Implications of models with Extra Dimensions on Flavor Physics, Cosmic Ray Physics.

C. S. KIM
Yonsei University, Korea

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I. Introduction

- ADD
- RS

II FCNC and ρ-constraint from RS

III CTP Violation from a tilted brane

IV Low Scale String Unification and Highest E. Cosmic Rays.

V Conclusions.

1. Gauge Hierarchy Problem

- $m_{EW} \sim 10^2$ GeV
  $M_{pl} \sim 10^{19}$ GeV $\Big\} \Rightarrow$ Why ?

- recent developments in string theory

  +

  ignorance of gravity

  $\Downarrow$

  "Extra" Dimensions

- 3 classes
  - large & flat extra dim.
    ; ADD
  - small & flat extra dim.
    accessible to the SM fields
  - a slice of AdS
    ; Randall-Sundrum ✓

$\boxed{2}$ Large Extra Dimensions

- Arkani-Hamed, Dimopoulos, Dvali '98
- ∃ only a single fundamental scale

  : M_{ew}

- M_{pl} ; effective scale.

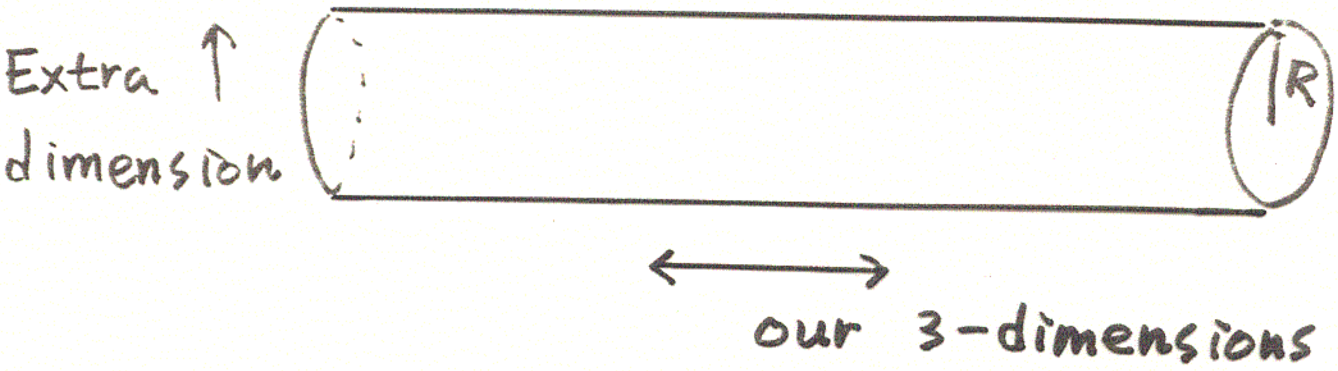
$\boxed{Q}$ How come $M_{pl} \gg M_{ew}$?

Ⓐ · $(4+n)$-dimensional spacetime

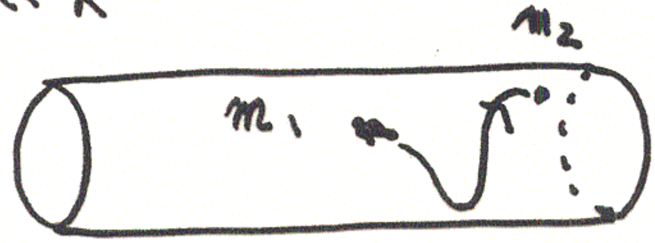
· ∃ Large extra compact space!

$\downarrow$

w/ finite size R.



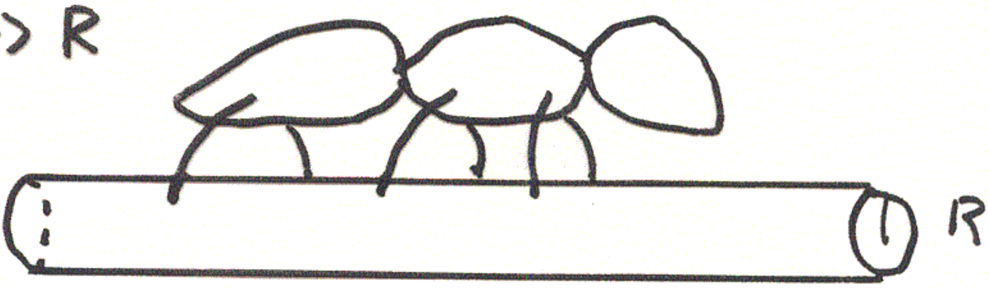
• $r \ll R$



Gauss law, surface $\sim r^{n+2}$

$$F = \frac{m_1 m_2}{M_s^{n+2}} \frac{1}{r^{n+2}}$$

• $r \gg R$



$$F = \frac{1}{M_s^{n+2} R^n} \frac{m_1 m_2}{r^2}$$

$$L = (M_{pl})^{-2}$$

$$\boxed{M_{pl}^2 = M_s^{n+2} R^n}$$

- $M_{pl} \uparrow$ as $R \uparrow$

- We want $M_s \sim 1$ TeV $\approx 10^3$ GeV
- $n=1$, $R \simeq 10^{13}$ cm $\longrightarrow$ X
- $n=2$, $R \sim$ mm

cf) current macroscopic gravity exp. $\sim$ cm

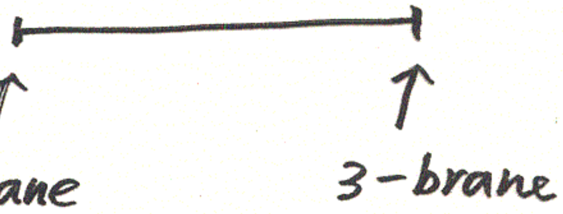
below mm, $F_{gravity}$

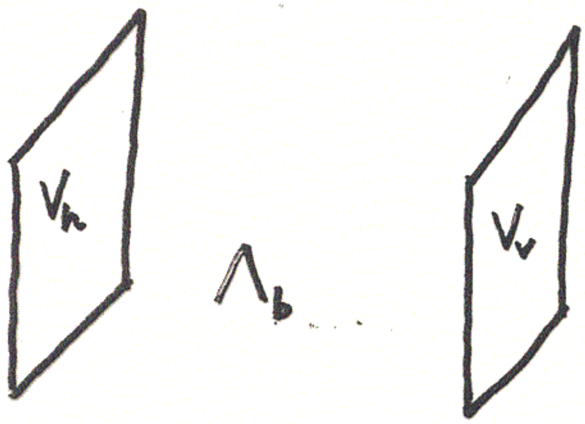
$\frac{1}{r^2} \longrightarrow \frac{1}{r^4}$

2. RS model

- a single extra dim.

; $S^1/\mathbb{Z}_2$:





$\Downarrow$

curve the space-time.

w/ 4-D Poincare invariance

$$d\tau^2 = e^{-2k r_c |\phi|} \eta_{\mu\nu} dx^\mu dx^\nu - r_c^2 d\phi^2$$

- $V_h = -V_v = -\dfrac{\Lambda_b}{k}$
- $0 \le |\phi| \le \pi$
- r_c : the size of the extra dim.

$\boxed{2}$ How about "the hierarchy prob."?

· in RS geometry,

our induced metric

$$\boxed{g_{\mu\nu}^{vis} = e^{-2kr_c\pi} \eta_{\mu\nu}}$$

? our brane is at $y = r_c\pi$

cf. $g_{\mu\nu}^{hid} = \eta_{\mu\nu}$

• Action of H on our brane

$$S = \int d^4x \left[e^{-2kr_c\pi} \eta^{\mu\nu} \partial_\mu H_0^\dagger \partial_\nu H_0 - e^{-4kr_c\pi} m_0^2 H_0^2 \right.$$

$$\left(\partial_\mu = \frac{\partial}{\partial x^\mu} \right)$$

· canonical kinetic terms

$$S = \int d^4x \left[\eta^{\mu\nu} \partial_\mu H^\dagger \partial_\nu H \cdots \right.$$

$$\therefore \quad H = e^{-kr_c\pi} H_0$$

$$S = \int d^4x \left[\eta^{\mu\nu} \partial_\mu H^\dagger \partial_\nu H - (e^{-kr_c\pi} m_0)^2 |H|^2 \cdots \right]$$

$$m_{phy} = e^{-kr_c\pi} m_0$$

$$\wr \qquad\qquad\qquad \wr$$

$$M_{ew} \qquad\qquad M_{pl}$$

for $kr_c \sim 12$

- Solving the hierarchy problem w/o another hierarchy.

