Title: String Theory Lecture

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Collection: String Theory 2023/24

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$$\partial X = \sum a_n e^{-ns}$$

$$T = -\frac{1}{2} \lim \left(\partial X(s) \partial X(s') - \frac{1}{(s-s')^2} \right)$$

$$T = -\frac{1}{24} + \sum_n L_n e^{-ns}$$

$$L_n = \frac{1}{2} \sum_m : a_{n-m} a_m :$$

$$\left[\frac{1}{(s-s')^2} - \frac{1}{(s-s')^2} \right]$$

$$\{ s, s \}$$

$$\left(\frac{}{(s-s')^2} \right)$$

$$[L_n, a_m] = m\, a_{n+m}$$

$$[L_n, X(s)] = e^{ns} \partial_s X(s)$$

$$[L_n, \partial X(s)] = \partial (e^{ns} \partial_s X) = e^{ns} \partial (\partial X) + n e^{ns} \partial_s X$$

$$[L_n, \partial X(s) \partial X(s')] = \cdots$$

$$[L_n, T(s)] = e^{ns} \partial_s T(s) + 2n e^{ns} T(s) + \frac{n^3}{12} e^{ns}$$

$T^{ab} = 0$

$\langle PHYS | T | PHYS \rangle = 0$

$\langle PHYS | L_m | PHYS \rangle = 0$

$L_m | PHYS \rangle = 0 \quad m > 0$

