K2K ν_μ disappearance analysis with and expanded fiducial volume at Super-Kamiokande

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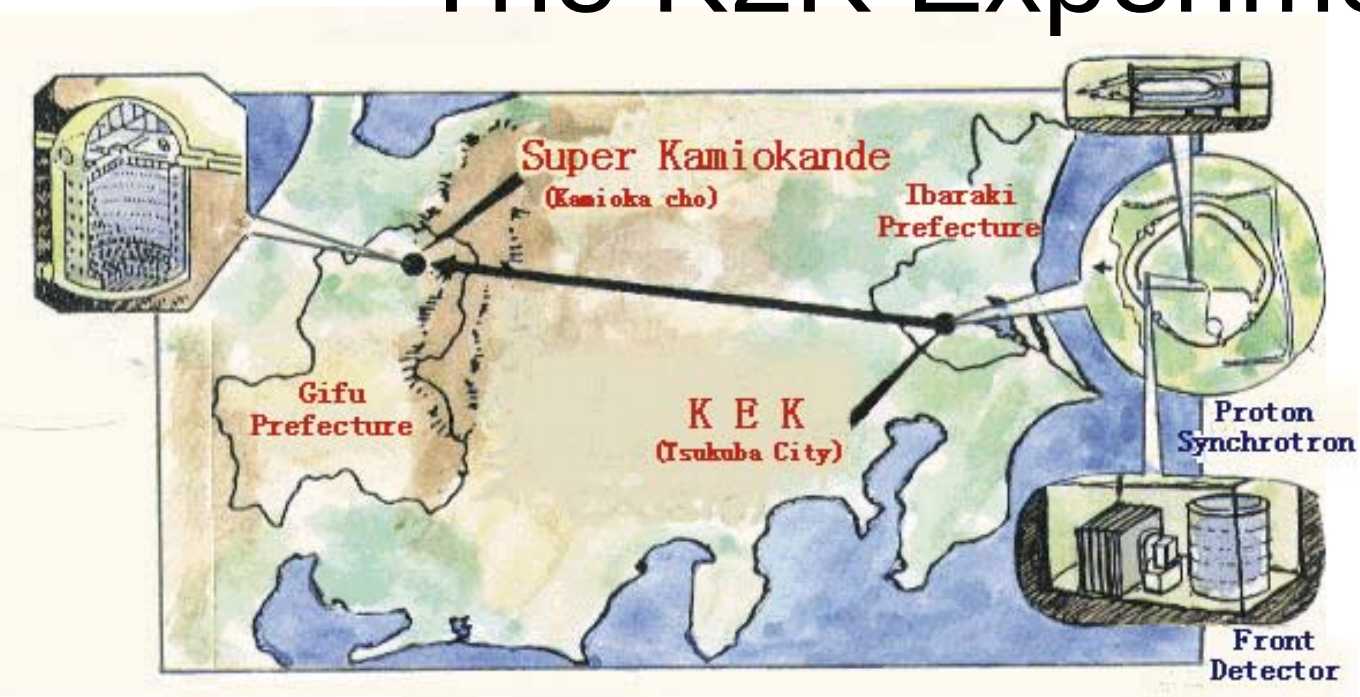
The K2K Experiment



Verify atmospheric neutrino oscillation parameters with a man-made neutrino beam

Assuming 2 Flavor Oscillations:

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

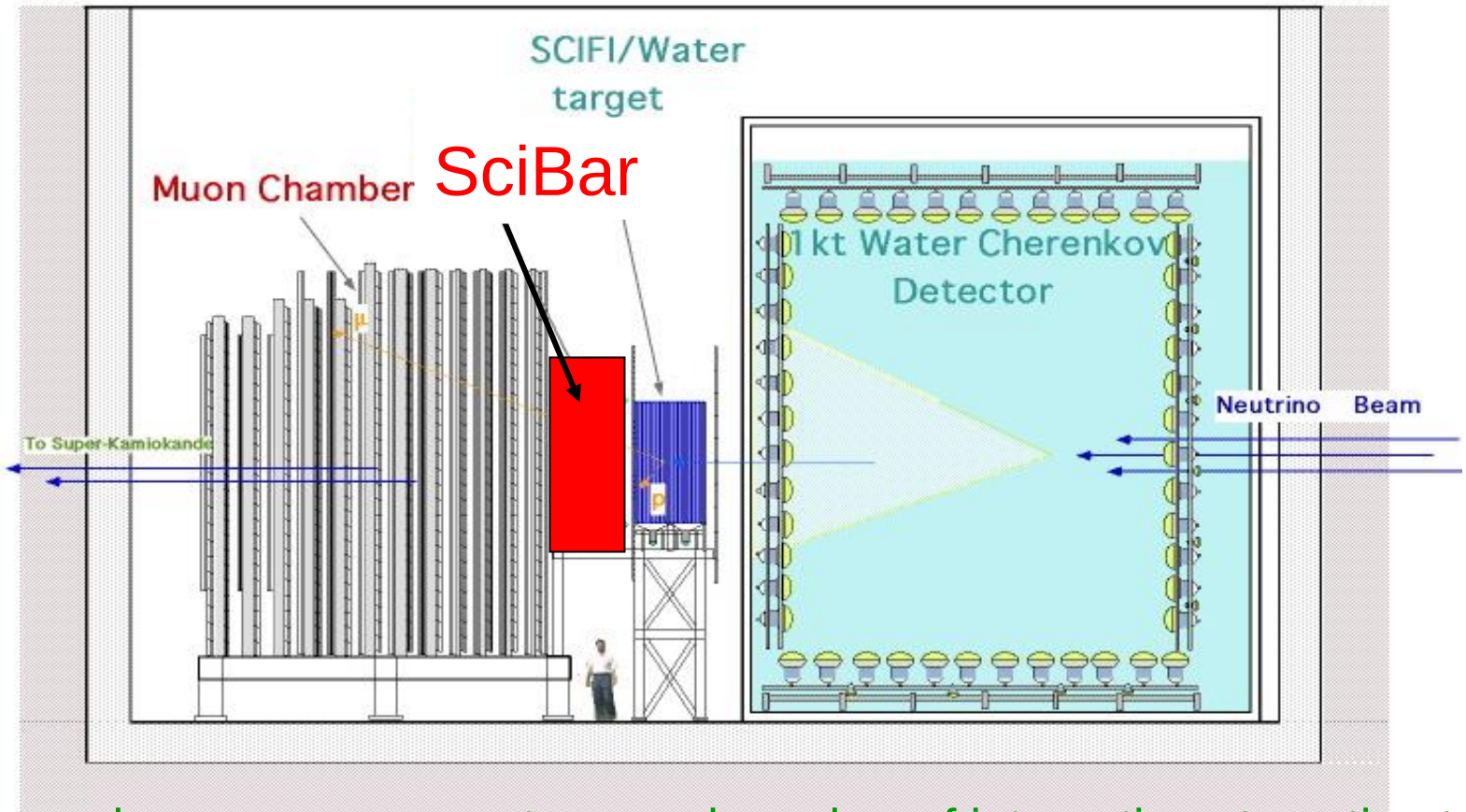
$\sin^2 2\theta = 1.0$ and

$\Delta m^2 \sim 2\text{-}3 \times 10^{-3}\ \text{eV}^2$

L = 250km

E_{peak} = 1 GeV

K2K-II Near Detector



Measures beam energy spectrum and number of interactions to estimate number of events & energy spectrum at far detector

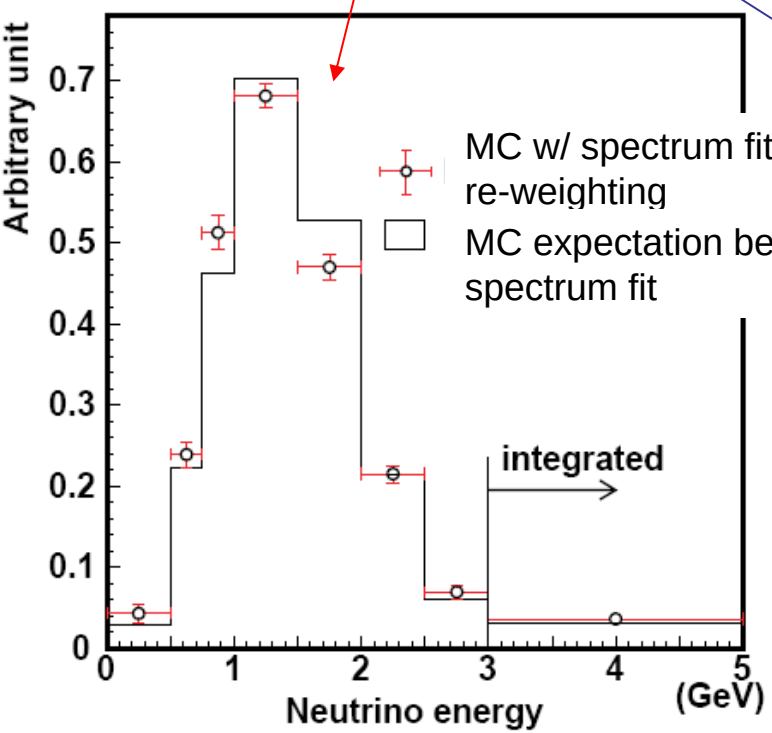
*Lead Glass EM Calorimeter in K2K-I replaced by SciBar for K2K-II

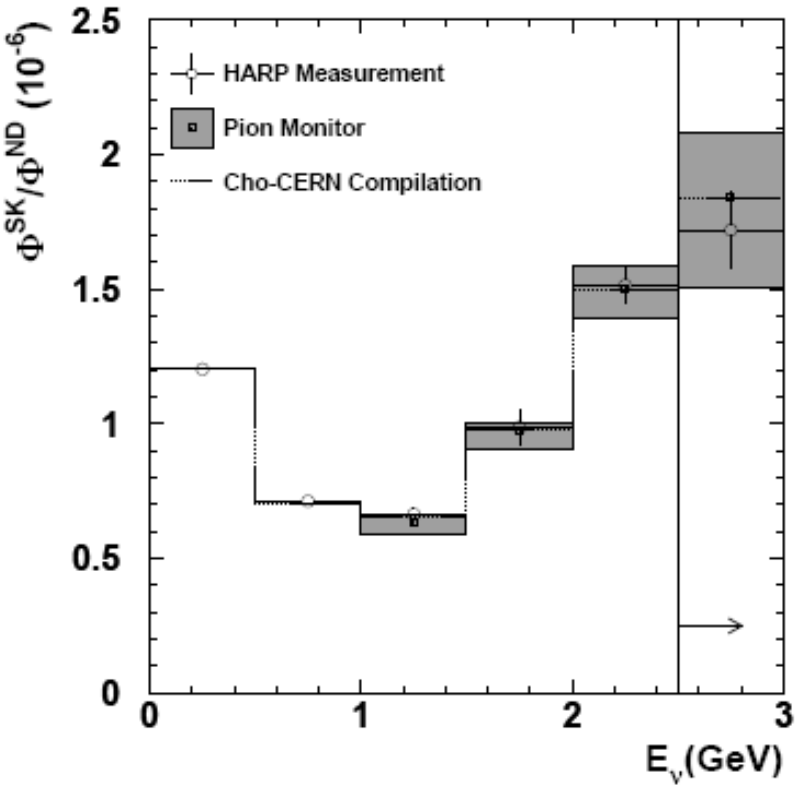
Expected Neutrino Flux @ SK

Want to estimate neutrino flux at the far detector using the following formula:

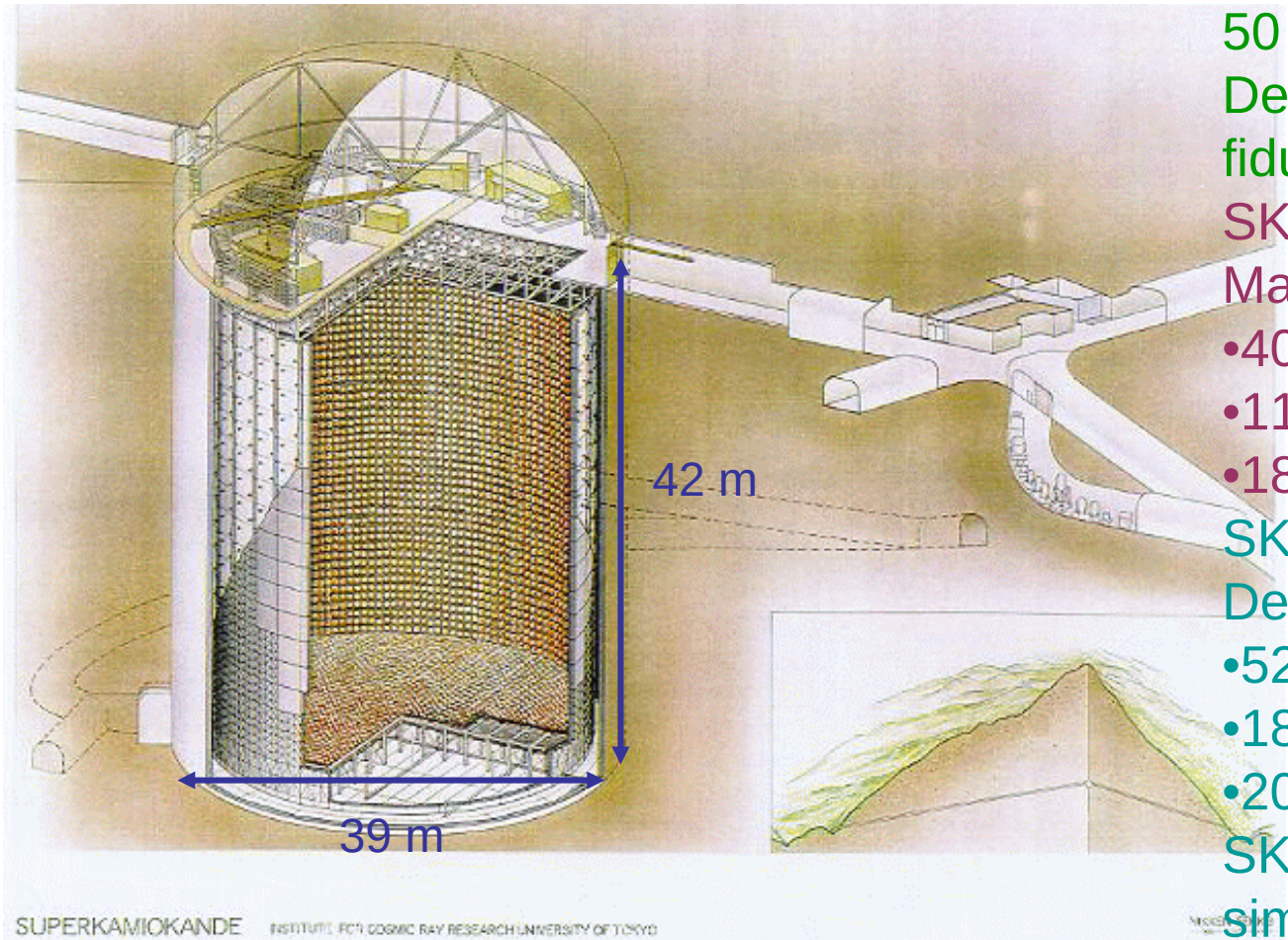
$$\Phi^{SK} = \Phi^{ND}(E_\nu) \cdot R^{F/N}(E_\nu) \cdot \left(1 - P\left(E_\nu; \Delta m^2, \sin^2 2\theta\right)\right)$$

$$R^{F/N} = \frac{\Phi^{SK}(E_\nu)}{\Phi^{ND}(E_\nu)}$$





Far Detector: Super Kamiokande



50 kton H2O Cherenkov Detector (22.5 kton fiducial)

SK-I:
March 1996 – July 2001
- 40% photo coverage
- 11146 20” PMTs
- 1885 8” PMTs

