Atmospheric Neutrino Flux Calculation

M. Honda @ NuInt15, Oosaka

Based on the work published as the HKKM paper series, and a preliminary work with recent Cosmic Ray observations. (AMS02, BESS-polar, and others)

Components of the Calculation

- Primary Cosmic Rays Model
  AMS01 and BESS observation for < 100 GeV
  JACEE and RUNJOB for > 3 TeV and the interpolations

- Hadronic interaction Models
  DPMJET-III (>5GeV) and NUCRIN (<5GeV) in HKKM04 and HKKMS07.
  DPMJET-III (>32GeV) and JAM (<32GeV) in HKKM11 and HAKKM15.
  They are modified in the Muon Calibration

- Atmosphere Model
  US-starndard'76 before HAKKM15
  NRLMSISE-00 in HAKKM15

- Geomagnetic Model
  IGRF00 (HKKM04) ～ IGRF10 (HAKKM15)

3D-Calculation Scheme

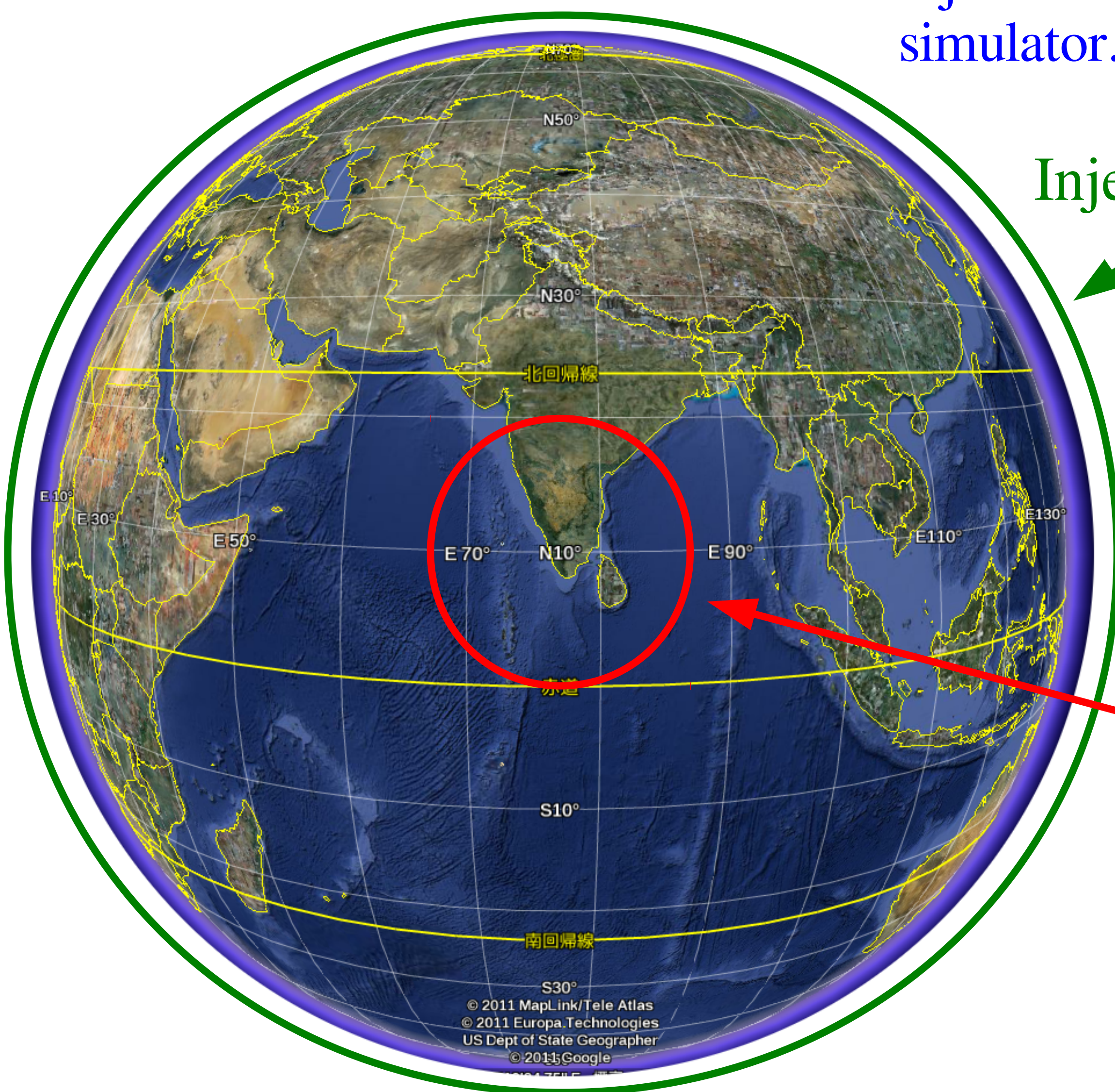
Re = 6378km

Simulation Sphere (Rs = 10 x Re)

Cosmic rays go out this sphere are discarded. Also the cosmic rays reach this sphere in back tracing from the injection sphere are fed to the simulator.

Injection Sphere (Re +100lm)

Cosmic Rays are sampled and injected here



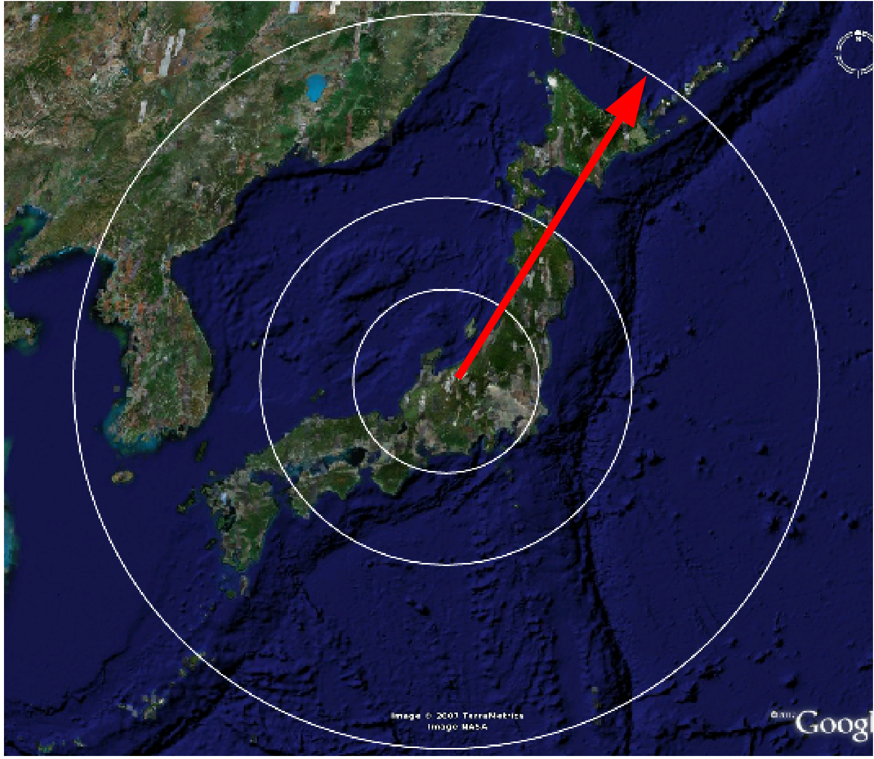
Virtual Detector

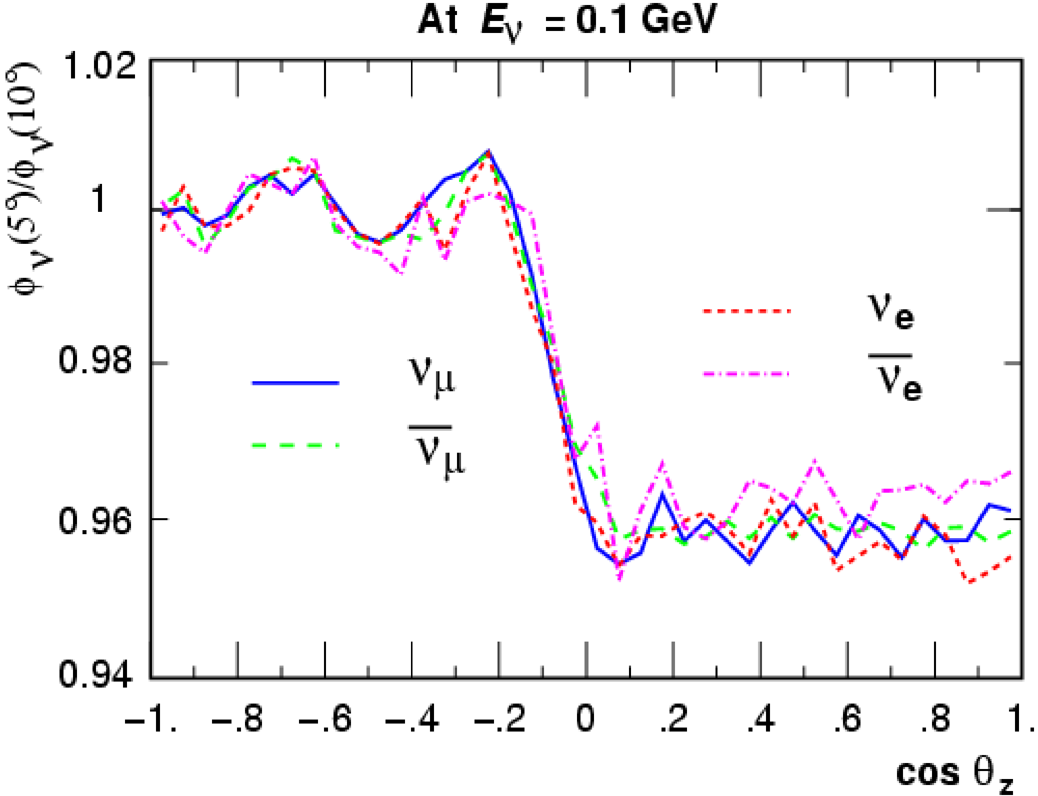
All neutrinos path through are used for the flux calculation.

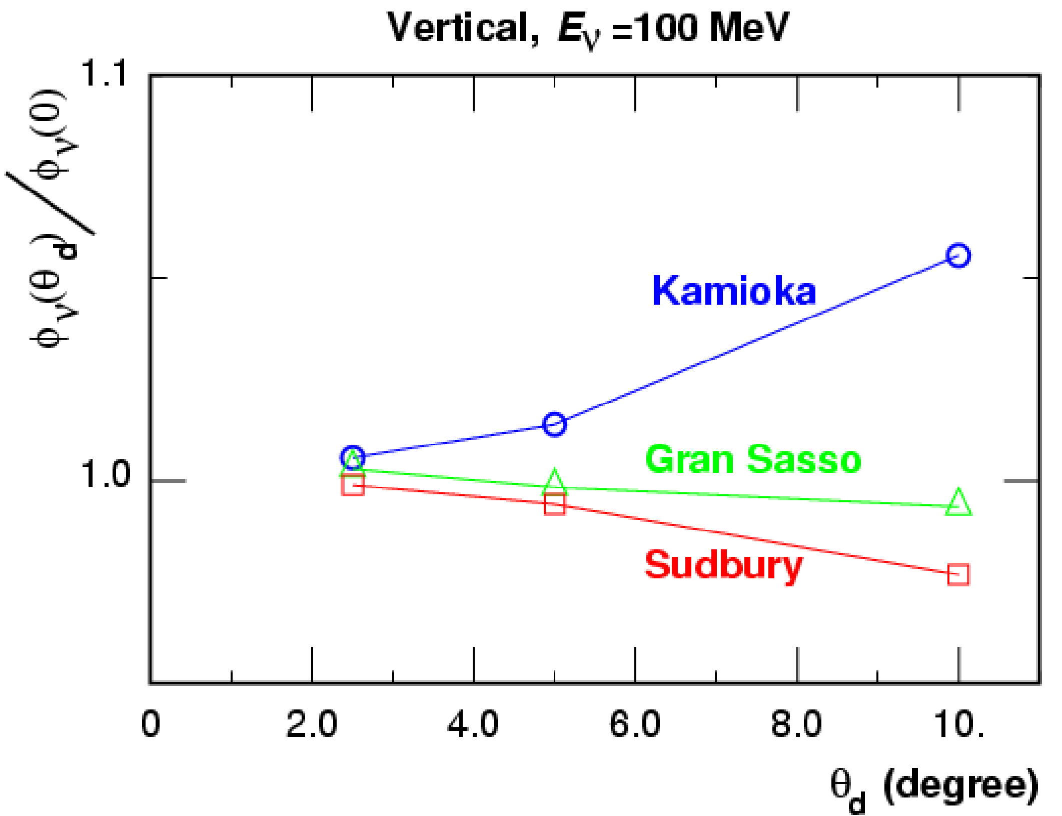
Error due to the large size
Virtual Detector

In HKKM07 (PRD 2007), we took

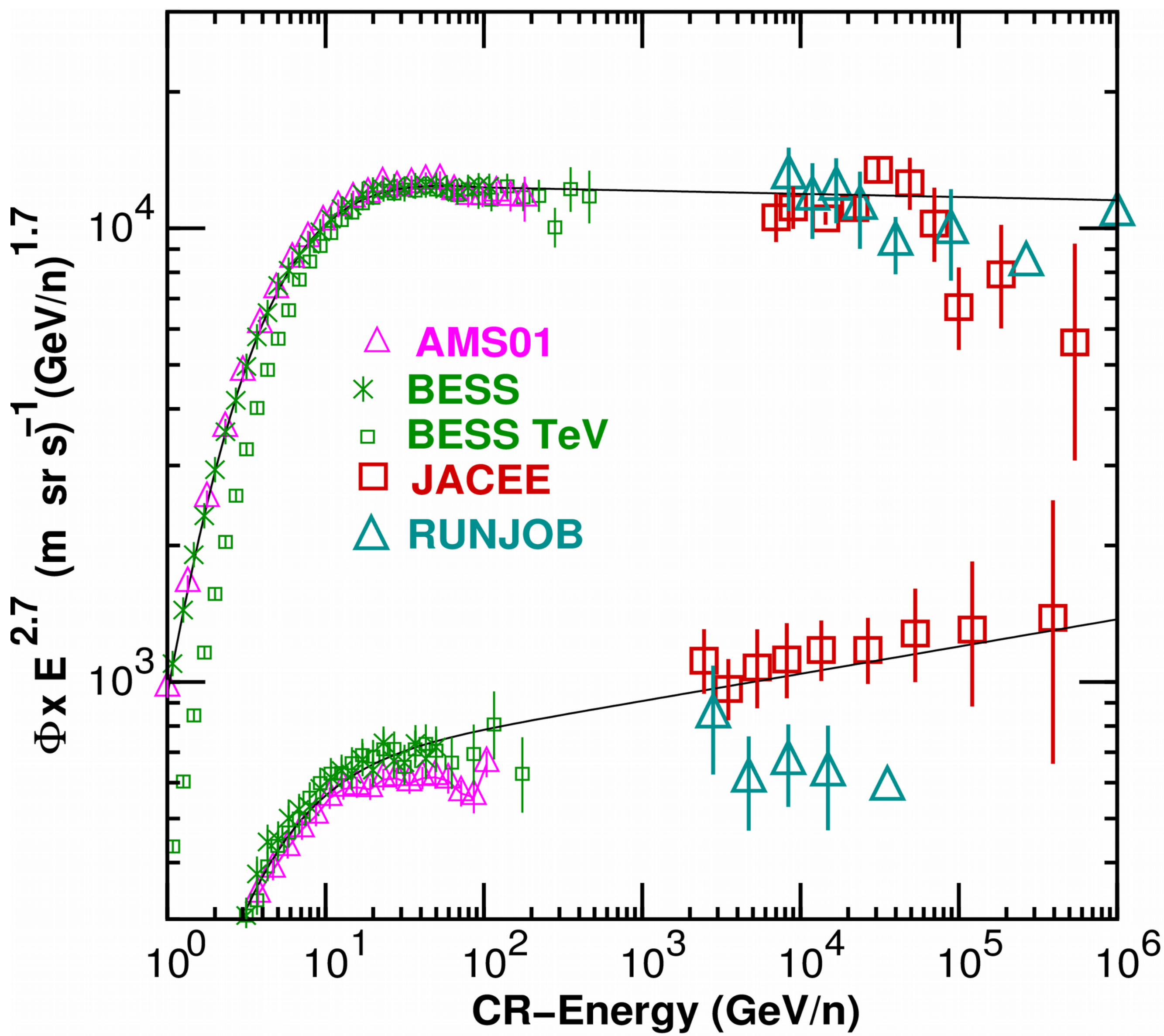
$$\phi_\nu(0) \simeq -\frac{1}{3}\phi_\nu(10) + \frac{4}{3}\phi_\nu(5)$$

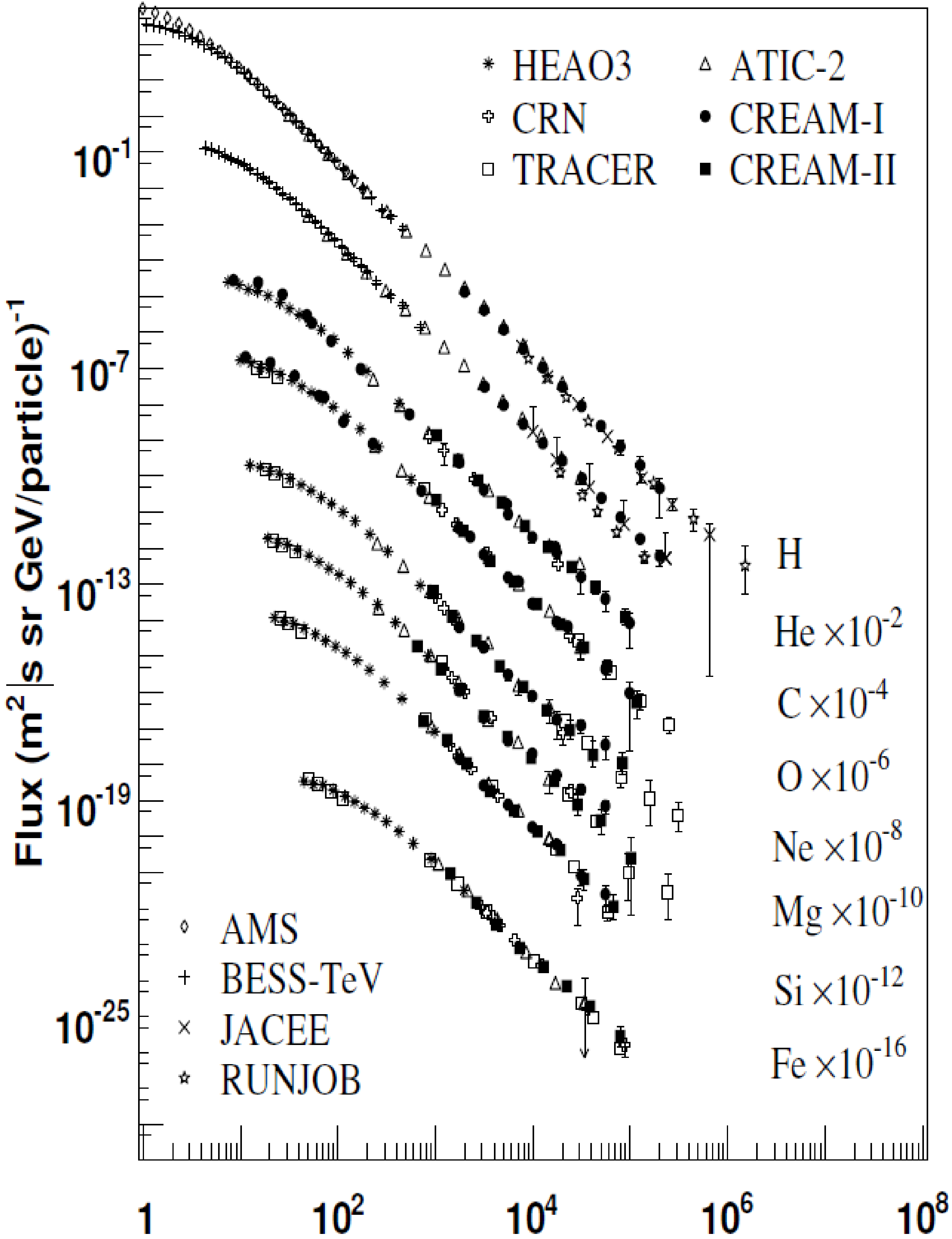






Our primary Cosmic Ray model and reference data





From
E.S. Seo @ ICRC2009

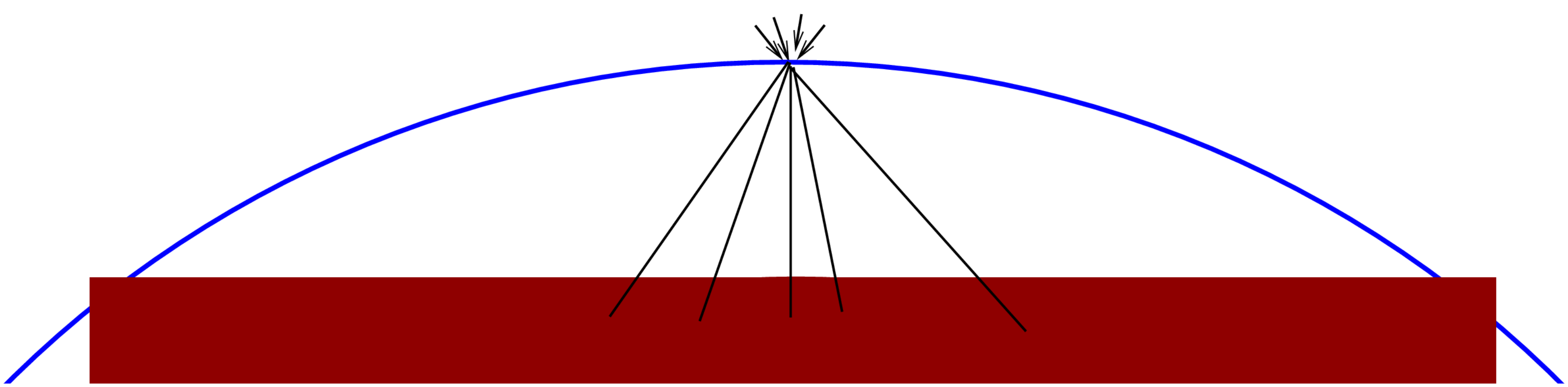
Other chemical compositions are also considered in the calculation, but they give small contributions.

Examination of Interaction Model with muon flux.

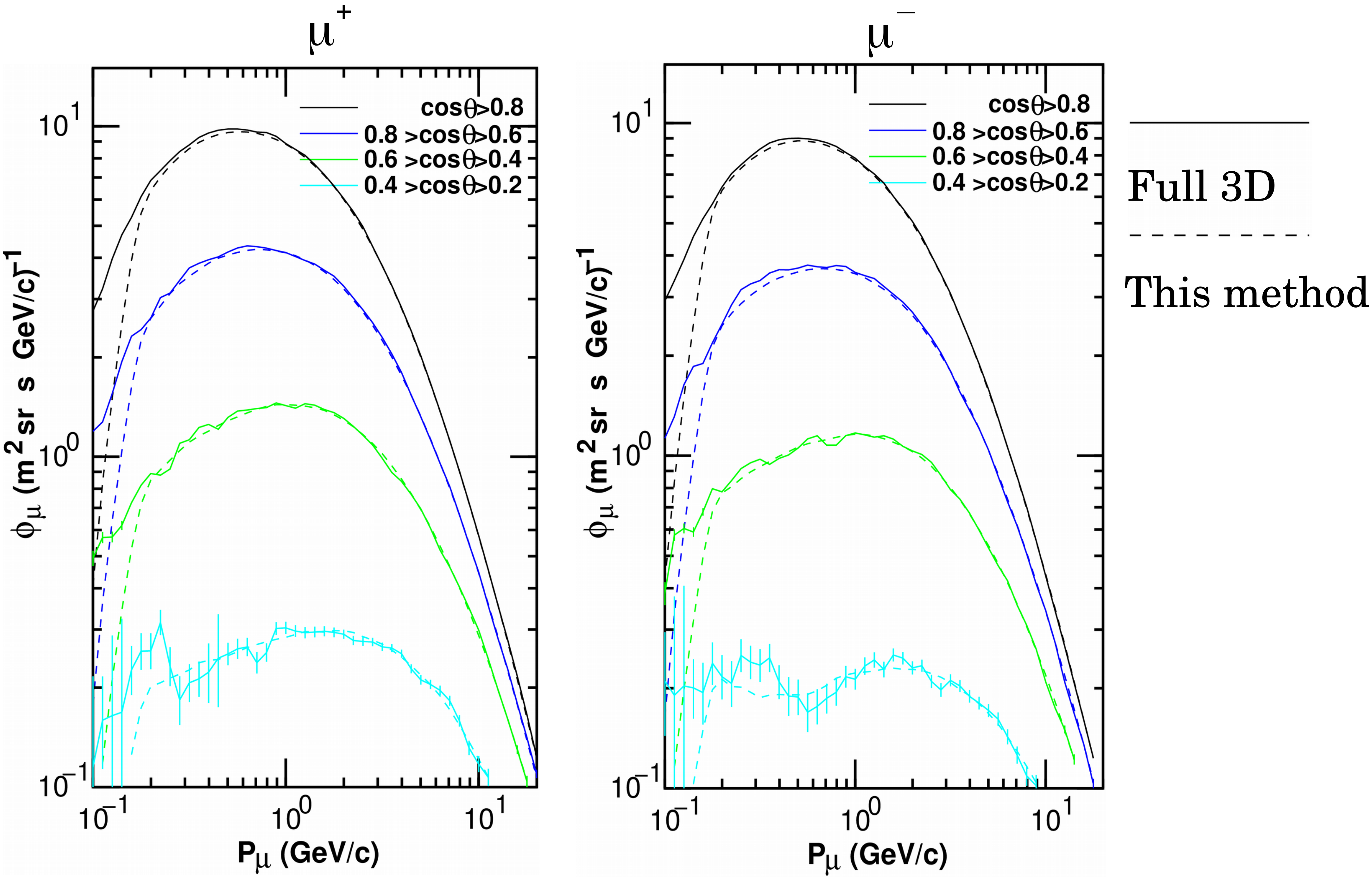
(Muon calibration of interaction model)

As the muon flux is a "local quantity" ($\gamma ct \sim$ 60km for 10 GeV muons), a first calculation method is available.

Inject cosmic rays at a point of injection sphere just above the observation point, and collect the muons on all the surface of Earth, then consider the muons are observed at the observation point.

