Low String Scale Scenario: Motivation and Phenomenology

KITP, April 1, 2003

Univ. of Wisconsin - Madison
Tao Han

from HE Cosmic Neutrinos
TeV String Resonances
Low String Scale Scenario: Motivation and Phenomenology

J. Friess, T. Han, and D. Hooper: Phys. Lett. B547, 31 (2002);

Tao Han
Univ. of Wisconsin - Madison

TEV String Resonances from HE Cosmic Neutrinos

KITP, April 1, 2003
• Low Energy Constraints
• Open String Amplitudes as Massless Particle Scattering
• Low String Scale Scenario: Motivation and Phenomenology

KITP, April 1, 2003

Univ. of Wisconsin - Madison
Tao Han

from HE Cosmic Neutrinos
TeV String Resonances
TeV String Resonances

• String Resonance Signal from Cosmic Neutrinos
• Low Energy Constraints
• Open String Amplitudes as Massless Particle Scattering
• Low String Scale Scenario: Motivation and Phenomenology

KITP, April 1, 2003

Univ. of Wisconsin - Madison

Tao Han
TeV String Resonances from HE Cosmic Neutrinos

- Low String Scale Scenario: Motivation and Phenomenology
- Open String Amplitudes as Massless Particle Scattering
- String Resonance Signal from Cosmic Neutrinos
- Low Energy Constraints

Summary

KITP, April 1, 2003
Univ. of Wisconsin - Madison
Tao Han
Motivation

What if the string scale is near TeV?*

Motivation

What if the string scale is near TeV?

No large mass hierarchy

Rich phenomenology at TeV scale:

Cosmological implications (DM, $\nu$, cosm. const. ...)

Astro-particle physics signals (SN, NS, HECR ...)

Low energy effects/constraints

Collider searches: Kaluza-Klein, stringy states, brane ...

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

‡ N. Arkani-Hamed et al. (1998); I. Antoniadis et al. (1998); K. Dienes et al. (1998).
Motivation

What if the string scale is near TeV? 

\[ M_W^{\text{TeV}} \]

No large mass hierarchy

Flavor physics

Nucleon stability

Coupling unification (power-law running)

The size/stabilization of extra dimensions

Challenges to model-building:

Cosmological implications (DM, \( m_{\nu} \), cosm. const. …)

Astro-particle physics signals (SN; NS; HECR …)

Collider searches: Kaluza-Klein, stringy states, br’s …

Rich phenomenology at TeV scale:

I. Antoniadis et al. (1998); N. Arkani-Hamed et al. (1998); I. Antoniadis et al. (1998);

J. Lykken (1990); I. Antoniadis et al. (1998); N. Arkani-Hamed et al. (1998); I. Antoniadis et al. (1998).

...
Phenomenology

**Physical Scales:**

- **String scale:**
  \[ M_S = \frac{1}{\alpha'} \]

- **Quantum gravity scale:**
  \[ \frac{M^8}{G_N} \]

- **Relation between model-dependent and\(\mathcal{M}_W\):**
  \[ \mathcal{M}_W \approx \text{(a few)(few)} \text{ or } \mathcal{M}_W = \mathcal{M} \]

- **For (4+n)-dimensional string:**
  \[ \frac{M^8}{G_N} \]

- **String scale:**
  \[ \frac{\mathcal{M}_S}{\mathcal{M}} = \mathcal{M}_W \]

**Phenomenology**
Phenomenology

Physical Scales:

String scale:
\[ M^2_S = \frac{\pi T}{\alpha'} = \frac{1}{\alpha'} \]

Quantum gravity scale:
\[ \frac{1}{8\pi G} = \{ M^2_{pl} \text{ for 4-dim} \} \]

Relation between \( M^2_S \) and \( M^2_D \):

Model-dependent:

In traditional string:
\[ M^2_S = \frac{gM^4_{pl}}{4} = 2.4 \times 10^{18} \text{ GeV} \]

With large extra-dim.

\[ \sqrt{g} \approx \frac{gM^2_{pl}}{R^n} \approx S^2 \]

Quantum gravity scale:
\[ \frac{\sqrt{g}}{1} = 2\pi \approx S \]

String scale:
\[ \gamma = \frac{\gamma}{2} = S^2 \]

Physical Scales:
Observable signals

- At “low” energies
  - “very low”: \( E \ll \frac{1}{R}, \ M_S \):  
    - 4−dim effective theory: as the Standard Model;
    - very weak effects from gravity ...