SK-II:
Dec. 2002 – Oct. 2005
- 5200 20” PMTs
- 1885 8” PMTs
- 20% photo coverage

SK-I & SK-II response similar for 1Rμ events

SK-III: July 2006 -

Expected Event Number/Energy Spectrum @ SK

$$N_{\rm exp}^{\rm SK}(\Delta m^2, \sin^2 2\theta) \equiv N_{\rm int}^{\rm 1KT} \cdot \frac{\rho^{\rm SK}}{\rho^{\rm 1KT}} \cdot \frac{\rm M^{SK}}{\rm M^{1KT}} \cdot \frac{\rm POT^{SK}}{\rm POT^{1KT}} \cdot C_{\nu_e}$$

measured number of interactions in 1KT

Correction factor of ν_e contamination @ KT

Ratio of fiducial masses

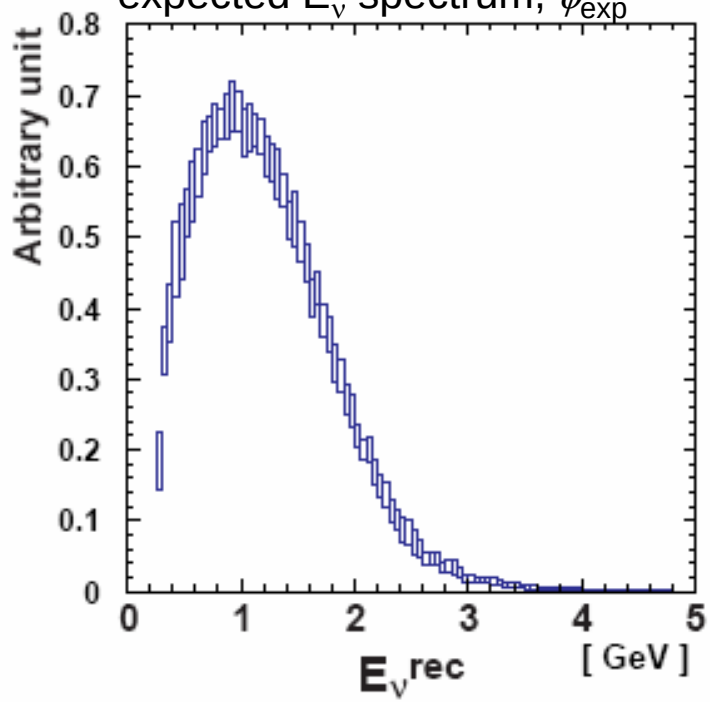
$$\rho = \int dE_\nu \Phi(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon(E_\nu)$$ = expected neutrino event rate/unit mass

Flux H_20 cross section detector efficiency

$$\phi_{\rm exp}^{\rm SK} = \int dE_\nu \cdot \Phi^{\rm SK}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{\rm 1R\mu}^{\rm SK}(E_\nu) \cdot r(E_\nu; E_\nu^{\rm rec})$$

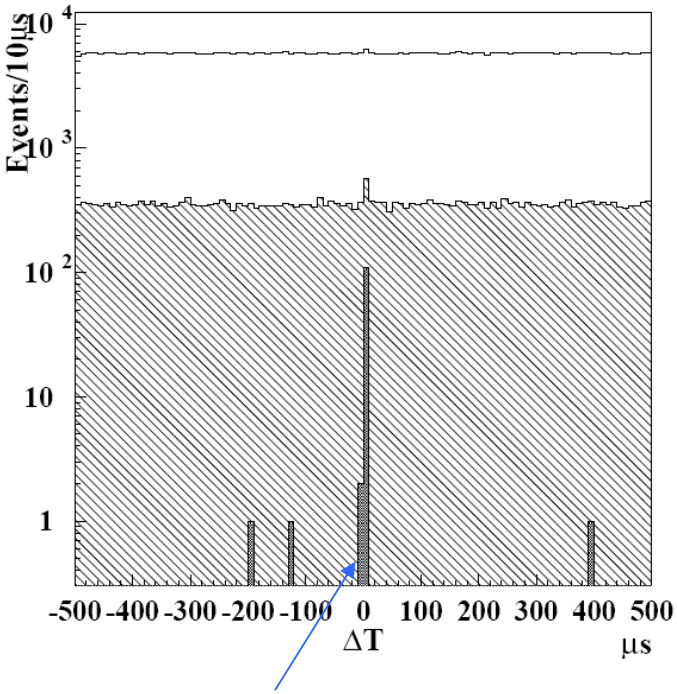
Prob. of reconstructing $E_\nu^{\rm True}$ as $E_\nu^{\rm rec}$

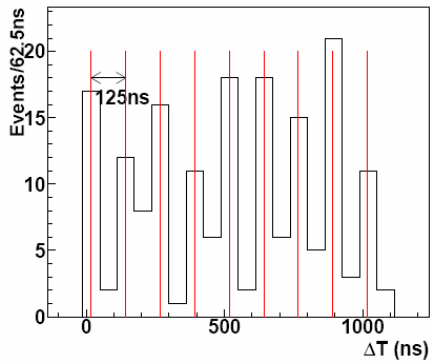
Reconstructed ν energy from expected E_ν spectrum, $\phi_{\rm exp}^{\rm SK}$

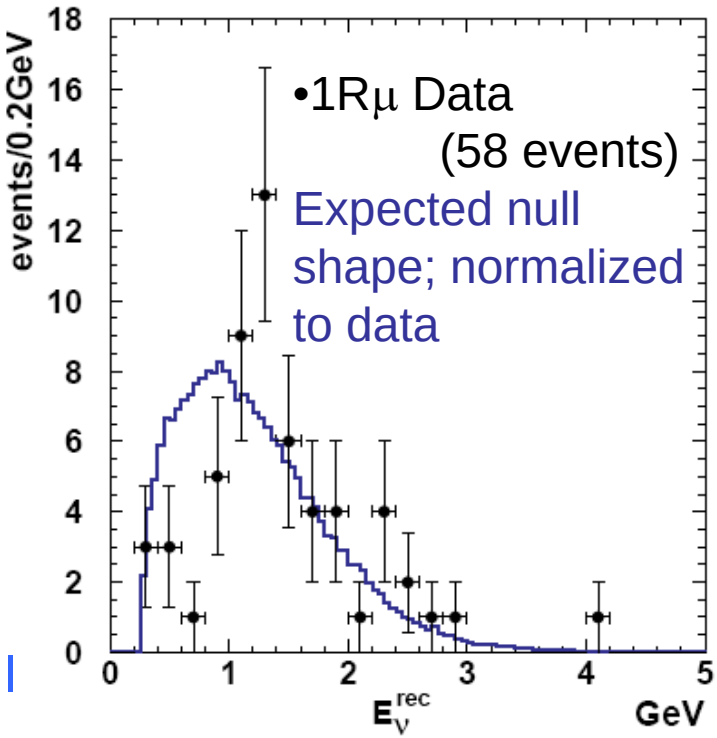


Expected event number without oscillations: $N^{\rm SK}_{\rm exp} = 158.1^{+\ 9.2}_{-\ 8.6}$

K2K Events at SK







112 events total (158.1 exp.) for K2K-I and K2K-II

58 of 112 events are 1Rμ used in the shape fit

K2K-I: 55 obs. (30 1Rμ)

K2K-II: 57 obs. (28 1Rμ)

Oscillation Analysis Likelihood

The total likelihood definition: $L = L_{\#\text{ of events}} \times L_{shape} \times L_{syst}$

Event # likelihood based on Poissonian probability

$$L_{\#\text{ of events}} = \frac{\left(N_{\exp}\right)^{N_{obs}}}{N_{obs}!} e^{-N_{\exp}}$$

N_{exp} is calculated from N_{SK}^{exp} for each experimental configuration and added

N_{obs} is the number of observed events

Shape likelihood is a PDF utilizing the expected neutrino energy spectrum formula

$$L_{shape} = \prod_{i=1}^{N_{1R\mu}^{K2K-I}} \phi_{\exp,K2K-I}^{SK}\left(E_{\nu,i}^{rec};\Delta m^2,\sin^2 2\theta\right) \times \prod_{i=1}^{N_{1R\mu}^{K2K-II}} \phi_{\exp,K2K-II}^{SK}\left(E_{\nu,i}^{rec};\Delta m^2,\sin^2 2\theta\right)$$

Systematic error terms are in sets where Δf_j is the deviation from the nominal value and M_j is the error matrix for the jth set of parameters

$$L_{syst} \equiv \prod_{j=1}^{N_{syst}} \exp\left(-\Delta f_j^T \left(M_j\right)^{-1} \Delta f_j\right)$$

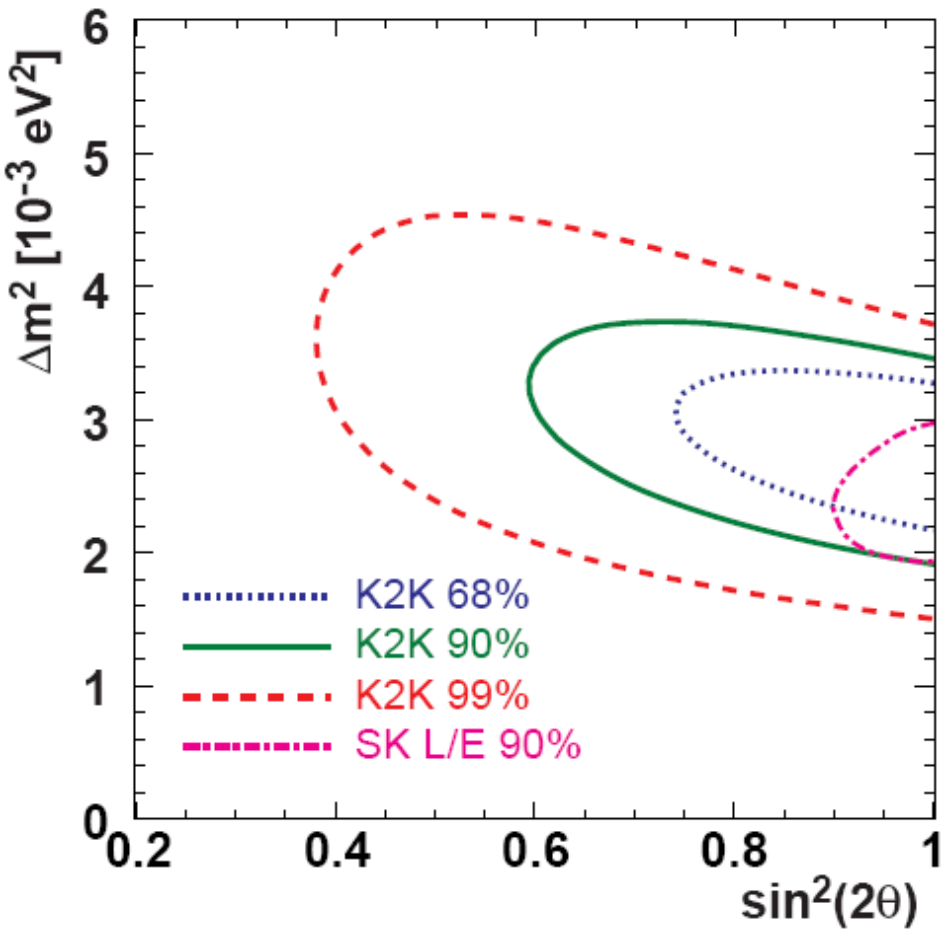
Official FV Neutrino Oscillation Fit Results

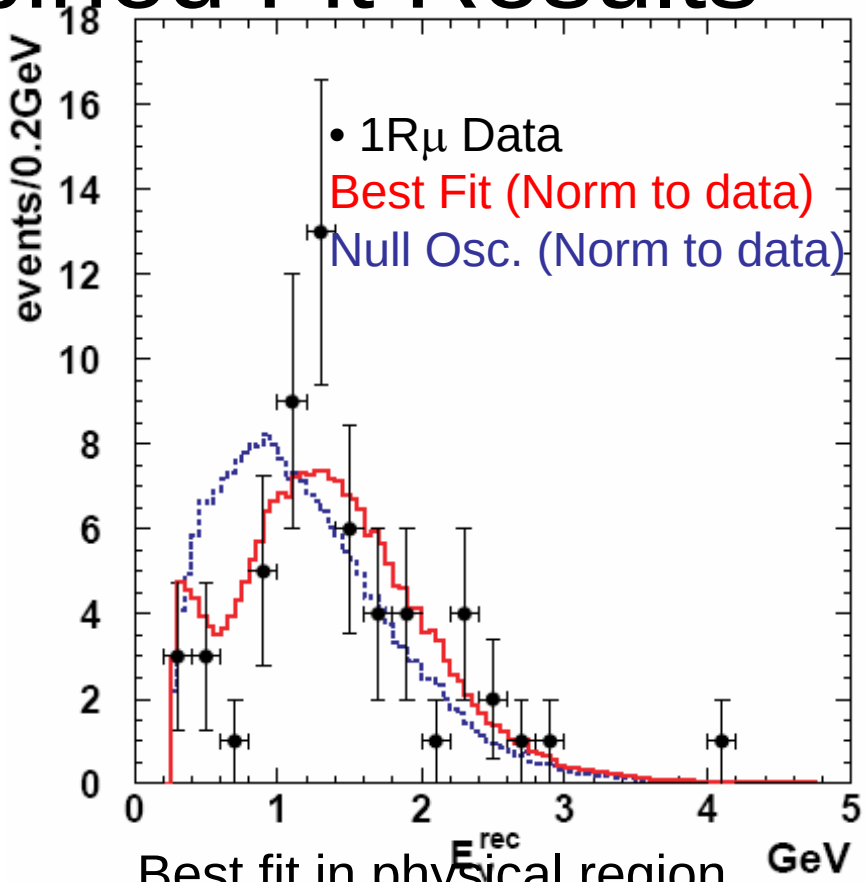
Run Period	Fit type	All Parameter Space		Physical Region Only	
		Δm^2 [eV^2]	$\sin^2 2\theta$	Δm^2 [eV^2]	$\sin^2 2\theta$
K2K-I & K2K-II	Combined	0.00255	1.19	**0.00275**	**1.00**
	Shape Only	0.00277	1.25	0.00295	1.00
K2K-I	Combined	0.00277	1.08	0.00289	1.00
K2K-II	Combined	0.00236	1.35	0.00264	1.00

	K2K-I	K2K-II	K2K-all
Number of events	0.5%	2.3%	0.06% (3.4σ)
E_ν^{rec} spectrum shape	7.5%	5.0%	0.42% (2.9σ)
Combined (number of events and E_ν spectrum shape)	0.18% (3.1σ)	0.56% (2.8σ)	**0.0015%** (4.3σ)

 Phys. Rev. D **74**, 072003 (2006)

Official FV Combined Fit Results





$1.9\times10^{-3} \leq \Delta m^2 \leq 3.5\times10^{-3}$ eV^2 (@ 90%C.L.)

KS data vs. fit: 37%

Best fit in physical region oscillation parameters used:

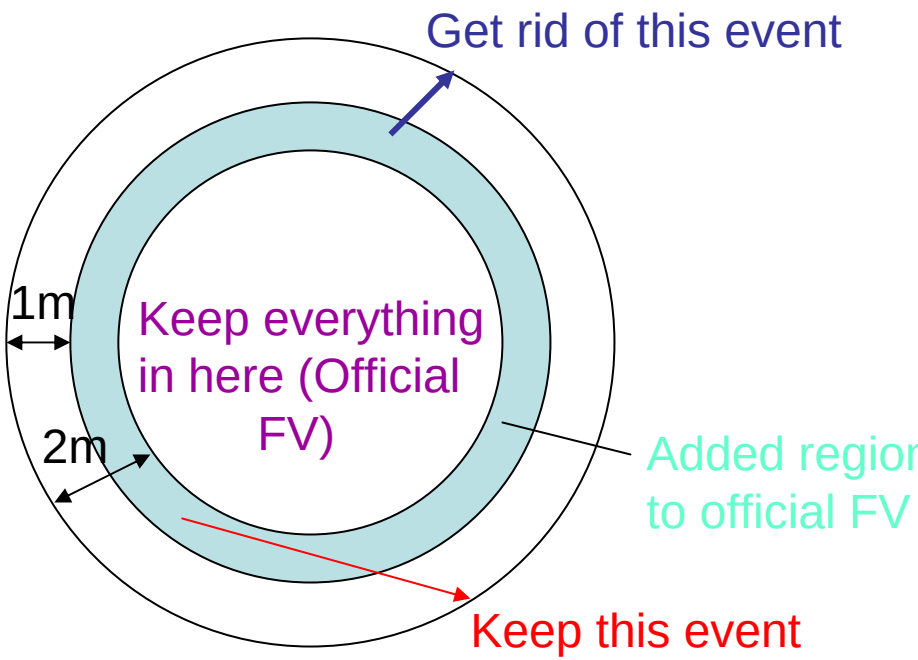
$\sin^2 2\theta = 1.00$

$\Delta m^2 = 0.00275$ eV^2

Motivation for FV Expansion

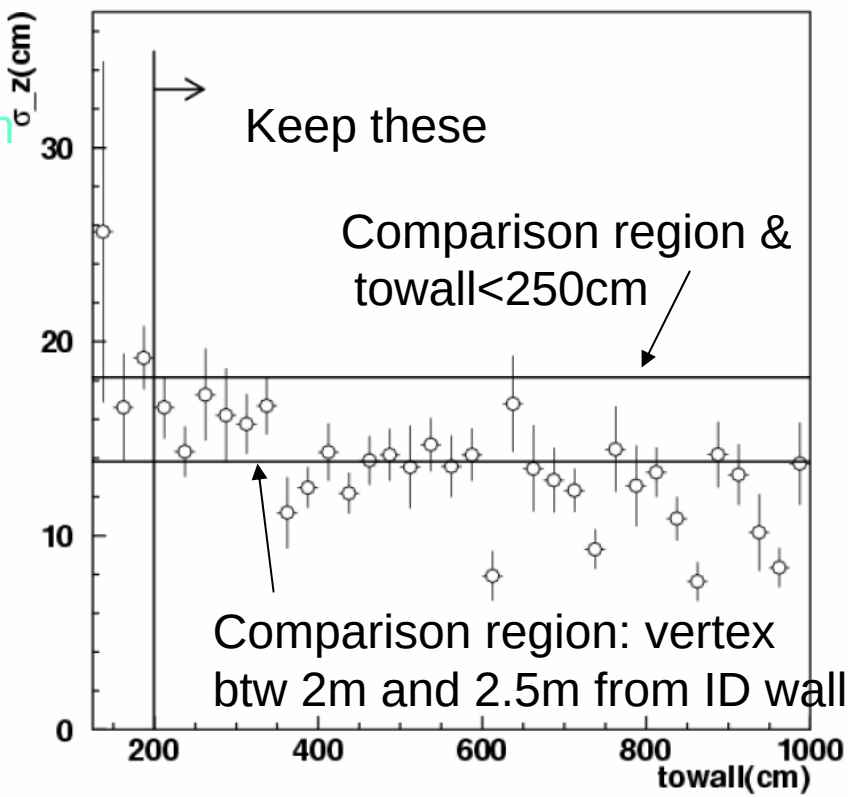
- K2K is a statistics limited experiment
  - 58 1Rμ events, and 112 overall, used in the oscillation analysis
- Official FV of SK: reconstructed vertex at least 2 m away from the Inner Detector PMT plane (dwall>2m)
  - Fiducial mass is 22.5 kton; Inner Detector is 32.5 kton
- Expanding the FV gives additional events “for free”
  - e.g.: an increase in FV from dwall>2 m to dwall>1 m increases the event sample size by 20%
  - use events outside Official FV going into the tank which have similar event reconstruction as events in the Official FV

