Jet Signals for Low Mass Strings at the LHC

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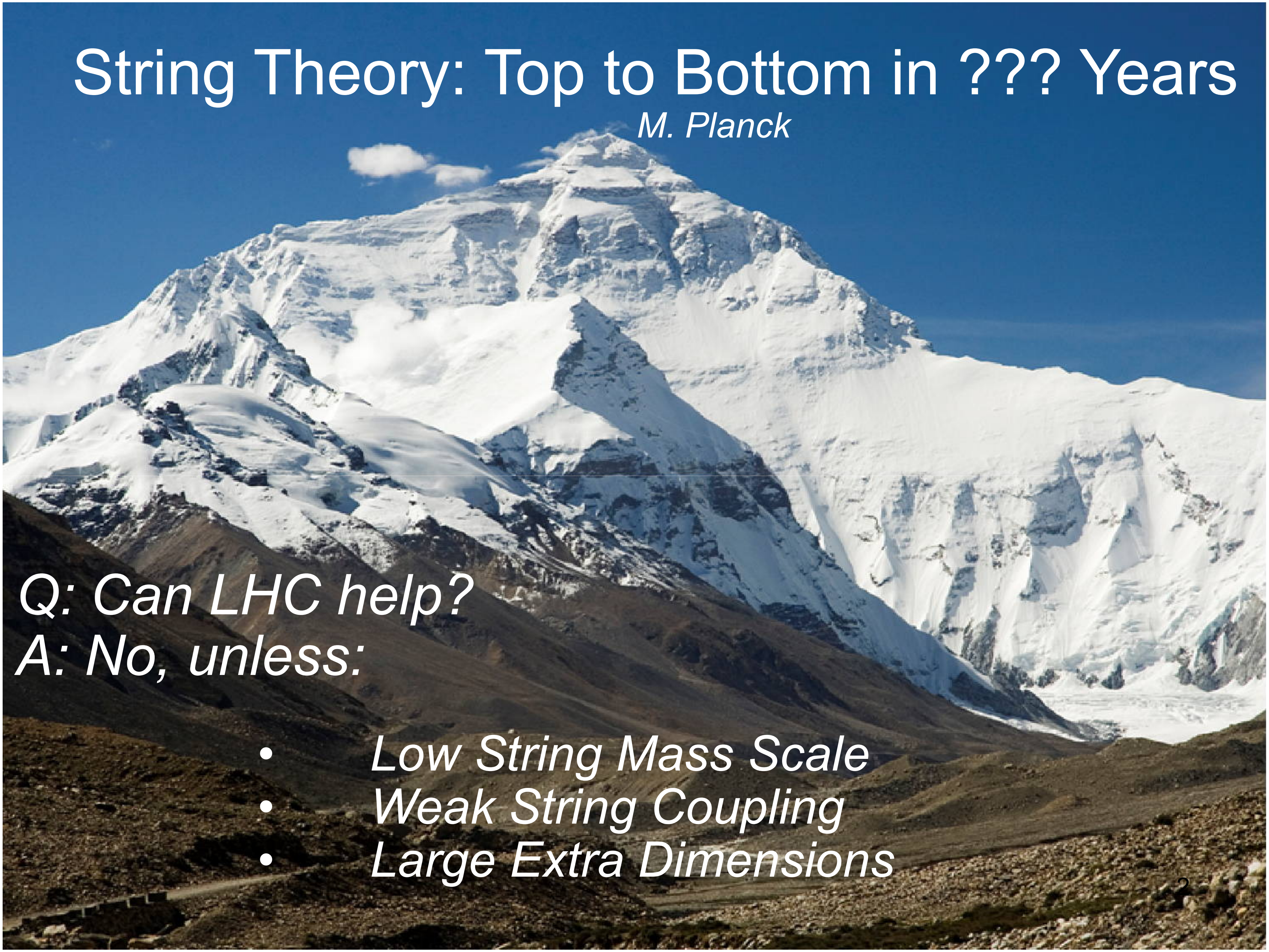


String Theory: Top to Bottom in ??? Years

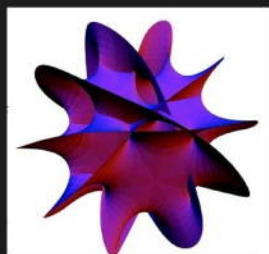
M. Planck

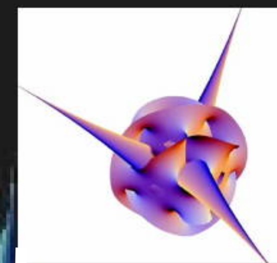
Q: Can LHC help?
A: No, unless:

- *Low String Mass Scale*
- *Weak String Coupling*
- *Large Extra Dimensions*

So what's the problem?

Difference between theory and "models"





LANDSCAPE

- Problem appears in "compactification" d=10 ⟶ d=4
- d=4 particle spectrum depends on the shape and size of extra dimensions (moduli)
- Billions of possible compactifications but no selection principle thus no predictions

⟶Billions of "models"   Lerche, Lüst, Schellekens (1986), Douglas (2003)

CONCLUSION OF THIS TALK: SUPERSTRING THEORY MAKES PRECISE, MODEL-INDEPENDENT PREDICTIONS (valid for all compactifications).
CAN BE TESTED AT THE LHC…   provided that…
IN THIS WAY, THE LANDSCAPE PROBLEM CAN BE RELEGATED TO THE NEXT GENERATION OF STRING THEORISTS

Outline

I. D-branes and all that : general setup

II. Jet tests at LHC: model-independent signals of TeV-scale (super)strings

L. Anchordoqui, H. Goldberg, S. Nawata, TRT: **0712.0386**, **0804.2013**
L. Anchordoqui, H. Goldberg, TRT: **0806.3420**
St. Stieberger, TRT: **hep-th/0607184**, **hep-th/0609175**, **0708.0574**

