The Interaction Model suggested by AMS02 Observation and resulting atmospheric Neutrino Flux

M. Honda @ HESZ-2015 in Nagoya

This talk is based on the work presented in HKKMS and HKKM papers (PRD 2007 and 2011), and an extension of the preliminary work presented in EDS Bois Workshop (Dec. 2011) held in Qui-Nhon Vietnum using the cosmic ray data before AMS02.

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 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

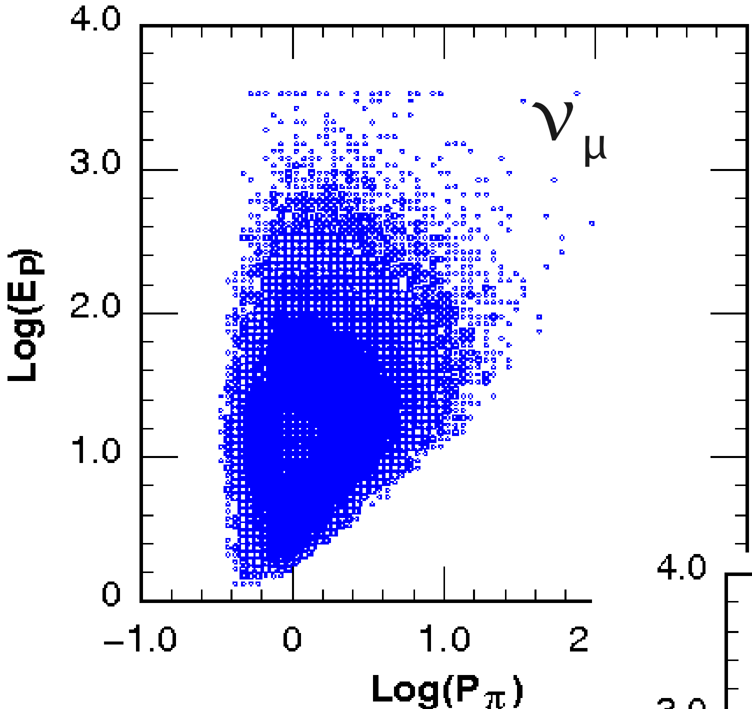
$R_{cut} = R_{cut}(R_{cr}, latt., long., \theta, \varphi)$: Geomagnetic field

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

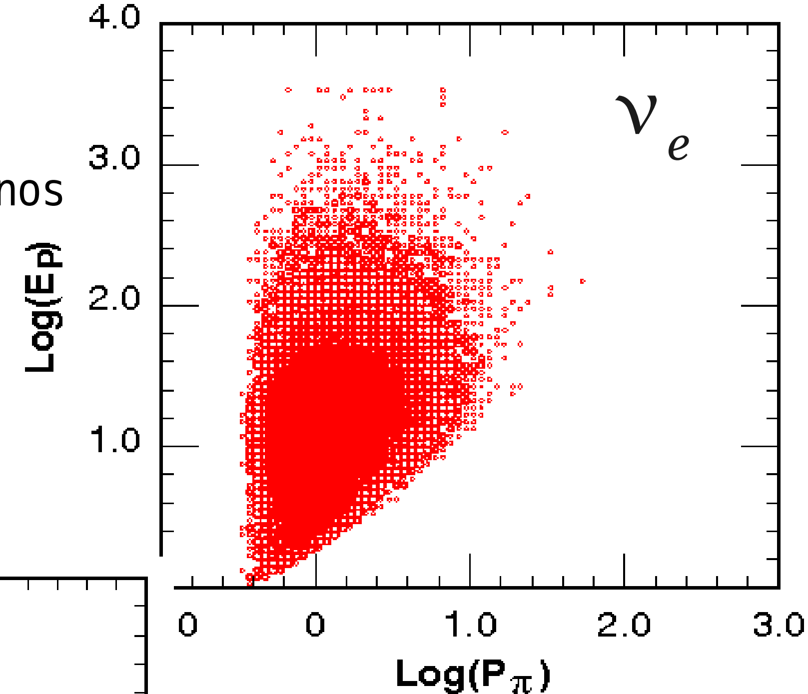
$Y_{\mu} = Yield_{\mu}(h, \theta)$: Hadronic Interaction Model, Air Profile, and meson decay

This formula illustrates 1D calculation well

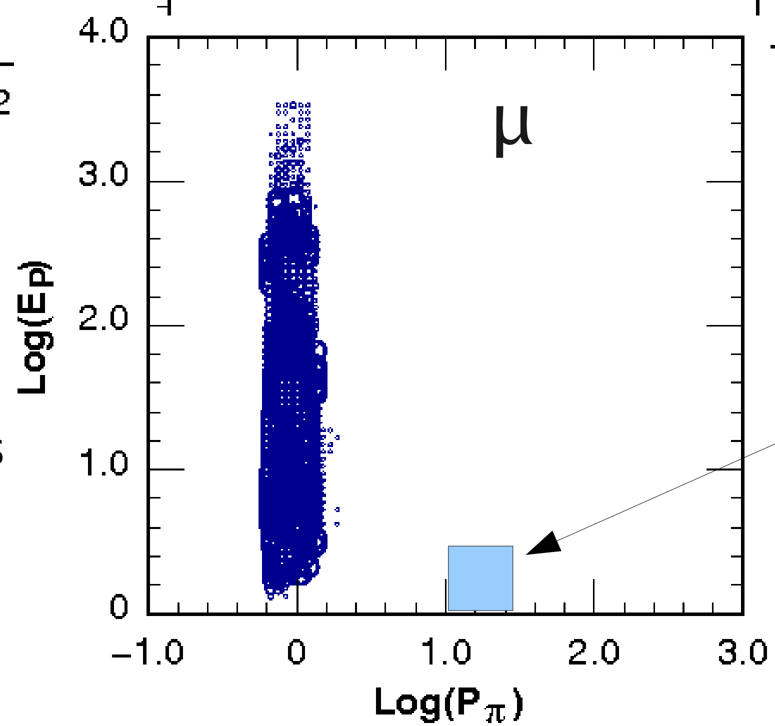
Analysis of calculation error:
Give Variations in the phase space and compare the variation of neutrino flux and the Maximum variation of muon flux in 0.5 ~ 2 GeV/c (μ+)
And 0.5 ~ 4 GeV/c (μ-), where BESS Balloon observation was available.



Phase space for 0.32 GeV neutrinos

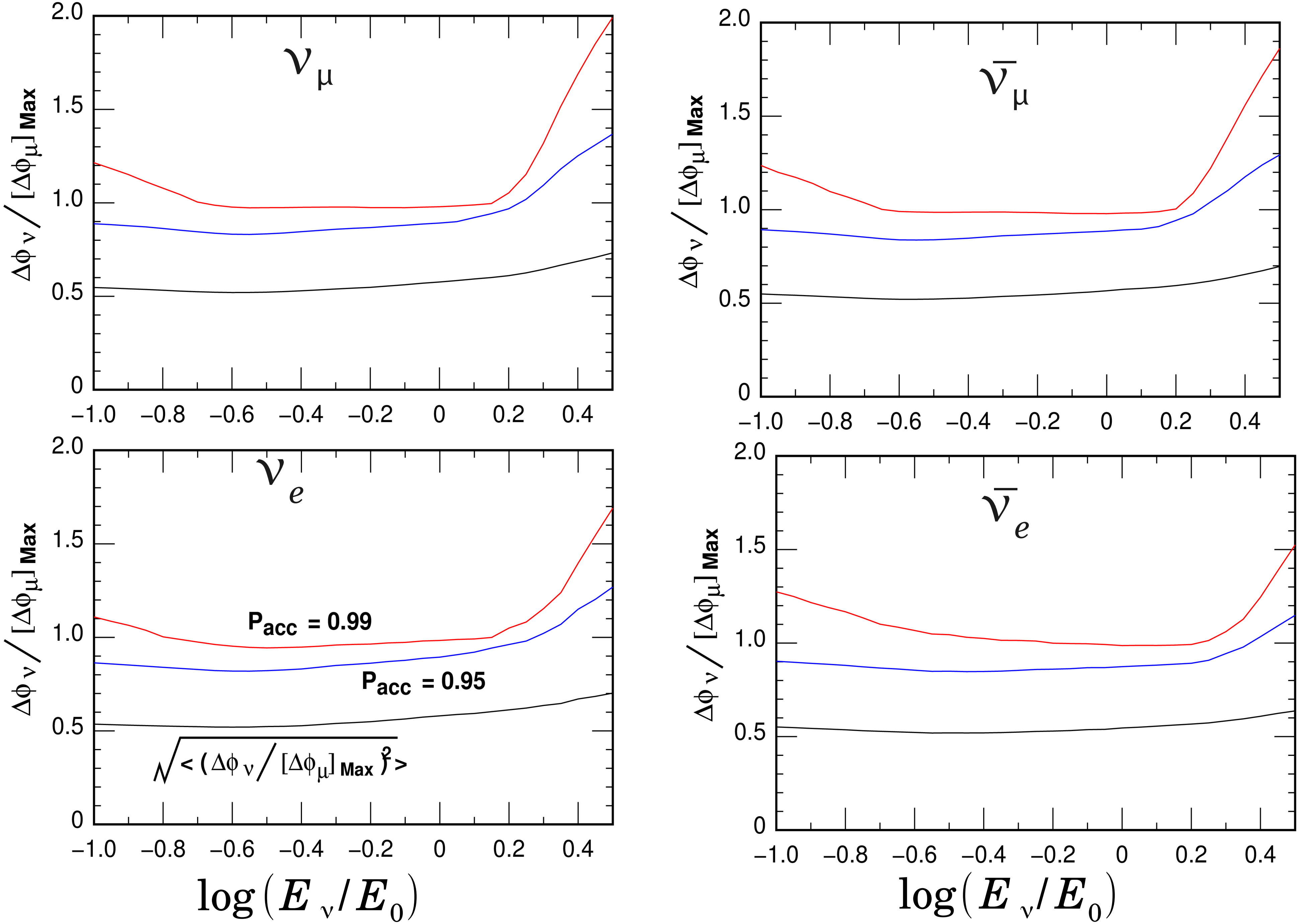


Phase space for corresponding muons



Size of Phase space to give the variation

Possible variation of neutrino flux when m flux below $\sim 3\times E_0$ is reconstructed with variation of Δ_μ

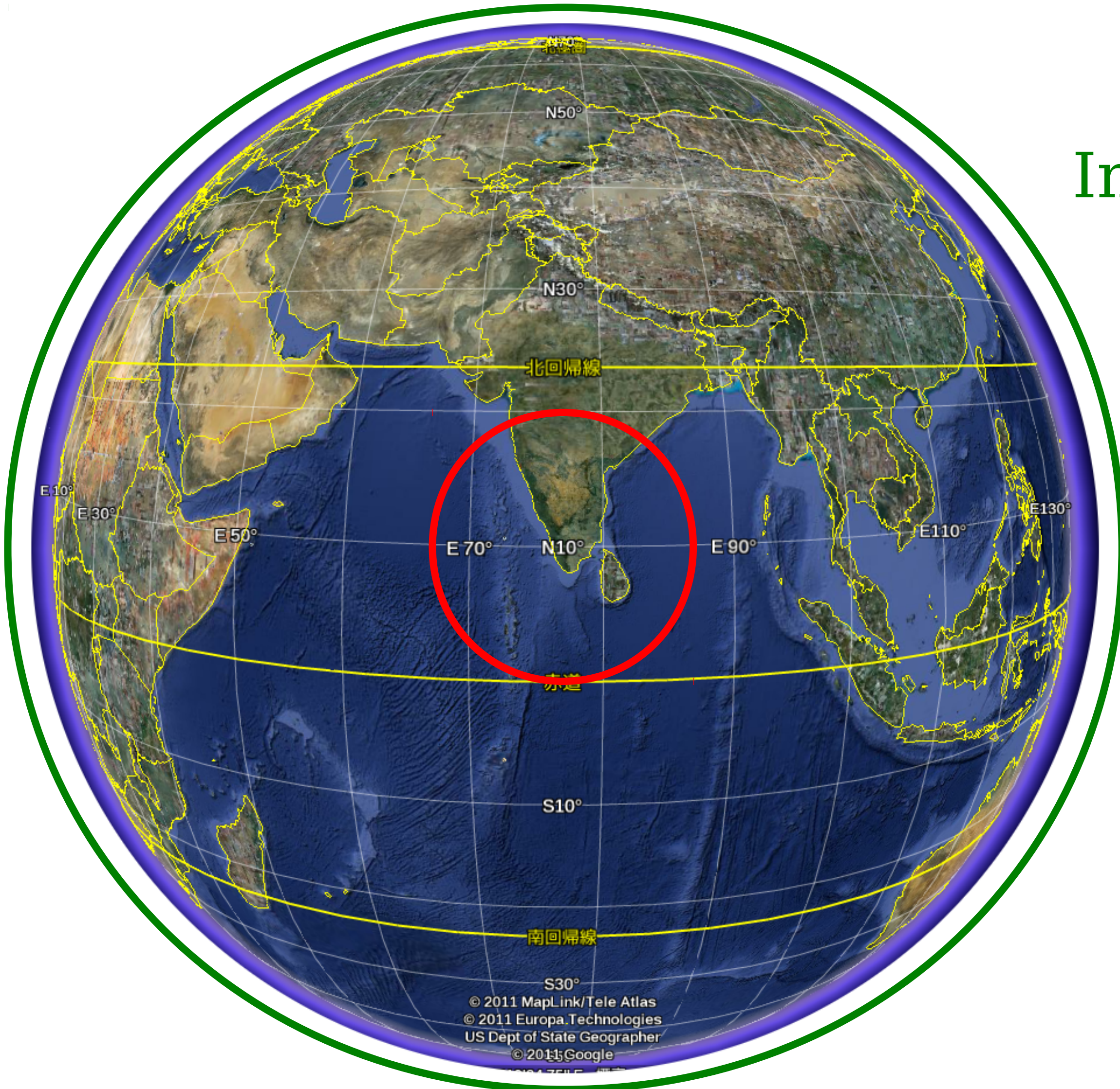


3D-Calculation Geometry

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

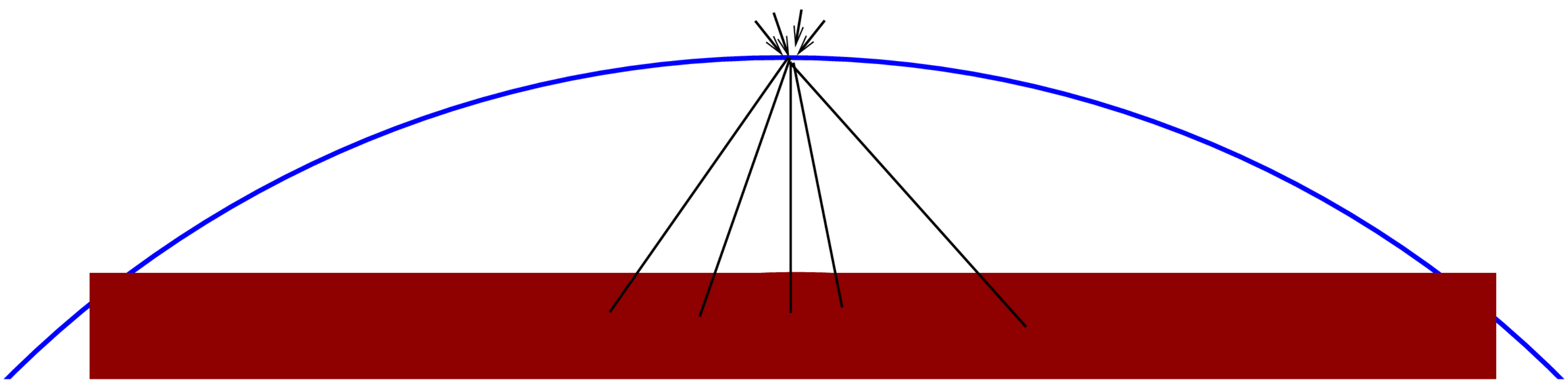
Virtual Detector

All neutrinos path through are recorded

Muon flux calculation

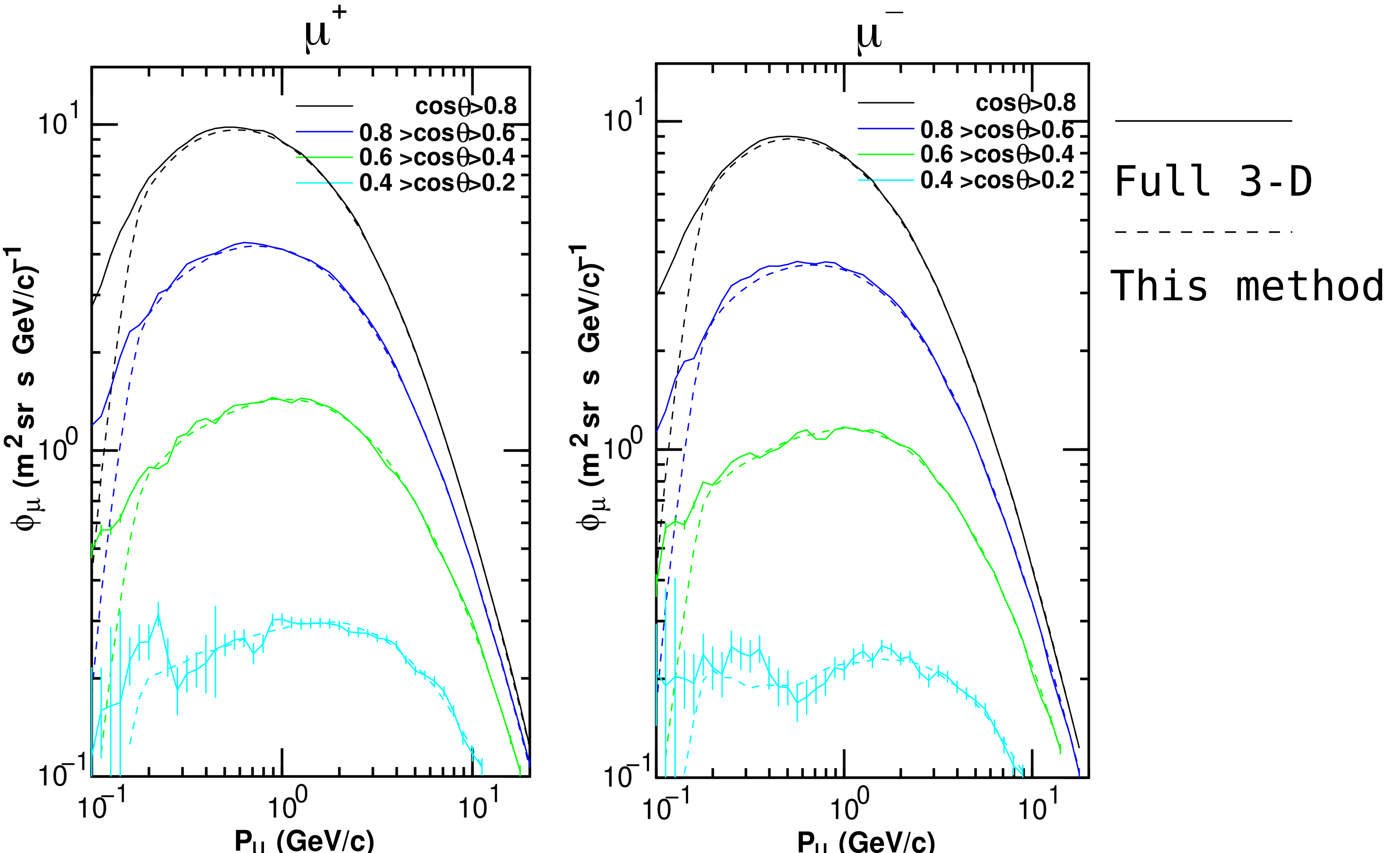
Low energy muon flux is a "local quantity"

$\gamma c\tau \sim$ 60km for 10 GeV muons
$\sim$ 0.5 degree in the angle
at the center of the earth



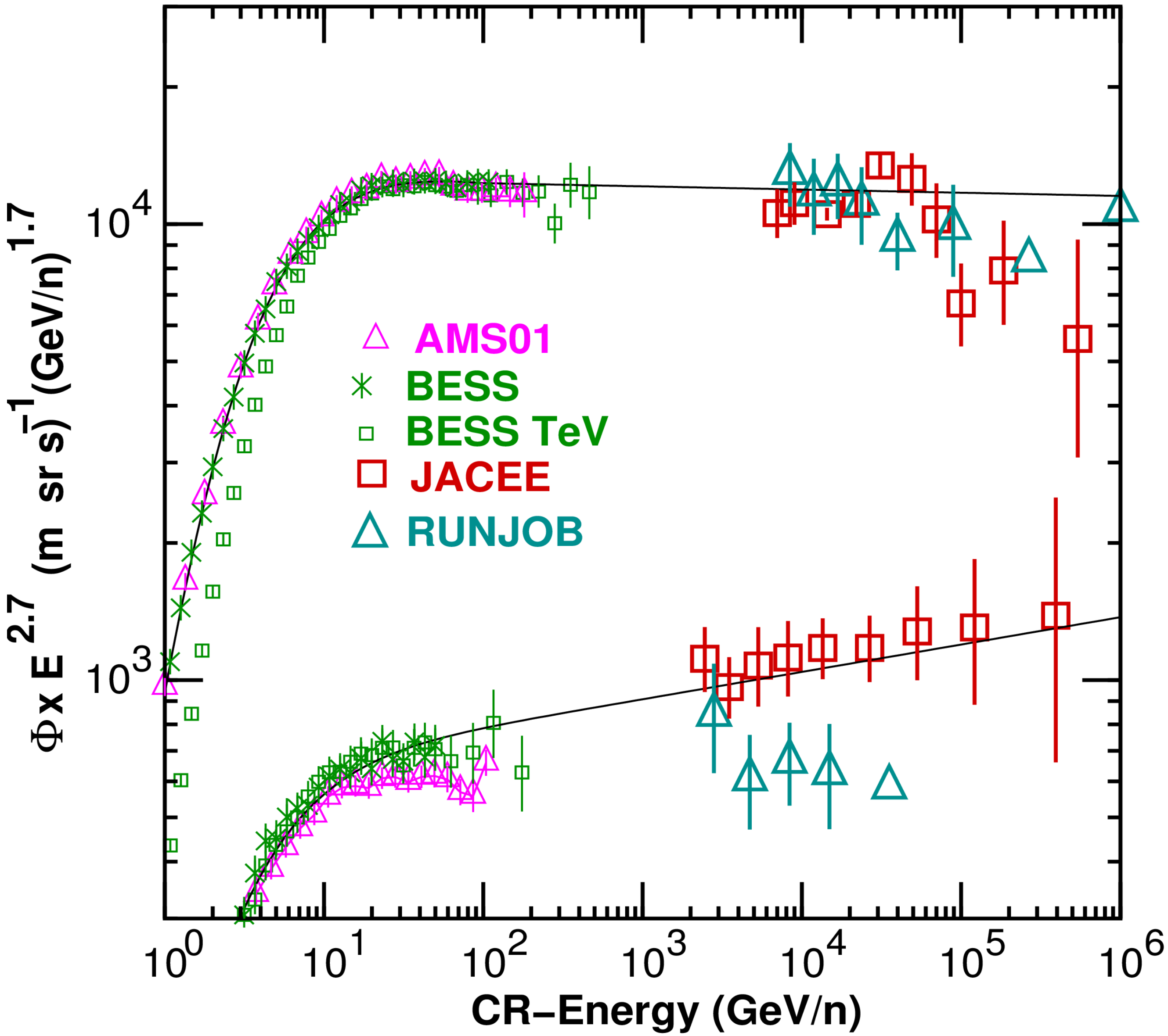
Therefore, calculation of muon flux is very fast.

Comparison with full 3-D calculation



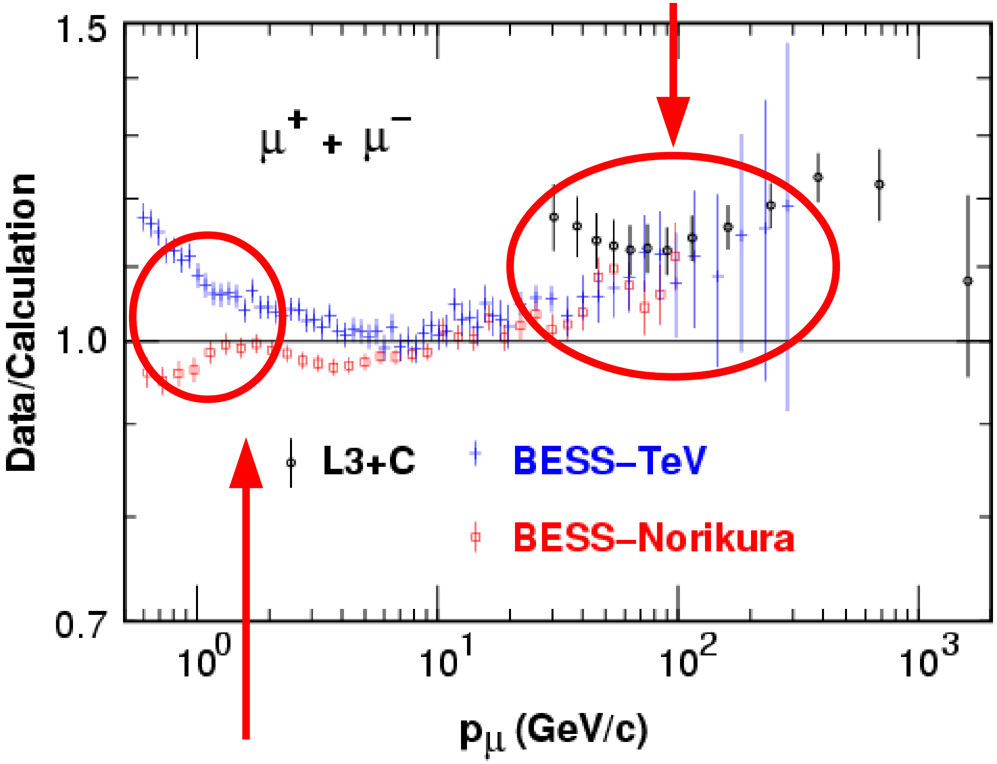
This method seems to be OK above 0.2 GeV.
But, one must be careful to use this method for the low energy region and horizontal directions.

