Low-Scale String Resonances at the Large Hadron Collider

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String Theory

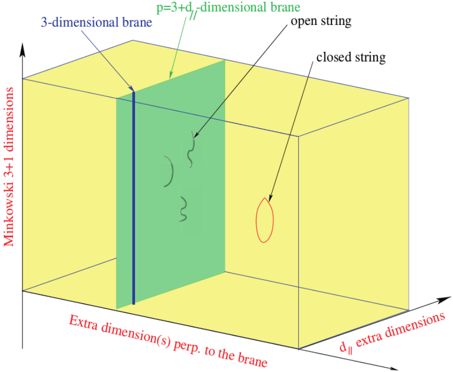
Instead of zero-dimensional particles in Standard Model (SM), there are one-dimensional strings, either closed or open.

If we look at them from large distances, they look like zero-dimensional particles.

Their excitations will determine the properties of the particles.

- Free parameters: *String Scale* $\mathrm{M_s}$, *Coupling Constant* $\mathrm{g_s}$
- Higher dimensions

D-branes



- Dynamical objects which satisfy the boundary conditions of the end points of the **open** strings
- Bosons are due to the open strings ending on stacks of D-branes
- Fermions are due to the open strings stretching between D-branes

We consider the extensions of the SM based on open strings ending on D-branes

Antoniadis I. (2007) The Physics of Extra Dimensions. In: Papantonopoulos L. (eds) The Invisible Universe: Dark Matter and Dark Energy. Lecture Notes in Physics, vol 720. Springer, Berlin, Heidelberg

Scattering Amplitudes in String Theory

Field theory scattering amplitudes multiplied by Veneziano Factors. For example, for the $gq \to gq$ subprocess

$$|\mathcal{M}(gq \to gq)|^2 = \mathrm{g}^4 \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} \left[V_s V_u - \frac{2}{9} \frac{1}{\hat{s}\hat{u}} (\hat{s} V_s + \hat{u} V_u)^2 \right], \qquad (1)$$

where g is the QCD coupling constant, $(\hat{s},\ \hat{t},\ \hat{u})$ are the partonic Mandelstam variables and Vs are the Veneziano factors.

Veneziano Factors

Veneziano factors are given in terms of Gamma functions, which can be written as

$$V_t \equiv V(s,t,u) = \sum_{n=1}^{\infty} \frac{\hat{s}\hat{u}}{(\hat{s}+\hat{u})M_s^2} \frac{M_s^{2-2n}}{n!} \frac{1}{\hat{s}-nM_s^2} \left[\prod_{J=1}^{n} (\hat{u}+M_s^2 J) \right], \quad (2)$$

$$V_u \equiv V(s,u,t) \quad (3)$$

$$V_s \equiv V(t,s,u) \quad (4)$$

The expansion in the s-channel in Eq.(2) has an infinite number of resonances at $\sqrt{n}M_s$, which are called *Regge Excitations*.

At low energies ($\hat{s} << M_s$, $\hat{s} \to 0$ or $M_s \to \infty$), Veneziano factors will approach unity and QCD scattering amplitudes are retrieved, Eq.(1).

Low-Scale String Theory

Superstring theory implies a 10-dimensional world. By compactifying the extra 6 dimensions, we get the physical 4D space-time.

The Planck scale is defined as

$$M_{Pl}^2 = \frac{8}{g_s^2} M_s^8 \frac{V_6}{(2\pi)^2}, \tag{5}$$

where, V_6 is the volume of the compactified extra dimensions.

If the size of the extra dimensions is large, string scale M_s can be much lower than the Planck scale, $M_s \sim \mathcal{O}$ TeV.

Proton-Proton Cross-Section

Convolution of the scattering amplitudes with the parton distribution functions

$$\frac{d\sigma}{dM} = \sum_{ij} \int \int dydYC_{(M,s,y,Y)} f_i f_j |\mathcal{M}_{(ij \to kl)}|^2 \tag{6}$$

$M \to$ Invariant mass of the incoming partons

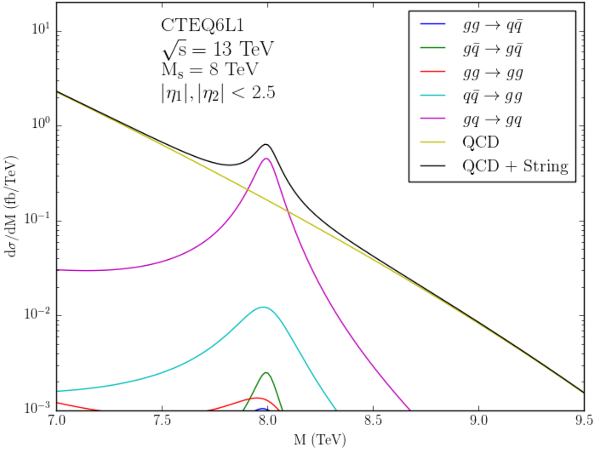
$f_i, f_j \to$ Probability density of finding a parton having a fraction of the proton's four-momentum, i.e. parton distribution functions (PDFS)

