(Some of the)
Lateset results from Super-Kamiokande

Yoshinari Hayato (Kamioka, ICRR)
for the SK collaboration

1. About Super-Kamiokande
2. Solar neutrino studies in SK
3. Atmospheric neutrino studies in SK
4. Nucleon decay search

Super-Kamiokande Collaboration

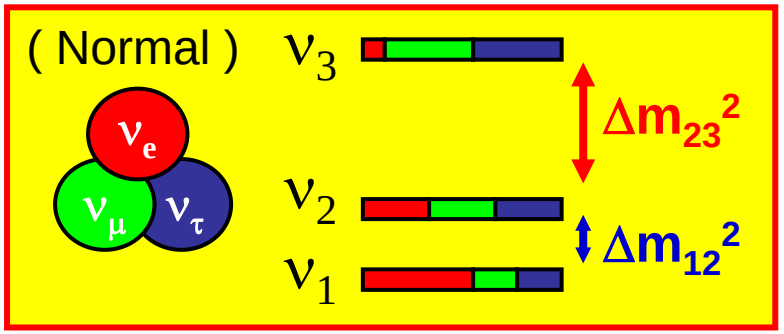
~120 collaborators, 31 institutions, 6 countries

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
IPMU, Univ. of Tokyo, Japan
Boston University, USA
Brookhaven National Laboratory, USA
University of California, Irvine, USA
California State University, Dominguez Hills, USA
Chonnam National University, Korea
Duke University, USA
Gifu University, Japan
University of Hawaii, USA
Kanagawa, University, Japan
KEK, Japan
Kobe University, Japan
Kyoto University, Japan
Miyagi University of Education, Japan
STE, Nagoya University, Japan
SUNY, Stony Brook, USA
Niigata University, Japan
Okayama University, Japan
Osaka University, Japan
Seoul National University, Korea
Shizuoka University, Japan
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Tokai University, Japan
University of Tokyo, Japan
Tsinghua University, China
Warsaw University, Poland
University of Washington, USA
Autonomous University of Madrid, Spain

From PRD81, 092004 (2010)

Neutrino Mixing

Neutrino mixing parameters



- 3 mass states
  (2 mass differences)
  - Δm_{12}^2 : Solar ν & Reactor experiments $6\sim8\times10^{-5}\,eV^2$
  - Δm_{23}^2 : Atm. ν & Accl. LBL ν experiments $2\sim3\times10^{-3}\,eV^2$
- 3 mixing angles & 1 CPV phase

Maki-**N**akagawa-**S**akata **Matrix (U_{ij})**

$$|\nu_l\rangle = \Sigma U_{li}|\nu_i\rangle$$

Weak — Mass eigenstates

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

$s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

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

(Solar + Reactor) — $\sin^2\theta_{12}\sim0.3$

(Atm. + Accl.) — $\sin^2 2\theta_{23}\sim1$ (>0.9)

(Reactor) @ $\Delta m_{23}^2 \sim 2\times10^{-3}\,eV^2$ — $\sin^2 2\theta_{13} < 0.2$

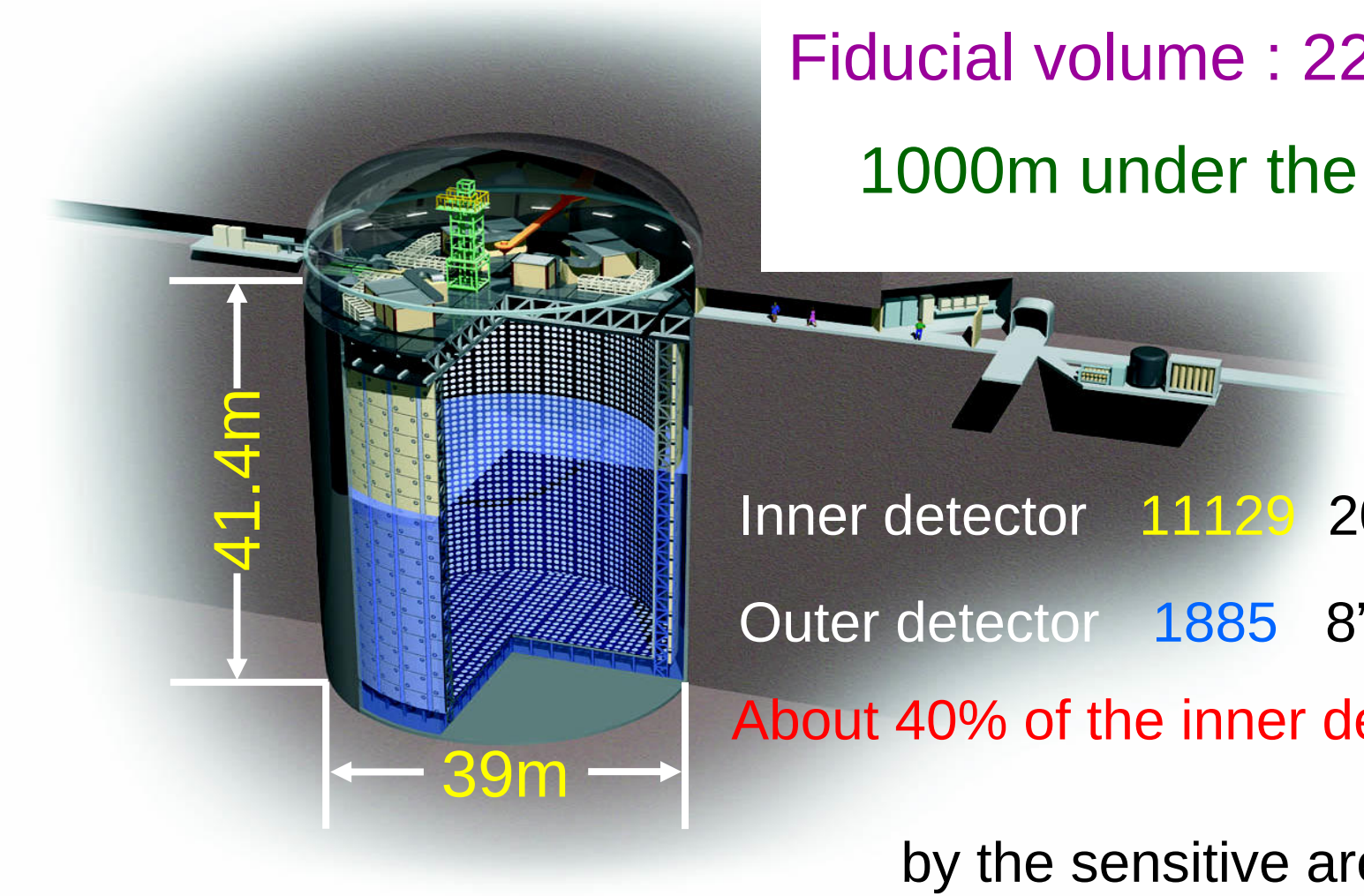
Upper bound!

1. Super-Kamiokande detector

50000 tons Ring imaging Water Cherenkov detector

Fiducial volume : 22.5 ktons

1000m under the ground



Inner detector 11129 20” PMTs

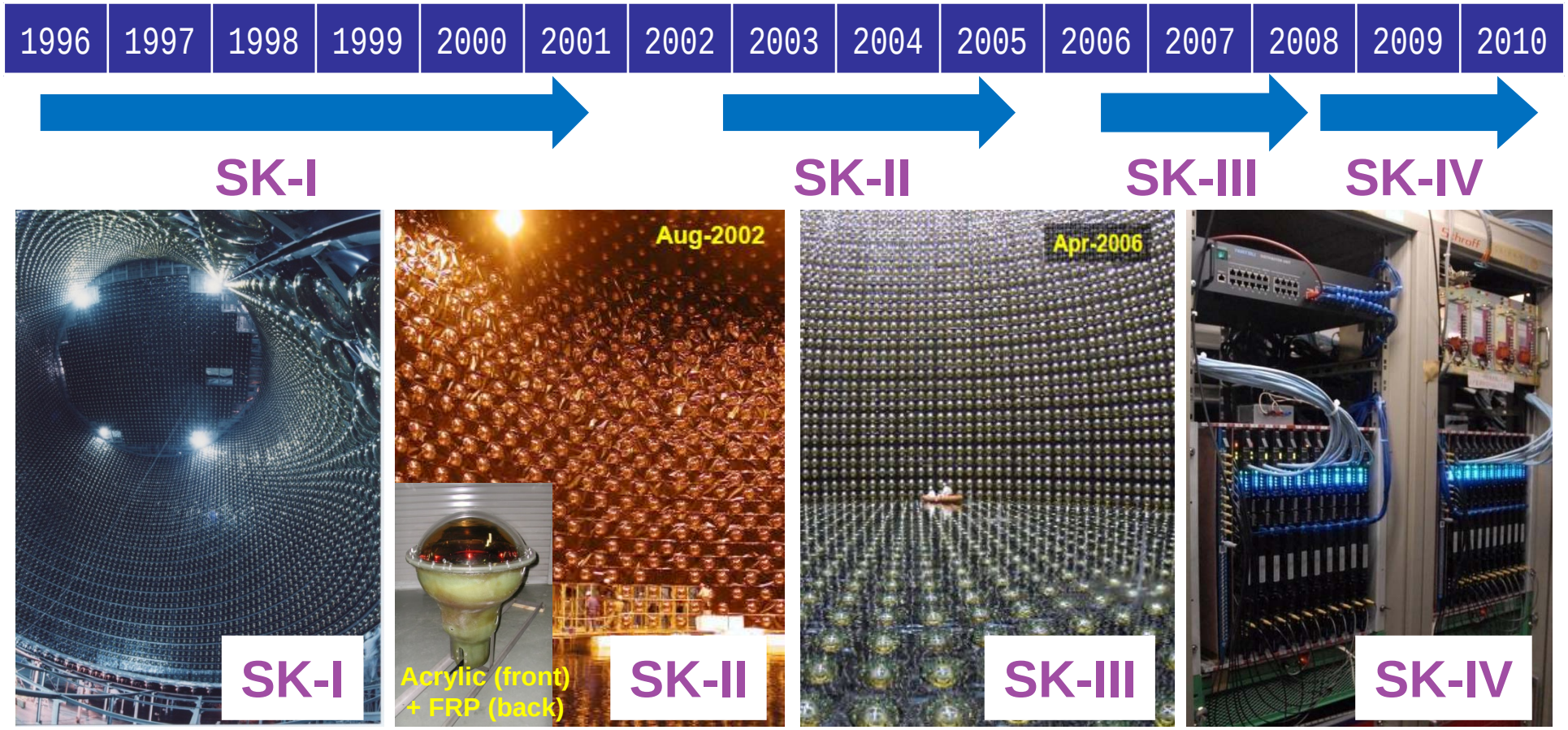
Outer detector 1885 8” PMTs

About 40% of the inner detector is covered by the sensitive area of PMT.

It is possible to observe ~ 20 atmospheric and solar neutrinos everyday.

1. Super-Kamiokande detector

History of the SK detector



11146 ID PMTs (40% coverage)

5182 ID PMTs (19% coverage)

11129 ID PMTs (40% coverage)

Electronics Upgrade

1. Super-Kamiokande detector

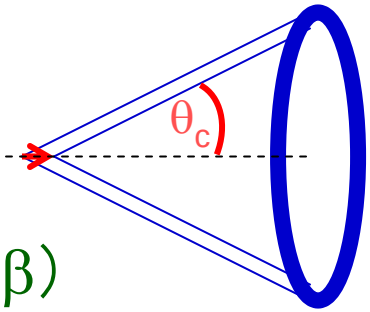
Ring imaging water Cherenkov detector

Cherenkov light

emission : if $n \cdot \beta > 1$

n : refractive index

$\beta = p / E$



direction : $\cos\theta_c = 1/(n \cdot \beta)$

$n_{water} \sim 1.33$ ➔ $\theta_c \sim 42$ degree.

of emitted Cherenkov photons

➔ ~ 340 photons / 1cm

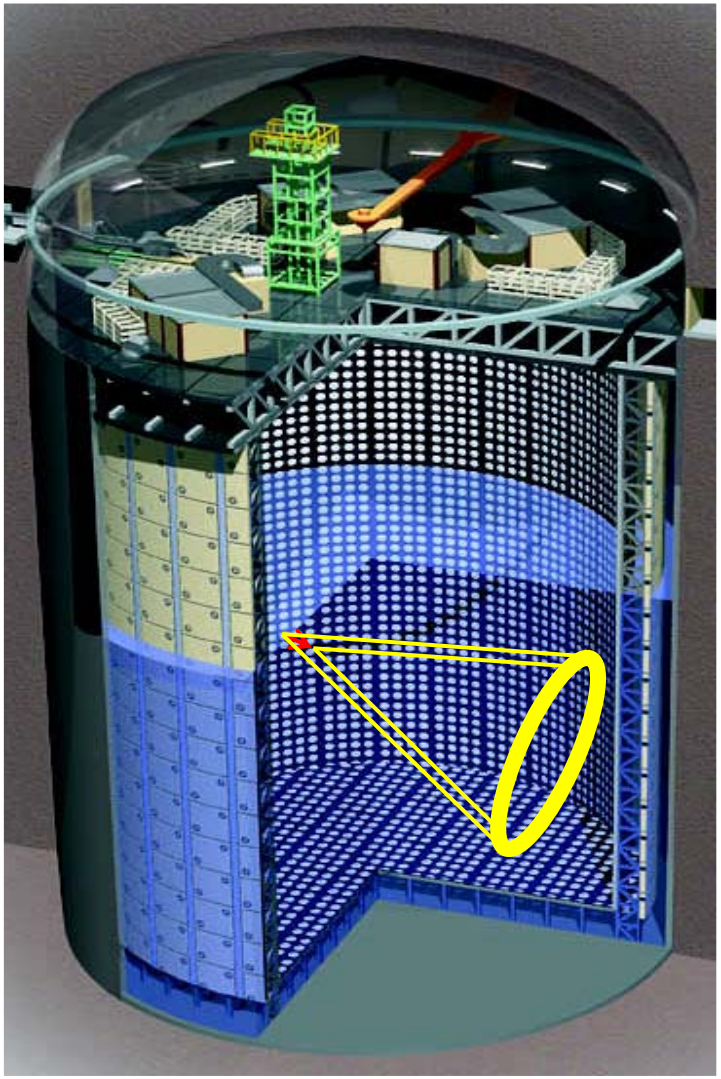
$$\frac{d^2 N_{photon}}{d\lambda dL} = \frac{2p\alpha Z^2}{\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right)$$

Sensitive wave length of PMT: 300 ~ 600nm)

Cherenkov angle θ=42 degree, Z (charge) =1

Detected # of photons used are much smaller.

PMT quantum efficiencies, PMT coverage, light absorption in the water etc..



1. Super-Kamiokande detector

Ring imaging water Cherenkov detector

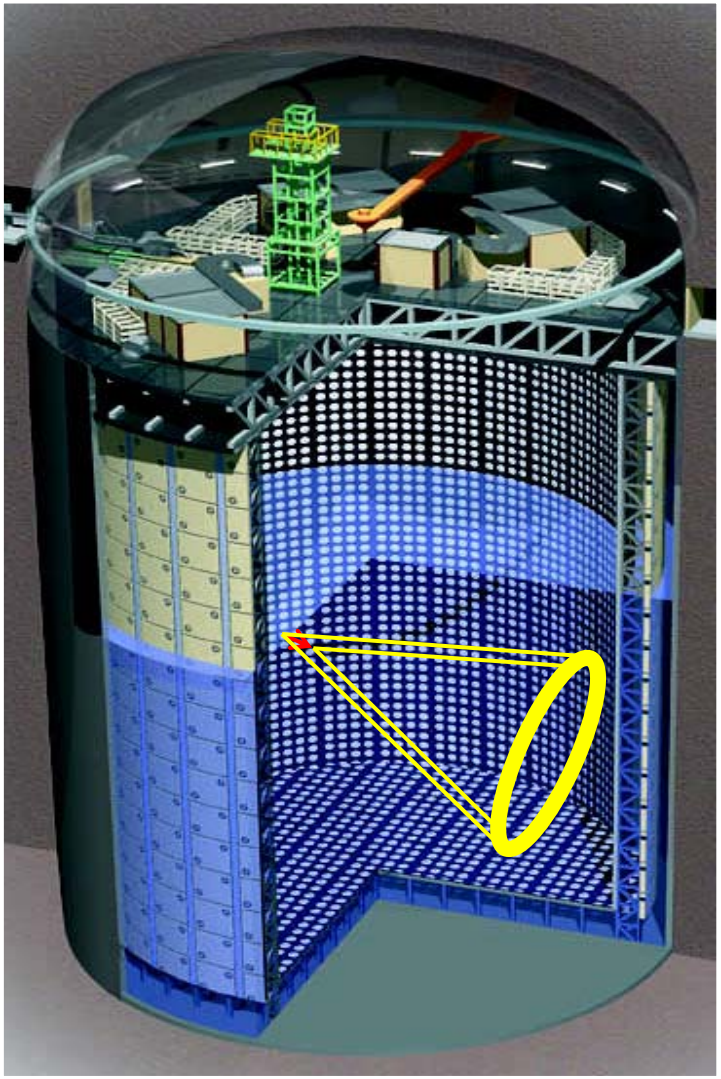
Event reconstruction methods

Amount of the Cherenkov photons
∝ Momentum of the particle
➡ Use observed # of photons
to reconstruct energy.

