Low scale strings and photon jets at the LHC

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- **D-branes and all that**
- **Extra $U(1)$'s in D-brane constructions**
- **Photons and gluons as quiver neighbors**
- **Jet tests at LHC**

L. Anchordoqui, HG, T. Taylor, S. Nawata, arXiv:0712.0386 [hep-ph]

TeV scale strings

- **Large extra spatial dimensions and D-brane constructs allow**

→ **low string scale compatible with weak 4-D gravity**

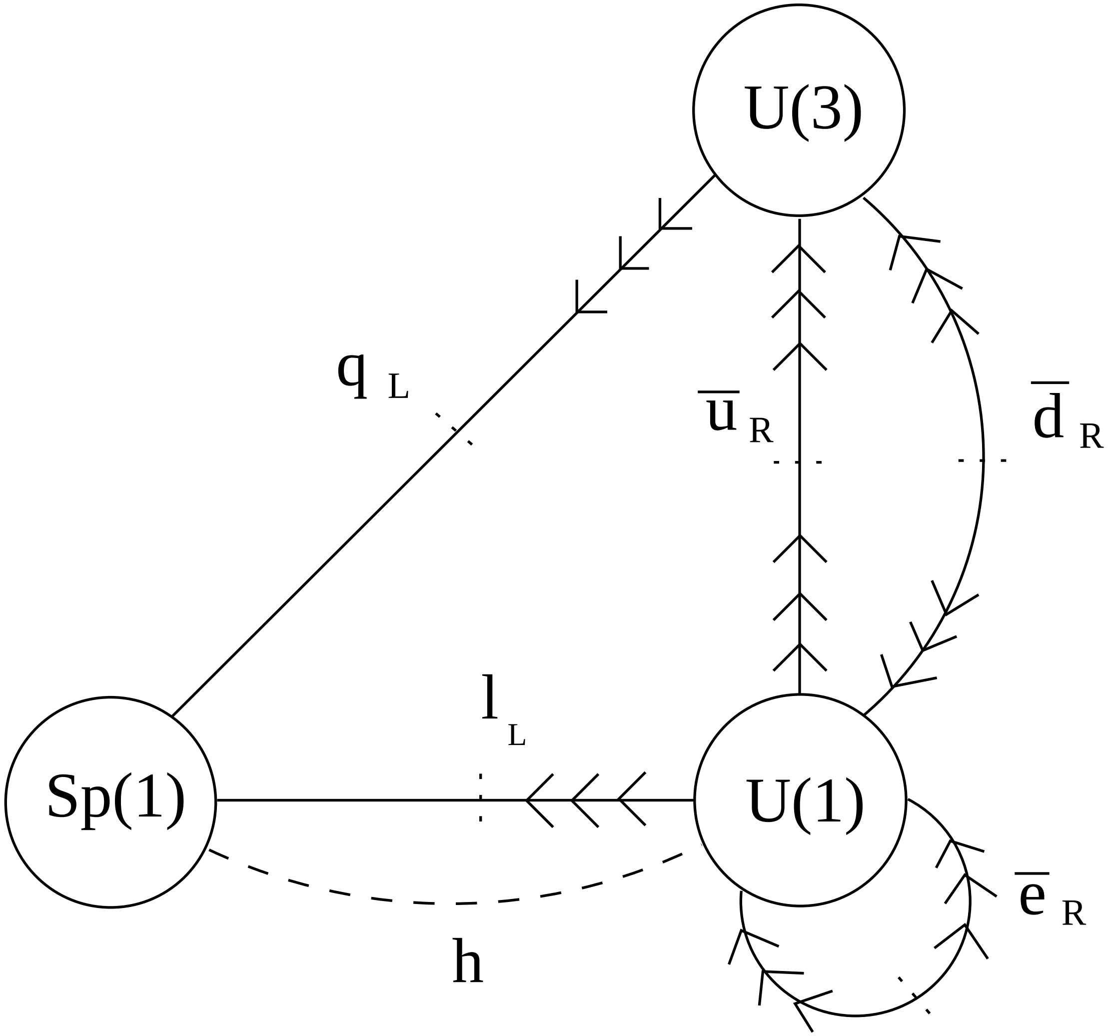
$$M_{\mathrm{Pl}}^2 \sim M_s^2\,(M_s R)^n$$

