

Title: PSI 2015/2016 More/Beyond Standard Model - Lecture 2

Date: Feb 23, 2016 09:00 AM

URL: <http://pirsa.org/16020067>

Abstract:

$$S = \int d^4x \sqrt{g} \left(\frac{M_{\text{Pl}}^2}{2} R + \mathcal{L}_{\text{SM}}(g) + \mathcal{L}_\phi \right)$$

$$g_{\mu\nu}(x) = \eta_{\mu\nu} + h_{\mu\nu}(x)/M_{\text{Pl}}^2$$

Effective Field Theory (EFT)

$$E \ll M_{\text{Pl}}$$

$$(\partial^2 - \partial^4/M_{\text{Pl}}^2) \phi$$

$$S = \int d^4x \sqrt{g} \left(\frac{M_{\text{Pl}}^2}{2} R + \mathcal{L}_{\text{SM}}(g) + \mathcal{L}_\Phi \right)$$

$$g_{\mu\nu}(x) = \eta_{\mu\nu} + h_{\mu\nu}(x)/M_{\text{Pl}}^2$$

Effective Field Theory (EFT)

$$E \ll M_{\text{Pl}}$$

$$(\partial^2 - \partial^4/M_{\text{Pl}}^2) \phi$$

1. E

$$\mathcal{L} = \mathcal{L}_{SM}(g) + \mathcal{L}_\nu$$

$$m_\nu = m_{SM} + h_{\nu\nu}(X)/M_{Pl}$$

(Theory (EFT))

$$(M_{Pl})^\phi$$

1. electroweak hierarchy
2. Cosmology -

$$\mathcal{L} = \mathcal{L}_{SM}(g) + \mathcal{L}_\Delta$$

$$\mathcal{L}_\Delta = \mathcal{L}_{nu} + h_{nu}(x)/M_{Pl}$$

(Theory (EFT))

$$(M_{Pl})^\dagger$$

1. electroweak hierarchy
2. Cosmology:
 - dark matter
 - (dark energy)
 - baryon asymmetry
3. Flavour:
 - $m_c \ll m_t$
 - ν masses
 - θ problem

Dimensional Analysis

$$S = \int d^d x \mathcal{L}$$

$$[x] = [L] = M^{-1}$$

$$[p] = [E] = M$$

$$[\partial] = M$$

$$[S] = 0$$

Dimensional Analysis

$$S = \int d^d x \mathcal{L}$$

$$[x] = [L] = -1$$

$$[p] = [E] = 1$$

$$[\partial] = M$$

$$[S] = 0$$

$$L \sim M^{-1}$$

Dimensional Analysis

$$[\mathcal{L}] = +d$$

$$S = \int d^d x \mathcal{L}$$

$$[x] = [L] = -1$$

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$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2$$

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$$L \sim M^{-1}$$

$$[\mathcal{L}] = +d$$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2$$

$$d = 2 + 2[\phi]$$

$$[\phi] = \left(\frac{d-2}{2}\right) \rightarrow 1$$

Dimensional Analysis

$$S = \int d^d x \mathcal{L}$$

$$[x] = [L] = -1$$

$$[p] = [E] = 1$$

$$[\partial] = M$$

$$[S] = 0$$

$$\mathcal{L} \sim M^d$$

$$[\mathcal{L}] = +d$$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2$$

$$d = 2 + 2[\phi]$$

$$[\phi] = \left(\frac{d-2}{2}\right) \rightarrow 1$$

$$\bar{\Psi} i \gamma^\mu \partial_\mu \Psi \Rightarrow d = 1 + 2[\Psi]$$

$$m^2 \phi^2 \rightarrow d = 2[m] + 2[\phi]$$

$$[m] = 1$$

$$[\lambda] = 0 \quad [\gamma] = 0$$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \underbrace{\frac{1}{2}m^2\phi^2}_{L_1} + \underbrace{\bar{\Psi}i\gamma^\mu\partial_\mu\Psi}_{\substack{1 \\ 1}} - M\underbrace{\bar{\Psi}\Psi}_1 - \frac{A}{3!}\phi^3 + \frac{\lambda}{4!}\phi^4 - \gamma\bar{\phi}\bar{\Psi}\Psi$$

$$[A] = 1$$

$$d=4: [\phi] = 1$$

$$[\psi] = \frac{3}{2}$$

$$m^2 \phi^2 \rightarrow d = 2[m] + 2[\phi]$$

$$[m] = 1$$

$$F_{\mu\nu} F^{\mu\nu} \quad \nearrow [A] = 1$$

$$\hookrightarrow (\partial_\mu A_\nu - \partial_\nu A_\mu)$$

$$[\lambda] =$$

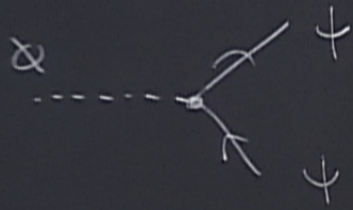
$$\mathcal{L} = \frac{1}{2} (\partial\phi)^2 - \frac{1}{2} m^2 \phi^2 + \bar{\Psi} i \gamma^\mu \partial_\mu \Psi - \underbrace{M \bar{\Psi} \Psi}_1 - \frac{A}{3!} \phi^3 - \frac{\lambda}{4!} \phi^4$$