Interaction position
~ starting point of the charged particle
➡ Use photon arrival timing.
Ring pattern is also used
for the precise reconstruction.

of the charged particles & γ
➡ # of the Cherenkov rings

Also, electrons generated
by the decay of μ, π etc.
gives useful information.



1. Super-Kamiokande detector

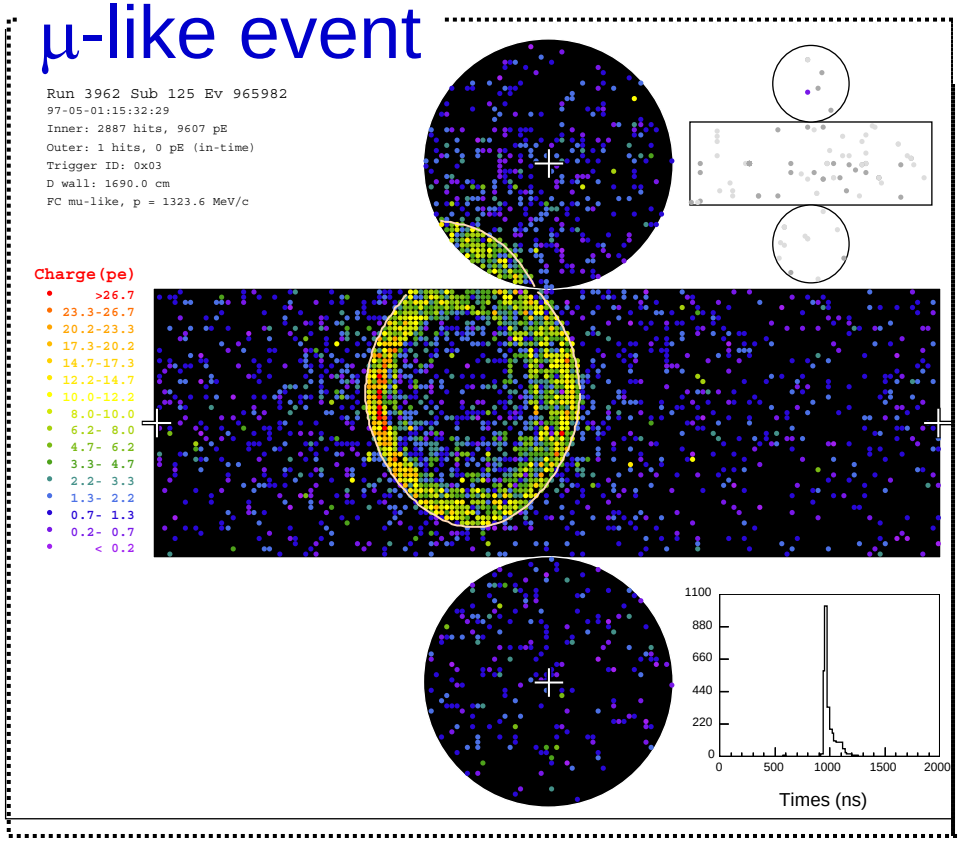
Ring imaging water Cherenkov detector

Pattern of the Cherenkov ring depends on the particle type

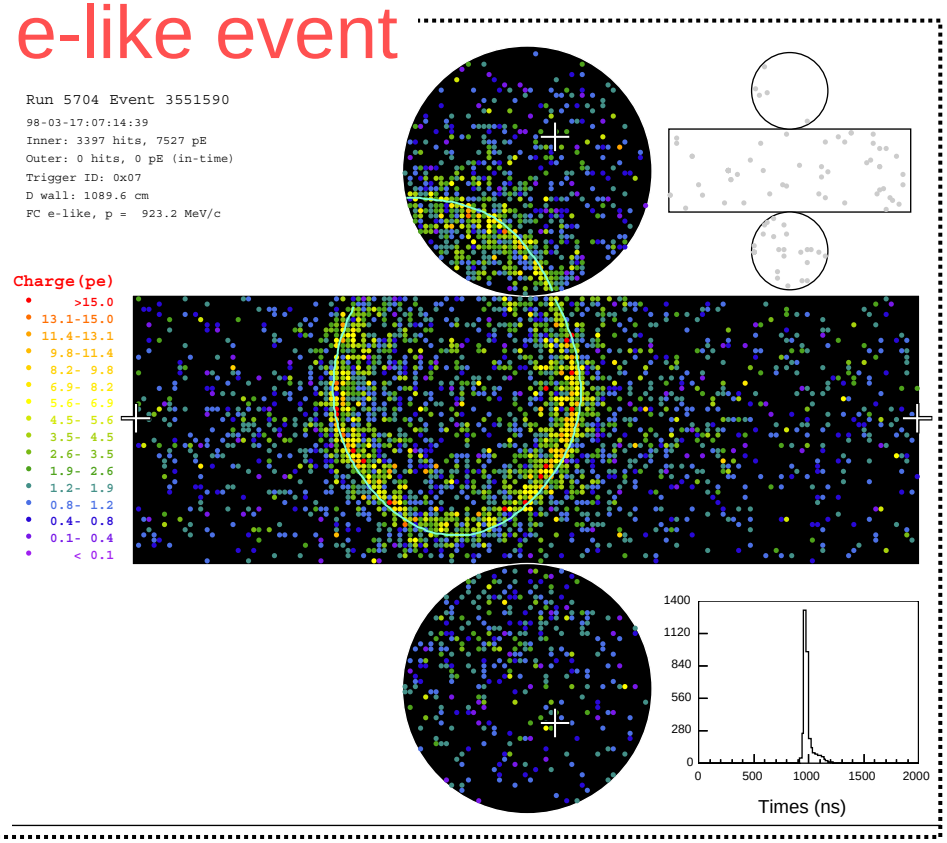
Particle type can be identified using the shape of the ring.

Electron (or gamma) generates electro-magnetic shower and ring is more diffused compared to the muon.

μ-like event



e-like event

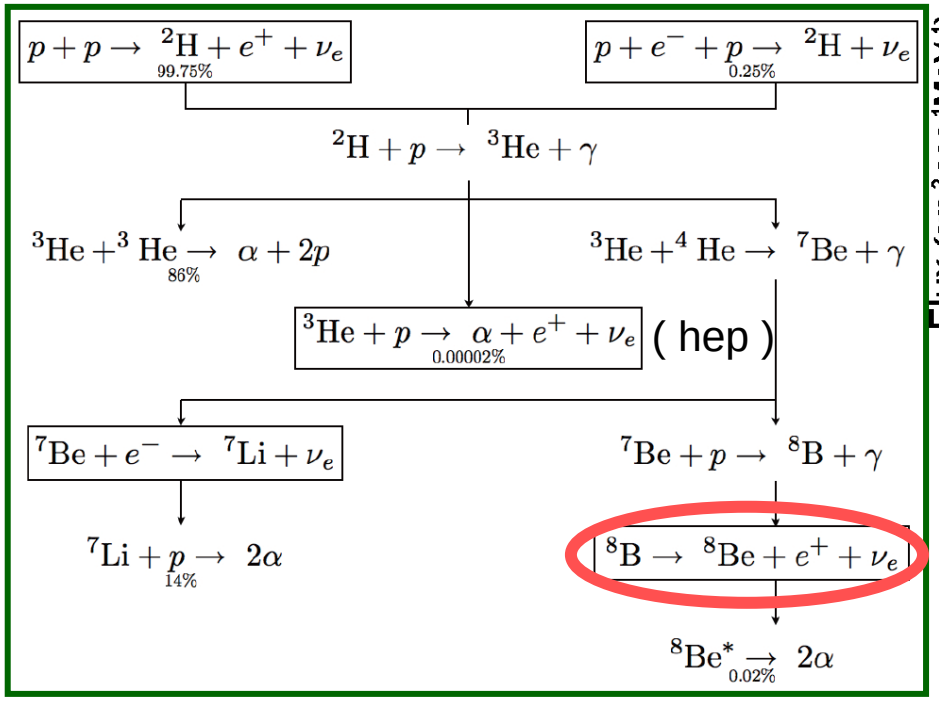


Solar neutrino

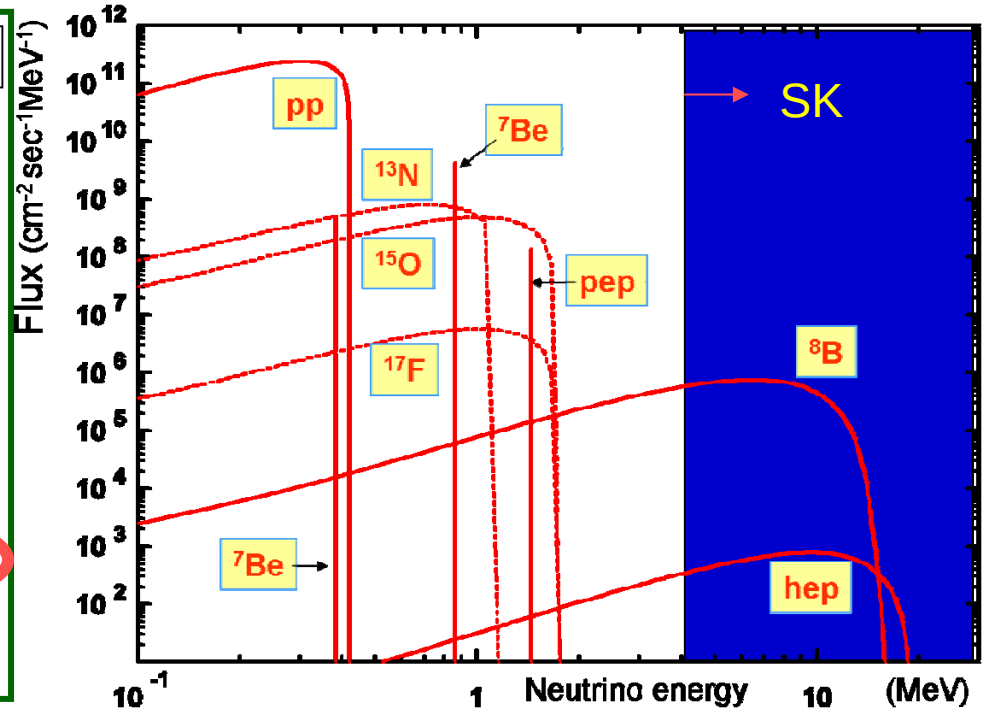
Solar neutrino is produced by the nuclear fusion reaction

$4p \rightarrow \alpha + 2e^{+} + 2\nu_e$ (*pp* chain , ~ 99% luminosity)

pp chain



Energy spectrum of solar ν



SK : Sensitive to the ^{8}B neutrinos & hep neutrinos

(Energy threshold ~ 5MeV)

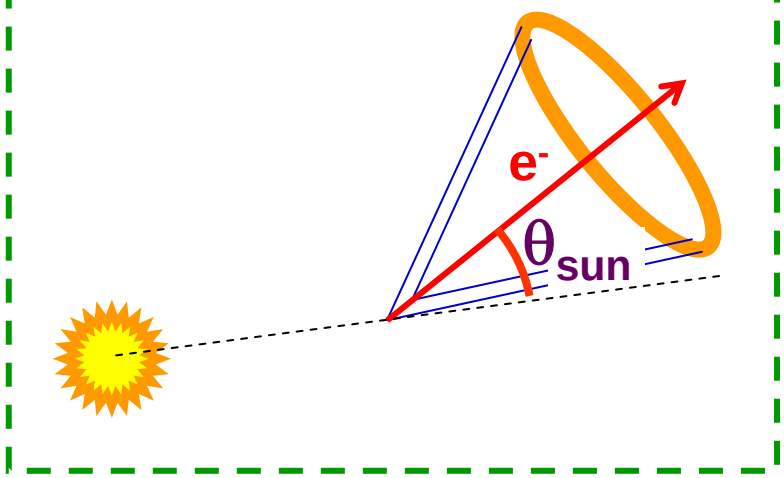
Solar neutrino observation in SK

- Use neutrino-electron scattering ($\nu + e \rightarrow \nu + e$)

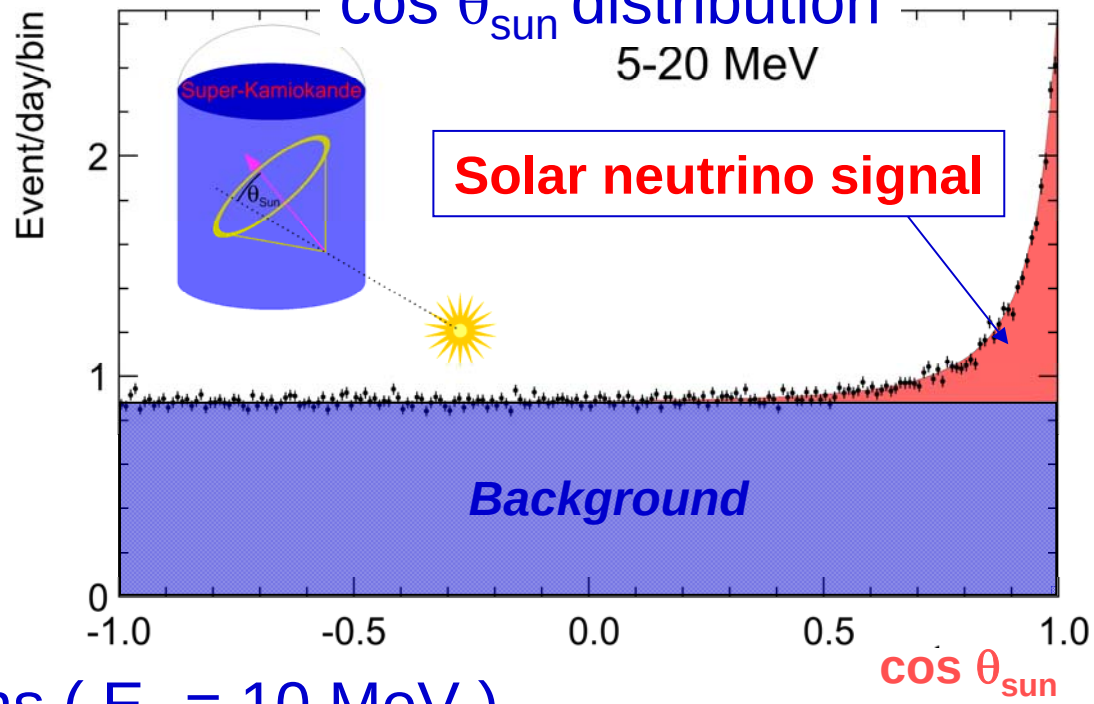
  Correlation between the ν and electron is very strong.

  Use "cos θ_{sun}" distribution to identify solar neutrino

Definition of θ_{sun}



cos θ_{sun} distribution



- Interaction cross-sections (E_ν = 10 MeV)

$\sigma(\nu_e + e^- \rightarrow \nu_e + e^-)$ ~ 9.5×10^{-44} cm^2

$\sigma(\nu_{\mu,\tau} + e^- \rightarrow \nu_{\mu,\tau} + e^-)$ ~ 1.6×10^{-44} cm^2

Solar neutrino observation in SK

Reconstruction of the low energy events

- Energy reconstruction

  Use # of PMT hits

  # of PMT hits ~6hit / MeV (SK-I, III, IV)

- Vertex reconstruction

  Use timing of PMT hits

Resolutions

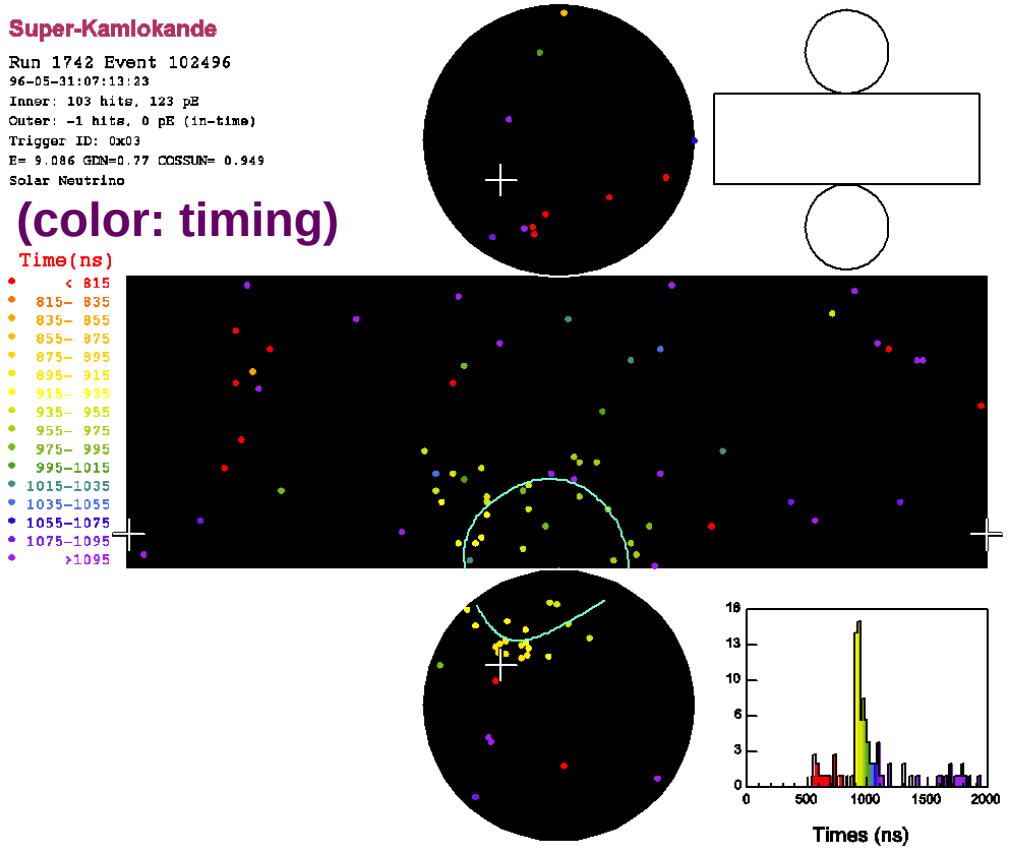
(for 10MeV electrons)

- **Energy** **14%**
- **Vertex** **55cm (SK-III)**
  87cm (SK- I)
- **Direction** **23° (SK-III)**
  26° (SK- I)

(Improved reconstruction was used in the SK-III analysis)

Typical solar ν event candidate

E_e = 9.1MeV, $\cos\theta_{sun}$ = 0.95



Possible signature of the solar neutrino oscillation

1. Reduction of the # of events

Because of the oscillation, # of ν_e reduces
and # of the other ν flavors increases.