II. Top quark K-K mode mixing in RS

and ($B \to X_s \gamma$

(ρ-constraint.

C.S. Kim, J.D. Kim, Jeonghyeon Song

hep-ph/0204002

& Work in Progress.

- In the original RS scenario, the SM fields on our brane.

- Note the r_c is small. The SM fields in the bulk?

- Model I: A_M in the bulk; fermion on the wall.
  - $S_A = -\frac{1}{4}\int d^5x\sqrt{-G}\,G^{MK}G^{NL}F^a_{KL}F^a_{MN}$,
  - the odd Z_2-parity for the $A^a_5(x,\phi) \Rightarrow$ No $A^a_5(x,\phi)$ in $\mathcal{L}$.
  - $A^a_\mu(x,\phi) = \sum_{n=0}^\infty A^{a(n)}_\mu(x)\frac{\chi^{(n)}_A(\phi)}{\sqrt{r_c}}$,

$$\boxed{\mathcal{L}_4 = \sum_{n=0}^\infty\left[-\frac{1}{4}\eta^{\mu\kappa}\eta^{\nu\lambda}F^{a(n)}_{\kappa\lambda}F^{a(n)}_{\mu\nu} - \frac{M^{(n)\,2}_A}{2}\eta^{\mu\nu}A^{a(n)}_\mu A^{a(n)}_\nu\right].}$$

  - The bulk wave function $\Leftarrow$ the RS geometry.
    $\int_{-\pi}^{\pi} d\phi\,\chi^{(m)}_A(\phi)\chi^{(n)}_A(\phi) = \delta^{mn}$.
  - $M^{(n)}_A = x^{(n)}_A k_{EW} \Leftarrow$ the RS geometry.

T-3

- the coupling of $f - f' - W^{(n)}$: enhanced by $\sqrt{2\pi k r_c} \approx 8.4$.
- The precision electroweak data $\Rightarrow M_W^{(1)} \gtrsim 23$ TeV.
- $\Lambda_\pi \gtrsim 100$ TeV $\Rightarrow$ disfavored.

T-4

Model II: both the A and fermions in the bulk.

$$\boxed{S = \int d^5x \sqrt{-G}\left\{E^A_{\underline{A}}\left[\frac{i}{2}\,\bar{\Psi}\gamma^{\underline{A}} D_A \Psi\right] - m_\psi\,\mathrm{sgn}(\phi)\,\bar{\Psi}\Psi\right\}}$$

w/ h.c.

$\Downarrow$

No spin connecti

$$\gamma^{\underline{A}} = (\gamma^\mu, i\gamma_5)\ , \quad E^A_{\underline{A}} = \mathrm{diag}(e^\sigma, e^\sigma, e^\sigma, e^\sigma, 1/r_c)$$

$$\begin{aligned} S \;=\; \int d^4x \int d\phi\, r_c \Big\{ & e^{-3\sigma}\left(\bar{\Psi}_L\, i\partial\!\!\!/\, \Psi_L + \bar{\Psi}_R\, i\partial\!\!\!/\, \Psi_R\right) \\ & - \frac{1}{2r_c}\Big[\bar{\Psi}_L \left(e^{-4\sigma}\partial_\phi + \partial_\phi\, e^{-4\sigma}\right)\Psi_R \\ & \quad - \bar{\Psi}_R \left(e^{-4\sigma}\partial_\phi + \partial_\phi\, e^{-4\sigma}\right)\Psi_L\Big] \\ & - e^{-4\sigma}\, m_\psi\,\mathrm{sgn}(\phi)\left(\bar{\Psi}_L\Psi_R + \bar{\Psi}_R\Psi_L\right) \Big\}\,, \end{aligned}$$

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$$\Psi_{L,R}(x,\phi) = \sum_{n=0}^{\infty} \psi_{L,R}^{(n)}(x)\,\frac{e^{2\sigma(\phi)}}{\sqrt{r_c}}\,\hat{f}_{L,R}^{(n)}(\phi)$$

$$S = \sum_{n=0}^{\infty} \int \mathrm{d}^4x \left\{ \bar{\psi}^{(n)}(x)\, i\partial\!\!\!/\, \psi^{(n)}(x) - \underline{M_f^{(n)}\, \bar{\psi}^{(n)}(x)\, \psi^{(n)}(x)} \right\}$$

Z_2- symmetry constrains:

- $\bar{\Psi}\Psi = \bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L$: Z_2-odd
- If $f_L^{(n)}$ is Z_2-even ft $\chi^{(n)}$, $f_R^{(n)}$ is Z_2-odd $\tau^{(n)}$
- $f_{L,R}^{(n)} \Leftarrow$ RS geometry \$ m_ψ.
- For a given $\nu \equiv m_\psi / k \sim \mathcal{O}(1)$

$$
\begin{aligned}
\chi^{(n)}(\phi) &= \frac{e^{\sigma/2}}{N_\chi^{(n)}} \left[J_{1/2-\nu}(z^{(n)}) + \beta_\chi^{(n)} Y_{1/2-\nu}(z^{(n)}) \right] \\
\tau^{(n)}(\phi) &= \frac{e^{\sigma/2}}{N_\tau^{(n)}} \left[J_{1/2+\nu}(z^{(n)}) + \beta_\tau^{(n)} Y_{1/2+\nu}(z^{(n)}) \right]
\end{aligned}
$$

$$
\chi^{(0)}(\phi) = \frac{e^{\nu\sigma(\phi)}}{N_\chi^{(0)}}, \quad \tau^{(0)}(\phi) = 0
$$

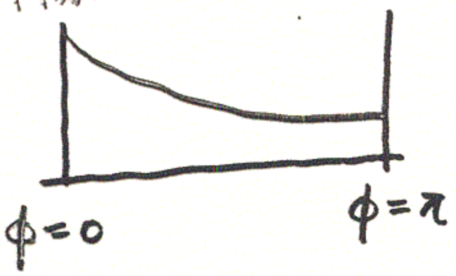
WHAT IS ν ? $\left(\nu \equiv m_\Psi / k\right)$

- $\Psi'(x, \phi)$: canonically re-scaled

$$S = \int d^5x \left[\Psi' i\gamma \Psi' + \cdots \right]$$

$$\Psi' = \frac{e^{\left(\frac{1}{2}+\nu\right) k r_c |\phi|}}{N'} \psi^{(0)}(x) + \cdots$$

If $\nu \ll -\frac{1}{2}$

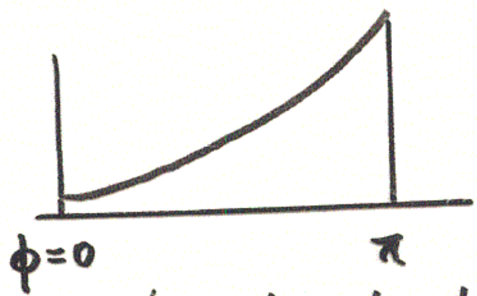


localized toward the Planck bra

- for $\nu \lesssim -0.5$,

$$g^{(n)} \ll g$$

If $\nu \gg 1$



localized closer to the TeV

Model $\boxed{\text{I}}$: relevant ! ($g^{(n)}$ large)

★ a subtle point when placing

- SM fermions in the RS bulk.
  - fermion field contents : doubled !

★ In the SM

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad u_R , \quad d_R$$

$$\mathcal{L}_m = - m \, \bar{u}_L u_R + h.c$$

· Two Dirac fields (u, d)

; enough

★ In the RS bulk,

Ψ : a definite reps. of a gauge gro

Ψ_L & Ψ_R : needed

w/ only Ψ_L

$\Rightarrow$ $f_{L,R}(\phi)$: cannot determined

T-9

- For each generation, introduce four Dirac fields

$$Q(x,\phi) = \begin{pmatrix} q_u(x,\phi) \\ q_d(x,\phi) \end{pmatrix}, \quad u(x,\phi), \quad d(x,\phi)$$

$$\mathcal{L} = -\sum_{n=1}^{\infty} M_f^{(n)} \left[\bar{q}_{uL}^{(n)} q_{uR} + \bar{u}_L^{(n)} u_R^{(n)} \right] + h.c..$$

NOT $\bar{q}_{uL}\, u_R$

- SM fields $\Rightarrow$ KK zero modes

$$Q(x,\phi) = \sum_n \frac{e^{2\sigma(\phi)}}{\sqrt{r_c}} \left[Q_L^{(n)}(x)\chi^{(n)}(\phi) + Q_R^{(n)}(x)\tau^{(n)}(\phi) \right]$$

$$u(x,\phi) = \sum_n \frac{e^{2\sigma(\phi)}}{\sqrt{r_c}} \left[u_L^{(n)}(x)\tau^{(n)}(\phi) + u_R^{(n)}(x)\chi^{(n)}(\phi) \right],$$

