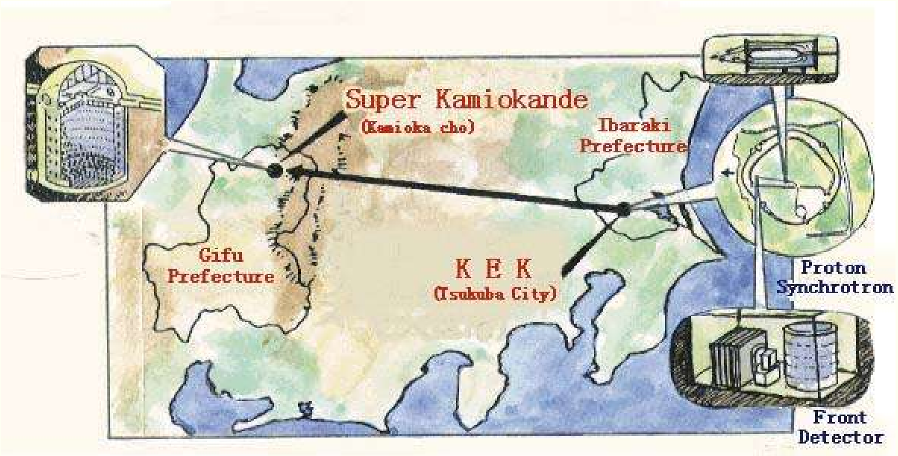
K2K Neutrino Oscillation



L. Ludovici (INFN Roma)
for the K2K Collaboration

June 22, 2005 NuFact 05 Frascati (Rome)

Laboratori Nazionali di Frascati

The K2K Collaboration

JAPAN: KEK, ICRR, University of Tokyo, Hiroshima University, Kobe University, Kyoto University, Niigata University, Okayama University, Osaka University, Tokyo University of Science, Tohoku University

KOREA: Chonnam National University, Dongshin University, Korea University, Seoul National University

USA: Boston University, Duke University, University of California Irvine, University of Hawaii, Massachusetts Institute of Technology, State University of New York, University of Washington

POLAND: Warsaw University, Solton Institute

CANADA: TRIUMF, University of British Columbia

ITALY: Rome University and INFN

FRANCE: Dapnia Saclay

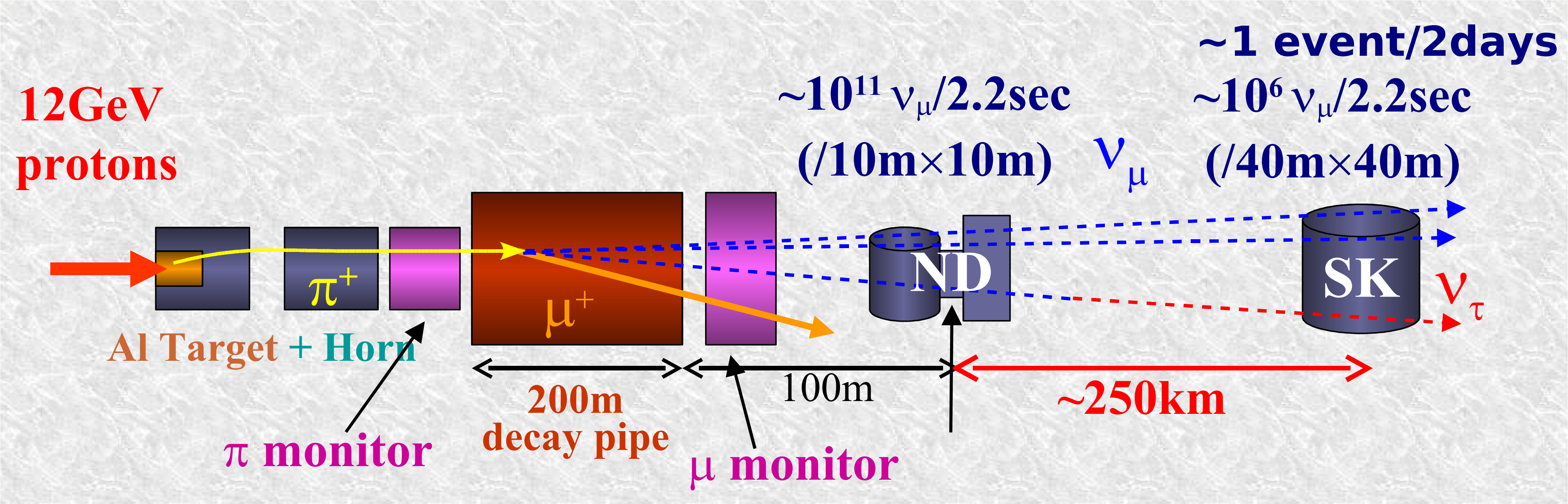
SPAIN: University of Barcelona, University of Valencia

