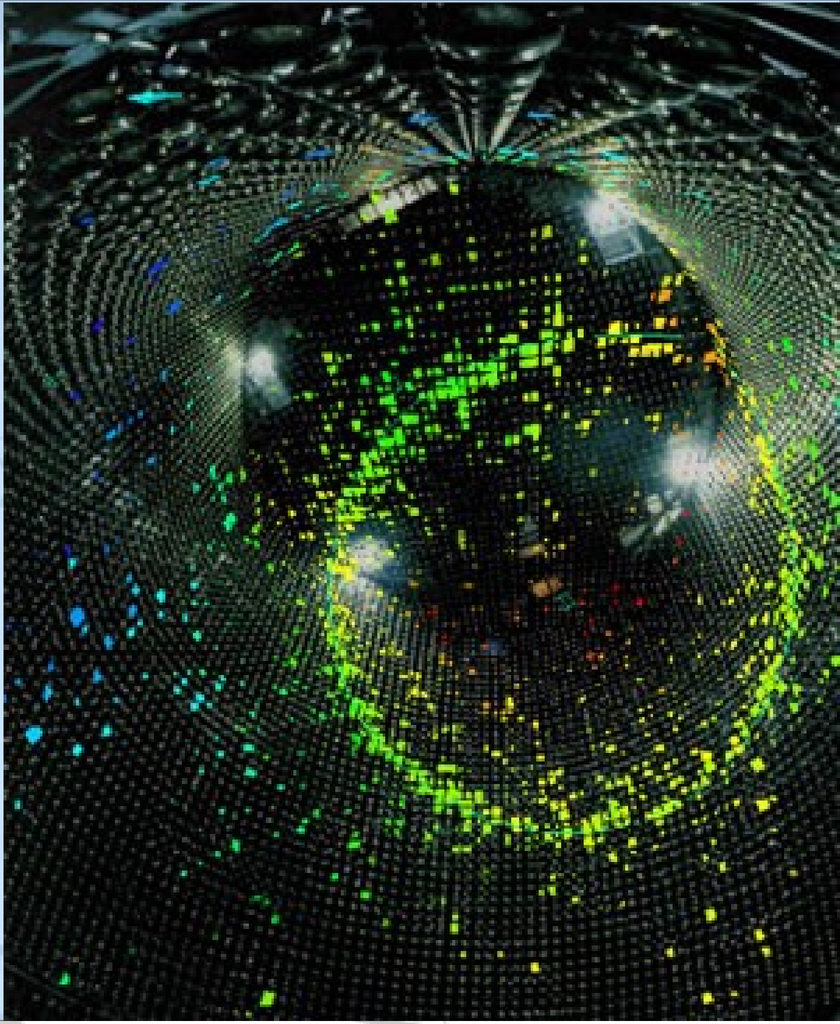
T2K Status

Francesca Di Lodovico

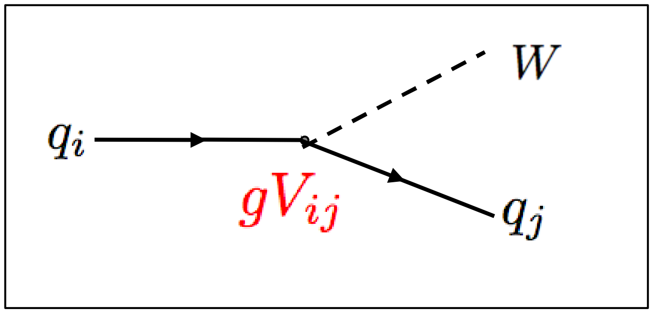
4th May 2011

NExT Meeting, Southampton



Neutrino Oscillations

- Evidence of solar and atmospheric neutrino oscillations in the 1960-'90.
- Similar mechanism as in the quark oscillation (CKM matrix) postulated.
- Free parameters: 3 angles, 1 phase



CKM matrix

$$\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$

- PMNS (Pontecorvo, Maki, Nagakawa, Sakata) matrix for neutrinos is:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Fields that interact via the weak interaction

Fields which propagate with definitive mass

Neutrino Oscillations

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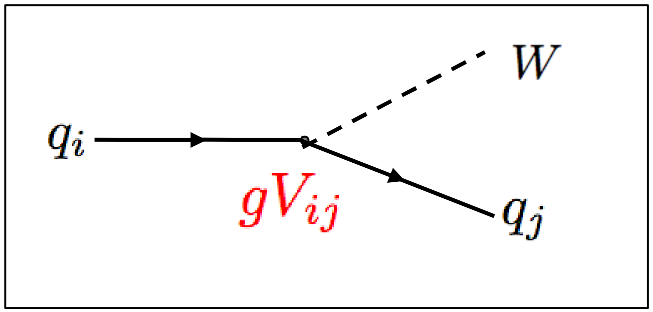

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- PMNS with “standard” parametrization (with $c_{i,j}= \cos\theta_{i,j}$, $s_{i,j}=\sin\theta_{i,j}$):

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

Three flavour effects are suppressed because ($\Delta m^2_{ij}=m^2_j-m^2_i$): $\Delta m^2_{21} << \Delta m^2_{31}$ and $\theta_{31}<<1$

Dominant oscillations are well described by effective two flavour oscillations

Neutrino Oscillations

- Evidence of solar and atmosperic neutrino oscillations in the 1960-1990.
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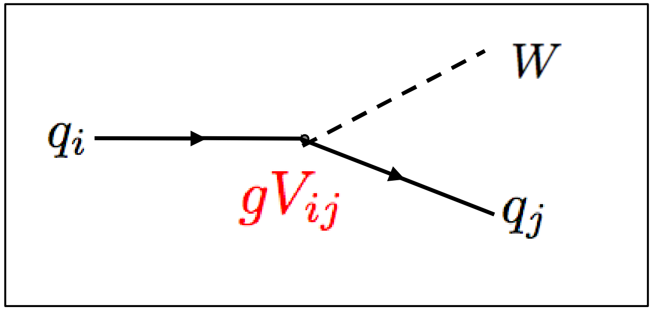
- Free parameters: 3 angles, 1 phase



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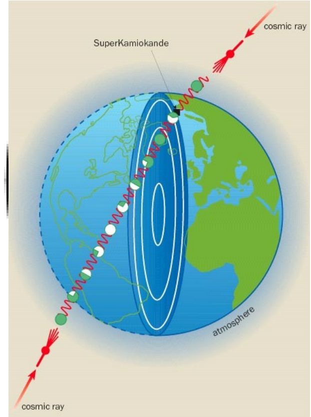

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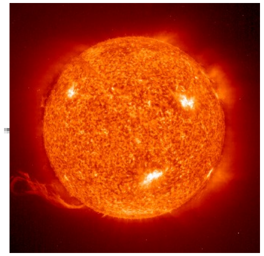


Three flavour effects are suppressed because ($\Delta m^2_{ij} = m^2_j - m^2_i$):
$\Delta m^2_{21} << \Delta m^2_{31}$ and $\theta_{31} << 1$

Dominant oscillations are well described by effective two flavour oscillations

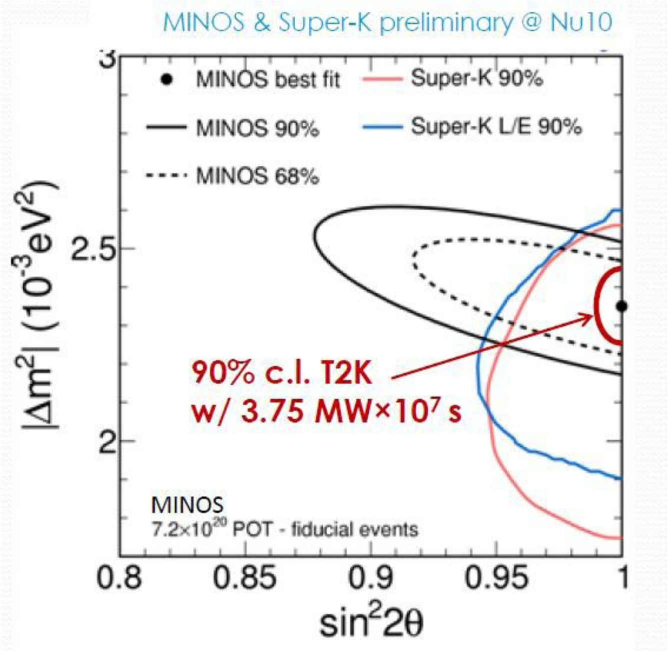
T2K Goals – oscillation physics

ν_μ disappearance:

$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32} L/E)$

How close to 45º is θ_{23}? (measure to ~1%)

Measure Δm^2_{32} to higher precision (< 1×10^{-4})

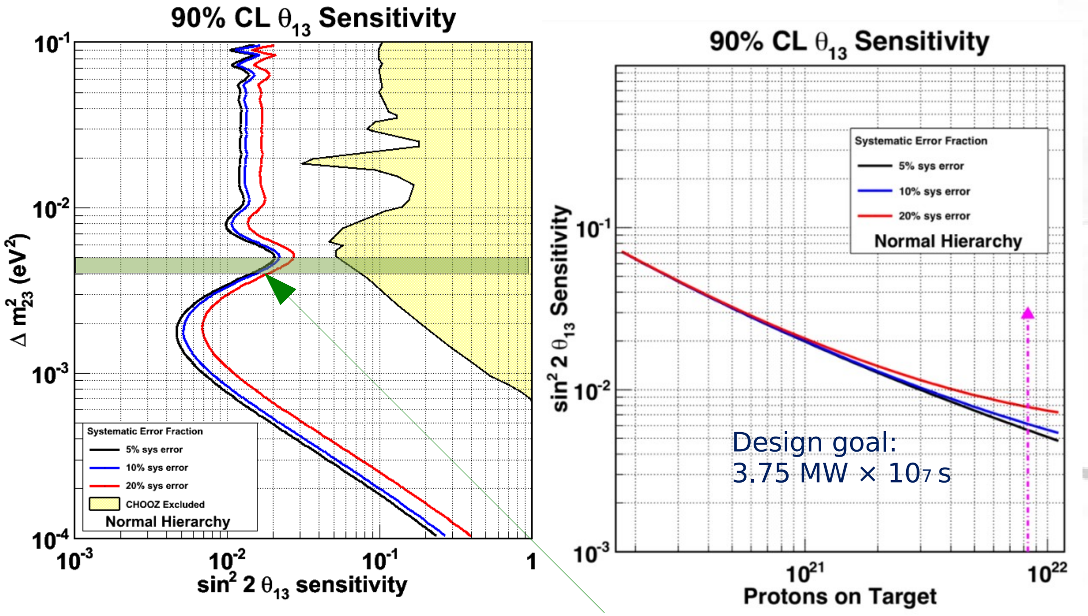


ν_e appearance:

$P(\nu_\mu \to \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2(1.27\Delta m_{33}^2 L/E)$

Improve upper limit on θ_{13} by > order of magnitude

Determine if θ_{13} is large enough to measure δ_{CP}



Sensitivity down to 0.006 ($\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV^2) at 90% CL

T2K Goals – oscillation physics

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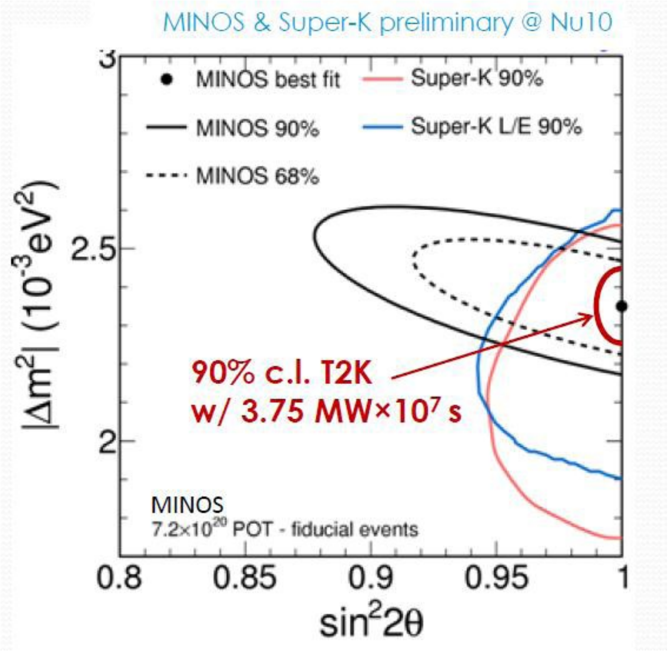

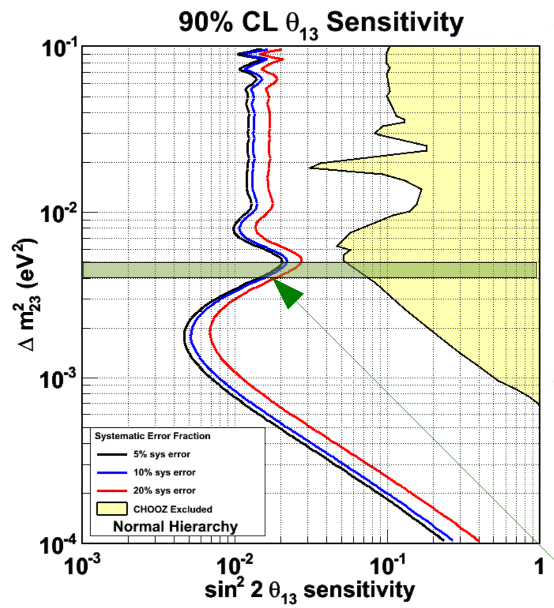

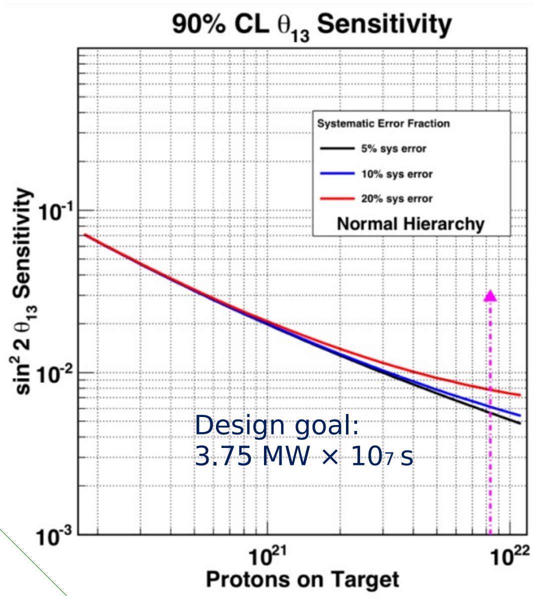

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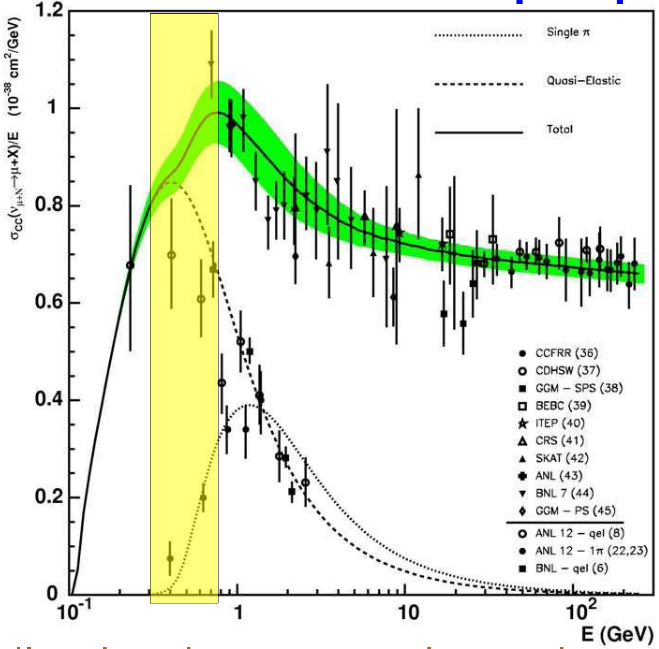
T2K Goals – Neutrino interactions

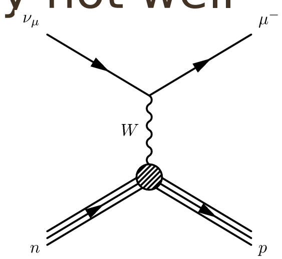
T2K is a multi purpose experiment.



Yellow bands correspond to region around T2K beam peak energy

Many measurements can be made with the near detector

Region around T2K beam energy not well measured



CCQE Charge Current Quasi-Elastic

- Dominates T2K energy region
- Well understood - characterize E_{beam}

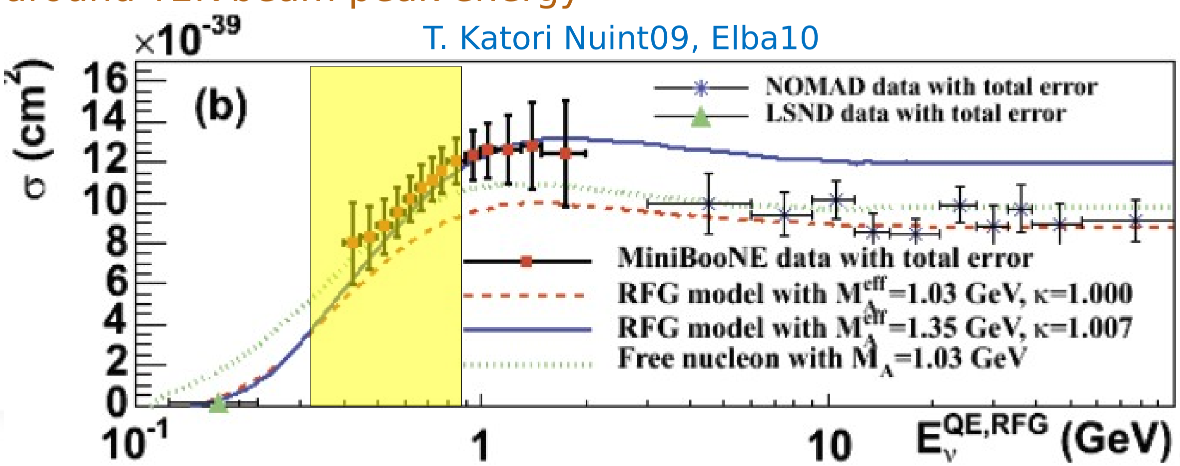
NC π± and CC π± (NC=Neutral Current, CC = Charged Current

- Background for disappearance measurement

NC π0

- Largest physics background to appearance measurement at SuperK

T. Katori Nuint09, Elba10



Interesting results elsewhere, for instance possible discrepancy between MiniBoone and Nomad.


