Sub-dominant Oscillations in Atmospheric Neutrino Experiments

Some unavoidably incomplete and personal considerations

.... with Apologies to all of you .....

Paolo Lipari
RCCN workshop
Dec. 2004

Future Studies with Atmospheric Neutrinos

Neutrino Physics has entered the

"Precision Era"

"Common Wisdom" :
.... From Natural Neutrinos to Reactor
and LBL Accelerator Neutrinos

The scientific interest for Atmospheric Neutrinos is not exausted.

Two Directions of interest

- Search for Non-Standard Effects (FCNC, VEP, ...)
- Contribution to Precision Parameter Determination

Fundamental Questions For Neutrino Oscillation Studies

- Measurement of θ_{13}
- Deviations of θ_{23} from Maximal Mixing
- Mass Hierarchy (Sign of Δm^2_{23})
- CP Violations (phase δ)

Can be Studied with Atmospheric Neutrinos

Majorana phases

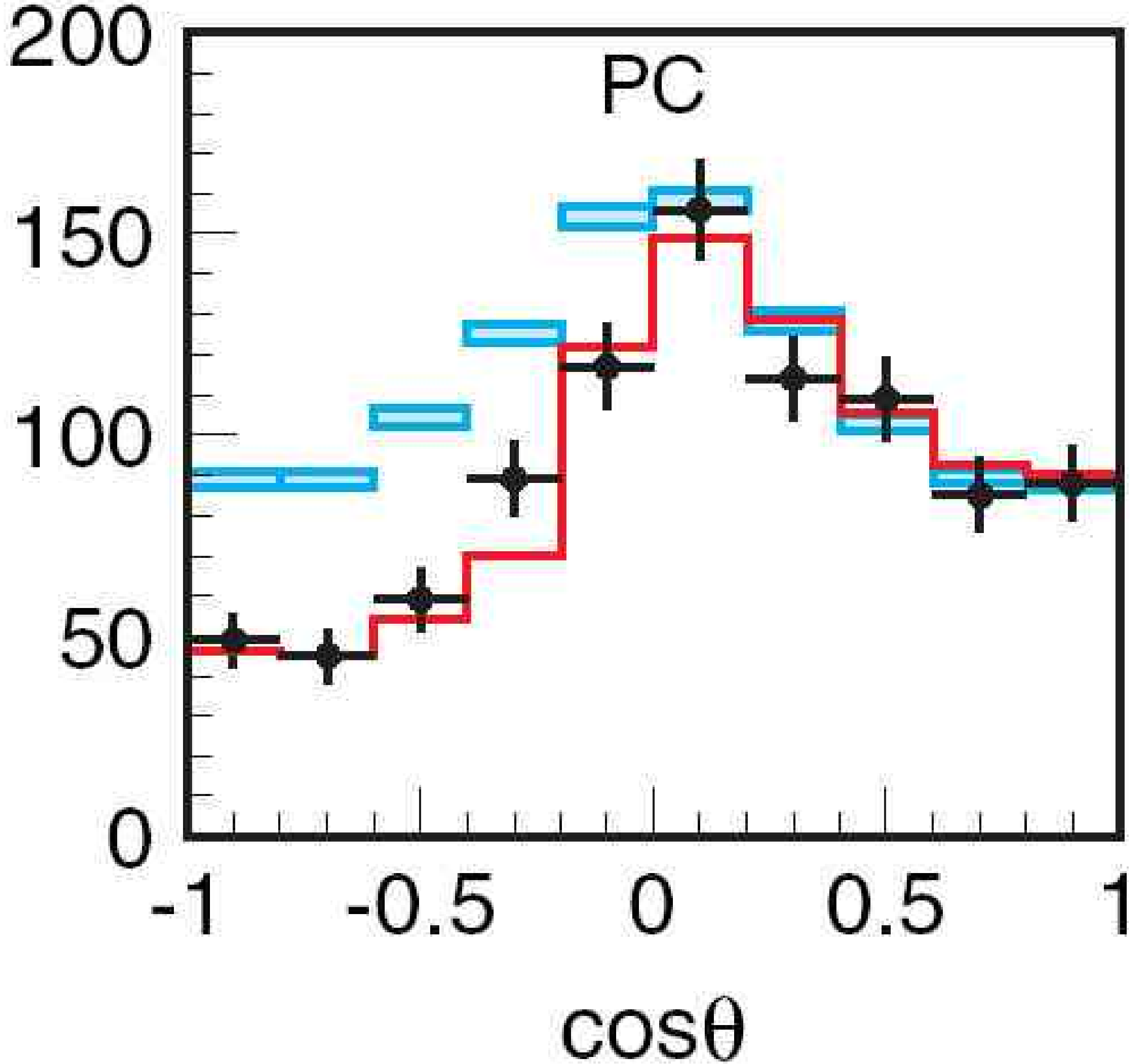
Absolute ν Masses

Measurement of θ_{23}

Standard Method $\sin^2 2\theta_{23}$

"New Method" $\sin^2 \theta_{23}$

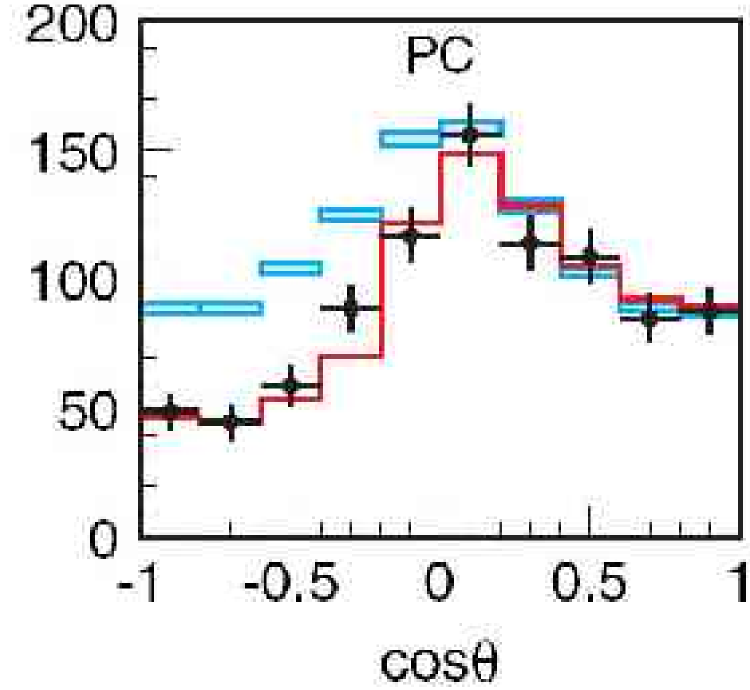
Standard Method



$$\frac{N_\mu}{N_\mu^\circ} \simeq 1 - \sin^2 2\theta_{23}\ \langle \text{Oscillation Phase} \rangle$$

$$\langle \text{Oscillation Phase} \rangle_{\text{Down}} \simeq 0$$

$$\langle \text{Oscillation Phase} \rangle_{\text{Up}} \simeq \frac{1}{2}$$



$$\sin^2 2\theta_{23} \simeq 2\ \left(1 - \frac{\text{Up}}{\text{Down}}\right)$$

$$N^0_{\rm Up} \simeq N^0_{\rm Down} \simeq 5.7\ ({\rm Kton\ year})^{-1}$$

$$\delta(\sin^2\ 2\theta_{23})_{\rm stat} \simeq \sqrt{\frac{3}{\rm N_{Down}}} \simeq \frac{0.07}{\sqrt{\rm Exposure(SK1)}}$$

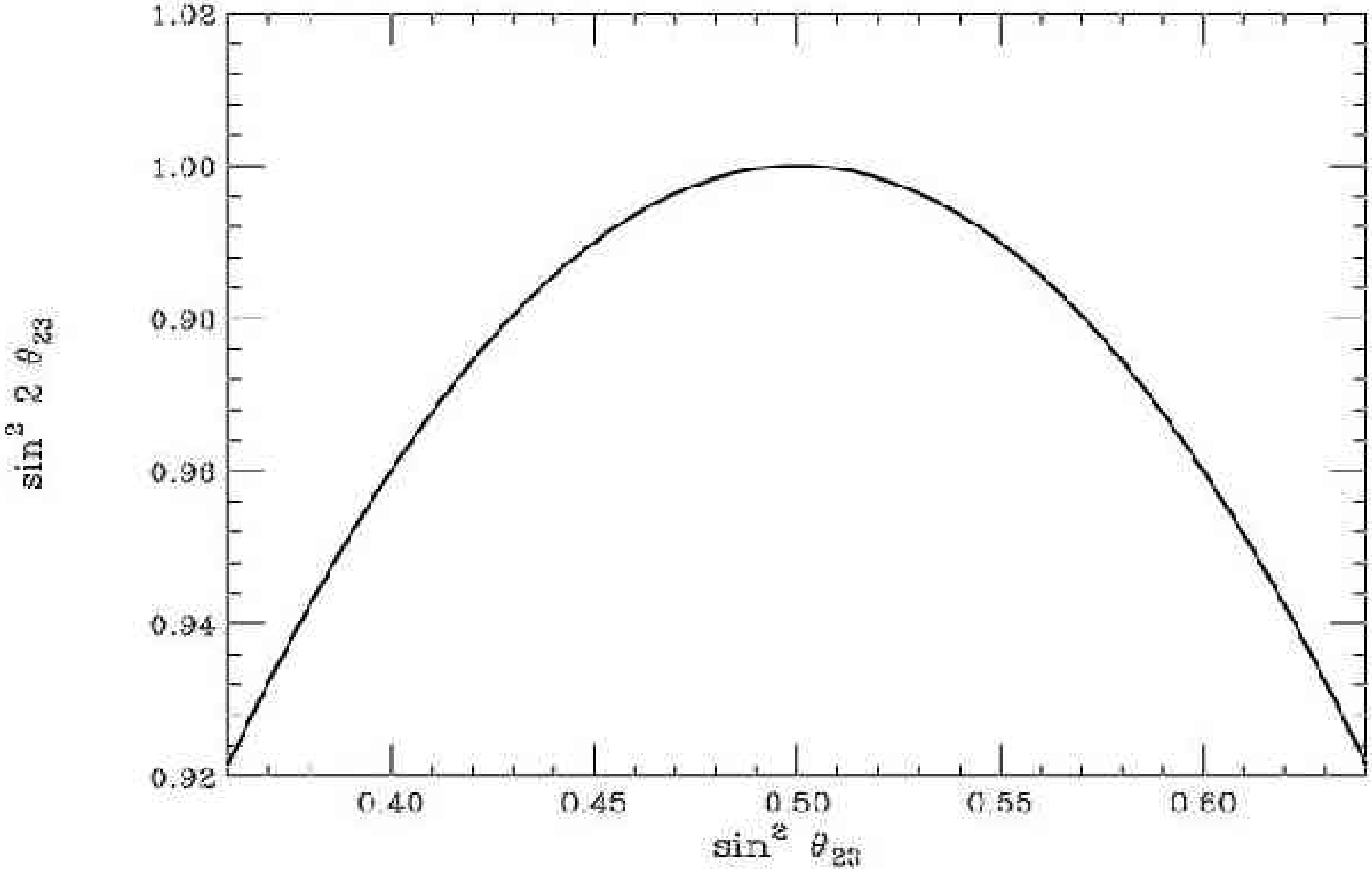
$$\rm Exposure = 50\ SK1$$

$$\delta(\sin^2\ 2\theta_{23})_{\rm stat} \simeq 0.01$$

$$\delta(\sin^2\ 2\theta_{23})_{\rm syst} \simeq 2\ \delta\left(\frac{U^0}{D^0}\right)$$

Systematic
Error under control

OCTANT AMBIGUITY



OCTANT AMBIGUITY

$$\sin^2 2\theta_{23} = 1 \pm 0.01$$
$$\sin^2 \theta_{23} = 0.5 \pm 0.05$$

$$\sin^2 2\theta_{23} = 0.96 \pm 0.01$$
$$\sin^2 \theta_{23} \in [0.4, 0.43] \oplus [0.57, 0.6]$$

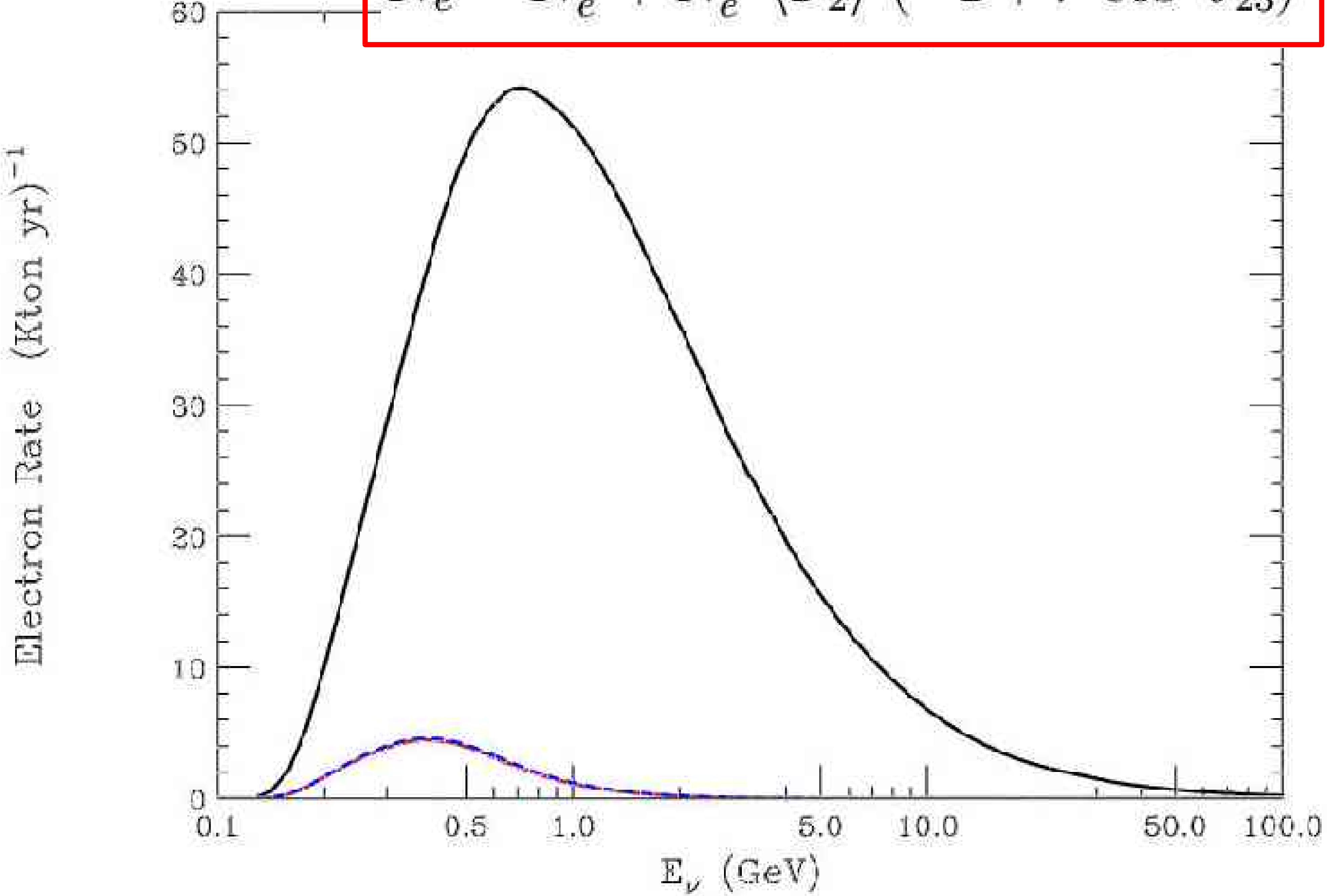
Subdominant Solar Effects

Oscillations due to the Solar Parameters

$$N_e = N_e^0 + N_e^0 \langle P_2 \rangle (-1 + r \cos^2 \theta_{23})$$

Combination of Appearance
and Disappearance

$$N_e = N_e^0 + N_e^0 \langle P_2 \rangle (-1 + r \cos^2\theta_{23})$$



$$N_e = N_e^0 + N_e^0 \, \langle P_2 \rangle \, (-1 + r \, \cos^2 \theta_{23})$$

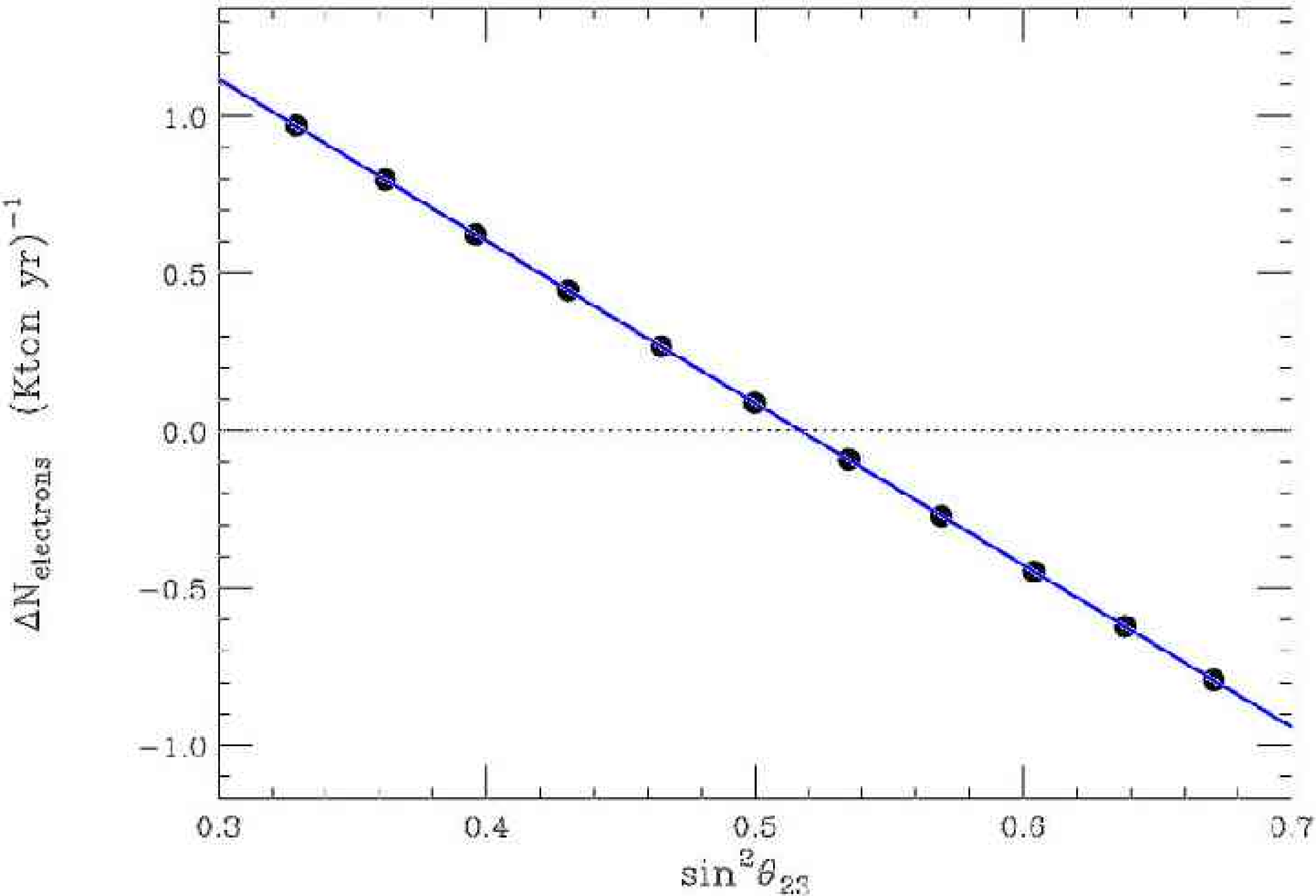
$$N_e = N_e^0 + N_e^0 \, \langle P_2 \rangle \, (1 - 2 \, \sin^2 \theta_{23})$$

$$N_e^{\rm SG} \simeq 29 + 2.3 \, (1 - 2 \, \sin^2 \theta_{23}) \, ({\rm Kton \; yr})^{-1}$$

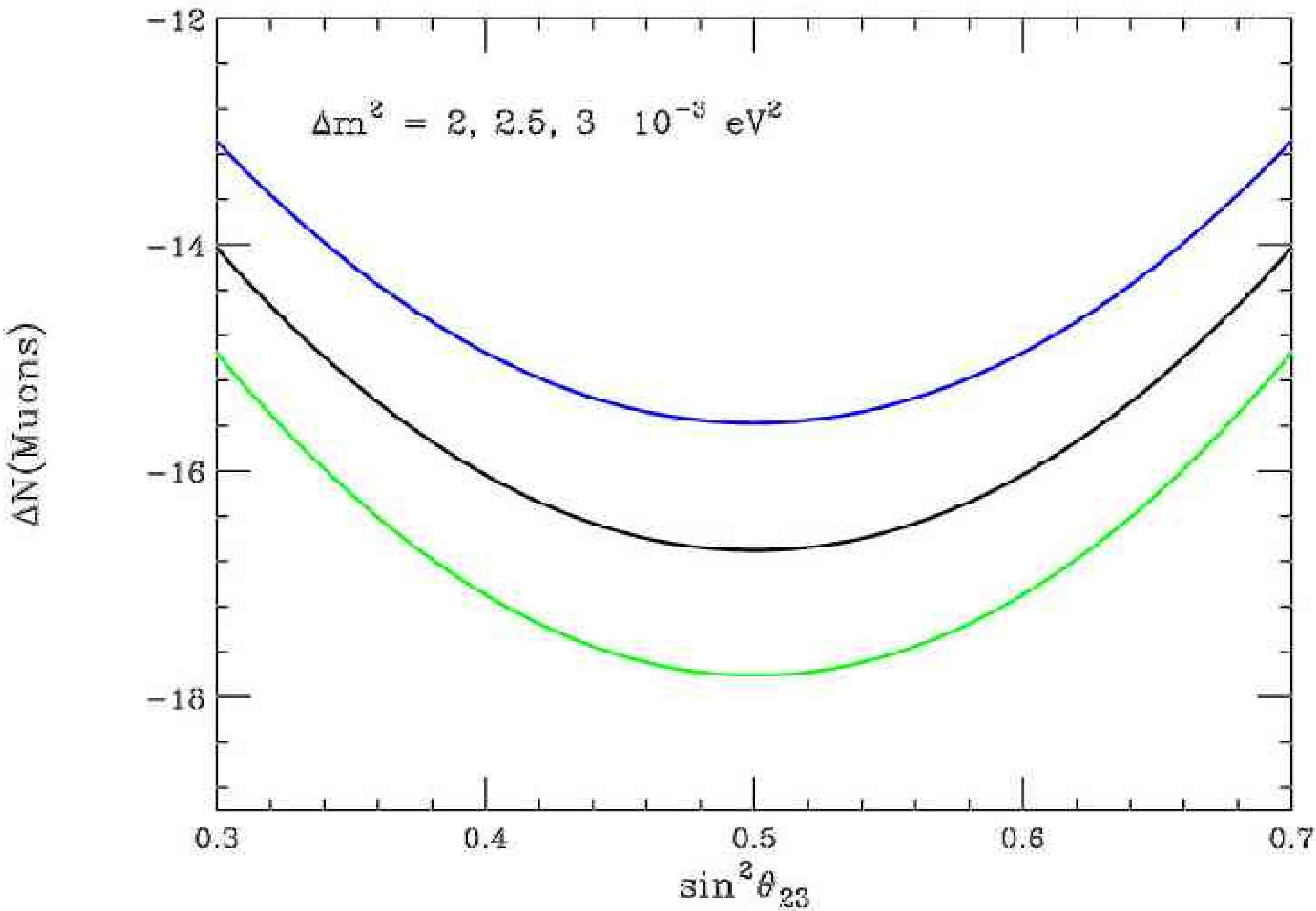
$$\sin^2 \theta_{23} \simeq \frac{N_e^0 (1 + \langle P_2 \rangle) - N_e}{2 \langle P_2 \rangle \, N_e^0}$$

Statistics

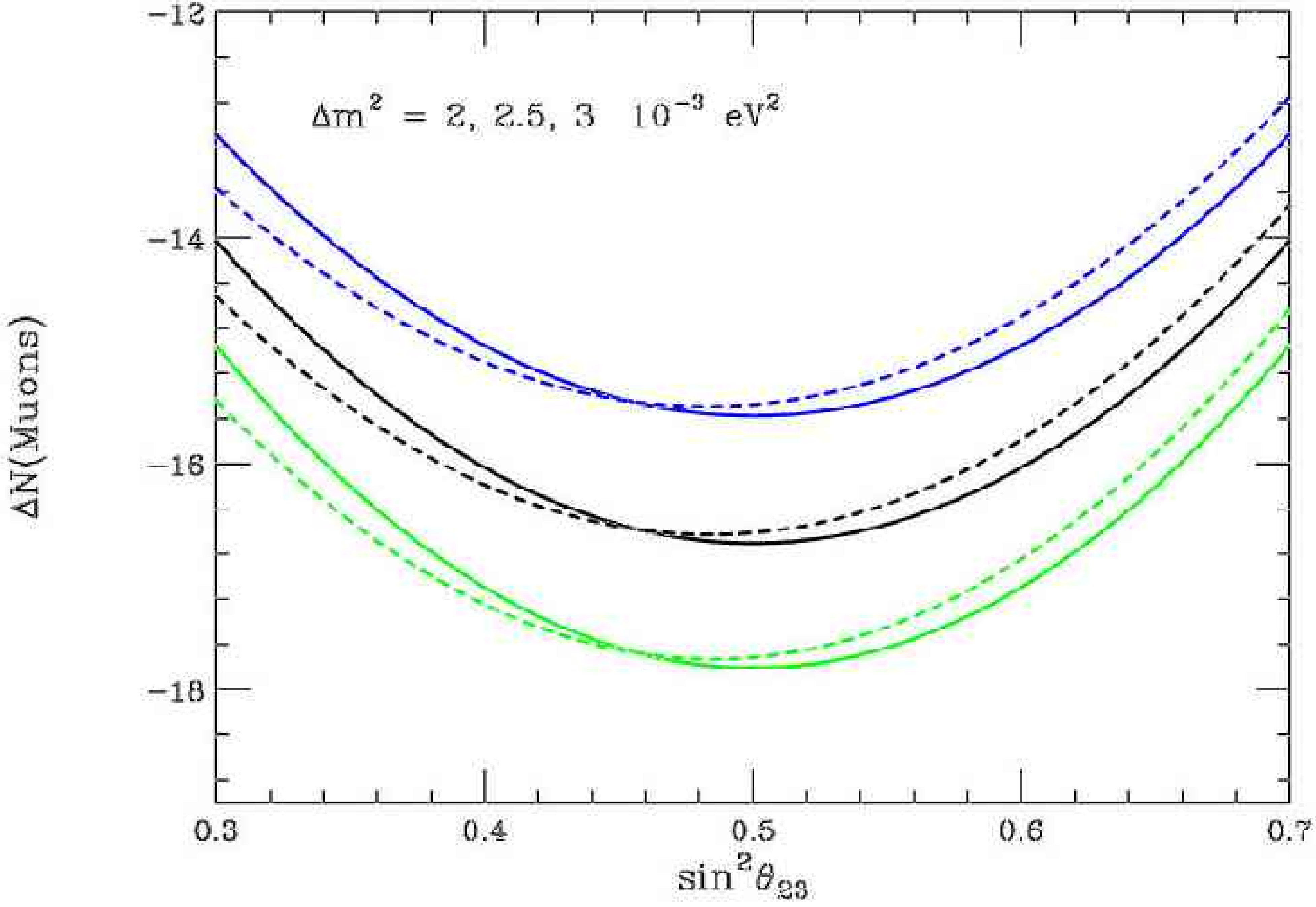
Control of Systematics



1.0
0.5
0.0
−0.5
−1.0
0.3
0.4
0.5
0.6
0.7
$\sin^2\theta_{23}$
$\Delta N_{electrons}$ $(\mathrm{Kton\ yr})^{-1}$



$\Delta m^2 = 2, 2.5, 3 \quad 10^{-3}$ eV^2
ΔN(Muons)
$\sin^2\theta_{23}$
-12
-14
-16
-18
0.3
0.4
0.5
0.6
0.7



$\Delta m^2 = 2,\ 2.5,\ 3\ \ 10^{-3}\ eV^2$
−12
−14
−16
−18
0.3
0.4
0.5
0.6
0.7
$\sin^2\theta_{23}$
ΔN(Muons)

Three Important Contributions of SuperKamiokande

Okumura	Measurement of θ_{13}
Nakayama	Deviations of θ_{23} from Maximal Mixing
Shiozawa	Large Exposure All effects Combined

Okumura	Measurement of θ_{13}
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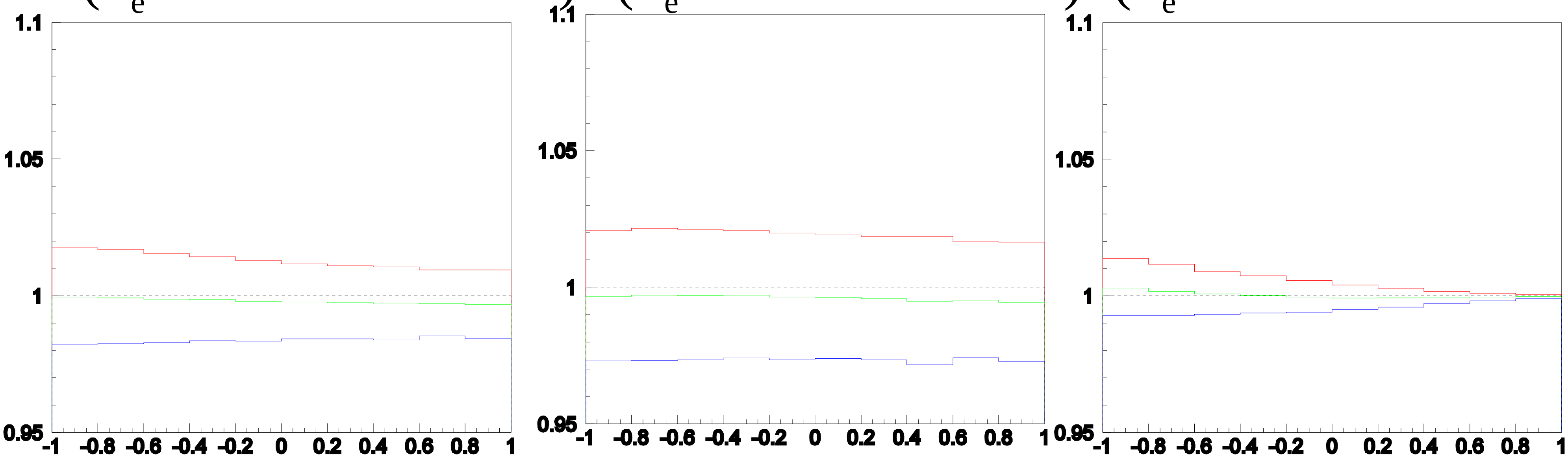
Shoei Nakayama

sub-GeV e-like zenith angle

X : zenith angle
Y : N_e (3 flavor) / N_e (2 flavor full-mixing)

sub-GeV e-like

(P_e :100 ~ 1330 MeV) (P_e :100 ~ 400 MeV) (P_e :400 ~ 1330 MeV)



$\sin^2{}_{23} = 0.4$

$\sin^2{}_{23} = 0.5$

$\sin^2{}_{23} = 0.6$

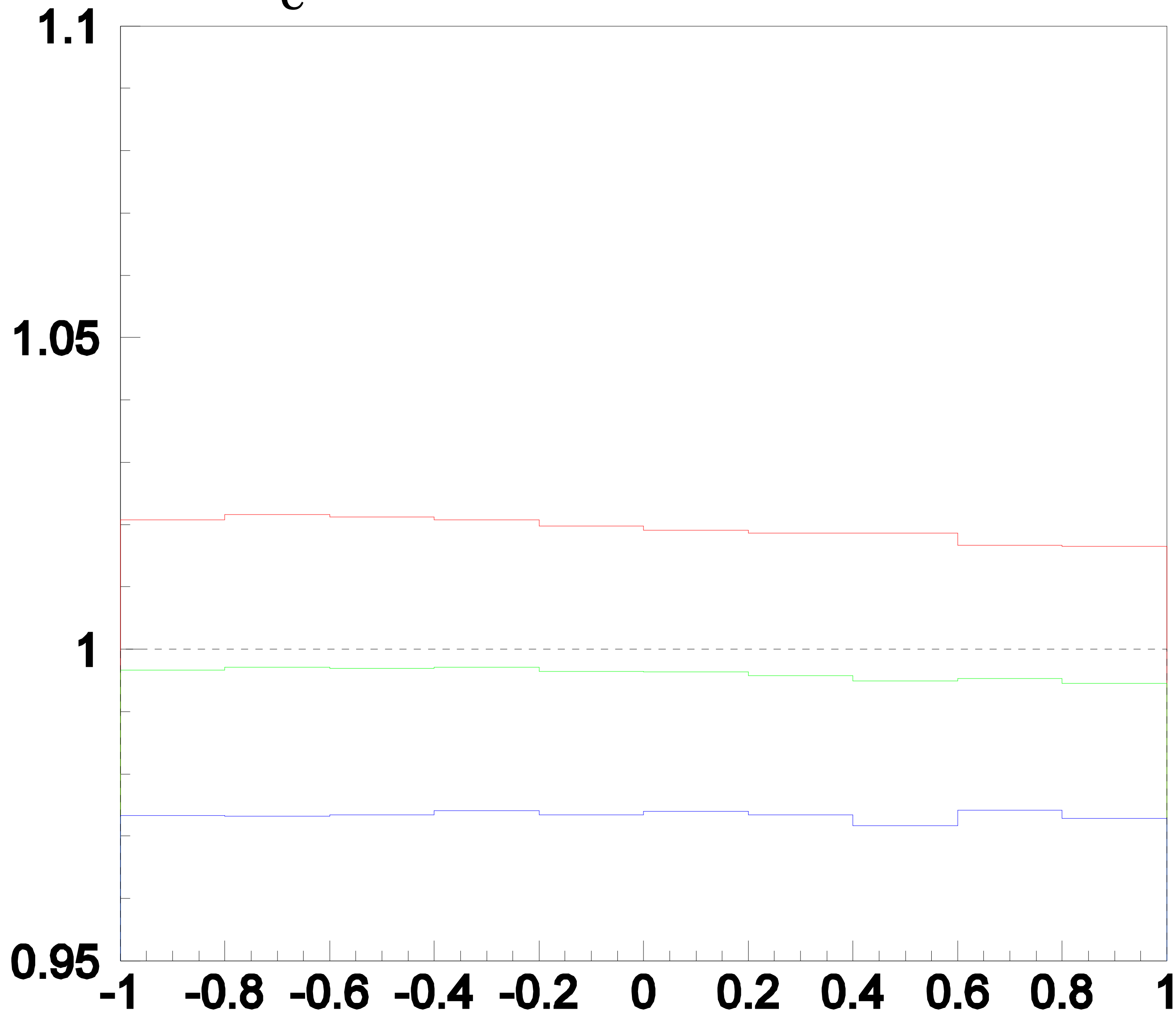
$\Delta m^2_{12} = 8.3 \times 10^{-5}\ eV^2$