Distance to wall (towall) (1Rμ events)



Will deposit light in less than 12 PMTs
poor vertex reconstruction

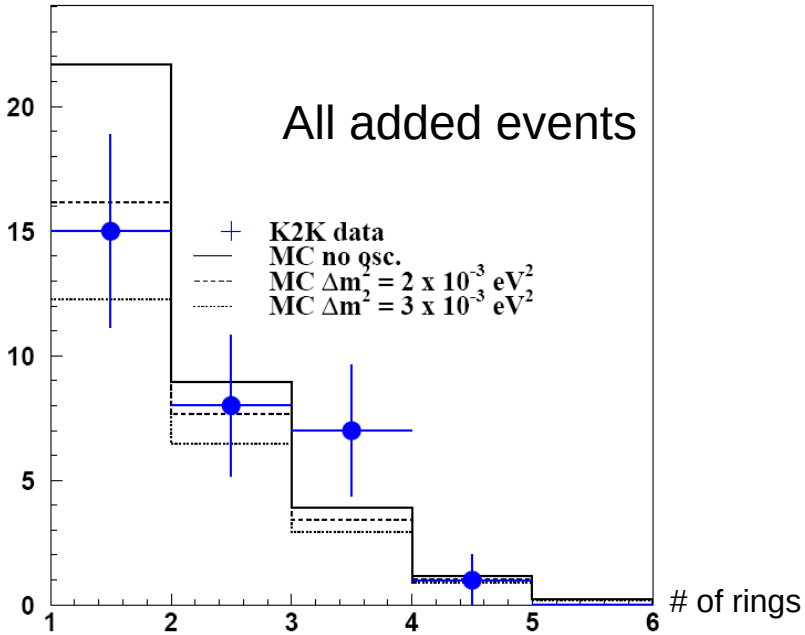
Will deposit light in approximately 12 PMTs or more for better vertex reconstruction

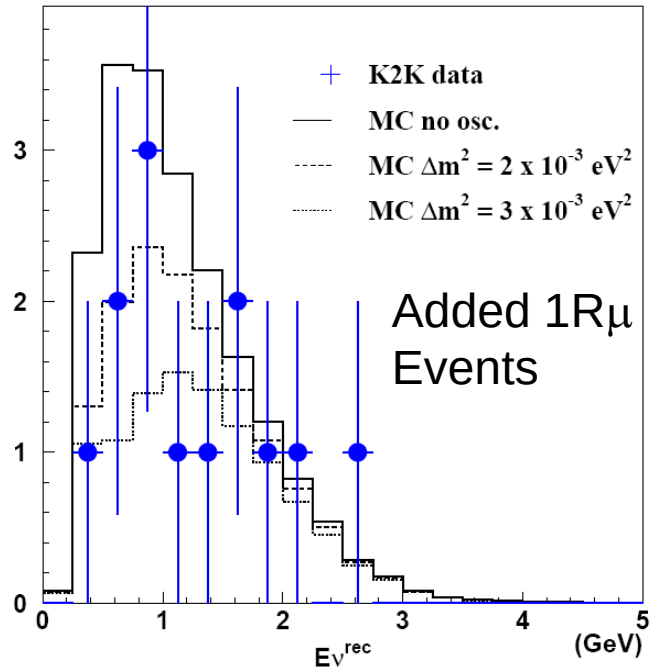


New cut: At least 1m away from the wall (dwall>1 m) and travel at least 2m before hitting it (towall>200 cm). Increases FV by 17%

$N_{exp}=183.3^{+10.7}_{-10.0}$ (no osc.)

Events Added to Official FV





Run Period	Expected # In Added Region	Actual # In Added Region	Sigma
K2K-I	9.69±1.31	21±4.58	2.4
K2K-II	9.93±1.32	10±3.16	0.02
K2K-I&II	19.62±1.86	31±5.57	1.9

t-test is ~2σ

143 events total in expanded FV

Expected # = % increase estimated by MC multiplied by # of observed events in OFV

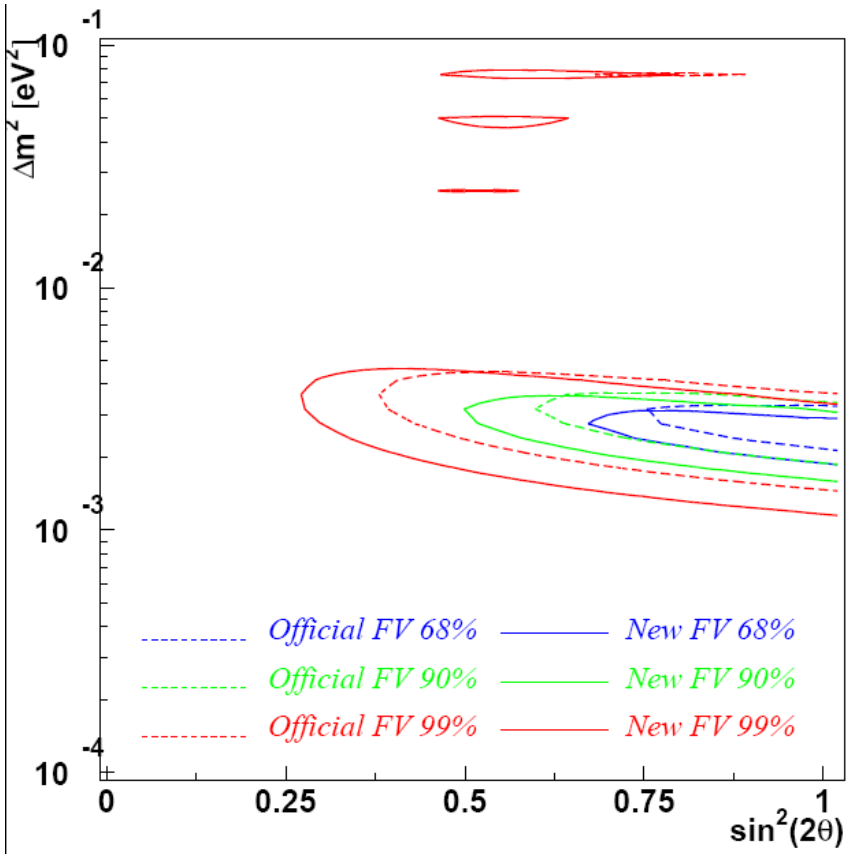
New FV Neutrino Oscillation Fit Results

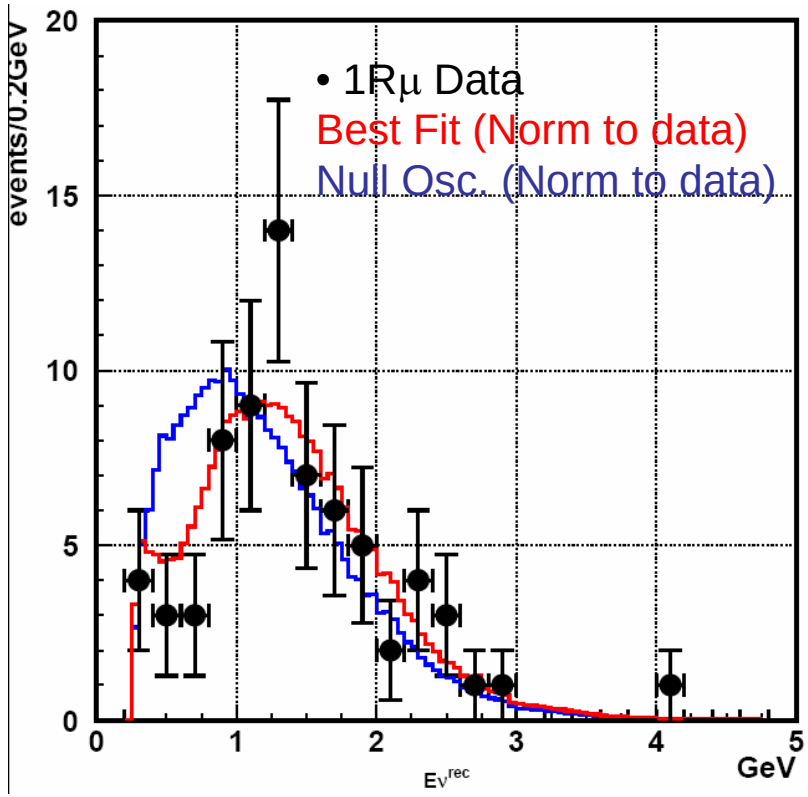
Run Period	Fit type	All Parameter Space		Physical Region Only	
		Δm^2 [eV^2]	$\sin^2 2\theta$	Δm^2 [eV^2]	$\sin^2 2\theta$
K2K-I & K2K-II	Combined	0.00231	1.12	0.00245	1.00
	Shape Only	0.00261	1.21	0.00279	1.00
K2K-I	Combined	0.00236	0.85	0.00236	0.85
K2K-II	Combined	0.00238	1.42	0.00270	1.00

	K2K-I	K2K-II	K2K-all
Number of events	7.5%	2.2%	0.52% (2.8σ)
E_ν^{rec} spectrum shape	27%	1.4%	0.49% (2.8σ)
Combined (number of events and E_ν spectrum shape)	6.5% (1.9σ)	0.14% (2.3σ)	**0.018%** (3.7σ)

Loss of significance as compared to OFV (4.3σ)

New FV Combined Fit Results





Best fit in physical region oscillation parameters used:

$\sin^2 2\theta = 1.00$

$\Delta m^2 = 0.00245$ eV^2

KS: 64% (37% for Official FV)

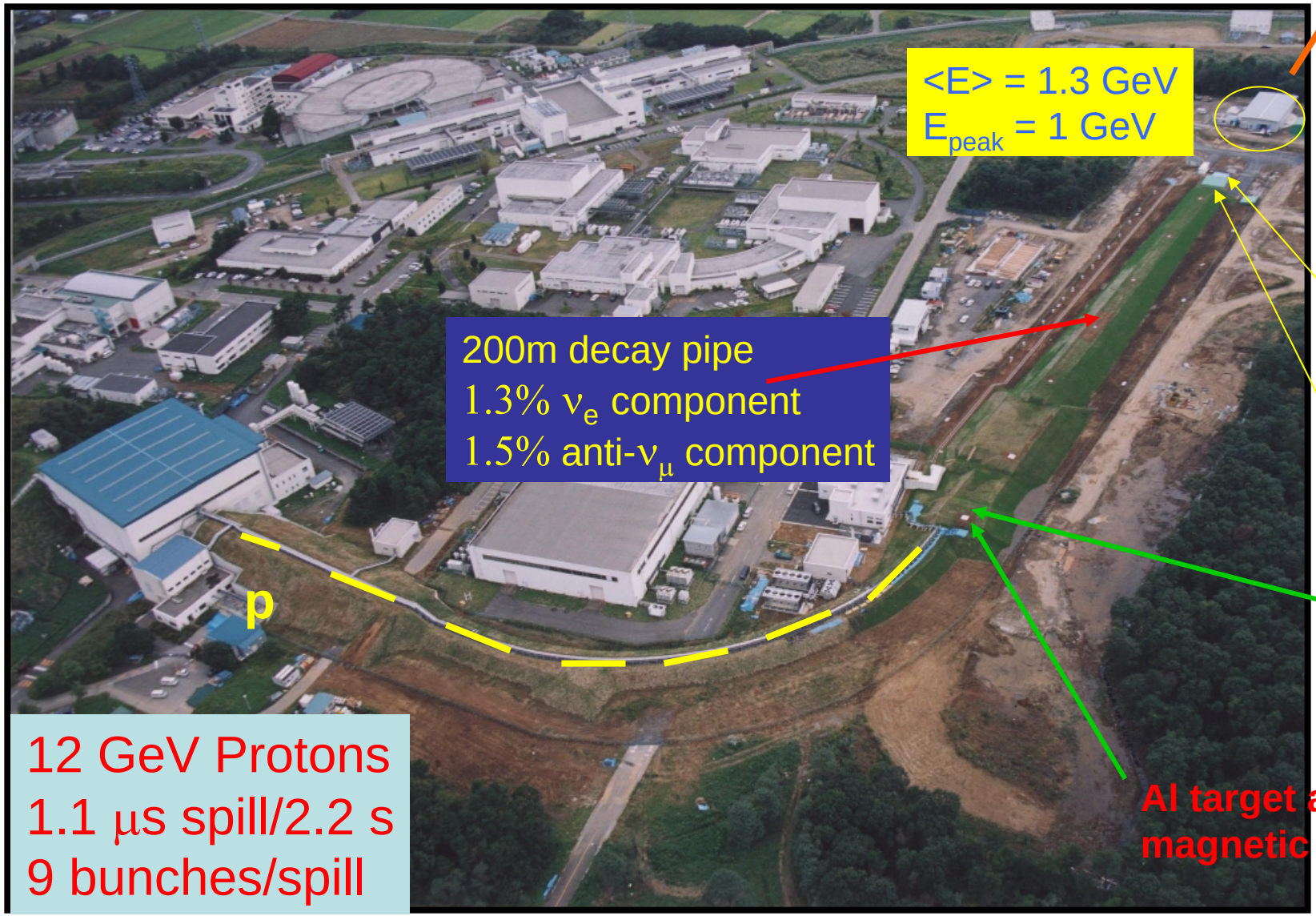
$1.6\times10^{-3} \leq \Delta m^2 \leq 3.1\times10^{-3}$ eV^2 (@ 90% C.L.)

