Study of the Interaction Model Using Atmospheric muons for the calculation of Atmospheric Neutrino Flux

M.Honda

14Th Blois Workphops on
Elastic and Diffractive Scattering

Gaisser Formula for the illustration (by T.K.Gaisser at Takayama, 1998)

$$\Phi_\nu = \Phi_{primary} \otimes R_{cut} \otimes Y_\nu$$

$$\Phi_\mu = \Phi_{primary} \otimes R_{cut} \otimes Y_\mu$$

Where

$\Phi_{primary}$: Cosmic Ray Flux

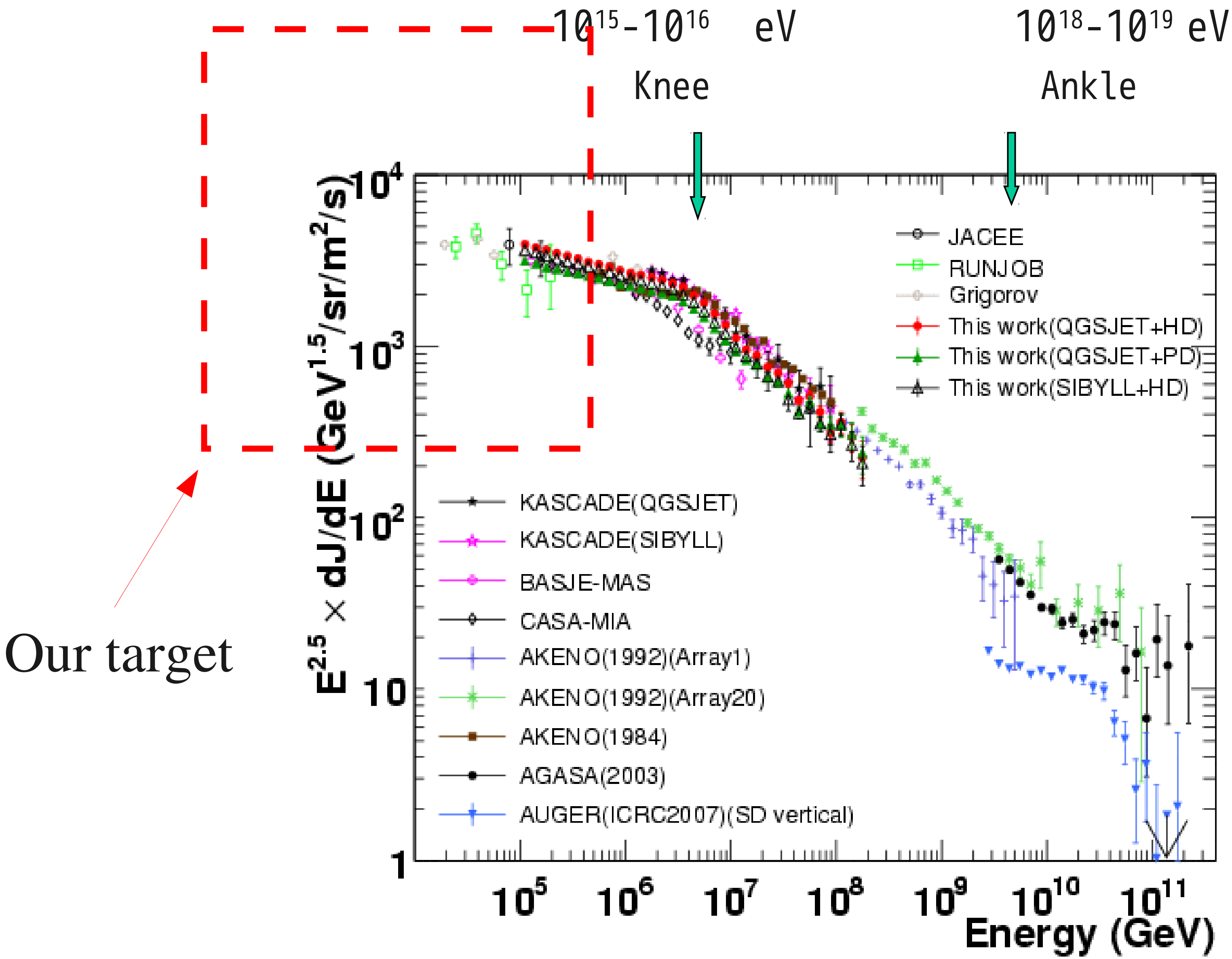
$R_{cut} = R_{cut}(R_{cr}, latt., long., \theta, \phi)$: Geomagnetic field

$Y_\nu = Yield_\nu(h, \theta)$: Hadronic Interaction Model, Air Profile, and meson-muon decay

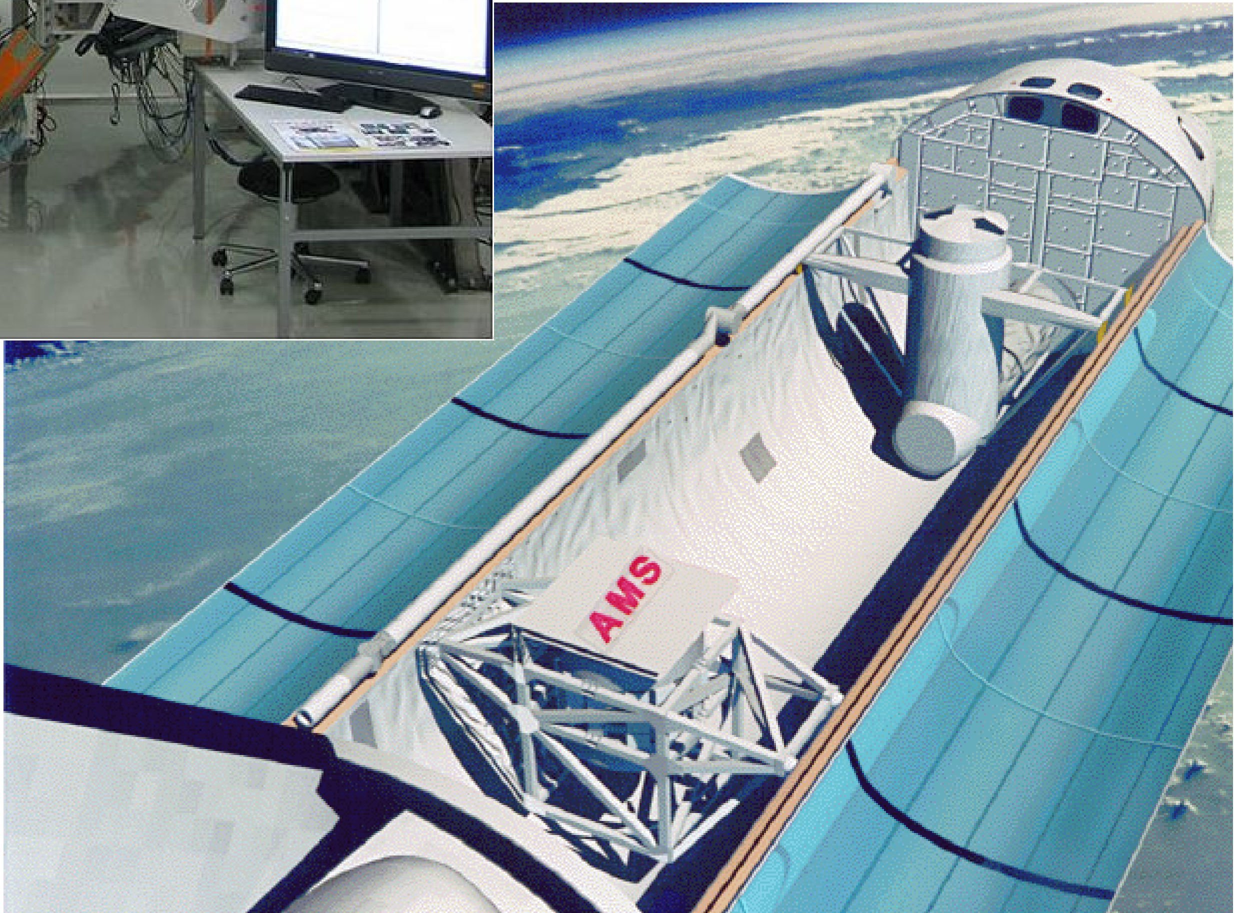
$Y_\mu = Yield_\mu(h, \theta)$: Hadronic Interaction Model, Air Profile, and meson decay

From the talk of M.Shibata, this conf.

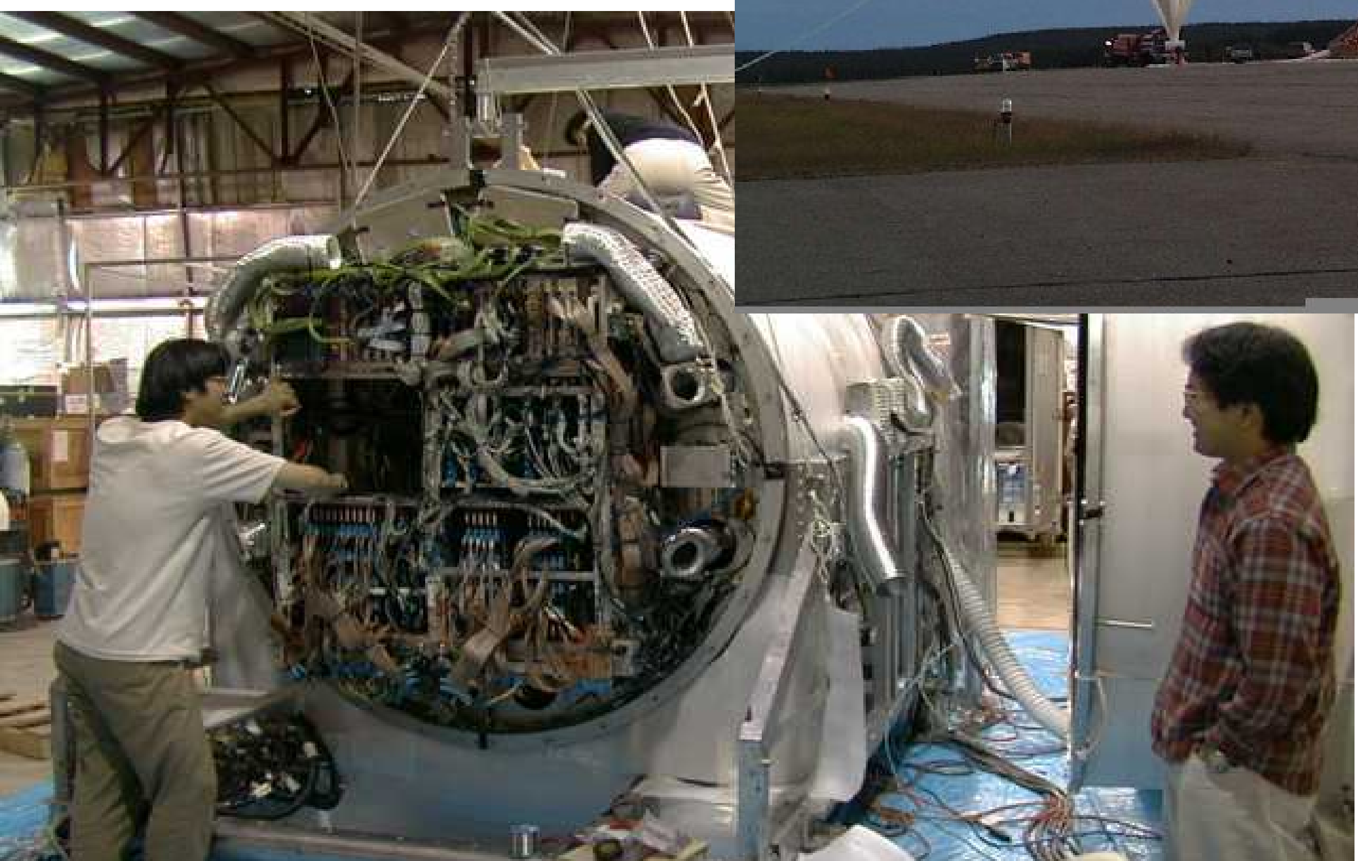
CR spectrum in wide range



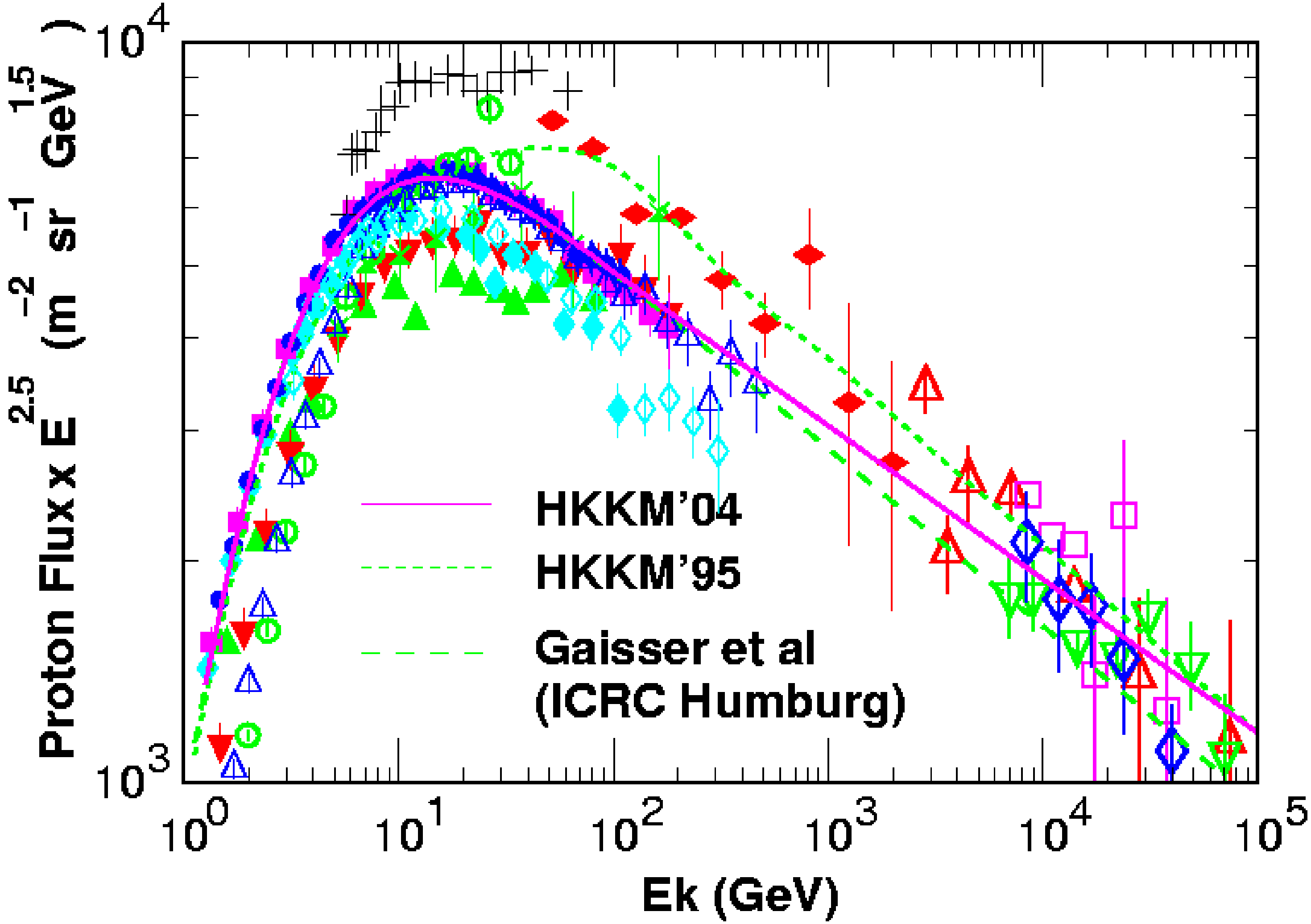
AMS-I



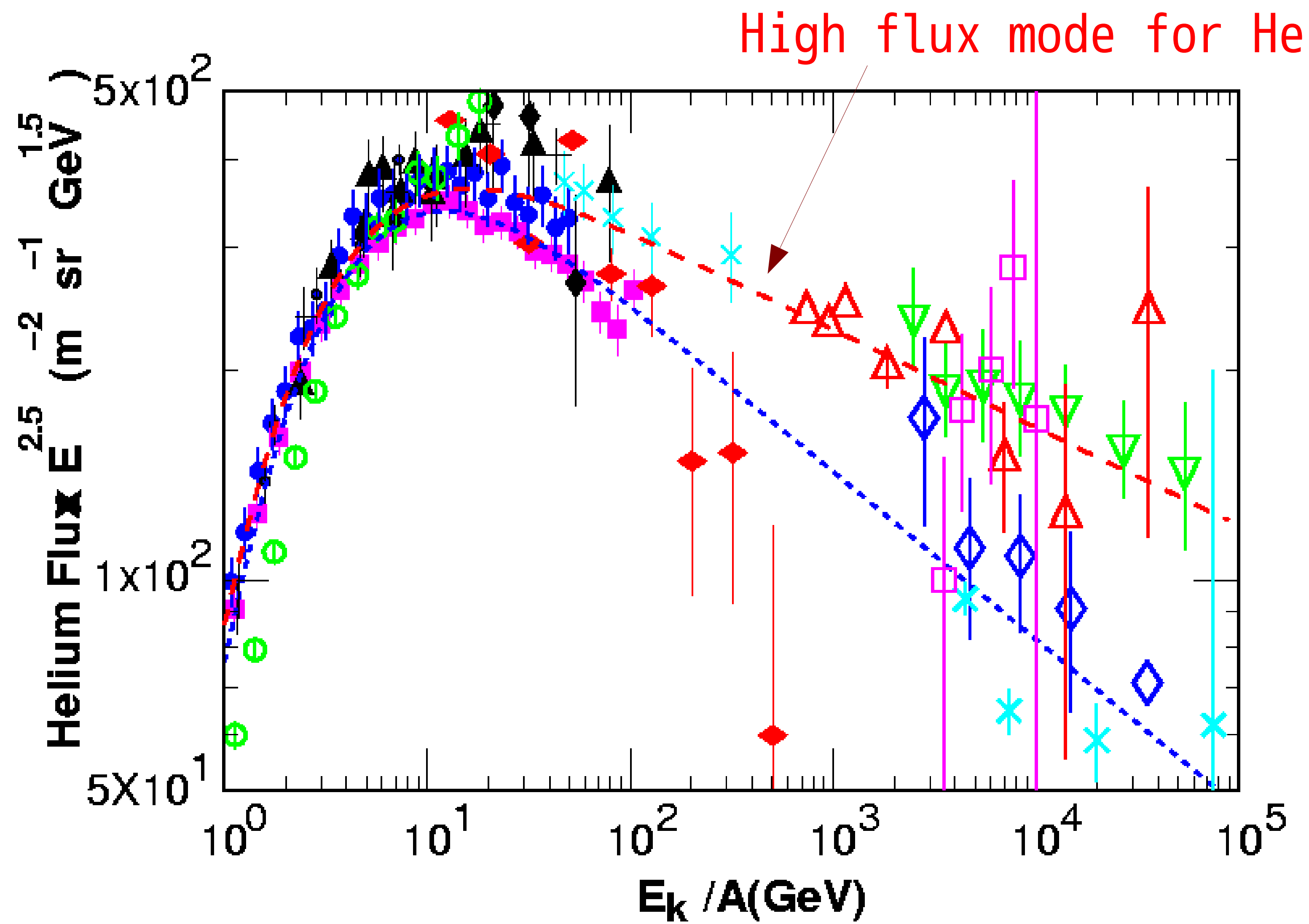
BESS



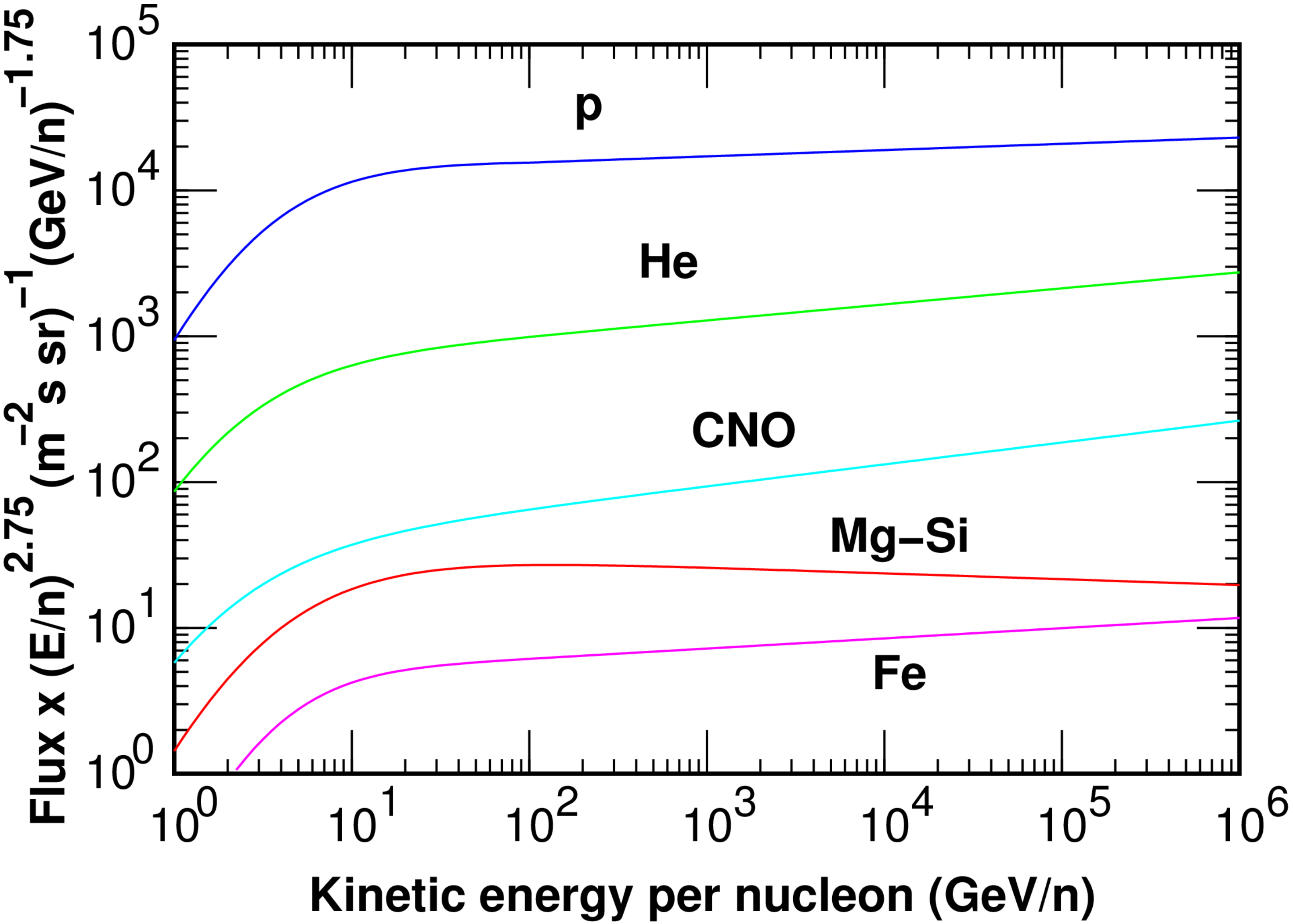
Flux Model for Cosmic Ray Protons



Primary flux model for Cosmic Ray Heliums



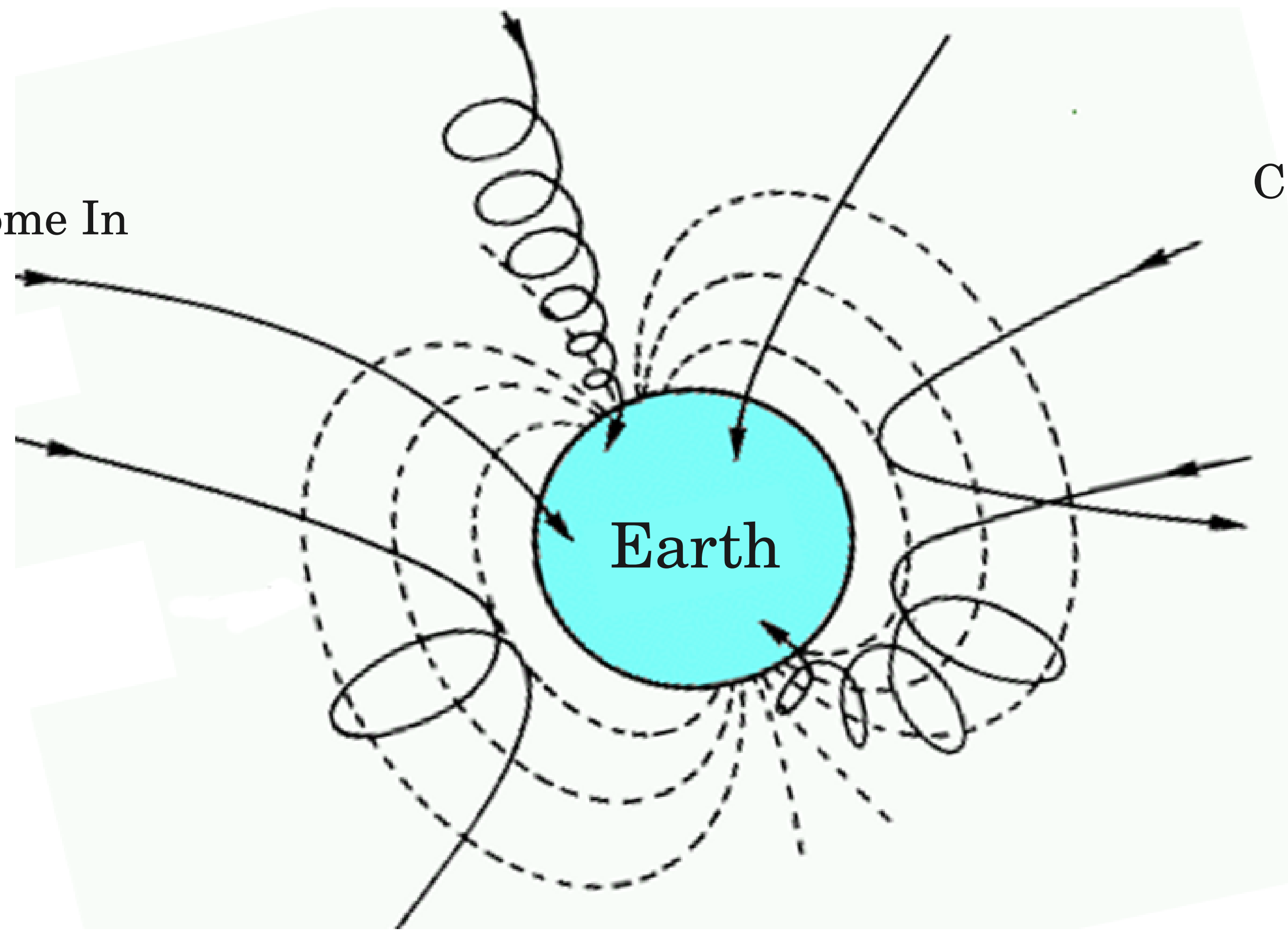
Flux model for all chemical composition



Ref: PRD70 043006 (2004)