$$[A] = 1$$

$$d=4: [\phi] = 1$$

$$[\psi] = \frac{3}{2}$$

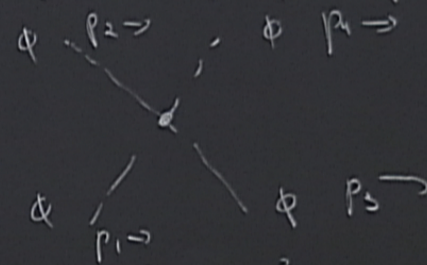
$$\Gamma(\phi \rightarrow \bar{\psi} \psi) \sim y^2 m$$



$m = \text{mass of } \phi$

$$M \ll m$$

$$\phi \phi \rightarrow \phi \phi \quad (\text{in limit of } y \rightarrow 0, A \rightarrow 0)$$



$$s = (p_1 + p_2)^2 \gg m^2$$

$$t = (p_1 - p_3)^2$$

$$u = (p_1 - p_4)^2$$

$$\psi \sim y^2 m$$

$\phi \phi \rightarrow \phi \phi$ (in limit of $y \rightarrow 0, A \rightarrow 0$)
 $\phi \xrightarrow{p_2} \quad \phi \xrightarrow{p_4}$

$$\sigma \sim \frac{1}{s}$$

$\phi \xrightarrow{p_1} \quad \phi \xrightarrow{p_3}$

$$s = (p_1 + p_2)^2 \gg m^2$$

$$t = (p_1 - p_3)^2$$

$$u = (p_1 - p_4)^2$$

$\phi\phi \rightarrow \phi\phi$ (in limit of $y \rightarrow 0, A \rightarrow 0$)

$\phi \xrightarrow{p_2} \phi \xrightarrow{p_1}$

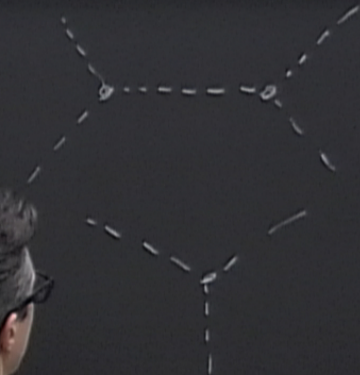
$$\sigma \sim \frac{\lambda^2}{s}$$

$\phi \xrightarrow{p_1} \phi \xrightarrow{p_3}$

$$\left\{ \begin{array}{l} s = (p_1 + p_2)^2 \gg m^2 \\ t = (p_1 - p_3)^2 \\ u = (p_1 - p_4)^2 \end{array} \right.$$

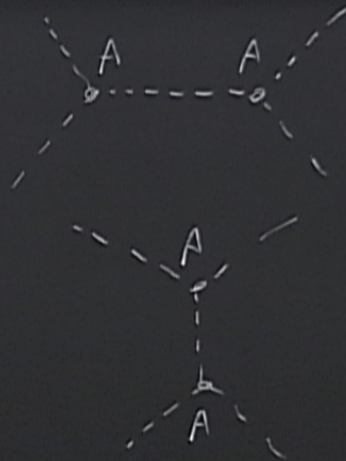
$$t = (p_1 - p_3)^2$$

$$u = (p_1 - p_4)^2$$



in limit of $y \rightarrow 0, A \rightarrow 0$)

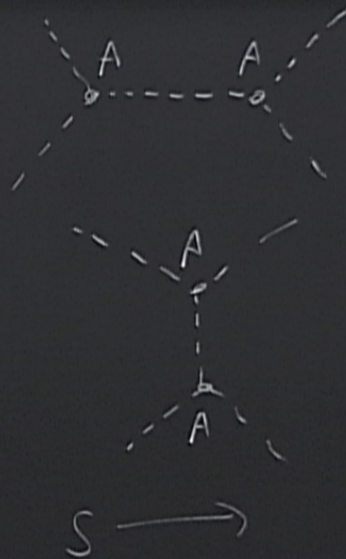
$$\sigma \sim \frac{\lambda^2}{S}$$



$$\sigma \sim A^4$$

in limit of $y \rightarrow 0, A \rightarrow 0$)

