大気ニュートリノフラッス計算

本田守広＠宇宙ニュートリノ研究会
(2016-02-20)

1, 大気ニュートリノフラックス計算の簡単な概説

2, 大気モデルNRLMISSIE-00を用いた、神岡以外のサイトおける大気ニュートリノフラックス（HAKKM PRD2015）。

3, AMS02,BESS-polarなどの、新しい観測をとりいれた一次宇宙線モデルを用いた計算と、これまでの計算結果との予備的比較。

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.

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

A symbolic formula to illustrate 1D-calculation

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

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

Where

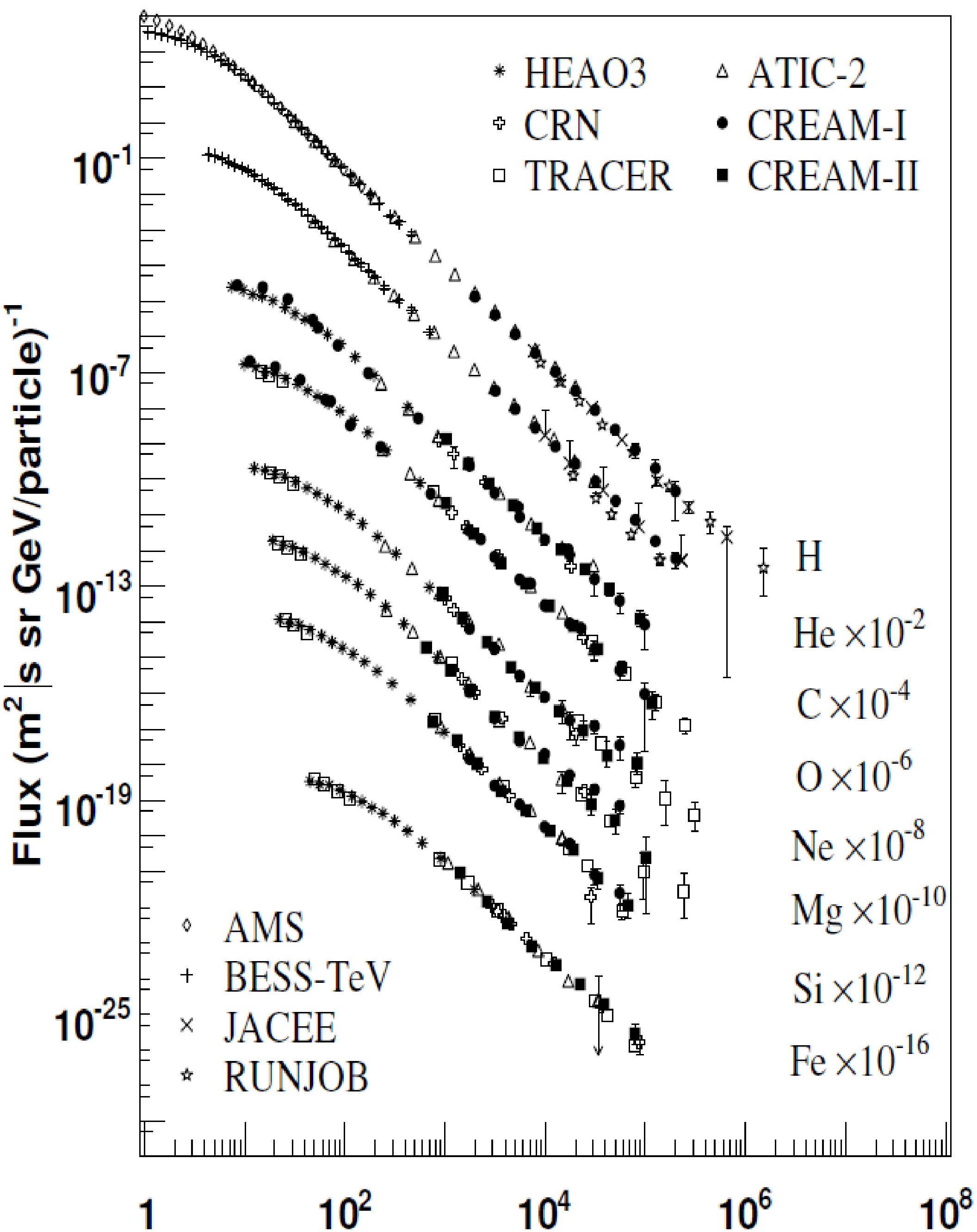
$\Phi_{primary}$: Cosmic Ray Flux

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

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

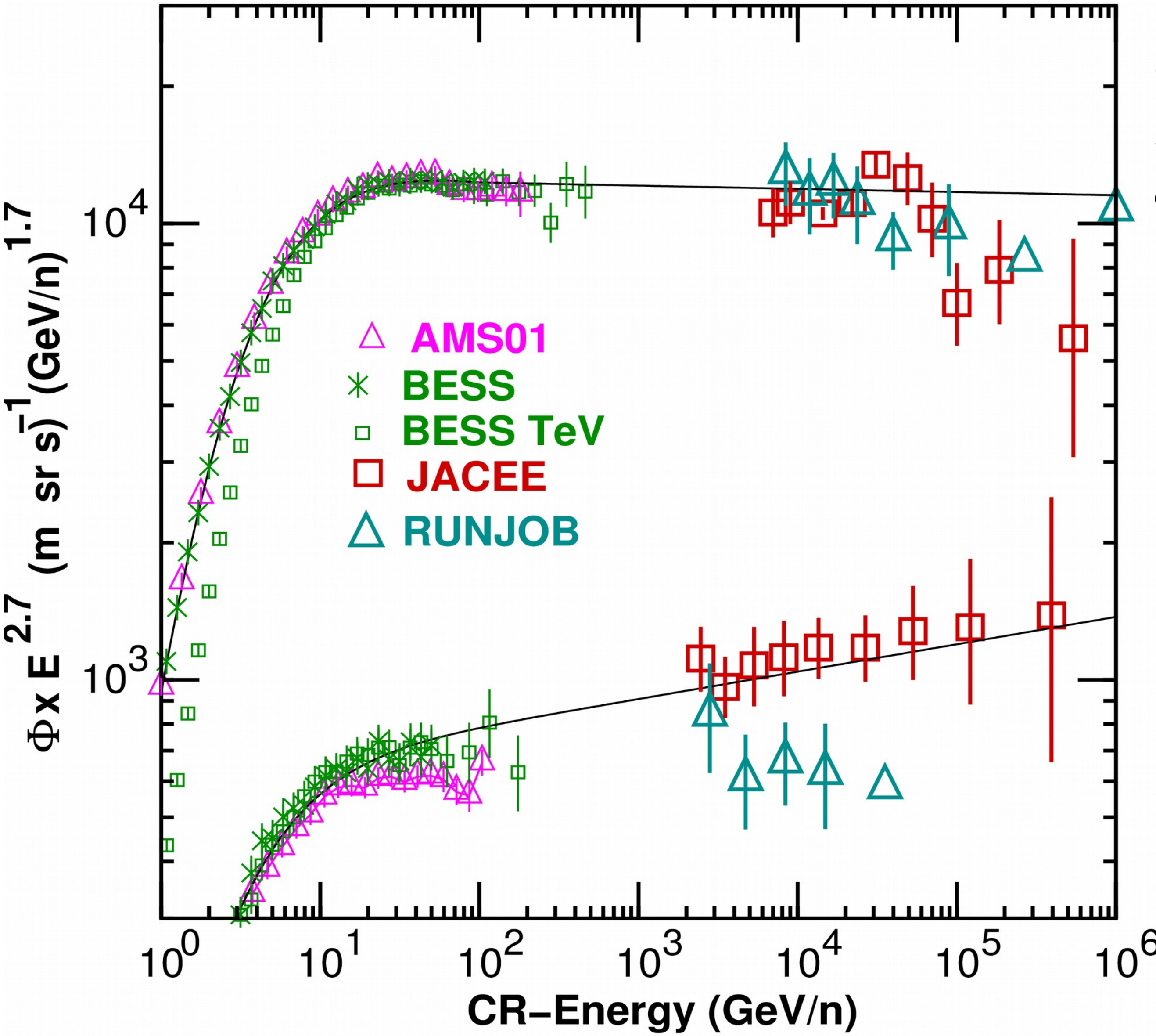
$Y_\mu = Yield_\mu(h, \theta)$: Hadronic Interaction Model, Air Profile, and meson decay

Primary Cosmic Ray Spectra

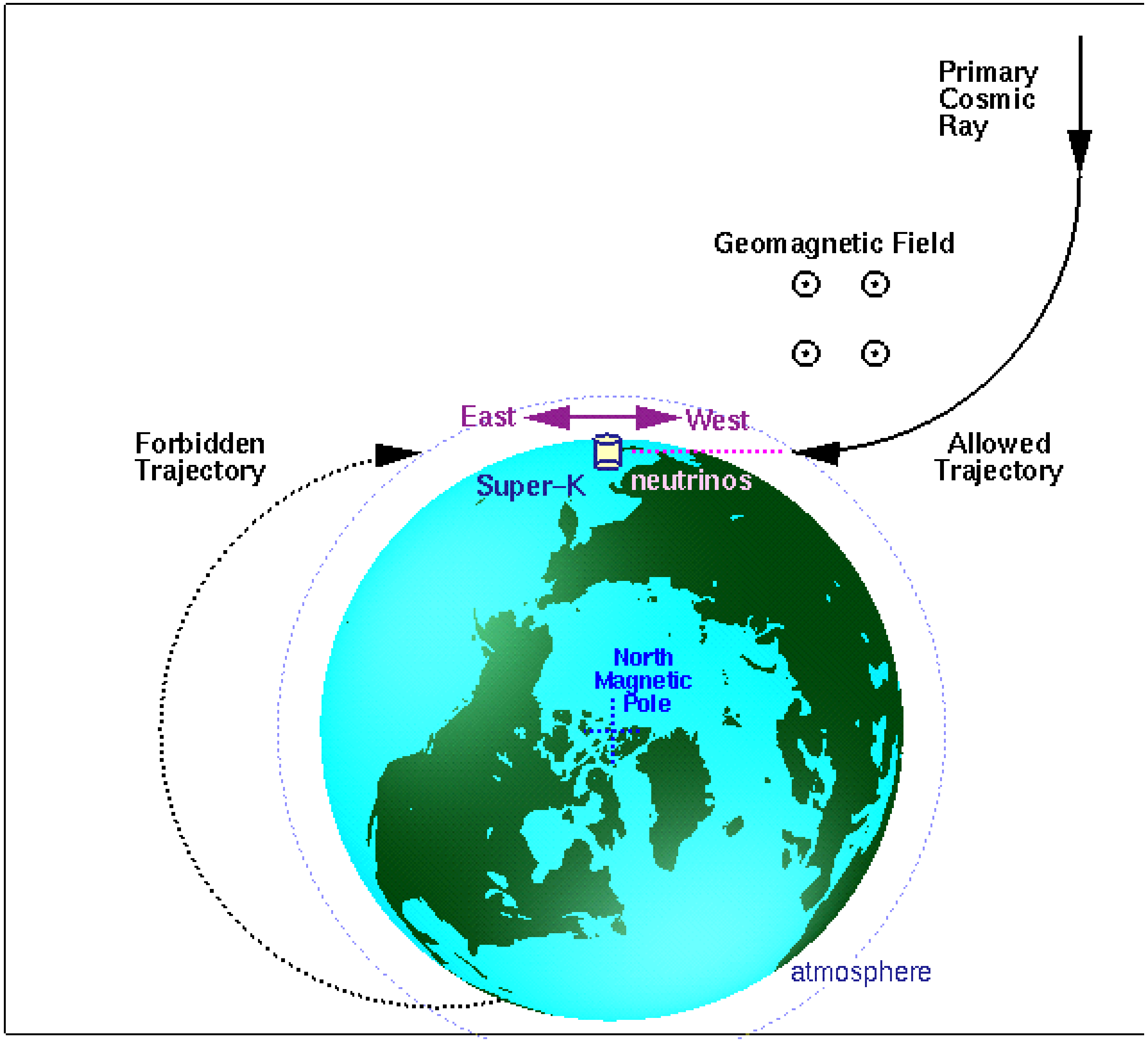


From
E.S. Seo @ ICRC2009

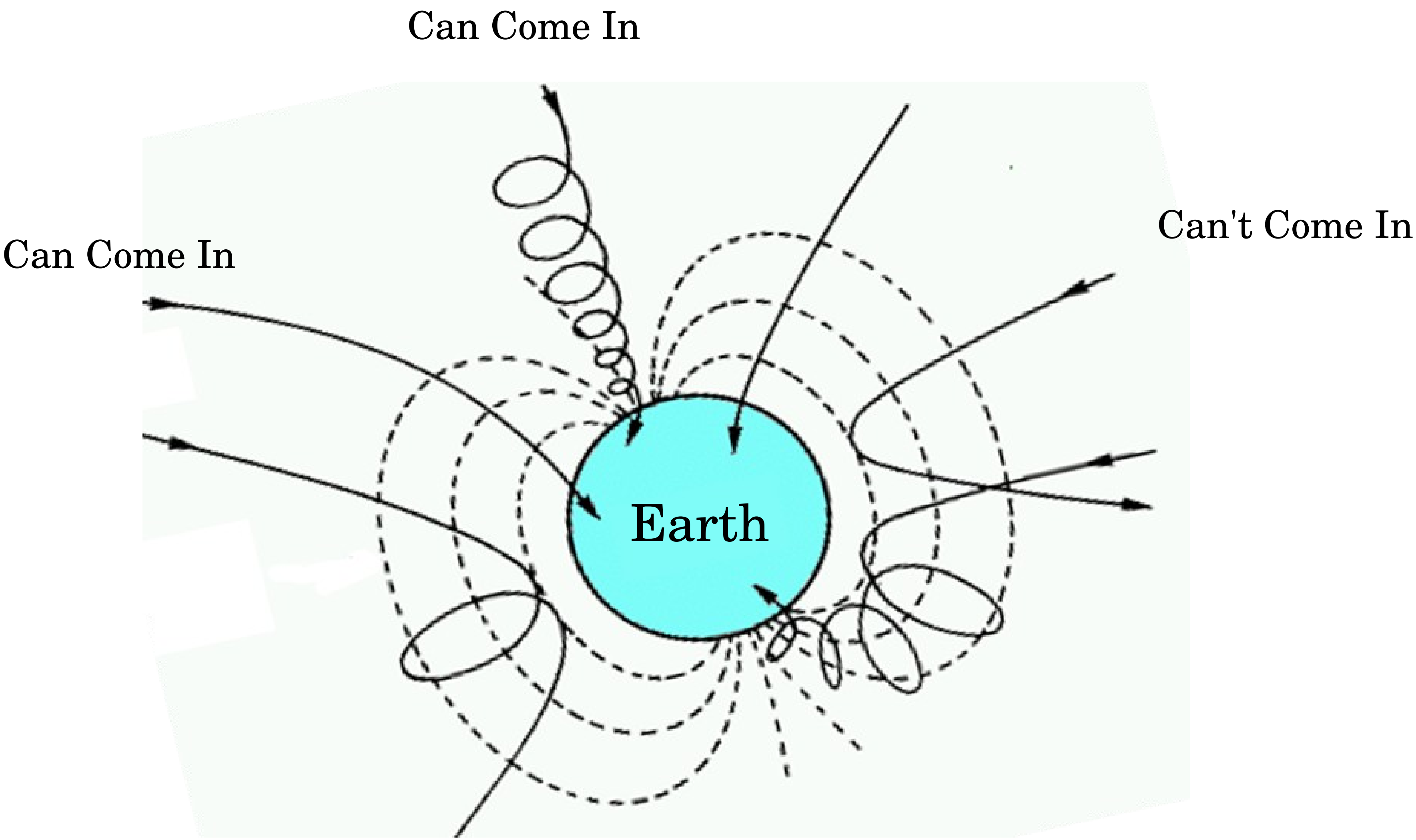
Primary Cosmic Ray Model and referred data



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

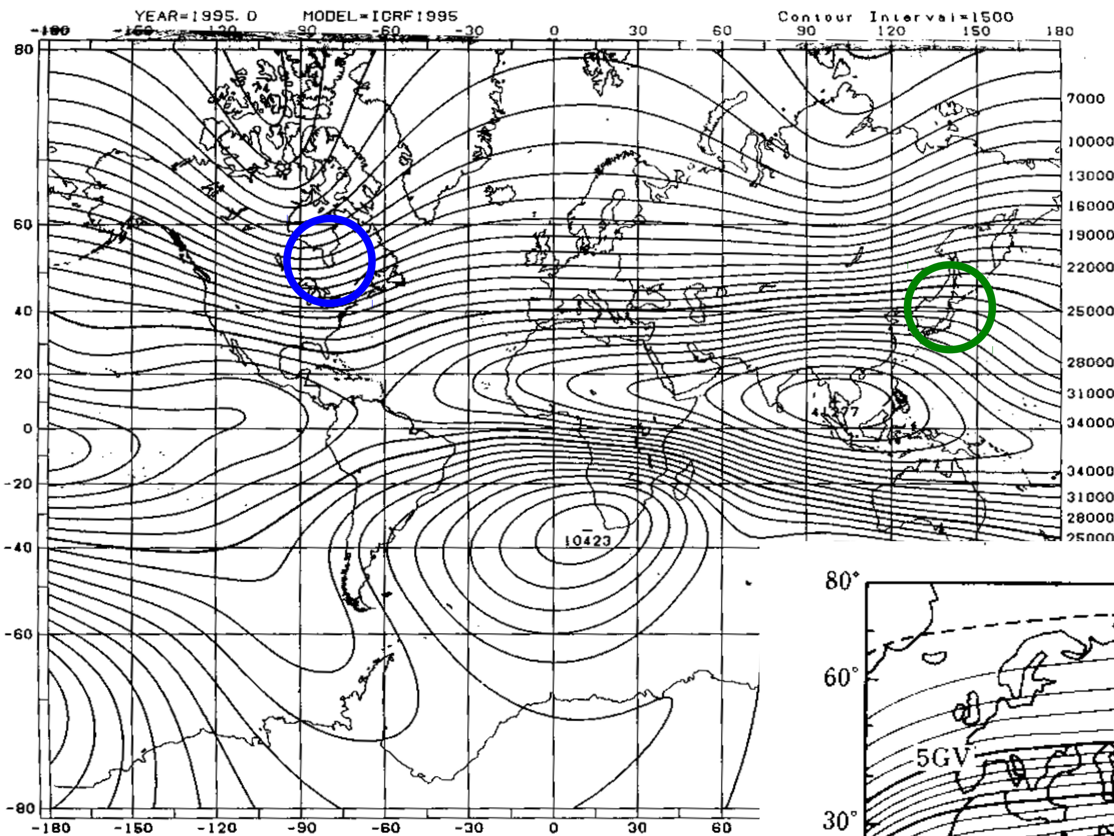

Primary
Cosmic
Ray
Geomagnetic Field
East
West
Forbidden
Trajectory
Allowed
Trajectory
Super–K
neutrinos
North
Magnetic
Pole
atmosphere

Rigidity Cutoff and Geomagnetic Field (cartoon)



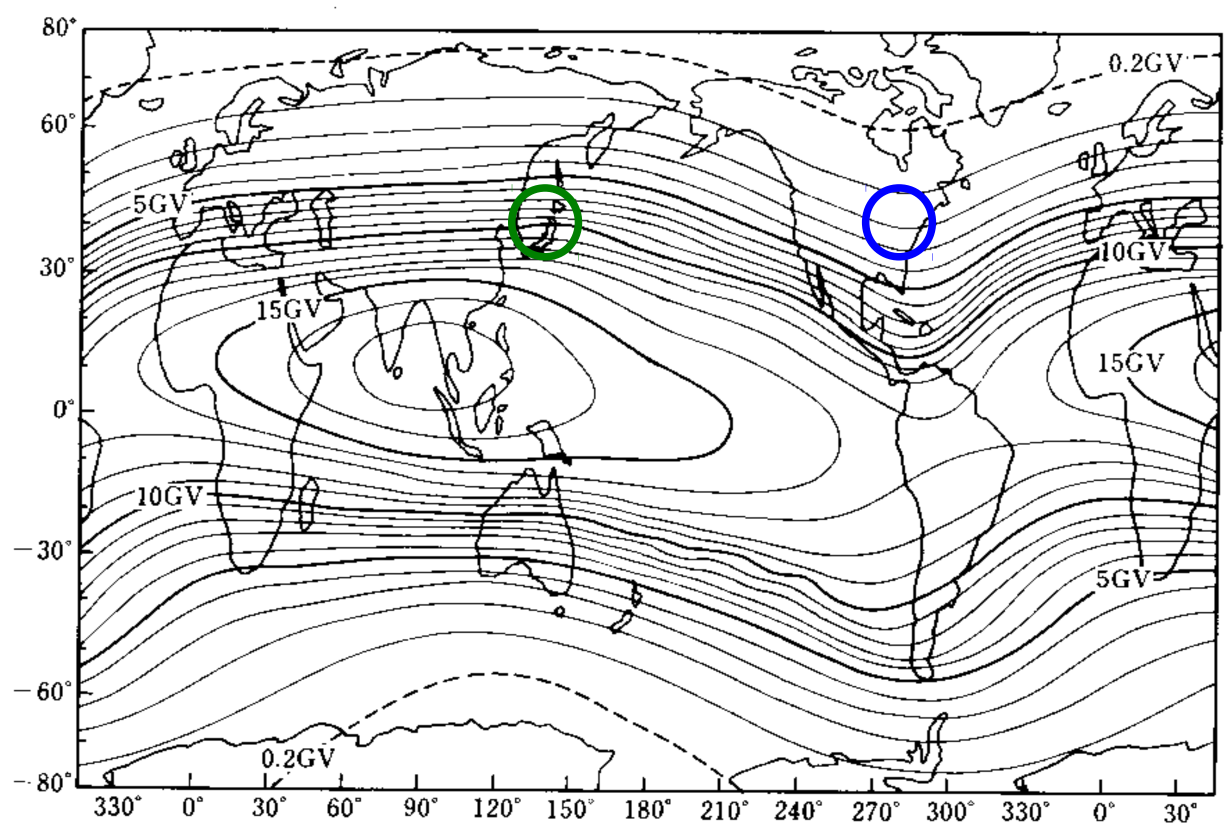
Rigidity Cut Off

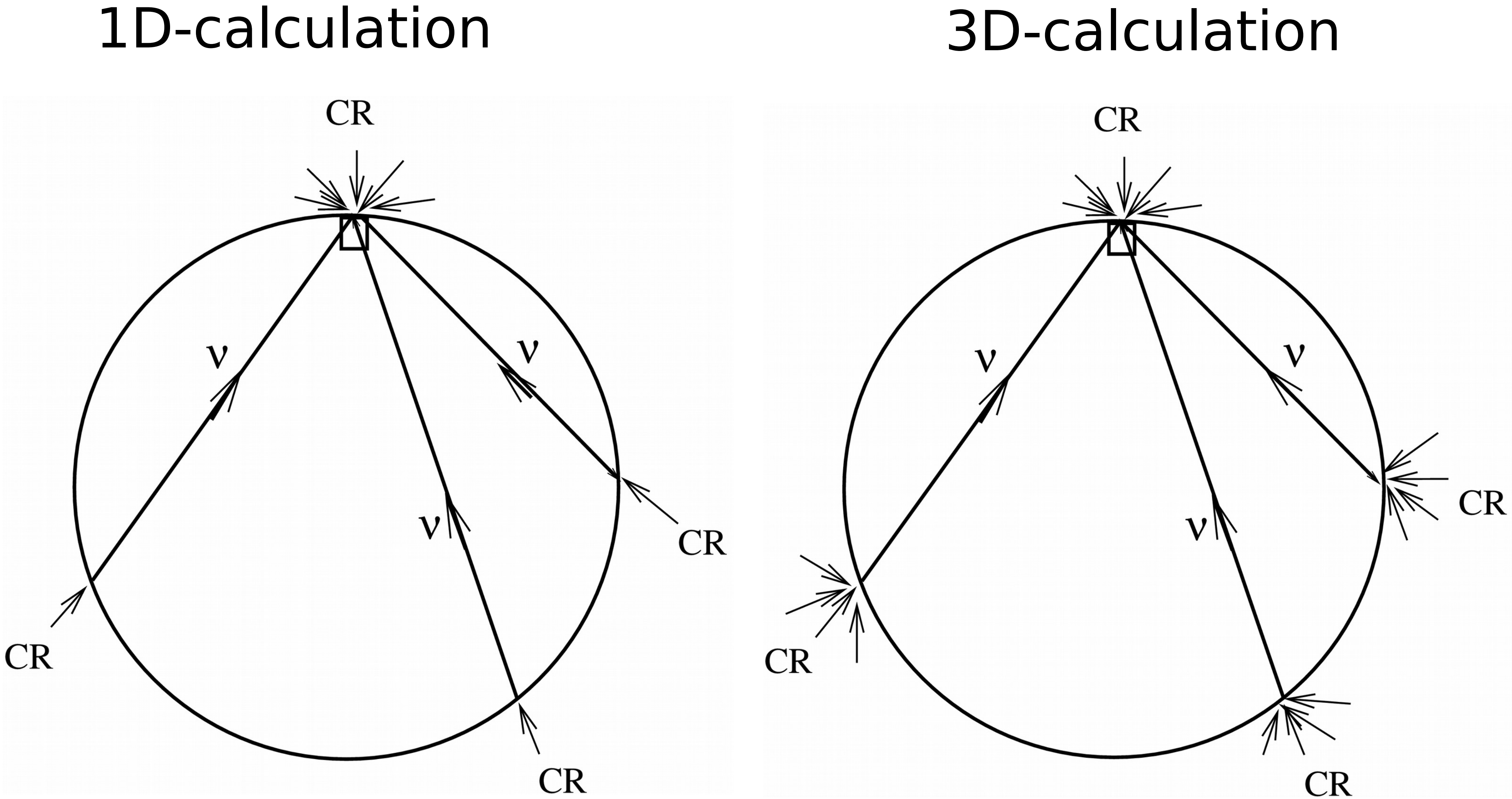
Difference for sites is determined by geomagnetic field



Horizontal component of geomagnetic field (IGRF2000)

Rigidity Cutoff for vertical Cosmic rays




1D-calculation
3D-calculation
CR
CR
CR
CR
ν
ν
ν
ν
ν
ν
CR
CR
CR
CR

Why 1D calculation is so preferred ?