D.Luest, St. Stieberger, TRT:

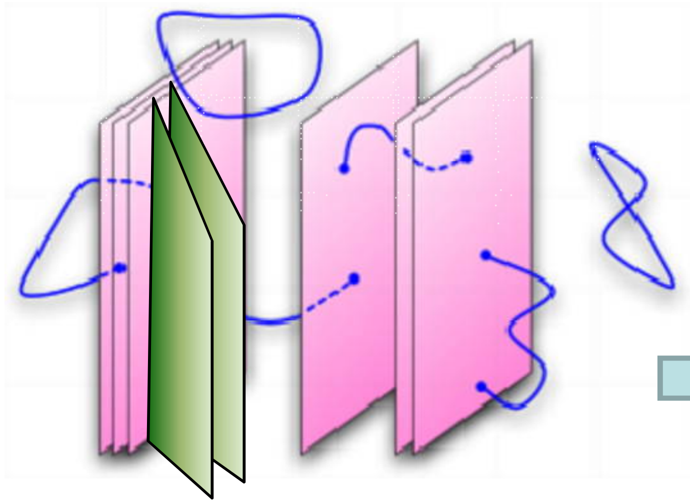
"The LHC String Hunter's Companion"

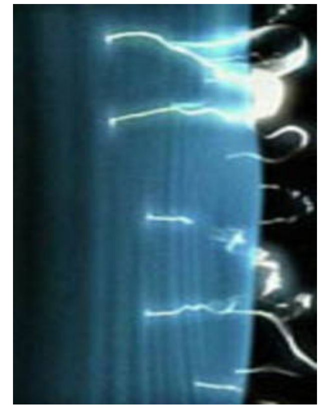
0807.3333 [Nucl.Phys.B 808:1-52, 2009]

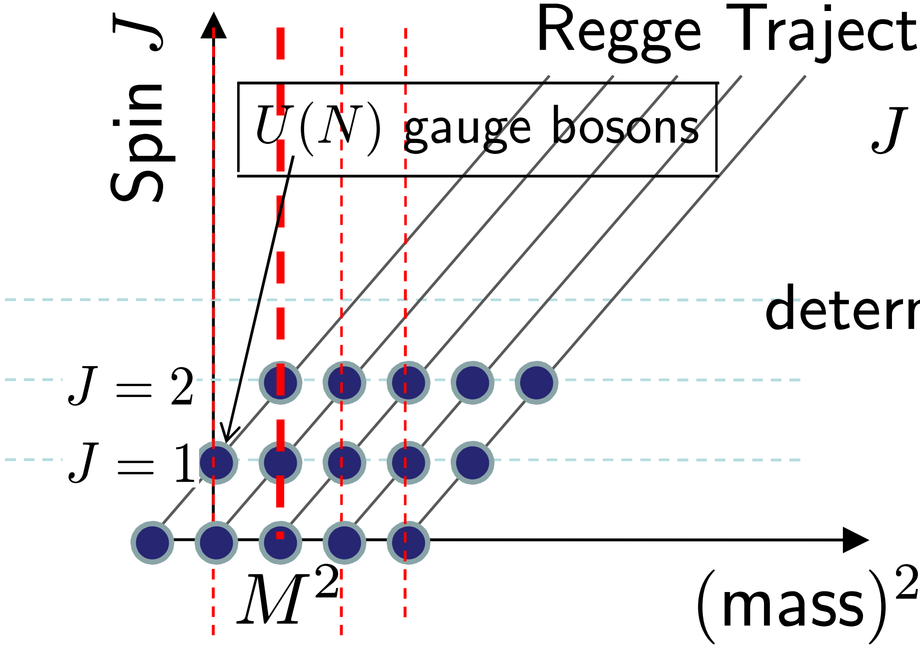
This talk: A.G.L.N.S.T: **0808.0497, 0904.3547**

Work in progress: Oliver Schlotterer's talk

D-branes and all that I







Regge Trajectories of Vibrating Strings:

$$J = J_0 + \alpha' m^2$$

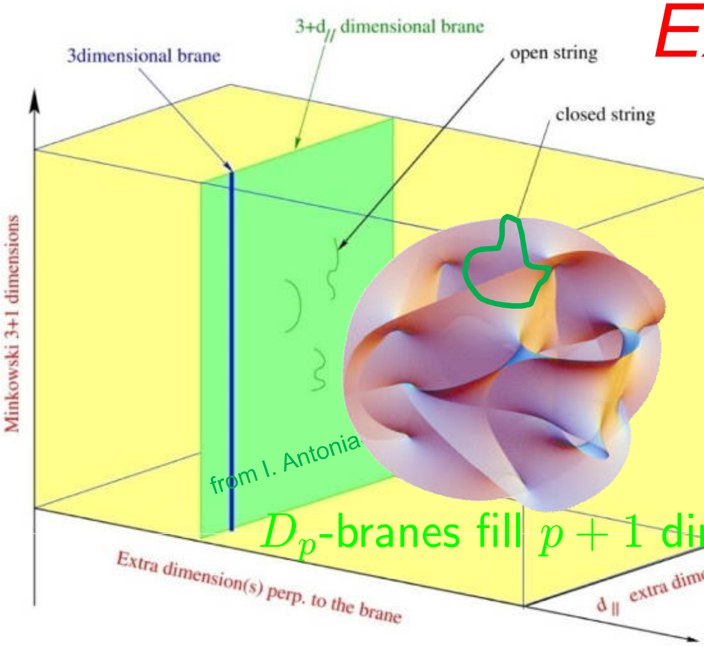
Regge Slope α'
determines the fundamental mass scale

$$M^2 = \frac{1}{\alpha'}$$

String "Threshold"

D-branes and all that

Extra Dimensions



D_p-branes fill $p+1$ dimensions

Universal Parameters: mass M, coupling g

Model-dependent:
Calabi-Yau, D-brane configurations
$\longrightarrow$ volume $\mathbf{V_6}$, moduli VEVs...

