The T2K Neutrino Oscillation Experiment

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Workshop on Next generation Nucleon decay and Neutrino detectors
2007

Outline

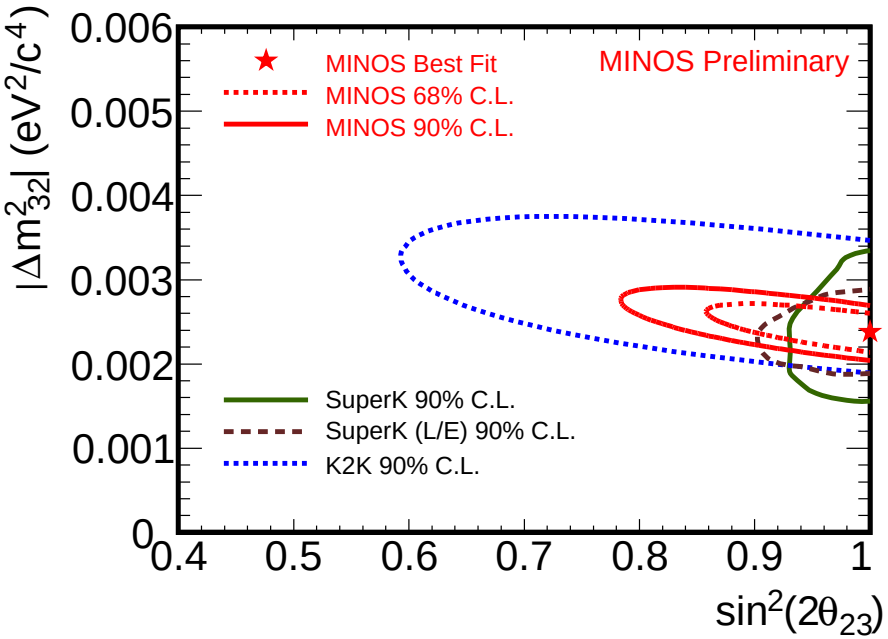
Neutrino oscillations observed

- Neutrino disappearance - oscillations confirmed
- Neutrinos have non-zero mass

Atmo's & Long-baseline

ν_μ disappearance

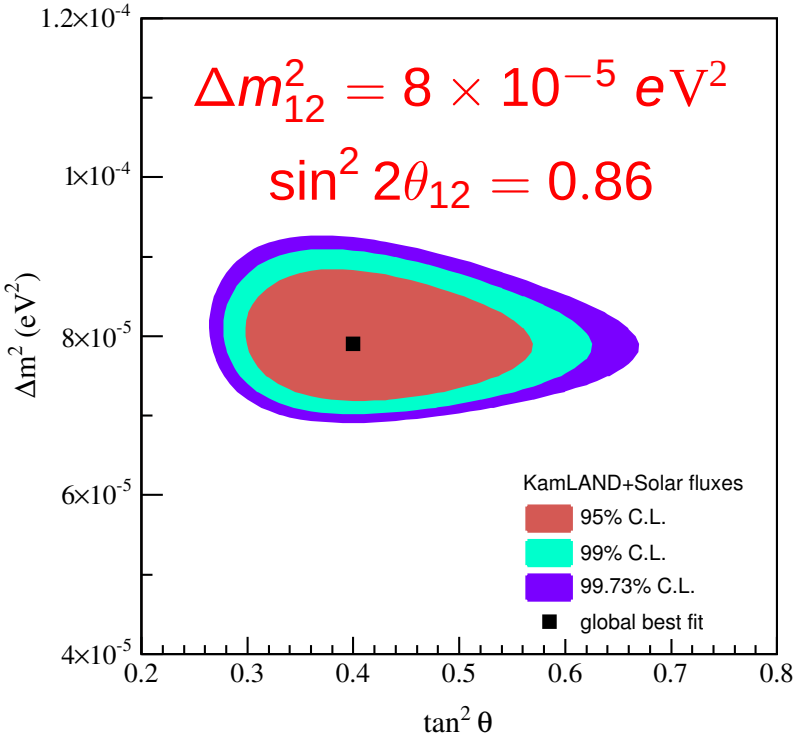
$$|\Delta m^2_{23}| = (2.2\text{–}2.6) \times 10^{-3}\ eV^2$$
$$\sin^2 2\theta_{23} > 0.9$$



KamLAND & Solar

ν_e disappearance

$$\Delta m^2_{12} = 8 \times 10^{-5}\ eV^2$$
$$\sin^2 2\theta_{12} = 0.86$$



The Parameters

$$\begin{array}{ccccc} \text{Flavour} & & \text{Unknown} & & \text{Mass} \\ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = & \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmo's \& Long BL}} & \overbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}} & \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{KamLAND \& Solar}} & \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \end{array}$$

where $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$

- Is $\sin^2 2\theta_{23}$ maximal?
- θ_{13} known to be small
- Reactor $\bar{\nu}_e$ disappearance experiments $\sin^2 2\theta_{13} < 0.19$
- No information on δ

T2K goals

Initial Goals

- Refine ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\Phi_{23}$$
$$\equiv 1 - \sin^2 2\theta_{\mu\tau}\sin^2\Phi_{23}$$

- Measure ν_e appearance:

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Phi_{23}$$
$$\equiv \sin^2 2\theta_{\mu e}\sin^2\Phi_{23}$$

Where:

$$\Phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E} = \frac{1.27(\Delta m^2_{ij}/\mathrm{eV}^2)(L/\mathrm{km})}{E/\mathrm{GeV}}$$

Future Goals

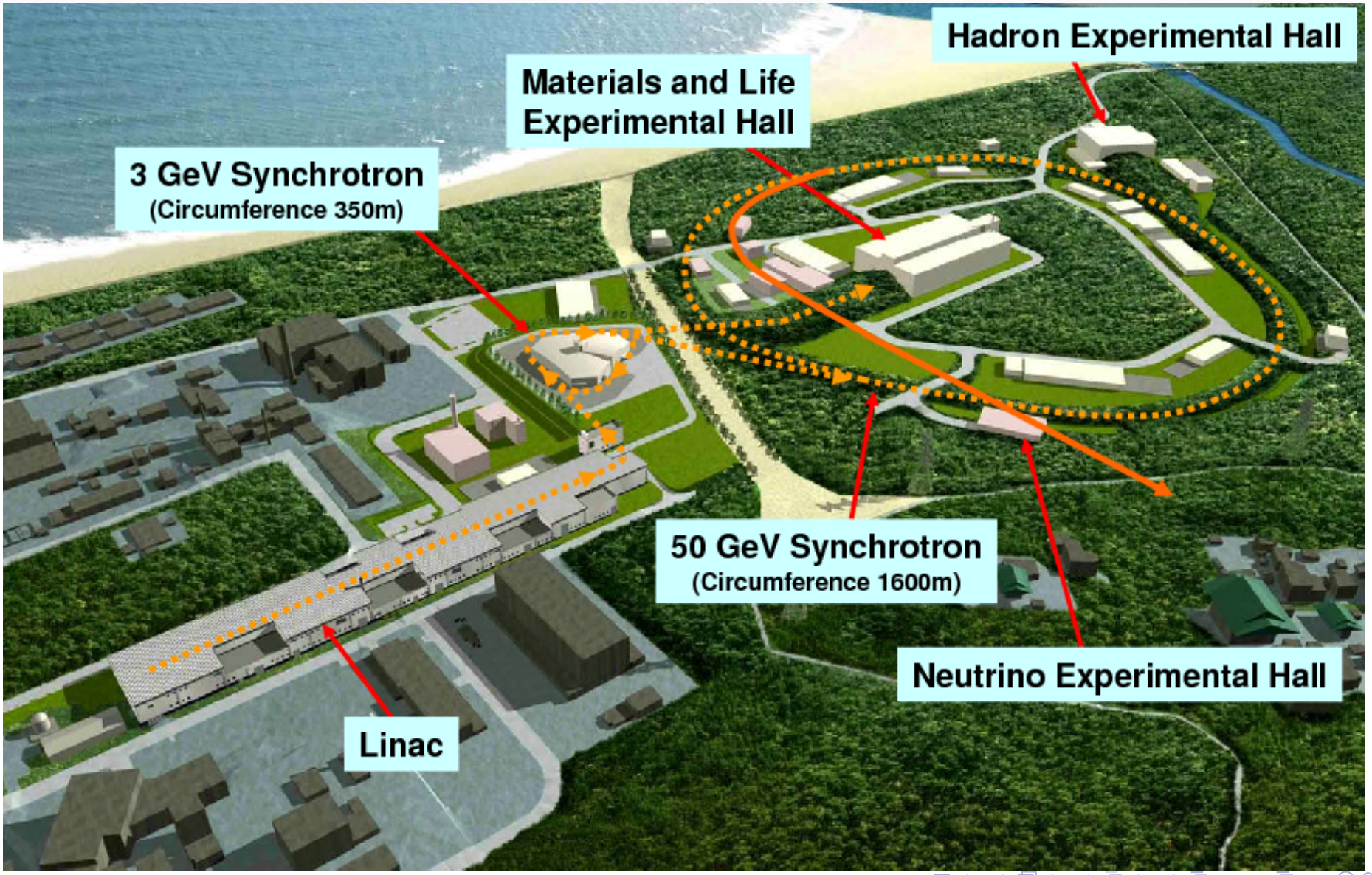
- Refine ν_e appearance
- IF $\nu_\mu \to \nu_e$ is sufficiently large:
  - look for *CPV* with $\bar{\nu}_\mu$ beam

$$A_{\mathrm{CP}} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} = \frac{\Delta m^2_{12}}{4E}\frac{\sin 2\theta_{12}}{\sin\theta_{13}}\sin\delta$$