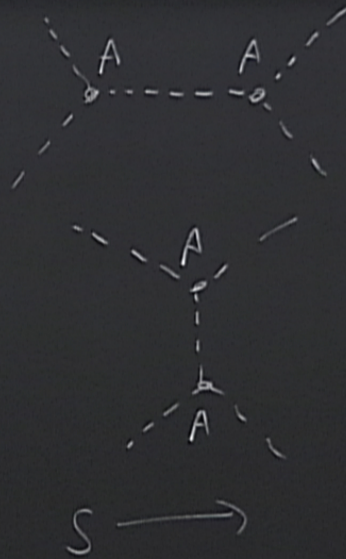
$$\sigma \sim \frac{\lambda^2}{S}$$



$$\sigma \sim \frac{A^4}{S^3}$$

in limit of $y \rightarrow 0, A \rightarrow 0$)

$$\sigma \sim \frac{\lambda^2}{S}$$



$$\sigma \sim \frac{A^4}{S^3}$$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_0^2\phi^2 - \frac{\lambda_0}{4!}\phi^4, \quad d=4$$

$$\cancel{\times} = -i\lambda_0 \quad \cdots \quad \frac{i}{p^2 - m_0^2 + i\epsilon}$$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_0^2\phi^2 - \frac{\lambda_0}{4!}\phi^4, \quad d=4$$

$$\text{X} = -i\lambda_0 \quad \text{---} \quad \frac{i}{p^2 - m_0^2 + i\epsilon}$$

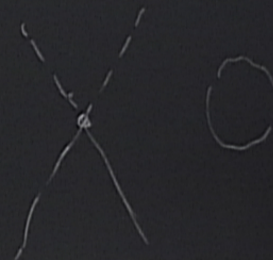
$\Gamma^{(2n)}$ = 1PI connected 2n-point functions



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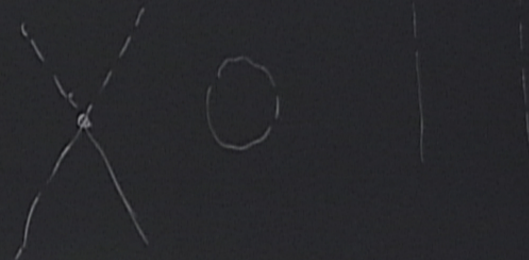
$\Gamma^{(2n)}$ = 1PI connected $2n$ -point functions



$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_0^2\phi^2 - \frac{\lambda_0}{4!}\phi^4, \quad d=4$$

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$\Gamma^{(2n)}$ = IPI connected 2n-point functions



$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_0^2\phi^2 - \frac{\lambda_0}{4!}\phi^4, \quad d=4$$

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$\Gamma^{(2n)} = \text{1PI connected } 2n\text{-point functions}$



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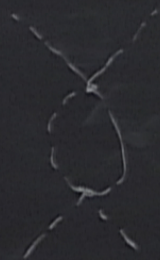
$\Gamma^{(2n)} = \text{1PI connected } 2n\text{-point functions}$



$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_0^2\phi^2 - \frac{\lambda_0}{4!}\phi^4, \quad d=4$$

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$\Gamma^{(2n)} = \text{1PI connected } 2n\text{-point functions}$

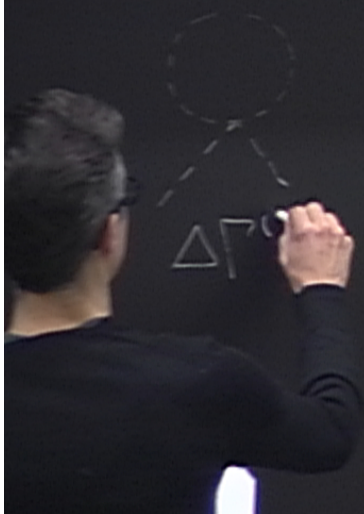


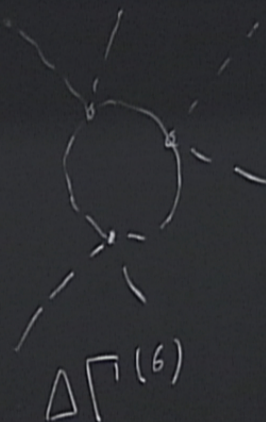
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$$\text{---} \times \text{---} = -i\lambda_0 \quad \text{---} \text{---} \text{---} = \frac{i}{p^2 - m_0^2 + i\epsilon}$$

$\Gamma^{(2n)}$ = 1PI connected $2n$ -point functions with ext. propagators removed

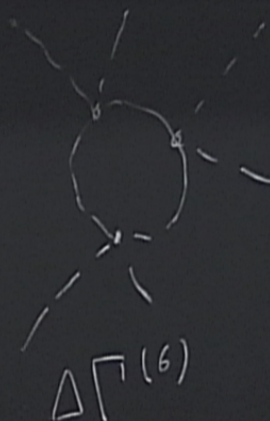
$\Gamma^{(2n)} = \text{1PI}$ connected $2n$ -point functions with ext. propagators removed