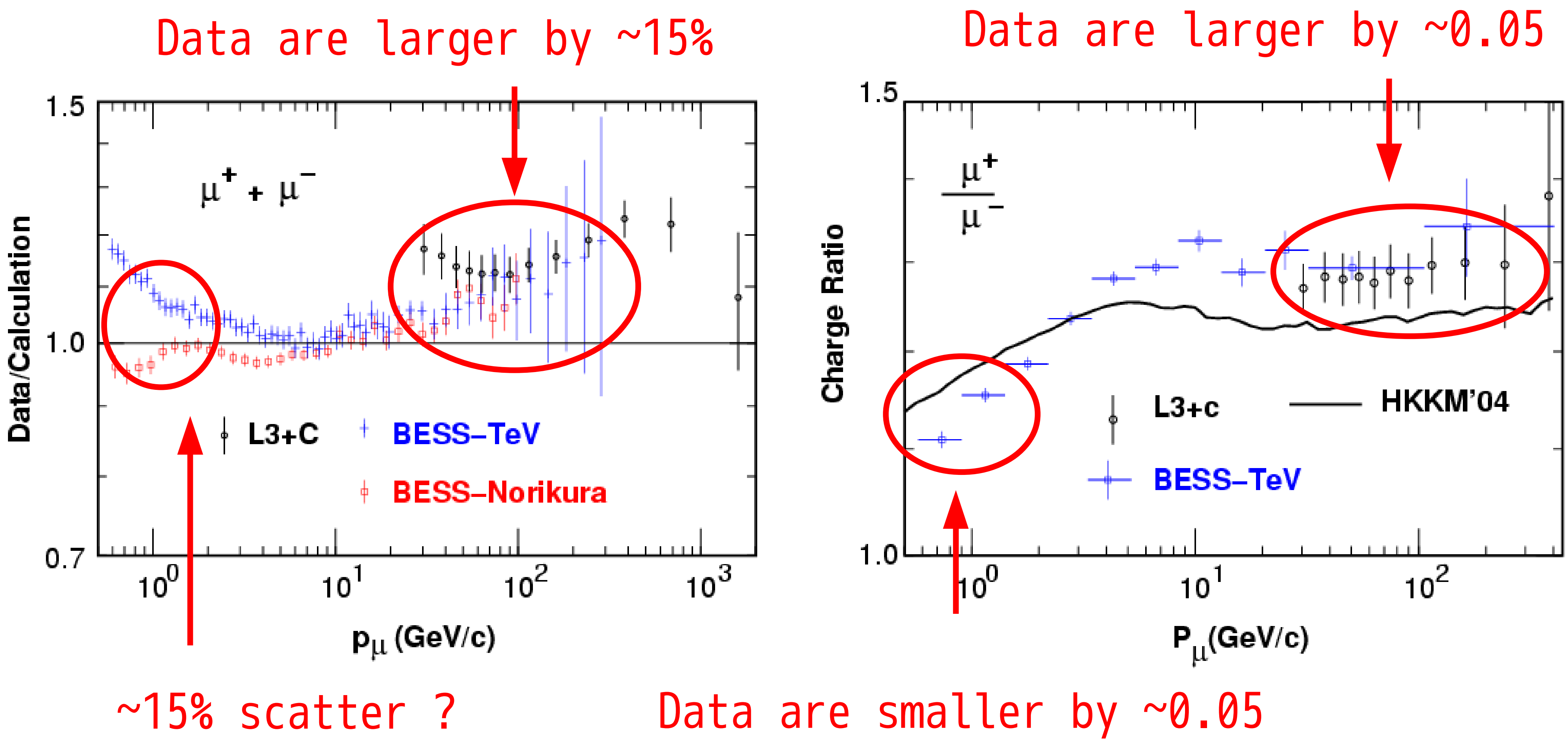


Comparison with full 3D calculation



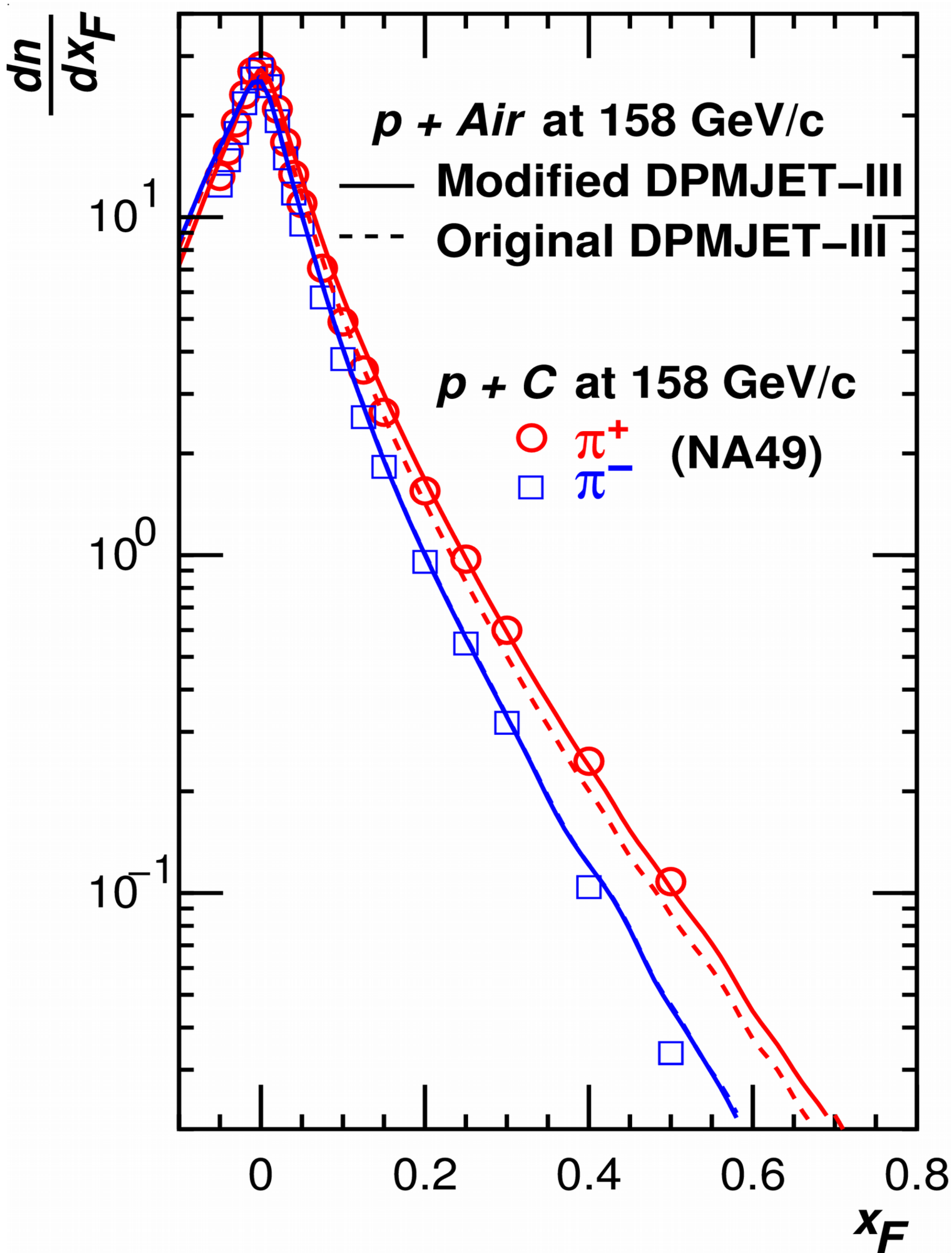
This method works above 0.2 GeV/c.

Comparison with precision muon measurements

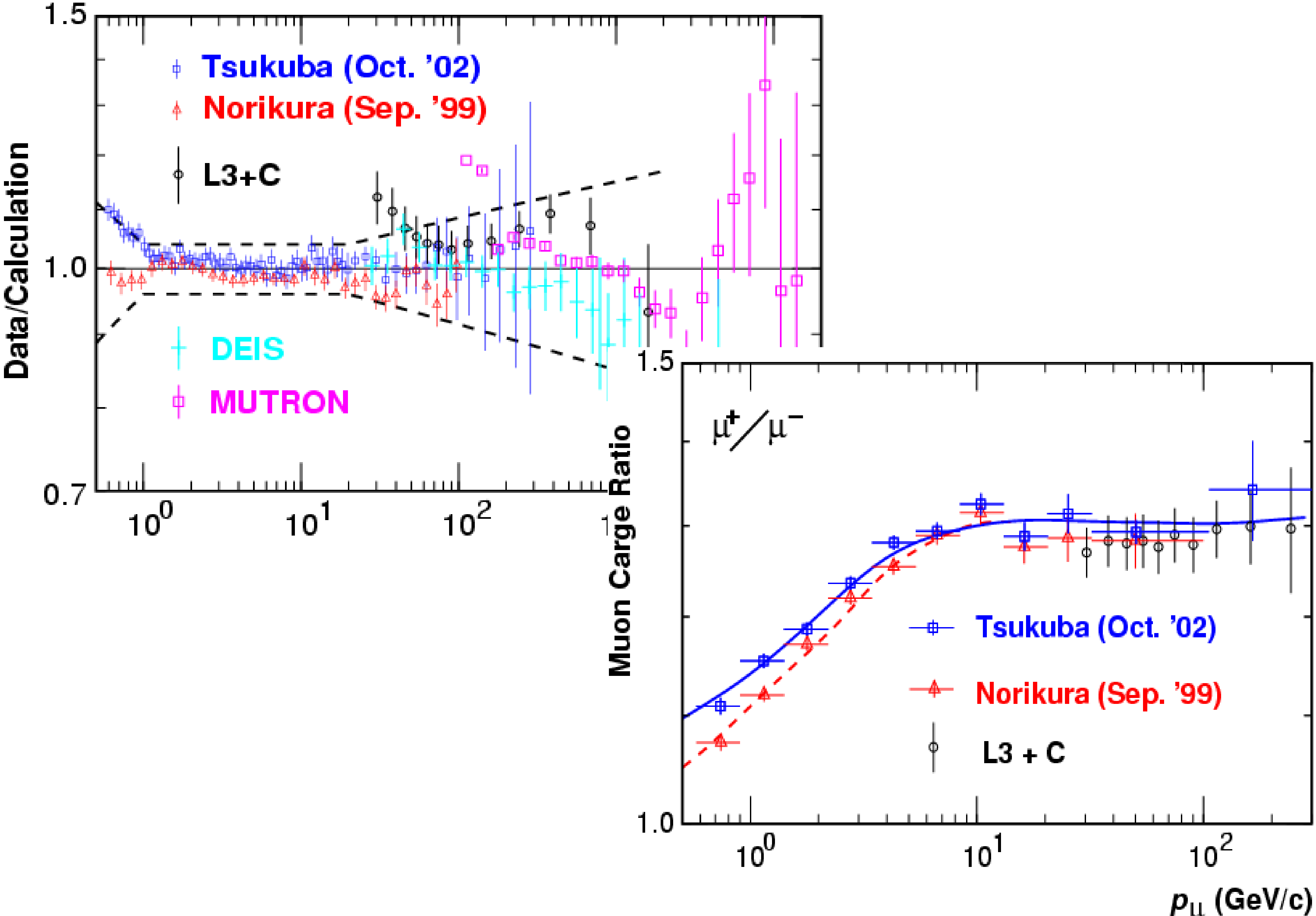


==> DPMJET-III Should be Modified

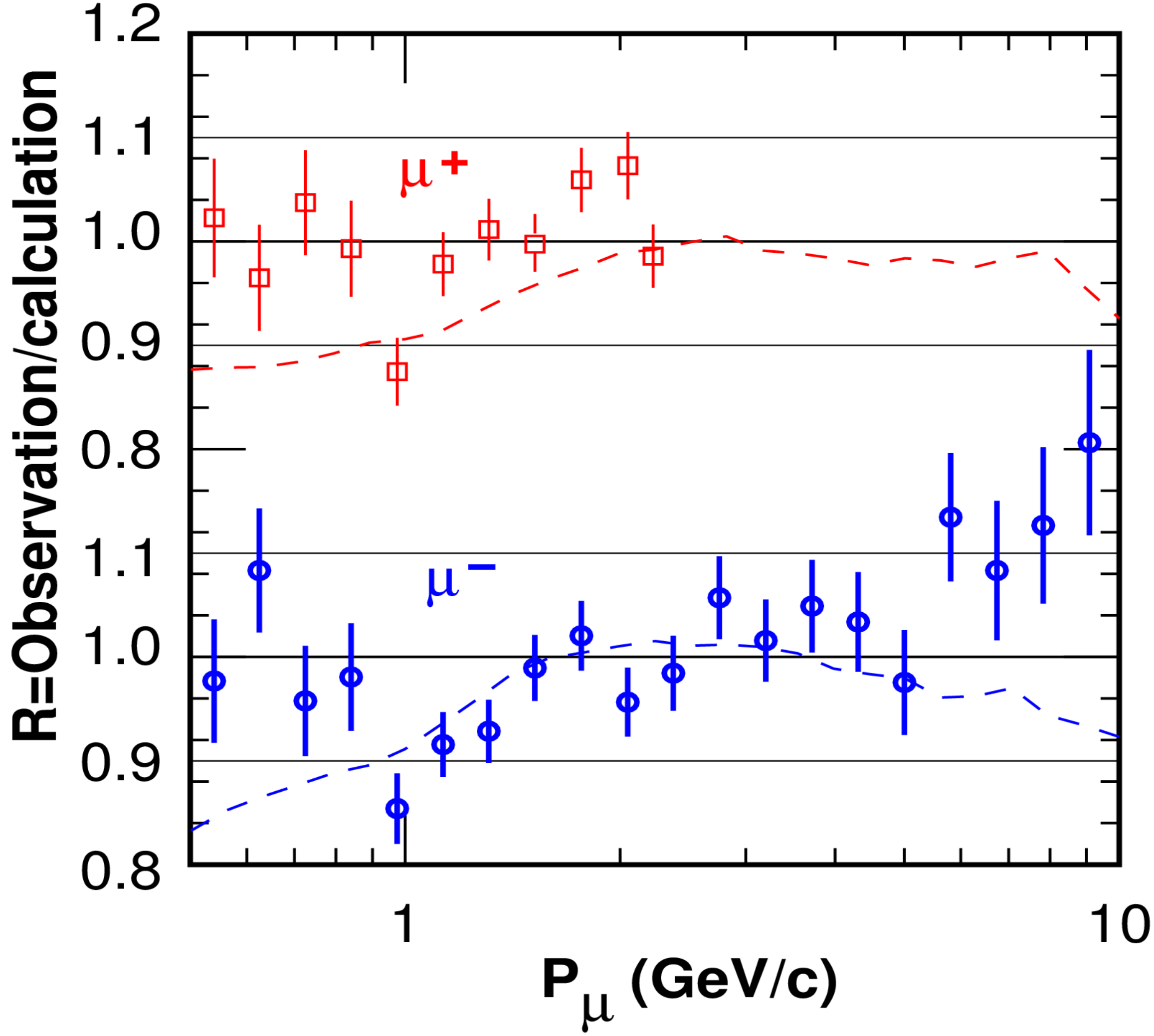
(modified) DPMJET-III vs NA49



Comparison AFTER the modification

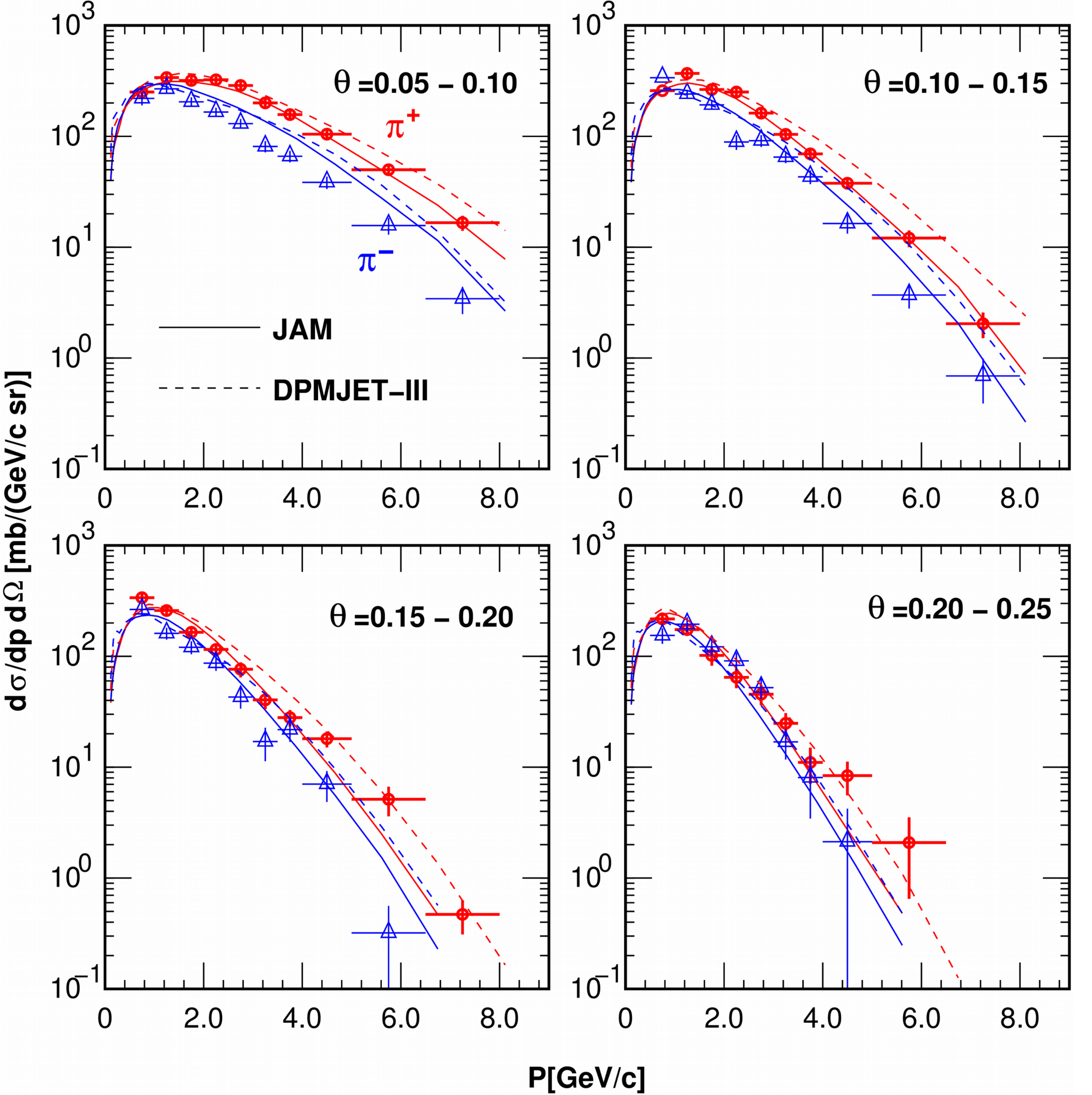


JAM + Modified DPMJET-II vs Muons at the Balloon altitude
(HKKM11)



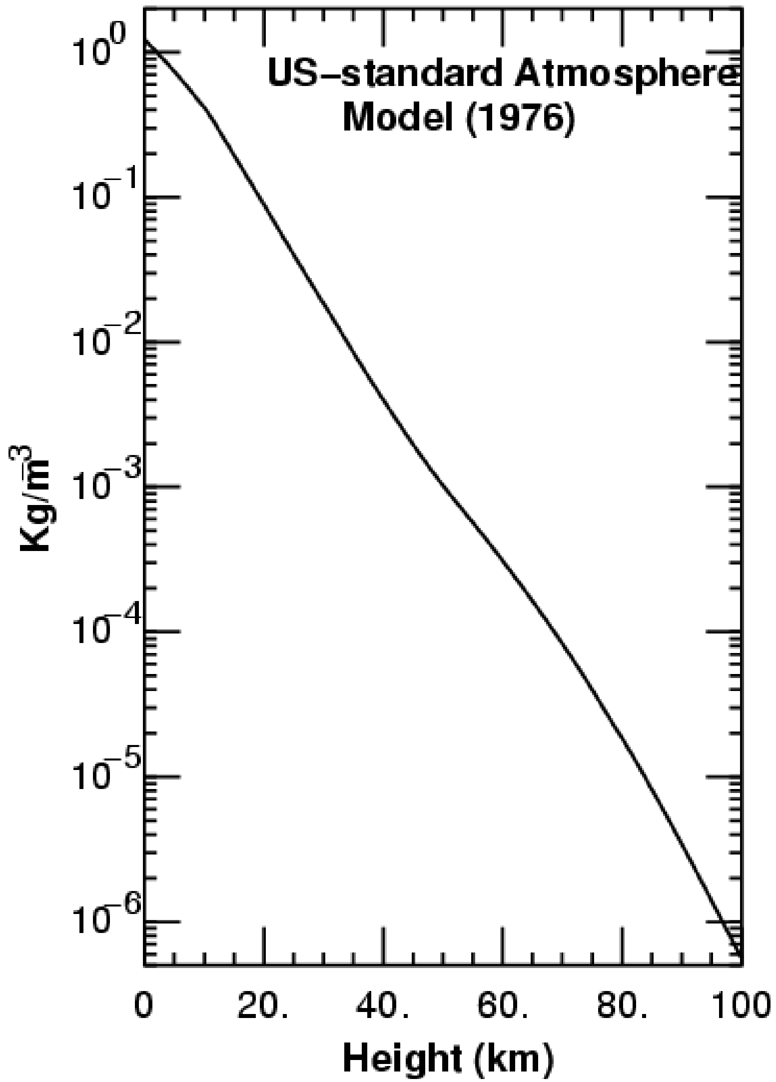
Good agreement ! → Use DPMJET-III above 32 GeV and JAM below 32 GeV

JAM vs HARP

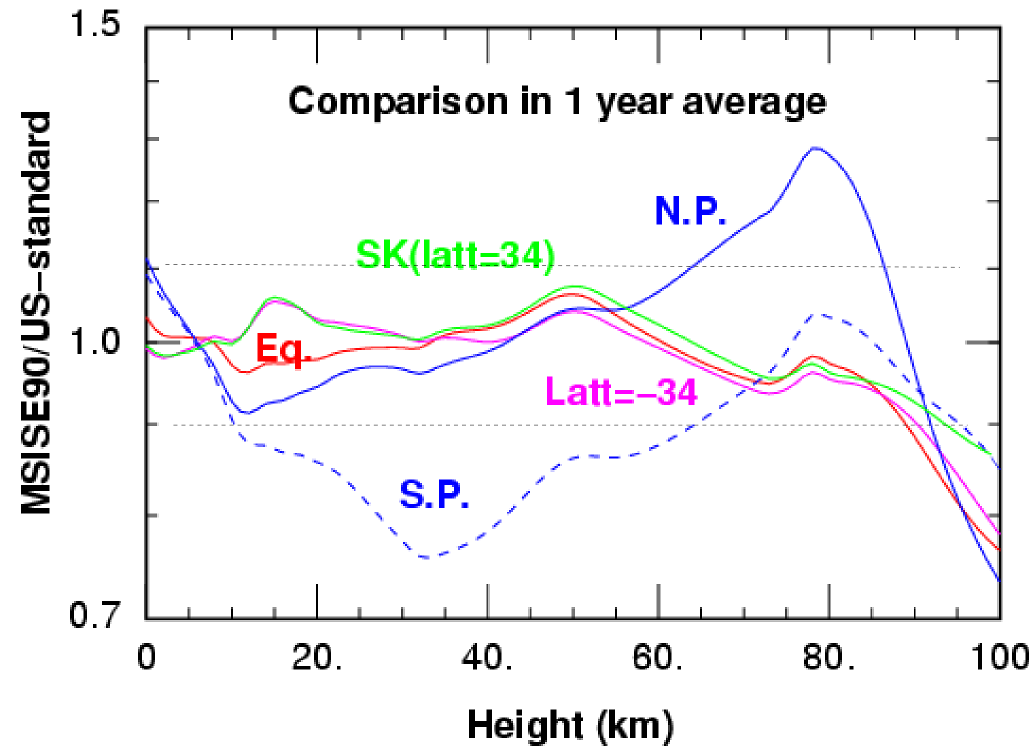


θ =0.05 – 0.10
θ =0.10 – 0.15
θ =0.15 – 0.20
θ =0.20 – 0.25
π+
π−
JAM
DPMJET-III
dσ/dp dΩ [mb/(GeV/c sr)]
P[GeV/c]

Atmosphere Model

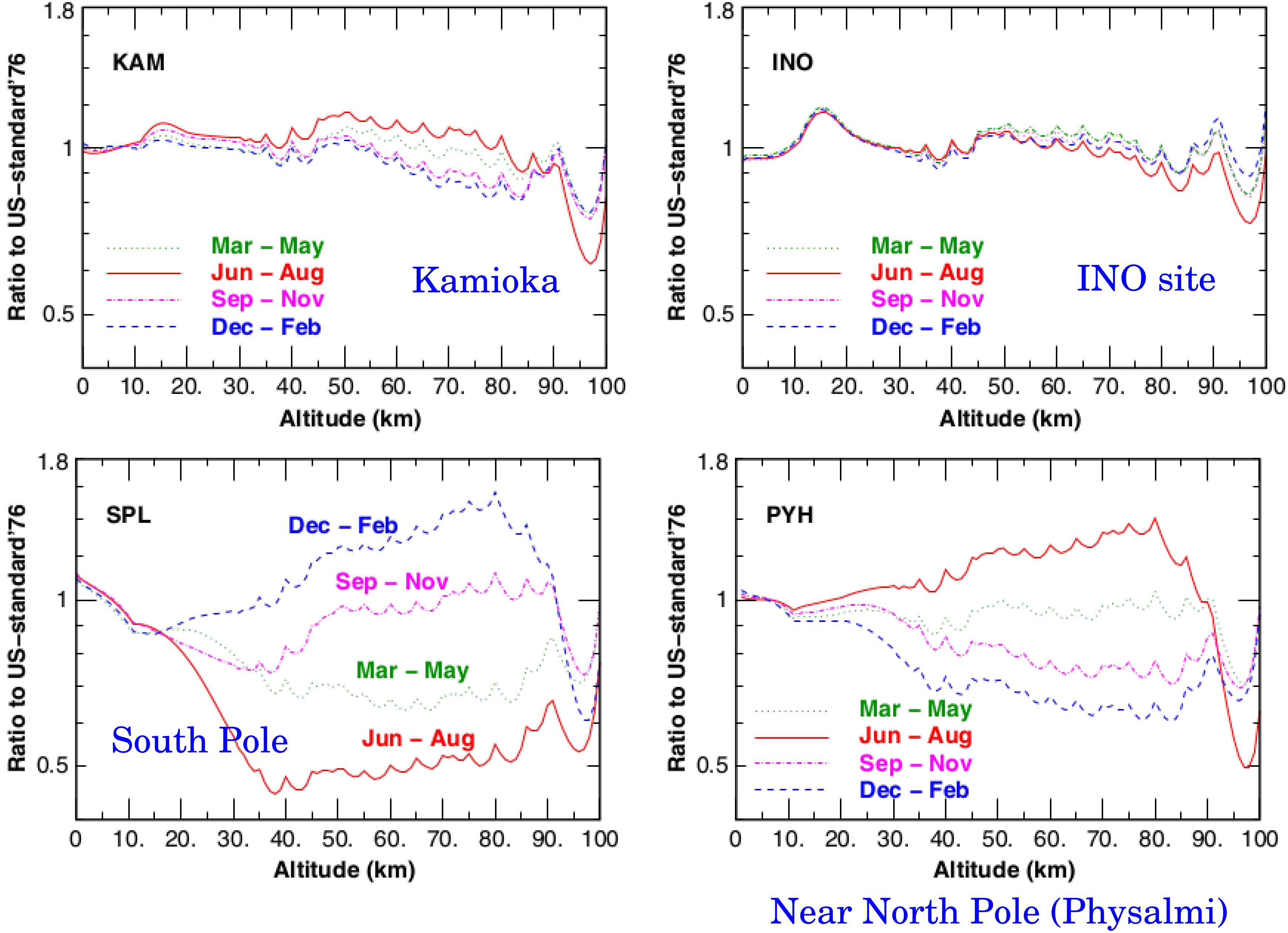


Air density comparison with MSISE90



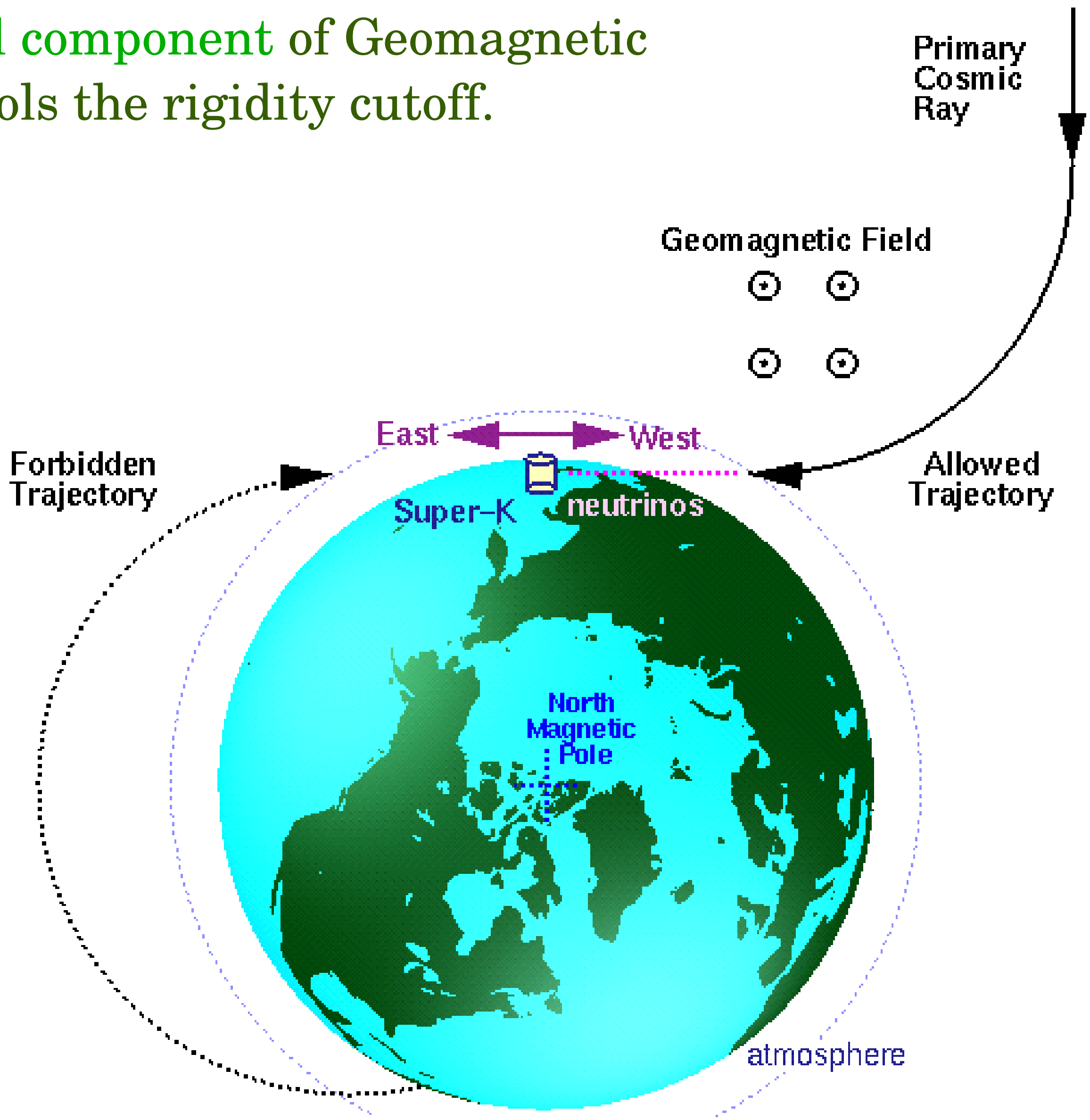
US-starndard'76 may be used as the global approximation of the Atmosphere.

