TeV String Resonances from HE Cosmic Neutrinos

Tao Han
Univ. of Wisconsin - Madison

KITP, April 1, 2003

- Low String Scale Scenario: Motivation and Phenomenology

J. Friess, T. Han, and D. Hooper: Phys.Lett.**B547**, 31(2002);
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- String Resonance Signal from Cosmic Neutrinos
- Summary

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Motivation

What if the string scale is near TeV?*

*I. Antoniadis (1990); J. Lykken (1996).

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What if the string scale is near TeV?*

- ▷ No large $M_W - M_{pl}$ mass hierarchy †

- ▷ Rich phenomenology at TeV scale:

Collider searches: Kaluza-Klein, stringy states, bh's ...
Low energy effects/constraints
Astro-particle physics signals (SN; NS; HECR ...)
Cosmological implications (DM; m_ν; cosm. const. ...)
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Astro-particle physics signals (SN; NS; HECR ...)
Cosmological implications (DM; m_ν; cosm. const. ...)
...

▷ Challenge to model-building:

The size/stabilization of extra dimensions
Coupling unification (power-law running)
Nucleon stability
Flavor physics
...

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Phenomenology

Physical Scales:

String scale: $M_S^2 = 2\pi T = 1/\alpha'$

Quantum gravity scale:

$$\frac{1}{8\pi G_N} = \begin{cases} M_{pl}^2 & \text{for 4-dimensions} \\ M_D^{n+2} R^n & \text{for (4+n)-dim} \end{cases}$$

Relation between M_S and M_D : model-dependent

$$M_S \approx g^a M_D \quad \text{or} \quad M_D \approx (\text{a few}) \times M_S.$$

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In traditional string:

$$M_S = g M_{pl} = 2.4 \times 10^{18} g \text{ GeV}$$

With large extra-dim.

$$M_S \approx g^b M_D = g^b \times \left(\frac{M_{pl}^2}{R^n}\right)^{\frac{1}{n+2}} \rightarrow \text{TeV achievable !}$$

Observable signals

▷ At "low" energies

- "very low": $E \ll 1/R,\ M_S$:

4−dim effective theory: as the Standard Model;

very weak effects from gravity ... ...

(e.g., the case of traditional string)

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(e.g., the case of traditional string)

- march into the extra-dimensions: $1/R < E \ll M_S$,

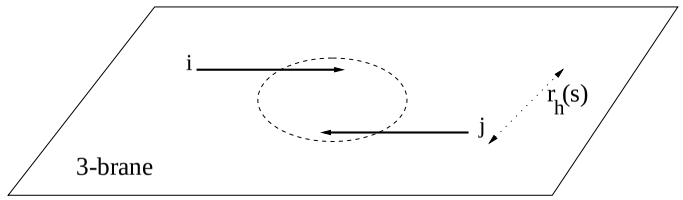
$(4+n)$−dim physics directly probed, and gravity effects observable:* mainly via light KK gravitons of mass

$$m_{KK} \sim 1/R,$$

or whatever propagate there ⇒ an effective theory (SM+KK).

*N. Arkani-Hamed, Dimopoulos, Dvali (1998); Giudice, Rattazzi, Wells (1999); Han, Lykken, Zhang. (1999); Mirabelli, Peskin, Perelstein (1999); J. Hewett (1999); T. Rizzo (1999). ...

▷ At "trans Planckian" energies $E > M_D, M_S$:
$(4+n)-$dim physics directly probed;
gravity dominant: black hole production[‡]
$M_{bh} = \sqrt{s} > M_D$ for $b < r_{bh}$.



[‡]T. Banks and W. Fischler (1999); E. Emparan et al. (2000); S. Giddings and S. Thomas (2002); S. Dimopoulos and G. Landsberg (2001).