$\langle PHYS | L_{-m} = 0$

$(L_0 - \boxed{1}) | PHYS \rangle$

$D = 26$

$|NULL\rangle = L_{-m} | \cdots \rangle$

$KER(L_m, L_0 - 1)$

$KER(L_m, L_0 - 1) \cap IM(L_{-m})$

$T^{ab} = 0$

$\langle PHYS | T | PHYS \rangle = 0$

$\langle PHYS | L_m | PHYS \rangle = 0$

$L_m | PHYS \rangle = 0 \quad m > 0$

$\langle PHYS | L_{-m} = 0$

$(L_0 - \boxed{1}) | PHYS \rangle$

$= 26$

A^0

X^μ

$|NULL\rangle = L_{-n} | \cdots \rangle$

$$\frac{KER\,(L_n\,,\,L_0 - 1)}{KER(L_n, L_{0-1}) \cap IM\,(L_{-n})}$$

$a_n \quad \bar{a}_n$

$L_{-n}|\cdots\rangle$

$L_n, L_0 - 1)$

$M(L_{-n})$

X^μ

$[a^\mu_n, a^\nu_m] = n\delta_{n+m,0}\,\eta^{\mu\nu}$

$\langle p|a^\mu_{-1}\, a^\nu_1|p\rangle = \eta^{\mu\nu}\delta(p-p')$

$|p\rangle$

$a^\mu_{-1}|p\rangle \;,\; \bar{a}^\mu_{-1}|p\rangle$

$a^\mu_{-1}\bar{a}^\nu_{-1}|p\rangle + \cdots$

$\partial X \quad \bar{\partial} X$
$a_n \quad \bar{a}_n$

$|NULL\rangle = L_{-n}|\cdots\rangle$

