T2K: First Results

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Fermilab Short Baseline Neutrino Workshop

Motivation

θ_{13}:

- Last unmeasured parameter in neutrino mixing matrix ($\sin^2 2\theta_{13} < 0.15$)
- “Gate keeper” to CP violation in neutrino oscillations



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Atmospheric oscillation parameters θ_{23}, Δm^2_{23}

- Maximal mixing ($\theta_{23} = 45^0$)? Precision measurement needed
- possible clues to illuminate structure of neutrino mixing matrix



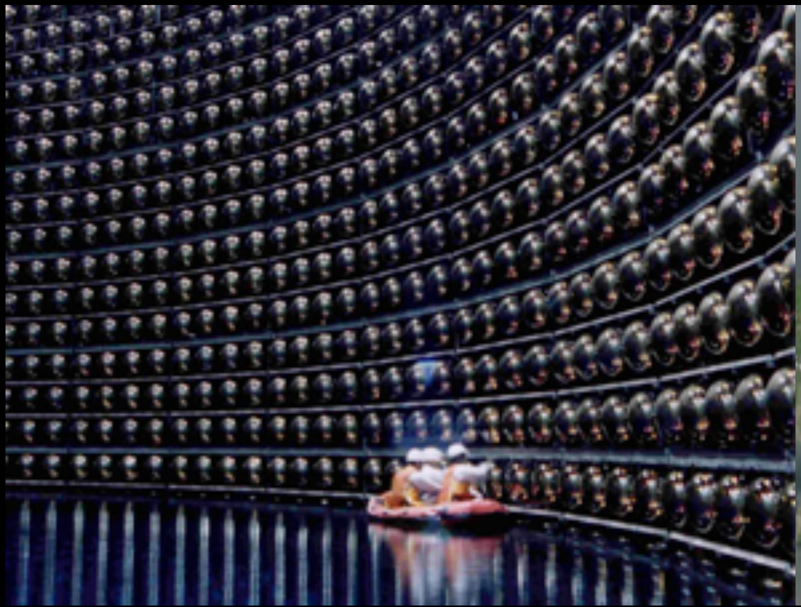
Motivation

"Tokai-to-Kamioka":

- high sensitivity search for $\nu_\mu \rightarrow \nu_e$ appearance due to θ_{13}
- high precision measurement of ν_μ disappearance due to θ_{23}, Δm^2_{23}

by sending high intensity ~600 MeV ν_μ beam 295 km

- from Tokai (J-PARC)
- to Kamioka (Super Kamiokande detector)



~500 collaborators from 59 institutions 12 nations,

T2K:

"Tokai-to-Kamioka":

- high sensitivity search for $\nu_\mu \rightarrow \nu_e$ appearance due to θ_{13}
- high precision measurement of ν_μ disappearance due to θ_{23}, Δm^2_{23}

by sending high intensity E~600 MeV ν_μ beam L=295 km

- from Tokai (J-PARC)
- to Kamioka (Super Kamiokande detector)

With known Δm^2 values, chosen L/E maximizes oscillation probabilities

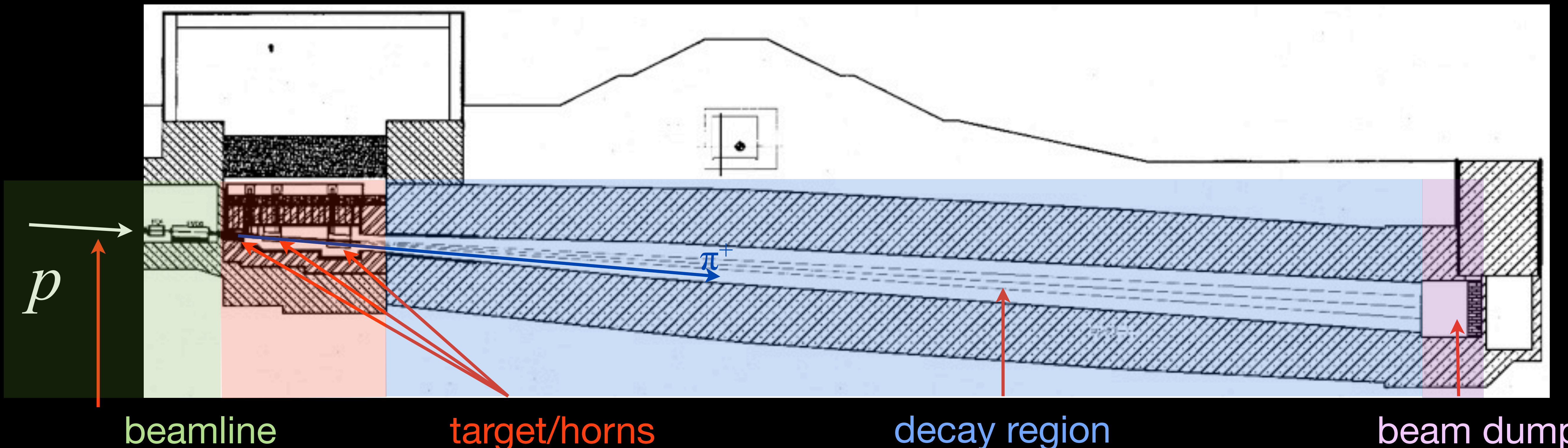
B. Kayser, NuSAG Mar 2006

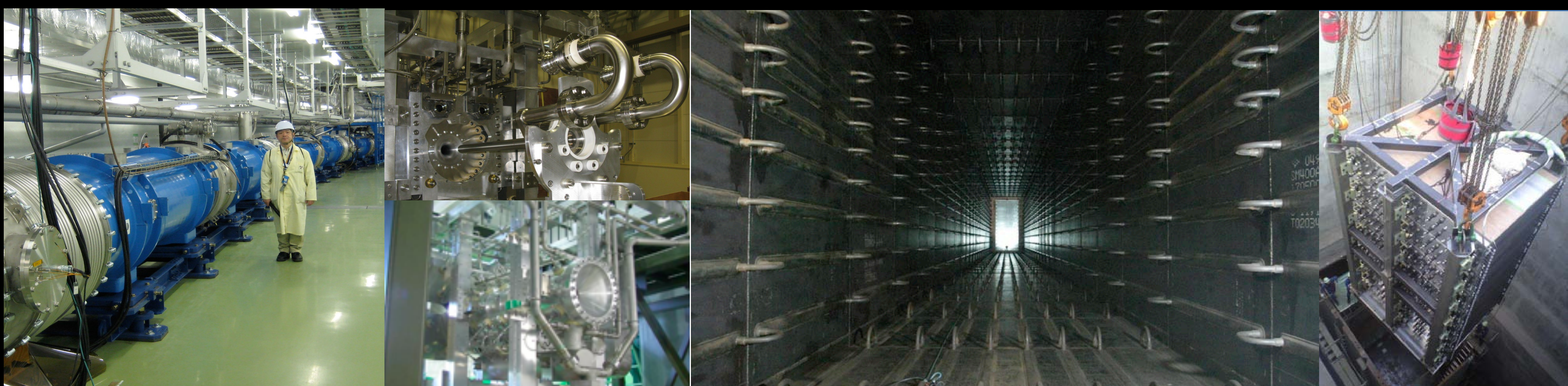
$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \quad &\sim \quad \sin^2 2\theta_{13} \sin^2 \theta_{23} \times \sin^2 \Delta_{31} \\
&+ \quad \sin 2\theta_{13} \cos \theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \times \sin \Delta_{31} \sin \Delta_{21} \cos(\Delta_{32} \pm \delta) \\
&+ \quad \sin^2 2\theta_{12} \cos^2 \theta_{23} \cos^2 \theta_{13} \times \sin^2 \Delta_{21}
\end{aligned}
$$

$$\Delta_{ij} = 1.27 \Delta m^2_{ij} (L/E)$$

$$P(\nu_\mu \not\rightarrow \nu_\mu) \sim \sin^2 2\theta_{23} \sin^2 \Delta_{23}$$

Producing ν_μ beam



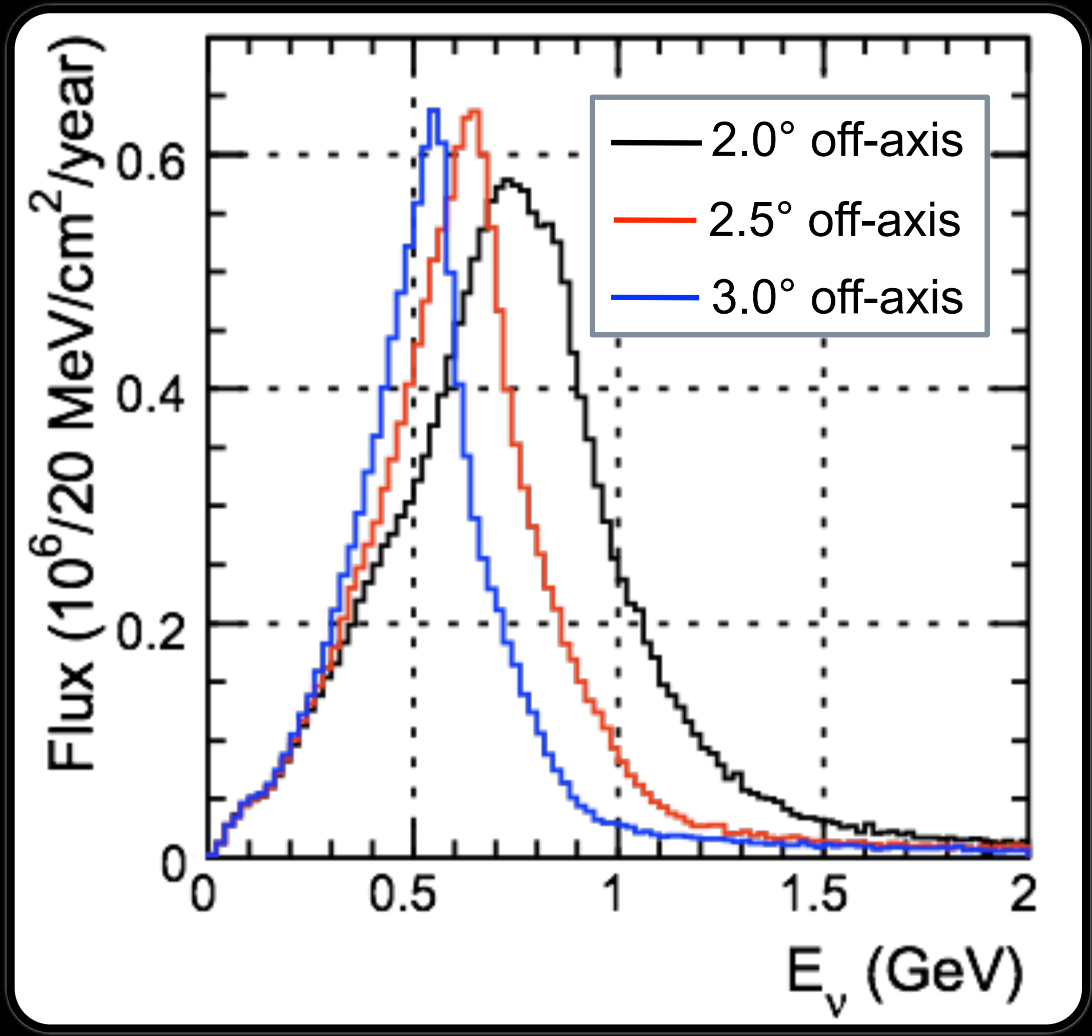


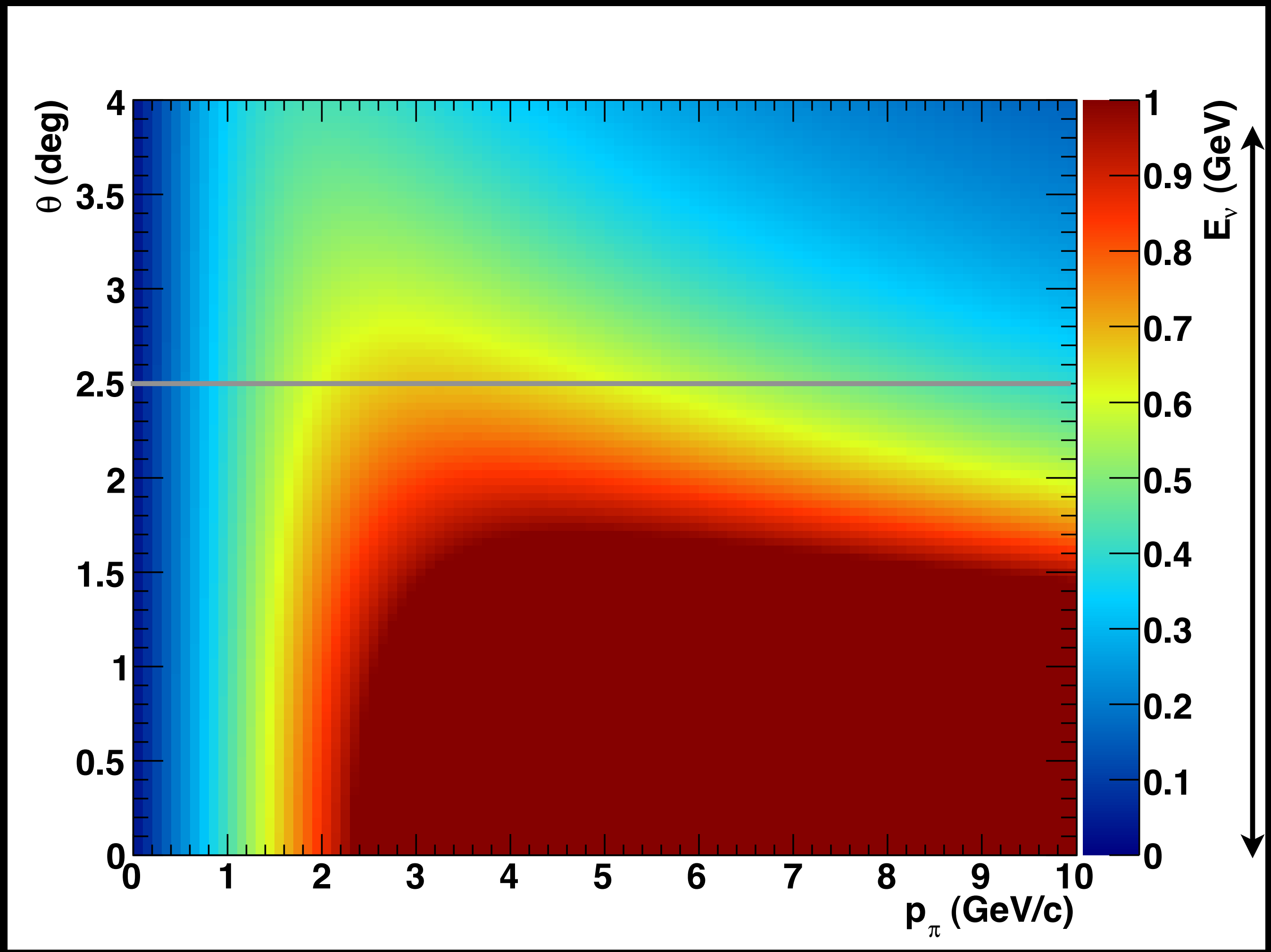
Neutrino beam produced by π^+ decays from 30 GeV protons
from J-PARC Main Ring interacting on carbon target

Off-Axis Beam Concept

- Pions (and neutrinos) produced with wide energy spectrum
- Relativistic kinematics can be exploited to produce “narrow” band neutrino beam

$$p(30\mathrm{GeV}) + \mathrm{C} \rightarrow \pi^+ + X$$
$$\hookrightarrow \nu_\mu + \mu^+$$

