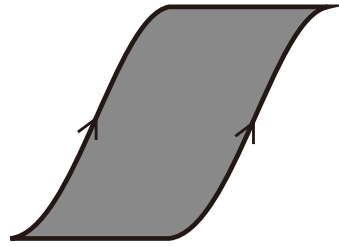
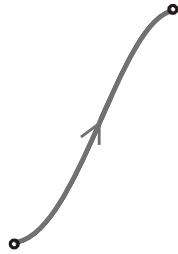


Warm-up: A quick review on superstring theory

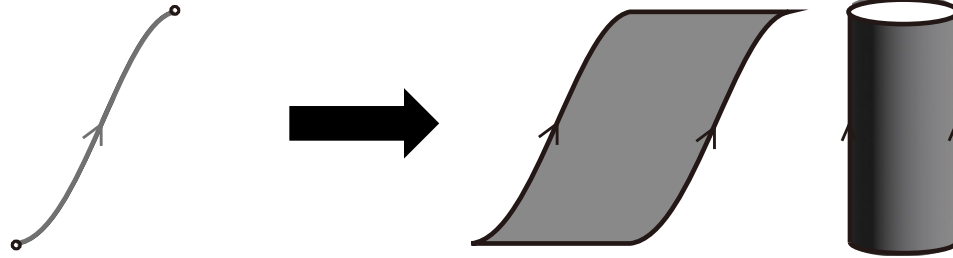
Warm-up: A quick review on superstring theory



$$S_{\text{pp}} = -m \int d\tau \sqrt{-\eta_{\mu\nu} \dot{X}^\mu \dot{X}^\nu}$$

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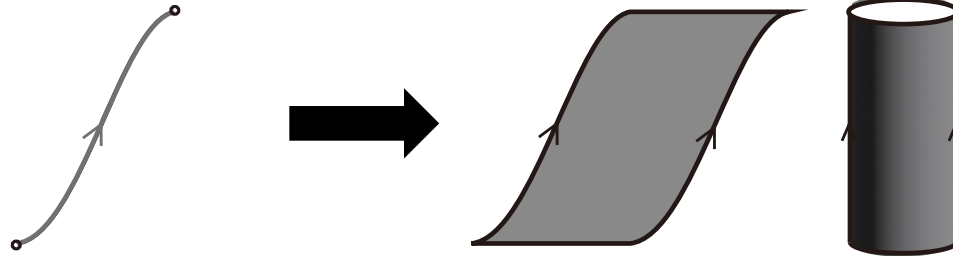
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String Theory is a **sigma model** on the worldsheet. It turns out string theory can be described by a **free CFT** on the worldsheet:

$$S_{\text{P}} = \underbrace{\frac{1}{2\pi\alpha'} \int d^2z \partial X^\mu \bar{\partial} X_\mu}_{\text{Free Boson}} + \underbrace{\frac{1}{2\pi} \int d^2z (b \bar{\partial} c + \tilde{b} \partial \tilde{c})}_{\text{Ghost Fields}} + \underbrace{\lambda \chi}_{\text{Topological Term}}$$

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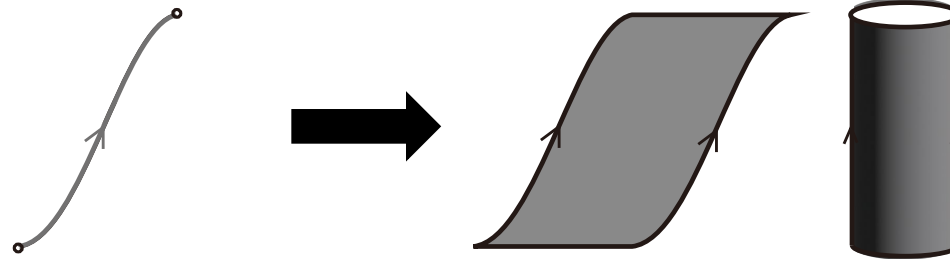
X^μ : Rieman surface \hookrightarrow our spacetime

b, c : fix the **diff** \times **weyl** gauge

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Unlike QFT, string theory's interactions are **intrinsic** and **unique**.

