CALCULATION of the ATMOSPHERIC ν RATES.

(1) Elements entering the calculation.

(2) Uncertainties in the prediction.

(3) Impact of these uncertainties in the study of the relevant 'NEW PHYSICS'.

(4) Possible directions of work to reduce the systematic uncertainties.

Paolo Lipari

Venezia 24 Feb 1999

The Need for 'NEW PHYSICS' to describe the data of atmospheric neutrinos from Super–Kamiokande (and other detectors: IMB, MACRO, Soudan-2) is *close* to be **established**.

The presence of ν–oscillations is the simplest, most natural and *most successful* extension of the standard model capable of describing the experimental results.

The prediction (within the Standard Model) of the atmospheric neutrino event rates does have significant uncertainties, but these **cannot** 'explain' the experimental results.

These uncertainties can have a significant impact in the 'extraction' of the NEW PHYSICS from the data. For example in the determination of the oscillation parameters Δm^2, $\sin^2 2\theta$

A Full Clarification of what is the new physics involved is a long Term (many years) project

Number of σ's from No Oscillations

Maximal Mixing

$$\frac{\frac{1}{2}-1}{\frac{1}{2}+1} = \frac{-1}{3}$$

5.4

↳ >6.0

7.2

5.7

3.7

The situation :

Up-Down asymmetry

$$A = \frac{U - D}{U + D}$$

$$A_{subGeV} = -0.150 \pm 0.028 \pm 0.01$$

$$A_{multiGeV} = -0.311 \pm 0.043 \pm 0.01$$

Double Ratios

$$R = (\mu/e)_{data} \ / \ (\mu/e)_{MC}$$

$$R_{subGeV} = 0.668 \ ^{+0.026}_{-0.023} \pm 0.007 \pm 0.052$$

$$R_{multiGeV} = 0.663 \ ^{+0.044}_{-0.041} \pm 0.013 \pm 0.078$$

The experimental studies on atmospheric neutrinos are entering a new phase of *precision* measurements.

New goals:

1. Determine the functional form for the probability $P_{\nu_\mu \to \nu_\mu}(E_\nu, L)$.
2. Measure the parameters Δm^2, $\sin^2 2\theta$.
3. Verify if standard ν–oscillations are uniquely determined as the origin of the effects discovered.
4. Oscillations, even if a single Δm^2 is relevant, *necessarily* involve at the same time transitions between all flavors:

   $\nu_\mu \leftrightarrow \nu_\tau$, $\nu_e \leftrightarrow \nu_\mu$, $\nu_e \leftrightarrow \nu_\tau$

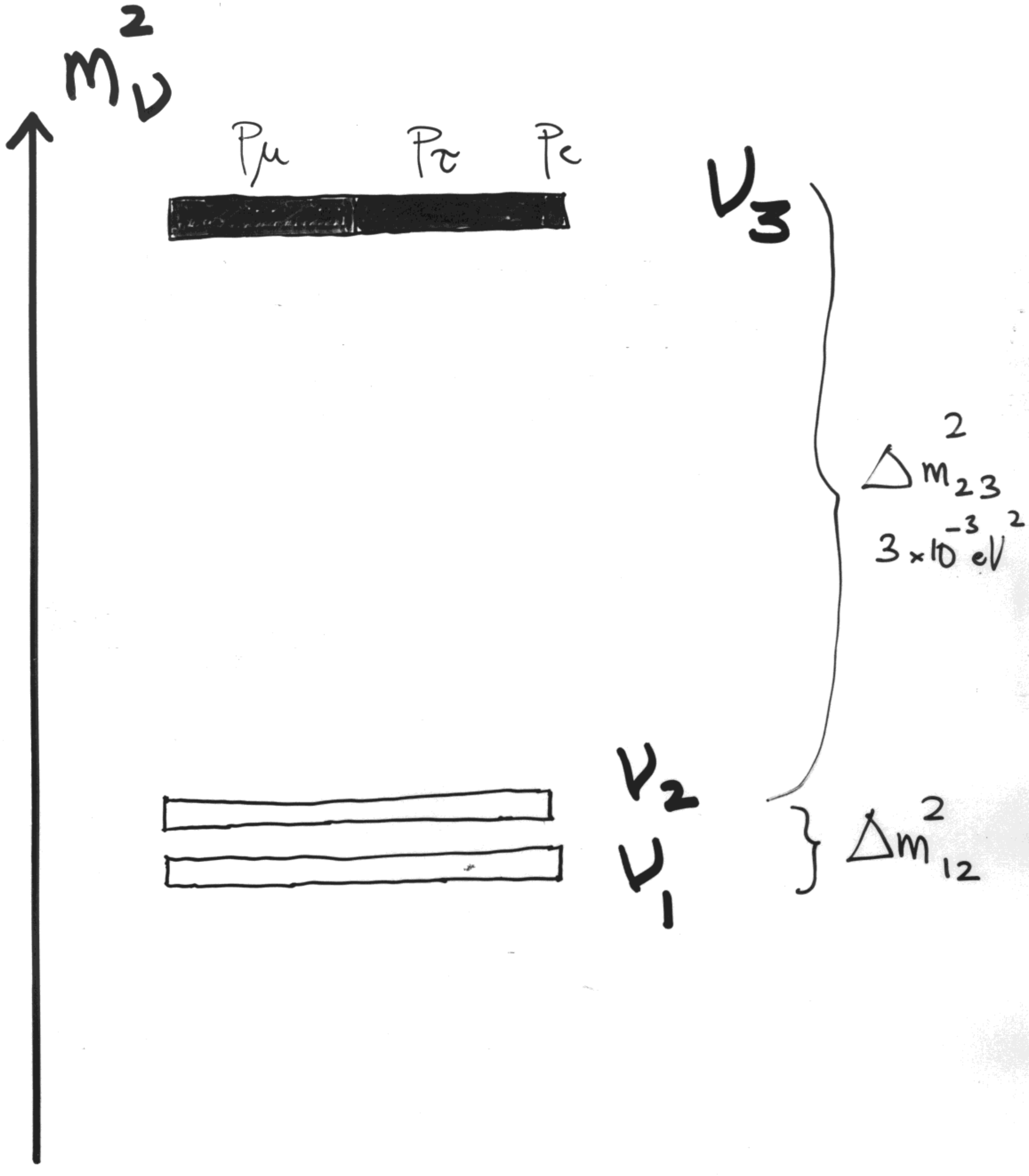
   Measure (or put limits on) all transitions.
5. Study the Large Mixing angle solution of the solar neutrino problem with atmospheric neutrinos.

[redacted]

Large Mixing angle solution of the Solar ν problem $\sim 10^{-5} - 10^{-4}\ eV^2$

Can be studied with atmospheric ν !!

[Smirnov, Peres hep-ph/9902312]



m_ν^2
P_μ
P_τ
P_e
ν_3
Δm^2_{23}
$3 \times 10^{-3}\,eV^2$
ν_2
ν_1
Δm^2_{12}

To perform these studies, it will always be important to consider combinations of quantities where the systematic uncertainties cancel (as in the ratios μ/e, U/D).

But uncertainties in the predictions of the fluxes can be an important limiting factor in the sensitivity.

The **requirements** on the estimate of the neutrino fluxes and cross sections are becoming **more stringent**. There is a need for more accurate calculations.

Main Elements in the calculation of the atmospheric neutrino rates.

1. Primary Cosmic Ray flux (protons $\sim 80\%$, Helium, $\sim 15\%$)
2. Data on hadronic interactions

   $p + Air \to p, n, \pi^{\pm}, K^{\pm}, \ldots$
3. Description of the 'target region' (atmospheric density, mountain profiles).
4. Compute Geomagnetic effects.
5. A computer code for the generation of hadronic showers. 1D vs 3D
6. Description of the Neutrino cross sections.

$$\begin{pmatrix} e \\ \mu \end{pmatrix} = \Phi_p \otimes Y_{p \to \nu} \otimes \sigma_\nu$$

$\vec{B}_\oplus$, Solar modulation

$\sigma_{hadronic}$

The fluxes of atmospheric neutrinos have two fundamental properties that are **self–calibrating**:

- The Neutrino Fluxes are UP–DOWN symmetric

$$\phi_{\nu_\alpha}(E_\nu, \theta) \simeq \phi_{\nu_\alpha}(E_\nu, \pi - \theta)$$

- The ν_μ and ν_e fluxes are related to each other:

Double Ratio

$$\phi_{\nu_\mu}(E, \theta) = r(E_\nu, \theta) \cdot \phi_{\nu_e}(E, \theta)$$

$$\simeq \text{“}2\text{”} \cdot \phi_{\nu_e}(E, \theta)$$

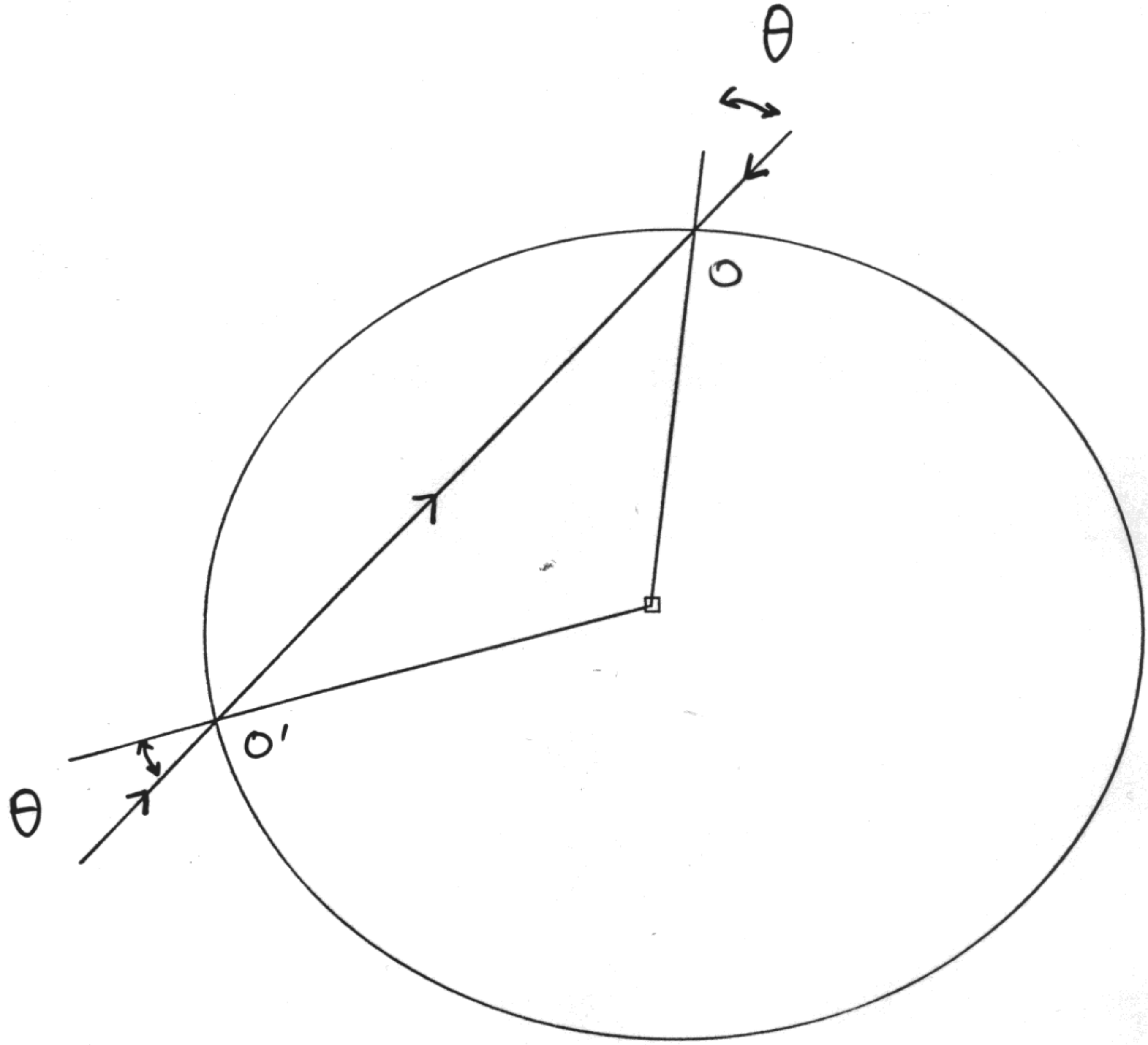
$$\phi_{\nu_j}(E, \theta) = \phi_{\nu_j}(E, \pi - \theta)$$

A GEOMETRY THEOREM

SPHERICAL SYMMETRY ==> UP-DOWN SYMMETRY

+ (No oscillations)

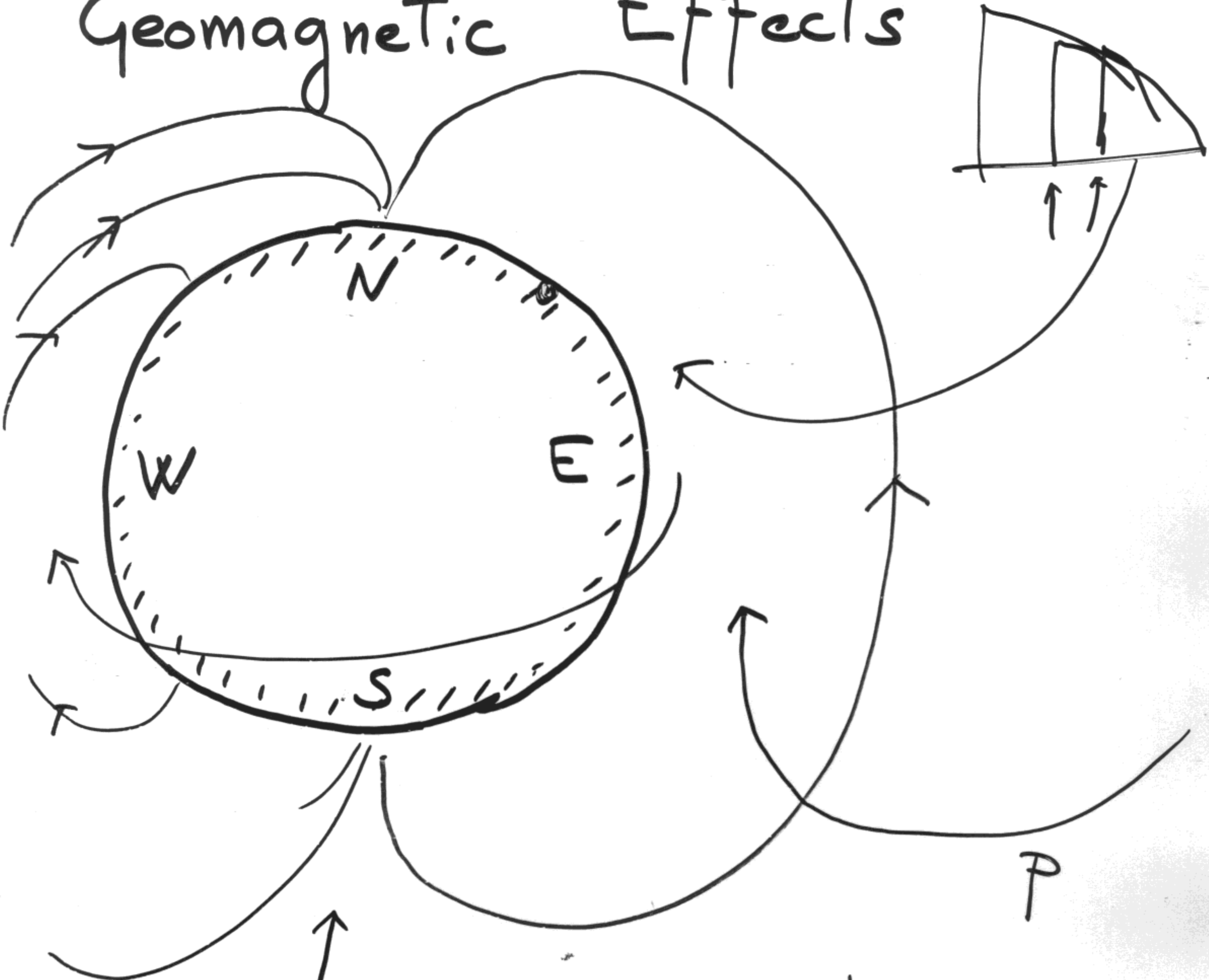
of the neutrino fluxes



Violations of Spherical symmetry.