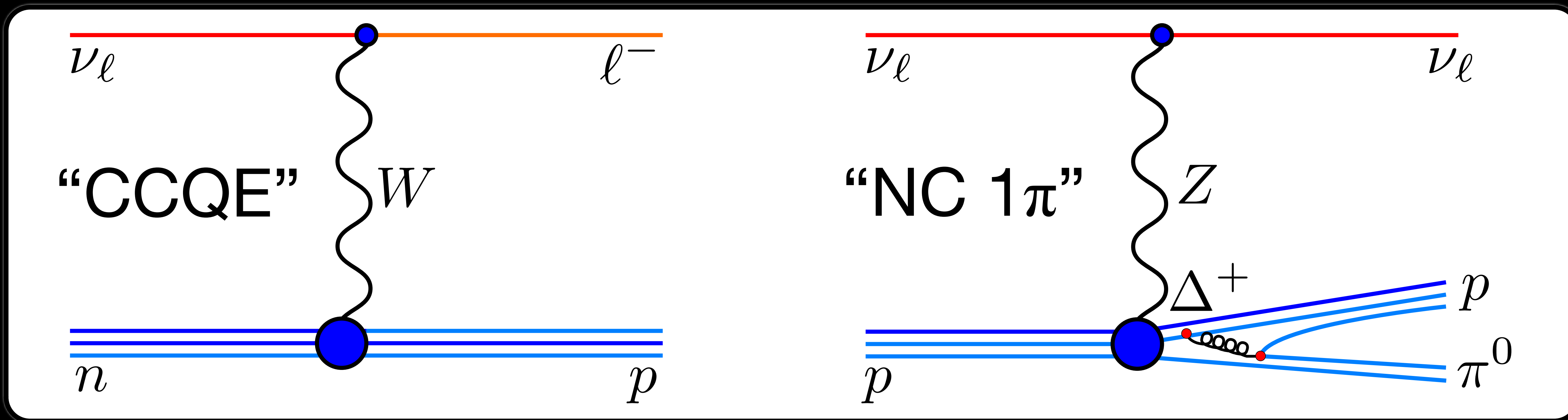




vertical axis rescaled 0-1 GeV

- Tune angle to maximize flux at oscillation maximum
- Reduce high energy neutrinos

Neutrino Interactions

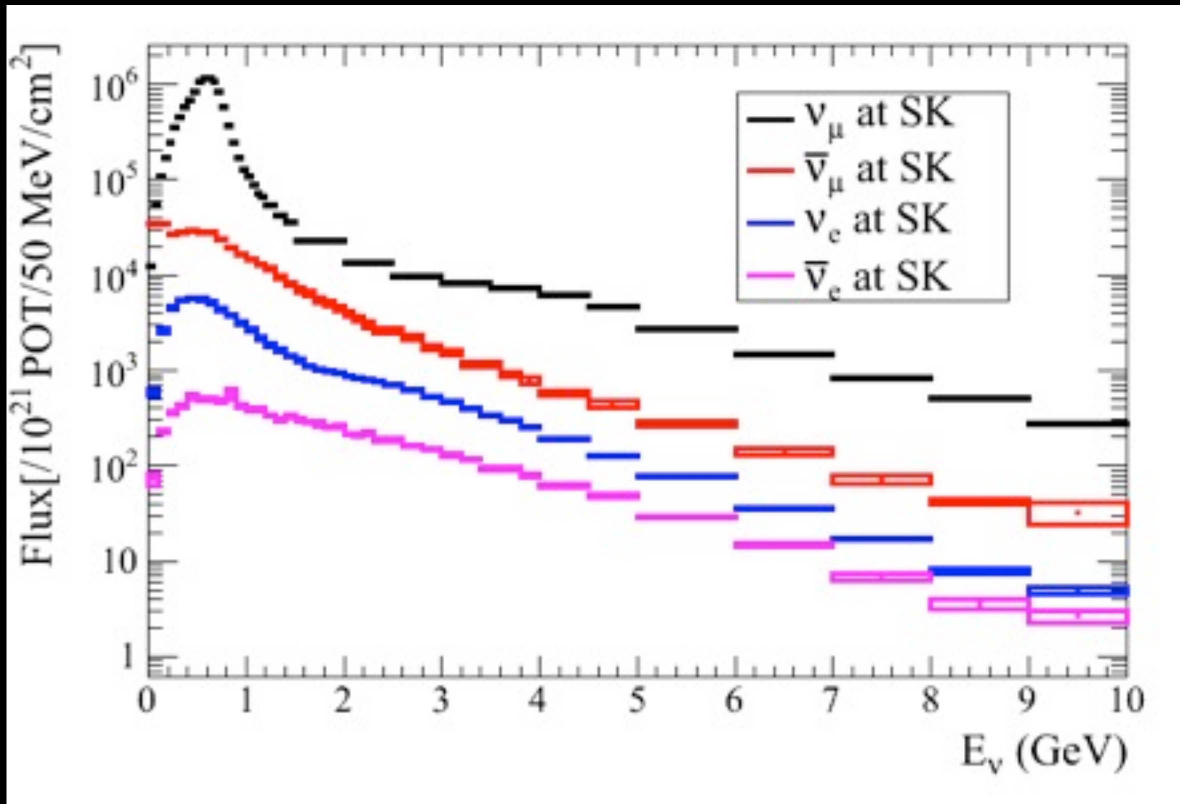


$\nu_\ell + n \rightarrow \ell^- + p$

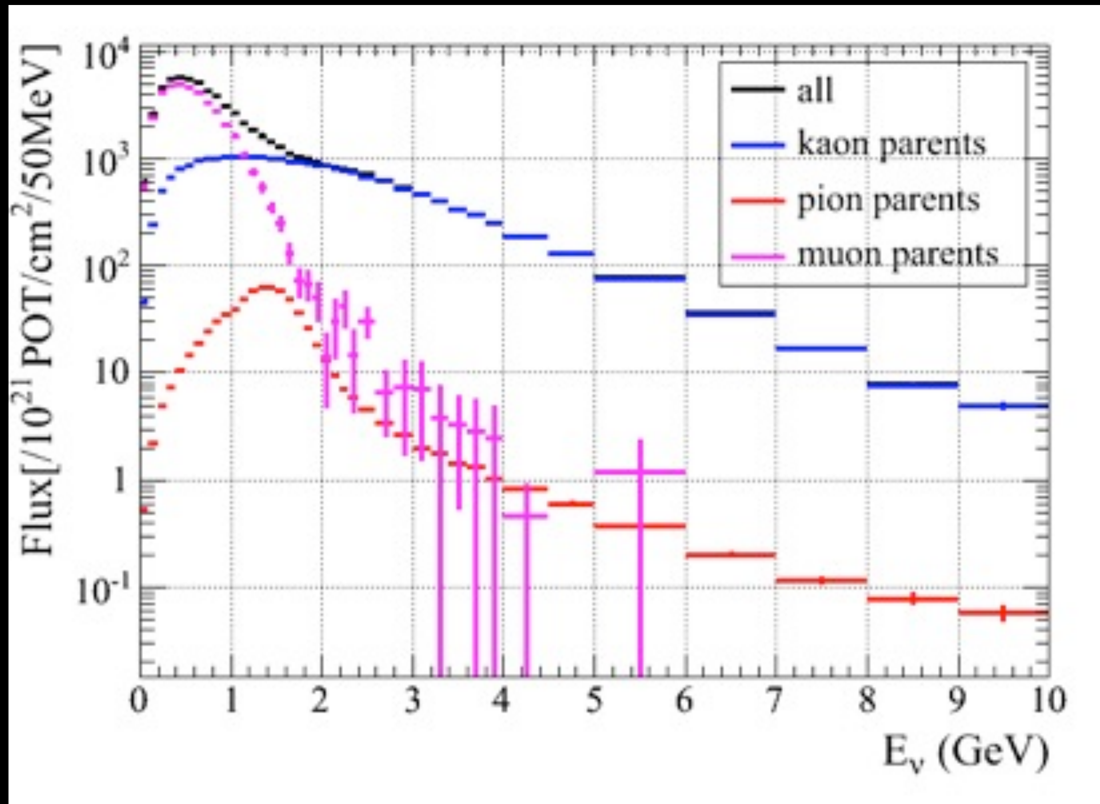
$\nu_\ell + p \rightarrow \nu_\ell + p + \pi^0$

- At ~1 GeV, interactions dominated by "quasi-elastic"
  - CC allows flavor-tagging (ν_e vs. ν_μ)
  - neutrino energy via lepton momentum
- Single pion production (CC and NC):
  - misidentification as CCQE results in incorrect neutrino energy
  - photons from $\pi^0 \rightarrow \gamma + \gamma$ may be misidentified as electrons

Neutrino flux

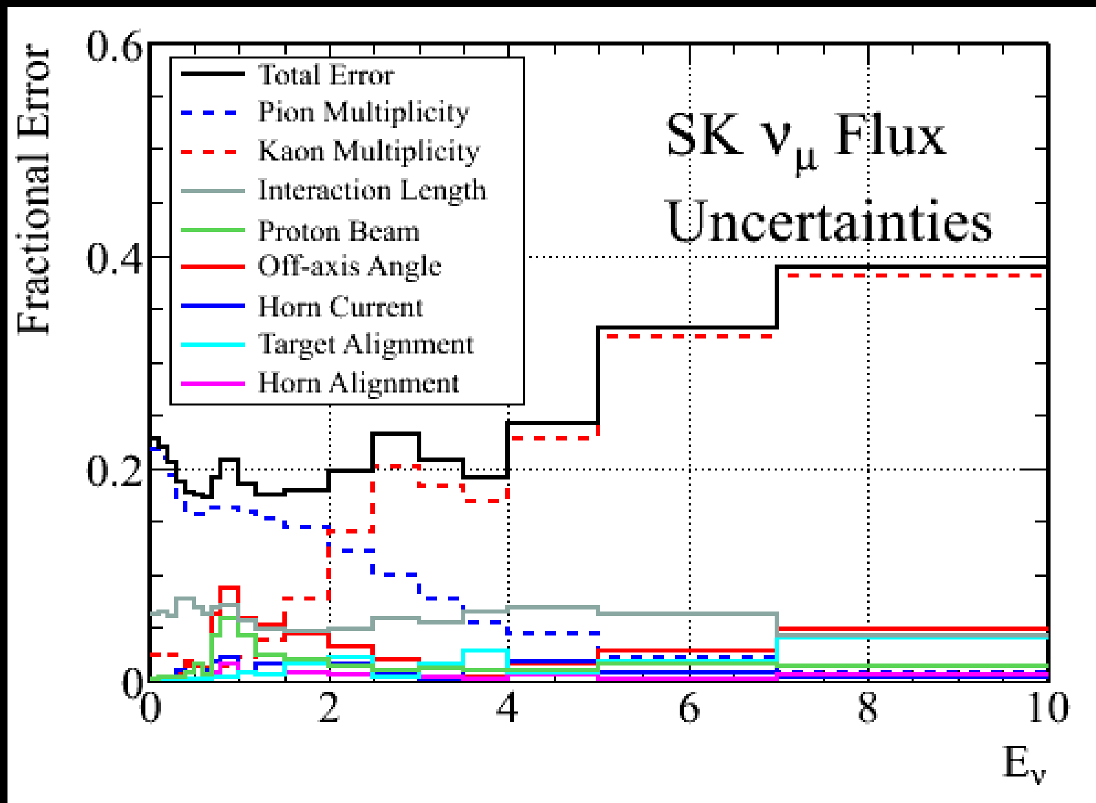


ν_e flux

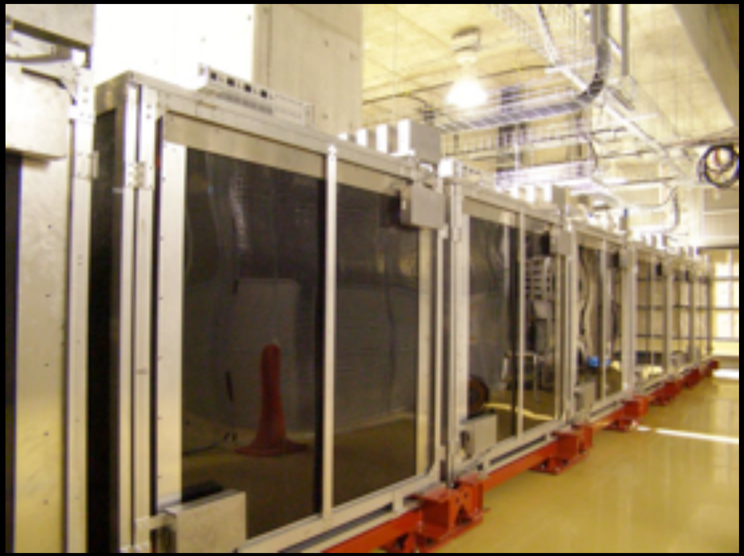


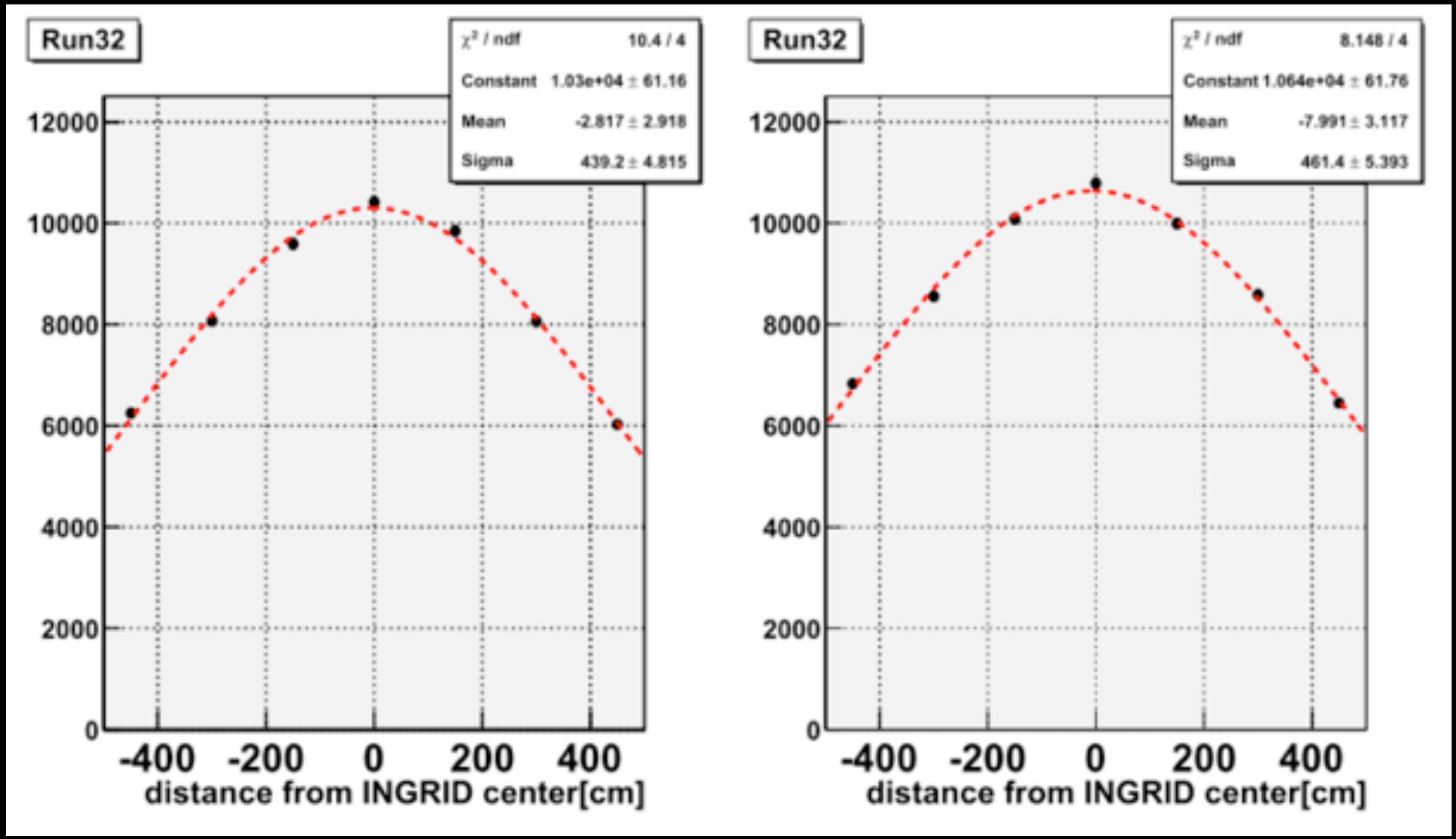
Neutrino flux predicted by detailed MC simulation tuned with:

- Preliminary NA61 $\pi^\pm$ production data
- Other external data for K, hadron interaction cross sections.
- Measurements from beam monitors, neutrino beam direction.



