SK　大気ニュートリノ

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大気ニュートリノ観測データ

- SK-I ~15,000 events (1996/5~2001/7)
- SK-II ~ 2,700 events (2003/1~2004/2)

One of main tools to explore neutrino sector

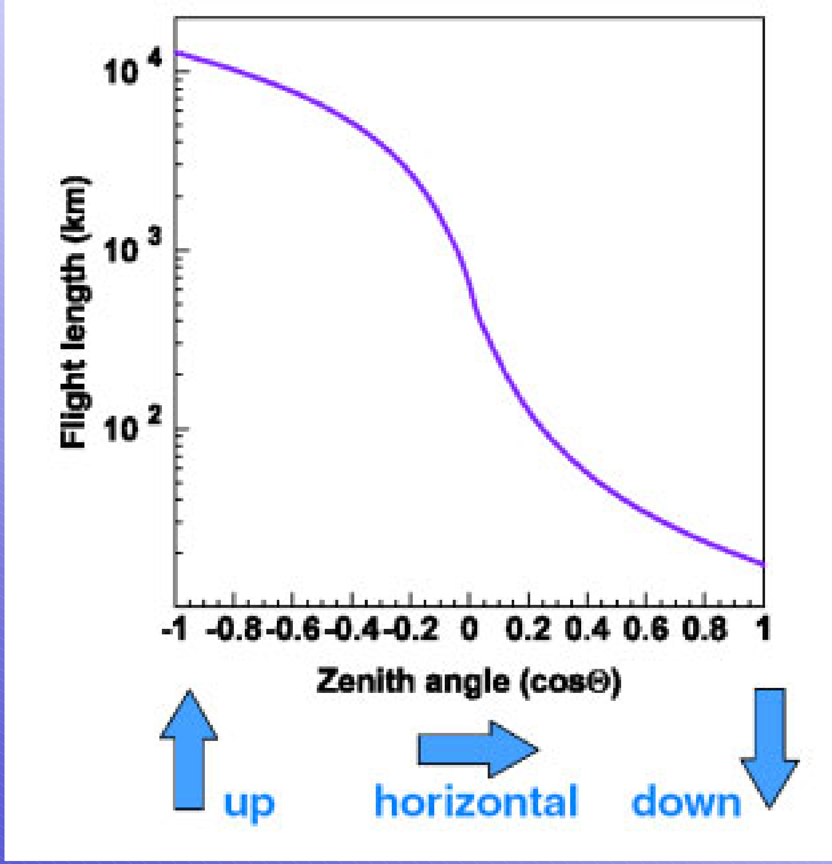
- **measurements of $\theta 23$ and $\Delta m^2 23$** ---- **paper almost ready**
- **L/E analysis** ---- **hep-ex/0404034**
  - **observing "oscillations" and test of various alternative hypotheses**
- **$\nu\tau$ appearance** ---- **under study**
- **3-flavor analysis** ---- **preliminary results**
  - **nonzero $\theta 13$?**
  - **$\Delta m^2 23$(normal) or $\Delta m^2 23<0$(inverted)**
- **mixing with sterile ν**
- **CPT violation test**
- **Exotic scenarios (ν decay, LxE etc.)**

} **papers in progress**

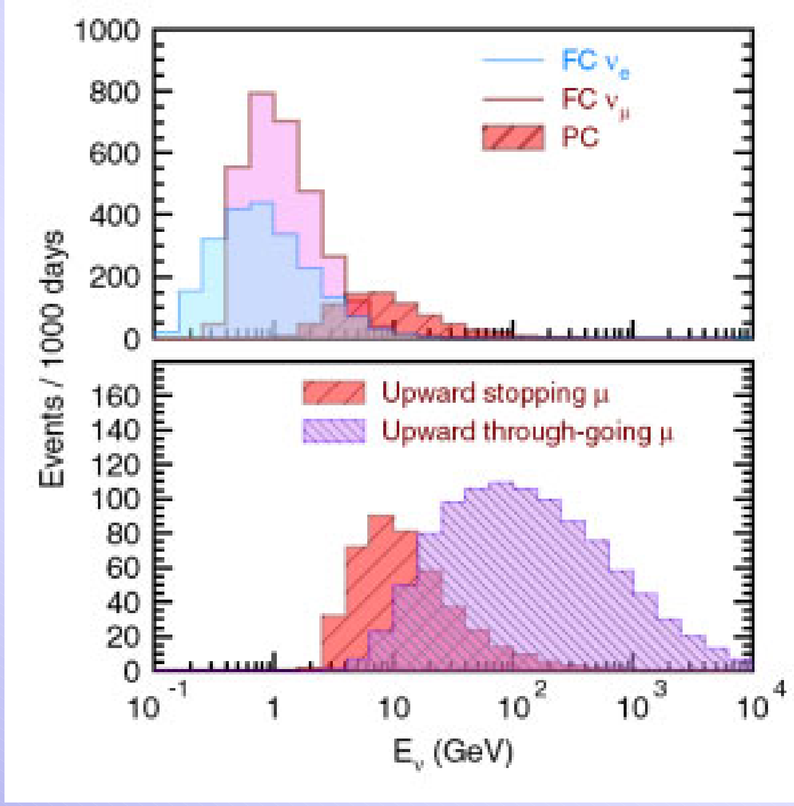
Neutrino oscillations in atmospheric ν

$$P(\nu\mu \rightarrow \nu\tau) = \sin^2 2\vartheta \sin^2\left(\frac{1.27\times\Delta m^2(eV^2)\times L(km)}{E_\nu(GeV)}\right)$$

L(path length)=10~13000km
3 decades

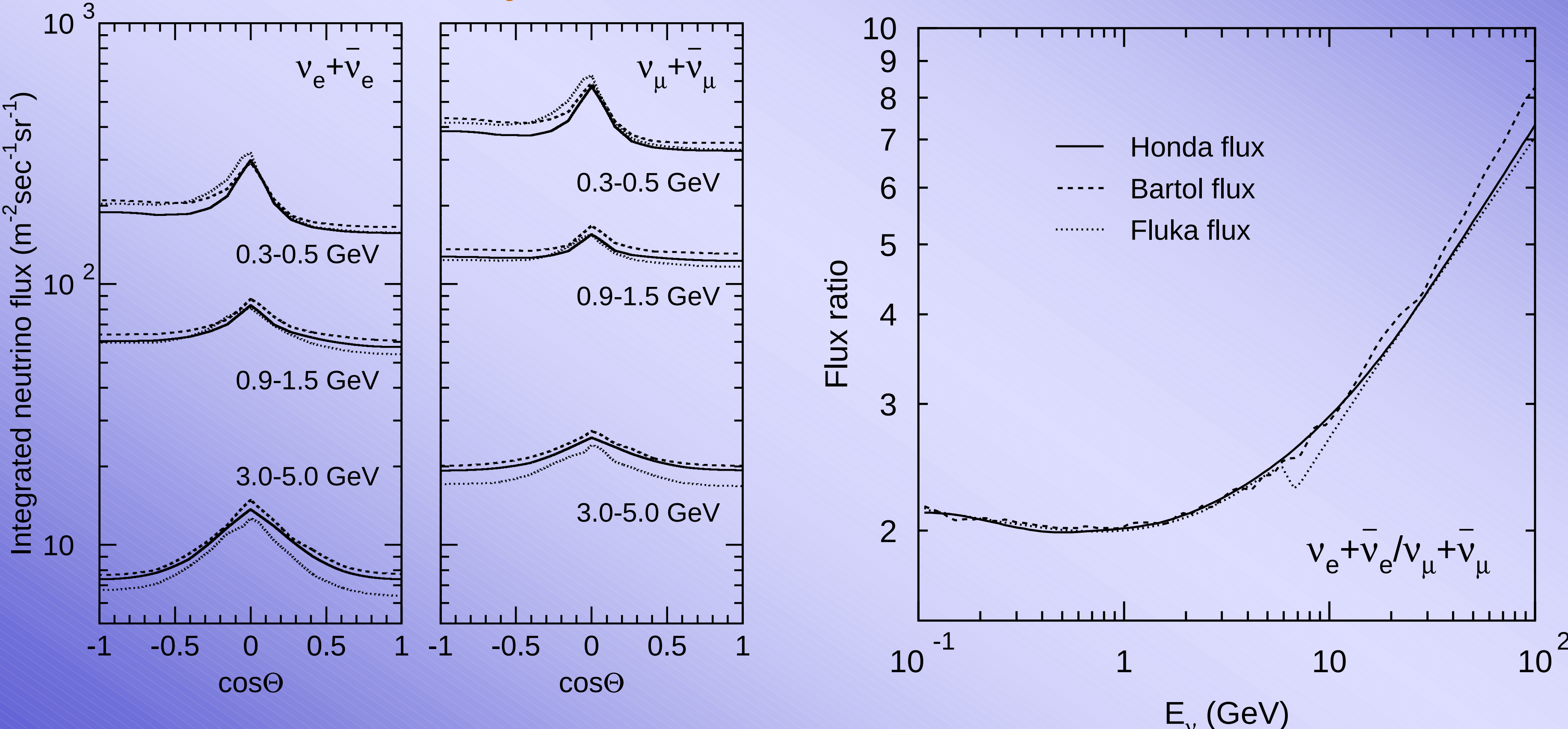


E(ν energy)=100MeV~10TeV
5 decades



Flux calculations

3D MC calculation of neutrino flux w/ taking into account
- measured primary flux
- geomagnetic effect
- solar activity

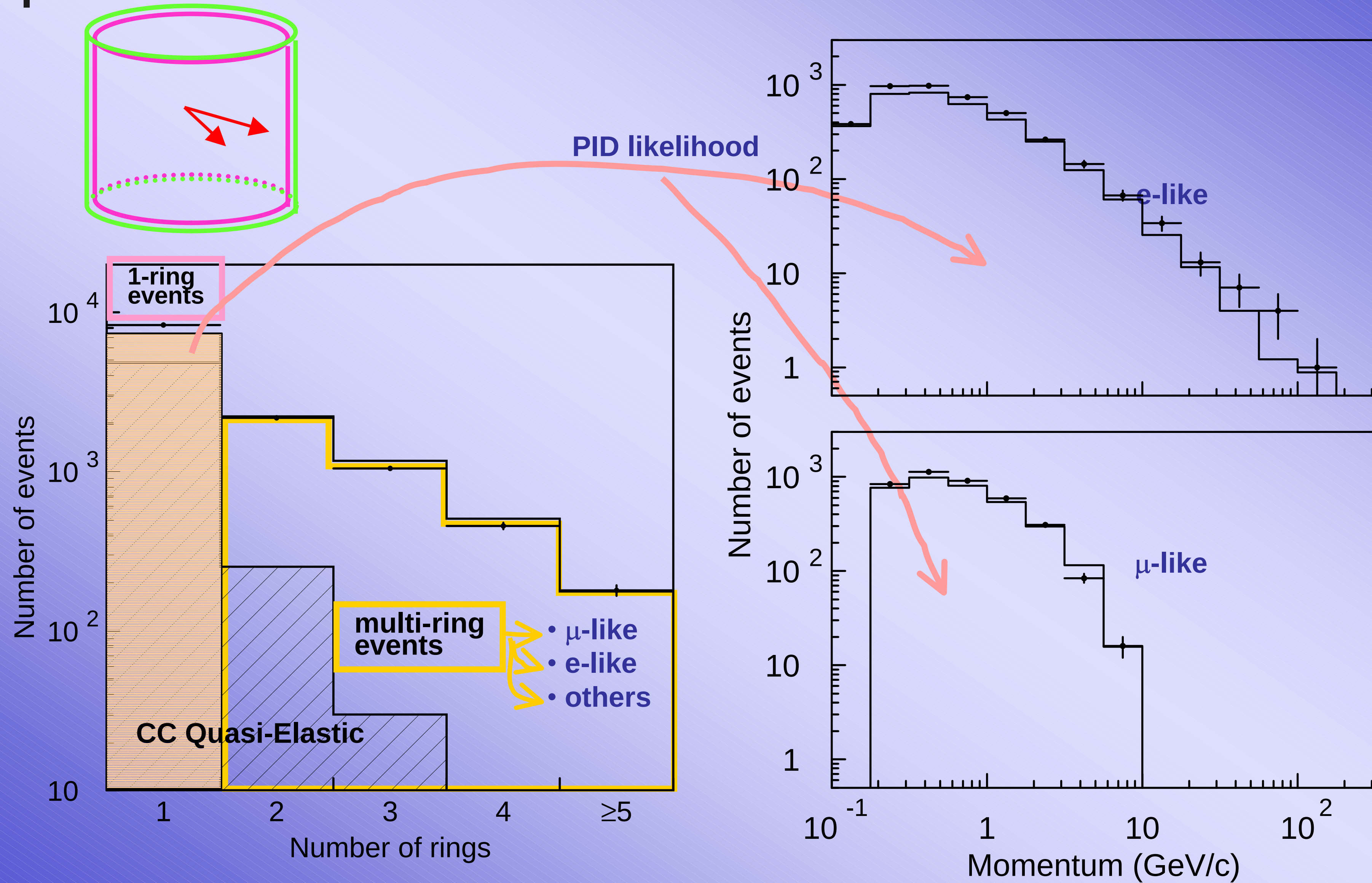


Up/down symmetric above a few GeV

νμ/νe uncertainty is better than 5%

Event category 1 (fully contained events)

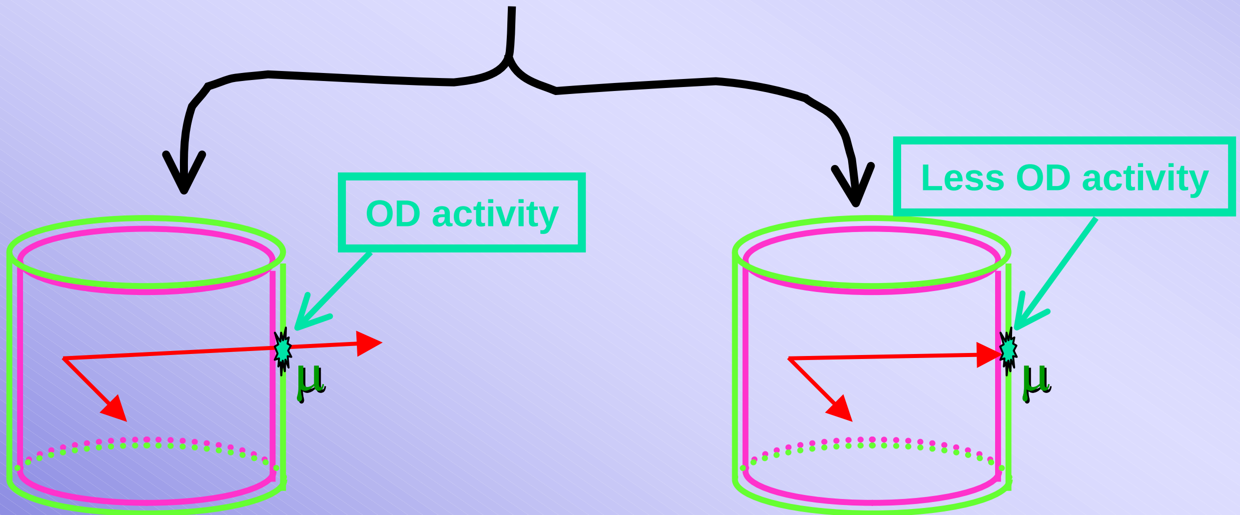
Fully Contained (FC)



Event category 2 (PC and upμ)

PID likelihood method and # of Cherenkov rings are not used.