E133°
E135°
Kobe
Osaka
Kyoto
Kanazawa
Kanazawa
Tsu
Gifu
Nagoya
Gifu
E137°
Super-K
Nagano
Nagano
Japan
Sado
Kofu
Shizuoka
Niigata
E139°
Maebashi
Hachioji
Saitama
Honshu
Kanagawa
Tokyo
Yokohama
N37°
Kawasaki
Tokyo
Fukushi
Funabashi
Chiba
Mito
N35°
Chiba
J-PARC
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© 2007 Europa Technologies
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E141°
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%


Super-Kamiokande
(Kamioka)
Super-K
E137°
J-PARC
(Tokai)
νμ
BEAM
Kobe
Osaka
Kyoto
Kanazawa
Tsu
Gifu
Nagoya
Nagano
Japan
Sado
Kofu
Shizuoka
Niigata
E139°
Maebashi
Hachioji
Saitama
Honshu
Kanagawa
Tokyo
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Kawasaki
Fukushi
Funabashi
Chiba
N35°
E141°
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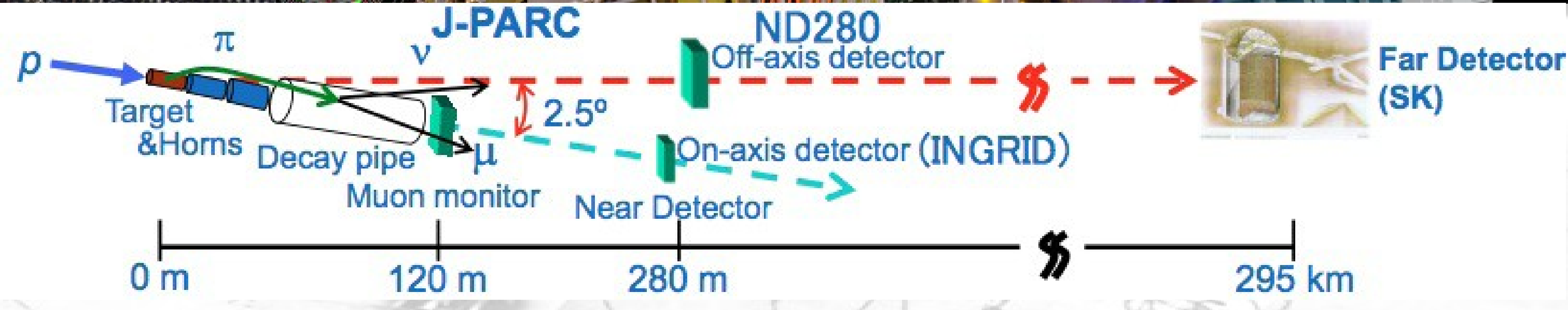
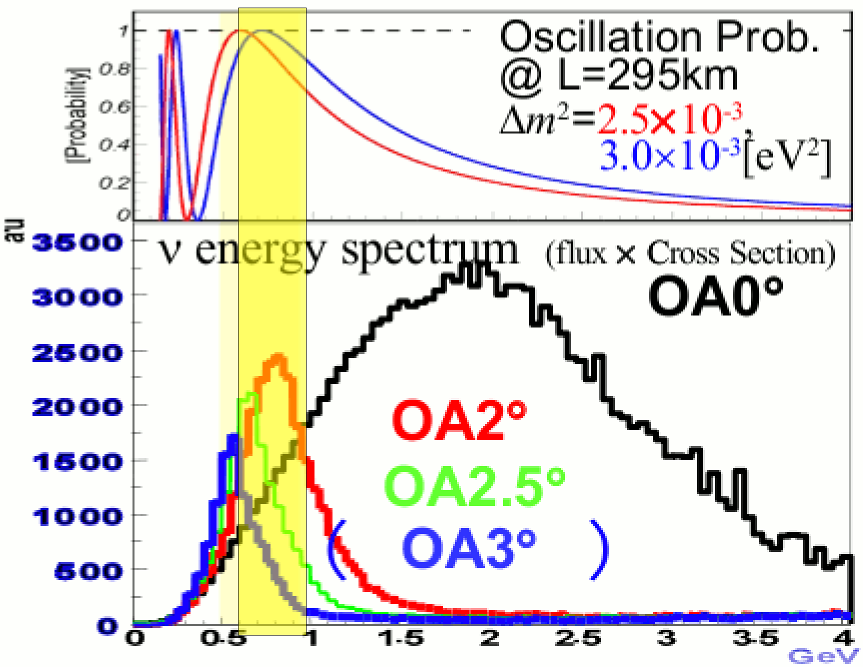
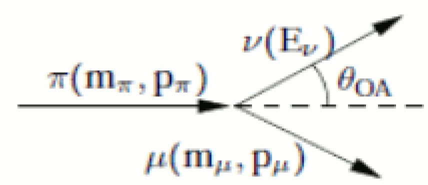
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%

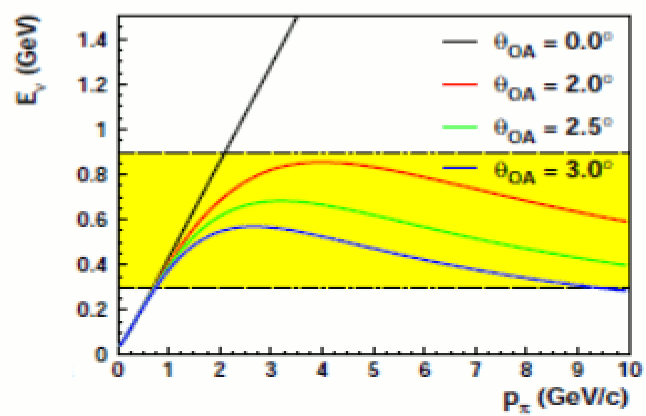
Off-axis beam







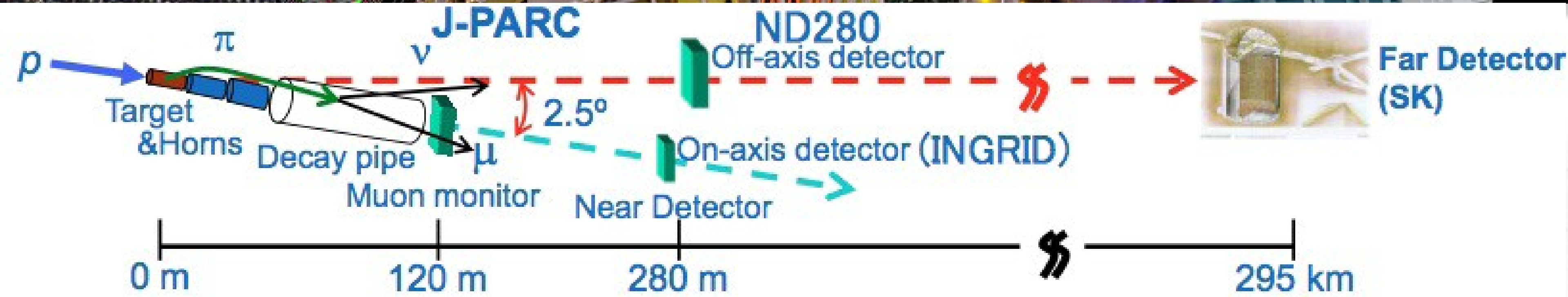
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta_{OA})}$$

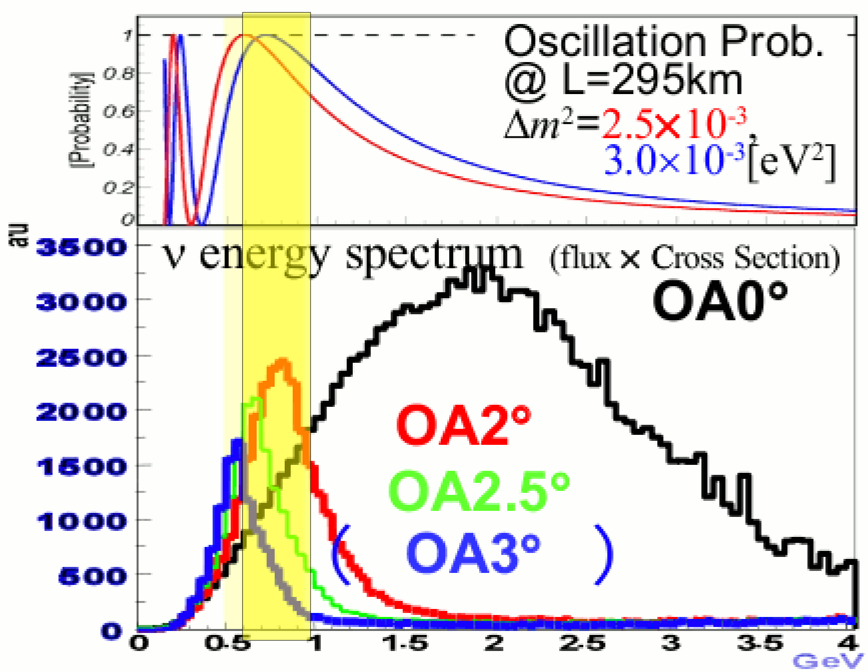


Concentrate ν_μ flux at one energy

Backgrounds lower: NC or other feed-down from high→low energy, ν_e (3-body decays)

Off-axis beam

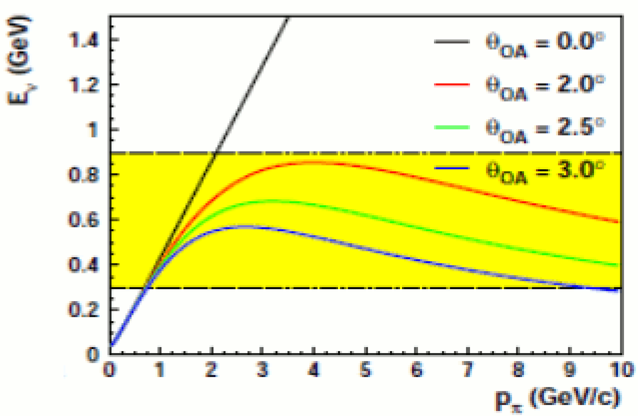




Almost monochromatic beam at ~600MeV.

Take advantage of Lorentz Boost and 2-body kinematics.

Pure ν_μ beam with <1% ν_e contamination



Concentrate ν_μ flux at one energy

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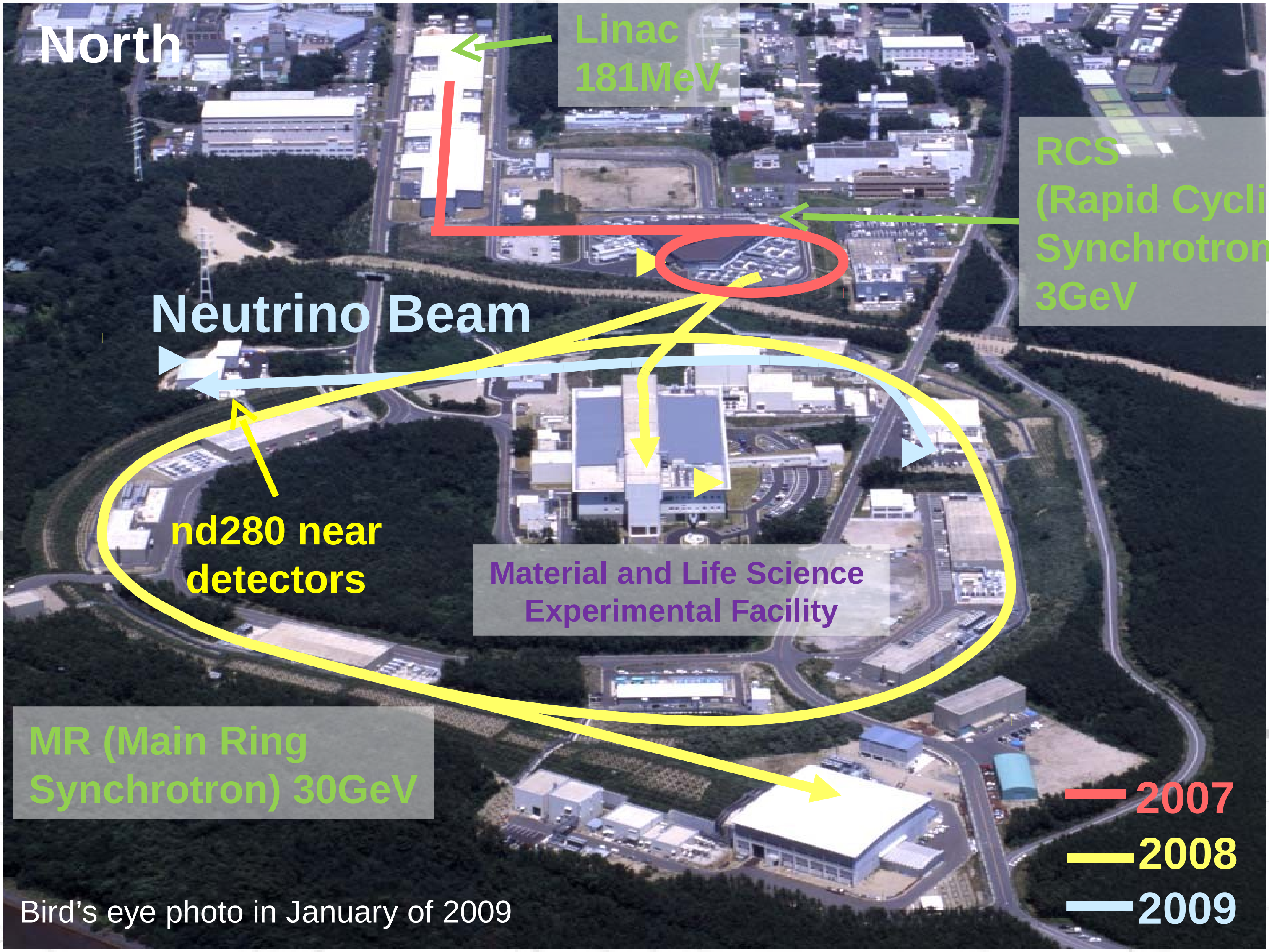
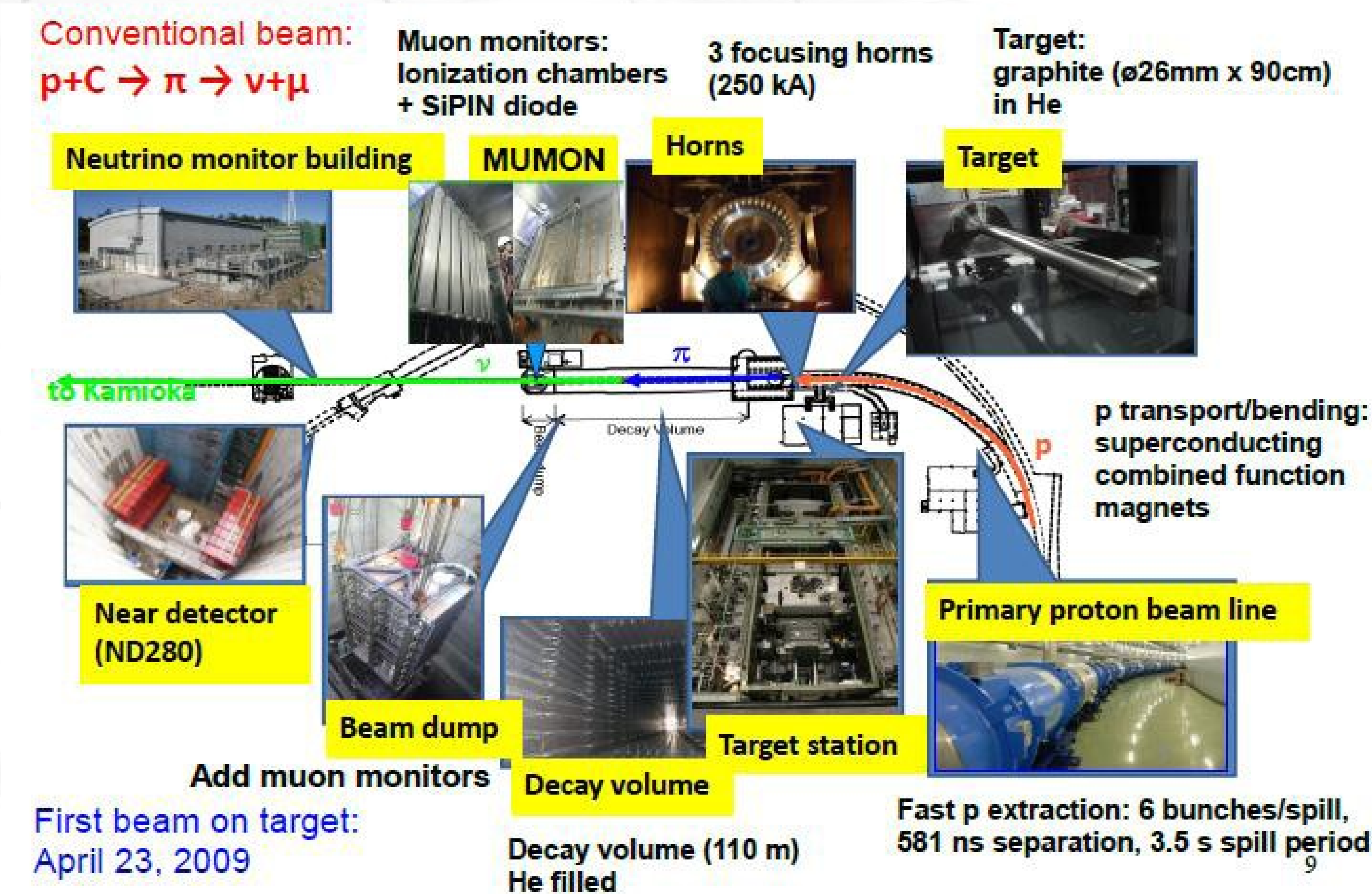
J-PARC facility