➡ Due to the difference of the cross-sections,
observed # of events are reduced.

Interaction cross-sections (E_ν = 10 MeV)

$\sigma(\nu_e + e^- \rightarrow \nu_e + e^-)$ **~ 9.5 x 10^{-44} cm^2**

$\sigma(\nu_{\mu,\tau} + e^- \rightarrow \nu_{\mu,\tau} + e^-)$ **~ 1.6 x 10^{-44} cm^2**

2. Day / Night event rate difference

When the neutrino goes through the core of the earth,
the oscillation probability is affected by the MSW effect.

3. Gradual change of the oscillation effect

Transition from the matter effect dominant region
to the vacuum oscillation dominant region
could be observed by lowering the energy threshold.

Solar neutrino observation in SK

Preliminary

Data summary (Latest data sets from SK-III)

- Total live time — 548 days, $E_{total} \geq 6.5$ MeV
  289 days, $E_{total} > 5.0$ MeV
- Energy region — $E_{total} = 5.0 \sim 20.0$ MeV
- ^{8}B neutrino flux — 2.32+/-0.04(stat.)+/-0.05(syst.)

  ($\times 10^6$/cm^2/s)

  SK- I 2.38+/-0.02(stat.)+/-0.08(syst.)

  SK-II 2.41+/-0.05(stat.)+0.16/-0.15(syst.)

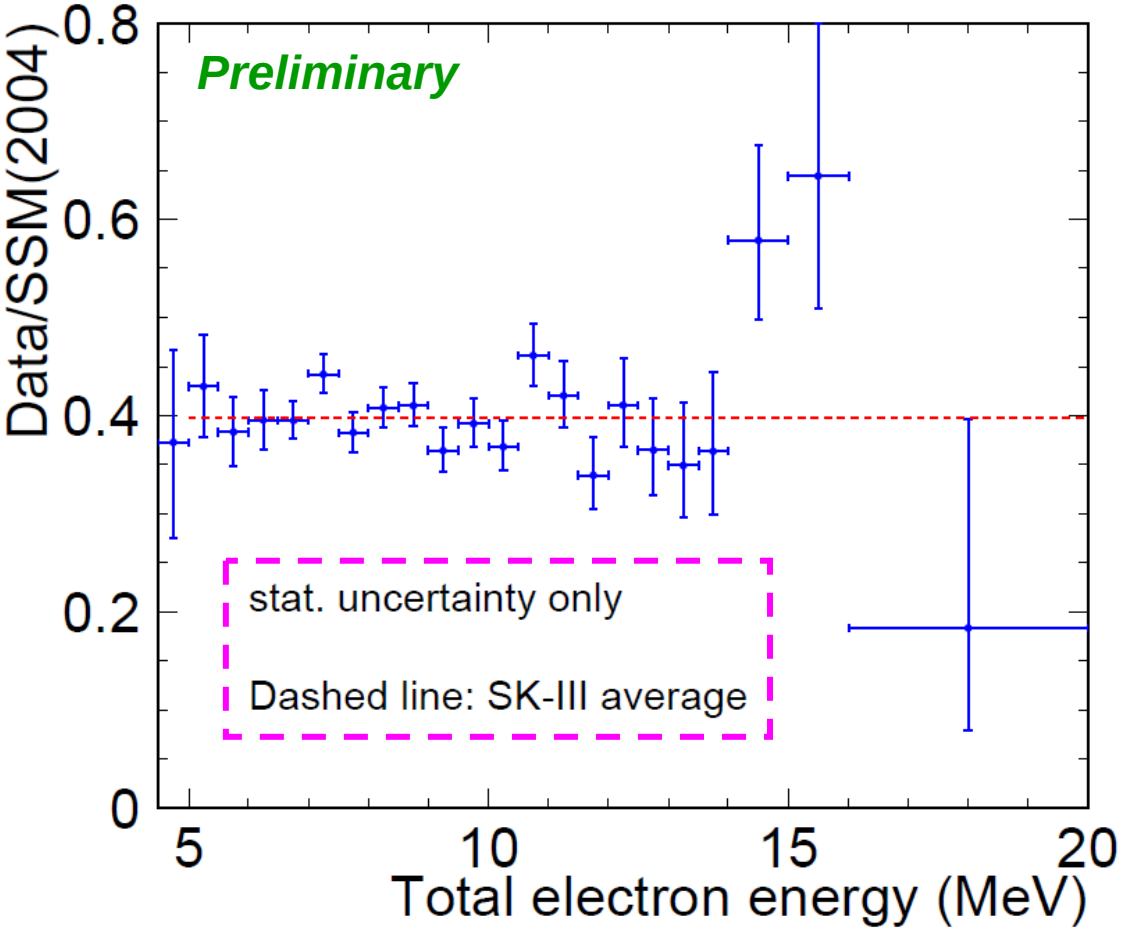
  (Using Winter06 ^{8}B spectrum)
- Day / Night ratio

$$A_{DN} = \frac{(\Phi_{Day} - \Phi_{Night})}{(\Phi_{Day} + \Phi_{Night})/2}$$

$$= -0.056 \pm 0.031(\text{stat.}) \pm 0.013(\text{syst.})$$

Solar neutrino observation in SK

Observed electron energy spectrum divided by the expectation from ^{8}B neutrino



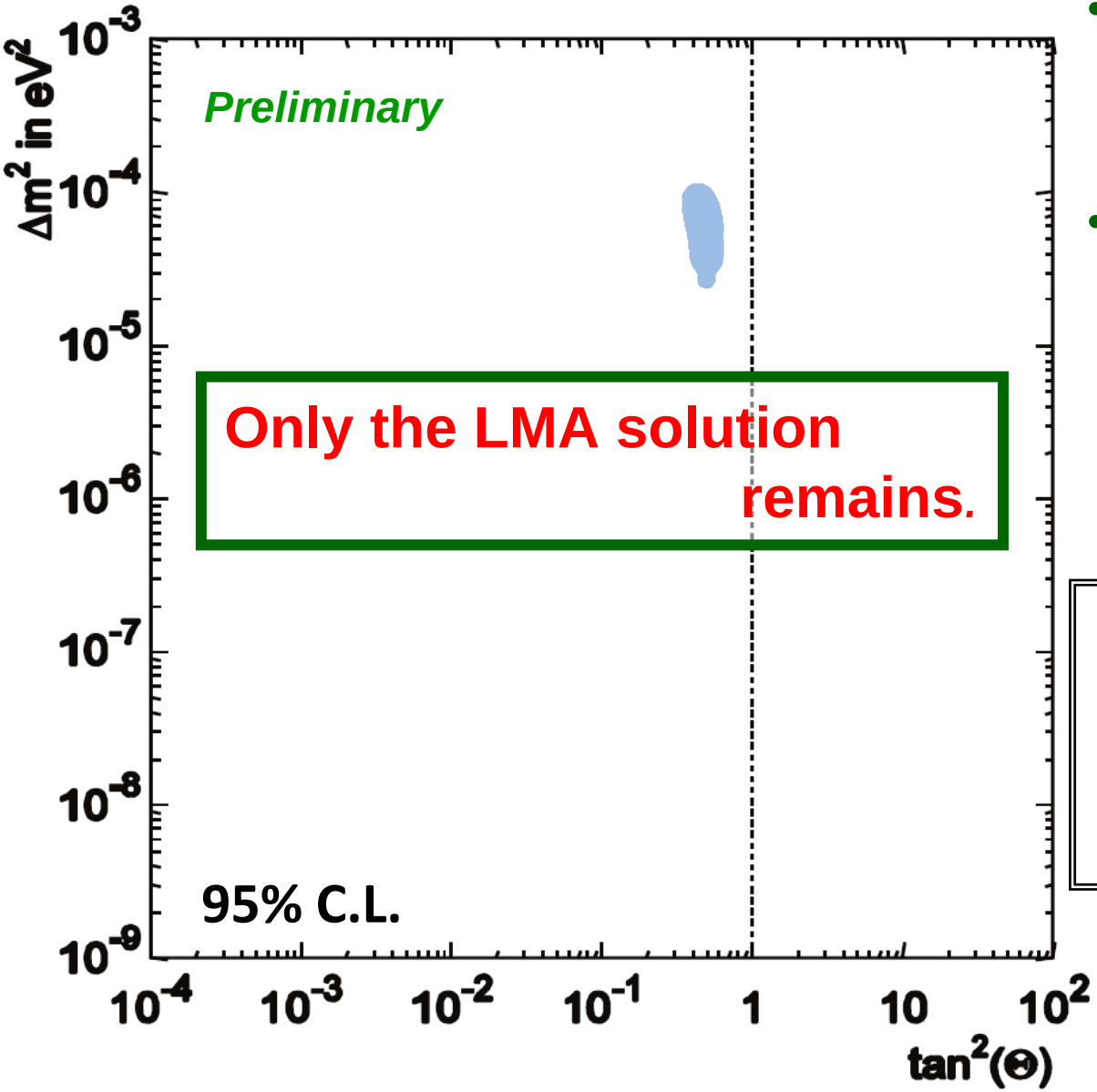
Consistent with flat

So far, no apparent energy distortion is observed.

***) Lowest energy bin (4.5-5.0 MeV) is not used in the neutrino oscillation analysis.**

Solar neutrino oscillation analysis results 1

2-flavor SK-I/II/III with flux constraint

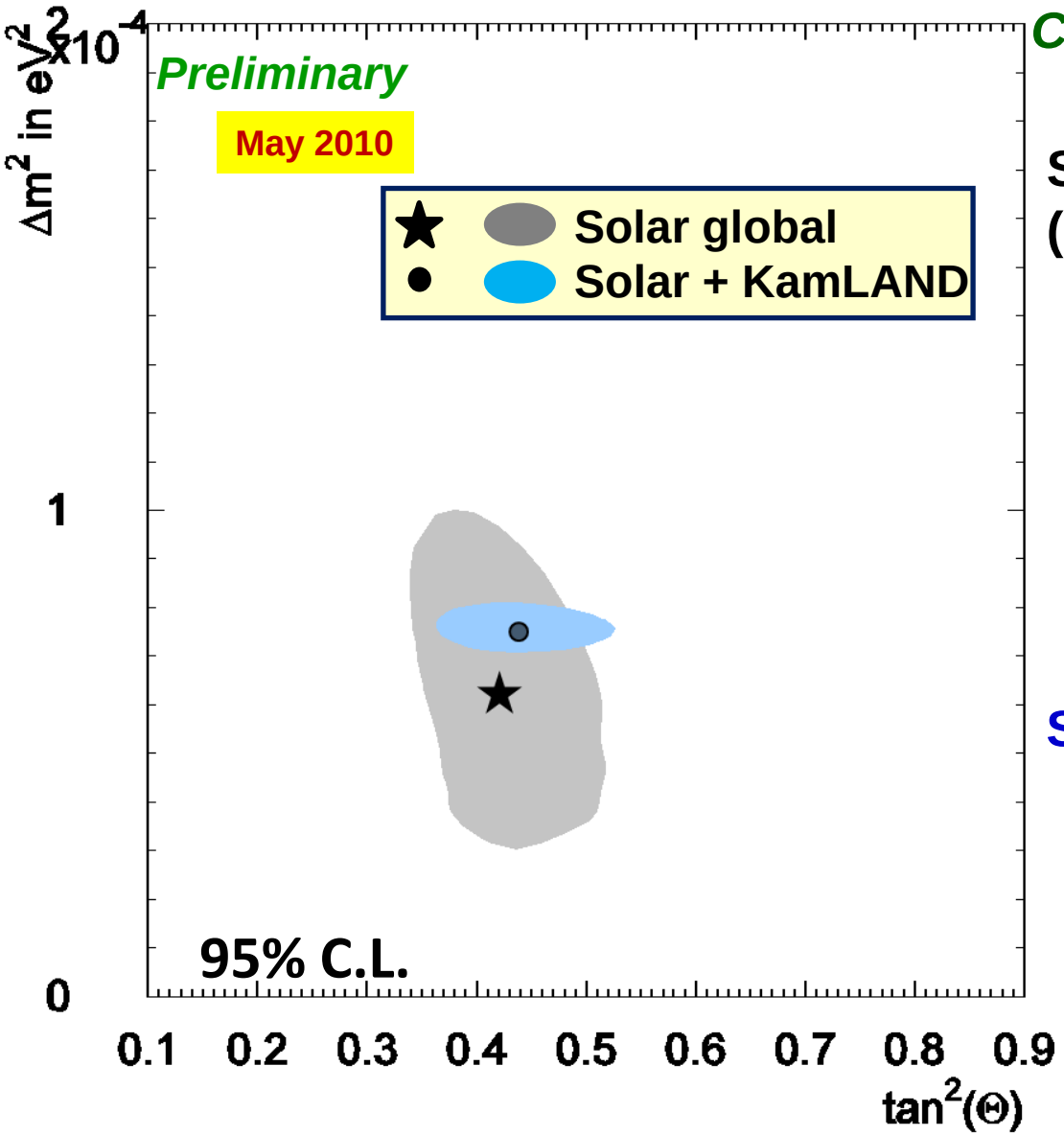


- **^{8}B rate is constrained by SNO(NCD+LETA) NC flux**
  = (5.14+/-0.21) $10^6 cm^{-2} s^{-1}$
- *hep* rate is constrained by SSM flux with uncertainty(16%).

Min χ^2 = 48.8
Δm^2 = 6.1×10^{-5} eV^2
$\tan^2\theta$ = 0.48
Φ_{B8} = $0.89 \times \Phi_{B8,SSM}$

Solar neutrino oscillation analysis results 2

2-flavor global analysis



Combine the results from the other experiments.

Solar global
(SK + SNO + Cl + Ga + Borexino)

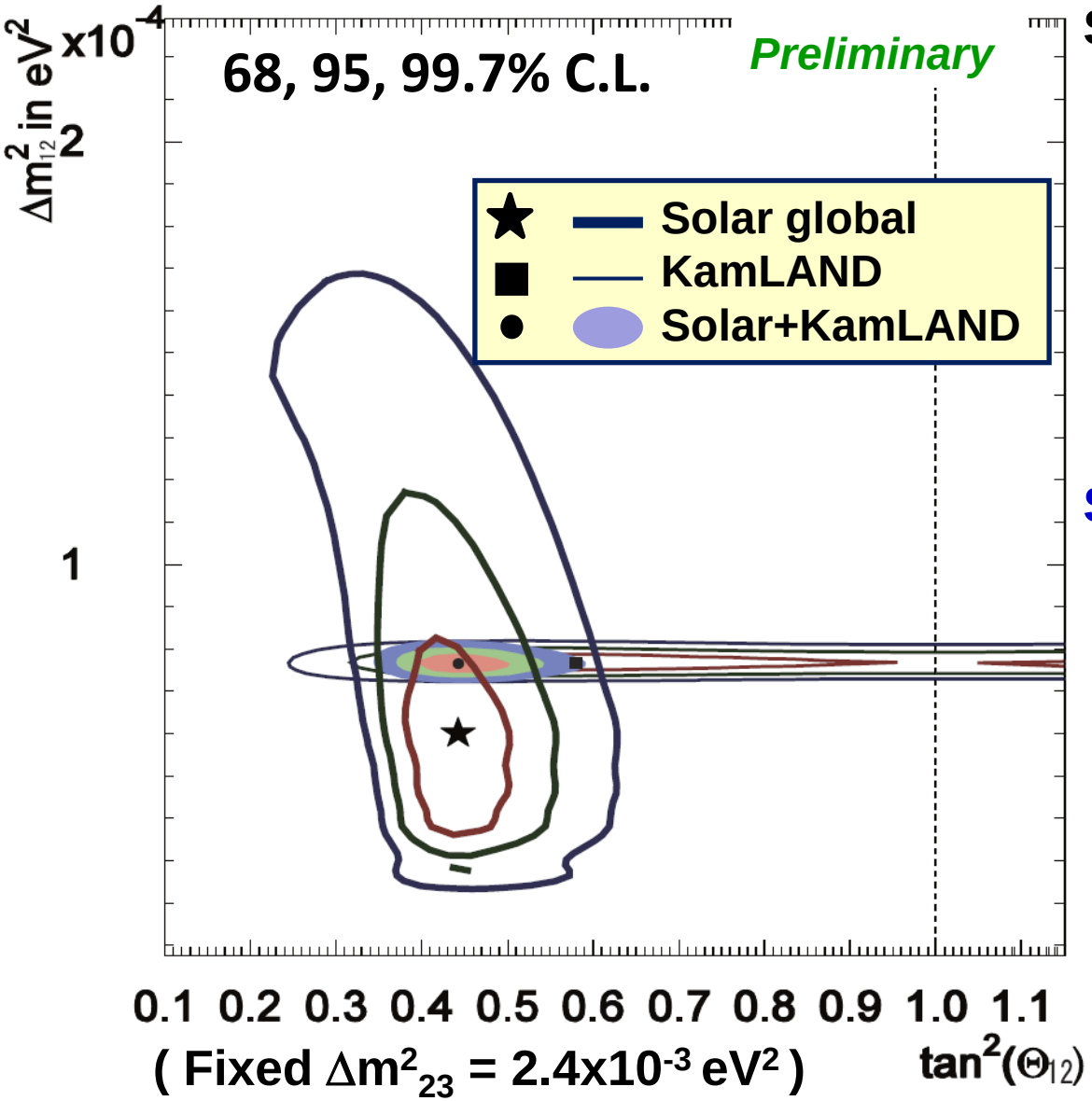
Min χ^2 = 53.7
$\Delta m^2 = 6.2 \times 10^{-5}$ eV^2
$\tan^2\theta = 0.42$
$\Phi_{B8} = 0.92 \times \Phi_{B8,SSM}$

