Run 1 and 2 Results from T2K

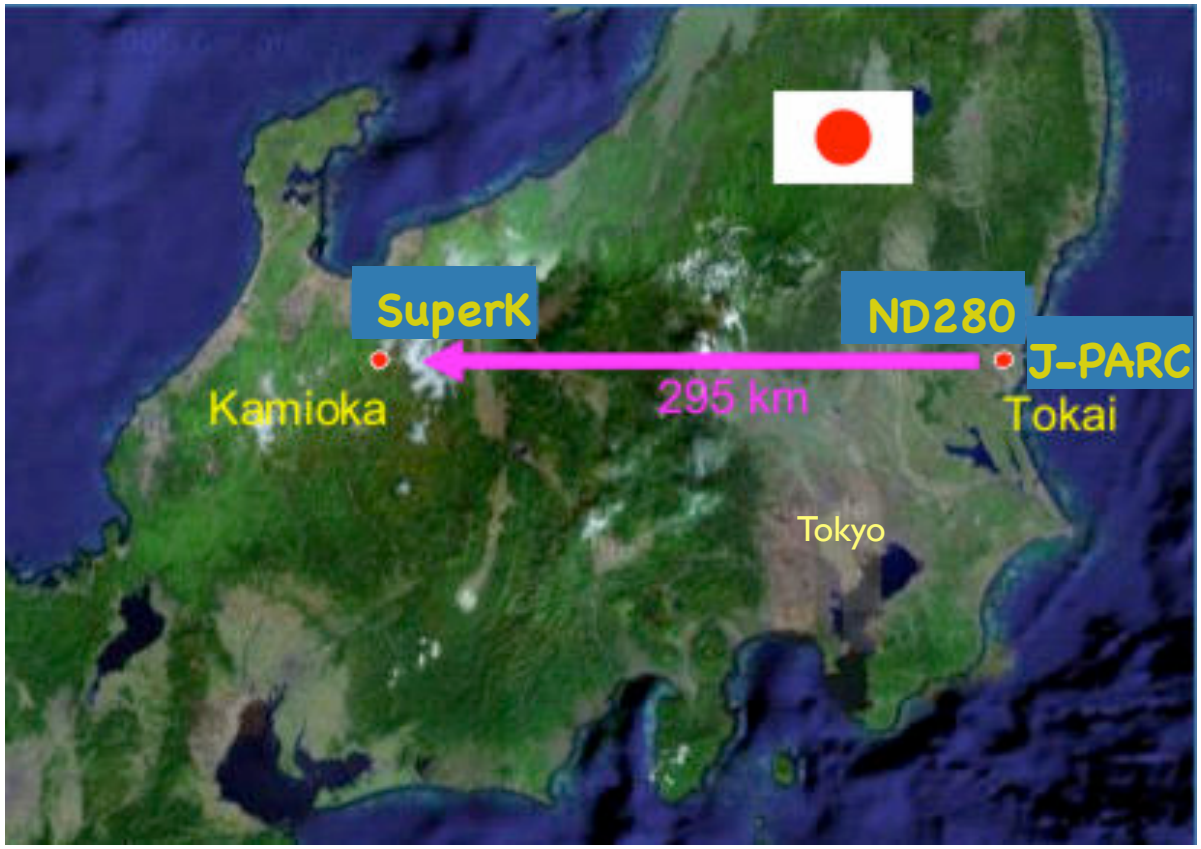
Alysia Marino, University of Colorado at Boulder

INFO 11, July 18, 2011

Outline

- T2K Physics Goals
- T2K Beamline
- T2K Near Detectors
- T2K Far Detector
- ν_μ Disappearance Results
- ν_e Appearance Results

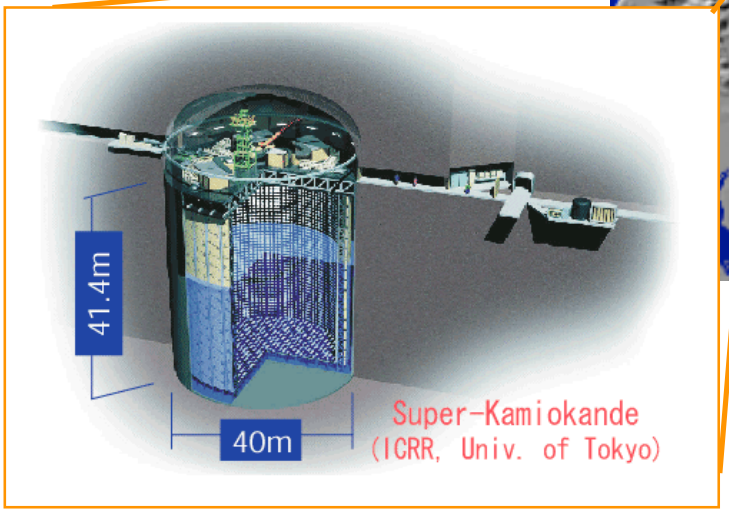
T2K: Tokai-to-Kamioka

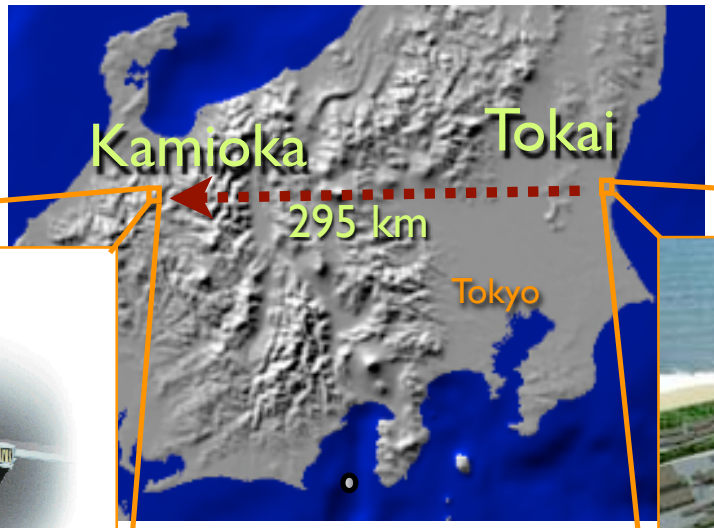


T2K Physics Goals

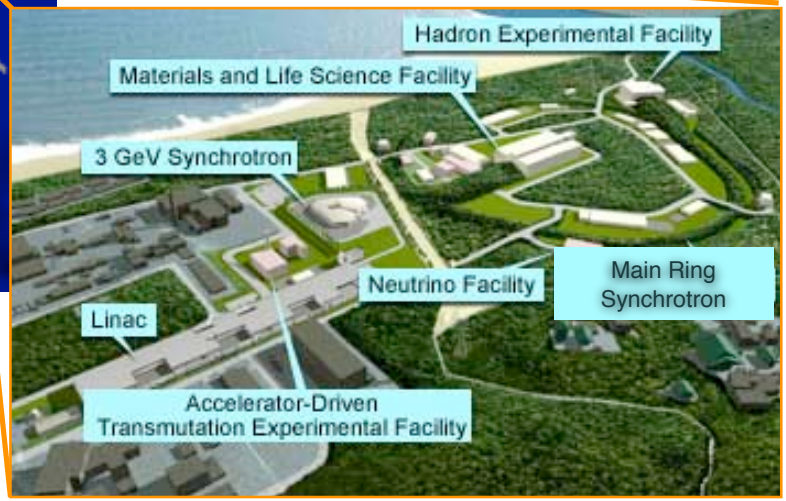
T2K Project

Super-Kamiokande Detector

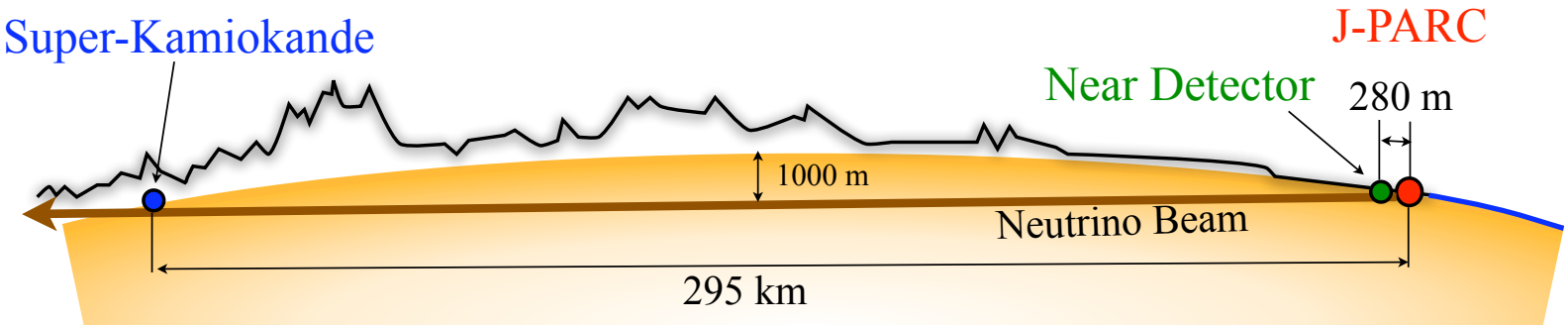




J-PARC Facility (Tokai)
Accelerator+Near Detector



- Long-baseline neutrino experiment with detectors at near and far locations
- Neutrino beam travels 295 km across Japan

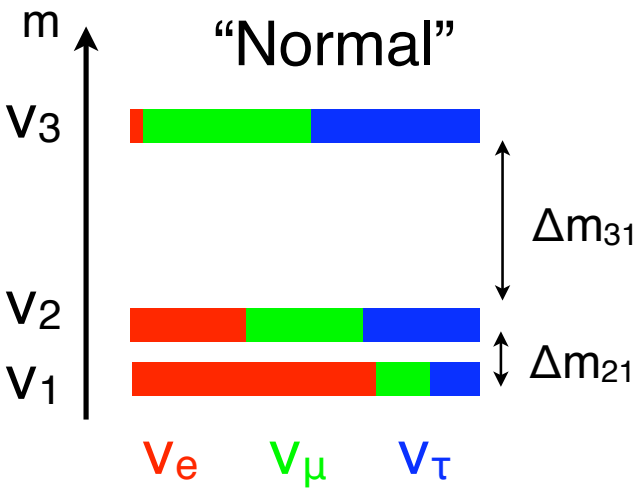


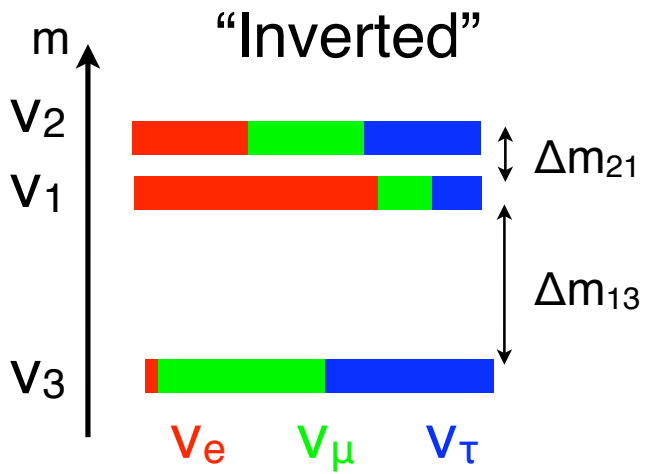
T2K Collaboration

- ~500 people, 59 institutions
- Japan
  - ICRR, KEK, Kobe U, Kyoto U, Miyagi U of Education, Osaka City U, U of Tokyo
- UK
  - Oxford, Imperial College London, Lancaster U, Queen Mary U of London, Sheffield U, STFC/RAL/Daresbury Lab, U of Liverpool, U of Warwick
- U.S.A.
  - Boston U, Brookhaven Lab, Colorado State U, Duke U, Louisiana State U, Stony Brook U, UC Irvine, U of Colorado, U of Pittsburgh, U of Rochester, U of Washington
- Canada
  - U of British Columbia, U of Regina, TRIUMF, U of Toronto, U of Victoria, York U
- France
  - CEA/DAPNIA Saclay, IPN Lyon, LLR Ecole Polytechnique, LPNHE-Paris
- Switzerland
  - Bern, ETHZ, U of Geneva
- Poland
  - IFJ PAN Cracow, IPJ Warsaw, Technical University Warsaw, U of Silesia, Warsaw U, Wroclaw U
- Spain
  - IFIC Valencia, Barcelona/IFAE
- Russia
  - INR
- Italy
  - INFN-Bari, INFN-Rome, Napoli, Padova, Rome
- Korea
  - Chonnam National U, Dongshin U, Seoul National U,
- Germany
  - RWTH Aachen U

Neutrino Masses

- Neutrino mass states area mixture of neutrino flavor states.





- Interference between the energy eigenstates means that probability of observing a given neutrino flavor will vary with time.
- The Unitary MNSP matrix relates the mass states to the flavor states

Mixing Matrix

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

where $s_{ij} = sin(\theta_{ij})$ and $c_{ij} = cos(\theta_{ij})$

Mixing Matrix

θ_{23} and Δm_{32}^2
Atmospheric/
Accelerator neutrinos
(Super-K, K2K, MINOS)
$\theta_{23} \sim 45^o$

δ, θ_{13} and Δm_{31}^2
CP-violating Phase
& Cross terms
Not definitively measured yet!
$\sin^2\theta_{13} < 0.15$ from CHOOZ

θ_{12} and Δm_{21}^2
Solar neutrinos/
reactor anti-neutrinos
(SNO, Super-K, KamLAND)
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  - Improve on the measurements of θ_{23},Δm^2_{32} by observing disappearance of ν_μ

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- With a beam of muon neutrinos T2K aims to
  - Improve on the measurements of θ_{23},Δm^2_{32} by observing disappearance of ν_μ
  - Make measurements of θ_{13} by searching for appearance of ν_e

Oscillation Probability

- For the distance/energy scale relevant for T2K, oscillation effects are dominated by $m_3 \leftrightarrow m_2$ and $m_3 \leftrightarrow m_1$ mixing
- ν_μ Disappearance

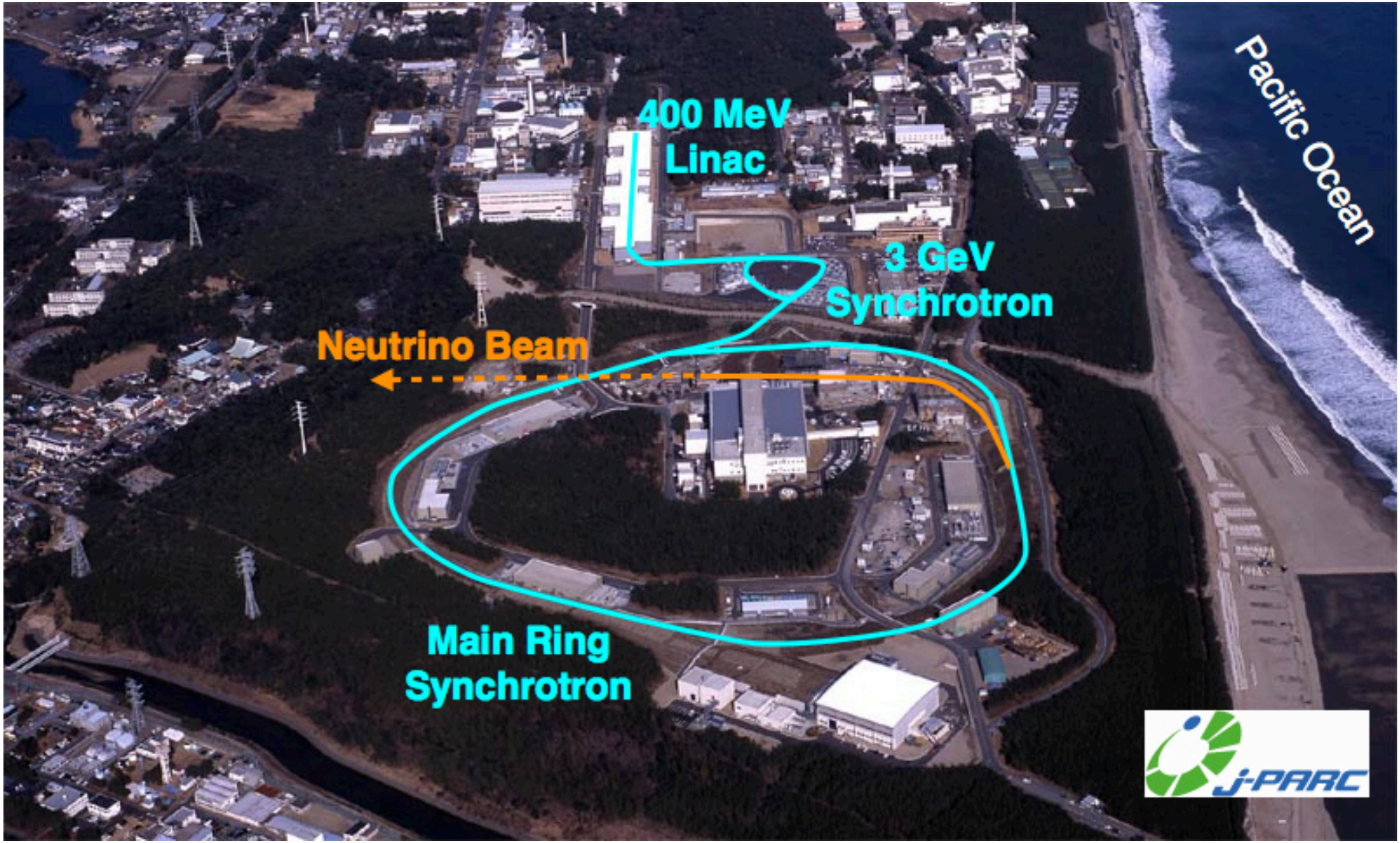
$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - sin^2 2\theta_{23} \cdot (1.27 \Delta m^2_{32} L/E)$$

- ν_e Appearance

$$P(\nu_\mu \rightarrow \nu_e) \simeq sin^2 2\theta_{13} \cdot sin^2 \theta_{23} \cdot sin^2 (1.27 \Delta m^2 L/E)$$

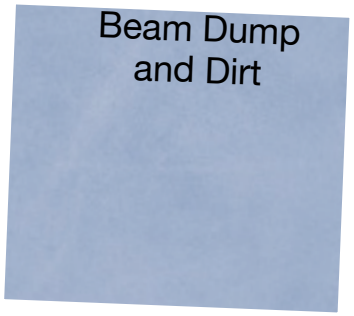
T2K Neutrino Beam

J-PARC Accelerator Chain



T2K Neutrino Beam

Side View of T2K Beam (not to scale!)



T2K Neutrino Beam

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1. 30 GeV protons strike graphite target, producing πs and Ks

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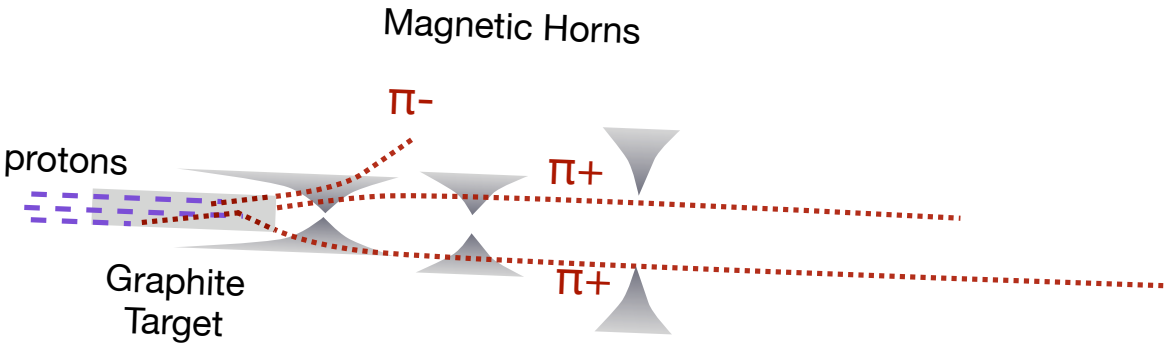

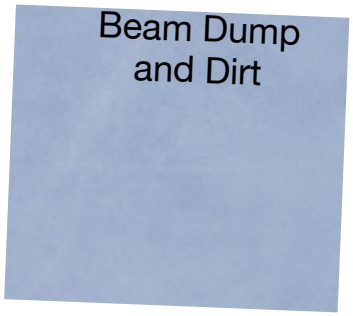

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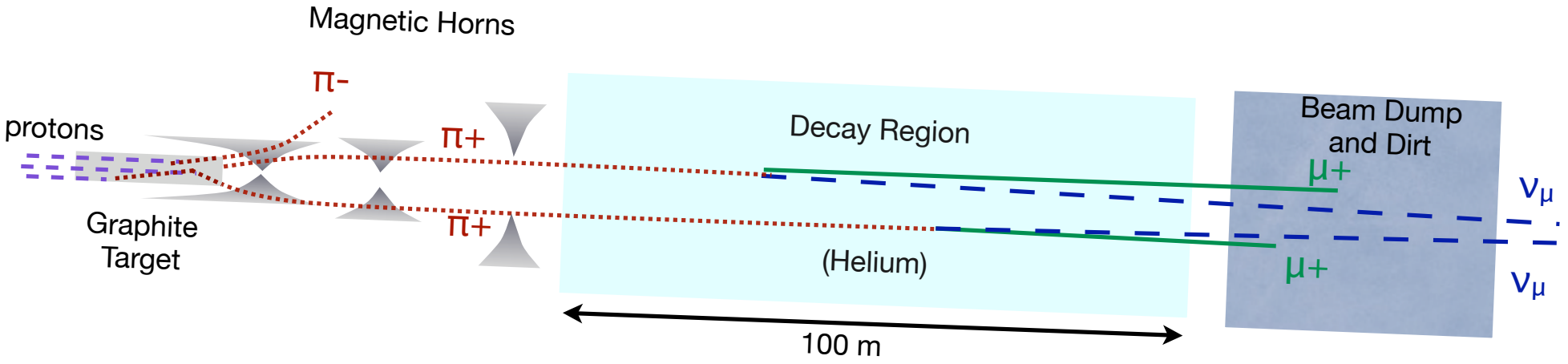

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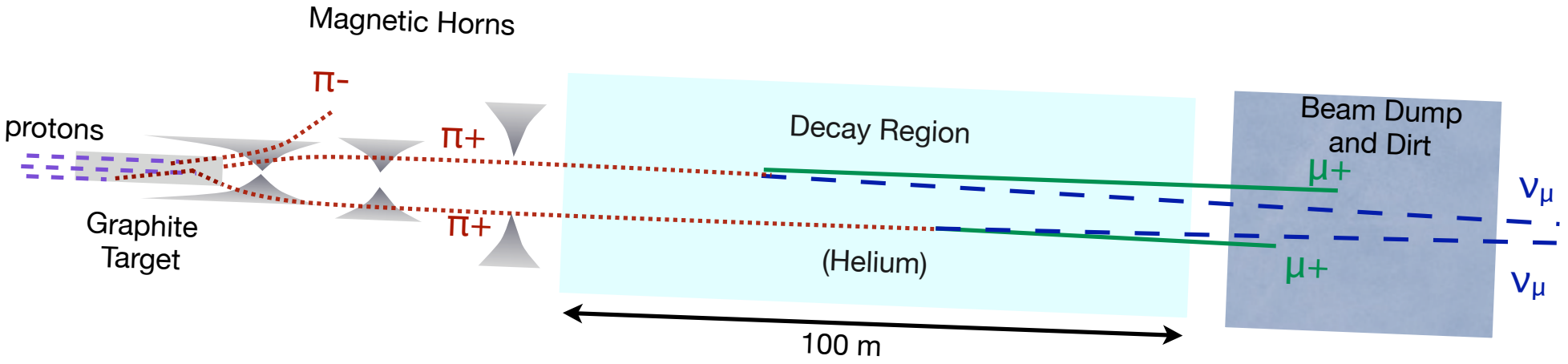

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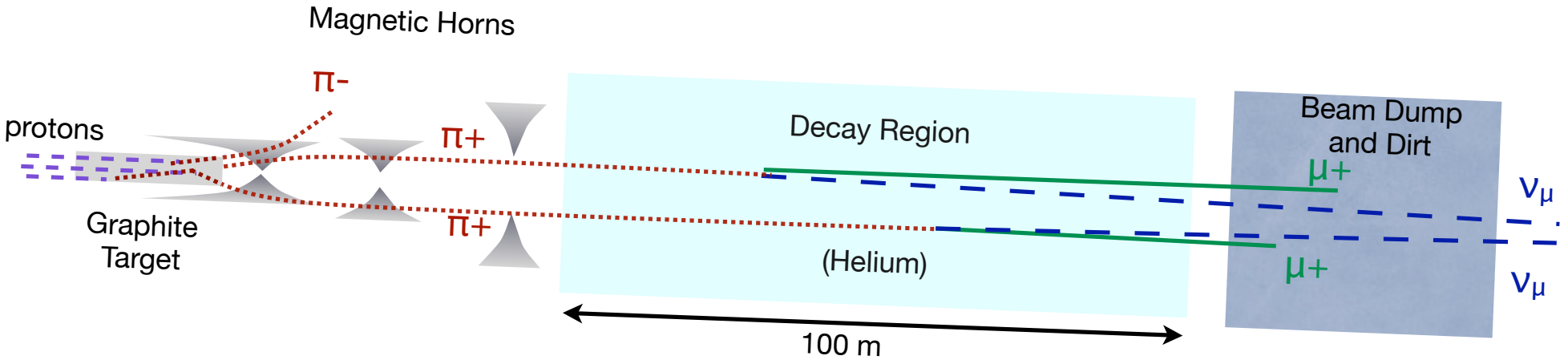

