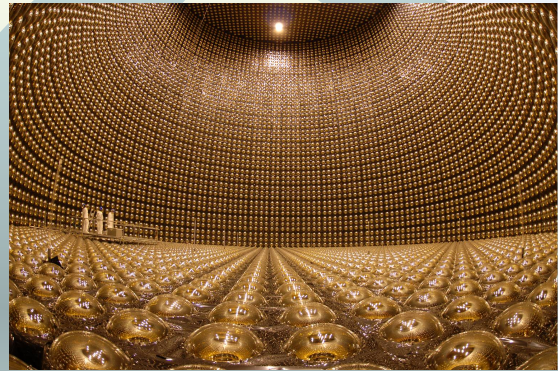


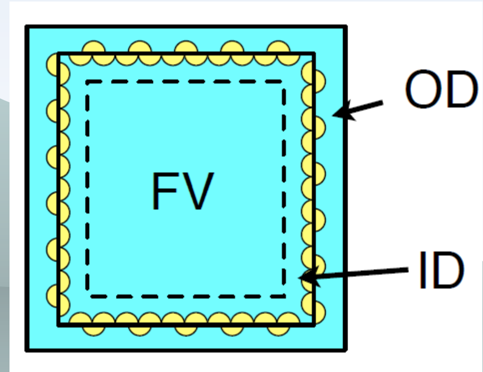
Far Detector: Super-Kamiokande



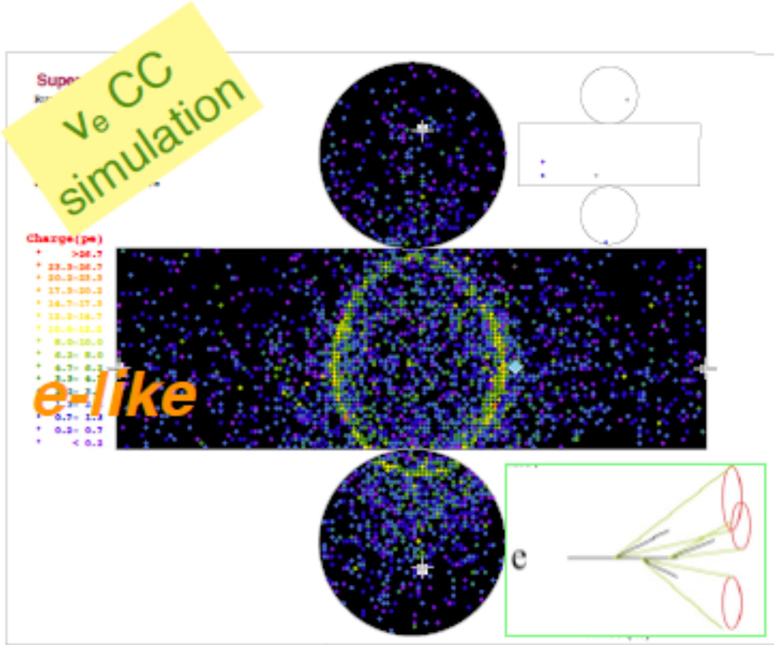


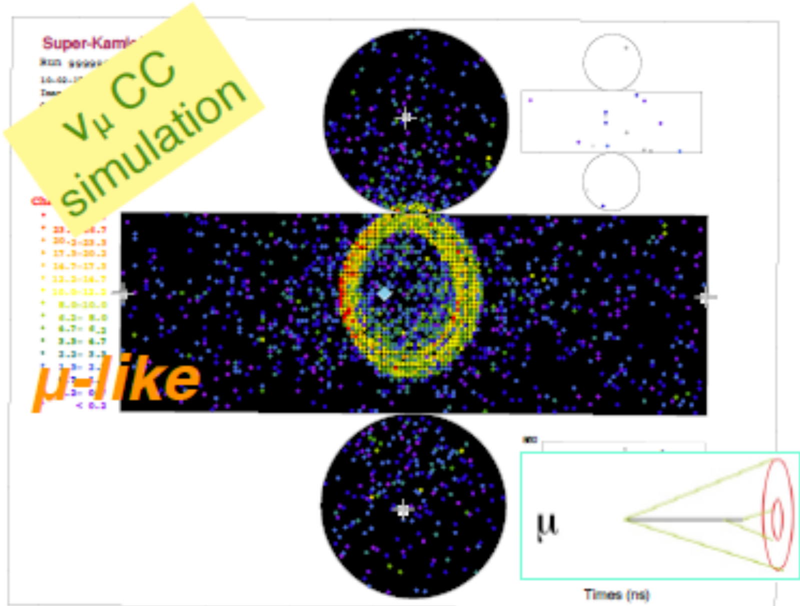
- Water Cherenkov detector operational since 1996
- Total volume: 50kton (Fiducial volume: 22.5kton)
- 11129 20" PMTs in inner detector (ID)
- 1885 8" PMTs in outer detector (OD)
- New dead time less readout electronics since 2008 summer.
- T2K event trigger by accelerator timing sent online



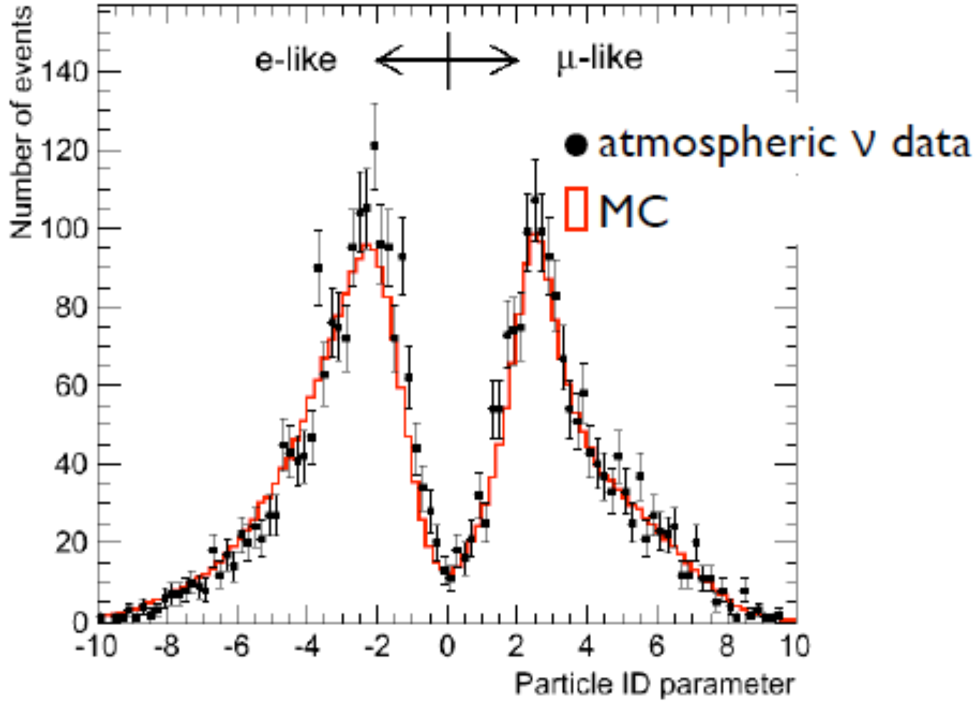


Electron-like and muon-like event at SK



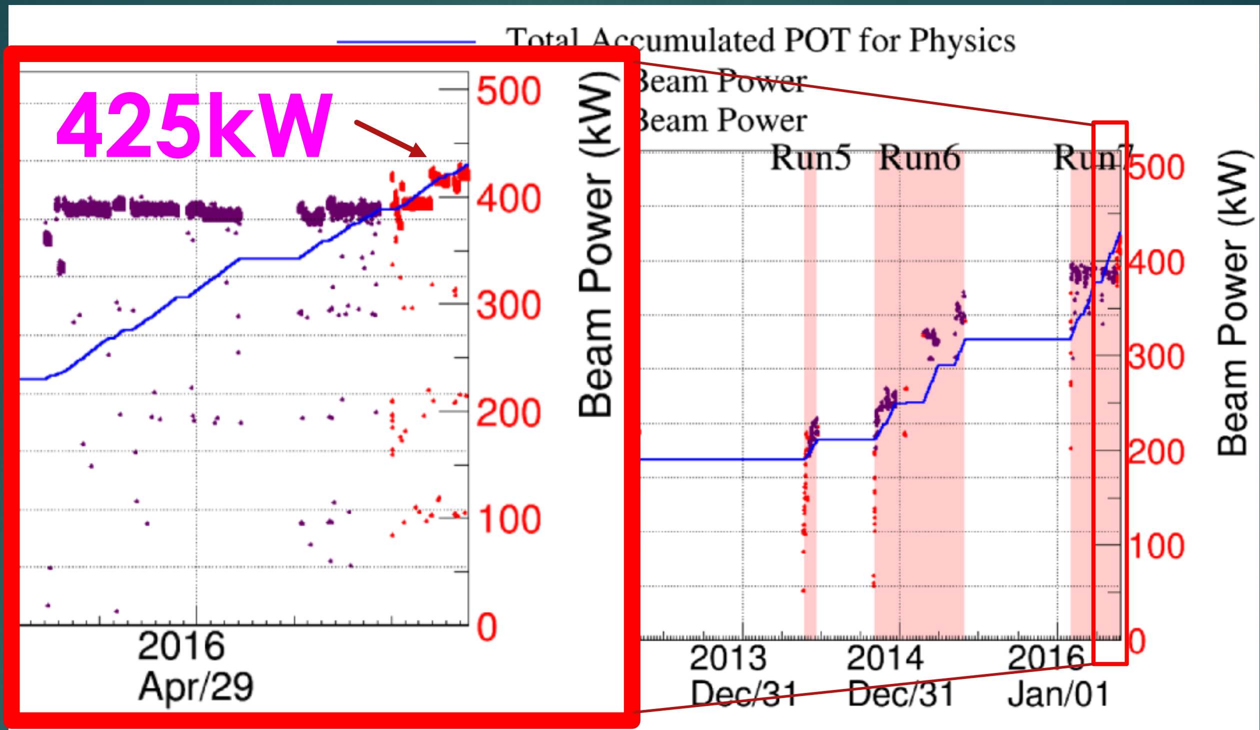


Particle identification using ring shape & opening angle



Probability that μ is mis-identified as electron is ~1%

Data taking history



- Stable operation at **425kW** achieved (first design goal: 750kW)
  - (Ep=30GeV) x (**220Tp**/5us pulse) x (2.48sec cycle) World record!
- Number of protons on target (POT)
  - 15.1×10^{20} accumulated (7.6×10^{20} for nu & 7.5×10^{20} anti-nu)
  - 78×10^{20} aimed as original T2K goal
- **Aim to operate 440kW and beyond after Summer 2016 at newly established operation parameter with higher stability**

Experimental principle

- **Predict SK observations (ν_μ, ν_e): $N_{\mu/e}(p_\nu,P_{osc})$ BASED ON T2K ND280 &NA61 measurements as precisely as necessary**

Flux at SK — Osc. Prob. — Cross sect. — Det. Eff. — SK Det. Response

$$N_{SK}^{pred}\left(\boldsymbol{p}_\nu\right) = \Phi_{SK}^{\exp}\left(E_\nu^{true}\right)\cdot P_{osc}\left(E_\nu^{true}\right)\cdot \sigma_{SK}\left(\boldsymbol{p}_\nu\right)\cdot \varepsilon_{SK}\left(\boldsymbol{p}_\nu\right)\cdot f\left(\boldsymbol{p}_\nu, E_\nu^{true}\right)$$

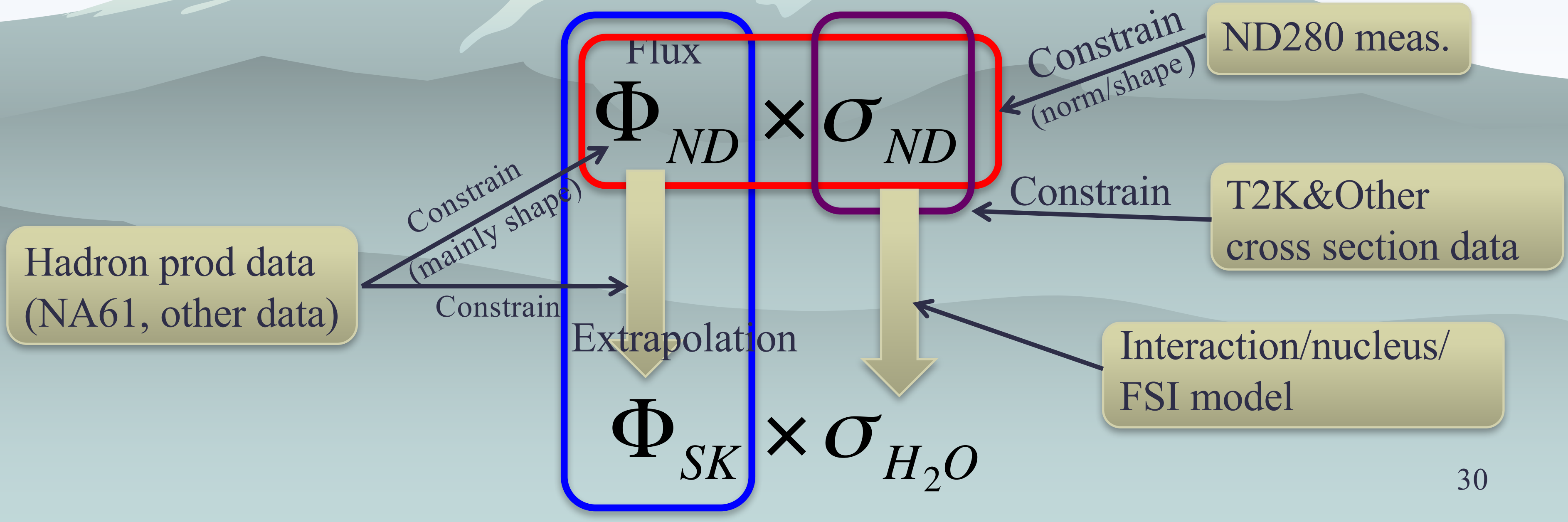
$\boldsymbol{p}_\nu^{rec}$: Measured kinetic variables of ν eg. E_ν or (p_ν,θ_ν)

E_ν^{true}: True neutrino energy

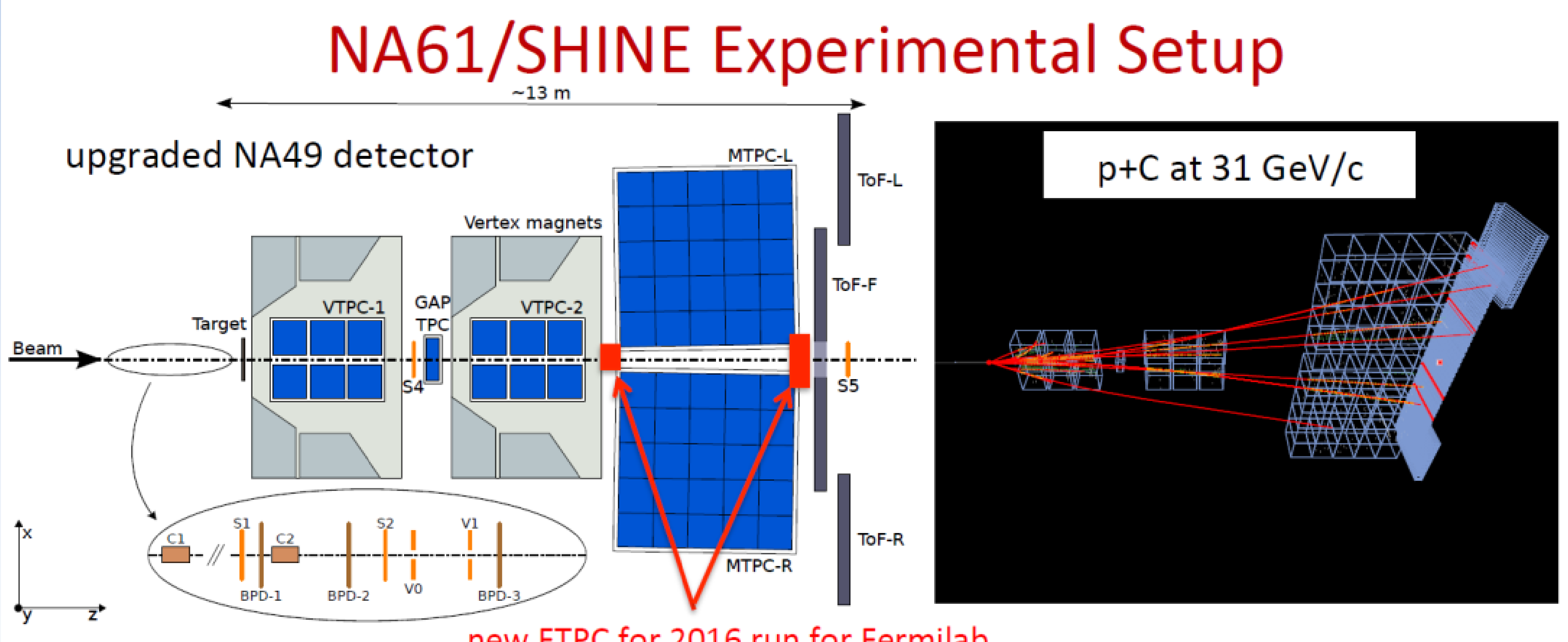
$\Updownarrow$

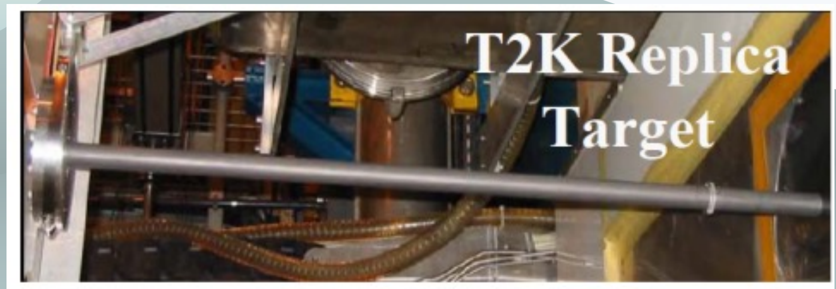
$$N_{SK}^{obs}\left(\boldsymbol{p}_\nu\right)$$

Then compare w/ SK observation ➔ Measure excess or constrain oscillation parameters



Hadron production measurements



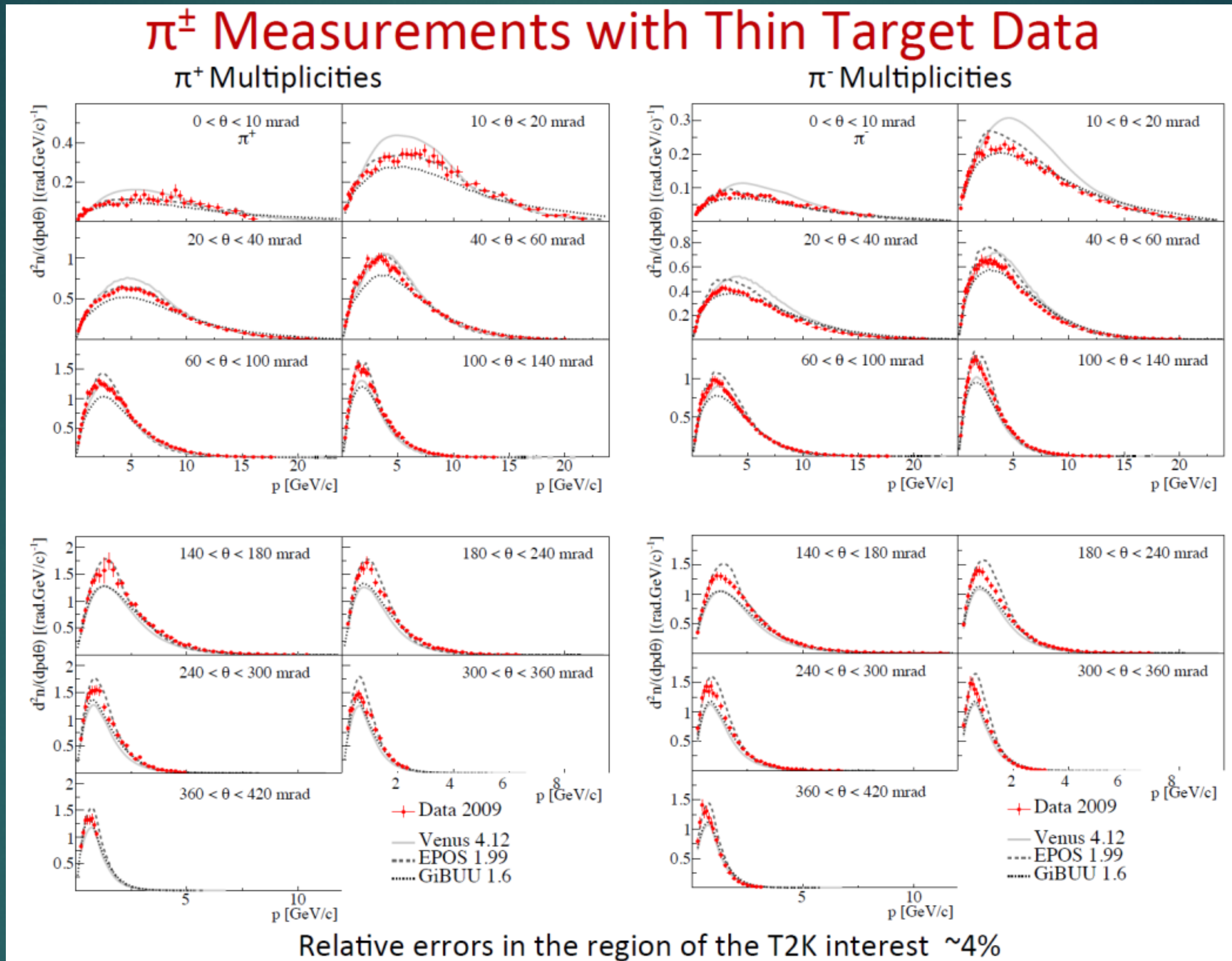


- The NA61/Shine experiment @ CERN
- Hadron production from 30GeV protons on carbon
- Measurements
  - Thin target (2cmt)
  - Thick replica taget (90cm)

