How to recognize different types of trees from quite a long way away

Daniel Härtl

Max-Planck-Institut für Physik, München

IMPRS Young Scientist Workshop at Ringberg Castle

July 28, 2010

No. 1
The Larch

The Pink Lecture Series: Strings at the TeV Scale

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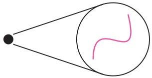
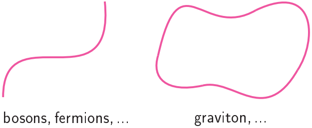
Outline

String Theory in a Nutshell

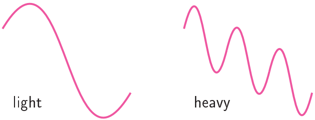
- Point particles are in fact strings.



- They can be open or closed.



- String masses arise from oscillations.



- Strings propagate in 10-dimensional spacetime.

  $\Rightarrow$ Compactification: $\mathcal{M}_{10} = \mathbb{R}^{(3,1)} \times \mathcal{Y}_6$.

Energy Scales in Quantum Gravity

- Four-dimensional gravity becomes strong at the Planck scale

$$M_{\mathrm{Pl},4} = \sqrt{\frac{\hbar c}{G}} \sim 10^{19}\ \mathrm{GeV}\,.$$

- TeV scale quantum gravity is possible in theories with n large extra-dimensions of size R [ADD '98]:

$$(M_{\mathrm{Pl},4})^2 \sim (M_{\mathrm{Pl},4+n})^{2+n}\ R^n\,.$$

- For string compactifications to $D = 4$ the string scale M_S satisfies

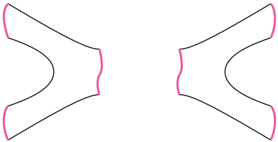
$$(M_{\mathrm{Pl},4})^2 \sim g_S^{-2}\,(M_S)^8\ V_6\,.$$

- Strings could be discovered at LHC if $g_S < 1$, $M_S \sim \mathcal{O}(\mathrm{TeV})$.

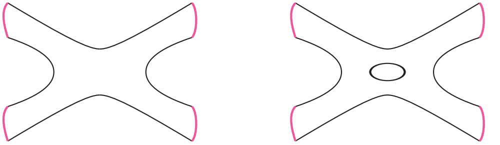
- Gravitational constraints from phenomenology, astrophysics and cosmology demand $M_S > 1$ TeV [ADD '98].

Open String Interactions

Strings can interact in two ways, i.e. by joining and splitting.



Open string diagrams then look like



String diagrams are 2d surfaces in 10d space-time.

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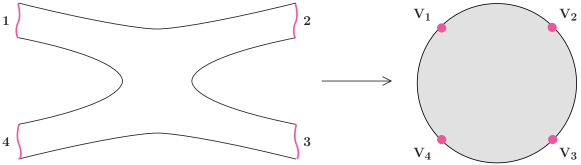
Disk Diagrams

Using the Riemann mapping theorem tree-level diagrams can be mapped onto the unit disk $\mathbb{D}$.



The V_i's are vertex operators creating and annihilating string states.

Riemann Mapping Theorem

If $U \subset \mathbb{C}$ is open and simply connected, there exists a unique biholomorphic mapping f from U onto the open unit disk $\mathbb{D}$.

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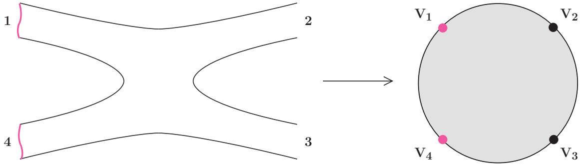

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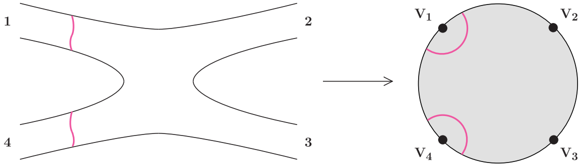

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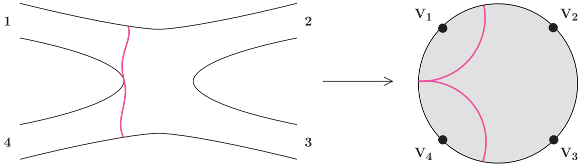

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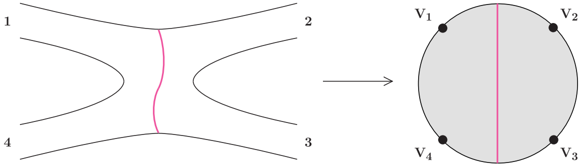

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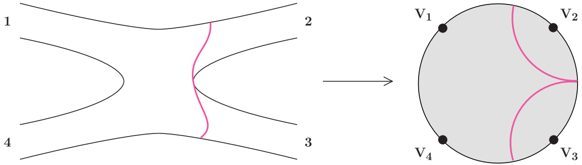

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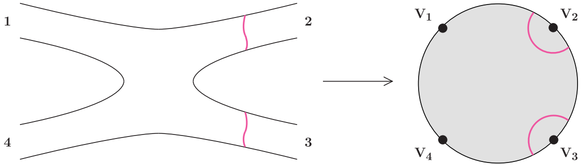

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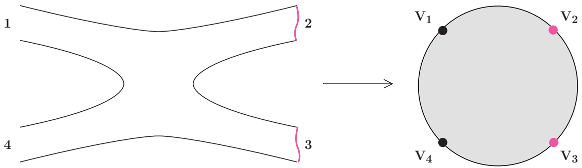