→ **Regge recurrences in TeV region**

- **Open strings can terminate on stack of N identical D branes**

→ **$U(N)$ gauge group for each stack** [Polchinski]

Quivers



Berenstein, Pinansky, hep-th/0610104; Antoniadis et al, hep-ph/0004214

Gauge fields

- $U(3)$: 8 $SU(3)$ gluons, additional $U(1)$ (C_μ) coupled to baryon number
- $U(2)$: 3 $SU(2)$ $W's$, additional $U(1)$ (X_μ)
- $U(1)$: another extra $U(1)$ (B_μ)

Y_μ (hypercharge) = linear comb of C_μ, X_μ, B_μ

Conversely,

$$C_\mu = \kappa\, Y_\mu + \dots$$

Gauging baryon number

- If left unbroken, long range force coupled to baryon number – violation of principle of equivalence (among other problems)

- If broken via a Higgs mechanism, break global baryon number at TeV scale → fast proton decay

- In string theory, $B_{\mu\nu}$ Kalb-Ramond fields which couple to U(1) gauge fields (Green-Schwarz)→ massive gauge boson, global baryon number preserved

  [for review, see Ghilencea,Ibanez,Irges,Quevedo]

$\boxed{gg \to \gamma g}$

- Does not exist at tree level in field theory
- But does exist at “tree (i.e. disk) level in string theory
- Involves only gauge bosons, so is independent of the fermion embeddings
- Idea is that

$$\begin{aligned}\mathcal{M}(gg \to \gamma g) &= \sin\theta_W\ \mathcal{M}(gg \to Yg) \\ &= \kappa\ \sin\theta_W\ \mathcal{M}(gg \to Cg)\end{aligned}$$

Amplitudes

The basic string partial amplitude is [Stieberger and Taylor]

$$A(1^-,2^-,3^+,4^+) = 2\,g^2\,\mathrm{Tr}\;(T^{a_1}T^{a_2}T^{a_3}T^{a_4}) \cdot \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 41\rangle} V(k_1,k_2,k_3,k_4)$$

where

$$V(k_1,k_2,k_3,k_4) = \Gamma(1-s)\;\Gamma(1-u)/\Gamma(1+t)$$

$$\langle ij\rangle = \bar{u}_L(k_i)u_R(k_j)$$

- Chan-Paton factors are fixed- they could not have been obtained by reference to field theory!
- Reflects $\mathcal{O}(g)$ coupling to resonances

Squared average

Now permute, square, sum, average, and project onto photon:

$$
\begin{aligned}
|\mathcal{M}(gg \to g\gamma)|^2 &= g^4 Q^2 C(N) \\
&\cdot \left\{ \left| \frac{s\mu(s,t,u)}{u} + \frac{s\mu(s,u,t)}{t} \right|^2 \right. \\
&+ \left. (s \leftrightarrow t) + (s \leftrightarrow u) \right\}
\end{aligned}
$$

- $\mu(s,t,u) = \Gamma(1-u)\left(\frac{\Gamma(1-s)}{\Gamma(1+t)} - \frac{\Gamma(1-t)}{\Gamma(1+s)}\right)$
- $Q^2 = \frac{1}{6}\,\kappa^2\,\sin^2\theta_W$
- $C(N) = \frac{(N^2-4)}{2N(N^2-1)}$

Limiting cases

At low energies $s, t, u \ll M_s^2$

$$|\mathcal{M}(gg \to g\gamma)|^2 \;\approx\; g^4\, Q^2\, C(N)\, \frac{\pi^4}{4M_s^8}(s^4+t^4+u^4)$$

Note that (unwanted) zero mass poles have cancelled - not trivial! Usually implemented by hand through choice of Chan-Paton factor.

(see, however, Cullen et al., hep-ph/0001166) Other work on colliders:
P. Burikham et al.,hep-ph/0411094; P. Meade, L. Randall, arXiv:0708.3017.