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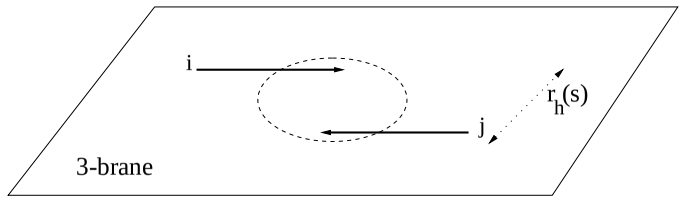

M_{BH}	$n = 4$	$n = 6$
5 TeV	1.6×10^5 fb	2.4×10^5 fb
7 TeV	6.1×10^3 fb	8.9×10^3 fb
10 TeV	6.9 fb	10 fb

copiously produced at the LHC and other TeV-scale experiments !*

‡T. Banks and W. Fischler (1999); E. Emparan et al. (2000); S. Giddings and S. Thomas (2002); S. Dimopoulos and G. Landsberg (2001).

*Criticism: M. Voloshin (2001).

▷ In between? $E \sim M_D, M_S$: Things are more involved.

- stringy states significant:[§]

$$\mathcal{M}(\text{close-string}) \sim g^2 \times \mathcal{M}(\text{open-string})$$

- s-channel poles as resonances:[†]

$$\mathcal{M}(s,t) \sim \frac{t}{s - M_n^2}, \quad M_n = \sqrt{n} M_S.$$

[§] G. Shui and H. Tye (1998); K. Benakli (1999).

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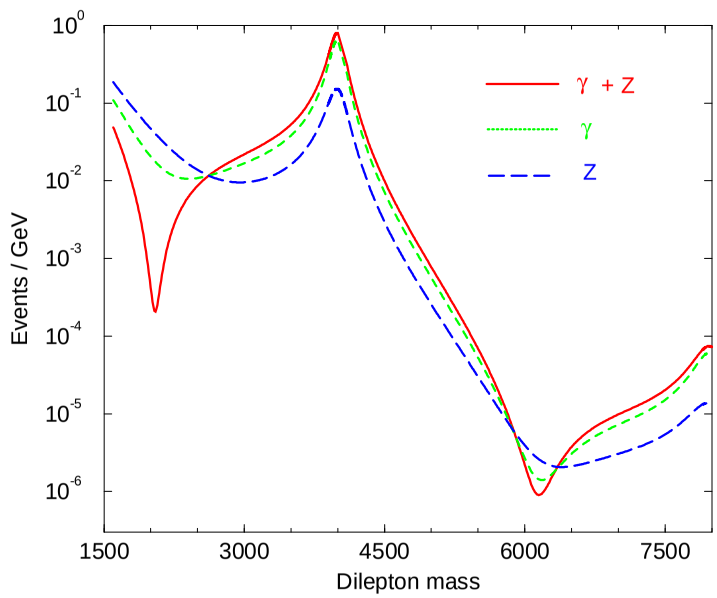

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String Scattering Amplitude

The general tree-level open-string amplitude[¶]

$$\mathcal{M}(1,2,3,4) = g^2[A_{1234}\cdot S(s,t)\cdot T_{1234} + A_{1324}\cdot S(t,u)\cdot T_{1324} + A_{1243}\cdot S(s,u)\cdot T_{1243}\ ]$$

- The Veneziano amplitude: (basically)

$$S(s,t) = \frac{\Gamma(1-\alpha' s)\Gamma(1-\alpha' t)}{\Gamma(1-\alpha' s-\alpha' t)} \quad \stackrel{\alpha' s\to 0}{\longrightarrow} 1.$$

$\Rightarrow$ String resonances at poles:

$$\alpha' s = n \text{ or } \sqrt{s} = \sqrt{n} M_S.$$

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- The Chan-Paton factors: $T_{1234} \propto tr(\lambda_1\lambda_2\lambda_3\lambda_4) + tr(\lambda_4\lambda_3\lambda_2\lambda_1)$

model-dependent (on the SM embedding).

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- The color-ordered kinematical factors:[†] $A_{1234} = A(s,t,u)$.

[¶]Garousi and Myers (1996); Hashimoto and Klebanov (1997); Cullen, Perelstein, Peskin (2000).

[†]Mangano and Parke, Phys. Rept. (1991).