On-axis: (INGRID)





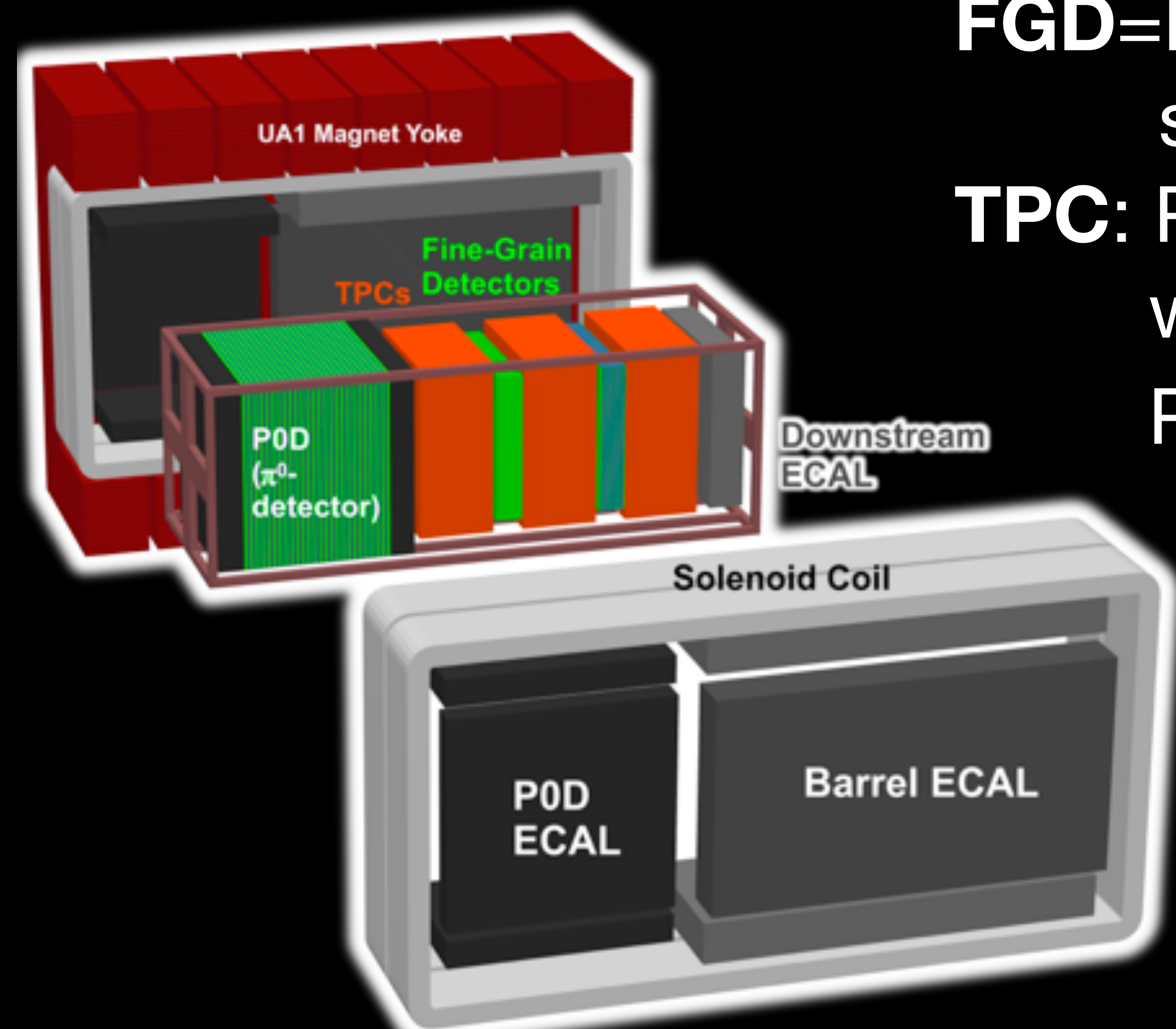
“GRID” of neutrino detectors:

- Fe/Scintillator trackers
- event rate allows ~daily monitor of profile

- Measure center of beam with profile of interaction rate module-to-module
- Beam axis within 1 mrad of nominal

Off-axis detectors

UA1 magnet 0.2 T



Tracker: 3 TPC/2 FGD

FGD=Fine Grained Detector (1 ton)
scintillator tracker with ~1x1 cm^2 bars

TPC: Precise kinematic reconstruction of ν_μ CC
with 0.2 T magnetic field
Particle ID for beam ν_e (~10^3 rejection)

ECAL

Pb/scintillator tracking calorimeter for photon detection and e/μ/π identification of tracks

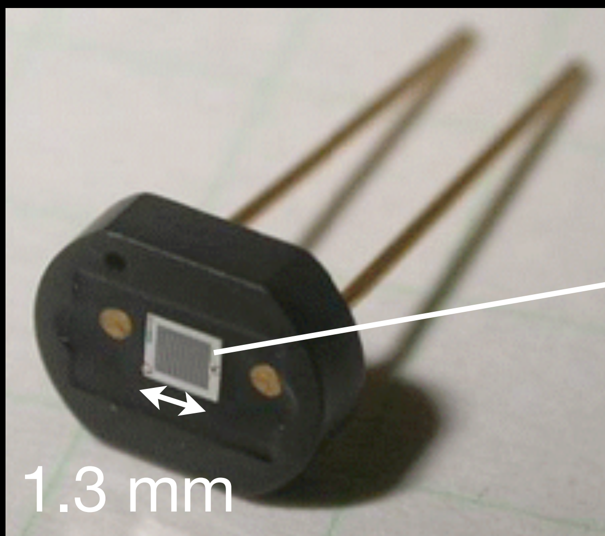
P0D

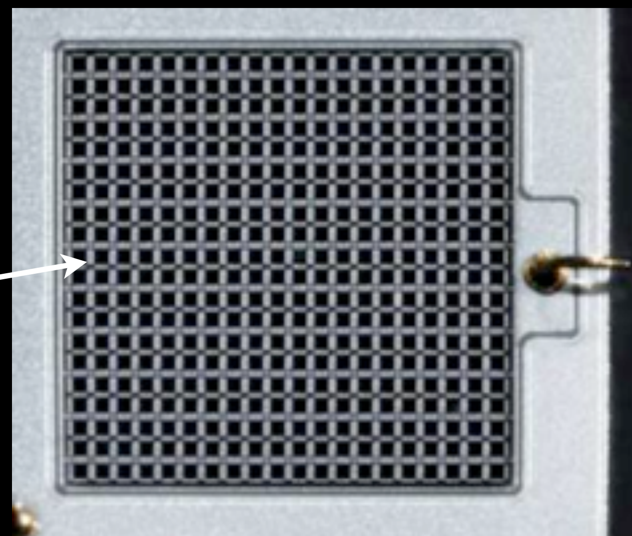
scintillator/(brass/Pb) tracker optimized for π^0 detection via photon shower identification

SMRD:

scintillator planes instrumenting magnet yoke for muon detection

Scintillation Detectors





Multi-pixel Photon Counter (MPPC)

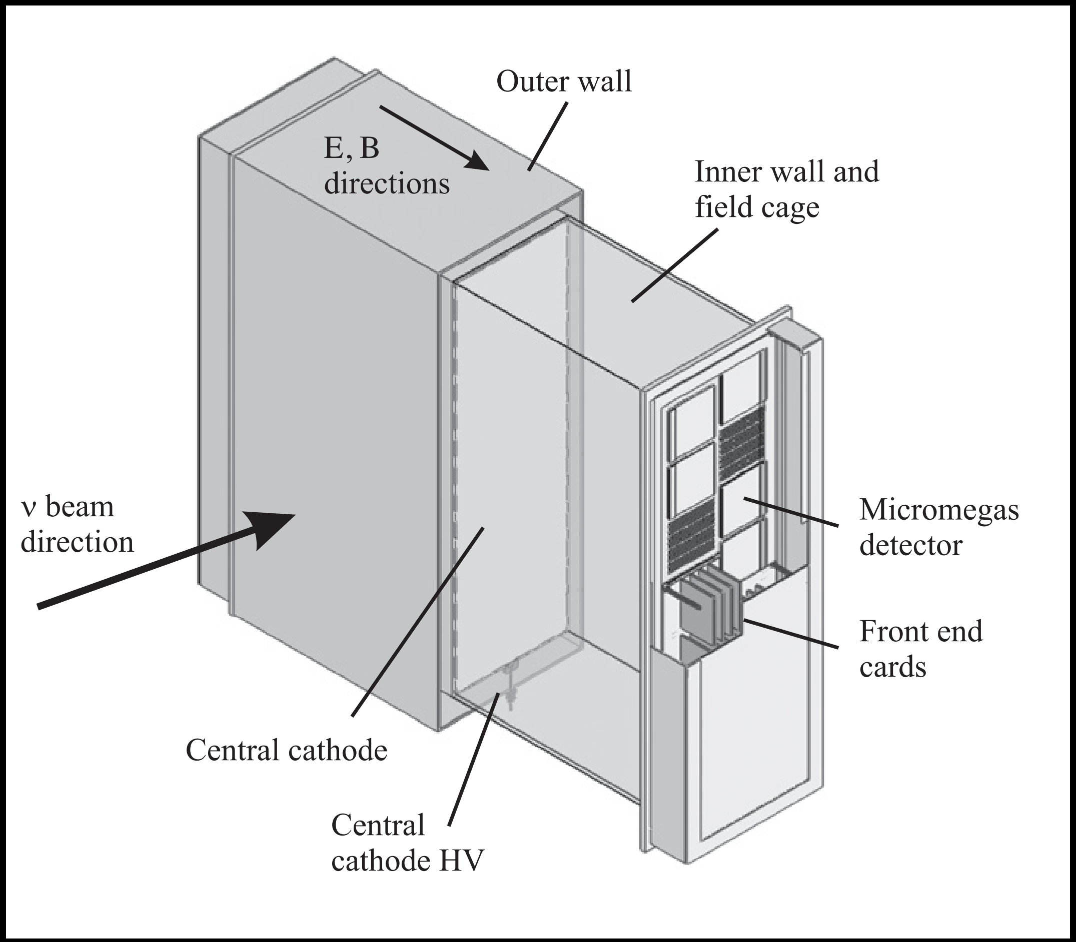
- array of silicon photodiodes operated in in limited Geiger mode
- 1.3 x 1.3 mm^2 with 667 pixels