1. $$\frac{\text{3D efficiency}}{\text{1D efficiency}} \sim \frac{[\mathit{Area\ of\ virtual\ detector}]}{[\mathit{Area\ of\ the\ surface\ of\ Earth}]}$$

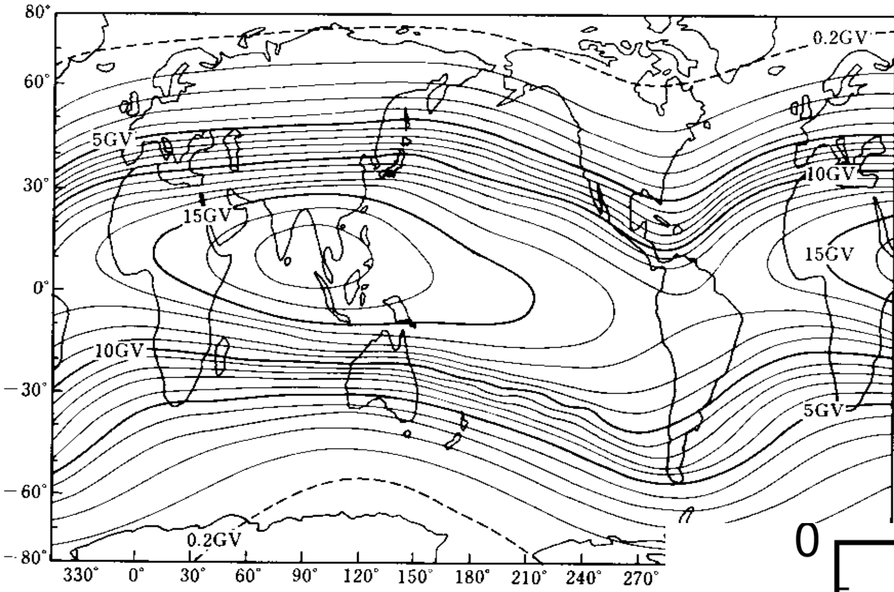
2. Angles in Hadronic Interactions

$$\Delta\theta \sim \frac{p_t}{E_\pi} \sim \frac{0.3}{E_\pi/1\mathrm{GeV}} \sim \frac{0.1}{E_\nu/1\mathrm{GeV}}$$

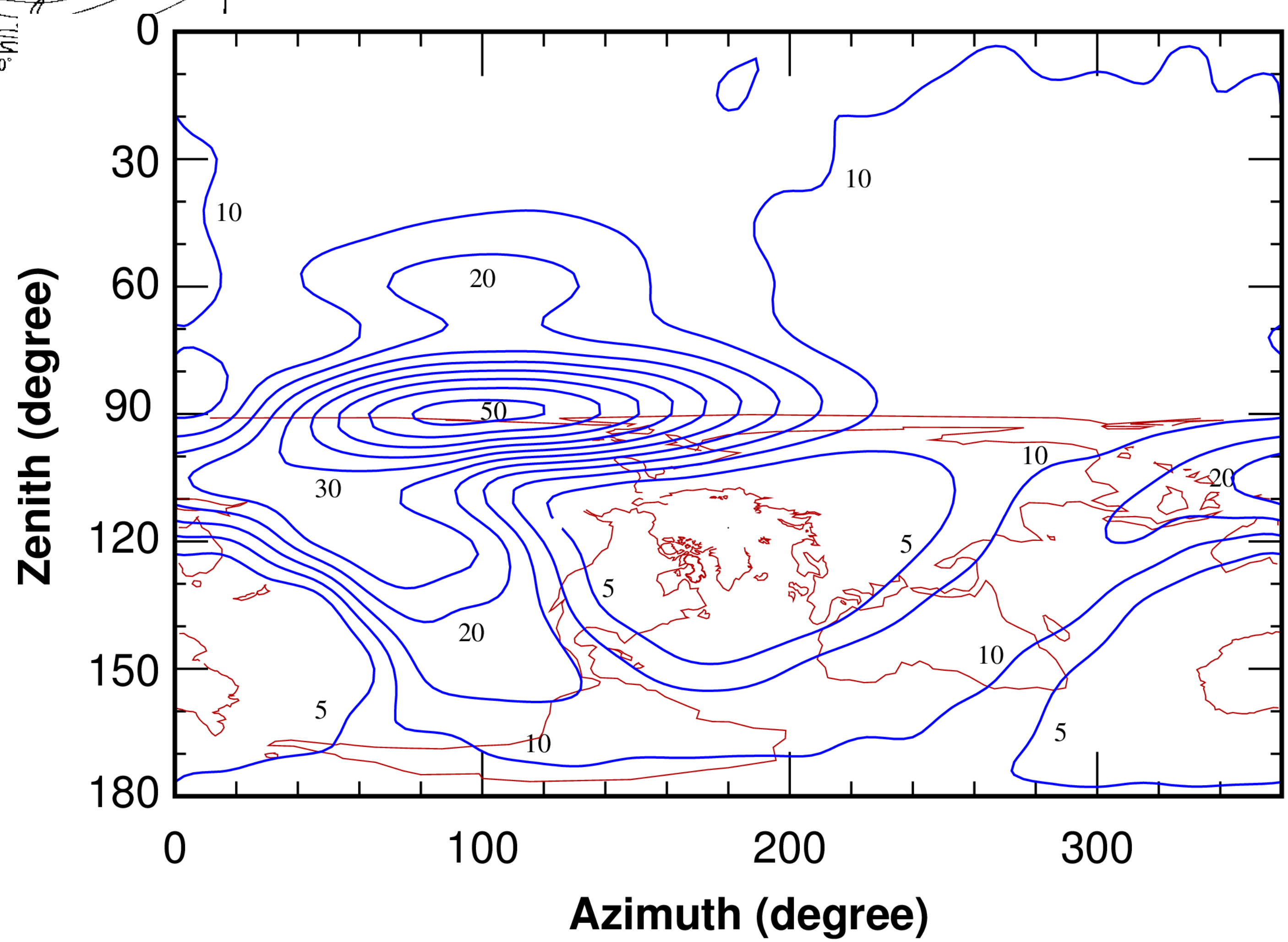
3. Muon Curvature is energy independent and is ~ 5 degree

General understanding *before* Fluka group 3D calculation

2 and 3 are not important

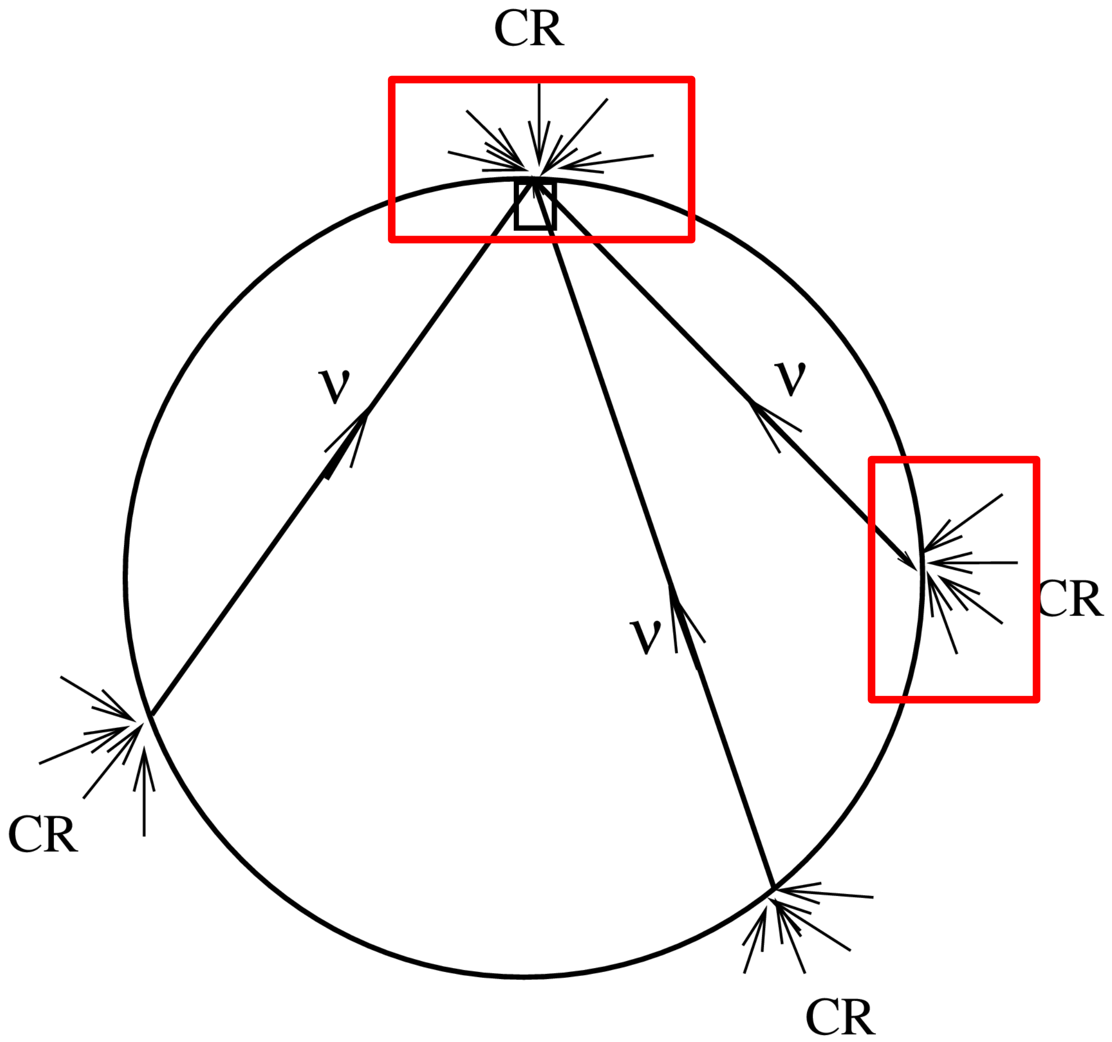


Rigidity Cutoff for
Virtical direction



Rigidity Cutoff
For SK direction

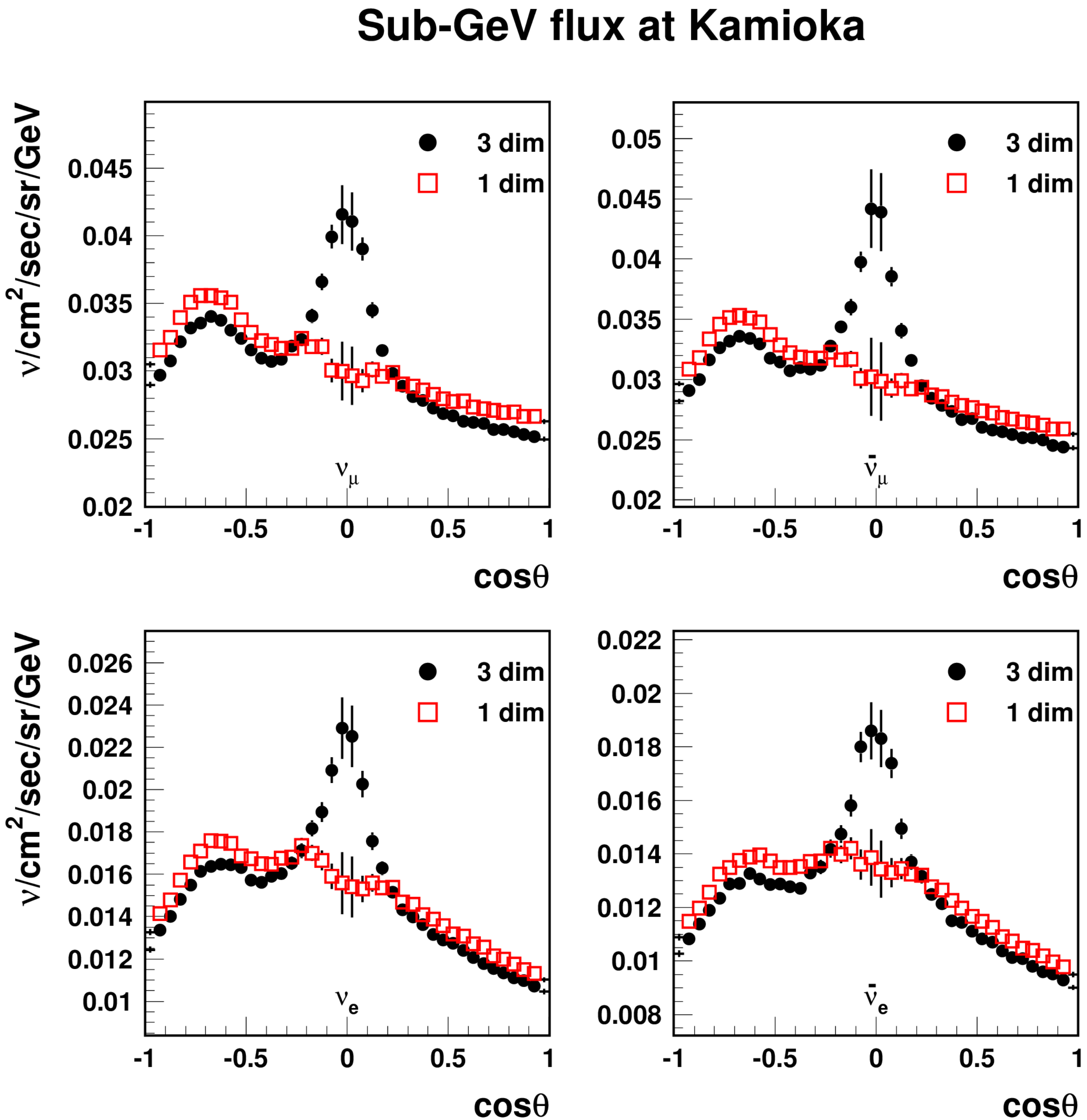
3D-calculation by Fluka group (Battistoni et al. 1999 &2002)



Use CR downward simulations at a site at other sites on Earth, changing the rigidity cutoff.

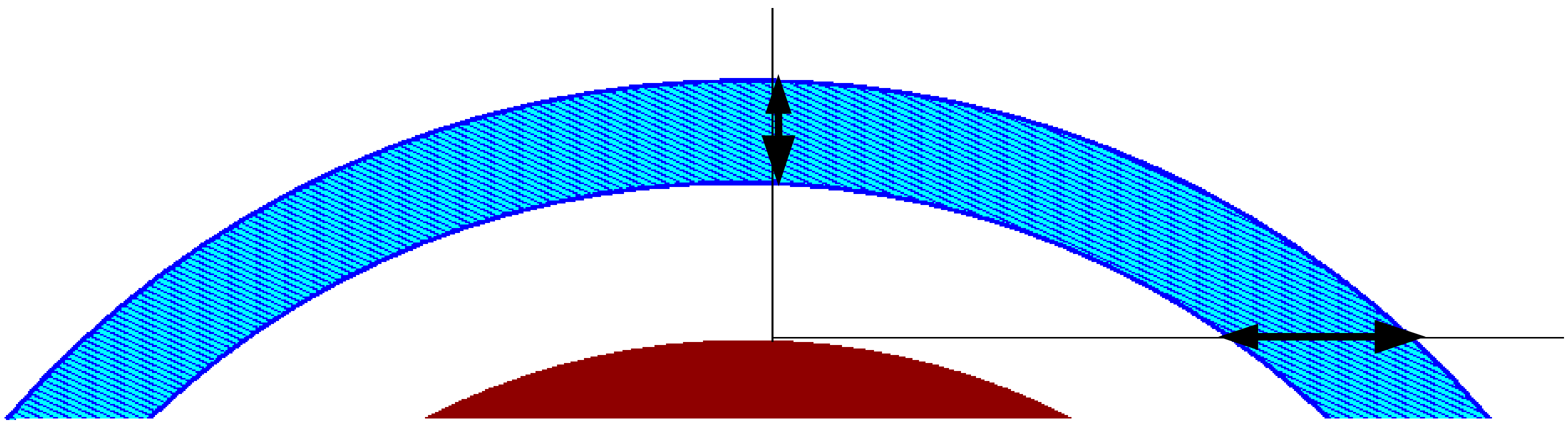
Geomagnetic Field in Atmosphere is not considered.

Horizontal enhancement of neutrino flux



(Battistoni et al. Astropart. Phys 1999)

Yet another interpretation for horizontal enhancement

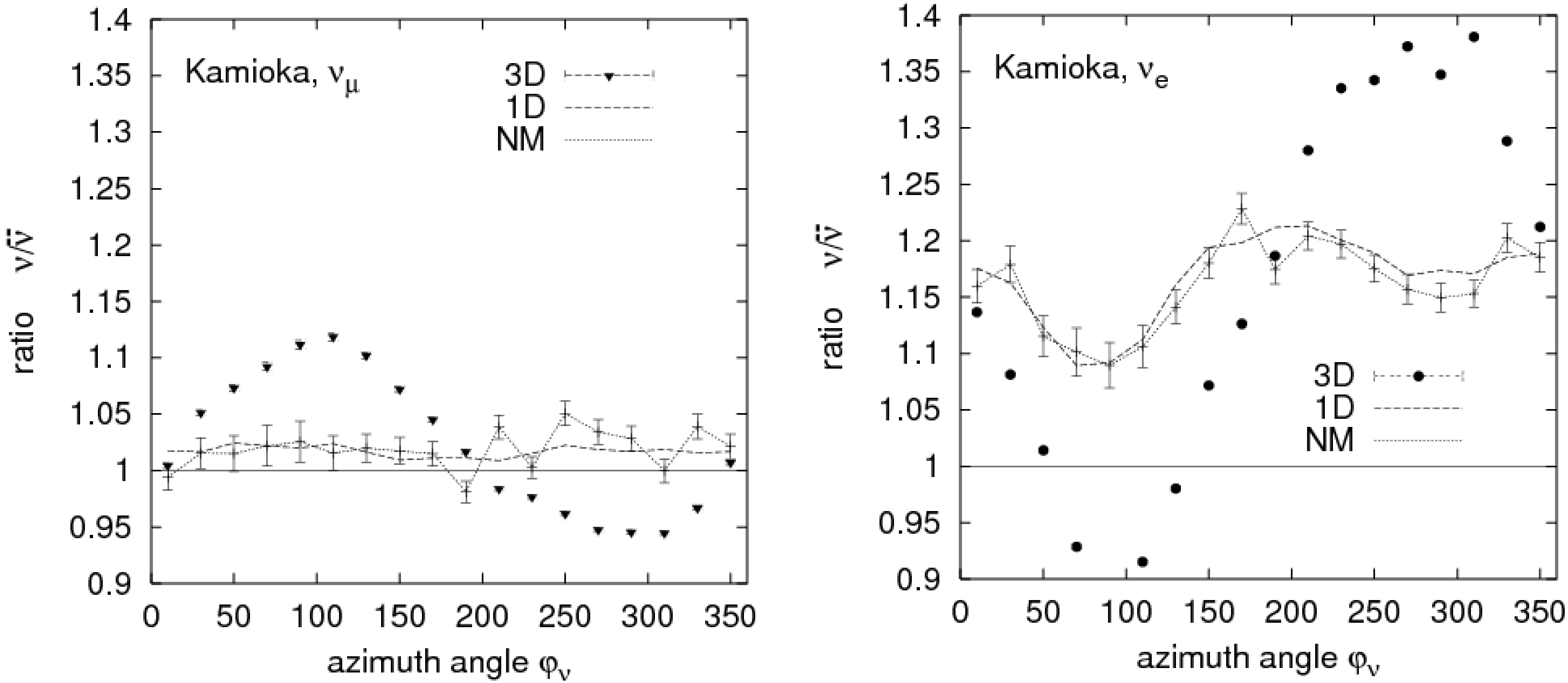


Longer integration length in the neutrino production zone for horizontal directions

100MeV neutrino image of Earth

OR

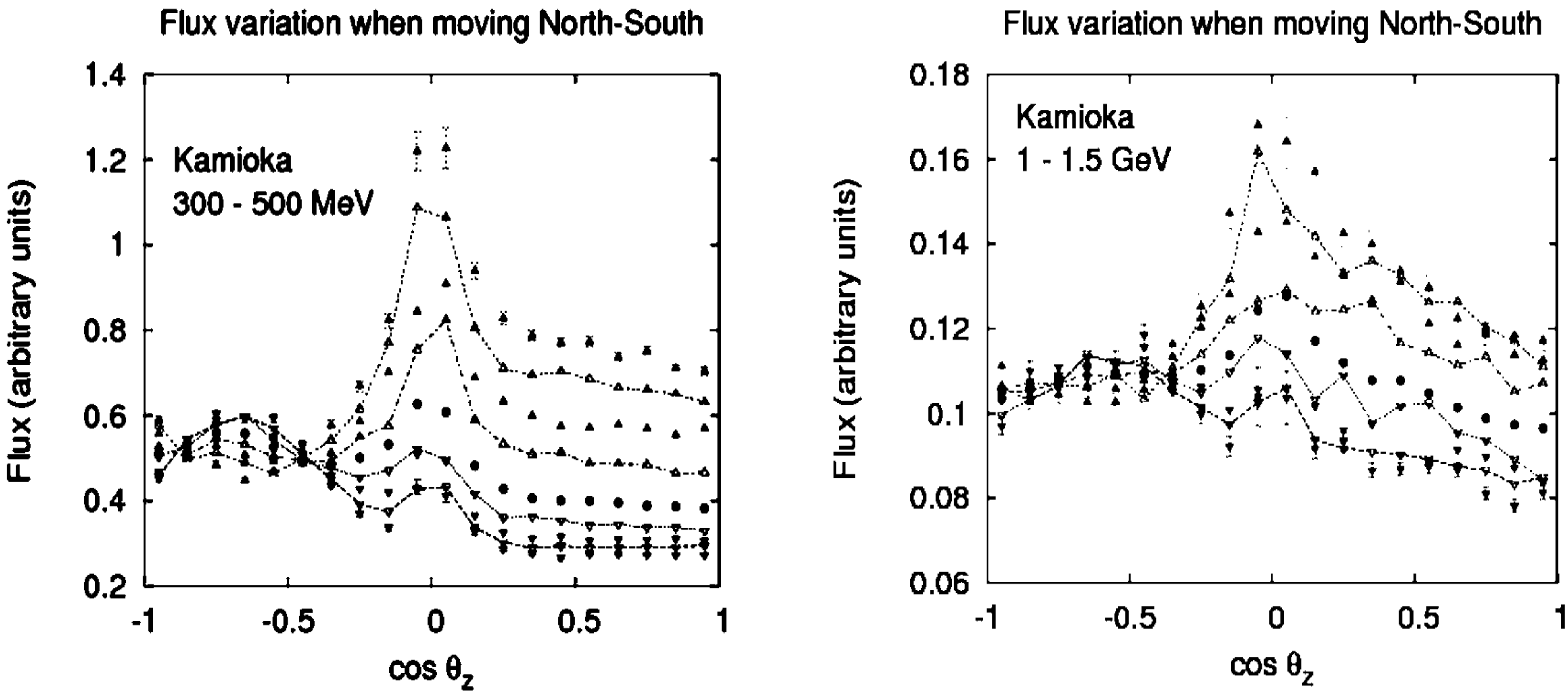
3D-calculation by Bartol Group considered realistic magnetic field in the air, with many fine tunings for efficiency.



(Barr et al, PRD 2004)

The importance of magnetic field in atmosphere is first stressed by P. Lipari (Astropart. Phys. 14, 2000) and HKKM2001 (PRD 2001)

3D-calculation by Bartol group showing neutrino flux is very position sensitive



(Barr et al, PRD 2004)

HKKM 大気ニュートリノフラックス計算.

1. Inclusive interaction code を使った完全な3次元計算
   created from the output of established code.
   => ~a few 100 times faster than original code.
   => Easy to modify the secondary spectra.

2. Muon calibration による相互作用のチューニング

3. Virtual detector correction を用いた、比較的大きな
   ヴァーチャルdetector

4. 現実に近い、地磁気モデル、大気モデル
   IGRF および NRLMSISE-00（HKKM2015).

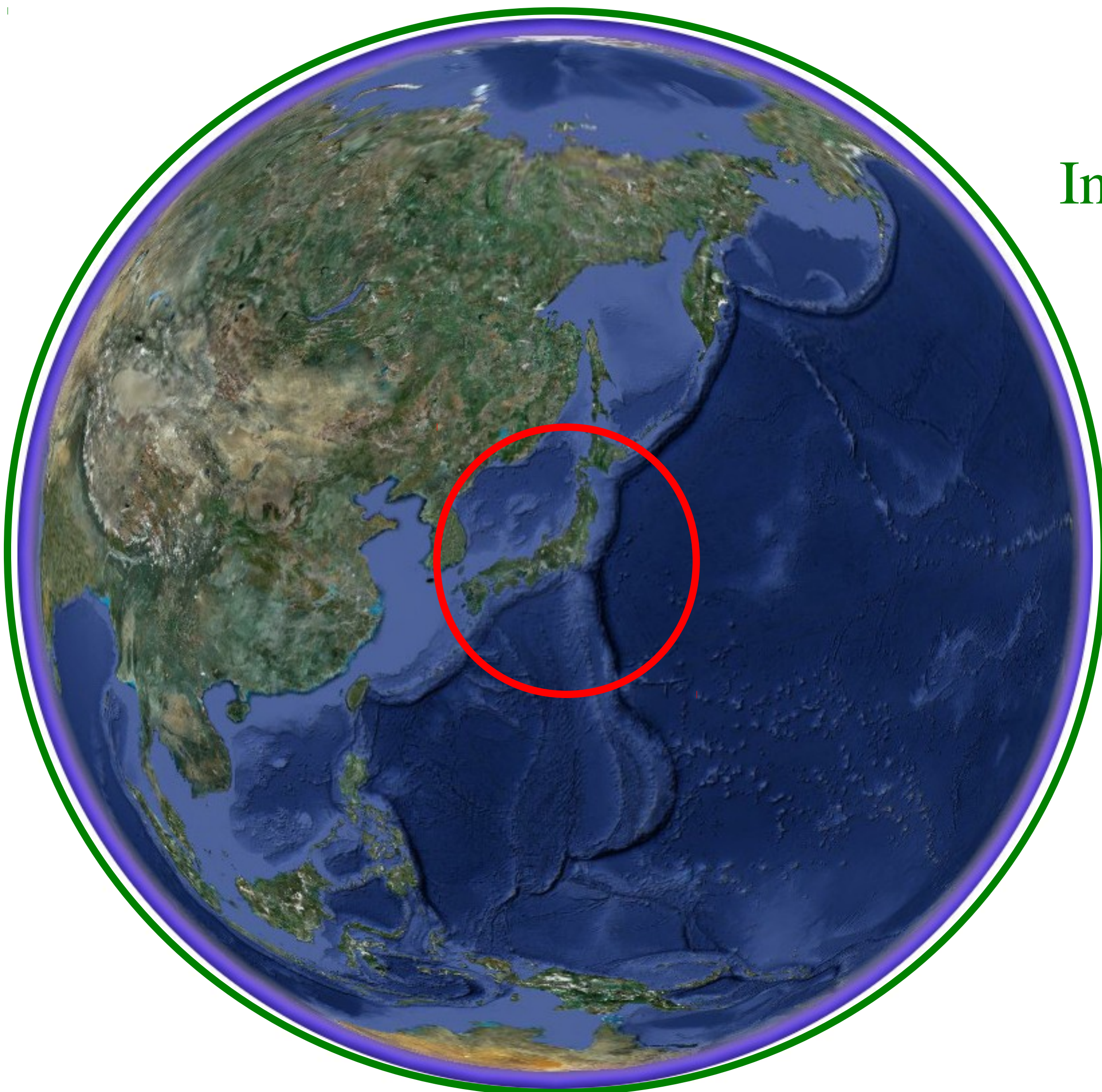
5. New Cosmic Ray Spectra Model (preliminary).

