# 2KM water Cherenkov detector: $\nu_e$ appearance analysis

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# Outline

- Interaction / Simulation update
- 2KM reconstruction updates
- $\nu_e$ appearance analysis

# I. Interaction / Simulation update

- Neutrino interactions parametrization
- GEANT4 simulation
- Monte Carlo files / generated livetime

# Neutrino interactions parametrizations

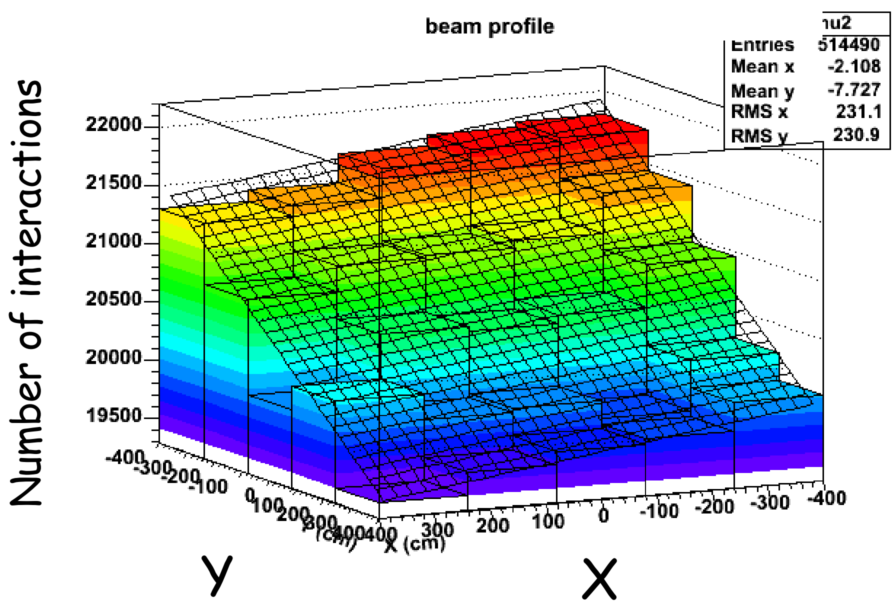
Neutrino interactions are simulated in 2 steps :

1. Make neutrino 4-vectors $(E, \vec{p})$ using the JNUBEAM ν flux simulator
2. Use NEUT to generate the actual interactions

In order to simulate $5.10^{21}$pot in 100 tons @ 2KM, we need approx. 3-4 million events.

Using the same method as SK, keeping several important effects :

1. correlation between vertex position and ν energy aka "running of the off-axis peak" (50 MeV from top of tank to bottom)
2. Non uniform distribution of vertices over the 2KM detector surface (consequence of the off-axis beam)




beam profile is parametrized by a plane

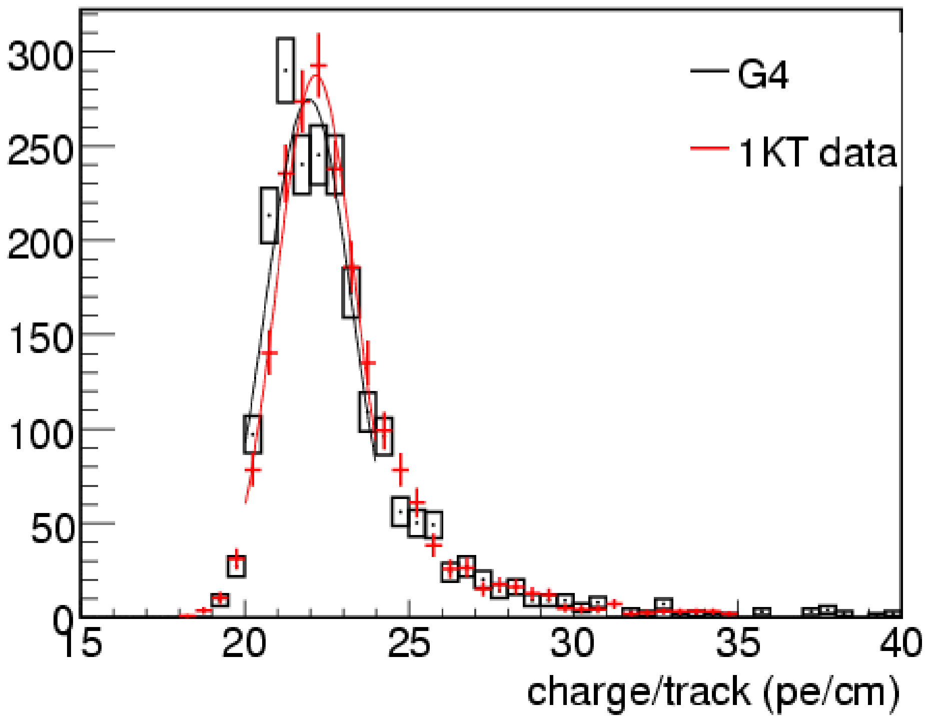
# GEANT4 simulation : improvements

- Retuned reflections and scattering lengths to match through-going muon data
- Updated PMT digitization code
- Changed hadronic models in GEANT4 (see J. Raaf's talk)

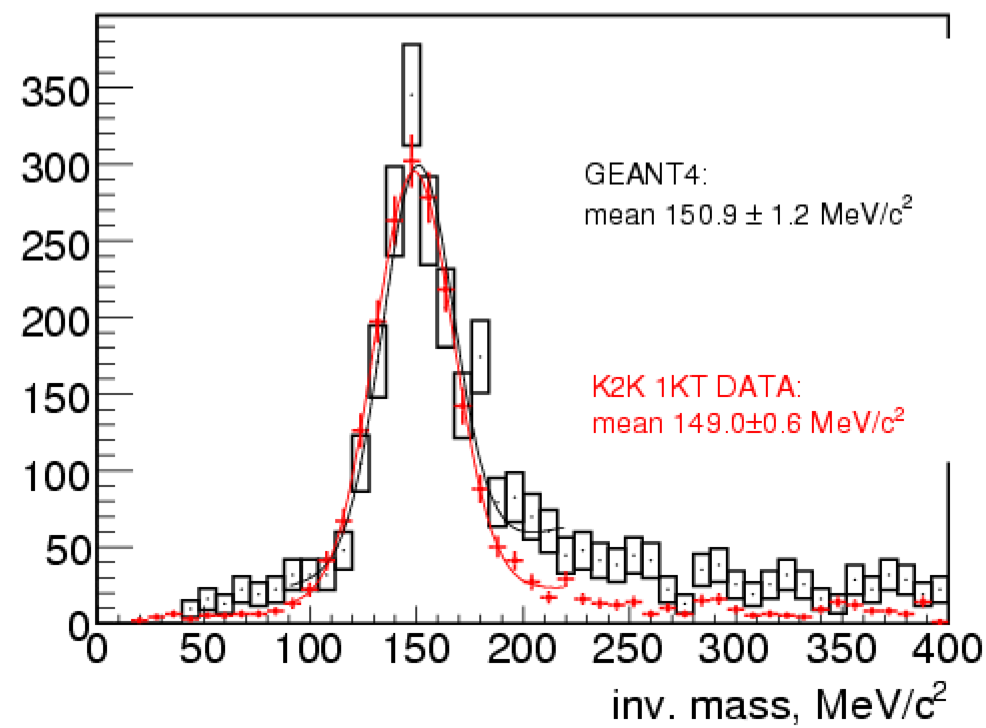
# GEANT4 simulation : energy scale tuning