Flux Model in 2004

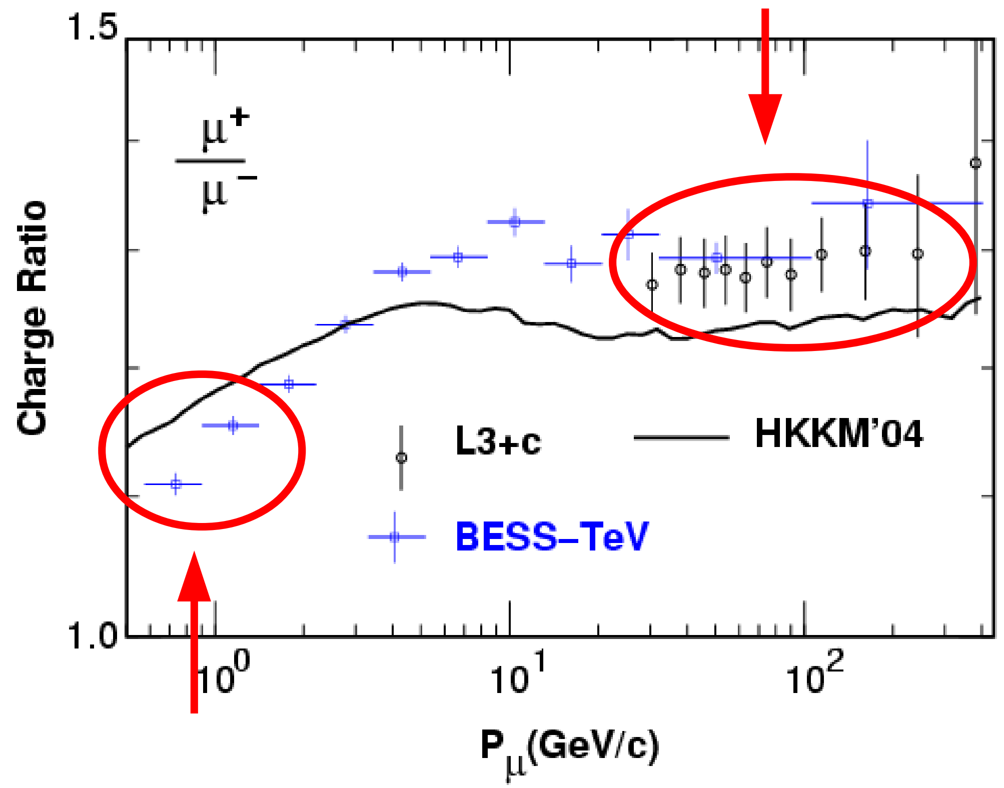


Comparison with precision muon measurements

Data are larger by ~15%



Data are larger by ~0.05



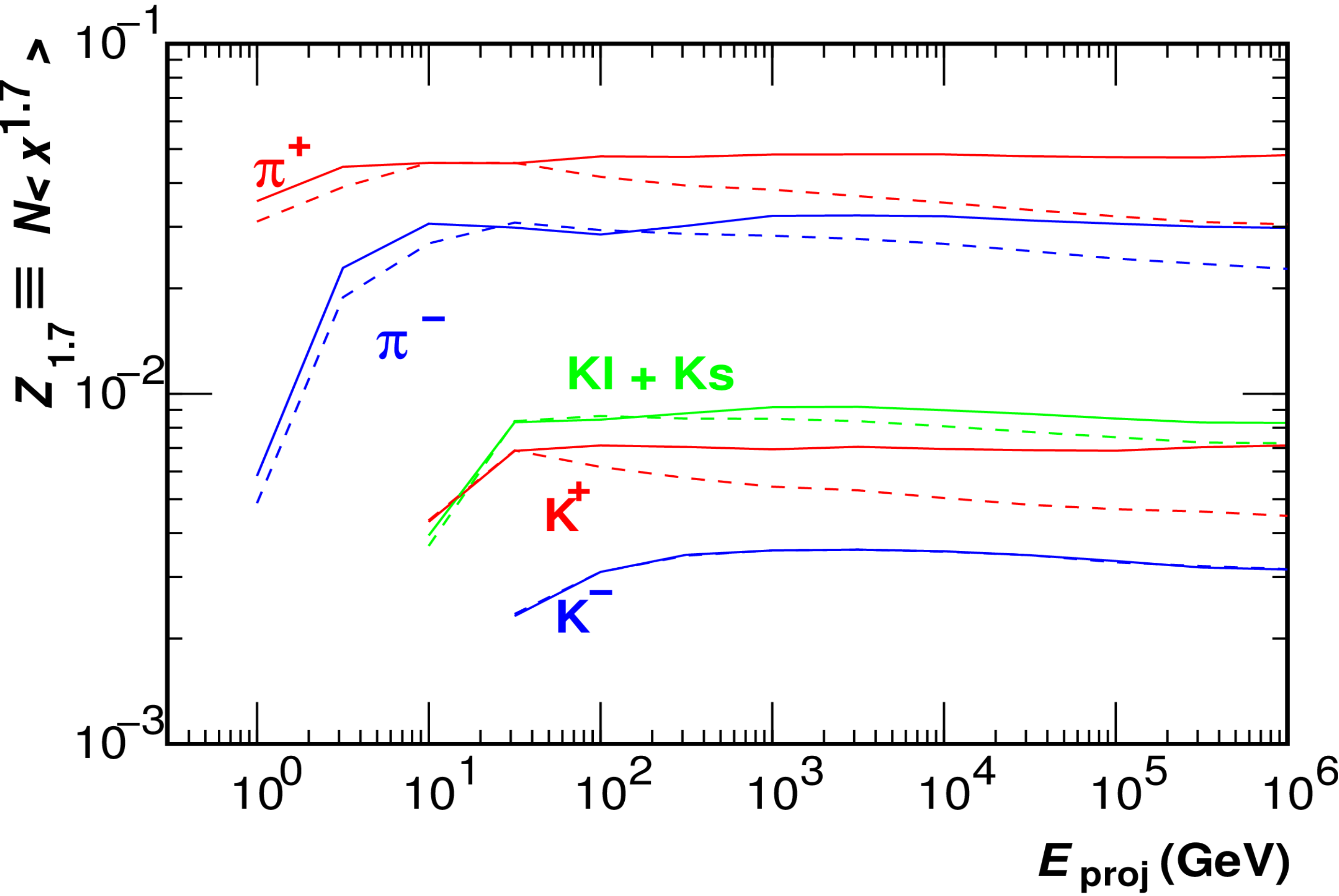
~15% scatter ?

Data are smaller by ~0.05

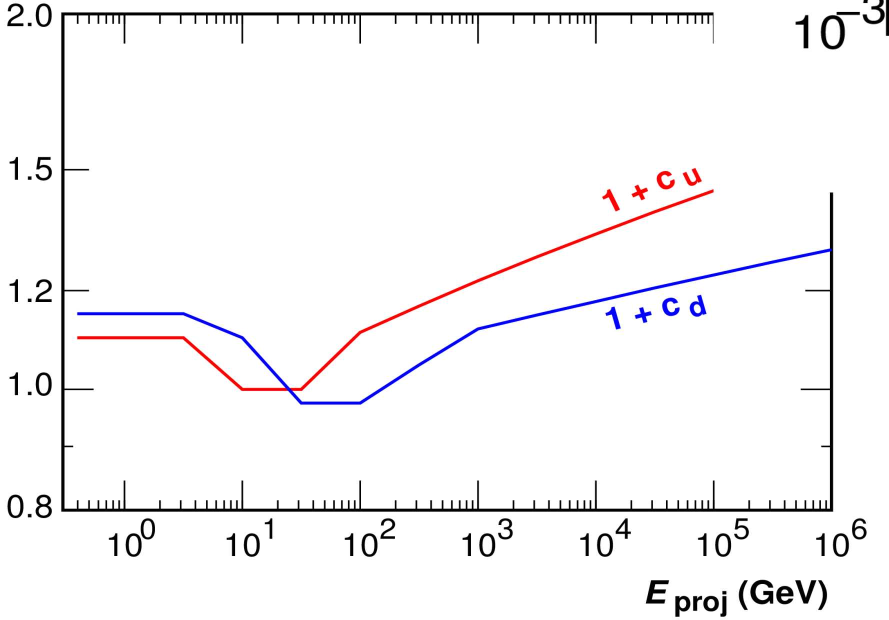
==> DPMJET-III Should be Modified

Modification of Int. Model (SHKKM 2006)

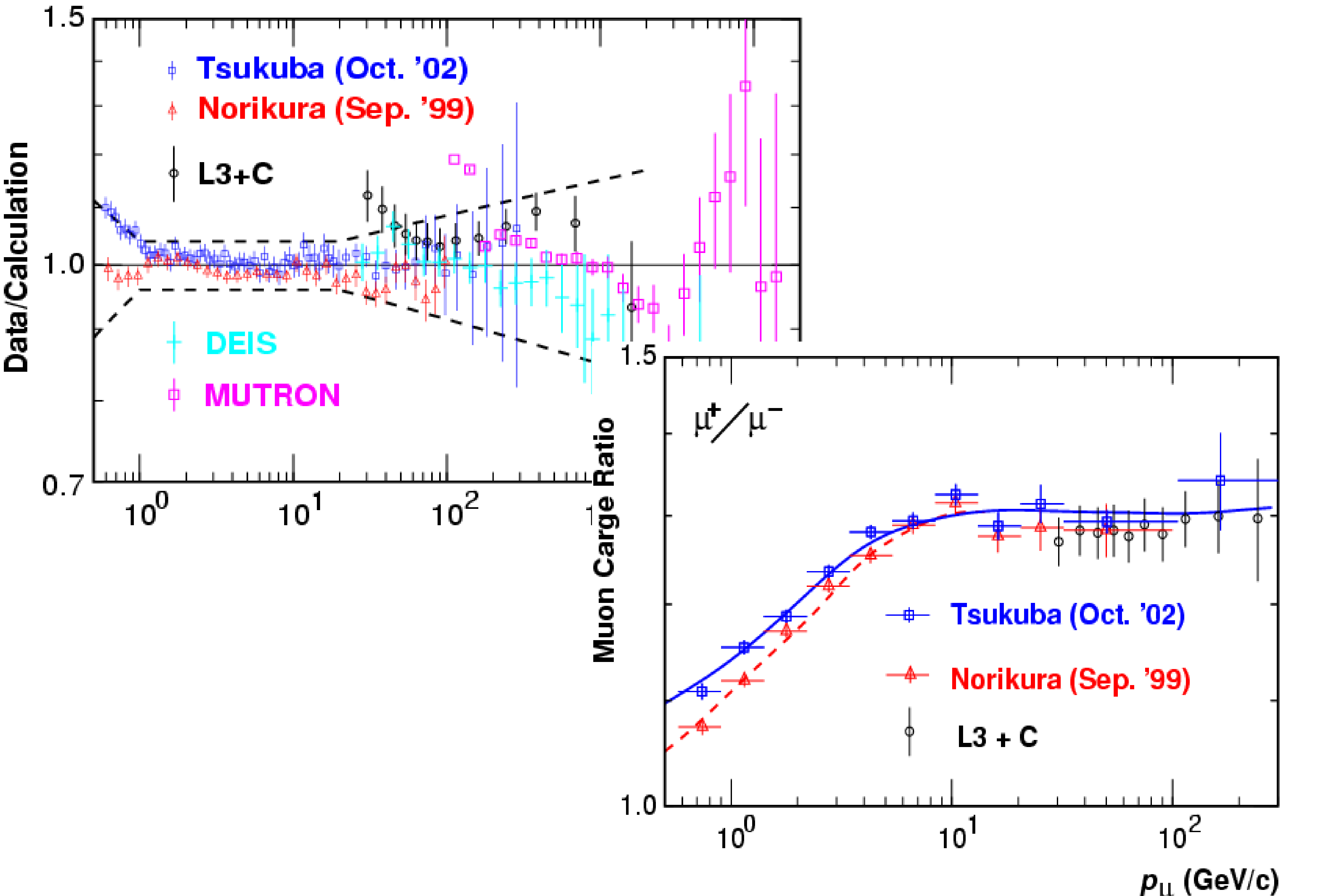
Z-Factor



Modification parameter

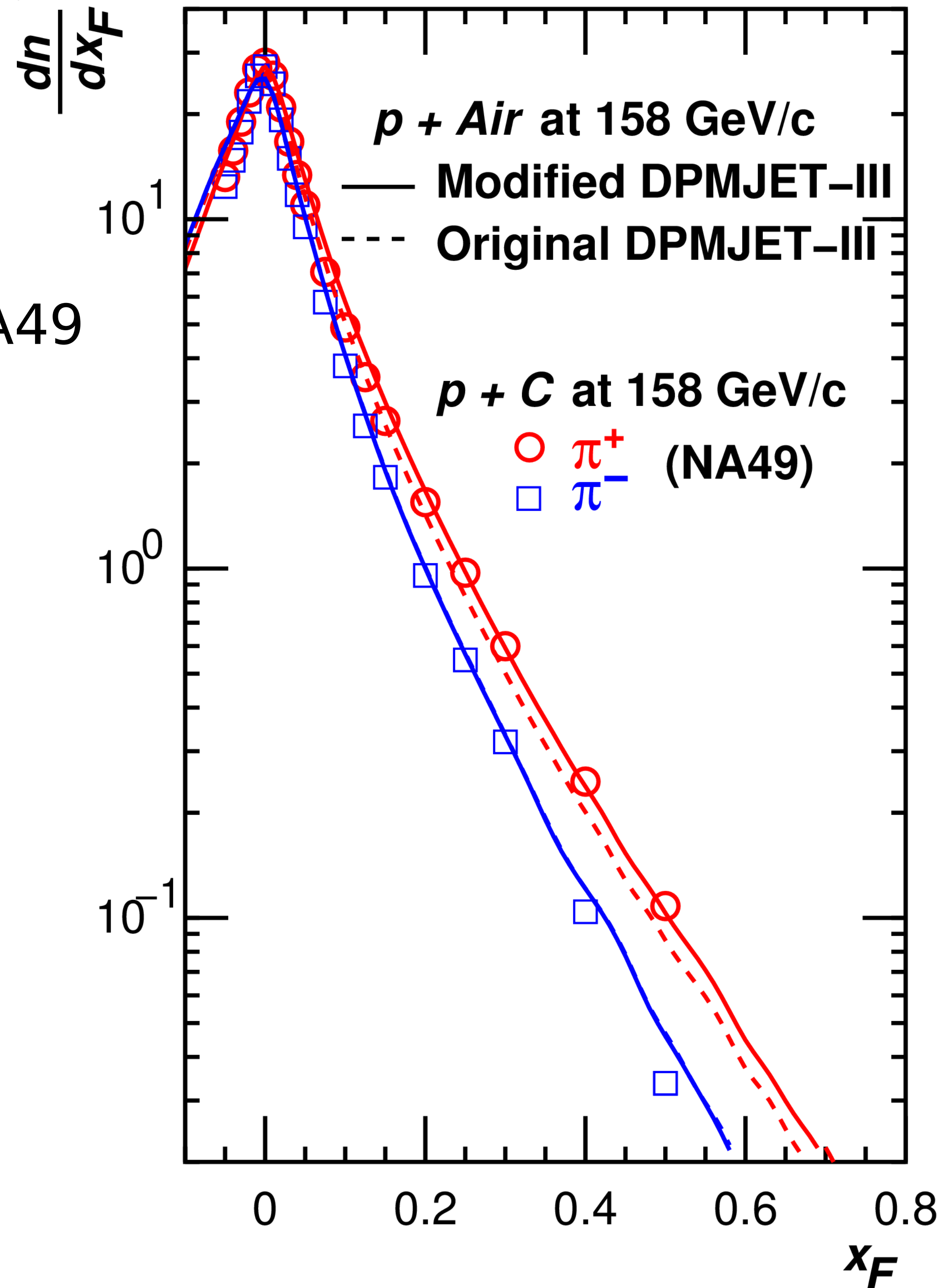


Comparison AFTER the modification

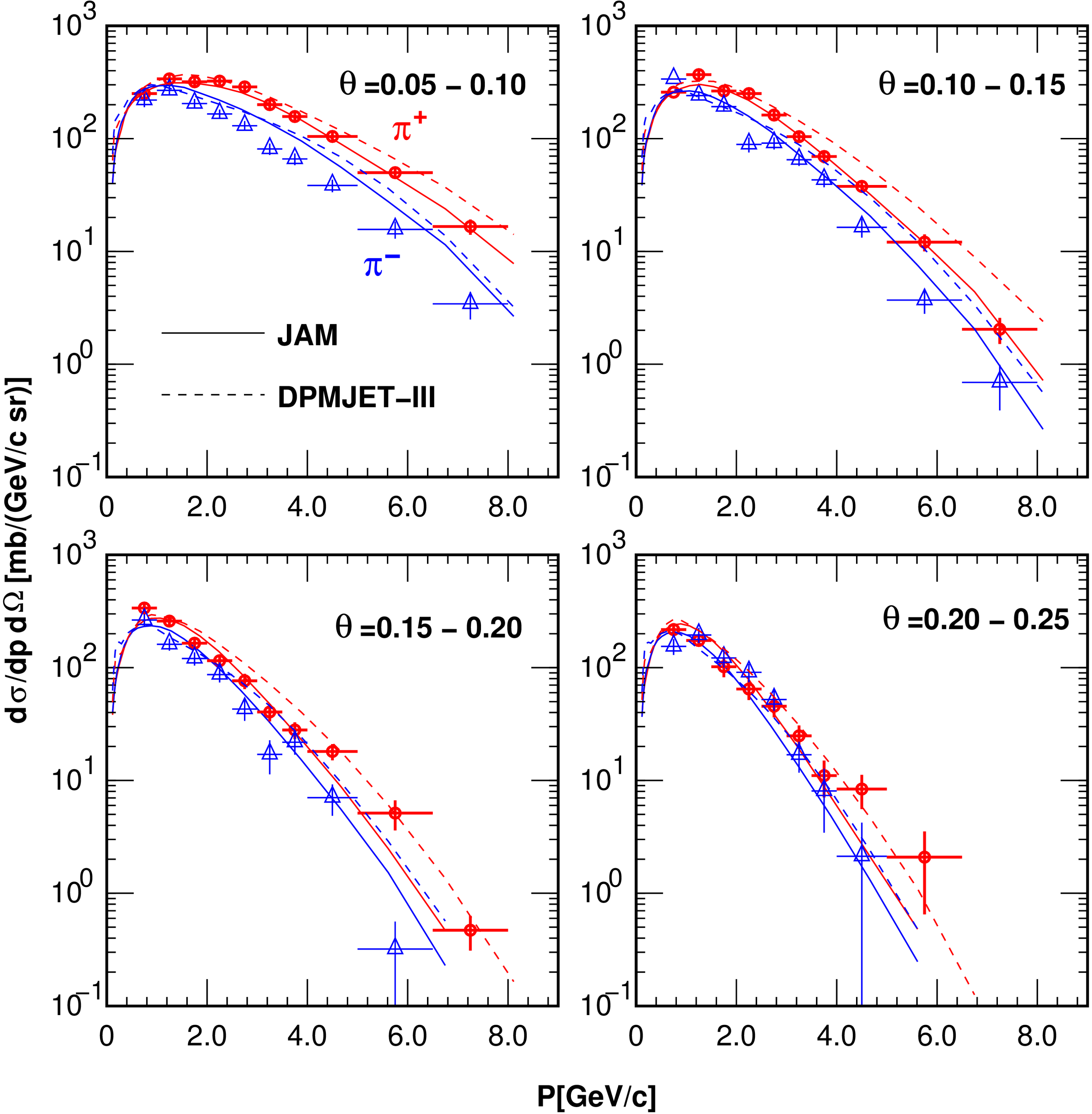


Comparison with Accelerator data

Modified DPMJET-III vs NA49

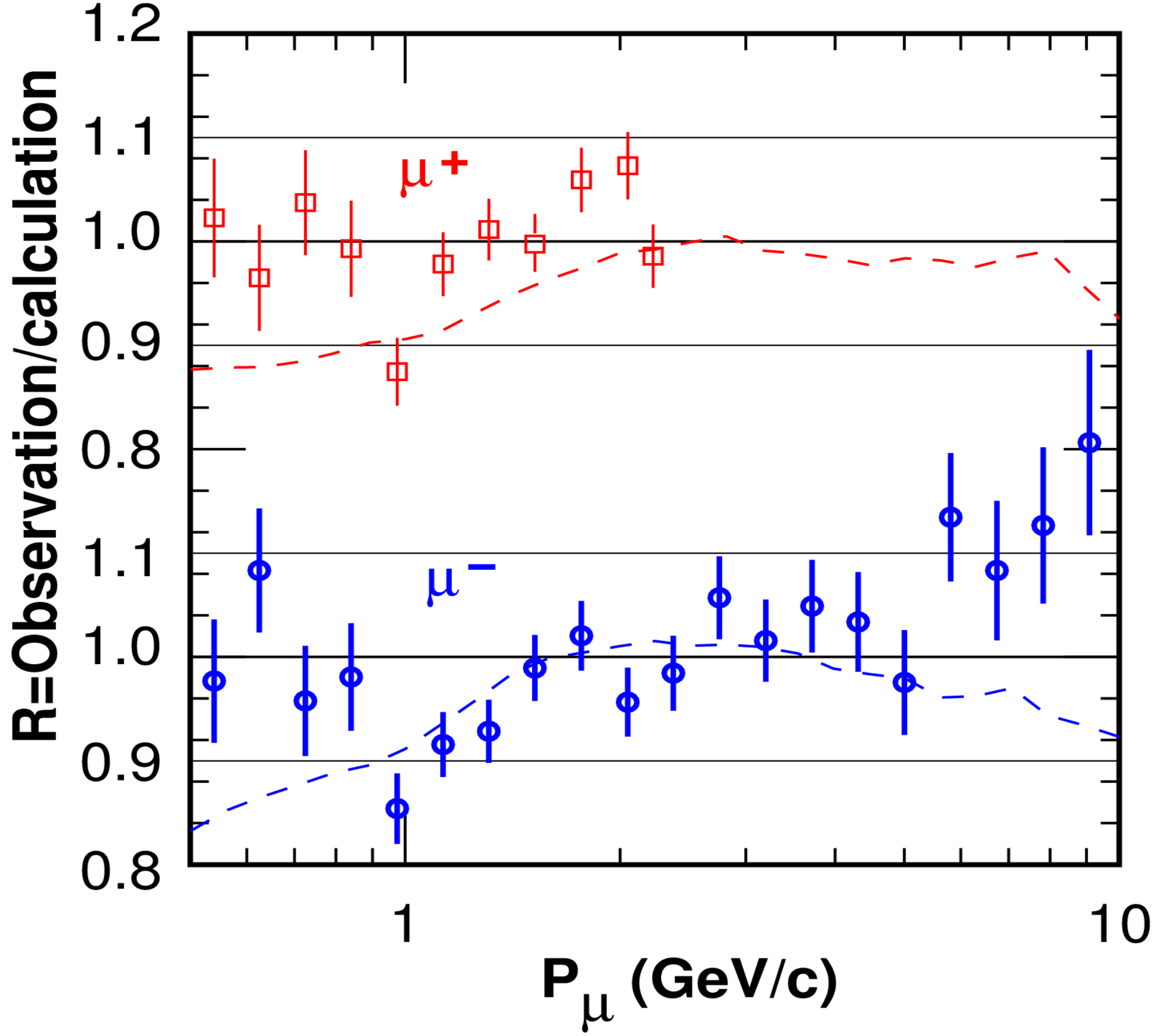


JAM vs HARP



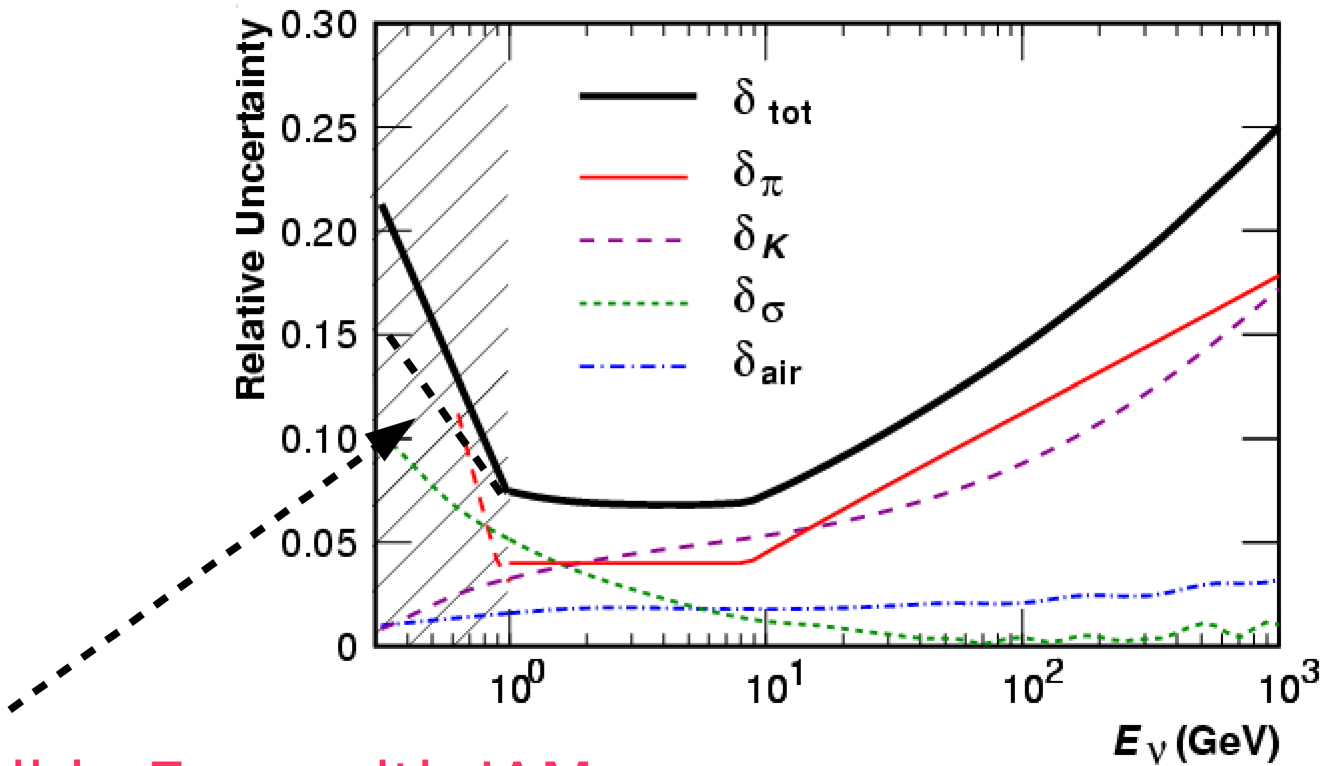
θ =0.05 – 0.10
π+
π−
JAM
DPMJET−III
θ =0.10 – 0.15
θ =0.15 – 0.20
θ =0.20 – 0.25
dσ/dp dΩ [mb/(GeV/c sr)]
P[GeV/c]

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



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

Possible Error in Atmospheric n-flux for HKKMS06



Possible Error with JAM (HKKM2011)