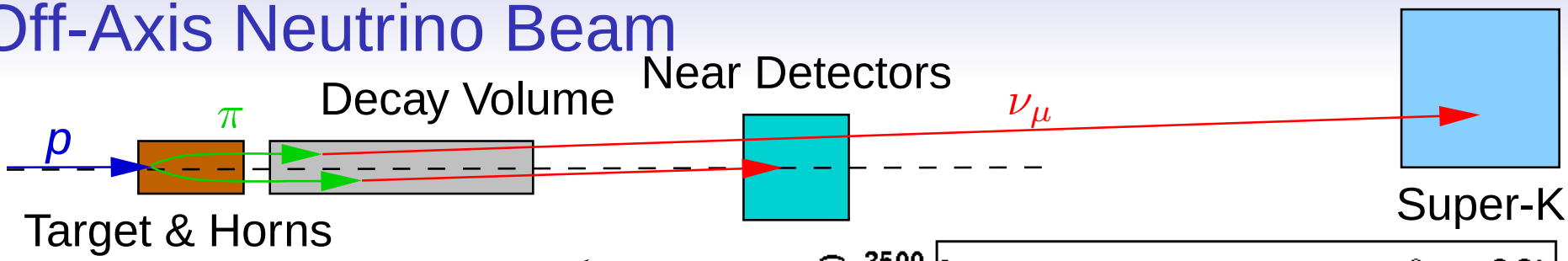
T2K

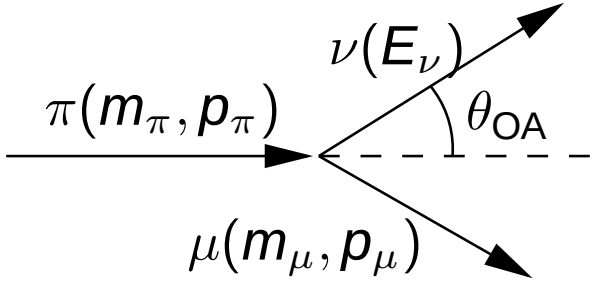
- Next generation long-baseline neutrino oscillation experiment
- Initial Phase - (0.75 MW- Super–K) $\sim$ K2K $\times$100
- Possible Secondary Phase: CPV - (4 MW- Hyper–K) $\sim$ Initial Phase $\times$100

Tokai site

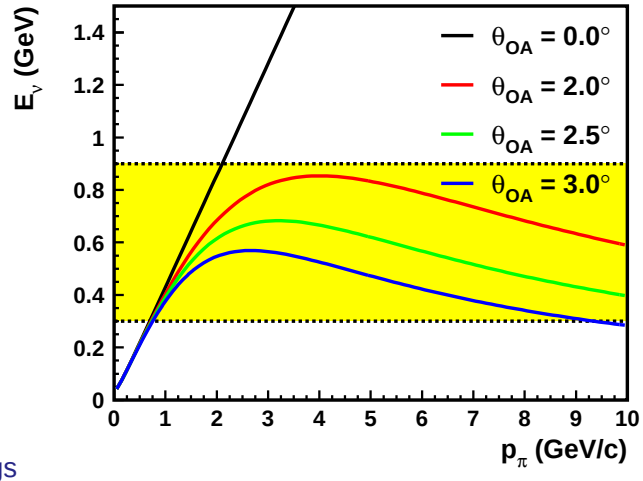

Hadron Experimental Hall
Materials and Life Experimental Hall
3 GeV Synchrotron
(Circumference 350m)
50 GeV Synchrotron
(Circumference 1600m)
Neutrino Experimental Hall
Linac