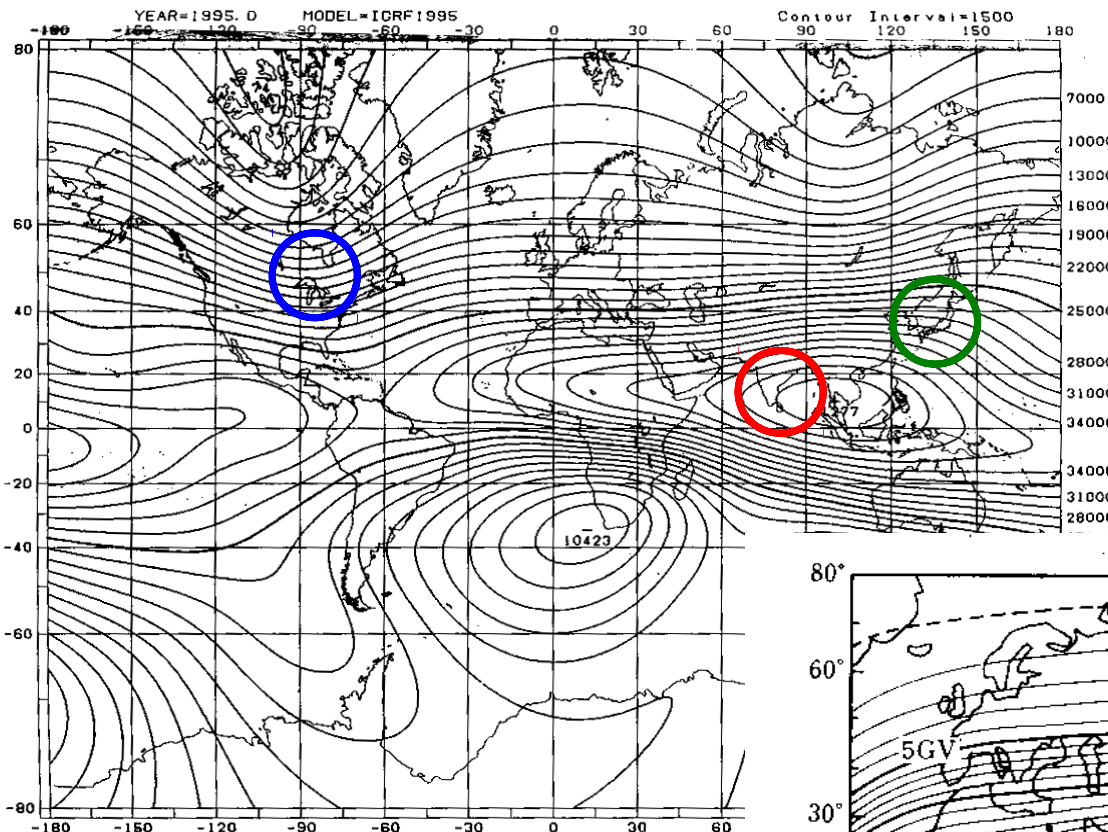
Rigidity Cutoff and Geomagnetic Field (cartoon)

i



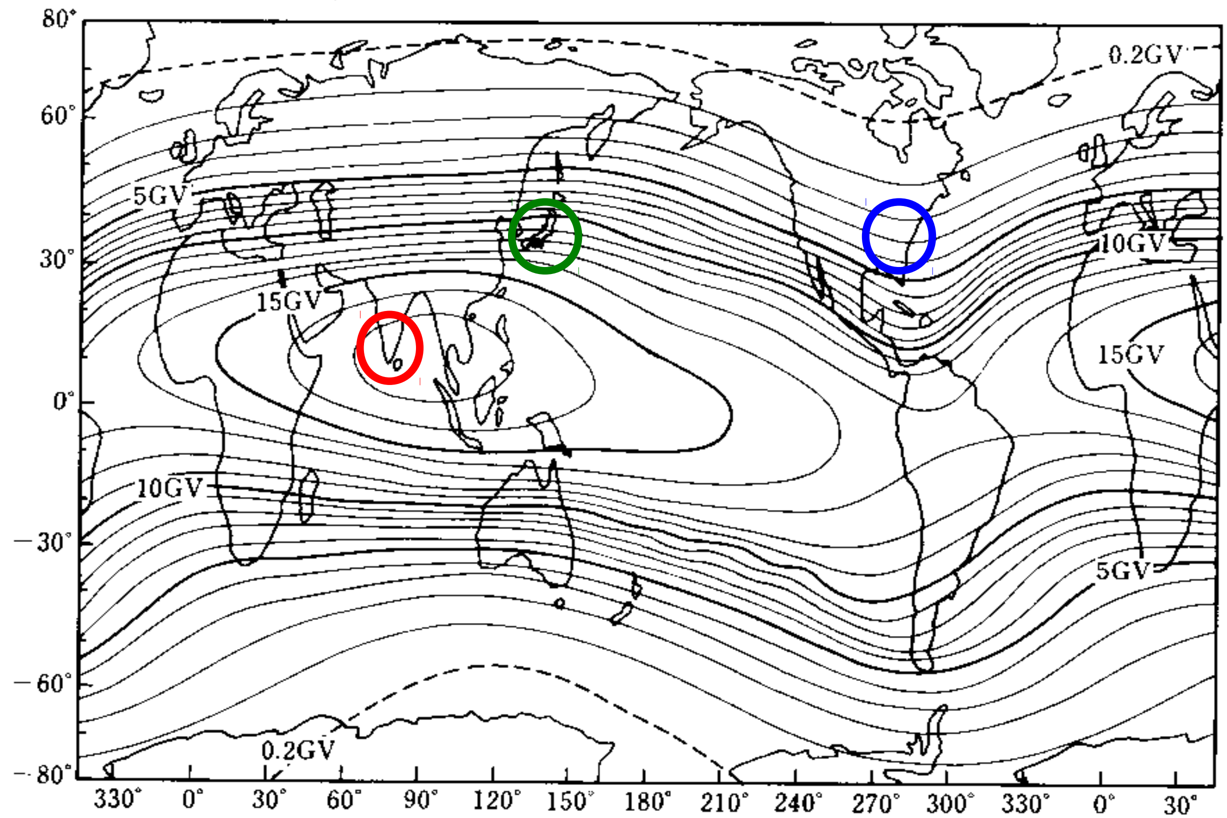
Rigidity Cut Off

Rigity Cutoff and Geomagnetic Field

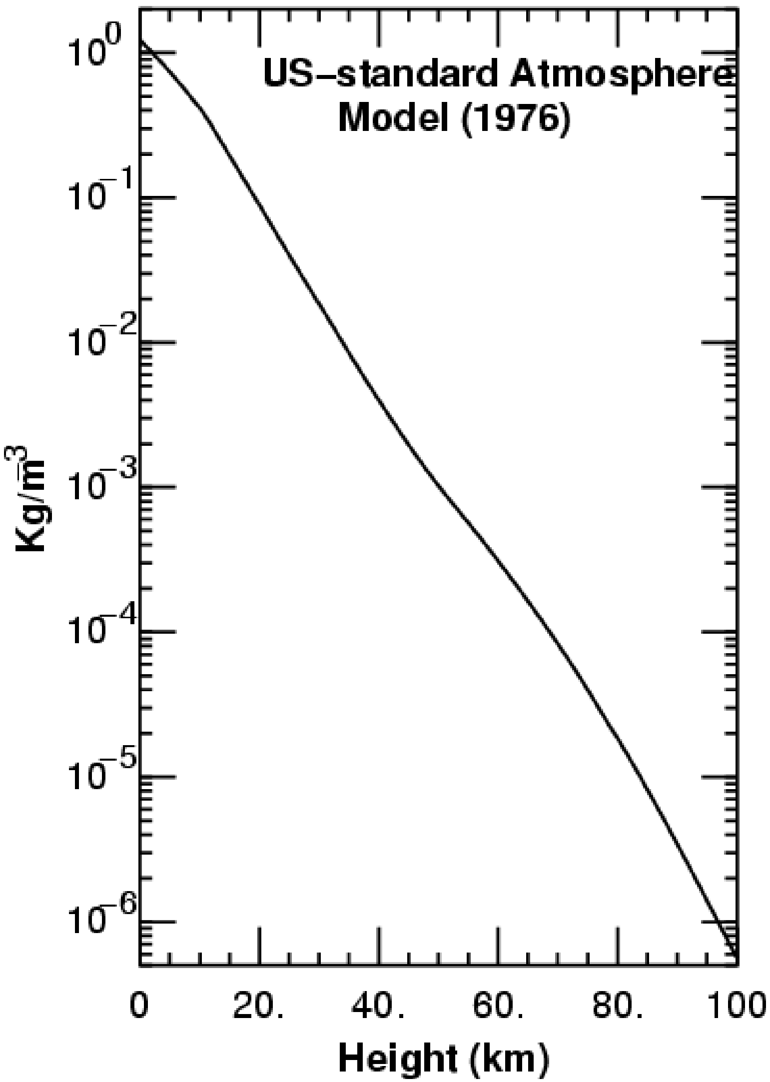


Horizontal component of geomagnetic field (IGRF2000?)

Rigidity Cutoff for vertical Cosmic rays

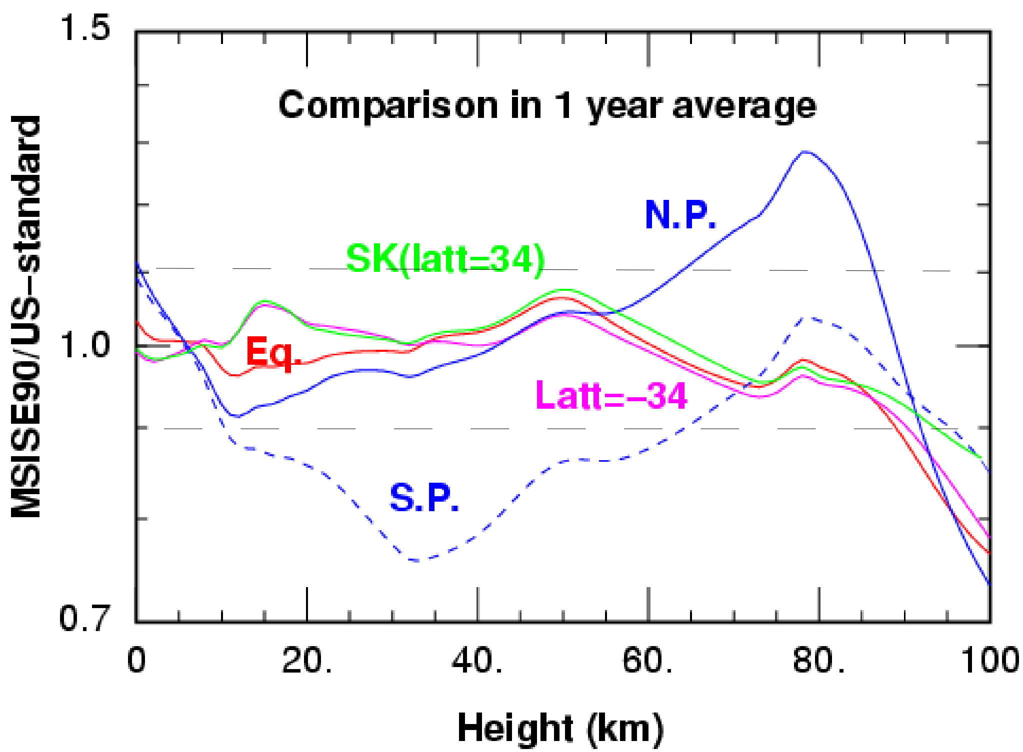


Model for Aiar Profile



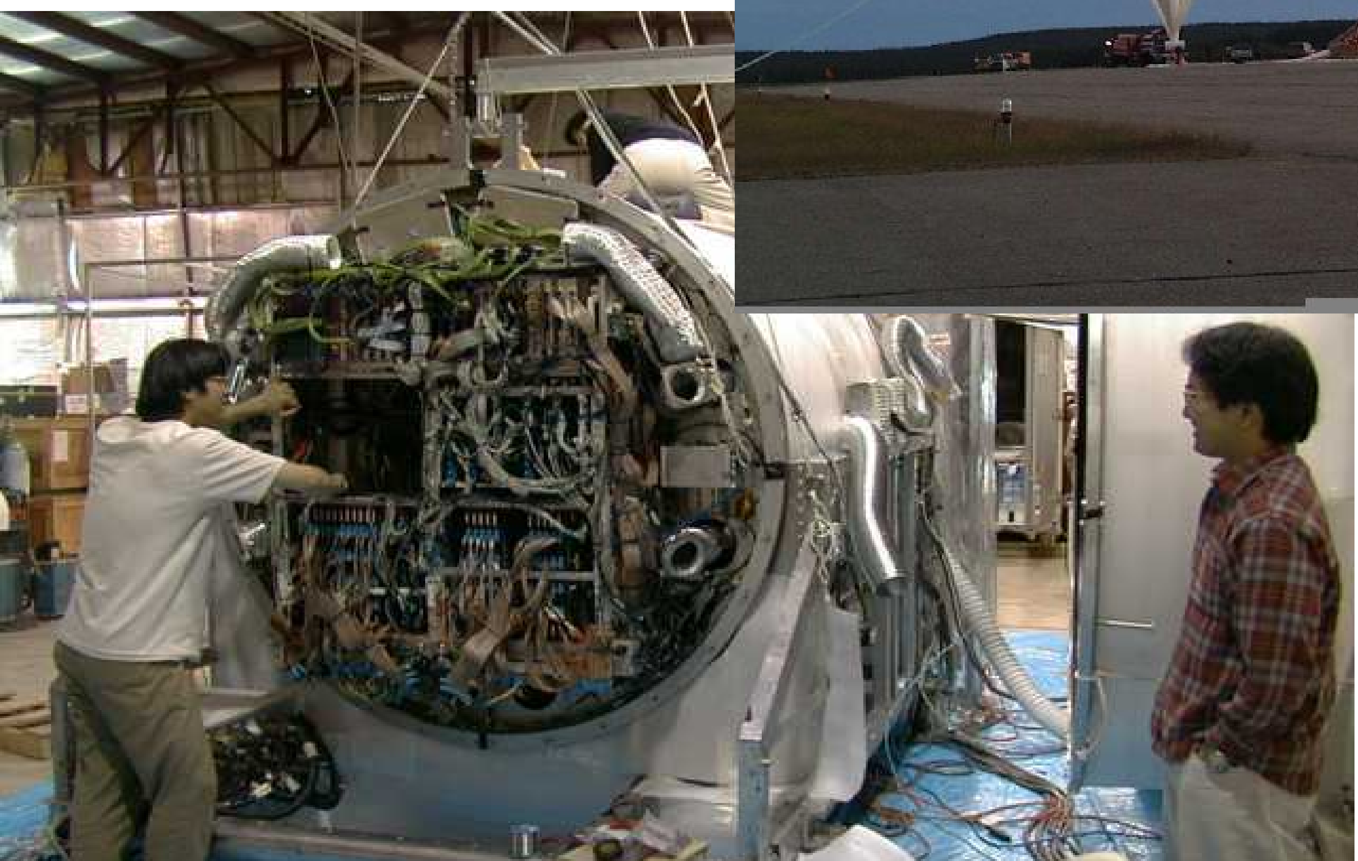
New air profile models. also exit

Air density comparison with MSISE90



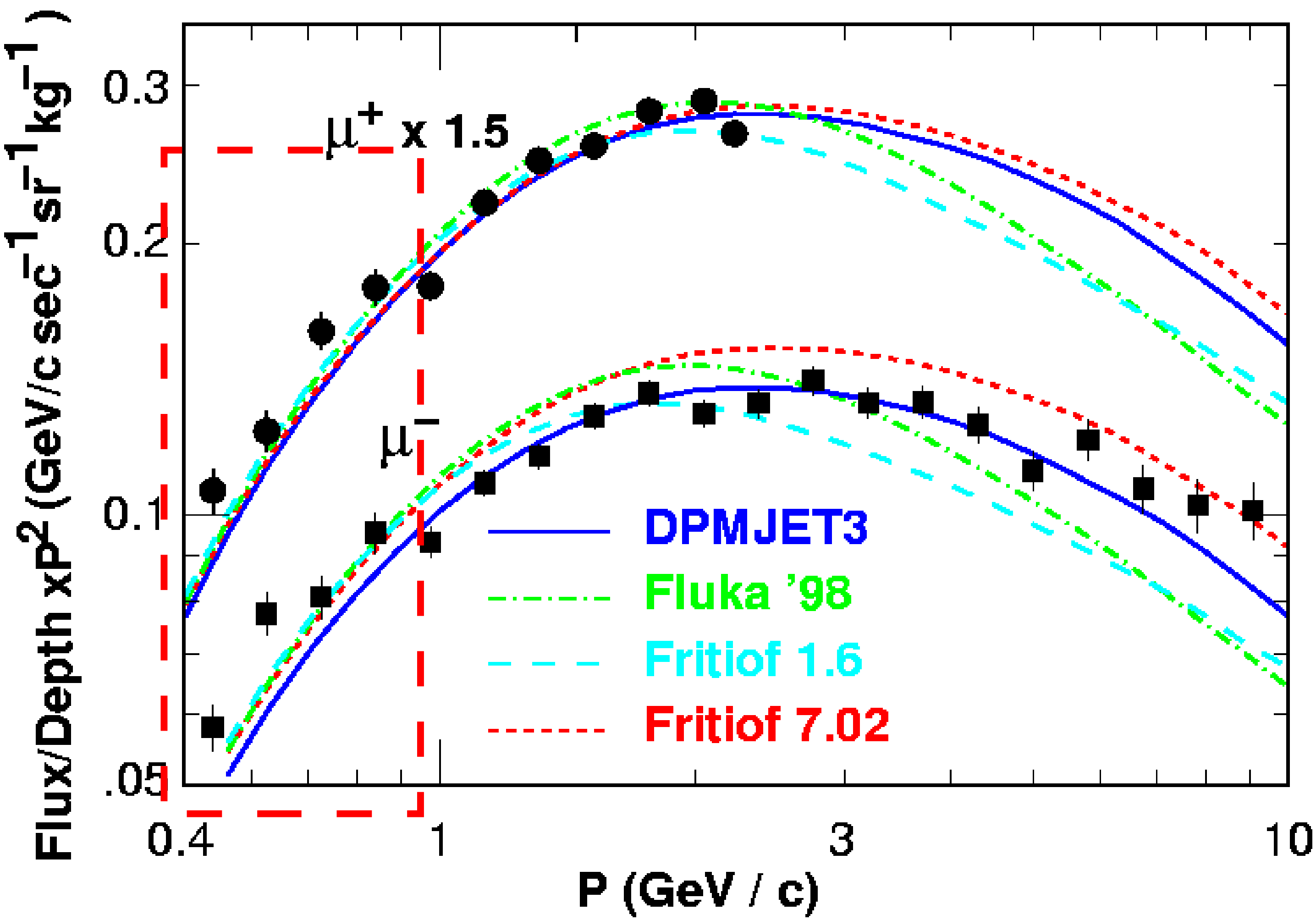
US-starndard may be used as the global approximation of the atmosphere

BESS also observed Atmospheric muons at Balloon altitude and Ground.



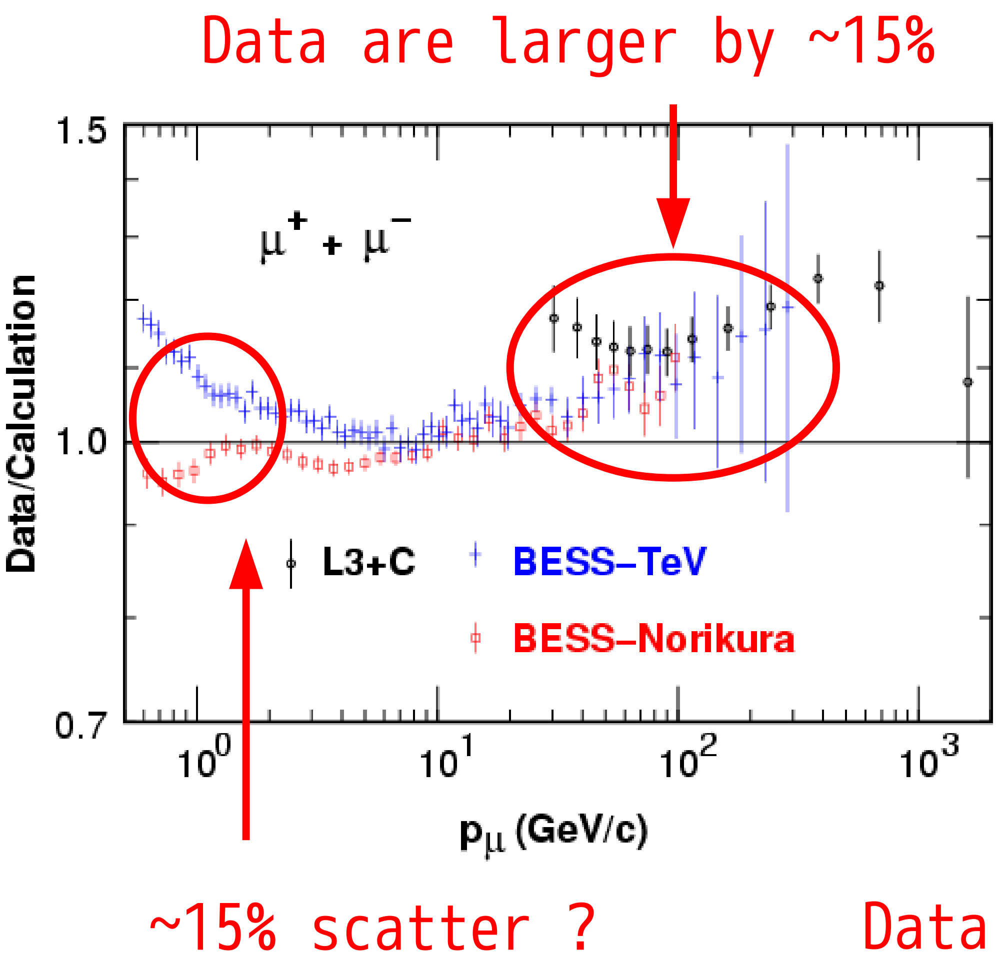
Selection of Interaction Model

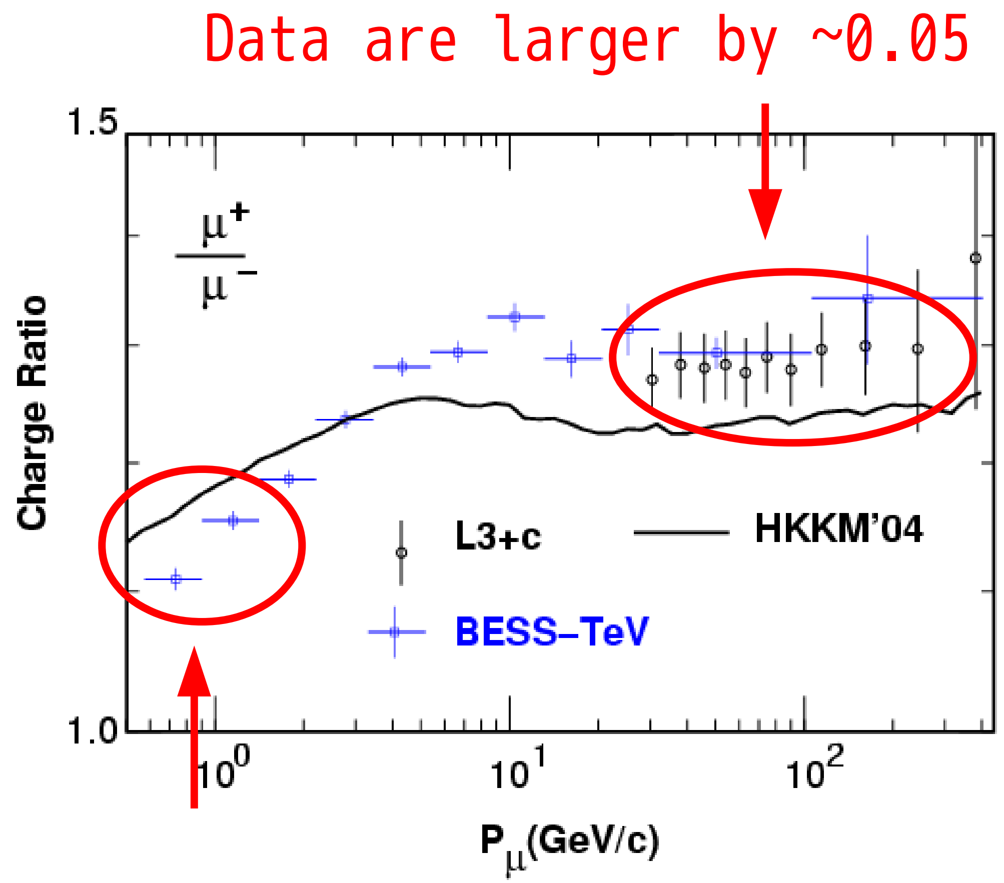
The muon flux at Balloon Altitude is good test bench of the Interaction model. DPMJET-III is good !



