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Atmospheric Muon and Neutrino fluxes, and Hadronic Interaction

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T. Sanuki, K.Abe, S.Haino,
J.Nishimura, and A. Okada.

Plan of talk

1. Overview of the calculation of atmospheric neutron flux
   - Primary flux of cosmic rays
   - Interaction model

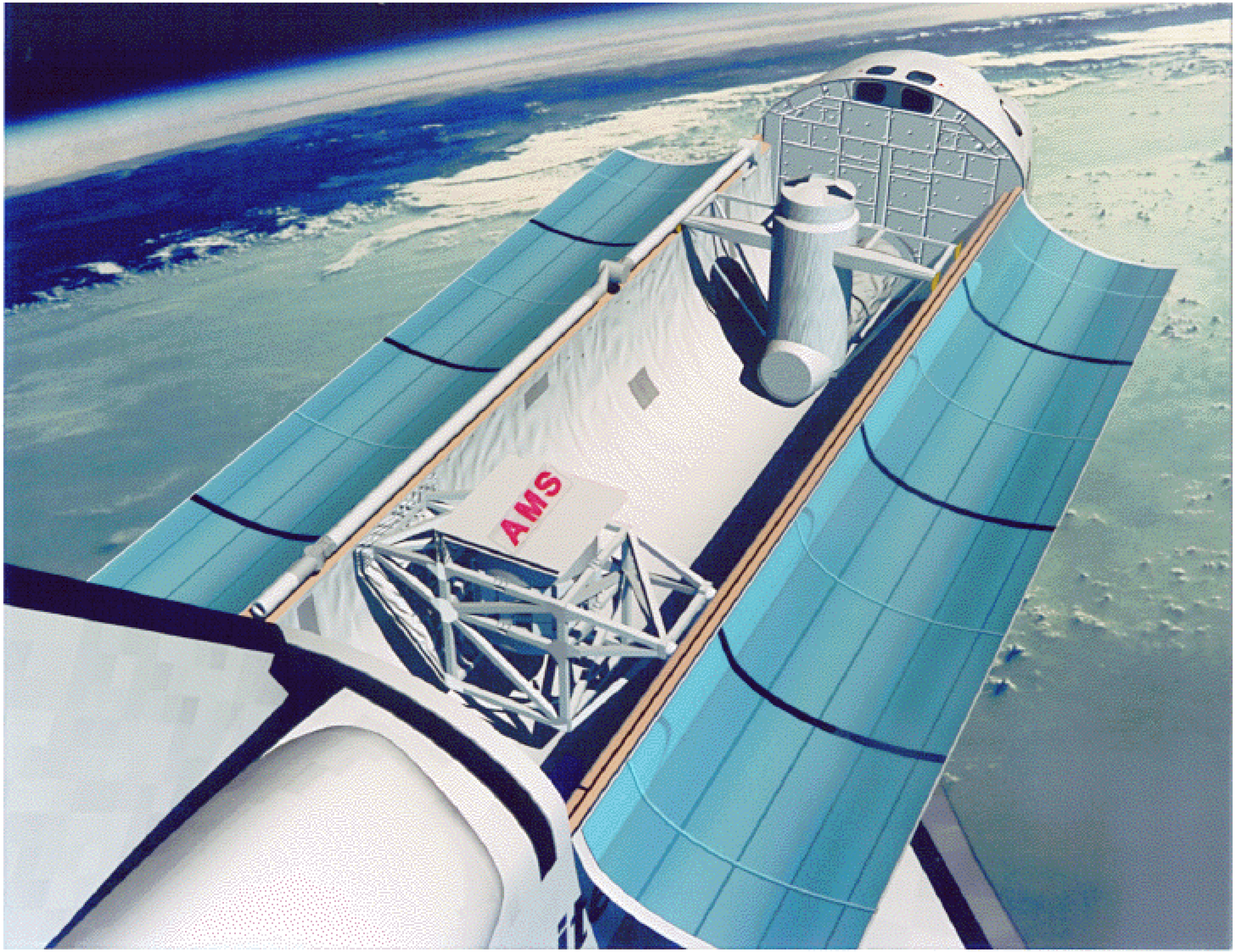
   - Calculation scheme
   - Atmosphere model

   - Geomagnetic field and rigidity cutoff
   - Solar modulations

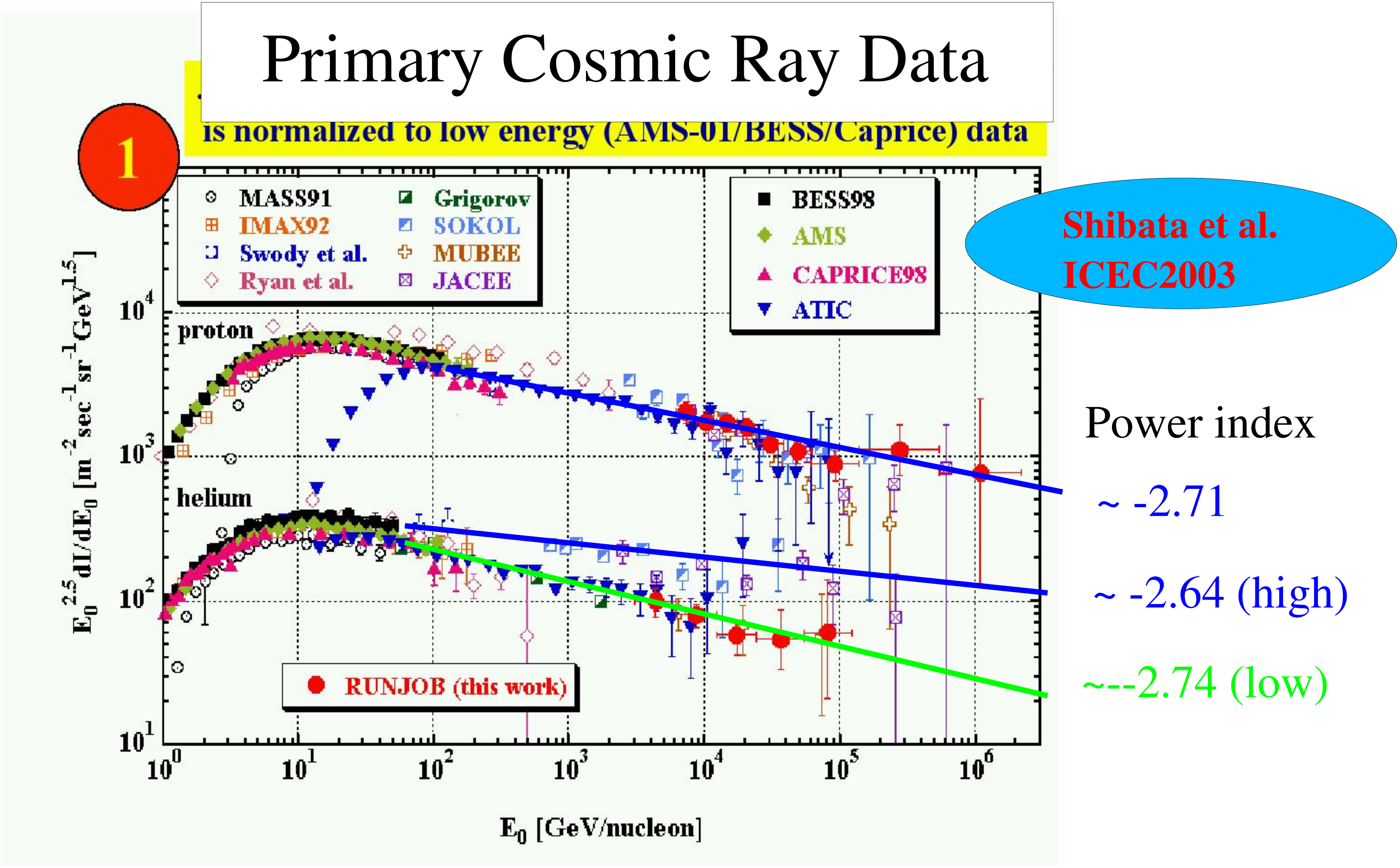
2. Study of interaction model with muon flux

   - x-base or rapidity base ?
   - Comparison with observed muon data

Primary Cosmic Ray Fluxes

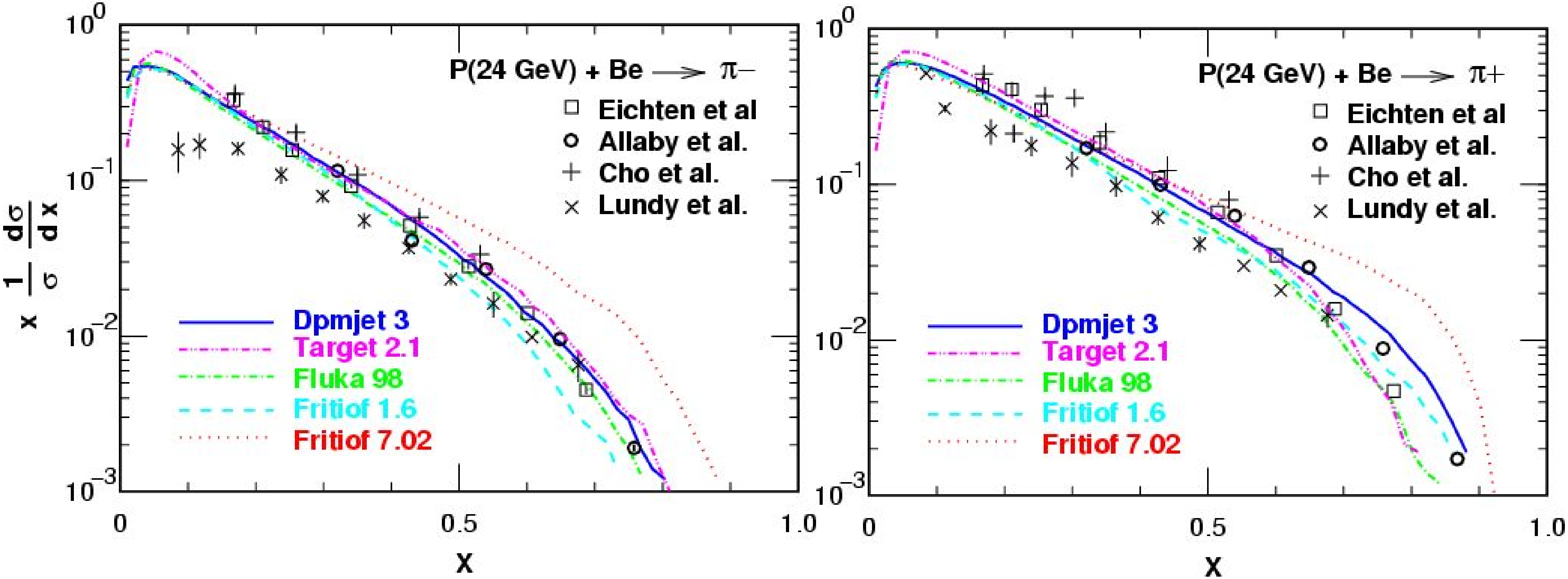


Primary Cosmic Ray Data



- Primary proton flux observed by AMS and BESS agrees each other within the error of 5% below 100 GeV
- He spectrum still has the large scatters. (We use high model)

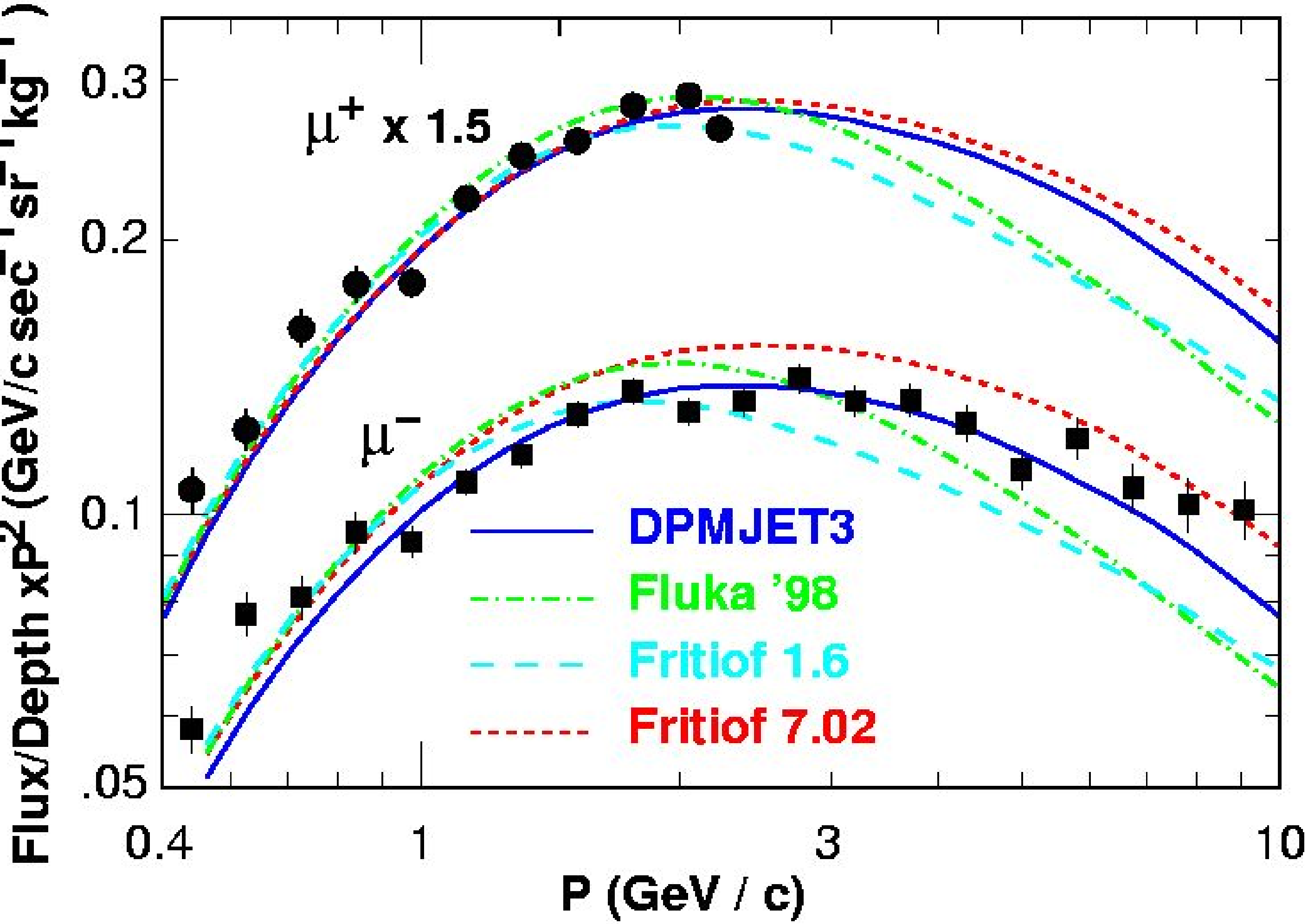
Interaction Model



It is difficult to discriminate the interaction model with accelerator data.

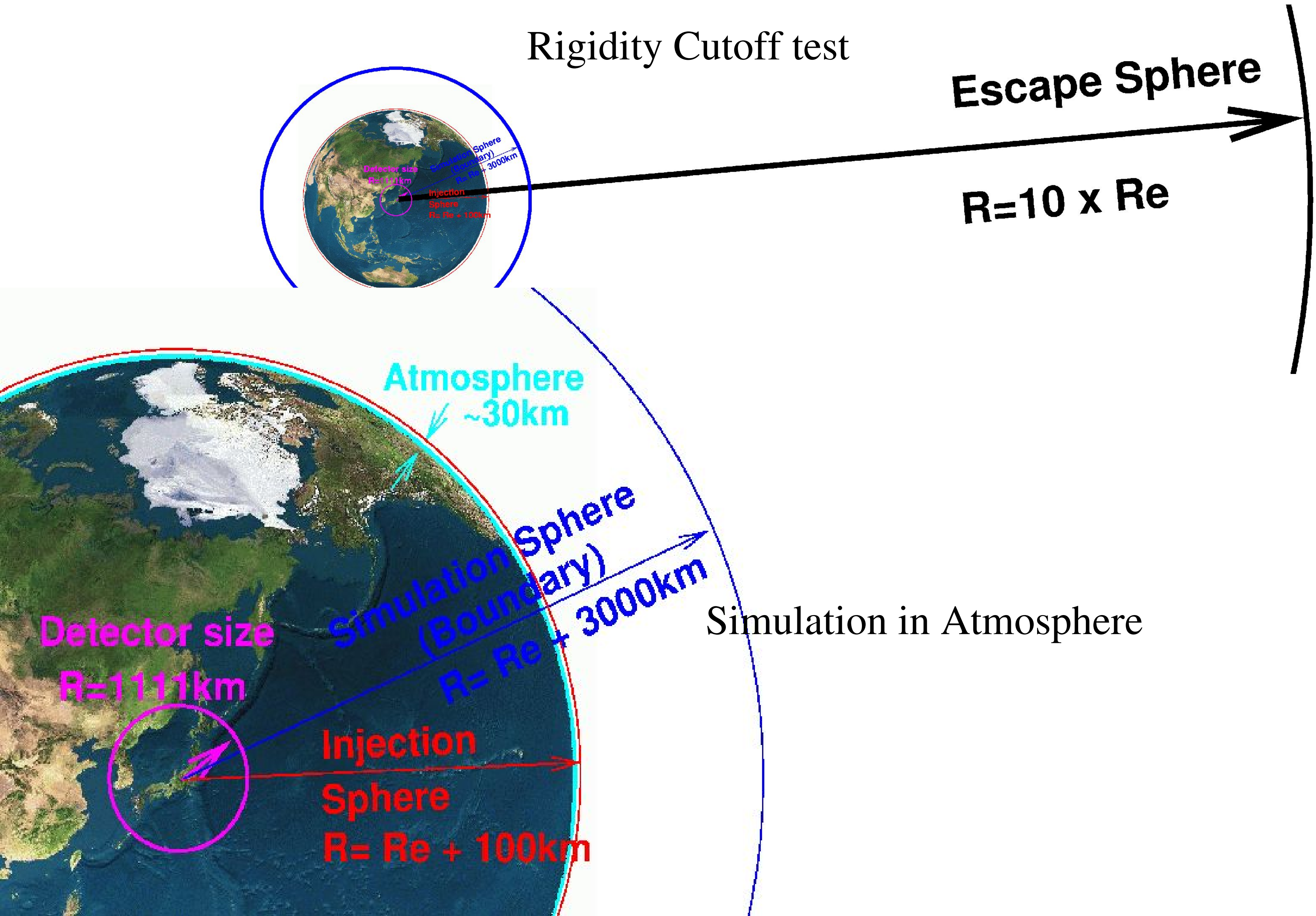
Test of Interaction Model at Balloon Altitude

Comparison in [Flux/depth]



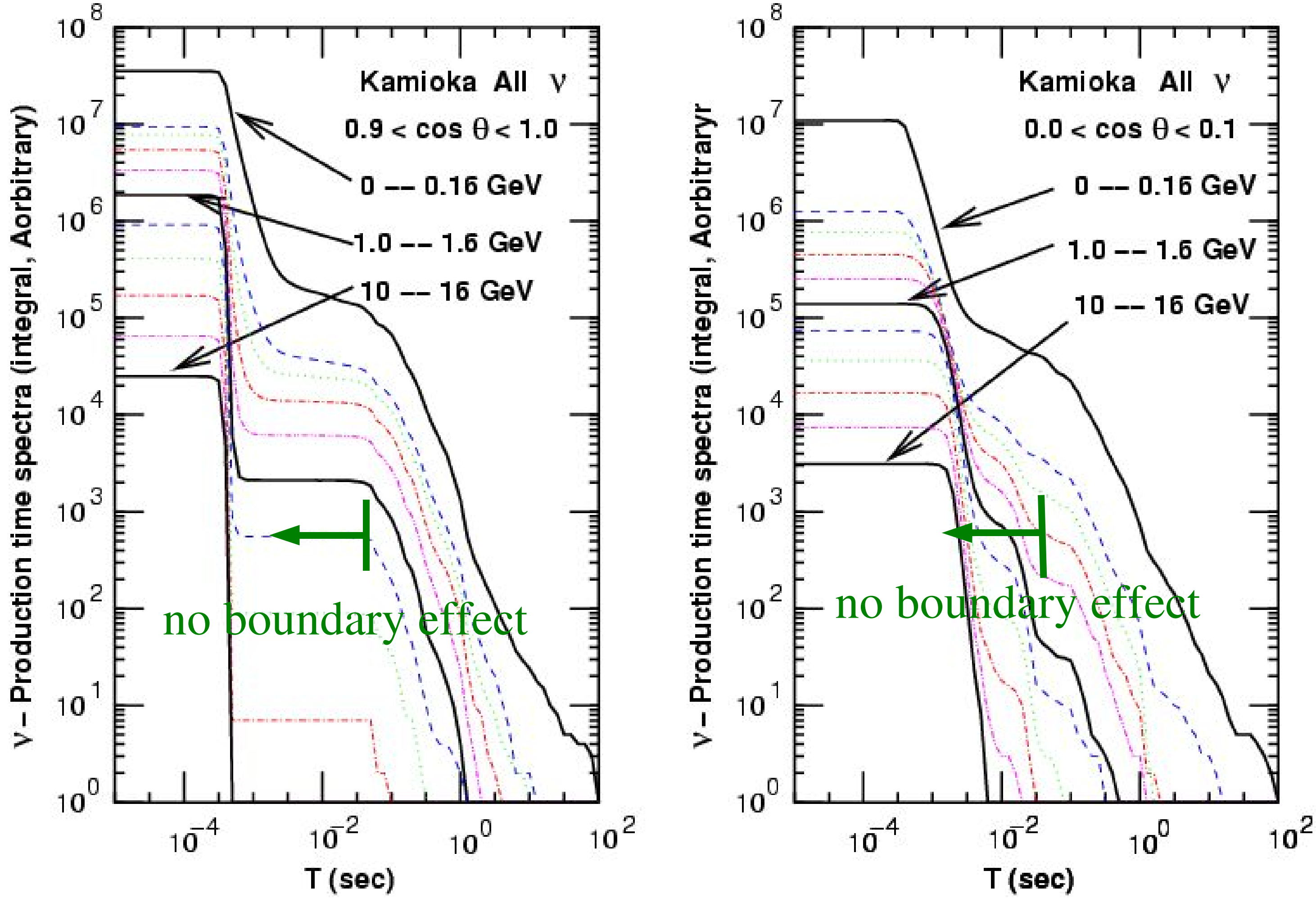
DPMJET-III show the best agreement

Calculation Scheme (Re = 6378km)



Size of Simulation Sphere

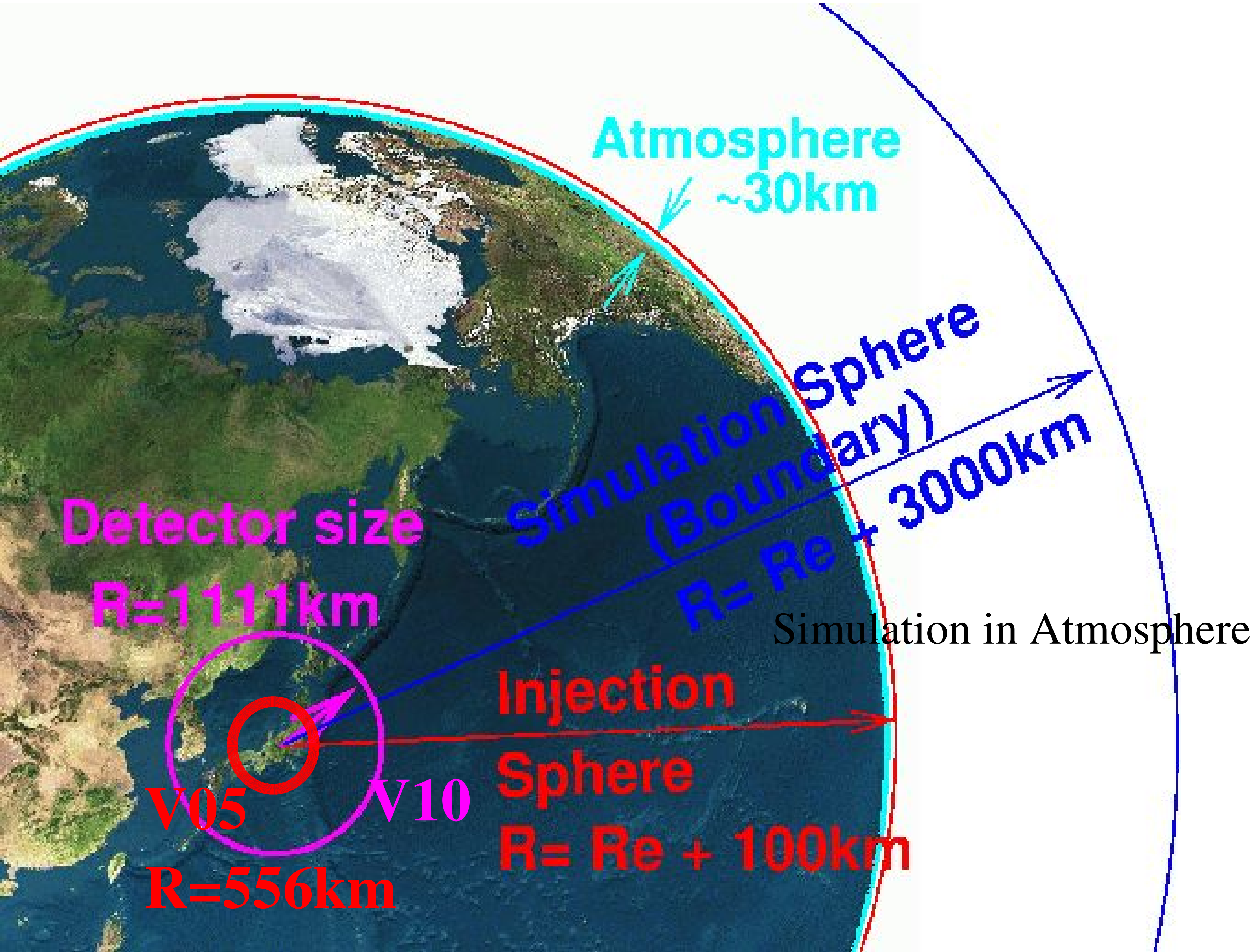
Neutrino production time



The particle produced within 0.02 sec is free from the boundary at Re + 3000km

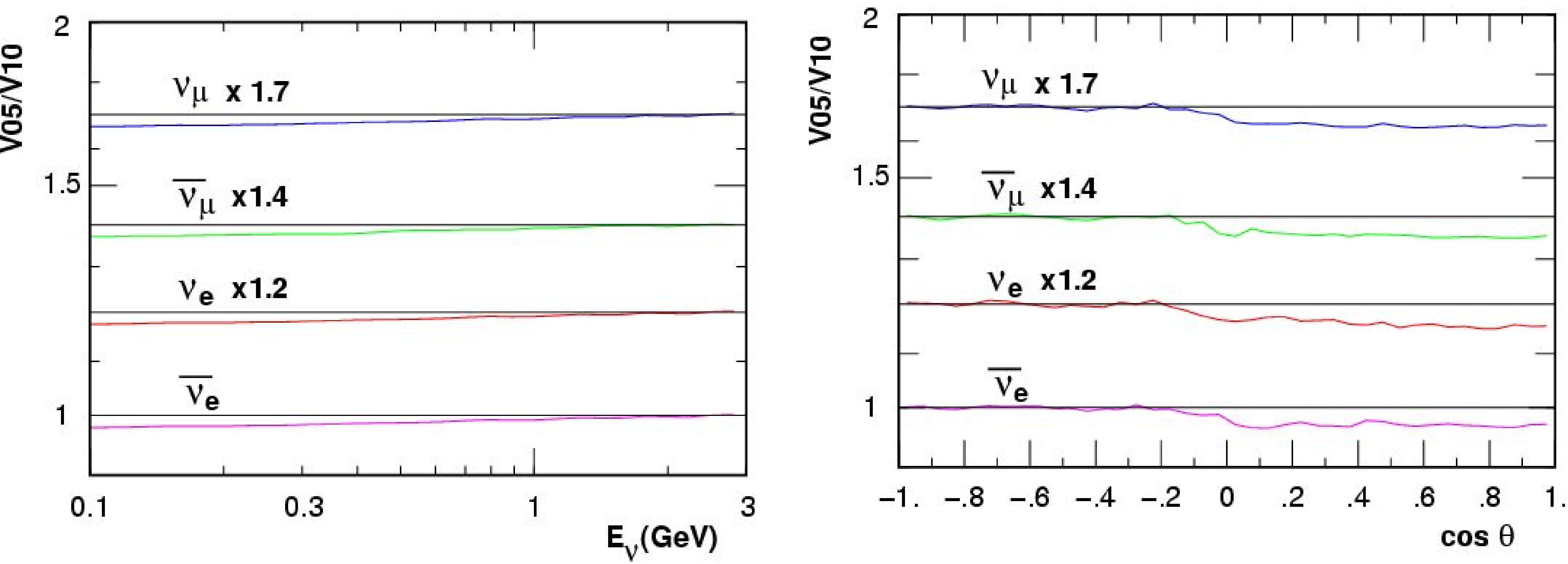
Size of the virtual detector

(Re = 6378km)