SWITZERLAND: Geneva University

RUSSIA: INR-Moscow

Since 2002 for K2K-II

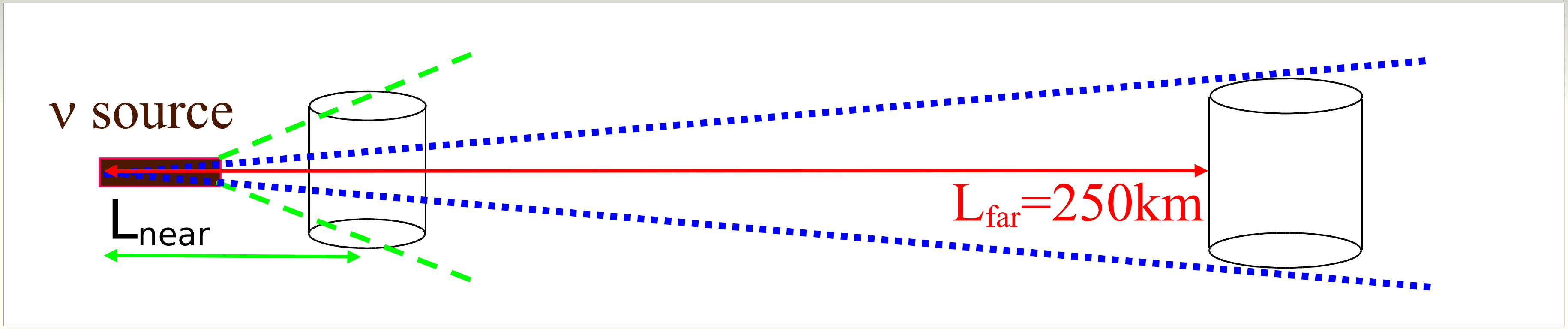
K2K Conceptual Layout

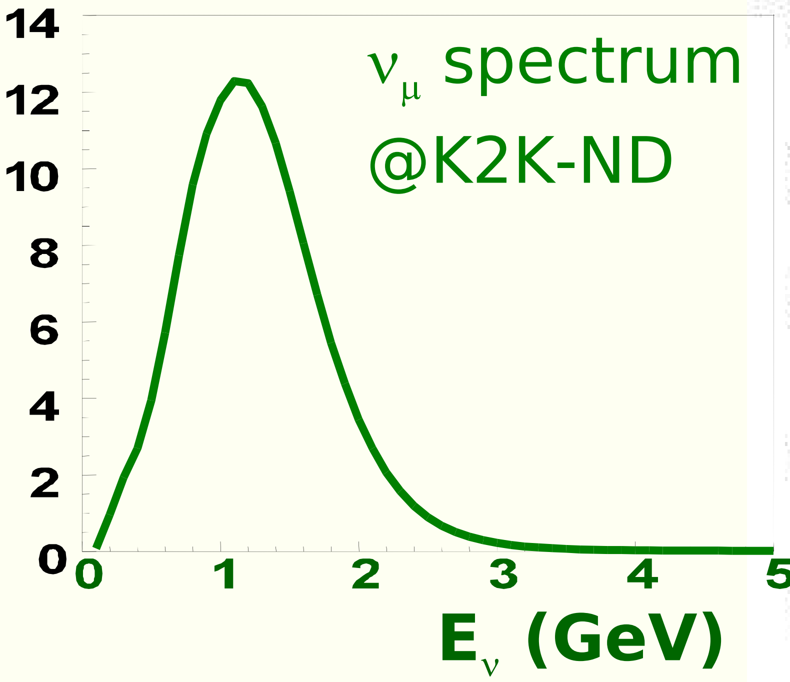


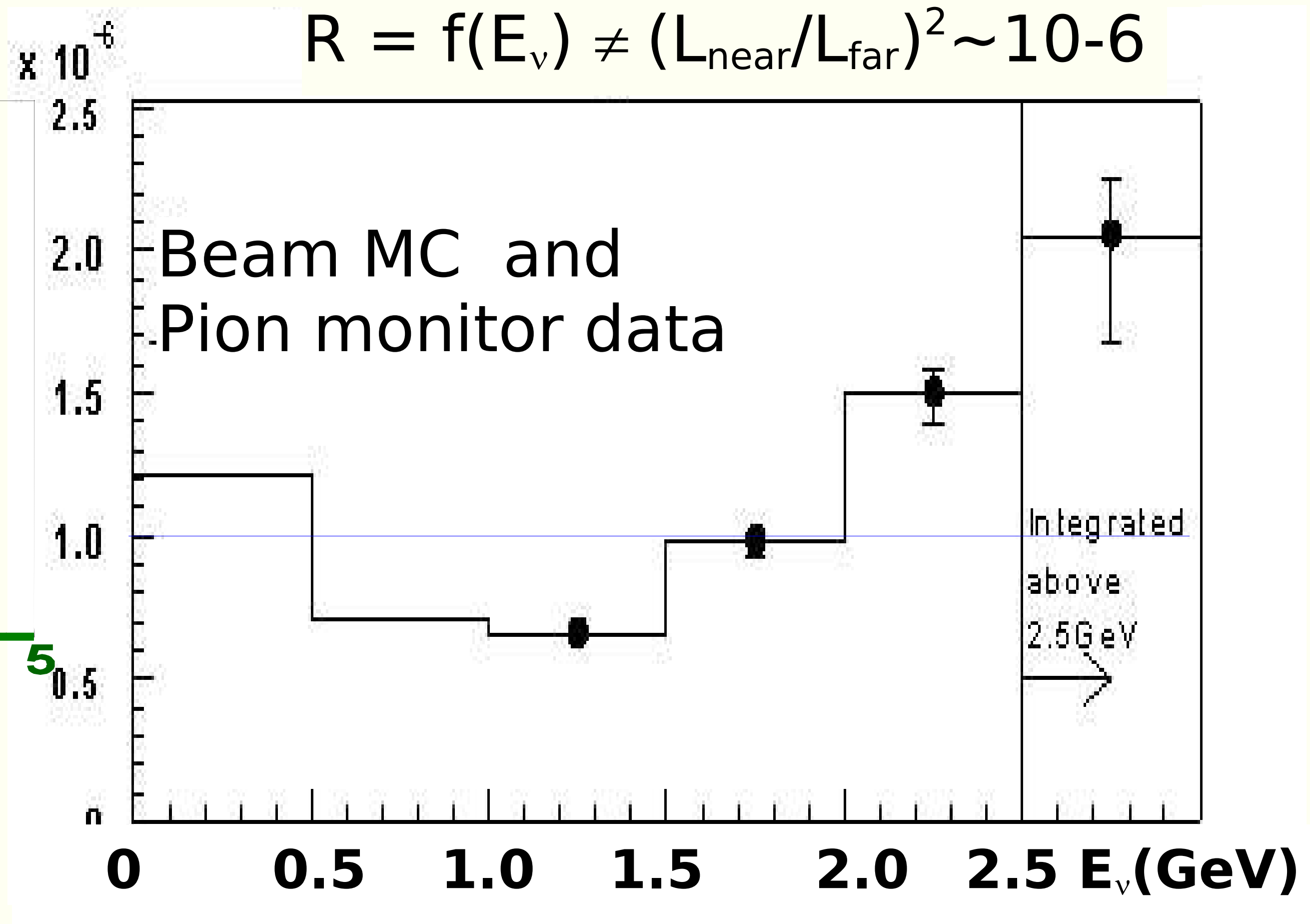
K2K signature of neutrino oscillation

- Reduction of ν_μ events
- Distortion of ν_μ energy spectrum

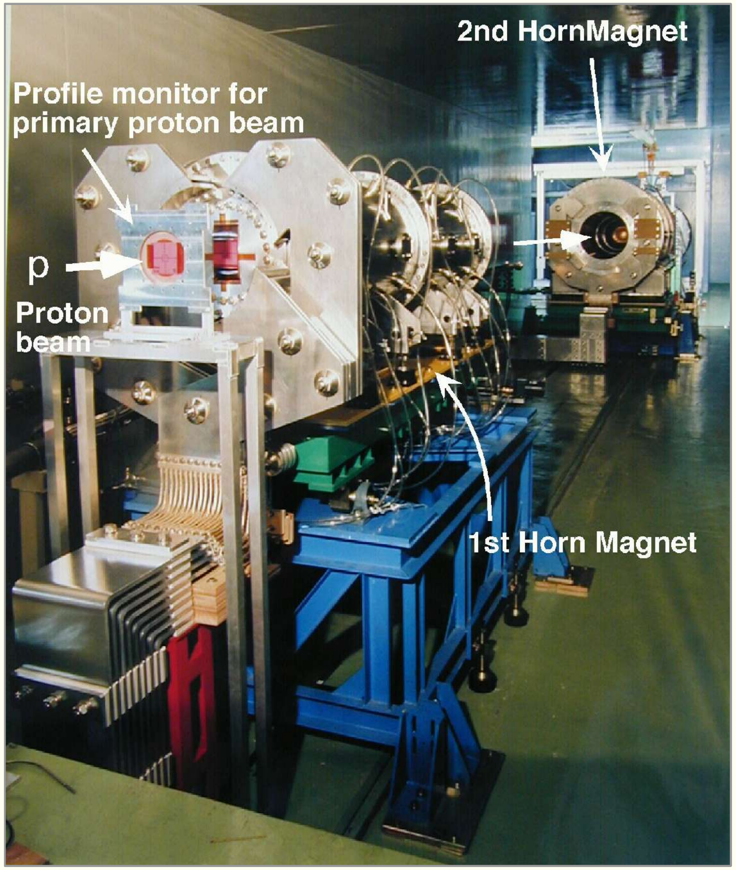
Far/Near Ratio

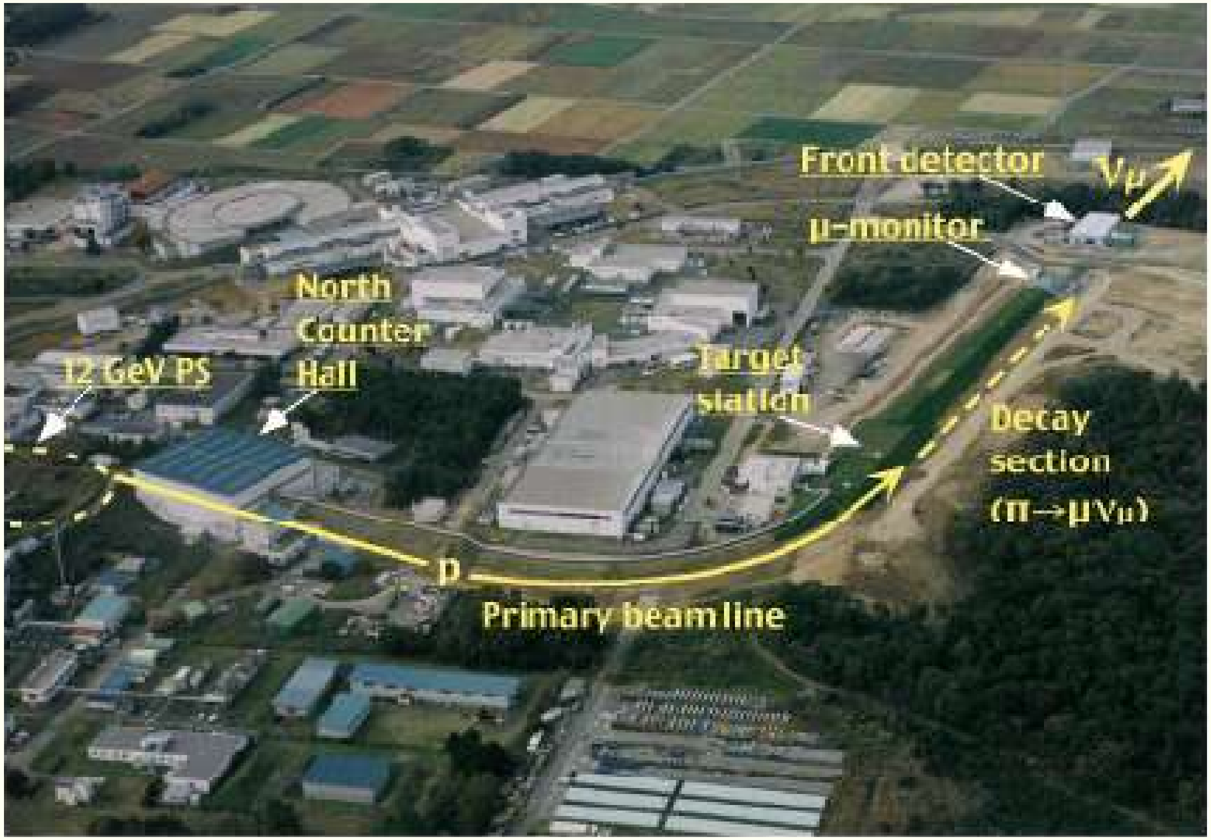






Neutrino Beam

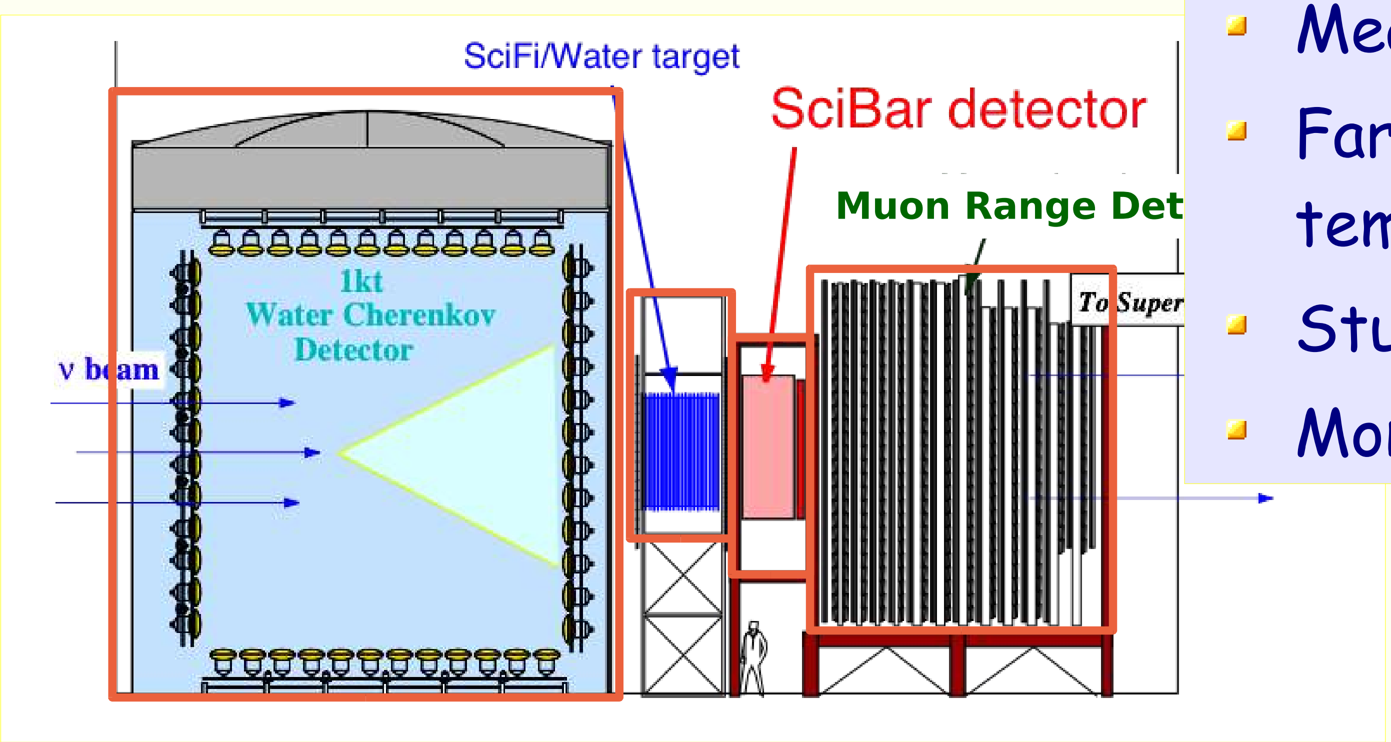




12 GeV protons
1.1μs spill/2.2s
6x10^{12} p/spill
Al target
Two horns focussing

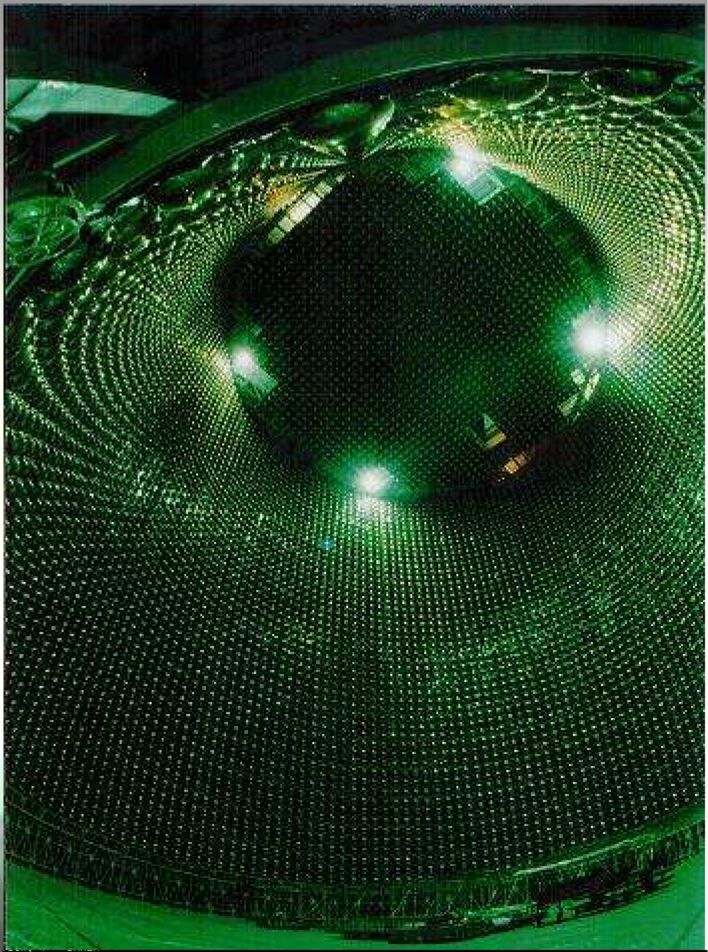
Near Detector Layout

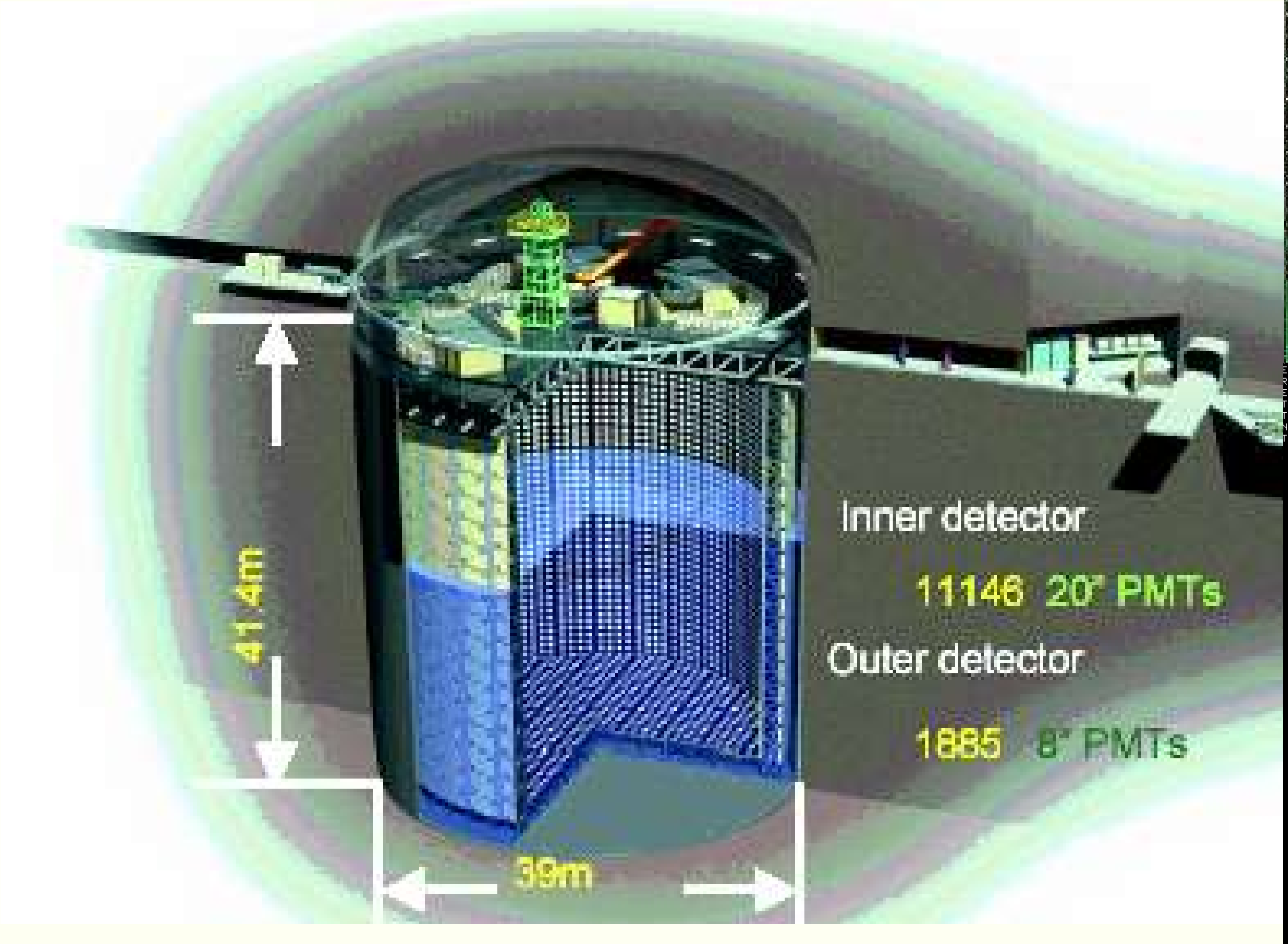
- 1KT Water Cherenkov (1KT)
- Scintillating-fiber/Water sandwich (SciFi)
- Lead Glass calorimeter (LG) before 2002
- Scintillator Bar Detector (SciBar) after 2003
- Muon Range Detector (MRD)

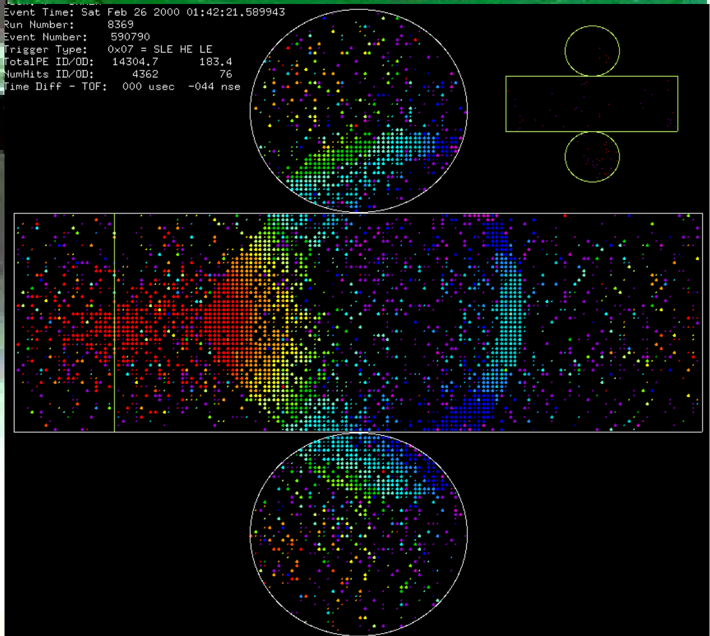


- Measure neutrino flux
- Far/Near: detector systematics, C vs O
- Study ν properties
- Monitor ν beam stability