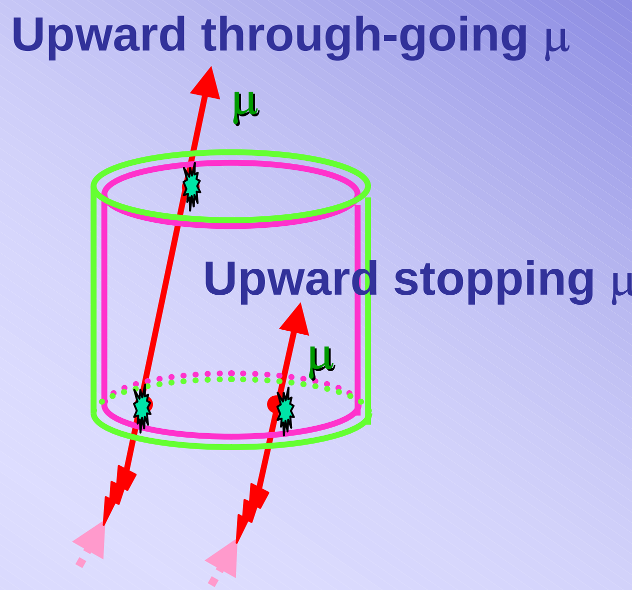
Partially Contained (PC)



OD through going PC

OD stopping PC

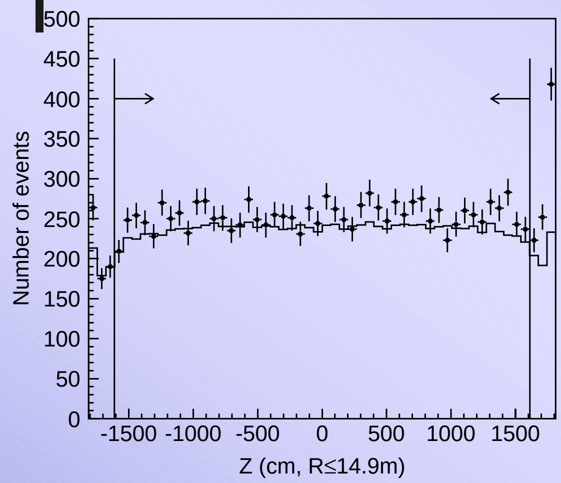
Upward μ



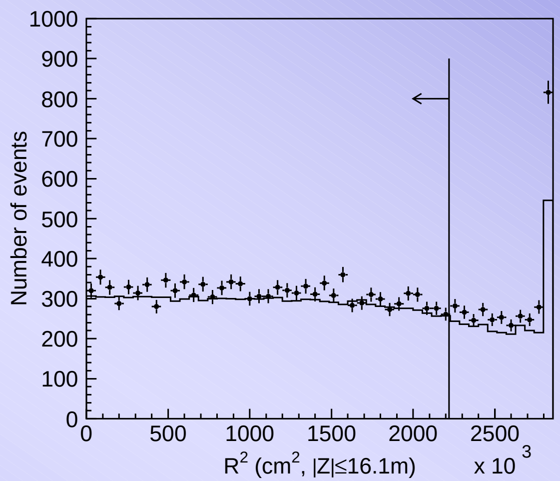
- discrimination of PC stop and through by deposited energy in the outer detector
- PC stop is a kind of FC events and energy can be reconstructed.

- target is rock (water for FC and PC)
- different energy scale and detection technique

vertex distributions and BG

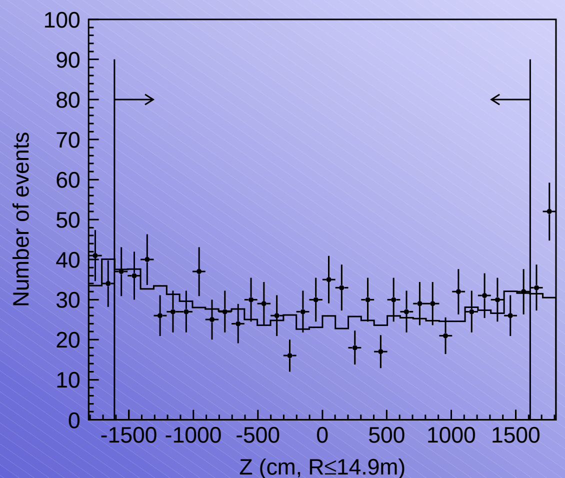


FC, Z(cm)

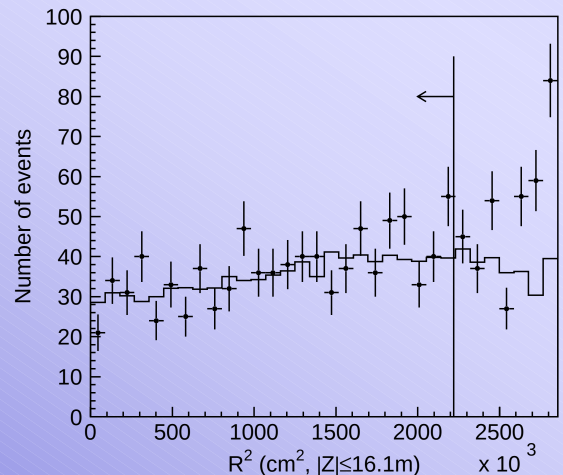


FC, R2(cm2)

Non ν BG in fiducial volume
- **cosmic mu 0.07% (Sub-GeV)**
  0.09% (Multi-GeV)
- **neutron 0.1% (e-like)**
- **PMT flasher 0.42%(Sub-GeV e)**
  0.16%(Multi-G e)



PC, Z(cm)



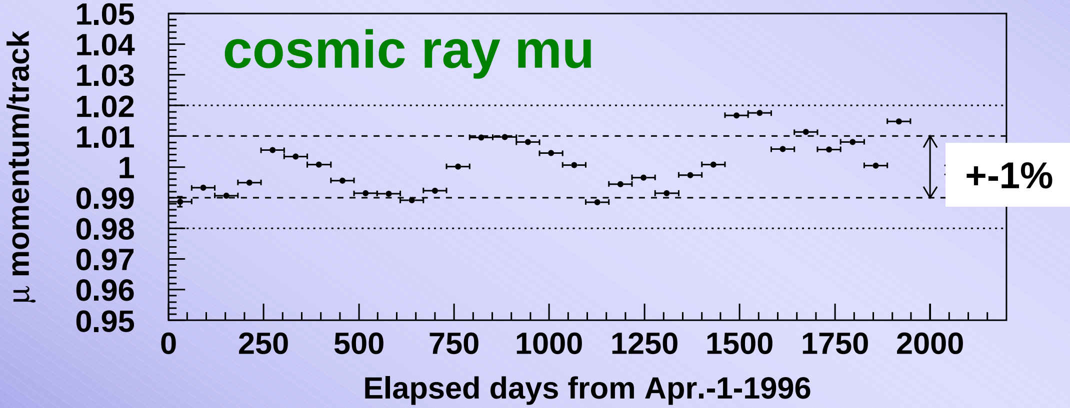
PC, R2(cm2)

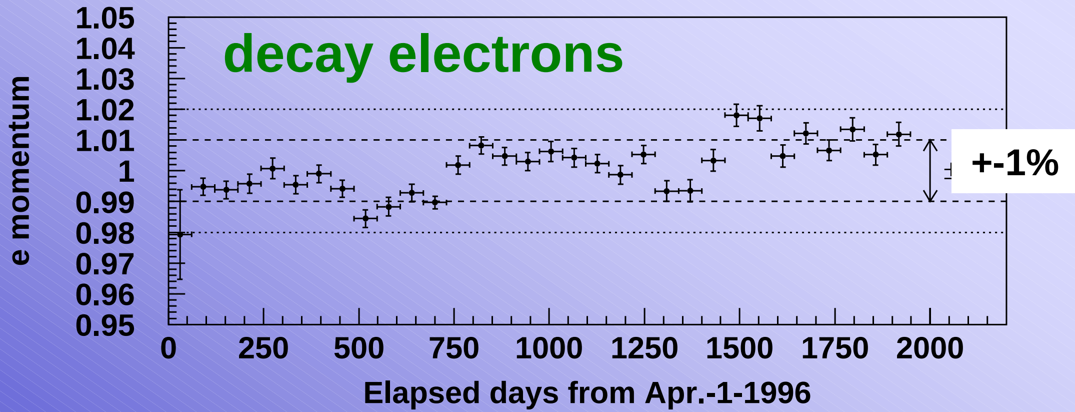
Non ν BG in fiducial volume
- **cosmic mu 0.2%**

Very clean ν sample

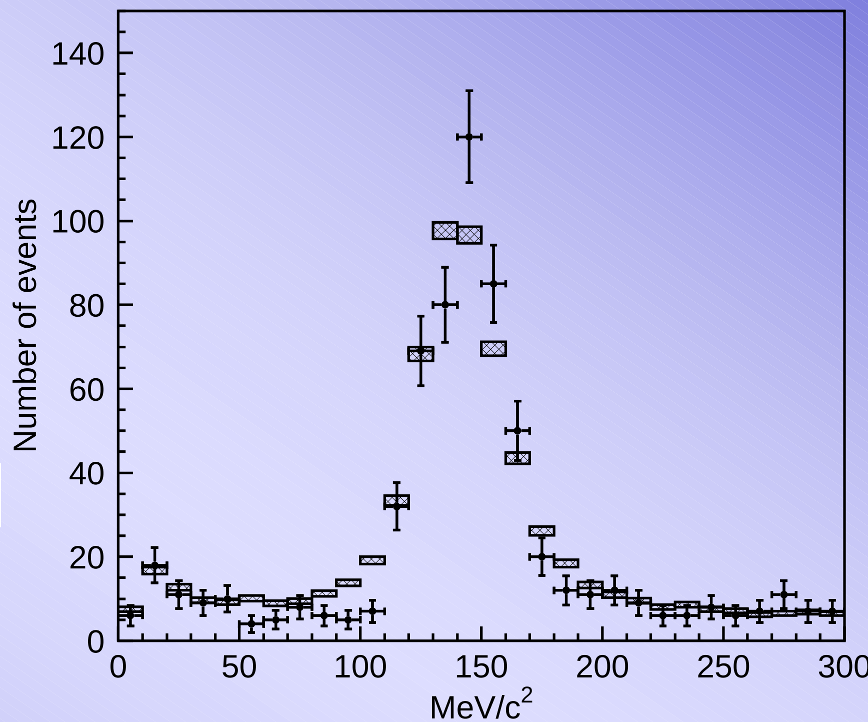
energy reconstruction

Full SK-I period





π0 invariant mass



Corrected for light attenuation length in water
Time variation of E scale ~ 0.9%

E scale difference < 1.8%
(decaye, pi0, cosmic mu)

energy scale uncertainty of neutrino detection < 2.0%

2 flavor oscillation analysis

List of updated systematic errors

a. Combined
   a. Overall normalization
   b. Relative norm. FC/PC
   c. Relative norm. ustop/upthr

b. Neutrino flux
   a. Numu/nue below 5GeV
   b. Numu/nue above 5GeV
   c. anti-nue/nue below 10GeV
   d. Anti-nue/nue above 10GeV
   e. Anti-numu/numu below 10GeV
   f. Anti-numu/numu above 10GeV
   g. Up/down ratio
   h. Horizontal-vertical in FC/PC
   i. Neutrino flight length
   j. Energy spectrum
   k. K/pi ratio
   l. Sample-by-sample normalization (FC multi-GeV mu)
   m. Sample-by-sample normalization (PC and upstop)