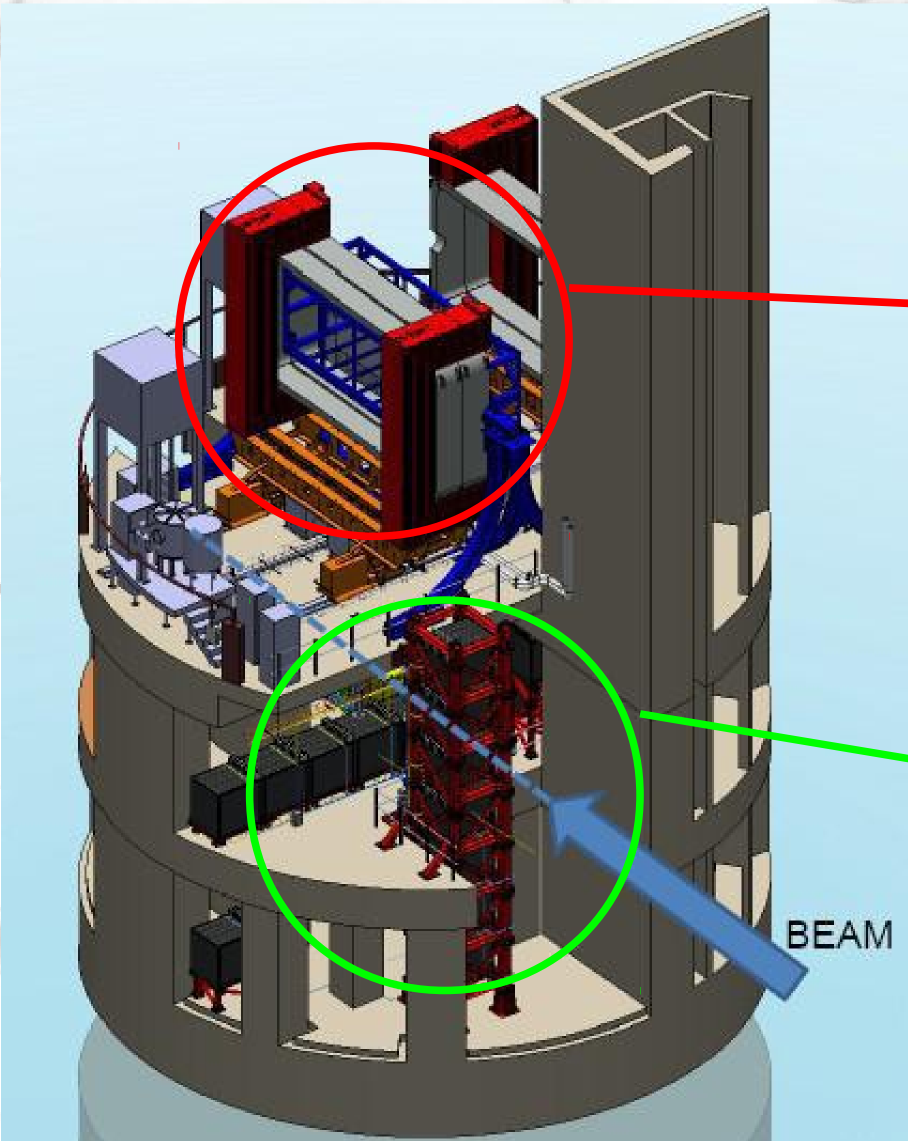
Bird's eye photo in January of 2009

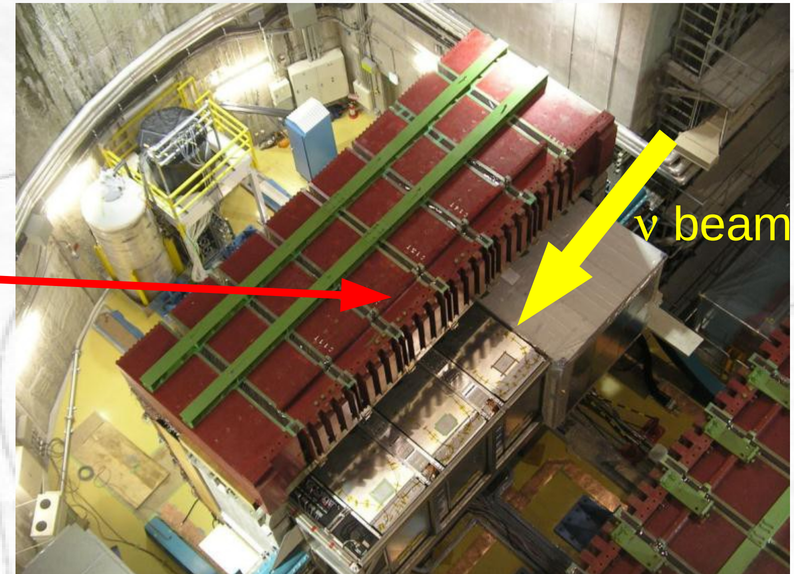
T2K Beamline



Near detectors

Goal: Characterize the ν_μ beam before propagation to far detector



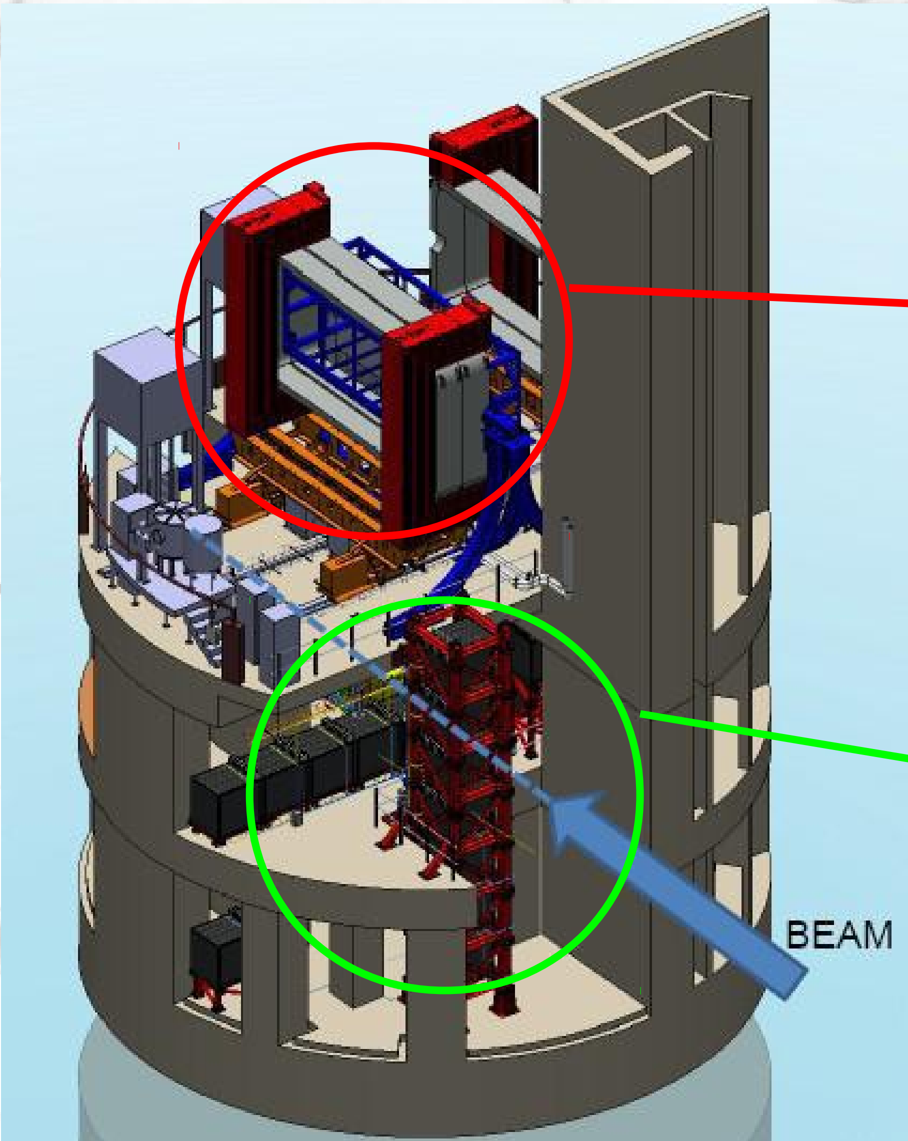


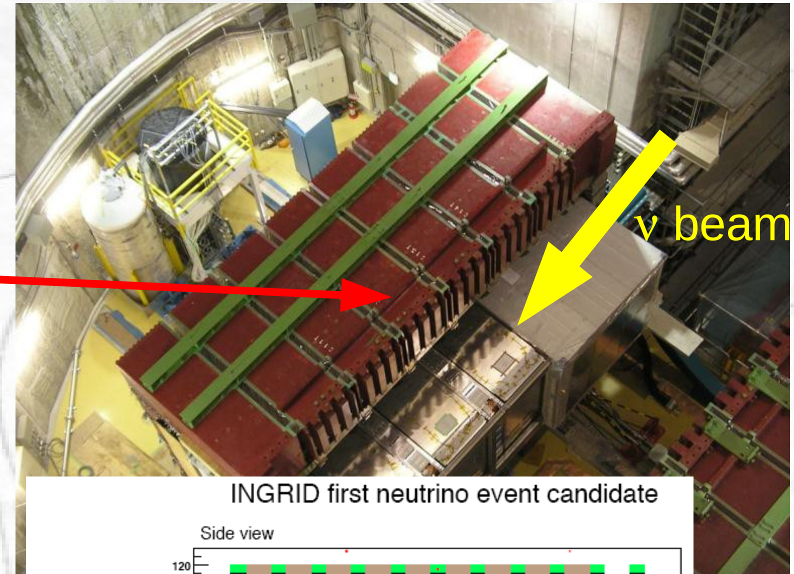
View of off-axis ND280 detector from above (magnet half open): monitor at SK direction.

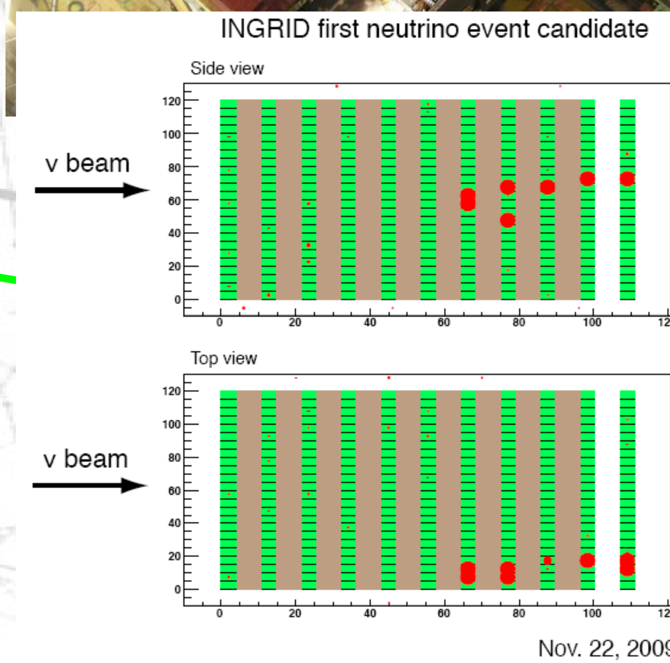
View of INGRID on-axis monitor (vertical modules): monitor at beam direction

Near detectors

Goal: Characterize the ν_μ beam before propagation to far detector







axis
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RID on-
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beam

ND280

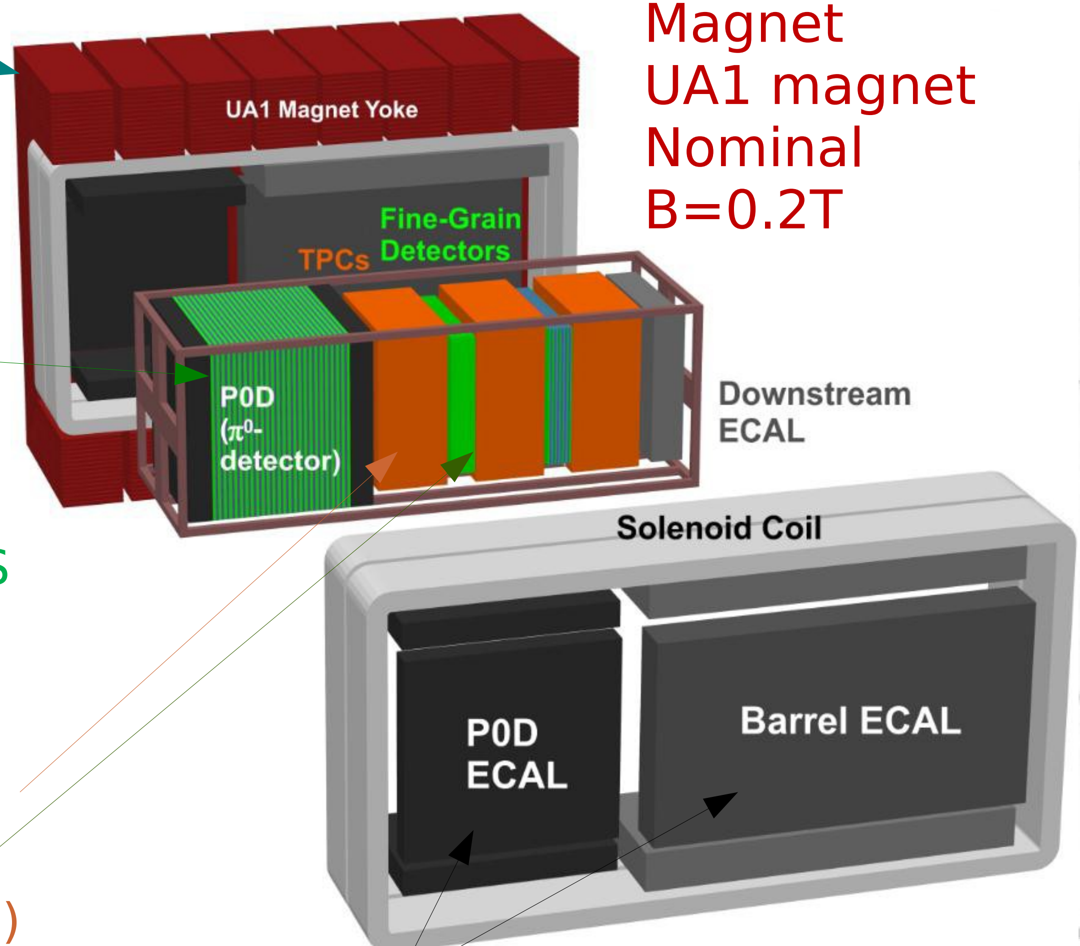
Side Muon Range Detector
Scintillator interleaved into magnet yoke
192 hor. and 248 vert. modules

PiZero Detector
Optimized for $\pi 0$ rate measurement
Measure beam νe
40 layers of x-y scint. Bars w/ WS fibers
Water target + US/DS ECALs

TPCs
FDetection of charged particles
Excellent PID (dE/dx) Readout: MicroMegas (7mm x 10mm pads)

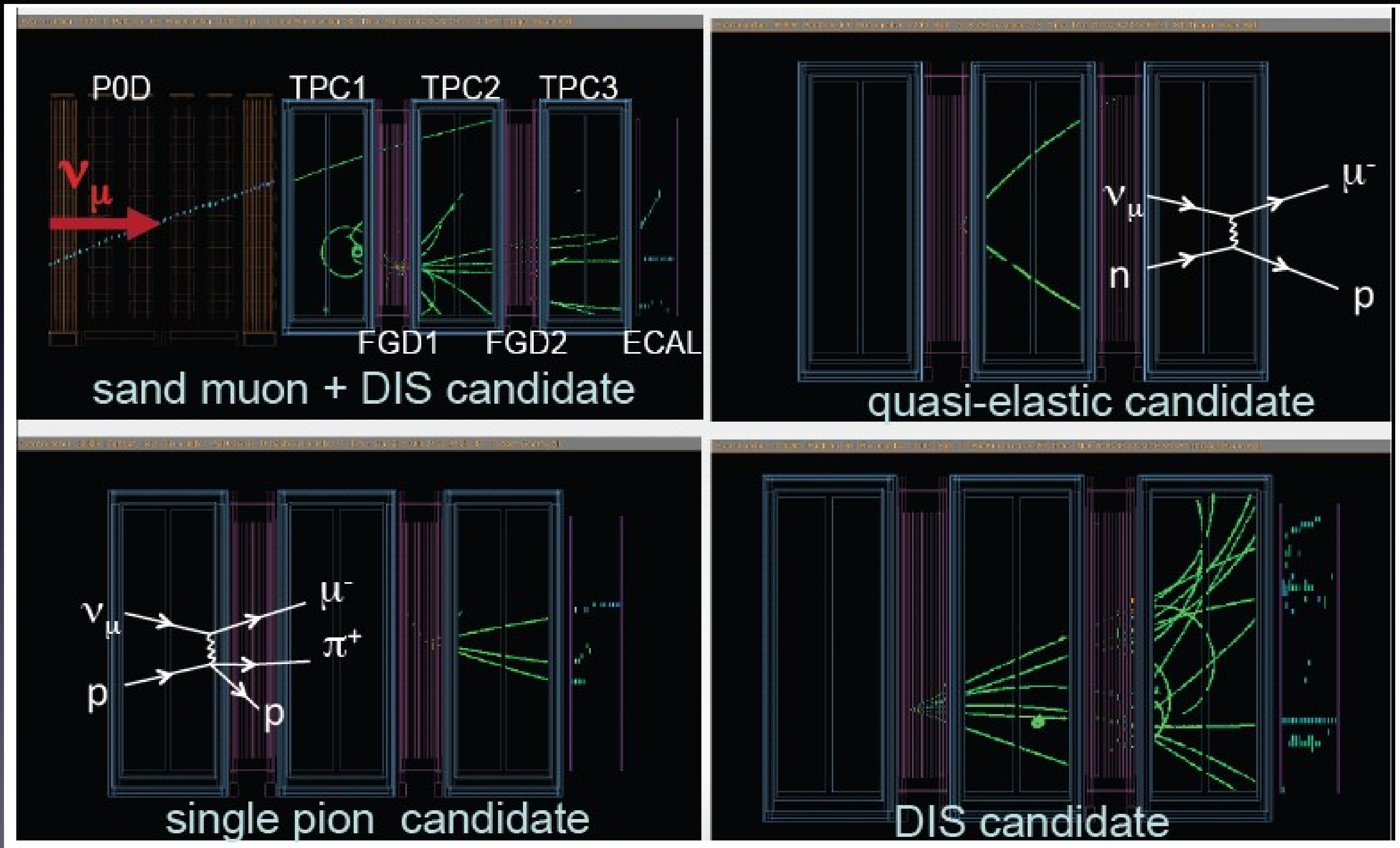
Fine Grained Detectors
Target mass for tracker
Fine grain scintillator bars (1cm x 1cm)
Capable of detecting recoil protons

Magnet
UA1 magnet
Nominal
B=0.2T

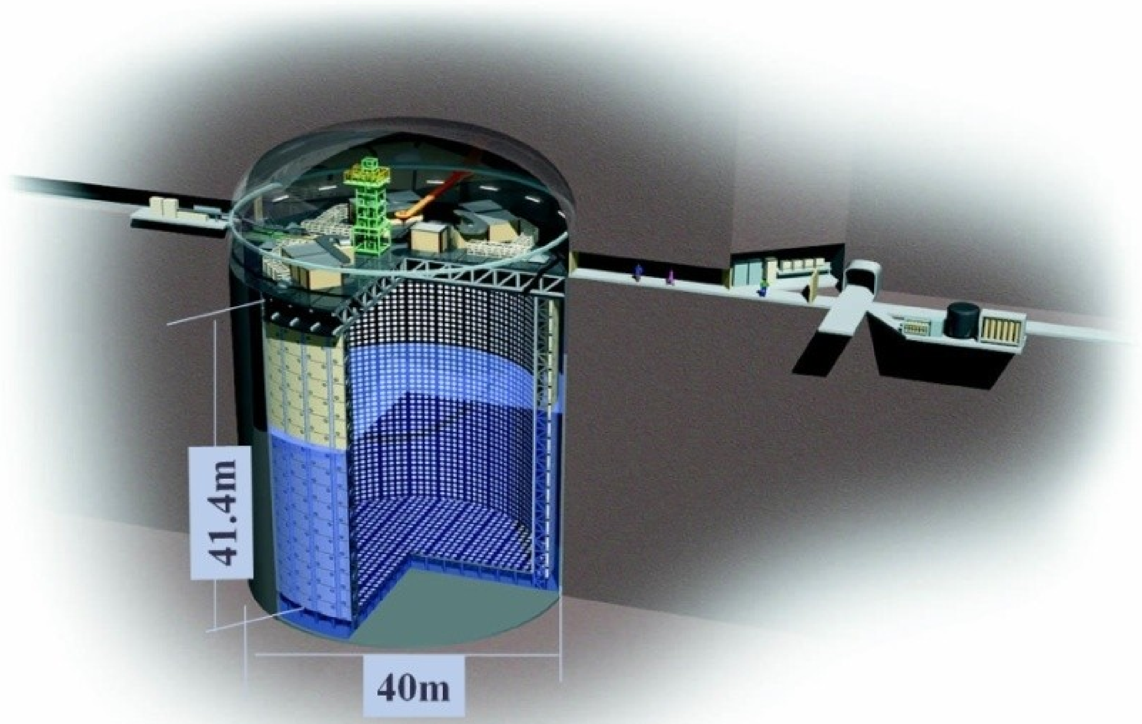


ECALs
Capture $\gamma/e/\mu$ escaping P0D and tracker
Scintillating layers and Pb absorber

ND280 off-axis event gallery



Super-Kamiokande



50 kton water Cherenkov detector

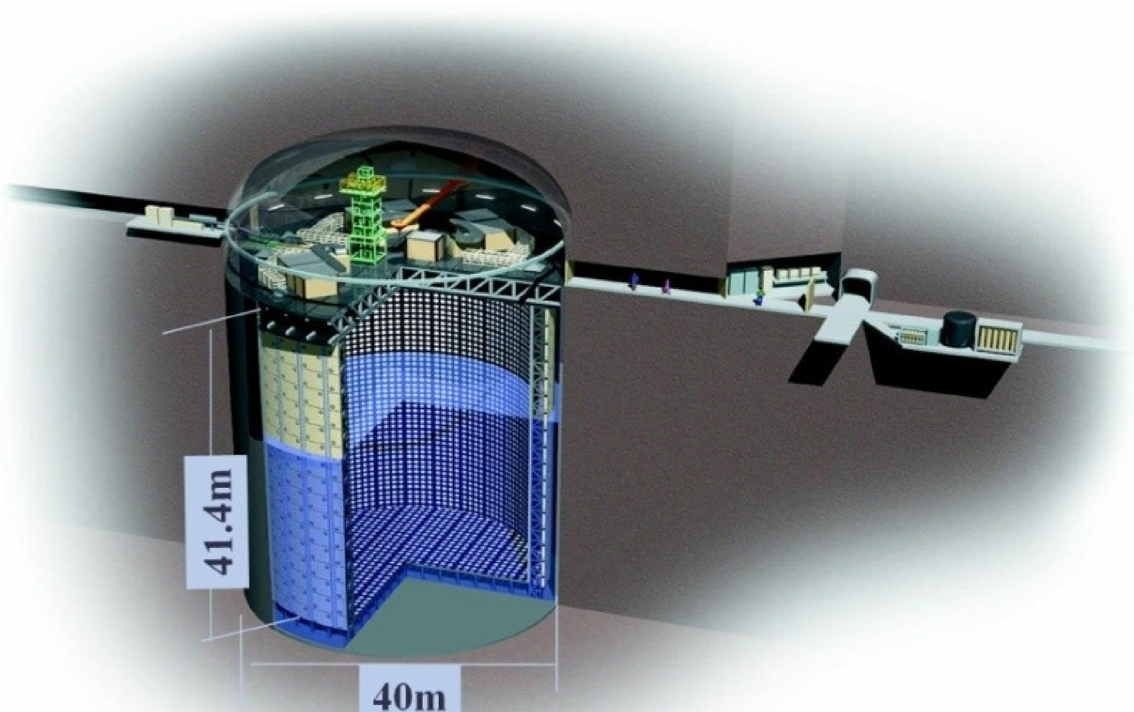
Located in a drive-in Zinc mine near Kamioka
1000 m rock overburden.