Atmosphere model (NRLMSISE-00) and seasonal variations

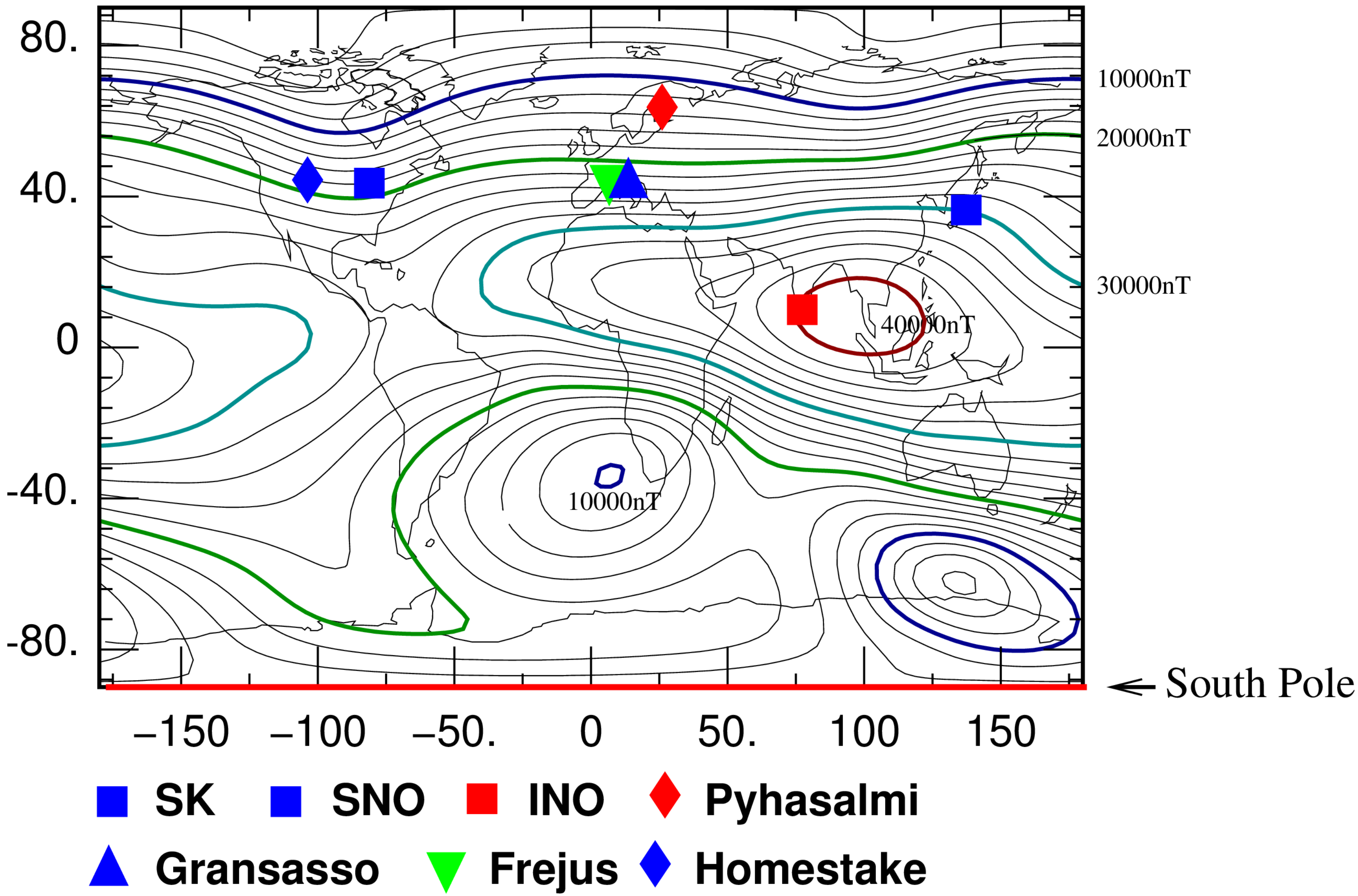


Geomagnetic Field

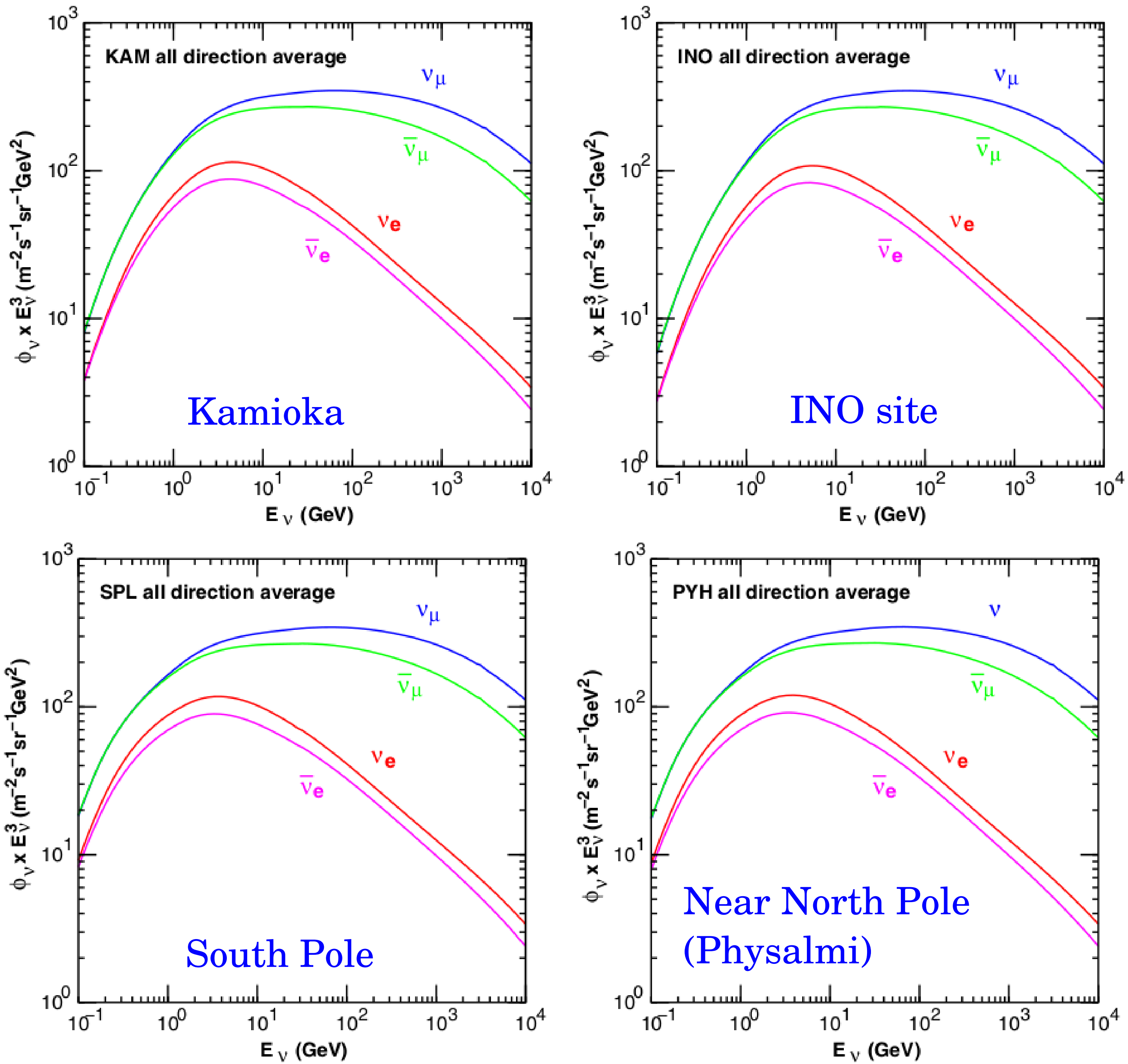
Horizontal component of Geomagnetic field controls the rigidity cutoff.

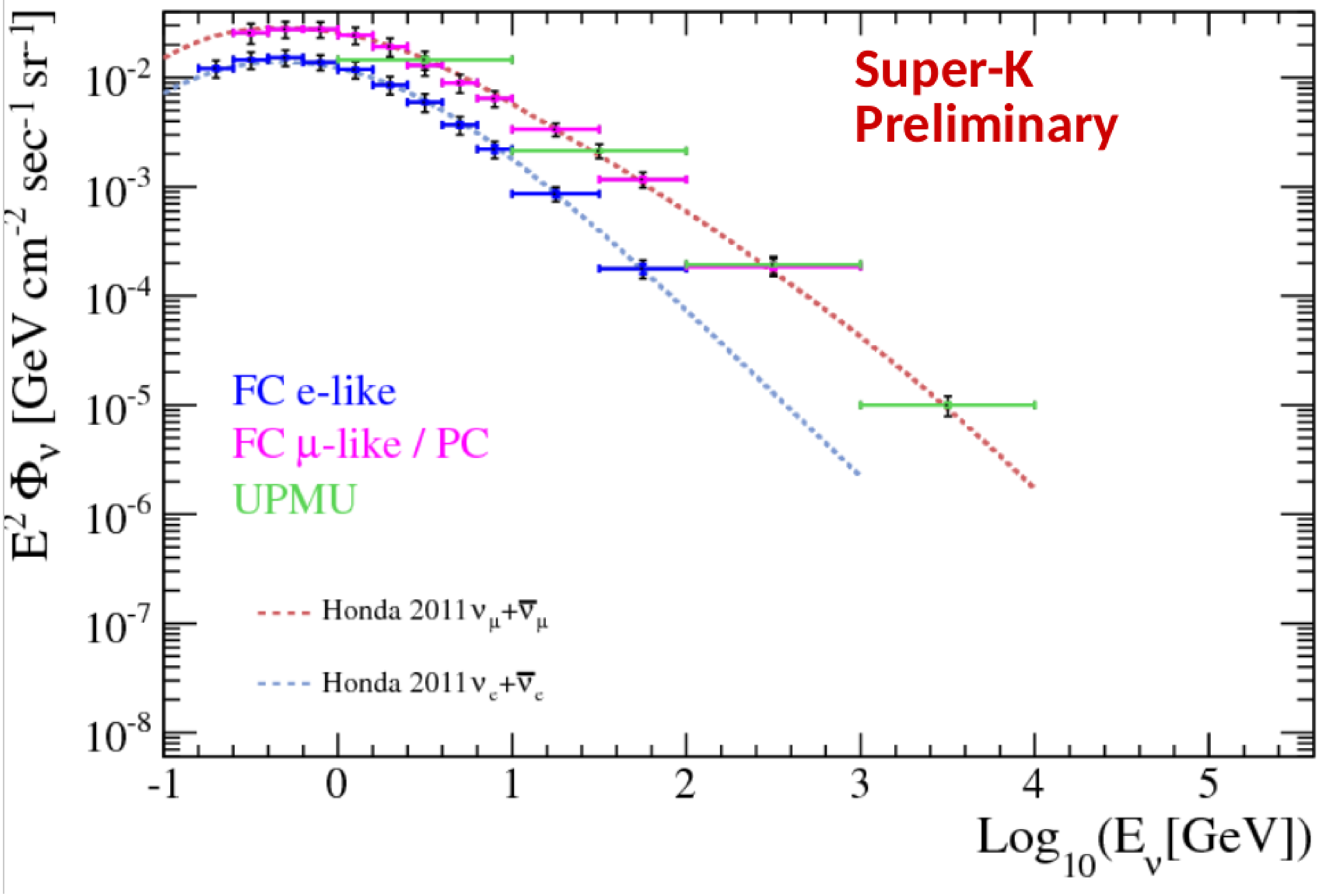


Horizontal component of Geomagnetic Field with IGRF10 and Atmospheric Neutrino Observing sites.



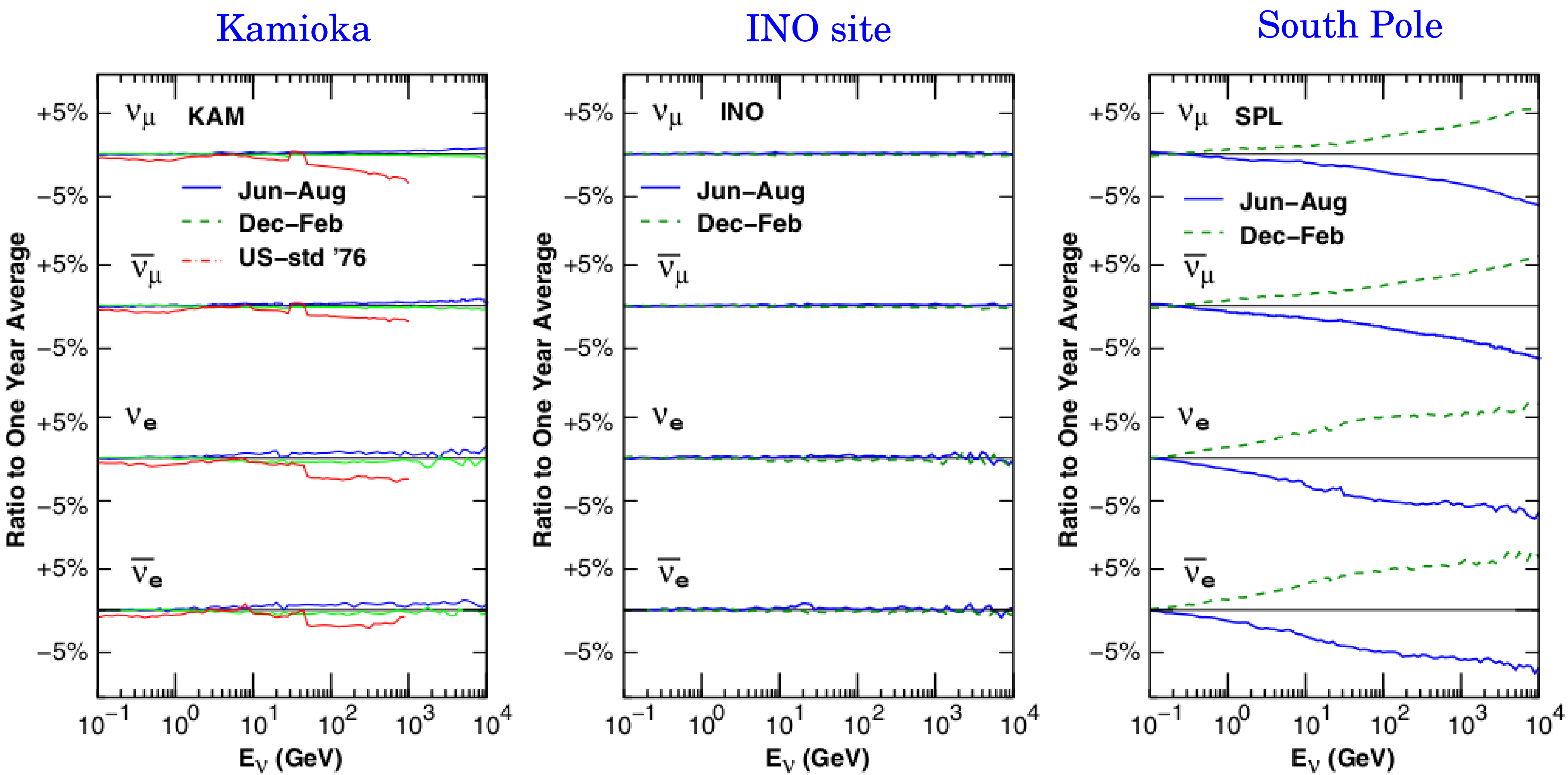
Calculated Atmospheric Neutrino Flux averaged over all directions



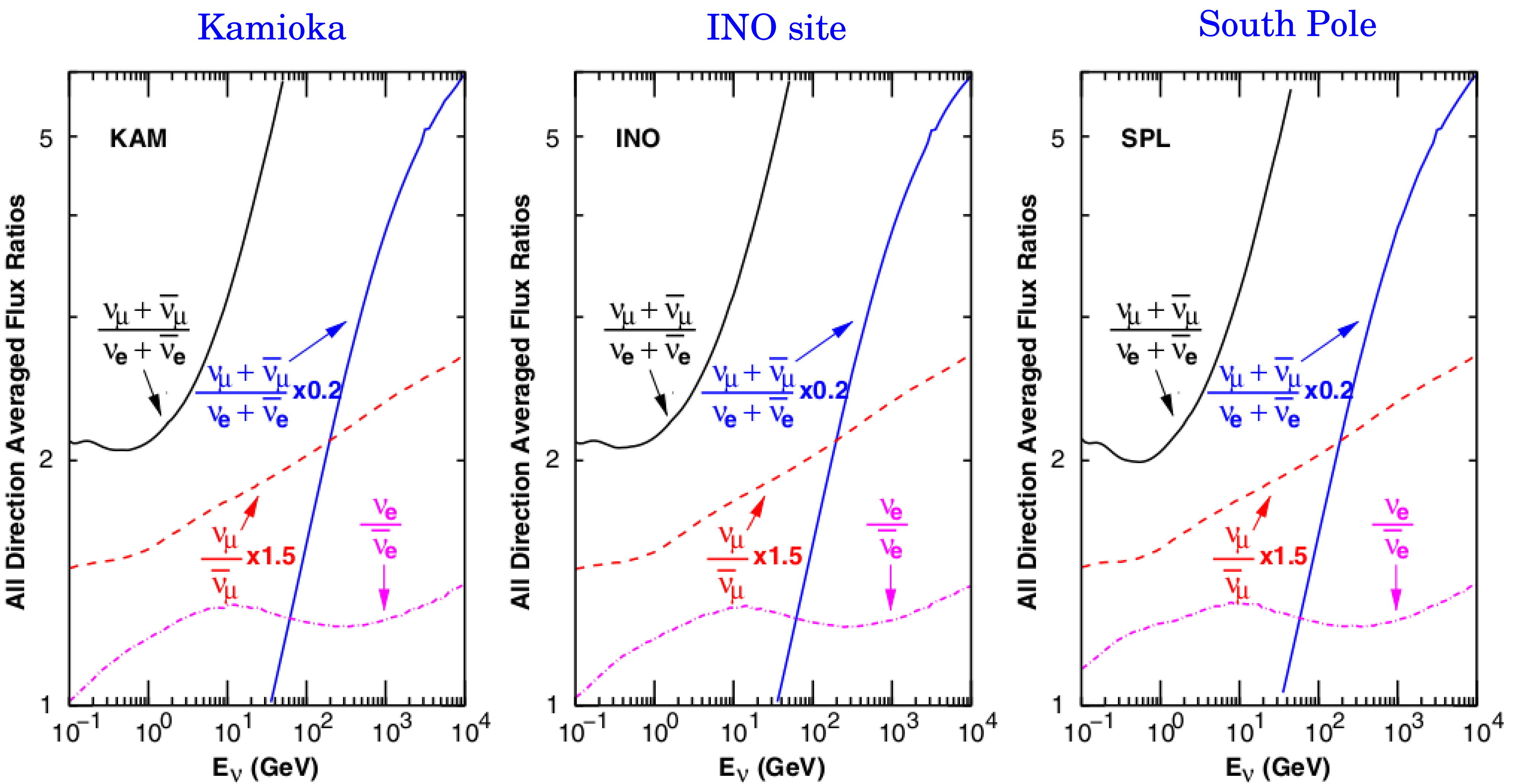


From K.Okumura in ICRC2015

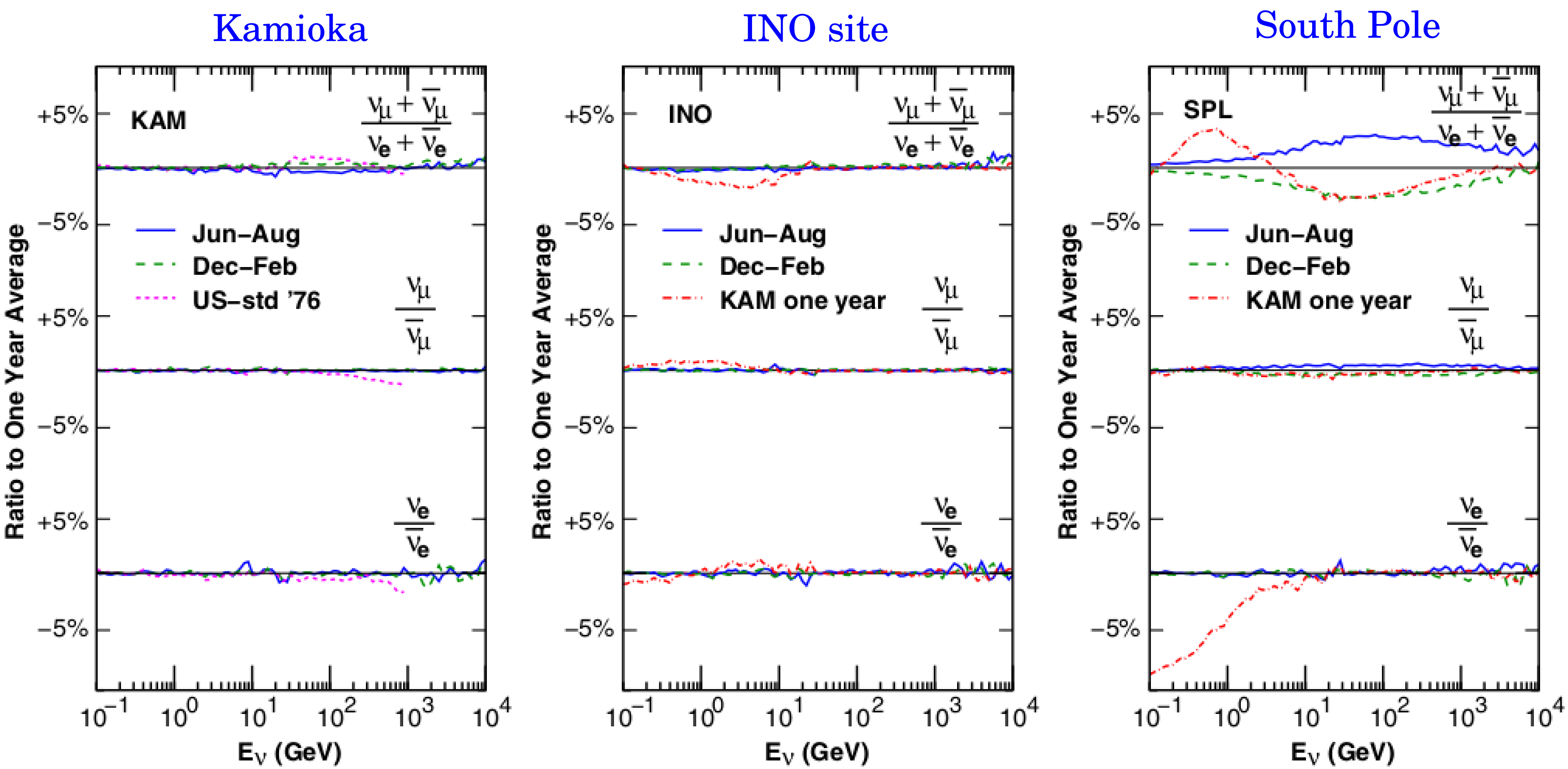
Seasonal Variation of Atmospheric Neutrino flux



Flavor Ratios of Atmospheric Neutrino

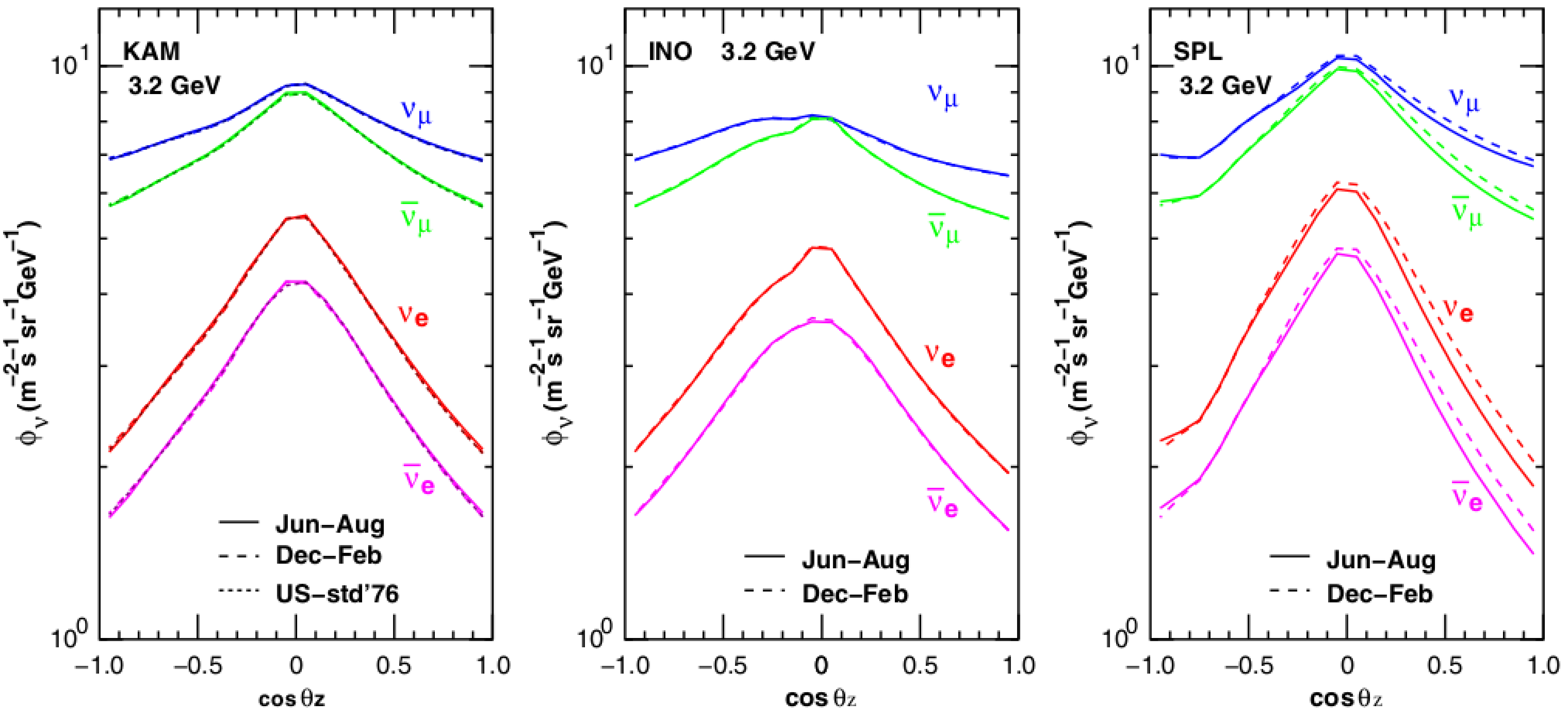


Seasonal and Site Variation of Atmospheric Neutrino Flavor Ratios

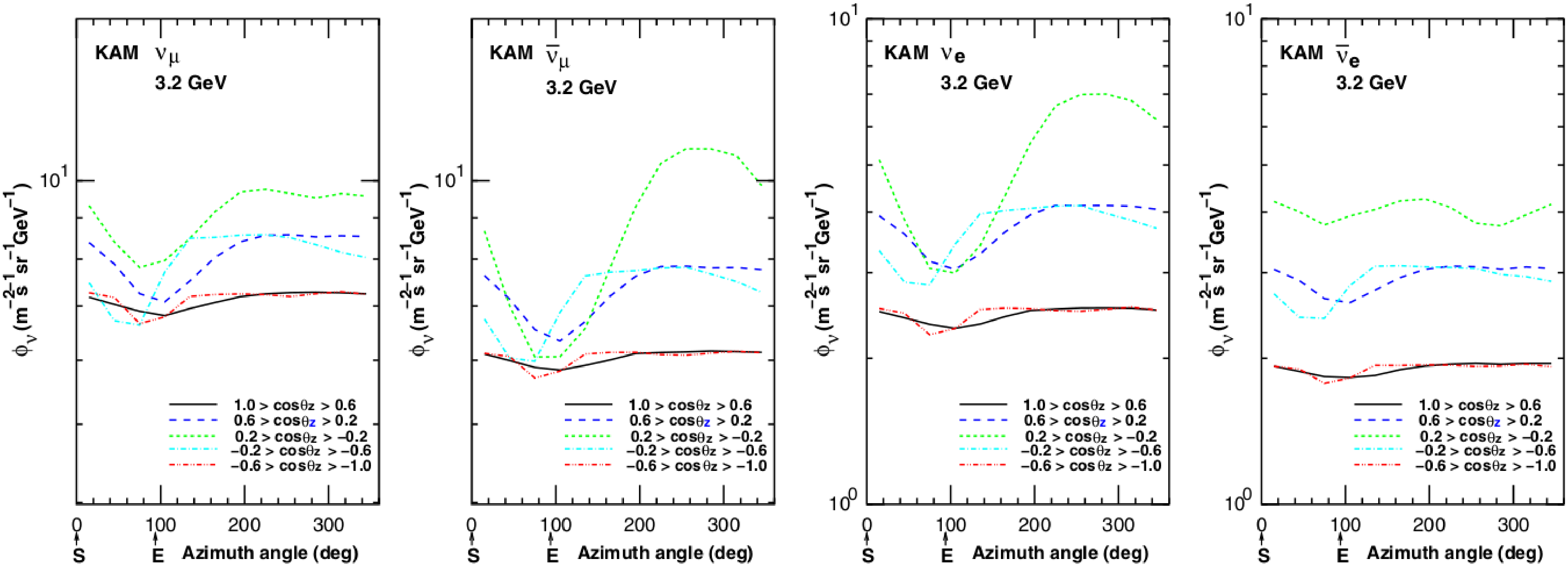


The variation of $\frac{\nu_\mu+\bar\nu_\mu}{\nu_e+\bar\nu_e}$ at South Pole and the difference from Kamioka are almost equal to the largest estimation of its uncertainty.