Near string threshold $s \approx M_s^2$

$$|\mathcal{M}(gg \to g\gamma)|^2 \approx 4g^4Q^2C(N)\frac{M_s^8 + t^4 + u^4}{M_s^4[(s - M_s^2)^2 + (\Gamma M_s)^2]}$$

Phenomenology

- At collider, resonance formation and decay will populate the high p_T region

- SM processes for $pp \longrightarrow \gamma + jet$

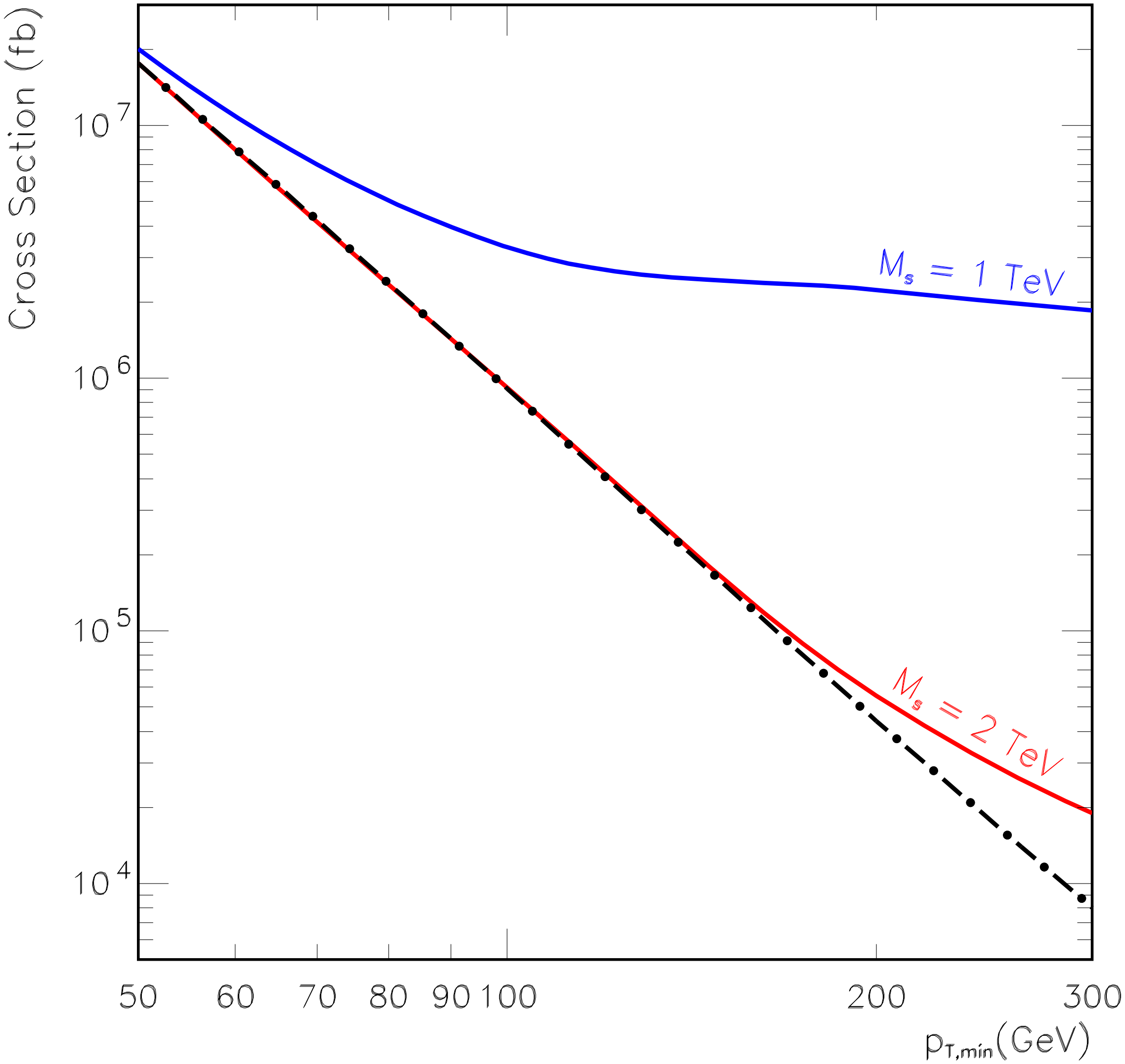
$$gq \longrightarrow \gamma q, \qquad g\bar{q} \longrightarrow \gamma\bar{q} \qquad q\bar{q} \longrightarrow \gamma g$$