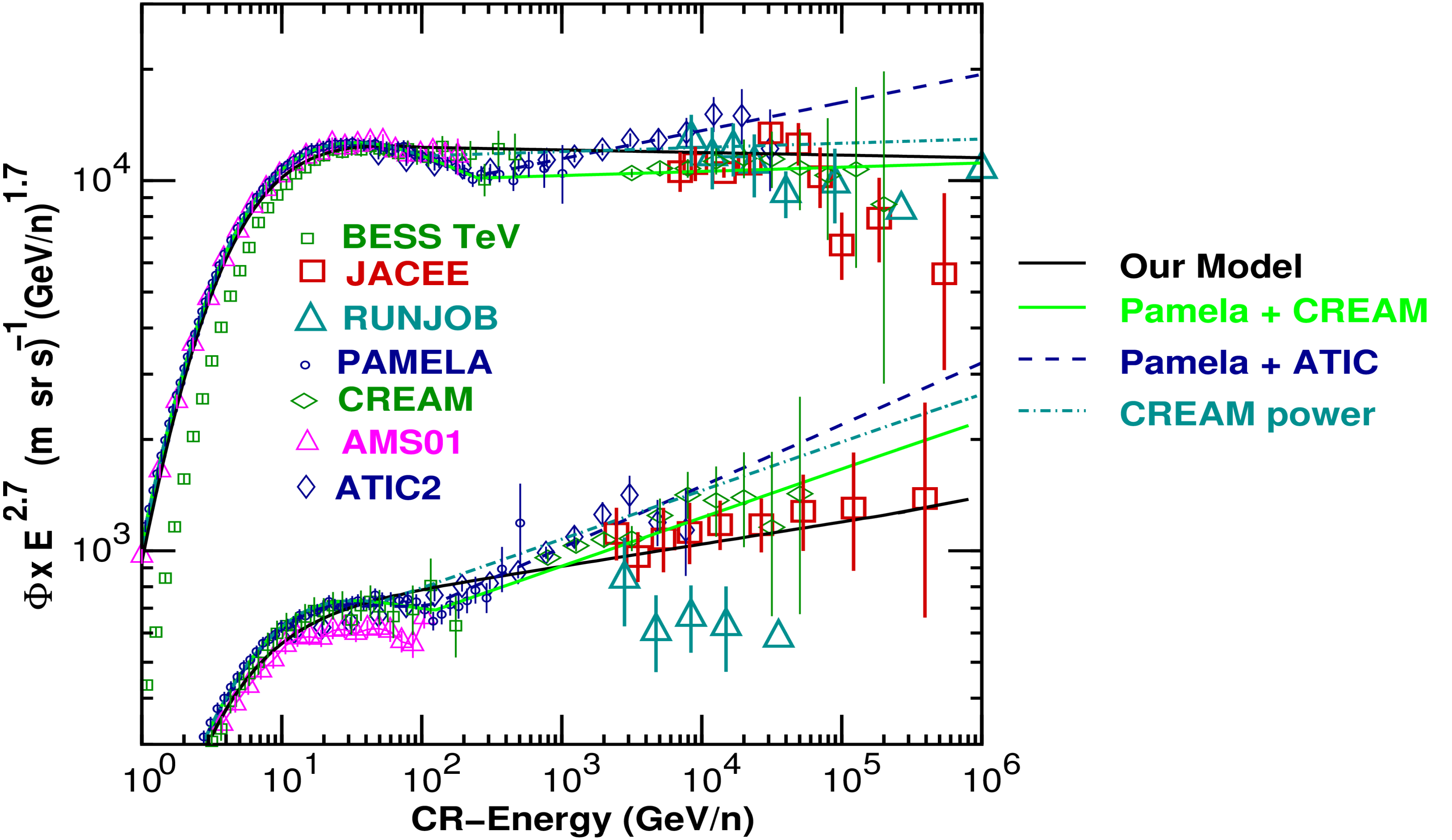
δ_π μ -observation error + Residual of reconstruction

δ_K Kaon production uncertainty

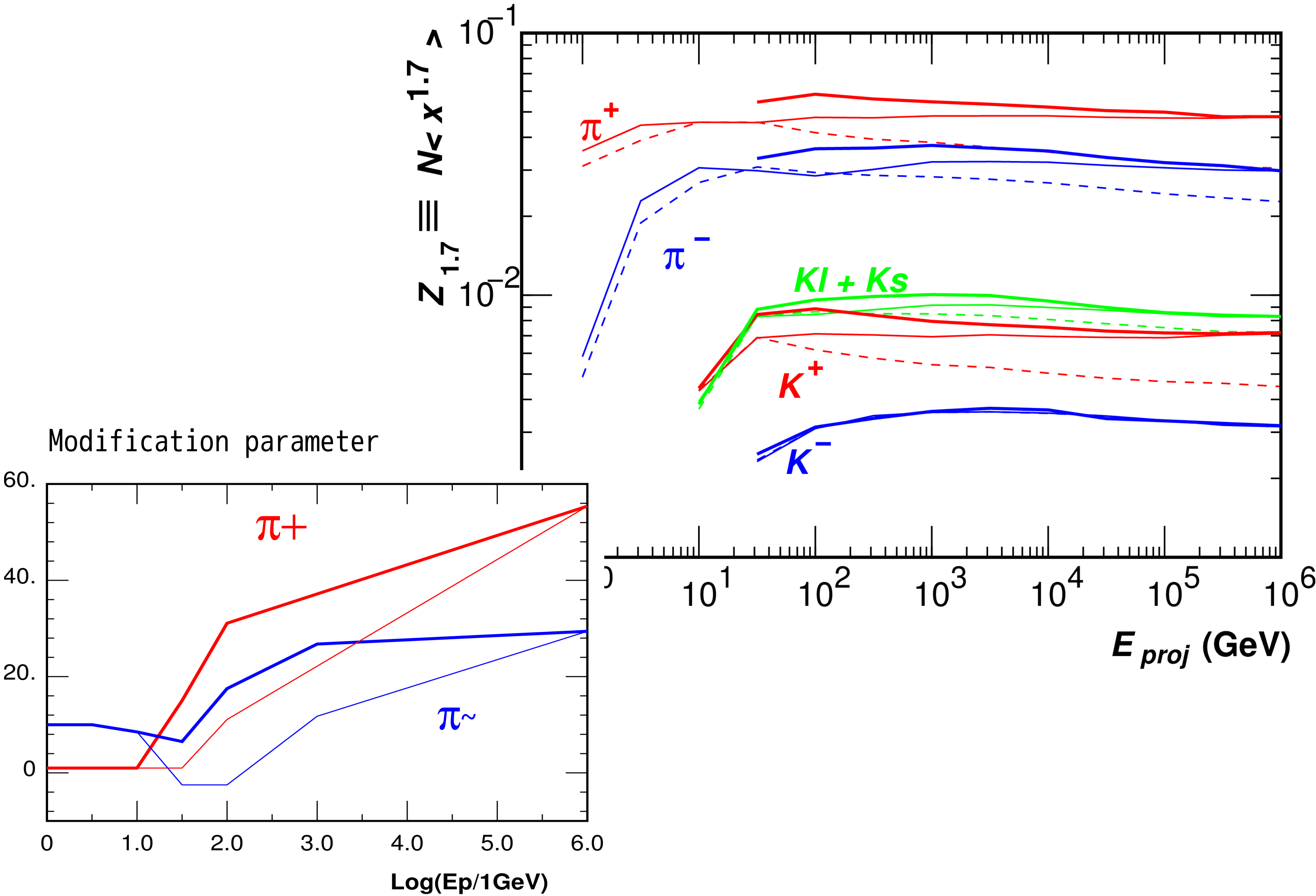
δ_σ Mean free path (interaction crossection) uncertaint

δ_{air} Atmosphere density profule uncertainty

Cosmic ray observations by Dec 2011 and the Models

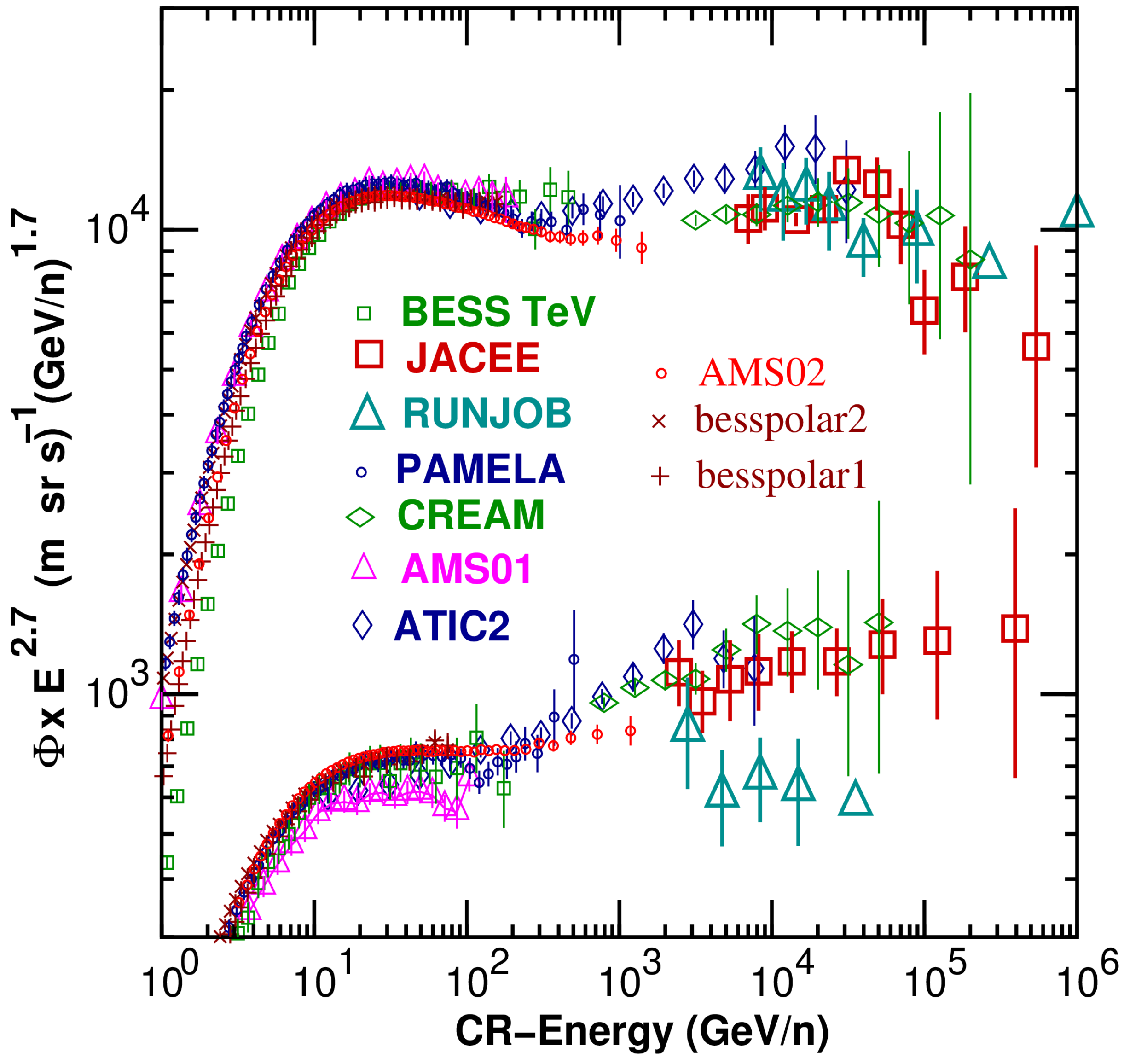


Modified Z-factor

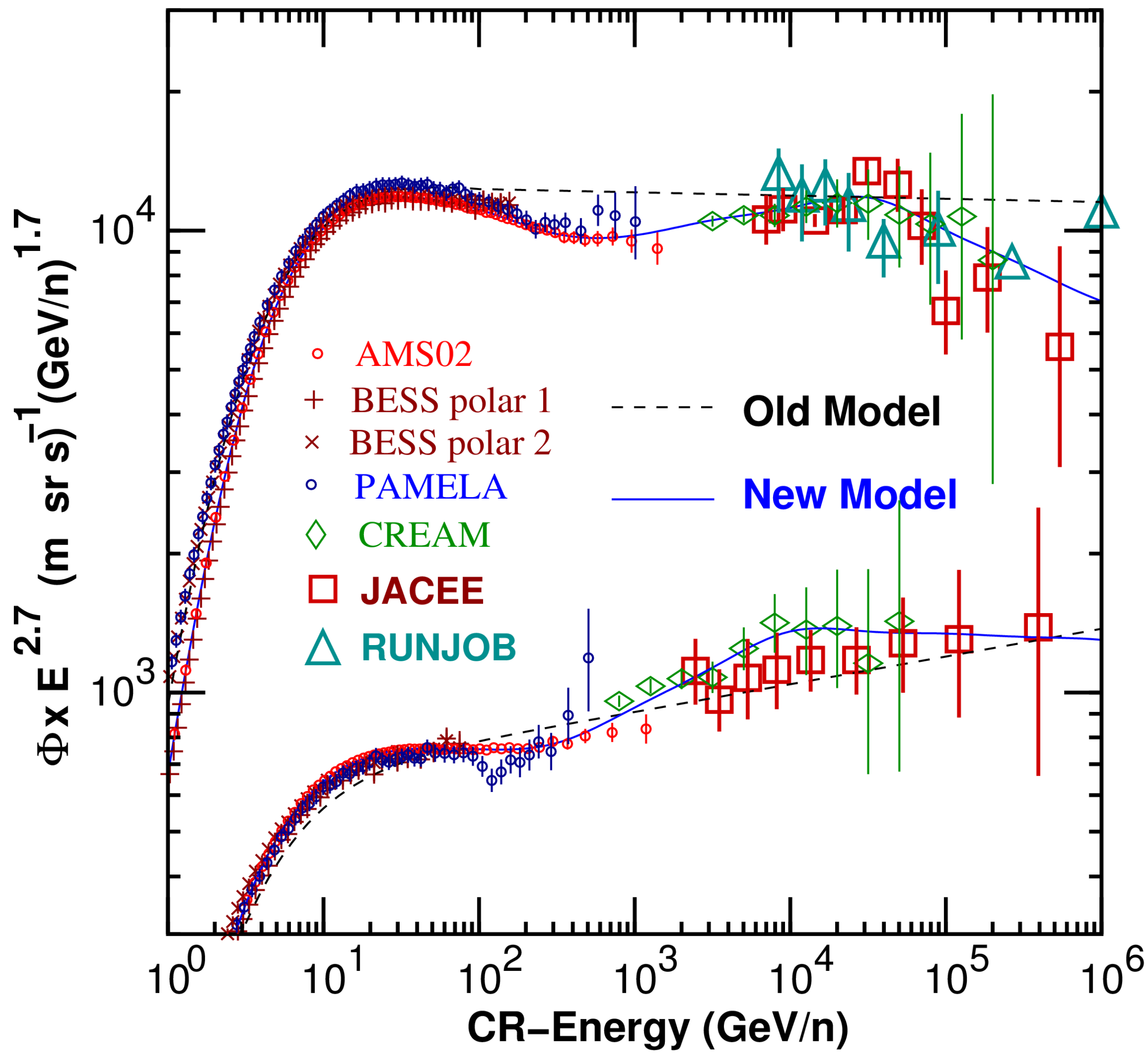


And AMS02 starts providing the data.

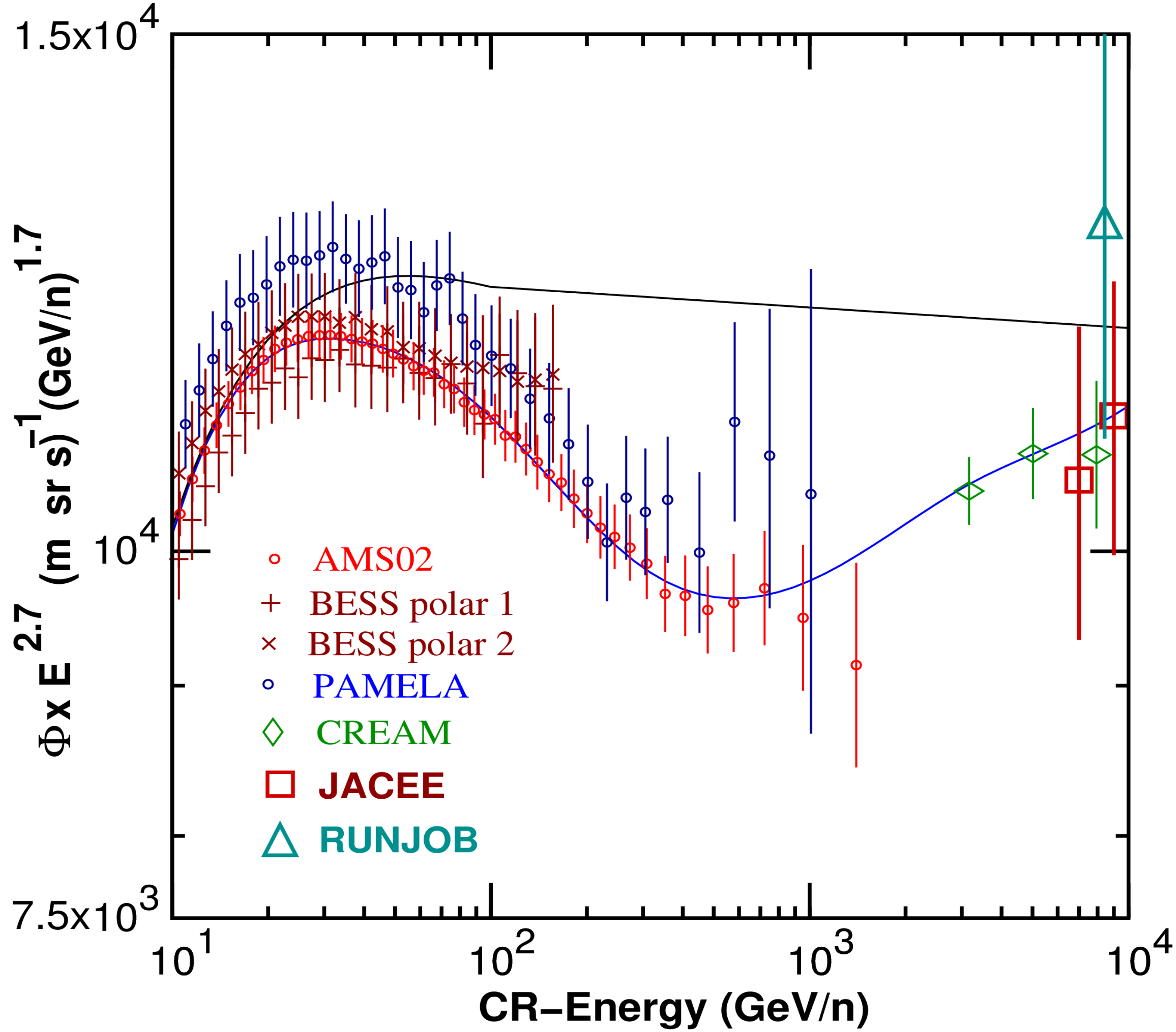
In 2015, AMS02 and Polar BESS joined



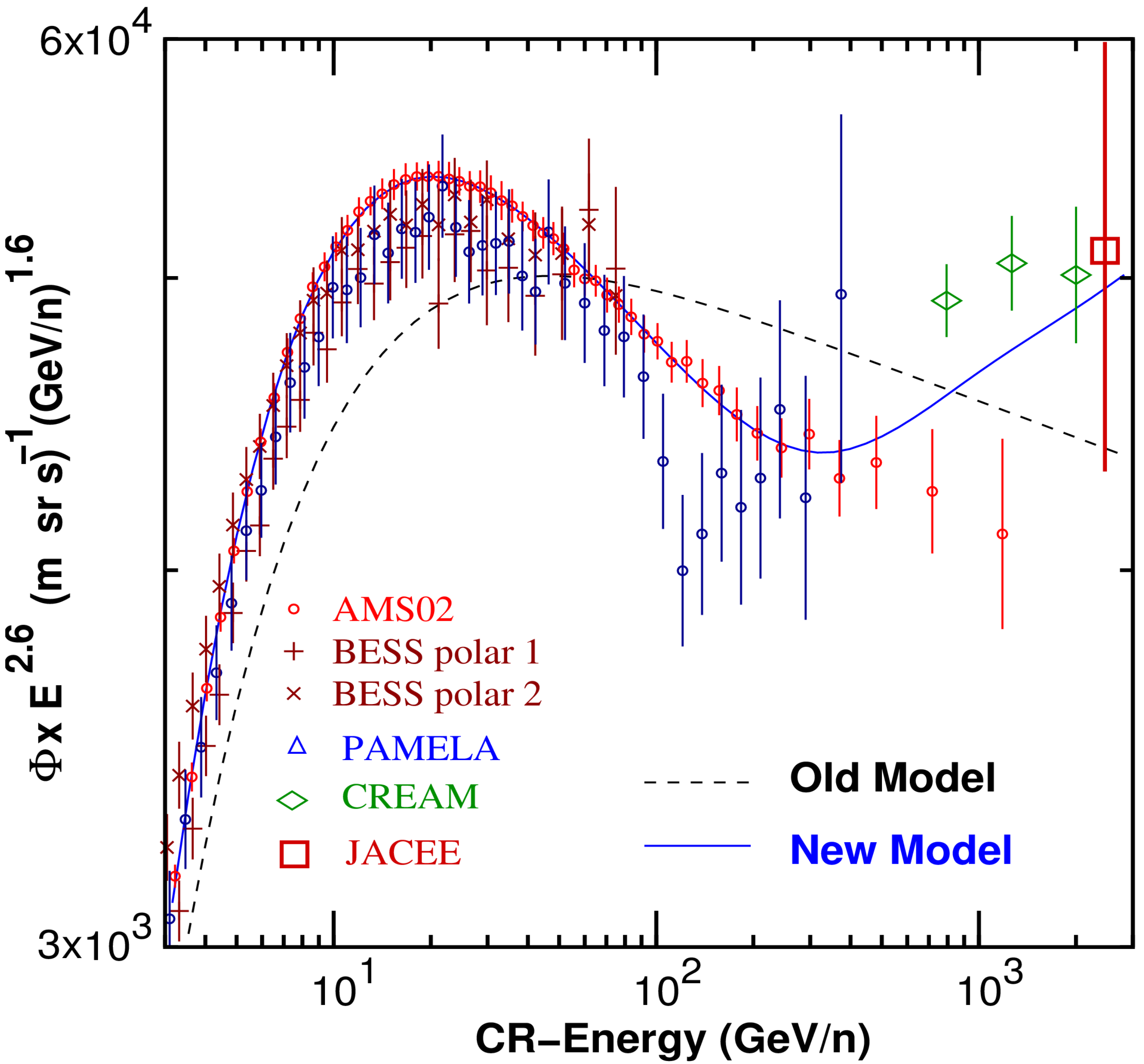
Cosmic ray spectra Model with AMS02 and Polar Bess



