MACRO at GRAN SASSO

Monopole, Astrophysics, and Cosmic Ray Observatory

Earliest MACRO Data Contained Evidence for Neutrino Oscillations

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When you have eliminated the impossible, whatever remains, however improbable, must be the truth. – Sherlock Holmes

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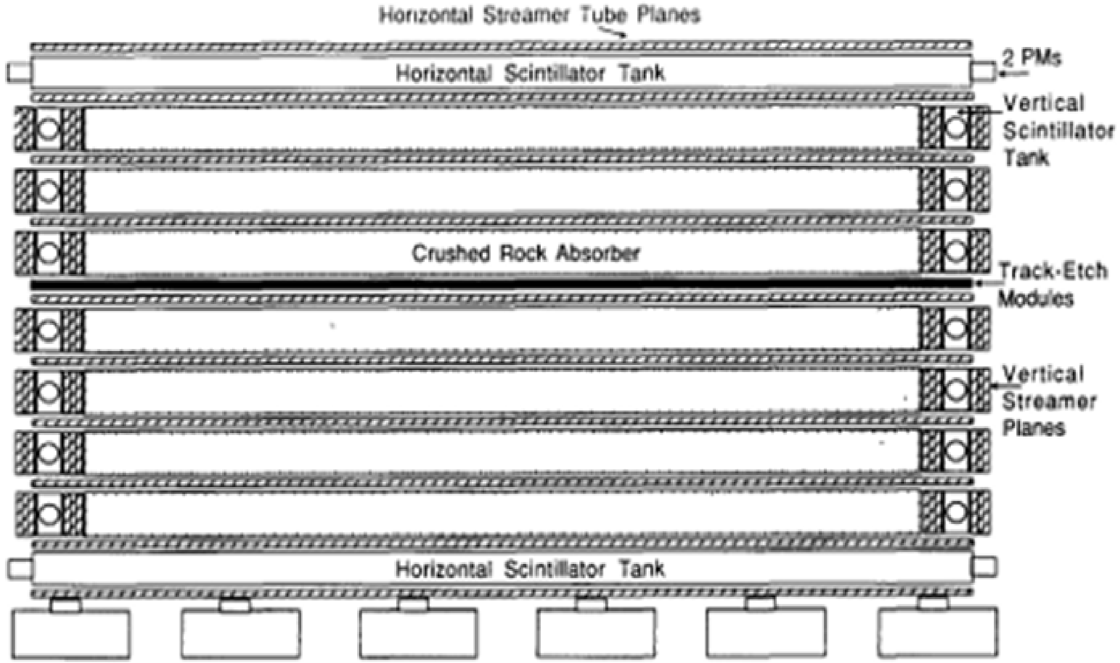
ABSTRACT

The earliest data collected by MACRO was analyzed for upward going muons, indicative of neutrino interactions in the ground a few meters below the detector. The sources of these neutrinos were expected to be from pion/kaon decay due to cosmic ray interactions, and, at much lower intensities, galactic (e.g., X-ray binaries) or extra-galactic (e.g., Active Galactic Nuclei) sources. When data from the first super-module's inaugural run was analyzed, a lower number of upward going muons was observed than expected, albeit not up to the standard of statistical significance required, and was dismissed as a statistical anomaly. Other aspects of the analysis however, lent credence to the veracity of the finding. This analytical approach is described in detail.

First Supermodule

- Central and bottom scintillator planes only
  - ERP muon trigger
- Streamer tubes and strips
  - Bari ST trigger
- Data set
  - Runs 5 – 440, 22 Feb – 30 May 89
  - Runs 673 – 4162, 10 Oct 89 – 15 Nov 91
  - Live time: 557d 01h 45m
- Custom analysis software
  - Calibration
  - Tracking
  - Prediction/expectation



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Timeline

- October 1990
  - Capri Collaboration Meeting
    - Low up μ event rate discussed
    - Detailed analysis on detector efficiencies as source of low rate
- October 1991
  - Bologna Collaboration Meeting
    - Low up μ event rate looks real
    - Detailed analysis of other potential reasons for low rate
      - Statistical fluke, hitherto undiscovered detector inefficiency, MC error, *et al*.
- March 1993
  - Caltech Collaboration Meeting
    - Low up μ event rate must be real