Strength of Gravitational Interactions: $M^2_{\rm Planck} = \ldots \frac{M^2}{g^2} \times \frac{\mathbf{V_6}}{(\alpha')^3} \approx 10^{38}\ {\rm GeV}^2$

$G_{\rm Newton} = M^{-2}_{\rm Planck}$

$\downarrow$

$M \sim 1$ TeV possible for "large" $\mathbf{V_6}$ with typical $R \sim 1$ nm – 1 mm

Lykken; Antoniadis, Arkani-Hamed, Dimopoulos, Dvali

Standard Model (and a little BSM) Fields

Intersecting Branes

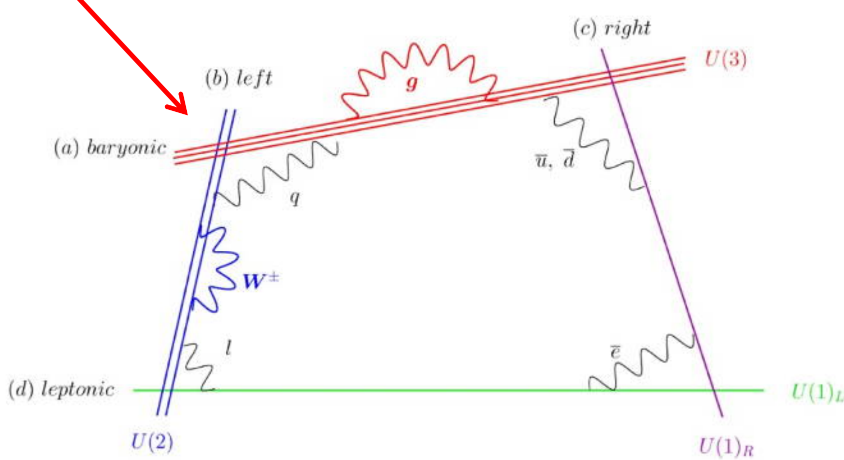
- "Stack" of N D-branes $\rightarrow U(N) = SU(N) \times U(1)$ gauge group

- Gauge bosons from strings ending on **ONE** stack e.g. $U(3)$ baryonic stack yields the gluon octet g AND a C-boson (anomalous, needs recycling)

- $SU(3) \otimes SU(2) \otimes U(1)_Y \longrightarrow$ at least **3** stacks but easier with **4**

Chiral matter from strings stretching between **TWO** stacks of D-branes intersecting at angle:

- e.g. $U(3) \cap U(2)$ intersection $\rightarrow$ $(3, 2)$ left-handed quark doublets etc



Blumenhagen, Kors, Lüst, Stieberger

Particle ZOO

- Kaluza-Klein excitations from large extra dimensions

  masses $\sim \frac{1}{R_\perp}$, can be as low as 10^{-3} eV, but harmless because sterile

- Kaluza-Klein excitations along D-branes

  masses $\sim \frac{1}{R_\|}$, should be near string scale M

Cullen, Perelstein, Peskin;
Meade, Randall ;
Dimopoulos, Landsberg

- **Regge Recurrences**

masses $\sim M$, hopefully near 1 TeV

- Black Holes masses $\sim \frac{M}{g^2} > M$ if $g < 1$ (weak string coupling)

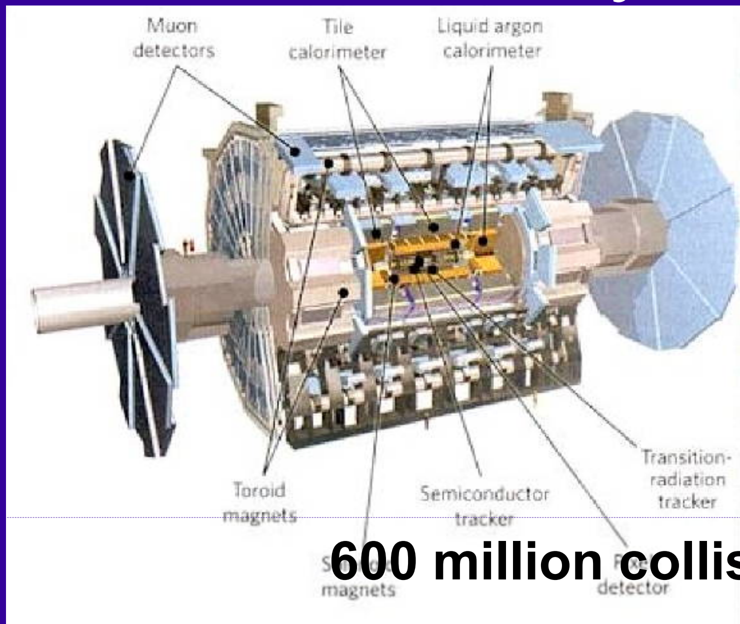
Typical LHC-testable parameters:

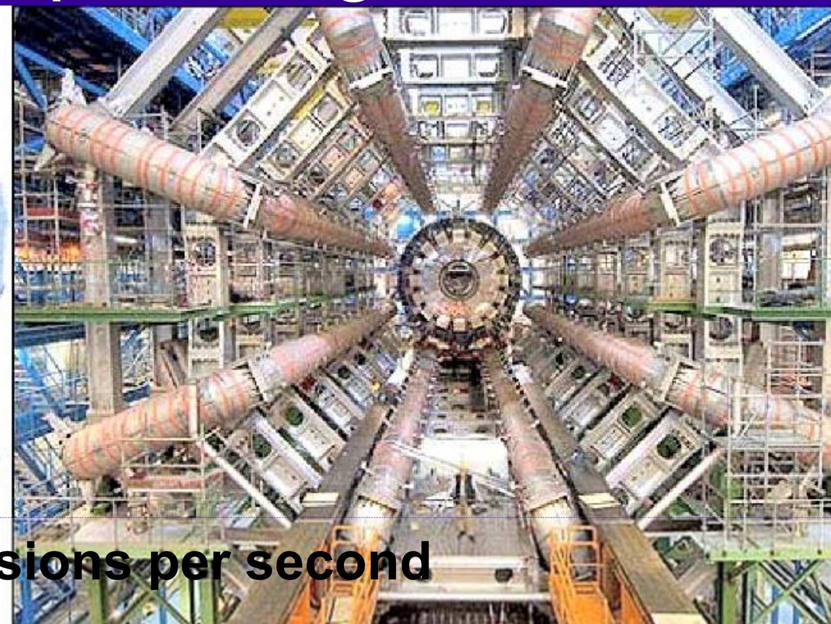
$$g^2 \approx 0.2 \qquad M_{KK}^{QCD} \approx M \qquad M_{KK}^{E-W} \approx 0.70M$$

$$M < 3.5 - 6.8 \text{ TeV}$$

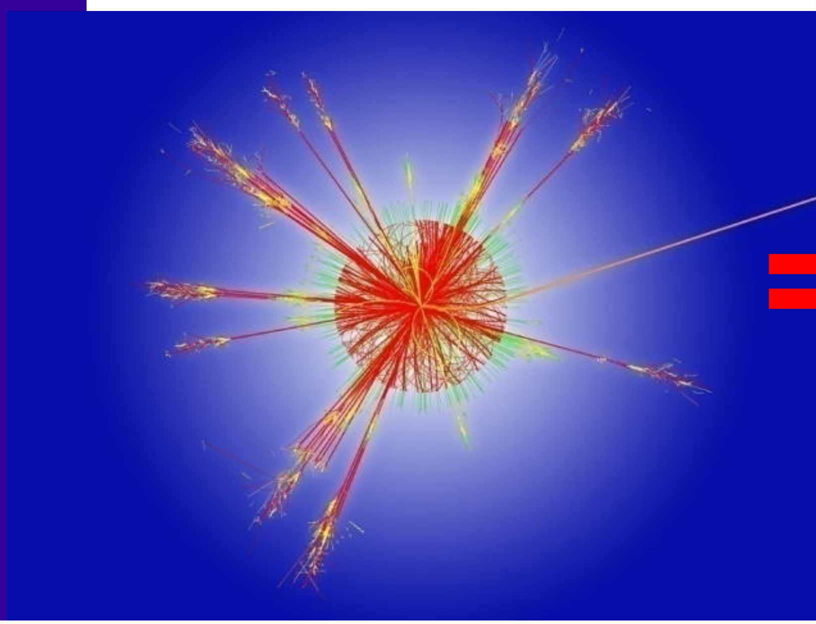
LHC Jet Factory

XXIst Century Superstring Collider





600 million collisions per second



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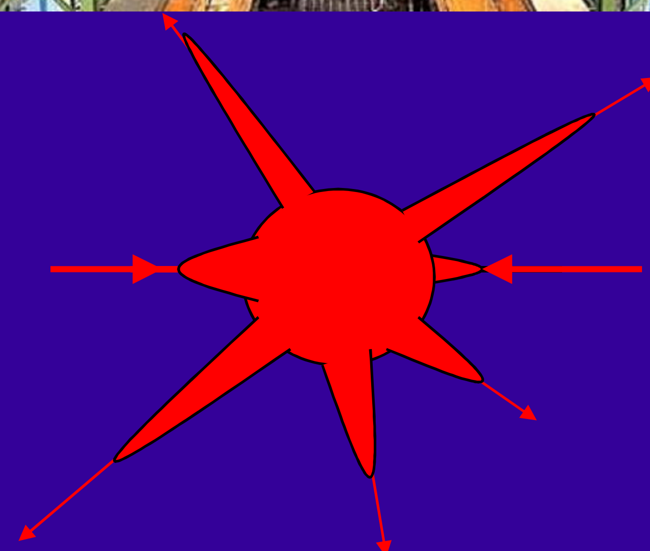
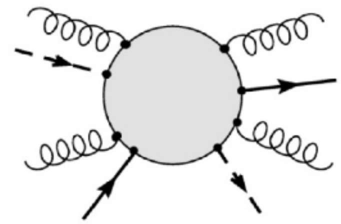
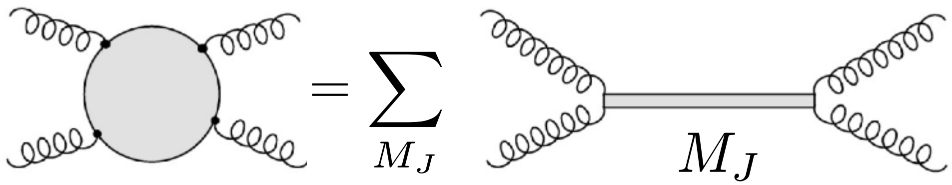


Jet Signals for M ~ 1 TeV Strings

Effects of Regge Recurrences in Parton Collisions



- **Weak string coupling** - leading order: Disk diagrams
- Encompass all Regge recurrences at **tree** level (in effective field theory):