Geomagnetic effects

Geomagnetic Effects



Forbidden Trajectories

$q = +e$

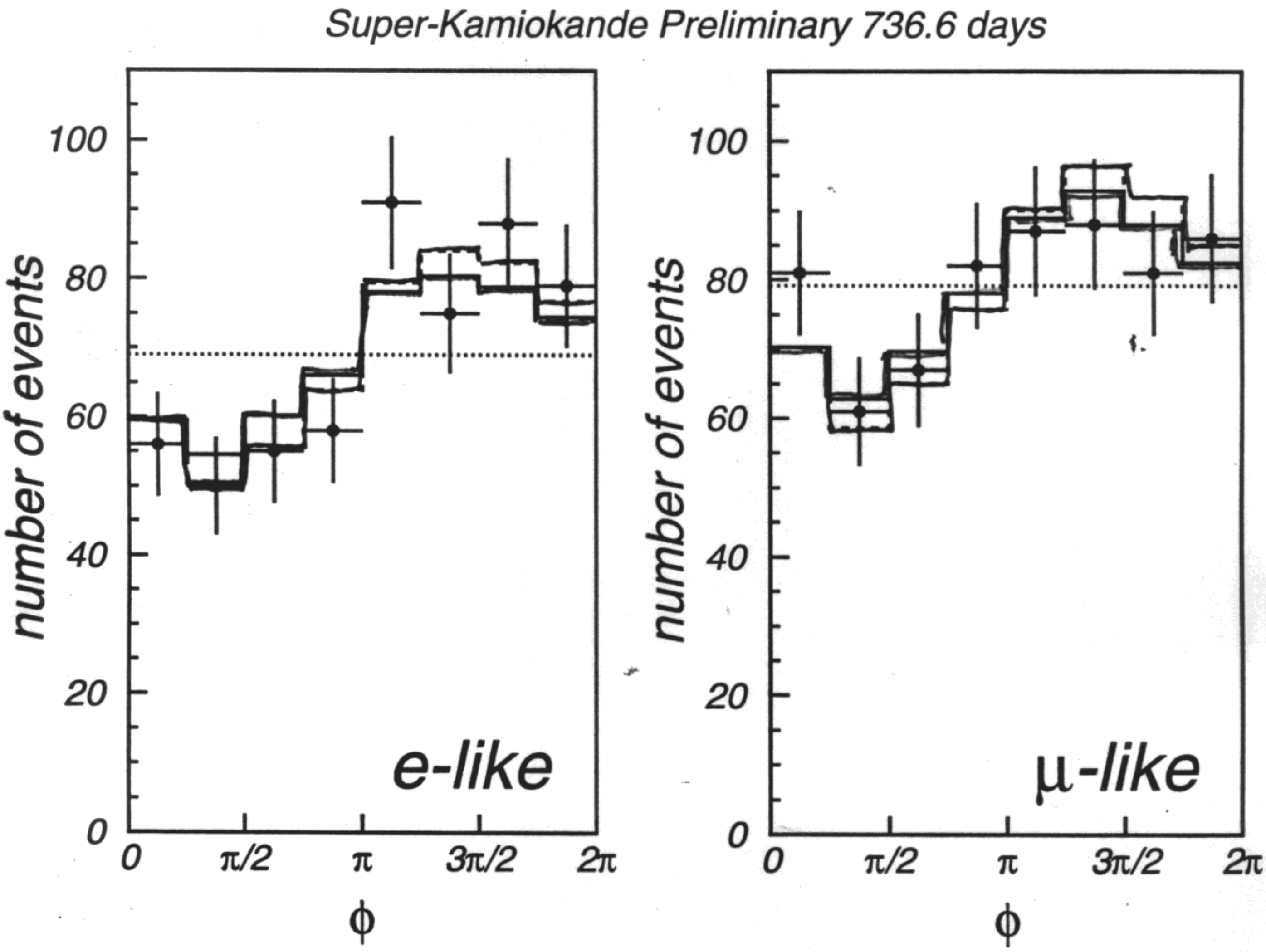
$P_{cutoff}(\vec{x}_{det}, \Omega)$

$= 0 - \sim 57\,\text{GeV}$

Latitude Effect
East-West effect

Measurement of the Azimuthal dependence confirms geomagnetic effects ~ correct

— Honda et al.
— Bartol

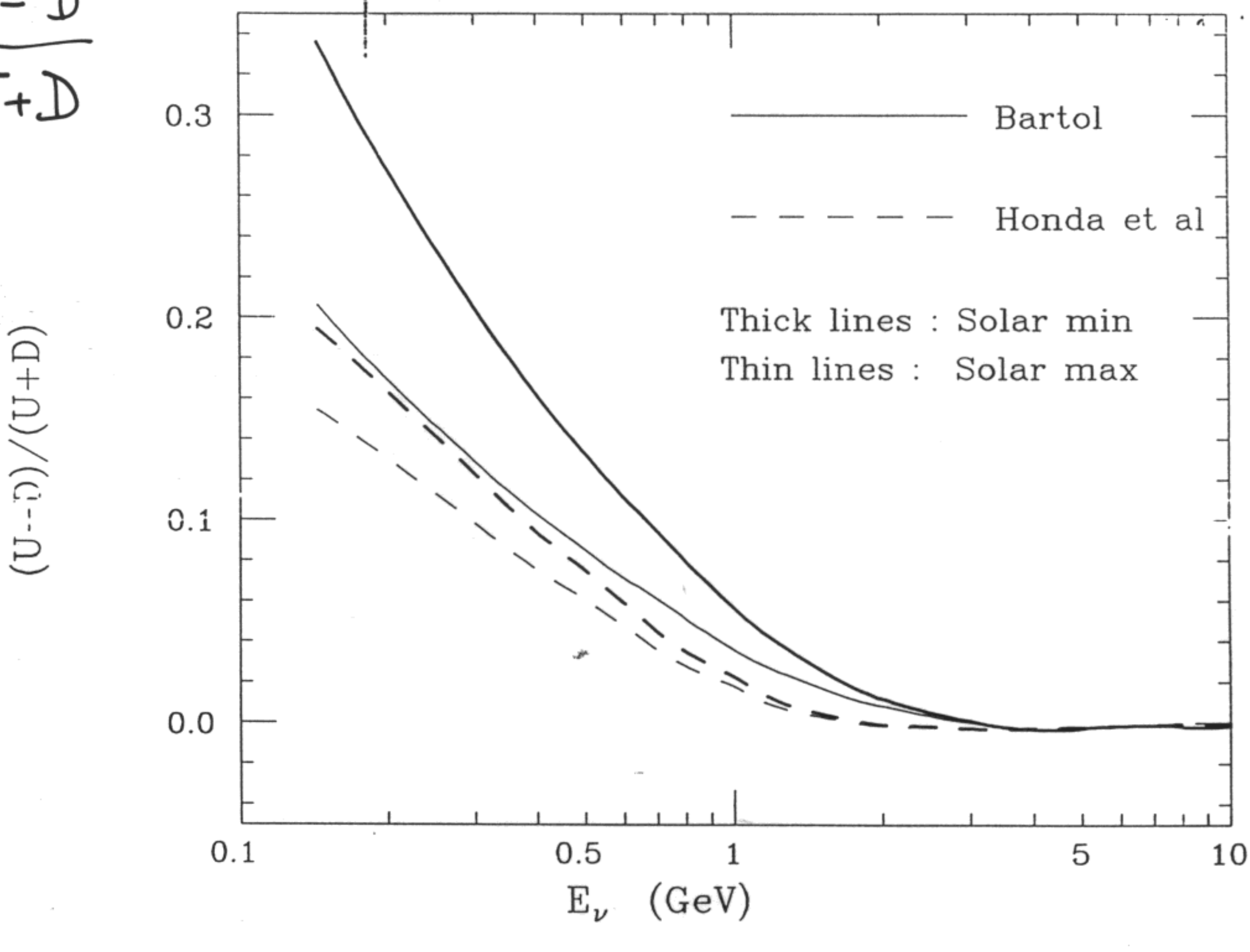


Violations of Up-Down symmetry at low ν Energy.

Kamiokande mine
No oscillation prediction

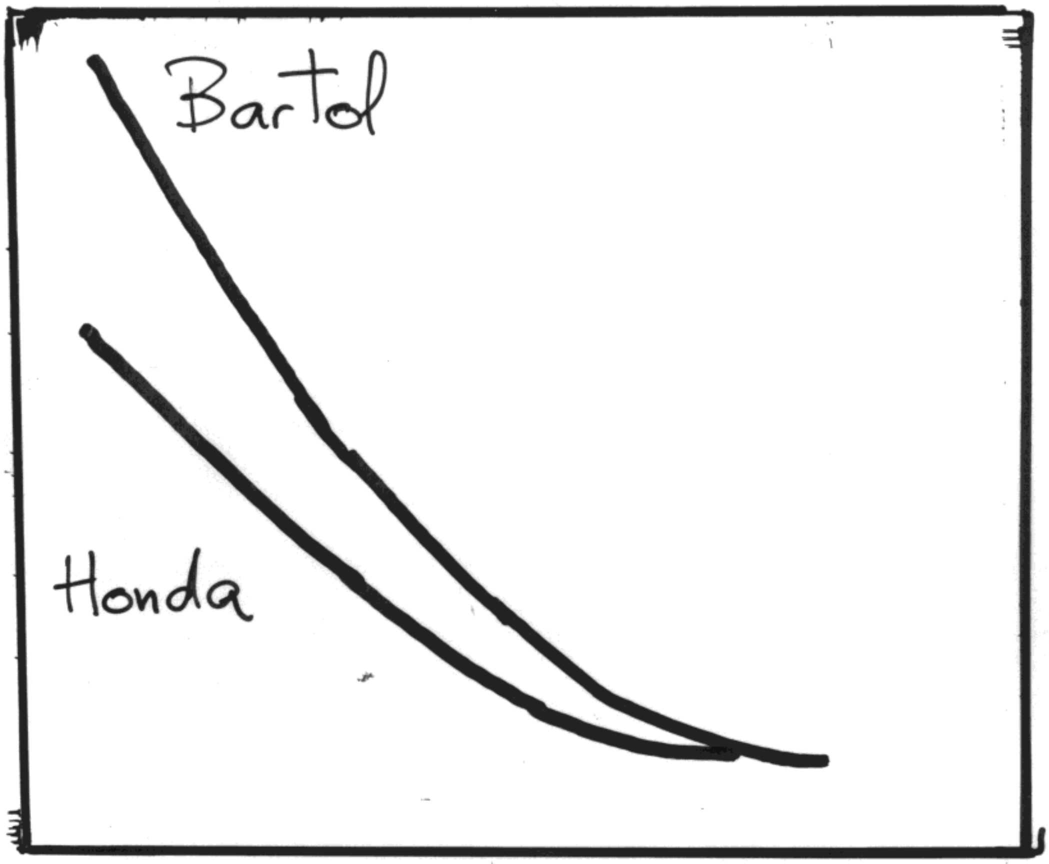
$\mu^{\pm}$ events
U: $\cos\theta < -0.2$
D: $\cos\theta > +0.2$

$\frac{U-D}{U+D}$



Kamioka : in the absence of oscillations

Up > Down.



$E_\nu = 0.3\ GeV$

$A = \begin{matrix} +0.12 \\ +0.20 \end{matrix}$

In the Absence of Oscillations

KAMIOKA : $UP > DOWN$

Soudan : $UP < DOWN$

Soudan

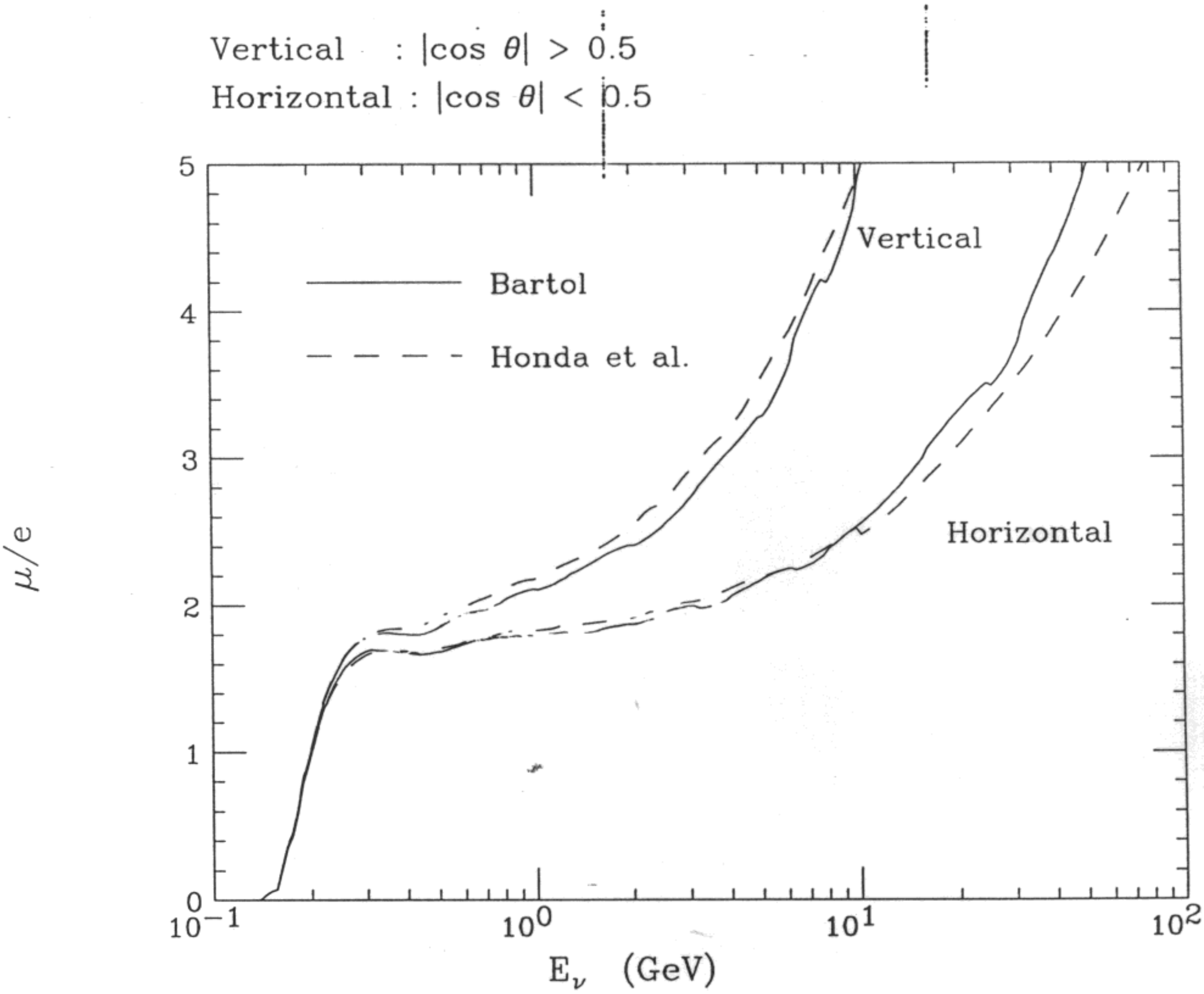
close to magnetic pole $\lambda_{mag} \sim 55^\circ$
Down–going flux: small suppression
Up–going flux $\sim$ average suppression.
(sees entire earth):

Kamioka

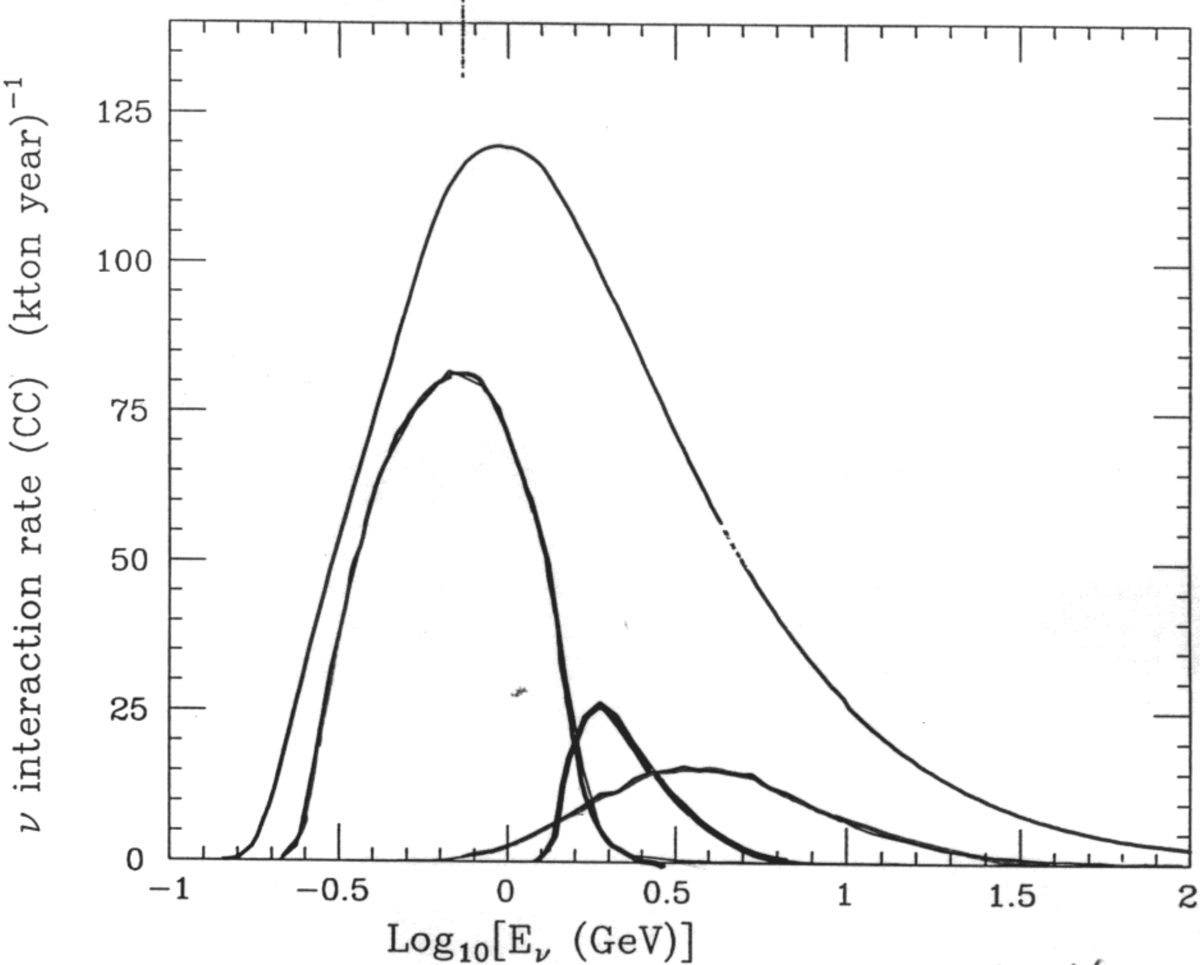
close to magnetic equator $\lambda_{mag} \sim 29^\circ$
Down–going flux: large suppression
Up–going flux: $\sim$ average suppression