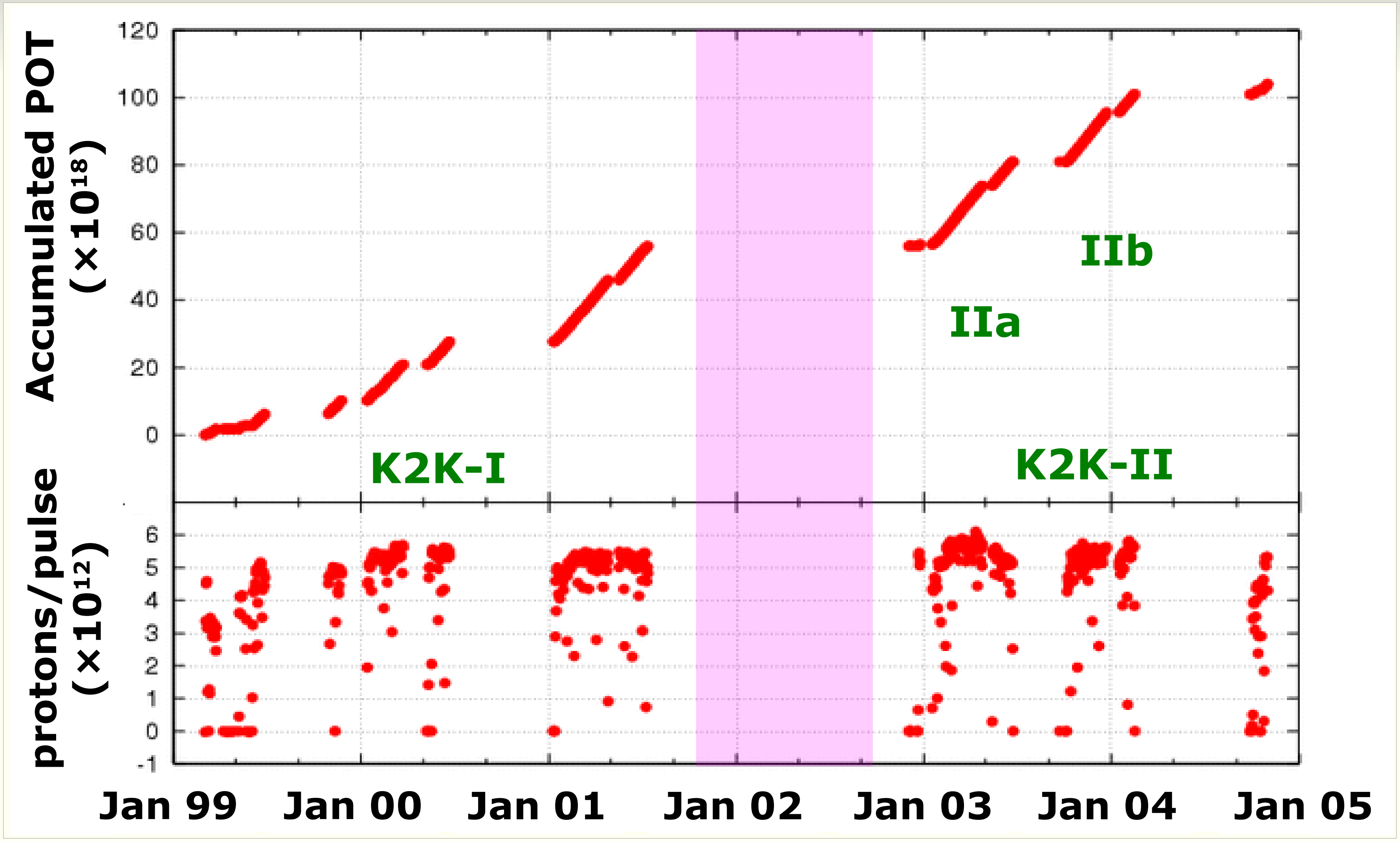
SuperKamiokande







Protons on Target

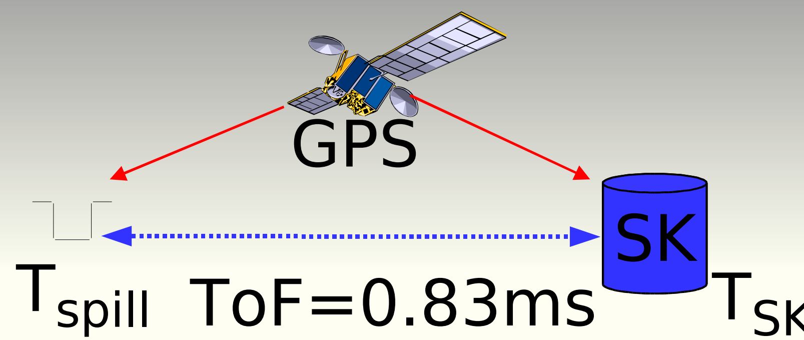


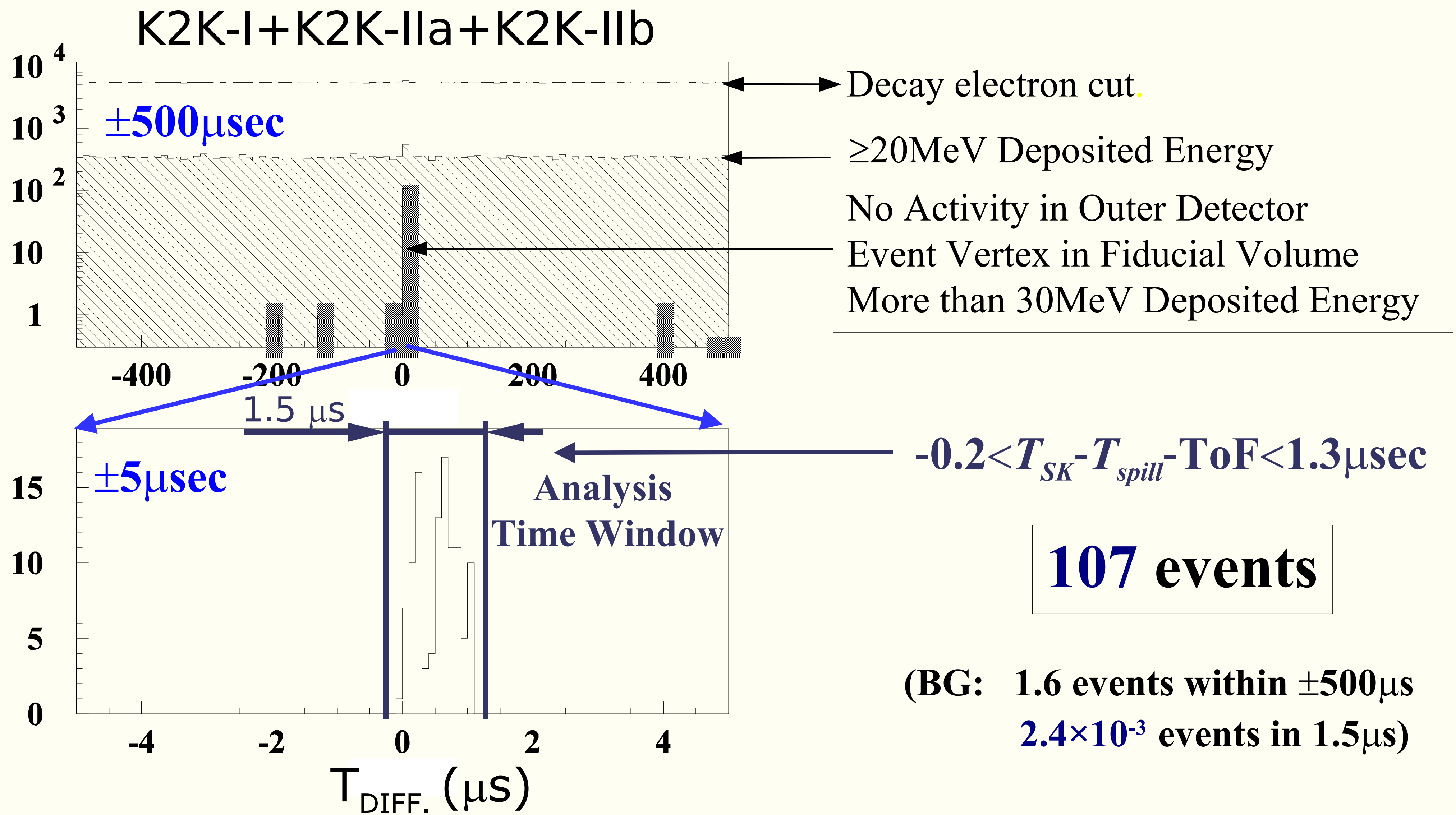
This analysis: K2K-I+K2K-IIa&b

$10.1\ 10^{19}$ PoT delivered

$8.9\ 10^{19}$ PoT for physics analysis

SuperKamiokande Events



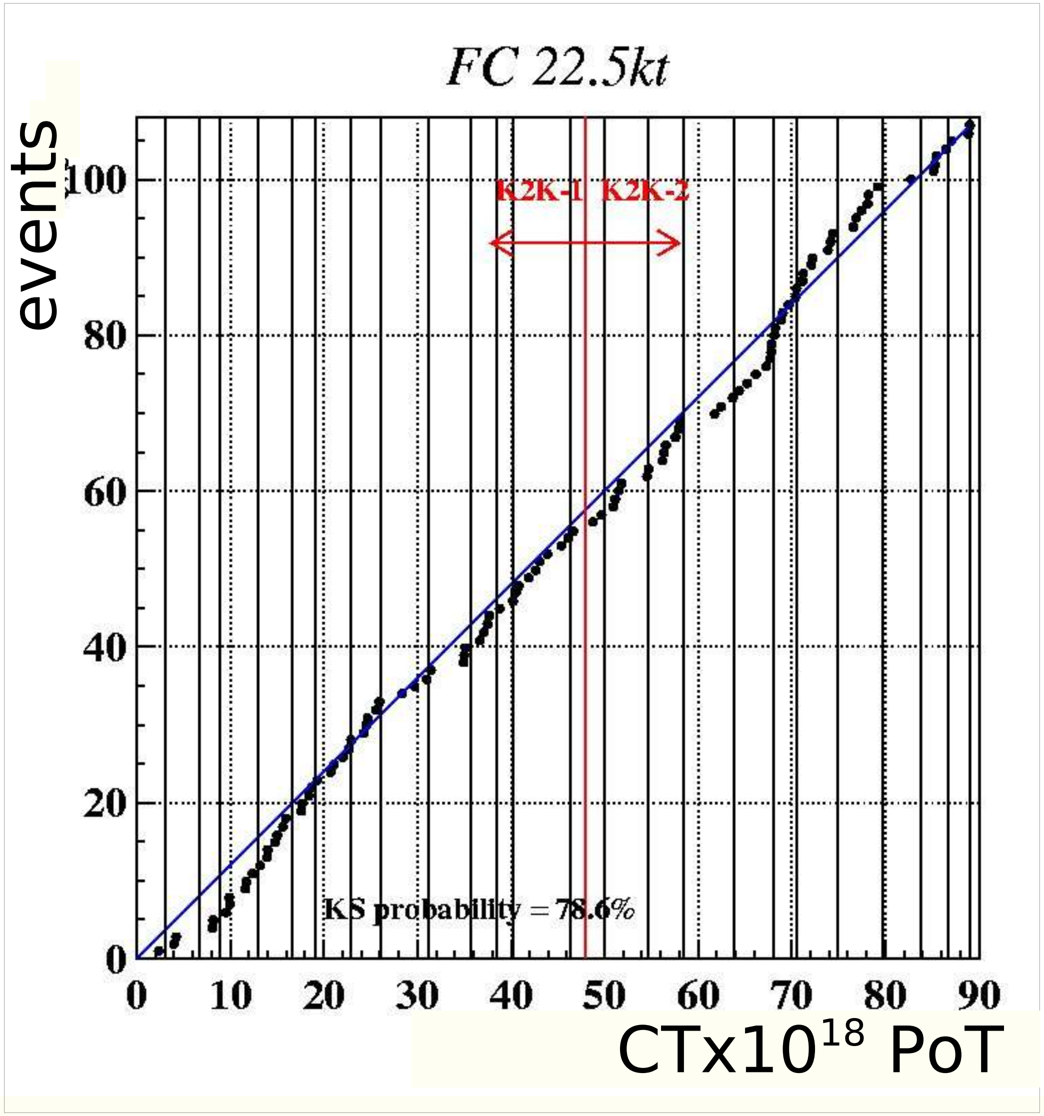


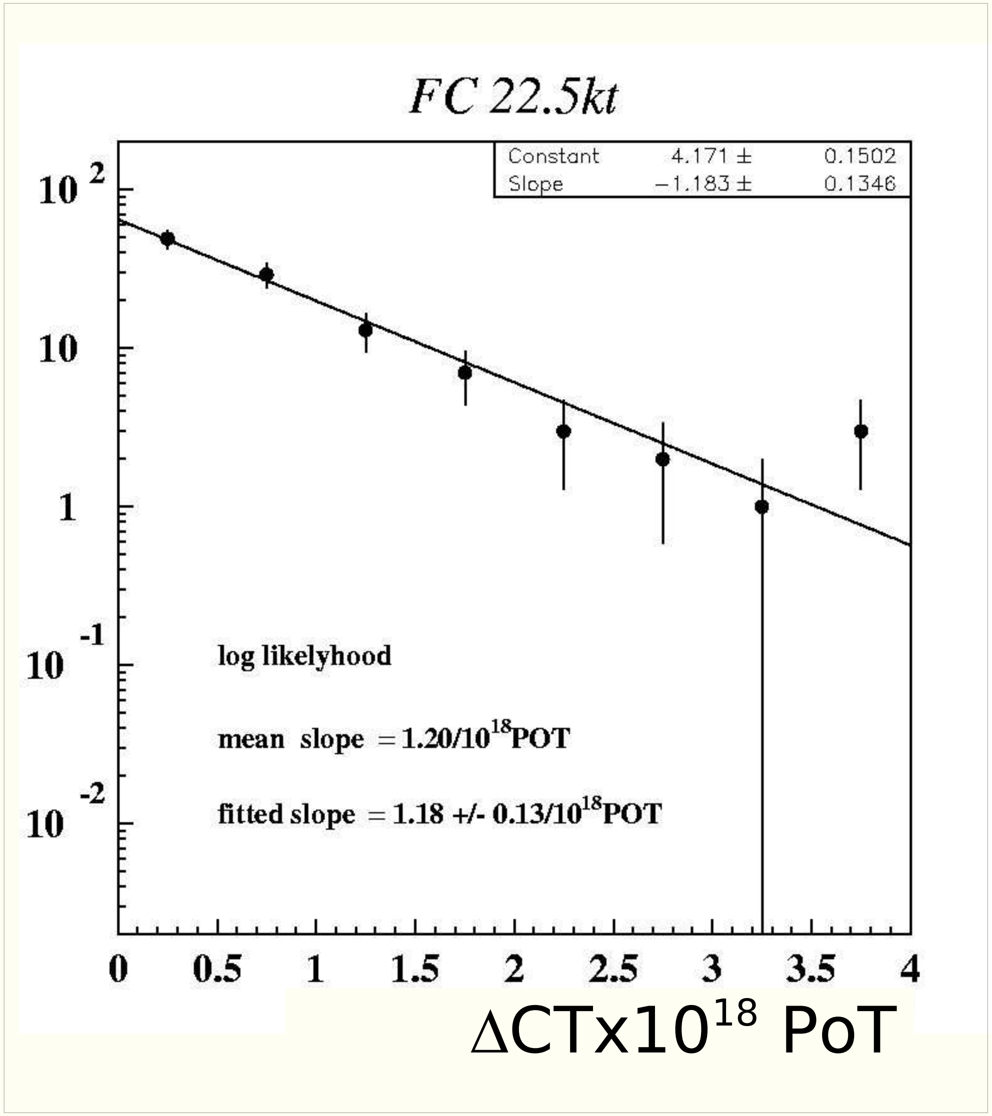
$-0.2 < T_{SK} - T_{spill} - \text{ToF} < 1.3\mu\text{sec}$

107 events

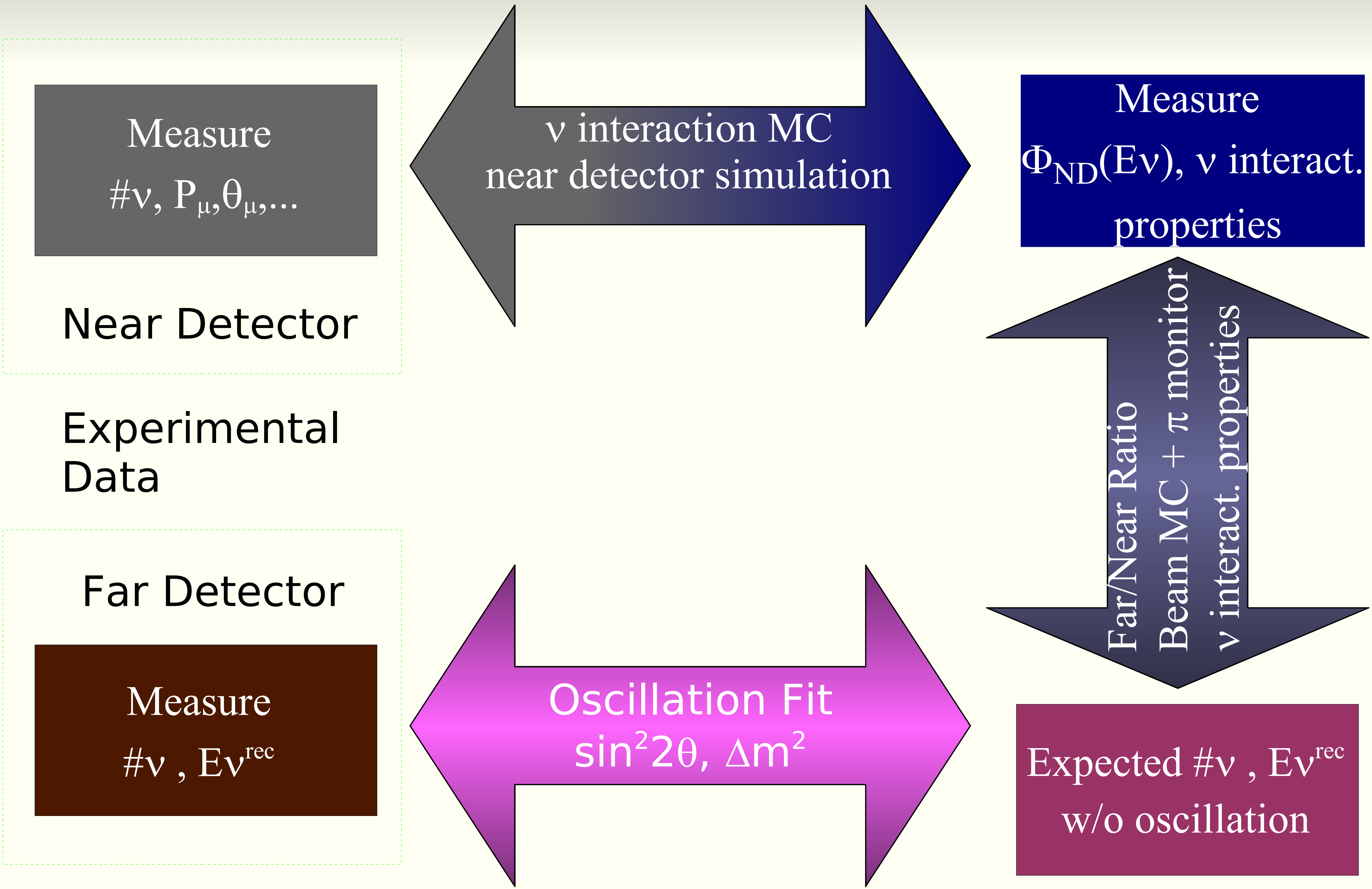
(BG: 1.6 events within ±500μs
2.4×10^{-3} events in 1.5μs)

SK Events


FC 22.5kt
events
100
80
60
40
20
0
K2K-1 K2K-2
KS probability = 78.6%
0 10 20 30 40 50 60 70 80 90
CTx10^18 PoT