Water filled cavern divided into a cylindrical inner detector (ID) and outer detector (OD)

ID & OD optically separated

Electronics updated in 2006 (SK-IV). Continuous data taking now possible.

Super-Kamiokande

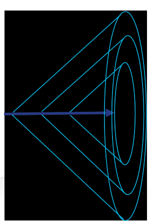


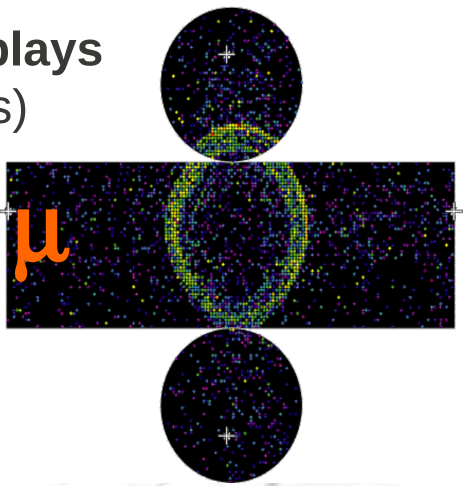
50 kton water Cherenkov detector

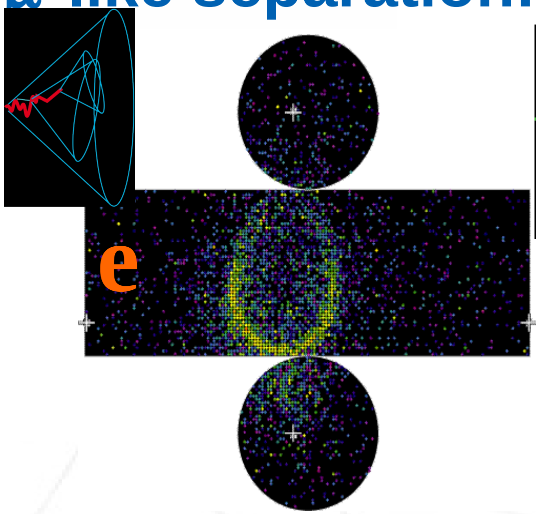
Located in a drive-in Zinc mine near Kamioka
1000 m rock overburden

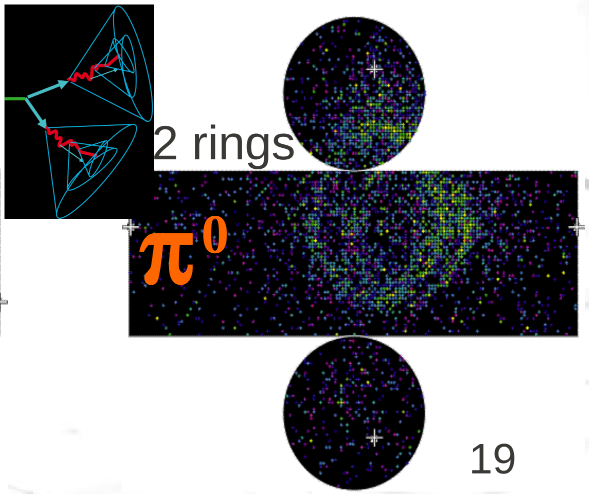
Good e-like(shower ring)/μ-like separation: mis-PID probability ~ 1%

Event displays
(MC events)
•Cherenkov radiation

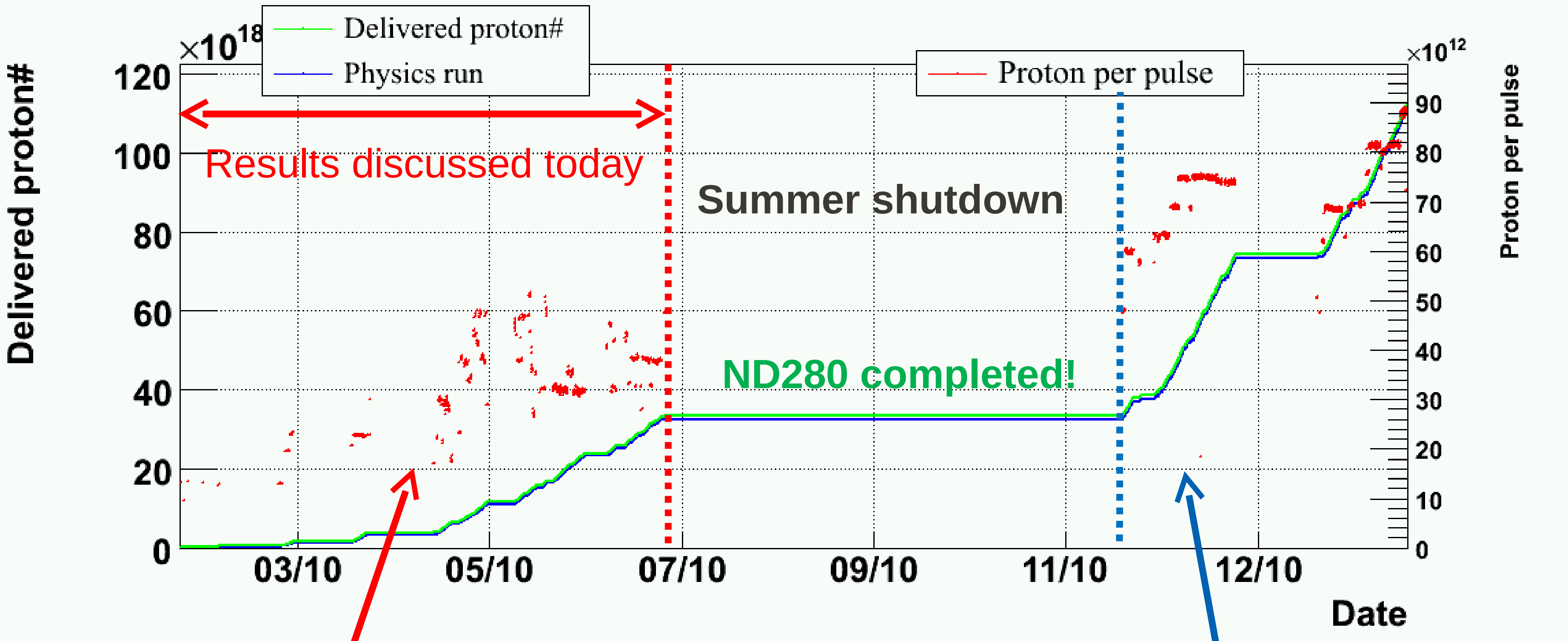








Delivered Protons on Target

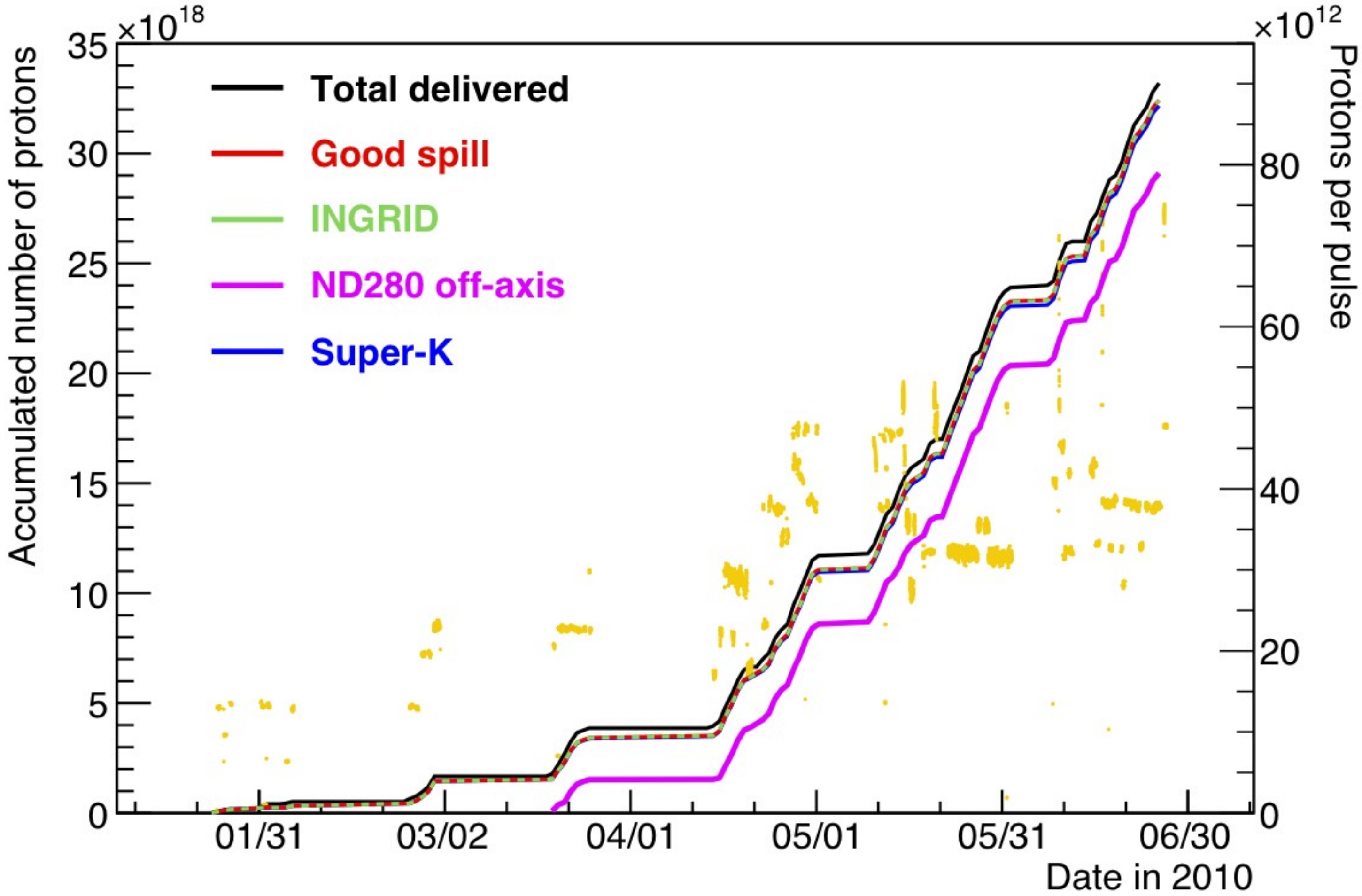


T2K run 1 (Jan. to Jun. 2010)
- **6 bunches/spill**, **3.5 s** spill period
- 3.23×10^{19} POT for T2K analysis
- ~**50 kW** operation

T2K run 2 (Nov. 2010 March)
- **8 bunches** (new extraction kicker)
- **3.2 s** spill period
- ~**135 kW** operation

Protons on Target for run1

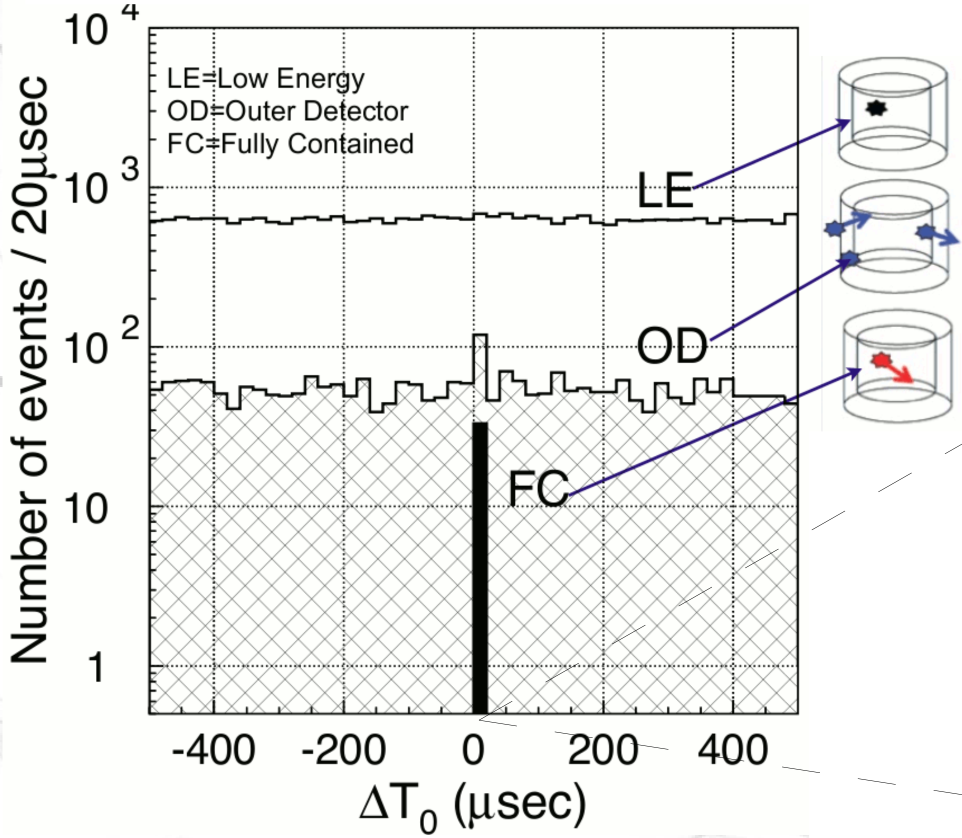
- 3.23×10^{19} POT for T2K analysis.
- The efficiency of all the detectors was close to 100%.



Identify beam-induced events at SK with GPS

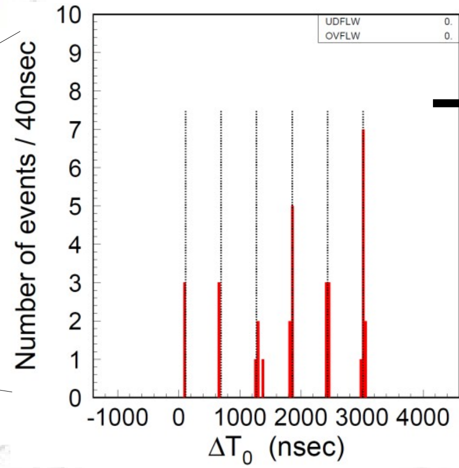
- Transfer beam spill information in real time
- Compare GPS time stamps of beam/SK trigger

ΔT_0=SK trigger time - beam trigger time

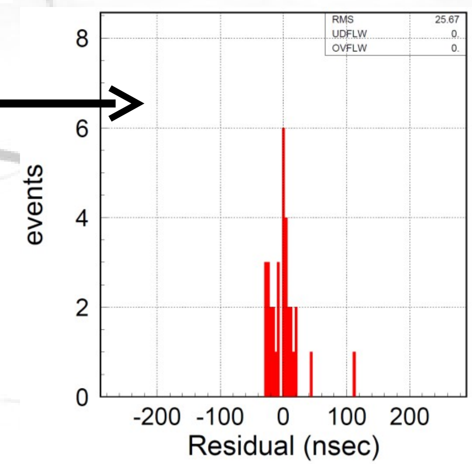


LE: Low energy triggered events
OD: Outer detector events
FC: Fully contained events

ΔT_0 for FC events



RMS 26 ns



SK event reduction (run1)

From ±500μs around beam spills			Data	MC		BG (12μs window)
				No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$	
Fully-Contained			33	54.5	24.6	0.0094
	Fiducial Volume, Evis > 30MeV		23	36.8	16.7	0.0011
		Single-ring μ-like (Pμ>200MeV/c)	8 (8)	24.6 (24.5 ±3.9)	7.2 (7.1 ±1.3)	-
		Single-ring e-like (Pe>100MeV/c)	2 (2)	1.9 (1.5 ±0.7)	1.5 (1.3 ±0.6)	-
		Multi-ring	13	10.2	8.0	-

Single Ring Samples (similar to samples used in the analyses):

- Event is fully contained inner detector
- In fiducial volume and visible energy is >30 MeV
- Event contains only 1 ring
- PID identifies ring as muon or electron

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Clear indication of oscillation in 1-ring μ sample

Analysis Flow for run1 Data

Neutrino flux prediction
- Proton beam data
- Hadron production data

ND280 (near) Detector Measurements
- ν_μ CC inclusive selection
- Measure: $R_{Data/MC} = \frac{N^{Data}_{\mu CC,ND280}}{N^{MC}_{\mu CC,ND280}}$

Neutrino cross-sections
- Tuning to external data
- Interaction models and parameters variation

SK (far) Detector Measurements
- Data reduction and classification
- Compute signal and background expectations (counting)

$$N^{MC}_{signal} = \int dE_\nu \underbrace{\Phi_\mu(E_\nu)}_{\text{flux}} \times \underbrace{\sigma(E_\nu)}_{\text{cross-section}} \times \underbrace{\varepsilon(E_\nu)}_{\text{efficiency}} \times \underbrace{P(\nu_\mu \to \nu_e; E_\nu; \theta_{13}, \Delta m^2_{13})}_{\text{oscillation}}$$

- Correct normalization using ND280 measurement

$$N^{\exp}_{SK} = R_{Data/MC} \times \left(N^{MC}_{signal} + N^{MC}_{bkg}\right)$$

- Evaluate systematic errors
- Extract oscillation parameters

Analysis Flow for run1 Data

Neutrino flux prediction

- Proton beam data
- Hadron production data

ND280 (near) Detector Measurements

- ν_μ CC inclusive selection
- Measure: $R_{Data/MC} = \frac{N^{Data}_{\mu CC,ND280}}{N^{MC}_{\mu CC,ND280}}$

Neutrino cross-sections

- Tuning to external data
- Interaction models and parameters variation

SK (far) Detector Measurements

- Data reduction and classification
- Compute signal and background expectations (counting)

$$N^{MC}_{signal} = \int dE_\nu \underbrace{\Phi_\mu(E_\nu)}_{\text{flux}} \times \underbrace{\sigma(E_\nu)}_{\text{cross-section}} \times \underbrace{\varepsilon(E_\nu)}_{\text{efficiency}} \times \underbrace{P(\nu_\mu \to \nu_e; E_\nu; \theta_{13}, \Delta m^2_{13})}_{\text{oscillation}}$$

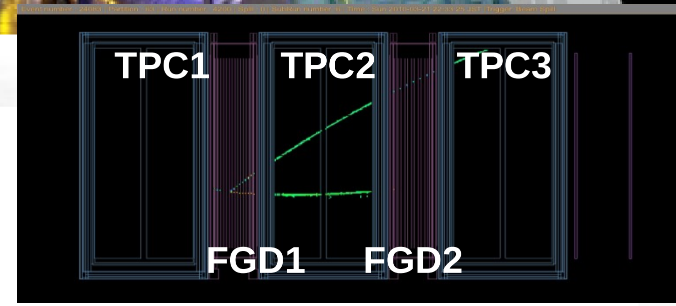
- Correct normalization using ND280 measurement

$$N^{\exp}_{SK} = R_{Data/MC} \times \left(N^{MC}_{signal} + N^{MC}_{bkg} \right)$$

- Evaluate systematic errors
- Extract oscillation parameters

I will concentrate only on the measurements at the near and far detectors. Spare slides contain the other information.