Massless Particle Scattering in SM

Following the procedure above, one obtains general scattering amplitudes for massless SM particles as string zero-modes:

- The color-ordered kinematical factors $A's$ are the helicity amplitudes, for instance:

$g_- g_+ g_+ g_-$:	$A_{1234} = -4g^2\langle 14\rangle^4/(\langle 12\rangle^2\langle 13\rangle^2)$
	$A_{1324} = -4g^2\langle 14\rangle^2/\langle 13\rangle^2$
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	$A_{1243} = -4g^2\langle 14\rangle^3/(\langle 12\rangle^2\langle 13\rangle)$
$f_- \bar{f}_+ f_+ \bar{f}_-$:	$A_{1234} = -4g^2\langle 14\rangle^3/(\langle 12\rangle^2\langle 13\rangle)$
	$A_{1324} = -4g^2\langle 14\rangle/\langle 13\rangle$
	$A_{1243} = -4g^2\langle 13\rangle\langle 14\rangle/\langle 12\rangle^2$

where $\langle ij\rangle \equiv \overline{\psi_-(p_i)}\psi_+(p_j)$,* a spinor product.

*see, *e. g.*, Mangano and Parke, Phys. Rept. (1991).

- The Chan-Paton factors?

Cullen, Peskin and Perelstein (2000): took weakly coupled Type IIB string theory, embedded QED in U(N=4) super Y-M theory:

$$e_L^+ = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \qquad e_L^- = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}, \qquad \gamma = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

The Chan-Paton factors are evaluated to be

T = 1/4, 1/2, and alike.

String amplitudes are obtained, like:

$$\mathcal{M}(e_L^- e_R^+ \to e_R^- e_L^+) = -2g^2 \frac{t}{s} S(s,t),$$

with $g = e$, QED amplitudes are reproduced.

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with $g = e$, QED amplitudes are reproduced.

However, it cannot be achieved to include the full SM sector (without unwanted extra states) ...

Our approach:

Instead of constructing the Chan-Paton factors explicitly, we take them as model-parameters $T's$, to be determined by matching the SM amplitudes at low energies.*

*Cornet, Illana and Masip (2001); Friess, Han, Hooper (2002).

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We thus obtain open-string scattering amplitudes for (zero-mode) SM particles†

- By construction, it leads to correct (massless) SM amplitudes at $s \ll M_S^2$;
- It becomes "stringy" for $s \sim M_S^2$.

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No (new) statement for EWSB and SUSY breaking ...

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Low Energy Constraint on M_S

Explicit stringy amplitudes

Consider a typical process:

$$e_L q_L \to e_L q_L$$

we have

$$\mathcal{M}_{string} = g^2[\frac{s}{t}S(s,t)T_{1234} + \frac{s^2}{tu}S(t,u)T_{1324} + \frac{s}{u}S(u,s)T_{1243}]$$

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$$\mathcal{M}_{string} \approx g^2\ [\frac{s}{t}(T_{1234} - T_{1324}) + \frac{s}{u}(T_{1243} - T_{1324})]$$

matching the SM amplitude:

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Then

$$\mathcal{M}_{string} = \mathcal{M}_{SM}S(s,t) + g_L^2\frac{s}{tu}T\ [uS(s,t) + sS(t,u) + tS(u,s)].$$

where $0 \leq T \leq 1$.

Induced Contact Interactions

Far below the resonance $M_S^2 \gg s$,

$$S(s,t) \approx 1 - \frac{\pi^2}{6}\frac{st}{M_S^4} + ...$$

$$\mathcal{M}_{string} \approx \mathcal{M}_{SM}(1 - \frac{\pi^2}{6}\frac{st}{M_S^4}) - g_L^2(3T)\frac{\pi^2}{6}\frac{s^2}{M_S^4}$$

and thus:

$$\Delta\mathcal{M}_{SM} \sim \frac{st}{M_S^4}\mathcal{M}_{SM} + g_L^2 T\frac{s^2}{M_S^4},$$