$\Delta m^2_{23} = 2.5 \times 10^{-3}\ eV^2$

$\sin^2 2\theta_{12} = 0.82$

Sub-GeV e-like

P_e = 100 – 400 MeV



$\sin^2{}_{23} = 0.4$

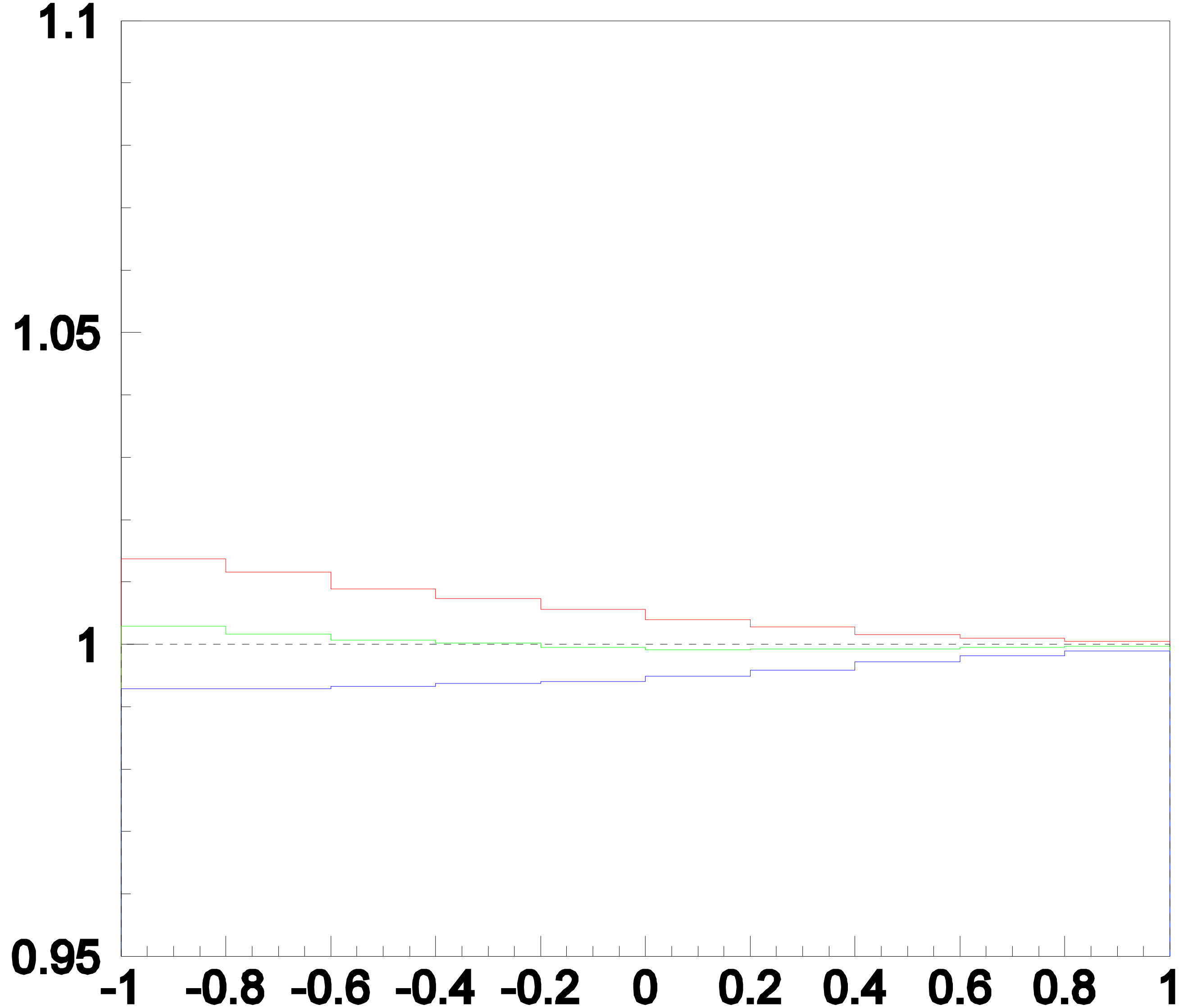
$\sin^2{}_{23} = 0.5$

$\sin^2{}_{23} = 0.6$

Shoei Nakayama

Sub-GeV
e-like

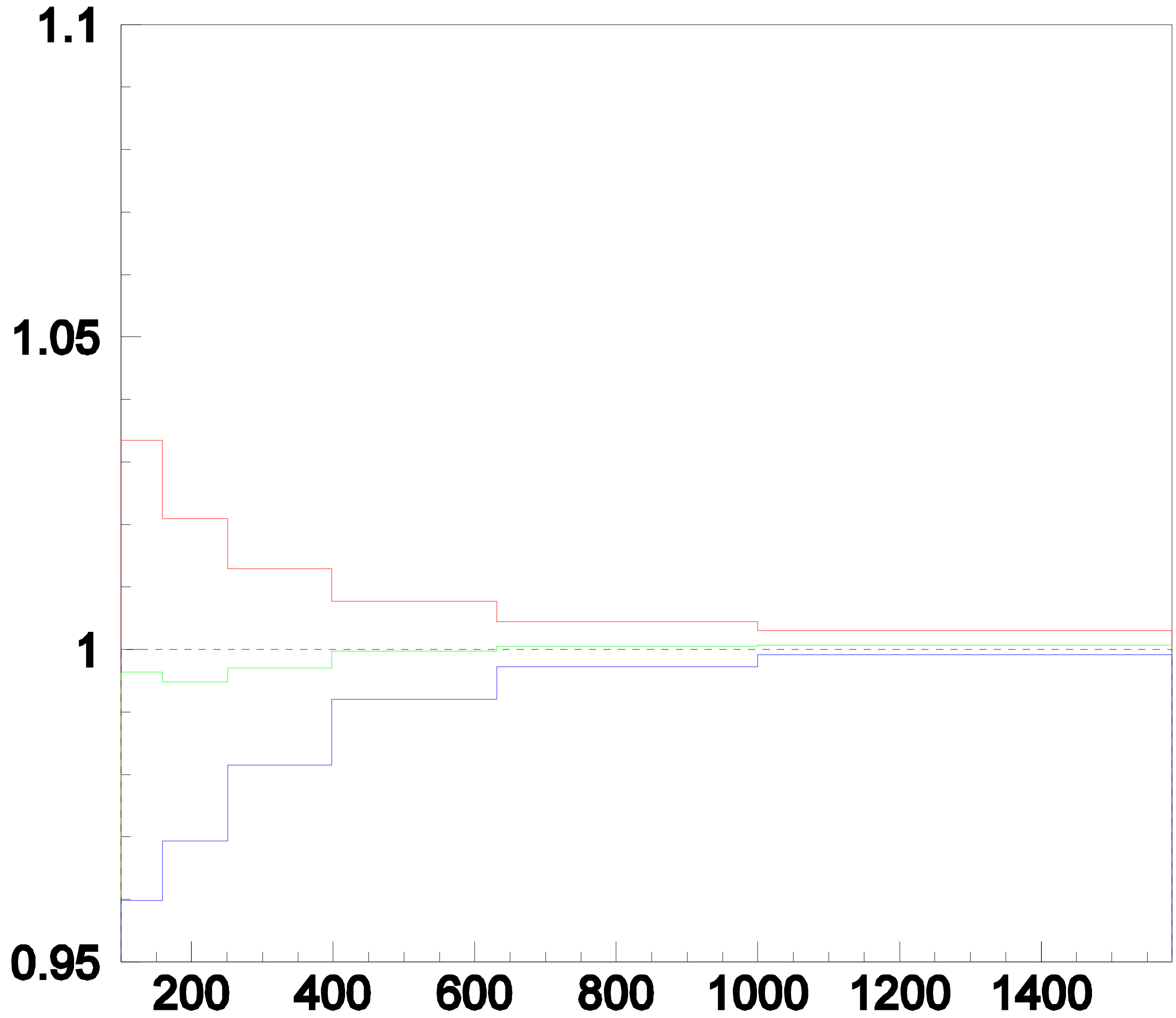
$P_e = 400 - 1300$ MeV



$\sin^2 {}_{23} = 0.4$
$\sin^2 {}_{23} = 0.5$
$\sin^2 {}_{23} = 0.6$

Shoei Nakayama

Sub-GeV e-like

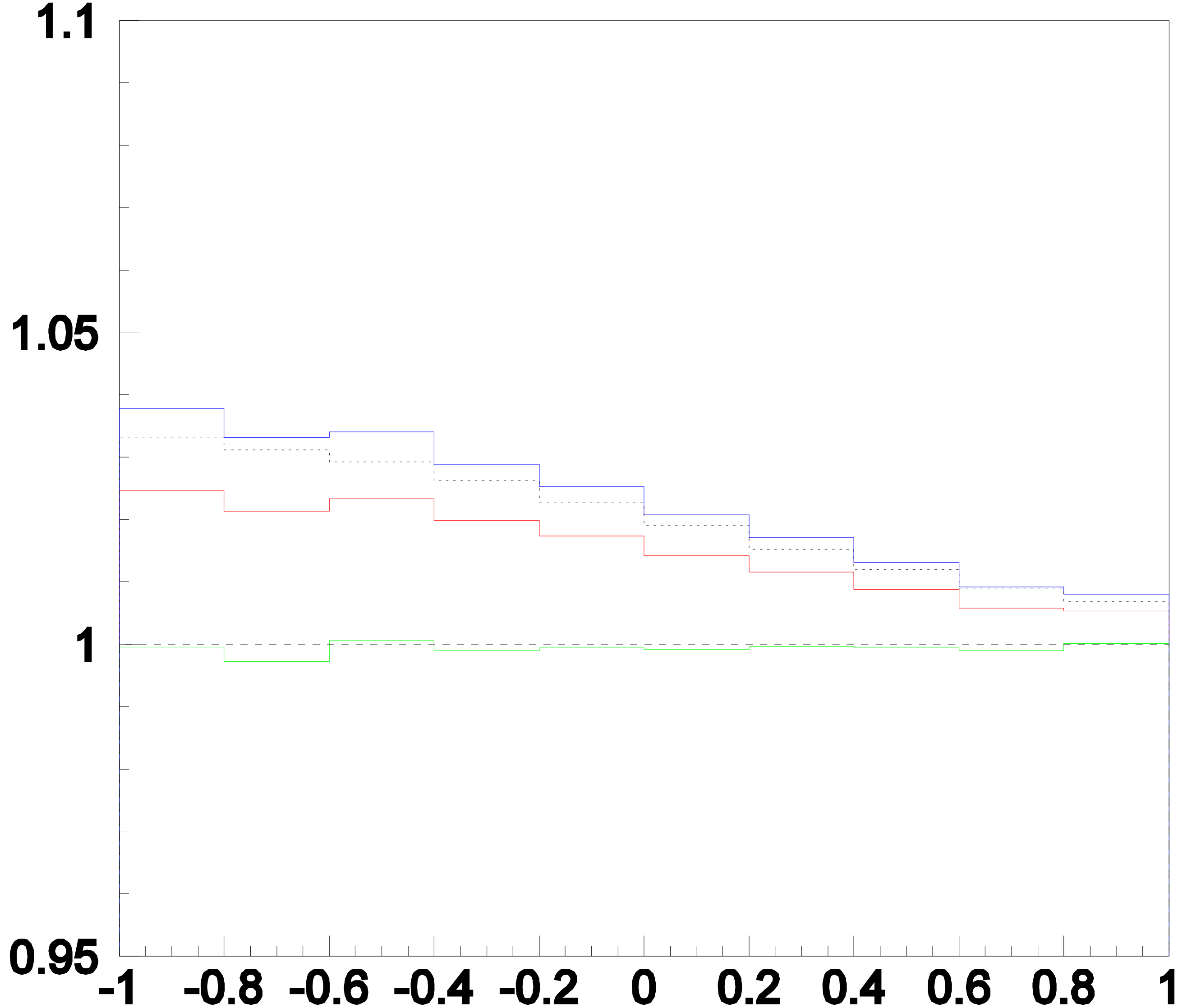


sin² 23 = 0.4
sin² 23 = 0.5
sin² 23 = 0.6

Shoei Nakayama

P = 200 – 1330 MeV

Sub-GeV mu-like



$\sin^2{}_{23} = 0.4$

$\sin^2{}_{23} = 0.5$

$\sin^2{}_{23} = 0.6$

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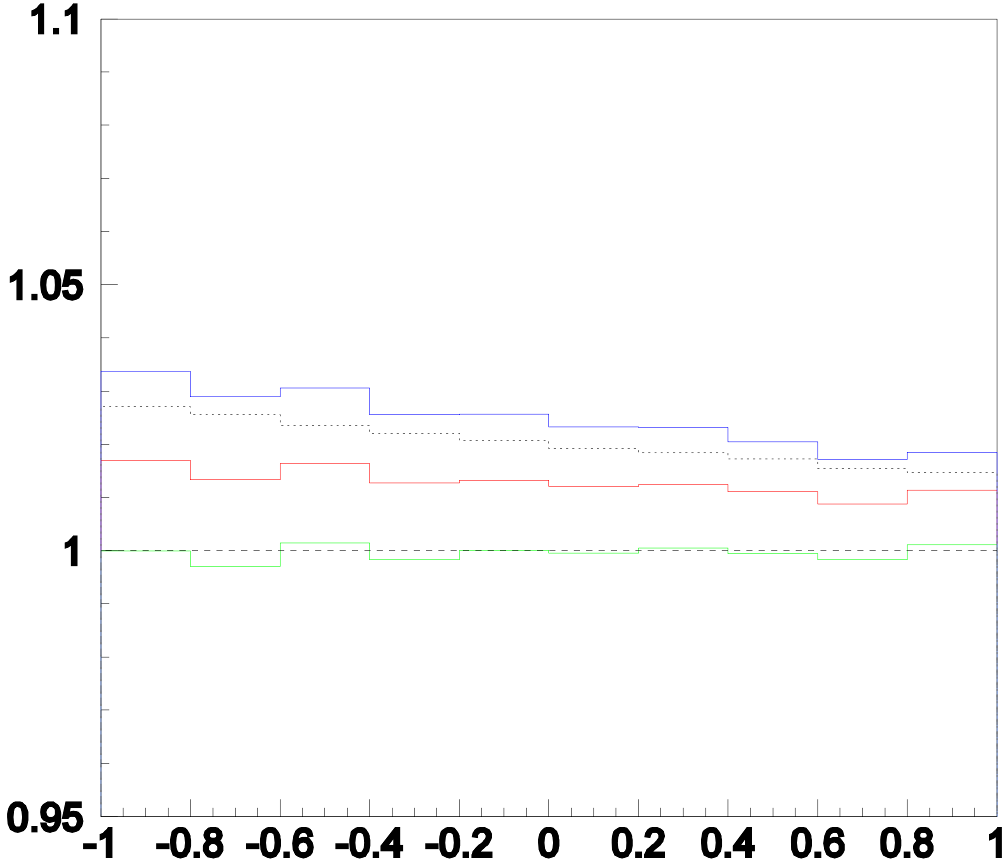
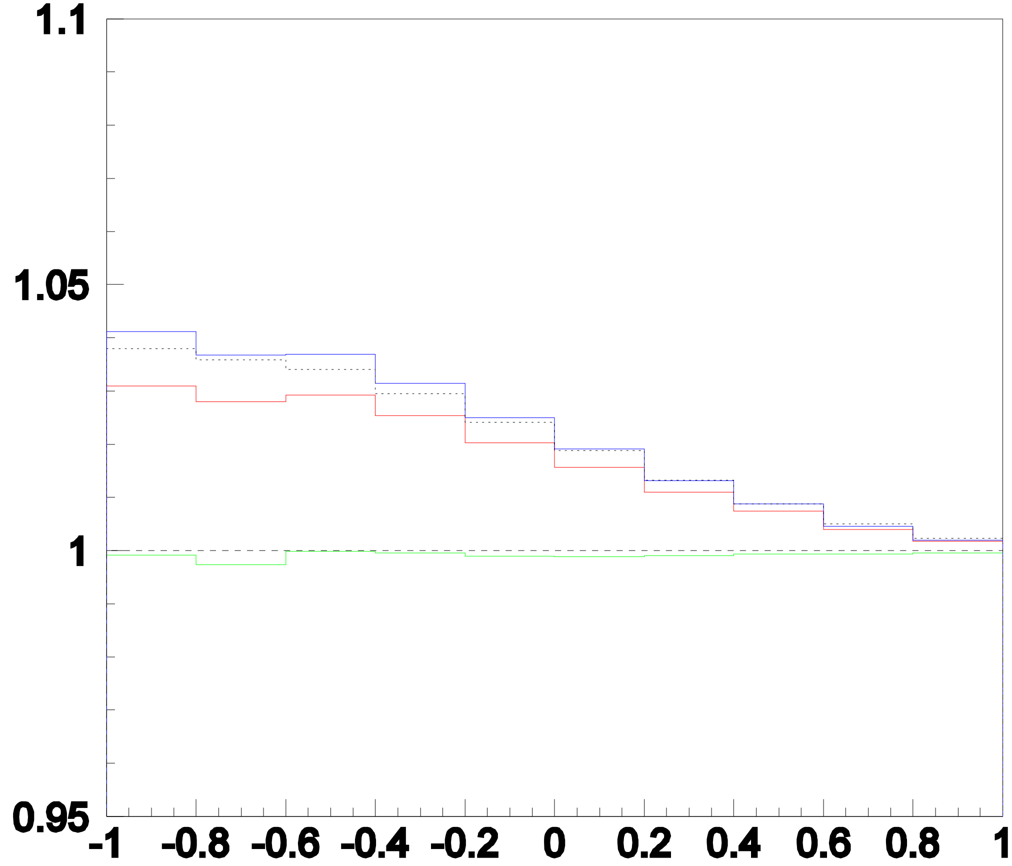
Sub-GeV
mu-like

P = 200 – 400 MeV



P = 400 – 1330 MeV



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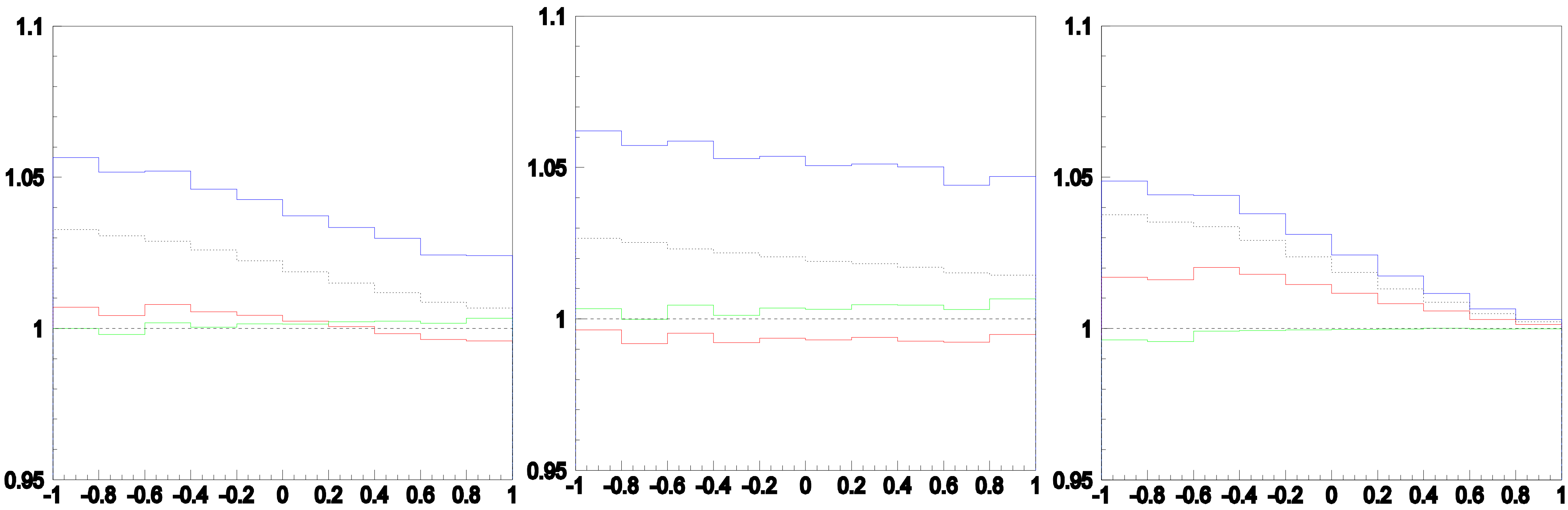
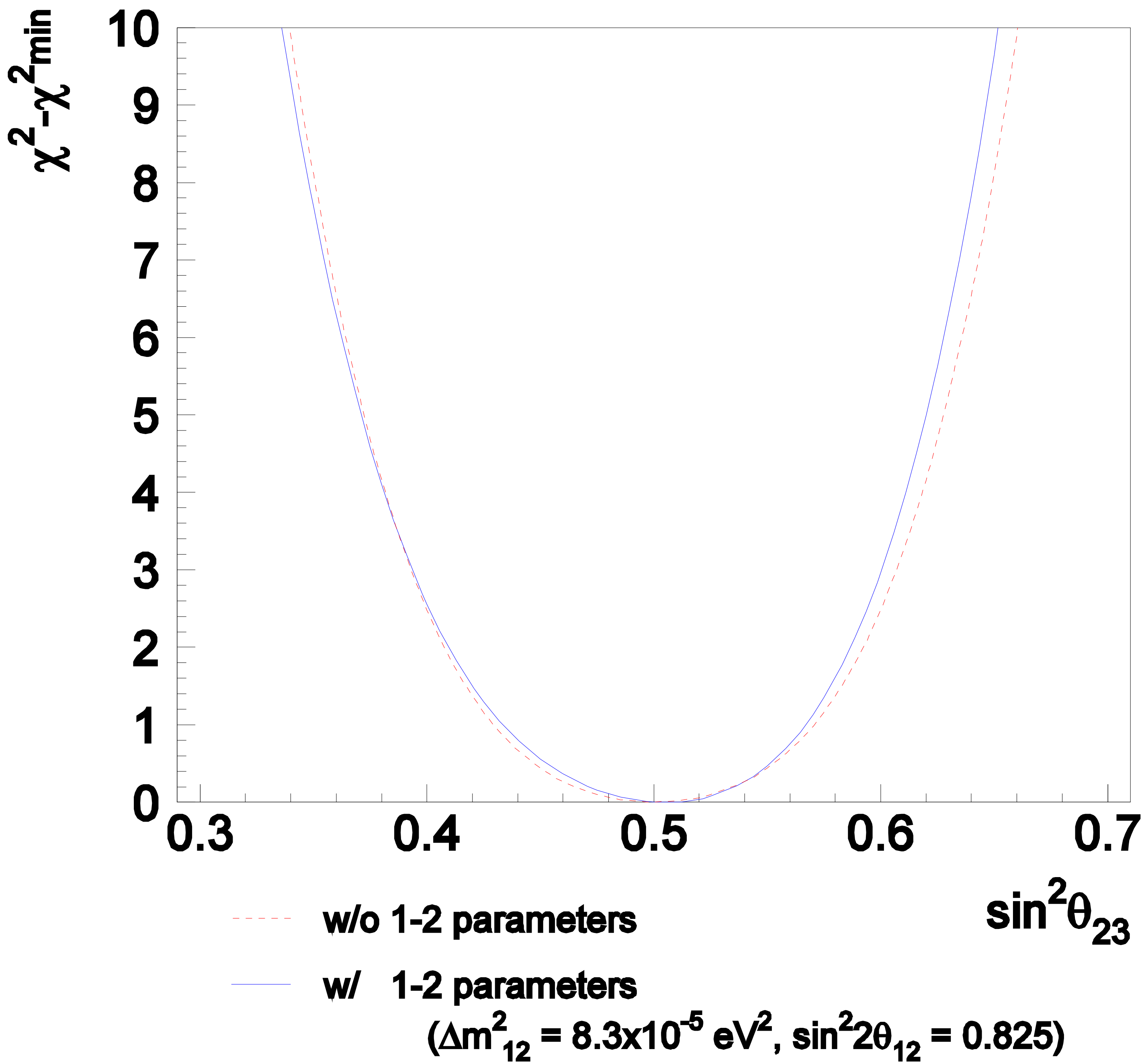
Sub-GeV /e ratio (zenith angle dependence)



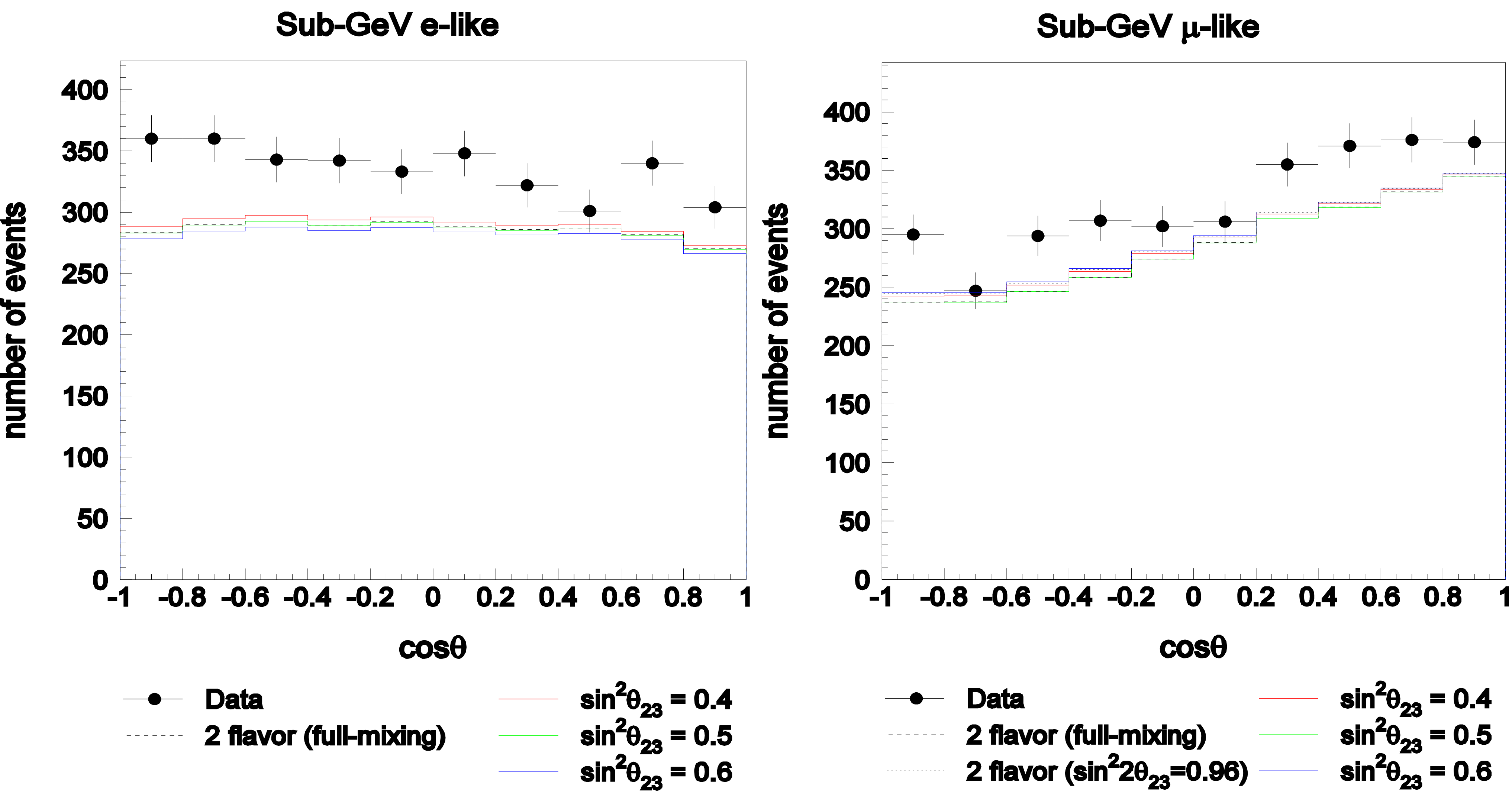
Shoei Nakayama

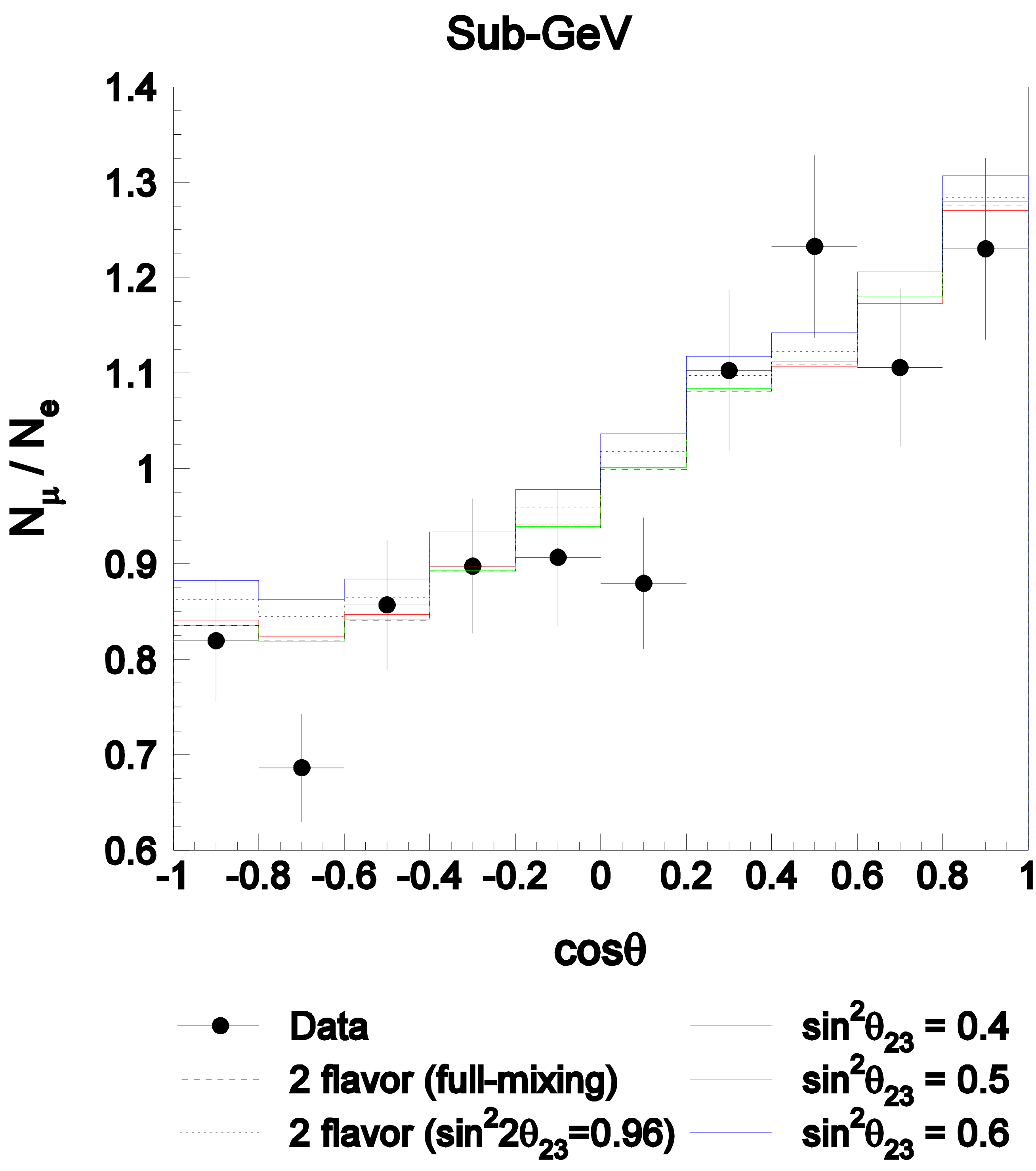


χ^2 distribution
as a function of $\sin^2\theta_{23}$
where Δm^2_{23} is chosen
to minimize χ^2

Shoei Nakayama

Sub-GeV Zenith Angle distribution





Sub-GeV
/e Ratio
Zenith Angle
distribution

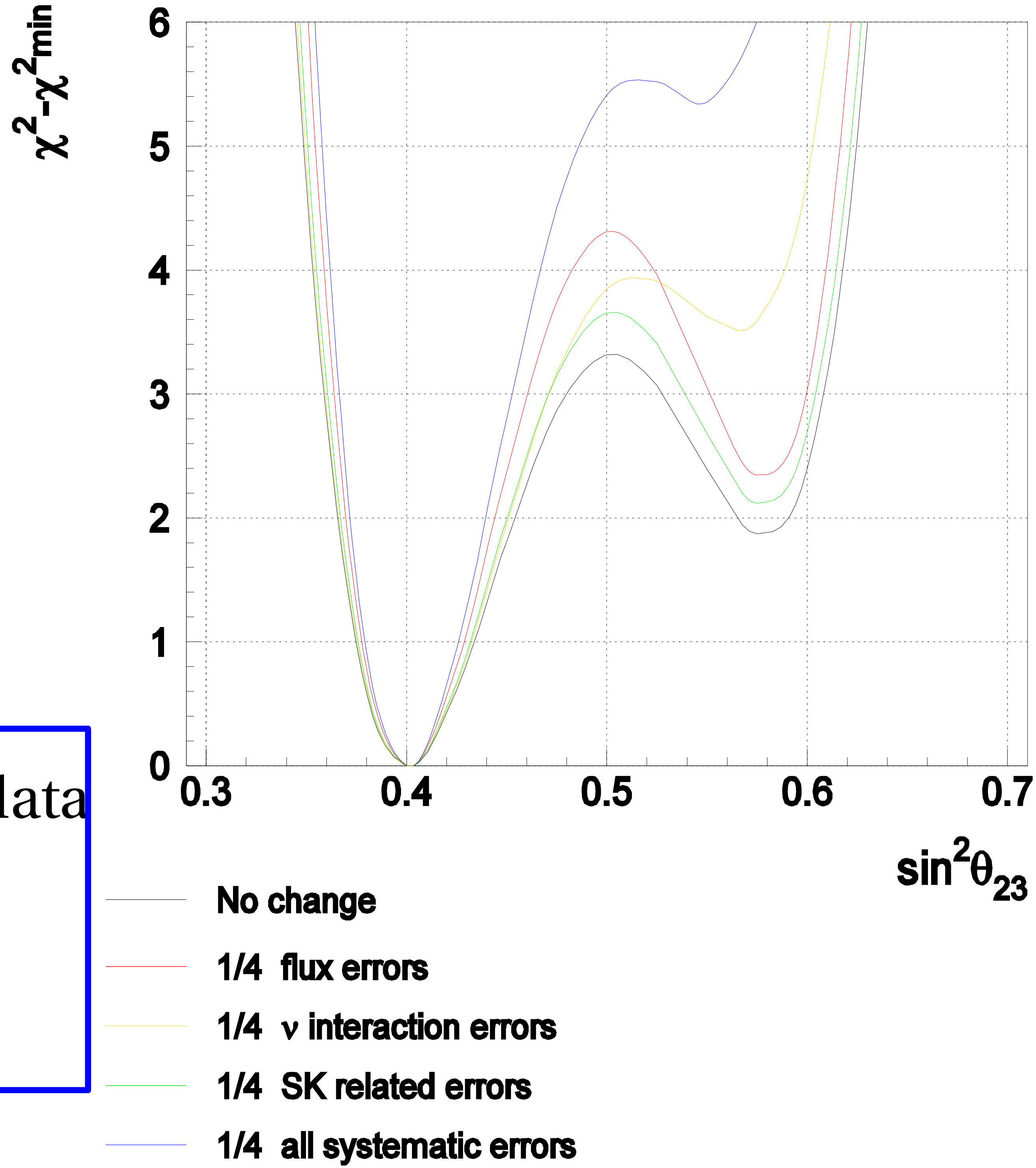
ANALYSIS of EFFECT of SYSTEMATIC ERRORS

True : $\sin^2\theta_{23} = 0.4$

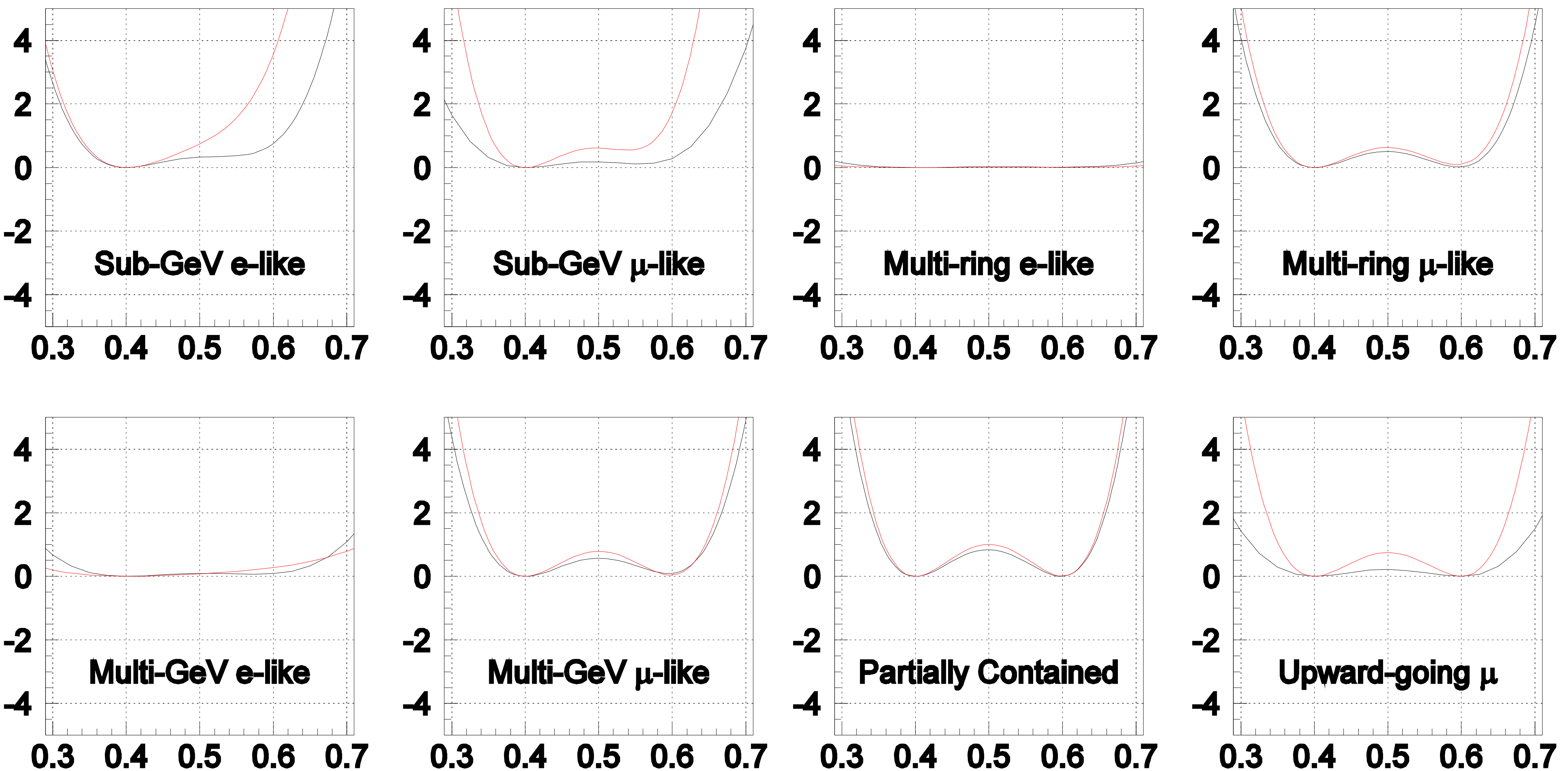
Test: 20 years of MC data

($\sin^2\theta_{23} = 0.4$,

$\Delta m^2_{23} = 2.5 \times 10^{-3}\ eV^2$)

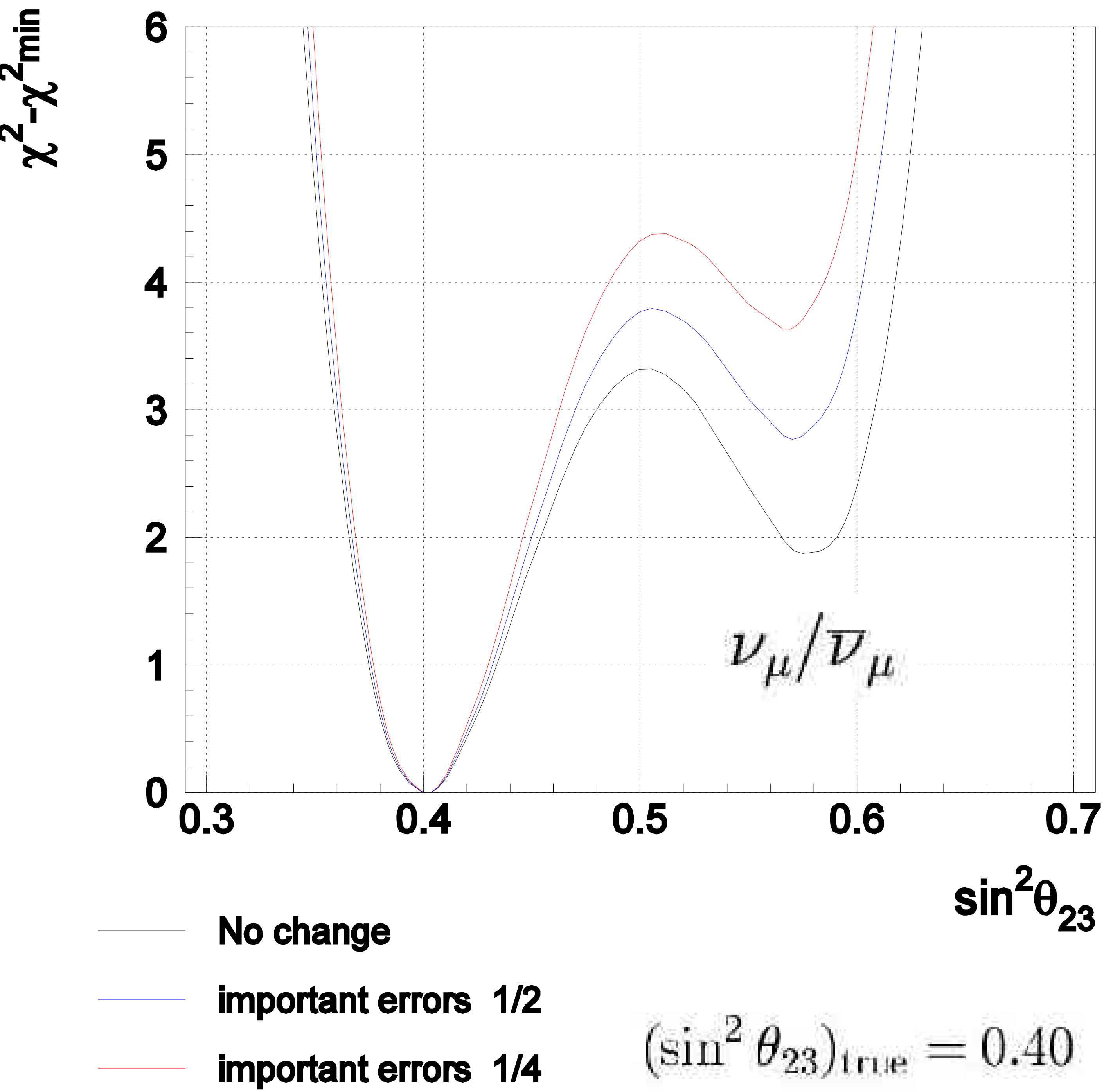


χ^2 contribution from sub-samples



Sub-GeV samples determine the octant

Multi-GeV (and PC) determine the allowed interval



Identification of 7 Most Important Sources of Systematic Uncertainty:

Axial Mass

QE Model

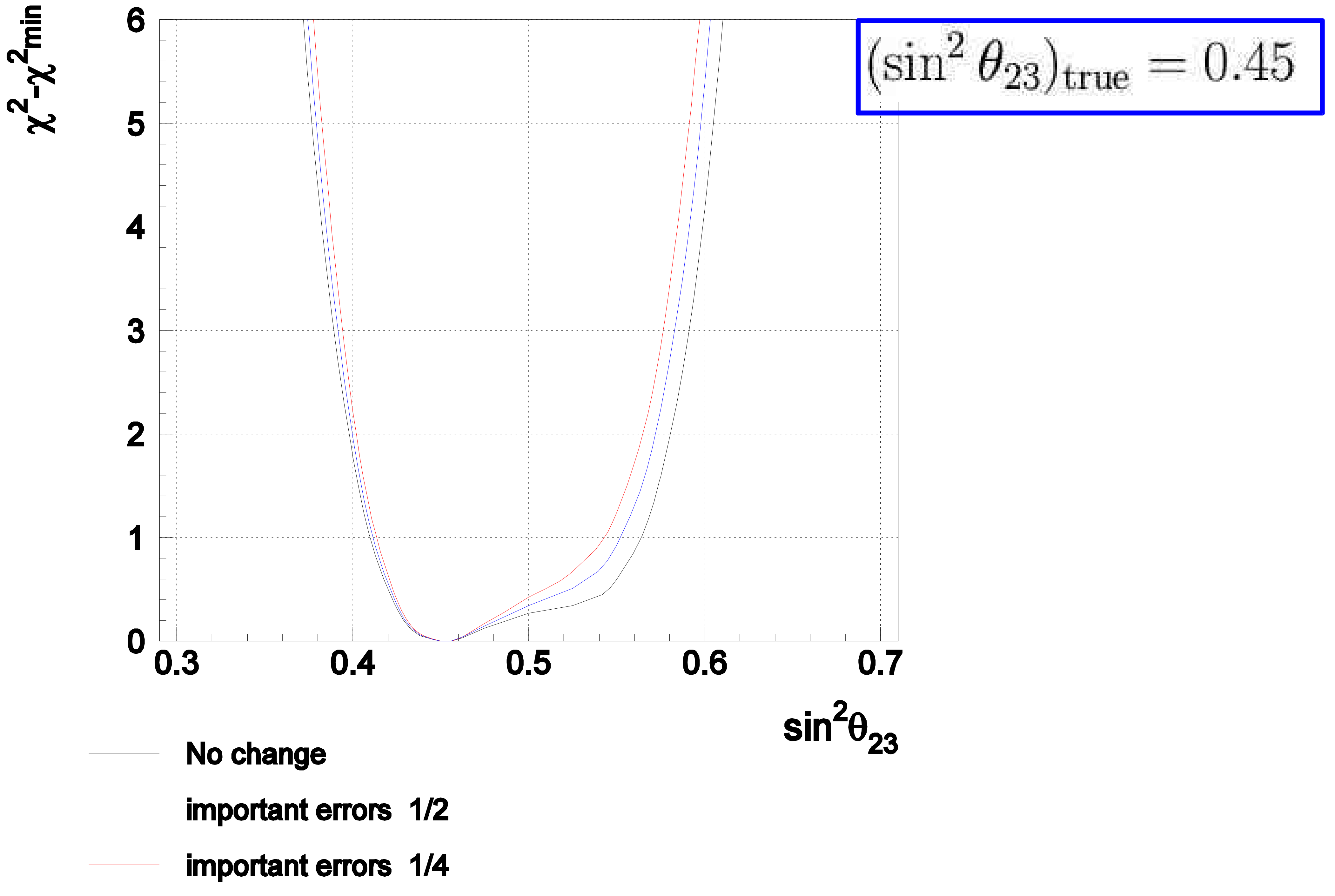
NC / CC

$(\nu_\mu + \overline{\nu}_\mu)/(\nu_e + \overline{\nu}_e)$

$\nu_\mu/\overline{\nu}_\mu$

$\nu_e/\overline{\nu}_e$

Up/Down



$(\sin^2\theta_{23})_{true} = 0.45$
$\chi^2 - \chi^2_{min}$
0
1
2
3
4
5
6
0.3
0.4
0.5
0.6
0.7
$\sin^2\theta_{23}$
No change
important errors 1/2
important errors 1/4