$\bar{L}_n \quad \bar{L}_{0-1}$
$KER(L_n, L_{0-1})$

$KER(L_n, L_{0-1}) \cap IM\left(\frac{L_{-n}}{\bar{L}_{-n}}\right)$

X^μ

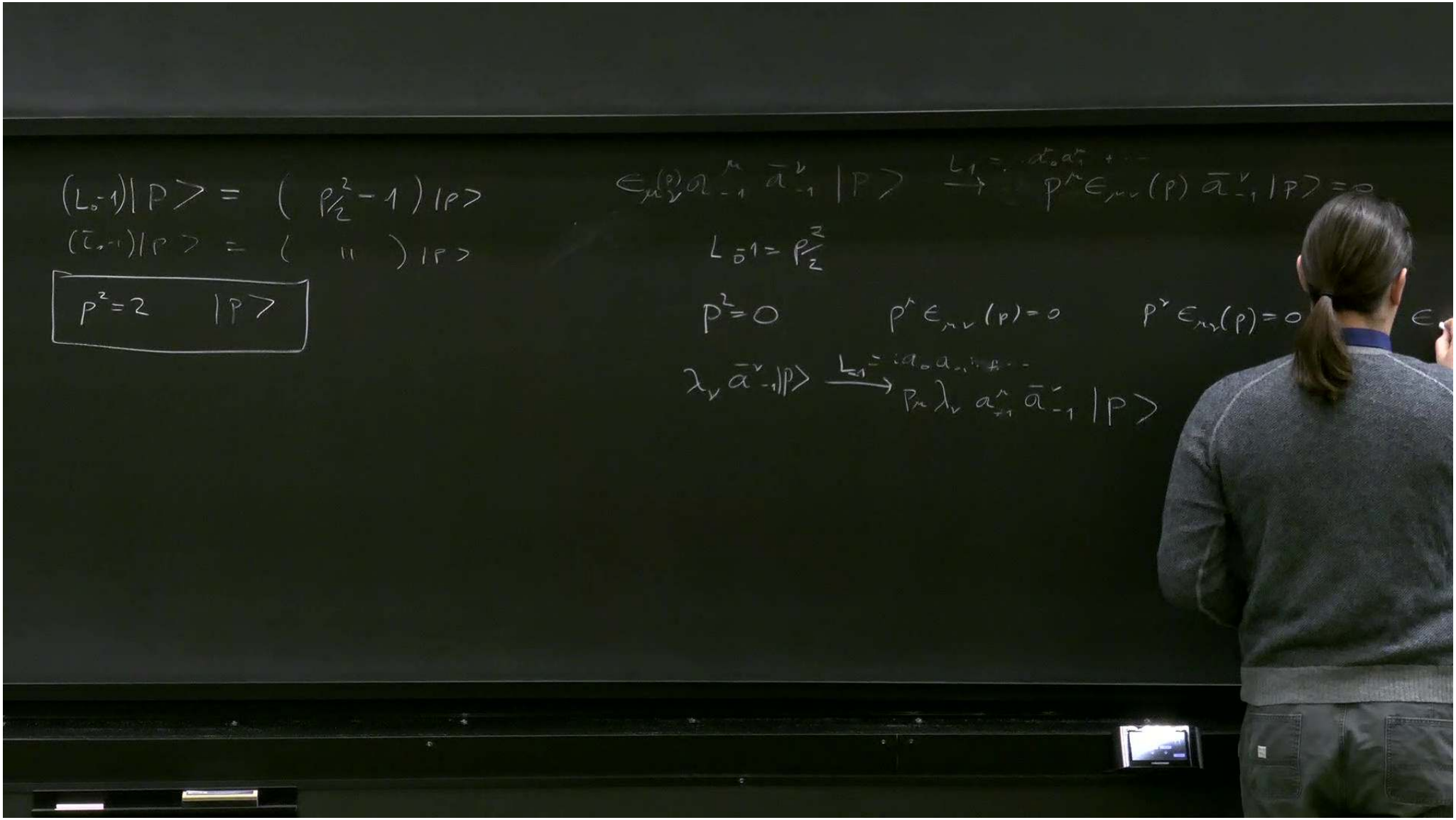
$[a^\mu_n, a^\nu_m] = \ldots$

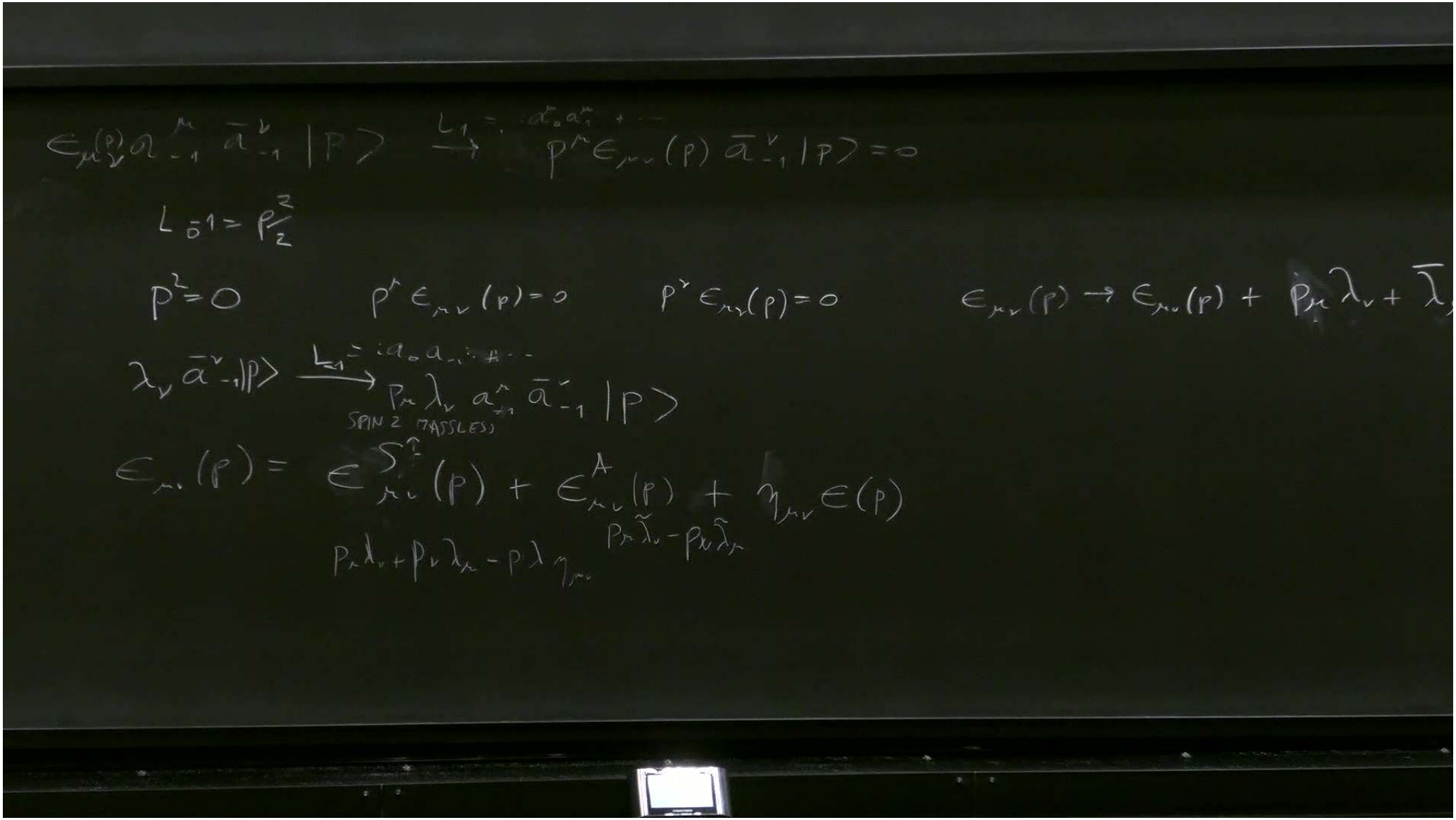
$\langle p | a^\mu_{-1} \; a^\nu_1 | p \rangle = \eta^{\mu\nu}$

$|p\rangle$

$a^\mu_{-1}|p\rangle \;, \; \bar{a}^\mu_{-1}|p\rangle$

$a^\mu_{-1}\bar{a}^\nu_{-1}|p\rangle + \cdots$


$(L_0 - 1)|p\rangle = (p_2^2 - 1)|p\rangle$
$(\bar{L}_0 - 1)|p\rangle = (\quad " \quad)|p\rangle$
$p^2 = 2 \quad |p\rangle$
$\epsilon_{\mu\nu}(p) a_{-1}^{\mu} \bar{a}_{-1}^{\nu} |p\rangle \xrightarrow{L_1 = \ldots} p^{\mu} \epsilon_{\mu\nu}(p) \bar{a}_{-1}^{\nu} |p\rangle = 0$
$L_0 1 = p_2^2$
$p^2 = 0$
$p^{\nu} \epsilon_{\mu\nu}(p) = 0$
$p^{\nu} \epsilon_{\mu\nu}(p) = 0$
$\lambda_{\nu} \bar{a}_{-1}^{\nu} |p\rangle \xrightarrow{\bar{L}_1 = \ldots} p_{\mu} \lambda_{\nu} a_{-1}^{\mu} \bar{a}_{-1}^{\nu} |p\rangle$