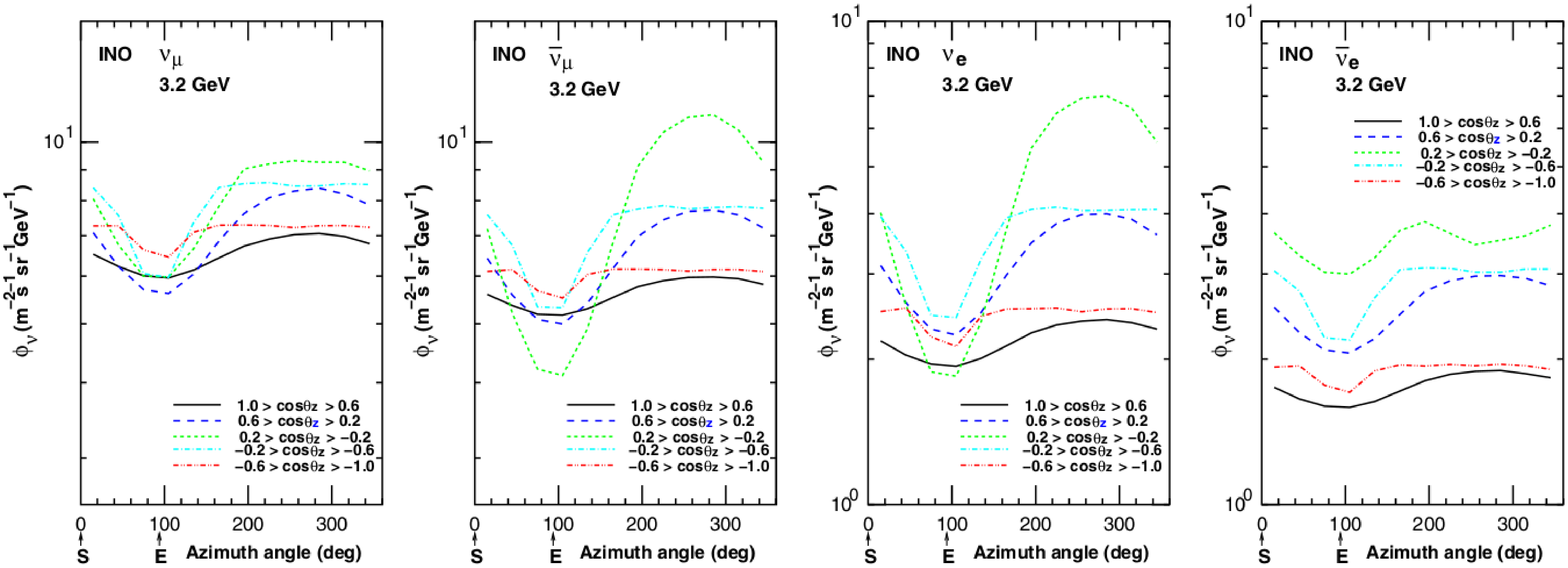
Zenith Angle Variation of Neutrino Fluxes at 3.2 GeV



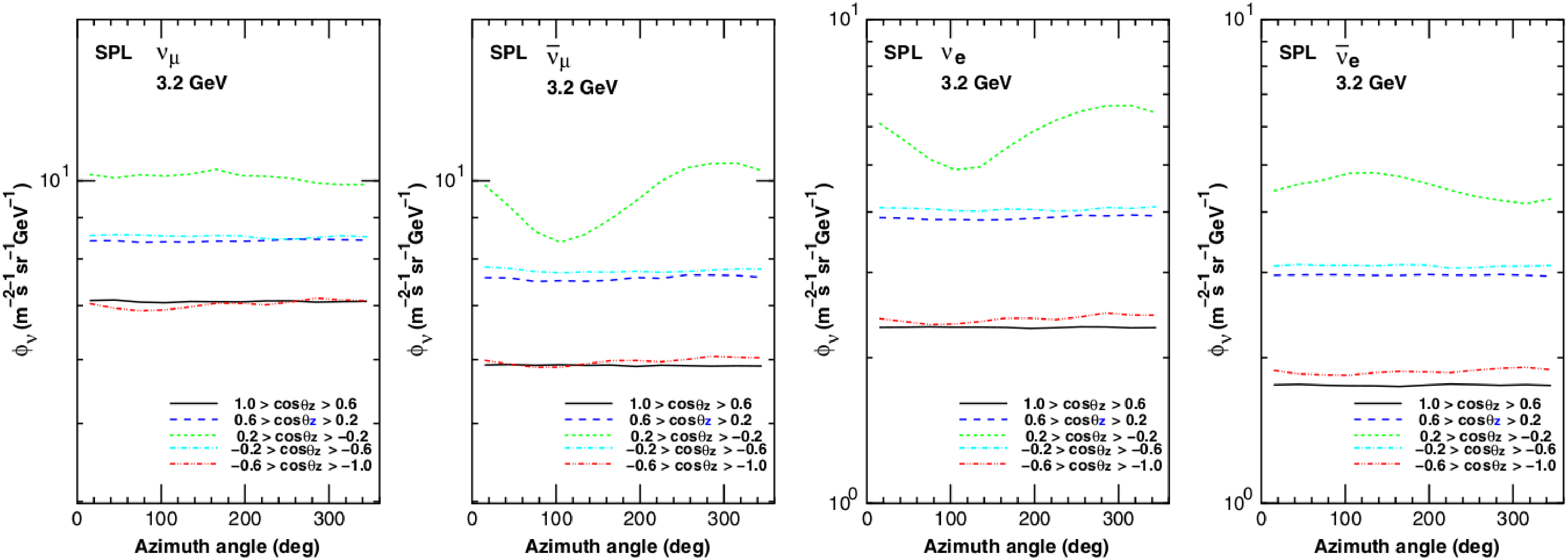
Azimuth Angle Variation of Neutrino Fluxes at 3.2 GeV in Kamioka



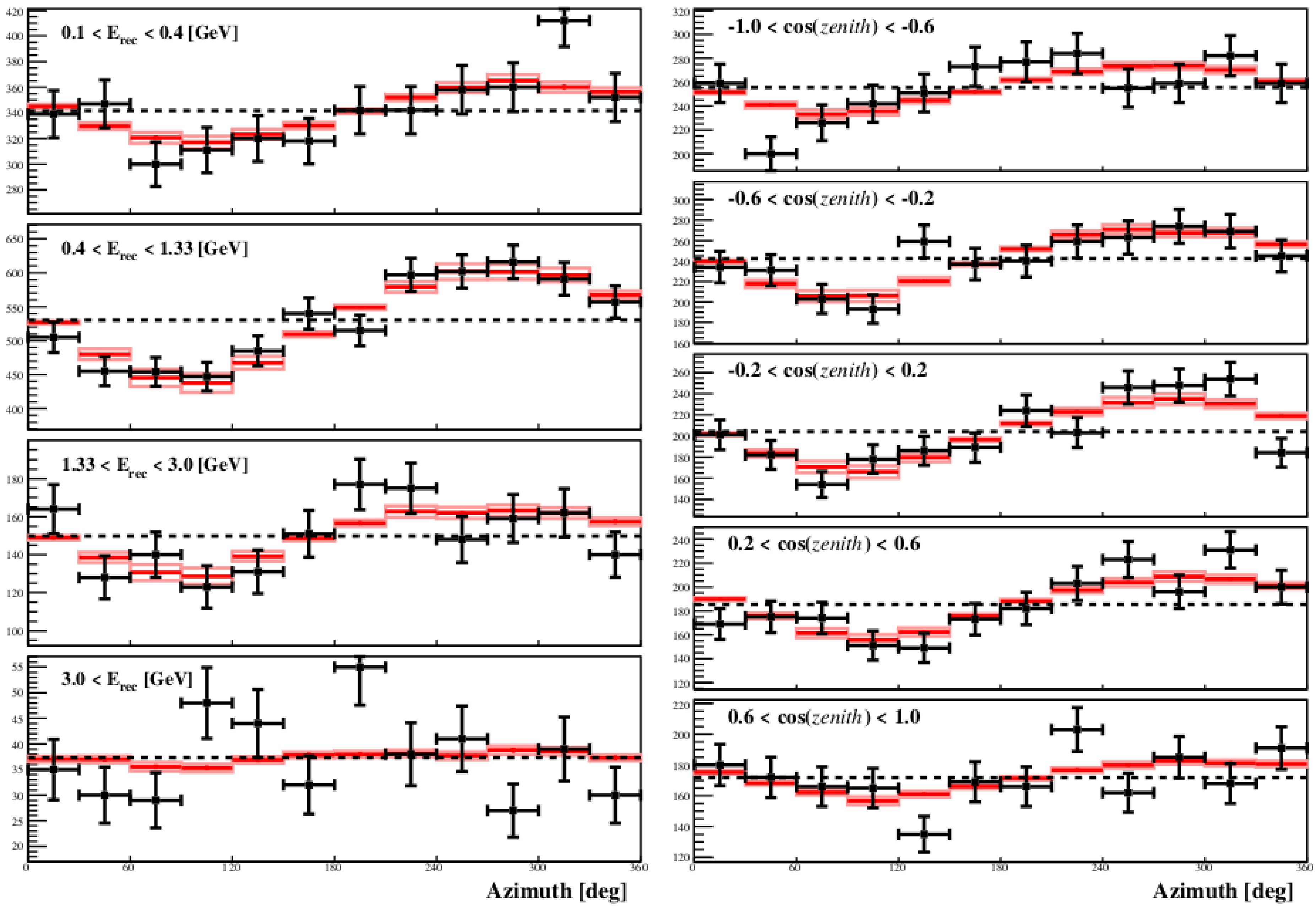
Azimuth Angle Variation of Neutrino Fluxes at 3.2 GeV in INO site



Azimuth Angle Variation of Neutrino Fluxes at 3.2 GeV at Suth Pole



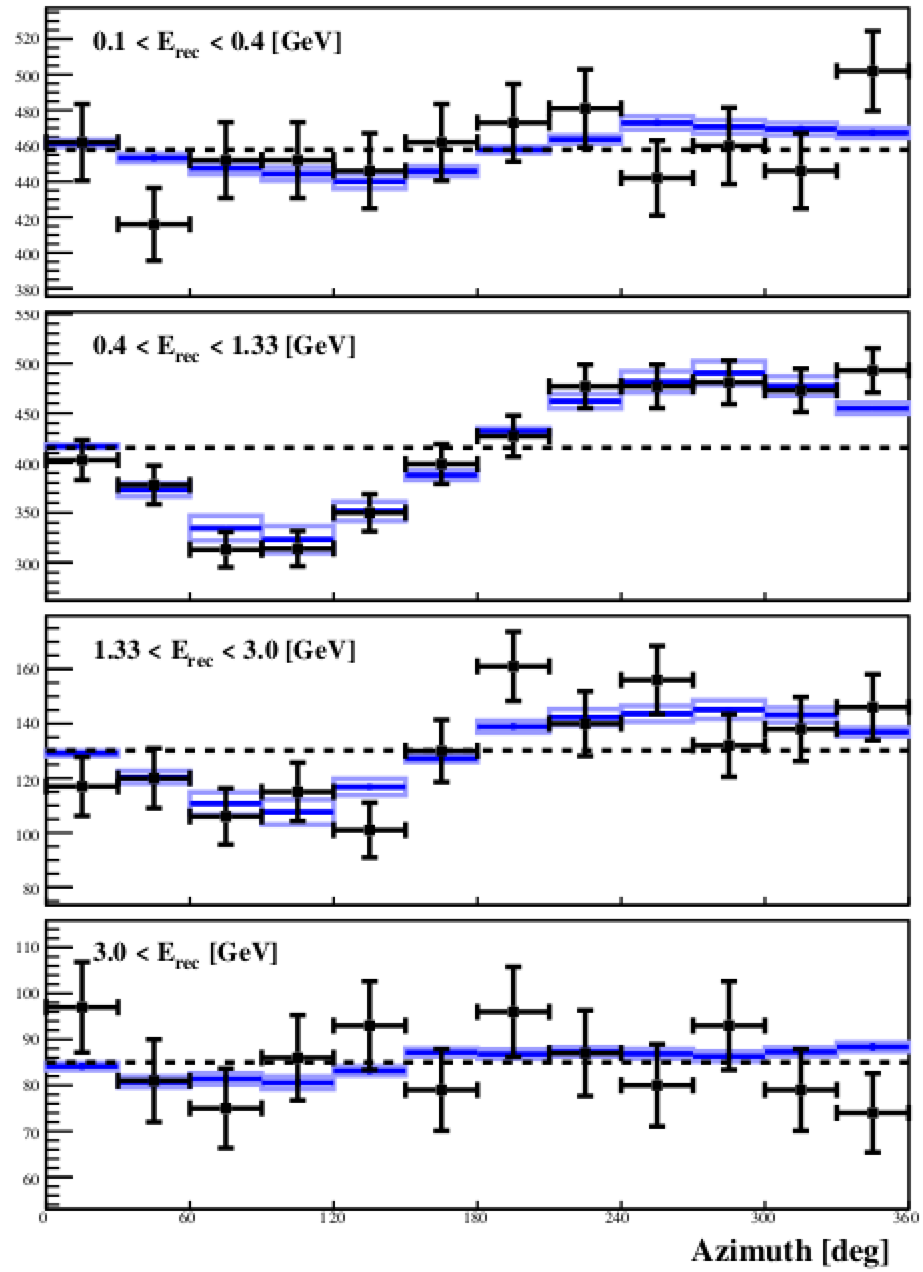
Observed Azimuthal Variation of ν_e flux (from PHD thesis of E.Richard)



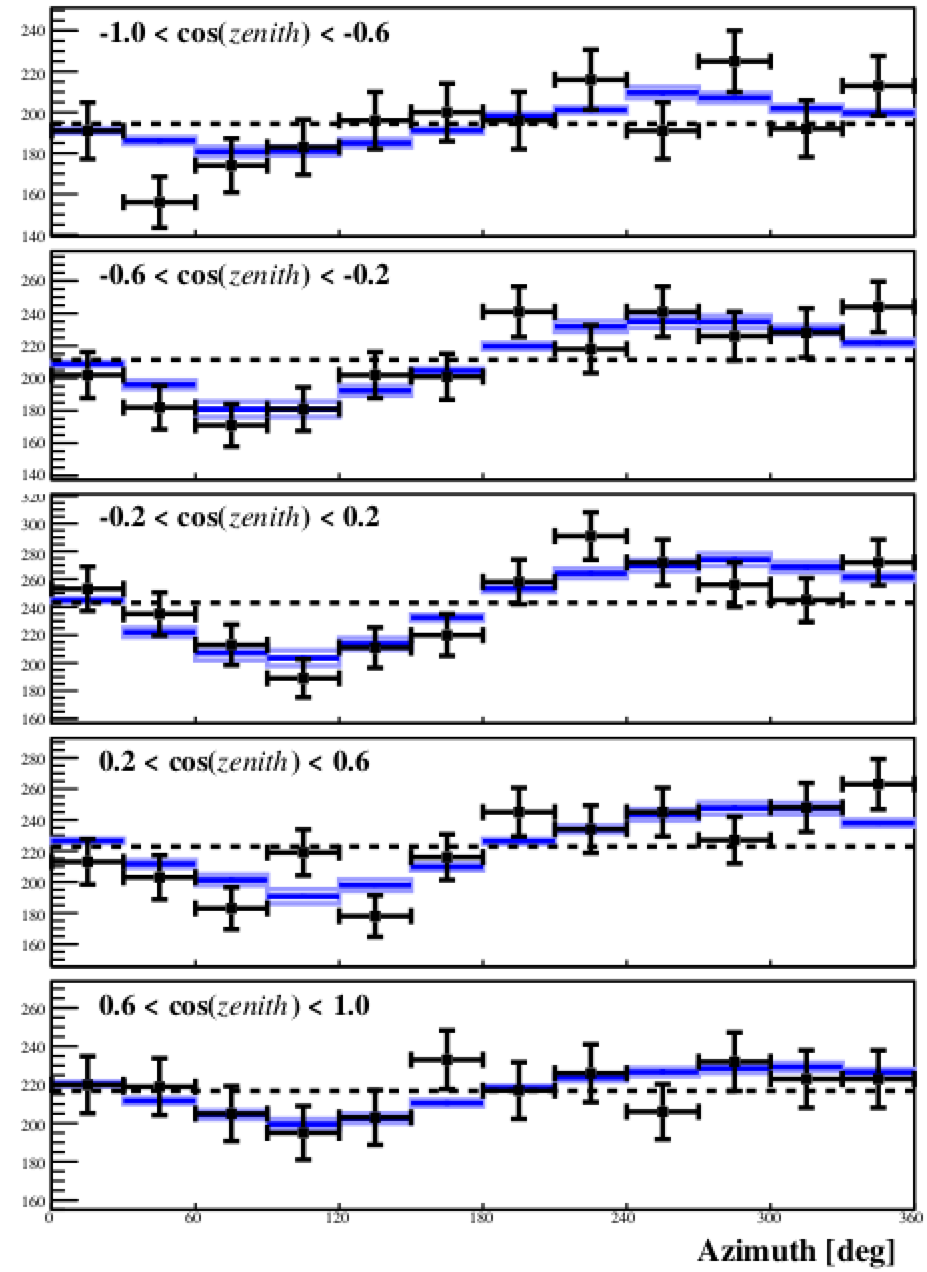
Energy Binned All Azimuth angles

Zenith Angle Binned All Energies

Observed Azimuthal Variation of ν_μ flux (from PHD thesis of E.Richard)

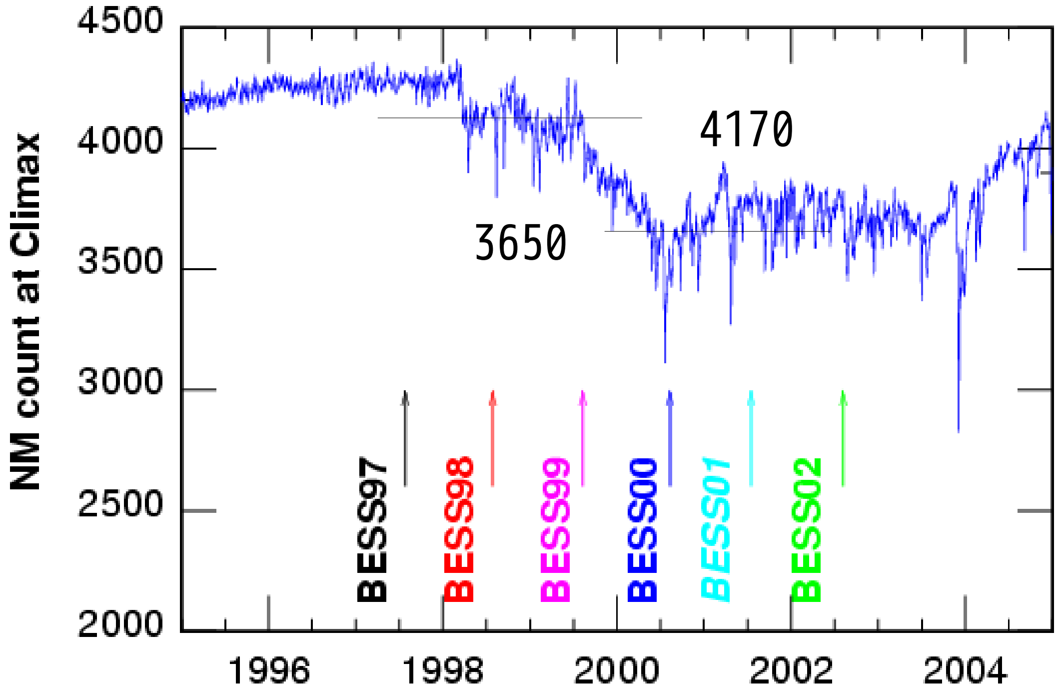


Energy Binned All Azimuth angles



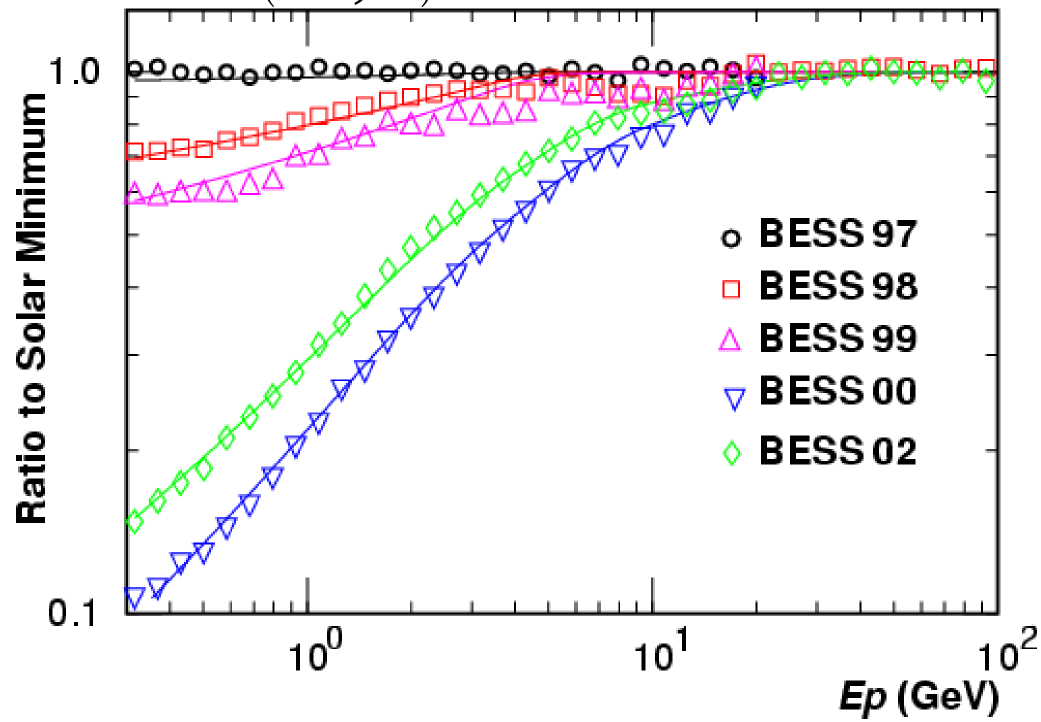
Zenith Angle Binned All Energies

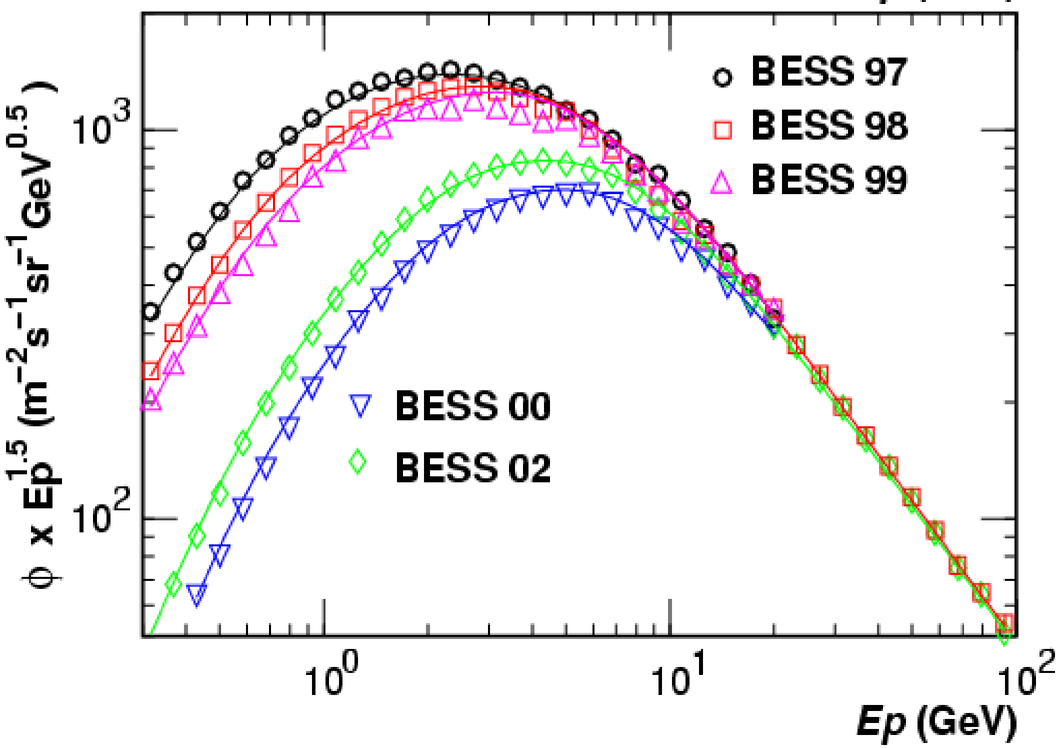
Solar Modulation of Primary Cosmic Rays and Atmospheric Neutrino



BESS flight

$M(N, r)$: modulation function



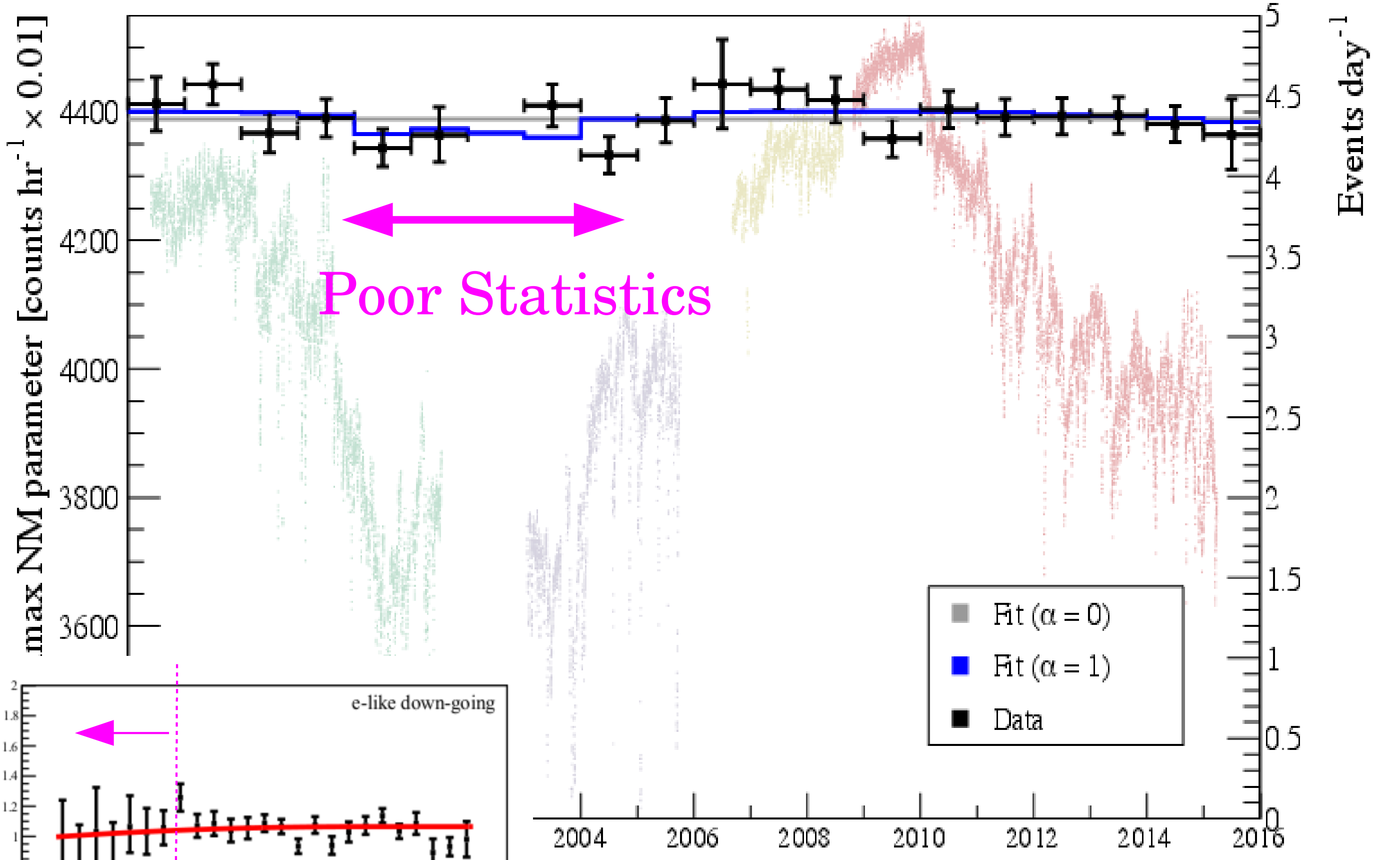


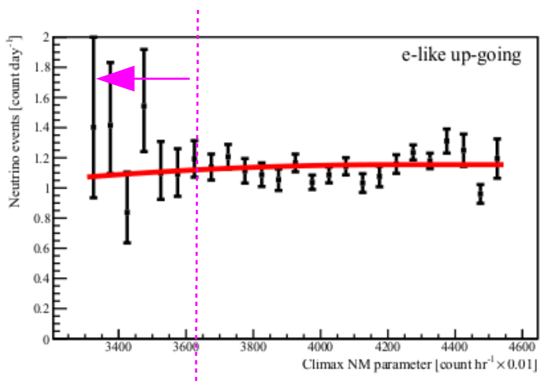
$$\phi_i(N, E_k) = \phi_i^{min}(E_k) \cdot M(N, r)$$

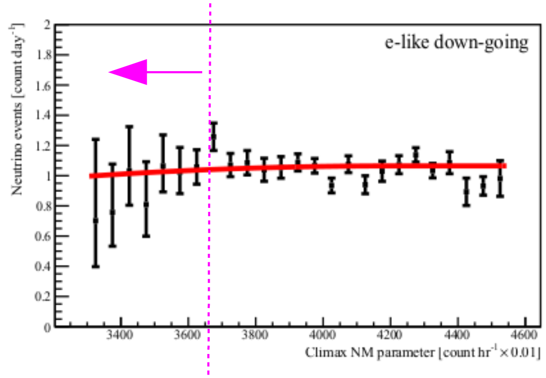
$$\phi_i^{min}(E_k) \equiv \phi_i^{1997}(E_k)$$

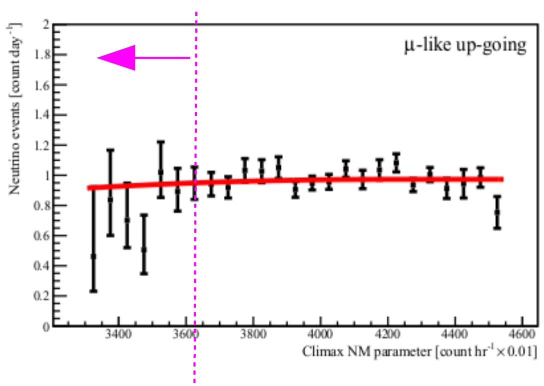
Solar Modulation of Atmospheric Neutrinos