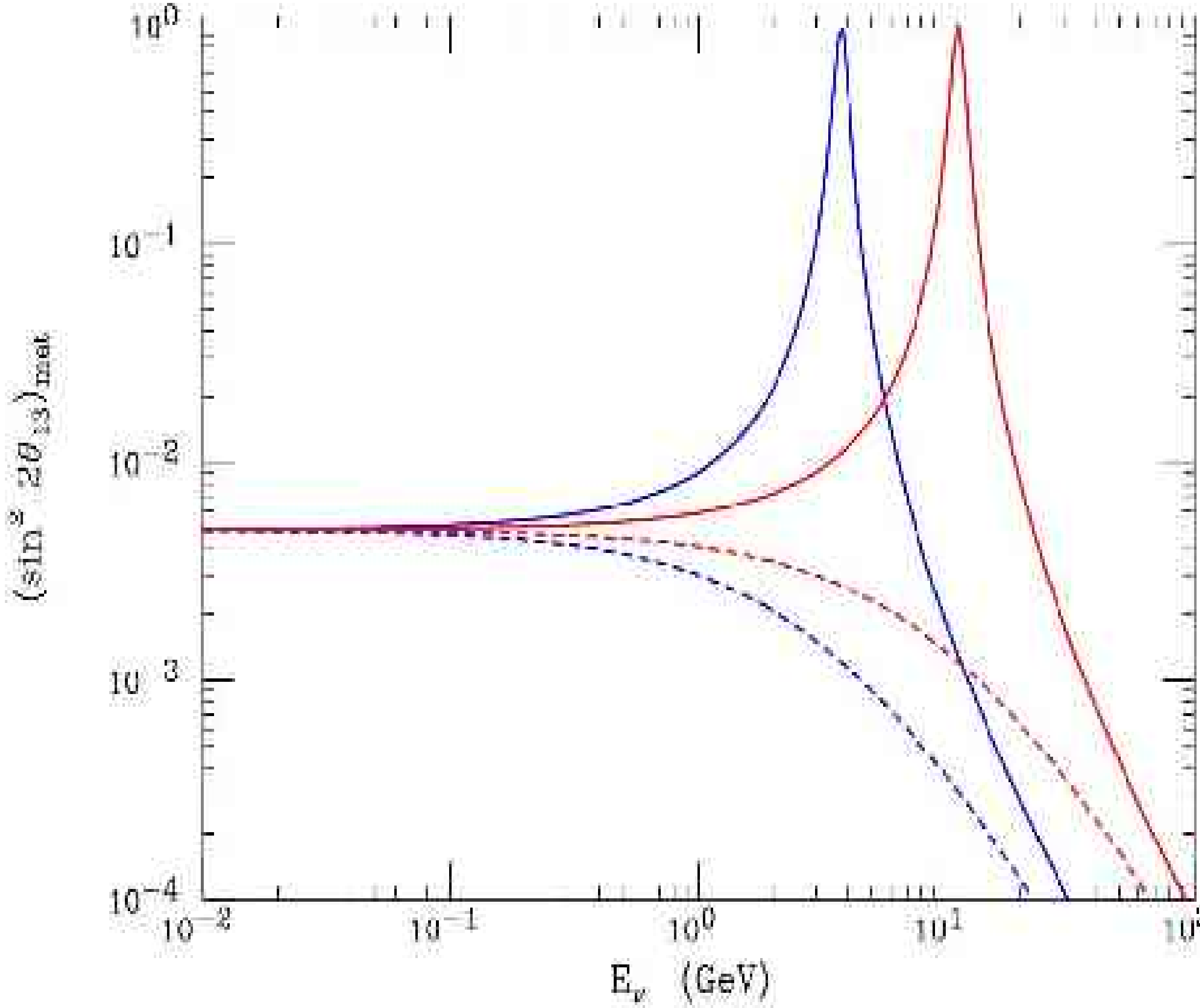
Okumura	Measurement of θ_{13}
Nakayama	Deviations of θ_{23} from Maximal Mixing
Shiozawa	Large Exposure All effects Combined

$$\frac{\Delta m^2_{23}}{2E} \simeq \sqrt{2}\, G_F\, N_e$$

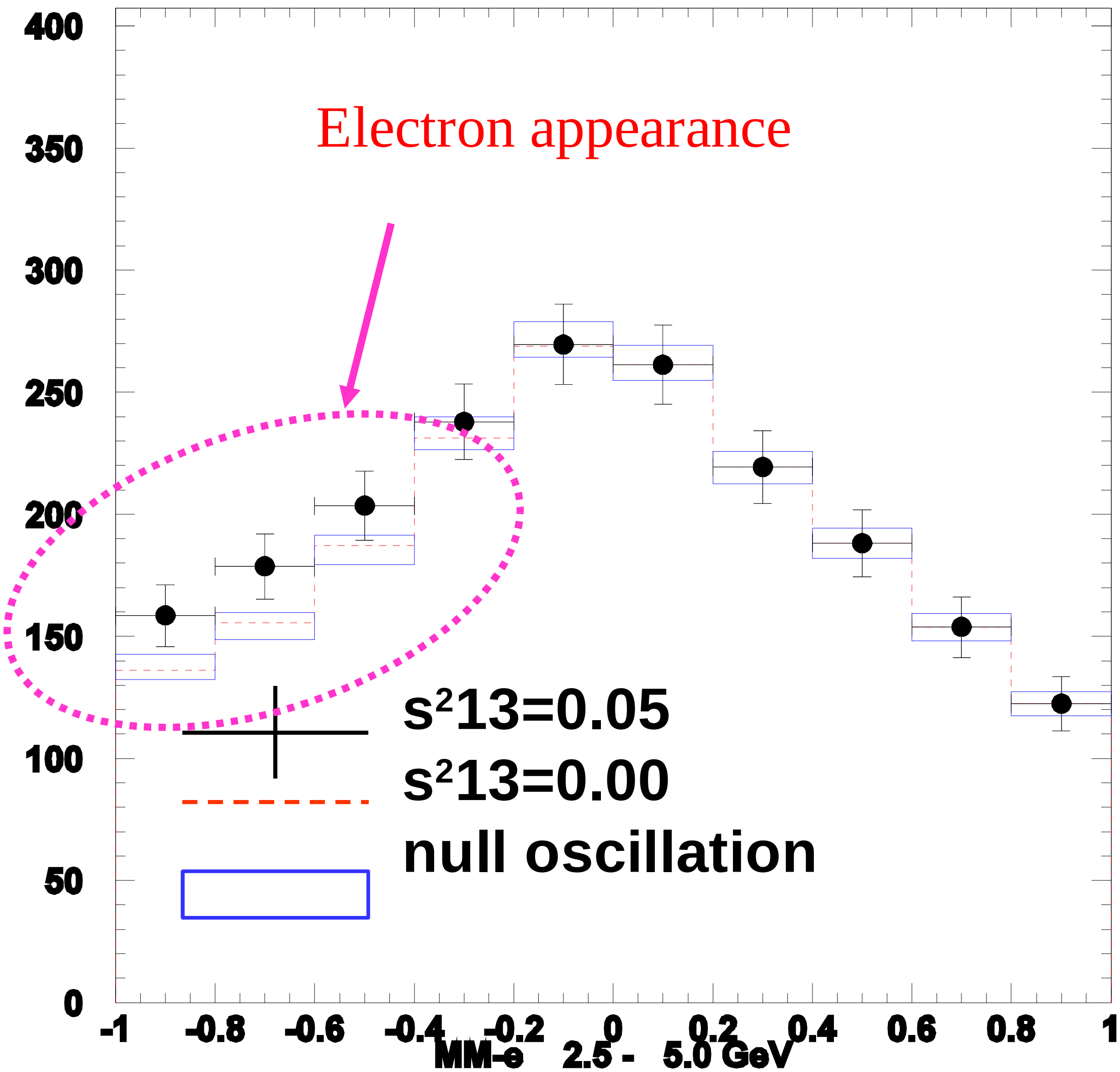
$$E_{\text{mantle}} \simeq 7.5 \text{ GeV}$$

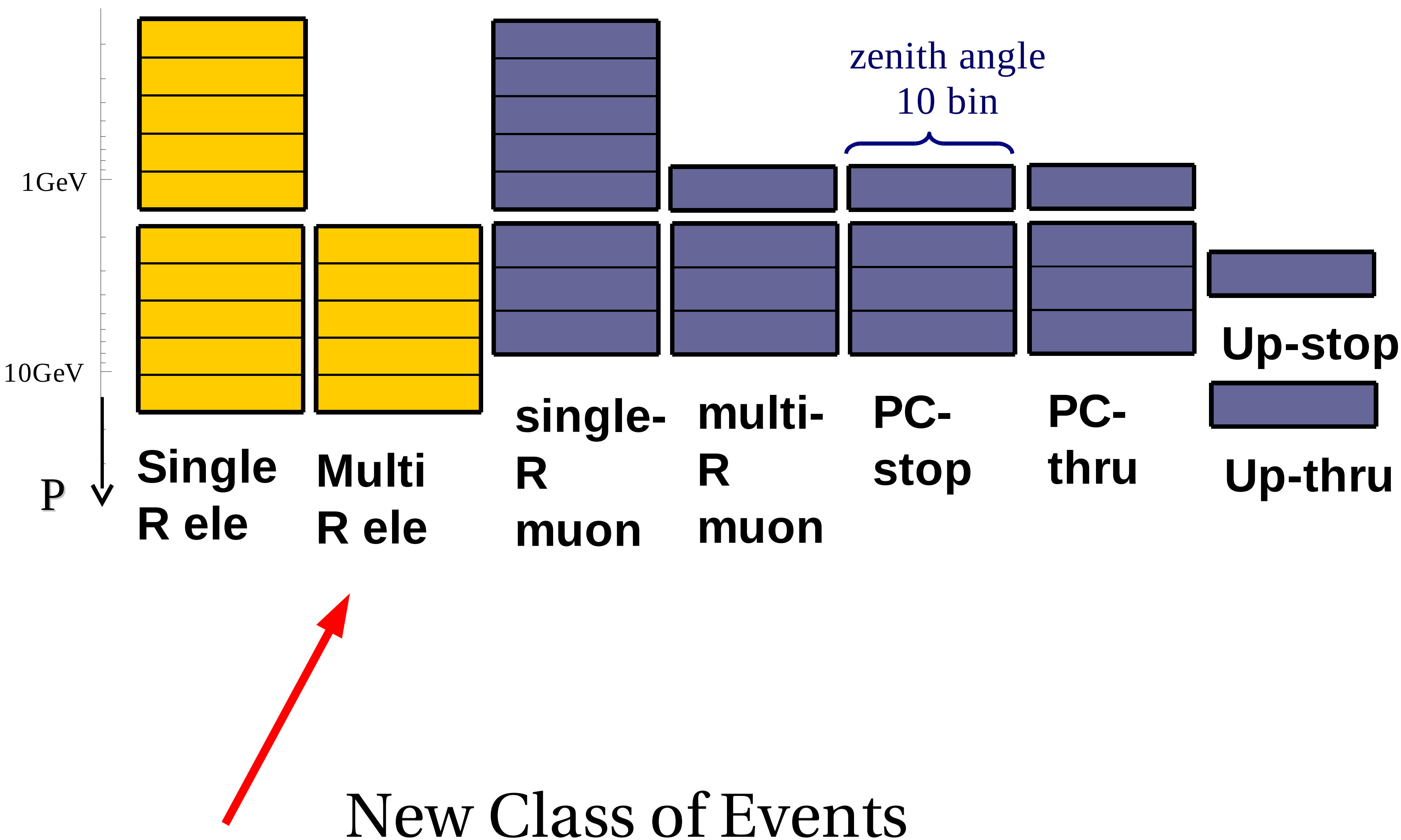
$$E_{\text{core}} \simeq 2.5 \text{ GeV}$$

θ_{13} Oscillations



1+multi-ring, e-like, 2.5 - 5 GeV





New Class of Events

List of systematic errors

b. Combined
- overall normalization
- relative norm. FC/PC
- relative norm. upstop/upthru

c. Neutrino flux
- $\nu\mu/\nu e$ below 5GeV
- $\nu\mu/\nu e$ above 5GeV
- anti-$\nu e/\nu e$ below 10GeV
- anti-$\nu e/\nu e$ above 10GeV
- anti-$\nu\mu/\nu\mu$ below 10GeV
- anti-$\nu\mu/\nu\mu$ above 10GeV
- UP/DOWN ratio
- Horizontal-vertical in FC/PC
- Neutrino flight length
- Energy spectrum
- K/pi ratio
- Sample-by-sample normalization (FC multi-GeV μ)
- Sample-by-sample normalization (PC and upstop)

d. Neutrino interactions
- QE
- Single-π production
- DIS
- DIS Bodek
- Coherent π production
- NC/CC
- Low energy QE
- Axial vector mass (M_A)
- Hadron simulator
- Nuclear effect

b. SK

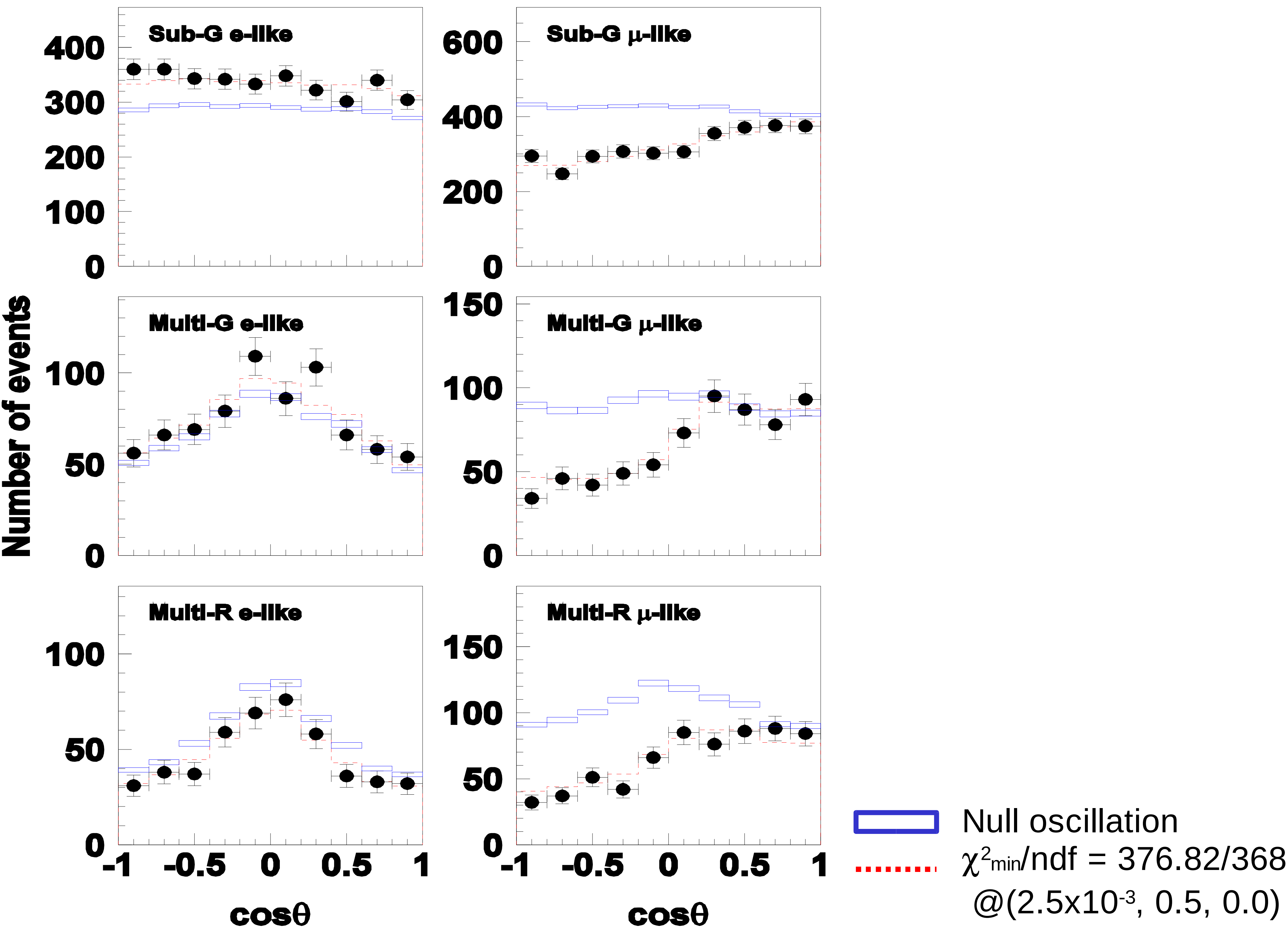
1. Event selection
   - FC reduction
   - PC reduction
   - Upmu efficiency
   - Upmu 1.6GeV cut
   - Flasher BG
   - Cosmic mu BG

3. Event reconstruction
   - Ring-counting
   - Single-R PID
   - Multi-R PID
   - Energy calibration
   - Up/down asymmetry of energy

5. Others
   a. Tau

6. 3flavor analysis
   - Upthru BG in horizontal bin
   - Upstop BG in horizontal bin
   - Non νeCC in multi-G single-R electron
   - Non νeCC in multi-G multi-R electron
   - Normalization of multi-R electron

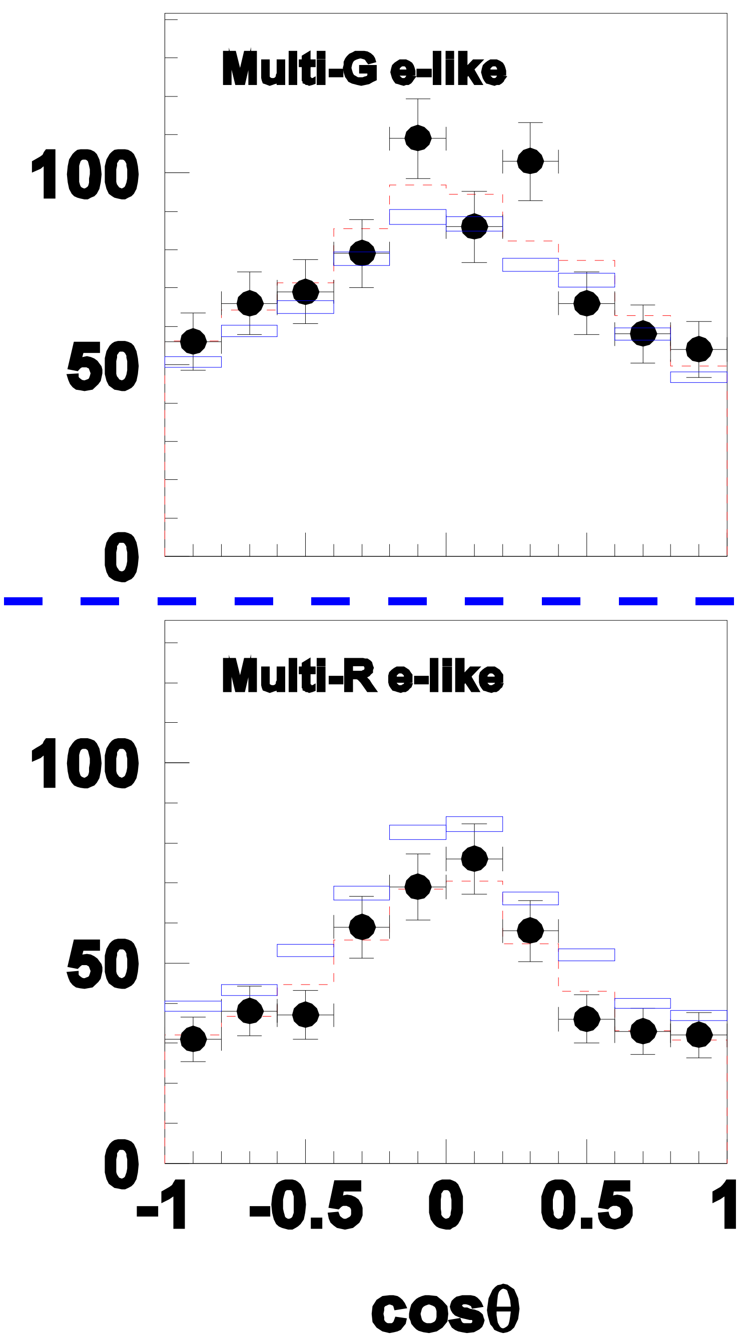
Total number of errors: 44

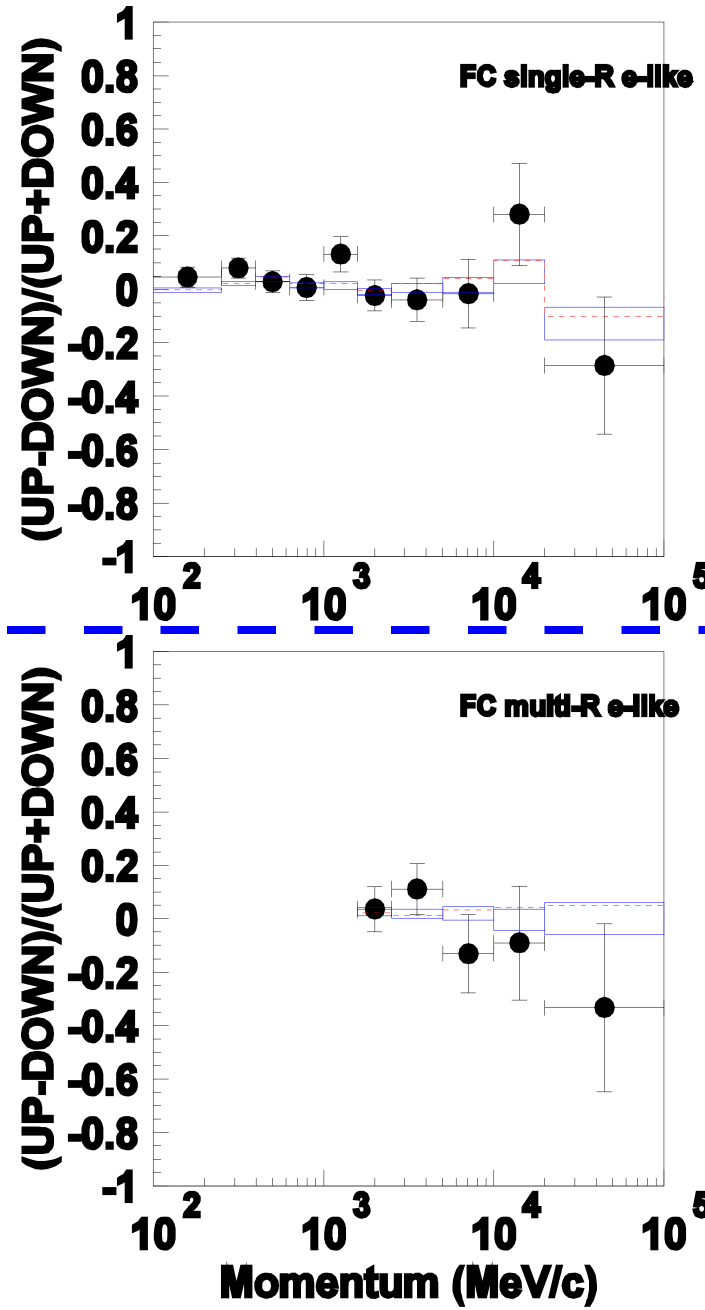


Sub-G e-like
Sub-G μ-like
Multi-G e-like
Multi-G μ-like
Multi-R e-like
Multi-R μ-like
Number of events
cosθ
cosθ
Null oscillation
χ2min/ndf = 376.82/368
@(2.5x10-3, 0.5, 0.0)

Zenith Angle

Up/Down Asymmetry



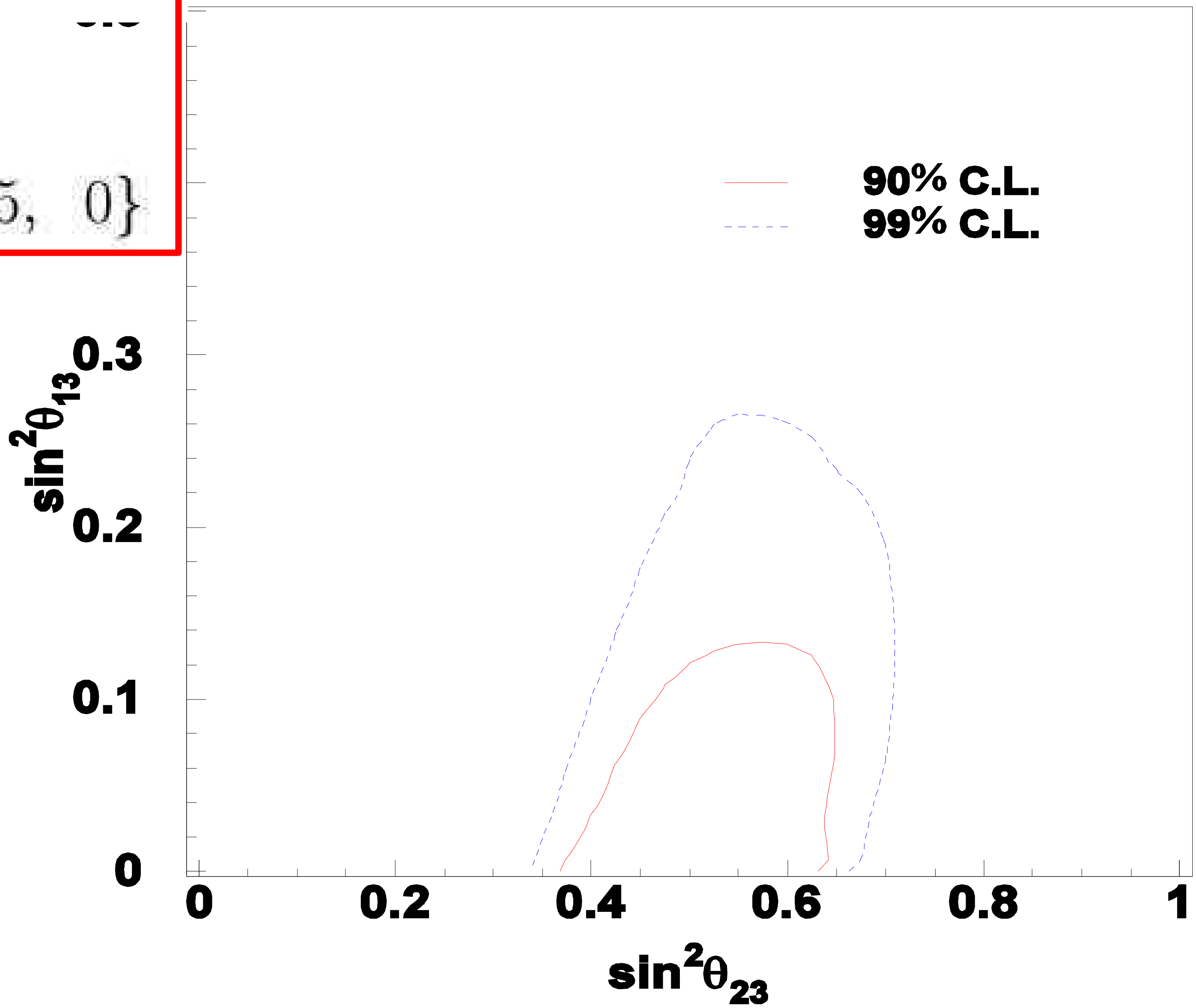


3 Parameter Fit

$$\{\Delta m^2, \ \sin^2\theta_{23}, \ \sin^2\theta_{13}\}$$

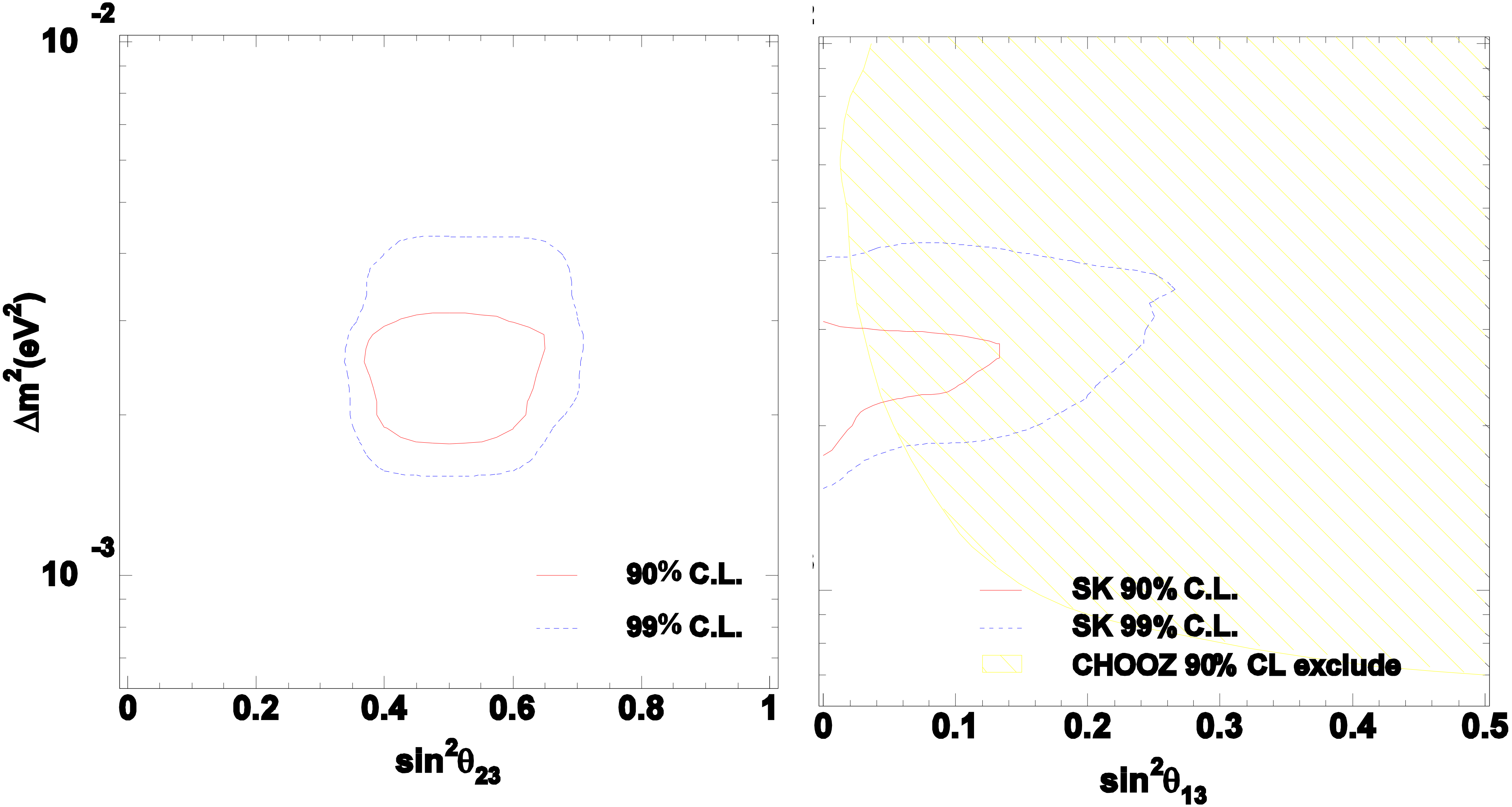
Best Fit Point:

$$\{2.5\times10^{-3}\ \mathrm{eV}^2, \ 0.5, \ 0\}$$

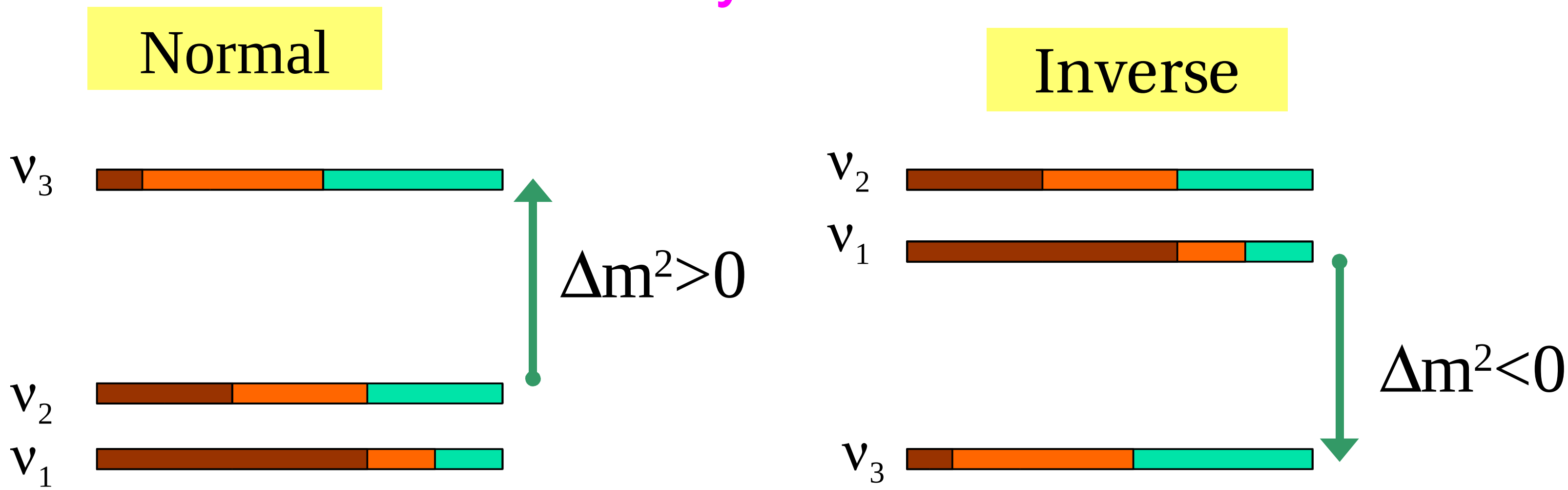


Allowed region by 3 flavor analysis

Normal hierarchy



Normal ($\Delta m^2>0$) or inverse ($\Delta m^2<0$) mass hierarchy ?



Matter effect is different btwn normal / inverse mass hierarchy:

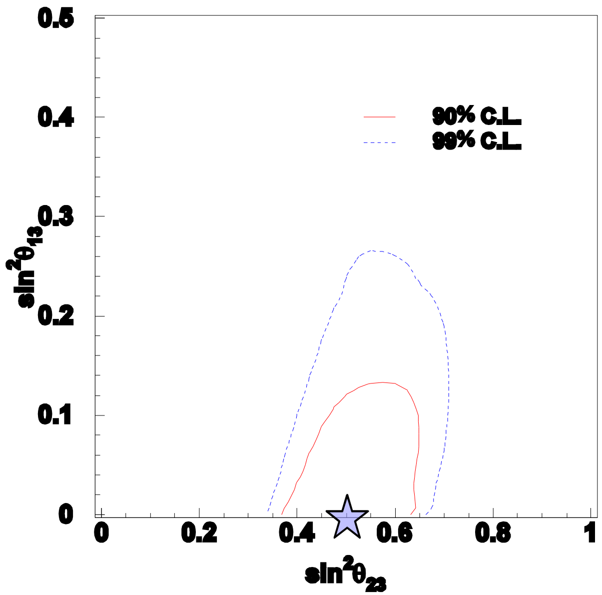
	neutrino	anti-neutrino
$\Delta m^2>0$	enhanced	suppressed
$\Delta m^2<0$	suppressed	enhanced

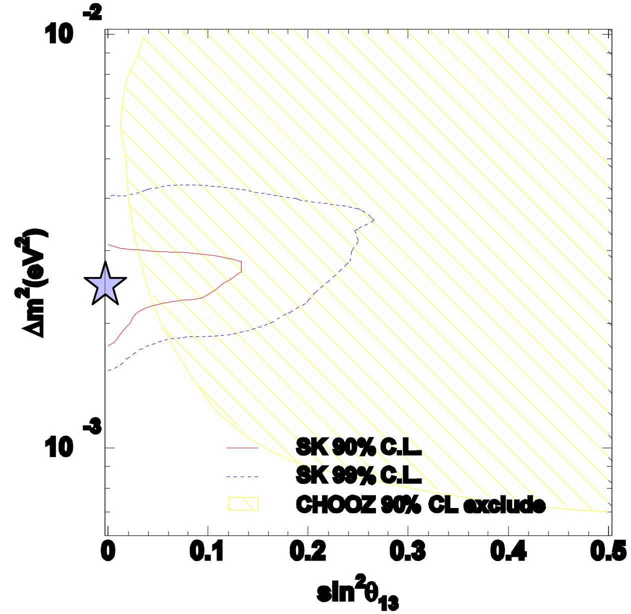
Basically, water Cherenkov detector cannot discriminate neutrino/anti-neutrino event-by-event basis, but small effect can be obtained in multi-GeV electron sample due to the difference of cross section, etc..