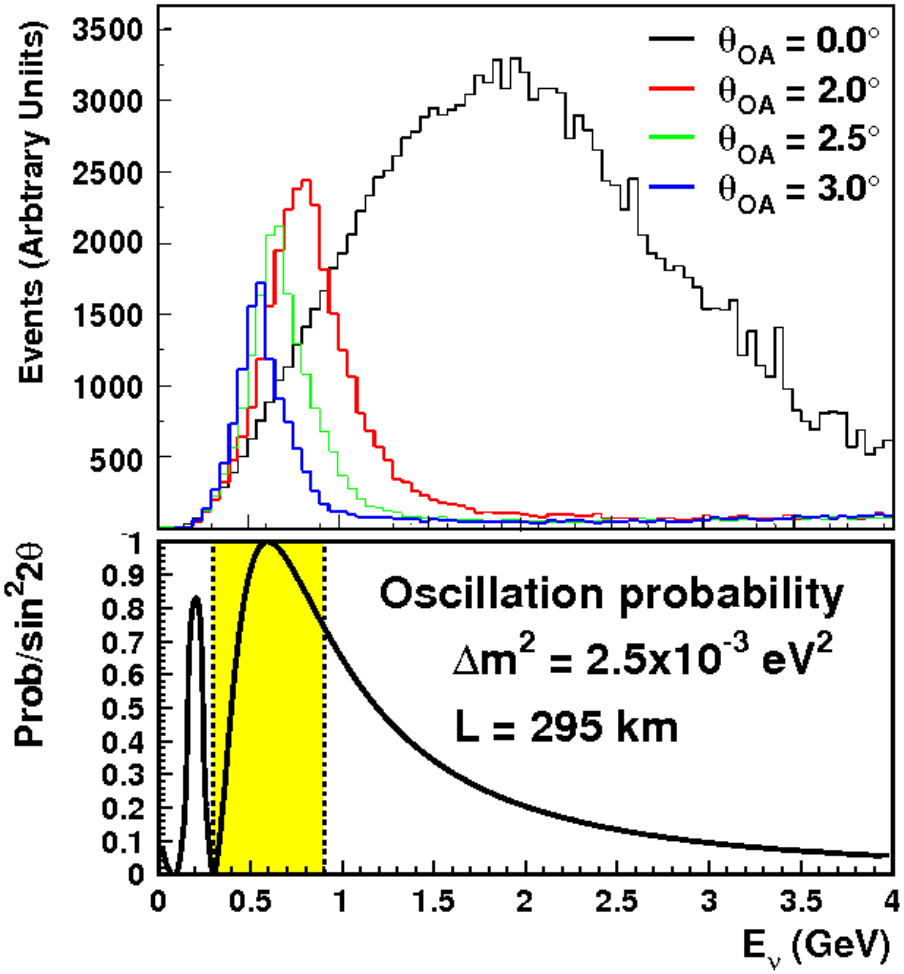
Off-Axis Neutrino Beam



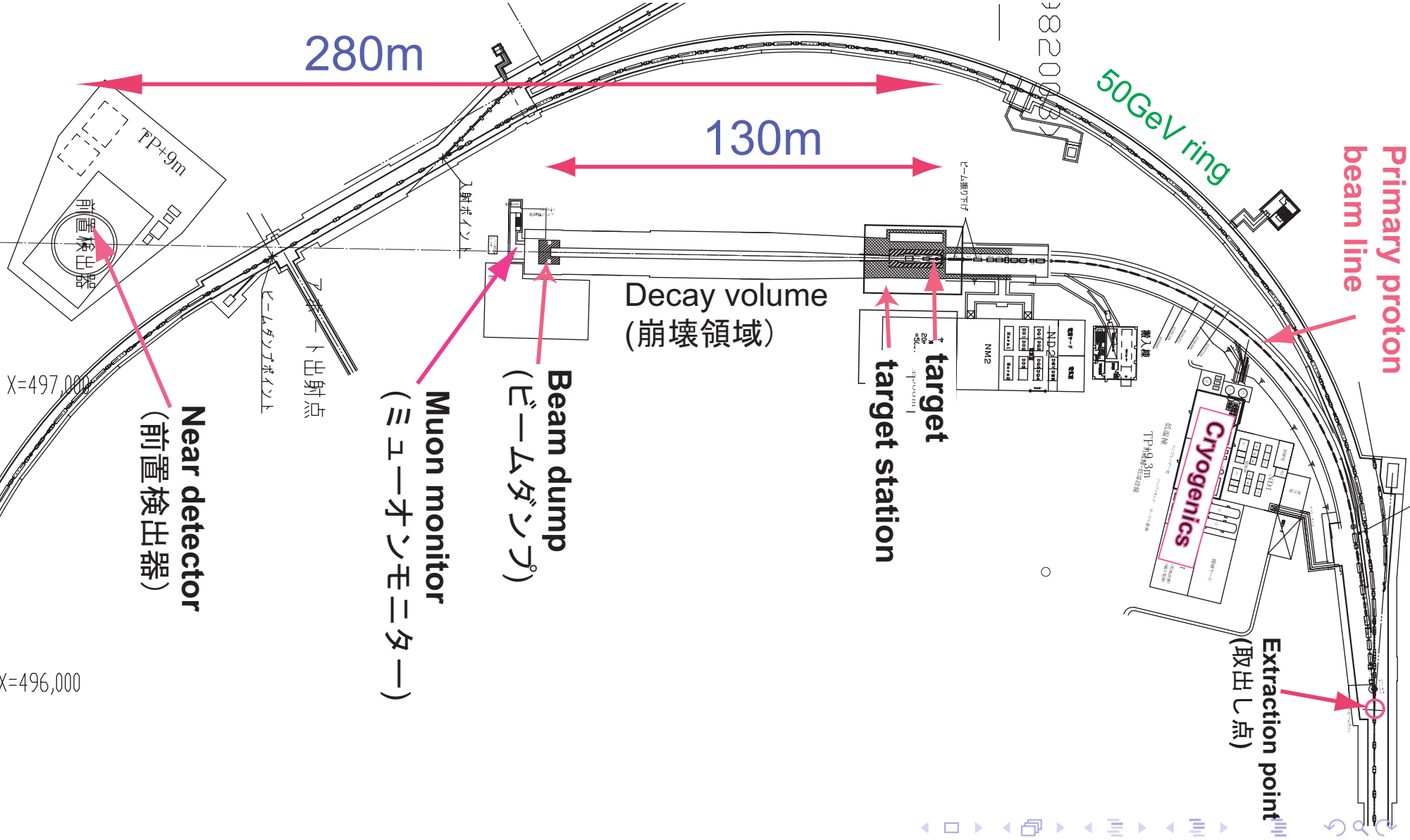


$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta_{OA})}$$

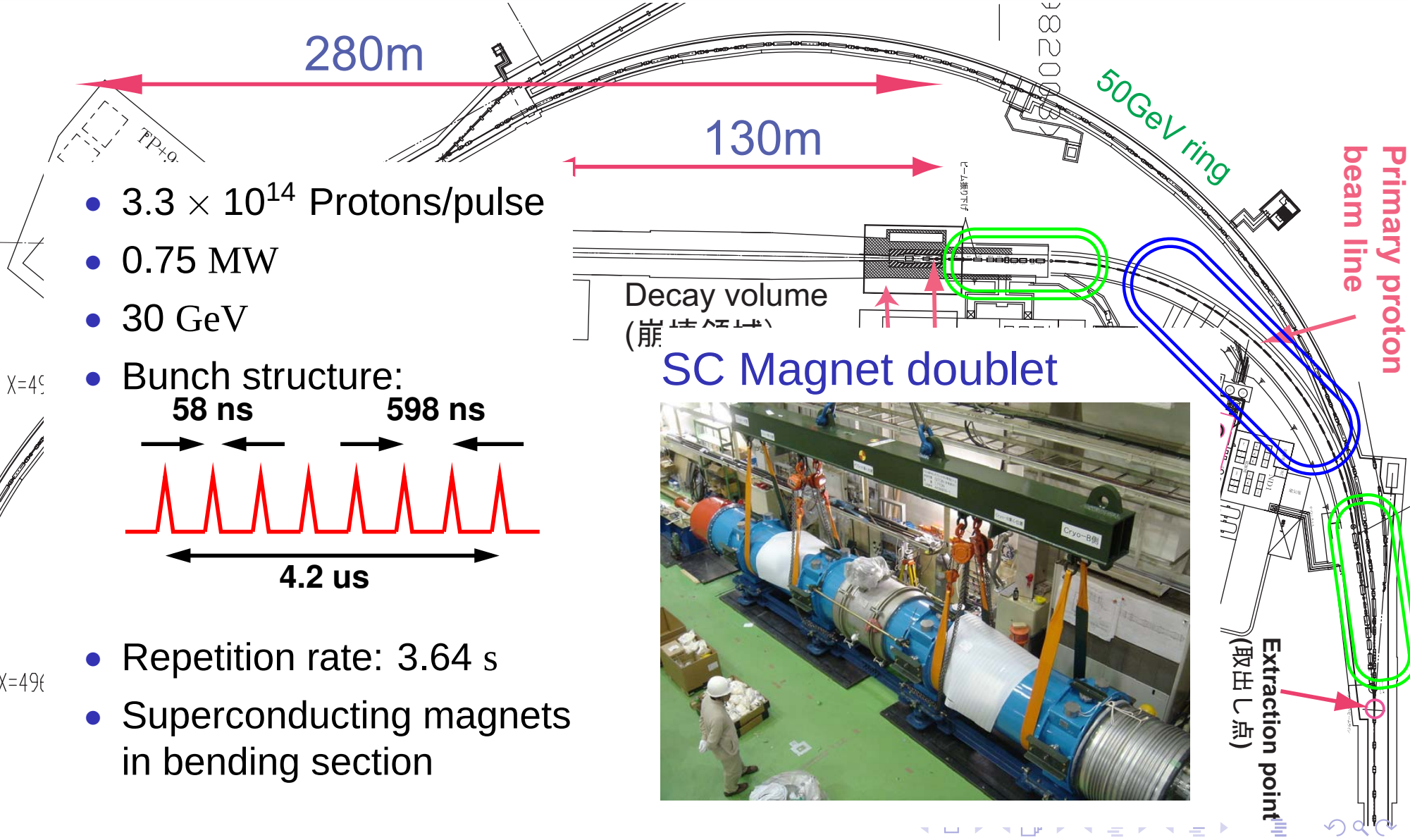




Beamline


Primary proton beam line
50GeV ring
Cryogenics
Extraction point (取出し点)
target
target station
NM2
130m
Decay volume (崩壊領域)
Beam dump (ビームダンプ)
Muon monitor (ミューオンモニター)
Near detector (前置検出器)
280m
FP+9m
X=497,000
X=496,000

Proton Beamline



- 3.3×10^{14} Protons/pulse
- 0.75 MW
- 30 GeV
- Bunch structure:

- Repetition rate: 3.64 s
- Superconducting magnets in bending section

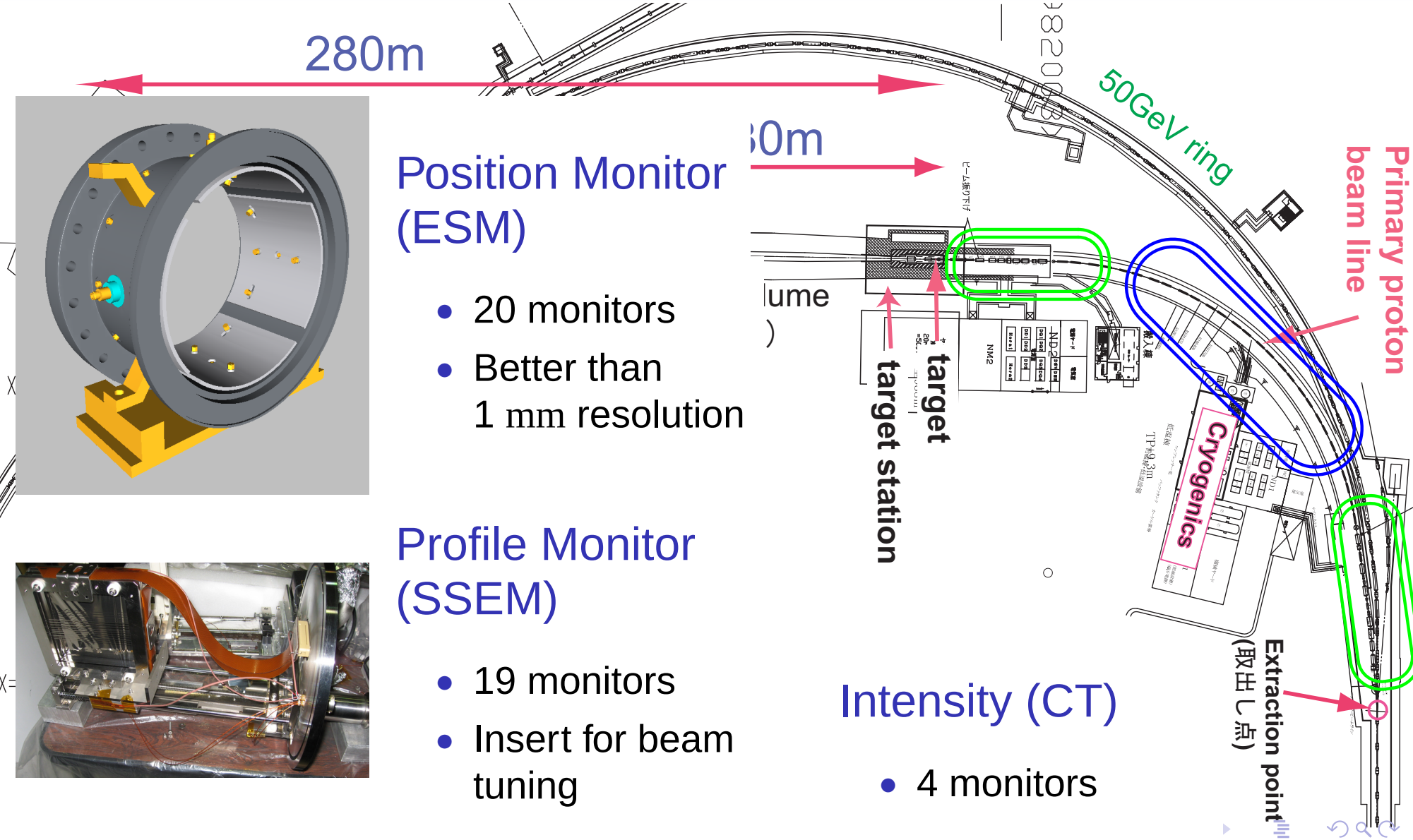
Proton Beamline - Monitors

Position Monitor (ESM)

- 20 monitors
- Better than 1 mm resolution

Profile Monitor (SSEM)