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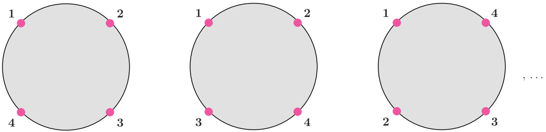
The Full Amplitude

One has to sum over all cyclic non-equivalent configurations



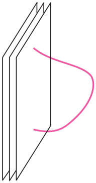
and integrate over the vertex operator positions z_i

$$\mathcal{A}(1,\ldots,N) \propto \int \prod_{i=1}^{N} \mathrm{d}z_i \sum_{\sigma\in S_{N-1}} \left\langle V_1(z_1)\, V_{\sigma(2)}(z_{\sigma(2)}) \ldots V_{\sigma(N)}(z_{\sigma(N)})\right\rangle .$$

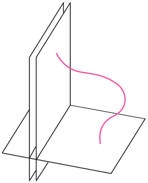
Challenges:

- Integration,
- Interacting CFT of ψ & S fields in $\langle V_1 \ldots V_n \rangle \rightarrow$ [DH, Schlotterer, Stieberger '09].

Strings & Branes & Gauge Theories

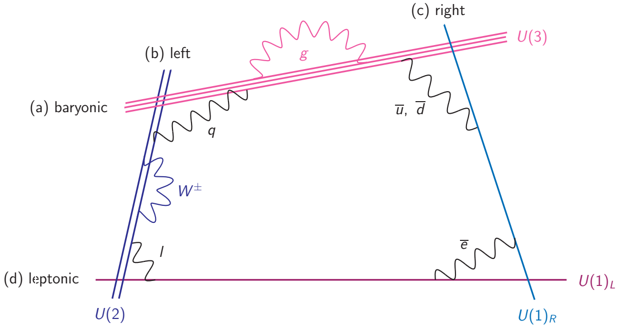


U(N) gauge bosons,



chiral fermions.

The SM from intersecting D6-branes:



Stringy QCD results

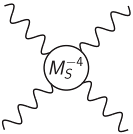
All tree-level amplitudes $pp \to pp$ are of the form [Lüst, Stieberger, Taylor '08]

$$\mathcal{A}(k_1, k_2, k_3, k_4, M_S) \sim \frac{s\,u}{t\,M_S^2}\; B(-s/M_S^2, -u/M_S^2)\,,$$

where s, u, t are the Mandelstam variables and $B(x, y)$ is the Euler beta function.

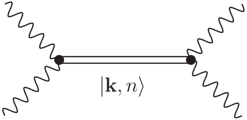
- M_S-expansion:

$$\mathcal{A} \sim \frac{t}{s} - \frac{\pi^2}{6}\, t\, u\, M_S^{-4} + \mathcal{O}(M_S^{-6})\,.$$



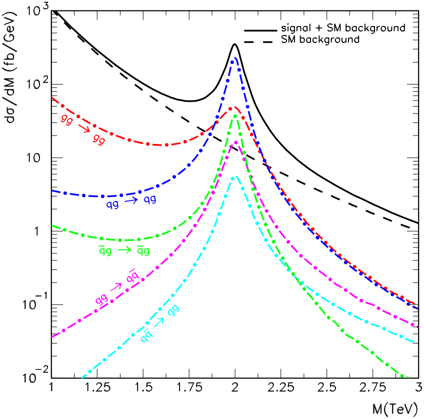
- pole-expansion:

$$B = -\sum_{n=0}^{\infty} \frac{M_S^{2-2n}}{n!}\, \frac{1}{s - nM_S^2} \left[\prod_{J=1}^{n} (u + M_S^2 J)\right]$$



Stringy Phenomenology

- Production of Regge-excitations [Lüst, Stieberger, Taylor et al. '08]



,

- model-dependent corrections from $qq \to qq$ [Lüst, Stieberger, Taylor et al. 09],
- photons at tree-level [Anchordoqui, Taylor et al. '08]: $gg \to g\gamma$, $gg \to \gamma\gamma$.

Conclusion

- You should now be able to recognize the larch from a long way away.
- You should watch Monty Python's Flying Circus.

Conclusion

- TeV scale quantum gravity can be realized in theories with large extra dimensions.
- String theory is the natural playground for such theories.
- LHC might discover stringy effects.

Thanks for your attention.

Vertex Operators

The vertex operators for gluons and fermions are

$$V_{A^a}(z,\xi,k) \;=\; g_A\;\lambda^a\;\; e^{-\phi(z)} \quad \xi^\mu\;\psi_\mu(z)\;e^{i\,k_\nu X^\nu(z)}\,,$$
$$V_{\psi^\alpha_\beta}(z,u,k) \;=\; g_\psi\;\lambda^\alpha_\beta\; e^{-\phi(z)/2}\;u^\lambda\;S_\lambda(z)\;e^{i\,k_\nu X^\nu(z)}\,\Xi(z)\,,$$

where $\begin{matrix}\psi^\mu\\ S_\alpha\end{matrix}$ is an external (4d) $\begin{matrix}\text{vector}\\ \text{spin field}\end{matrix}$, e^{ikX^ν} is the momentum part, and Ξ is an internal (6d) field.

The correlation function of vertex operators factorizes

$$\langle V_1(z_1)\ldots V_N(z_N)\rangle \propto \underbrace{\langle\mathcal{O}_X\rangle\cdot\langle\mathcal{O}_\Xi\rangle}_{\text{well-known}}\cdot\langle\mathcal{O}_{\psi,S}\rangle\,.$$

A formula for arbitrary ψ-S correlators at tree-level can be found in [DH, Schlotterer, Stieberger '09].