Due to the power-suppressed corrections, the constraints from HERA, Tevatron etc. are not very strong

$$M_S \gtrsim 0.7 - 1.0 \text{ TeV}.$$

The string resonances

Near the resonances, $s \approx M_S^2$,

$$S(s,t) \approx \frac{t}{s - M_s^2} + \frac{t(t/M_S^2 + 1)}{s - 2M_s^2} + ...$$

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Treat the resonances individually

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\mathcal{M}_{string} \approx \quad & g_L^2\left(2Q_eQ_q \sin^2\theta_{\mathrm{W}} \frac{s}{t} + \frac{2g_L^e g_L^q}{\cos^2\theta_{\mathrm{W}}} \frac{s}{t - M_Z^2}\right) && \text{SM term} \\
+ \quad & g_L^2(C + 2T)\frac{s}{s - M_s^2} && 1^{\text{st}} \text{ resonance} \\
+ \quad & g_L^2 C \frac{s\cos\theta}{s - 2M_s^2} && 2^{\text{st}} \text{ resonance} \\
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and need to include the total width

$$\Gamma_n = \frac{g_L^2}{2\pi} \frac{|T|}{2J+1} \sqrt{n} M_S.$$

Neutrino-Nucleon Scattering

- Consider the dominant process:*

$$\nu g \to \nu g$$

- Identify $(\nu, g, g, \nu) \to (1, 2, 3, 4)$, we have

$$\mathcal{M}(\nu_L g_R \to \nu_L g_R) = -4g^2 \frac{1}{t}\sqrt{\frac{-u}{s}} \times [uS(s,t)T_{1234} + sS(t,u)T_{1324} + tS(s,u)T_{1243}]$$

In the low-energy limit, matching the SM amplitude:

$$0 = u\ T_{1234} + s\ T_{1324} + t\ T_{1243} \implies T_{1234} = T_{1324} = T_{1243} \equiv T$$

Typically, $T \sim 1/4 - 1/2$.

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Typically, $T \sim 1/4 - 1/2$.

- Physics of the stringy states:

in s and u channels: fermionic "Lepto-gluons" ν_8;

what's in t channel? bosons in $SU_c(3)$ and $SU_L(2)$? or pomerons?

*For the νq process, Cornet, Illana and Masip (2001).

We have the full (well-behaved) amplitude,
but the resonances dominate at high energies.

- Regge poles in Veneziano amplitudes:

$$S(s,t) \approx M_S^2 \sum_{n=1}^{\infty} \frac{(t/M_S^2)(t/M_S^2+1)\cdots(t/M_S^2+n-1)}{(n-1)!(s-nM_S^2)}$$

Assuming pole-dominance (good approximation):

$$\mathcal{M}(\nu_L g_R \to \nu_8 \to \nu_L g_R) \approx \sum_{n=1}^{\infty} A_n$$

$$A_n = \frac{8g^2 T n M_S^2}{s - nM_S^2} \sum_{J=3/2}^{n+1/2} \alpha_n^J d_{3/2,3/2}^J$$

each A_n represents a stringy resonance of mass $\sqrt{n}M_S$.

Assuming the elastic channel dominant:

$$\Gamma((\nu_8)_n^J \to \nu_L g_R) = \frac{g^2}{2\pi}\frac{|T|}{2J+1}\sqrt{n}M_S\left|\alpha_n^J\right|$$

$\nu - N$ scattering cross section

- With narrow-width approx., the parton-level cross section is

$$\sigma_n = \tilde{\sigma}_n \delta(1 - nM_S^2/s)$$
$$\tilde{\sigma}_n \equiv \frac{2\pi g^2 |T|}{nM_S^2}$$