Example of simulation / reconstruction tuning : charge scale and energy scale using K2K 1kton data

Cosmic through-going muons




Beam $\nu_\mu$ events, 2 e-like rings



# Current T2K MC statistics

2KM water Cherenkov detector MC :

- $\nu_e$ : 250,000 events (total), 93,000 events in 100t FV --> 17.1 years
- $\nu_\mu$ : ~2.3 million events (total), 840,000 events in 100t FV --> 3.4 years

(was 0.3yr in march05)

Files are available at http://www.phy.duke.edu/~mfguest/2km-04b-ntuples

SK water Cherenkov detector MC :

- $\nu_e$ : 450,000 events in the FV
- $\nu_\mu$ : 40,935 events in the FV

(See J. Raaf's talk)

# II. 2KM reconstruction updates

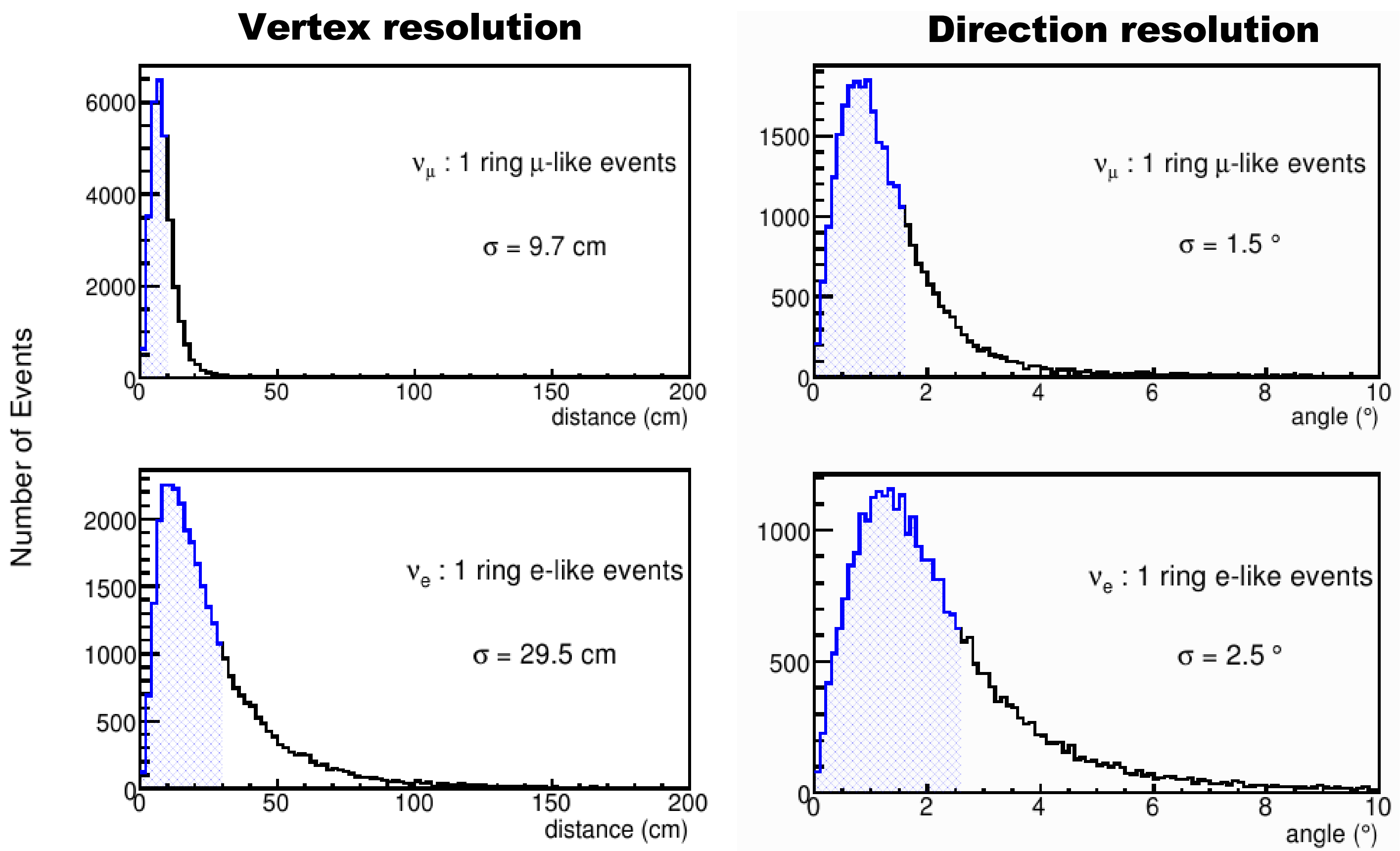
- Vertex fitters
- Ring counting
- PID
- POLfit

# 2KM reconstruction : introduction

- Based on 1KTon software
- Modified to accept 2KM simulated data
- All the standard reconstruction programs were tuned to take into account specific 2KM behaviour
- Check that performance is similar to SK's using mono-energetic $e/\mu$ events & T2K beam