- N-gluon amplitudes (also with one quark-antiquark pair) are **universal**:

  do **NOT** depend on compactification details and are exactly the same with or without SUSY. Reason: Momentum conservation in compact directions parallel to D-brane

  For more than 2 fermions, amplitudes are model-dependent (KK propagating in intermediate channels)
- These **universal amplitudes** are almost everything that you need to study the dominant contributions to parton scattering: 4 and more fermions are suppressed by color factors (however, valence qq ⟶ qq can be important, see later…)
- **Universal** deviations from the standard model expected in jet distributions if *M* ~ 1 TeV: higher-dimensional operators relevant below string threshold ; then resonance effects near string threshold – starting from massive spin 0,1, 2 at $\hat{s} \approx M^2$

Jets are the "smoking gun" of low mass strings

Gluon Disk Amplitudes

- Universal **SUSY** (same as N=4 of tree-level QCD) $\Rightarrow$ helicity selection rules: MHV, NMHV, . . .

Stieberger, TRT

- String effects inside Veneziano-Virasoro-Shapiro formfactors
- Example: Four-gluon amplitude (pure MHV)

$$V_t = \frac{\Gamma(1-\frac{s}{M^2})\Gamma(1-\frac{u}{M^2})}{\Gamma(1+\frac{t}{M^2})} = 1 - \frac{\pi^2}{6}\frac{su}{M^4} + \dots$$

poles at $s = nM^2$

Notation: $\langle ij \rangle \sim \sqrt{(p_i + p_j)^2}$

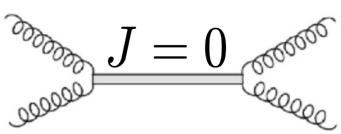
$$\mathcal{M}(g_1^-, g_2^-, g_3^+, g_4^+) \;=\; 8\, g^2 \langle 12\rangle^4 \;\times$$

$$\Big(\frac{V_t}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 41\rangle}[d^{a_1a_2a_3a_4} + \tfrac{1}{12}(f^{a_1a_4n}f^{a_2a_3n} - f^{a_1a_2n}f^{a_3a_4n})]$$

$$+ \frac{V_s}{\langle 14\rangle\langle 42\rangle\langle 23\rangle\langle 31\rangle}[d^{a_1a_2a_3a_4} + \tfrac{1}{12}(f^{a_2a_4n}f^{a_3a_1n} - f^{a_2a_3n}f^{a_1a_4n})]$$

$$+ \frac{V_u}{\langle 13\rangle\langle 34\rangle\langle 42\rangle\langle 21\rangle}[d^{a_1a_2a_3a_4} + \tfrac{1}{12}(f^{a_3a_4n}f^{a_1a_2n} - f^{a_3a_1n}f^{a_2a_4n})] \Big)$$

- First resonance at $s = M^2$: $\quad \mathcal{M} \approx 32 g^2 \sum_a d^{a_1a_2a}d^{a_3a_4a}\frac{M^2}{s - M^2}$



($J = 2$ resonance in t-channel)

From “The LHC String Hunter’s Companion”

Table 6: *Gluon-quark scattering.*

subprocess	$\lvert\mathcal{M}\rvert^2/g^4$
$gq \to gq$	$\frac{s^2+u^2}{t^2}\left[V_sV_u - \frac{4}{9}\frac{1}{su}(sV_s+uV_u)^2\right]$
$gq \to Aq$	$-\frac{1}{3}Q_A^2\,\frac{s^2+u^2}{sut^2}(sV_s+uV_u)^2$
$gq \to Bq'$	$-\frac{1}{6}\lvert T^B_{q\bar{q}'}\rvert^2\,\frac{s^2+u^2}{su}V_t^2$ $\quad(*)$

Table 7: *Quark-quark scattering.*

subprocess	$\lvert\mathcal{M}\rvert^2/g^4$
$qq \to qq$	$\frac{2}{9}\frac{1}{t^2}\left[\left(sF^{bb}_{tu}\right)^2+\left(sF^{cc}_{tu}\right)^2+\left(uG^{bc}_{ts}\right)^2+\left(uG^{cb}_{ts}\right)^2\right]$ $+\frac{2}{9}\frac{1}{u^2}\left[\left(sF^{bb}_{ut}\right)^2+\left(sF^{cc}_{ut}\right)^2+\left(tG^{bc}_{us}\right)^2+\left(tG^{cb}_{us}\right)^2\right]-\frac{4}{27}\frac{s^2}{tu}\left(F^{bb}_{tu}F^{bb}_{ut}+F^{cc}_{tu}F^{cc}_{ut}\right)$
$qq' \to qq'$	$\frac{2}{9}\frac{1}{t^2}\left[\left(sF^{bb}_{tu}\right)^2+\left(sG^{cc'}_{tu}\right)^2+\left(uG^{bc}_{ts}\right)^2+\left(uG^{bc'}_{ts}\right)^2\right]$

Lowest Massive Regge Excitations (n=1)

- Gluonic resonances: $G^*,\ C^*\ :\ J = 0,\ 1,\ 2$

Table 1: Partial and total widths, in GeV, of the lowest Regge excitation of the $U(3)$ gauge bosons. All quantities are to be multiplied by M/TeV.

From Anchordoqui, Goldberg, TRT: 0806.3420.