Seems not so good at low energy

However, when compare with high precision muon measurements

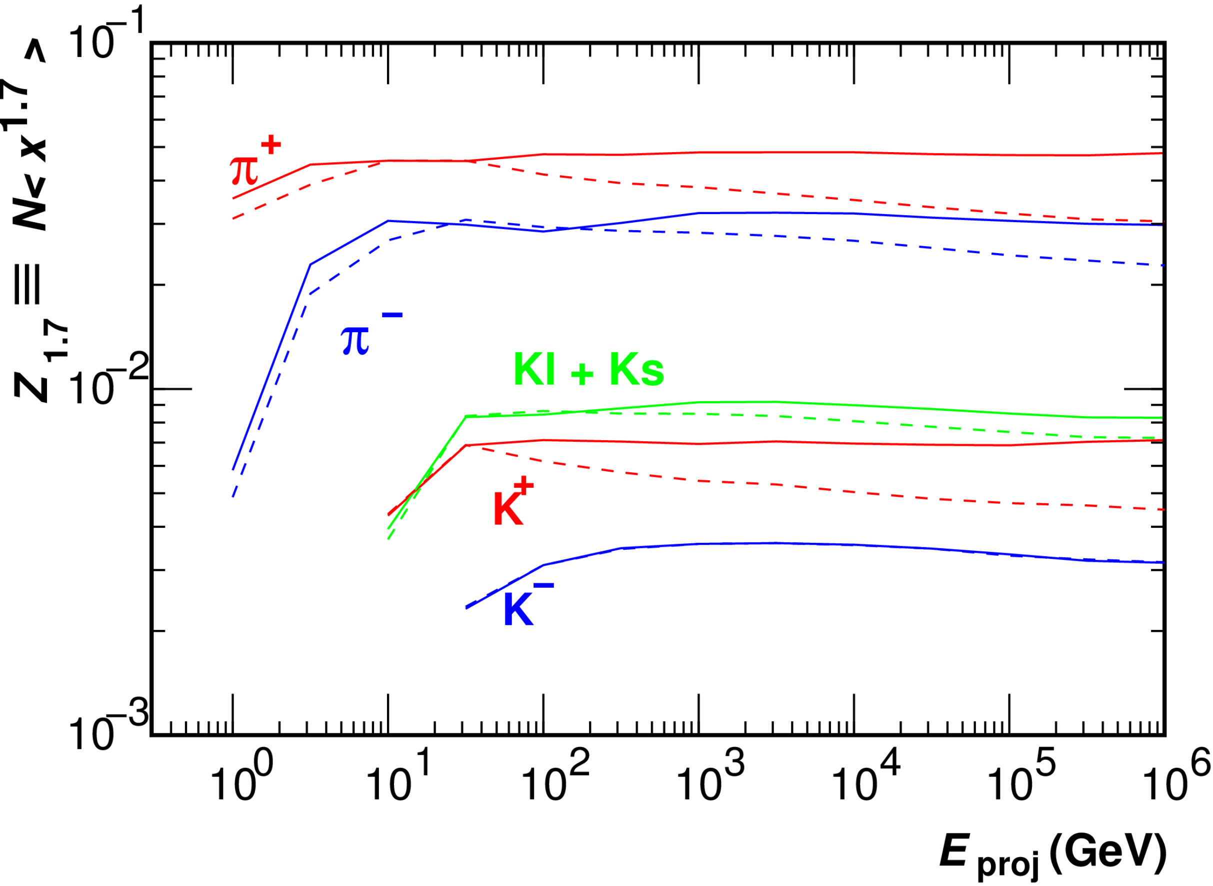


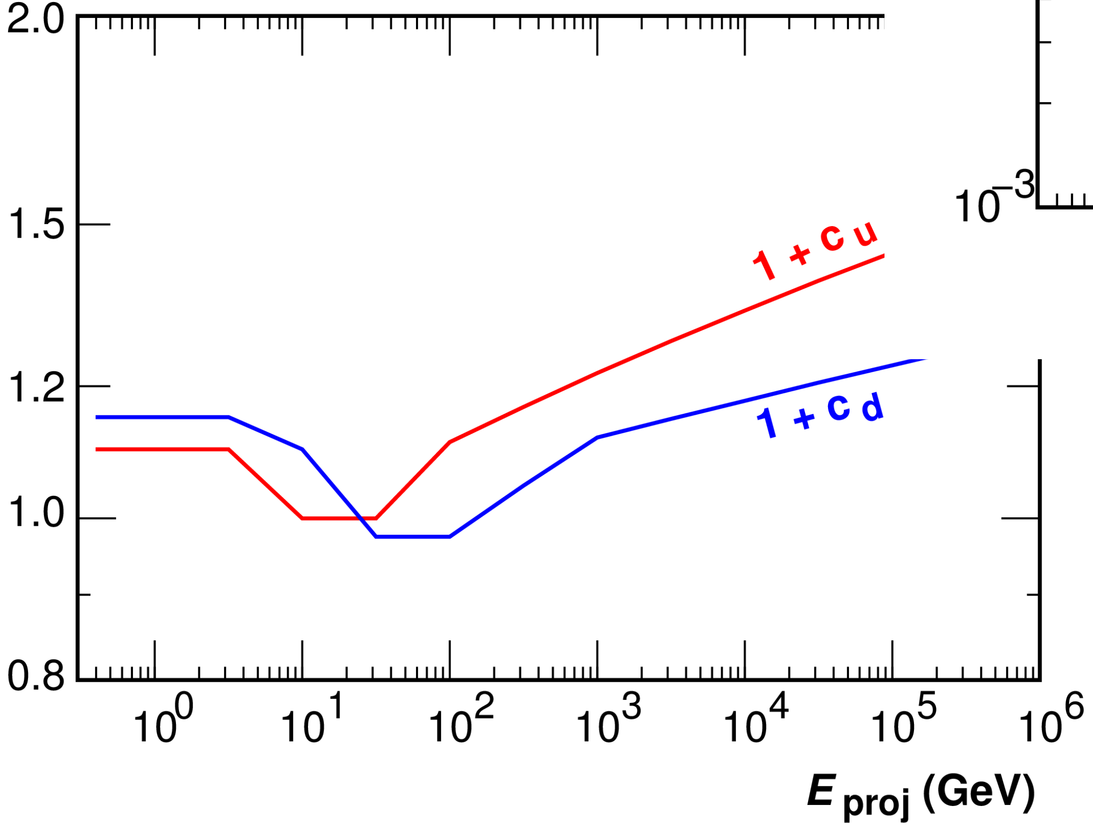


==> DPMJET-III Should be Modified

Modification of Int. Model (SHKKM 2006)

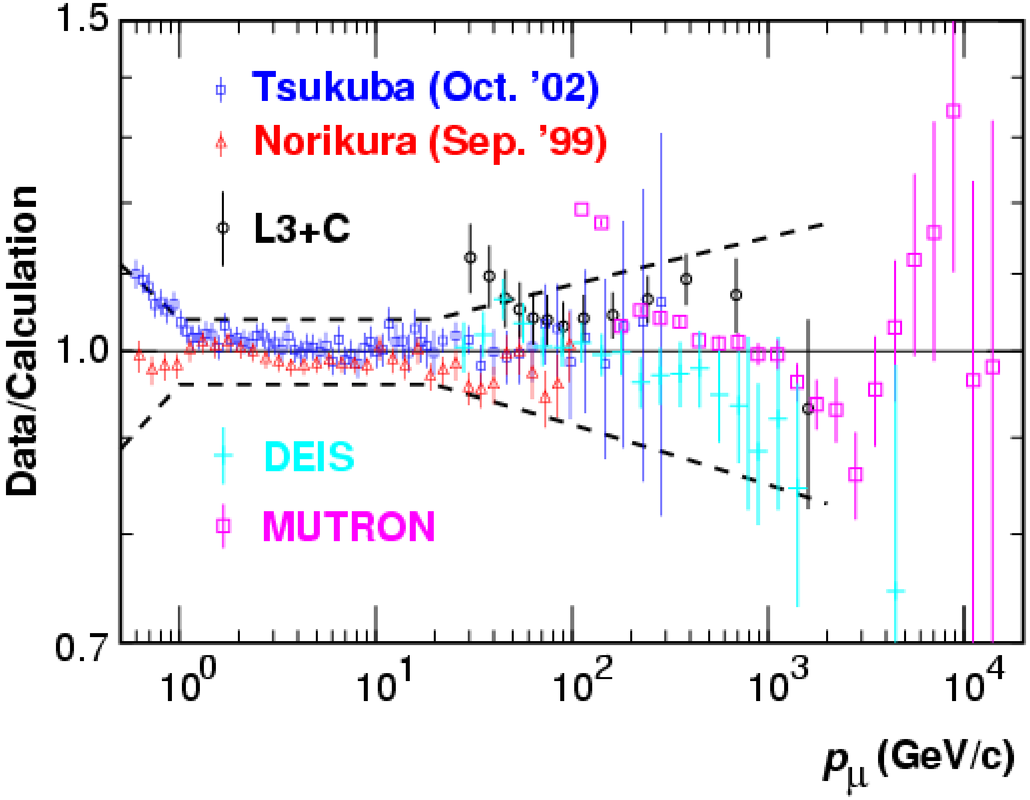
Z-Factor →

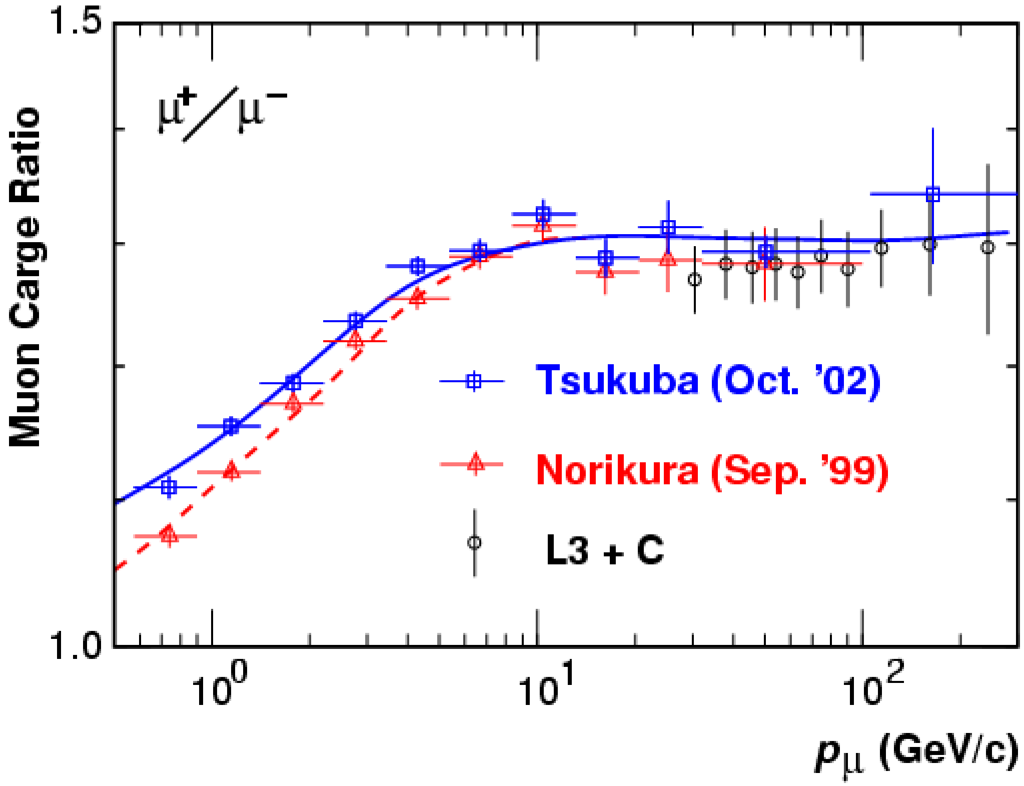




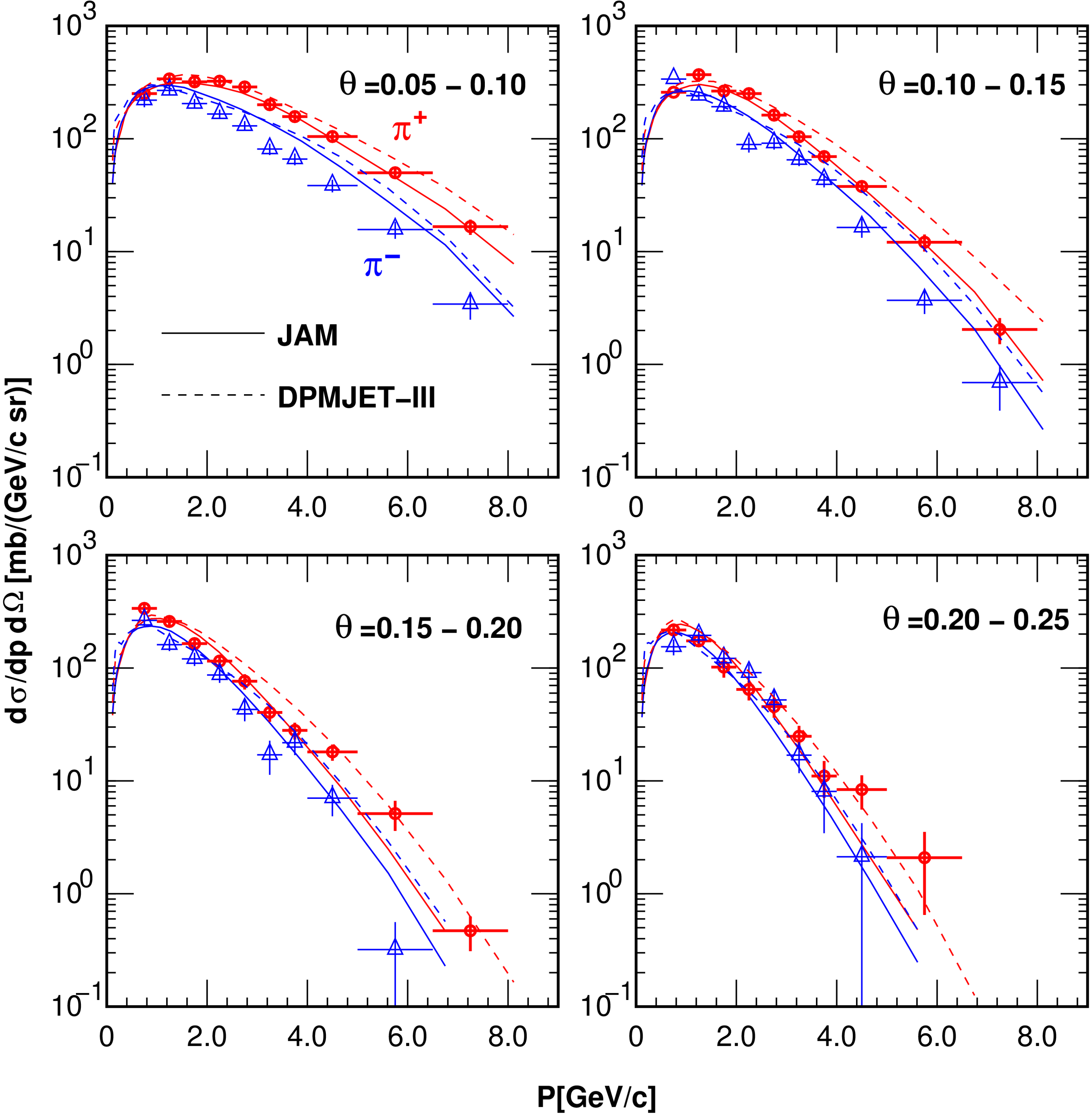
<--- Modification parameter

Comparison AFTER modification

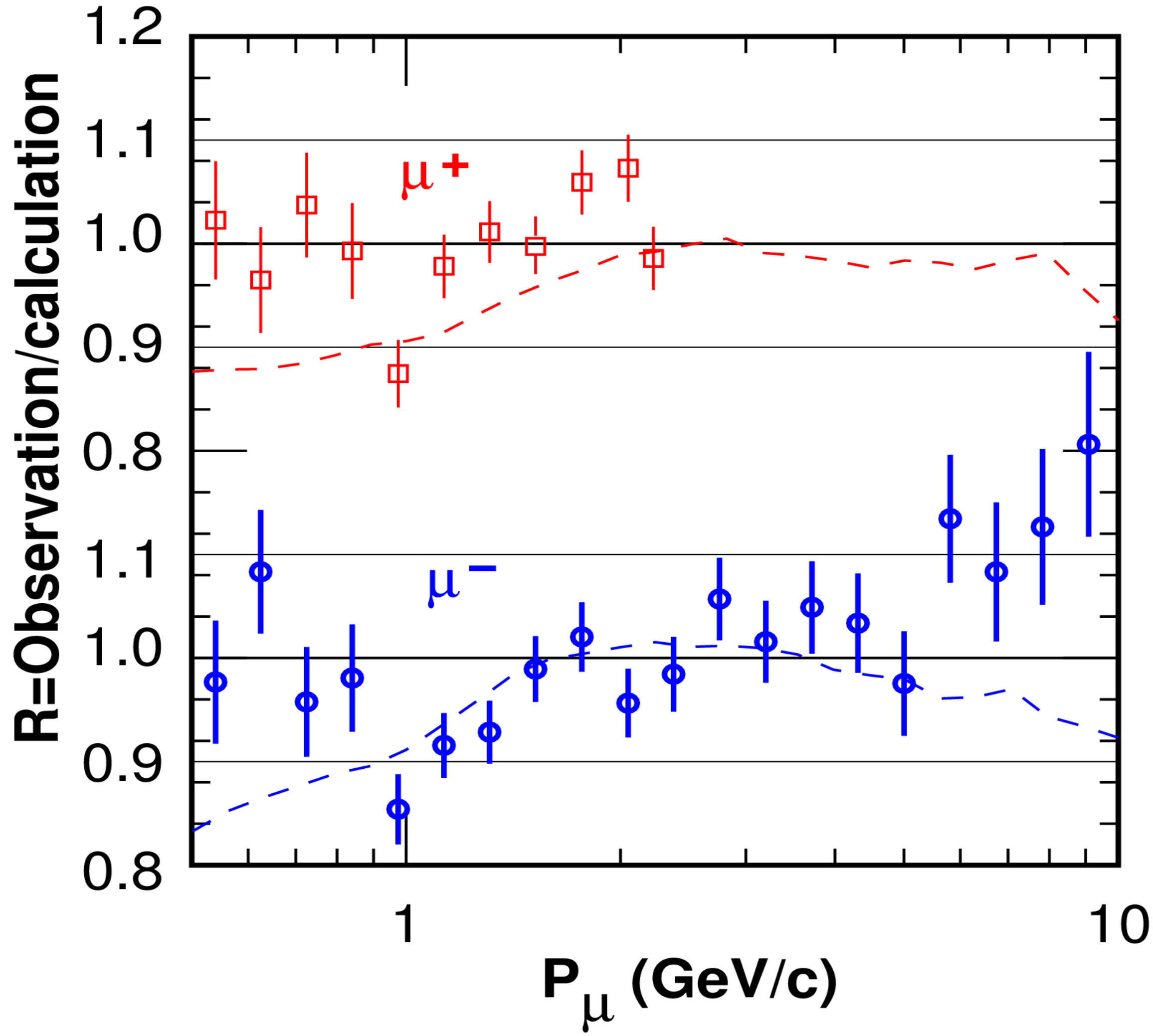




JAM
Interaction model

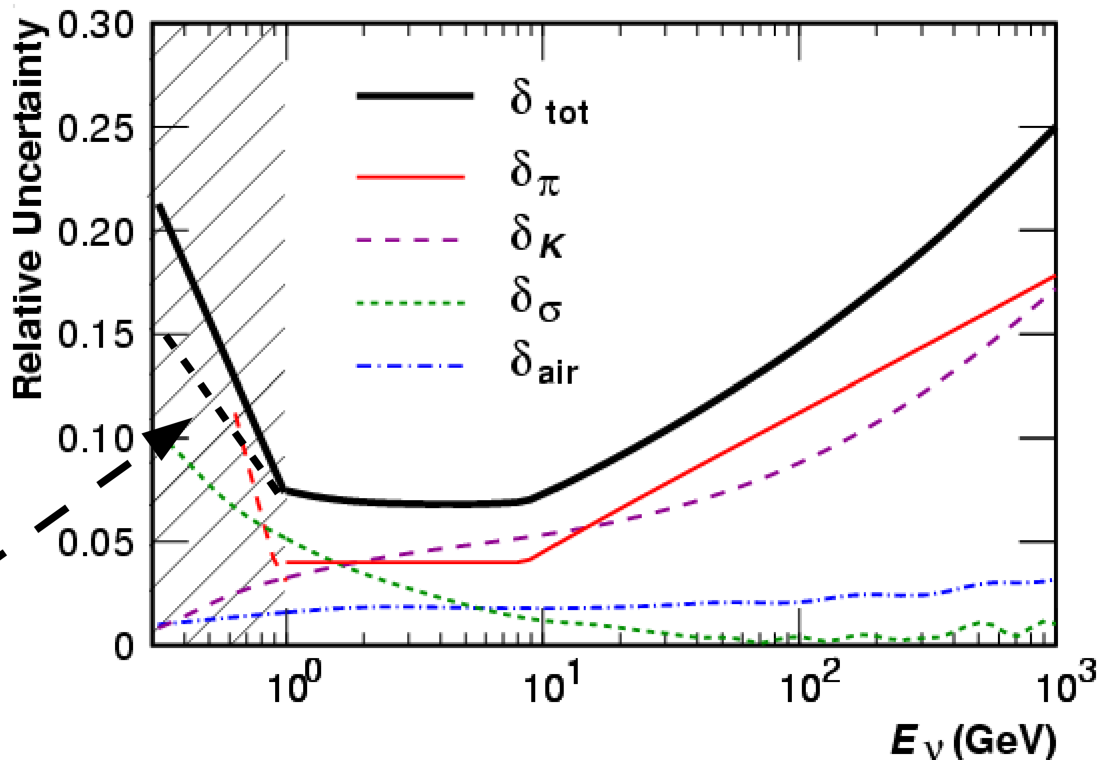


JAM + Modified DPMJET-II vs Muons at the Balloon altitude



Good agreement ! → Use DPMJET-III above 32 GeV and JAM below 32 GeV

Possible Error in Atmospheric ν-flux for HKKMS06



Error with JAM (HKKM2011)