Solar global + KamLAND

Min χ^2 = 57.7
$\Delta m^2 = 7.6 \times 10^{-5}$ eV^2
$\tan^2\theta = 0.44$
$\Phi_{B8} = 0.89 \times \Phi_{B8,SSM}$

Solar neutrino oscillation analysis results 3

3-flavor analysis: θ_{12} - Δm_{12}^2



(Fixed $\Delta m^2_{23} = 2.4\times10^{-3}$ eV^2)

Solar global

Min $\chi^2 = 52.8$
$\Delta m^2 = 6.0 \times 10^{-5}$ eV^2
$\tan^2\theta = 0.44$
$\sin^2\theta_{13} = 0.010$
$\Phi_{B8} = 0.92 \times \Phi_{B8,SSM}$

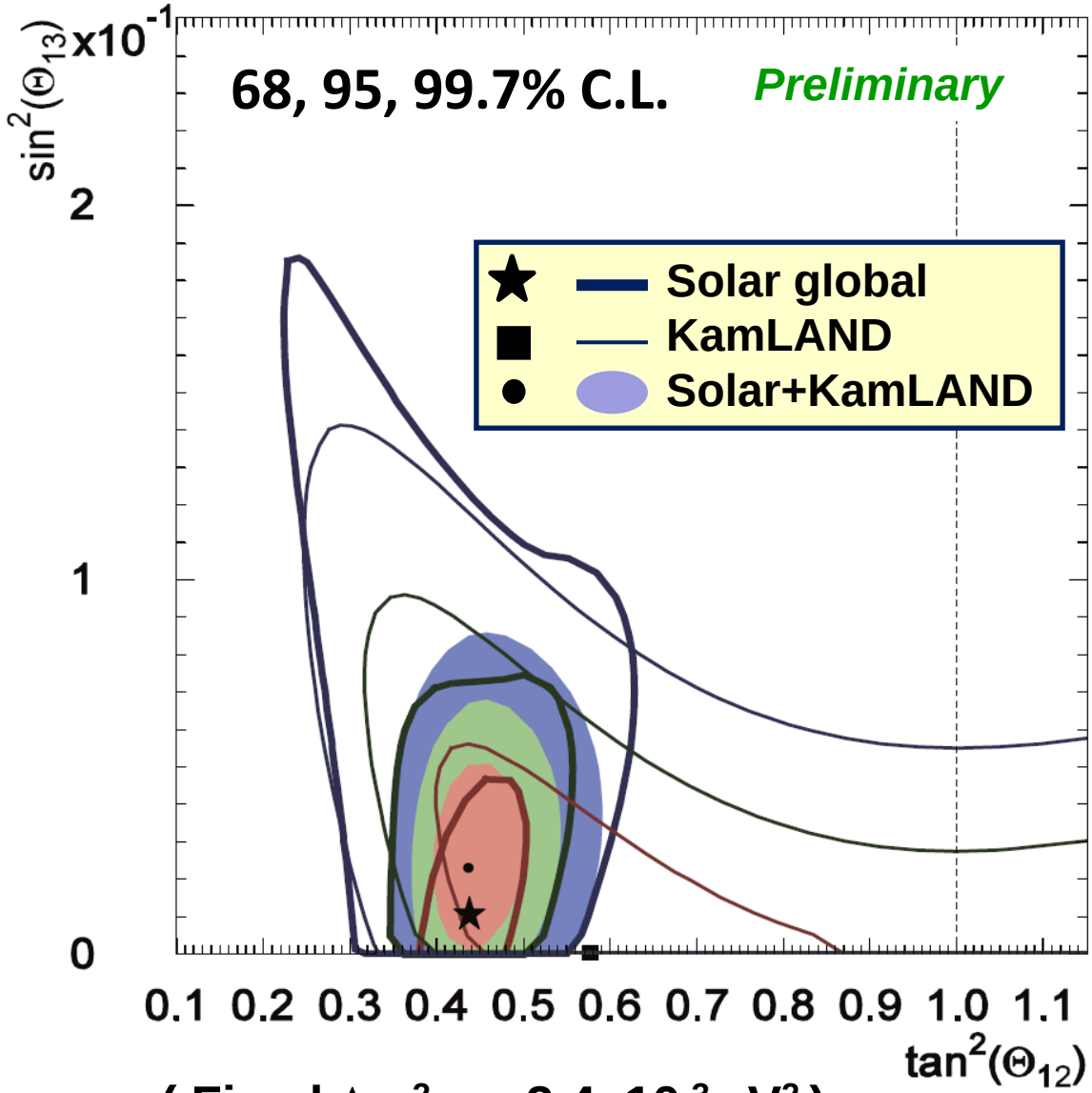
Solar global + KamLAND

Min $\chi^2 = 71.2$
$\Delta m^2 = 7.7 \times 10^{-5}$ eV^2
$\tan^2\theta = 0.44$
$\sin^2\theta_{13} = 0.025$
$\Phi_{B8} = 0.91 \times \Phi_{B8,SSM}$

Consistent with the 2 flavor analysis

Solar neutrino oscillation analysis results 4

3-flavor analysis: θ_{12} - θ_{13}



(Fixed $\Delta m^2_{23} = 2.4\times10^{-3}$ eV^2)

Solar global

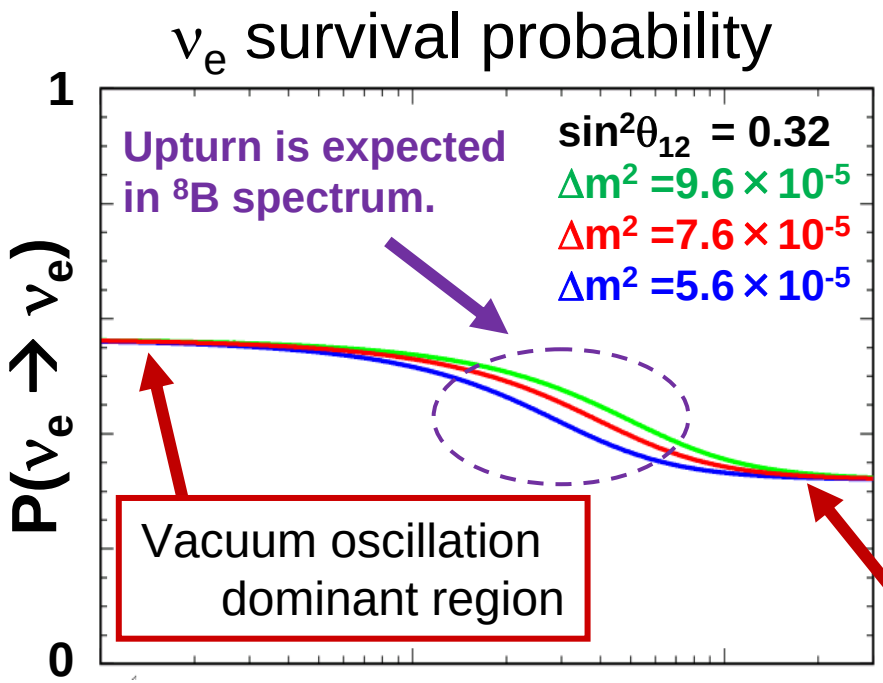
$\sin^2\theta_{13}<0.060$ @95%C.L.

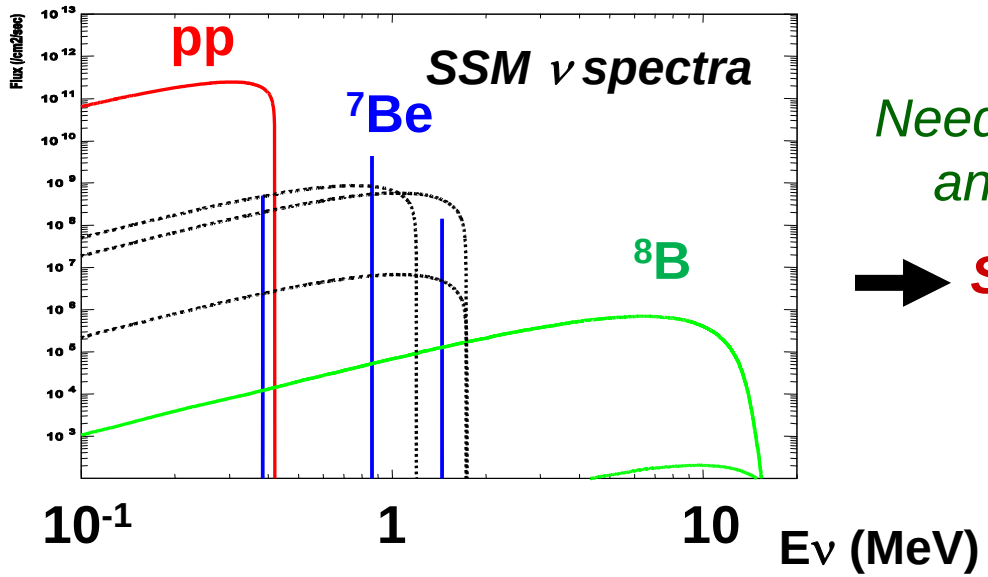
Solar global + KamLAND

$\sin^2\theta_{13}=0.025^{+0.018}_{-0.016}$ (<0.059 @95%C.L.)

Cf. SNO 3 flavor results
$\sin^2\theta_{13}=0.020+0.021-0.016$ (<0.057 @95%C.L.)
Ref. PRC81, 055504 (2010)

Future prospect ~ solar neutrino measurement





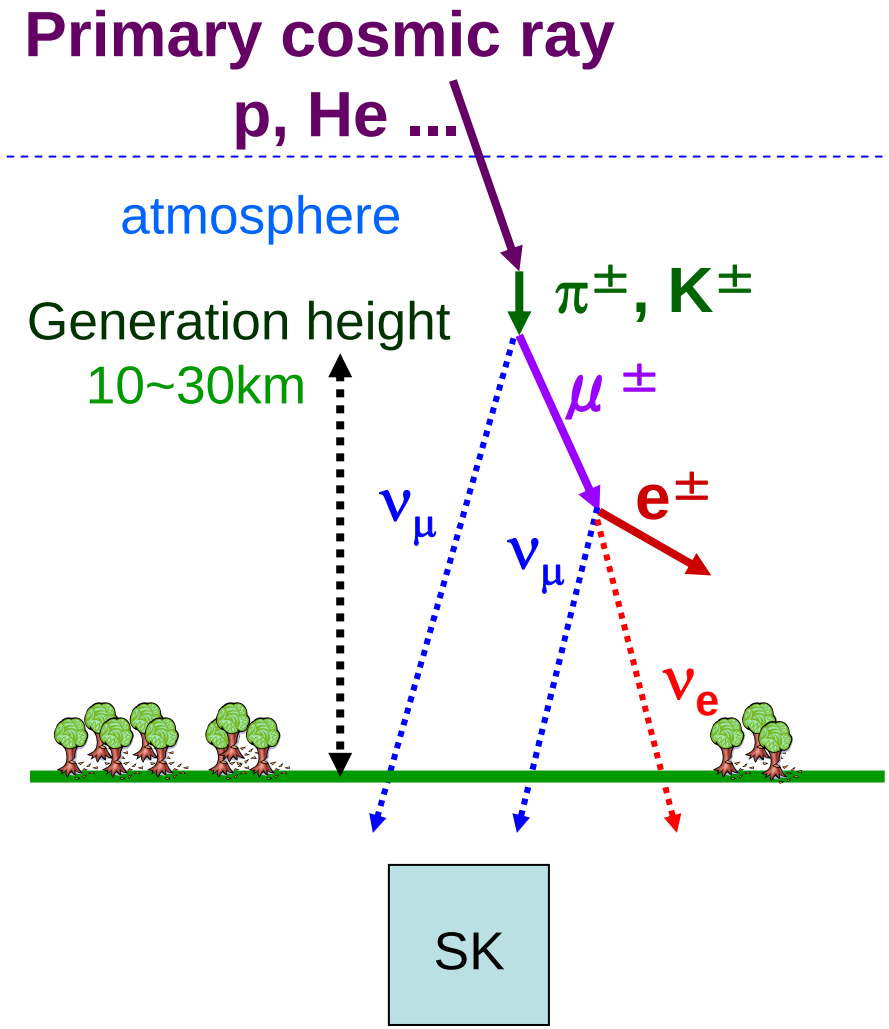
If we can obtain
high purity solar ν sample
in the low energy region,
it will be possible
to observe upturn in SK.

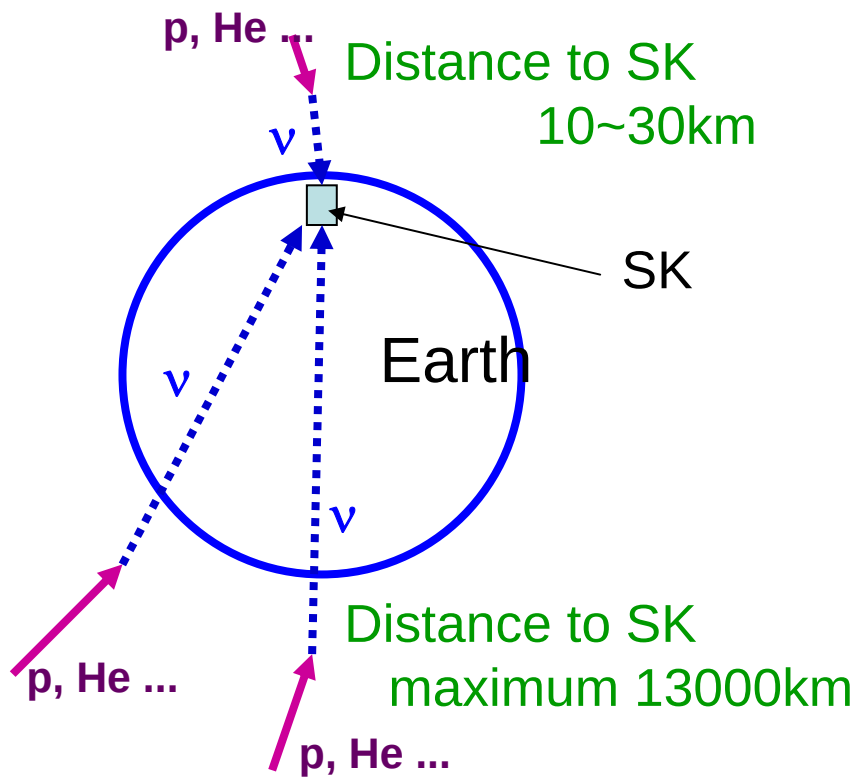
Need to reduce background events,
and also the systematic uncertainties.

Study is going on
and collecting data
with SK4 detector.

Atmospheric neutrino

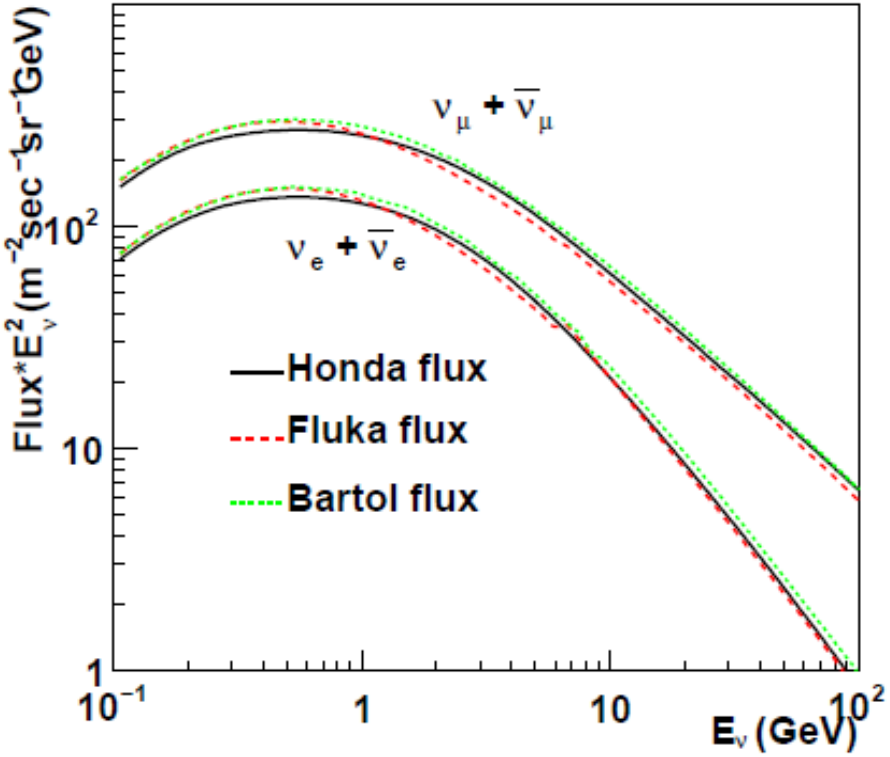
Primary cosmic ray（mainly protons）hit air in atmosphere and generate pions, kaons and other particles.
And then, those particles decay into neutrinos.





