Low scale strings and dijets at the LHC

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- **D-branes and all that**
- **Regge vs. KK or winding modes**
- **Dijet signals at the LHC**

L. Anchordoqui, HG, D. Lüst, S. Nawata, S. Stieberger, T. Taylor,
PRL 101, 241803 (2008)

TeV scale strings

- Large extra spatial dimensions and D-brane constructs allow

$\longrightarrow$ low string scale compatible with weak 4-D gravity – in toroidal compactification

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

$\longrightarrow$ Regge recurrences in TeV region

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

$\longrightarrow$ $U(N)$ gauge group for each stack if images under orientifolding are different from themselves

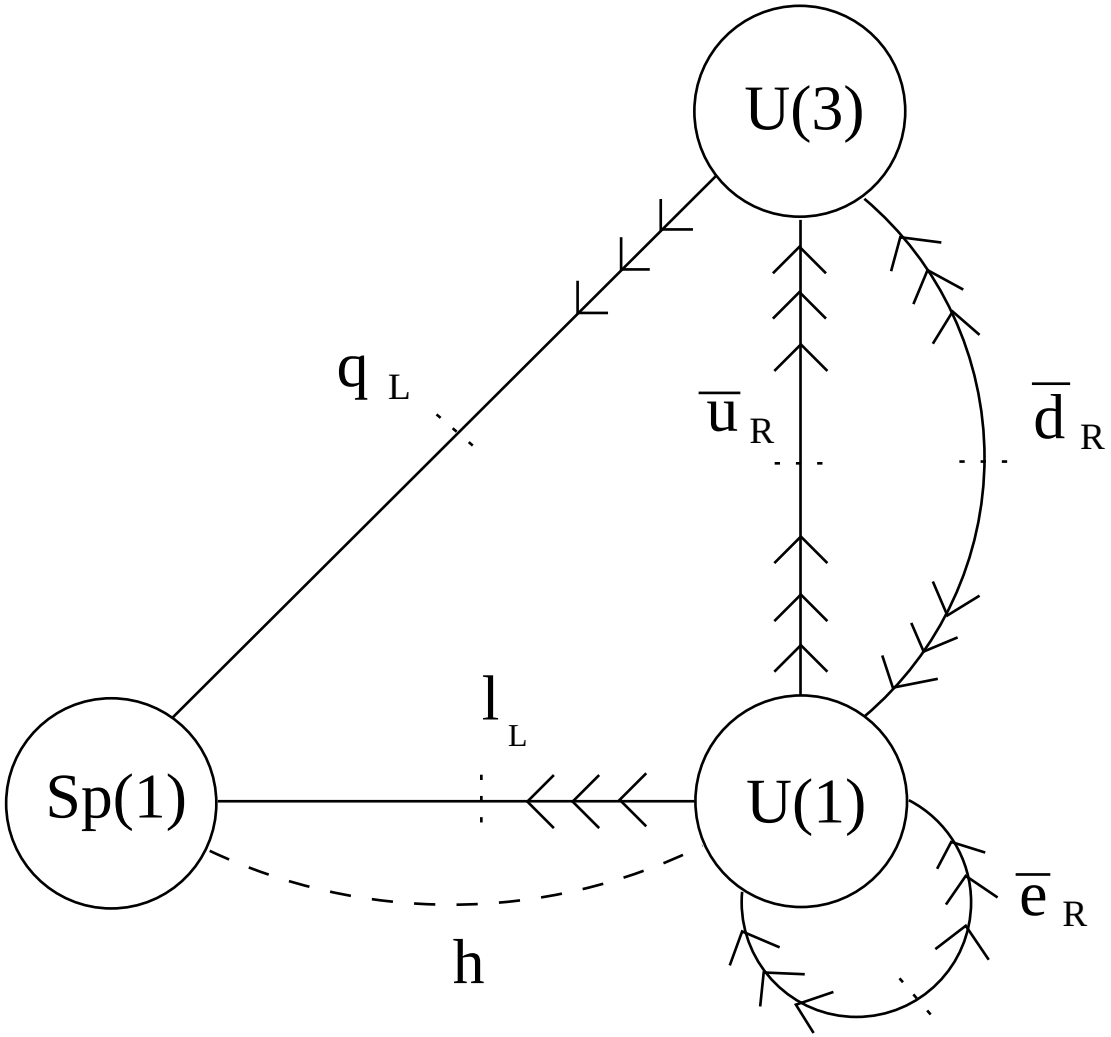
TeV scale strings (cont'd)

$\rightarrow$ $Sp(N)$ or $SO(N)$ gauge group for each stack if they self-image under orientifolding