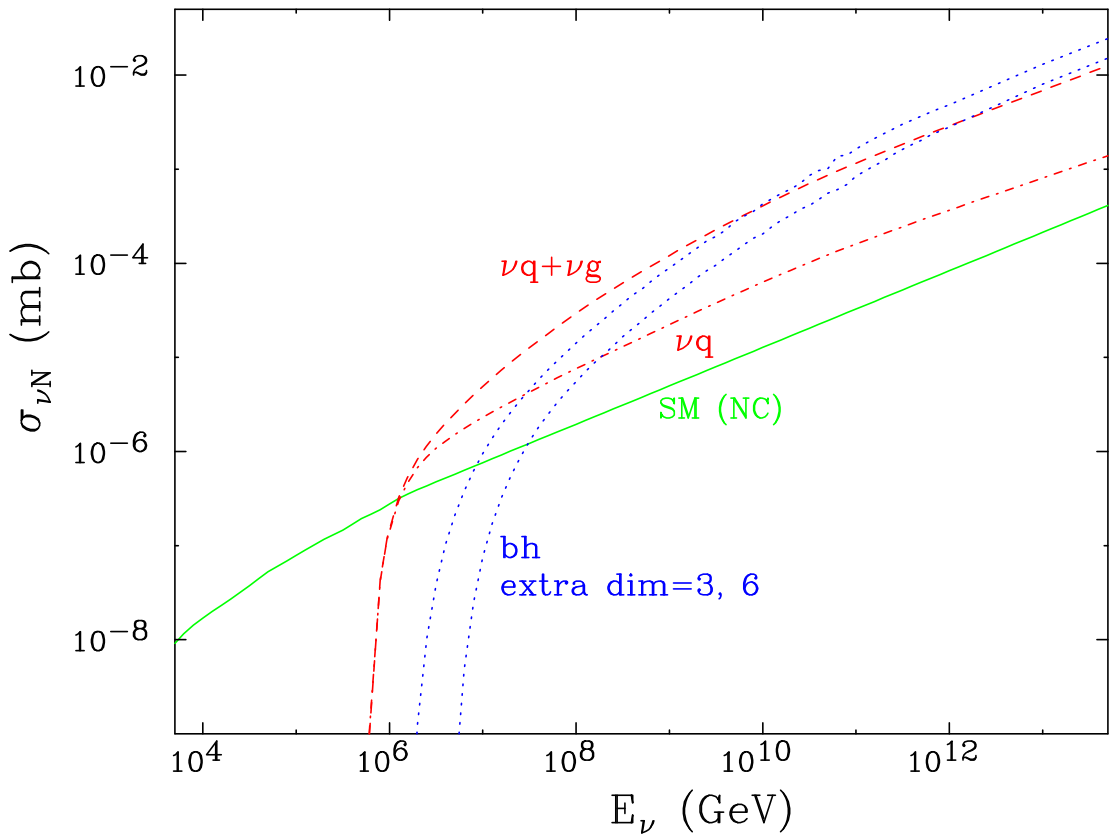
- For $E_{cm}^2 = S > nM_S^2$, sum over the resonances and the partons:

$$\sigma(\nu_L N) = \sum_{n=1}^{n_{cut}} \sum_f \tilde{\sigma}_n(\nu_L f)\ xf(x, Q^2)$$

where $x = nM_S^2/S$, the parton energy fraction.

(We take $n_{cut} = 50$, but it makes only 10% difference for 20-80.)

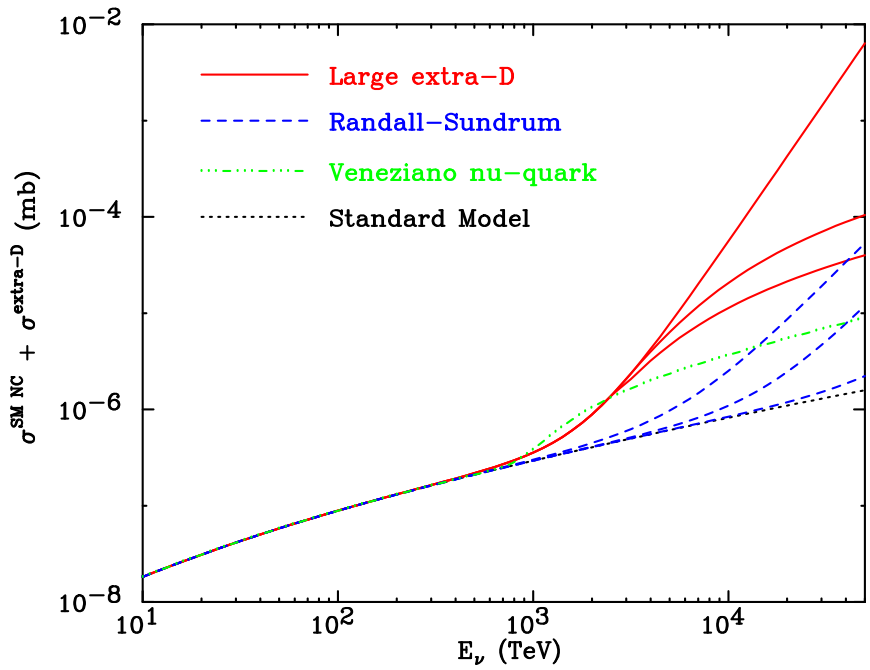
$\nu - N$ scattering cross section: Results