# 2KM reconstruction : vertex fitter

Tuned ring-edge finding routine and MS-fit calling sequence



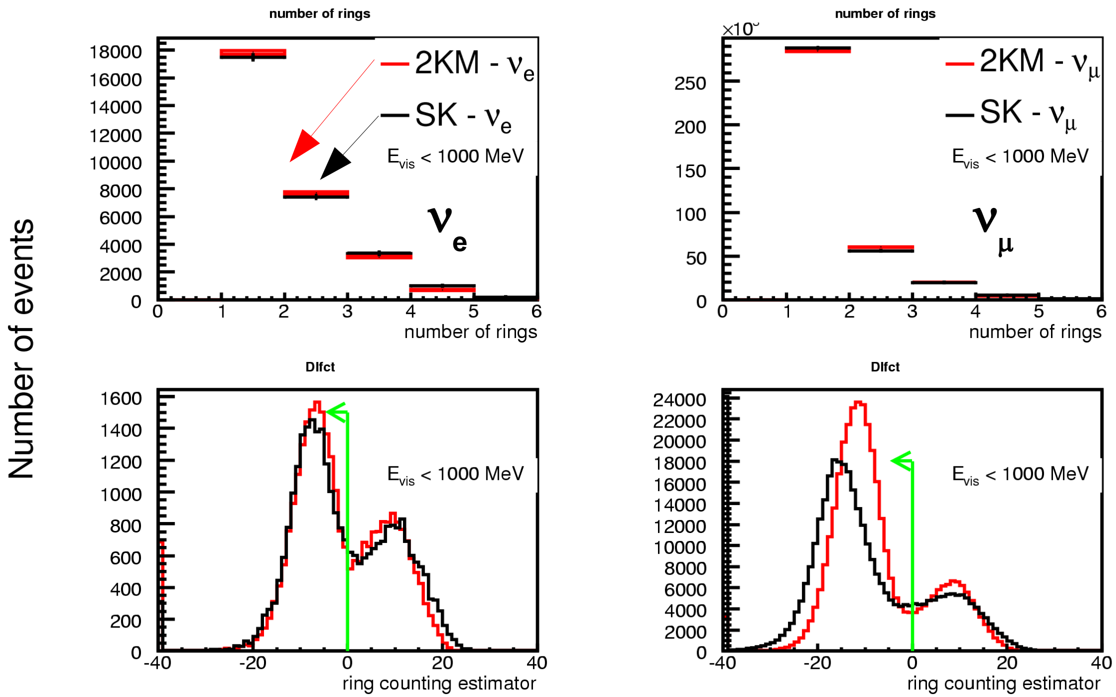

**Vertex resolution :**

Better than SK for $\nu_\mu$ (23.9cm), similar for $\nu_e$

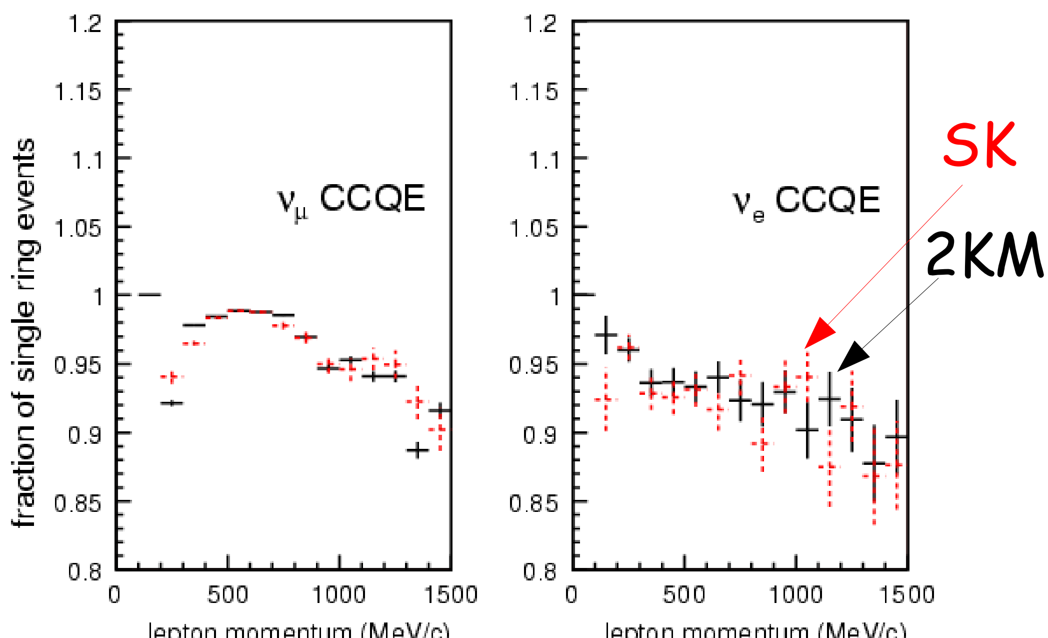
**Direction resolution :**

Better than SK (resp. 2.0°& 3.3°)

# 2KM reconstruction : ring counting



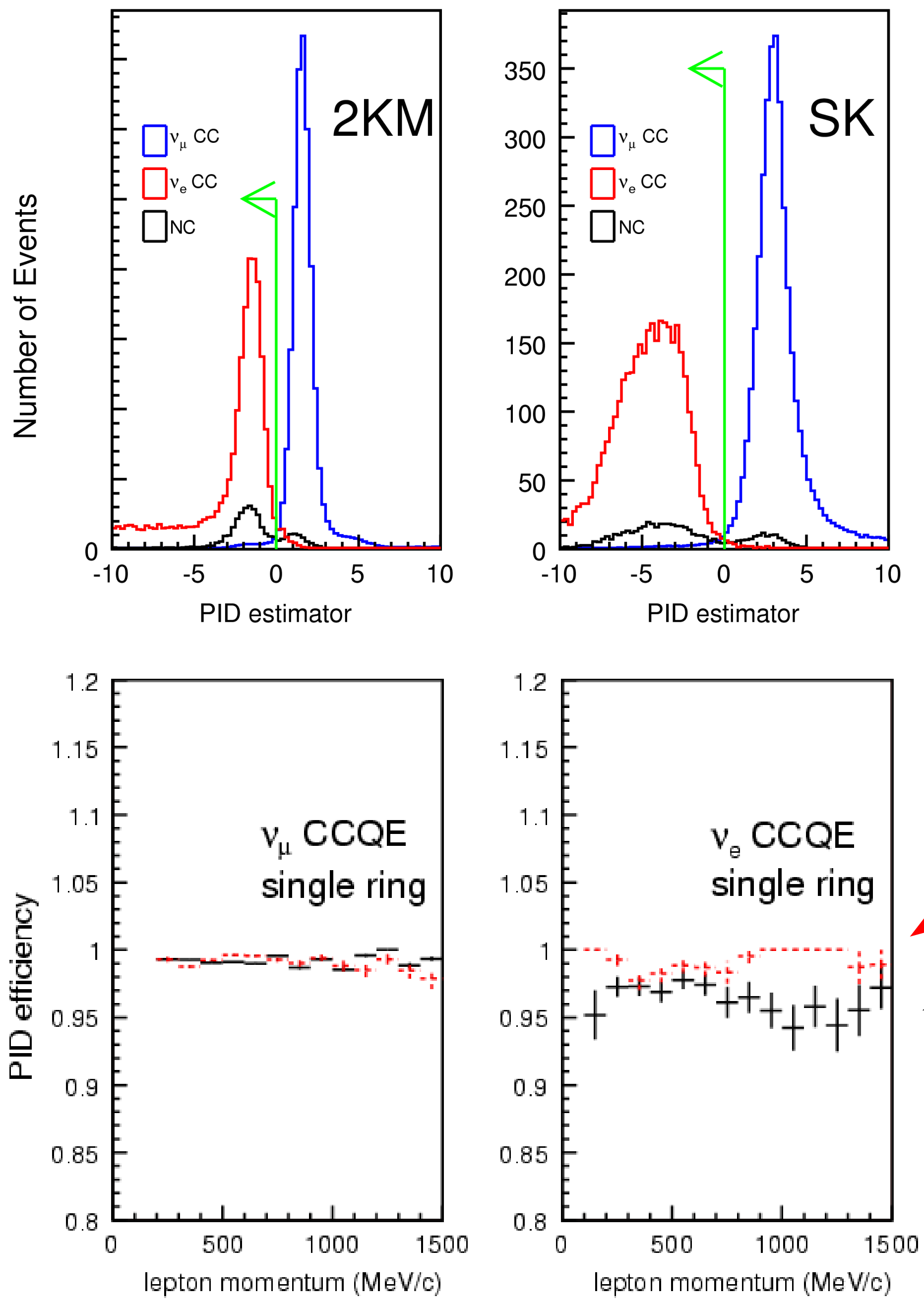

Ring counting performance is almost identical to SK for $E_{vis}$ < 1 GeV (where the signal region is)