It's All About the Calibration

- Mechanical (geometry)
  - Location of streamer tubes and strips
    - Survey provided
  - Location of scintillator tanks
    - Surveyed *in situ*
- Electrical
  - TDC and ADC calibration
    - Pedestals
    - Timing offsets
    - Gains
  - 13 calibrations performed (~ one per live month)

- TDC Calibration
  - Used sample of through-going muons
    - One ERP and Stream Tube muon trigger
    - One reconstructed track in each streamer tube view
    - One and only one scintillator channel hit in each layer
    - Streamer tube track must pass through both tanks with a minimum 19 cm path length
    - About 40% of all through-going muons in sample

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Scintillator Position and Time of Flight

- Position in Scintillator
  - $R_{SC} = k_0 T_0 - k_1 T_1 + C_R$
    - Where ks are conversion gains (cm/digital clock tick)
    - Ts are TDC data
    - C_R is a delay offset
    - R_{SC} is the distance from "0" tank end
    - Gains and offset determined by linear least squares minimization

- Time of Flight
  - $tof = 0.5\nu^{-1}[(k_0 T_0 + k_1 T_1)_C - (k_0 T_0 + k_1 T_1)_B] + C_{tof}$
  - Where ν is speed of light in scintillator
  - C_{tof} is a timing offset
  - tof is the time of flight measured by streamer tube track (path length between scintillators divided by speed of light in vacuum)
  - Corrections due to PMT pulse height variations ("time walk") were performed

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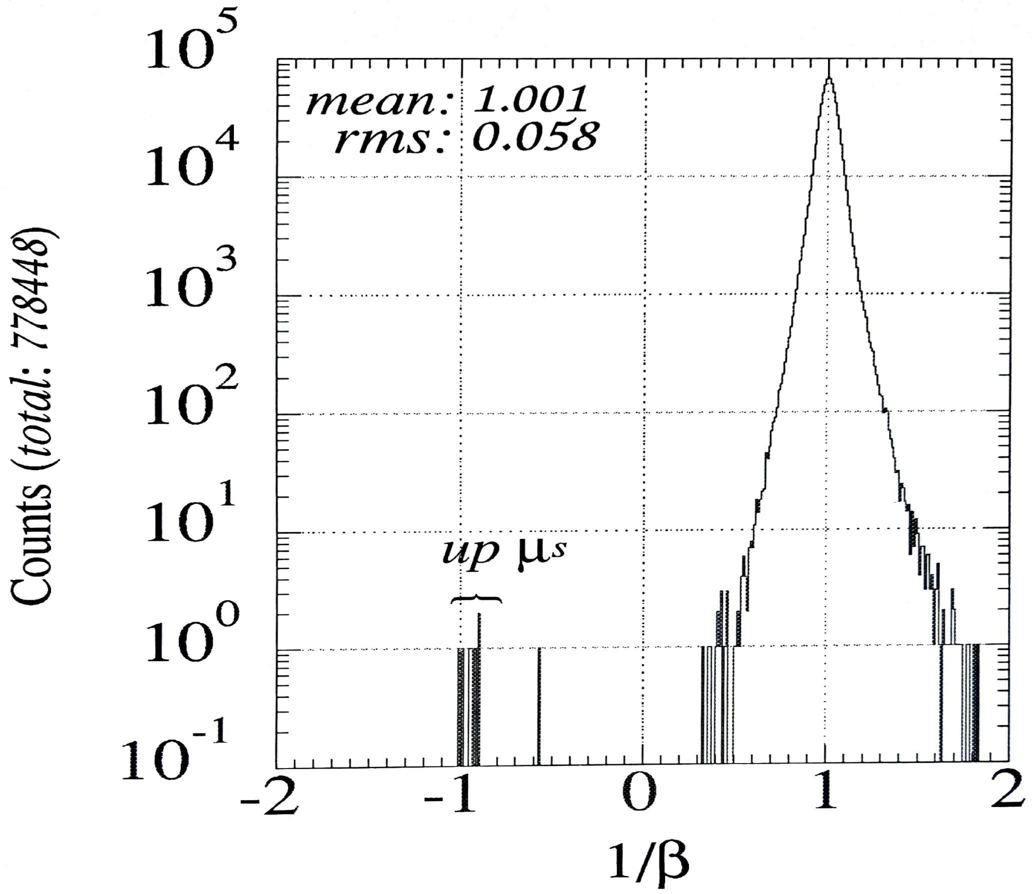
Event Selection