- Matter fields are in bifundamental representations (N_a, N_b) or $(N_a, \bar{N}_b)$ located at intersections of D-branes

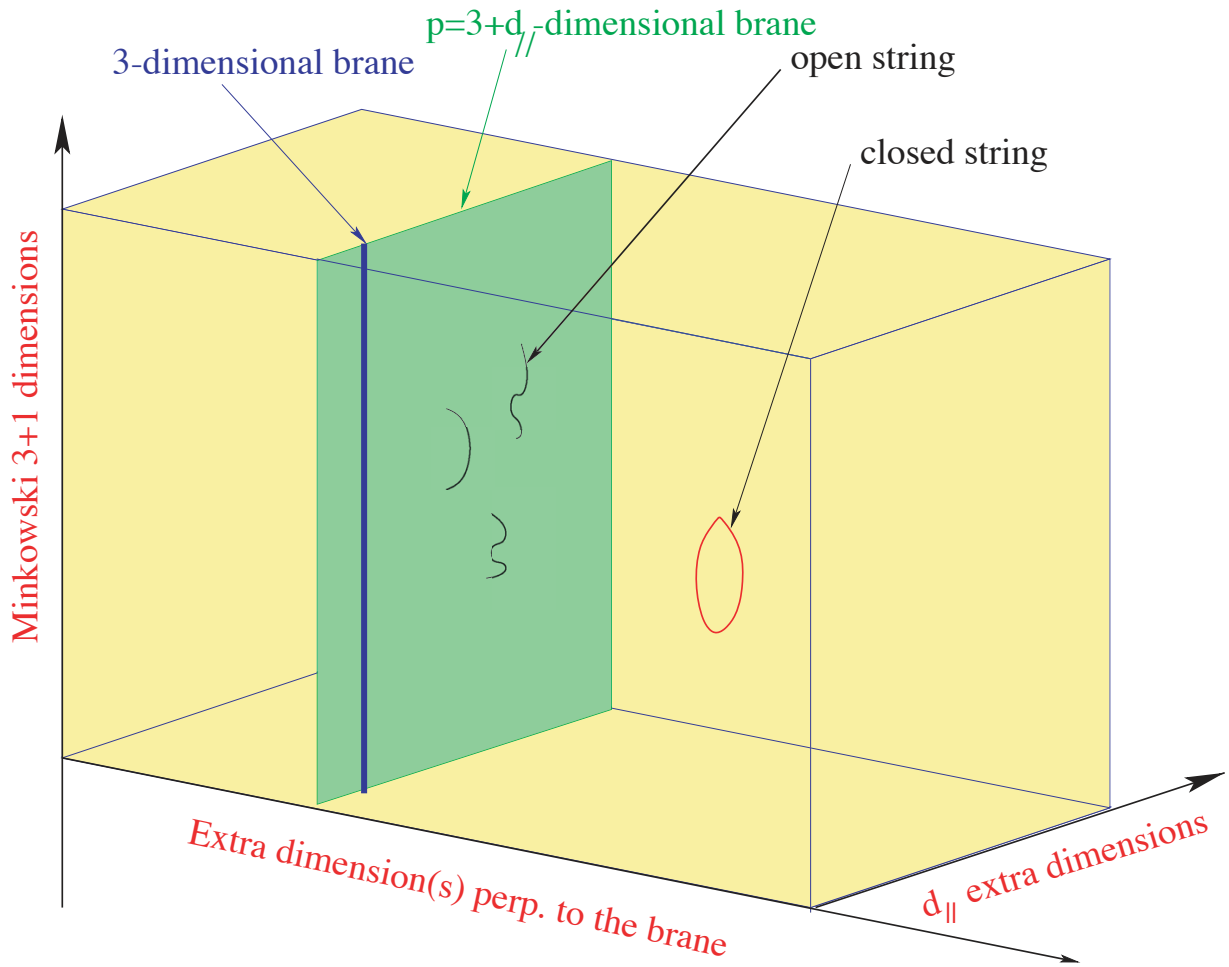
- Regge vs. KK/winding modes

Quivers



Berenstein, Pinansky, [hep-th/0610104]; Antoniadis, Kiritsis, Tomaras, [hep-ph/0004214]

Parallel and perpendicular extra dimensions



Antoniadis [hep-th/0710.4267]

Gauge fields

- $U(3)$: 8 $SU(3)$ gluons, additional $U(1)$ (C_μ) coupled to baryon number with strength $g_3/\sqrt{6}$
- $U(2)$: 3 $SU(2)$ $W's$, additional $U(1)$
- **Minimal:** $Sp(1)$: 3 $W's$, no additional $U(1)$
- $U(1)$: another $U(1)$ (B_μ)

Y_μ (hypercharge) $=$ linear combination of C_μ and other U(1)'s

Charge assignments, anomalies

- With Q_B assignments $(0, -1, 1, 1, 2)$ for $(q_L,\ u_R,\ d_R,\ \ell_L,\ e_R)$, the hypercharge

$$Q_Y = \tfrac{1}{6}\, Q_{U(3)} - \tfrac{1}{2}\, Q_{U(1)}$$

  is free of gauge and mixed anomalies.

