Present and Future of Super-K and LBLE in Japan

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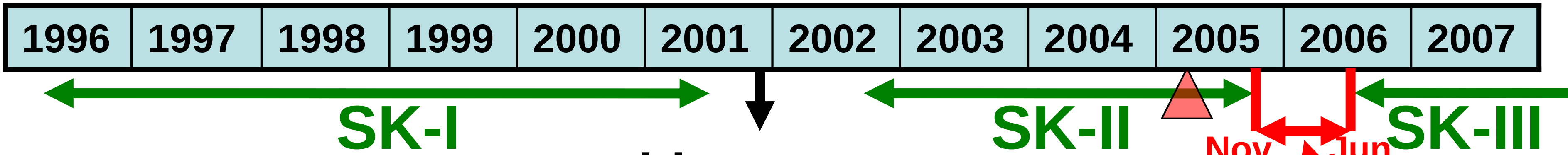
2005.02.23
Neutrino Telescope
@Venice

Schedule for full restoration (SK-III)

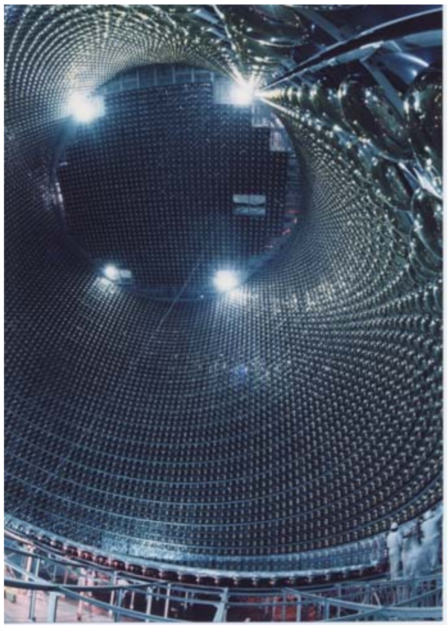


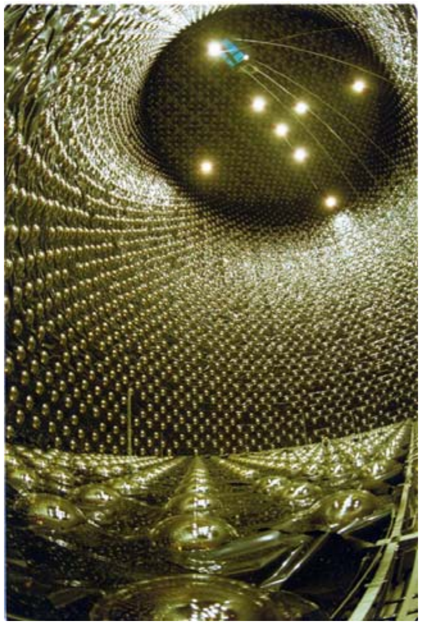
accident

Lost 6777 PMTs

SK full reconstruction

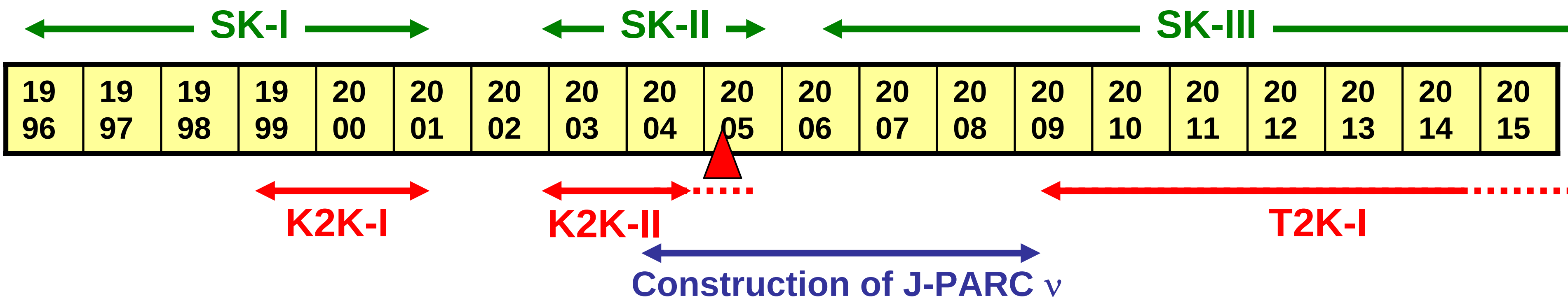
Data taking June-2006





# of ID PMTs	11,146	5,182	11,146
Photo-coverage	40%	19%	40%
Cherenkov light yield	~6 p.e./MeV	~2.8 p.e./MeV	~6 p.e./MeV
Energy threshold	5 MeV	8 MeV	4 MeV
		Acrylic(13cm) + FRP cases	

Longer term commission and LBLE

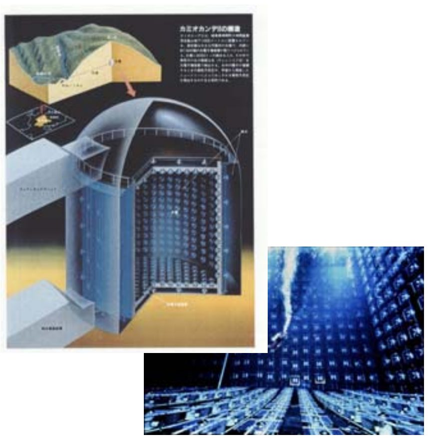


	K2K	T2K-I
Machine Energy	12GeV	40GeV
Machine Power	0.0052 MW	0.75 MW
Beam Intensity	6×10^{12} ppp	330×10^{12} ppp
Repetition Rate	0.45	0.275
Mean ν energy	1.4 GeV	0.7GeV
Aiming POT's	10^{20} POT	5×10^{21} POT
Total events	~150(~100obs.)	11000

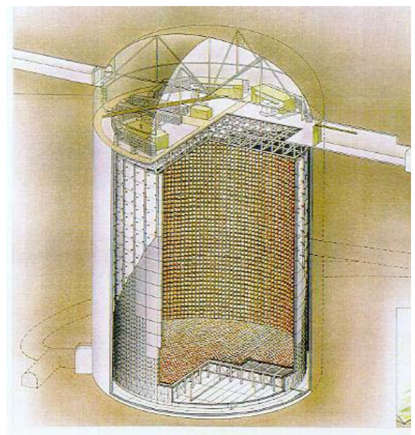
Wider Range View for Water Cherenkov Detectors

80's	90's	00's	10's	20's	30's

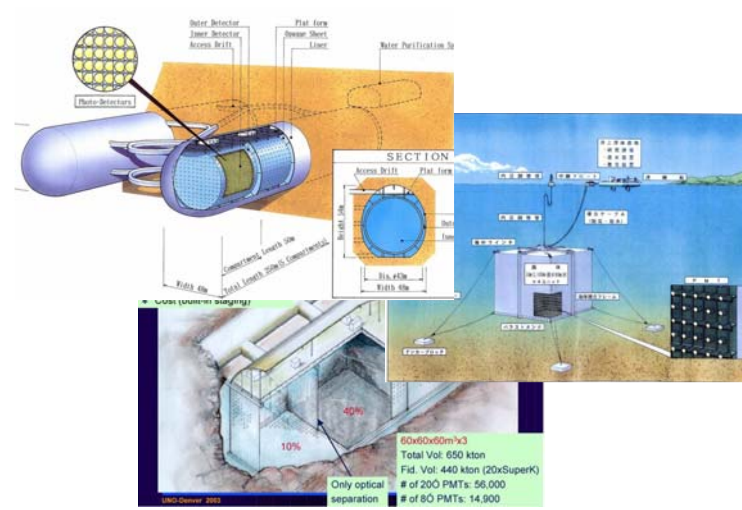
A few thousand tons
Kamiokande, IMB



50, 000 tons
Super-K



Mega ton detectors



Supernova ν
Atm-ν anomaly
Solar-ν Problem

Neutrino Oscillations
- **Atm-ν and Solar-ν**
- **man-made ν**

θ_{23}, Δm^2_{23}, θ_{12}, Δm^2_{12}
θ_{13} (?)
Supernova ν (?)

Neutrino Oscillation
- **θ_{13}, CPV (?)**

Supernova ν (?)
Supernova Relic ν (?)
Proton decay (?)

T. Nakaya's talk

Atmospheric Neutrinos

-- Present and Future --

Δm_{23}^2 and $\sin^2 2\theta_{23}$

$\Delta m^2=(1.5\sim3.4)\times10^{-3}, \sin^2 2\theta>0.92$

$(\chi^2_{min}=37.7/40$ d.o.f)

3 flavor analysis

New

$\sin^2\theta_{13} < 0.14$ (90% C.L.)

$0.36<\sin^2\theta_{23}<0.65$

effect of Δm_{12} and θ_{12}

L/E Analysis

Oscillatory behavior

Seen at $3 \sim 4\ \sigma$ level

New — Tau appearance

Observed:

155 ± 50(stat) $\pm^{12}_{72}$ (Osc Par)

Expected:

79 ± 30(syst)

Better determination

of Δm^2 $((1.9\sim3.0)\times10^{-3}\text{eV}^2)$

Future

θ_{13}: determination

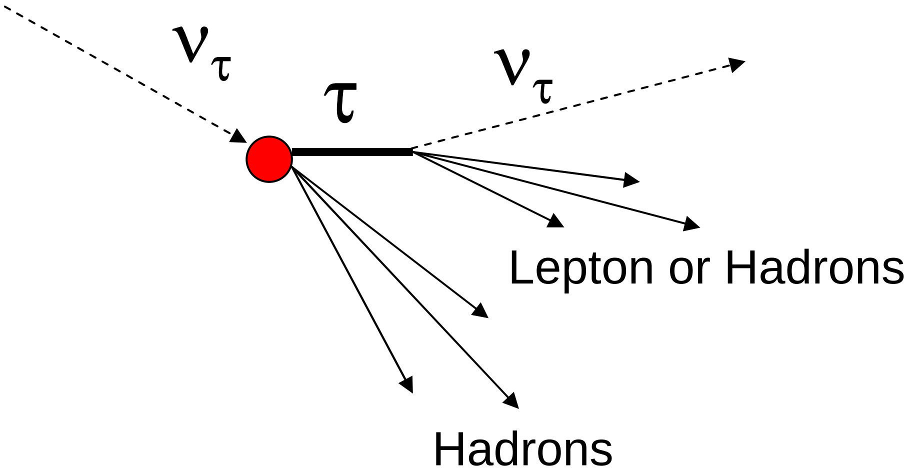
θ_{23}: deviation from 45°

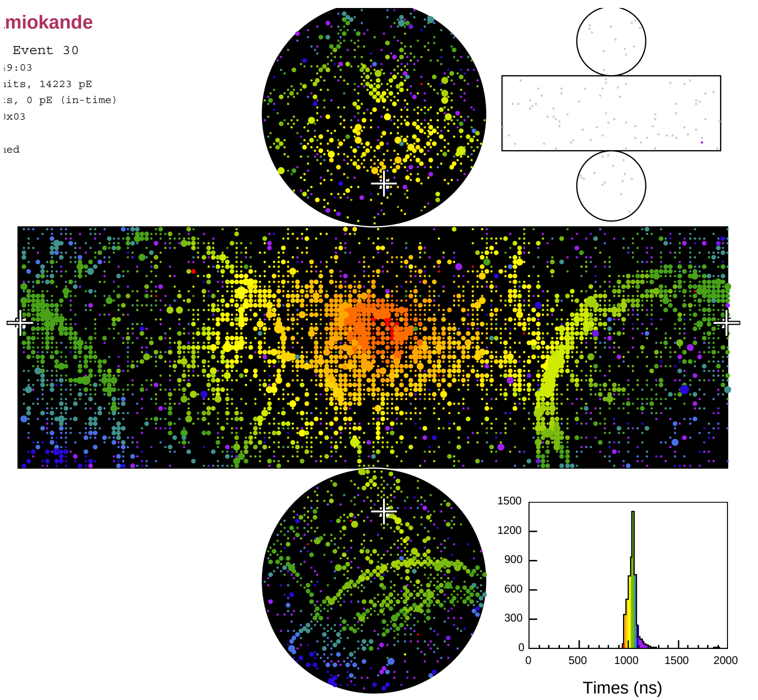
octant of θ_{23}

Mass hierarchy

CP phase

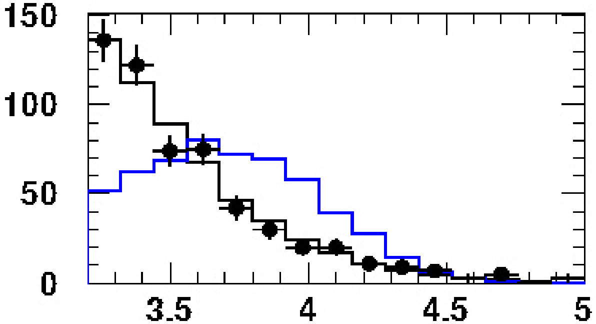
Search for τ appearance



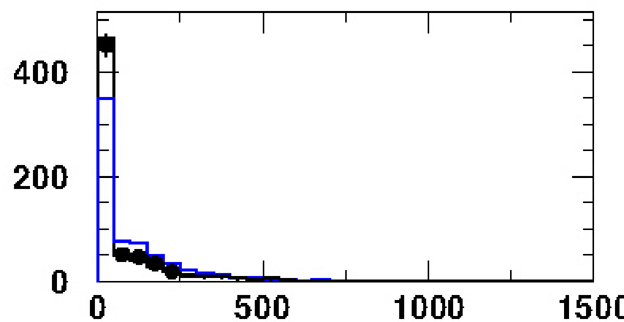


- τ events cannot be identified by event-by-event basis
  - Many Hadrons
- Need statistical analysis
  - characteristics of τ production
- Low rate
  - 1 CC ν_τ FC ev /kton/yr
- BG ~ 130 ev /kton/yr

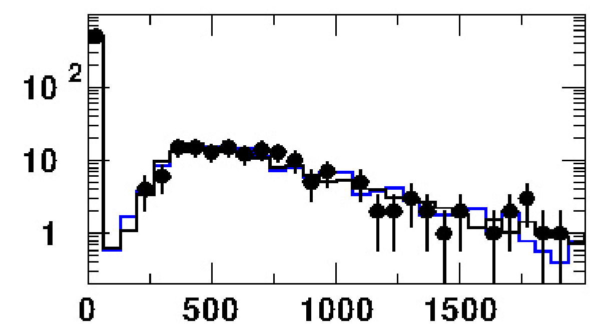
Selection and Variables



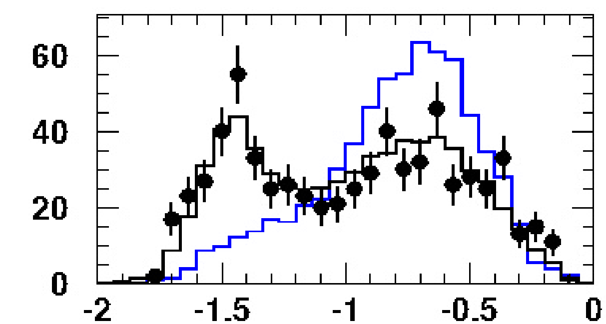
Visible energy



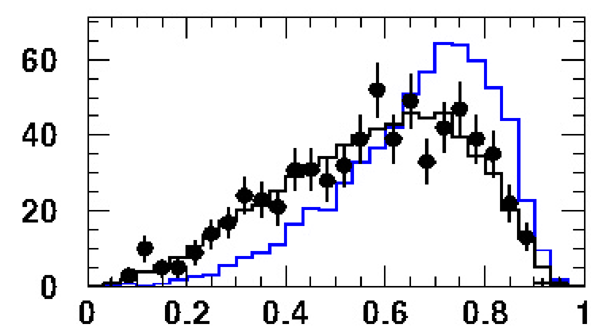
d_{max} (to μ→e electron vtx)



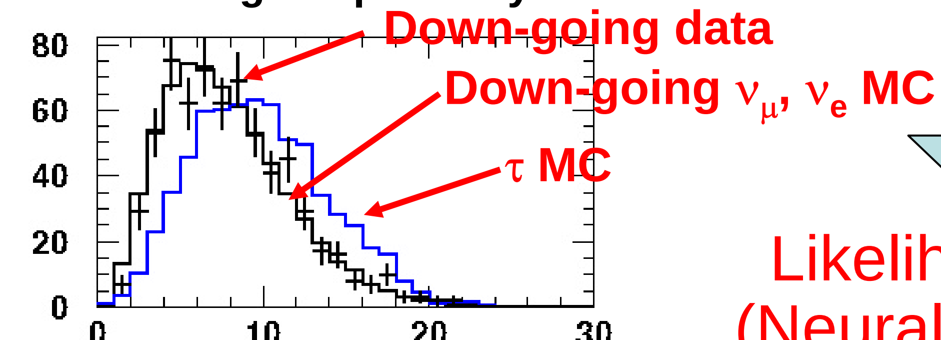
Pmax (μ-ring)