Atmospheric neutrino

Atmospheric neutrino Energy spectrum (flux * E_ν^2)



Atmospheric neutrino has broad energy spectrum.

(less than 100 MeV to higher than TeV)

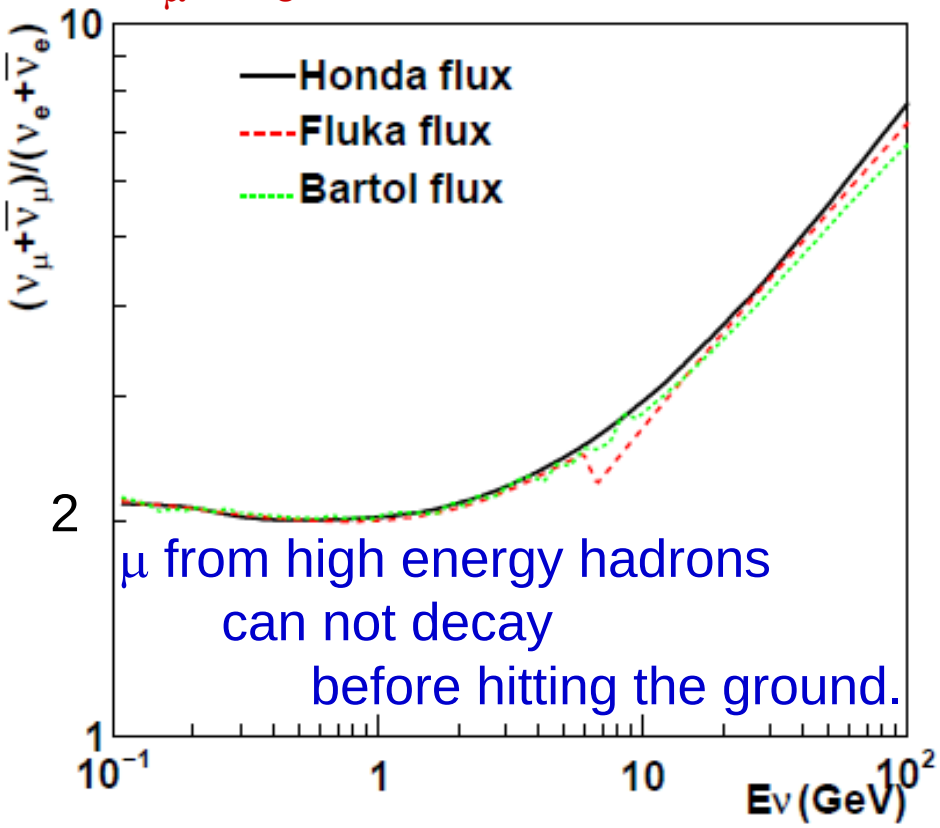
Atmospheric ν production dominant process

$$\pi^+ \rightarrow \nu_\mu + \mu^+$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

(and charge conjugate)

→ $\nu_\mu / \nu_e \sim 2$ **(low energy region)**



μ from high energy hadrons can not decay before hitting the ground.

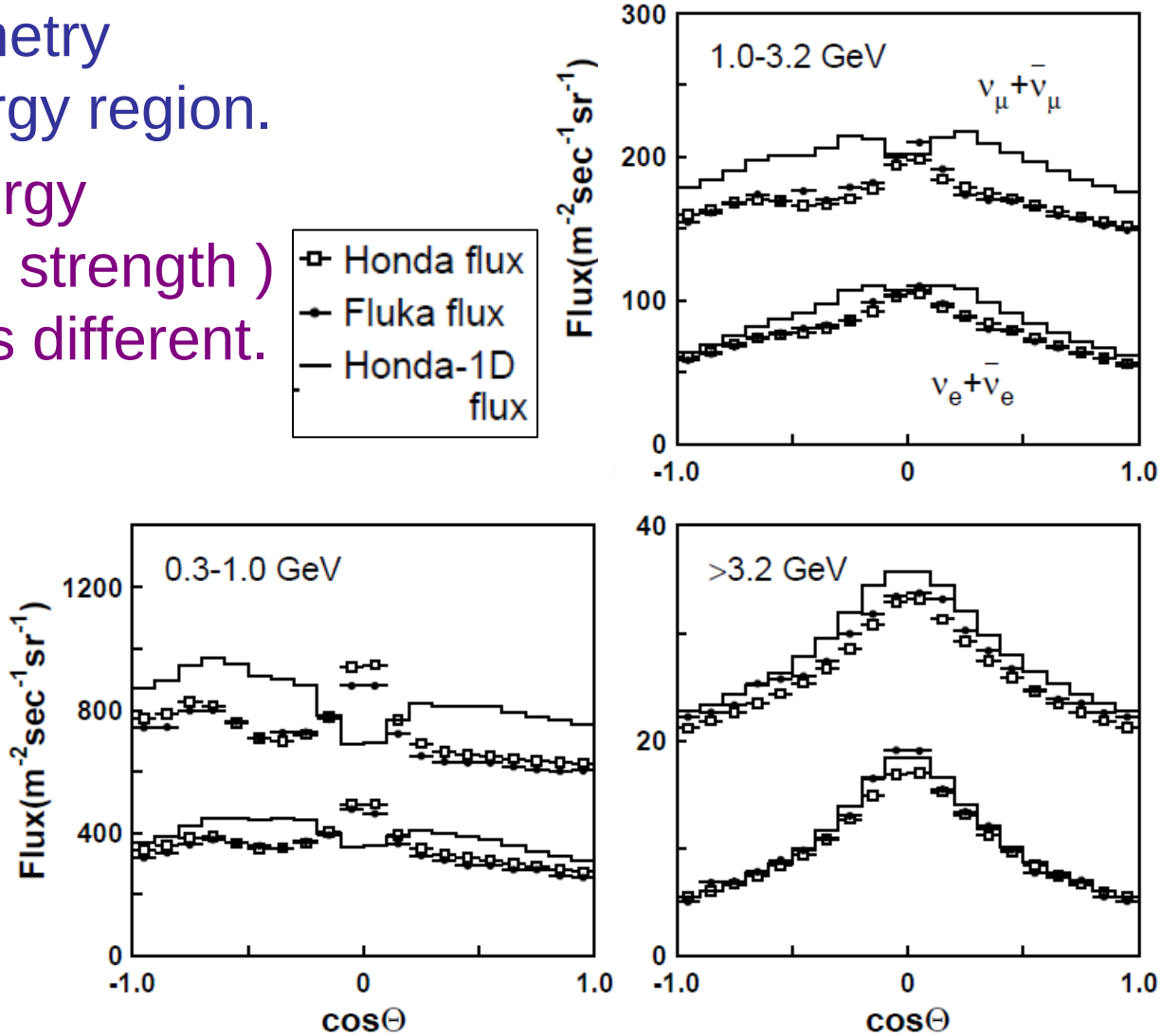
Atmospheric neutrino

Zenith angle distribution of atmospheric neutrinos

Symmetric in the high energy region as expected.

But there is asymmetry
in the lower energy region.

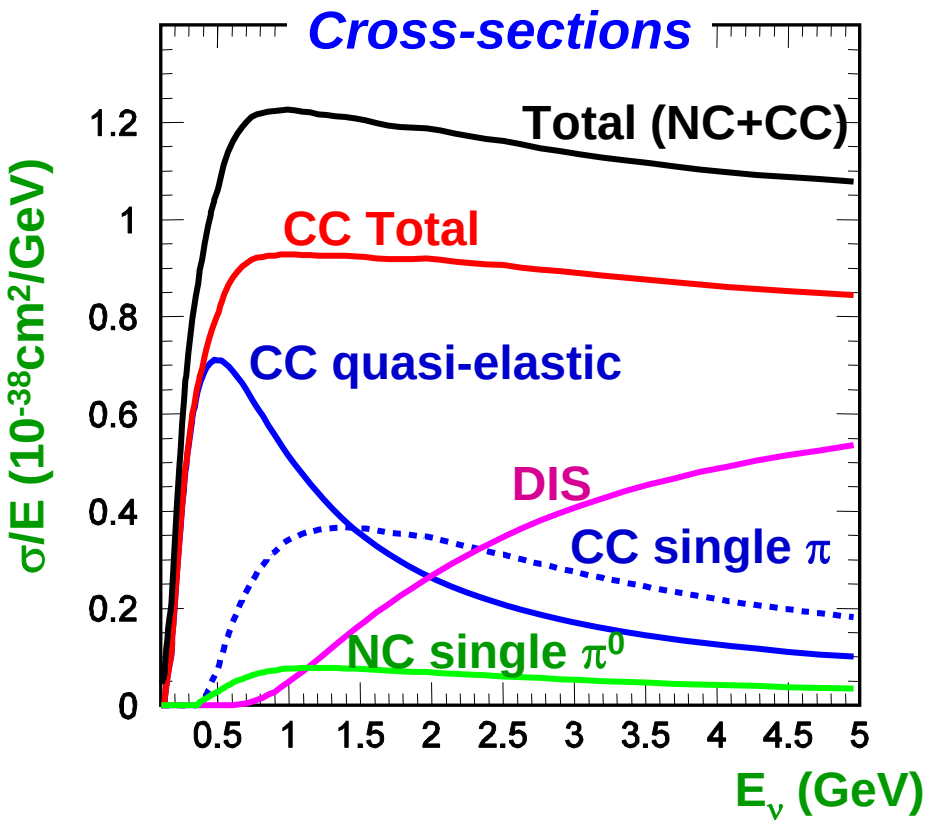
Proton cutoff energy
(magnetic field strength)
is different.

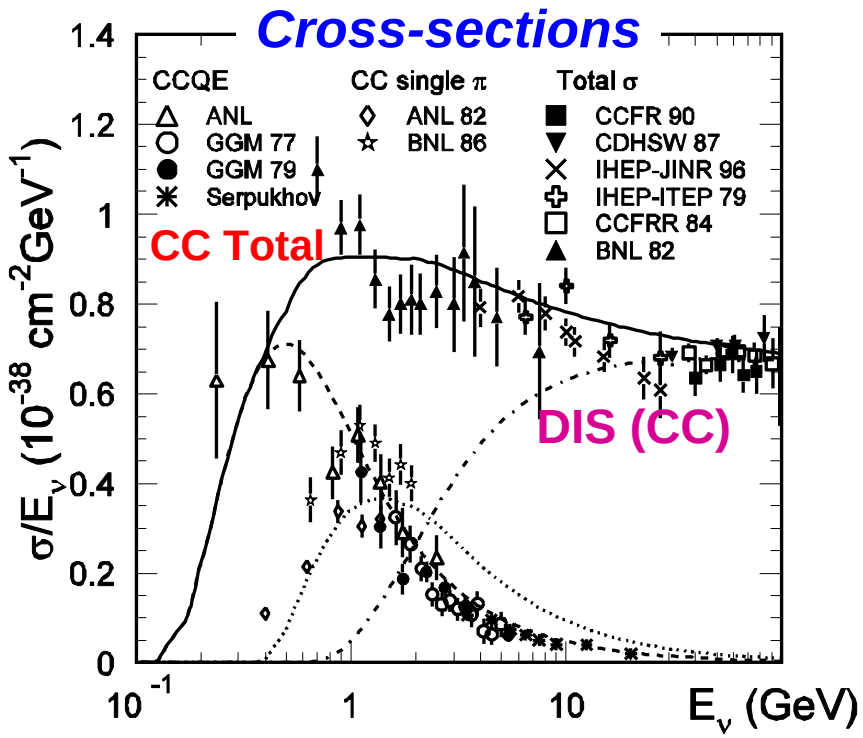


Atmospheric neutrino interactions

Charged current quasi-elastic scattering	$\nu + n \rightarrow l^- + p$
Neutral current elastic scattering	$\nu + N \rightarrow \nu + N$
Single π,η,K resonance productions	$\nu + N \rightarrow l + N' + \pi\ (\eta,K)$
Coherent pion productions	$\nu + X \rightarrow l + X' + \pi$
Deep inelastic scattering	$\nu + N \rightarrow l + N' + m\pi(\eta,K)$

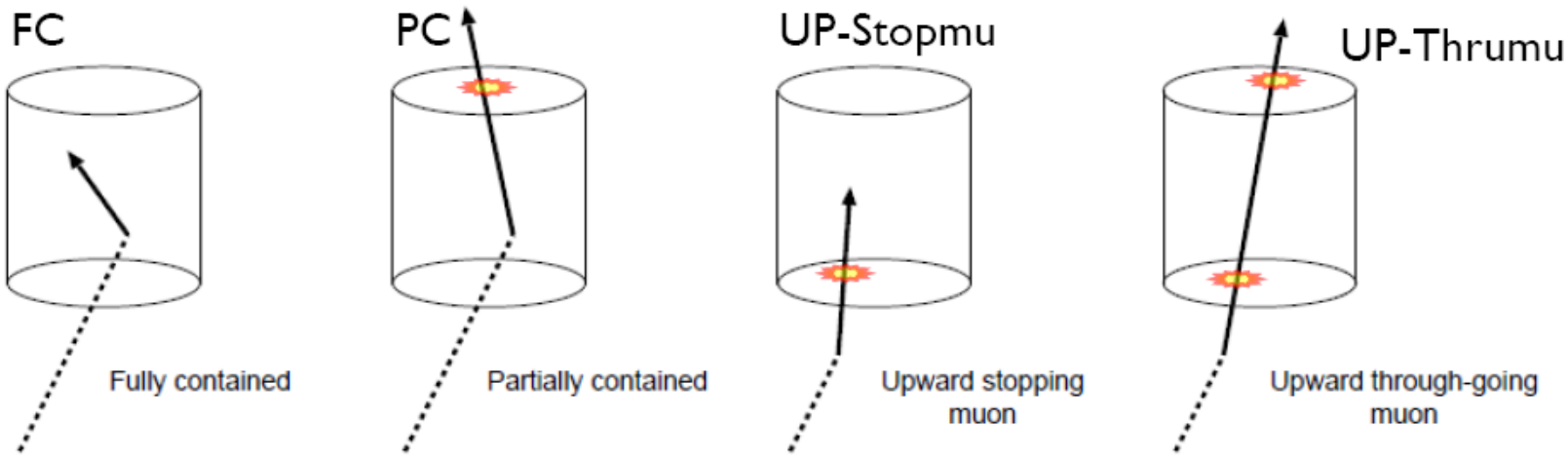
(*l* : lepton, N,N' : nucleon, m : integer)