- The orthogonal charges $Q_{Y'}$ suffer from anomalies

- Cancel via Green-Schwartz mechanism - coupling $\eta F \wedge F$ to RR closed string two-form field

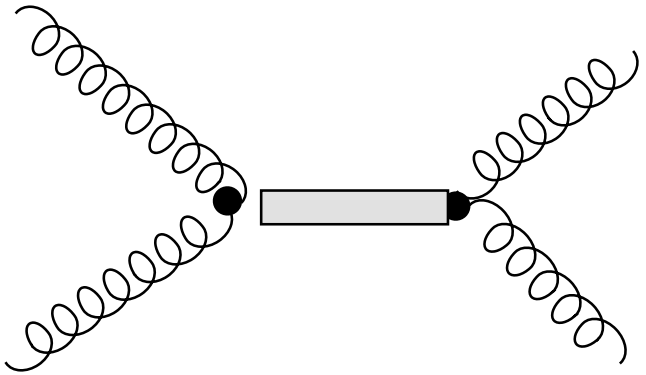
Gauging baryon number

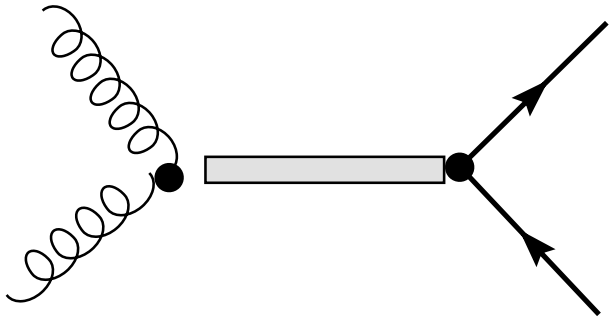
- If left unbroken, long range force coupled to baryon number – violation of everything
- If broken via a Higgs mechanism, break global baryon number at TeV scale $\longrightarrow$ fast proton decay
- Mixing $B \wedge F$ with closed string two-form $B_{\mu\nu}$ $\longrightarrow$ mass for Y', global baryon number preserved. Akin to Stückelberg mechanism
- Allows TeV BH production in νp collisions w/out violation of baryon number via BH

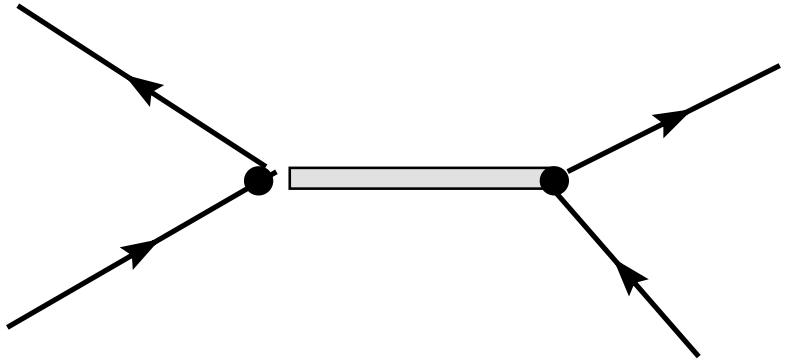
Model independence on the color brane

- Consider scattering on the U(3) brane, involving quarks and gluons
- Gluons live only on a single stack of color branes, don't see other branes
- Momentum in all the $p-3$ extra parallel dimensions conserved, so **4-point functions** $gg \longrightarrow gg,\ q\bar{q} \longrightarrow gg,\ qg \longrightarrow qg$ do not excite KK or winding modes – **only Regge recurrences independent of compactification.**
- Not so for $qq \longrightarrow qq$ – these live on intersecting branes, and parallel momentum not conserved – **KK/winding modes involved.**

QCD processes







Amplitudes

The basic string amplitude for one ordering (out of six)of 4 $U(3)$ gauge bosons is

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

where

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

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

S. Stieberger and T. R. Taylor, hep-th/0609175

Notes

- Only one basic amplitude (MHV, or Maximum Helicity Violating) Parke and Taylor, PRL 1986

- Origin is relation to single 4 scalar amplitude in $N = 2$ supersymmetry

- Obtained as scattering of open strings: insertion of 4 vector vertex functions on the boundary of the disk, which is projection of upper half plane of world sheet complex coordinate

- Similarly for $gg q\bar{q}$.