- Main criteria: ERP ^ Bari ^ 1 reconstructed track in each view
  - 1 388 584 total events
- From these, select only those events which have at least one ERP hit for the bottom and central scintillators layers only
  - 868 616 events
- Additional cuts
  - Track must pass through one “hit” tank in each layer
  - ADC/TDC data valid
  - |TDC pos – Track pos| ≤ 75 cm
  - $0.5 \leq E/\langle E \rangle \leq 5$ (pulse height consistency)
  - $(E_{max}/E_{min})_{tank\ end} \leq 1.5$
  - Vert face channels < 2
  - ➔ **<u>778 448 events in final data sample</u>**

Detection Efficiency

- Cut efficiency is calculated
  - $\varepsilon_{cut} = 778448 / 868616 = 0.896$
- Determine trigger efficiency by studying (see my Capri ‘90 talk for full details)
  - $N_{obs} = \varepsilon_{ERP}\, \varepsilon_{Bari}\, \varepsilon_{Tr}\, N$
  - $\varepsilon_{ERP} = 0.975$ (ERP trigger w/ hit in each horizontal plane)
  - $\varepsilon_{Bari} = 0.995$ (Bari streamer tube trigger)
  - $\varepsilon_{Tr} = 0.960$ (track reconstruction)
- Net efficiency
  - $\varepsilon = \varepsilon_{ERP}\, \varepsilon_{Bari}\, \varepsilon_{Tr}\, \varepsilon_{cut} =$ **<u>0.835</u>**

Down and Up μ Counts



What is Expected?

- Downward muons
  - Produced from π and K decay
  - Use Gaisser (1989) absolute flux
  - Propagate through Gran Sasso rock overhead to produce muon flux at MACRO
  - Monte Carlo simulation provides event rate
    - And “calibrates” MACRO’s effective area

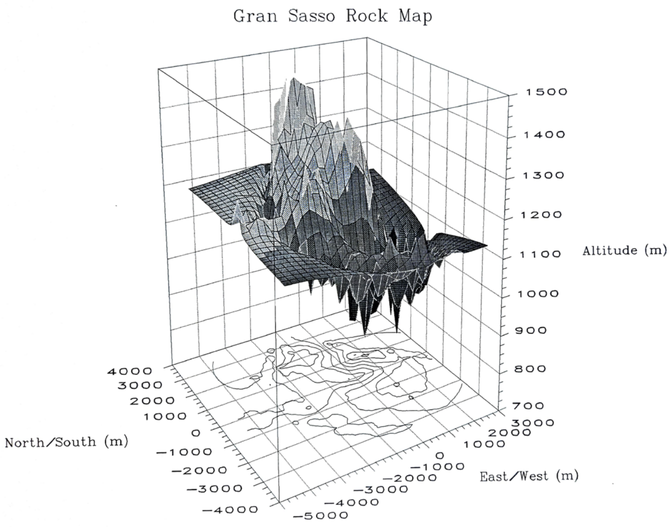
Use muon and neutrino fluxes from Gaisser (1989):

$$\frac{d^2N_\mu}{dE\,d\Omega} = N(E)\left[\frac{A_{\pi\mu}}{1+\frac{B_{\pi\mu}E\cos\theta}{\epsilon_\pi}} + \frac{0.635\,A_{K\mu}}{1+\frac{B_{K\mu}E\cos\theta}{\epsilon_K}}\right]$$