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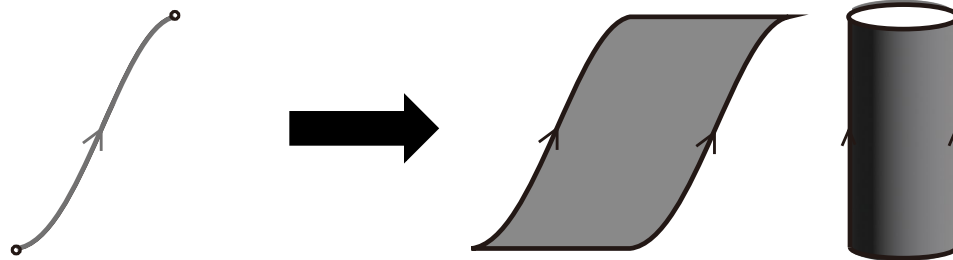
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To avoid conformal anomalies, central charge should be zero, which implies **D=26, 10**

String Amplitudes: Bosonic String

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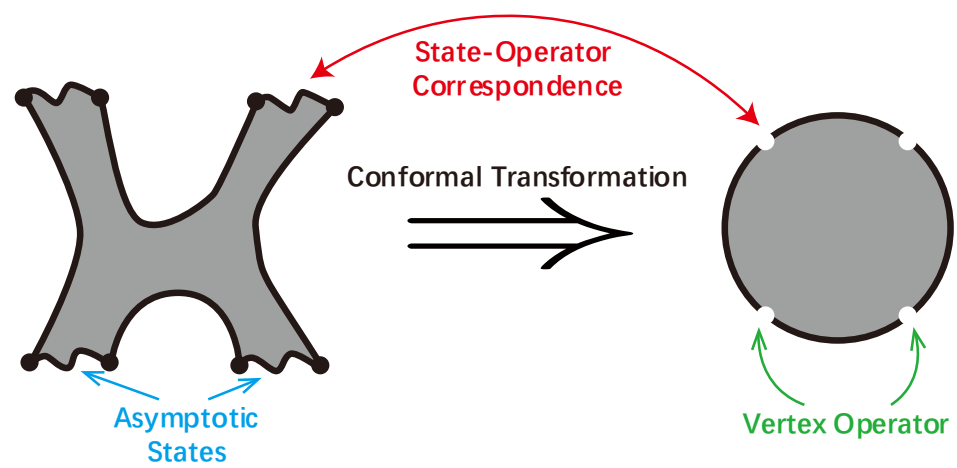
Tachyon $|0; k\rangle \cong e^{ik \cdot X(0,0)}$:

Photon $\alpha_{-1}^i |0; k\rangle \cong \partial X^\mu e^{ik \cdot X}$:

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$$V = cU$$



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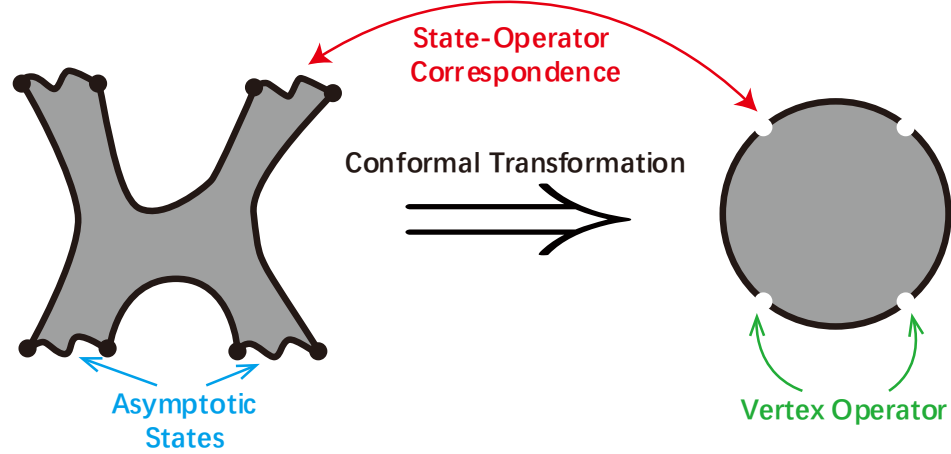
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$$\begin{aligned}
 &S_{j_1 \dots j_n}(k_1, \dots, k_n) \\
 &= \sum_{\text{compact topologies}} \int \frac{[dX dg]}{V_{\text{diff} \times \text{Weyl}}} \exp(-S_X - \lambda \chi) \prod_{i=1}^n \int d^2 \sigma_i g(\sigma_i)^{1/2} V_{j_i}(k_i, \sigma_i) \\
 &\sim \underbrace{e^{-\lambda \chi}}_{\text{Topological Expansion}} \underbrace{\int_{\mathcal{M}_{g,n}} d^\mu t}_{\text{Moduli Space}} \int \frac{d^2 z_1 \dots d^2 z_n}{V_{\text{CKG}}} \underbrace{\langle V_1 U_2 \dots U_{n-2} V_{n-1} V_n \rangle}_{\substack{\text{Integrated Vertex Operator} \\ \text{Unintegrated Vertex Operator}}} + \dots
 \end{aligned}$$

Annotations for the diagram:

- Topological Expansion:** Points to the $e^{-\lambda \chi}$ term.
- Moduli Space:** Points to the $\int_{\mathcal{M}_{g,n}} d^\mu t$ term.
- Fix 3 points on the sphere:** Points to the V_{CKG} term.
- Spherical Topology:** Points to the $\langle V_1 U_2 \dots U_{n-2} V_{n-1} V_n \rangle$ term.
- Integrated Vertex Operator:** Points to the $U_2 \dots U_{n-2}$ part of the correlator.
- Unintegrated Vertex Operator:** Points to the $V_1 V_{n-1} V_n$ part of the correlator.
- non-tivial Topologies:** Points to the ellipsis $+\dots$.

String Amplitudes: Bosonic String

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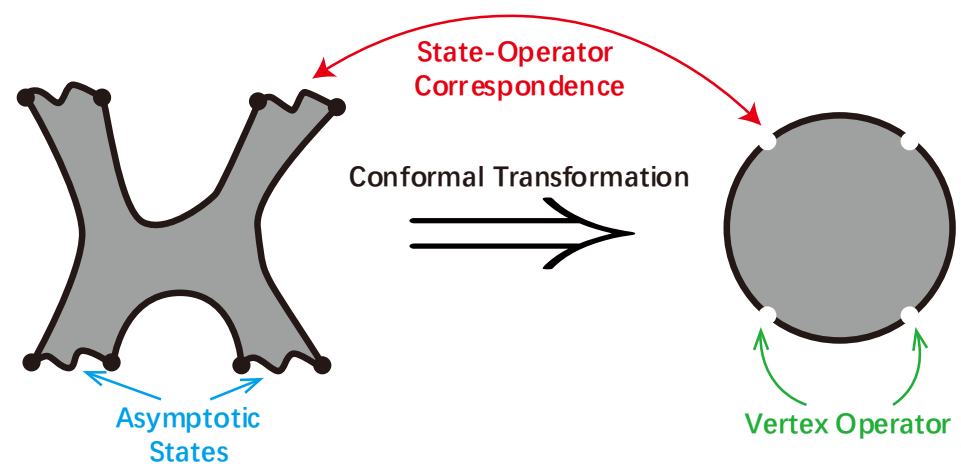
$$\int_{\mathcal{M}_{g,n}} d^\mu t : \text{integrate over all complex structures}$$
$$e^{\lambda\chi} : \text{sum over worldsheet topologies}$$
$$\int d^2 z : \text{Amplitudes independent of worldsheet coordinates}$$