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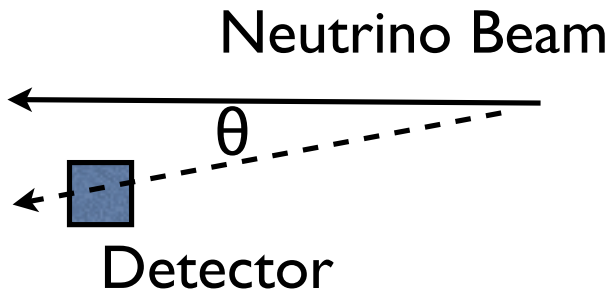
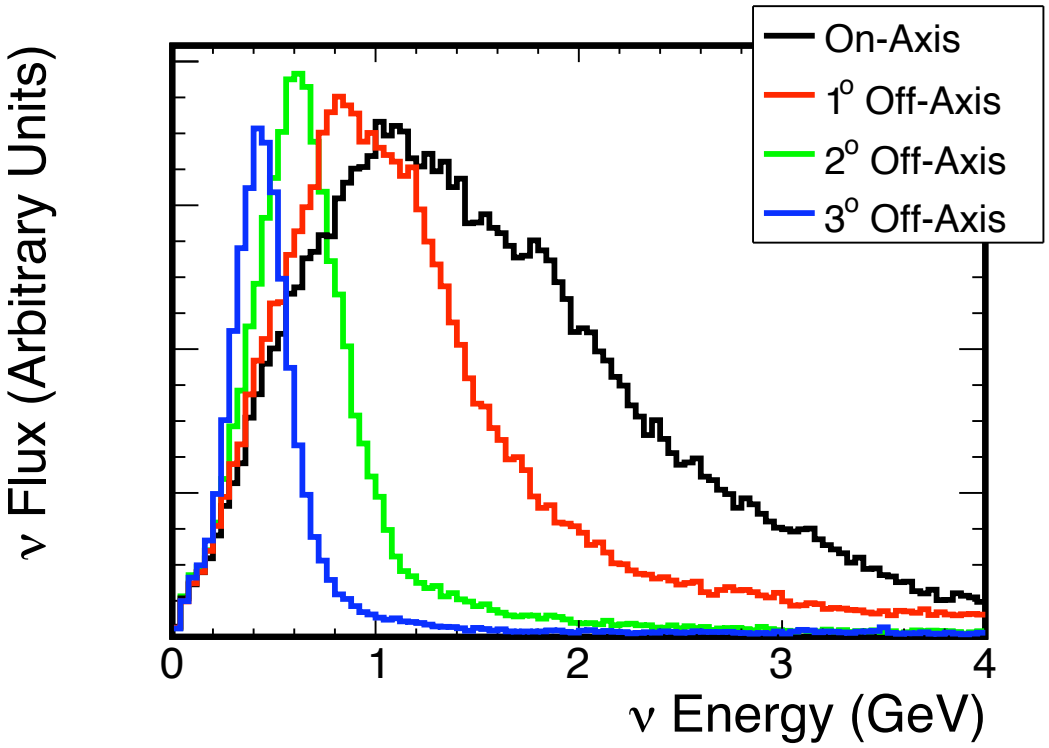
   - T2K Beam is ~95% ν_μ, 4% $\bar{\nu}_\mu$, 1% ν_e
   - Can make a $\bar{\nu}_\mu$ beam by changing sign of horn current

"Off-Axis" Beam

- Both T2K detectors are 2.5° off ν beam axis
- Smaller ν flux, but more low energy flux, and νs are in a very narrow energy range

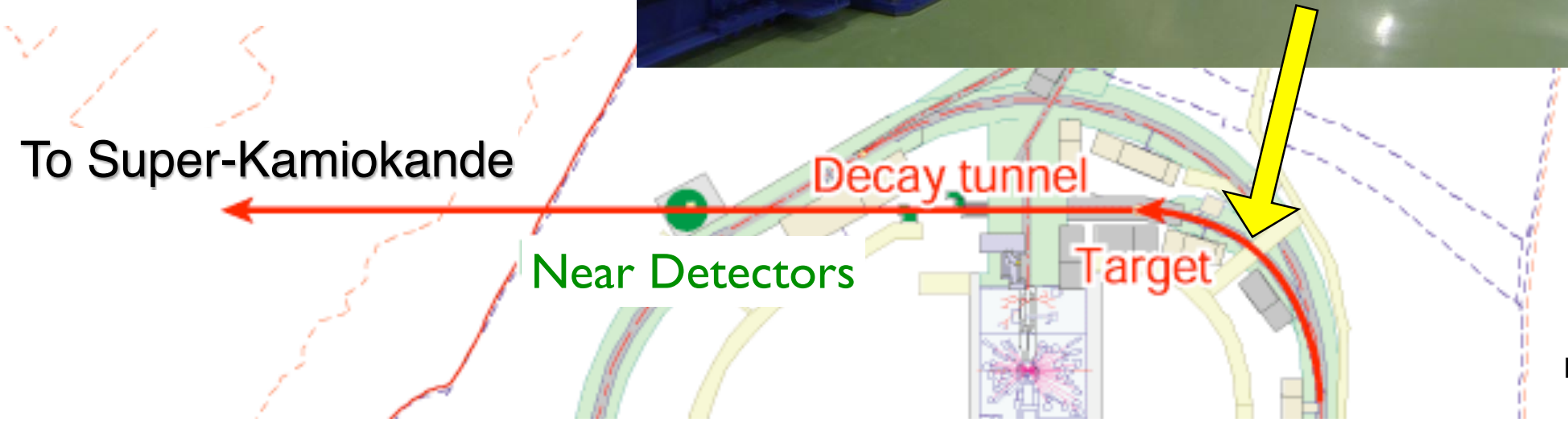
- Oscillations depend on L/E so narrow E range is preferable
- Reduces background from high-energy NC π^0 interactions





T2K Neutrino Beam

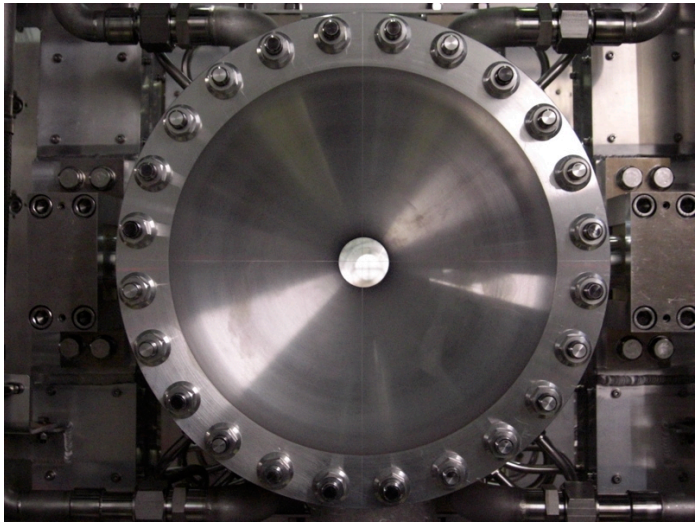
- Initiated by a 30 GeV proton beam at J-PARC
- Designed for 750 kW
- Proton pulse is 5.2 μsec wide
- 1 pulse every 3.04 seconds



Target Area

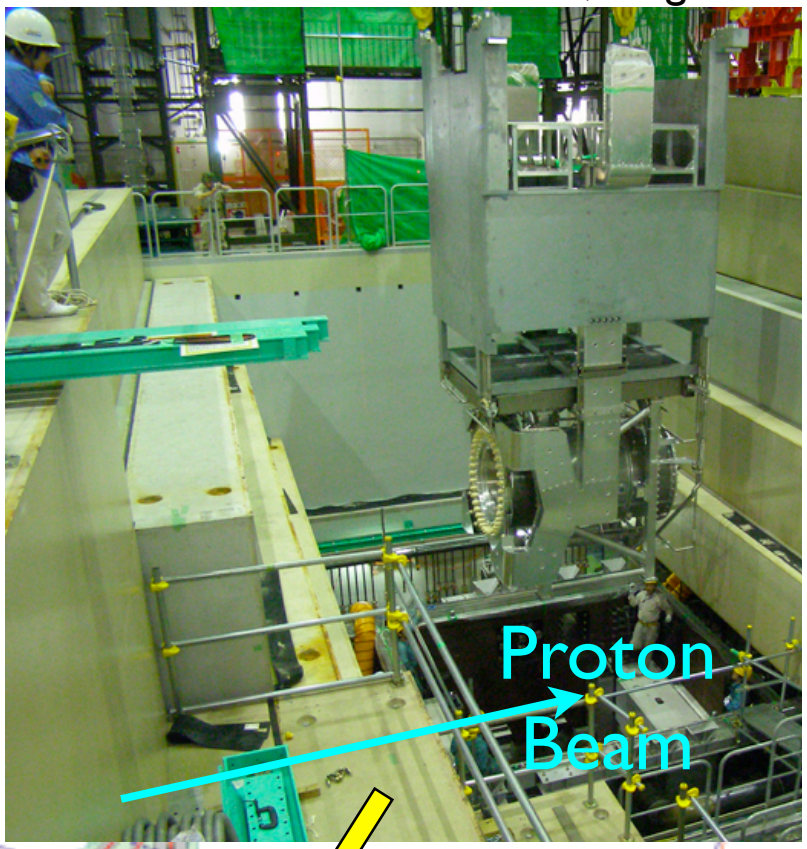
- Target and first horn installed Jan 2009

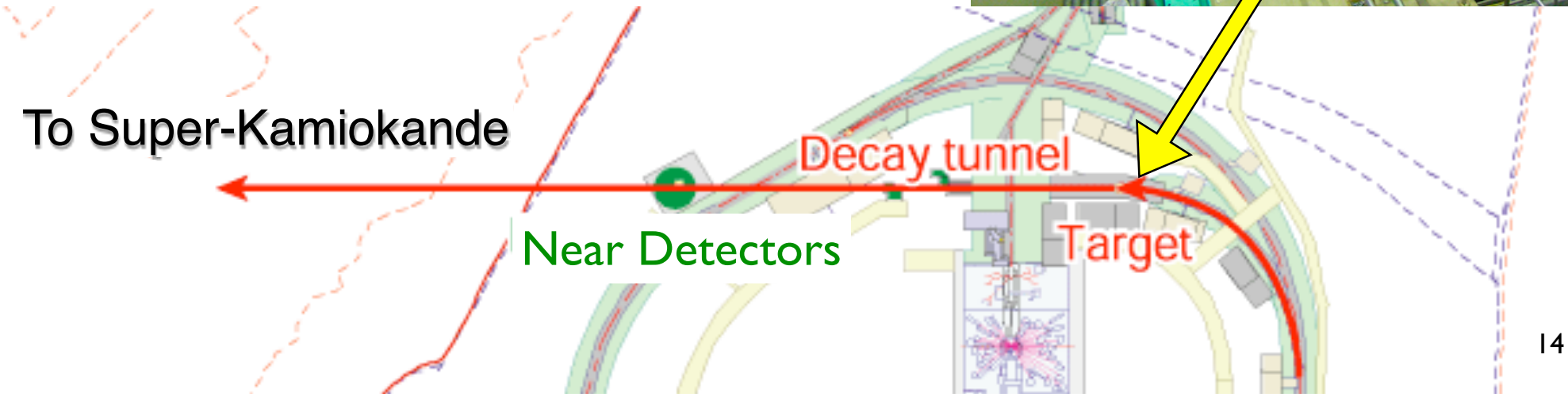
Target



Horn #1, Sept 2008

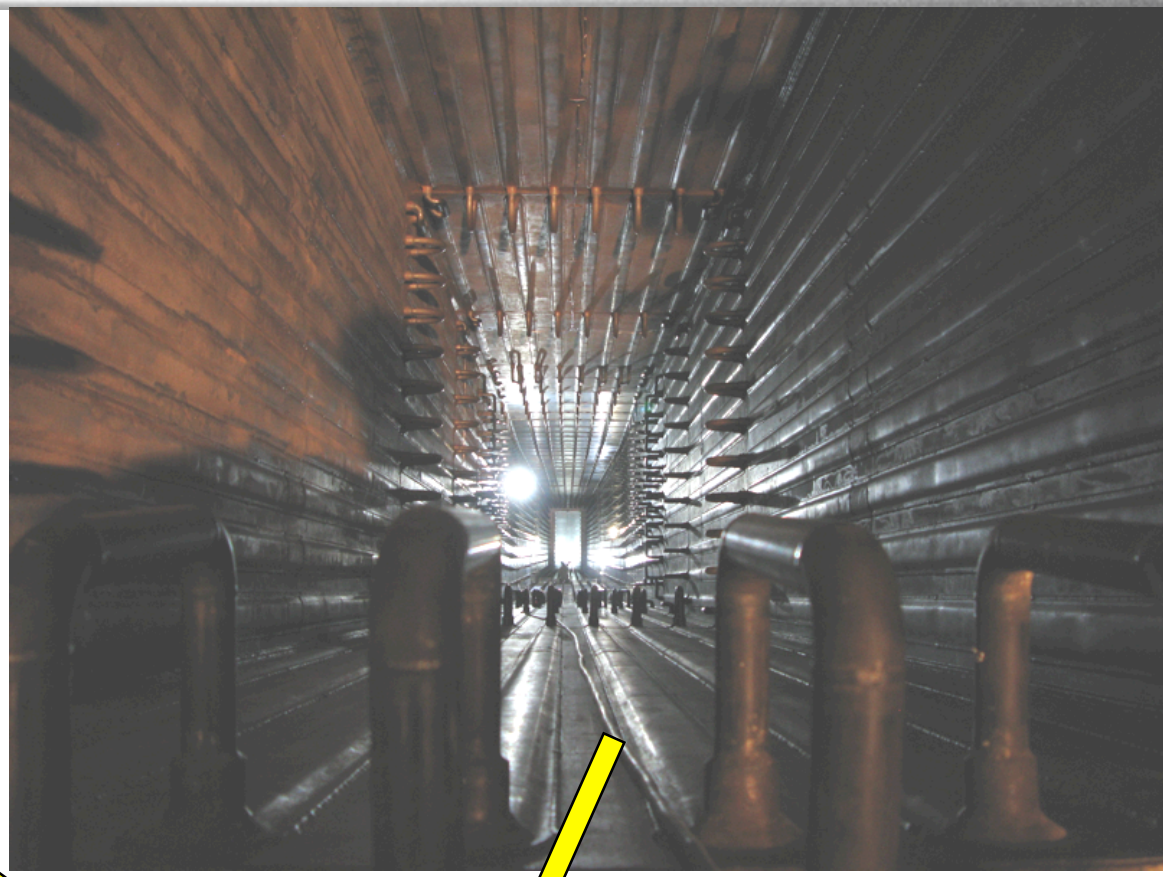
Horn #3 installation, Aug 2009

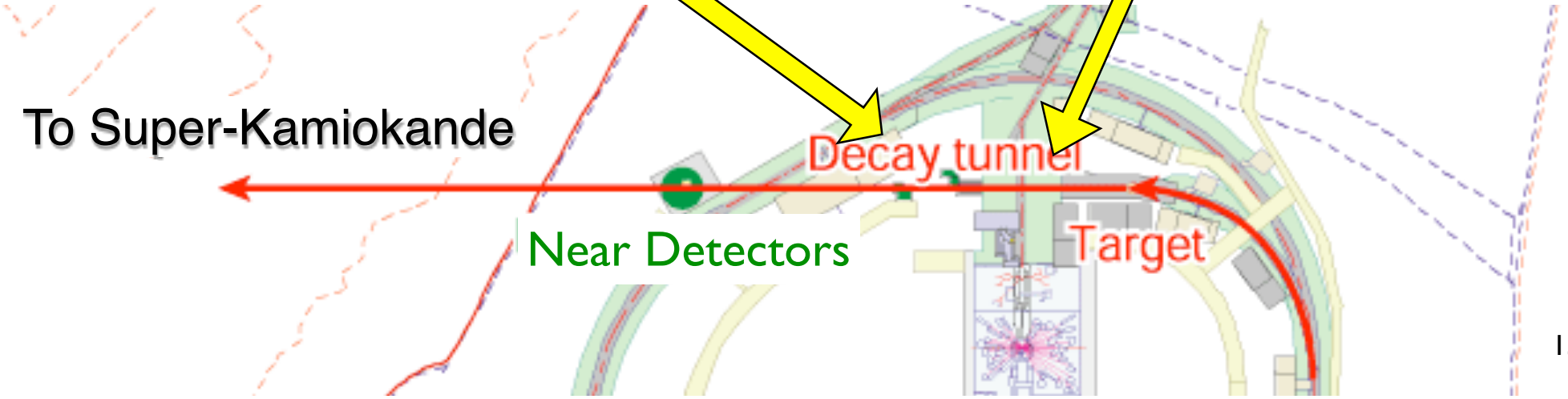




Decay Area


Oct 2008
KATO
T2K
Beam
Absorber




To Super-Kamiokande
Decay tunnel
Near Detectors
Target

First Protons on Target!

April 24, 2009

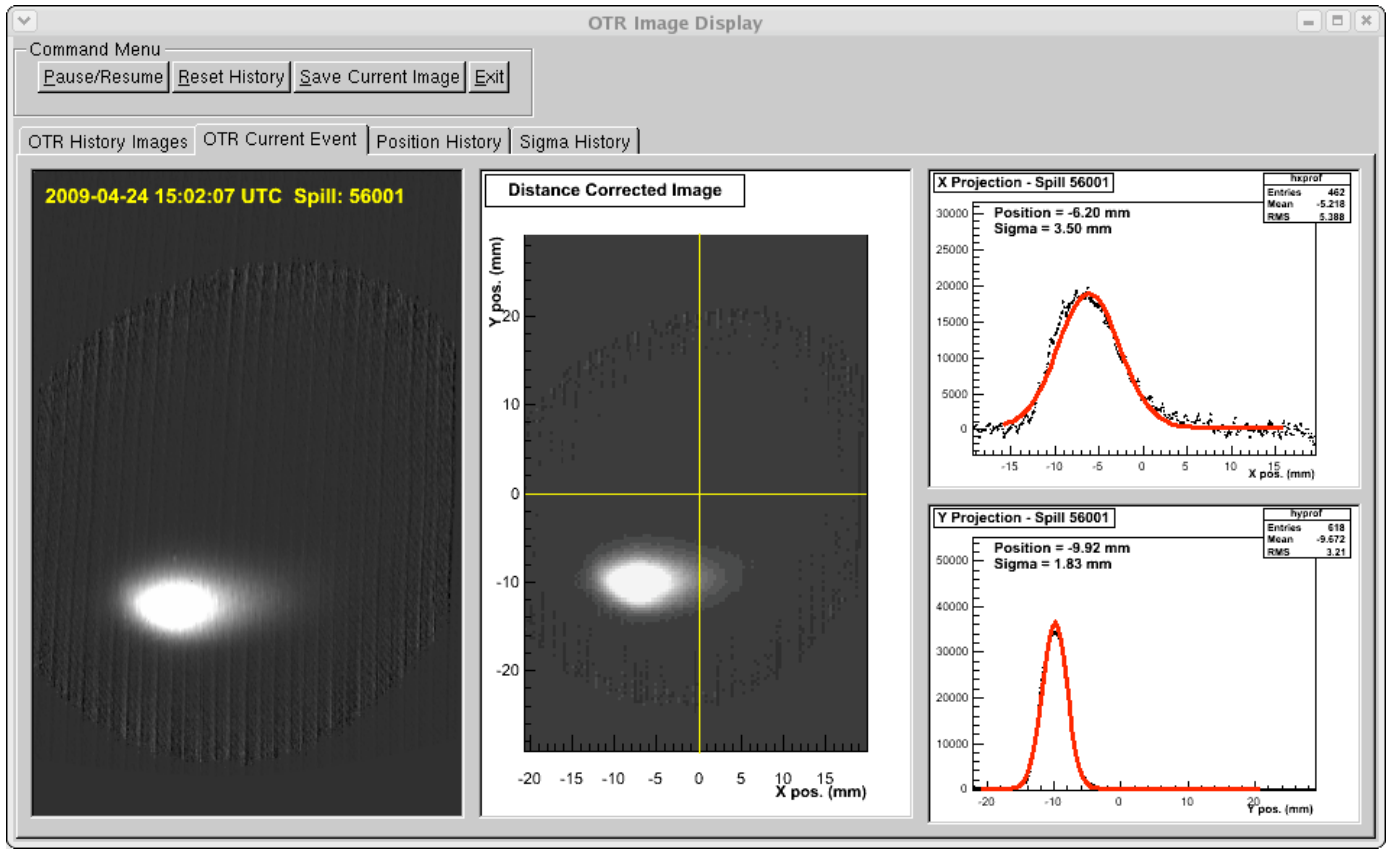
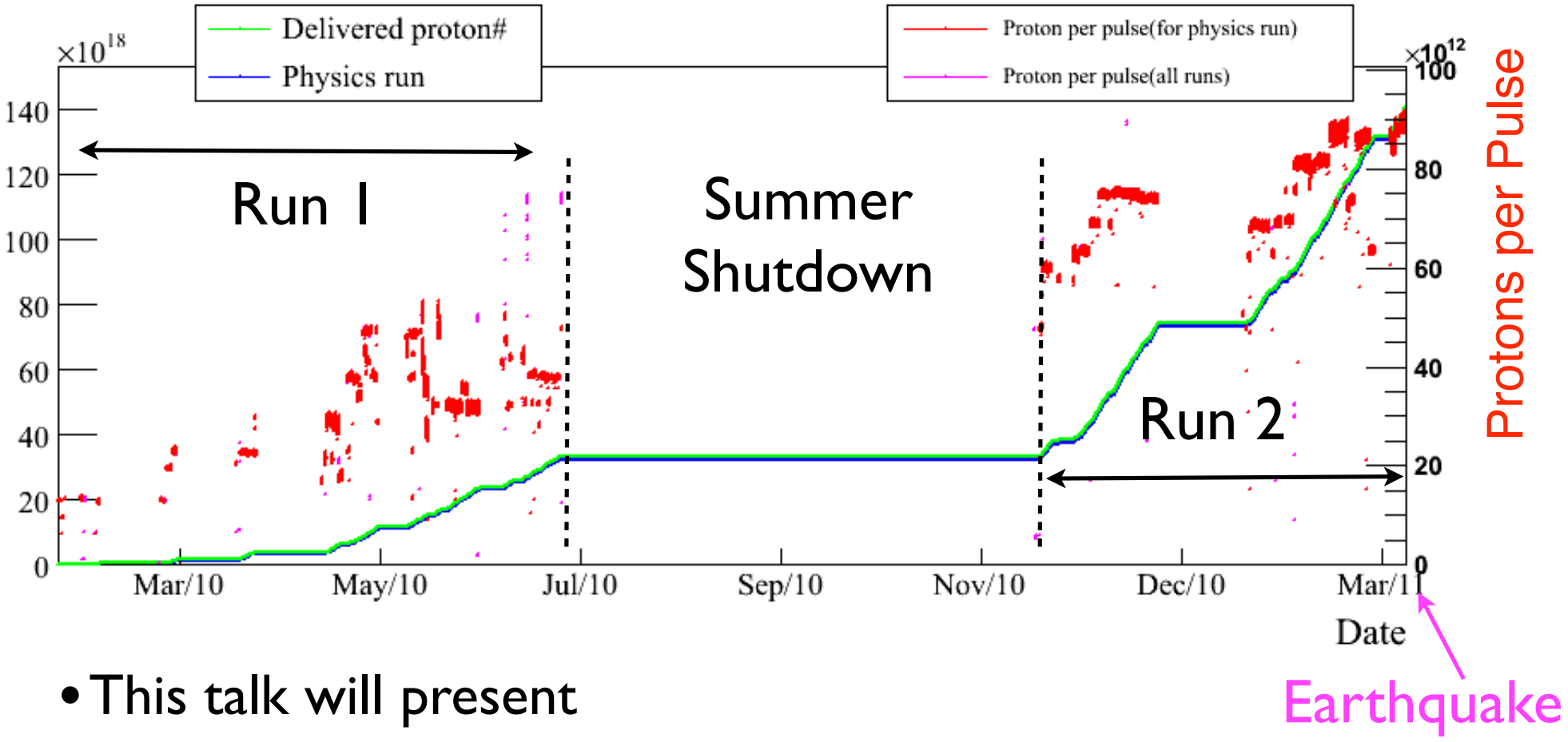


Image in proton beam position monitor 30 cm before target

Beam Delivered to Date



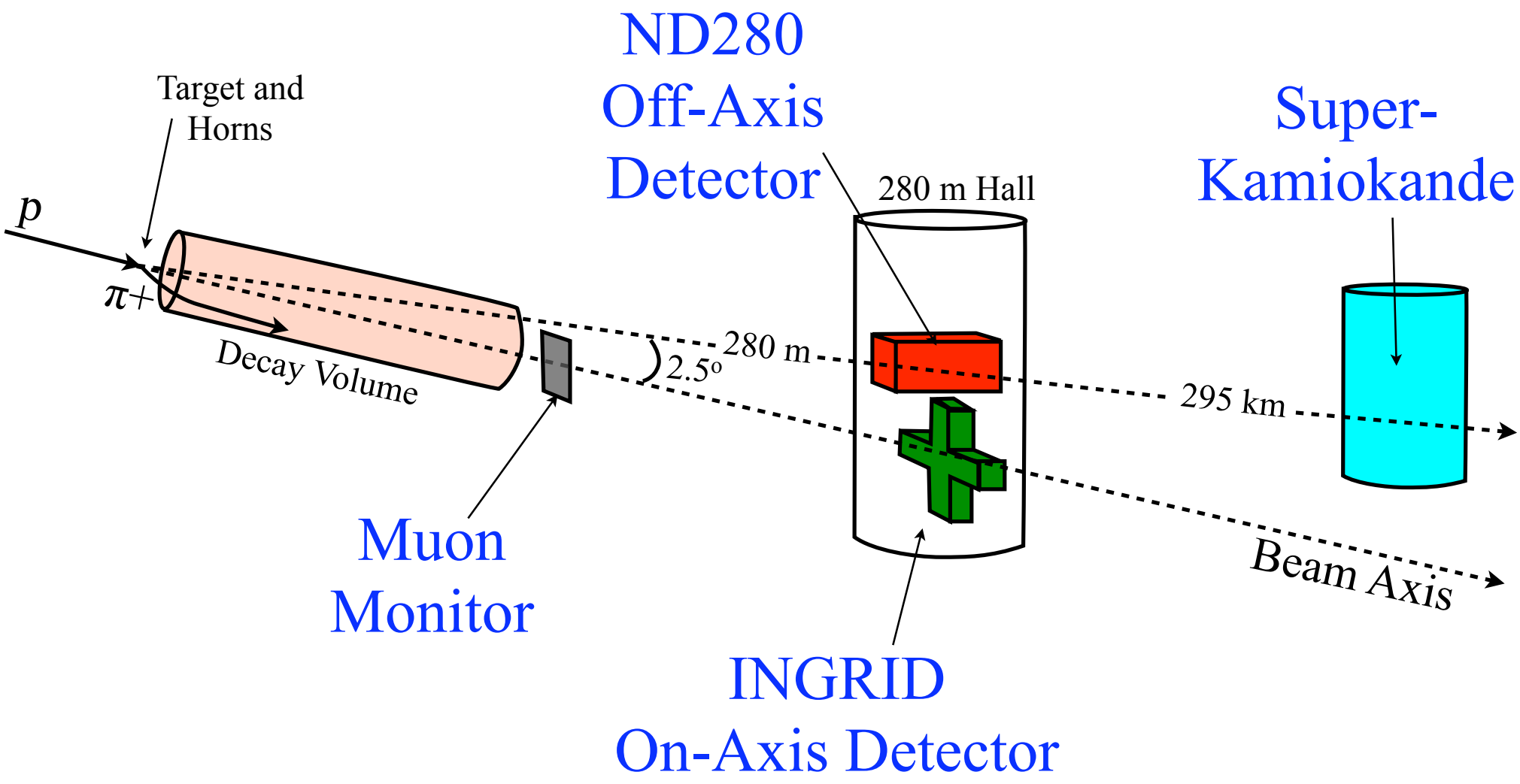
- This talk will present
  - ν_μ results for Run 1 data
  - ν_e results for Run 1+2 data
- Total protons on target delivered for analysis = 1.43×10^{20}, 2% of T2K's final goal