3D-Calculation Geometry

Re = 6378km

Simulation Sphere (Rs = 10 x Re)

Cosmic rays go out the sphere in the back trace pass the rigidity cutoff test.
Cosmic rays go out the sphere in the simulation are discarded.



Injection Sphere (Re +100lm)

Cosmic Rays are sampled and injected on this sphere.

Virtual Detector

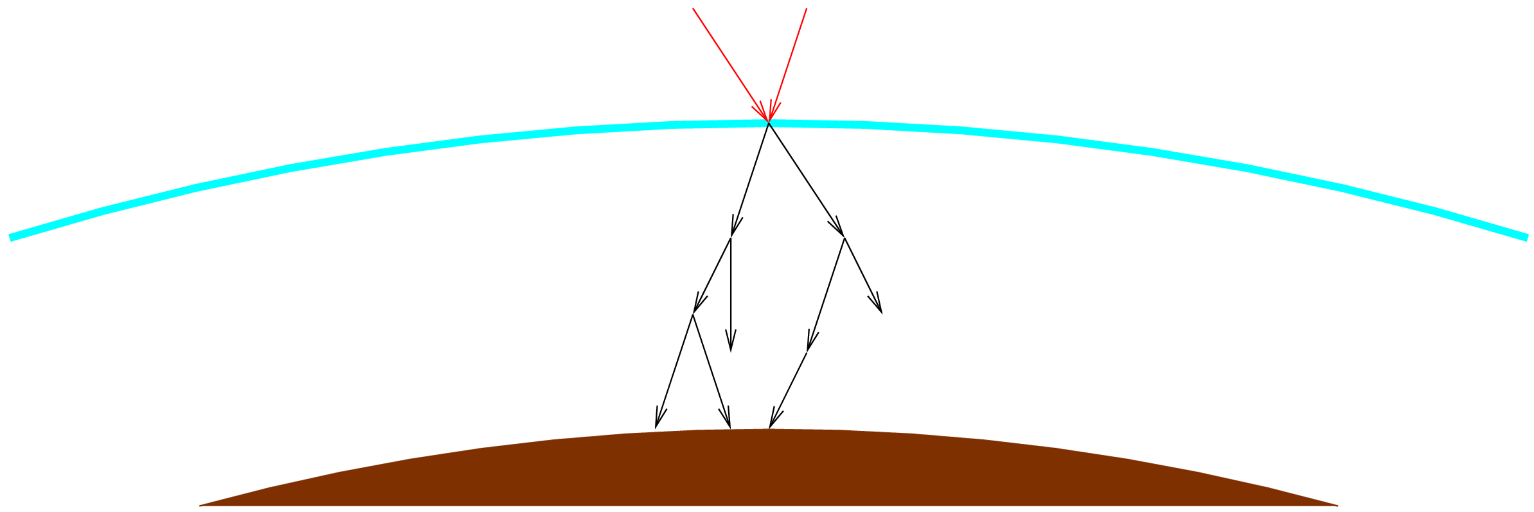
Neutrinos path inside the circle are used to calculate the neutrino flux.

Muon Calibration of Interaction Model

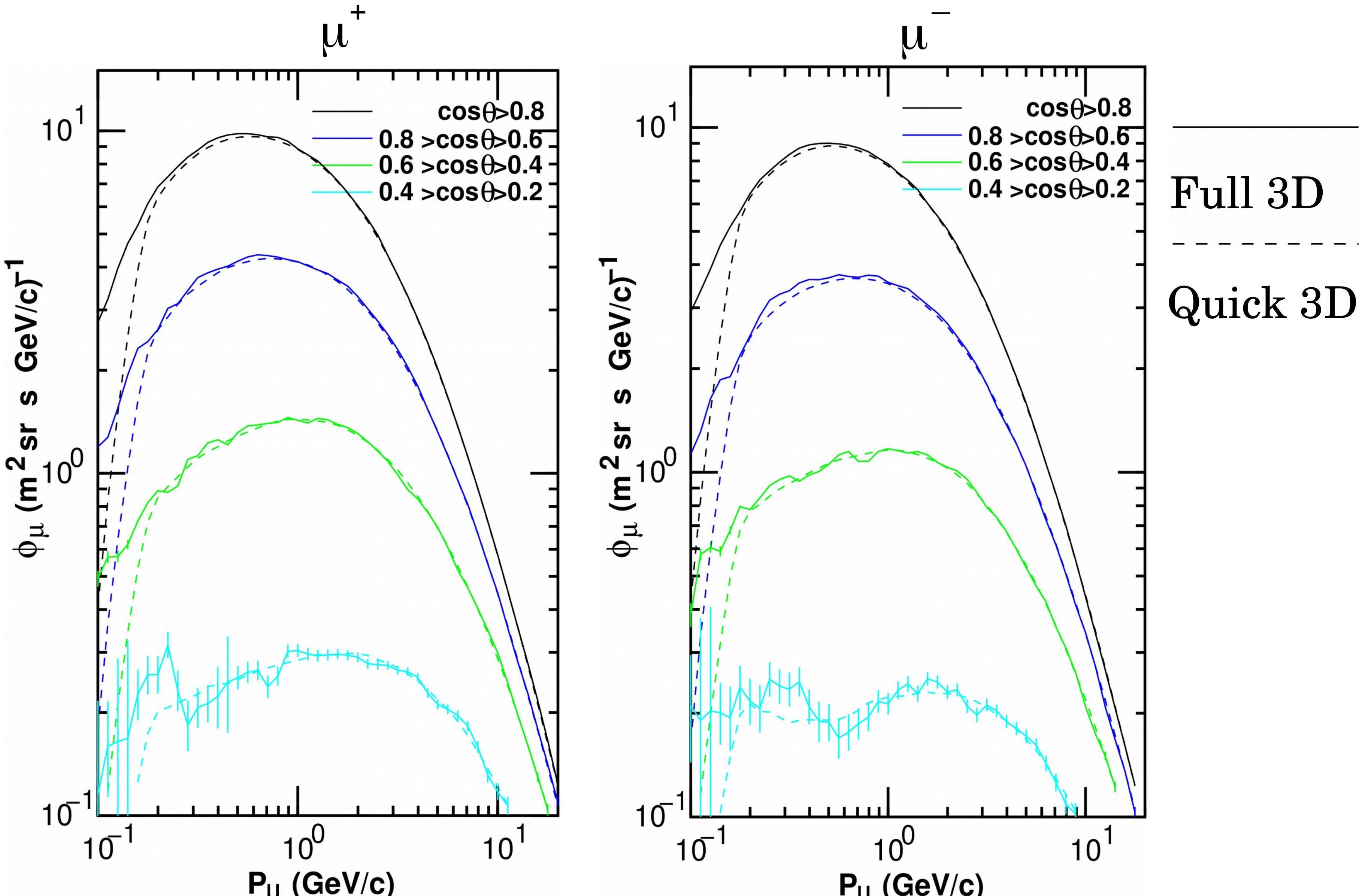
Quick 3D calculation of muon flux.

As the muon flux is a "local quantity" ($\gamma ct \sim$ 60km at10 GeV),
We can calculate it in a quick calculation method:

1. Inject cosmic rays just above the observation point,
2. Analize all the muons reach the surface of Earth.

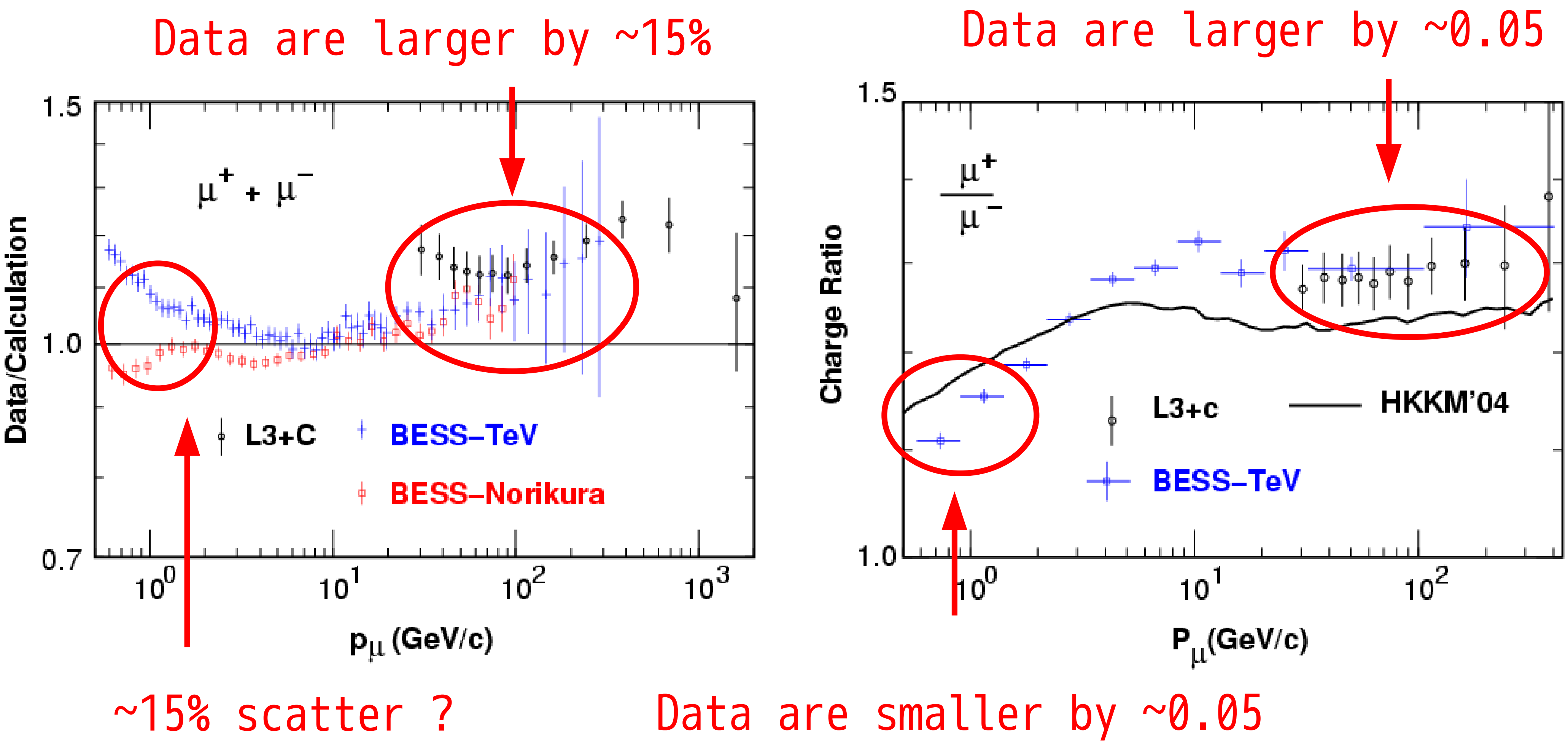


Comparison with full 3D calculation for muon



This method seems to be OK above 0.2 GeV.
But, one must be careful to use this method for the low energy region and horizontal directions.

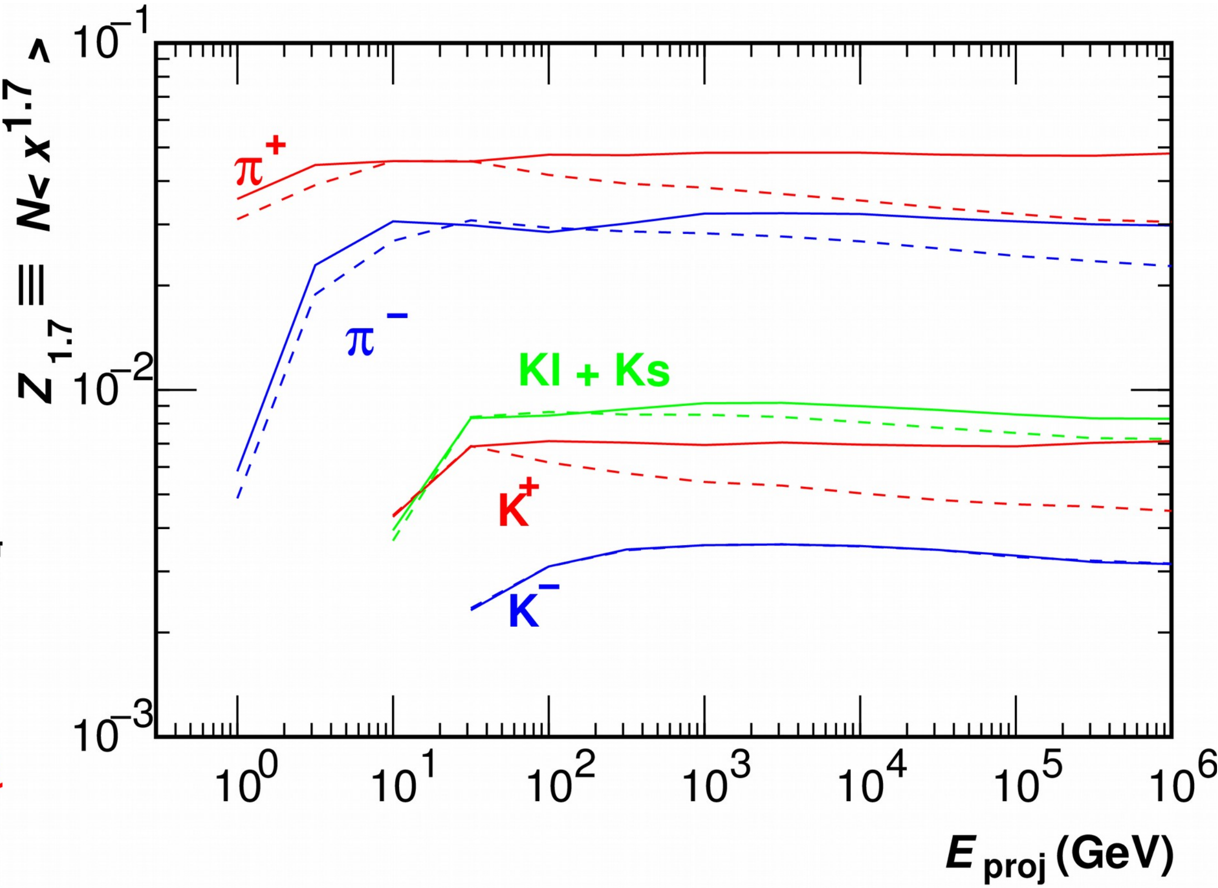
Compare with high precision muon measurements

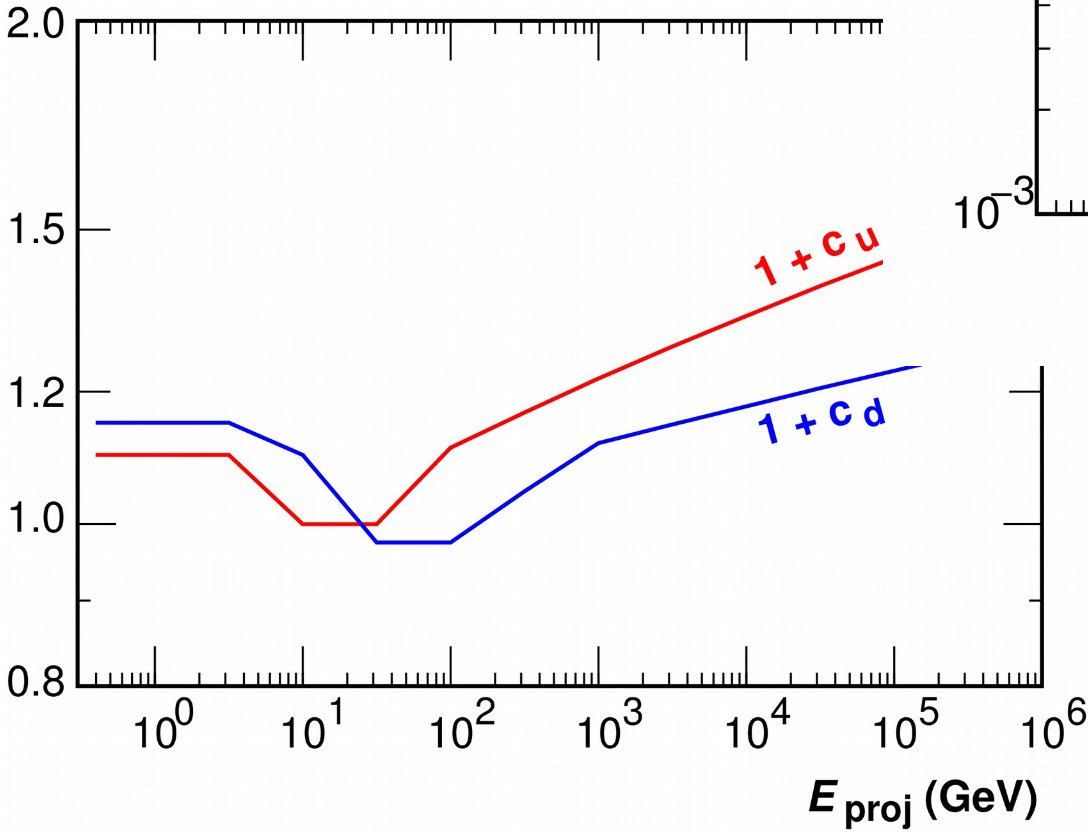


==> DPMJET-III Should be Modified

Modification of Int. Model (SHKKM 2006)