μ/e as a function of E_ν θ_ν

$$\mu/e = r(E_\nu, \theta_\nu)$$

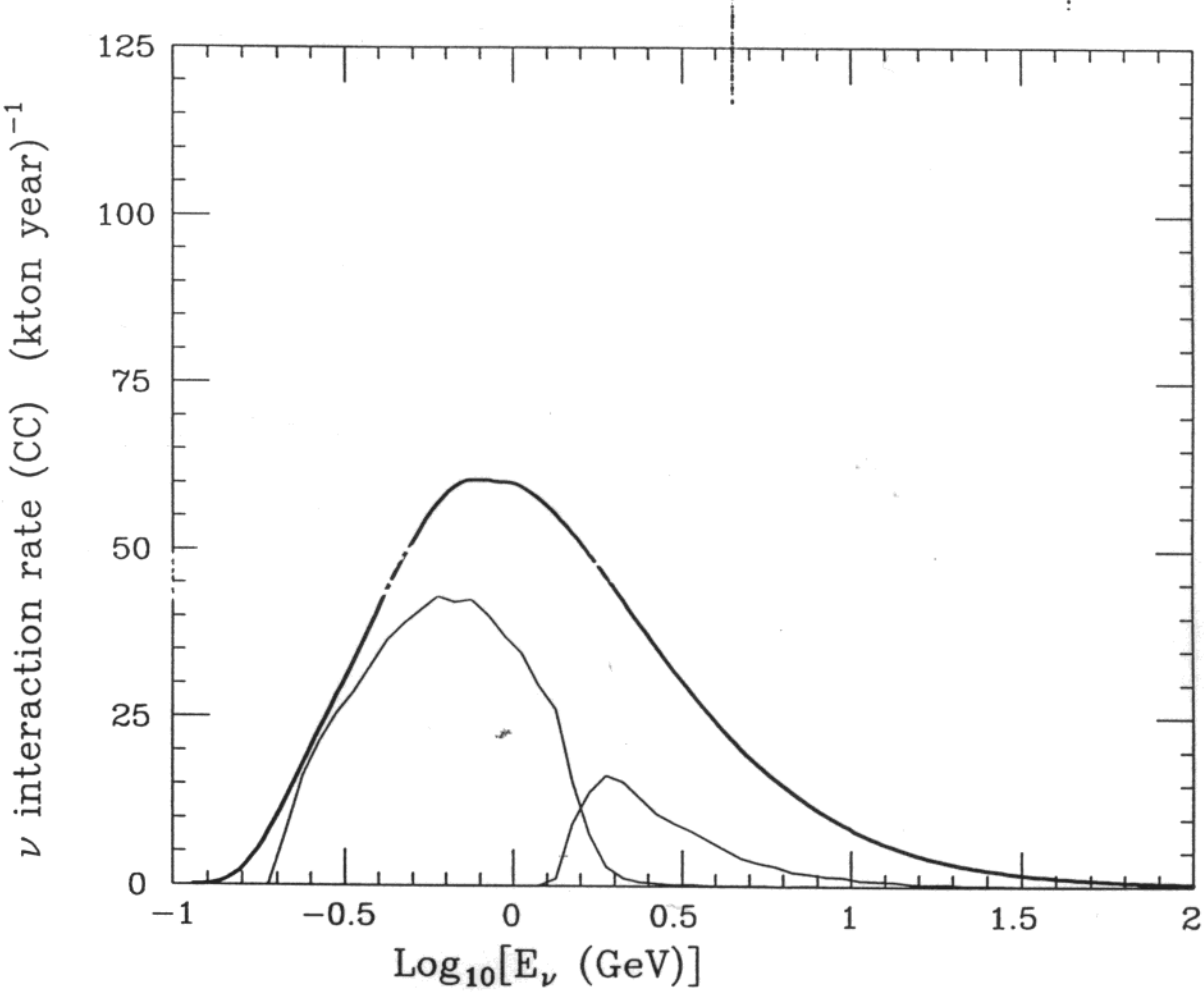


Neutrino Energy Distribution of μ events in SuperKamiokande



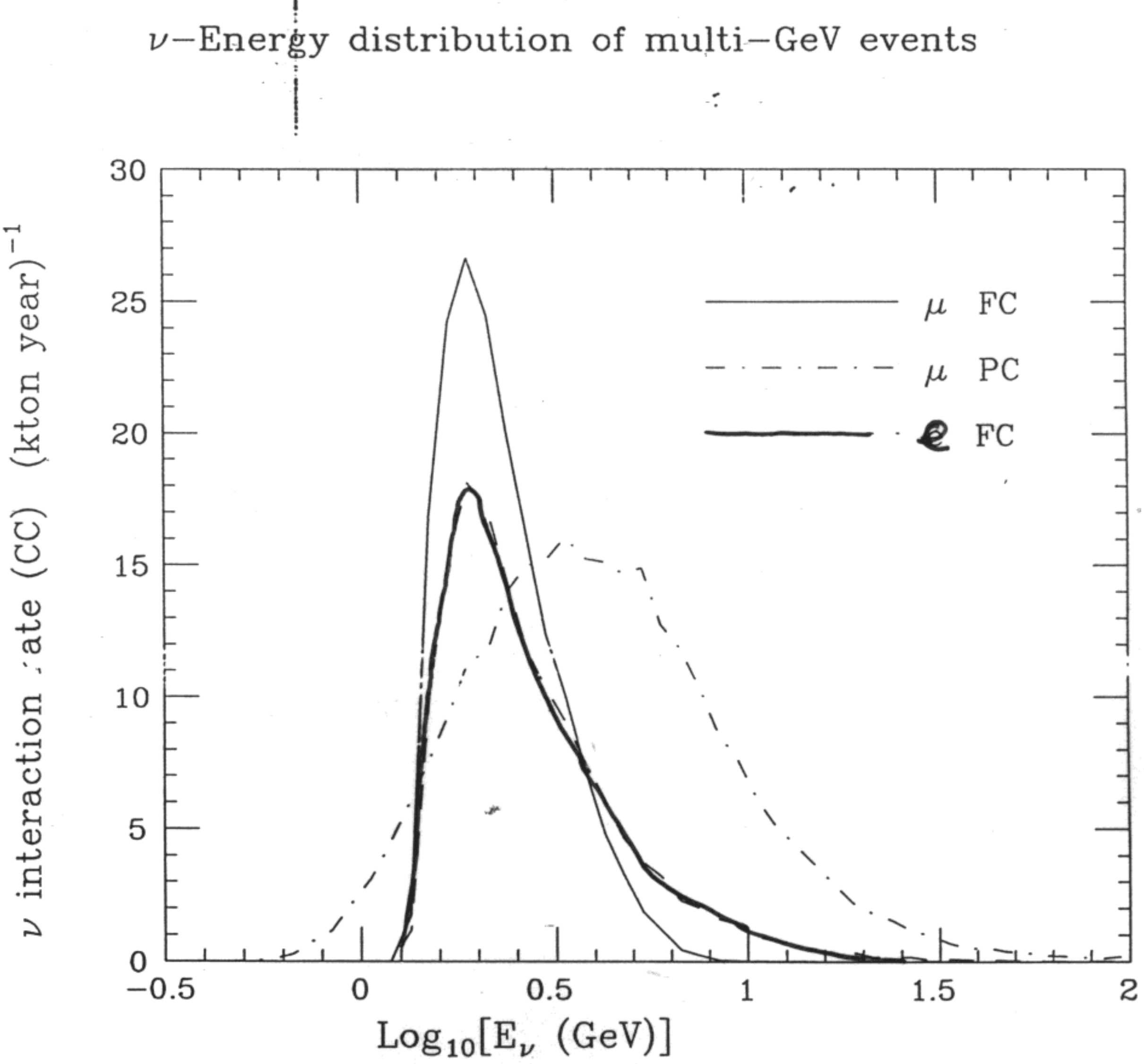
subGeV multiGeV Partially contained

e - events.



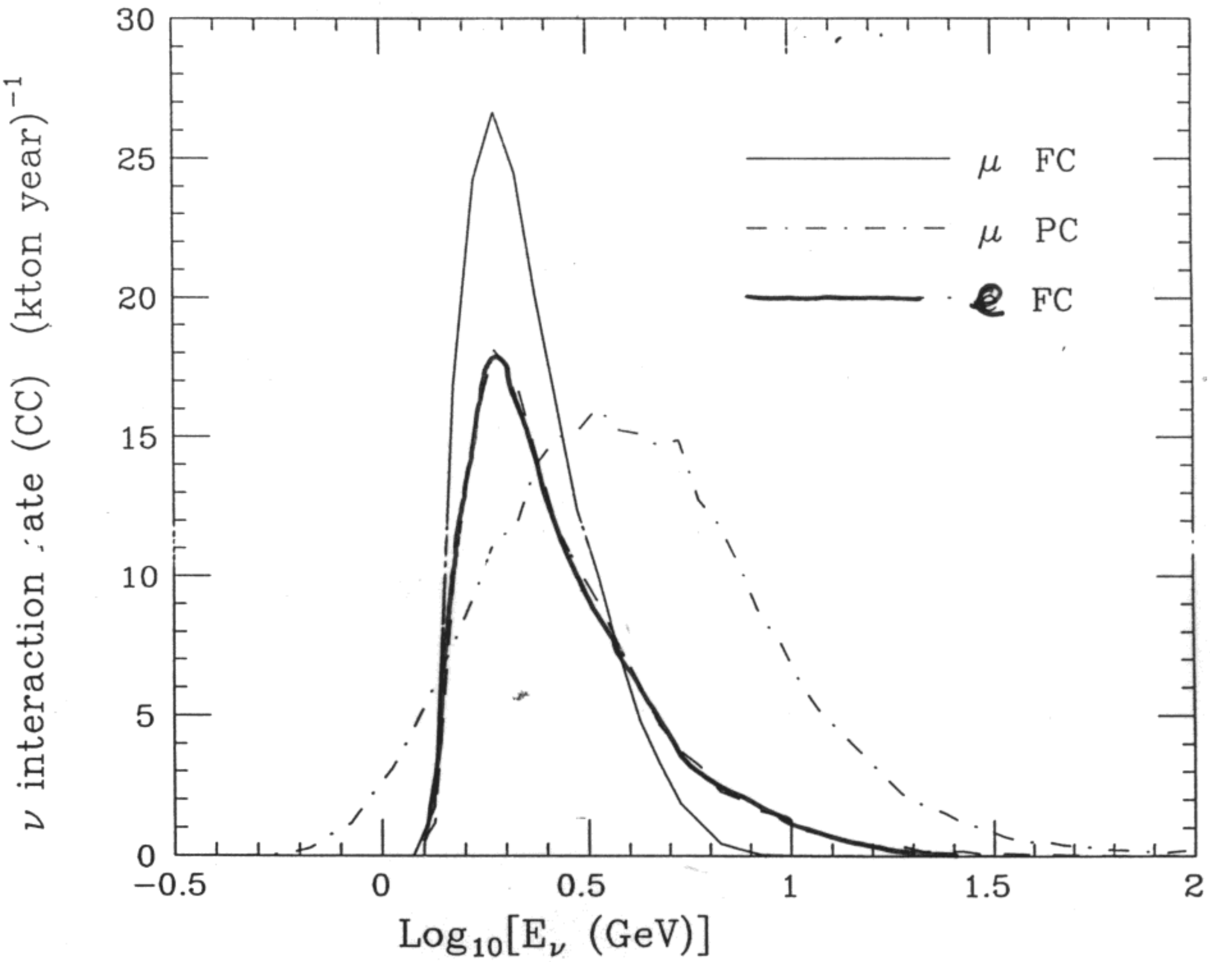
125
100
75
50
25
0
ν interaction rate (CC) (kton year)$^{-1}$
−1
−0.5
0
0.5
1
1.5
2
Log$_{10}$[E$_\nu$ (GeV)]

Energy response for μ and e is not identical.



Energy response for μ and e is not identical.

ν–Energy distribution of multi–GeV events



"Problems"

① The "NORMALIZATION" problem.

(Too many electrons?)

② Determination of parameters

(Kamioka versus SK
33 Kt → 45 kt)

(Δm^2 crucial for future planning)

③ Soudan-2 and Zenith angle

(Why Soudan does not see a modulation?)

④ Upward going Muons.

[Zenith angle distribution of MACRO
Baksan, IMB.

The "normalization problem"

$$e_{DATA} \simeq \cancel{1.20}\ e_{MC}$$
$$\hookrightarrow 1.09$$

$$e_{MC} = \Phi_p \otimes Y_{p\to\nu} \otimes \sigma_\nu$$

- $\Phi^{p}_{Honda} \sim 1.20\ \Phi_p$ (recent measurements)

  [$\Phi^{p}_{Bartol} \sim 1.05\ \Phi_p$ (recent)]

- $Y_{p\to\nu}$ (Fluka) $\sim 0.85\ Y_{p\to\nu}$ (Bartol)

- σ_ν (SK new) $>$ σ_ν (SK old)

Same Φ_ν
Bartol

$e_{Data} \sim 1.09\ e_{MC}$ SK

$e_{Data} \sim 0.86\ e_{MC}$ Soudan-2

Something is "wrong" and should be understood.

Possibilities:

- Different Descriptions of σ_ν in the MC of SK and Soudan-2
- $\sigma_\nu(^{16}O)$ $\sigma_\nu(^{56}Fe)$
  different Nuclear effects
- Shape of Energy Spectrum $\Phi_\nu(E_\nu)\,\sigma(E_\nu)$ incorrectly predicted.

The Normalization (in a sense) is NOT a problem.

it cancels in the ratios μ/e $\frac{U}{D}$

Super Kamiokande Fit
leave the normalization a FREE parameter

hower.
To Test the normalization is an important check of the calculation $\otimes$ analysis $\otimes$ systematic.

+ Can become useful / important for some analysis

The proton Flux

~80% ✓ ✓

Two results in contradiction

$$\Phi_p^{\text{WEBBER}} / \Phi_p^{\text{SEO et al}} \cong 1.60$$

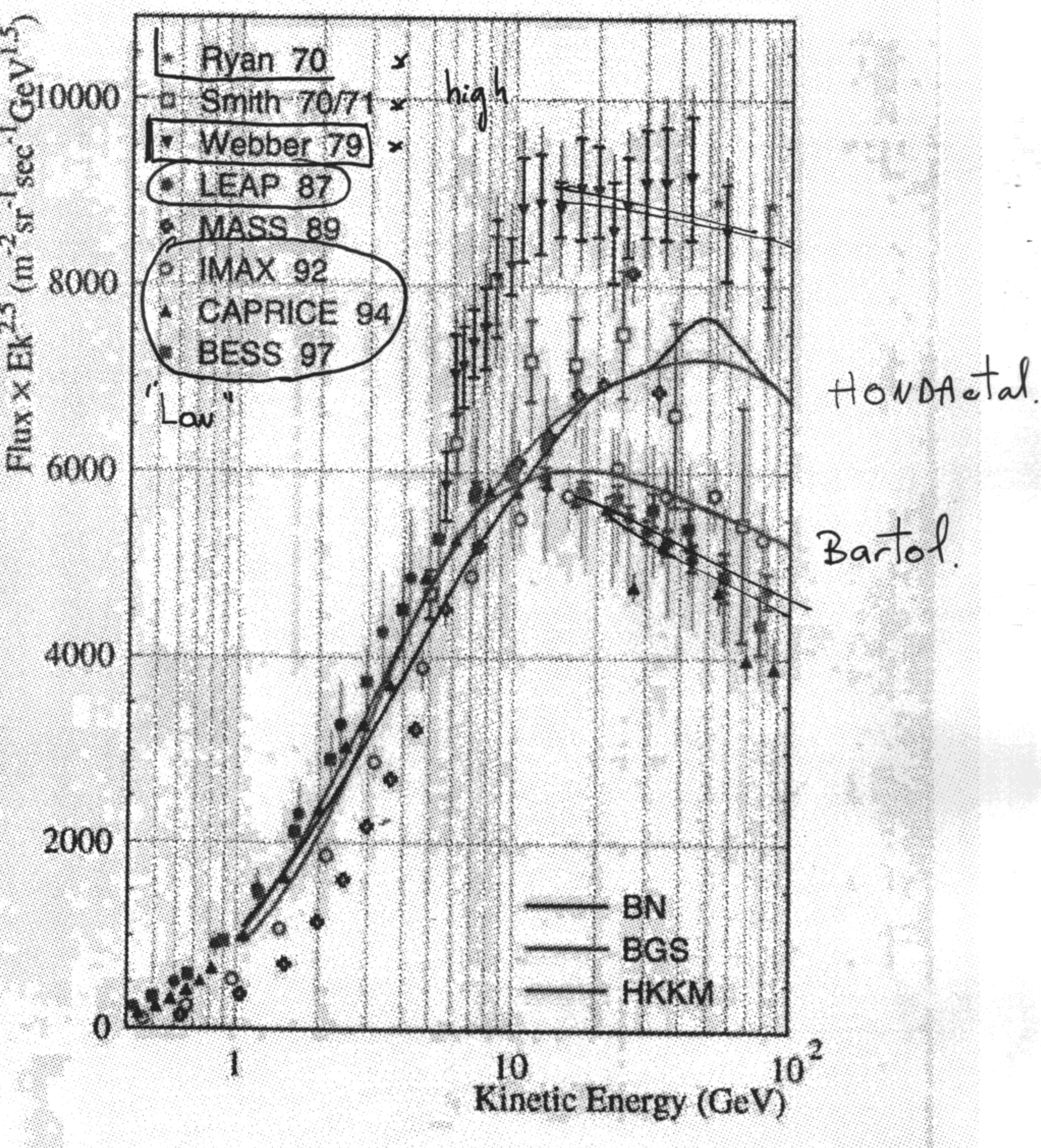
$$(E_p \simeq 30\ \text{GeV})$$

4 "new" measurements

IMAX 92
CAPRICE 94
BESS 97

compatible with each other (~10%)

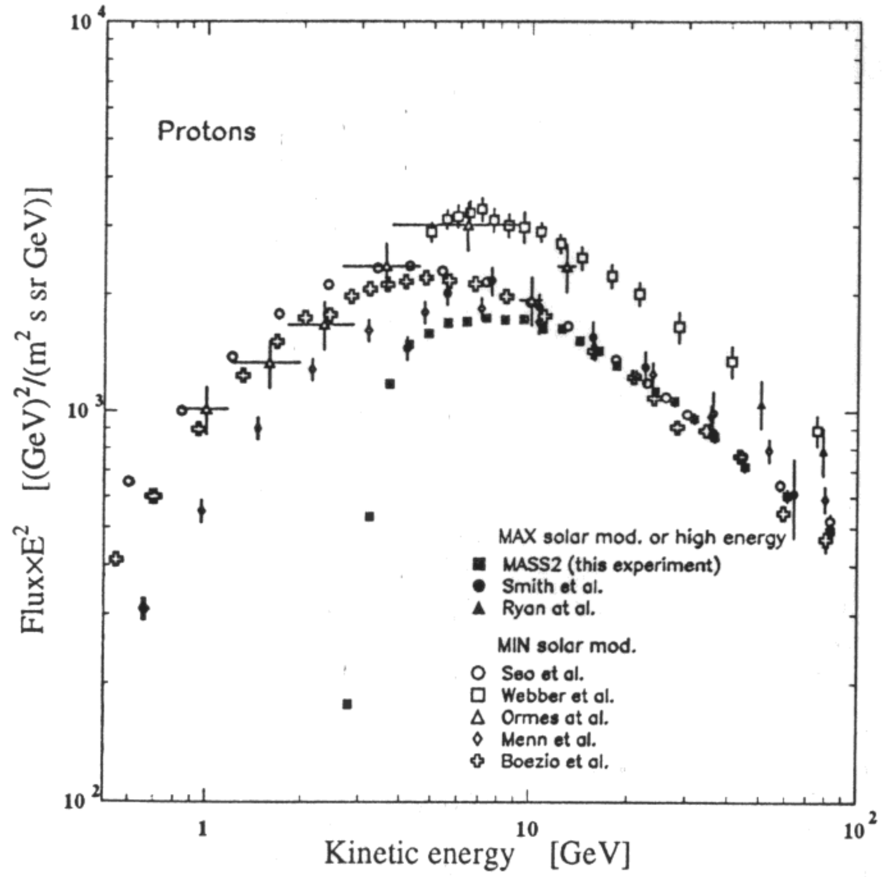
MASS-2 (This conference) compatible with low normalization

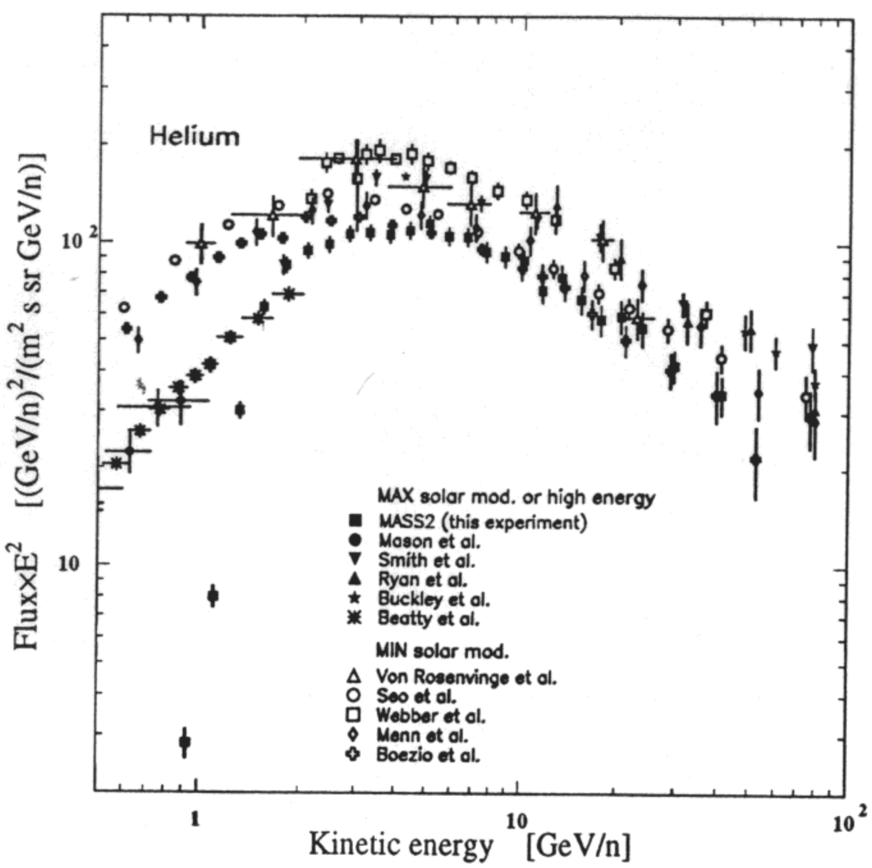


Ryan 70
Smith 70/71
Webber 79
LEAP 87
MASS 89
IMAX 92
CAPRICE 94
BESS 97
high
'Low'
Flux × Ek^2.5 (m^-2 sr^-1 sec^-1 GeV^1.5)
10000
8000
6000
4000
2000
0
1
10
10^2
Kinetic Energy (GeV)
BN
BGS
HKKM
HONDA et al.
Bartol.

