Search for String Resonances With the ATLAS Detector

Fairhurst Lyons

Supervisor: D. Gingrich

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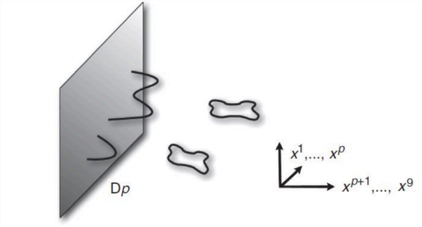
University of Alberta

String Theory I

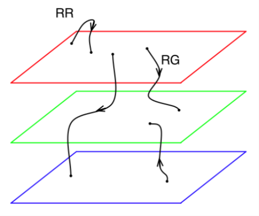
- Proposed alternative to SM describing all fundamental forces
- Instead of 0-d particles have 1-d strings (open or closed)
- Many string theories exist, we are interested in D-brane model
- Dp-brane is membrane with p spatial dimensions
- Point $\rightarrow$ D0-brane, line $\rightarrow$ D1-brane, plane $\rightarrow$ D2-brane, etc...
- Closed strings propagate freely, open string ends attached to D-brane



Source: [1]

String Theory II

- Particles created by excitations of strings
- Closed strings lead to gravitons
- Gluons come from strings with ends attached to stack of 3 colour D-branes (top image)
- Quarks stretch between stack of 3 colour D-branes and stack of 2 weak D-branes
- Requires 10 spacetime dimensions
- Extra 6 spatial dimensions compactified (bottom image)
- Only gravity propagates in extra dimensions, SM fields restricted to 3-d space [2]



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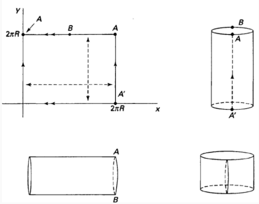


Source: [2]

Problem with SM

- Large gap between $M_{Planck} \sim 10^{19}$ GeV and $M_{EW} \sim 10^3$ GeV
- Assume d-dimensional quantum gravity scale $M_d \sim 10^3$ GeV
- 4-d gravity weak as observed
- $M_{Planck} \sim V_6 M_d$ where V_6 is volume of 6 compactified dimensions
- M_d small so V_6 large
- Some extra dimensions should be large
- Observed hierarchy explained [4]

Experimental Observation I

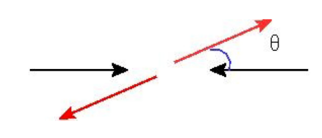
- Interaction cross sections include massive string excitations
- String scale where string effects become noticeable $M_s \sim M_d \sim 10^3$ GeV
- Amplitudes must reduce to SM in low energy limit
- Introduce Veneziano factor which multiplies QFT amplitudes to give Veneziano amplitudes
- Veneziano factor $\rightarrow 1$ for low E_{CM}, large for $E_{CM} \sim M_s$
- This Veneziano amplitude has resonances of excited string states
- Observed in colliders as increased cross section over SM prediction when $E_{CM} \sim M_s$ [4]

Experimental Observation II

- Looking for deviation from SM at LHC
- String resonances can occur in pp collisions
- Compare QCD prediction to observed Invariant Mass ($M = \sqrt{\hat{s}}$) of quark/gluon interactions
- Search M distribution for resonant deviation from smooth background at TeV scale [4]
- Simulate events according to theoretical string amplitudes and compare with data from LHC
- Search Variable: dijet invariant mass

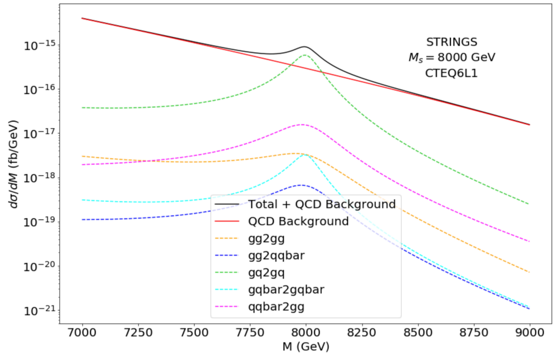
STRINGS Generator

- STRINGS-2.00 [5]
- Python Monte Carlo particle interaction simulator
- Generator creates $2 \to 2$ processes with quarks and gluons
  - $gg \to gg$
  - $gg \to q\bar{q}$
  - $g\bar{q} \to g\bar{q}$
  - $gq \to gq$
  - $q\bar{q} \to gg$
- Events generated and total cross section calculated based off of scattering amplitudes in [6]



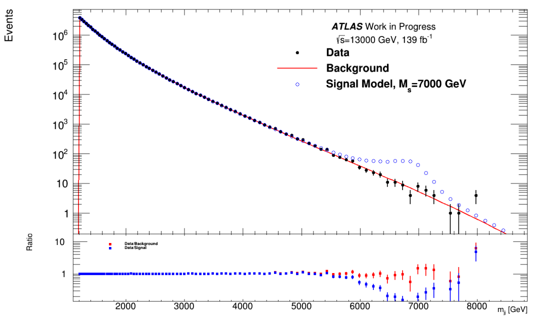
Analysis

- Model is signal and background together, this is compared to data
- Background from Pythia dijet Monte Carlo QCD simulations
- Signal from STRINGS generator
  - 5 samples: $M_s = 7000, 7500, 8000, 8500, 9000$ GeV
- Data from ATLAS detector 2015-2018
- Pictured: Differential cross sections with $M_s = 8000$ GeV and PDF CTEQ6L1 generated by STRINGS [5]



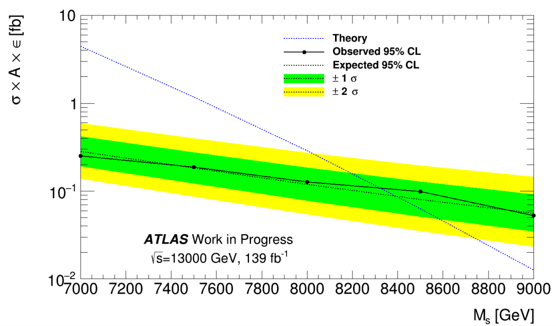
Model vs Data

- Compare model (signal + bkg) to data
- Pictured: data, background, signal model with $M_s = 7000$ GeV
- No significant deviation from expected background
- No resonance observed in data, background fits better than model



Limit Setting

- Signal model constrained using Confidence levels (CLs) [7]
- 95% CL sets upper limits on observable signal ($\sigma \times A \times \epsilon$)
- σ = cross section, A = Acceptance, ϵ = detector efficiency
- Compute 95% CL upper signal limit for $M_s = 7000 - 9000$ GeV
- Using string resonance model cross sections we set lower limit $M_s > 8300$ GeV at 95% CL



Summary

- String theory can be probed at LHC
- Theory predicts resonance in pp collisions at $E_{CM} \sim M_s$
- Compare theoretical cross sections to observation
- No resonance in data
- Lower limit $M_s > 8300$ GeV set with 95% confidence
- Higher energies to be investigated after LHC/ATLAS upgrades

References

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