V_{CKG} : Conformal symmetries help us fix some points

V: inserted at fixed punctures

U: integrated over the worldsheet

$\langle \dots \rangle$: Tree-level correlation functions
can be computed using the OPE



The diagram illustrates the derivation of the topological expansion from the path integral representation of the partition function. It shows the following steps:

- Topological Expansion:** The partition function is expressed as a sum over compact topologies, weighted by $e^{-\lambda\chi}$.
- Moduli Space:** The integral over the moduli space $\mathcal{M}_{g,n}$ is shown, with a green arrow indicating the transition from the compact topologies to the moduli space.
- Fix 3 points on the sphere:** The integral over the moduli space is shown, with a purple arrow indicating the transition from the moduli space to the sphere.
- Spherical Topology:** The integral over the sphere is shown, with a black arrow indicating the transition from the sphere to the spherical topology.
- Integrated Vertex Operator:** The integral over the sphere is shown, with a blue arrow indicating the transition from the sphere to the integrated vertex operator.
- Unintegrated Vertex Operator:** The integral over the sphere is shown, with a red arrow indicating the transition from the sphere to the unintegrated vertex operator.
- non-trivial Topologies:** The final result is shown as a sum of terms, with a black arrow indicating the transition from the spherical topology to the non-trivial topologies.

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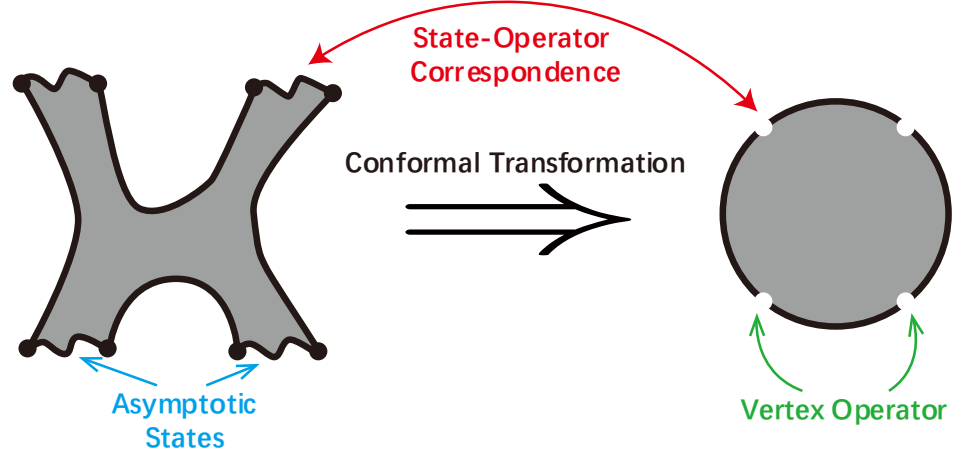
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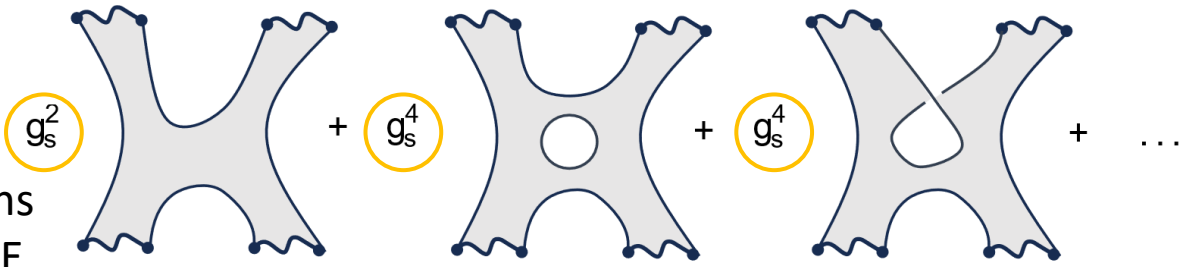