At this conference

Results III: primaries with MASS2 and CAPRICE





$E_p = 30$ GeV

$$\Phi_{Honda} \simeq 1.20 \; \Phi_{data\ \text{"new"}}$$

$$\Phi_{Bartol} \simeq 1.05 \; \Phi_{data\ \text{"new"}}$$

In First approximation should reduce MC prediction accordingly

Can the difference between

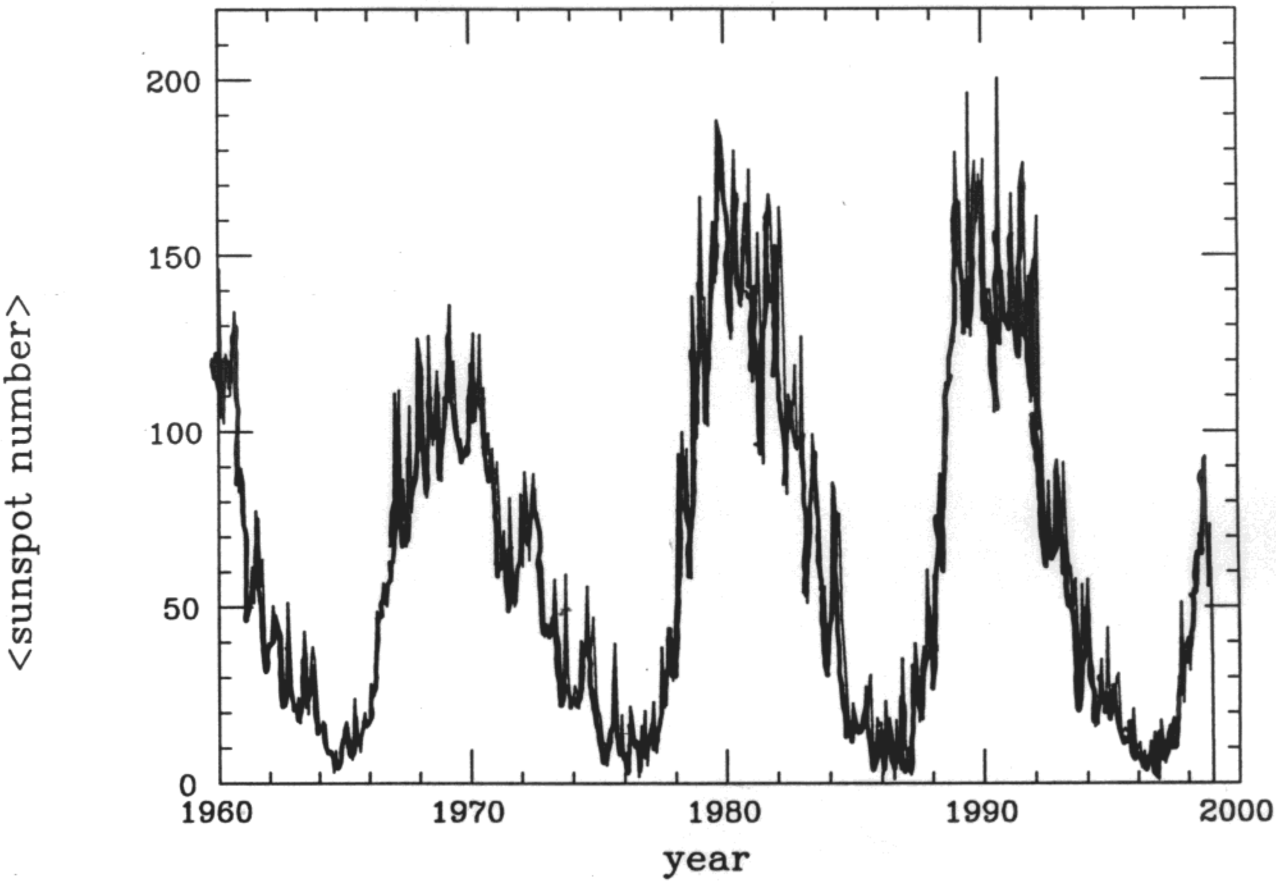
WEBBER – Seo et al.

explained as a time variation?

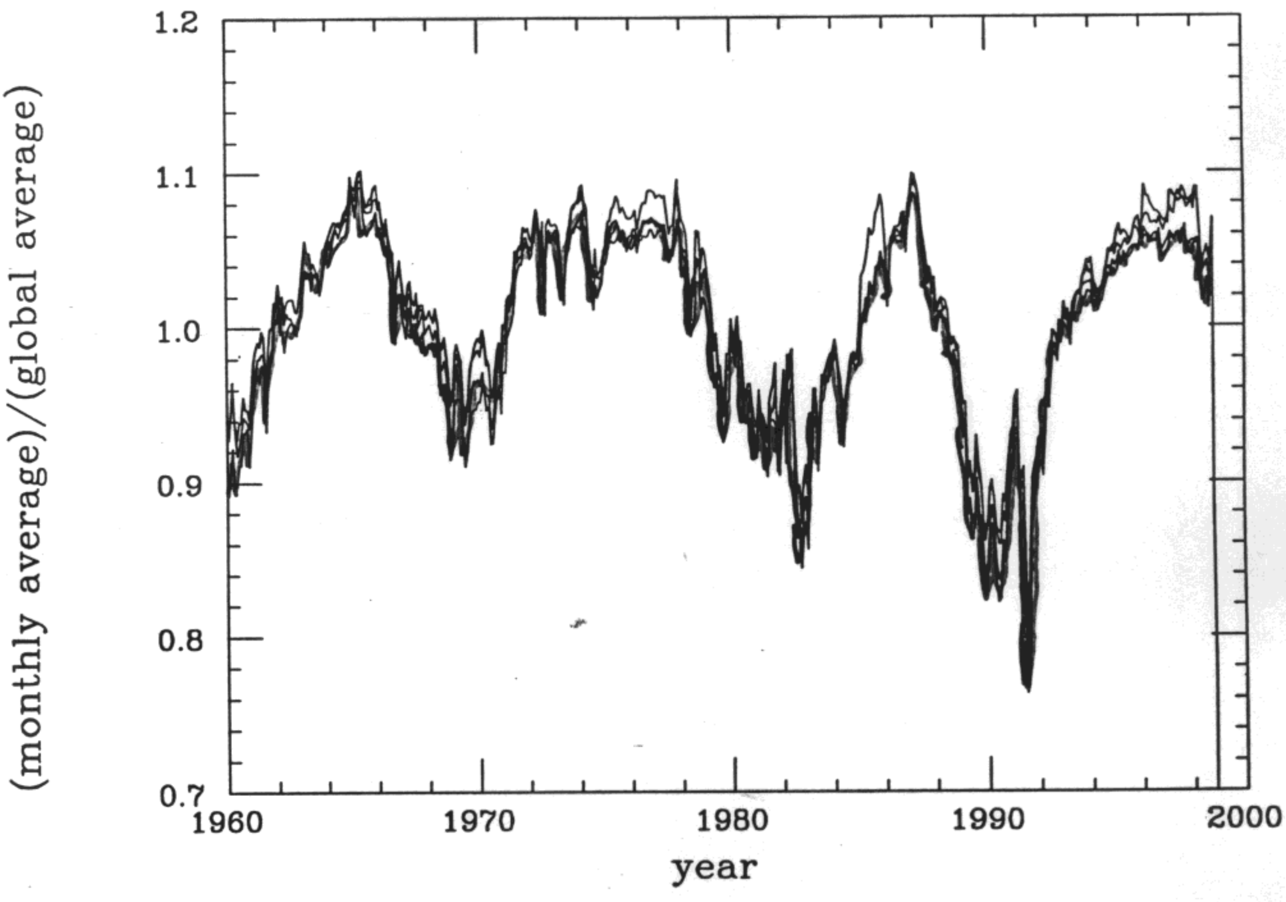
$[\Phi_n/\Phi_L \sim 1.60$ at $30\ GeV]$

Answer: **NO**

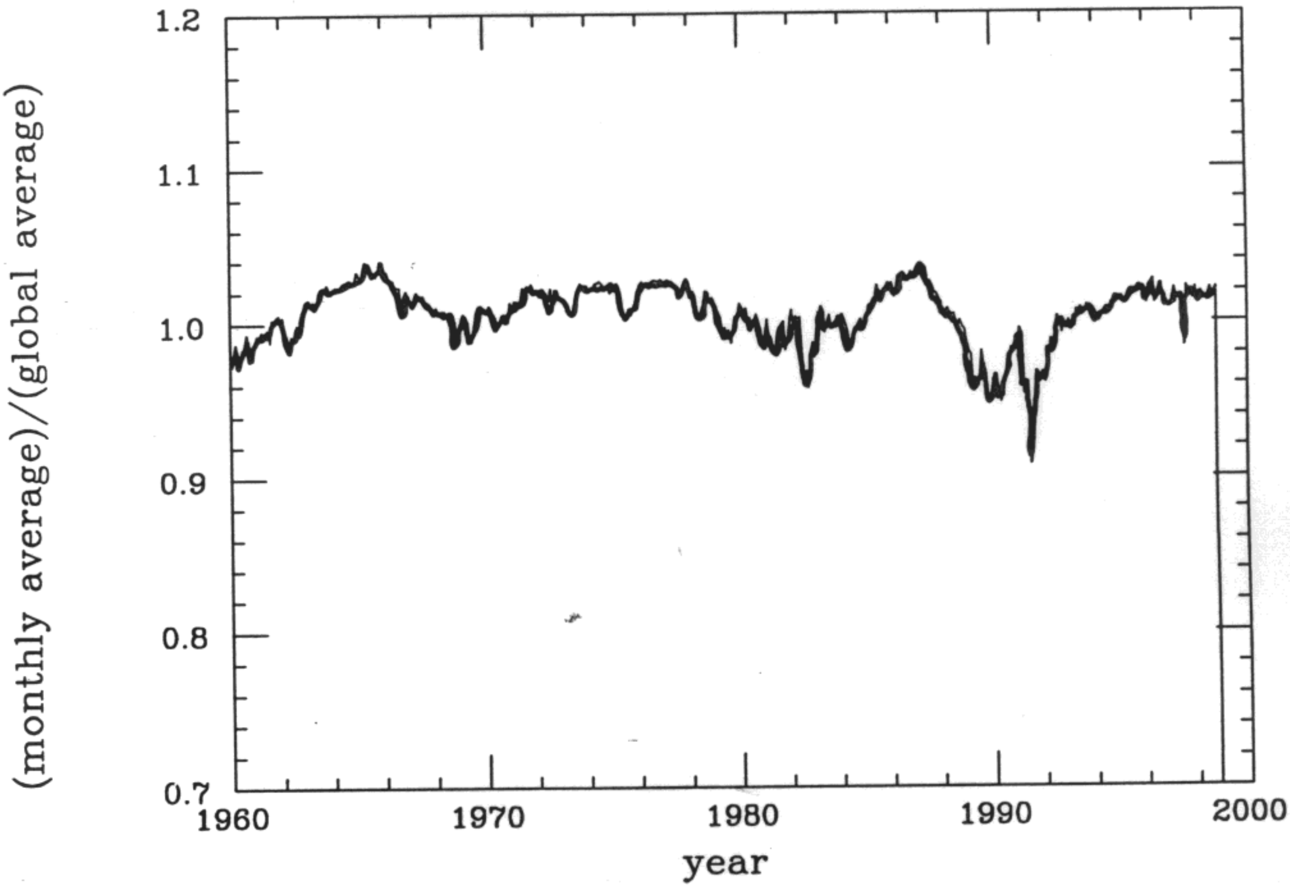
Solar Activity



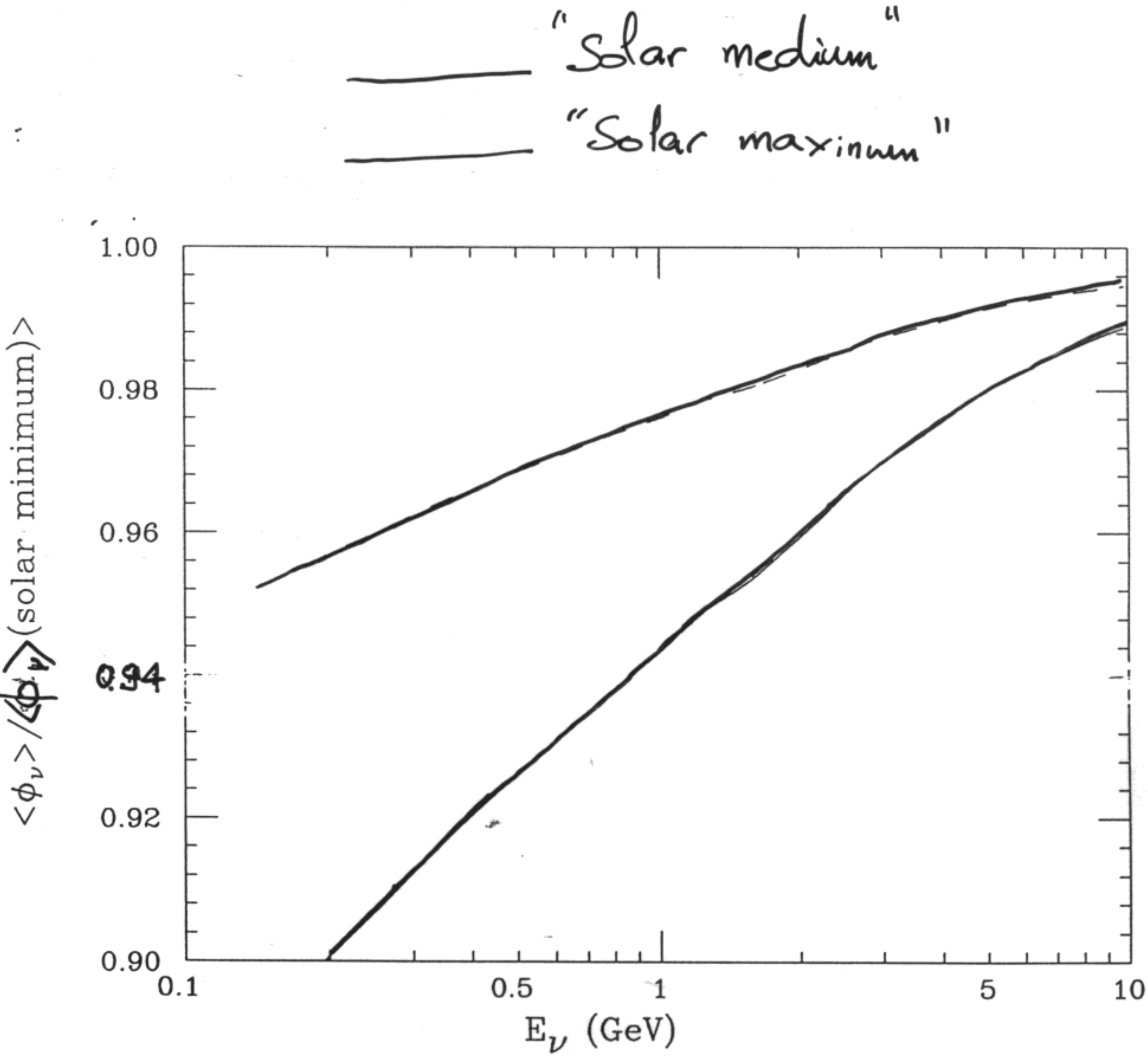
Neutron monitor Counting Rate
($E_{cutoff, vertical} < 2$ GeV)



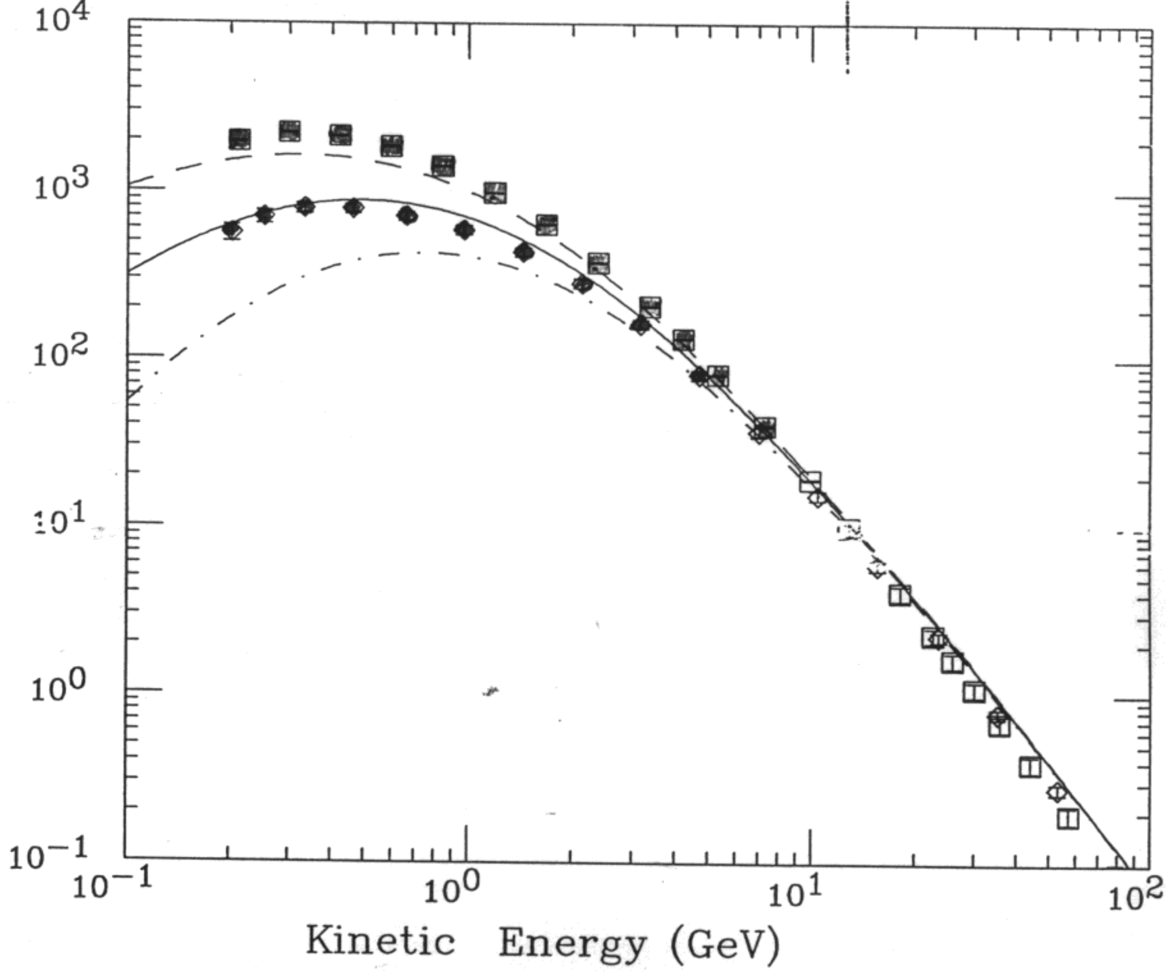
Neutron monitor at Halcakala Ecutoff = 14 GeV



Solar Modulation of the Neutrino flux



Modulation parametrized with form $\exp\left[-\frac{k(t)}{E_0}\right]$



Example of the sensitivity to the Montecarlo calculation.