δ_π μ -observation error + Residual of reconstruction

δ_K Kaon production uncertainty

δ_σ Mean free path (interaction crossection) uncertainty

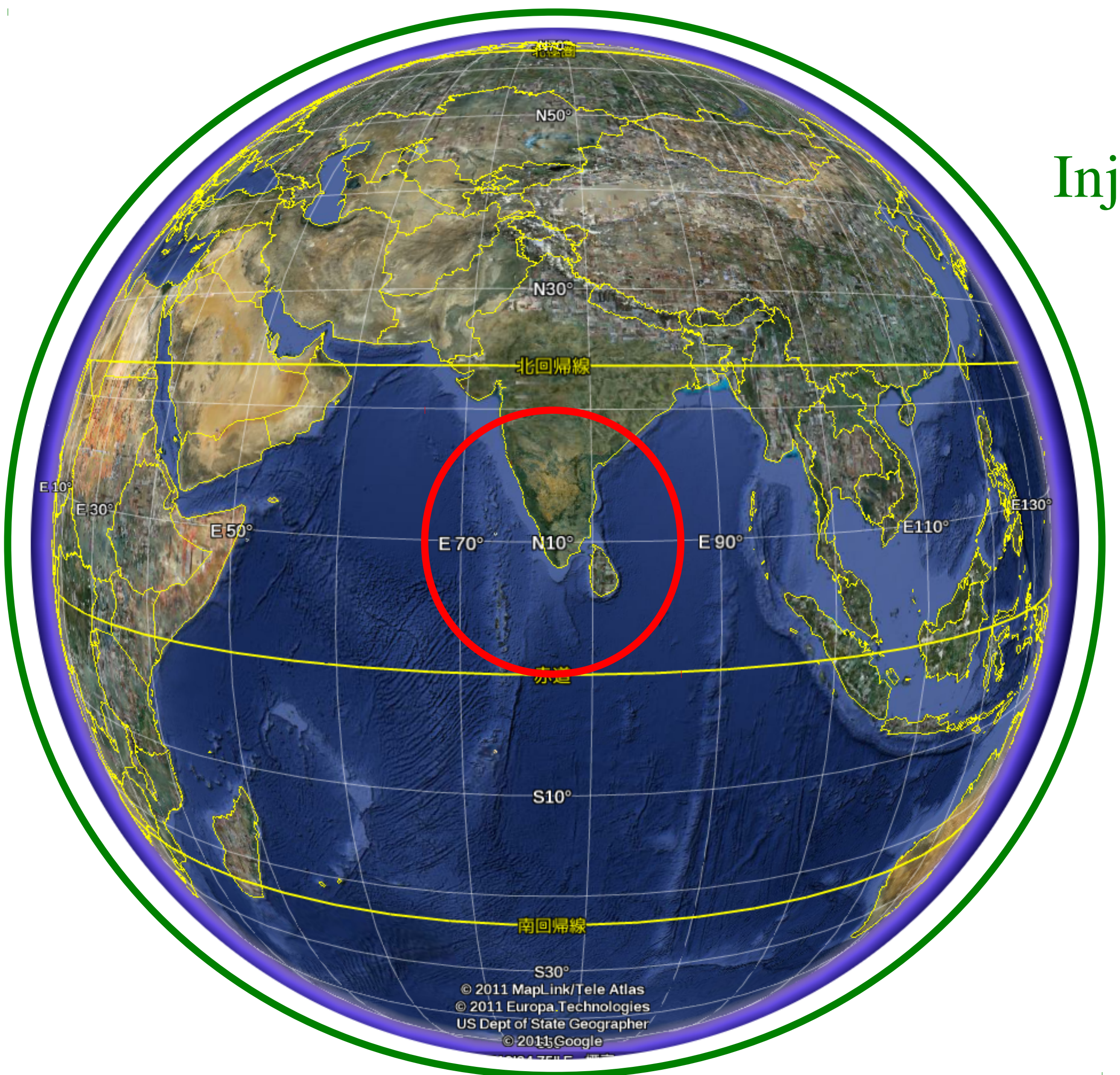
δ_{air} Atmosphere density profule uncertainty

3D-Calculation

Re = 6378km

Simulation Sphere (Rs = 10 x Re)

Cosmic ray go out this sphere are discarded.
Cosmic rays go beyond are pass the rigidity cutoff test



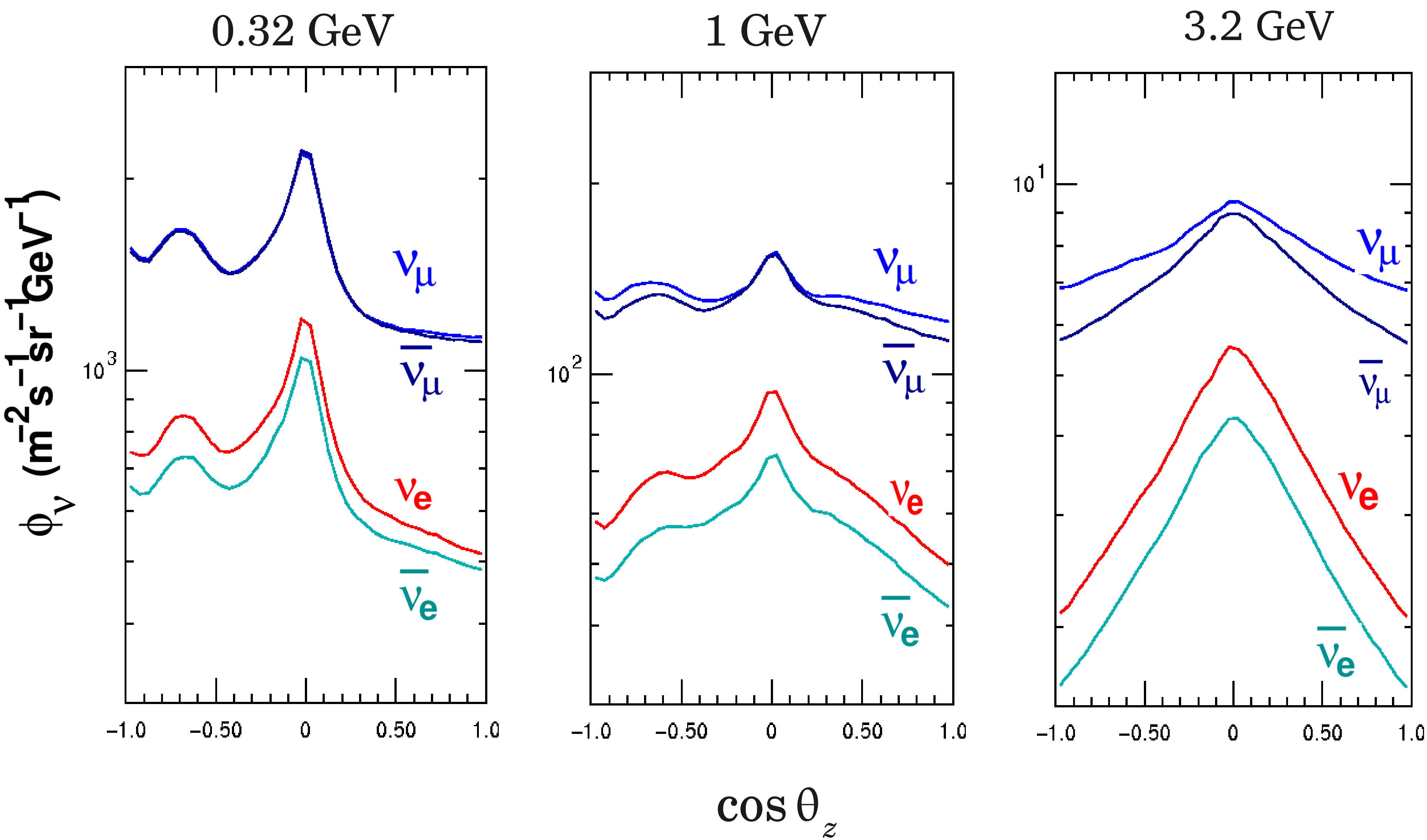
Injection Sphere (Re +100lm)

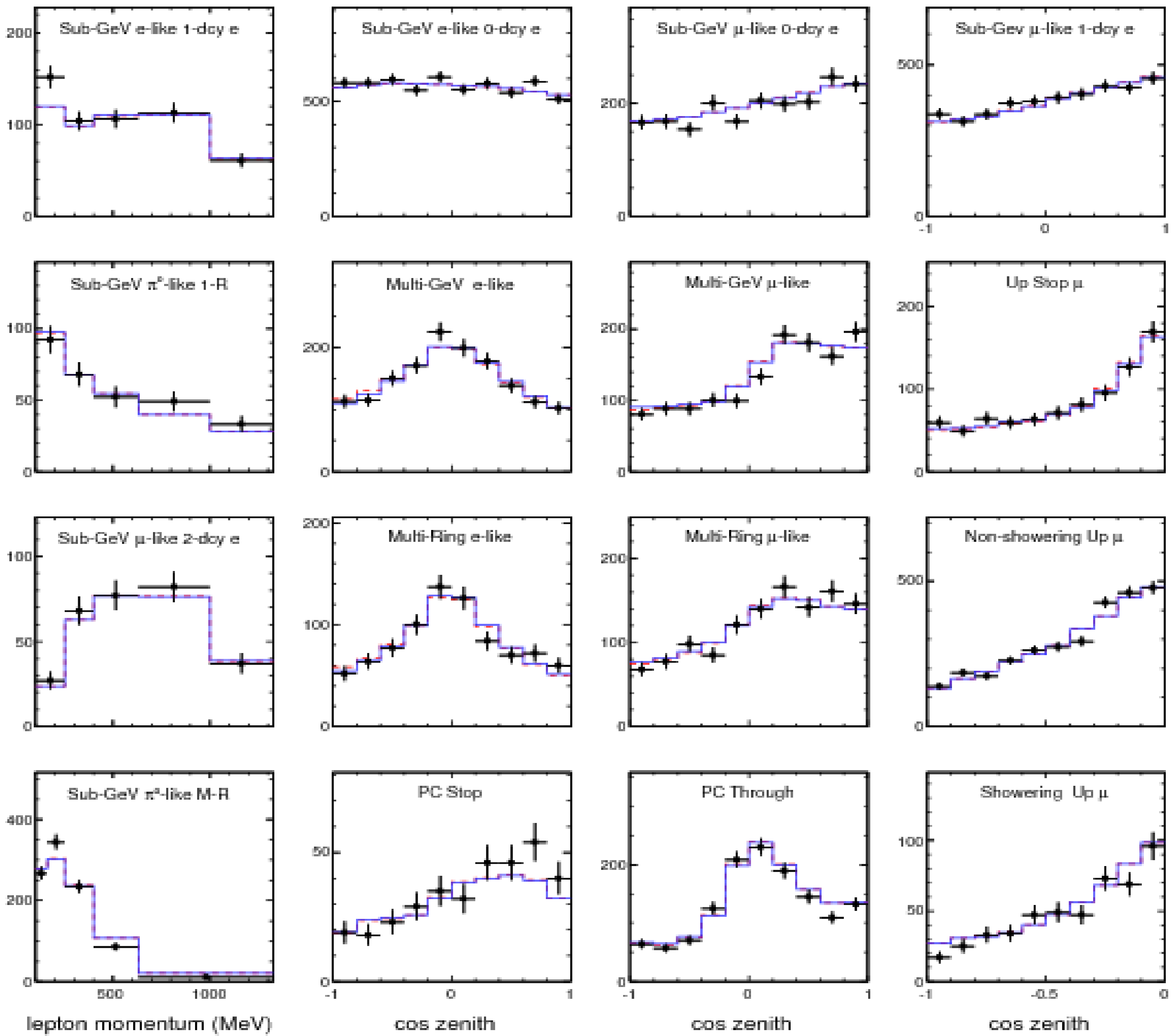
Cosmic Rays are sampled and injected here

Virtual Detector

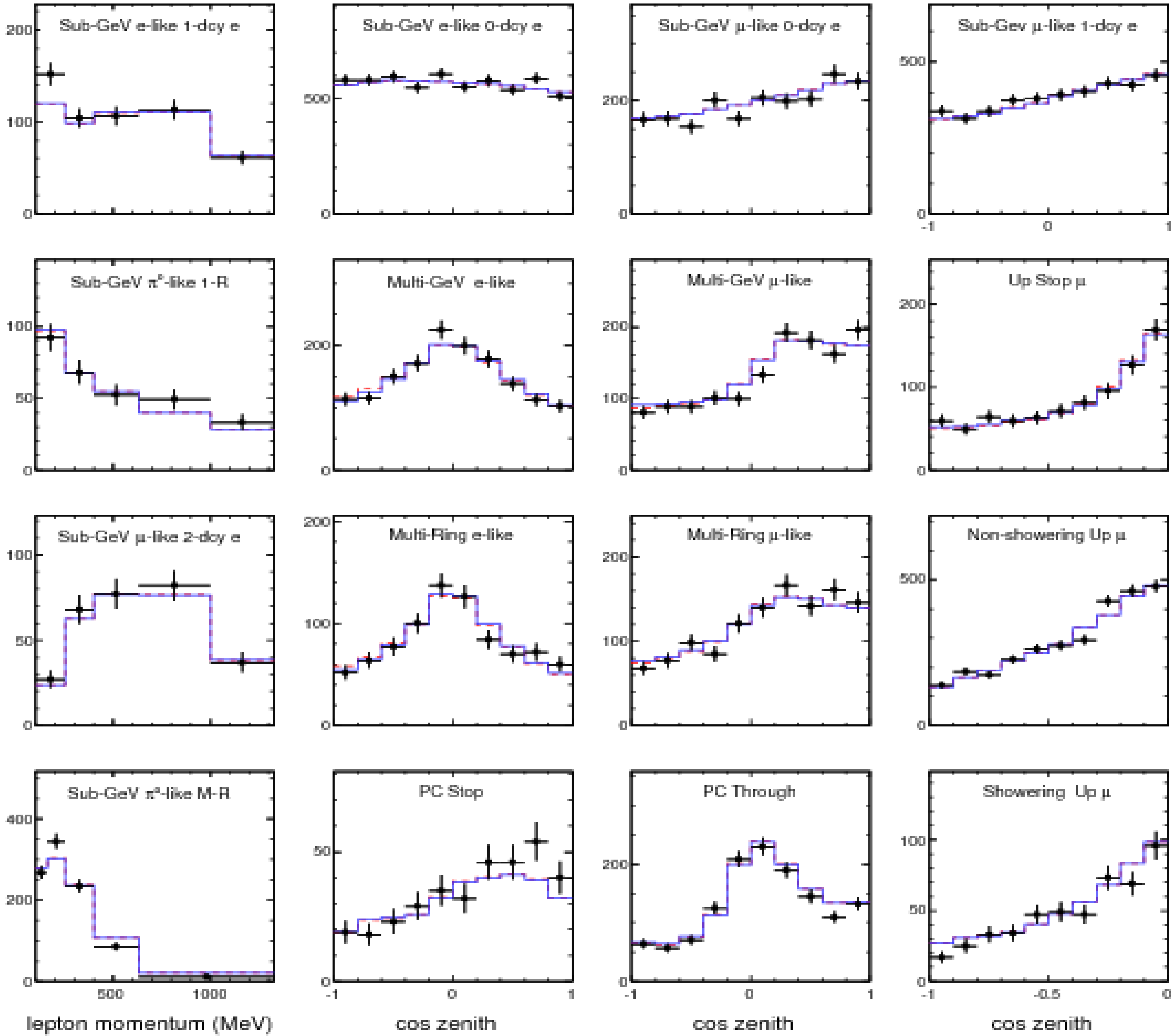
All neutrinos path through are recorded

Zenith angle variation of neutrino fluxes averaged over all azimuth angles at SK



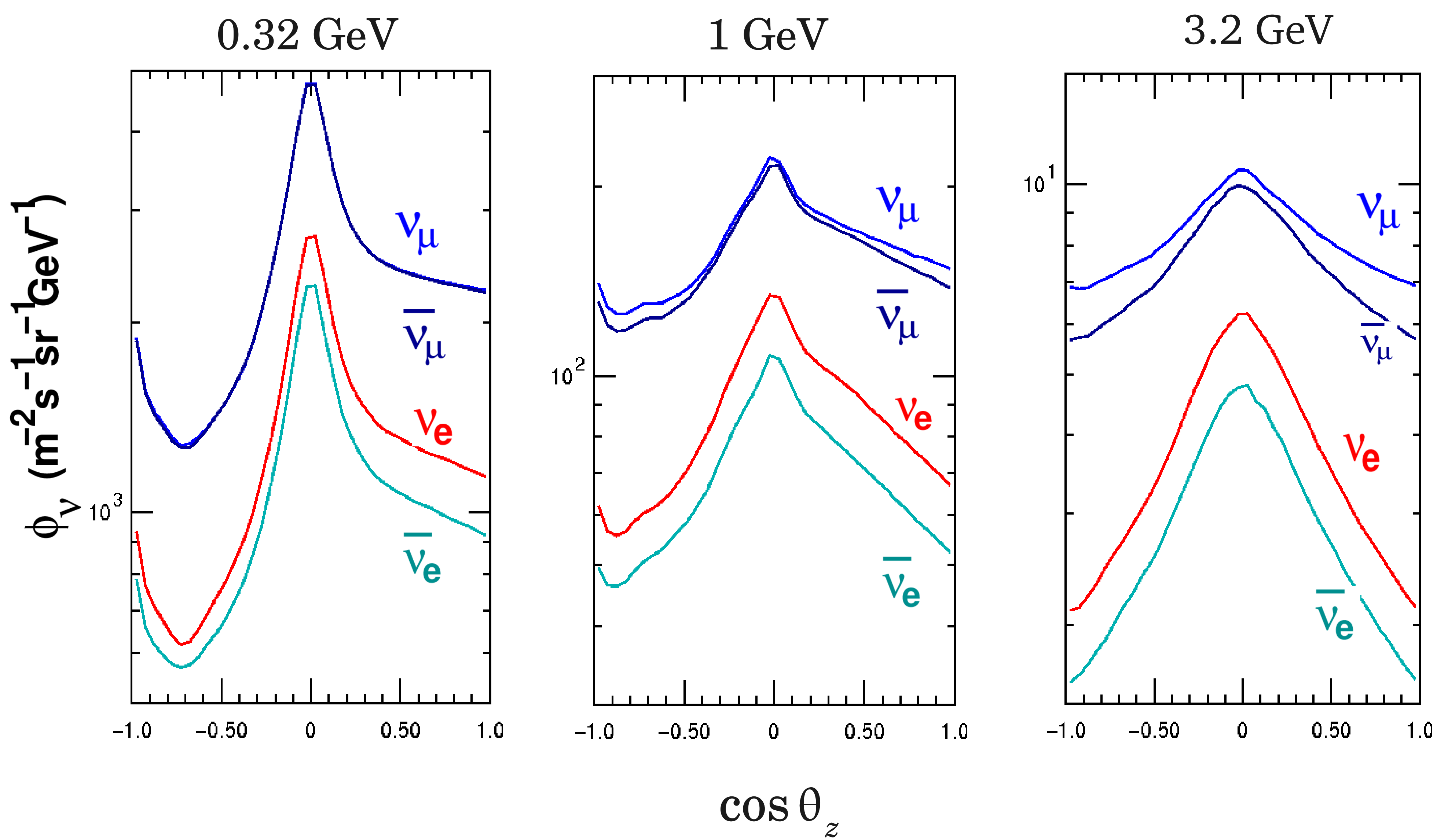


Sub-GeV e-like 1-dcy e
Sub-GeV e-like 0-dcy e
Sub-GeV μ-like 0-dcy e
Sub-Gev μ-like 1-dcy e
Sub-GeV π⁰-like 1-R
Multi-GeV e-like
Multi-GeV μ-like
Up Stop μ
Sub-GeV μ-like 2-dcy e
Multi-Ring e-like
Multi-Ring μ-like
Non-showering Up μ
Sub-GeV π⁰-like M-R
PC Stop
PC Through
Showering Up μ
lepton momentum (MeV)
cos zenith
cos zenith
cos zenith

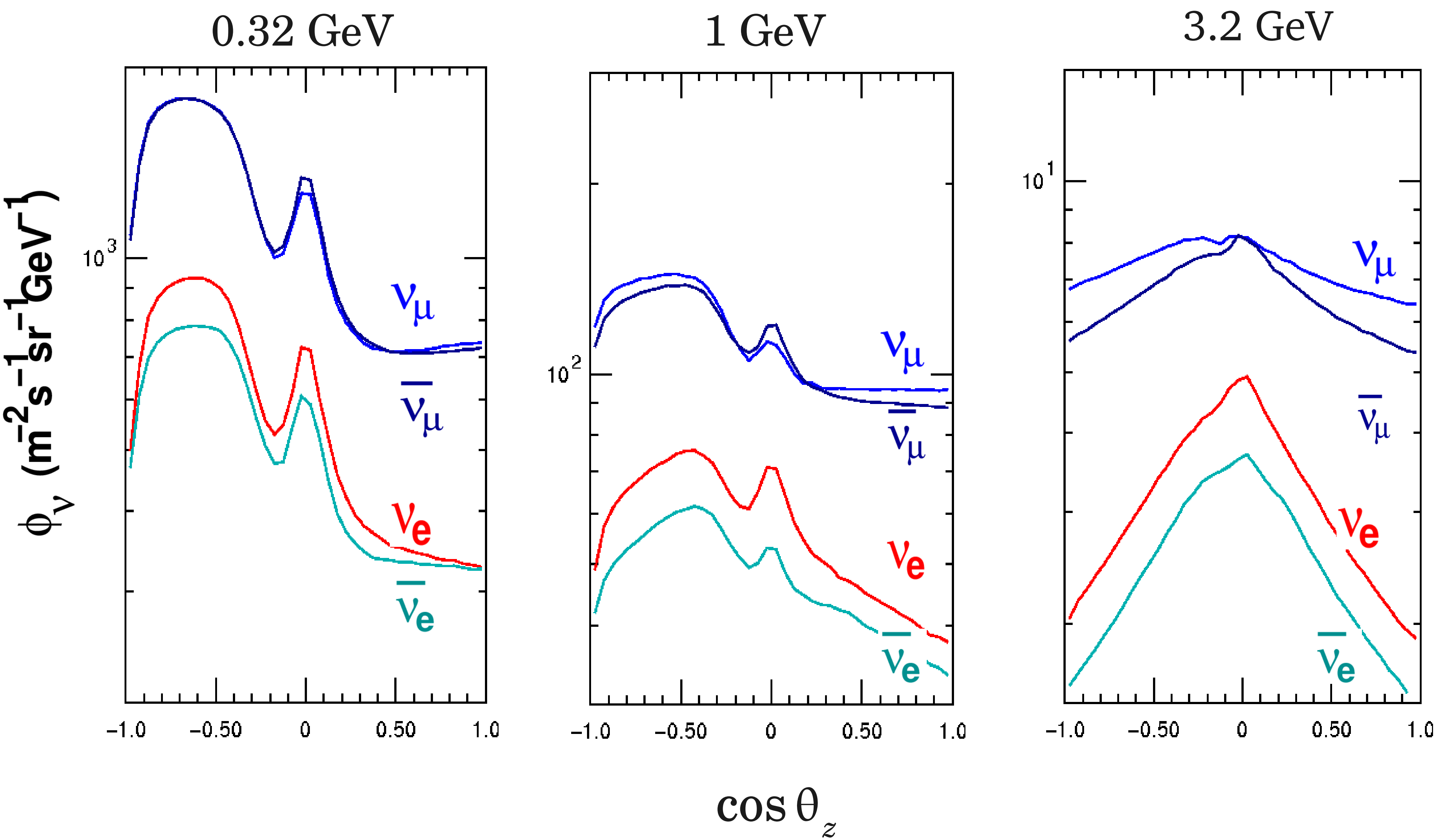


Sub-GeV e-like 1-dcy e
Sub-GeV e-like 0-dcy e
Sub-GeV μ-like 0-dcy e
Sub-Gev μ-like 1-dcy e
Sub-GeV π⁰-like 1-R
Multi-GeV e-like
Multi-GeV μ-like
Up Stop μ
Sub-GeV μ-like 2-dcy e
Multi-Ring e-like
Multi-Ring μ-like
Non-showering Up μ
Sub-GeV π⁰-like M-R
PC Stop
PC Through
Showering Up μ
lepton momentum (MeV)
cos zenith
cos zenith
cos zenith

Zenith angle variation of neutrino fluxes averaged over all azimuth angles at SNO