Comparison of the results between V10 and V05

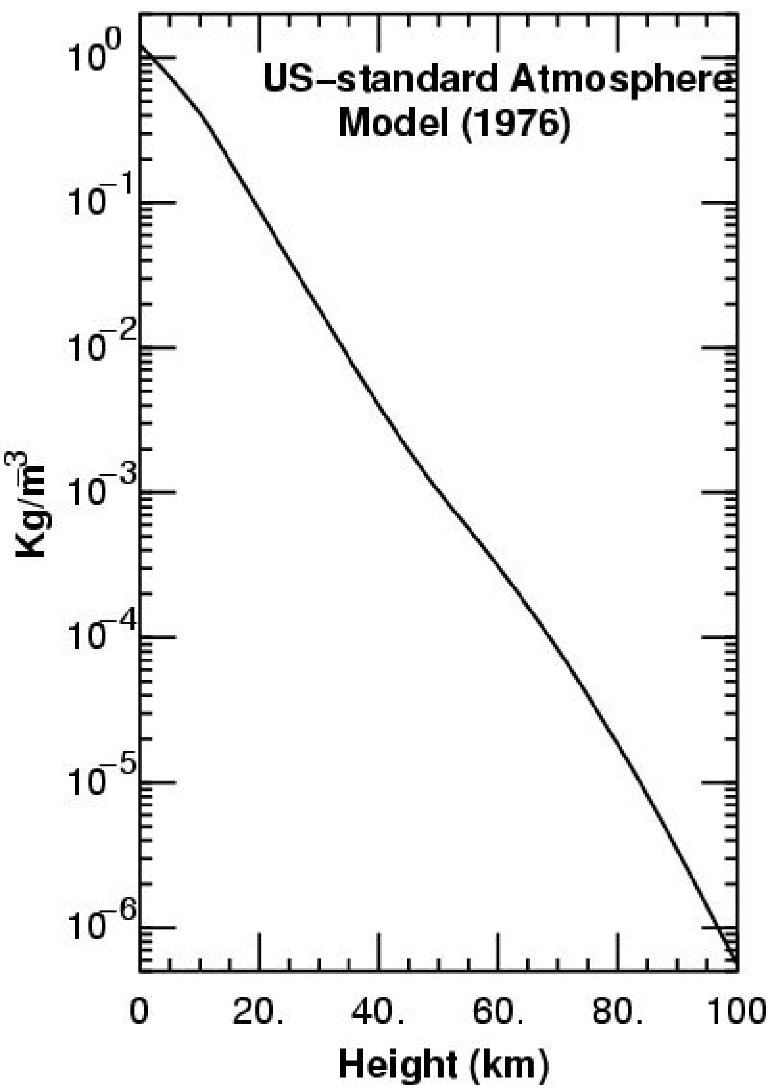
All direction average | at 0.3 GeV/c

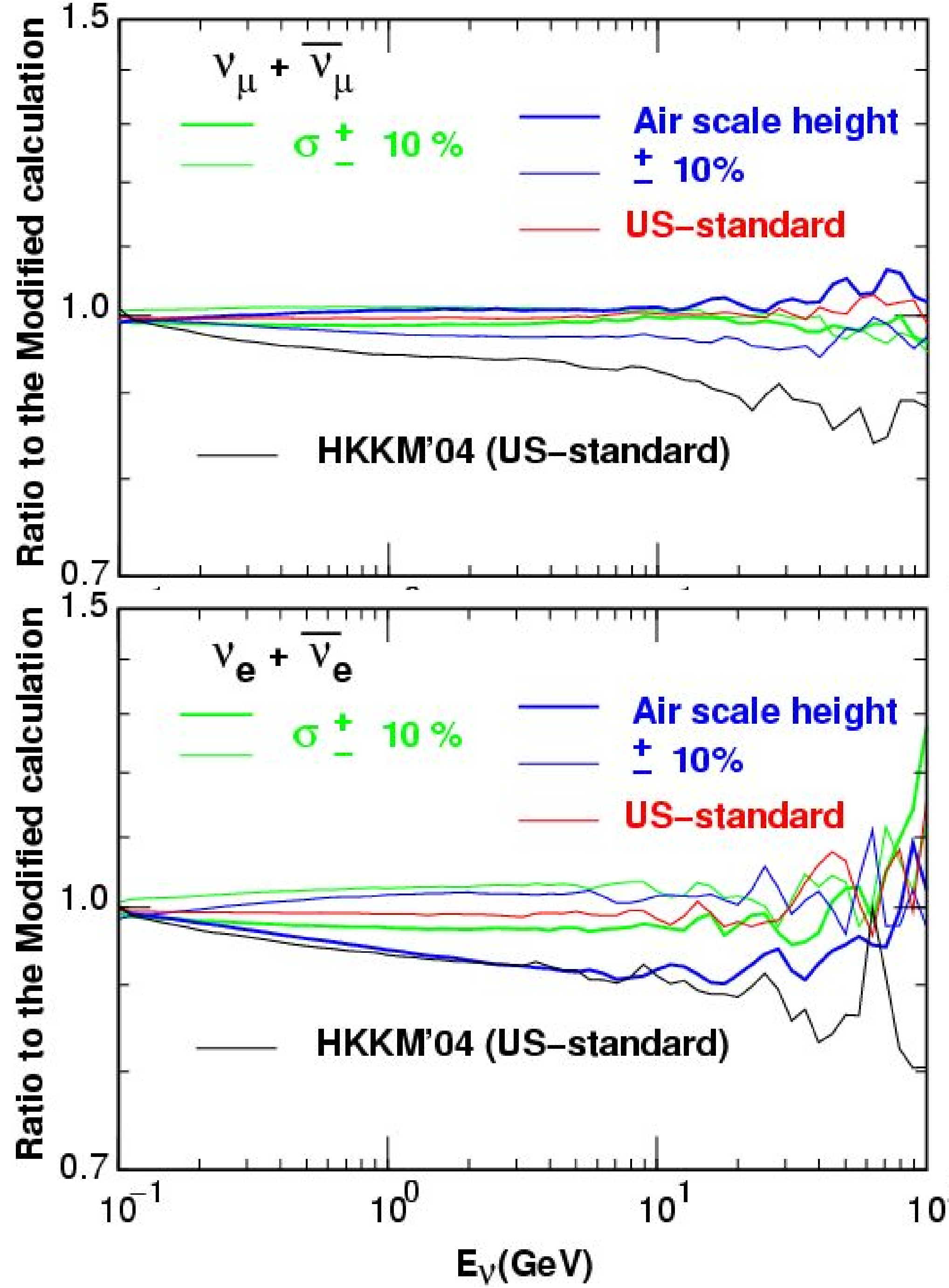


The results of V10 seems good enough, but now we have the results with smaller virtual detector V05

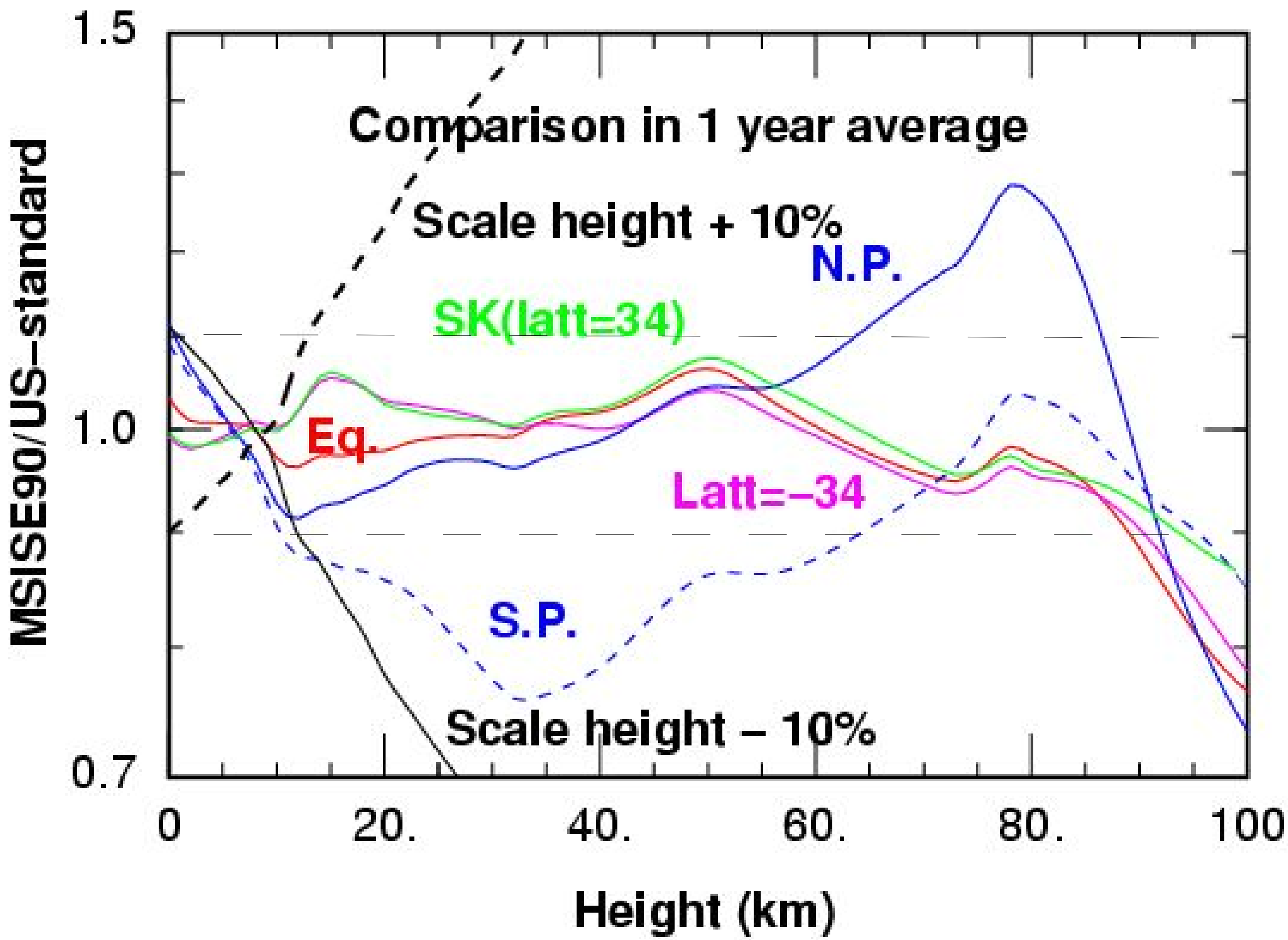

Atmosphere
NISHIKAWA

Model for Atmosphere

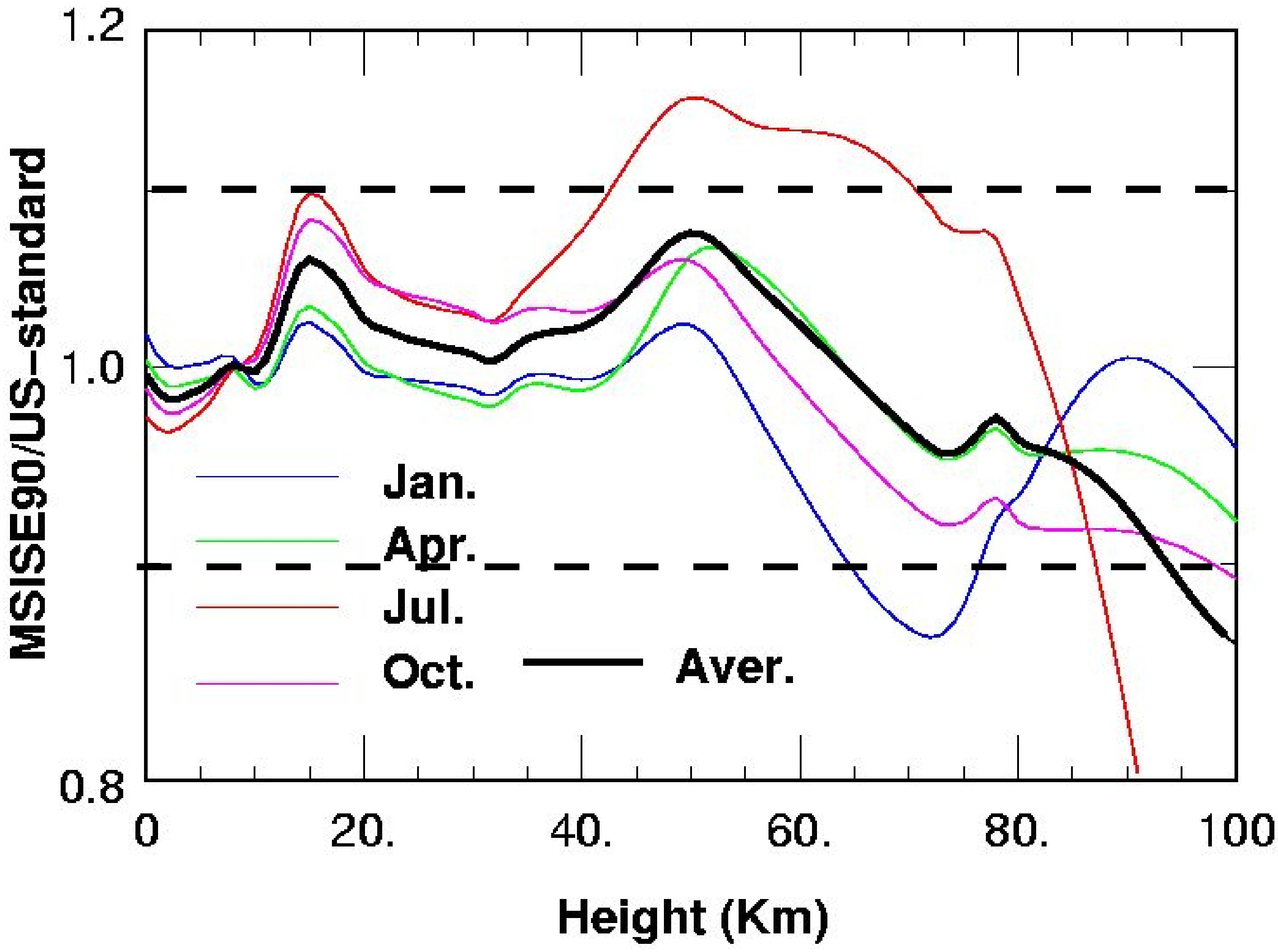




Comparison with newer atmosphere model based on the observation (MSISE90)

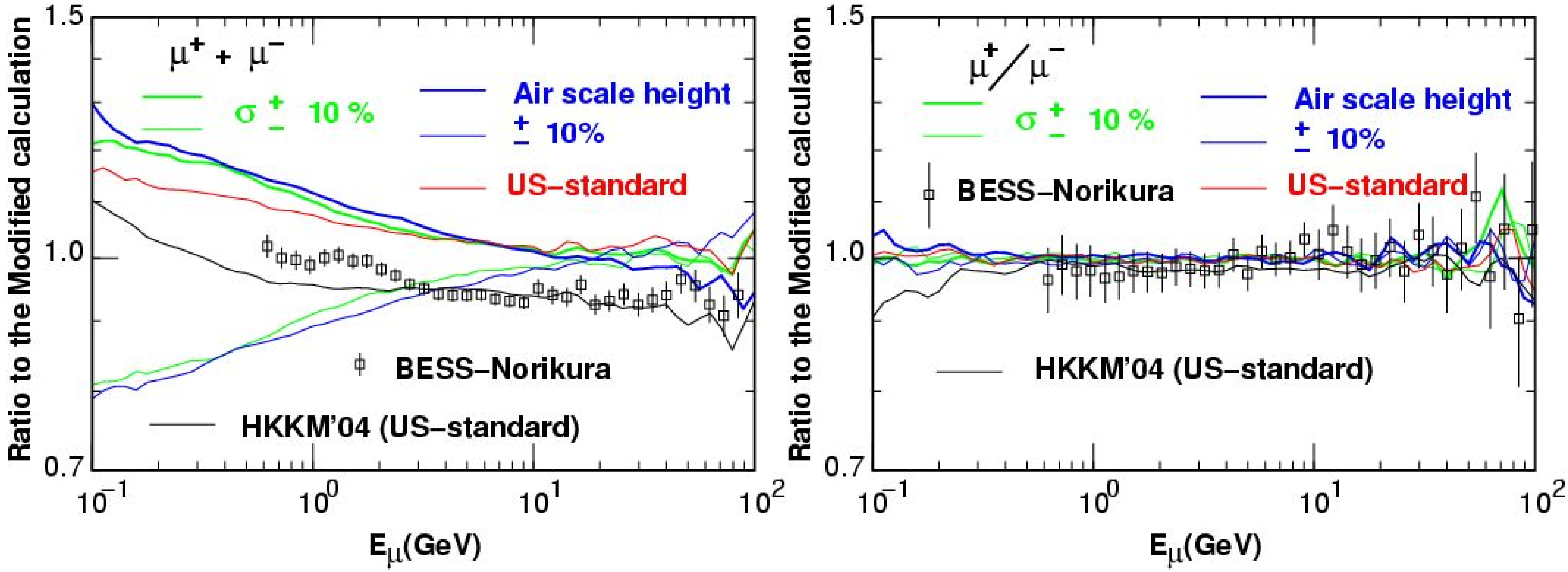


Atmosphere : Seasonal variation



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

Muon flux and Calculation conditions

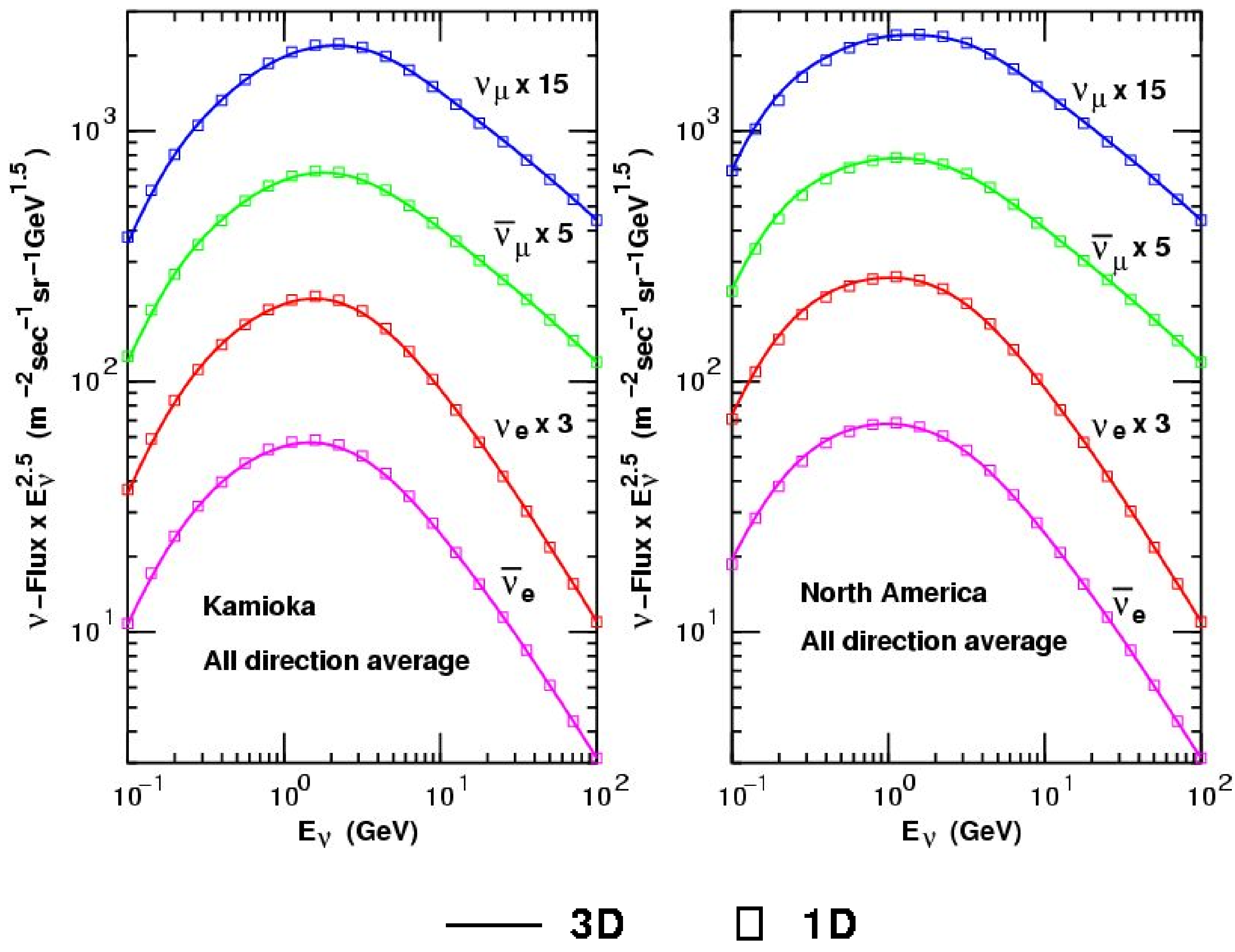


The Meteorological Data, continued to MSISE90 for higher altitude, is used as the atmosphere model.

These calculation condition is the source of the systematic error for the calculation of atmospheric neutrino flux !