Log of sphericity



Clustered sphericity



\# of ring candidates

Pre-selection

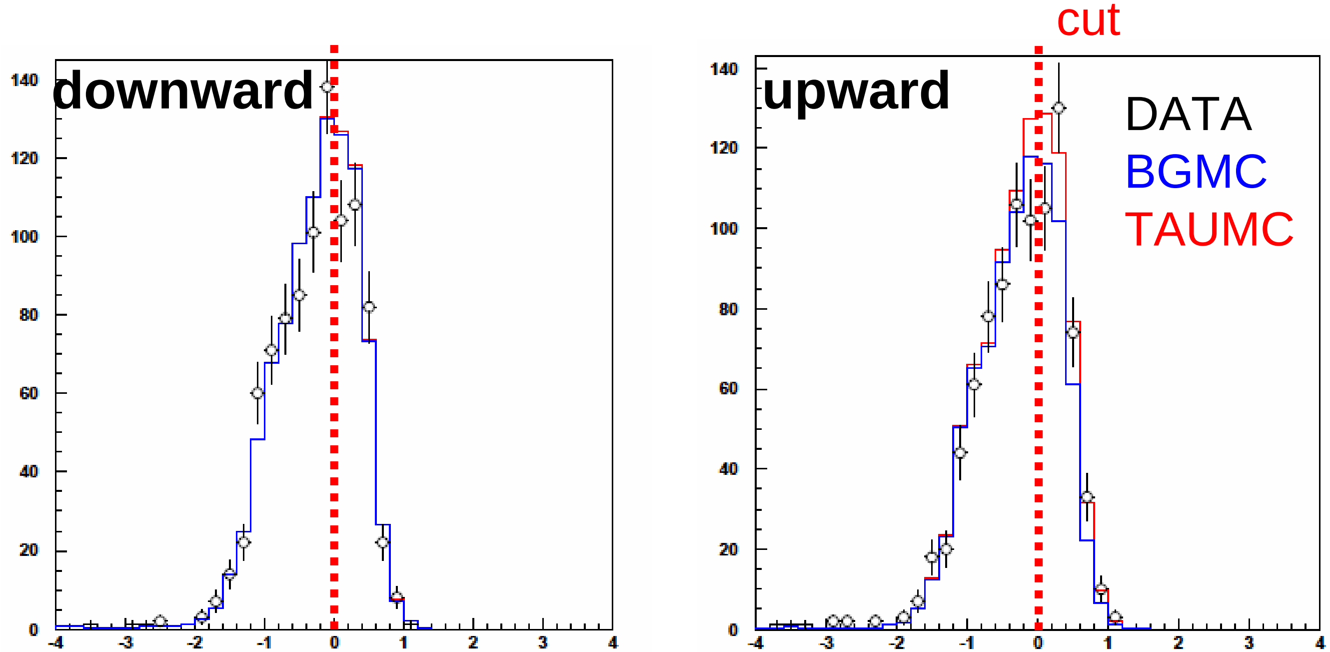
1) **Fiducial volume:**
   2m from the ID PMTs
2) **Visible energy (Evis)**
   > 1.33GeV
3) **Most energetic ring:**
   e-like

↓

Likelihood and
(Neural Network)

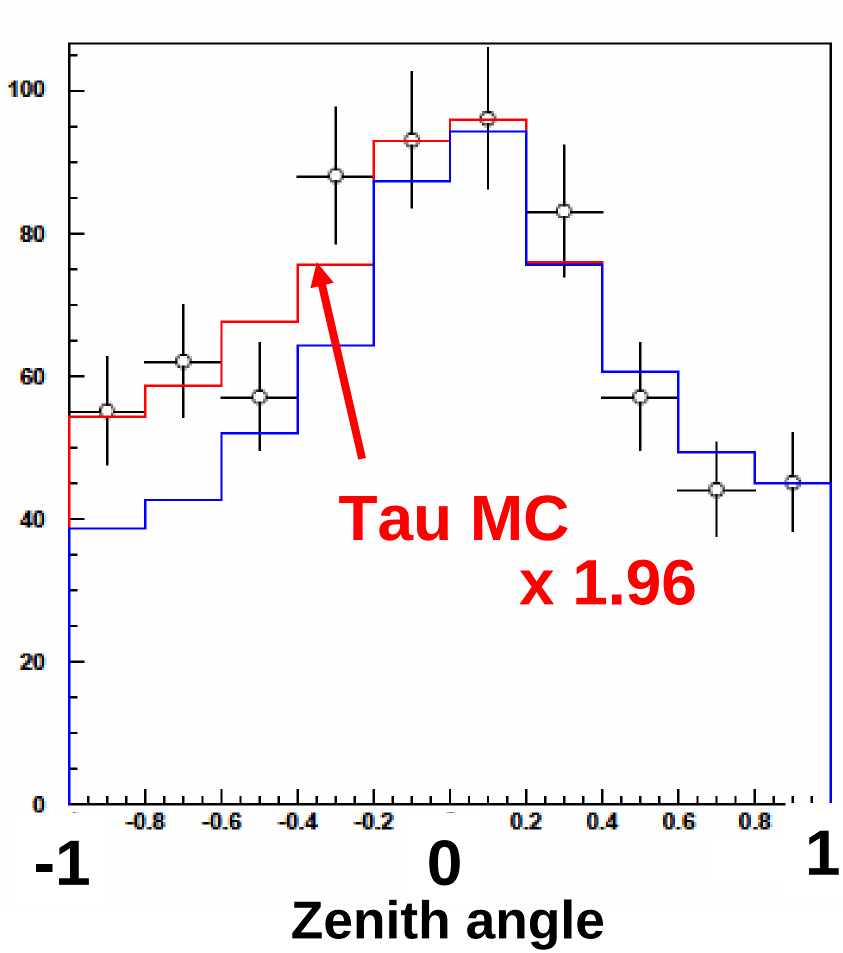
Event reductions

	Atm ν MC(100yr) (no osci.)	τ CC MC(200yr) (w/ osci.)
Generated events	482760 (100%)	3891(100%)
Fiducial vol. & Evis >1.33	81950 (17%)	2504(64%)
Most energetic = e	43616 (9%)	2249(58%)
Likelihood selection	16234 (**3.4**%)	1650(**42**%)



Likelihood Distributions

Tau Results



$$f(\cos(\theta)) = a * Tau + b * BG$$

Result:

a = 1.96±0.63 ; b = 0.92

Expected : 33.6 events

Data : 66±21 events

Efficiency(42%)

Total tau events

Expected: 79±30(syst) ev.

Data: 155±50(stat/syst) $\pm^{12}_{72}$ (osc. parm)

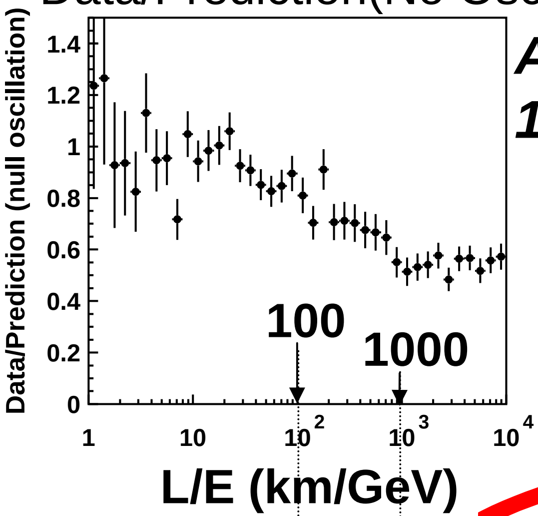
Cf. Neural Network

Expected: 79±29(syst) ev.

Data: 155±50(stat/syst) $\pm^{0}_{53}$ (osc. parm)

Parameter determination and L/E analysis

Data/Prediction(No Osc)

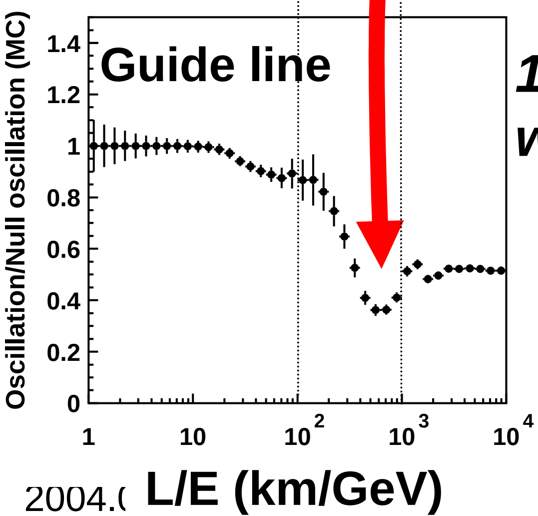


All the data 1489.2days

Aim of the L/E analysis

- **Observe oscillation pattern → direct oscillatory evidence**
- **Distinguish other exotic hypotheses in L/E**
- **Strong constraint on Δm^2 ($\lambda/E=4\pi/\Delta m^2$: Position of Dip)**

Select events only with good L/E resolution : $\Delta(E/L) < 70\%$



100 yr MC w/ selection

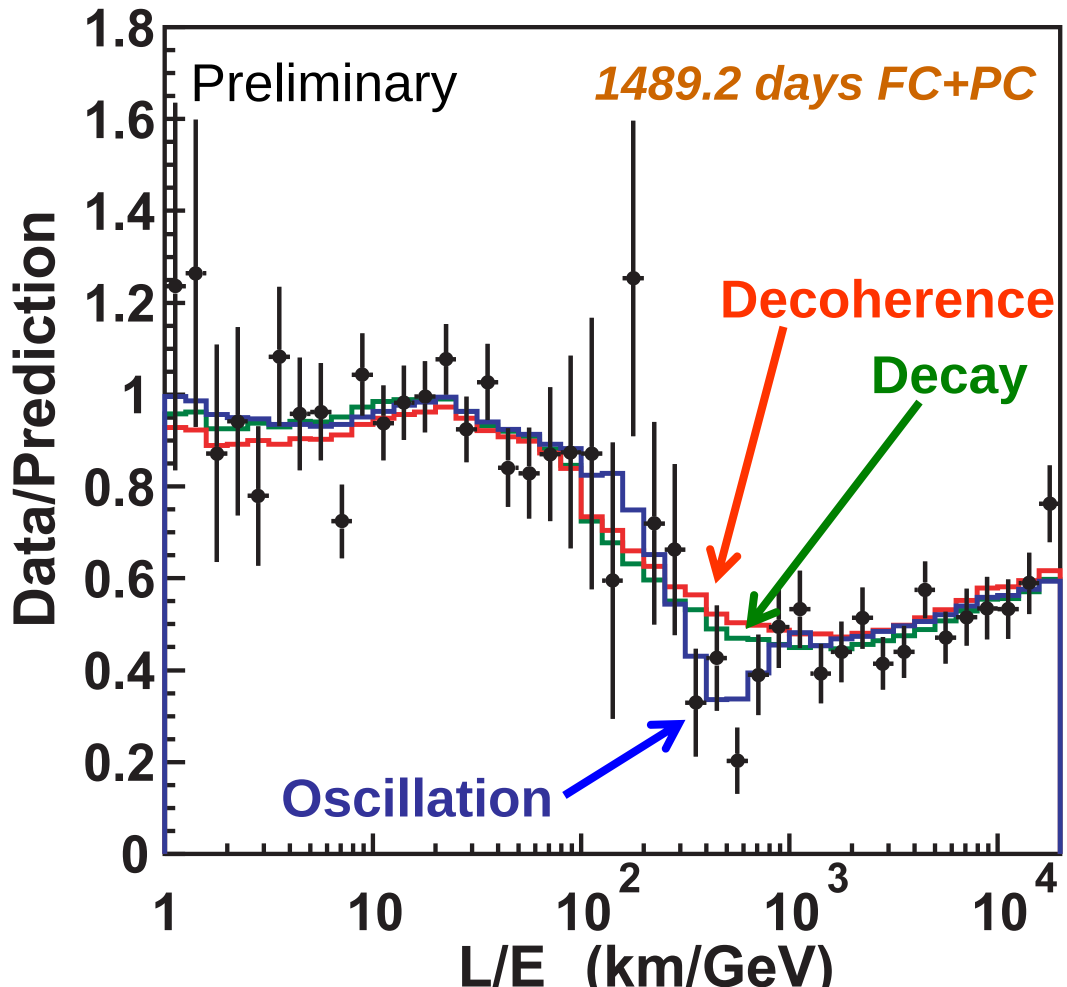
Rejected events

horizontally going events:
→ due to large dL/dcosθ

low energy events:
→ due to large scattering angle

2726 events (3726 ev. expected)
~ 1 /5 of total data

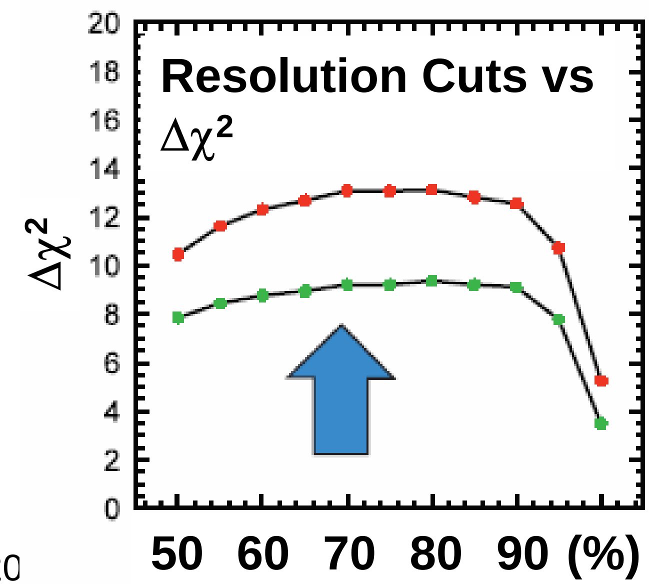
Result of L/E analysis



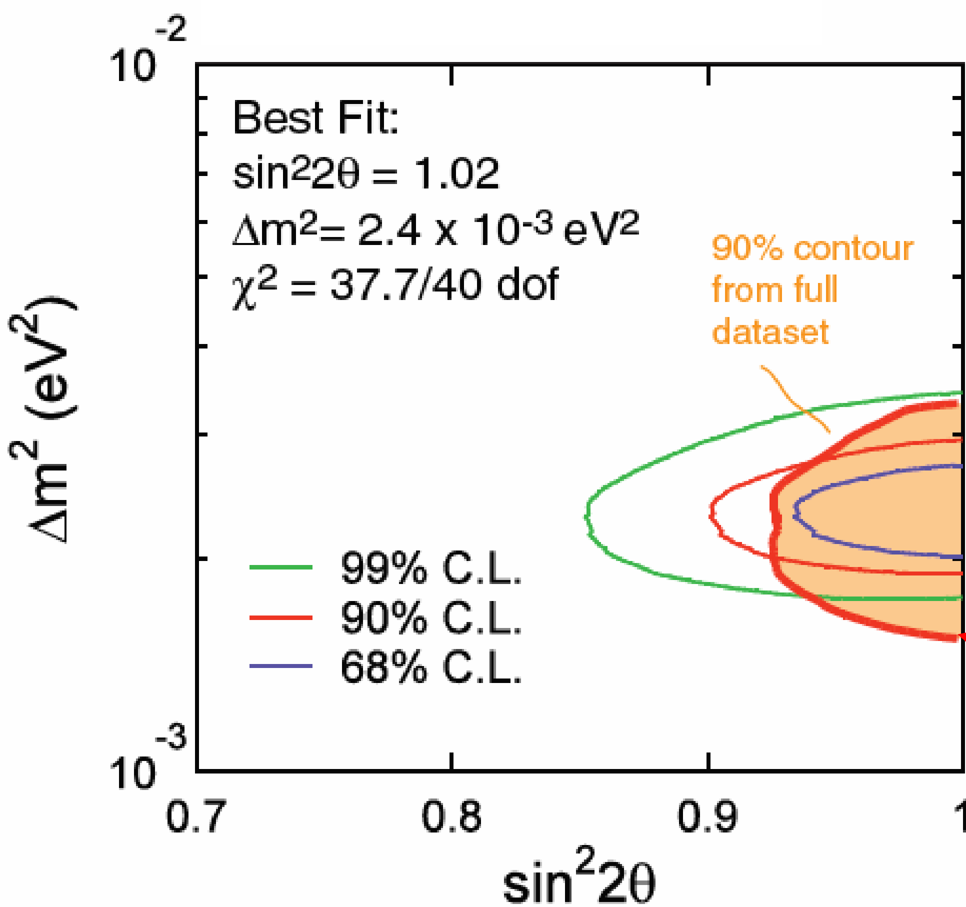
- The first dip has been observed at ~500km/GeV
- This provide a strong confirmation of neutrino oscillation
- The first dip observed cannot be explained by other hypotheses

3.4 σ to decay

3.8 σ to decoherence



Constraint on the neutrino oscillation parameters from L/E analysis



Best Fit:

$\Delta m^2=2.4\text{x}10^{-3}, \sin^2 2\theta=1.00$

$\chi^2_{min}=37.8/40$ d.o.f.

($\sin^2 2\theta=1.02$, $\chi^2_{min}=37.7/40$ d.o.f)

Allowed region (@90%C.L.)
$1.9\text{x}10^{-3} < \Delta m^2 < 3.0\text{x}10^{-3}$ eV^2
$0.90 < \sin^2 2\theta$

Consistent with the standard zenith angle analysis

$1.5\text{x}10^{-3} < \Delta m^2 < 3.4\text{x}10^{-3}$ eV^2
$\sin^2 2\theta > 0.92$ (@90%C.L.)