$\epsilon_{\mu\nu}(p)\, a^{\mu}_{-1}\, \bar{a}^{\nu}_{-1}\,|p\rangle \xrightarrow{L_1 = \sum a_0 a_1 + \cdots} p^{\mu}\epsilon_{\mu\nu}(p)\,\bar{a}^{\nu}_{-1}\,|p\rangle = 0$
$L_0 - 1 = \frac{p^2}{2}$
$p^2 = 0$
$p^{\mu}\epsilon_{\mu\nu}(p) = 0$
$p^{\nu}\epsilon_{\mu\nu}(p) = 0$
$\epsilon_{\mu\nu}(p) \to \epsilon_{\mu\nu}(p) + p_{\mu}\lambda_{\nu} + \bar{\lambda}$
$\lambda_{\nu}\bar{a}^{\nu}_{-1}|p\rangle \xrightarrow{L_1 = \sum a_0 a_1 + \cdots} p_{\mu}\lambda_{\nu}\, a^{\mu}_{-1}\,\bar{a}^{\nu}_{-1}\,|p\rangle$
SPIN 2 (MASSLESS)
$\epsilon_{\mu\nu}(p) = \epsilon^{S}_{\mu\nu}(p) + \epsilon^{A}_{\mu\nu}(p) + \eta_{\mu\nu}\epsilon(p)$
$p_{\mu}\lambda_{\nu} + p_{\nu}\lambda_{\mu} - p\lambda\,\eta_{\mu\nu}$
$p_{\mu}\tilde{\lambda}_{\nu} - p_{\nu}\tilde{\lambda}_{\mu}$

PARTICLE $\int ds + \int A_\mu dx^\mu$

STRING $\int dA + \int B_{\mu\nu} \frac{\partial x^\mu}{\partial \sigma^1} \frac{\partial x^\nu}{\partial \sigma^2}$

$H_{\mu\nu\sigma} = \epsilon_{\mu\nu\sigma\tau} \partial_\tau \phi$

$B_{\mu\nu} \to B_{\mu\nu} + \partial_\mu \Lambda_\nu - \partial_\nu \Lambda_\mu$

$1)|p\rangle$

$)|p\rangle$

$\epsilon_{\mu\nu}(p)\, a_{-1}^{\mu}\, \bar{a}_{-1}^{\nu}|p\rangle \xrightarrow{L_1 = \ldots a_0 a_1 + \ldots} p^{\mu}\epsilon_{\mu\nu}(p)\, \bar{a}_{-1}^{\nu}|p\rangle = 0$