Summary

- K2K's final official neutrino oscillation results in Phys. Rev. D **74**, 072003 (2006)
  - Null hypothesis excluded at 4.3σ
  - $\sin^2(2\theta) = 1.00$
  - $\Delta m^2 = 2.75 \times 10^{-3}$ eV^2
- Expanded fiducial volume excludes null hypothesis at 3.7σ (New FV) and 3.5σ (Upstream-shifted FV; see backup slides) with better consistency between data and fitted MC
  - 0.0025 eV^2 (New FV), 0.0024 eV^2 (Upstream FV)
  - $\sin^2(2\theta) = 1.00$

Backup Slides

Beamline



To SK

Near detector

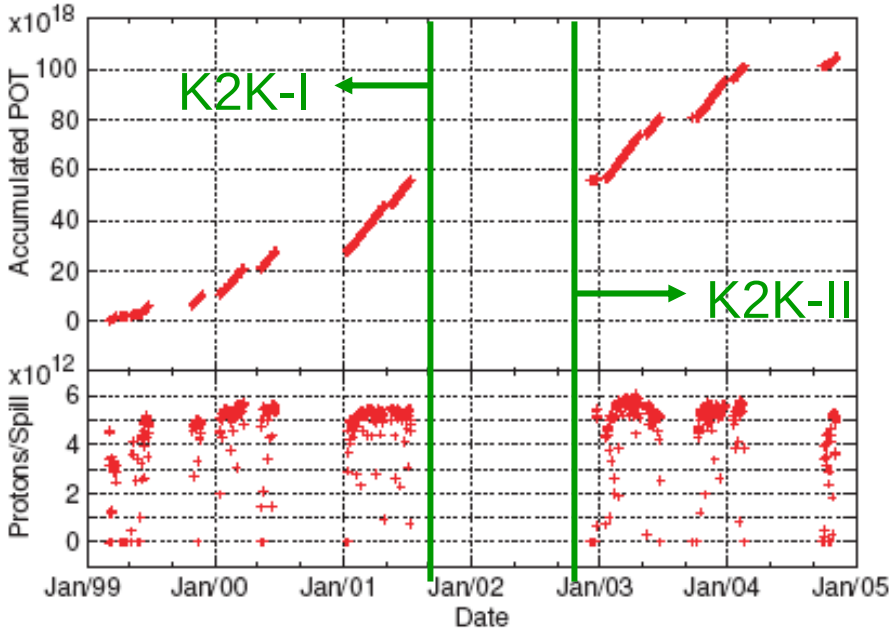
muon monitor

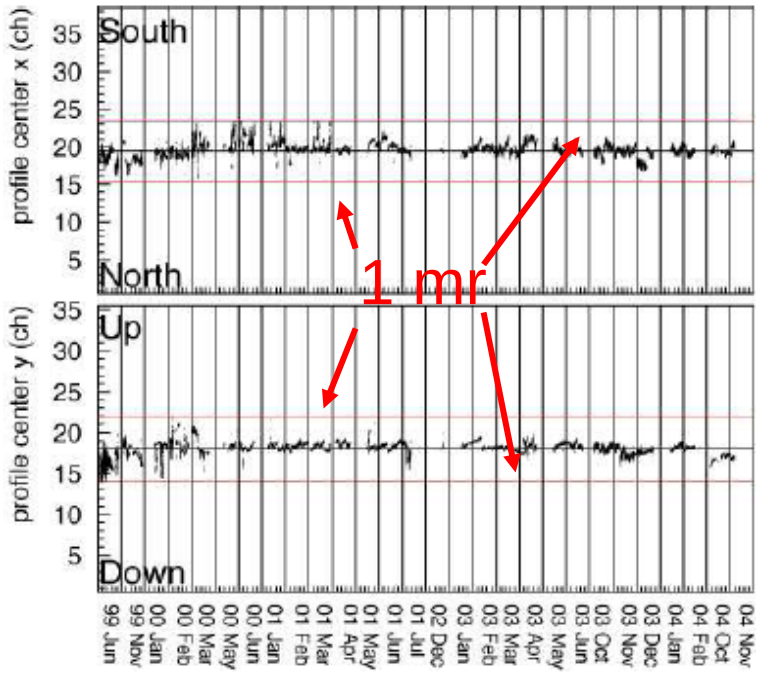
Beam dump

pion monitor

Al target and magnetic horns

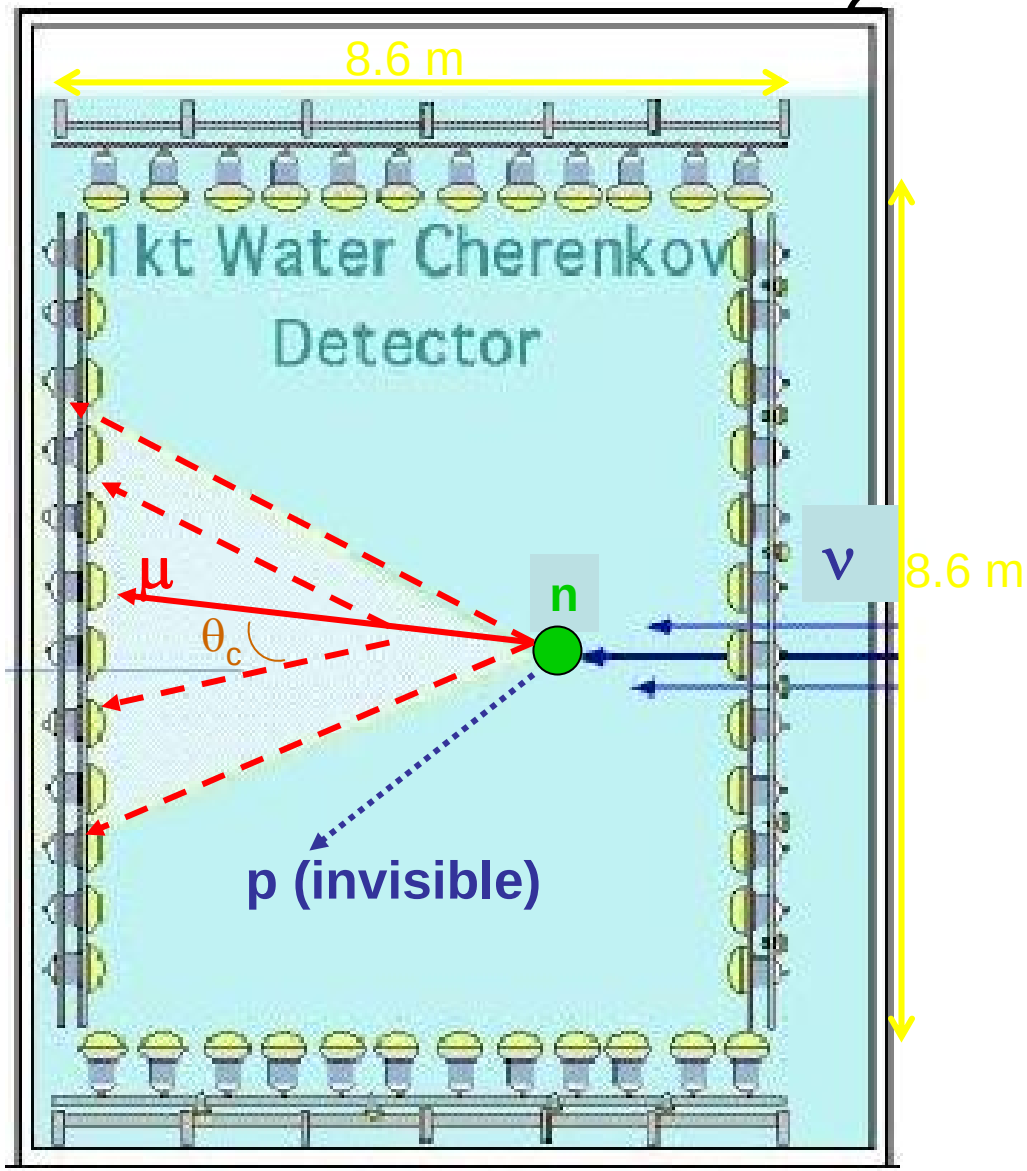
POT Delivered & Beam Stability





1.04x10^{20} POT are delivered, 92.23x10^{18} POT for analysis
47.93x10^{18} POT for K2K-I & 44.30x10^{18} POT for K2K-II
Beam direction w/in 1mr of the far detector for data taking

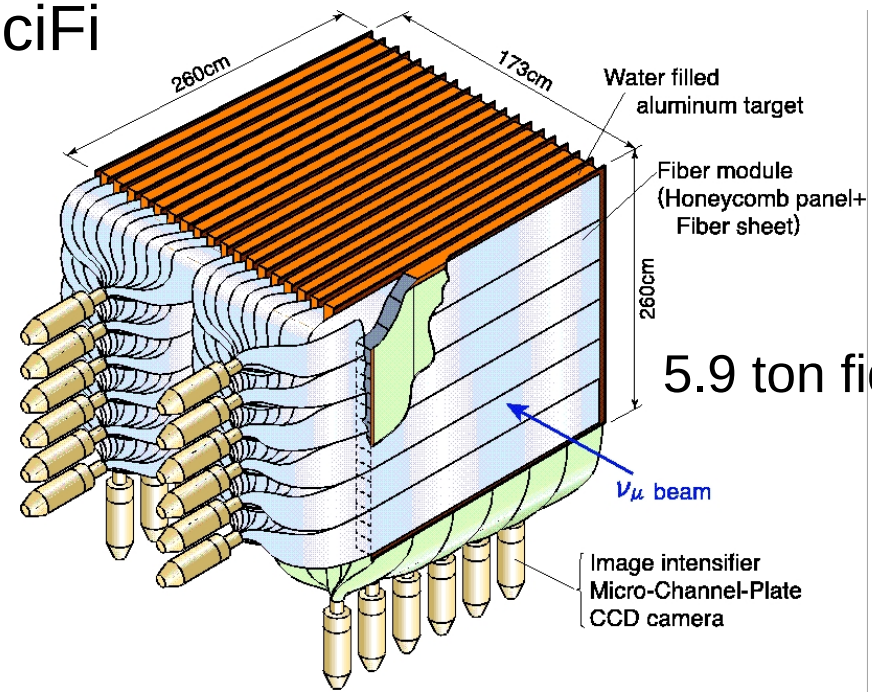
1kton H_20 Detector



- Measure # of interactions, their rate, & energy spectrum
- Same technology as SK: cancels some systematic errors
- Same 40% photocathode coverage as Super Kamiokande (680 20” PMTs)
- OD vetoes beam-induced muons (68 8” PMTs)
- 25 ton fiducial oriented along beam path

Fine Grained Detector

SciFi



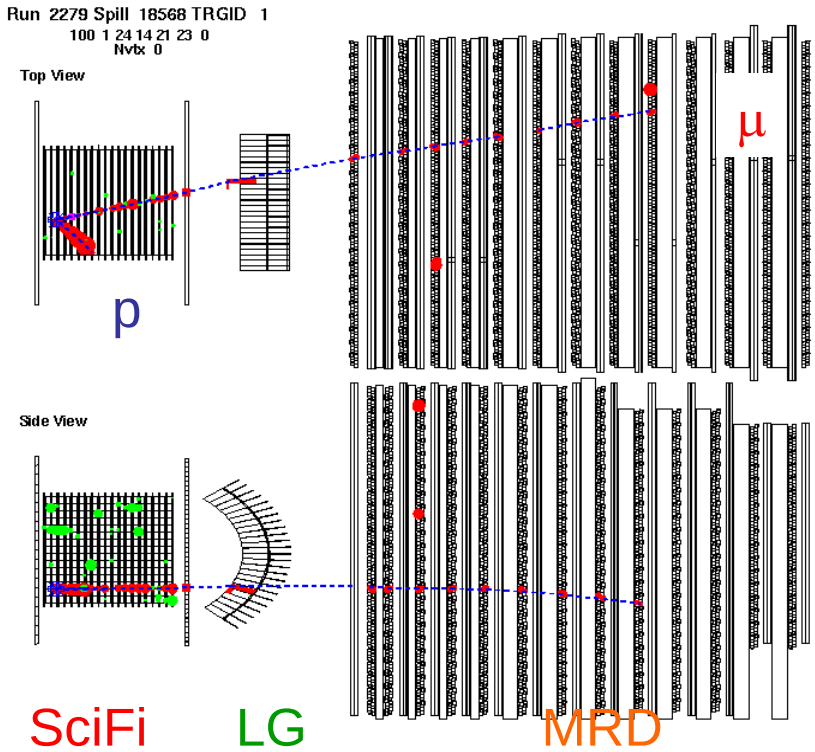
5.9 ton fiducial

FGD = SciFi +LG+ MRD

Scintillating Fiber Tracker

Lead Glass EM Calorimeter

Muon Range Detector



proton momentum threshold p_p > 600 MeV/c

SciFi used to measure beam characteristics

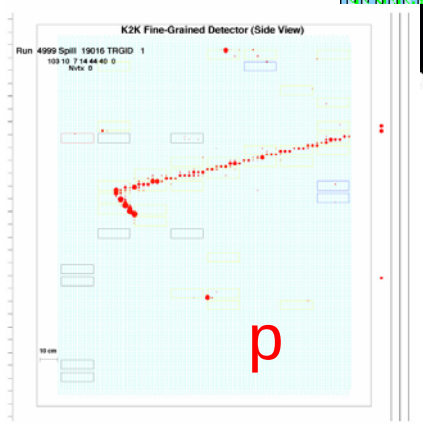
E_ν>1 GeV (check #)

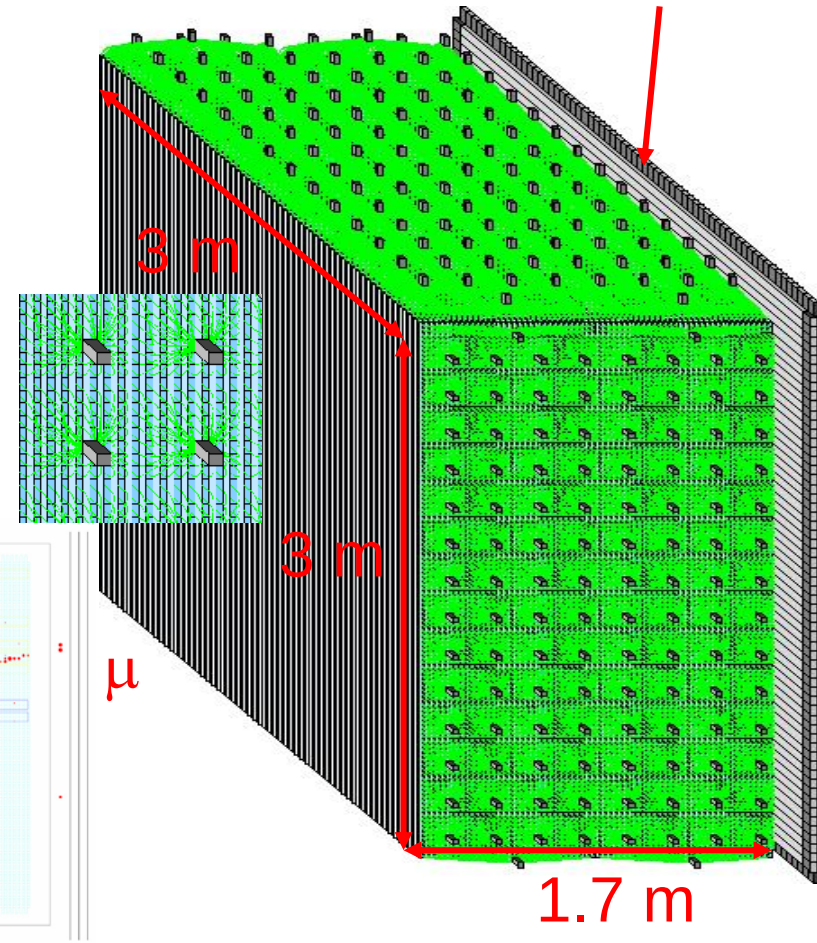
LG measured ν_e contamination by energy deposit

MRD measures high E μ and beam direction

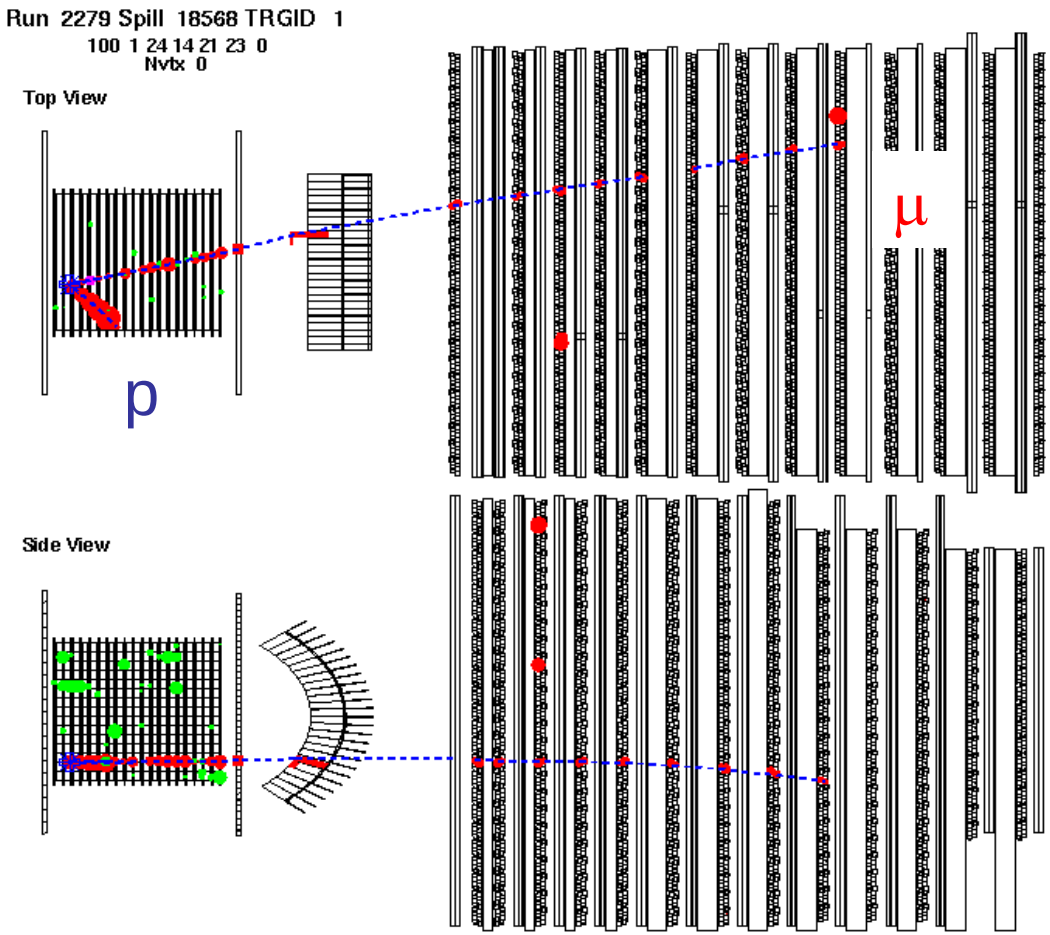
SciBar Detector

- Replaced Lead Glass Detector for K2K-II
- Lower proton threshold (p_p>450 MeV/c) to measure lower energy beam characteristics
- Scintillating Bars w/ WLS fibers attached to MAPMTs
- EC measures ν_e contamination