Ring counting efficiency for CCQE $\nu$ interactions drops off because 2nd ring is found

Similar @ SK & 2KM

# 2KM reconstruction :  PID




Tuned PID pattern for new geometry

Shape is somewhat different because of pattern differences

$\nu_e$ rescaled to same number as $\nu_\mu$

ID probability is almost the same

SK

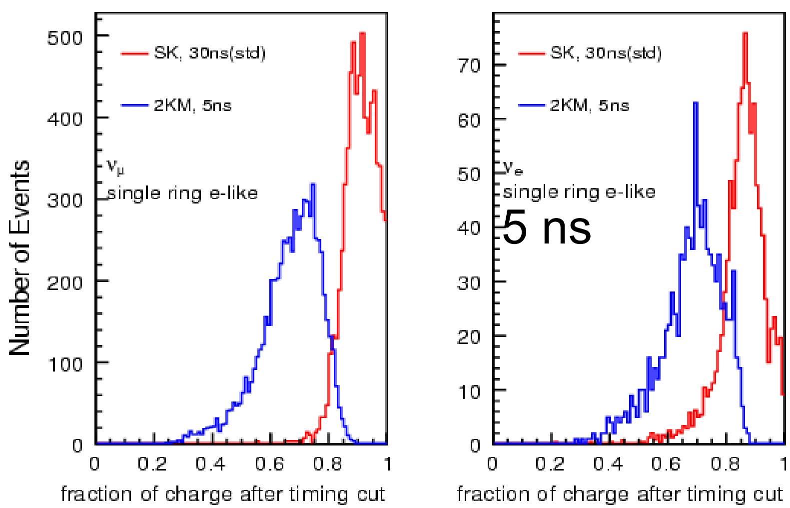
2KM

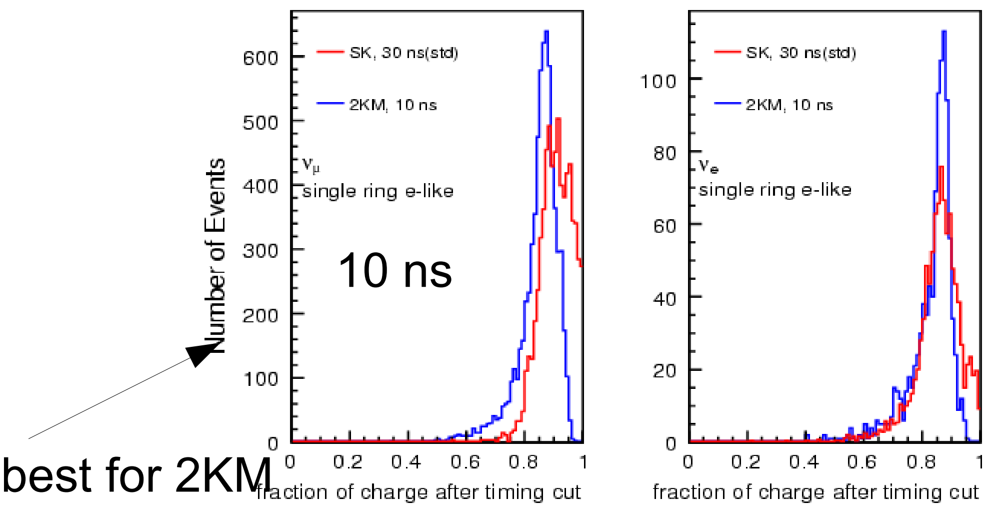
# 2KM reconstruction : polfit timing cut

Timing cut removes scattered and reflected light; width at SK is 30 ns.

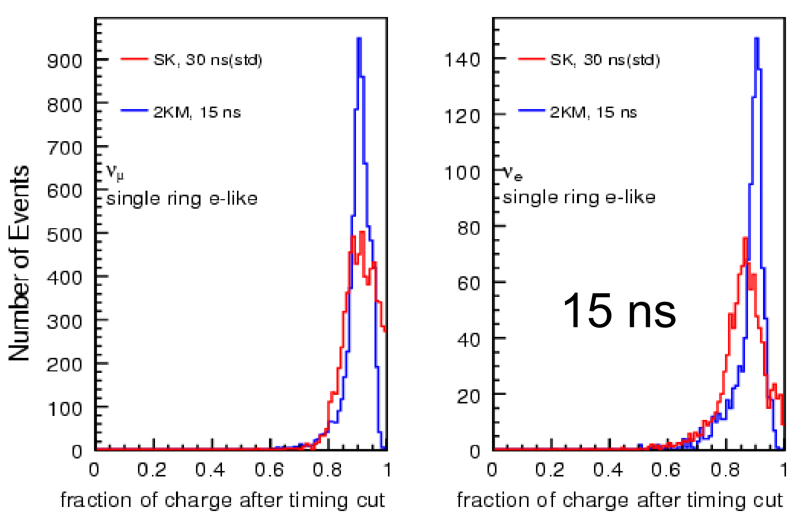
Tune the cut to keep the same fraction of light as at SK

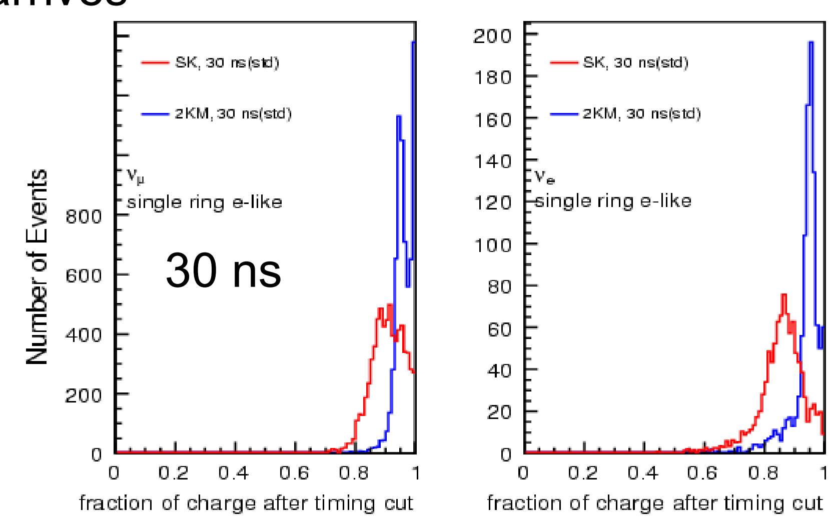
Using single ring, e-like events from numu & nue @ SK & 2KM