$L_0 - 1 = \frac{p^2}{2}$

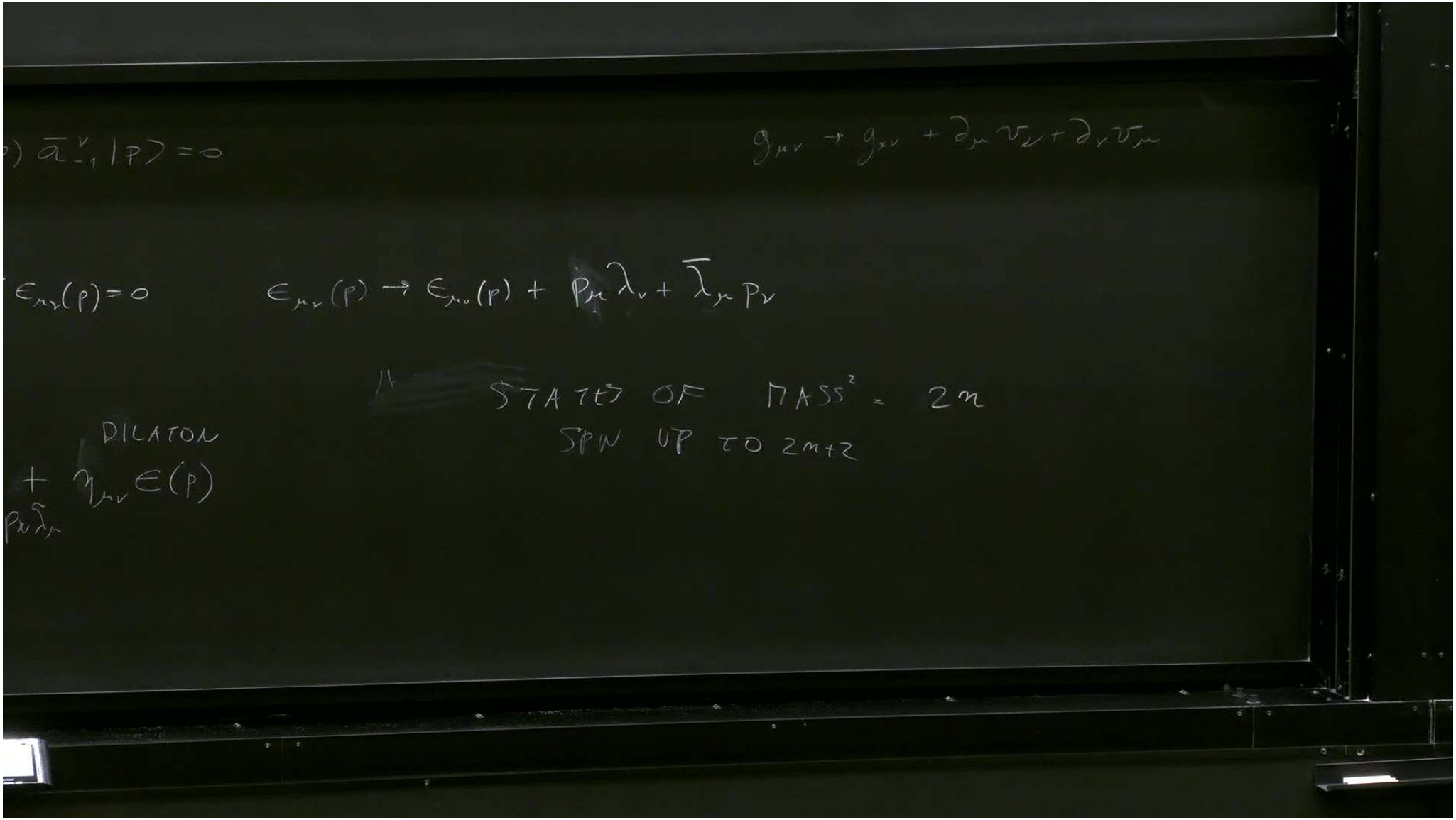
$p^2 = 0 \qquad p^{\mu}\epsilon_{\mu\nu}(p) = 0 \qquad p^{\nu}\epsilon_{\mu\nu}(p) = 0 \qquad \epsilon_{\mu\nu}(p) \to \epsilon_{\mu\nu}(p) + p_{\mu}$

$\lambda_{\nu}\bar{a}_{-1}^{\nu}|p\rangle \xrightarrow{L_{-1} = i a_0 a_{-1} + \ldots} p_{\mu}\lambda_{\nu}\, a_{-1}^{\mu}\, \bar{a}_{-1}^{\nu}|p\rangle$

SPIN 2 MASSLESS — B-FIELD — DILATON

$\epsilon_{\mu\nu}(p) = \epsilon_{\mu\nu}^{S}(p) + \epsilon_{\mu\nu}^{A}(p) + \eta_{\mu\nu}\epsilon(p)$

$p_{\mu}\lambda_{\nu} + p_{\nu}\lambda_{\mu} - p\lambda\eta_{\mu\nu} \qquad p_{\mu}\tilde{\lambda}_{\nu} - p_{\nu}\tilde{\lambda}_{\mu}$