Normal vs Inverse hierarchy

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

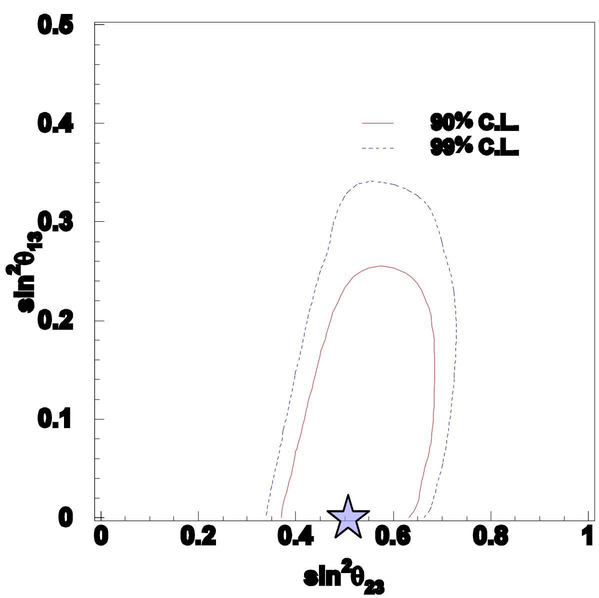
χ^2_{min}/ndf = 376.82/368
@(2.5x10^{-3}, 0.5, 0.0)

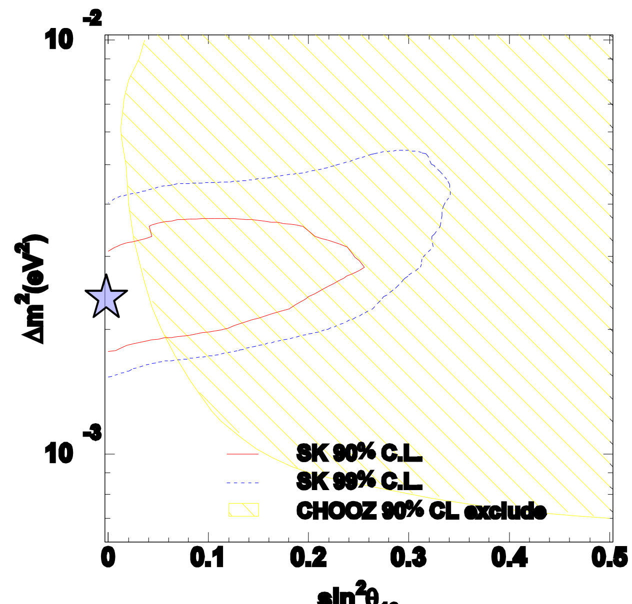




Inverse ($\Delta m^2 < 0$)

χ^2_{min}/ndf = 376.76/368
@(2.5x10^{-3}, 0.525, 0.00625)





Okumura	Measurement of θ_{13}
Nakayama	Deviations of θ_{23} from Maximal Mixing
Shiozawa	Large Exposure All effects Combined

Masato Shiozawa

Future Possibilities
of Atmospheric Neutrino Experiments

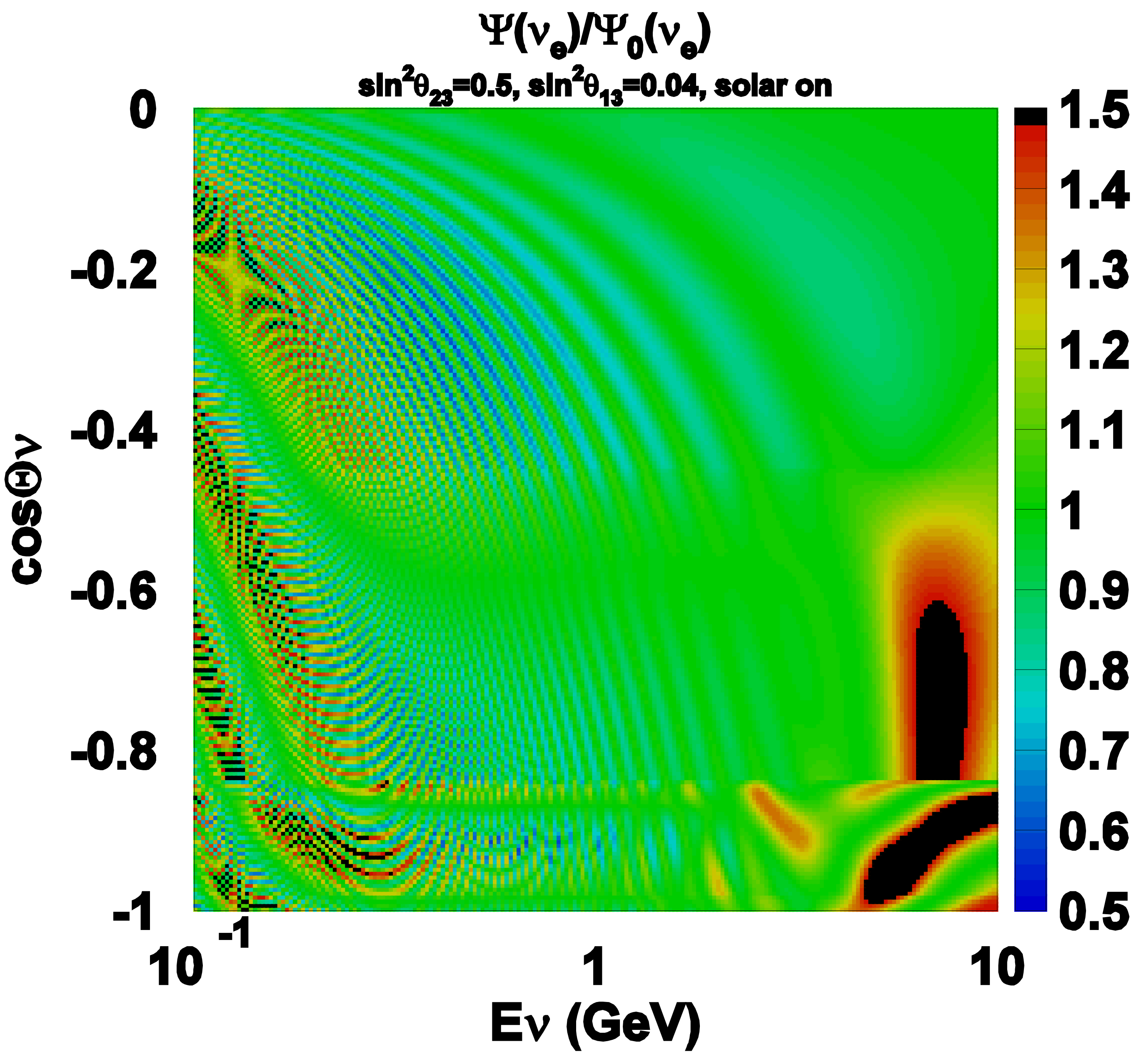
20 years of SK (5 * SK-I)
80 years of SK (20 * SK-I)

$$\Delta m^2_{12} \qquad \theta_{12}$$
$$\Delta m^2_{23}$$

All Oscillation Parameters
3 Well Measured by other experiments

3 to be determined
4 * 4 * 4 = 64 MC calculations

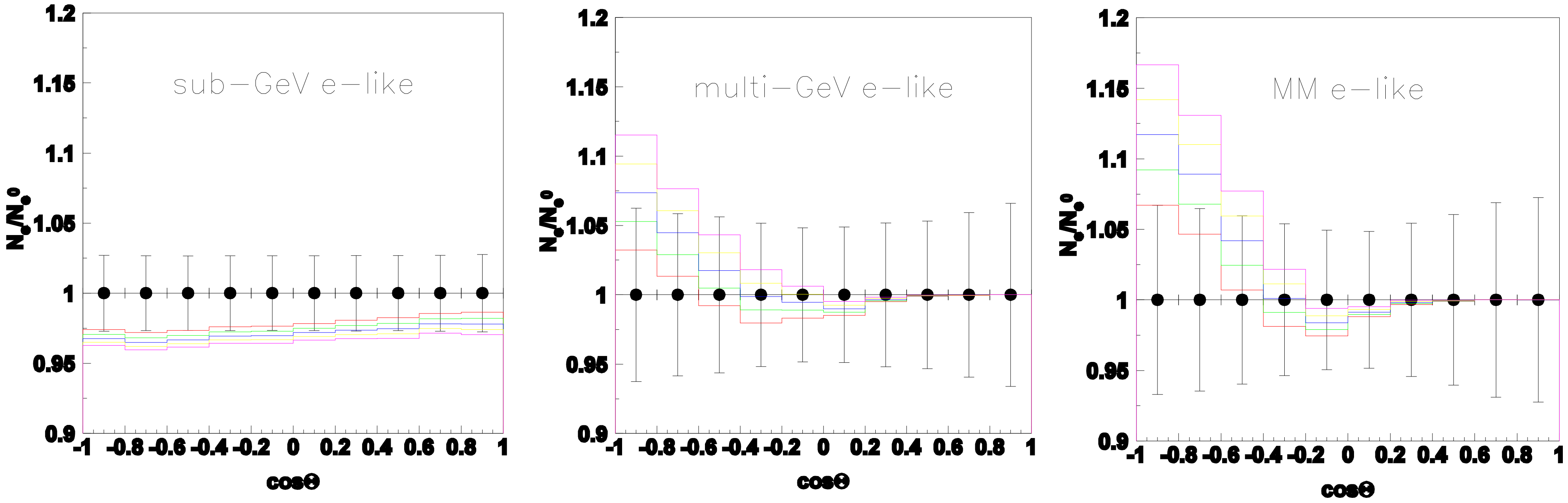
$$\theta_{23} \qquad \theta_{13} \qquad \delta$$



Ψ(νe)/Ψ0(νe)
sin²θ23=0.5, sin²θ13=0.04, solar on
cosΘν
Eν (GeV)
0
-0.2
-0.4
-0.6
-0.8
-1
10^-1
1
10
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5

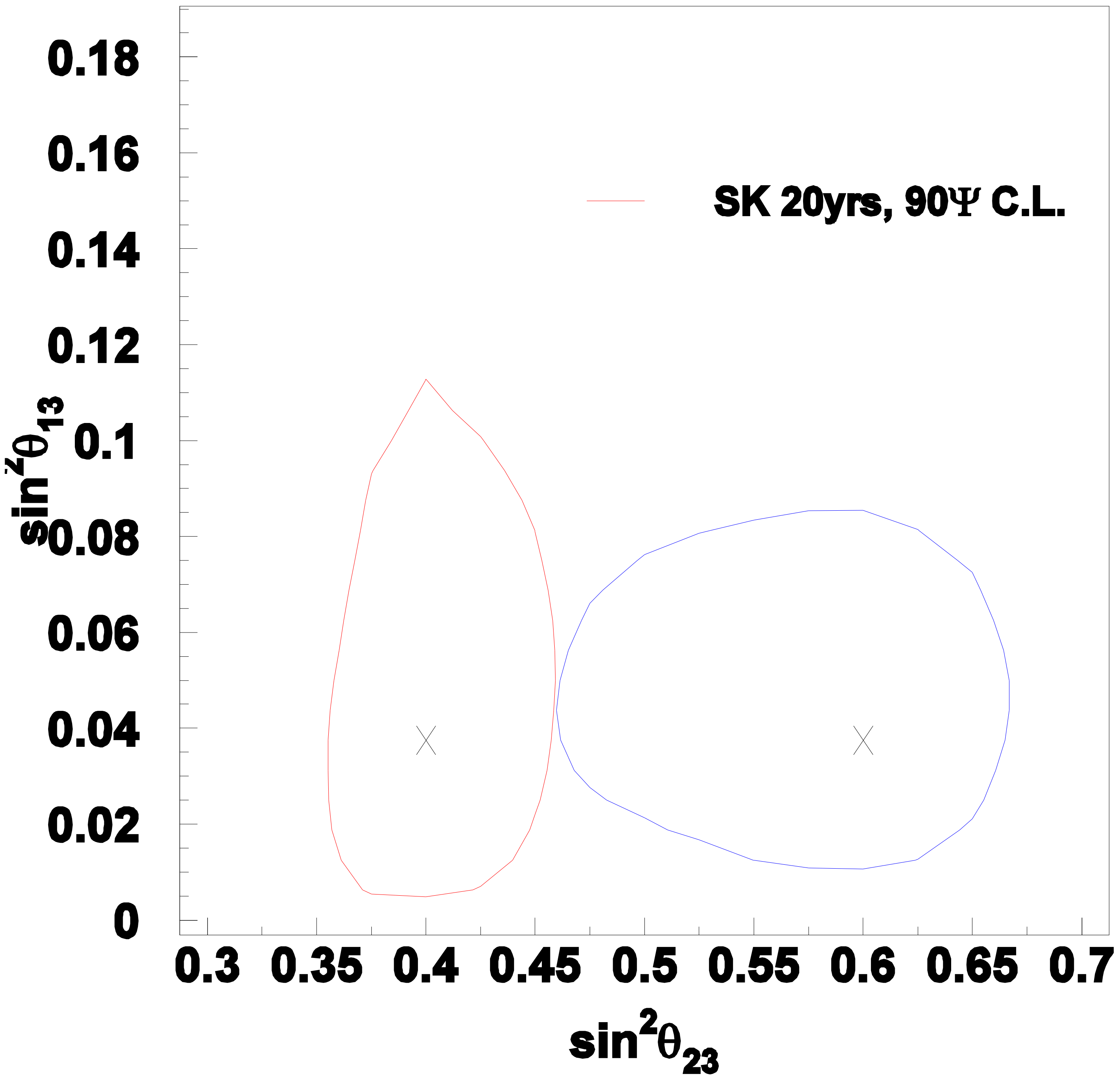
$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.4 ~ 0.6
$s^2\theta_{13}$=0.04
δcp=45°
Δm^2_{12}=8.3e-5
Δm^2_{23}=2.5e-3

no osc. with 20yrs stat.error
s^2_{23}=0.40
0.45
0.50
0.55
0.60



20 SK years

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.4$ or 0.6
$s^2\theta_{13}=0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3e-5$
$\Delta m^2_{23}=2.5e-3$

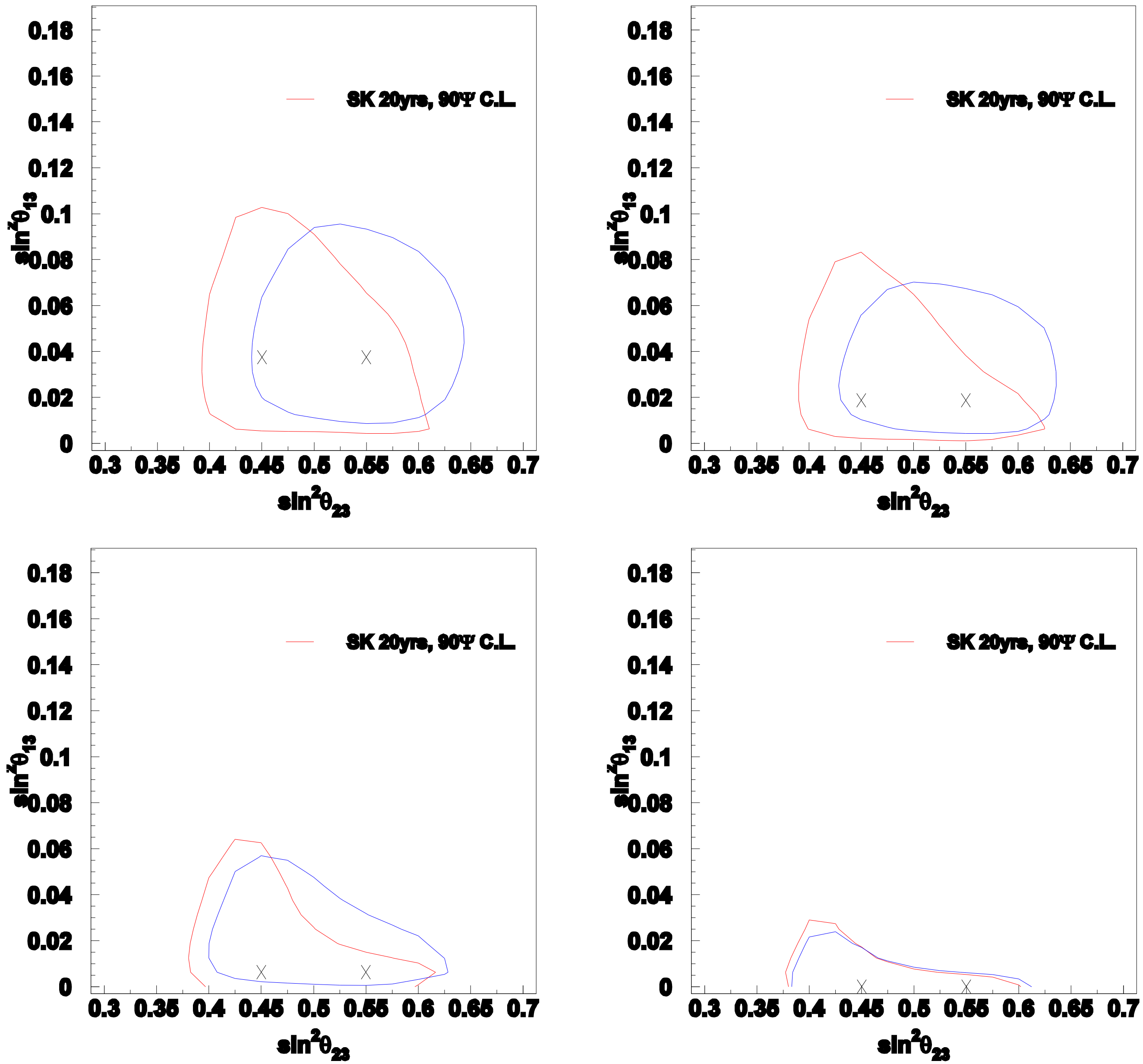


20 SK years

$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.45 or 0.55
$s^2\theta_{13}$=0.00~0.04
δcp=45^o
Δm^2_{12}=8.3e-5
Δm^2_{23}=2.5e-3

$s^2\theta_{23}$ = 0.45 or 0.55
$s^2 2\theta_{23}$ = 0.99

With 20yrs SK, discrimination is very hard.

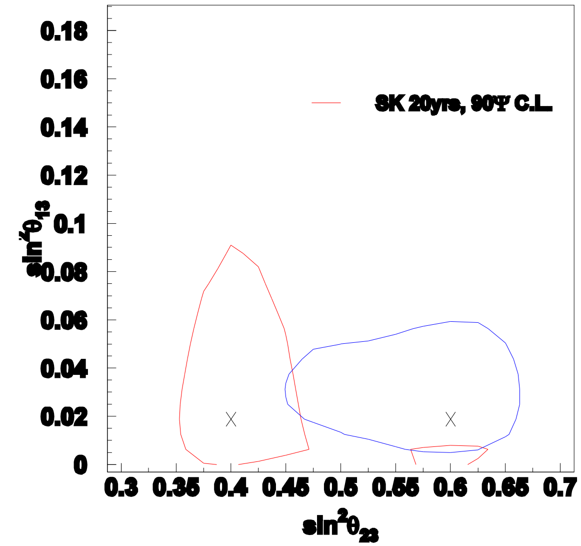


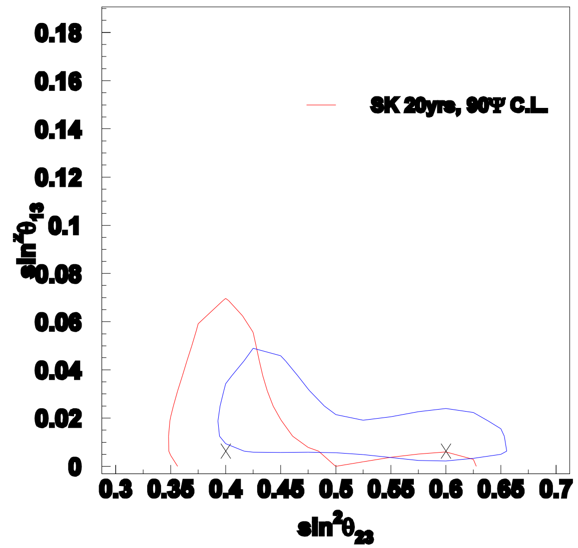
20 SK years

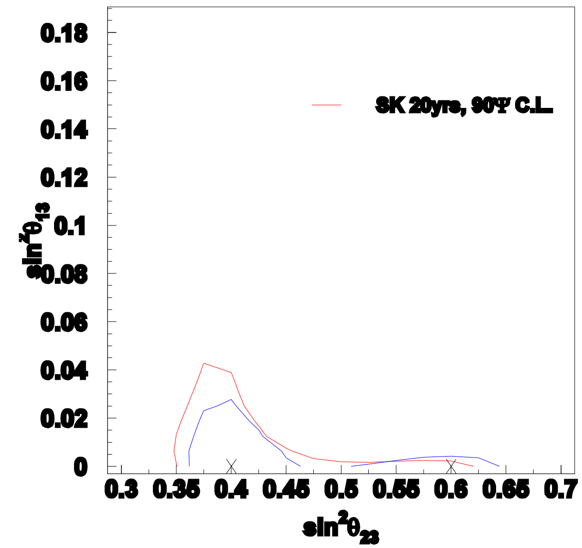
$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.4 or 0.6
$s^2\theta_{13}$=0.00~0.04
δcp=45^o
Δm^2_{12}=8.3e-5
Δm^2_{23}=2.5e-3

$s^2\theta_{23}$ = 0.40 or 0.60
$s^2 2\theta_{23}$=0.96

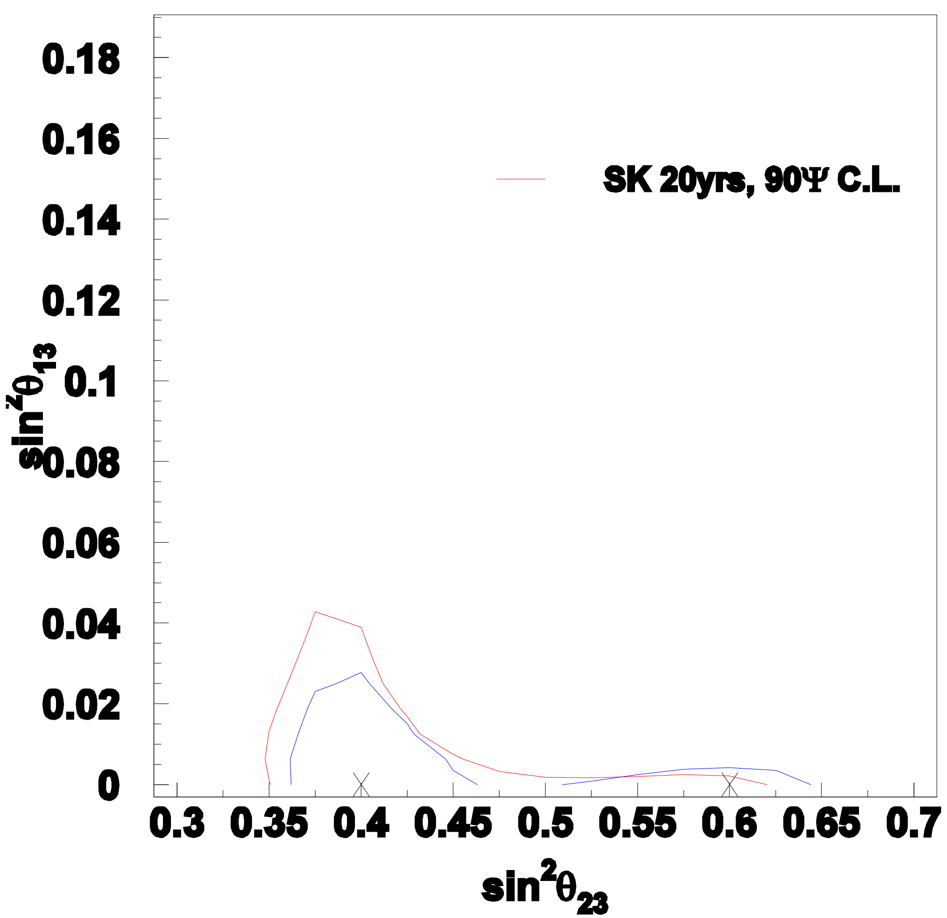
With 20yrs SK, discrimination is possible for large θ_{13}.



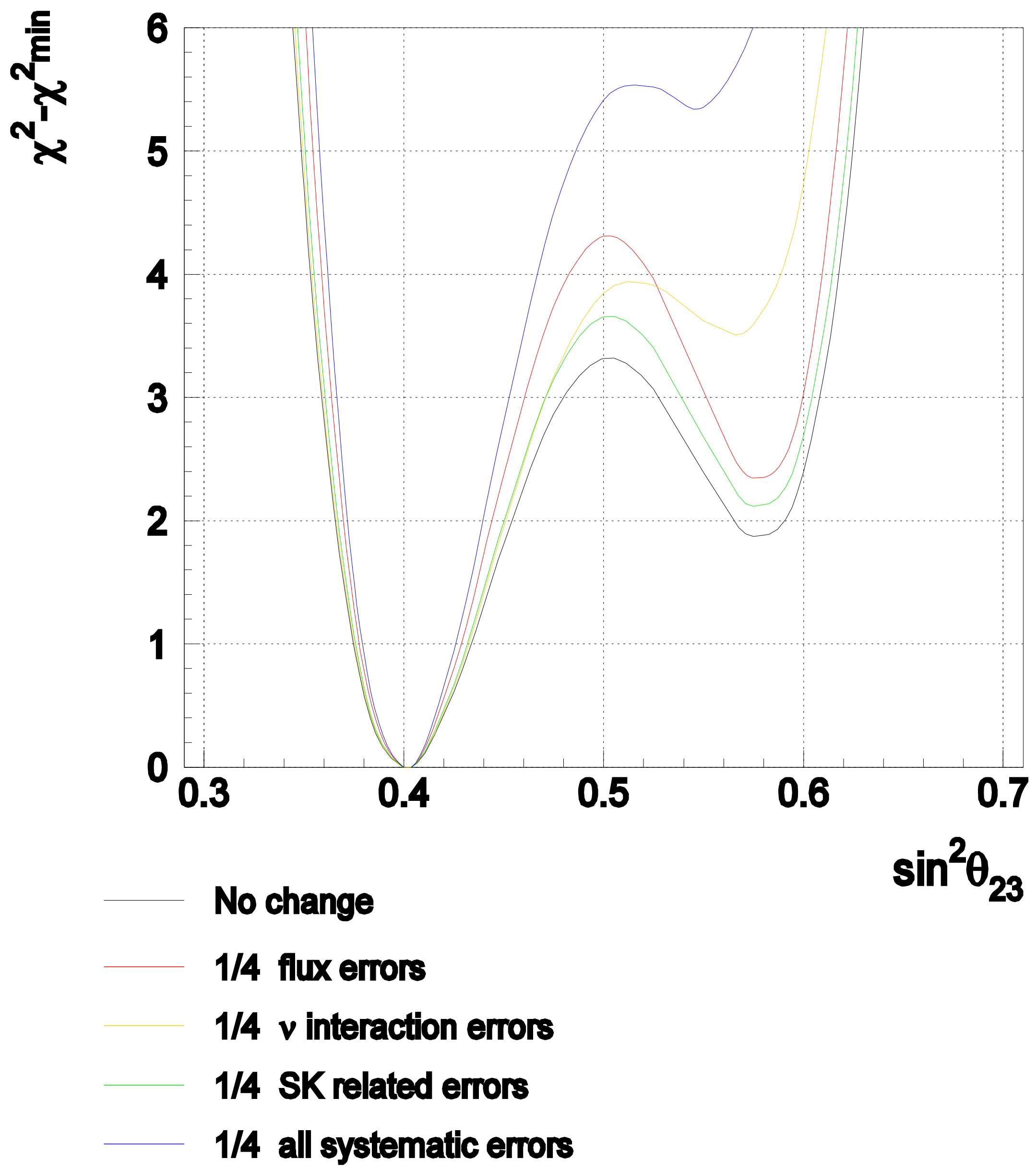




Shiozawa



Nakayama

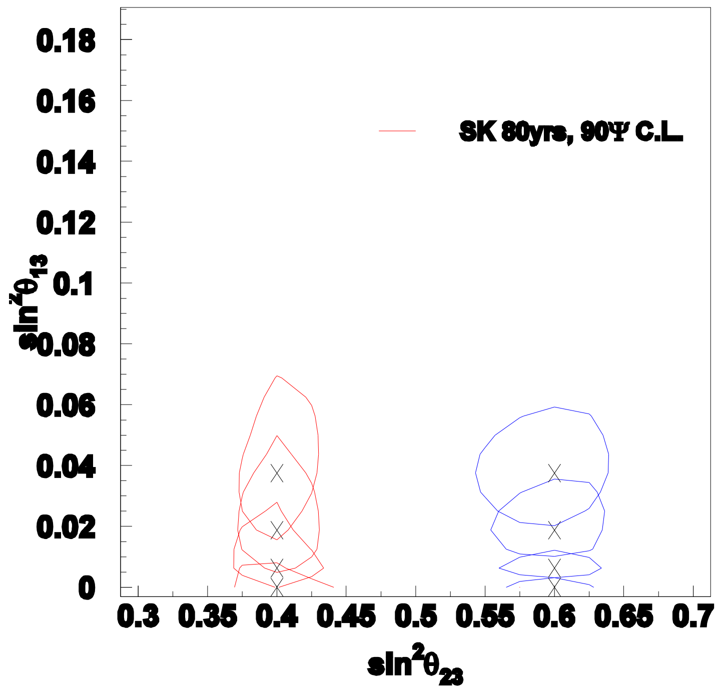


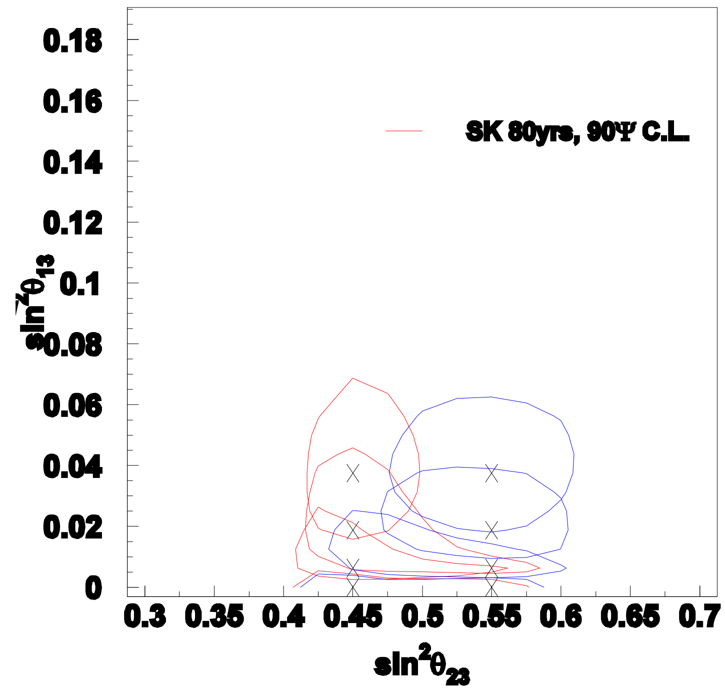
80 SK years

s²2θ₁₂=0.825

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

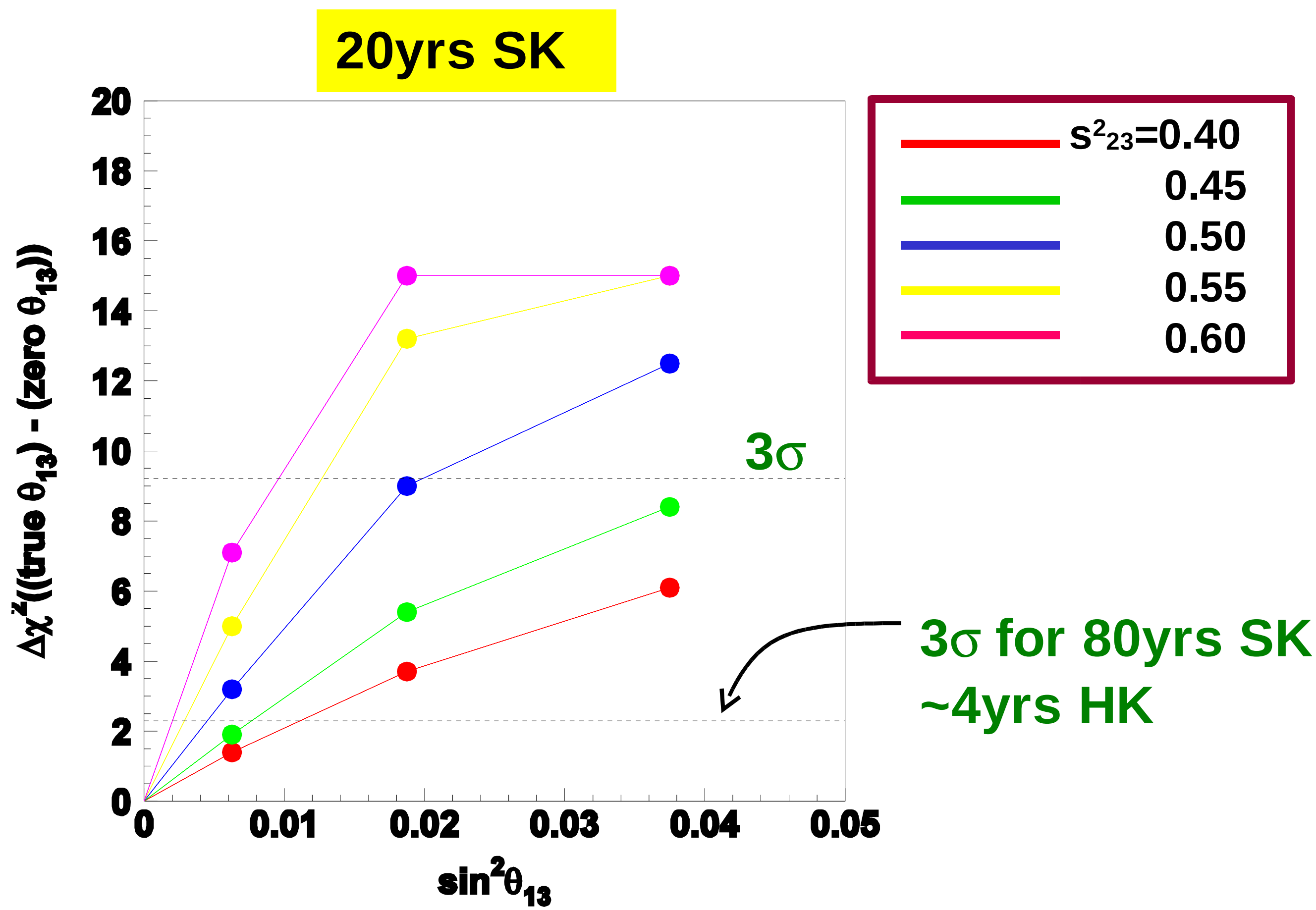
80yrs SK ~ 4yrs HK





With 80yrs SK, discrimination is better and possible for many test points.

- $s^2 2\theta_{12}=0.825$
- $s^2\theta_{23}=0.40 \sim 0.60$
- $s^2\theta_{13}=0.00\sim0.04$
- $\delta cp=45^o$
- $\Delta m^2_{12}=8.3e\text{-}5$
- $\Delta m^2_{23}=2.5e\text{-}3$

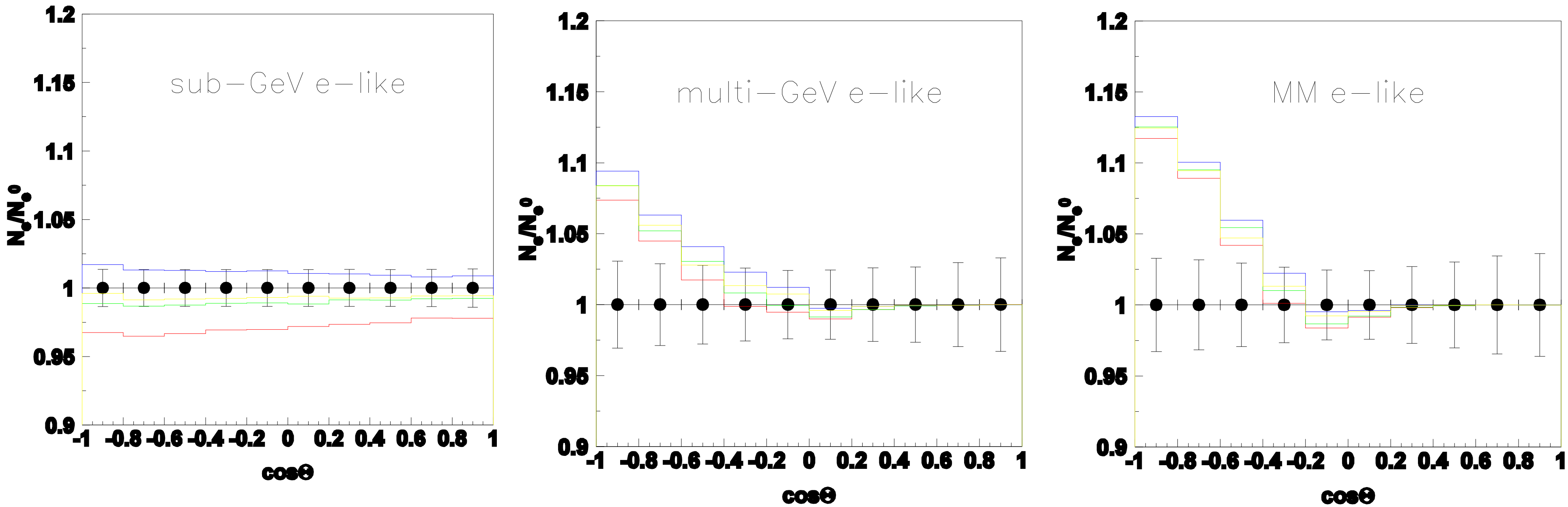


Positive signal for nonzero θ_{13} can be seen if θ_{13} is near the CHOOZ limit and $s^2\theta_{23} > 0.5$

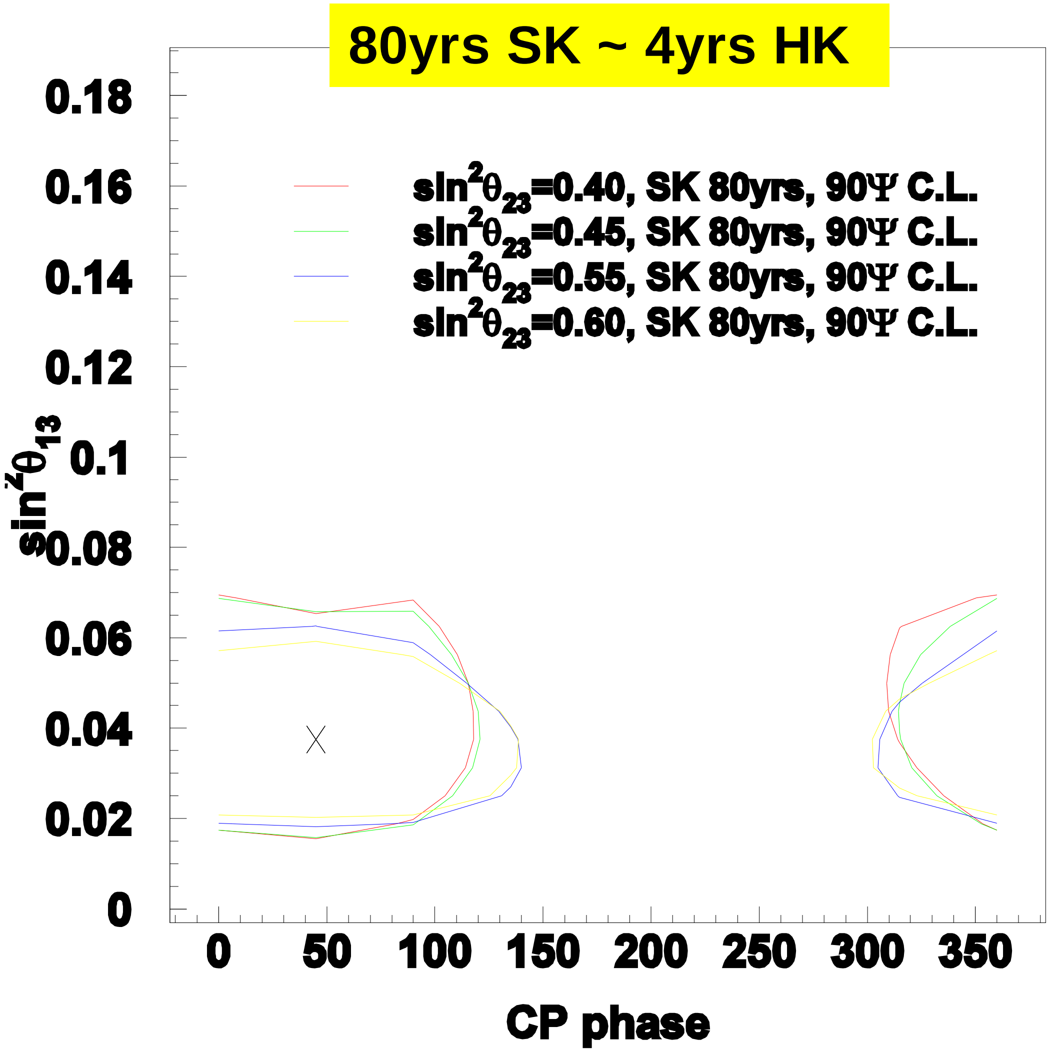
Measurement of Delta

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.5$
$s^2\theta_{13}=0.04$
$\delta cp=0^o \sim 360^o$
$\Delta m^2_{12}=8.3e\text{-}5$
$\Delta m^2_{23}=2.5e\text{-}3$

- (black) no osc. with 80yrs stat.error
- (red) $\delta_{CP}=$ 45°
- (green) 135°
- (blue) 225°
- (yellow) 315°



$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.4 ~ 0.6
$s^2\theta_{13}$=0.04
δcp=45°
Δm^2_{12}=8.3e-5
Δm^2_{23}=2.5e-3



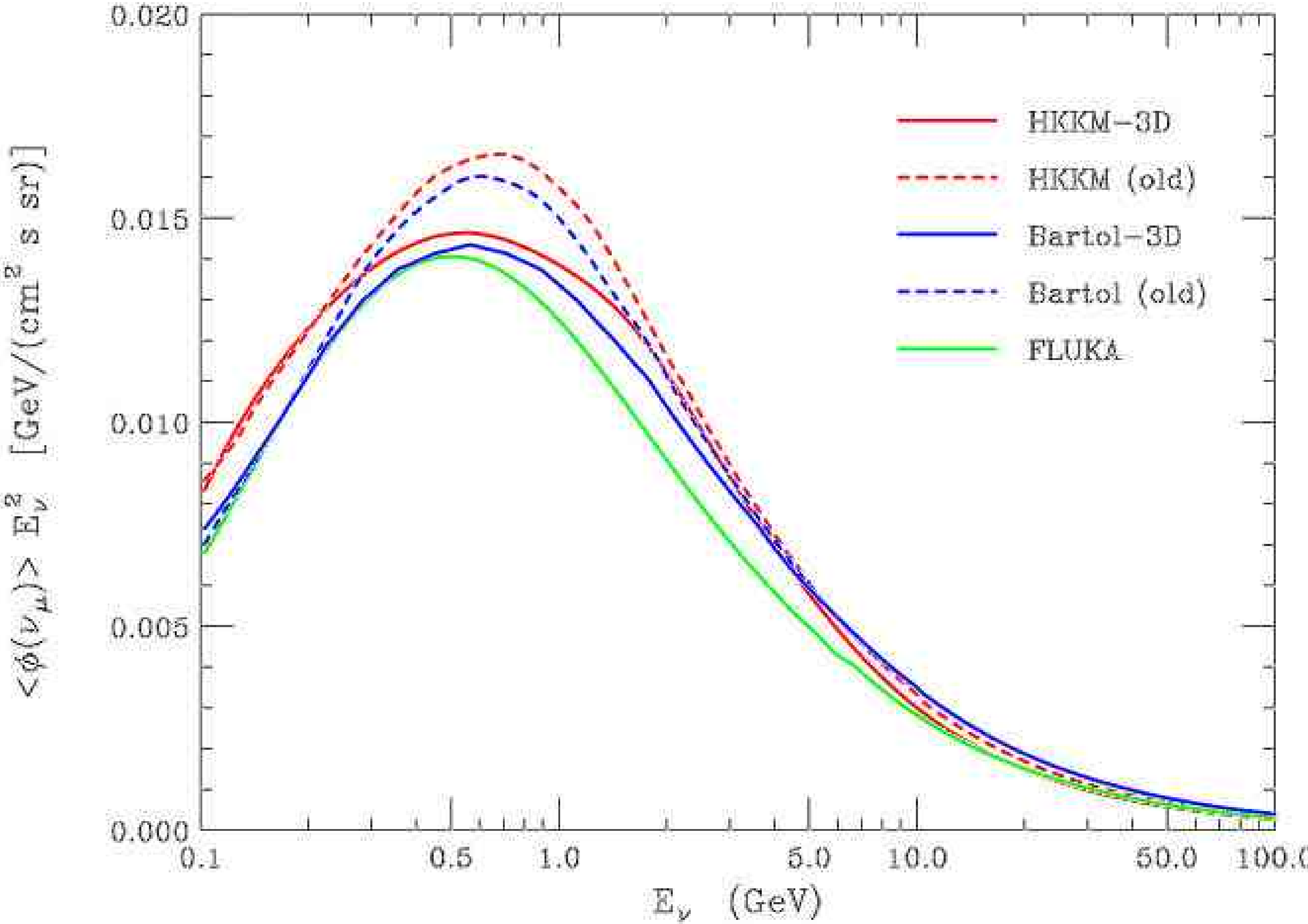
δ_{CP} dependence on θ_{23} is not large.