Resonant cross sections

- **Go to resonant poles at $s = M_s^2$:**
  bosonic $g^*,\ C^*,\ J = 0,\ 2$;
  fermionic $q^*,\ J = 1/2,\ 3/2$

- **Soften to Breit Wigner form, obtaining vertex functions and widths by factorizing amplitudes at the pole. Example:**

$$\begin{aligned}
\Gamma^{J=2}(g^* \to gg) &= (1/6)\ (g^2/4\pi)\ M \\
\Gamma^{J=2}(g^* \to gC) &= (2/15)\ (g^2/4\pi)\ M \\
\Gamma^{J=2}(g^* \to q\bar{q}) &= (3/20)\ (g^2/4\pi)\ M
\end{aligned}$$

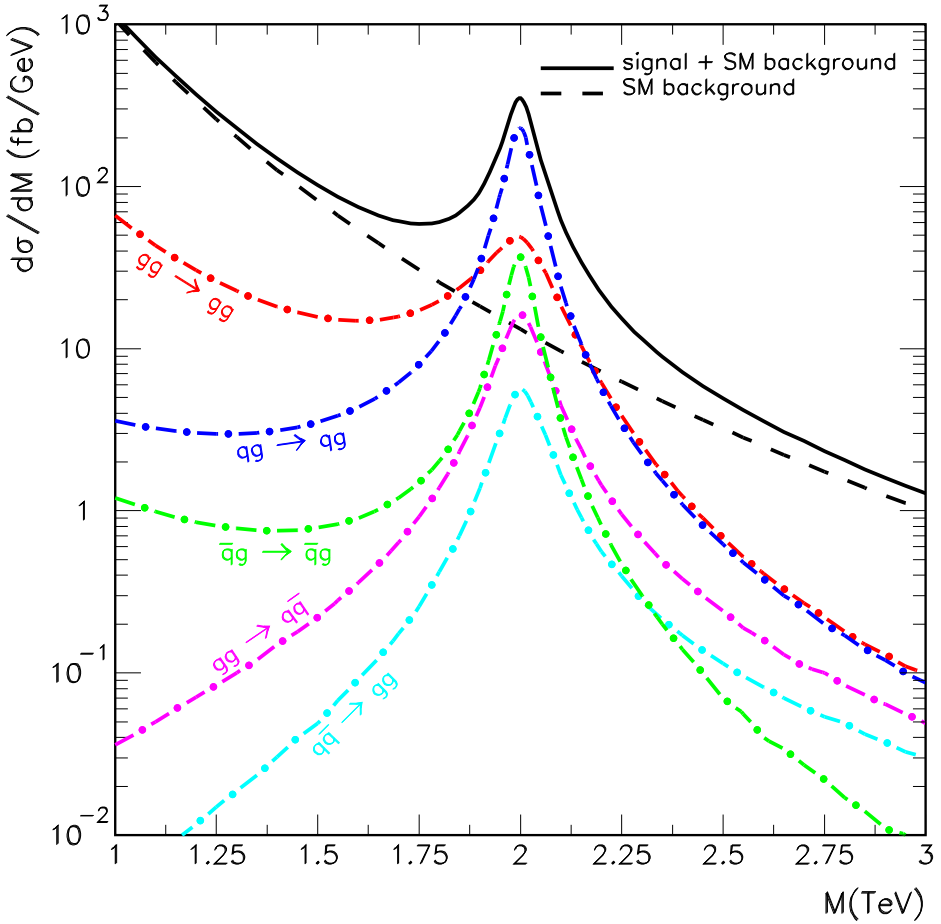
L. A. Anchordoqui, HG and T. R. Taylor, Phys. Lett. B 668, 373 (2008)