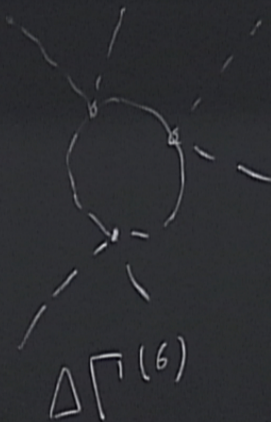


$$\Delta\Gamma(2n) \sim \lambda_0^n \int \frac{d^4 q}{(2\pi)^4} \left(\frac{1}{q^2 - m_0^2 + i\epsilon} \right)^n$$



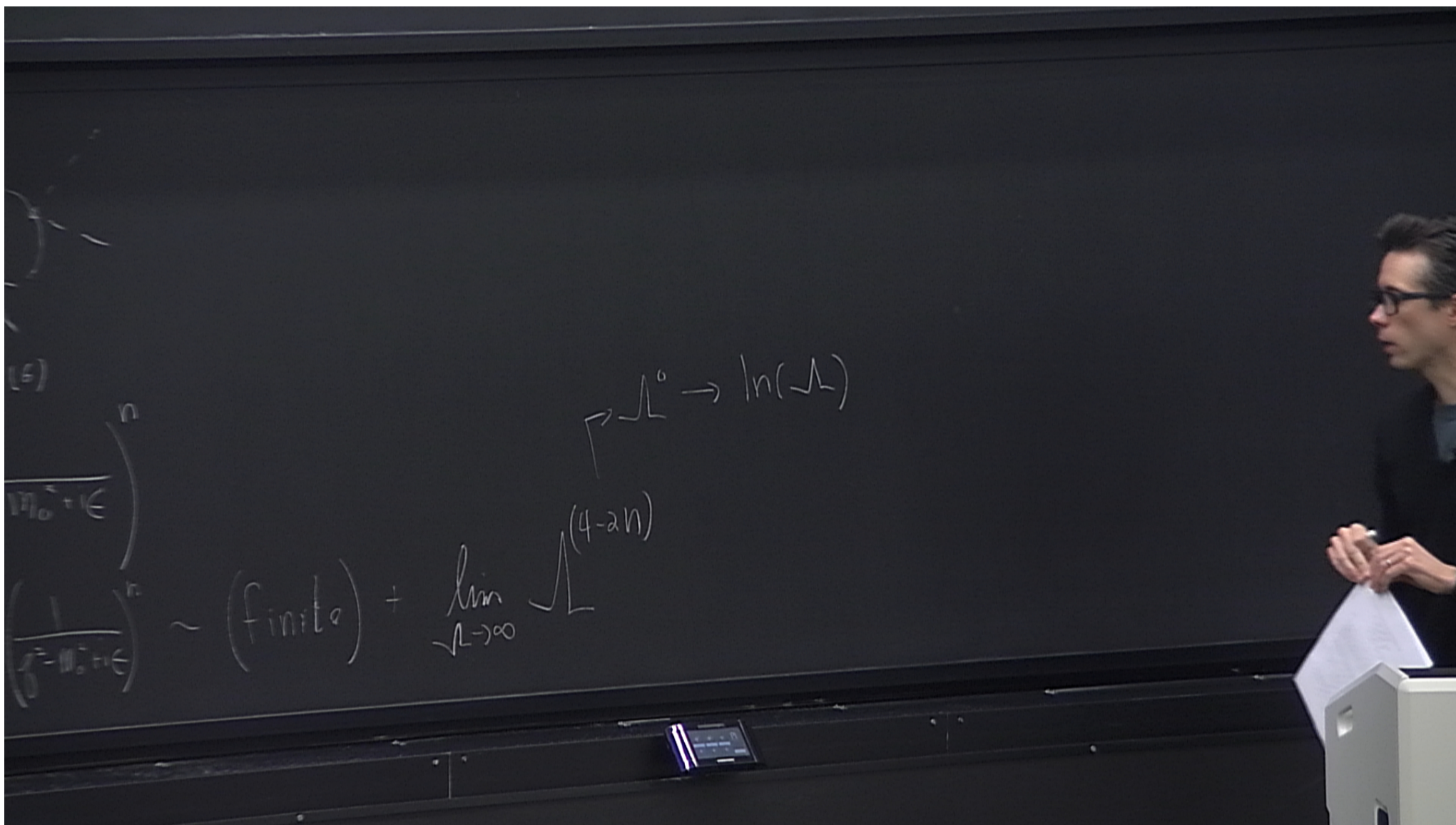