Allowed region in the $(\Delta m^2, \sin^2 2\theta)$ plane of SuperKamiokande data.

[for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations]

Two modifications of the Super-Kamiokande Monte Carlo

(with respect to MC in the paper "Evidence for oscillations")

- Honda et al. flux
  Solar medium → Solar minimum

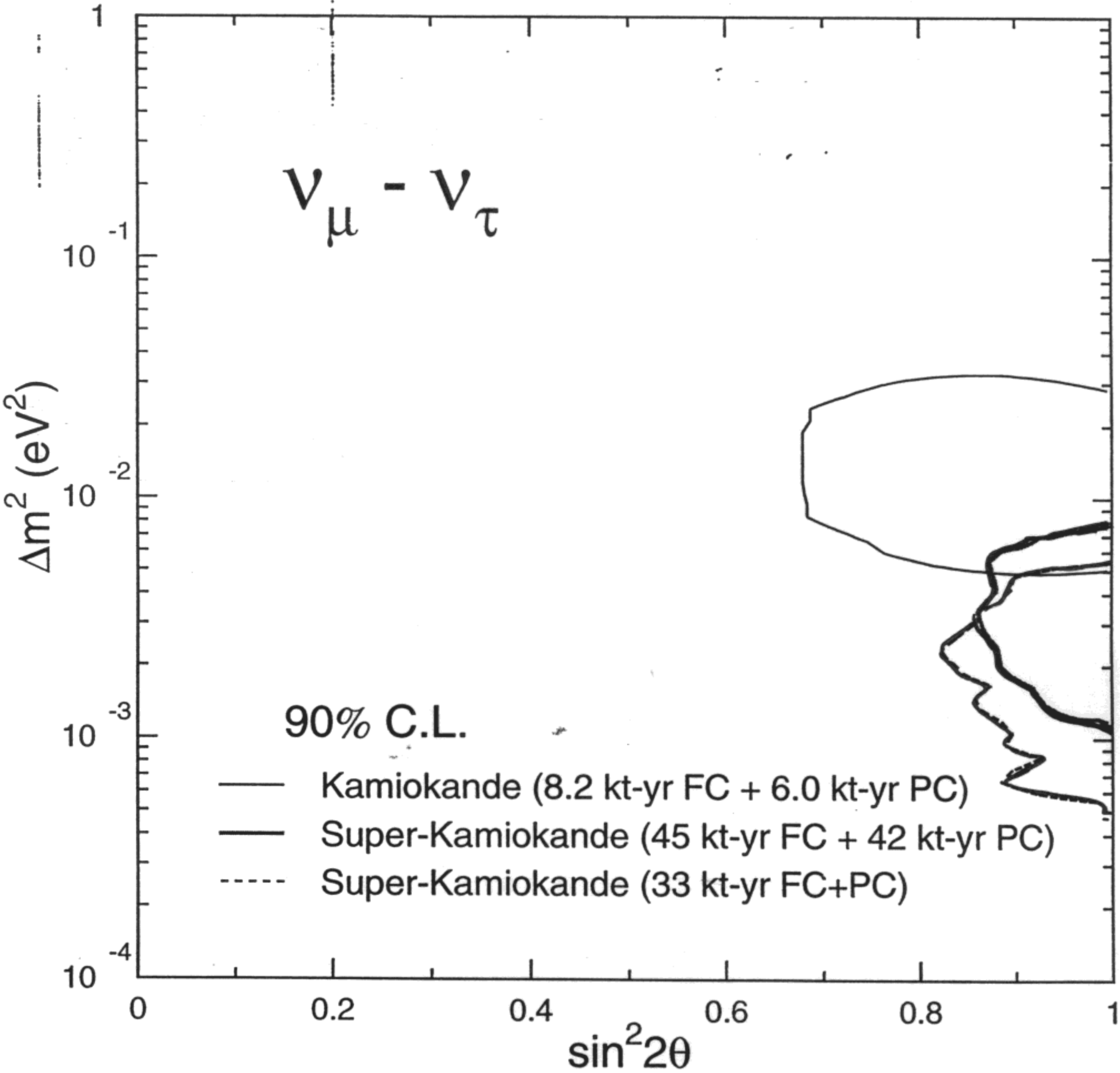
- Parton Distribution Functions (description of DIS in σ_ν)
  CCFR → GRV94

Ratio (Old–Montecarlo)/(New–Montecarlo)

~ +10%	sub–GeV	e-like	1.041
	sub–GeV	μ–like	1.045
	sub–GeV	multi-ring	1.209
~ +15%	multi–GeV	e–like	1.084
	multi–GeV	μ–like	1.030
	multi–GeV	multi-ring	1.214
	partially contained		1.070

Allowed region of SK changed

33 kton yr ⟶ 45 kton yr.



The allowed region of SK has changed significantly for the increased exposure

33 → 45 kton yr

[+ 36% of exposure]

Lowest allowed Δm^2 (90% CL) higher by a factor ~ 2.5

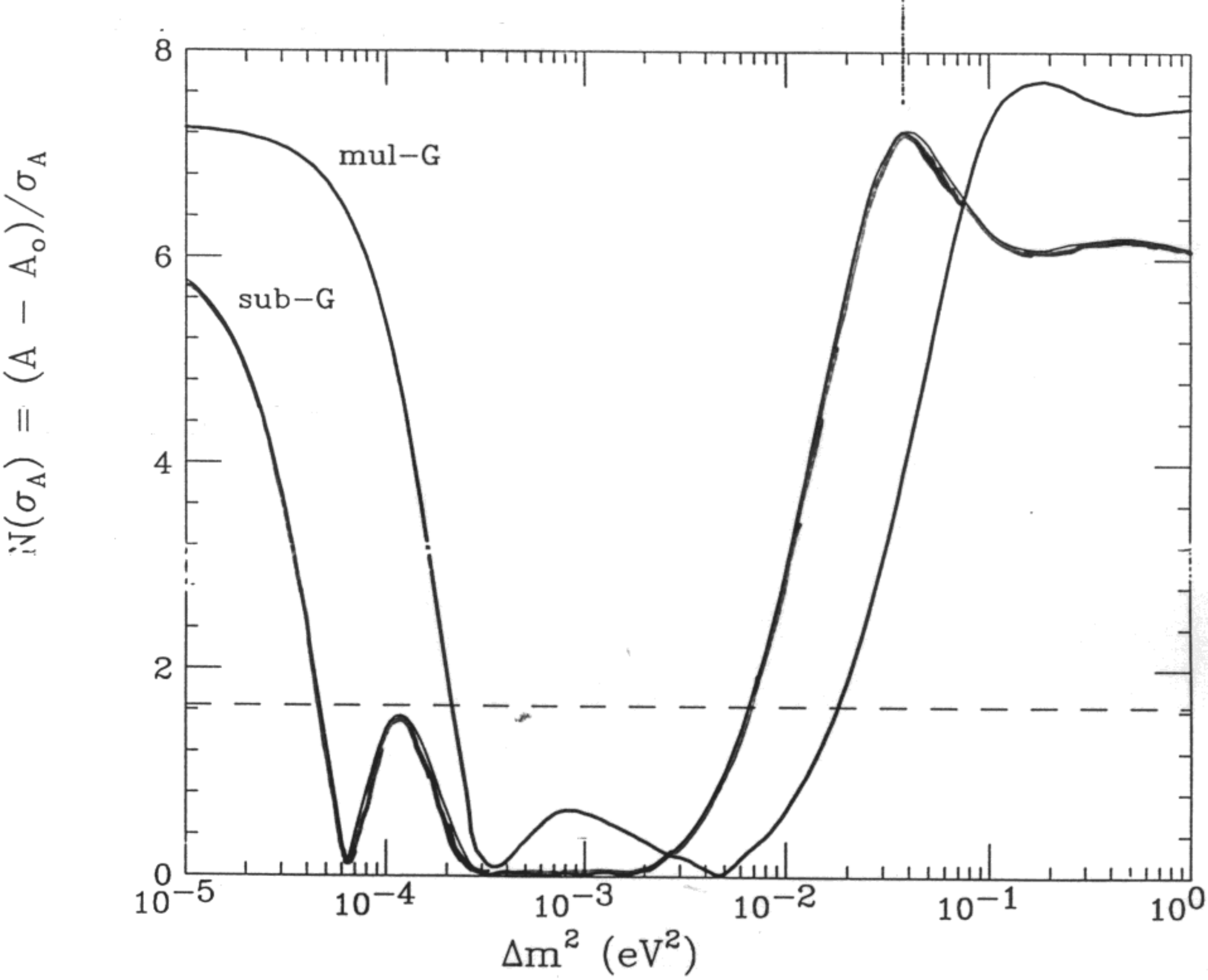
[A "Christmas gift" for LBL programs]

At least some, and probably most of this change is due to the different Montecarlo.

$A(\text{sub-GeV}) = -0.150 \pm 0.028$

$A(\text{multi-GeV}) = -0.311 \pm 0.043$

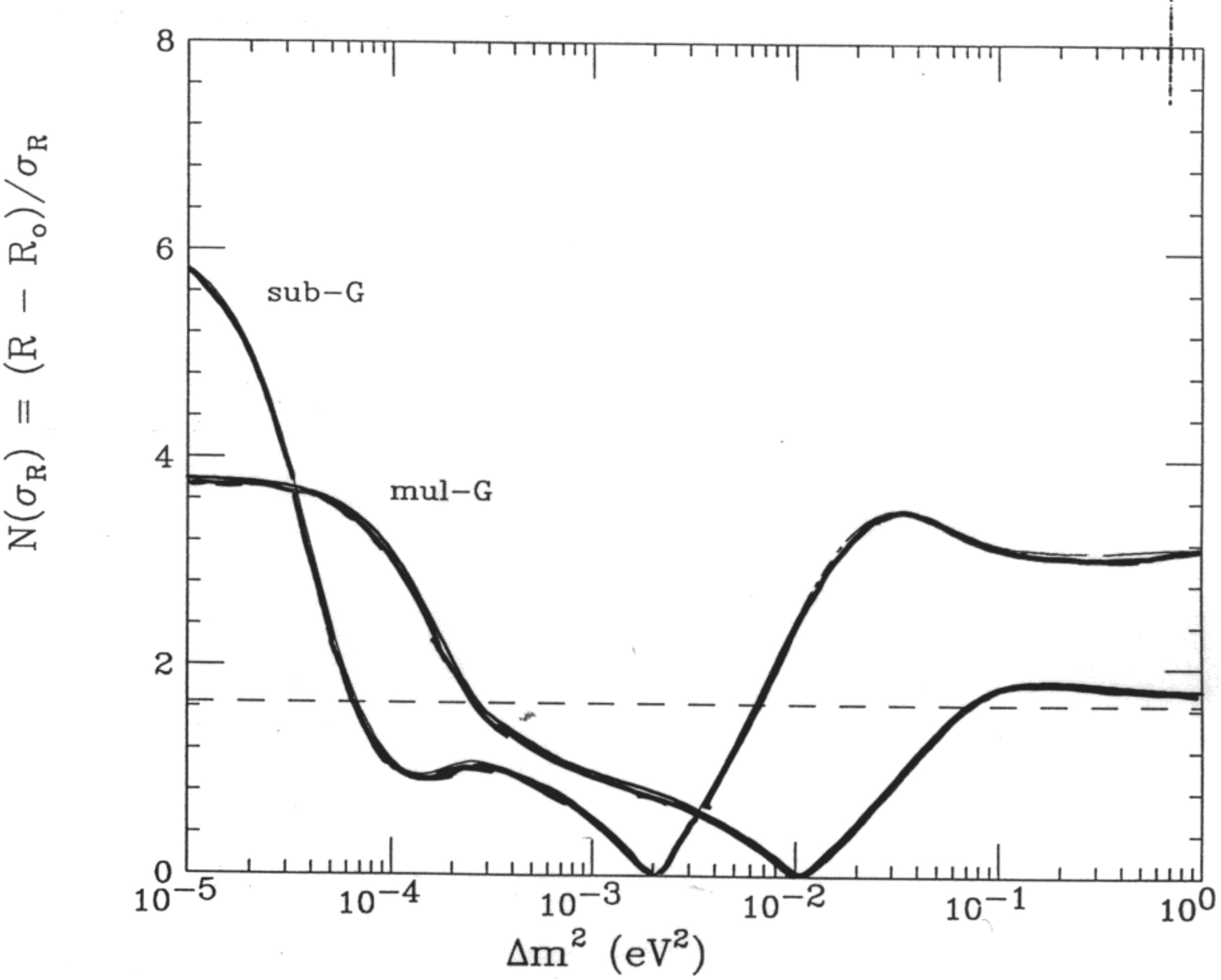
Up–Down asymmetry: $A = (U-D)/(U+D)$



Double Ratio : $R = (\mu/e)_{data} / (\mu/e)_{MC}$

Maximal Mixing

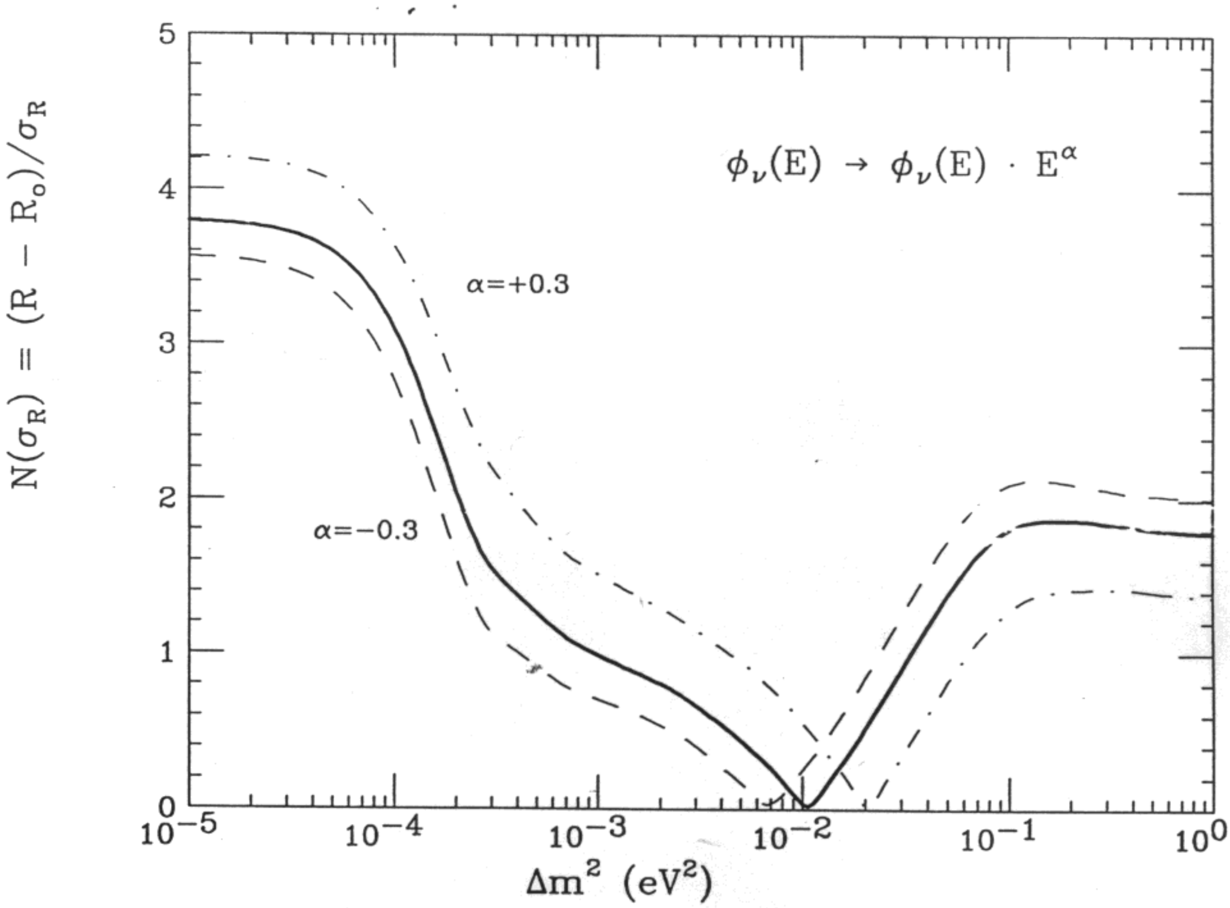
R=1 → R=1/2




Allowed region.
Lower limit
multiGeV Double Ratio
Upper limit
Up/Down
subGeV

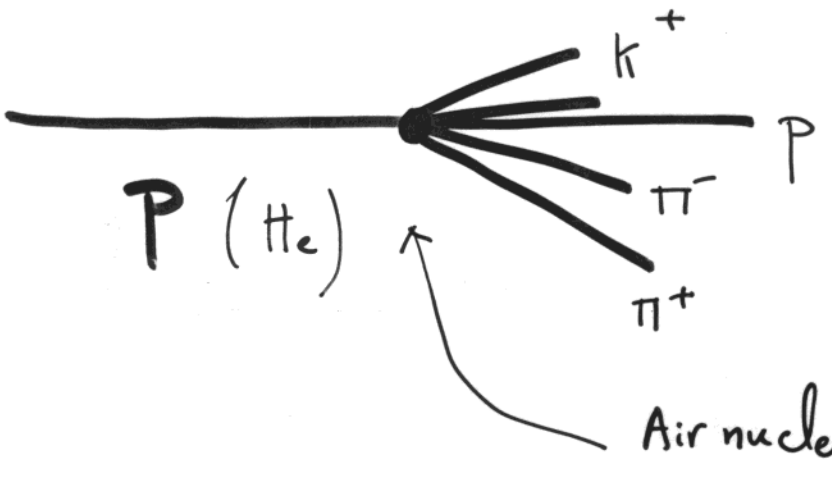
Effect of a modification of the [shape] of the energy spectrum.

$E^{\pm 0.3}$



Hadronic interaction.

Important source of systematic uncertainty.