(e.g., the case of traditional string)
Observables\makebox{signals} \Rightarrow \text{an effective theory} (\text{SM+KK}).

\[ m_{\text{MK}} \sim \frac{1}{R} \]

\[ \text{observable: mainly via light KK gravitons of mass} \]

\[ \text{very weak effects from gravity: } 4-\text{dim} \text{ physics directly probed, and gravity effects} \]

\[ \frac{E}{M^S} \gg 1 \]

\[ \text{March into the extra-dimensions: } \]

\[ \text{e.g., the case of traditional string} \]

\[ \text{very low energies: } \]

\[ \text{At low energies} \]
At "trans Planckian" energies $E > M^D$, gravity is dominant: black hole production is directly probed; $\mathcal{M}^b > q$ for $q > t^b$. Gravity dominates: black hole production is directly probed; $\mathcal{M}^b < s \wedge = \mathcal{M}^b$. Banks and W. Fischler (1999); E. Emparan et al. (2000); S. Giddings and S. Thomas (2002); S. Dimopoulos and G. Landsberg (2001).
At "trans-Planckian" energies \( E > M_D \), gravity dominant: black hole production \( M_{BH} \) copiously produced at the LHC and other TeV-scale experiments.

\[
\begin{array}{ccc}
\text{10 TeV} & 10 \text{fb} & 6.9 \text{ fb} \\
7 \text{ TeV} & 6.1 \times 10^3 \text{ fb} & 8.9 \times 10^3 \text{ fb} \\
5 \text{ TeV} & 2.4 \times 10^3 \text{ fb} & 1.6 \times 10^5 \text{ fb}
\end{array}
\]

\( W_{BH} \)

\[ n = 6 \quad 4 = n \quad H_{BH} \]

\( 3\)-brane

\( \gamma \)

\( W_{BH} \) for \( q > t_{\gamma} \). Gravity dominant: black hole production \( M_{BH} \) copiously produced at the LHC and other TeV-scale experiments.


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

\( \star \)
In between?

E ∼ MD, MS:

Things are more involved.


• Stringy states significant:

§ Accomando, Antoniadis, Benakli (2000); Cullen, Perelstein, Peskin (2000).

s-channel poles as resonances:

\[ s \mid W^{uW/uW - s} \sim (t \omega) W, W \mid \]

\( W(\text{close-string}) \times W(\text{open-string}) \)

\[ \sim \quad B. \]

In between?
Things are more involved.

\[ S_{\mathcal{W}}\mu^\Lambda = \mu\mathcal{W} \quad \frac{\mu\mathcal{W} - s}{t} \sim (i\sigma^2)\mathcal{W} \]

- Channel poles as resonances:
  - \( \mathcal{W} \) (close-string) \( \times \) \( \mathcal{Z} \) (open-string)

- Stringy states significant:
  - \( S_{\mathcal{W}}\mu^\Lambda \mathcal{W} \sim \mathbb{E} \) in between?
The general tree-level open-string amplitude

\[ \mathcal{M} = \text{string scattering amplitude} \]
The general tree-level open-string amplitude.

String Scattering Amplitude

The Veneziano amplitude: (basically)

\[ S_{\text{Veneziano}} = s^\Lambda \quad \text{or} \quad u = s \rho \]

\[ \alpha' s \rightarrow 0 \quad \Rightarrow \quad \text{String resonances at poles:} \]

\[ \frac{L(1) - s \rho}{(s \rho - 1)(s \rho - L) - L} = (t, s) S \]

\[ \alpha' s = n \quad \text{or} \quad \sqrt{s} = \sqrt{n} M \]

- The Veneziano amplitude,
- The Chan-Paton factors:

\[ T_{1234} \propto \text{tr} \left( \lambda_1 \lambda_2 \lambda_3 \lambda_4 \right) + \text{tr} \left( \lambda_4 \lambda_3 \lambda_2 \lambda_1 \right) \]

- model-dependent (on the SM embedding).