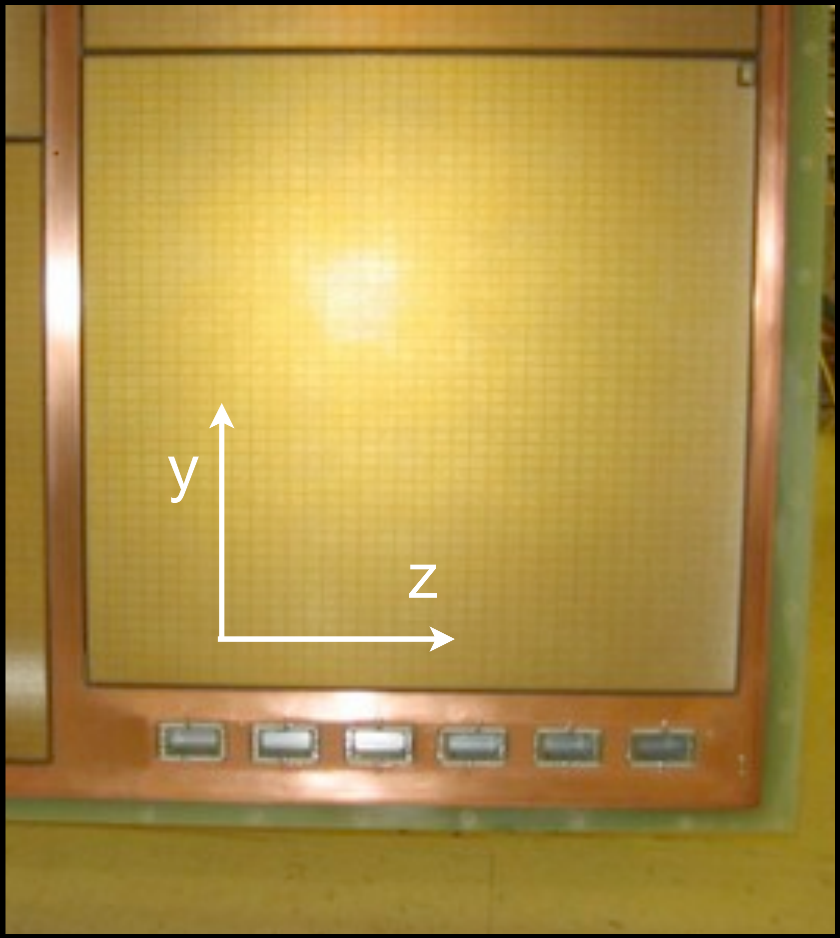
>50000 devices in first large scale use

MPPC coupled to fibers

Cross section of scintillator bar

TPCs

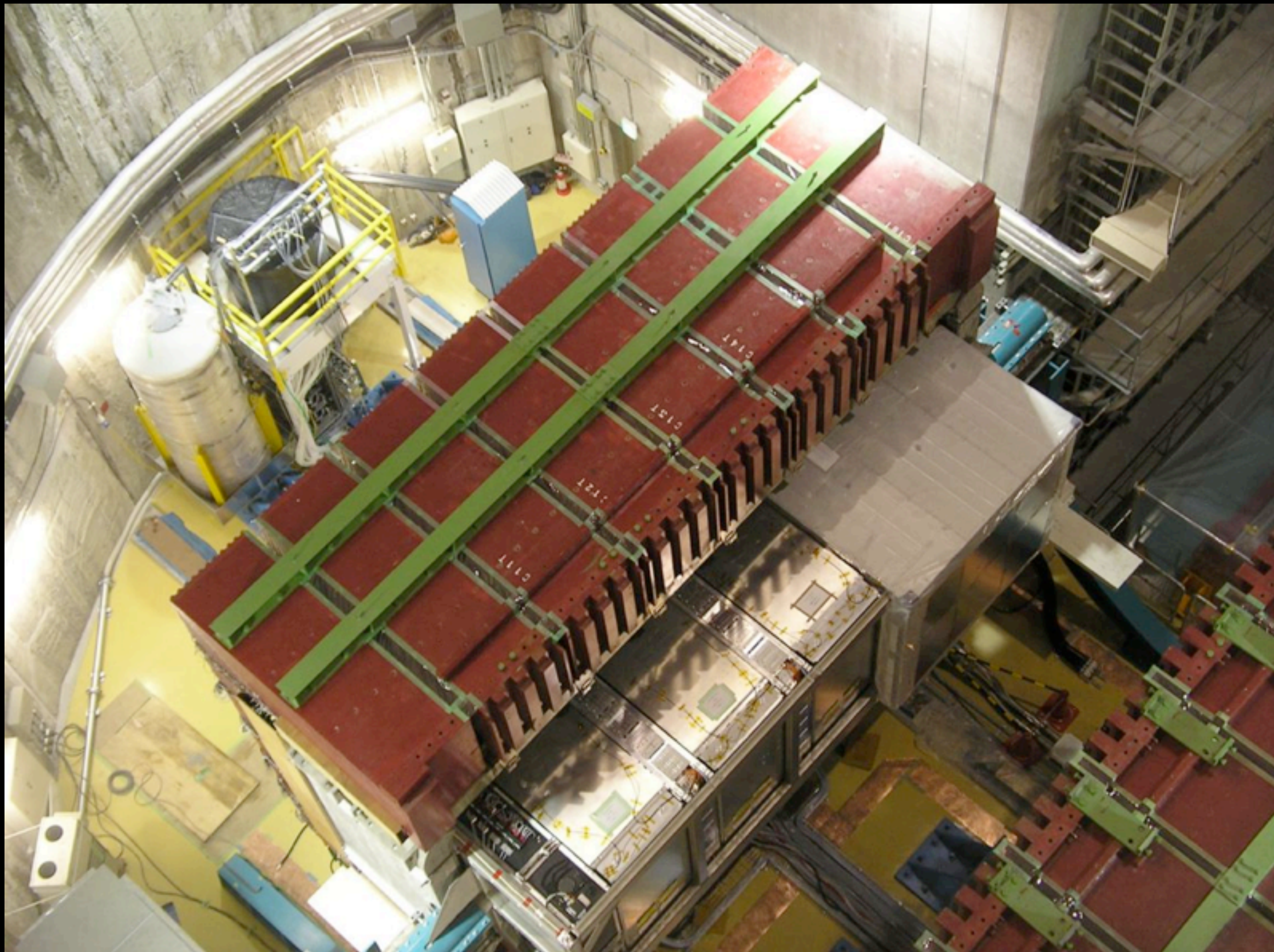




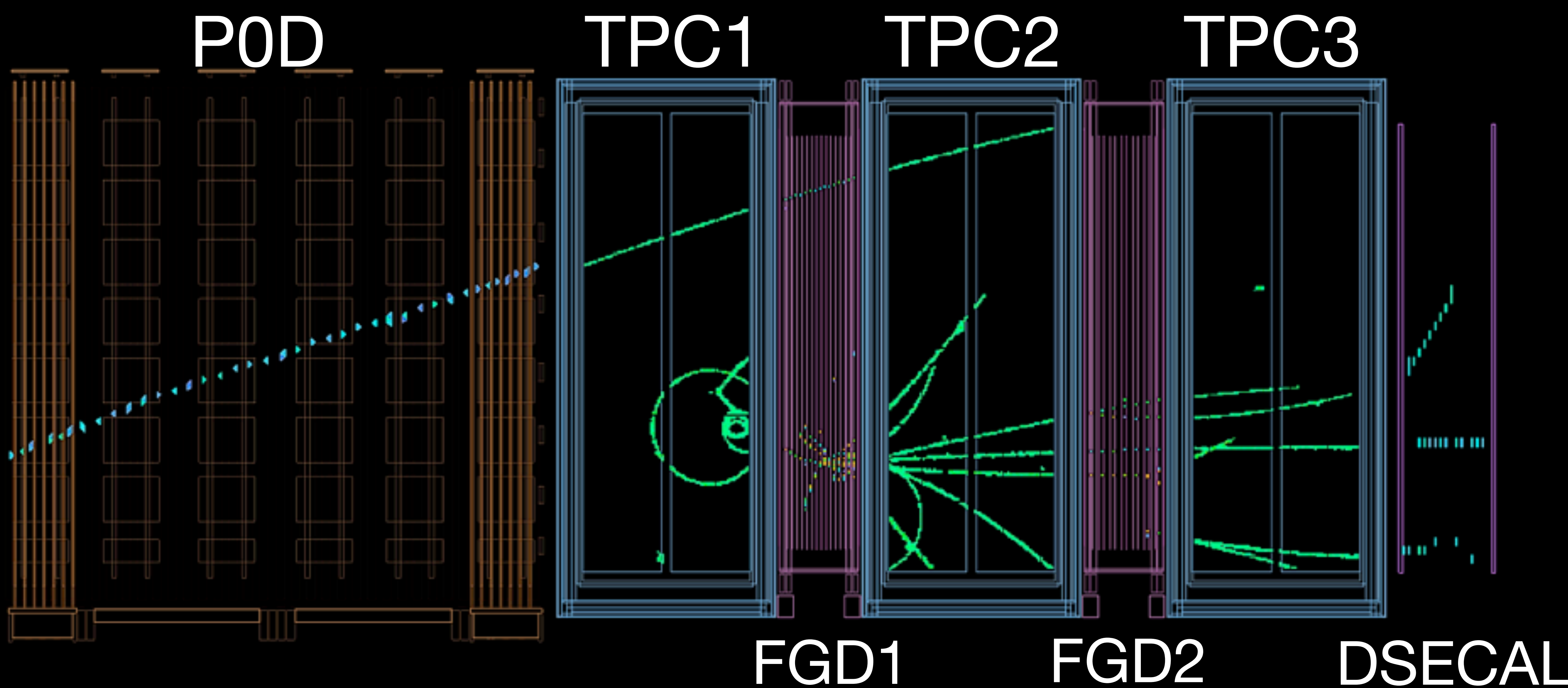
3 Large volume TPCs with MicroMegas amplification/readout

- Ionization measurement for >3 σ separation between e/μ
- <10% momentum resolution at p=1 GeV/c
- scale uncertainty < 2%

Completed Product:

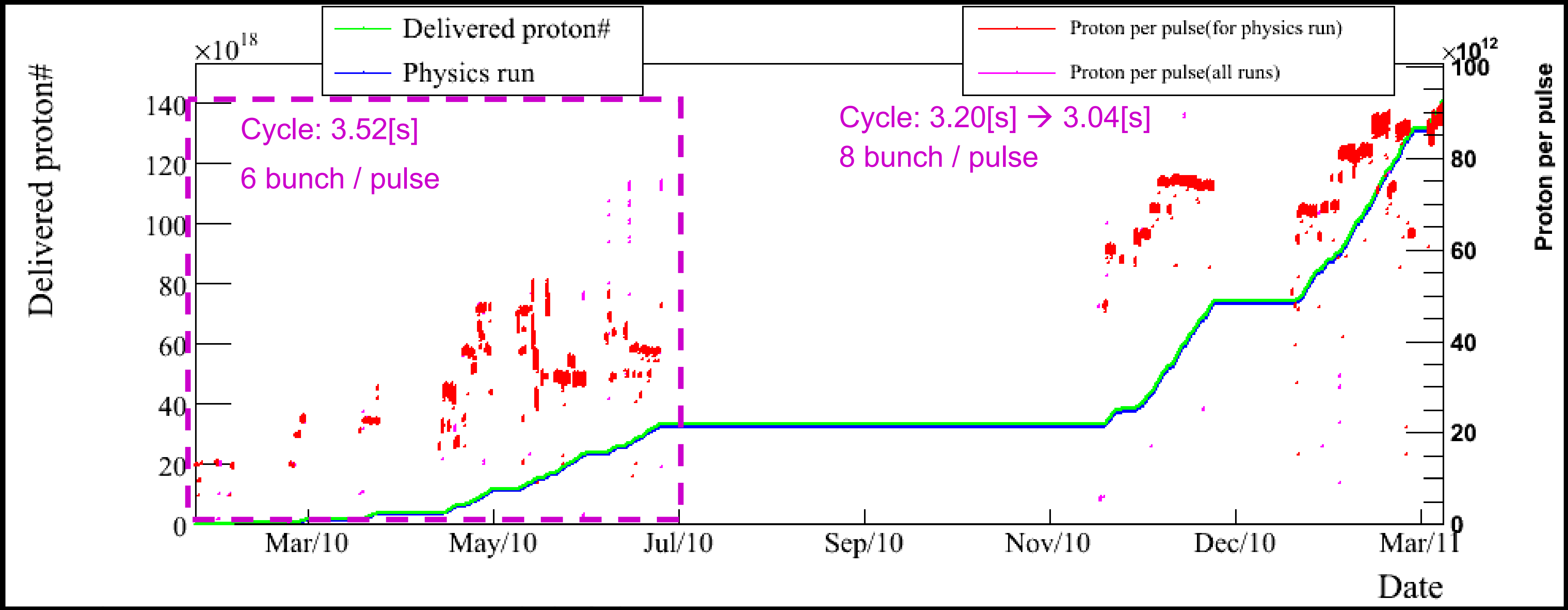


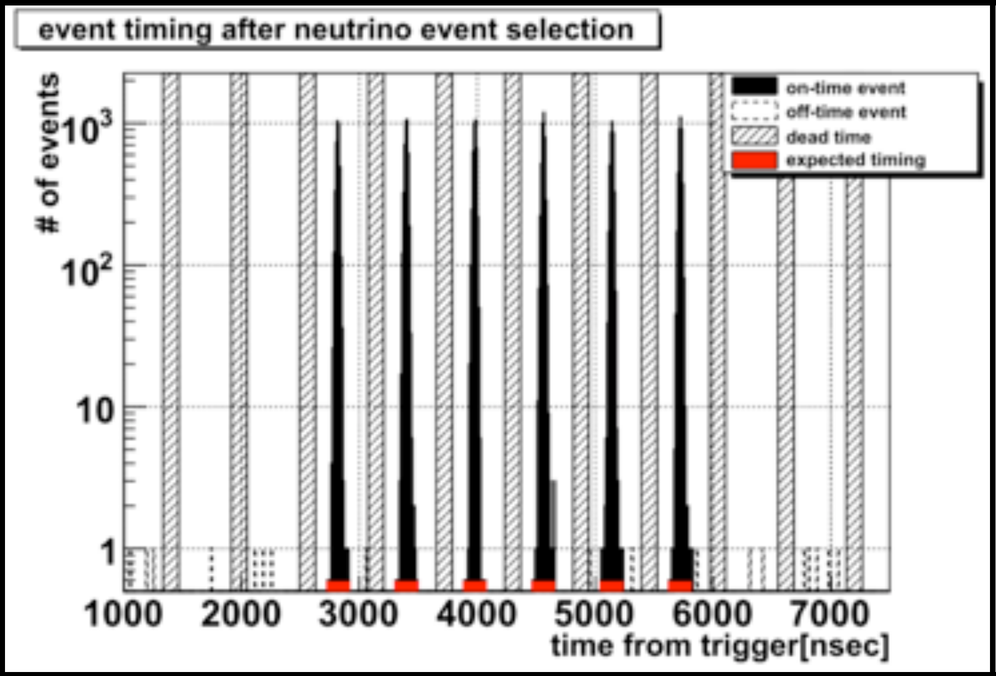
Event:



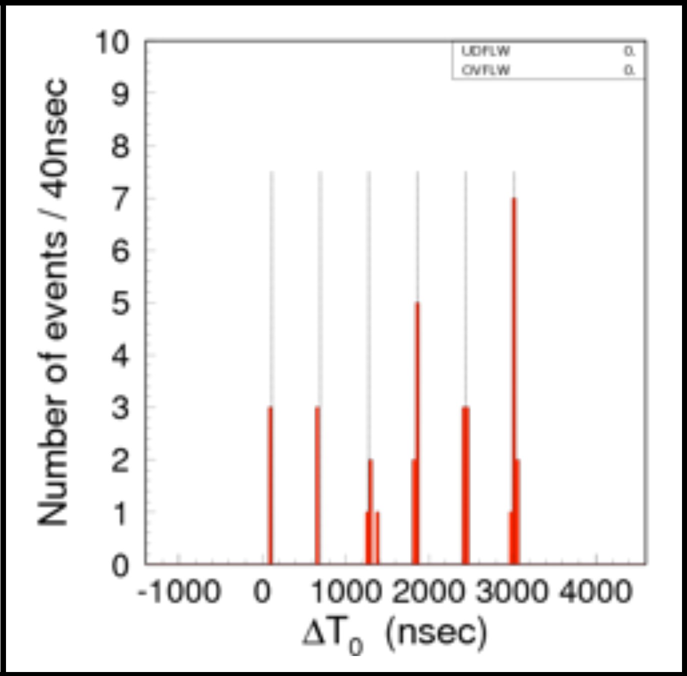
- High energy deep-inelastic scattering event with muon from upstream interaction

Beam Delivery





near detector



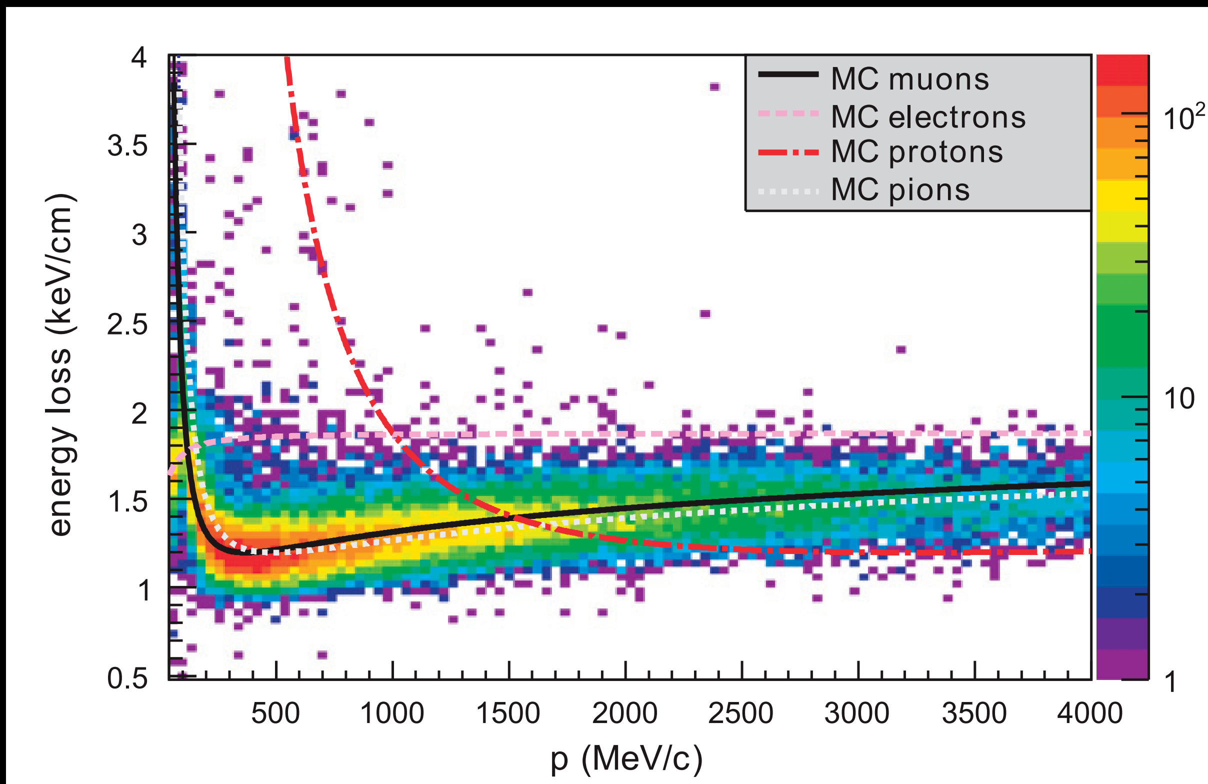
far detector

O(10^{14})/pulse delivered in 6(8) bunches in 3.5(3.2) sec cycle.