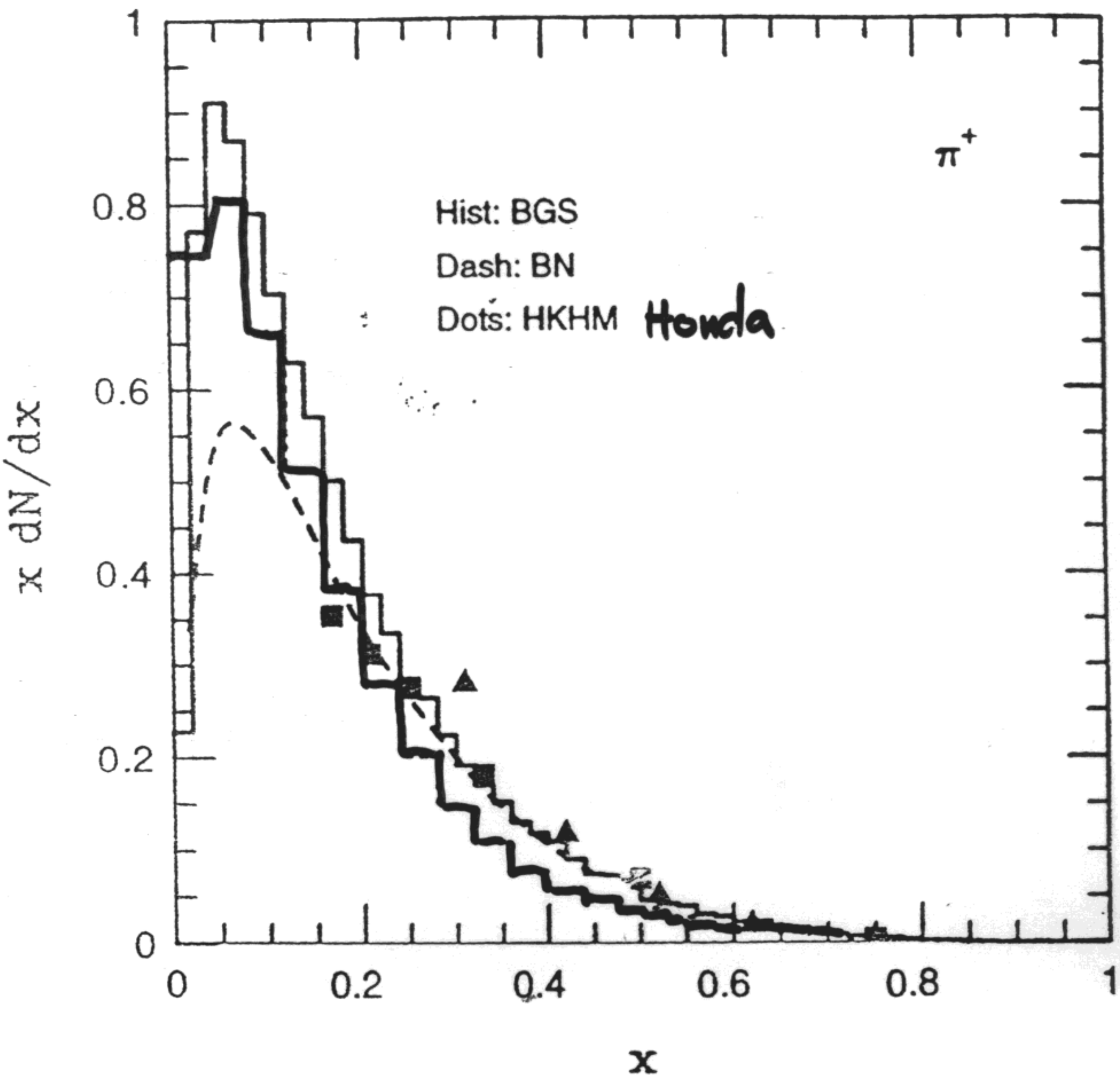


Multiplicity
Energy distribution
Flavor composition.

Need INPUT from experiment

[Only little data is available]

Inclusive particle Production

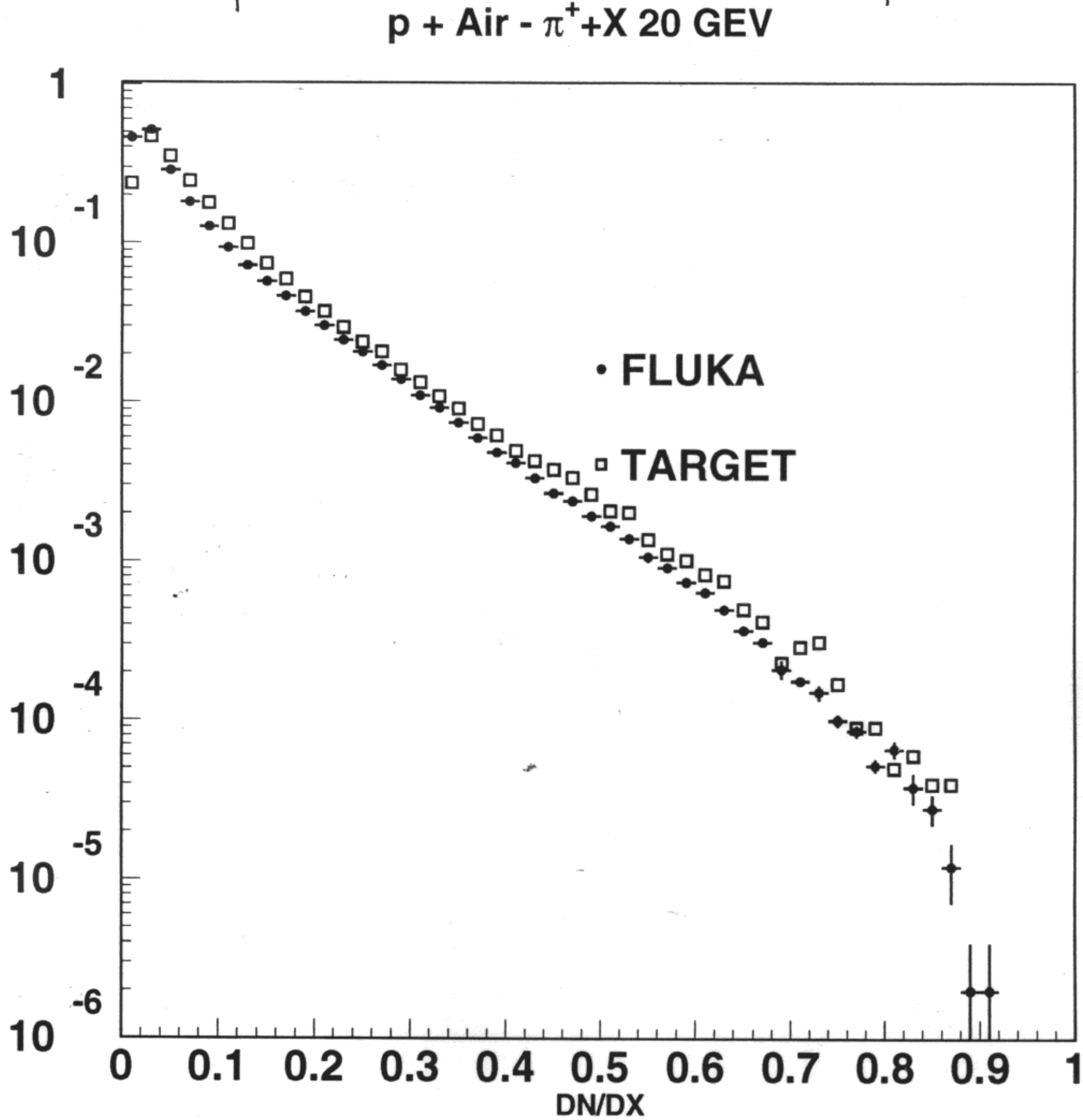


$$p\, Be \rightarrow \pi^+ + \ldots \qquad E_p = 24\ GeV$$

$$x = \frac{E_{\pi^+}}{E_p}$$

Comparison of Fluka with TARGET computer code used by Bartol.

$$Y_{p\to\nu}(\text{Fluka}) = 0.85\, Y_{p\to\nu}(\text{Bartol})$$



(Target = Bartol)

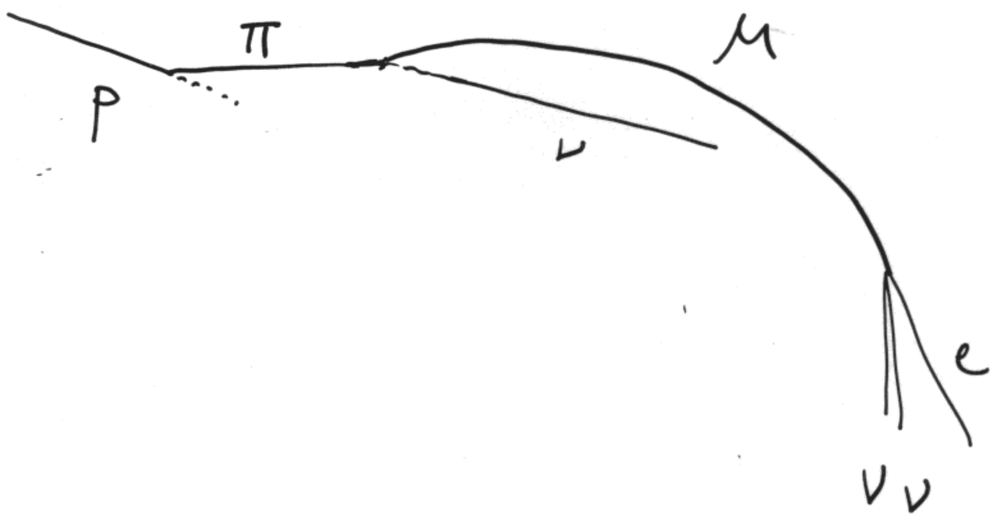
The most important known limitation of the current calculations of the atmospheric neutrino fluxes is the fact that they are **1-Dimensional**.

The Angle between ν and primary particle is not negligible:

$$\langle \theta_{p\nu} \rangle \simeq (5^\circ\text{–}10^\circ)/E_\nu(\text{GeV}).$$

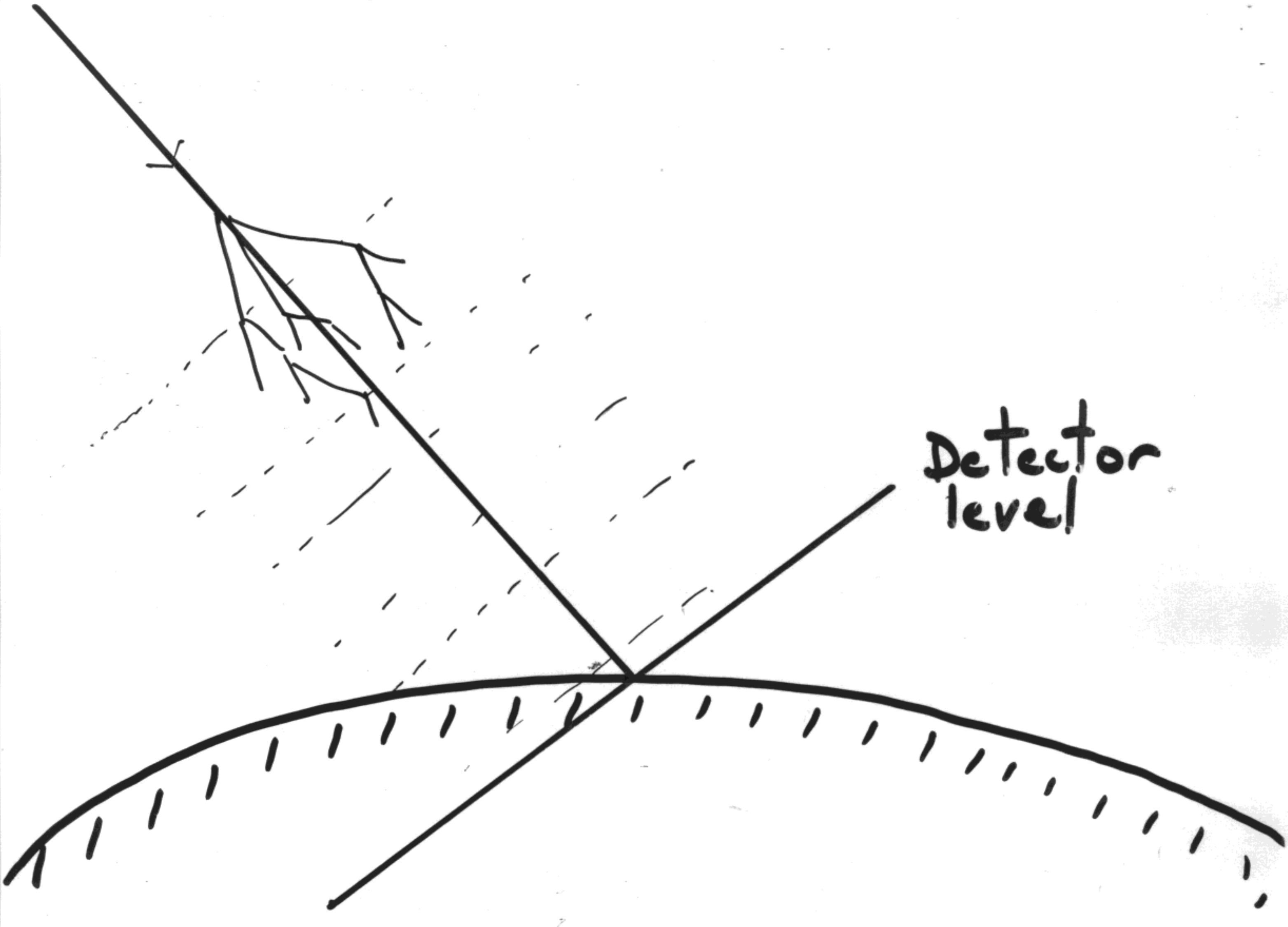
$$\theta_{p\nu} = \theta_{p\pi} + \theta_{\pi\nu}$$

$$= \theta_{p\pi} + \theta_{\pi\mu} + \theta_{\mu,B} + \theta_{\mu\nu}$$



Calculations are 1-dimensional

ν collinear with primary.



[No $B_{\oplus}$ during shower Development]

Two dominant sources of $\theta_{p\nu}$:

(i) the $p_\perp$ of the parent meson

$$\langle \theta_{p\pi} \rangle \simeq \frac{\langle p_\perp \rangle_\pi}{E_\pi} \simeq \frac{350\ MeV}{4E_\nu} \simeq \frac{5^\circ}{E_\nu(GeV)}$$

(Other deviations are smaller:

$\langle p_\perp \rangle_\pi \simeq 350$ MeV

$p_\perp^{max}(\pi \to \mu\nu) = 30$ MeV

$p_\perp^{max}(\mu \to e\nu\nu) = 50$ MeV)

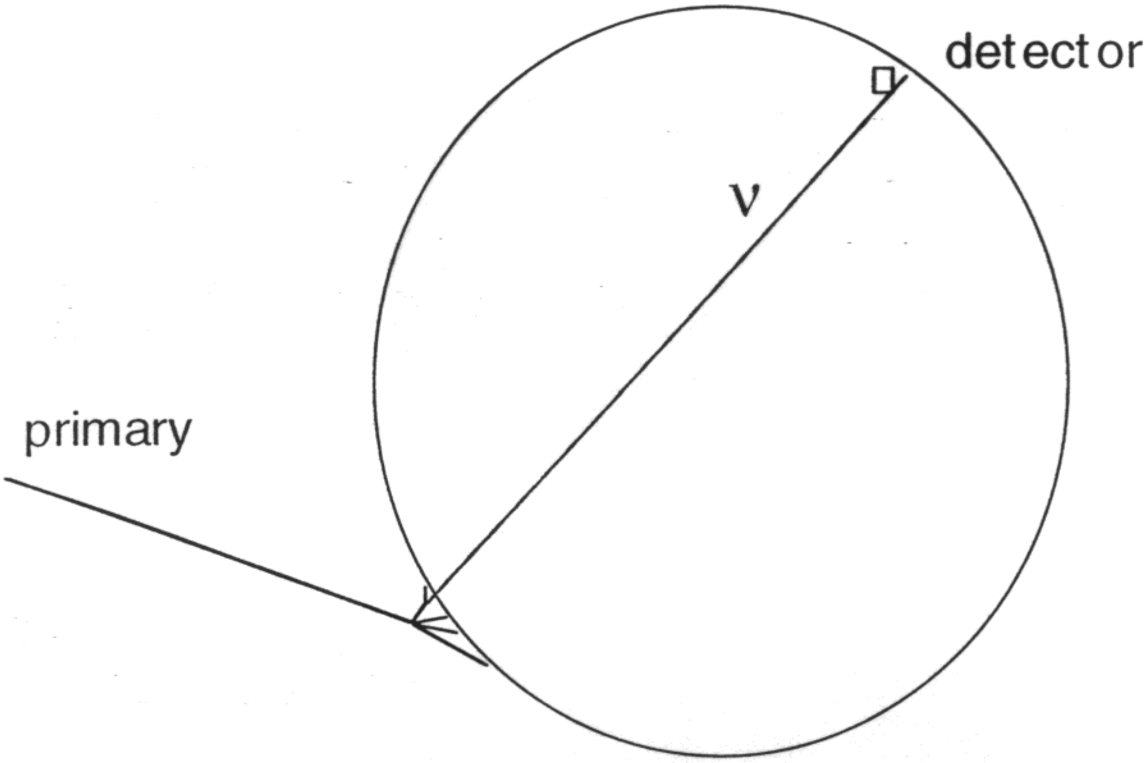
(ii) μ deviation in the geomagetic field:

$$\langle \theta_{\mu,B} \rangle \simeq \frac{L_\mu}{r_{gyro}} \simeq \frac{(3^\circ \div 10^\circ)}{p_\mu(GeV)}$$

$$r_{gyro} = \frac{p_\mu c}{B_\perp} = \frac{74\ km}{p_\mu(GeV)} \left(\frac{0.45}{B_\perp(Gauss)} \right)$$

A 3-D calculation of the Neutrino Fluxes is "expensive"
in computer time. "Brute Force" is Very Expensive.