Data to constrain T2K flux:

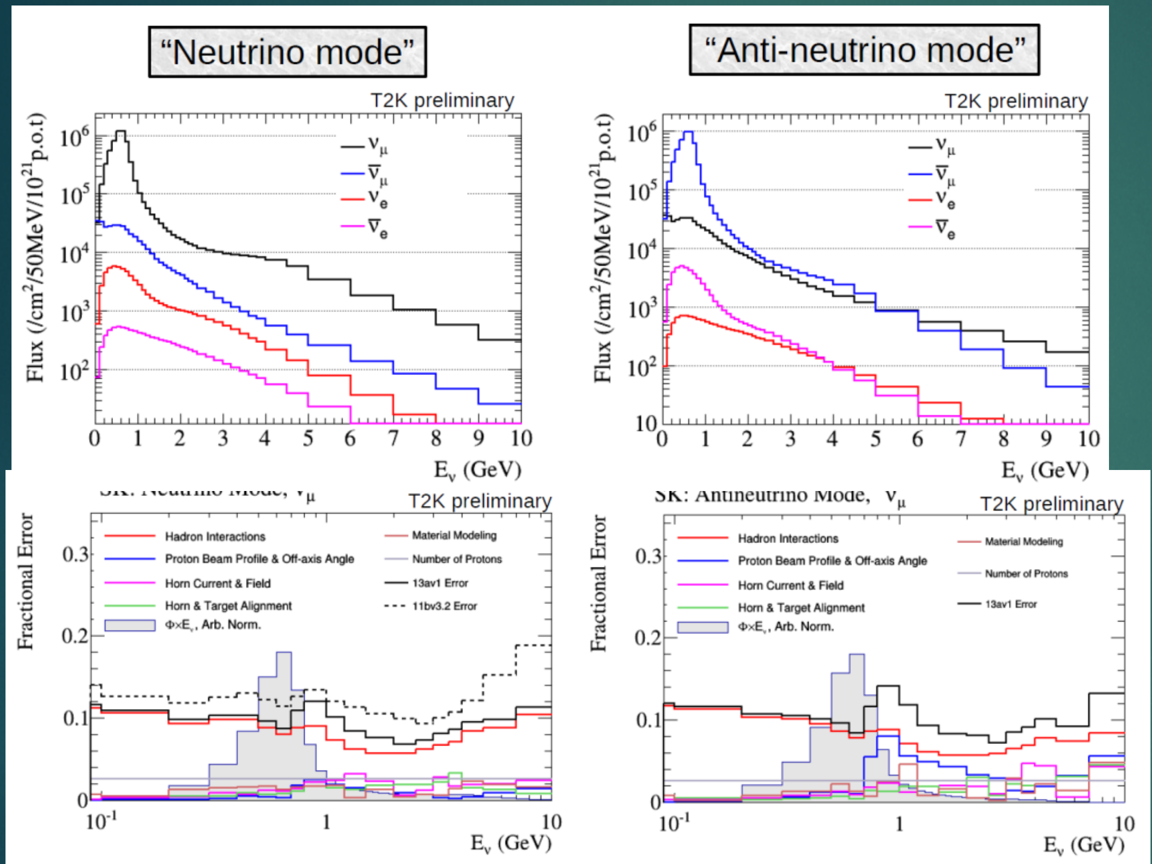
Beam+Target	p[GeV/c]	Year	$N_{triggers}$ [10^6]
p+C	31	2007	0.7
p+T2K Replica	31	2007	0.2
p+C	31	2009	5.4
p+T2K Replica	31	2009	2.8
p+T2K Replica	31	2010	10.0

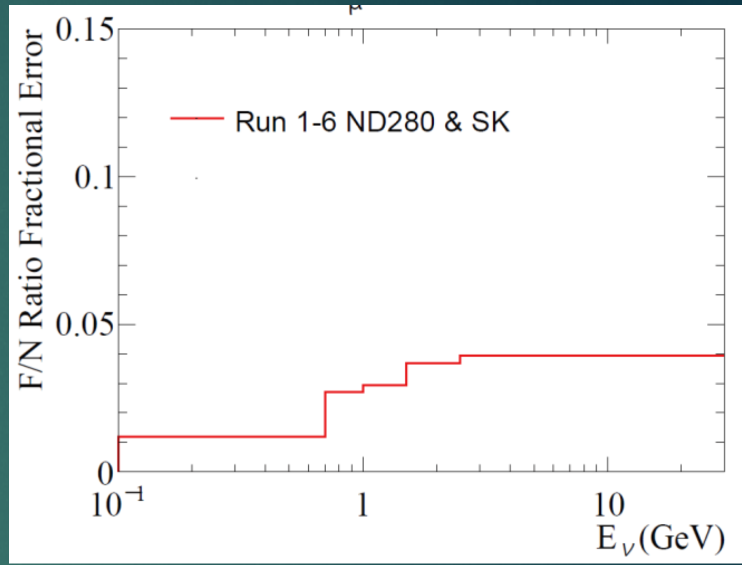
Results from thin target



- Comprehensive precise measurements
- Indispensable to predict flux/flux extrapolation precisely based on data

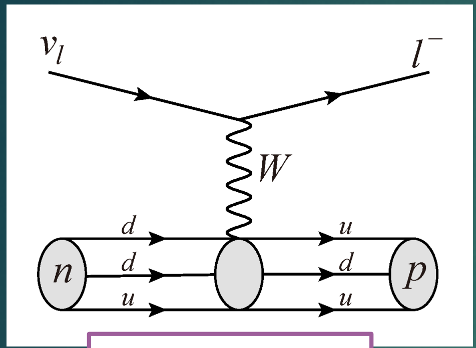
Neutrino flux predictions





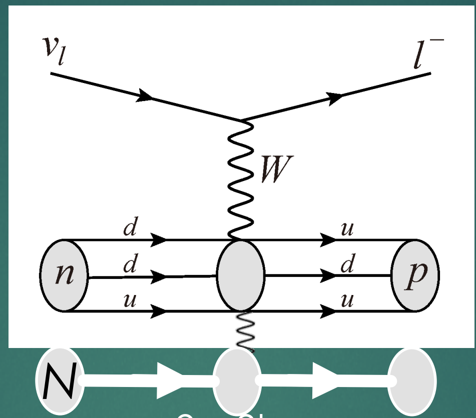
- Absolute flux prediction with ~10% uncertainties
- Near to far extrapolation ~ a few % level

Neutrino interactions and energy reconstruction

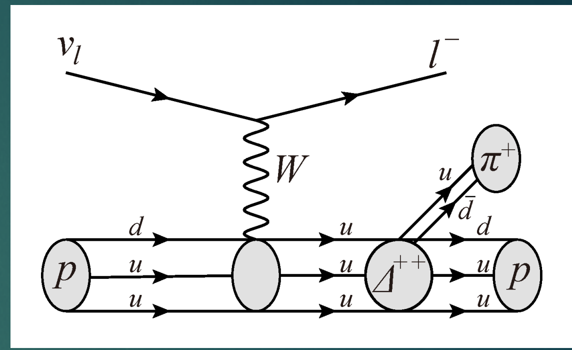


Main Signal

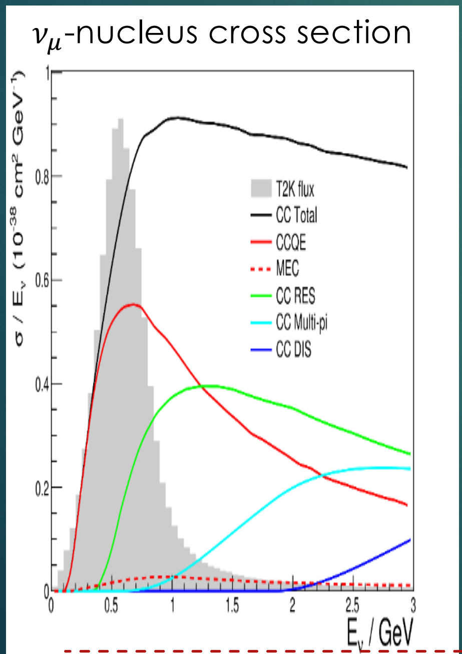
CCQE
(Charged Current Quasi-Elastic)



2p-2h



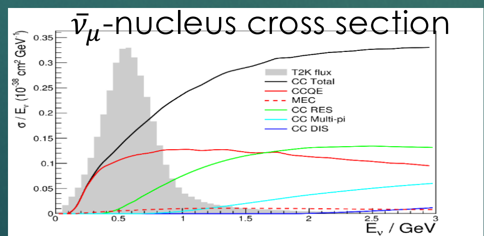
CC resonant-pion production

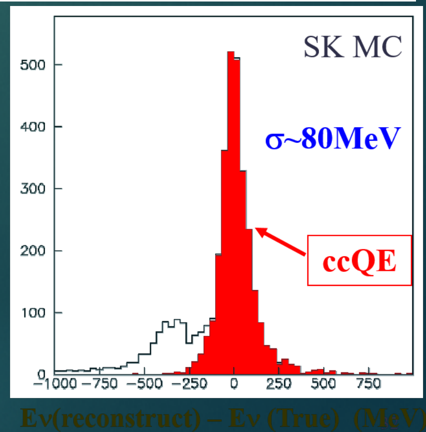


Assume CCQE(2body), from lepton 4-mom.,

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

$\bar{\nu}$ cross section is ~1/3 of ν

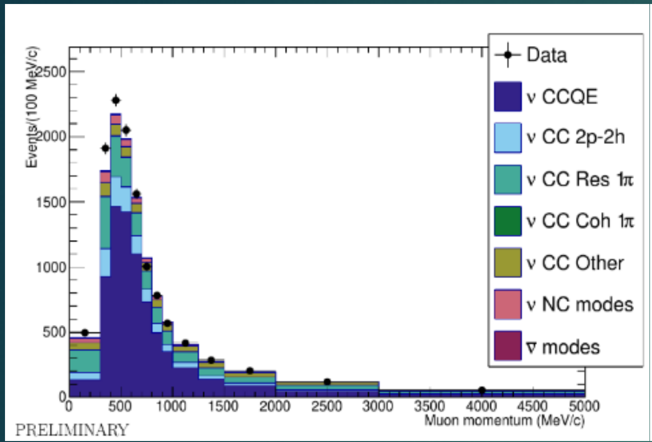


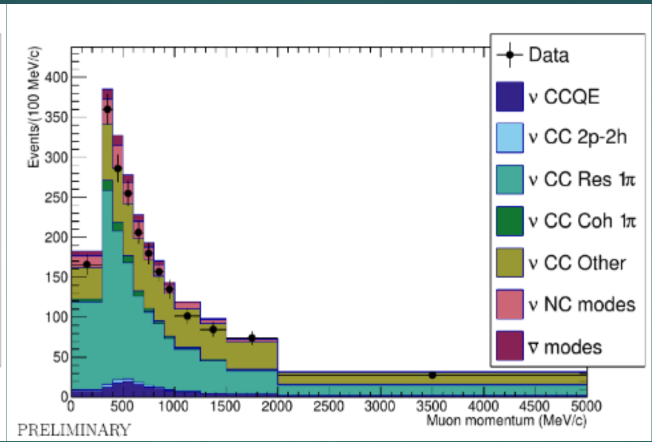


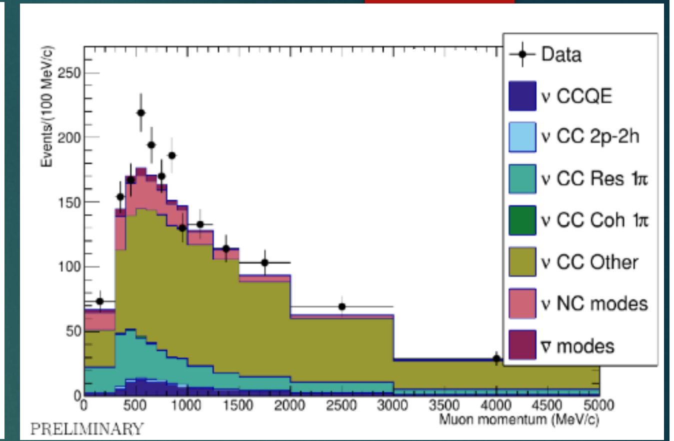
CC0π sample

CC1π+ sample

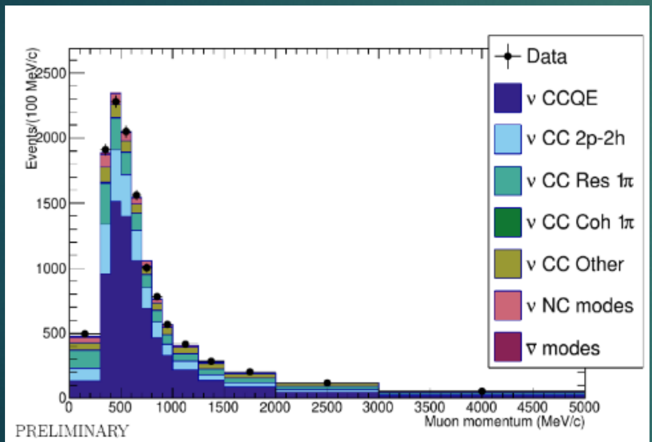
CC other sample

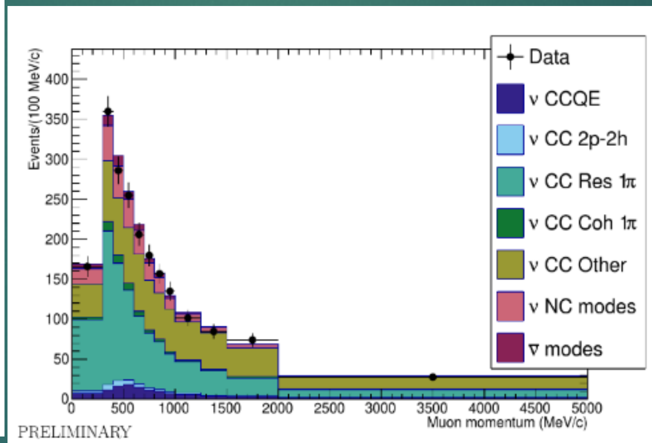


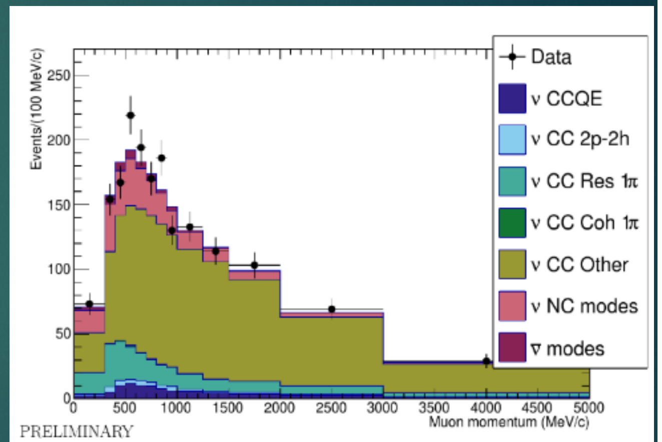




tuning flux and cross section by fitting data ((p, θ) distribution of samples)