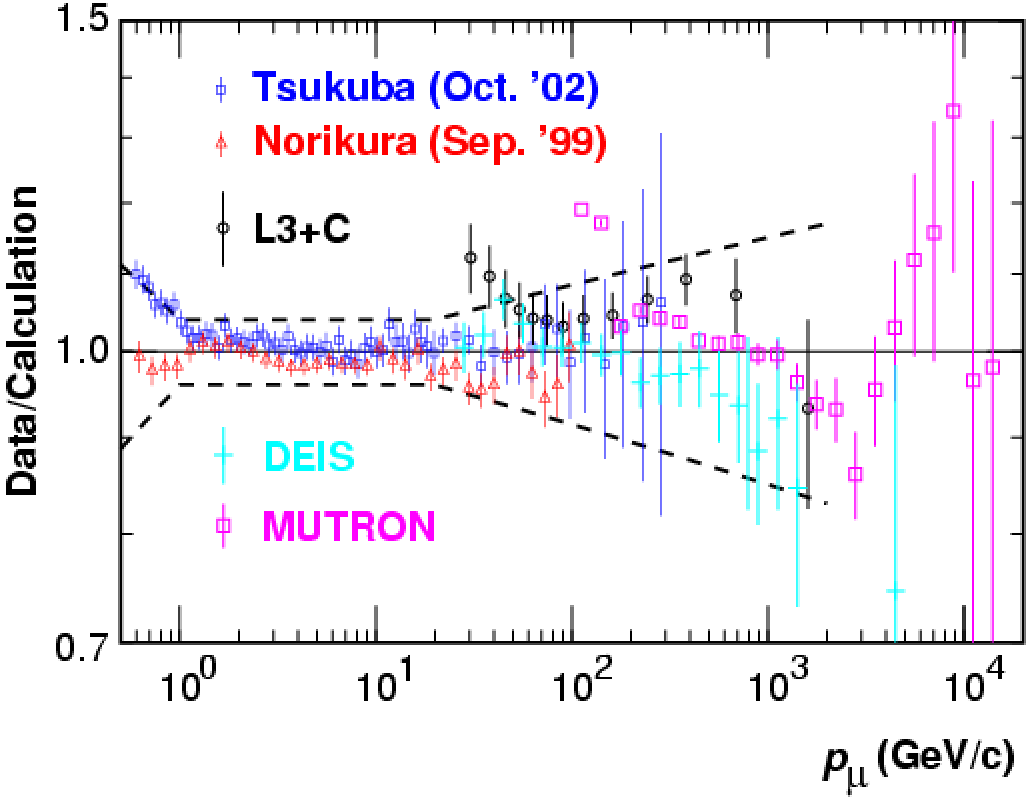
Z-Factor →

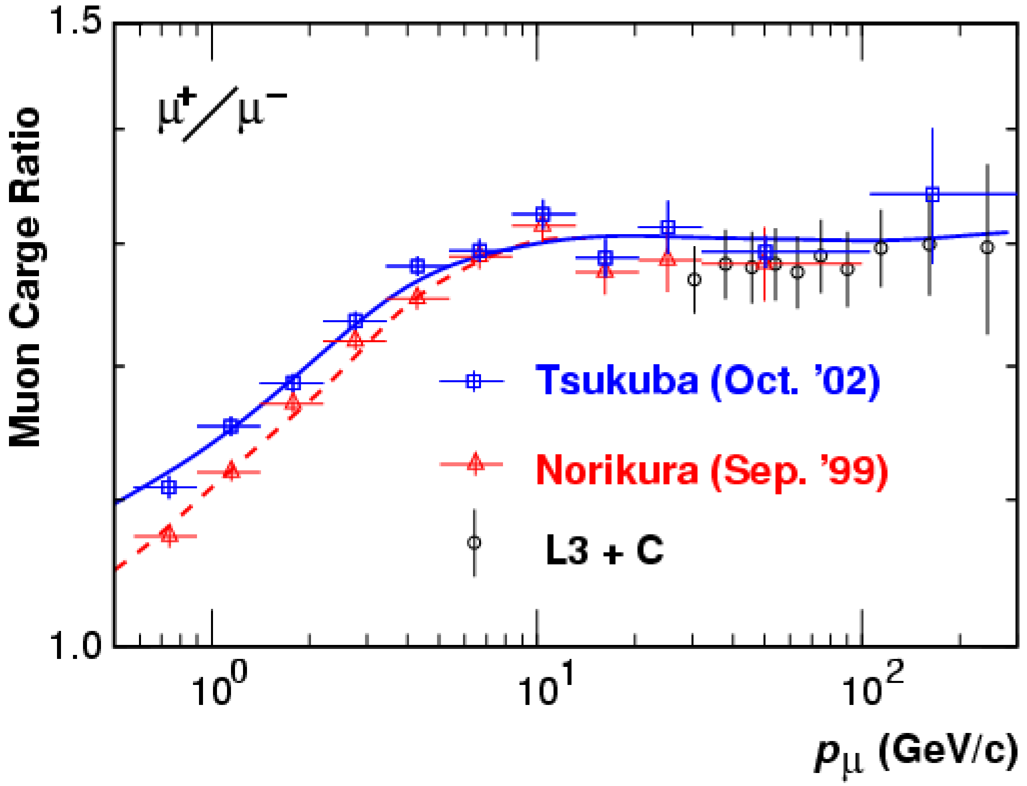




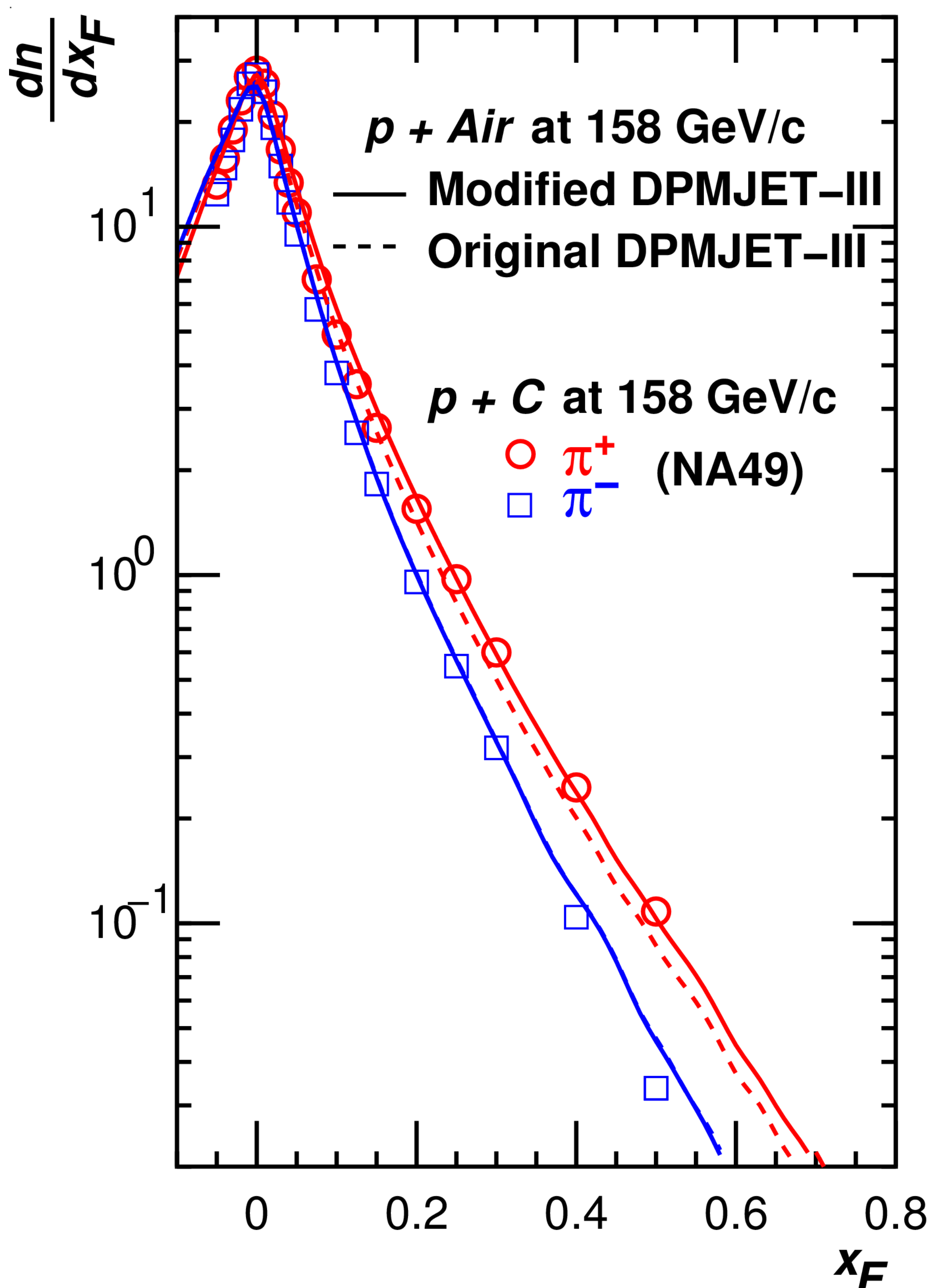
<--- Modification parameter

Comparison AFTER the modification

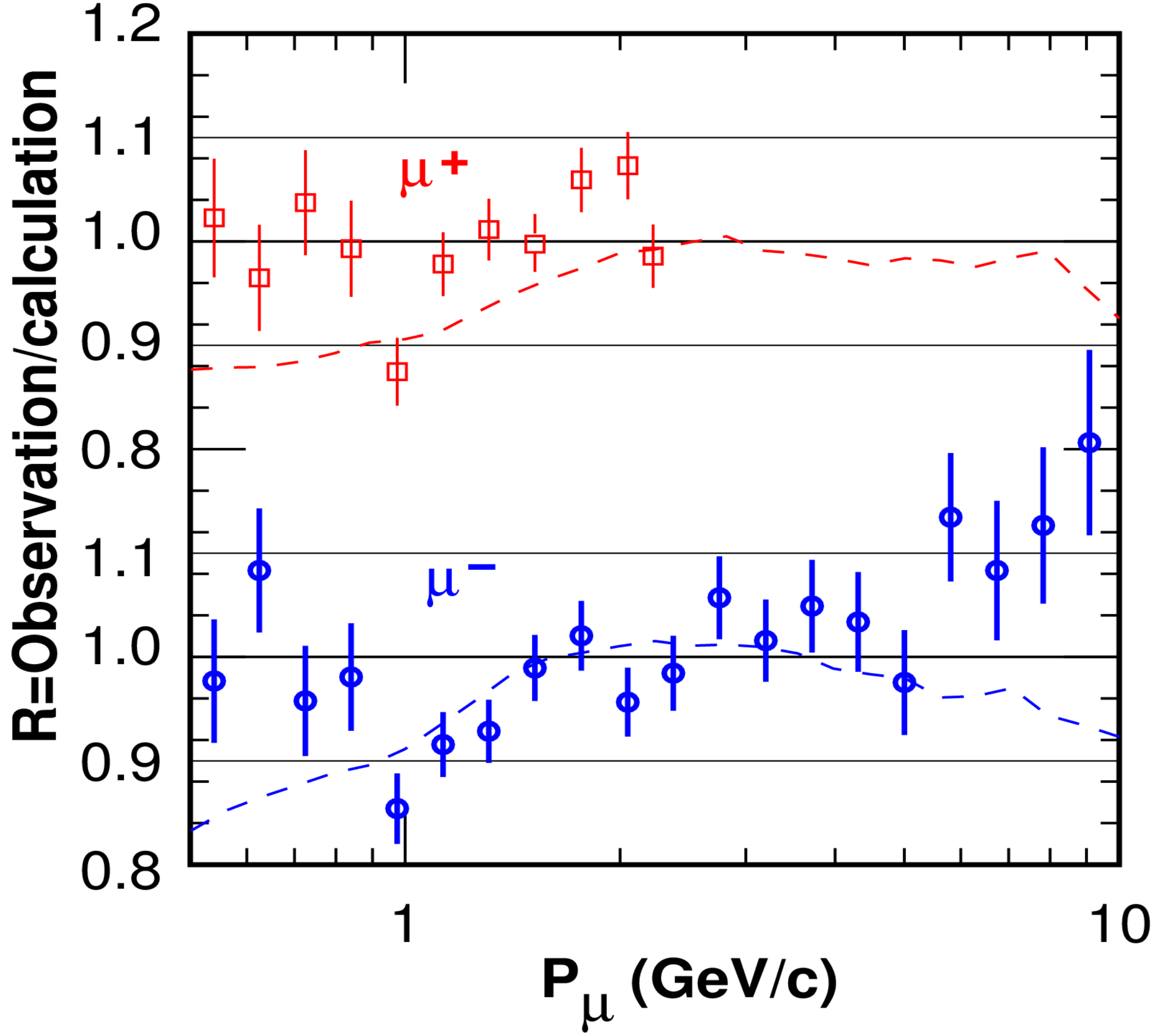




Comparison
with
Accelerator data



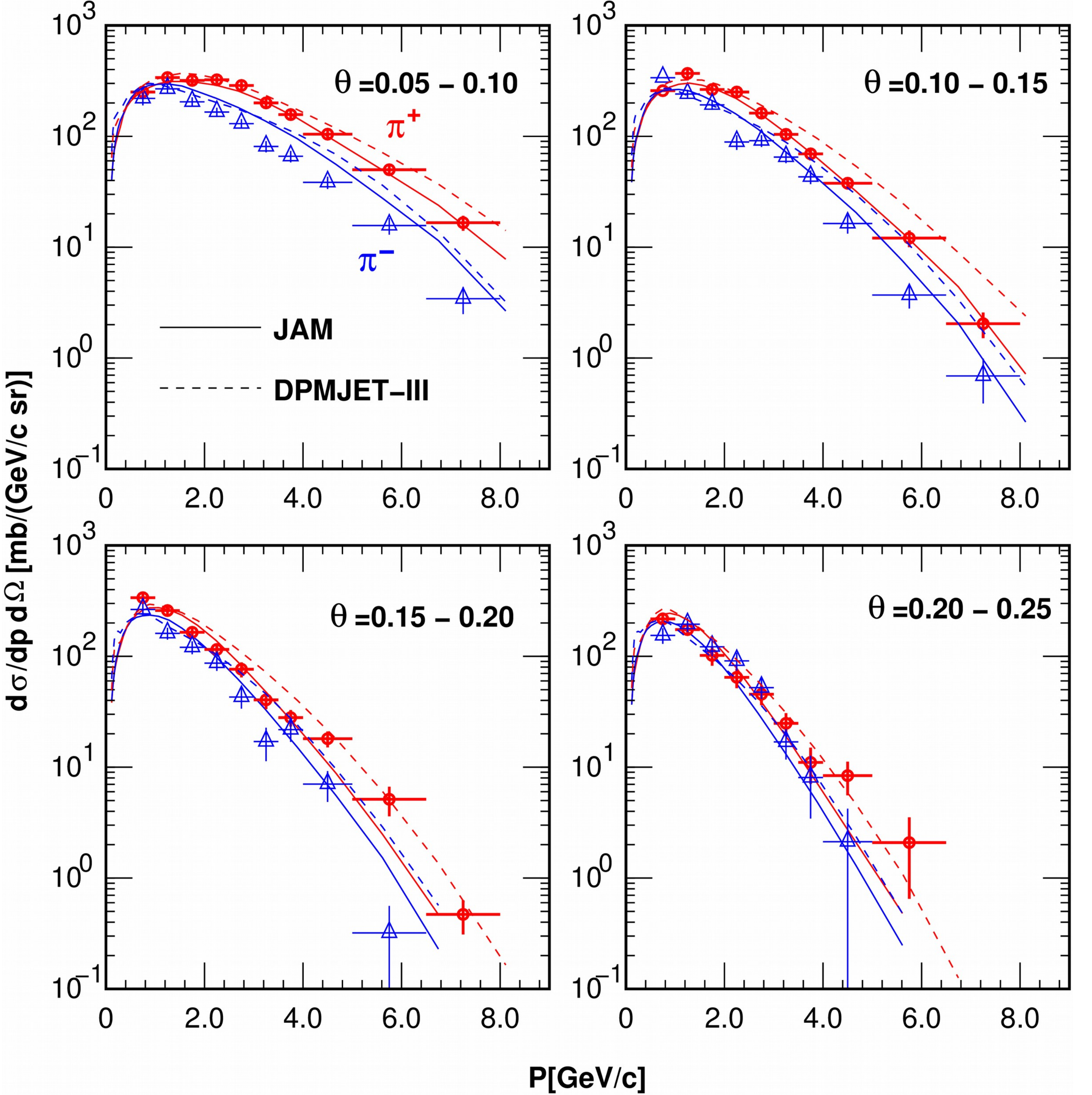
JAM + Modified DPMJET-II vs Muons at the Balloon altitude (HKKM2011)



Good agreement !

Use DPMJET-III above 32 GeV
and JAM below 32 GeV

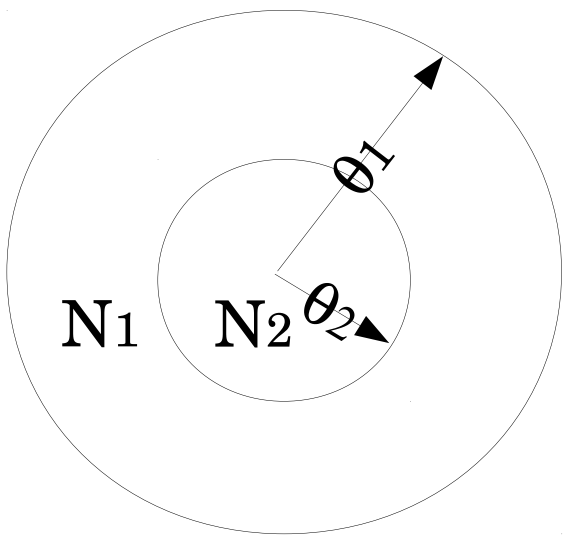
JAM vs HARP



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]

Virtual detector correction

Averages in $\theta<\theta_1$ and $\theta<\theta_2$ can be written with the central value φ_0 as



$$\phi_1 \simeq \varphi_0 + \varphi' \theta_1^2$$

$$\phi_2 \simeq \varphi_0 + \varphi' \theta_2^2$$

where φ' is a constant.

Then we can calculate the central flux value as

$$\varphi_0 \simeq \frac{\theta_1^2 \phi_2 - \theta_2^2 \phi_1}{\theta_1^2 - \theta_2^2} = \frac{\phi_2 - r^2 \phi_1}{1 - r^2} \quad \text{for} \quad r = \left(\frac{\theta_2}{\theta_1}\right), \; r < 1$$

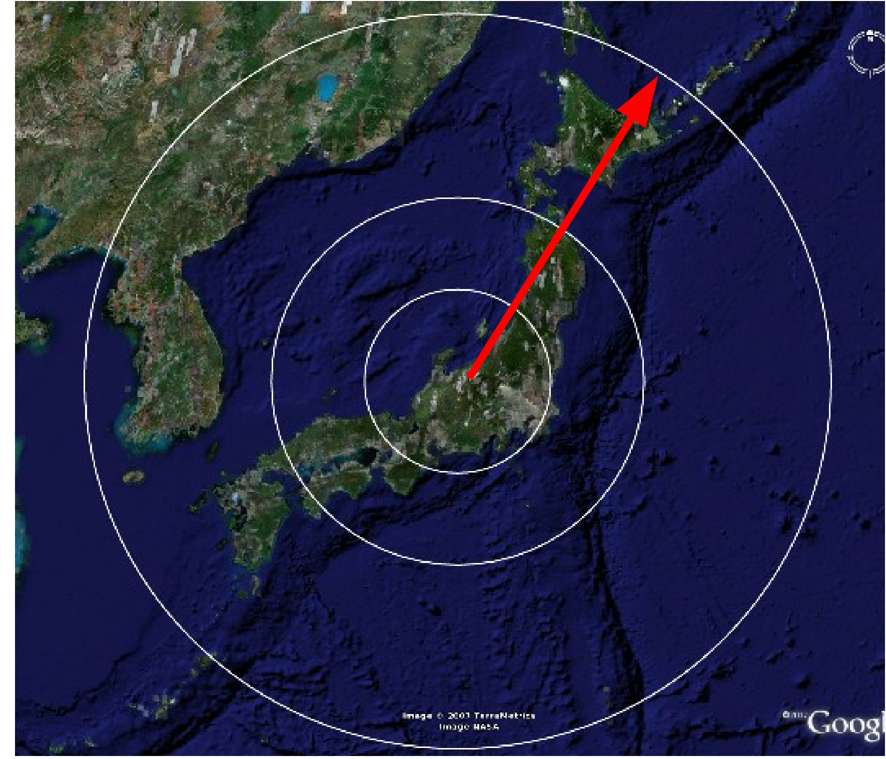
Apply this relation to the MC results

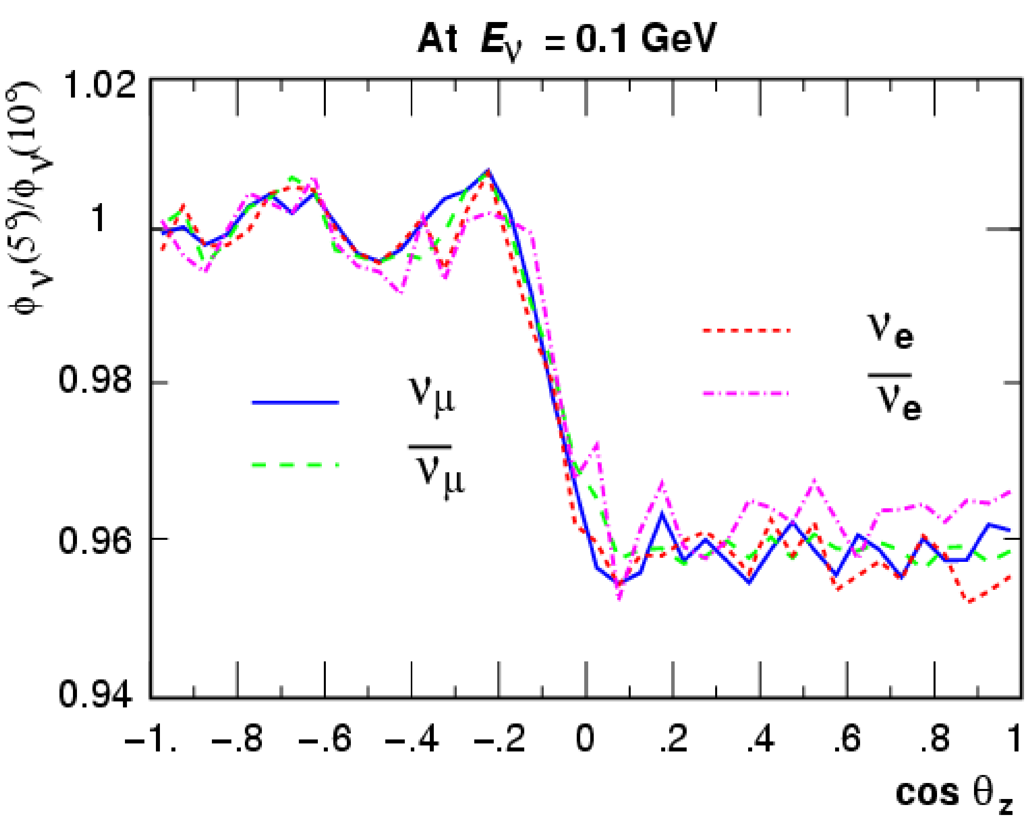
$$\phi_1 = \frac{N_1}{T \pi \theta_1^2}, \quad \phi_2 = \frac{N_2}{T \pi \theta_2^2}$$

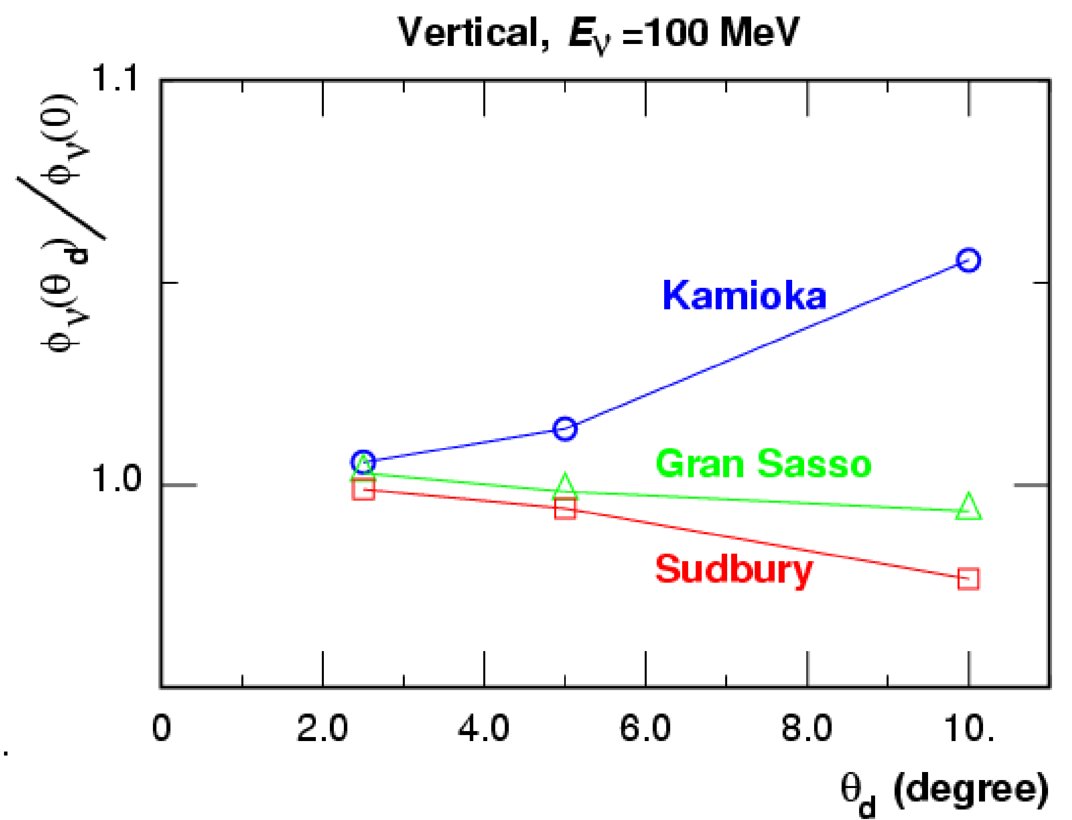
Error due to the large size Virtual Detector

In HKKM06 (PRD 2007), we took

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

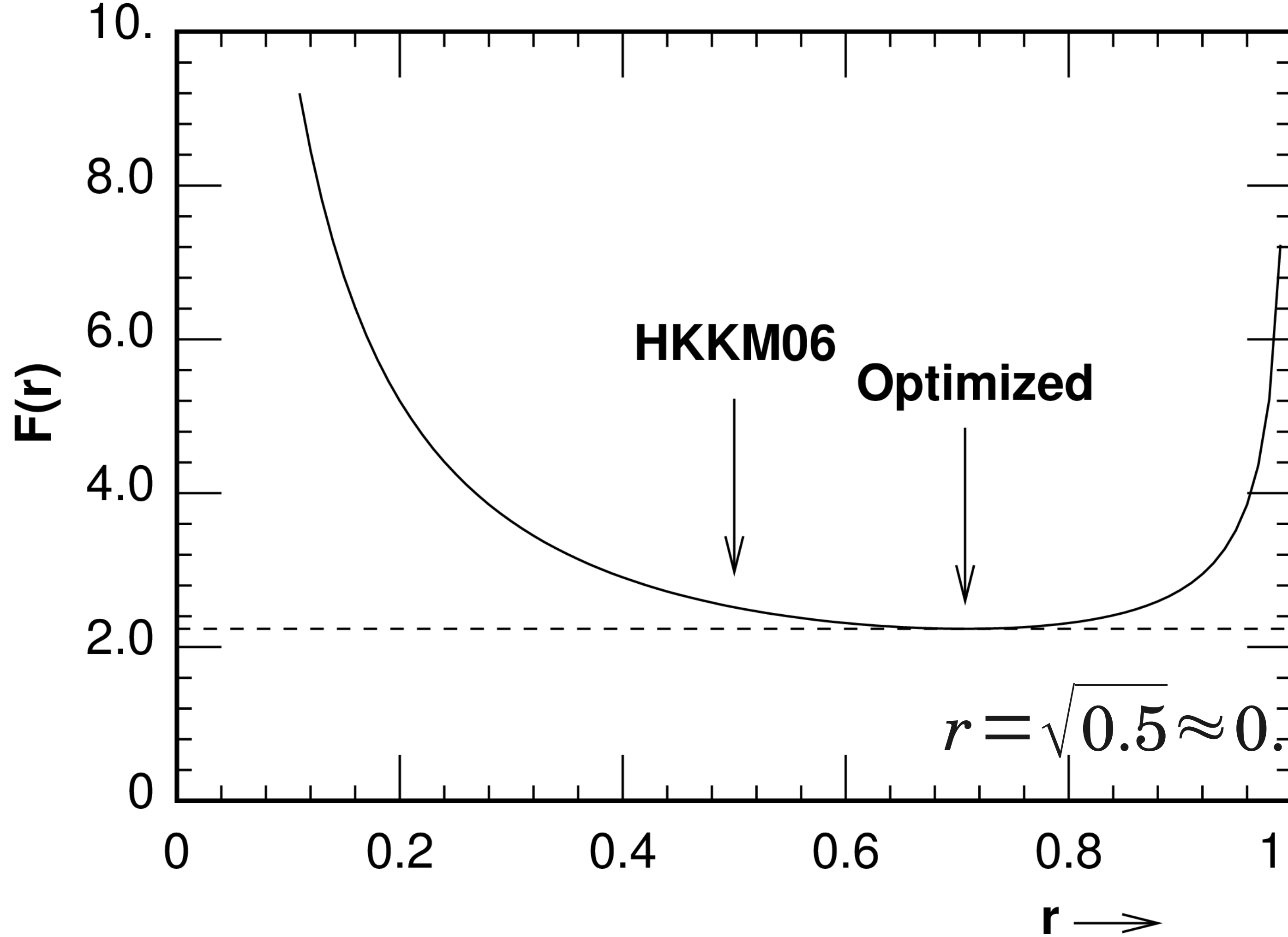






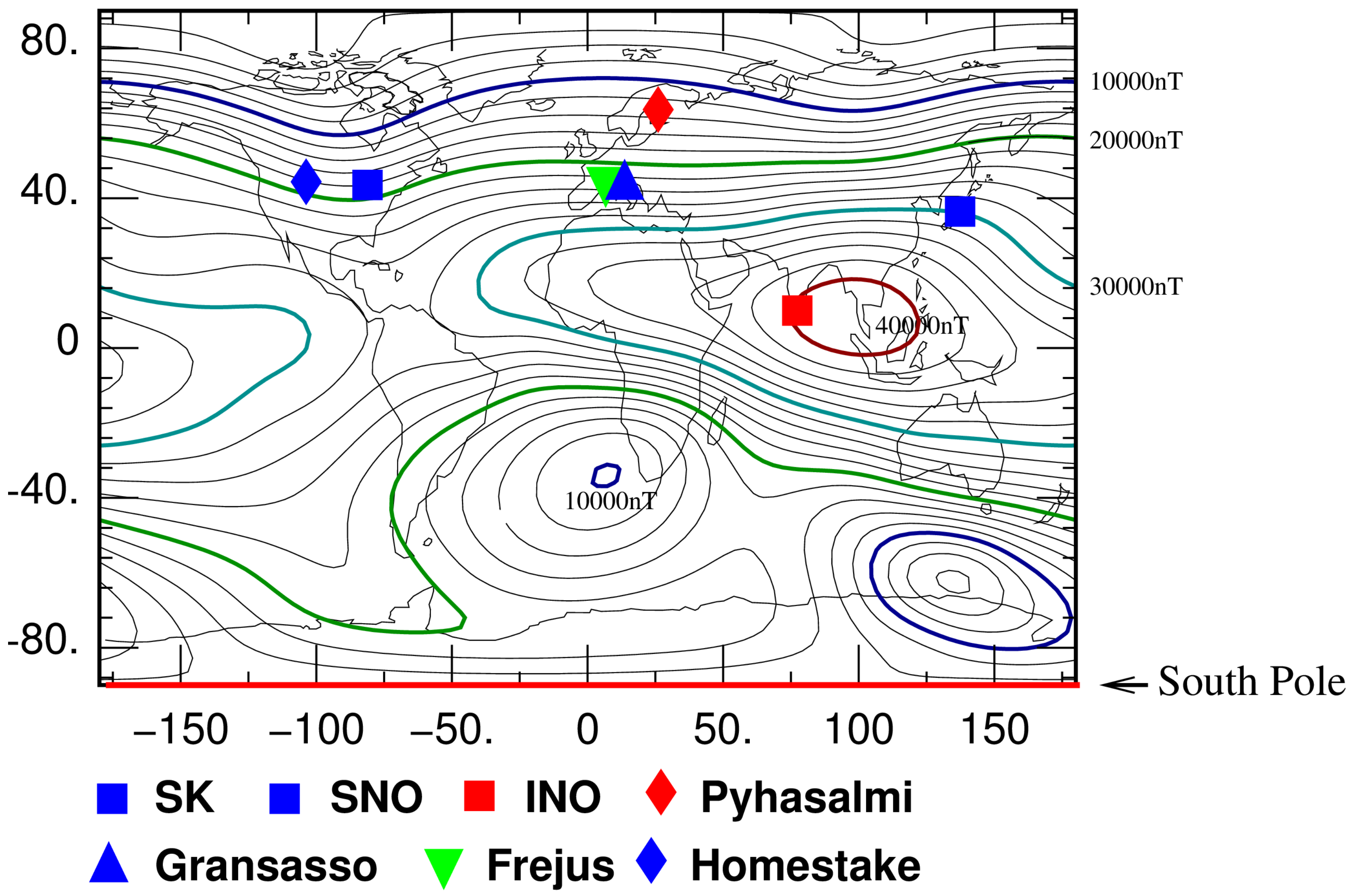
Optimized $r = (\frac{\theta_2}{\theta_1})$ value, which minimize the stat. error