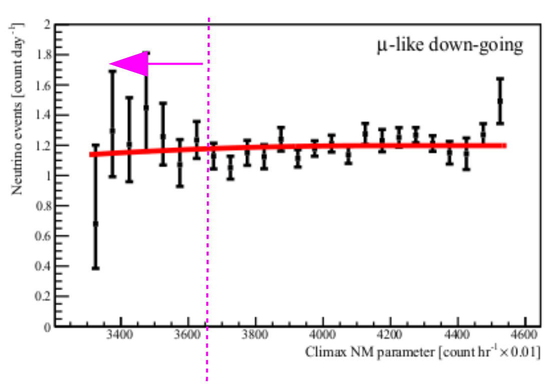
From PHD thesis of
E. Richard







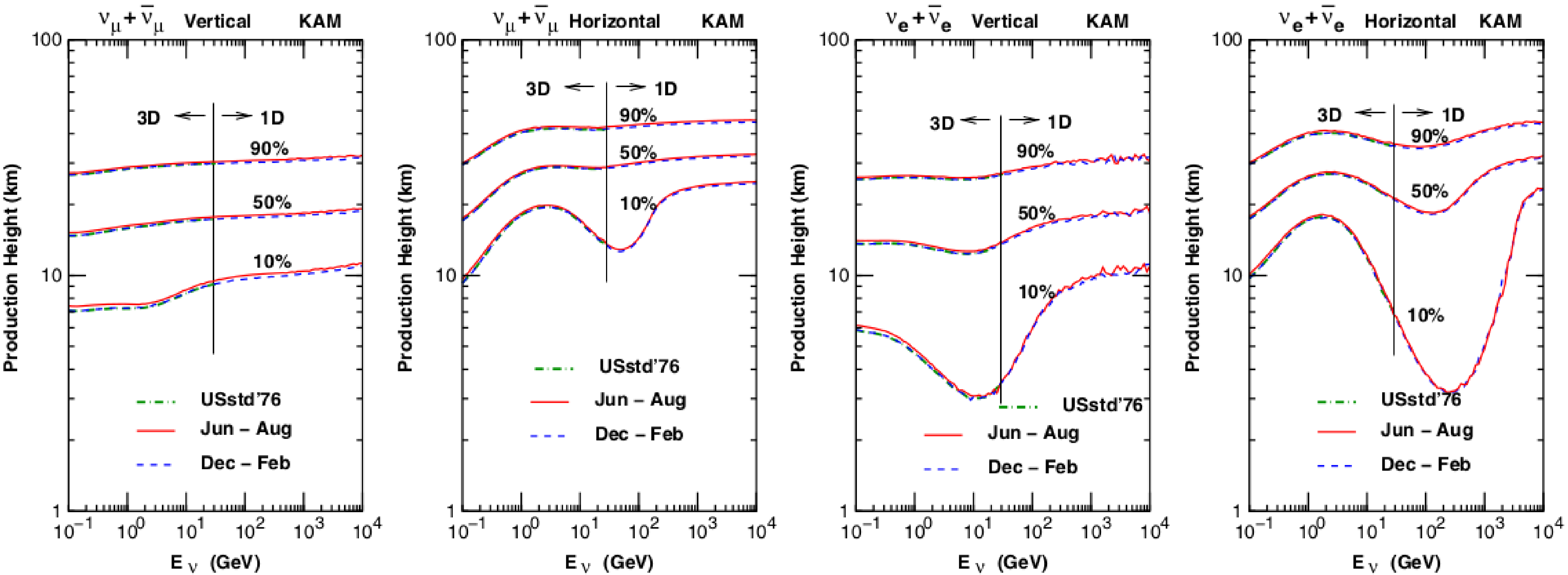




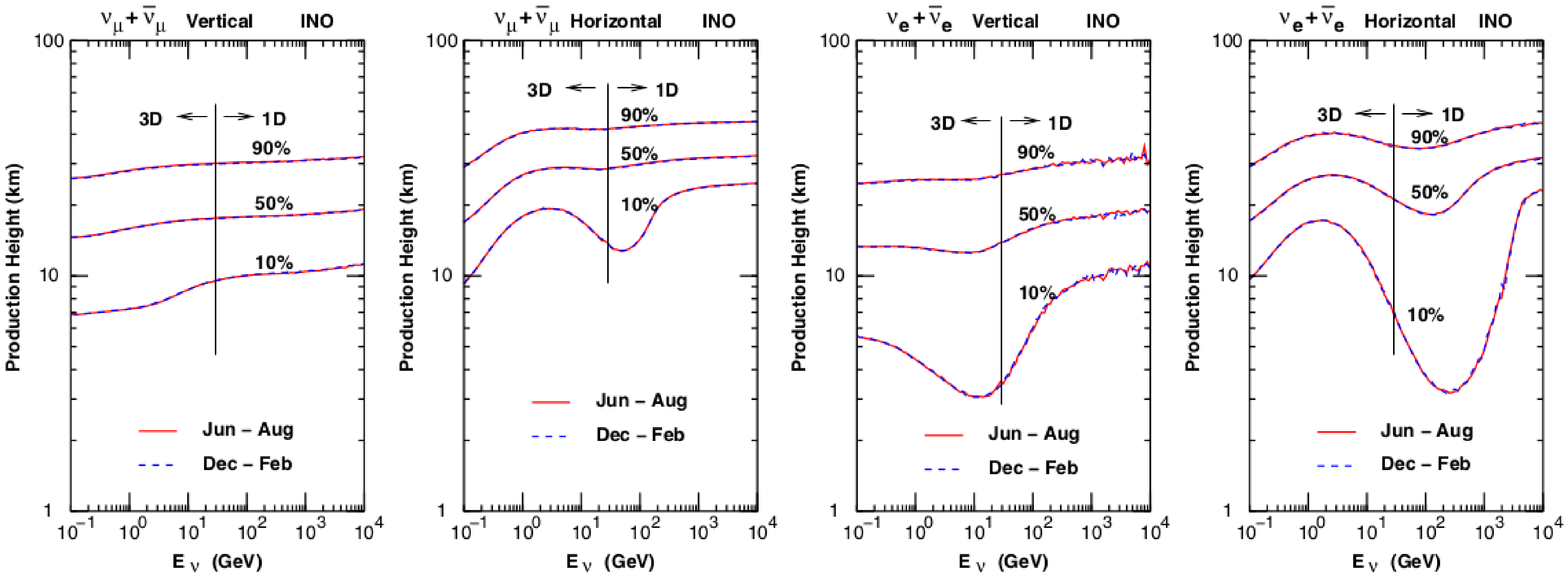
Best fit corresponds to 62 % of the predicted variations

Amplitude of variation is determined in the poor statistics region.

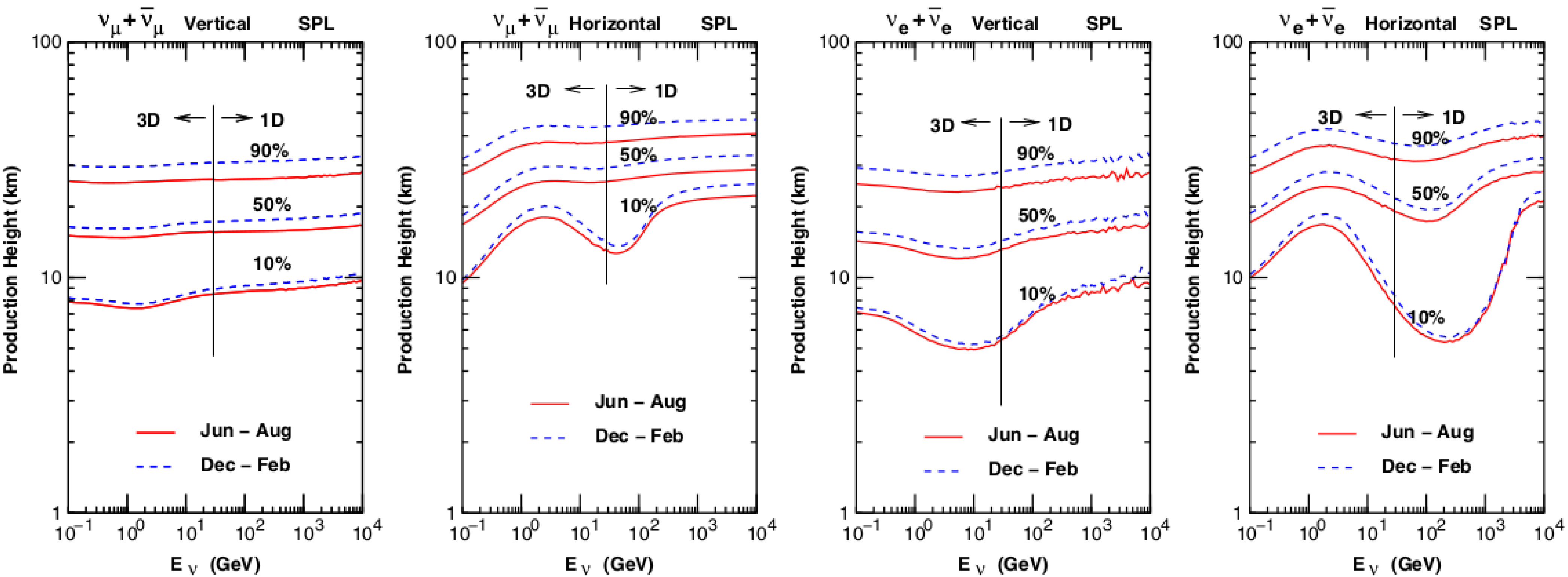
Cumulative Neutrino Production Height in Kamioka (summed over all azimuth angles)



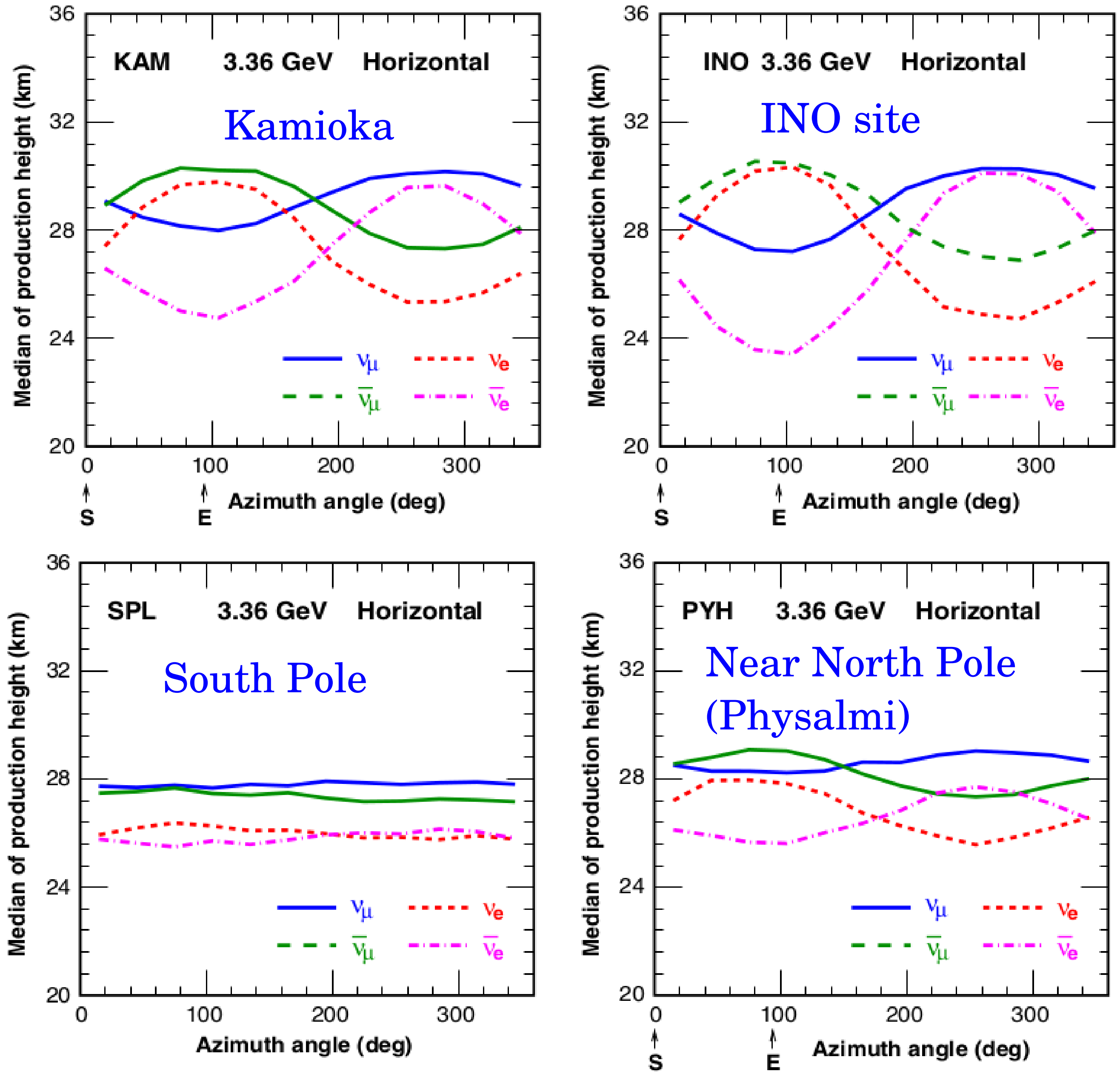
Cumulative Neutrino Production Height in INO site (summed over all azimuth angles)



Cumulative Neutrino Production Height in South Pole (summed over all azimuth angles)



Azimuth Angle Variaiton of Neutrino Production Height and Seasonal Variations

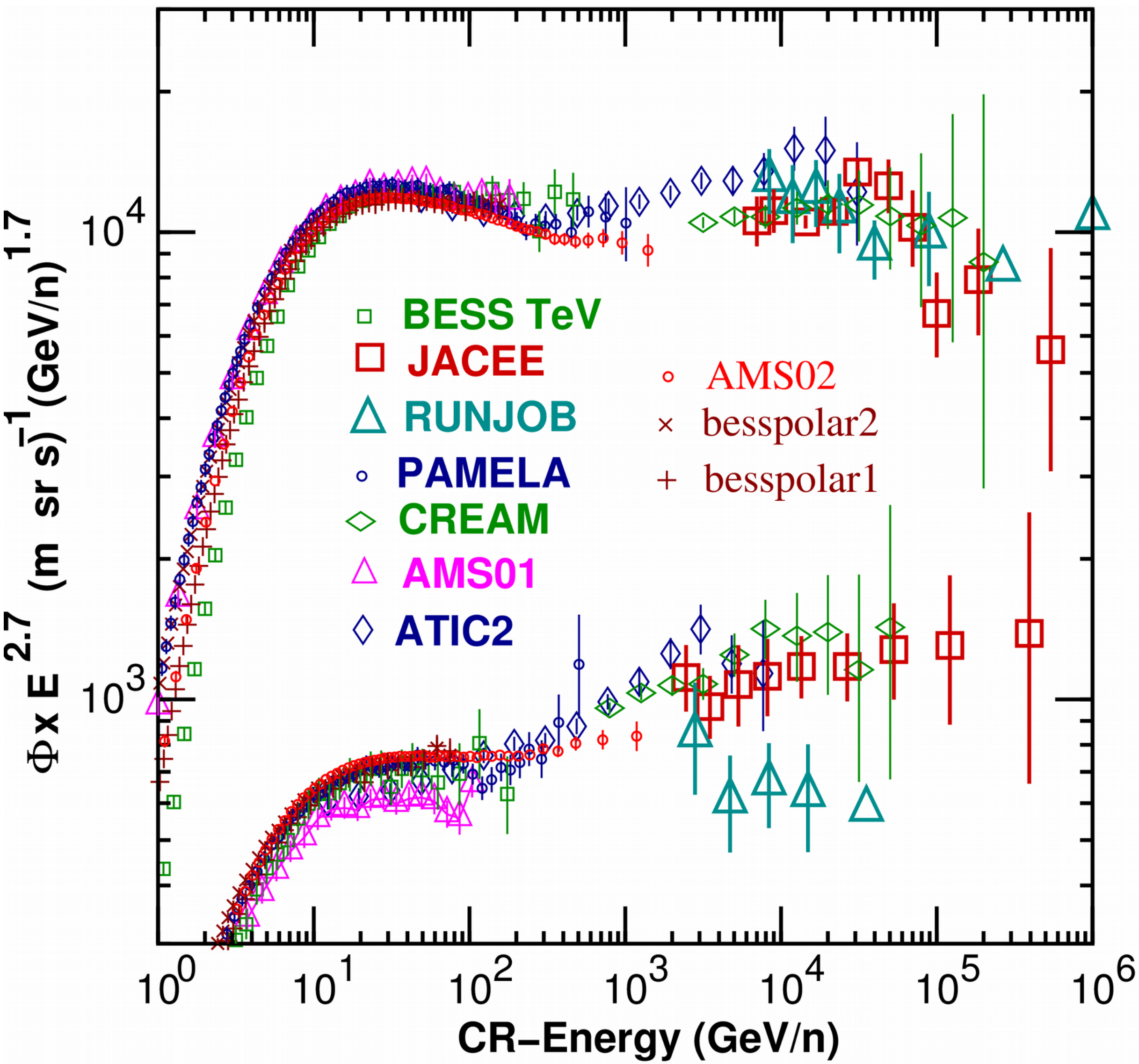


Impact of AMS02

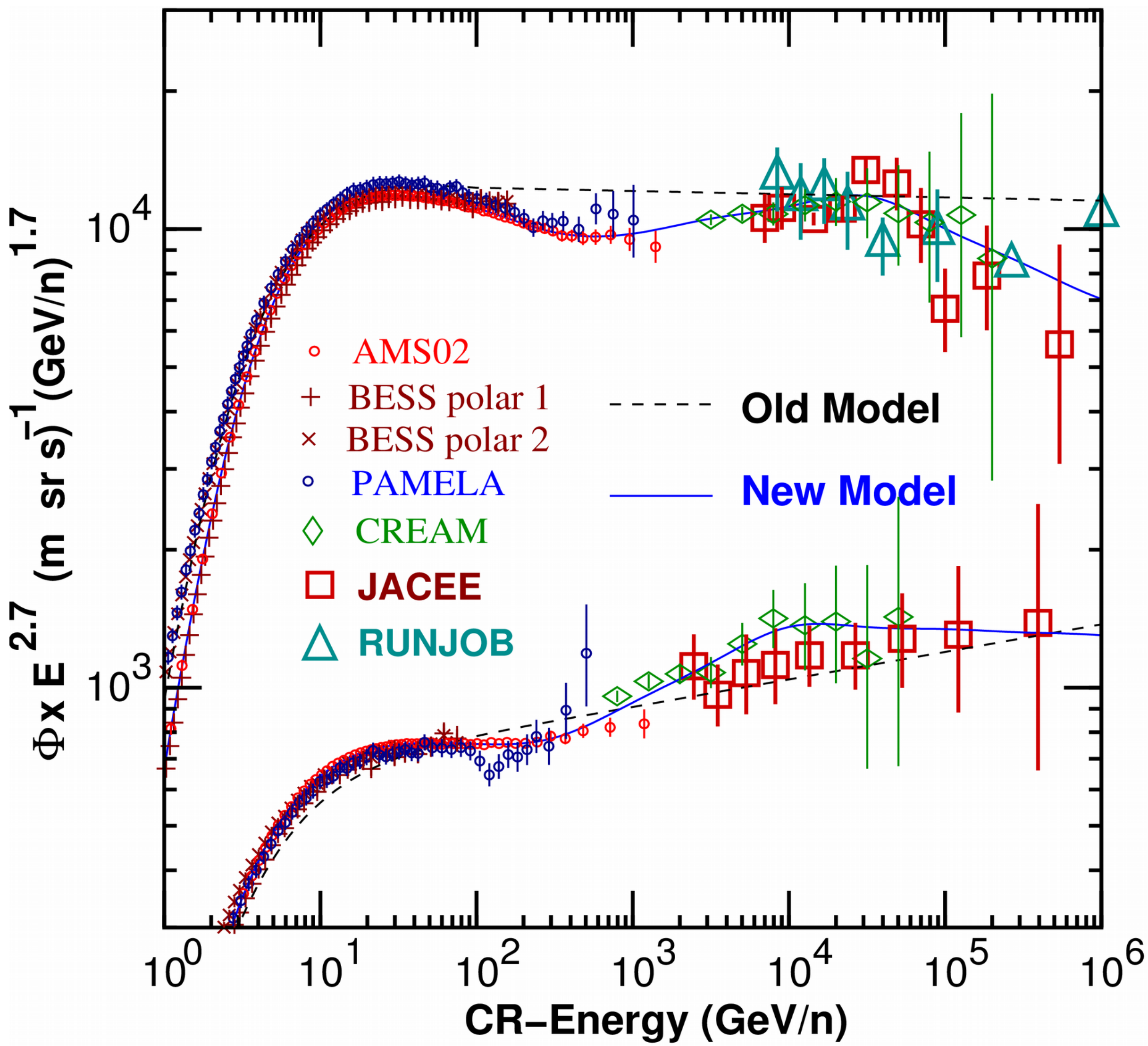
and

BESS-polar

Recent Cosmic Ray observation and available High Energy data

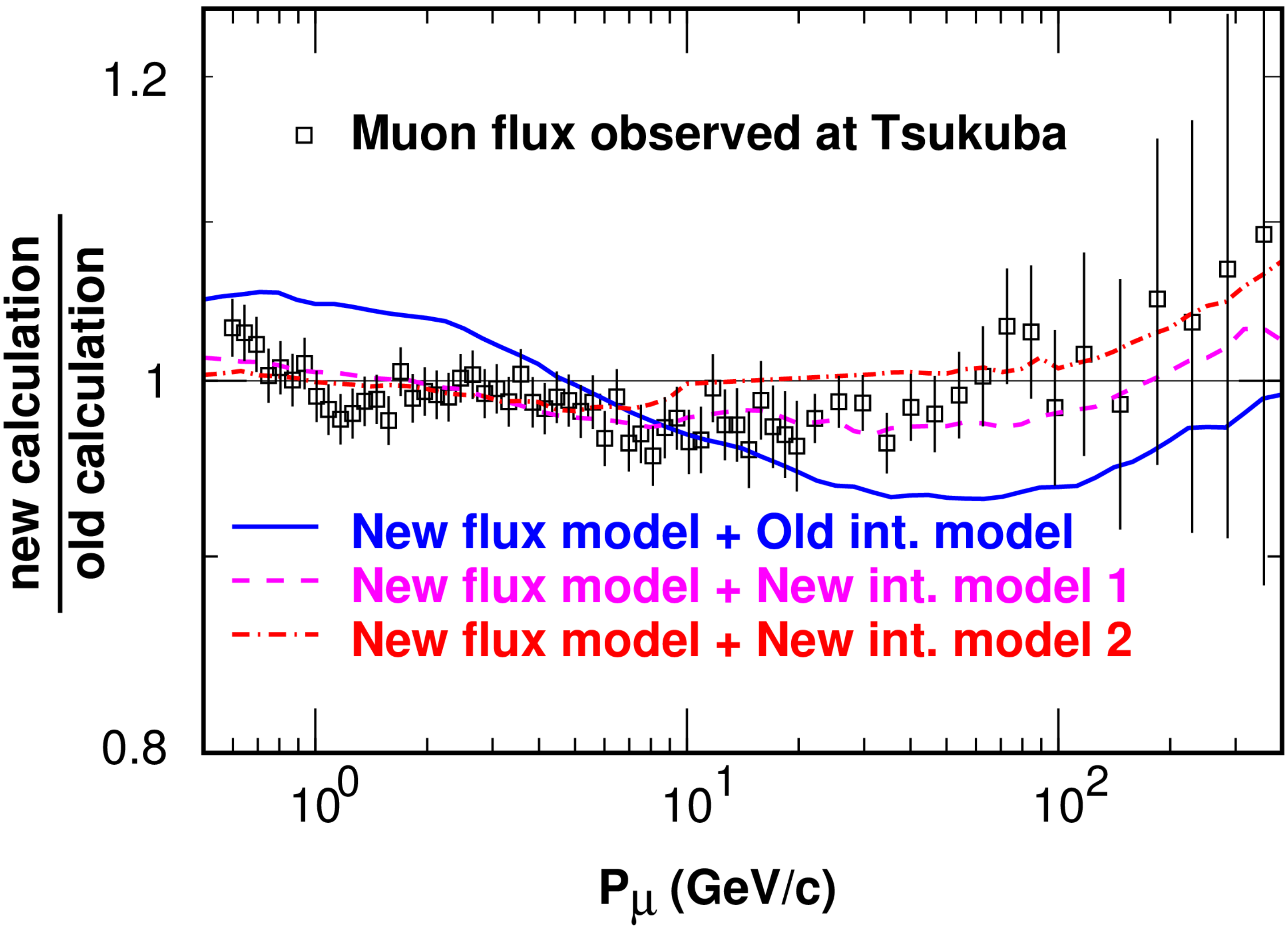


New Cosmic Ray Model with AMS02 and BESS-polar

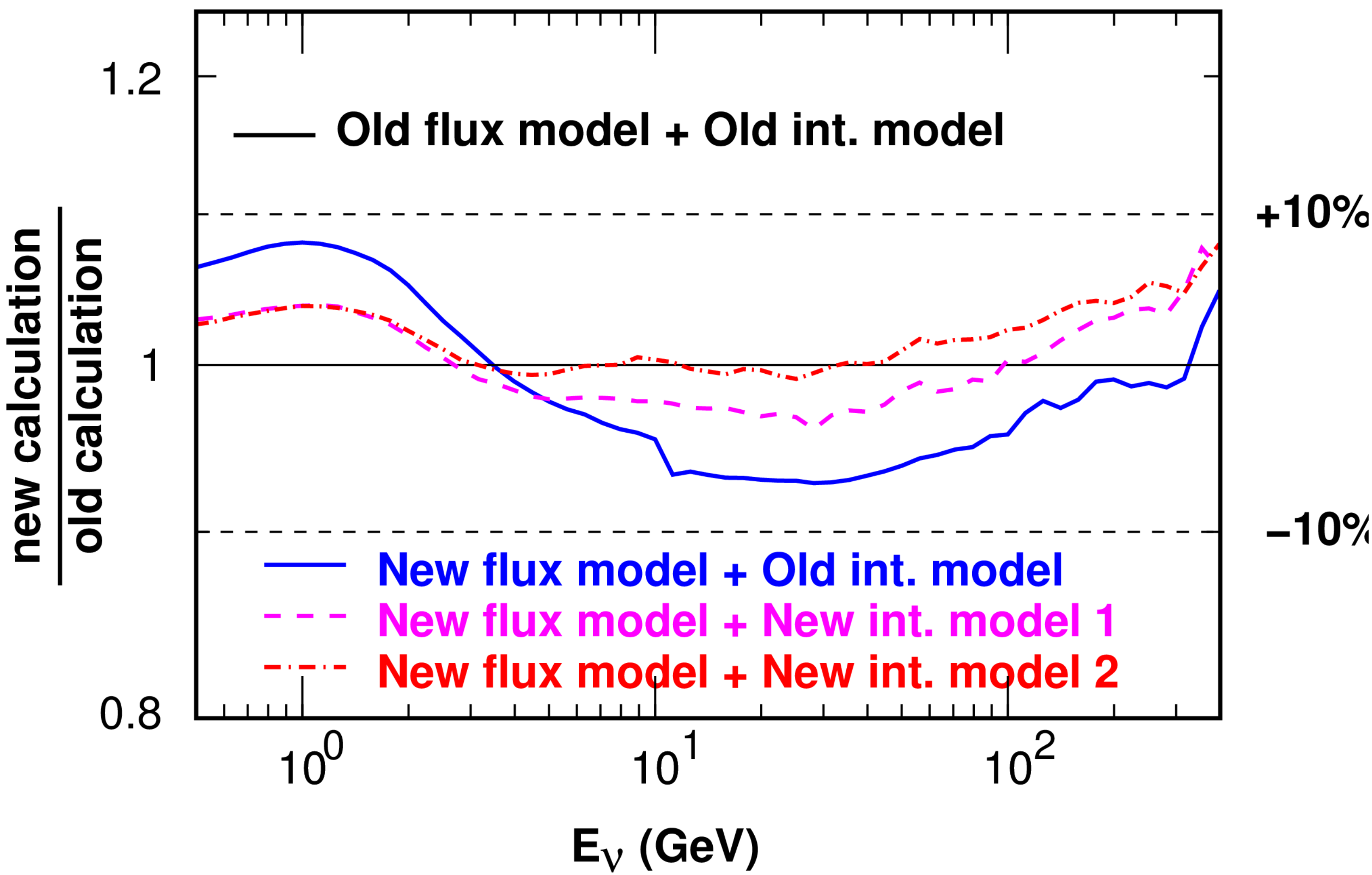


Discarded some data from model construction.