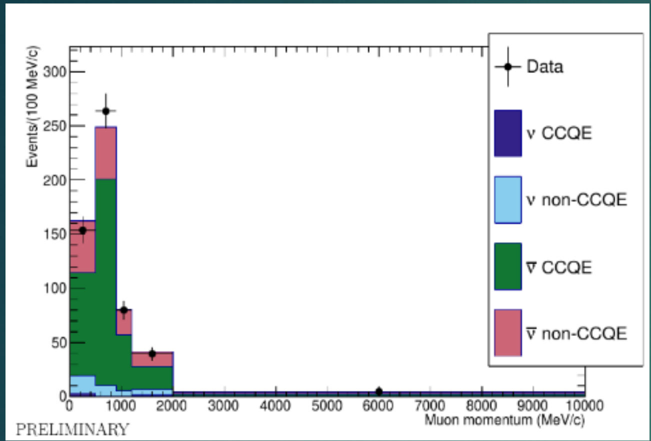




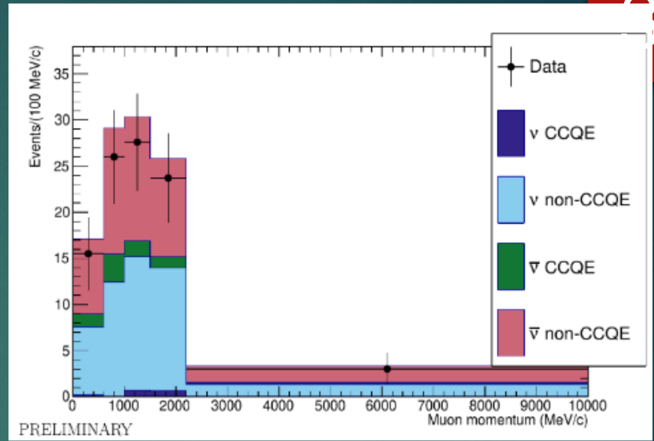
neutrino measurement at ND280

antineutrino measurement at ND280

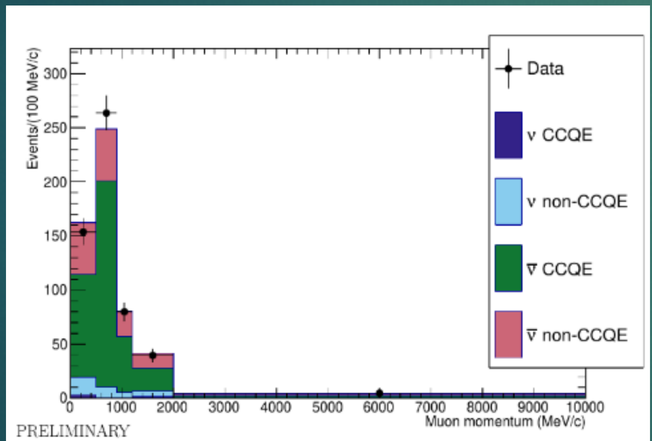
CC 1track sample

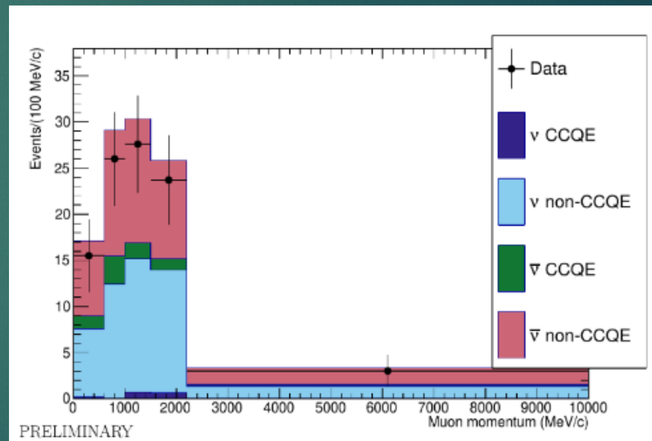


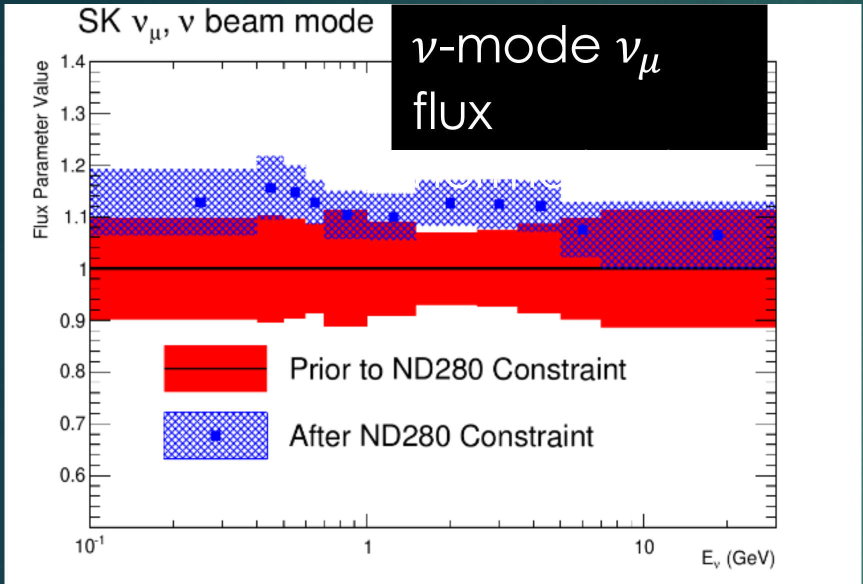
CC >1 track sample

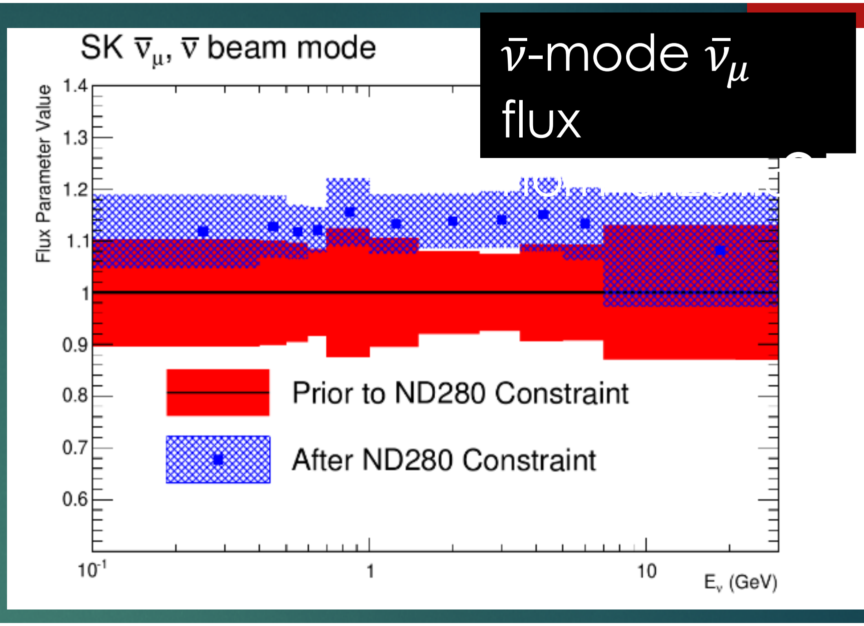


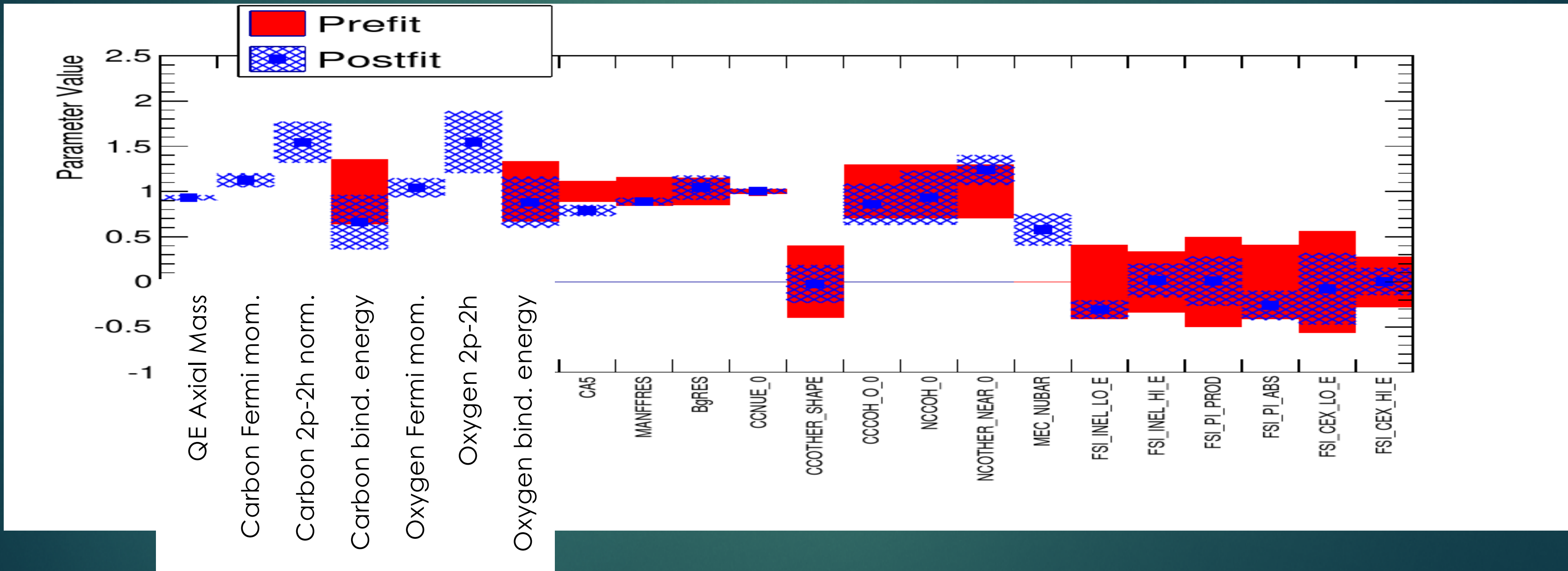
tuning flux and cross section by fitting data ((p, θ) distribution of samples)







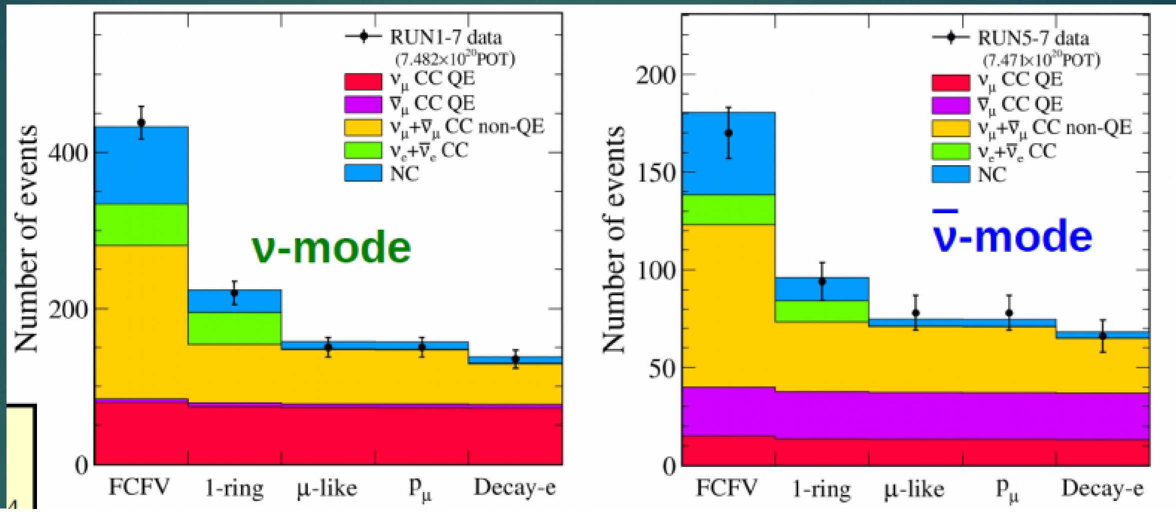


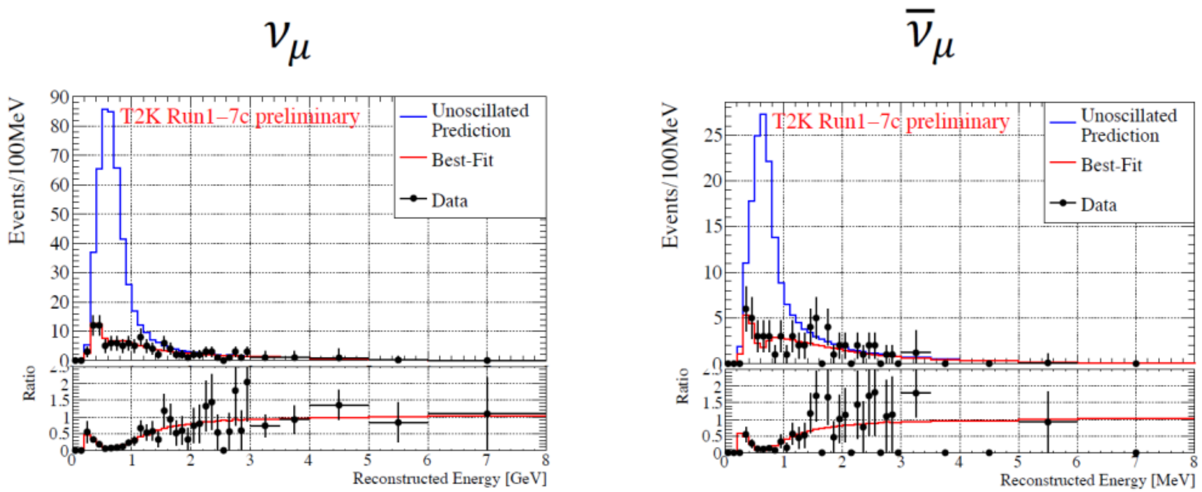


flux and cross section tuning by ND280 data

Far detector & oscillation analysis

(anti-)nu disappearance





135 events observed

(+10 events since Neutrino 2016)

(135.8 events expected)

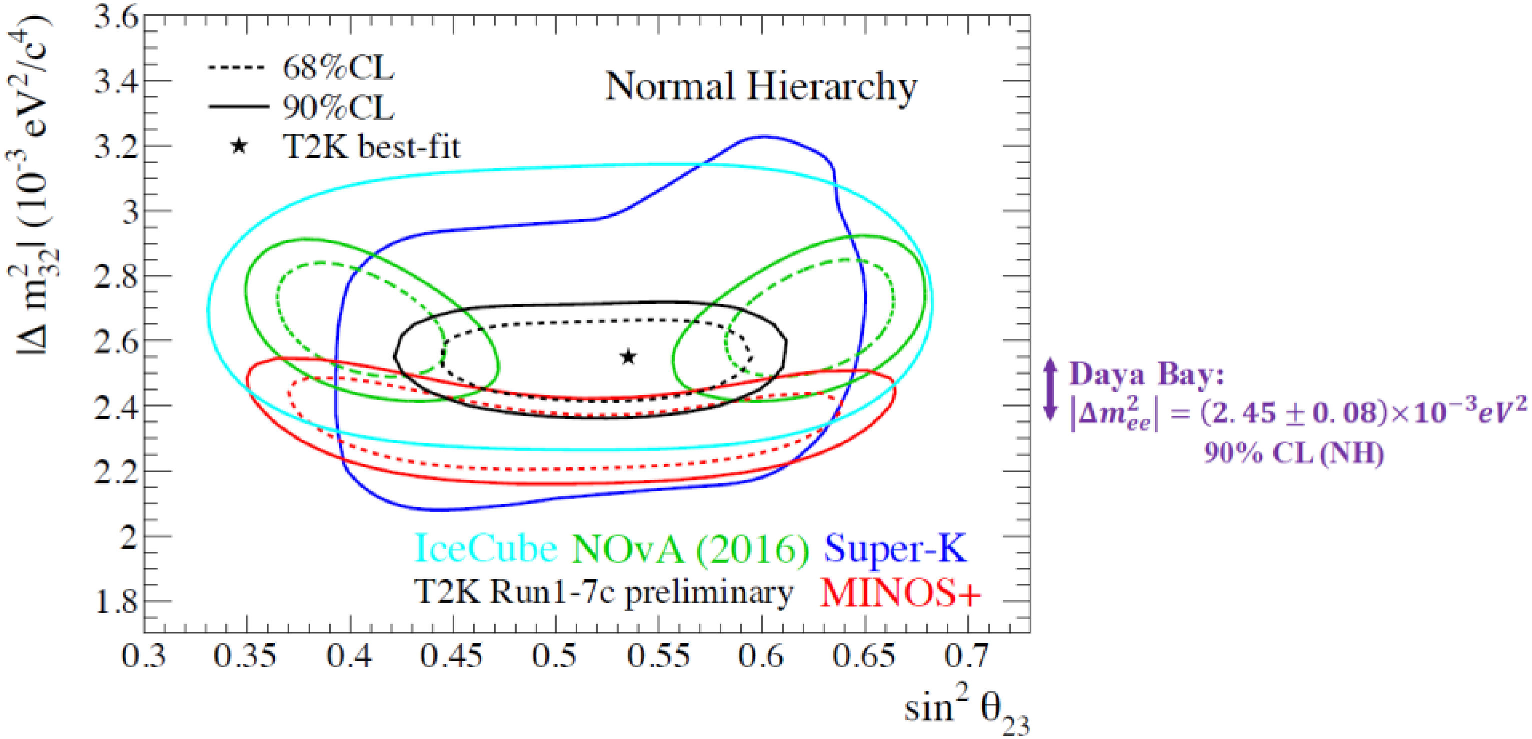
66 events observed

(64.2 events expected)

(anti-)nu disappearance

θ_{23} and Δm^2_{32}

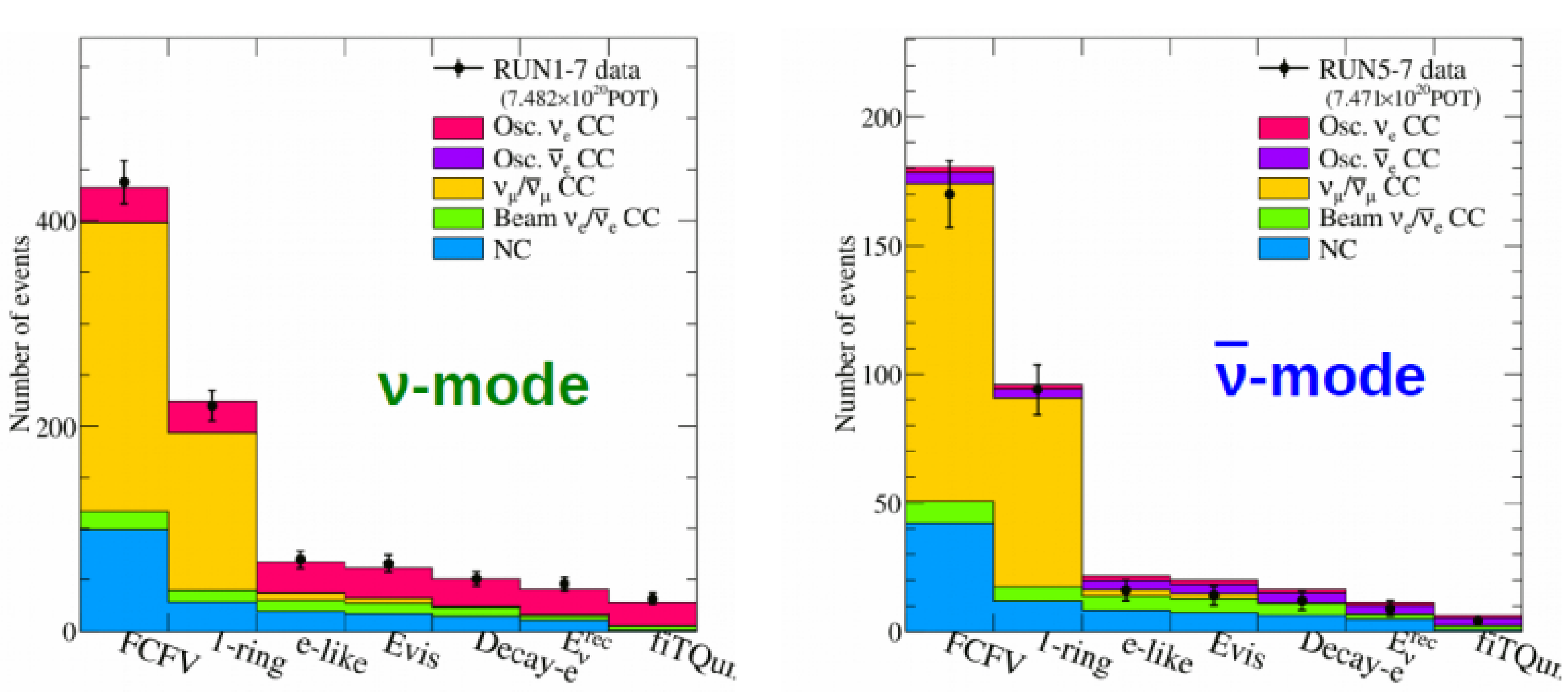
- Consistent with maximal mixing



	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$\lvert\Delta m^2_{32}\rvert[10^{-3}\mathrm{eV}^2]$	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

(Anti-)ν_e appearance

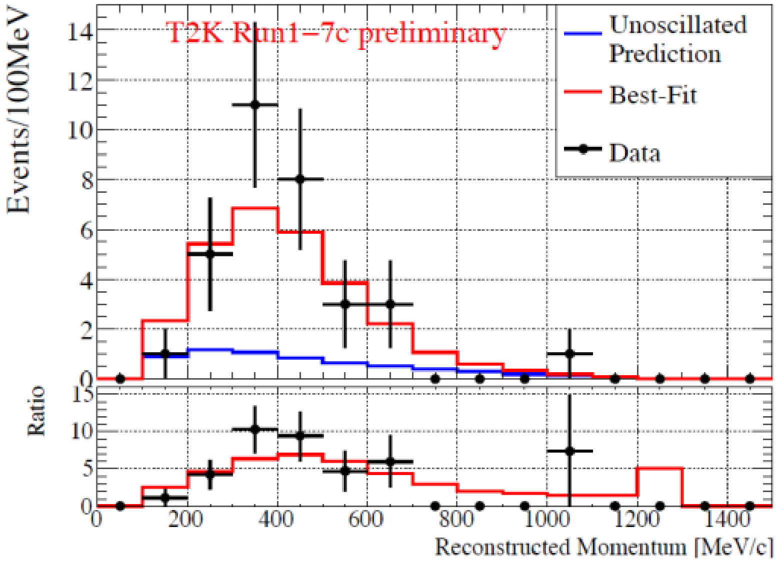
Event selection



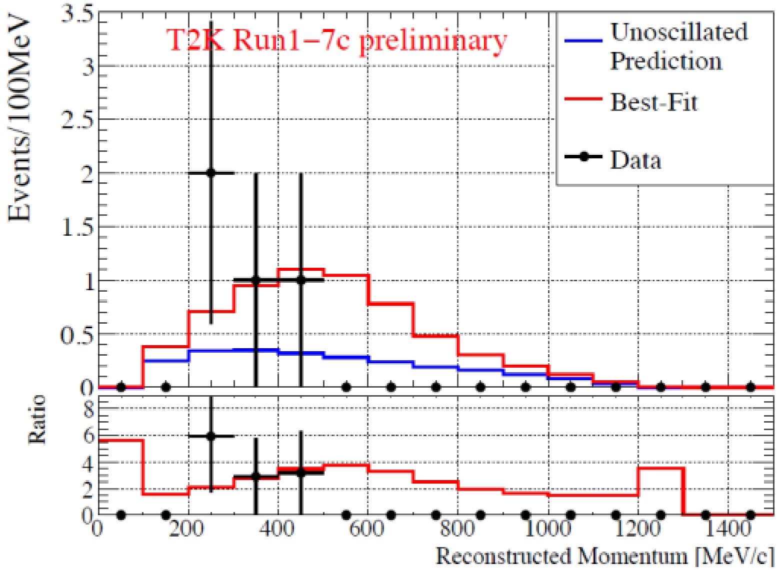
(Anti-)ν_e appearance

Full Joint Fit Analysis

ν_e



$\bar{\nu}_e$



32 events observed

(+0 events since Neutrino 2016)

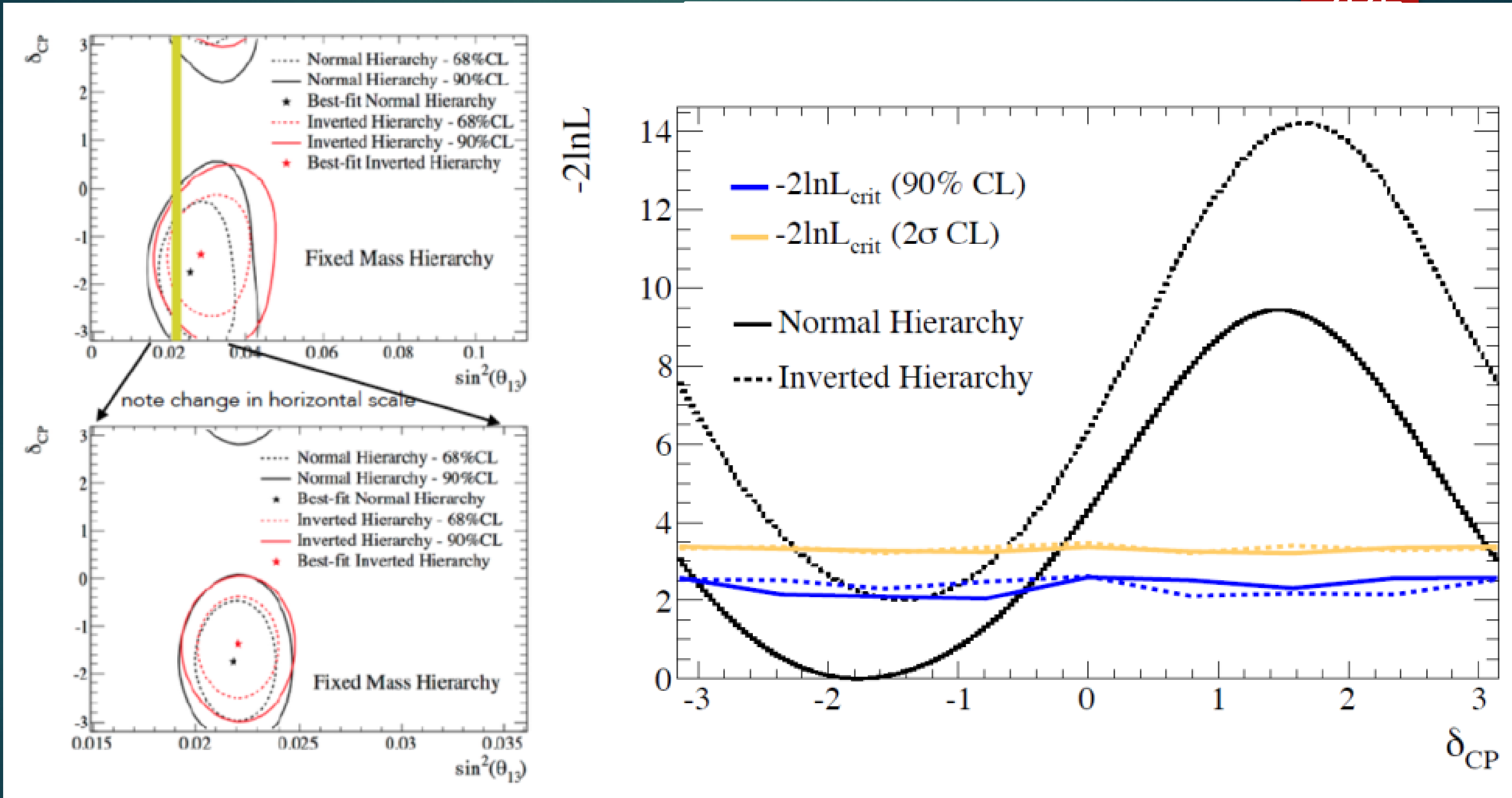
4 events observed

	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4

Uncertainty on the predicted number of events

Source of Uncertainty	ν 1Re	$\bar{\nu}$ 1Re	ν 1Re/$\bar{\nu}$ 1Re
SK Detector	2.3%	3.1%	1.6%
SK Final State and Secondary Interactions	2.6%	2.4%	3.5%
Flux and X-sec constrained by ND280	2.9%	3.2%	2.3%
NC 1γ	1.5%	3.0%	1.5%
ν_e and $\bar{\nu}_e$	2.6%	1.5%	3.1%
NC Other	0.2%	0.3%	0.2%
Total	5.5%	6.3%	5.9%

CP measurement



- Excluded CP symmetry at 90% CL
- Indicate maximum CPV at δ=-90deg??