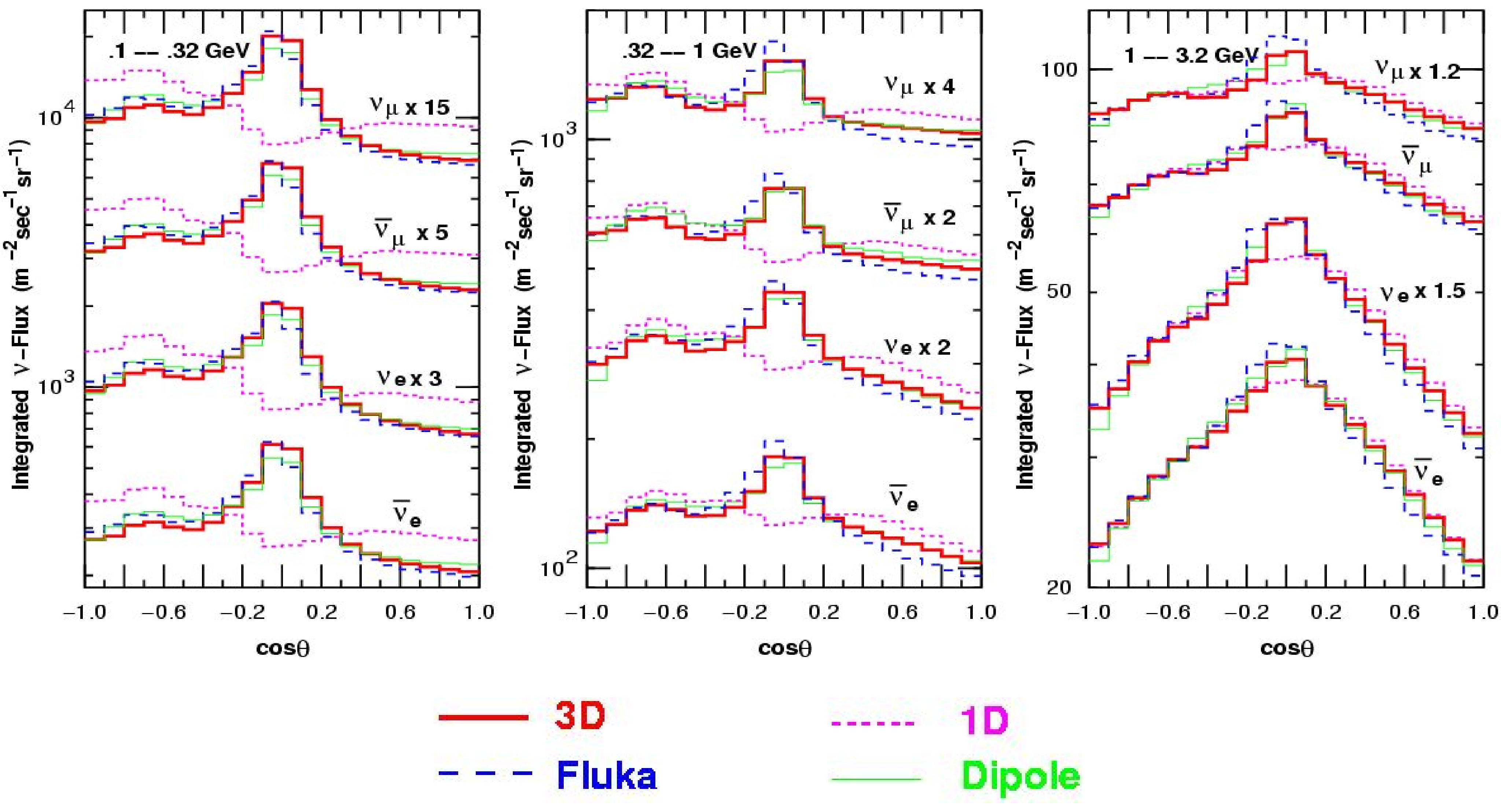
Summary of Calculated Atmospheric Neutrino Flux

Neutrino fluxes : All-direction average



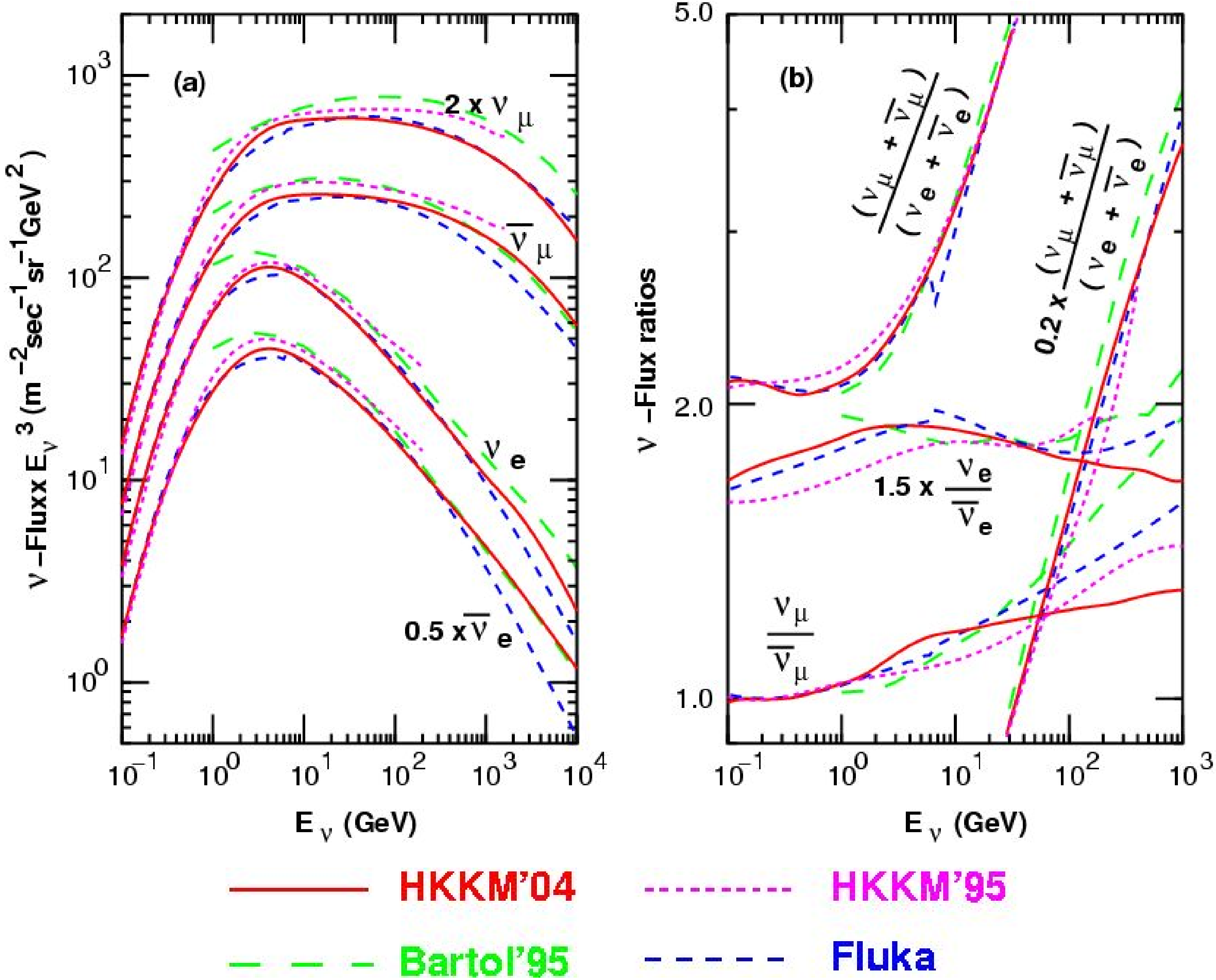
Both almost agree each other

Zenith angle dependence

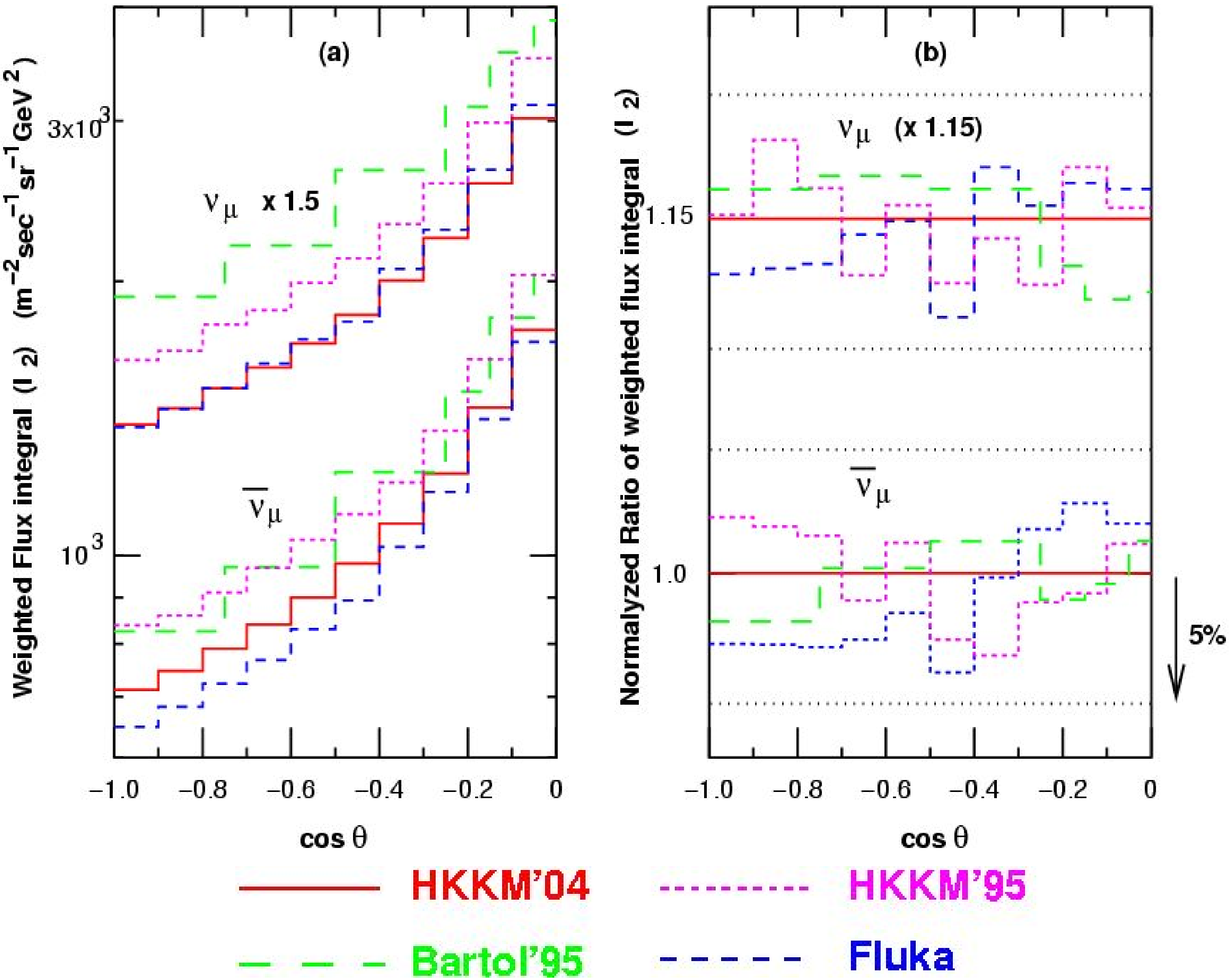


Large horizontal enhancement at low energy in 3D

High Energy Neutrino Fluxes



Zenith Angle dependence at High Energy



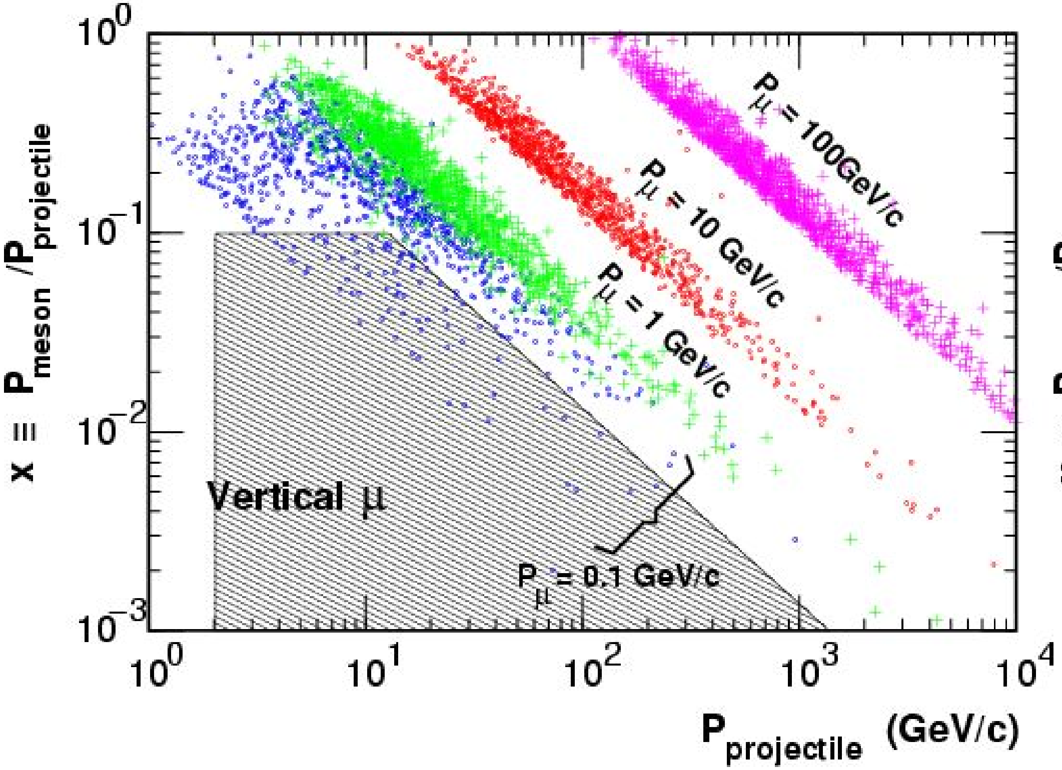
Almost the Same Slope among Different Calculations


Further Study of Interaction Model for
Better Prediction of the
Atmospheric Neutrino Flux

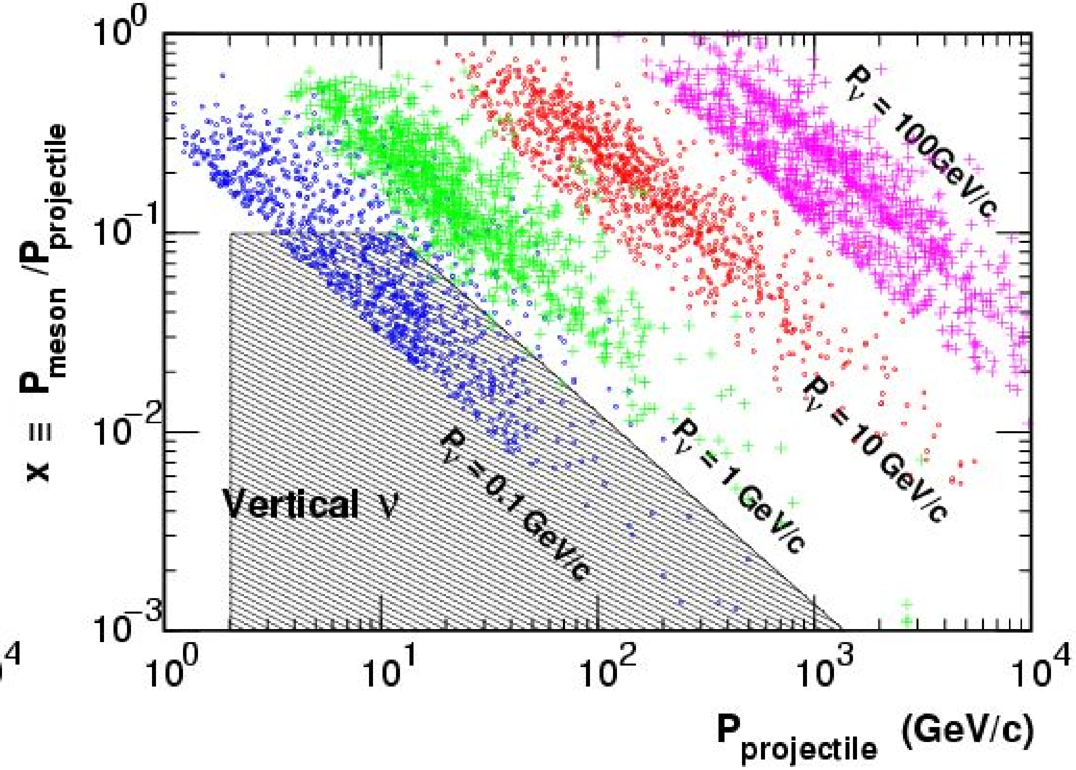
Mesons' phase space in the hadronic interaction

relevant to fixed momentum muons and neutrinos at ground level.

Muons

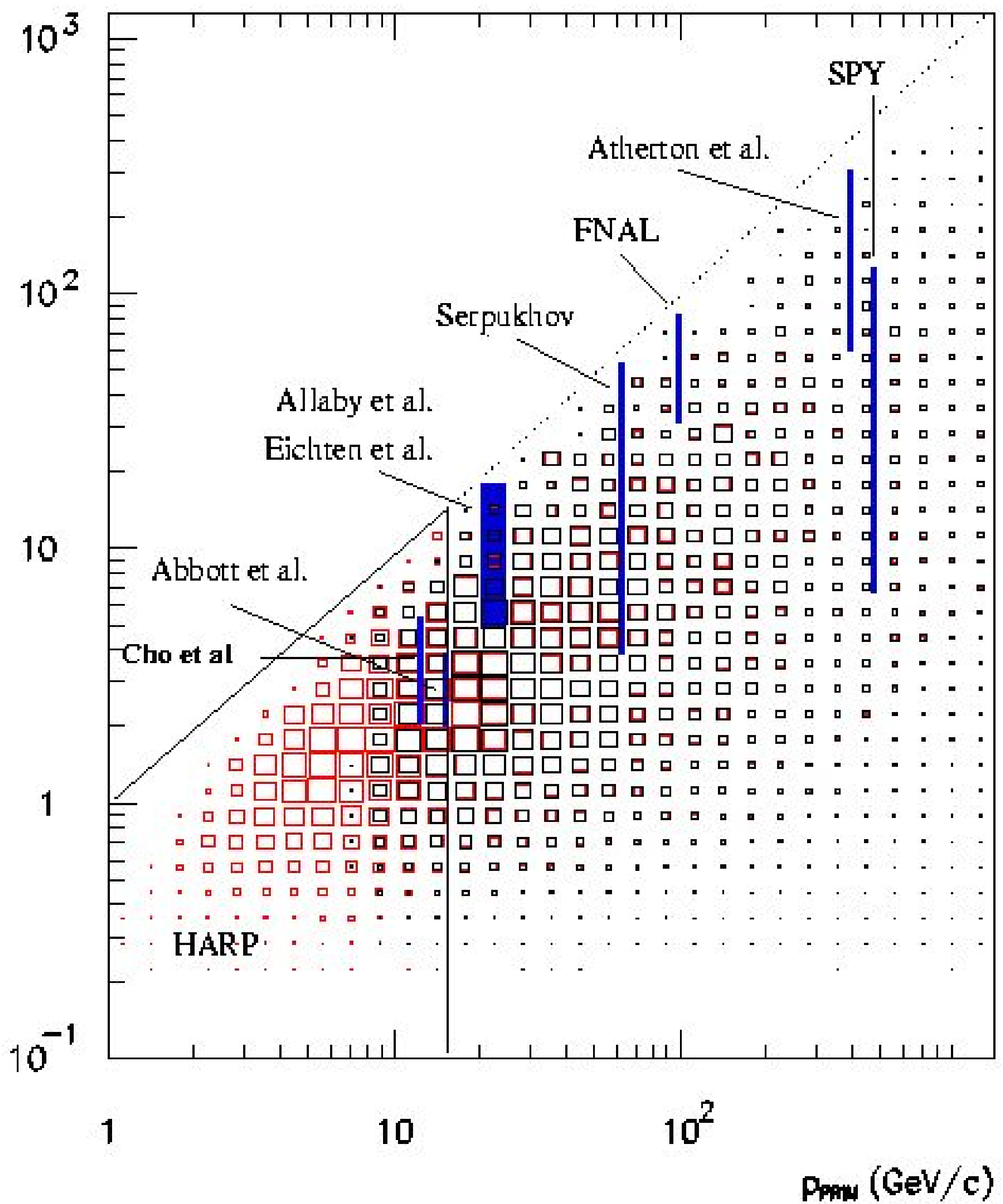


Neutrinos



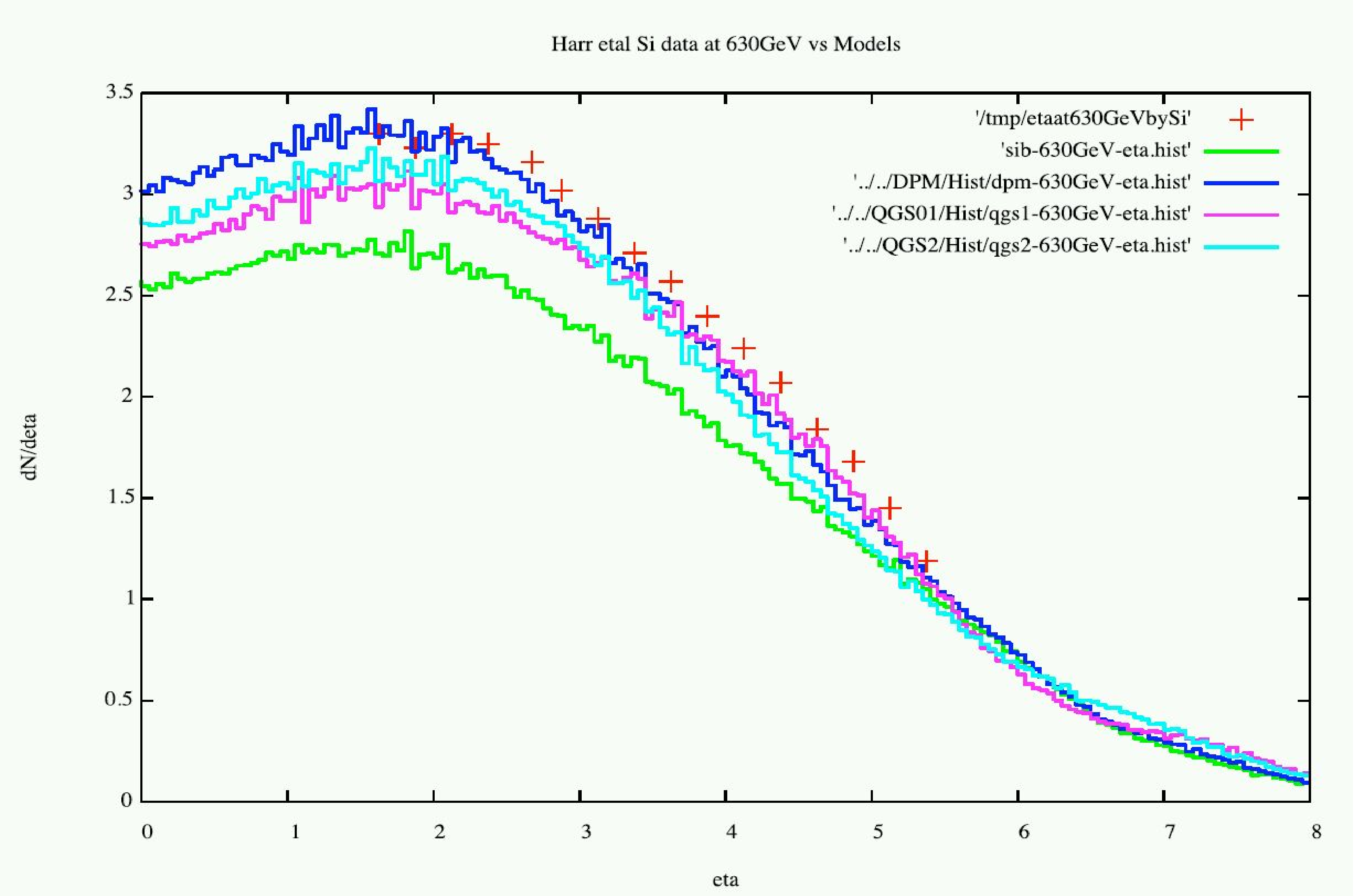
Good correlation above 1 GeV/c !

Summary of x-based Accelerator data

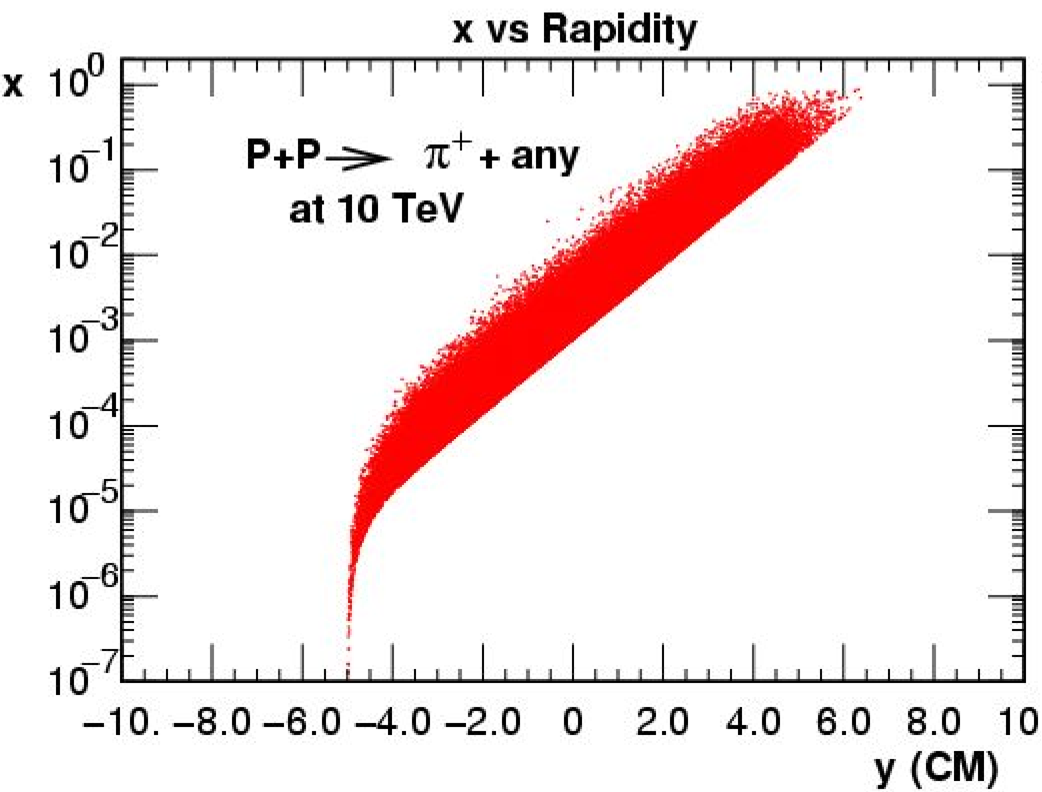


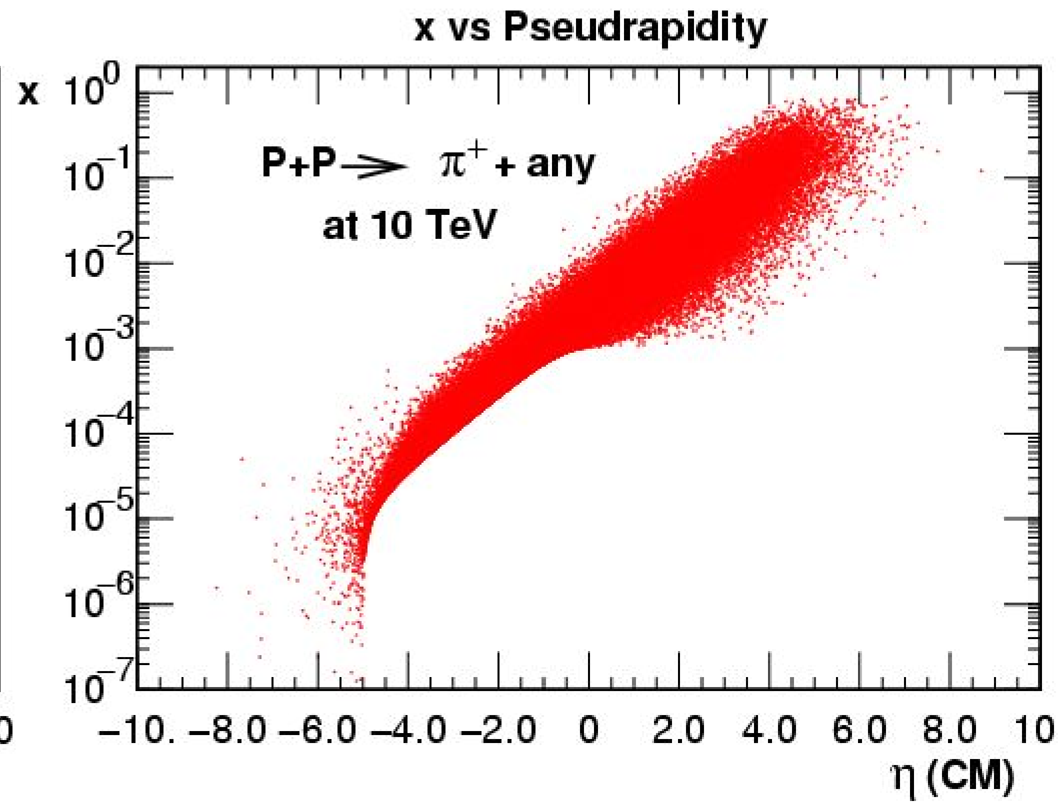
Comparison of Interaction model in pseudrapidity