145 kW operation achieved (goal 750 kW)

3.23x10^{19} POT from 2010 analyzed thus far

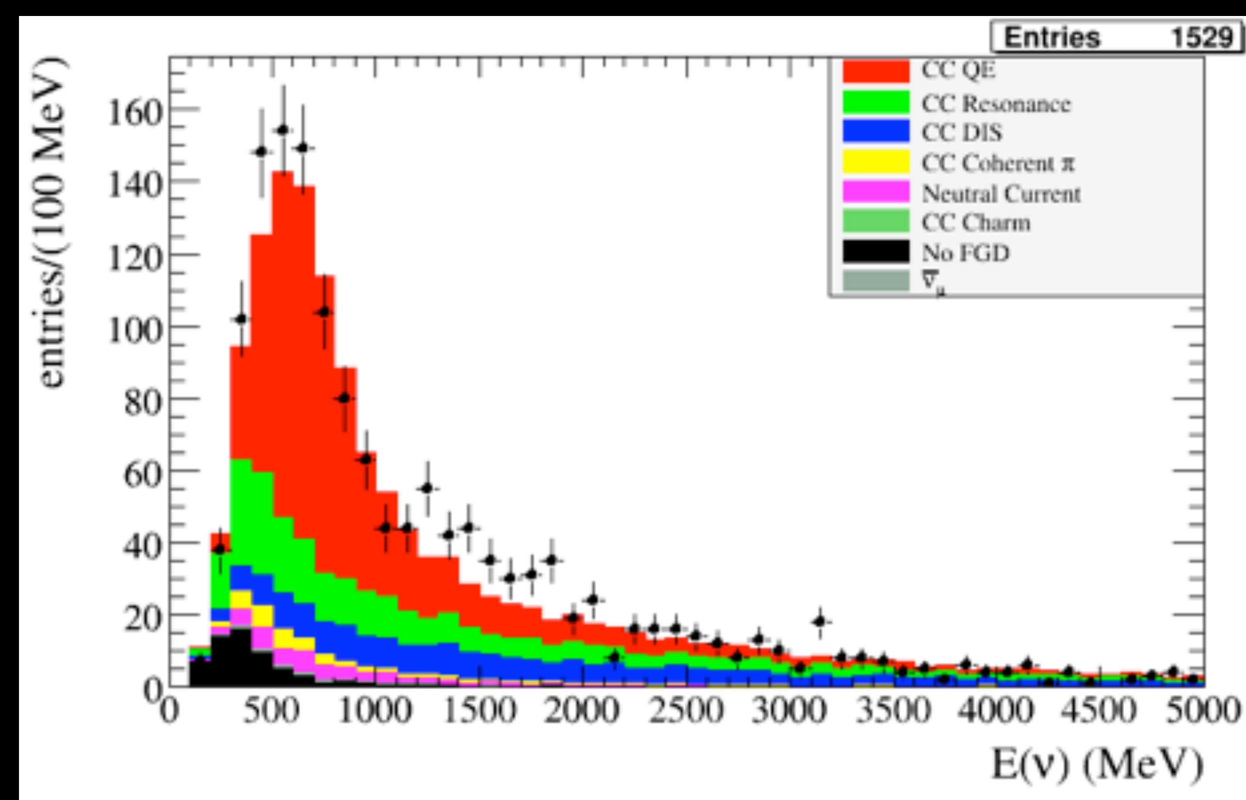
ν_μ CC interactions



"inclusive" ν_μ CC selection

- forward negative muon in TPC
- match to FGD to determine vertex
- veto on upstream TPC1

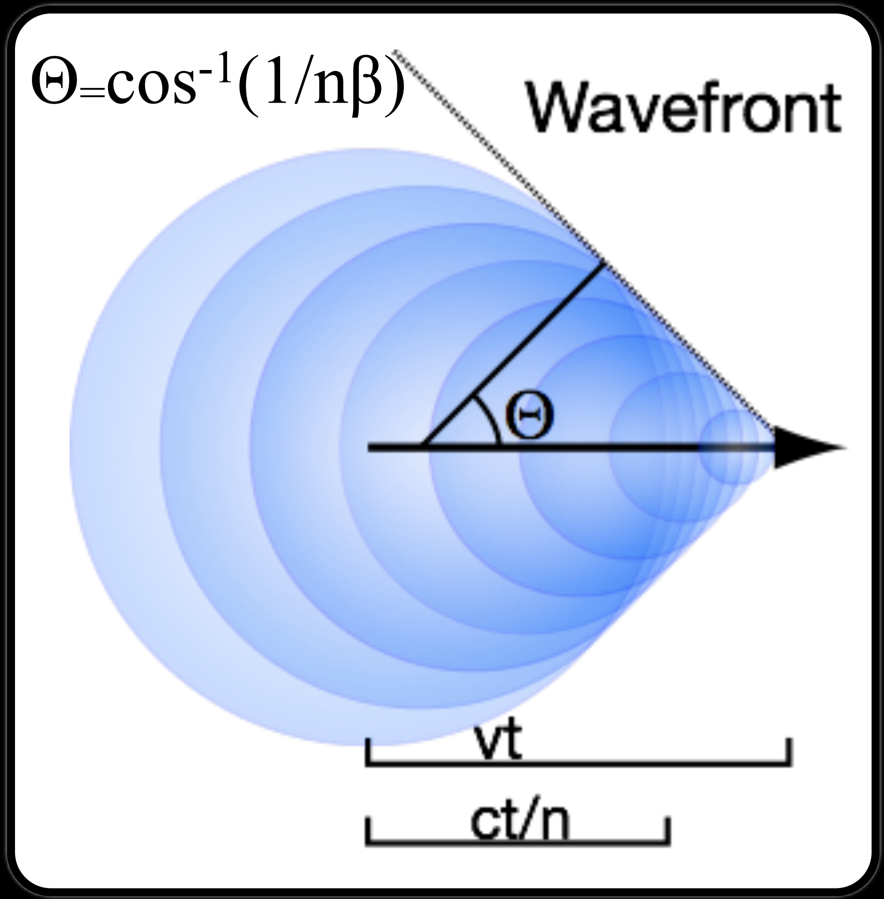
Near detector "normalization" measurement corrects predicted far detector event rates



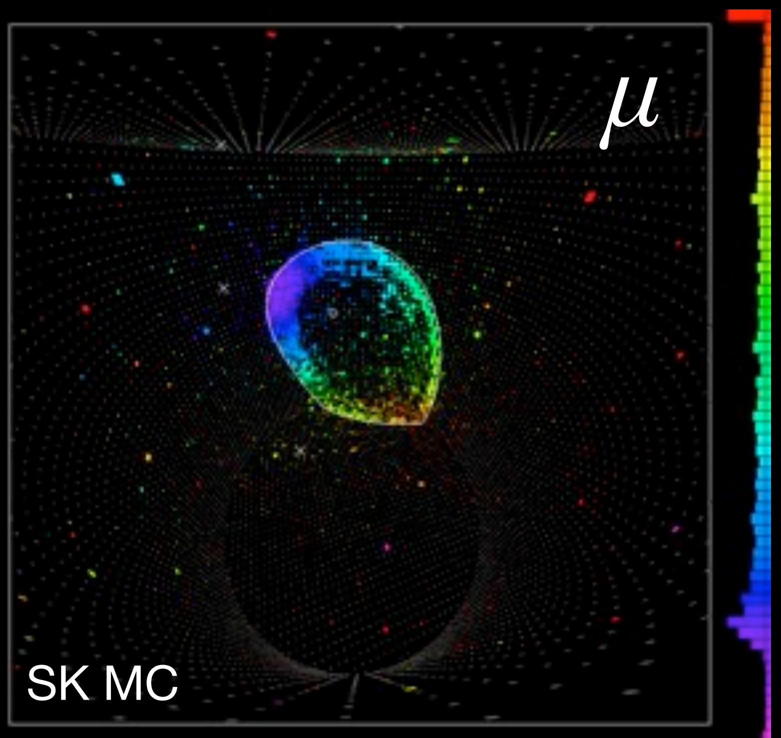
Observed rate relative to expectation is

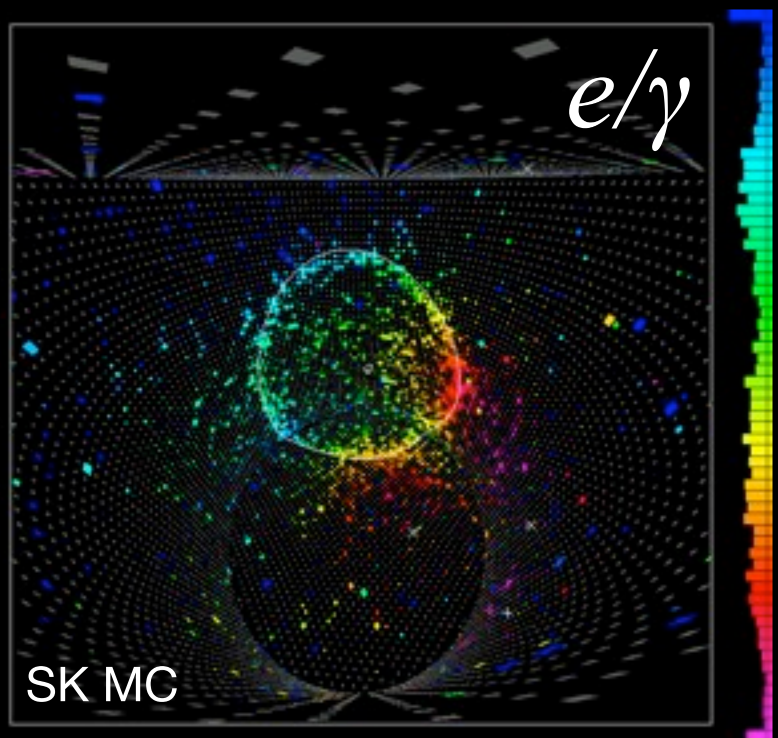
$$R = 1.061 \pm 0.027(\mathrm{stat})^{+0.044}_{-0.038}(\mathrm{det.\ sys.}) \pm 0.039(\mathrm{phys.\ model})$$

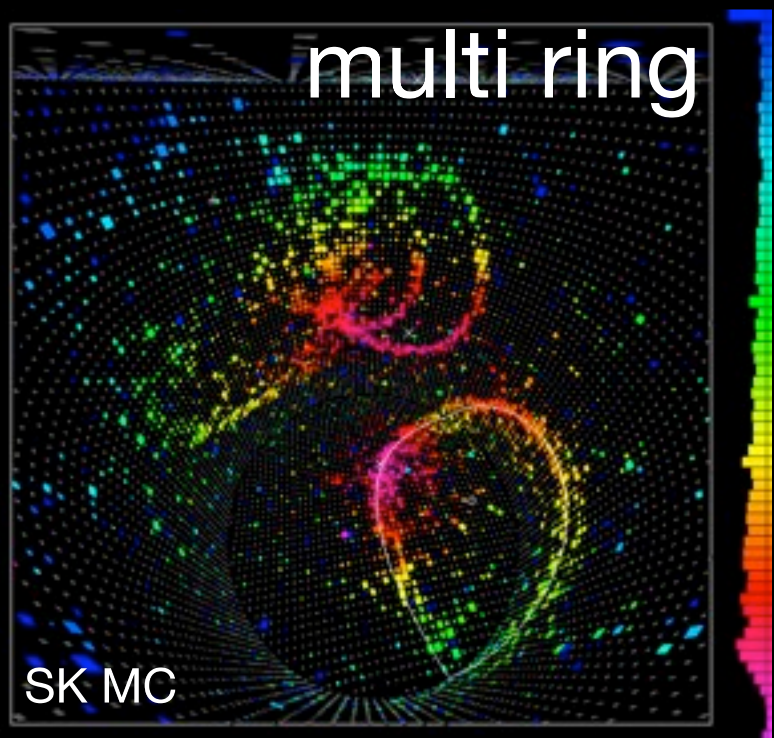
Cherenkov Radiation



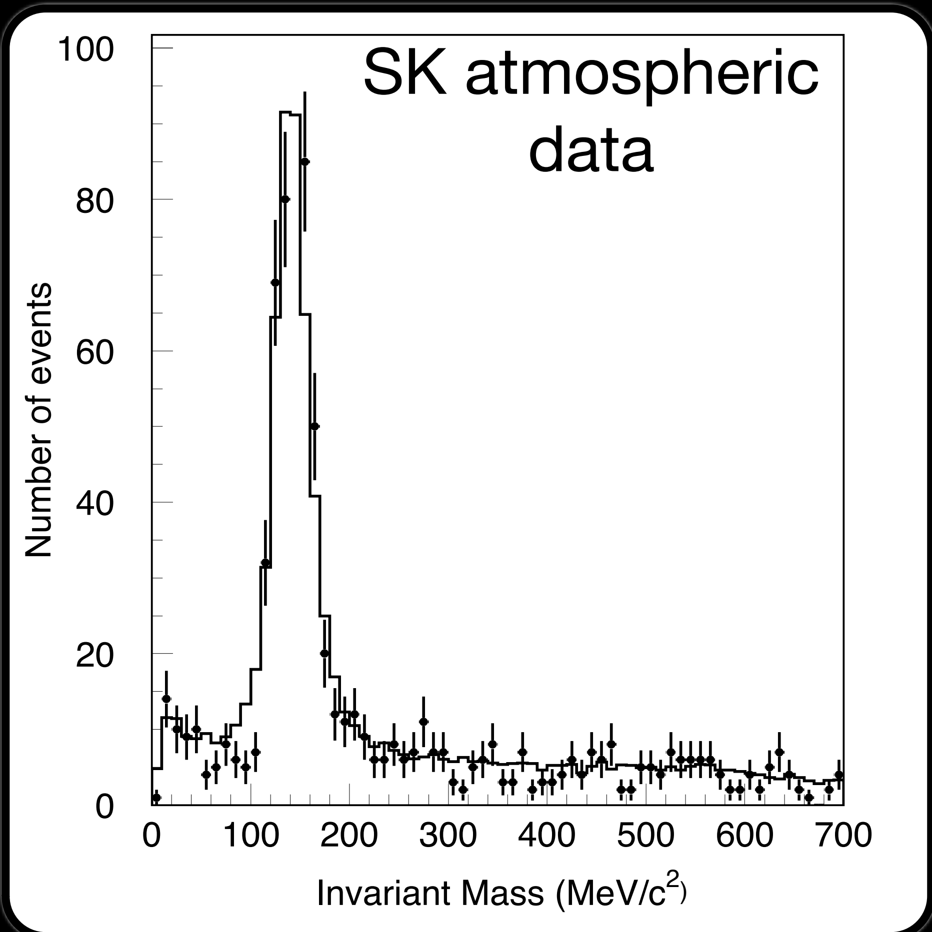
- EM radiation by charged particles with v > c_n
- Detected by >10K photomultiplier tubes
  - sensitive to single photons (40% coverage)
  - O(ns) time resolution
- Particle can be identified by ring profile
  - “muon” vs. e/γ (EM shower)