Discussion of Systematic Uncertainties

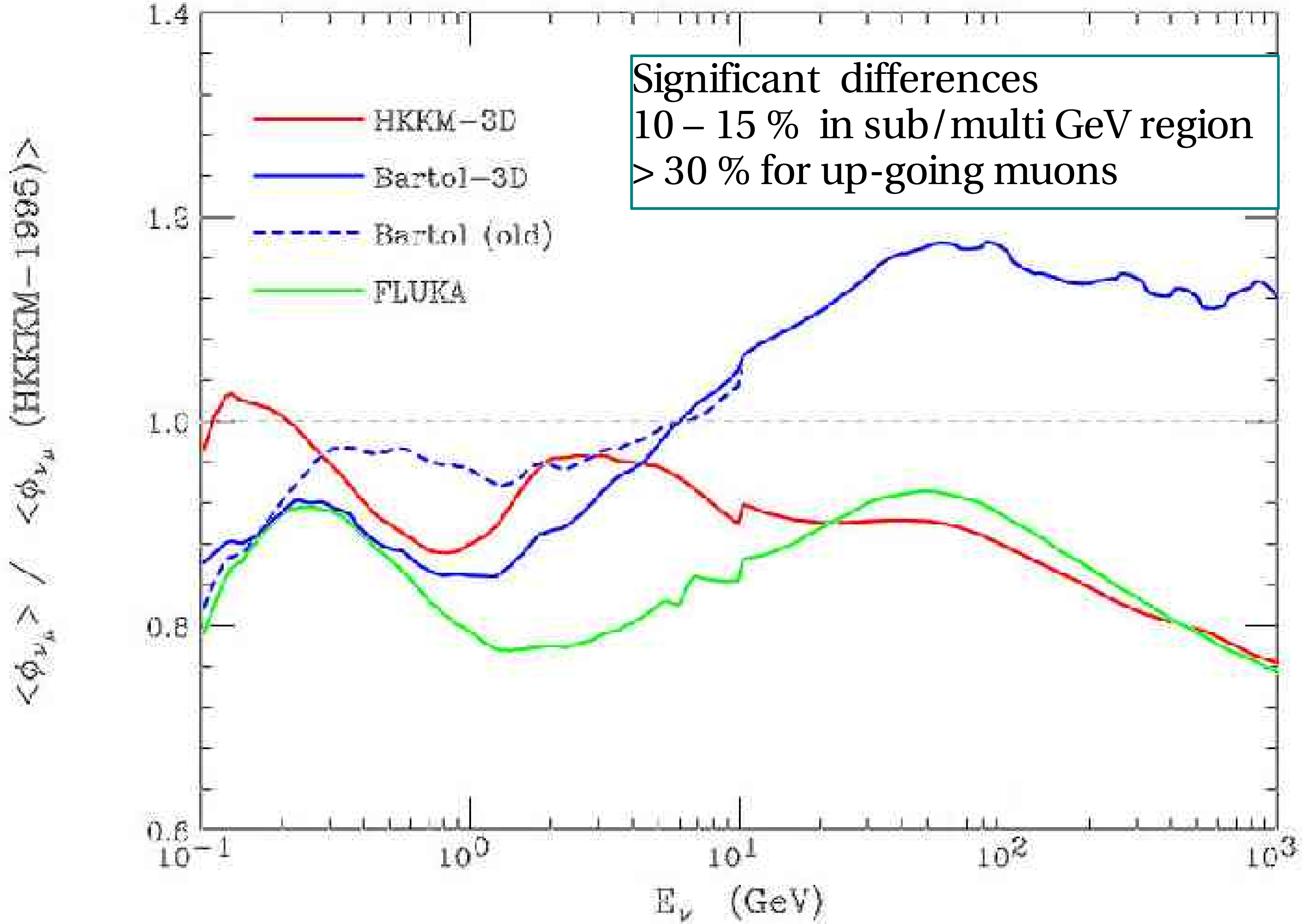
- Neutrino Fluxes
- Neutrino Cross Sections

The ATMOSPHERIC NEUTRINO FLUXES

Angle Averaged Fluxes



Comparison: Model / HKKM-1995



The allowed intervals for the neutrino fundamental parameters (Masses, mixings)
will depend (in Bayesian sense) on our beliefs
about the theoretical errors.

This seems to be happening NOW,
and it will be a much more significant
problem for future precision studies

Very Important to have a
well defined, more systematic,
more rigorous, more consistent
way to describe QUANTITAVELY
what we believe are
the uncertainties in the flux

Elements for the prediction of the Atmospheric Neutrino Fluxes:

- Primary Cosmic Ray Flux
- Geomagnetic Effects
- Hadronic Interaction Modeling
- Calculation Method:

MUON MEASUREMENT CONSTRAINTs

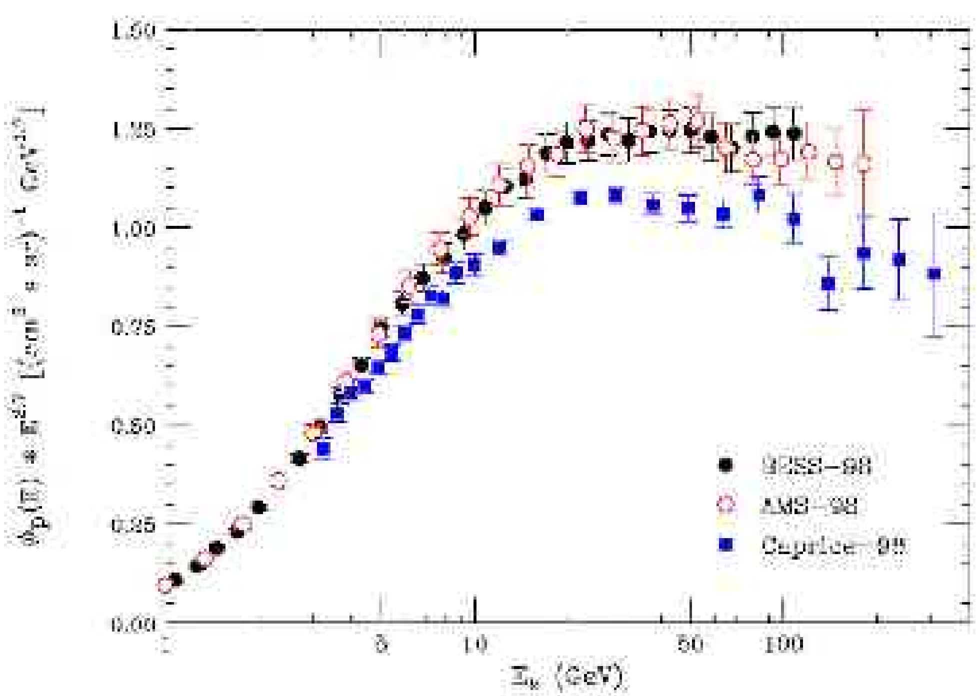
Talks of

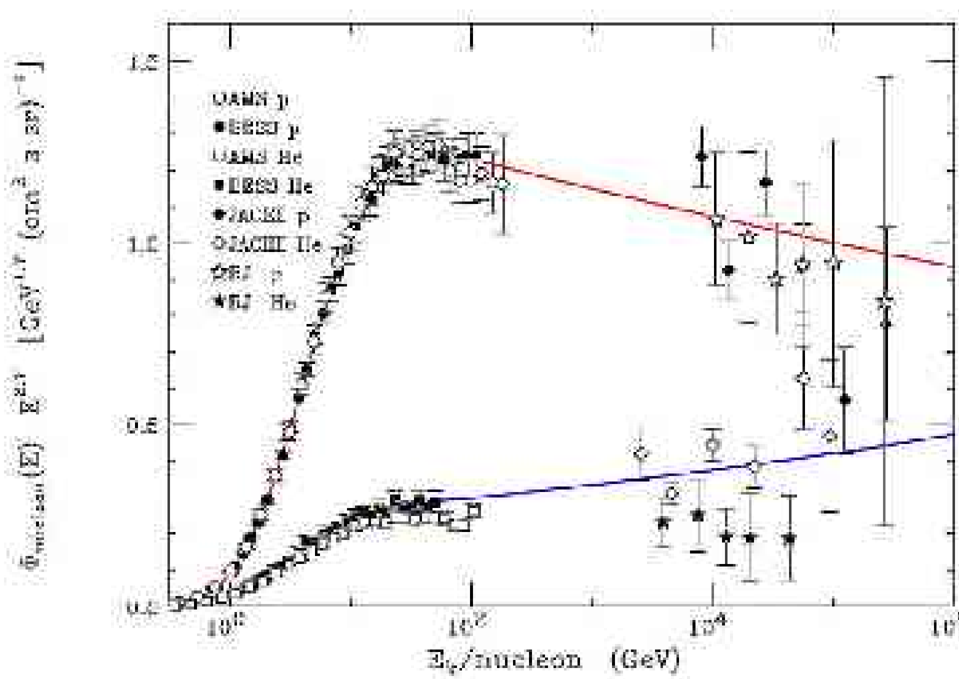
M.Honda (HKKM calculation)

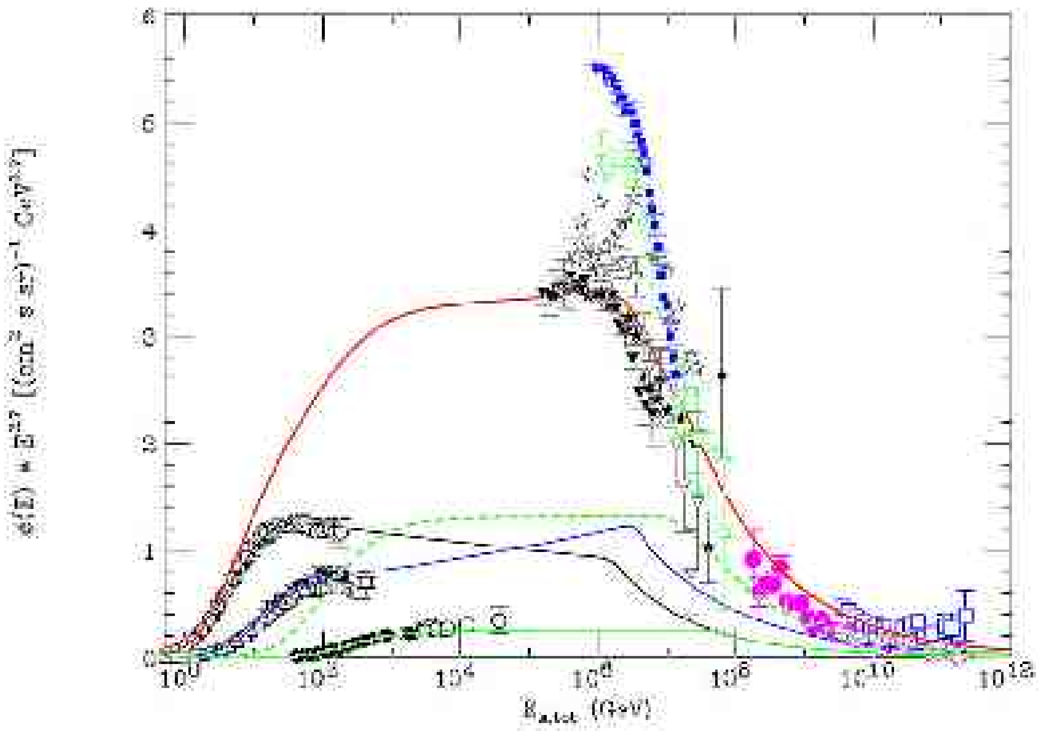
Giles Barr (Bartol calculation)

PRIMARY COSMIC RAYS

- Understand better Solar Modulation Effects
- Solve the BESS-AMS/Caprice discrepancy at 10-100 GeV
- Poor measurements in the region
  200 GeV -   EAS (> 10^{14} eV)

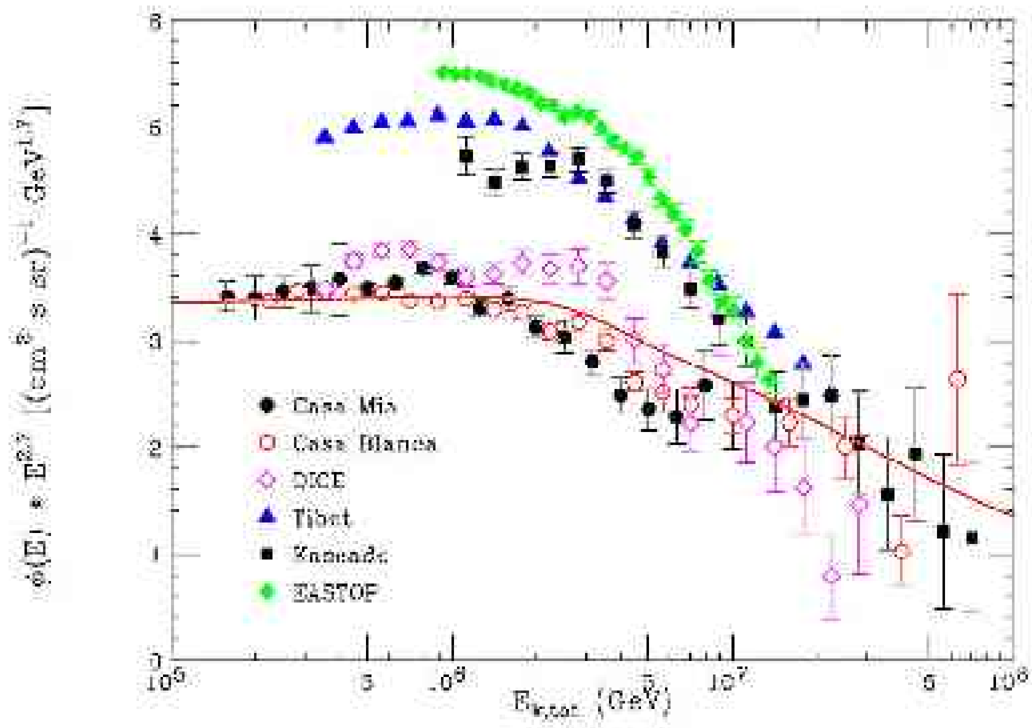




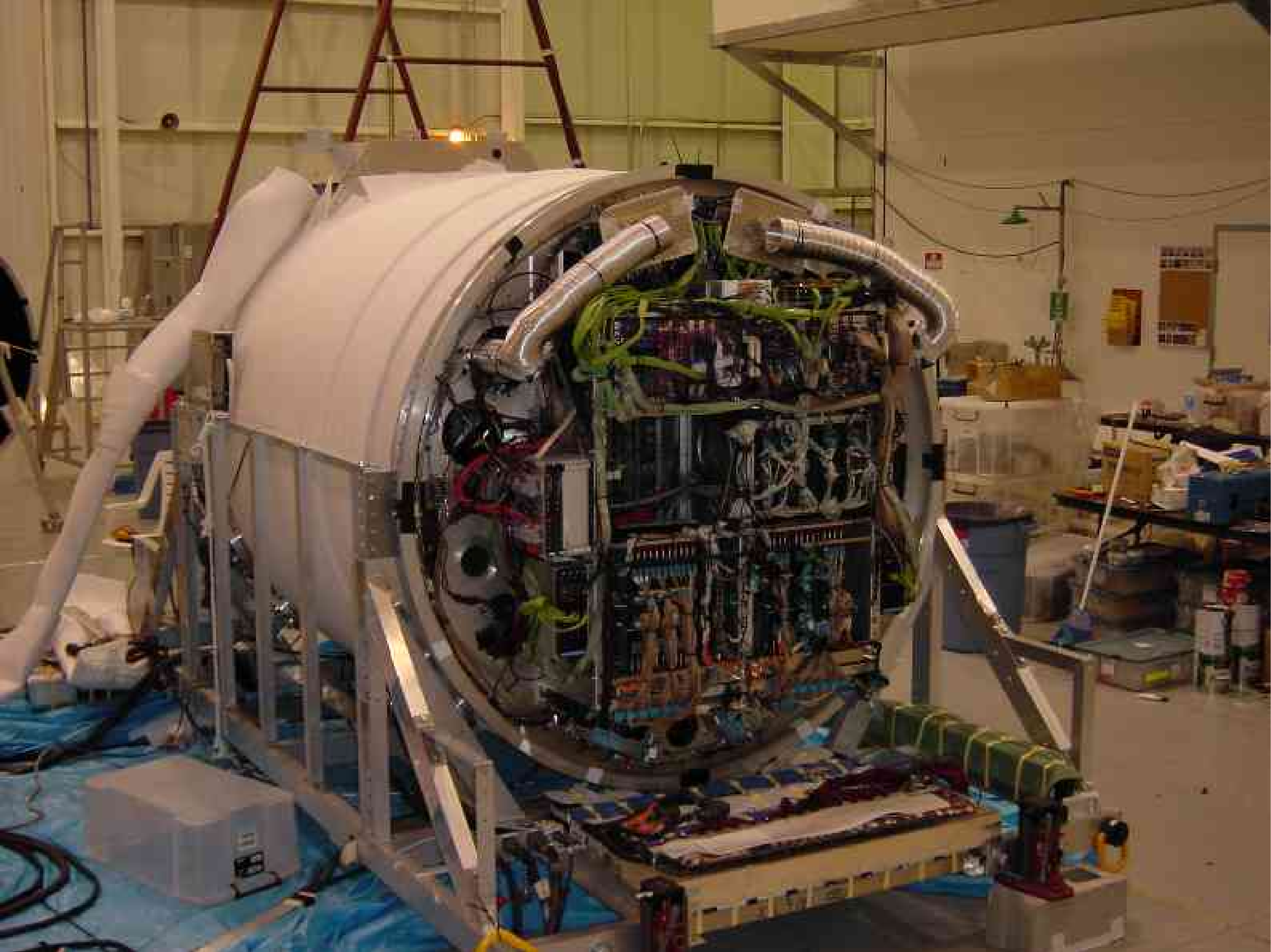


Comparison with
Air Shower Experiments
at the knee ~10^{15} - 10^{16} eV

Great importance
for Cosmic Ray
Measurements
in the “knee” region
and beyond

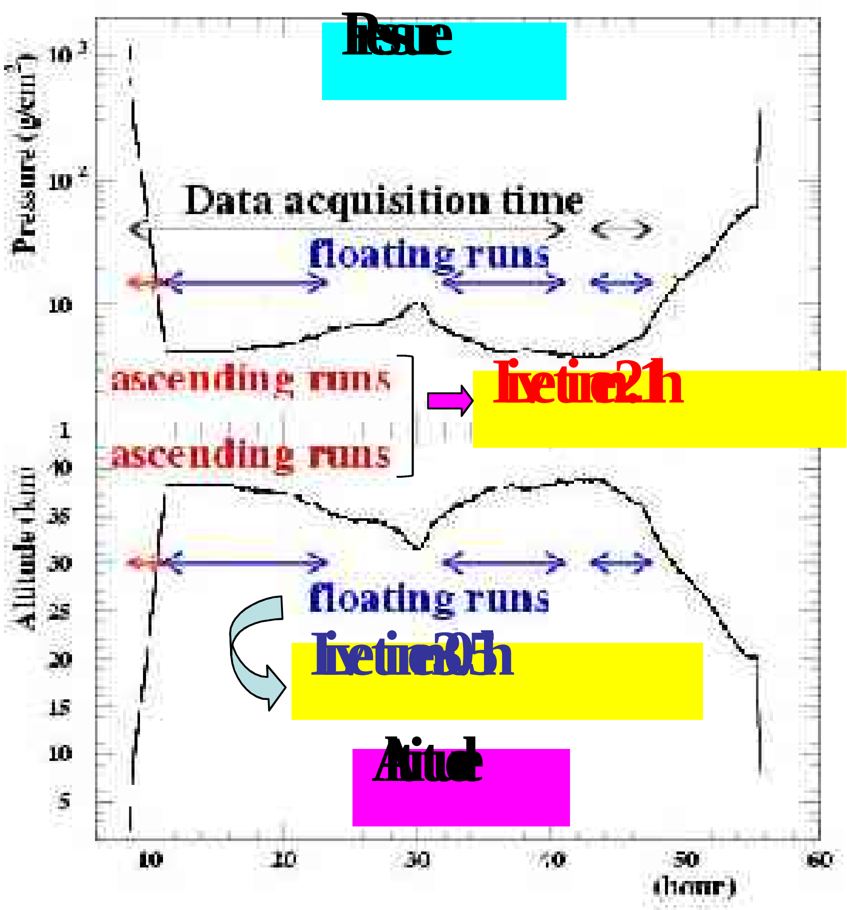


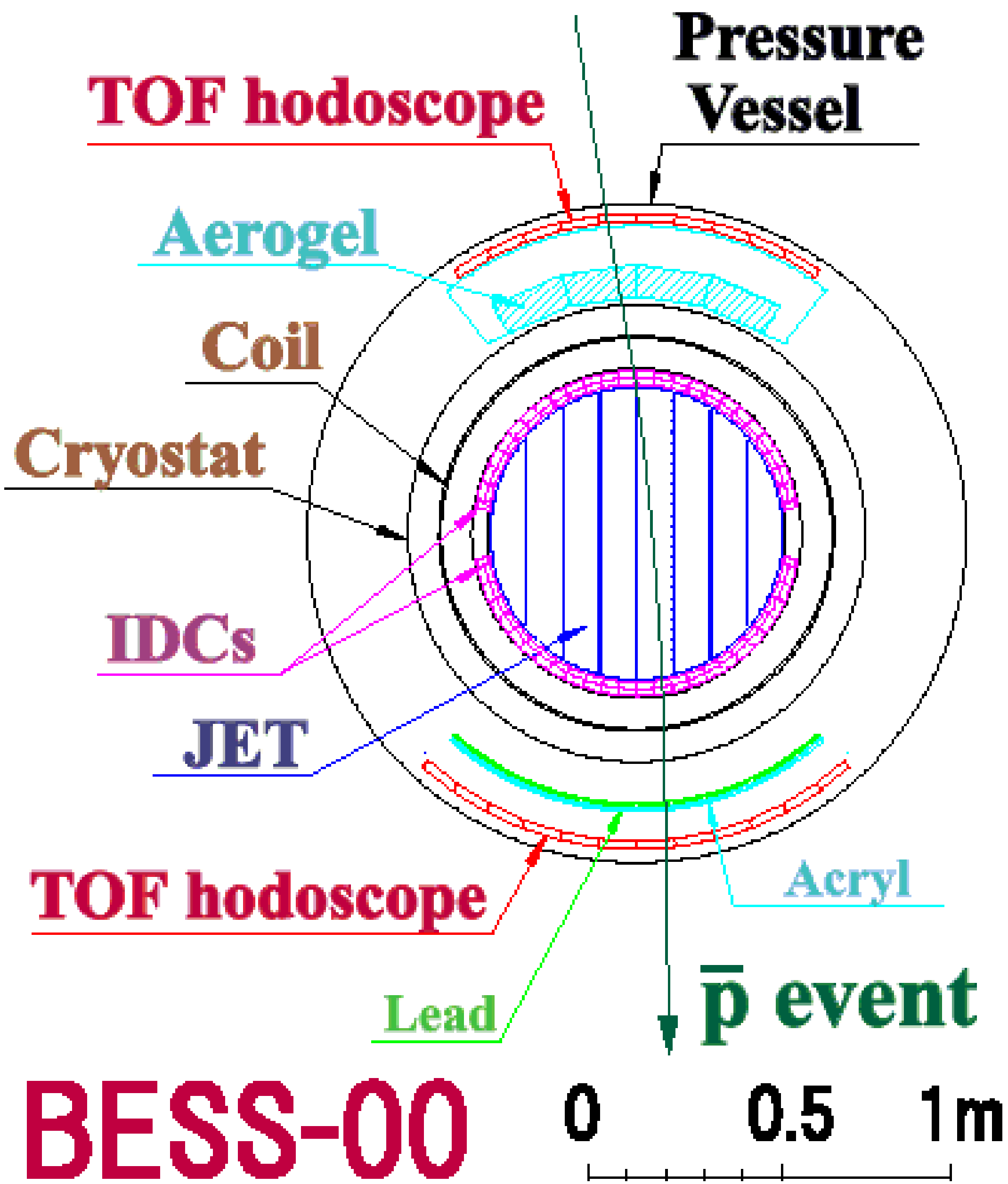
BESS



Flight Map of BESS

Summary of BESS-2000

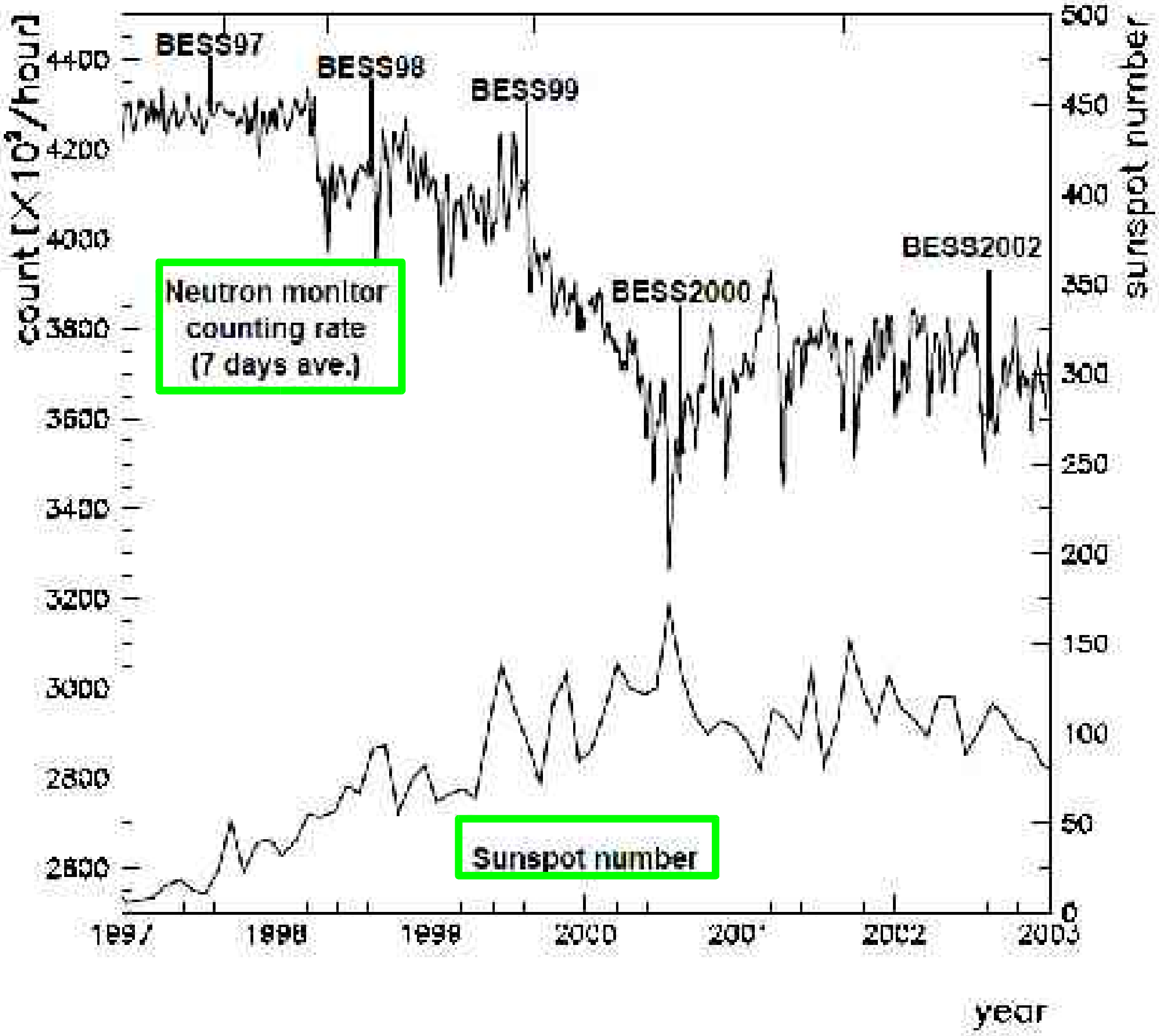


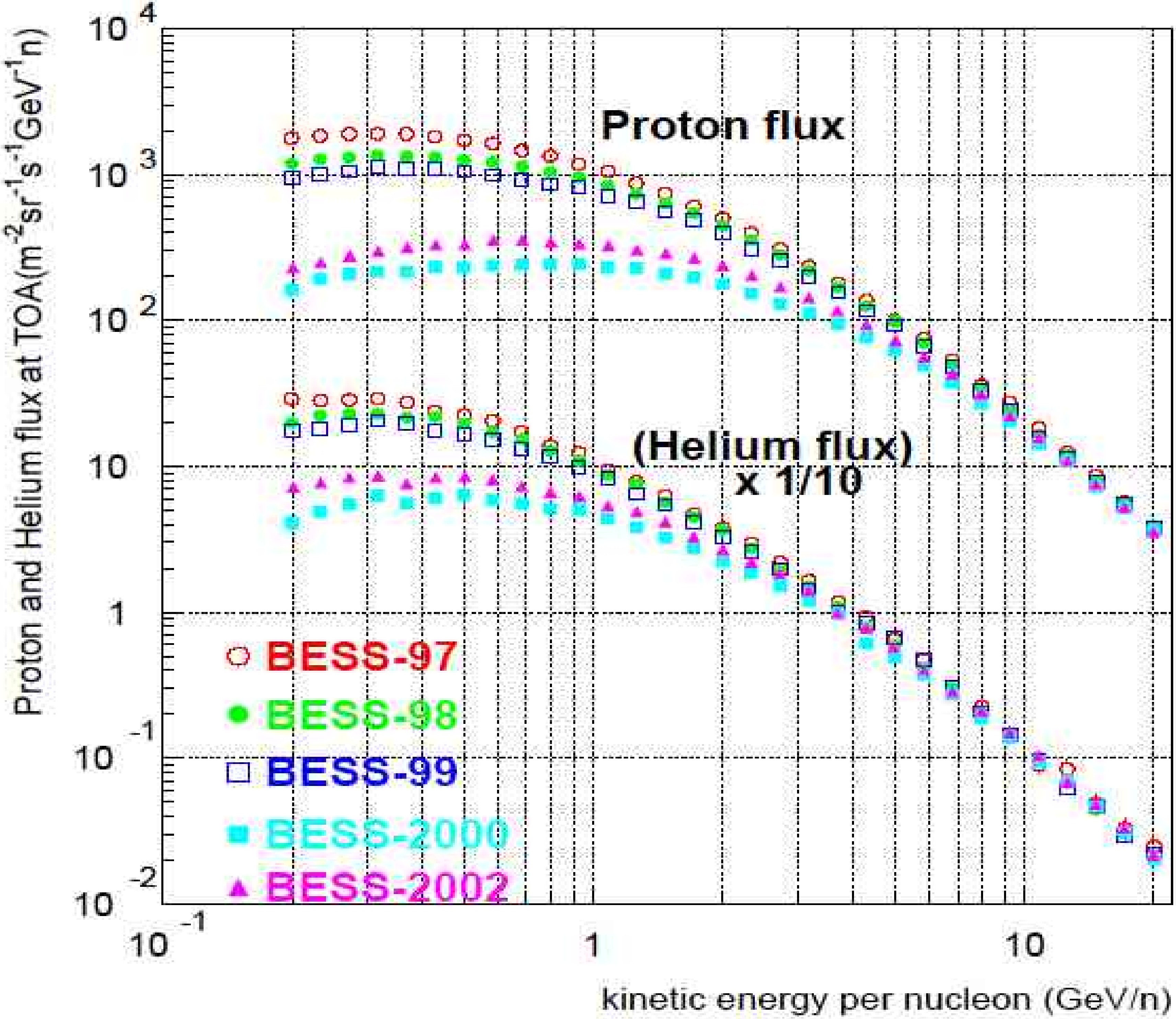


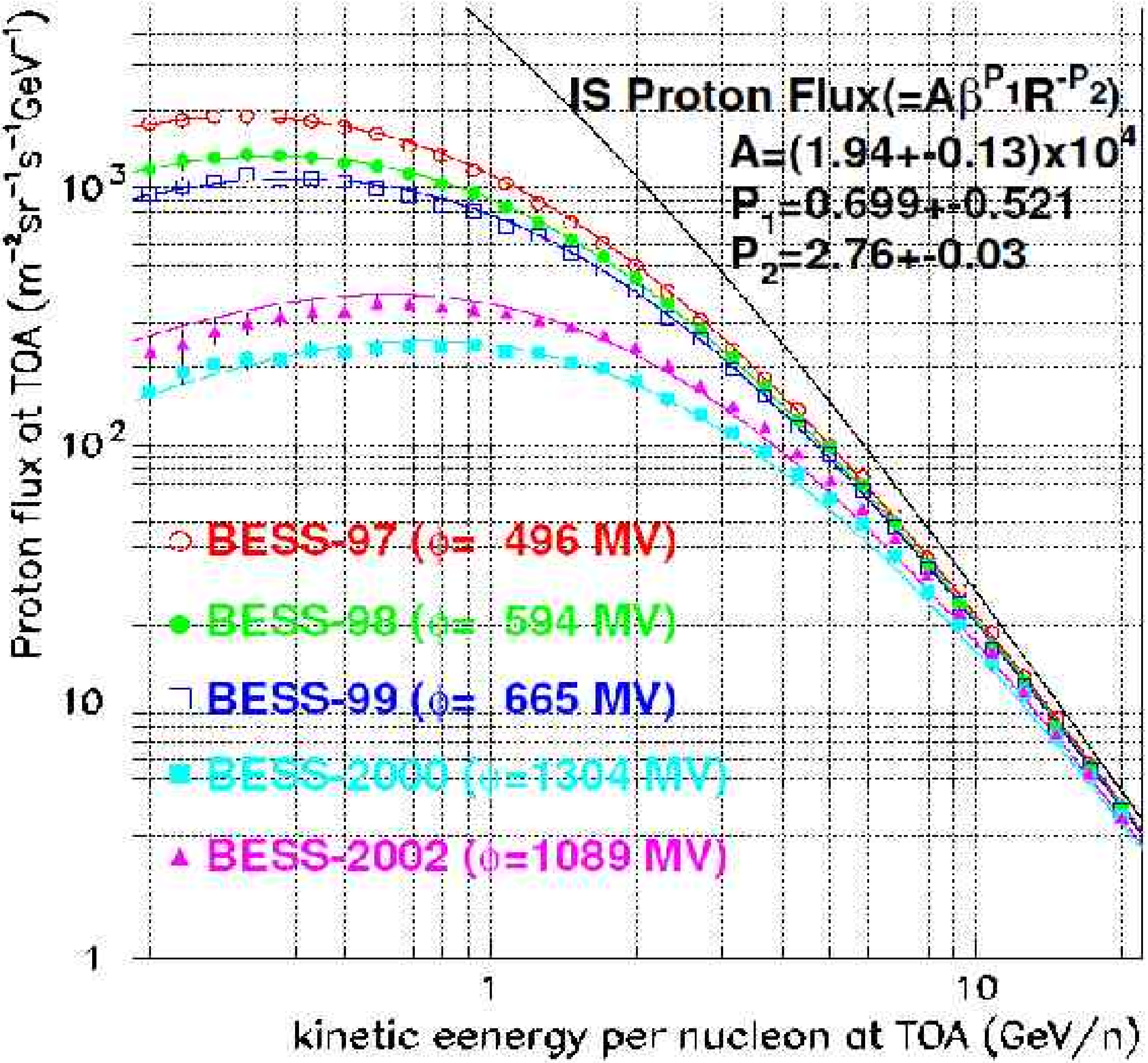
Pressure
Vessel
TOF hodoscope
Aerogel
Coil
Cryostat
IDCs
JET
TOF hodoscope
Acryl
Lead
$\bar{p}$ event
0
0.5
1m

BESS-00

Climax neutron monitor & Sunspot number




Proton flux
(Helium flux)
x 1/10
BESS-97
BESS-98
BESS-99
BESS-2000
BESS-2002
Proton and Helium flux at TOA($m^{-2}sr^{-1}s^{-1}GeV^{-1}n$)
kinetic energy per nucleon (GeV/n)

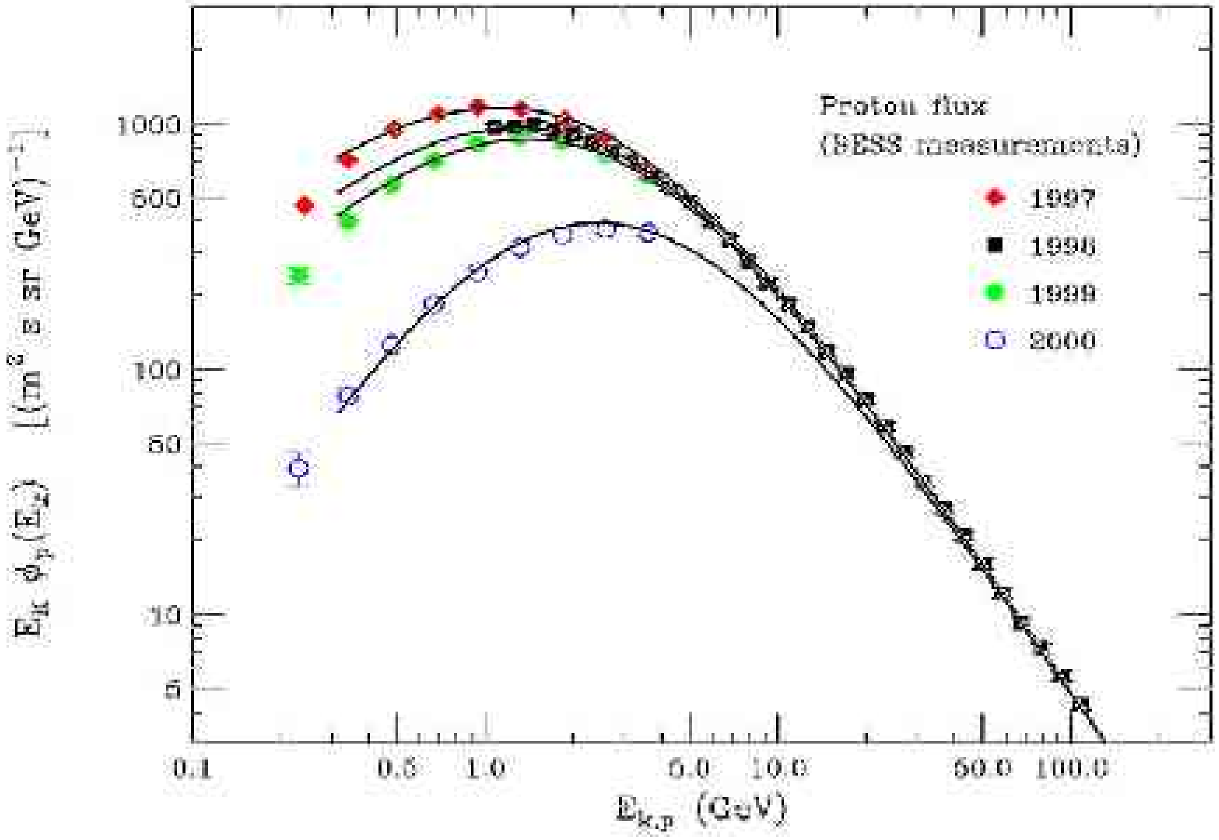


IS Proton Flux(=Aβ^P1R^-P2)
A=(1.94+-0.13)x10^4
P1=0.699+-0.521
P2=2.76+-0.03
BESS-97 (φ= 496 MV)
BESS-98 (φ= 594 MV)
BESS-99 (φ= 665 MV)
BESS-2000 (φ=1304 MV)
BESS-2002 (φ=1089 MV)
Proton flux at TOA (m^-2sr^-1s^-1GeV^-1)
kinetic eenergy per nucleon at TOA (GeV/n)

