Alternative Signature of TeV Strings

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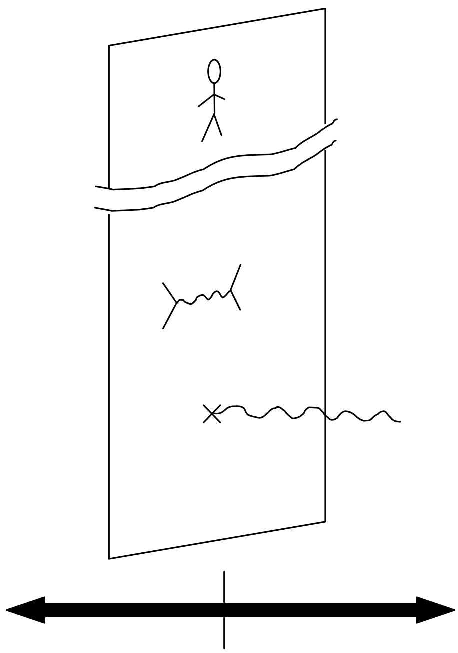
- Introduction
  - Large Extra Dimensions
  - Signature of TeV strings
    1. Regge resonances
    2. BH/SB production
    3. OURS!
- Our prediction
  - Hard scattering amplitudes in string theory
  - Stringy form factors in TeV scale string theory
  - Exponential suppression of high p_T jet productions in LHC.
- Conclusions & Discussions

Large extra dimensions

(Arkani-Hamed, Dimopoulos & Dvali '98)



- We are living in 3-brane in (4+n)-dim
- SM fields are trapped on the brane
- Only gravity may propagate in bulk

L∼mm-fm
for n=2-6 large dimensions.

L: size of extra dimension
M_P: 4-dimensional Planck scale
M: (4+n)-dim Planck scale

Gauss law → $M^{2+n} = M_P^{\,2}\, L^{-n}$

free! ← exp free

Fundamental gravitational scale may be as low as M ∼ TeV!

- Accessible!!
- Solution to the hierarchy m_{Higgs}/M_P

Extra dimensions are **not** new.

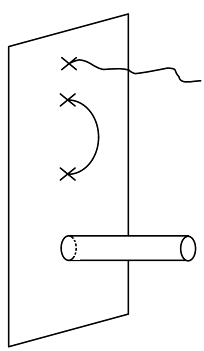
- It was proposed **20 years ago**.

  (Rubakov & Shaposhnikov ’83,“Do we live inside a domain wall?”; also, Antoniadis ’90, “A possible new dimension at a few TeV.”)

- However, just putting **δ** -functions in the (higher-dim) action **by hand** does not look very nice.

↓ (…years of silence…)

- Discovery of D-branes in **string theory** nicely provided theoretical background (Polchinski ’95).



D-brane:

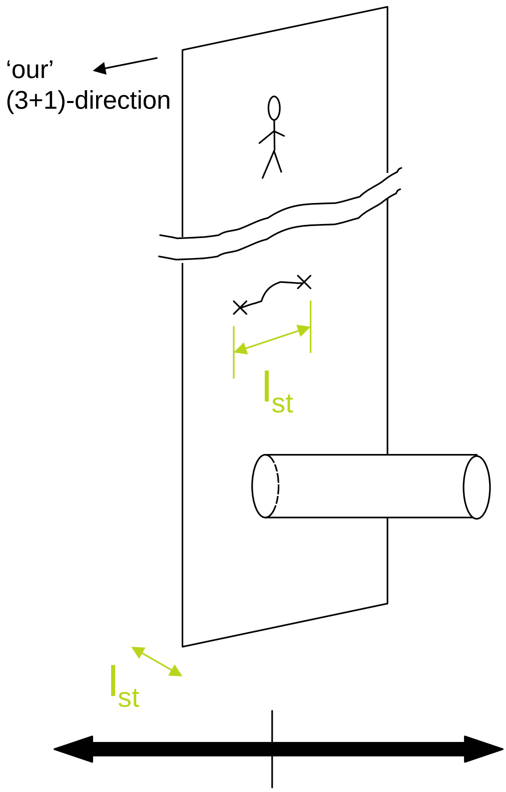
a dynamical object on which strings can end;

(or in other words, collection of open string end points)

Only string theory can supply the basis.
→ It is important to consider string realization of large extra dimension.