Signal/Background

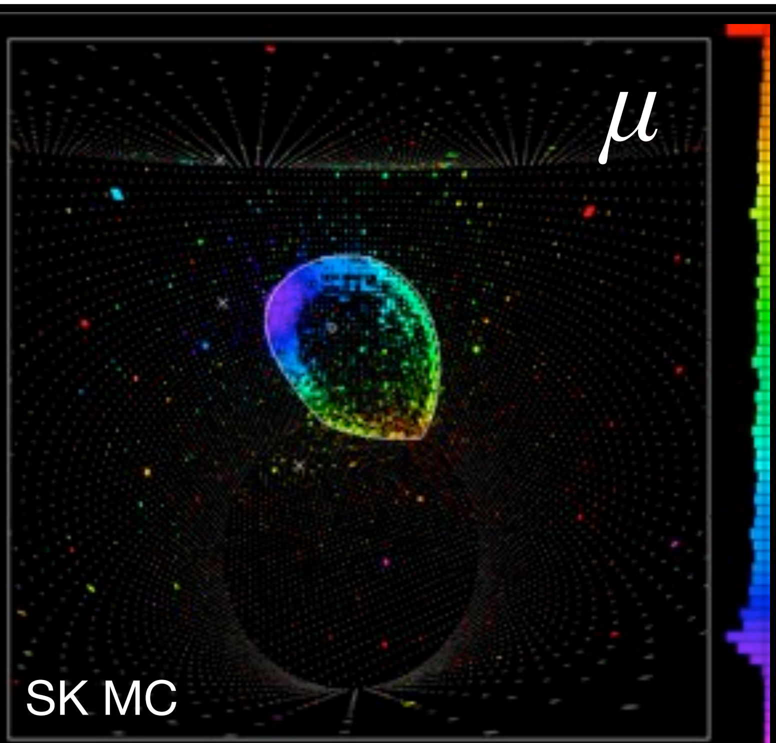


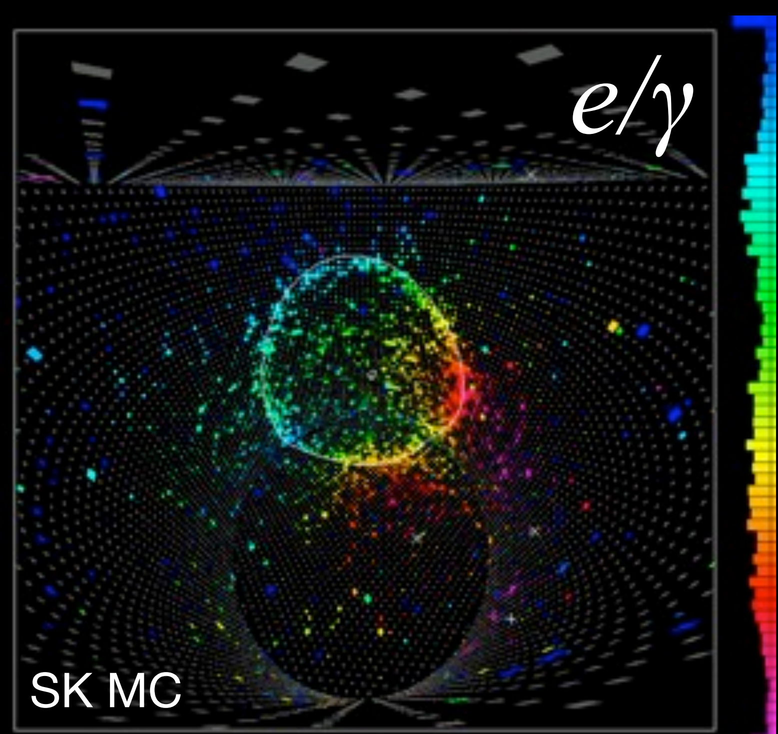
$$\nu_\ell + n \rightarrow \ell^- + p$$

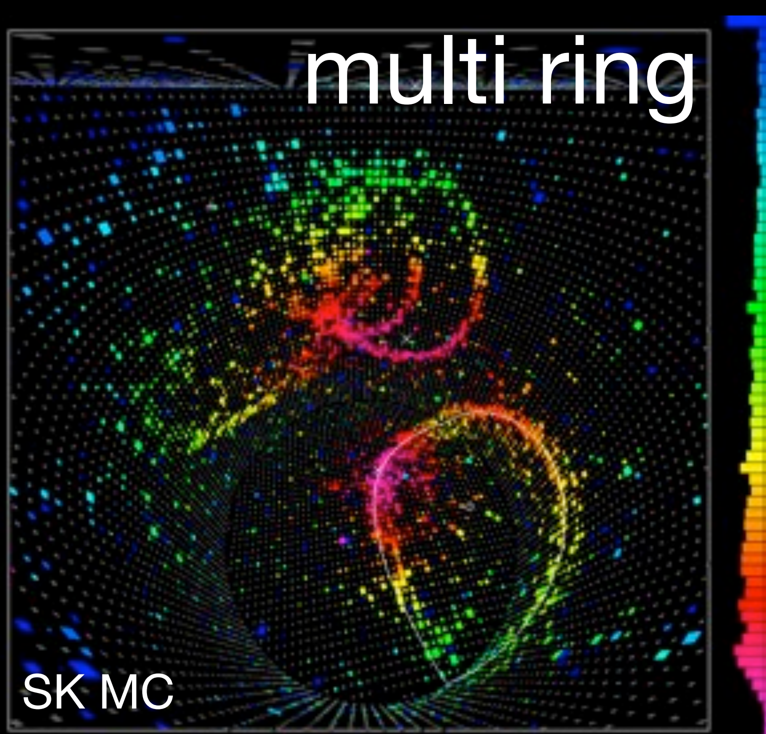
- CCQE appears as single μ or e ring
- E_ν by energy/direction relative to beam.

$$\nu_\ell + (n/p) \rightarrow \nu_\ell + (n/p) + \pi^0$$

- Rings from $\pi^0 \rightarrow \gamma + \gamma$ rejected via 2-ring reconstruction and invariant mass cut
- π^+ rejected by decay electron requirements

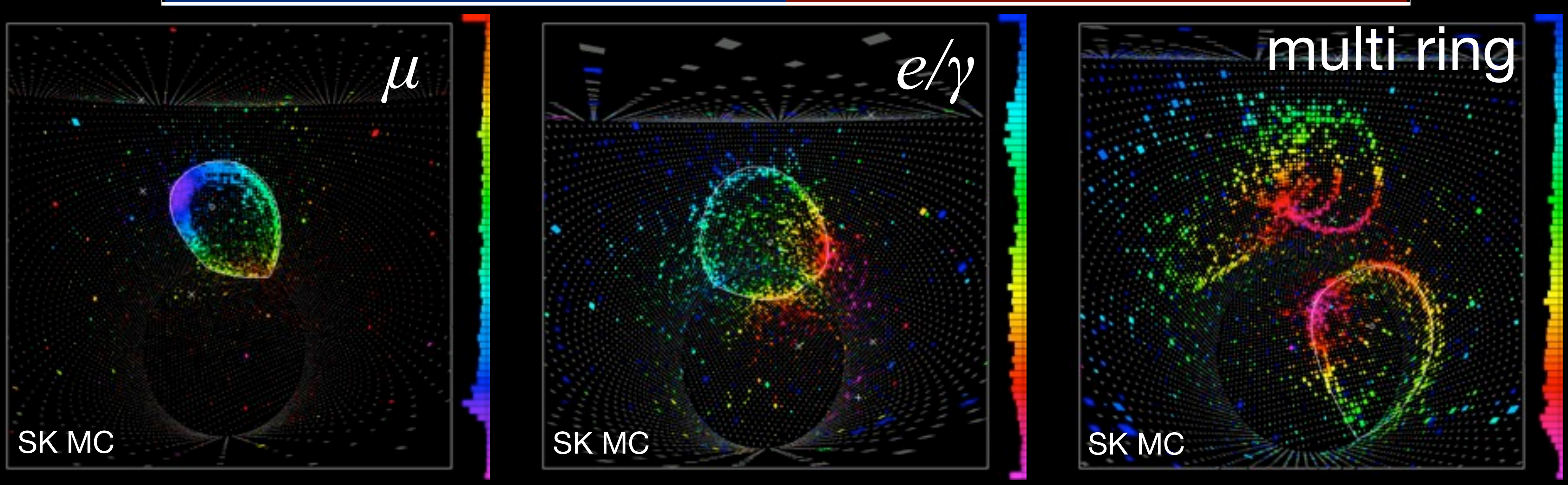




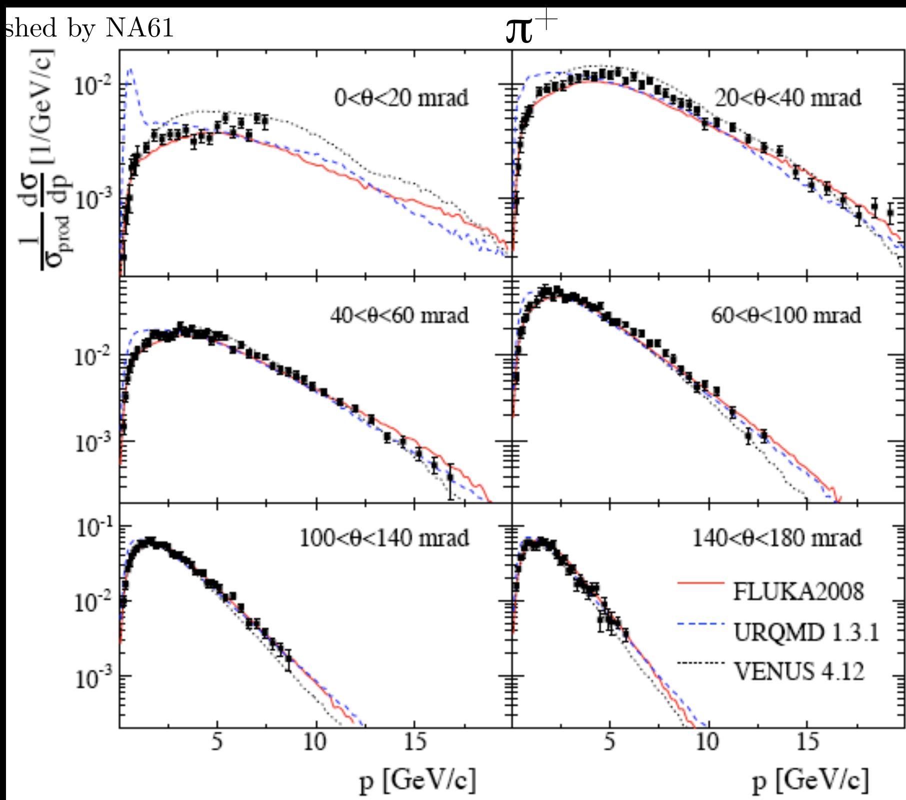


Event Selection

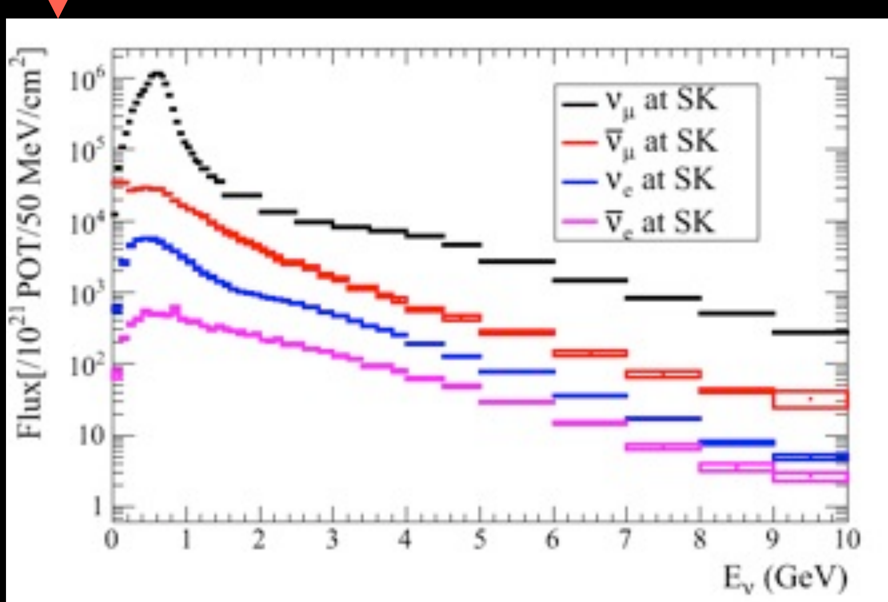
ν_e selection	ν_μ selection
Fully contained, vertex in fiducial volume	
Visible energy > 100 MeV	Visible energy > 30 MeV
Number of Rings = 1	
Ring is e-like	Ring is μ-like
No decay electrons	0 or 1 decay electrons
$\gamma\gamma$ mass < 105 MeV/c^2	-
E_ν<1250 MeV	-
-	μ momentum > 200 MeV/c



Far Detector Prediction:



beam simulation



Neutrino flux prediction

- external input (primary beam parameters, muon/neutrino profile, π/K measurements)
- MC accounts to simulate focussing, geometry.

Neutrino interaction model

- encapsulate accumulated knowledge of neutrino interactions data and modelling

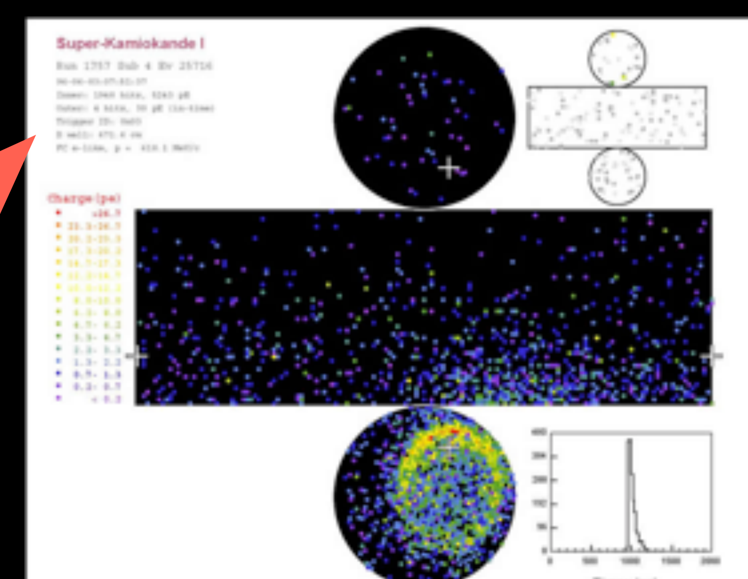
Near Detector data:

- Correct prediction based on observed rate

neutrino event generator

$$\nu_\ell + A \rightarrow \ell + X$$
$$\nu_\ell + A \rightarrow \nu_\ell + X$$

detector simulation



Systematic Uncertainties

Error source	Signal (%)	Background (%)
Normalization	1.4	1.4
Energy Scale	0.3	0.5
Ring counting	3.9	8.4
Muon PID	-	1.0
Electron PID	3.8	8.1
π^0 mass cut	5.1	8.7
Decay electron	0.1	0.3
π^0 rejection	-	5.9

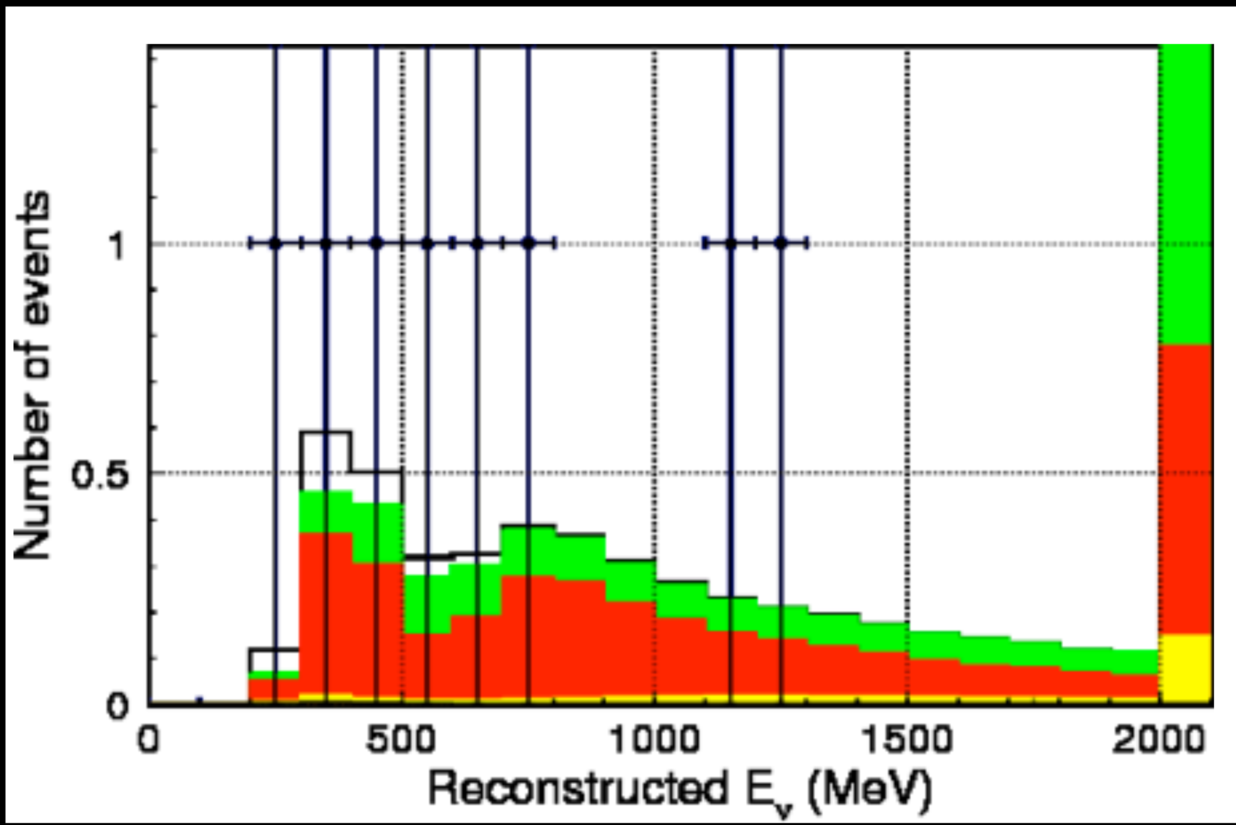
Far detector uncertainties

- Far detector systematics determined from control samples (atmospheric neutrinos, “hybrid” π^0, etc.)
- Cross section uncertainties dominated by FSI and CCQE modelling