Solar Modulation Effects

Long time Integration Problem
Obtain an observable
(for example:
Neutron Monitor Data)
to predict the Solar Modulation

BESS protons



Hadron Production Measurements

Giles Barr

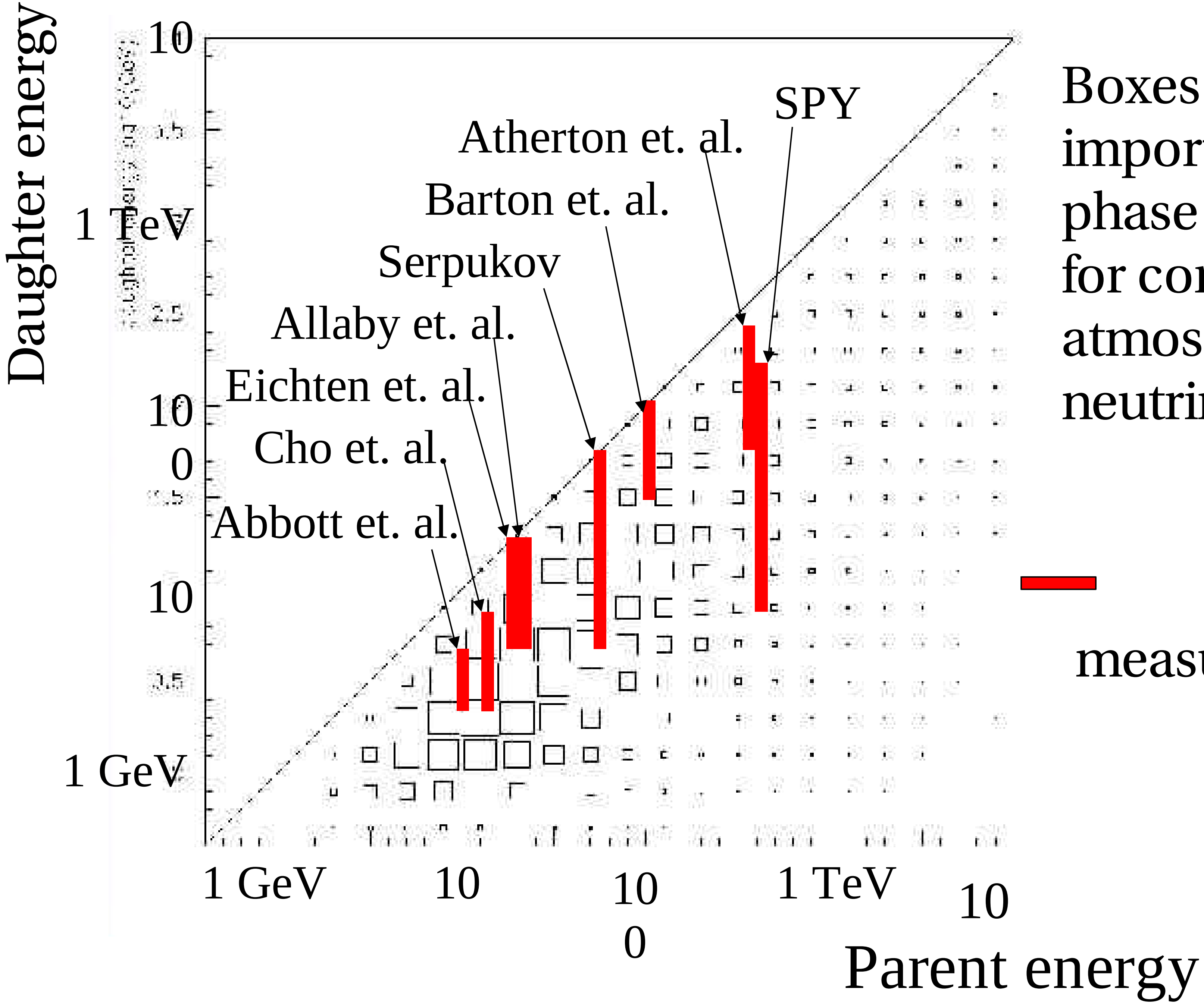
NEW High Quality Data will soon arrive

HARP : 3-15 GeV

MIPP : 5 – 120 GeV

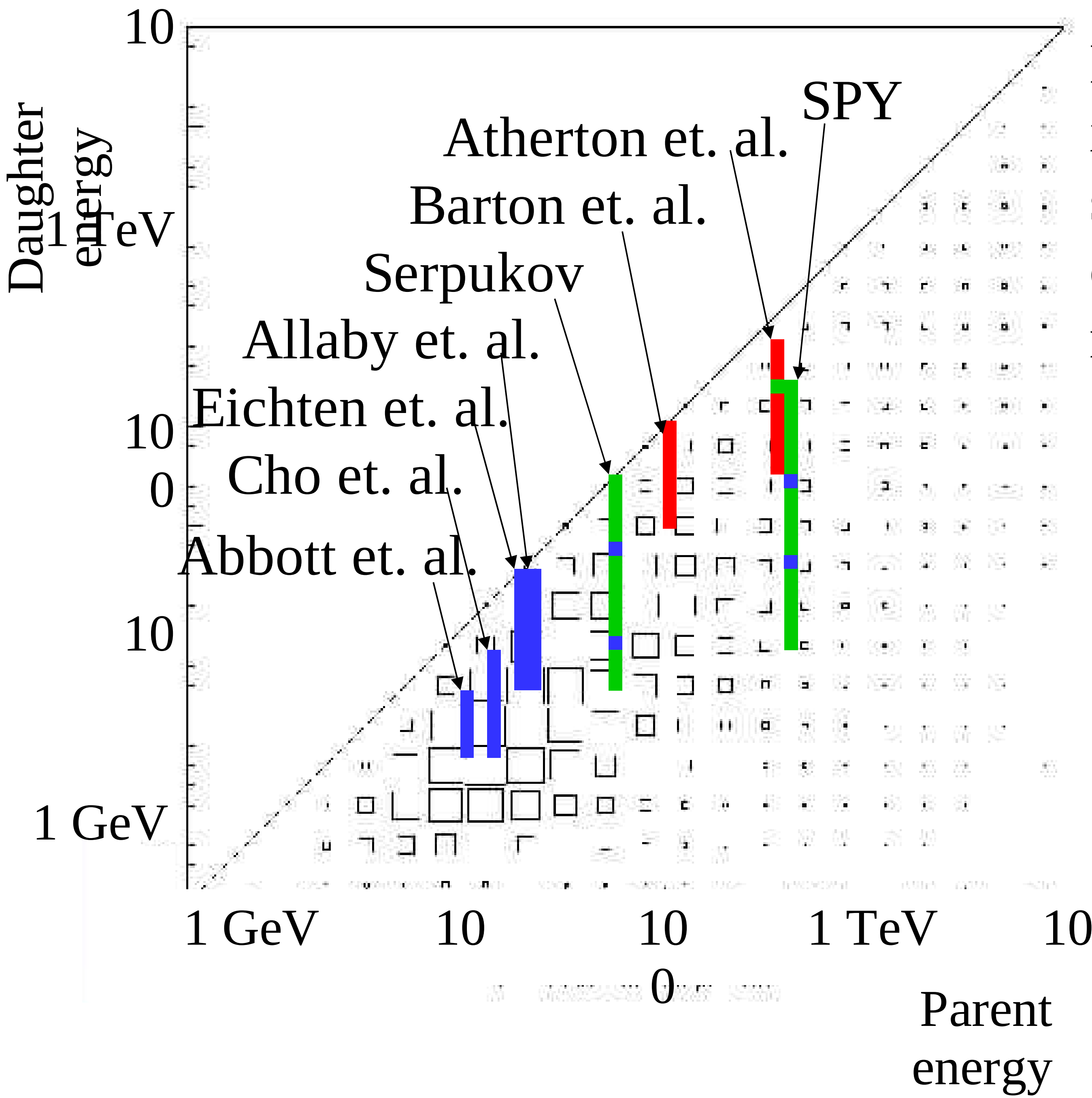
NA49 : 100, 158 GeV

Existing measurements



Boxes show importance of phase space region for contained atmospheric neutrino events.

P_T range covered



Boxes show importance of phase space region for contained atmospheric neutrino events.

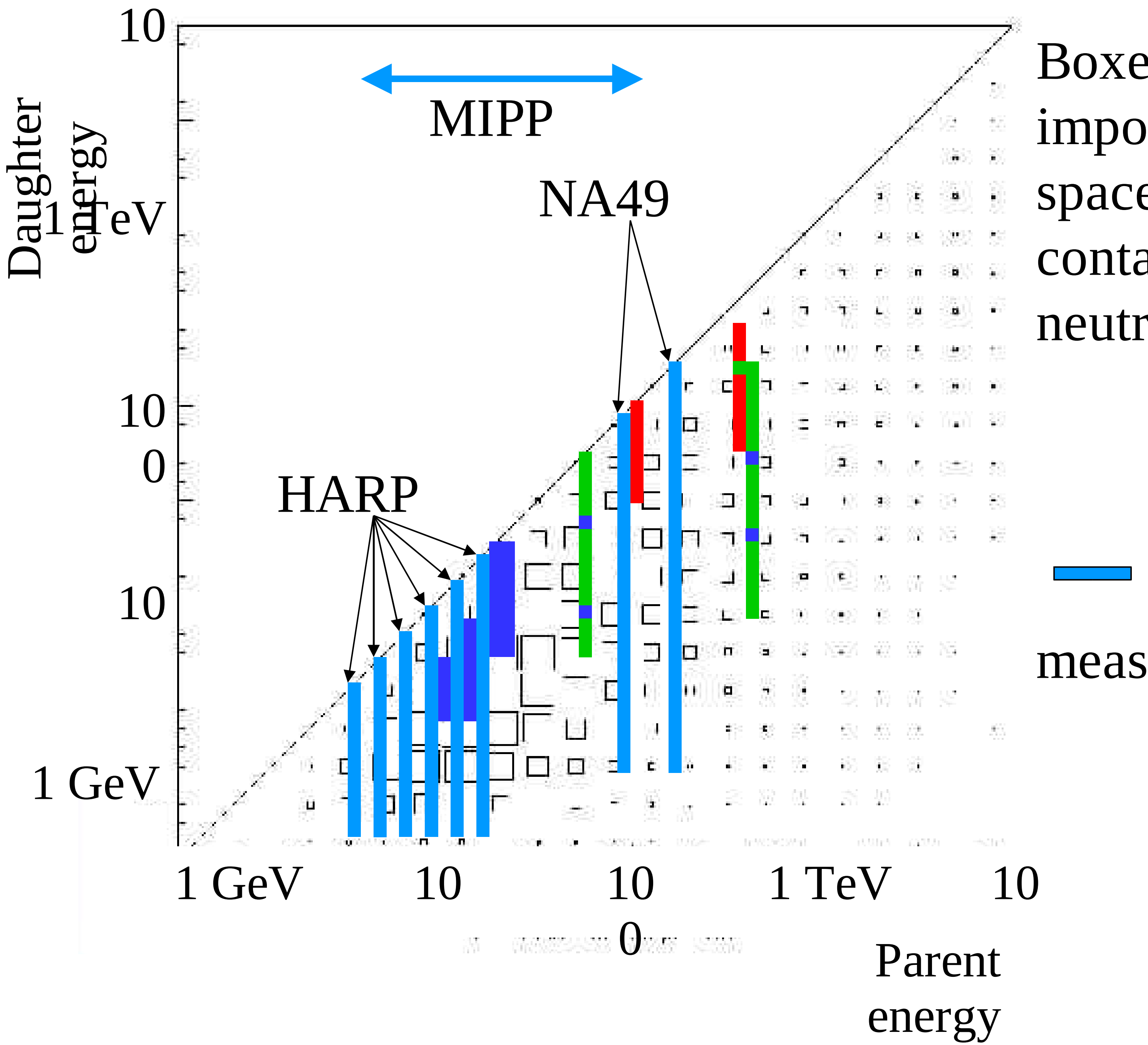
Measurements.

1-2 p_T points

3-5 p_T points

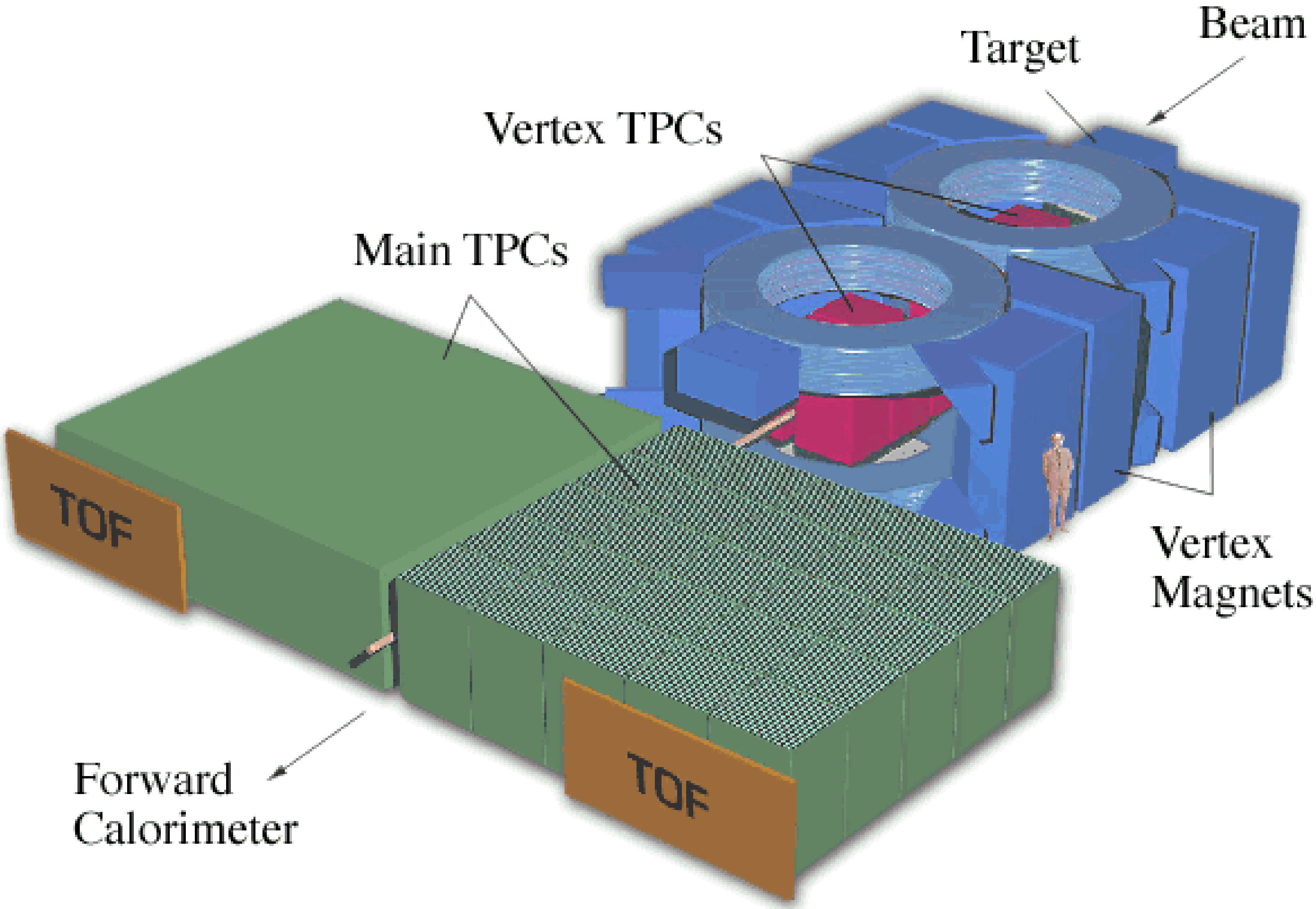
>5 p_T points

New measurements

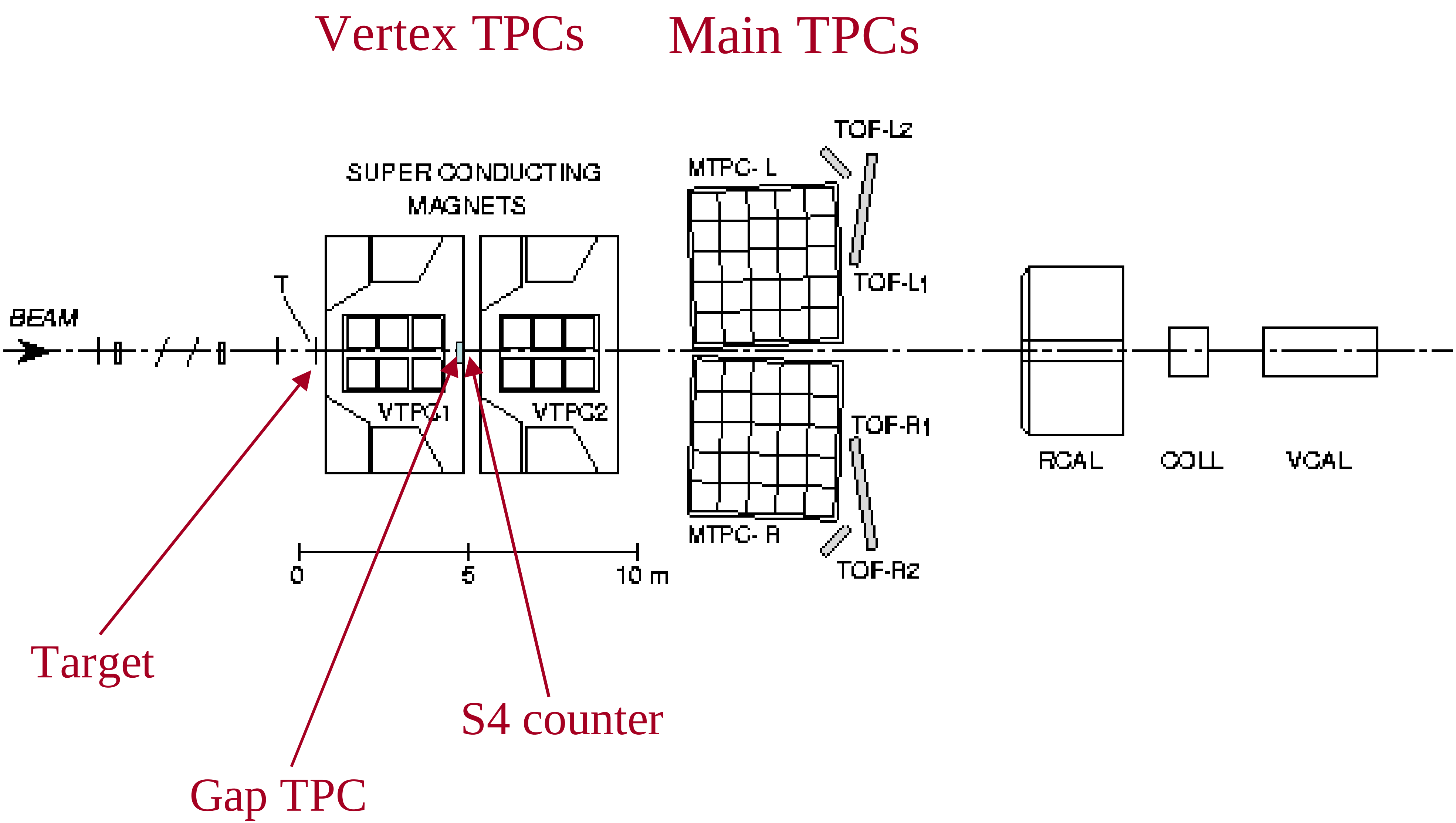


Boxes show importance of phase space region for contained atmospheric neutrino events.

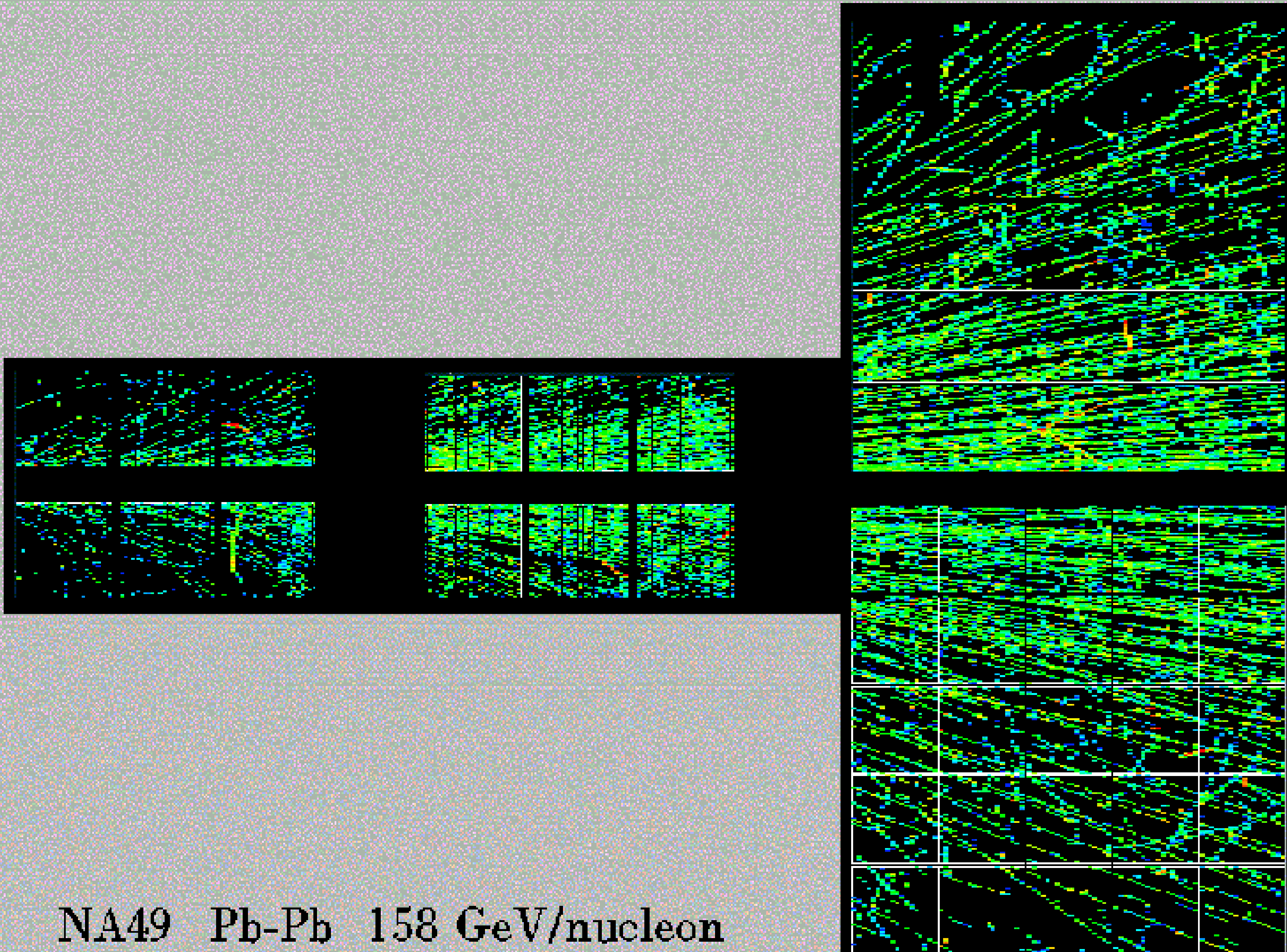
NA49


Beam
Target
Vertex TPCs
Main TPCs
TOF
TOF
Vertex Magnets
Forward Calorimeter

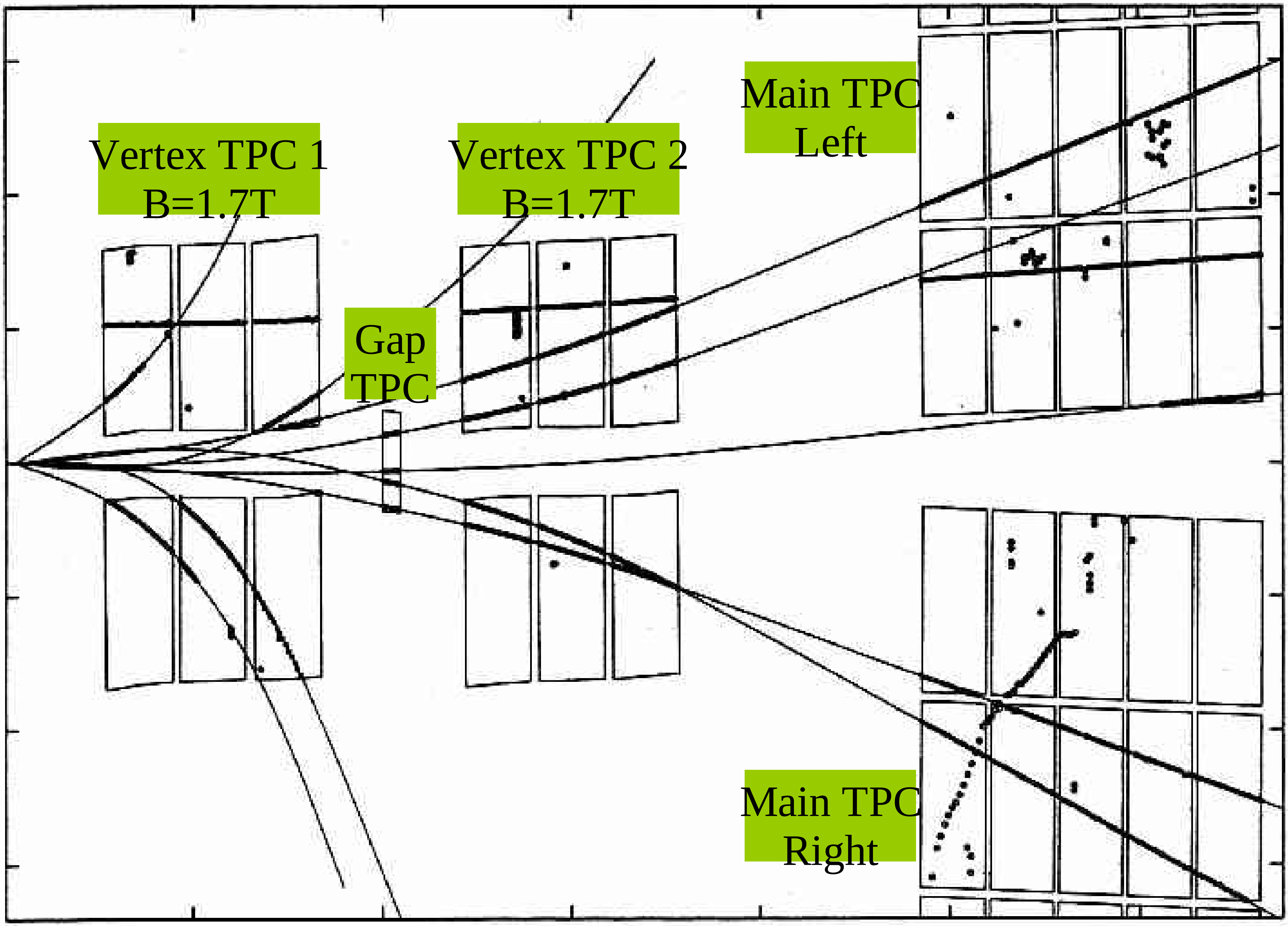
NA49 setup



Vertex TPCs
Main TPCs
TOF-L2
MTPC- L
SUPER CONDUCTING
MAGNETS
TOF-L1
T
BEAM
VTPC-1
VTPC2
TOF-R1
RCAL
COLL
VCAL
MTPC- R
TOF-R2
0
5
10 m
Target
S4 counter
Gap TPC



NA49 Pb-Pb 158 GeV/nucleon


Vertex TPC 1
B=1.7T
Vertex TPC 2
B=1.7T
Main TPC
Left
Gap
TPC
Main TPC
Right

Special Run
Motivated by Cosmic Ray Studies
(and Neutrino Flux calculation in particular)
Giles Barr a key person in the proposal (P322)

proton + Carbon interactions

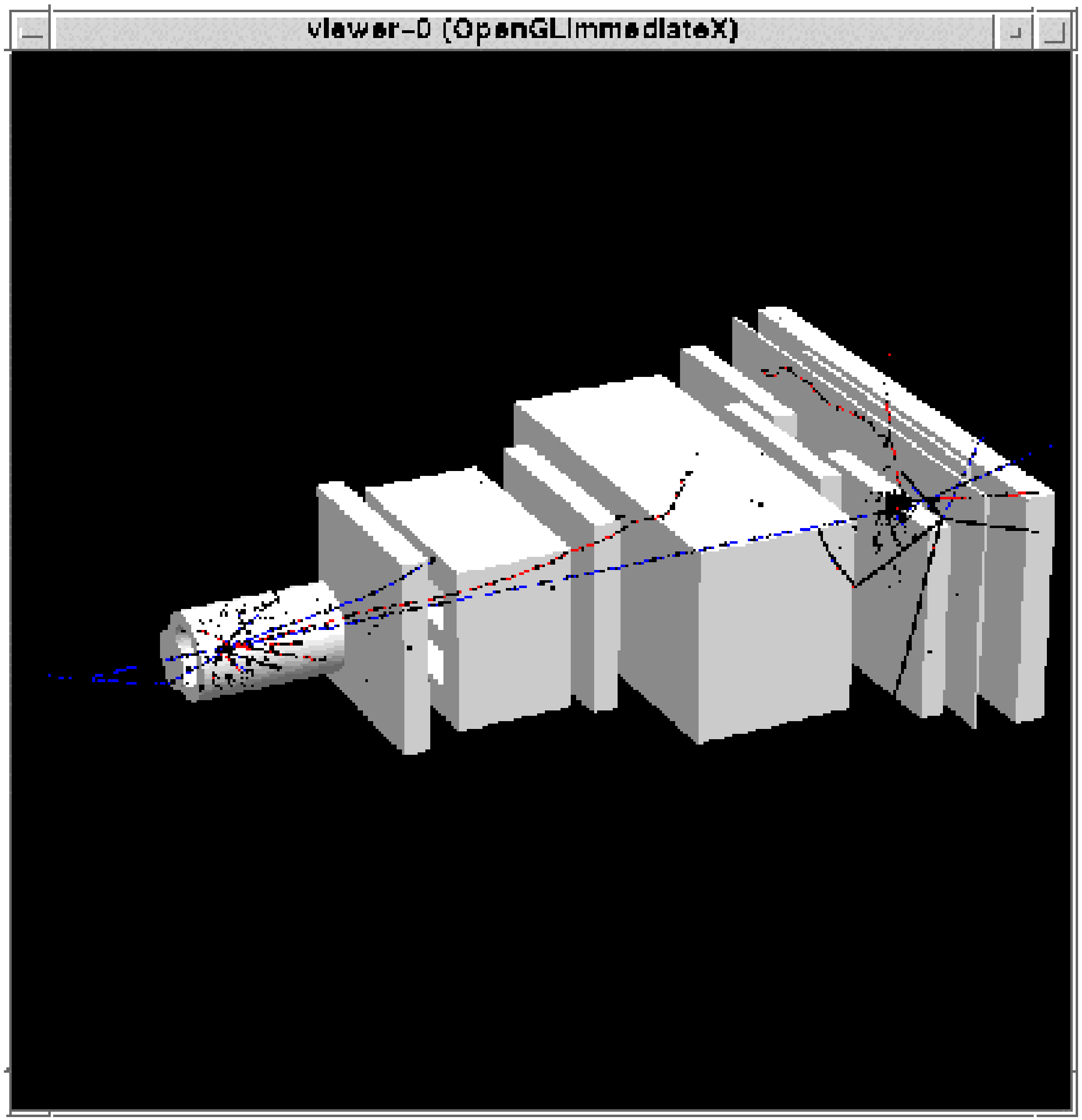
can compare to pp interactions

158 GeV (500K triggers)
100 GeV (160K triggers)

High Quality Data

HARP Experiment

3-15 GeV protons on different target



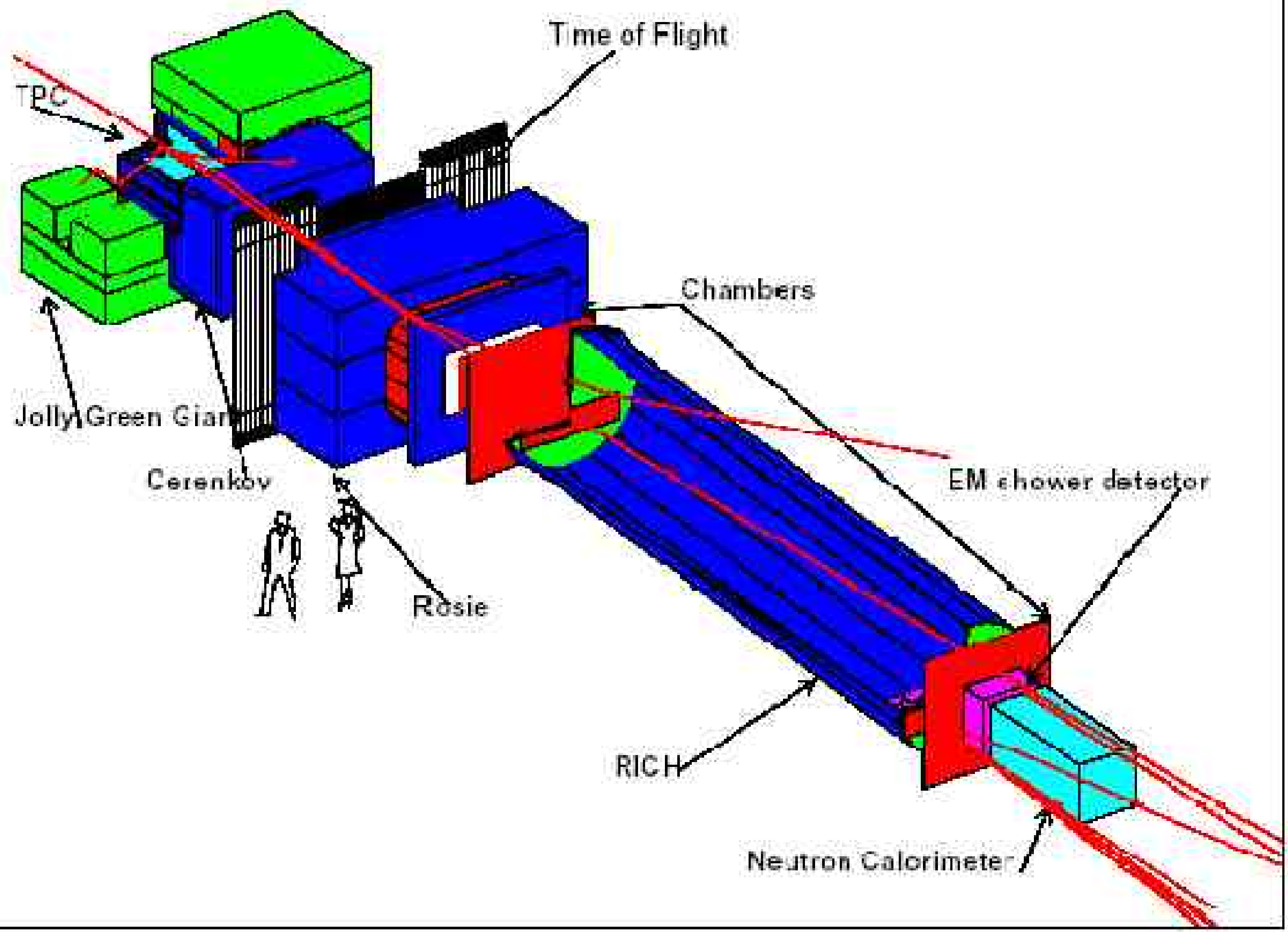
Data Collected
and under Analysis

Performances probably
a little below expectations
but very valuable

MIPP

Main Injector Particle Production Experiment (FNAL-E907)

Horizontal cut plane



.ug

Target	Physics	Data Points	Primary proton Average Intensity/spill	Total number of Primary Protons
Numi 1	MINOS	3.3	125000	2.06E+10
NUMI 2	MINOS	3.3	125000	2.06E+10
H2	Scaling	6	9.76E+09	2.93E+15
N2	Atmospheric ν	4	9.76E+09	1.95E+15
Be	pA	2	9.76E+09	9.76E+14
Be	Survey	1	9.76E+09	4.88E+14
C	Survey	1	9.76E+09	4.88E+14
Cu	pA	2	9.76E+09	9.76E+14
Cu	Survey	1	9.76E+09	4.88E+14
Pb	pA	2	9.76E+09	9.76E+14
Pb	Survey	1	9.76E+09	4.88E+14
Total		26.6		9.76E+15

Broad Goal
Obtain large bstatistics of unbiased
complete coverage
hadron production data

Atmospheric Neutrinos
Nitrogen Target
5,15,25,5,70,90 GeV
complementary to HARP

Atm. muon & neutrino

1. Near top of the Atmosphere
   5 - 30 g/cm^2
   balloon floating altitude

2. Inside the Atmosphere
   5 - 800 g/cm^2
   balloon as(des)cending

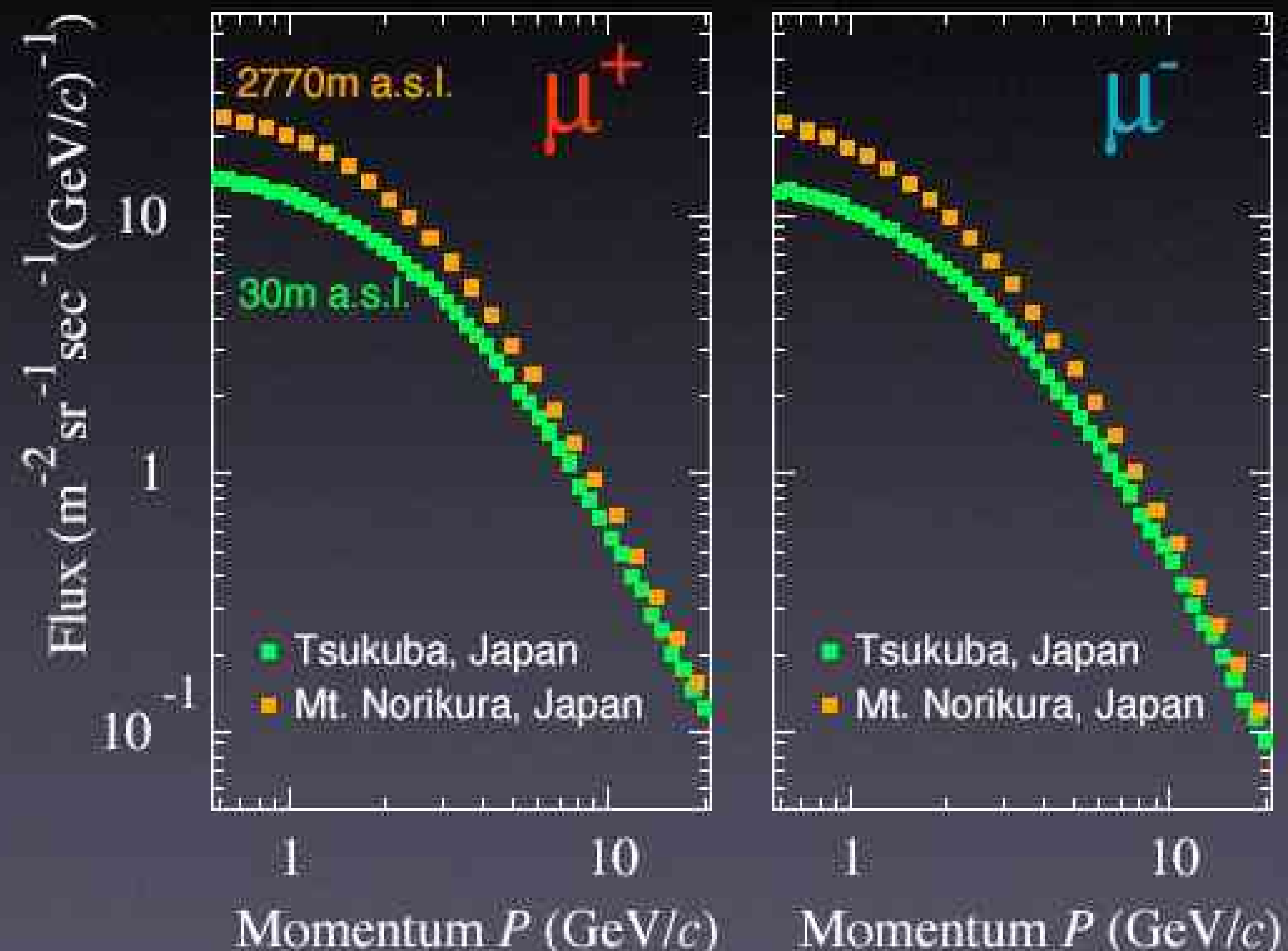
3. On the ground
   800 - 1000 g/cm^2
   ground/mountain