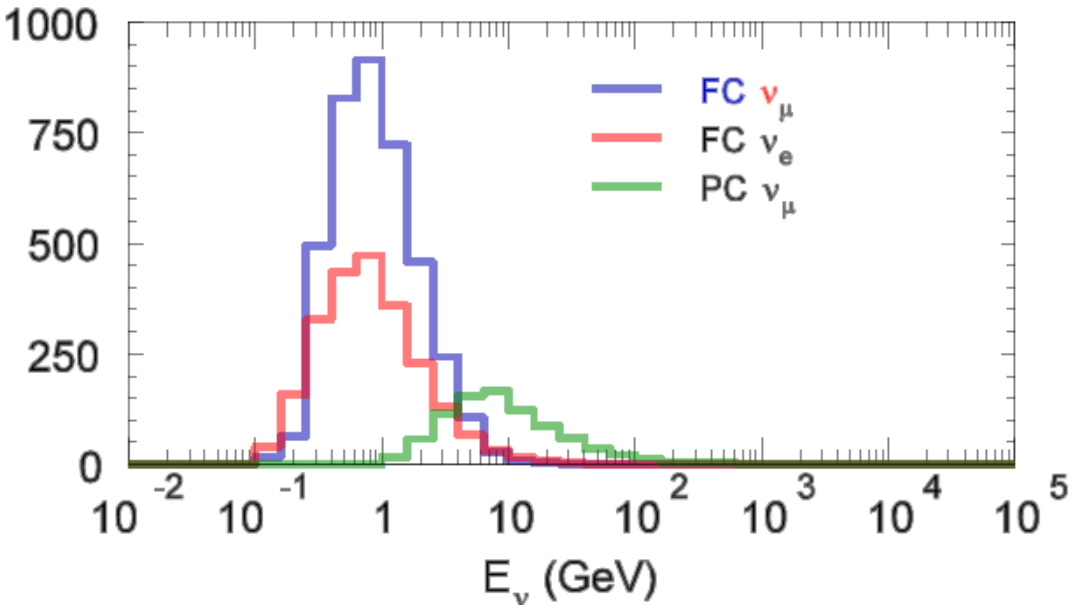


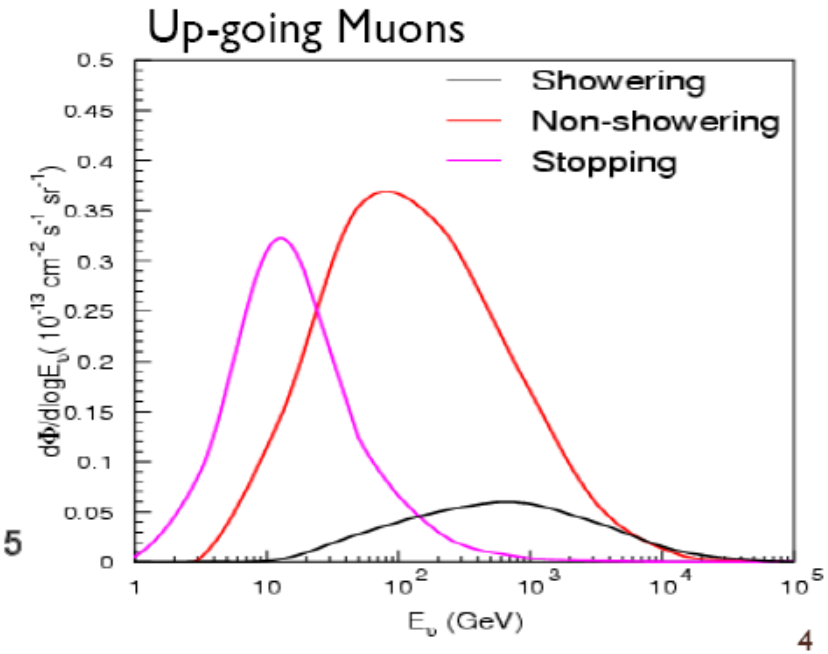
Atmospheric neutrino observation in SK

~ Event types ~



- **Energy spectrum of neutrino**





Atmospheric neutrino observation in SK

Event reconstruction

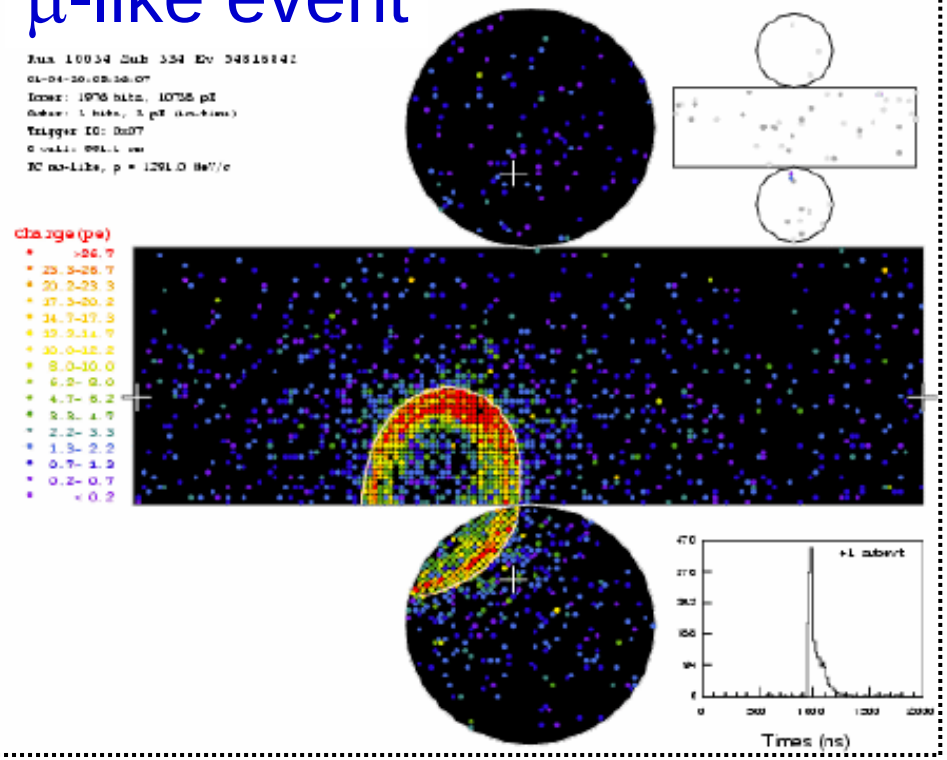
- Energy reconstruction
  Total charge
- Particle type identification
  Charge distribution
  (ring shape)
- Vertex reconstruction
  Use timing of PMT hits
  (for multi ring events)
  Additionally, use charge distribution
  for single ring events.

Reconstruction performances

(for Sub-GeV 1 ring)

- Particle ID > 99%
- Energy
  ~ 3% (μ > 250MeV/c)
  < 4% (e > 500MeV/c)
  ~ 5% (e @ 300MeV/c)
- Vertex ~30cm
- Direction 2~3°

μ-like event



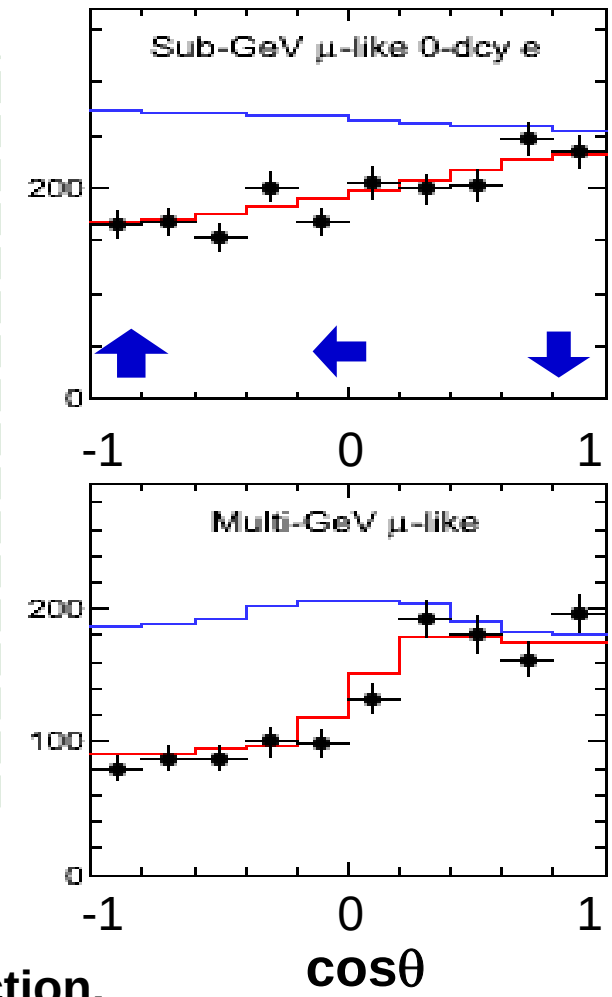
Oscillation analysis using atmospheric neutrino

1. Zenith angle analysis

Fit observed zenith-angle / momentum distributions

Events are split into several sub-samples

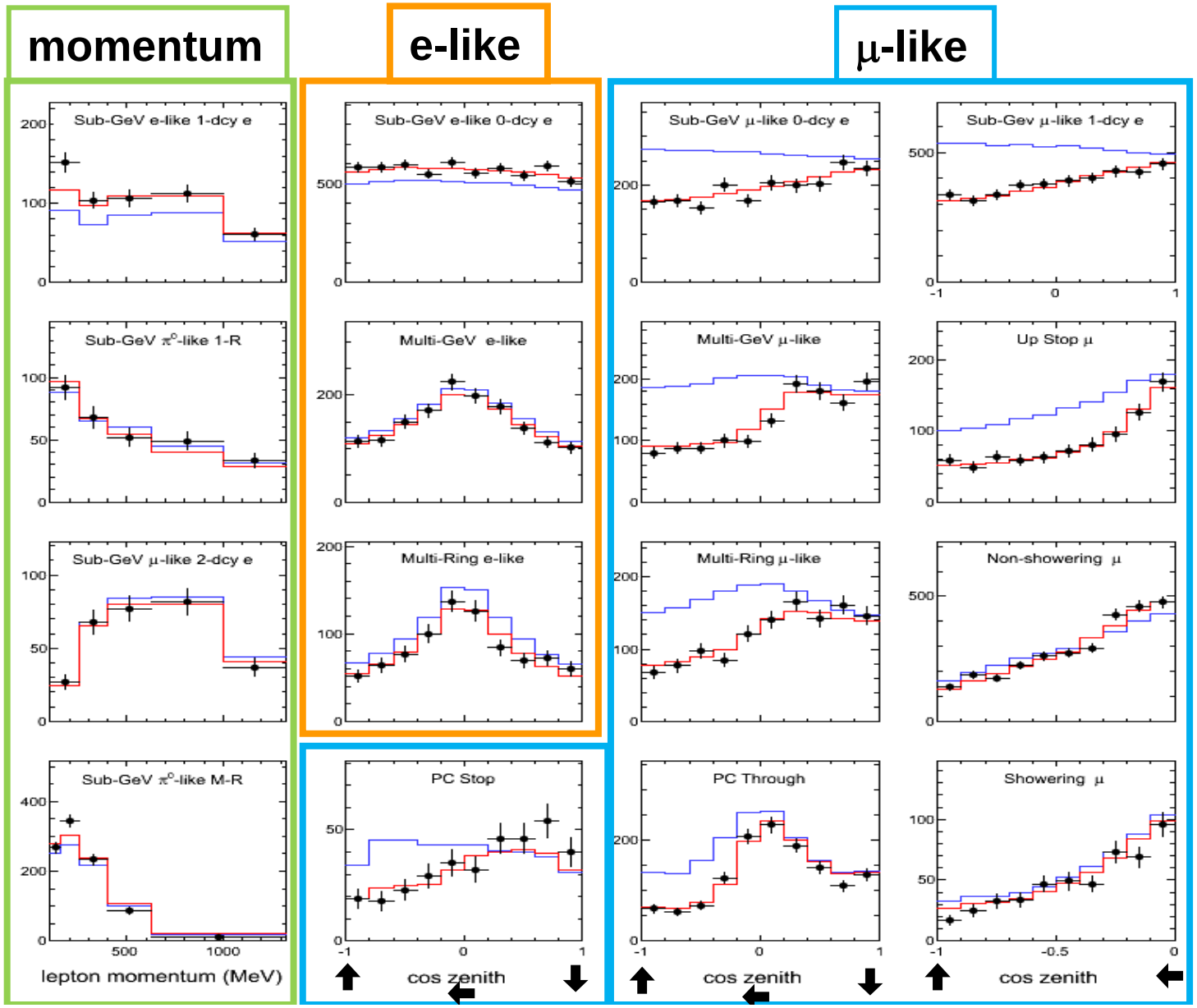
- **Event type**
  - **Fully contained,**
  - **Partially contained,**
  - **Upward through going μ,**
  - **Upward stop showering μ,**
  - **Upward stop non-showering μ,**
  - **π^0-like**
- **Energy range**
- **# of rings (1-ring, multi-ring)**
- **PID (m-like, e-like)**
- **# of decay electrons**



(Some of the samples,
whose zenith angle distribution
do not have correlation with neutrino direction,
are not split in zenith-angle bin.)

Atmospheric neutrino data sample

Zenith angle & lepton momentum distributions



SK-I+II+III

Preliminary

Live time:

SK-I

1489d (FC,PC)

1646d (Up μ)

SK-II

799d (FC,PC)

827d (Up μ)

SK-III

518d (FC,PC)

636d (Up μ)

— null osc.

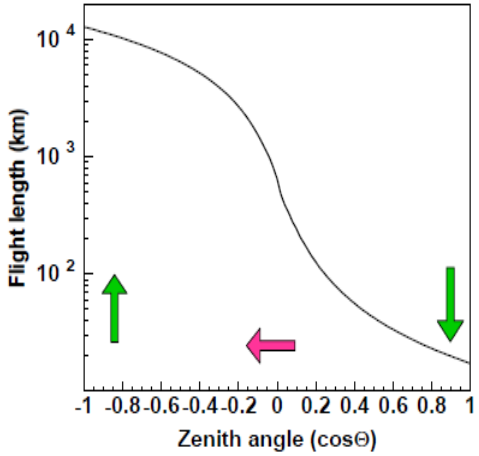
— ν_μ–ν_τ osc.

(best fit)

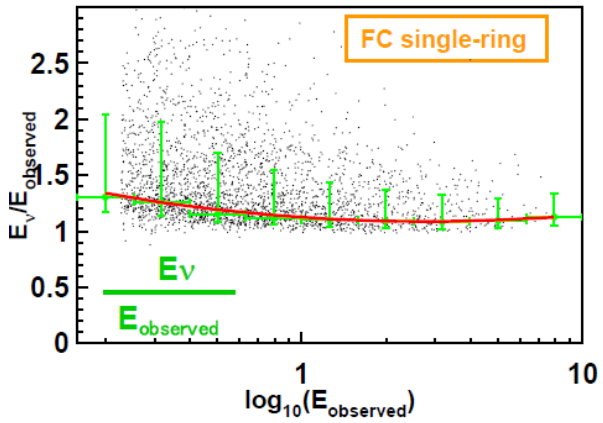
Oscillation analysis using atmospheric neutrino

2. L/E analysis

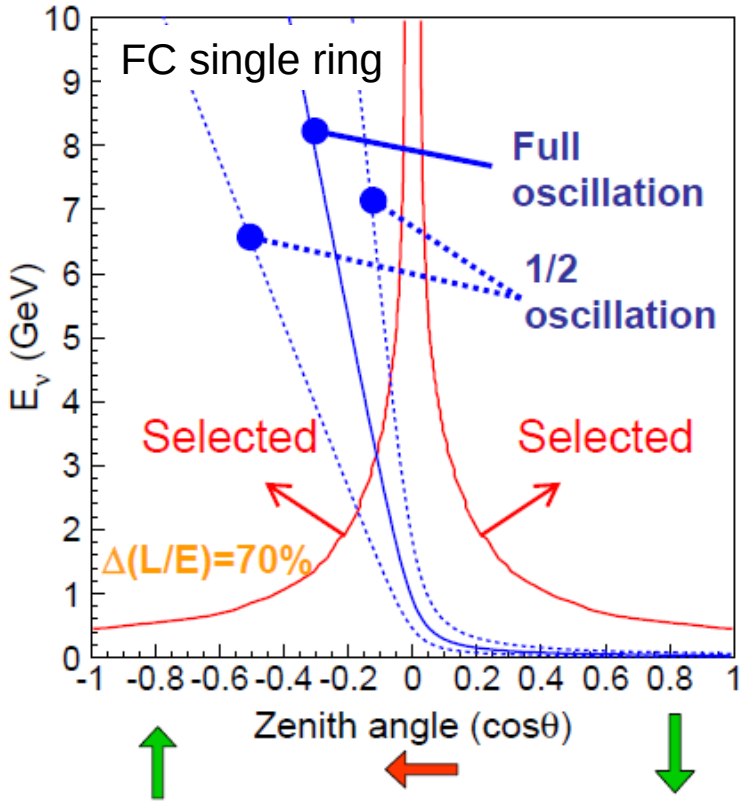
Estimate flight length using observed particle direction.



Estimate neutrino energy from the observed energy (via Monte-Carlo simulation)

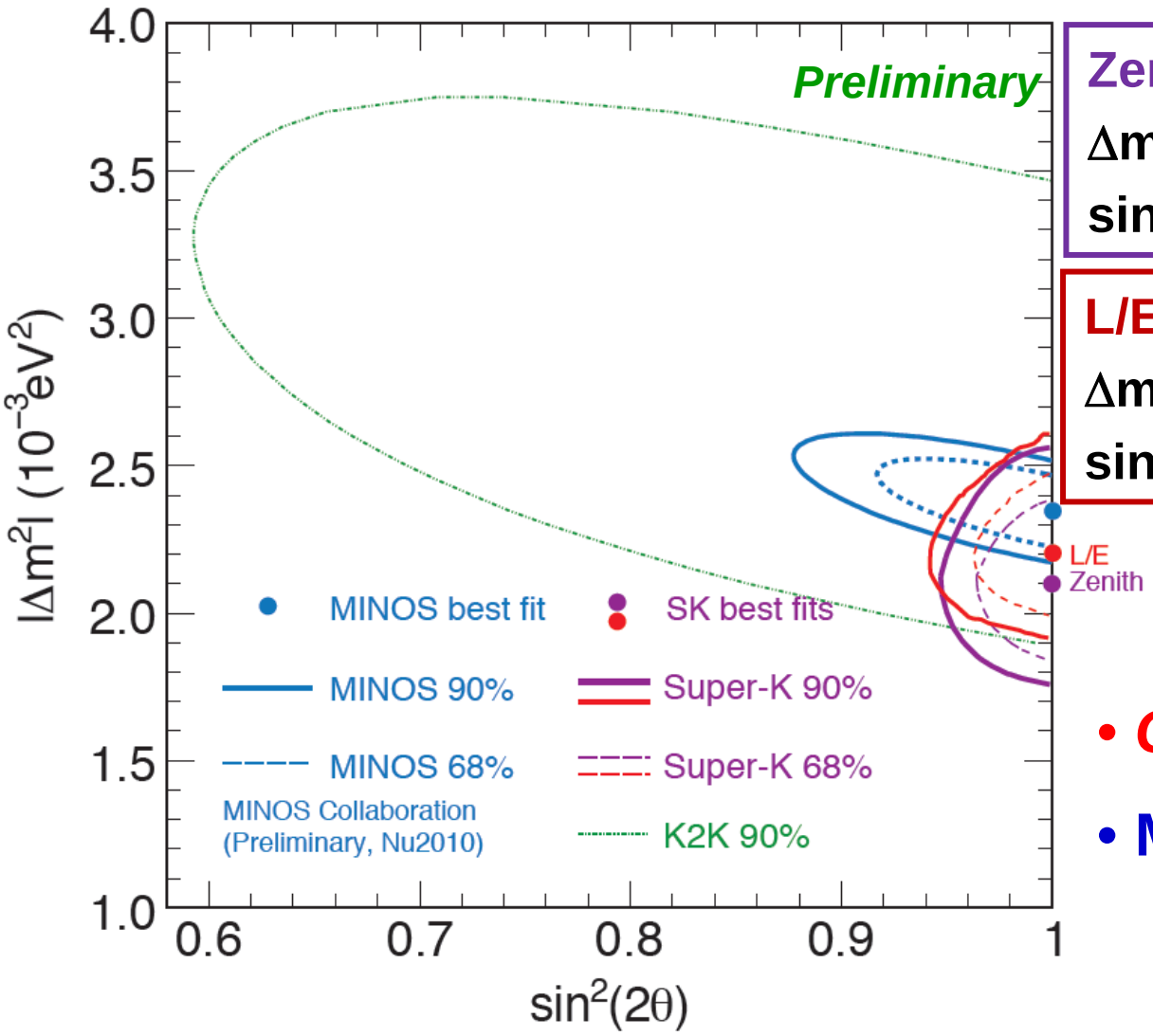


Select
"high L/E resolution" region.