"Inefficient"



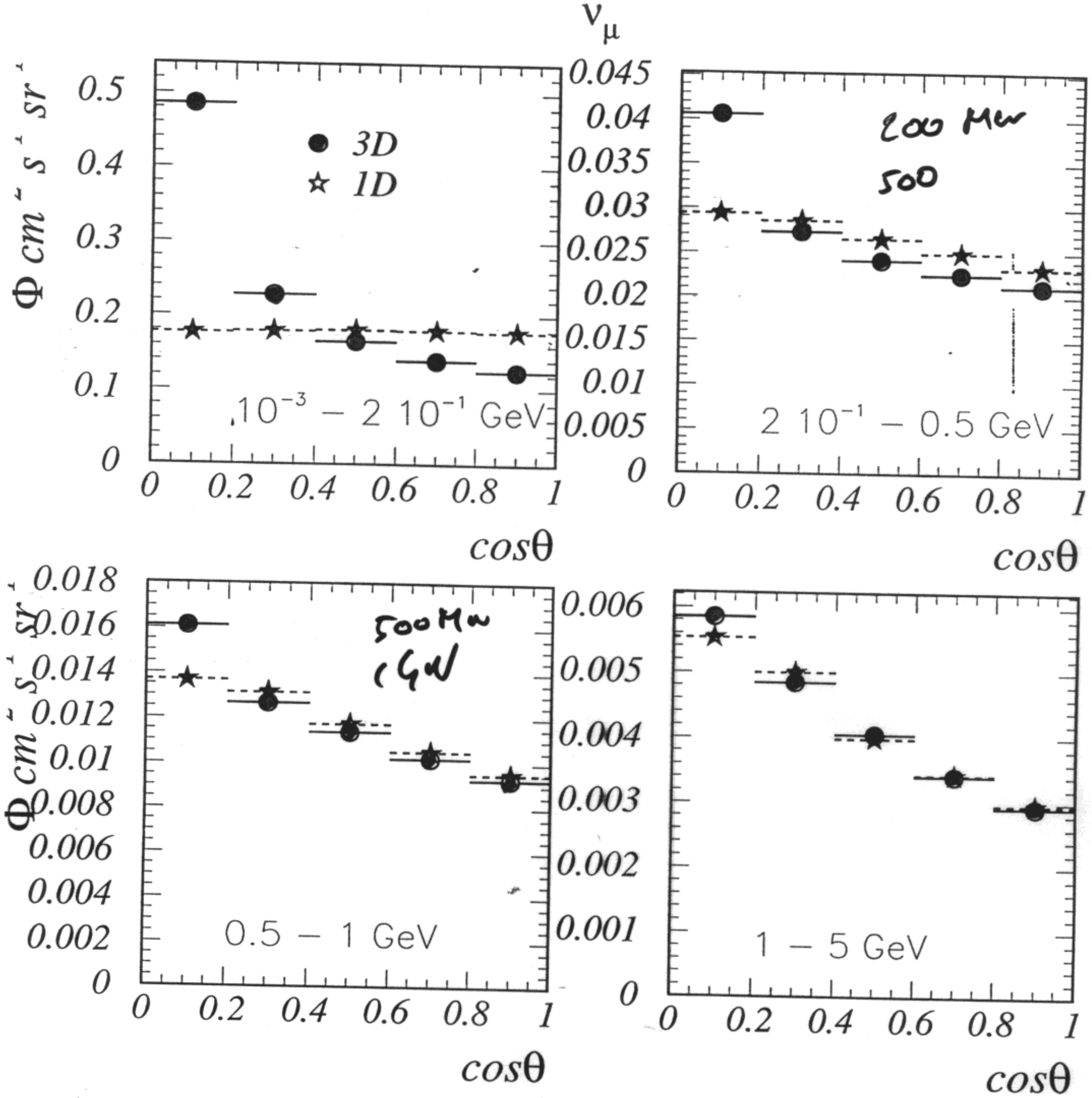
Battiston, Ferrari et al.

A Test Calculation has been performed with FLUKA ν under the assumption of :

SPHERICAL SYMMETRY (Switch off all Magnetic Fields)

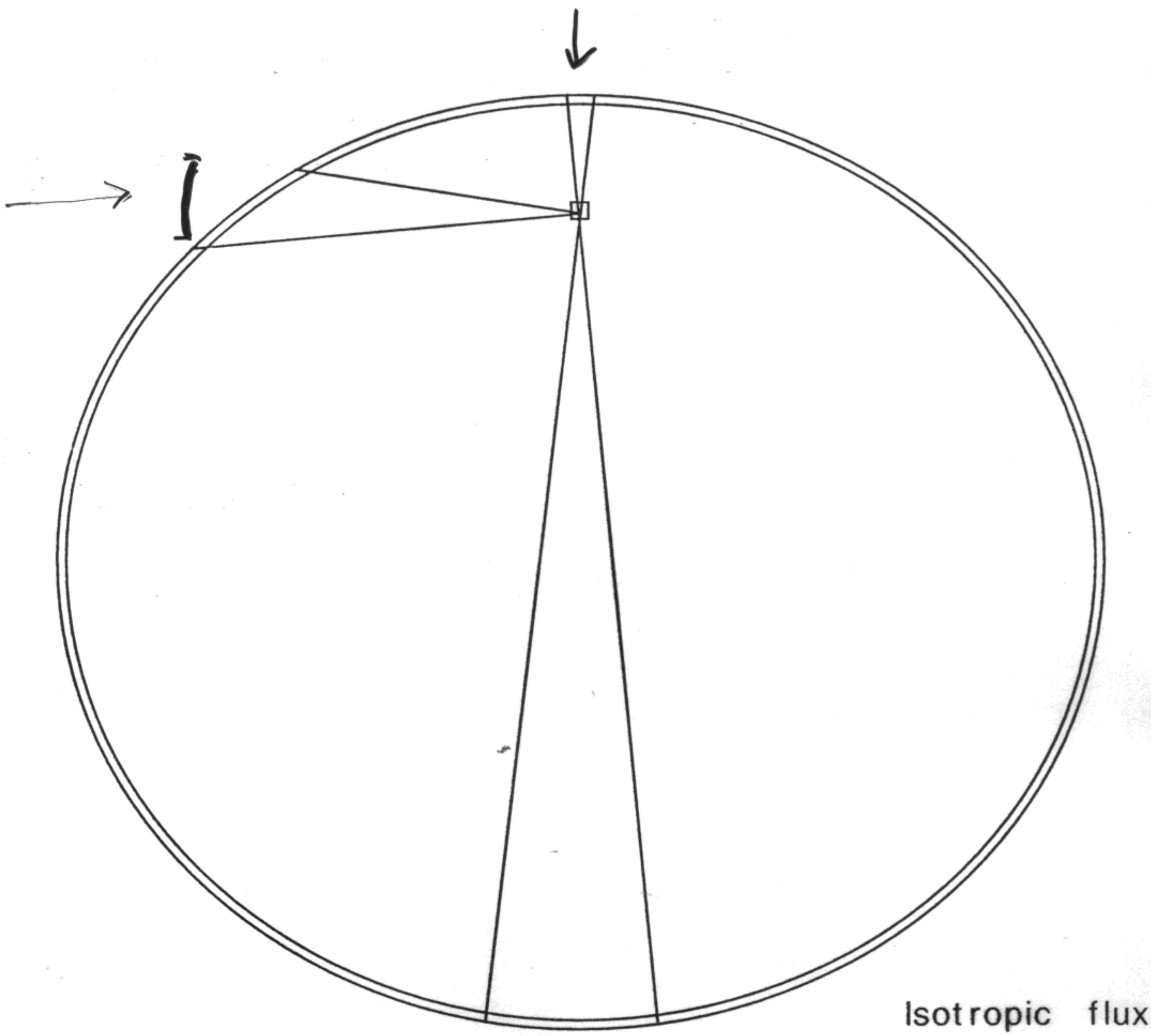
The entire surface of the earth can be considered as the "detector".

Two calculations with full 3D
will be available soon.



ν_μ
Φ cm⁻² s⁻¹ sr⁻¹
3D
1D
10⁻³ – 2 10⁻¹ GeV
2 10⁻¹ – 0.5 GeV
0.5 – 1 GeV
1 – 5 GeV
cosθ
200 MeV
500
500 MeV
1 GeV

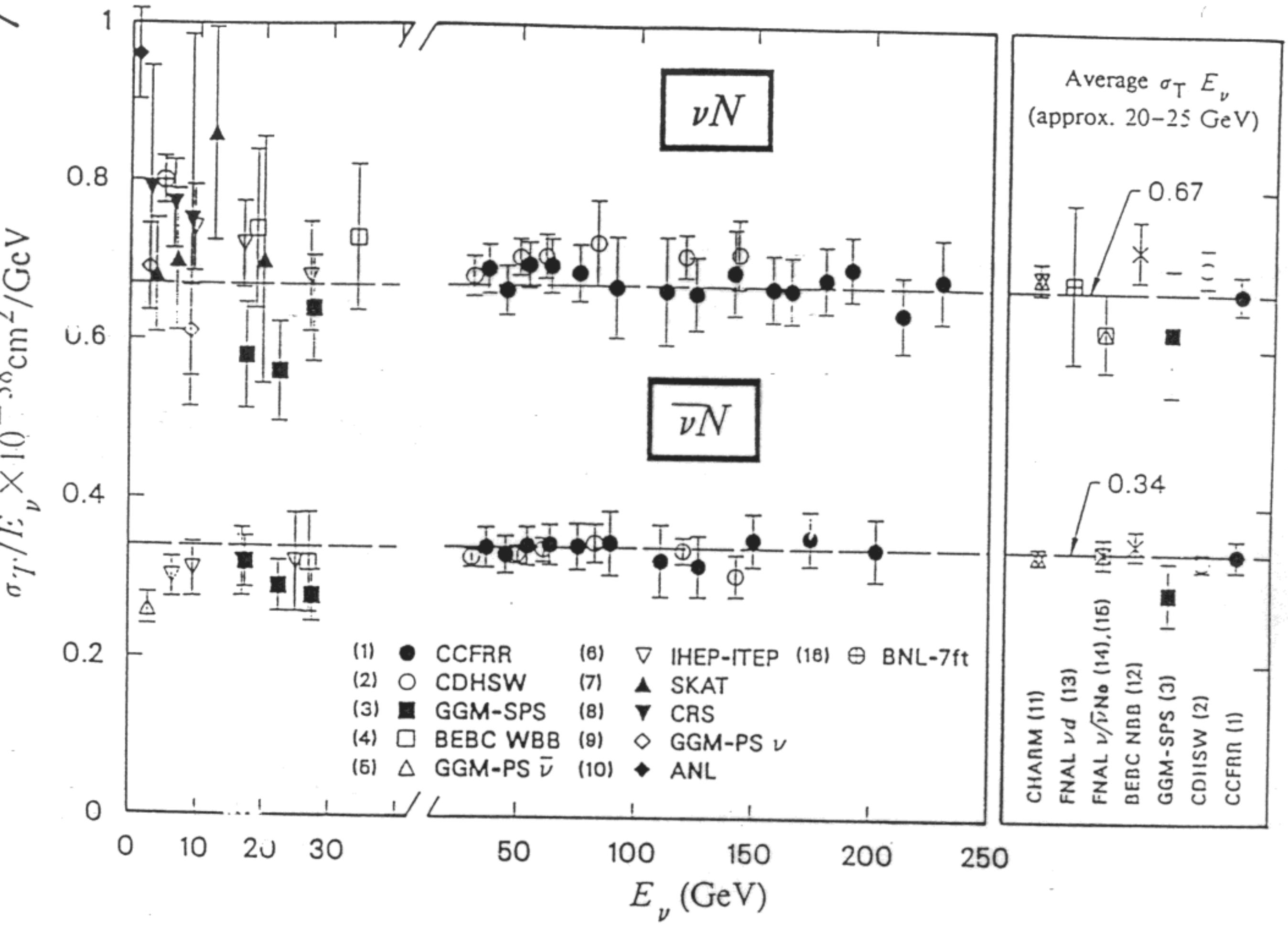
For large primary-neutrino angle
the Angular distribution of the neutrinos is modified in a 3-D calculation: the horizontal flux is enhanced



1D

$$dN(\Omega) = \frac{\left(L^2(\Omega)\, d\Omega \right)}{4\pi L^2(\Omega)}$$

$\sigma_\nu / E_\nu \; (10^{-38} \, cm^2 / GeV)$



[Neutrino CC cross section] $\propto E_\nu$

Uncertainties in the ν cross section

- Quasi elastic scattering
  Nuclear Effects.

- Resonance Production

- "Deep Inelastic Scattering"
  [multiple -π production"]

[Absorption or interaction
of secondary particles in the nucleus]

The Description of the Neutrino cross section is an important source of systematic uncertainty for atmospheric ν's.

Importance comparable to uncertainties on $\Phi_\nu \times \sigma_\nu$

Detailed studies are needed.

It would be desirable and healthy if the different experimental groups could compare and exchange their Montecarlo codes.

[Careful Respect of "Intellectual Property"]

Soudan-2

Non
Detection of a zenith angle modulation of μ- events.

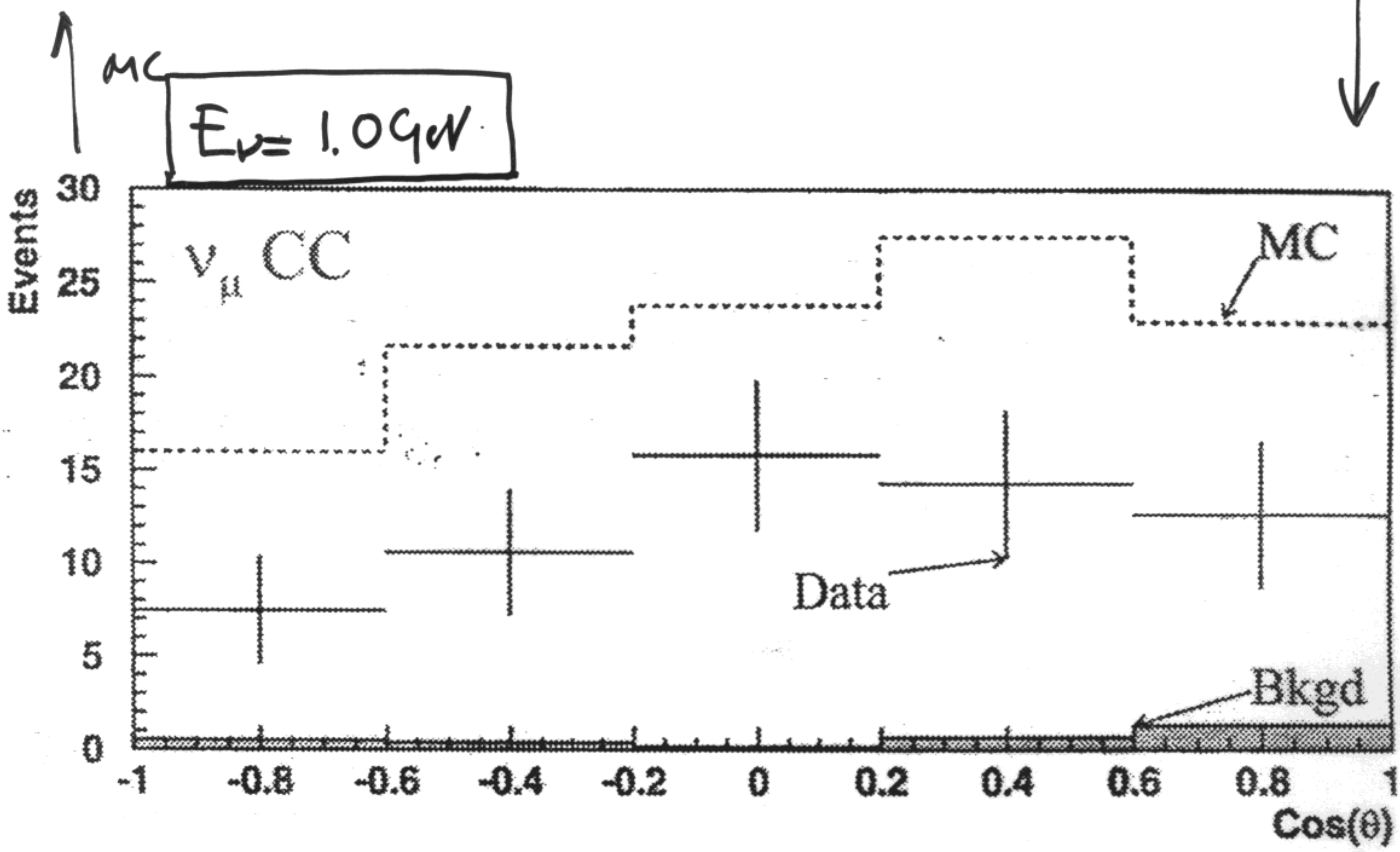
- Detailed calculation of the No-oscillation asymmetry.

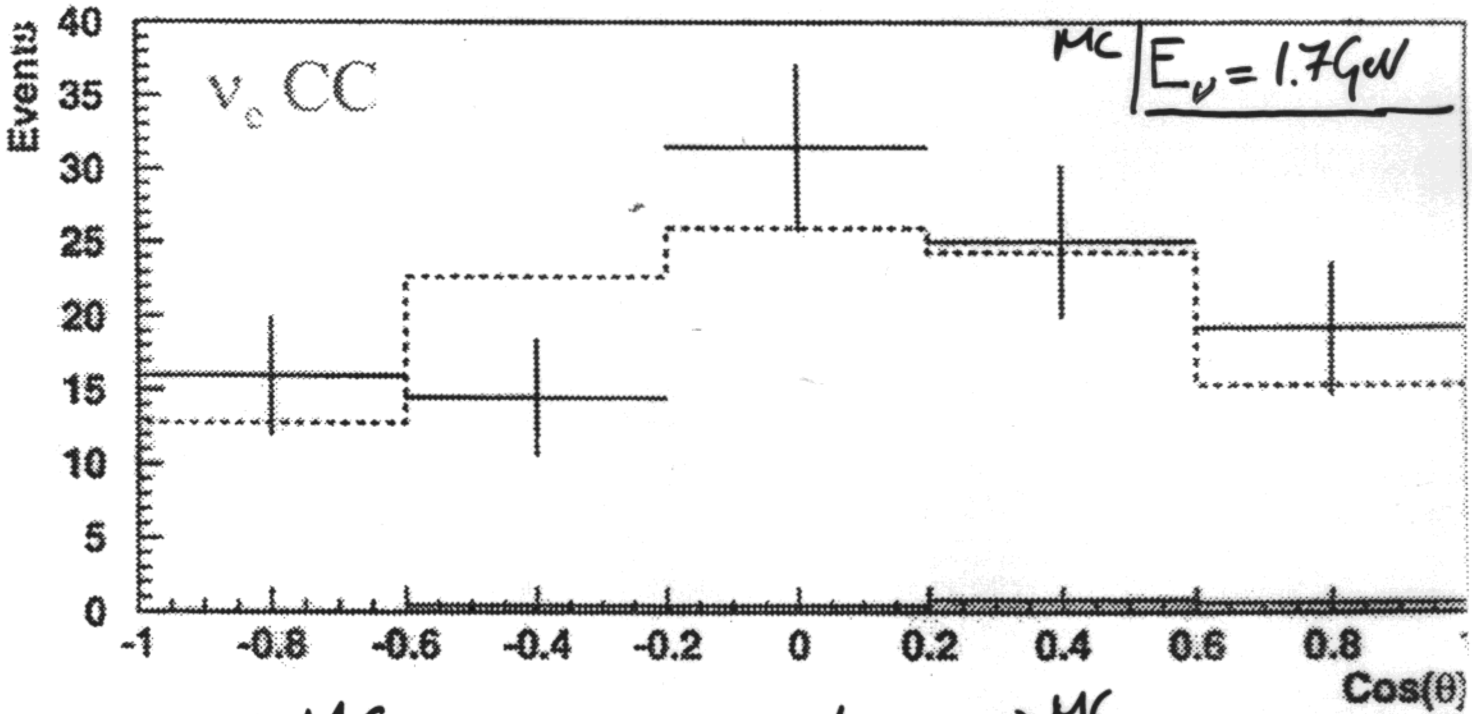
  $A_{no\text{-}oscillation} < 0 \; (\sim -0.14)$

- Correction of ν-direction using Recoil-proton.