Data: Silicon Calorimter data (Harr et al. PL B366 (1996) 434)



Rapidity vs Feynman $x (\equiv \frac{p}{p_{proj}})$





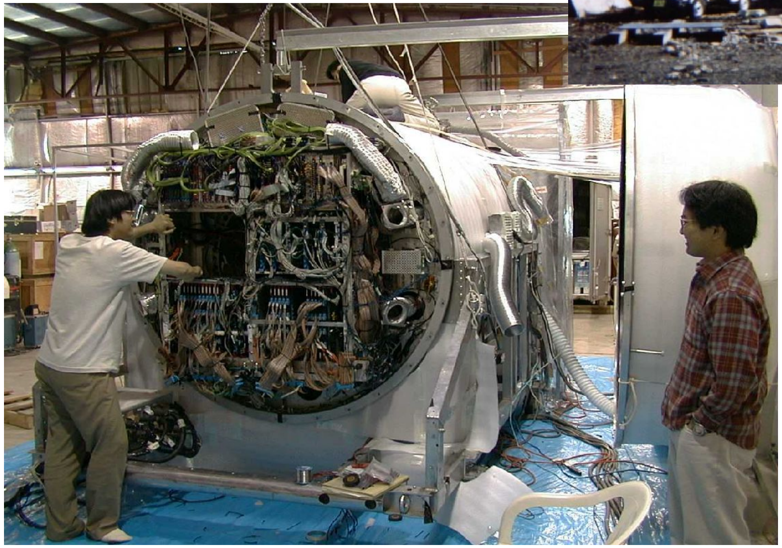
Muon Observations

Balloon Altitude

L3+C

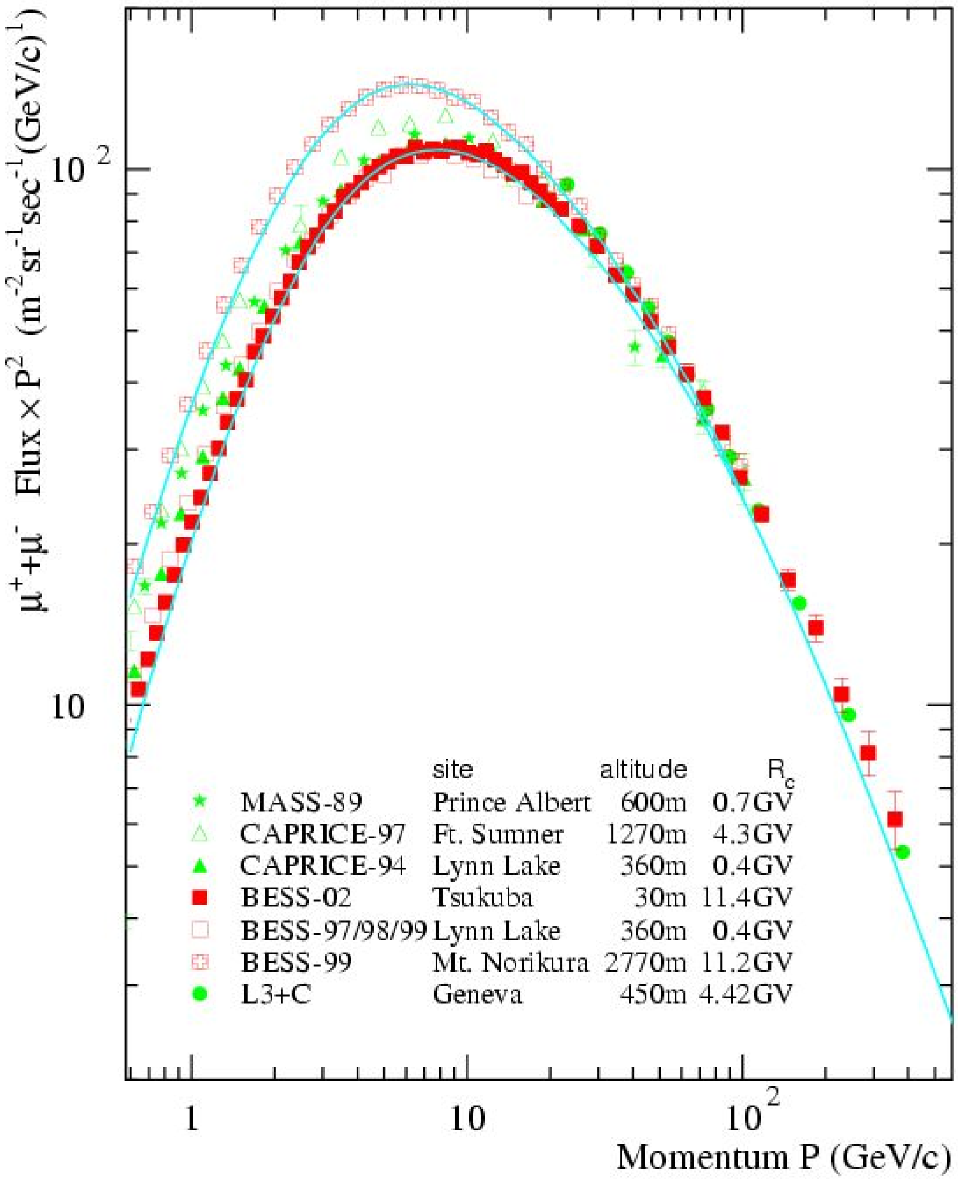
Mt Norikura

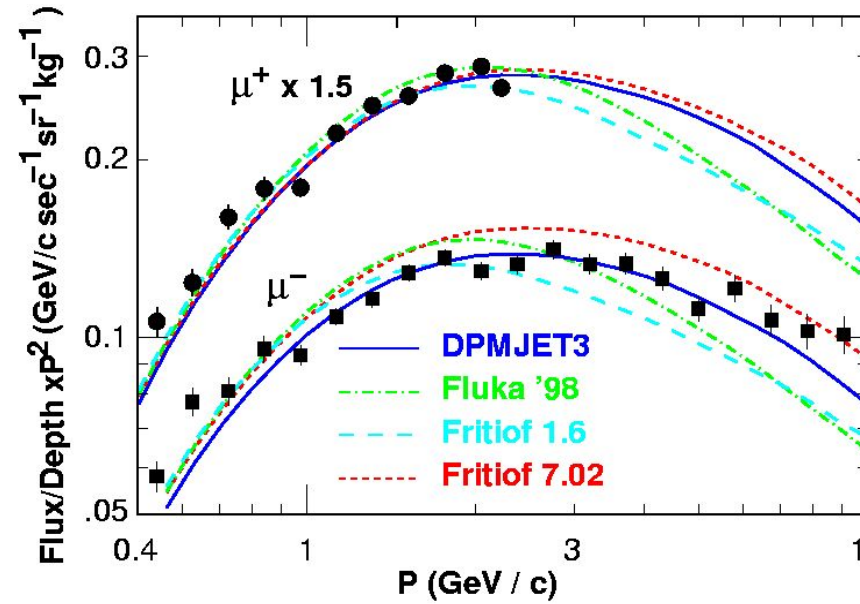
BESS

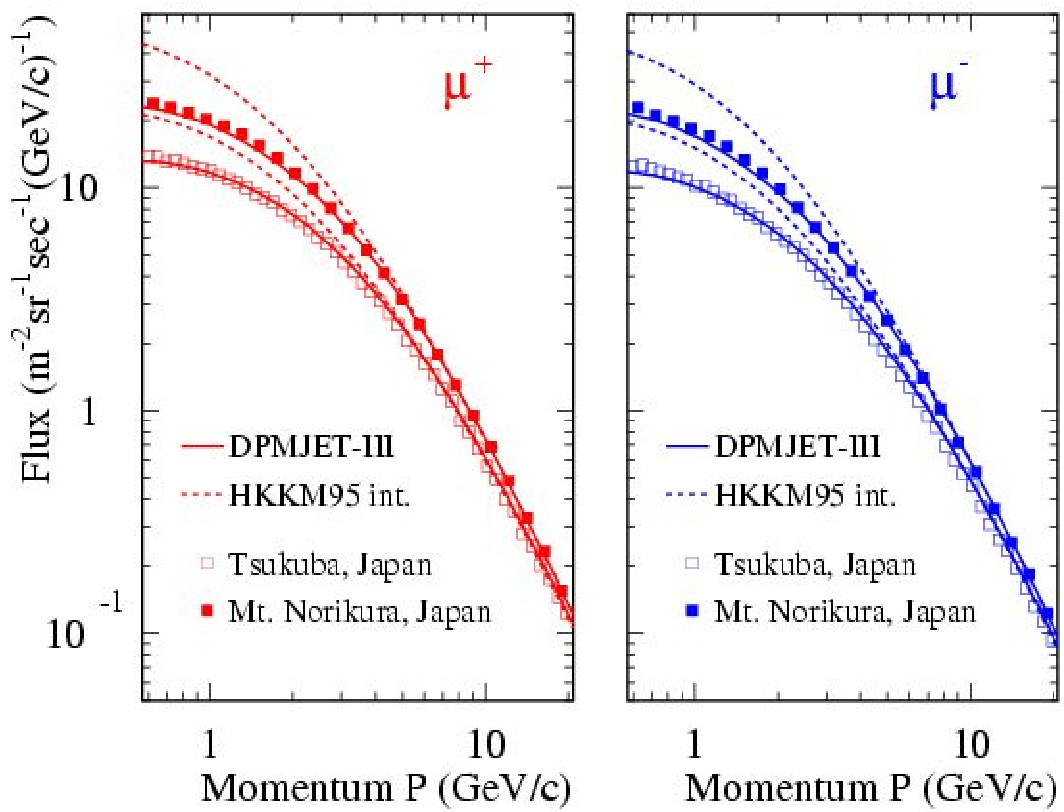


Tsukuba (KEK)

Muon Observations Data

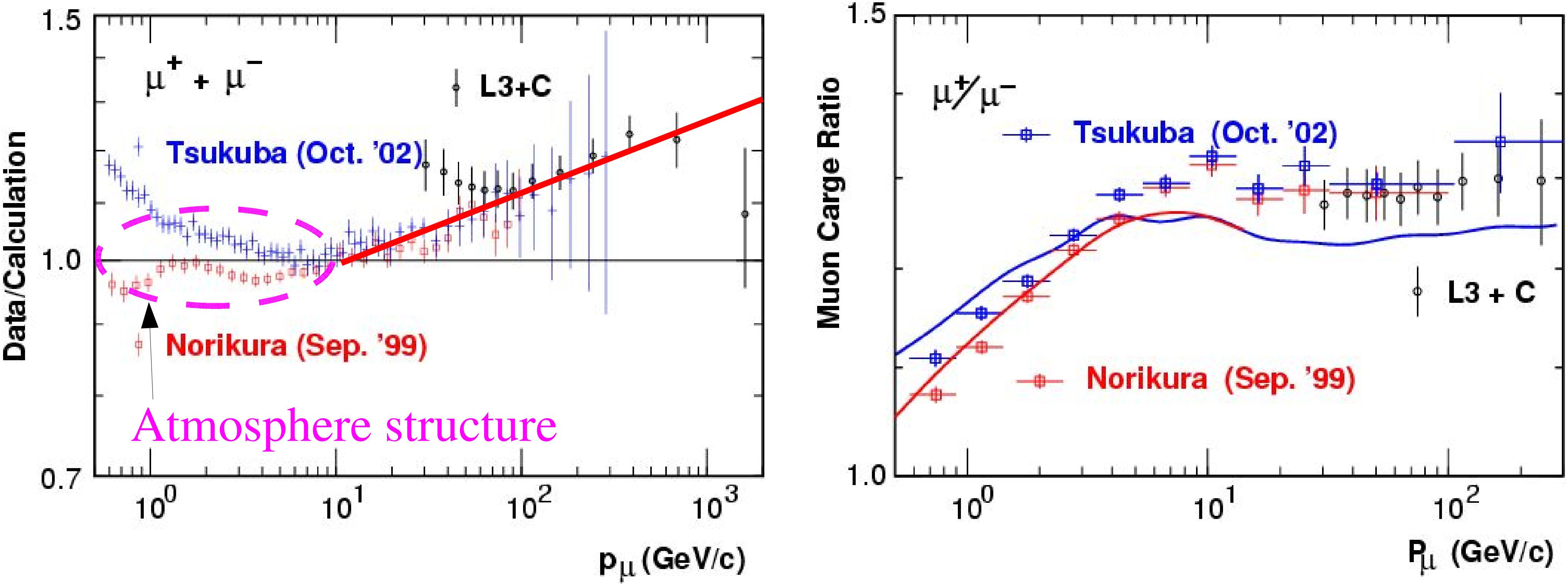






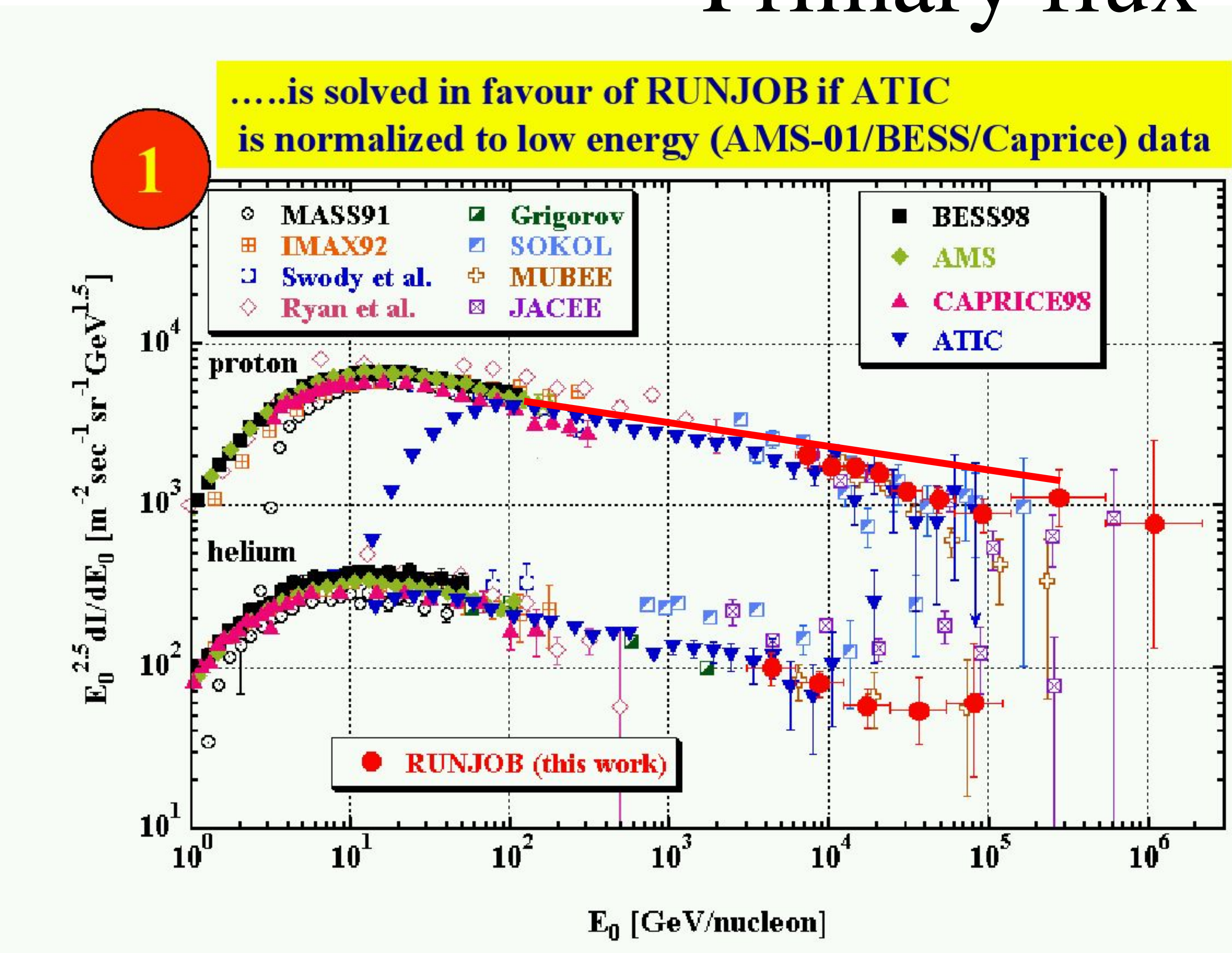
Comparison of Muon Flux Calculated in HKKM04 and Observed Data.

The differences are ~5% in absolute value for 1 ~ 30 GeV/c, and ~ 5% in charge ratio for all momentums.

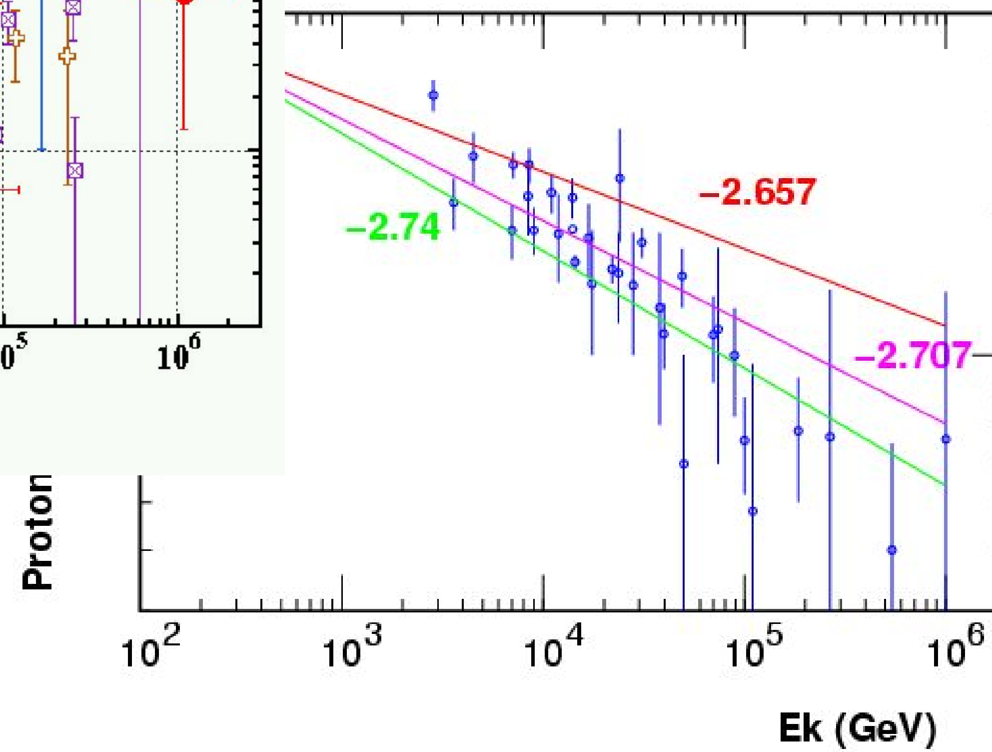


The difference of the absolute value increases at high energies, as $\sim(P/10\,GeV)^{0.05}$.

Primary flux ?

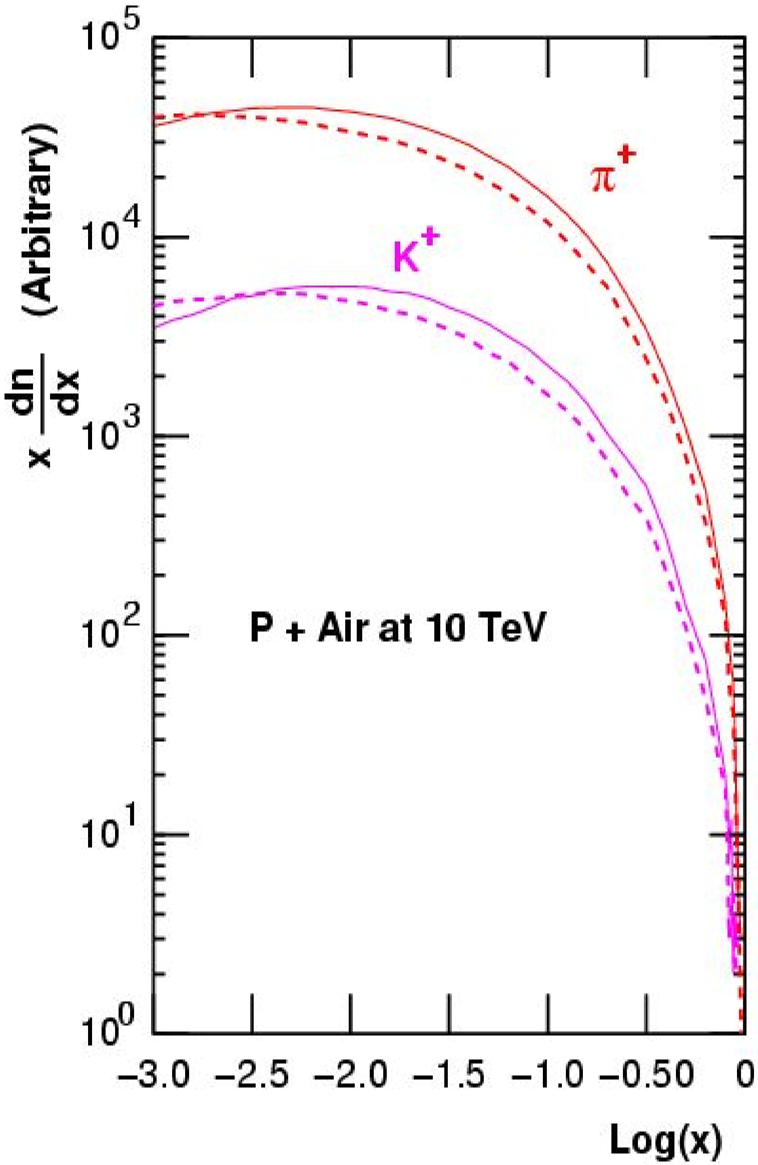


Change of power index from -2.71 to -2.66 above 100 GeV



It is difficult to explain the charge ratio with primary flux only.

Modification of the interaction model



0. Base is the inclusive DPMJET-III.

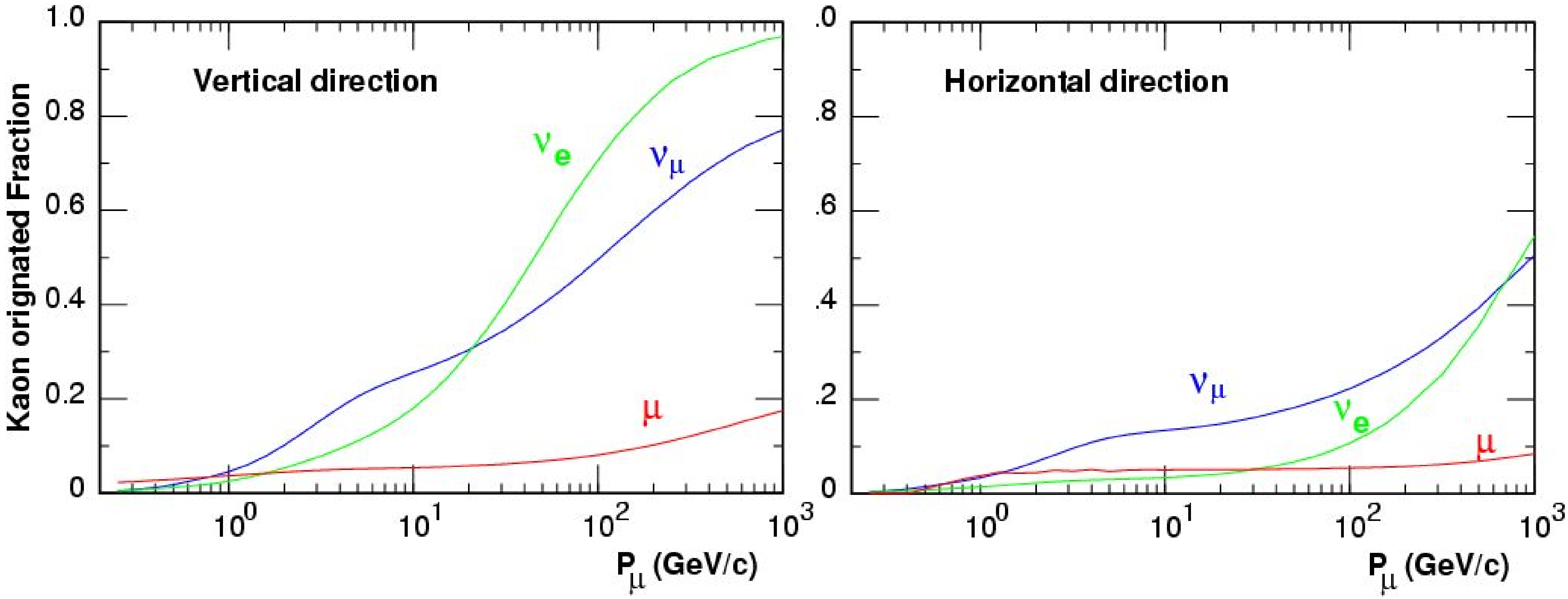
1. The average energy of secondary mesons which have the same valence quark as the projectile are modified by the change of the x-distribution shape. $(x_i = E_i / E_{proj})$

2. Conserve the multiplicity of secondary particles.

3. Nucleons are the counter-balance for the energy conservation.

4. Iso-symmetry (symmetry under $u \leftrightarrow d$ exchange) is retained.

The Contribution of Kaons is Largely Different for Muons and Neutrinos at High Energies.