Low energy ν
Bad directional resolution
Horizontal dir.
Large dL/dcosθ

Oscillation analysis using atmospheric neutrino
2 flavor oscillation (SK I + II + III)



Zenith Physical Region (1σ)

Δm_{23}^2=2.11+0.11/-0.19 x10^{-3}

$\sin^2 2\theta_{23}$>0.96 (90%C.L.)

L/E Physical Region (1σ)

Δm_{23}^2=2.19+0.14/-0.13 x10^{-3}

$\sin^2 2\theta_{23}$>0.96 (90%C.L.)

- ***Consistent results***
- **Most stringent limit for $\sin^2 2\theta_{23}$.**

Oscillation analysis using atmospheric neutrino
3 flavor oscillation (SK I + II + III)

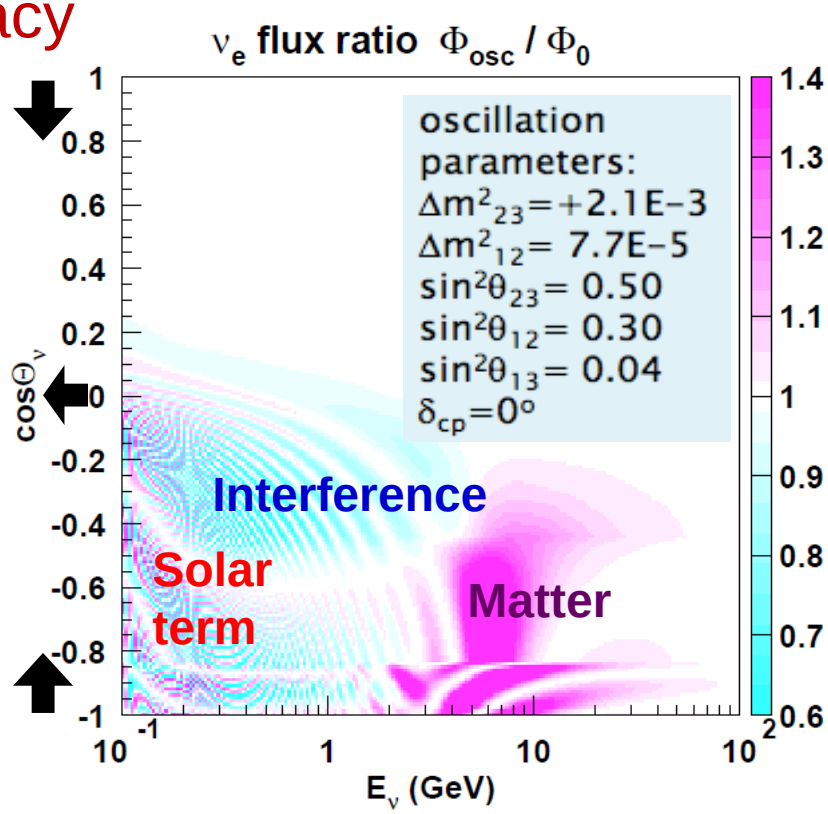
Include the contributions from matter effect and solar term in the oscillation analysis.

- Matter effect θ_{13} and mass hierarchy
  Possible ν_e enhancement in several GeV passed through the earth core
- Solar term θ_{23} octant degeneracy
  Possible ν_e enhancement in sub-GeV
- Interference ***(when $\sin^2\theta_{13}$ >~0.05)***
  CP phase could be studied.

Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) + \Delta_2(\Delta m^2_{12}) + \Delta_3(\theta_{13}, \Delta m^2_{12}, \delta)$$

← **Matter effect**
← **Solar term**
← **Interference**

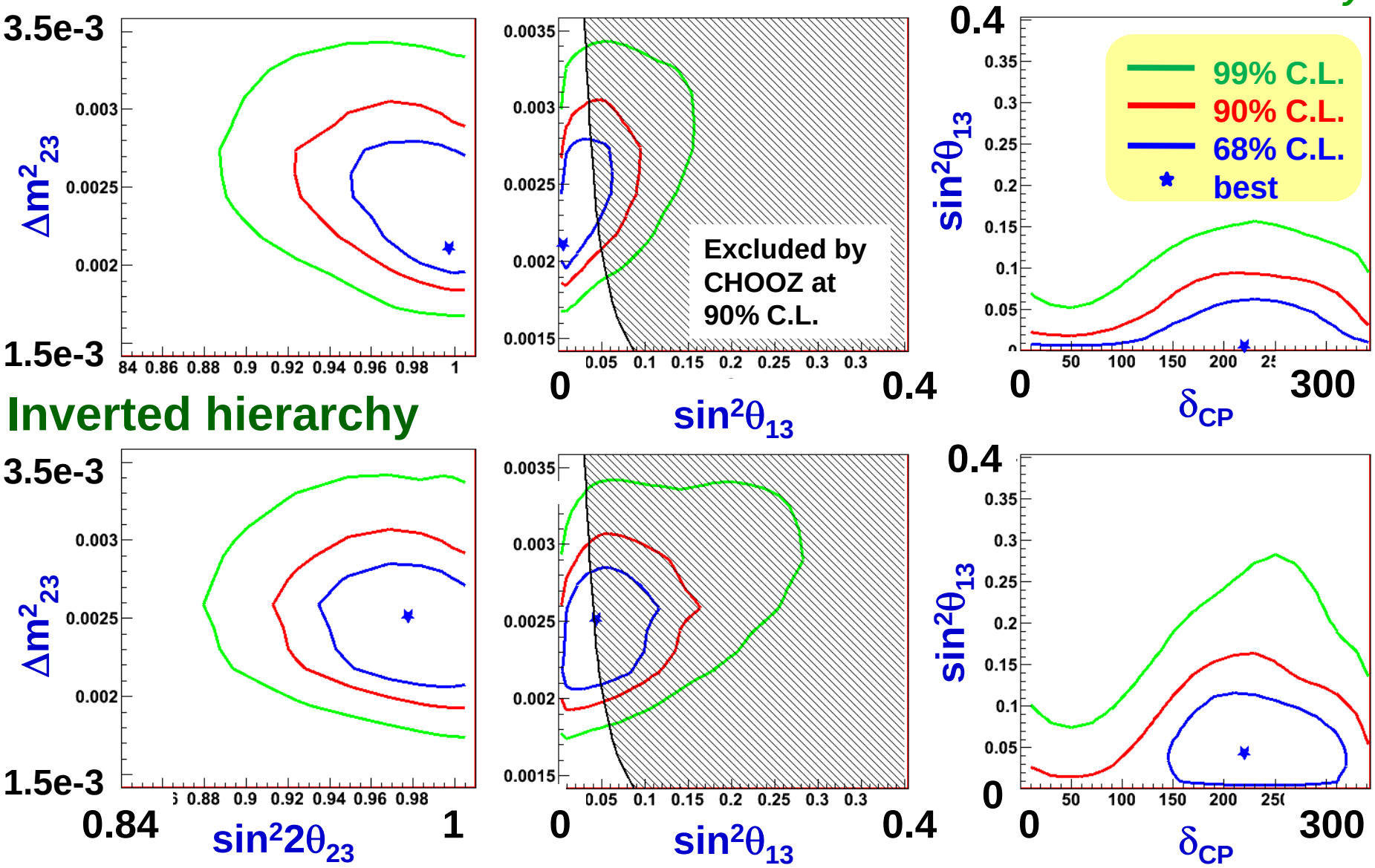


Oscillation analysis using atmospheric neutrino

3 flavor oscillation (SK I + II + III)

Normal hierarchy

Preliminary

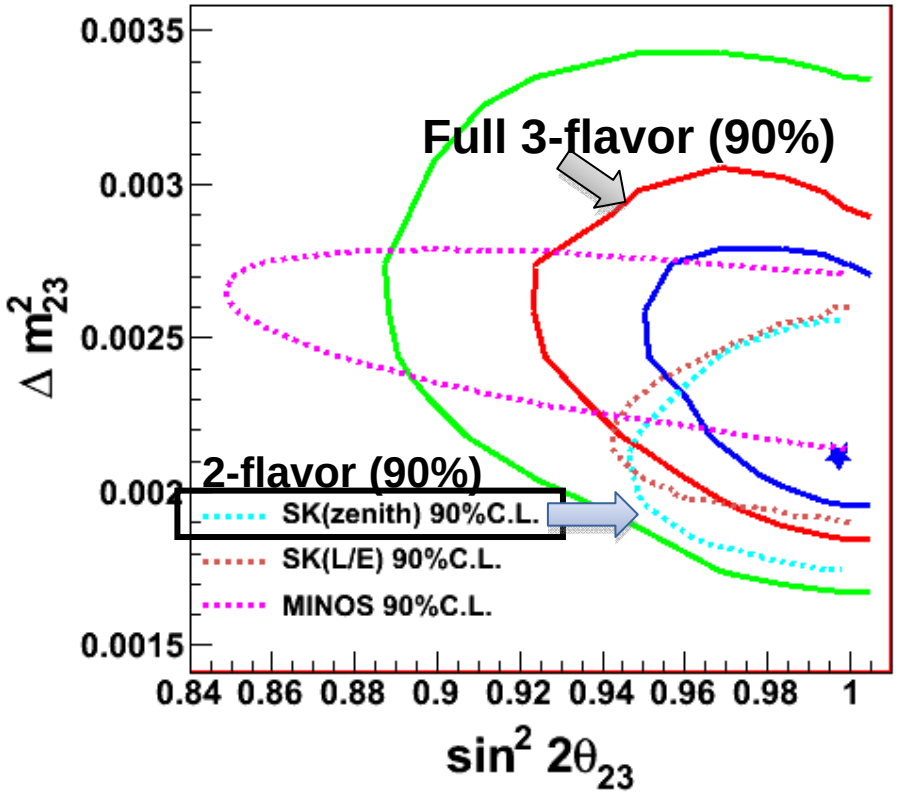


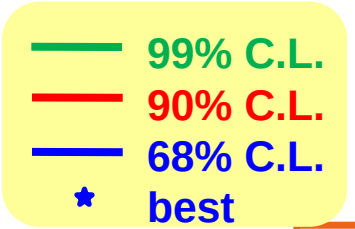
Inverted hierarchy

Oscillation analysis using atmospheric neutrino

Comparisons (2 flv. vs 3 flv.)

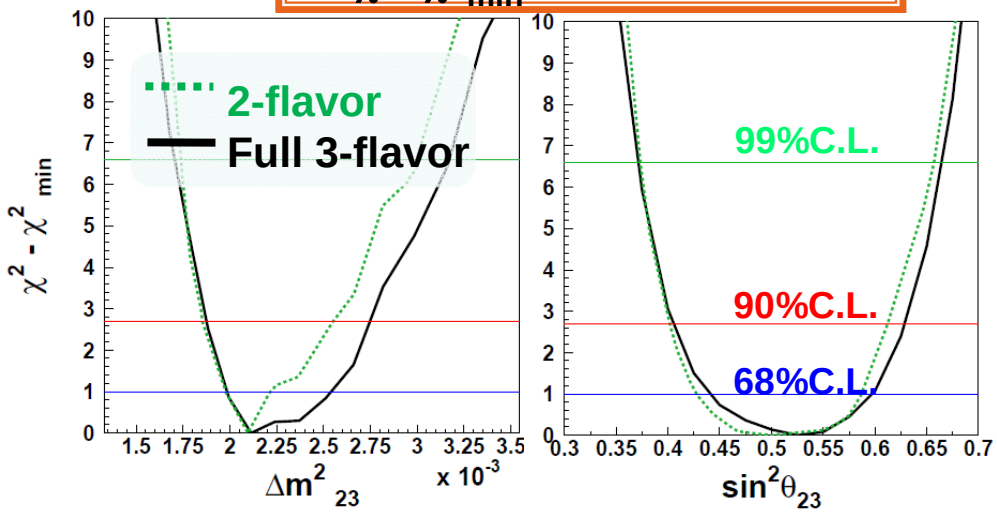
Normal hierarchy





Preliminary

$\chi^2 - \chi^2_{min}$ distributions



90%C.L. allowed region (1dof, $\chi^2=\chi^2_{min}+2.71$)

2 analyses give consistent results.
No deviation of $\sin^2\theta_{23}$ from 0.5.

Full 3-flavor (NH)	*Global-best*
$(1.88< \Delta m^2_{23} <2.75)\times10^{-3}$	$(2.22<\Delta m^2_{23}<2.60)\times10^{-3}$
$0.406 < \sin^2\theta_{23}< 0.629$	$0.401 < \sin^2\theta_{23}< 0.615$
$(0.93 < \sin^2 2\theta_{23})$	$(0.95 < \sin^2 2\theta_{23})$

Oscillation analysis using atmospheric neutrino
Comparisons (hierarchy)

May 2010

Normal hierarchy (NH)

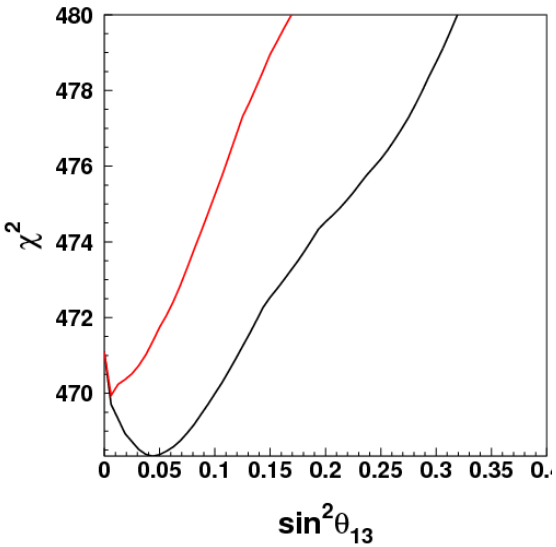
χ^2_{min}= 469.94/416dof

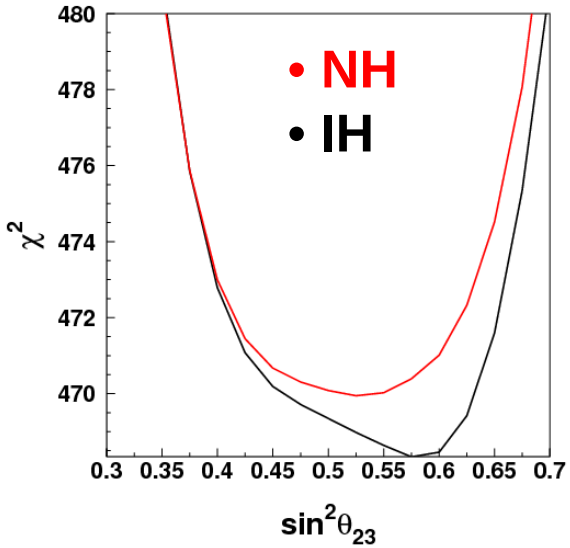
Inverted hierarchy (IH)