  [Test experimentally ?
  a Soudan module at KEK ?]

Soudan-2 (Gallagher at ICHEP '98)

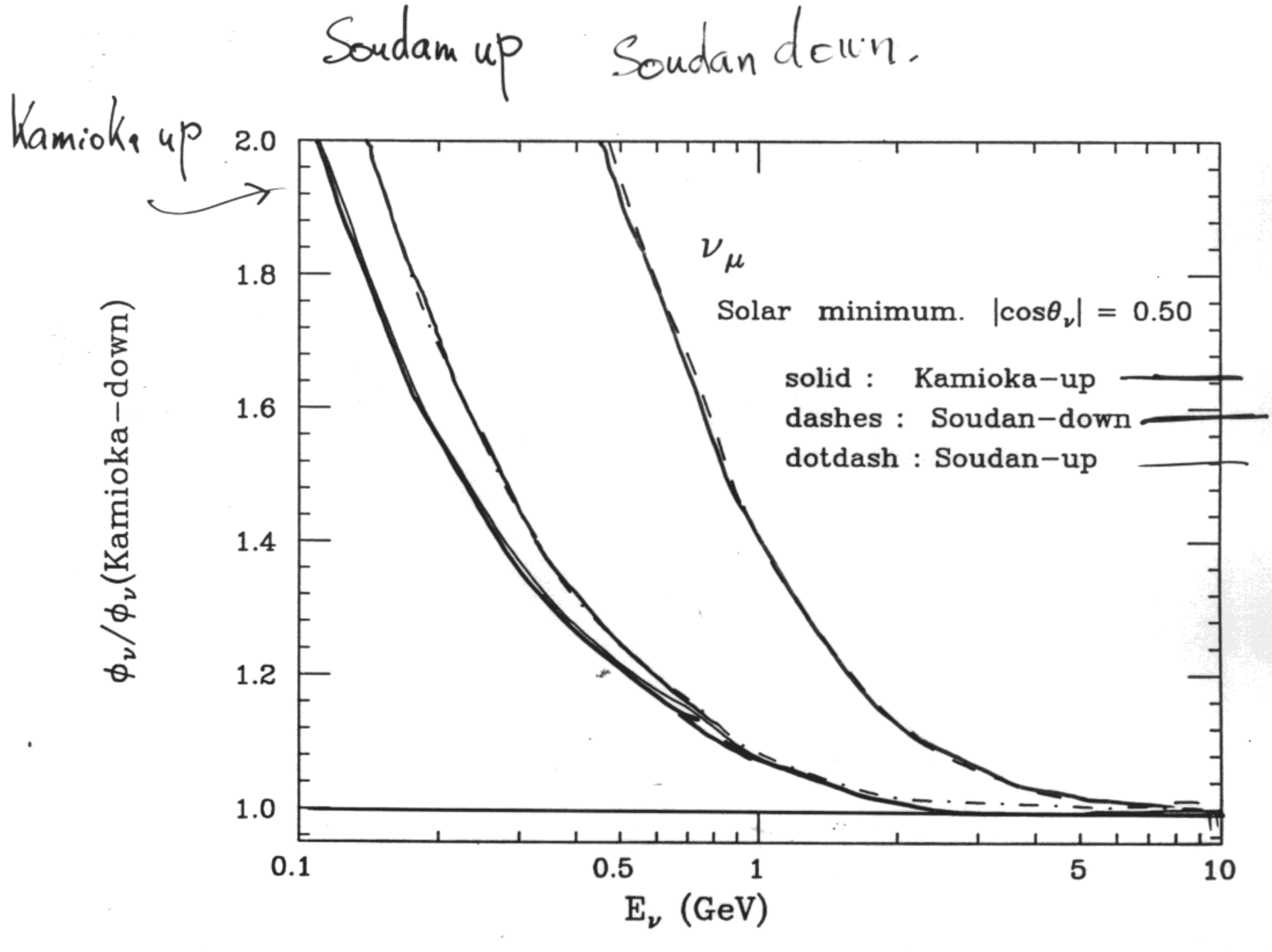




$$\left(\frac{\text{Up}}{\text{Down}}\right)^{MC}_{\mu} = 0.74 \qquad \left(\frac{\text{Up}}{\text{Down}}\right)^{MC}_{e} = 0.95$$

Comparison of Fluxes at Kamioka and Soudan

$\cos\theta_\nu = \pm 0.50$



$$\nu_\mu + {}^{16}O \rightarrow \mu^- + p + \text{"Spectator Nucleons"}$$

$$({}^{56}Fe)$$

$$\vec{p}(\nu) = \underbrace{\vec{p}(\mu^-) + \vec{p}(\text{proton})}_{\vec{p}(\nu_{\text{reconstructed}})} + \vec{p}(\text{Spectator})$$

Question: How well

$$\vec{p}(\mu^\pm) + \vec{p}(\text{proton})$$

traces

$$\vec{p}(\nu)$$

?

For ϕ_ν

Importance of Muon measurement

constraint

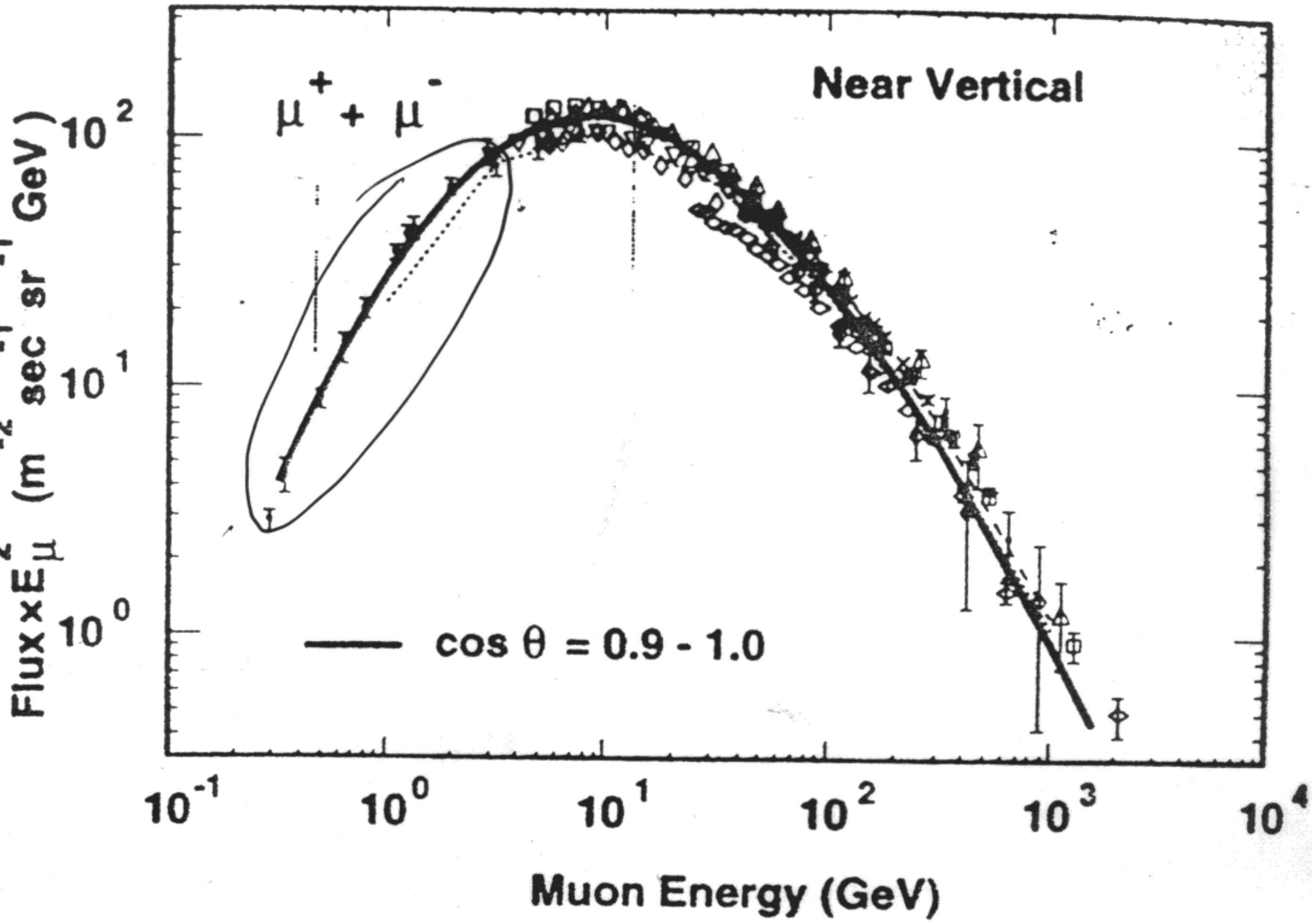
$$\pi^+ \rightarrow \boxed{\mu^+} \; \nu_\mu$$
$$\quad\quad \hookrightarrow e^+ \; \nu_e \; \bar{\nu}_\mu$$

at High Altitude (Balloons
Planes?)

+ Sea Level.

[Agreement between Honda + Bartol is not accidental : Fit the same μ at Ground level]

Honda et al.

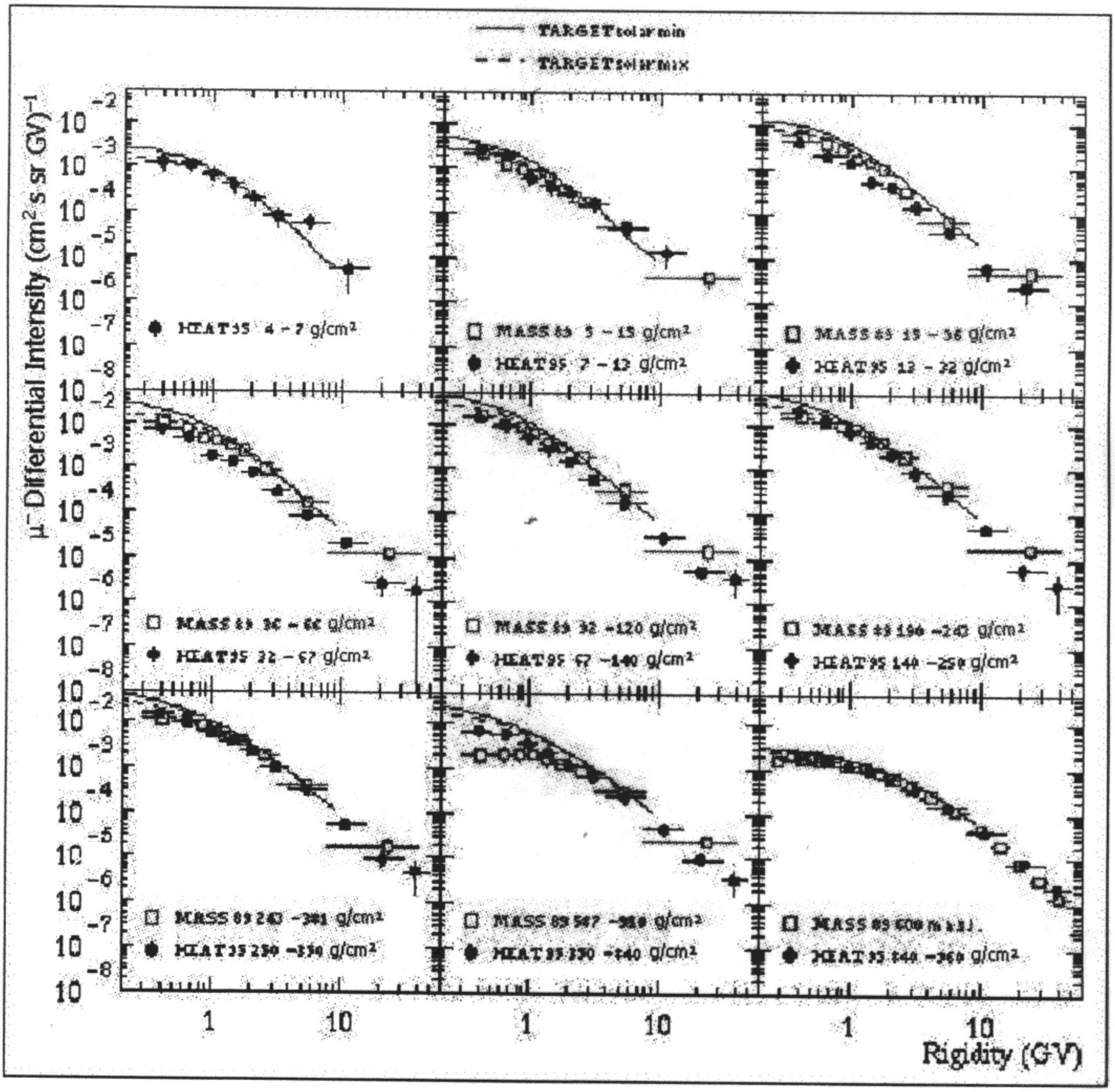


Constraint of $\mu^\pm$ measurement at the ground. [1971 Allkofer et al.)

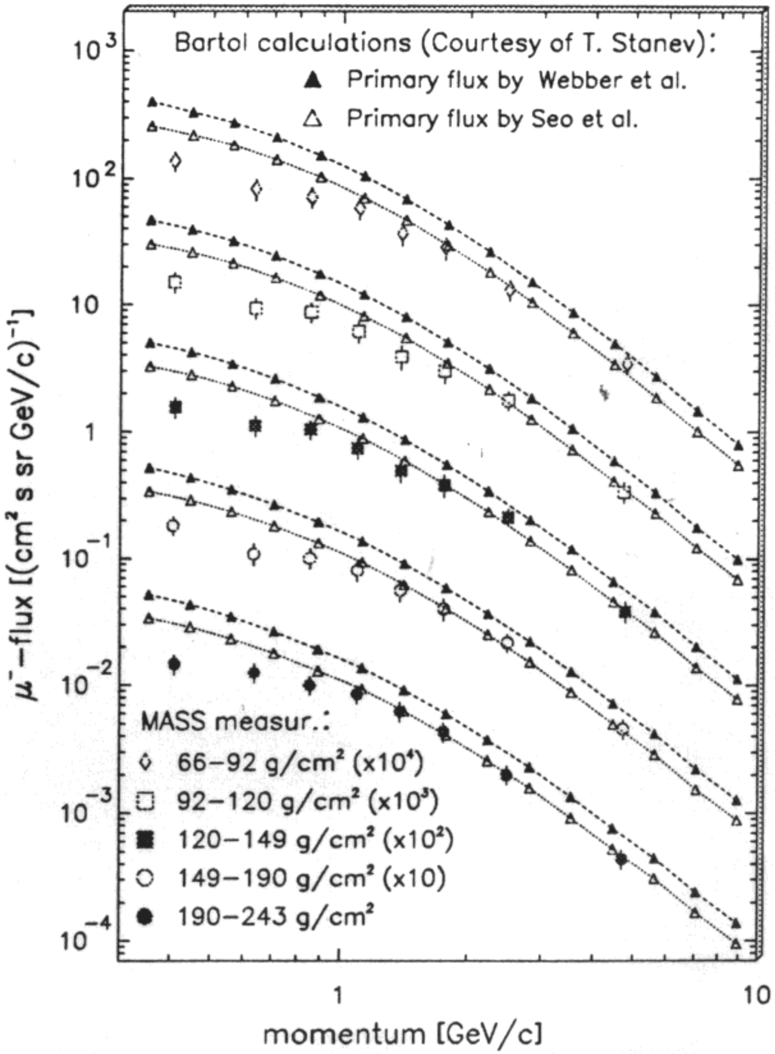
Low energy points <u>1 experiment</u>

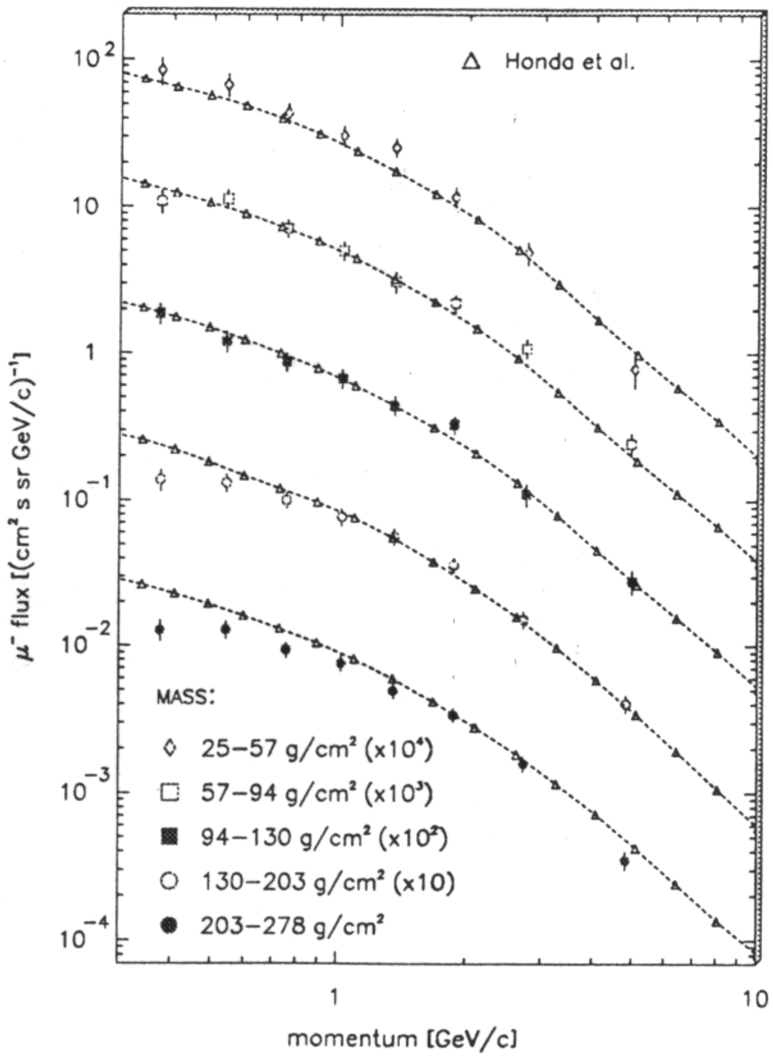
Stephane Coutu ICHEP - Vancouver

μ^- Differential Spectra



Results I: Muon Spectra in the Atmosphere





Summary

The results on atmospheric ν have (nearly) established the existence of New Physics beyond the Standard Model. [ν – Oscillation]

Prepare an experimental program to fully explore and study in detail this New Physics. An extraordinary challenge and opportunity.

Program to improve the quality of the Predictions

Summary

The results on atmospheric ν have (nearly) established the existence of New Physics beyond the Standard Model. [ν - Oscillation]

Prepare an experimental program to fully explore and study in detail this New Physics. An extraordinary challenge and opportunity.

Program to improve the quality of the Predictions

Things to do

1. Complete a full 3-D calculation

2. Provide better Input
   - Primary flux ✓
   - Hadronic interactions

     few GeV — 100 GeV p on "Air" Targets (Carbon...)
   - Low Energy ν - Cross section.

     [The KEK beam to SK]

3. Provide a better constraint

   μ measurements. • Ground • High altitude