TeV scale string theory

(Antoniadis, Arkani-Hamed, Dimopoulos & Dvali '98)



$L \sim 10^3 \times l_{st}$

- We are living in the D3-brane.
- SM fields = massless modes of open strings
- gravitons = massless modes of closed strings

$l_{st} = (\alpha')^{1/2}$: string length $\sim (\mathrm{TeV})^{-1}$

Simplest case:

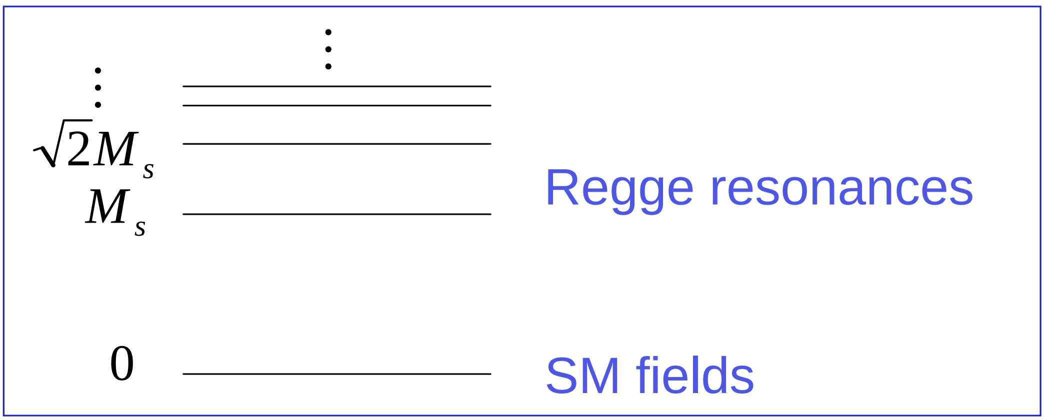
- 6 spatial dimension:
  compactified with $L \sim$ fm
- our (3+1)-dim:
  not compactified (or compactified with lengh scale larger than the Universe)

Note: **The only difference** (with conventional scenario) is the **compactification scale**, which is **totally free parameter!**

Signatures of TeV strings

1. String massive modes (Regge resonances)

(Dudas & Mourad '99,
Accomando, Antoniadis & Benakli '99,
Cullen, Perelstein & Peskin '00)



○ direct observation (determines M_s)

✕ **difficult to exclude other possibilities**
(especially in hadron colliders such as LHC)

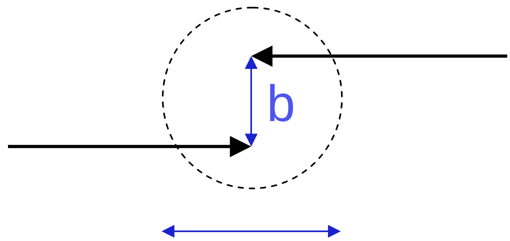
e.g. "techni-hadrons" or other exited states
from **other field theoretical models**
such as
technicolor or preon (sub-quark) models

↓

Complementary signature WANTED

2. Black hole production (at LHC)

(Giddings & Thomas ’01, Dimopoulos & Landsberg ’01)



R_S: Schwarzshcild radius of the BH with $M_{\mathrm{BH}} = \sqrt{\hat{s}}$

BH is produced whenever $b < R_S$?
→ Production cross section of BH is πR_S^2?

This claim is based on the classical hoop conjecture applied to quantum process of parton scatterings.

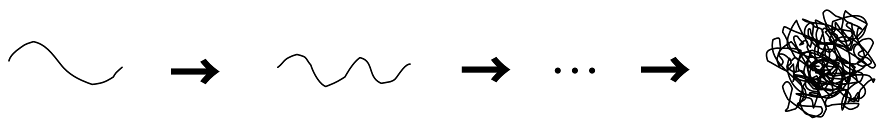
Still being debated.

- Voloshin ’01
  - cross section: exponentially suppressed by exp[-(Euclidian action)].
  - CPT therem tell us that “few partons→BH” is rare because “BH→few partons” is rare.
- Giddings ’01
  - Classically allowed process is not suppressed.
  - T-conjugate of BH should be white hall!
- Voloshin ’01
  - πR_S^2 would lead to exponentially growing cross section (with energy) due to many “small” BH productions.