Japanese Earthquake and Tsunami

- Super-Kamiokande was not damaged by the earthquake
- No tsunami damage at J-PARC, but there has been some earthquake damage to the roads, utilities and buildings on site.
- All indications are that the **damage is repairable**.
- Latest recovery schedule aims to restart the beam by the **end of 2011**

T2K Near Detectors

T2K Detectors



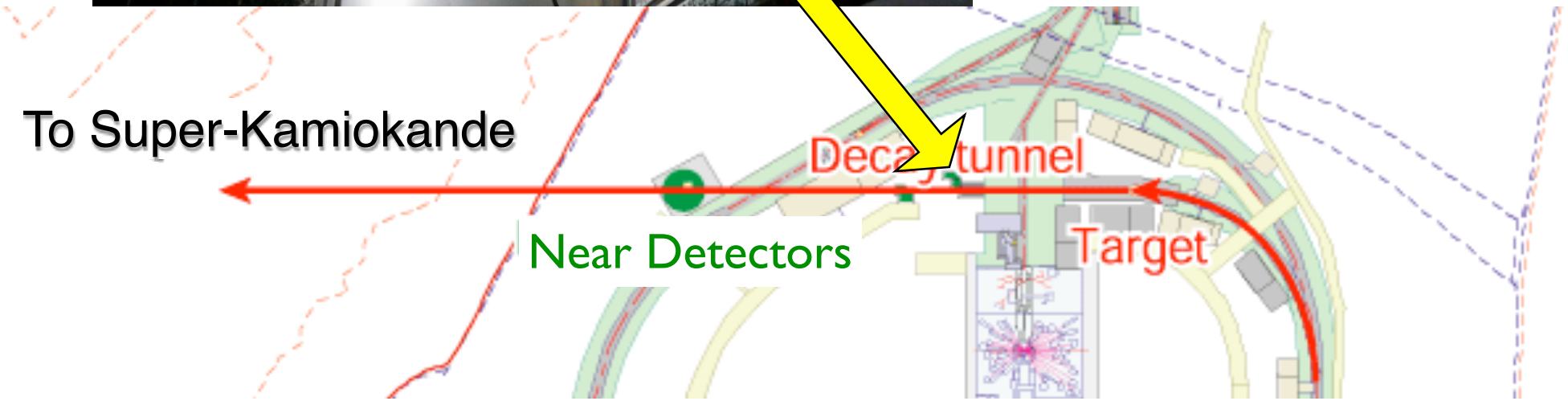
Not to scale!

MUMON - Muon Monitor

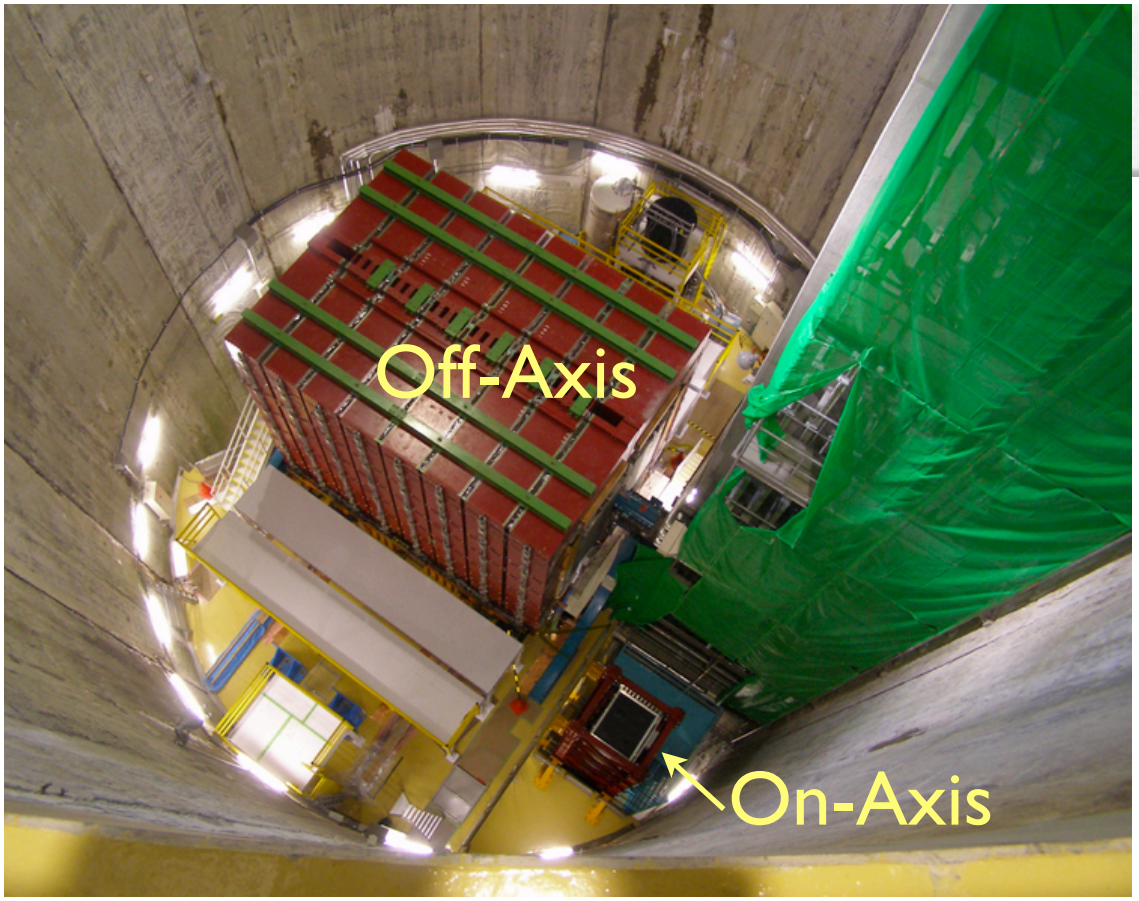
Ionization chambers

Si PIN Photo diodes

- Muon monitor is located just after the beam dump
- Measures direction and intensity of beam

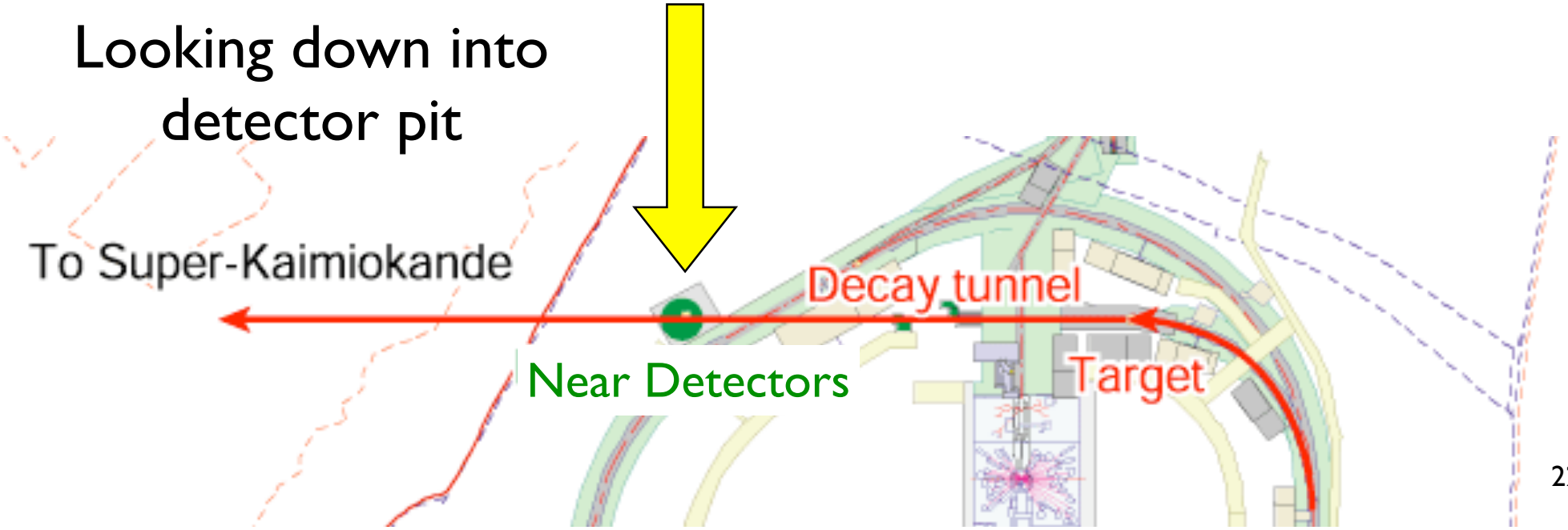


Detector Hall



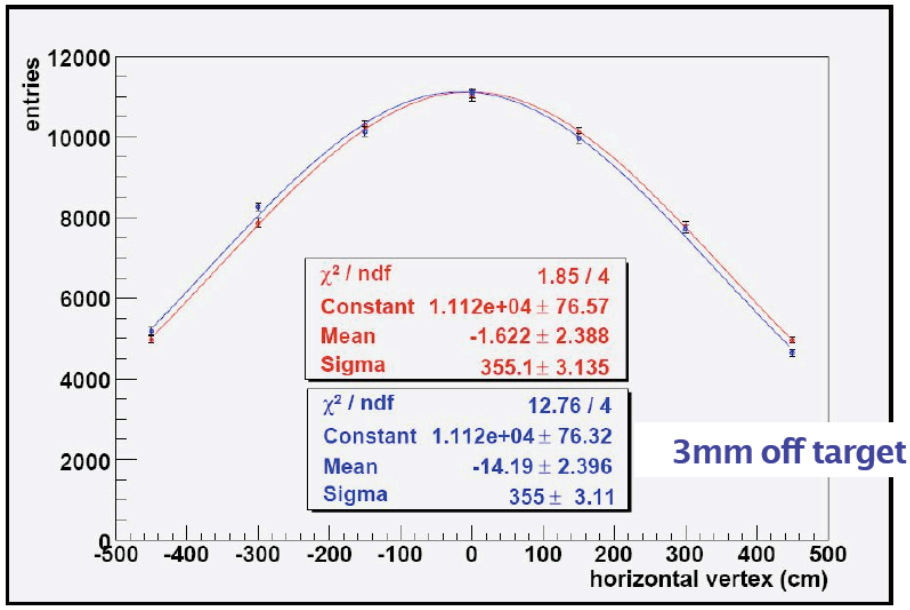
- Cylindrical cavity, 36 m deep, 19 m diameter
- Houses an off-axis and on-axis detector
- Detectors installed in late 2009

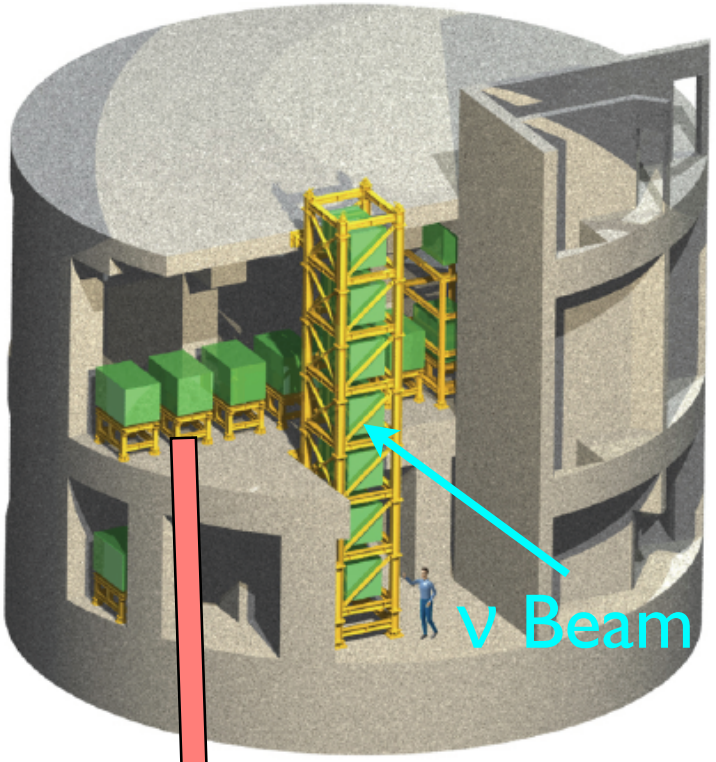
Looking down into detector pit

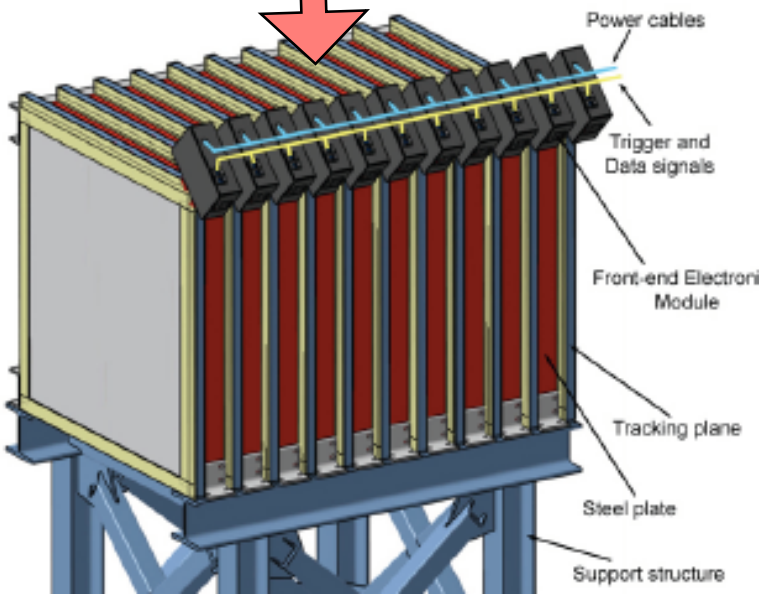


INGRID: On-Axis Near Detector

- 280 m from target
- 16 modules in a cross shape
- Modules have alternating steel and scintillator layers
- Comparing # tracks seen in each module gives the center of the ν beam