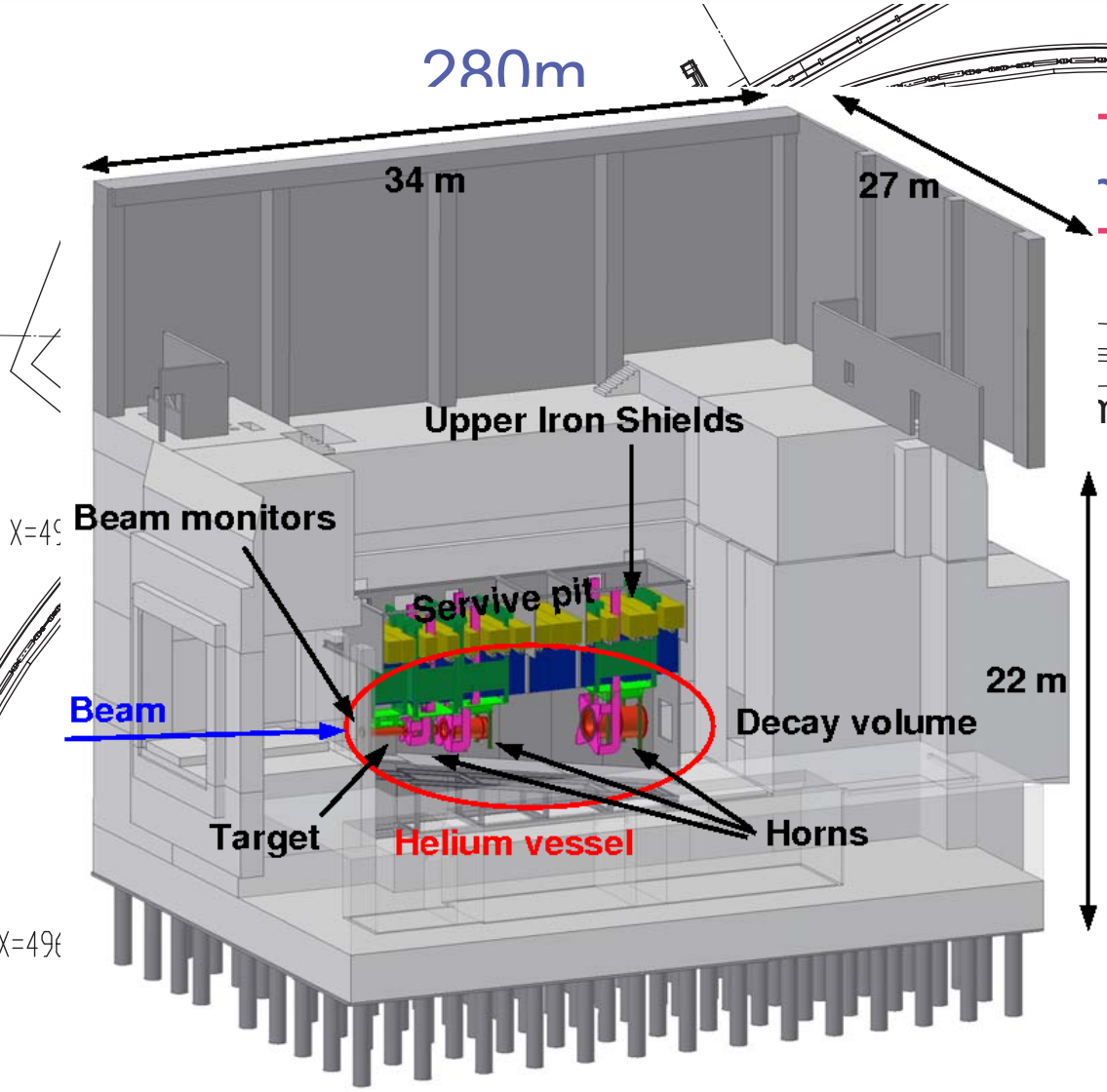
- 19 monitors
- Insert for beam tuning

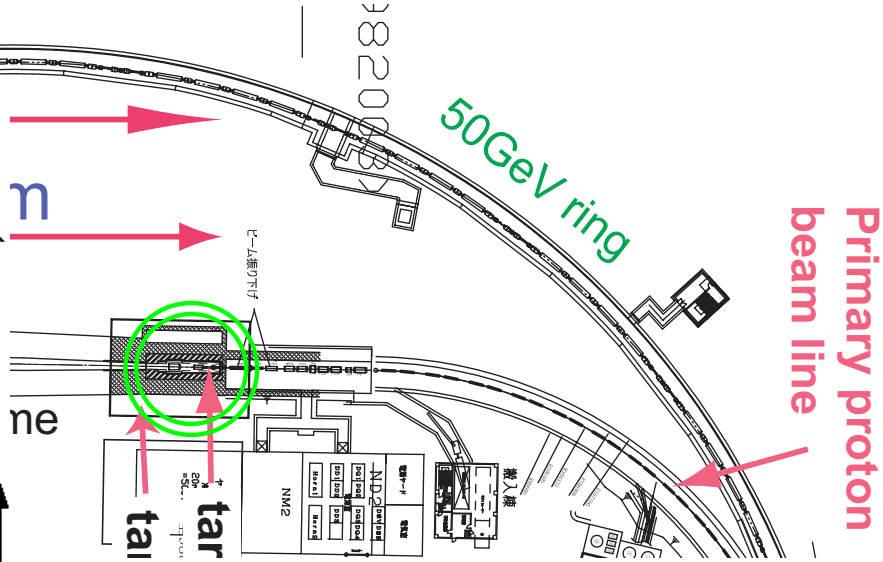


Intensity (CT)

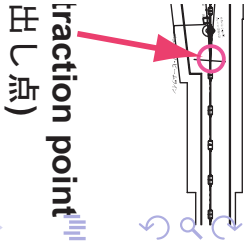
- 4 monitors

Target Station

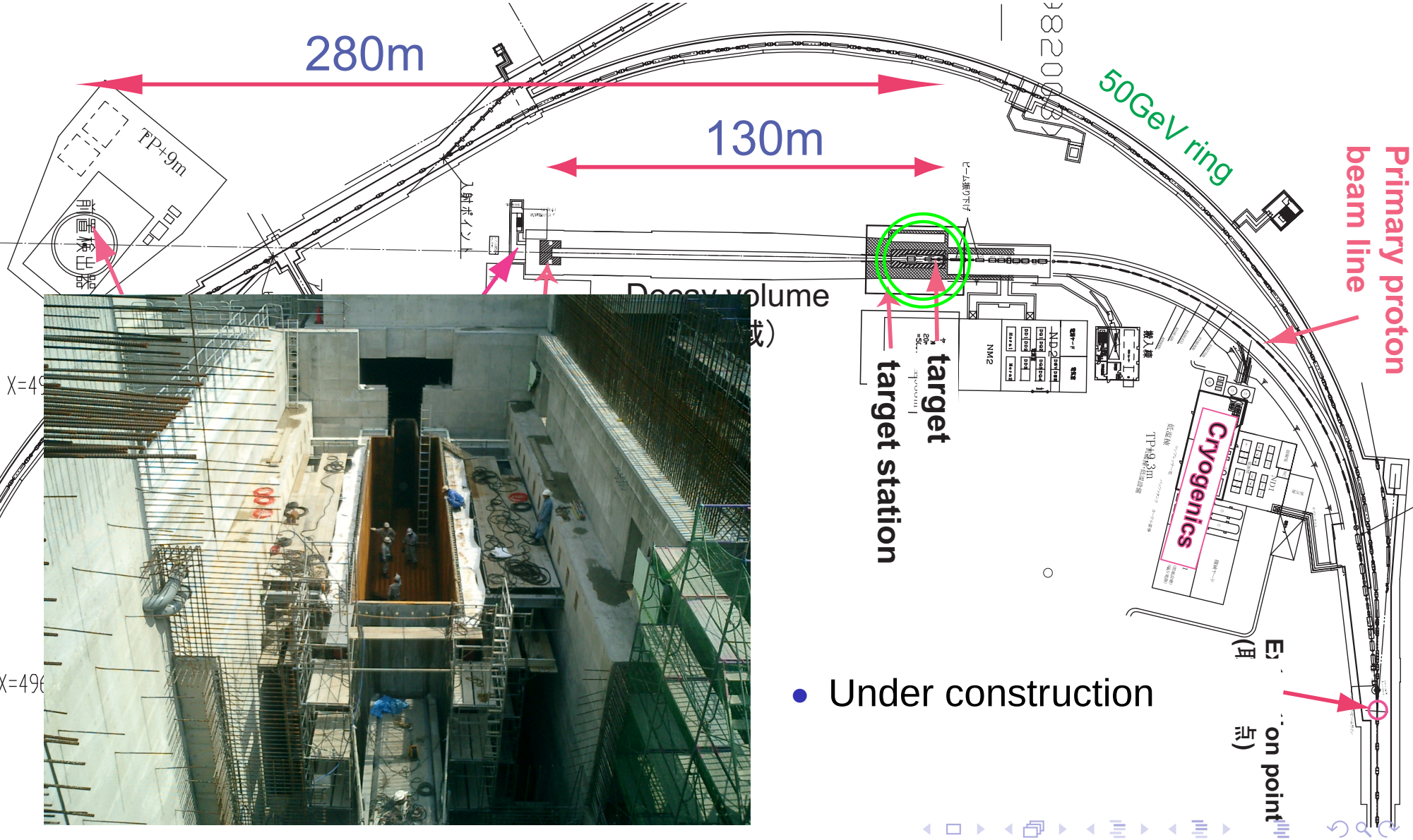




- He vessel (reduce NO_x & Tritium creation)
- Highly radio active (10 $\mathrm{Sv/h}$)
- Remote handling required for maintenance