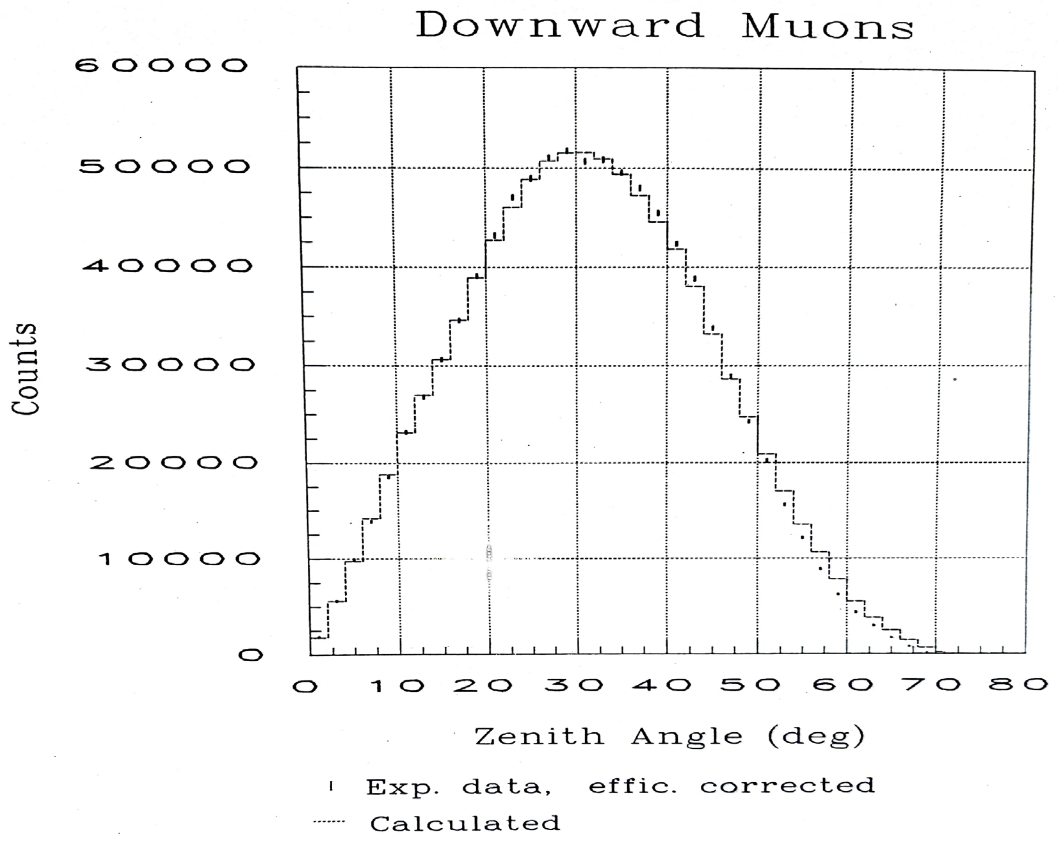
$$\frac{d^2N_\nu}{dE\,d\Omega} = N(E)\left[\frac{A_{\pi\nu}}{1+\frac{B_{\pi\nu}E\cos\theta}{\epsilon_\pi}} + \frac{0.635\,A_{K\nu}}{1+\frac{B_{K\nu}E\cos\theta}{\epsilon_K}}\right]$$