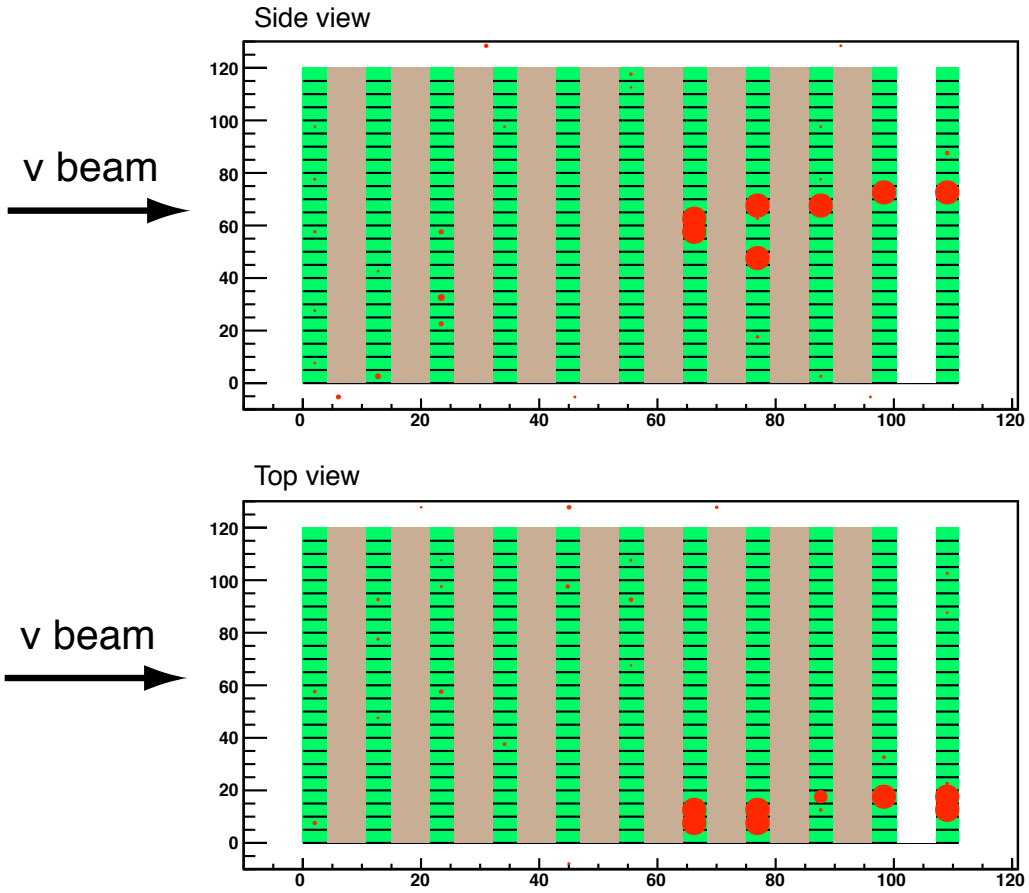


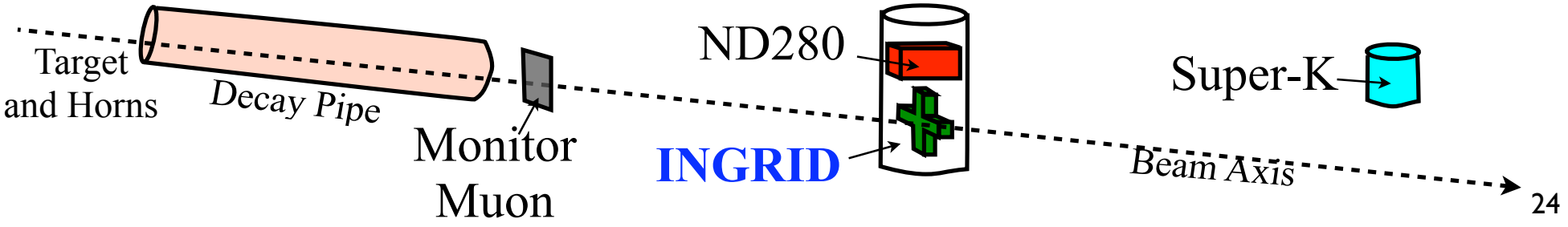




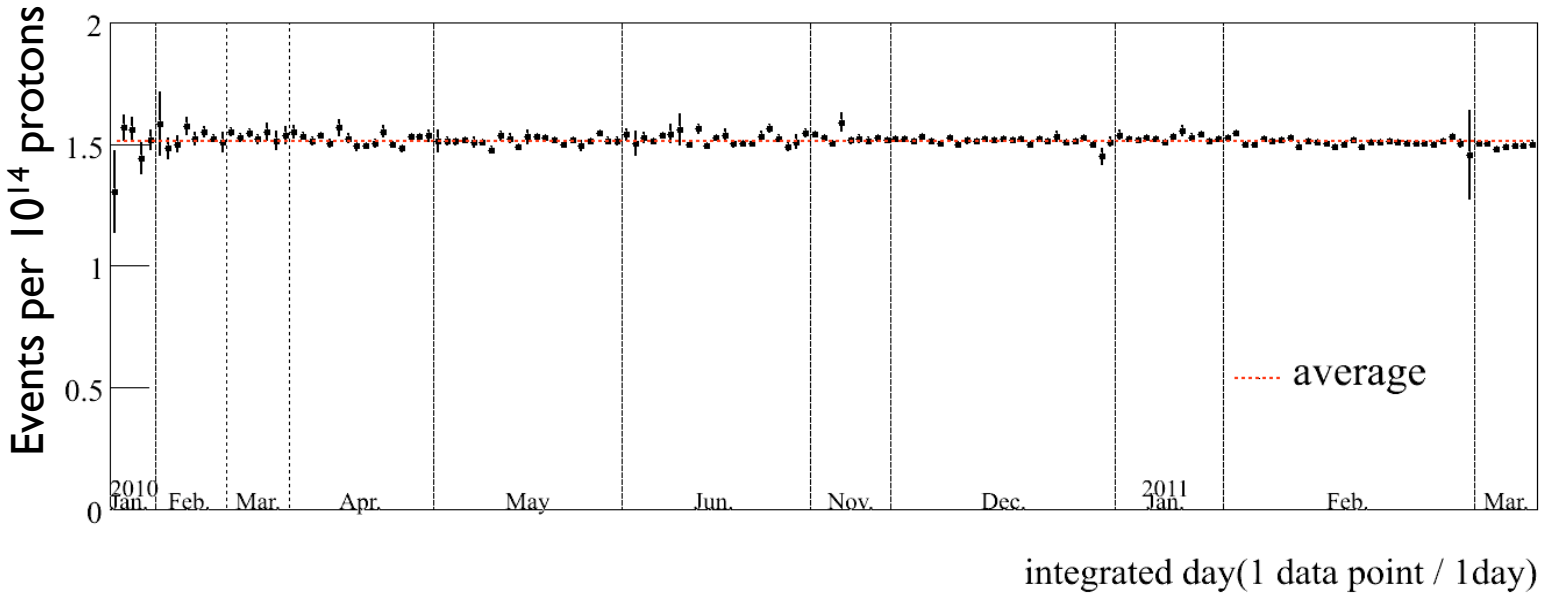
First Event in INGRID

Nov. 22, 2009

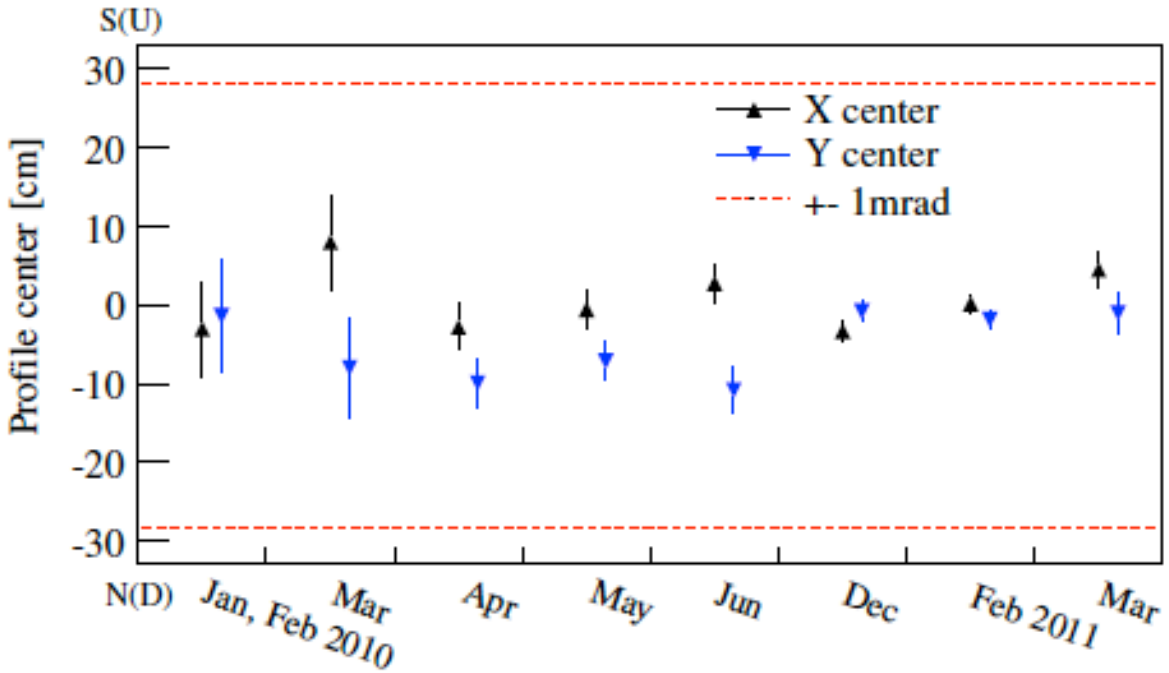




INGRID Stability

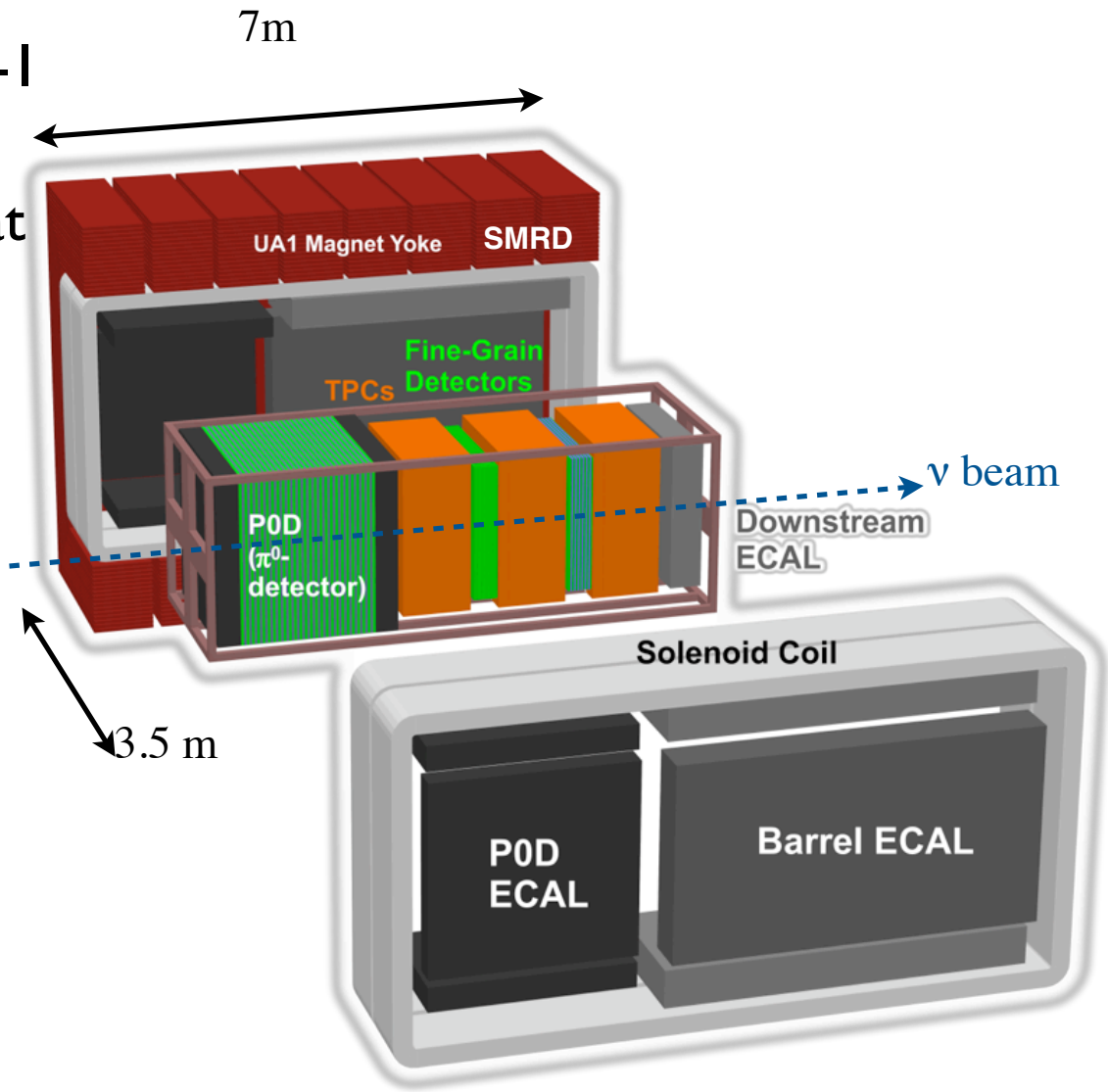


- Beam event rates and directions are stable over the entire run

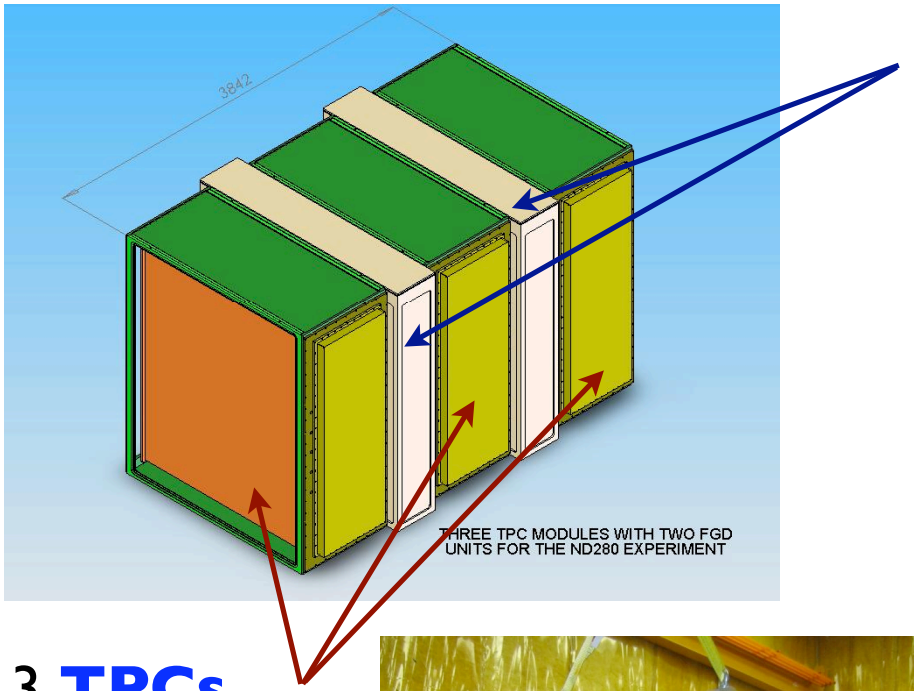


ND280: Off-Axis Near Detector

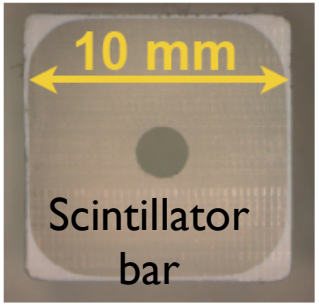
- Fully installed
- Everything is inside the 0.2 T UA-1 magnet
- ~ 10,000 ν interactions per day at full beam power
- Tracker
  - Distinguishes particles due to dE/dx
  - Uses track curvature to determine momenta
- Pi-Zero Detector
  - Optimized to measure π^0 production
- ECAL
  - Catches γ's that have not interacted elsewhere in the detector
- Side Muon Range Detector
  - Measures momenta of lateral muons
  - Muon trigger for calibration purposes



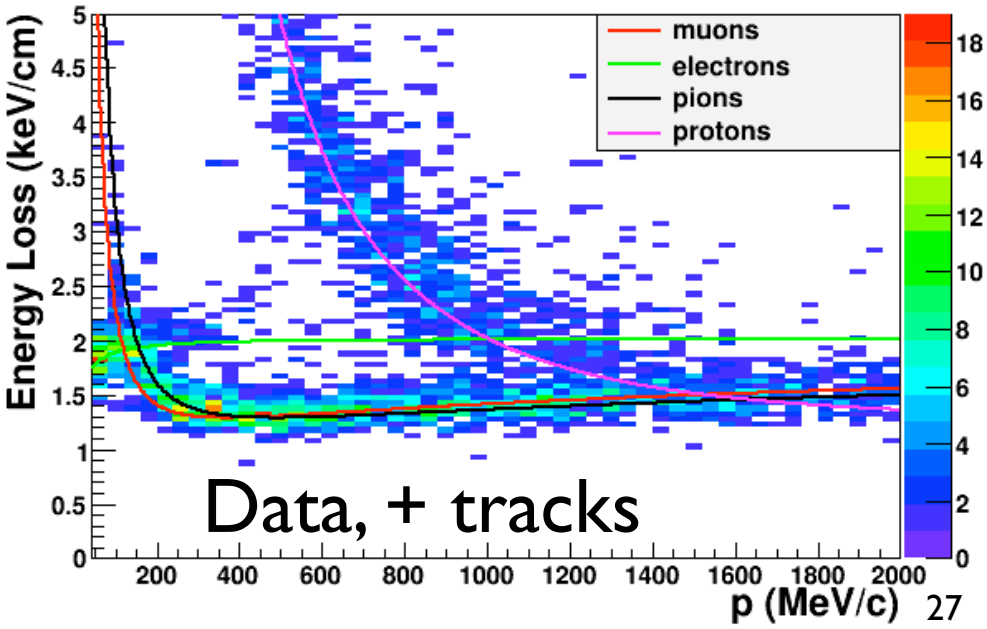
ND280 Tracker



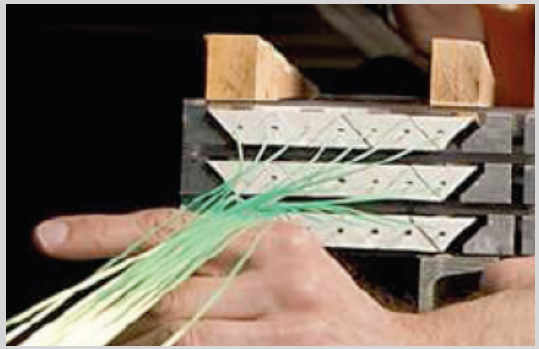
- 2 **Fine Grained Detectors**
- 1 cm square scintillator bars
- Fiber running through the bar is coupled to Si PM



- 3 **TPCs**
- Read out with MicroMegas detectors with 0.7mmx1mm pads



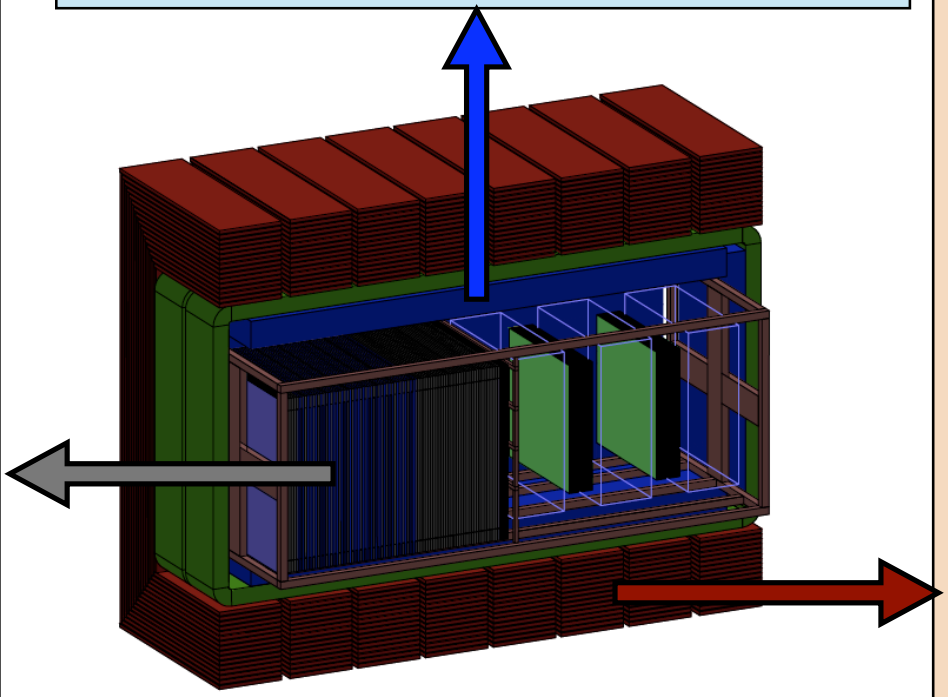
ND280 P0D + ECAL + SMRD

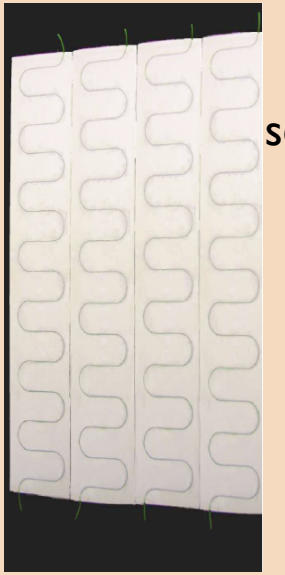


P0D scintillator

P0D at J-PARC

ECAL assembly at Lancaster

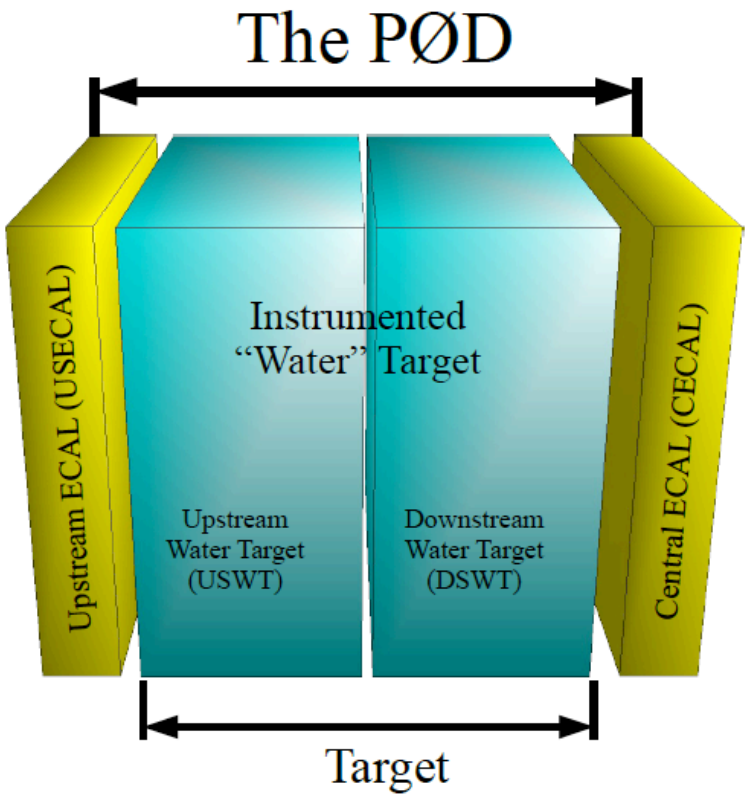




SMRD scintillator planks

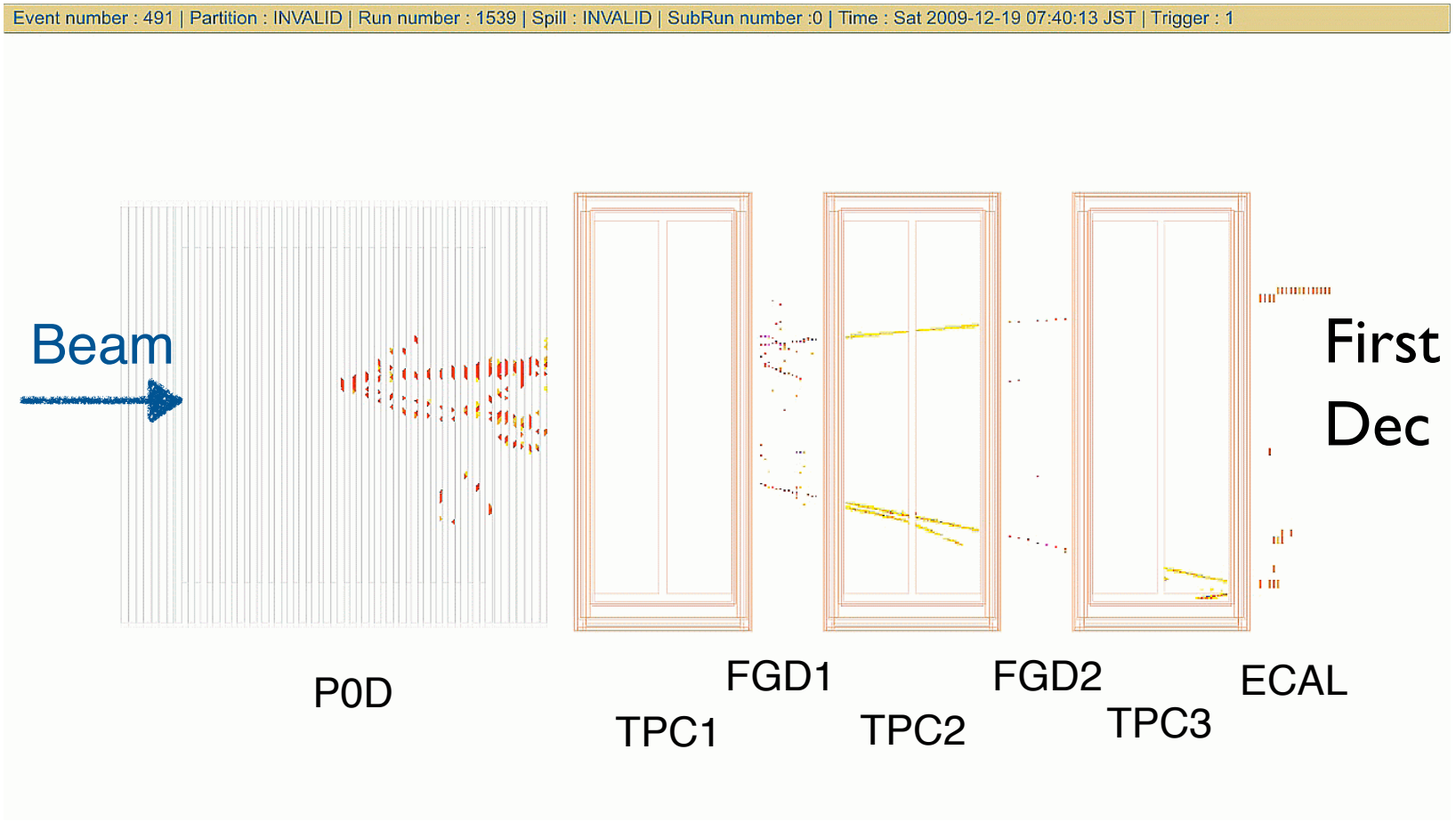
SMRD installation

Water Targets

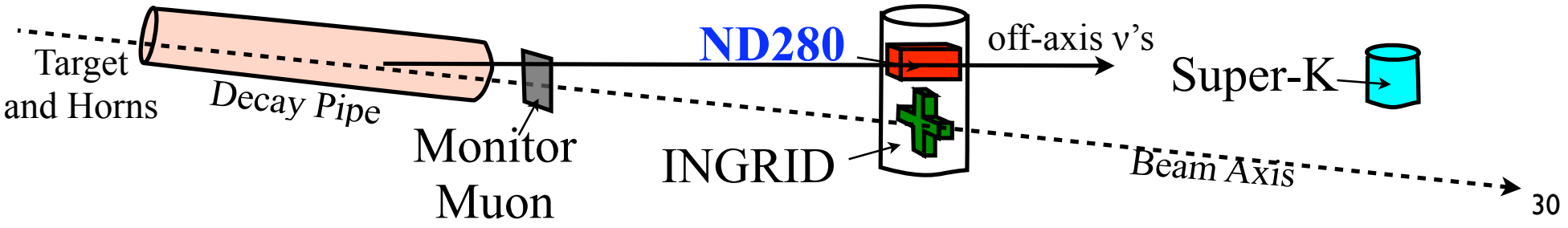


- POD: 25 "bladders" that can be filled with 2 tonnes of H_2O are interspersed inside P0D. Will take data with and without H_2O
- FGD: One of the FGD modules has polycarbonate panels filled with H_2O. Will compare rates in two FGDs.

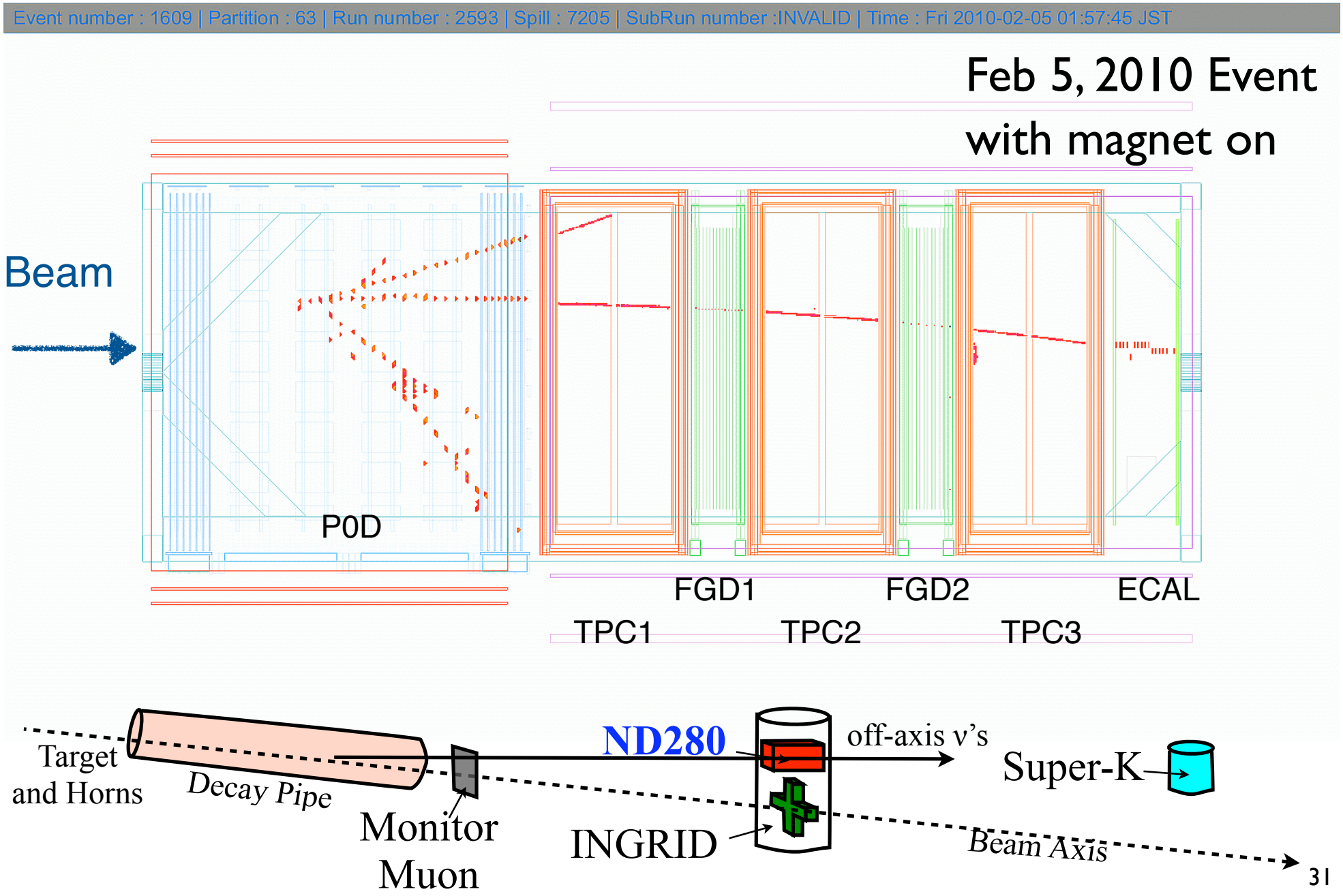
First Event in ND280



First Beam Event
Dec 19, 2009



Another ND280 Event



Neutrino Signals

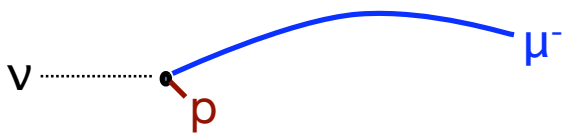
- **Golden mode**: Charged-Current Quasi Elastic (CCQE)

$$\nu_l + n \rightarrow p + l^-$$

- Flavor of l^- is the ν flavor
- Energy and θ of l^- give a good measurement of the ν energy

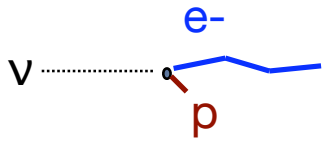
ν_μ signal

$$\nu_\mu + n \rightarrow p + \mu^-$$



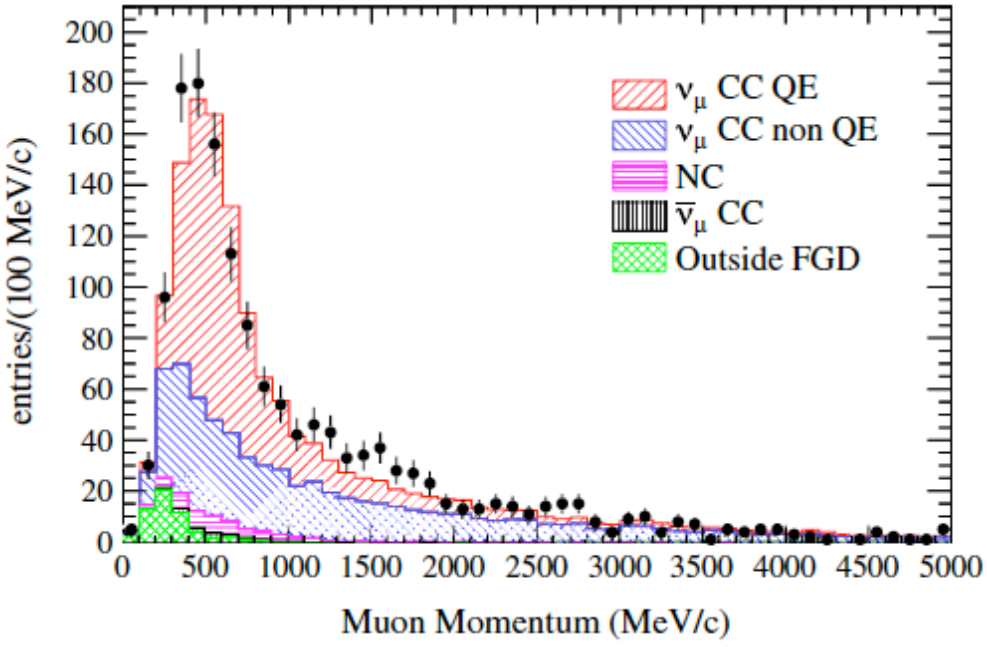
ν_e signal

$$\nu_e + n \rightarrow p + e^-$$



ν_μ CC Events in ND280

- Selection
  - Vertex in FGD fiducial volume
  - At least one negative muon-like track in the TPC
  - No track in upstream TPC
- Muon momentum distribution agrees well with Monte Carlo
- 1529 events / 2.9 x10^{19} p.o.t.