ND280 off-axis CC measurement w/ FGD and TPC

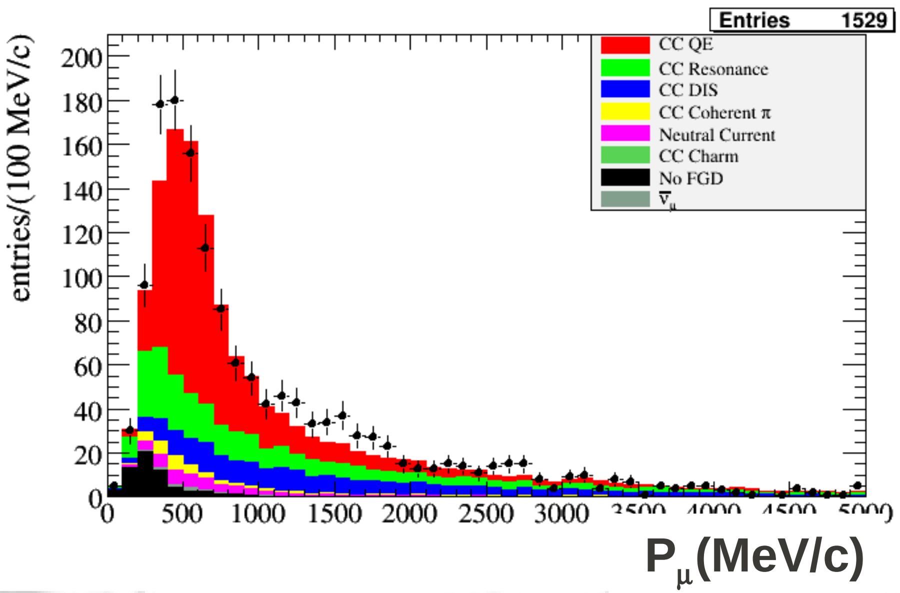


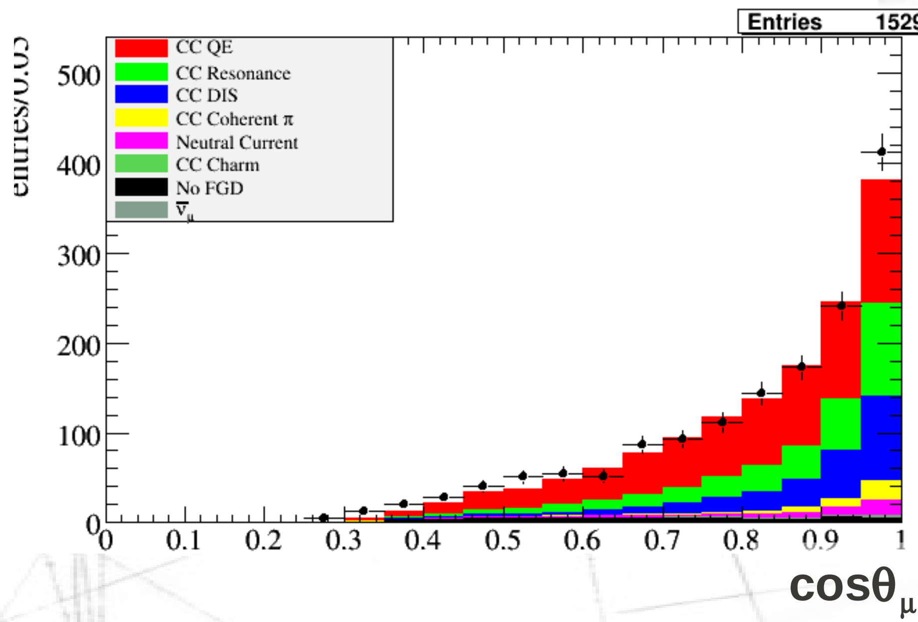
CC event selection

(1) TPC1 has no track

(2) TPC2 (or 3) has ≥ 1 track with negative charge (to select μ)

(3) Track in TPC2 (or 3) starts from FV of FGD1 (or 2)





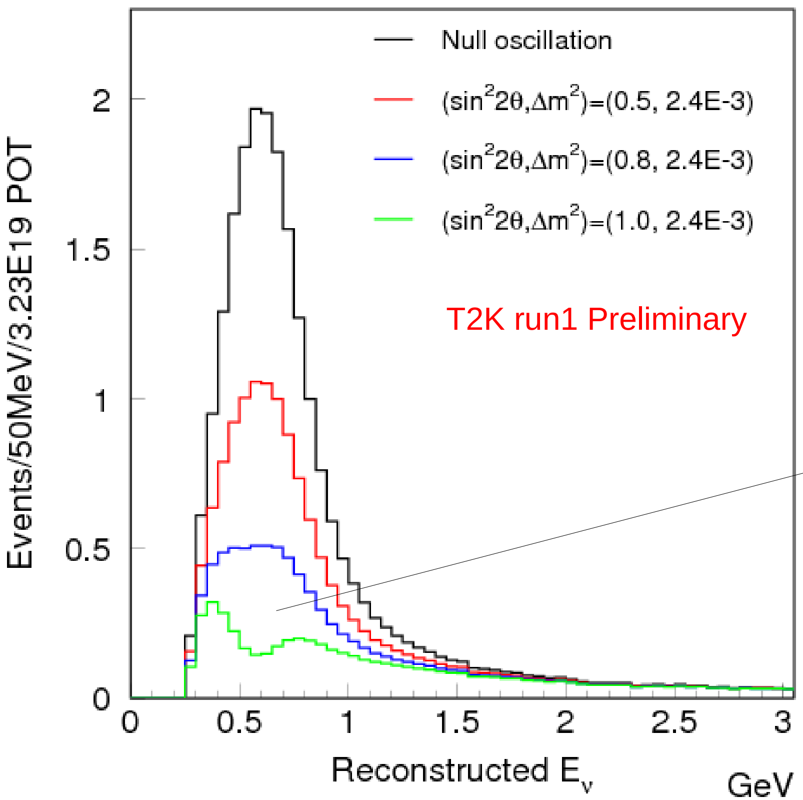
- **Event rate:** expectation vs. observation **($R_{data/MC} = N_{data} / N_{MC}$)**

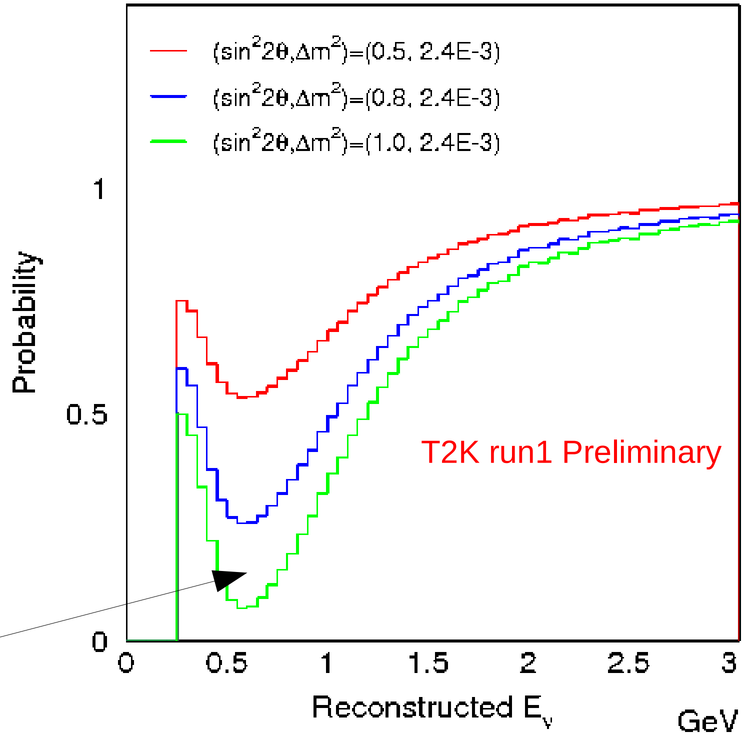
$$R_{data/MC} = 1.061 \pm 0.028 (stat.)^{+0.044}_{-0.038} (det.\ sys.) \pm 0.039 (phys.\ model)$$

ν_μ Disappearance Analysis

- Aimed at precise measurement of the 23 sector.

Expected spectrum for different parameter oscillation hypotheses





T2K off-axis configuration ➠ strong dependence on oscillation parameters in region of interest

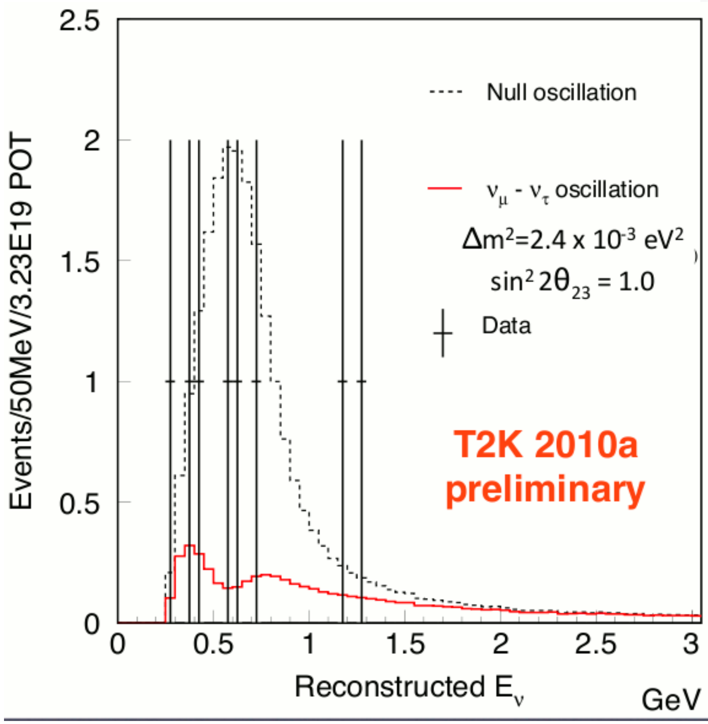
ν_μ Disappearance Analysis

- Event selection for muon disappearance measurement after SK reduction.

T2K-SK events	Data	MC		Acc.BG (12μs window)
		No oscillation	W/ oscillation	
Fully-Contained	33	54.5	24.6	0.0094
Fiducial Volume, E_{vis} > 30MeV	23	36.8	16.7	0.0011
Single-ring μ-like P_μ>200MeV/c	8	24.5±3.9	7.1±1.3	-
+ number decay-e <=1 & Erec<10 GeV	8	22.8±3.2	6.3±1.0	-

Δm^2=2.4×10-3 eV^2
$\sin^2 2\theta_{23}$ = 1.0

Reconstructed energy assuming QE systematics

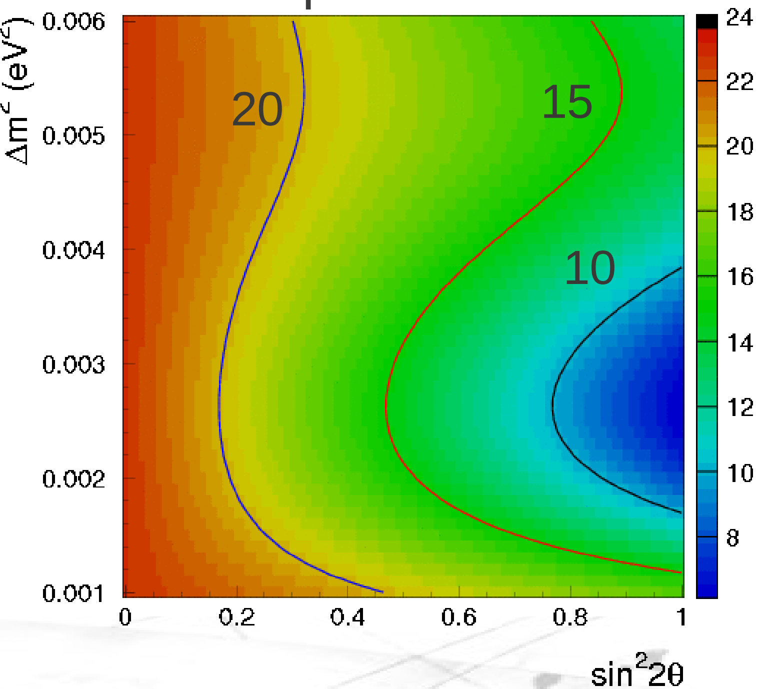


ν_μ Disappearance Results

8 candidate events observed at SK. Expectations:

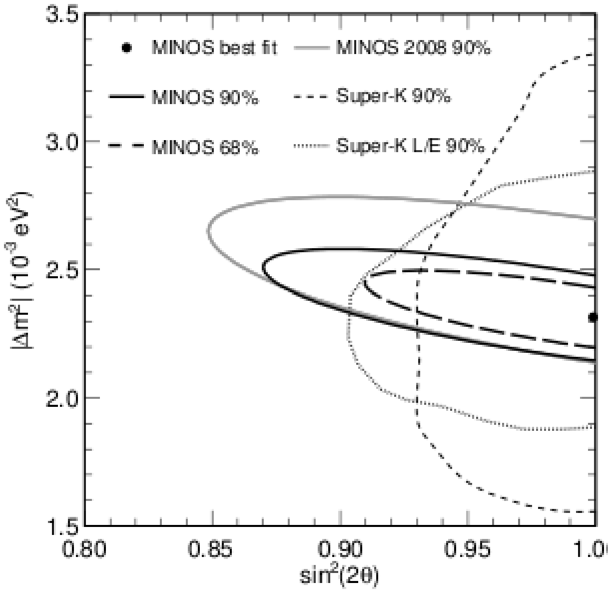
Osc. Hypothesis	Expected Events	Syst. Error
No oscillation	22.81	3.19
$\Delta m_{23}^2 = 2.4\times10^{-3}\ eV^2$ $\sin^2(2\theta_{23})=1.0$	6.34	1.04

Expected observed events as function of osc. parameters



Parameter fitting underway – T2K plans to release the results in the near future.

Consistent with MINOS, SK



MINOS: arXiv:1103.0340

ν_e Appearance Analysis

- Event selection for electron appearance measurement.

T2K-SK events	Data	MC		Acc. BG (12μs window)
		No oscillation	With oscillation and $\theta_{13}=0$	
Fully-Contained	**33**	54.5	24.6	0.0094
Fiducial Volume, E_{vis} > 30MeV	**23**	36.8	16.7	0.0011
Single-ring e-like P_e>100MeV/c	**2**	1.5±0.7	1.3±0.6	-

Δm^2=2.4×10-3 eV^2
$Sin^2 2\theta_{23}$ = 1.0

Cut	Events
Fully contained, fiducial cut (FCFV)	23
Single ring e-like, E>100 MeV	2
# of decay electron =0	1
Reconstructed invariant mass assuming 2γ rings exist <105MeV	1
Reconstructed ν energy < 1250 MeV	1
Events in 2010a sample	**1**

Further cuts applied on events from T2K reduction.
Final signal efficiency 65.9%

ν_e Appearance Analysis

- Event selection for electron appearance measurement.

T2K-SK events	Data	MC		Acc. BG (12μs window)
		No oscillation	With oscillation and $\theta_{13}=0$	
Fully-Contained	**33**	54.5	24.6	0.0094
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Single-ring e-like P_e>100MeV/c	**2**	1.5±0.7	1.3±0.6	-

$\Delta m^2=2.4\times 10\text{-}3\ eV^2$
$\sin^2 2\theta_{23} = 1.0, \theta_{13}=0$

Cut	Events
Fully contained, fiducial cut (FCFV)	23
Single ring e-like, E>100 MeV	2
# of decay electron =0	1
Reconstructed invariant mass assuming 2γ rings exist <105MeV	1
Reconstructed ν energy < 1250 MeV	1
Events in 2010a sample	**1**

Further cuts applied on events from T2K reduction.
Final signal efficiency 65.9%

ν_e Appearance Systematics

- Estimated combined total systematic error from each source group on electron events in SK, constrained by ND280 normalization.

Error source	N_{SK}^{sig}	N_{SK}^{bkg}	N_{SK}^{s+b}	N_{ND}	N_{SK}^{bkg}/N_{ND}	N_{SK}^{s+b}/N_{ND}
SK Efficiency	$\pm$ 7.6	$\pm$ 15.8	$\pm$ 9.5		$\pm$ 15.8	$\pm$ 9.5
Cross section	$\pm$ 9.7	$\pm$ 13.9	$\pm$ 9.9	$\pm$ 8.4	$\pm$ 14.3	$\pm$ 10.6
Beam Flux	$\pm$ 22.0	$\pm$ 18.1	$\pm$ 20.5	$\pm$ 19.8	$\pm$ 8.9	$\pm$ 11.9
ND Efficiency				$^{+5.6}_{-5.2}$	$^{+5.6}_{-5.2}$	$^{+5.6}_{-5.2}$
Overall Norm.					$\pm$ 2.7	$\pm$ 2.7
Total	$\pm$ 25.2%	$\pm$ 27.8%	$\pm$ 24.7%	$^{+22.2}_{-22.1}$%	$^{+23.9}_{-23.8}$%	$^{+19.5}_{-19.4}$%

★ ~24% total systematic error for background only hypothesis
★ ~20% total systematic error for signal + background hypothesis

Δm^2=2.4×10-3 eV^2
$\sin^2 2\theta_{23}$ = 1.0,
$\sin^2 2\theta_{23} = 0.1$

Expected Number of SK Events

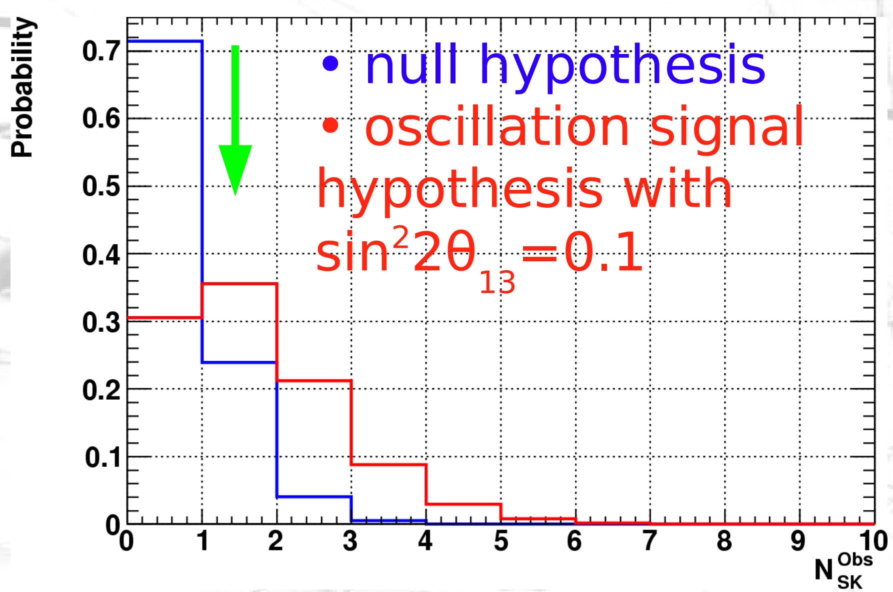
Source	Estimated number
Beam ν_μ (CC+NC)	0.13
Beam $\bar{\nu}_\mu$ (CC+NC)	0.01
Beam ν_e (CC)	0.16
Total background	**0.30 ± 0.07 (syst.)**
Total sig.+background	**1.20 ± 0.23 (syst.)**

#events normalized to p.o.t. and corrected for ND280 νμ CC measured normalization

- Assumed oscillation parameters for signal:

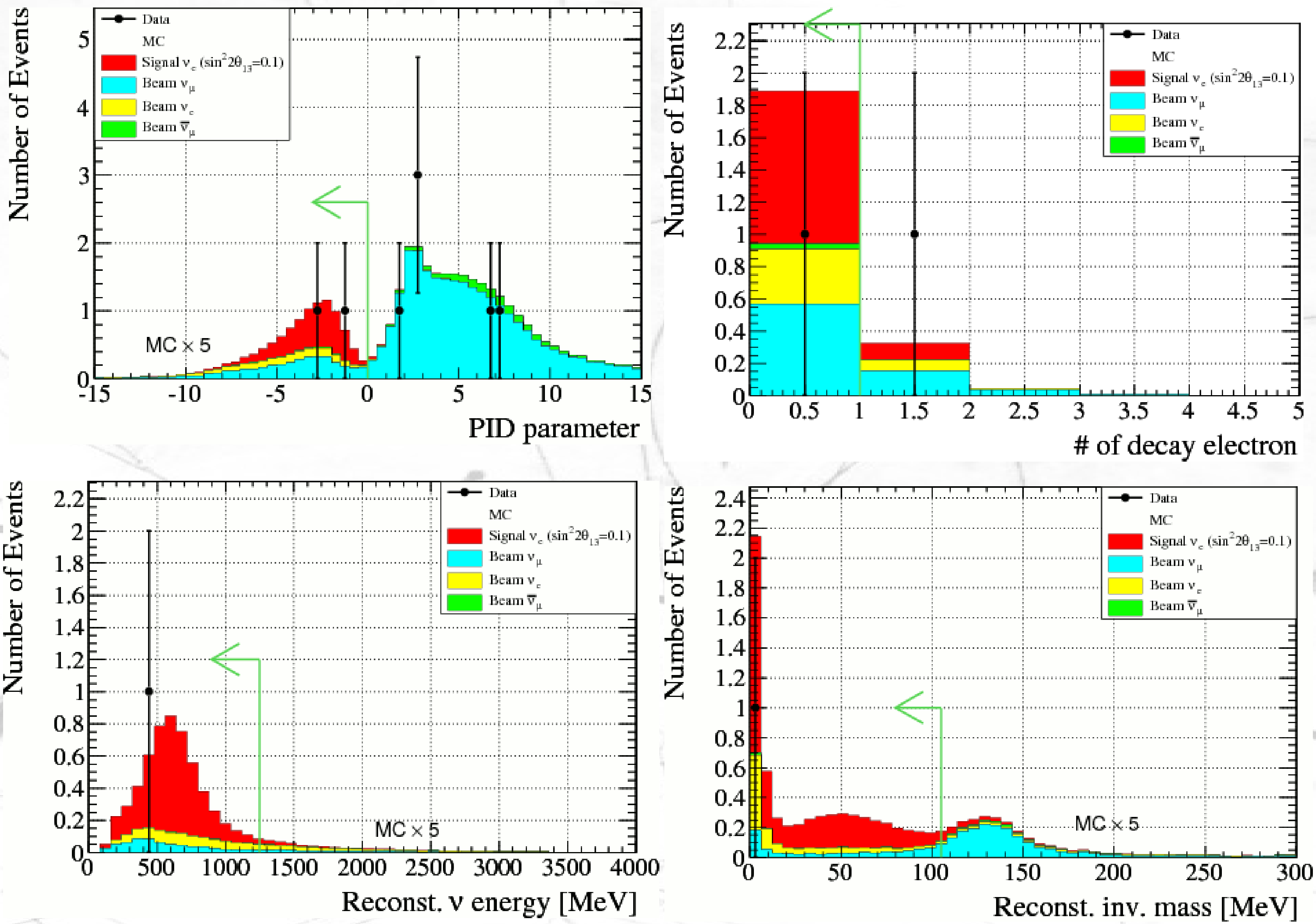
$\Delta m^2 = 2.4\times10\text{-}3\ eV^2$
$\sin^2 2\theta_{23} = 1.0$
$\sin^2 2\theta_{13} = 0.1$

T2K run1 Preliminary

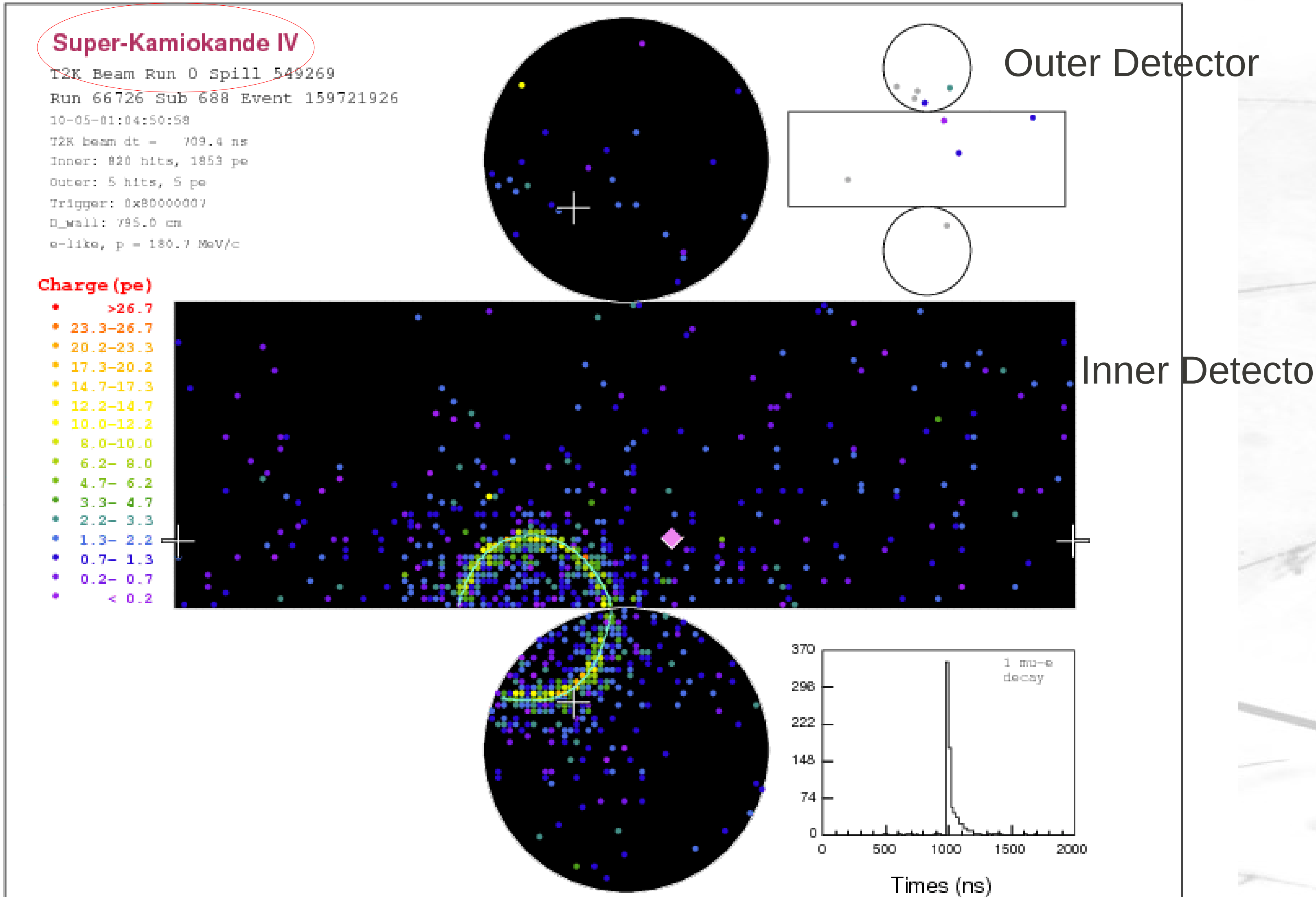


~29% probability to observe >=1 event when expected average = 0.3 event

Sequential Selection Cuts



run1 ν_e CC Signal Candidate at SK



ν_e appearance upper limit results

- Two independent analyses give consistent results.
- Difference from confidence interval method:

Feldmann Cousins:

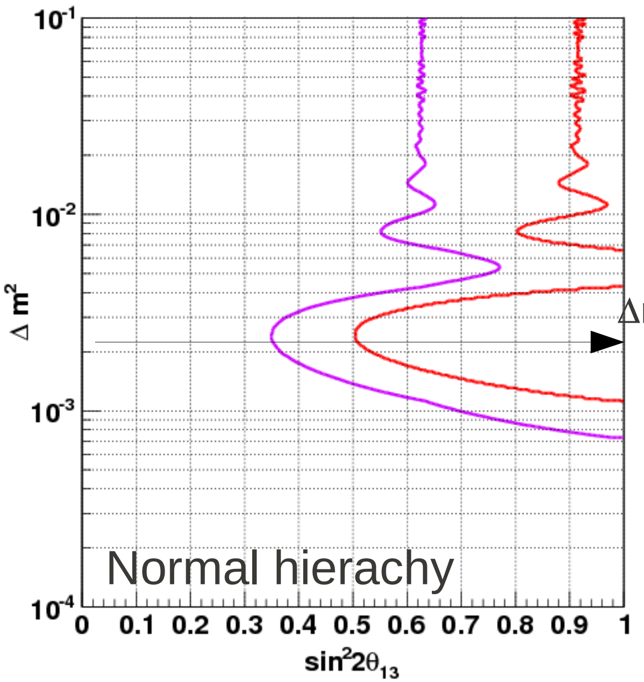
Δm_{23}^2=2.4×10-3 eV^2

$\sin^2 2\theta_{23}$ = 1.0

Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m_{23}^2 > 0$)	0.50	0.35
Inverted ($\Delta m_{23}^2 < 0$)	0.59	0.42

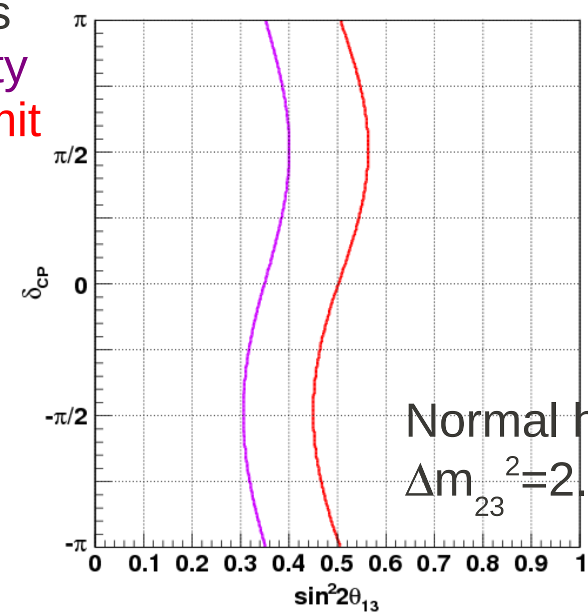
Classical 1-sided limit:

Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m_{23}^2 > 0$)	0.44	0.32
Inverted ($\Delta m_{23}^2 < 0$)	0.53	0.39



Δm_{23}^2=2.4×10-3 eV^2

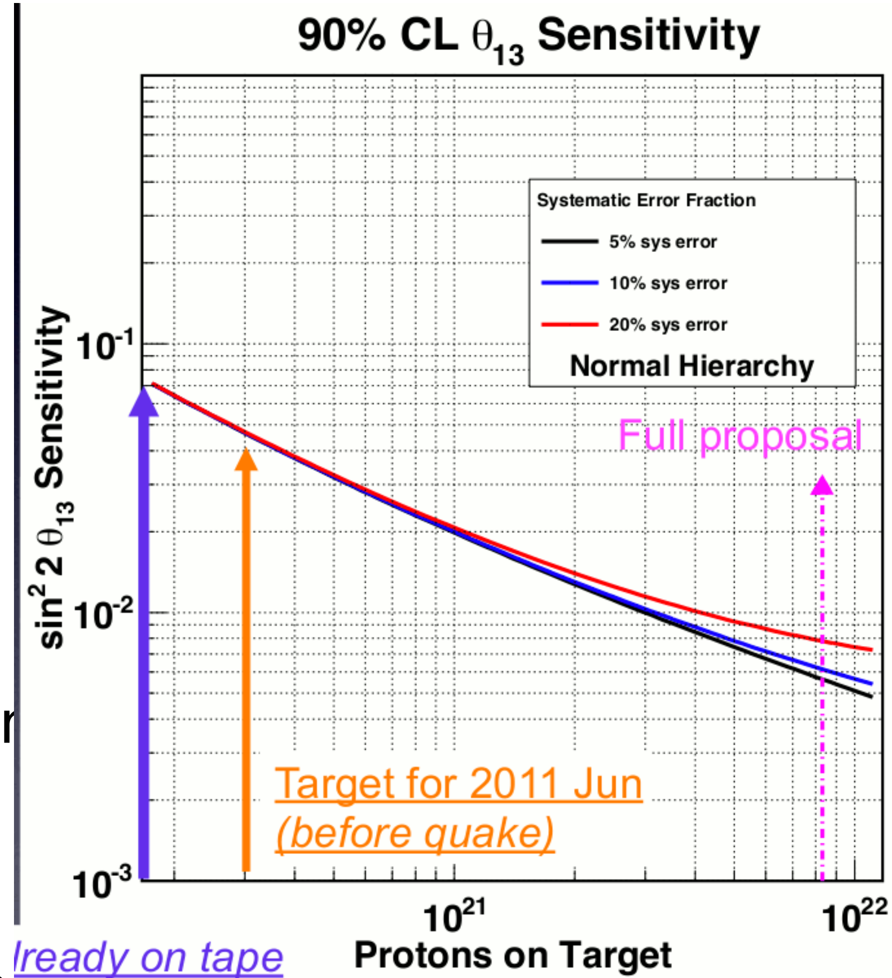
Feldman Cousins
90% CL sensitivity
90% CL upper limit



Normal hierachy
Δm_{23}^2=2.4×10-3 eV^2

Prospects for updated results

- 1.45x10^{20} p.o.t. on tape = 73kW*1e^{7} s = 4.5x(2010a)
- Aim at 3x10^{20} p.o.t. = 150kW*1e^{7} s by July 2011 (quake→??)
- Analysis improvements underway
- New NA61 results → systematic error uncertainty fror hadron production will be reduced.
- Spectrum measurement in ND and near/far ratio to reduce model dependence



11 March 2011, 14:46 JST

Current Status

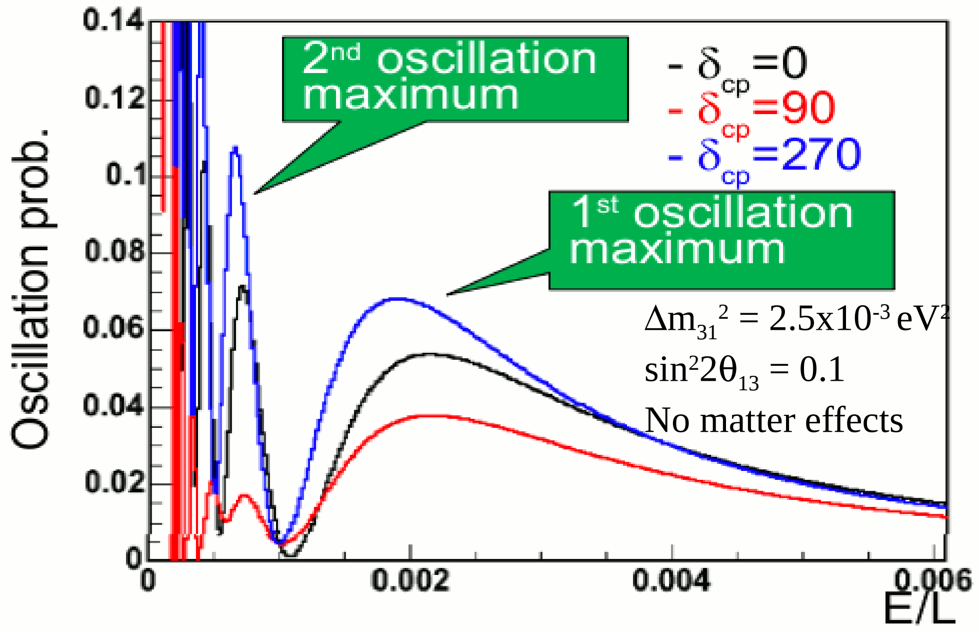
Risk Assessment Table in the T2K UK proposal:

Risk	Effect	Risk Factor			Level	Mitigation
		L	I	LxI		
General						
Natural disaster	End of Project	1	5	5	Medium	Design equipment to meet strict Japanese building specifications designed to cope with natural events.
Damage of major components in transport, shipping, installation	Delay of schedule and added FTEs	2	2	4	Medium	Packing, handling and contingency
Loss of key staff	Delay of schedule and added FTEs	2	3	6	Medium	Shared responsibilities
Loss of workforce (eg. illness, inability to recruit or retain staff, delays in RA appointments etc.)	Delay of schedule and added FTEs	2	2	4	Medium	Flexibility and contingency
Loss of supplier	Delay to schedule and added FTEs	1	3	3	Medium	Identifying alternative suppliers
Major price fluctuations	Higher cost; de-scope project	2	2	4	Medium	Factor into working allowance; plan for de-scoping
External schedule delays (eg. delay in vendor delivery schedule test–beam	Schedule push-back; manpower reallocation	2	2	4	Medium	Possible storage plans; plan for minor schedule slippage

- Much exterior damage, but inside equipment shows no major damage so far.
- We have are in middle of the damage assessment and recovery plan drafting.
- We will try to restart toward the end of the year.

T2K upgrade: CP Violation

Oscillation probabilities for $\nu_\mu \rightarrow \nu_e$ for different values of the oscillation parameter.



CP violation can be studied either:

- comparing $P(\nu_\alpha \rightarrow \nu_\beta)$ versus $P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta)$, where ν_α and ν_β are two neutrino flavours

or

- comparing the first and second oscillation peaks.

CP violation can't be observed in $\nu_\alpha \rightarrow \nu_\alpha$ as it is related to $\overline{\nu}_\alpha \rightarrow \overline{\nu}_\alpha$ by CPT.

CP violation in the neutrino sector can be responsible for the current matter-antimatter asymmetry in the universe through leptogenesis.

T2K upgrade

Main goal of future T2K experiment at J-PARC

- Search for CP violation in ν oscillation.

Future T2K upgrade proposals for far detector

- LAr TPC @ ~660km
  - On-axis, Measure the 2nd oscillation maximum
- Hyper-K @ ~300km
  - Off-axis, Measure ν and anti-ν difference

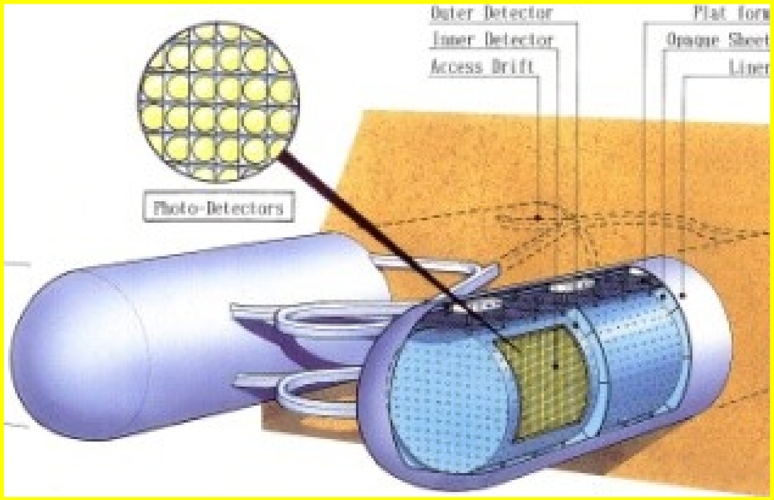
J-PARC: Accelerator & ν beam-line

- Current: 30GeV, ~120kW beam supplied to T2K
  → Aiming (before quake) ~400kW in 2012 in current power-up scenario

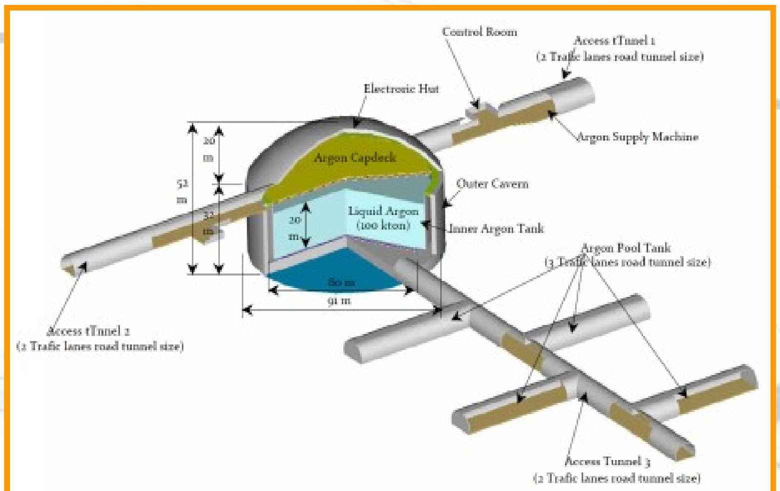
J-PARC upgrade plan

- ~1.7MW by improving the each components.
- Strategy: Increasing the repetition rate & protons/pulse.