Quark Based modification

For proton $(u\,u\,d)$ and neutron $(u\,d\,d)$ projectiles

π^+	π^-	π^0
$(u\,\bar{d})$	$(d\,\bar{u})$	$(u\,\bar{u}+d\,\bar{d})/2$
K^+	K^-	K^0
$(u\,\bar{s})$	$(s\,\bar{u})$	$(s\,\bar{d}) \leftrightarrow (d\,\bar{s})$ Oscillations

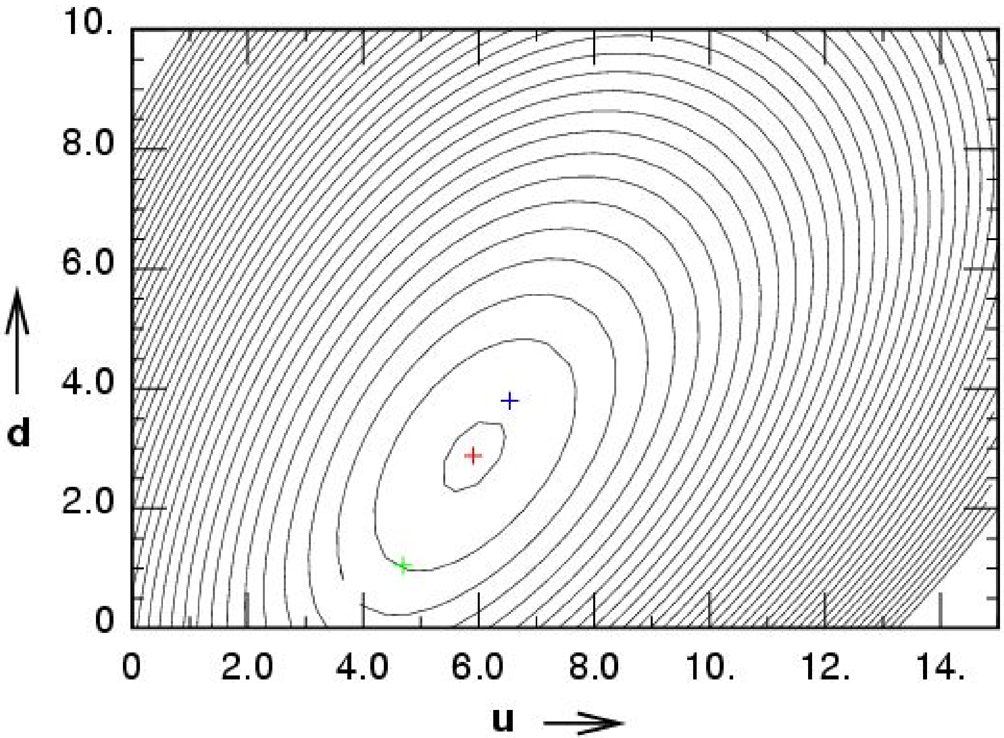
The magnitude of variations for $\begin{Bmatrix} \pi^0 & K^+ \\ \pi^0 & K^0 \end{Bmatrix}$ are $\begin{Bmatrix} ½ & 1 \\ ½ & ½ \end{Bmatrix}$ of $\begin{Bmatrix} \pi^+(u) \\ \pi^-(d) \end{Bmatrix}$

Note, π^0 is bilinear to u and d-variations.

No variation for K^-

Parameter search using muon data

parameter search (example)

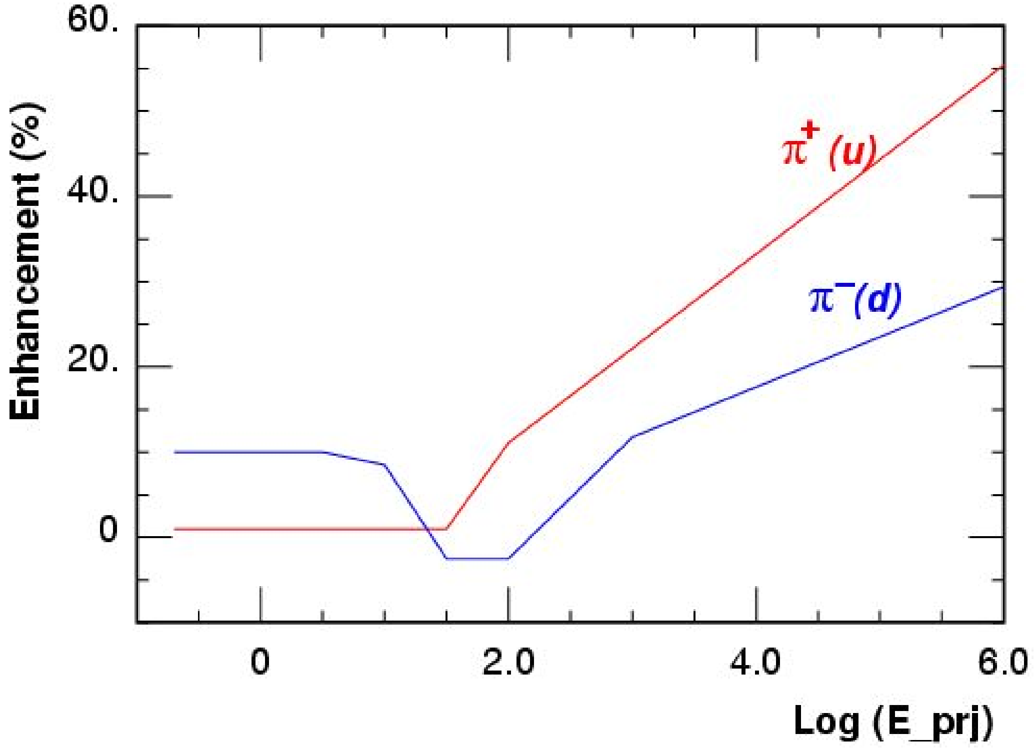


Vertical all: x,y,z = 5.91000E+00 2.88000E+00 2.23195E+01

L3+c : x,y,z = 6.54000E+00 3.80000E+00 5.32674E+00

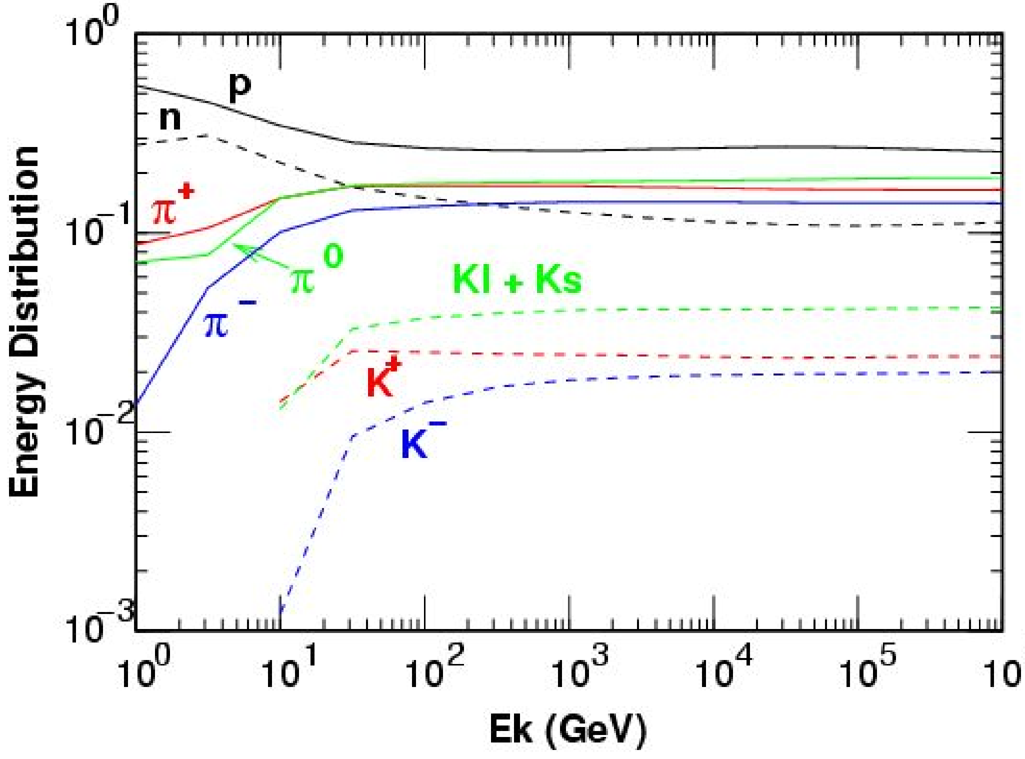
BESS: x,y,z = 4.69000E+00 1.05000E+00 3.82626E+00

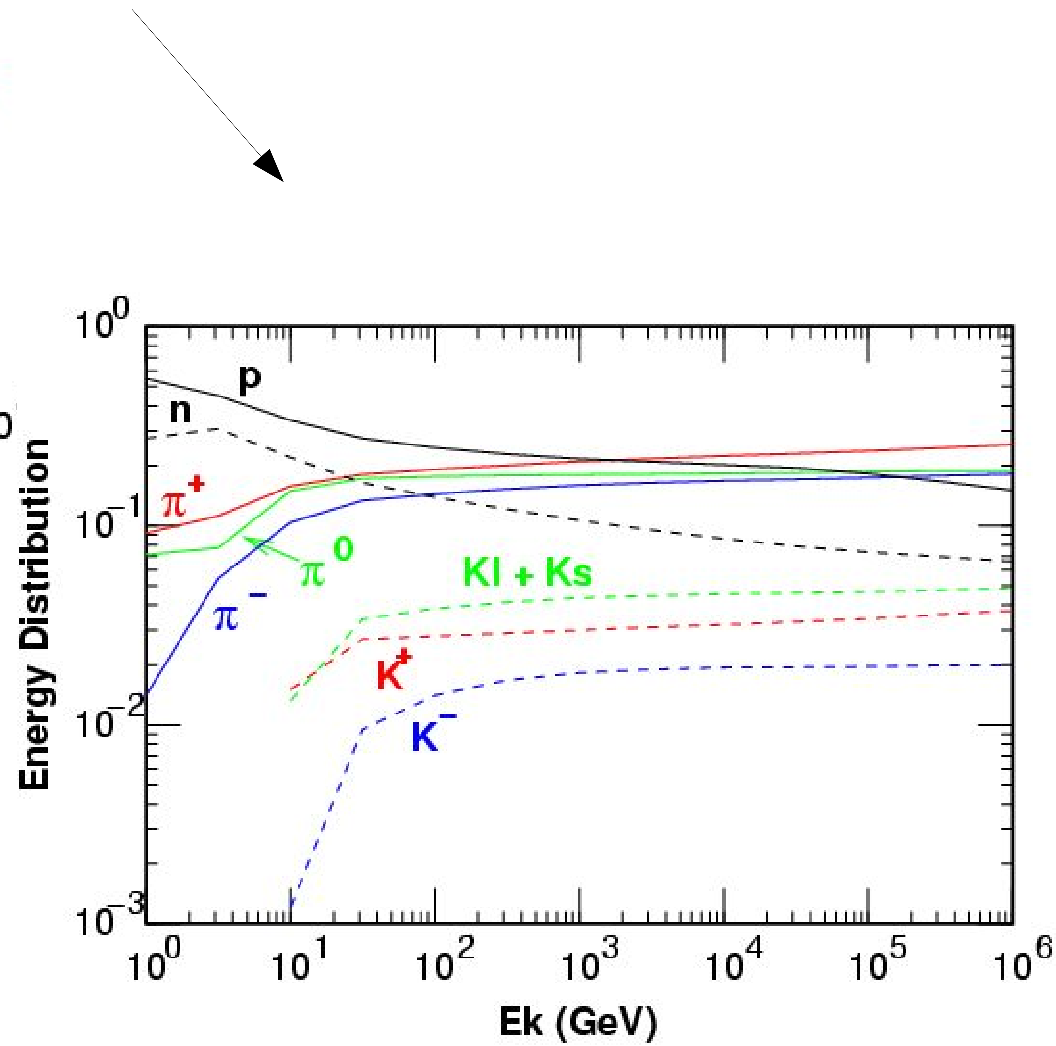
Magnitude of variation as the function of projectile energy



Before and After the Interaction Modification (I)

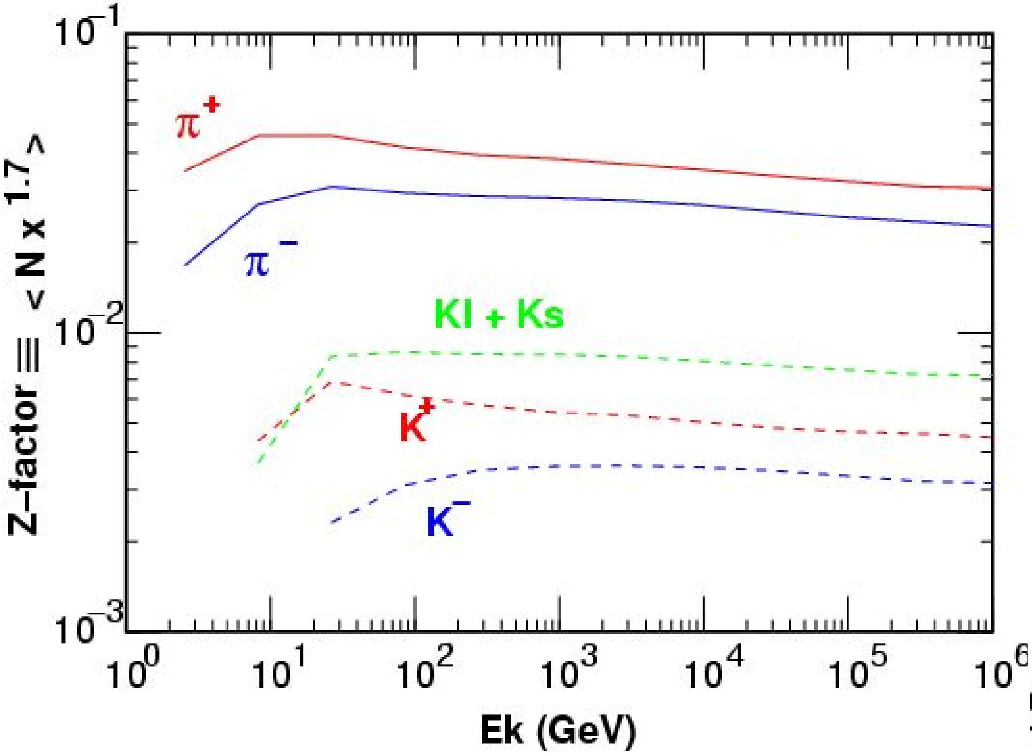
Energy distribution

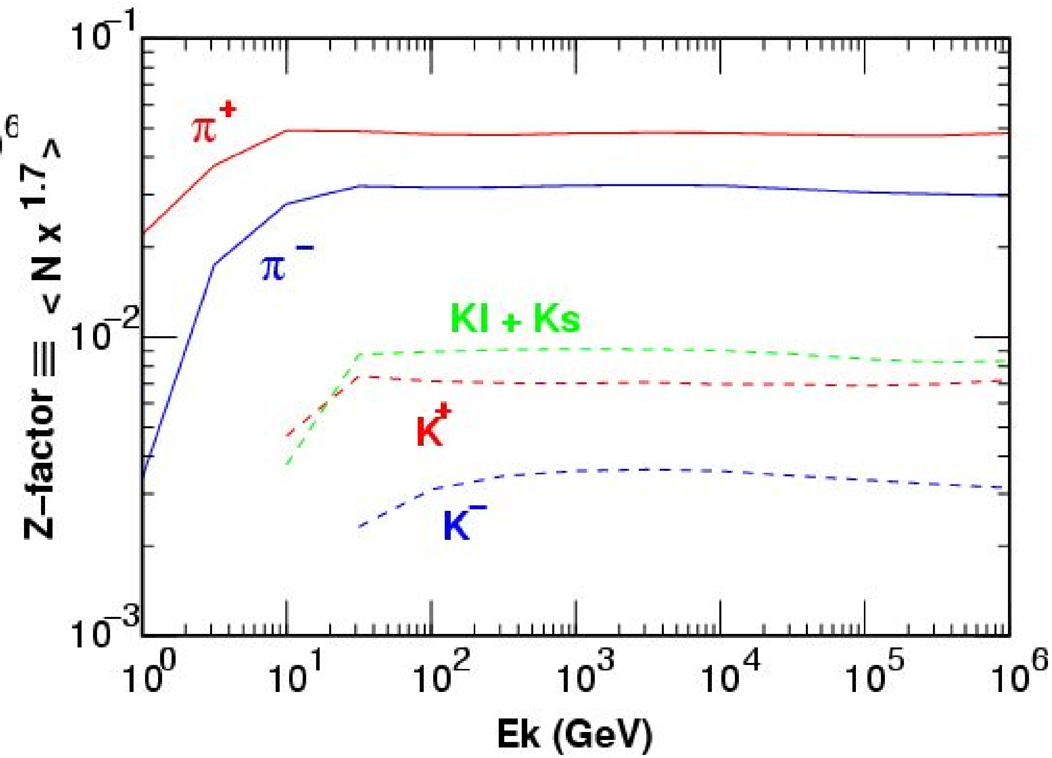




Before and After the Interaction Modification (II)

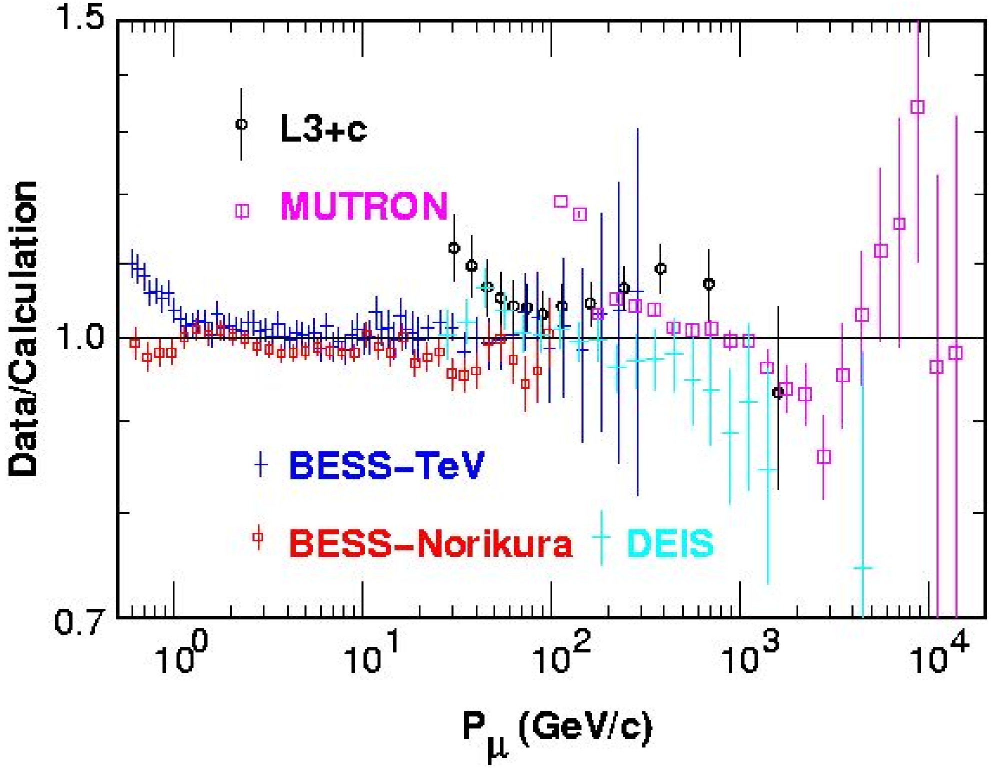
Z-factor $(Z \equiv N_i < x^{1.7} >)$

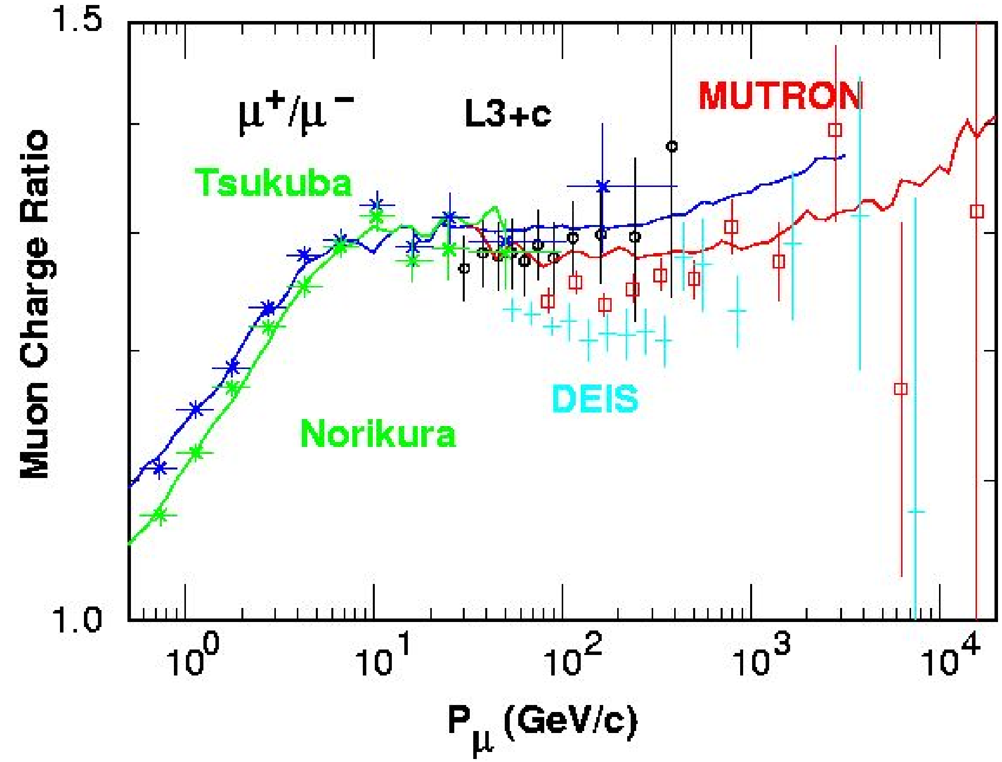




Modified interaction model recover the scaling hypothesis.

Comparison of Modified Results with the Observations

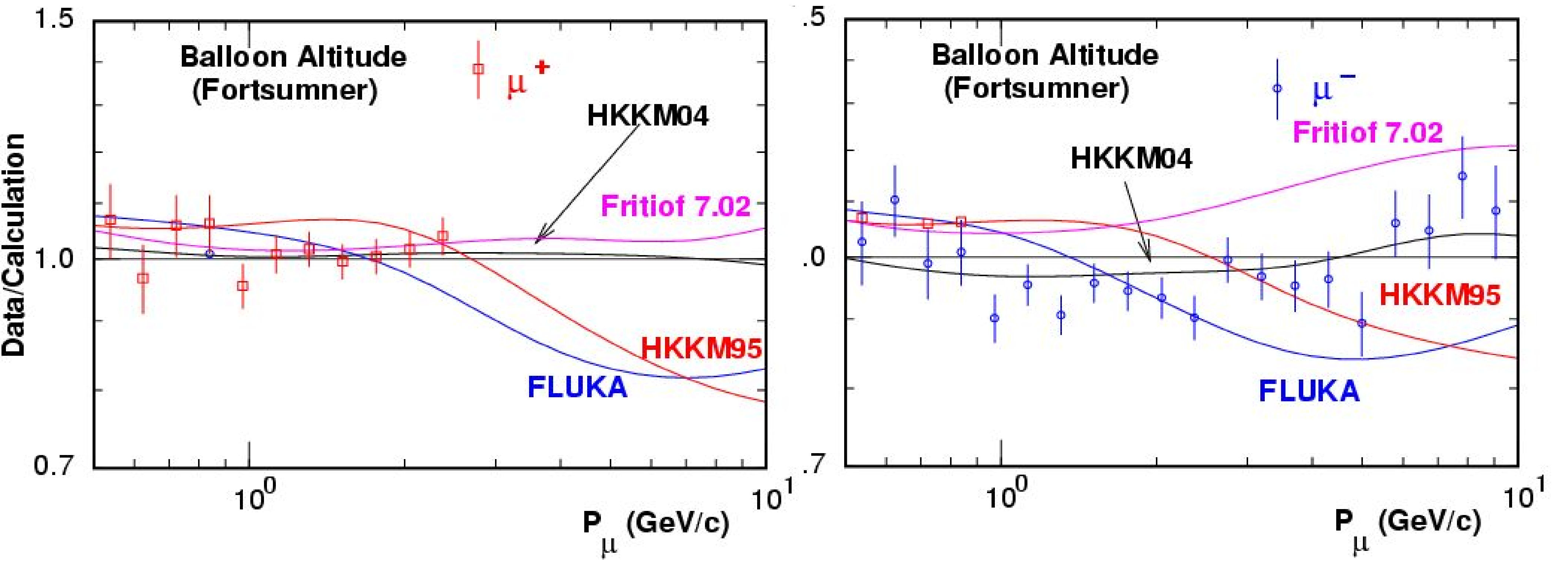




The calculation and data agree well within 10 % in 0.5 GeV/c ~1 TeV/c, and < 5% in 1~30GeV/c.