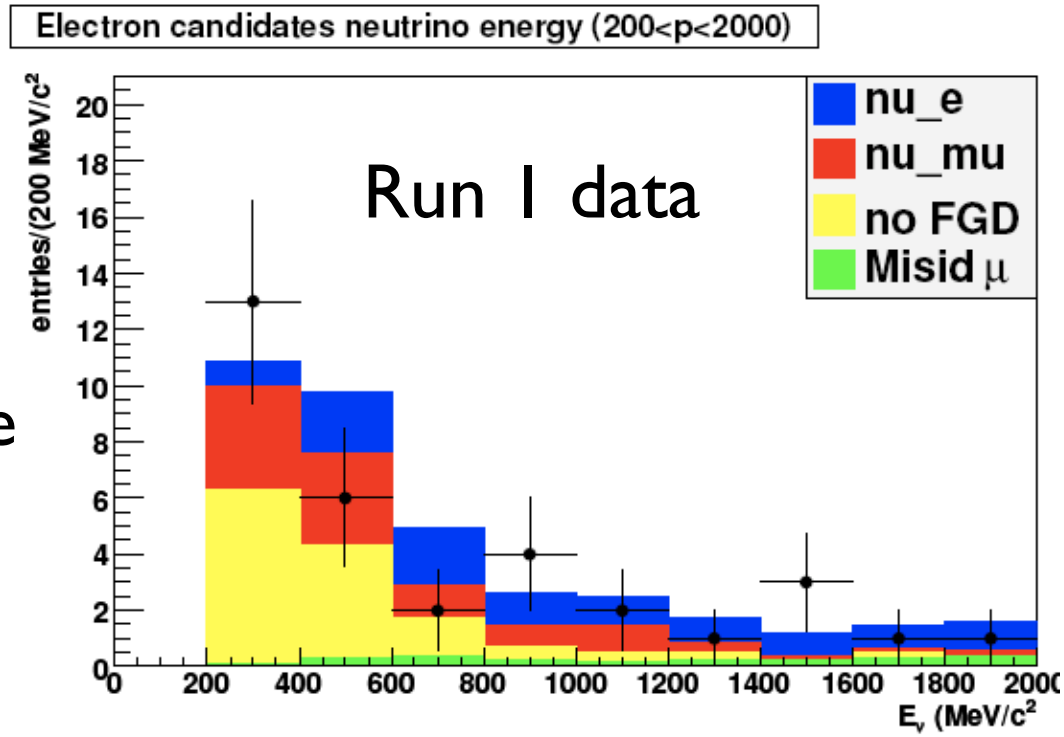


Run 1 data

$$\frac{R_{ND}^{\mu\,Data}}{R_{ND}^{\mu\,MC}} = 1.036 \pm 0.028(stat.) \pm^{0.044}_{0.037} (det.syst.) \pm 0.038(phys.model)$$

ν_e CC Events in ND280

- Selection
  - Vertex in FGD fiducial vol
  - No track in upstream TPC
  - Highest momentum track is negative and has electron-like in PID in TPC
  - If 2 track event, M_{inv} < 100
  - 0<p<2000 MeV



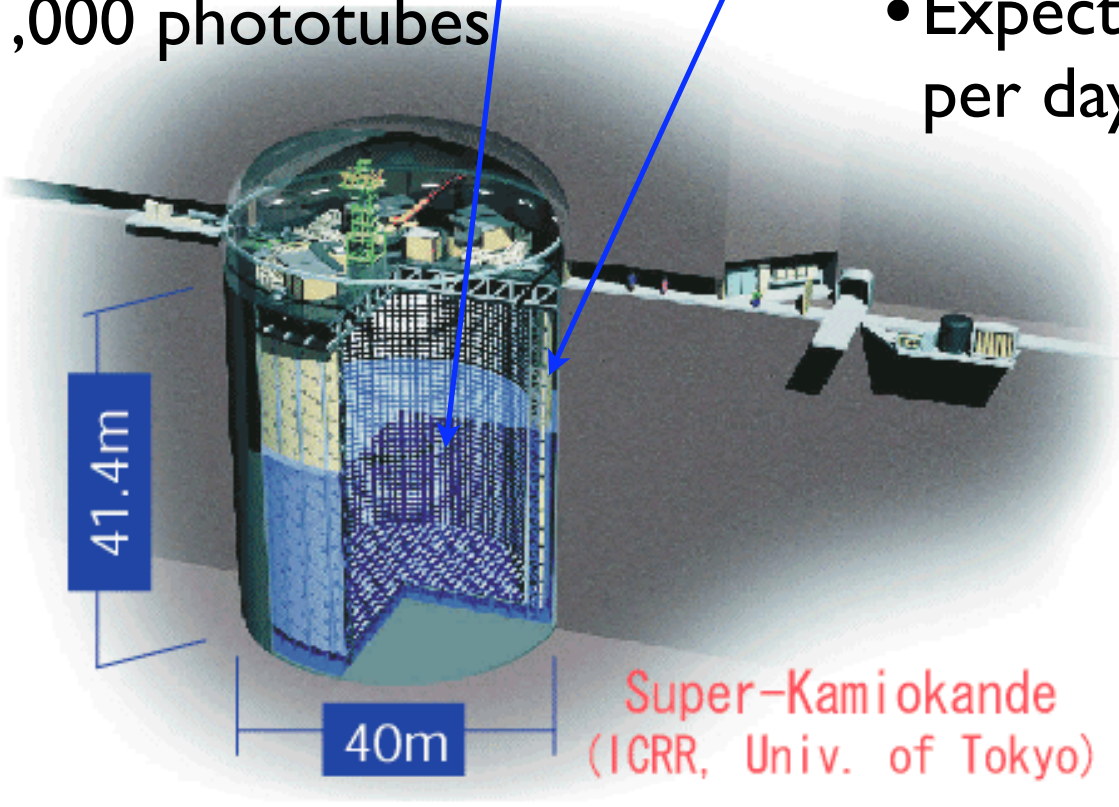
- Max likelihood fits gives
  - ~8 ν_e events/2x10^{19} protons
  - $(\nu_e/\nu_\mu)_{Data}$ = 1±0.7(stat.)±0.3(syst.)%

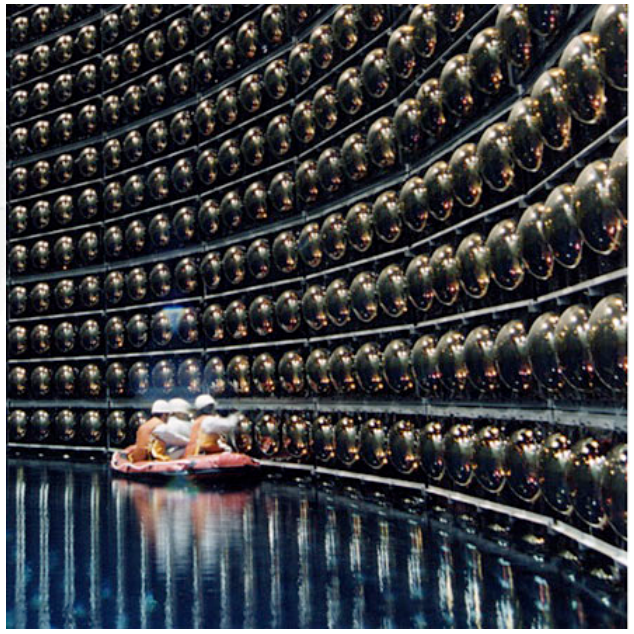
$$\frac{(\frac{N_{\nu_e}}{N_{\nu_\mu}})_{Data}}{(\frac{N_{\nu_e}}{N_{\nu_\mu}})_{MC}} = 0.6 \pm 0.4(stat.) \pm 0.2(syst.)$$

T2K Far Detector: Super-Kamiokande

Super-Kamiokande: Far Detector

- Began data taking in 1996
- Large volume water Cerenkov detector
- 50 kton of pure H_2O (22.5 kton fiducial volume)
- 11,000 phototubes
- Outer layer with 1885 phototubes to reject external events
- Use GPS to synch events to the beam time
- Expect a handful of events per day at full beam power.

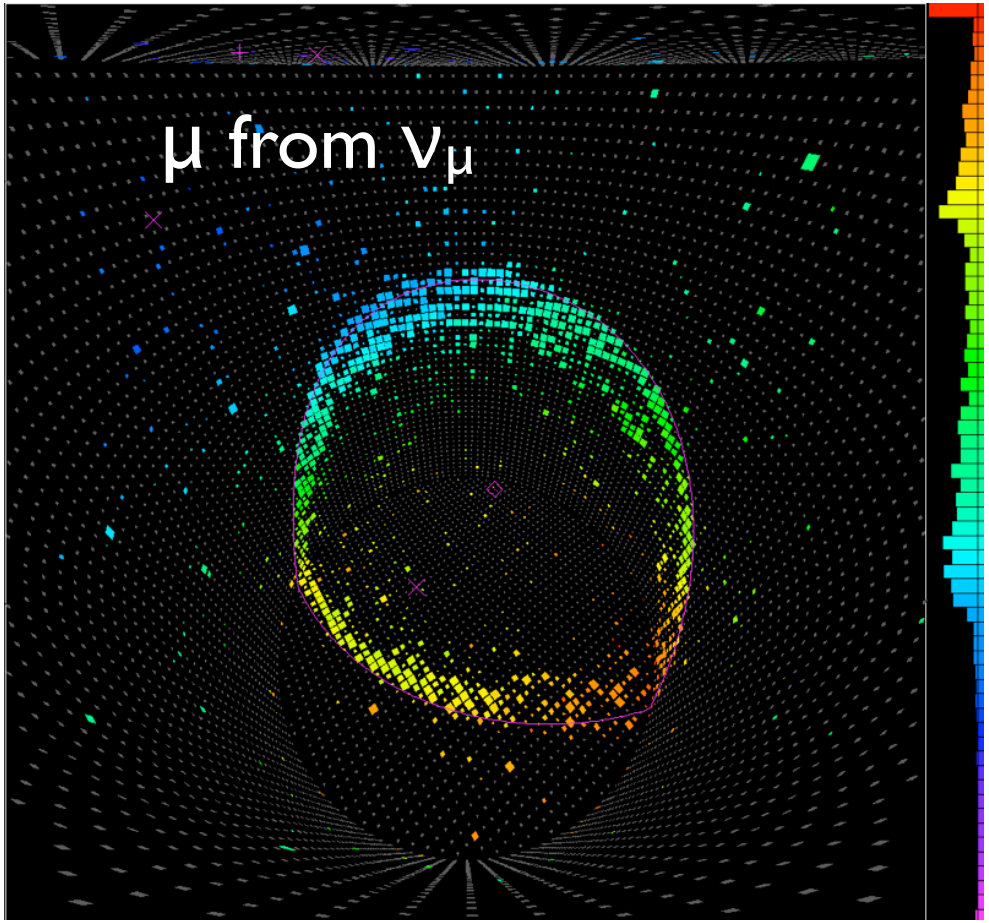


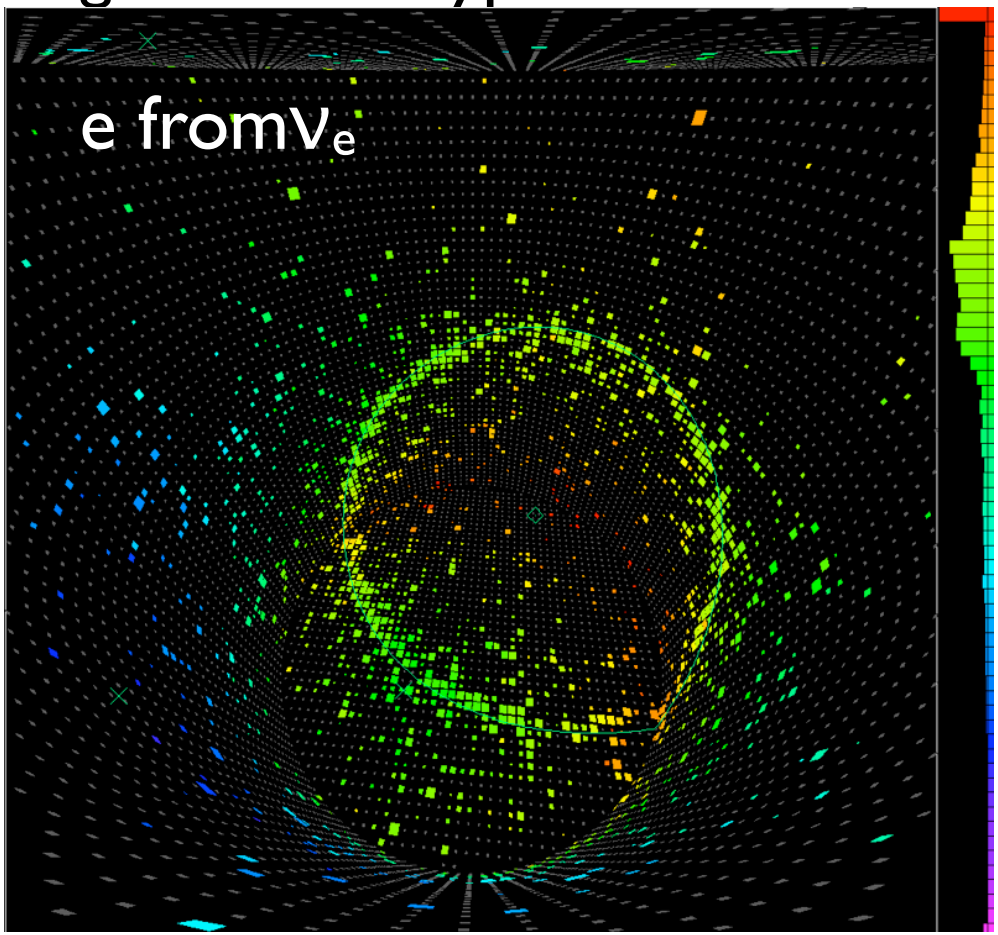


Neutrino Events

- Rings of Cerenkov light
- μ's produce a sharp ring
- e's produce a fuzzy ring
- π_0 produce 2 fuzzy rings
- Use pattern recognition to distinguish event types

2 MC events

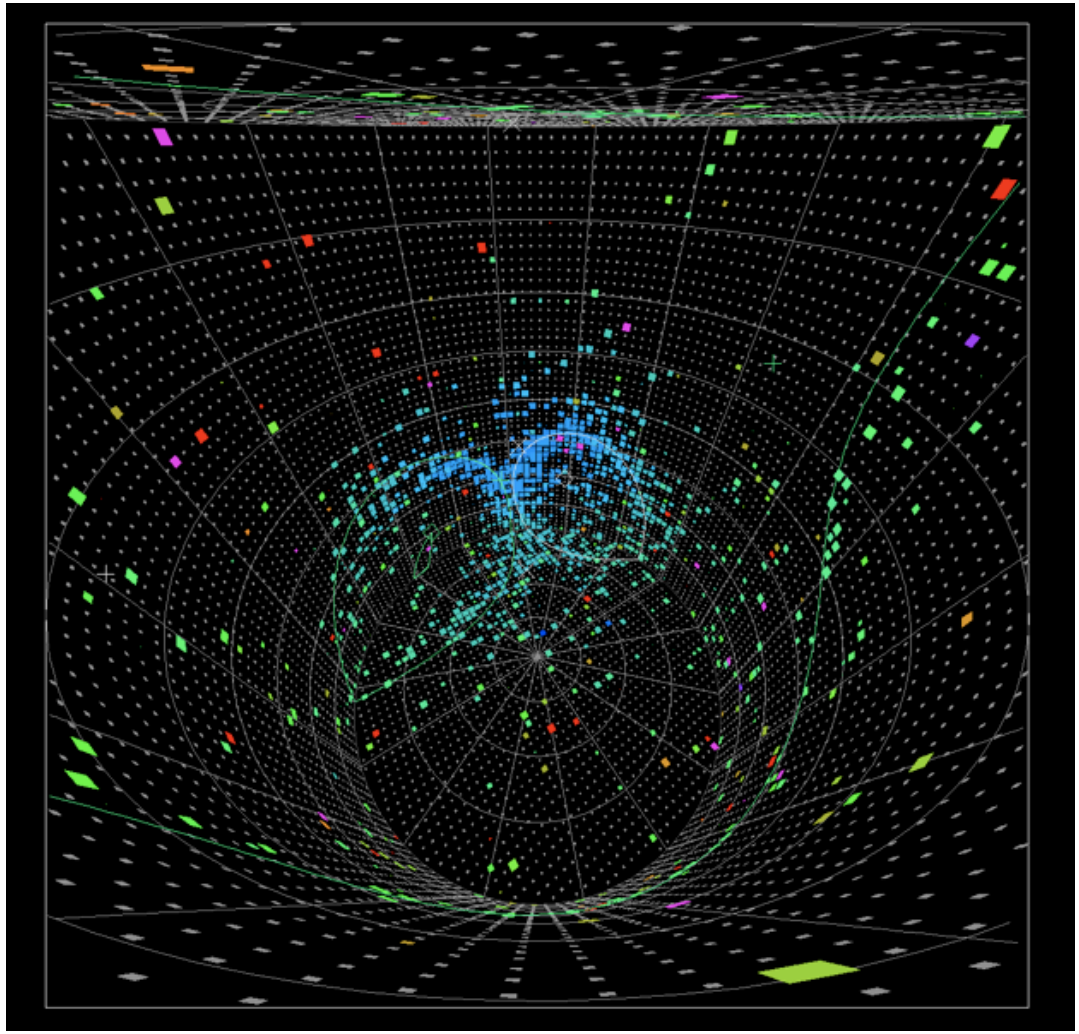


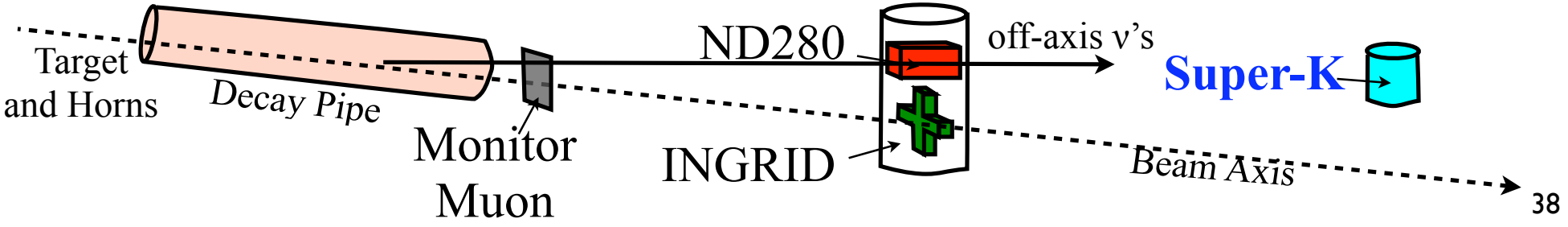


First T2K Beam Event in Super-K

Feb 24, 2010

- Fully contained event
- 3 rings
- Invariant mass of two most prominent rings is 133 MeV
- Visible energy 230 MeV

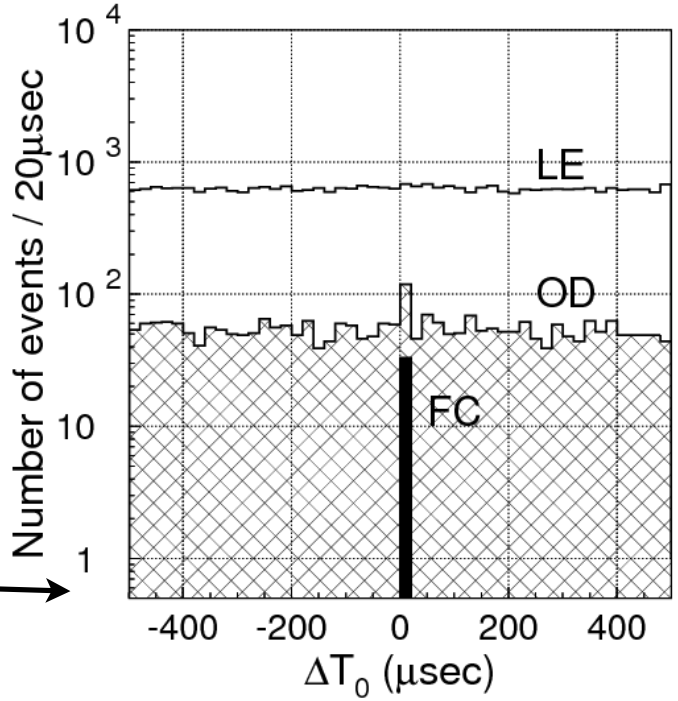


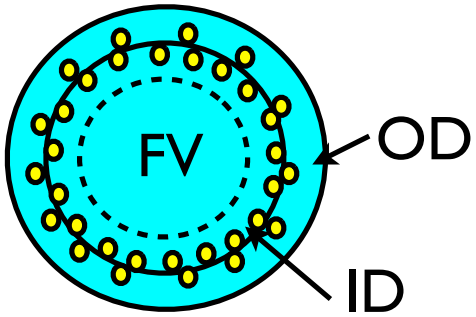


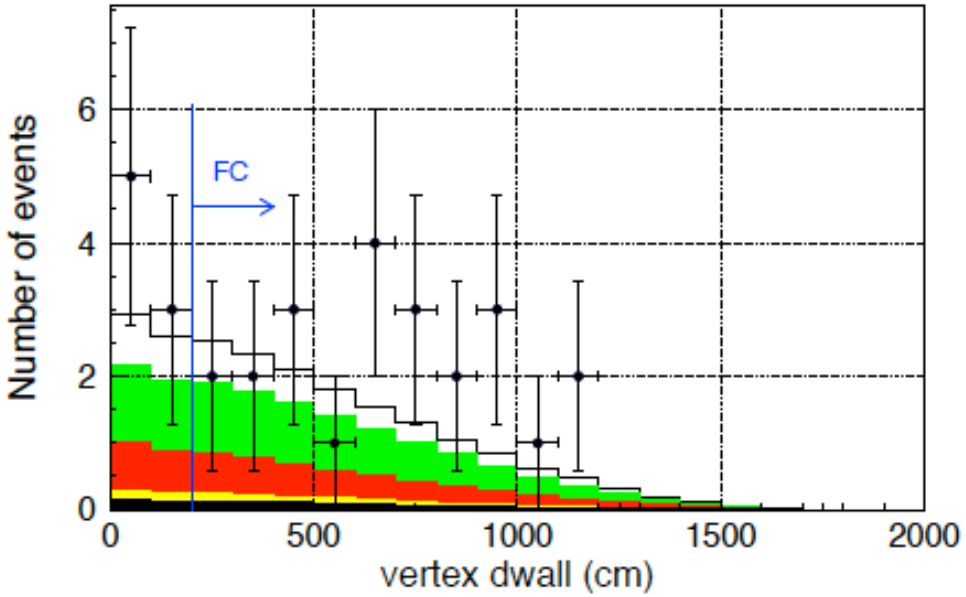
ν_μ Disappearance Results for Run 1 3.23×10^{19} p.o.t.s

ν_μ Event Selection

- Sample of fully contained mu-like single ring events
- Selection cuts
  1. Coincident with beam time
  2. <16 hits in outer detector
  3. vertex>200 cm from inner detector walls

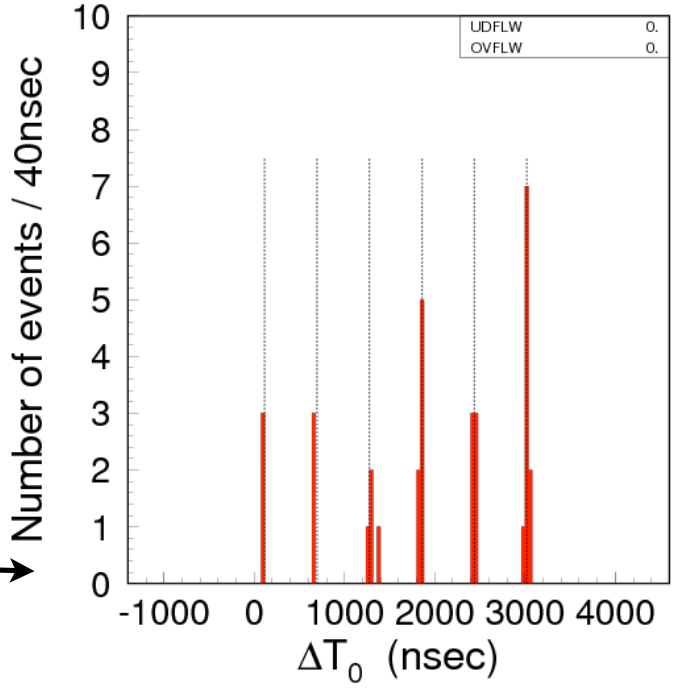


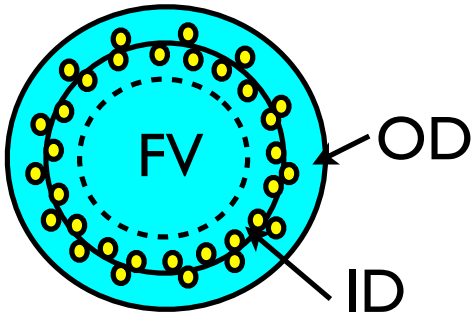


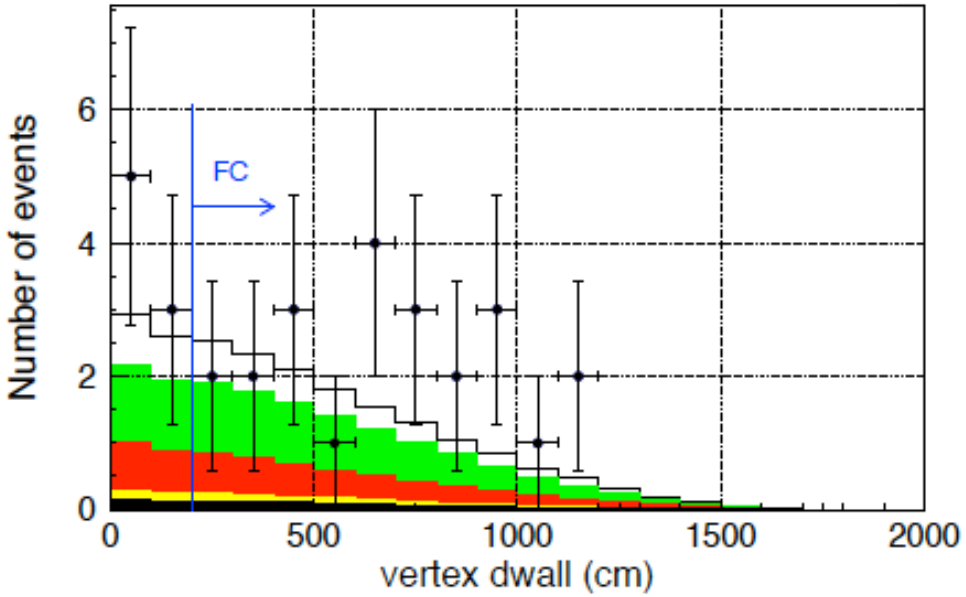


ν_μ Event Selection

- Sample of fully contained mu-like single ring events
- Selection cuts
  1. Coincident with beam time
  2. <16 hits in outer detector
  3. vertex>200 cm from inner detector walls