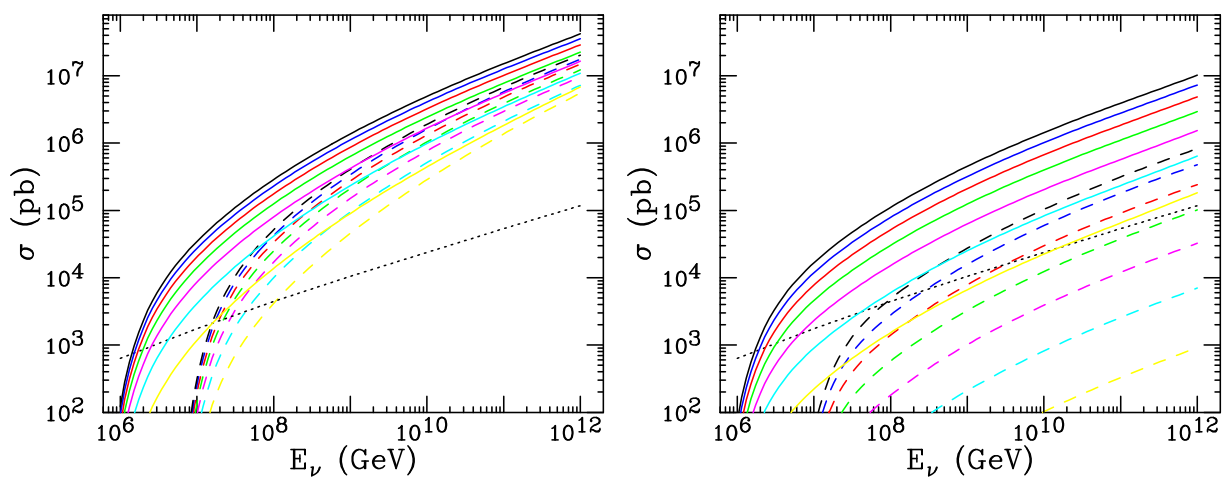
The SM neutral current prediction (solid green), string state contributions (red), and the black hole production (blue dots) with 3 (upper) and 6 extra dimensions. M_S=1 TeV and $T = 1/2$.
In our convention, $M_S \approx (1.6 - 3) M_D$ for $n = 3 - 7$.

- Not enough to explain UHECR near $E_\nu \sim 10^{20}$ eV.

For comparison,
KK graviton signals
at lower energies:*



For black hole signals at higher energies:†



*Alvarez-Muniz *et al.*, hep-ph/0107057

†Anchordoqui *et al.*, hep-ph/0112247

HE Cosmic Neutrinos

- ▷ Cosmic rays: Natural HE beams
- ▷ ν's:¶ Avoiding the GZK bound $E \sim 10^{20}$ eV.