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Topological Expansion Fix 3 points on the sphere Spherical Topology Integrated Vertex Operator Unintegrated Vertex Operator non-trivial Topologies



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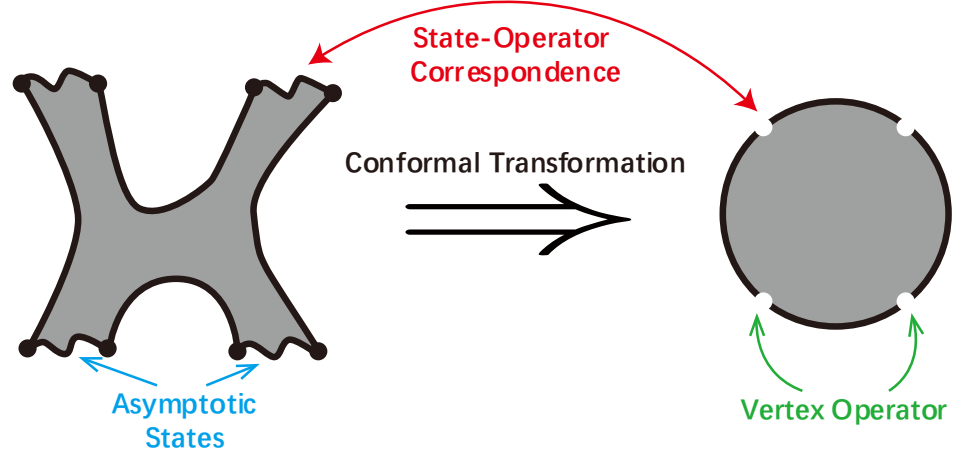
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QFT: off-shell correlation function $\xrightarrow{\text{LSZ Formula}}$ on-shell amplitudes

String Theory: we only know how to define the on-shell amplitudes directly!

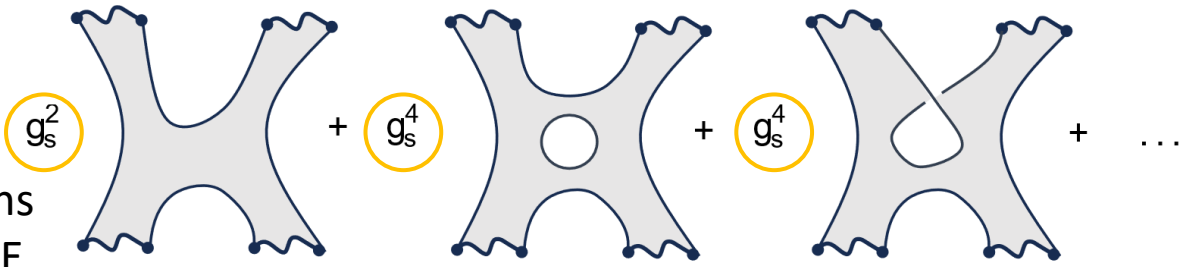


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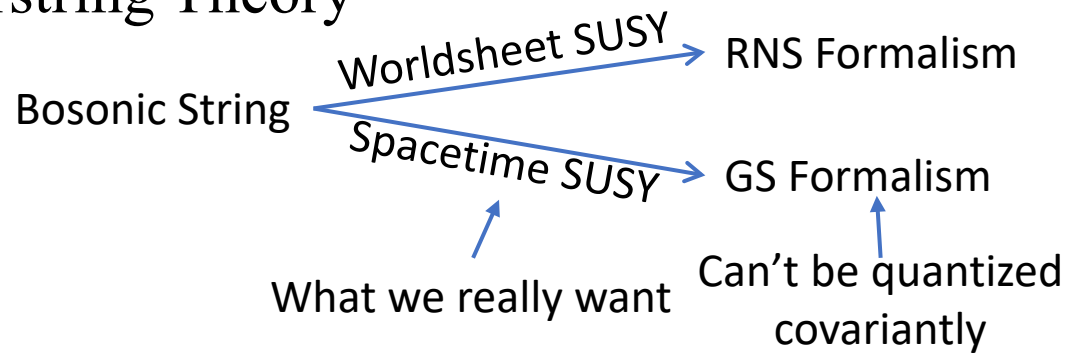