Muon Calibration of Interaction Model with New Cosmic Ray Model

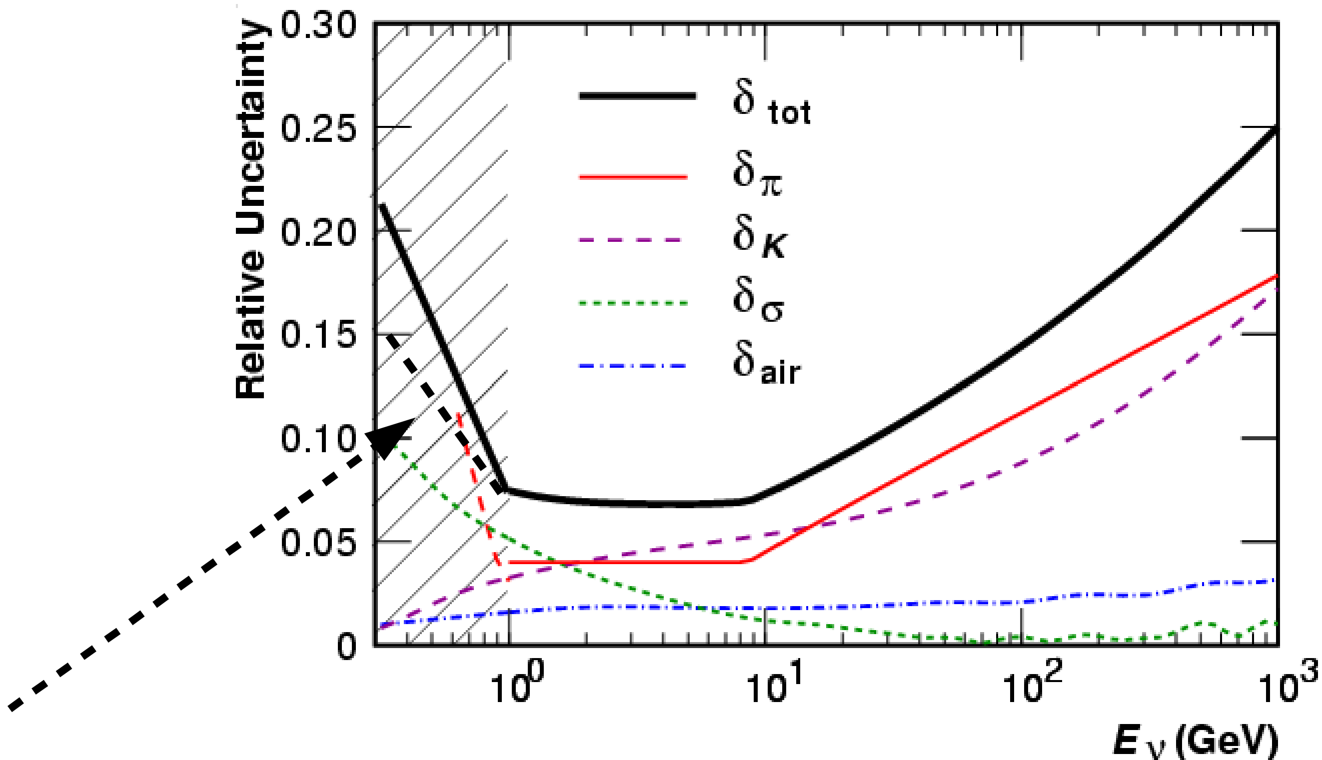


Resulting Neutrino Flux (all ν sum)



Muon calibration works !

Possible Error in Atmospheric ν-flux (HKKMS07)



Possible Error with JAM (HKKM11)

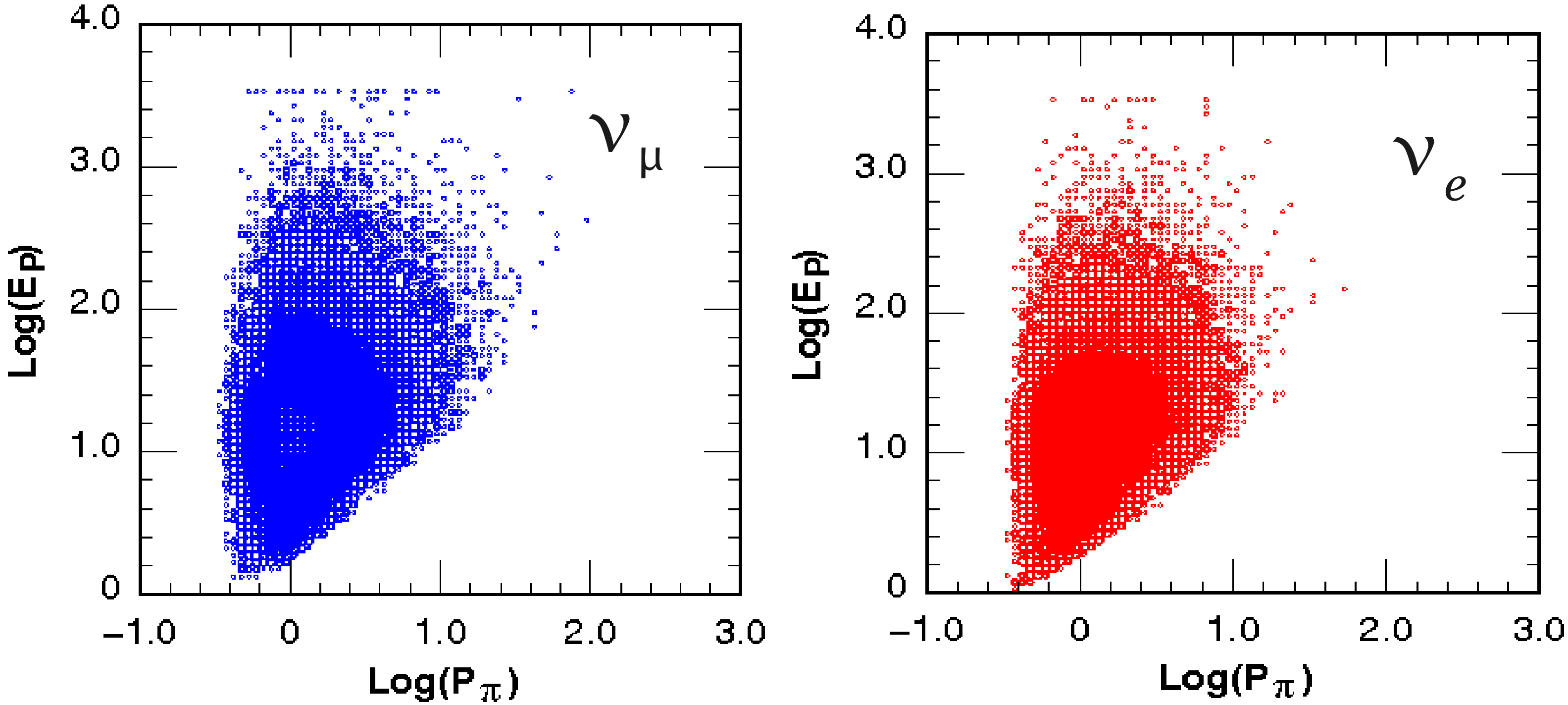
δ_{π} μ -observation error + Residual of reconstruction

δ_{K} Kaon production uncertainty

δ_{σ} Mean free path (interaction crossection) uncertainty

δ_{air} Atmosphere density profule uncertainty

To reduce the lower energy uncertainties, we need



Phase space of $p + N(air) \rightarrow \pi + X$ for 0.32 GeV neutrinos.

1. Good accelerator experiment which covers all the phase space,
or
2. Observation of muon flux at high altitude.

Cosmic Rays in atmosphere

$$p_{CR} + [Air] \rightarrow \begin{pmatrix} n^{\pm} \cdot \pi^{\pm} \\ m \cdot \pi^{0} \end{pmatrix} + X(p, n, K, ...)$$

$$\pi^{0} \rightarrow 2\gamma$$

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\mu^{\pm} \rightarrow \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu}) + e^{\pm}$$

Atmospheric Neutrino

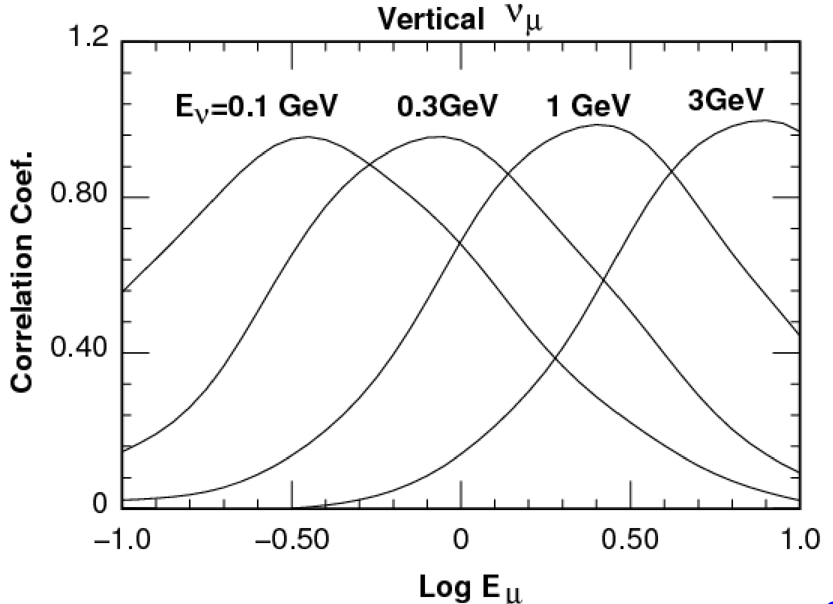
$$\nu_{\mu} : \nu_{e} \approx 2:1$$

$\gamma, e^{\pm} \rightarrow$ EM-cascade → Air Shower

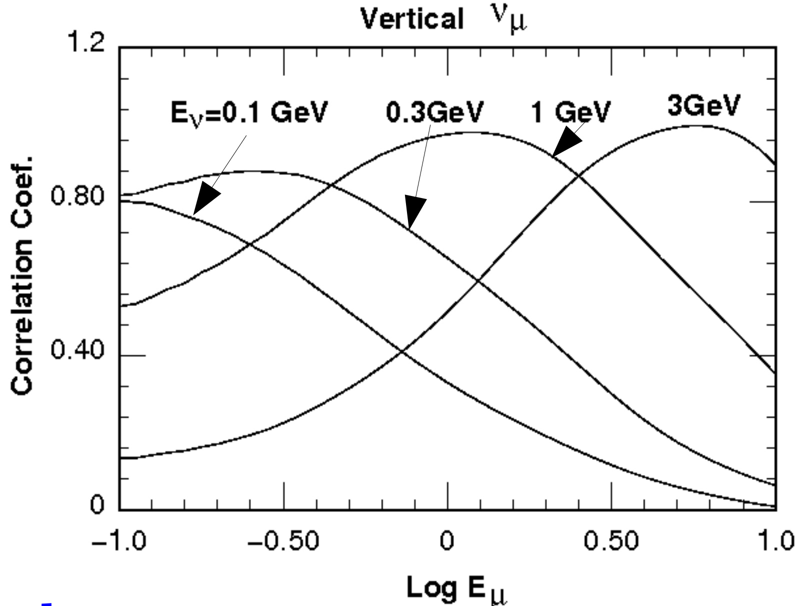
Other p's, n's, and sometimes π's repeat above interactions.

Correlated Muon energy to fixed Energy Neutrinos

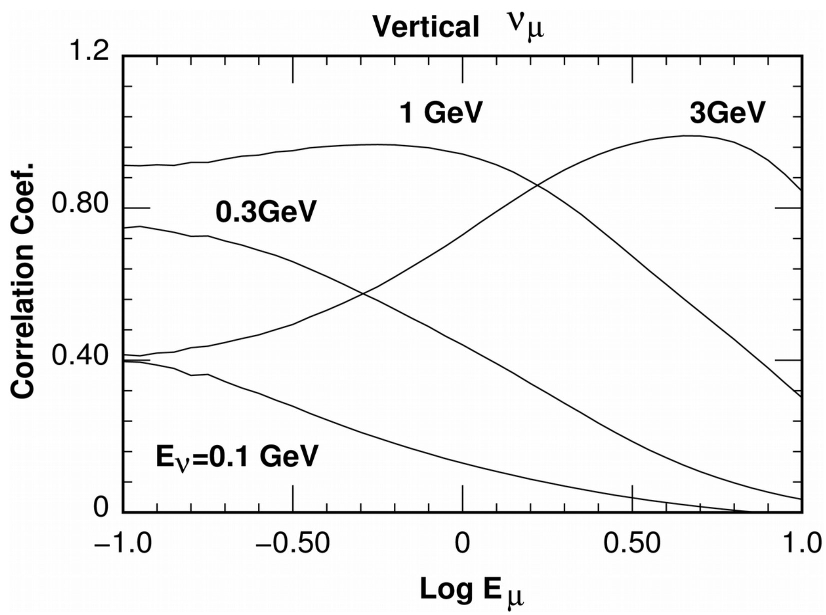
Balloon Altitude



Mt Norikura (2776m a.s.l



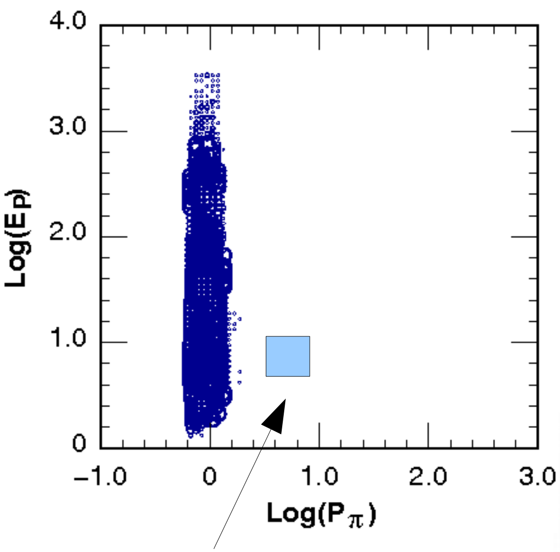
Sea Level



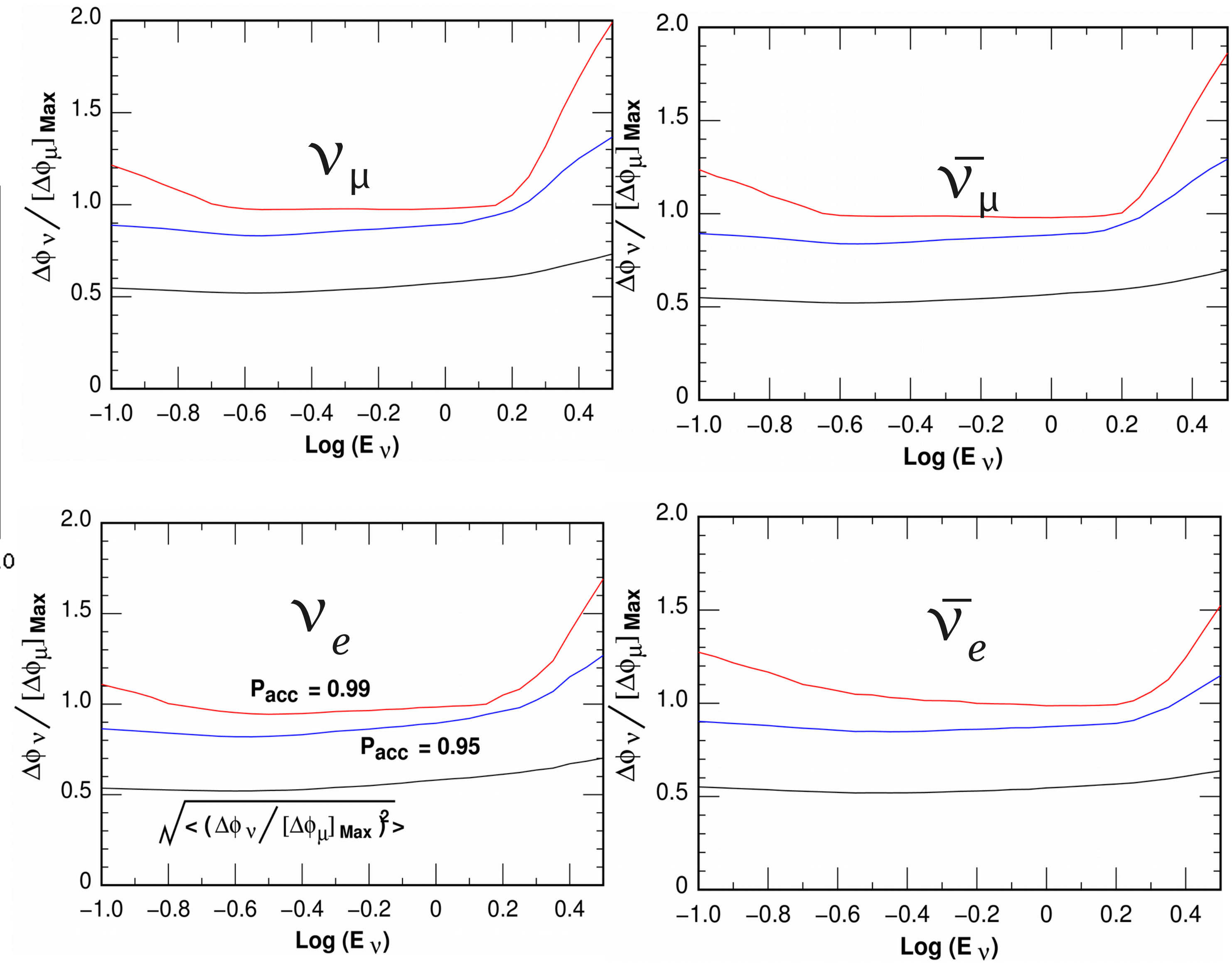
Variation study of muon flux at balloon altitude and neutrino

Possible variation of neutrino flux when μ flux below ~ 3 GeV/c is reconstructed within the variation of Δ_μ

Phase space of $p + N(air) \rightarrow \pi + X$ for muons



Size of Phase space to give the variation



Summary

- The calculation of atmospheric neutrino flux in HKKM is reviewed.
- It is noteworthy that some of predicted features of atmospheric neutrino flux are now observed in SK.
- With NRLMSISE-00 atmosphere model, we find a large seasonal variation of neutrino flux at polar region at the energies lower than we expected. This also cause a large variation in $\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$ ratio.

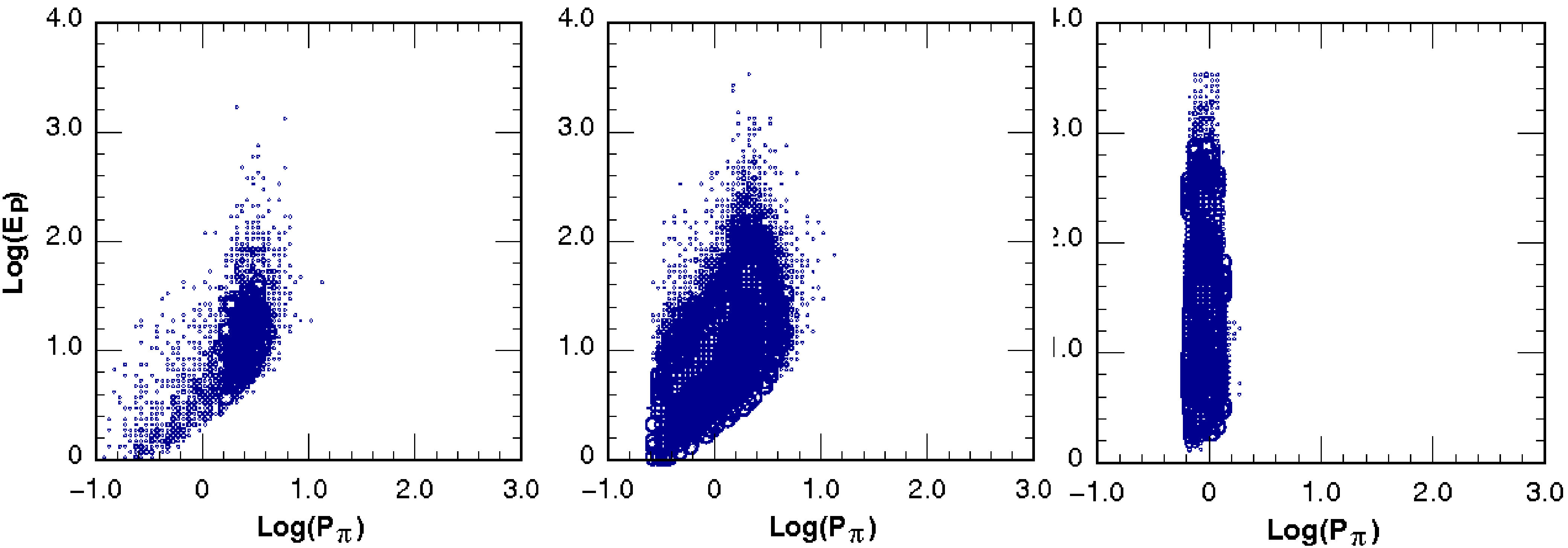
- A study with the preliminary Cosmic Ray Model based on AMS02 and BESS-polar is presented. However, when the interaction model is modified to reproduce the atmospheric muon observations, the calculated atmospheric neutrino flux is very similar to the one calculated with old primary flux model.

- We are planning the improvement of the low energy atmospheric neutrino calculation to reduce the uncertainty.

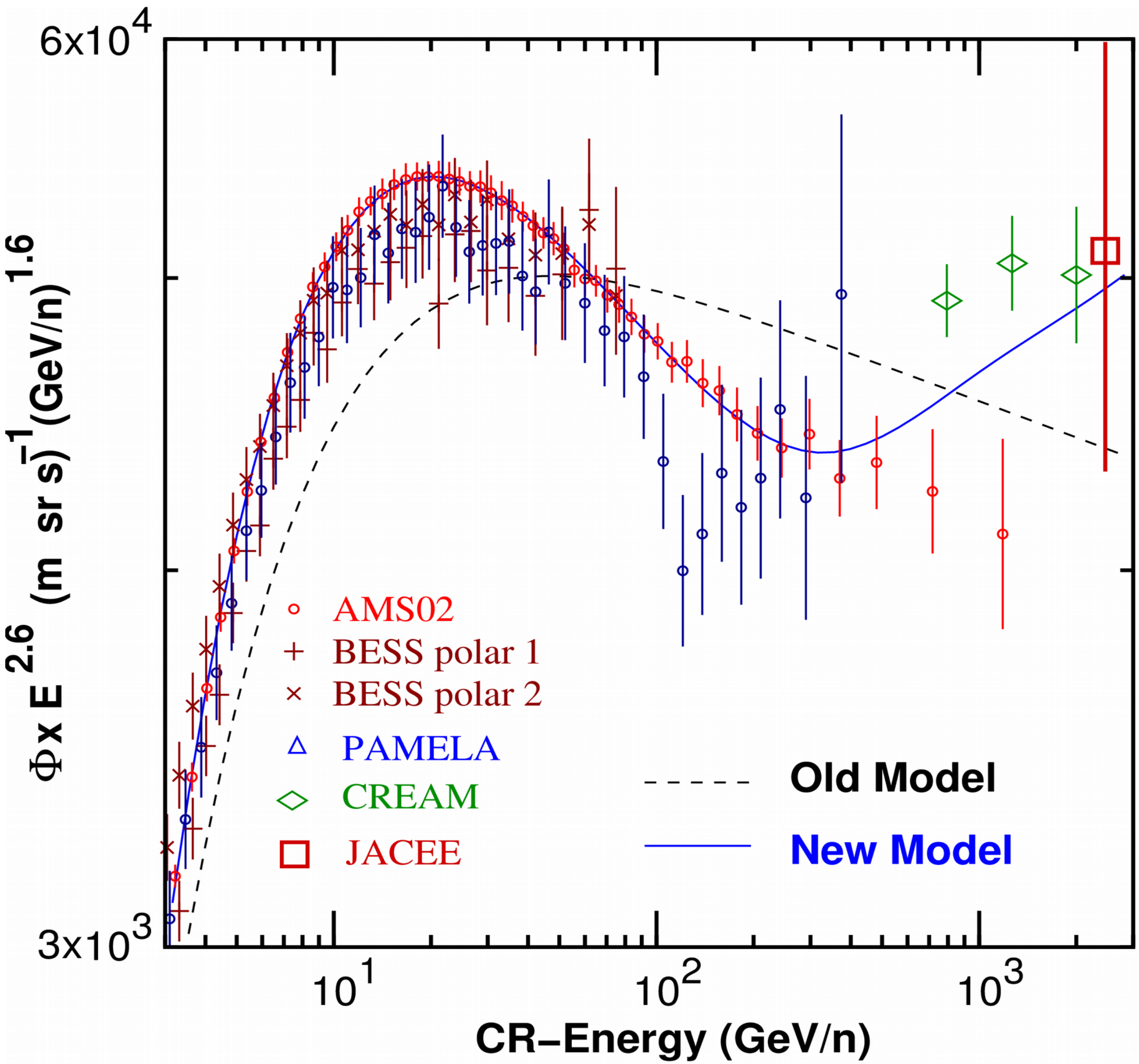
Back up

Typical Phase Space of $p + N(air) \rightarrow \pi + X$ interaction to produce muons related to ~0.32 GeV neutrinos.

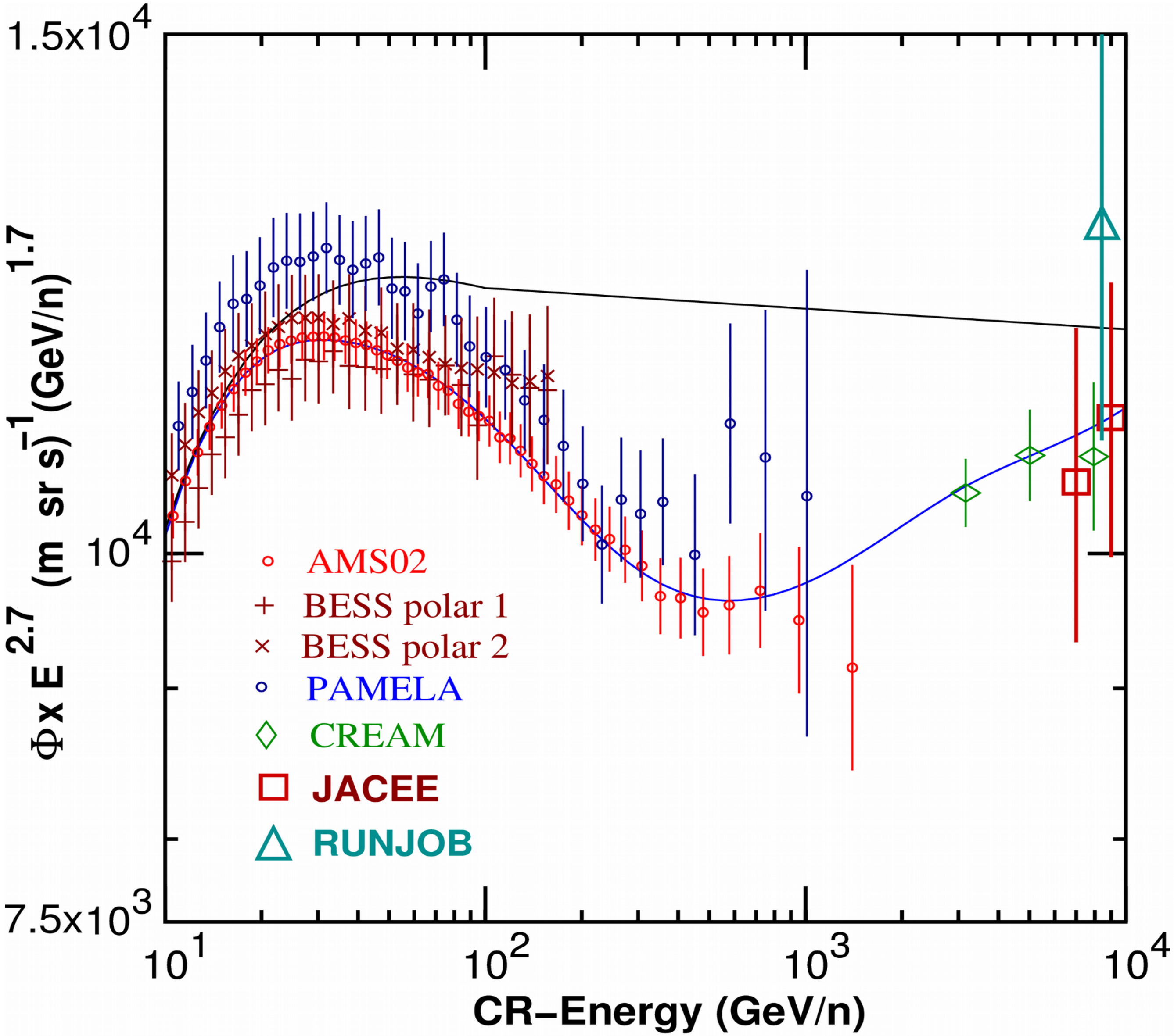
At sea level | On Mt. Norikura | Balloon altitude