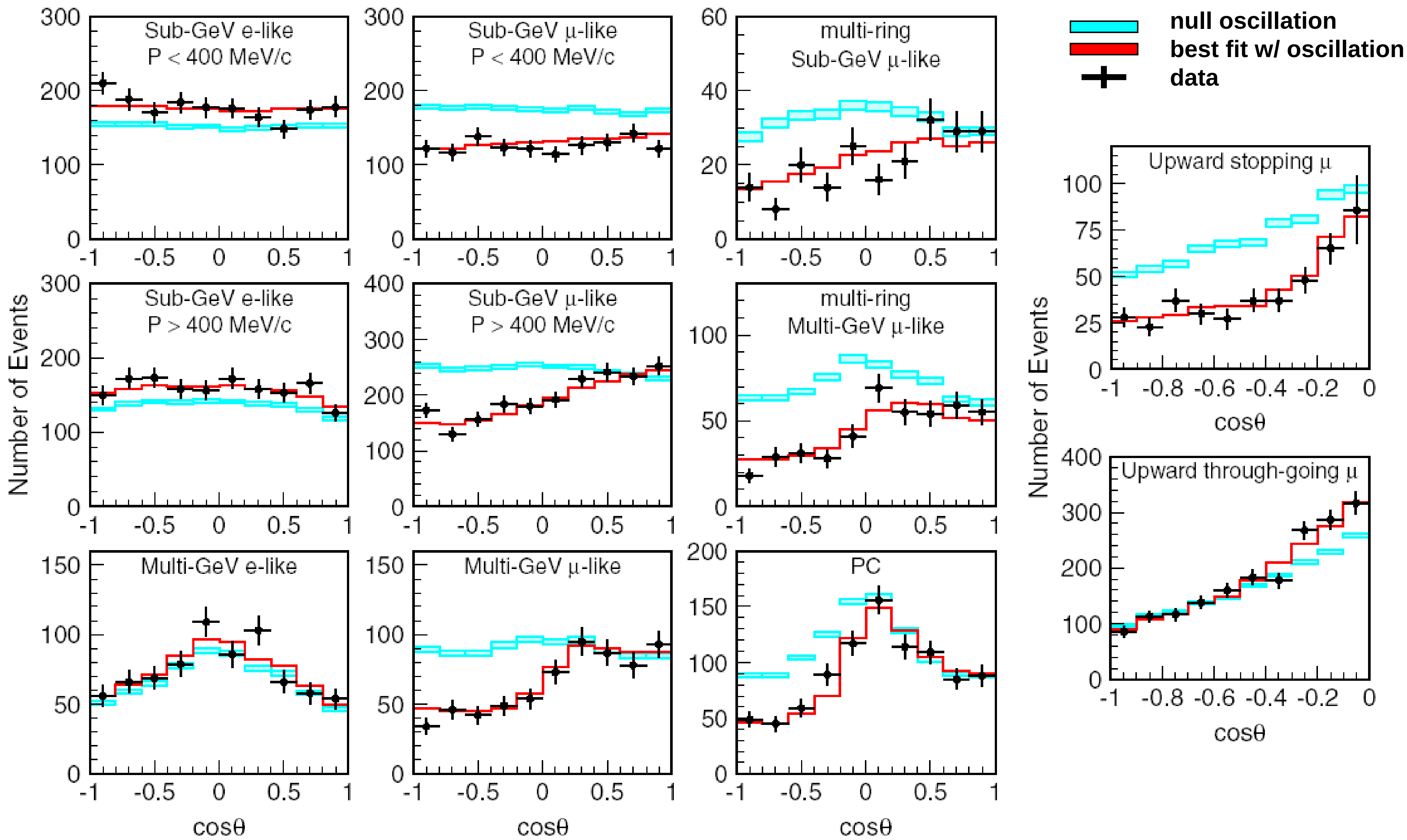
c. interactions
   a. QE
   b. Single-pi
   c. DIS
   d. DIS Bodek
   e. Coherent pi
   f. NC/CC
   g. Low energy QE
   h. M_A
   i. Hadron simulator
   j. Nuclear effect

d. Event selection
   a. FC reduction
   b. PC reduction
   c. Upmu efficiency
   d. Upmu 1.6GeV cut
   e. Flasher BG
   f. Cosmic mu BG

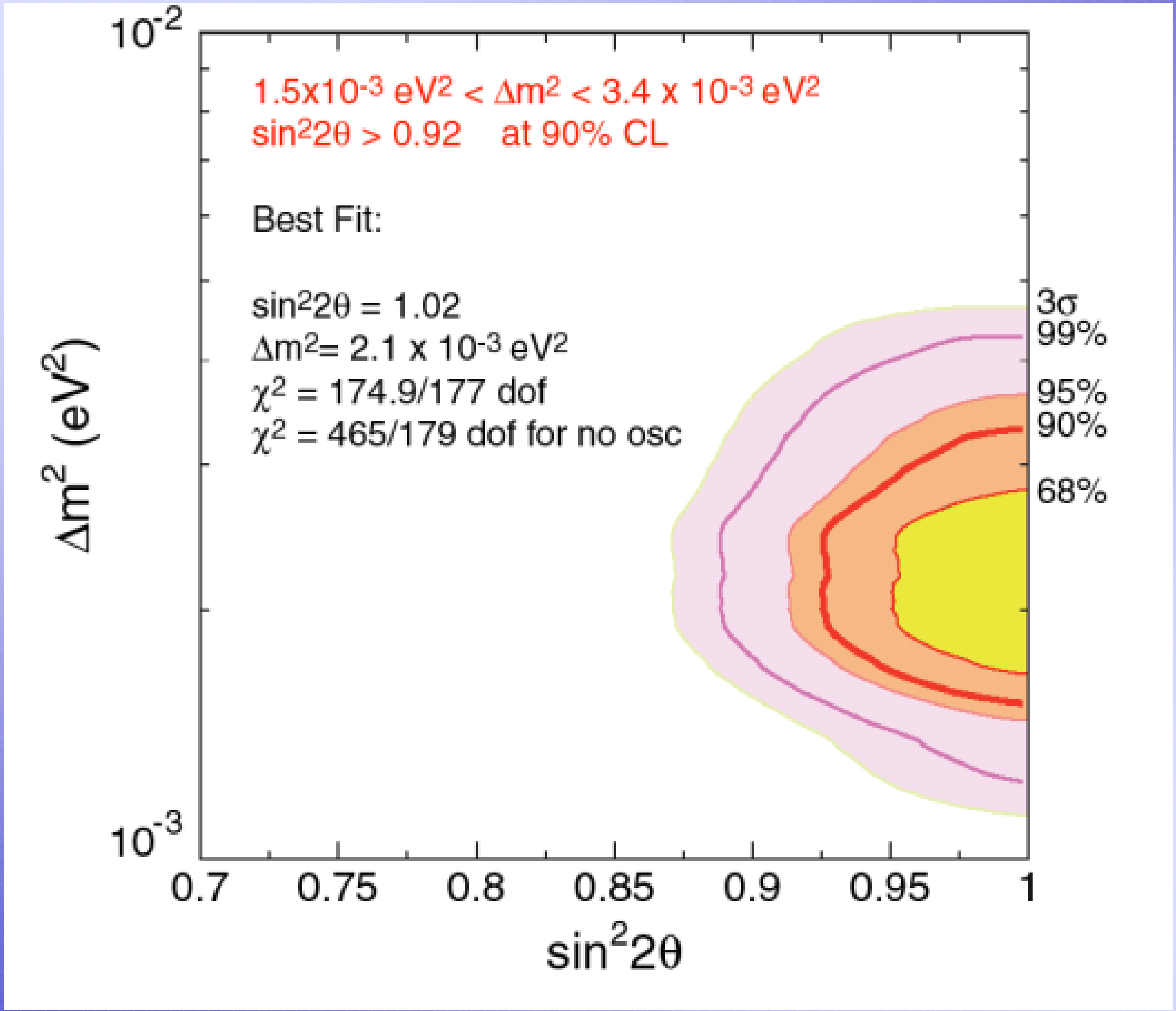
e. Event reconstruction
   a. Ring-counting
   b. Single-R PID
   c. Multi-R PID
   d. Energy calibration
   e. Up/down asymmetry of energy

f. Others
   a. Tau

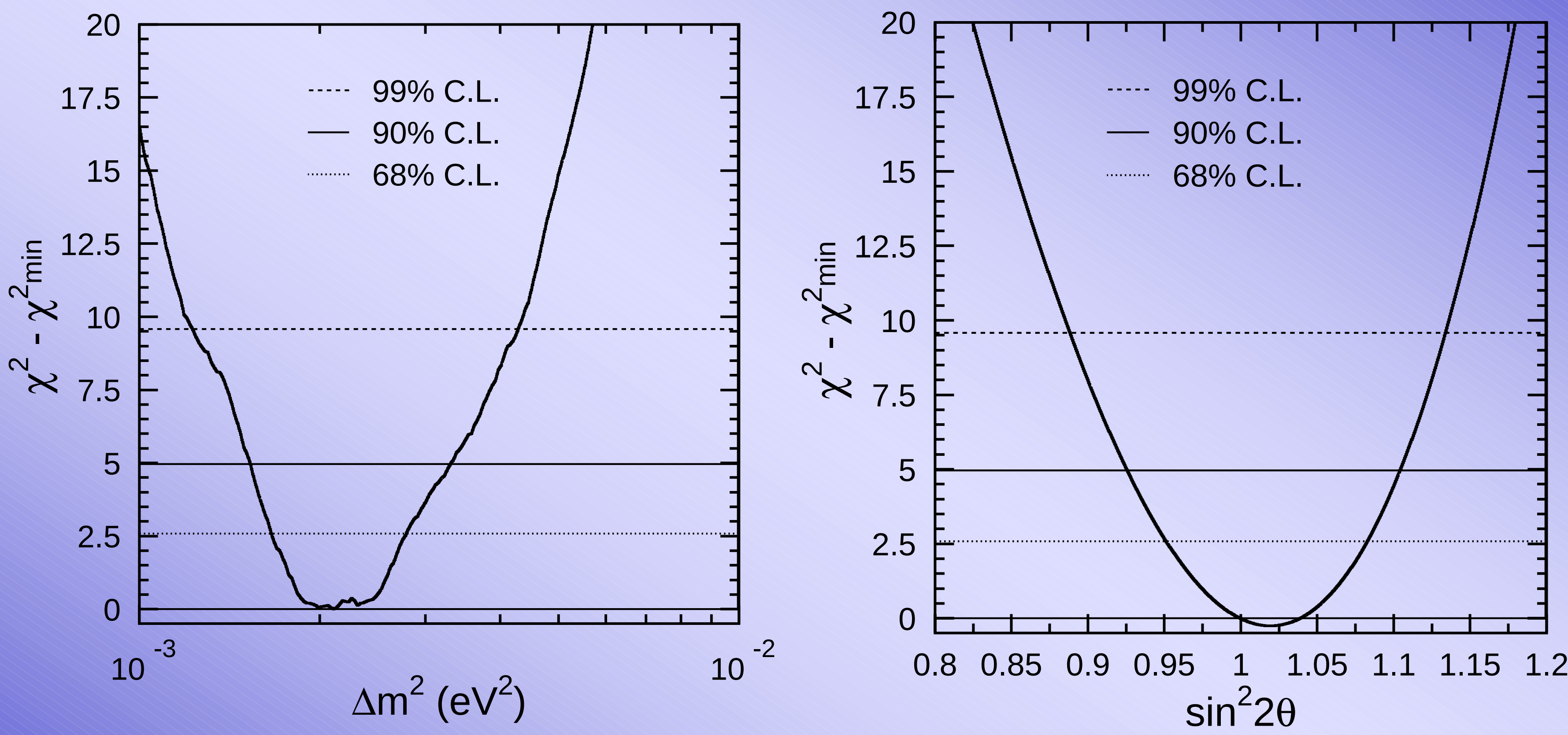
zenith angle distributions



Allowed region for $\nu_\mu \leftrightarrow \nu_\tau$

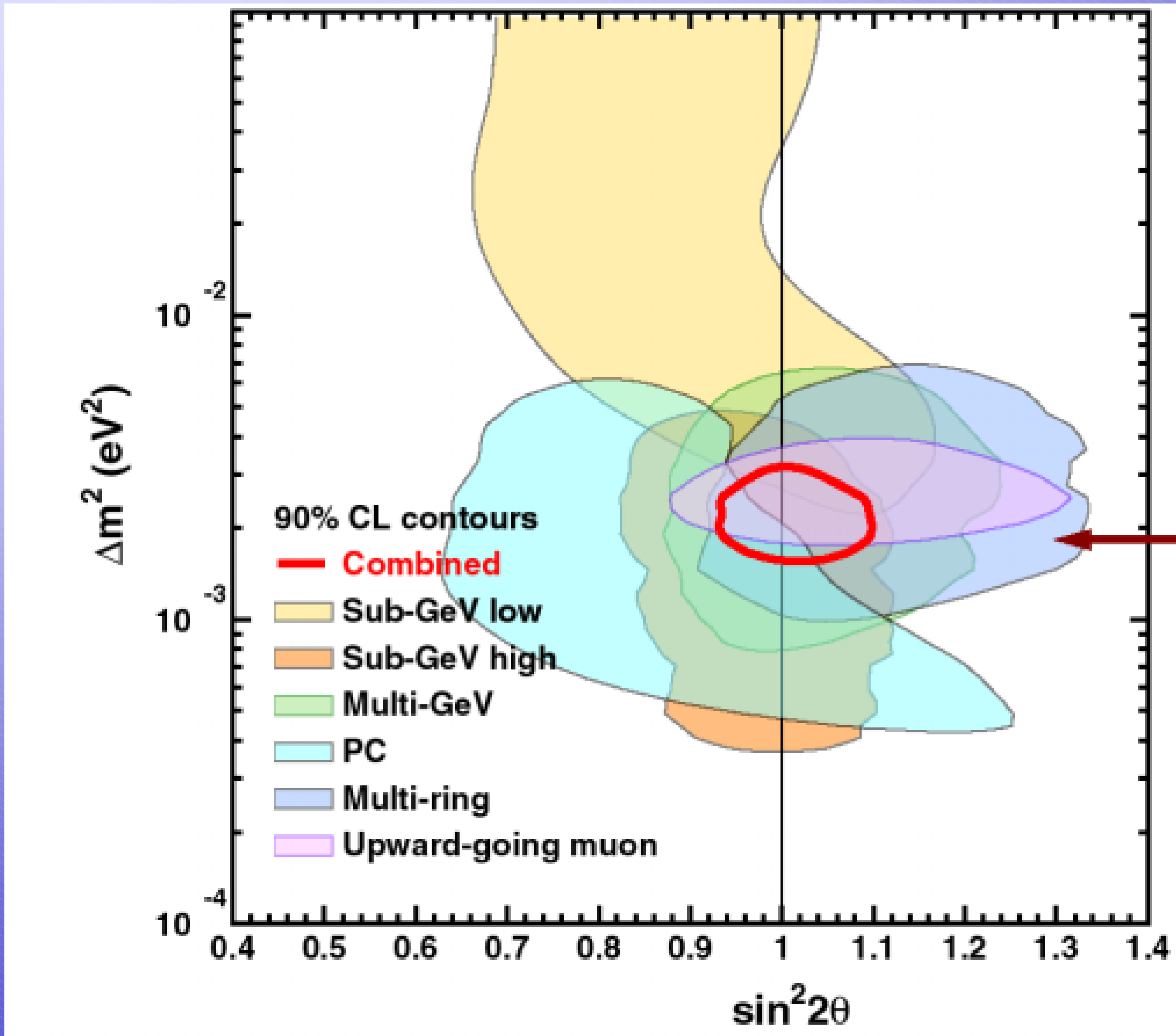


χ^2 distributions



χ^2 is rather flat btw 2~2.5x10^{-3} eV^2

Contours by sub-samples



All sub-samples suggests consistent parameter regions.

