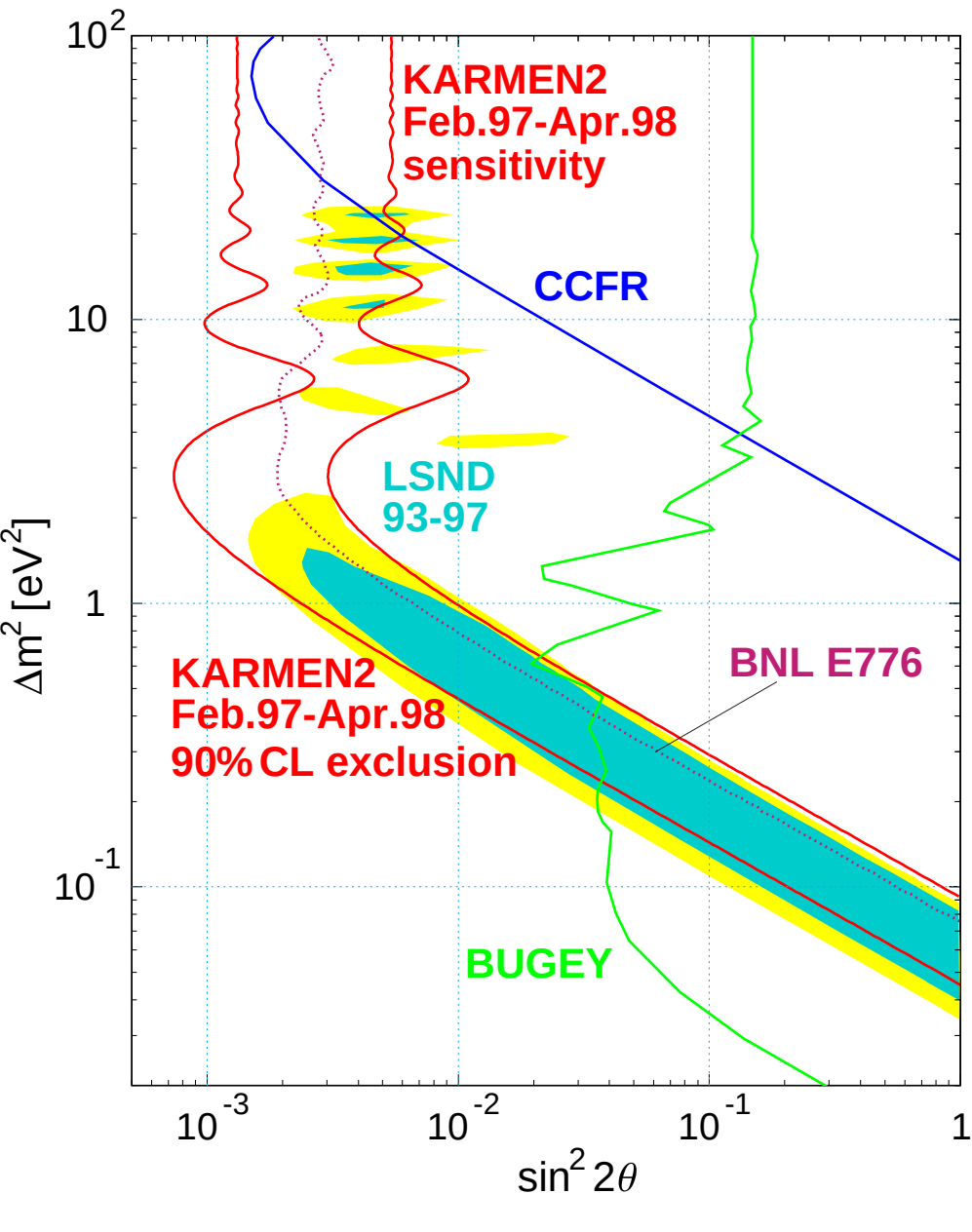
V. A. Naumov

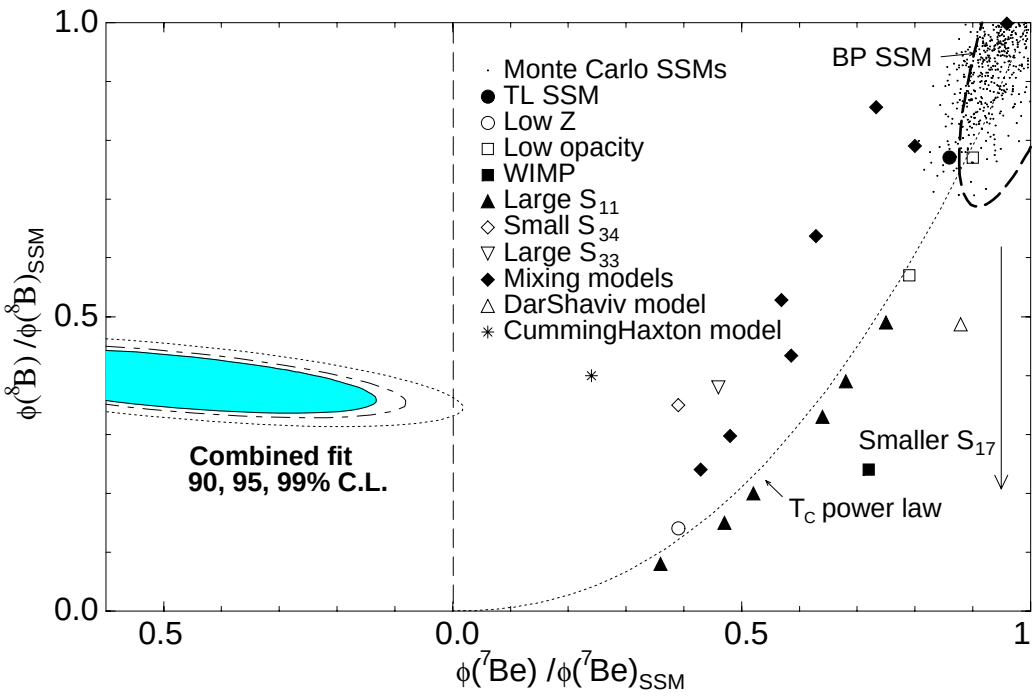
Physics of Atmospheric Neutrinos

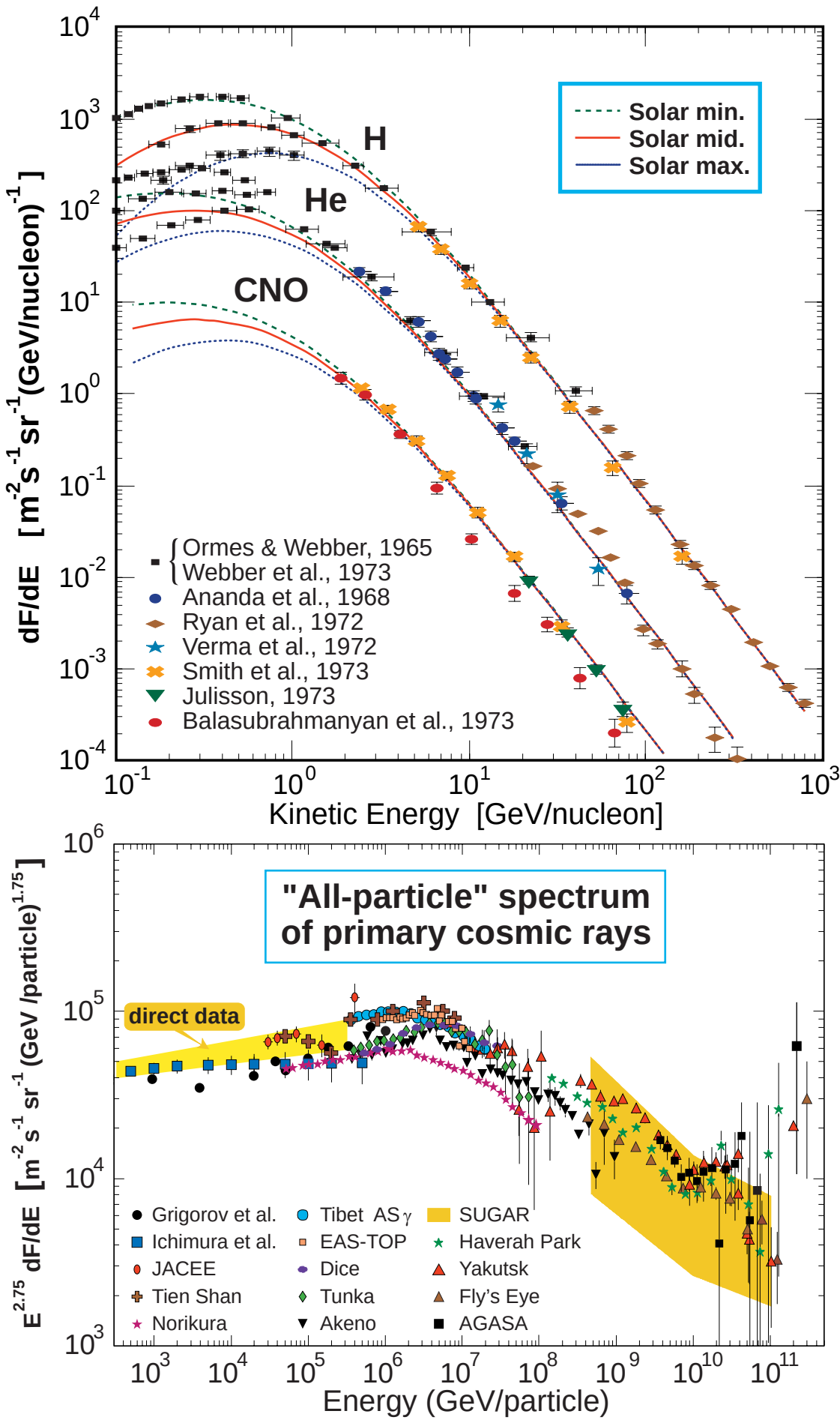
Abstract

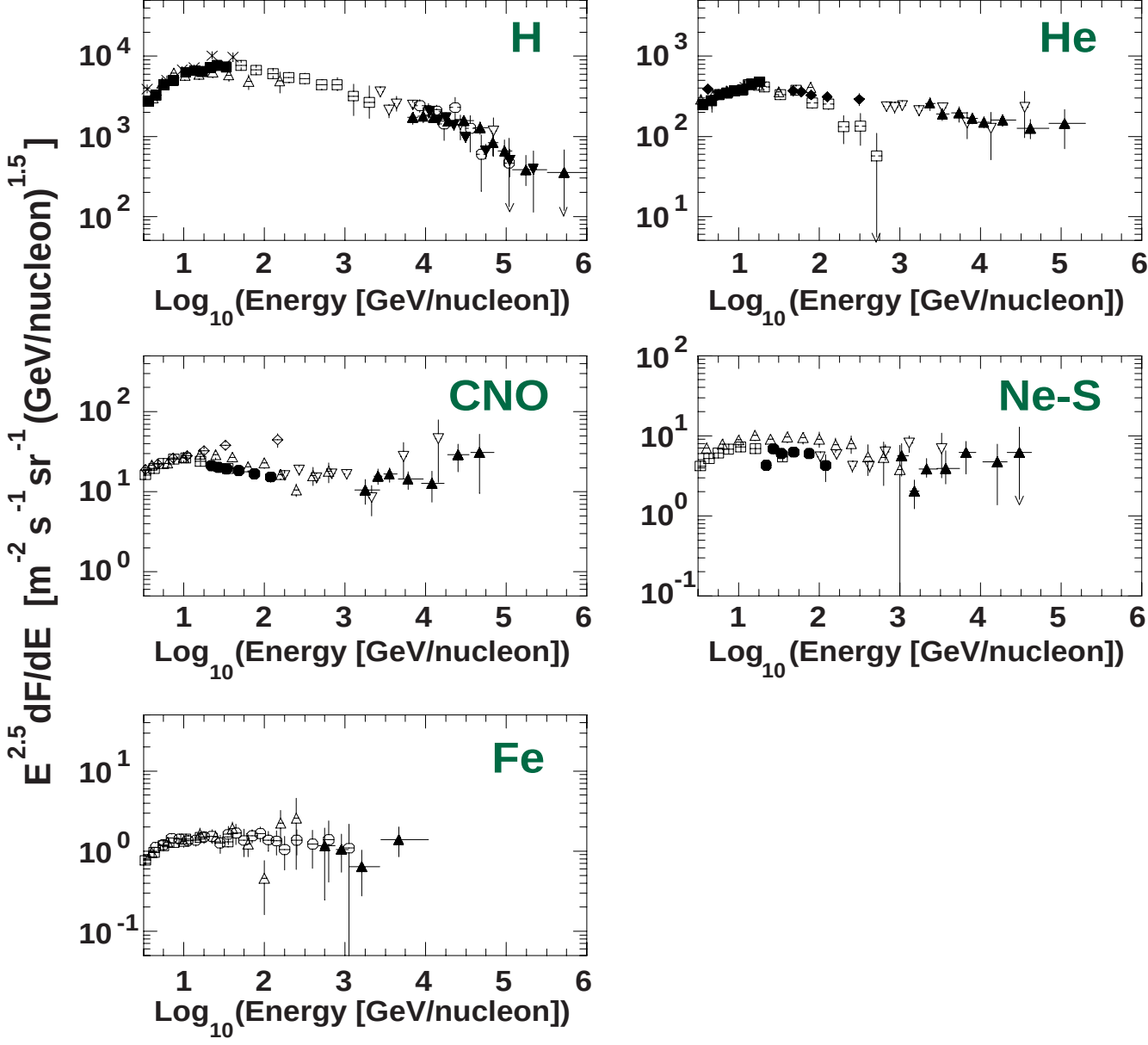
The lecture reviews the physics of neutrino production in the atmosphere, the detection methods, and the results obtained with large underground neutrino detectors.