Garousi and Myers (1996); Hashimoto and Klebanov (1997);
Cullen, Perelstein, Peskin (2000).
The general tree-level open-string amplitude:

\[ W_{(1,2,3,4)} = \Delta_{0}^{\bar{3},4} \Delta_{\bar{3},4} \cdot (n,s) S_{(n,s)} + \Delta_{0}^{\bar{3},4} \Delta_{\bar{3},4} \cdot (n,t) S_{(n,t)} + \Delta_{0}^{\bar{3},4} \Delta_{\bar{3},4} \cdot (n,s) S_{(n,t)} + \Delta_{0}^{\bar{3},4} \Delta_{\bar{3},4} \cdot (n,t) S_{(n,s)} \]

The Veneziano amplitude (basically):

\[ S_{W}^{\text{MW}} = s^{\Delta} \quad \text{or} \quad u = s_{\rho} \]

String resonances at poles:

\[ \frac{(t,\rho - s_{\rho} - I)(I - s_{\rho} I)}{(I - s_{\rho} I)_{L}(s_{\rho} I - I)} = (t,s) S \]

The Chan-Paton factors:

\[ T_{1234} \propto \text{tr} (\lambda_{1} \lambda_{2} \lambda_{3} \lambda_{4}) + \text{tr} (\lambda_{4} \lambda_{3} \lambda_{2} \lambda_{1}) \]

Model-dependent (on the SM embedding).

The color-ordered kinematical factors:

\[ A_{1234} = A^{(s,t,n)} \]

String scattering amplitude

\[ \text{String resonances at poles:} \]

\[ \text{The Veneziano amplitude} \]

\[ \text{The Chan-Paton factors} \]

\[ \text{The color-ordered kinematical factors} \]

\[ \text{The Chan-Paton factors:} \]

\[ T_{1234} \propto \text{tr} (\lambda_{1} \lambda_{2} \lambda_{3} \lambda_{4}) + \text{tr} (\lambda_{4} \lambda_{3} \lambda_{2} \lambda_{1}) \]

\[ \text{Model-dependent (on the SM embedding).} \]

\[ \text{The Chan-Paton factors:} \]

\[ T_{1234} \propto \text{tr} (\lambda_{1} \lambda_{2} \lambda_{3} \lambda_{4}) + \text{tr} (\lambda_{4} \lambda_{3} \lambda_{2} \lambda_{1}) \]

\[ \text{The Chan-Paton factors:} \]

\[ T_{1234} \propto \text{tr} (\lambda_{1} \lambda_{2} \lambda_{3} \lambda_{4}) + \text{tr} (\lambda_{4} \lambda_{3} \lambda_{2} \lambda_{1}) \]

\[ \text{Model-dependent (on the SM embedding).} \]

\[ \text{The Chan-Paton factors:} \]

\[ T_{1234} \propto \text{tr} (\lambda_{1} \lambda_{2} \lambda_{3} \lambda_{4}) + \text{tr} (\lambda_{4} \lambda_{3} \lambda_{2} \lambda_{1}) \]

\[ \text{Model-dependent (on the SM embedding).} \]

\[ \text{The Chan-Paton factors:} \]

\[ T_{1234} \propto \text{tr} (\lambda_{1} \lambda_{2} \lambda_{3} \lambda_{4}) + \text{tr} (\lambda_{4} \lambda_{3} \lambda_{2} \lambda_{1}) \]

\[ \text{Model-dependent (on the SM embedding).} \]

\[ \text{The Chan-Paton factors:} \]

\[ T_{1234} \propto \text{tr} (\lambda_{1} \lambda_{2} \lambda_{3} \lambda_{4}) + \text{tr} (\lambda_{4} \lambda_{3} \lambda_{2} \lambda_{1}) \]

\[ \text{Model-dependent (on the SM embedding).} \]
Massless Particle Scattering in SM

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

\[ \phi(d) + \bar{\phi}(d) - \phi \equiv \langle \bar{\sigma} \rangle \]

where

\[ \langle \bar{\sigma} \rangle \equiv \sum_{\text{spinor product}} \left( \frac{g^2}{4} \right)^2 \]

\[ \langle \bar{\sigma} \rangle \equiv \sum_{\text{spinor product}} \left( \frac{g^2}{4} \right)^2 \]

\[ \langle \bar{\sigma} \rangle \equiv \sum_{\text{spinor product}} \left( \frac{g^2}{4} \right)^2 \]