L/E analysis

L/E analysis

Neutrino oscillations:

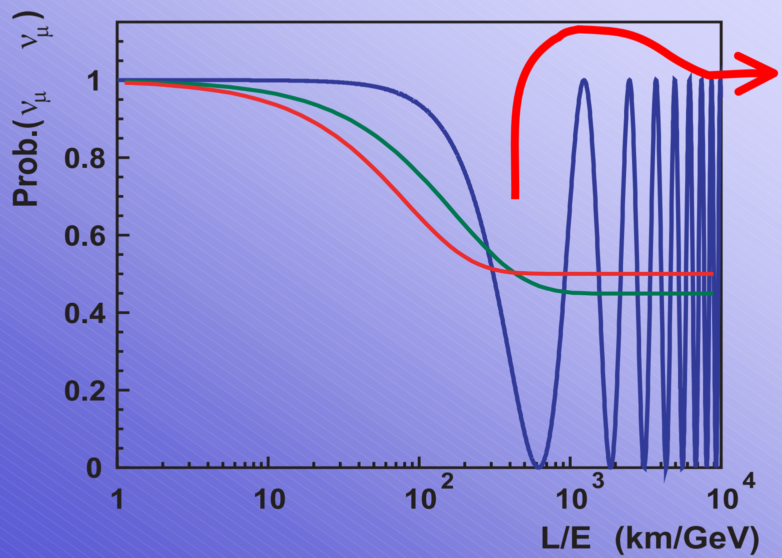
$$P(\nu\mu \rightarrow \nu\mu) = 1 - \sin^2 2\vartheta \sin^2\left(1.27\frac{\Delta m^2 L}{E_\nu}\right)$$

Neutrino decay :

$$P(\nu\mu \rightarrow \nu\mu) = \left(\cos^2\vartheta + \sin^2\vartheta \times \exp\left(-\frac{m}{2\tau}\frac{L}{E_\nu}\right)\right)^2$$

Neutrino decoherence :

$$P(\nu\mu \rightarrow \nu\mu) = 1 - \frac{1}{2}\sin^2 2\vartheta\left(1 - \exp(-\gamma_0\frac{L}{E_\nu})\right)$$



Need high resolution L/E

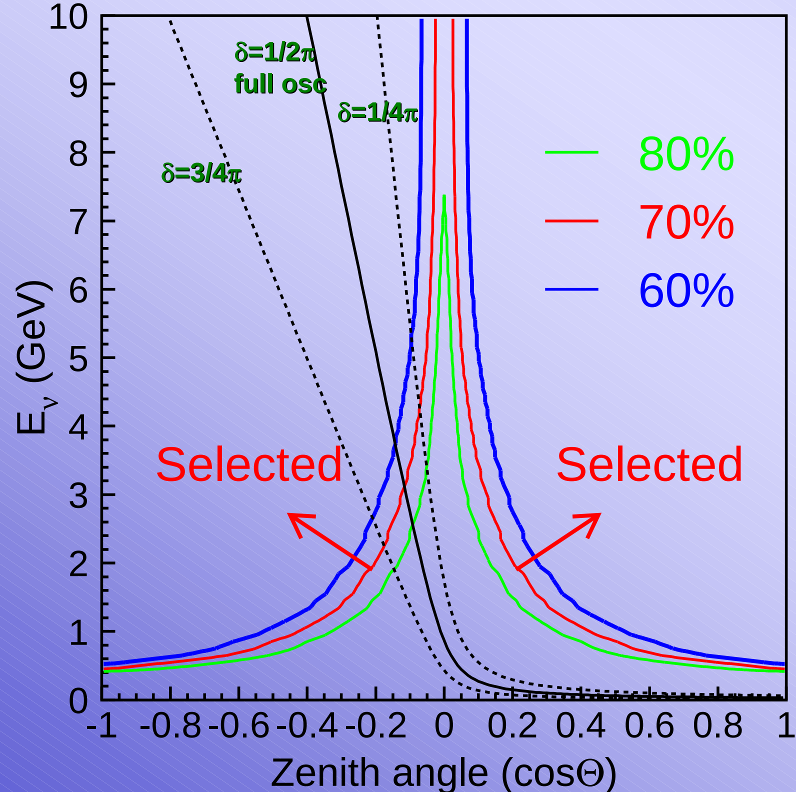
to observe direct evidence for “oscillations”.

to constraint on Δm^2 from the dip position.

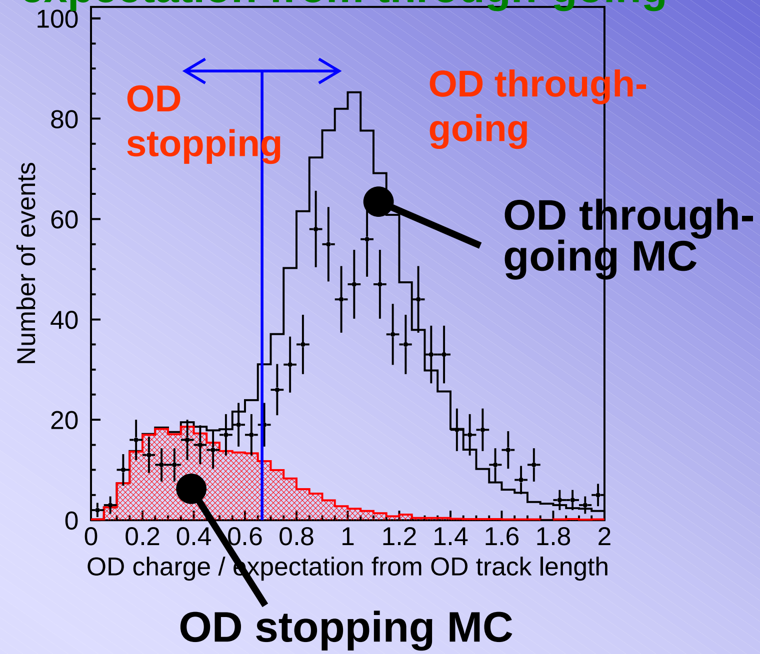
to help rejecting other hypothesis.

High resolution, high statistics

1. expand fiducial volume (22.5→26.4kton)
   - high statistics
2. separate PC muons that stop in OD
   - better energy measurement
3. selection by 70% (L/E) resolution



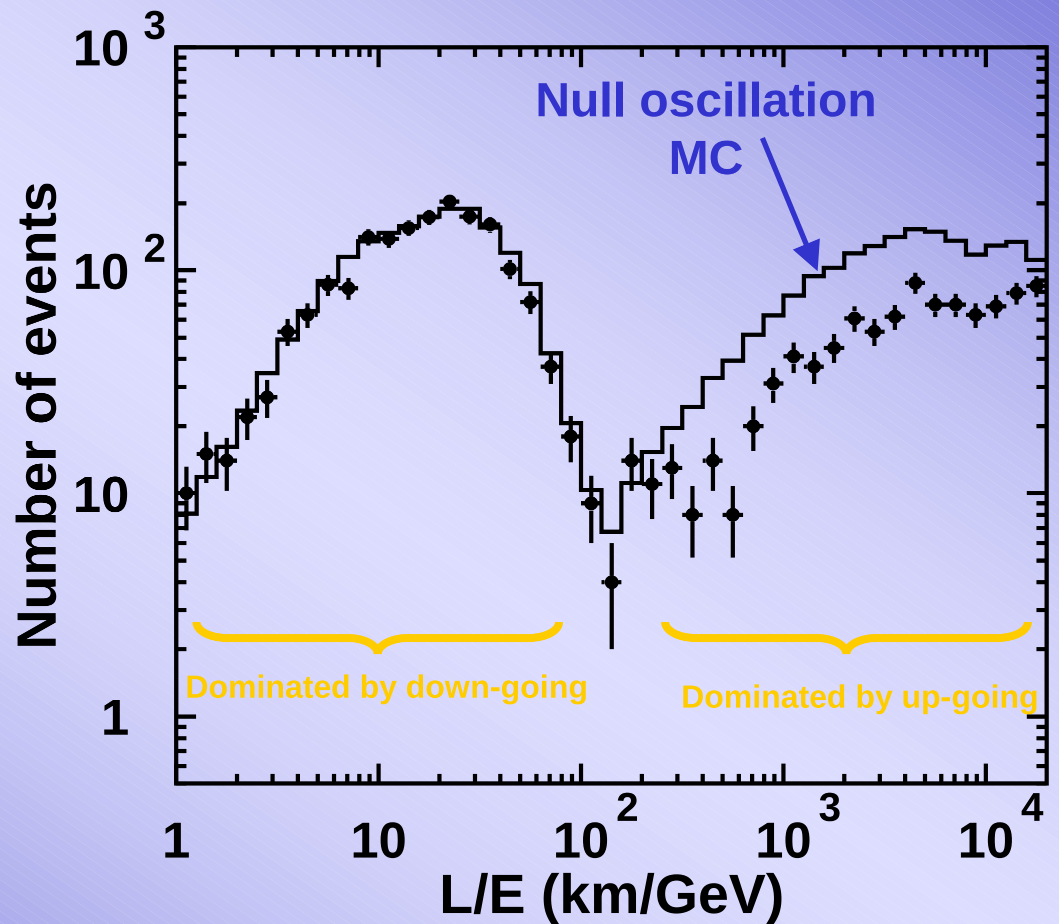
observed charge / expectation from through-going



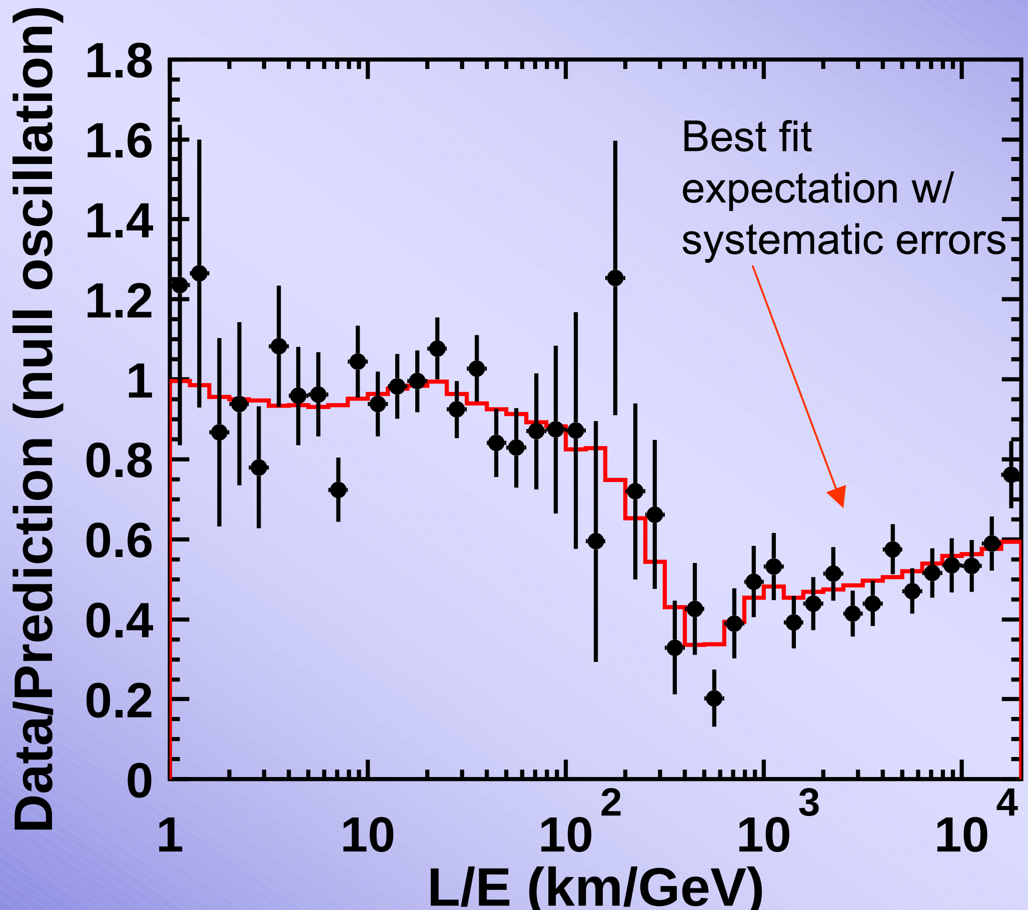
Event summary of high resolution sample

FC	Data	MC	CC ν_μ
single-ring	1619	2105.8	(98.3%)
multi-ring	502	813.0	(94.2%)
PC			
stopping	114	137.0	(95.4%)
through-going	491	670.4	(99.1%)