- The charged current interactions: b/w q_u and q_d:

$$S_{f\bar{f}'W^{\pm}} = \int d^4x \frac{g}{\sqrt{2}} \left[\sum_{n,m,l=0}^{\infty} \bar{q}_{uL}^{(n)} \not{W}^{+(l)} q_{dL}^{(m)} C_{nml}^{\bar{f}f'W} \right] + h.c.,$$

$$C_{nml}^{\bar{f}f'W} = \sqrt{2\pi} \int_{-\pi}^{\pi} d\phi \, e^{\sigma} \chi^{(n)}(\phi) \chi^{(m)}(\phi) \chi_A^{(l)}(\phi).$$

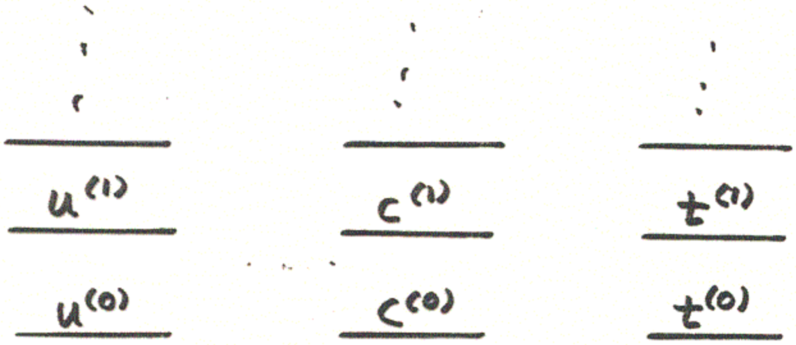
- All the quarks : KK modes

  $\mapsto$ dangerous FCNC

- the simplest way

  ; m_ψ : universal for all quarks

- $M_f^{(n)} \leftarrow$ RS geometry & m_ψ



$$M_u^{(n)} = M_c^{(n)} = M_t^{(n)}$$

- Unitarity condition $(\lambda_u + \lambda_c + \lambda_t = 0)$

$$\mapsto \sum_{i=u,c,t} \lambda_i F(x_i) = F(x) \sum \lambda_i = 0$$

* Another source for mass

; Yukawa interaction w/ Higgs

$\mapsto$ Mixing in the KK modes : ignored

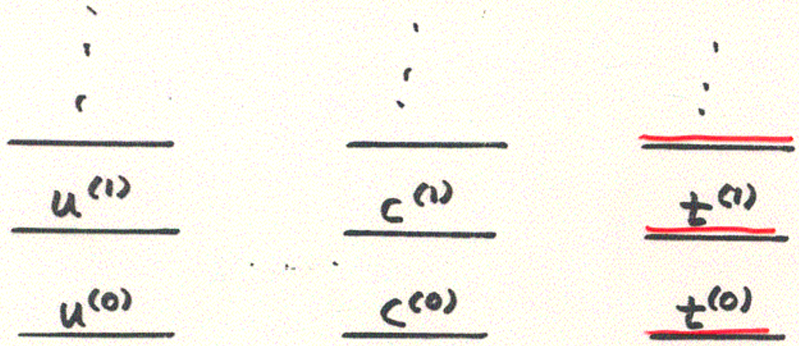
- All the quarks : KK modes

  $\Rightarrow$ dangerous FCNC

- the simplest way

  ; m_ψ : universal for all quarks

- $M_f^{(n)} \Leftarrow$ RS geometry & m_ψ



$\Rightarrow$ FCNC

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* Another source for mass

; Yukawa interaction w/ Higgs

: ignored

$\Rightarrow$ Mixing in the KK modes

T-Tz''

- At least one Higgs doublet field must be confined on our brane.
- If the Higgs field is also in the bulk,

$$M_A^{(1)2} = \frac{m_{bulk}^2}{2\pi k r_c}$$

- No warp factor $\Rightarrow$ Gauge hierarchy problem has returned.

five-dimensional Yukawa coupling

- $S \supset -\frac{\lambda_5}{k}\int d^5x\sqrt{-G}\left[\bar{Q}(x,\phi)\cdot H(x)d(x,\phi)\right]\delta(\phi-\pi)$
- SSB $\Rightarrow H^0 \to v_5 + H'^0$.
- $\boxed{\mathcal{L}_4 = \frac{\lambda v_4}{\sqrt{2}}\left(\bar{q}_{uL}^{(0)} + \hat{\chi}_1\bar{q}_{uL}^{(1)} + \cdots\right)\left(u_R^{(0)} + \hat{\chi}_1 u_R^{(1)} + \cdots\right)}$

$$\lambda = \lambda_5(1+2\nu)/2(1-\epsilon^{1+2\nu}),$$

$$v_4 = \epsilon v_5,\ \hat{\chi}_n \equiv \chi^{(n)}(\pi)/\chi^{(0)}.$$

- No $q_{uR}^{(n)}$ and $u_L^{(n)}$ due to Z_2 odd parity. $\epsilon \equiv e^{-kr_c\pi} \ll 1$.

Mass matrix of top quark KK modes

- Fermion field contents: doubled

$$\mathcal{L}_m = -\left(\bar{u}_R^{(0)}\,\bar{u}_R^{(1)}\cdots|\bar{q}_{uR}^{(1)}\cdots\right)\begin{pmatrix}\mathcal{M}_Y & \mathcal{M}_{KK}\\ \mathcal{M}_{KK}^\dagger & 0\end{pmatrix}\begin{pmatrix}q_{uL}^{(0)}\\ q_{uL}^{(1)}\\ \vdots\\ \hline u_L^{(1)}\\ \vdots\end{pmatrix}$$

$[(2n+1)\times(2n+1)]$

$$\mathcal{M}_Y = m_0\begin{pmatrix}1 & \hat{\chi}_1 & \cdots\\ \hat{\chi}_1 & \hat{\chi}_1^2 & \cdots\\ \vdots & \vdots & \ddots\end{pmatrix},\ \mathcal{M}_{KK} = k_{EW}\begin{pmatrix}0 & 0 & \cdots\\ x_f^{(1)} & 0 & \cdots\\ 0 & x_f^{(2)} & \cdots\\ \vdots & \vdots & \ddots\end{pmatrix}$$

$$m_0 = \frac{\lambda v_4}{\sqrt{2}} \sim \mathcal{O}(M_W)$$

- Diagonalized by

$$\mathcal{N}\mathcal{M}_q\mathcal{N}^T = \mathrm{diag}(m_q, M_1, M_2, \cdots),$$

- $n_\infty(\to \infty)$: the number of the KK states.
- $q_{uL}^{(n)}$ (involved in the charged current interactions) : a mixture of KK mass eigenstates $(2n_\infty + 1)$ $u_L'^{(j')}$

$$q_{uL}^{(i)} = \sum_{j'=0}^{2n_\infty} \mathcal{N}_{(j',i)} u_L'^{(j')}, \quad (i = 0, \cdots, n_\infty).$$

- $\mathcal{L} = \frac{g}{\sqrt{2}} \left(\sum_{m=0}^{n_\infty} C_{0ml}^{btW} \mathcal{N}_{(j,\, m)} \right) \bar{b}_L^{(0)} \gamma^\mu t_L'^{(j)} W_\mu^{(l)} + h.c.$

constraints from $B \to X_s \gamma$

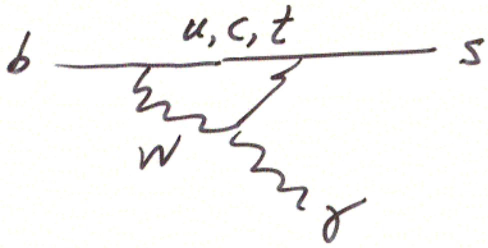
$$\frac{\Gamma(B \to X_s \gamma)}{\Gamma(B \to X_c e \bar{\nu}_e)} \simeq \frac{\Gamma(b \to s\gamma)}{\Gamma(b \to c e \bar{\nu}_e)} \equiv R_{quark}$$

$$= \frac{\lambda_t^2}{|V_{cb}|^2} \frac{6\alpha}{\pi f(z)} F(z) \left(|D(m_b)|^2 + A \right) \quad \text{at NLO-QCD}$$

$$f(z = m_c^2/m_b^2) = 1 - 8z^2 + 8z^3 - z^4 - 12 z^2 \ln z$$

$$F(z) = \frac{1}{K(z)} \left(1 - \frac{8}{3} \frac{\alpha_s(m_b)}{\pi} \right)$$

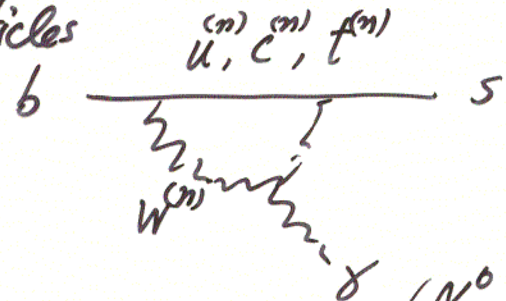
$$\lambda_i \equiv V_{ib}^* V_{is}$$



$\Downarrow$

All external particles $\Rightarrow$ SM particles

$\chi_A^{(0)}$ = constant.