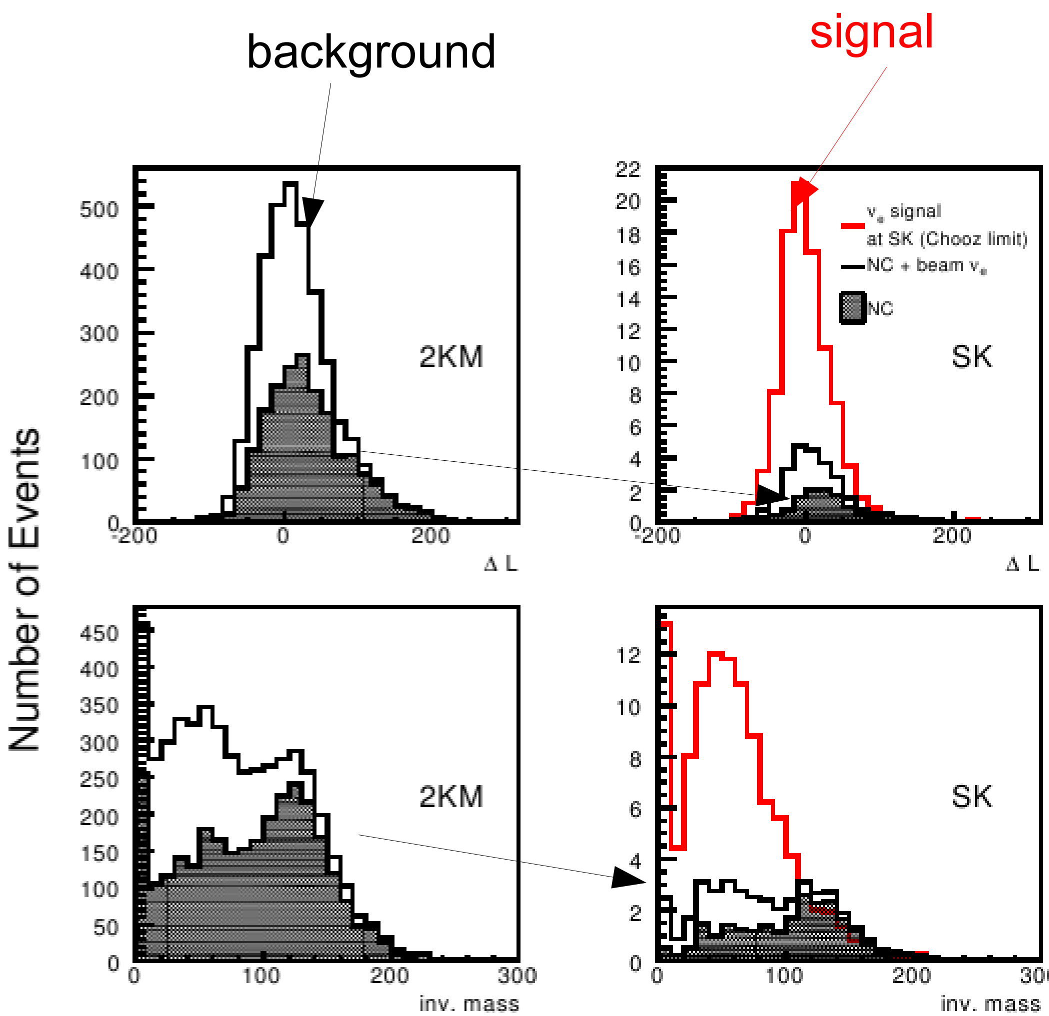

10 ns is best for 2KM
The 2KM tank is smaller so indirect light arrives earlier



# 2KM reconstruction : POLfit

- Use polfit2 at 2KM & SK for this analysis
- Compare 2KM with BG at SK Signal @ Chooz limit shown at SK



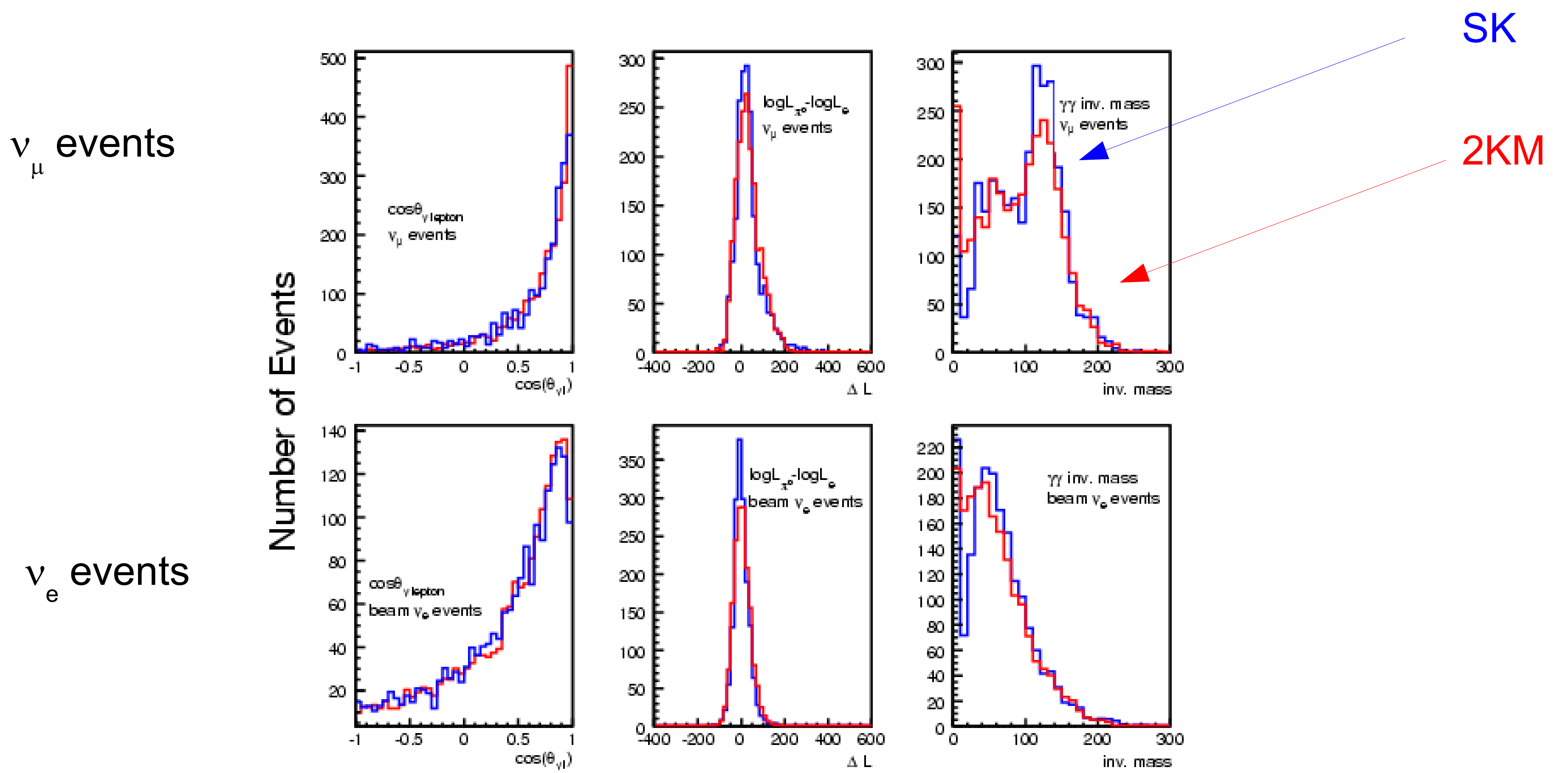

Events passing all $\nu_e$ selection criteria except the one being studied
FCFV, 1ring, e-like, no decay e-,
$\cos\theta_{\nu l} < 0.9$ , $0.35\ GeV < E\nu < 0.85\ GeV$