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

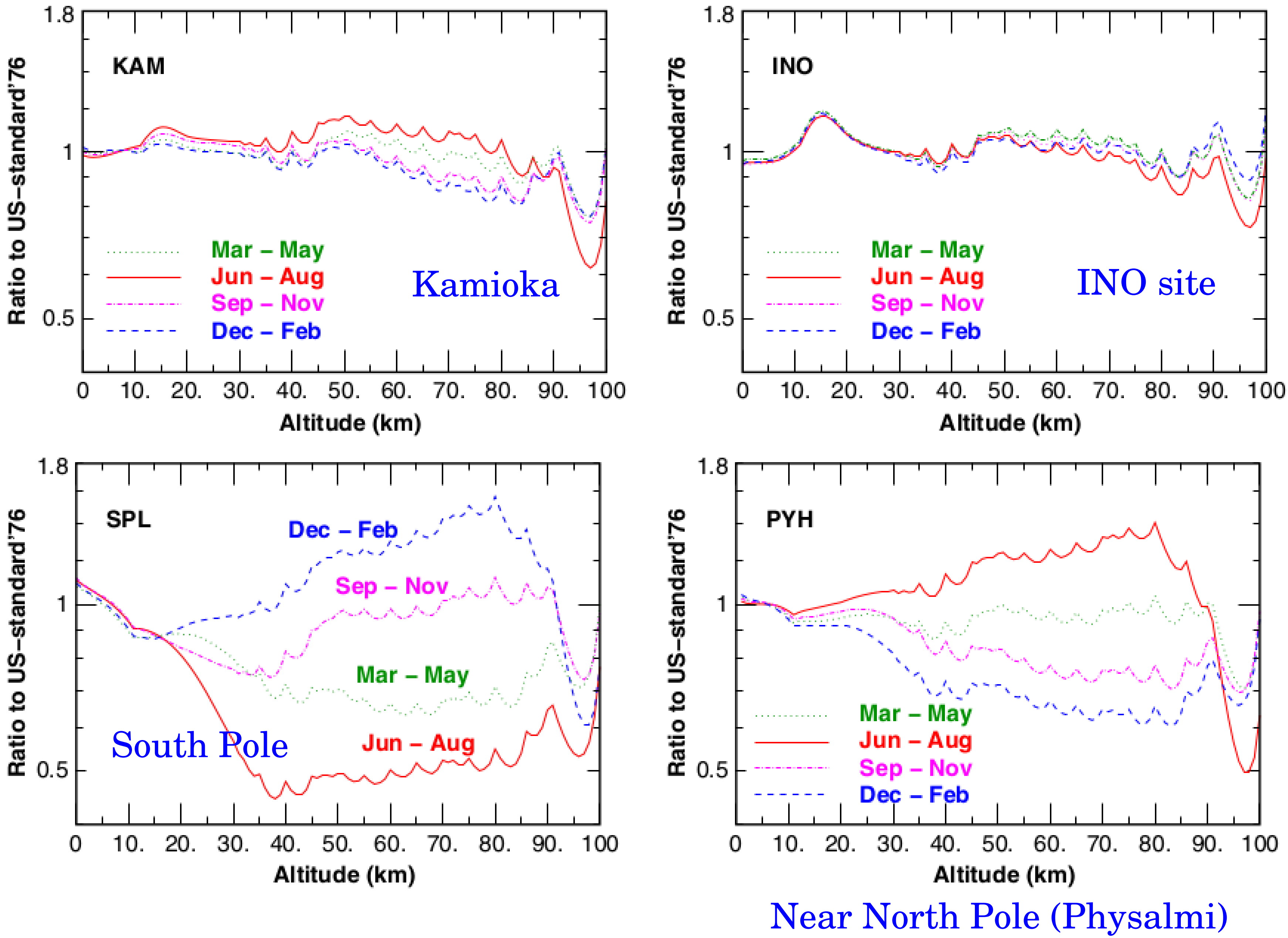


$$r = \sqrt{0.5} \approx 0.7071$$

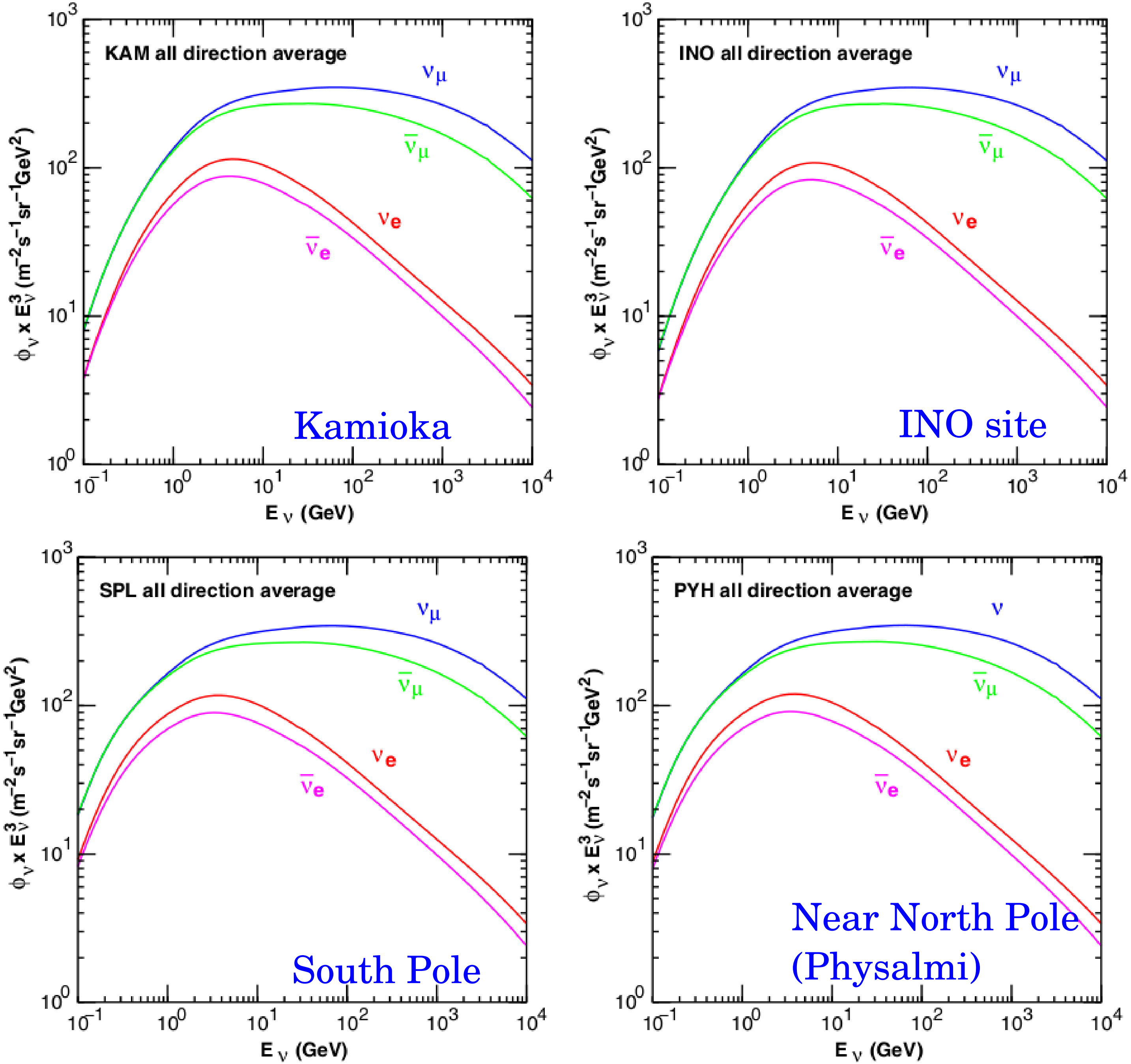
Presently going calculation (with M.S. Athar)



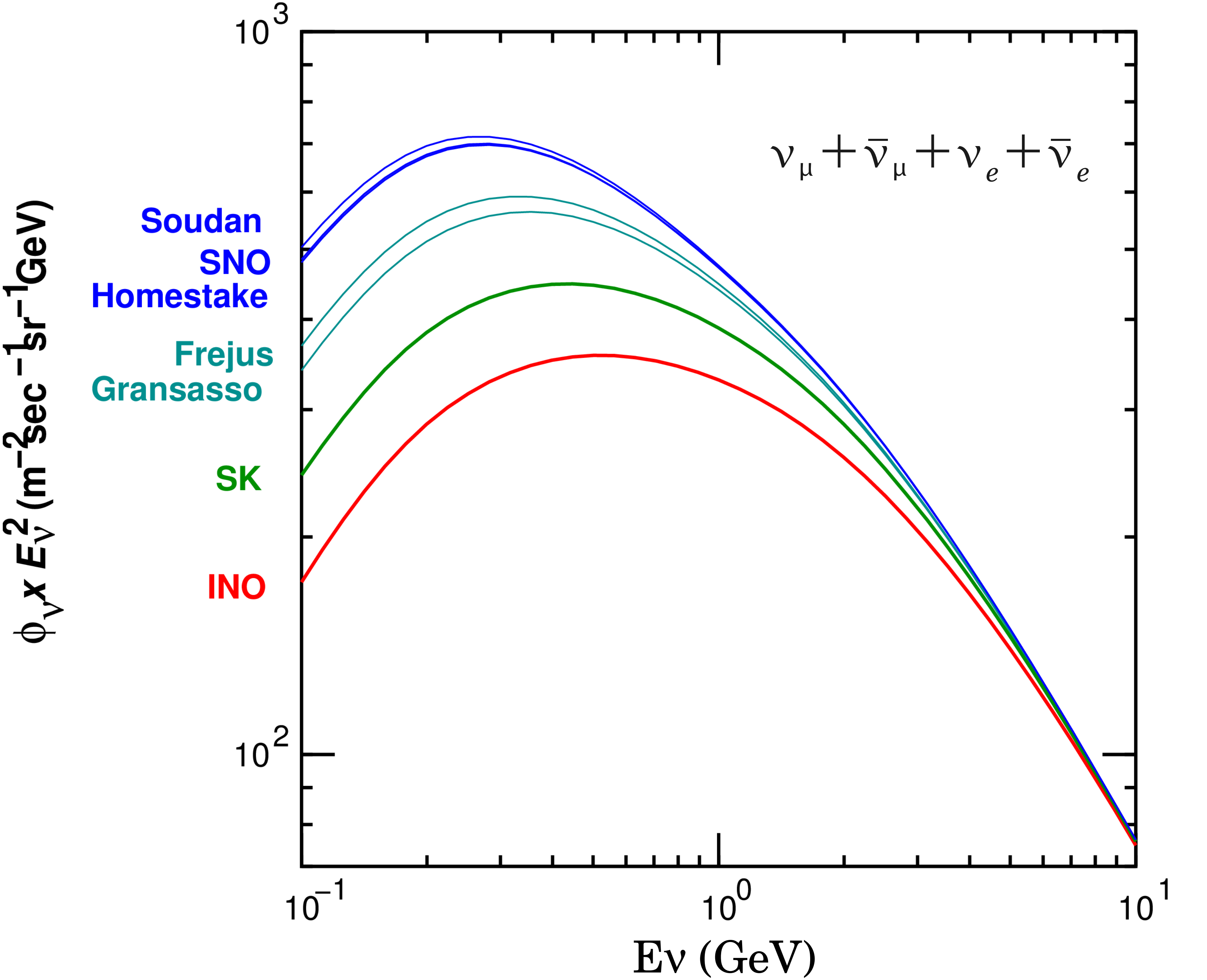
Atmosphere model (NRLMSISE-00) and seasonal variations



Calculated Atmospheric Neutrino Flux averaged over all directions

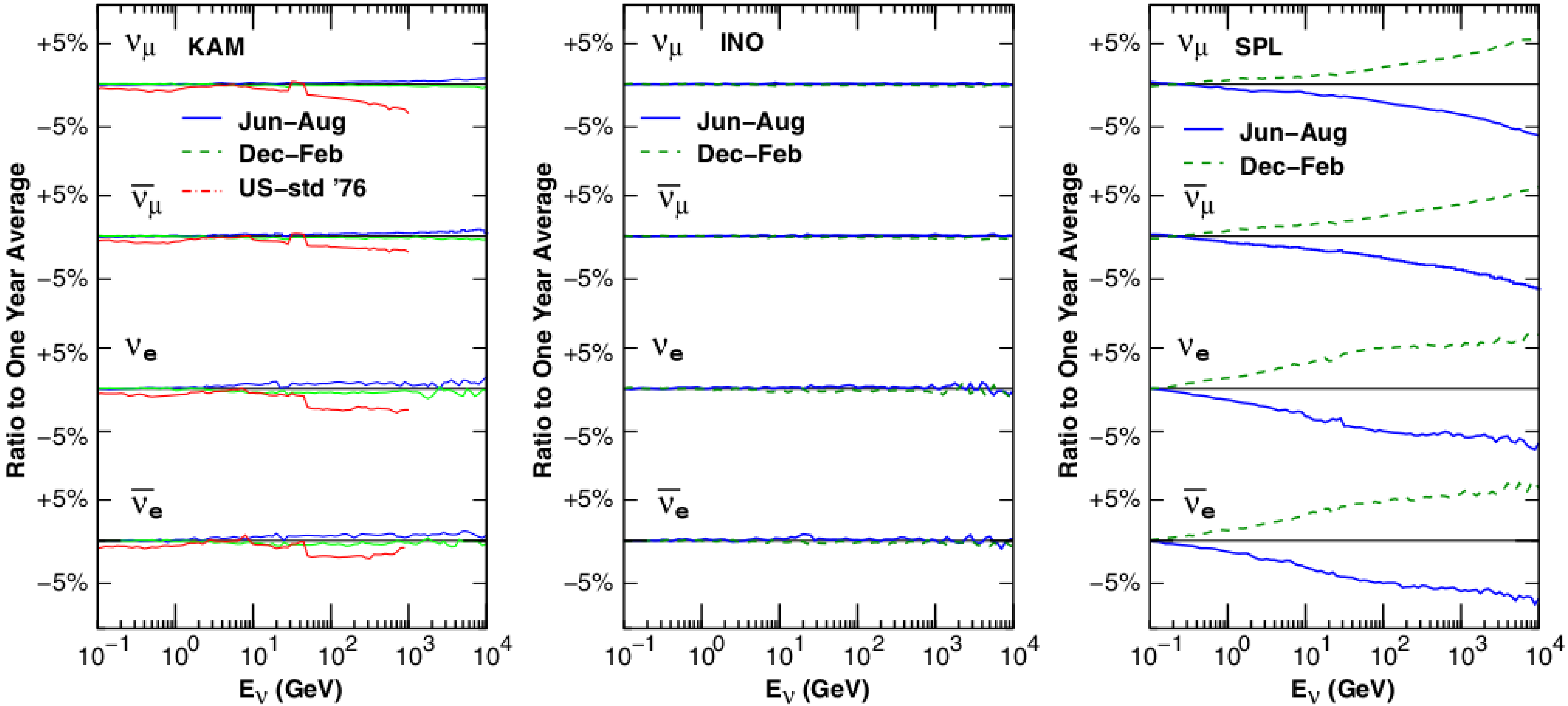


Sum of averaged neutrino flux over all directions

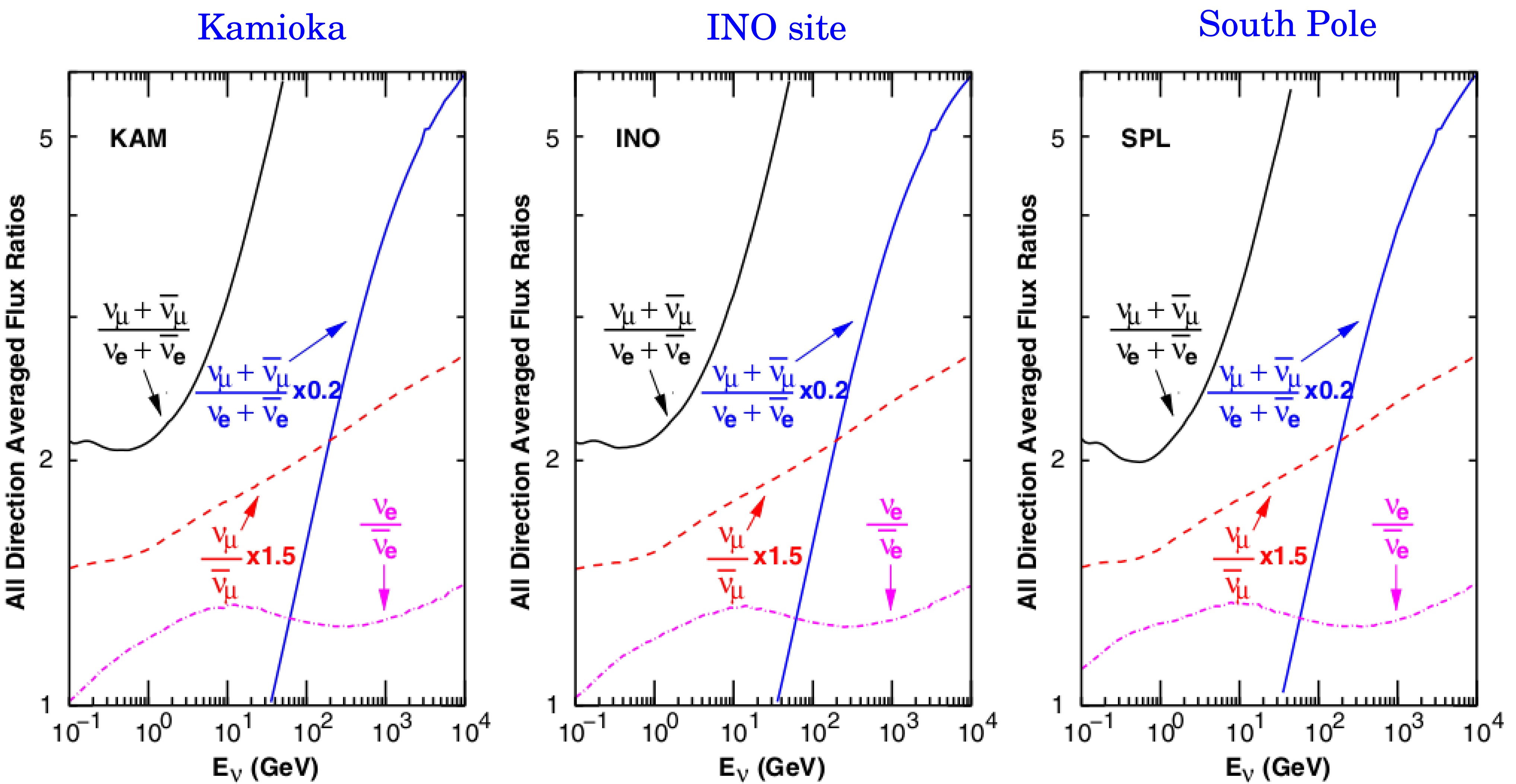


Seasonal Variation of Atmospheric Neutrino flux

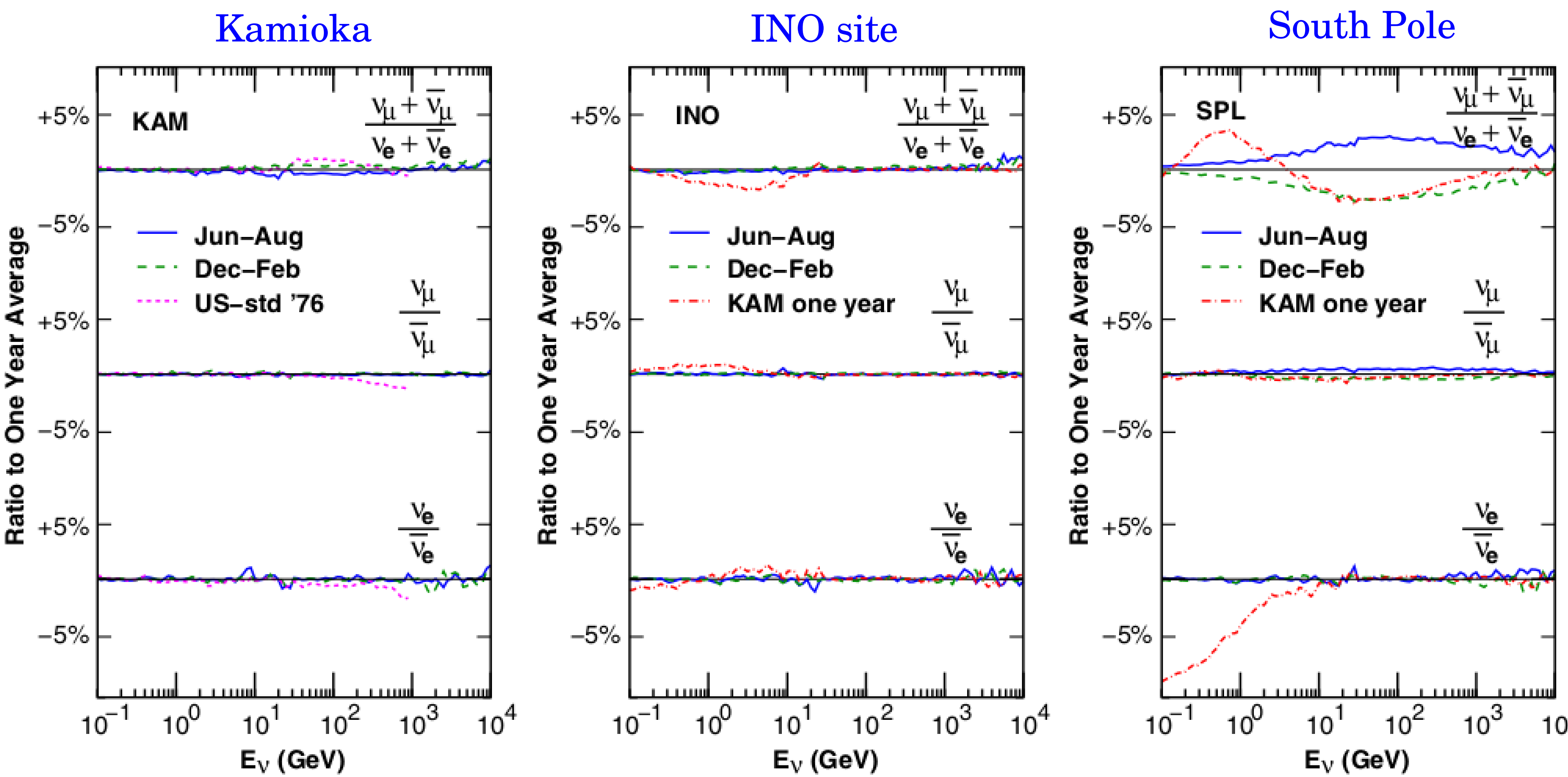
Kamioka INO site South Pole



Flavor Ratios of Atmospheric Neutrino Flux

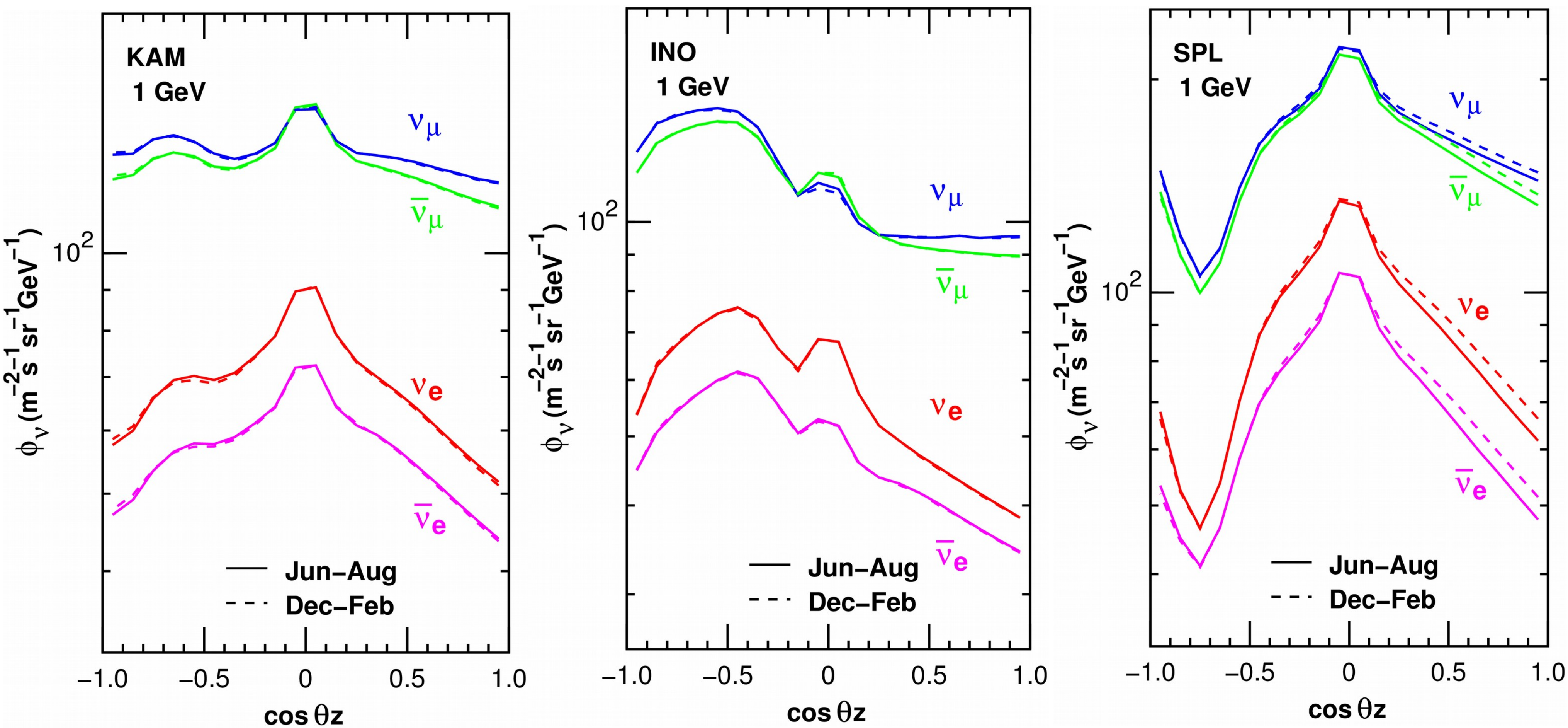


Seasonal and Site Variation of Atmospheric Neutrino Flavor Ratios

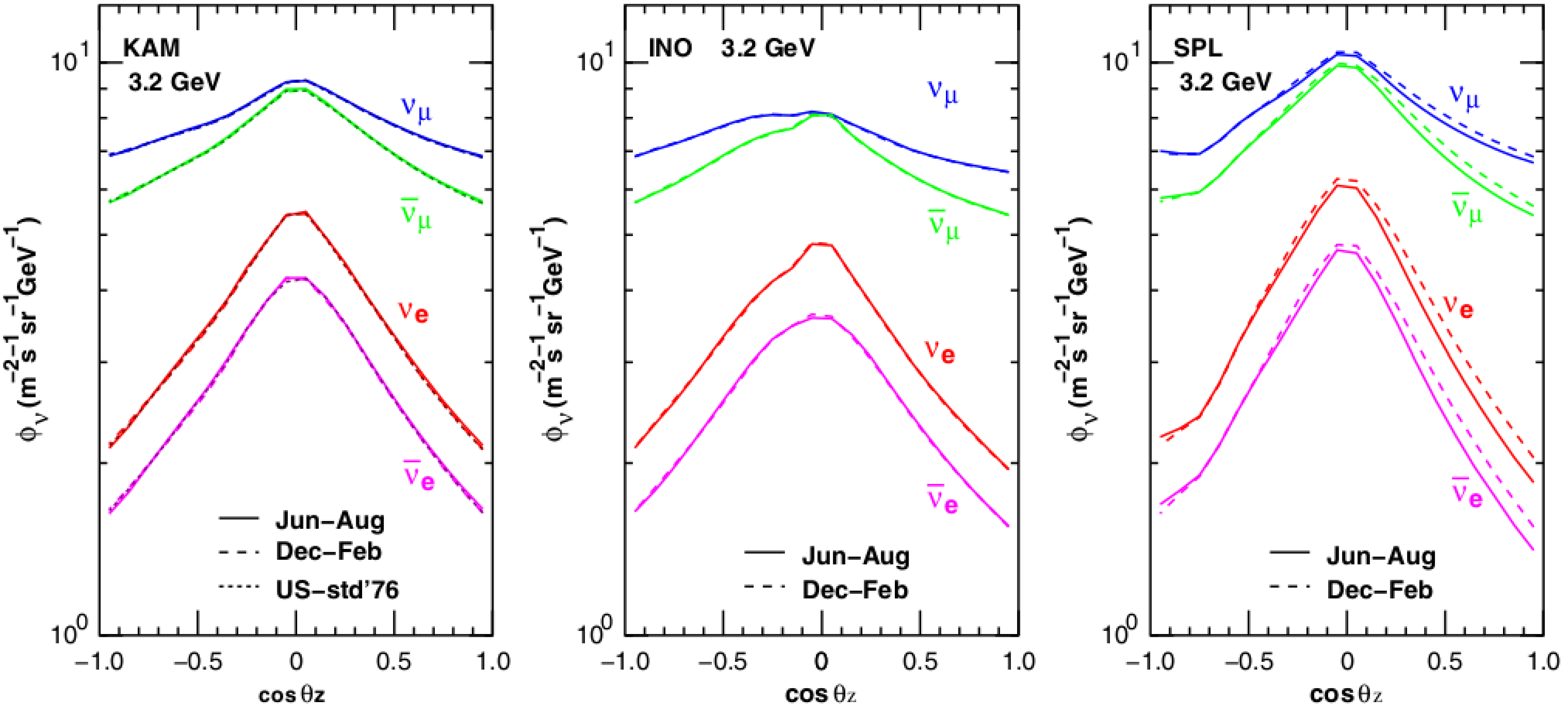


The variation of $\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$ at South Pole and the difference from Kamioka are almost equal to the largest estimation of its uncertainty.