$\bar{a}_{-1}^{\nu}|p\rangle = 0$
$g_{\mu\nu} \to g_{\mu\nu} + \partial_\mu v_\nu + \partial_\nu v_\mu$
$\epsilon_{\mu\nu}(p) = 0$
$\epsilon_{\mu\nu}(p) \to \epsilon_{\mu\nu}(p) + p_\mu \lambda_\nu + \bar{\lambda}_\mu p_\nu$
STATES OF MASS^2 = 2n
SPIN UP TO 2n+2
DILATON
$+ \eta_{\mu\nu} \epsilon(p)$
$p_\nu \tilde{\lambda}_\nu$

$|p\rangle = (p_2^2 - 1)|p\rangle$

$|p\rangle = (\quad\quad)|p\rangle$

$2 \quad |p\rangle$

$\epsilon_{\mu\nu}(p)\, \alpha_{-1}^{\mu}\, \tilde{\alpha}_{-1}^{\nu}\, |p\rangle \xrightarrow{L_1 = \alpha_0 \alpha_1 + \cdots} p^{\mu}\epsilon_{\mu\nu}(p)\, \tilde{\alpha}_{-1}^{\nu}|p\rangle = 0$

$L_0 = p_2^2$

$p^2 = 0 \qquad p^{\mu}\epsilon_{\mu\nu}(p) = 0 \qquad p^{\nu}\epsilon_{\mu\nu}(p) = 0 \qquad \epsilon_{\mu\nu}($

$\lambda_{\nu}\tilde{\alpha}_{-1}^{\nu}|p\rangle \xrightarrow{L_{-1} = \alpha_0 \alpha_{-1} + \cdots} p_{\mu}\lambda_{\nu}\, \alpha_{-1}^{\mu}\, \tilde{\alpha}_{-1}^{\nu}|p\rangle$

SPIN 2 MASSLESS

$\epsilon_{\mu\nu}(p) = \epsilon_{\mu\nu}^{S}(p) + \epsilon_{\mu\nu}^{A}(p) + \eta_{\mu\nu}\epsilon(p)$

B-FIELD

DILATON

$p_{\mu}\lambda_{\nu} + p_{\nu}\lambda_{\mu} - p\lambda\eta_{\mu\nu} \qquad p_{\mu}\tilde{\lambda}_{\nu} - p_{\nu}\tilde{\lambda}_{\mu}$

$(L_0 - 1)|PHYS\rangle$

$D = 26$

$c = 26, \quad \Delta = 1$

$(L_0 - 1)|P\rangle = (p_L^2 - 1)|P\rangle$

$(\bar{L}_0 - 1)|P\rangle = (\quad " \quad)|P\rangle$

$p^2 = 2 \quad |P\rangle$

$\epsilon_{\mu\nu}(p)\, \alpha_{-1}^{\mu} \bar{\alpha}_{-1}^{\nu} |P\rangle \xrightarrow{L_1 = \alpha_0 \alpha_{-1} + \cdots} p^{\mu} \epsilon_{\mu\nu}(p)\, \bar{\alpha}_{-1}^{\nu}$

$L_0 1 = p_L^2$

$p^2 = 0 \qquad p^{\mu} \epsilon_{\mu\nu}(p) = 0 \qquad p^{\nu} \epsilon_{\mu\nu}(p) =$

$\lambda_{\nu} \bar{\alpha}_{-1}^{\nu} |P\rangle \xrightarrow{L_1 = \alpha_0 \alpha_{-1} + \cdots} p_{\mu} \lambda_{\nu}\, \alpha_{-1}^{\mu} \bar{\alpha}_{-1}^{\nu} |P\rangle$

(SPIN 2 MASSLESS) (B-FIELD)

$\epsilon_{\mu\nu}(p) = \epsilon_{\mu\nu}^{S}(p) + \epsilon_{\mu\nu}^{A}(p) + \eta_{\mu\nu}$

$p_{\mu}\lambda_{\nu} + p_{\nu}\lambda_{\mu} - p\lambda\, \eta_{\mu\nu} \qquad p_{\mu}\tilde{\lambda}_{\nu} - p_{\nu}\tilde{\lambda}_{\mu}$