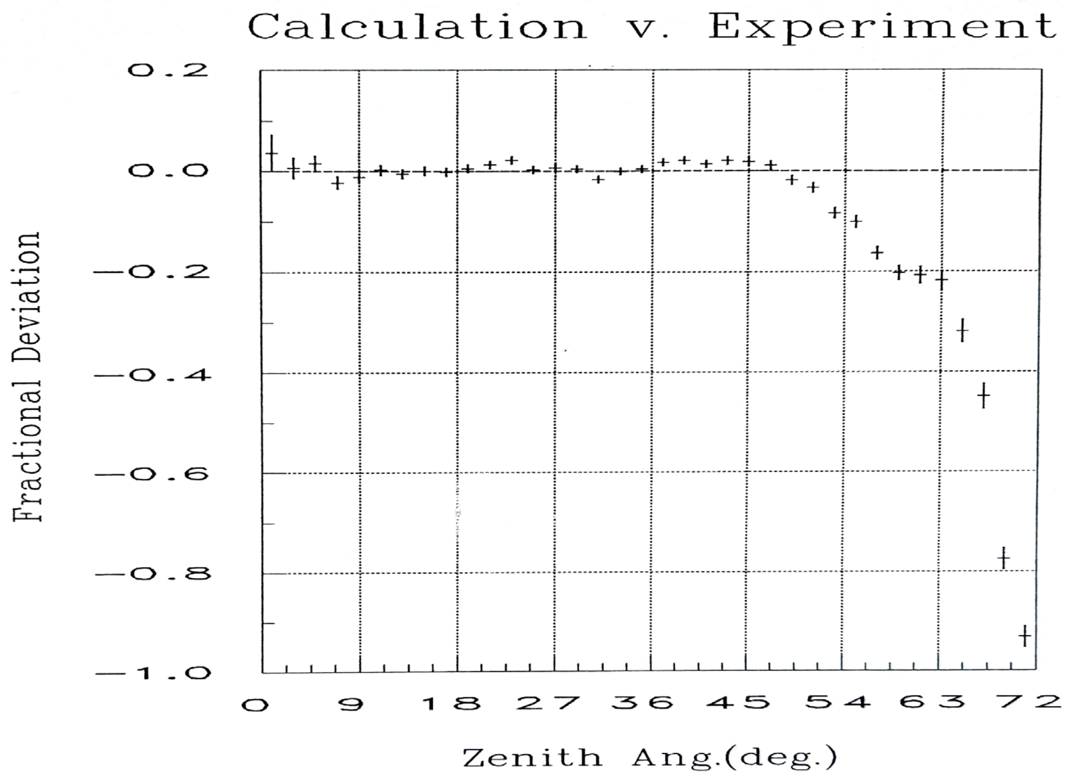
$N(E) = 1.8\,E^{-2.7}$ } Primary flux

NB: This simple forms are valid only for $\theta \leq 60°$



Down μ:
Experiment v Theory





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Upward μ

- Compute differential cross section using suitable set of structure functions
- Do MC simulation to determine flux of upward m that reach MACRO from ν's interacting with earth
- Compute event rate with detector MC

Everything is in place except for $\frac{d\sigma}{dE_\mu}$. Start w/ doubly differential cross section:

$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2 M_p E_\nu}{\pi} \frac{M_W^4}{[2ME_\nu xy + M_W^2]^2} \times \left\{ \left(1-y+\frac{Mxy}{2E_\nu}\right) F_2^{cc}(x,Q^2) + y^2\, 2x\, F_1^{cc}(x,Q^2) \pm \left(y-\frac{y^2}{2}\right) x F_3(x,Q^2) \right\}$$

Structure function definitions: D.W. Duke & J.F. Owens, Phys. Rev. D30, 49(1984).

$Q_0 := 2$ — ***Q^2 dependence threshold, GeV***

$\Lambda := .2$ — ***Low Energy cutoff, GeV***

$C_1 := \ln\left(\frac{Q_0^2}{\Lambda^2}\right)$

$z(x,E_\nu,E_\mu) := \Phi\left[2\cdot M\cdot x\cdot(E_\nu - E_\mu) - Q_0^2\right]\cdot \ln\left[\frac{\ln\left[\frac{2\cdot M\cdot(E_\nu-E_\mu)\cdot x}{\Lambda^2}\right]}{C_1}\right]$ — ***Structure fn. parameter***

$\eta_1(z) := 0.419 + 0.004\cdot z - 0.007\cdot z^2$ $\quad \eta_3(z) := 0.763 - 0.237\cdot z + 0.026\cdot z^2$