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

\[ A_{1243} = \frac{-4 g^2 \langle 14 \rangle}{\langle 12 \rangle \langle 13 \rangle} \]

\[ A_{1324} = \frac{-4 g^2 \langle 14 \rangle}{\langle 13 \rangle} \]

\[ A_{1234} = \frac{-4 g^2 \langle 14 \rangle}{\langle 12 \rangle \langle 13 \rangle} \]

where \( \langle ij \rangle \equiv \psi \langle p_i \rangle \psi \langle p_j \rangle \), as a spinor product.

\[ \langle \bar{\sigma} \rangle \equiv \sum_{\text{spinor product}} \left( \frac{g^2}{4} \right)^2 \]

\[ \langle \bar{\sigma} \rangle \equiv \sum_{\text{spinor product}} \left( \frac{g^2}{4} \right)^2 \]

\[ \langle \bar{\sigma} \rangle \equiv \sum_{\text{spinor product}} \left( \frac{g^2}{4} \right)^2 \]


The weakly coupled Type IIB string theory embedded QED in $\mathcal{N}=4$ super Y-M theory:

String amplitudes are obtained, alike:

\[ T = \frac{1}{4}, \frac{1}{2}, \text{ and alike.} \]

The Chan-Paton factors are evaluated to be:

\[ \left( \begin{array}{cc} I & 0 \\ 0 & I \end{array} \right) \frac{2}{I} = \frac{2}{I} \quad , \quad \left( \begin{array}{cc} 0 & I \\ 0 & 0 \end{array} \right) \frac{\sqrt{2}}{I} = \frac{\sqrt{2}}{I} \quad , \quad \left( \begin{array}{cc} 0 & 0 \\ I & 0 \end{array} \right) \frac{\sqrt{2}}{I} = \frac{\sqrt{2}}{I} \]

with $g = e$, QED amplitudes are reproduced.
The Chan-Paton factors are evaluated to be

\[ \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \frac{2}{1} = \gamma, \quad \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \frac{2}{1} = \gamma^+, \quad \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \frac{2}{1} = \gamma^- \]

String theory, embedded QED in $\mathcal{N}=4$ super Y-M theory:

Cullen, Peskin and Perelstein (2000): took weakly coupled Type IIIB

However, it cannot be achieved to include the Full SM sector

without unwanted extra states)

\[ \frac{s}{4} \]
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).
Our approach:

Instead of constructing the Chan-Paton factors explicitly, we take them as model parameters $T_s$, to be determined instead of constructing the Chan-Paton factors explicitly.

We thus obtain open-string scattering amplitudes for zero-mode SM particles.

By construction, it leads to correct (massless) SM amplitudes at low energies.

It becomes "stringy" for $s \gg M^2_S$.

We then matching the SM amplitudes at low energies.

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

By construction, it leads to correct (massless) SM amplitudes.

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

We thus obtain open-string scattering amplitudes for zero-mode SM particles.

$s \sim M^2_S$ for $s \gg M^2_S$.
Our approach:

Instead of constructing the Chan-Paton factors explicitly, we take them as model-parameters $L_s J_s$, to be determined by matching the SM amplitudes at low energies. By constraining the Chan-Paton factors explicitly, we thus obtain open-string scattering amplitudes for SM amplitudes at $s \gg \mathcal{M}^2$. By construction, it leads to correct (massless) zero-mode SM particles. It becomes "stringy" for $s \sim \mathcal{M}^2$.

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

Our approach:

\[ \mathcal{M}_W \sim s \]\n
Cornet, Illana and Masip (2001); Friess, Han, Hooper (2002).

\[ \mathcal{M}_W \gg s \]\n
Burikham and Han, to appear.
Low Energy Constraint on $\mathcal{M}$

Consider a typical process:

Explicit stringy amplitudes

$\mathcal{M}$
Consider a typical process: 

\[ M_{\text{String}} = g^2 \left[ s t (T_{1234} - T_{1324}) + s u (T_{1243} - T_{1324}) \right] \approx M_{\text{SM}} \]

Matching the SM amplitude:

\[ \left[ (T_{1244} - 4T_{1234}L)(nL)S_{\frac{n}{s}} + 4T_{1234}L(nL)S_{\frac{n}{s}} \right] \approx 6_{\text{string}} M \]

In the low-energy limit:

\[ \left[ 4T_{1244}(sL)S_{\frac{n}{s}} + 4T_{1234}(tL)S_{\frac{n}{s}} \right] \approx 6_{\text{string}} M \]