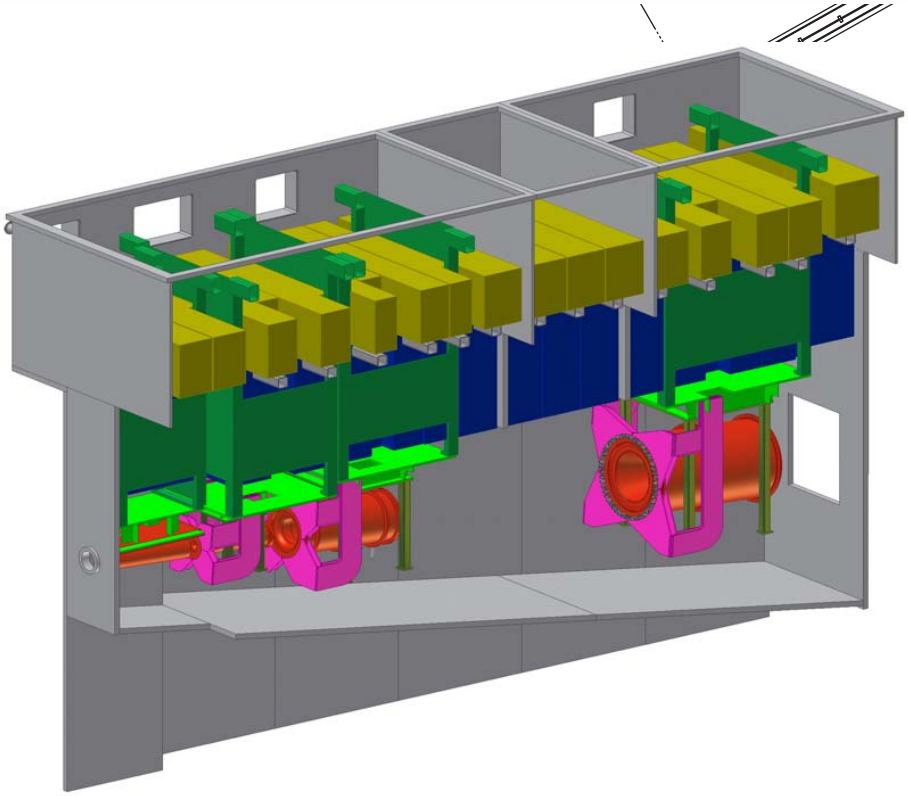


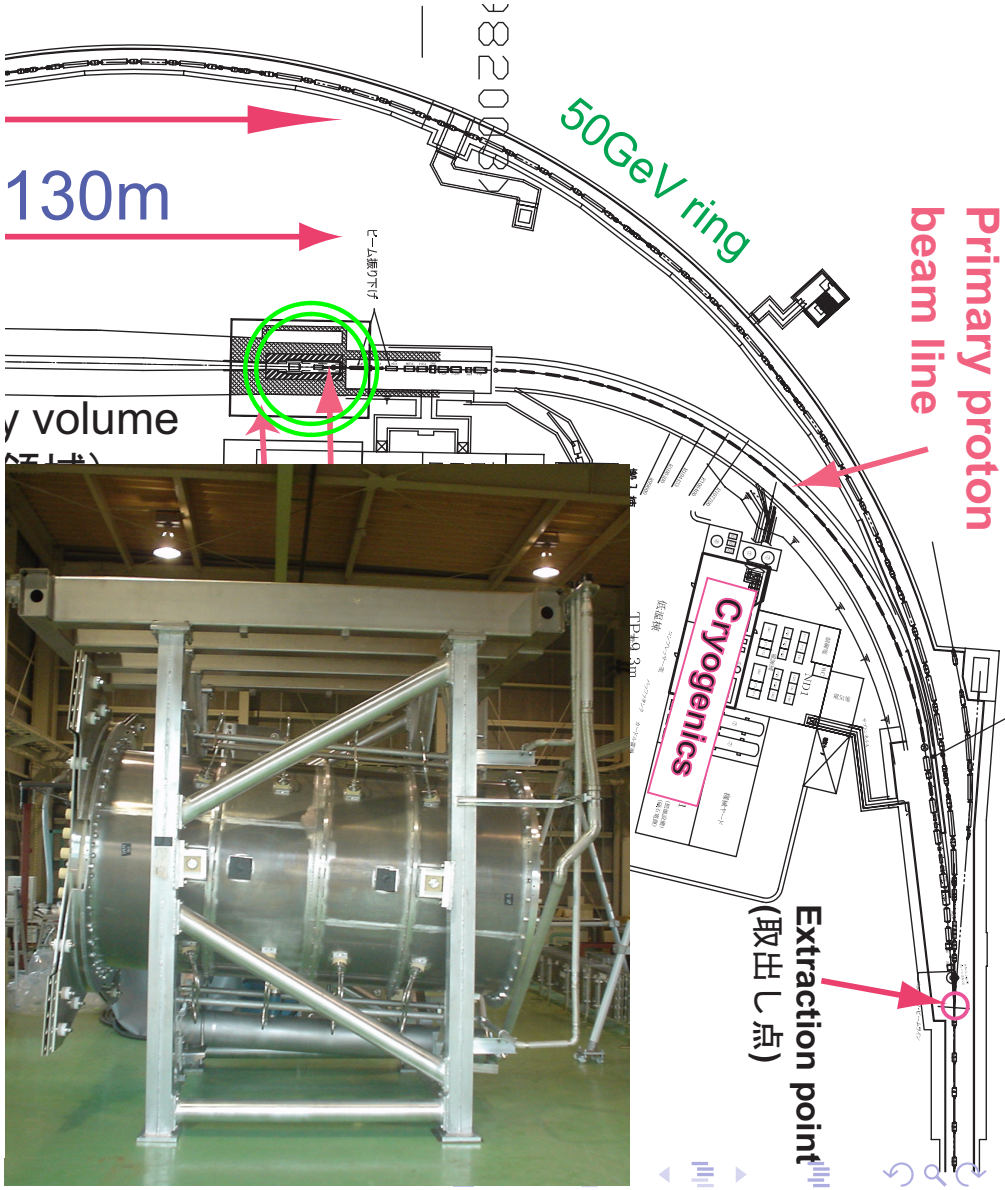
Target Station



- Under construction

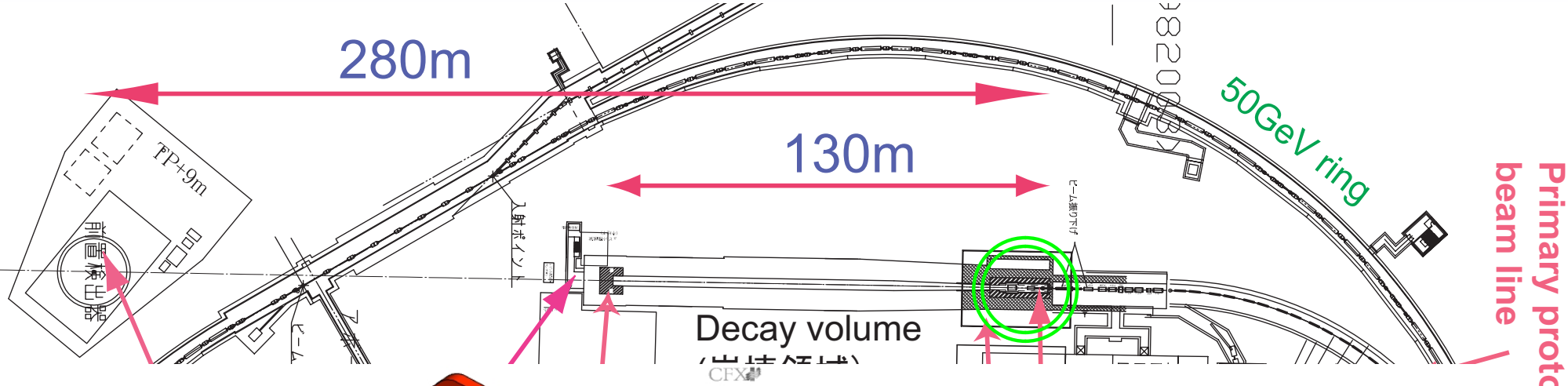
Horns

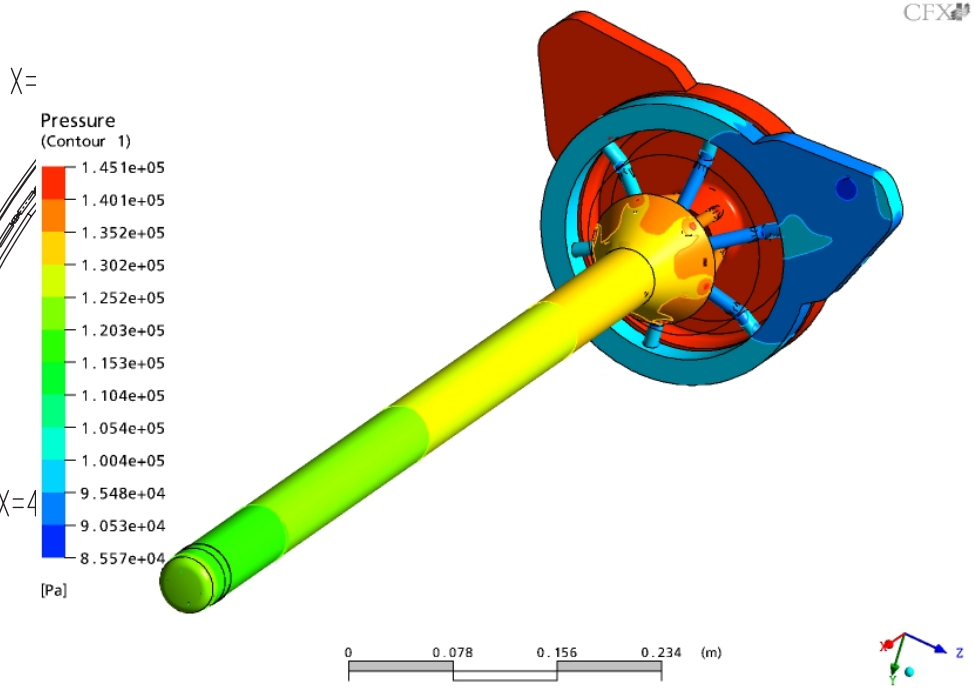




- Three horns
- Prototypes made for each type
- Tested to 320 kA
- Target located in 1st horn

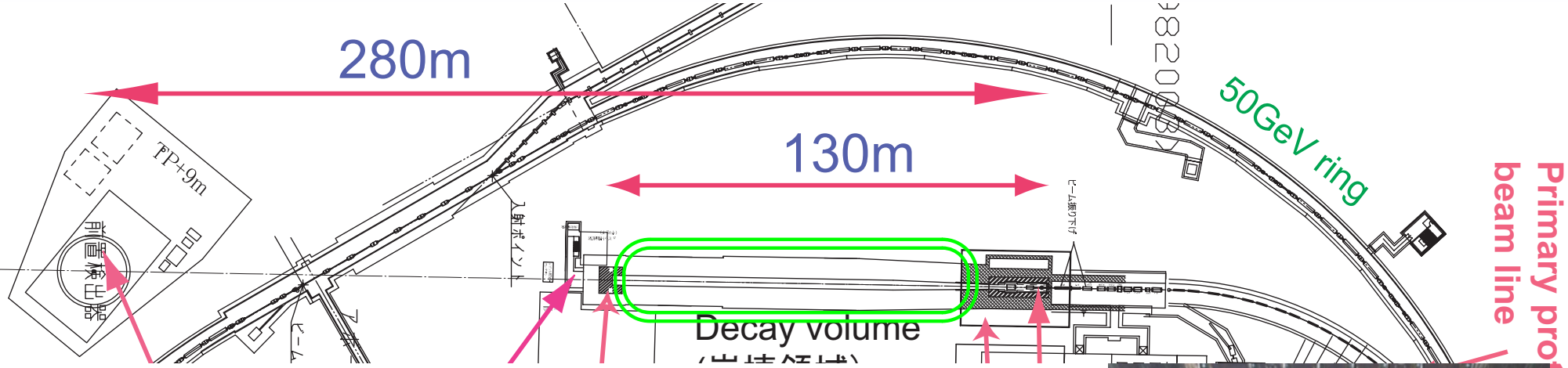
Target





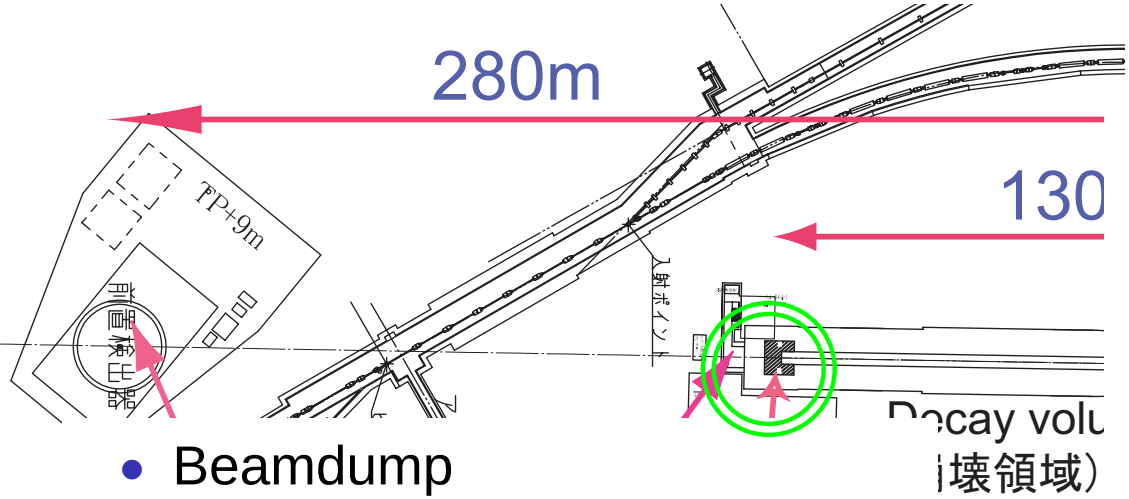
- Isotropic Graphite (IG-430)
- Encapsulated in Titanium alloy tube
- L = 90 cm, ϕ=26 mm
- Energy Deposit: 20 kW
  - Helium cooled
  - $\Delta T_{pulse} = 200\ ^{\circ}\mathrm{C}$