$\eta_2(z) := 3.46 + 0.724\cdot z - 0.066\cdot z^2$ $\quad \eta_4(z) := 4.00 + 0.627\cdot z - 0.019\cdot z^2$

$\gamma_{ud}(z) := 4.40 - 4.86\cdot z + 1.33\cdot z^2$ $\quad \gamma_d(z) := -0.421\cdot z + 0.033\cdot z^2$

$N_{ud}(z) := 3\cdot\left[\frac{\Gamma(\eta_1(z))\cdot\Gamma(\eta_2(z)+1)}{\Gamma(\eta_1(z)+\eta_2(z)+1)}\cdot\left(1+\frac{\gamma_{ud}(z)\cdot\eta_1(z)}{\eta_1(z)+\eta_2(z)+1}\right)\right]^{-1}$

$N_d(z) := \left[\frac{\Gamma(\eta_3(z))\cdot\Gamma(\eta_4(z)+1)}{\Gamma(\eta_3(z)+\eta_4(z)+1)}\cdot\left(1+\frac{\gamma_d(z)\cdot\eta_3(z)}{\eta_3(z)+\eta_4(z)+1}\right)\right]^{-1}$

$V(x,z) := N_{ud}(z)\cdot x^{\eta_1(z)}\cdot(1-x)^{\eta_2(z)}\cdot(1+\gamma_{ud}(z)\cdot x)$ — ***Valence quark structure fn***

$d(x,z) := N_d(z)\cdot x^{\eta_3(z)}\cdot(1-x)^{\eta_4(z)}\cdot(1+\gamma_d(z)\cdot x)$ — ***Down quark str. fn. for proton***

$A_S(z) := 1.265 - 1.132\cdot z + 0.293\cdot z^2$ $\quad A_c(z) := 0.135\cdot z - 0.075\cdot z^2$ $\quad A_G(z) := 1.56 - 1.71\cdot z + 0.638\cdot z^2$

$a_S(z) := -0.372\cdot z - 0.029\cdot z^2$ $\quad a_c(z) := -0.036 - 0.222\cdot z - 0.058\cdot z^2$ $\quad a_G(z) := -0.949\cdot z + 0.325\cdot z^2$

$b_S(z) := 8.05 + 1.59\cdot z - 0.153\cdot z^2$ $\quad b_c(z) := 6.35 + 3.26\cdot z - 0.909\cdot z^2$ $\quad b_G(z) := 6.0 + 1.44\cdot z - 1.05\cdot z^2$

$\alpha_S(z) := 6.31\cdot z - 0.273\cdot z^2$ $\quad \alpha_c(z) := -3.03\cdot z + 1.50\cdot z^2$ $\quad \alpha_G(z) := 9.0 - 7.19\cdot z + 0.255\cdot z^2$

$\beta_S(z) := -10.5\cdot z - 3.17\cdot z^2$ $\quad \beta_c(z) := 17.4\cdot z - 11.3\cdot z^2$ $\quad \beta_G(z) := -16.5\cdot z + 10.9\cdot z^2$

$\gamma_S(z) := 14.7\cdot z + 9.80\cdot z^2$ $\quad \gamma_c(z) := -17.9\cdot z + 15.6\cdot z^2$ $\quad \gamma_G(z) := 15.3\cdot z - 10.1\cdot z^2$

$S(x,z) := \frac{1}{6}\cdot\left[A_S(z)\cdot x^{a_S(z)}\cdot(1-x)^{b_S(z)}\cdot\left(1+\alpha_S(z)\cdot x+\beta_S(z)\cdot x^2+\gamma_S(z)\cdot x^3\right)\right]$ — ***Sea Quarks***