$s \to$ Centre of mass energy of the partons

$y = \frac{y_1 - y_2}{2}, Y = \frac{y_1 + y_2}{2}, \; y_{1,2} = \frac{1}{2} ln \frac{E_{1,2} + p_{z1,2}}{E_{1,2} - p_{z1,2}} \to$ Rapidity of Partons

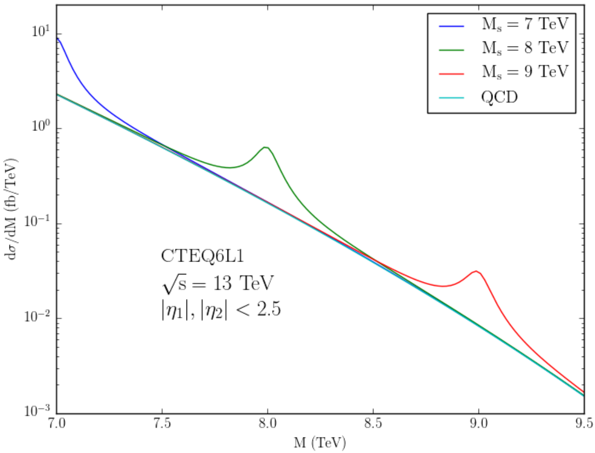
$(M, y, Y) \to$ Independent variables

Differential Cross-Sections



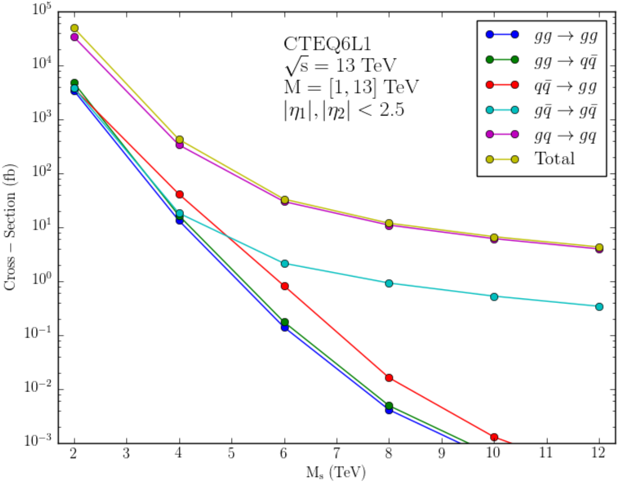
Simulated signal is added to the simulated Standard Model QCD

Differential Cross-Sections



Signal added to the Standard Model QCD for different string sacles

Cross-Sections



STRINGS Monte Carlo Event Generator

- Manual → ArXiv:1811.07458
- Project → strings.hepforge.org

Based on the cross-sections and decay widths, we write a Monte Carlo event generator for the production and decay of the string resonances, such that electric charge, quark flavour and colour are conserved.

$$G(M) \equiv \frac{d\sigma}{dM} = \sum_{ij} \int \int dydYF(M, y, Y) \tag{7}$$

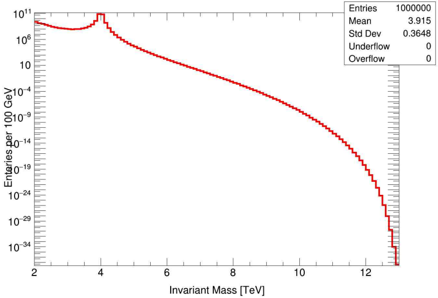
1. Produce the differential cross-sections for the subprocesses $G(M)$
2. Using $G(M)$, suprocess and M are determined
3. Putting back M and subprocess type in Eq.7, y and Y are generated
4. Using (M, y, Y), the four-momenta of the partons are calculated

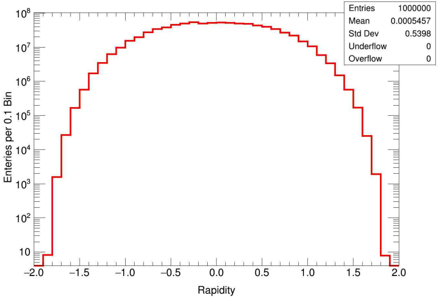
STRINGS-1.00

- Written entirely in Python 2
- The only dependency is "LHAPDF 6" library and it should be installed
  - A library which contains the PDF sets
- It takes 27 input variables
- Capable of producing first and second string resonances
  - Interference between first and second resonances is not considered
- Capable of producing QCD tree-level diparton processes
- The output is saved in a Les Houches Event (LHE) file
  - A standard format to save the events' information, e.g. Four momenta of the incoming and outgoing partons, etc.