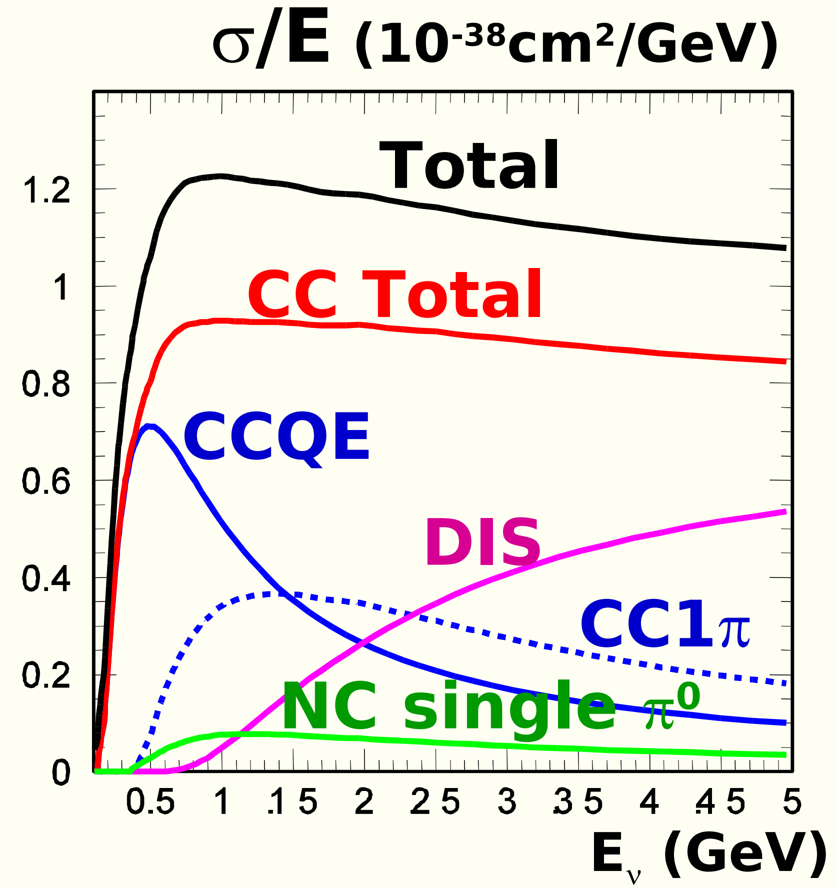

FC 22.5kt
Constant 4.171 ± 0.1502
Slope −1.183 ± 0.1346
10^2
10
1
10^-1
10^-2
log likelyhood
mean slope = 1.20/10^18POT
fitted slope = 1.18 +/- 0.13/10^18POT
0 0.5 1 1.5 2 2.5 3 3.5 4
ΔCTx10^18 PoT

Analysis Strategy



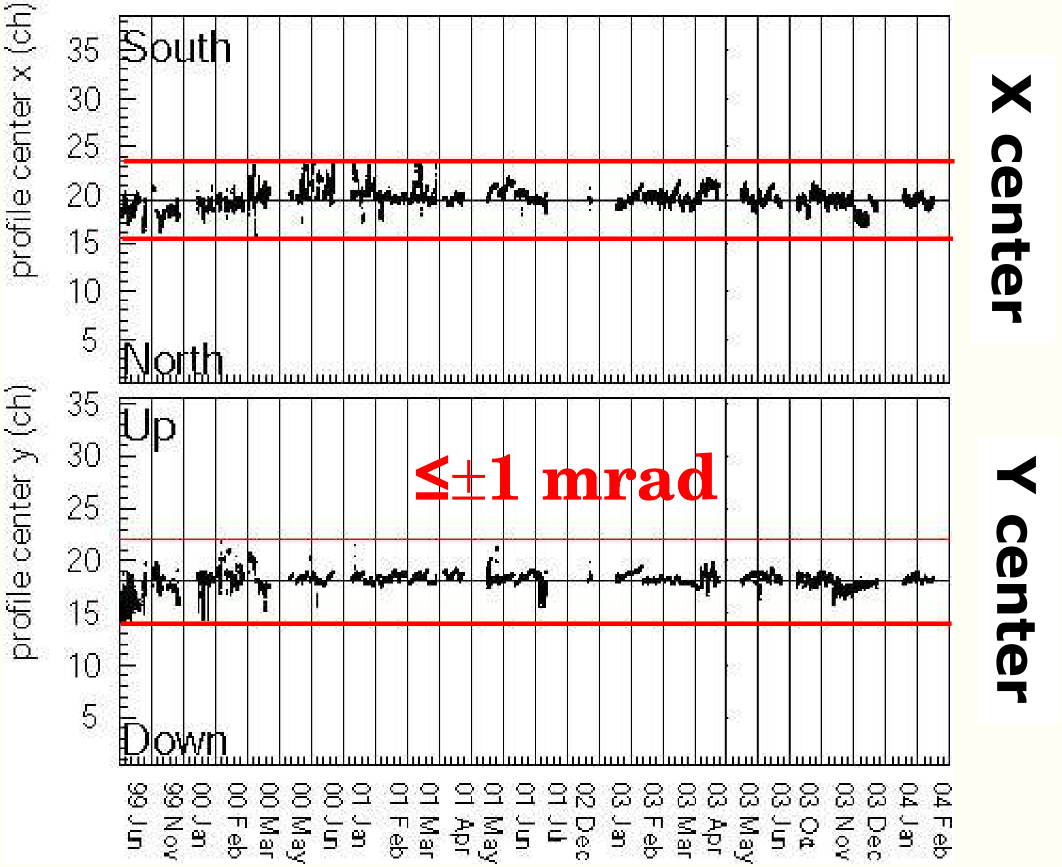
Neutrino Interaction MC (NEUT)

- CC quasi-elastic (CCQE)
  Smith and Moniz with M_A=1.1GeV
- CC (resonance) single π (CC1π)
  Rein and Seghal with M_A=1.1GeV
- DIS
  GRV94+JETSET with Bodek and Yang corrections
- CC coherent
  Rein and Sehgal with Marteau's cross-section rescale
- Neutral Currents
- Nuclear effects
  Oxygen, Carbon

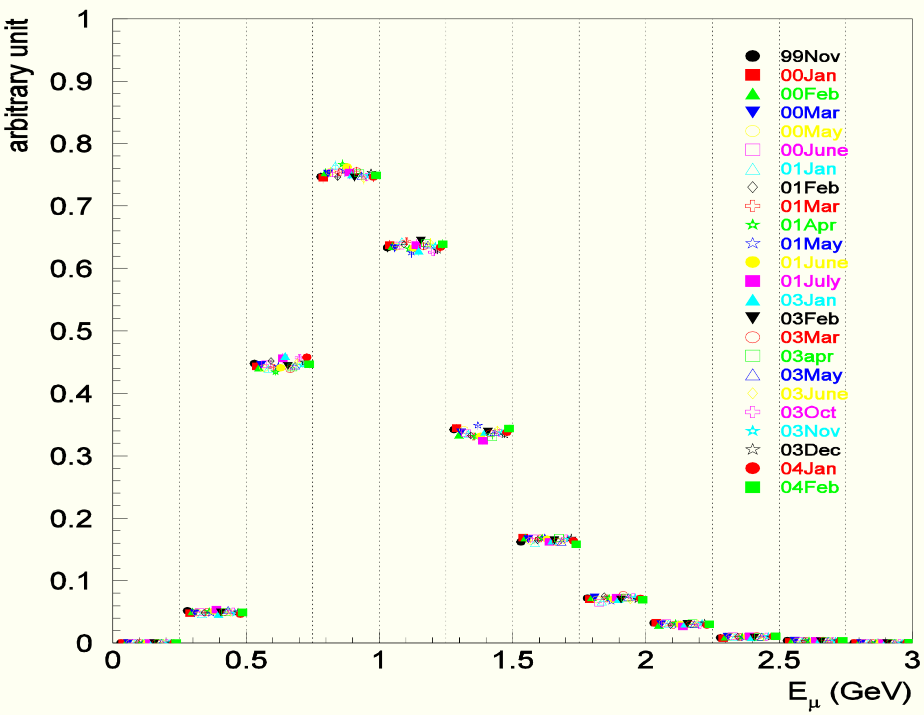


MRD: Neutrino Beam Stability

MRD muon direction



MRD Muon Spectrum



Beam proved stable over more than 5 years

1KT: N_{SK}

Water Cherenkov replica of Super-K (scale 1/50, ~1/1000 fidcial)

Most of detector systematics cancel in the extrapolation

$$N_{SK}^{\exp} = N_{KT}^{obs} \bullet \frac{\int \Phi_{SK}(E_\nu)\sigma(E_\nu)dE_\nu}{\int \Phi_{KT}(E_\nu)\sigma(E_\nu)dE_\nu} \bullet \frac{M_{SK}}{M_{KT}} \bullet \frac{\varepsilon_{SK}}{\varepsilon_{KT}}$$

≡Far/Near Ratio ~1×10^{-6} (from MC)

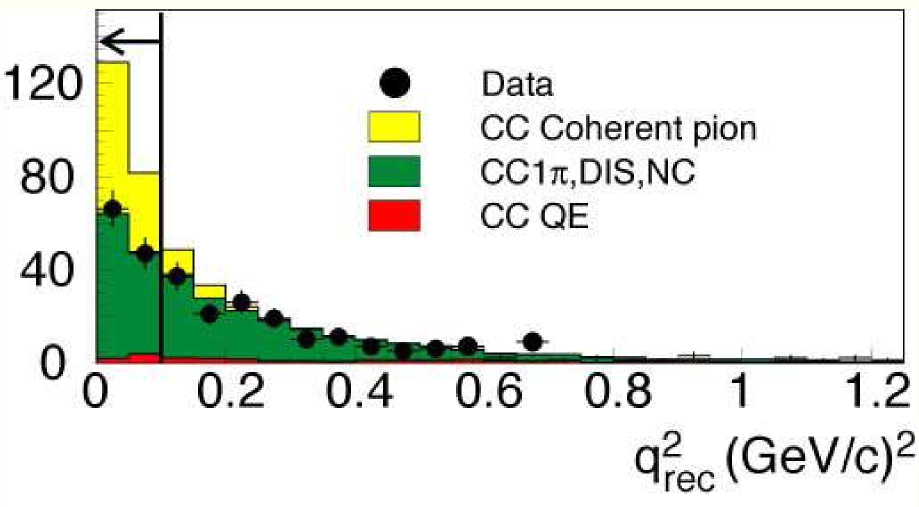
M:	Fiducial mass	M_{SK}=22,500ton,	M_{KT}=25ton
ε:	efficiency	$\varepsilon_{SK\text{-}I(II)}$=77.1(78.2)%,	ε_{KT}=74.5%

$N_{SK}^{exp} = 150.9^{+11.6}_{-10.0}$ ⟺ $N_{SK}^{obs} = 107$

Low q2 Deficit

- A deficit at low q^2 for non-QE events is observed
- Two fenomenological models fit our data:
  - Suppression of CC1π as q^2/A for <A=0.100.03(GeV/c^2)
  - No coherent pion production

- The oscillation result is insensitive to the choice

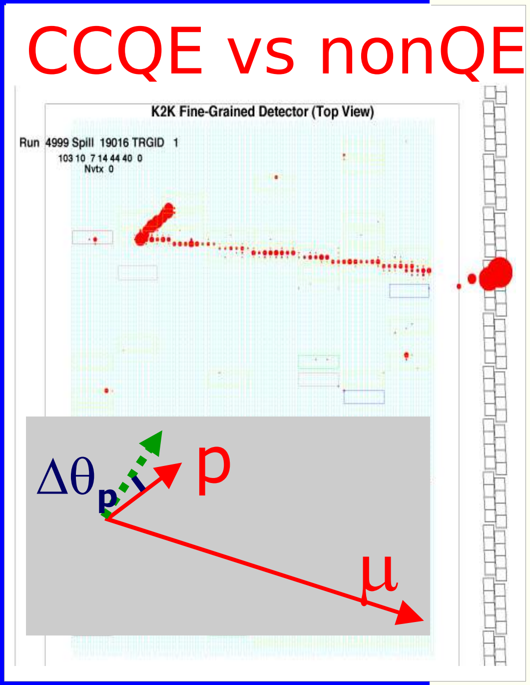


"Search for coherent charged pion production in neutrino-carbon interactions"
hep-ex/0506008, Subm. to PRL

see F.Sanchez talk

Near Detector Spectrum measurement

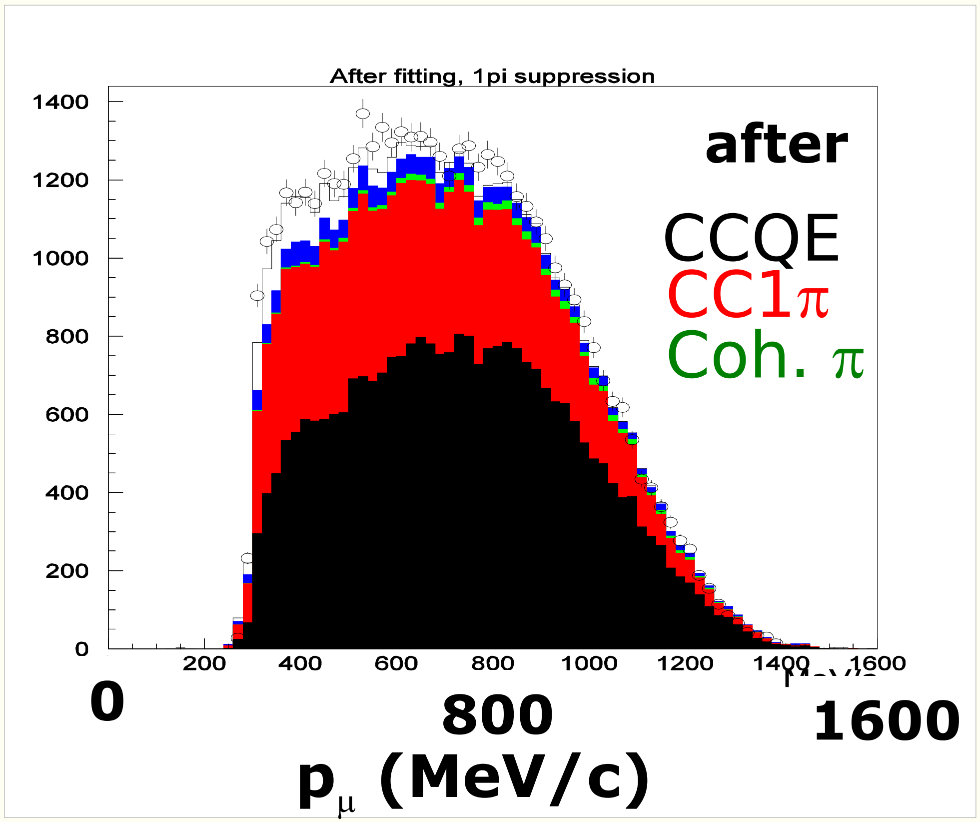
- 1KT Water Cherenkov detector (H,O target)
  1. Fully contained one-ring muon-like sample
- SciFi fiber tracker (H,O target)
  2. Single-muon track sample
  3. Two-track QE sample ($\Delta\theta_p$<25°)
  4. Two-tracks nonQE sample ($\Delta\theta_p$>30°)
- SciBar fine-grained scintillator (H,C target)
  5. Single-muon track sample
  6. Two-track QE sample ($\Delta\theta_p$<25°)
  7. Two-tracks nonQE sample ($\Delta\theta_p$>25°)