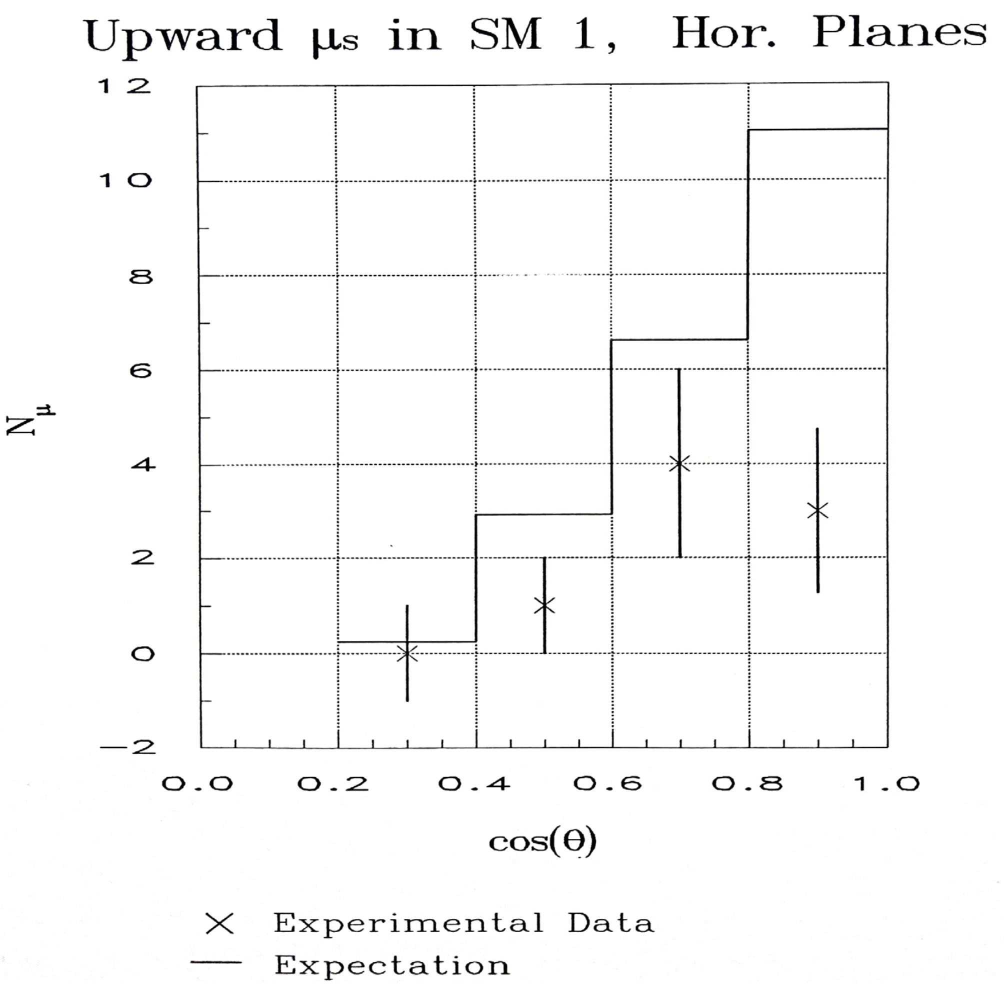
$c(x,z) := \left[A_c(z)\cdot x^{a_c(z)}\cdot(1-x)^{b_c(z)}\cdot\left(1+\alpha_c(z)\cdot x+\beta_c(z)\cdot x^2+\gamma_c(z)\cdot x^3\right)\right]$ — ***Charmed Quarks***

$G(x,z) := \left[A_G(z)\cdot x^{a_G(z)}\cdot(1-x)^{b_G(z)}\cdot\left(1+\alpha_G(z)\cdot x+\beta_G(z)\cdot x^2+\gamma_G(z)\cdot x^3\right)\right]$ — ***Gluons***

$N_{sf}(z) := \int_0^1 V(x,z)\,dx + 6\cdot\int_0^1 S(x,z)\,dx + \int_0^1 G(x,z)\,dx + 2\cdot\int_0^1 c(x,z)\,dx$ $\quad z0 := .25$ $\quad N_{sf}(z0) = 1$