High purity & high resolution muon sample



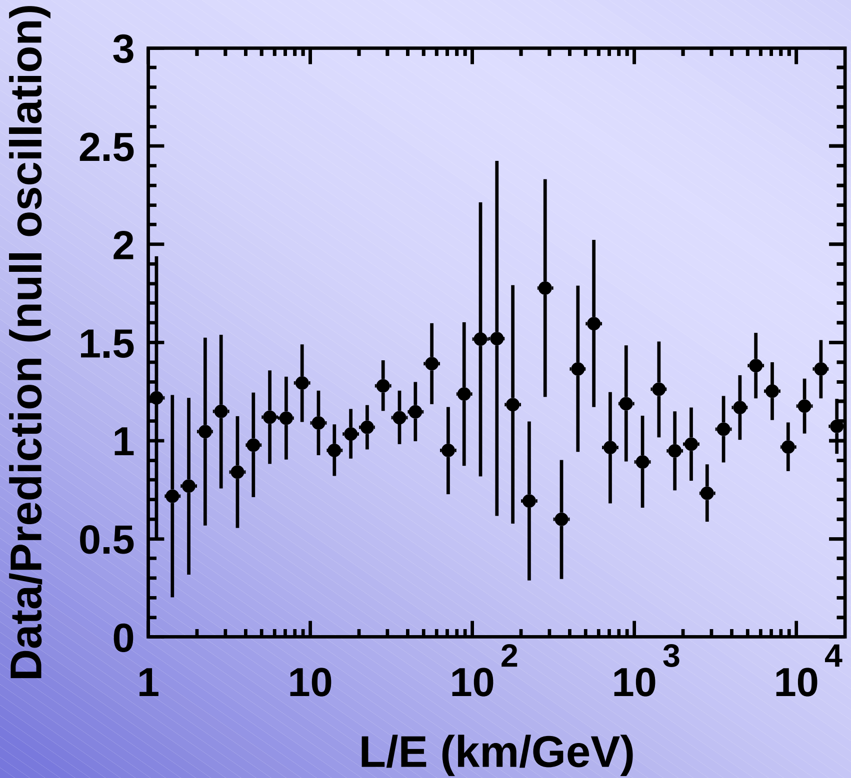
Data/MC for high resolution events



First dip is seen as expected by neutrino oscillation

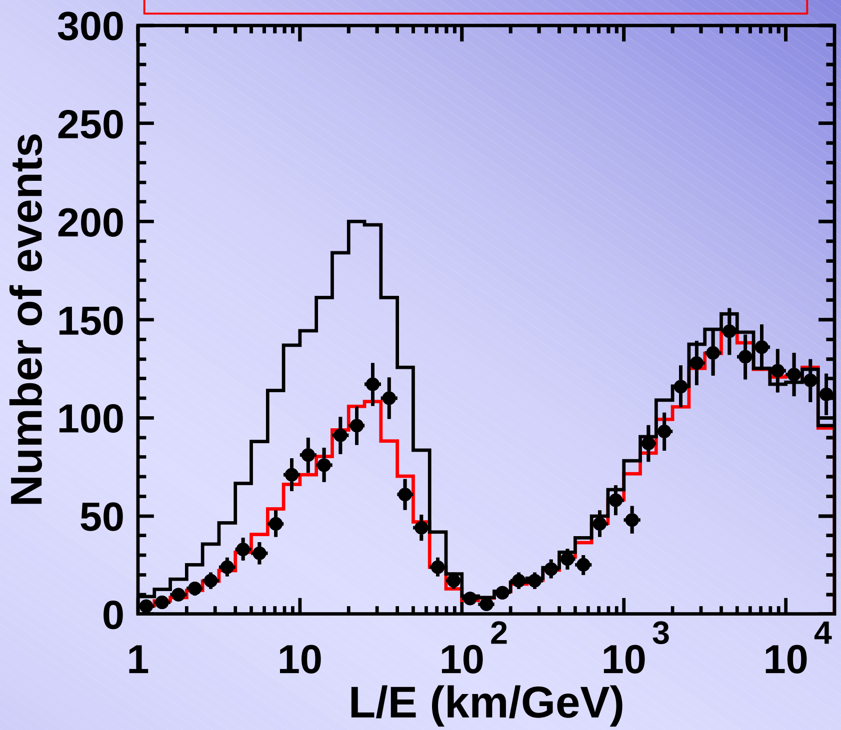
Systematic checks

Electron sample



Flat L/E distribution is observed as is expected.

zenith angle is inverted.
cosθ → -cosθ



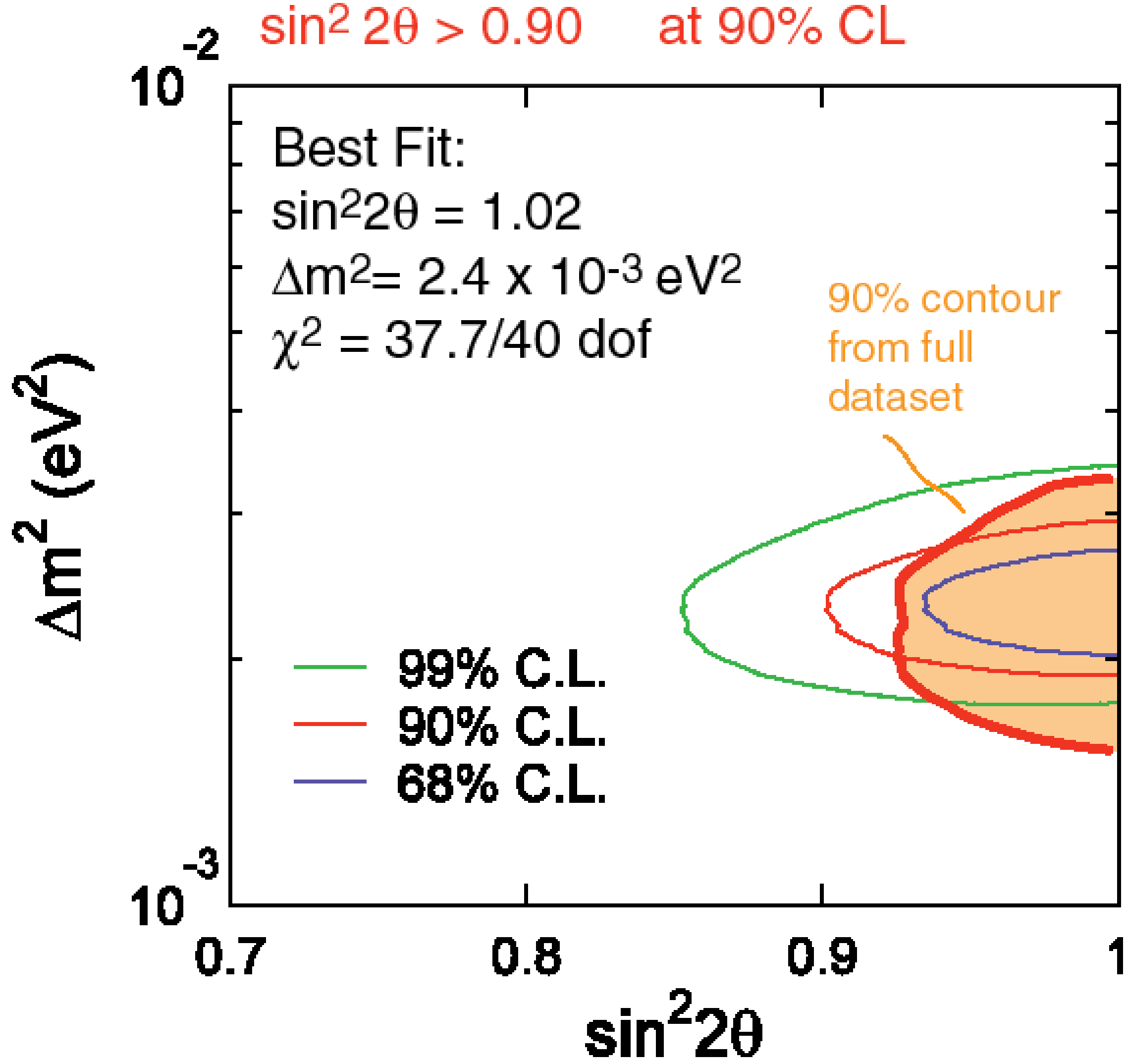
No dip is observed as is expected for wrong L assignments.

→ No systematic bias is seen.