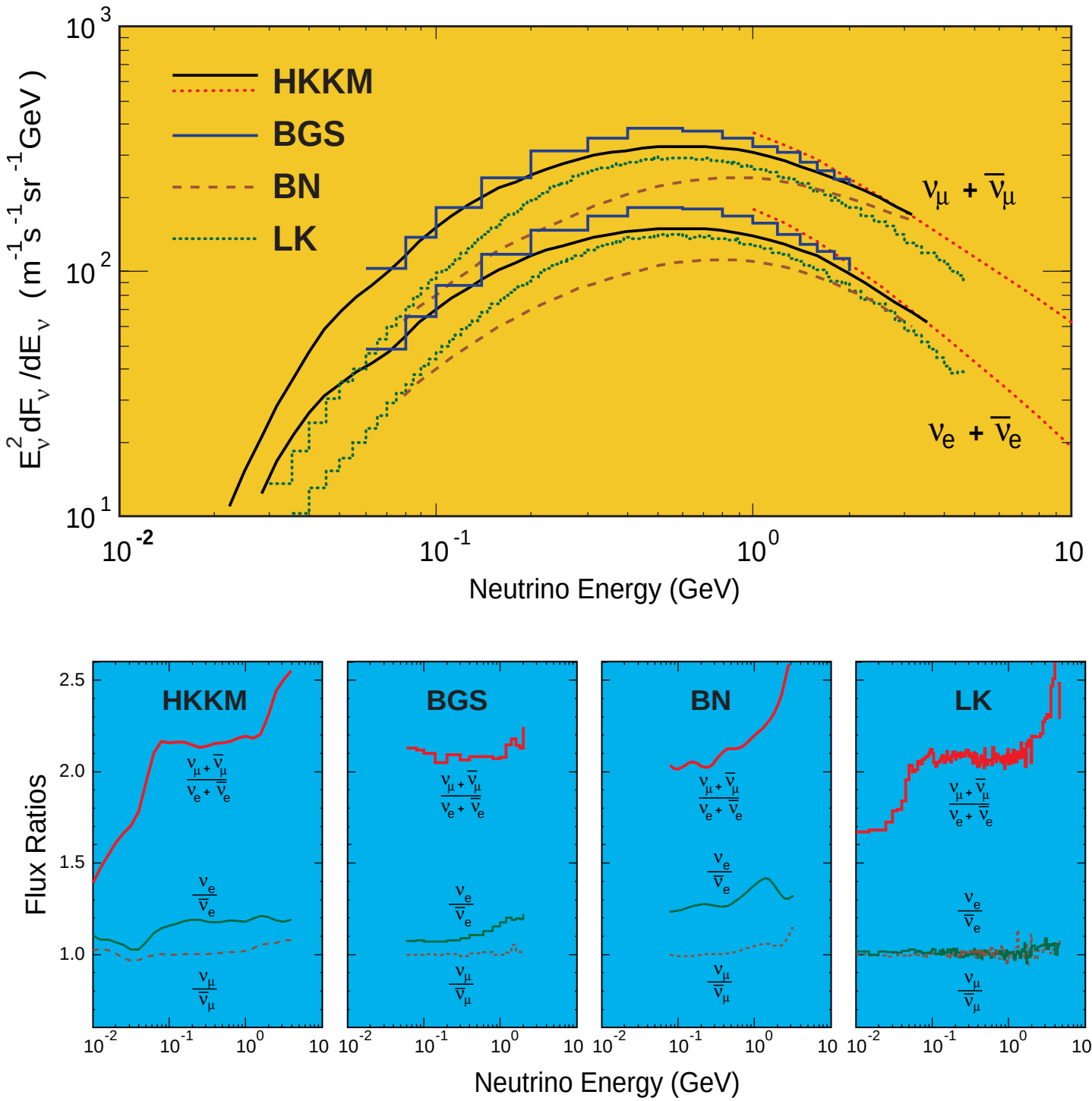
Contents of the lecture.

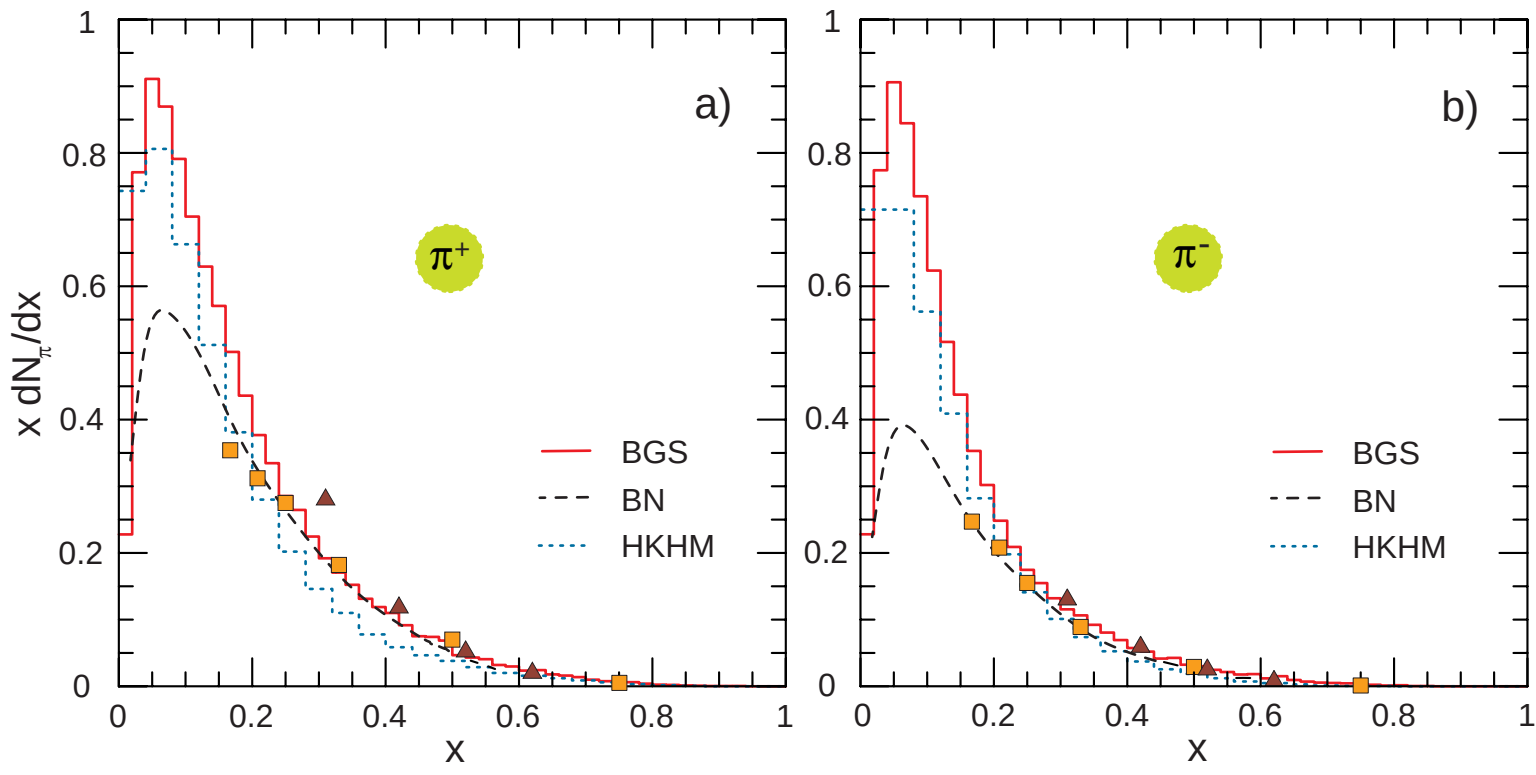

KARMEN2
Feb.97-Apr.98
sensitivity
CCFR
LSND
93-97
KARMEN2
Feb.97-Apr.98
90% CL exclusion
BNL E776
BUGEY
10^2
10
1
10^{-1}
Δm^2 [eV^2]
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$

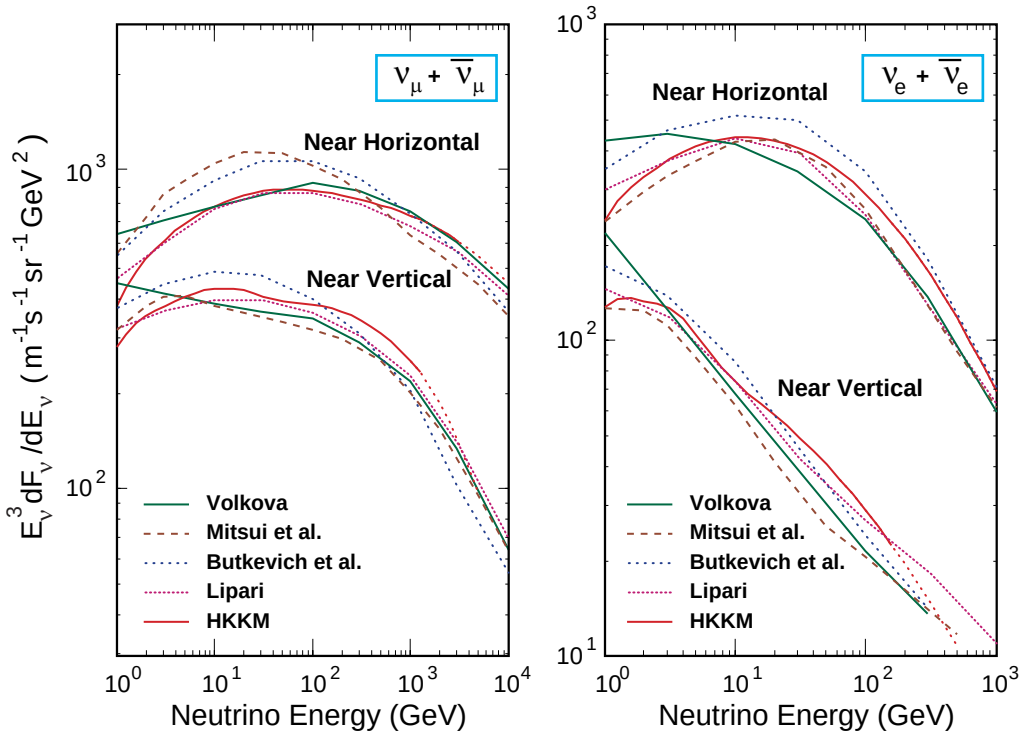

1.0
0.5
0.0
0.5
0.0
0.5
1
$\phi(^8B)\ /\phi(^8B)_{SSM}$
$\phi(^7Be)\ /\phi(^7Be)_{SSM}$
Monte Carlo SSMs
TL SSM
Low Z
Low opacity
WIMP
Large S_{11}
Small S_{34}
Large S_{33}
Mixing models
DarShaviv model
CummingHaxton model
BP SSM
Combined fit
90, 95, 99% C.L.
Smaller S_{17}
T_c power law

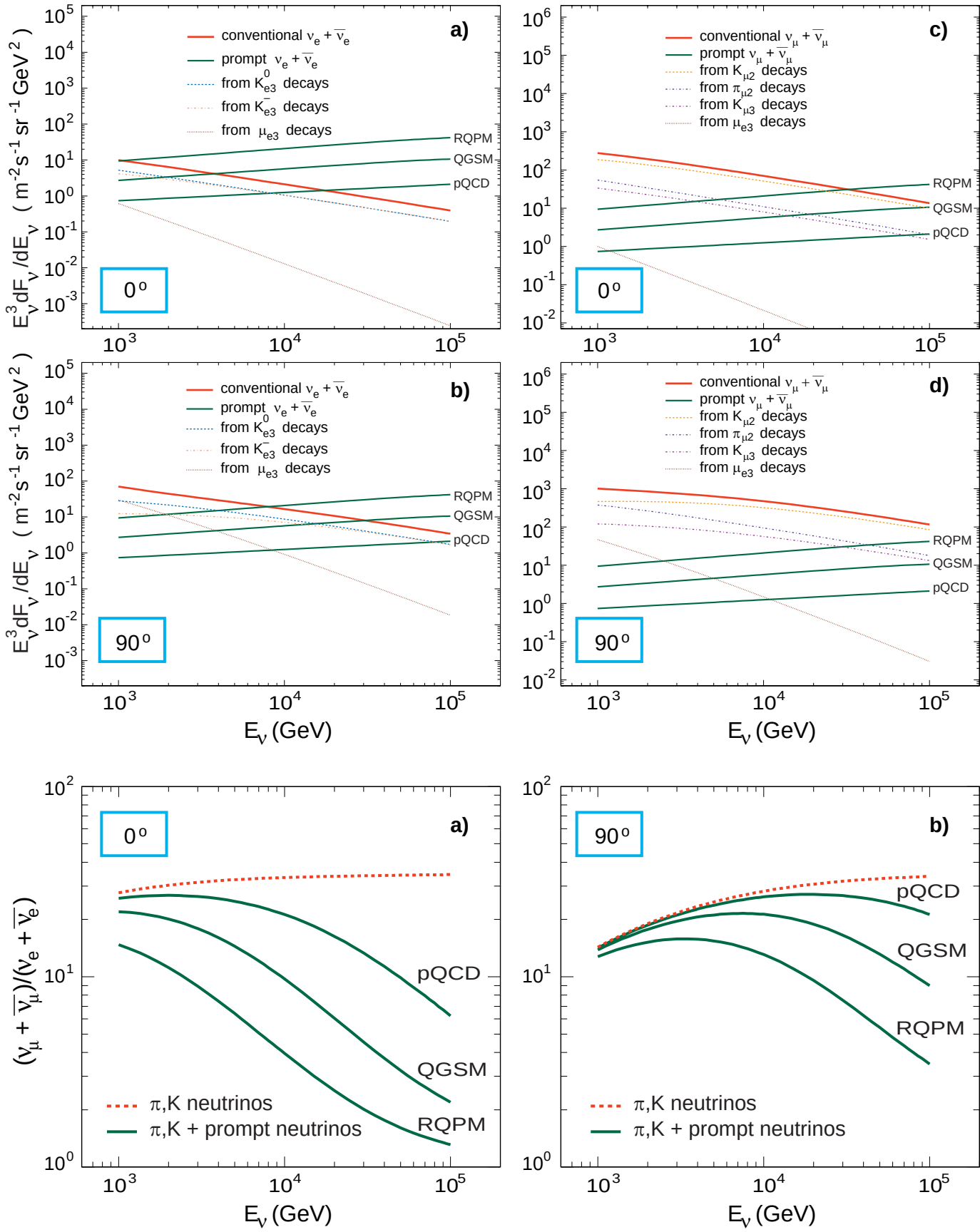

Solar min.
Solar mid.
Solar max.
H
He
CNO
Ormes & Webber, 1965
Webber et al., 1973
Ananda et al., 1968
Ryan et al., 1972
Verma et al., 1972
Smith et al., 1973
Julisson, 1973
Balasubrahmanyan et al., 1973
dF/dE [m-2s-1sr-1(GeV/nucleon)-1]
Kinetic Energy [GeV/nucleon]
"All-particle" spectrum of primary cosmic rays
direct data
Grigorov et al.
Ichimura et al.
JACEE
Tien Shan
Norikura
Tibet ASγ
EAS-TOP
Dice
Tunka
Akeno
SUGAR
Haverah Park
Yakutsk
Fly's Eye
AGASA
E2.75 dF/dE [m-2 s-1 sr-1 (GeV /particle)1.75]
Energy (GeV/particle)