# 2KM reconstruction : POLfit (cont'd)

Using events after passing all criteria except the one under study

FCFV, 1ring, e-like, no decay e-, cos $\theta_{\nu l}$ < 0.9 , 0.35 GeV < E$\nu$ < 0.85 GeV

Compare distributions for the background at SK and 2KM



# III. $\nu_e$ appearance analysis

- Selection @ SK & 2KM
- Extrapolation
- Analysis systematics
- Other systematics
- Results

# $\nu_e$ appearance analysis : selection cuts

- Compare selection efficiencies at SK & 2KM

( Numbers of events correspond to $5.10^{21}$ pot = "5 years" )

- Determine a conservative estimate of the systematics on background "prediction" from 2KM

## $\nu_e$ appearance cuts

**2KM**

- **FV 100t** ( -415cm<Z<215cm && sqrt(x^2+y^2)<225cm)
- **FC** (max charge on a PMT < 100 p.e.)
- **Evis** > 100 MeV
- **1 ring, e-like**
- **No decay electron** : use MC info to compute decay e- detection probability and use random numbers
- **$\cos\theta_{\nu e} < 0.9$** (coherent pi0 suppression)
- **Polfit $M_{\gamma\gamma}$ < 100 MeV/c²**
- **$\Delta$log-likelihood < 80**

**SK**

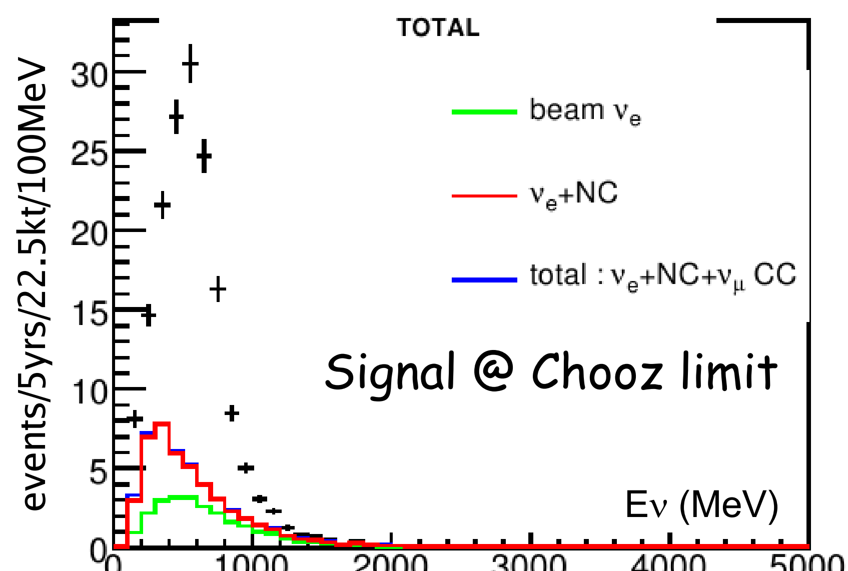
- **FV 22.5 kt** (distance to wall > 200 cm)
- **FC** (# of OD clusters < 10)
- **Evis** > 100 MeV
- **1 ring, e-like**
- **No decay electron** : use reconstructed decay e- info
- **$\cos\theta_{\nu e} < 0.9$** (coherent pi0 suppression)
- **Polfit $M_{\gamma\gamma}$ < 100 MeV/c²**
- **$\Delta$log-likelihood < 80**

# Selection efficiencies at SK

At Super-K , 22.5 kt, 5 years, $\Delta m^2_{23}$ = 2.5e-3 eV²:

| | νμ CC mis-ID | NC | Beam νe | Signal (chooz) |
|---|---|---|---|---|
| FC,FV,Evis>100 (MeV) | 2081.7 | 801.37 | 182.9 | 217.9 |
| Single ring | 983 (47.2%) | 214.7 (26.8%) | 89 (48.7%) | 1843 (84.6%) |
| E-like | 39.0 (1.9%) | 168.3 (21.0%) | 86.7 (47.4%) | 182.2 (83.6%) |
| No decay e- | 13.6 (0.65%) | 149.9 (18.7%) | 72.4 (39.6%) | 166.4 (76.2%) |
| 0.35<Eν<0.85 (Gev) | 1.37(0.07%) | 50.8 (6.3%) | 20.7 (11.3%) | 127.2 (58.3%) |
| $\cos\theta_{\nu lepton}$<0.9 | 1.025 (0.05%) | 35.8 (4.5%) | 17.5 (9.6%) | 111.4 (51.1%) |
| Polfit Mγγ < 100 MeV/c² | 0.47 (0.02%) | 11.8 (1.5%) | 13.9 (7.6%) | 94.1 (43.2%) |
| ΔlogLikelihood < 80 | 0.35(0.017%) | 9.8 (1.2%) | 13.5 (7.4%) | 91.9 (42.2%) |

- Efficiencies very similar to the previous analysis (0.03%, 1.06%, 7%, 42% respectively)
- Bug fix in official SK event rates : reduced by ~5% (10% in signal region)