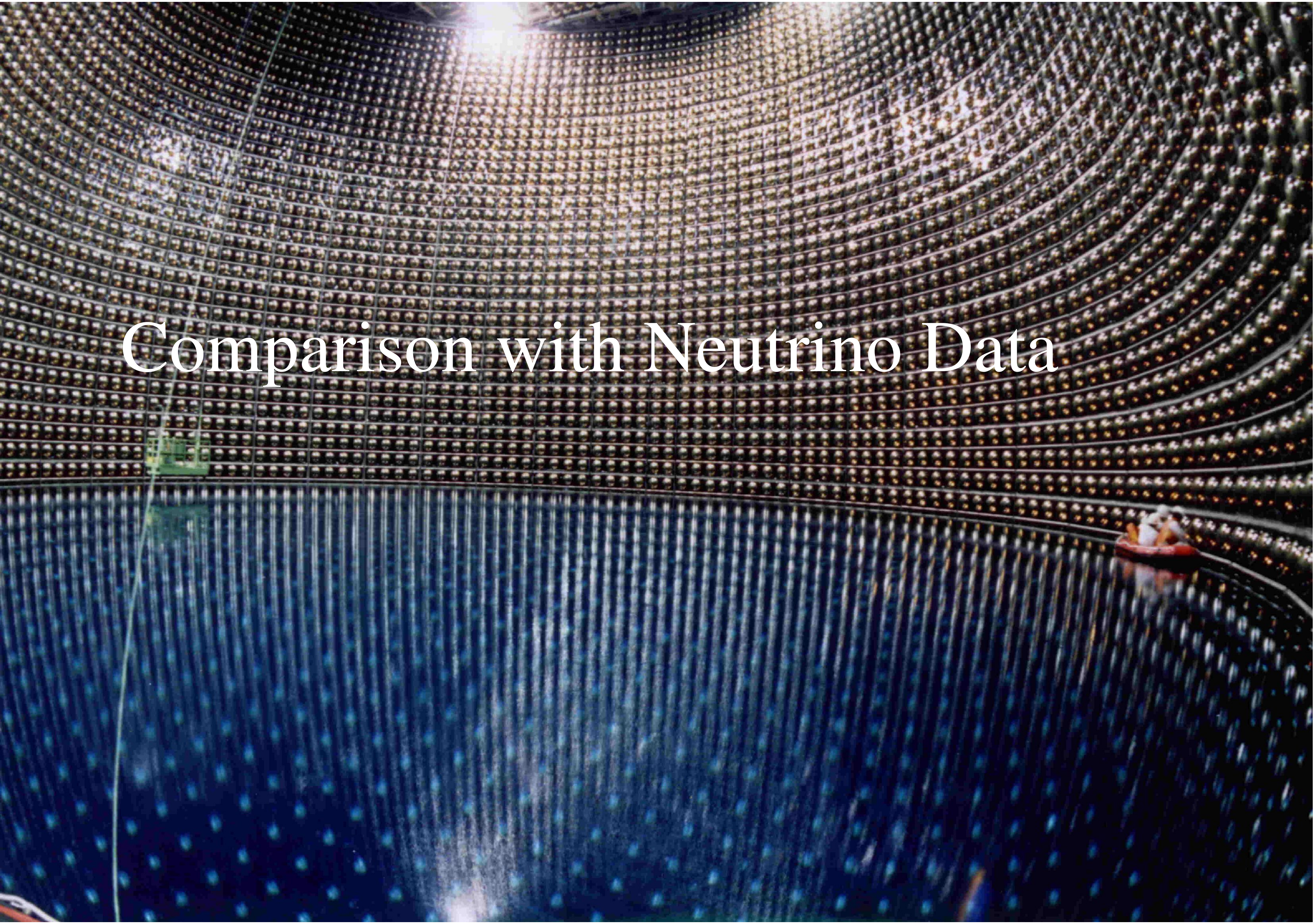
Muons at balloon altitude

Comparison of <Flux / depth> between calculation and observation

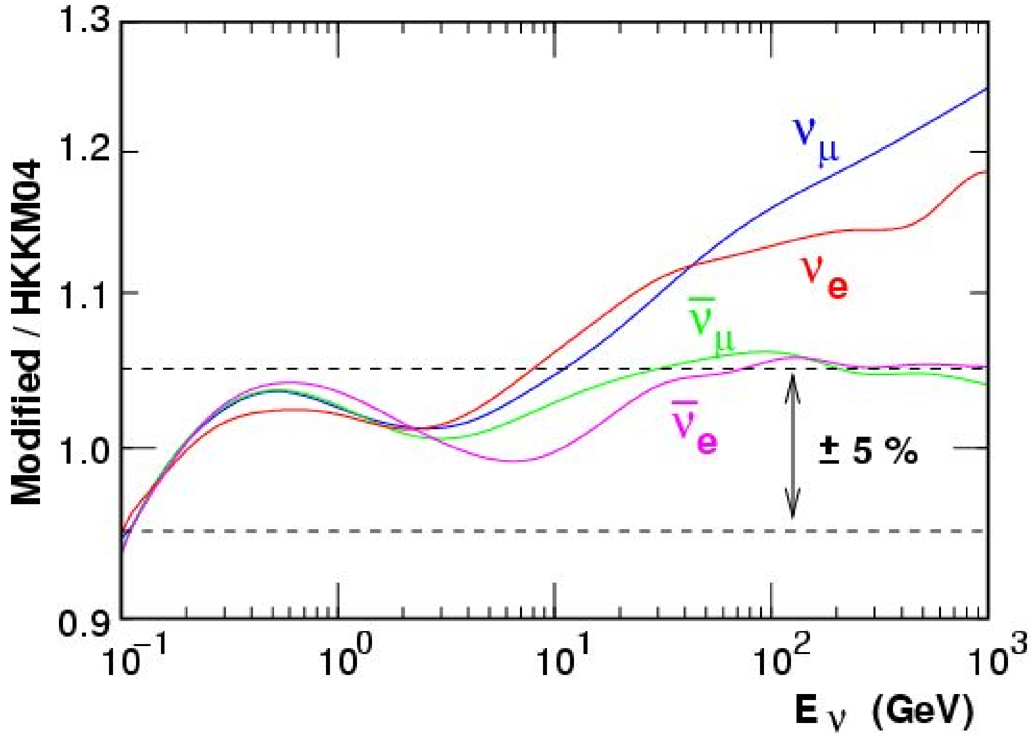


Agreement is better in the original DPMJET-III,
but Modified one is not so bad !

Comparison with Neutrino Data



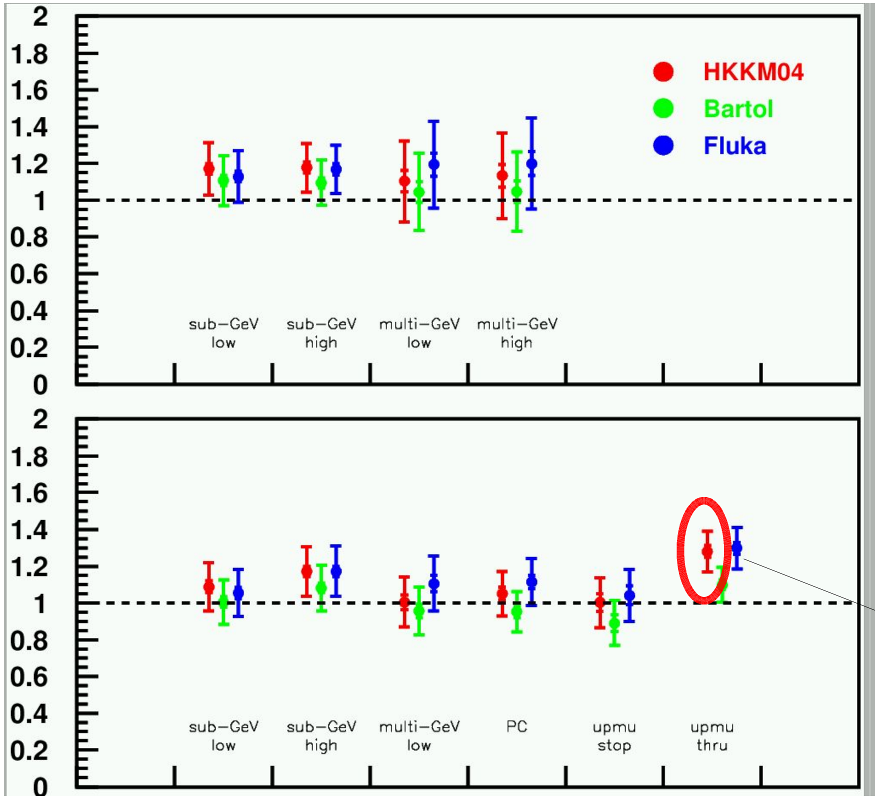
Comparison of Modified Neutrino Flux with HKKM04



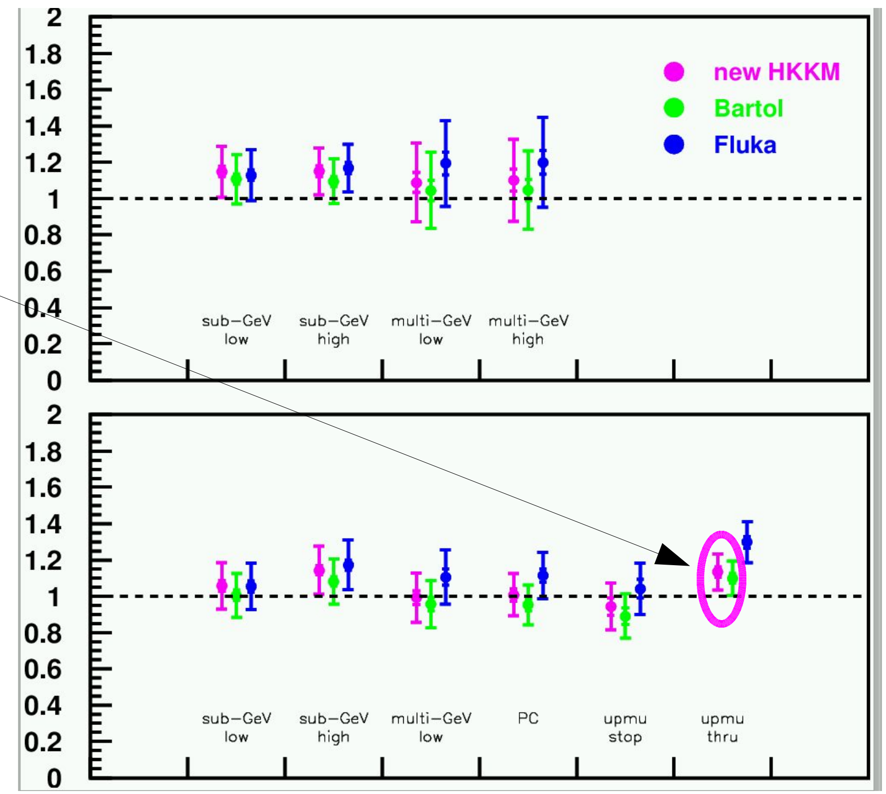
They agree within 5% below 10 GeV.

Comparison with Neutrino data

Before the modification



After the modification



Our assumption for Kaon is supported by the data !

Summary

- DPMJET-III is good interaction model for

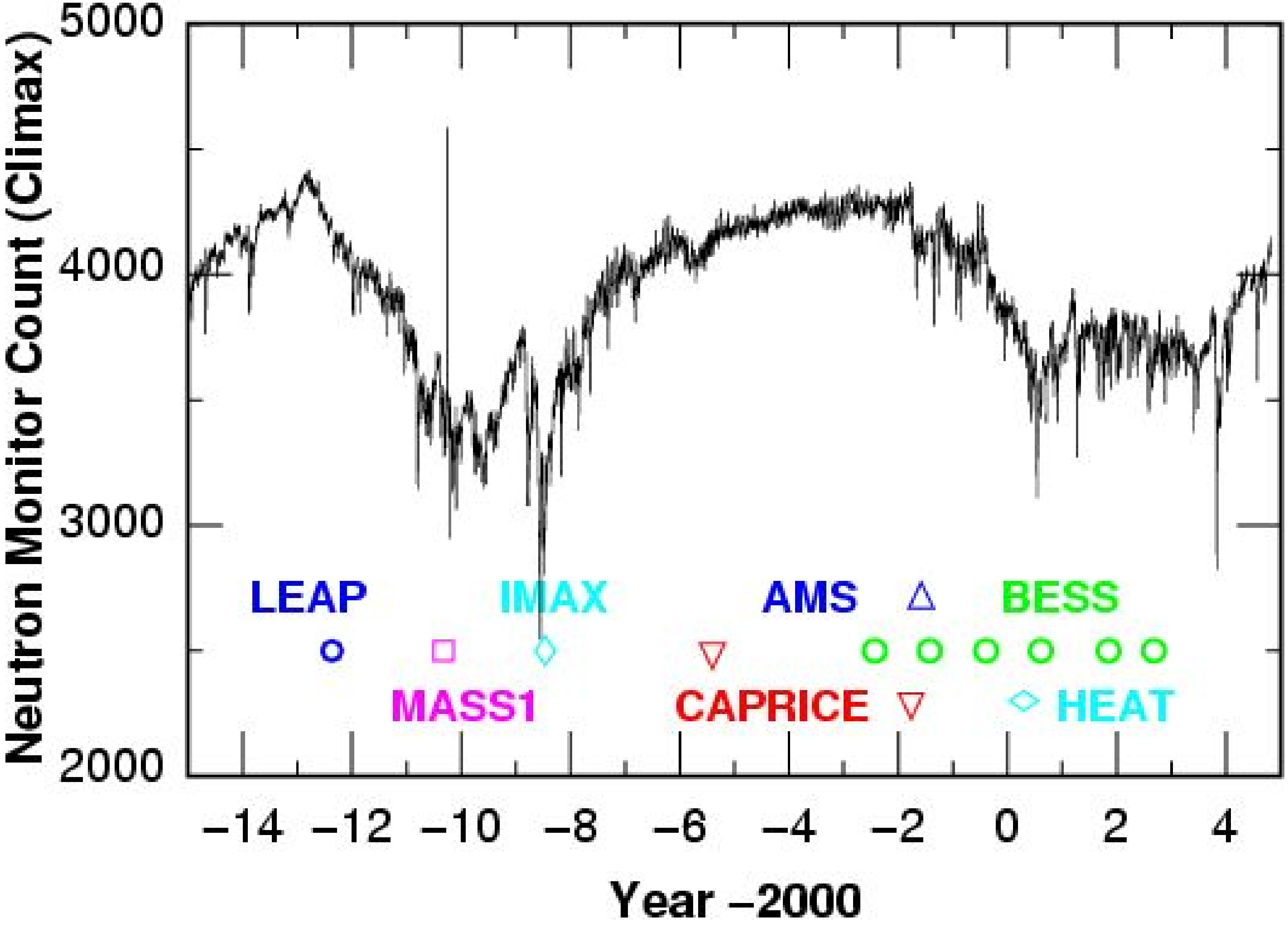
$E_{\mu,\nu} \leqslant 10\, GeV/c \quad (E_{proj} \leqslant 100\, GeV)$

- However, it need to be modified to explain the muon observations. $(E_{proj} \geqslant 100\, GeV)$

- We need an assumption for Kaon production for the calculation of the atmospheric neutrino flux.
A "proper" assumption make the neutrino flux largely increased above 100 GeV, in agreement with the SK observation.

- Feynman x-base analysis in Collider is preferable at x ~ 0.1 for each particle.

Modulation by the Solar Activity



Spectra Modulation Formula

$$F_{p,He}(E_k, N) = F_{mod}(N, r) \cdot F^0_{p,He}(E_k)$$

and

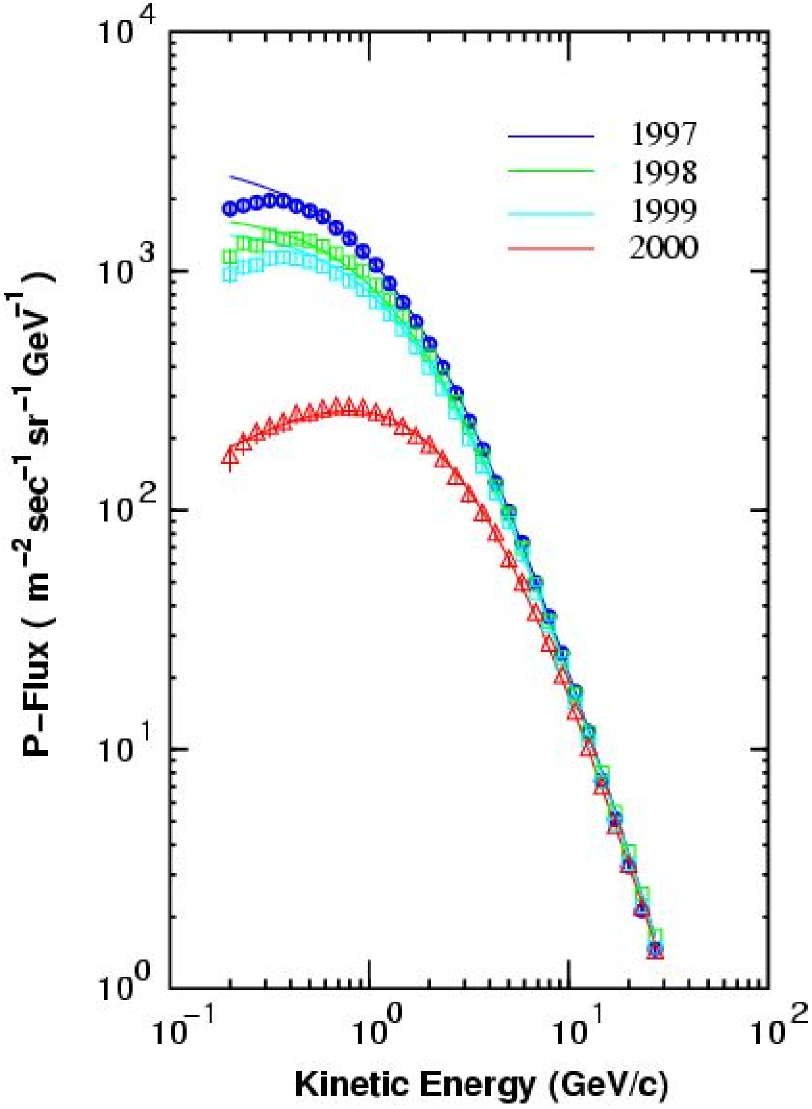
$$F_{mod}(N, r) = \exp\left(\frac{A + B \cdot N}{C + D \cdot N + r^e}\right),$$