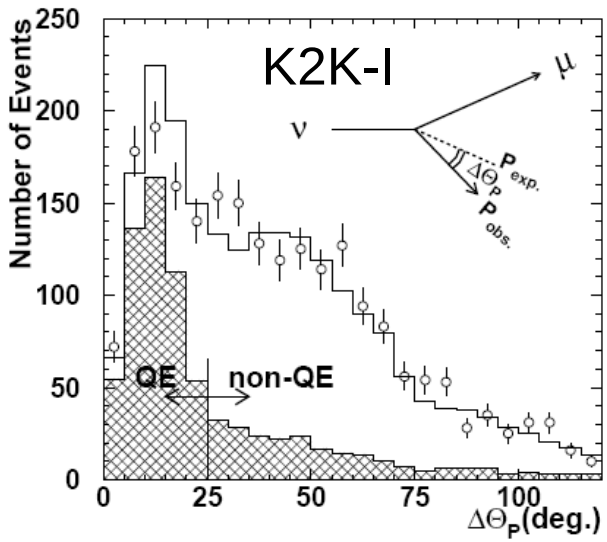


FGD Event

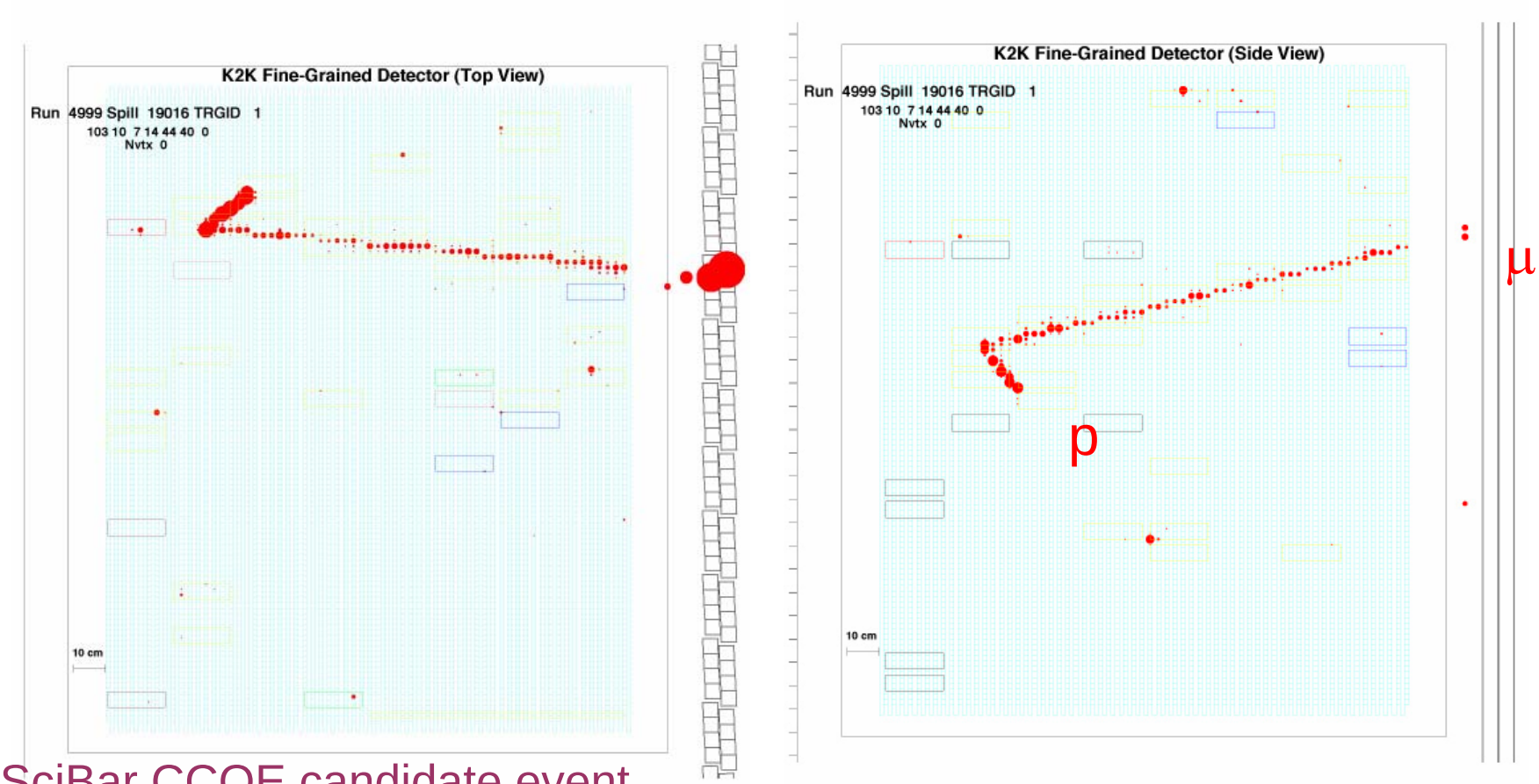


Single μ track: reconstruct E_ν assuming CCQE interaction

2 Track events are divided between quasi-elastic (QE) and non-QE:



SciBar Event



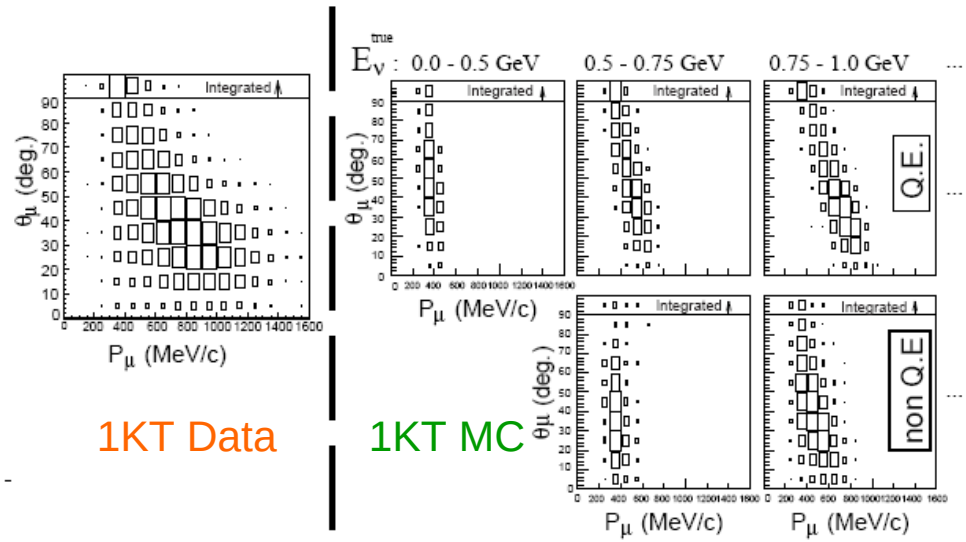
SciBar CCQE candidate event
2 track QE sample for spectrum fit
QE/non-QE cut same as SciFi (see previous page)

Near Detector Energy Spectrum Fit

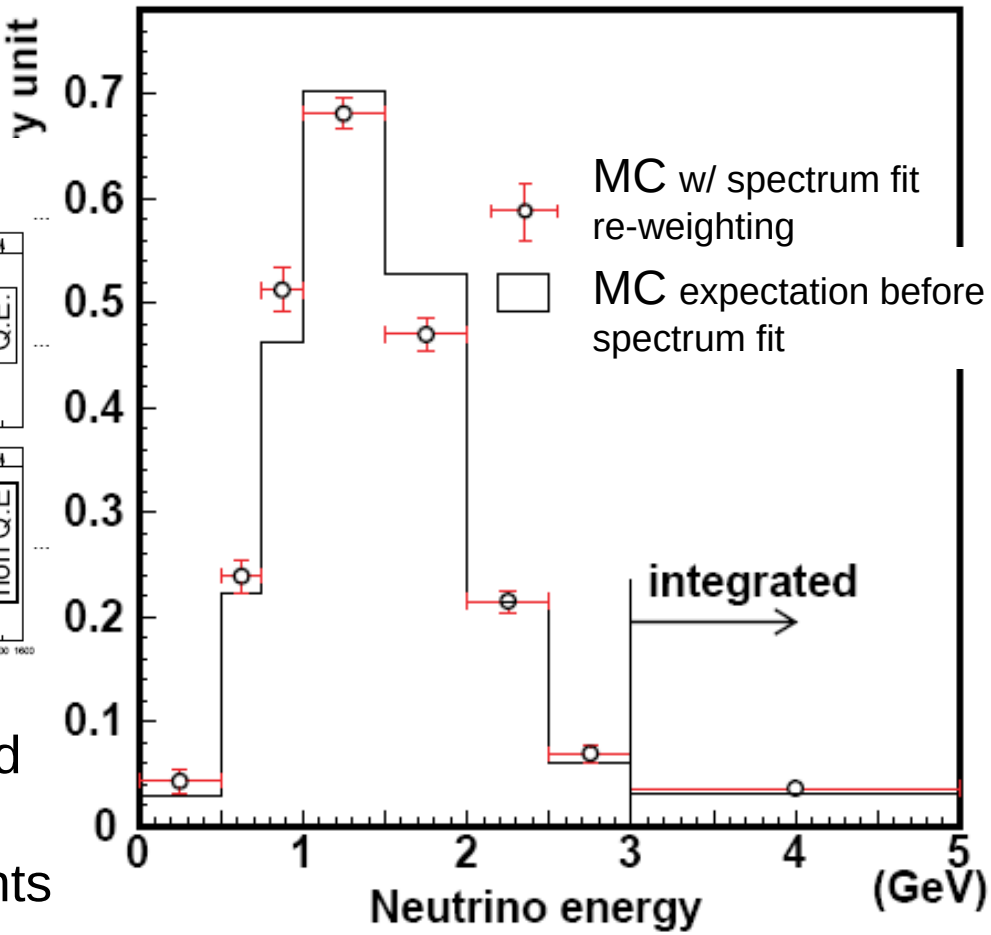
Near detector data samples for fit:

1KT: 1Rμ

SciFi, SciBar: 1 track, 2 track QE,
2 track non-QE

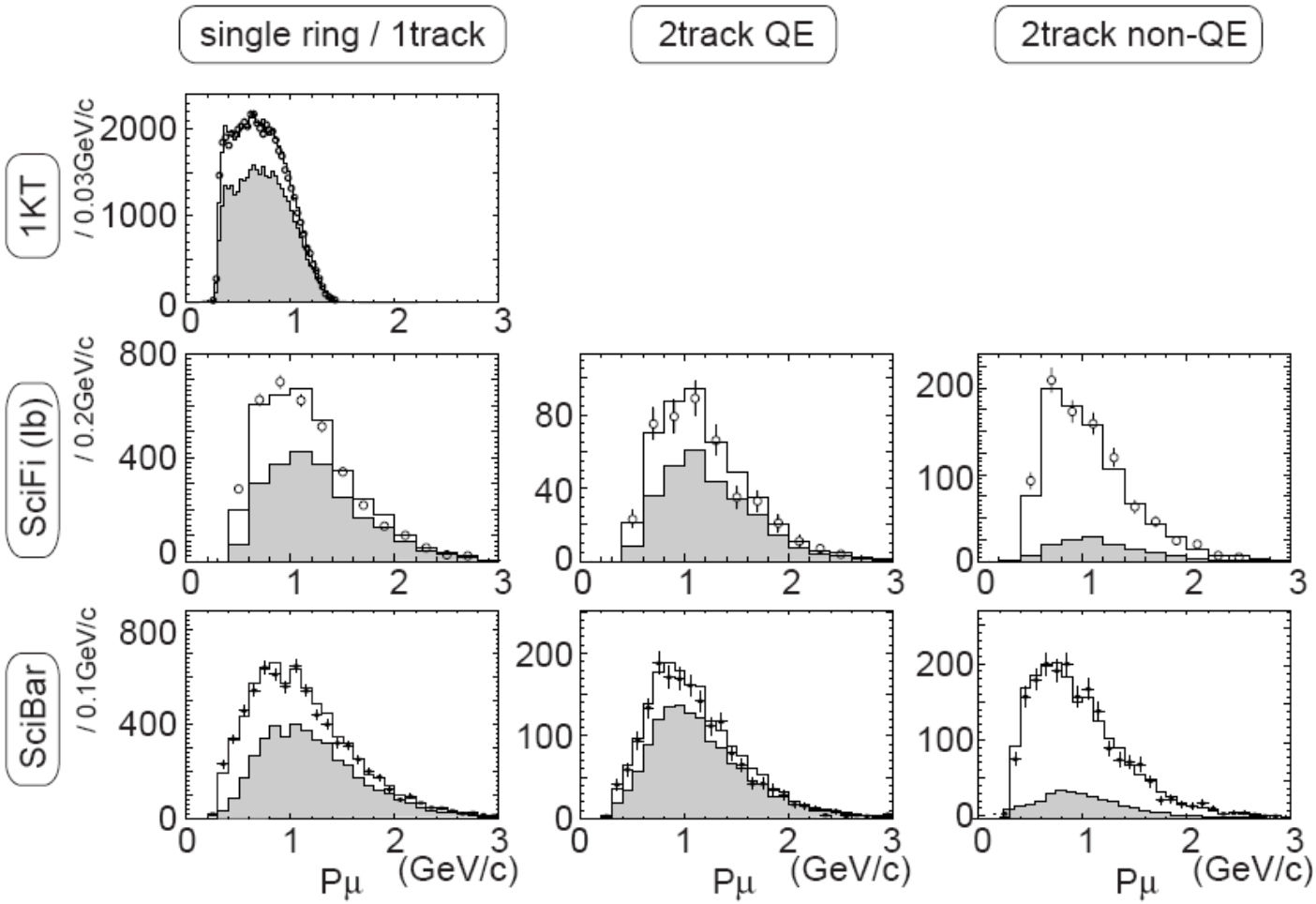


Beam MC

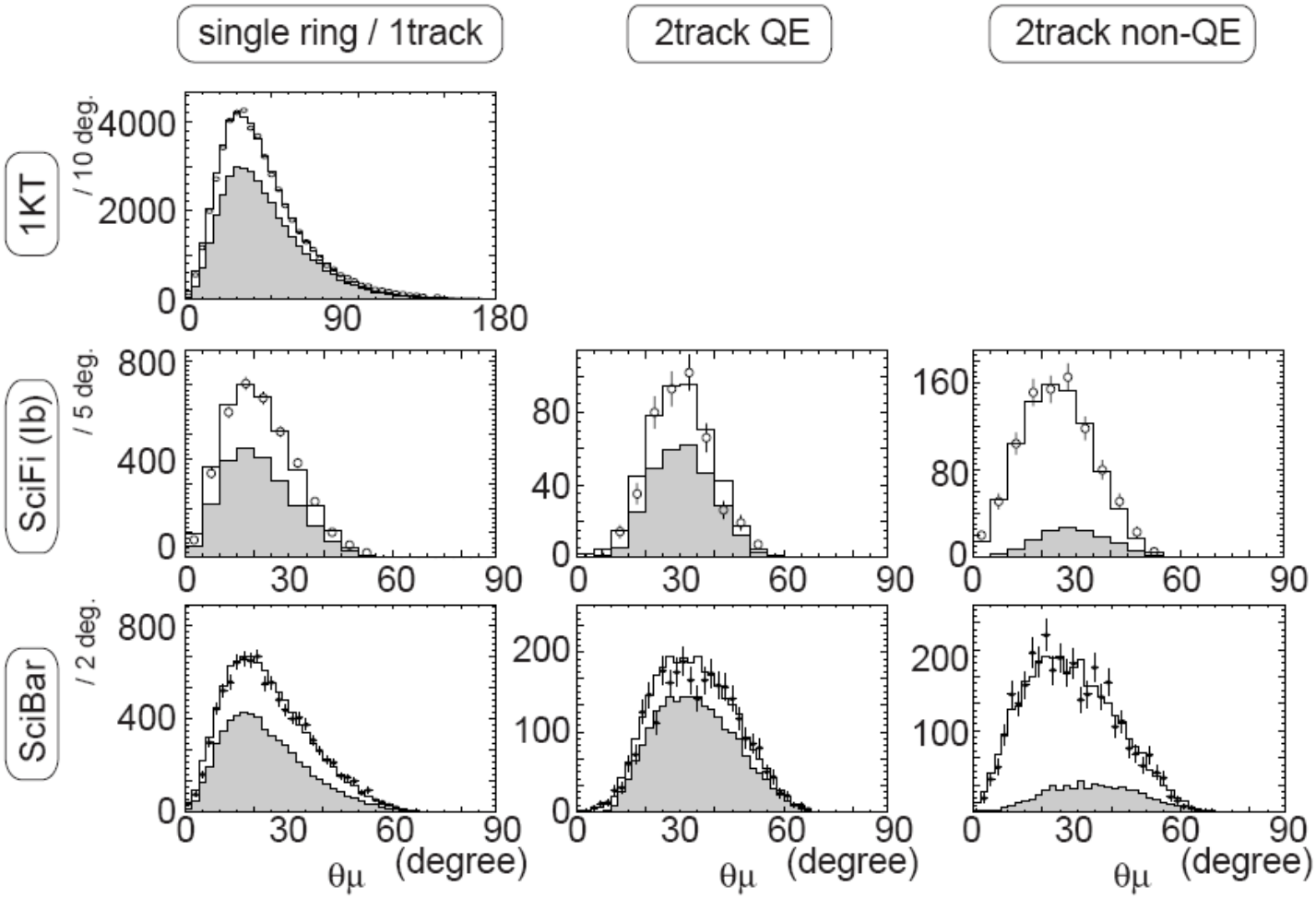


MC with spectrum fit re-weighting used in extrapolation to Far Detector of expected spectrum/number of events