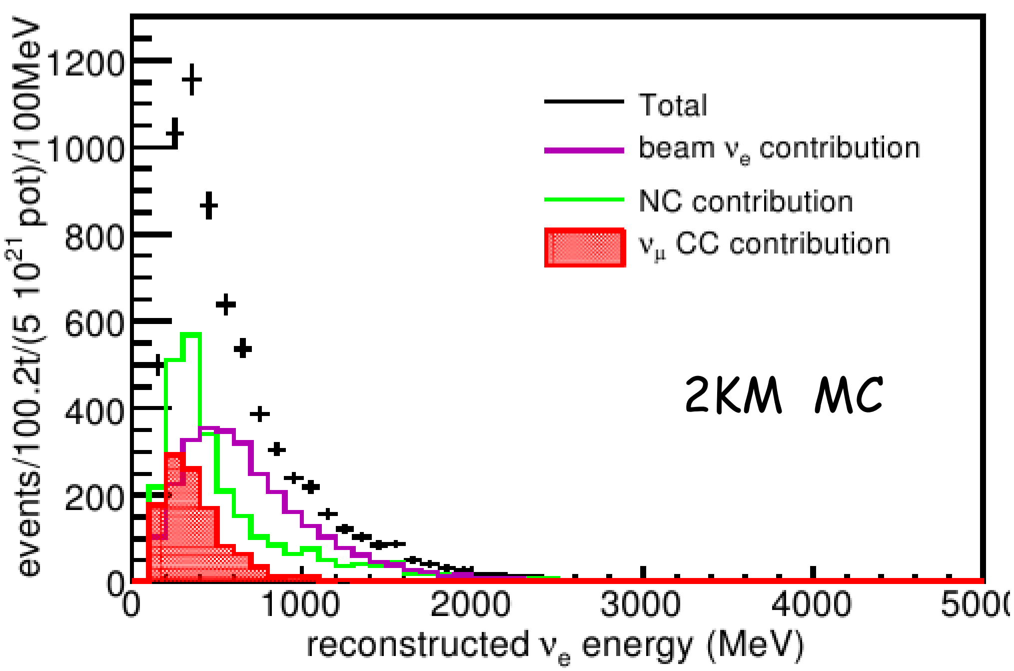


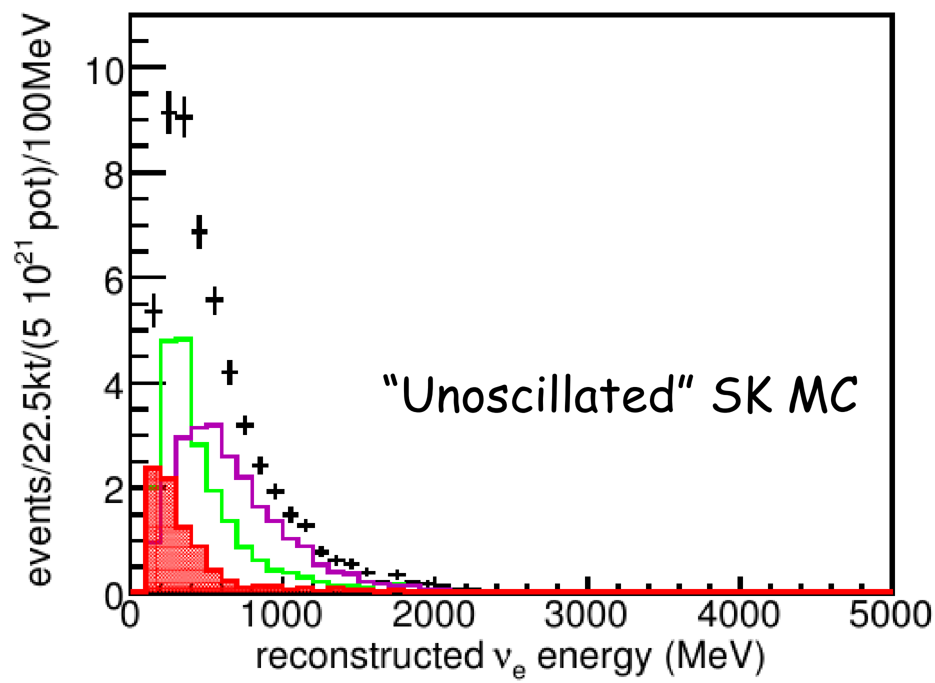
# Selection efficiencies at 2KM

| | νμ CC mis-ID | NC | Beam νe |
|---|---|---|---|
| FC,FV,Evis>100 (MeV) | 564229.1 | 93804.6 | 20250.25 |
| Single ring | 426562 (75.6%) | 26206 (27.9%) | 10535 (52%) |
| E-like | 12263.7 (2.2%) | 20971 (22.4%) | 10113 (49.9%) |
| No decay e- | 3283.7 (0.57%) | 17240.8(18.4%) | 8032.9 (39.7%) |
| 0.35<Eν<0.85 (Gev) | 1223.3 (0.22%) | 6938.8 (7.4%) | 2422.4 (12.0%) |
| $Cos\theta_{\nu lepton}$<0.9 | 963.9 (0.17%) | 4641.8 (4.9%) | 2080.9 (10.3%) |
| Polfit Mγγ < 100 MeV/c² | 536.5 (0.095%) | 1389.8 (1.48%) | 1646.6 (8.13%) |
| ΔlogLikelihood < 80 | 468.7 (0.083%) | 1086.2 (1.16%) | 1585.5 (7.83%) |
| SK, ALL CUTS | 0.35 (0.013%) | 9.8 (1.2%) | 13.5 (7.4%) |

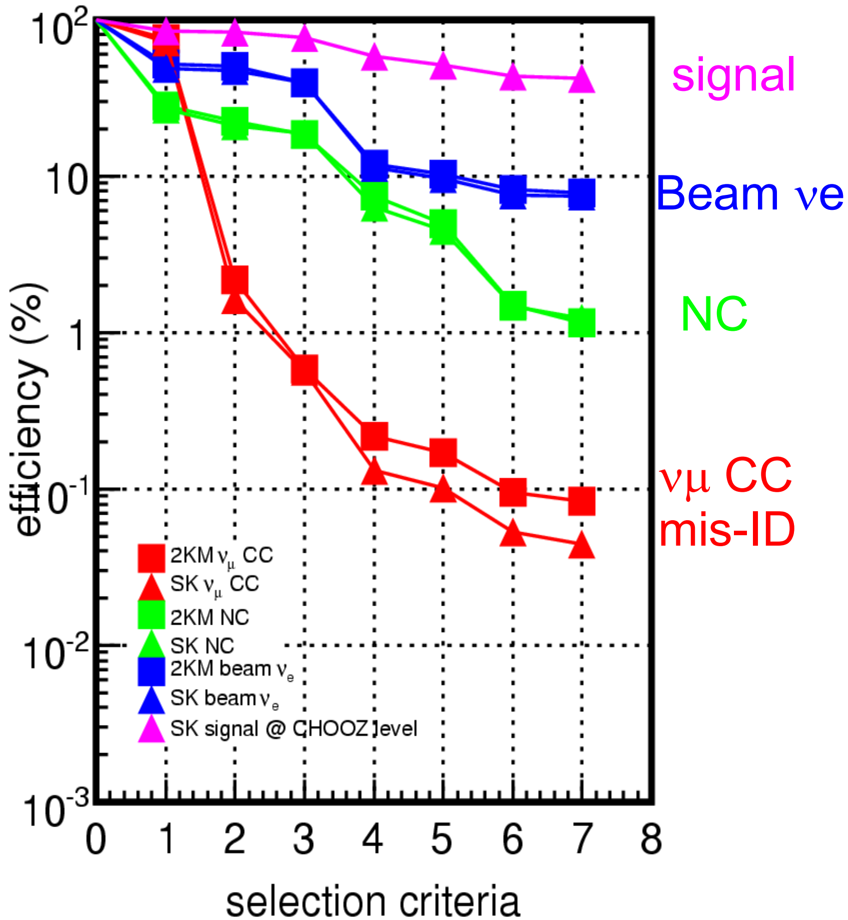
Oscillations cause differences

NC and $\nu_e$ are almost identical !