Example

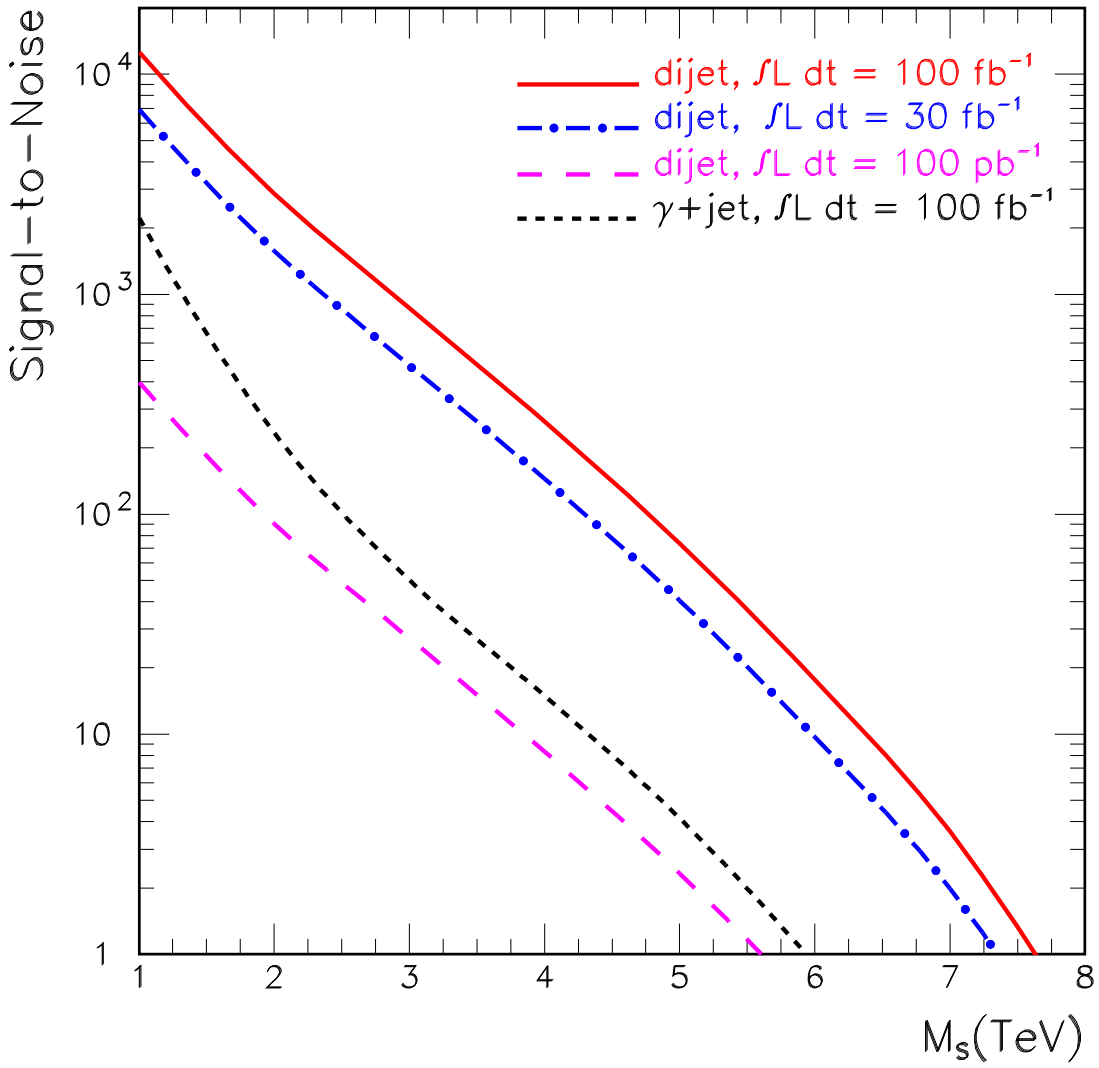
$$
\begin{aligned}
|\mathcal{M}(gg \to gg)|^2 \;=\; & \frac{19}{12}\,\frac{g^4}{M_s^4}\,\Big\{ \\
& W_{g^*}^{gg\to gg}\left[\frac{M_s^8}{(s-M_s^2)^2+(\Gamma_{g^*}^{J=0}\,M_s)^2}\right. \\
& \left.+\frac{t^4+u^4}{(s-M_s^2)^2+(\Gamma_{g^*}^{J=2}\,M_s)^2}\right] \\
& +W_{C^*}^{gg\to gg}\left[\frac{M_s^8}{(s-M_s^2)^2+(\Gamma_{C^*}^{J=0}\,M_s)^2}\right. \\
& \left.+\frac{t^4+u^4}{(s-M_s^2)^2+(\Gamma_{C^*}^{J=2}\,M_s)^2}\right]\Big\}
\end{aligned}
$$

Cuts, $d\sigma/dM$

- **Set (parton)jet rapidity cuts $|y_1|,\ |y_2| < 1$ transverse momenta $p_{1,2}^{\mathrm{T}} > 50\ \mathrm{GeV}$**