oscillation analysis by L/E analysis

$1.9\times10^{-3}\ eV^2 < \Delta m^2 < 3.0 \times 10^{-3}\ eV^2$

$\sin^2 2\theta > 0.90$ at 90% CL

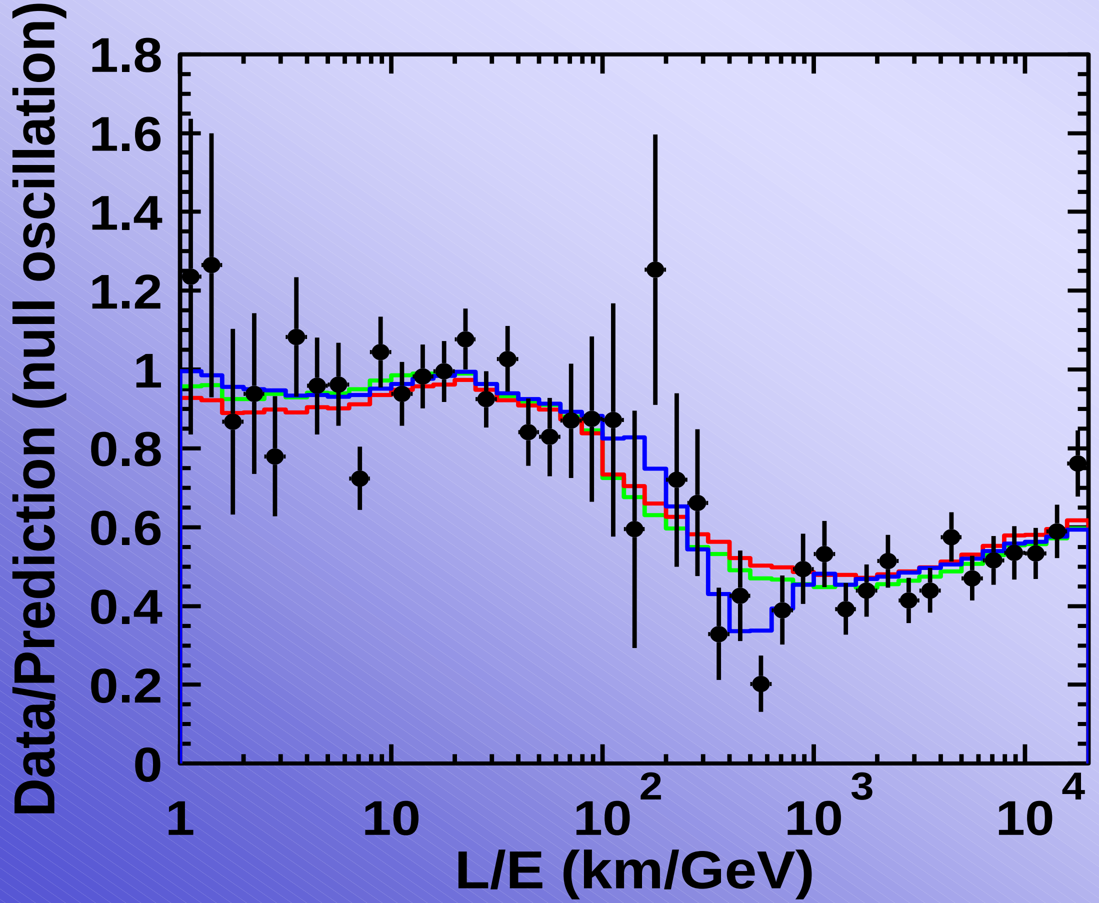


Test for ν decay & ν decoherence

Oscillation χ^2_{min}=37.9/40 d.o.f

Decay χ^2_{min}=49.1/40 d.o.f → $\Delta\chi^2$ =11.3

Decoherence χ^2_{min}=52.4/40 d.o.f → $\Delta\chi^2$ =14.5



$\Delta\chi^2$ =11.4 for ν decay

→ 3.4 σ

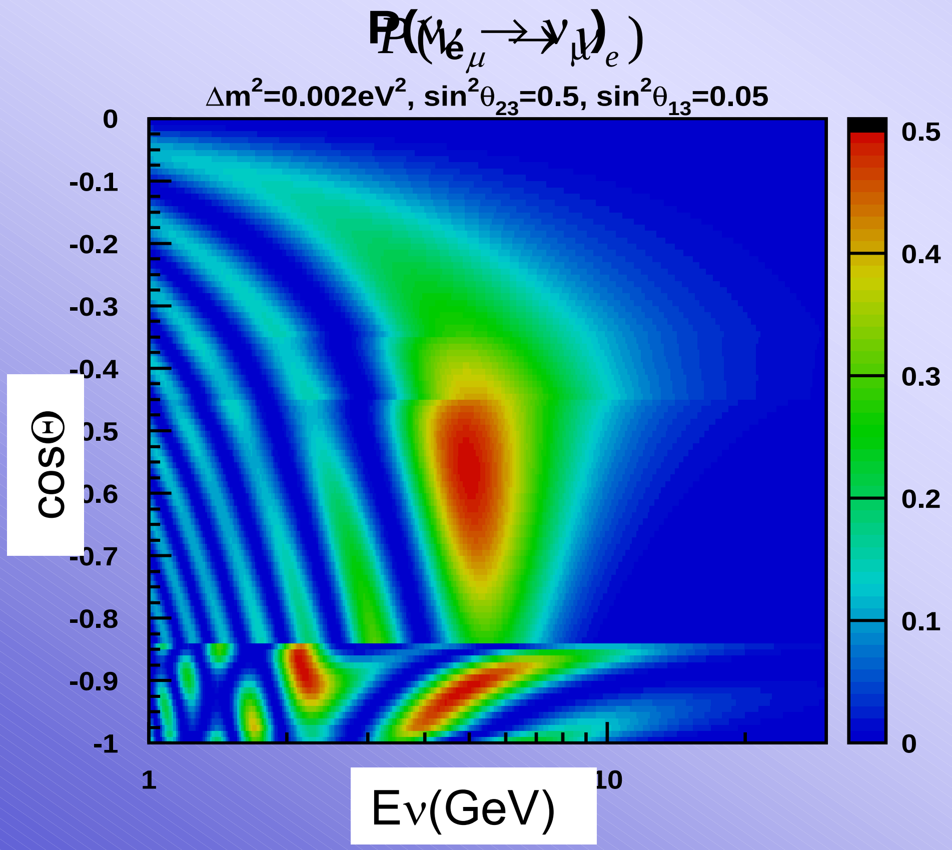
$\Delta\chi^2$ =14.6 for ν decoherence

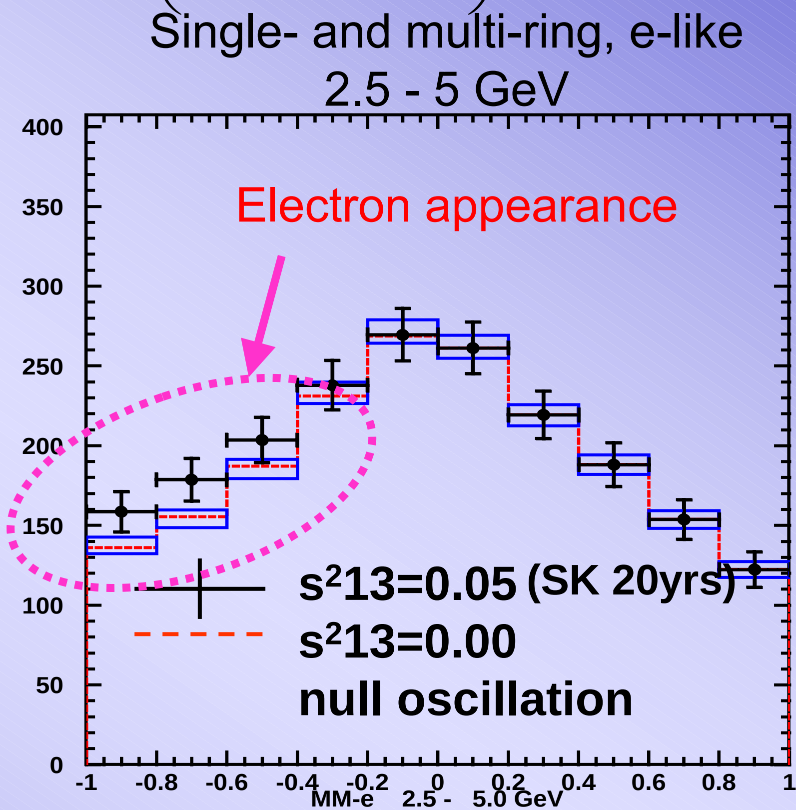
→ 3.8 σ

3 flavor oscillation analysis

Search for non-zero θ_{13}

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \cdot \sin^2\theta_{13} \cdot \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$



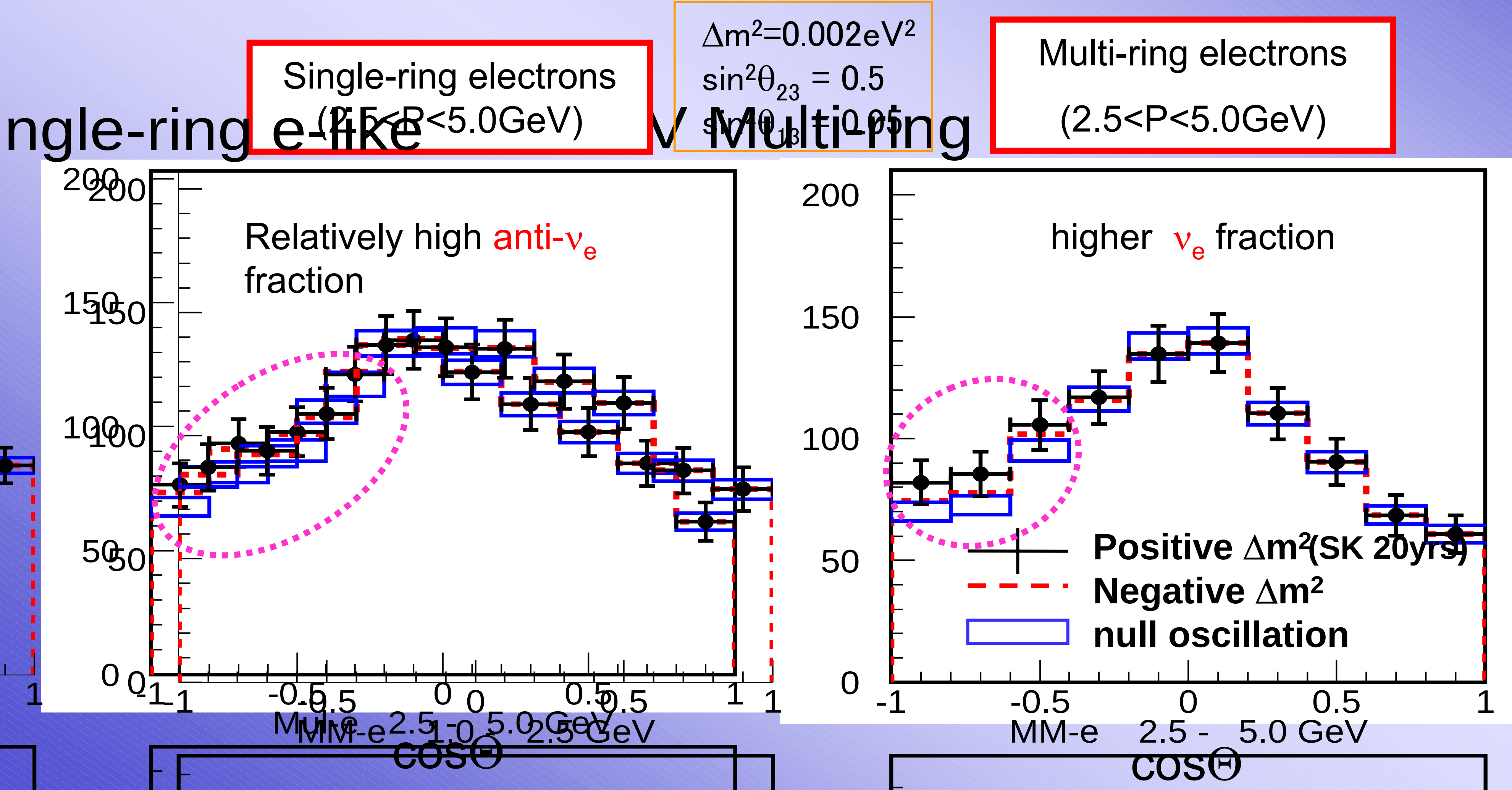


Electron appearance in multi-GeV upward going events.

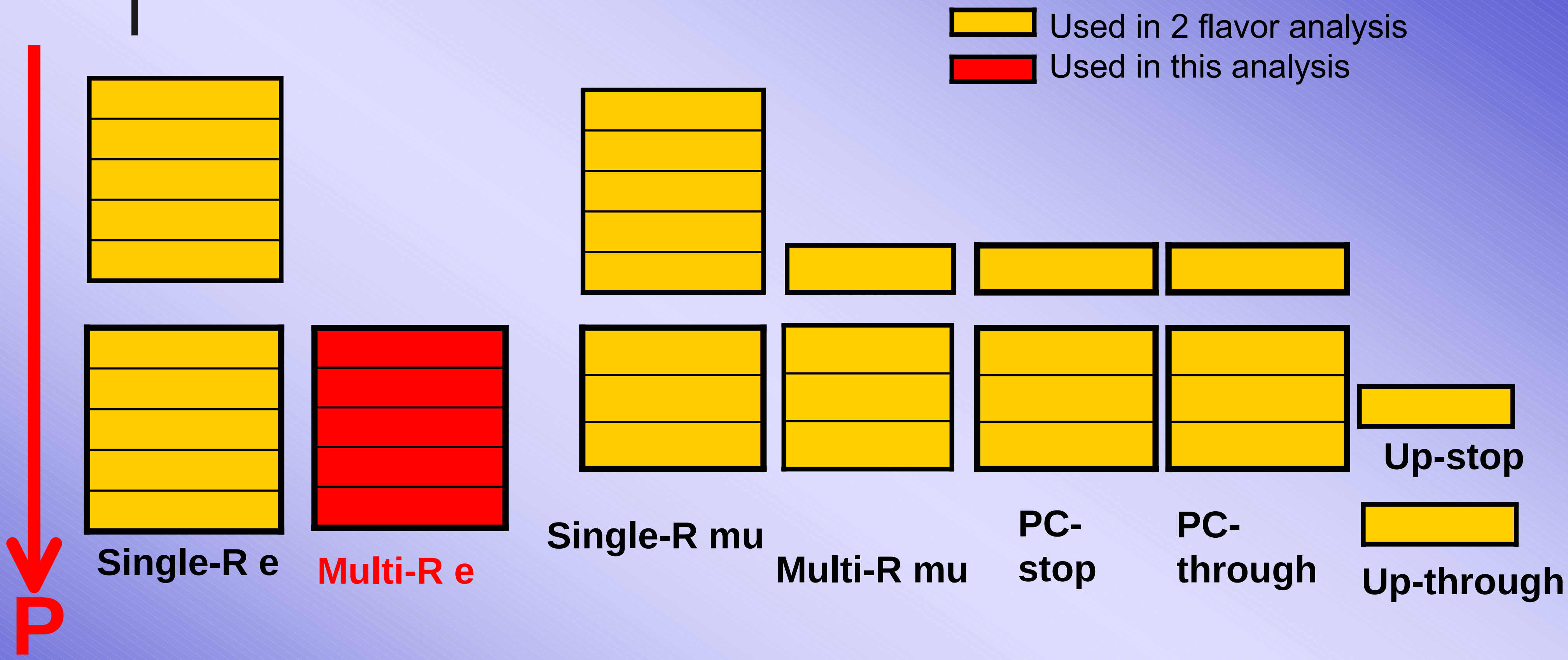
(And stronger muon disappearance in multi-GeV upward going events.)

positive VS negative Δm^2

- positive $\Delta m2$ → resonance only in νe
- negative $\Delta m2$ → resonance only in anti-νe