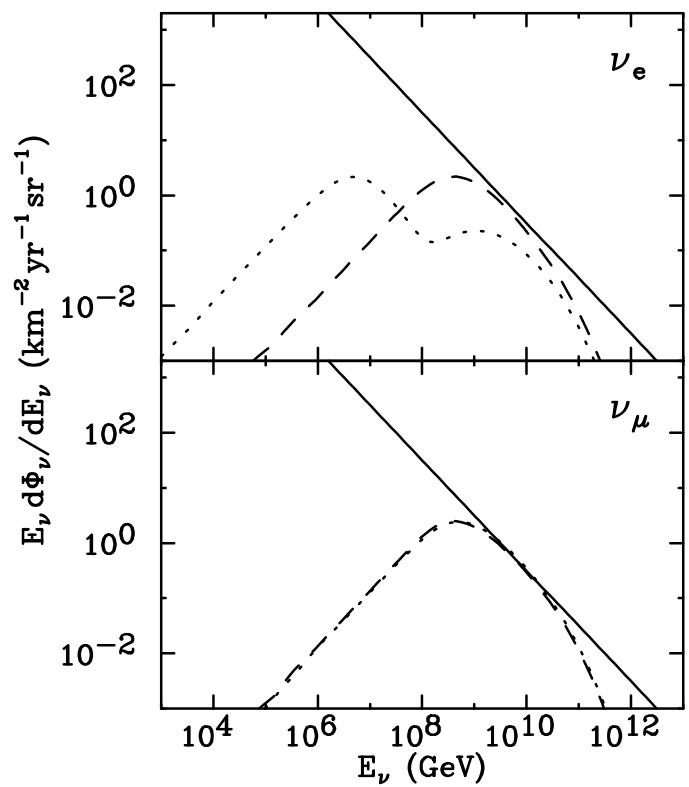
Assumed Fluxes:

- Cosmogenic ν (dashed) $\bar{\nu}$ (dotted) (HECR off CMB);†

- The Waxman-Bahcall flux (Point sources):*

$E^2 d\Phi/dE \approx 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

Determining ν-flux would be the 1st goal for HE cosmic neutrino experiments.



¶T.J. Weiler (2001); A. Kusenko (2002).

†F. Stecker (1979).

*Waxman and Bahcall (1999).

HE Neutrino detectors

Auger air shower Observatory:

3000 km^2 fluorescence detector.

we look for quasi-horizontal air-shower events.

IceCube km^2 ν Detector:

ice Cerenkov detector at the South Pole.

we look for both contained and through events.

Many studies on low-gravity scale models:[†] [‡]

[†] Nussinov and Shrock (1999); Domokos and Kovesi-Domokos (1999); Jain *et al.*, (2000); Alvarez-Muniz *et al.*, (2002).

[‡] Feng and Shapere (2002); Emparan *et al.*, (2002); Ringwald and Tu (2002); Anchordoqui and Goldberg (2002).

Our results from string resonances:

Auger (events/yr)	WB Flux	Cosmogenic Flux
SM ($E_{\rm sh}^{\rm th} = 10$ PeV)	0.66	0.20
$M_S = 1$ TeV	3.15	1.25
$M_S = 2$ TeV	0.96	0.34

IceCube (events/yr)	WB Flux		Cosmogenic Flux	
	Down	Up	Down	Up
SM ($E_{\rm sh}^{\rm th} = 250$ TeV)	8.4	1.8	0.15	0.012
$M_S = 1$ TeV	14.8	2.2	0.72	0.024
$M_S = 2$ TeV	8.7	1.9	0.22	0.016

- Auger Observatory: less sensitive to fluxes;
- IceCube: More events from down-going;
- Both detectors may lead to observable events:

with a few years data-taking, if $M_S \sim 1 - 2$ TeV.

Summary

With $M_S \sim 1$ TeV and R (possibly) large,

- At low energies: $1/R < E \ll M_S$,

gravity effects observable, mainly via light KK gravitons of mass $m_{KK} \sim 1/R$.

- At "trans Planckian" energies: $E > M_D, M_S$,

gravity-effects dominant, (mainly) via black hole production.

- Near the string scale: $E \sim M_D, M_S$,

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We constructed the open-string amplitudes

▷ reproduce the SM particle amplitudes at low energies.

▷ the low-energy constraints not severe (yet).

▷ applied to $\nu - g$ cosmic neutrinos:

the signal observation promising in the near future.

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More to do:

† More collider consequences in details.

† Explore the theoretical construction/embedding for SM particles.

† Explore the effects of gravity effects (close-string, loops).