Near Detector Data w/ Spectrum Fit Weighted Beam MC (1)

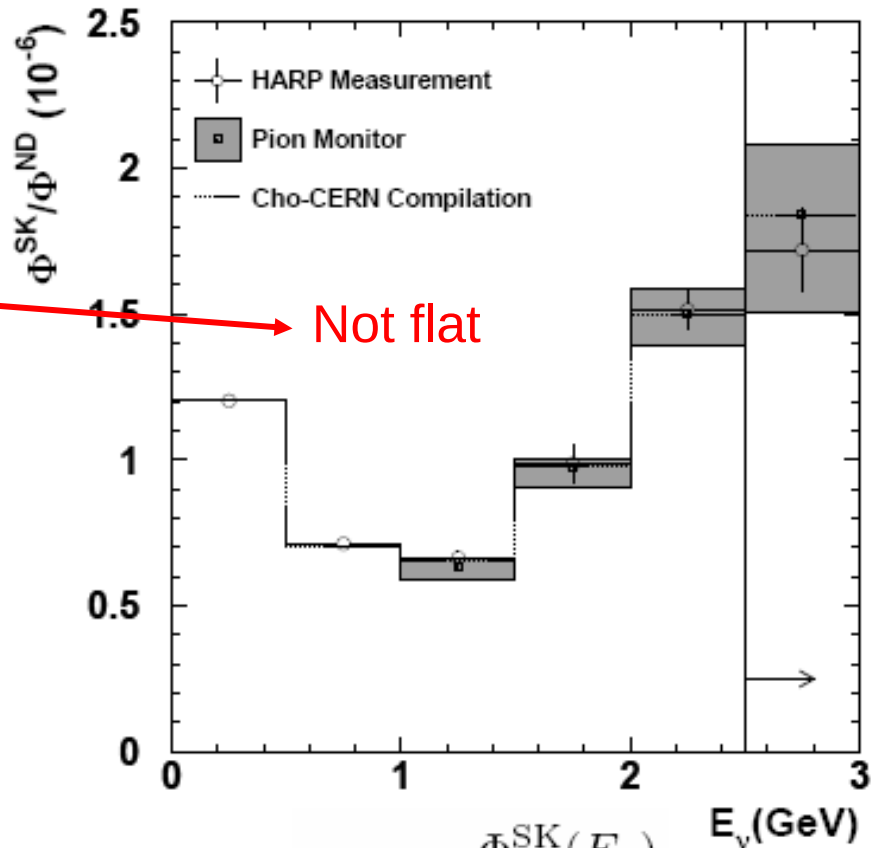


Near Detector Data w/ Spectrum Fit Weighted Beam MC (2)



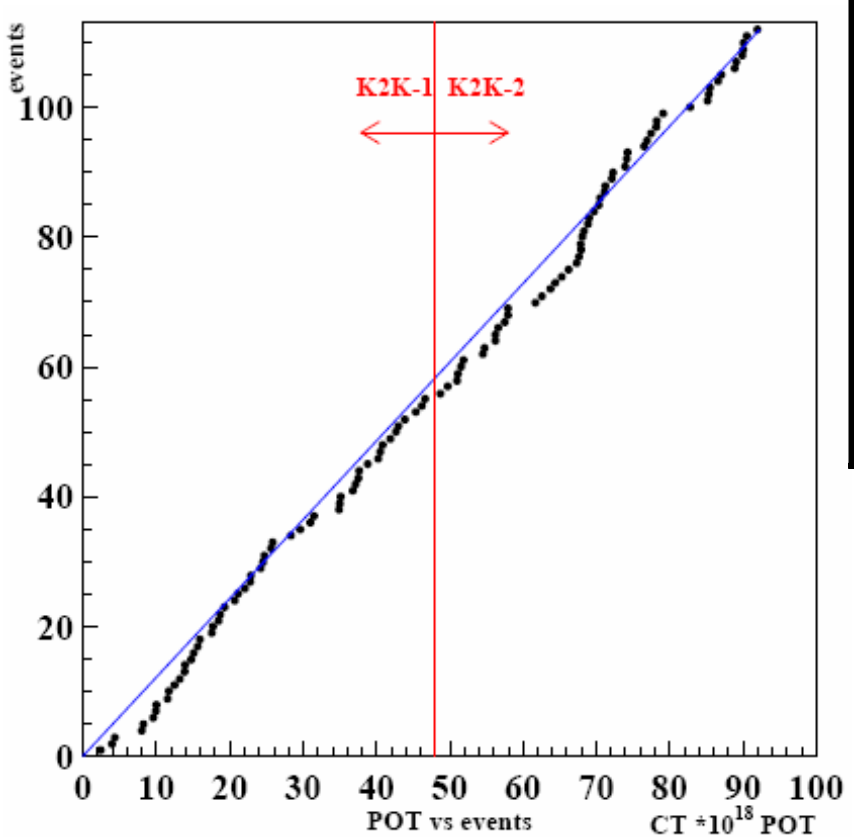
Far/Near Flux Ratio

- F/N ratio from beam simulation used to extrapolate # of events at SK & its energy spectrum
- Not a simple L^{-2} extrapolation
- Pion production & errors estimated using the HARP experiment w/ same proton beam energy and target material



$$R^{\mathrm{F/N}} = \frac{\Phi^{\mathrm{SK}}(E_\nu)}{\Phi^{\mathrm{ND}}(E_\nu)}$$

SK Data Summary/Comparison



Run Period	K2K-I	K2K-II
Total Events	55	57
1Rμ Events	30	28

Binned KS test of 1Rμ events in SK-I & SK-II is 90%

KS: 79% between data and expected event rate

SK Performance Comparison

	SK-I	SK-II
Energy Scale	2.0%	2.1%
Single ring/multi-ring separation error	5.9%	5.4%
μ-like mis-ID'd	0.8%	1.1%
Contamination from ν_e	0.6%	0.4%

Systematic Errors

# of events systematic errors	K2K-I	K2K-II
Reduction	<1%	<1%
Fiducial Volume Cut	2%	2%
Decay e bckgd.	0.1%	0.1%
MC statistics	0.6%	0.6%
Total	3%	3%

Energy Spectrum Systematics

K2K-I (GeV)	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-
ring counting	3.4%	2.7%	3.0%	4.5%	4.5%
particle ID	0.9%	0.3%	0.5%	0.4%	0.4%
vertex	2.0%	2.0%	2.0%	2.0%	2.0%
total	4.1%	3.4%	3.6%	4.9%	4.9%

K2K-II (GeV)	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-
ring counting	5.3%	4.1%	3.7%	3.8%	3.8%
particle ID	2.6%	0.4%	0.3%	0.6%	0.6%
vertex	2.0%	2.0%	2.0%	2.0%	2.0%
total	6.2%	4.6%	4.2%	4.3%	4.3%

	K2K-I	K2K-II
Energy Scale	2.0%	2.1%

Fractional error matrix for F/N ratio ($\times 10^{-3}$):

Energy Bin	1	2	3	4	5	6
1	0.187	0.002	−0.036	−0.372	−0.281	0.240
2	0.002	0.728	0.868	1.329	0.698	−1.398
3	−0.036	0.868	1.304	2.122	1.041	−2.040
4	−0.372	1.329	2.122	4.256	2.165	−3.799
5	−0.281	0.698	1.041	2.165	1.779	−2.678
6	0.240	−1.398	−2.040	−3.799	−2.678	7.145

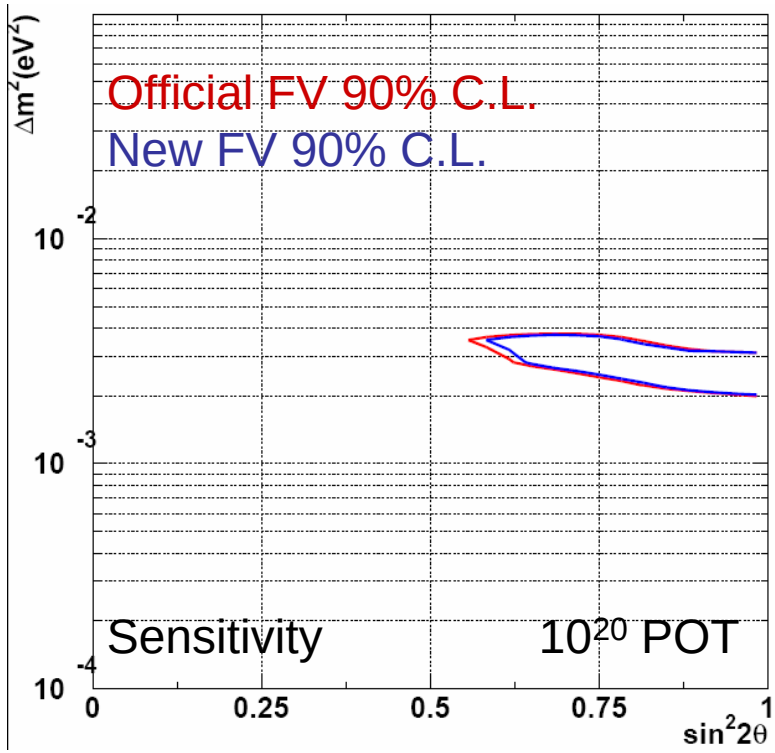
N^{int}_{1KT} sys. error:

Source	Error (%)
Fiducial volume	± 3.0
Energy scale	± 0.3
FADC stability	± 0.8
FADC cut position	± 1.5
Event rate	± 2.0
Background	± 0.5
Multi-interaction	± 0.7
Total	± 4.1

Systematic errors are small compared to statistical errors

K2K FV Increase Sensitivity

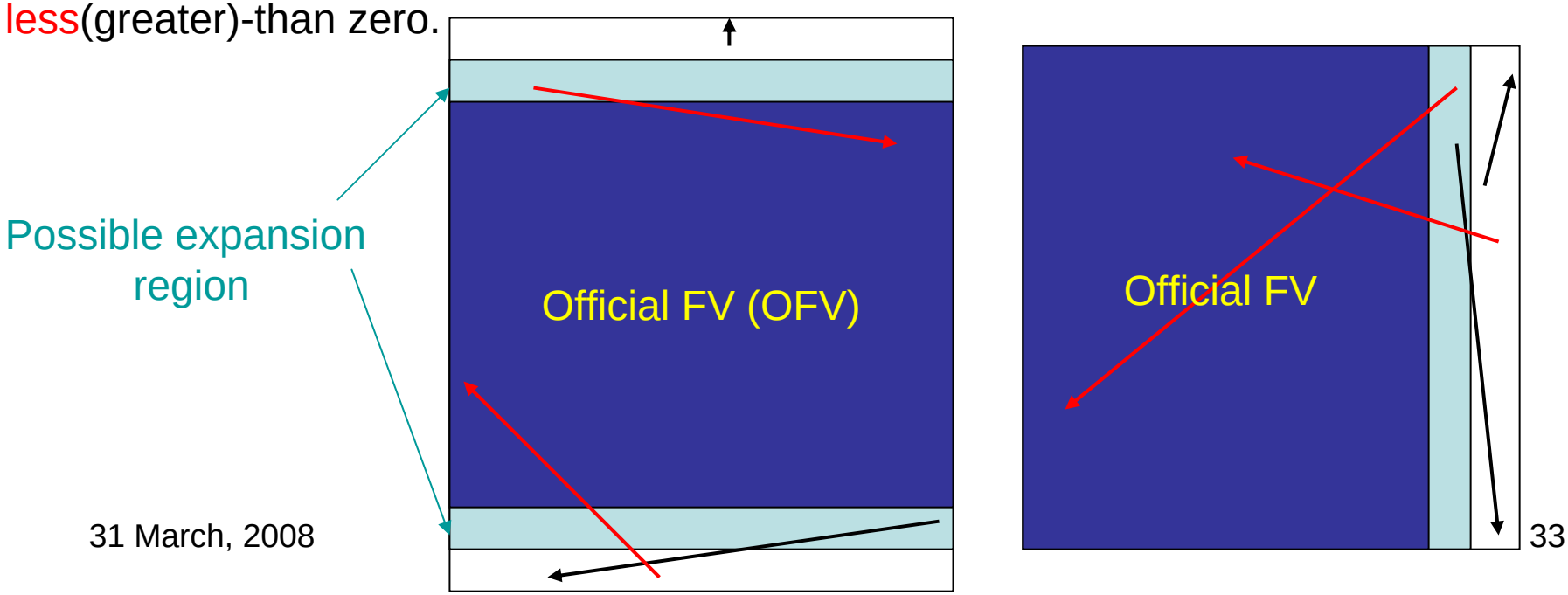
- Using cuts described later, a 16% increase in the FV will slightly decrease the allowed region sensitivity
- No study has been done to expand FV
  - Expanded FV for the SK L/E analysis



Outside FV Comparison

- Compare Vertex reconstruction in z/r outside the official FV vs. inside the OFV for different event classes
  - OFV: reconstructed vertex at least 2 m away from ID PMT plane
- Compare incoming vs. outgoing events at the same time.

Incoming(Outgoing): vertex position multiplied by cos(θ) of the particle direction is less(greater)-than zero.