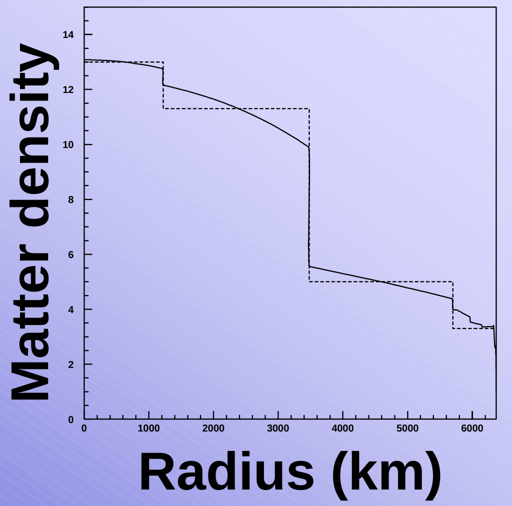


Binning for 3flavor analysis

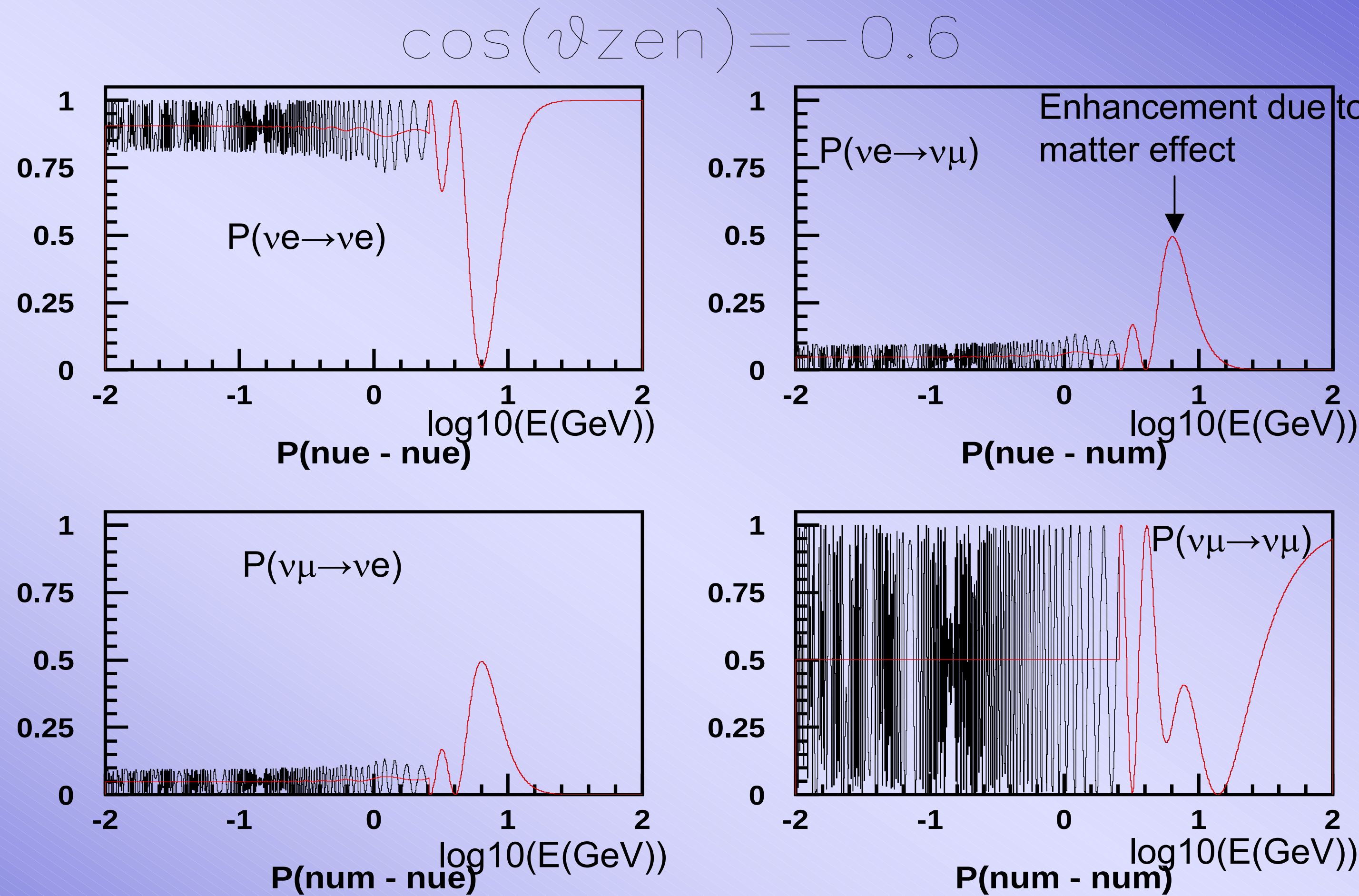


Use multi-ring electrons to increase electron sample.
Finer electron/muon binning to increase sensitivity to oscillation parameters.
37 momentum bins x 10 zenith bins = 370 bins in total

oscillation probability w/ matter effect



Approximation by four layers w/ constant matter densities.



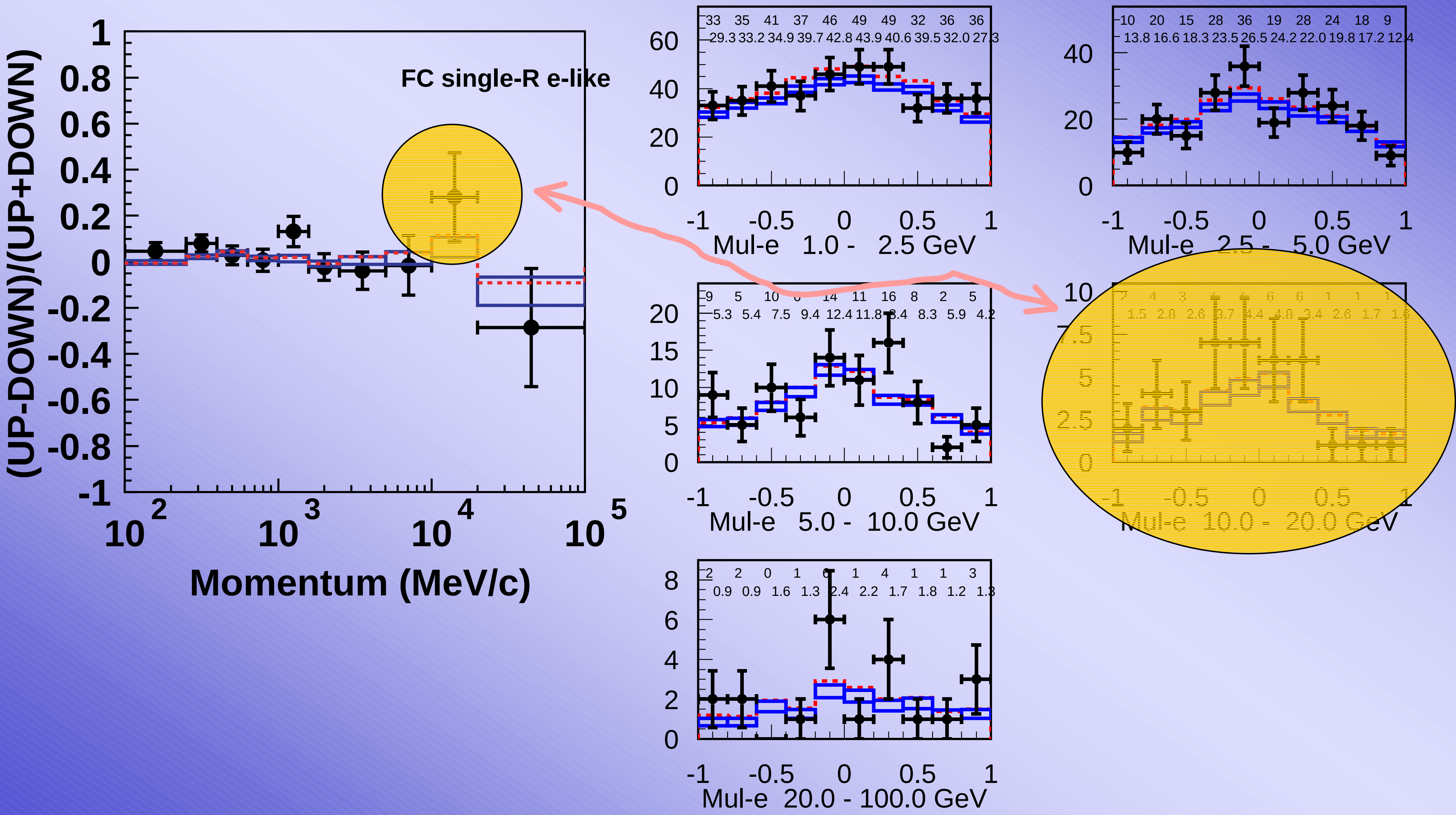
Oscillation parameters:

$\Delta m^2 = 2.0\times10^{-3}$ eV^2

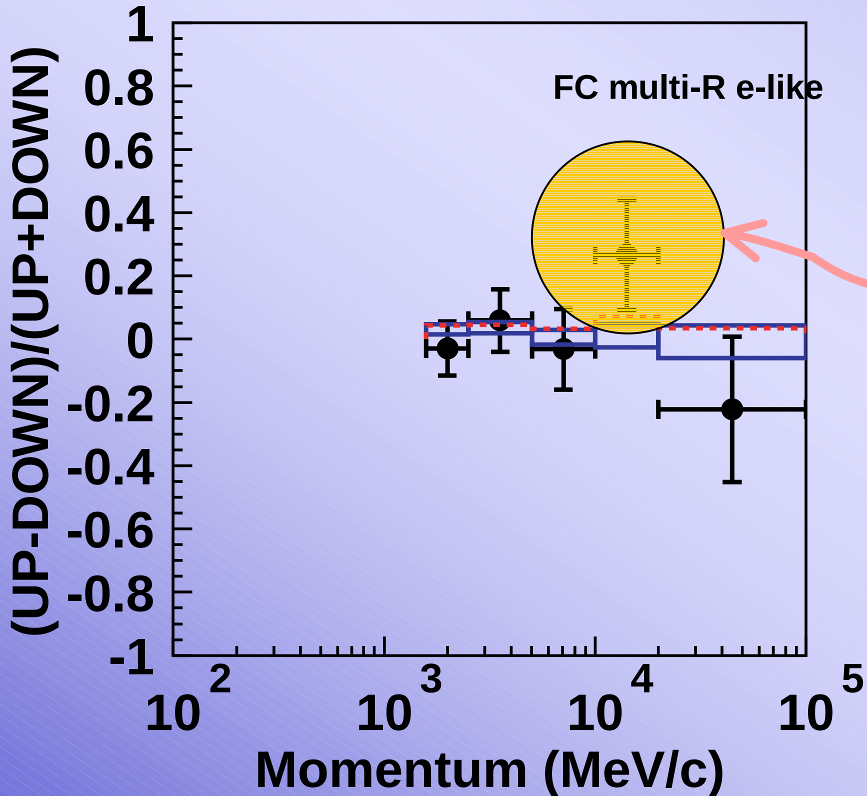
$\sin^2\theta_{23}=0.5$, $\sin^2\theta_{13}=0.05$, $\cos\theta_{zenith}=-0.6$

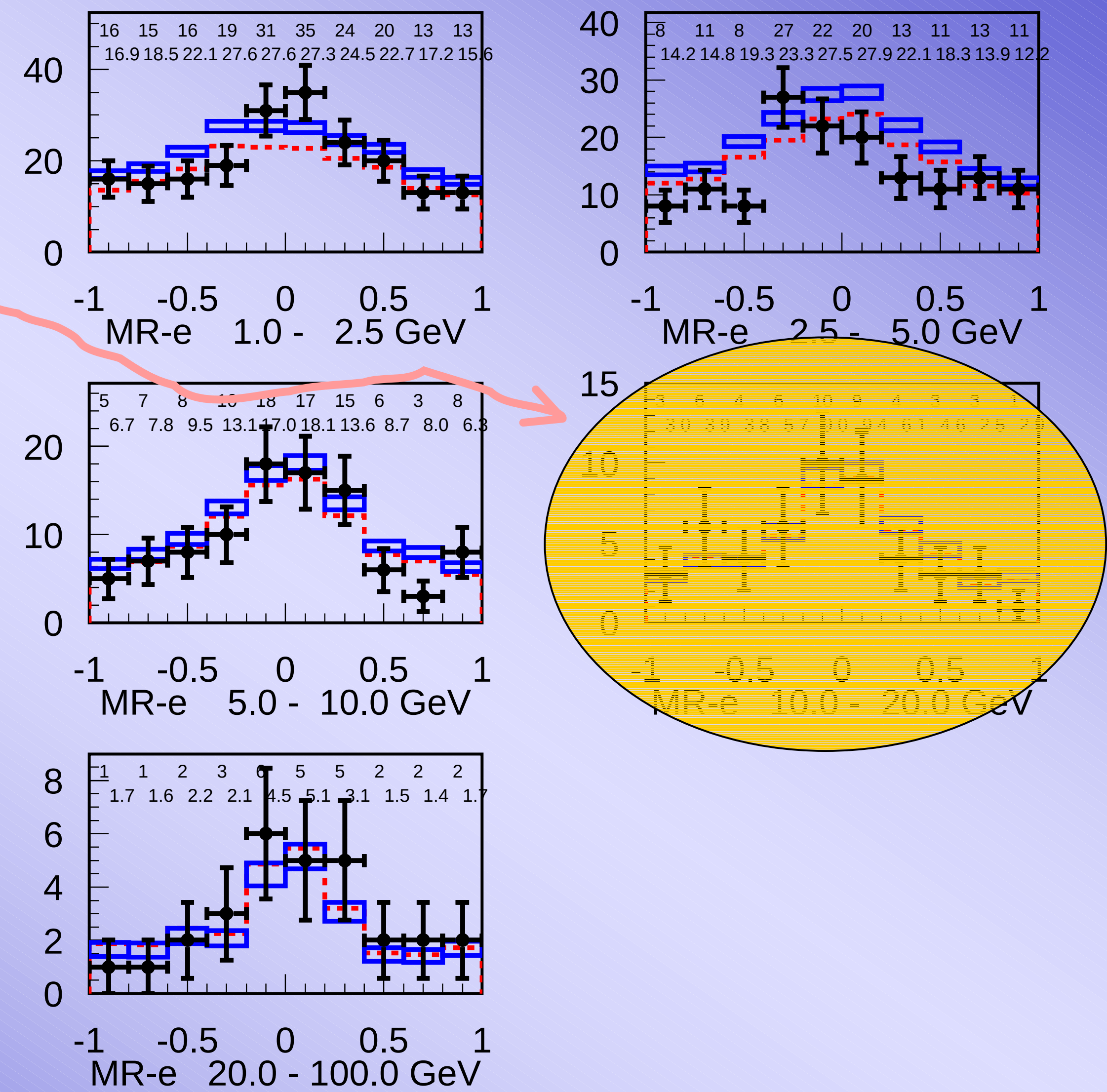
—— Averaged probability

single-ring electrons



multi-ring electrons



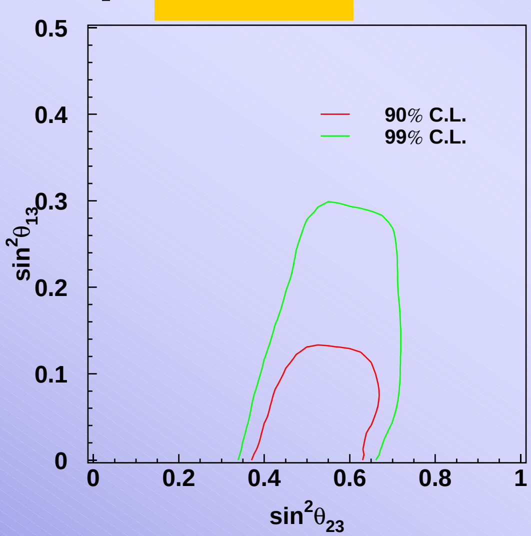


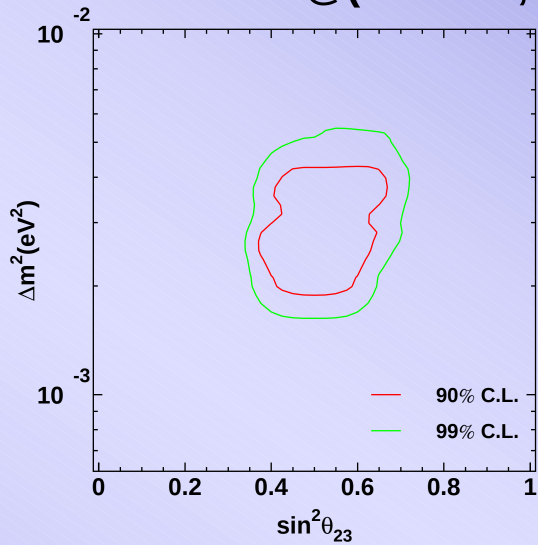
No significant excess of upward electrons both in single-R and multi-R electron sample.