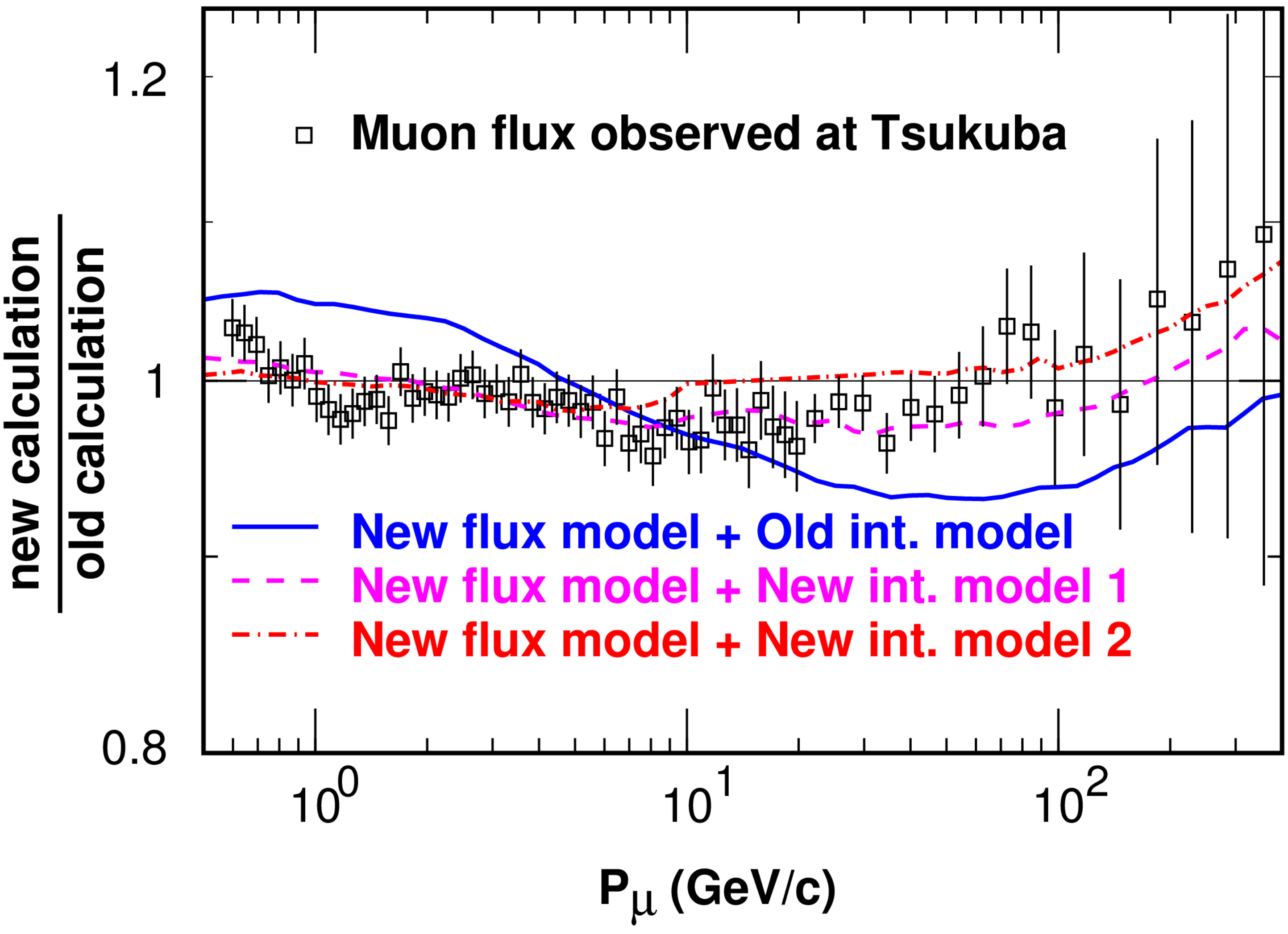
Close Up of Proton Cosmic Rays



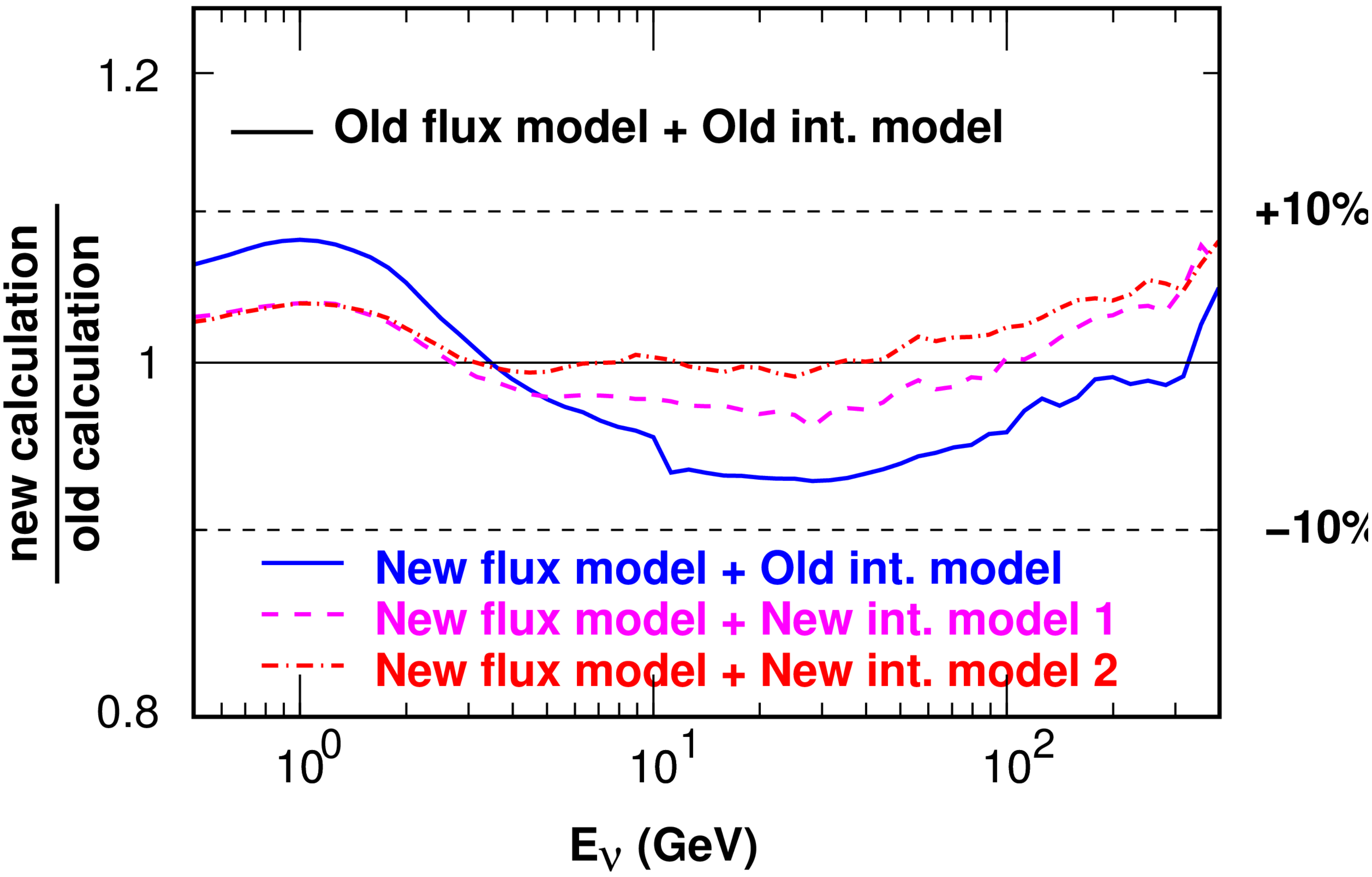
Close Up of Helium Cosmic Rays



Tuning of Interaction model with new cosmic ray model

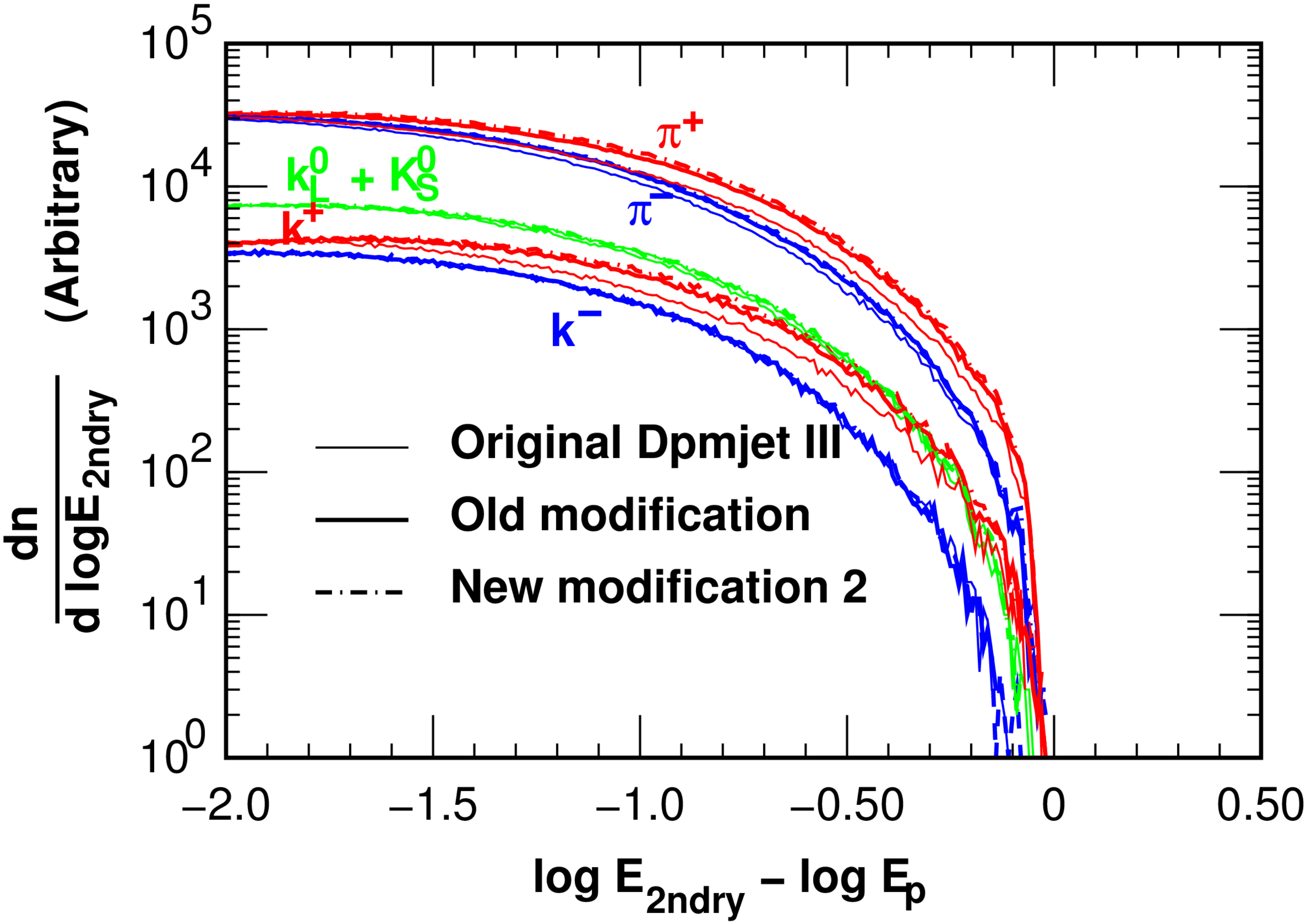


Resulting Neutrino Flux (all ν sum)

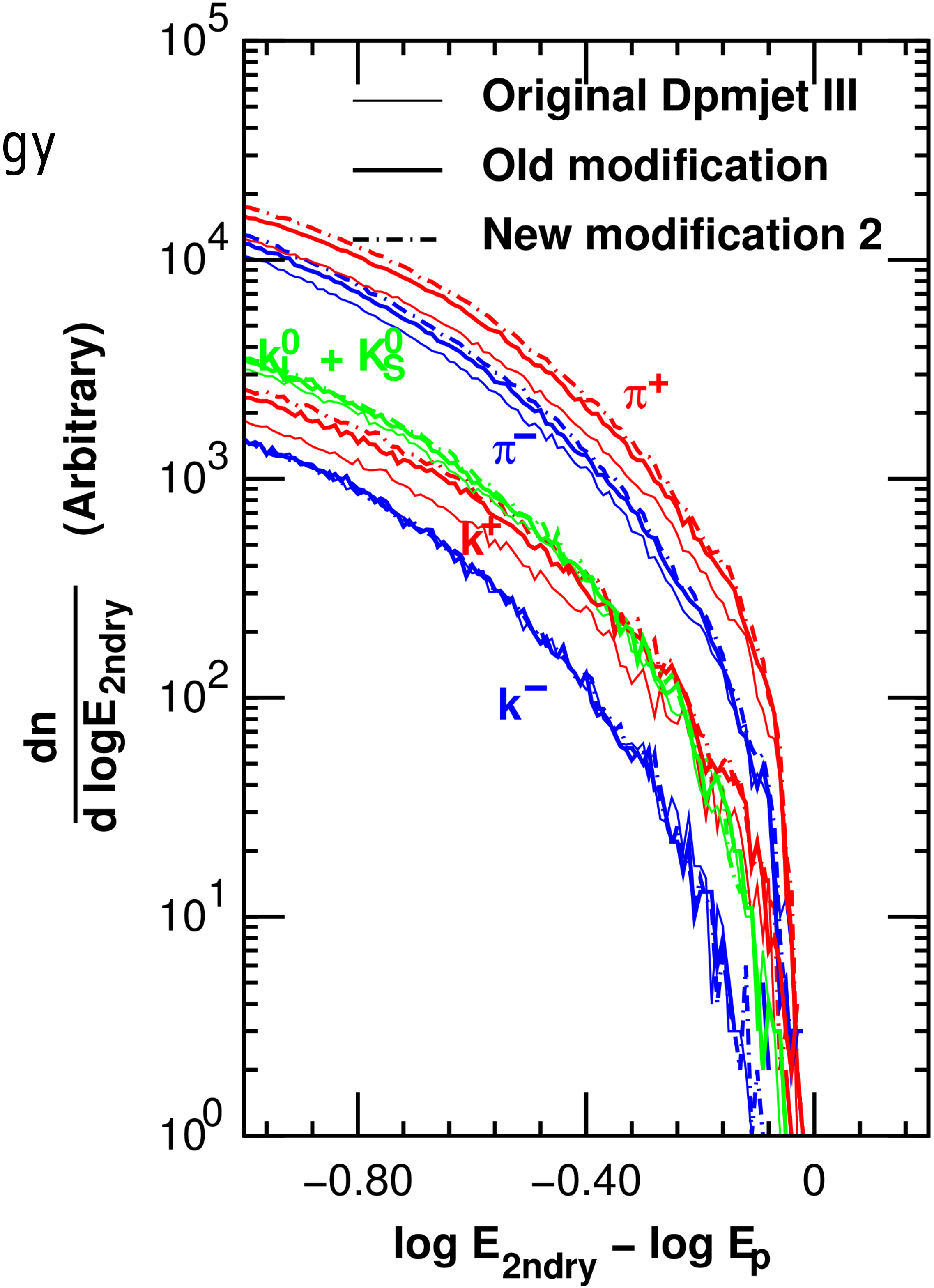


Muon Tuning works !

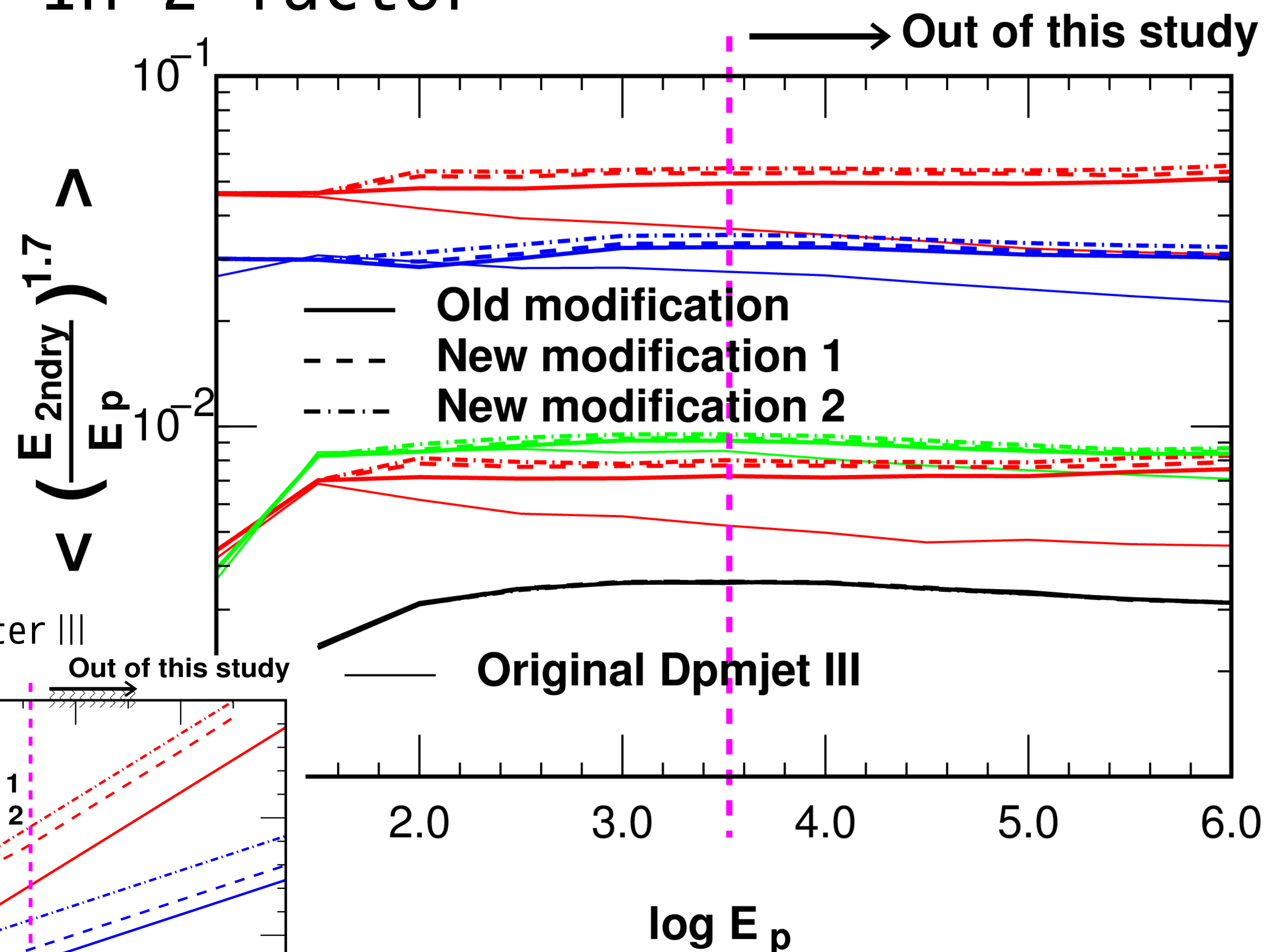
Comparison of secondary spectra at 1 TeV



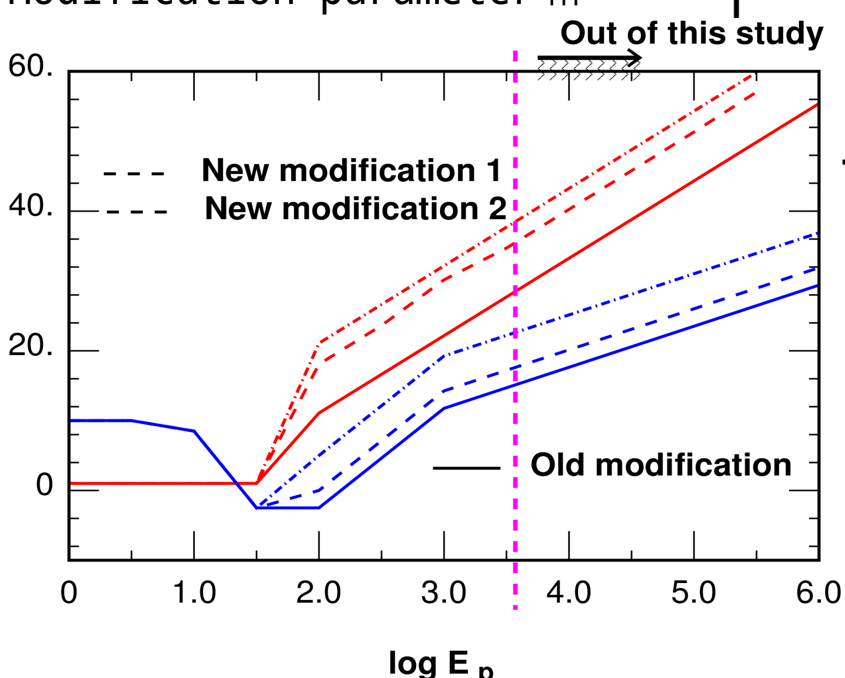
High secondary energy region close up



Comparison in Z-factor



Modification parameter III



Summary

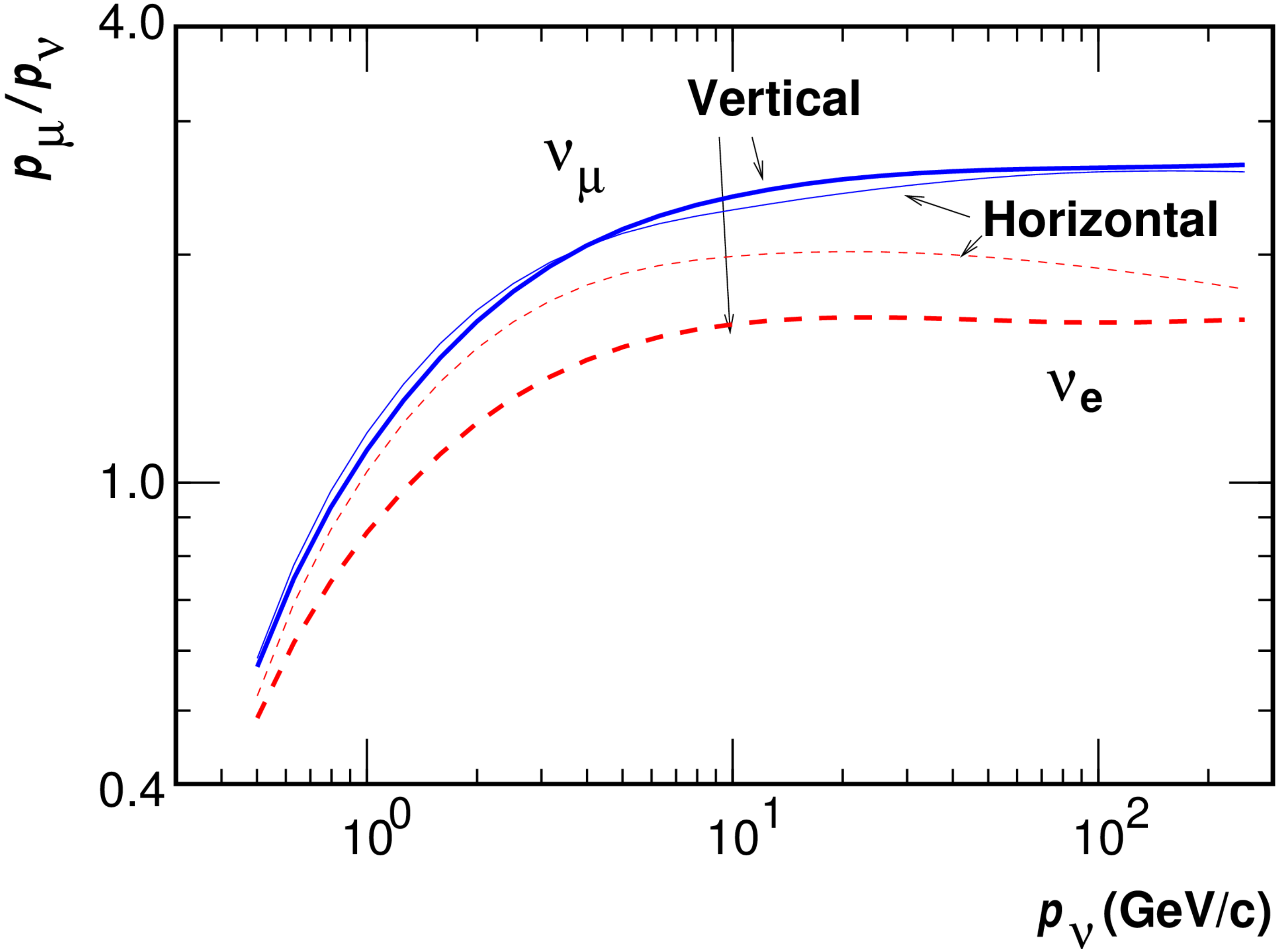
1. The calibration of the interaction model using the atmospheric muon flux seems to work well with the AMS02 and BESS polar measurements.

2, The change of atmosperic neutrino flux with new flux model is less than 10% with old interaction model.
But, with atmospheric muon flux calibration, the change is reduced well less than 5%.
The modification from old interaction model is not so large.

3. The reach of this study is just up to a few TeV, due to the lack of accurate cosmic ray data. => Future cosmic ray study.
Also, we need the knowledge of K/pi ratio at those energies.
=> RHIC (?)