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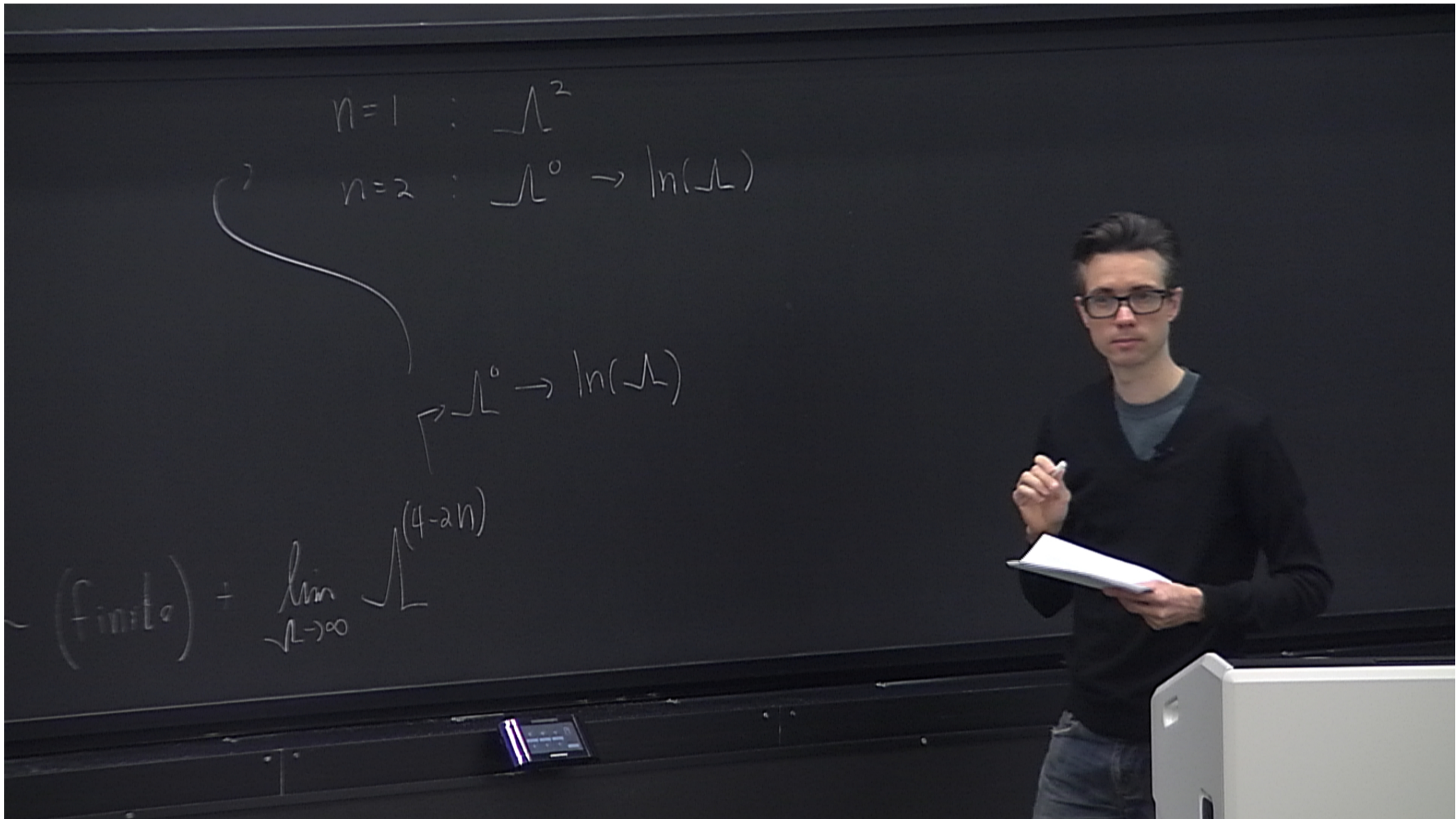
$$\sim \lambda_0^n (\#) \int_0^1 dq \, q^3 \left(\frac{1}{q^2 - m_0^2 + i\epsilon} \right)^n$$