$\Downarrow$

$$C_{nm0}^{WWA} = \delta_{nm}, \quad C_{nm0}^{ffA} = \delta_{nm}$$

(χ_A^0 = bulk wave ftn. of photon zero-mode)

$\Downarrow$

contribution via n-th up-type quark and m-th W-boson is same as SM except for the internal mass and additional three-point ~~ftn~~ coupling (D)

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All the KK modes of bulk gauge bosons and up-type quarks in the RS scenario with the unitarity condition of $\lambda_u + \lambda_c + \lambda_t = 0$

$$D(x^t_{(0,0)}) \quad \Rightarrow \quad \left[\sum_{l=0}^{n_\infty} \sum_{j'=0}^{2n_\infty} \left(\sum_{m=0}^{n_\infty} C^{btW}_{0ml} N_{(j',m)} \right)^2 D(x^t_{(j',l)}) - \sum_{j,l=1}^{n_\infty} \left(C^{btW}_{0jl} \right)^2 D(x^{(0)}_{(j,l)}) \right]$$

$$x^q_{(i',l)} \equiv \left(\frac{M_q^{(i')}}{M_W^{(l)}} \right)^2$$

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- In the limit of $\mathcal{M}_Y \ll \mathcal{M}_{KK}$ $(\nu \gtrsim -0.3)$,

$$D(x^t_{(0,0)}) \Rightarrow D(x^t_{(0,0)}) + \mathcal{O}(\delta^2)$$

- Well behaved.

<Numerical Results>

- The Effects of the RS−bulk SM on the $b \to s\gamma$
  ; m_0, $k_{EW} (\equiv k e^{-k r_c \pi})$, $\nu (= \frac{m_\psi}{k})$

- $D^{RS}(m_W)$ is finite as $n_c \to \infty$?
  n_c : the cut-off of KK #.
- In priciple,
  1. Diagonalize $(\infty \times \infty)$ $\mathcal{M}_{top}$
  2. Obtain the mass eigenstates and $\mathcal{N}$
  3. Truncate the KK contribution at n_c

- In reality
  1. $\Rightarrow$ impossible

  - consider $(2n_\infty + 1) \times (2n_\infty + 1)$ matrix
  - Truncate at $n_c < n_\infty$