Saclay contributions include

- Magnet Safety System (Neutrino Beam Line),
- TPC (Micromegas, Front End Electronics, Back End Electronics),
- TPC Simulation and Reconstruction, ND280 numu analysis,
- nue analysis, sterile neutrino search, CC0pi cross section,
- T2K oscillation analyses
- Leadership in T2K (EC, ND convener, ND upgrade leader, chair of many committees, etc)
- Indispensable essential contributions to T2K

Suwa Prize in 2013 to neutrino beam group

T2K Beam Group wins 2013 Suwa Prize

December 25, 2013

The T2K Neutrino Beam group was awarded the 2013 Suwa Prize by the FAS (Foundation for High Energy Accelerator Science), for their contribution to the discovery of electron neutrino appearance by creating and operating the highest intensity neutrino beam facility. The Beam Group is responsible for design, operation, and maintenance of equipment that monitors the extracted J-PARC proton beam and directs it onto the neutrino production target

Thank you Saclay team for successful collaboration

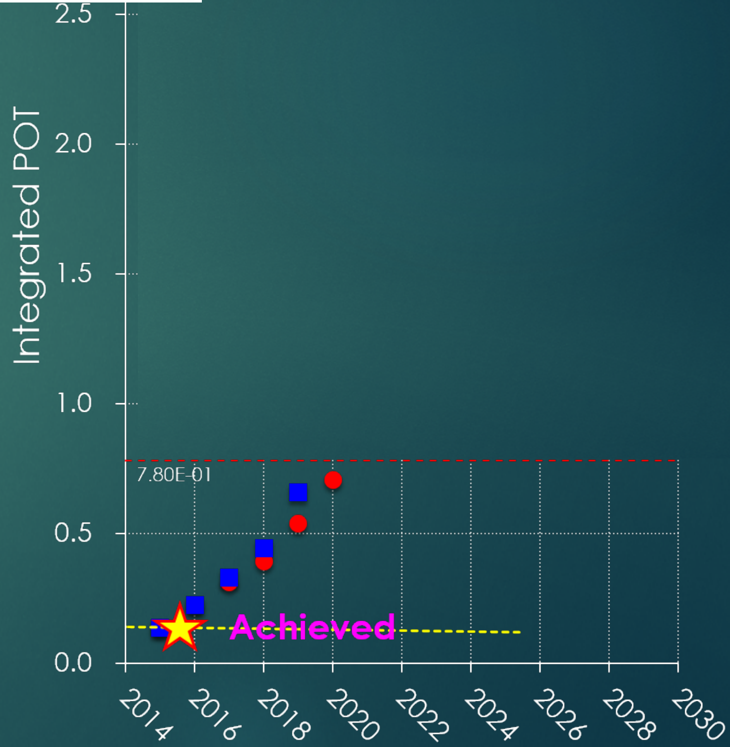
Magnet Safety System team

- Saclay is one of very few institutes in T2K contributed to Neutrino beam facility which was to realize unprecedented beam power and critical to T2K success
- In addition to essential contributions to near detector and analysis and all aspects!

Near and middle term future

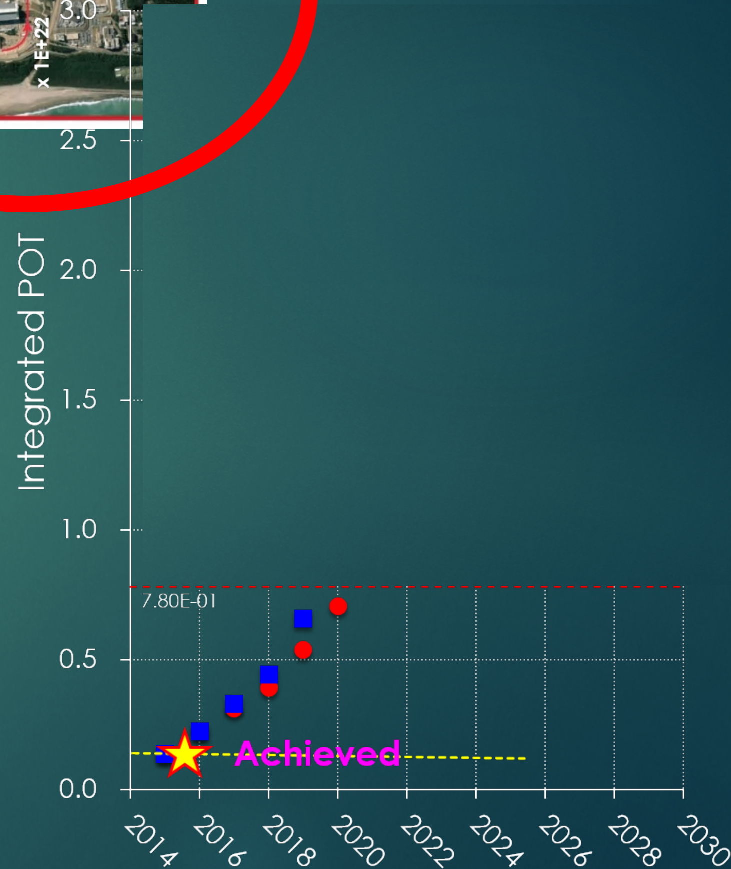
T2K (Tokai to Kamioka) (2010~)

- Beam power : 750kW (org goal)
- POT goal : 7.8×10^{21}
  (~1.5×10^{21} now)
- Distance : 295km
- Detector : SK (22.5kt)
- Physics
  - **Discovery ν_e appearance**
  - **Start searching for CP violation**
  - Contribution to mass hier. determ.
  - Neutrino int. cross sec.



T2K-II (~2020~)

- Beam power : **1300** kW
- POT goal : **$20\text{x}10^{21}$ + 50% stat**
  (~$1.5\text{x}10^{21}$ now)
- Distance : 295km
- Detector : SK (22.5kt)
- Physics
  - **Evidence of CP violation at > 3σ ($\delta = -\frac{\pi}{2}$)**
  - Contribution to mass hier. determ.
  - Neutrino int. cross sec.



Path toward 1.3MW

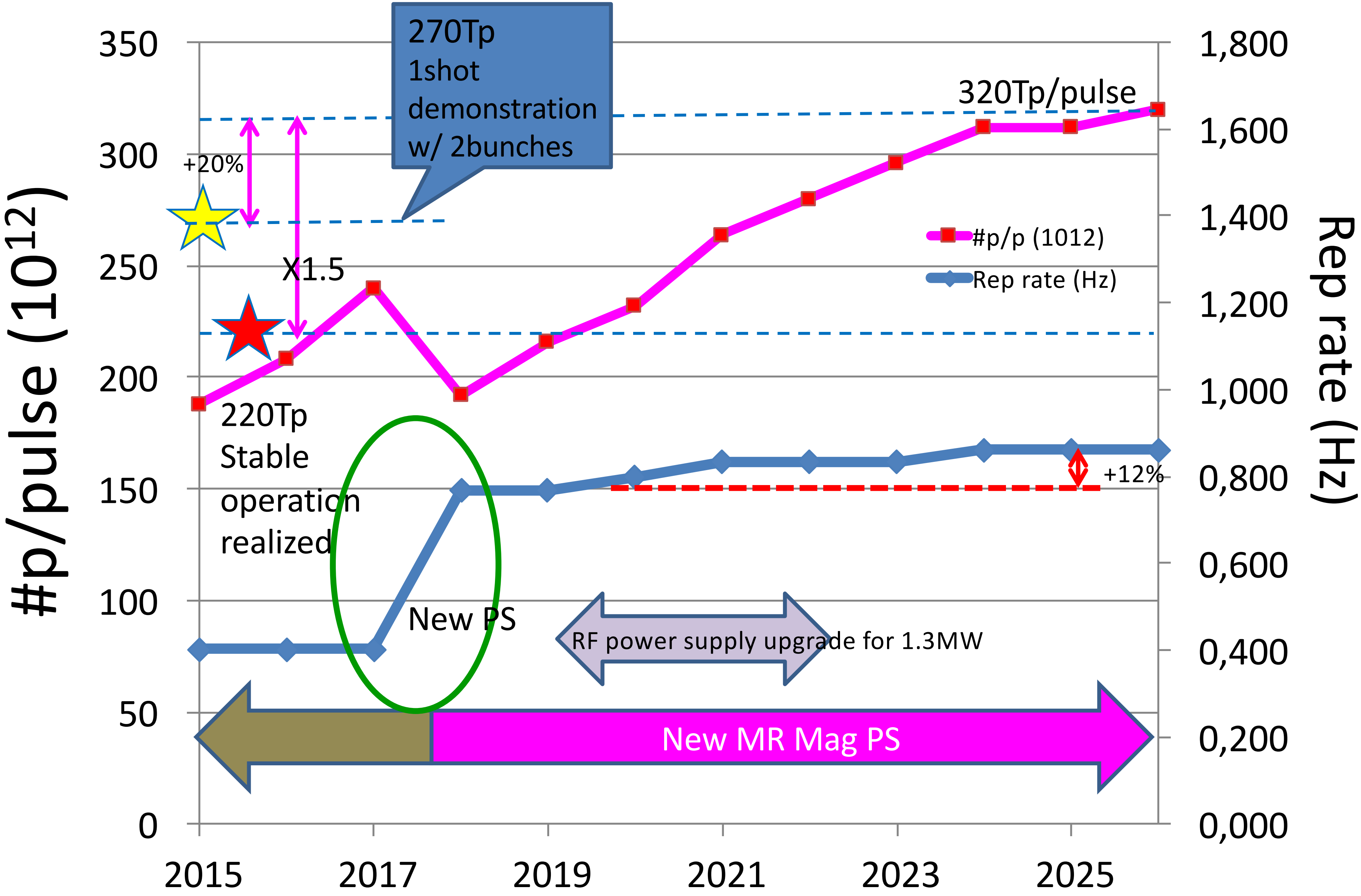
- Strategy

Beam Power (kW)	425 (Achieved)	810	Demonstrated	1326 (Goal for T2K-II)
#p/p(10^{12})	220	220	270	320
Rep T (s)	2.48	1.3	shots	1.16

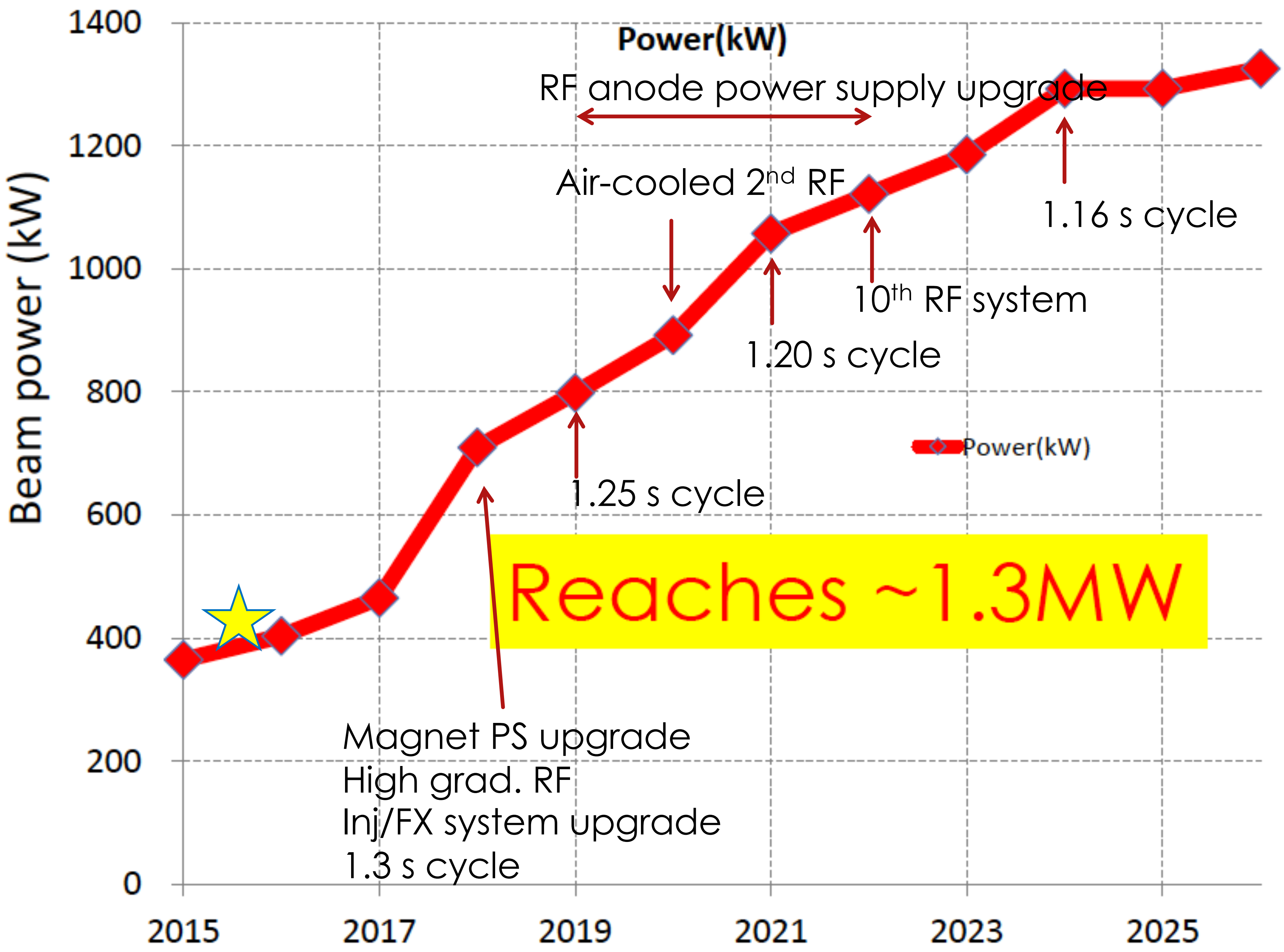
- Method
  - Higher rep rate: **Funding started**
    - MR magnet power supply upgrade
    - MR RF upgrade (High grad/PS)
    - MR Fast Extraction Kicker upgrade
  - Higher #p/p
    - MR RF upgrade (PS)
    - MR Beam monitor upgrade
      - Precise beam control for Higher ppp

After funding for 750kW design power is secured, only with modest investment mainly on RF PS enables >1.3MW

Assumed #p/p & rep cycle

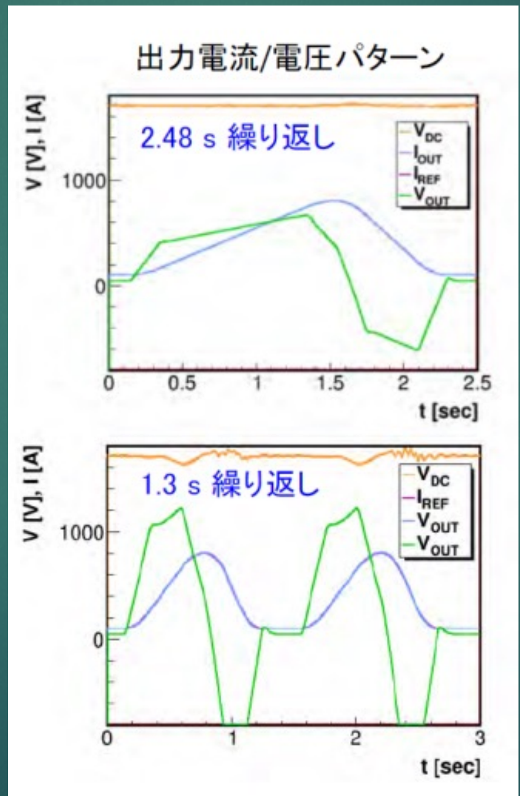


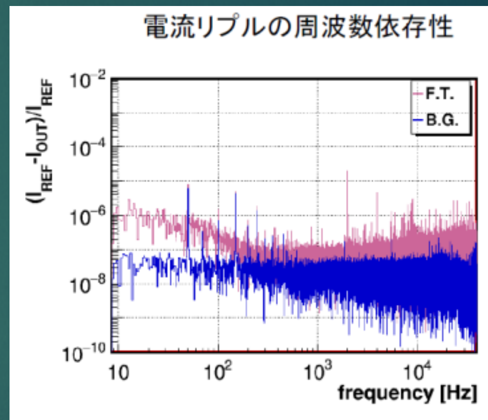
Beam power projection



MR magnet power supply upgrade for higher rep rate

- Funded for 2016-2018
- First Q-mag PS completed, installed, being tested





Will be used from Oct, 2016

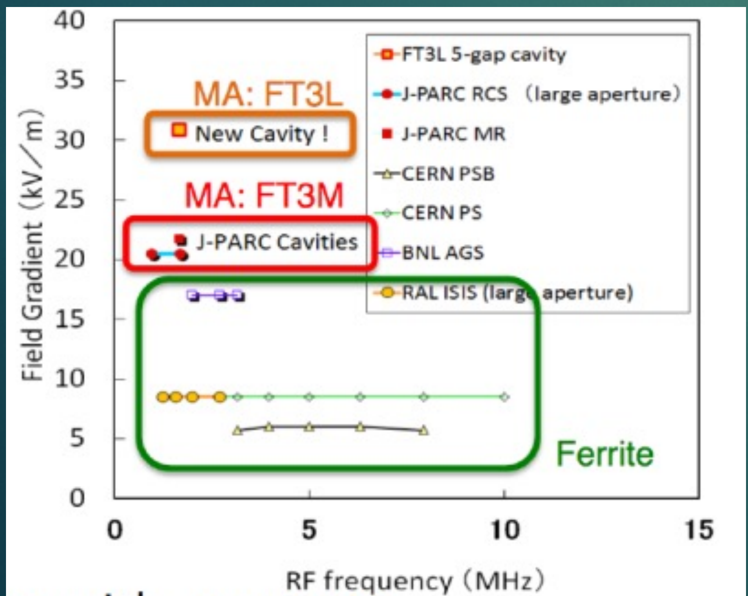
Building construction for new MR mag PS

D4予定地は林の伐採が終了

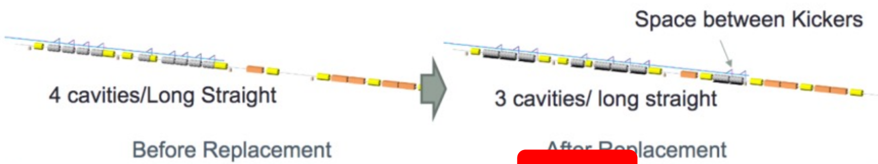
2017年度内に電源棟は
すべて完成する予定

RF upgrade for higher rep rate/higher intensity

- Replace to Higher gradient RF cavity
  - All 9 cavities were replaced. Completed!
- Add higher harmonics RF cavities
  - Planned in 2017 Summer shutdown



MR RF Upgrade Plan



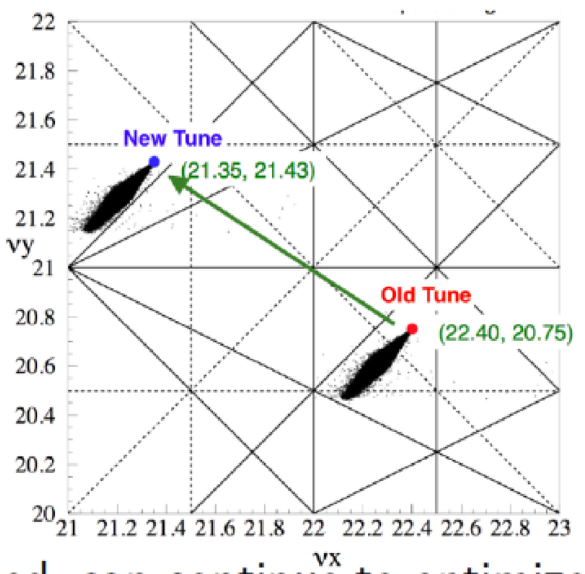
	2013	2014	2015	2016	2017	2018
	Li 400 MeV	Li 50mA				MR 1.3-sec operation
Present FT3M cavities	9	8	4	0	0	0
New FT3L Cavities	0	1	5	9	9	9
New FT3L 2nd cavity	0	0	0	0	2	2
Available voltage	315 kV	355 kV	485 k	602 kV	02 kV	602 kV
(2nd Harmonic)	(35 kV)	(70 kV)	(70 k	(70 kV)	70 kV)	80 kV
Number of cavity cells	27	29	36	43	43	43+8(2nd)

Required voltage 280 kV(~2017), 540 kV(2018~)

Continuing efforts for higher p/b

New MR Betatron Tune for Higher Power

- Resonance diagram shows tune regions (points), betatron resonances (lines)
  - Avoid resonances (lines) to enhance accelerator stability
  - Left plot: J-PARC MR betatron tune resonance diagram

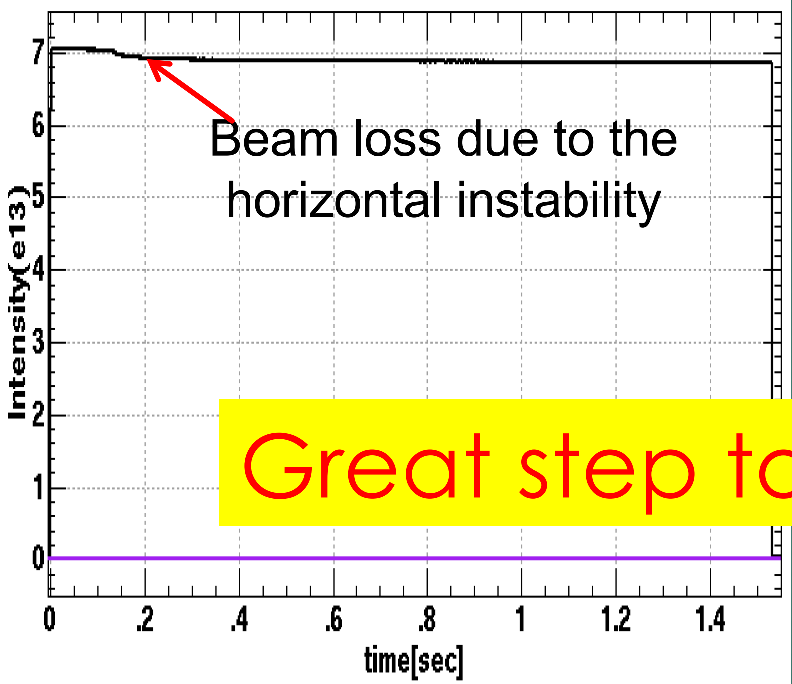


- Now that new tune has been established, can continue to optimize :
  - RCS beam parameters (painting, tune, and chromaticity) for MR
  - RF voltage pattern for fundamental and 2nd harmonic
  - Compensation kicker for new tune point
  - Collimators for loss localization
  - Octupole magnets (Currently 2 magnets are being used)
  - Trim quadrupole and trim sextupole patterns
  - Beam optics at extraction timing for beam loss reduction
  - Instability damping with intra-bunch feedback and chromaticity

High Intensity demonstration

- at the new betatron tune (22.239, 21.310) -

High power trial with two bunches



Extracted beam : 6.82e13 ppp (132 kW eq.)