Stronger constraint on Δm^2 even with fewer events

Three flavor analysis

Atmospheric ν K2K | Upper limit CHOOZ | unknown | Solar ν KamLAND

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

$$\approx\begin{pmatrix}c_{12}&s_{12}&s_{13}e^{-i\delta}\\-c_{23}s_{12}&c_{23}c_{12}&s_{23}\\s_{23}s_{12}&-s_{23}c_{12}&c_{23}\end{pmatrix}\quad for\ \begin{pmatrix}s_{13}=\sin\theta_{13}:small\\c_{13}=\cos\theta_{13}\to 1\end{pmatrix}$$

Oscillation effects in electron appearance

$$\frac{\Psi(\nu_e)}{\Psi_0(\nu_e)} - 1 \cong P_2(r \cdot c_{23}^2 - 1)$$

Solar term

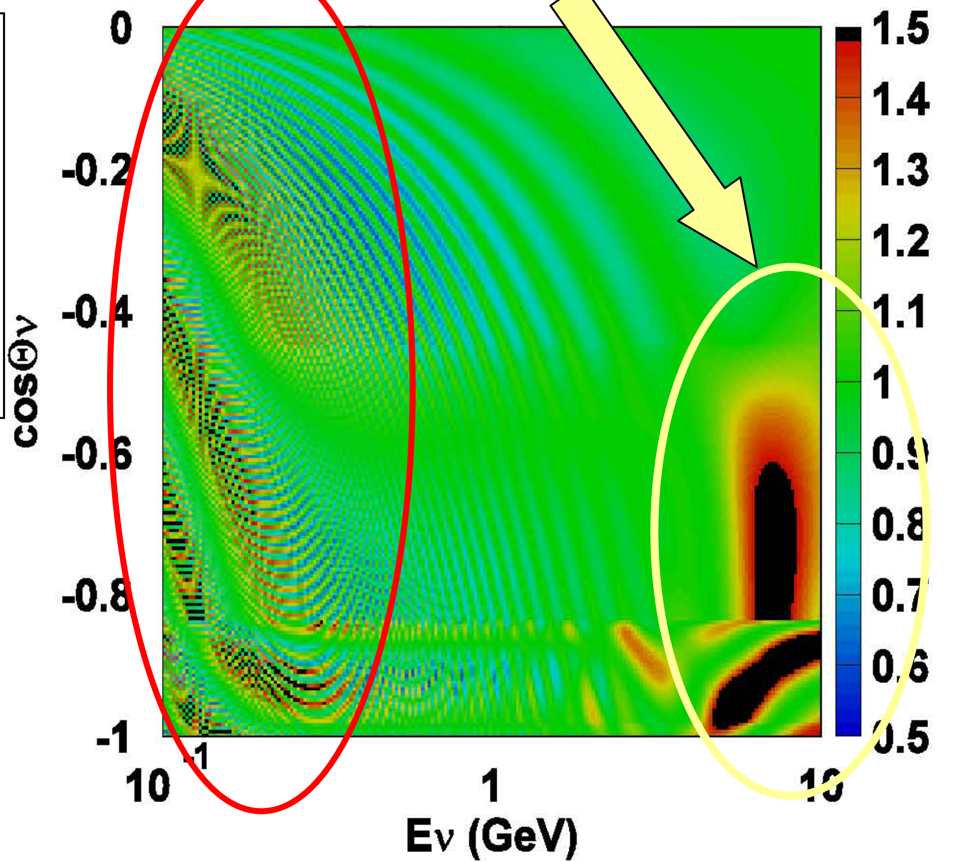
$$- r \cdot \tilde{s}_{13} \cdot \tilde{c}_{13}^2 \cdot \sin 2\vartheta_{23}(\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2)$$

Interference

$$+ 2\tilde{s}_{13}^2(r \cdot s_{23}^2 - 1)$$

θ_{13} term

- r : μ/e flux ratio (~2 at low energy)
- ~ : mixing angle in matter
- $P_2 = |A_{e\mu}|^2$: $\nu_e \rightarrow \nu_{\mu\tau}$ in matter
- $R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$
- $I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$



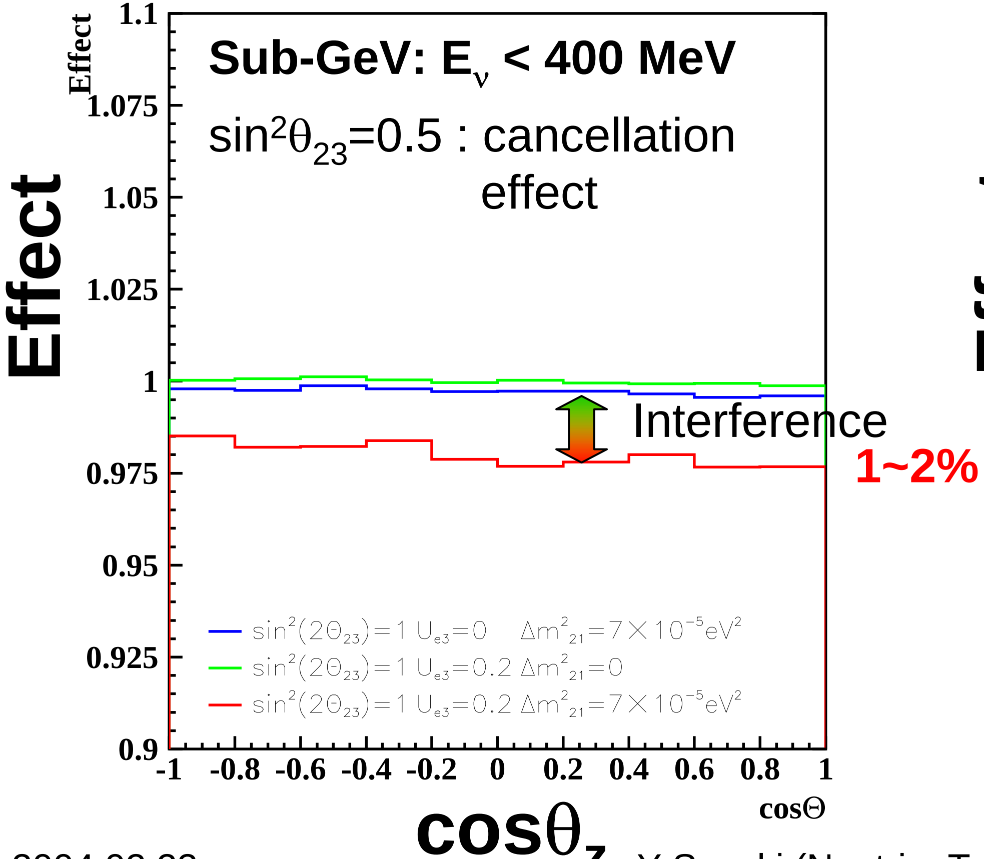
See for example:
Parse and Smirnov
hep-ph/0309312

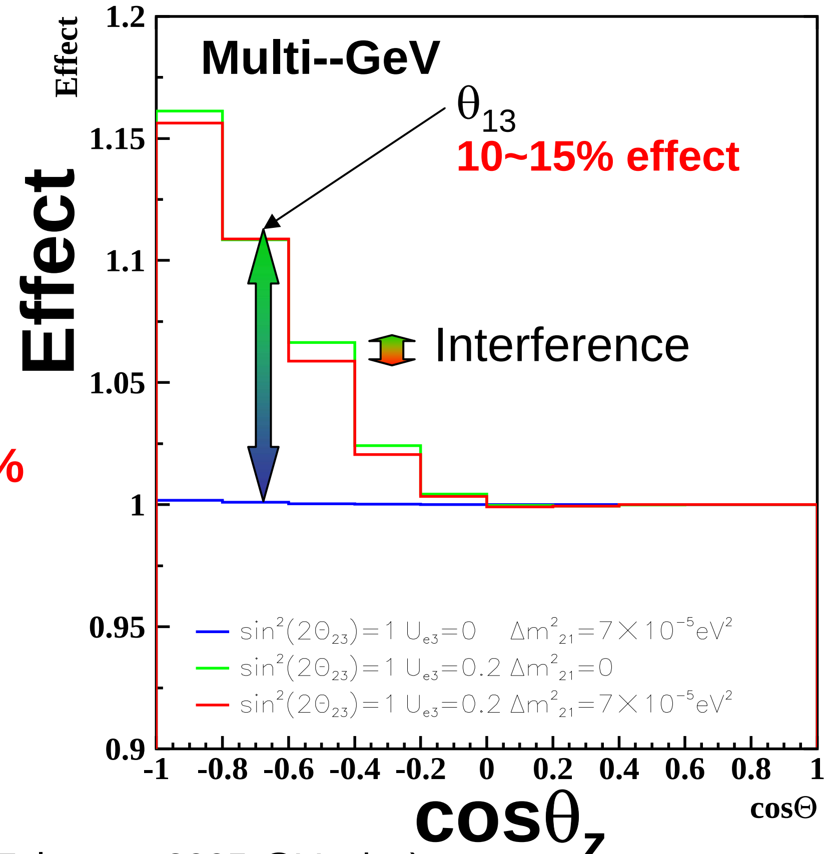
$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.4$
$s^2\theta_{13}=0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3\times10^{-5}$
$\Delta m^2_{23}=2.5\times10^{-3}$

Order estimate of the effect of Solar term and $\sin\theta_{13}$

- **$\sin\theta_{13}=0.2$ (No solar)**
- **$\Delta m_{12}^2=7\times10^{-5}eV^2$, $\sin^2 2\theta_{12}=0.8$, ($\sin^2\theta_{13}=0$)**
- **Interference**

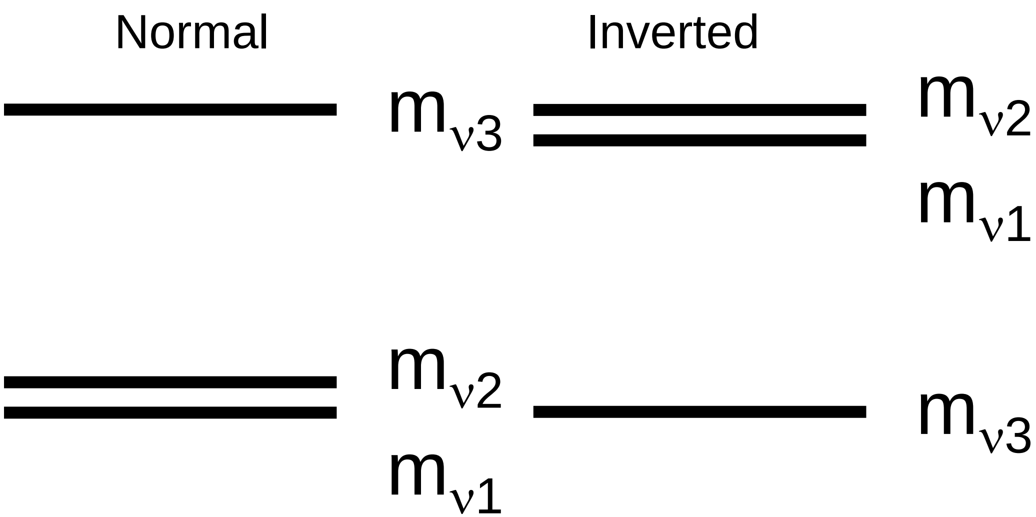
$\sin^2\theta_{23}=0.5$: case for $\sin^2\theta_{23}\neq0.5$ will be discussed later





Search for non-zero θ_{13} in SK data

Assumption in SK analysis



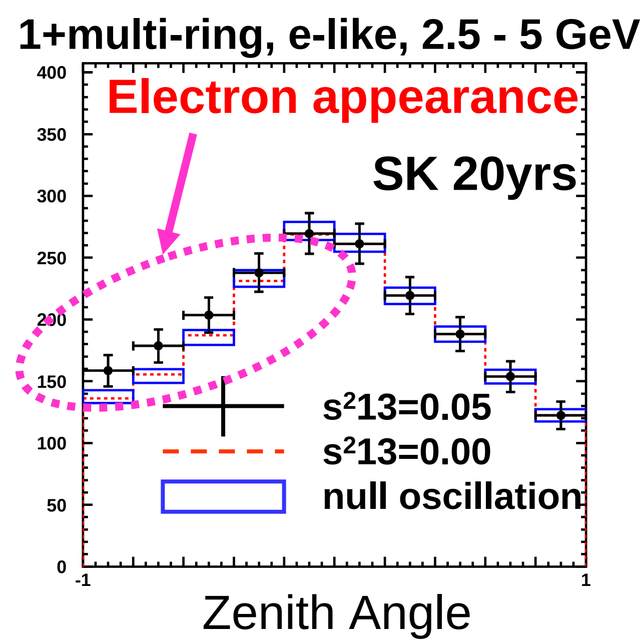
$\Delta m_{12}=0$

$\Delta m_{13}= \Delta m_{23}$

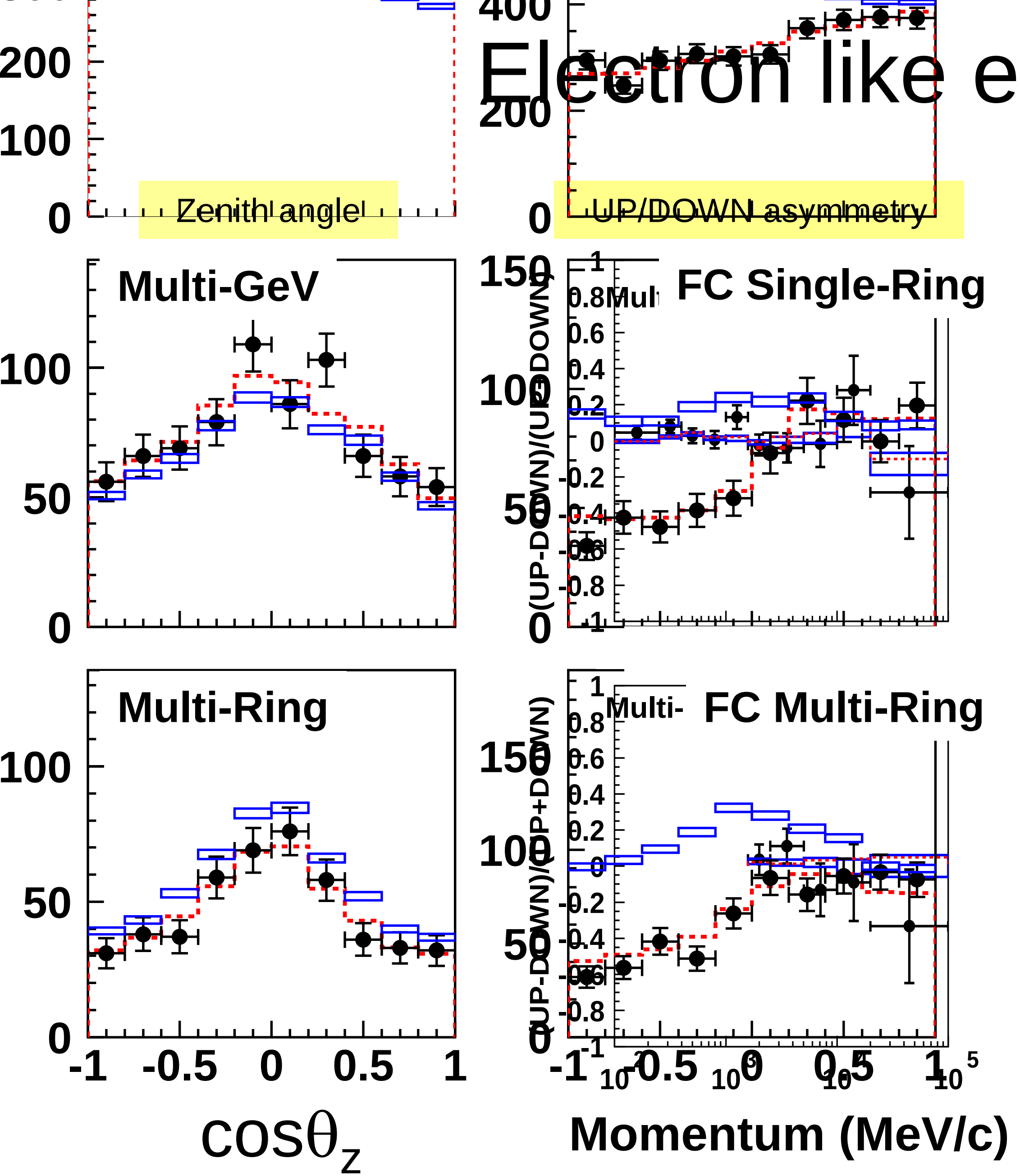
$\Delta m_{13}^2, \theta_{23}, \theta_{13}$

Normal:
matter effect for neutrinos
Inverted:
matter effect for anti-ν

Expected electron appearance
In 2~10 GeV up-going events
due to matter effects



Electron like events



No significant excess due to matter effect was seen in upward-going multi-GeV, multi-Ring electron sample

Range of the parameters at 90% C.L.