Validation Plots

Using the output LHE files, we can histogram the kinematic variables.





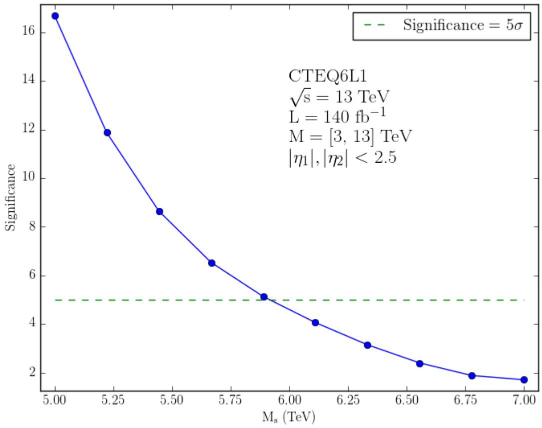
Parton-Level Discovery Potential

L $\equiv$ Luminosity
$\sigma_s \equiv$ Signal's cross-section
S $\equiv$ Number of signal events
B $\equiv$ Number of background (Standard Model QCD) events

We require two conditions for the discovery of the signals

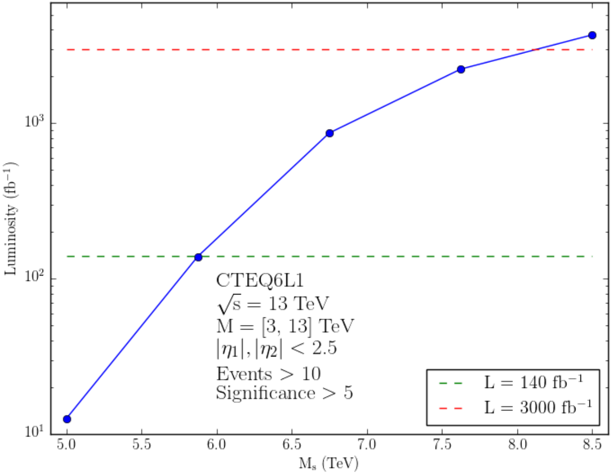
1. Number of signal events above background $\equiv L\sigma_s > 10$
2. Significance $\equiv \dfrac{S}{\sqrt{B}} > 5$

Discovery Potential

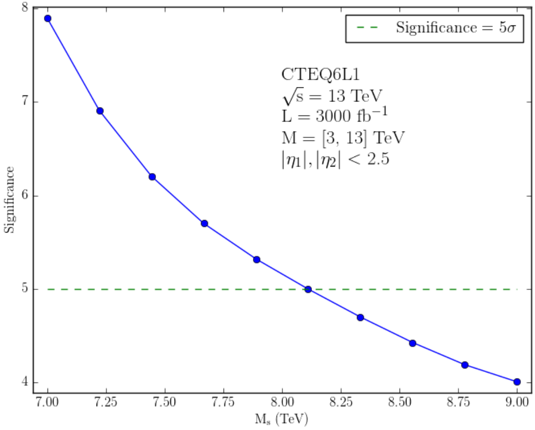


Highest $M_s = 5.91$ TeV

Required Luminosity for Discovery



Discovery Potential



Highest $M_s = 8.12$ TeV

Summary

- String scale of the string theory corresponds to energies of the order of 10^{19} GeV $\rightarrow$ Not accessible by any collider
- String scale of the low-scale string theory can be of the order of a few TeV
- STRINGS is written based on cross-sections and decay widths in low-scale string theory
  - Manual $\rightarrow$ ArXiv:1811.07458
  - Project $\rightarrow$ strings.hepforge.org
- STRINGS is used to study the discovery potential of the string resonances
  - For L $= 140$ fb^{-1} , the highest detectable string scale is 5.91 TeV
  - For L $= 3000$ fb^{-1} , the highest detectable string scale is 8.12 TeV
- These calculations are done with no signal to background optimization. The entire mass range was used.

Thank you!