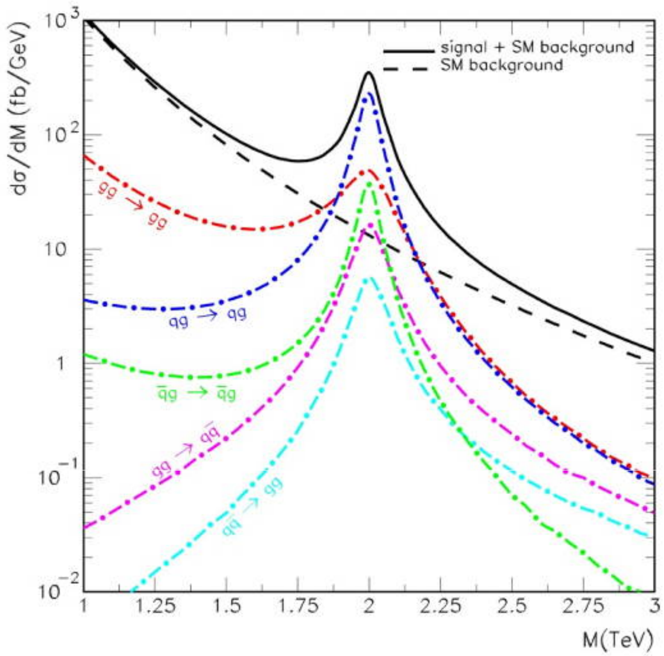
channel	$J=0$		$J=2$	
	G^*	C^*	G^*	C^*
GG	41.6	133.3	16.7	53.3
GC	33.3	–	13.3	–
CC	–	16.7	–	6.6
$q\bar{q}$	0	0	15.0	15.0
all	75.0	150.0	45.0	75.0

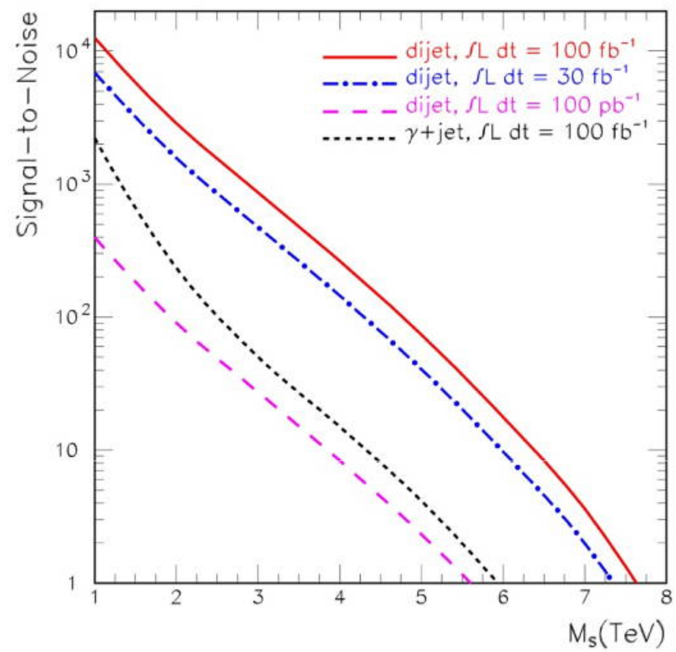
$J=1$ is special: does not couple to gg. Accessible in $q\bar{q}$ only. VERY narrow: $\Gamma \approx 8.3$ GeV $\times M/$TeV.

- Quark resonances: $q^*\ :\ J = 1/2,\ 3/2$

- All decay widths are **universal**: same for all D-brane configurations and compactifications
- Spin encoded in angular distributions

Brute force bump-hunting (CTEQ6D)