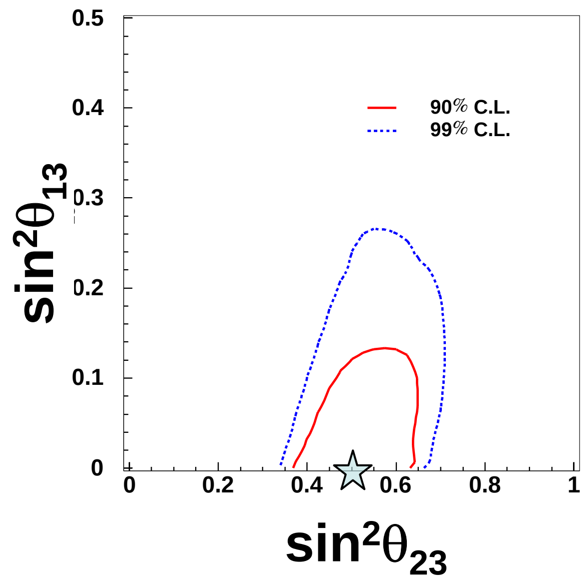
$\sin^2\theta_{13} < 0.14$

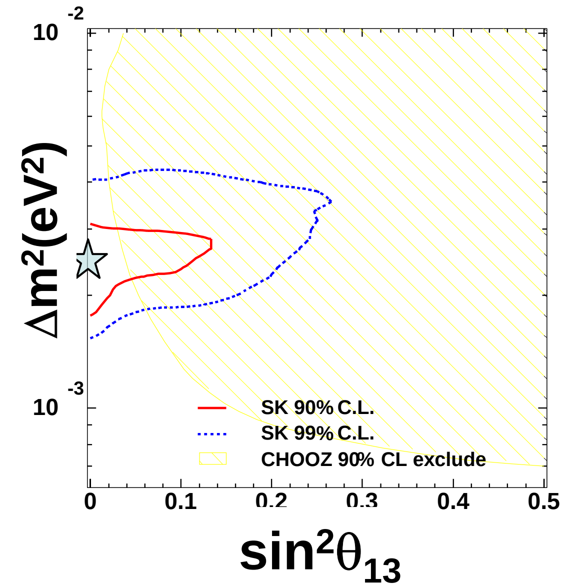
$0.36 < \sin^2\theta_{23} < 0.65$

Normal vs Inverse hierarchy

Normal ($\Delta m^2>0$)

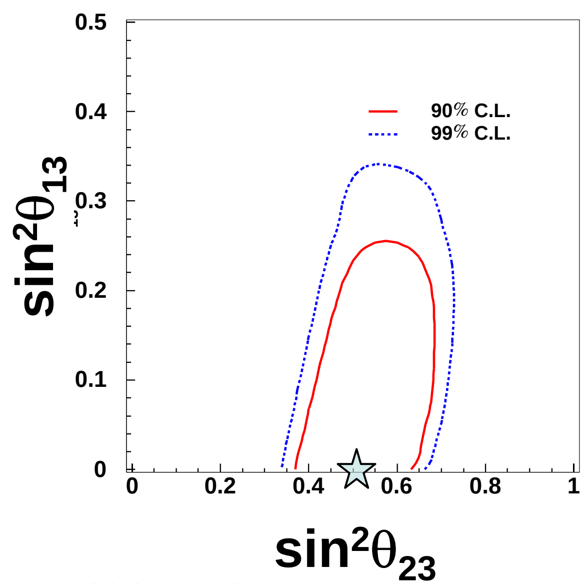
$\chi^2_{min}/ndf = 376.82/368$
@$(2.5\times10^{-3}, 0.5, 0.0)$

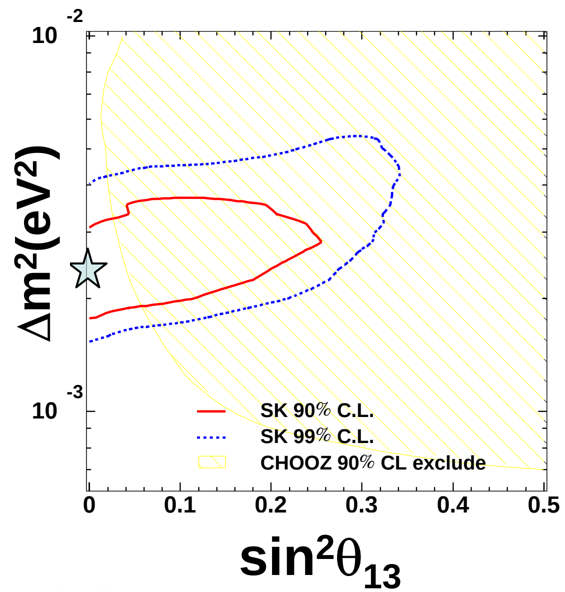




Inverse ($\Delta m^2<0$)

$\chi^2_{min}/ndf = 376.76/368$
@$(2.5\times10^{-3}, 0.525, 0.00625)$





Effect of solar term to determine θ_{23}

- Effect of solar term should appear in the low energy data even if $\sin^2\theta_{13}=0$ (no interference)
- The effect is very small for $\cos^2\theta_{23}=0.5$ due to the cancellation effect ($\nu_\mu/\nu_e=2$).

$$\frac{\Psi(\nu_e)}{\Psi_0(\nu_e)} - 1 \cong P_2(r \cdot \cos^2\theta_{23} - 1)$$ **; In low energy r ~ 2**

~ 0 for $\cos^2\theta_{23} = 0.5$

< 0 for $\cos^2\theta_{23} < 0.5$

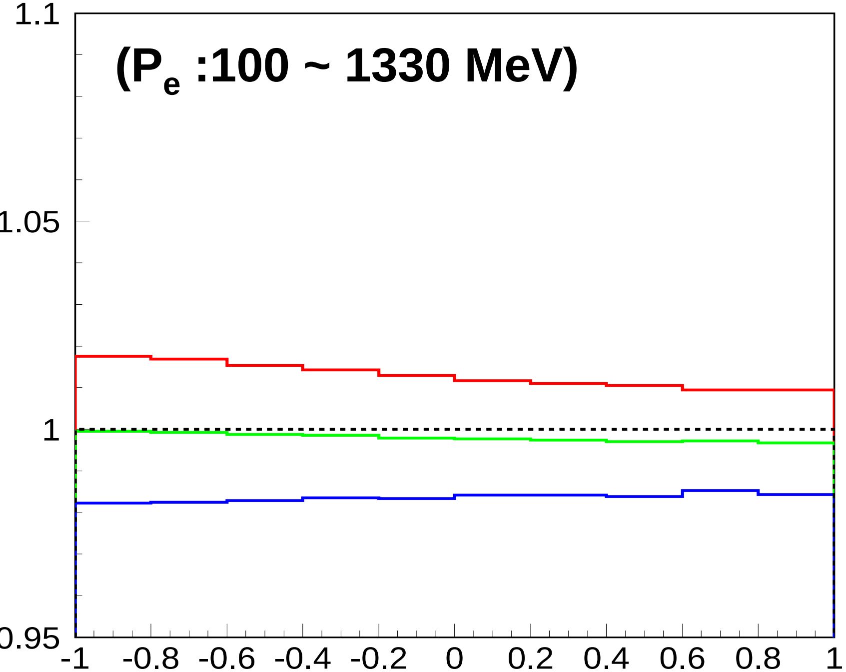
> 0 for $\cos^2\theta_{23} > 0.5$

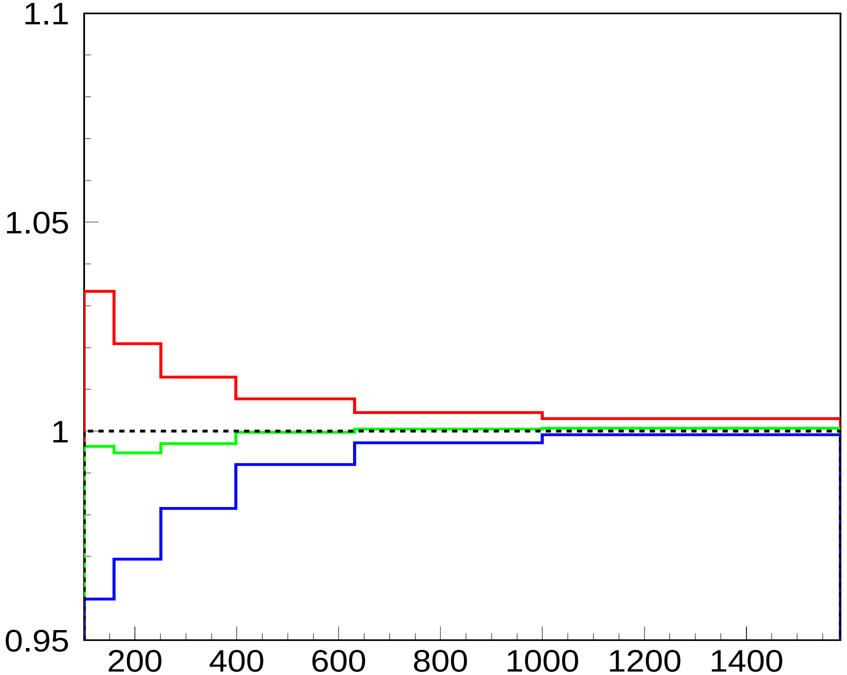
However because of the cancellation effect,
it is possible to determine the deviation from maximal θ_{23}
and octant of θ_{23}

$\sin^2\theta_{23}$ dependence

N_e(3 flavor) / N_e(2 flavor full-mixing)

sub-GeV e-like events



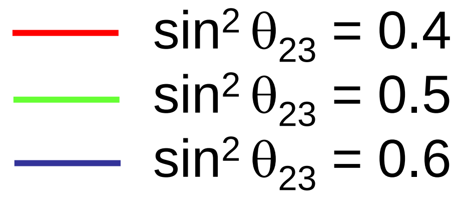


$\sin^2\theta_{13} = 0$

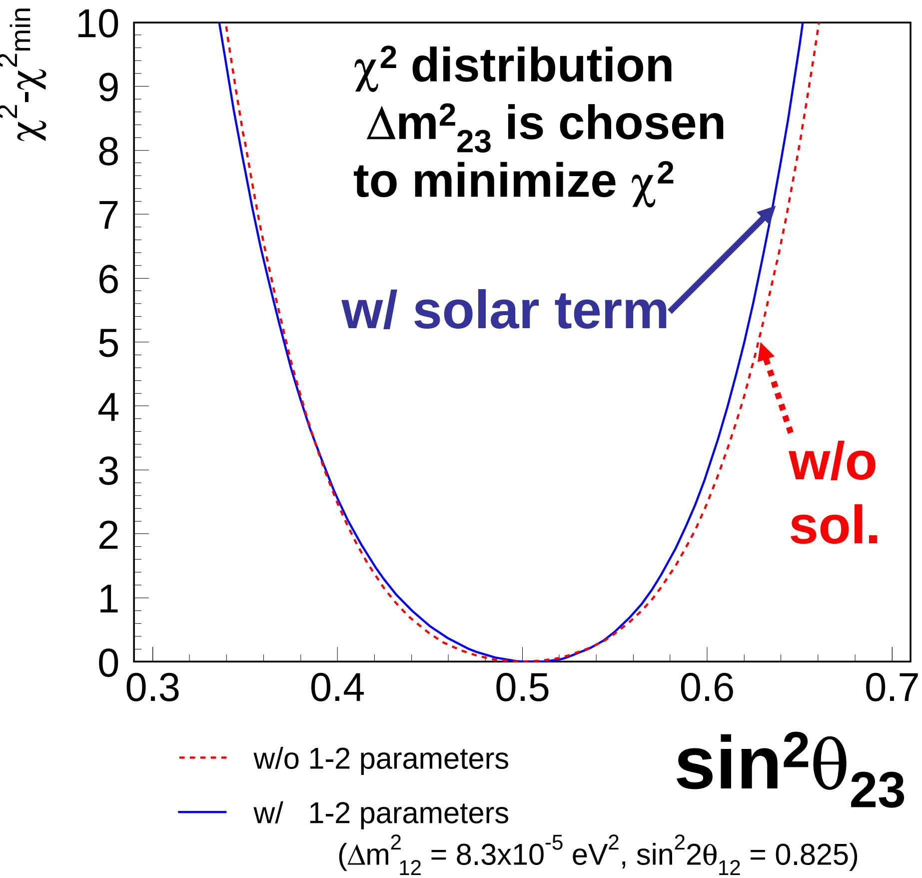
$\Delta m^2_{12} = 8.3 \times 10^{-5}\ \mathrm{eV}^2$