where

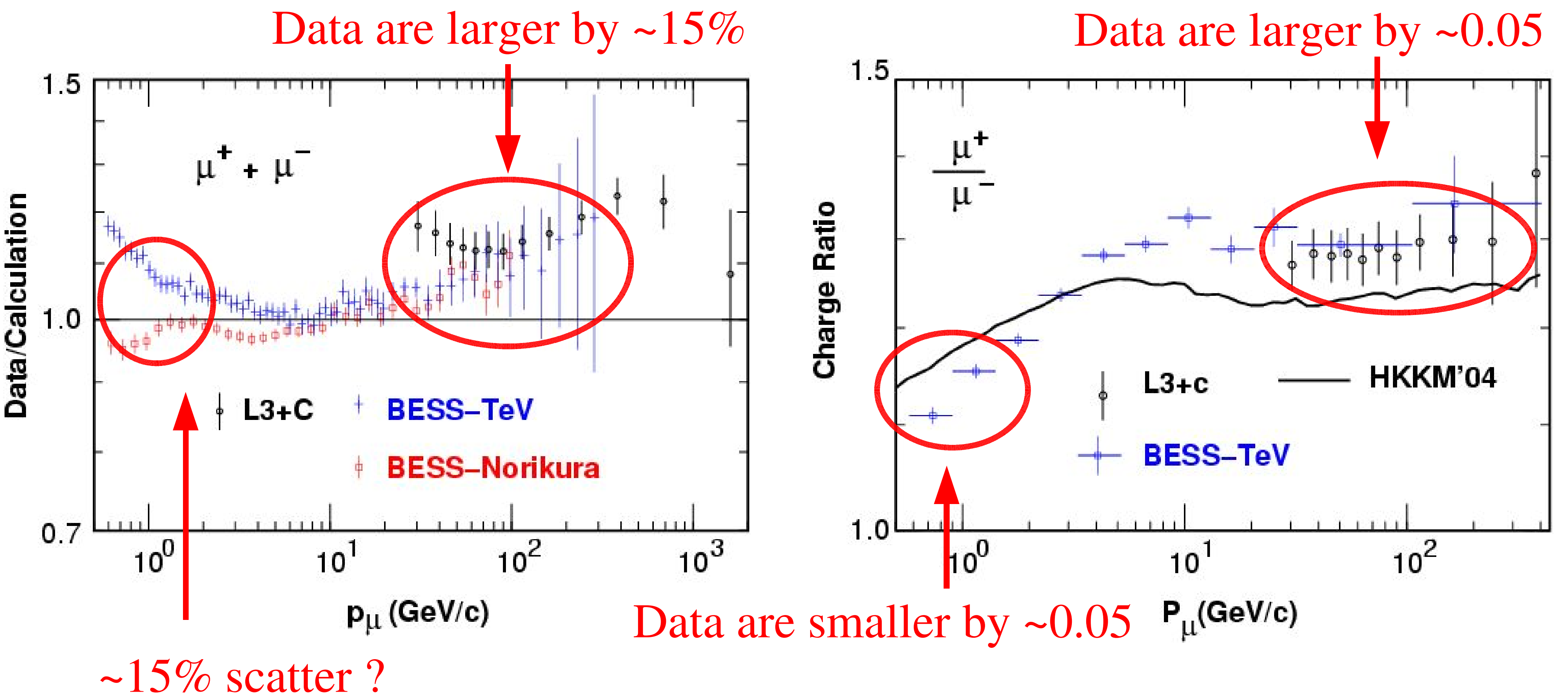
N : Neutron Monitor counts

$$r = \sqrt{(E_k + m_p)^2 - m_p^2} \quad \text{(for proton)}$$

$$r = \frac{1}{2}\sqrt{(E_k + m_p)^2 - m_p^2} \quad \text{(for Helium)}$$

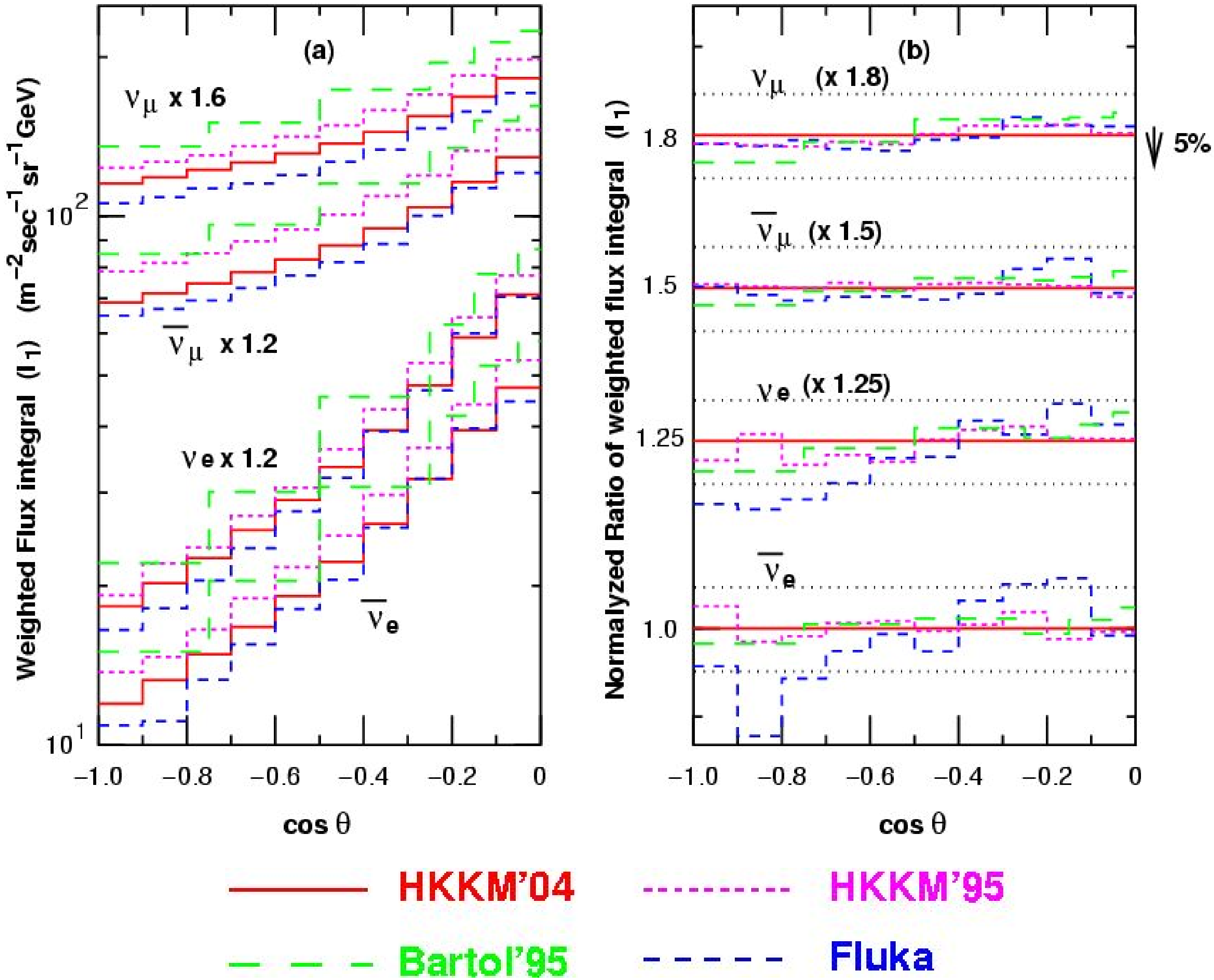


Comparison with high precision muon observations

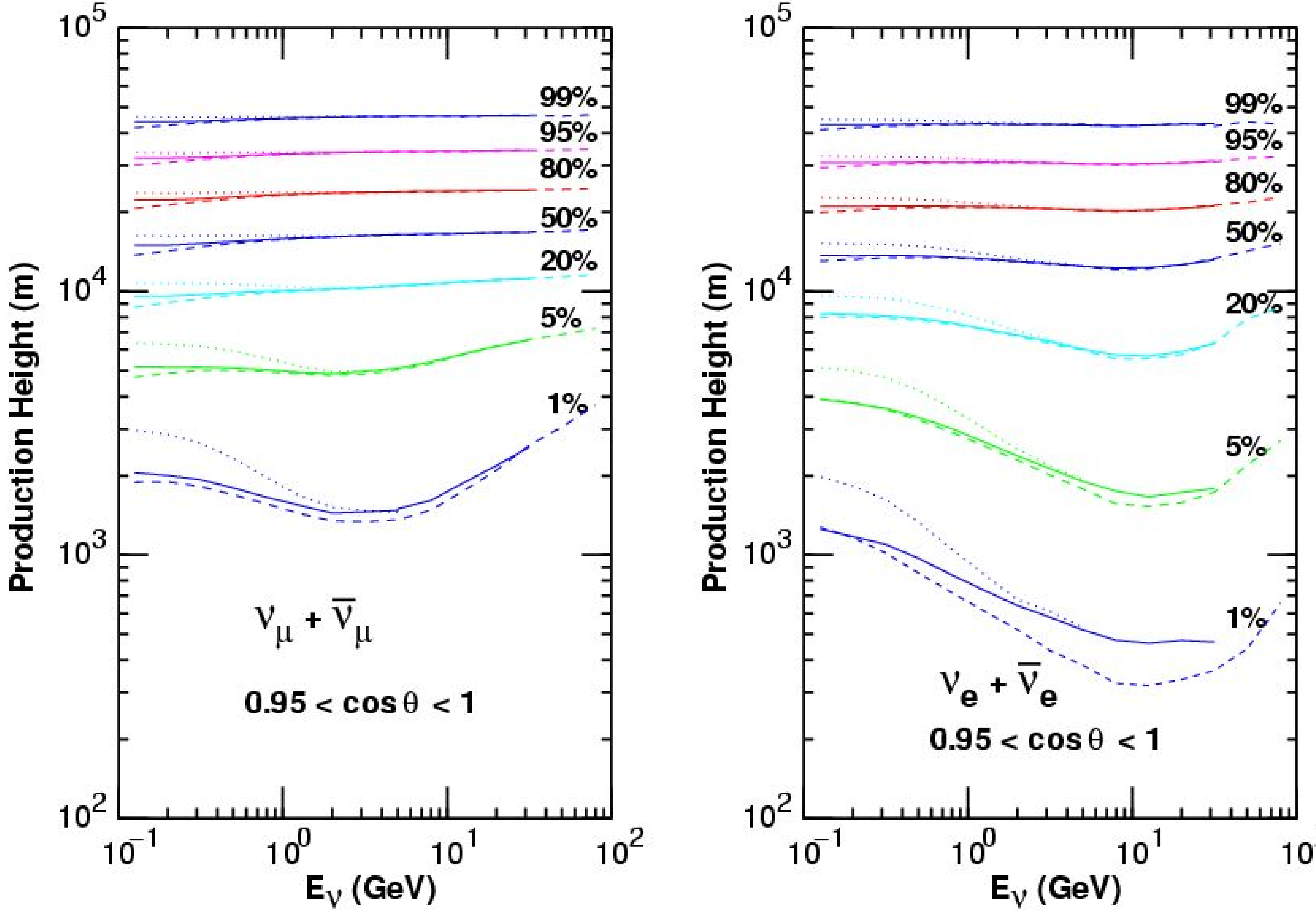


DPMJET-III Should be Modified

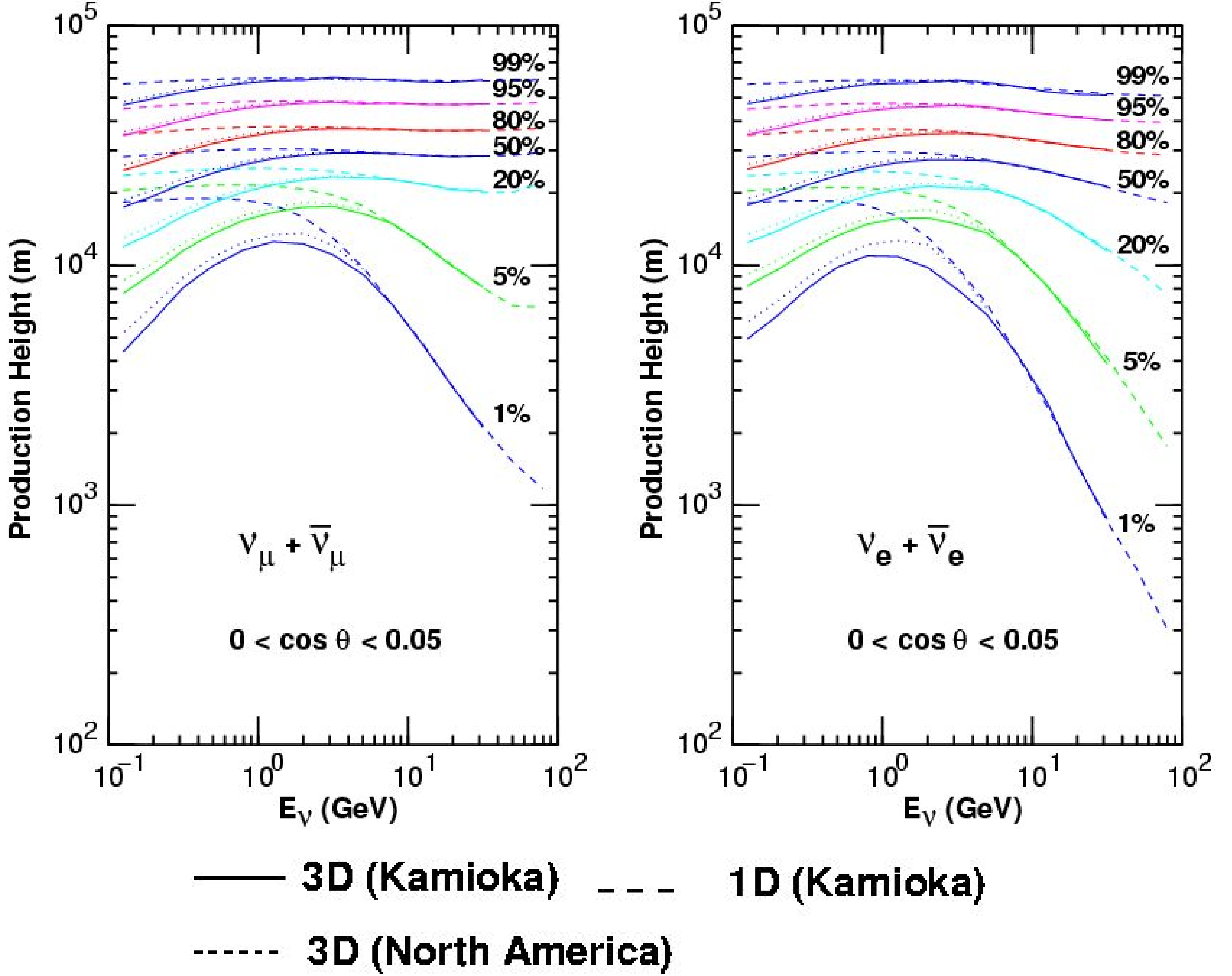
High Energy neutrino fluxes



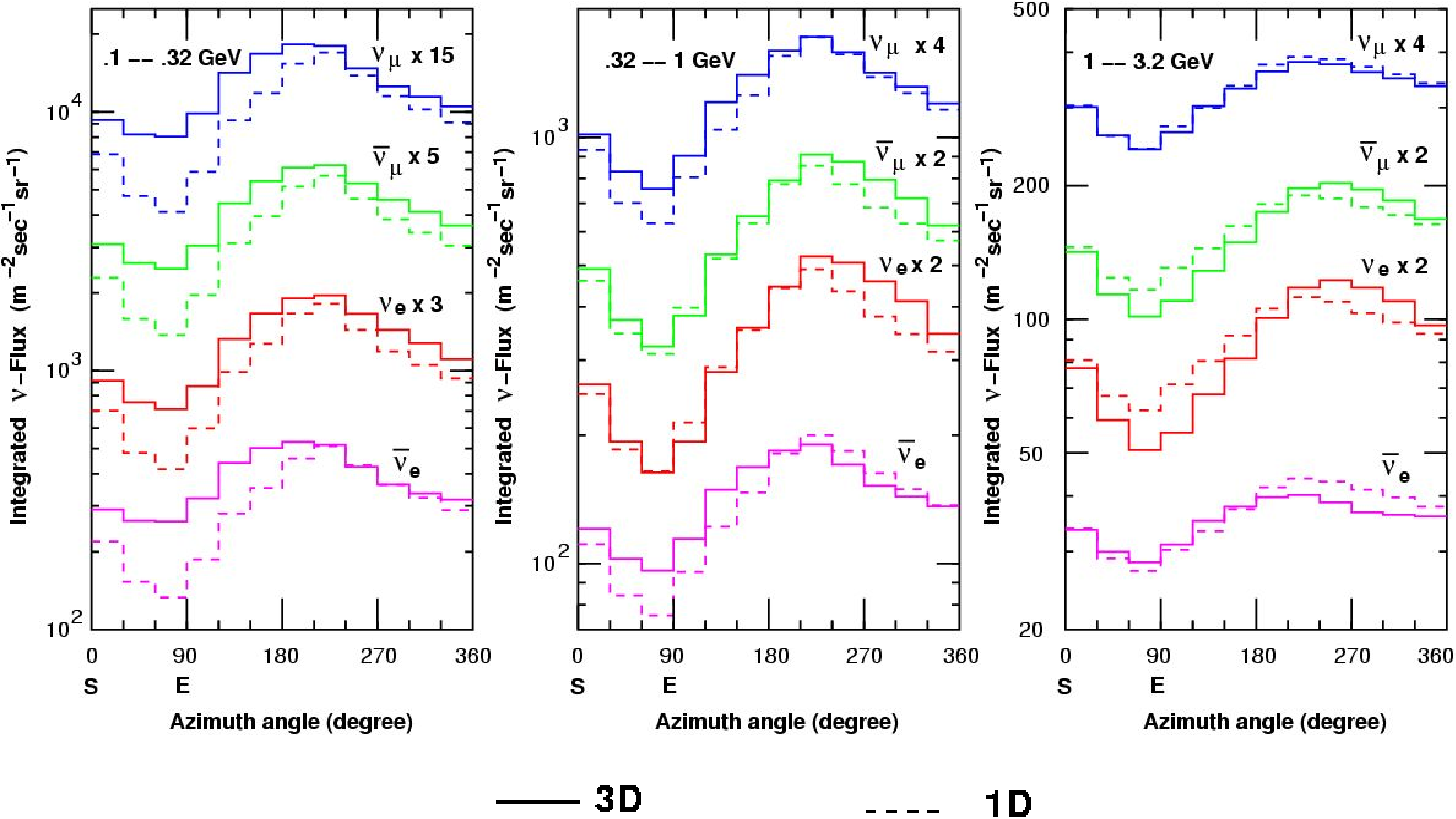
Production Height : vertical directions



Production Height : horizontal directions

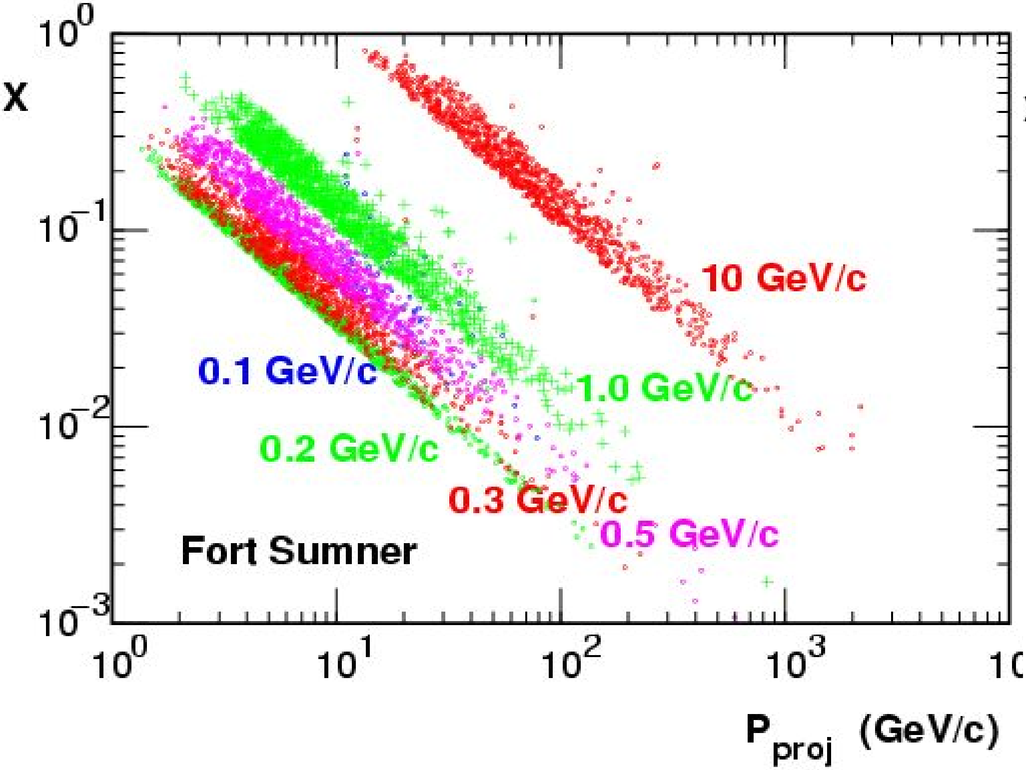


Azimuth angle dependence

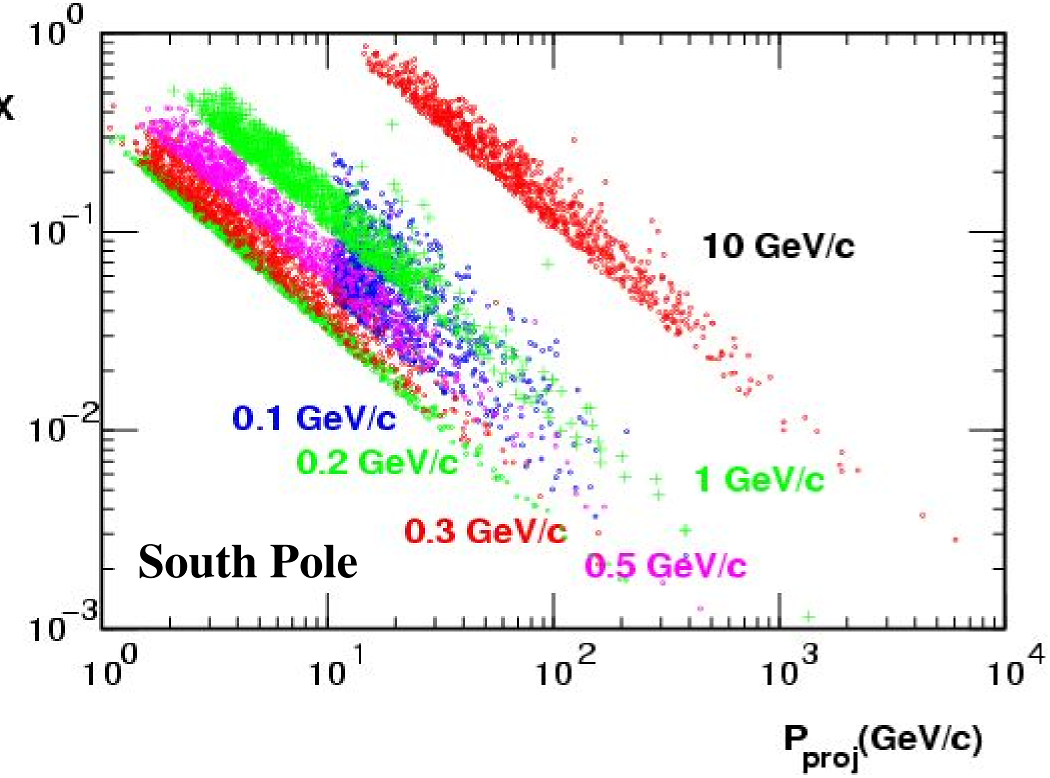


Phase Space for Muons at Balloon Altitude

Rigidity cut at 3.2 GV



Rigidity cut < 1 GV



The phase spaces for muons below 1 GeV/c are well resolved for each momentum

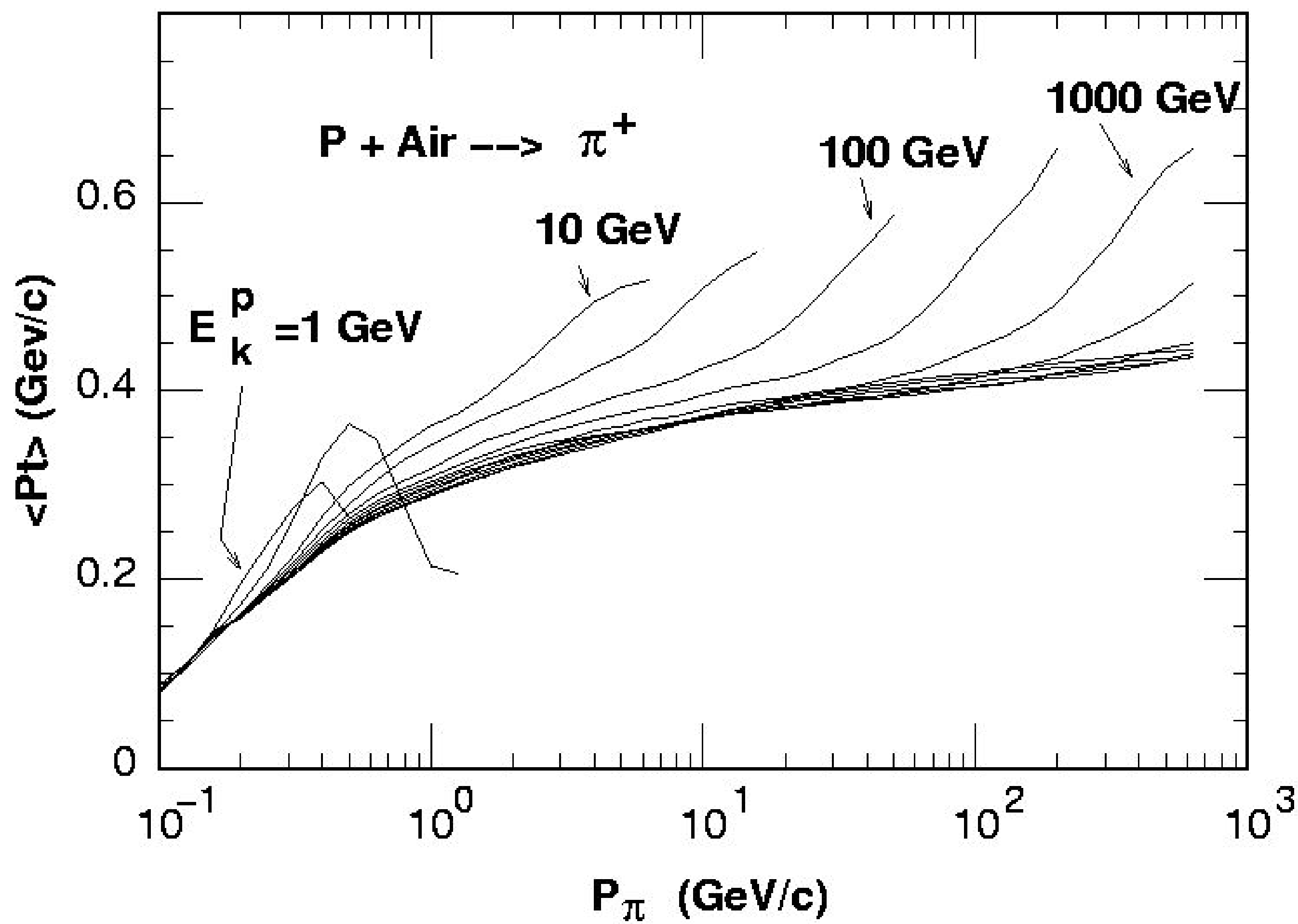
Transverse Momentums

<pt> calculated with DPMJET-III

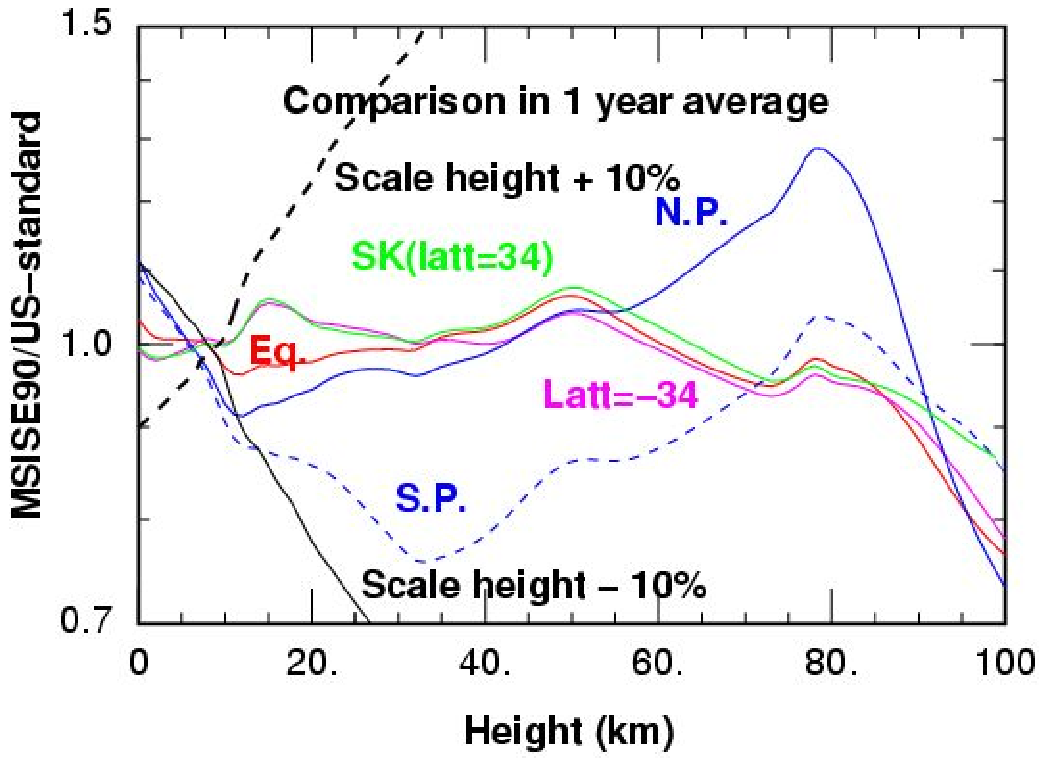
Sample a scattering angle following the probability :

$$\propto \exp(a \cdot \cos\theta) \cdot d\cos\theta$$

"a" is determined so that it reproduce the <pt> for secondary particles for various projectile energy.



Scale height change by $\pm 10\,\%$



Larger than most of variations

Kinematical consideration by Rapidity

$$y = \frac{1}{2} \ln \left\{ \frac{E + p_z}{E - p_z} \right\} \simeq \ln(2\gamma)$$

For a projectile proton at 10TeV : $y_0 = 9.9$

Center of mass : $y_{cm} \simeq 5$

For secondaries

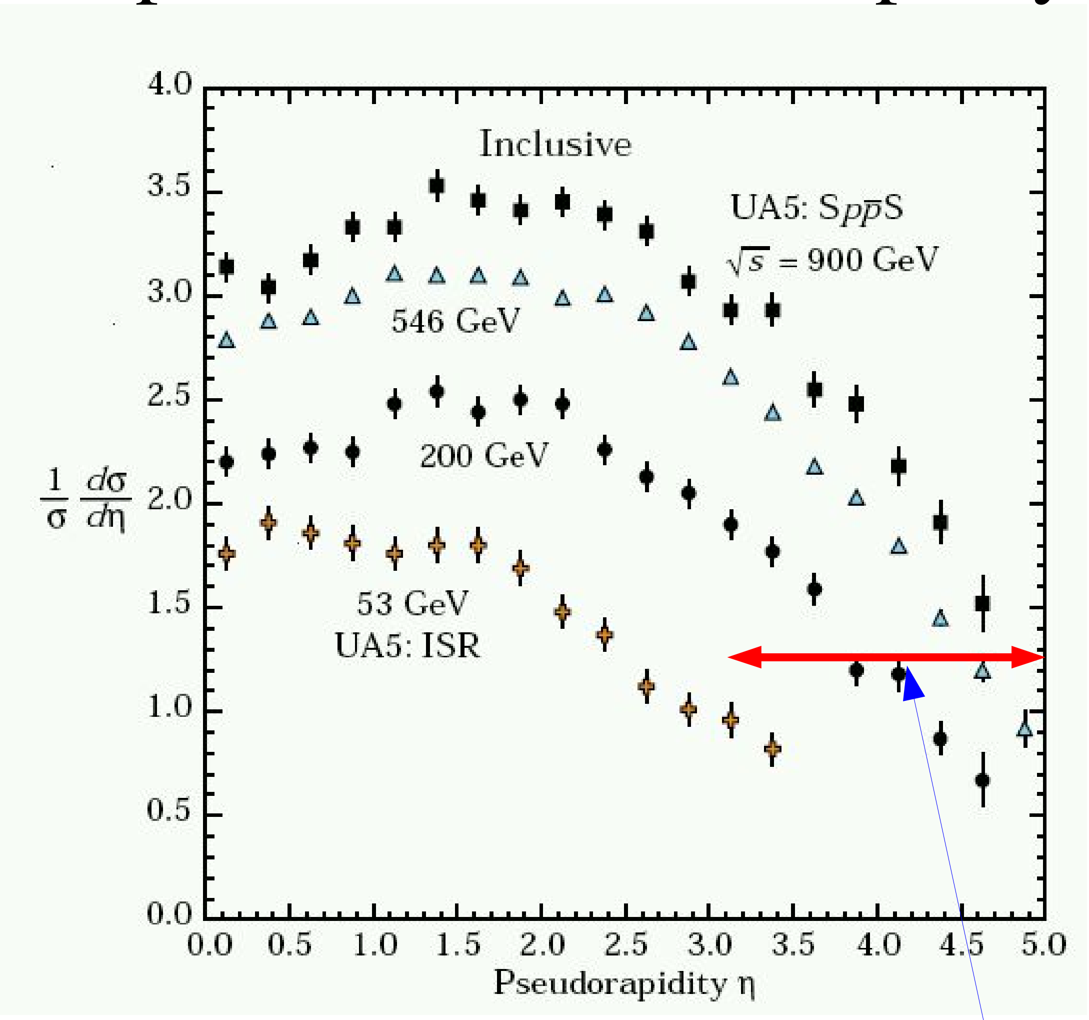
$$y = \frac{1}{2} \ln \left\{ \frac{E + p_z}{E - p_z} \right\} \simeq \ln(2\gamma') \qquad \gamma' = \sqrt{\frac{E^2}{m^2 + P_t^2}}$$