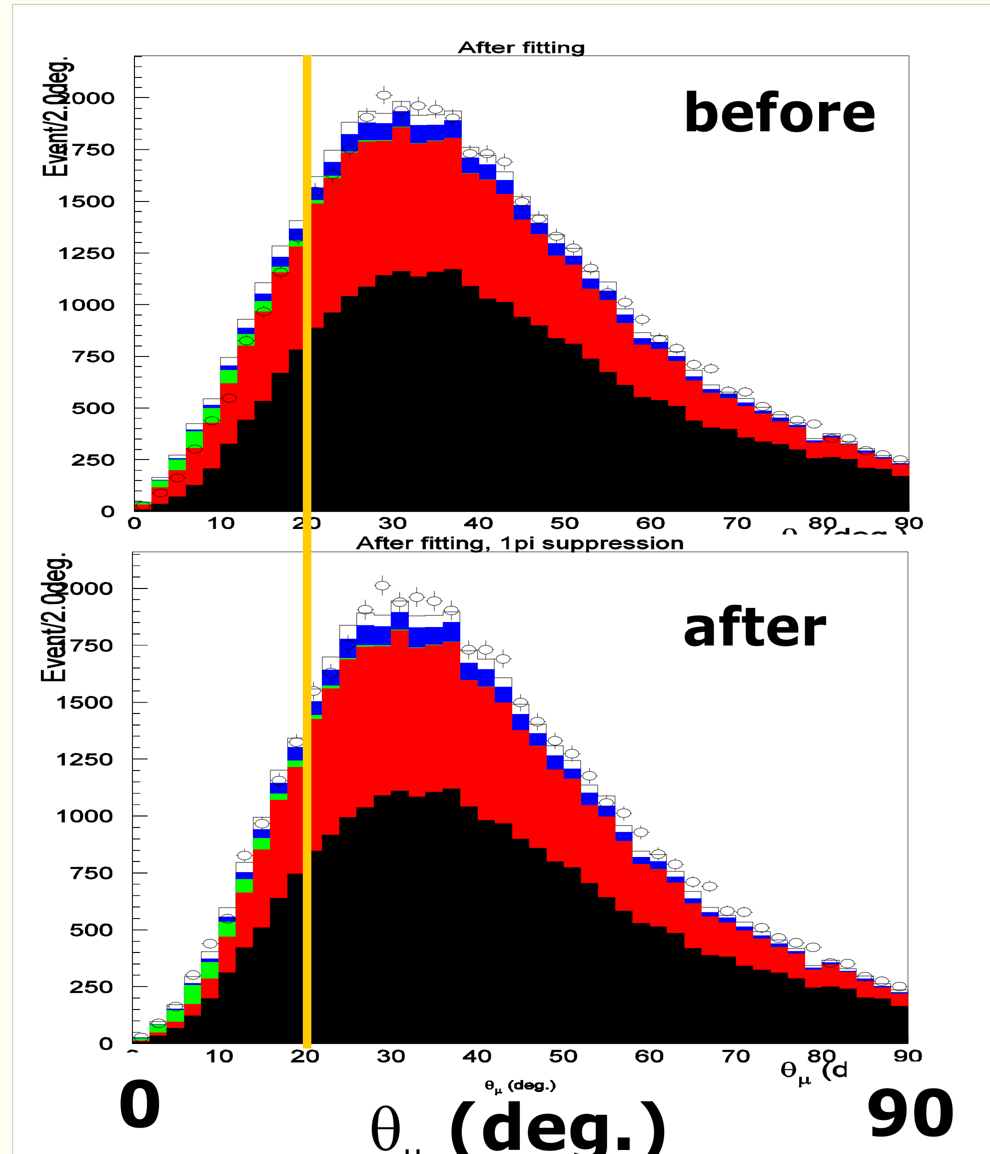


For each event we measure P_μ, Θ_μ

After the low q^2 correction, all data samples agree

Example: 1KT 1Ring μ-like





Effect of low q^2 correction
(here CC1π suppression)

Spectrum Fit from P_μ, Θ_μ Distributions

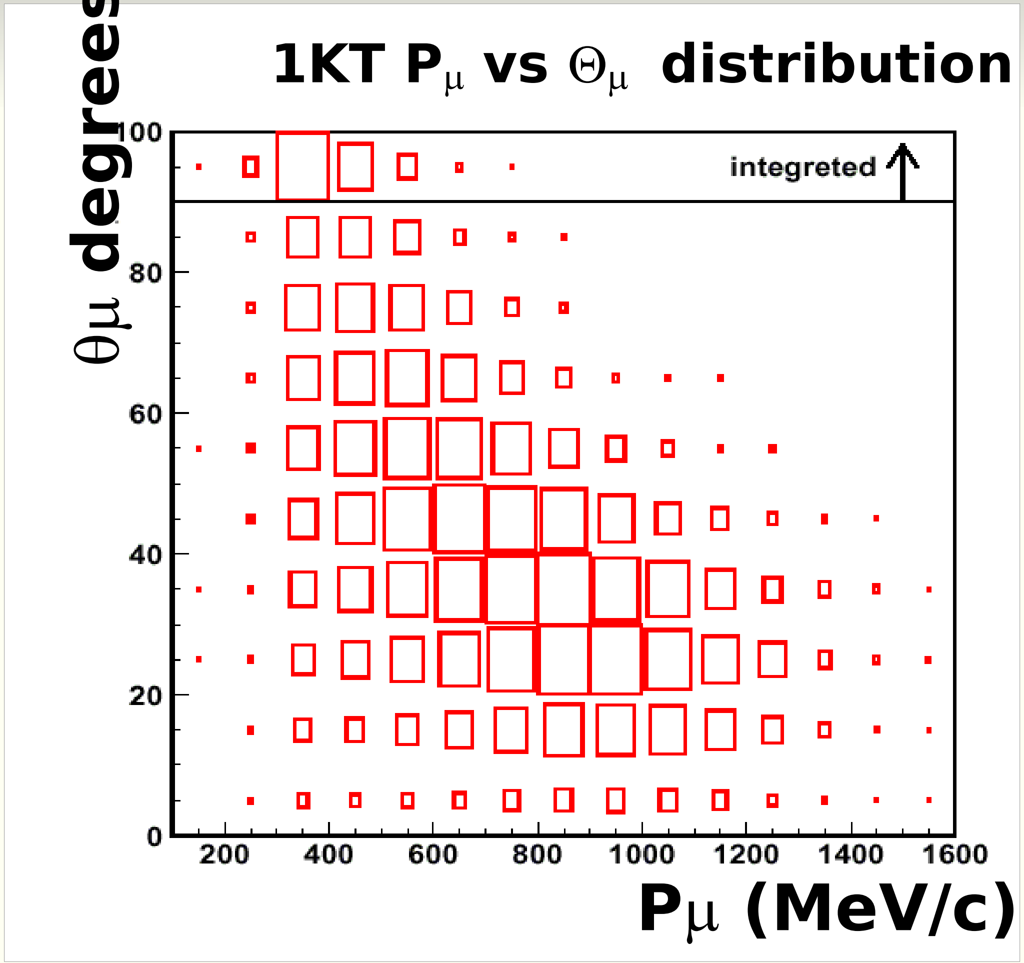
Free parameters of the fit

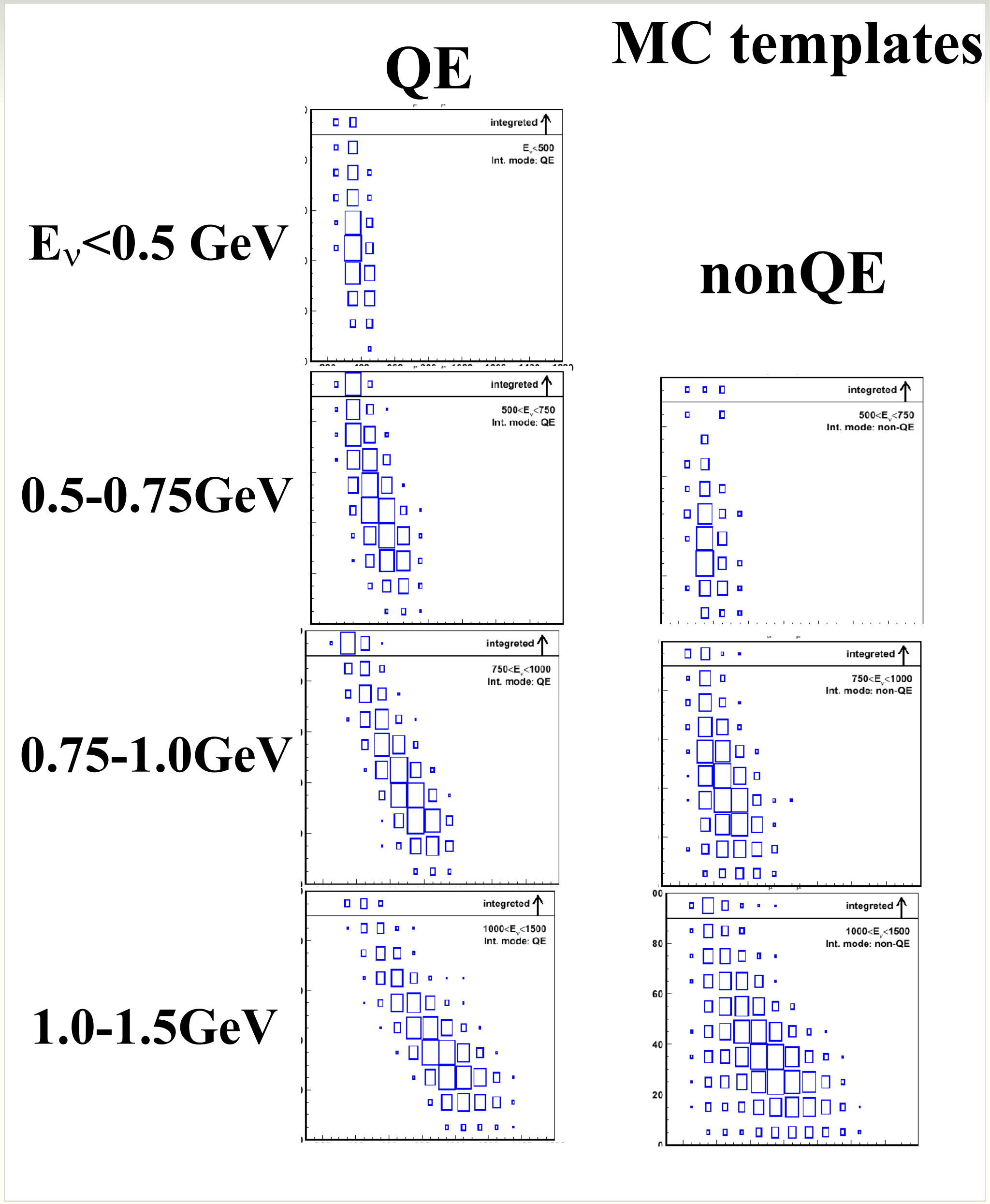
- flux in 8 energy bins $\Phi(E\nu)$
- nonQE/QE
- detector uncertainties (energy scale, efficiencies,...)
- nuclear effect uncertainties (proton and pion rescattering)

Strategy

- fit $\Phi(E\nu)$ flux without low angle data
- apply either low q^2 CC1π or coherent pion suppression
- fit nonQE/QE for the entire angular range
- Use $\Phi(E\nu)$, nonQE/QE to calculate the spectrum at Super-K

Example of Spectrum fit



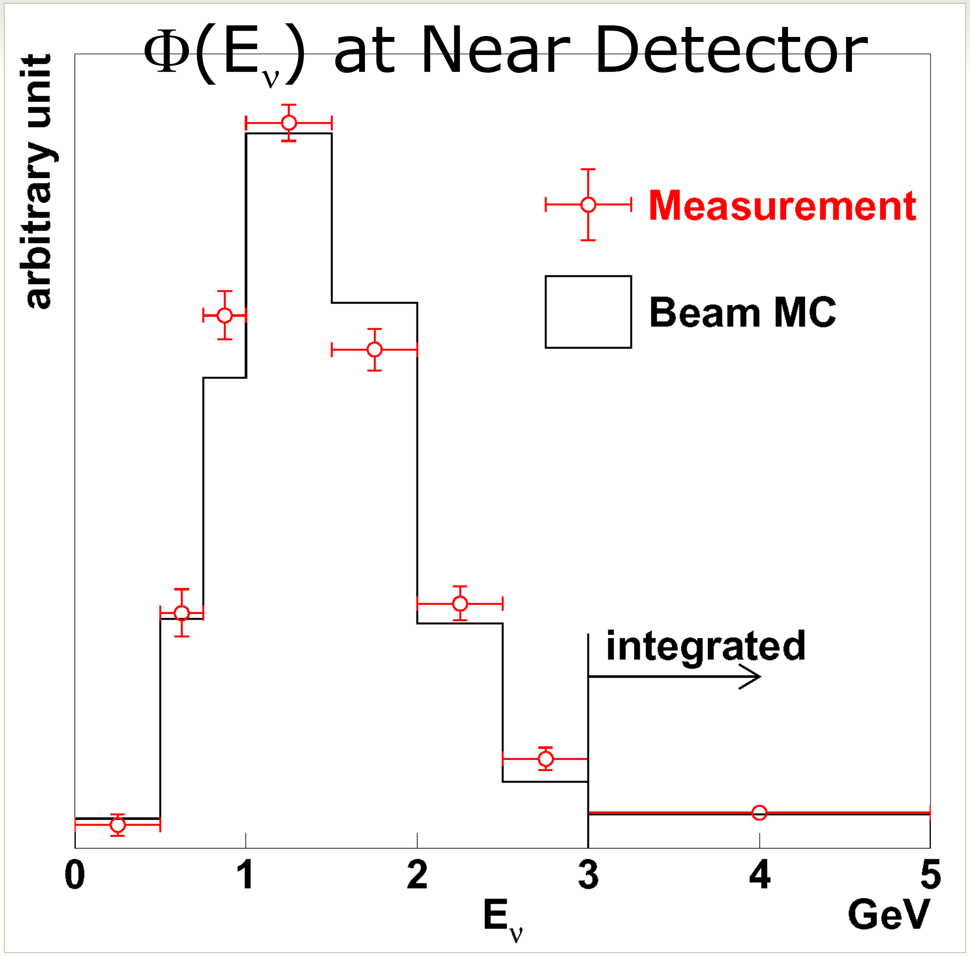


Free parameters of the fit:
relative flux $\Phi(E\nu)$ (8 bins)
ratio nonQE/QE

Spectrum Fit Results

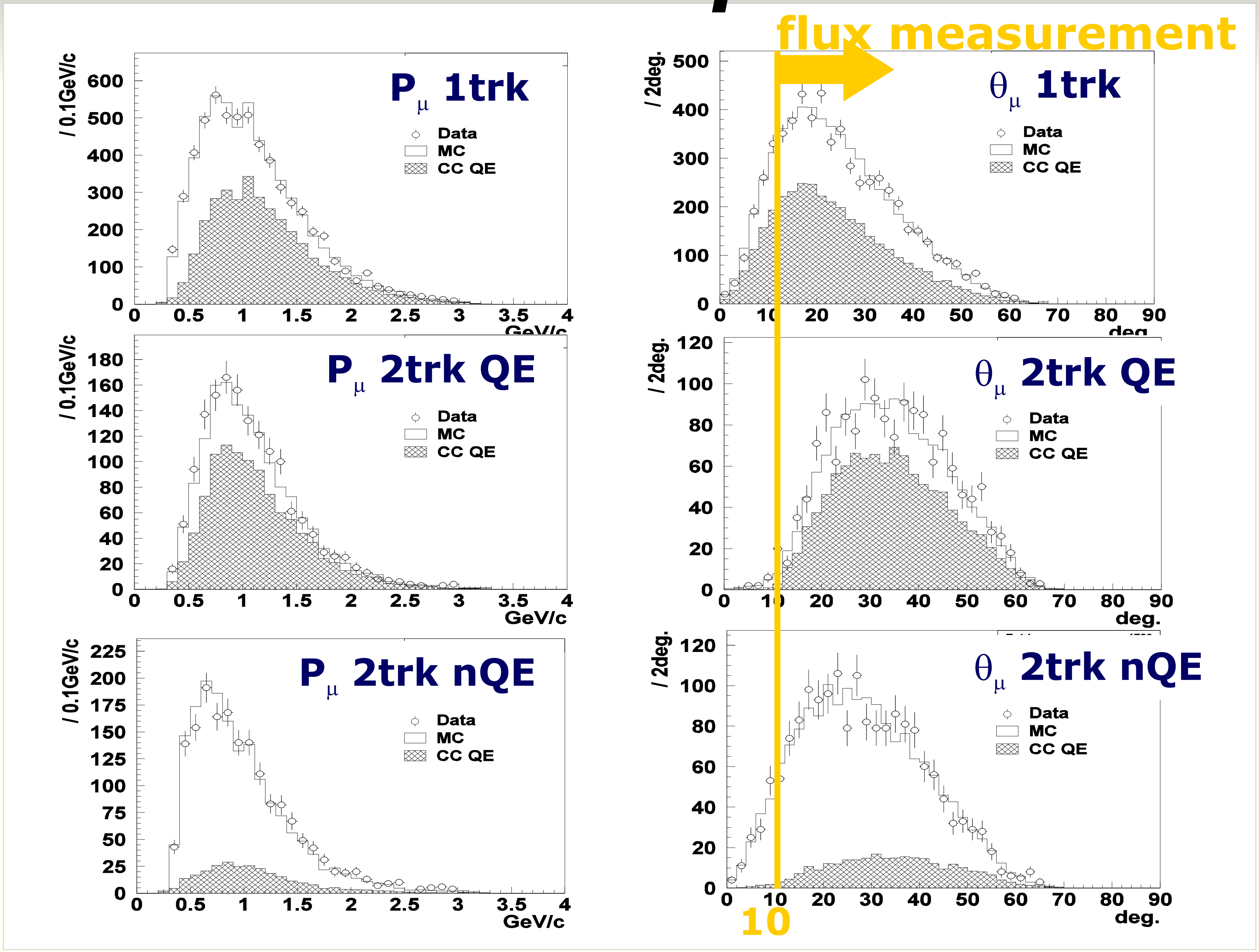
$\Phi1$ ($E\nu <$ 500)= 0.78±0.36
$\Phi2$ (500≤ $E\nu <$ 750)= 1.01±0.09
$\Phi3$ (750≤ $E\nu <$1000)= 1.12±0.07
$\Phi4$ (1000≤ $E\nu <$1500)= 1.00
$\Phi5$ (1500≤ $E\nu <$2000)= 0.90±0.04
$\Phi6$ (2000≤ $E\nu <$2500)= 1.07±0.06
$\Phi7$ (2500≤ $E\nu <$3000)= 1.33±0.17
$\Phi8$ (3000≤ $E\nu$)= 1.04±0.18
nonQE/QE = 1.02±0.10