Superstring Theory

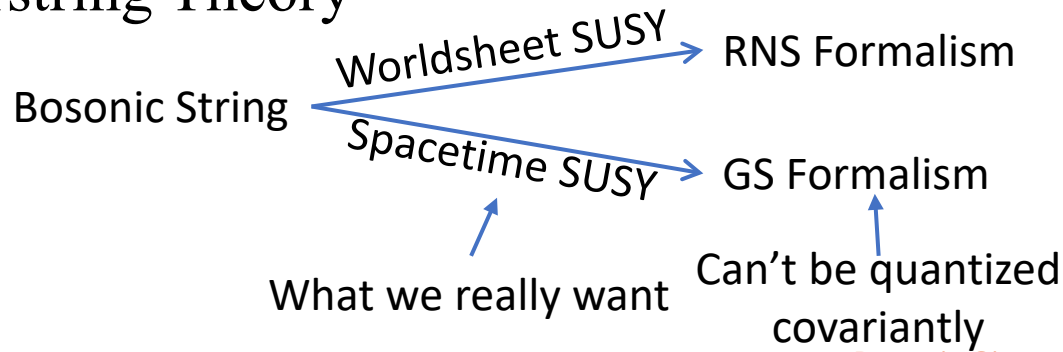
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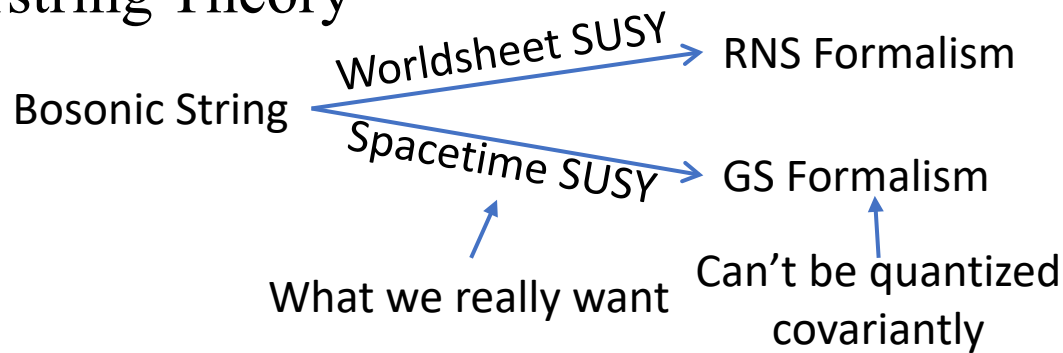
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 But \mathcal{H}_{CQ} is **non-SUSY**!

1-loop modular invariance



We need **GSO projection**



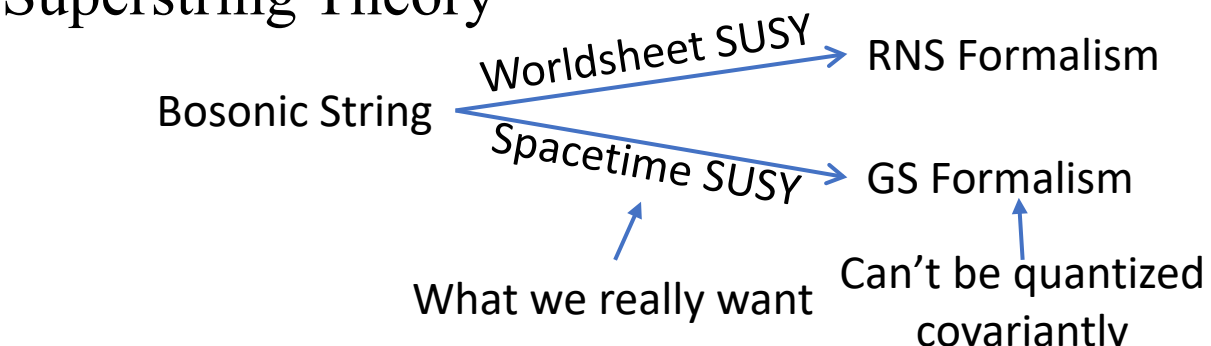
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Type IIA\B superstring

SUSY is hidden, not broken!