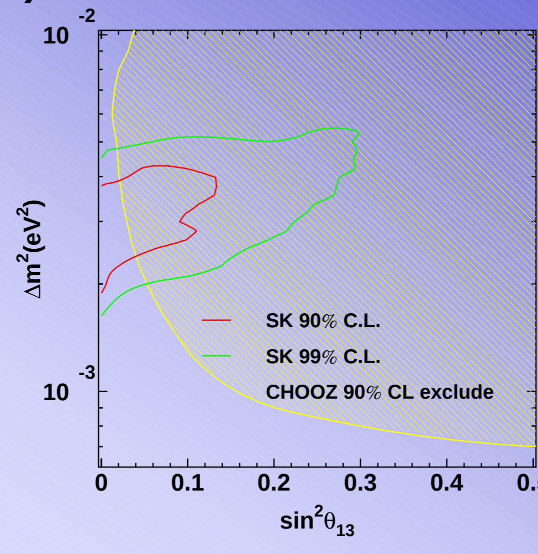
oscillation fit for normal and inverse hierarchy

$\Delta m^2 > 0$

$\chi^2_{min}/ndf = 380.36/368$ @$(2.7\times10^{-3}, 0.5, 0.0)$

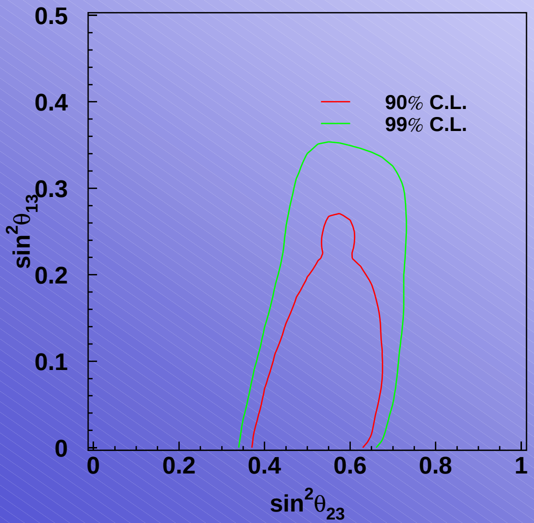


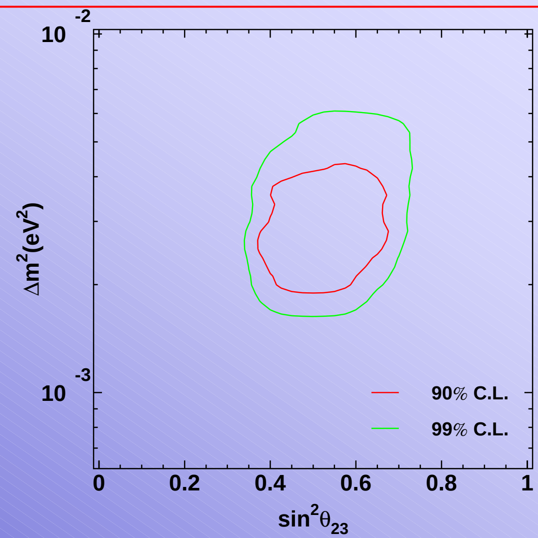


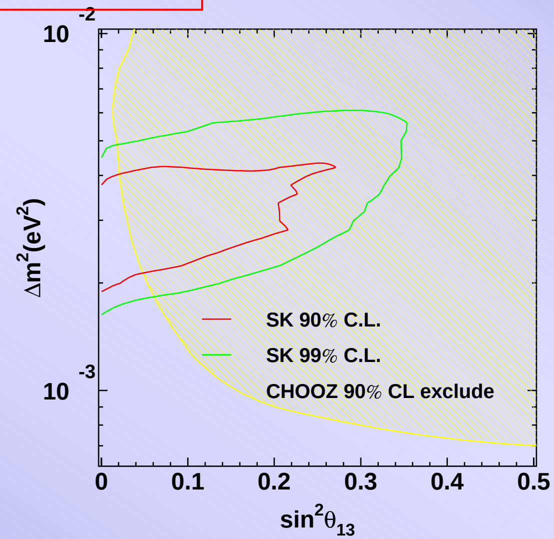


$\Delta m^2 < 0$

$\chi^2_{min}/ndf = 380.30/368$@$(2.7\times10^{-3}, 0.525, 0.00625)$



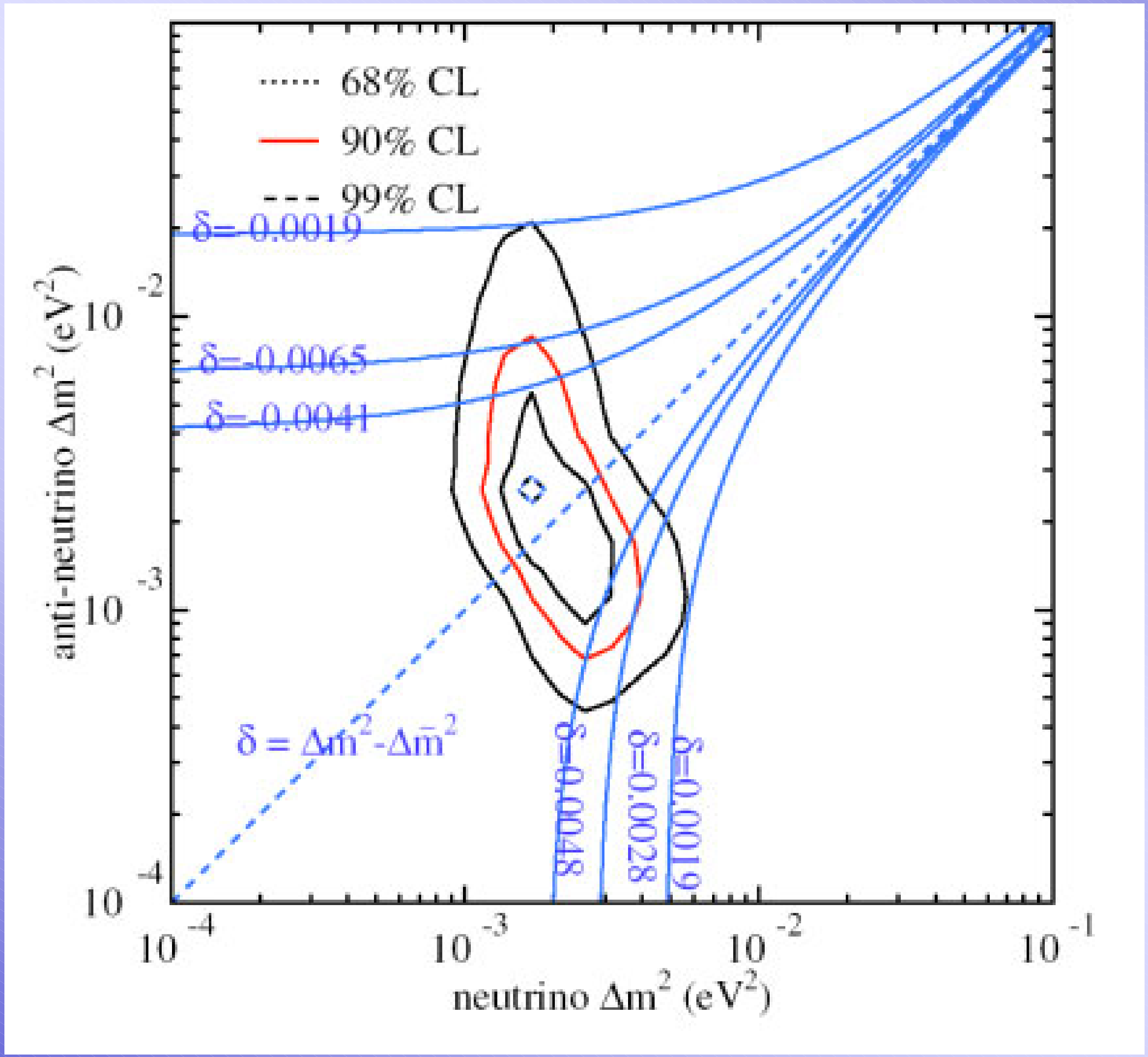




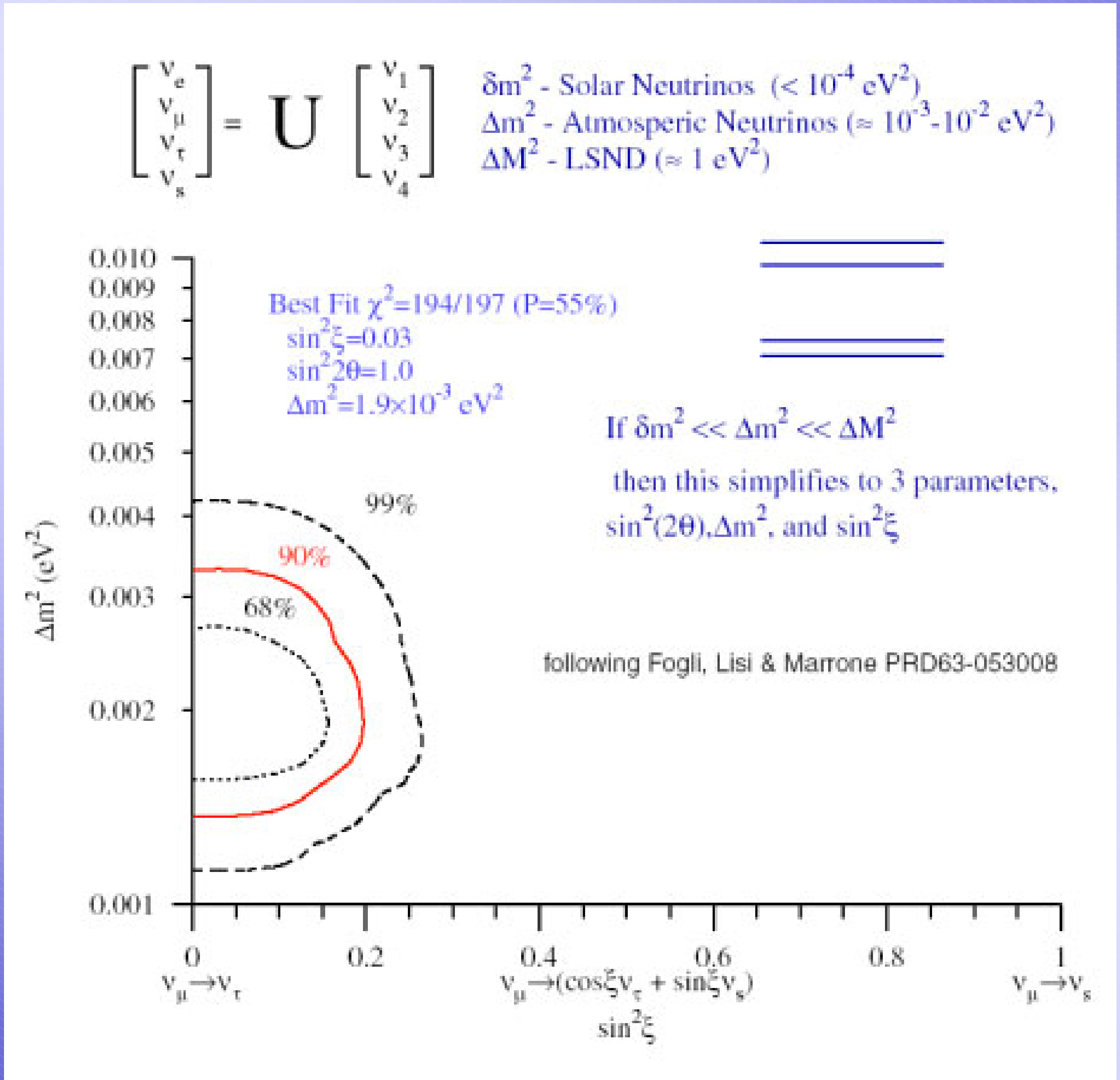
exotic scenarios

CPT violation

allow for different mixing and Δm^2 for ν and anti-ν



ν sterile admixture



conclusion

I. Atmospheric neutrinos are powerful tools to explore the lepton sector
   i. $\theta 23$ and $\Delta m23$ measurements
   ii. evidence for oscillatory signature
   iii. exclude ν decay and ν decoherence
   iv. search for $\theta 13$
   v. test of exotic scenarios (CPT, sterile ν, LxE…..)

II. In near future
   i. more data (SK-II)
   ii. improve $\theta 23$ and $\Delta 23$ measurements (zenith, L/E analyses)
   iii. $\nu\tau$ appearance
   iv. improve $\theta 13$ sensitivity