	Beam loss[Watt]	
INJ(K1+K2+K3+K4)	144	7.43e+11
P2 --> +90ms	241	1.00e+12
P2+90ms --> +120ms	31	1.30e+11
P2+100ms ---> EXT		1.83e+11

Total beam loss ~ 420 W

Great step toward >1MW

Near future tunable knobs to reduce beam loss:
Injection kicker improvement, BxB feed-back, 2nd harmonic cavity, VHF cavity, etc.

Bunch number	repetition period (sec)	#p/pulse (10^{12})equiv	Beam power (kW)	Beam loss (kW)	Notes
2	2.48	**270**	132	0.42	measurement
8	2.48	**270**	530	1.7	estimation
8	1.3	**270**	1000	3.2	estimation

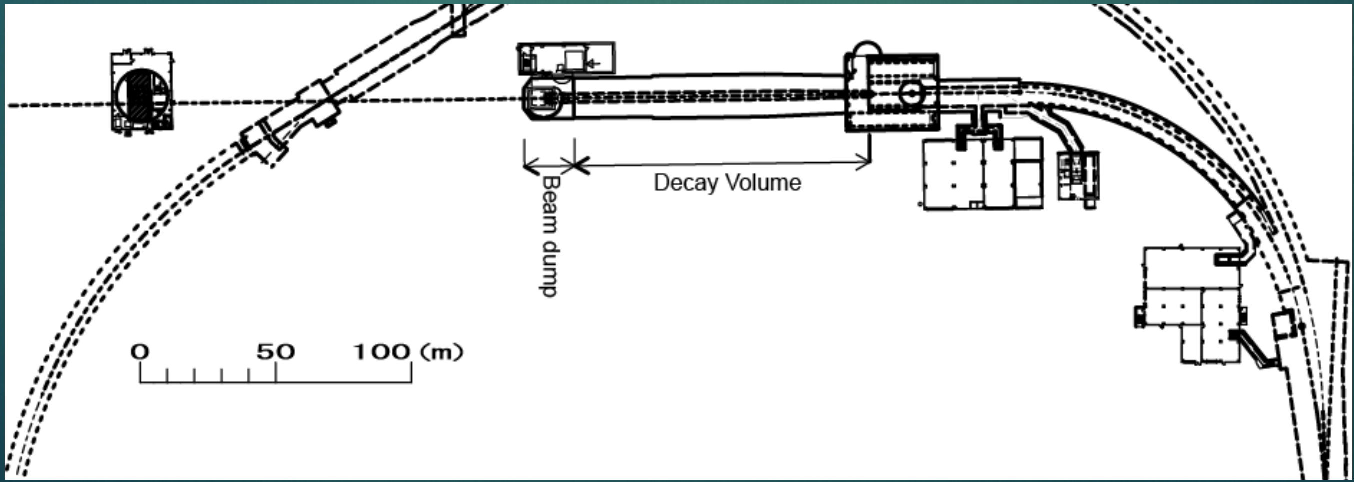
Neutrino beam facility upgrade

- Original design principle/specification
  - 750kW for replaceable components
  - >3MW for irreplaceable parts (Decay volume, Dump, etc)
  - 750kW = 30GeV x **(330Tp/5us pulse)** x (2.10s cycle)
- Goal
  - 1.3MW = 30GeV x **(320Tp/5us pulse)** x (1.16s cycle)
    - Similar impulse thermal shock!

Beam Power	# of protons/pulse	Rep. rate
350 kW (achieved)	1.8×10^{14}	2.48 sec.
750 kW (proposed) [original plan]	2.0×10^{14} [3.3×10^{14}]	1.30 sec. [2.10 sec.]
1.3 MW (proposed)	3.2×10^{14}	1.16 sec.

Neutrino beam facility upgrade

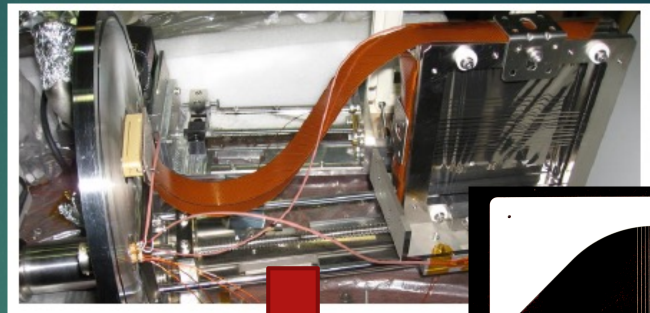
- To achieve >1.3MW facility with > 20~30yrs durability
  - Upgrade proton beam monitors for higher beam power
  - Upgrade of DAQ system for higher rep. rate
  - Upgrade electromagnetic horns system
    - Add 1 PS, 2 Transformer to operate 3 horns in parallel
  - Cooling capability upgrade for target/horns/beam windows
  - Upgrade of capacity of radioactive waste (water, ..)
  - Understanding radiation damage and development of radiation resistant beam line components, beam windows, etc

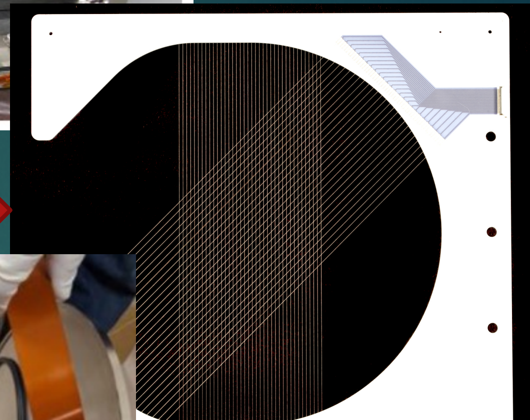


Proton Beam Monitor R&D

- Profile monitor upgrade 1
  - 5um[t] Ti foil Segmented Secondary Emission monitor (SSEM) at present
  - ➔ FNAL-style Wired SEM (WSEM) optimized for J-PARC beam in collaboration with FNAL
  - 5 planes (2 full monitors + 1 spare plane) shipped to J-PARC in Jan 2016
  - First test monitor was installed and to be tested soon!
- Profile monitor upgrade 2
  - New Beam Induced Fluorescence (BIF) Monitor under development
    - Non destructive, can be always in beam
    - Optical system(fiber), Vacuum/gas injection system being tested

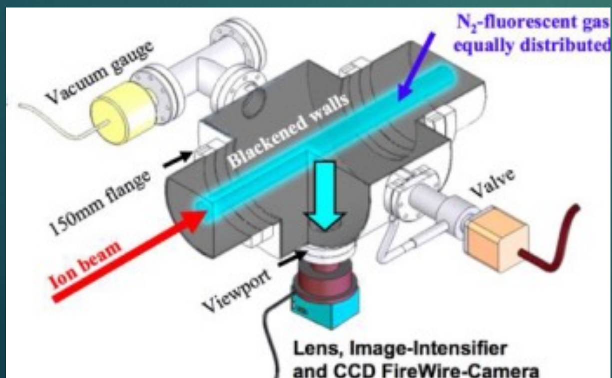
5μm[t] Ti foil strips



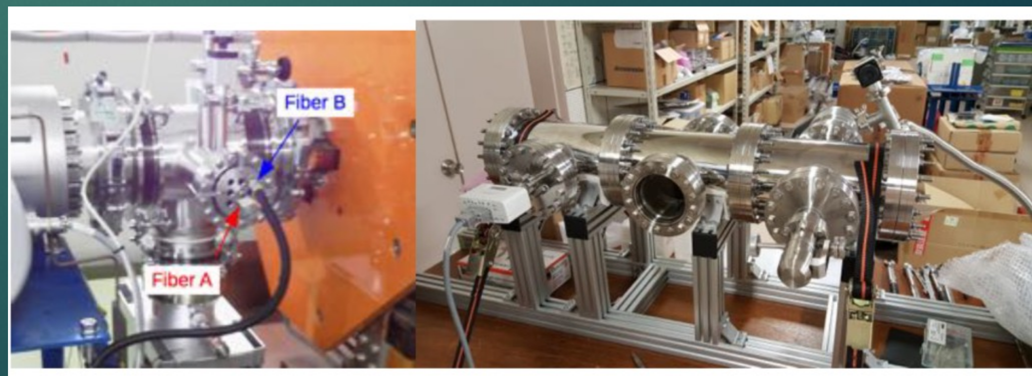


New Monitor

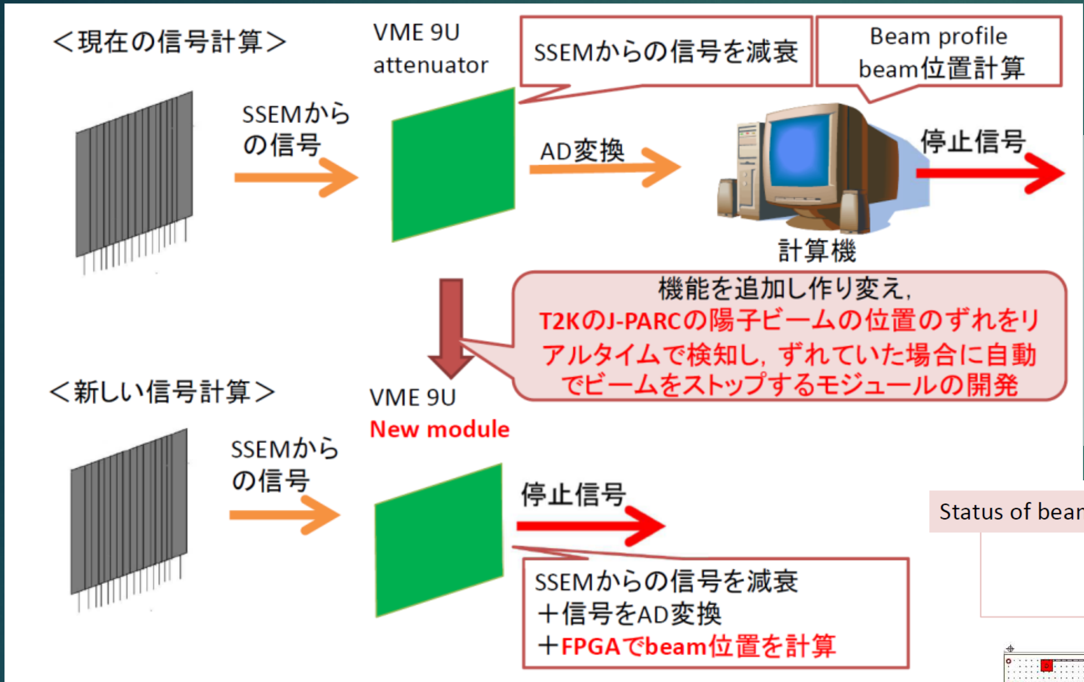
BIF (image)

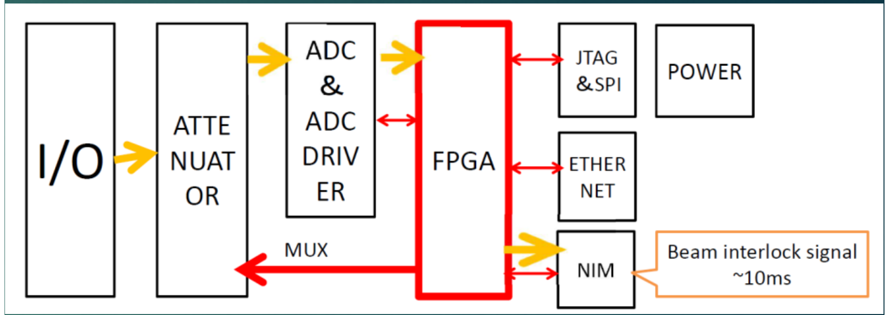


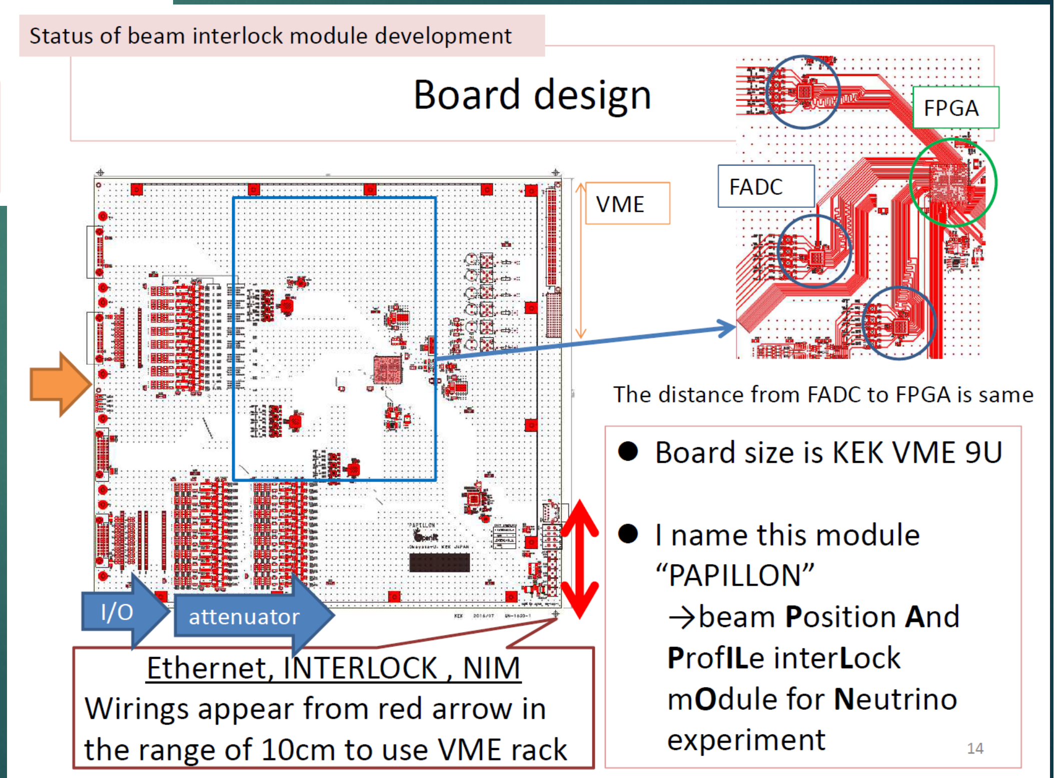
BIF tests



DAQ upgrade development

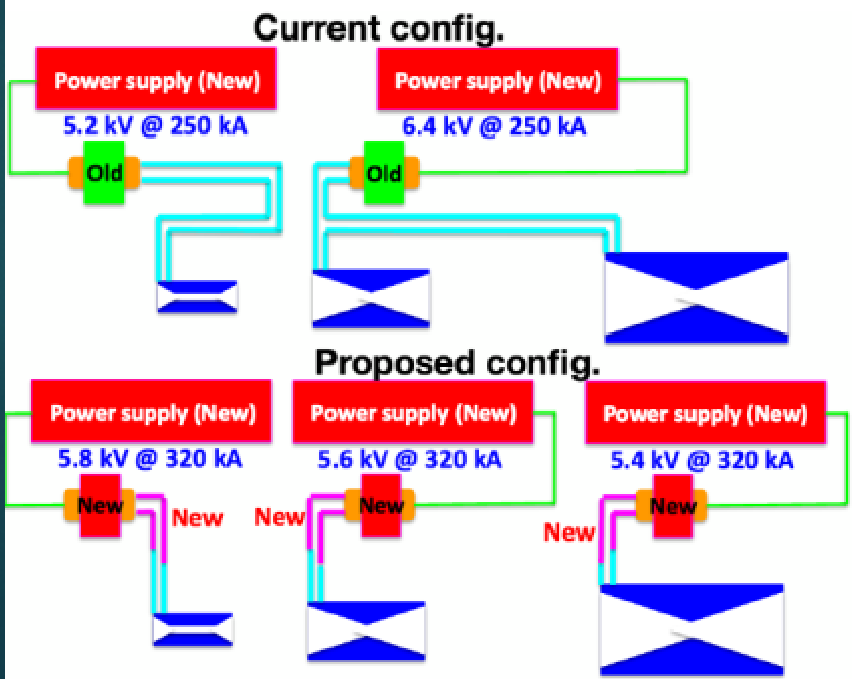


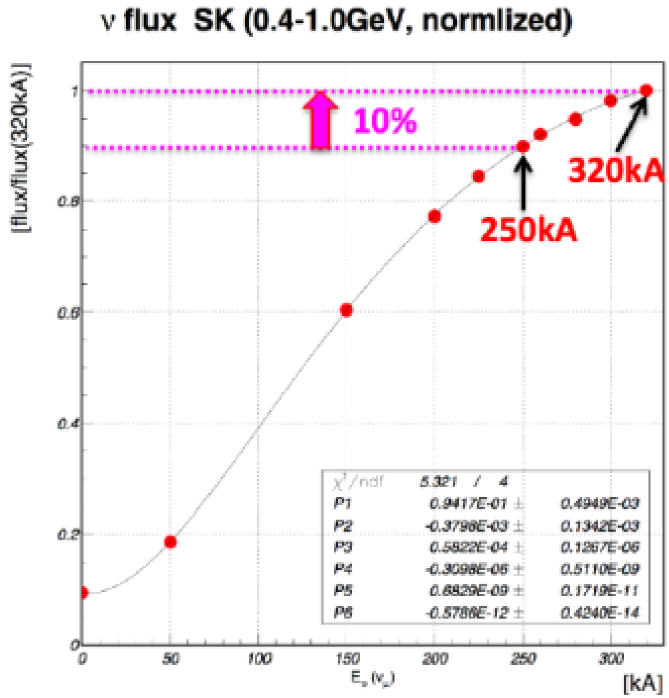




J-PARC Horn Power Supply Upgrade for $\pm 250 \rightarrow \pm 320$ kA

- Move from 2 to 3 power supplies
  - New power supplies with energy recovery system
  - New striplines with low R & L
  - New transformers optimized for 320 kA operation
  - 10% increase in neutrino flux at far detector
  - 5~10% reduction of wrong-sign neutrinos around peak energy
- Upgrade planned in ~2017