Decay Volume



- 94 m
- Helium filled
- Water cooled

Beamdump & Muon Monitors

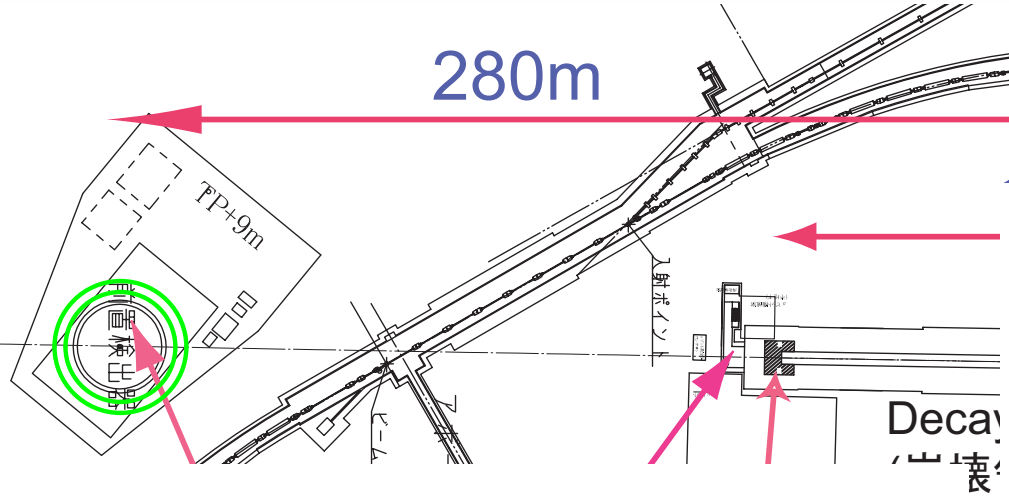


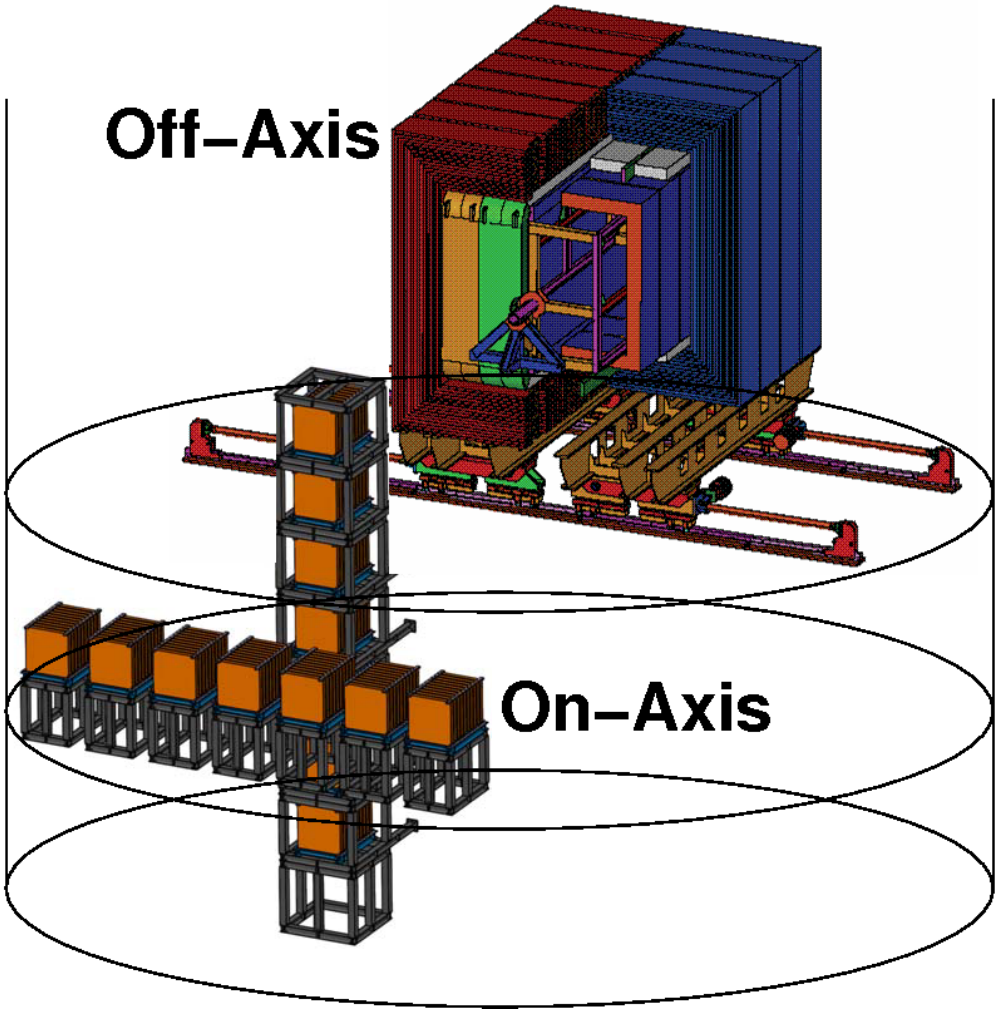
Beamdump

Primary proton beam line

- Beamdump
  - Graphite blocks
  - $\sim 3\ \mathrm{m} \times 3\ \mathrm{m} \times 5\ \mathrm{m}$
  - Al pipes for water cooling
  - $t_{max} \simeq 500\ ^{\circ}\mathrm{C}$(Graphite), $90\ ^{\circ}\mathrm{C}$(Al) @ $3\ \mathrm{MW}$
- Muon Monitors
  - planes of semiconductors and ionisation chambers
  - placed behind beam dump
  - profile centre precision: $3\ \mathrm{cm}$

Near Detectors at 280 m

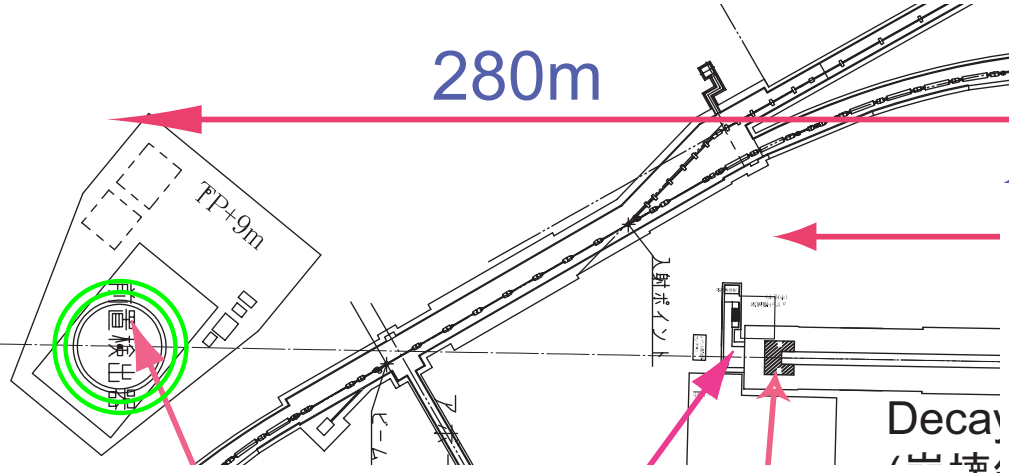


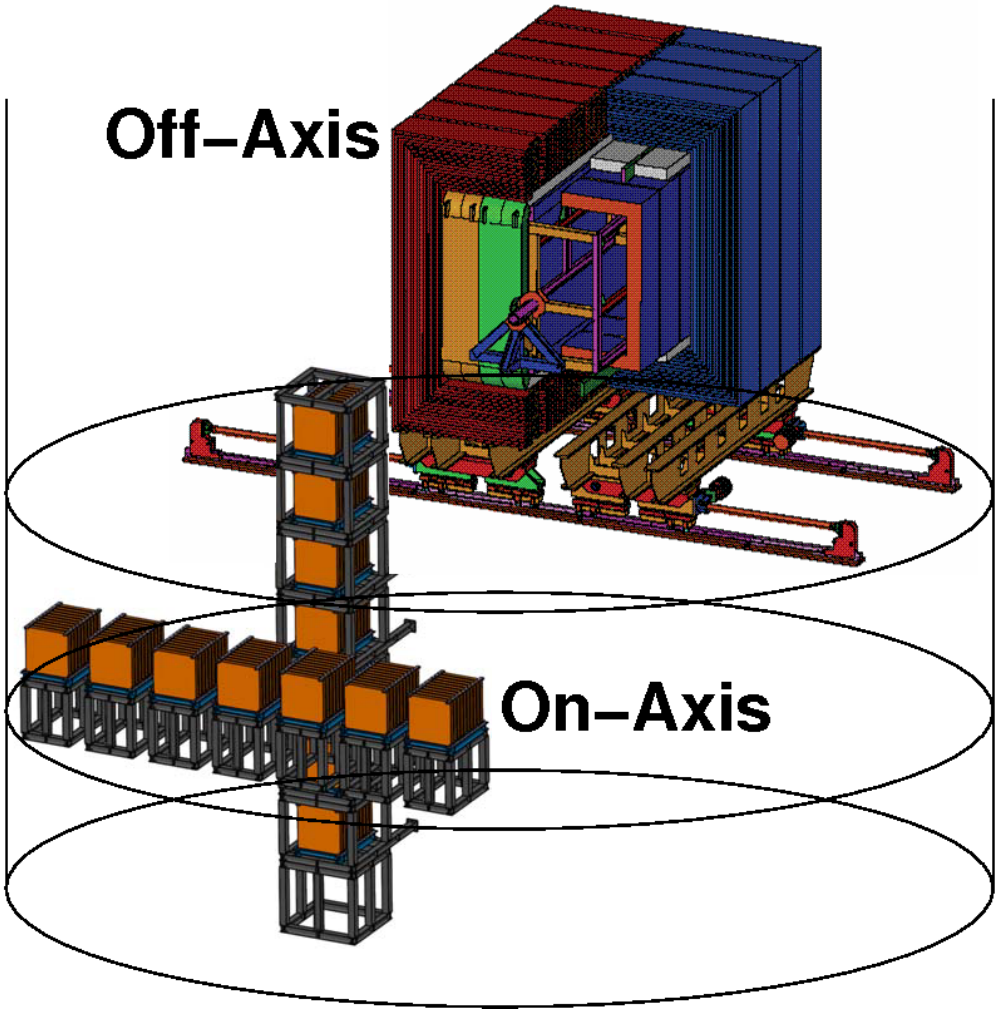


INGRID (On-Axis)

- Iron-scintillator stacks
- 10 m × 10 m coverage
- Monitor ν_μ beam
  - Profile
  - Direction
- $\sigma_\theta = 0.18$ mrad
- Shift resolution corresponds to 1 mm at target