We have:

Table\[\begin{array}{c}
  e L e L \\
  e L e L
\end{array}\]

Consider explicit stringy amplitudes.
Consider a typical process:
\[ e_L^q L \rightarrow e_L^q L \]
we have
\[ \mathcal{M}_{\text{string}} = g^2 \left[ s_t S^2(T_{1234} - T_{1324}) + s_u T_{1243} - T_{1324} \right] \]

In the low-energy limit,
\[ \mathcal{M}_{\text{string}} \approx \mathcal{M}_{\text{SM}} \]

Matching the SM amplitude:
\[ \left[ (s, n) S^4 + (n', t) S^4 + (t', s) S^4 \right] \frac{g^2}{s} e^L q^L = \mathcal{M}_{\text{SM}}\]

Low Energy Constraint on \( \mathcal{M}_{\text{string}} \)

Then
\[ \mathcal{L} + \mathcal{L} = 4 \mathcal{L}_{1234} \]
\[ \mathcal{L} \equiv \mathcal{E}_{1243} \]

Matching the SM amplitude:
\[ \left[ (s, n) S^4 + (n', t) S^4 + (t', s) S^4 \right] \frac{g^2}{s} e^L q^L \approx \mathcal{M}_{\text{SM}} \]

Explicit stringy amplitudes
Induced Contact Interactions

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

\[
\frac{S_{W}}{s} g_{s}^{6} \left( (1 s) - (1 s) - 1 \right) W \approx 6 W
\]

\[
\ldots + \frac{S_{W}}{s} g_{s}^{6} - 1 \approx (1 s) S
\]

Far below the resonance, we have

\[
\Delta M \approx S_{W} \left( W + M_{W} \right) \approx W
\]

and thus:

\[
\frac{S_{W}}{s} \left( g_{s}^{6} \right) - (1 s) W \approx 6 W
\]

\[
\ldots + \frac{S_{W}}{s} g_{s}^{6} - 1 \approx (1 s) S
\]

\[
S_{W} \approx M_{W} \approx 0.7 - 1.0 \text{ TeV}
\]
Near the resonances, 
\[ s \approx M^2 S, \]
\[ S(s,t) \approx t S(s) + \frac{\hat{S} M - s}{\hat{S}^2} \approx (t, s) S \]
\[ \frac{\hat{S} M}{2} \approx s, \]

The string resonances
The string resonances

Near the resonances, \( s \approx M_S^2 \),

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

Treat the resonances individually

\[
\mathcal{M}_{string} \approx \begin{align*}
&\ g_L^2 \left( 2Q_e Q_q \sin^2 \theta_w \frac{s}{t} + \frac{2g_L^c g_L^q}{\cos^2 \theta_w} \frac{s}{t - M_Z^2} \right) \quad \text{SM term} \\
+ &\ g_L^2 (C + 2T) \frac{s}{s - M_S^2} \quad \text{1st resonance} \\
+ &\ g_L^2 C \frac{s \cos \theta}{s - 2M_S^2} \quad \text{2nd resonance} \\
+ &\ ......
\end{align*}
\]
Near the string resonances' SM

\[
\left. \begin{array}{c}
S_{\text{Z}} \approx \frac{g^2}{\lambda s} Q_e Q_q \cos^2 \theta_w s + \frac{g L}{\lambda s} C + 2 \mathcal{B} \\
S_{\text{W}} \approx \frac{g^2}{\lambda s} Q_e Q_q \sin^2 \theta_w s + \frac{g L}{\lambda s} C + 2 \mathcal{B} \\
\end{array} \right. 
\]

Treat the resonances individually

\[
\ldots + \frac{g W^2 - s}{(1 + \frac{s W}{t}) t} + \frac{g W - s}{t} \approx (t', s) S
\]

\[
S_{\text{Z}} \approx s' \sqrt{\frac{\mathcal{F}}{\pi}}
\]

and need to include the total width

\[
\Gamma_n = \frac{g^2 L^2 \pi}{|T|} \left| \frac{T}{2} \right| + \sqrt{n M_S}.
\]
Consider the dominant process:

For the $\nu g$ process, Cornet, Illana and Masip (2001).