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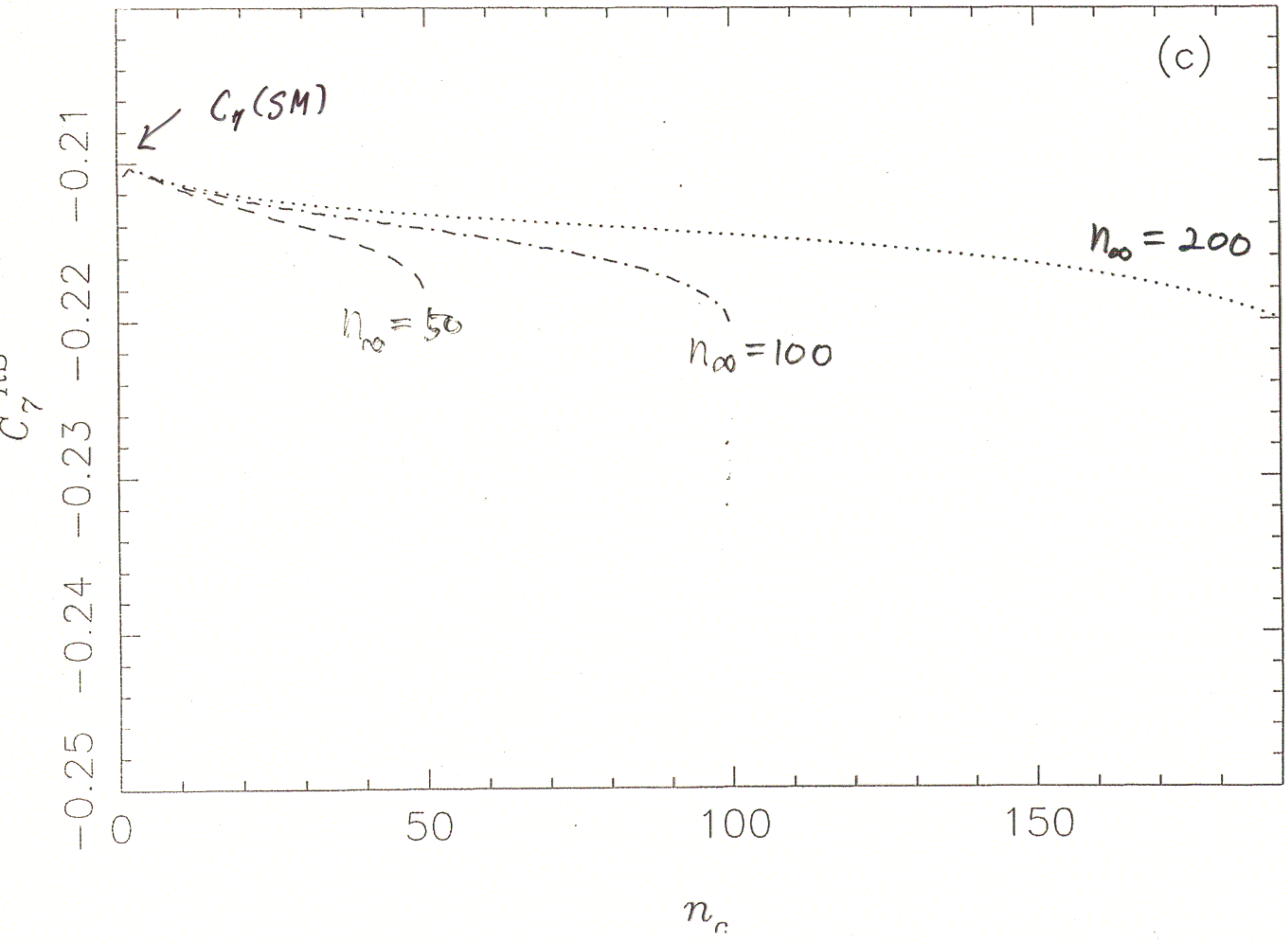
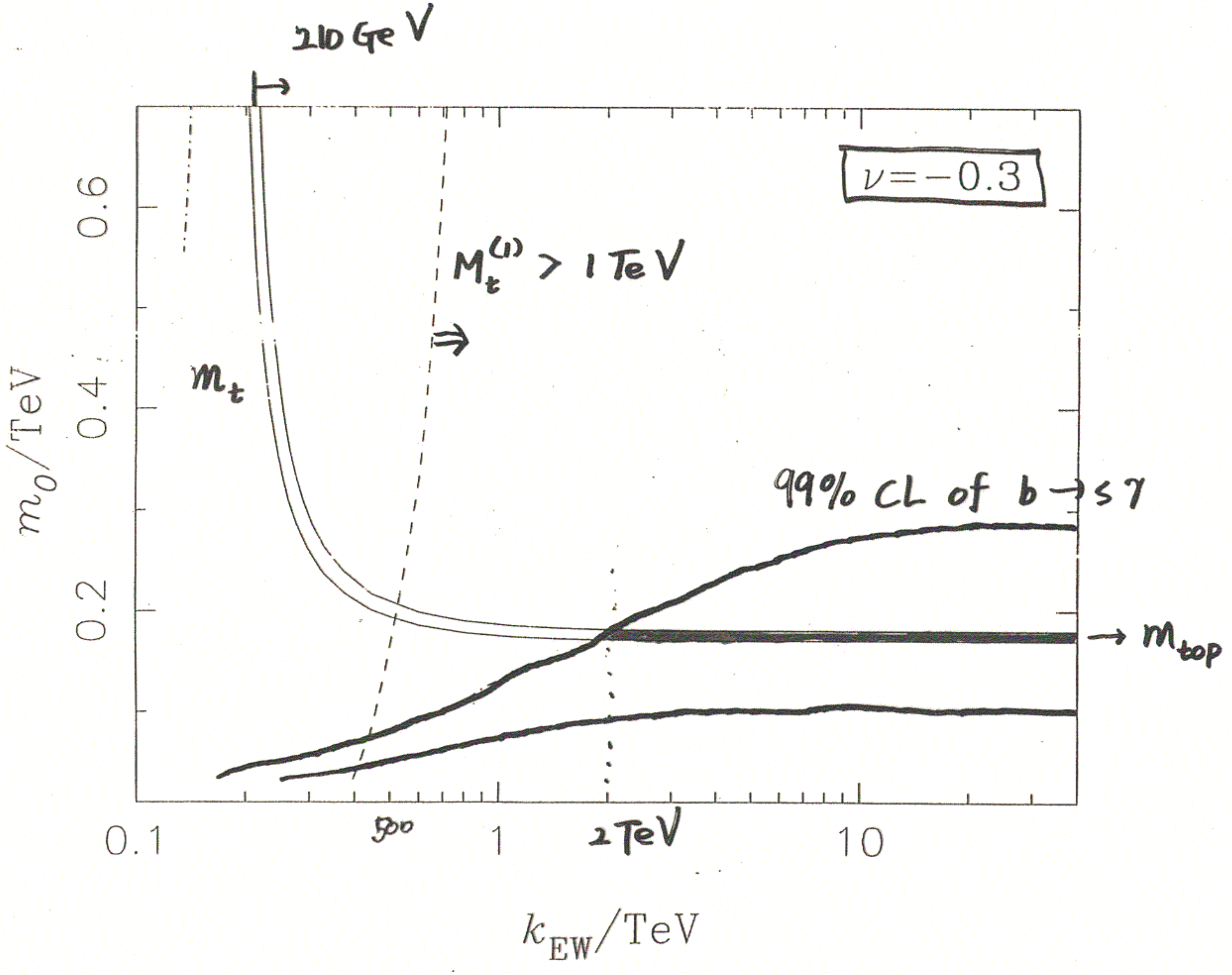
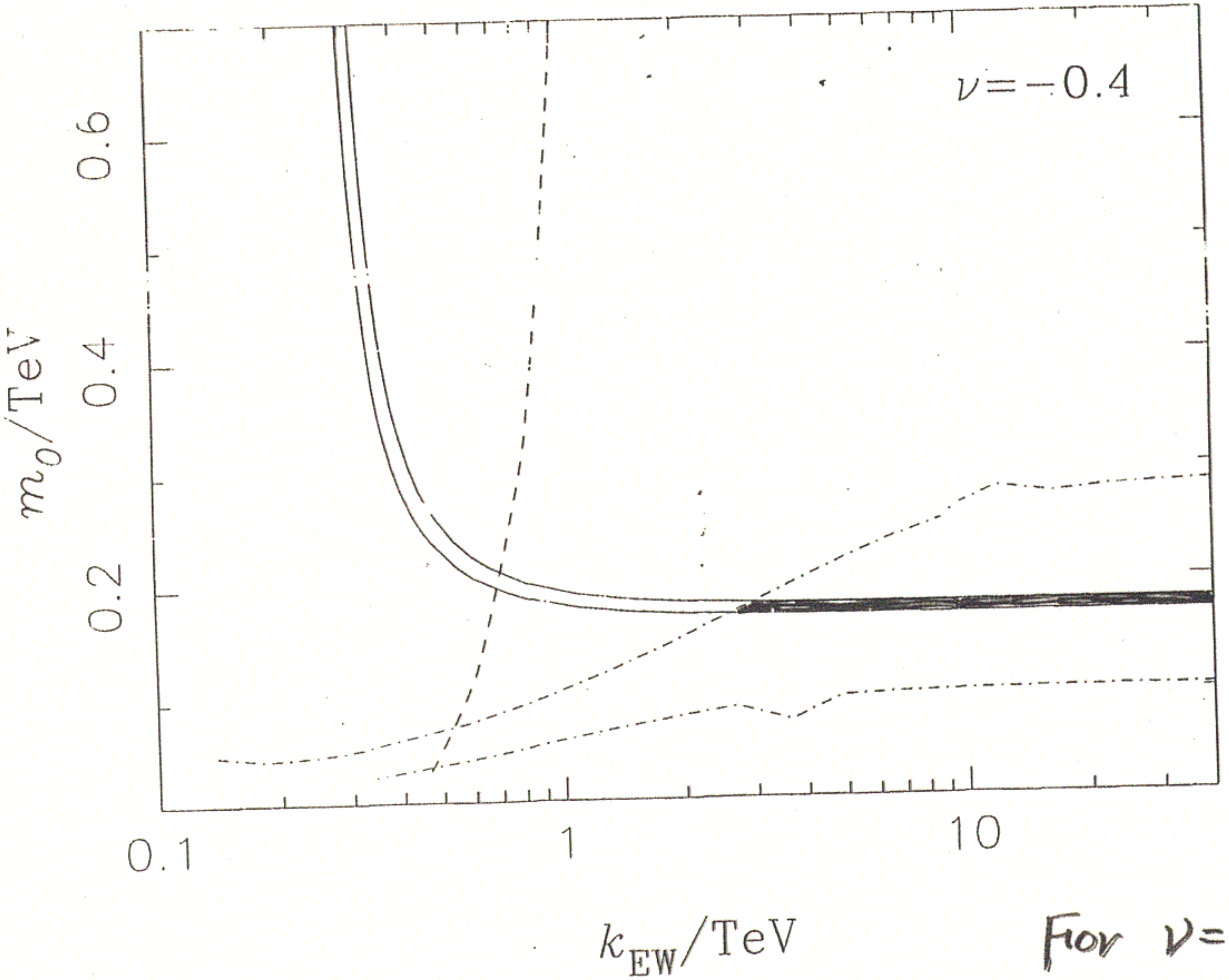

(c)
$C_7(SM)$
$n_\infty = 200$
$n_\infty = 50$
$n_\infty = 100$
C_7^{RS}
−0.25
−0.24
−0.23
−0.22
−0.21
0
50
100
150
n_c



(25)
T-22
210 GeV
$\nu = -0.3$
$M_t^{(1)} > 1$ TeV
m_t
99% CL of $b \to s\gamma$
$\to m_{top}$
0.6
0.4
0.2
m_0/TeV
0.1
500
1
2 TeV
10
k_{EW}/TeV

(24) 7-23



For $\nu = -0.5$, $k_{EW} \gtrsim 5$

Role of ρ-parameter.

- its quantum correction increases as the 2-fermion mass difference in related intermediate SU(2)-doublet increases.

$\Rightarrow$ current exp. constraint for new physics:

$$\Delta\rho_{N.P} < 2\times 10^{-3}$$

- non-degenerate SU(2)-doublet (f_1, f_2) (color-triplet) yields

$$\Delta\rho = \frac{3G_F}{8\sqrt{2}\pi^2}\Delta m^2$$

$$\Delta m^2 \equiv m_1^2+m_2^2 - \frac{4m_1^2 m_2^2}{m_1^2-m_2^2}\ln\frac{m_1}{m_2}$$

$$\simeq \begin{cases} m_1^2 & \text{for } m_1 \gg m_2 \\ (m_1-m_2)^2 & \text{for } m_1 \simeq m_2 \end{cases}$$

$\Rightarrow$ PDG : the sum of contributions from possible non-degenerate SU(2) color-triplet fermions beyond S.M.

$$\sum_i \Delta m_i^2 \lesssim (115\ \text{GeV})^2 \qquad (95\%\ \text{C.L.})$$

(if $m_{Higgs} < 1$ TeV).