Discovery reach at LHC



Results

- **Within a few years of data collection, string scales up to 6.8 TeV open to discovery at 5σ**

- **Very early in the initial run (100 pb^{-1}) resonant mass as large 4 TeV observable at 10σ**

previous discussion of dijet TeV-scale string resonances at LHC, see P. Burikham, T. Figy, T. Han, e-Print: hep-ph/0411094

Angular distributions: the R parameter

B. Abbott *et al*[DØ Collaboration] PRL 82, 2457 (1999)

- **QCD parton-parton cross sections dominated by t-channel exchanges $\longrightarrow$dijets at large rapidity**

- **Non-standard contact interactions or excitations of resonances $\longrightarrow$ more isotropic distribution $\longrightarrow$ more uniform distribution in rapidity.**

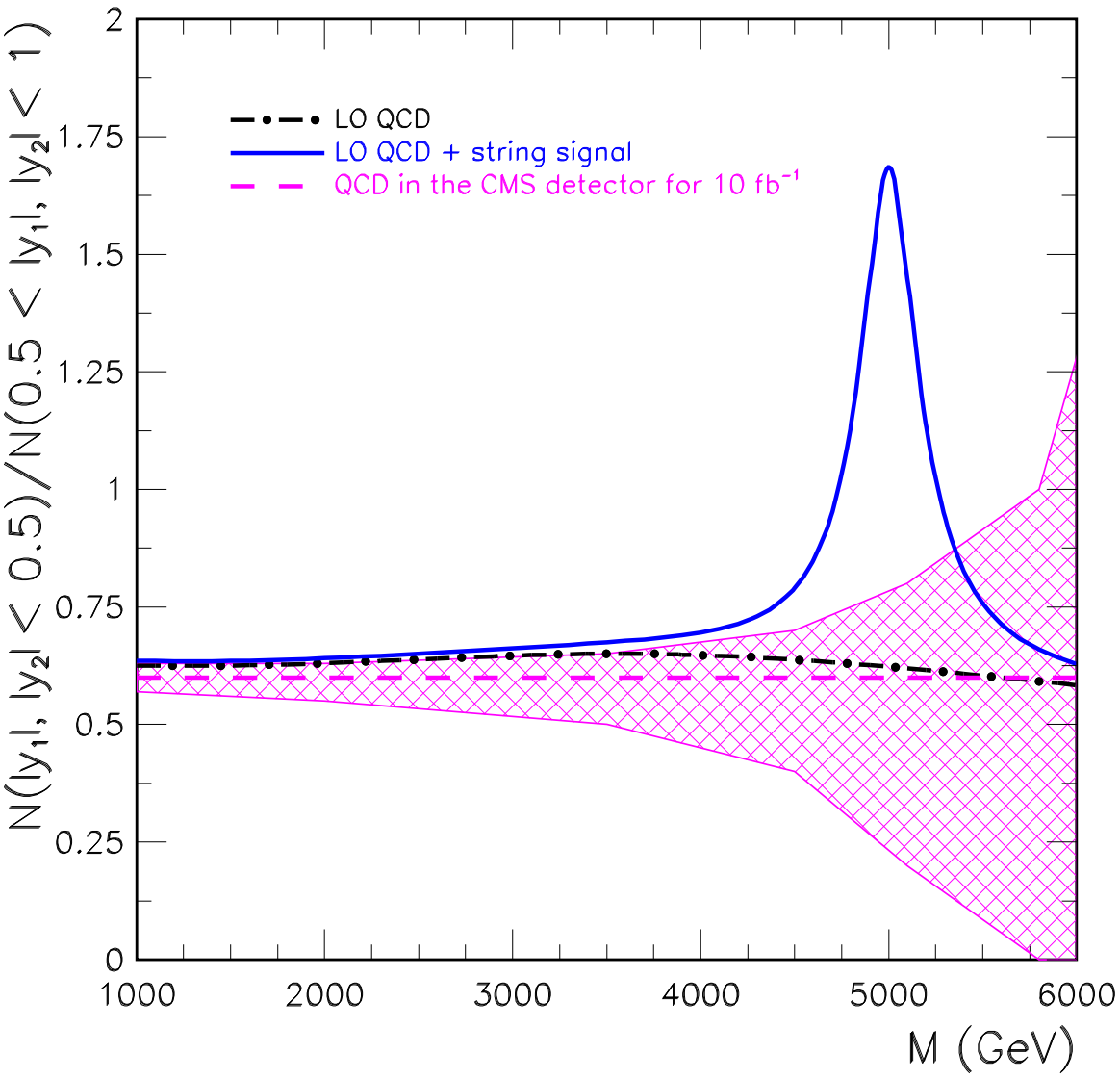
- **Define**

$$R = \frac{N_{\rm ev}(|y_1|, |y_2| < 0.5)}{N_{\rm ev}(0.5 < |y_1|, |y_2| < 1.0)}$$