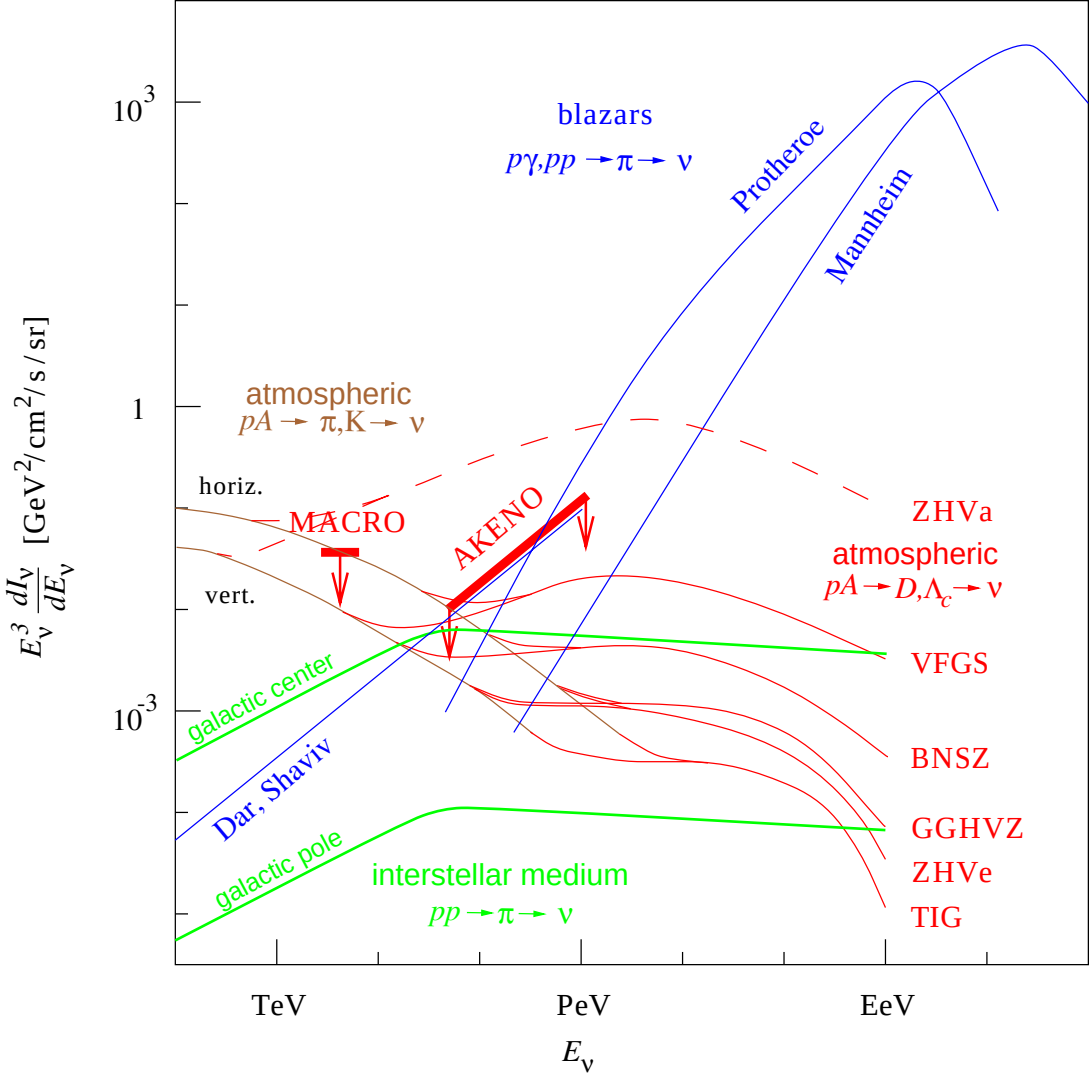

H
He
CNO
Ne-S
Fe
$E^{2.5}$ dF/dE [m^{-2} s^{-1} sr^{-1} $(GeV/nucleon)^{1.5}$]
Log_{10}(Energy [GeV/nucleon])


HKKM
BGS
BN
LK
$\nu_\mu + \bar{\nu}_\mu$
$\nu_e + \bar{\nu}_e$
$E_\nu^2 dF_\nu / dE_\nu$ ($m^{-1} s^{-1} sr^{-1} GeV$)
Neutrino Energy (GeV)
Flux Ratios
$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$
$\frac{\nu_e}{\bar{\nu}_e}$
$\frac{\nu_\mu}{\bar{\nu}_\mu}$

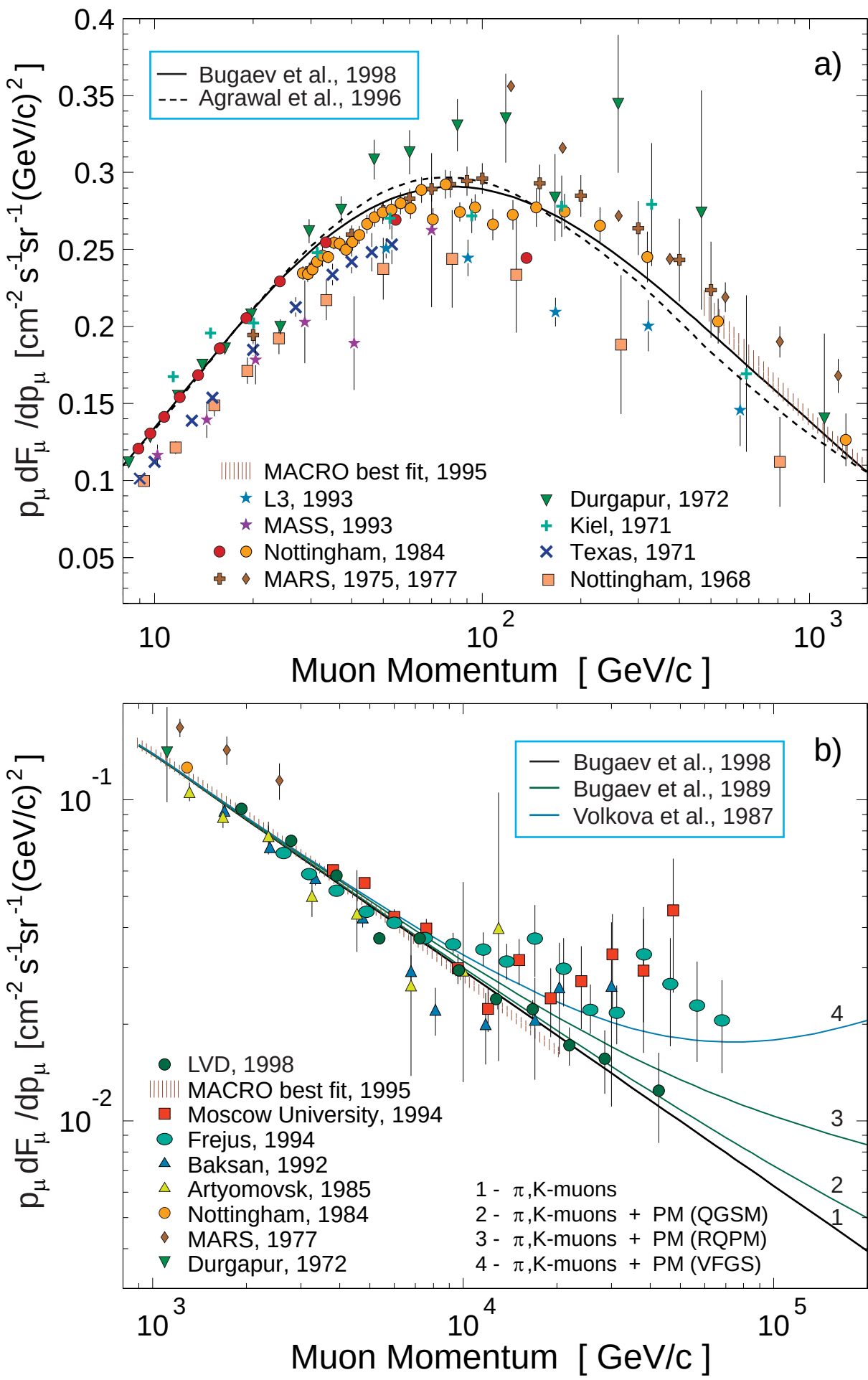

a)
b)
π^+
π^-
BGS
BN
HKHM
x dN$_\pi$/dx
x
0
0.2
0.4
0.6
0.8
1

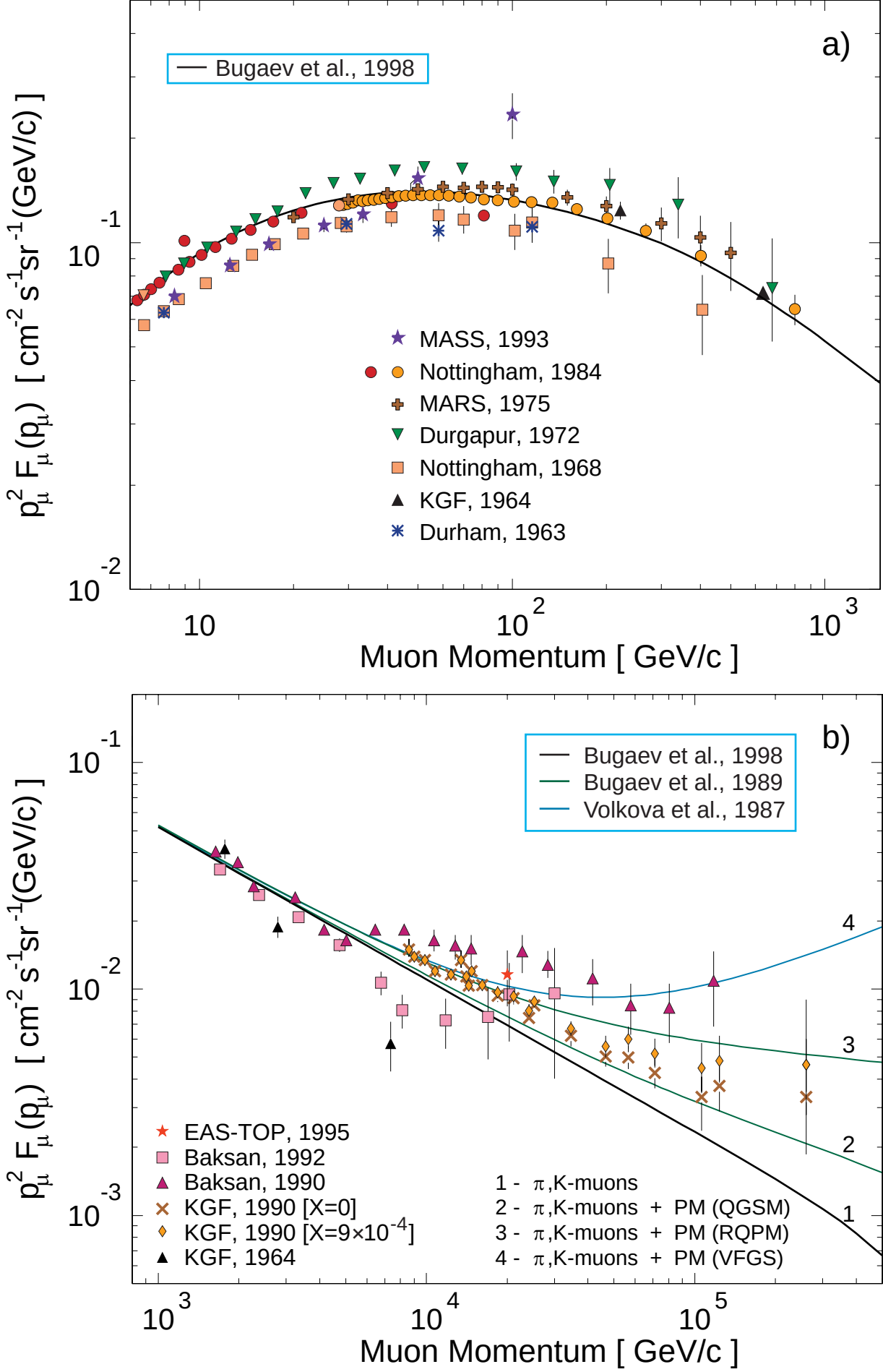

$\nu_\mu + \overline{\nu}_\mu$
Near Horizontal
Near Vertical
$E_\nu^3 dF_\nu / dE_\nu$ ($m^{-1} s^{-1} sr^{-1} GeV^2$)
10^3
10^2
Volkova
Mitsui et al.
Butkevich et al.
Lipari
HKKM
10^0
10^1
10^2
10^3
10^4
Neutrino Energy (GeV)
$\nu_e + \overline{\nu}_e$
Near Horizontal
Near Vertical
10^3
10^2
10^1
Volkova
Mitsui et al.
Butkevich et al.
Lipari
HKKM
10^0
10^1
10^2
10^3
Neutrino Energy (GeV)

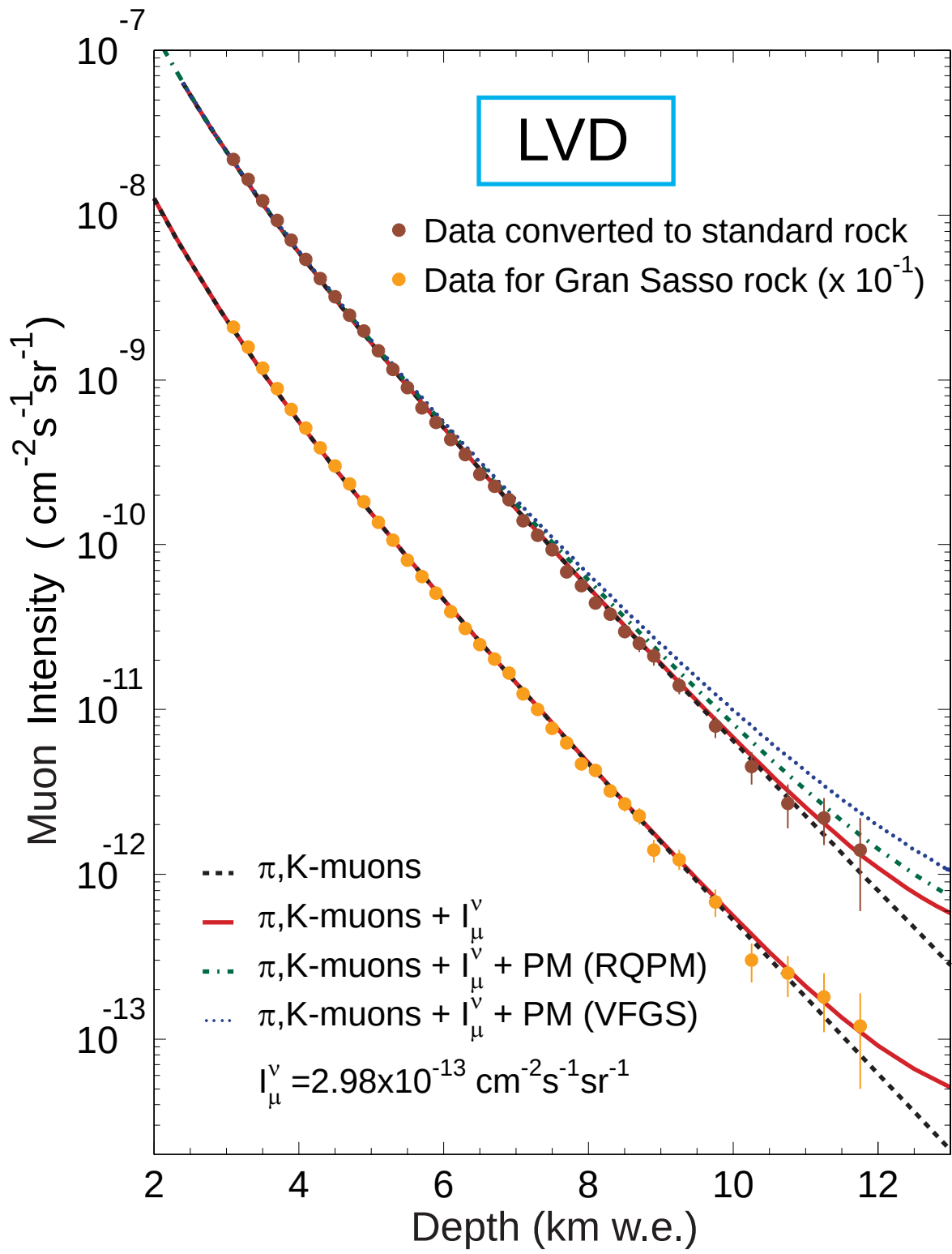

a)
conventional $\nu_e + \bar{\nu}_e$
prompt $\nu_e + \bar{\nu}_e$
from K^0_{e3} decays
from K^-_{e3} decays
from μ_{e3} decays
RQPM
QGSM
pQCD
0°
c)
conventional $\nu_\mu + \bar{\nu}_\mu$
prompt $\nu_\mu + \bar{\nu}_\mu$
from $K_{\mu 2}$ decays
from $\pi_{\mu 2}$ decays
from $K_{\mu 3}$ decays
from μ_{e3} decays
b)
90°
d)
$E_\nu^3 dF_\nu/dE_\nu$ ($m^{-2} s^{-1} sr^{-1} GeV^2$)
E_ν (GeV)
a)
b)
$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$
pQCD
QGSM
RQPM
π,K neutrinos
π,K + prompt neutrinos