Not yet established.

Stringy justification of BH formation

(Dimopoulos & Emparan '01)

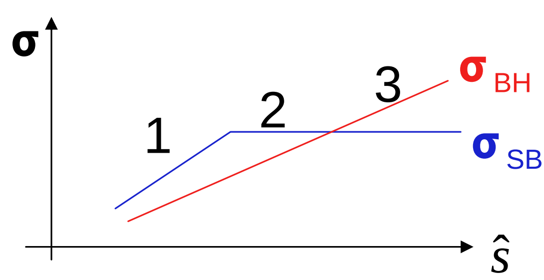


Highly excited string state is …… string ball!

- String ball is believed to behave similarly (or identically) to BHs.
- Correspondence between BH and massive string state is confirmed in entropy counting.

(Horowitz & Polchinski '96 '97)

1. Production cross section of string massive mode (i.e. string ball) is obtained by applying **optical theorem** to the **tree level** string amplitude. → $\sigma_{\mathrm{SB}} \propto \hat{s}$
2. As we raise $\hat{s}$, $\boldsymbol{\sigma}_{\mathrm{SB}}$ hits **unitarity bound**, above which $\boldsymbol{\sigma}_{\mathrm{SB}}$ is (claimed to be) **constant**.
3. As we raise energy further, production cross section of BH $\propto \hat{s}^{1/n+1}$ becomes bigger than $\boldsymbol{\sigma}_{\mathrm{SB}}$ (at some **correspondent point**). BH picture is (claimed to be) valid above it.



Difficulties:

- There are **no evidence** of the correspondence for dynamical process (S-matrix).
- Black hole formation is non-perturbative process while string massive mode production may be calculated at the tree level.

↓

- Deeper understanding of the correspondence is required.

In summary:

Alternative and complementary signature to Regge resonance, SB or BH production WANTED

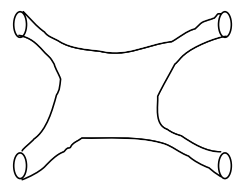
3. Exponential suppression of high p_T jet production (OURS)

Hard scatterings in string theory

(Gross & Mende '87, '88)

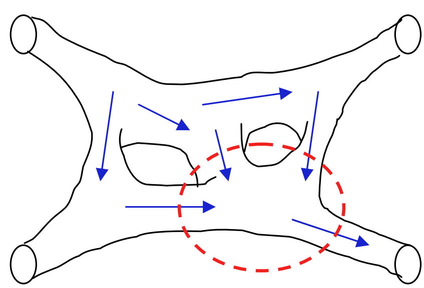
We can explicitly calculate and show that any **tree level** cross sections are **exponentially suppressed** in the high energy limit $s \to \infty$.

$$A \sim \exp[-s/M_s^2]$$



Therefore, higher order amplitude are dominated by processes where momentum transfer is **divided equally**.

→ All sub-processes are hard.



→ We may use saddle point method to obtain

$$A(s,t) \sim \exp[-\frac{s}{M_s^2} f(\theta)/N]$$

at the N-th order perturbation.

$$\boxed{0 < f(\theta) < O(1), \quad f(0) = f(\pi) = 0}$$

$$\boxed{\sin^2(\theta/2) = -t/s}$$

Universal behavior

$$A(s,t) \sim \exp[-\frac{s}{M_s^2} f(\theta)/N]$$

$\boxed{0 < f(\theta) < O(1), \quad f(0) = f(\pi) = 0}$ $\boxed{\sin^2(\theta/2) = -t/s}$

- Regge region ($\theta \sim 0$) is not exponentially suppressed.
  $\rightarrow$ We have to see hard scattering region,
  i.e. high p_T region $\theta \sim \pi/2$
  to see this effect.

- This behavior is independent of
  - the theory (bosonic, super, hetero etc.)
  - the external states (of the scattering)
  - the perturbative vacuum.

- The origin of this universality is that the integrand is controlled by the plane wave part of the vertex operator, exp[ipX].

- The series of leading terms in this limit $A \sim \exp[-s/N]$ is badly divergent.