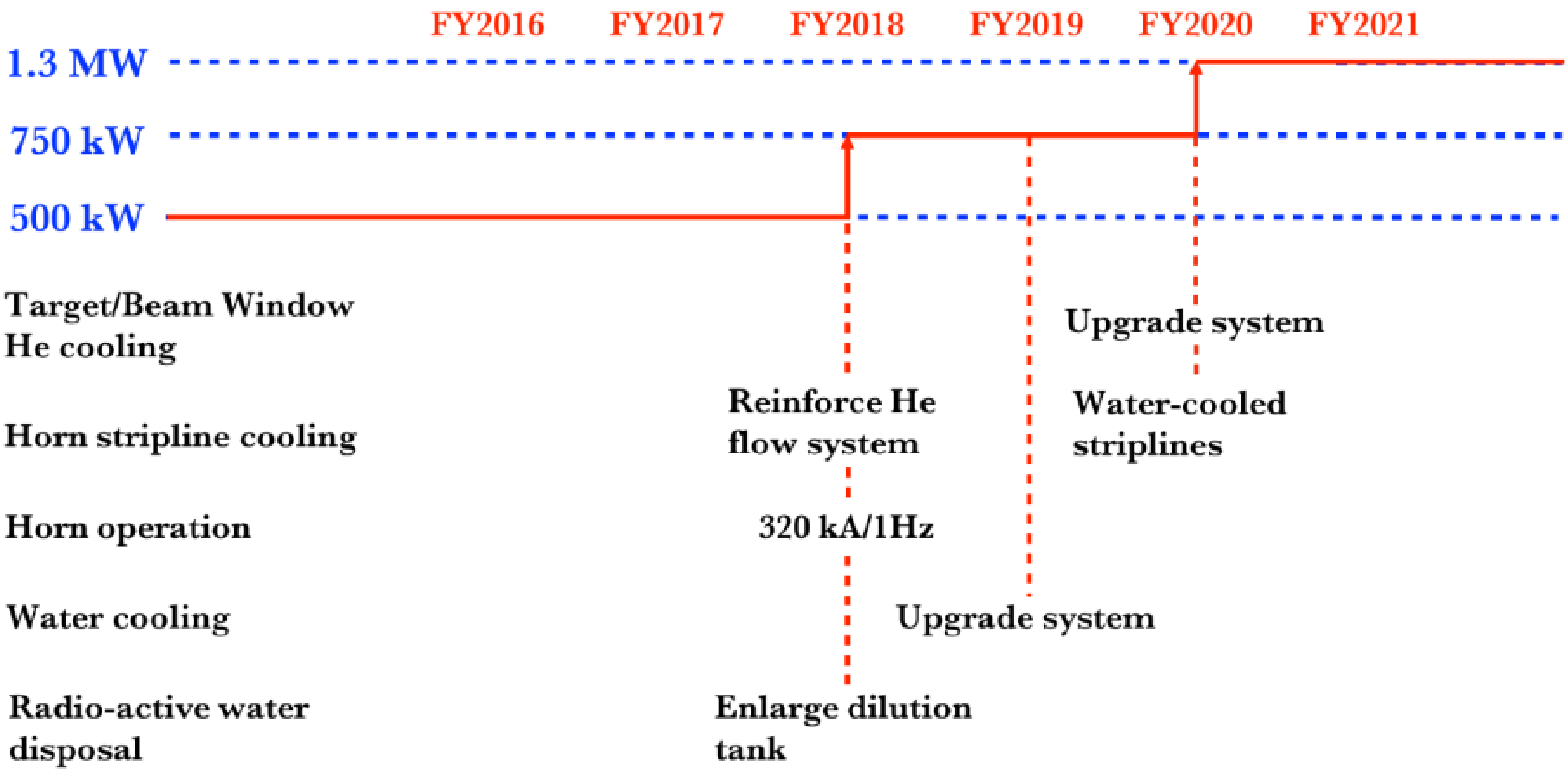
Flux Improvement @ 320 kA

M.Friend, Nu2016

Secondary beam line upgrade

Component	Limiting Factor	Current Acceptable Value	Upgraded Acceptable Value
Target	Thermal Shock	3.3×10^{14} ppp	3.3×10^{14} ppp
	Cooling Capacity	0.75 MW	>1.5 MW
Horn	Conductor Cooling	2 MW	2 MW
	Stripline Cooling	0.54 MW	>1.25 MW
	Hydrogen Production	1 MW	>1 MW
	Operation	2.48 s & 250 kA	1 s & 320 kA
He Vessel	Thermal Stress	4 MW	4 MW
	Cooling Capacity	0.75 MW	>1.5 MW
Decay Volume	Thermal Stress	4 MW	4 MW
	Cooling Capacity	0.75 MW	>1.5 MW
Beam Dump	Thermal Stress	3 MW	3 MW
	Cooling Capacity	0.75 MW	>1.5 MW
Radiation	Radioactive Air Disposal	1 MW	>1 MW
	Radioactive Water	0.5 MW	0.75→1.3 or 2 MW

Secondary Beamline Upgrade Schedule



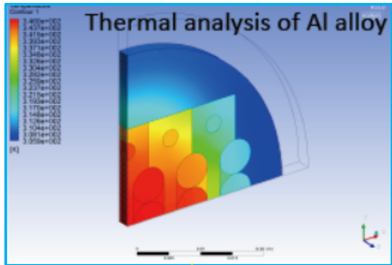
RaDIATE

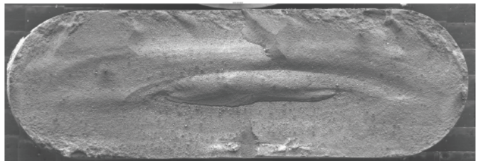
Radiation Damage In Accelerator Target Environments

radiate.fnal.gov

- To solve a world’s common problem to understand the effect of radiation damage on target/window materials, accelerator & fission/fussion communities’ researchers & engineers work together.
- J-PARC neutrino was an active partner since 2014
- From JFY2016 J-PARC plan to join officially

Neutrino Beam Window
Ti Alloy ~1x10^{21} pot
~1 Displacement Per Atom
(Existing data up to ~0.3DPA)





Fermilab | University of Oxford | Science & Technology Facilities Council | Brookhaven National Laboratory | Pacific Northwest National Laboratory | Los Alamos National Laboratory | FRIB | European Spallation Source | Oak Ridge National Laboratory | Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas | Argonne National Laboratory

2016~ CERN GSI

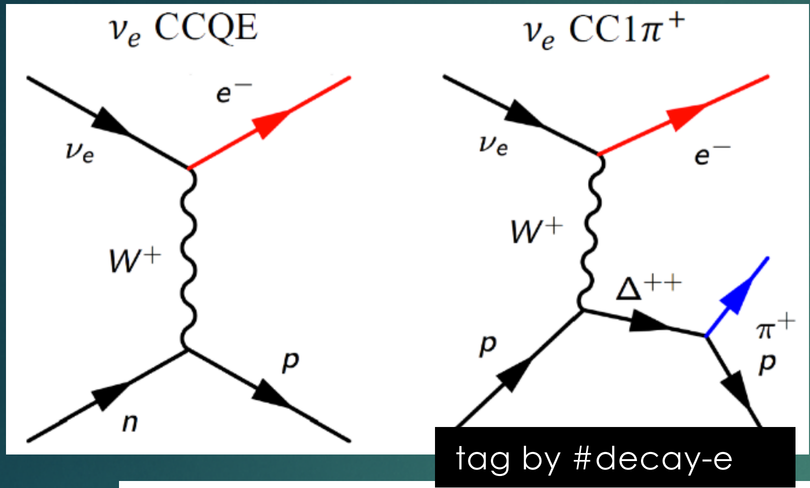
NuMI graphite broken target Post-Irradiation Examination (PIE) at PNNL: Swelling effect observed

New Irradiation Run at BNL (2017 February ~)

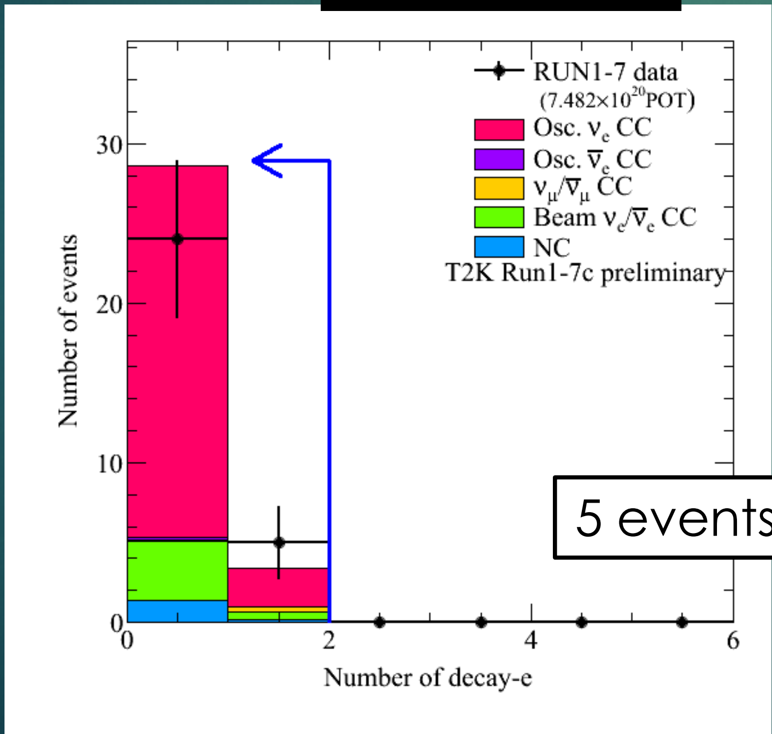
Analysis improvements for T2K2 for higher statistics

- Add new event sample
  - Present target signal sample: (2-body) CCqe: ν_e+n → e- + p
    - Single electron-like Ch. Ring, No decay electron
  - Add nue sample (e-like ring) with additional activities
    - Decay electron, another ring from pion(s)
  - 35% more events.
- Enlarging the fiducial volume
  - +10~15% more events
- **In total ~50% increase**
  - (with flux increase)

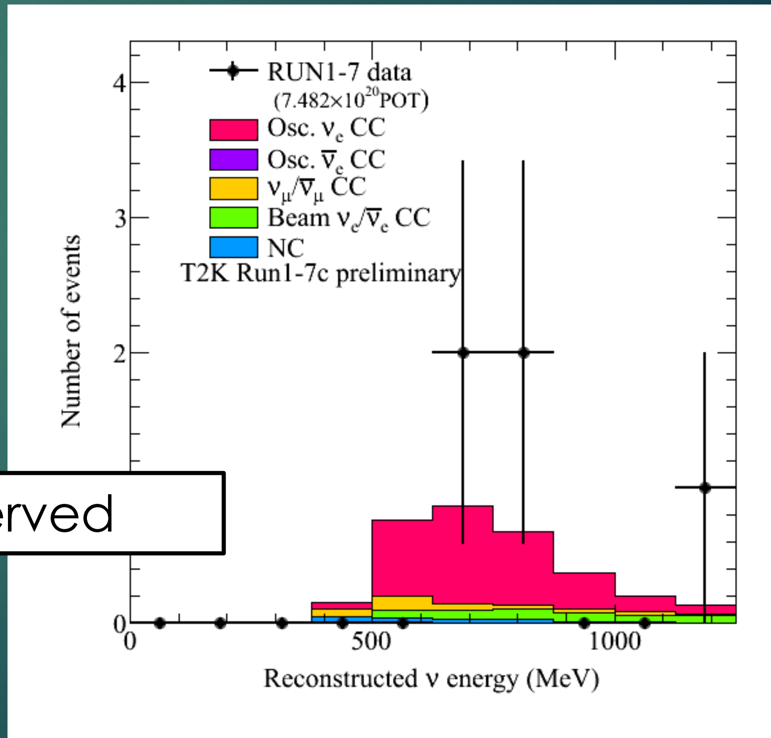
Example of additional samples:CC1pi+ sample



~10% increase of statistics



5 events observed



Improving systematic errors for T2K2

- Present ~6% error → ~4%
  - Dominant source: Cross section errors

T2K 2016 systematic error

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

Goal

~4%

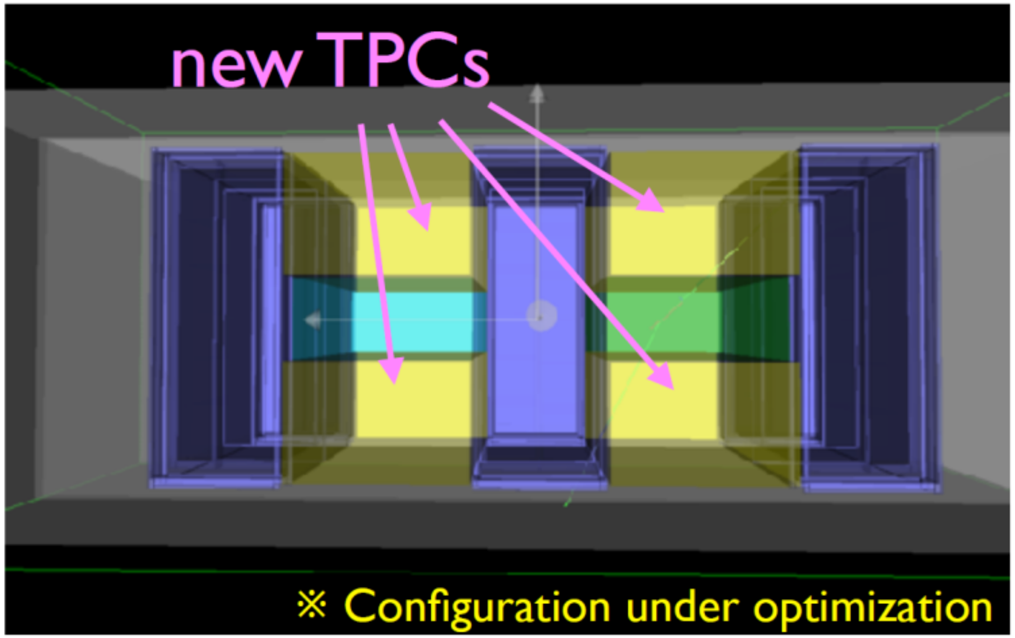
Improving cross section errors: Near detector upgrades

- Under design in T2K
- Expand angular acceptance
- Conceptual design now
- Tech design ~2017, const. ~2020
- Workshop for TPC near detector @ CERN, Nov 8-9
  https://indico.cern.ch/event/568177/

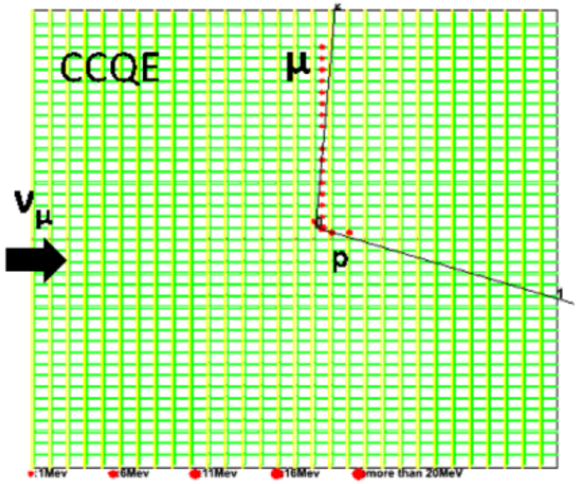
ND upgrade task force

Masashi Yokoyama and Marco Zito

With many young guys



Event display (MC)

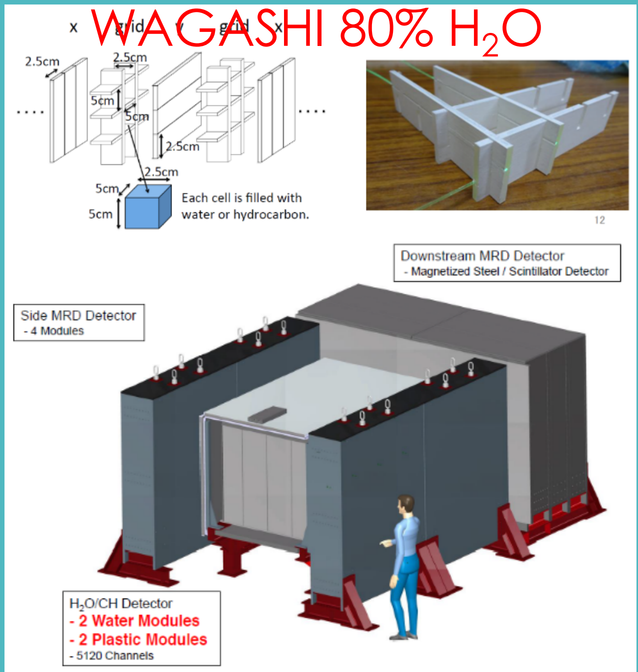


Large angular acceptance detector with plastic scintillator grid (WAGASCI)

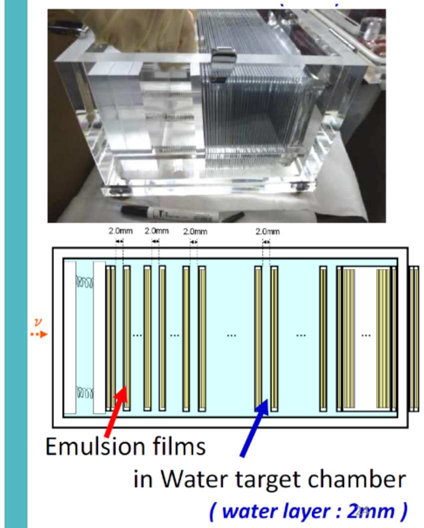
koyama (UTokyo)