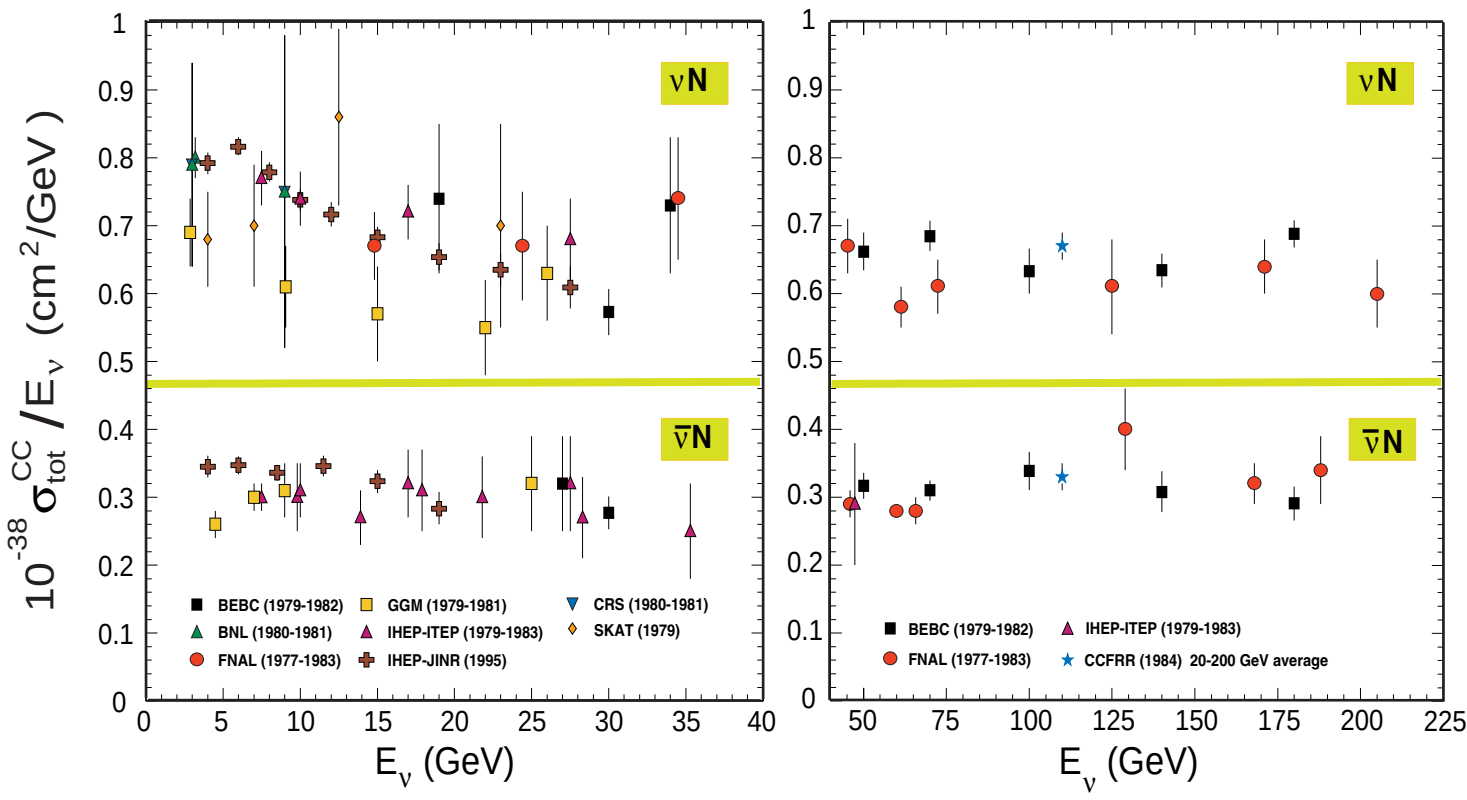


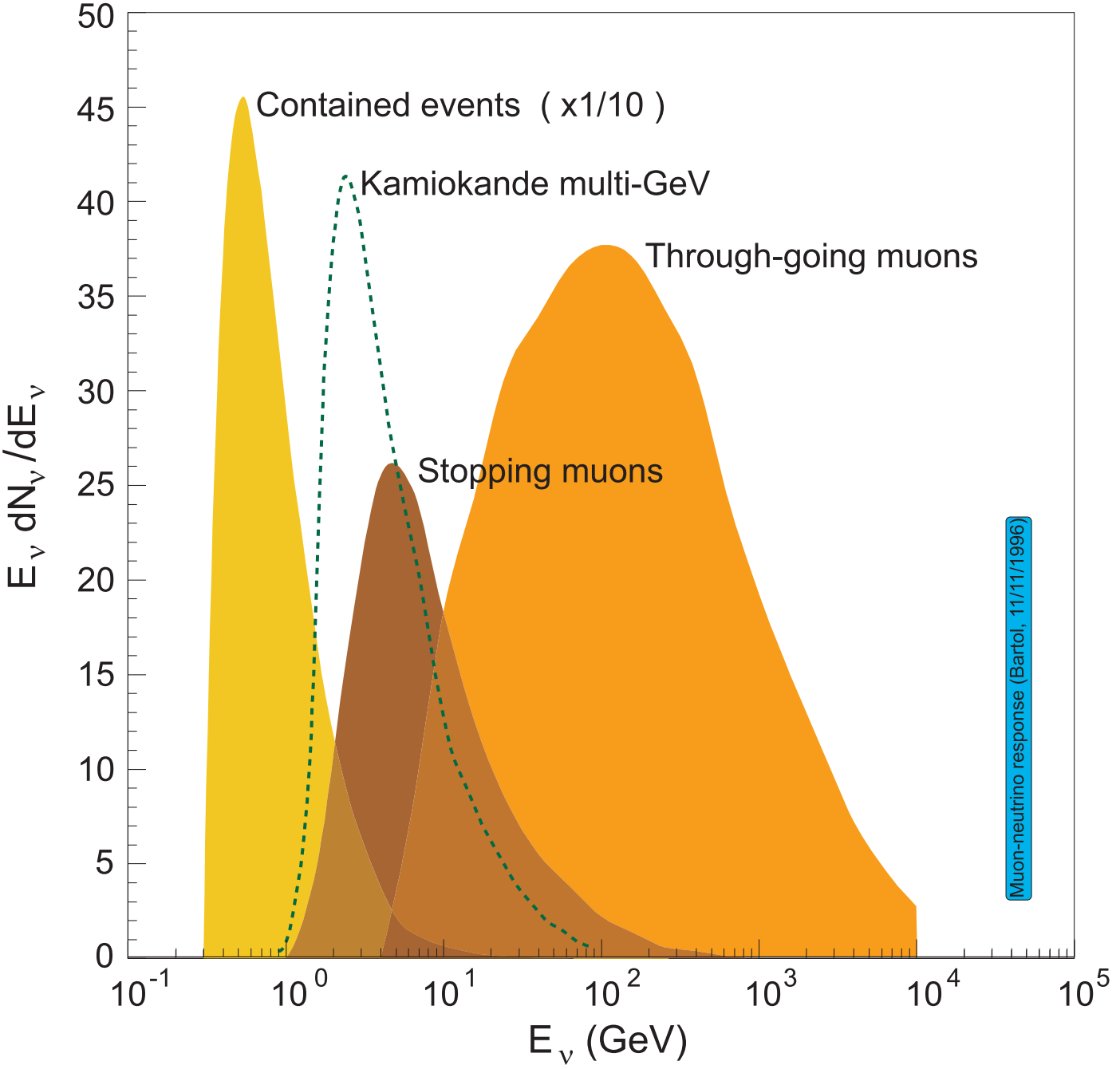
Selected predictions for high-energy neutrino fluxes
(from P. Gondolo, Proc. of the 4th SFB-375 Ringberg Workshop on Neutrino Astrophysics, Oct. 20-24, 1997)


a)
Bugaev et al., 1998
Agrawal et al., 1996
MACRO best fit, 1995
L3, 1993
MASS, 1993
Nottingham, 1984
MARS, 1975, 1977
Durgapur, 1972
Kiel, 1971
Texas, 1971
Nottingham, 1968
$p_\mu dF_\mu / dp_\mu$ [cm^{-2} s^{-1}sr^{-1}(GeV/c)^2]
Muon Momentum [GeV/c]
b)
Bugaev et al., 1998
Bugaev et al., 1989
Volkova et al., 1987
LVD, 1998
MACRO best fit, 1995
Moscow University, 1994
Frejus, 1994
Baksan, 1992
Artyomovsk, 1985
Nottingham, 1984
MARS, 1977
Durgapur, 1972
1 - π,K-muons
2 - π,K-muons + PM (QGSM)
3 - π,K-muons + PM (RQPM)
4 - π,K-muons + PM (VFGS)
$p_\mu dF_\mu / dp_\mu$ [cm^{-2} s^{-1}sr^{-1}(GeV/c)^2]
Muon Momentum [GeV/c]


a)
Bugaev et al., 1998
MASS, 1993
Nottingham, 1984
MARS, 1975
Durgapur, 1972
Nottingham, 1968
KGF, 1964
Durham, 1963
$p_\mu^2 F_\mu(p_\mu)$ [$cm^{-2} s^{-1} sr^{-1} (GeV/c)$]
Muon Momentum [GeV/c]
b)
Bugaev et al., 1998
Bugaev et al., 1989
Volkova et al., 1987
EAS-TOP, 1995
Baksan, 1992
Baksan, 1990
KGF, 1990 [X=0]
KGF, 1990 [X=9×10^{-4}]
KGF, 1964
1 - π,K-muons
2 - π,K-muons + PM (QGSM)
3 - π,K-muons + PM (RQPM)
4 - π,K-muons + PM (VFGS)
$p_\mu^2 F_\mu(p_\mu)$ [$cm^{-2} s^{-1} sr^{-1} (GeV/c)$]
Muon Momentum [GeV/c]


LVD
Data converted to standard rock
Data for Gran Sasso rock (x 10^-1)
π,K-muons
π,K-muons + I_μ^ν
π,K-muons + I_μ^ν + PM (RQPM)
π,K-muons + I_μ^ν + PM (VFGS)
I_μ^ν =2.98x10^-13 cm^-2s^-1sr^-1
Muon Intensity (cm^-2s^-1sr^-1)
Depth (km w.e.)
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
2
4
6
8
10
12

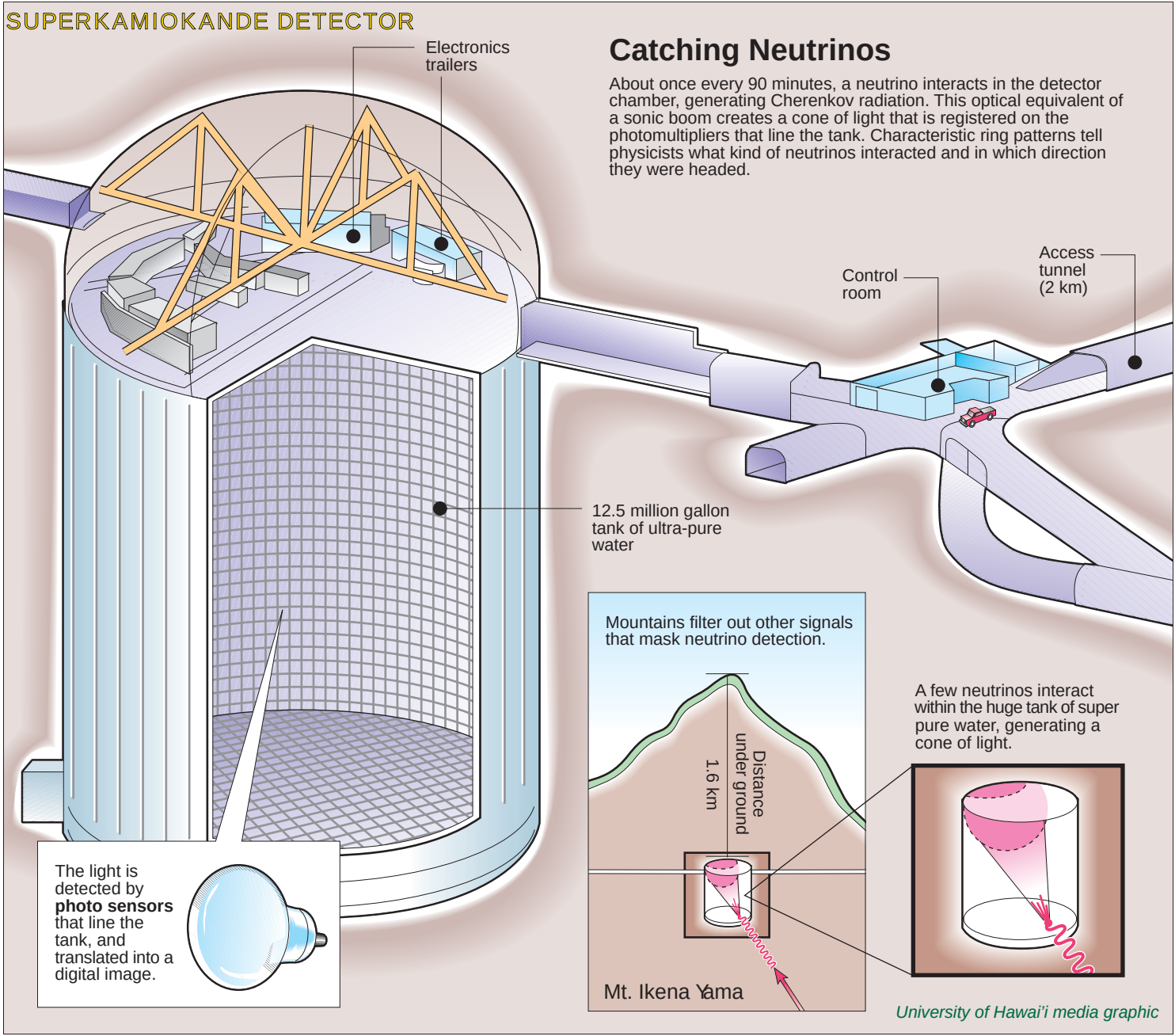

$10^{-38}\,\sigma_{tot}^{CC}/E_\nu$ (cm^2/GeV)
νN
$\bar{\nu}$N
BEBC (1979-1982)
GGM (1979-1981)
CRS (1980-1981)
BNL (1980-1981)
IHEP-ITEP (1979-1983)
SKAT (1979)
FNAL (1977-1983)
IHEP-JINR (1995)
CCFRR (1984) 20-200 GeV average
E_ν (GeV)


Contained events (x1/10)
Kamiokande multi-GeV
Through-going muons
Stopping muons
Muon-neutrino response (Bartol, 11/11/1996)
$E_\nu\ dN_\nu/dE_\nu$
E_ν (GeV)
50
45
40
35
30
25
20
15
10
5
0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