5-D Fermion action for 3rd generation:

$$S = \int d^4x \int d\phi \sqrt{-G} \{ E_a^A [i\bar{Q}\gamma^a D_A Q + i\bar{t}\gamma^a D_A t + i\bar{b}\gamma^a D_A b] + h.c.$$

$$- \operatorname{sign}(\phi) [m\bar{Q}Q + m'\bar{t}t + m''\bar{b}b] \}$$

5-D action for Yukawa interaction with confined Higgs Field:

$$S_{ffH} = -\frac{\lambda_5}{k} \int d^4x \int d\phi \sqrt{-G} [\bar{Q}(x,\phi) \cdot H(x) b(x,\phi) + \epsilon^{ab} \bar{Q}(x,\phi)_a \cdot H(x)_b t(x,\phi) + h.c.] \delta(\phi - \pi)$$

after spontaneous symmetry breaking ($H^0 \to v_5 + H'^0$):

4-D effective Lagrangian for Yukawa interaction:

$$\mathcal{L}_{eff} = \frac{\lambda_t v}{\sqrt{2}} (\bar{q}_{tL}^{(0)} + \hat{\chi}_1 \bar{q}_{tL}^{(1)} + \cdots)(t_R^{(0)} + \hat{\chi}'_1 t_R^{(1)} + \cdots)$$

$$+ \frac{\lambda_b v}{\sqrt{2}} (\bar{q}_{bL}^{(0)} + \hat{\chi}_1 \bar{q}_{bL}^{(1)} + \cdots)(b_R^{(0)} + \hat{\chi}''_1 b_R^{(1)} + \cdots)$$

$$(\nu = m/k, \quad \nu' = m'/k, \quad \nu'' = m''/k)$$

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FIGURES

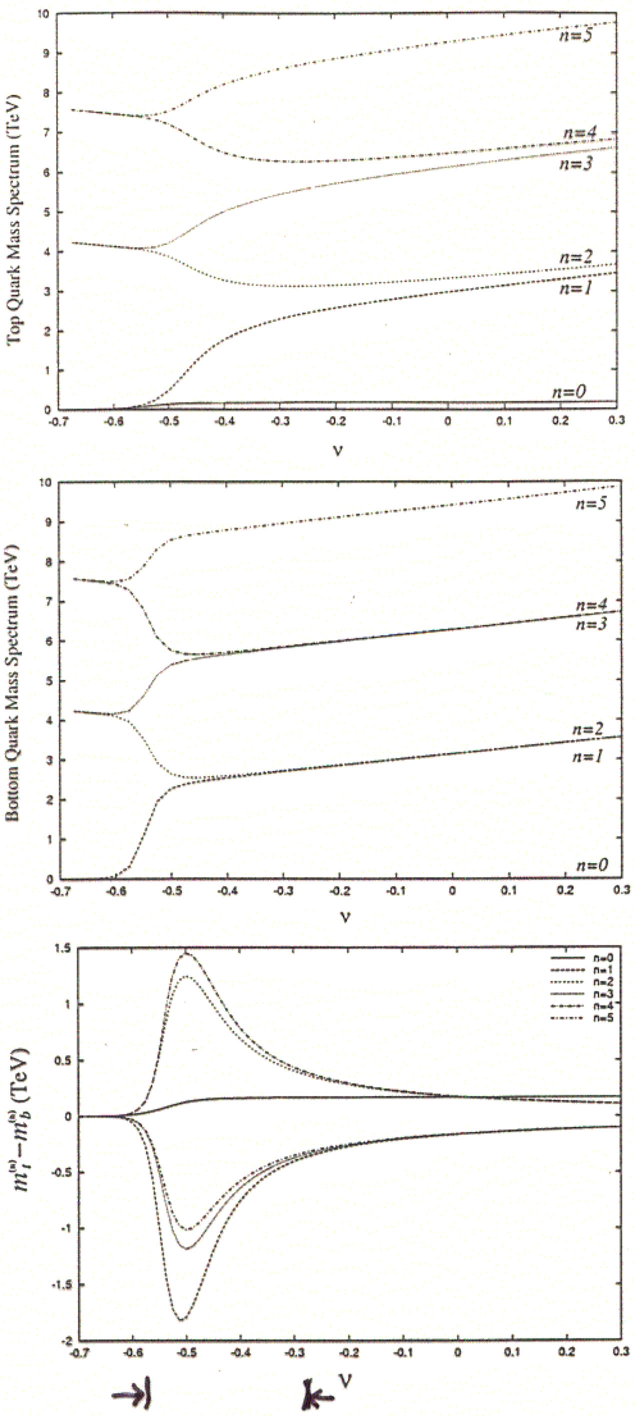
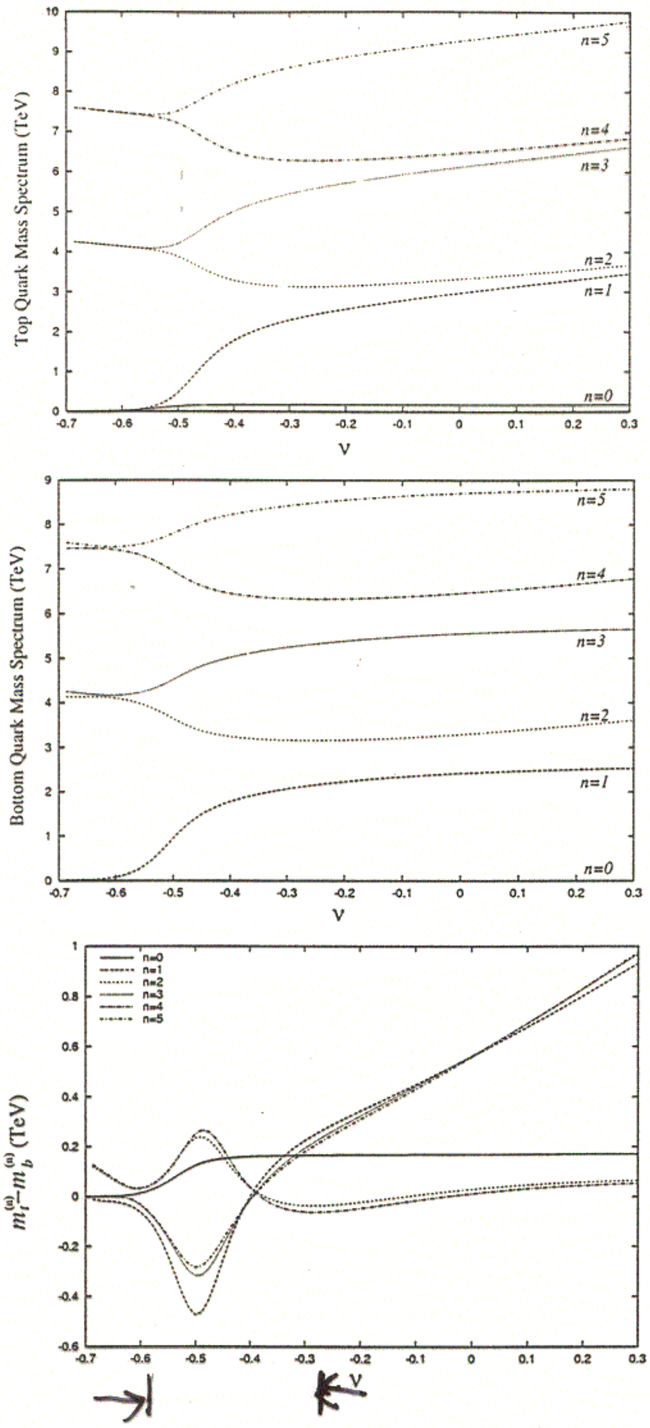


FIG. 1.

$$m = m' = m''$$
$$(\nu = \nu' = \nu'' \equiv \nu)$$

T-27



$(\nu''=-0.6)$

FIG. 2.