Close Up for Helium

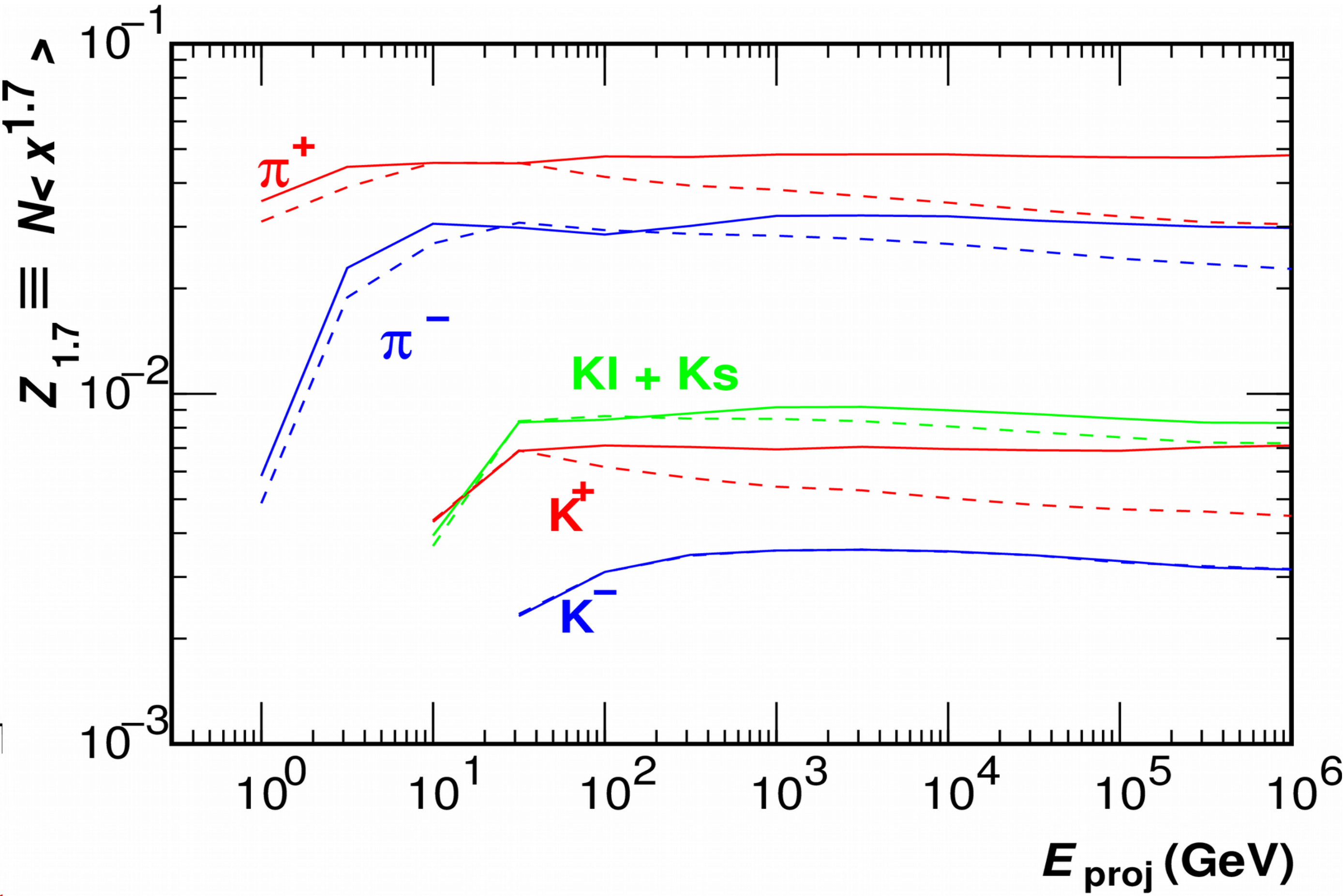


Close Up for Proton

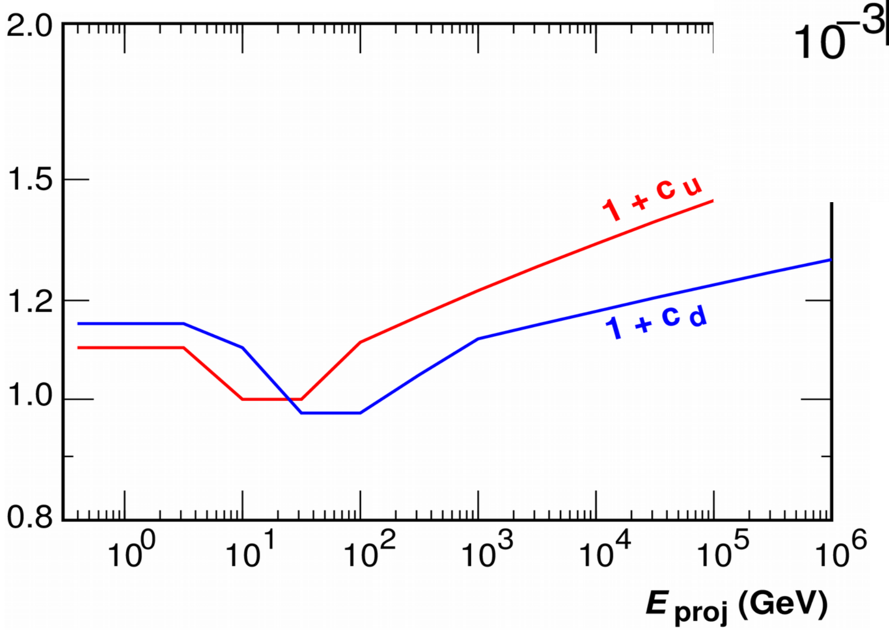


Modification of Int. Model (SHKKM 2006)

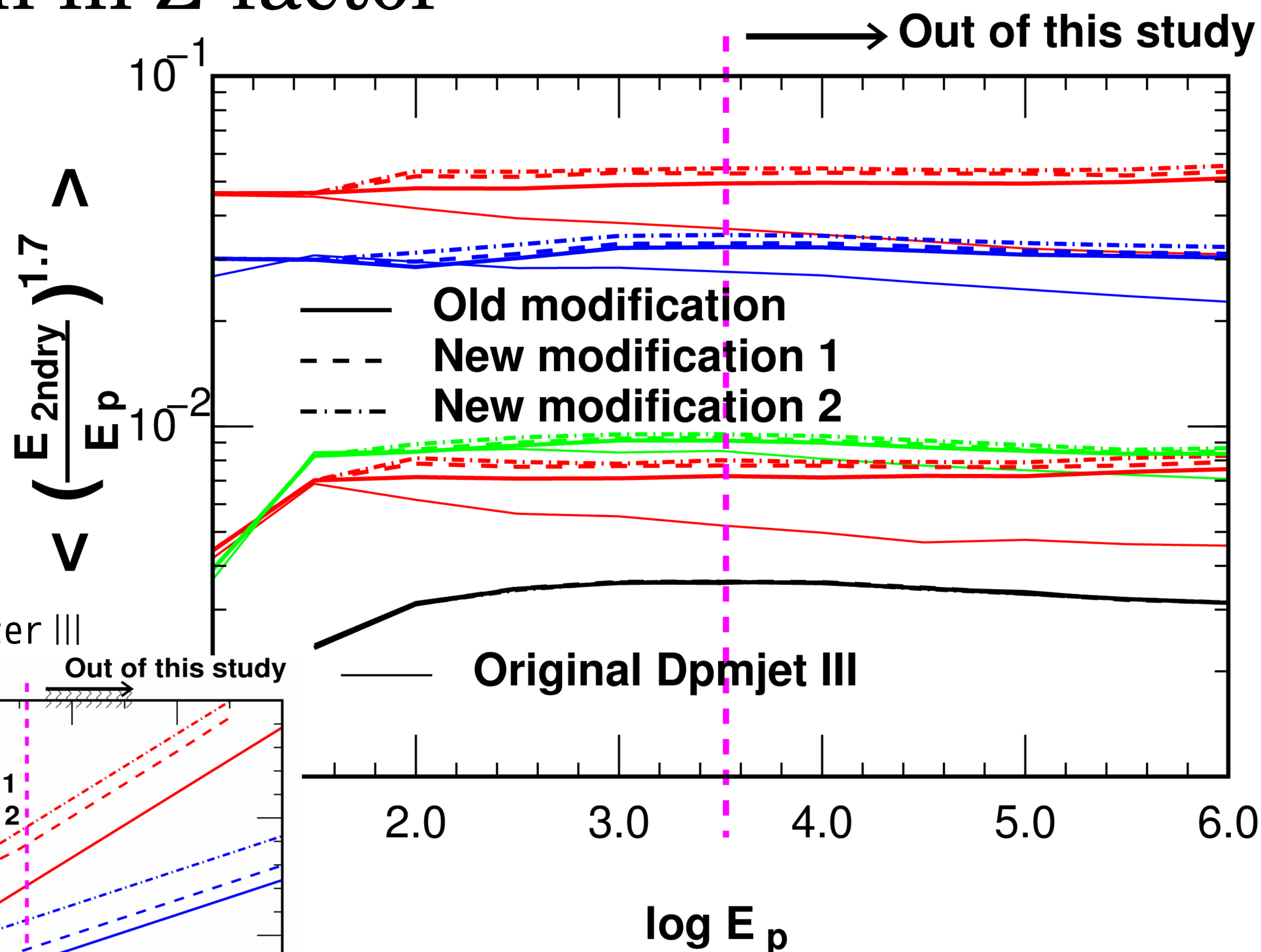
Z-Factor

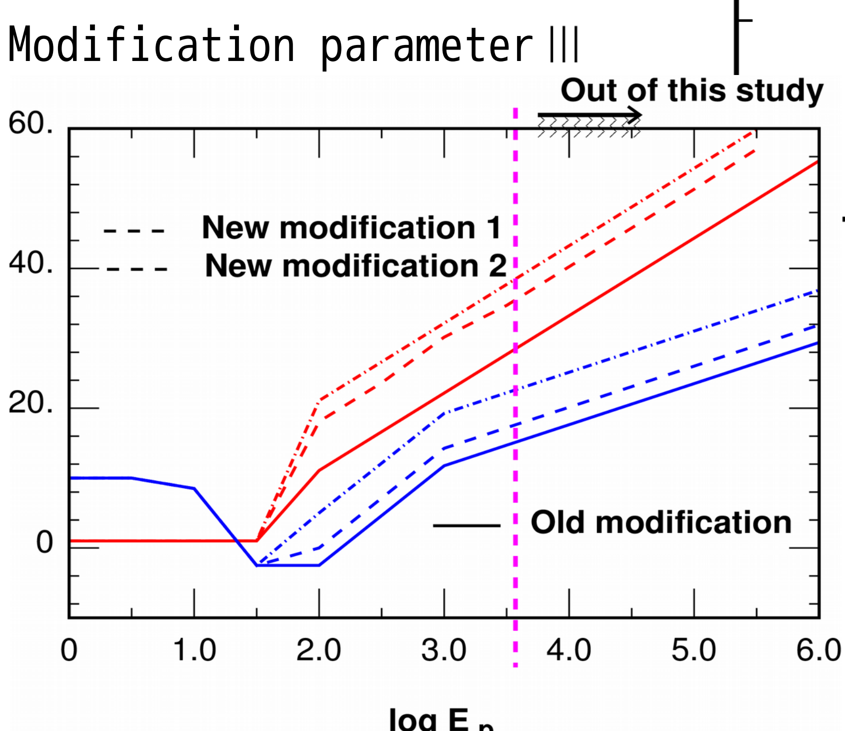


Modification parameter

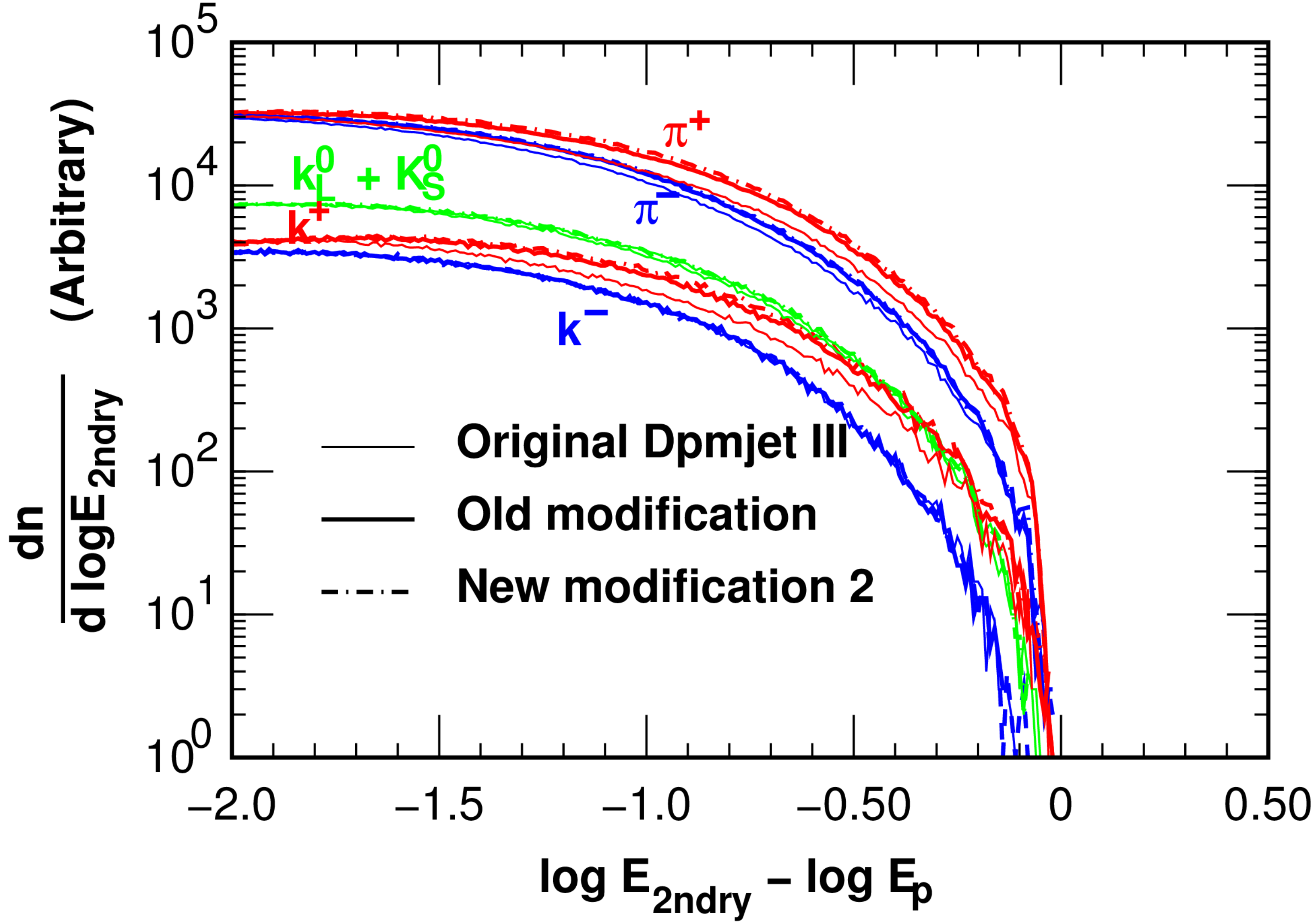


Comparison in Z-factor

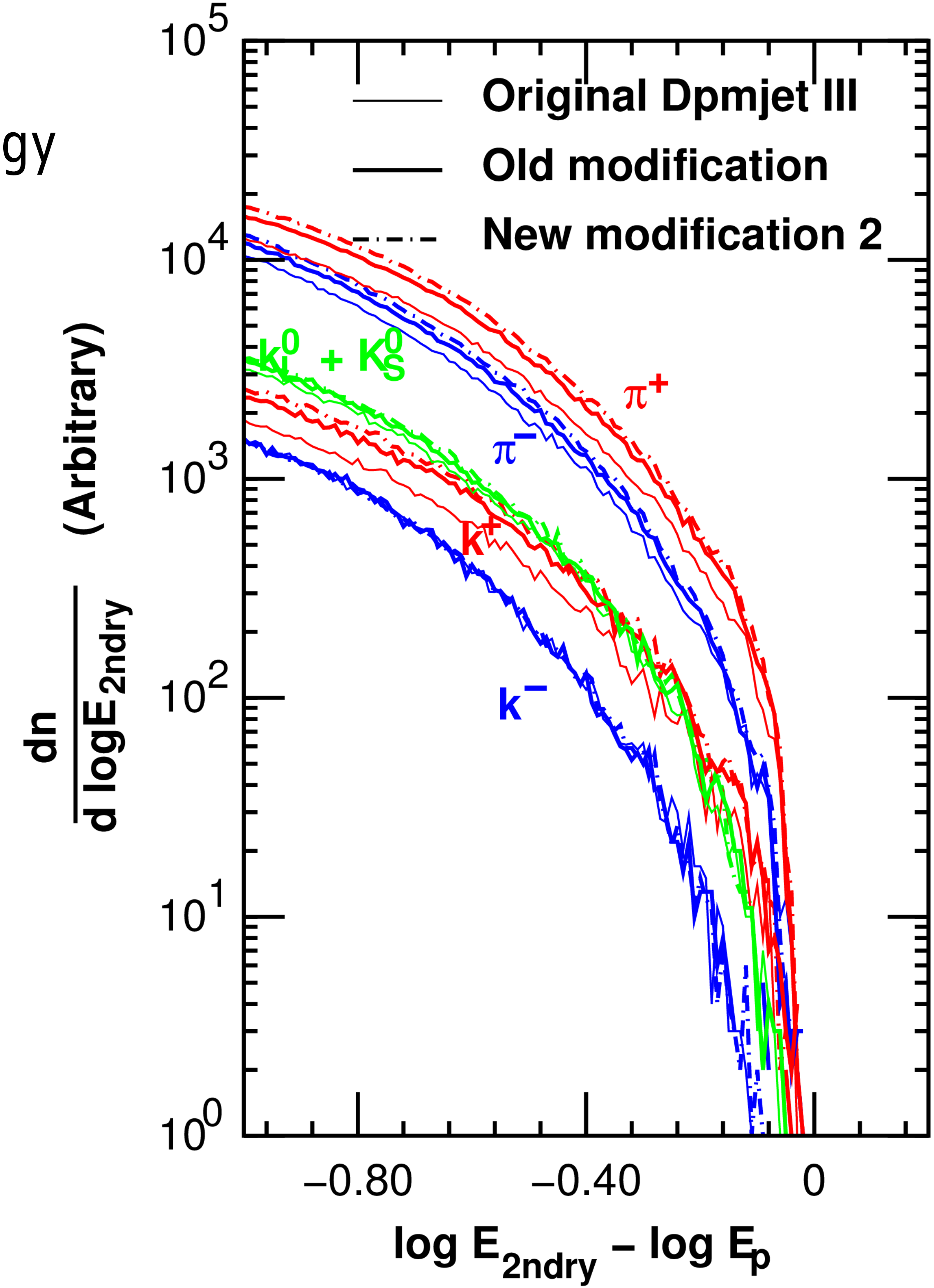




Comparison of secondary spectra of interaction models at 1 TeV



High secondary energy region close up



Gaisser Formula for 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

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

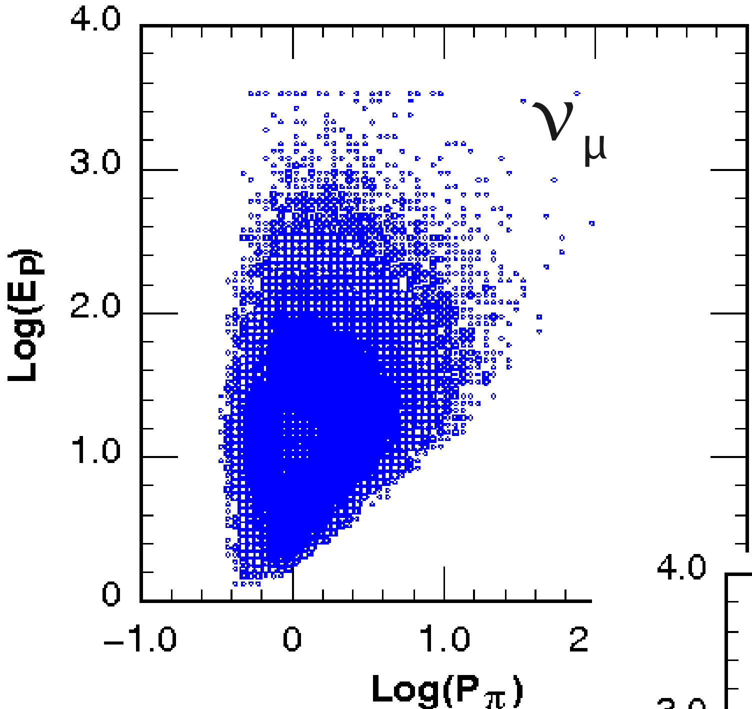
$Y_\nu = Yield_\nu(h, \theta)$: Hadronic Interaction Model, Air Profile, and meson-muon decay

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

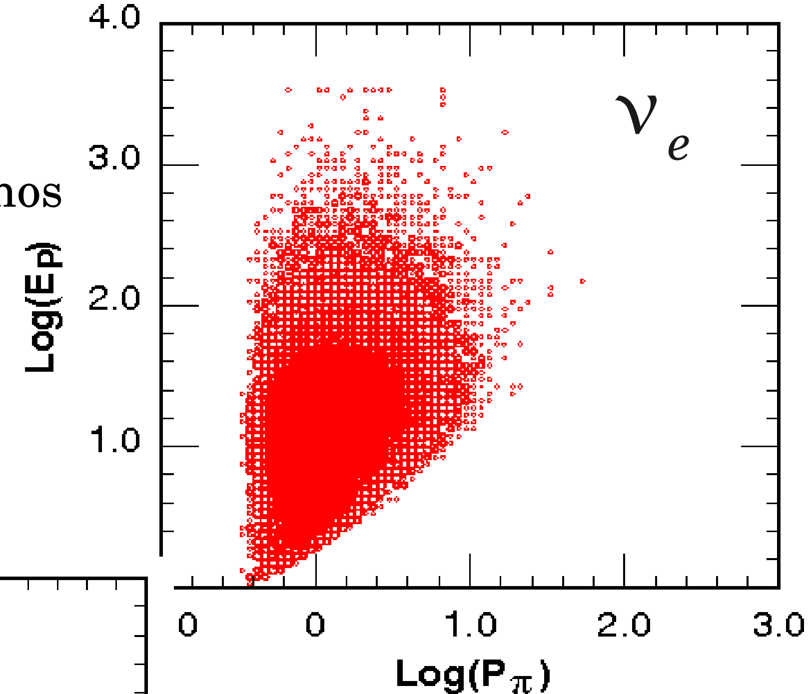
This formula illustrates 1D-calculation well

The improvement of lower energy uncertainty

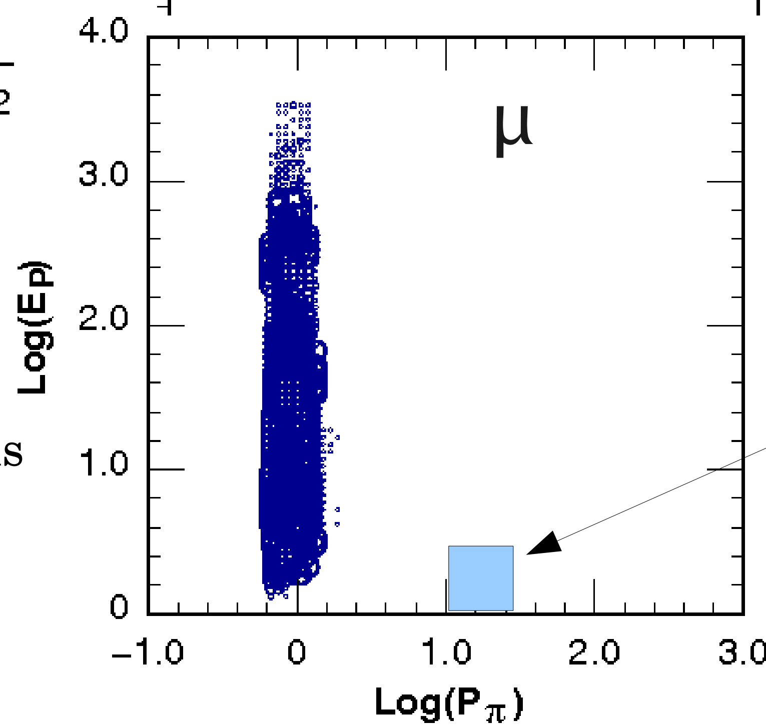
Give Variations in the phase space and compare the variation of neutrino flux and the Maximum variation of muon flux in 0.5 ~ 2 GeV/c (μ+) And 0.5 ~ 4 GeV/c (μ-), where BESS Balloon observation was available.



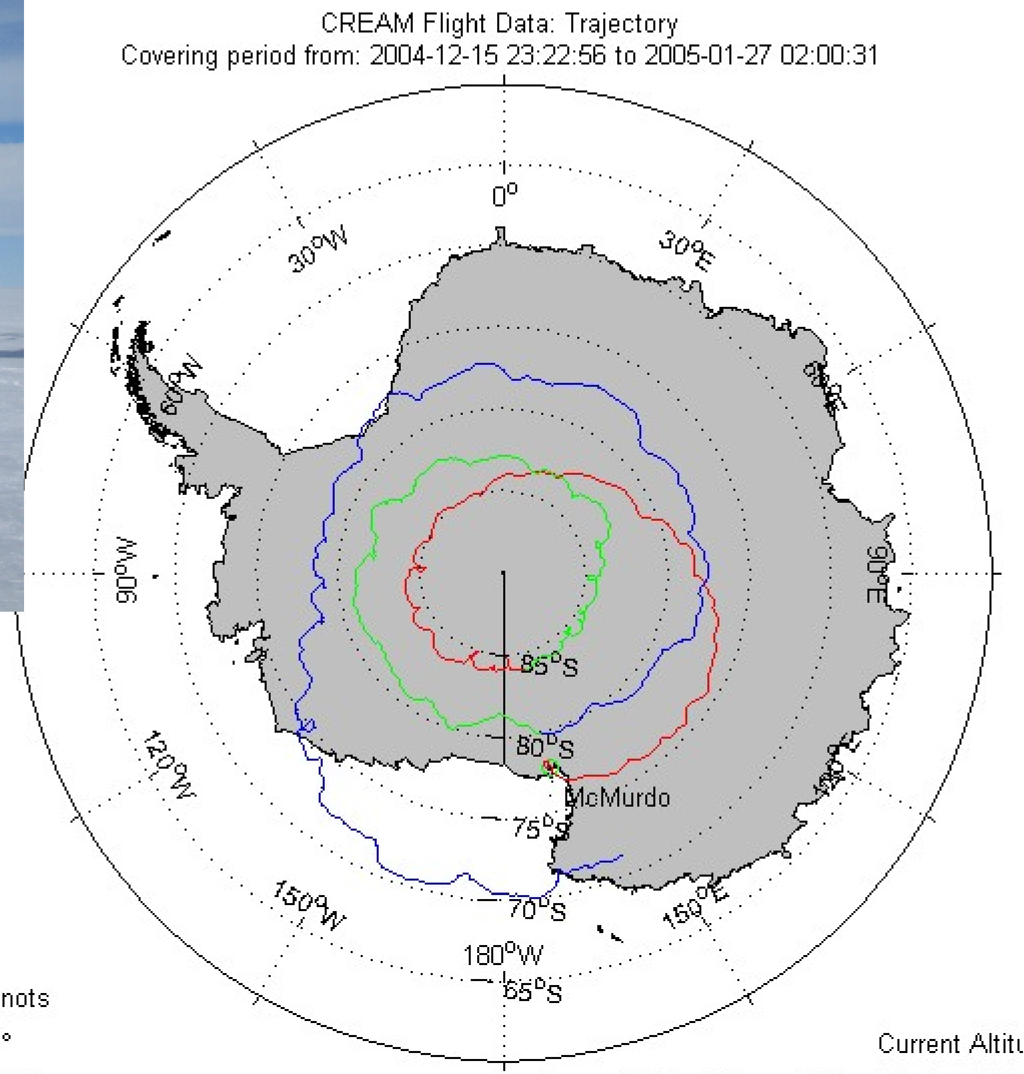
Phase space for 0.32 GeV neutrinos



Phase space for corresponding muons



Size of Phase space to give the variation



Current Speed: 17.2 knots

Current Course: 128.1°

Current Lat: -71°17′3.72″

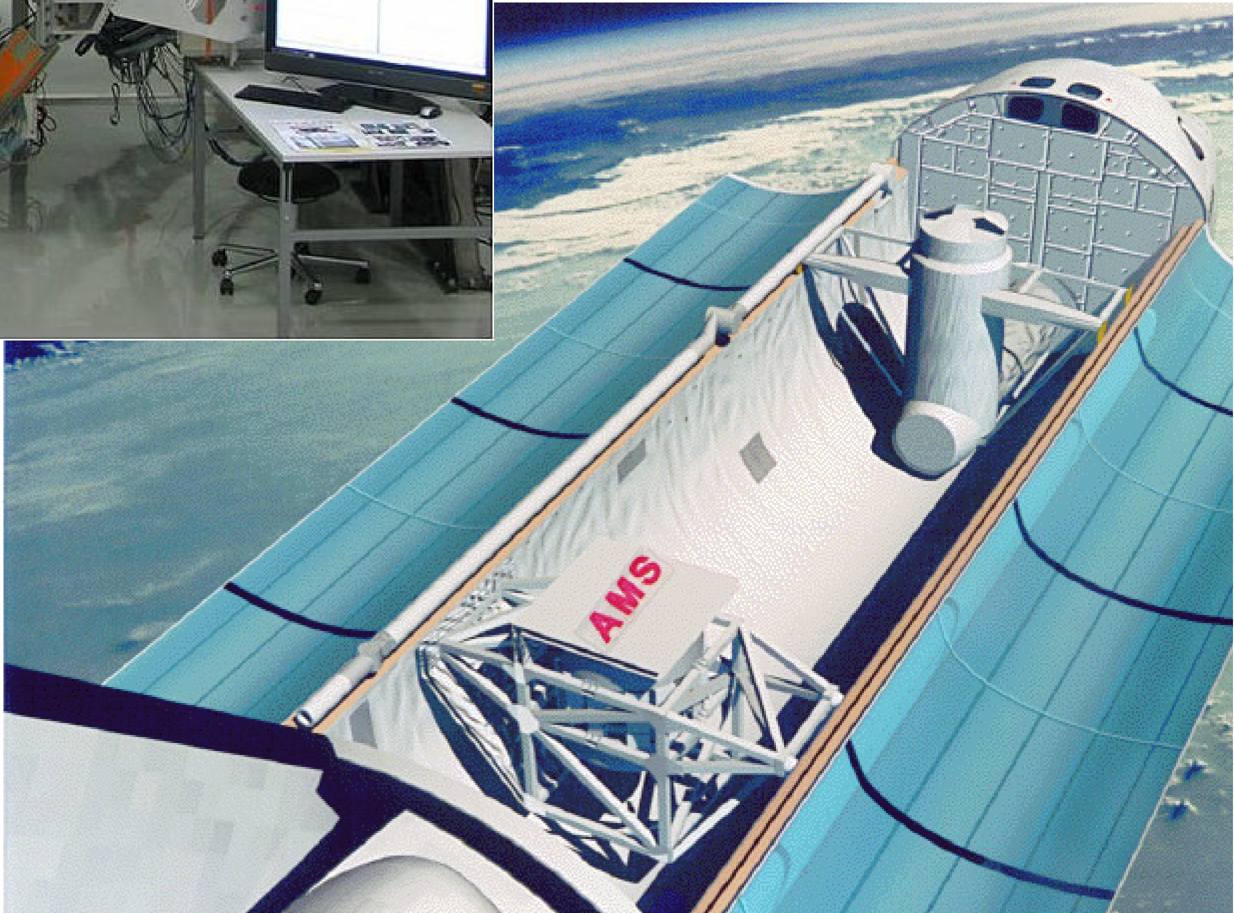
Current Lon: 157°52′54″

Current Altitu

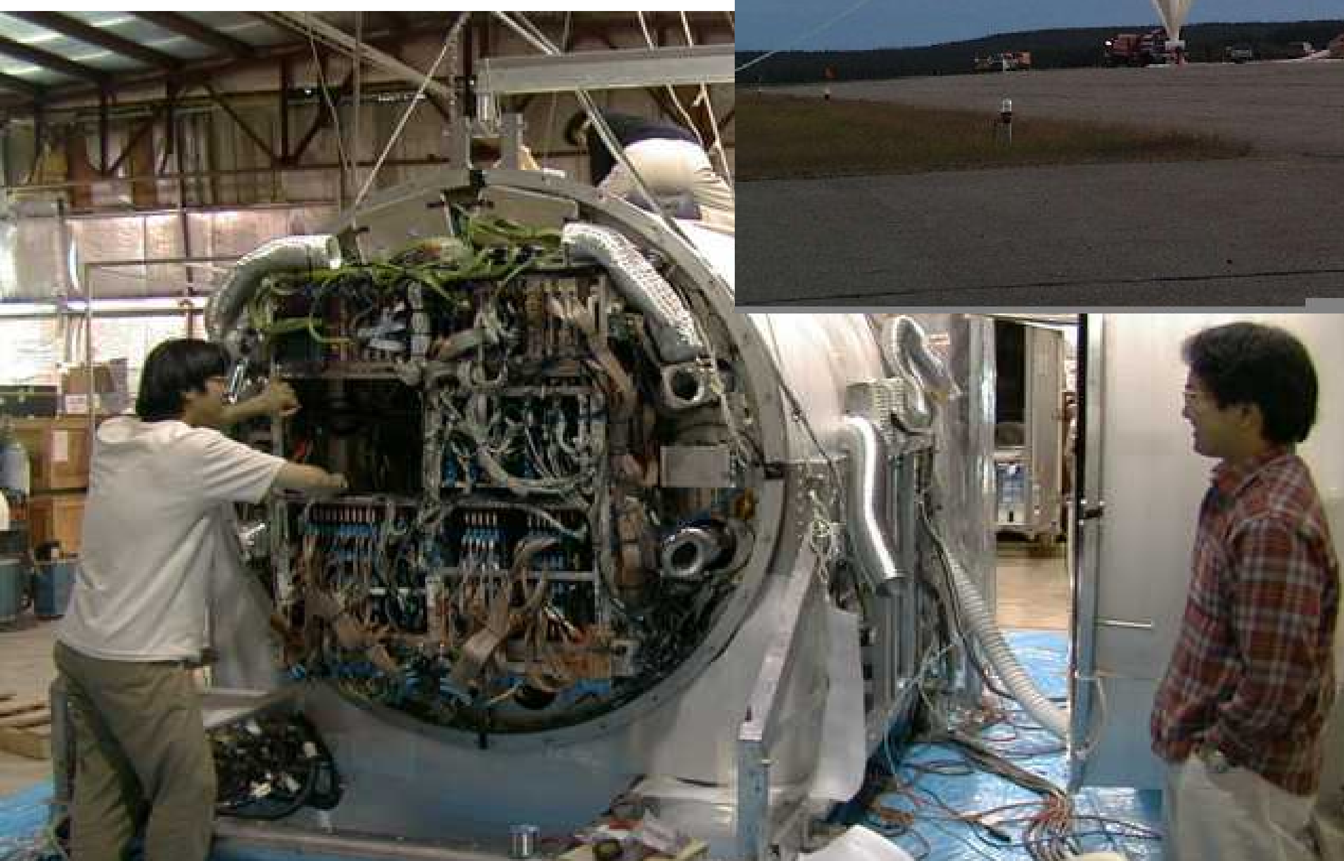
Current MET: 41 days 21 hrs 31 mins 30.7