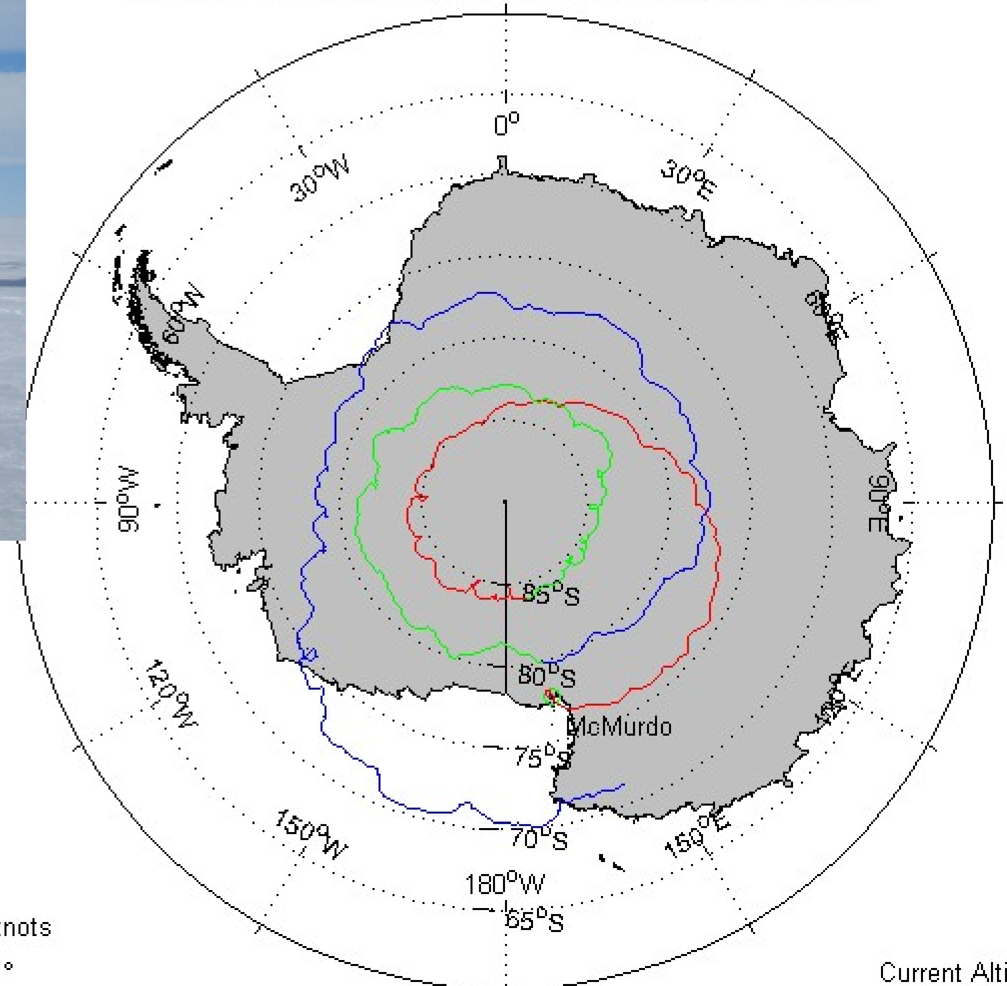


Zenith angle variation of neutrino fluxes averaged over all azimuth angles at INO



CREAM Flight Data: Trajectory

Covering period from: 2004-12-15 23:22:56 to 2005-01-27 02:00:31



Current Speed: 17.2 knots

Current Course: 128.1°

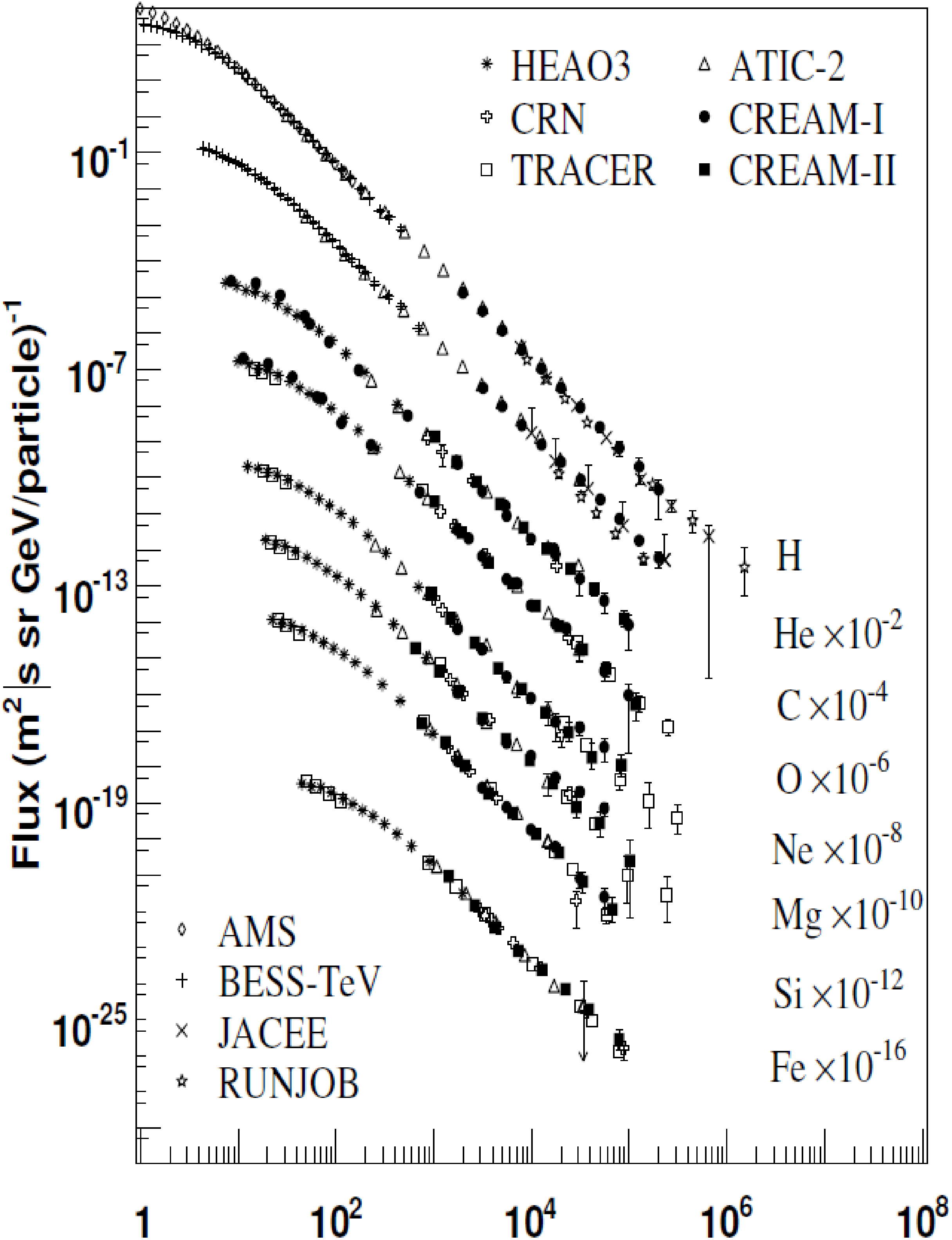
Current Lat: -71°17′3.72″

Current Lon: 157°52′54″

Current Altitu

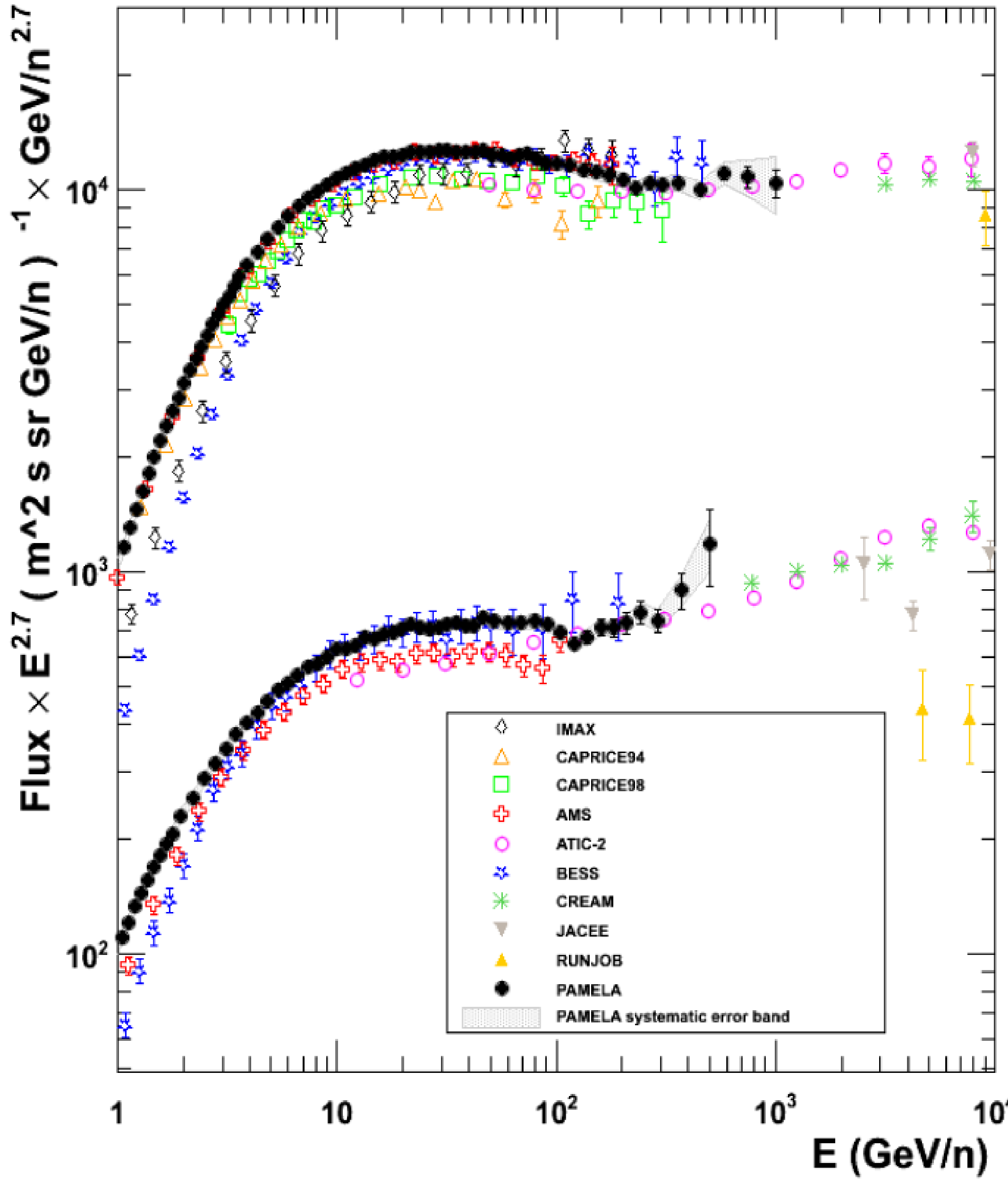
Current MET: 41 days 21 hrs 31 mins 30.7

Current Time: 2005-

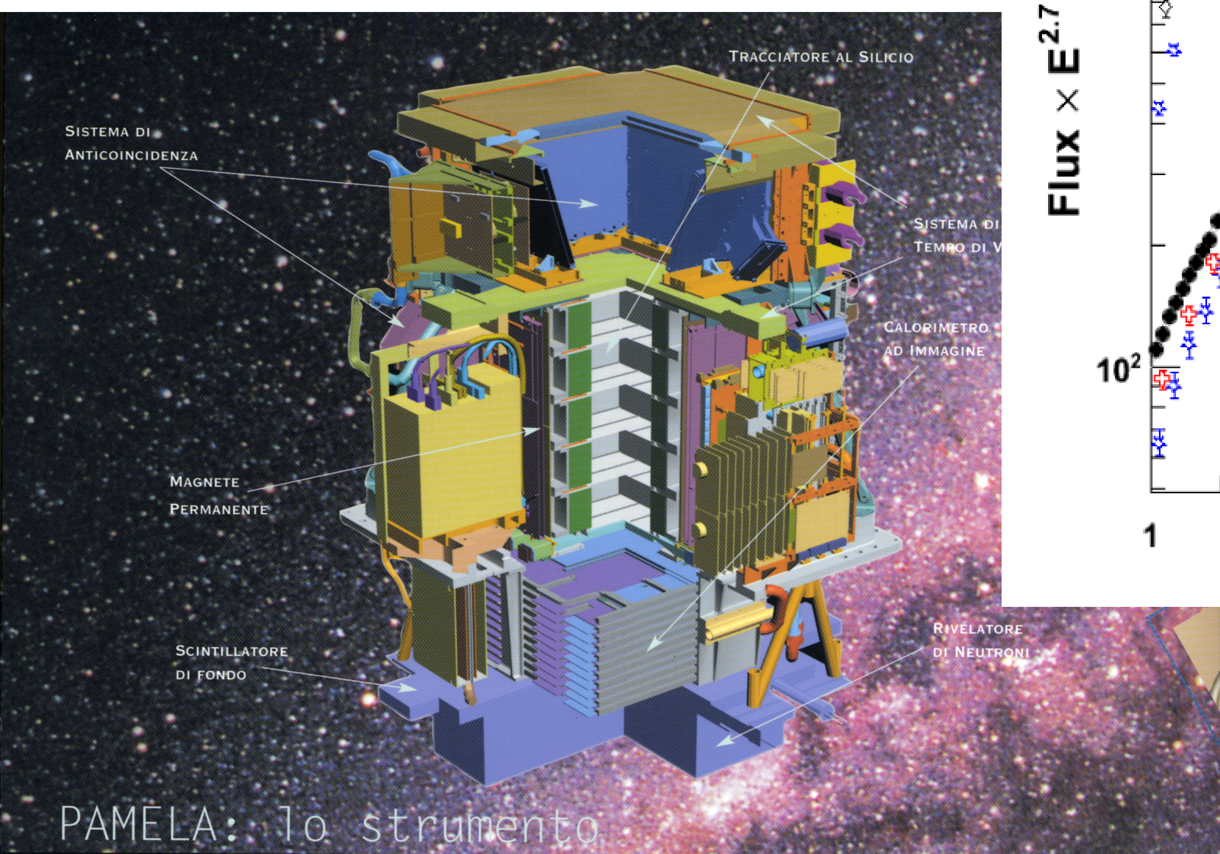


Recent compilation
E.S. Seo @ ICRC2009

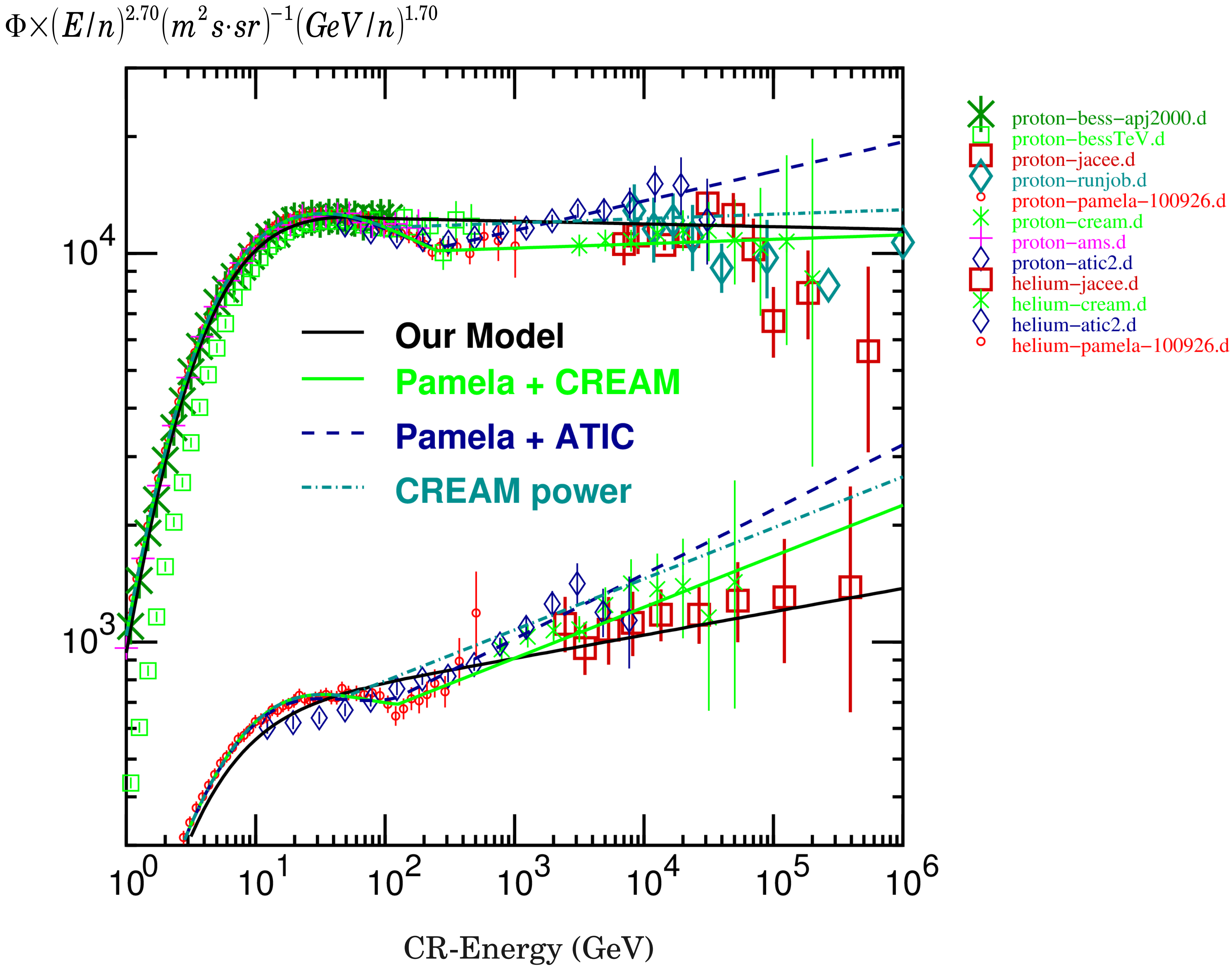
Pamela



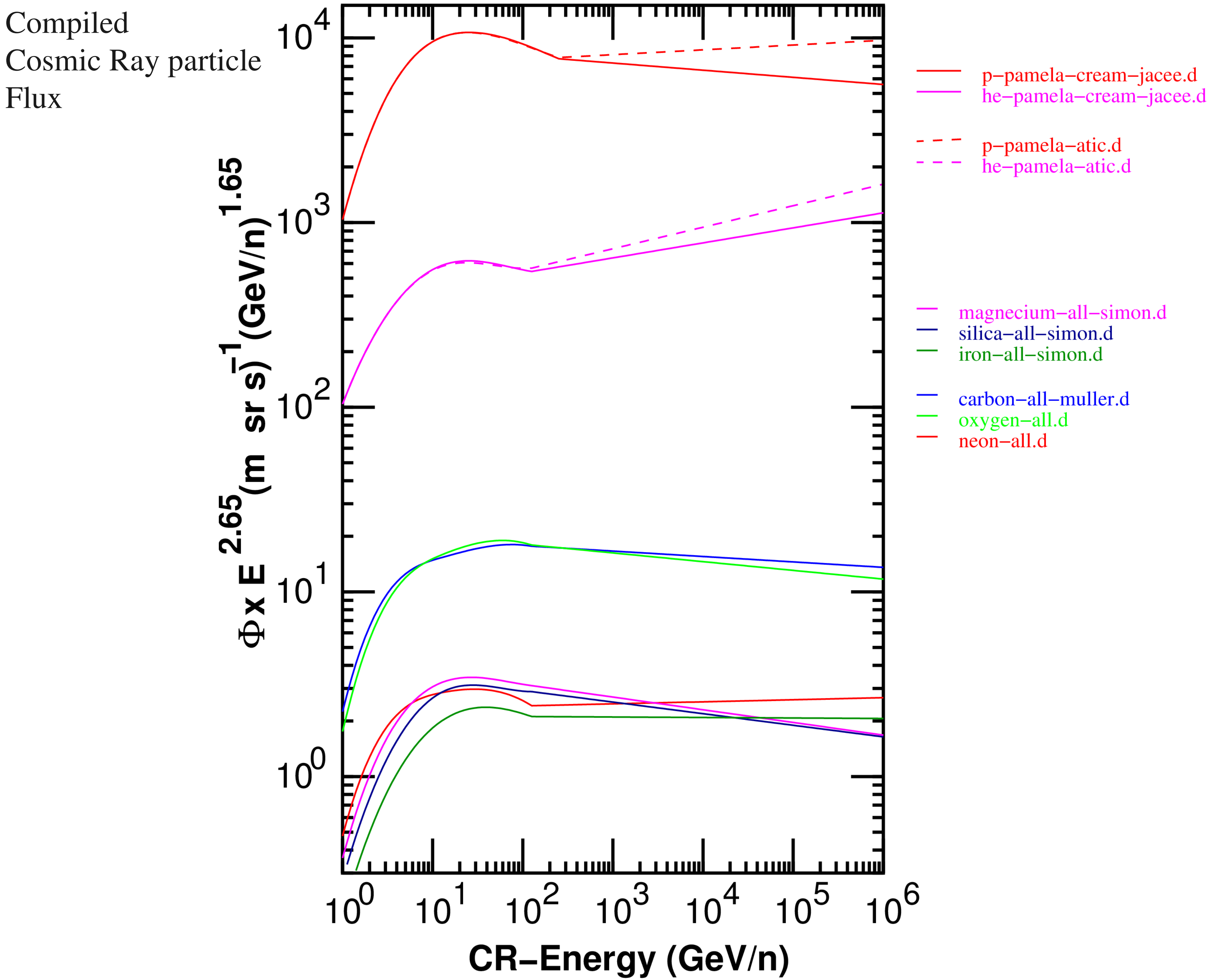
Flux × E^2.7 (m^2 s sr GeV/n)^-1 × GeV/n^2.7
10^4
10^3
10^2
1
10
10^2
10^3
10^4
E (GeV/n)
IMAX
CAPRICE94
CAPRICE98
AMS
ATIC-2
BESS
CREAM
JACEE
RUNJOB
PAMELA
PAMELA systematic error band

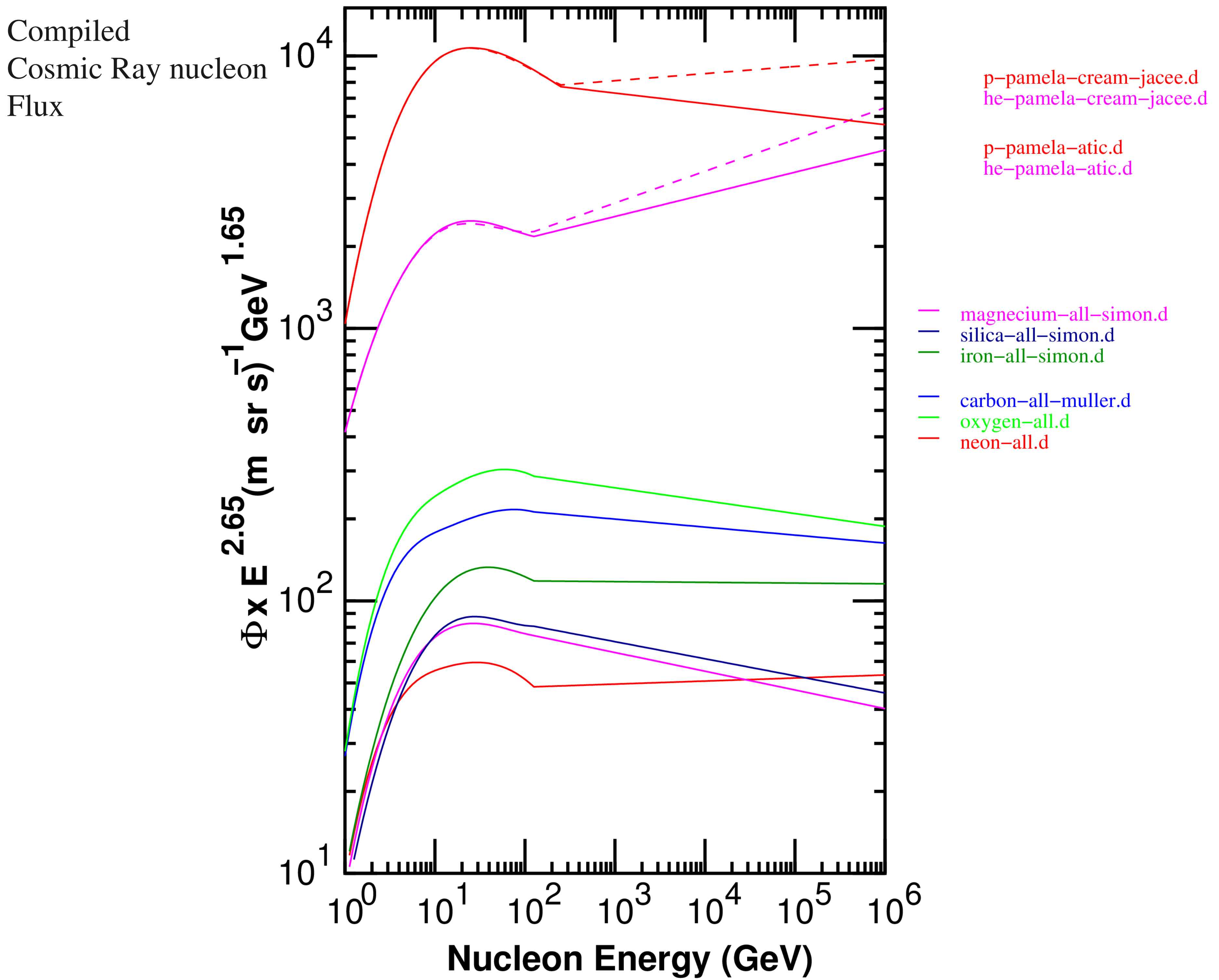


Tracciatore al Silicio
Sistema di Anticoincidenza
Sistema di
Tempo di V
Calorimetro ad Immagine
Magnete Permanente
Scintillatore di fondo
Rivelatore di Neutroni
PAMELA: lo strumento