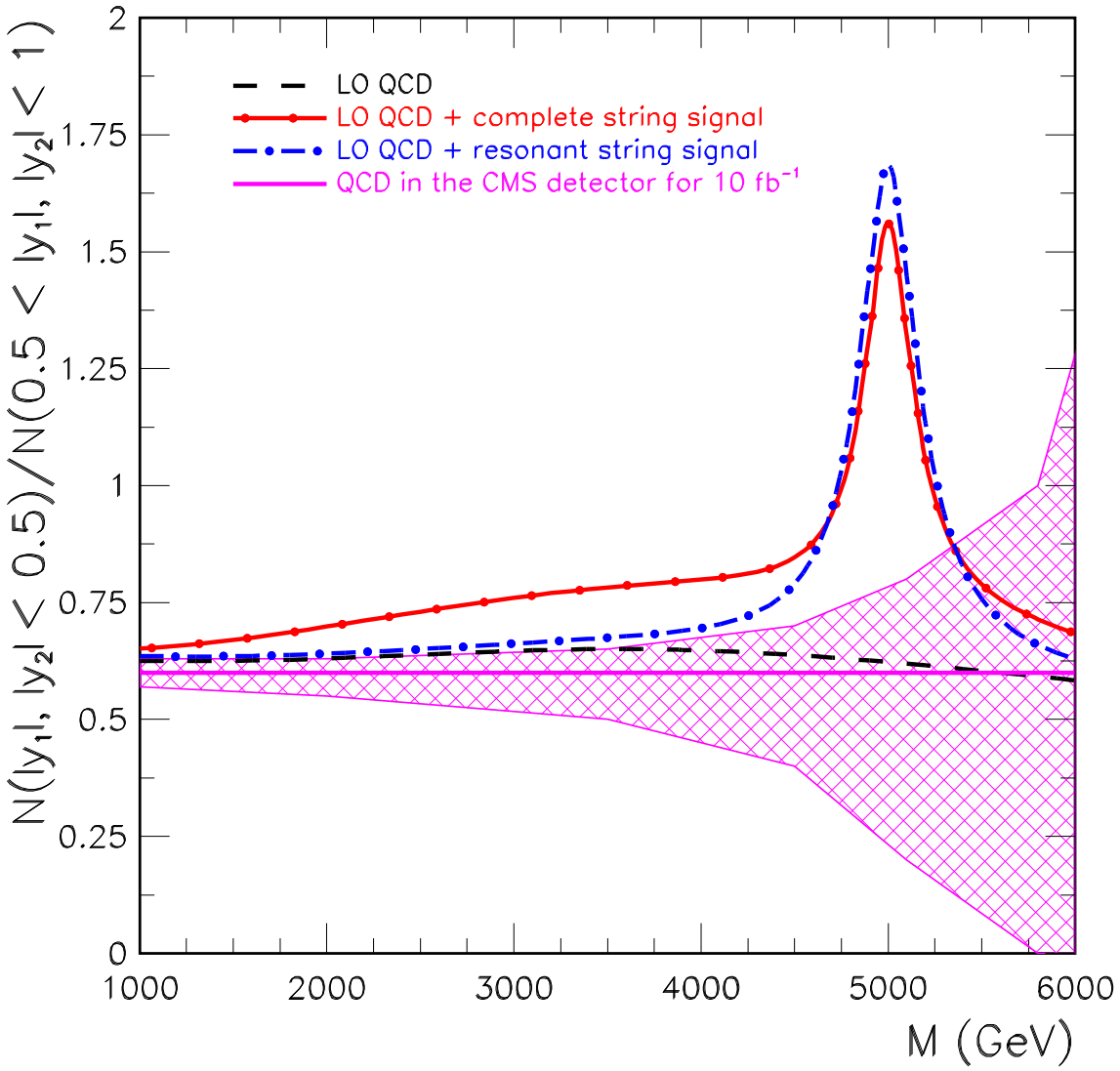
- **For QCD $R \simeq 0.6$ independent of M**

For previous discussion of R parameter in string theory dijets, see P.Meade and L.Randall, arXiv:0708.3017