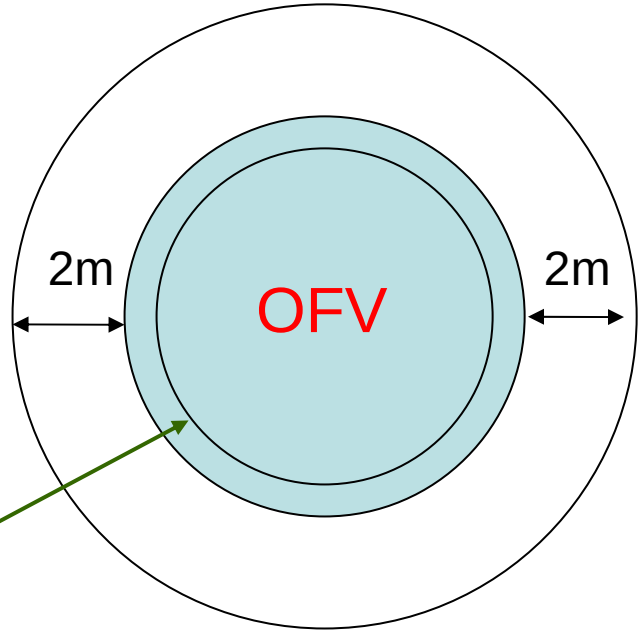


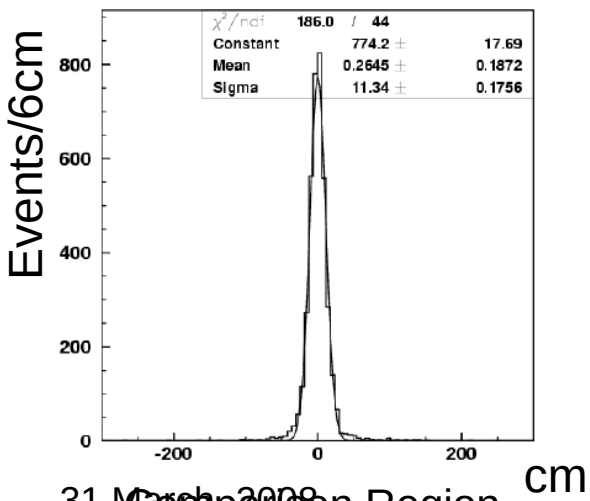
New FV Cut

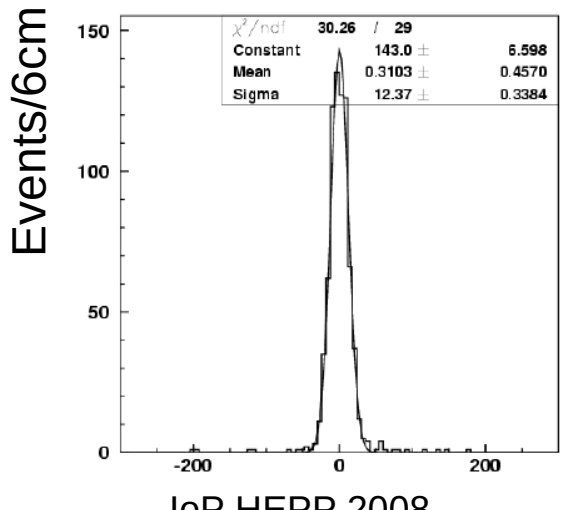
- Dwall>100cm for all K2K-I
  - towall>200cm for 1 ring events
  - $\text{towall}_{\text{eff}}$>250cm for multi-ring events
- Dwall>100cm for all K2K-II
  - towall>200cm(300cm) for 1 ring μ-(e-)like events
  - $\text{towall}_{\text{eff}}$>300cm for multi-ring events

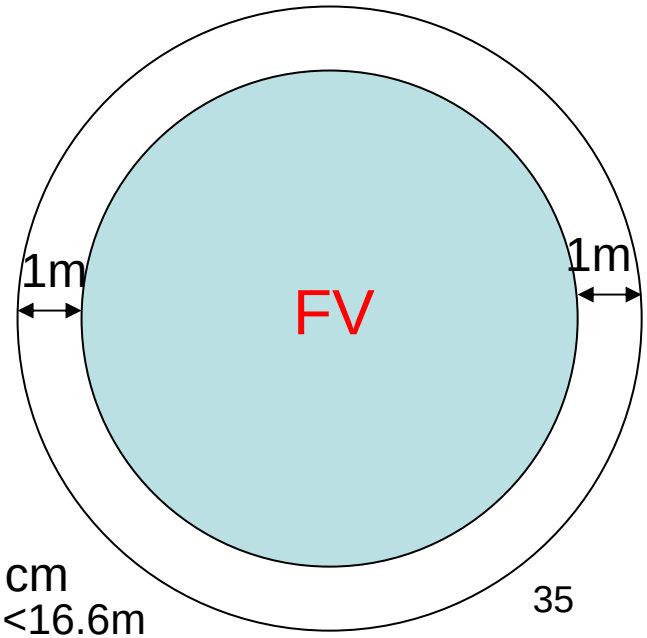
Dwall Selection

- OFV says each event must be at least 2m away from the ID wall (dwall>2 m)
- Find region outside of this that has similar event reconstruction as first 0.5m inside official FV
- Compare difference between incoming and outgoing events





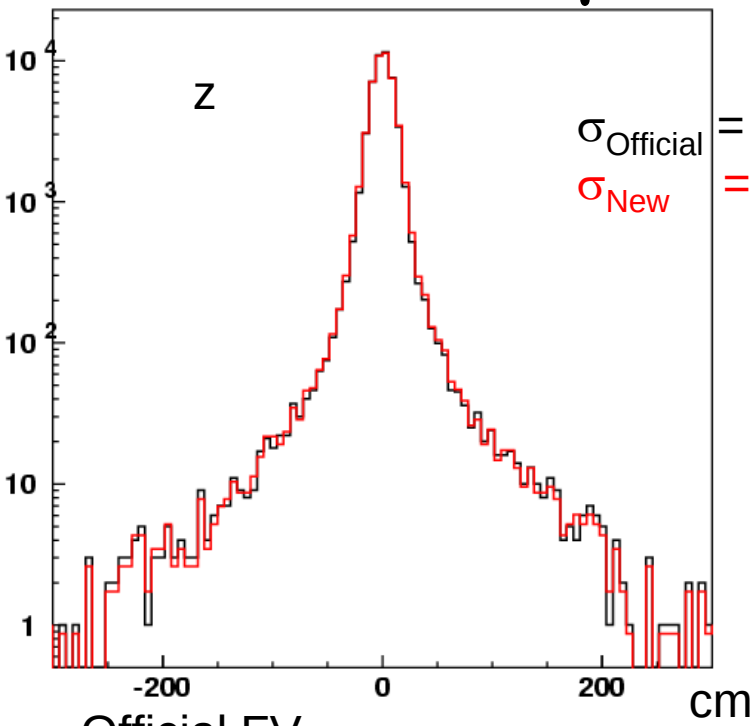




Checks on MC in New FV

- After new FV selection criteria is determined, the following are checked:
  - Vertex resolution (shown below)
  - Particle mis-identification percentage
  - Ring mis-counting percentage (shown below)
  - Angular resolution
  - Percent of events in vertex and angular resolution tails

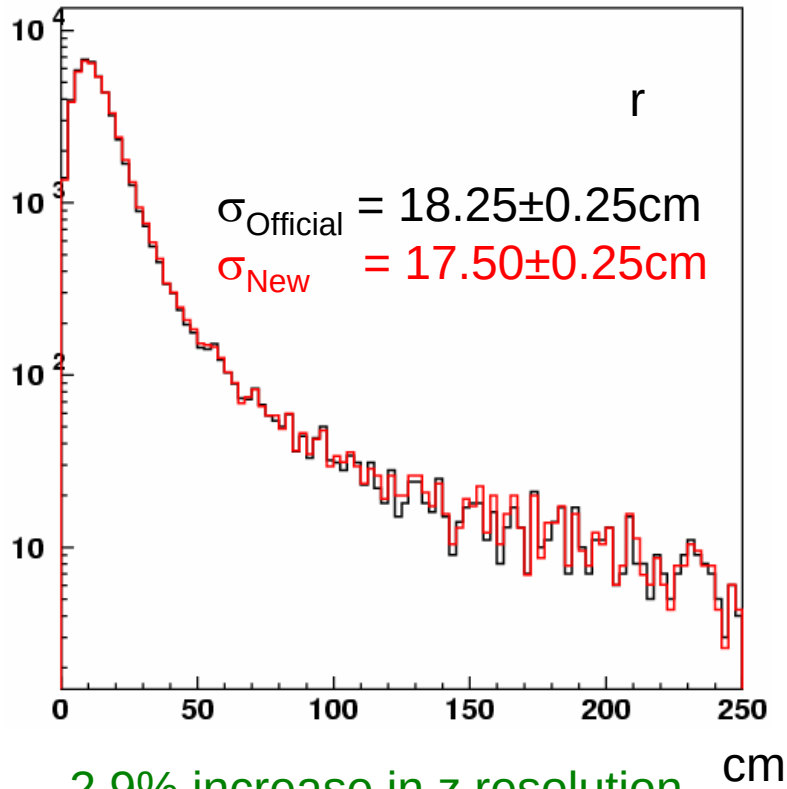
K2K-I 1Rμ Resolution Comparison



Official FV

New FV (normalized to OFV histogram area)

16.1% increase in MC events



While statistically different, added events follow same distribution as official FV events

Tails match up very well

2.9% increase in z resolution

-4.1% increase in r resolution

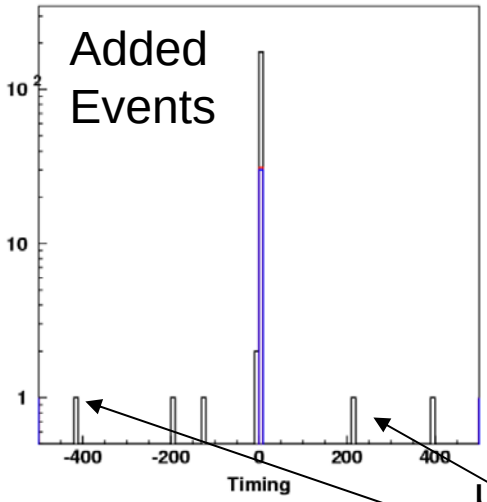
Similar for other event classes

K2K μ-like Cherenkov Ring Mis-Counting

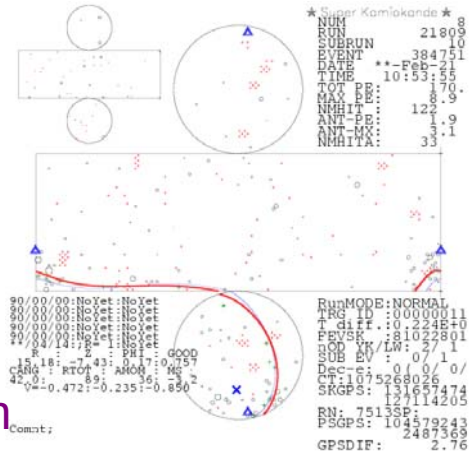
Sample	% mis-counted
OFV K2K-I	7.29+/-0.38
2m-2.5m K2K-I	10.00+/-1.56
Added Events K2K-I	9.20+/-1.10
New FV K2K-I	7.54+/-0.36
OFV K2K-II	5.78+/-0.33
2m-2.5m K2K-II	6.02+/-1.14
Added Events K2K-II	6.85+/-0.88
New FV K2K-II	5.93+/-0.31

- CCQE ν_μ events checked to find mis-counted events
  - CCQE events should have only 1 Cherenkov ring (proton below Cherenkov threshold)
  - % mis-counted are the % of CCQE events found with more than 1 ring
- OFV and New FV are consistent

Timing of Added K2K Events

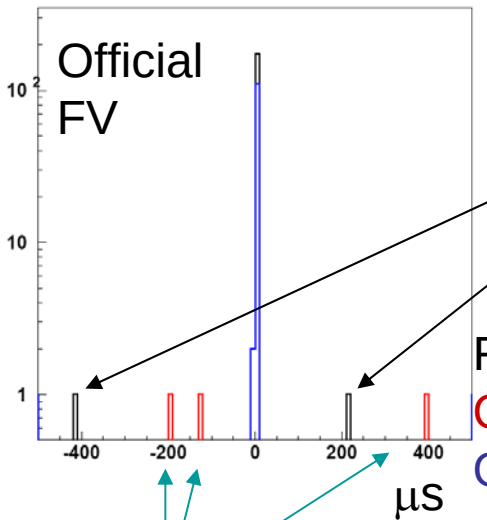


FC events before FV Cut: 181
Events added to Official FV: 32
Added events after timing cut: 31



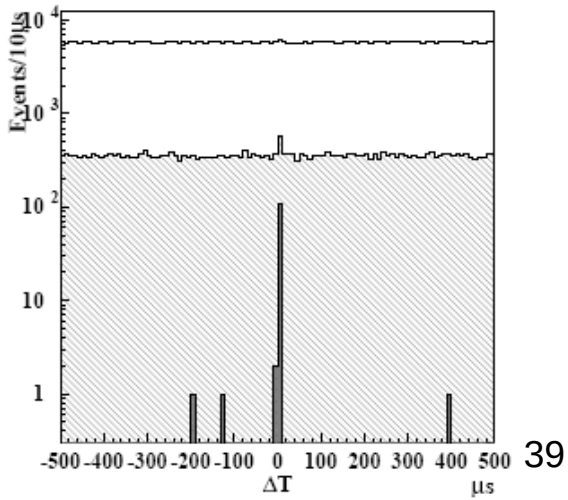
Only decay electron event in New FV is cut based on timing information

ΔT = 2.79μs
E = 34.87 MeV



2 FC events here are outside FV definition

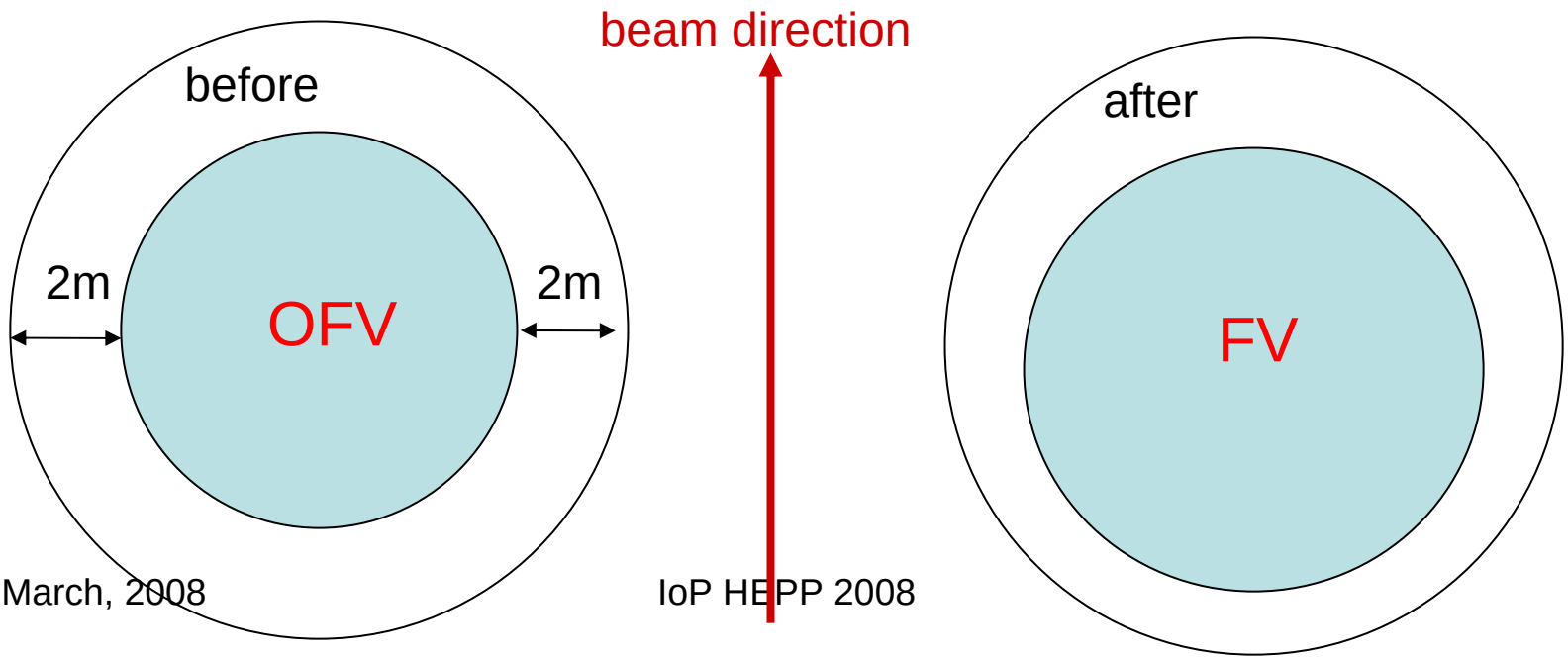
FC events before FV Cut: 181
Official FV: 115
Official FV after timing cut: 112



3 events consistent w/ 2.3 expected atmospheric events

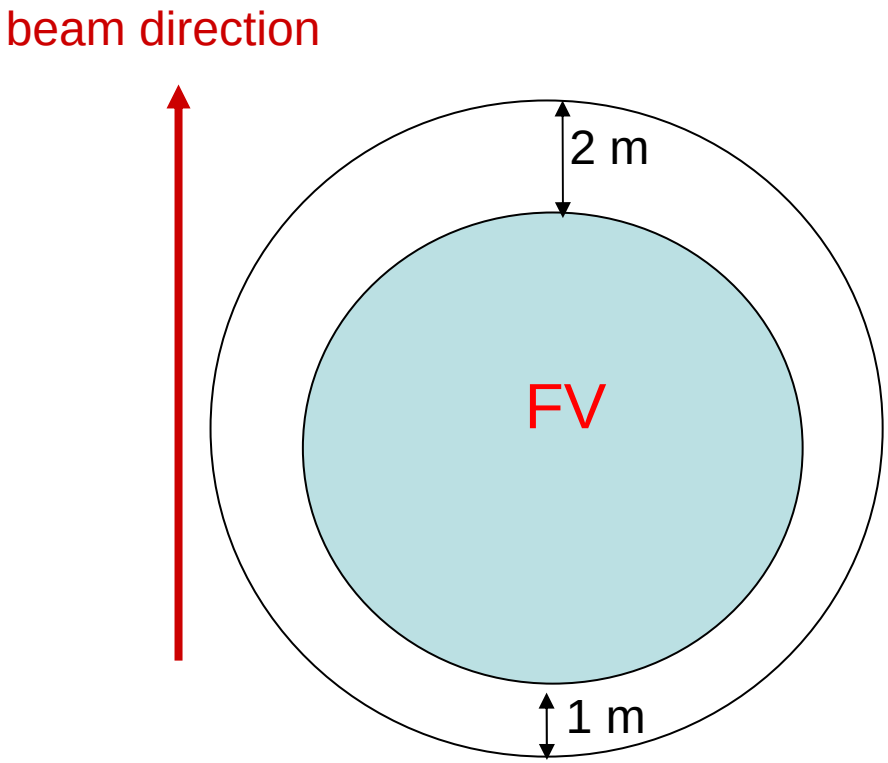
Upstream shift of FV

- Previous expansion general for either SK or K2K, but K2K beam is coming from a known direction
  - Test for T2K: may be a way to include more signal events without greatly increasing background in ν_e appearance search
- Is it possible to shift FV upstream in the beam direction?