lead to rapid $\sim p_T^{-5}$ falloff

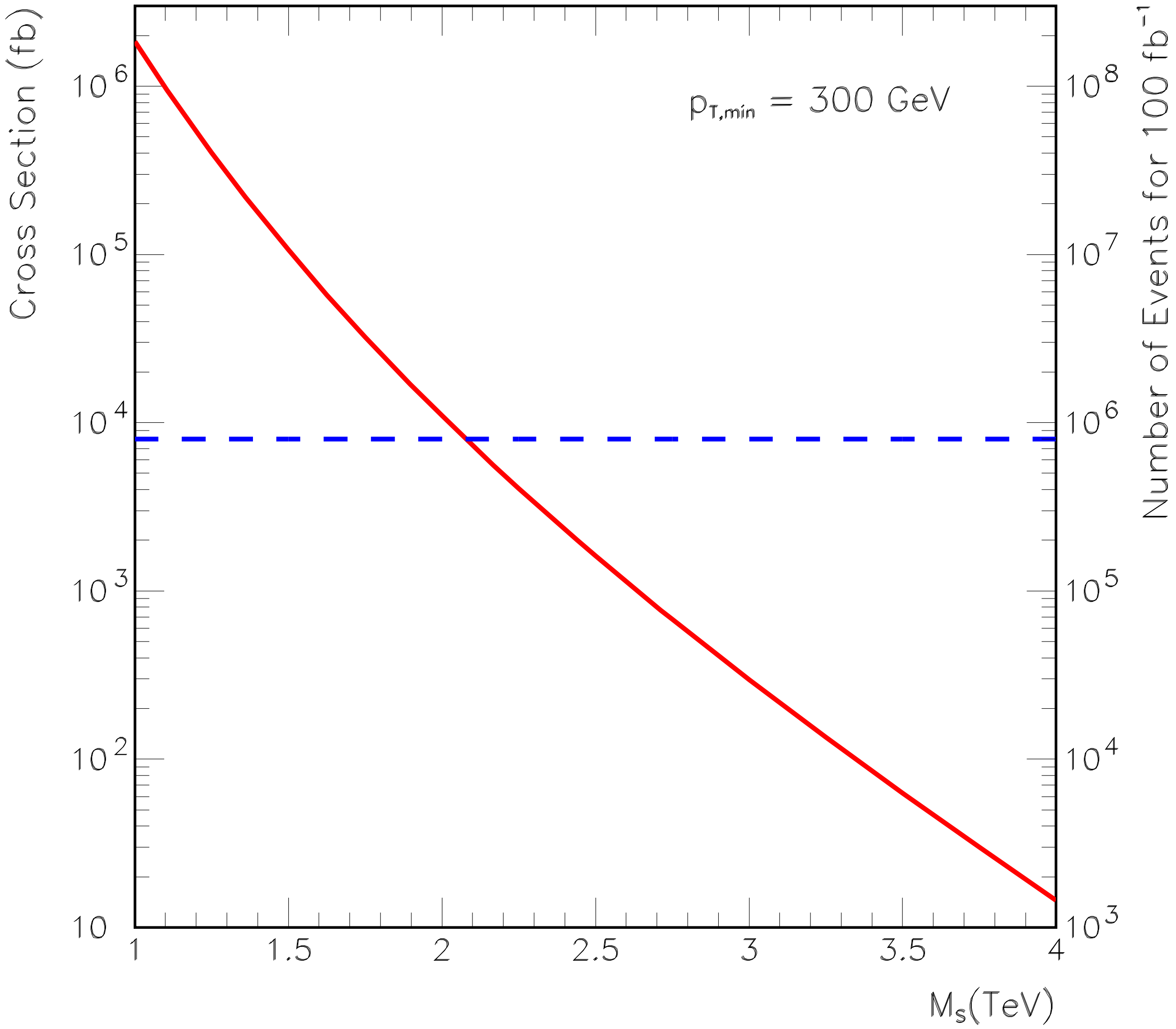
- Take as our signal N_{ev} above SM background for integrated cross section

$$\sigma(pp \longrightarrow \gamma + jet)|_{p_{\mathrm{T}}(\gamma) > p_{\mathrm{T,min}}}$$