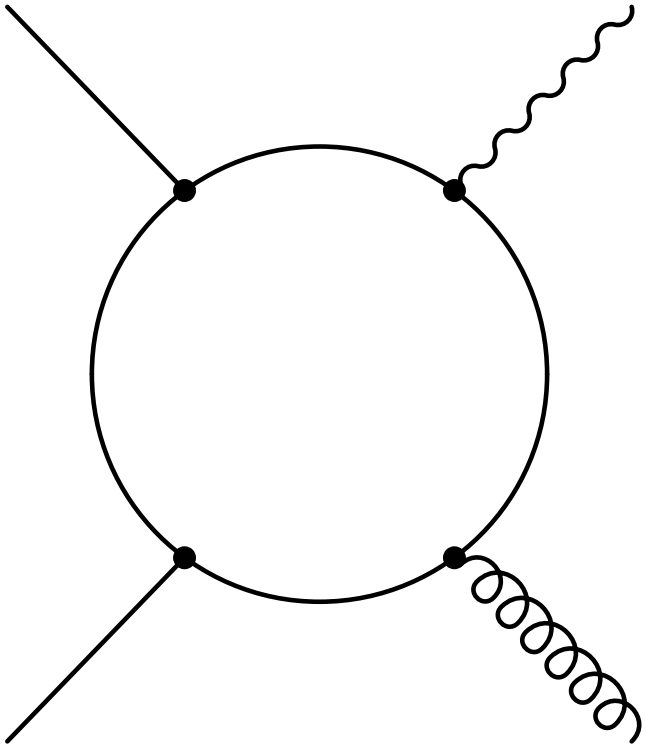
Regge in the R plot

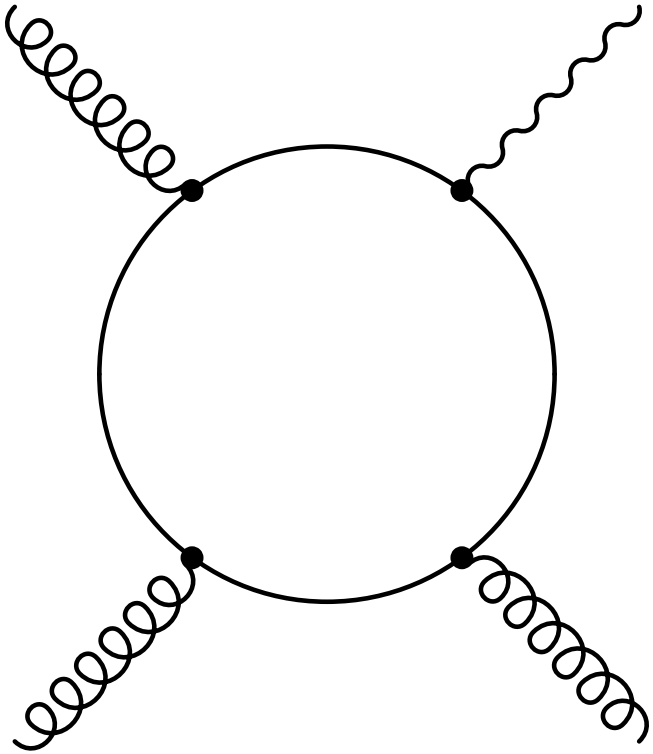


qq in the R plot



Photon processes





$gg \to \gamma g$

L. Anchordoqui et al, PRL 100, 171603 (2008); PR D78, 016005 (2008)

- Does not exist at tree level in field theory
- But does exist at tree (i.e. disk) level in string theory: U(1) field on color stack has photon component
- Involves only gauge bosons on a single stack, so is independent of fermion embeddings on the intersecting stacks
- Need to impose isolation procedure to greatly reduce π^0 background

Conclusions

- We have calculated the discovery reach at LHC for TeV-scale open string theory via the mass spectrum and angular distribution of dijets
- The key provided by quiver assignments – gauge supermultiplets on single stack of D-branes, matter supermultiplets bifundamental asignments at intersecting stacks
- In this picture, for all the $2 \longrightarrow 2$ partonic subprocesses, except for $qq \longrightarrow qq,\ q\bar{q} \longrightarrow q\bar{q},$, the string amplitude is completely determined –
  - no arbitrary Chan-Paton factors
  - no dependence on compactification scheme
  - no dependence on fermion embeddings

Conclusions (concluded)

- Even with the 4-fermion processes omitted from the signal but included in the QCD background, the resonant signal for the first Regge recurrence can attain discovery at 5σ for strings scales as high as 6.8 TeV
- Discovery is greatly enhanced through observation of angular distributions as manifest in the R parameter
- Observation of $\gamma+$ jet can provide independent corroborating evidence if the string scale is smaller than 5 TeV