$$\Delta\Gamma^{(2n)} \sim \lambda_0^n \int \frac{d^4 q}{(2\pi)^4} \left(\frac{1}{q^2 - m_0^2 + i\epsilon} \right)^n$$

$$\sim \lambda_0^n (\#) \int_0^1 dq \, q^3 \left(\frac{1}{q^2 - m_0^2 + i\epsilon} \right)^n \sim (\text{finite}) + \lim_{L \rightarrow \infty} L^{(4-2n)}$$



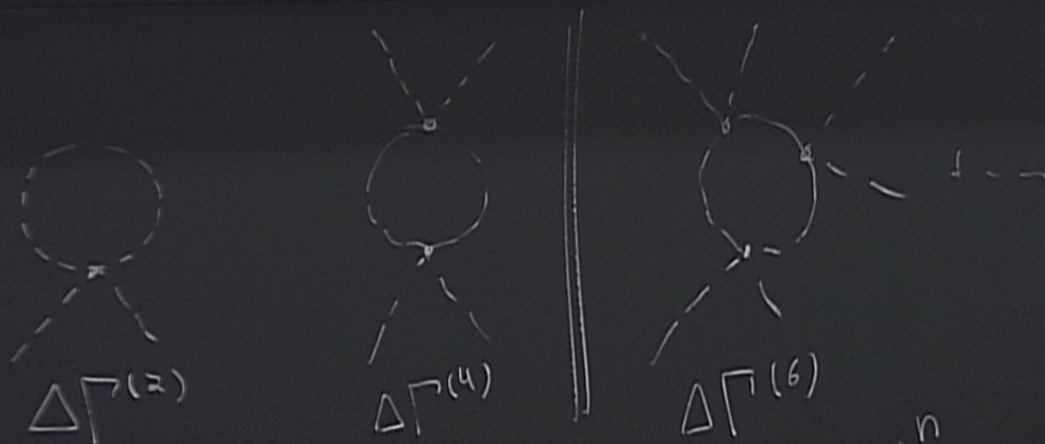


$$n=1 : \mathcal{L}^2$$

$$n=2 : \mathcal{L}^0 \rightarrow \ln(\mathcal{L})$$

$$\mathcal{L}^0 \rightarrow \ln(\mathcal{L})$$

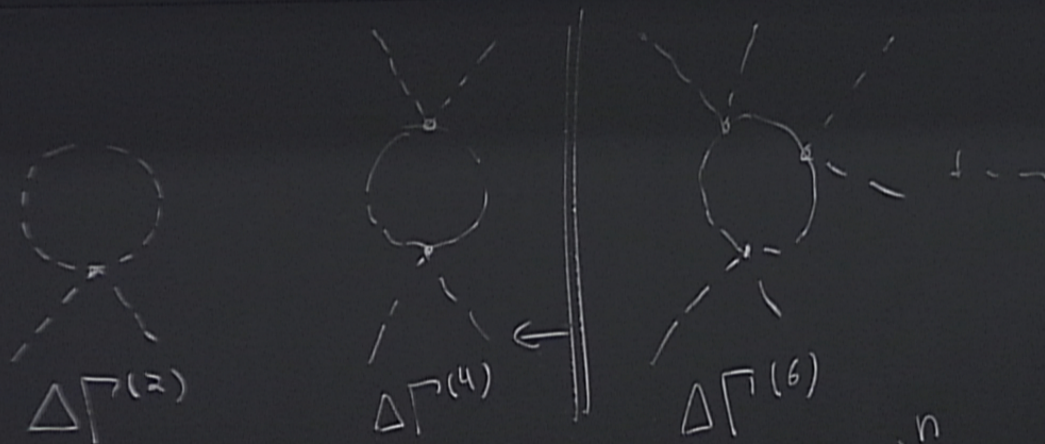
$$(finite) + \lim_{\mathcal{L} \rightarrow \infty} \mathcal{L}^{(4-2n)}$$



$n=1$:

$n=2$:

$$\begin{aligned}
 \Delta\Gamma(2n) &\sim \lambda_0^n \int \frac{d^4 q}{(2\pi)^4} \left(\frac{1}{q^2 - m_0^2 + i\epsilon} \right)^n \\
 &\sim \lambda_0^n (\#) \int_0^1 dq \, q^3 \left(\frac{1}{q^2 - m_0^2 + i\epsilon} \right)^n \sim (\text{finite}) + \lim_{L \rightarrow \infty} \int \text{diagram}^{(4-2n)}
 \end{aligned}$$



$n=1$:

$n=2$:

$$\Delta\Gamma(2n) \sim \lambda_0^n \int \frac{d^4 q}{(2\pi)^4} \left(\frac{1}{q^2 - m_0^2 + i\epsilon} \right)^n$$

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$$\begin{aligned}
 \mathcal{L} &= \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_0^2\phi^2 - \frac{\lambda_0}{4!}\phi^4 \\
 \phi &= Z^{\frac{1}{2}}\tilde{\phi} = \frac{1}{2}Z(\partial\tilde{\phi})^2 - \frac{1}{2}Zm_0^2\tilde{\phi}^2 - \frac{\lambda_0 Z^2}{4!}\tilde{\phi}^4 \\
 &= \frac{1}{2}(\partial\tilde{\phi})^2 - \frac{1}{2}m^2\tilde{\phi}^2 - \frac{\lambda}{4!}\tilde{\phi}^4 \\
 &\quad + \frac{1}{2}\delta Z(\partial\tilde{\phi})^2 - \frac{1}{2}\delta m^2\tilde{\phi}^2 - \frac{\delta\lambda}{4!}\tilde{\phi}^4 \\
 \delta Z &= (Z-1), \quad \delta m^2 = Zm_0^2 - m^2, \quad \delta\lambda = Z^2\lambda_0 - \lambda
 \end{aligned}$$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_0^2\phi^2 - \frac{\lambda_0}{4!}\phi^4$$

$$\begin{aligned}\phi = Z^{\frac{1}{2}}\tilde{\phi} &= \frac{1}{2}Z(\partial\tilde{\phi})^2 - \frac{1}{2}Zm_0^2\tilde{\phi}^2 - \frac{\lambda_0 Z^2}{4!}\tilde{\phi}^4 \\ &= \frac{1}{2}(\partial\tilde{\phi})^2 - \frac{1}{2}m^2\tilde{\phi}^2 - \frac{\lambda}{4!}\tilde{\phi}^4 \\ &\quad + \frac{1}{2}\delta Z(\partial\tilde{\phi})^2 - \frac{1}{2}\delta m^2\tilde{\phi}^2 - \frac{\delta\lambda}{4!}\tilde{\phi}^4\end{aligned}$$