Total background systematics

Error source	$N^{BKG}{}_{SK}$ (%)	N_{ND} (%)	$N_{BKG}{}^{SK}/N_{ND}$ (%)
SK Efficiency	±15.8	-	±15.8
Cross Section	±13.9	±8.4	±14.3
Beam Flux	±18.1	±19.8	±8.9
ND efficiency	-	$^{+5.6}_{-5.2}$	$^{+5.6}_{-5.2}$
Overall Norm	-	-	±2.7
Total	**±27.8**	$^{+22.2}_{-22.1}$	$^{+23.9}_{-23.8}$

μ Events in Far Detector



ν_μ CCQE selected by requiring

- contained event in fiducial volume of detector
- one muon-like Č ring
- at most one decay electron

"w/oscillation":
$\Delta m^2_{23} = 2.4\times10^{-3}$ eV^2
$\sin^2 2\theta_{23} = 1$

	Data	MC Expectation		Acc. Bg
		no oscillation	w/oscillation	12μs window
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	-
decay-e <=1 & E_{rec}<10 GeV	**8**	22.8±3.2	6.3±1.0	-

data consistent with previously measured Δm^2_{23}, θ_{23}

ν_e Selection

	Data	MC Expectation: no oscillation	MC Expectation: w/oscillation	Acc. Bg (12μs window)
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 E_e>100MeV/c	2	1.5±0.7	1.3±0.6	-

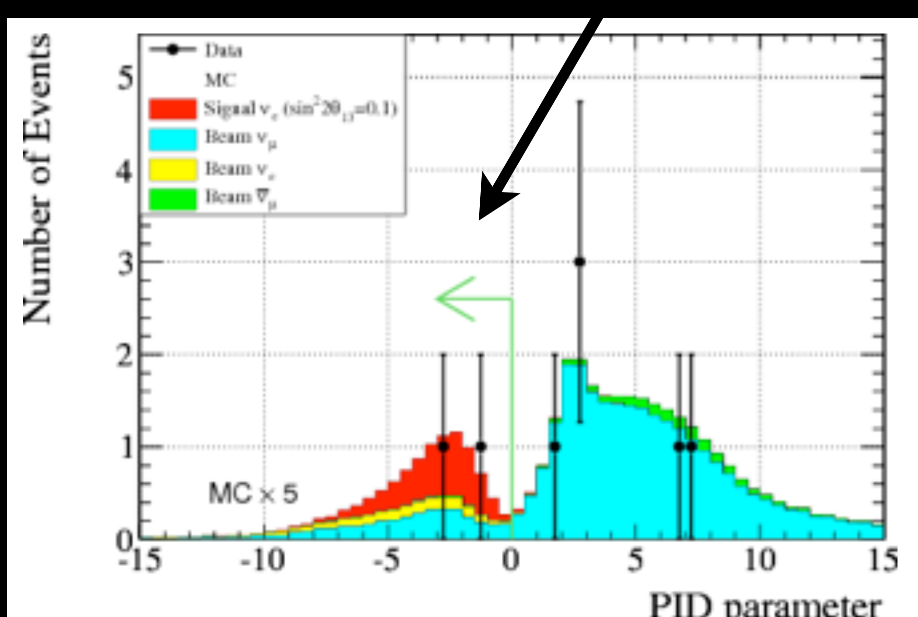
"w/oscillation":

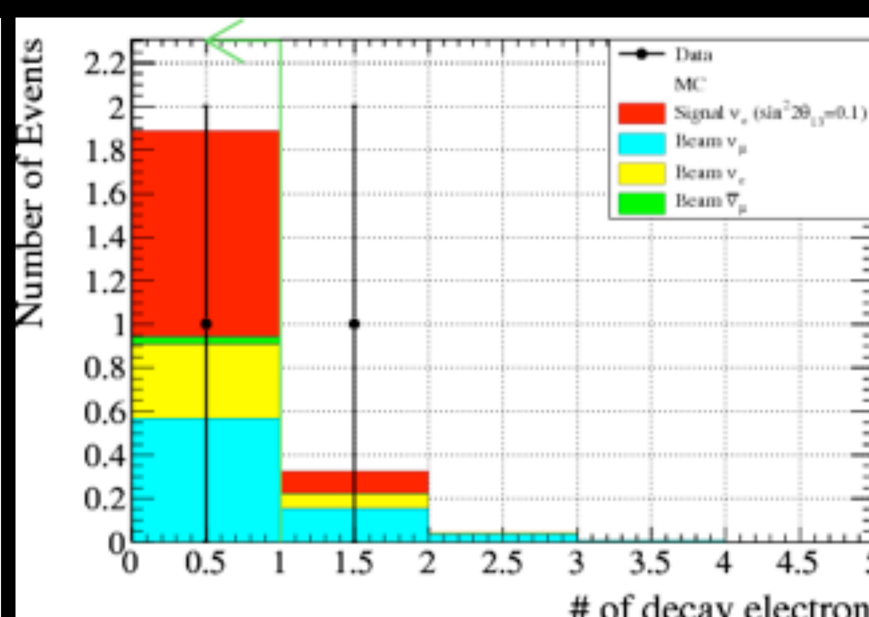
$\Delta m^2_{23} = 2.4\text{x}10^{-3}\ \text{eV}^2$