BESS Data summary

site	cutoff Rigidity	atm. pressure	date
Tsukuba Japan	11.4 GV	1030 g/cm^2	Dec. 95
			May. 97
			Nov. 97
			Oct. 02
Mt. Norikura	11.2 GV	740 g/cm^2	Sep. 99
Ft. Sumner NM, USA	4.3 GV	890 g/cm^2	Sep. 01
		800 to 5 g/cm^2	Sep. 01
		5 to 30 g/cm^2	
Lynn Lake MB, Canada	0.4 GV	1000 g/cm^2	Jul. 97
			Jul. 98
			Jul. 99
			Jul. 00
		800 to 5 g/cm^2	Aug. 99
			Aug. 00

Altitude

ex) BESS; Almost same condition except for altitude

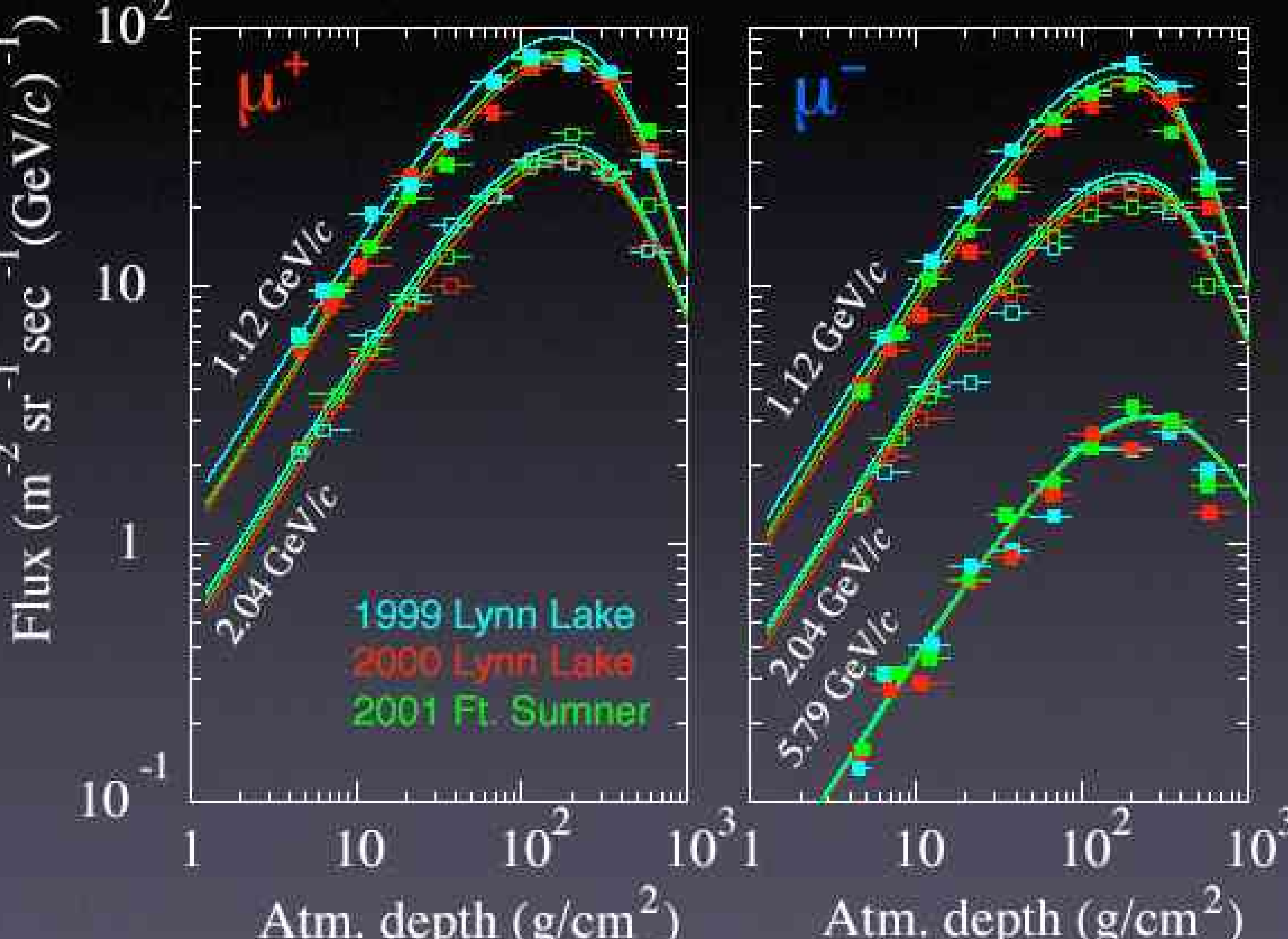


30~40% effect @1GeV/c

Huge effect on flux in low momentum region

Growth curve

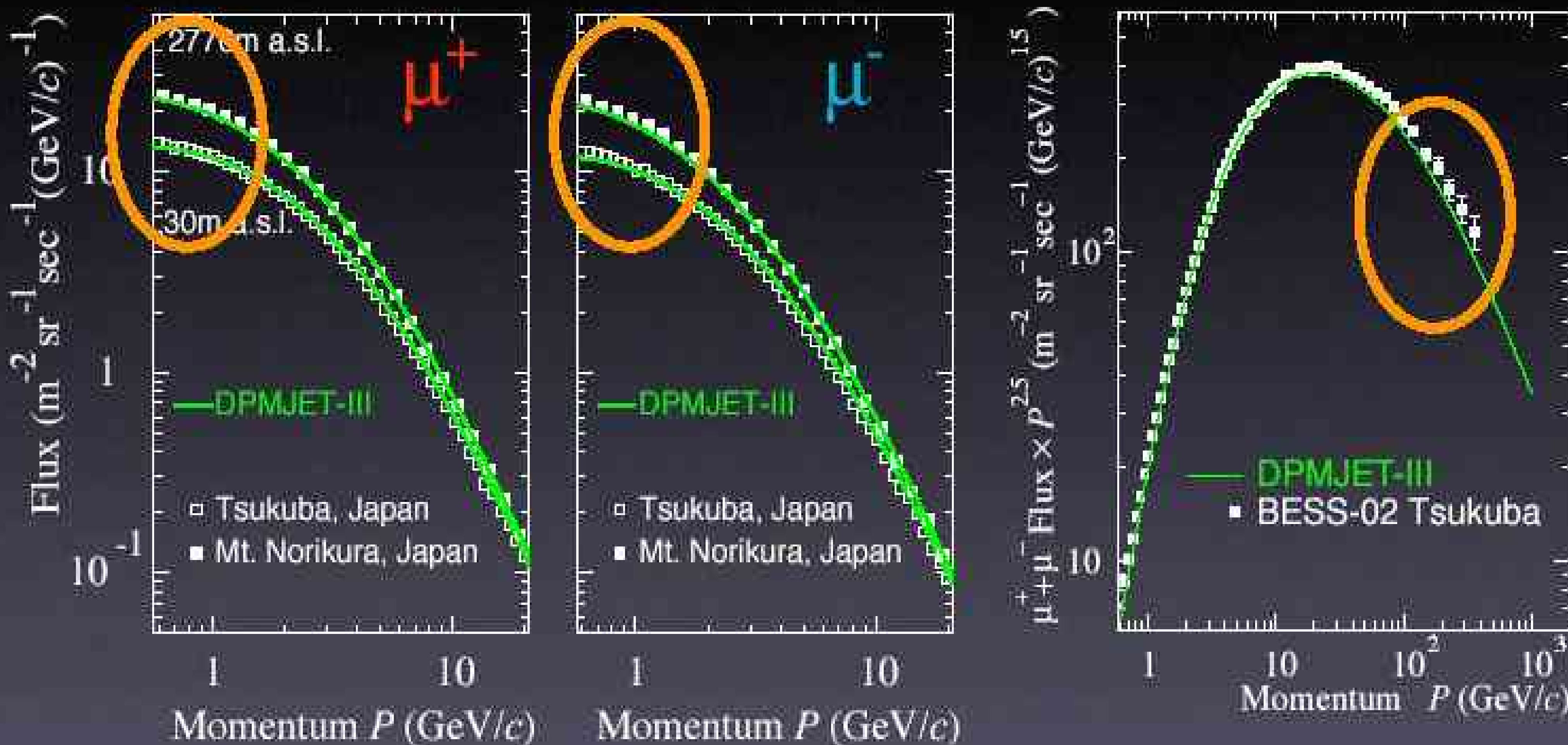
ex) BESS



Y. Yamamoto

Poor statistics

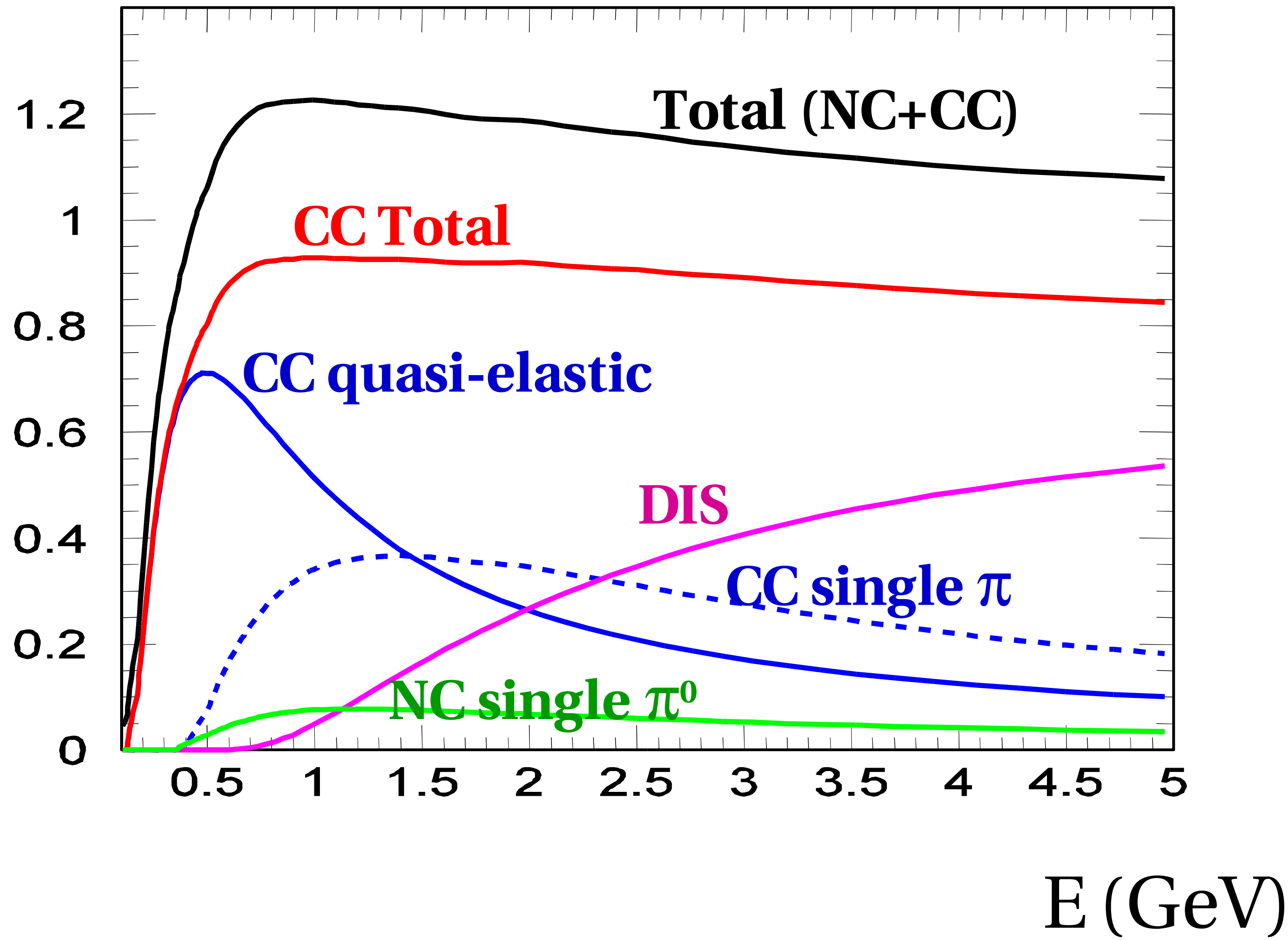
Not perfect ...



MC < DATA

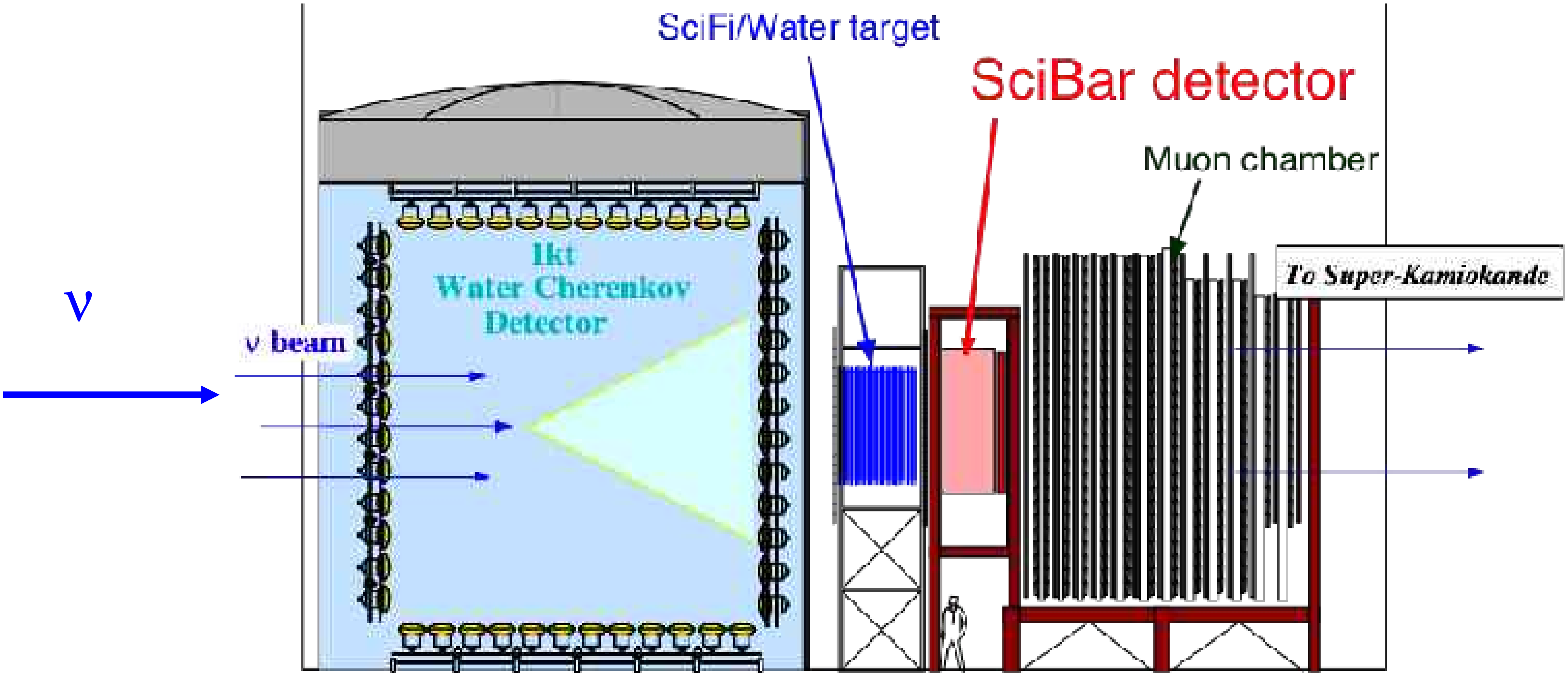
Honda-san's talk...

The NEUTRINO CROSS SECTION

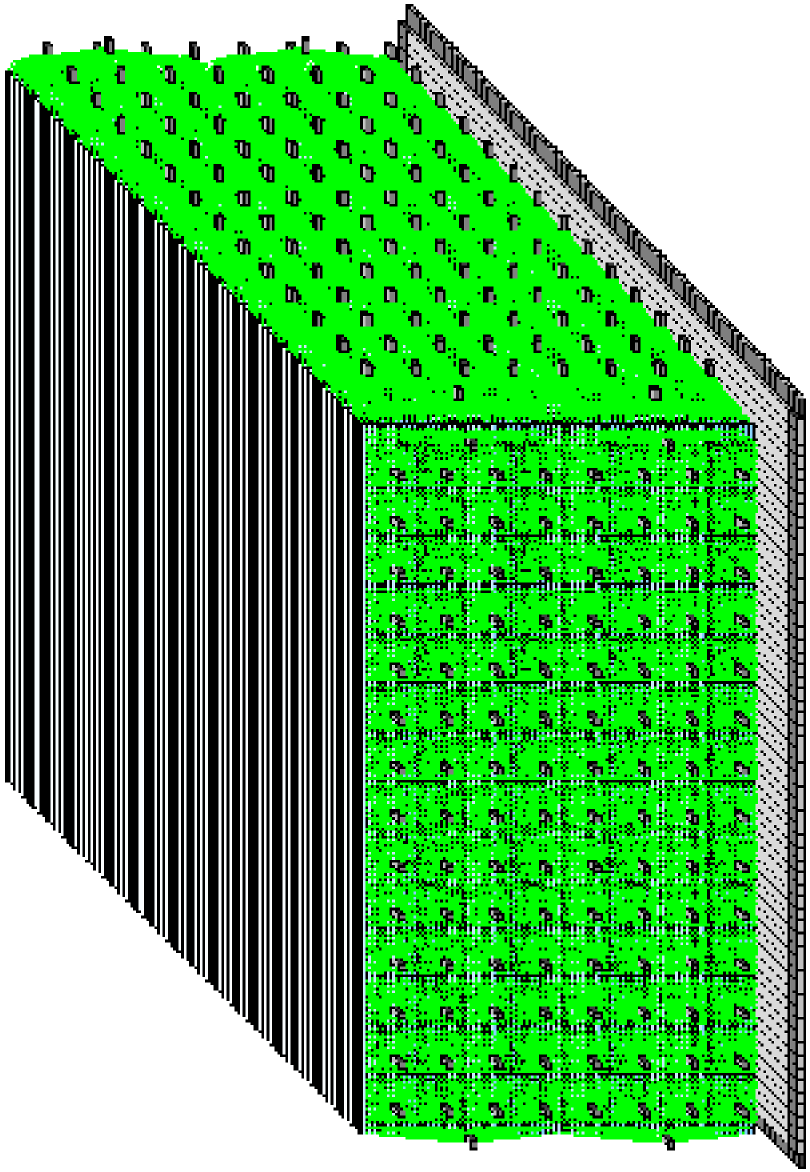

Total (NC+CC)
CC Total
CC quasi-elastic
DIS
CC single π
NC single π⁰
1.2
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
E (GeV)

New very Valuable Data on the Neutrino Interaction Properties from the Near Detector at K2K

Hasegawa (SciBar Detector)
Kameda (Kton detector)

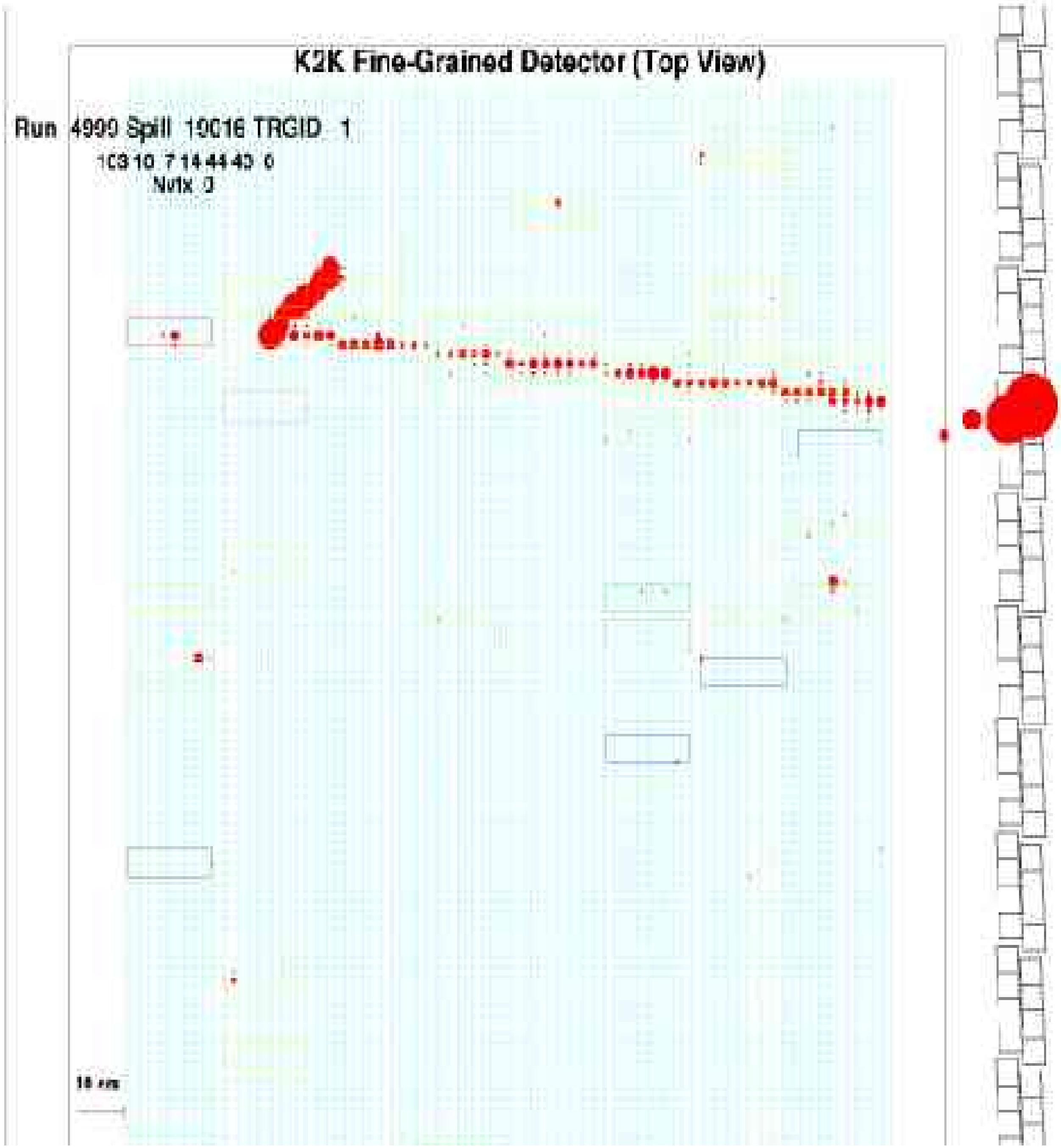

ν
ν beam
1kt
Water Cherenkov
Detector
SciFi/Water target
SciBar detector
Muon chamber
To Super-Kamiokande

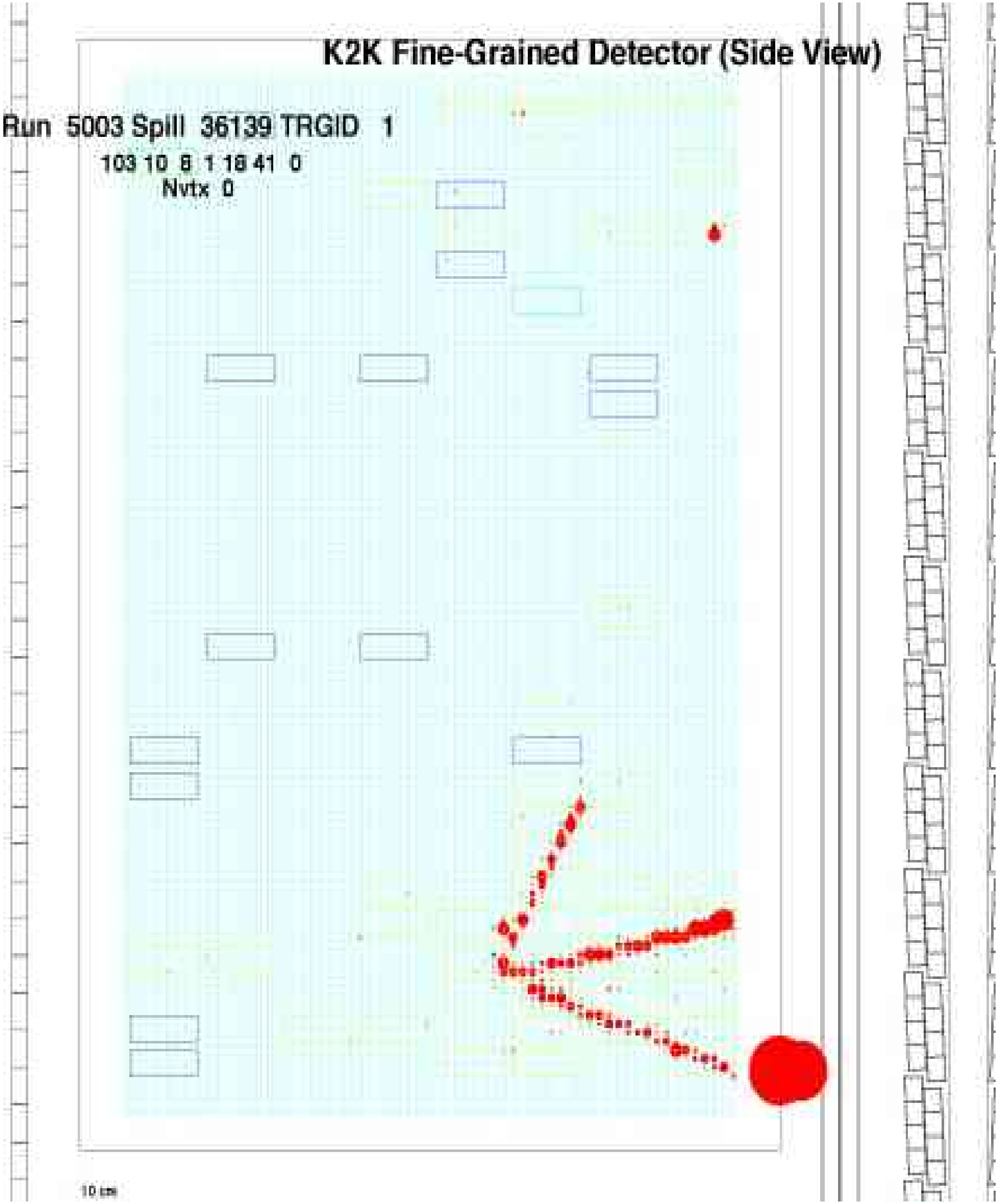
SCIBAR Detector

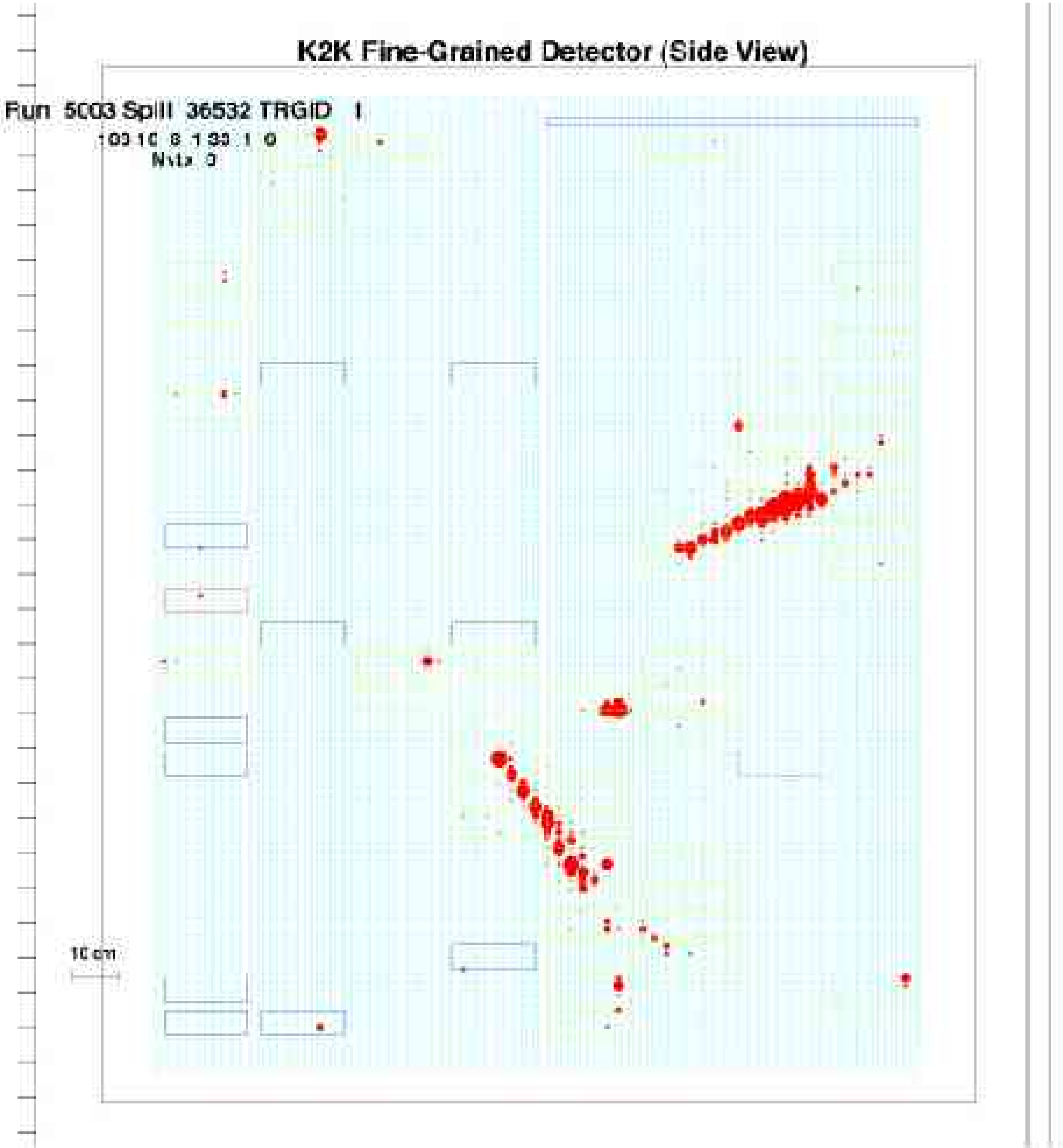


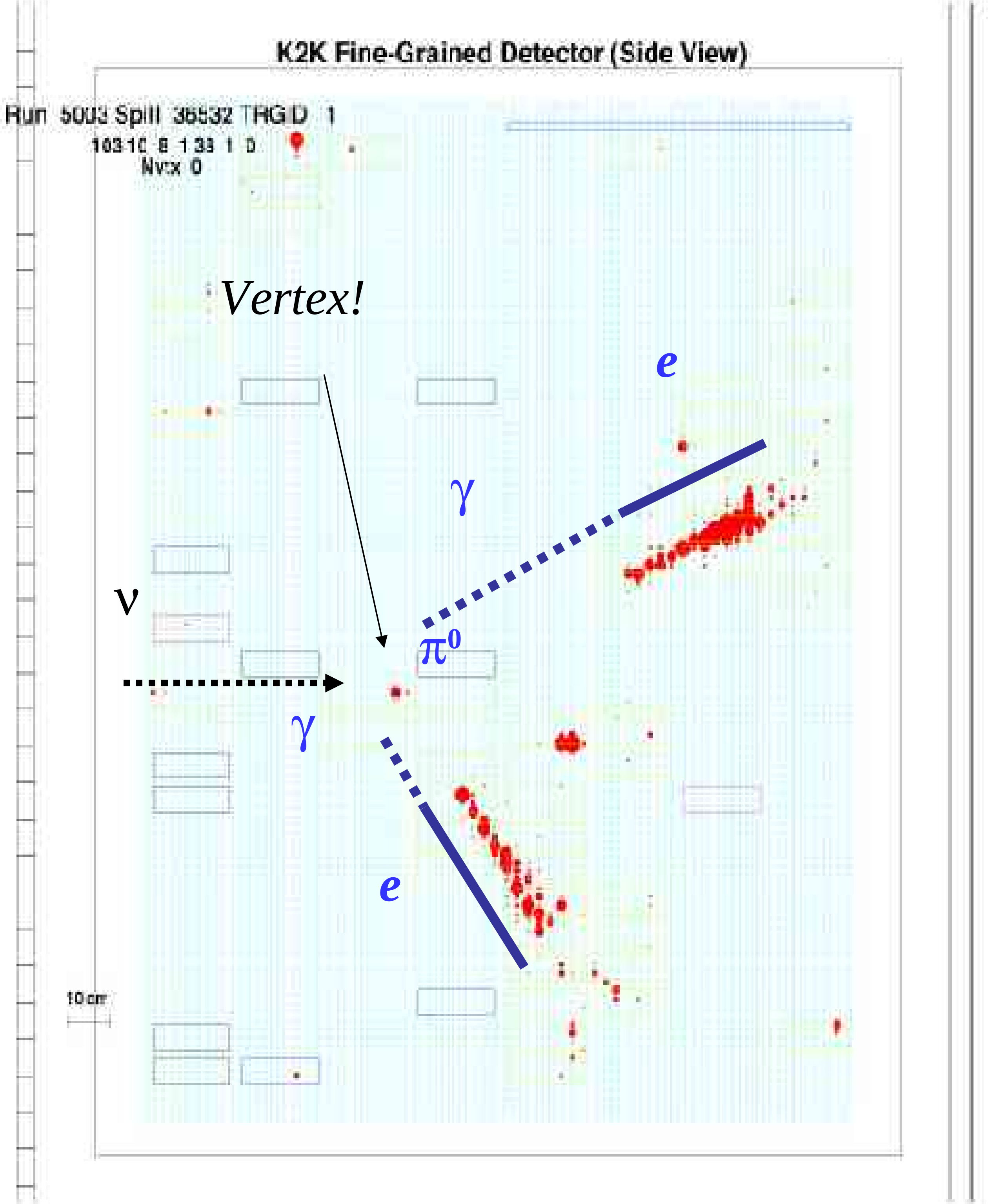
15,000 channels
(scintillator bars
2.5 * 1.3 * 300 cm^3

15 tons

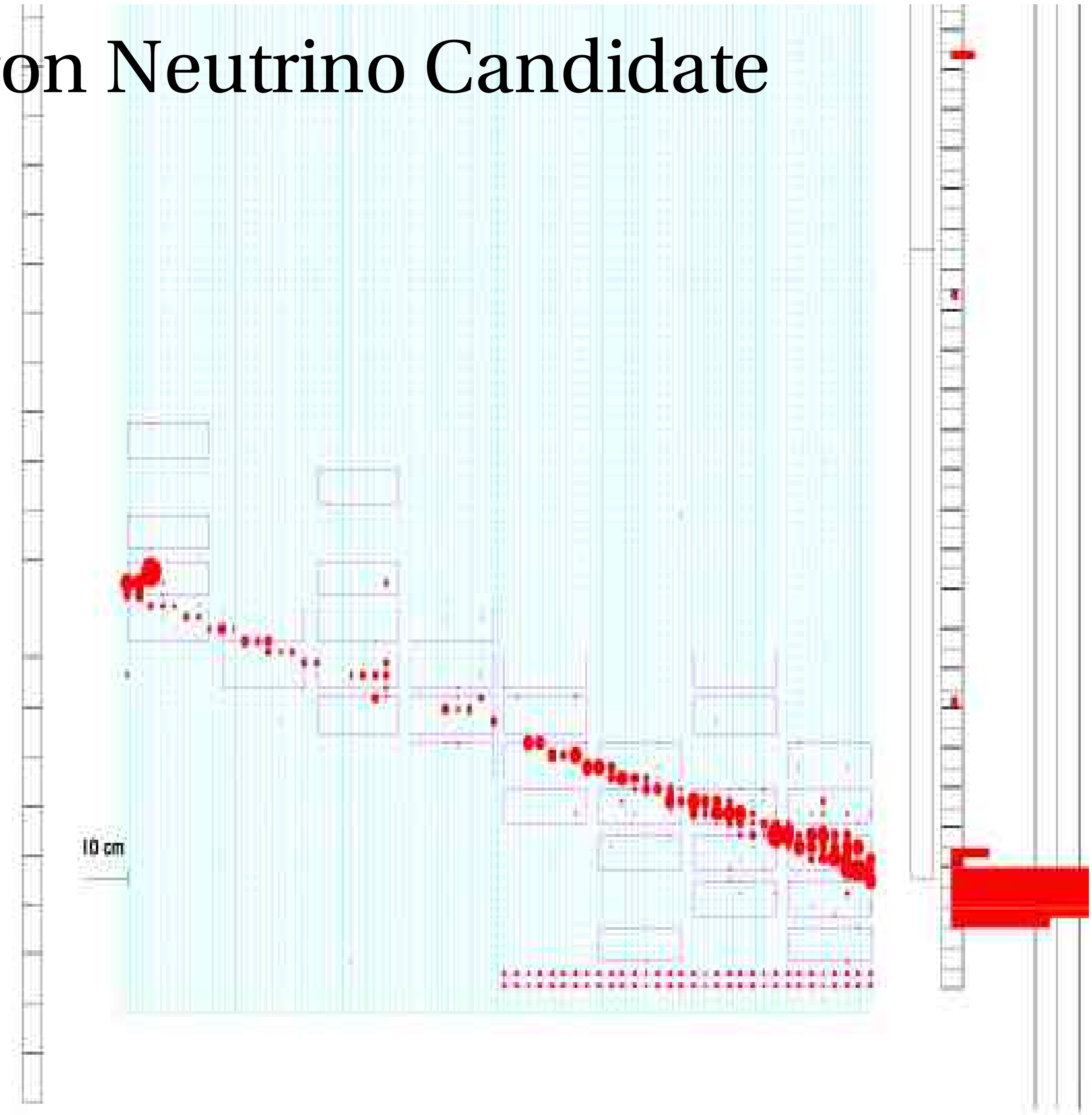

K2K Fine-Grained Detector (Top View)
Run 4990 Spill 19016 TRGID 1
103 10 7 14 44 40 0
Nvtx 0
10 cm

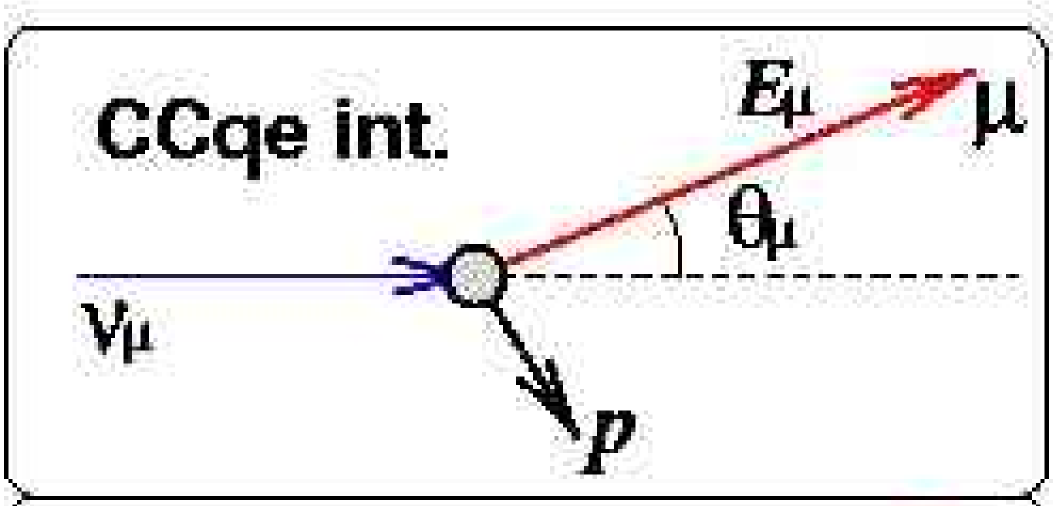

K2K Fine-Grained Detector (Side View)
Run 5003 Spill 36139 TRGID 1
103 10 8 1 18 41 0
Nvtx 0
10 cm