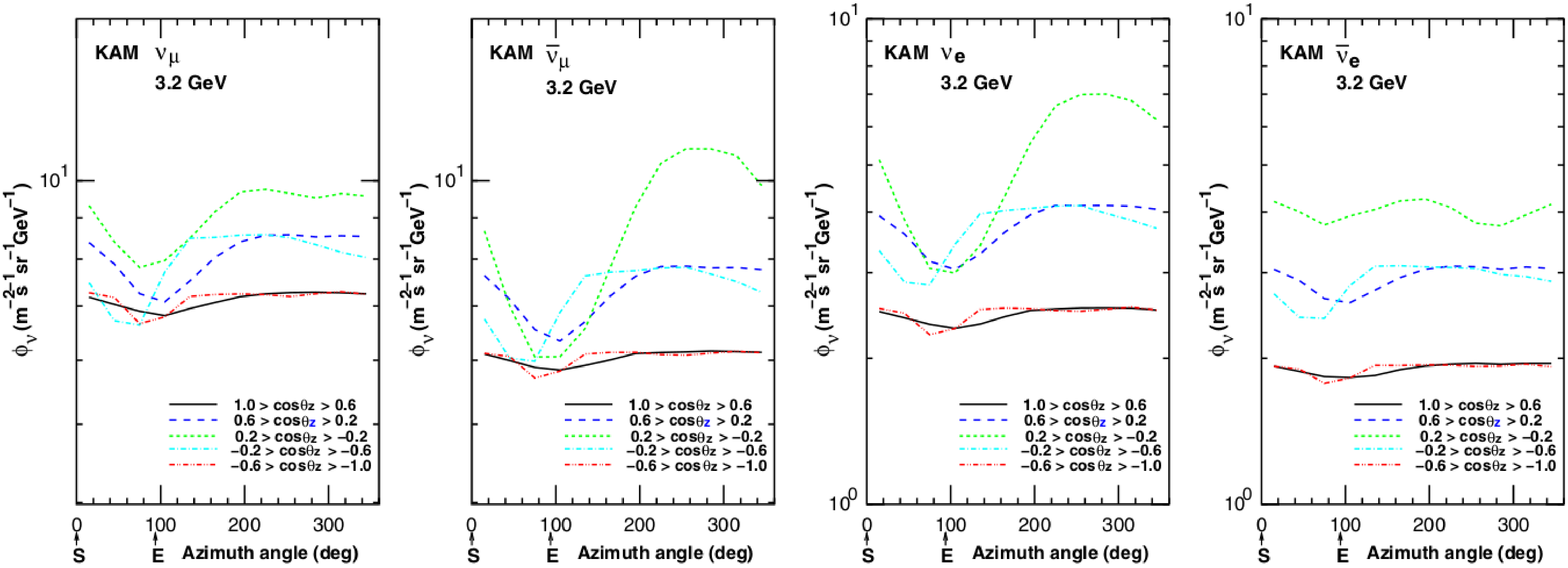
Zenith Angle Variation of Neutrino Fluxes at 1 GeV



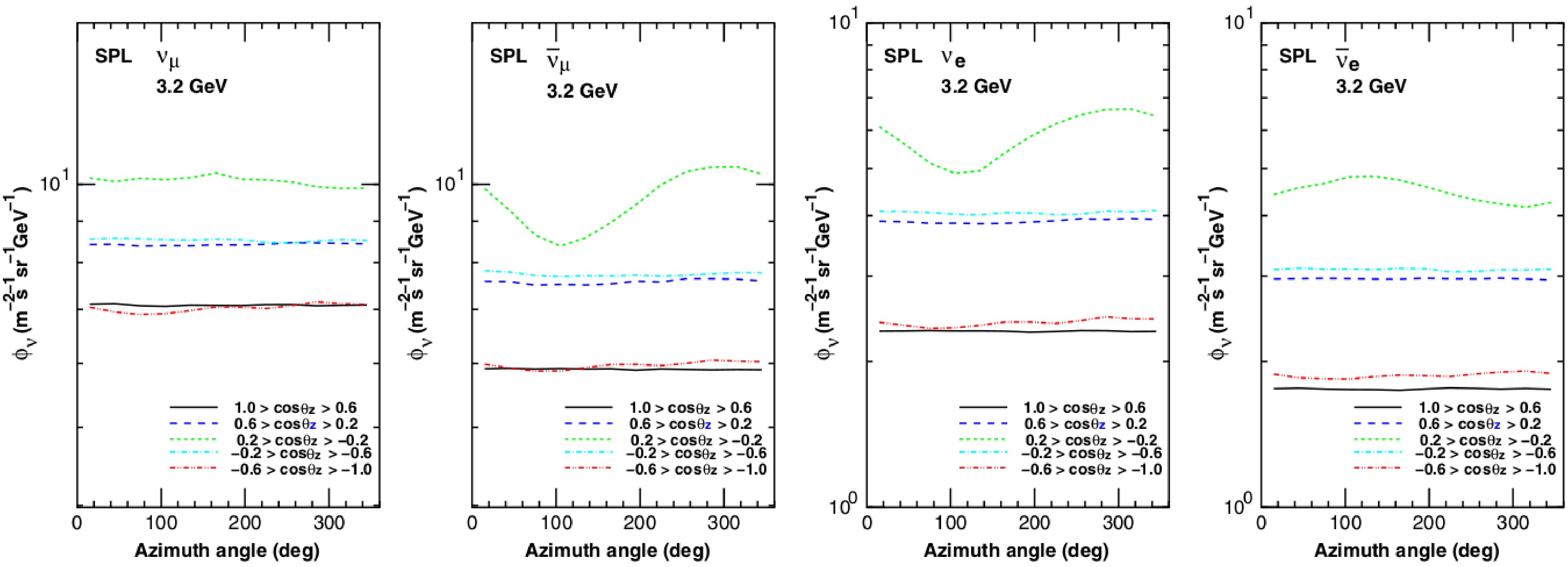
Zenith Angle Variation of Neutrino Fluxes at 3.2 GeV



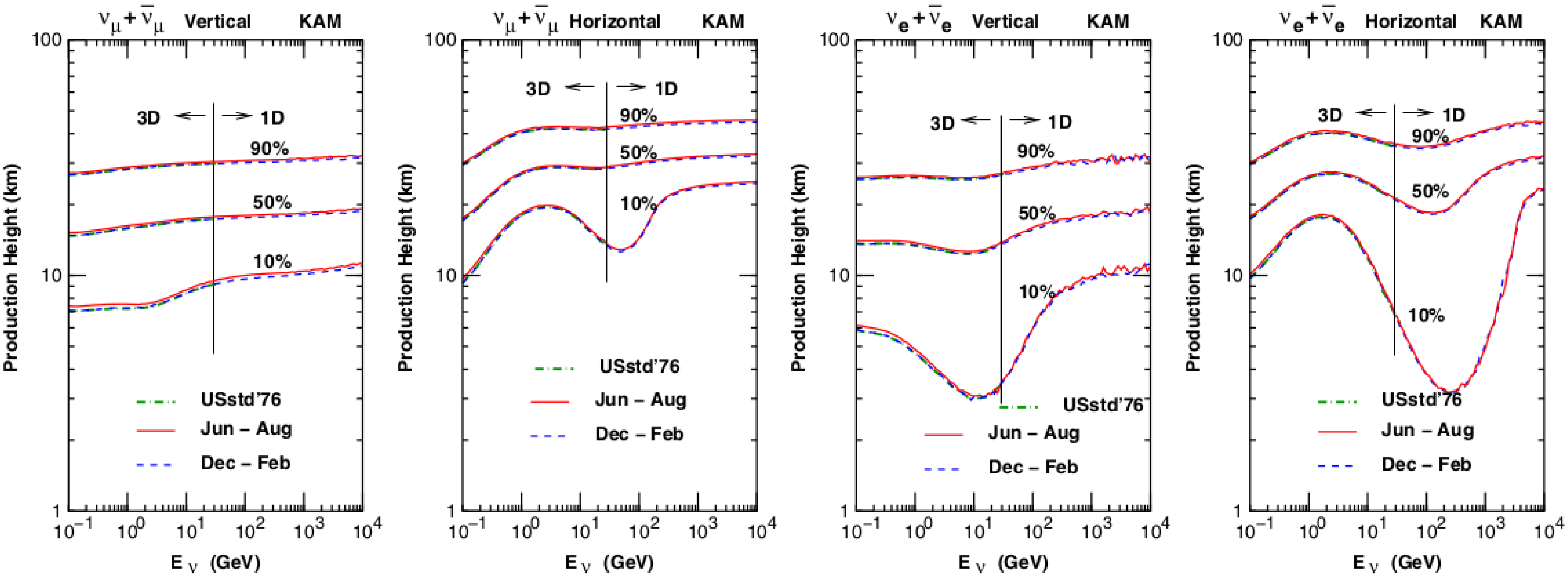
Azimuth Angle Variation of Neutrino Fluxes at 3.2 GeV at SK site



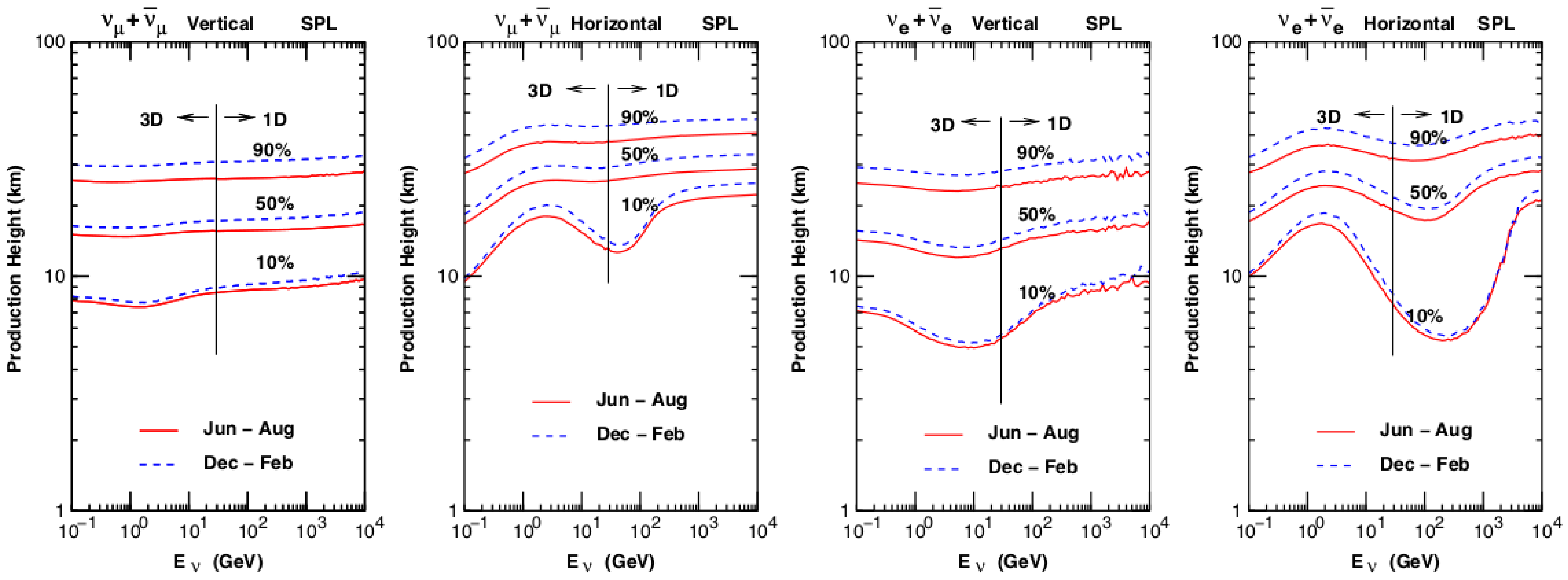
Azimuth Angle Variation of Neutrino Fluxes at 3.2 GeV at Suth Pole



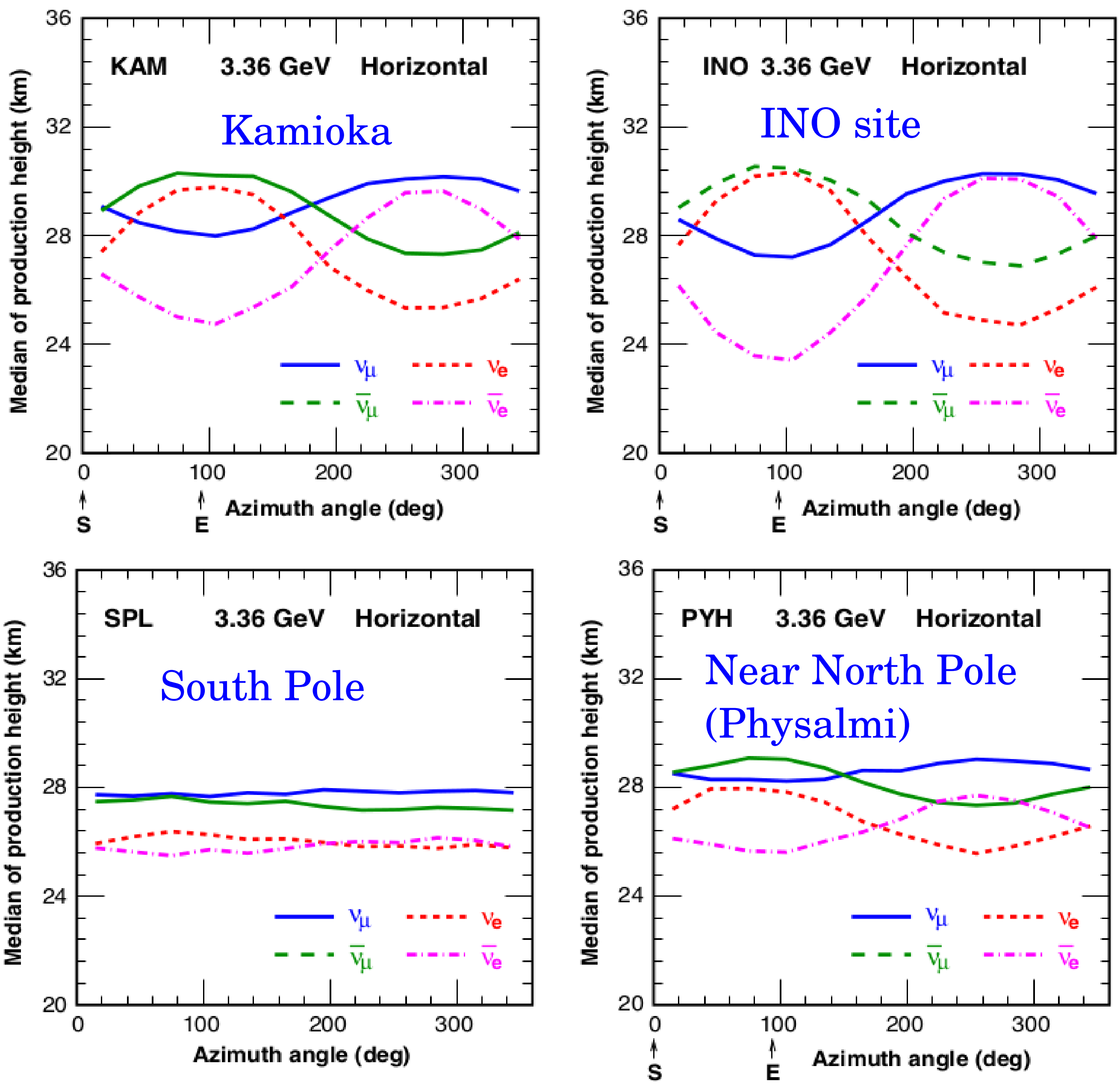
Cumulative Neutrino Production Height at SK site (Summed over all azimuth angles)



Cumulative Neutrino Production Height at South Pole (Summed over all azimuth angles)