χ^2=638.1 for 609 *d.o.f*



The nonQE/QE error takes into account the variation with different fit criteria:
nonQE/QE = 0.95 ± 0.04 (standard angular cut)
nonQE/QE = 1.02 ± 0.03 (CC1π suppression)
nonQE/QE = 1.06 ± 0.03 (no coherent pion)

Example: SciBar Data with Measured Spectrum



K2K/Super-K Data Sample

K2K-all (K2K-I, K2K-II)	DATA (K2K-I, K2K-II)	MC (K2K-I, K2K-II)
FC 22.5kt	**107** (55, 52)	**150.9** (79.1*, 71.8)
1-ring	**67** (33, 34)	**93.7** (48.6, 45.1)
1-ring μ-like	**57** (30, 27)	**84.8** (44.3, 40.5)
1-ring e-like	**10** (3, 7)	**8.8** (4.3, 4.5)
Multi Ring	**40** (22, 18)	**57.2** (30.5, 26.7)

K2K-I 47.9 10^{18} PoT

K2K-II 41.2 10^{18} PoT

Oscillation Analysis

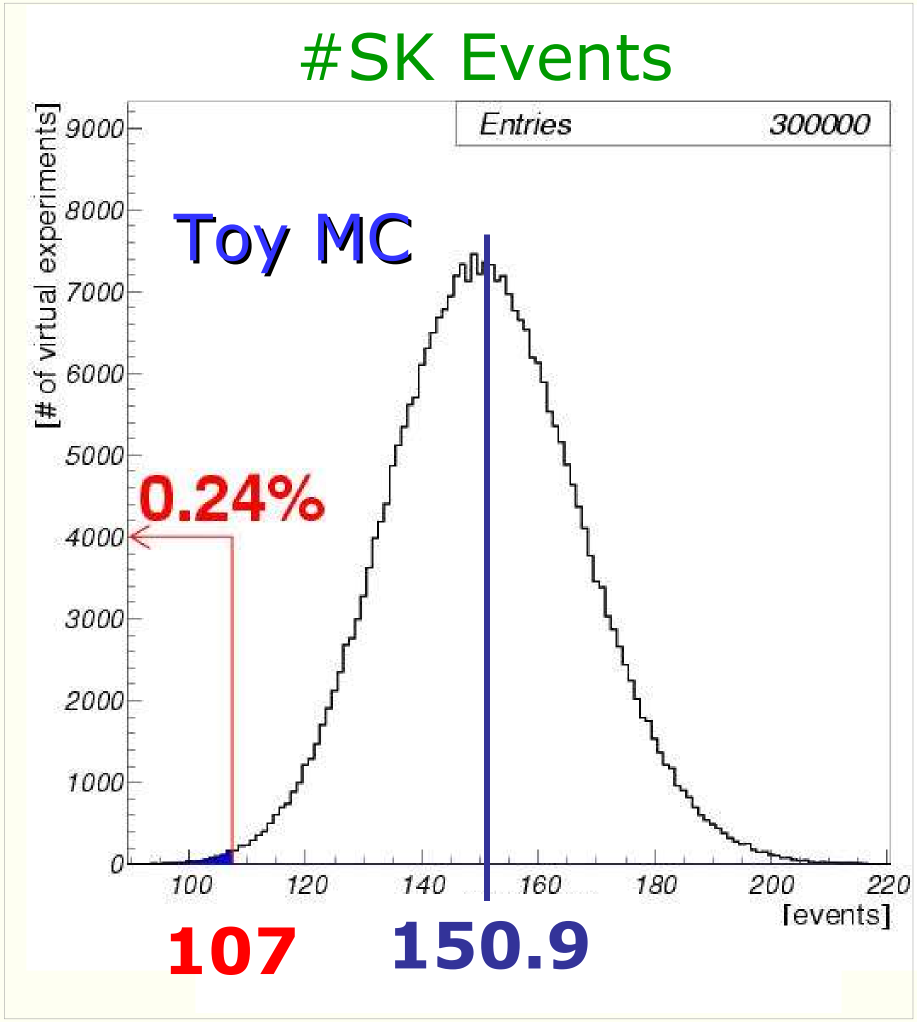
$$L(\Delta m^2, \sin 2\theta, f^x)$$
$$= L_{norm}(\Delta m^2, \sin 2\theta, f^x) \cdot L_{shape}(\Delta m^2, \sin 2\theta, f^x) \cdot L_{syst}(f^x)$$

- Total Number of neutrino events
- Reconstructed E_ν^{rec} spectrum shape for 1-ring μ-like events
- Systematic error terms, f^x

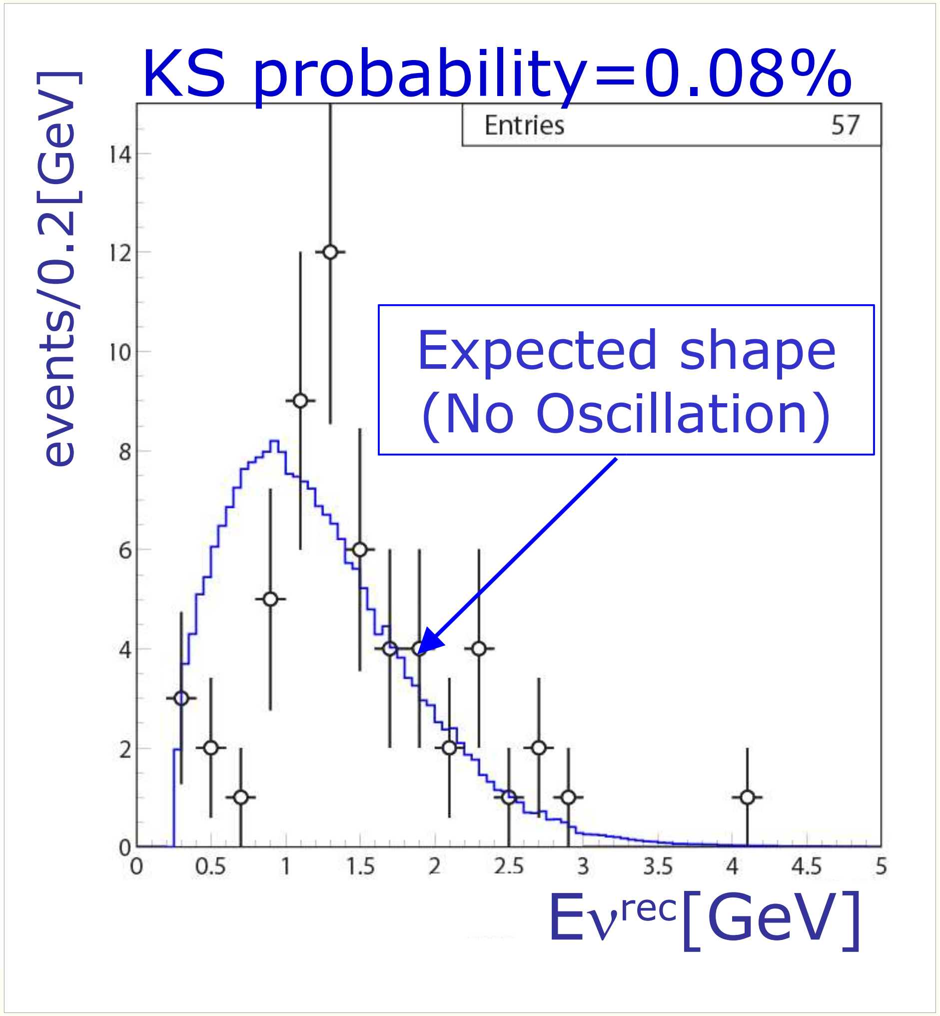
Systematic error terms include: normalisation, flux, nonQE/QE ratio, pion monitor and beam MC constraints, Super-K systematic uncertainties.

Compare with Null Oscillation

$$L_{norm}(f^x)$$



$$L_{shape}(f^x)$$



Best Fit of Oscillation Parameters

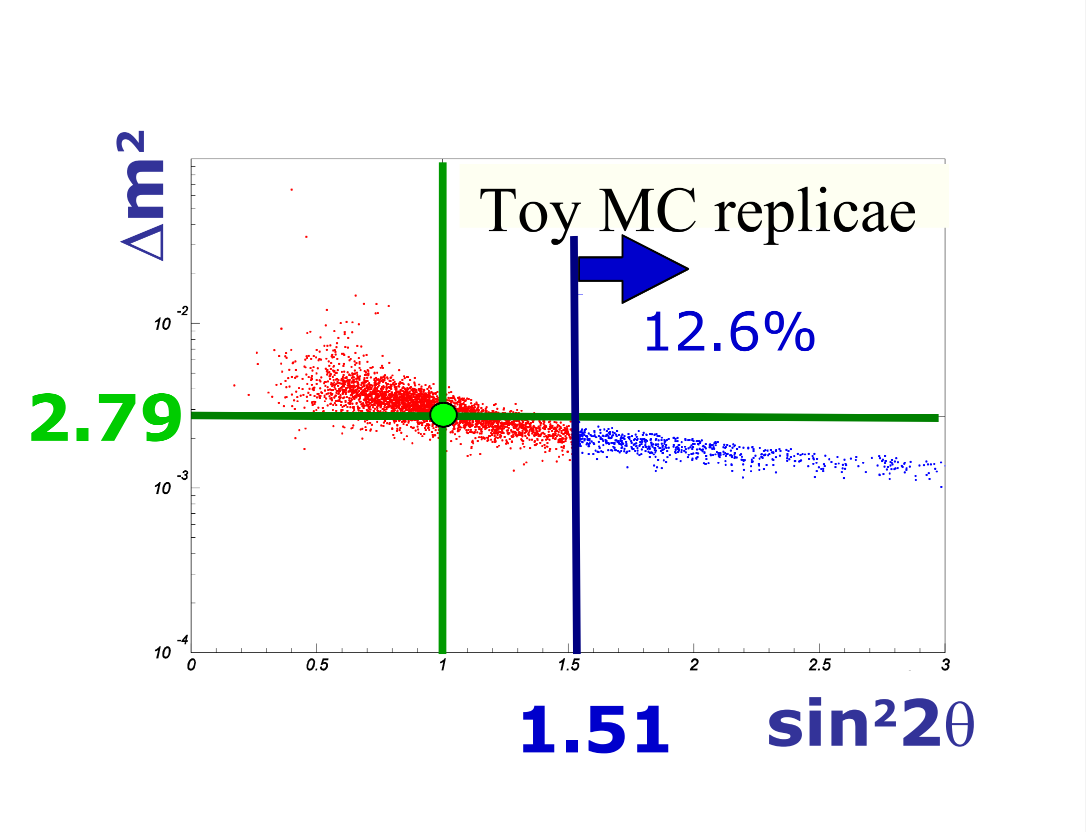
Best fit in the physical region:

$\sin^2(2\theta)=1.0$ $\Delta m^2=2.79\ 10^{-3}\ eV^2$

Highest likelihood for:

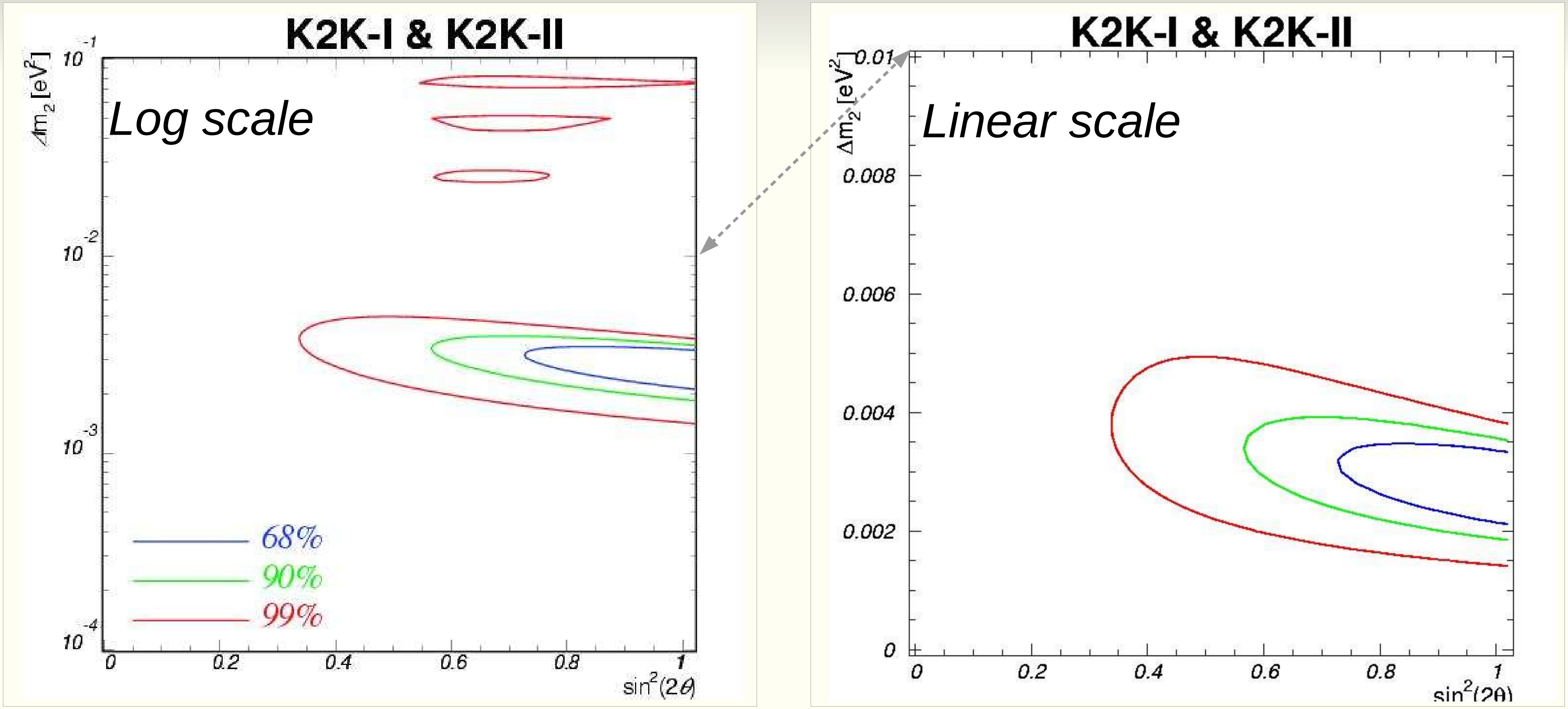
$\sin^2(2\theta)=1.51$ $\Delta m^2=2.19\ 10^{-3}\ eV^2$

The difference in these two fits is $\Delta Log=0.64$



A value $\sin^2(2\theta)>1.51$ can occur, due to a statistical fluctuations, with a probability of 12.6%.