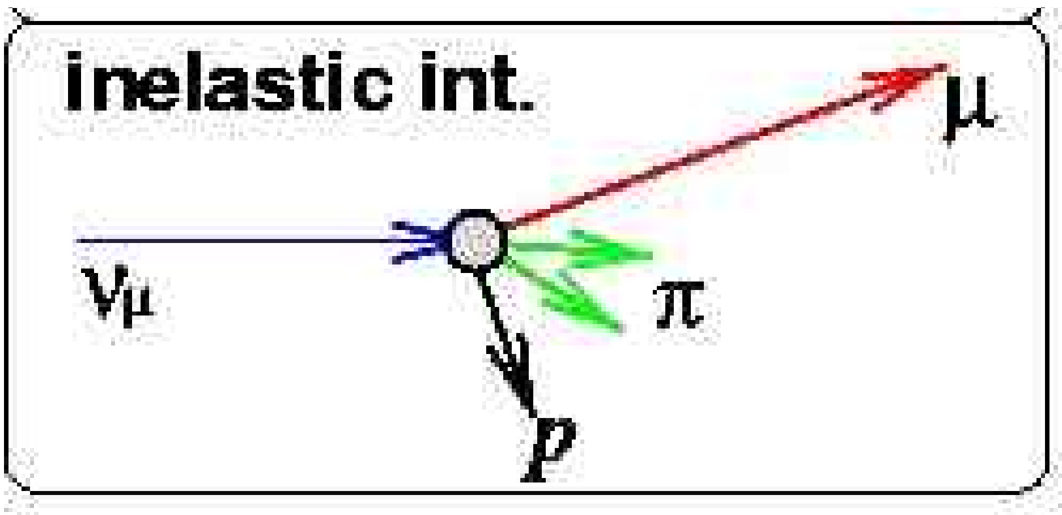

K2K Fine-Grained Detector (Side View)
Run 5003 Spill 36532 TRGID 1
Nvtx 0
10 cm


K2K Fine-Grained Detector (Side View)
Vertex!
ν
π0
γ
γ
e
e
10 cm

Electron Neutrino Candidate







Main Motivation is to measure the shape of the Energy Spectrum at the near site using QE reactions

Detector Installed Succesfully

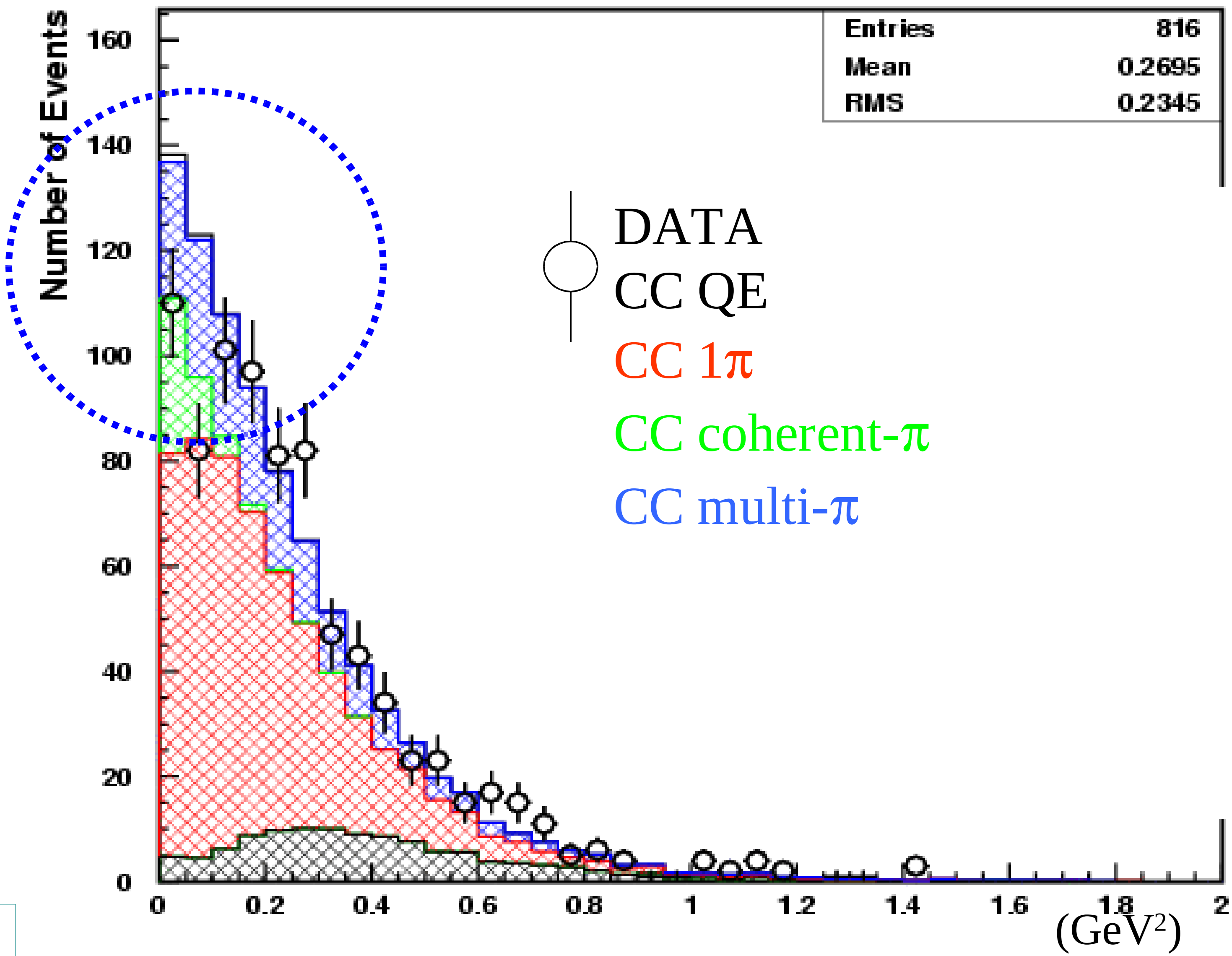
20 K Neutrino Events

First physics result will be released in the beginning of next year.

New Data :
New Phenomena

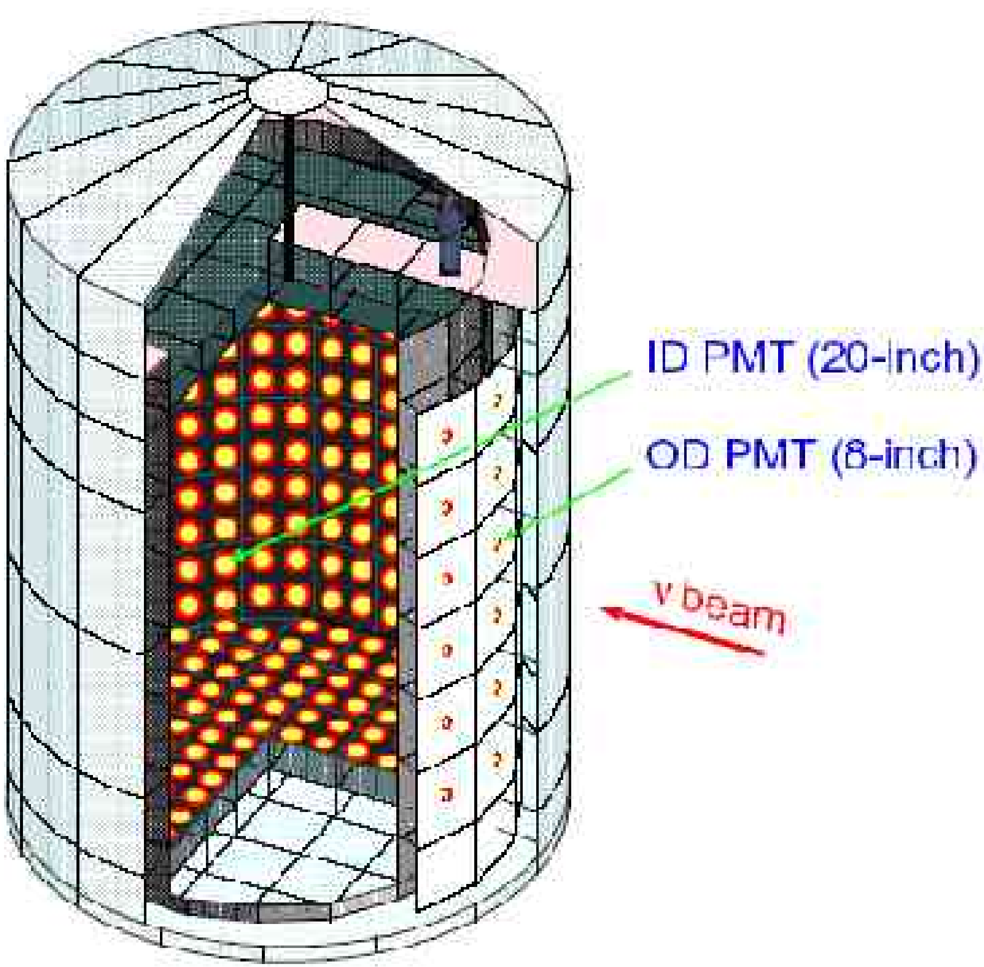
The "Low Q^2" Anomaly

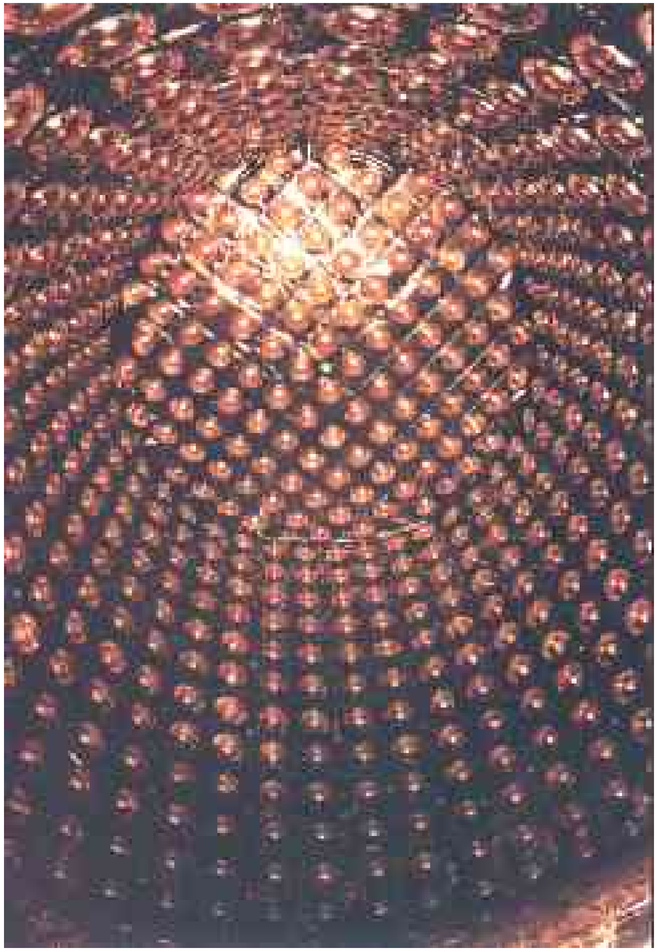
Scifi 2track nonQE enriched event



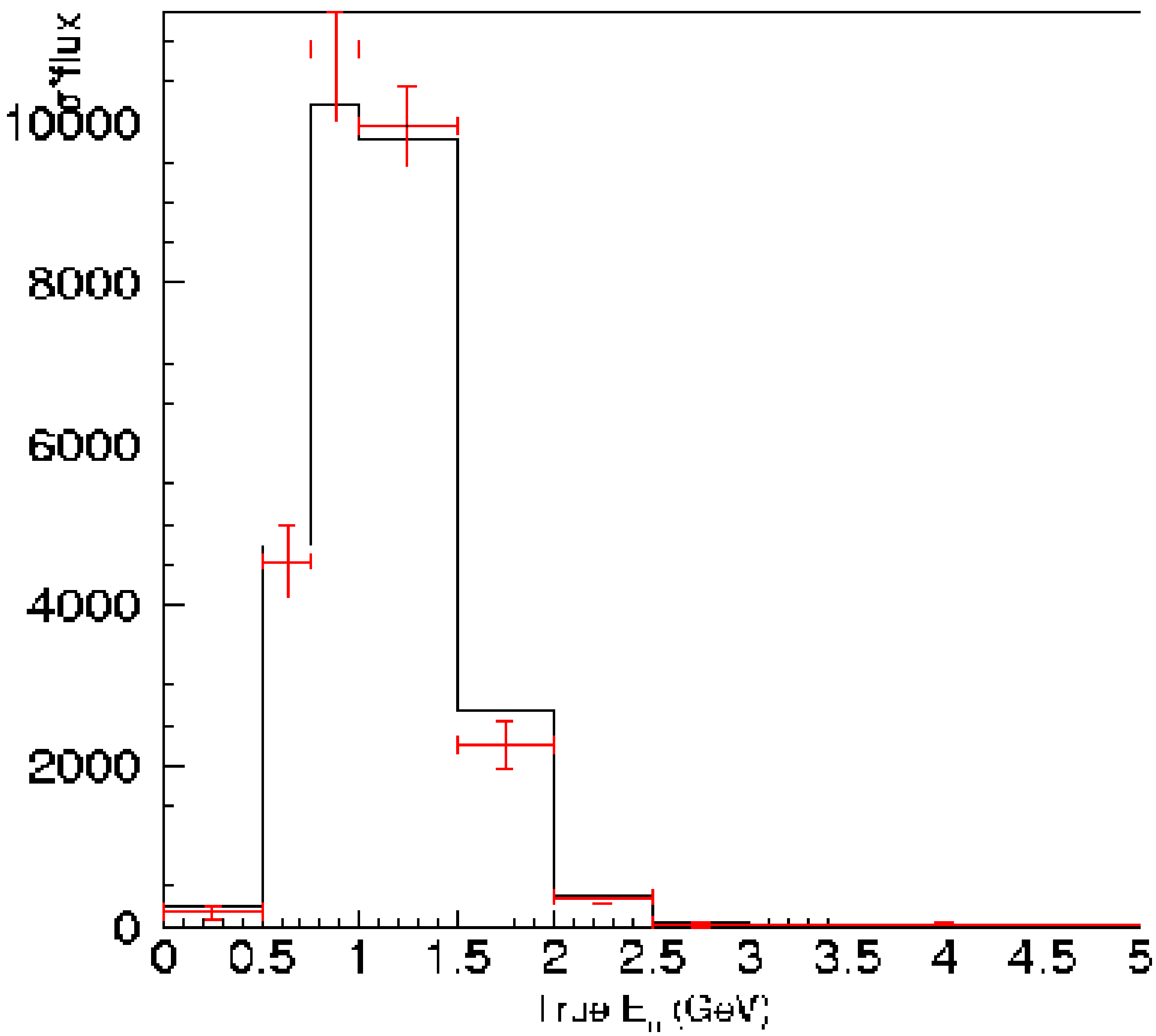
M. Hasegawa

1kton water Cherenkov detector





Jun Kameda



Reconstruction of the Neutrino Spectrum

π^0 event analysis

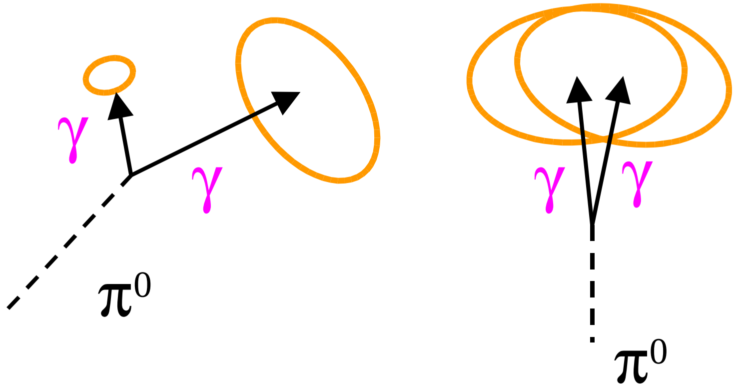
Motivation:

Precise understandnig of π^0 production rate
π^0 momentum/angle distribution is important for these analyses.

Main background for $\nu_\mu \rightarrow \nu_e$ search

$\pi^0 \rightarrow \gamma\gamma$ can mimic an electron

- asymmetric decay
- Cherenkov ring overlapping

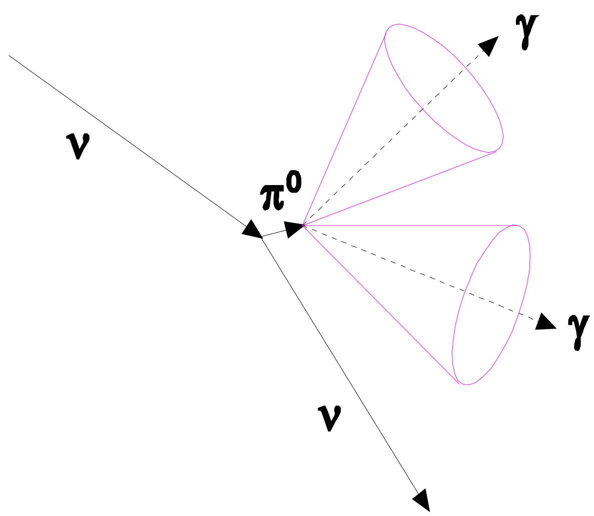


$\nu_\mu \rightarrow \nu_\tau$ / $\nu_\mu \rightarrow \nu_s$ separation

single π^0 events : good NC sample

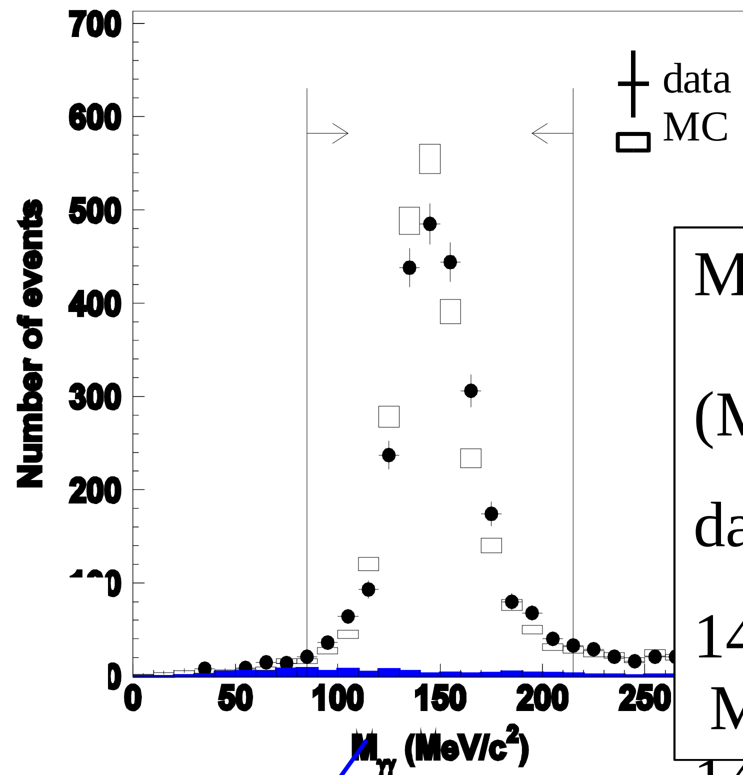
Data set

Period : 2000/Jan-Mar. 2001/Jan~Jul. (~ 3×10^{19} pot)



Selection Criteria of π^0 events

25t fiducial volume
Fully-Contained
number of rings = 2
both e-like PID
Mγγ : 85 ~ 215   MeV/c^2



Mass peak (MeV/c^2)
data : 147.4
MC : 144.1

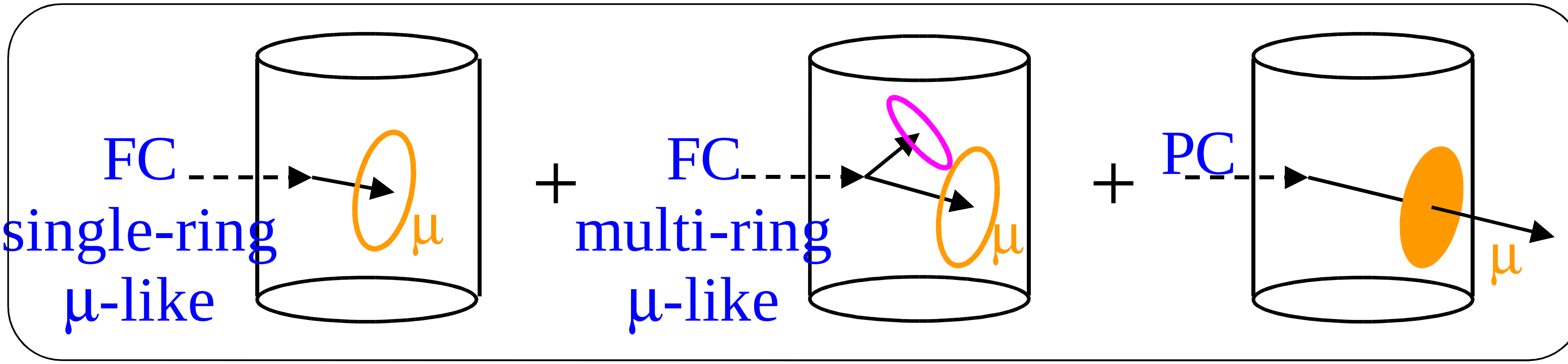
non-π^0 BG

very clean π^0 sample

FC 2ring π^0 : **2496** events

$N(\nu_\mu CC)$ as normalization :

νμCC enriched sample



$N(\nu_\mu CC) = N(FC\mu+PC)_{25t}^{obs} \times (1 - BG_{non\text{-}\nu}) \times \text{purity} \times \text{corrfid} / \text{eff}$

$= \mathbf{5.65 \pm 0.03 \pm 0.26 \ x\ 10^4}$ in 25 ton

stat. sys

Then,

stat. sys.

$$\frac{\sigma(NC1\pi^0)}{\sigma(\nu_\mu CC)} = 0.065 \pm 0.001 \pm 0.007$$

at the K2K beam energy, <Eν>~1.3 GeV

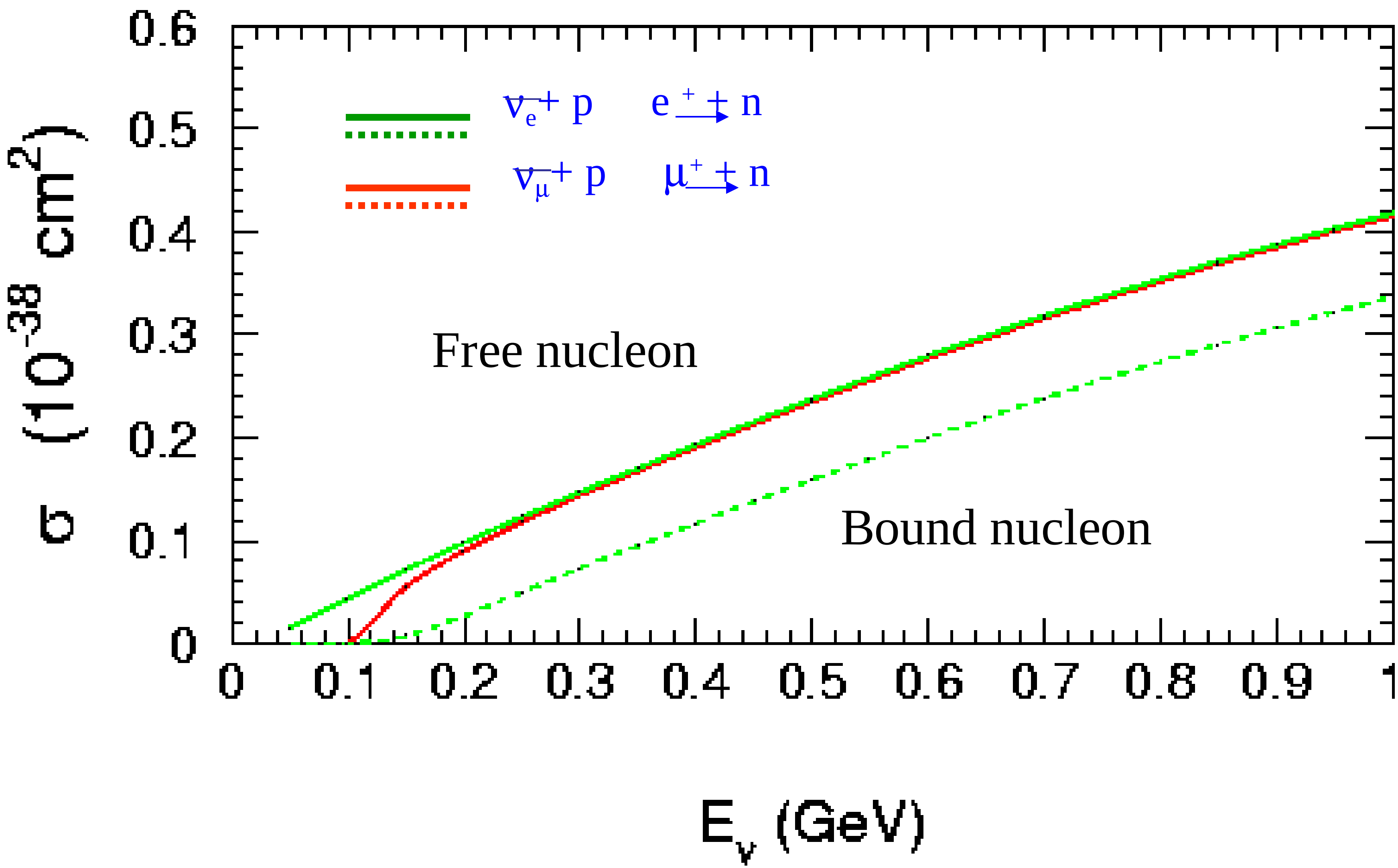
cf. $\sigma(NC1\pi^0) / \sigma(\nu_\mu CC) = 0.064$ from NEUT

NUCLEAR THEORY

and Neutrino Interactions

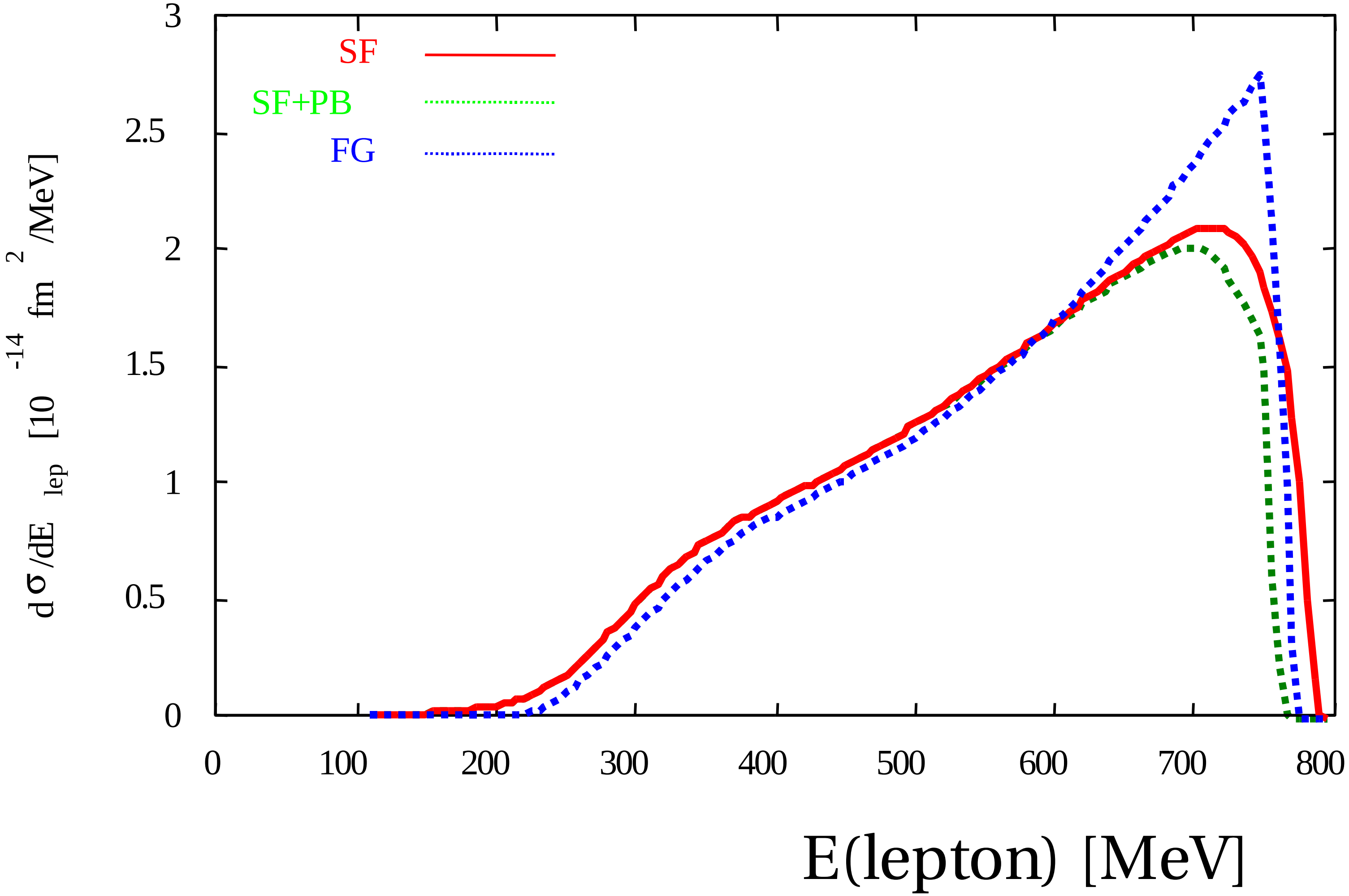
Beyond the Fermi Gas Model

NUCLEAR EFFECTS



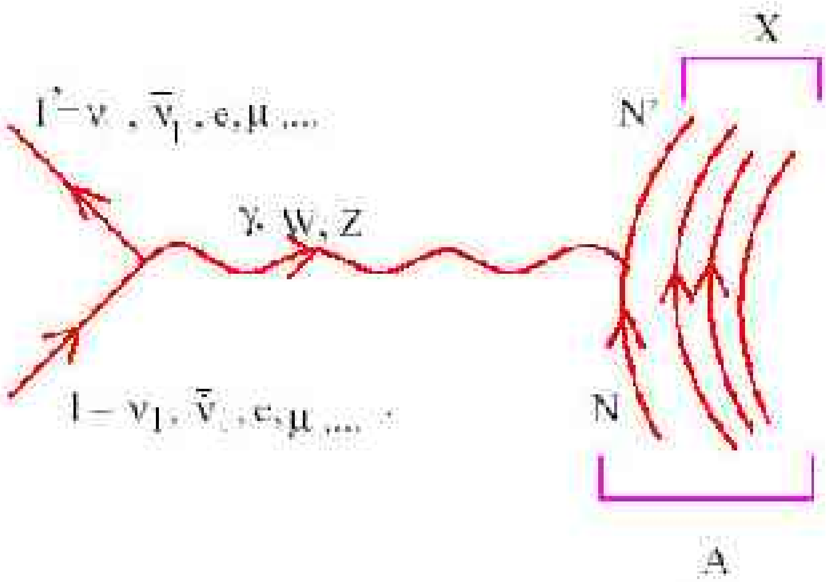
Jun Kameda

E = 800 MeV



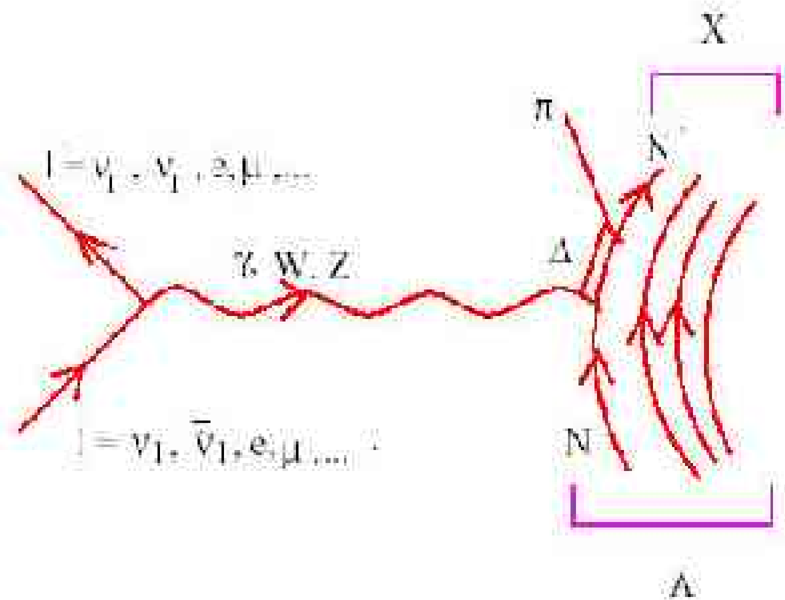
Nakamura, Sakuda, Seki

QUASIELASTIC PEAK



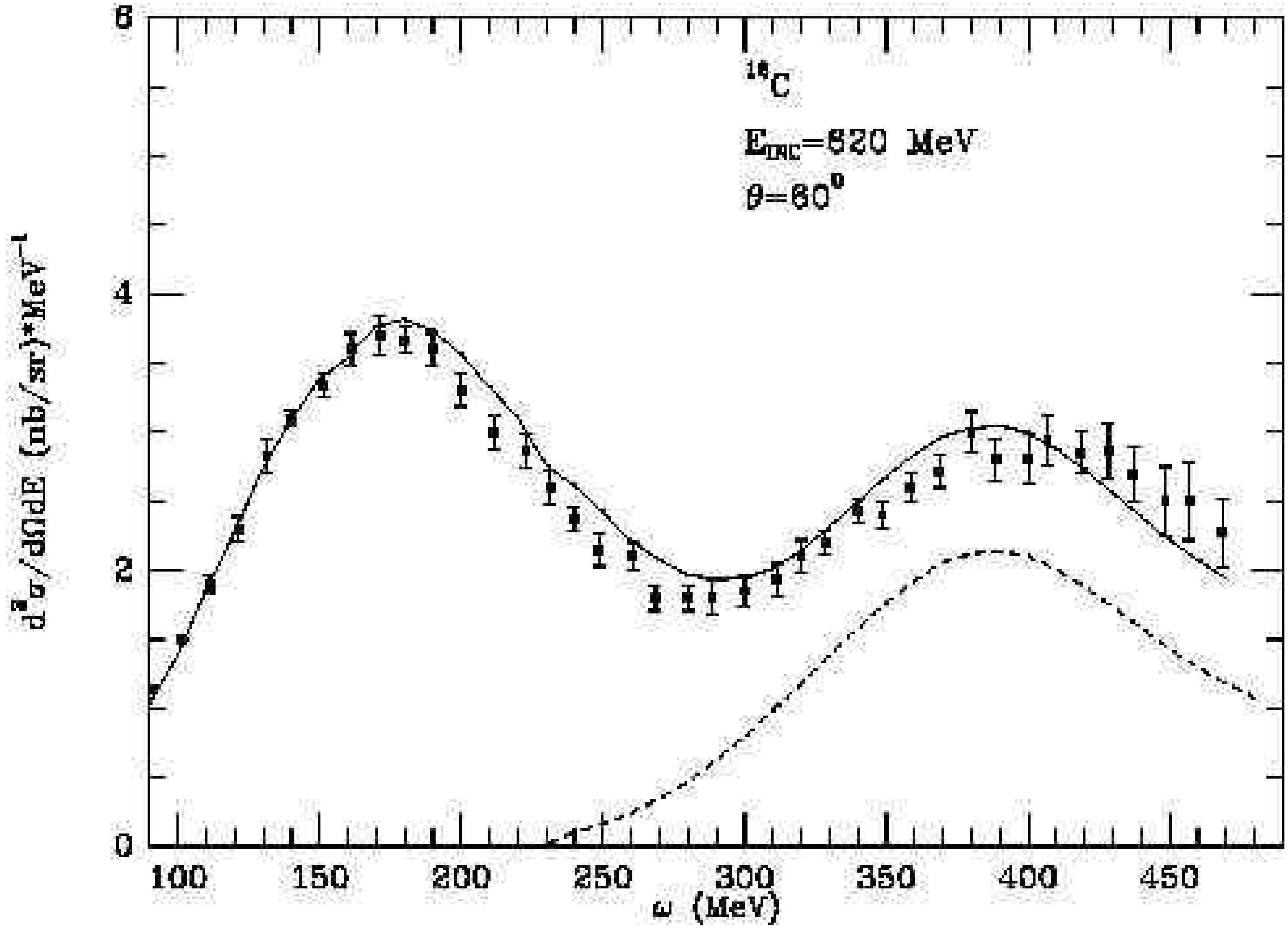
VIRTUAL γ / W / Z ABSORPTION BY ONE NUCLEON

Δ(1232) RESONANCE PEAK

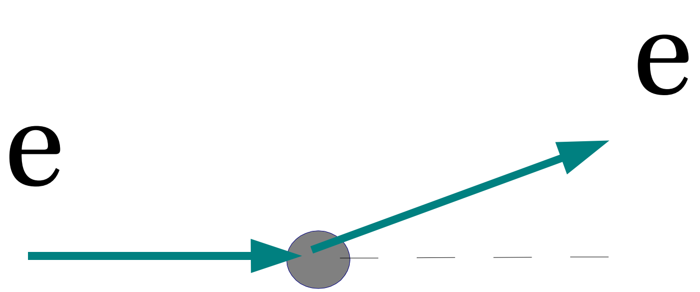


EXCITATION OF Δ(1232) DEGREES OF FREEDOM

Juan Nieves



$$e + {}^{12}\mathrm{C} \rightarrow e' + X$$



Juan Nieves

E_ν [MeV]		$\sigma\left({}^{16}\mathrm{O}(\nu_\mu,\mu^- X)\right)$ $[10^{-40}\ \mathrm{cm}^2]$			$\sigma\left({}^{16}\mathrm{O}(\bar{\nu}_\mu,\mu^+ X)\right)$ $[10^{-40}\ \mathrm{cm}^2]$		
		REL	NOREL	FSI	REL	NOREL	FSI
500	Pauli	460.0	497.0	431.6	155.8	168.4	149.9
	RPA	375.5	413.0	389.8	113.4	126.8	129.7
375	Pauli	334.6	354.8	292.2	115.1	122.6	105.0
	RPA	243.1	263.9	243.9	79.8	87.9	87.5
250	Pauli	155.7	162.2	122.5	63.4	66.4	52.8
	RPA	94.9	101.9	93.6	38.8	42.1	40.3

E_ν [MeV]		$\sigma\left({}^{16}\mathrm{O}(\nu_e,e^- X)\right)$ $[10^{-40}\ \mathrm{cm}^2]$			$\sigma\left({}^{16}\mathrm{O}(\bar{\nu}_e,e^+ X)\right)$ $[10^{-40}\ \mathrm{cm}^2]$		
		REL	NOREL	FSI	REL	NOREL	FSI
400	Pauli	389.4	416.6	352.5	130.0	139.1	121.0
	RPA	294.7	322.6	303.6	91.9	101.9	104.8
310	Pauli	281.4	297.4	240.6	98.1	104.0	87.2
	RPA	192.2	209.0	195.2	65.9	72.4	73.0
220	Pauli	149.5	156.2	121.2	60.7	63.6	51.0
	RPA	90.1	97.3	92.8	36.8	40.0	40.2

CONCLUSIONS

- The perspectives for future precision Studies with Atmospheric Neutrinos appear very interesting
- The potential for very interesting measurements exists even for a relatively modest increase in Exposure (20 SK-years)
- "Hyper-K" would offer even more interesting results.
- If the neutrino-Kami (one more time) are kind and theta(13) is just below the Chooz limit, life will be very interesting indeed !
- There is an important prize in the improvement of the theoretical prediction. It is worthwhile to invest work in this direction.

Additional Conclusion:

The Organization of the Workshop has been remarkable, in all its details !

Kajita Sensei,
dear Organizers

Thanks a lot
for a truly excellent meeting !