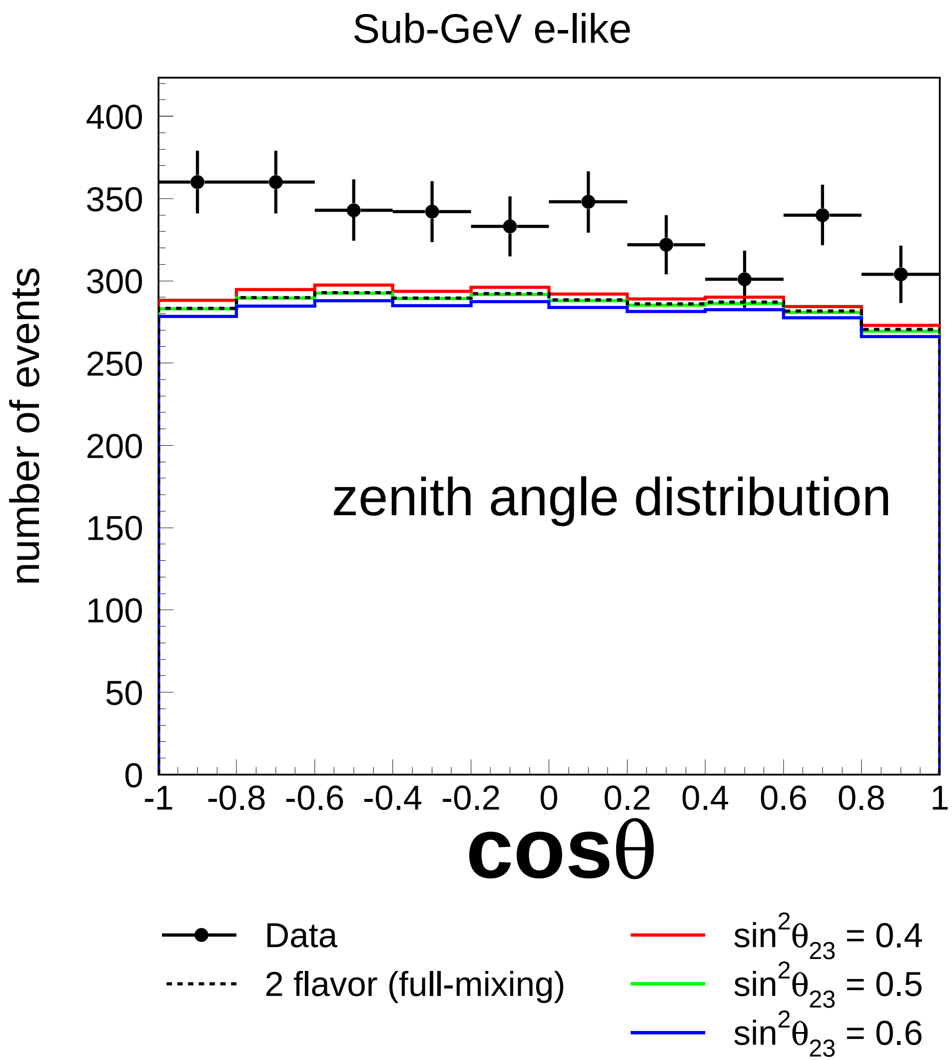
$\sin^2 2\theta_{12} = 0.83$

$(\tan^2\theta_{12} = 0.41)$



Results for the effect of the solar term

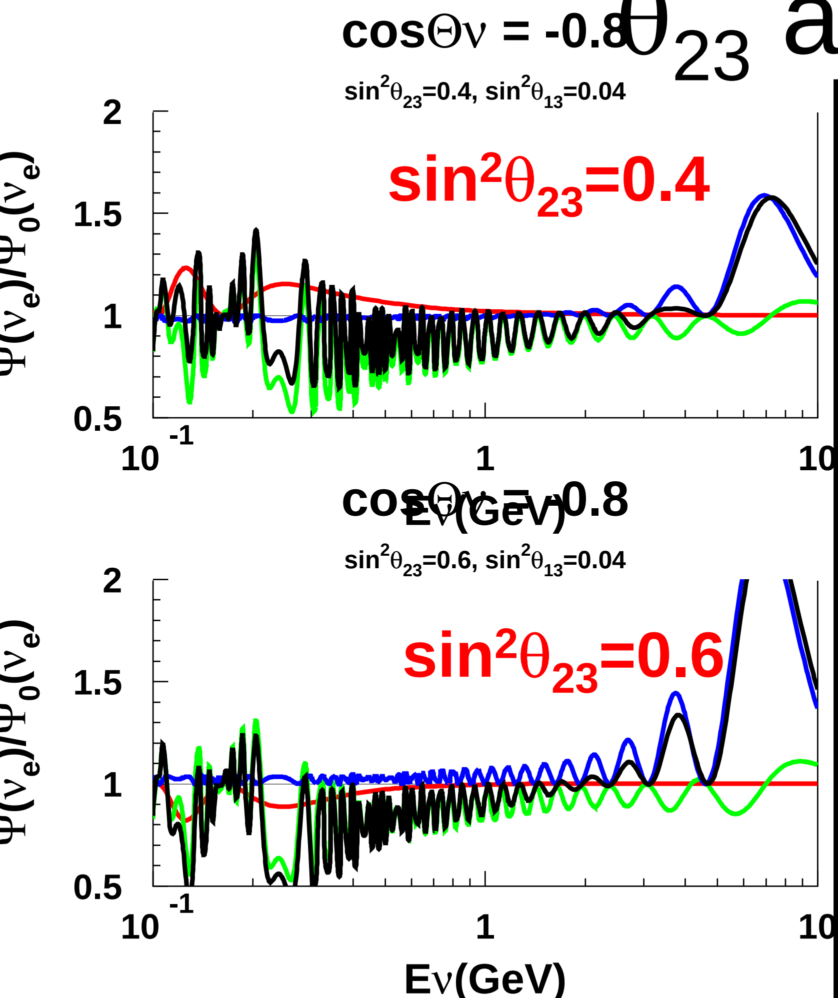


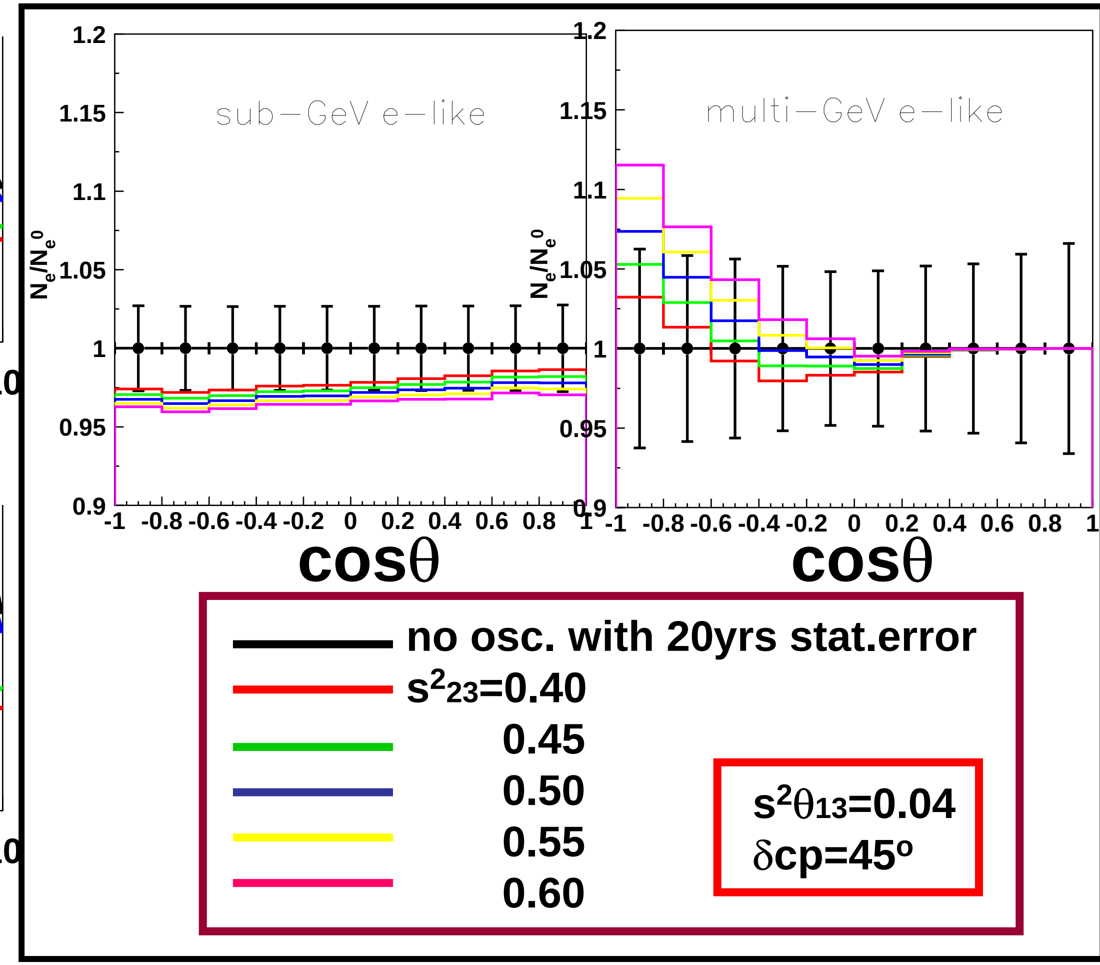


Future Possibility

- Full SK detector MC and SK reconstruction tools.
- Assuming 20 yrs of SK (or 80yrs of SK = 2 yrs of 1Mt)
- Fixed Parameters
  - $\Delta m^2_{23} = 2.5 \times 10^{-3} eV^2$ (positive)
  - $\Delta m^2_{12} = 8.3 \times 10^{-5} eV^2$
  - $\sin^2 2\theta_{12} = 0.825$
- 3 parameters in simulation
  - $\sin^2\theta_{23}$ = 0.40, 0.45, 0.50, 0.55, 0.60
  - $\sin^2\theta_{13}$ = 0.04, 0.02, 0.006, 0.00
  - $\delta_{CP} = 45^o, 135^o, 225^o, 315^o$

θ_{23} and Octant



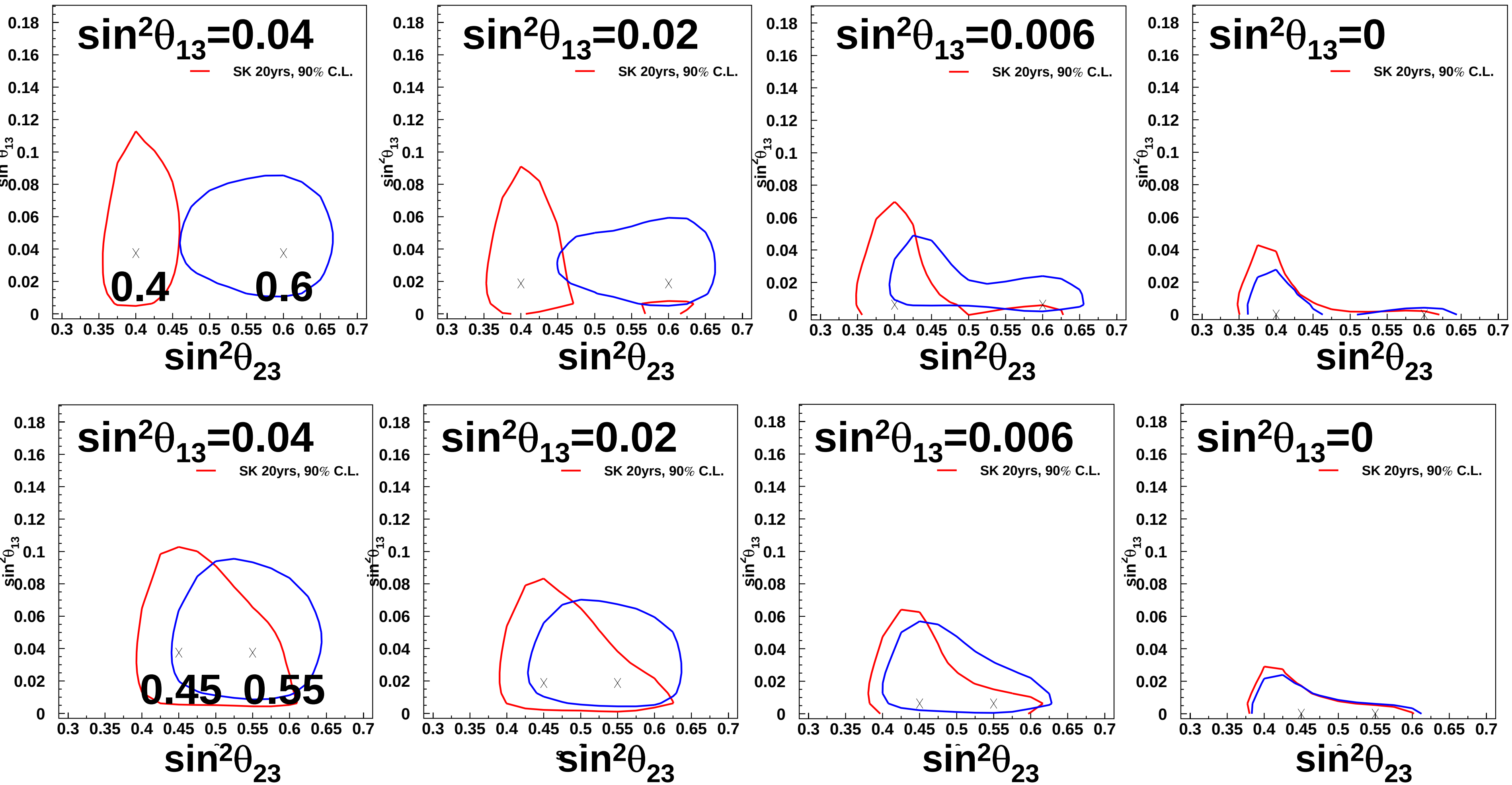


$s^2\theta_{13}=0.04$
$\delta cp=45^o$
$\cos\Theta\nu=-0.8$

- Total
- Solar term
- Interference
- θ_{13} term

Fixed
Δm^2_{23} = 2.5x10^{-3}eV^2 (positive)
Δm^2_{12} = 8.3x10^{-5}eV^2
$\sin^2 2\theta_{12}$ = 0.825

Discrimination of the θ_{23} octant

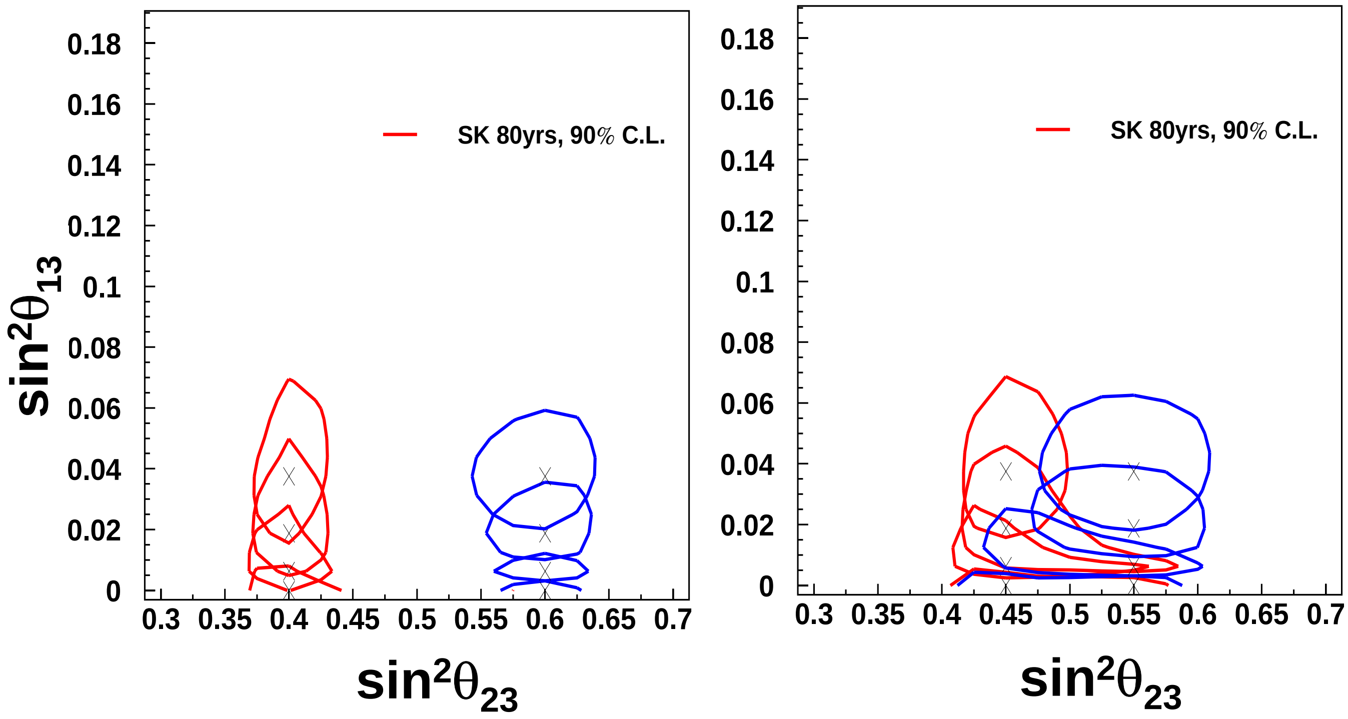


$\sin^2\theta_{23}$ = 0.40 or 0.60 ($\sin^2 2\theta_{23}$=0.96) : Possible for larger $\sin^2\theta_{13}$ for SK 20 yrs

$\sin^2\theta_{23}$ = 0.45 or 0.55 ($\sin^2 2\theta_{23}$=0.99) : Difficult for SK 20 yrs

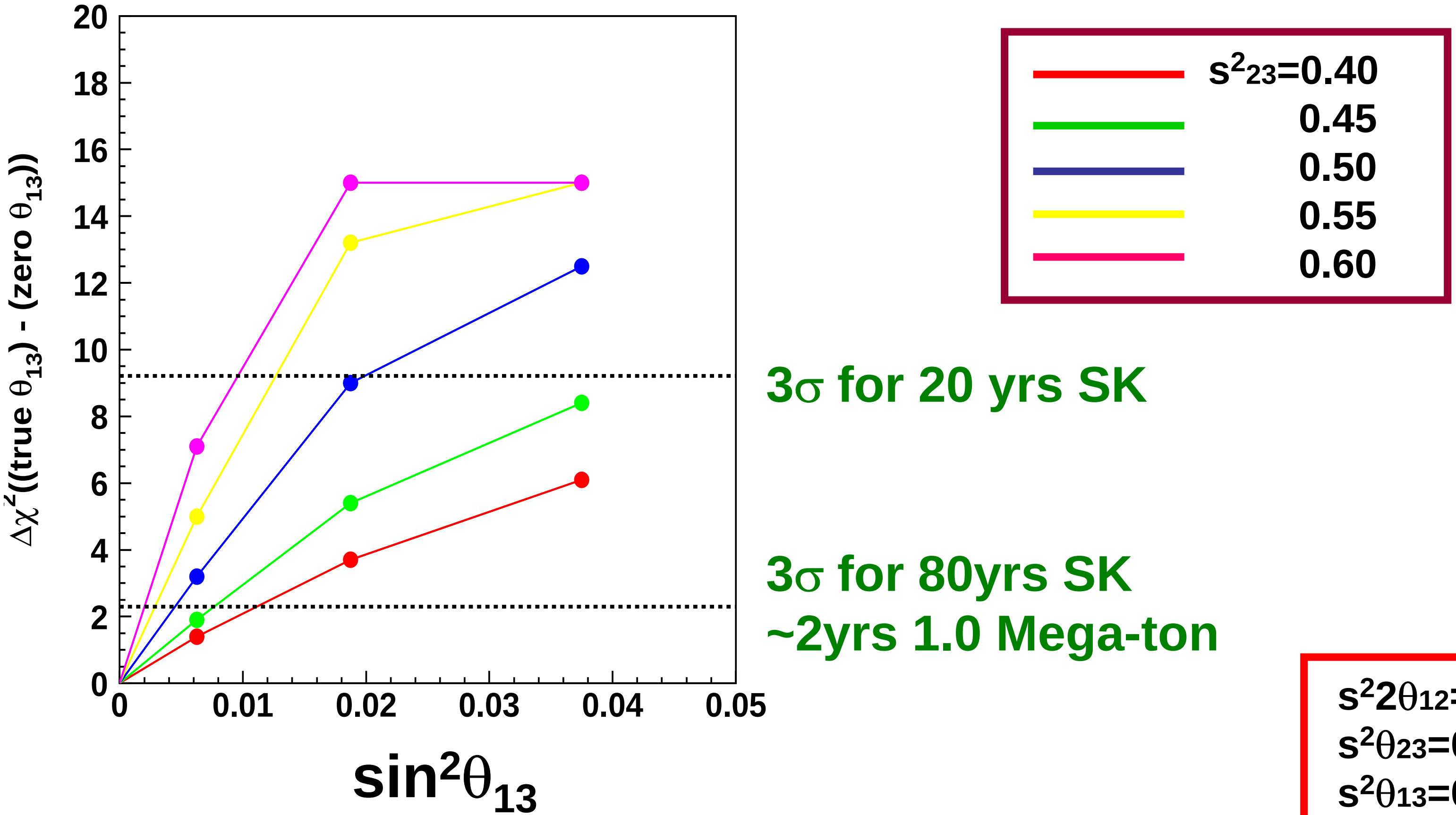
80yrs SK ~ 2yrs 1 mega-ton(fid)

$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.40 ~ 0.60
$s^2\theta_{13}$=0.00~0.04
$\delta cp=45^o$
$\Delta m^2_{12}=8.3x10^{-5}$
$\Delta m^2_{23}=2.5x10^{-3}$



With 80yrs SK, discrimination is possible for many parameter combinations

Non-zero θ_{13}



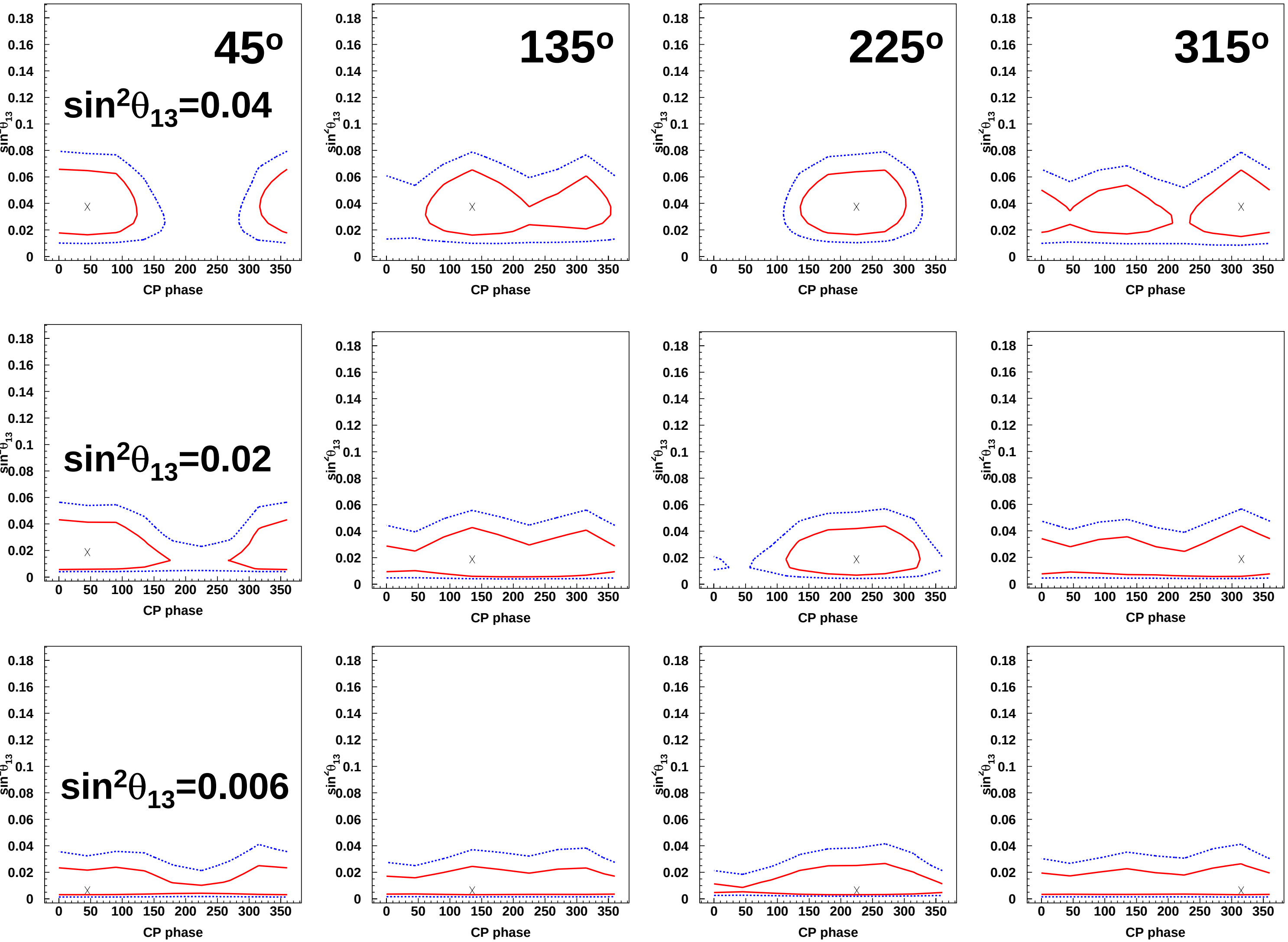
3σ for 20 yrs SK

3σ for 80yrs SK
~2yrs 1.0 Mega-ton

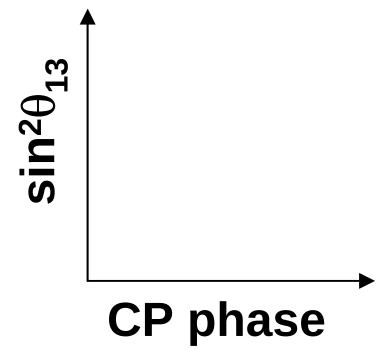
$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.40 ~ 0.60
$s^2\theta_{13}$=0.00~0.04
δcp=45°
Δm^2_{12}=8.3x10^{-5}
Δm^2_{23}=2.5x10^{-3}