Allowed Region

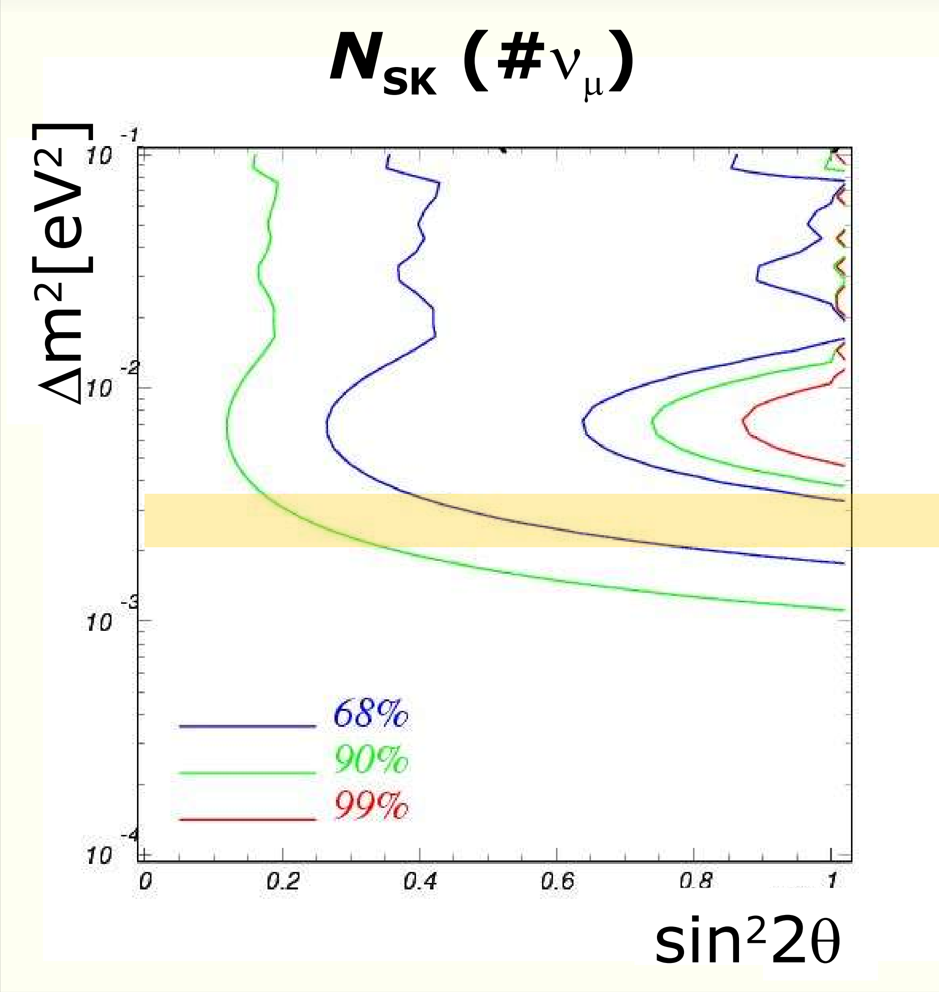


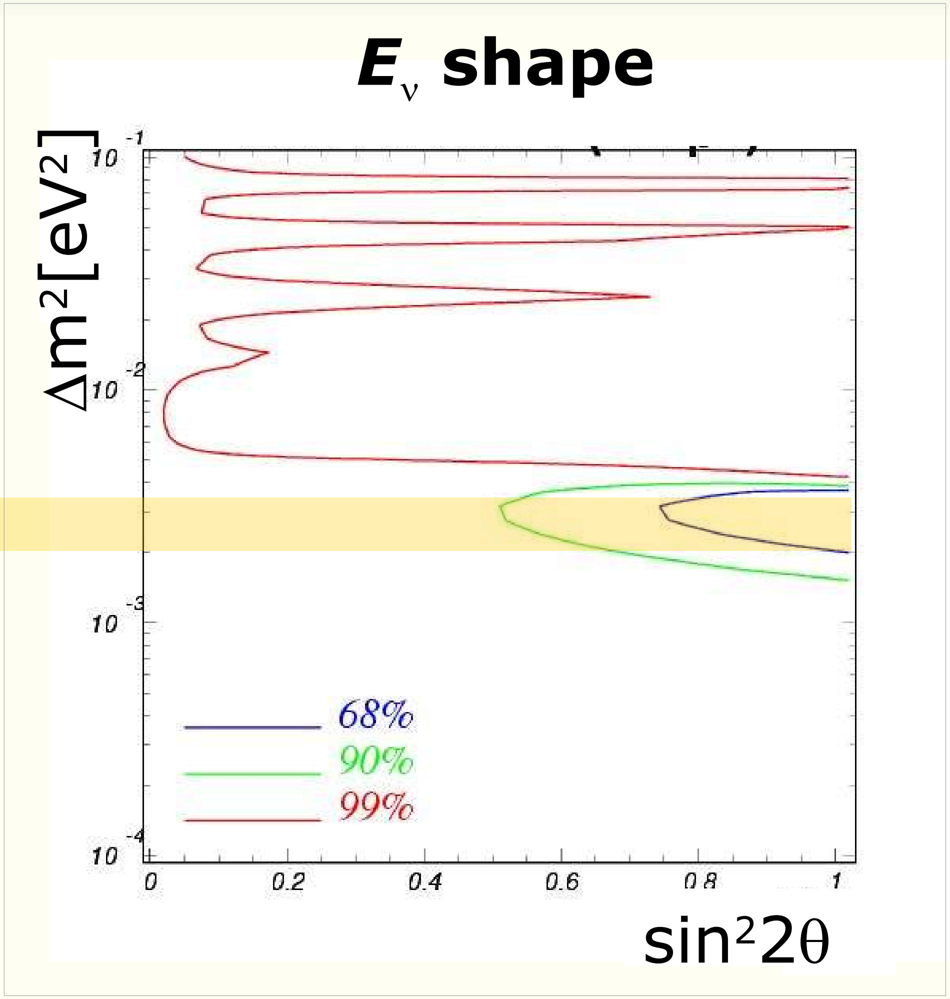
Δm^2 @ $\sin^2 2\theta = 1$:

$2.14 < \Delta m^2 < 3.37$ [eV] $\times 10^3$ @68%

$1.87 < \Delta m^2 < 3.58$ [eV] $\times 10^3$ @90%

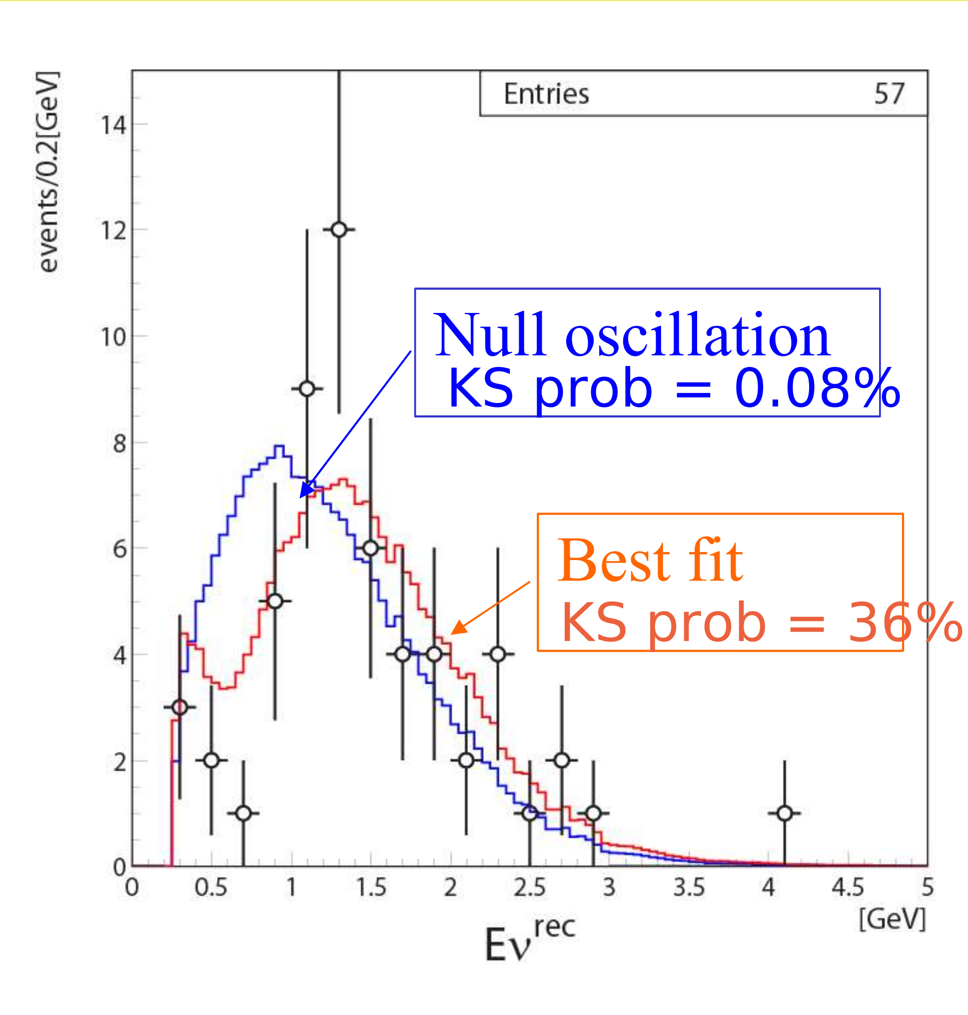
Disappearance & Shape





Allowed regions from ν_μ disappearance and distortion of E_ν spectrum are consistents

Fit and Data are Consistent



Best likelihood for:

$\sin^2 2\theta$ = 1.51

Δm^2 [eV^2] = 2.19×10^{-3}

Prob{$\sin^2 2\theta > 1.5$}|$_{BestFit}$=13%

Best fit (physical region):

$\sin^2 2\theta$ = 1.00

Δm^2 [eV^2] = 2.79×10^{-3}

Expected neutrino interactions at the best fit is 103.8, to be compared with 107 observed.

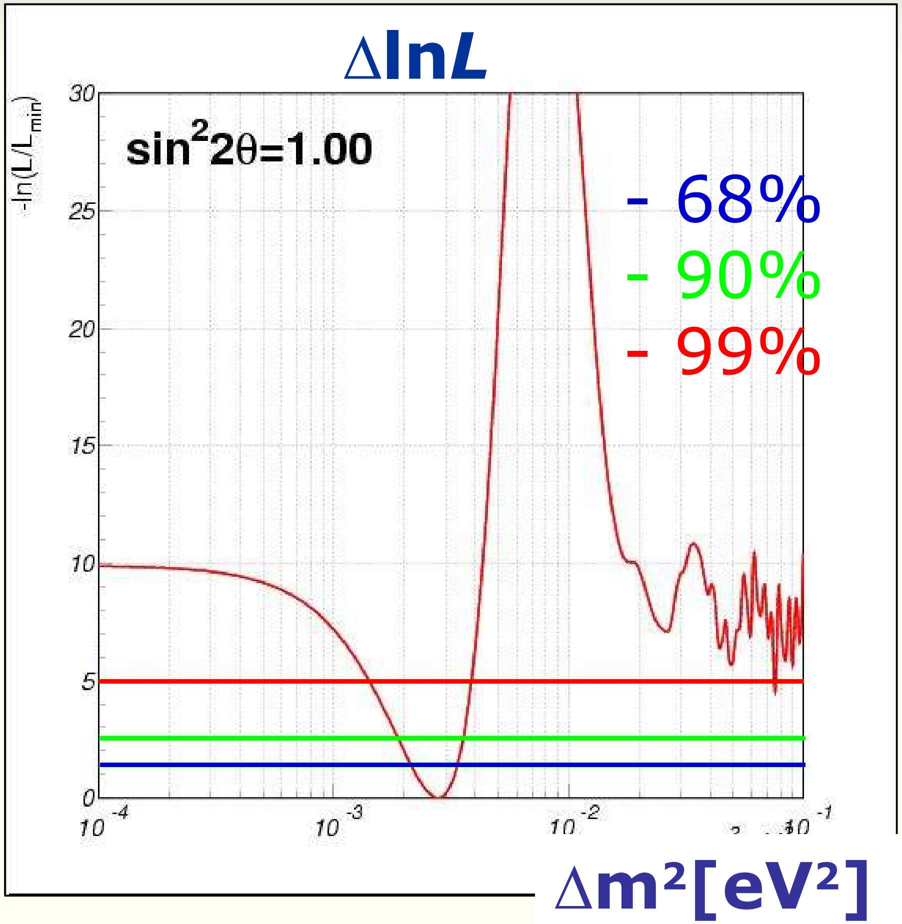
From LogL differences w.r.t. the best fit:

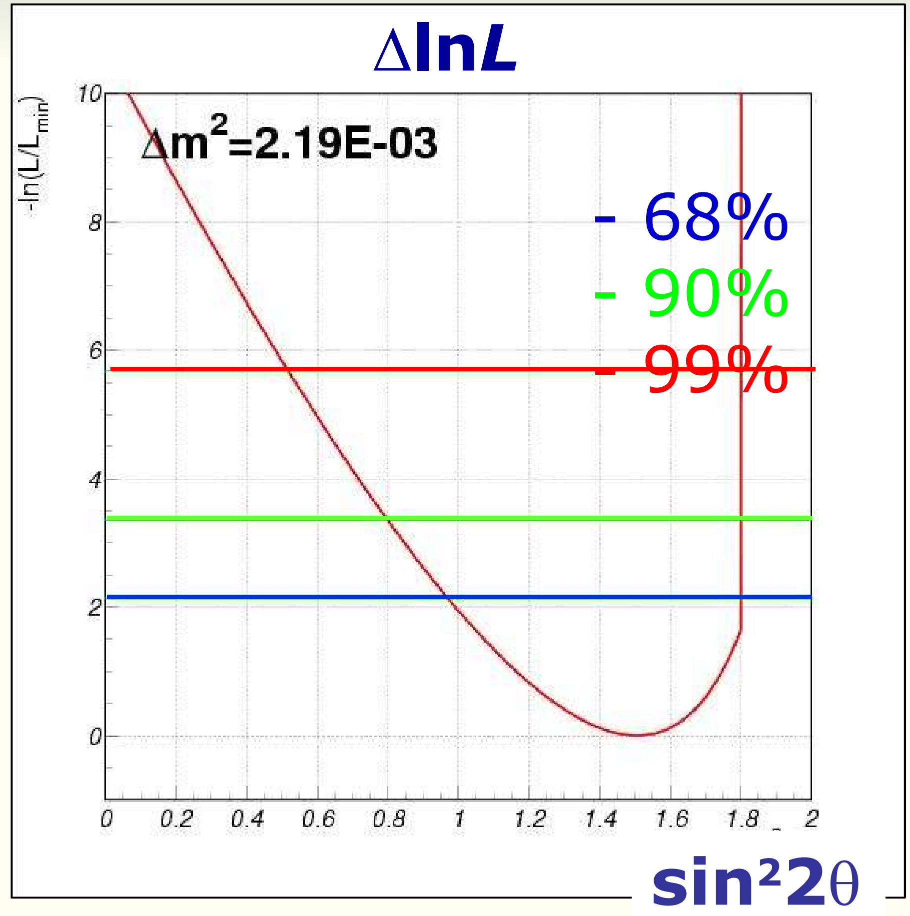
Prob{No Oscill} = 0.0050% (4.0σ) (shape+norm.)