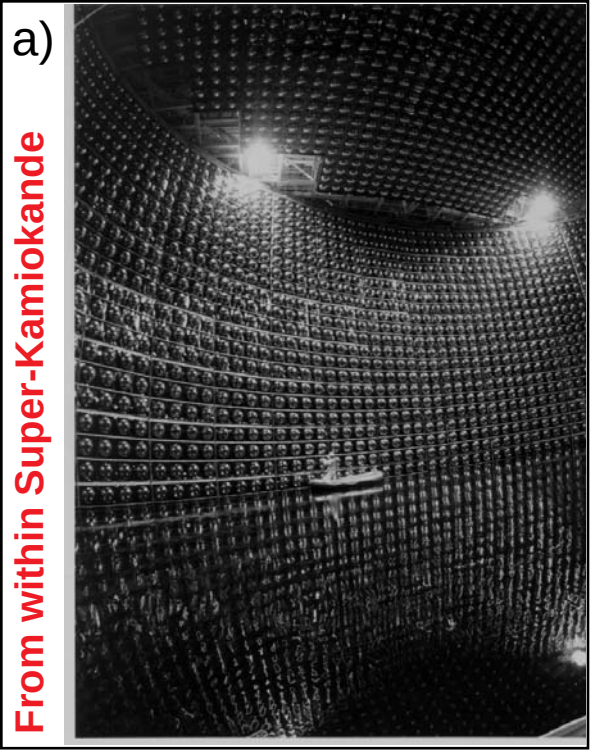
SUPERKAMIOKANDE DETECTOR

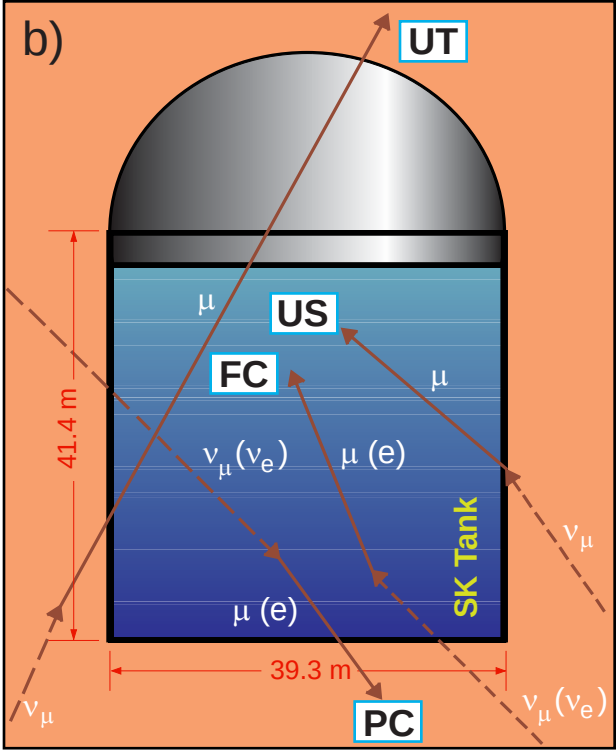
Catching Neutrinos

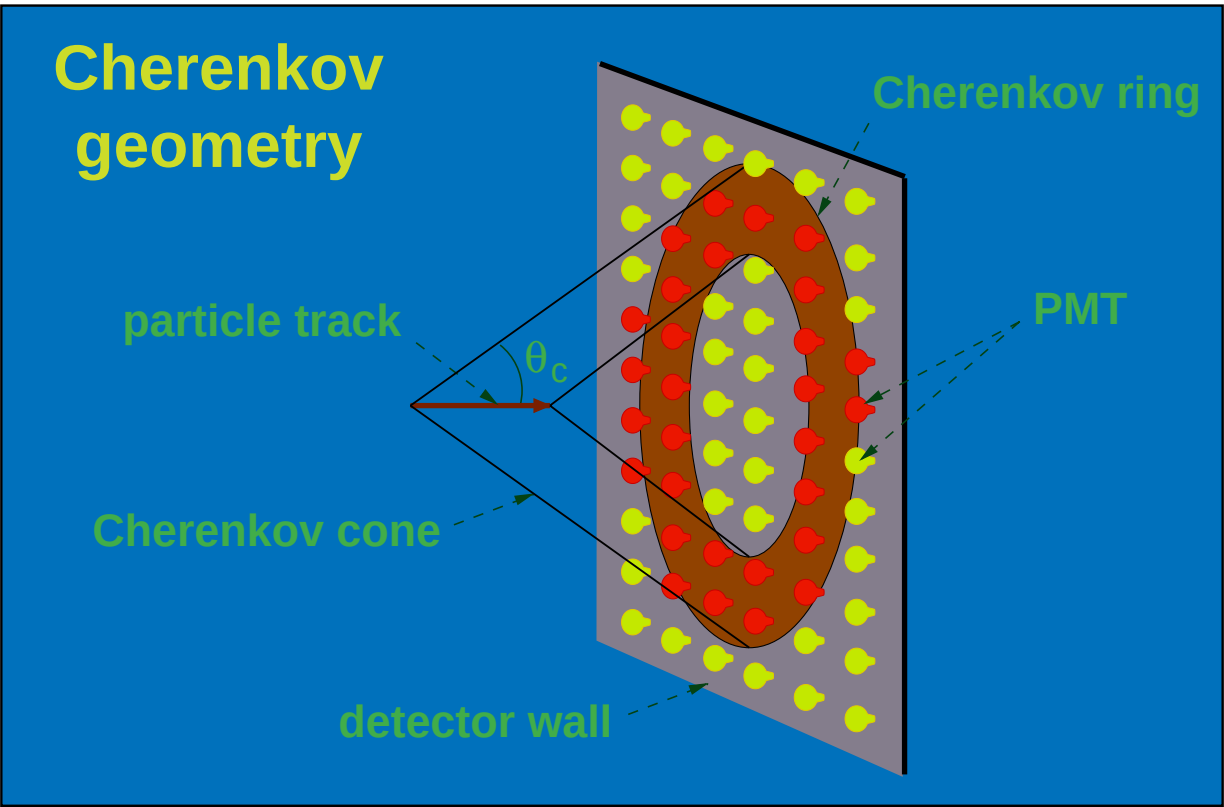
About once every 90 minutes, a neutrino interacts in the detector chamber, generating Cherenkov radiation. This optical equivalent of a sonic boom creates a cone of light that is registered on the photomultipliers that line the tank. Characteristic ring patterns tell physicists what kind of neutrinos interacted and in which direction they were headed.