Counterterms: $\delta Z = (Z-1)$, $\delta m^2 = Zm_0^2 - m^2$, $\delta\lambda = Z^2\lambda_0 - \lambda$

$$\frac{p \rightarrow}{\text{---} \times \text{---}} \quad \frac{1}{p^2 - m^2 + i\epsilon}$$

$$\frac{p \rightarrow}{\text{---} \times \text{---}} \quad i(\delta z p^2 - \delta m^2)$$

$$\text{---} \times \text{---} = -i\lambda$$

$$\text{---} \otimes \text{---} = -i\delta\lambda$$

$$\begin{array}{c}
 p \rightarrow \\
 \hline
 \\
 p \rightarrow \\
 \hline
 \times
 \end{array}
 \frac{1}{p^2 - m^2 + i\epsilon}
 i(\delta Z p^2 - \delta m^2)$$

$$\begin{array}{c}
 \diagup \\
 \times \\
 \diagdown
 \end{array}
 = -i\lambda$$

$$\begin{array}{c}
 \diagup \\
 \otimes \\
 \diagdown
 \end{array}
 = -i\delta\lambda$$

$$\begin{array}{c}
 \hline
 \\
 + \\
 \hline
 \times
 \end{array}
 \frac{1}{p^2}
 \frac{1}{p^2} (-im^2) \frac{1}{p^2}$$

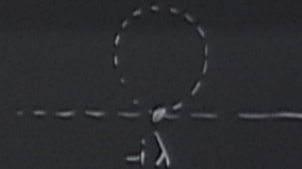
$$\begin{array}{c}
 + \\
 \hline
 \times \quad \times
 \end{array}
 \frac{1}{p^2} (-im^2) \frac{1}{p^2} (-im^2) \frac{1}{p^2}$$

$$\frac{1}{p^2} \left[1 + \frac{m^2}{p^2} + \left(\frac{m^2}{p^2} \right)^2 + \dots \right] = \frac{1}{p^2} \left(\frac{1}{1 - m^2/p^2} \right)$$

$$p^0 \rightarrow -i p_E^0$$

$$\hookrightarrow -p^2 \rightarrow p_E^2 = p_E^{0^2} + \vec{p}^2 \leq -\Lambda^2$$

$$\Delta\Gamma^{(2)}$$



$$-i p_E^0$$

$$p^2 \rightarrow p_E^2 = p_E^{0^2} + \vec{p}^2 \leq \Lambda^2$$

$$= \lambda$$



$$+ \frac{\times}{i(\delta z p^2 - \delta m^2)}$$

$$p^0 \rightarrow -i p_E^0$$

$$\hookrightarrow -p^2 \rightarrow p_E^2 = p_E^{0^2} + \vec{p}^2 \leq \Lambda^2$$

$$\Delta\Gamma^{(2)} = \lambda \int^{\Lambda} \frac{d^4 q_E}{(2\pi)^4} \frac{1}{q_E^2 + m^2} - p^2 \delta z + \delta m^2$$



The diagram shows a horizontal dashed line representing a propagator. On the left, there is a dashed circle (loop) attached to the line, with a dot on the line labeled $-i\lambda$. To the right of this, there is a plus sign followed by another dashed line segment with a cross (X) on it, and below it the expression $i(\delta z p^2 - \delta m^2)$.

$$p^0 \rightarrow -i p_E^0$$

$$\hookrightarrow -p^2 \rightarrow p_E^2 = p_E^{0^2} + \vec{p}^2 \leq \Lambda^2$$

$$\Delta\Gamma^{(2)} = \lambda \int^{\Lambda} \frac{d^4 q_E}{(2\pi)^4} \frac{1}{q_E^2 + m^2}$$

$$- p^2 \delta z + \delta m^2 + \text{diagram}$$

The diagram shows a horizontal dashed line with a point labeled $-i\lambda$. Above this point is a dashed circle with a cross inside, labeled g^2 . To the right of the circle is a plus sign followed by a term $\frac{\times}{i(\delta z p^2 - \delta m^2)}$.