χ^2_{min}= 468.34/416dof

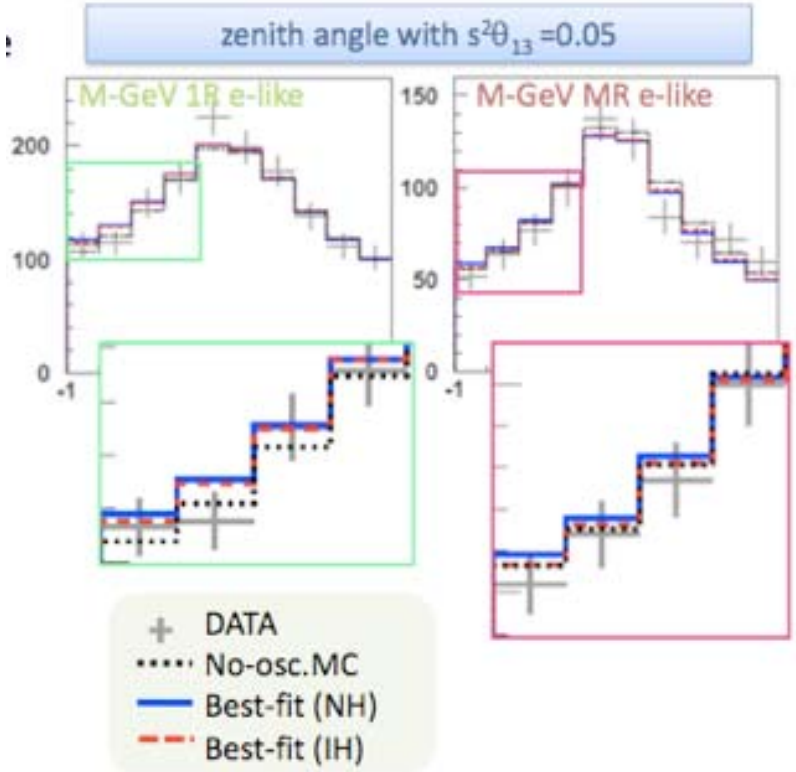
→ $\Delta\chi^2$ = 1.6

No significant difference





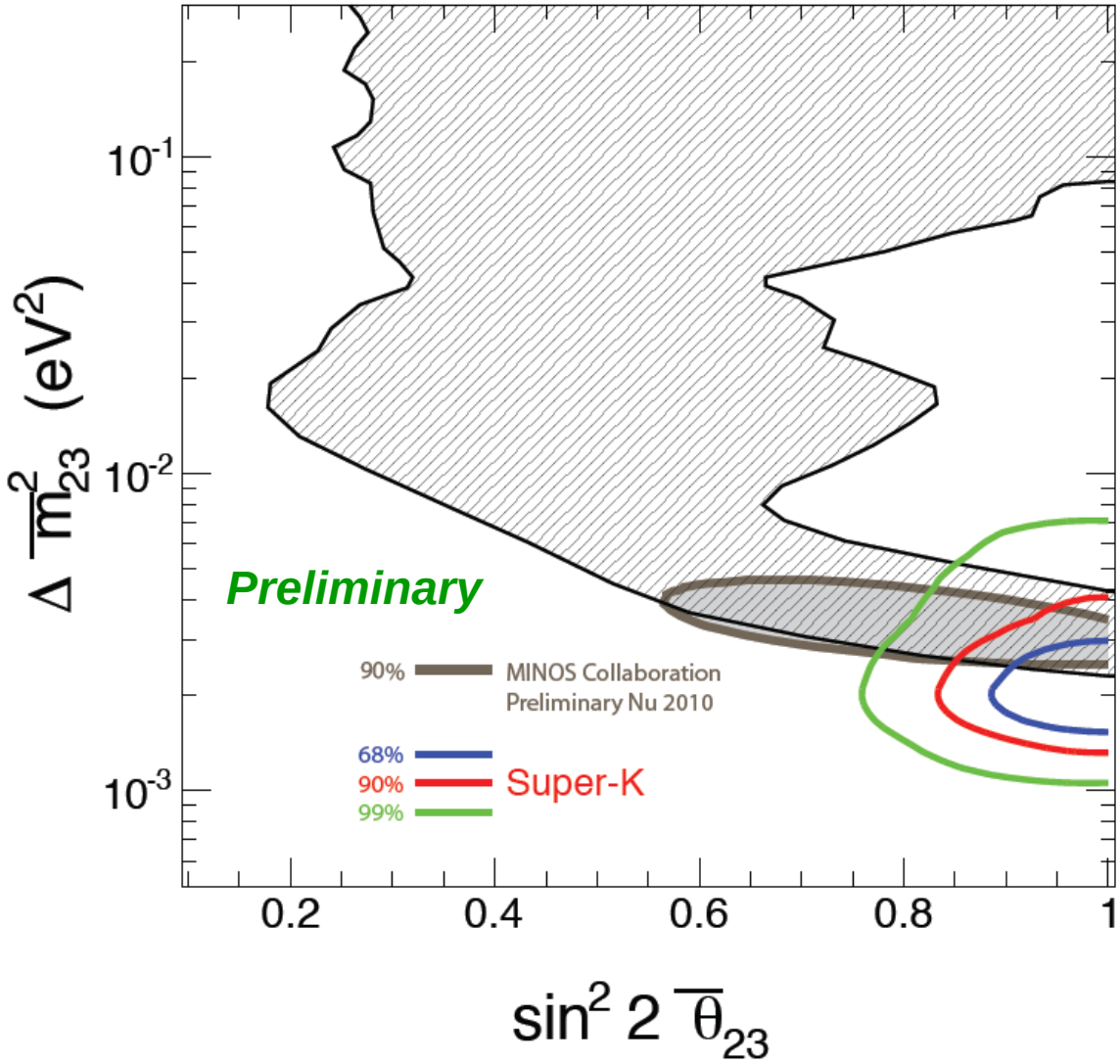
Multi-GeV samples tend to favor inverted hierarchy.



There are also some contributions from Multi-GeV μ-like samples favoring IH to NH.

Oscillation analysis using atmospheric neutrino CPT study

Usually, we assume CPT ↔ P($\nu \rightarrow \nu$) and P($\bar{\nu} \rightarrow \bar{\nu}$) are same.



Fit independently

SK-I+II+III

Neutrino:

$\Delta m_{23}^2 = 2.2 \times 10^{-3} eV^2$

$\sin^2 2\theta_{23} = 1.0$

Anti-neutrino:

$\Delta \overline{m}_{23}^2 = 2.0 \times 10^{-3} eV^2$

$\sin^2 2\overline{\theta}_{23} = 1.0$

No evidence for CPT violating oscillations

Nucleon decay search

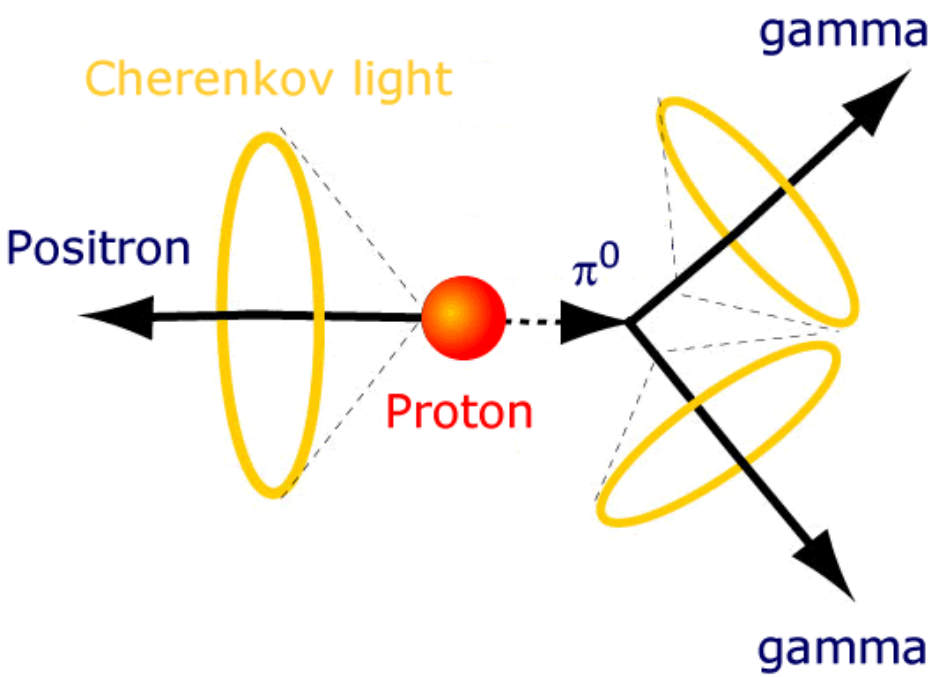
Grand Unification Theory (GUT) predicts the nucleon decay

One of the predicted nucleon decay mode

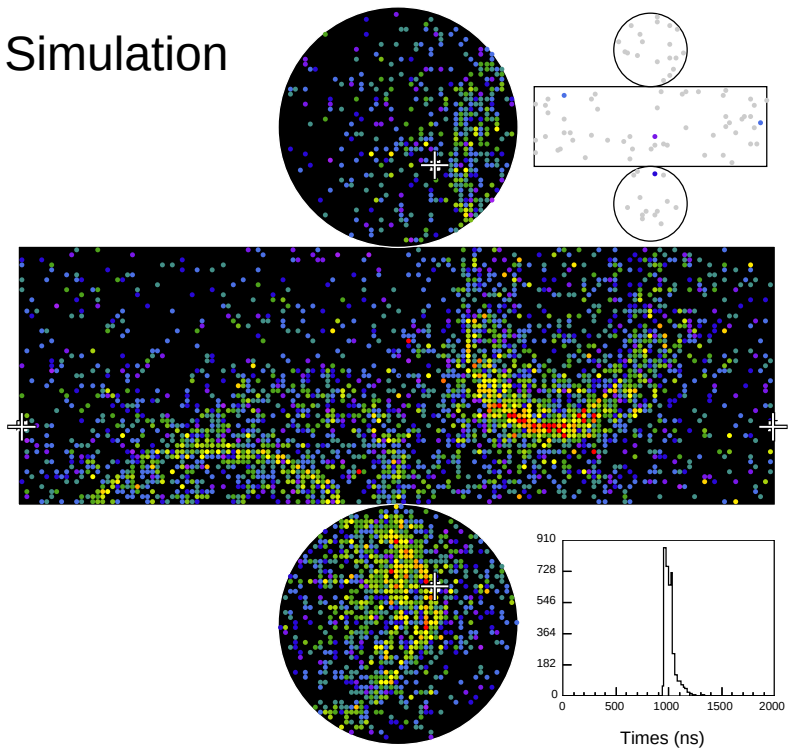
$$p \rightarrow e^{+} + \pi^{0}$$

Super-Kamiokande has very high efficiency in identifying both decay products e^{+} and π^{0}

Clear 3 e-like rings are expected to be observed.



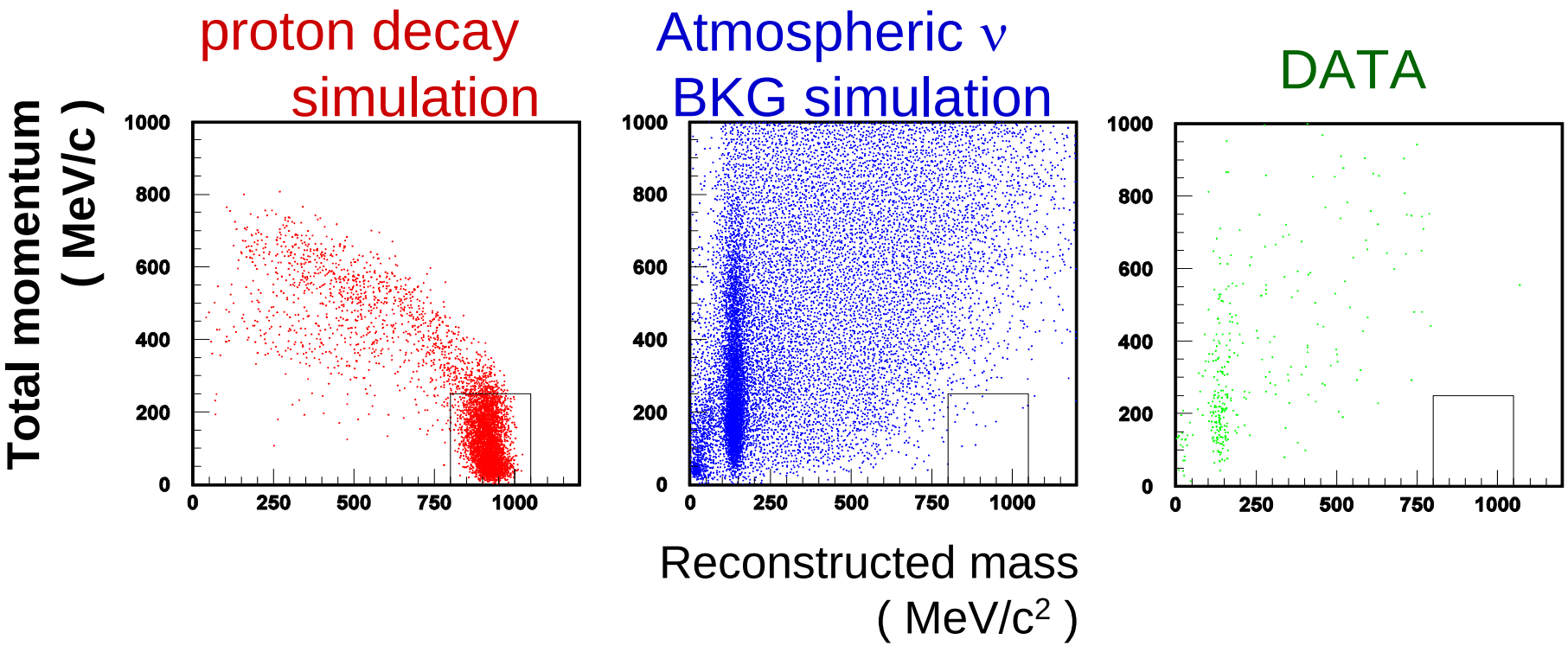
Simulation



Nucleon decay search $p \rightarrow e^+ + \pi^0$

Detection efficiency ~44% (SK-III)

Estimated background 0.37 (SK I + II + III, 172.8kton·year)



So far, no candidate events have been observed.

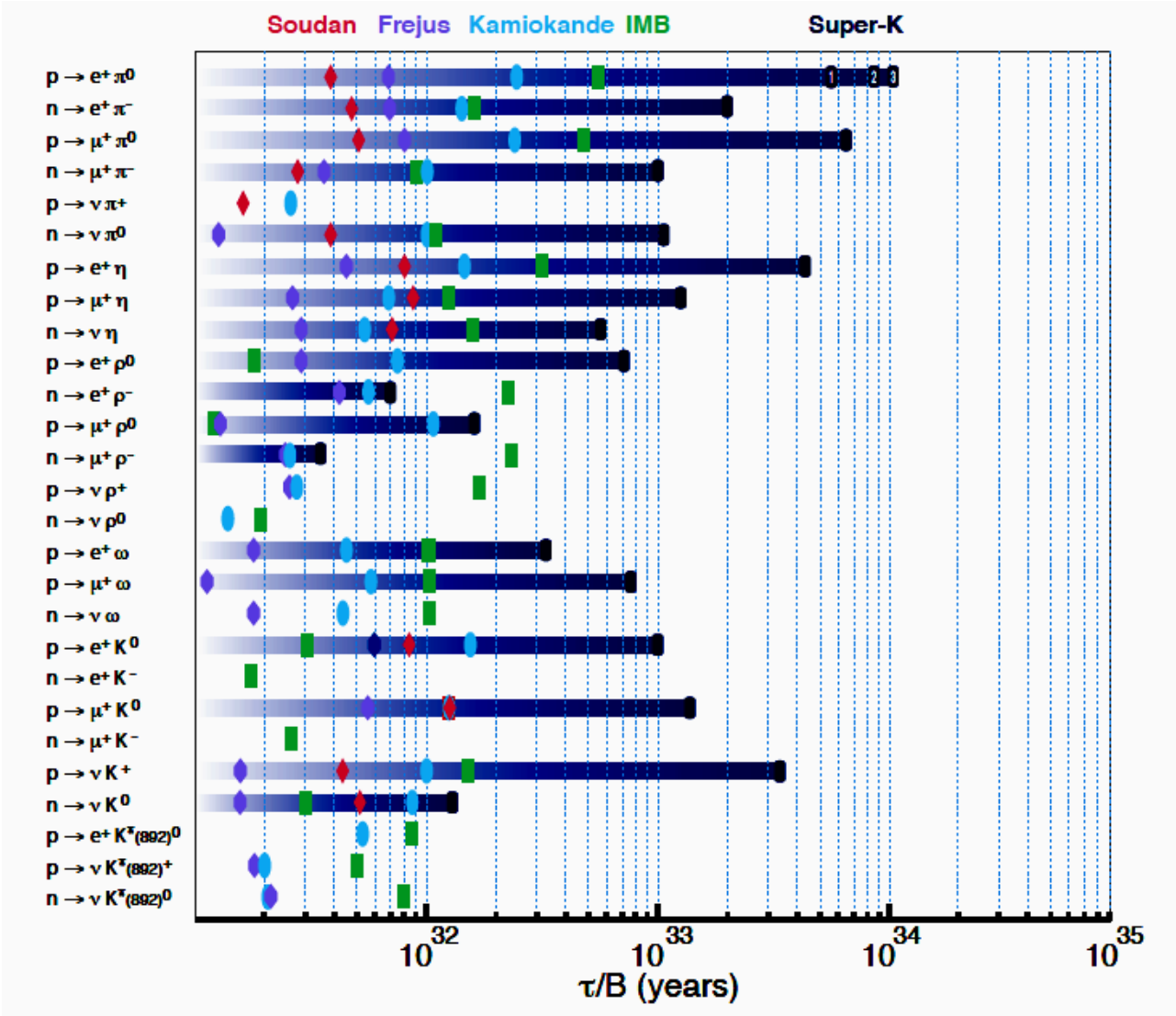
Partial lifetime limit 10.1×10^{33} year

Nucleon decay search

Many other decay modes have been studied.

$p \rightarrow \nu K^+$ $\tau/BR > 3.3 \times 10^{33}$ yr

etc…



Summary

- Super-Kamiokande has been running since 1996
  and collected large amount of
  solar and atmospheric neutrino data.
- Initially, we have been analyzing data with 2-flavor assumption.
- Recently, accumulated data became large enough
  to perform 3-flavor analysis.

This kind of “detailed precise analysis” was realized
by the improvements of the detector itself,
the analysis tools,
and the understanding of the detector.

Of course, various inputs from the other experiments
plays important role in these analyses.

Using the SK-IV data,
it will be possible to investigate
the neutrino properties more in detail.

Fin.