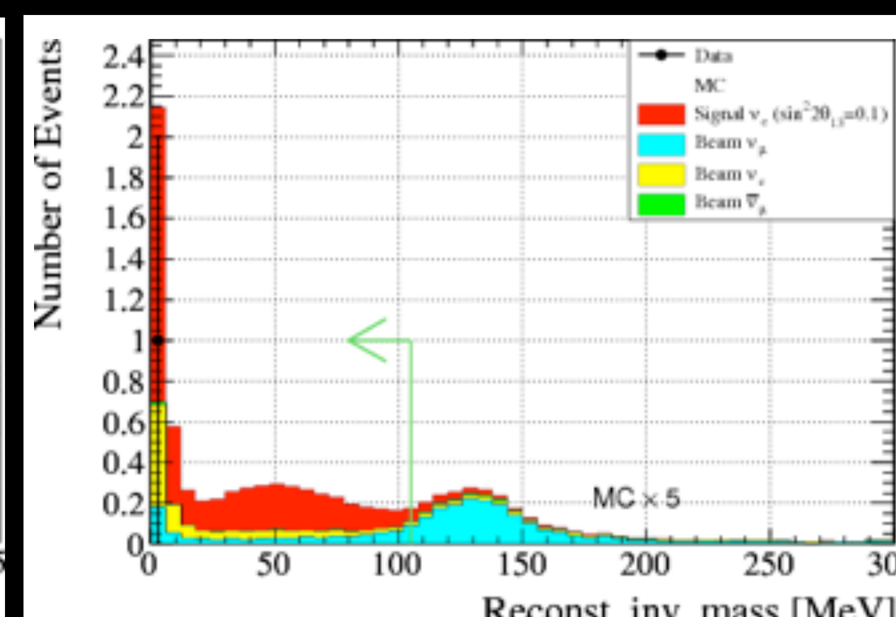
$\sin^2 2\theta_{23} = 1$

$\sin^2 2\theta_{13} = 0.1$

$\delta_{CP} = 0$

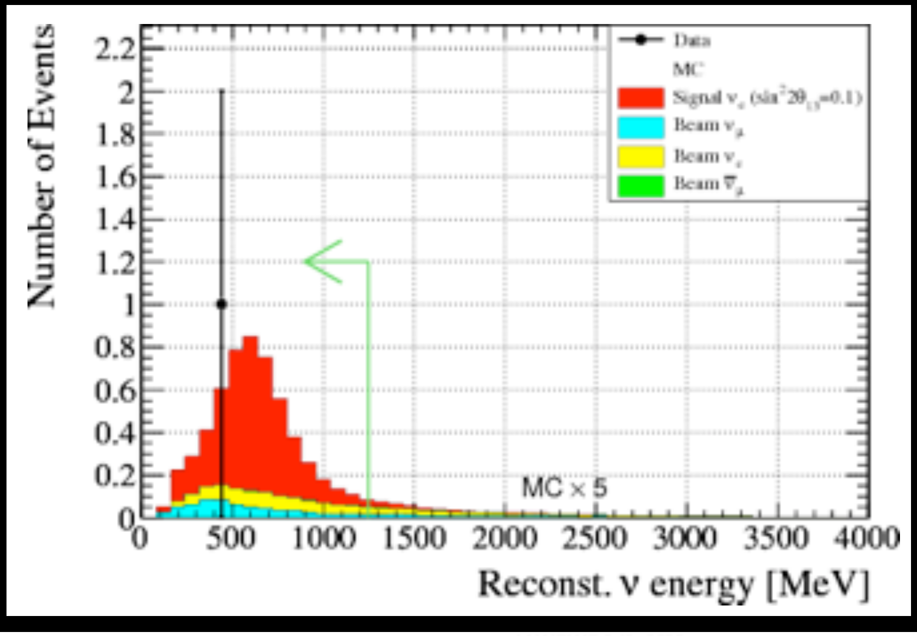




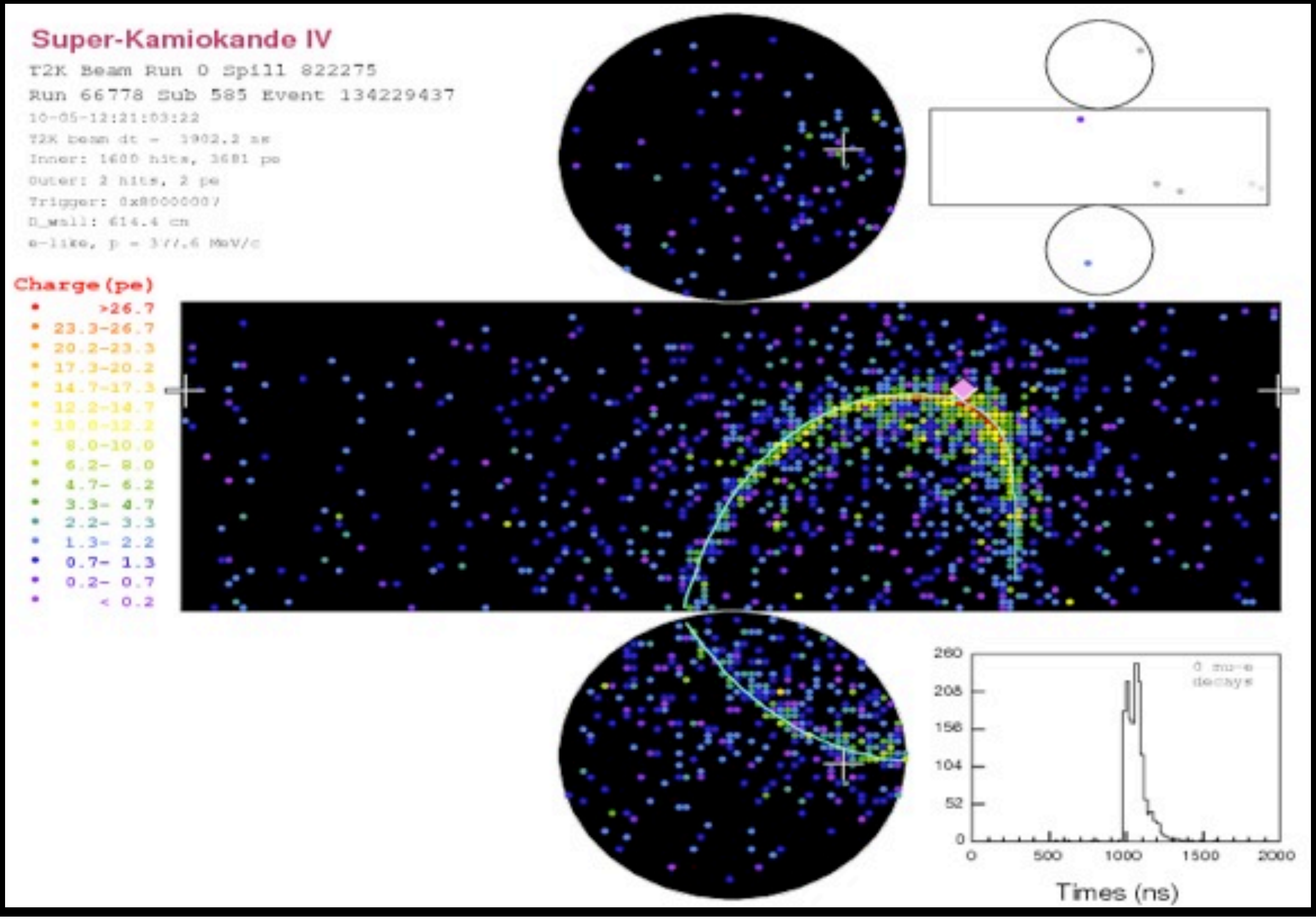


ν_e candidate event

Source	MC Expectation
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.)**

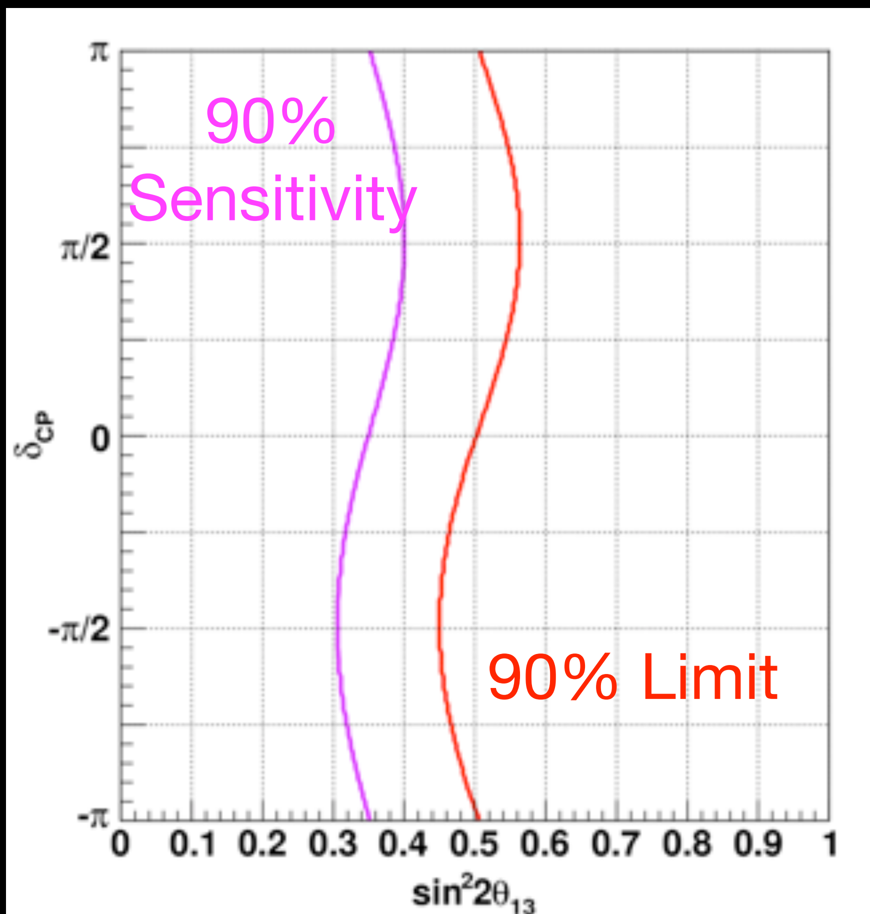


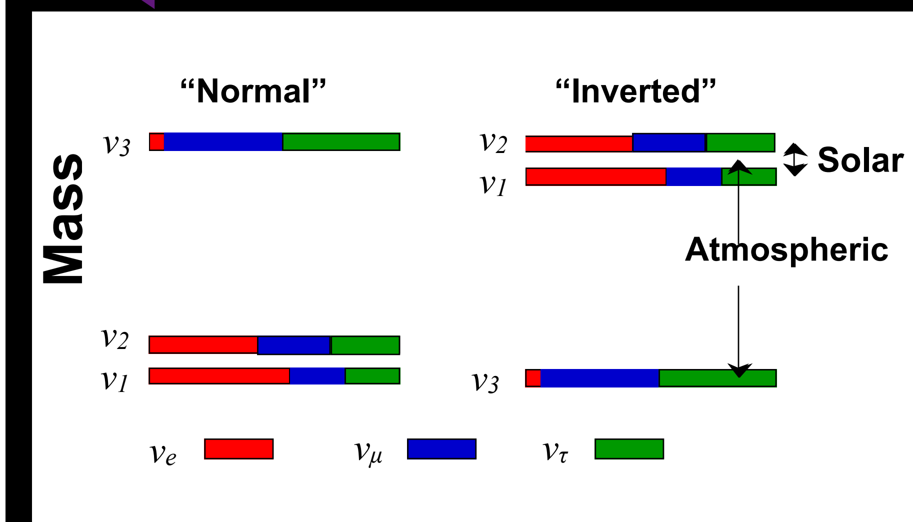
1 event remains with expected background of 0.30±0.07 events



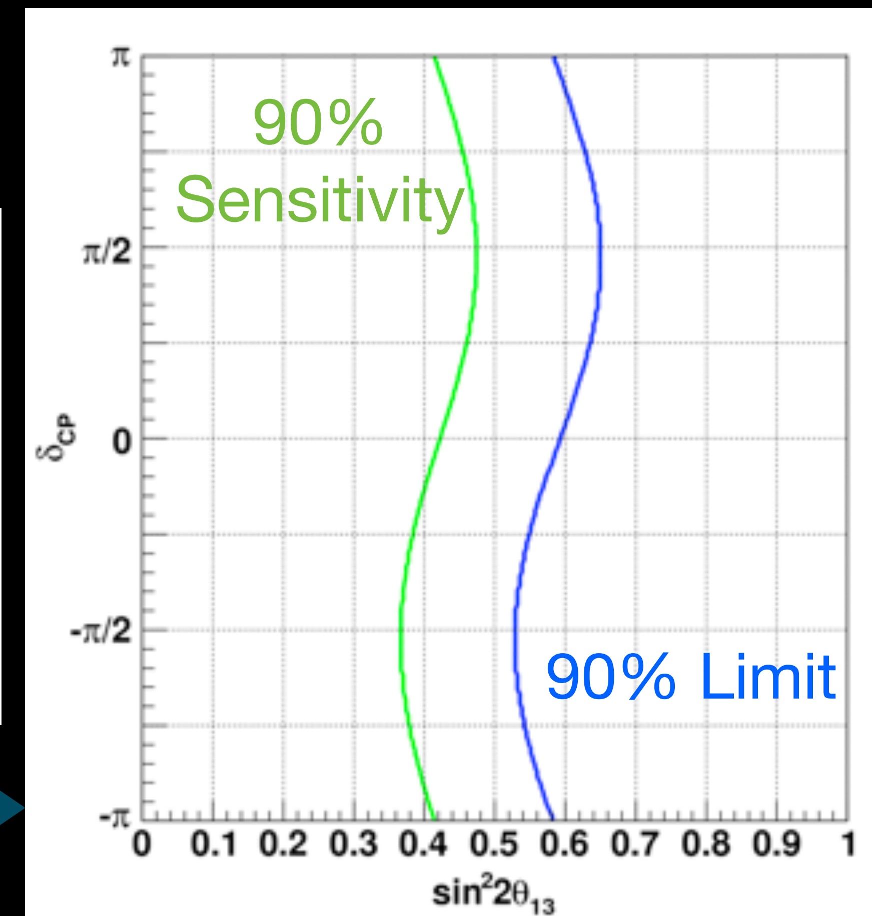
Result

“Normal” Hierarchy





“Inverted” Hierarchy

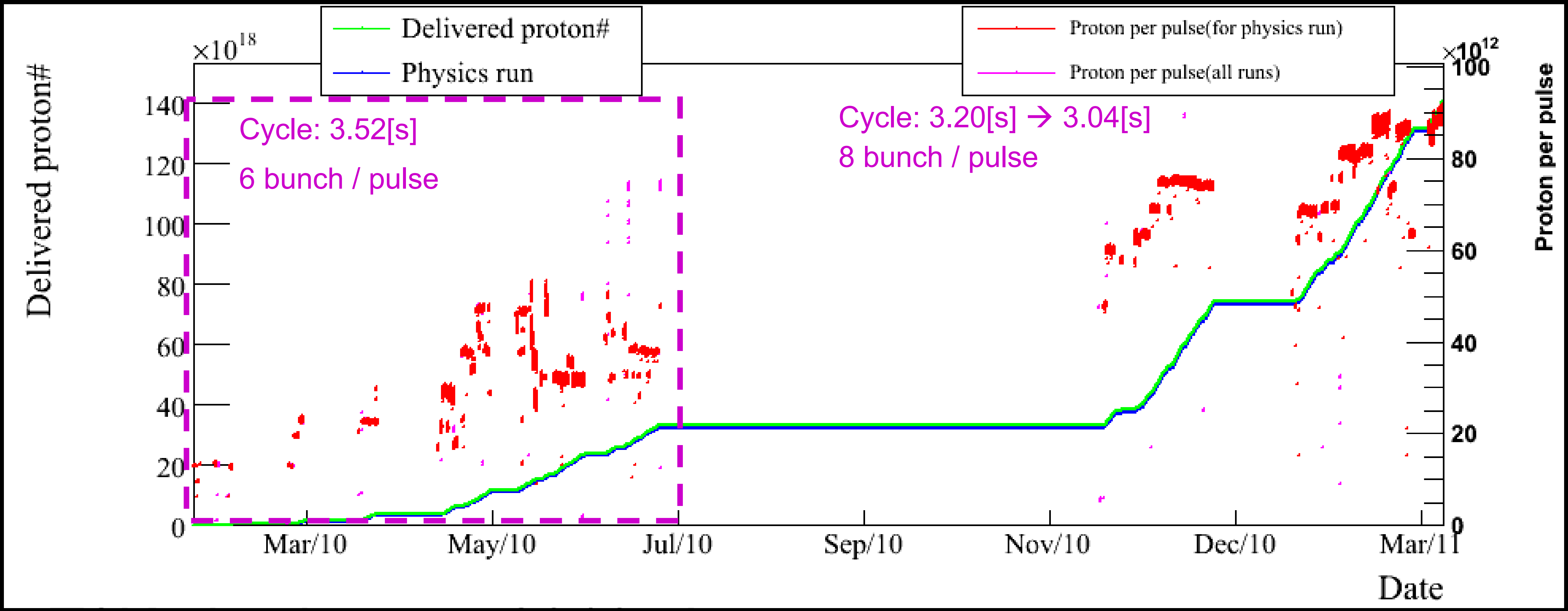


Exclusion versus oscillation parameters (θ_{13}, δ_{CP}, mass hierarchy)

For $\delta_{CP} = 0$

- Feldman Cousins method: $\sin^2 2\theta_{13} < 0.50$ (normal) / 0.59 (inverted)
- 1-sided upper limit: $\sin^2 2\theta_{13} < 0.44$ (normal) / 0.53 (inverted)

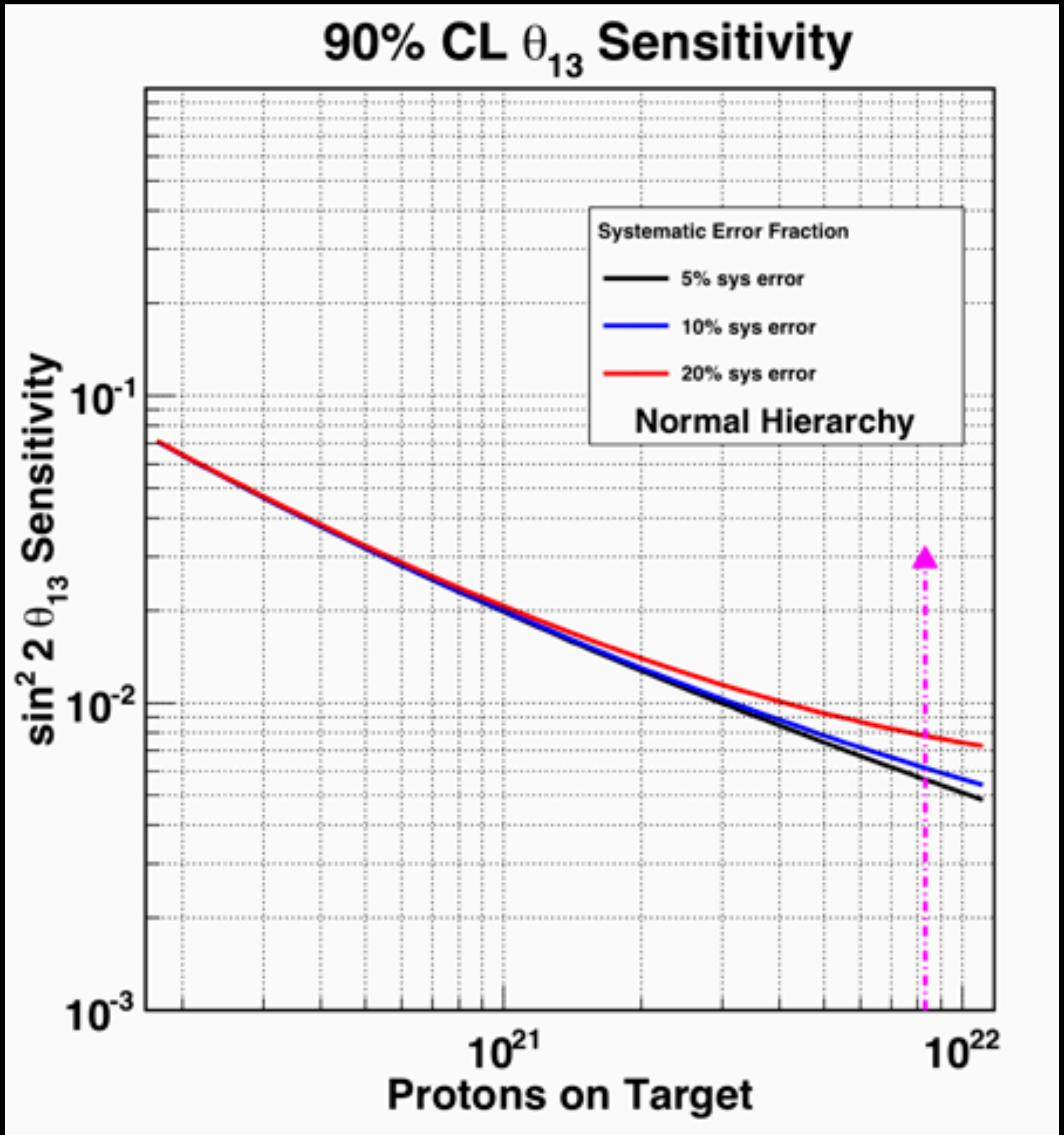
Current Status



Since November 2010

- Accumulated 1.45×10^{20} POT till March 2011
- ~4 times data presented here (3.23×10^{19} POT)
- analysis in progress

Looking Ahead:



Neutrino flux prediction

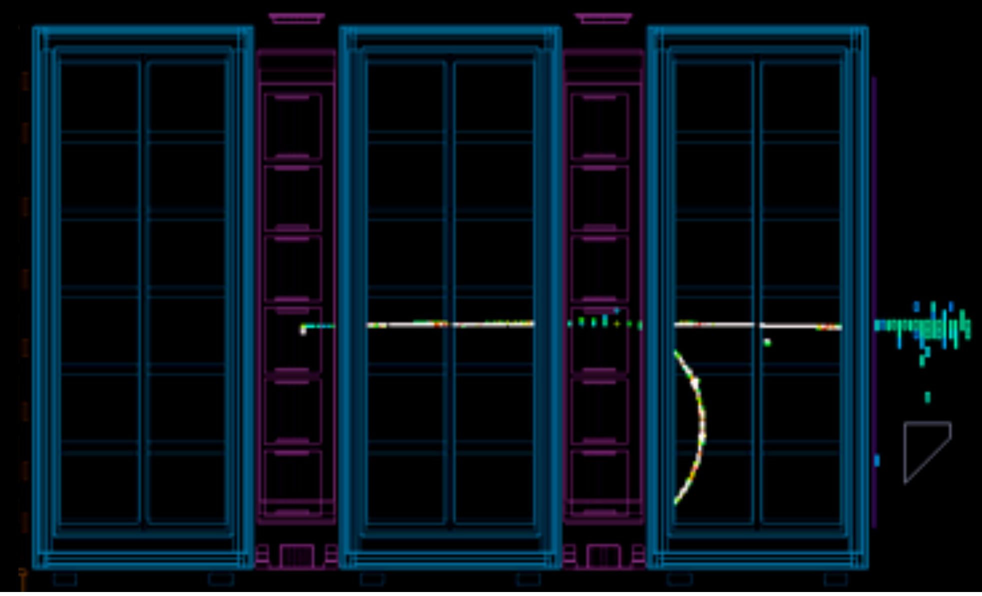
- improved $\pi^{\pm}$ measurements
- K production measurements
- full target measurement

Near Detector:

- ν_e and ν_μ spectrum measurement
- π^0 production
- ν interaction properties

Far Detector

- Improved selection and systematics



Ultimate sensitivity:
$\sin^2 2\theta_{13} \sim 0.006$ ($\delta_{CP} = 0$)
$\delta \sin^2 2\theta_{23} \sim 0.01$

Conclusions

- T2K has produced its first neutrino oscillation results
  - 3.23 x 10^{19} POT taken in first half of 2010
  - 8 ν_μ CCQE candidates at far detector consistent with past ν_μ disappearance experiments
  - 1 ν_e candidate with expected background of 0.30±0.07
- 1.45x10^{20} POT taken before March earthquake
  - expect θ_{13} sensitivity better than CHOOZ limit
  - analysis underway
- Tsunami from March earthquake did not reach J-PARC
  - all T2K collaborators safe
  - recovery assessments continue
  - We thank you for support and solidarity