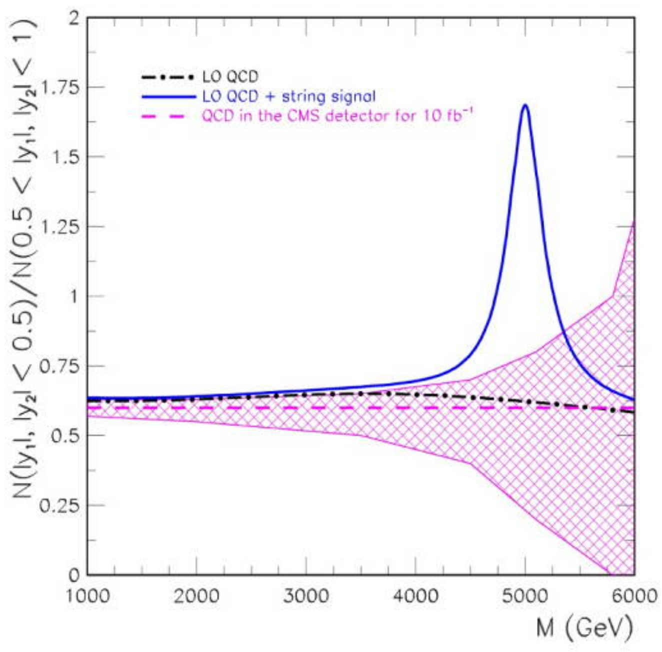


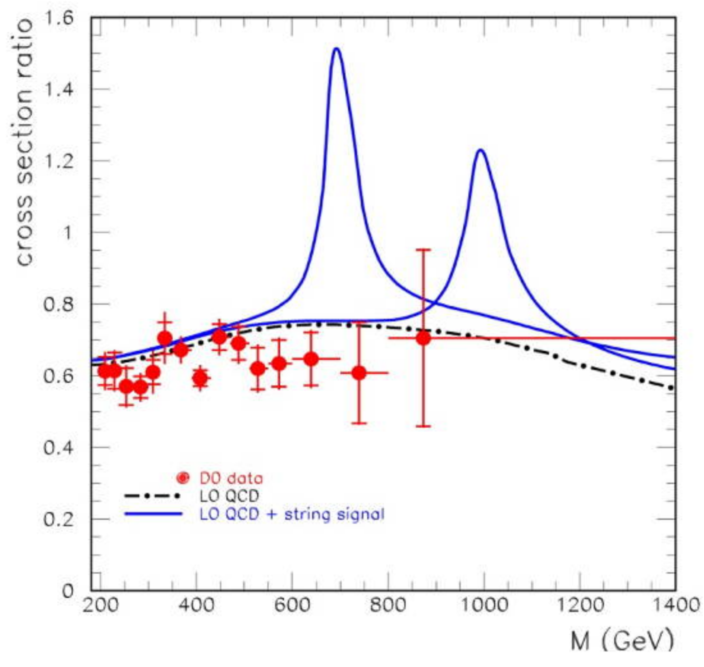
Left panel: $d\sigma/dM$ (units of fb/GeV) *vs.* M (TeV) is plotted for the case of SM QCD background (dashed line) and (first resonance, $M_s = 2$ TeV) string signal + background (solid line). The dot-dashed lines indicate the different contributions to the string signal ($gg \to gg$, $gg \to q\bar{q}$, $qg \to qg$, and $q\bar{q} \to gg$). *Right panel:* $pp \to$ dijet signal-to-noise ratio for three integrated luminosities.

Dijet angular distributions

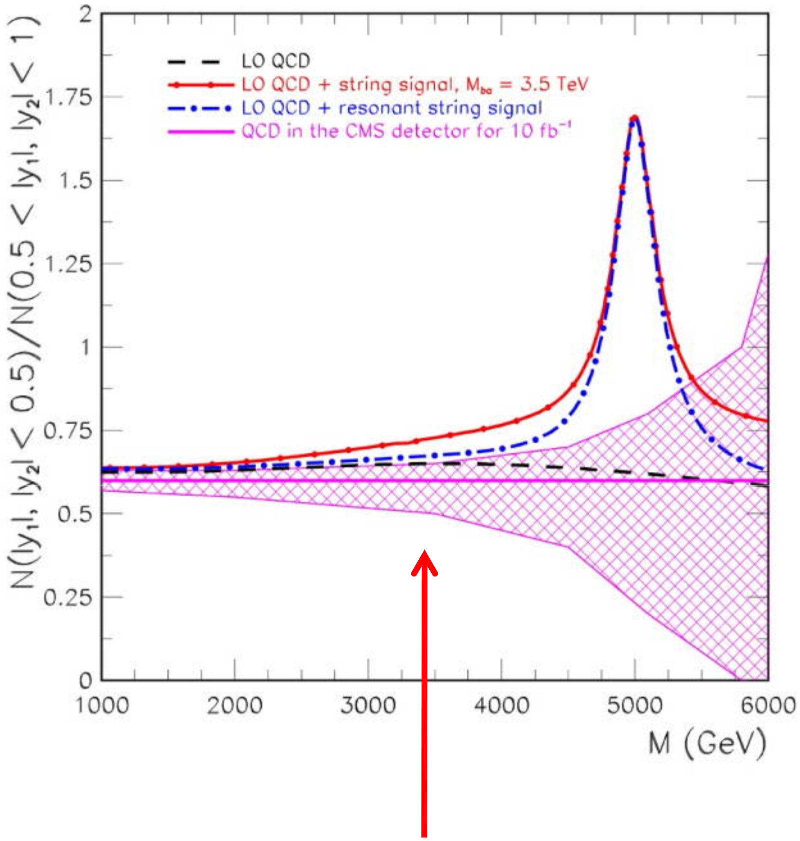
QCD parton-parton cross sections are dominated by t-channel exchanges that produce dijet angular distributions which peak at small center of mass scattering angles. In contrast, non–standard contact interactions or excitations of resonances result in a more isotropic distribution. In terms of rapidity variable for standard transverse momentum cuts, dijets resulting from QCD processes will preferentially populate the large rapidity region, while the new processes generate events more uniformly distributed in the entire rapidity region. To analyze the details of the rapidity space the DØ Collaboration introduced

$$R = \frac{d\sigma/dM|_{(|y_1|,|y_2|<0.5)}}{d\sigma/dM|_{(0.5<|y_1|,|y_2|<1.0)}}$$