Borel resummation

(Mende & Ooguri '90)

- It is possible to give **finite result** resummed to **all orders**:

$$A(s,t) \sim \exp[-\sqrt{\frac{s}{M_s^2}}\, f(\theta)]$$

by Borel transform techniques (inserting

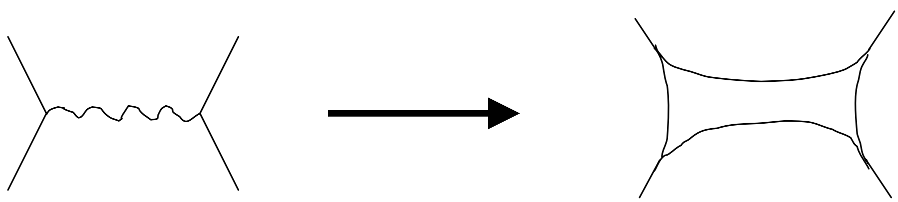
$$1 = \frac{1}{(10N)!}\int_0^\infty dt\, t^{10N} e^{-t}$$

in the sum).

Stringy form factors in TeV scale string theory

- At the tree level, it is shown that **every** SM amplitudes is multiplied by a **common** stringy form factor.

(Cullen, M. Perelstein & Peskin ’00)

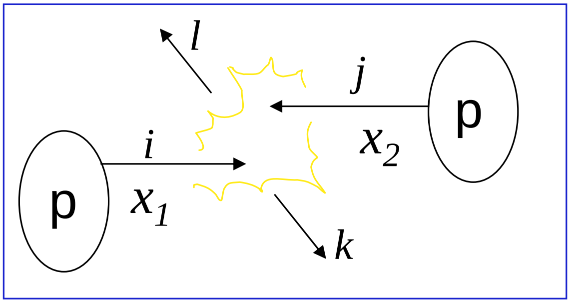


$$\left.\frac{d\sigma}{dt}\right|_{\mathrm{FT}} \qquad\qquad \left.\frac{d\sigma}{dt}\right|_{\mathrm{FT}} \times \left|A(s,t)\right|^2$$

We estimate the suppression effect using the resummed factor:

$$A(s,t) = \exp[-\sqrt{\frac{s}{M_s^2} f(\theta)}]$$

QCD jet production rate



$$\hat{s} = x_1 x_2 s$$

x_1 (x_2): momentum fraction carried by *i (j)*-parton.

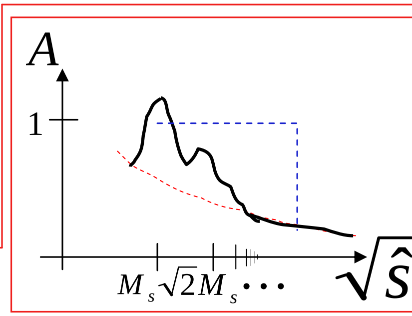
i,j,k,l: quark & gluon flavor

$$\sigma_{[p_T, p_T+\Delta p_T]}(s) =$$

$$\int_0^1 dx_1 \int_0^1 dx_2 \int_{(p_T, \Delta p_T, \hat{s})} d\hat{t}$$

$$\times \sum_{ijkl} \frac{1}{1+\delta_{kl}} f_i[x_1, Q_{(\hat{s},\hat{t})}] f_j[x_2, Q_{(\hat{s},\hat{t})}]$$

$$\times \left. \frac{d\hat{\sigma}_{ij\to kl}(\hat{s},\hat{t})}{d\hat{t}} \right|_{\mathrm{SM}} \left| A_{(\hat{s},\hat{t})} \right|^2$$



We adopt

$$\begin{cases} A(\hat{s},\hat{t}) = 1 & \text{for } \hat{s} < 10 M_s^2 \\ A(\hat{s},\hat{t}) = \exp\left[-\sqrt{\dfrac{\hat{s}}{M_s^2}}\, f(\theta)\right] & \text{for } \hat{s} \geq 10 M_s^2 \end{cases}$$

to avoid overestimating the suppression.

Conclusions

- High p_T jet productions are dramatically suppressed at LHC if $M_s < 2$ TeV. (Sufficient to be observed in the 1st year running!)
- This universal prediction of TeV scale string theory will confirm that preceding resonance observation is truly stringy.

Discussions

- Universal behavior → Leptons colliders will see stringy factor better.
- What happens if extra-dim is warped?
  (Polchinski & Strassler '01 claims power law damping.)
- Correspondence with BH production?
  Final radiation:
  BH → isotropic
  strings → concentrated on beam axis
  since **Regge region** is least suppressed.