# Efficiency differences




Event selection criteria

0 : FCFV, $E_{vis}$ >100 MeV

1 : 1R

2 : e-like

3 : no decay e- (non std cut)

4 : 0.35 GeV<$E_\nu^{rec}$<0.85 GeV

5 : $\cos(\theta_{\nu e})$<0.9

6 : $M_{\gamma\gamma}$ < 100.0 MeV/$c^2$

7: $\Delta$ L < 80.0

For each category of events ($\nu_\mu$ CC, NC, beam $\nu_e$) compare SK and 2KM efficiencies using “unoscillated” SK efficiencies

# Extrapolation from 2KM to SK

Simple scaling prediction with no corrections :

$$N_{sk} = N_{2km} \ (M_{sk}/M_{2km})(L_{sk}/L_{2km})^2(\epsilon_{sk}/\epsilon_{2km})$$

Assumed to be 1 here

For $\nu_\mu$ CC also apply $\nu$ oscillation “survival” probability

Get prediction of BG at SK from 2KM measurement assuming identical efficiencies & spectra -> simple scaling with squared distances and fiducial masses & no corrections

Systematics :

- Analysis cuts --> next slides
- Energy calibration --> next slides
- FV ~ 4 % = error @ SK + error @ 2KM in quadrature

# Extrapolation systematics : differences between SK & 2KM

- Compute the efficiency of each cut
- Use relative difference between SK & 2KM as a very conservative estimate of the systematic error on each cut
- Add in quadrature

$$\sigma^2 = \sum_i \left( \frac{\varepsilon_{SK,i} - \varepsilon_{2KM,i}}{\varepsilon_{2KM,i}} \right)^2$$

$$\frac{\varepsilon_{SK} - \varepsilon_{2KM}}{\varepsilon_{2KM}}$$

| FC,FV,Evis100-1000 | Beam νe | NC | νμ misID |
|---|---|---|---|
| 1R | -2.05% | 2.82% | 1.43% |
| E-like | 1.00% | -4.64% | -13.51% |
| No mu-e | 1.68% | 5.00% | 8.59% |
| cos(q)<0.9 | -0.60% | 6.27% | 2.23% |
| m_gg<100 | -1.38% | -1.93% | 2.37% |
| DL<80 | 0.64% | -2.50% | -10.01% |
| Enu | 0.30% | 3.76% | -30.50% |
| TOTAL | 3.28% | 10.86% | 36.05% |

Then weight the contributions according to the actual numbers of events :
13.0 beam $\nu_e$ CC events, 9.4 NC events & 0.7 $\nu_\mu$ CC events

TOTAL “ANALYSIS” ERROR = 1.13/23.01 = 4.9%

# Energy calibration systematics

Energy calibration errors are taken to be 2.1% at each detector, uncorrelated.

- Vary cuts by +/- 1 sigma corresponding to this uncertainty (Evis cuts, Eν cuts, polfit mass cuts)
- Relative variation of the final number is the error due to the energy calibration
- Add in quadrature SK and 2KM

| Energy scale | SK | 2KM |
|---|---|---|
| NC | 9.1% | 6.8% |
| νμ CC misID | 5.7% | 5.4% |
| Beam νe | 0.6% | 0.5% |

Combining "analysis" errors and energy calibrations errors in quadrature, and extrapolating to SK :

| | NC | Beam νe (CC) | νμ mis-ID (CC) |
|---|---|---|---|
| SK simulation | 10.15 | 13.23 | 0.35 |
| Prediction from 2km (±stat±syst) | 9.38±0.28±1.02 | 12.97±0.33±0.43 | 0.67±0.03±0.24 |

**Systematic error = 4.9% → including energy calibration = 6.8%**

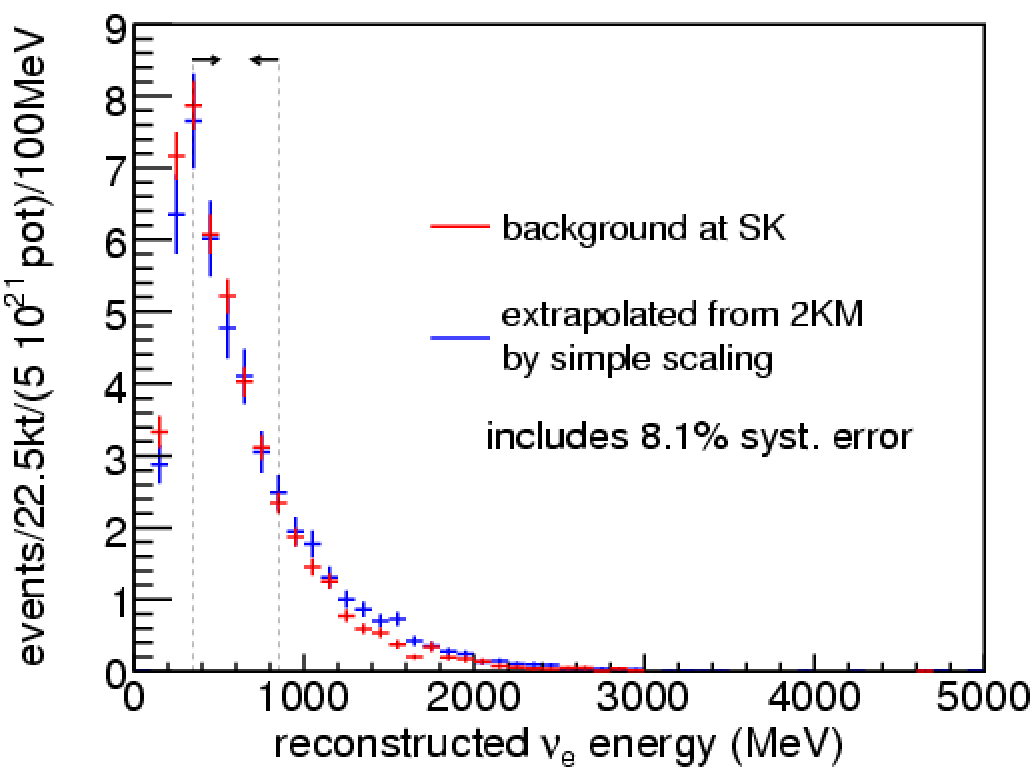
# Final result

Add 4% FV(=2.8% uncorrelated at both positions)

**Super-Kamiokande : 23.73 ± 20% (expected stat for 5 years)**

**scaled from 2KM : 23.01 ± 0.41 (exp. stat) ± 1.86 (syst)**
**= 23.01** ± 0.41 (exp.stat) **± 6.8%(analysis&energy)± 4% (FV)**
**= 23.01 ± 8.1 %**

Compare energy spectra @ SK and 2KM with systematic error : Excellent agreement !



# Conclusion

- Interaction / simulation :
  - Large statistics available at 2KM and SK
  - Improved GEANT4 MC
- 2KM reconstruction :
  - Improved reconstruction @ 2KM : vertex fit, ring counting, PID, POLfit
- Analysis :
  - Total BG at SK for 5 years is 23.8 events
  - Prediction from 2KM is 23.0 ± 8.1%, without any attempt to correct for anything (neither beam nor analysis differences between SK & 2KM)
  - Differences between the detectors contribute as 5%
  - Work on incorporating errors in full fit is in progress, will be shown by N. Tanimoto tomorrow in the SK session.