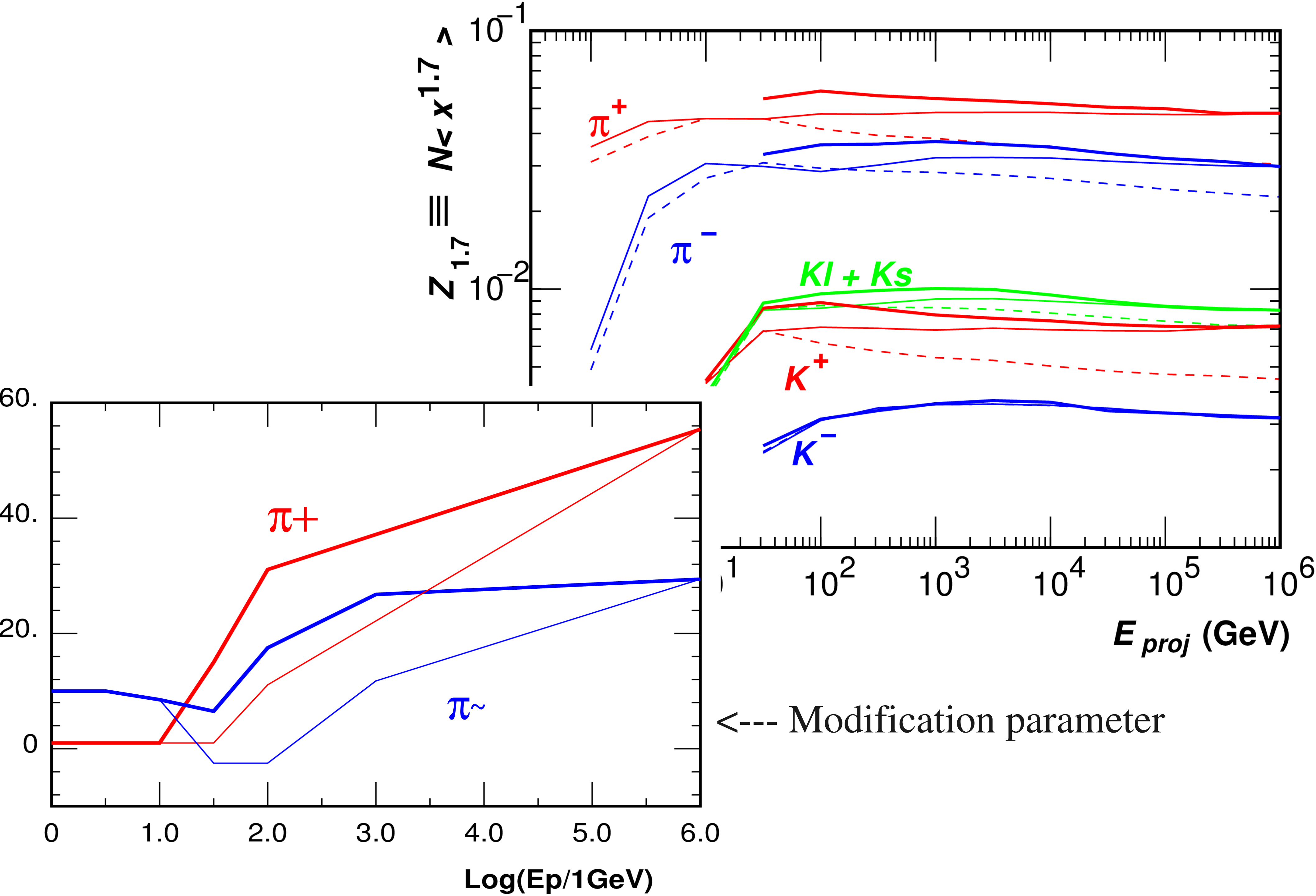
$\Phi\times(E/n)^{2.70}(m^2 s\cdot sr)^{-1}(GeV/n)^{1.70}$
10^4
10^3
10^0
10^1
10^2
10^3
10^4
10^5
10^6
CR-Energy (GeV)
Our Model
Pamela + CREAM
Pamela + ATIC
CREAM power
proton−bess−apj2000.d
proton−bessTeV.d
proton−jacee.d
proton−runjob.d
proton−pamela−100926.d
proton−cream.d
proton−ams.d
proton−atic2.d
helium−jacee.d
helium−cream.d
helium−atic2.d
helium−pamela−100926.d


Compiled
Cosmic Ray particle
Flux
Φ x E^2.65 (m sr s)^-1 (GeV/n)^1.65
CR−Energy (GeV/n)
10^0
10^1
10^2
10^3
10^4
10^5
10^6
p−pamela−cream−jacee.d
he−pamela−cream−jacee.d
p−pamela−atic.d
he−pamela−atic.d
magnecium−all−simon.d
silica−all−simon.d
iron−all−simon.d
carbon−all−muller.d
oxygen−all.d
neon−all.d



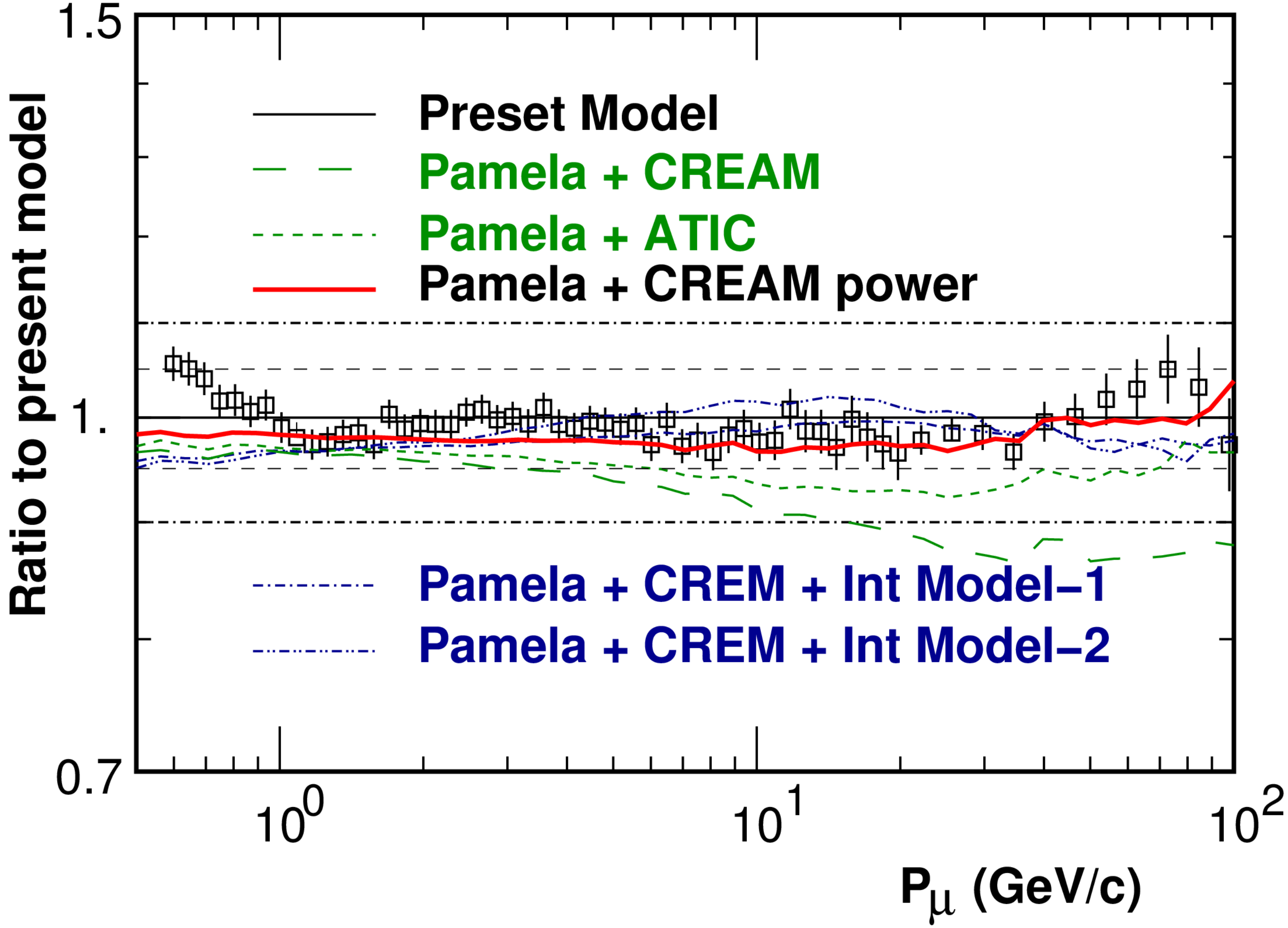
Compiled
Cosmic Ray nucleon
Flux
p−pamela−cream−jacee.d
he−pamela−cream−jacee.d
p−pamela−atic.d
he−pamela−atic.d
magnecium−all−simon.d
silica−all−simon.d
iron−all−simon.d
carbon−all−muller.d
oxygen−all.d
neon−all.d
Φ x E^2.65 (m sr s)^-1 GeV^1.65
Nucleon Energy (GeV)

Modified Z-factor (SHKKM 2006)

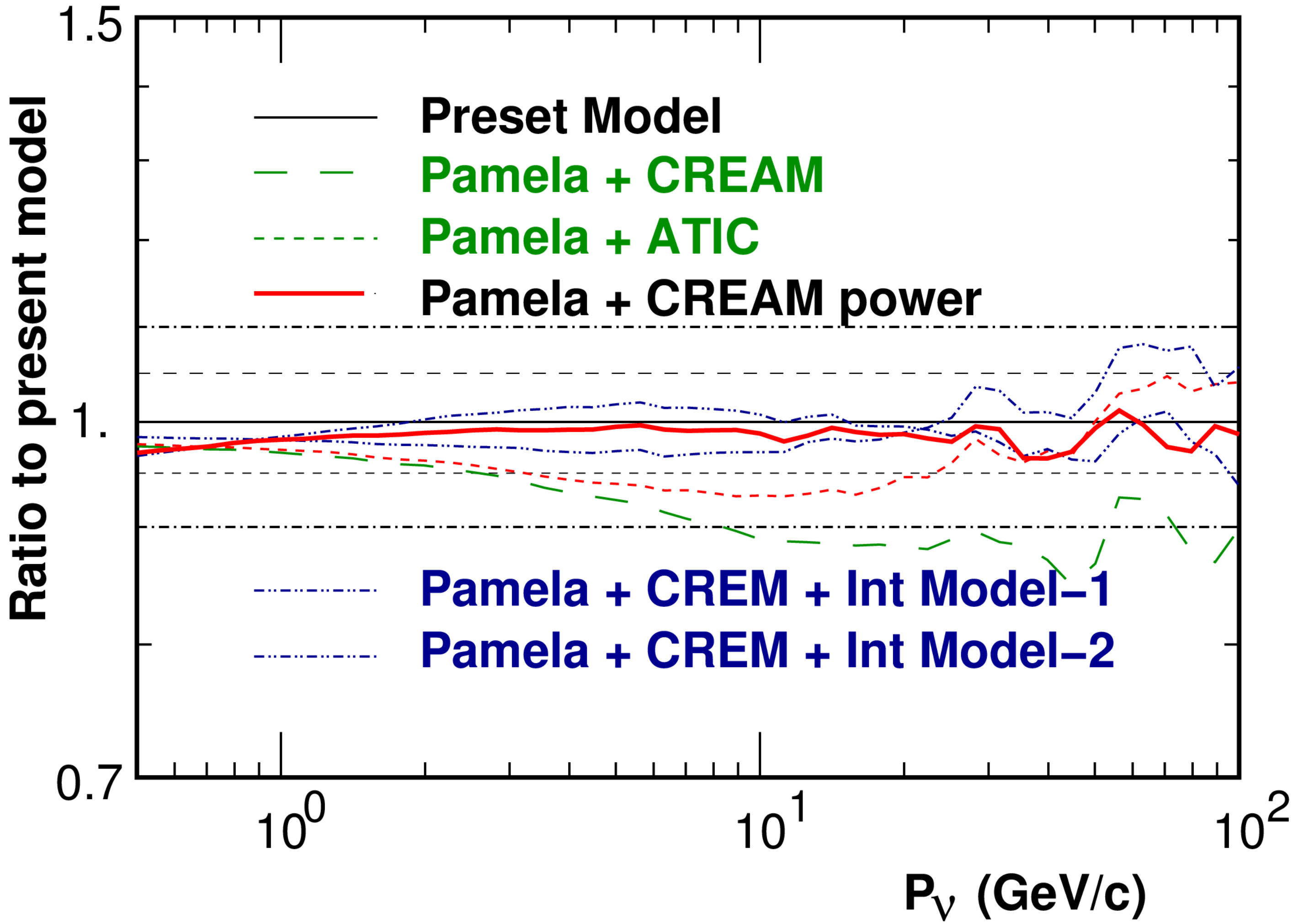


<--- Modification parameter

Tuning of Int. Model by atmospheric muons



Resulting Neutrino Flux (all ν sum)



Muon Tuning works Well, however,

However, AMS is just Launched,

Summary

- Whe have studied the hadronic interaction model usable in the calculation
- of the atmospheric neutrino flux

  using the primary flux model based on on AMS and BESS,

  and atmospheric muons observed by BESS and others.
- The procedure is repeated for Atic, Cream, and Pamela observations,

  and worked weill, and resulting neutrino flux is with former ones.
- However, there are still large uncertainty in the primary flux above 100 GeV,

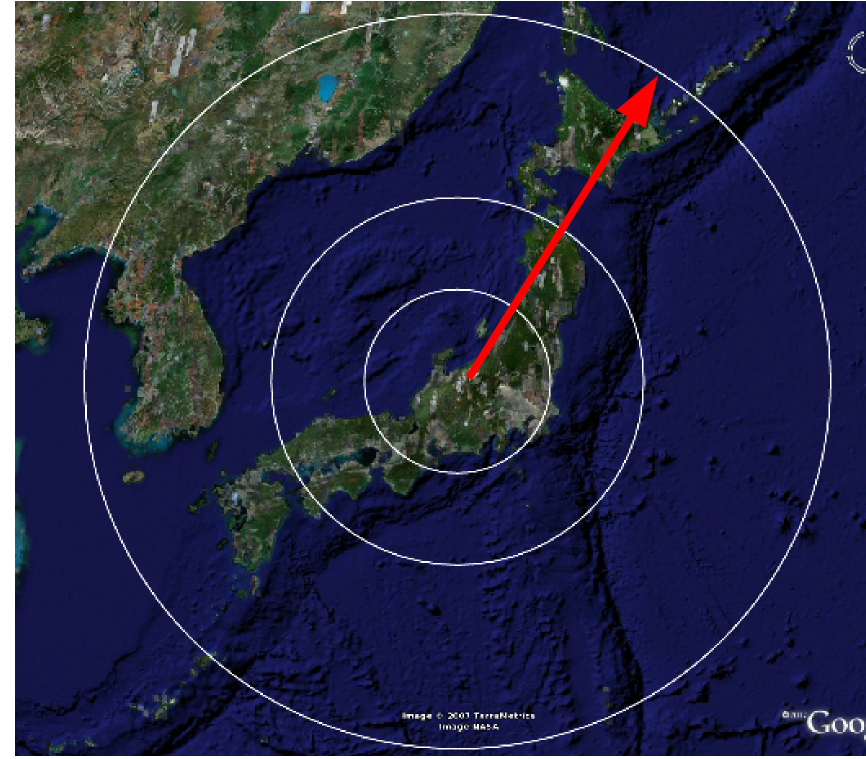
  and we should wait for AMS-II results.

- Go beyond 100 GeV with accuracy, we also need the information of

  KAON-productions. Please measure it accurately.

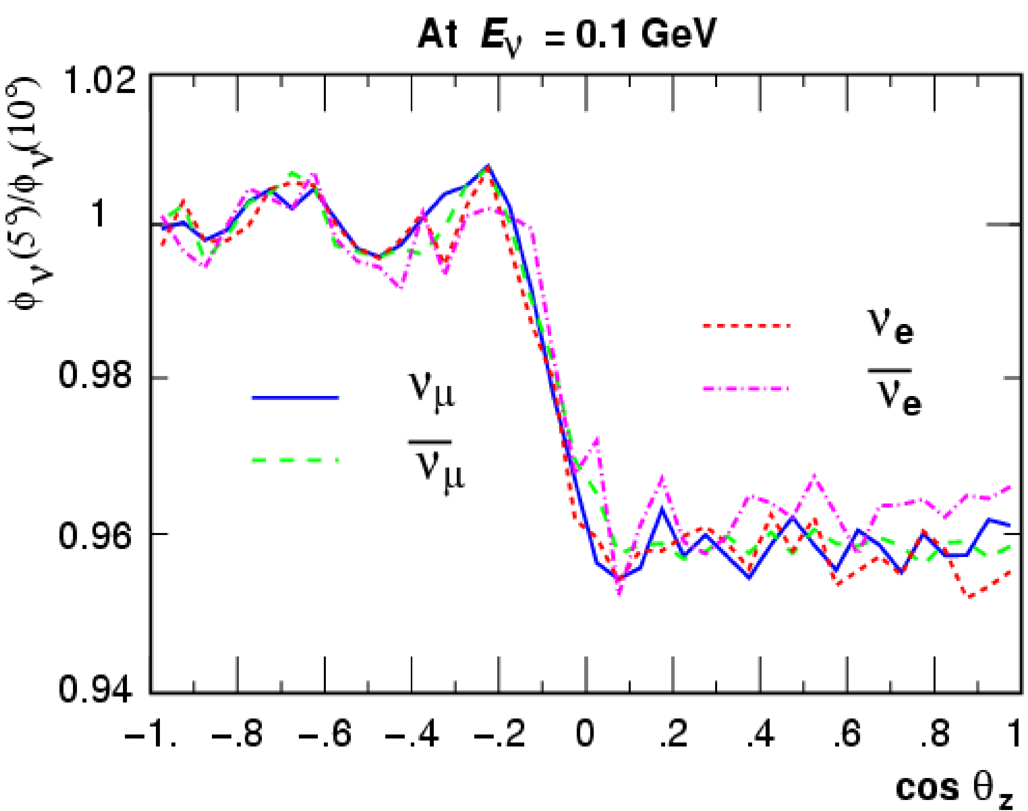
Back up

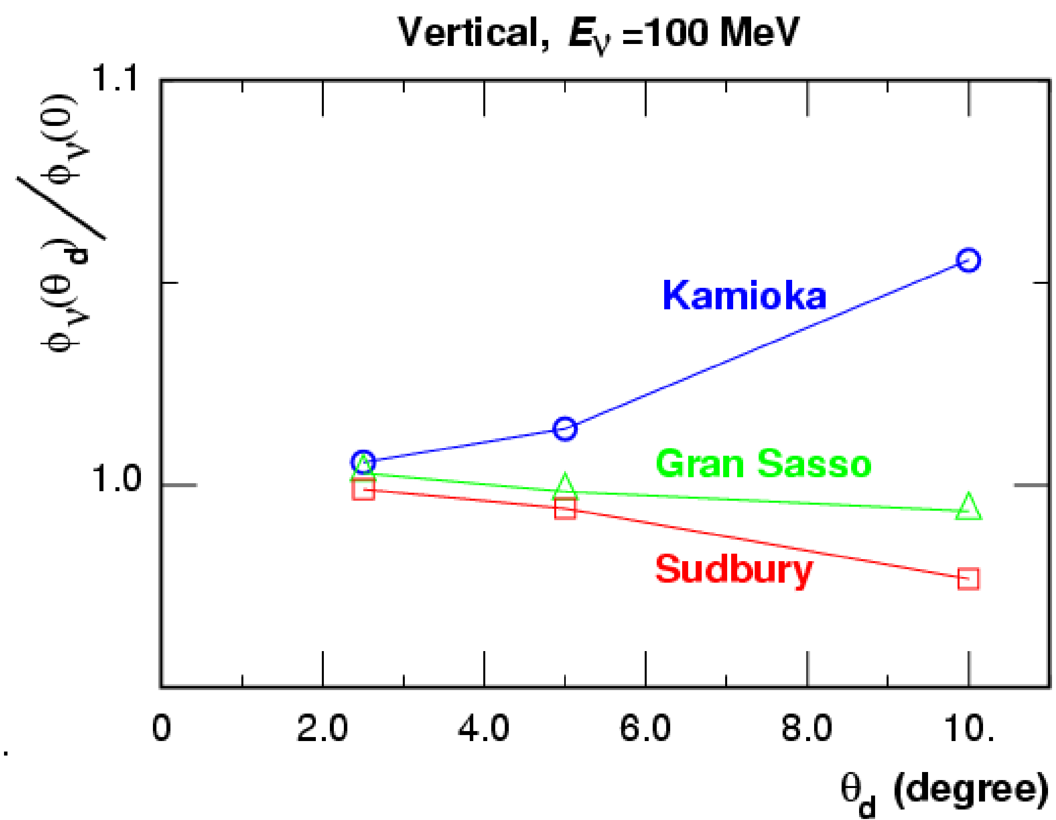
Error due to the large size Virtual Detector



In HKKM06

$$\phi_\nu(0) \simeq -\frac{1}{3}\phi_\nu(10) + \frac{4}{3}\phi_\nu(5)$$



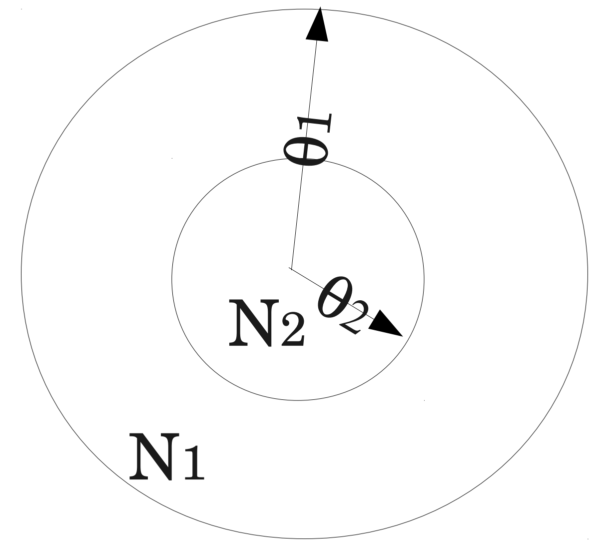


Optimization of size correction for virtual detector

Assume true flux value and average in the circle with radius $\theta 1$ and $\theta 2$ may be related as

$$\phi_1 = \phi_0 + \phi' \theta_1^2$$

$$\phi_2 = \phi_0 + \phi' \theta_2^2$$



Therefore the true value is calculated from $\phi 1$ and $\phi 2$ as;