Precision Tests: Signals of extra dimensions in valence quark scattering



$M_s = 5.0 \text{ TeV}, M_{KK} = 3.5 \text{ TeV}$

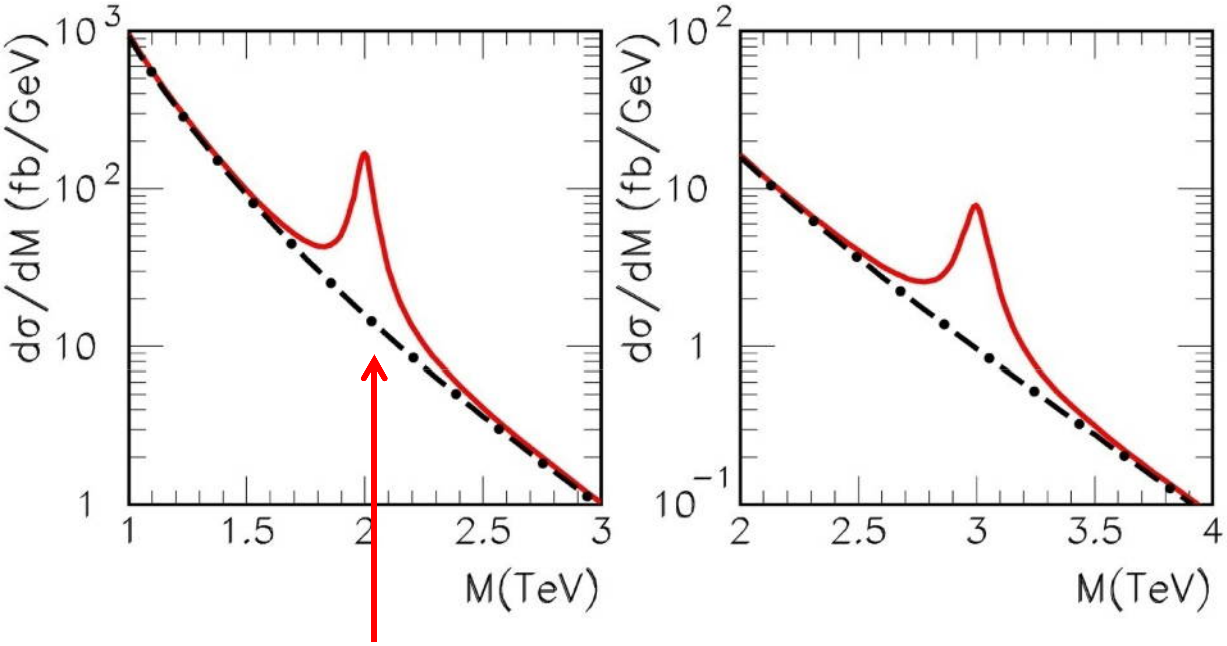
$3 \text{ TeV} < M < 3.5 \text{ TeV}$

tail of the Regge excitation: $S/\sqrt{B} = 100/48 = 2\sigma$

KK modes: $S/\sqrt{B} = 290/48 = 6\sigma$

Early Discovery?

$$\sqrt{s} = 10\ TeV \qquad \int \mathcal{L} \approx 10\ \mathrm{pb}^{-1}$$



$$S/\sqrt{B} = 204/19 > 10\sigma \text{ for } M_s = 2 \text{ TeV}$$

Concluding Remarks

• If Nature gracefully chose weakly coupled strings with M ~ 1 TeV, LHC will find them . . .

• LHC searches should focus on Regge resonances: string theory gives precise predictions for masses, spins, production rates and decays

• Jet distributions are particularly suitable for string searches because in the leading approximation (disk diagrams) they are universal, i.e. completely model-independent: do not depend on the compactification details, same with or without supersymmetry

• $M_s \sim 3.5 - 6.8$ TeV can be reached with sufficient patience and energy

• For $M_s < 3.5$ TeV, corroborative evidence from monojet, trijet, and dilepton plus jet configurations from $pp \to Z^0+$ jet channel

• Early discovery possible for $M_s < 3.0$ TeV

• It is possible that Nature made a different choice – we will know it very soon. . .

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Opinions expressed are those of the author and do not necessarily reflect the views of NSF.

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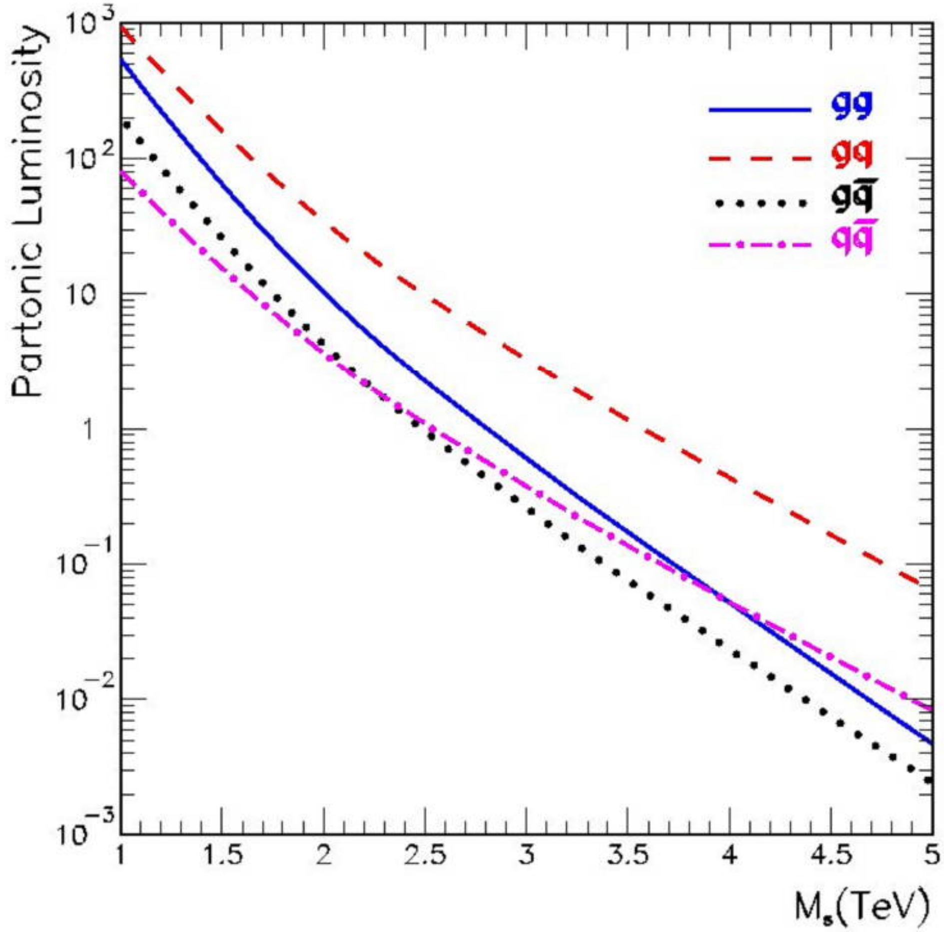

Partonic Luminosity
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
gg
gq
$g\bar{q}$
$q\bar{q}$
1
1.5
2
2.5
3
3.5
4
4.5
5
M_s(TeV)