$\nu = \nu' \neq \nu''$

$(m_{\bar{Q}Q} = m'_{\bar{u}u} \neq m''_{\bar{d}d})$

T-28

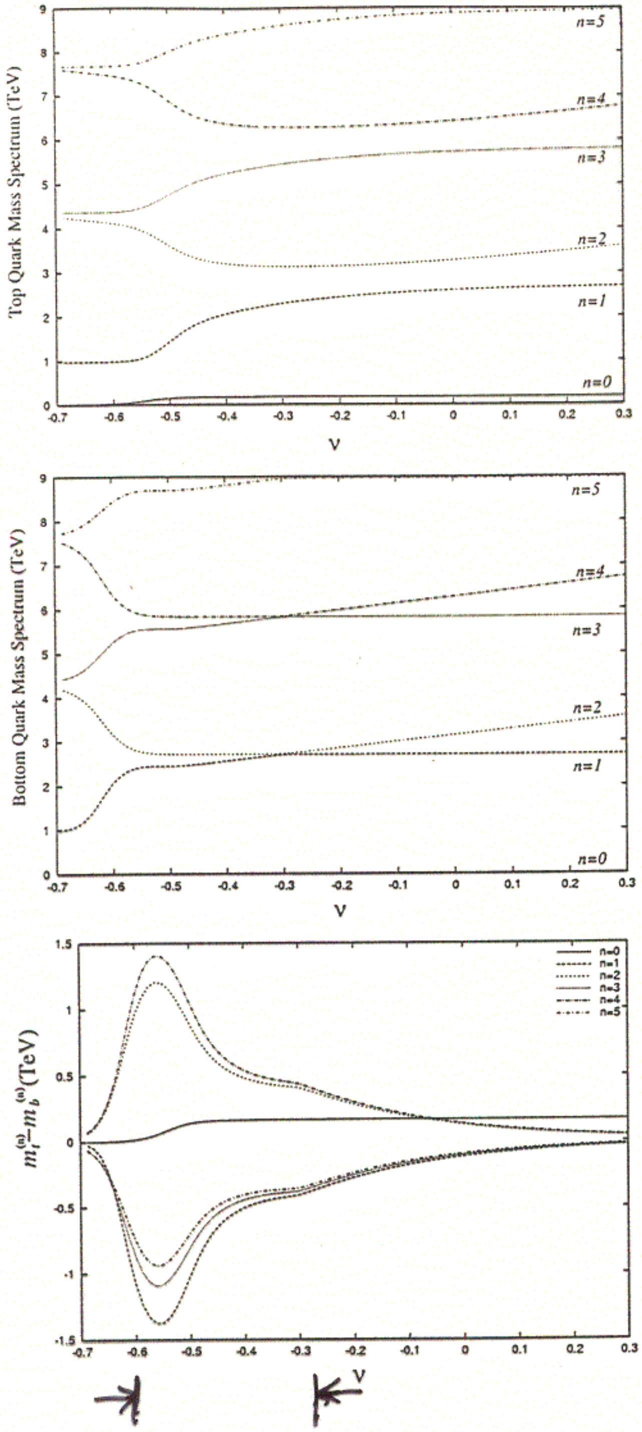


FIG. 3.

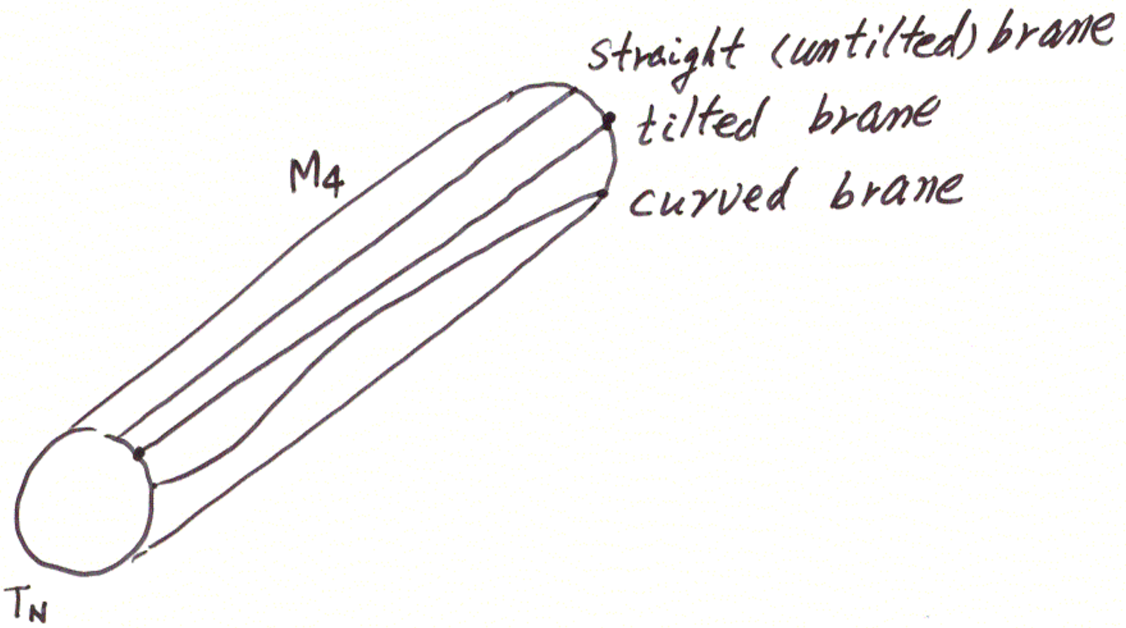
$\nu \neq \nu' = \nu''$

$(m_{\bar{Q}Q} \neq m_{\bar{u}u} = m_{\bar{d}d})$

T-29

III Spontaneous breaking of Lorentz and Rotation Invariances, CTP violations, from a tilted brane

- G. Dvali & M. Shifman, Phys. Rep. 320 (1999) 107
- G. Cvetic, S.K. Kang, C.S. Kim, K. Lee, Phys. Rev. D62 (2000) 057901



IV.

Low Scale String Unification and the Highest Energy Cosmic Rays

William S. Burgett[a], G. Domokos[b] and S. Kovesi-Domokos[b]
[a] Department of Physics, University of Texas at Dallas. [b] Department of Physics and Astronomy, The Johns Hopkins University.

- Cosmic ray protons of $E > 5 \times 10^9$eV produce pions on the CMBR and lose energy. (The Greisen-Zatsepin-Kuzmin effect.) More energetic protons must come from within ≈50mpc. However, there are no appropriate sources within such a distance. This is the puzzle of the trans-GZK cosmic rays.
- Our proposed solution:
  1. The primaries of trans-GZK cosmic rays are neutrinos, which can penetrate the CMBR;
  2. there is "new physics" at a scale of a few tens of TeV, similar to a strongly coupled string theory. Interactions are unified around the string scale.
- Around the characteristic scale, M, the neutrino-quark cross section grows rapidly, due to the excitation of leptoquark resonances, see Fig. 1. At still higher energies the cross section levels off: the leptoquarks are dual to Z-exchange in the crossed channel.
- The neutrino-quark cross section is folded in with the PDF: it shows the characteristic features as outlined, see Fig. 2.
- Such neutrino-induced showers have been simulated using the ALPS Monte Carlo package. Once the cross section grows to a few tens of mb, the depth of the initial interaction, X_0 (Fig. 3) and the location of the shower maximum, X_{max}, (Fig. 4) are comparable to proton induced showers.
- Future detectors (the Pierre Auger Observatory, EUSO, OWL...) will be able to test this scenario by a study of the particle number fluctuations.

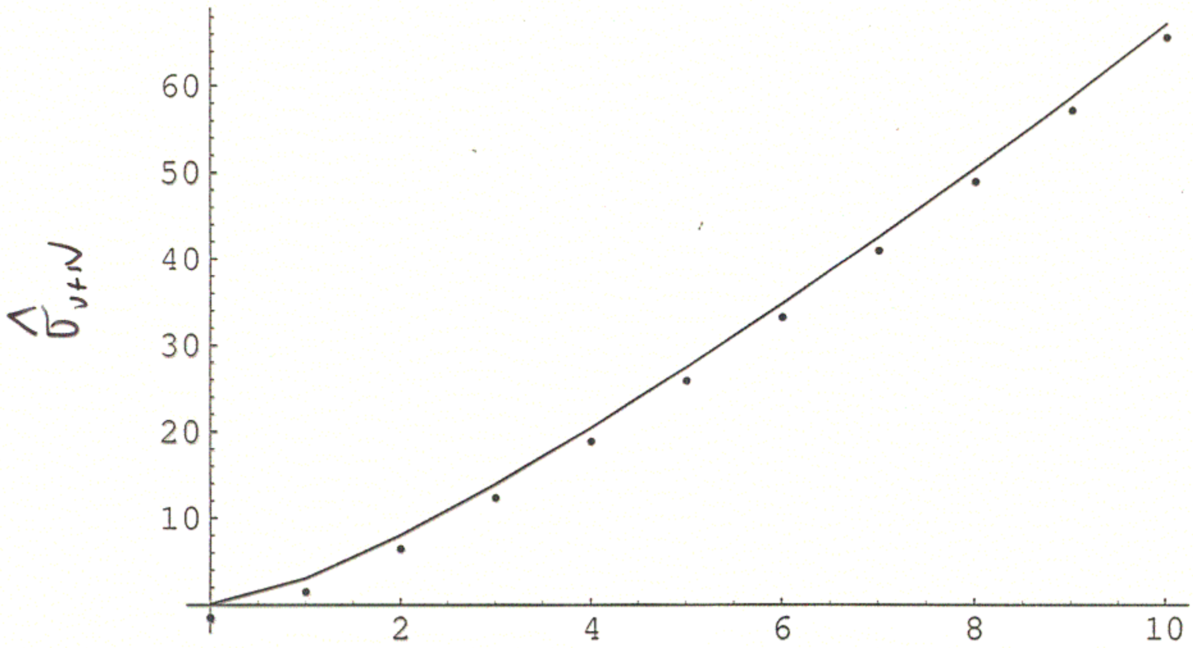


Figure 1: Level density as computed from the first few excitations of an open superstring. The points represent the number of levels calculated from the generating function. The continuous curve is the best fit, $d(N) \propto \exp(1.24N)$ with $N \approx \hat{s}/M^2$