Current Time: 2005-

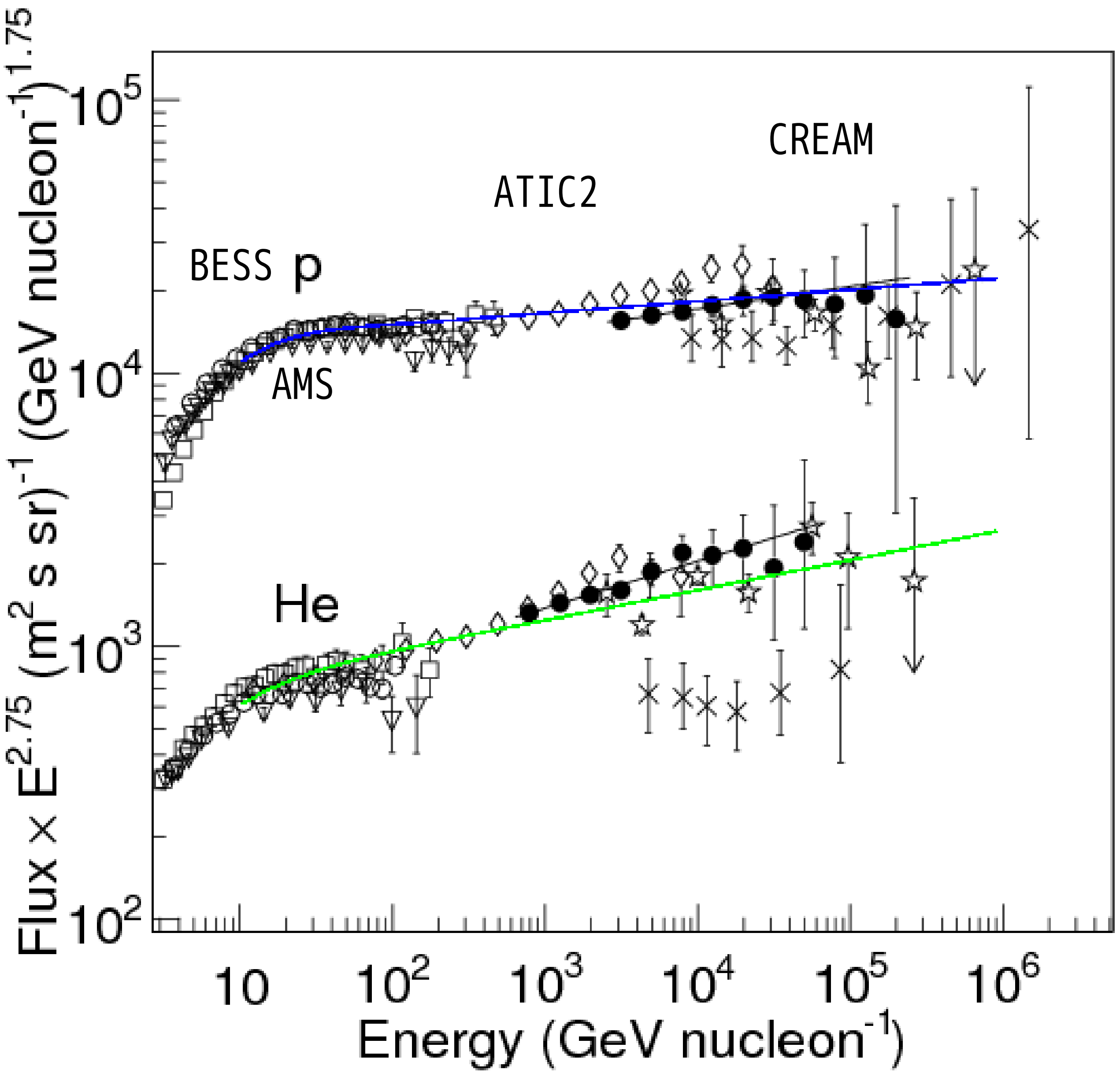
AMS-I



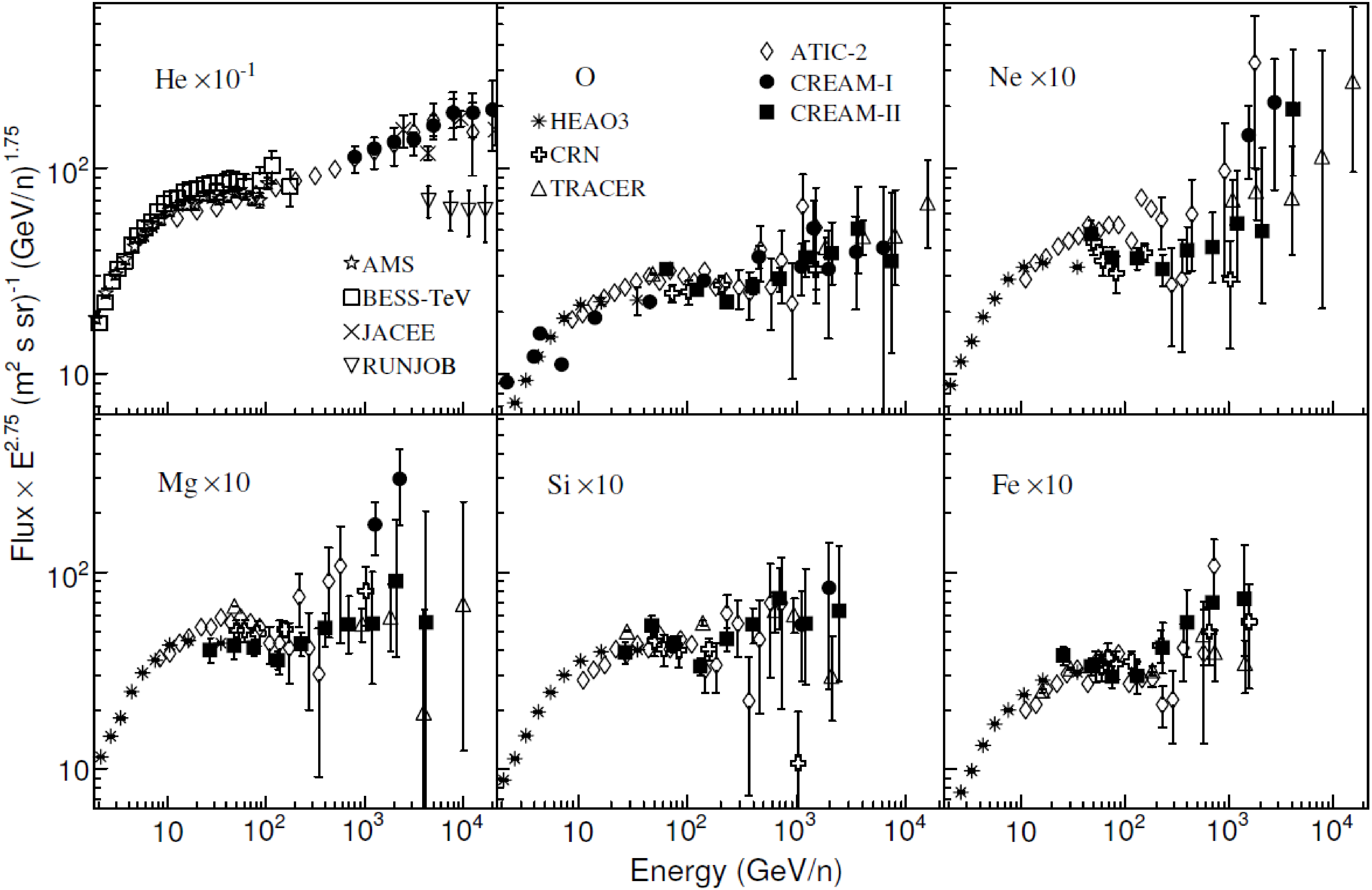
BESS also observed Atmospheric muons at Balloon altitude and Ground.



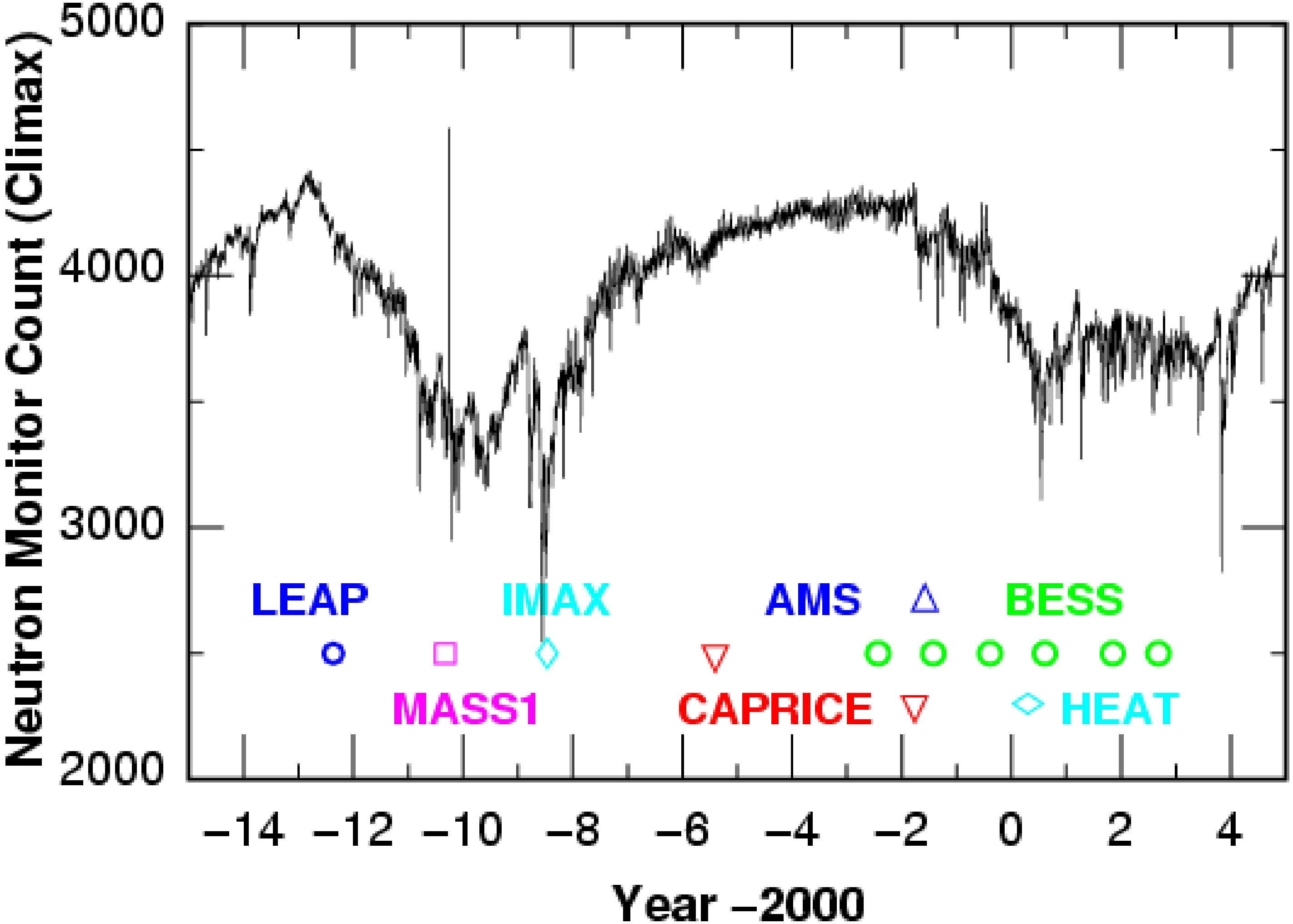
Comparison with recent observations.



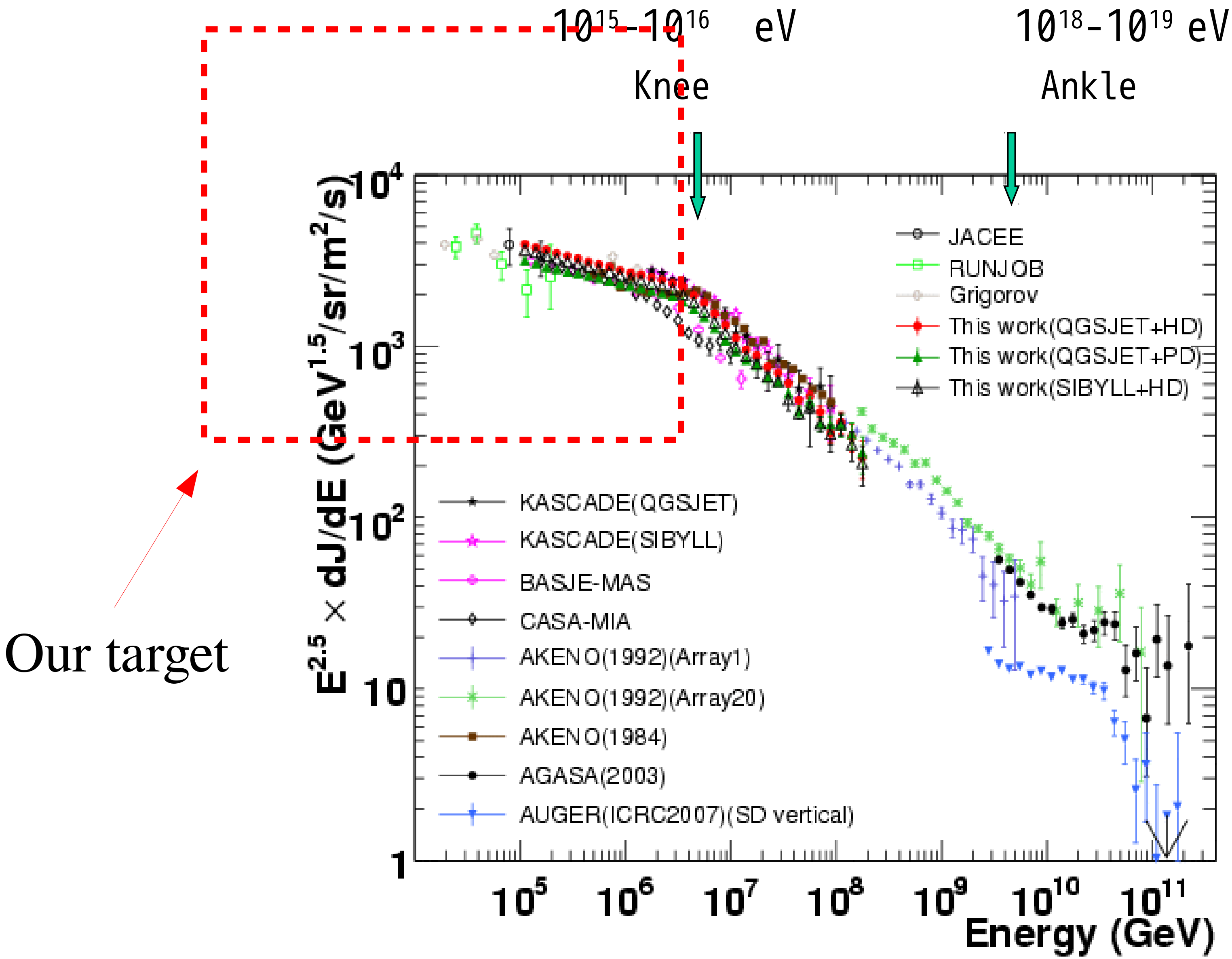
With expanded vertical axis



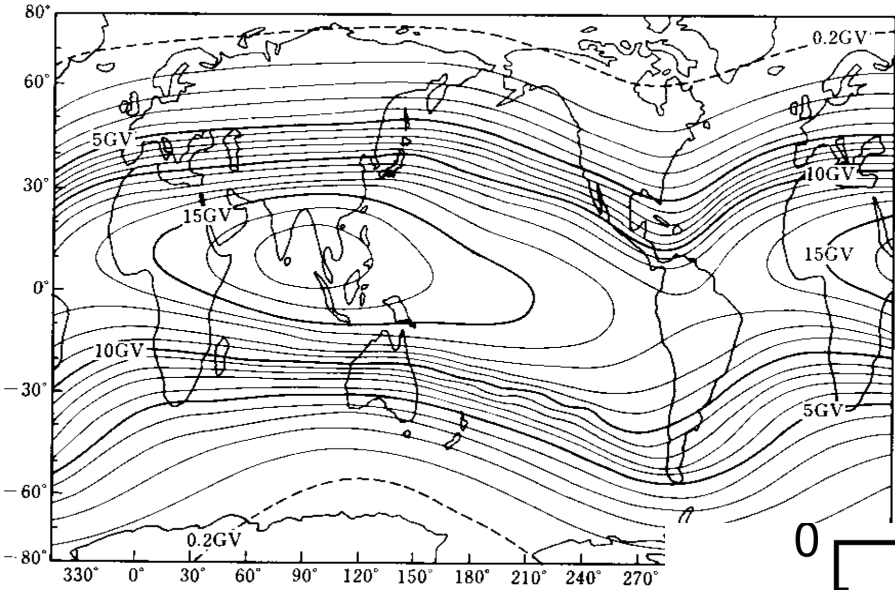
Modulation by the Solar Activity



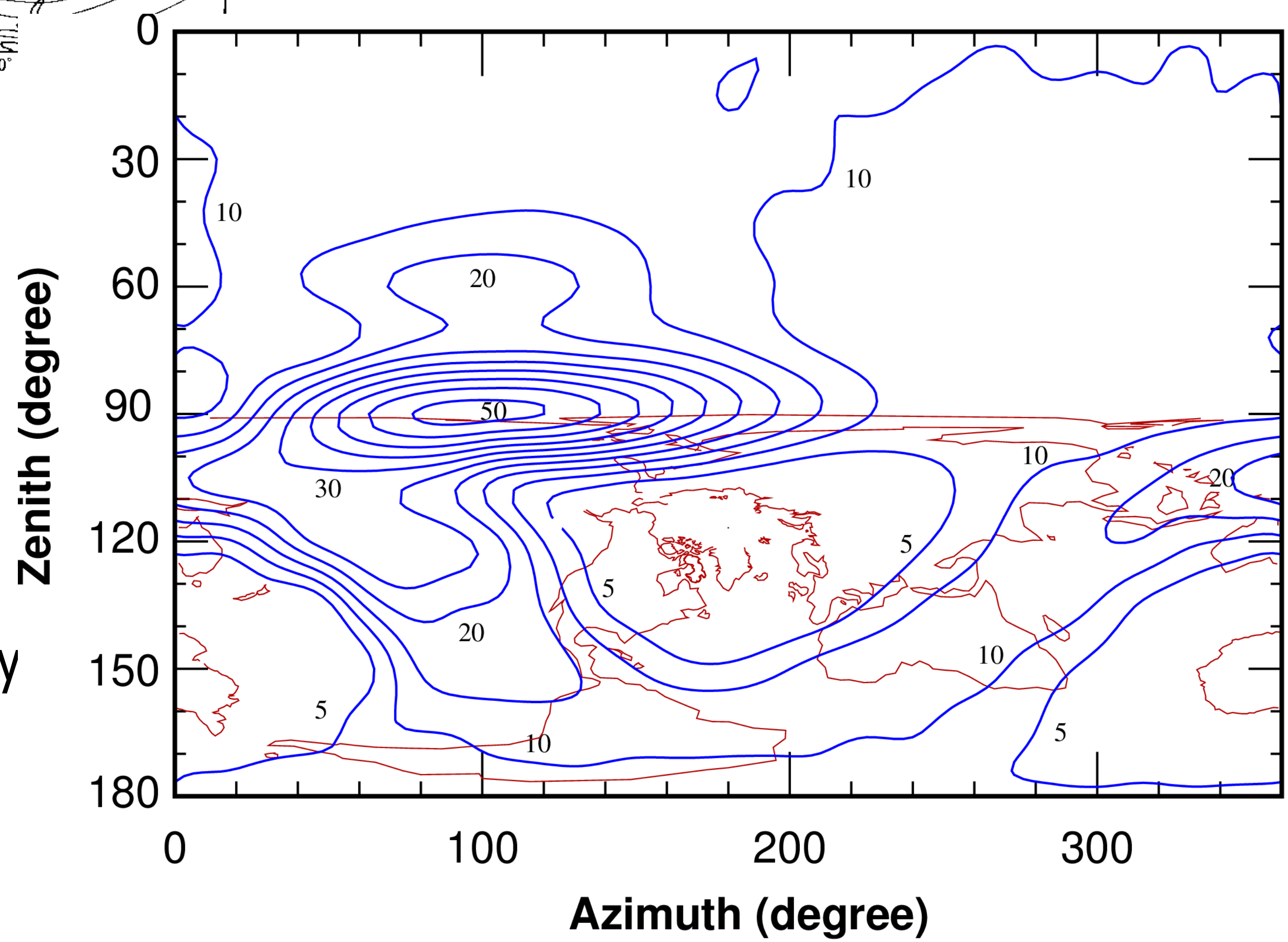
CR spectrum in wide range



Rigidity Cutoff for
Virtical direction



Directional Rigidity
Cutoff from SK

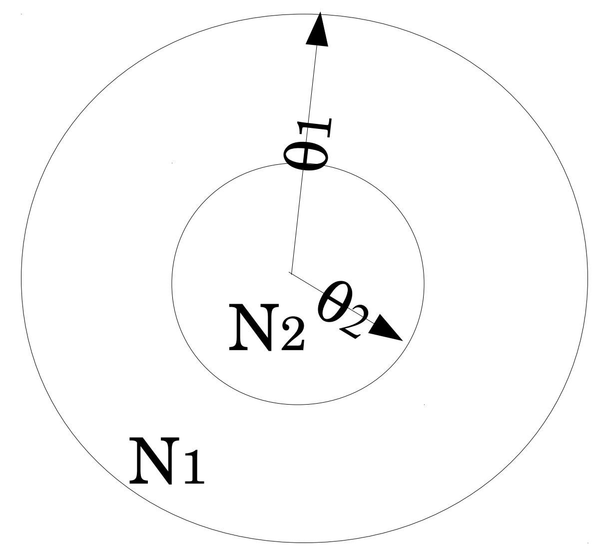


Size correction for virtual detector

Assume true flux value and average in the circle with radius θ1 and θ2 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 ϕ1 and ϕ2 as;

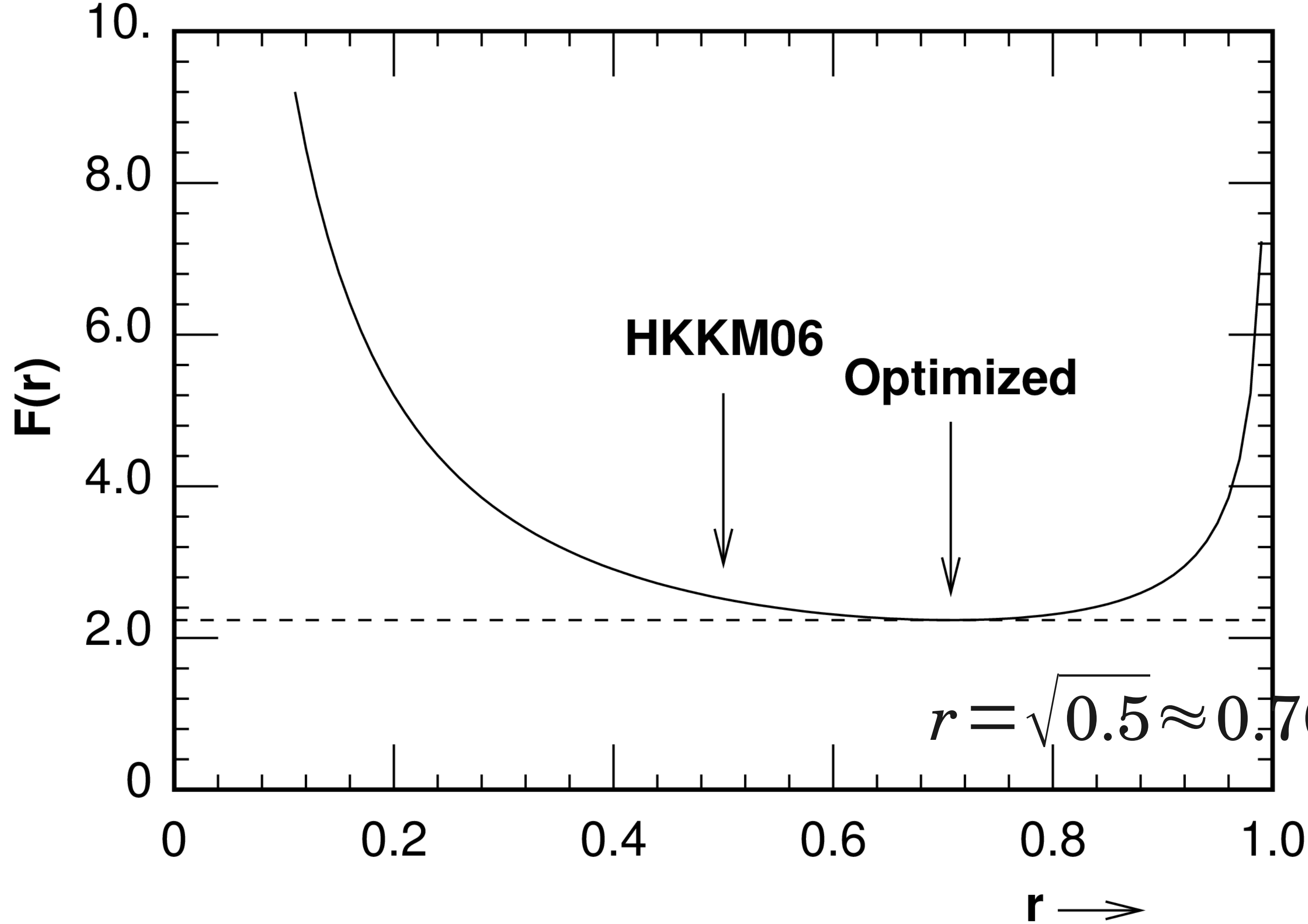
$$\phi_0 = \frac{\theta_1^2 \phi_2 - \theta_2^2 \phi_1}{\theta_1^2 - \theta_2^2} = \frac{\phi_2 - r^2 \phi_1}{1 - r^2} \qquad r = \left(\frac{\theta_2}{\theta_1}\right), \; r < 1$$

In terms of the sampled number $N1$ in the circle θ < θ1, and $N2$ in θ < θ2, ϕ1 and ϕ2 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 $r = (\frac{\theta_2}{\theta_1})$ value, which minimize the stat. error

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



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

上空のμと垂直下向き方向νのフラックスの相関係数