Azimuth Angle Variaiton of Neutrino Production Height

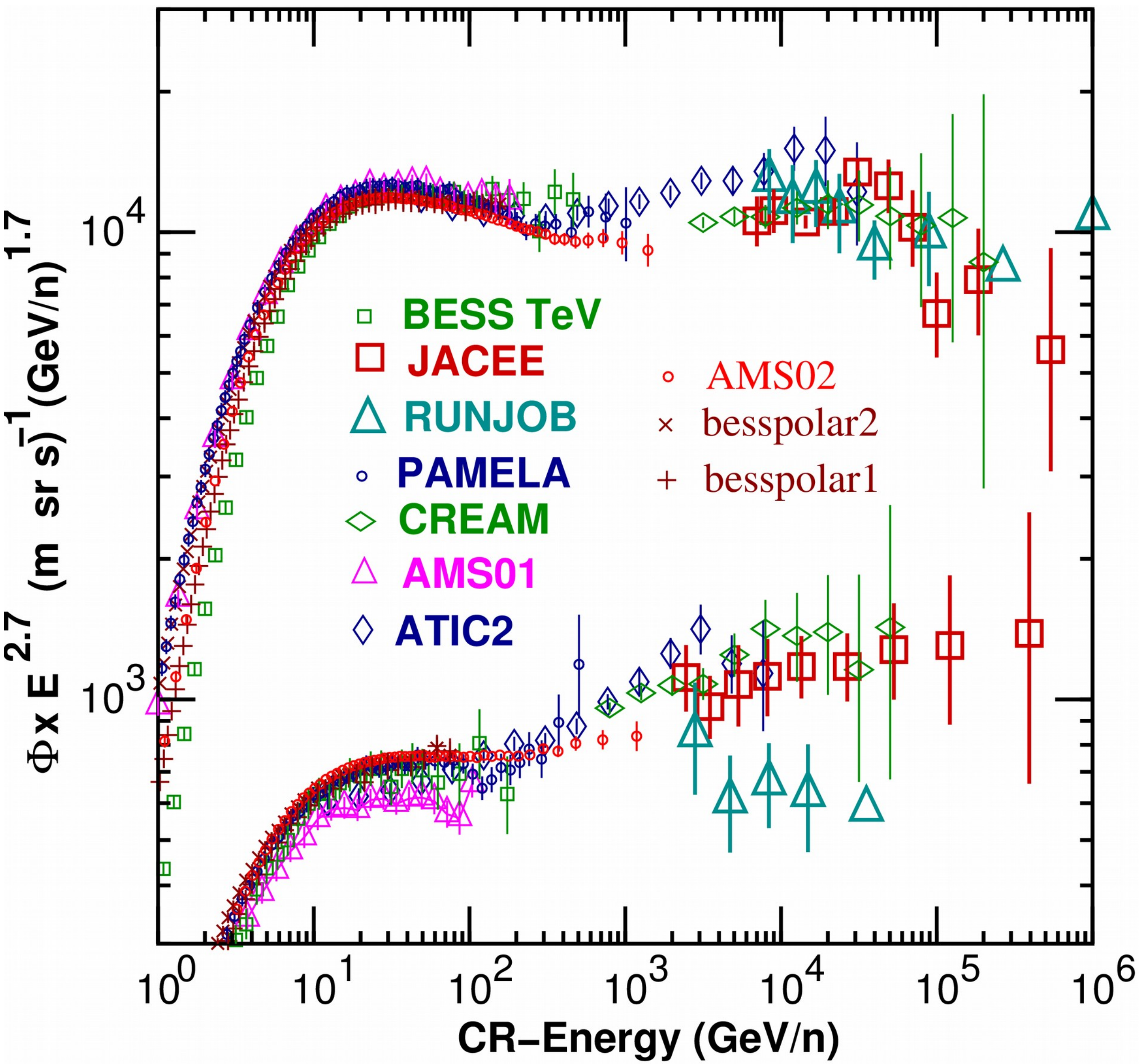


Impact of AMS02

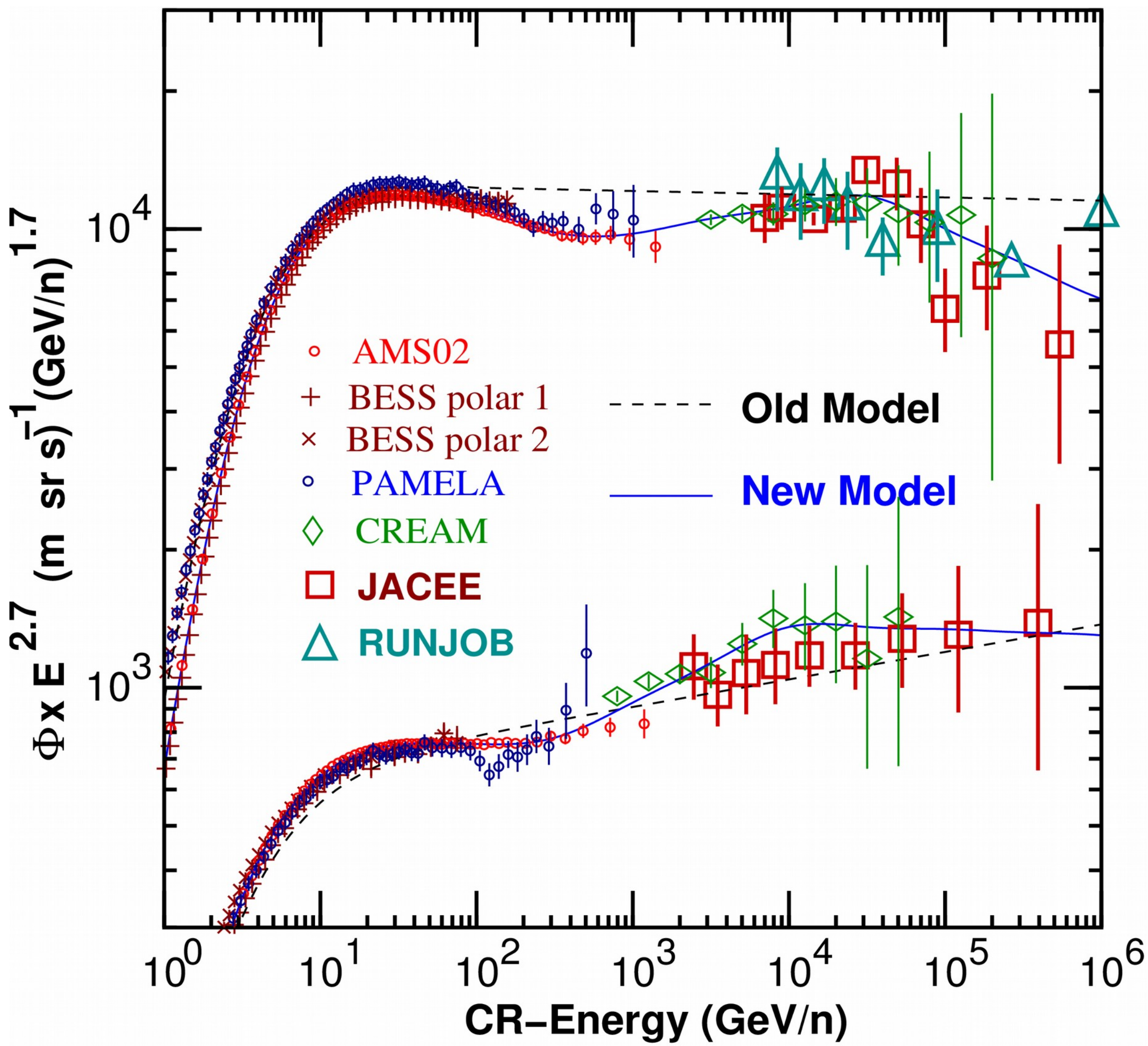
and

BESS-polar

Recent Cosmic Ray observation and available High Energy data

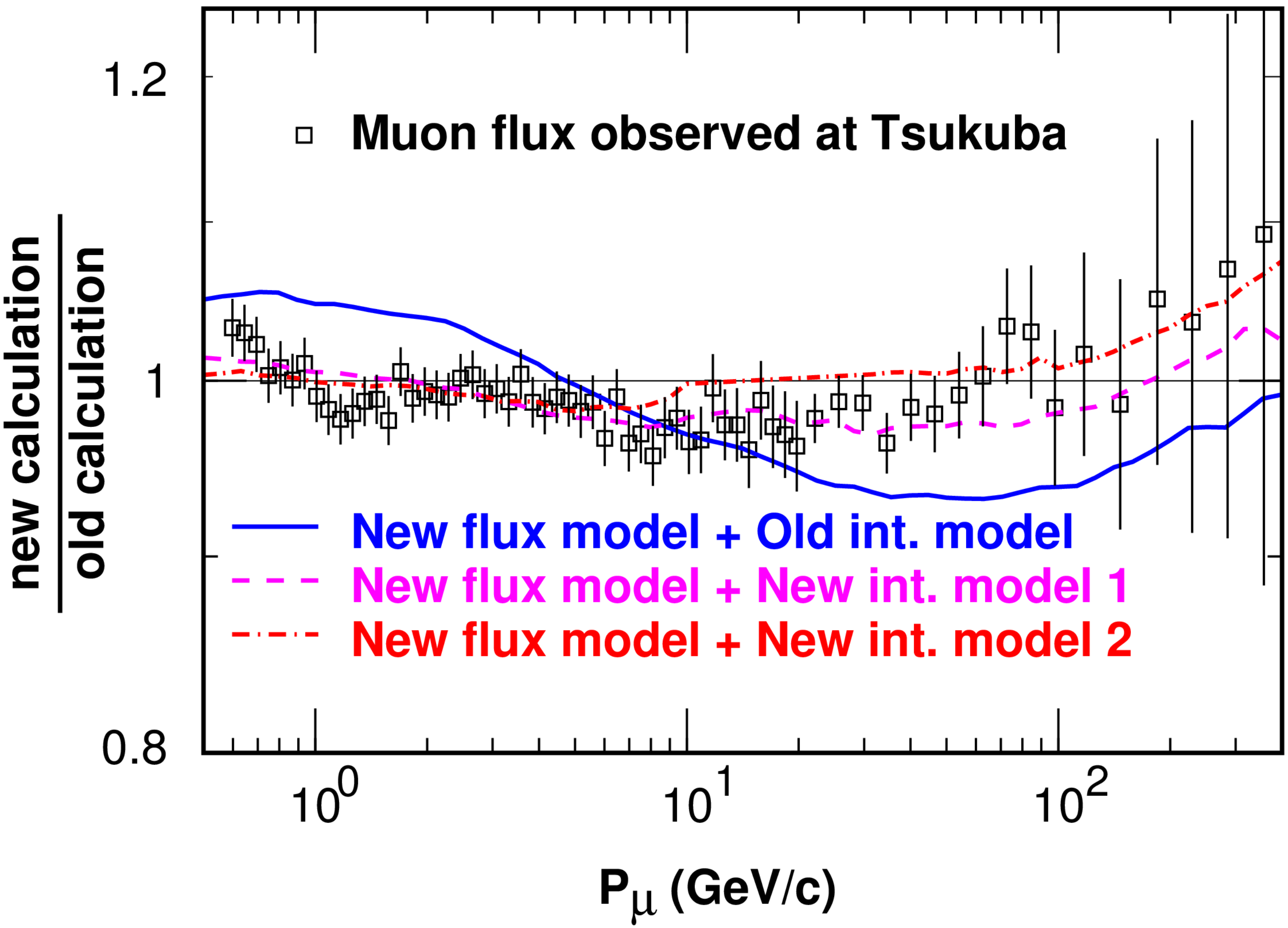


New Cosmic Ray Model with AMS02 and BESS-polar

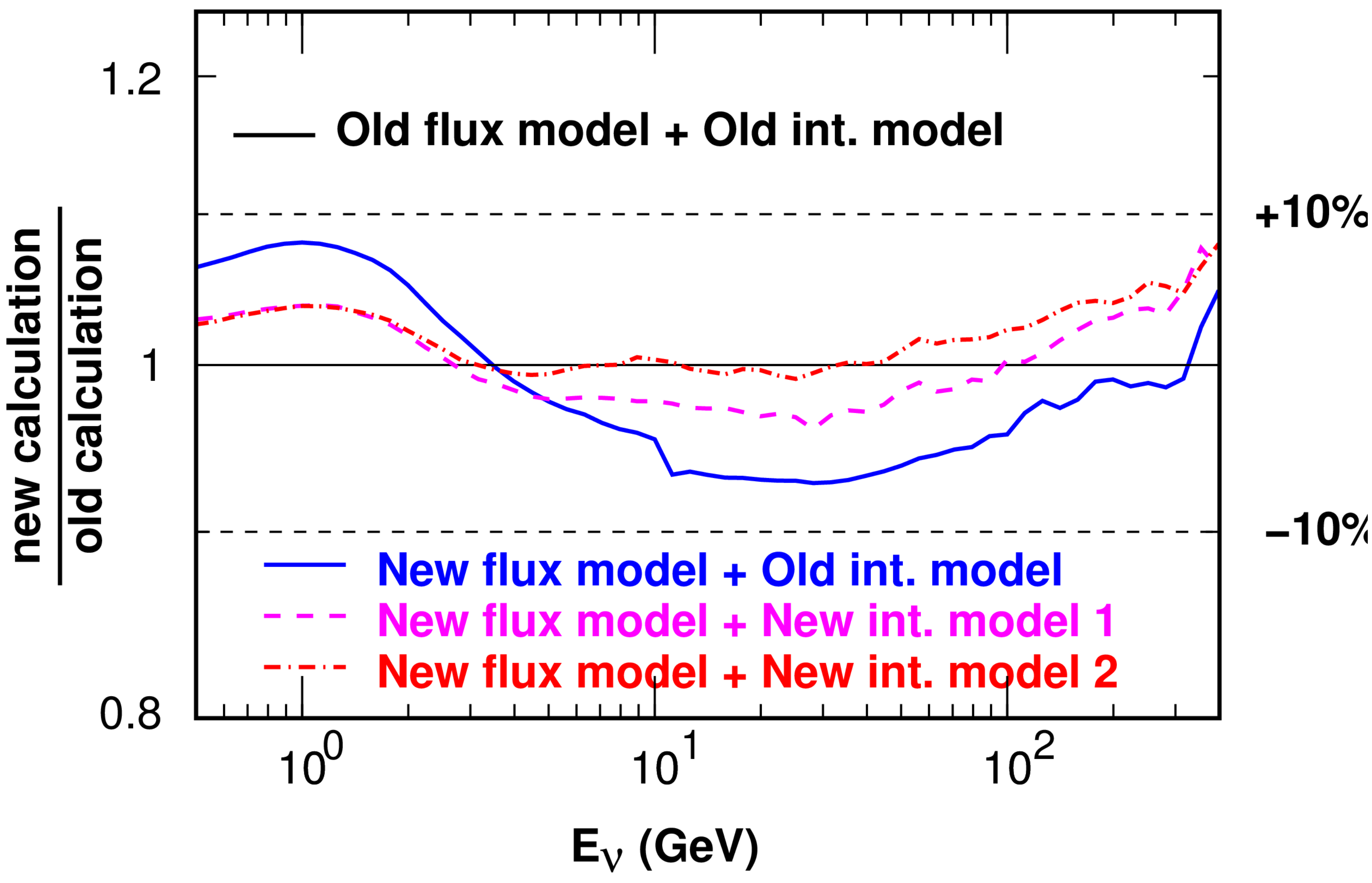


Discarded some data from model construction.

Muon Calibration of Interaction Model with New Cosmic Ray Model

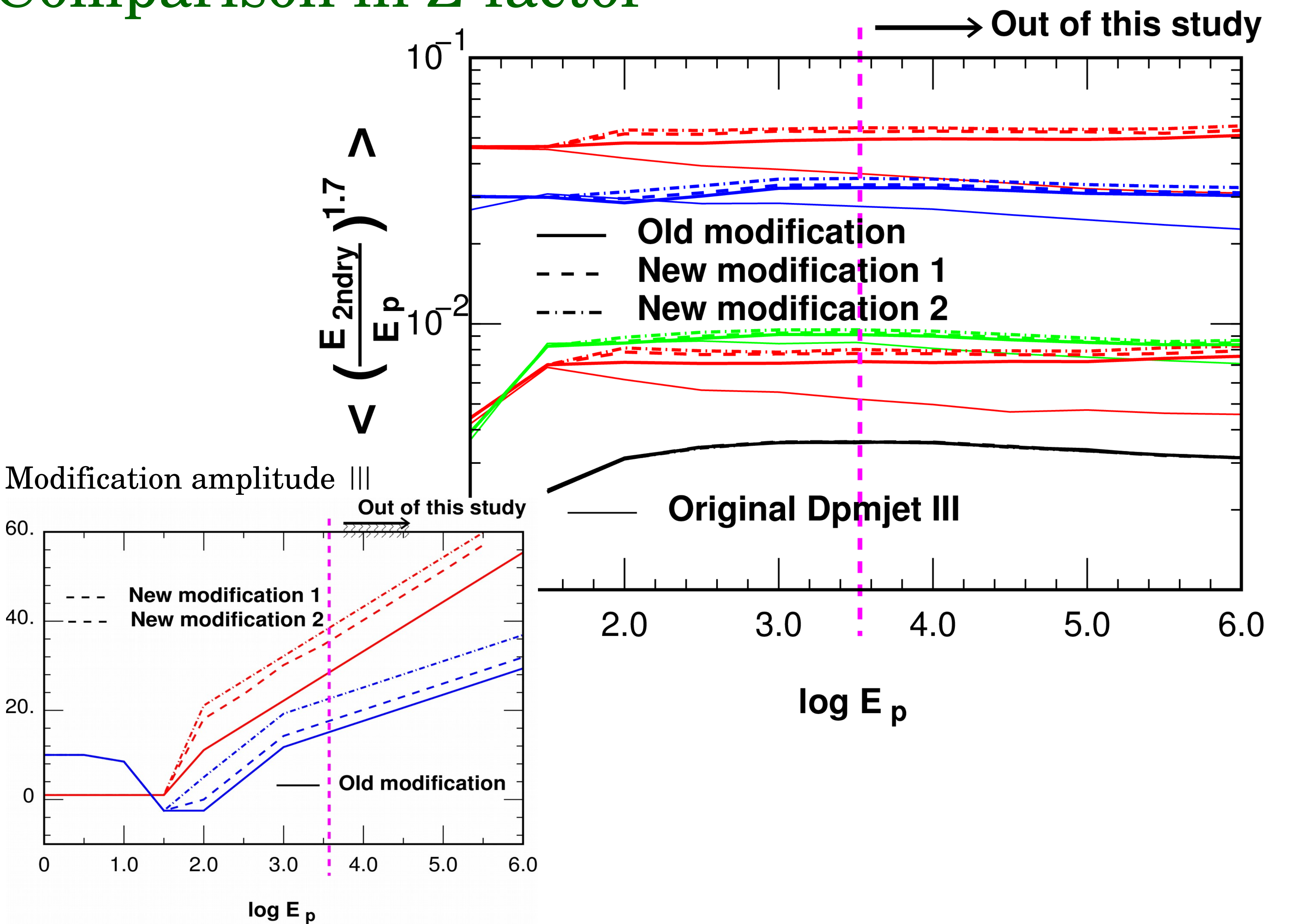


Resulting Neutrino Flux (all ν sum)

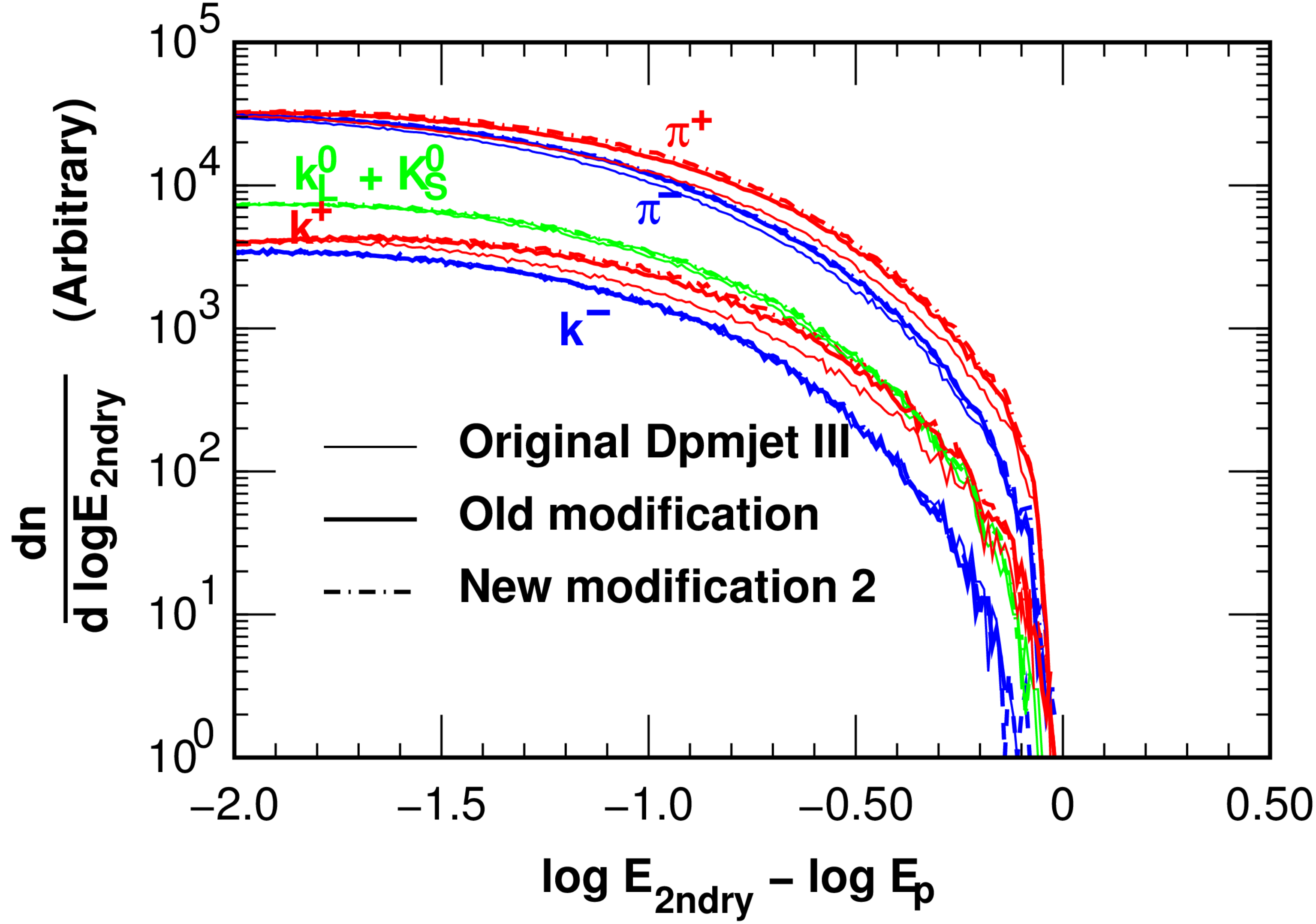


Muon calibration works !

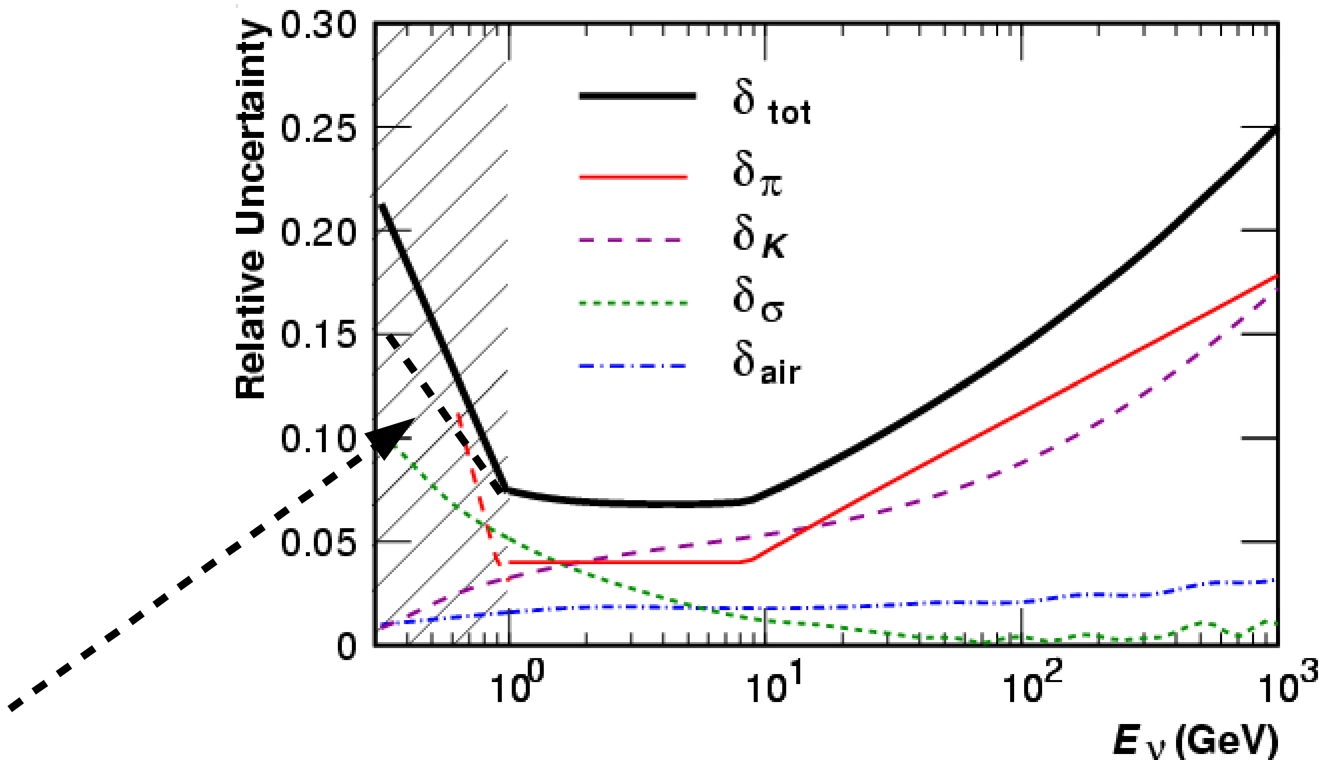
Comparison in Z-factor



Comparison of secondary spectra of interaction models at 1 TeV



Estimated Error in Atmospheric ν-flux Calculation (HKKMS07)



Possible Error with JAM (HKKM11)

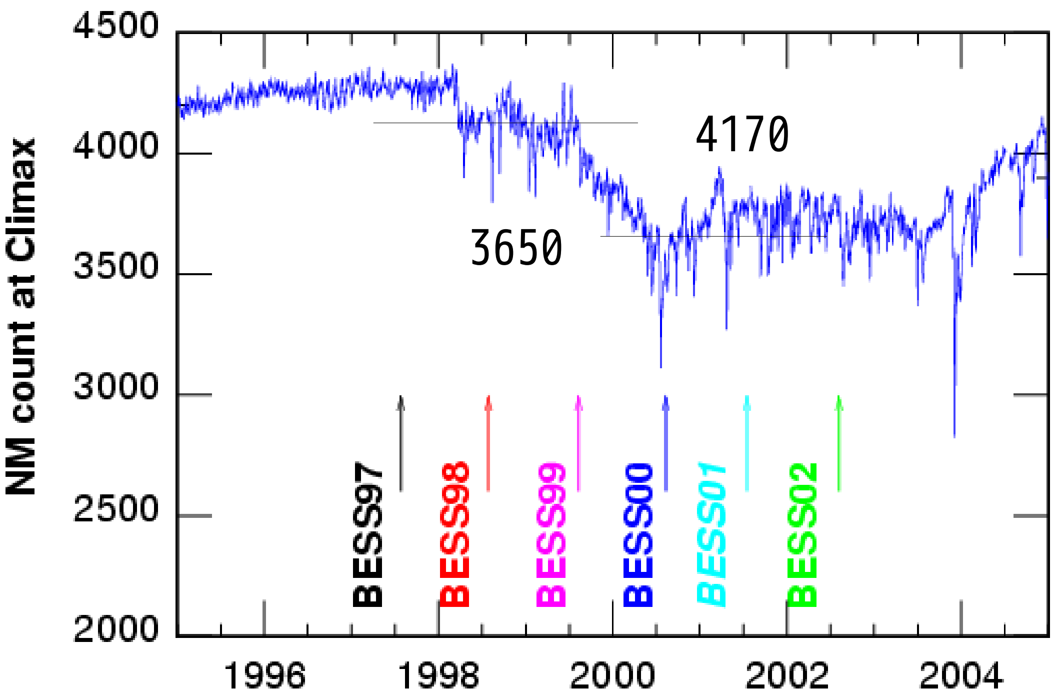
δ_π μ -observation error + Residual of reconstruction

δ_K Kaon production uncertainty

δ_σ Mean free path (interaction crossection) uncertainty

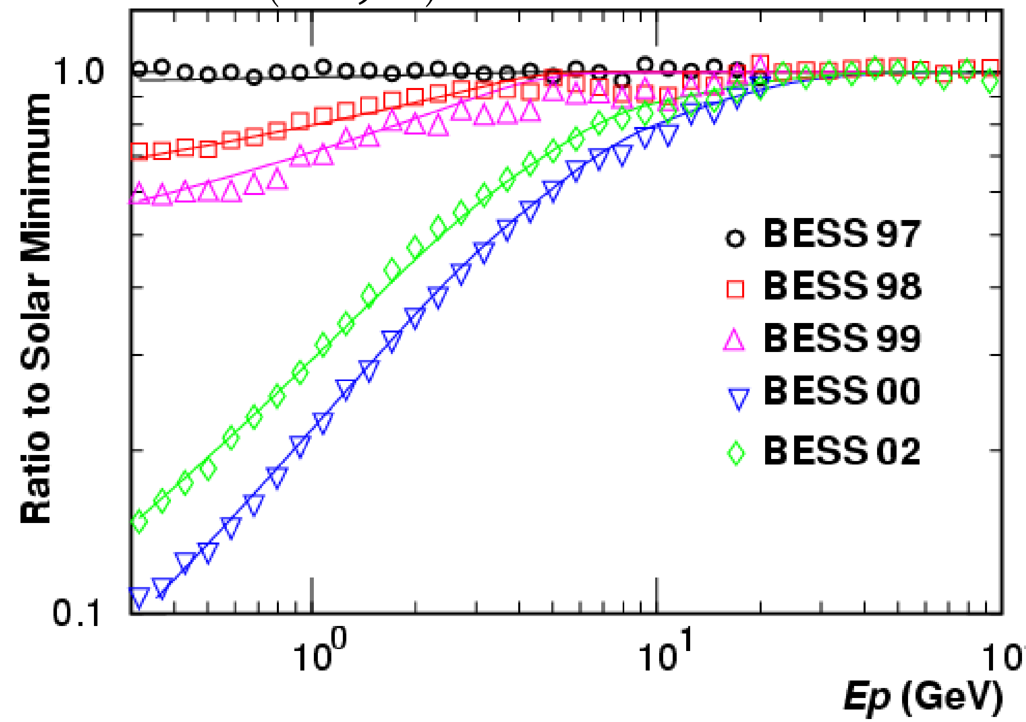
δ_{air} Atmosphere density profule uncertainty

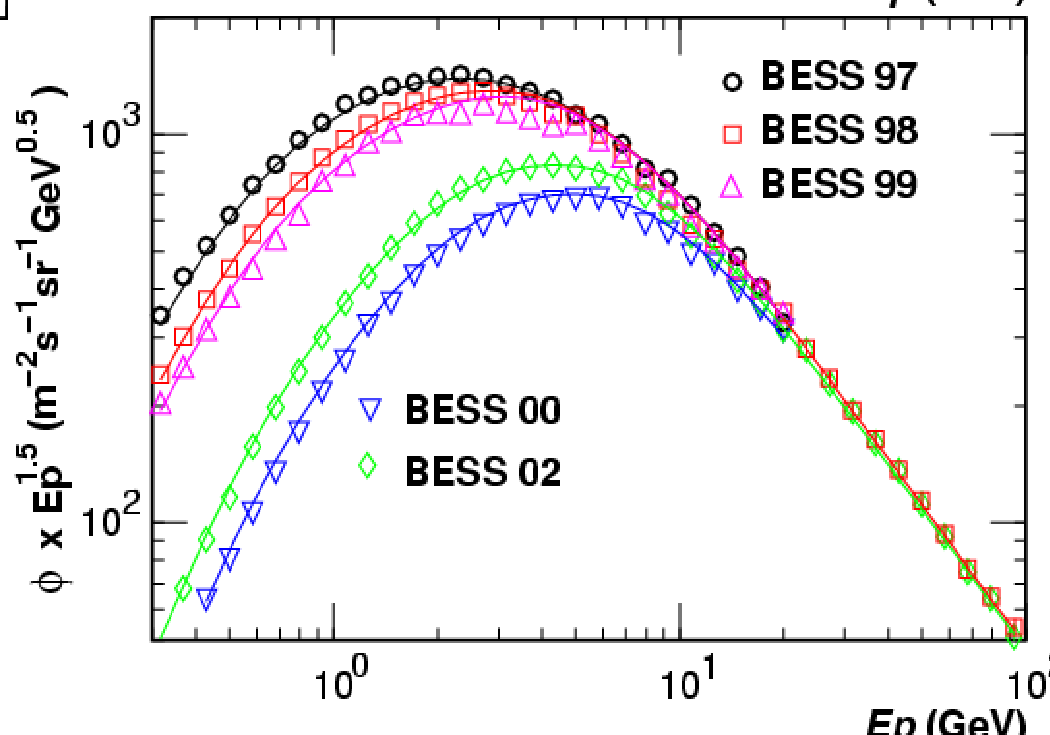
Solar Modulation of Primary Cosmic Rays and Atmospheric Neutrino