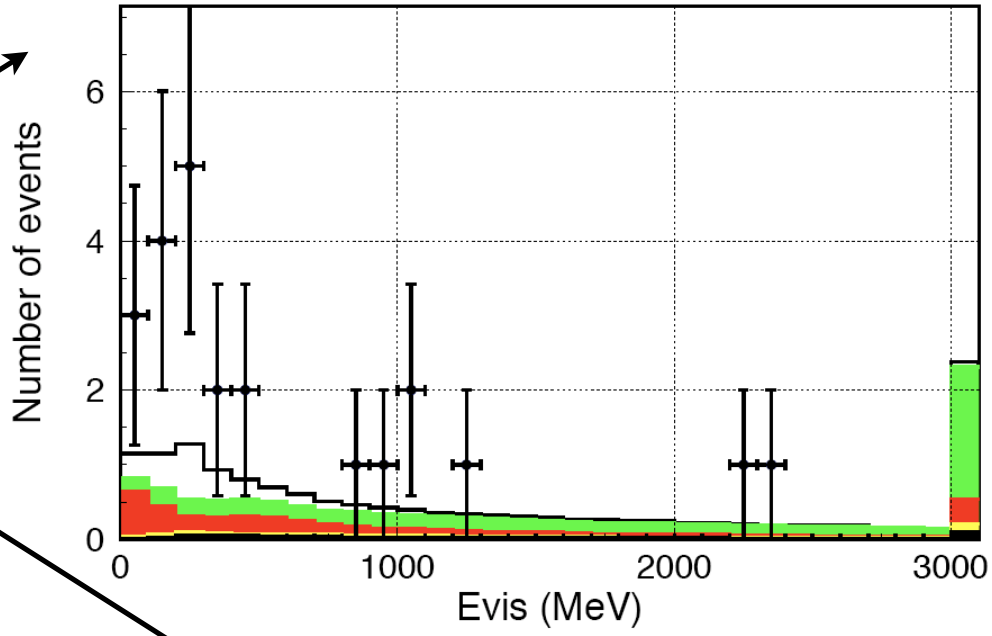


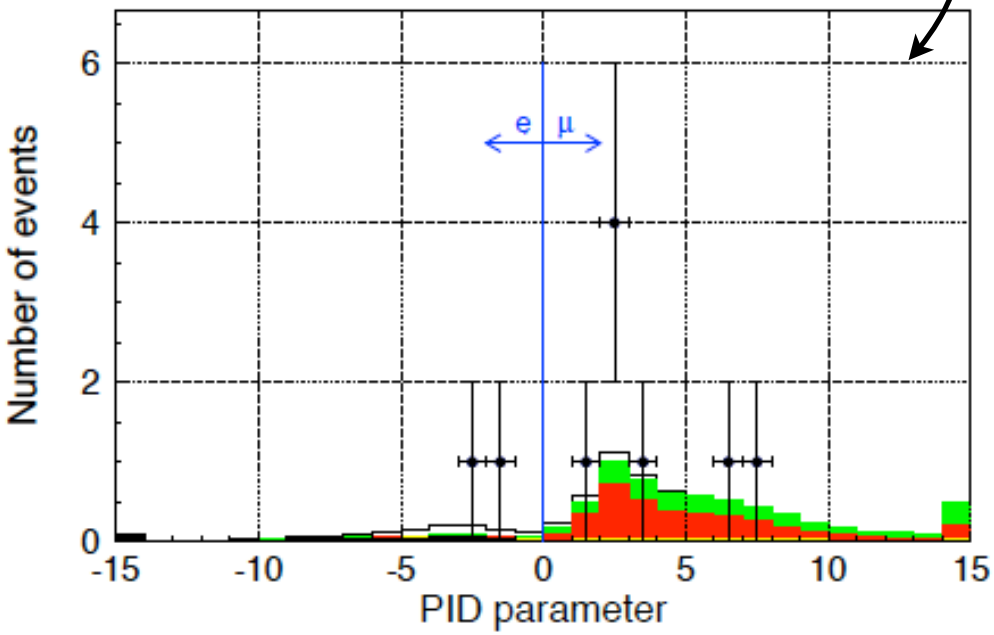


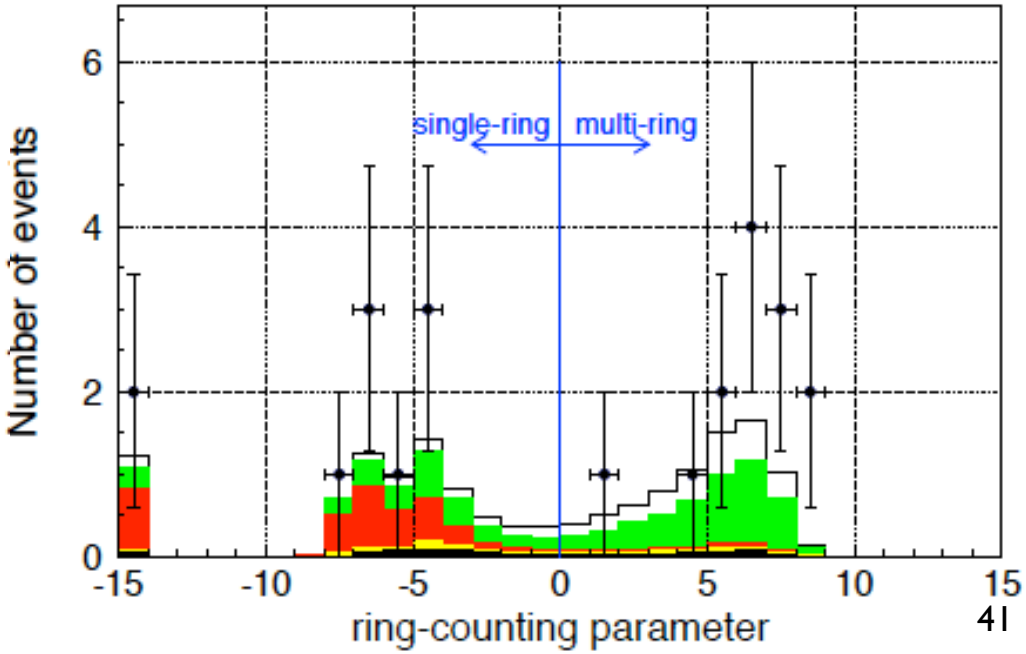


ν_μ Event Selection (cont.)

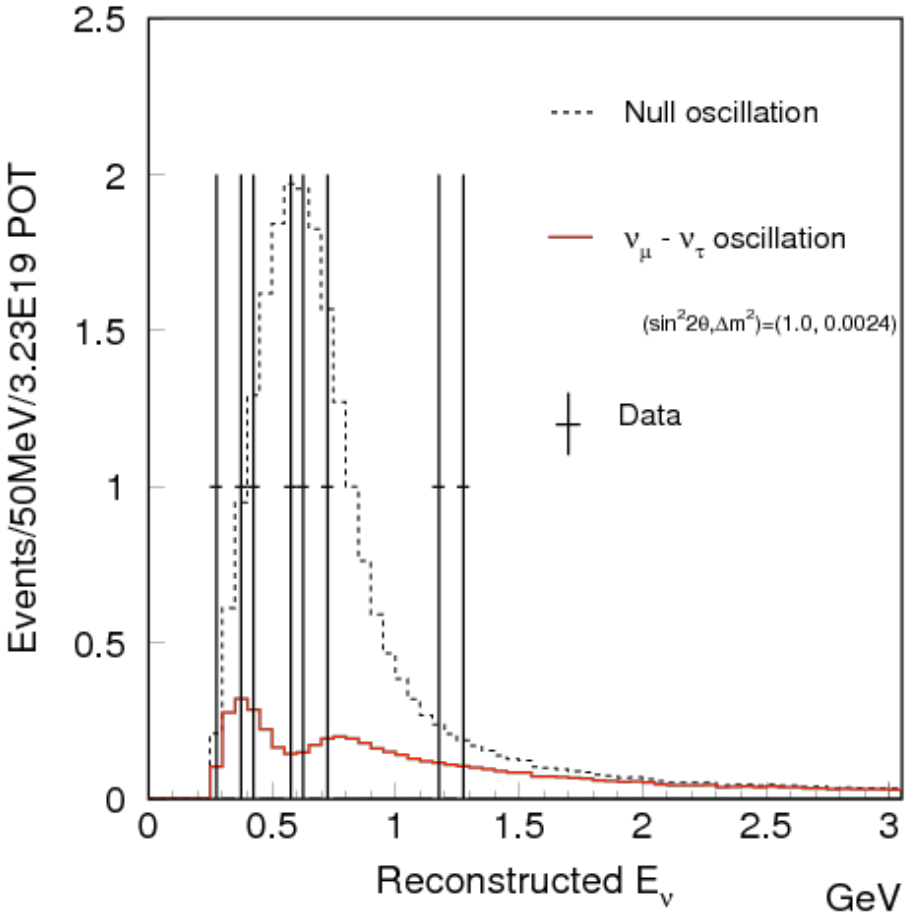
- Selection cuts (cont.)
  4. Visible energy > 30 MeV
  5. single ring
  6. μ-like ring
- **8 events remain**
- Expected 22.81±3.19(syst.) without oscillations

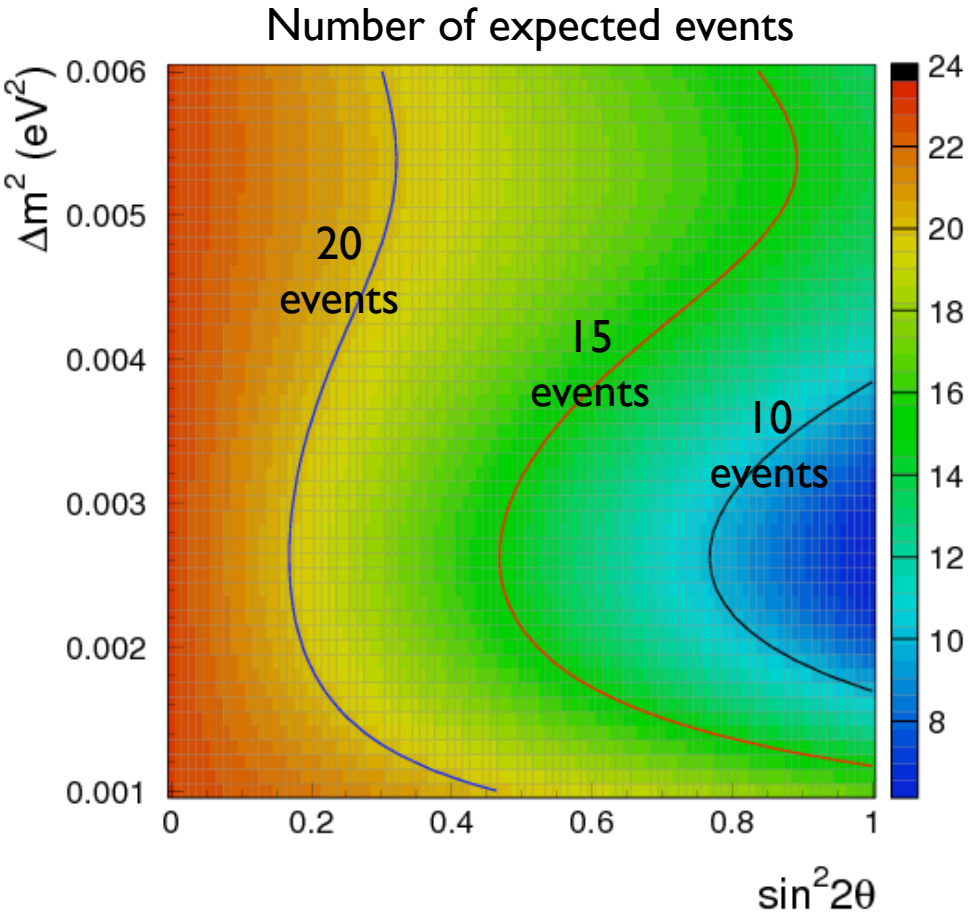






Oscillation Parameters





- In Run 1, observed 8 events
- For $\sin^2 2\theta_{23}=1.0$, $\Delta m_{23}^2=0.0024$ eV^2 expected 6.34±1.04(syst.) events
- Updated results for Run1+2 data will be public later this week

ν_e Appearance Results for Run 1+2 1.43×10^{20} p.o.t.s

(Accepted for Publication in PRL)

Eventual analysis strategy

- Predict **neutrino fluxes** using:
  - Beam MC
  - Hadron production measurements from CERN NA61

- **Near detecto**r analysis:
  - Detector MC using Neut (or Genie) generator
  - Measure beam flux × cross section at near detector for both ν_μ and ν_e
  - Compare to prediction

- Propagate near detector constraint to far detector using data/MC ratio and near→far **flux transfer function** developed from beam MC:
  - Predict event rates and spectra at Super-Kamiokande

- **Far detector** analysis:
  - Super-K detector MC using Neut (or Genie) generator
  - Measure event rates, spectra
  - Compare to unoscillated prediction→fit results to oscillation hypotheses

Run 1+2 ν_e appearance analysis strategy

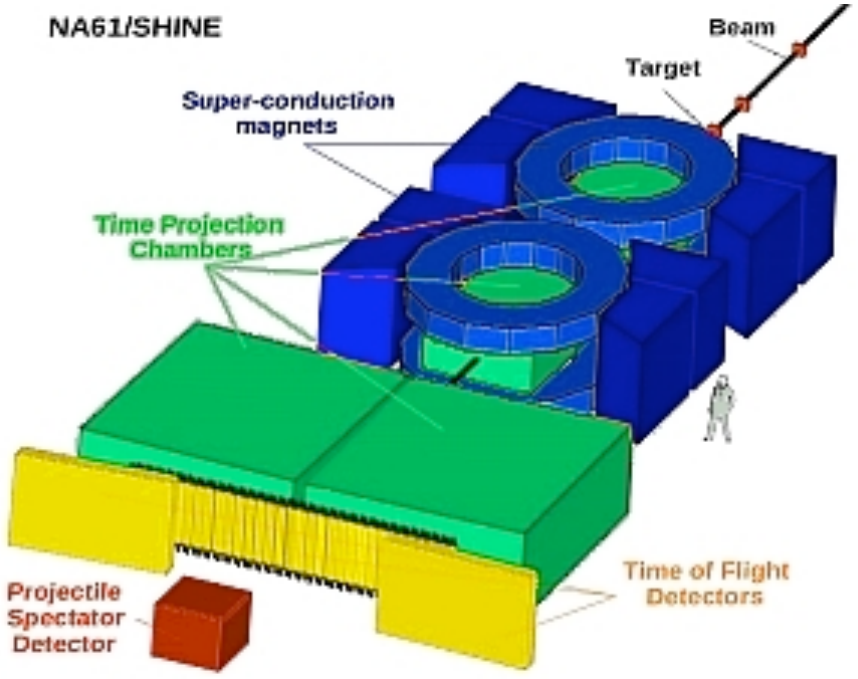
- Predict **neutrino fluxes** using:
  - Beam MC
  - Hadron production measurements from CERN NA61

- **Near detector** analysis:
  - Detector MC using Neut (or Genie) generator
  - **Inclusive** charged-current event selection; no energy cut

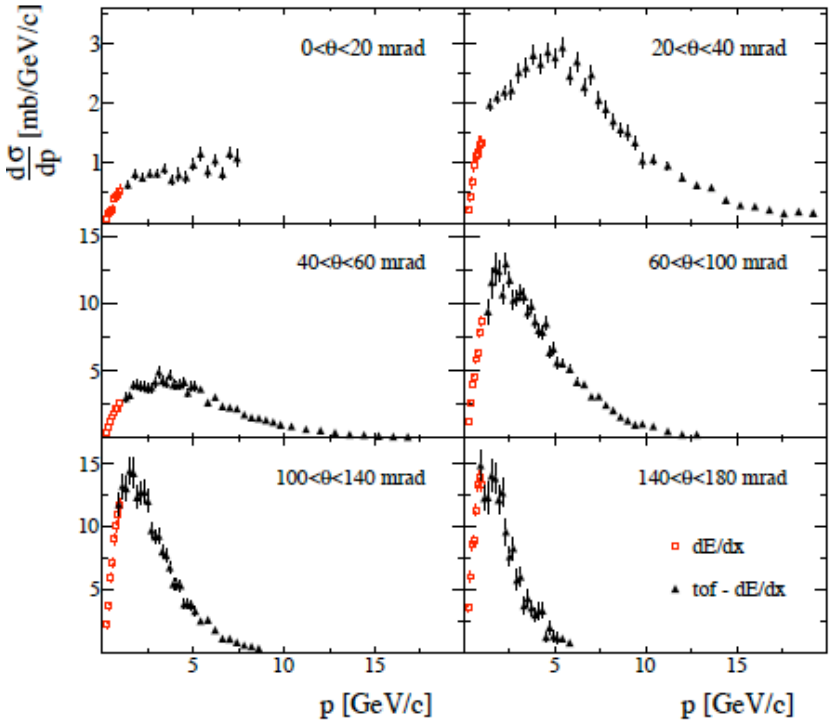
- Predict flux at Super-K using beam MC
- Reweight by near detector **Data/ MC ratio** for inclusive sample (no energy dependence)

- **Far detector** analysis:
  - Super-K detector MC using Neut (or Genie) generator
  - **Count events** that pass appearance cuts
  - Compare this number to oscillated prediction, form confidence regions in oscillation parameter space

Neutrino Flux Prediction (NA61)

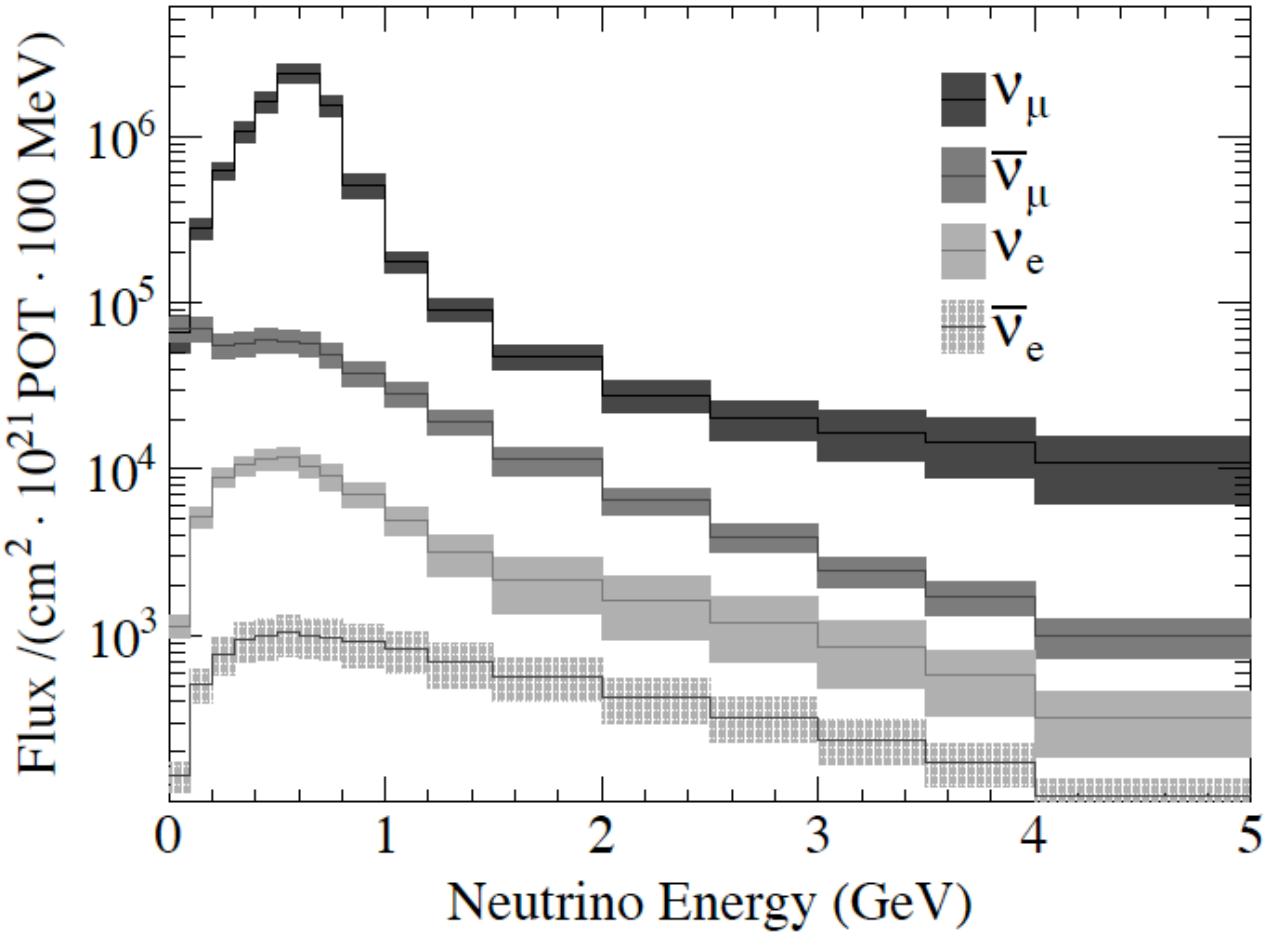


π+ Thin target data:
N. Abgrall *et. al.*, 1102.0983 [hep-ex], Submitted to Phys. Rev. C



- Simulation of primary and secondary π and κ production in the target is done with FLUKA, but is **tuned to experimental data** from the **NA61/Shine** experiment at CERN
- Has 95% coverage for ν pion parents
- FLUKA 2008 used to predict kaons and pions outside NA61 acceptance region.
- Geant3 used to simulate horn focussing and meson decay

Neutrino Flux at SK



- Inside NA61 region, measurement uncertainties are assigned.
- Outside NA61 region, 50% uncertainties are assigned to pions
- Kaon uncertainties come from a comparison of FLUKA to T. Eichten *et. al.*, Nucl. Phys. B **44** (1972)

Near Detector and Extrapolation

- A reminder from earlier in the talk:
  - $$\frac{R_{ND}^{\mu Data}}{R_{ND}^{\mu MC}} = 1.036 \pm 0.028(stat.) \pm^{0.044}_{0.037} (det.syst.) \pm 0.038(phys.model)$$
- Predicted number of events at SK is scaled by the data/MC comparison in the near detector

$$N_{SK}^{expected} = N_{SK}^{MC} \times \frac{R_{ND}^{\mu Data}}{R_{ND}^{\mu MC}}$$

- Scaling is done for both the intrinsic ν_e in beam and the NC background.