Back up

Corresponding muon momemtum

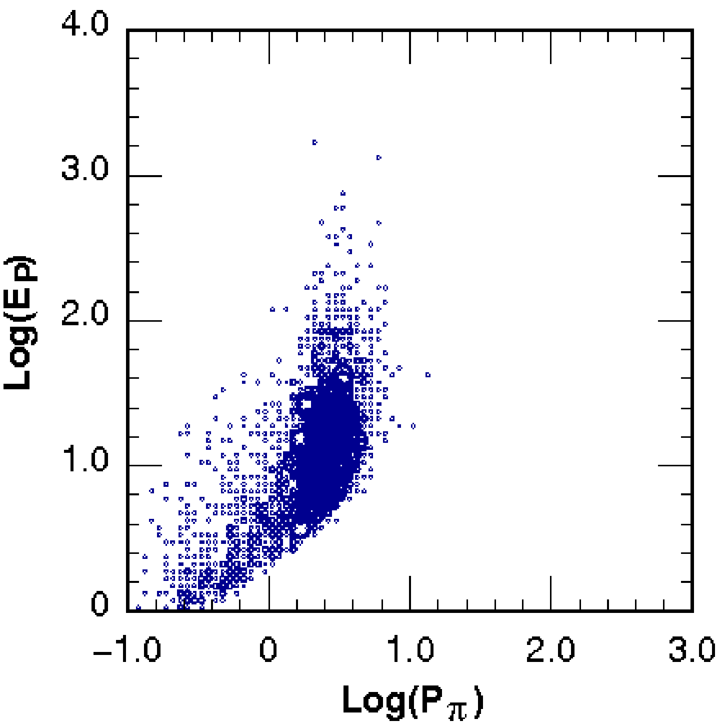


0.32 GeVのニュートリノに相関があるミューオンを作る

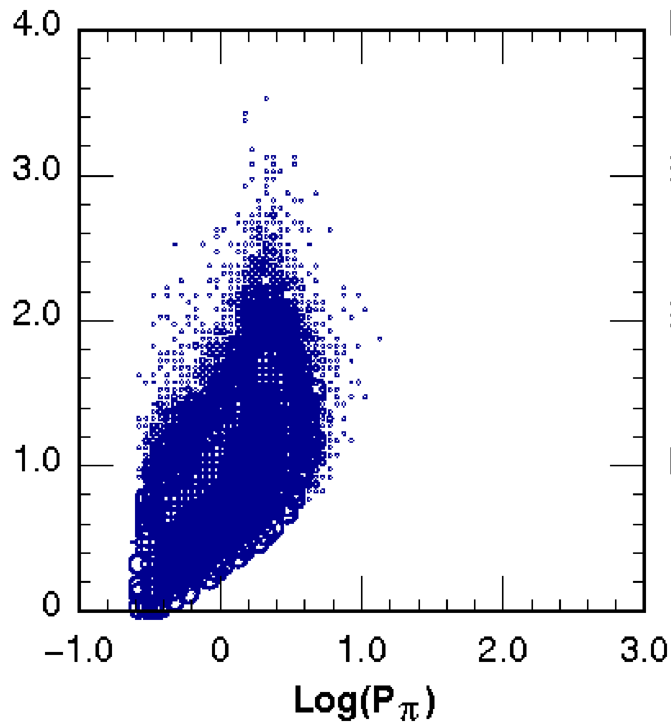
$$p+N(air)\rightarrow\pi+X$$

の*Phase Space*

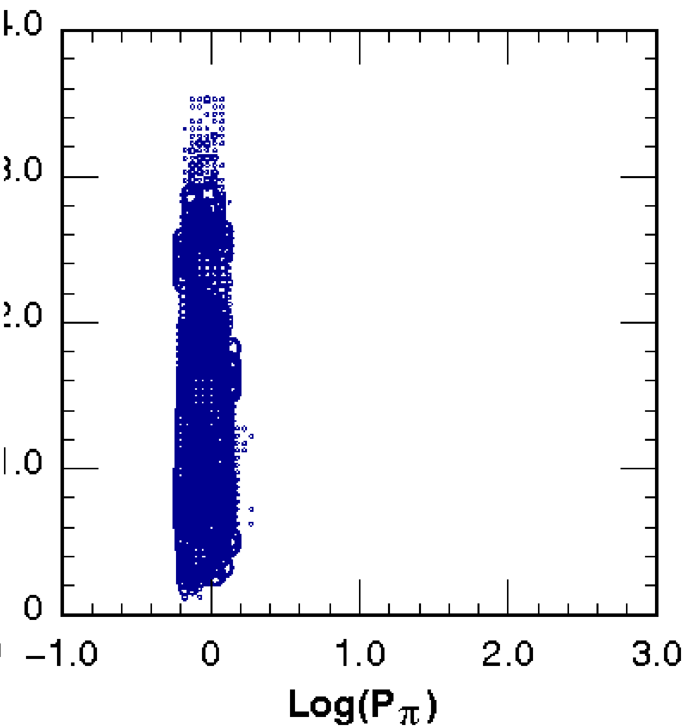
地上で観測されたμ



山(乗鞍)で観測されたμ



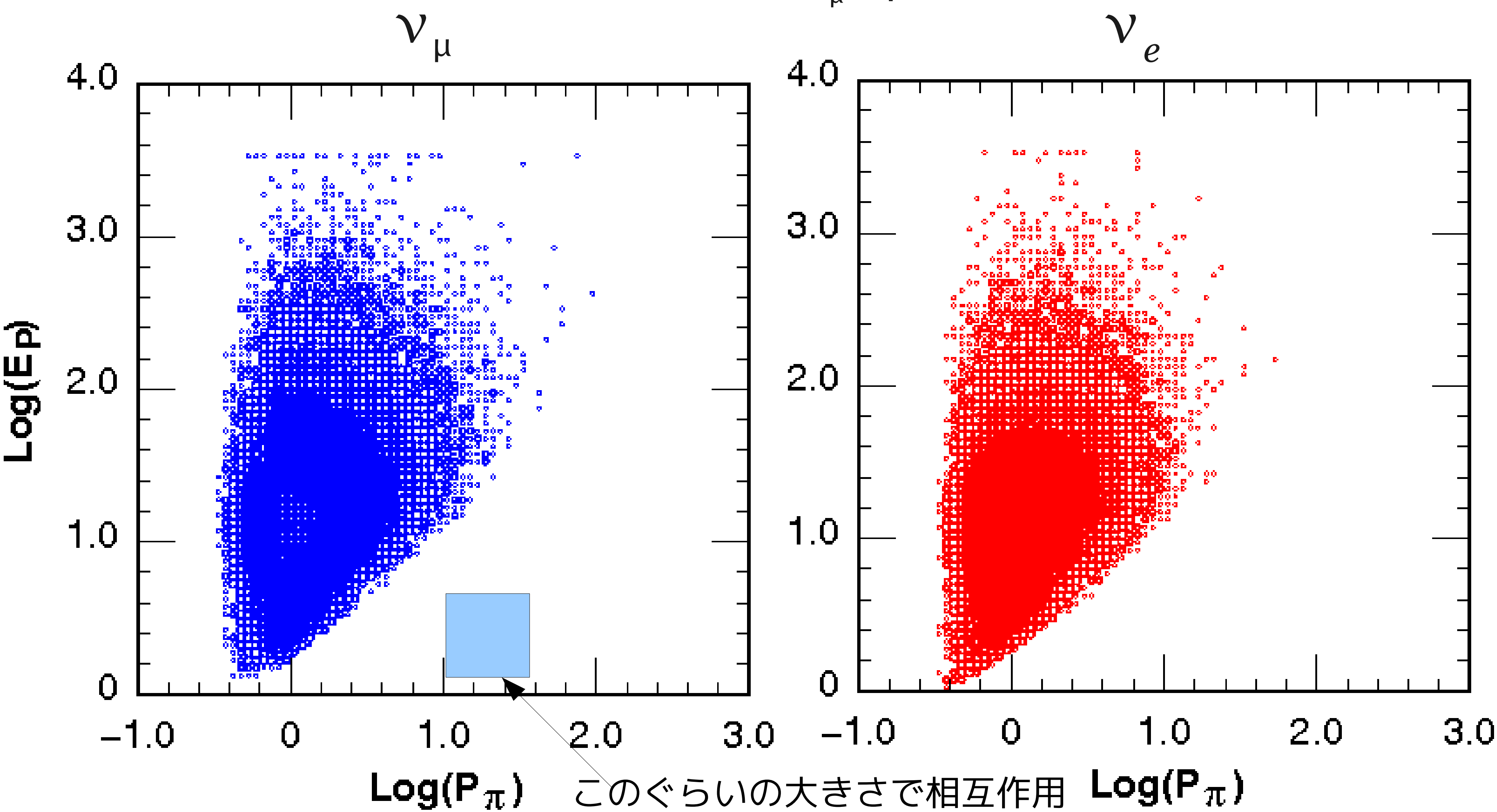
Balloon高度で観測されたμ



0.32 GeVのニュートリノに関わるPhase space

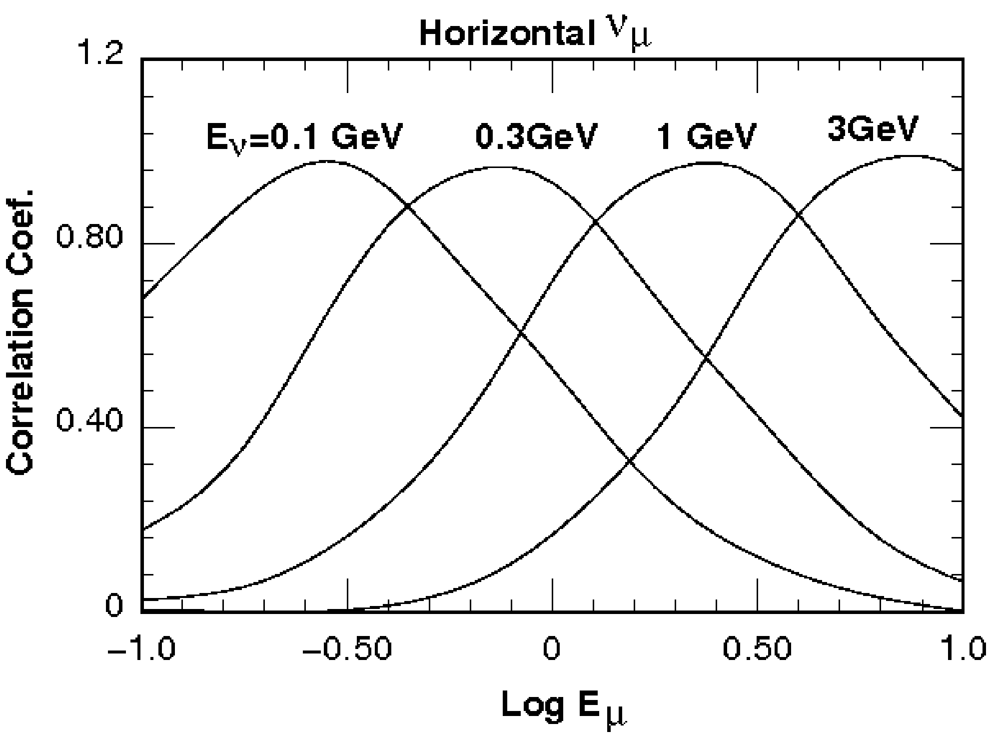
$$p + N(air) \rightarrow \pi + X$$

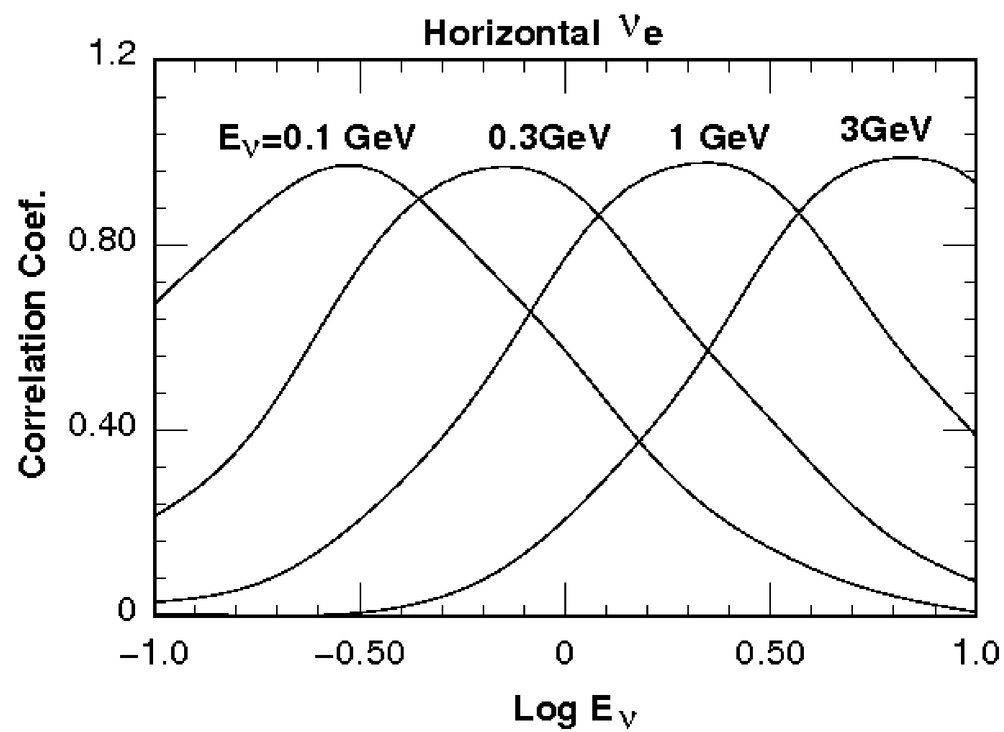
$$\pi \rightarrow \nu_\mu + \mu$$



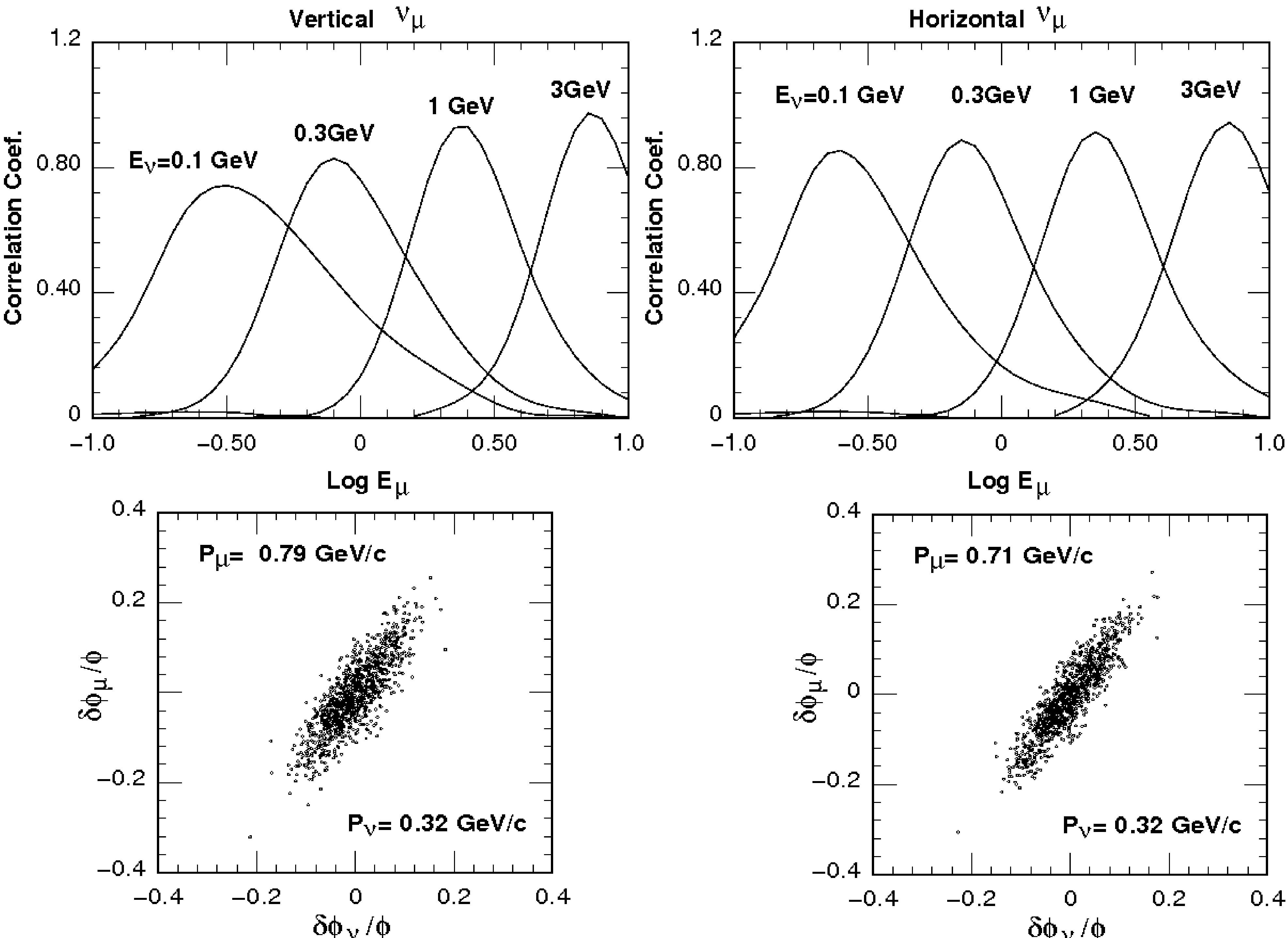
このぐらいの大きさで相互作用
が変した場合のμとνの変化

上空のμと水平方向νのフラックスの相関係数

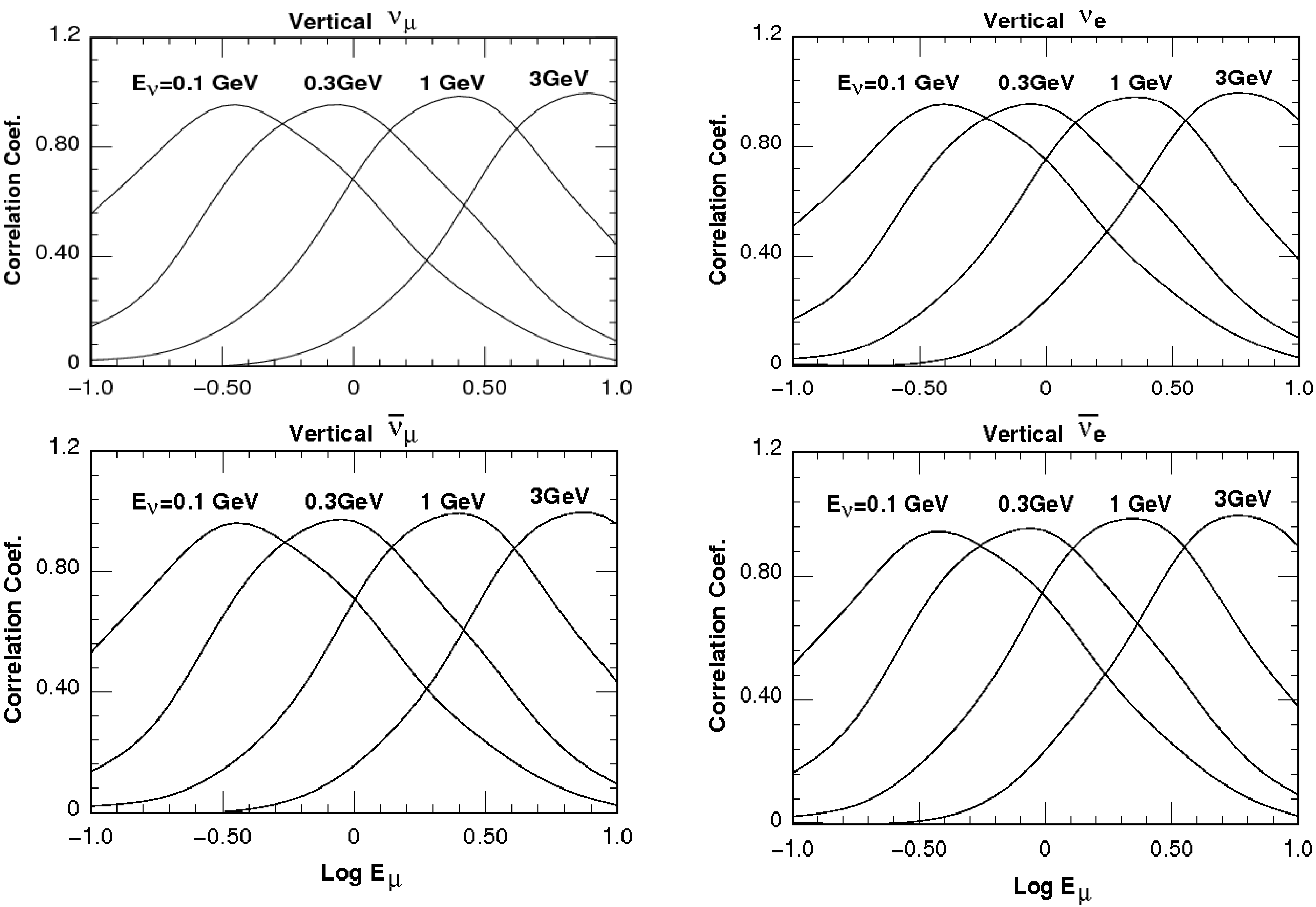




上空のμと垂直下向き方向νのフラックスの相関係数



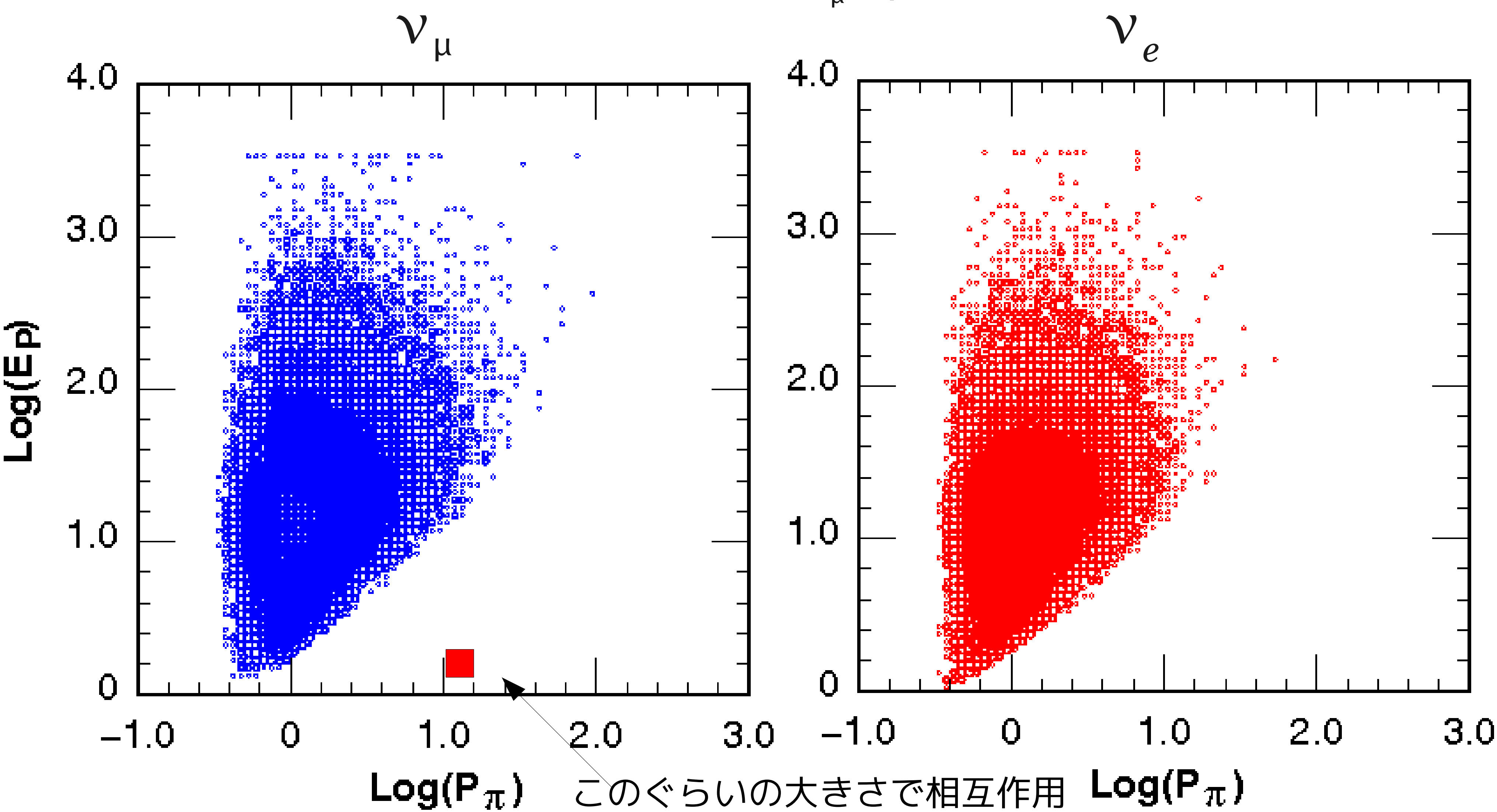
上空のμと垂直下向き方向νのフラックスの相関係数



0.32 GeVのニュートリノに関わるPhase space

$$p+N(air)\rightarrow \pi + X$$

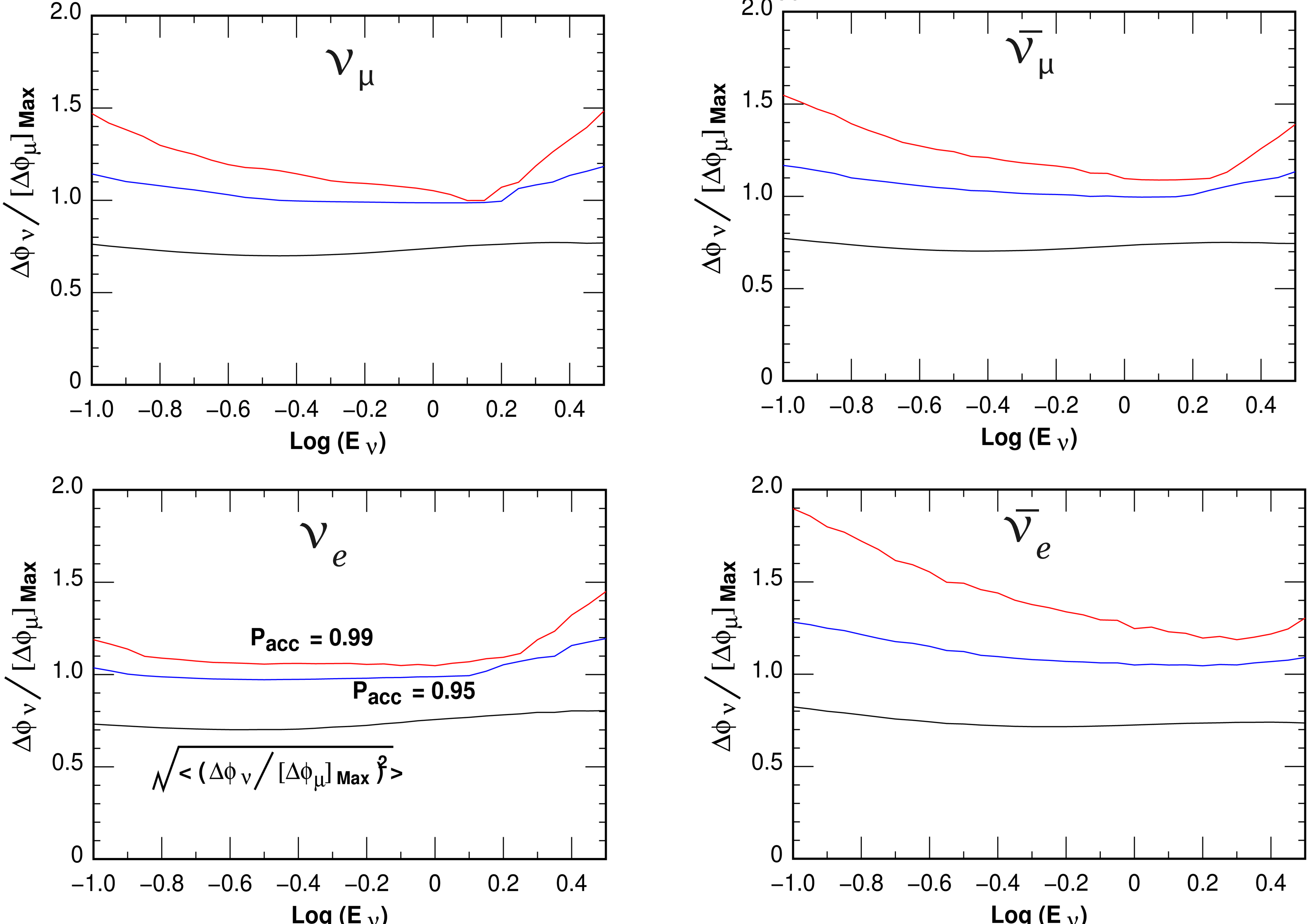
$$\pi \rightarrow \nu_\mu + \mu$$



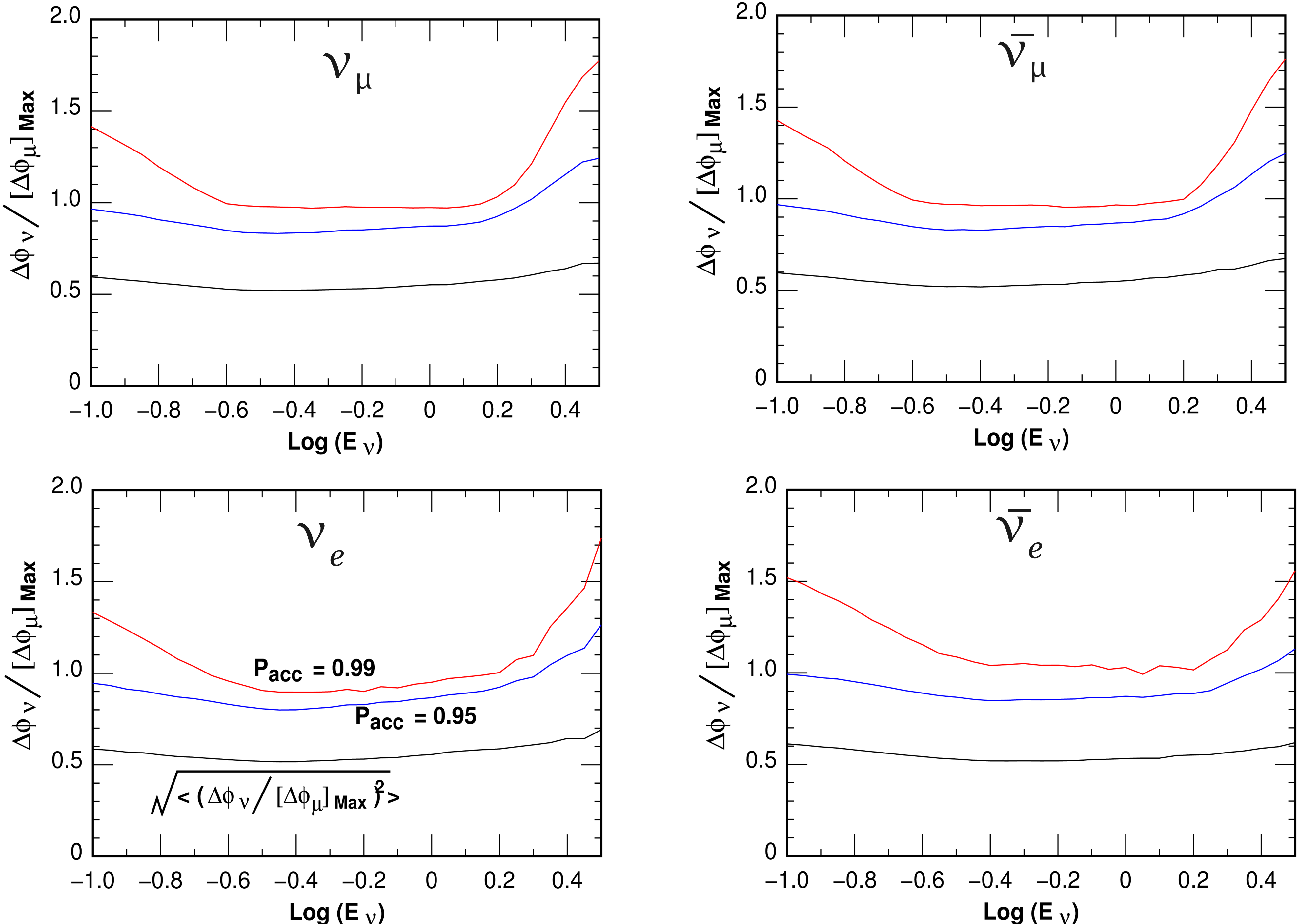
このぐらいの大きさで相互作用
が変した場合のμとνの変化

Accumulation probability(0.95, 0.09)と標準偏差

垂直下向き(variation type2)