BESS flight

$M(N,r)$: modulation function



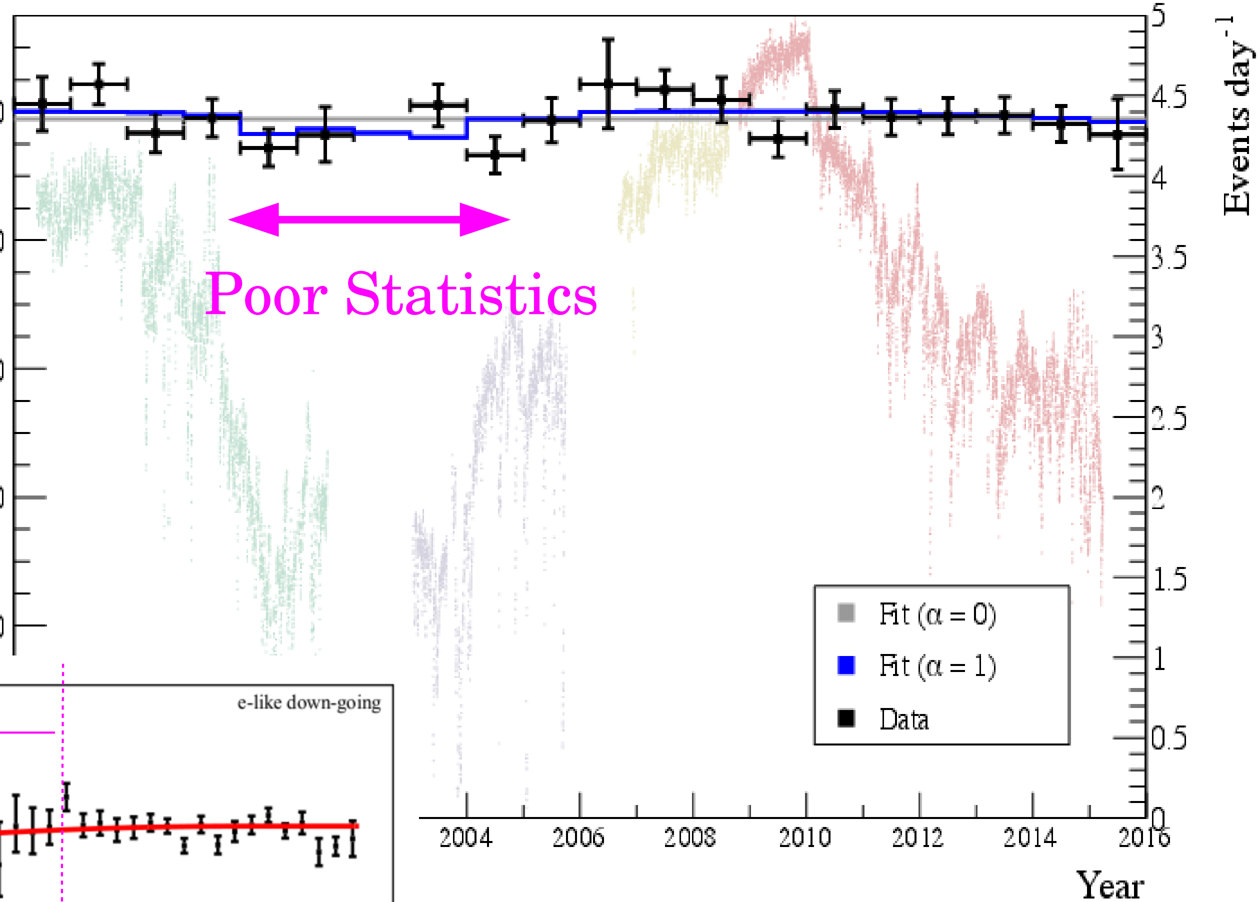


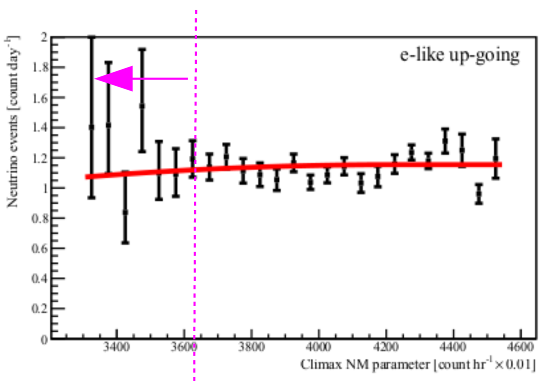
$$\phi_i(N, E_k) = \phi_i^{min}(E_k) \cdot M(N, r)$$

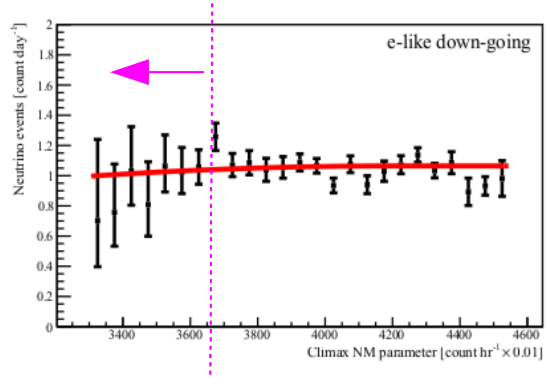
$$\phi_i^{min}(E_k) \equiv \phi_i^{1997}(E_k)$$

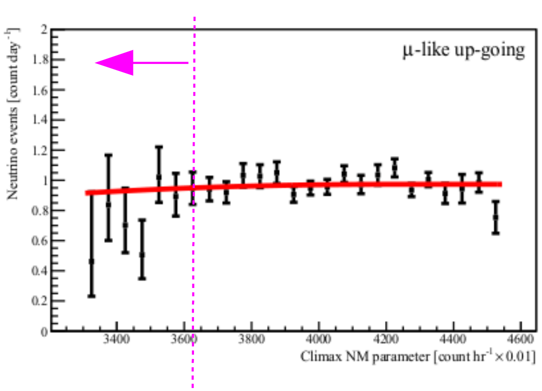
Solar Modulation of Atmospheric Neutrinos

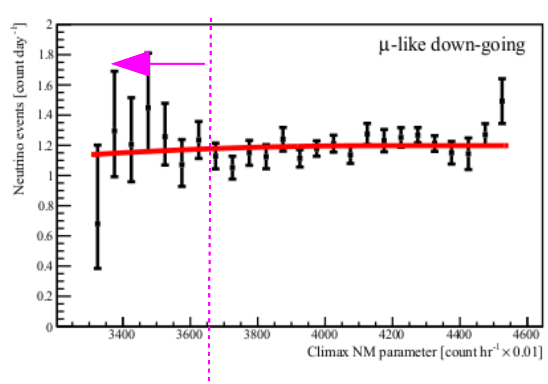
From PHD thesis of
E. Richard











Best fit corresponds to 62 %
of the predicted variations

Picked up mainly the
forbush decrease ?

まとめ

- 大気ニュートリノフラックス計算を、ごく簡単に解説した。

- NRLMSISE-00 大気モデルを用いたHKKM計算により、神岡以外のサイトにおける大気ニュートリノフラックスを調べた。
- 高緯度地方では大気構造により、低緯度地方では強い地磁気の水平成分により、神岡とは大きく異なる大気ニュートリノフラックスが予想される。特に高緯度地方では、比較的変化の少ないと考えられる $\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$ 比においても、神岡からの明らかな差異、また、季節変化が予想される。

- AMS02 and BESS-polarなどにより明かになった一次宇宙線スペクトルでの計算と、従来の一次宇宙線モデルでの計算とどのように異なるか予備的に調べたが、
- Muon calibration が一次宇宙線スペクトルの違いを吸収して、違いはこれまでの不定性の予想の範囲に収まる。

Back up

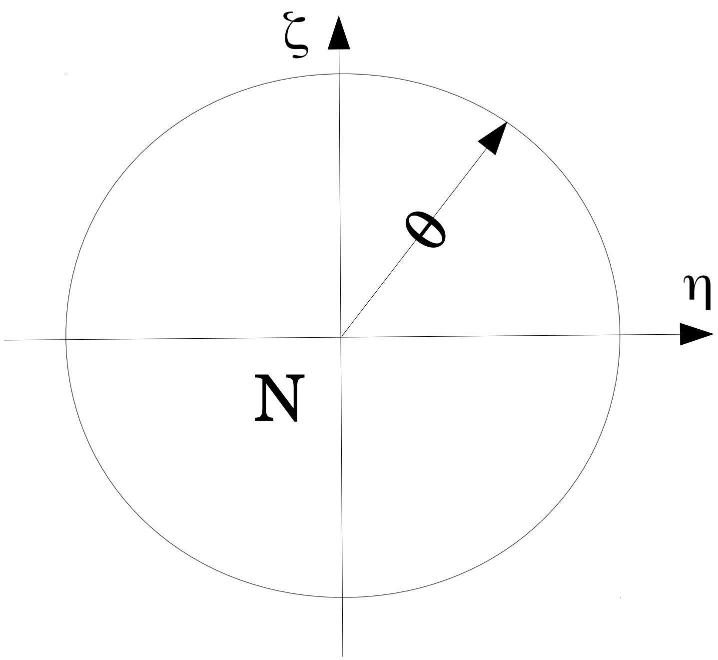
Assume the atmospheric neutrino flux is expanded as

$$\varphi(\zeta,\eta)=\varphi(0,0)+\frac{\partial\varphi}{\partial\zeta}\zeta+\frac{\partial\varphi}{\partial\eta}\eta+\frac{1}{2}\frac{\partial^2\varphi}{\partial^2\zeta}\zeta^2+\frac{\partial^2\varphi}{\partial\eta\partial\zeta}\zeta\eta+\frac{1}{2}\frac{\partial^2\varphi}{\partial^2\eta}\eta^2+....$$

Average in a virtual detector with radius θ is given as

$$\varphi_\theta\equiv\frac{1}{\pi\theta^2}\int_{\sqrt{\eta^2+\zeta^2}<\theta}\phi(\eta,\zeta)d\eta d\zeta=\frac{1}{\pi\theta^2}\int_{-\theta}^{+\theta}\int_{-\sqrt{\theta^2-\eta^2}}^{+\sqrt{\theta^2-\eta^2}}\phi(\eta,\zeta')d\zeta' d\eta$$

$$=\frac{1}{\pi\theta^2}\int_{-\theta}^{+\theta}\int_{-\sqrt{\theta^2-\zeta^2}}^{+\sqrt{\theta^2-\zeta^2}}\phi(\eta',\zeta)d\eta' d\zeta$$



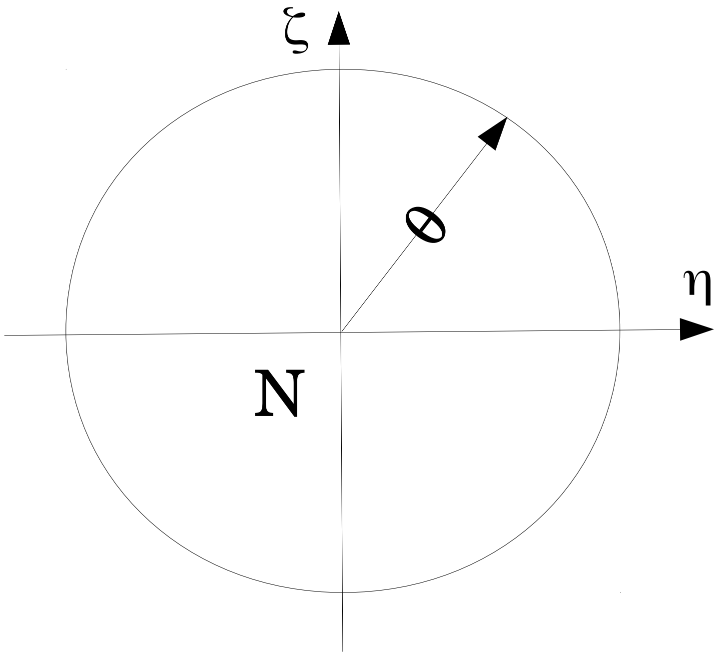
Assume the atmospheric neutrino flux is expanded as

$$\varphi(\zeta,\eta)=\varphi(0,0)+\frac{\partial\varphi}{\partial\zeta}\zeta+\frac{\partial\varphi}{\partial\eta}\eta+\frac{1}{2}\frac{\partial^2\varphi}{\partial^2\zeta}\zeta^2+\frac{\partial^2\varphi}{\partial\eta\partial\zeta}\zeta\eta+\frac{1}{2}\frac{\partial^2\varphi}{\partial^2\eta}\eta^2+....$$

Average in a virtual detector with radius θ is given as

$$\varphi_\theta\equiv\frac{1}{\pi\theta^2}\int_{\sqrt{\eta^2+\zeta^2}<\theta}\phi(\eta,\zeta)d\eta d\zeta=\frac{1}{\pi\theta^2}\int_{-\theta}^{+\theta}\int_{-\sqrt{\theta^2-\eta^2}}^{+\sqrt{\theta^2-\eta^2}}\phi(\eta,\zeta')d\zeta' d\eta$$

$$=\frac{1}{\pi\theta^2}\int_{-\theta}^{+\theta}\int_{-\sqrt{\theta^2-\zeta^2}}^{+\sqrt{\theta^2-\zeta^2}}\phi(\eta',\zeta)d\eta' d\zeta$$



$$\int_{\sqrt{\eta^2+\zeta^2}<\theta}\eta d\eta d\zeta=\int_{\sqrt{\eta^2+\zeta^2}<\theta}\zeta d\eta d\zeta=0$$

$$\int_{\sqrt{\eta^2+\zeta^2}<\theta}\eta\zeta d\eta d\zeta=0$$

(continued)

$$\int_{\sqrt{\eta^2+\zeta^2}<\theta} \eta^2 d\eta d\zeta = \int_{\sqrt{\eta^2+\zeta^2}<\theta} \zeta^2 d\eta d\zeta = \int_{-\theta}^{+\theta} \int_{-\sqrt{\theta^2-\zeta^2}}^{+\sqrt{\theta^2-\zeta^2}} \eta'^2 d\eta' d\zeta$$

$$= \frac{2}{3} \int_{-\theta}^{+\theta} \sqrt{\theta^2-\zeta^2}^3 d\zeta$$

$$= \frac{2}{3} \theta^4 \int_{-1}^{+1} \sqrt{1-t^2}^3 dt$$

$$= \frac{1}{4} \pi \theta^4$$

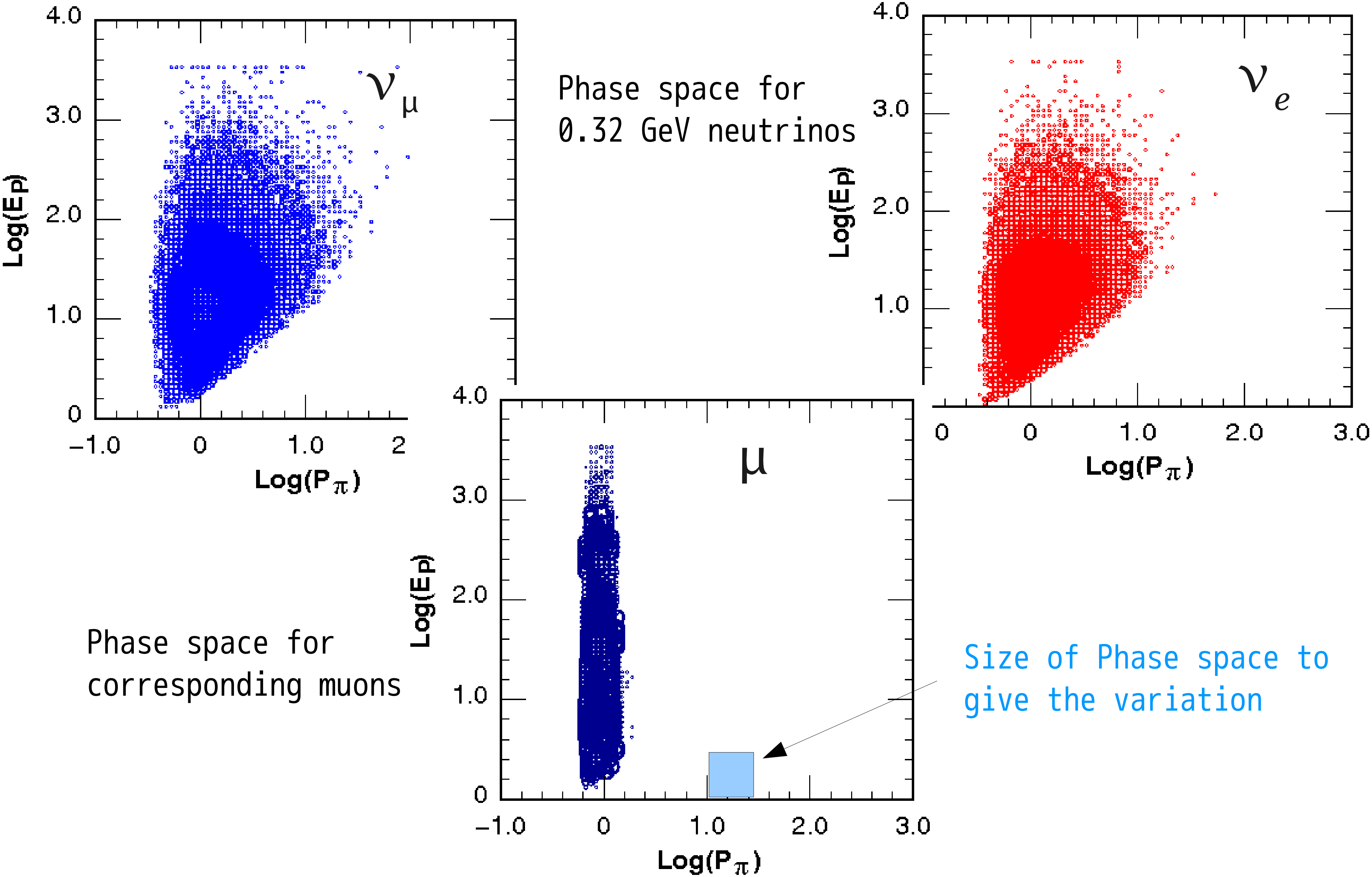
Then we get

$$\varphi_\theta \equiv \frac{1}{\pi\theta^2} \int_{\sqrt{\eta^2+\zeta^2}<\theta} \phi(\eta,\zeta) d\eta d\zeta = \phi(0,0) + \frac{1}{8} \left(\frac{\partial^2 \varphi}{\partial^2 \zeta} + \frac{\partial^2 \varphi}{\partial^2 \eta} \right) \theta^2 + \ldots.$$

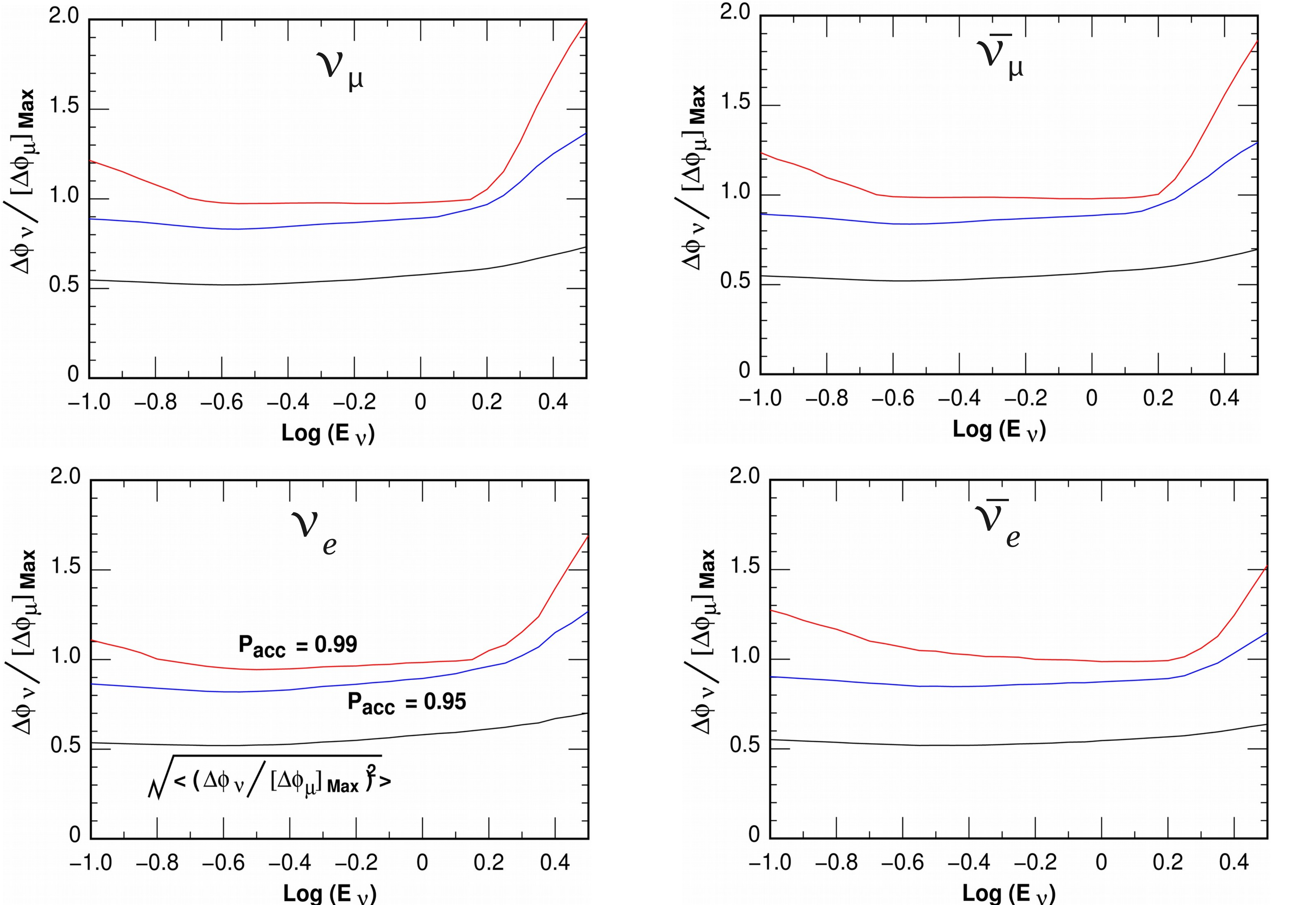
Note, the factor before θ^2 would be a little different, due to the Jacobian for the integration on a sphere.

Analysis of calculation error:

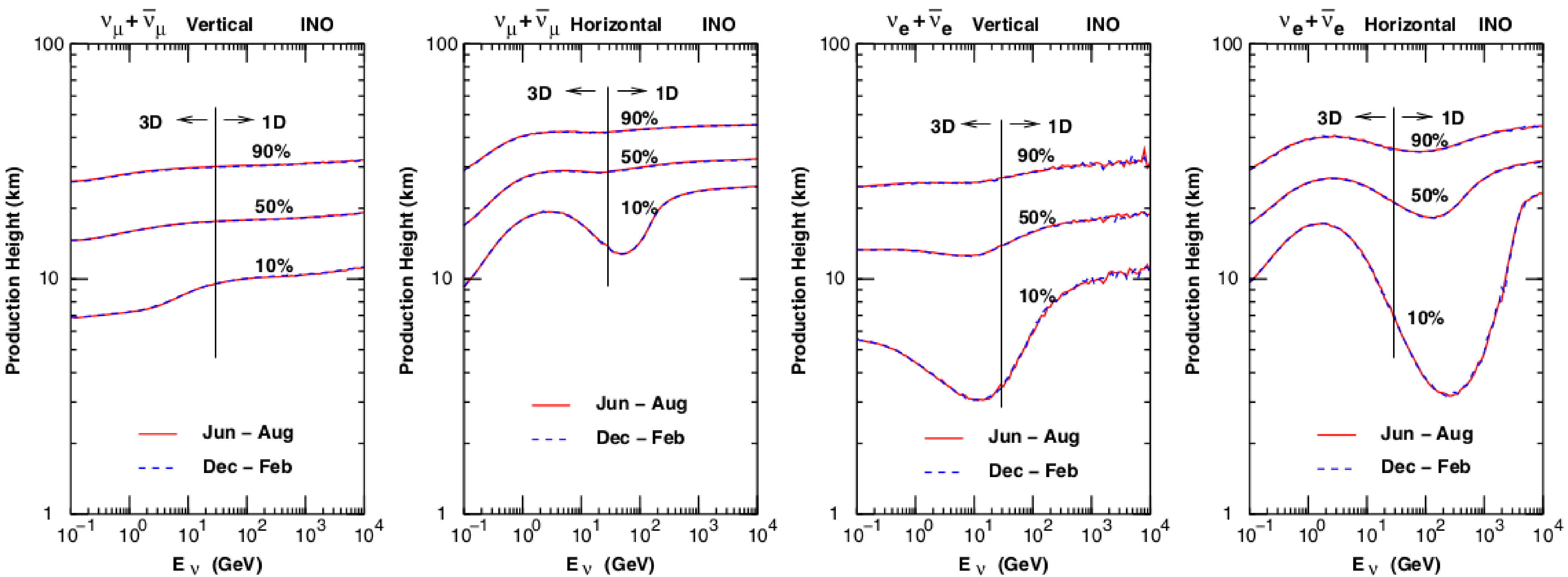
Give Variations in the phase space and compare the variation of neutrino flux and the Maximum variation of muon flux in 0.5 ~ 2 GeV/c (μ+) and 0.5 ~ 4 GeV/c (μ-), where BESS Balloon observation was available.



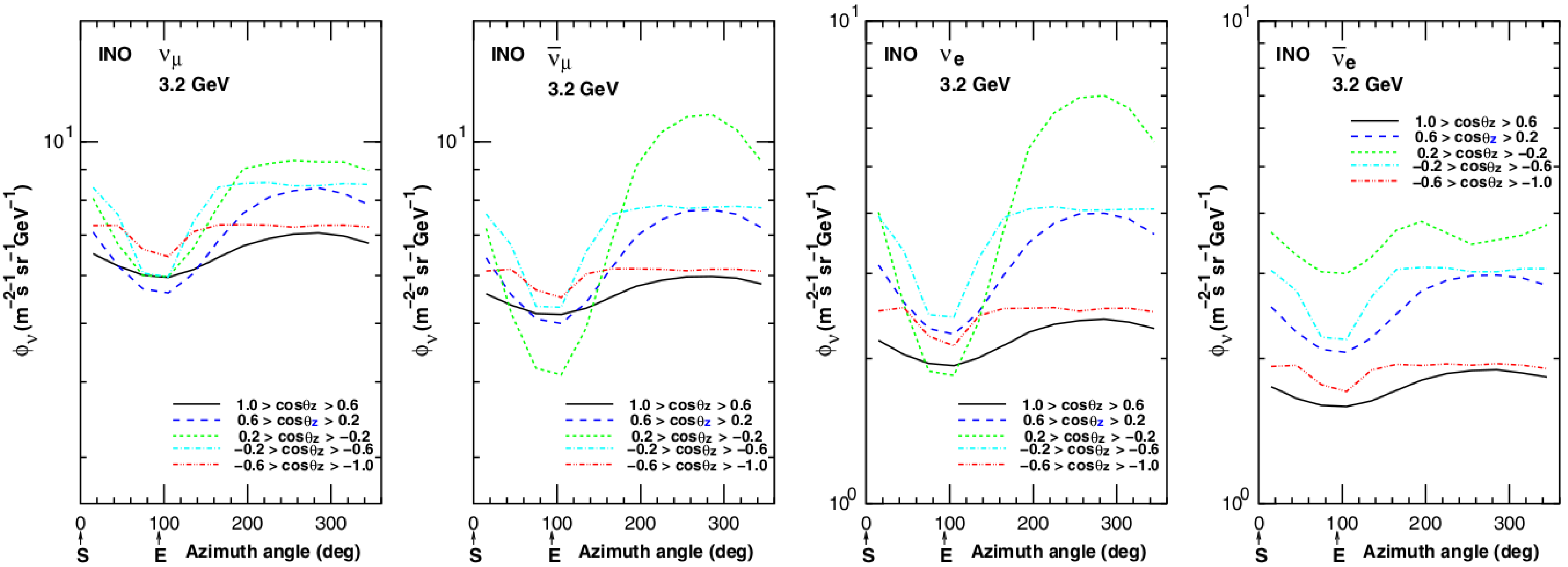
Vertical neutrino flux



Cumulative Neutrino Production Height at INO site (Summed over all azimuth angles)



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



Azimuth Angle Variation of Neutrino Fluxes at 1 GeV at SK site