ν_e Event Selection

Same as ν_μ cuts

ν_e Event Selection

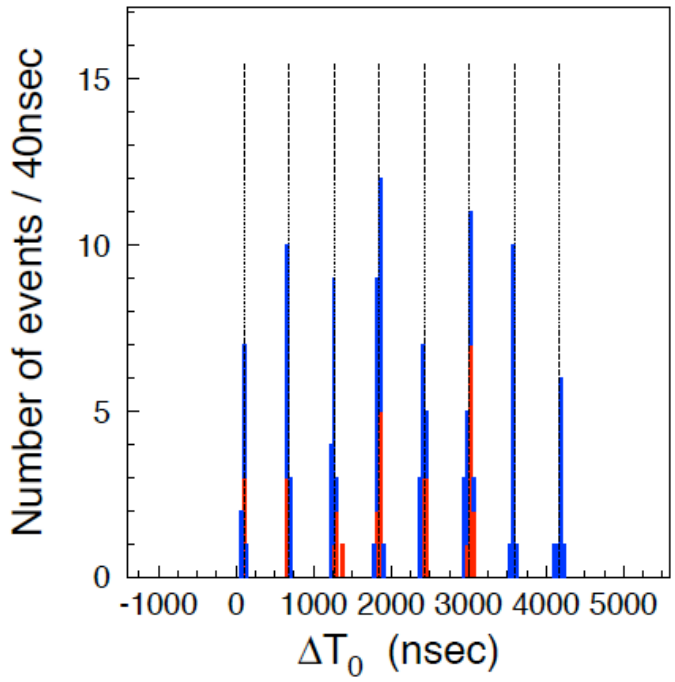
- Sample of fully contained e-like events
- Selection cuts

Same as ν_μ cuts

ν_e Event Selection

- Sample of fully contained e-like events
- Selection cuts

1. Coincident with beam time



Run 1
(6 bunches)

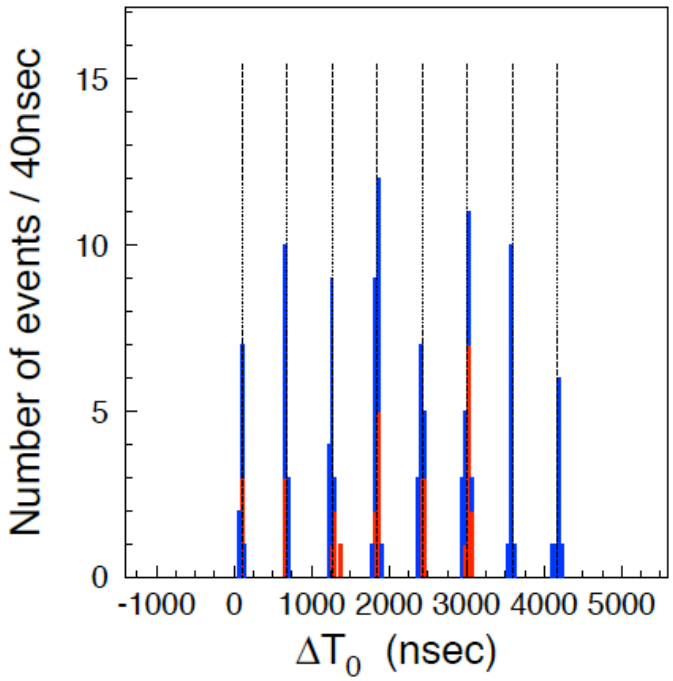
Run 2
(8 bunches)

Same as ν_μ cuts

ν_e Event Selection

- Sample of fully contained e-like events
- Selection cuts

1. Coincident with beam time
2. <16 hits in outer detector



Run 1
(6 bunches)

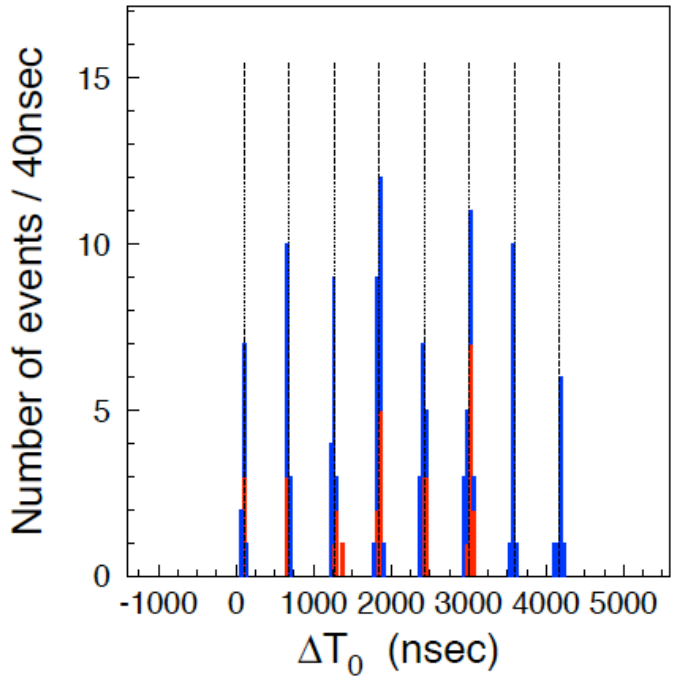
Run 2
(8 bunches)

Same as ν_μ cuts

ν_e Event Selection

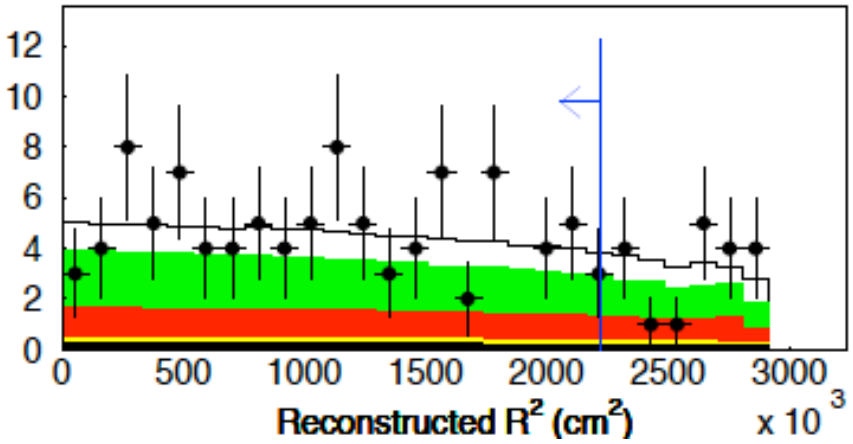
- Sample of fully contained e-like events
- Selection cuts

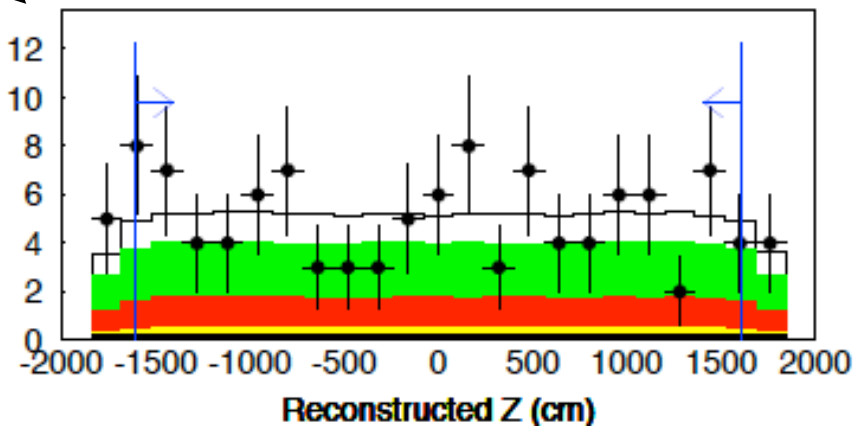
1. Coincident with beam time
2. <16 hits in outer detector
3. vertex>200 cm from inner detector walls



Run 1 (6 bunches)

Run 2 (8 bunches)





Same as ν_μ cuts

ν_e Event Selection (cont.)

Same as ν_μ cuts

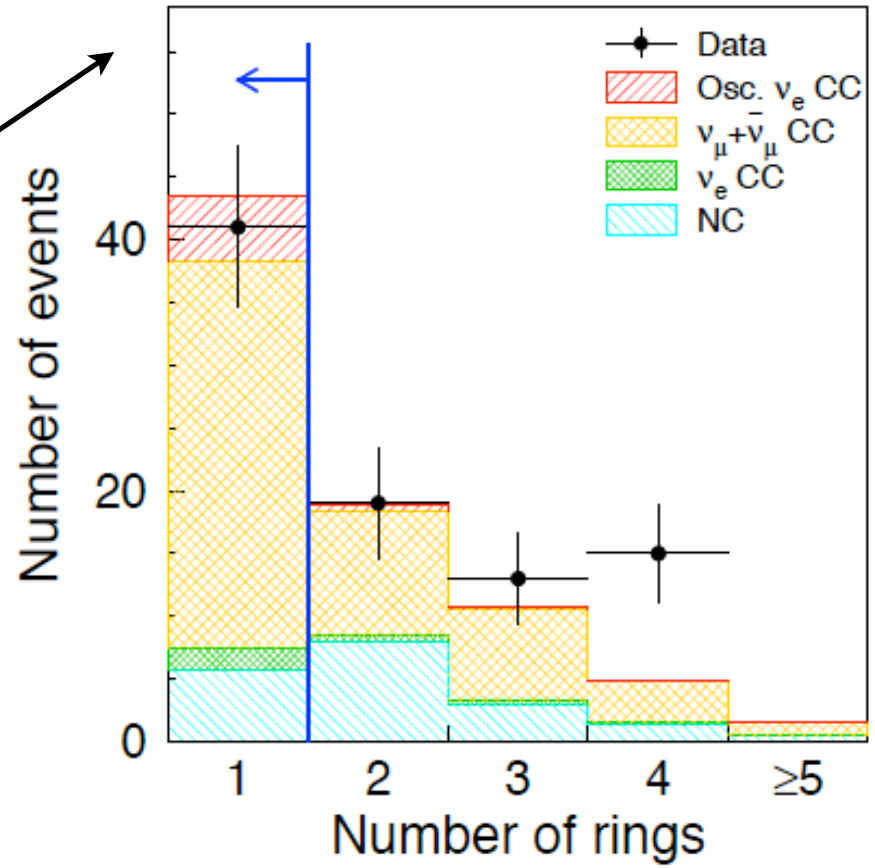
ν_e Event Selection (cont.)

- Selection cuts (cont.)

Same as ν_μ cuts

ν_e Event Selection (cont.)

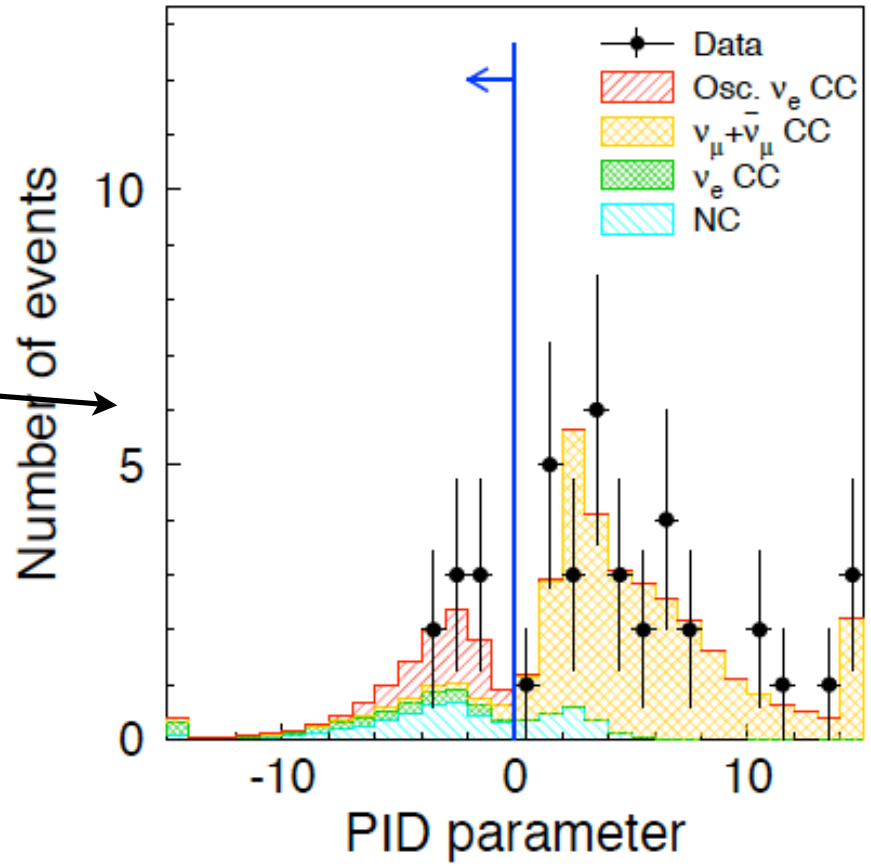
- Selection cuts (cont.)
  - 4. Single ring



Same as ν_μ cuts

ν_e Event Selection (cont.)

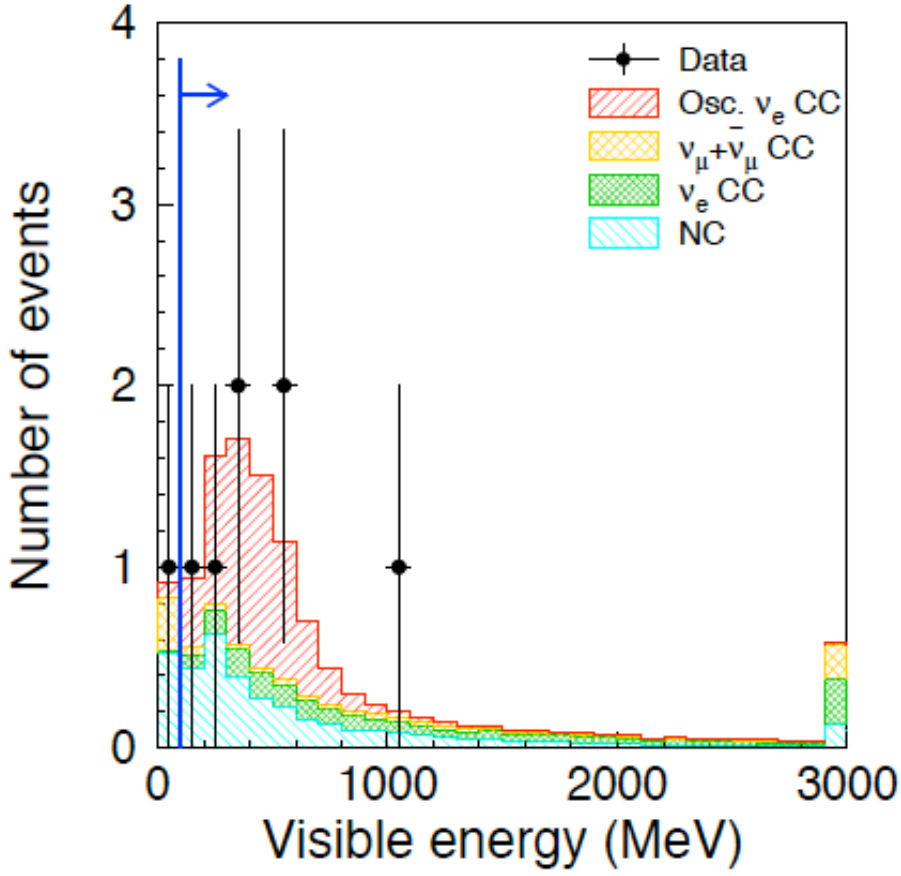
- Selection cuts (cont.)
  - 4. Single ring
  - 5. Ring is electron-like



Same as ν_μ cuts

ν_e Event Selection (cont.)

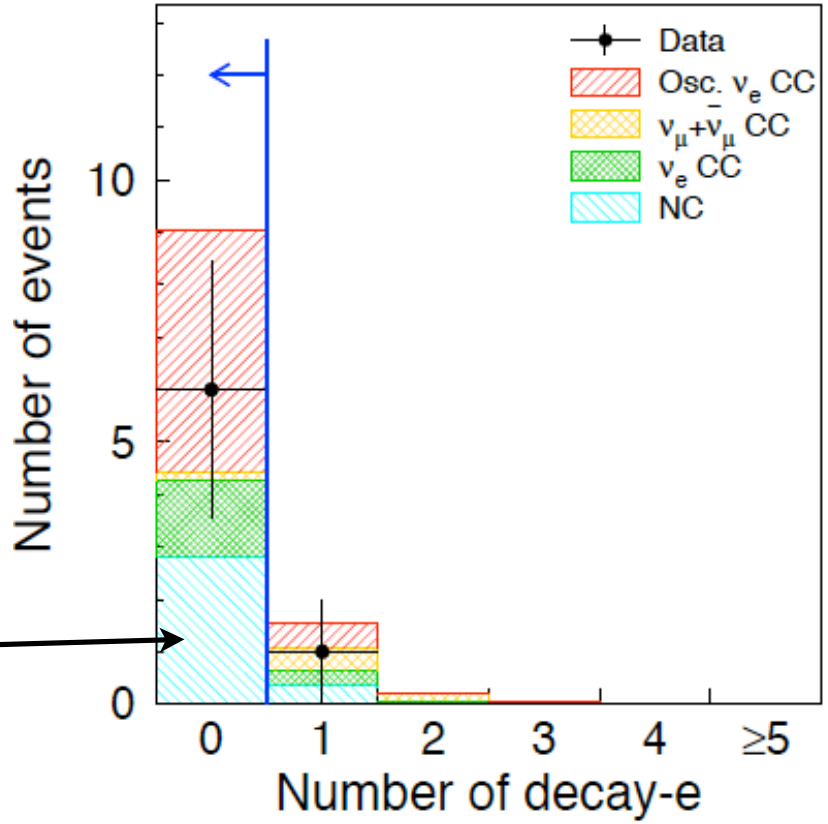
- Selection cuts (cont.)
  - 4. Single ring
  - 5. Ring is electron-like
  - 6. visible energy > 100 MeV



Same as ν_μ cuts

ν_e Event Selection (cont.)

- Selection cuts (cont.)
  - 4. Single ring
  - 5. Ring is electron-like
  - 6. visible energy > 100 MeV
  - 7. No decay electron observed



Same as ν_μ cuts

ν_e Event Selection (cont.)

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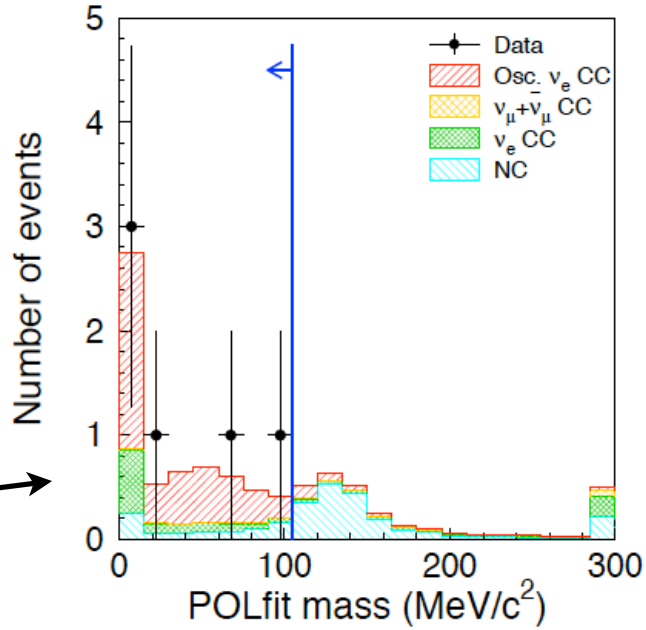

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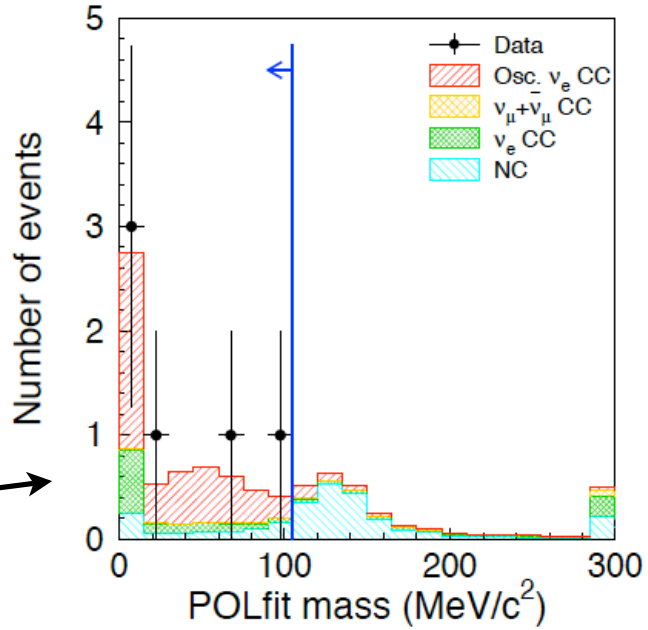

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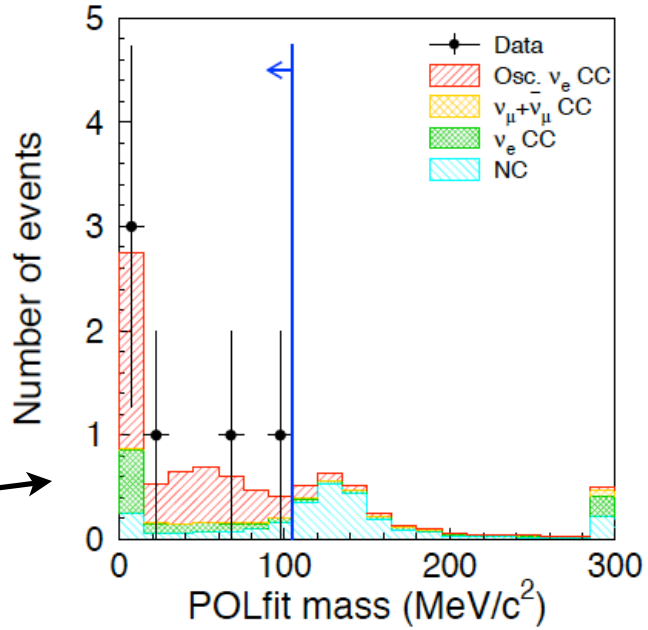

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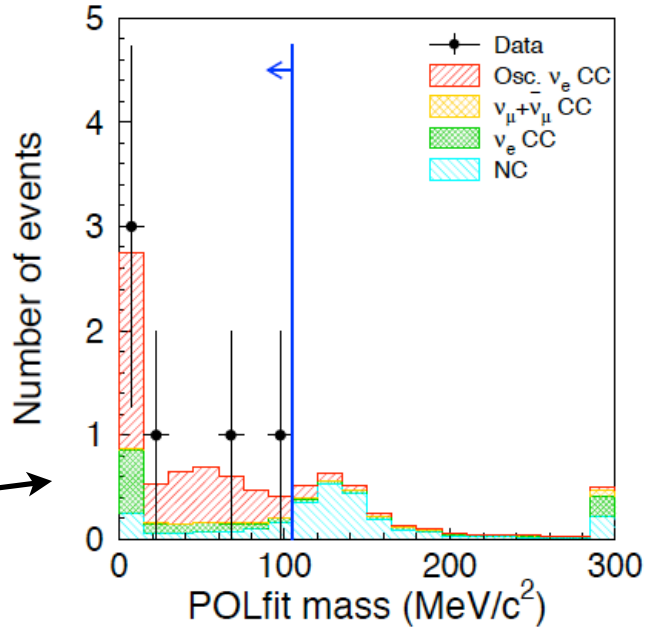

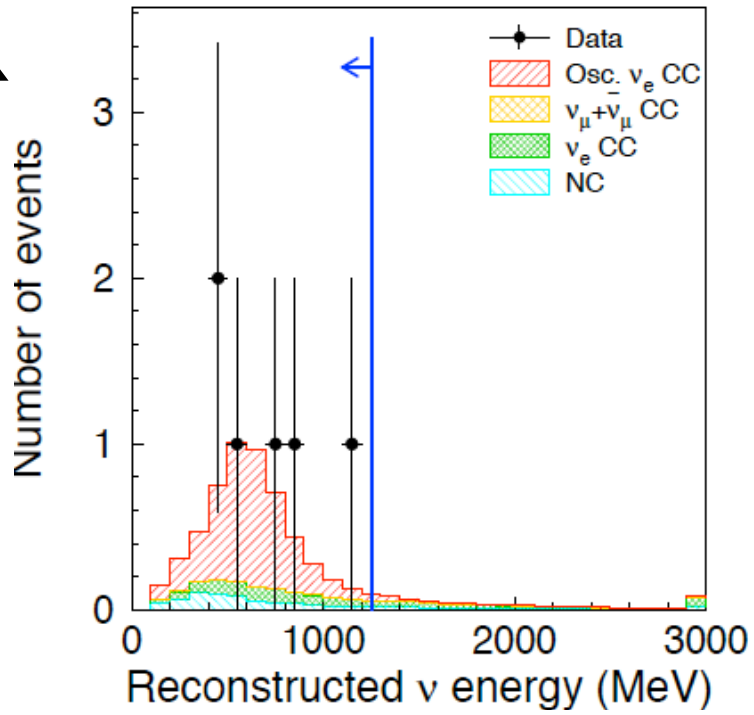

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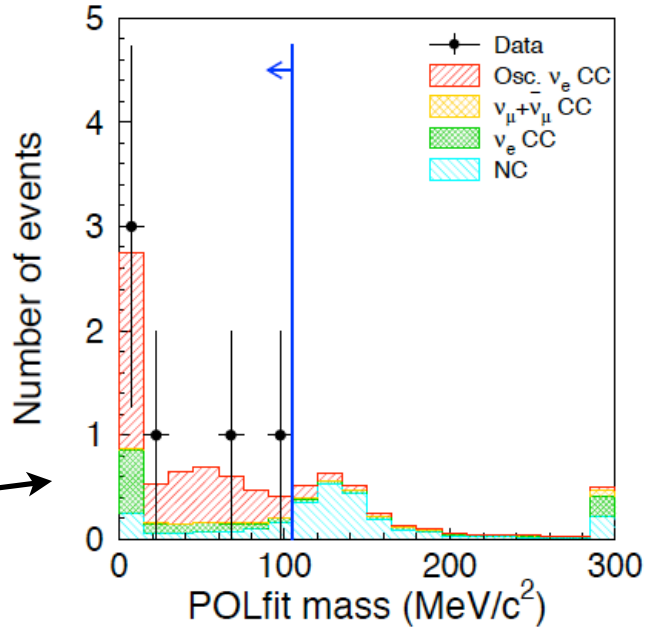