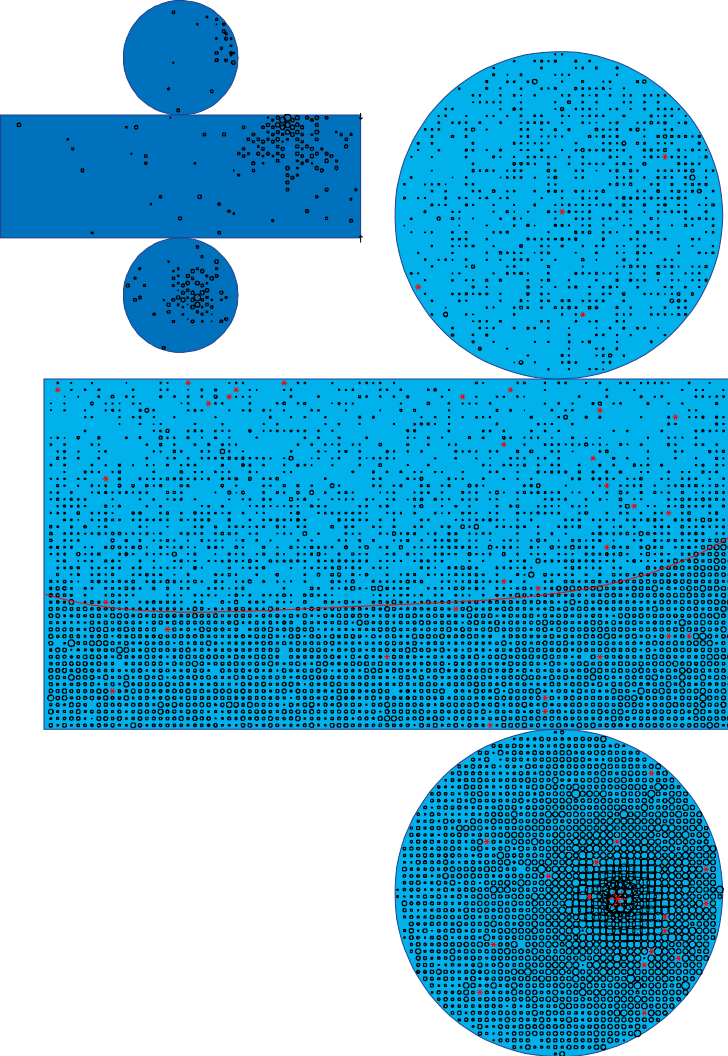


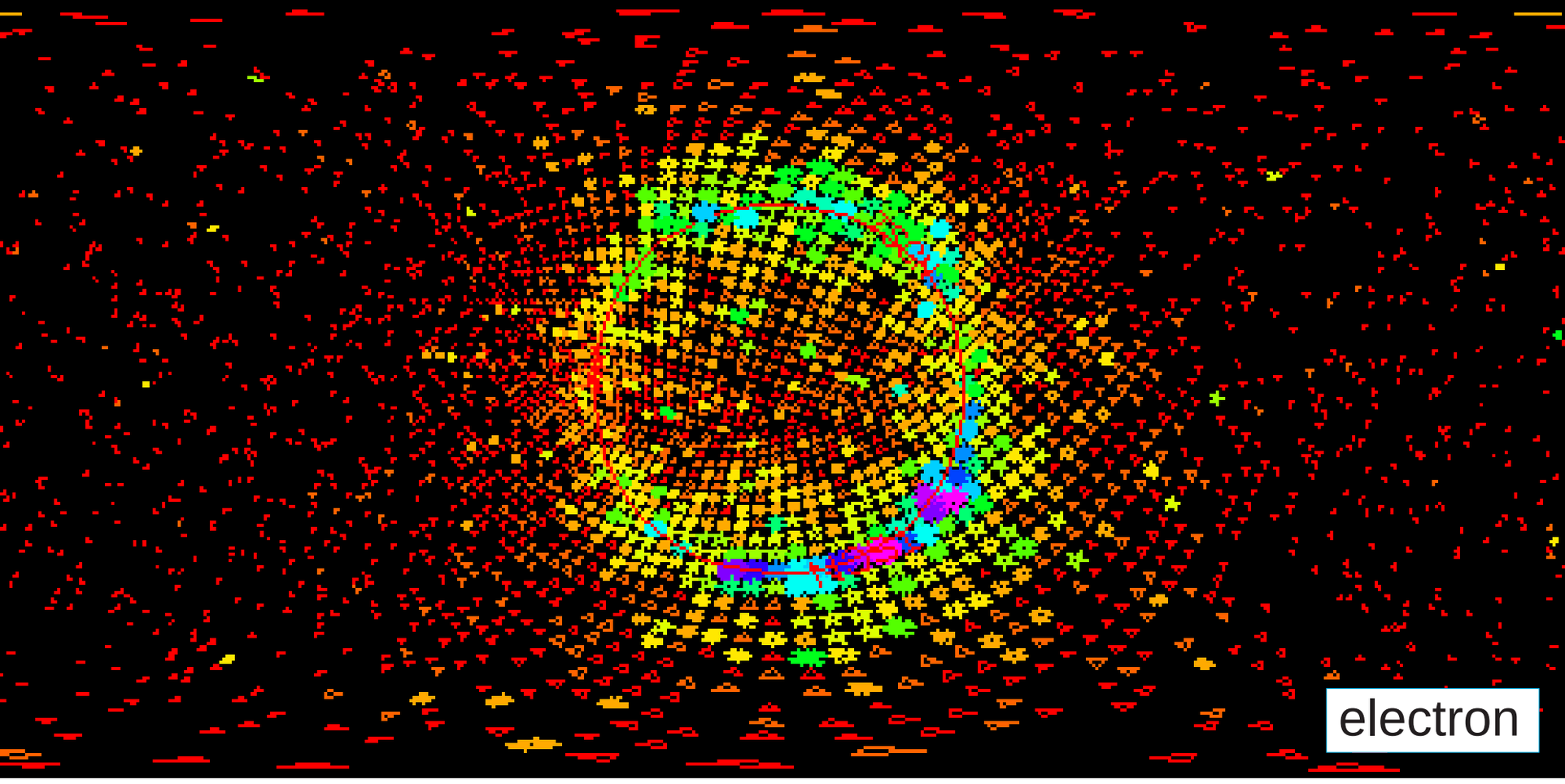
University of Hawai'i media graphic

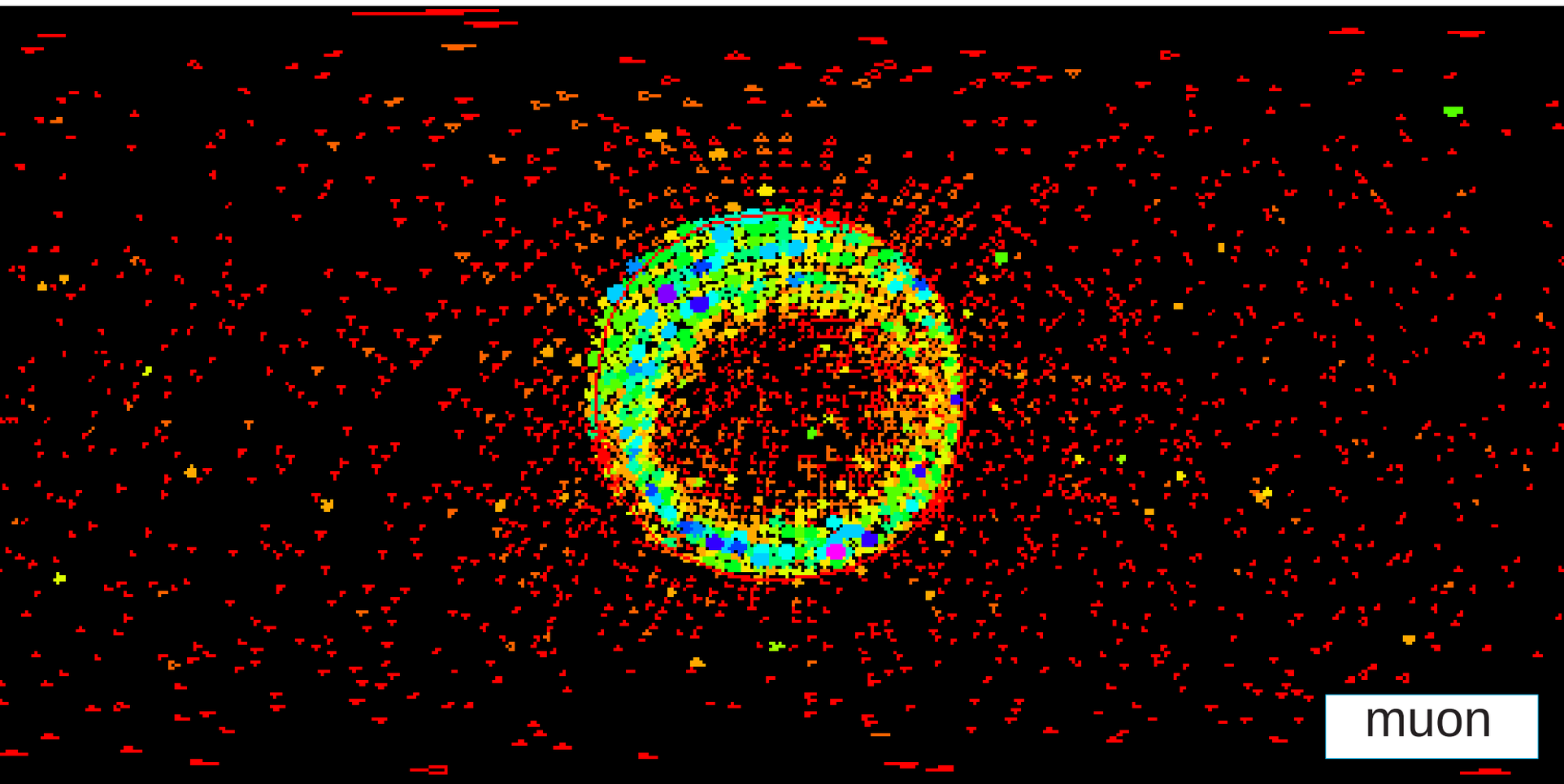

a)
From within Super-Kamiokande

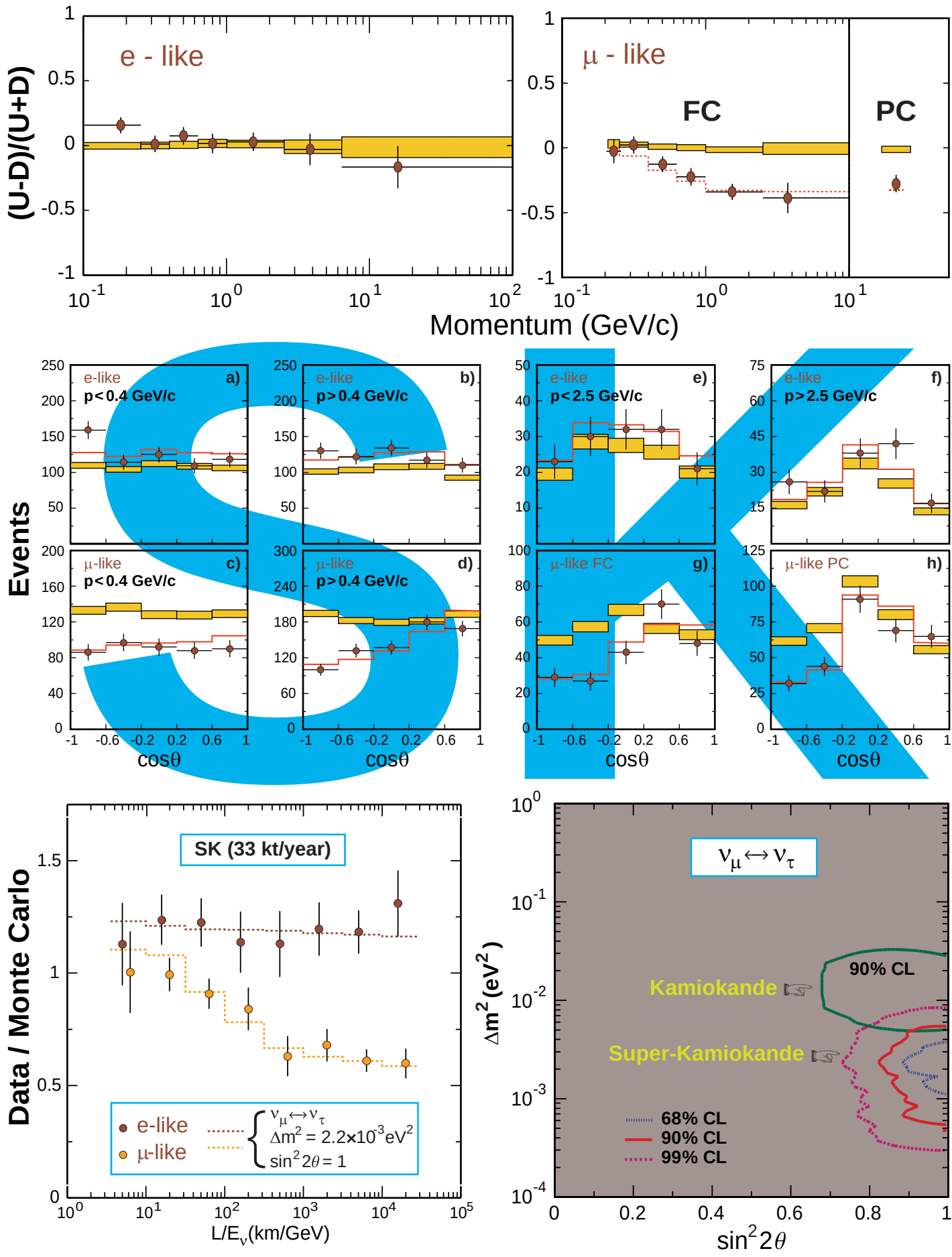

b)
UT
US
FC
PC
μ
μ
μ (e)
μ (e)
$\nu_\mu(\nu_e)$
ν_μ
ν_μ
$\nu_\mu(\nu_e)$
41.4 m
39.3 m
SK Tank

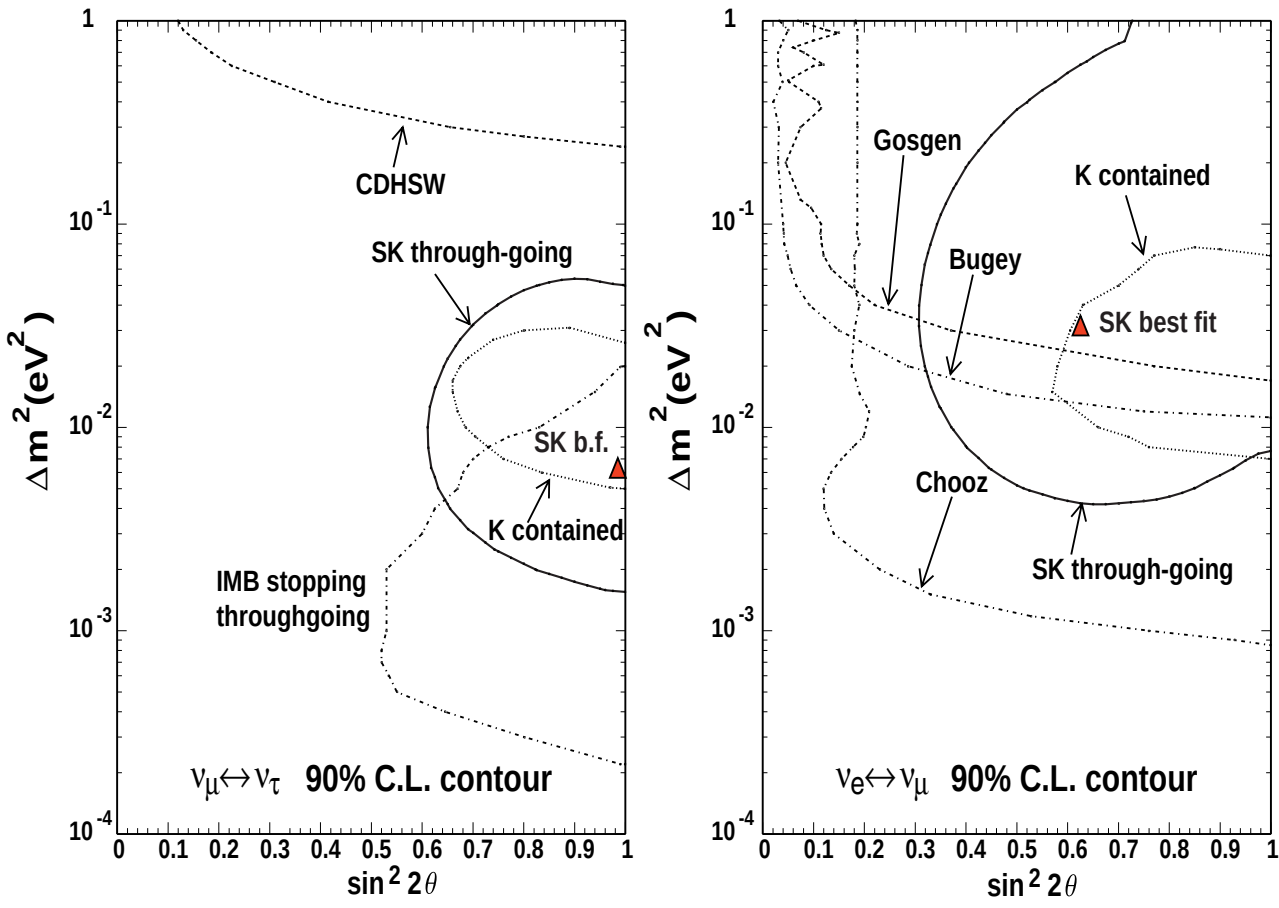

Cherenkov geometry
Cherenkov ring
particle track
θ_c
PMT
Cherenkov cone
detector wall

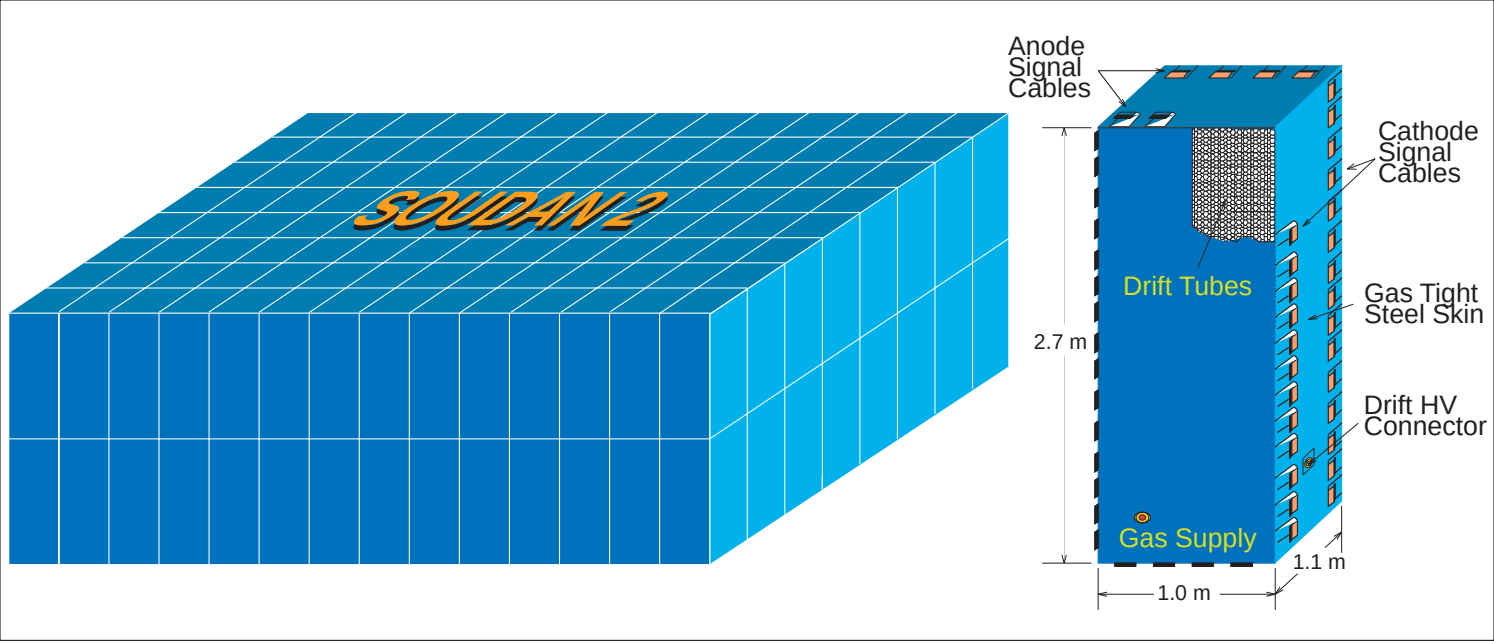

★ Super Kamiokande ★
NUM 33
RUN 1743
EVENT 188
DATE 96-May-31
TIME 21:43:51
TOT PE: 74546.4
MAX PE: 251.8
NMHIT : 8374
ANT-PE: 1719.3
ANT-MX: 43.0
NMHITA: 239
RunMODE:NORMAL
TRG ID :00001011
T diff.:0.467E+05us
: 46.7 ms
FSCC: 0
TDC0: -1129.0
Q thr. : 0.0
BAD ch.: masked
SUB EV : 0/ 0