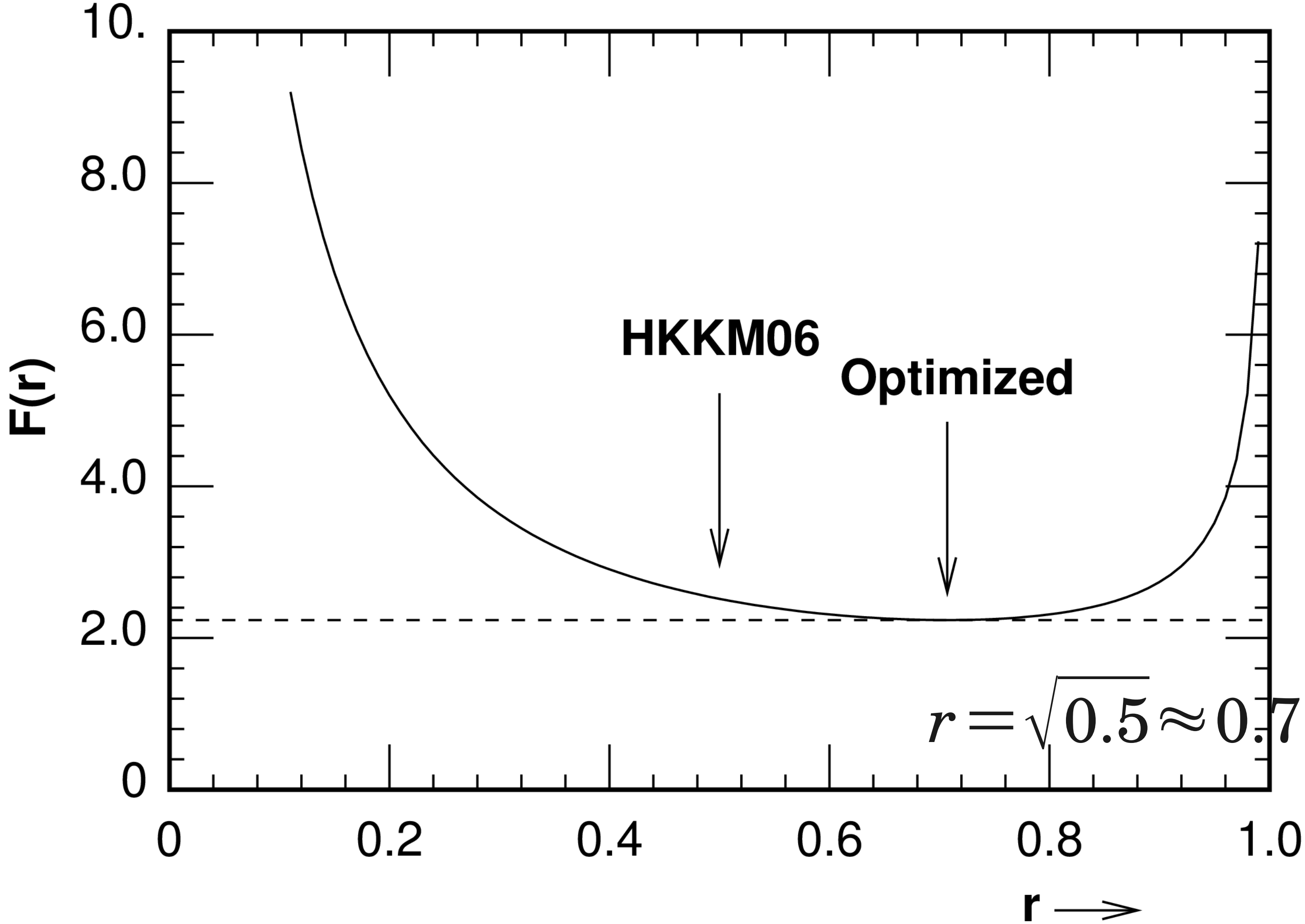
$$\phi_0 = \frac{\theta_1^2 \phi_2 - \theta_2^2 \phi_1}{\theta_1^2 - \theta_2^2} = \frac{\phi_2 - r^2 \phi_1}{1 - r^2} \qquad r = (\frac{\theta_2}{\theta_1}),\ r < 1$$

In terms of the sampled number $N1$ in the circle $\theta < \theta 1$, and $N2$ in $\theta < \theta 2$, $\phi 1$ and $\phi 2$ are given as

$$\phi_1 = \frac{N_1}{T \pi \theta_1^2}, \quad \phi_2 = \frac{N_2}{T \pi \theta_2^2}$$

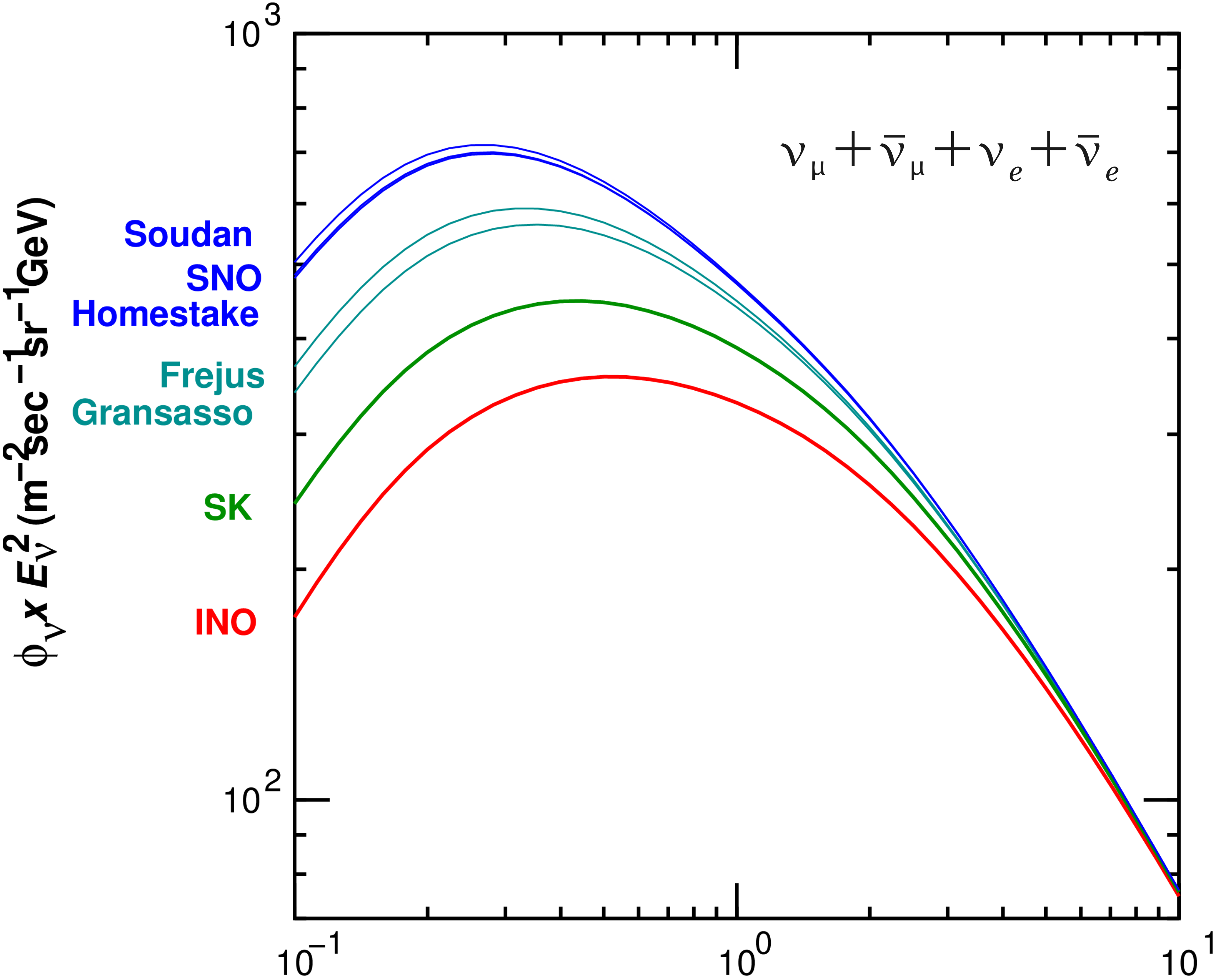
Optimized $r = \left(\frac{\theta_2}{\theta_1}\right)$ value, which minimize the stat. error

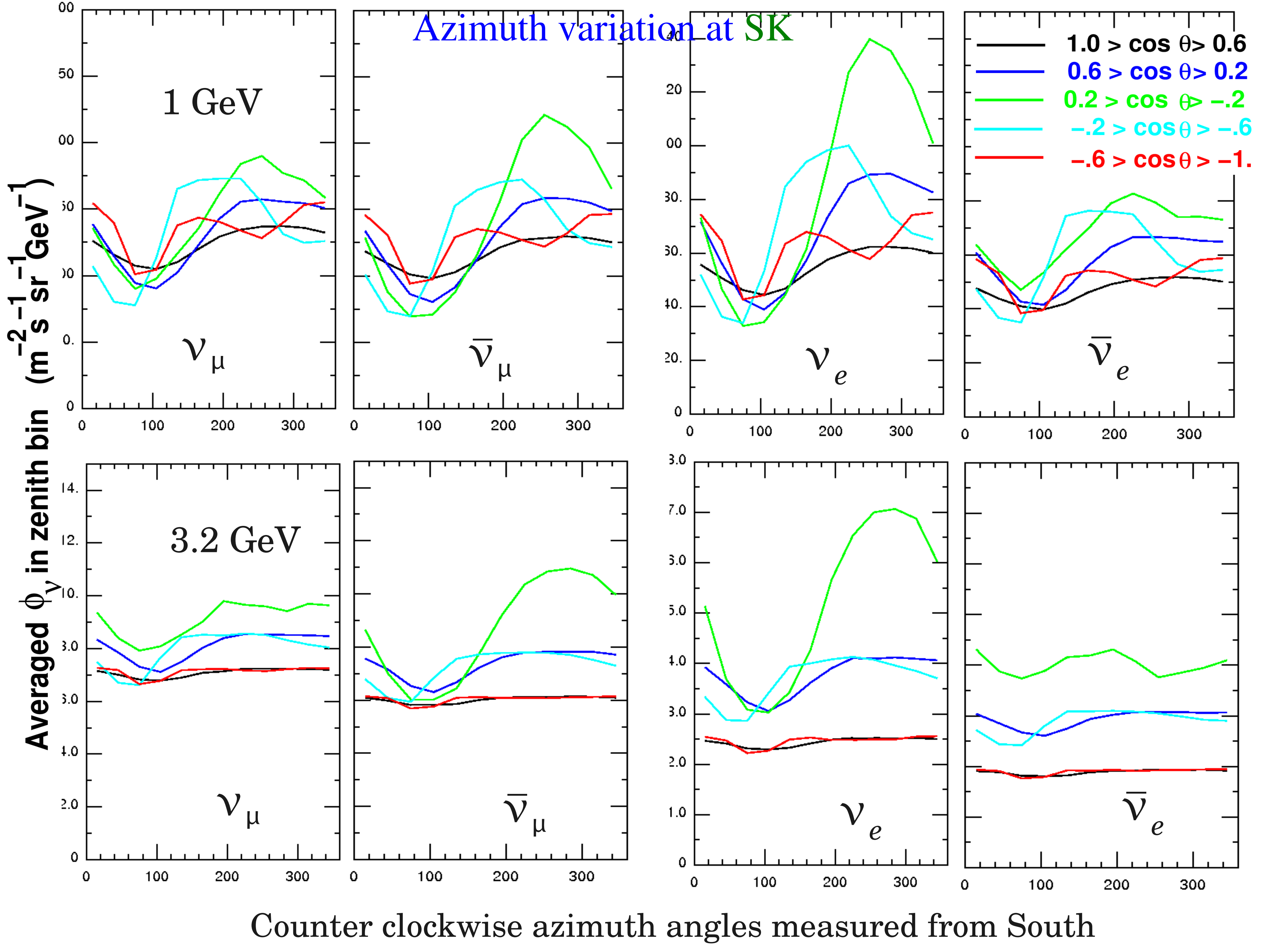
$$\frac{\Delta\phi_0}{\phi_0} = F(r)\cdot\frac{\Delta\phi_1}{\phi_1}$$



$r = \sqrt{0.5} \approx 0.7071$

Sum of averaged neutrino flux over all directions

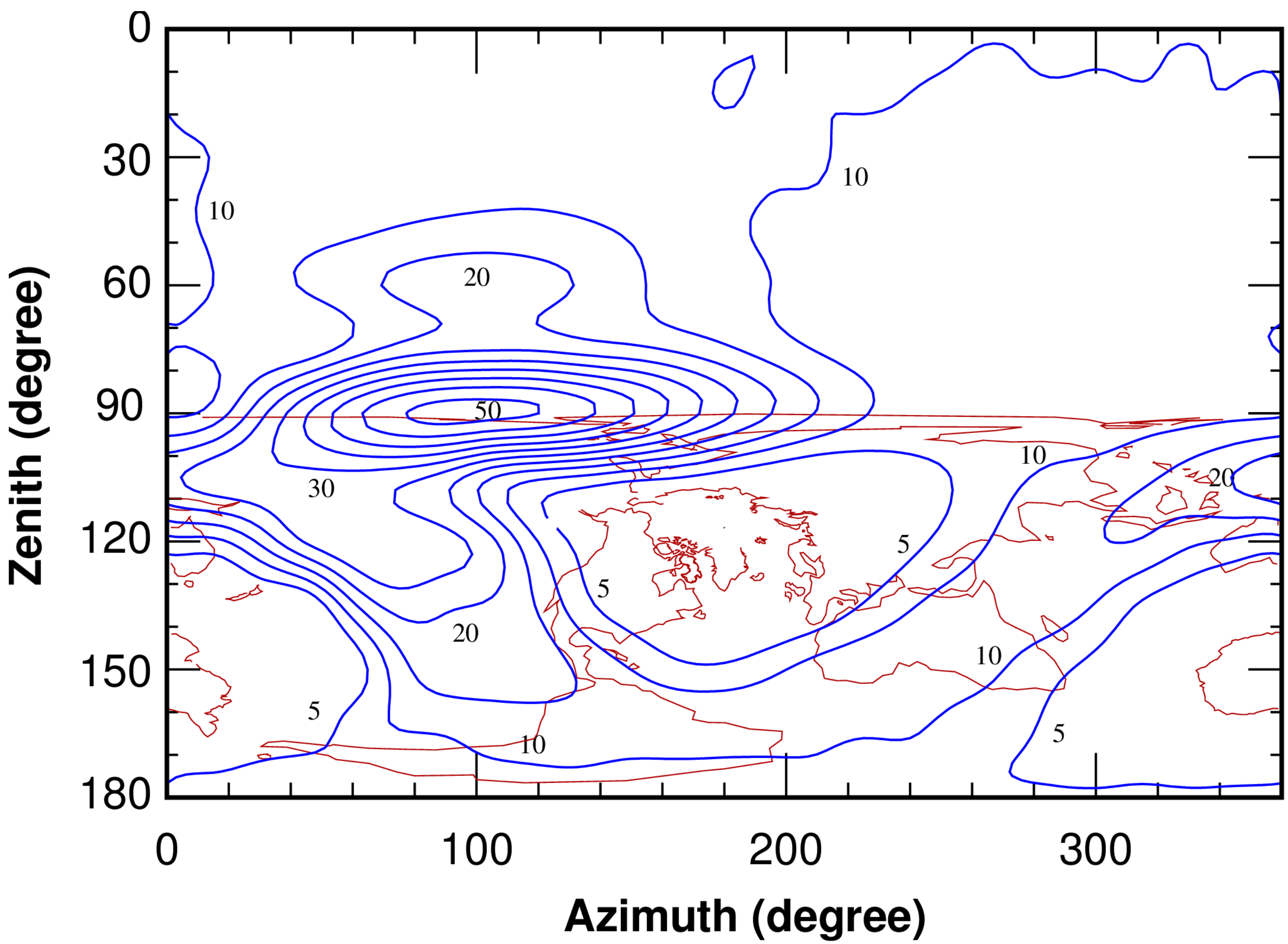




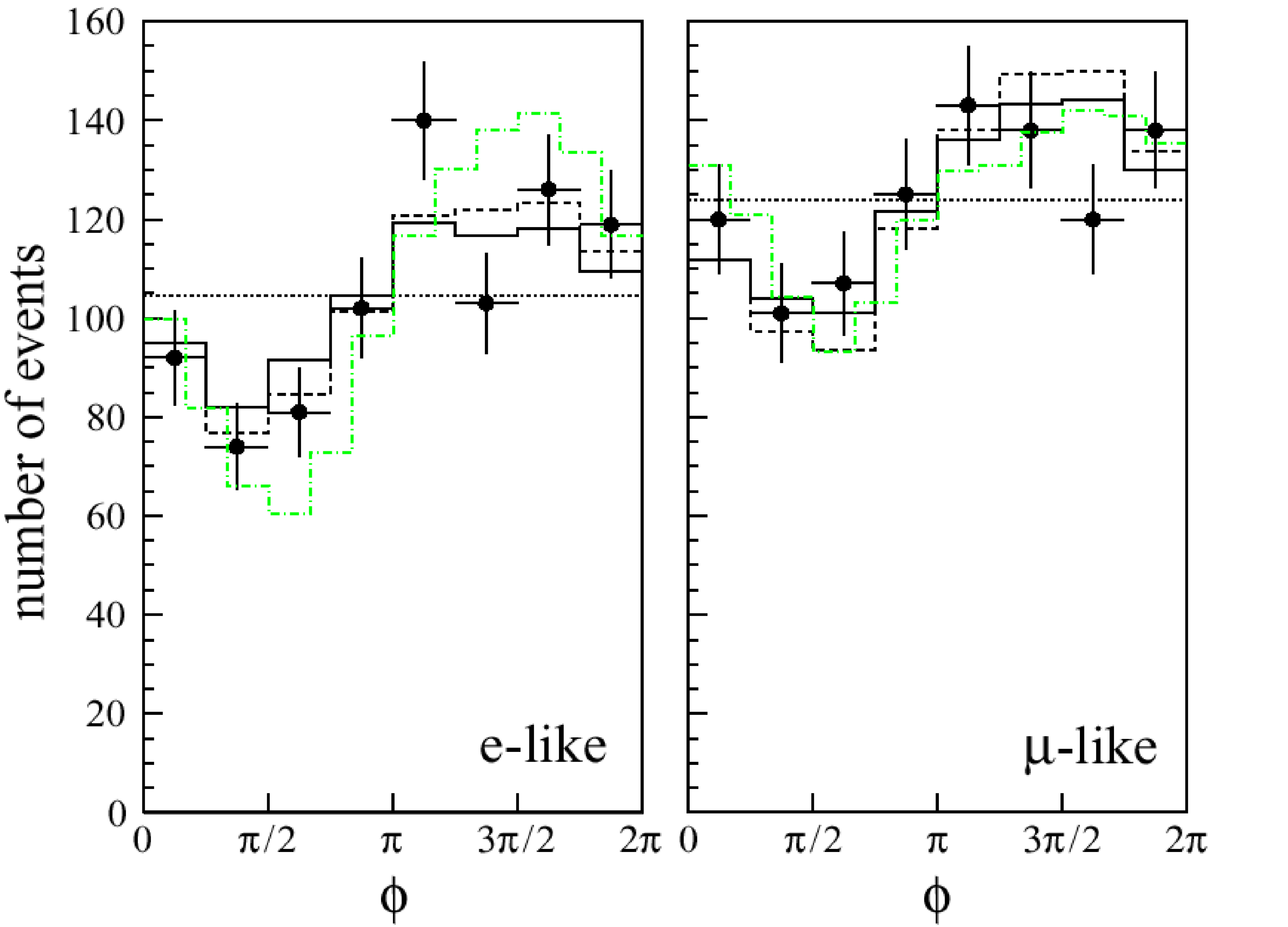
Azimuth variation at SK
1.0 > cos θ > 0.6
0.6 > cos θ > 0.2
0.2 > cos θ > -.2
-.2 > cos θ > -.6
-.6 > cos θ > -1.
1 GeV
3.2 GeV
Averaged ϕ_ν in zenith bin ($m^{-2}s^{-1}sr^{-1}GeV^{-1}$)
Counter clockwise azimuth angles measured from South

Rigidity cutoff contour map from SK

(NOT useful in 3D calculation)



Observed azimuth angle variation at Kamiokande



Muon bending

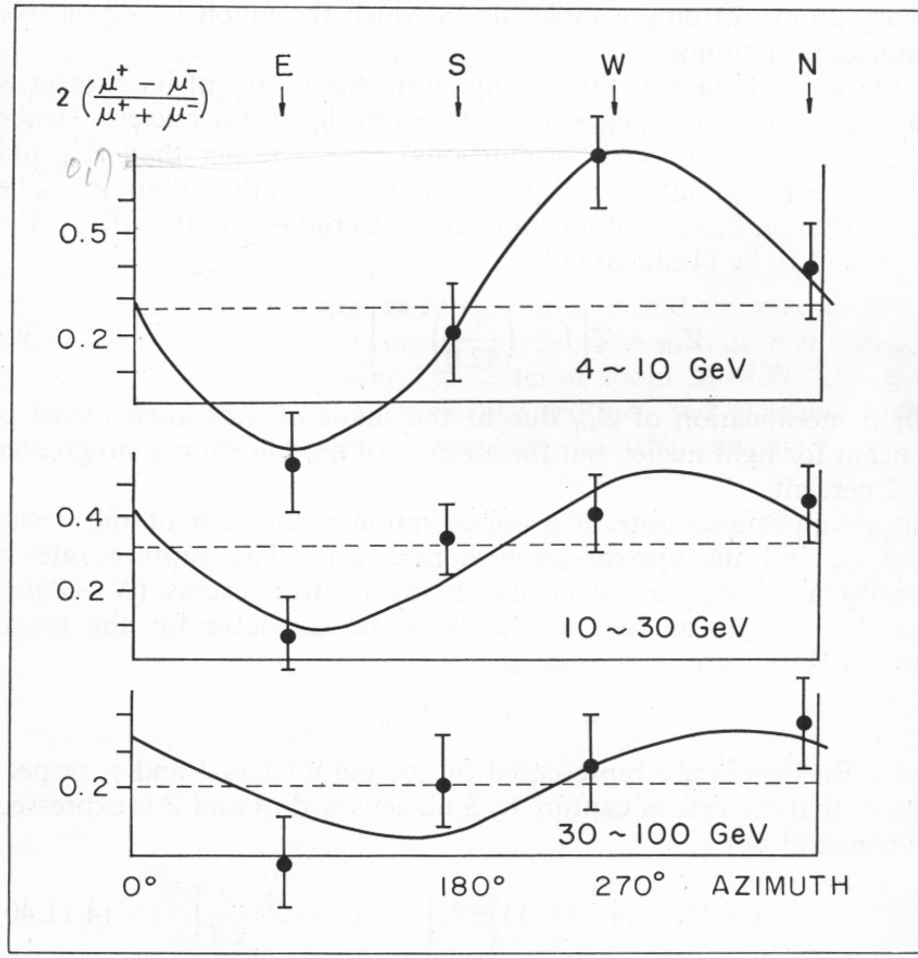
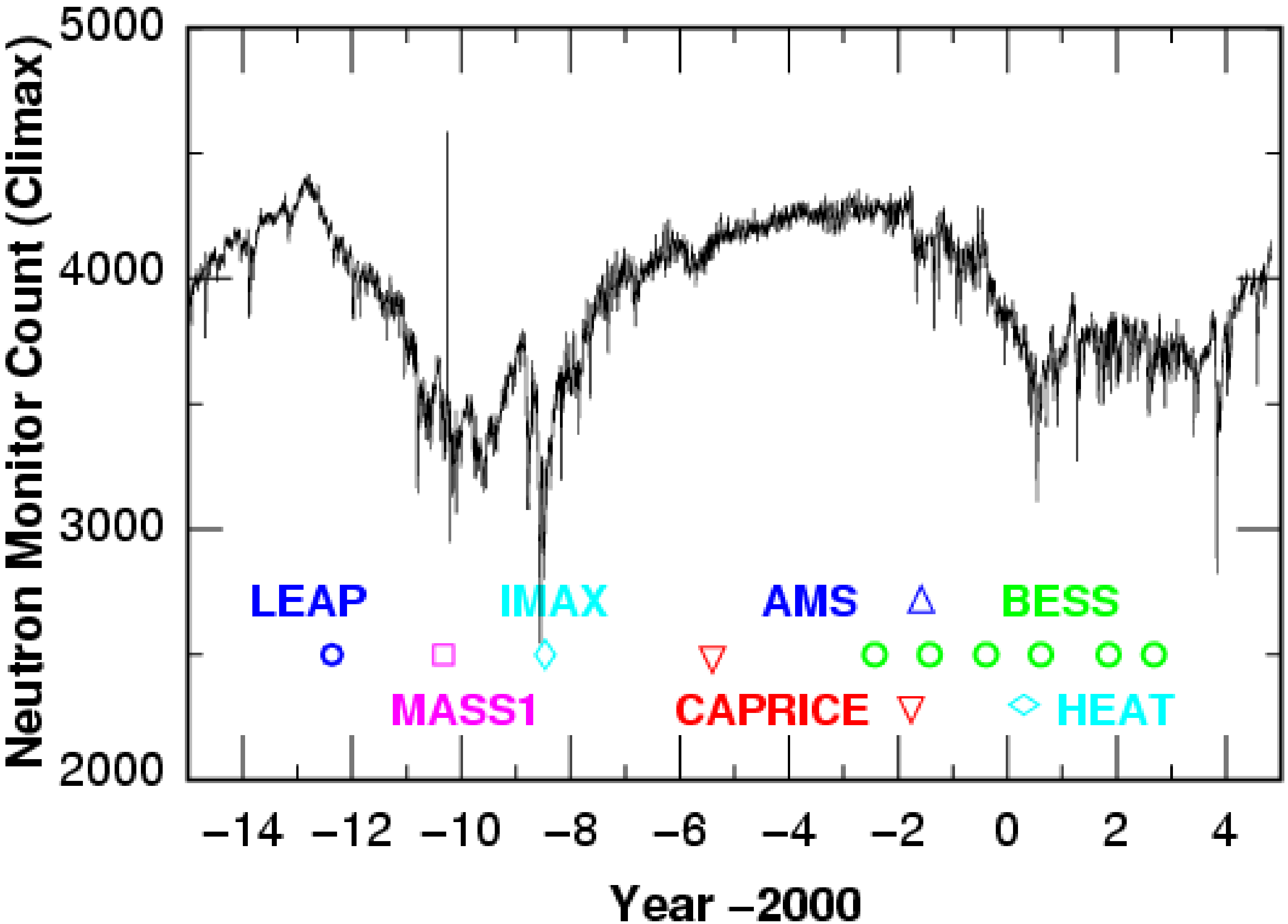


Fig. 4.27 Azimuth dependence of the positive excess of muons at zenith angle 78° at sea level. The energy intervals of sea-level muons are indicated (Kamiya 62).