= 0.74% (2.6σ) (shape only)

= 0.26% (3.0σ) (norm. only)

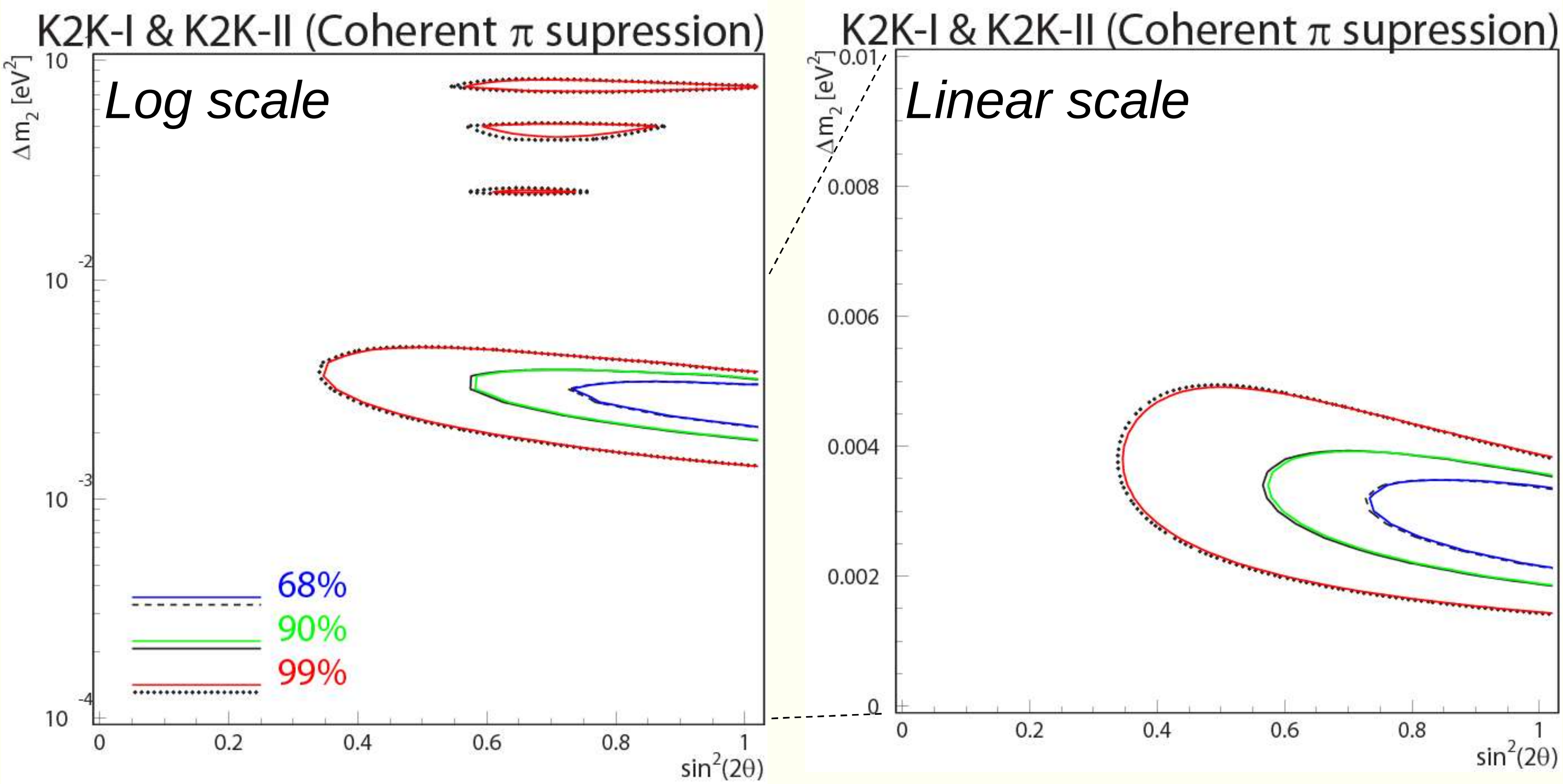
Log Likelihood difference from the minimum





$\Delta m^2 < (1.87 \sim 3.58) \times 10^{-3}$ eV² at $\sin^2 2\theta = 1.0$ (90% C.L.)

Coherent π vs Single π Suppression



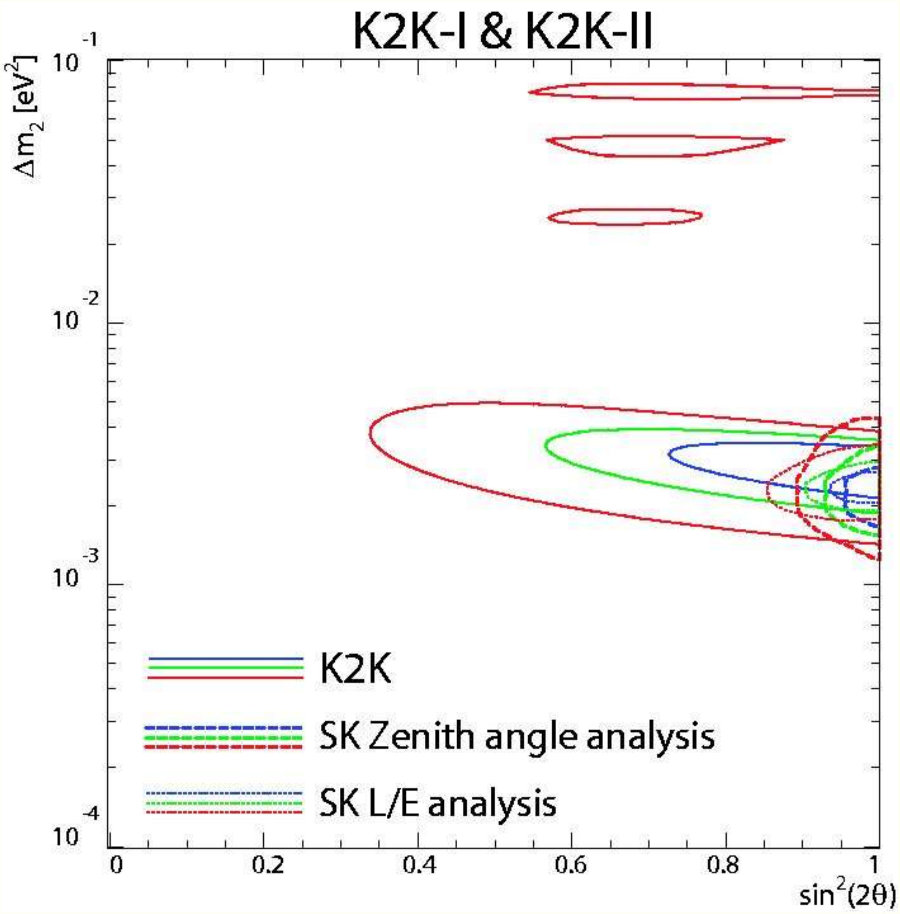
Color: Coherent-π suppression → Null Osci. prob. = 0.0044%(4.08σ)

Mono: CC-1π suppression 0.0050%(4.06σ)

Summary

With 8.9x1019 PoT, K2K confirms atmospheric neutrino oscillation at 4.0σ (PRL 94:081802,2005)

- Disappearance of $\nu\mu$ at 3.0σ
- Distortion of Eν spectrum at 2.6σ

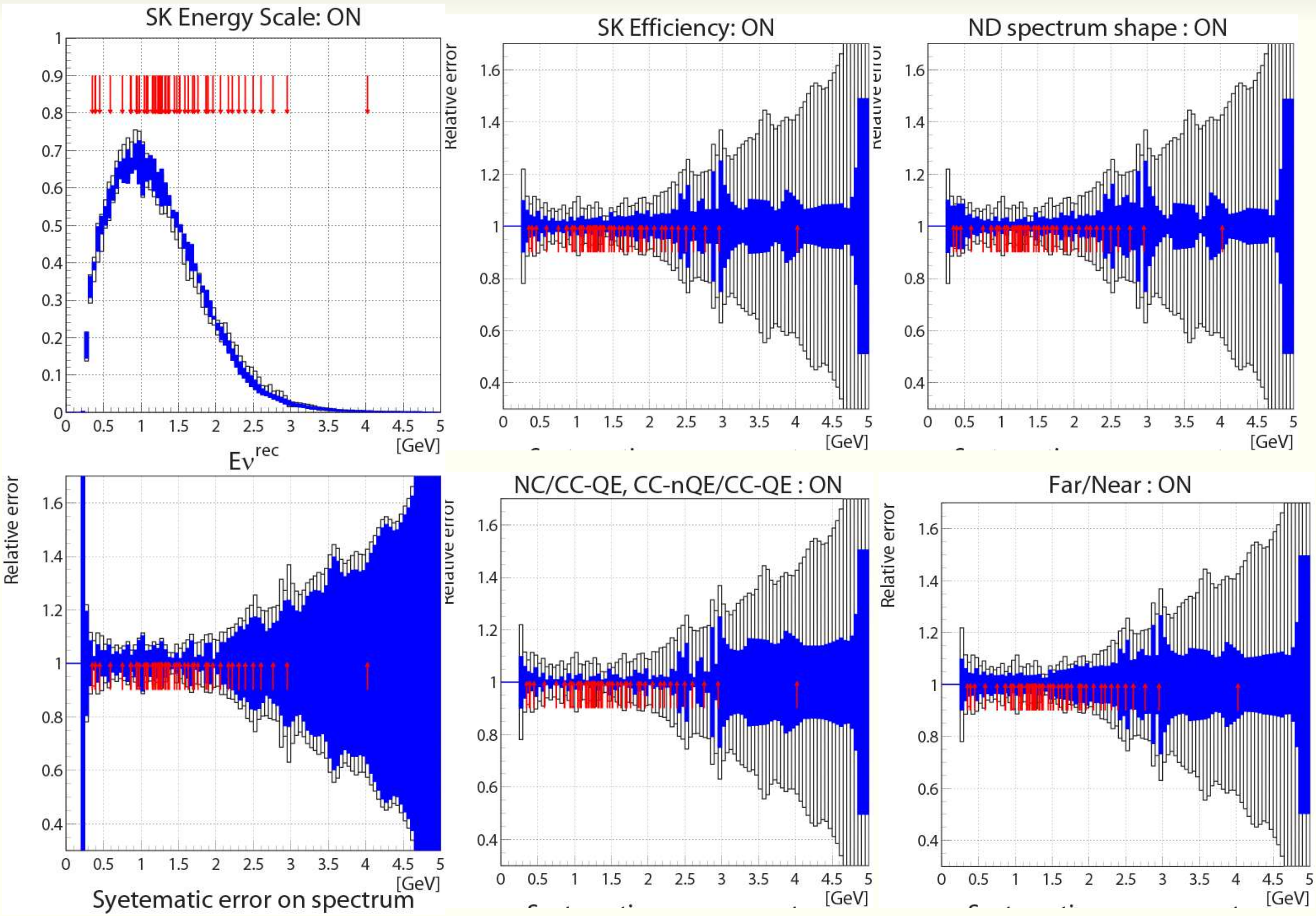


Extra Slides

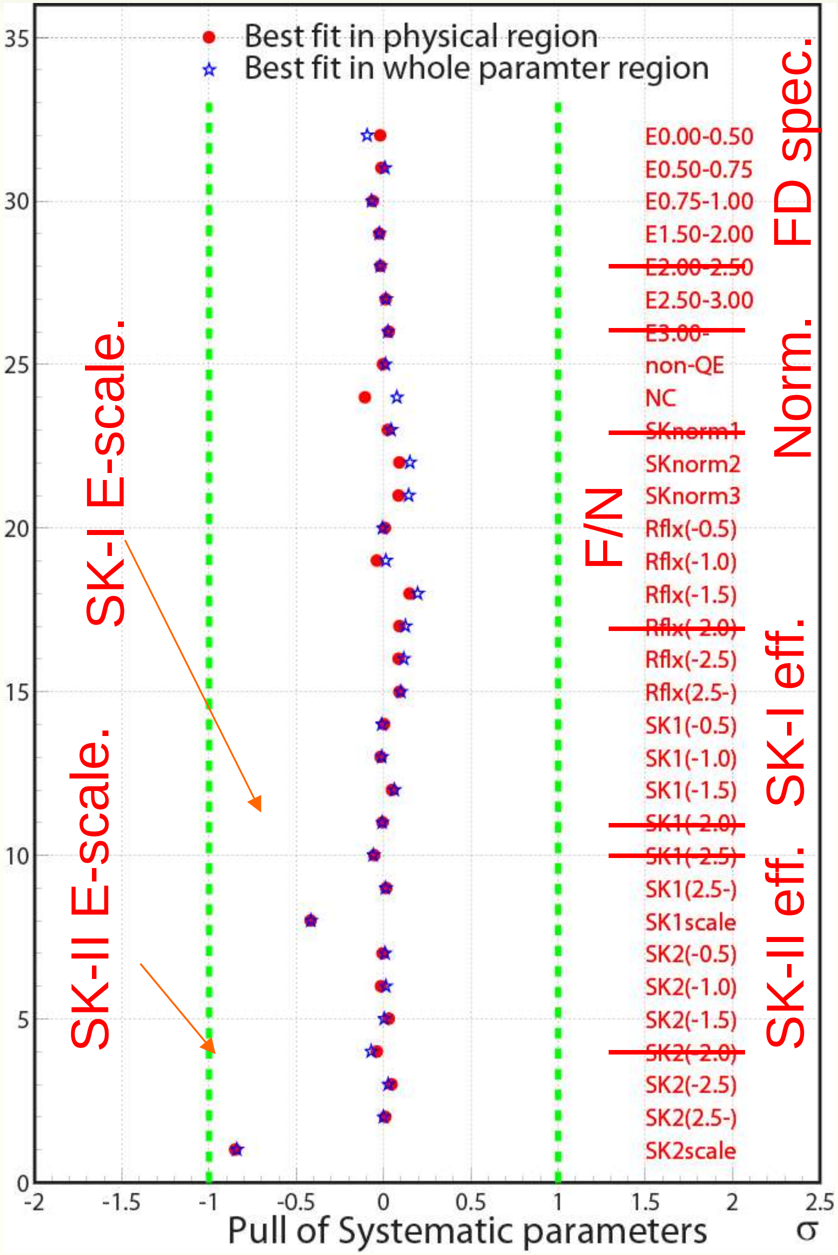
Syst. Error Contributions to Nsk

	Error	(relative error)
Far/Near	+7.7 -7.5	(+5.1%) (-5.0%)
Normalization	+7.6 -7.7	(+5.0%) (-5.1%)
NC/CC-QE, CC-nQE/QE	+0.7 -0.8	(+0.5%) (-0.5%)
ND spectrum	+1.0 -0.9	(+0.7%) (-0.6%)

Syst. Error Contributions to Spectrum

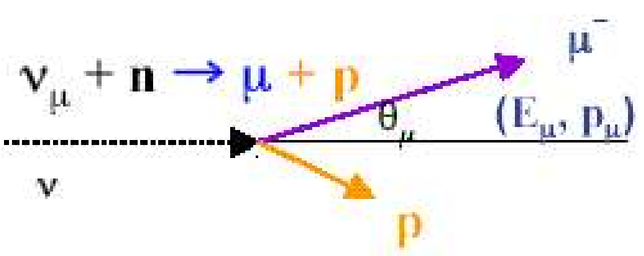


Pull of Syst. Parameters in the Fit

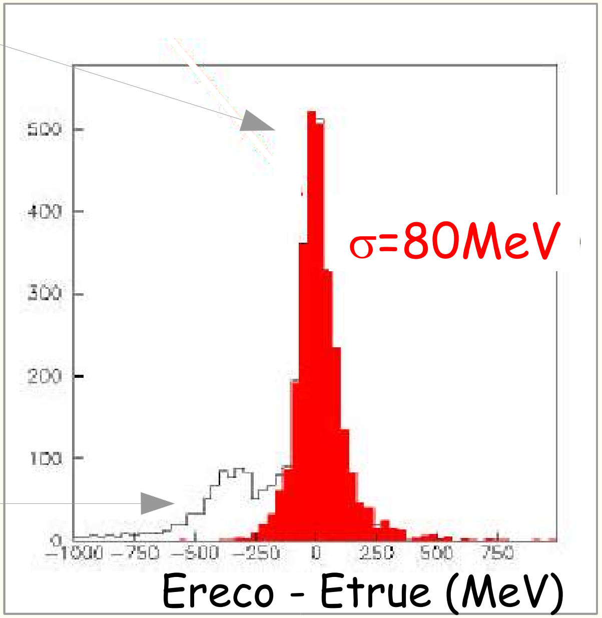


ν *Energy and QE/nonQE*

CC quasi-elastic (QE)



$$E_\nu^{\ rec} = \frac{(m_N - V)E_\mu - m_\mu^2/2 + m_N V - V^2/2}{(m_N - V) - E_\mu + p_\mu \cos\theta_\mu}$$



non Quasi-Elastic