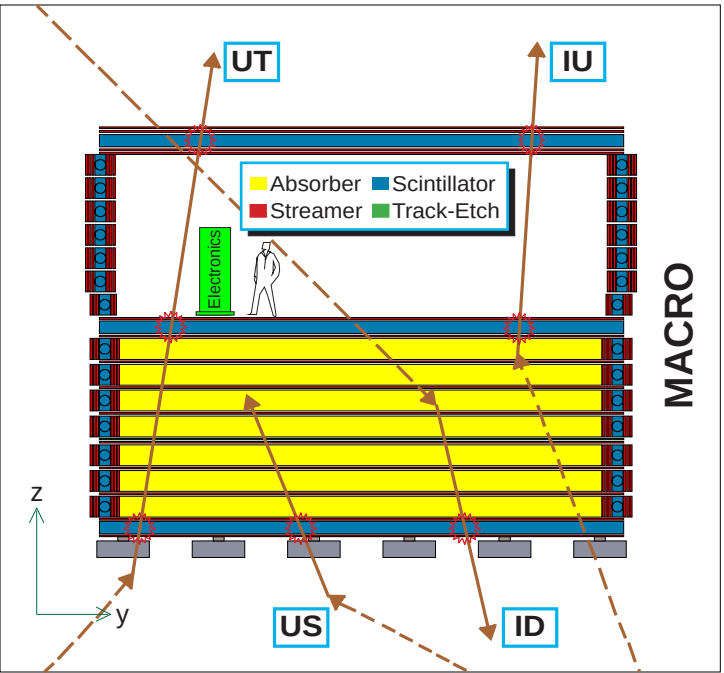

electron

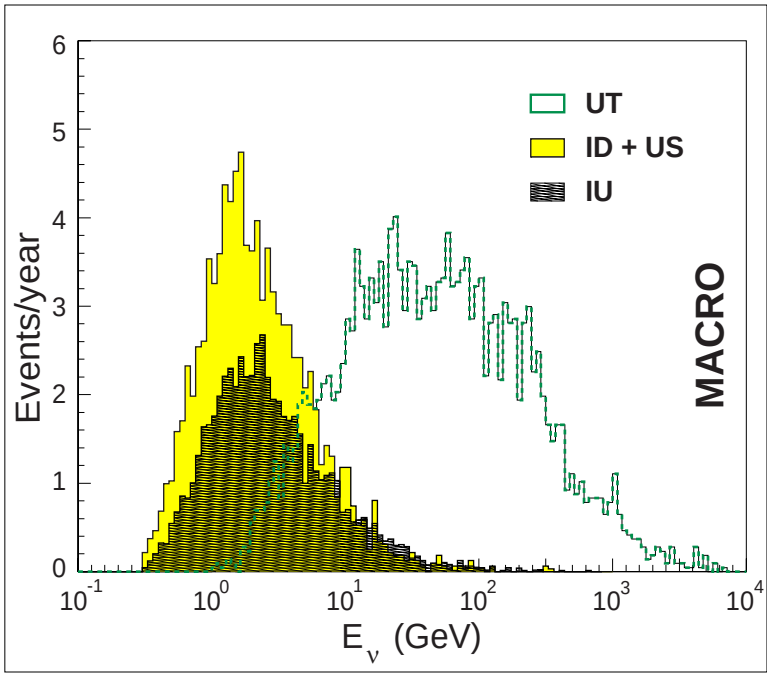

muon

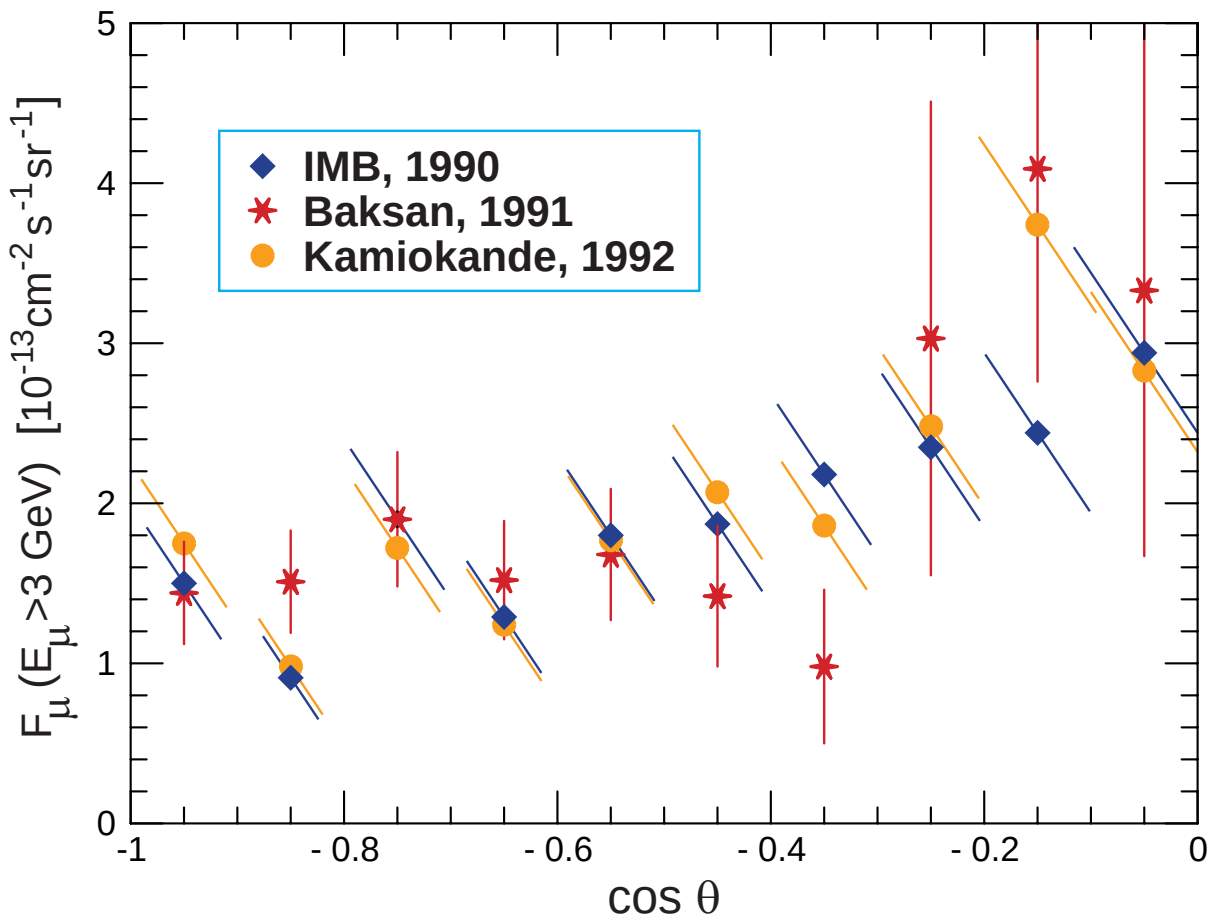

e - like
μ - like
FC
PC
(U-D)/(U+D)
Momentum (GeV/c)
Events
e-like
p<0.4 GeV/c
a)
e-like
p>0.4 GeV/c
b)
μ-like
p<0.4 GeV/c
c)
μ-like
p>0.4 GeV/c
d)
e-like
p<2.5 GeV/c
e)
e-like
p>2.5 GeV/c
f)
μ-like FC
g)
μ-like PC
h)
cosθ
SK (33 kt/year)
Data / Monte Carlo
e-like
μ-like
$\nu_\mu \leftrightarrow \nu_\tau$
$\Delta m^2 = 2.2\times10^{-3}$eV^2
$\sin^2 2\theta = 1$
L/E_ν(km/GeV)
$\nu_\mu \leftrightarrow \nu_\tau$
Kamiokande
Super-Kamiokande
90% CL
68% CL
90% CL
99% CL
Δm^2(eV^2)
$\sin^2 2\theta$


CDHSW
SK through-going
SK b.f.
K contained
IMB stopping
throughgoing
$\nu_\mu \leftrightarrow \nu_\tau$ 90% C.L. contour
$\Delta m^2 (eV^2)$
$\sin^2 2\theta$
Gosgen
K contained
Bugey
SK best fit
Chooz
SK through-going
$\nu_e \leftrightarrow \nu_\mu$ 90% C.L. contour
$\Delta m^2 (eV^2)$
$\sin^2 2\theta$


SOUDAN 2
Anode
Signal
Cables
Cathode
Signal
Cables
Drift Tubes
Gas Tight
Steel Skin
2.7 m
Drift HV
Connector
Gas Supply
1.1 m
1.0 m


UT
IU
Absorber
Scintillator
Streamer
Track-Etch
Electronics
MACRO
z
y
US
ID

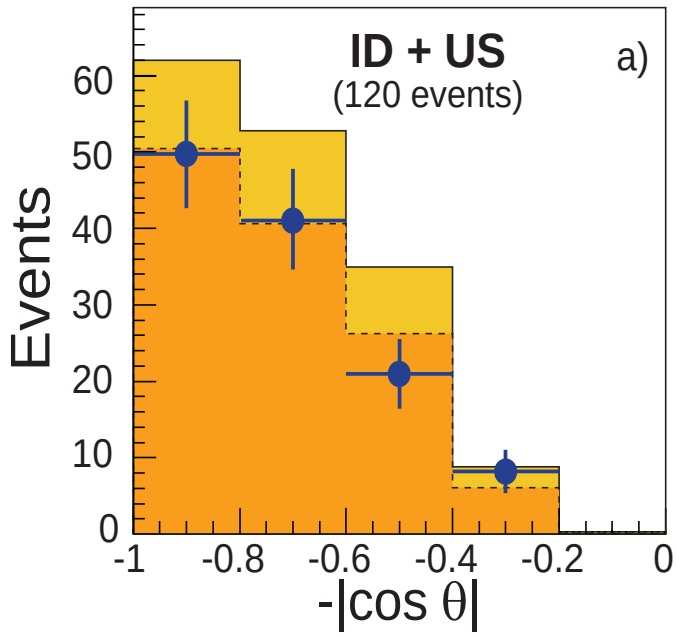

UT
ID + US
IU
Events/year
MACRO
E$_\nu$ (GeV)

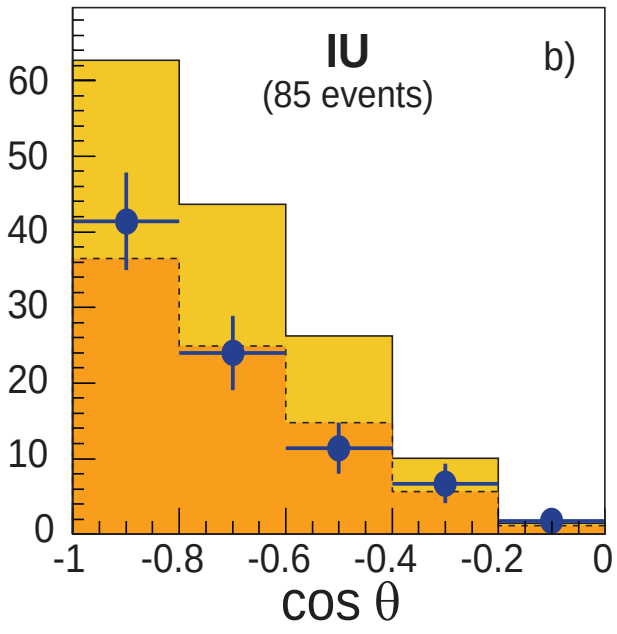


Measured rates

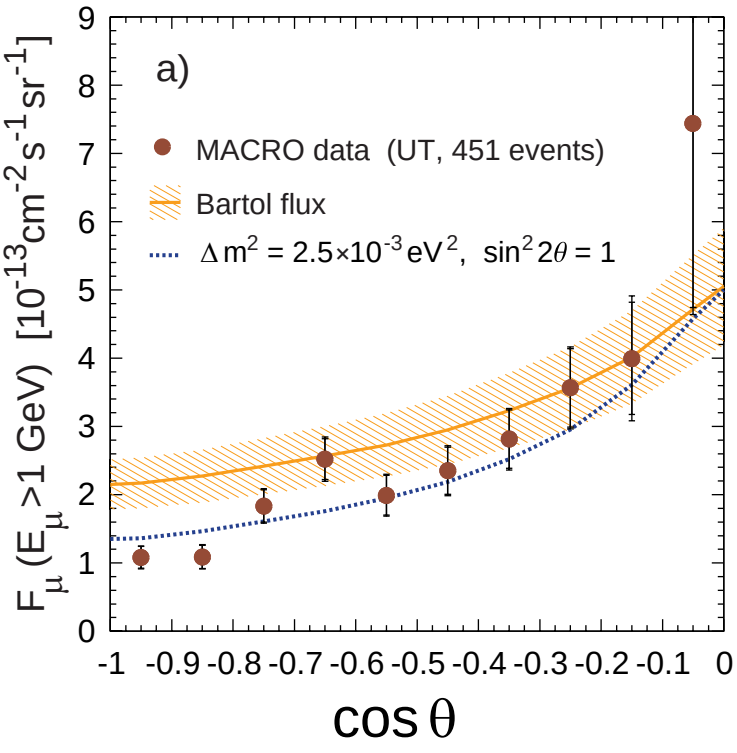
Experiment	Threshold (GeV)	$10^{-13} F_\mu (E_\mu > 3\ \text{GeV})$ $(\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1})$
IMB	2	1.92 – 0.11
Baksan	1	2.08 – 0.14
Kamiokande	3	2.04 – 0.13