Ideas of new detector

Already on-going projects

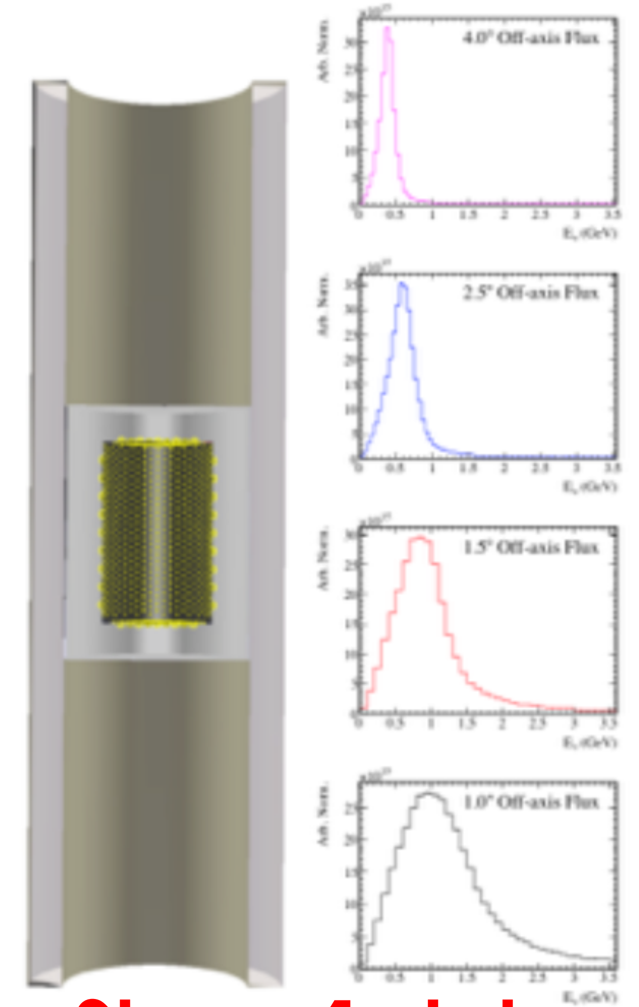


Water target emulsion chamber



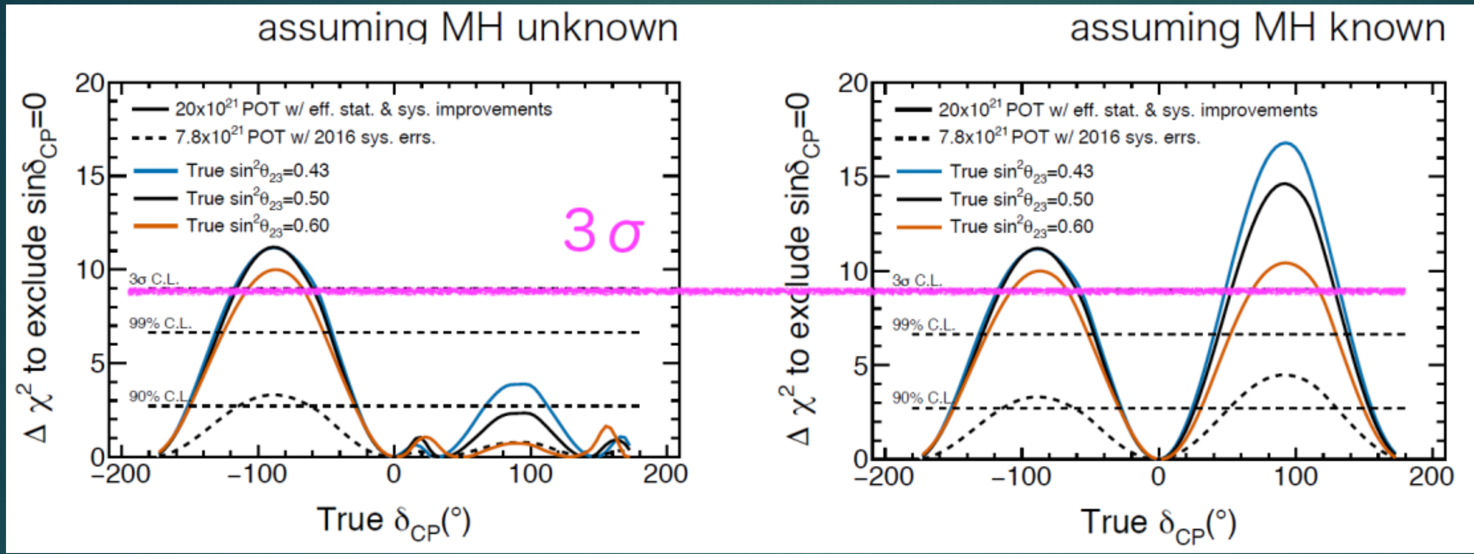
Ideas of new detectors

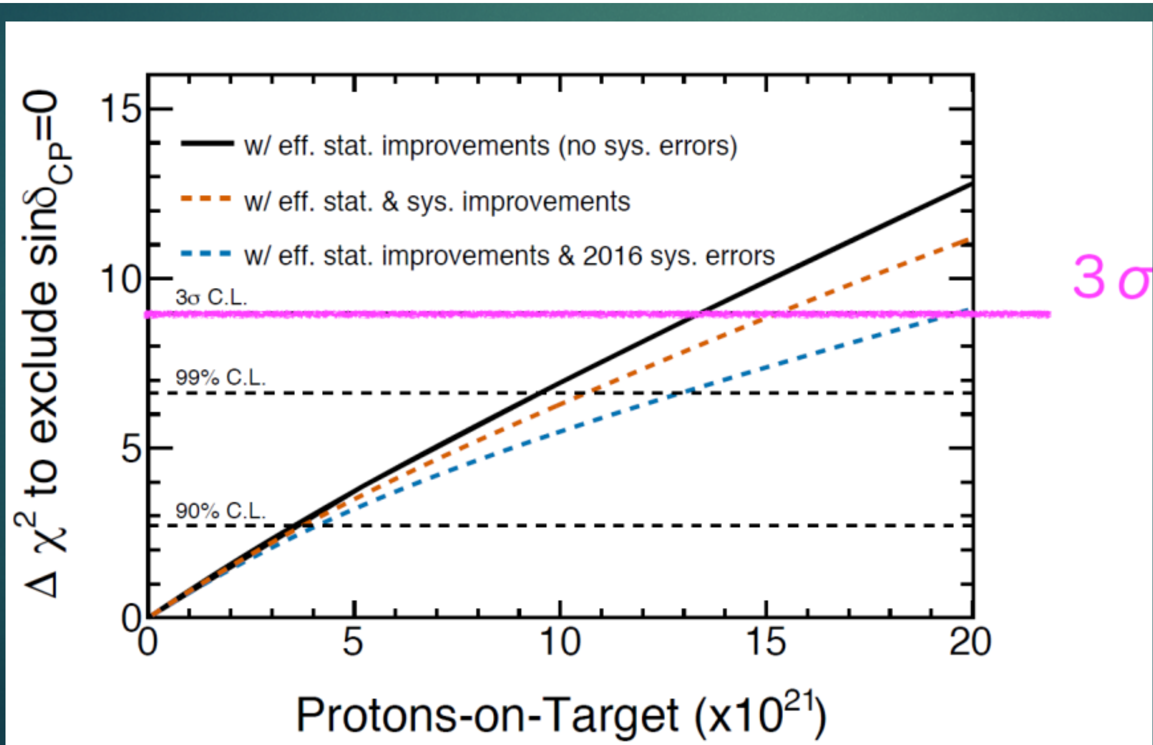
NuPRISM @~km



Stage-1 status

Physics sensitivities of T2K-II

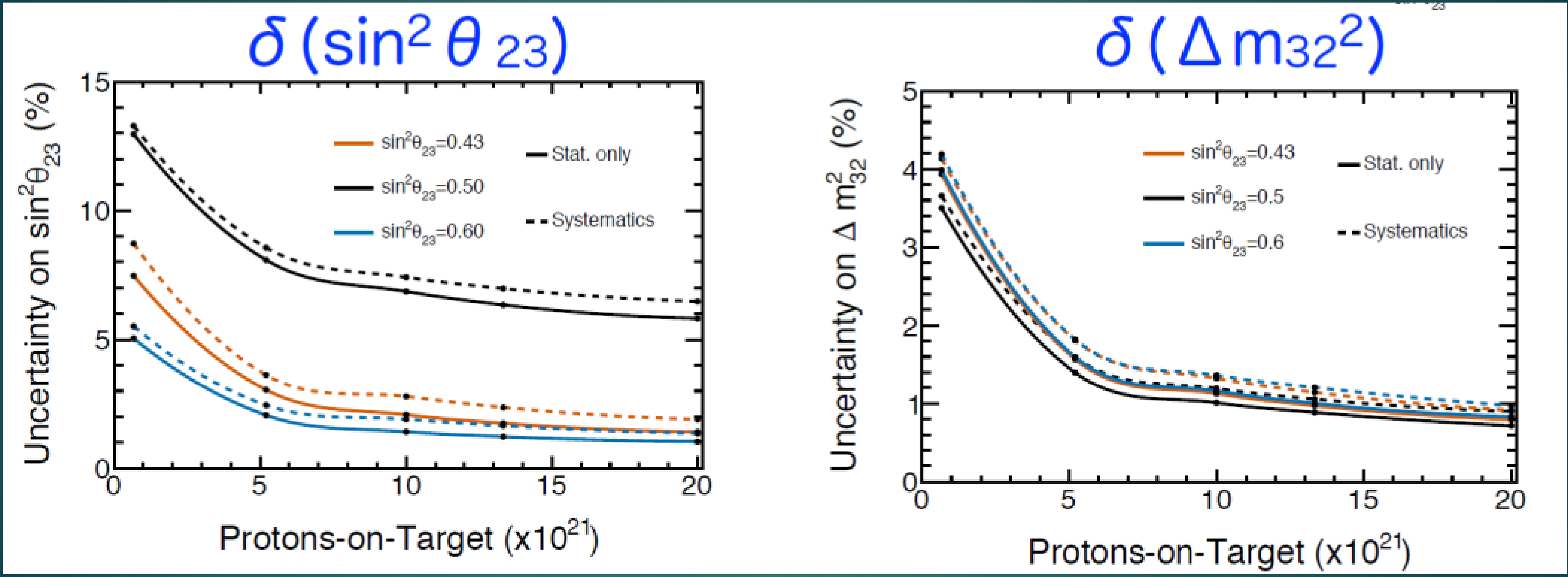




>3s evidence

If maximally violated!

Physics sensitivities of T2K-II



KEK Project Implementation plan (KEK-PIP)

- Prioritization of projects which require new funding requests
- External review (May 22,23, 2016)
  - Recommendations
  - https://www.kek.jp/ja/About/OrganizationOverview/Assessment/Roadmap/KEK-PIP_Evaluation.pdf
- KEK-PIP taking into account the recommendations
  - https://www.kek.jp/ja/About/OrganizationOverview/Assessment/Roadmap/KEK-PIP.pdf

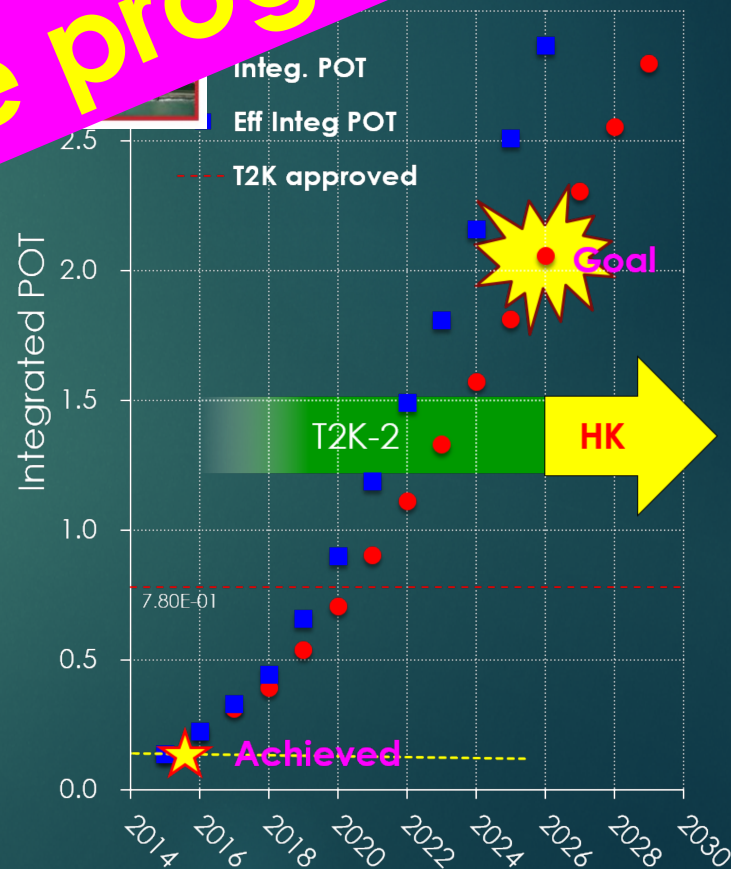
Project to be prioritized:
COMET II
J-PARC upgrade for Hyper Kamiokande
Hadron Hall Extension
H-line and g-2/EDM
LHC and ATLAS
Super Computer
RNB
Separate prioritization
Light Source

Upgrade of J-PARC for Hyper-K is highest priority

Hyper-Kamiokande (HK) (2026~)

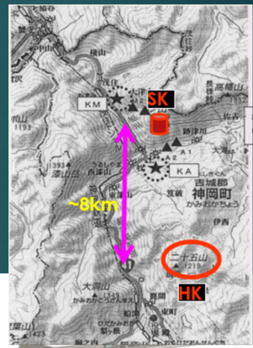
- Beam power : **1300 k**
- POT goal : **sec**
- Distan… km
- D… : **HK (190kt x2)**
  - …det in Korea(~1000km) under discussion
- …
  - **Observation of CP violation at 8σ ($\delta = -\frac{\pi}{2}$)**
  - **Precise measurement of CP phase**
  - **Discovery of proton decay w x10 sens.**
  - Determination of mass hier.

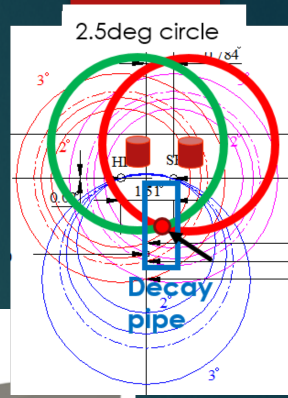
Seamless productive program!

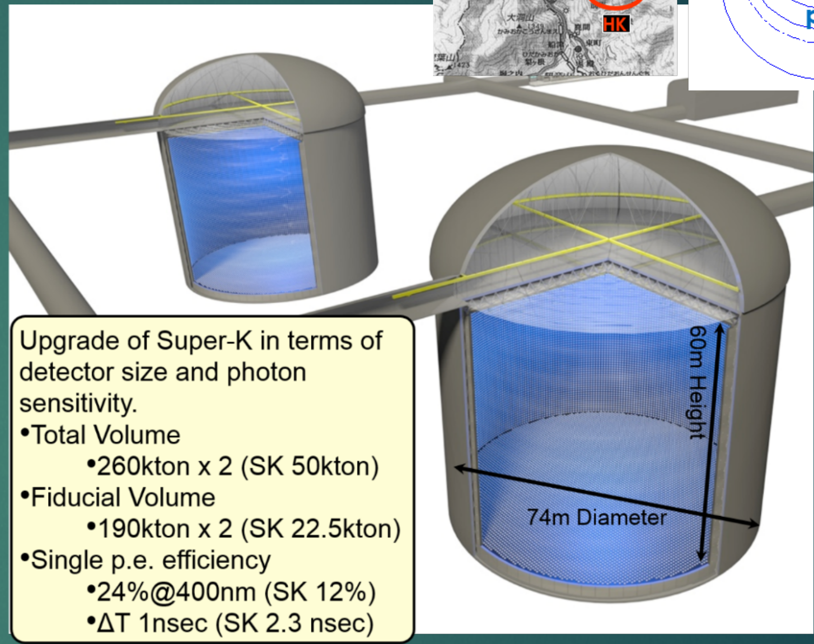


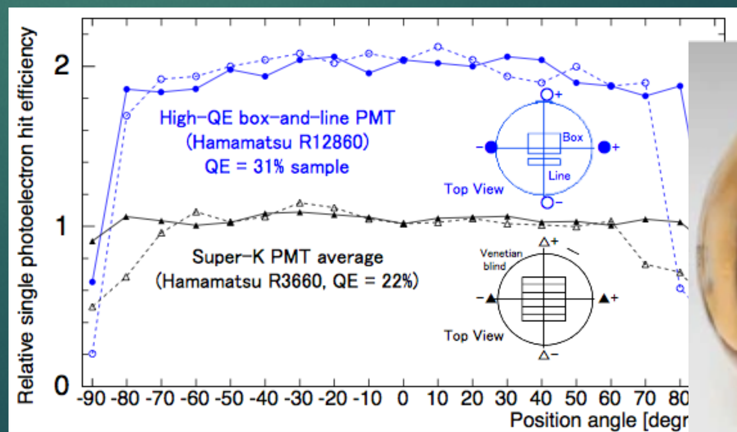
Hyper-Kamiokande

- Next-generation Water Ch detector
  - 260kt(190kt fid.mass) x 2
  - New PMT with x2 photo eff.
  - Staging
- Detector location (candidate)
  - ~8km south of SK
  - 295km from J-PARC, @ same off-axis angle
  - 650m overburden (1755m W.E.)
  - An idea of 2nd det in Korea as one of options
- Physics goals
  - Accelerator neutrino
    - CPV in neutrino
  - Non-accelerator/Astroparticle
    - Discovery of proton decay
    - Atm-nu
    - Solar-nu
    - Supernova (relic) nu



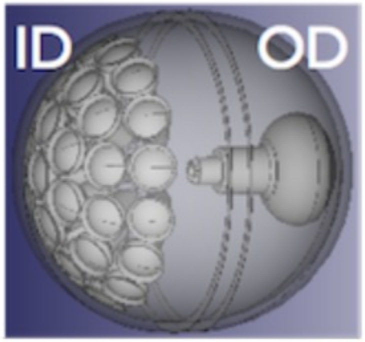


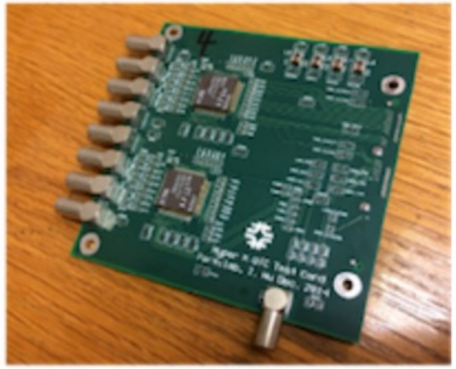


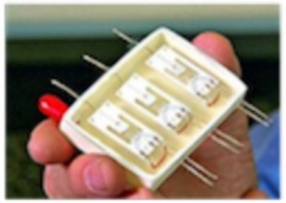


International R&D efforts

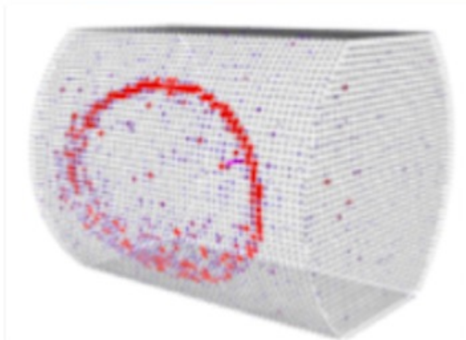
- Intense R&D work over the world
  - Sensor, calibration, electronics, DAQ, software, physics sensitivity…







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

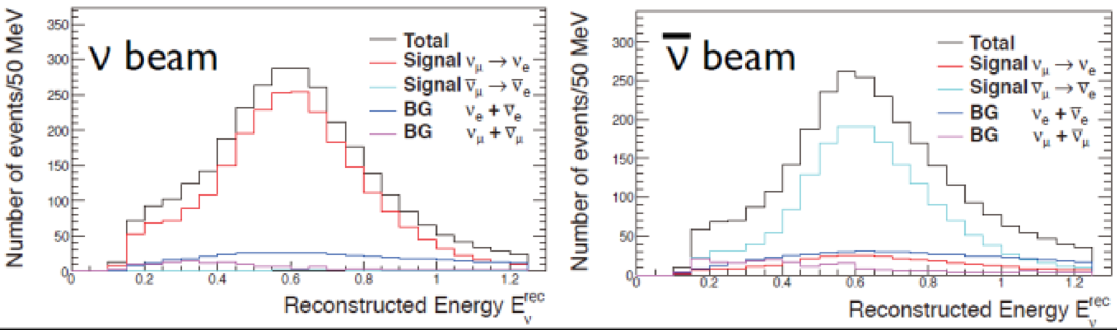


Expected events

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

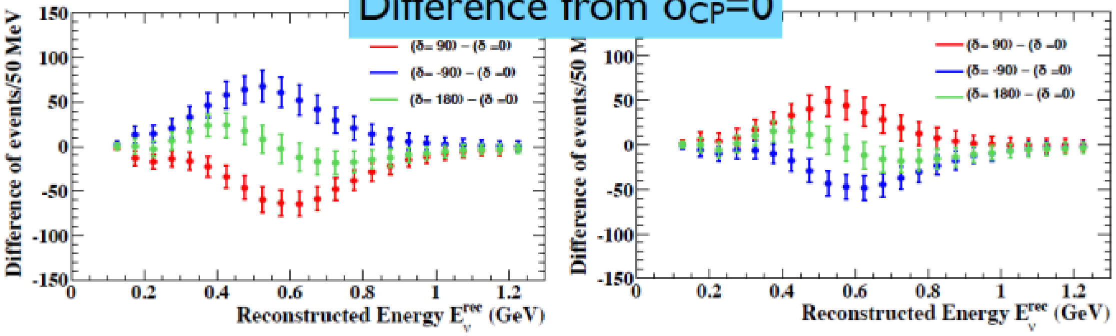
ν_e candidates

Using fiTQun for π^0 rejection



for δ=0	Signal (νμ→νe 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



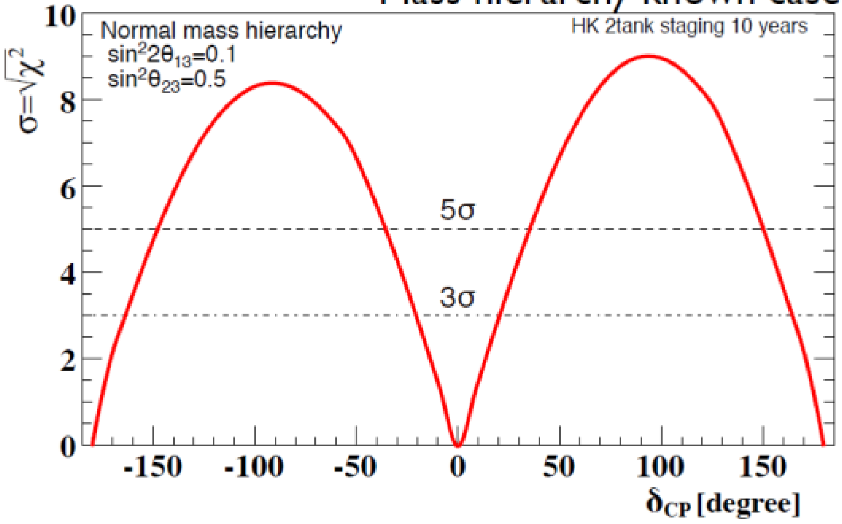
δ=0 and 180° can be distinguished using shape information

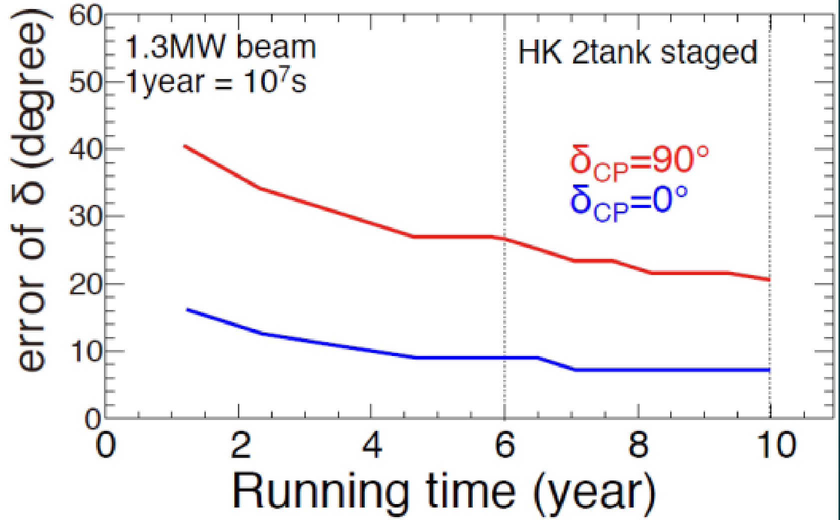
CPV sensitivity

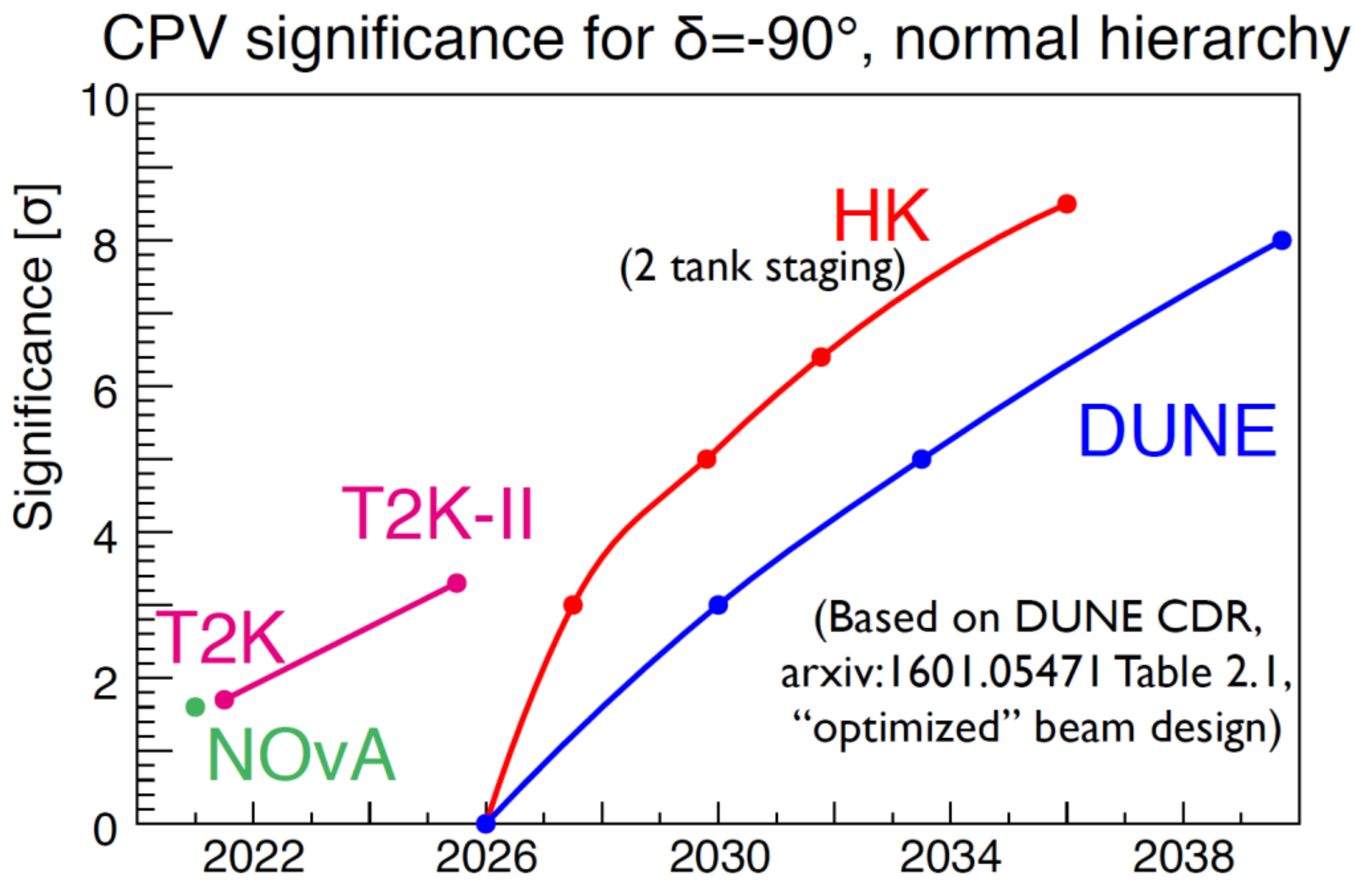
- Exclusion of $\sin\delta_{CP}$=0
  - >8σ(6σ) for δ=-90°(-45°)
  - ~80% coverage of δ parameter space with >3σ
- From discovery to δ_{CP} measurement:
  - ~7° precision possible