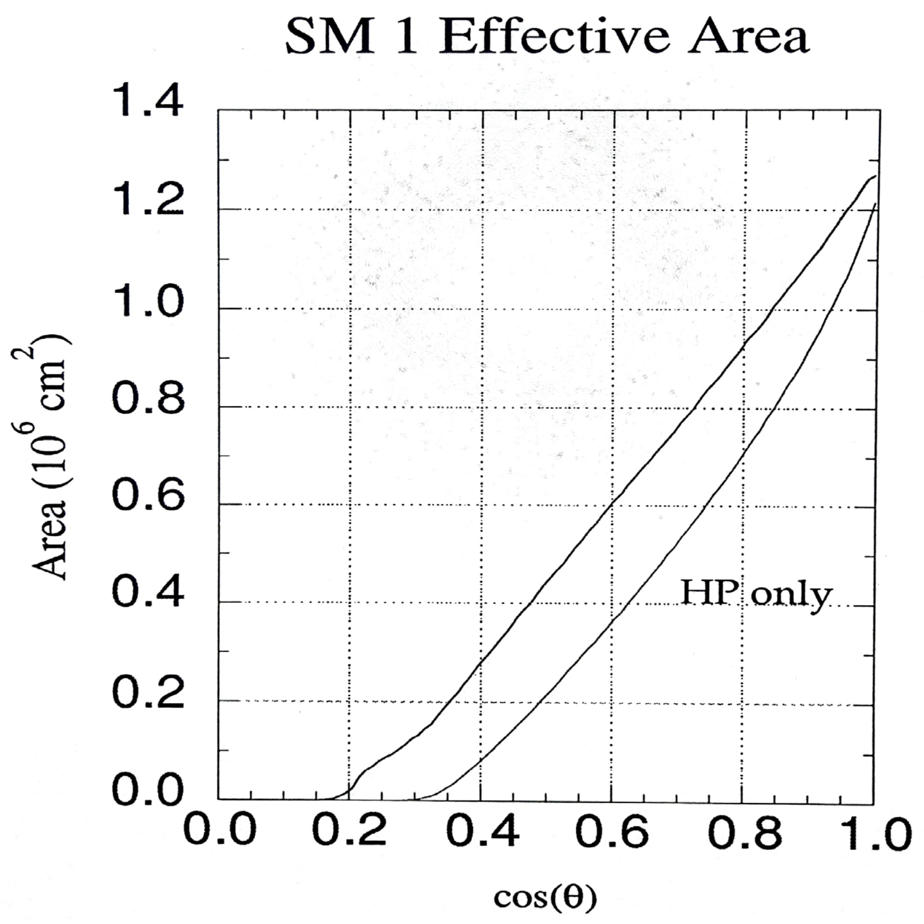
Observation v Expectation

- Reasonably good agreement with theory
  - EXCEPT for $0.8 < \cos(\theta) \leq 1.0$
- Possible explanations
  - Just unlucky
  - Detector efficiency less at small nadir angles
  - It's a ***real*** deficit



Eliminate the Impossible

- Just unlucky
  - Statistical argument is weak since MACRO has largest effective area at small zenith/nadir angles
    - Demonstrated by down muon observation
    - Effective area goes down by factor of two across histogram bins
- Detector efficiency
  - Looking at down muons, detector efficiency agrees well with calculated value at small zenith
  - Detector symmetry precludes up v down preference in efficiency



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More Impossibilities

- Other "plausible" sources of the deficit were proffered, but all turned out to be wild goose chases (caccia ai fantasmi)
    - Upward muon spectrum to soft to traverse detector, i.e., below energy threshold required to pass through detector
    - Track reconstruction efficiency at low energy ($E < 3$ GeV)
    - Error in cross section calculation
        - Does not explain anomaly in single nadir angle bin, i.e., all nadir angles should have been affected.
    - Model of the earth used in neutrino propagation MC contained errors

Whatever Remains, However Improbable…

- ***The upward μ deficit is real!***
  - MACRO is symmetric with respect to up v down
    - No preferred direction
  - Largest effective area at small zenith/nadir angles
    - Area at 45° is 58% of that at 0°
    - There should be many more events near 0° than 45°
  - This is the simplest explanation as required by Occam's Razor (although not guaranteed)

…Must Be the Truth!