Near Detectors at 280 m

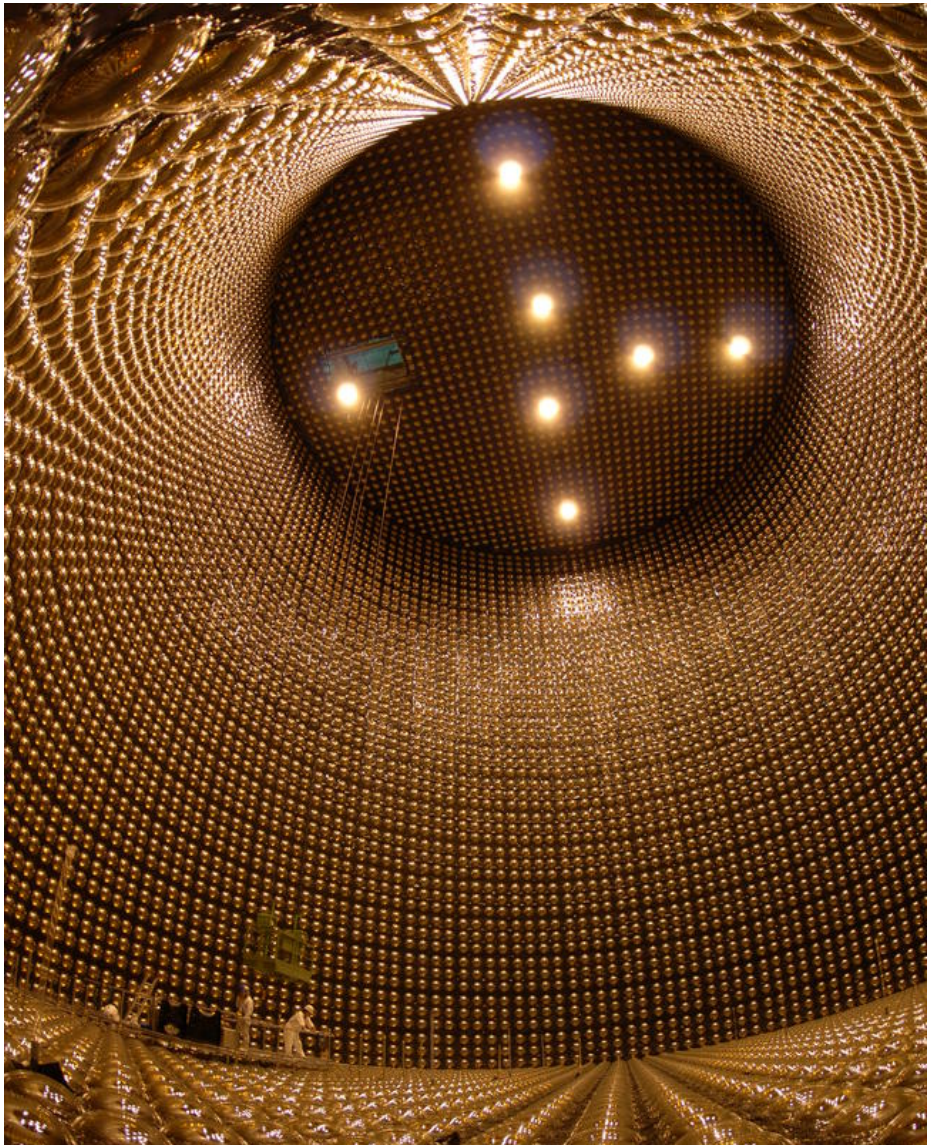




ND280 (Off-Axis)

- Meas. ν-flux in direction of SK
  - Both ν_μ and ν_e
  - Tracker for CC-QE kinem. (E_ν)
- Cross sections of ν interaction
  - CC-nQE vs CC-QE: for E_ν recon.
  - NC-π^0 production (fake ν_e)

Far Detector - Super-Kamiokande

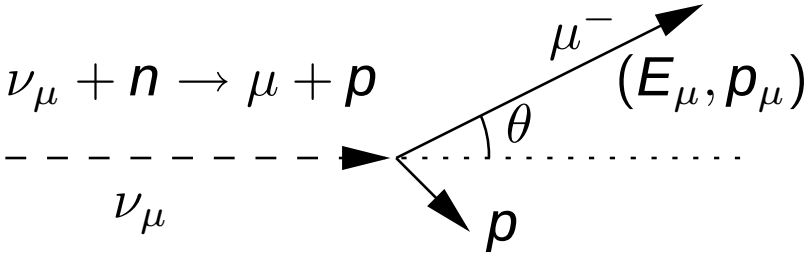


- $\phi \times h = 39\ \mathrm{m} \times 41\ \mathrm{m}$
- 11146(inner)+1885(outer) PMTs
- Fiducial volume 22.5 kt

E_ν Reconstruction

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{\mu\tau} \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

Signal



Charged Current Quasi-Elastic (CC-QE)

$$E_\nu^{\text{rec}} = \frac{m_n E_\mu - m_\mu^2/2}{m_n - E_\mu + p_\mu \cos\theta}$$

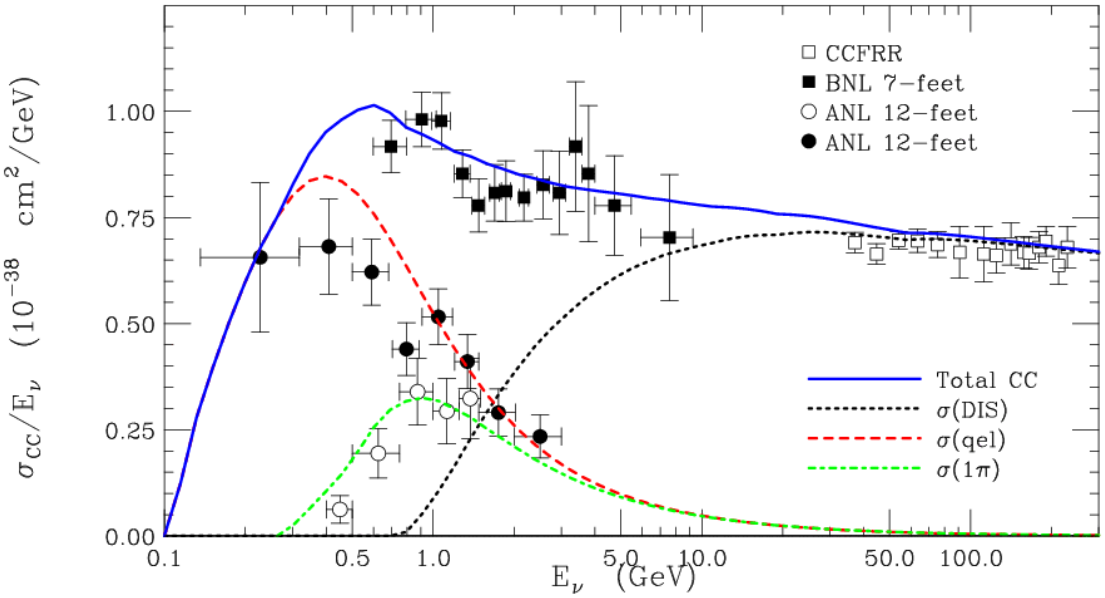
Fit cone to PMT hits to reconstruct E_ν:

- Utilise energy and timing info. from PMTs

For a 1 GeV μ achieve

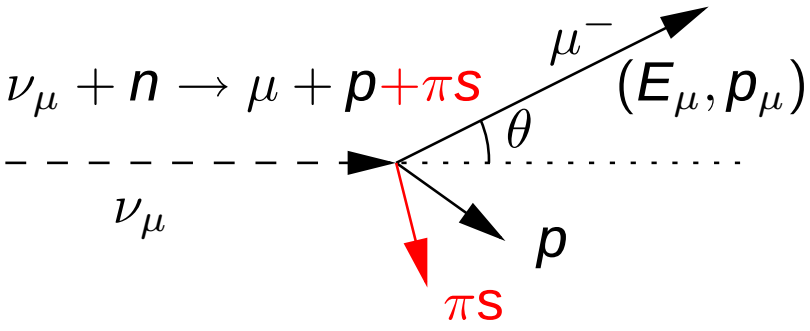
- $\sigma(E_\nu/E_\nu) \simeq 3\%$
- Flight direction 3%
- Vertex position 30 cm

ν_μ CC cross sections



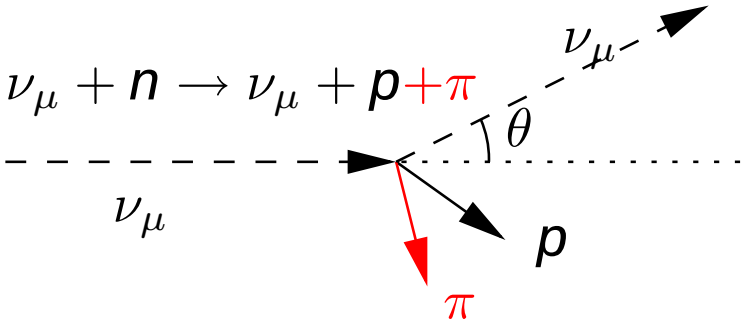
Backgrounds

CC-nQE



- Incorrect E_ν^{rec} determination

Neutral Current (NC)



- π^0 can look like electron
- Hampers $\nu_\mu \rightarrow \nu_e$ search

- Intrinsic ν_e content in beam
- Muon/Electron separation

Extracting Results

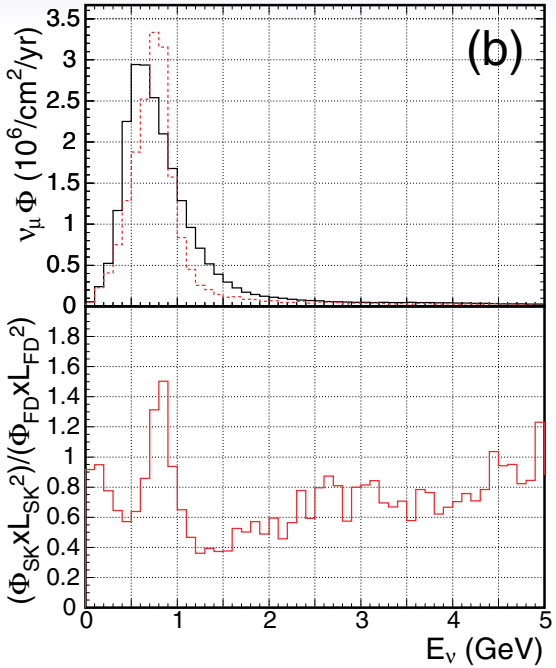
- ν_e appear.: Excess of # e^- over expected bkgd
- ν_μ disappear.: Deficit # μ^- & dist. of E_ν.