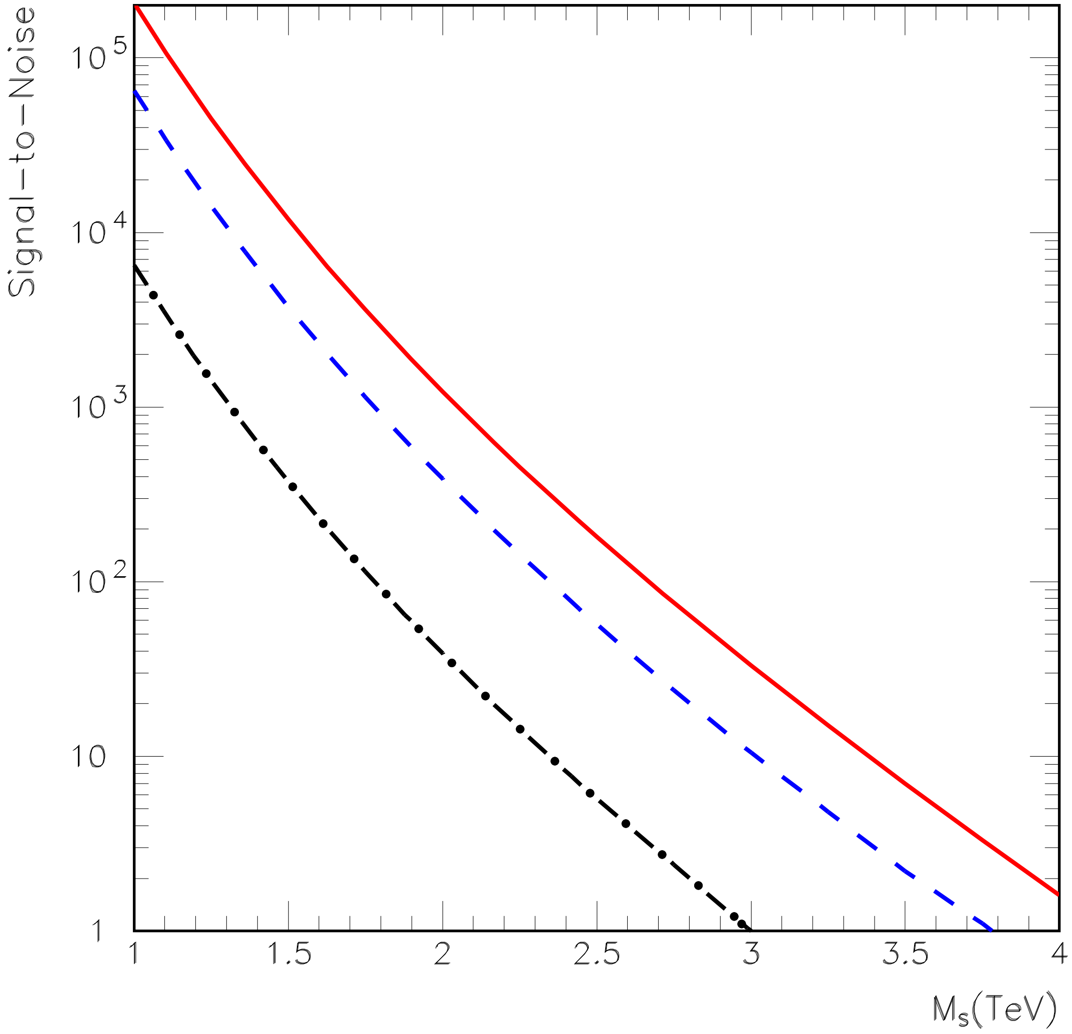
σ vs. $p_{\mathrm{T,min}}$



$N_{ev}/100\ \mathrm{fb}^{-1}$ vs. M_s



Signal-to-noise



$(\kappa^2, \text{eff}) = (0.1, 100\%)$; $(\kappa^2, \text{eff}) = (0.1, 10\%)$; $(\kappa^2,\text{eff}) = (0.01, 10\%)$

Remarks and Conclusions

- We have identified a tree-level process unique to strings, independent of embedding
- Discovery of TeV-scale string physics (at 5σ) possible for $M_s \leq 3.2$ TeV, with 10% $C - Y$ mixing, 10% γ detection efficiency
- Results are conservative in that
  - string corrections to SM processes not included
  - contribution from tails of higher resonances not included
- Future work: $pp \rightarrow Z + jet$; stringy corrections to SM processes.