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2× dilatino gravitino $2 \times 56 \oplus 8$ IIA: same chirality IIB: opposite chirality	$\tilde{\psi}_{-1/2}^i 0\rangle_{\text{NS}} \otimes \alpha; +\rangle_{\text{R}}$	$\tilde{\psi}_{-1/2}^i 0\rangle_{\text{NS}} \otimes \alpha; +\rangle_{\text{R}}$
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The definition of amplitudes is analogous to the bosonic string



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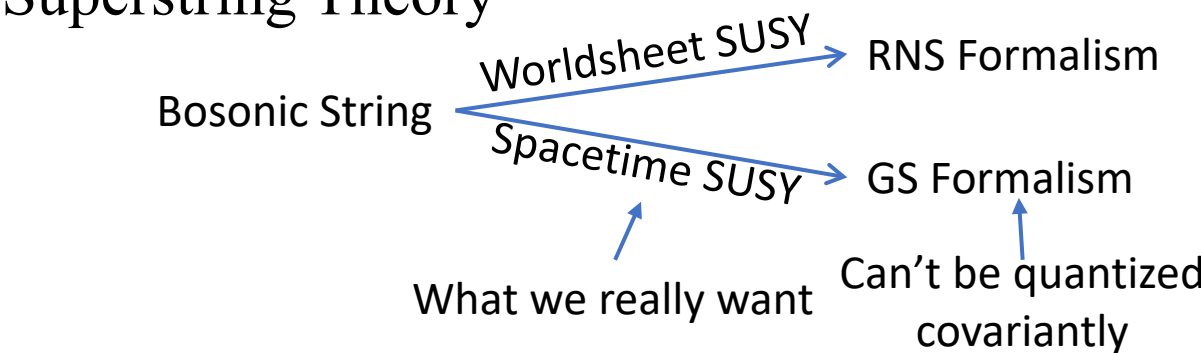
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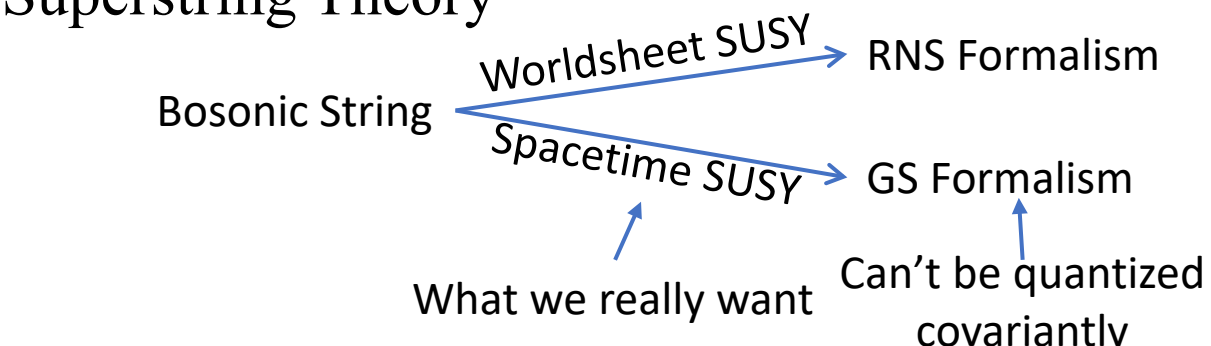
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 Spinor Formalism!