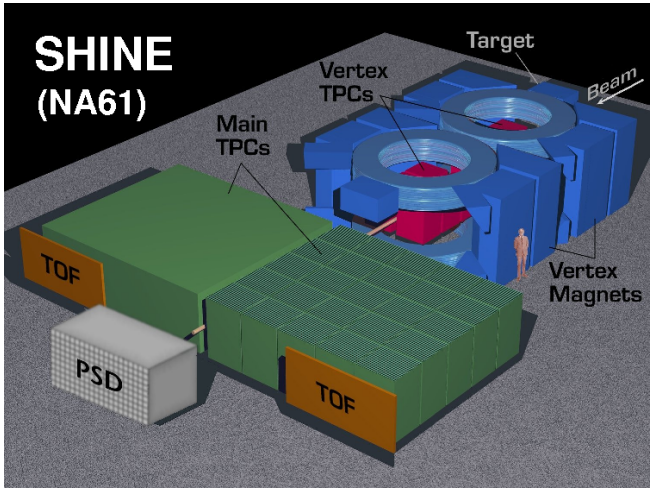
Event rate prediction:

$$N_{ND} = \phi_{ND}\sigma_{ND}$$
$$N_{SK} = \phi_{SK}\sigma_{SK}P_{osc}$$

- $\sigma_{SK,ND}$ studied with ND
- Treat Fluxes as ratio: $R_{N/F} = \frac{\phi_{SK}}{\phi_{ND}}$
  - Need to understand hadron production...

Compare: N_{SK}^{obs} to $N_{SK}^{pred} = N_{ND}^{obs} R_{N/F} \frac{\sigma_{SK}}{\sigma_{ND}}$





SHINE (NA49 upgraded to NA61)

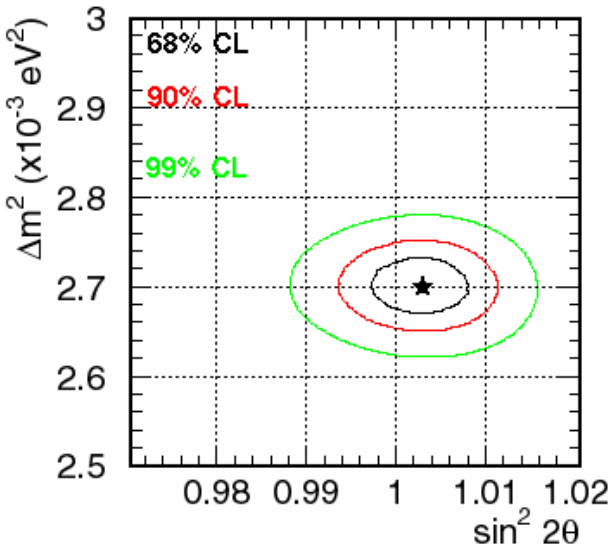
- $\pi^\pm$, $K^\pm$ & K^0 prod.
- Protons on Carbon target
- 30 GeV beam approved (seek 40 & 50 GeV)
- Matched to T2K conditions
- Understand hadron production: Use for $R_{N/F}$

ν_μ disappearance: θ_{23} and Δm^2_{23}

- 5 years (10^{21} POT/year)

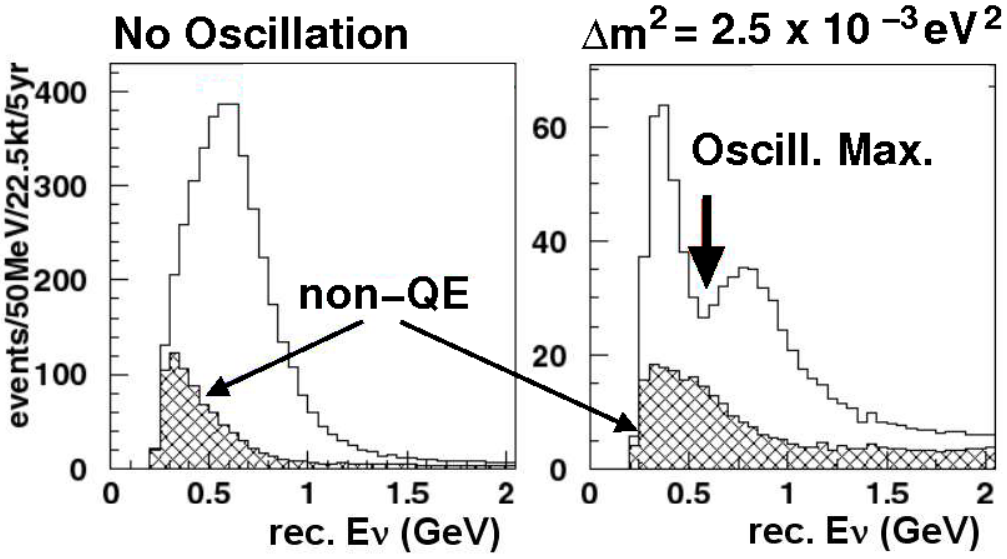
Achieved sensitivity

$\delta(\sin^2 2\theta_{23}) \simeq 0.01$
$\delta(\Delta m^2_{23}) < 10^{-4}\ eV^2$



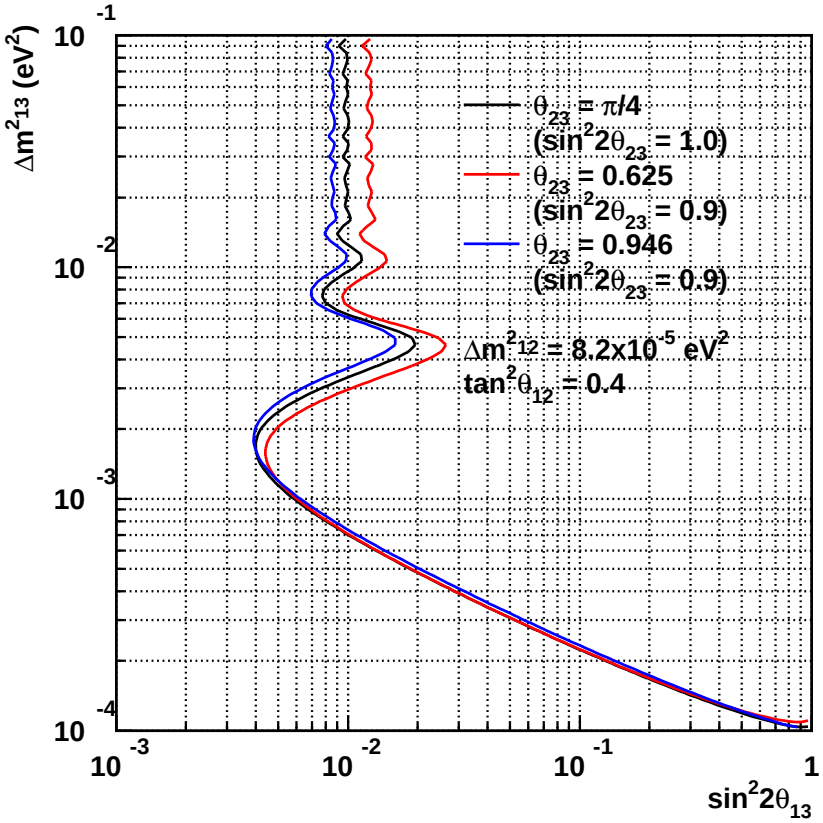
Systematic error req'ments

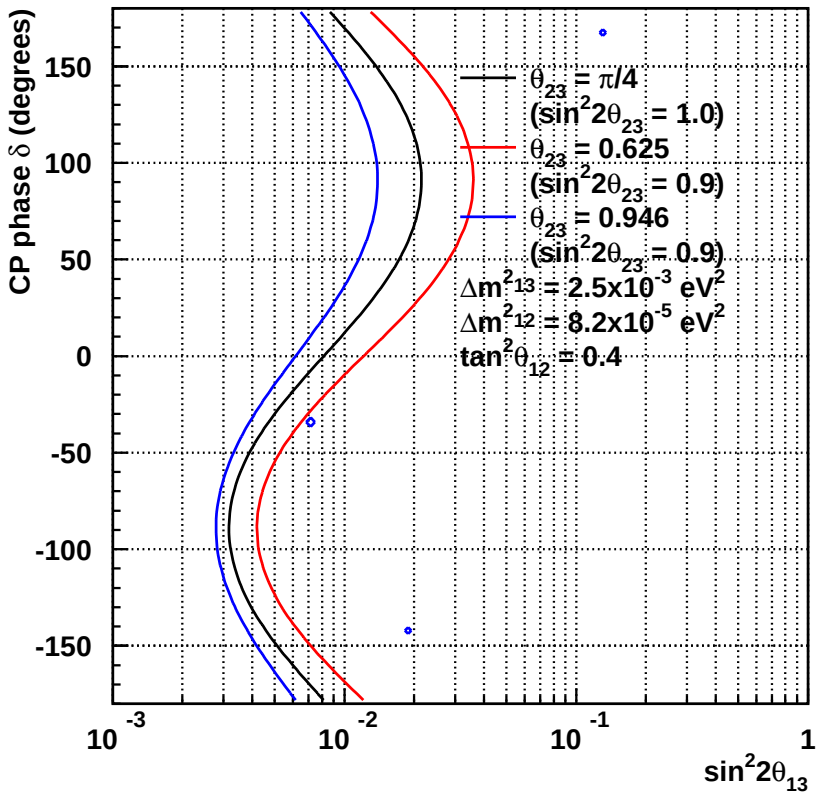
Source	Size
Non-QE/QE Ratio	$< 5\%$
Energy Scale	$< 2\%$
Flux Normalisation	$< 10\%$
Flux Width	$< 10\%$
Flux Shape	$< 20\%$



ν_e appearance: θ_{13}

- 5 years (10^{21} POT/year)
- Error on background estimation at 10%





$\sin^2 2\theta_{13} < 0.008$ (90% C.L.)
for: $\delta = 0$, $\Delta m^2_{13} = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$

- Factor 10 improvement on CHOOZ limits (for any δ)

Summary

- New accelerator facility: Large number of protons on target
- Off-axis beam: Narrow E_ν distribution tuned to oscillation maximum
- Extensive suite of beam monitors/near detectors
- Well established far detector
- Physics Prospects
  - Search for ν_e appearance: order magnitude improvement on $\sin^2 2\theta_{13}$
  - Precision measurements: $\delta(\sin^2 2\theta_{23}) \simeq 0.01$, $\delta(\Delta m^2_{23}) < 10^{-4}\ eV^2$
- T2K facility at J-PARC well underway
- Start Neutrino beam commissioning April 2009

Commissioning Plan