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

$$T \equiv L^{1234} = L^{1324} = L^{1423} = L^{1432} \Longleftrightarrow n L^{1234} + L n^{1324} + L n^{1243} = 0$$

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

$$W(\nu g \leftrightarrow \nu g) \mathcal{M}$$

Identity $(1', 2', 3', 4') \leftarrow (1, 2, 3, 4)$, we have

$$\nu g \leftarrow \nu g$$

Neutrino-Nucleon Scattering
Consider the dominant process:

\[ \nu g \rightarrow \nu g \]

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

\[ M(\nu L \rightarrow \nu L) = -4g^2 \frac{1}{s} \times [\nu S(s,t)T_{124} + \nu S(s,t)T_{1324} + \nu S(s,t)T_{1243}] \]

Identify \((\nu, g, g) \rightarrow (1, 2, 3, 4)\), we have

Typically, \( T \sim 1/4 - 1/2 \).

Physics of the stringy states:

- in \( s \) and \( u \) channels:
  - fermionic "Lepto-gluons" \( \nu_8 \)
  - bosons in \( SU(3) \) and \( SU(2) \)? or pomeron?

*For the \( \nu g \) 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:

\[ \lim_{t \to 0} |u^0| S_{Wu}^{1 + \frac{2\nu Z}{Z_0}} = (\mathcal{G} T u \leftarrow u^{(8 \nu)}(u)) \]

Assuming the elastic channel dominant:

\[ \sum_{n} \frac{A_n}{\alpha^2_{Jn} \Delta J_n^3 / 2} \approx (\mathcal{G} T u \leftarrow 8 \nu \leftarrow \mathcal{G} T u) \]

Assuming pole-dominance (good approximation):

\[ \sum_{n} \frac{A_n}{\sqrt{n M_S}} \]

Assuming pole-dominance:

\[ \sum_{\nu, J} \frac{(\mathcal{G} T u - s)_{\nu, J} (I - u)_{\nu, J}}{I - u + \frac{\mathcal{G} T u}{\nu}} \cdot (I + \frac{\mathcal{G} T u}{\nu}) \cdot \sum_{n} \frac{A_n}{\alpha^2_{Jn} \Delta J_n^3 / 2} \approx \langle t, s \rangle \]
\[
\frac{S/\sqrt{2}Wu}{|L|^2} \equiv u_\varrho
\]

\[
(s/\sqrt{2}Wu - 1)\varrho u_\varrho = u_\varrho
\]

(We take \( m_u = 50 \), but it makes only 10% difference for 20-80.)

\[
\text{\( S/\sqrt{2}Wu = x \), the parton energy fraction.}
\]

For \( E_2 \text{cm} = S > \frac{M^2}{S} \), sum over the resonances and the partons:

\[
\sigma(\nu L N) = n_{\text{cut}} \sum_{n=1}^f \tilde{\sigma}_n(\nu L f) x f(x, Q^2) = (N f)a
\]

With narrow-width approx., the parton-level cross section is \( \sigma \) scattering cross section \( N - \nu \)
Not enough to explain UHECR near $E \sim 10^{20}$ eV.

In our convention, $u = 1.6 - 3.6$ for $d = 3 - 7$.

In our conventions, $M_S = 1$ TeV and $T = 1/2$.

The SM neutral current prediction (solid green), string state contributions (red), and the black hole production (blue dots) with 3 (upper) and 6 extra (lower) dimensions. The SM neutral current prediction (solid green), string state contributions (red), and the black hole production (blue dots) with 3 (upper) and 6 extra (lower) dimensions.
For comparison, KK graviton signals at lower energies:

Alvarezmuniz et al., hep-ph/0112247

Anchordoqui et al., hep-ph/0110057

For black hole signals at higher energies:

For lower energies:

KK graviton signals

For comparison,
HE Cosmic Neutrinos

\[ E \sim 10^{20} \text{ eV}. \]

Assumed Fluxes:

- Cosmogenic \( \bar{\nu} \) (dashed)
- Cosmogenic \( \nu \) (dotted)
- HECR off CMB
-\( \nu \) (Heiles 1997)
-\( \bar{\nu} \) (Cardaci et al. 2001)
-\( \nu \) (Kusenko 2002)
-\( \bar{\nu} \) (Weiler 2001)

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

Determining \( \nu \)-flux would be the 1st goal for HE cosmic neutrino experiments.