For π at 1TeV $(x = 0.1)$

$y_\pi = 9.6 \ (p_t = 0) \qquad y_\pi = 8.1 \ (p_t = 0.6)$

It is not a one-to-one relation

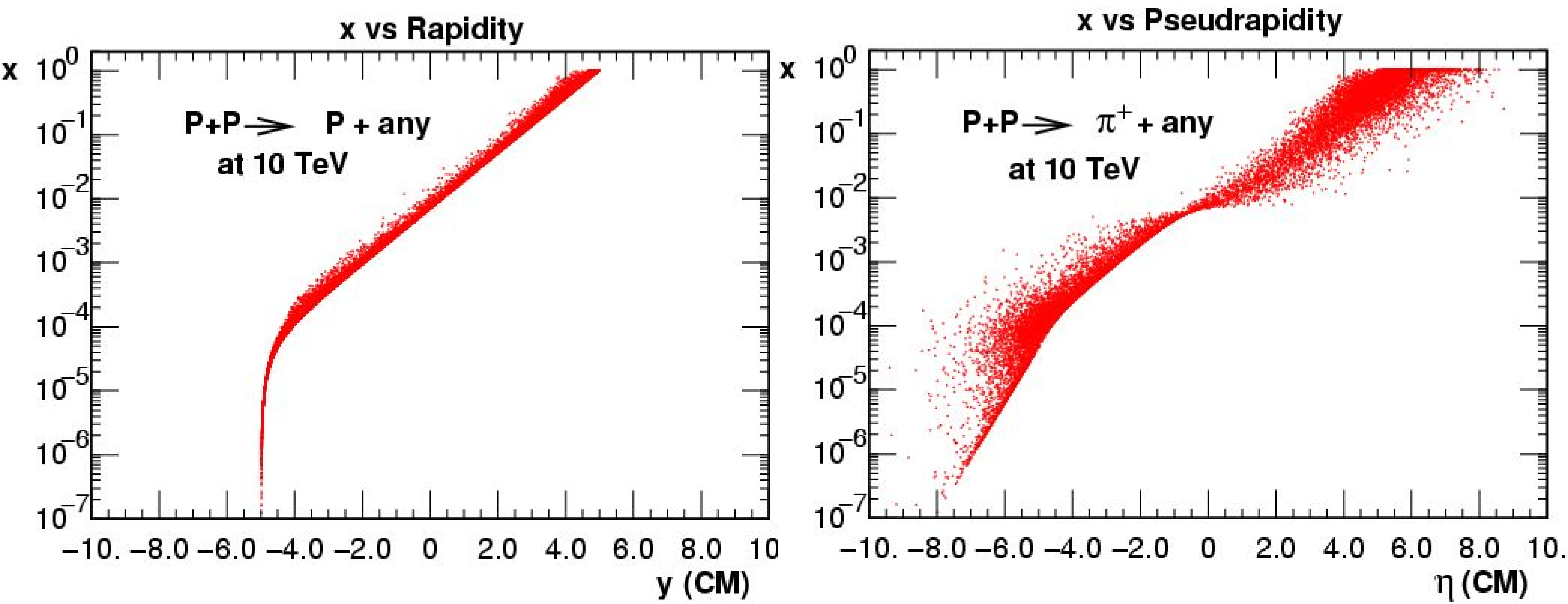
Experimental data for rapidity



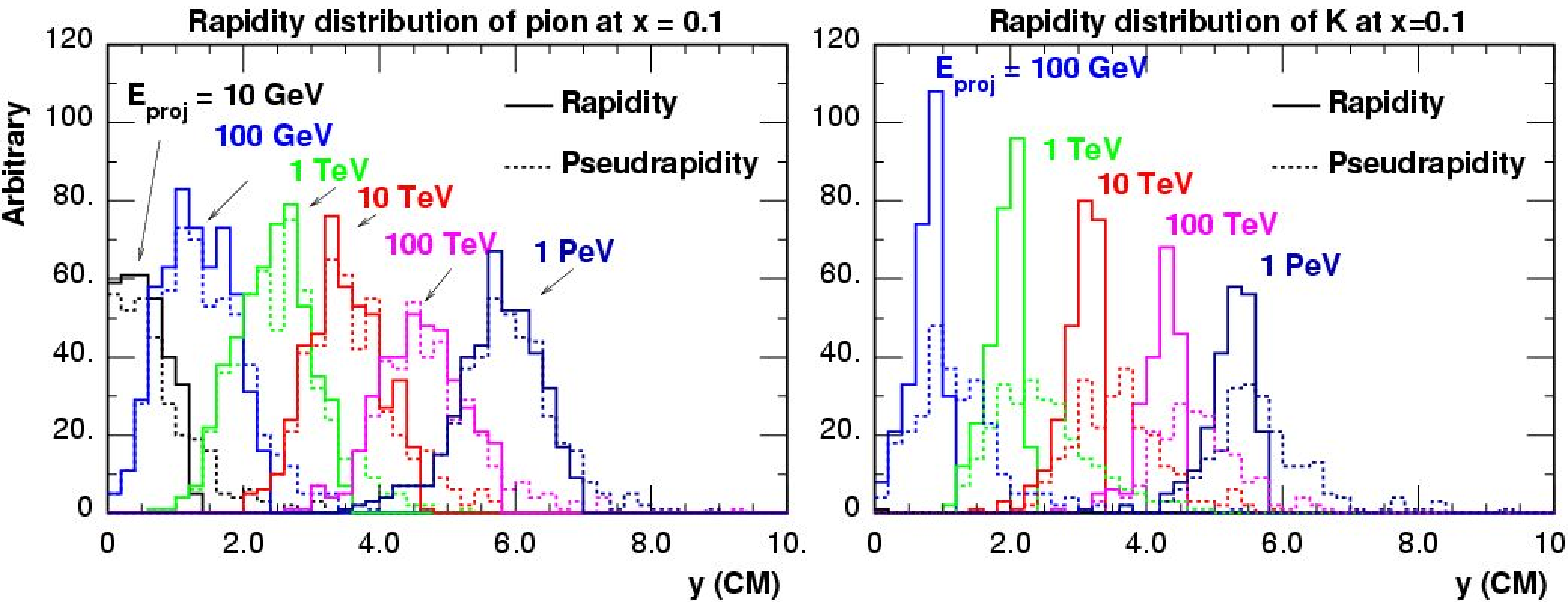
Projectile = 10 TeV ⟶ $\sqrt{s} = 140$ GeV

y-distribution of π at x = 0.1

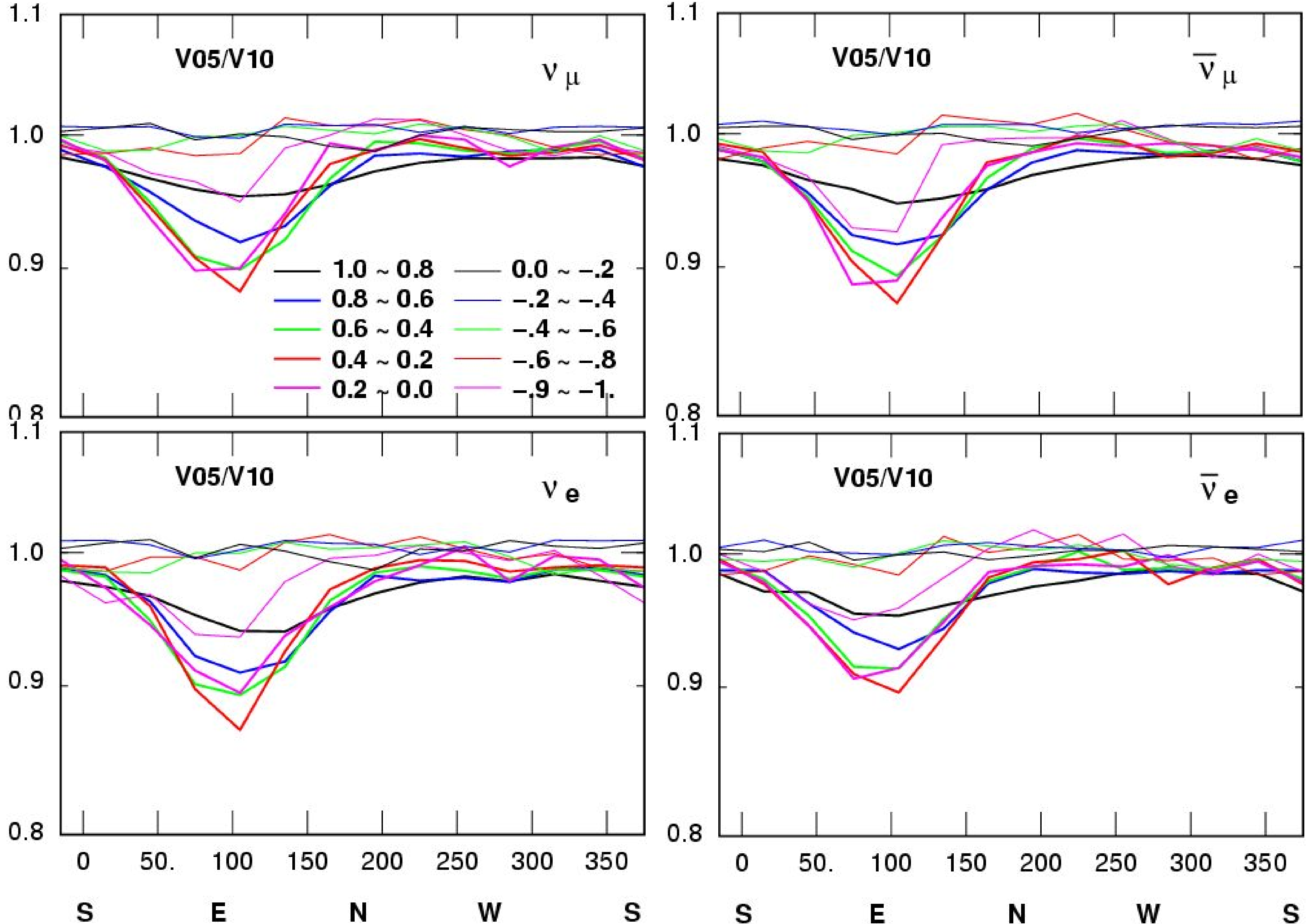
Rapidity vs Feynman $x \left(\equiv \dfrac{p}{p_{proj}}\right)$



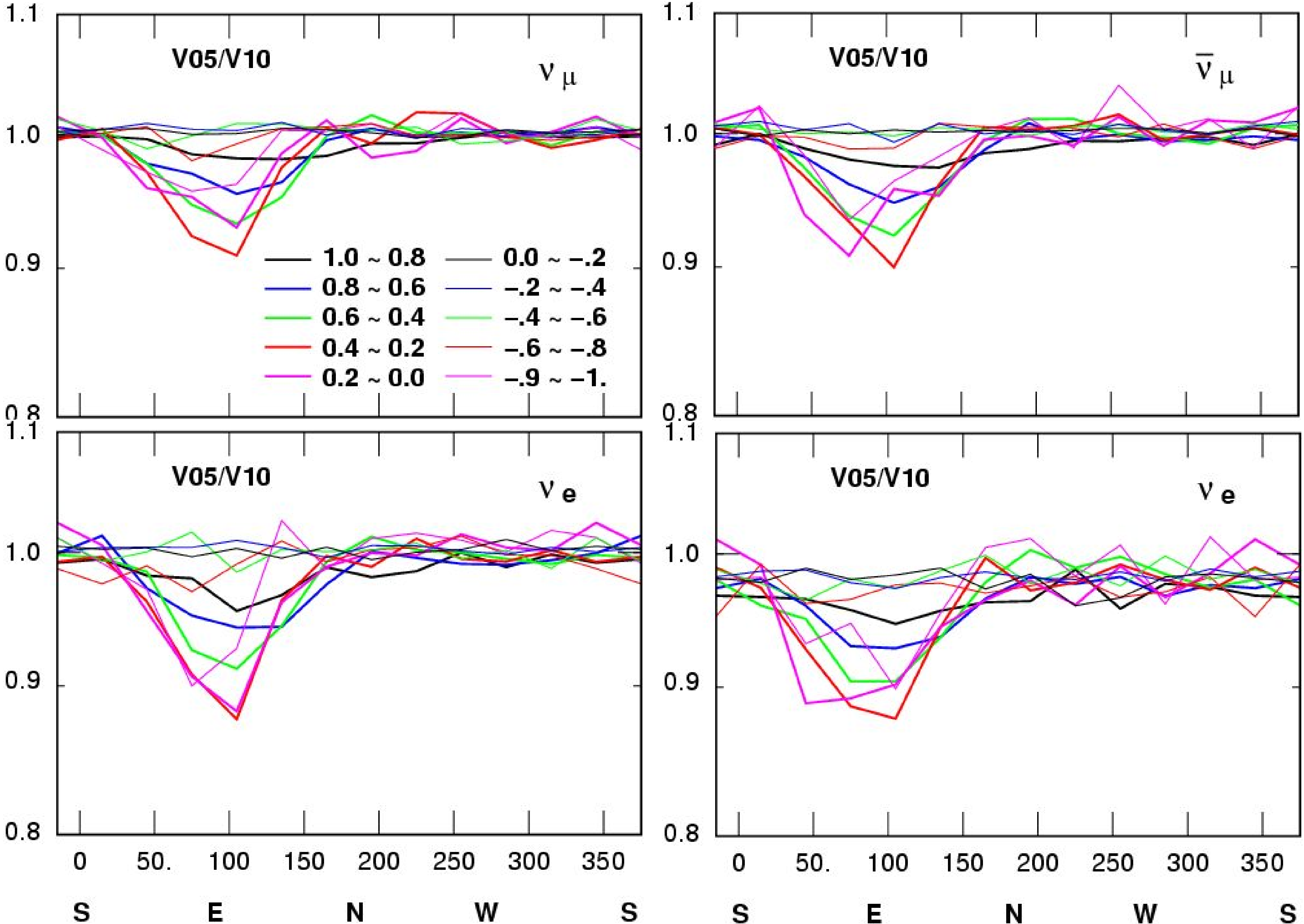
Rapidity vs Feynman x



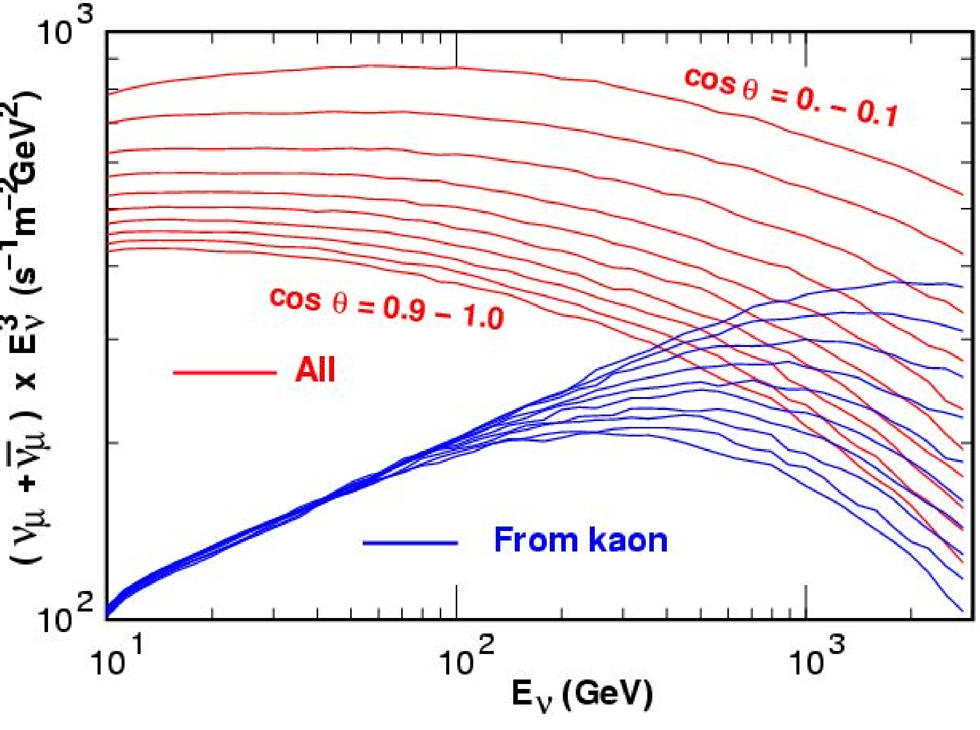
Comparison of the results between V10 and V05
Azimuth variation at 0.3 GeV/c



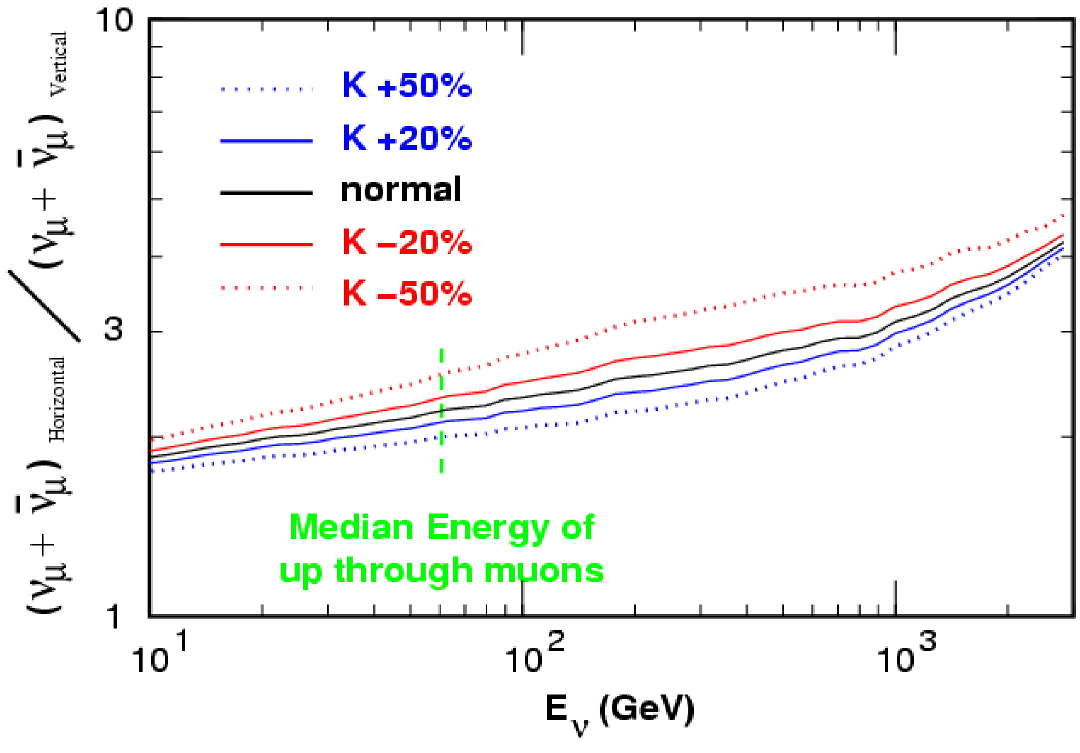
Comparison of the results between V10 and V05
Azimuth variation at 1 GeV/c



π / K -ratio and Angular dependence of Neutrino flux

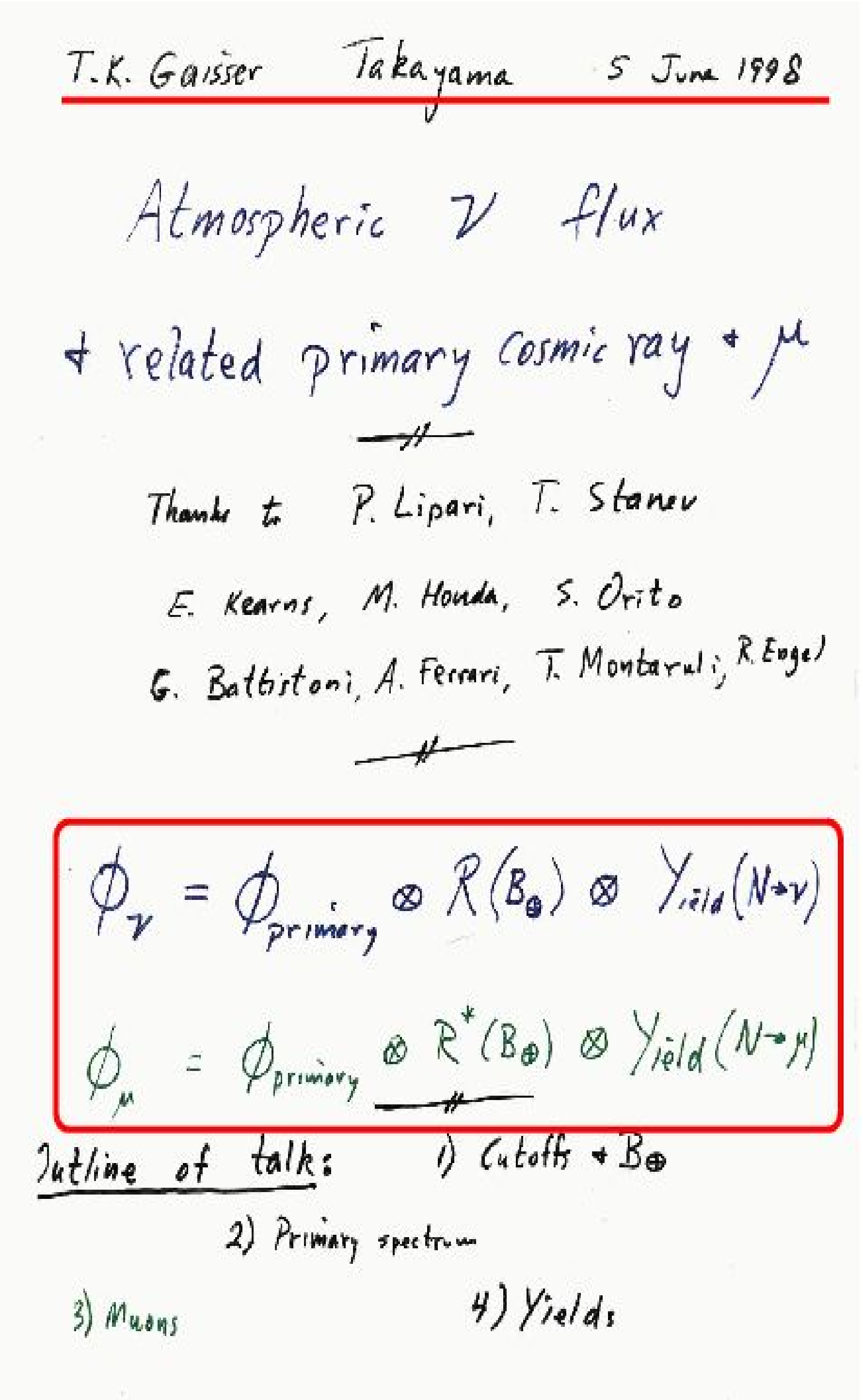


Kaon contribution for different zenith angles



Overview

- Primary cosmic ray flux
  Hamburg model
- Interaction model
  DPMJET-III
- Calculation scheme
- Atmosphere model
  US-standard 76
- Geomagnetic Model
  IGRF 2000 (2005)
- Solar modulationl
- etc



T.K. Gaisser Takayama 5 June 1998

Atmospheric ν flux

+ related primary cosmic ray + μ

Thanks to P. Lipari, T. Stanev

E. Kearns, M. Honda, S. Orito

G. Battistoni, A. Ferrari, T. Montaruli, R. Engel

$$\phi_\nu = \phi_{primary} \otimes R(B_\oplus) \otimes Yield(N \to \nu)$$

$$\phi_\mu = \phi_{primary} \otimes R^*(B_\oplus) \otimes Yield(N \to \mu)$$

Outline of talk: 1) Cutoffs + $B_\oplus$

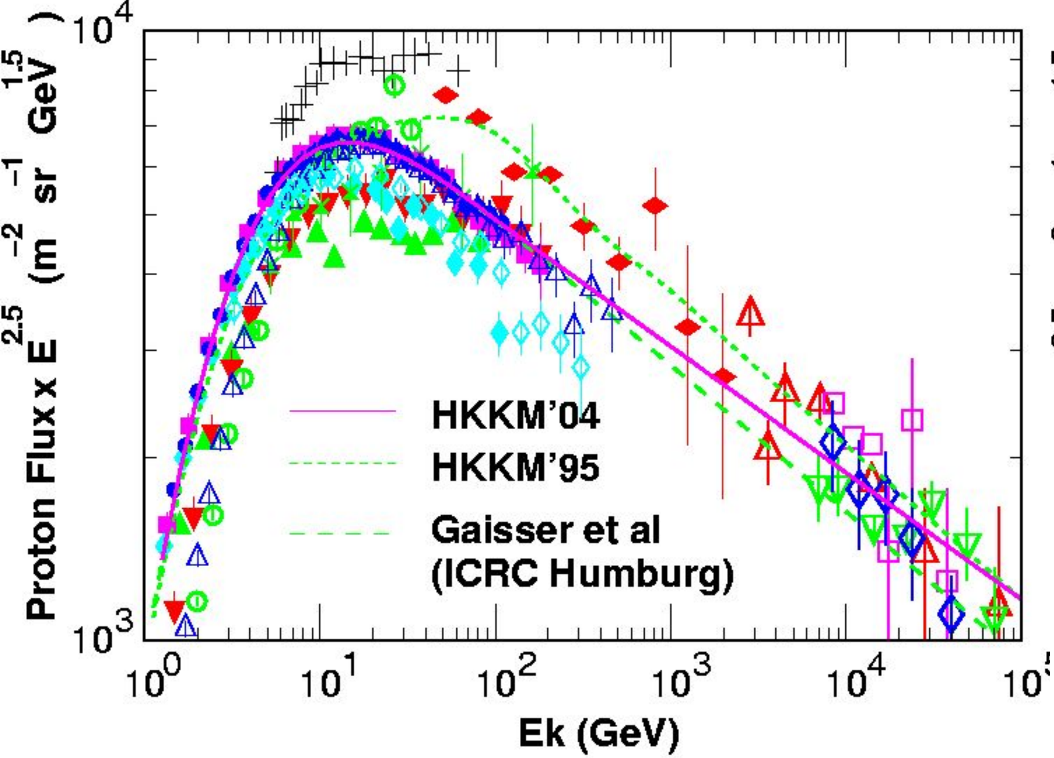
2) Primary spectrum

3) Muons

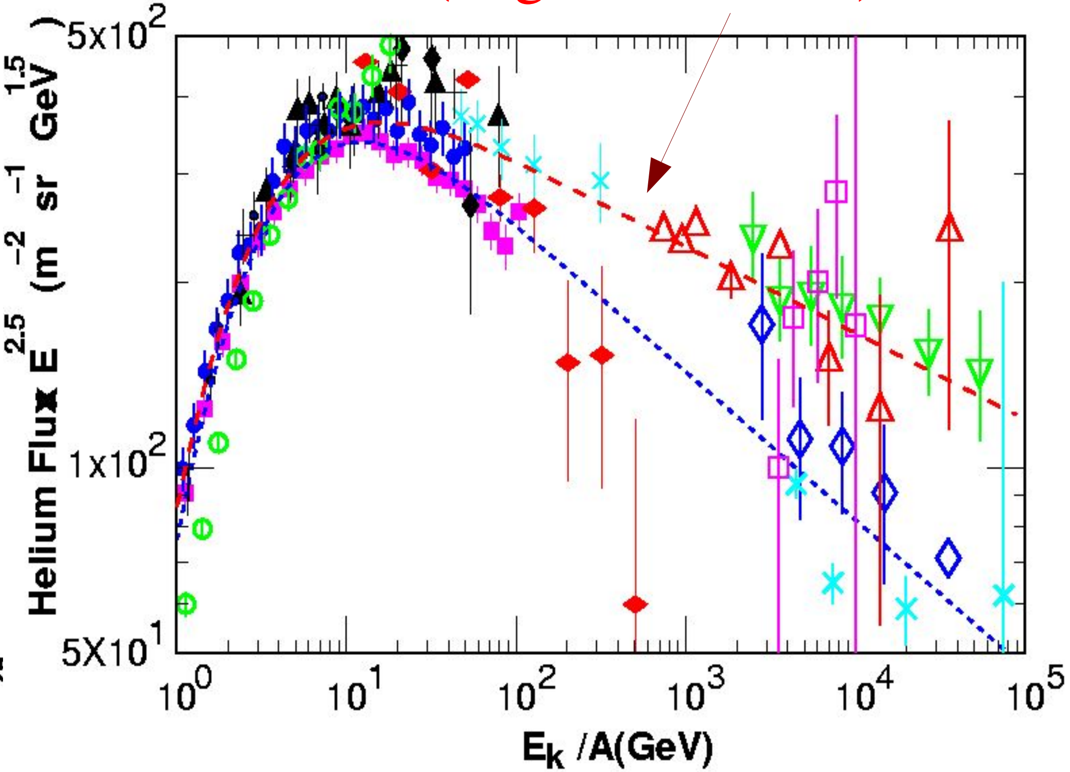
4) Yields

Primary Cosmic Ray Fluxes

Proton



He (High flux mode)



- Primary proton flux observed by AMS and BESS agrees each other within the error of 5% below 100 GeV
- He spectrum still has the large scatters