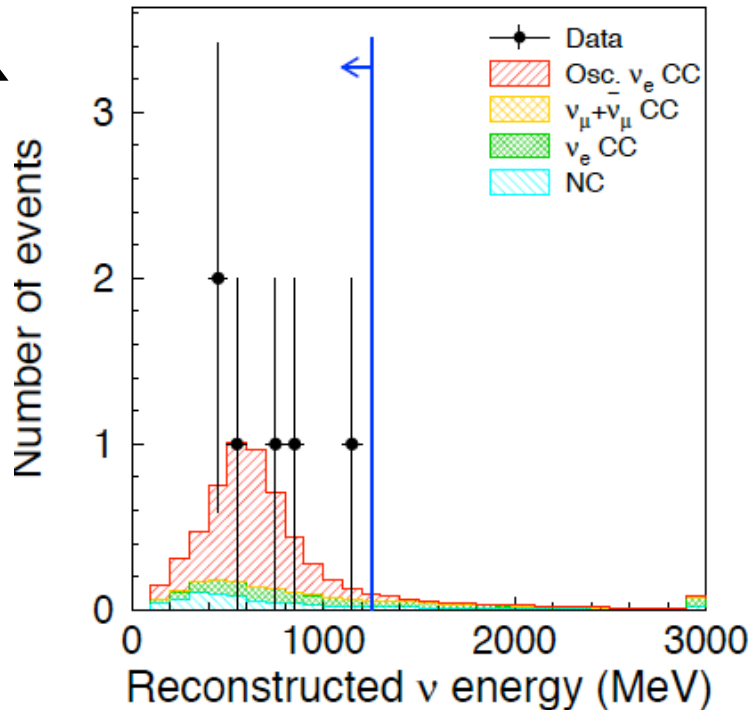

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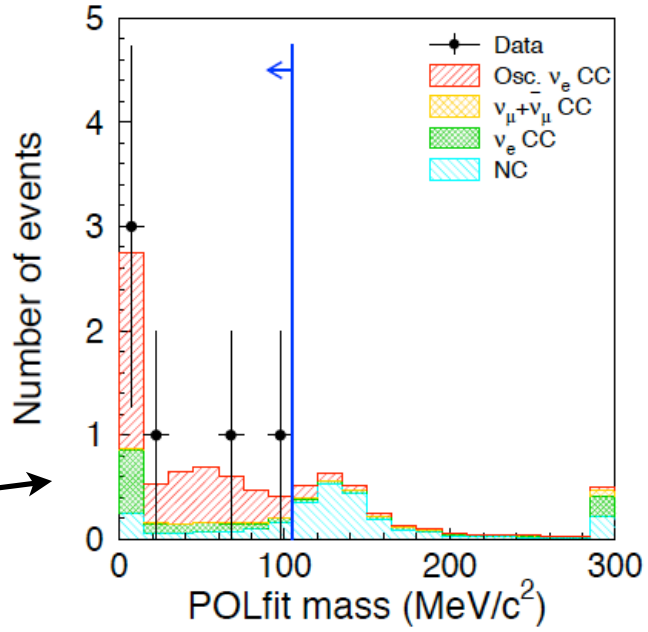

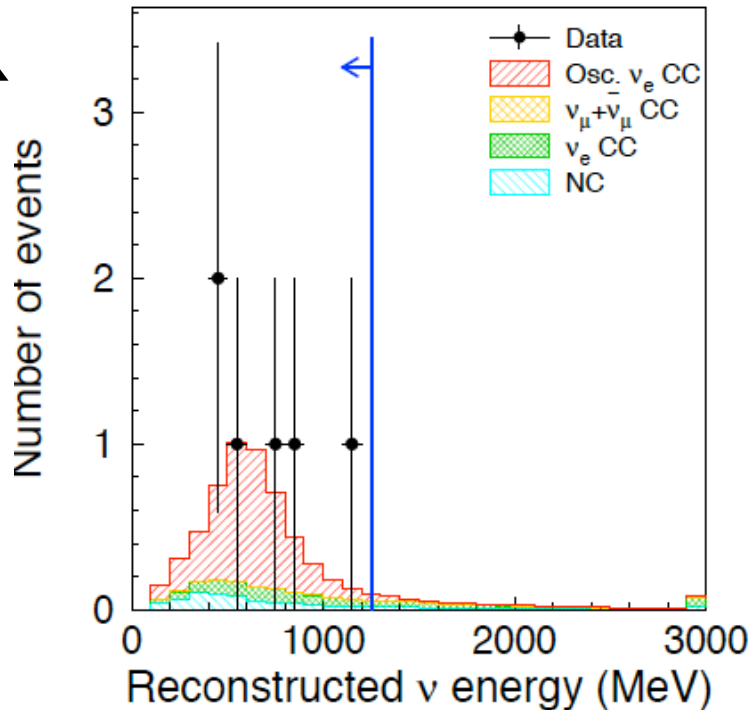

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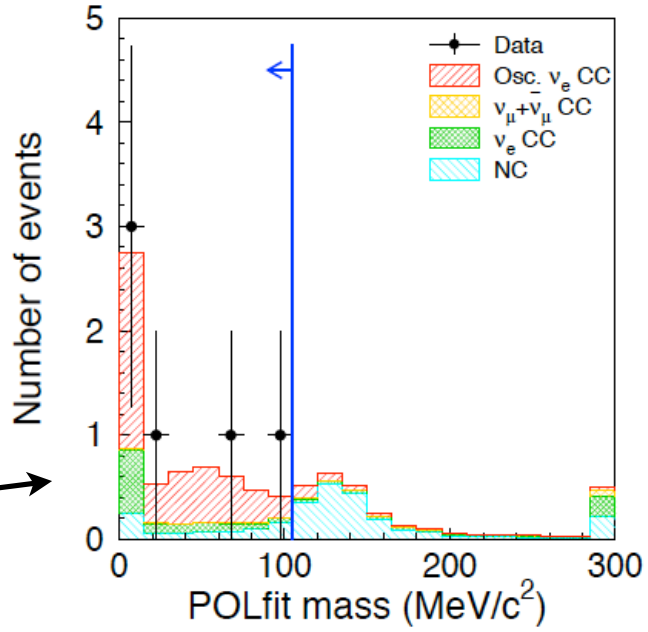
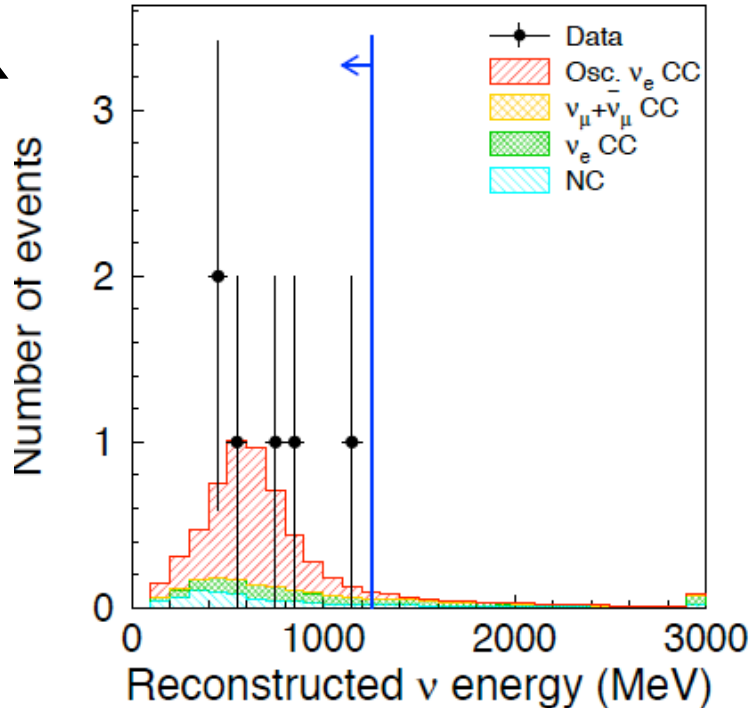
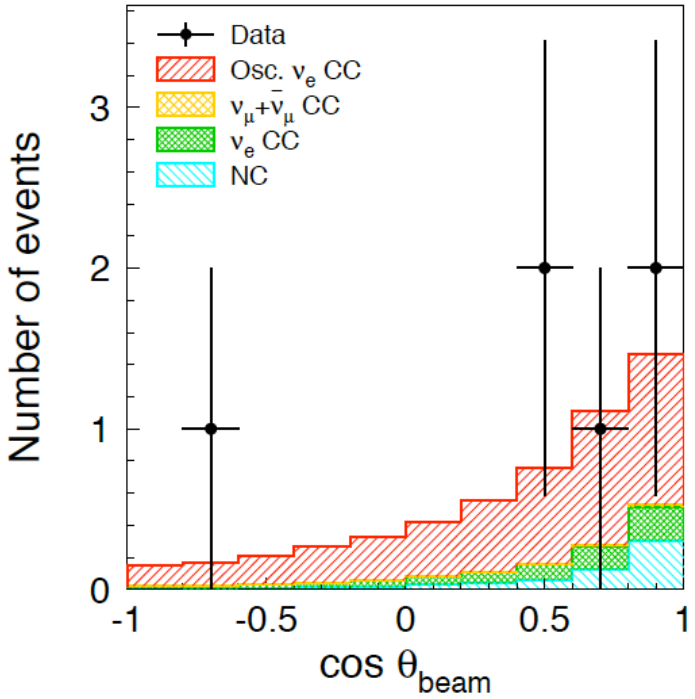
- **6 events observed**

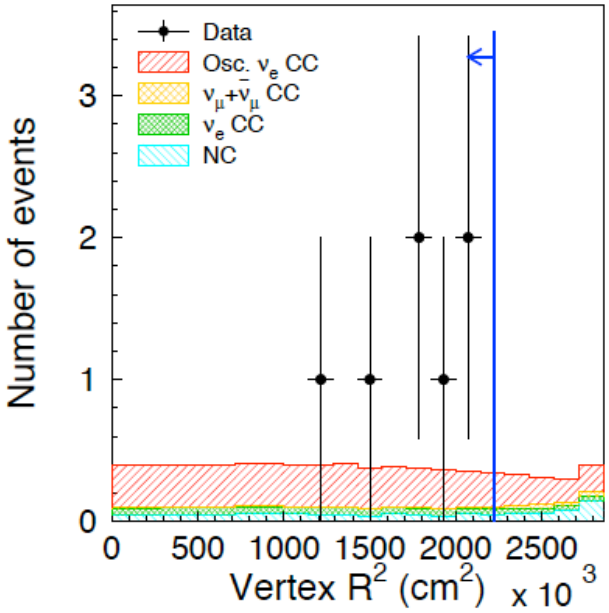


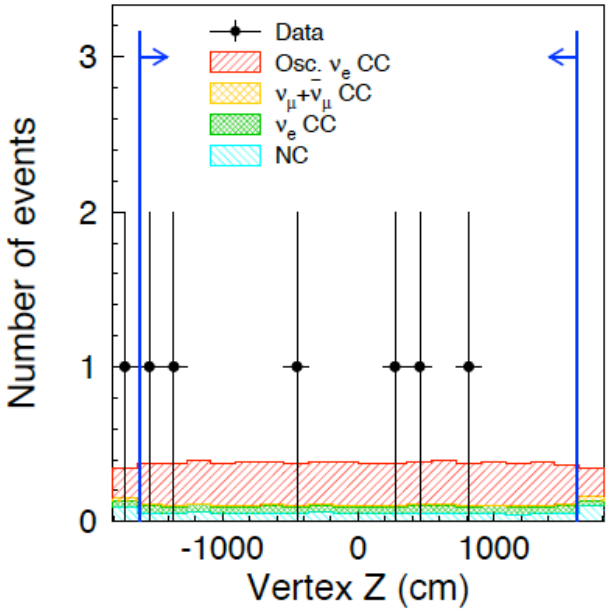


Event Distributions

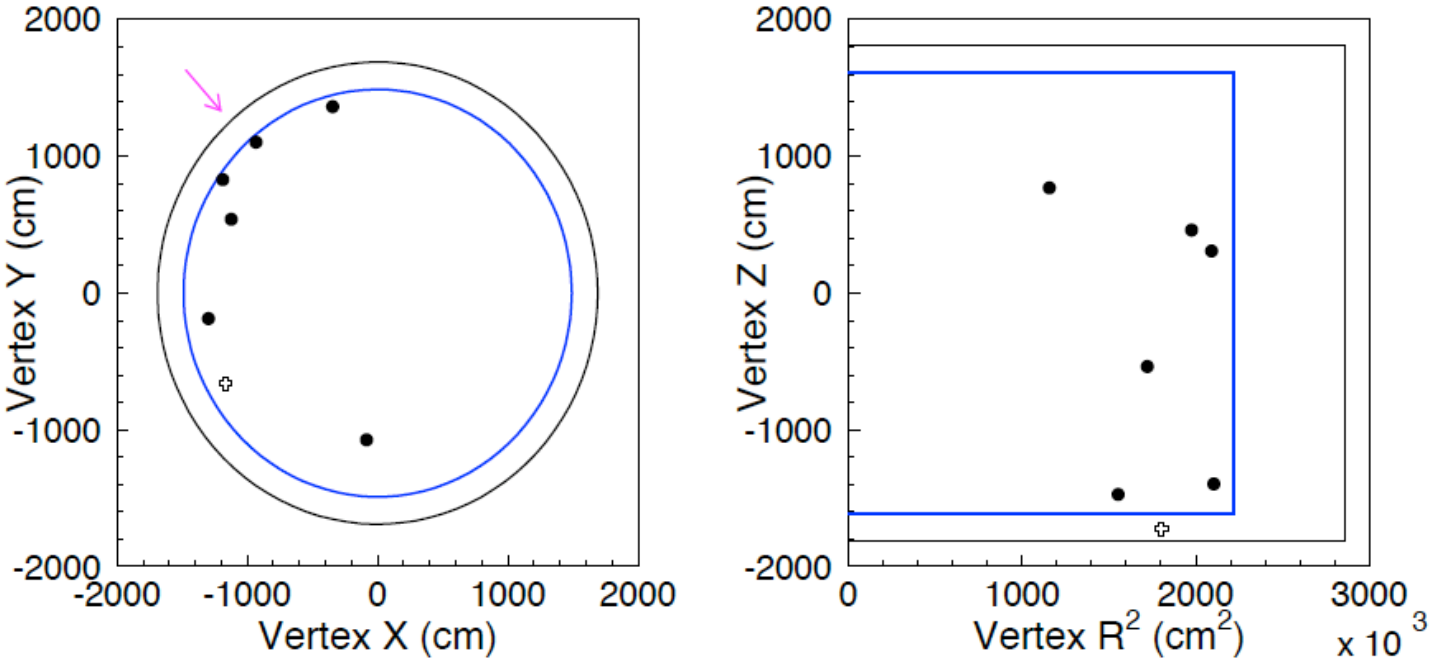
- Directional agreement of events is reasonable
- Many events at large r







Radial Distribution



- Checks of events at large r
  - Examined distribution of events outside fiducial volume, and see no evidence of an excess
  - No excess of events seen in upstream wall of outer detector
  - A toy MC of R^2 distribution was performed and 3% of the samples had a K-S test D_{obs} that was larger than the data

Predicted Events at SK

- Predict $N_{SK}^{expected}$ using Geant3 detector Monte Carlo, Neut neutrino interaction generator, and the ratio $R_{ND}^{\mu\ data}/R_{ND}^{\mu\ MC}$ obtained from Near Detector

Beam ν_e CC events	NC Background	Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)	$N_{SK}^{expected}$ Total
0.8	0.6	0.1	1.5

- For $\sin^2 2\theta_{13}=0.1$, $N_{SK}^{expected}$ (sig+bkg) = 5.5

Systematic Uncertainties

Source	$\delta N_{SK}^{expec}/N_{SK}^{expec}$ for $\sin^2 2\theta_{13}=0.0$
ν Flux	±8.5%
Near Det. Syst.	$\pm^{5.6}_{5.2}$ %
Near Det. Stat.	±2.7%
Cross Sect.	±14%
Far Det. Syst.	±14.7%
Total	$\pm^{22.8}_{22.7}$ %

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Source	Error on $N_{SK}^{expec}/R_{ND}^{\mu\ MC}$
π prod.	±2.5%
K prod.	±7.6
Nucleon Prod.	±1.4%
Prod. Cross Sect.	±0.7%
p beam position/ profile	±2.2%
beam direction	0.7%
Target align.	0.2%
Horn align.	0.1%
Horn current	0.3%
Total	**8.5%**

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Source	Systematic Error
TPC1 veto	±1.2%
TPC Efficiency	$\pm^{0}_{2}$ %
TPC chg misID	±1%
TPC-FGD matching	±2.1%
FGD mass	±0.5%
PID pull width	$\pm^{3}_{0}$ %
Low Gain MicroMegas	±0.4%
pile-up	±0.9%
cosmics	$\pm^{0}_{0.4}$ %
Out of FGD	±0.9%
M_A+M_V	±2.4%
Nucleon Ejection	±2.7%
FSI	±0.7%
Total	$\pm^{5.6}_{5.2}$ %

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Source	Systematic Error
CCQE	energy-dependent (7% at 500 MeV)
CC 1π	30% (<2GeV), 20%(>2GeV)
CC Coh. $\pi^{\pm}$	100%
CC other	30% (<2GeV), 25%(>2GeV)
NC $1\pi^0$	30% (<1GeV), 20%(>1GeV)
NC Coh. π	30%
NC Other π	30%
FSI	energy-dependent (10% at 500 MeV)
Total $\sin^2 2\theta_{13}=0$	**14%**
Total $\sin^2 2\theta_{13}=0.1$	**10.5%**

Systematic Uncertainties

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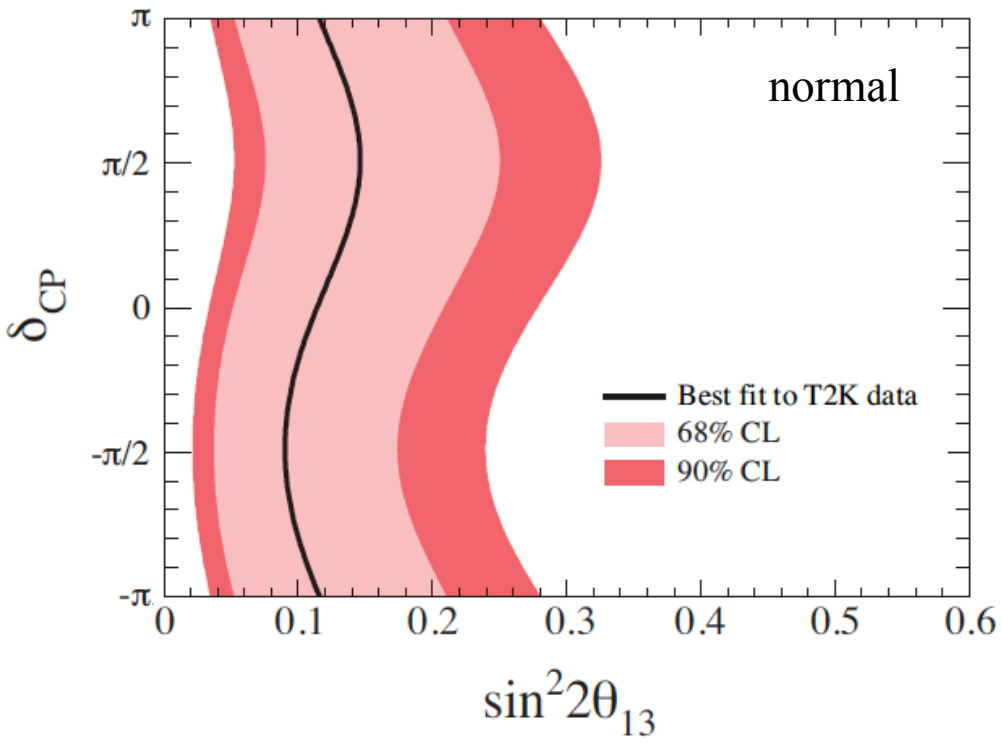
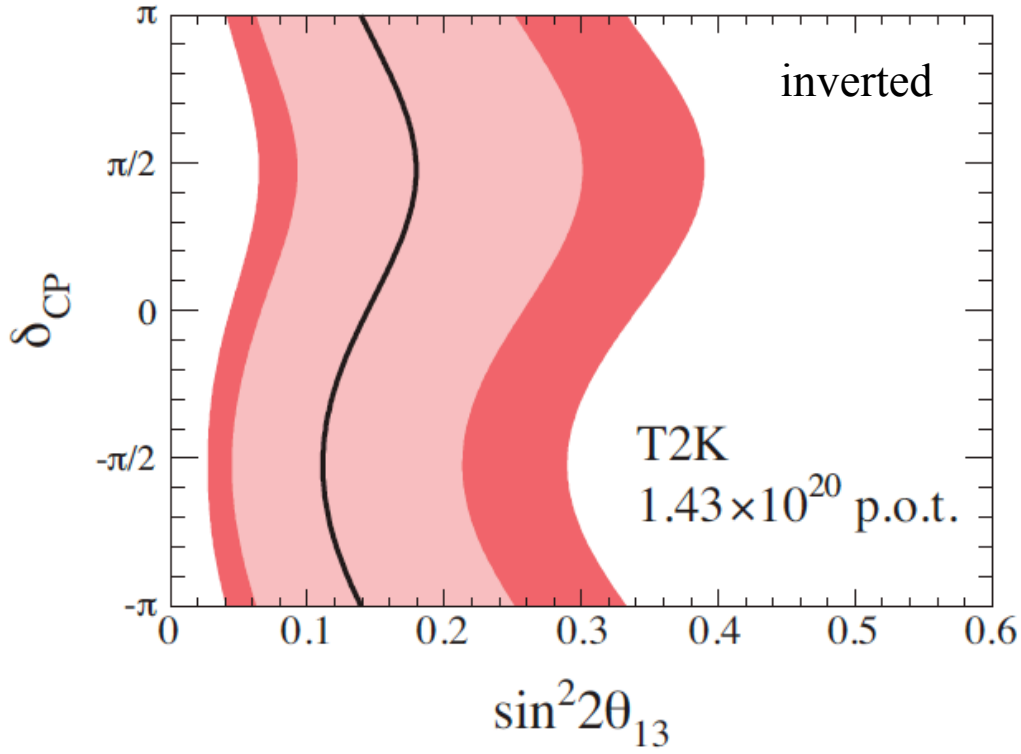
Source	Background δN_{SK}^{expec} / N_{SK}^{expec}	ν_e Signal δN_{SK}^{expec}/ N_{SK}^{expec}
π^0 rejection	3.6%	-
Ring Counting	8.3%	3.9%
e PID	8.0%	3.8%
Invariant mass	8.7%	5.1%
Fiducial vol.	1.4%	1.4%
E scale	1.1%	0.4%
decay e	0.3%	0.1%
μ PID	1.0%	-
Total	**15%**	**7.6%**

Results

- Observed number of events: **6**
- Predicted number of events:
  - **1.5±0.3(syst.)** ($\sin^2 2\theta_{13}=0.0$)
  - **5.5±1.0(syst.)** ($\sin^2 2\theta_{13}=0.1$)
- $\sin^2 2\theta_{13}=0.0$ is **excluded** at the **2.5σ level**

Allowed Parameters

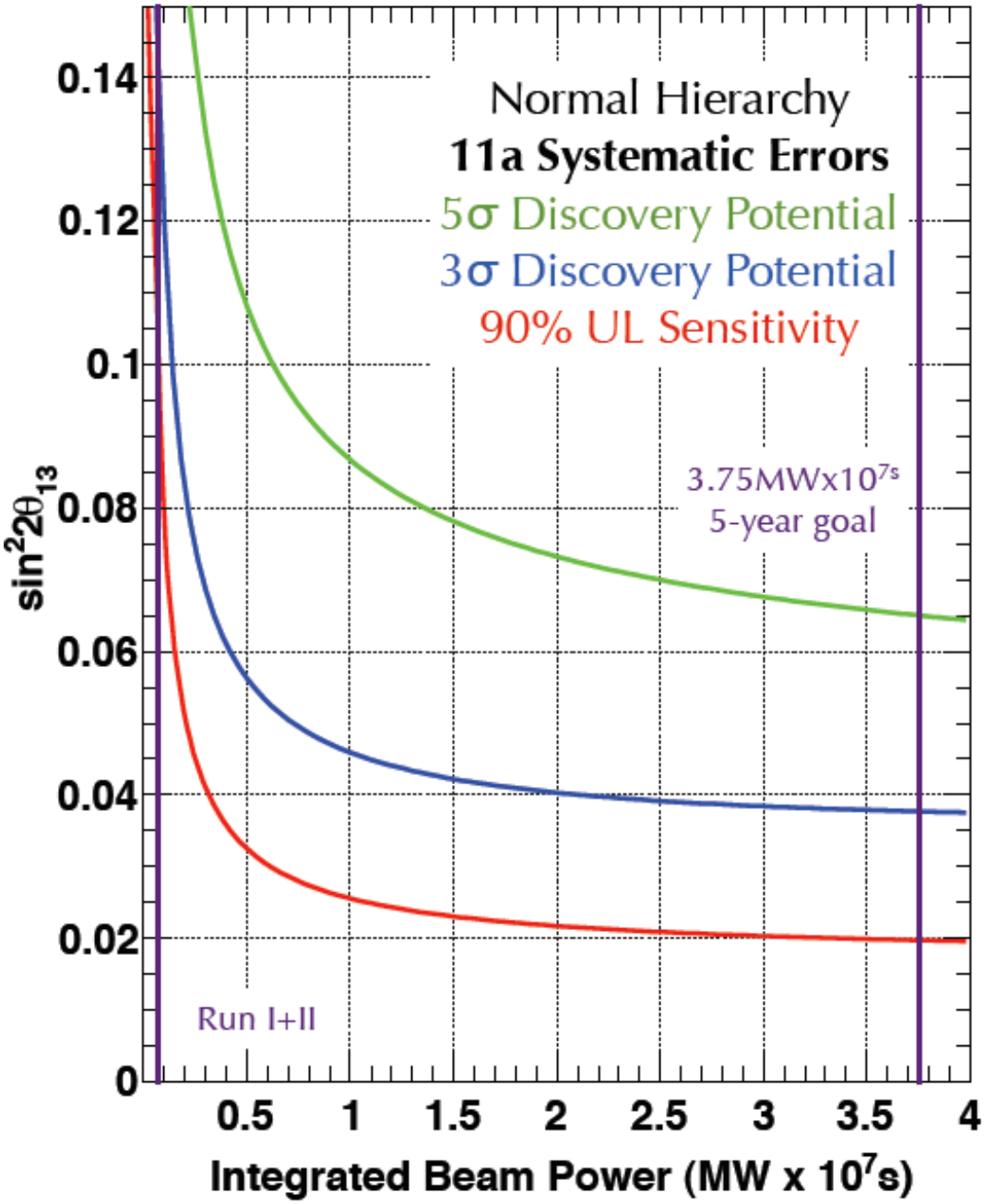




- A Feldman-Cousins prescription was used to fit for the allowed oscillation parameters.
- Above δ_{cp} , $\sin^2 2\theta_{13}$, and the mass hierarchy are allowed to vary, but $\sin^2 2\theta_{23}=1.0$, $|\Delta m_{23}^2|=2.4\times10^{-3}$ eV^2
- Best Fit ($\delta_{cp}=0$) $\sin^2 2\theta_{13}=0.11$ (normal); $=0.14$ (inverted)

Future Sensitivity

- Plot assumes the current systematic uncertainties



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- Stay tuned for more results!