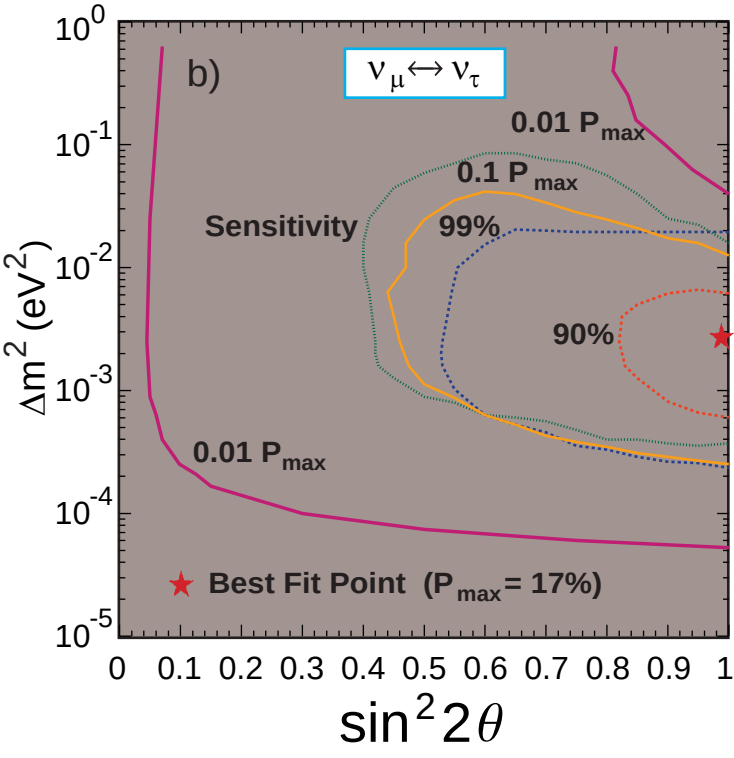
MACRO



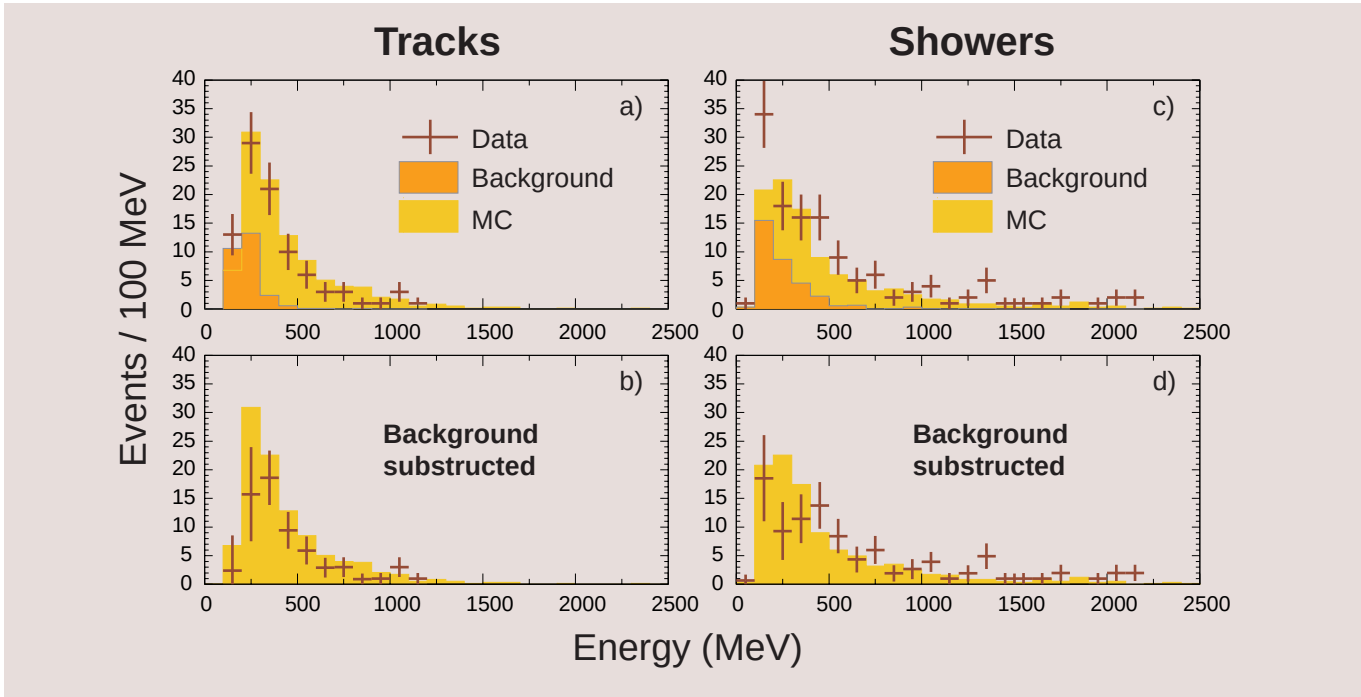


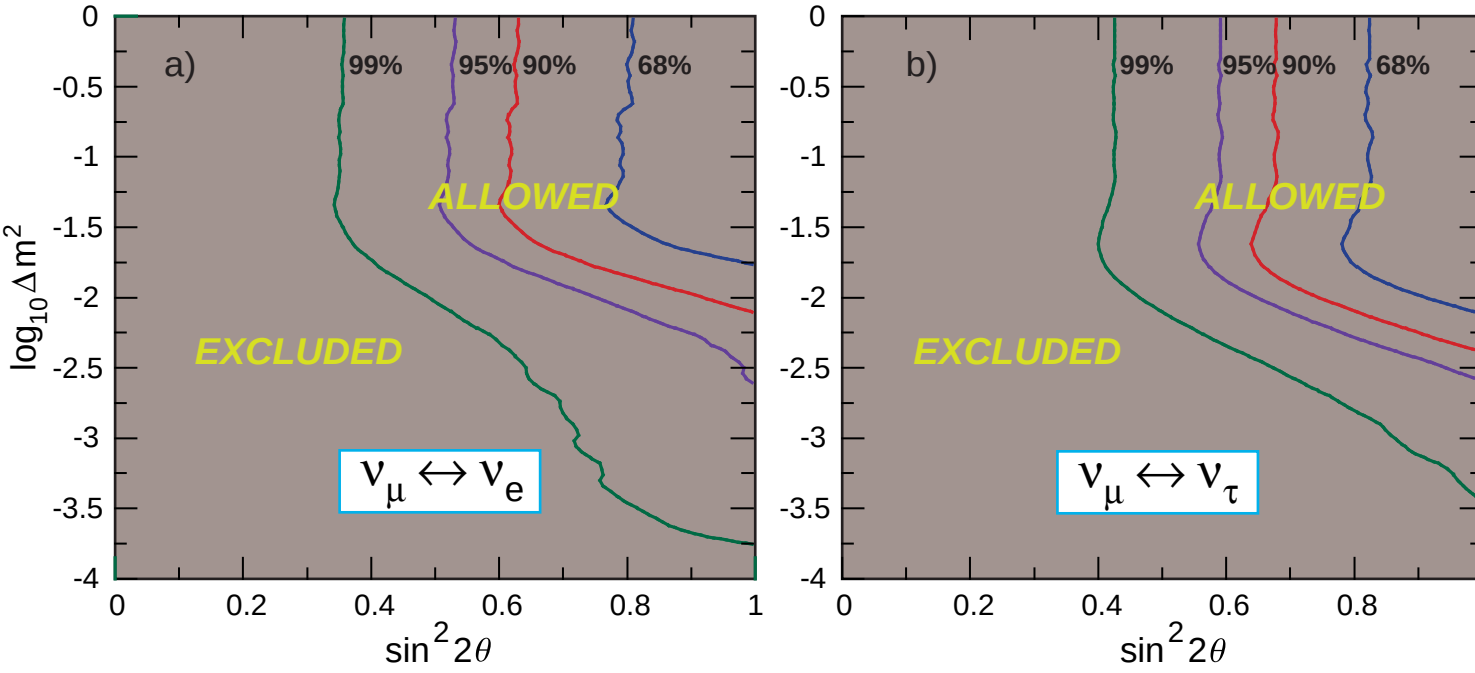
Event Topology	Ratio O/E without ν oscillations	Stat. Error	Syst. Error	Teor. Error	Ratio O/E with ν oscillations
ID+US	**0.75**	**0.07**	**0.08**	**0.19**	**0.98**
IU	**0.59**	**0.06**	**0.06**	**0.15**	**1.02**
UT	**0.74**	**0.036**	**0.046**	**0.13**	**1.05**

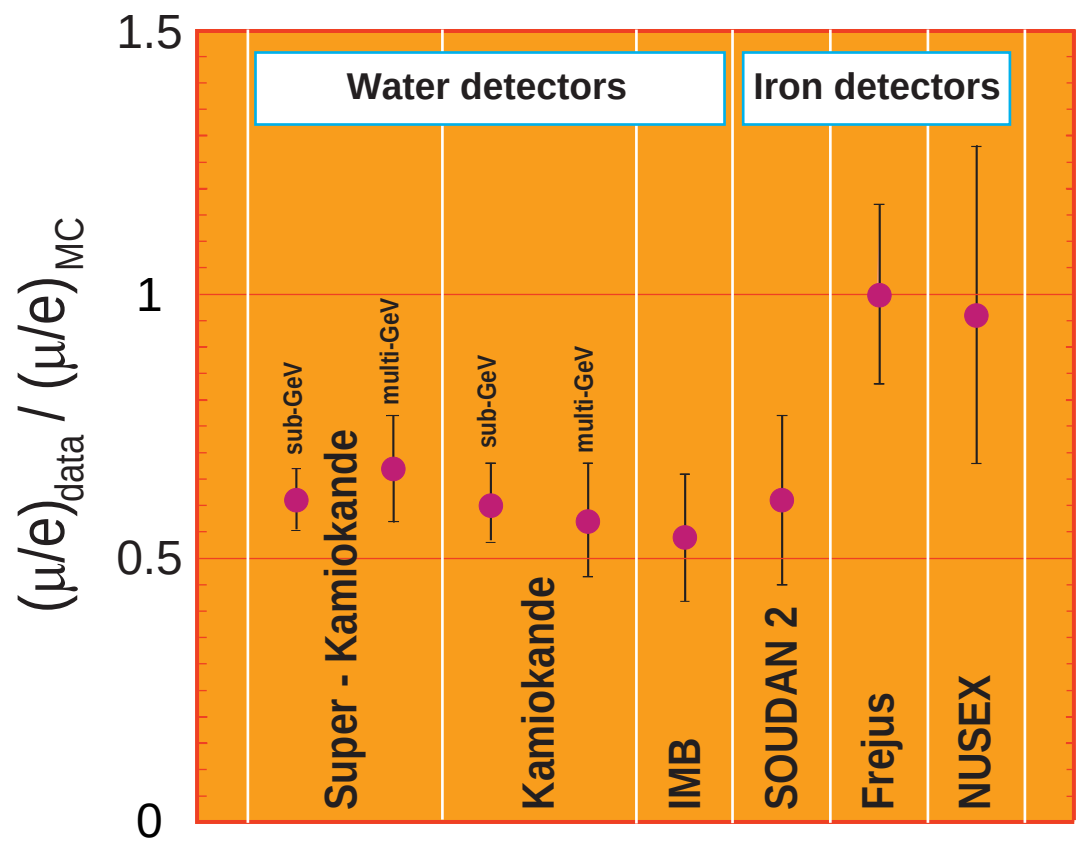


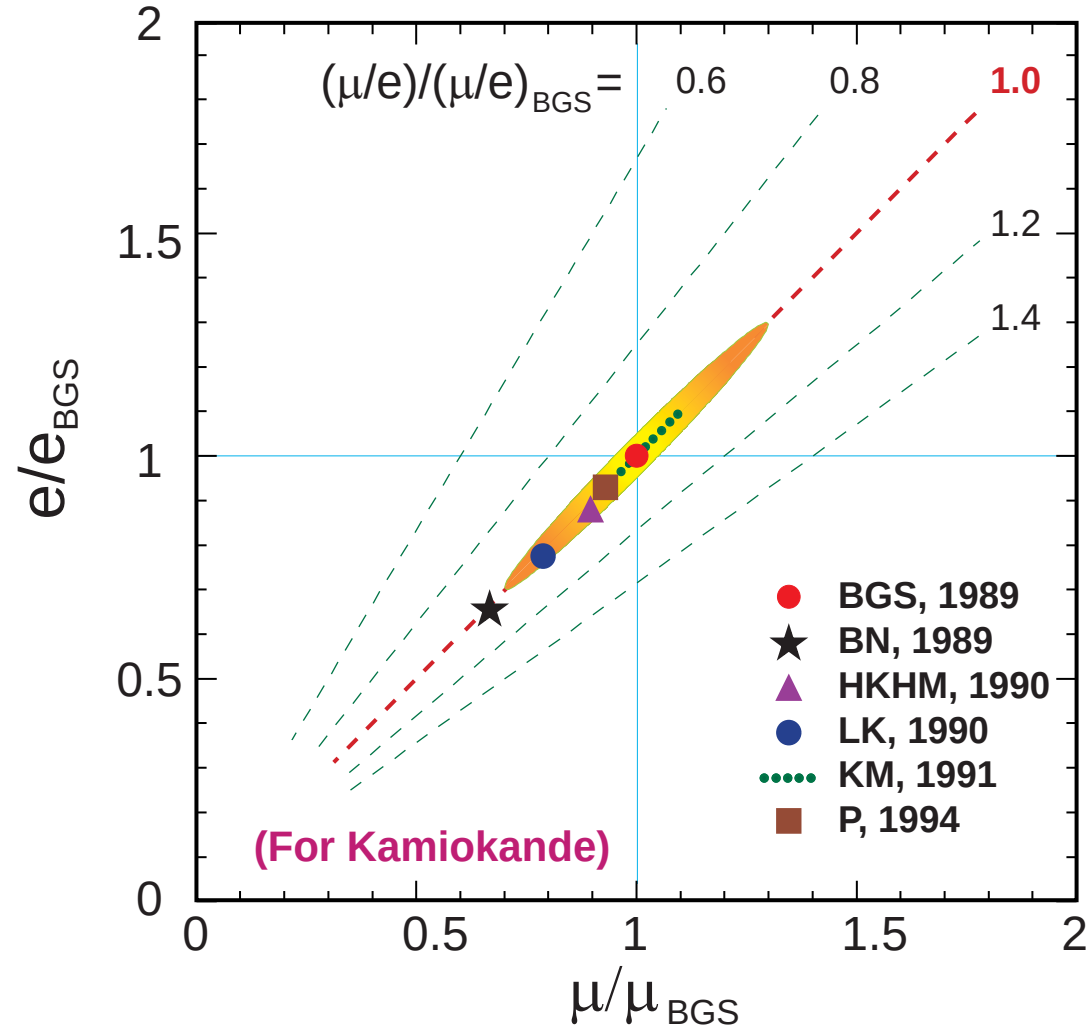


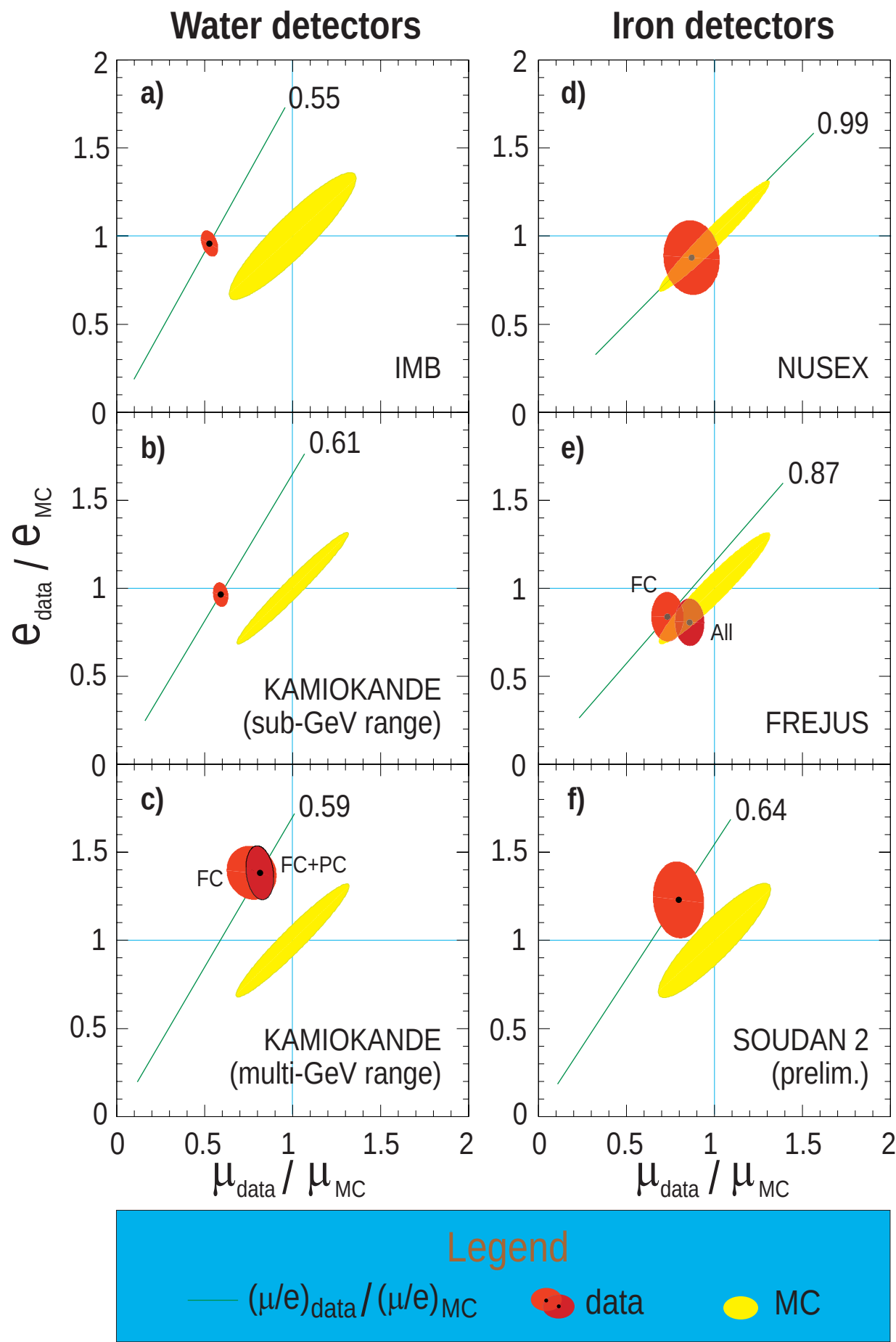
SOUDAN 2


Tracks
Showers
a)
b)
c)
d)
Data
Background
MC
Background substructed
Events / 100 MeV
Energy (MeV)


a)
b)
99%
95%
90%
68%
ALLOWED
EXCLUDED
$\nu_\mu \leftrightarrow \nu_e$
$\nu_\mu \leftrightarrow \nu_\tau$
$\log_{10}\Delta m^2$
$\sin^2 2\theta$


Water detectors
Iron detectors
$(\mu/e)_{data} / (\mu/e)_{MC}$
1.5
1
0.5
0
sub-GeV
multi-GeV
sub-GeV
multi-GeV
Super - Kamiokande
Kamiokande
IMB
SOUDAN 2
Frejus
NUSEX


$(\mu/e)/(\mu/e)_{BGS}$ =
0.6
0.8
1.0
1.2
1.4
e/e_{BGS}
2
1.5
1
0.5
0
0
0.5
1
1.5
2
μ/μ_{BGS}
BGS, 1989
BN, 1989
HKHM, 1990
LK, 1990
KM, 1991
P, 1994
(For Kamiokande)


Water detectors
Iron detectors
a)
0.55
IMB
b)
0.61
KAMIOKANDE
(sub-GeV range)
c)
0.59
FC
FC+PC
KAMIOKANDE
(multi-GeV range)
d)
0.99
NUSEX
e)
0.87
FC
All
FREJUS
f)
0.64
SOUDAN 2
(prelim.)
e_data / e_MC
μ_data / μ_MC
Legend
(μ/e)_data / (μ/e)_MC
data
MC