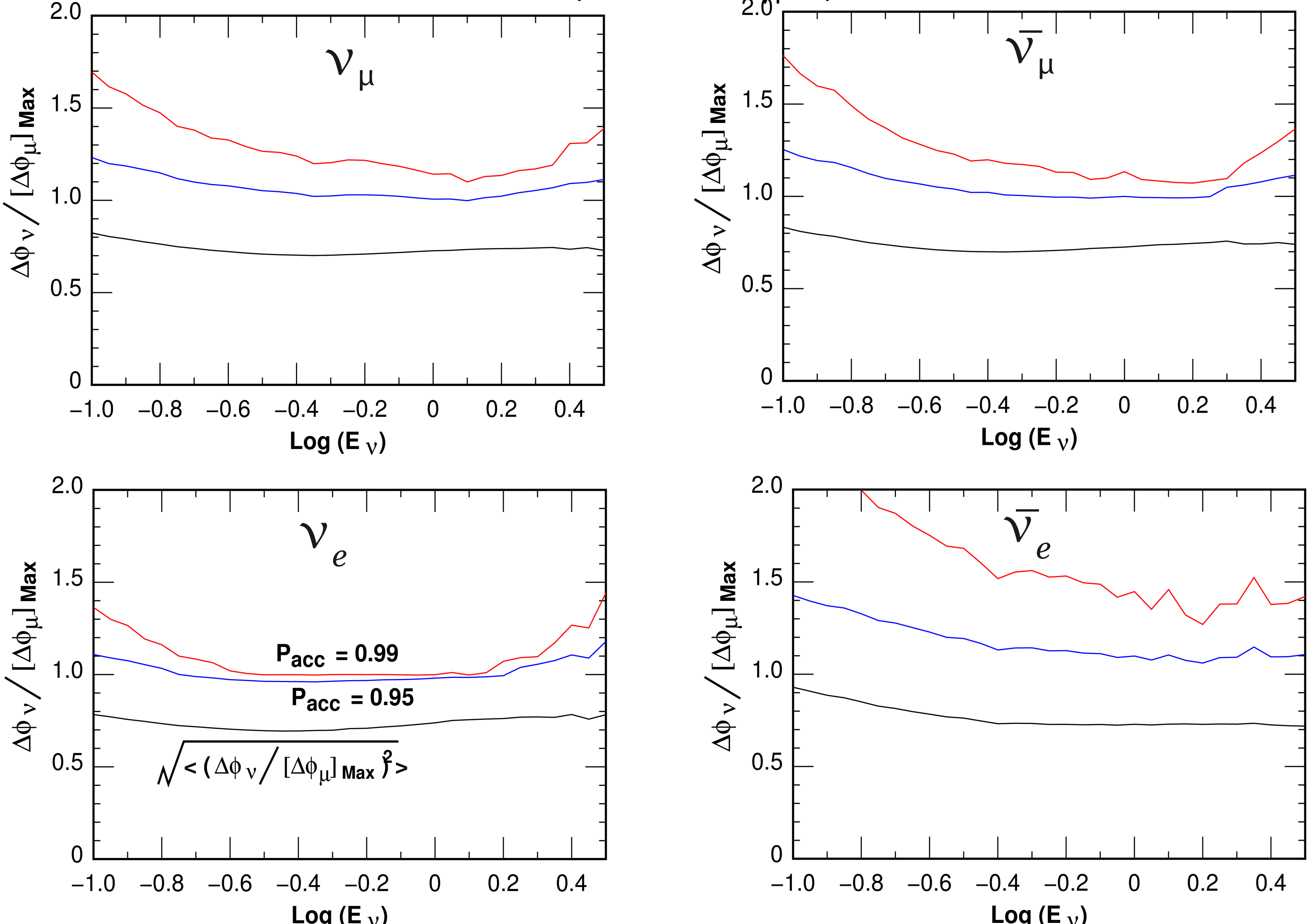


Horizontal neutrino flux



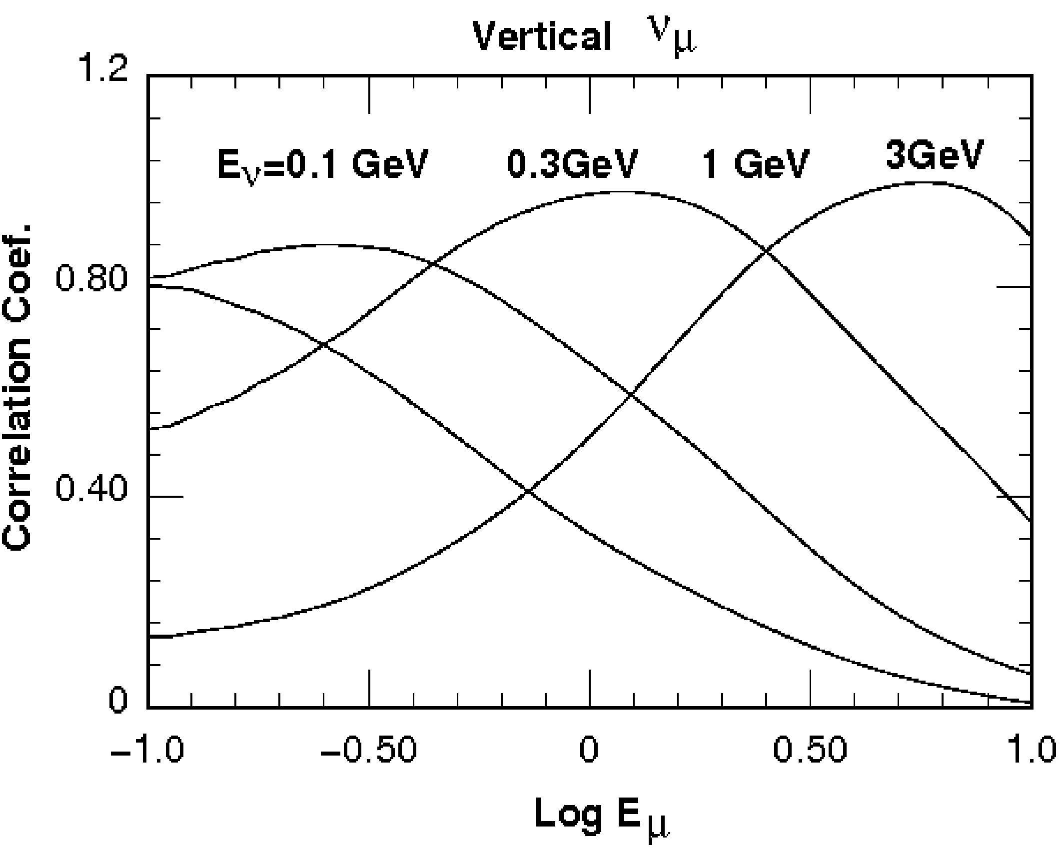
Accumulation probability(0.95, 0.09)と標準偏差

水平(variation type2)

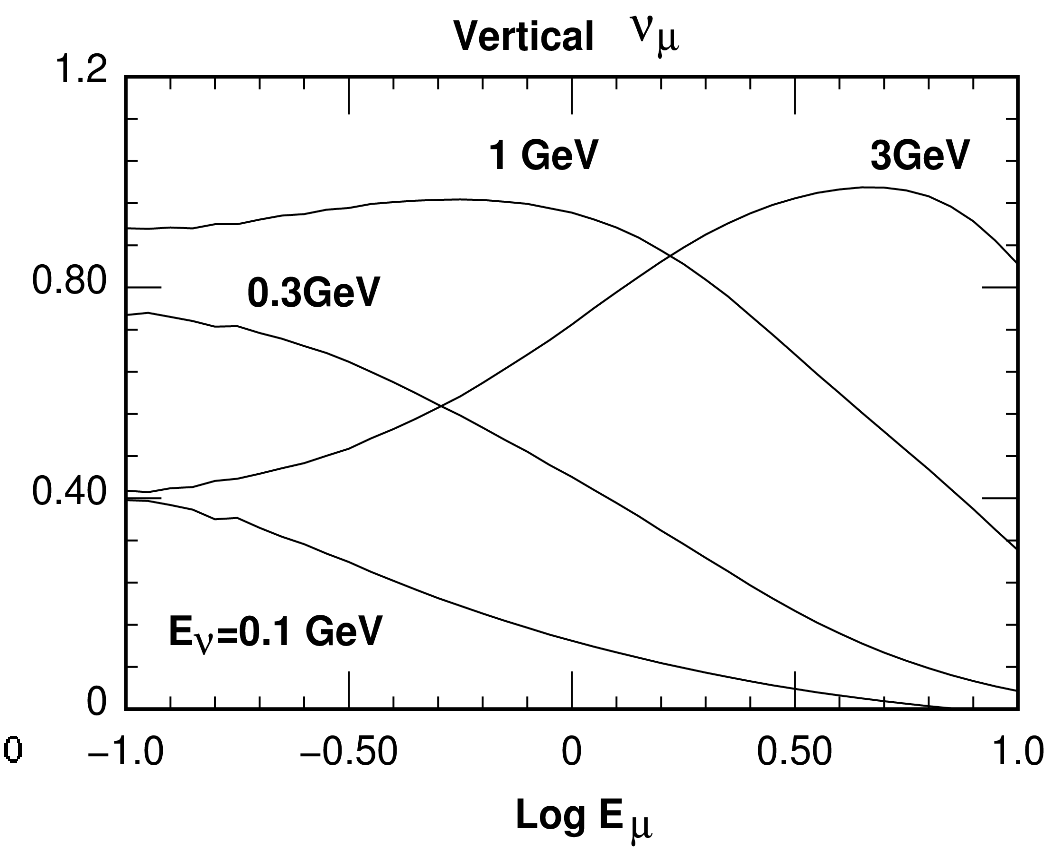


上空のμと垂直下向き方向νのフラックスの相関係数

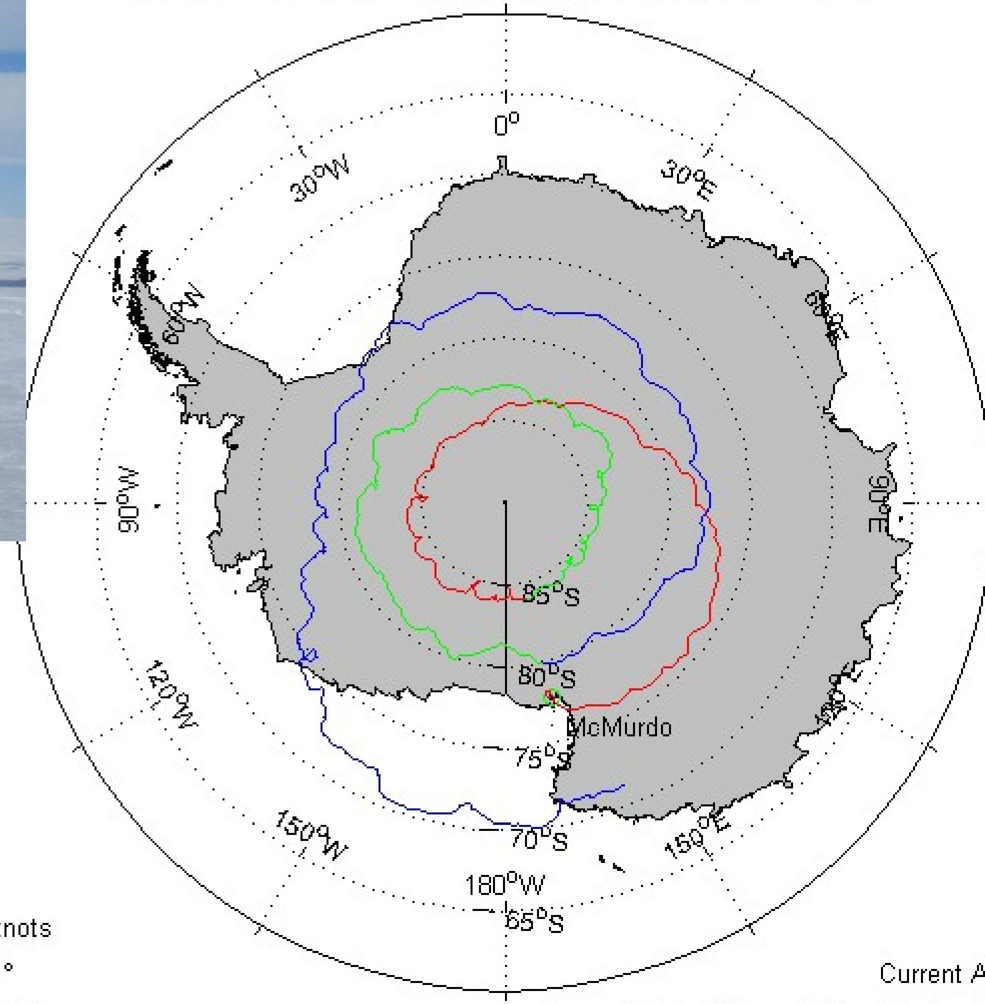
乗鞍高度



地上



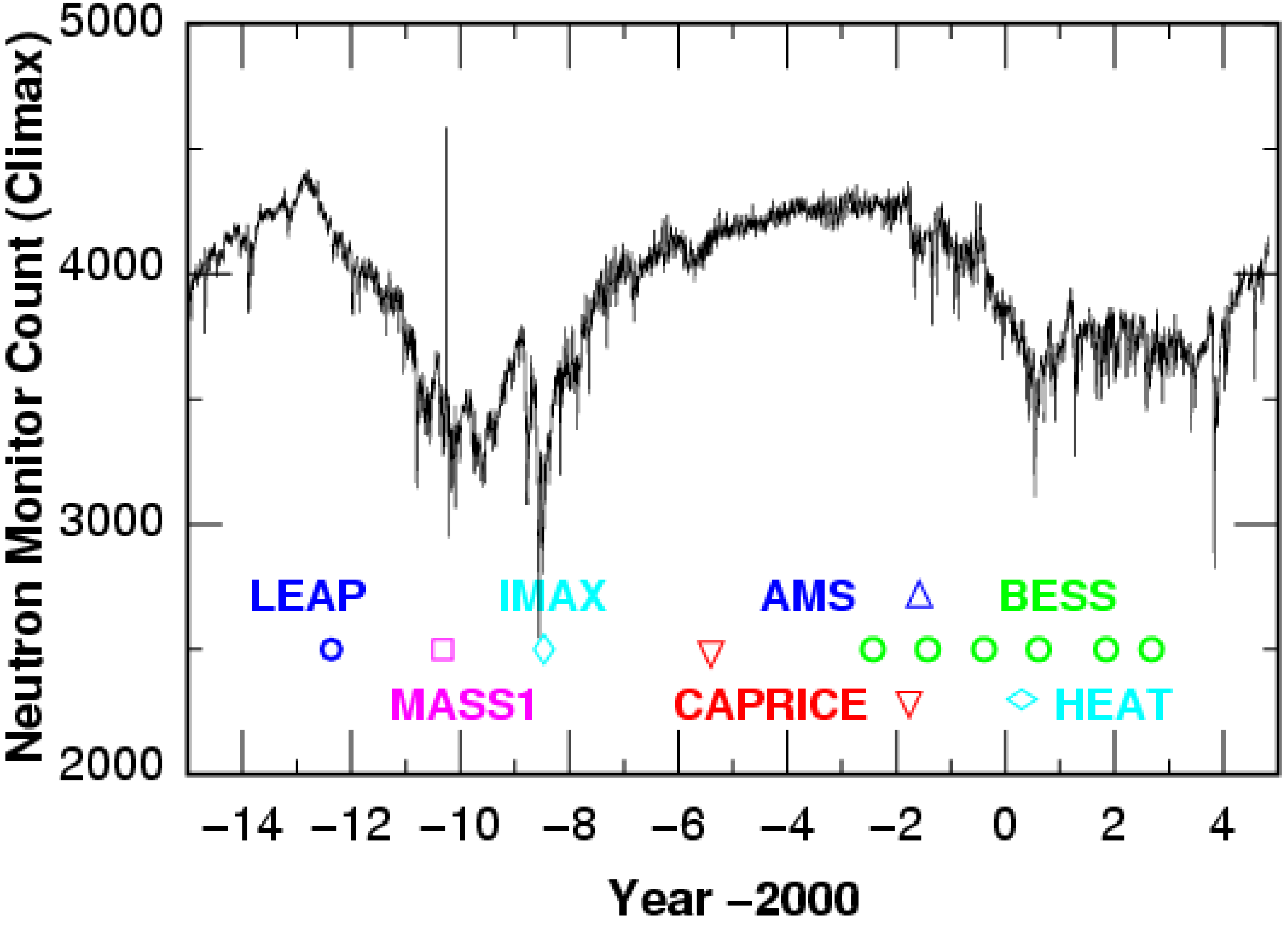
CREAM Flight Data: Trajectory
Covering period from: 2004-12-15 23:22:56 to 2005-01-27 02:00:31



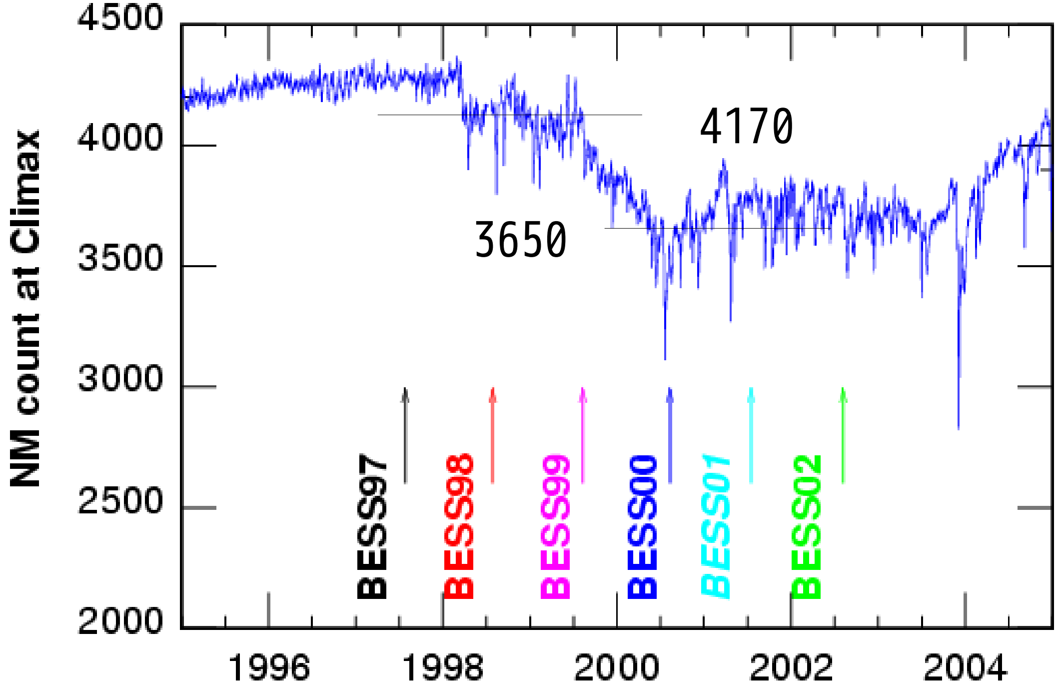
Current Speed: 17.2 knots
Current Course: 128.1°
Current Lat: -71°17′3.72″
Current Lon: 157°52′54″