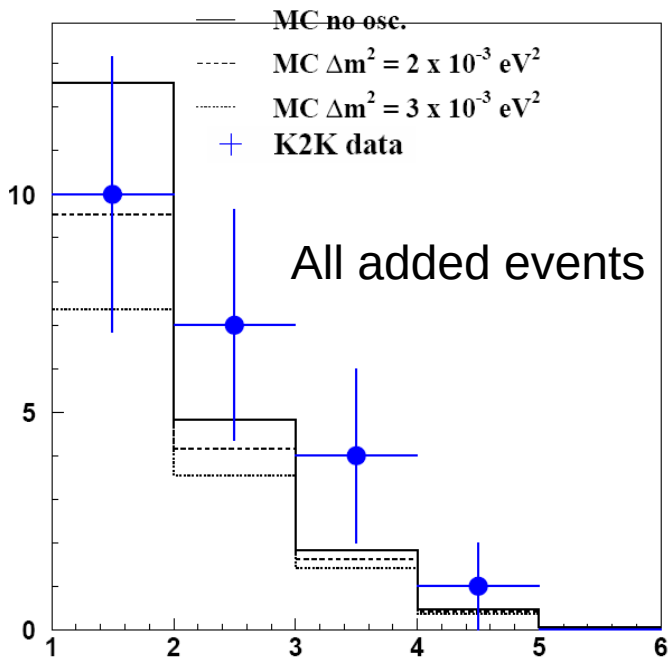


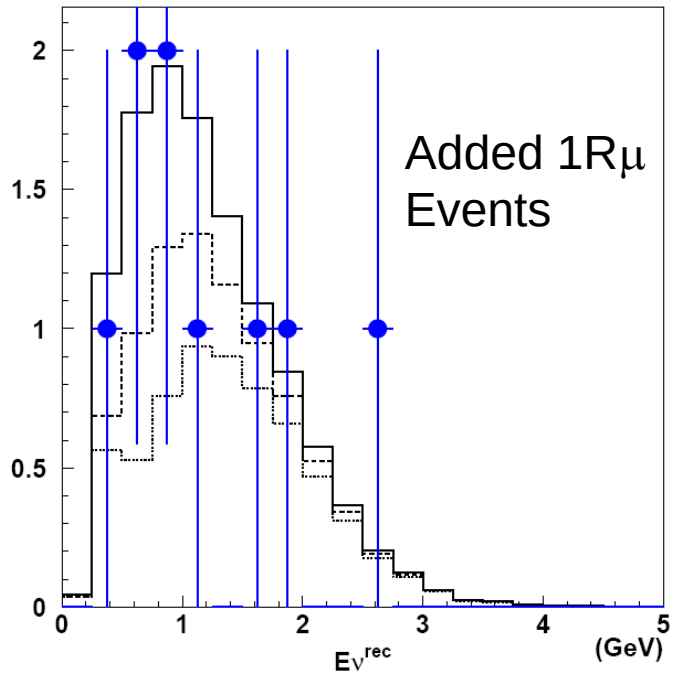
Upstream Shift

- From general expansion: dwall>1 m allowed for all event classes
- Keep most downstream point of FV at least 2 m away from wall
- Can move FV center 0.5m upstream in the beam direction
  - dwall>1.5 m equivalent



Added upstream events





Run Period	Expected # In Added Region	Actual # In Added Region	Sigma
K2K-I	5.26±0.71	14±3.74	2.3
K2K-II	5.50±0.73	8±2.83	0.9
K2K-I&II	10.76±1.02	22±4.69	2.3

t-test is 1.7σ

Expected # = % increase estimated by MC multiplied by # of observed events in OFV

Event Summary of Expanded FVs

New FV:

Total number of events expected in the case of no neutrino oscillations: $183.3^{+10.7}_{-10.0}$

Run Period	Total events observed in New FV	1Rμ events observed
K2K-I	76	39
K2K-II	67	32
K2K-I&II	143	71

Upstream FV:

Total number of events expected in the case of no neutrino oscillations: $170.9^{+9.5}_{-9.0}$

Run Period	Total events observed in New FV	1Rμ events observed
K2K-I	69	36
K2K-II	65	31
K2K-I&II	134	69

New FV Systematic Errors

Energy Spectrum Systematics

Sample \ [GeV]	0.0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-
K2K-I OFV	4.1%	3.4%	3.6%	4.9%	4.9%
K2K-II OFV	6.2%	4.6%	4.2%	4.3%	4.3%
K2K-I New	4.2%	3.4%	3.6%	4.9%	4.9%
K2K-II New	6.8%	4.6%	4.2%	4.3%	4.3%

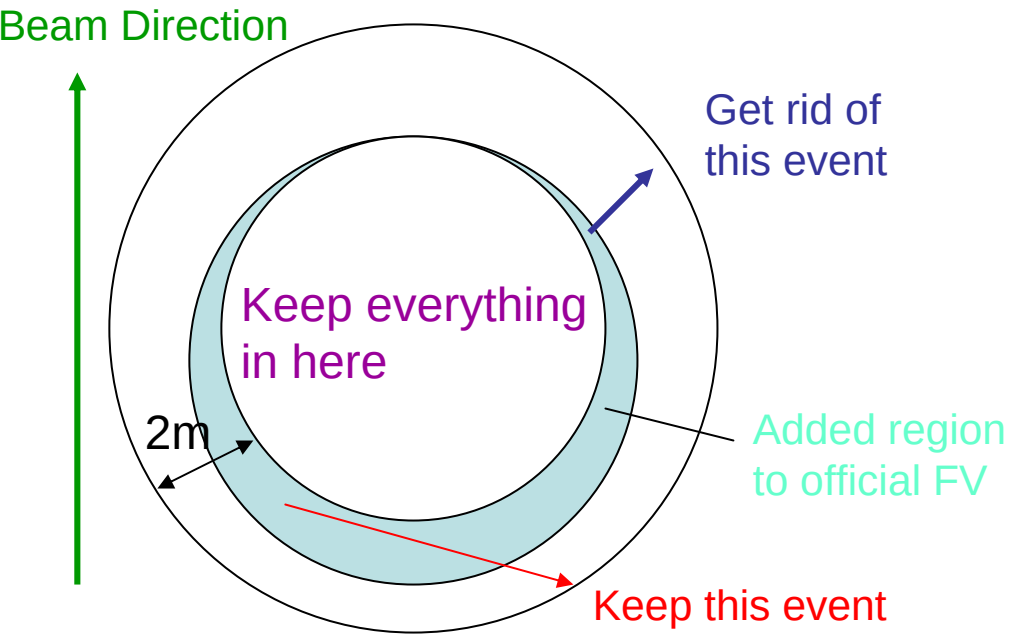
	K2K-I	K2K-II
Energy Scale	2.0%	2.1%

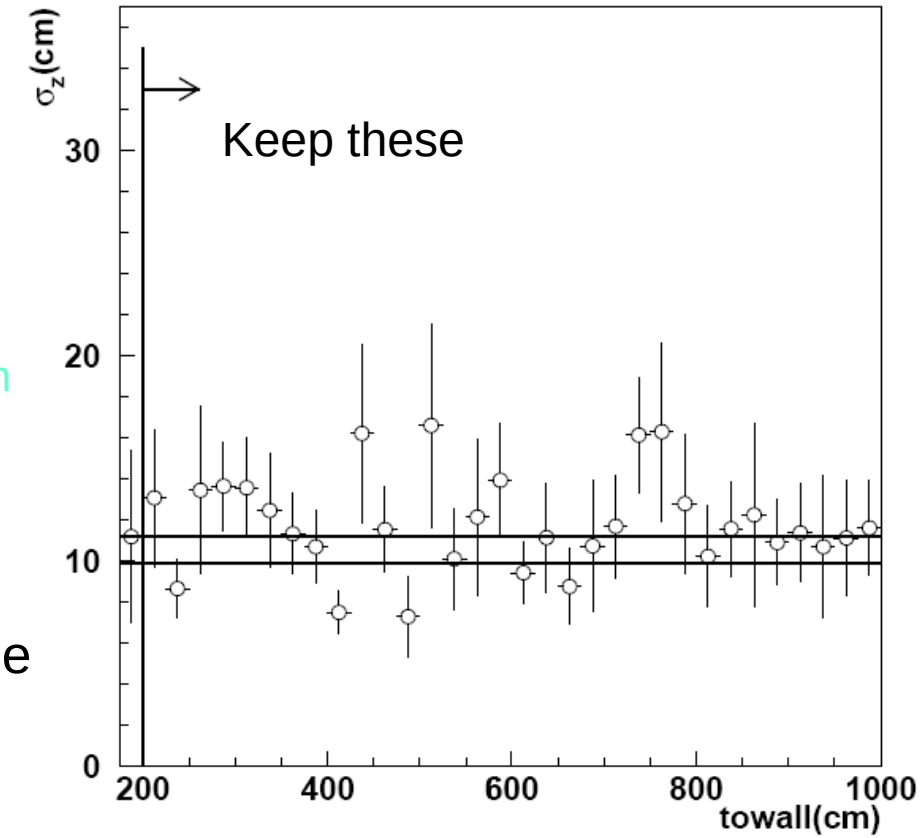
# of events systematic errors	K2K-I	K2K-II
Reduction	<1%	<1%
Fiducial Volume	2%	2%
Decay e bckgd.	0.1%	0.1%
MC statistics	0.6%	0.6%
Total	3%	3%

- No change in energy scale systematic error
- No change in systematic errors for the total number of events at SK
- Slight increase in lowest energy bin of energy spectrum systematic errors
  - Due to ring counting systematic error

Upstream towall selection

Take advantage of bias from beam direction





Upstream cut: At least 1m away from the wall (dwall>1 m) and travel at least 2m before hitting it (towall>200 cm) for 1R events and ($towall_{eff}$>200 cm) for multi-ring events.

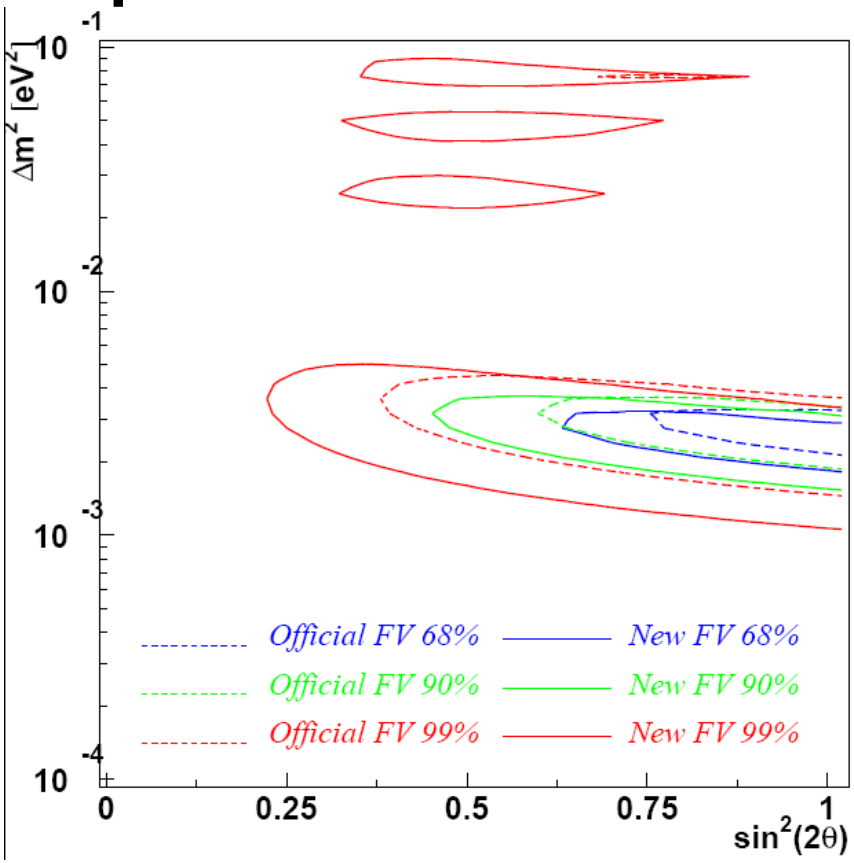
Upstream FV Neutrino Oscillation Fit Results

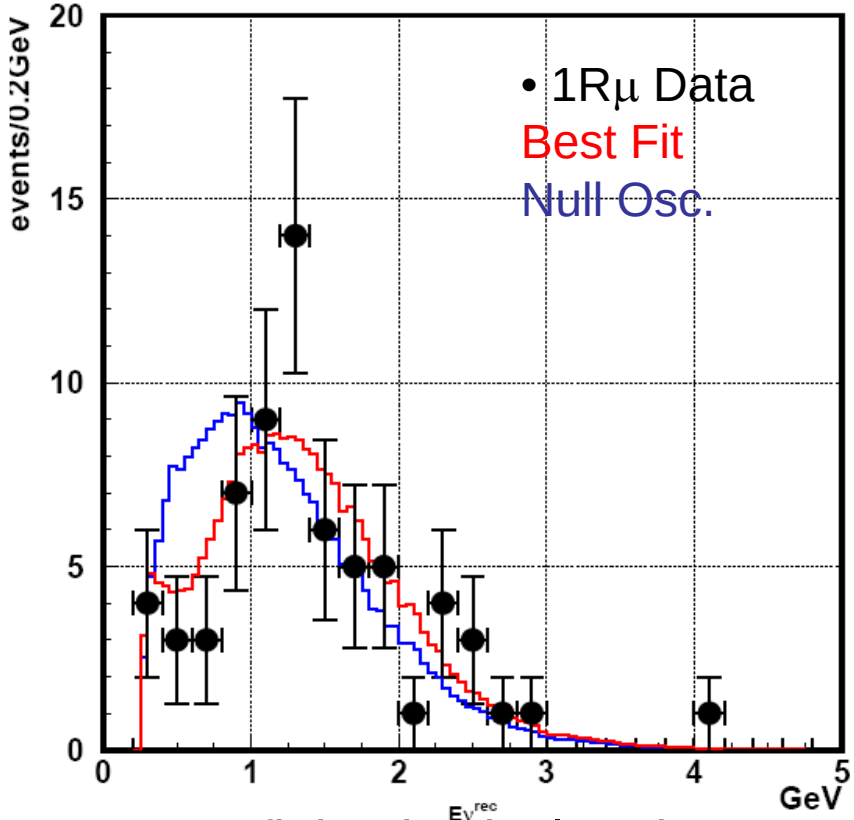
Run Period	Fit type	All Parameter Space		Physical Region Only	
		Δm^2 [eV^2]	$\sin^2 2\theta$	Δm^2 [eV^2]	$\sin^2 2\theta$
K2K-I & K2K-II	Combined	0.00236	1.07	0.00244	1.00
	Shape Only	0.00265	1.18	0.00281	1.00
K2K-I	Combined	0.00254	0.81	0.00254	0.81
K2K-II	Combined	0.00232	1.37	0.00261	1.00

	K2K-I	K2K-II	K2K-all
Number of events	5.6%	4.9%	0.76% (2.7σ)
E_ν^{rec} spectrum shape	34%	1.8%	0.76% (2.7σ)
Combined (number of events and E_ν spectrum shape)	5.9% (1.9σ)	0.44% (2.8σ)	**0.042%** (3.5σ)

Loss of significance as compared to OFV (4.3σ)

Upstream FV Combined Fit Results





Best fit in physical region oscillation parameters used:

$\sin^2 2\theta = 1.00$

$\Delta m^2 = 0.00244$ eV^2

KS: 68% (37% for Official FV)

$1.5\times10^{-3} \leq \Delta m^2 \leq 3.1\times10^{-3}$ eV^2 (@ 90% C.L.)