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

Mass hierarchy known case







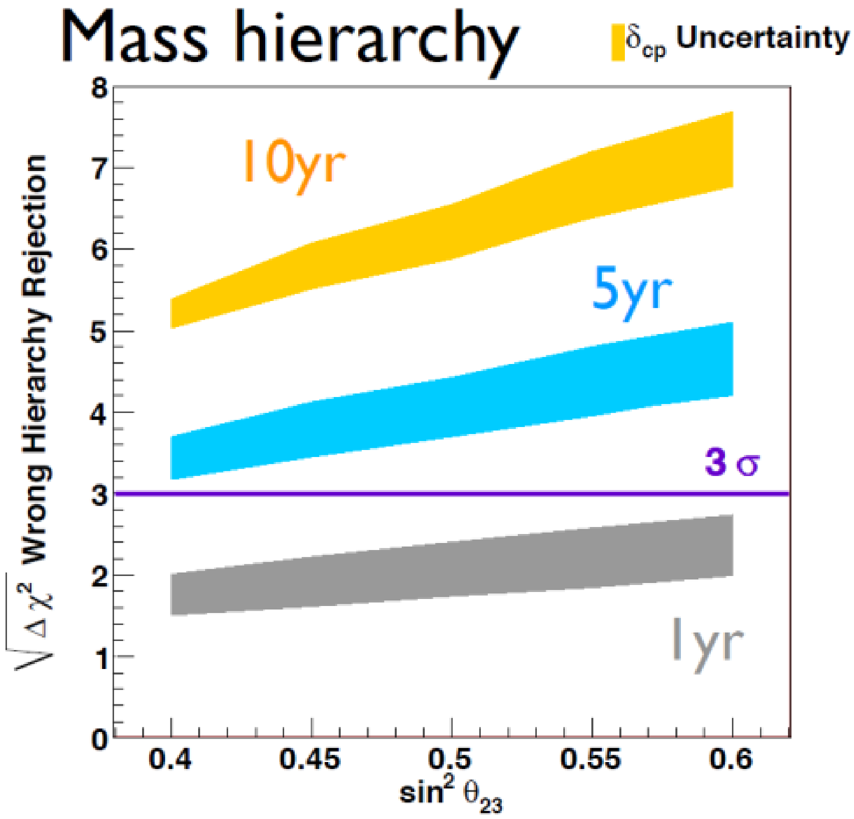
Strategy of Japan-based program

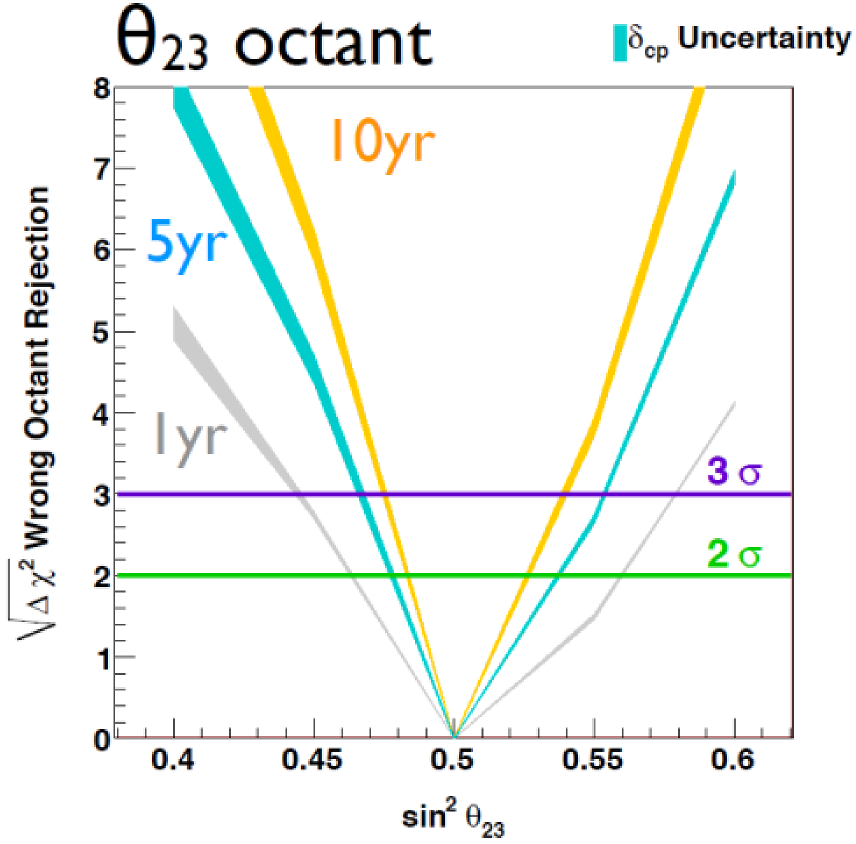
~3σ indication with T2K→T2K-II,

>5σ discovery and measurement with HK

Note: "exact" comparison sometimes difficult due to different assumptions

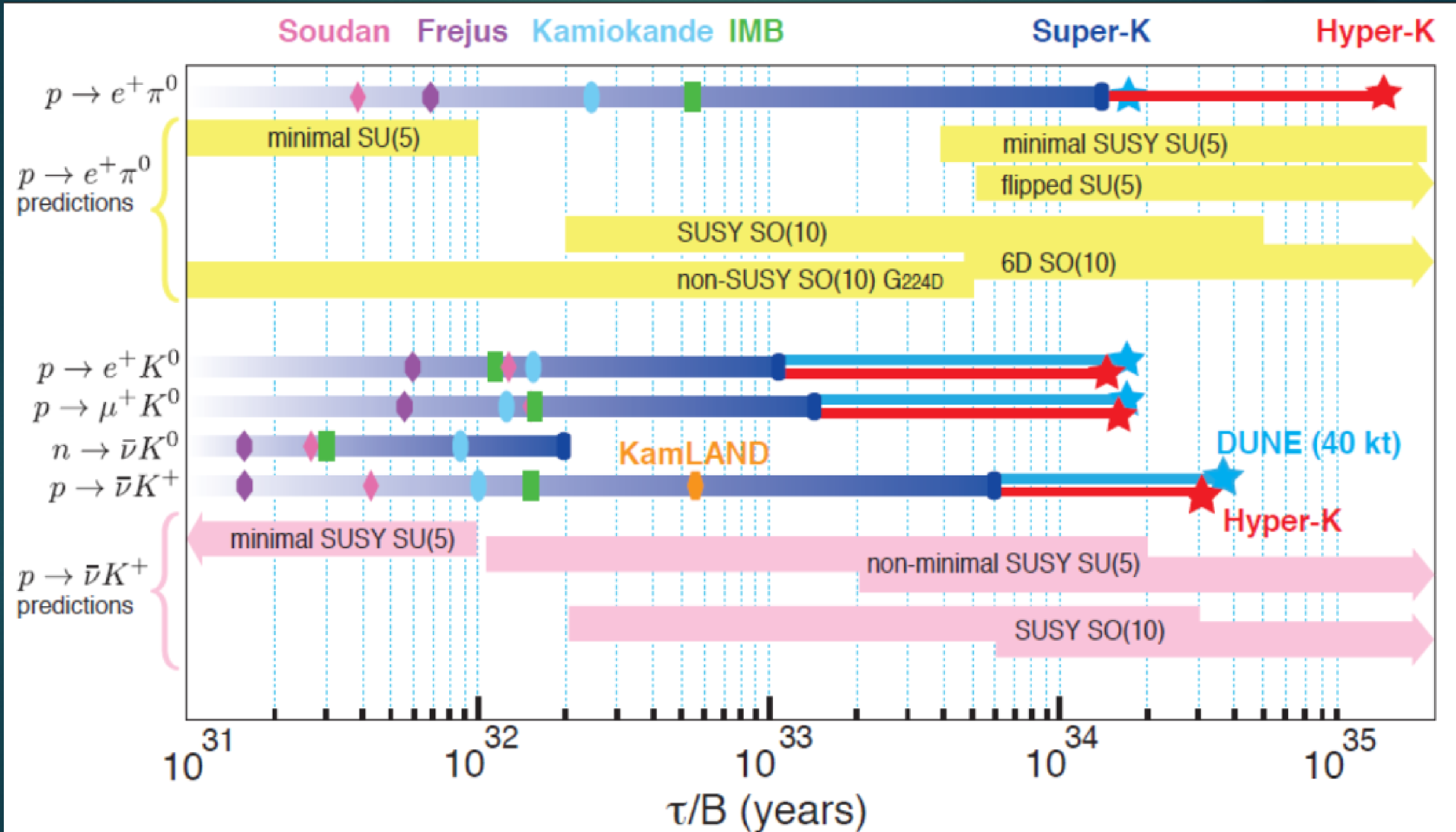
Beam + Atm ν combination





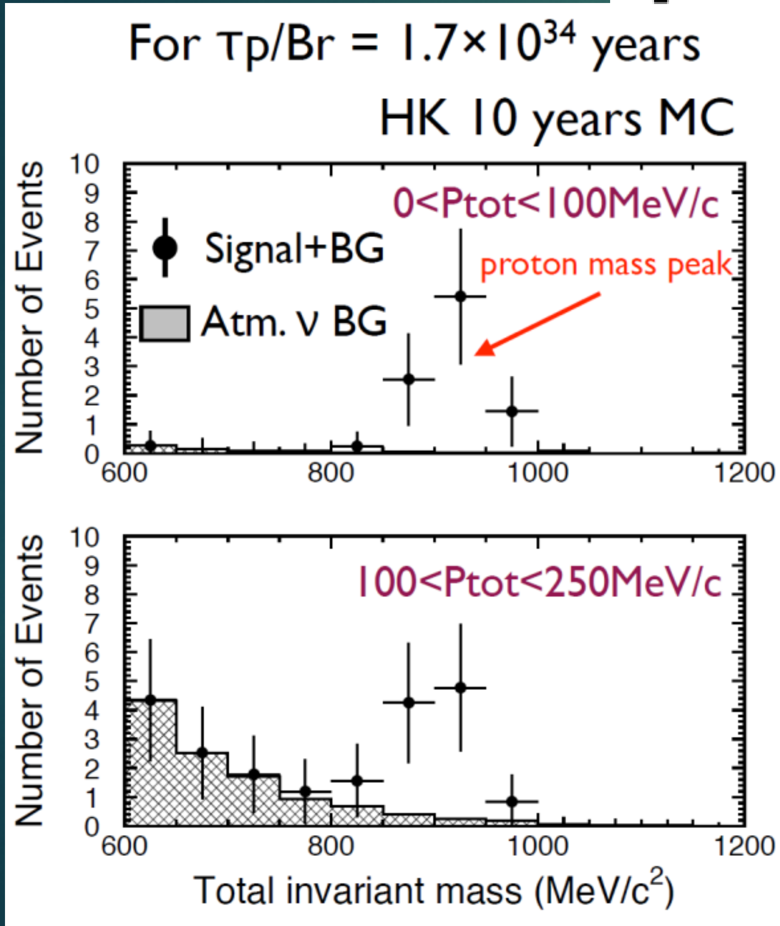
- Complementary information from beam and atm ν
- Sensitivity enhanced by combining two sources!

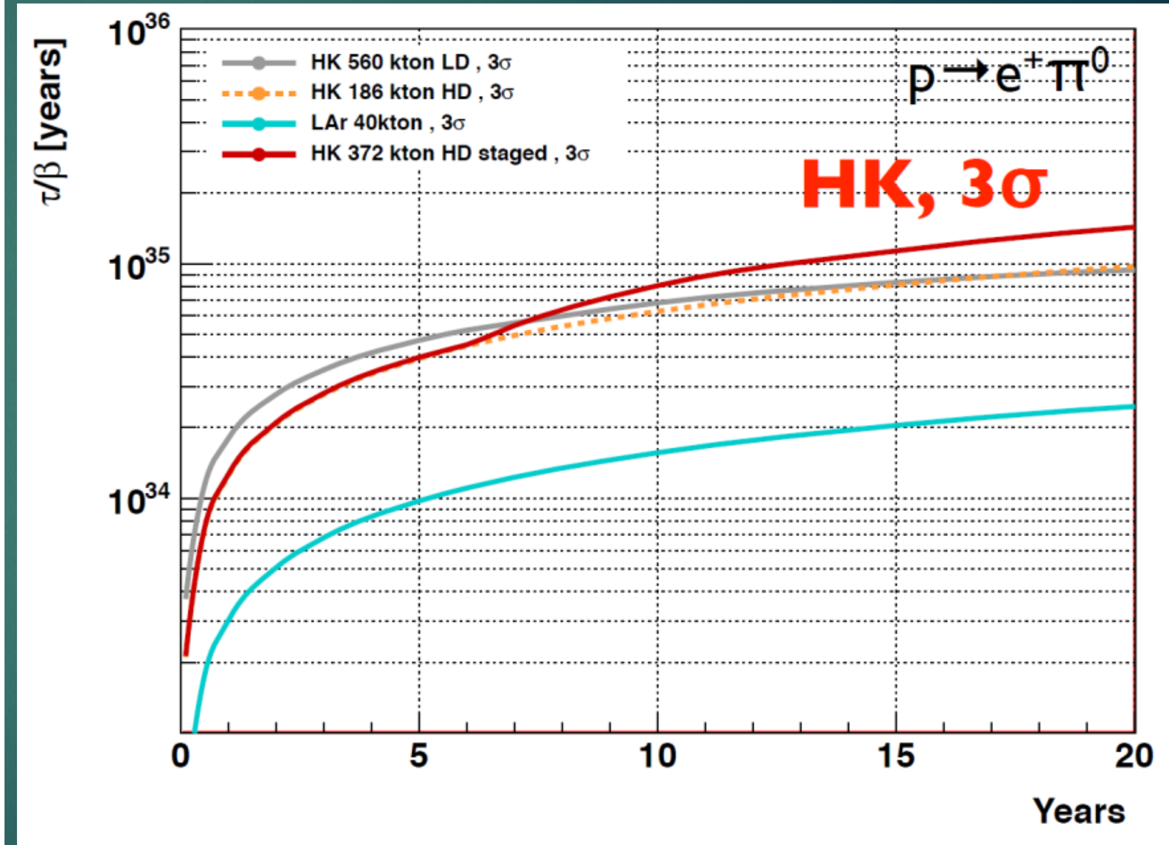
Nucleon decay search



Proton decay search

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





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

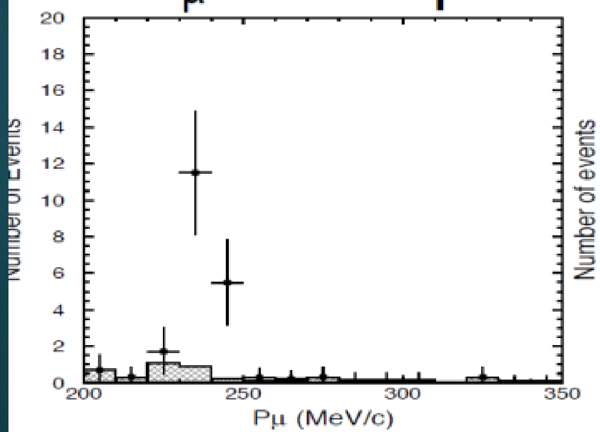
$p \rightarrow \bar{\nu}K^+$ sensitivity

- Clear signal can be seen for lifetime just above the current limit

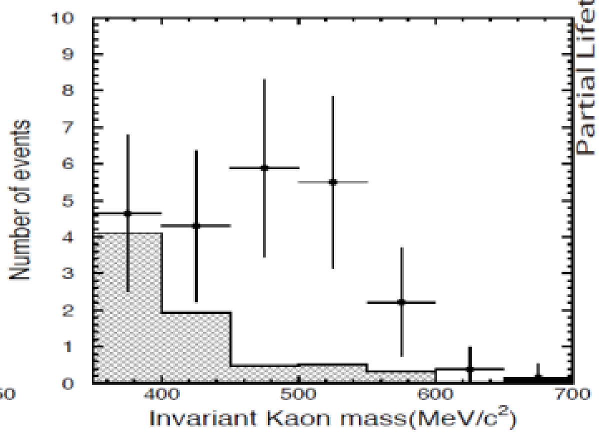
For $\tau p/Br = 6.6\times10^{33}$ years

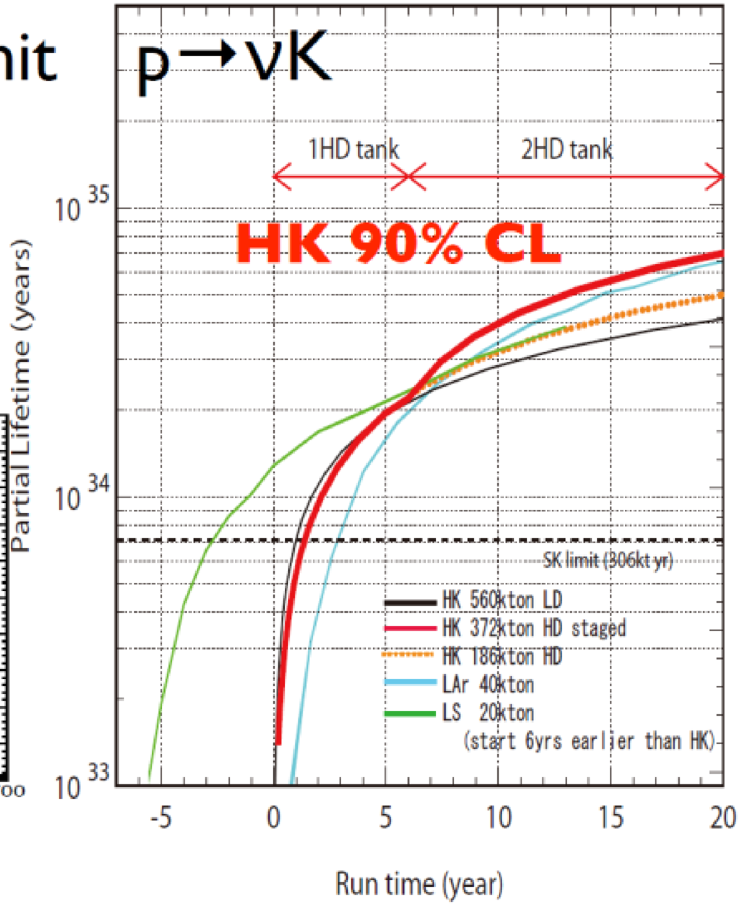
HK 10 years MC

P_μ for $K\rightarrow\mu\nu$



$K\rightarrow\pi\pi$





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

Summary

- J-PARC neutrino beam achieved 425kW stable operation
  - Accelerator demonstrated 1000kW equiv. shot
- T2K accumulated 15.1x10^{20} POT
- Precision measurements and first CPV search
  - Indicate maximum mixing for 2-3
  - Excluded CP symmetry at 90% CL. for the first time!
    - Indicate maximum violation??
- J-PARC plan to upgrade to 750kW and then 1.3MW
  - Budget for 750kW is started (FY2016-2018)
  - Modest upgrade and budget from 750kW to 1.3MW
  - **Highest priority project in KEK-PIP**
- T2K-II plan to accumulate 2e22POT by around 2024/2026
  - >3sigma sensitivity for maximum CP violation!
  - Stage-1 status given by PAC
- Hyper-Kamiokande with new design
  - 190kton x 2 staging
  - 8sigma CPV, x10 sensitivity on proton decay, mass hierarchy determination
  - Aim to start operation in 2026