Current Altitu
Current MET: 41 days 21 hrs 31 mins 30.7
Current Time: 2005-

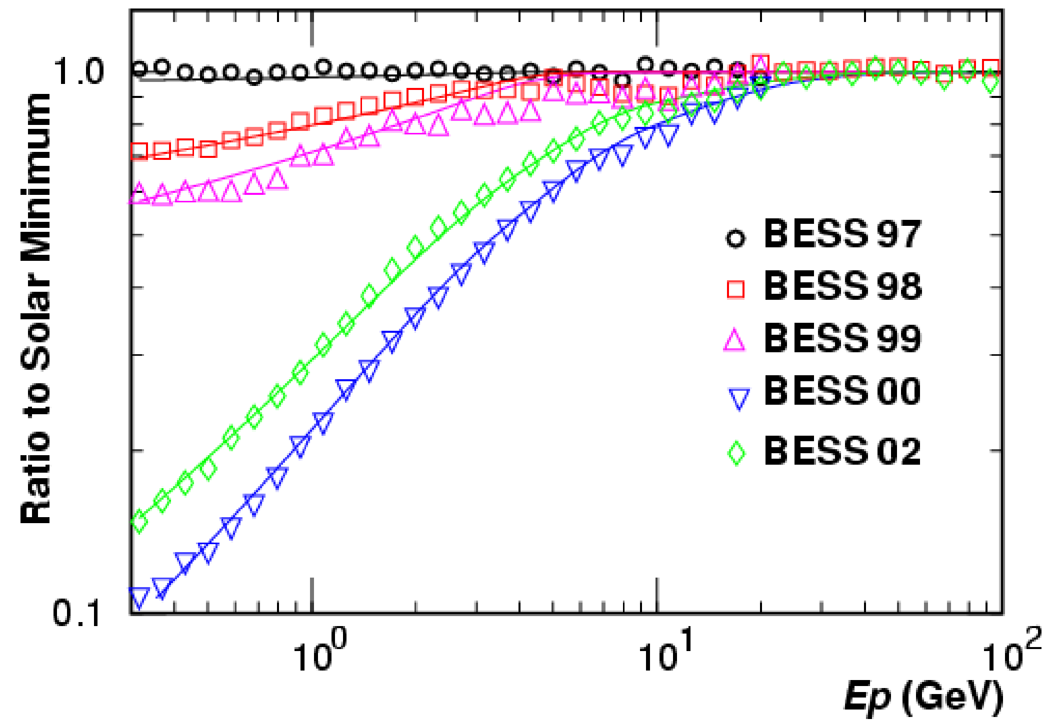
Modulation by the Solar Activity

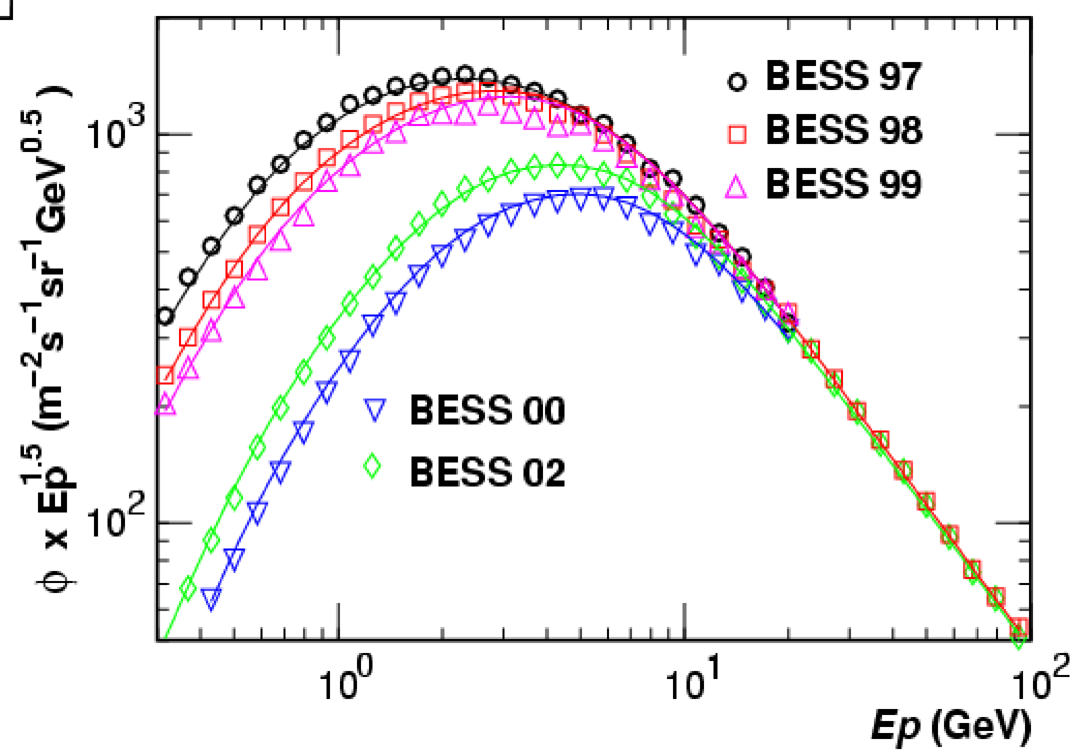


BESS flight



$M(N,r)$: Modulation function

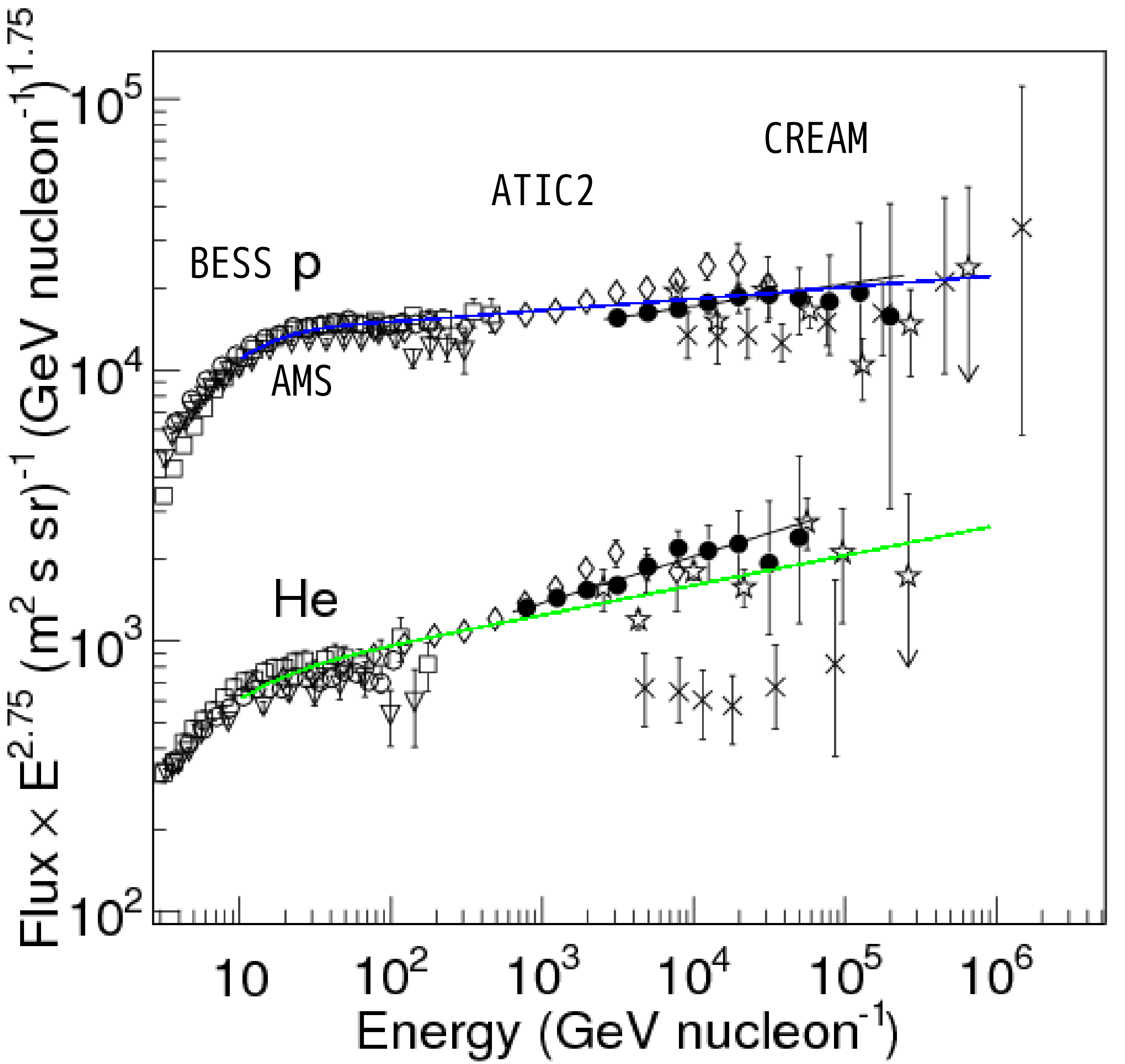




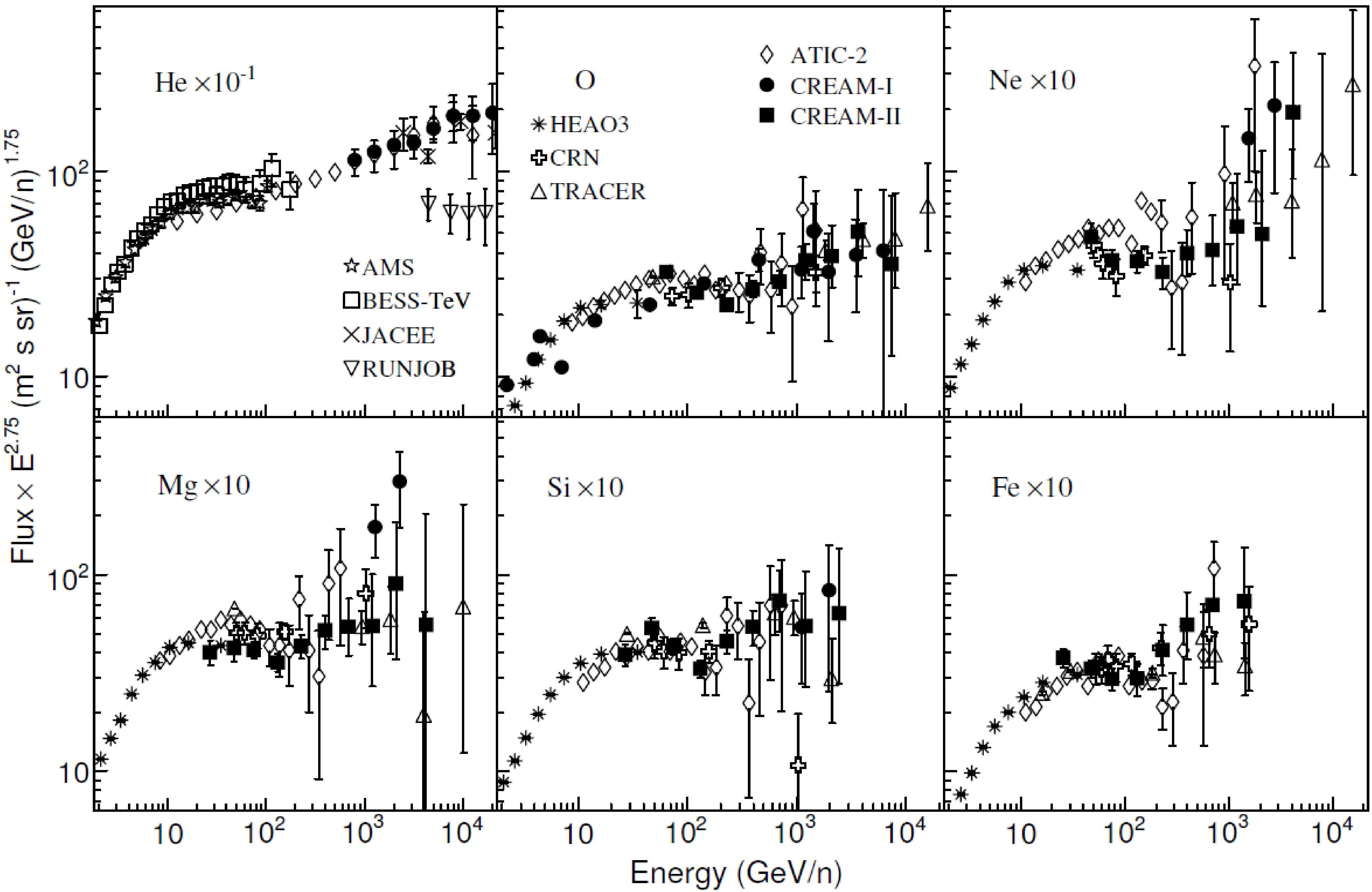
$$\phi_i(N, E_k) = \phi_i^{min}(E_k) \cdot M(N, r)$$

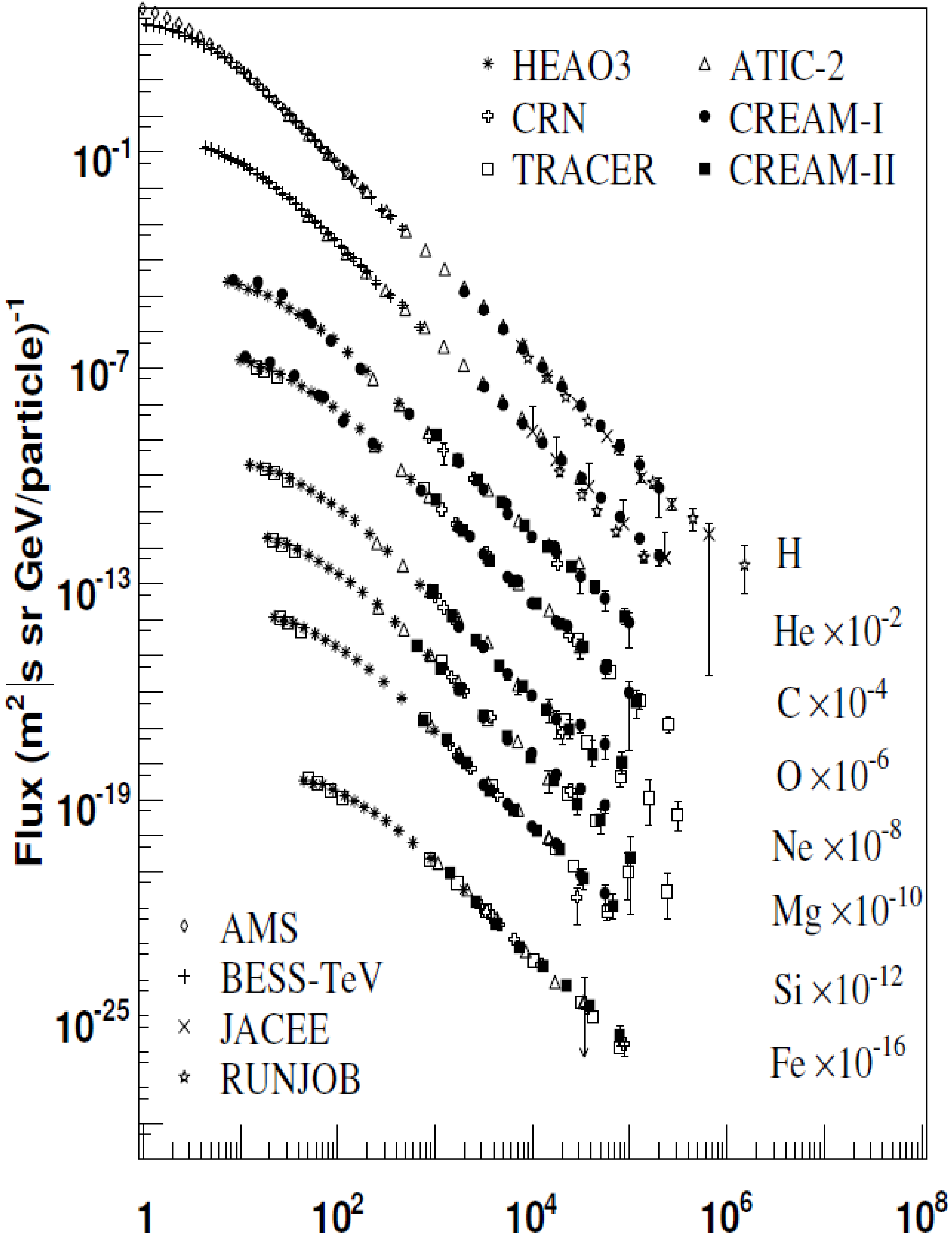
$$\phi_i^{min}(E_k) \equiv \phi_i^{1997}(E_k)$$

Comparison with recent observations.



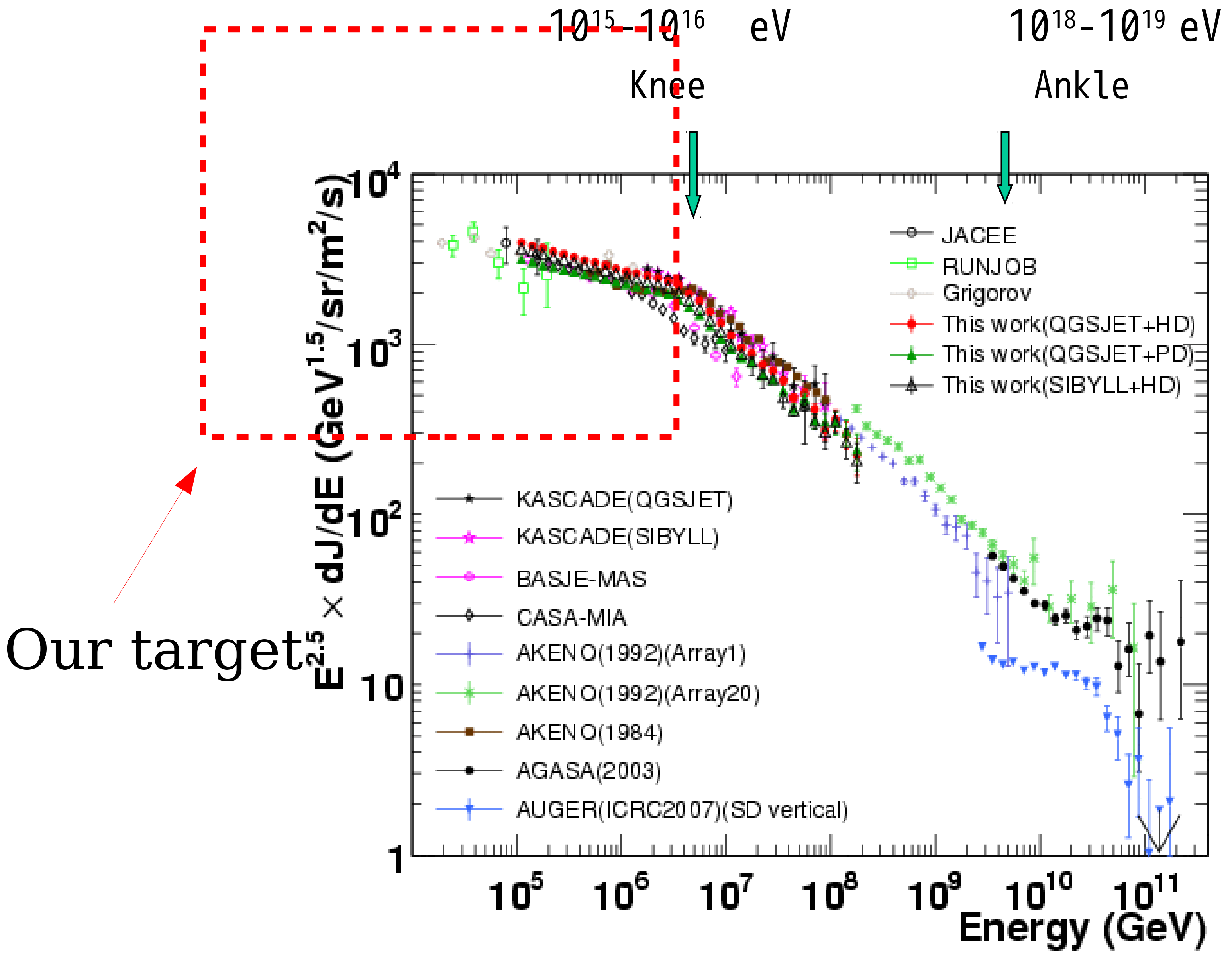
With expanded vertical axis



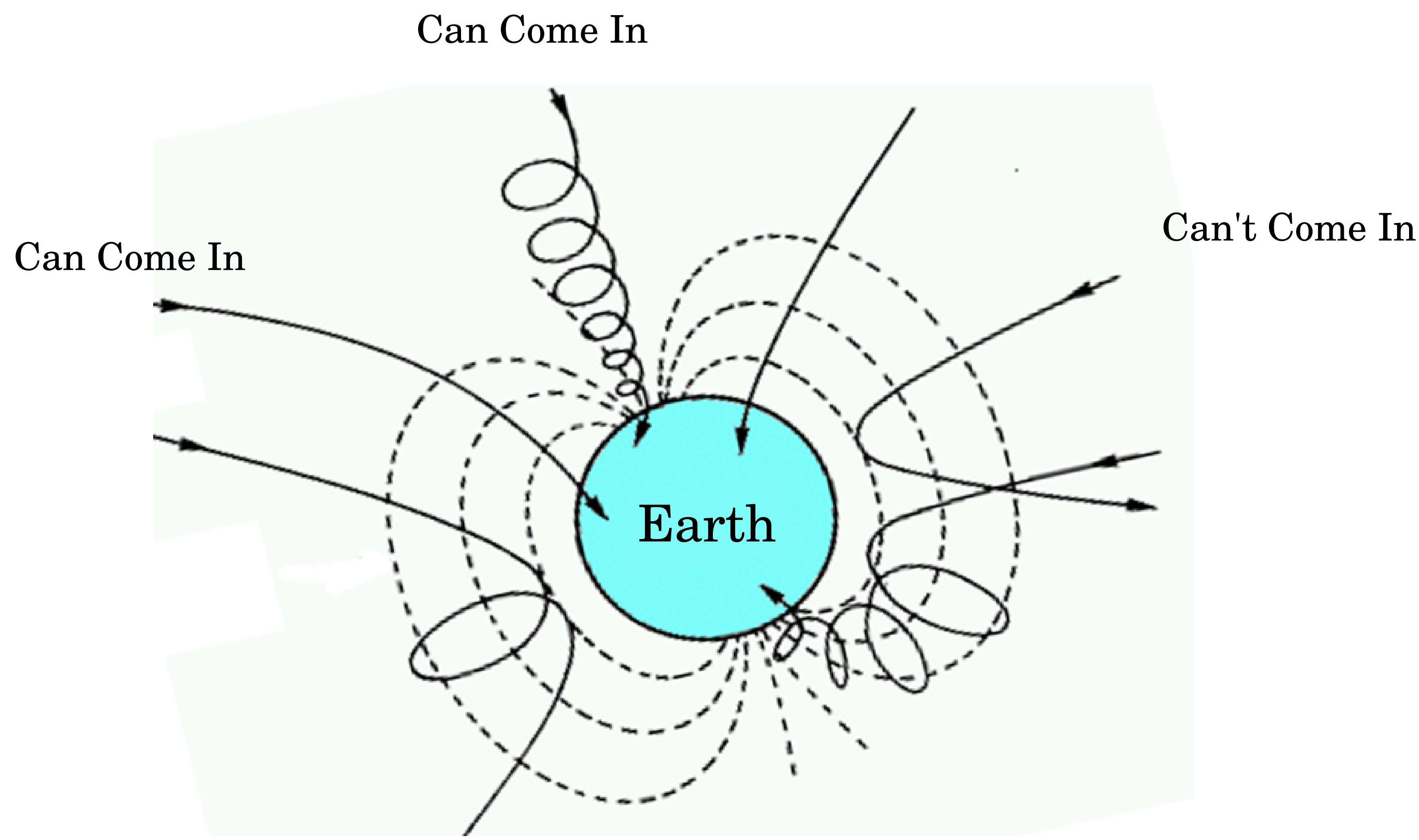


Recent compilation
E.S. Seo @ ICRC2009

CR spectrum in wide range

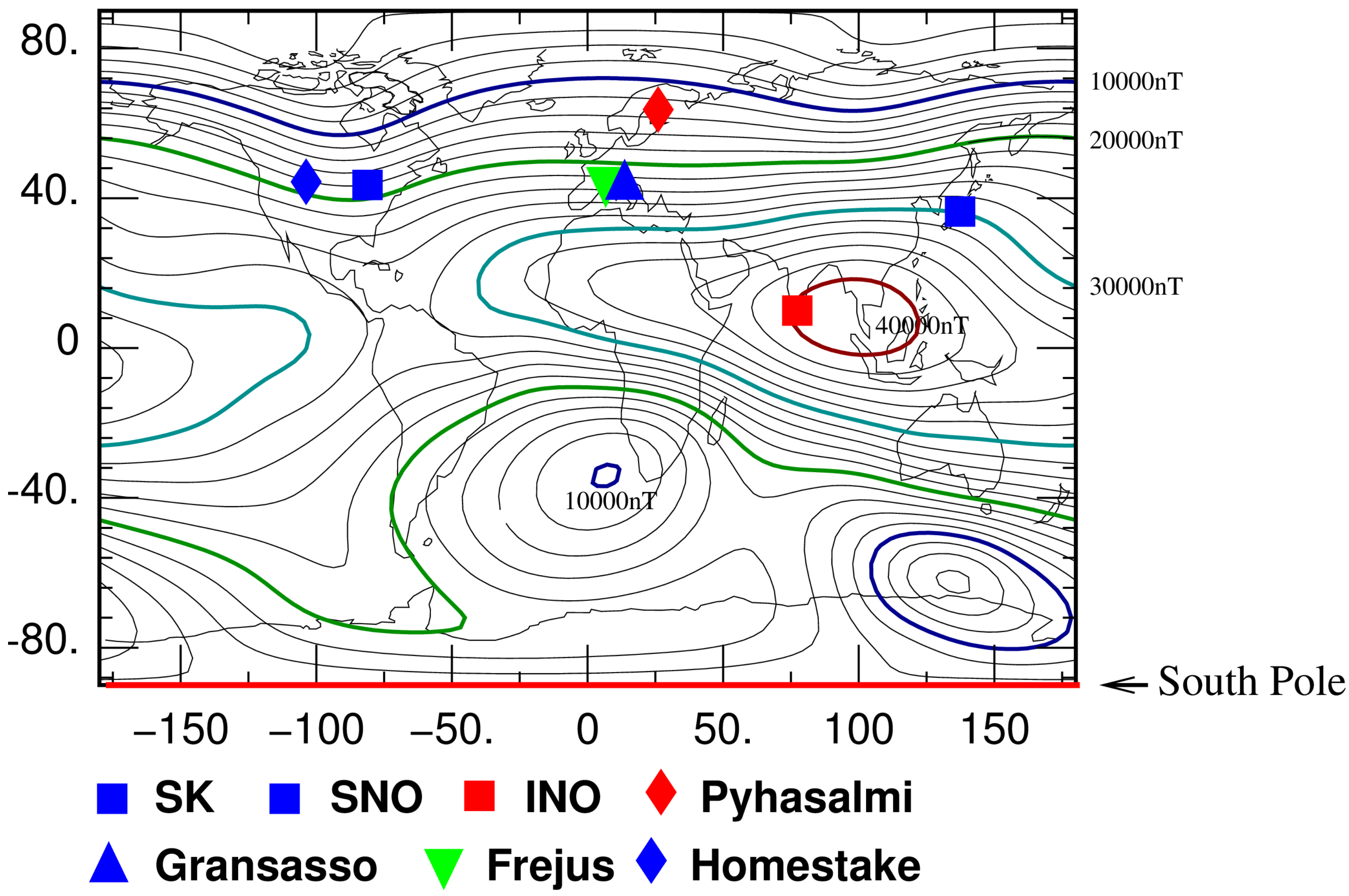


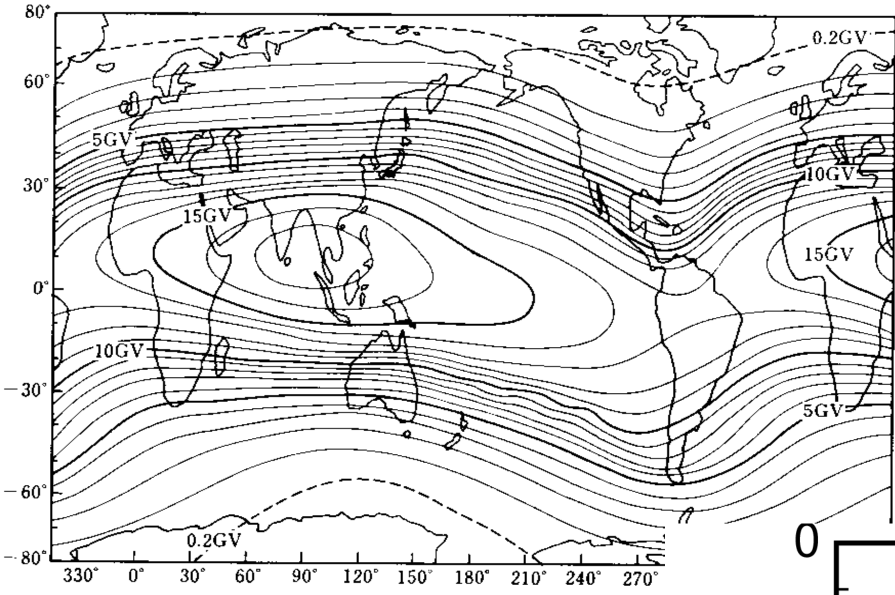
Rigidity Cutoff and Geomagnetic Field (cartoon)



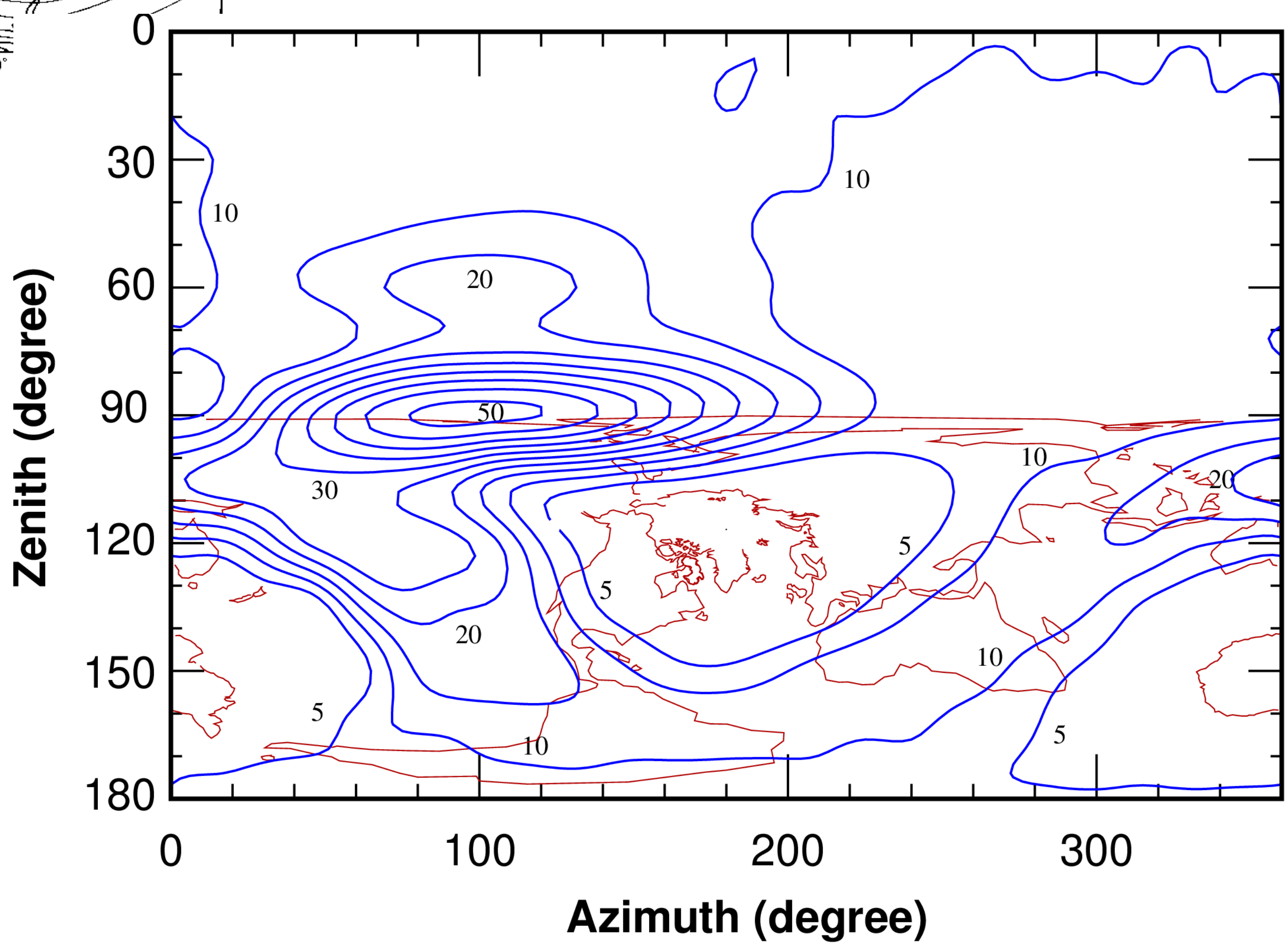
Rigidity Cut Off

Presently going calculation (with M.S. Athar)





Rigidity Cutoff for
Virtical direction



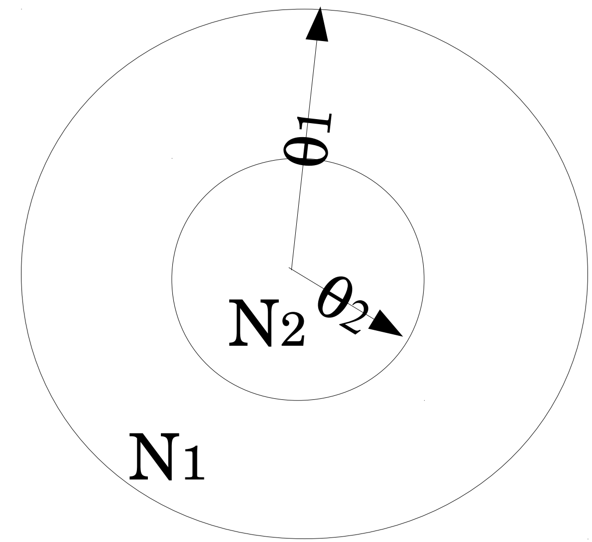
Rigidity Cutoff
For SK direction

Size correction for virtual detector

Assume true flux value and average in the circle with radius θ1 and θ2 may be related as