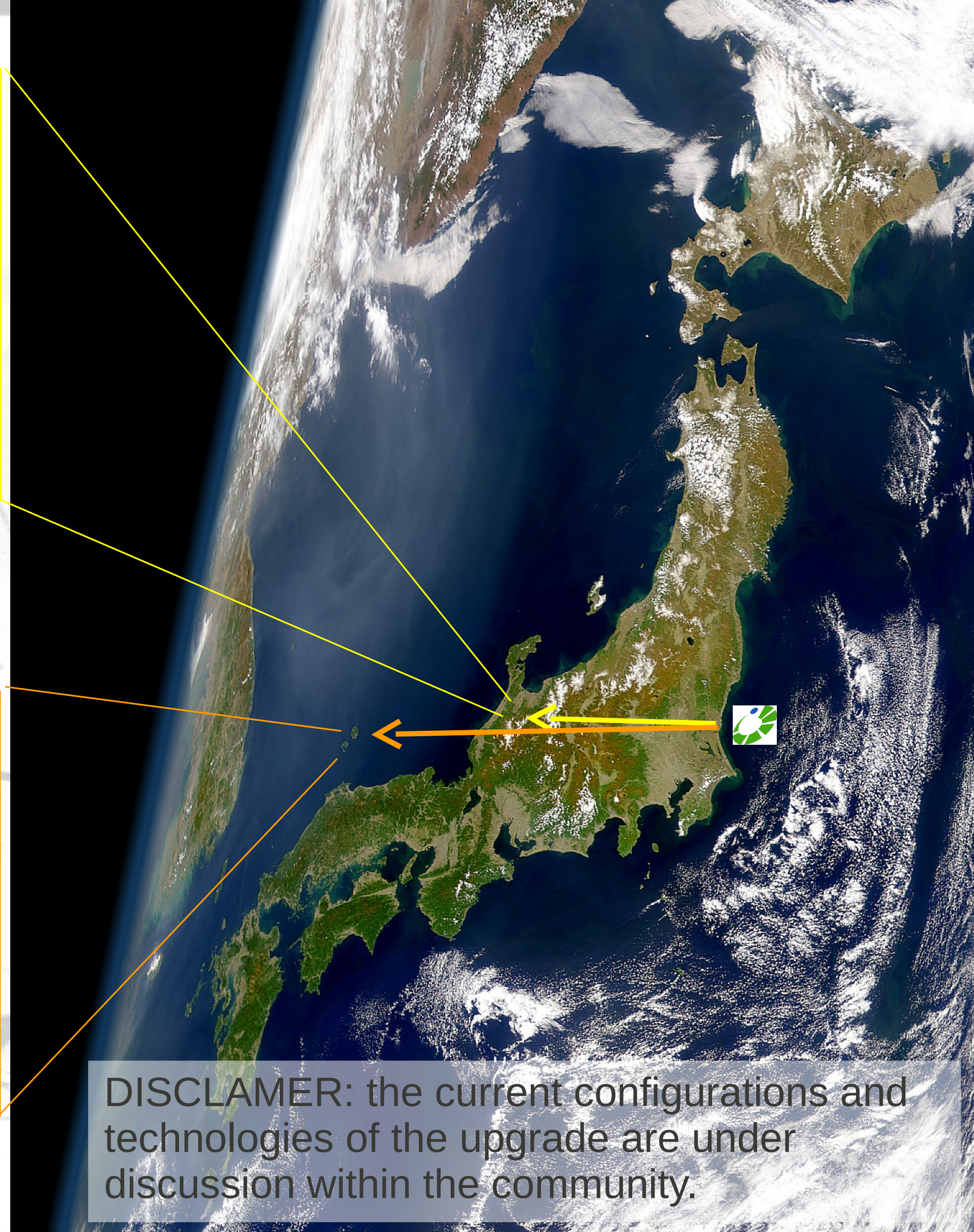
Kamioka L=295km OA=2.5deg



Okinoshima L=658km OA=0.78deg

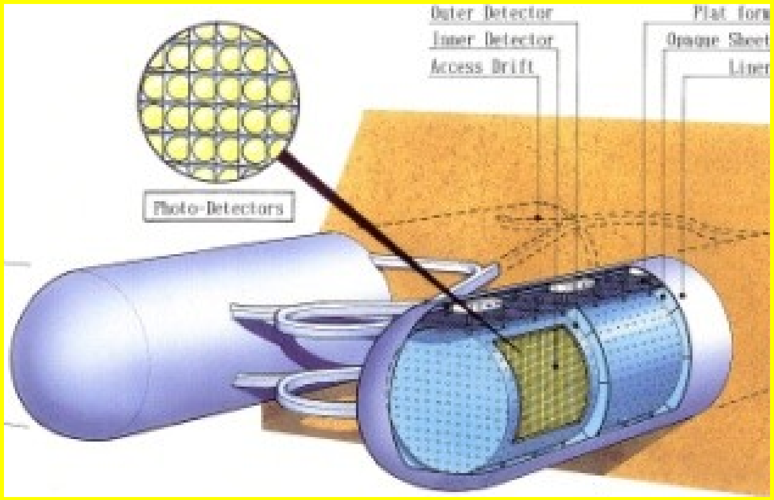


P32 proposal (Lar TPC R&D)
Recommended by J-PARC PAC
(Jan 2010), arXiv:0804.2111



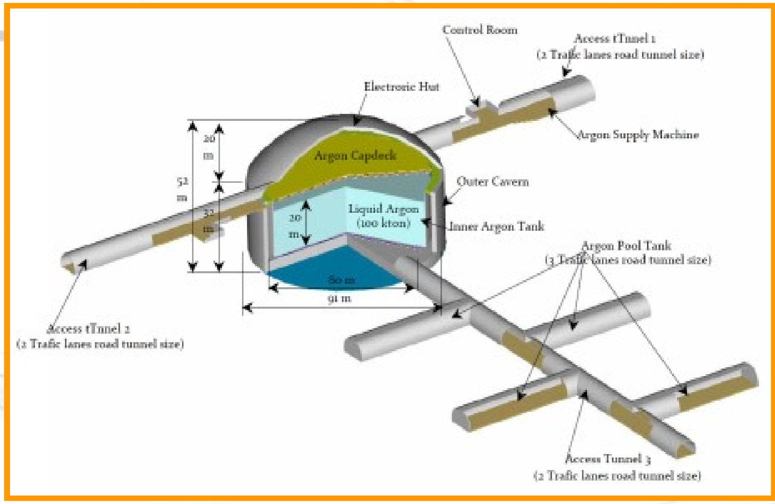
DISCLAMER: the current configurations and technologies of the upgrade are under discussion within the community.

Kamioka L=295km OA=2.5deg



- Baseline
  - Long:
    - ○ 2nd Osc. Max. at Measurable Energy
    - × Less Statistics
    - ? Large Matter Effect
  - Short:
    - ○ High Statistics
    - × 2nd Osc.Max.Too Low Energy to Measure
    - ? Less Matter Effect

Okinoshima L=658km OA=0.78deg



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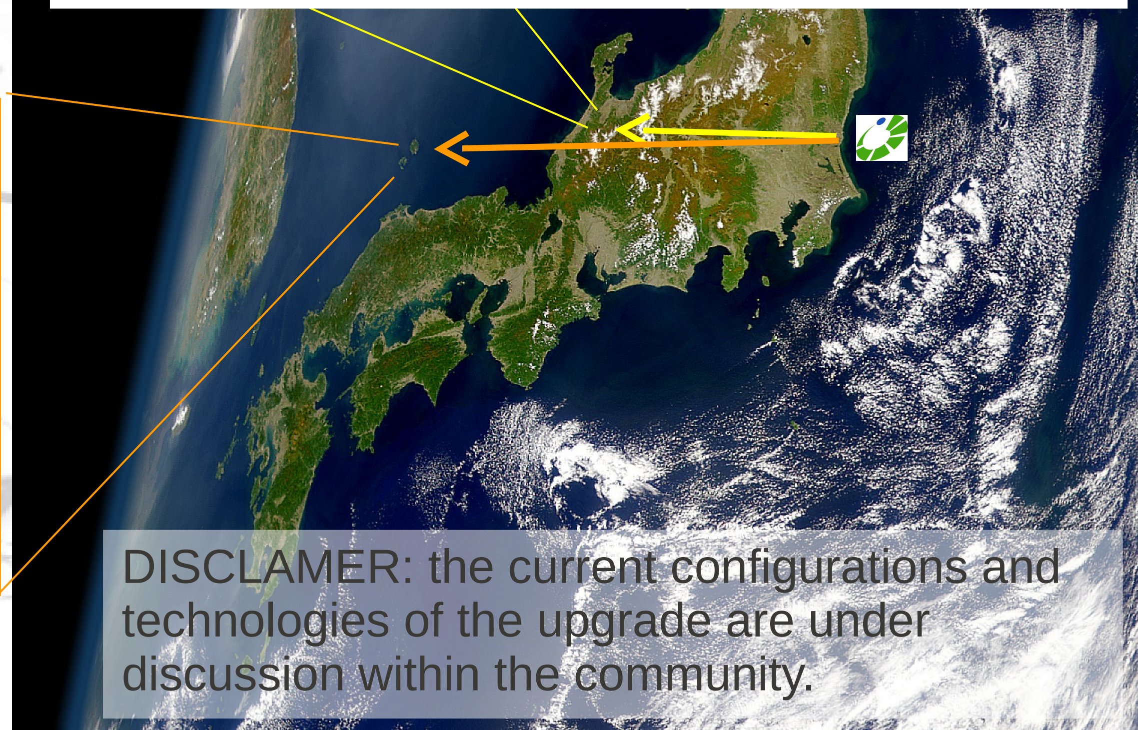


DISCLAMER: the current configurations and technologies of the upgrade are under discussion within the community.

Conclusions

- T2K searches for $\nu_\mu \rightarrow \nu_e$ & $\nu_\mu \rightarrow \nu_x$ oscillations and aims at determining the atmospheric sector parameters

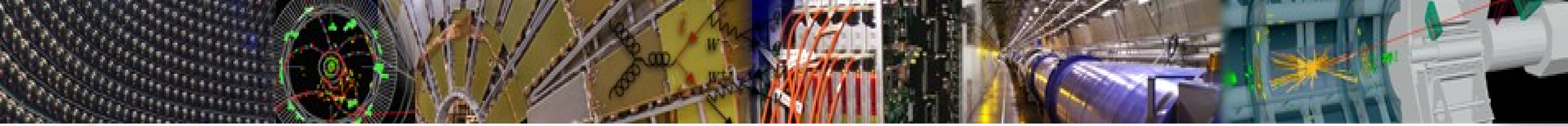
- T2K started physics running from Jan. 2010.

- We reported results from the first $\nu_\mu \rightarrow \nu_e$ oscillation analysis based on 3.23×10^{19} p.o.t. (2010 Jan.~ Jun):
    - # of observed events surviving all cuts = 1
    - # of expected background = 0.30 ± 0.07 (w/ $\theta_{13}=0$)

- The observed ν_μ CC candidates are consistent with the neutrino oscillation parameters measured by SK, K2K and MINOS.

- The total integrated proton intensity accumulated until the earthquake is 1.45×10^{20} p.o.t. and events are being analyzed. With this increased statistics, we expect a θ_{13} sensitivity better than that of CHOOZ. In addition, the analysis strategy will be improved.

Spare Slides



Well measured parameters

- 2 mass scales
  - atmospheric: Δm^2_{23}
  - solar: Δm^2_{21}
- 2 mixing angles
  - θ_{23} (from atmospheric)
  - θ_{12} (from solar/KamLAND)
- Mass ordering
  - solar: Δm^2_{21}

Unknown parameters

- Mixing angle
  - θ_{13} (limit only)
- CP phase
  - purely interesting!
- Mass ordering
  - Atmospheric Δm^2_{23}

$\nu_\mu \rightarrow \nu_e$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} T_1 + \alpha \sin 2\theta_{13} \overbrace{(T_2 - T_3)}^{\text{Interference}} + \alpha^2 T_4$$

Where:

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(A-1)\Delta]}{(A-1)^2} \quad \leftarrow \text{Atmospheric}$$

$$T_2 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}$$

$$T_3 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}$$

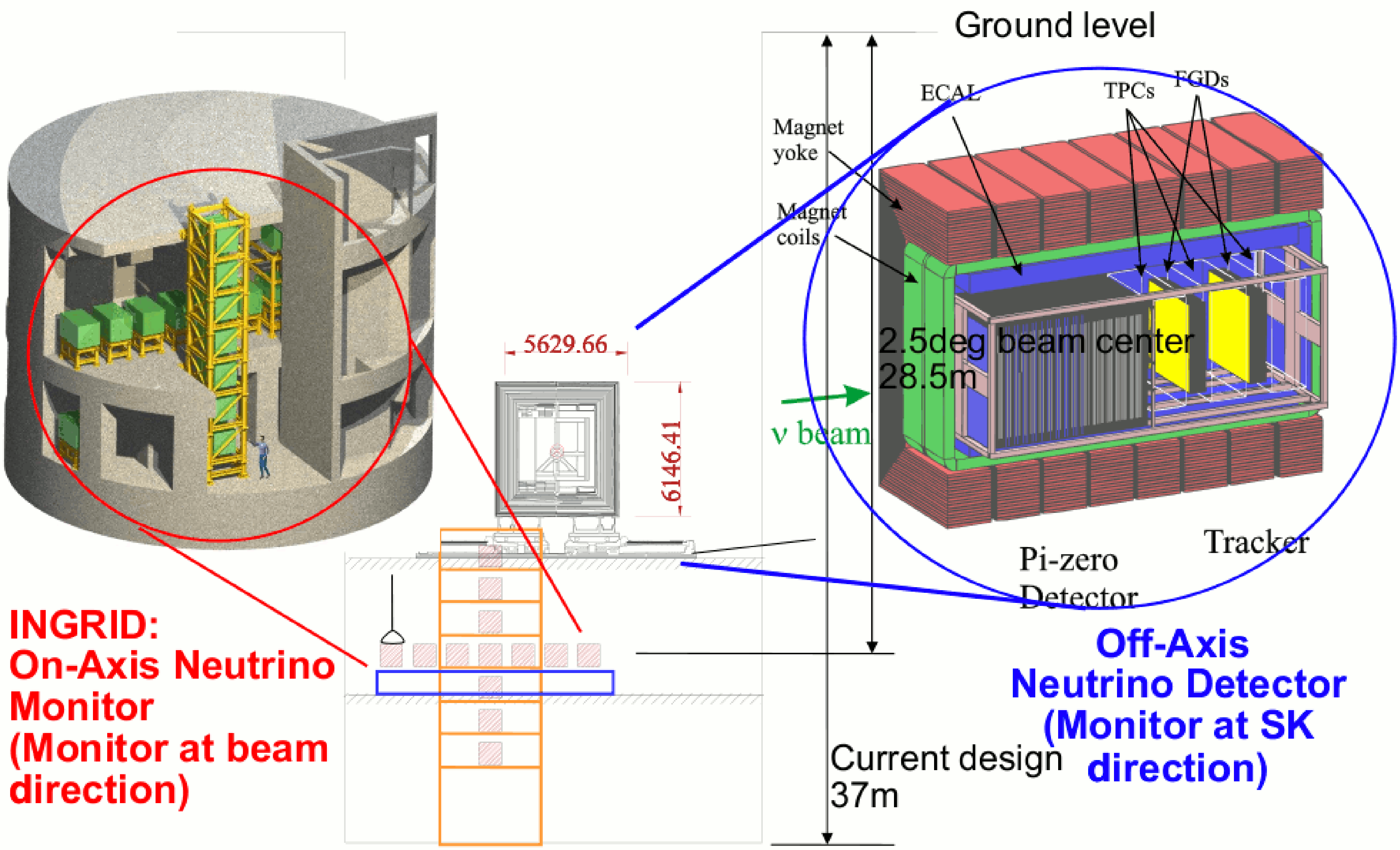
$$T_2 - T_3 = \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta_{CP}) \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}$$

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(A\Delta)}{A^2} \quad \leftarrow \text{Solar}$$

And:

$$A \equiv \frac{2EV}{\Delta m^2_{31}}, \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}, \quad \alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

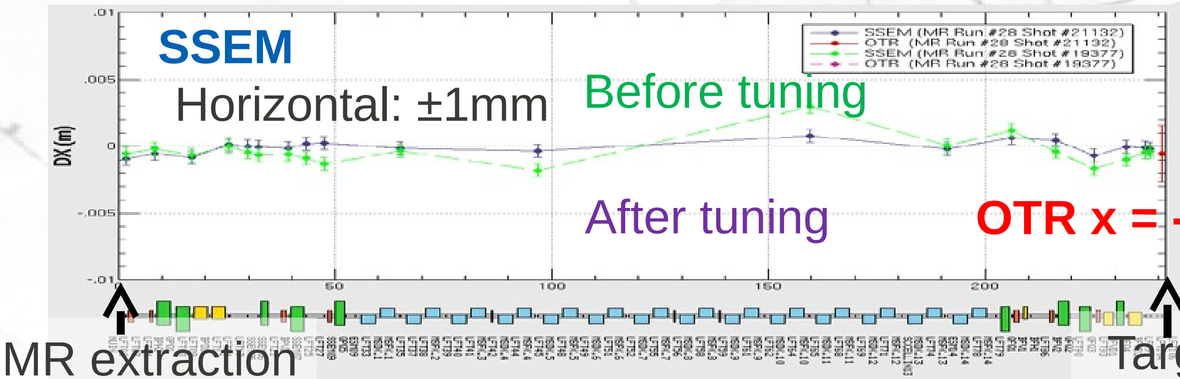
Near detectors



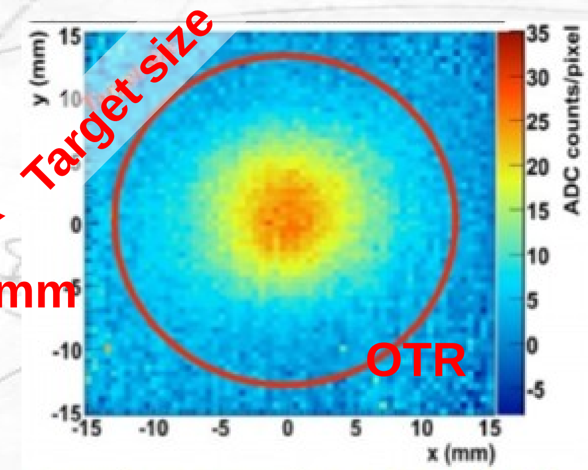
Beam Monitor Measurements

Primary proton beam monitoring

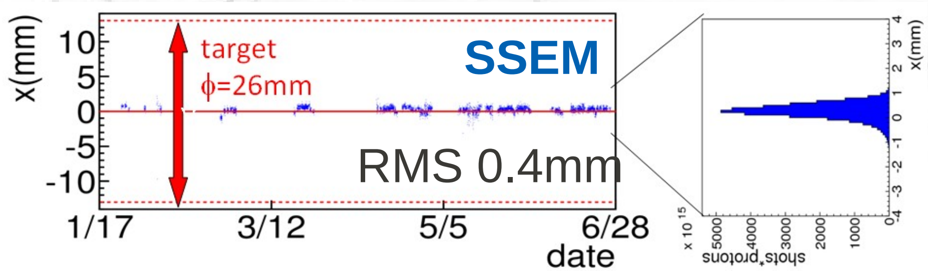
- **Beam orbit:** tuned within 2mm from design orbit.
  (Critical for controlling beam loss)

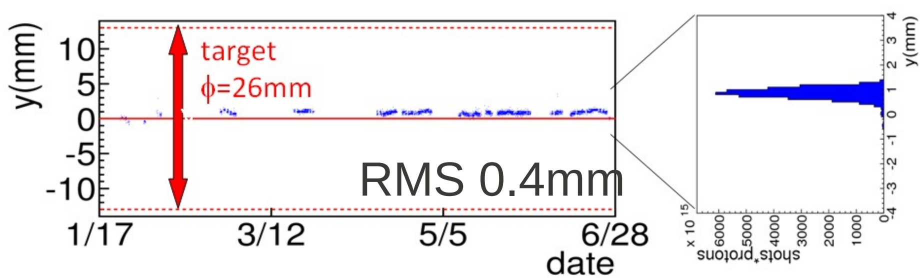


Proton beam hits center of target



- **Beam position on target:** Succeeded to control < 1mm during long term operation