Positive non-zero θ_{13} can be observed
for large θ_{13} (>(1/2)CHOOZ) and $\sin^2\theta_{23} \geq 0.5$

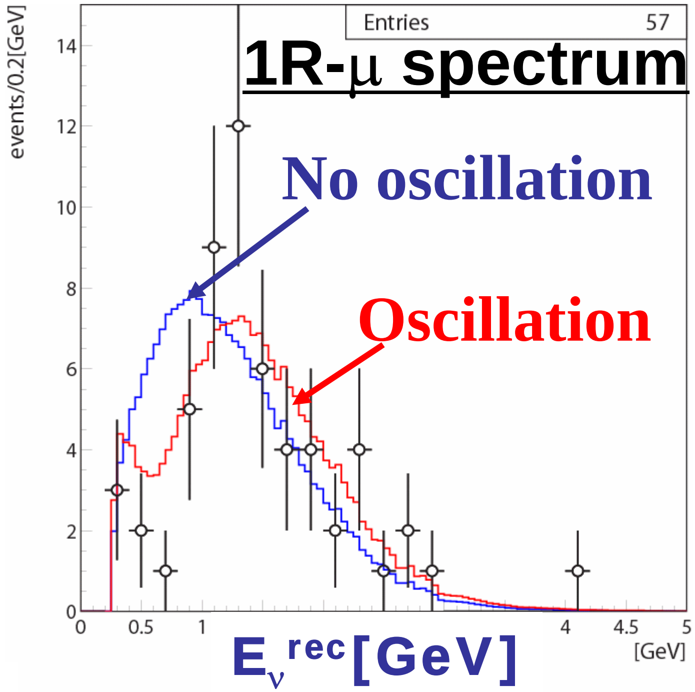
CP phase (2yrs of 1 Mega ton detector)

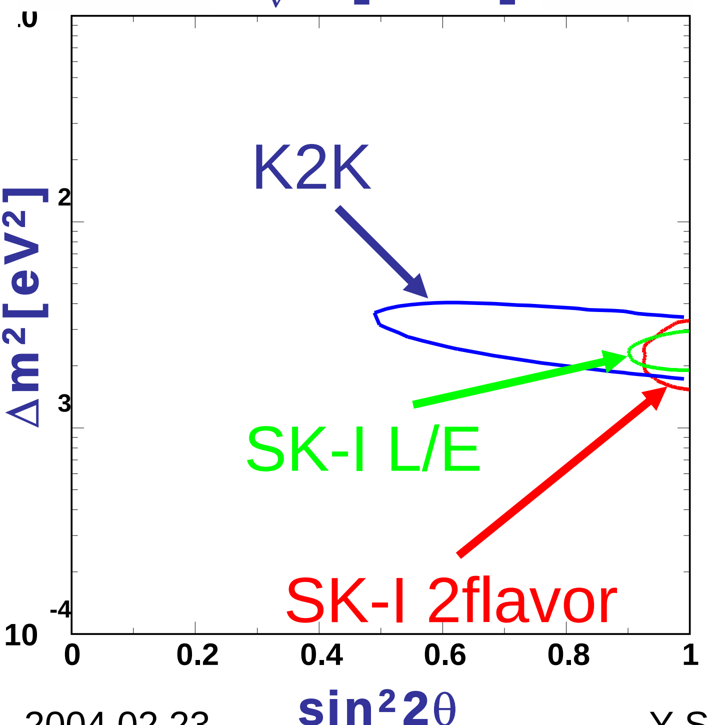


$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.5
$s^2\theta_{13}$=0.006~0.04
δcp=0°~360°
$\Delta m^2_{12}=8.3\times10^{-5}$
$\Delta m^2_{23}=2.5\times10^{-3}$



CP phase could be seen if θ_{13} is close to the CHOOZ limit.





K2K summary

- 8.9×10^{19} P.O.T.
  - Observed : 107 events
  - Expected : 150.9 $^{+11.5}_{-10.1}$ $\left(^{+7.7\%}_{-6.7\%}\right)$

Best fit:

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

Best in physical resion

$\sin^2 2\theta = 1.00$: $\Delta m^2 = 2.79 \times 10^{-3} eV^2$

Allowed region of Δm^2 @$\sin^2 2\theta = 1$

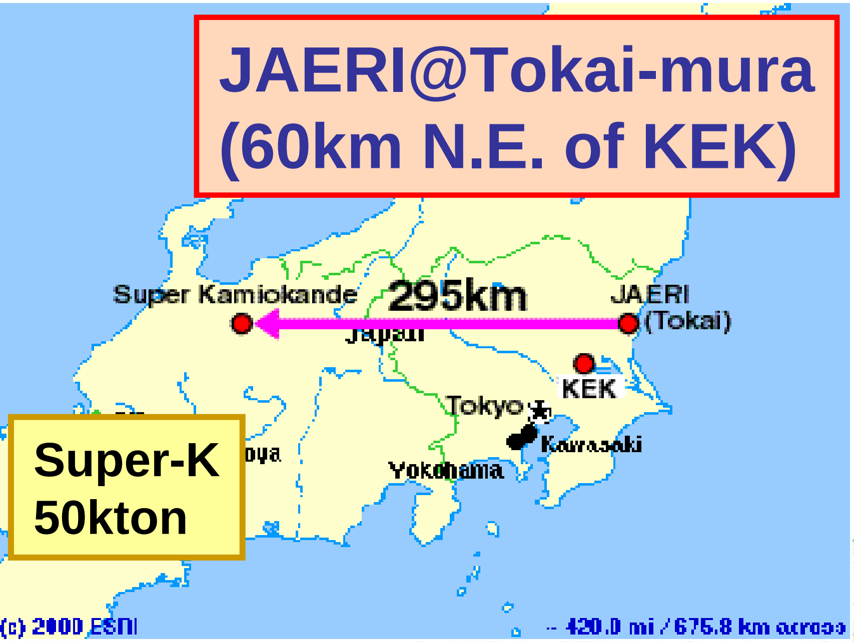
$1.9 \sim 3.6 \times 10^{-3}$ eV^2 (90%)

Null Oscillation Probability

number of events	0.26%
Spectrum	0.74%
Combined	0.005% (4.0σ)

Confirmation of the oscillation
Consistent with the Atm-ν oscillation

Long baseline neutrino oscillation experiment from Tokai to Kamioka （T2K） (~100xK2K)

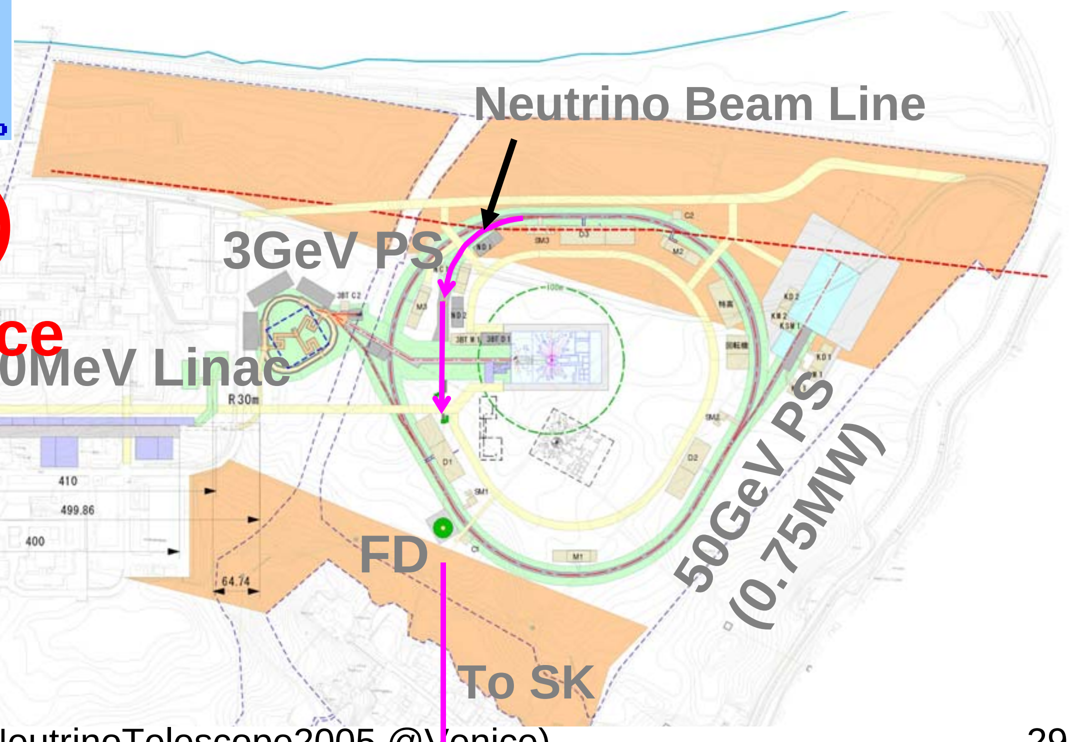


- J-PARC (50 GeV PS)
  - Construction: 2001~2007
  - Operation: 2008~
- T2K (Approved in Dec-03)
  - Construction: 2004~2008
  - Experiment: 2009 ~

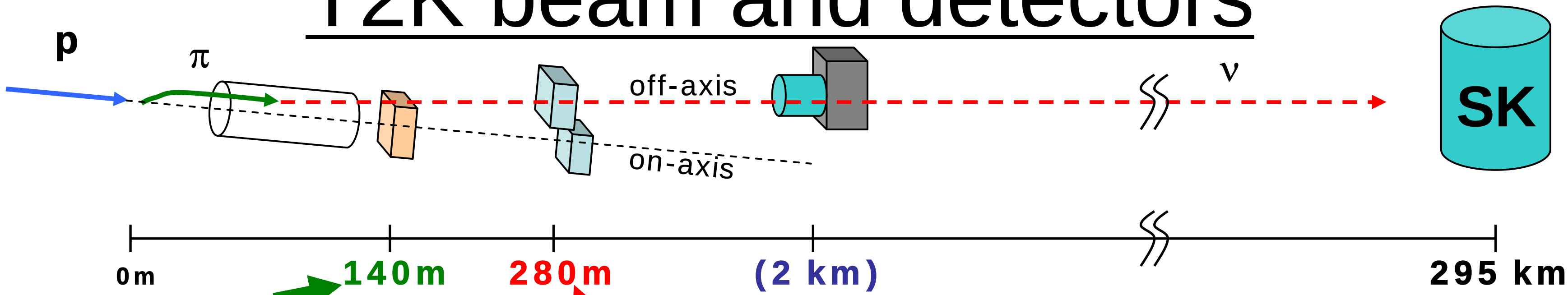
Phase 1 (0.75MW + SK)

- $\nu_\mu \rightarrow \nu_x$ disappearance
  - Precise Δm^2, $\sin^2 2\theta$
- $\nu_\mu \rightarrow \nu_e$ appearance
  - Finite θ_{13} ?

Phase 2 → Nakaya's Talk

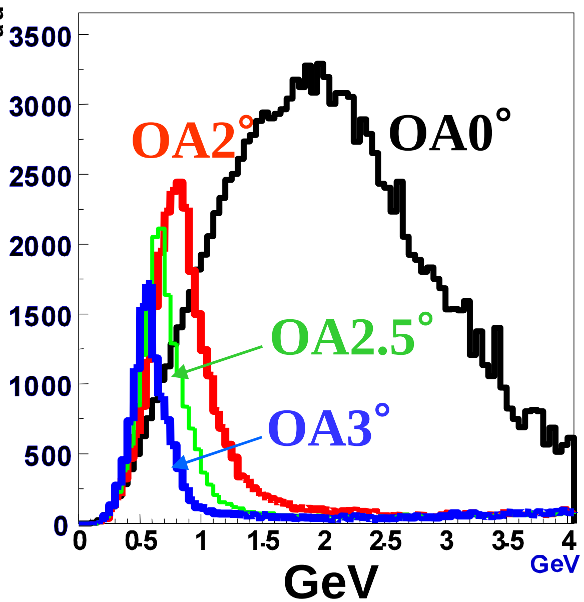


T2K beam and detectors



Muon monitor
spill by spill monitor

Off Axis Beam

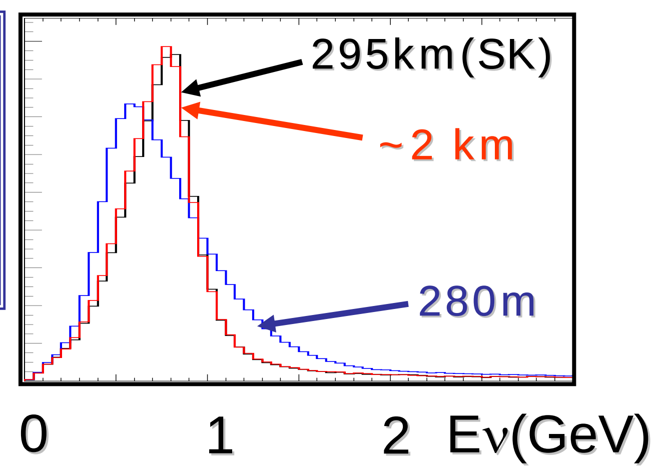


Quasi Monochromatic
2~3 times intense than NBB
Can be tuned at oscill. max.