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

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



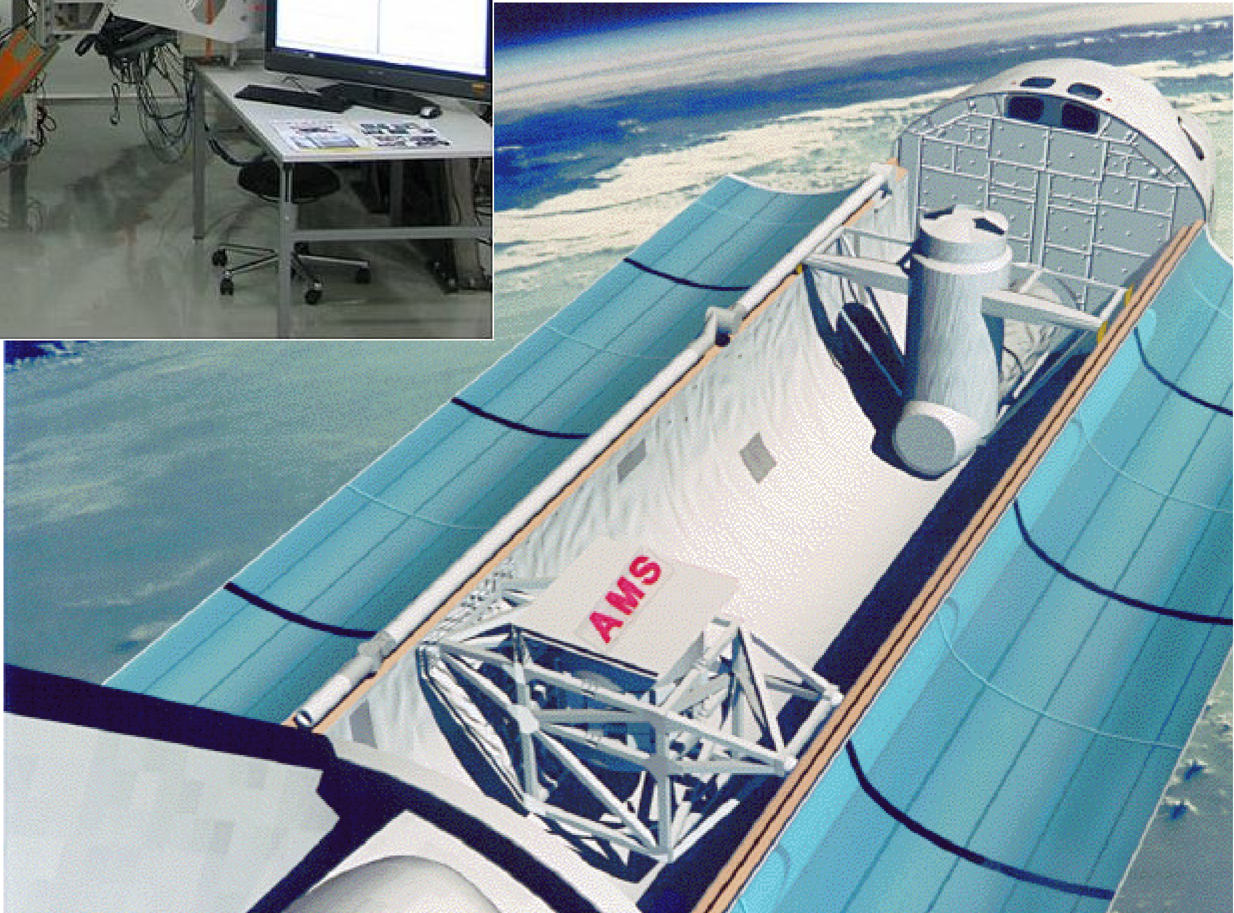
Therefore the true value is calculated from ϕ1 and ϕ2 as;

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

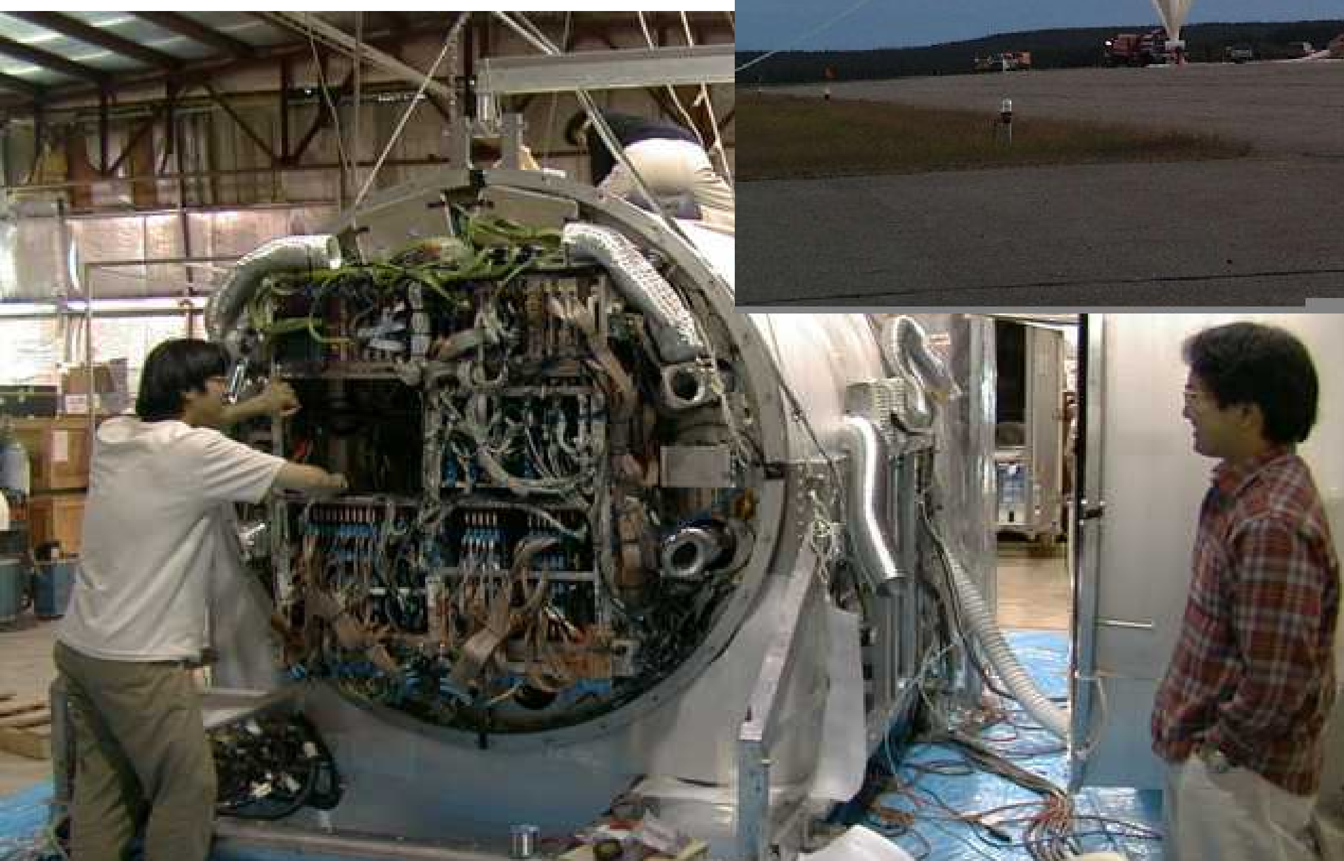
In terms of the sampled number $N1$ in the circle $\theta < \theta 1$, and $N2$ in $\theta < \theta 2$, ϕ1 and ϕ2 are given as

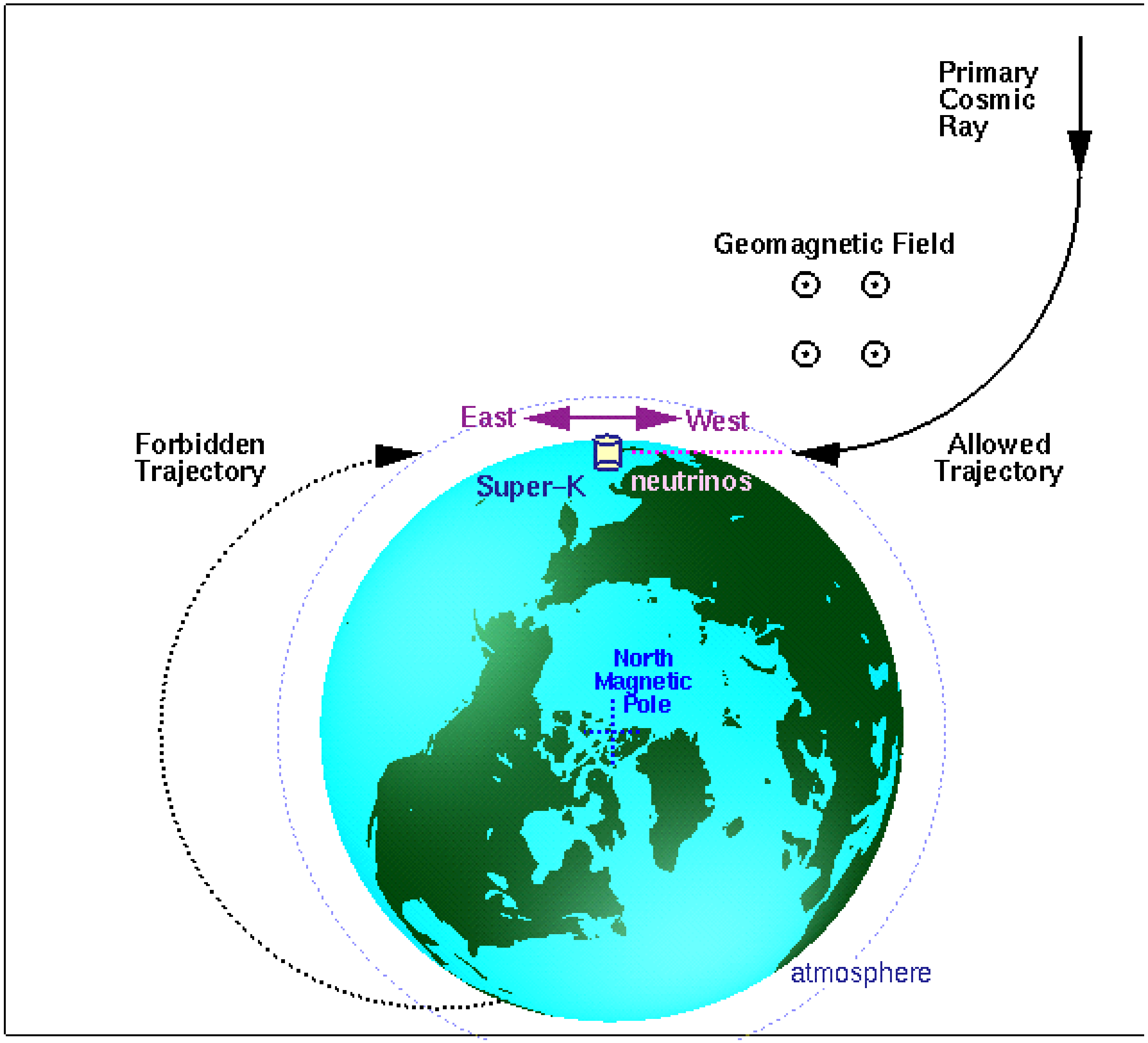
$$\phi_1 = \frac{N_1}{T \pi \theta_1^2}, \quad \phi_2 = \frac{N_2}{T \pi \theta_2^2}$$

AMS-I

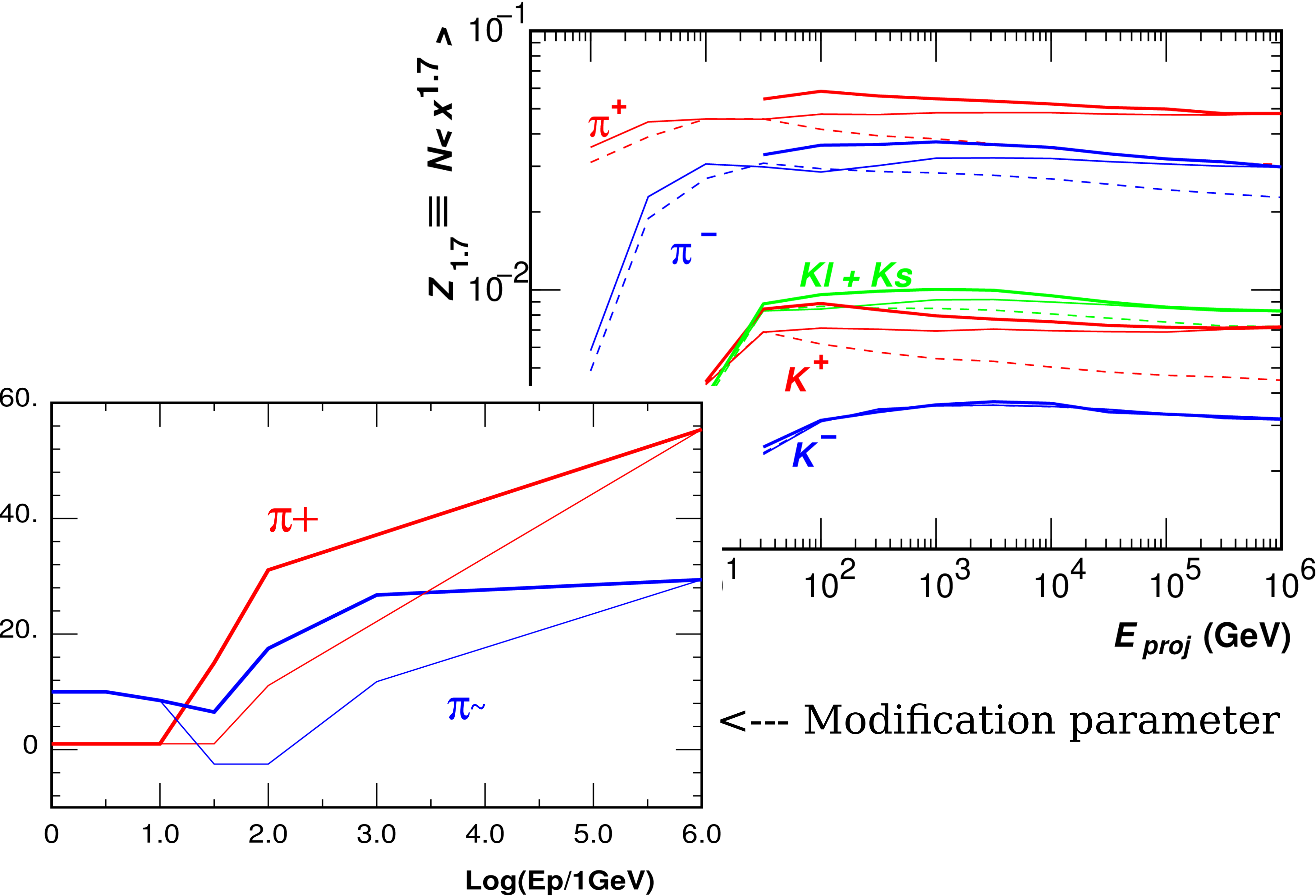


BESS also observed
Atmospheric muons
at Balloon altitude
and
Ground.




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

Modified Z-factor

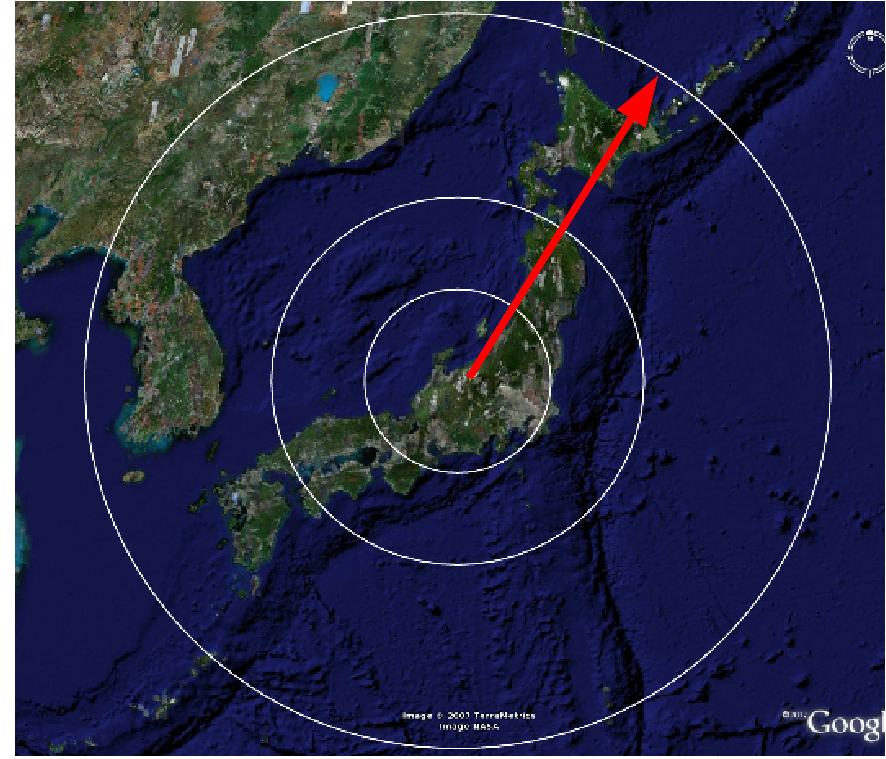


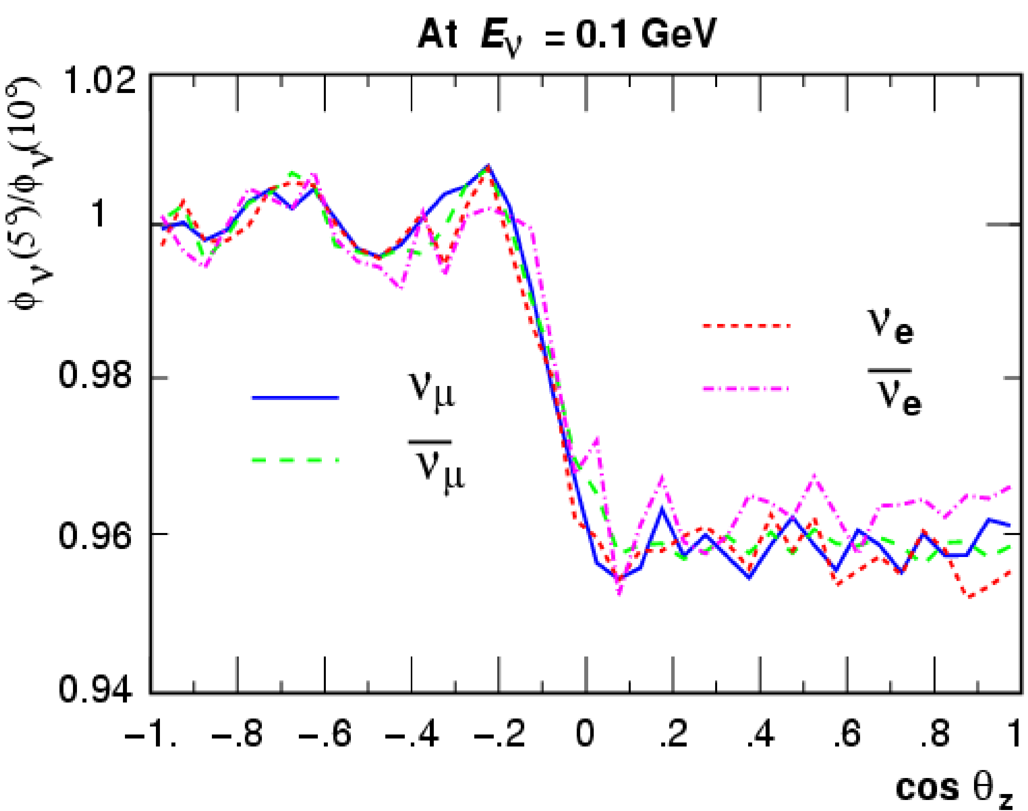
<--- Modification parameter

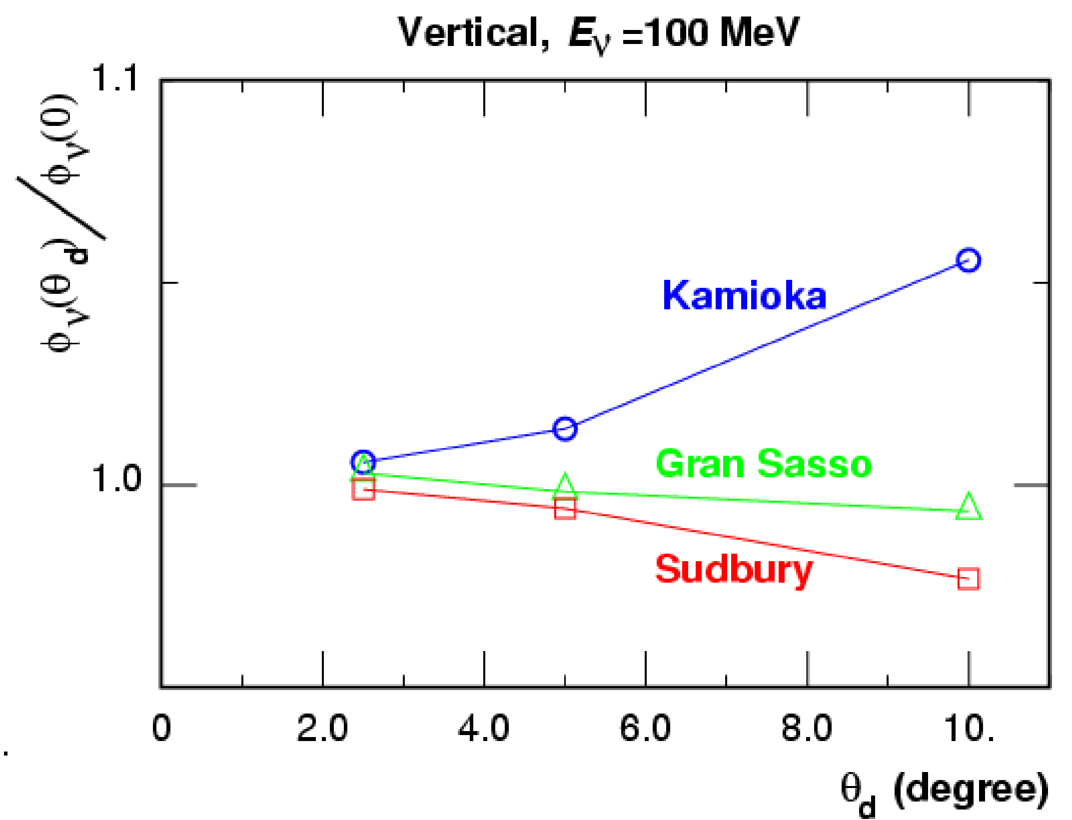
Error due to the large size Virtual Detector

In HKKM06 (PRD 2007), we took

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

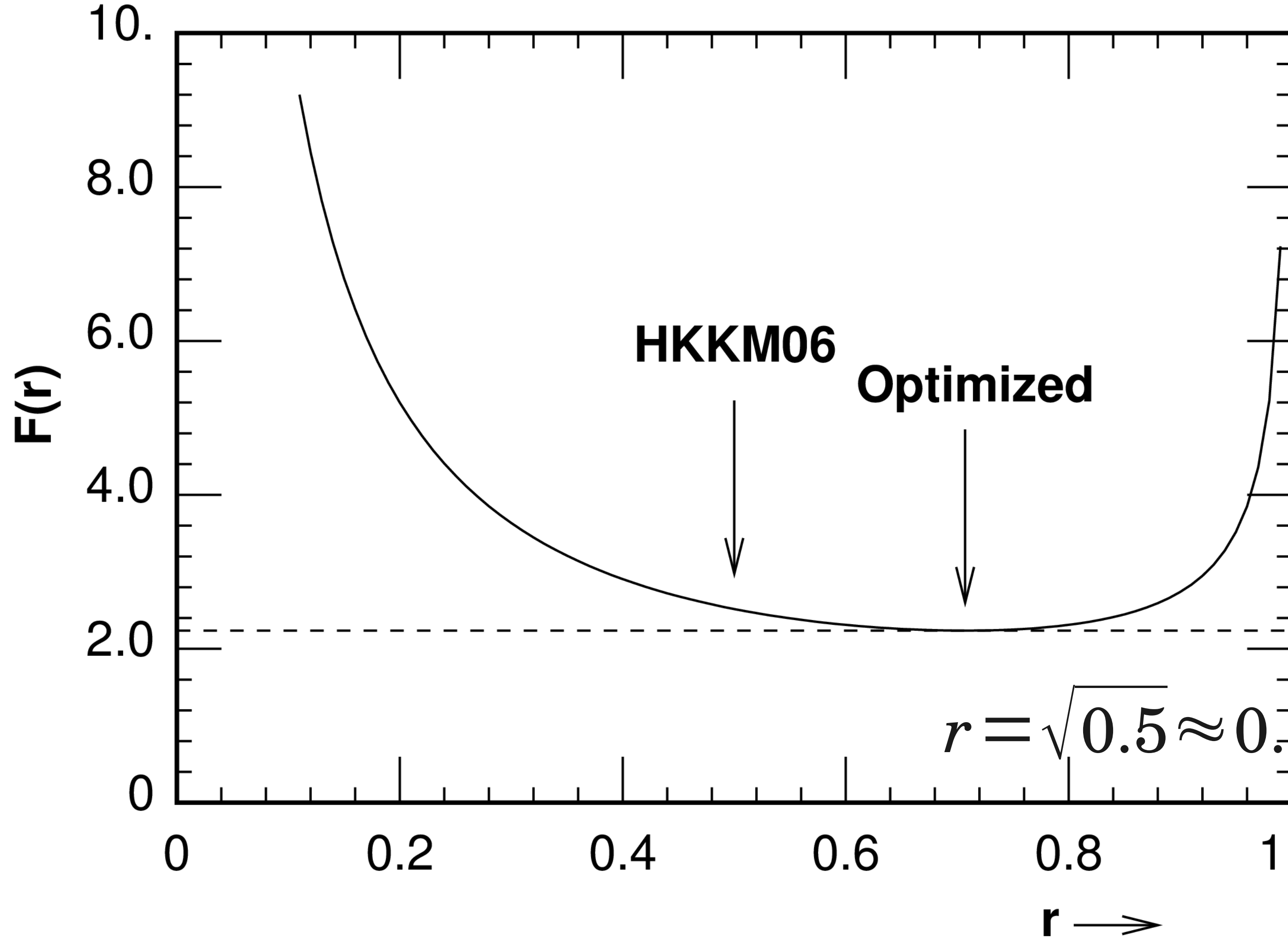






Optimized $r=(\frac{\theta_2}{\theta_1})$ value, which minimize the stat. error

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



$$r=\sqrt{0.5}\approx0.7071$$