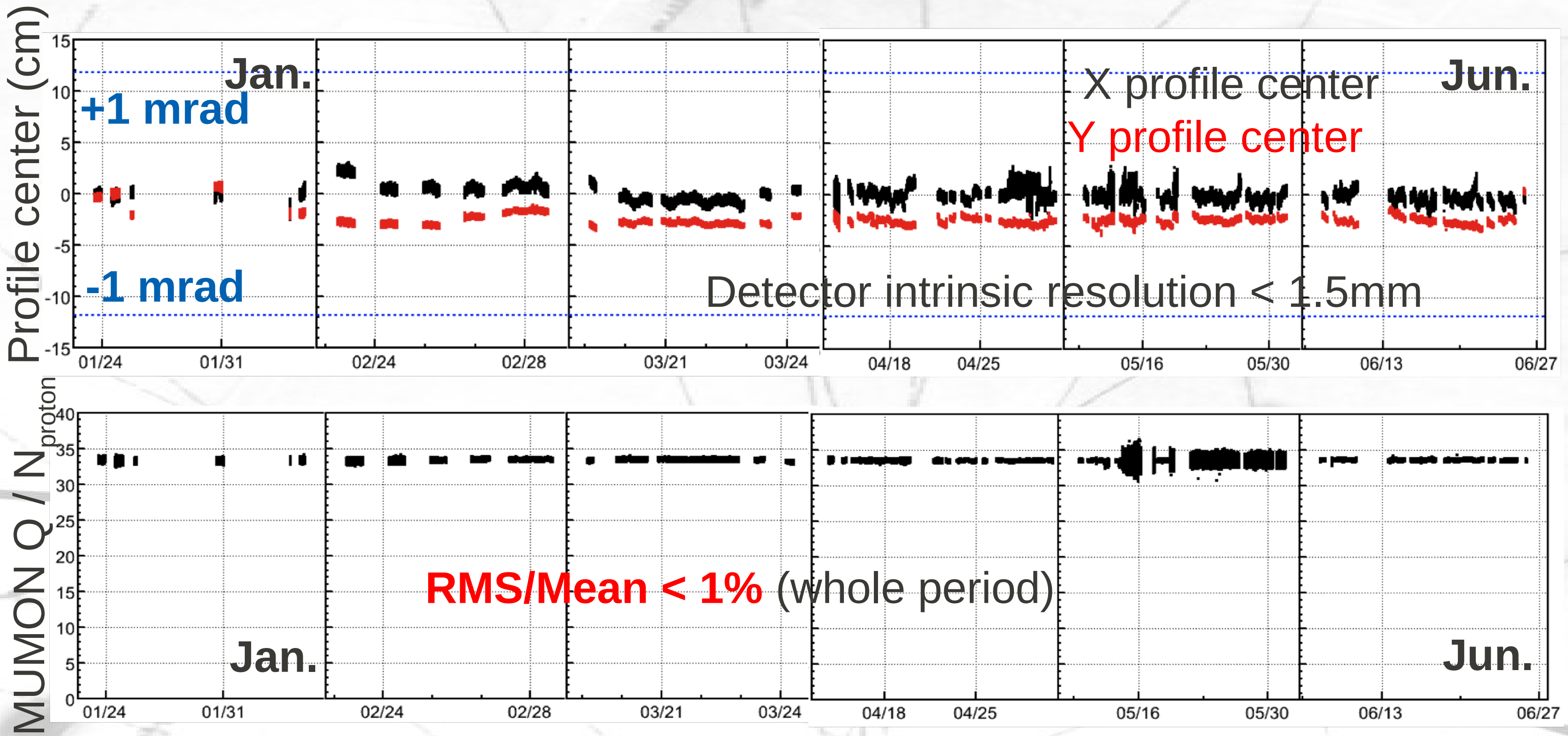


SSEM:
Segmented Secondary Emission Monitor

OTR:
Optical Transition Radiation detector

Beam Monitor Measurements

Secondary μ beam monitoring by MUMON



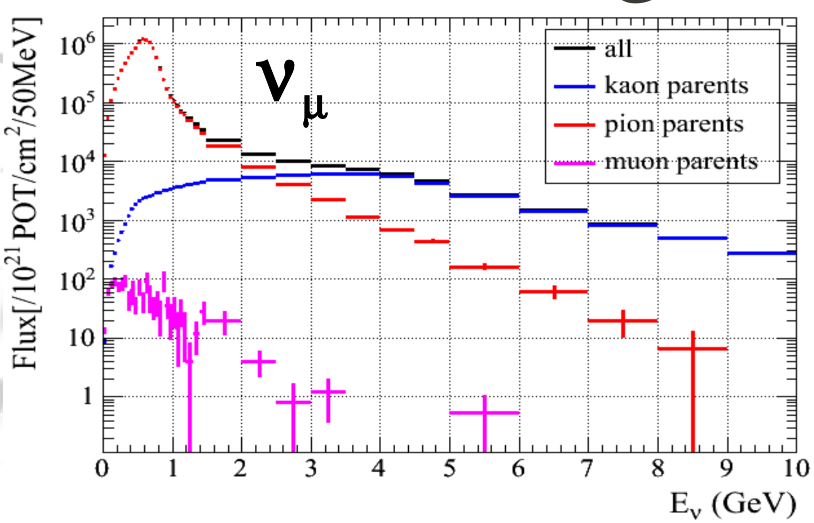
- **Beam direction** is controlled well within **1 mrad**. (1 mrad corresponds to 2% change in the SK flux at the peak energy, E_ν = 0.5 – 0.7 GeV)
- **Secondary beam intensity** (normalized by proton intensity) is stable within **1%** → reflects stability of targeting, horn focussing, etc

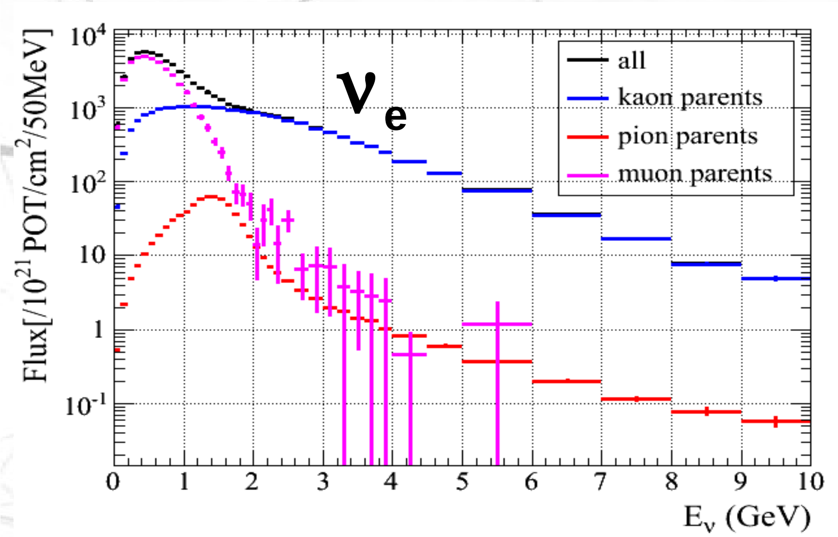
Flux Prediction

T2K neutrino beam simulation

- Use information by beam monitor/horn measurements
- Simulate Proton & Carbon interaction in target
  - Tune the pion production multiplicity and interaction rate based on the recent NA61/SHINE results
- Track particles exiting from target
- Simulate neutrino-producing decays

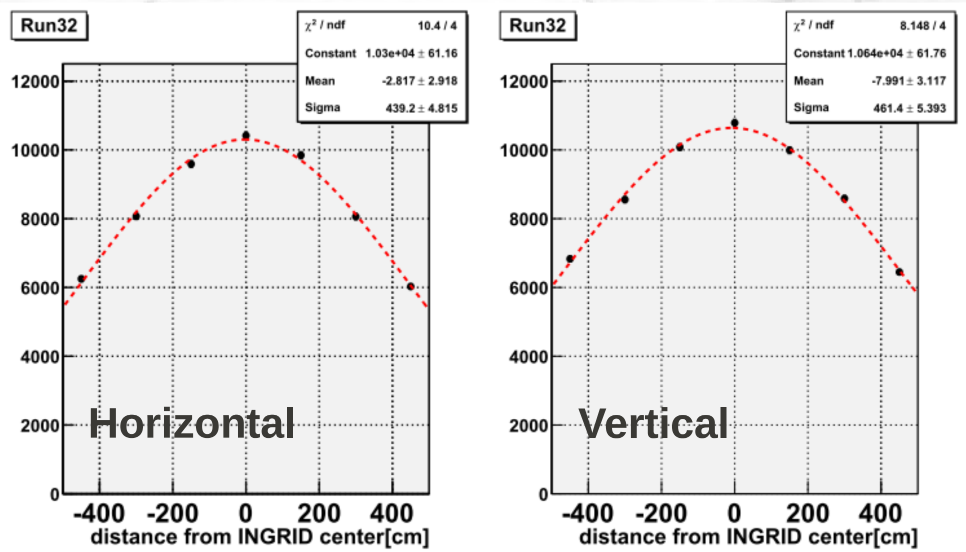
Predicted flux @ SK



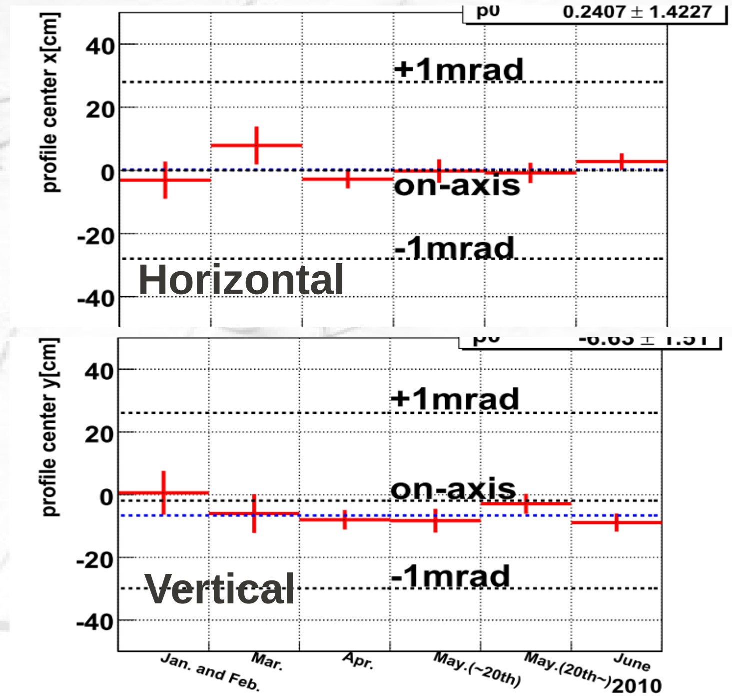


INGRID Measurements

ν beam profile



Profile center



- **Beam center**

  Horizontal = +0.2 ± 1.4(stat.) ± 9.2(syst.) cm

  Vertical = +6.6 ± 1.5(stat.) ± 10.4(syst.) cm (0.1 degree = 49cm @ INGRID)

  → **Off-axis angle = 2.519 ± 0.021 degrees**

- **Event rate:** expectation vs. observation ($R_{data/MC} = N_{data} / N_{MC}$)

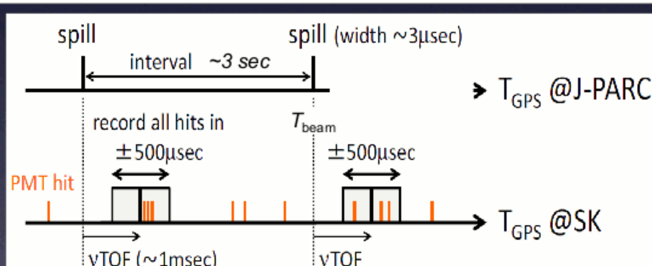
  → $R_{data/MC}$ **= 1.073 ± 0.001(stat.) ± 0.040(syst.)**

SK-spill synchronization

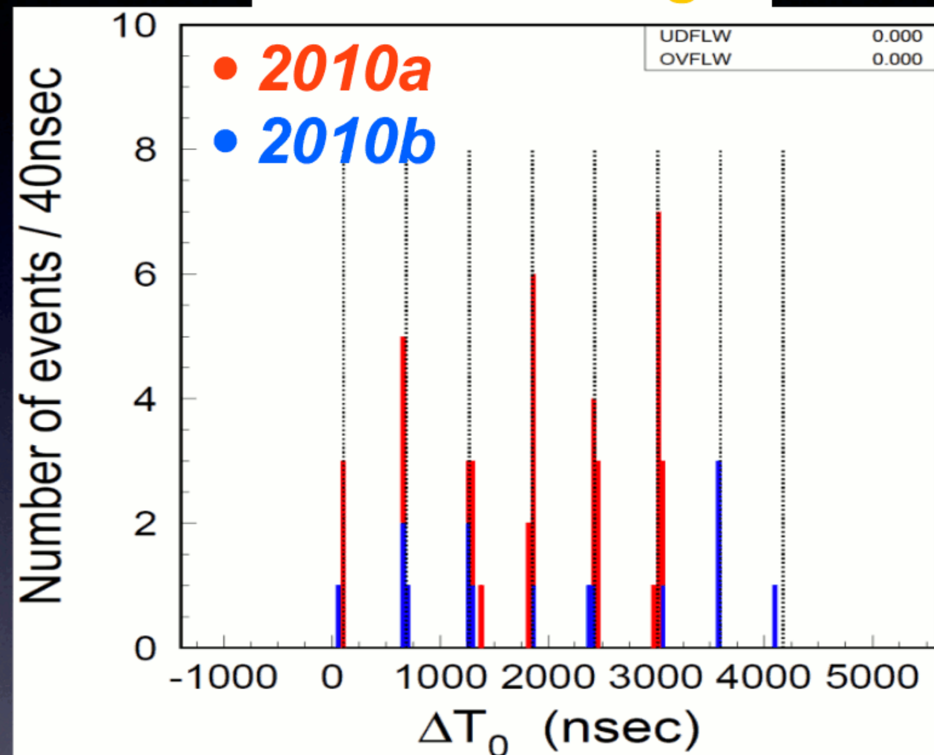
SK-spill synchronization

T2K

- Baseline measurement (Survey)
  - $L = 295{,}335 \pm 7$ m
    → ToF of ν = 985.132 ± 0.02 μsec (≡ νTOF)
  - Expected event timing @ SK (≡T_{SK})
    = Spill timing @ Tokai (≡T_{beam}) + νTOF.
- DAQ synchronization
  - SK signals in ±500μs timing window are recorded as "T2K beam events".
  - Stability of GPS is checked by comparing 2 GPS hardware and atomic clock.
    → Require |GPS1-GPS2| < 200nsec



Event timing

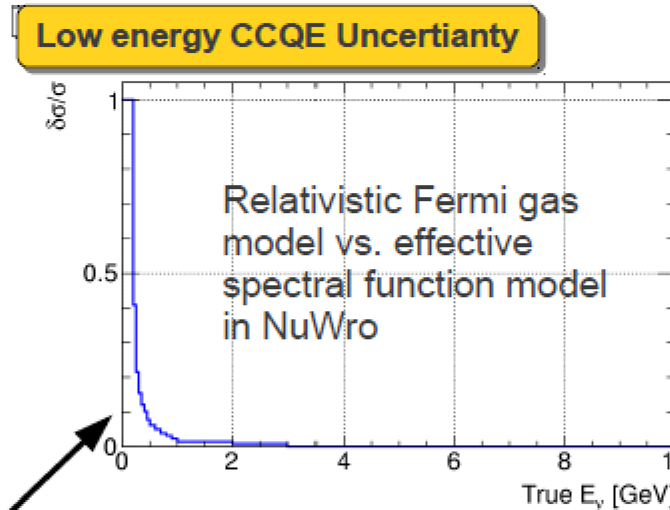


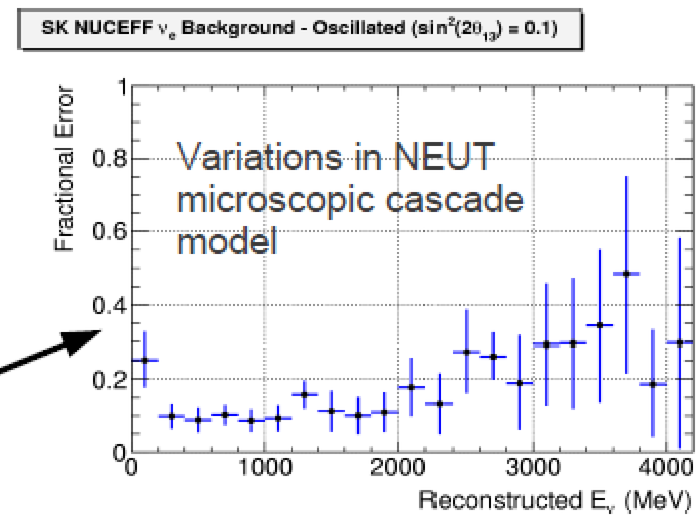
- *Event time distribution clearly shows MR beam bunch structure : very good synchronization between T2K beam and Super-K*
  Typical accuracy ~ 20 ns (worst case 150 ns)

Neutrino Interactions

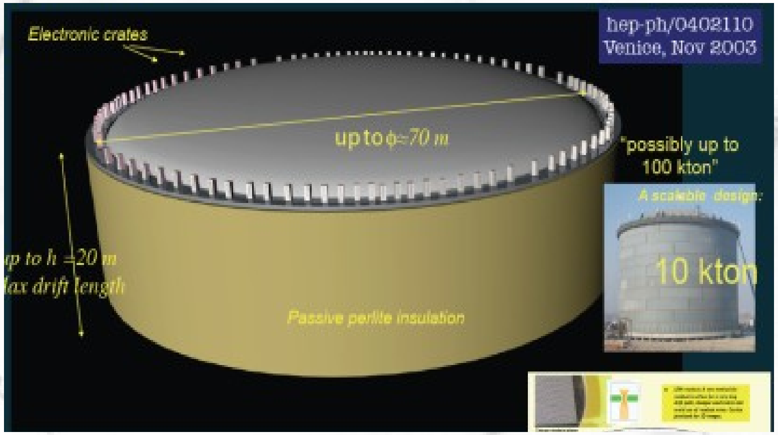
- NEUT and GENIE used to model neutrino interactions
- Uncertainties from:
  - Parameter variations in models, comparisons between models
  - Model comparisons to MiniBooNE, SciBooNE and SK atmospheric data

Category	Error [%]	
CC QE	Depends on true neutrino energy	
CC 1π	30 (E_ν<2 GeV)	20 (E_ν>2 GeV)
CC coherent π	100	
CC other	30 (E_ν<2 GeV)	25 (E_ν>2 GeV)
NC $1\pi^0$	30 (E_ν<1 GeV)	20 (E_ν>1 GeV)
NC coherent	30	
NC other	30	
FSI error	Depends on reconst. neutrino energy	





"Available" technologies



Liq Ar TPC

Aim O(100kton)

Electronic "bubble chamber"

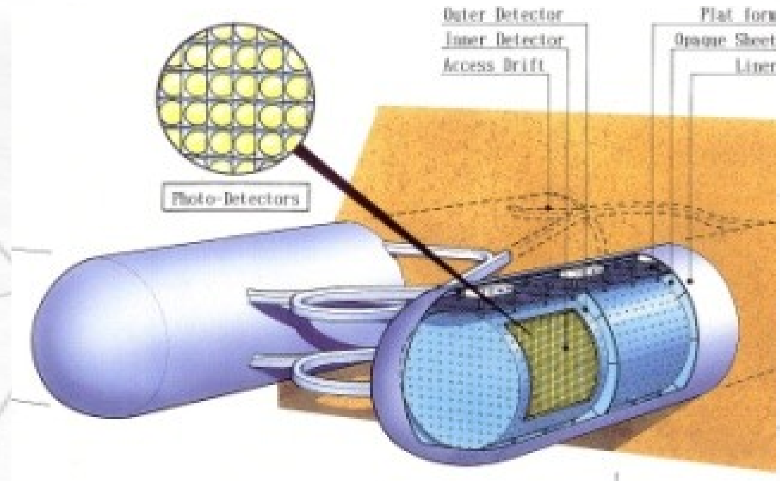
- Can track every charged particle
- Down to very low energy

Neutrino energy reconstruction by eg. total energy

- No need to assume process type
- Capable upto high energy

Good PID w/ dE/dx, π^0 rejection

Good at Wideband beam



Water Cherenkov

Aim O(1000kton)

Energy reconstruction assuming CCqe

- Effective < 1GeV

Good PID (μ/e) at low energy

Cherenkov threshold

Good at low E (<1GeV)
narrow band beam