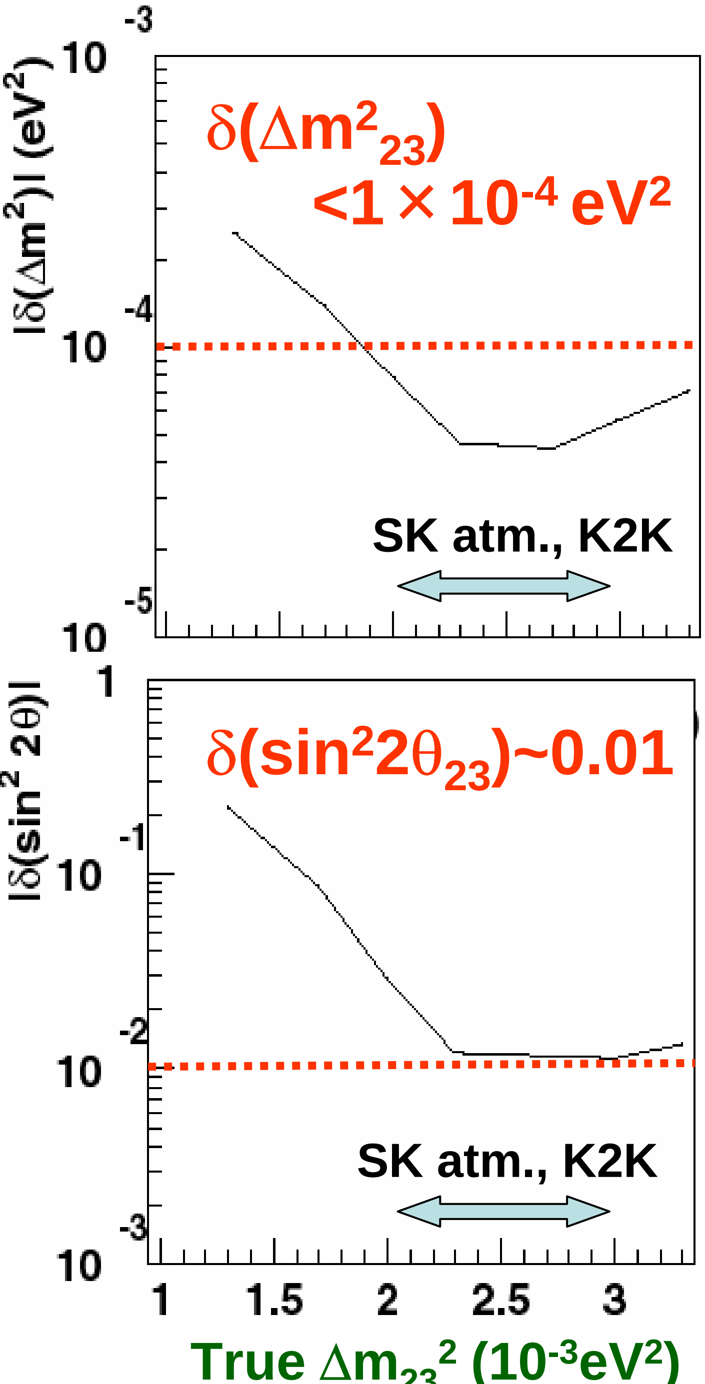
Near (280m) detector
on-axis: ν beam direction
off-axis: ν spectrum

2km detector
Eν spectrum
for better Far/Near
not approved yet

Statistics at SK
(OAB 2.5 deg,
5 yr, 22.5 kt)
~ 11,000 ν_μ tot
~ 8,000 ν_μ CC
ν_e ~0.4%
at ν_μ peak



Accuracy of θ_{23} , Δm_{23}



Both statistical (5yr operation) and expected systematic errors

Normalization	5%
nonQE/QE	5%
E scale	1%
Spectrum shape	20%
Spectrum width	5%

Current Accuracy from Atm-ν

$\delta(\Delta m^2_{23})$ ~$1\text{x}10^{-3}$ eV^2

$\delta(\sin^2 2\theta_{23})$ ~0.1

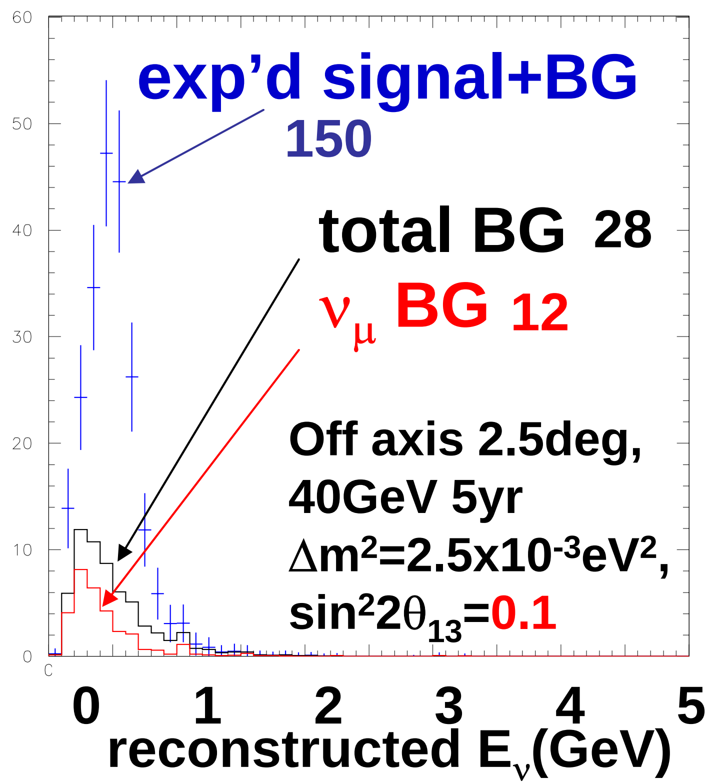
Sensitivity to θ_{13}

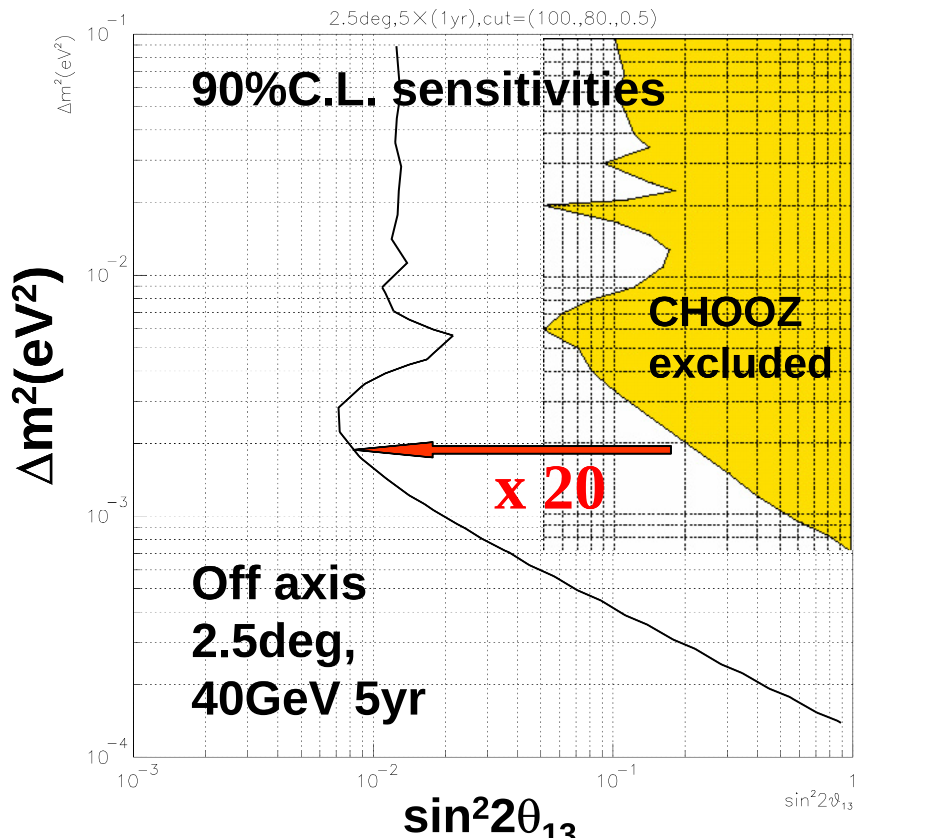
Signal: Single-R e-like (CC QE events)

BG: beam contained ν_e, Mis-reconstructed π^0

Selections:

- Single R elike, Evis > 100 MeV
- No decay-e
- E_ν^{rec} =0.35 ~ 0.85 GeV
- $\cos\theta_{\nu e}$ <0.9
- π^o-filter

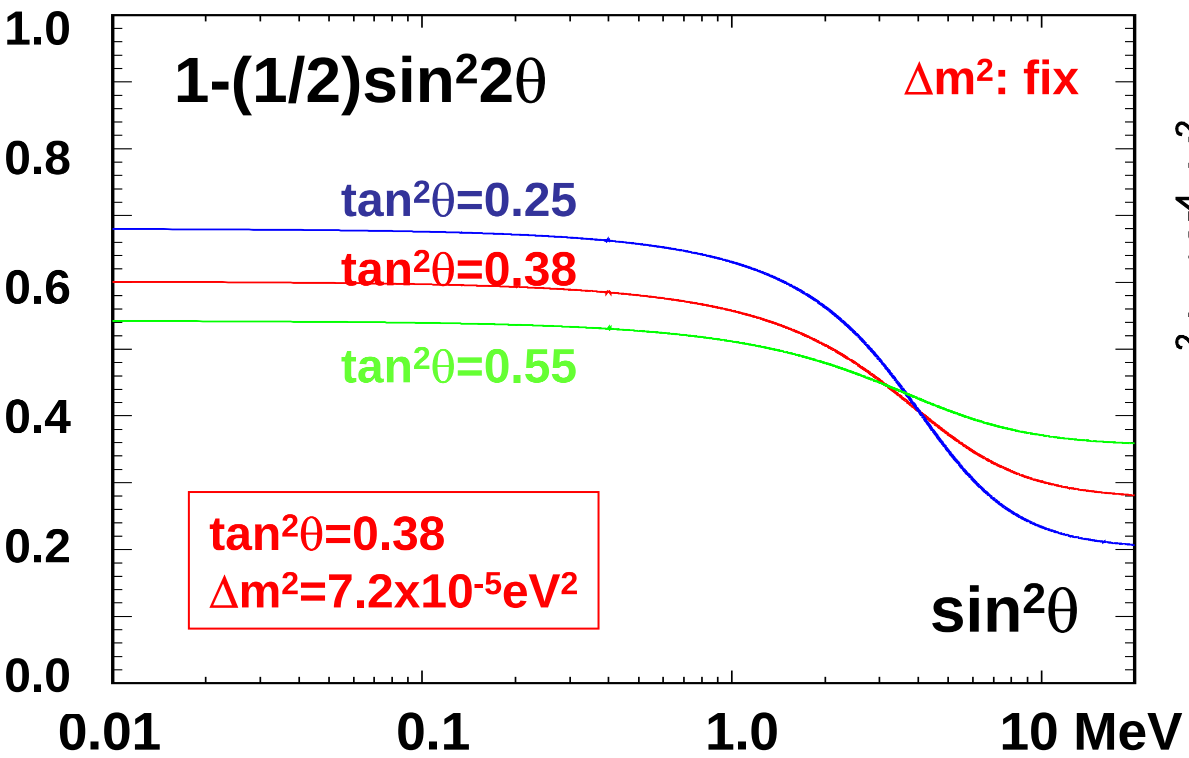


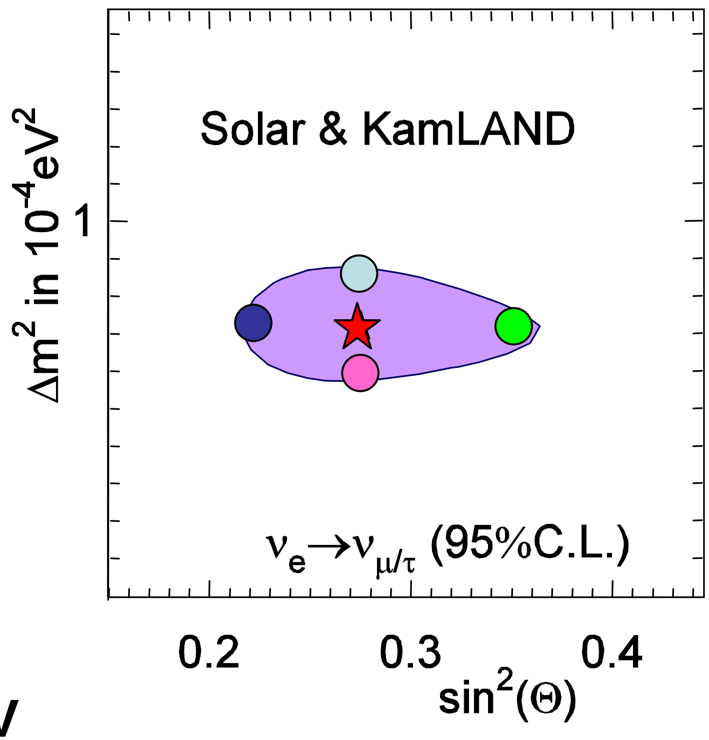


Solar LMA solutions

E <1 MeV: Vacuum $\theta_m \rightarrow \theta_V$ **➔ *P=1-(1/2)sin²2θ***

E >a few MeV: Adiabatic $P=\cos^2\theta\cos^2\theta_m+\sin^2\theta\sin^2\theta_m$ **➔ *P=sin²θ*** **($\theta_m \rightarrow \pi/2$)**





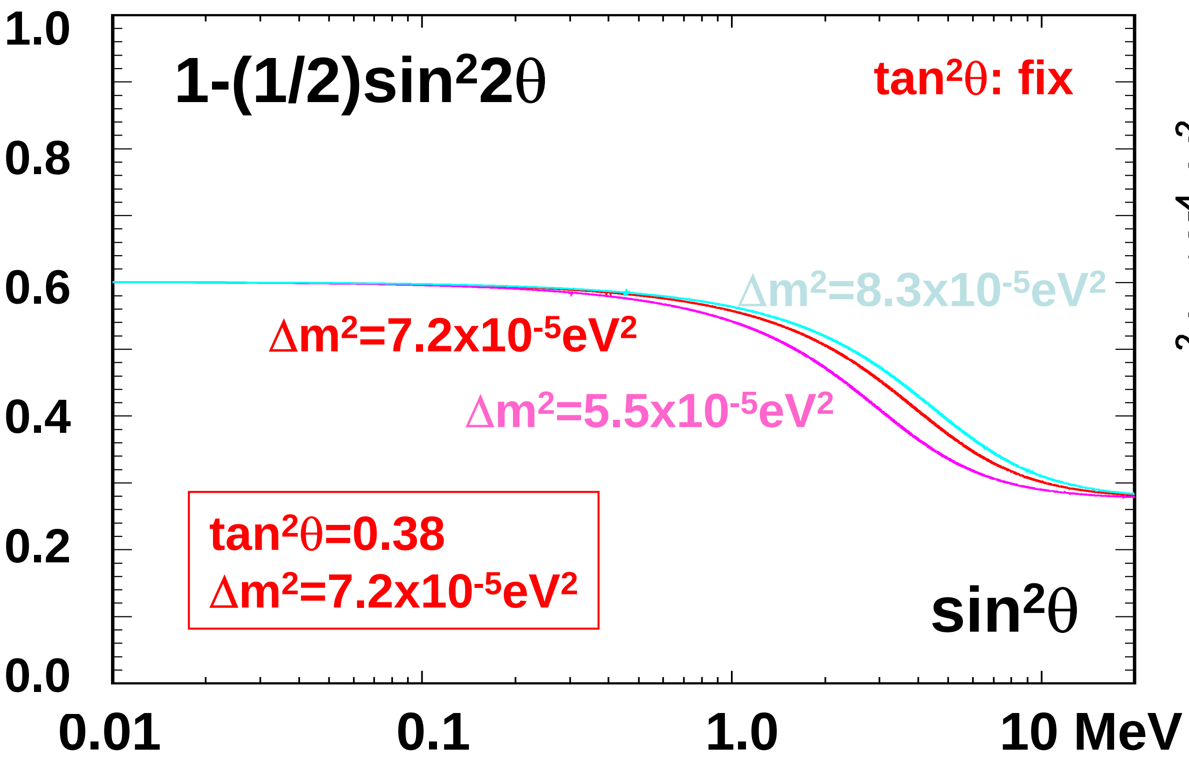
^8B spectrum measurement
→ low energy upturn (depends on θ_{12})

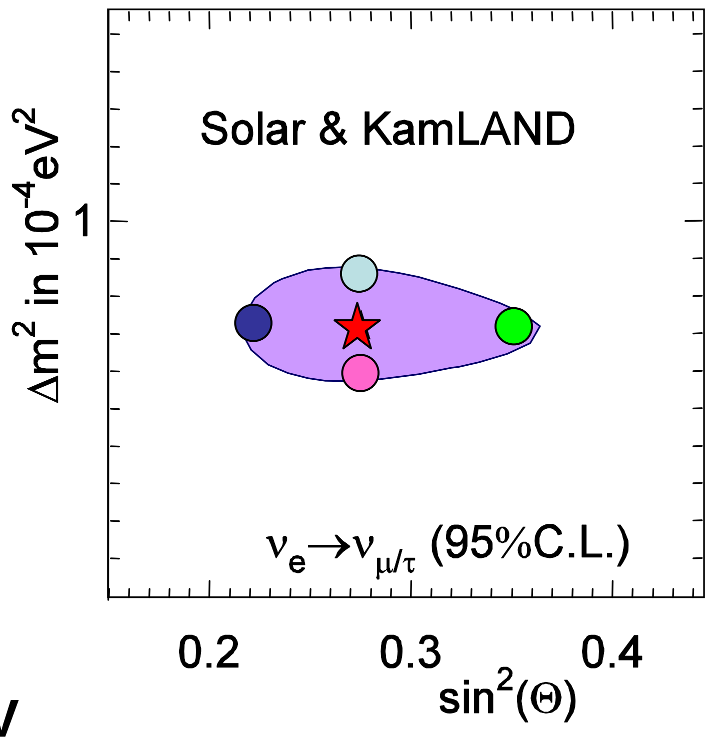
Solar LMA solutions

E <1 MeV: Vacuum $\theta_m \rightarrow \theta_V$ → $P=1-(1/2)\sin^2 2\theta$

E >a few MeV: Adiabatic $P=\cos^2\theta\cos^2\theta_m+\sin^2\theta\sin^2\theta_m$ → $P=\sin^2\theta$

($\theta_m \rightarrow \pi/2$)