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

\( \int E^2 d\Phi/dE \approx 10^{-8} \text{ GeV cm}^{-2} \text{ sr}^{-1} \text{s}^{-1} \)

Avoiding the GZK bound \( E \sim 10^{20} \text{ eV} \).
HE Neutrino detectors

Auger air shower Observatory:
3000 km$^2$ fluorescence detector.
we look for quasi-horizontal air-shower events.

IceCube km$^2$ $\nu$ Detector:
icel Cerenkov detector at the South Pole.
we look for both contained and through events.

Many studies on low-gravity scale models:\textsuperscript{†} \textsuperscript{‡}

\textsuperscript{†}Nussinov and Shrock (1999); Domokos and Kovesi-Domokos (1999); Jain \textit{et al.}, (2000); Alvarez-Muniz \textit{et al.}, (2002).
\textsuperscript{‡}Feng and Shapere (2002); Emparan \textit{et al.}, (2002); Ringwald and Tu (2002); Anchordoqui and Goldberg (2002).

Our results from string resonances:

<table>
<thead>
<tr>
<th>WB Flux</th>
<th>Auger (events/yr)</th>
<th>IceCube (events/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_S = 2 \text{ TeV}$</td>
<td>$W_{th} = 250 \text{ TeV}$</td>
<td></td>
</tr>
<tr>
<td>$M_S = 1 \text{ TeV}$</td>
<td>$W_{th} = 10 \text{ PeV}$</td>
<td></td>
</tr>
</tbody>
</table>

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

  - Auger: less sensitive to fluxes;
**Summary**

- **At low energies:** 
  \[ \frac{1}{R} \ll E \ll M_{\text{Pl}}, \quad M_{\text{Pl}} \sim \frac{1}{R} \]

  Gravity effects observable, mainly via light KK gravitons of mass \( m_{KK} \sim \frac{1}{R} \).

- **At "trans Planckian" energies:** 
  \[ E > M_{\text{Pl}}, \quad M_{\text{Pl}} > M_{\text{S}} \]

  Gravity effects observable, mainly via light KK gravitons.

- **Near the string scale:** 
  \[ E \sim \frac{1}{M_{\text{Pl}}}, \quad M_{\text{Pl}} \sim \frac{1}{R} \]

  String resonances dominant.
With $M_S \approx 1 \text{TeV}$ and $R$ (possibly) large,

- At low energies: $E \ll M_S$ and $R$ (possibly) large, gravity effects observable, mainly via light KK gravitons of mass $m_{KK} \sim \frac{1}{R}$.

- At trans-Planckian energies: $M_P \ll M_S$, gravity effects observable, mainly via light KK gravitons of mass $m_{KK} \sim \frac{1}{R}$.

- At near the string scale: $E \sim M_S$, gravity effects dominant (mainly) via black hole production.

We constructed the open-string amplitudes

- string-resonances dominant.

$\Delta$ applied to $b - a$ cosmic neutrinos: $E \sim M_S$. $\Delta$ the low-energy constraints not severe (yet).

$\Delta$ reproduce the SM particle amplitudes at low energies.

$\Delta$ we constructed the open-string amplitudes

Summary

$\Delta$ cosmic neutrinos: $E \sim M_S$.

$\Delta$ cosmic neutrinos: $E \sim M_S$.
With $M \sim 1\text{TeV}$ and $R$ possibly large,

**Summary**

- **At low energies:** $1/R < E \ll M_{\text{S}}$, gravity effects observable, mainly via light KK gravitons of mass $m_{\text{KK}} \sim 1/R$.
- **At trans Planckian energies:** $M_{\text{P}} \ll E < M_{\text{D}}, M_{\text{S}}$, string resonances dominant, mainly via black hole production.
- **At very high energies:** $E \gg M_{\text{S}}$, gravity effects observable, mainly via high KK gravitons or mass $m_{\text{KK}} \sim 1/R$.

We constructed the open-string amplitudes

- **Nearest the string scale:** $M_{\text{P}}, M_{\text{S}} \ll E \sim M_{\text{D}}, M_{\text{S}}$.
- **More to do:**
  - Explore the theoretical construction/embodiment for SM particles.
  - Explore the effects of gravity, effects (close-string, loops).
  - More collider consequences in details.
  - Applied to cosmic neutrinos: $b - \tau$.
  - The low-energy constraints not severe (yet).
  - Reproduce the SM particle amplitudes at low energies.
  - The signal observation promising in the near future.

We constructed the open-string amplitudes