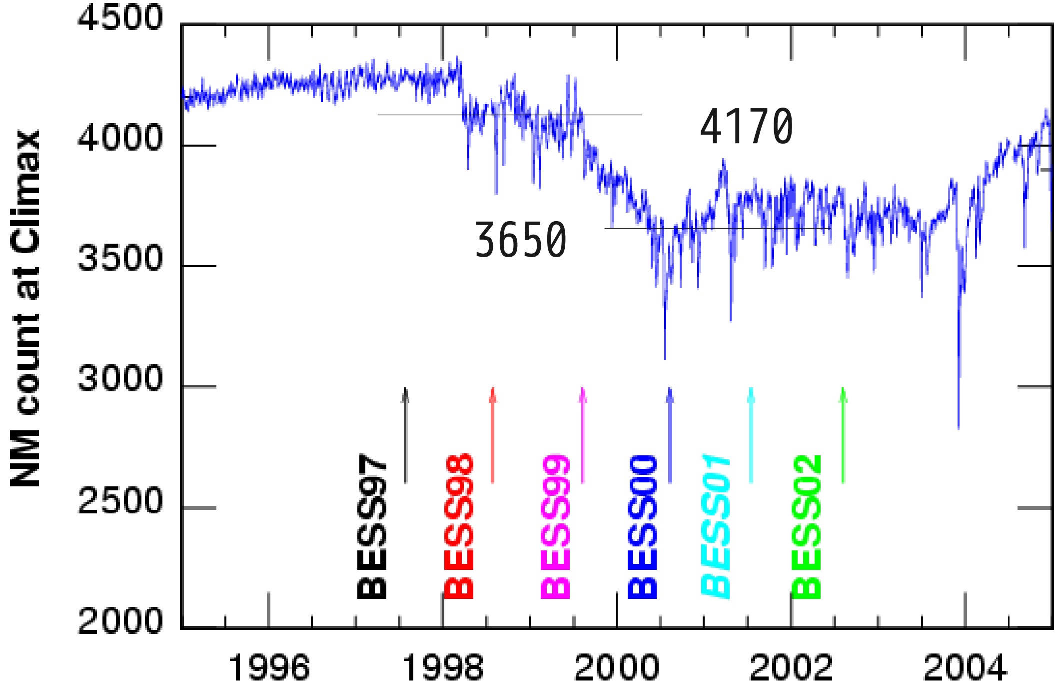
From Hayakawa "Cosmic Ray"

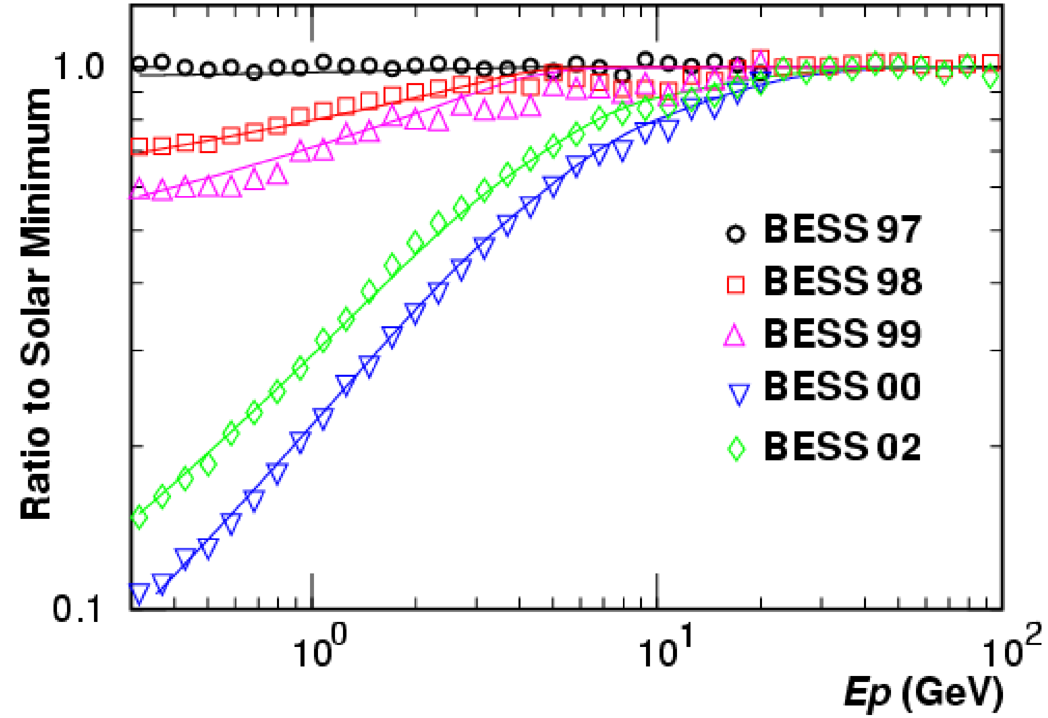
Modulation by the Solar Activity

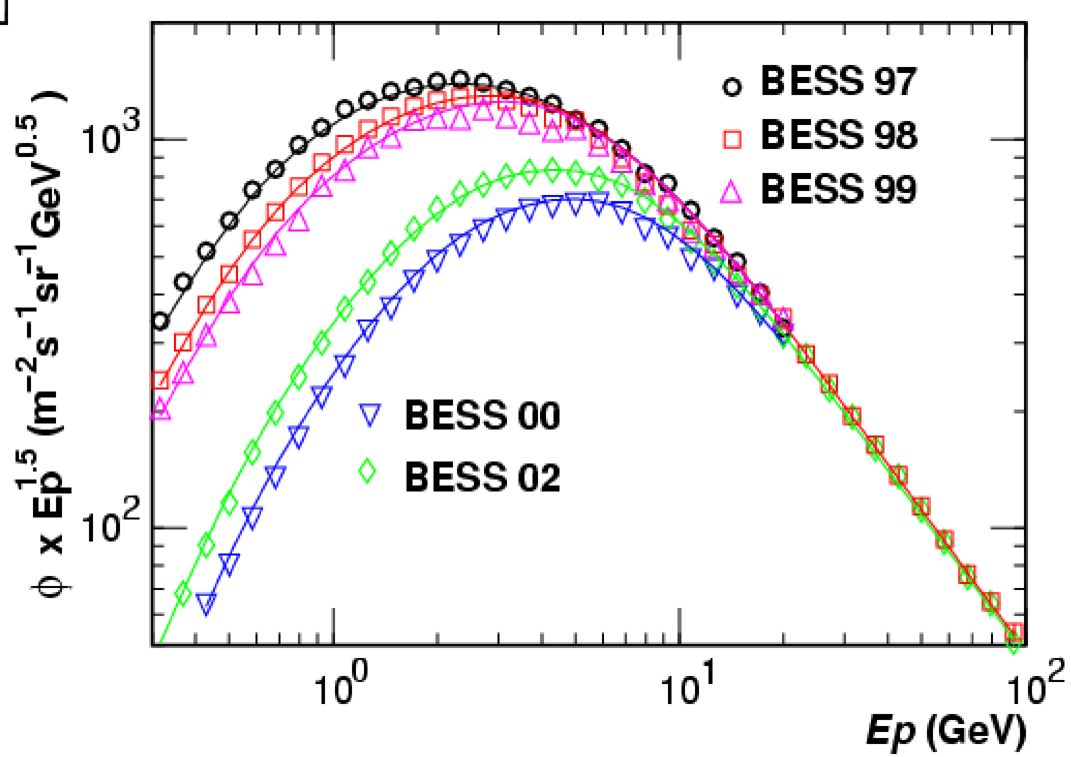


$M(N,r)$: Modulation function

BESS flight



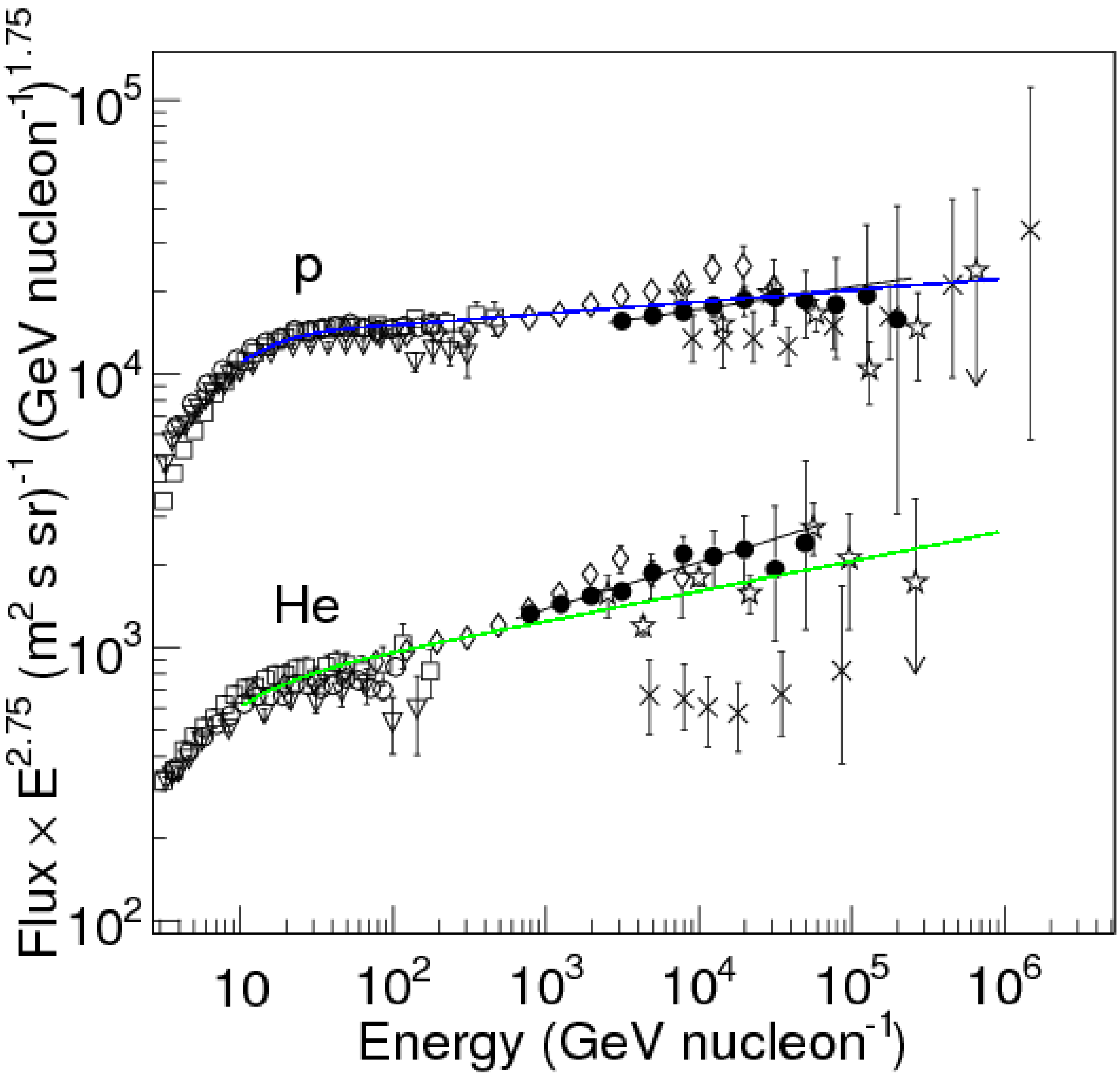




$$\phi_i(N,E_k)=\phi_i^{min}(E_k)\cdot M(N,r)$$

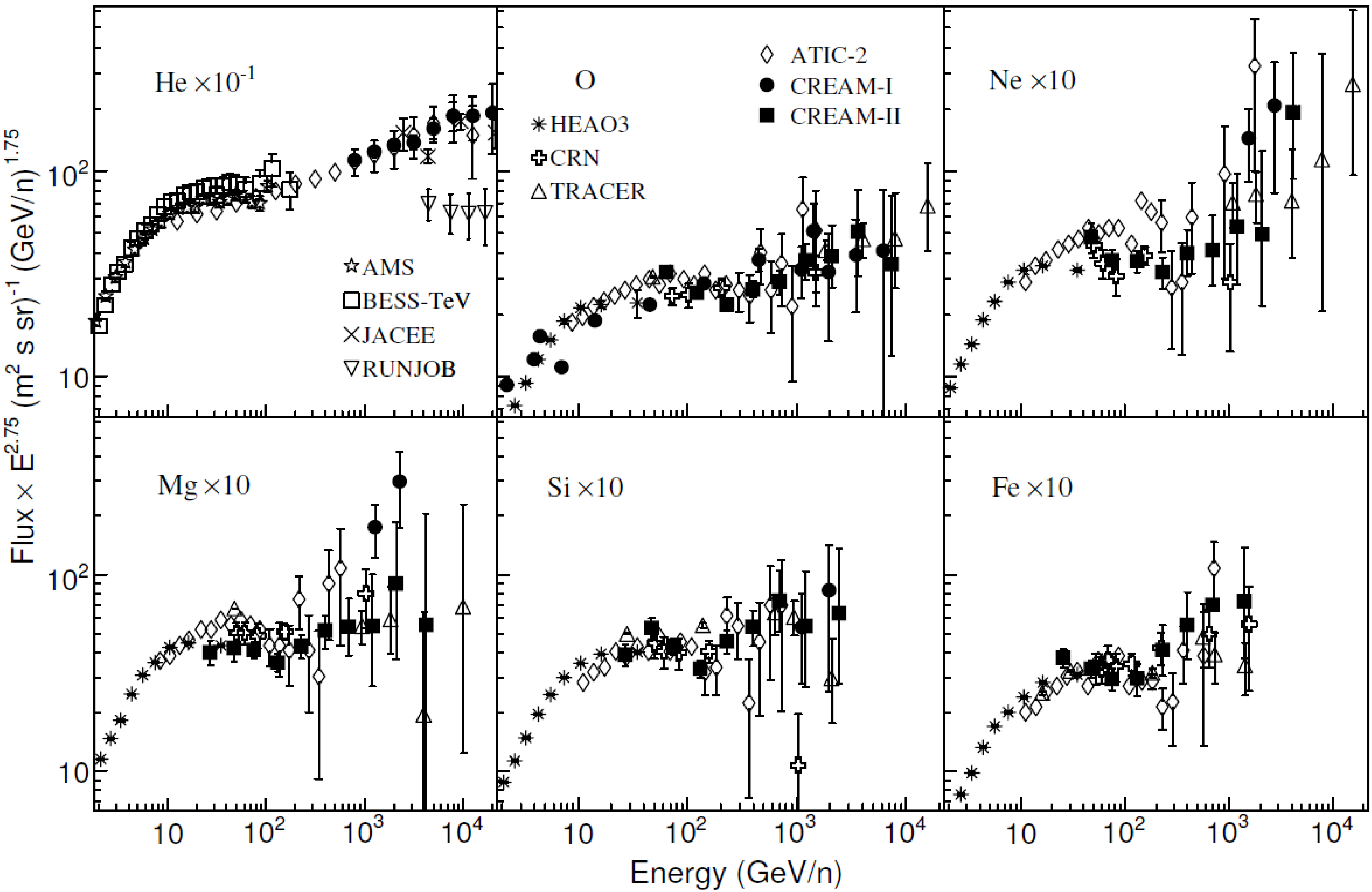
$$\phi_i^{min}(E_k)\equiv\phi_i^{1997}(E_k)$$

Compison with our primary flux model with
recent observations.



It may be the time to re-construct the primary flux model

With expanded vertical axis



Geomagnetic field model :　Japanese Science Almanac 2000

(Rikanennpyou 2000)

国際標準地磁気分布係数 (IGRF 1995)

	n	m	主磁場 (nT)	永年変化 (nT/年)		n	m	主磁場 (nT)	永年変化 (nT/年)		n	m	主磁場 (nT)	永年変化 (nT/年)
g	1	0	−29682	17.6	g	6	3	−172	1.9	g	9	0	4	0.0
g	1	1	−1789	13.0	h	6	3	67	−0.2	g	9	1	9	0.0
h	1	1	5318	−18.3	g	6	4	2	−0.2	h	9	1	−19	0.0
g	2	0	−2197	−13.2	h	6	4	−57	−0.9	g	9	2	1	0.0
g	2	1	3074	3.7	g	6	5	17	−0.2	h	9	2	15	0.0
h	2	1	−2356	−15.0	h	6	5	4	1.0	g	9	3	−12	0.0
g	2	2	1685	−0.8	g	6	6	−94	0.0	h	9	3	11	0.0
h	2	2	−425	−8.8	h	6	6	28	2.2	g	9	4	9	0.0
g	3	0	1329	1.5	g	7	0	78	−0.2	h	9	4	−7	0.0
g	3	1	−2268	−6.4	g	7	1	−67	−0.8	g	9	5	−4	0.0
h	3	1	−263	4.1	h	7	1	−77	0.8	h	9	5	−7	0.0
g	3	2	1249	−0.2	g	7	2	1	−0.6	g	9	6	−2	0.0
h	3	2	302	2.2	h	7	2	−25	0.2	h	9	6	9	0.0
g	3	3	769	−8.1	g	7	3	29	0.6	g	9	7	7	0.0
h	3	3	−406	−12.1	h	7	3	3	0.6	h	9	7	7	0.0
g	4	0	941	0.8	g	7	4	4	1.2	g	9	8	0	0.0
g	4	1	782	0.9	h	7	4	22	−0.4	h	9	8	−8	0.0
h	4	1	262	1.8	g	7	5	8	0.1	g	9	9	−6	0.0
g	4	2	291	−6.9	h	7	5	16	0.0	h	9	9	1	0.0
h	4	2	−232	1.2	g	7	6	10	0.2	g	10	0	−3	0.0
g	4	3	−421	0.5	h	7	6	−23	−0.3	g	10	1	−4	0.0
h	4	3	98	2.7	g	7	7	−2	−0.6	h	10	1	2	0.0
g	4	4	116	−4.6	h	7	7	−3	0.0	g	10	2	2	0.0
h	4	4	−301	−1.0	g	8	0	24	0.3	h	10	2	1	0.0
g	5	0	−210	0.8	g	8	1	4	−0.2	g	10	3	−5	0.0
g	5	1	352	0.1	h	8	1	12	0.4	h	10	3	3	0.0
h	5	1	44	0.2	g	8	2	−1	0.1	g	10	4	−2	0.0
g	5	2	237	−1.5	h	8	2	−20	−0.2	h	10	4	6	0.0
h	5	2	157	1.2	g	8	3	−9	0.4	g	10	5	4	0.0
g	5	3	−122	−2.0	h	8	3	7	0.2	h	10	5	−4	0.0
h	5	3	−152	0.3	g	8	4	−14	−1.1	g	10	6	3	0.0
g	5	4	−167	−0.1	h	8	4	−21	0.7	h	10	6	0	0.0
h	5	4	−64	1.8	g	8	5	4	0.3	g	10	7	1	0.0
g	5	5	−26	2.3	h	8	5	12	0.0	h	10	7	−2	0.0
h	5	5	99	0.9	g	8	6	5	0.2	g	10	8	3	0.0
g	6	0	66	0.5	h	8	6	10	−1.2	h	10	8	3	0.0
g	6	1	64	−0.4	g	8	7	0	−0.9	g	10	9	3	0.0
h	6	1	−16	0.3	h	8	7	−17	−0.7	h	10	9	−1	0.0
g	6	2	65	0.6	g	8	8	−7	−0.3	g	10	10	0	0.0
h	6	2	77	−1.6	h	8	8	−10	−0.6	h	10	10	−6	0.0

IGRF: International Geomagnetic Reference Field

1995.0 年に対する国際標準地磁気分布の実験式

$$X(\text{北向き})=\frac{1}{r}\frac{\partial V}{\partial \theta},\quad Y(\text{東向き})=\frac{-1}{r\sin\theta}\frac{\partial V}{\partial \lambda},\quad Z(\text{下向き})=\frac{\partial V}{\partial r}$$

ここに

$$V=a\sum_{n=1}^{n=10}\sum_{m=0}^{m=n}\left(\frac{a}{r}\right)^{n+1}\left[g_n^m\cos m\lambda+h_n^m\sin m\lambda\right]P_n^m(\mu)$$

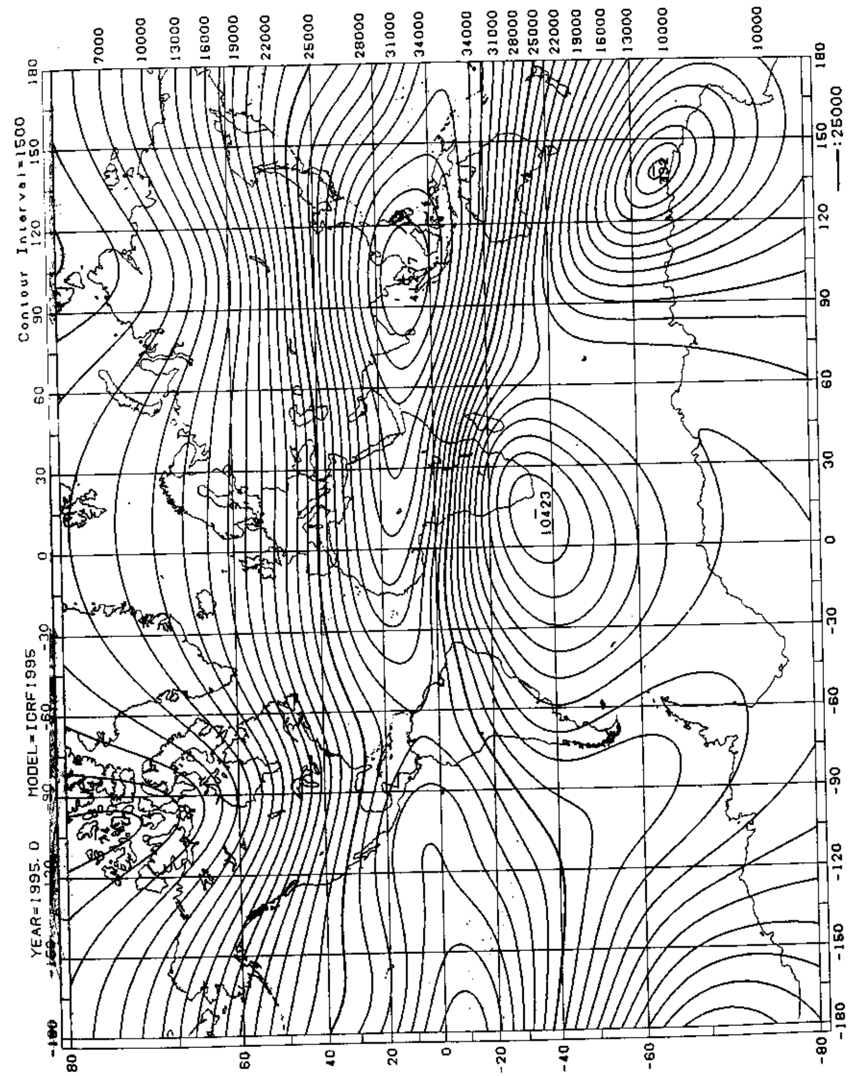
$$P_n^m(\mu)=\frac{1}{2^n n!}\left[\frac{\varepsilon_m(n-m)!(1-\mu^2)^m}{(n+m)!}\right]^{1/2}\frac{d^{m+n}(\mu^2-1)^n}{d\mu^{m+n}}$$

$$\begin{cases}\mu=\cos\theta\\ \varepsilon_m=1,\quad m=0\\ \varepsilon_m=2,\quad m\geqq 1\end{cases}$$

である．また，t_0 を 1995.0 年とすれば，他の年の係数値は

$$g_n^m(t)=g_n^m(t_0)+\dot{g}_n^m(t-t_0),\quad h_n^m(t)=h_n^m(t_0)+\dot{h}_n^m(t-t_0)$$

と表わすことができる．ここに，$\dot{g}_n^m$，$\dot{h}_n^m$ は g_n^m，h_n^m の永年変化を (nT/年) で与えるものである．



Latest is IGRF11 : http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html