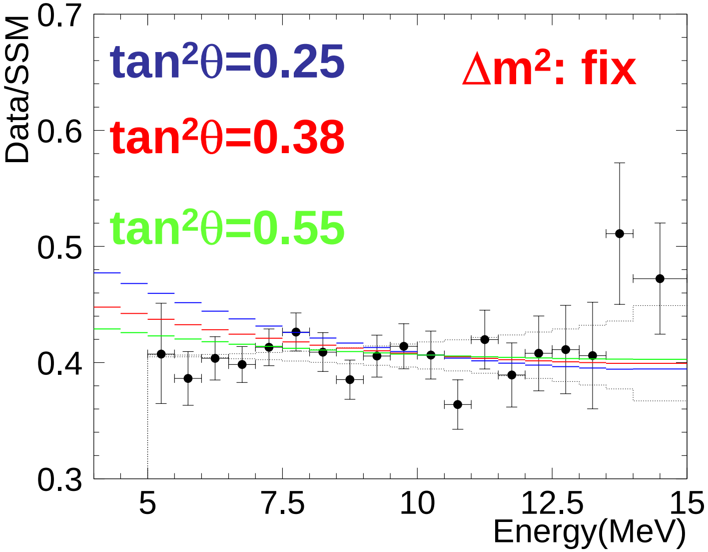


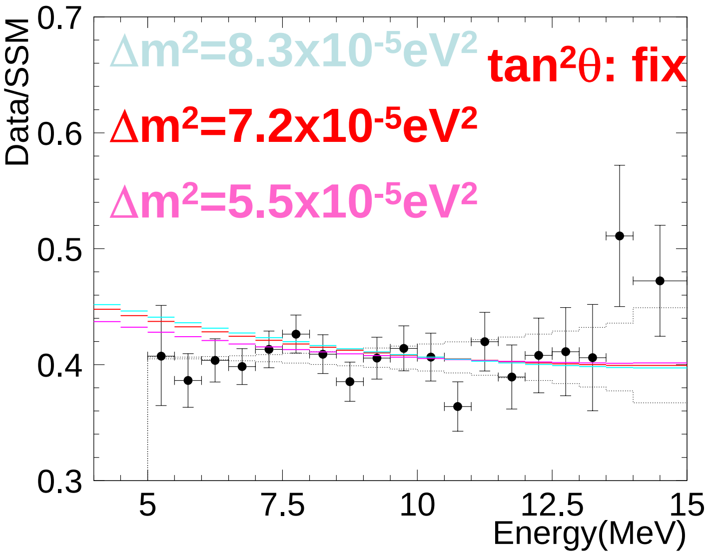


effect of different Δm^2 → small difference in the upturn

Expected low energy upturn

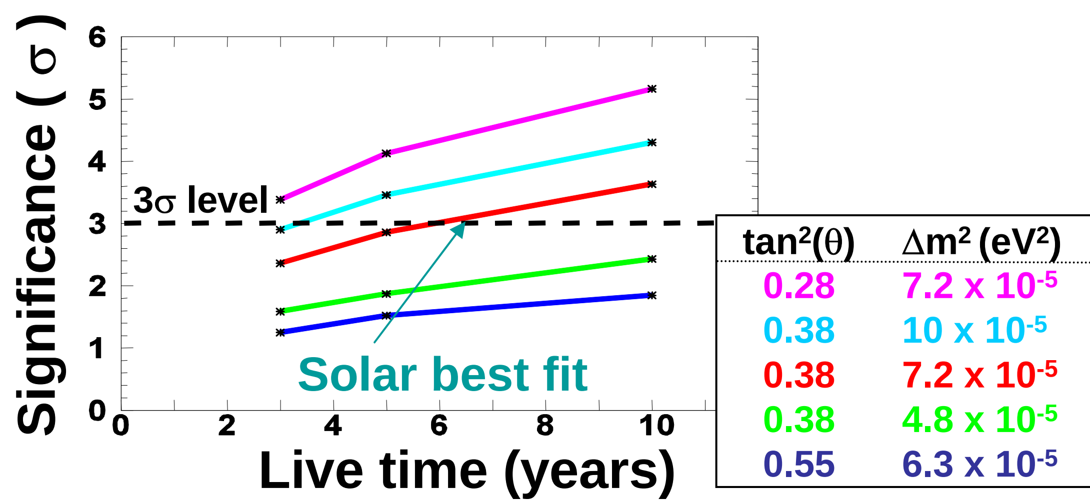
$\tan^2\theta=0.38$
$\Delta m^2=7.2\times10^{-5}eV^2$



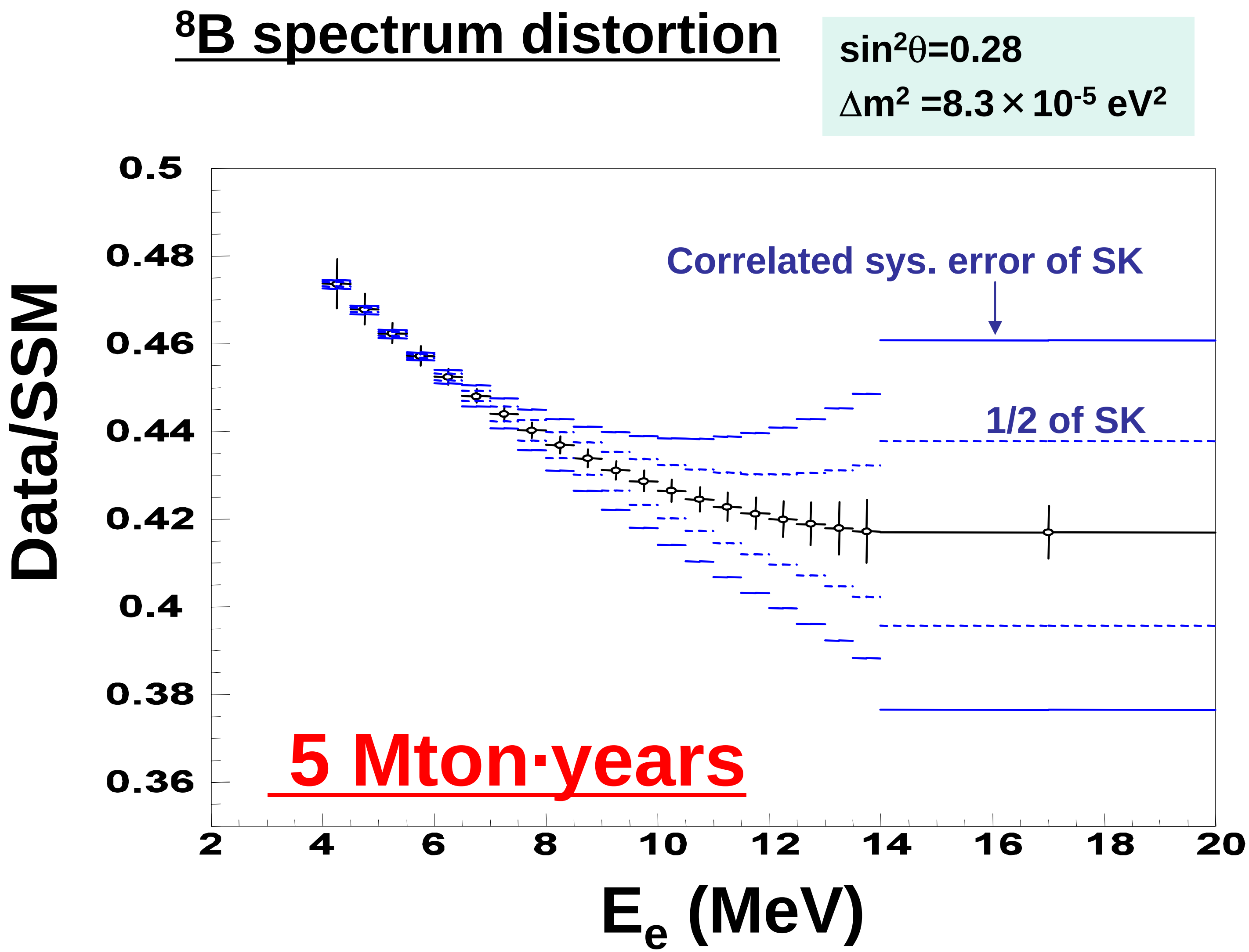


~10% upturn should be seen in future

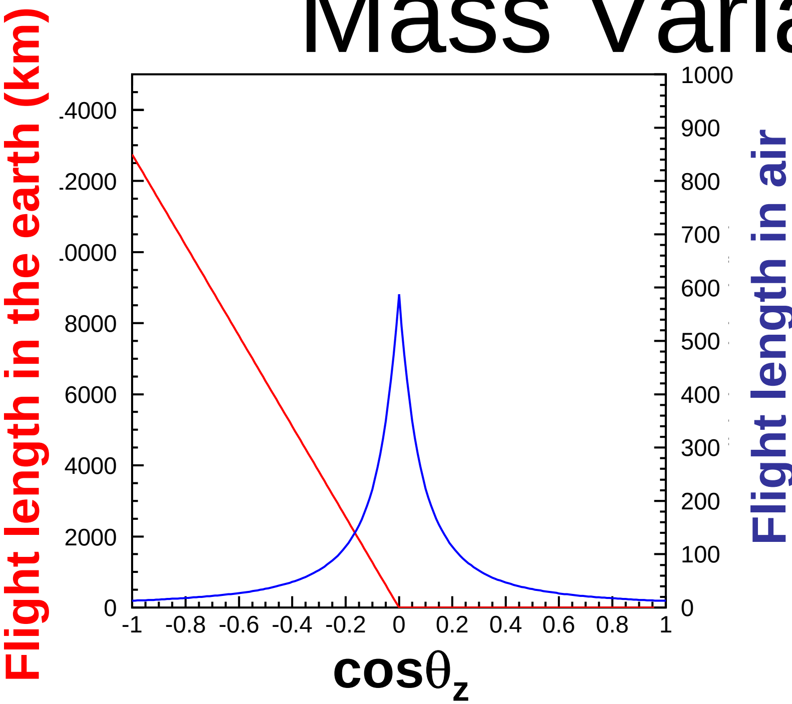
Correlated sys. error: x 0.5
4.0-5.5MeV background: x 0.3
(same BG as SK-I above 5.5MeV)
Energy Calib. (~±0.4%)
Better ^8B spectrum shape

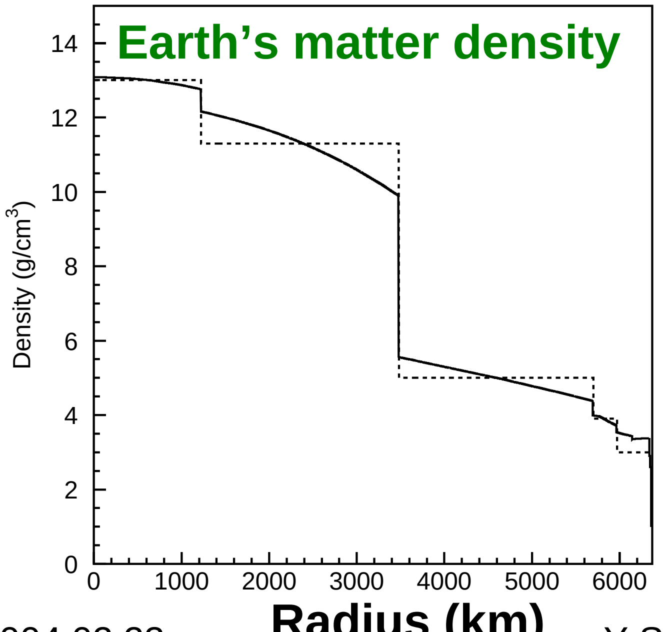


Sensitivity of the spectrum for Mton detector



Mass Variable Neutrinos？





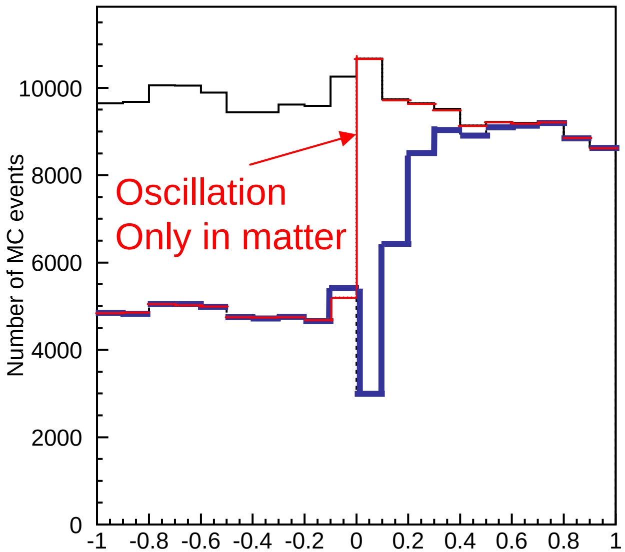
- Is Neutrino oscillation sensitive to the density dependent neutrino mass?
- Quick & dirty check:
  - No mass in vacuum
  - Finite mass in matter

    (no density dependence)

- Horizontal direction has most path in vacuum (air)

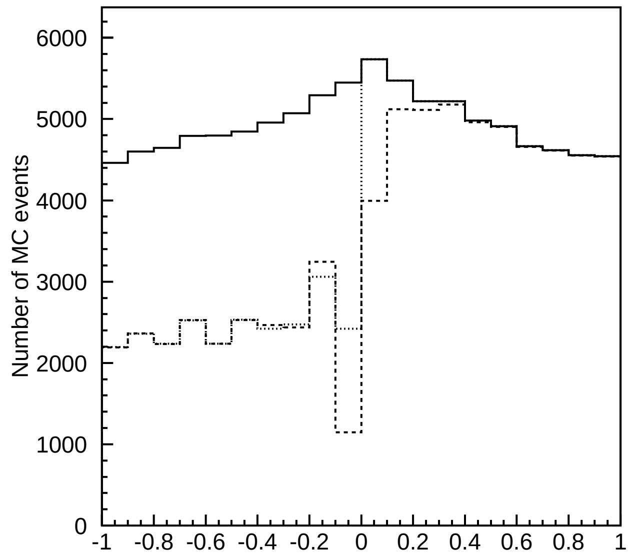
Zenith angle distribution of neutrinos

0.5 < Eν < 1.5 GeV



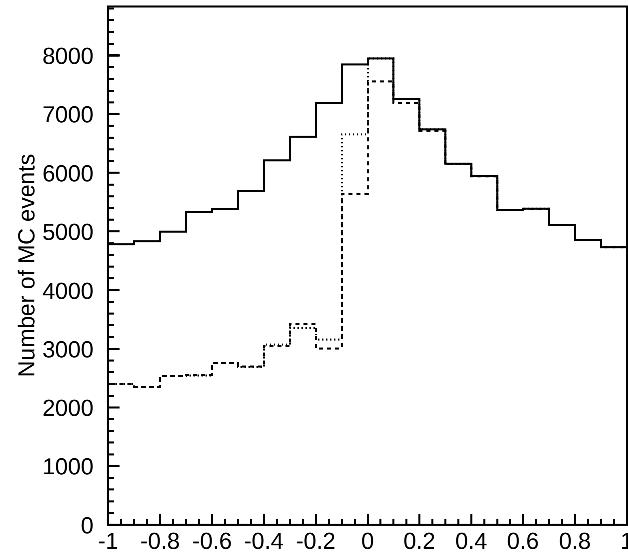
$\cos\theta_z$

1.5 < Eν < 3.0 GeV



$\cos\theta_z$

Eν < 3.0 GeV



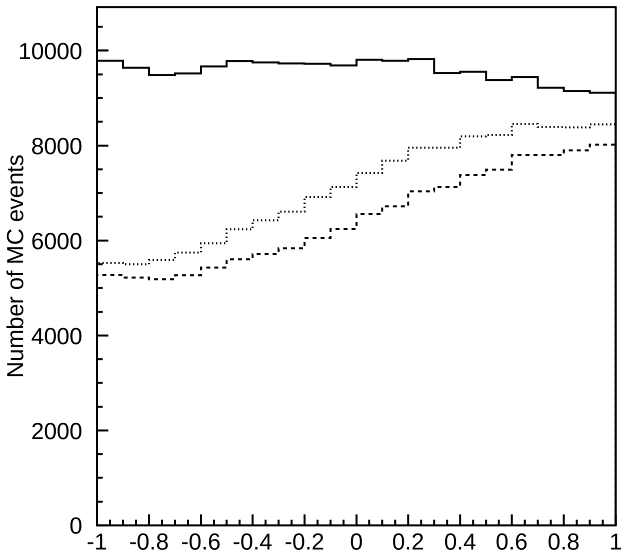
$\cos\theta_z$

Difference is seen

- Low energy region (< 3 GeV)
- Horizontal direction

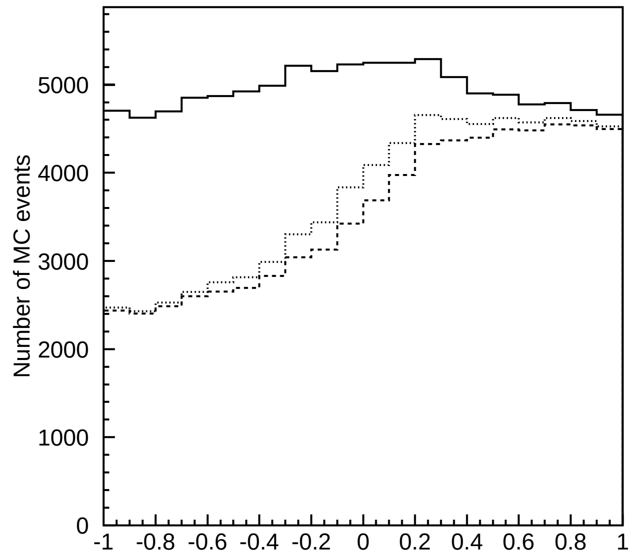
Zenith angle distribution of muons

0.5 < Eν < 1.5 GeV



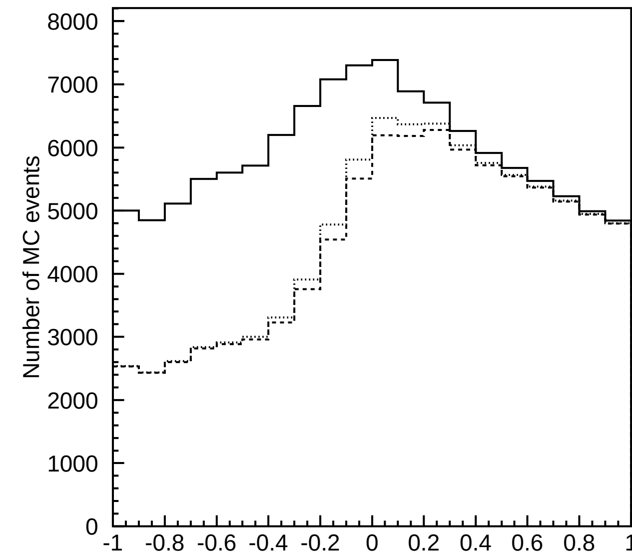
cosθ$_z$

1.5 < Eν < 3.0 GeV



cosθ$_z$

c **Eν < 3.0 GeV**



cosθ$_z$

Discrimination may be possible

→ Wait for a real analysis based on SK data