- Unitarity of S-matrix
- rapidly rising level density of resonances
- Unification of interactions at around scale M
- duality between resonances in a given channel and Regge exchange in X-ed channels.

$$\Rightarrow \hat{\sigma} \simeq \frac{16\pi}{\hat{s}} d(\hat{s})$$

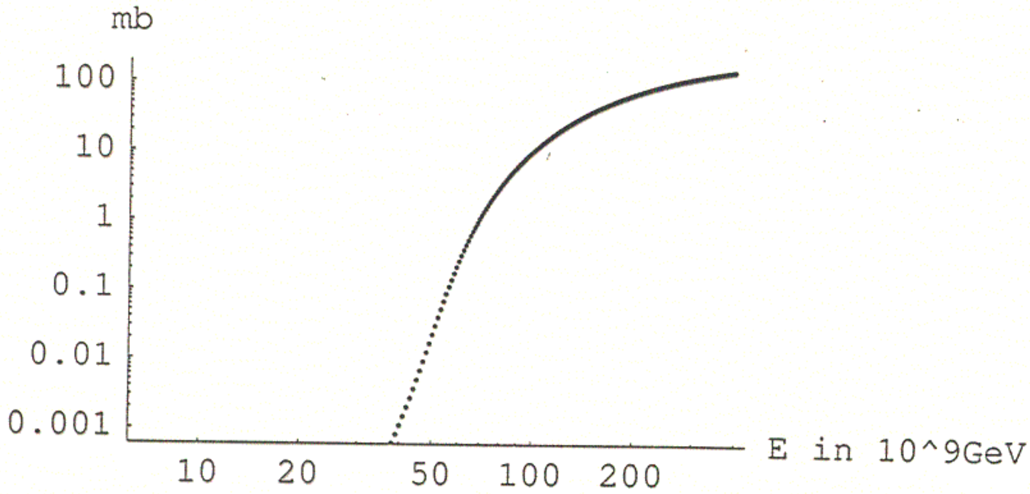


Figure 2: The neutrino-nucleon cross section in the low scale string model scheme. The string scale is approximately 80 TeV. Neutrino-parton cross sections have been integrated over the parton distribution using CTEQ6.

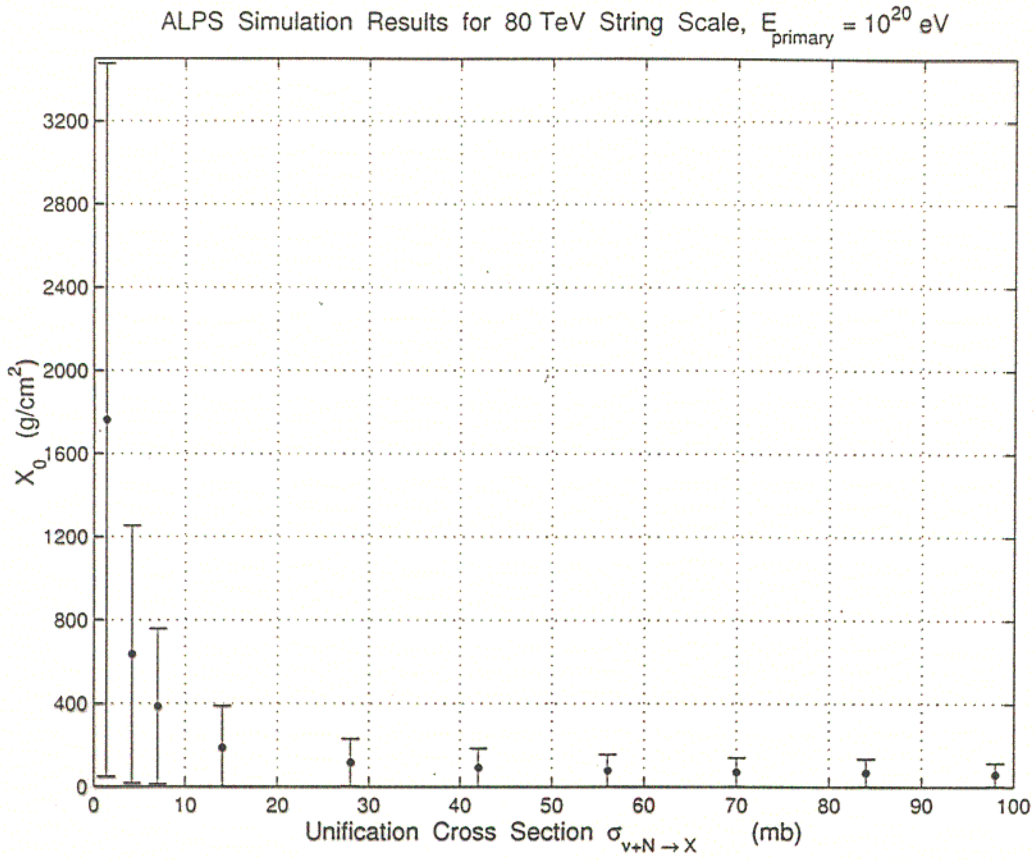


Figure 3: The distribution of the first interaction in the atmosphere: low scale string model, neutrino induced showers at trans-GZK energies. The string scale is approximately 80 TeV. Notice that the depth of the first interaction is comparable to that of hadronic interactions once the cross section becomes larger than about 20 mb

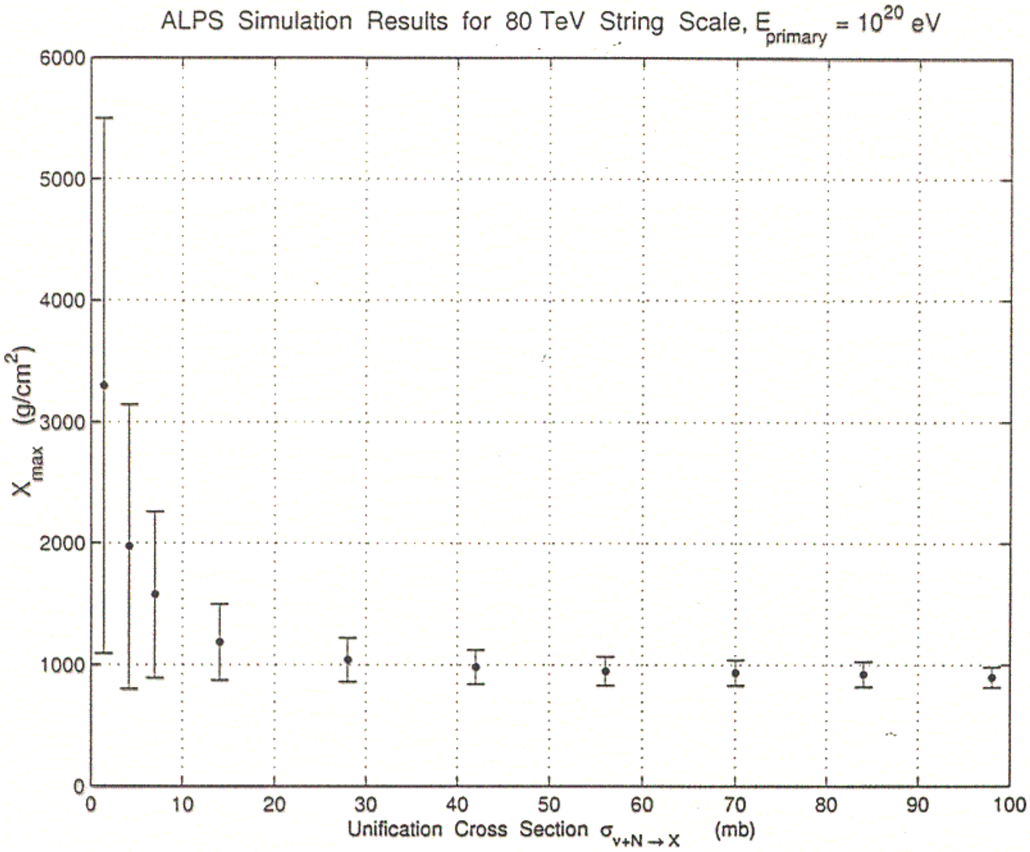


Figure 4: Distribution of the maxima of trans-GZK showers induced by neutrinos in a low scale string scheme. The string scale is approximately 80 TeV. Notice that a typical hadron induced shower peaks around 800 g/cm^2. This is indistinguishable from a neutrino induced shower in this scheme.