$$p^0 \rightarrow -i\phi^0 E$$

$$\Delta \Gamma^{(2)} = \lambda \int \frac{d^4 g_E}{(2\pi)^4} \frac{1}{g_E^2 + m^2}$$

$$= p^2 \left[\lambda A_1 \ln \left(\frac{\Lambda^2}{a_p p^2 + a_m m^2} \right) + \lambda A_2 - \delta z \right] - \lambda B_0 \Lambda^2 + \lambda B_1 m^2 \ln \left(\frac{\Lambda^2}{a_p p^2 + a_m m^2} \right)$$

$$\leftarrow \mathcal{L}^2 \quad \begin{array}{c} \text{---} \circ \text{---} \\ \text{---} \end{array} \quad + \quad \frac{x}{i(\delta z p^2 - \delta m^2)}$$

$p \rightarrow -i\lambda$

$$\begin{aligned} & - p^2 \delta z + \delta m^2 \\ & + \lambda A_2 - \delta z \Big] - \left[\lambda B_0 \mathcal{L}^2 + \lambda B_1 m^2 \ln \left(\frac{\mathcal{L}^2}{b_p p^2 + b_m m^2} \right) + \lambda B_2 m^2 - \delta m^2 \right] \end{aligned}$$

$$= \frac{1}{2}(\partial \tilde{\phi})^2 - \frac{1}{2}m^2 \tilde{\phi}^2 - \frac{\lambda}{4!} \tilde{\phi}^4$$

$$+ \frac{1}{2} \delta Z (\partial \tilde{\phi})^2 - \frac{1}{2} \delta m^2 \tilde{\phi}^2 - \frac{\delta \lambda}{4!} \tilde{\phi}^4$$

Counterterms: $\delta Z = (Z-1)$, $\delta m^2 = Z m_c^2 - m^2$, $\delta \lambda = Z^4 \lambda - \lambda$

$$\text{X} = -i\lambda$$

$$\text{X} = -i\delta\lambda$$

$$\text{X} = \frac{1}{p^2} (-m^2) \frac{1}{p^2} (-m^2) \frac{1}{p^2}$$

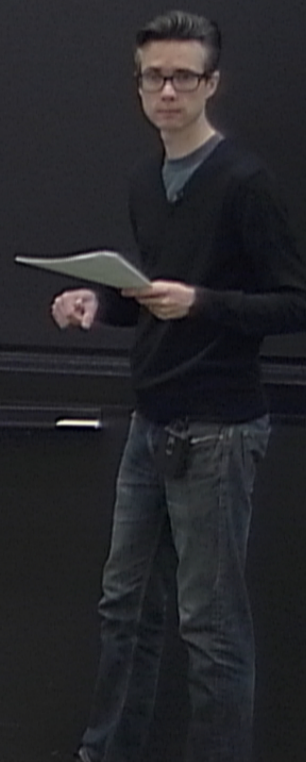
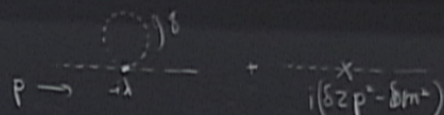
$$\frac{1}{p^2} \left[1 + \frac{m^2}{p^2} + \left(\frac{m^2}{p^2} \right)^2 + \dots \right] = \frac{1}{p^2} \left(\frac{1}{1 - m^2/p^2} \right)$$

$$p^0 \rightarrow -ip_E^0$$

$$\hookrightarrow -p^2 \rightarrow p_E^2 = p_E^0^2 + \vec{p}^2 \leq -L^2$$

$$\Delta \Gamma^{(2)} = \lambda \int^L \frac{d^4 q_E}{(2\pi)^4} \frac{1}{q_E^2 + m^2} - p^2 \delta Z + \delta m^2$$

$$= p^2 \left[\lambda A_1 \ln \left(\frac{L^2}{q_p p^2 + a_m m^2} \right) + \lambda A_2 - \delta Z \right] - \left[\lambda B_0 L^2 + \lambda B_1 m^2 \ln \left(\frac{L^2}{p_p p^2 + b_m m^2} \right) + \lambda B_2 m^2 - \delta m^2 \right]$$



$$p^2 \left[1 + \frac{p^2}{p^2} \left(\frac{p^2}{p^2} \right) \right] \left(\frac{p^2}{p^2} \right)$$

$$i(\delta z p^2 - \delta m^2)$$



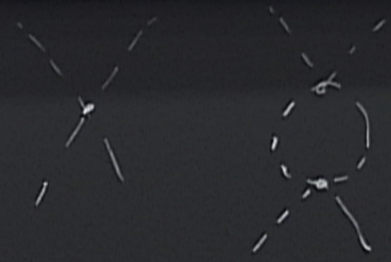
$$\Delta \Gamma^{(q)} = \lambda^2 \int \frac{d^4 q_E}{(2\pi)^4} \left(\frac{1}{q_E^2 + m^2} \right)^2 + \delta \lambda$$

$$= \lambda^2 \left[C_1 \ln\left(\frac{\Lambda^2}{s, t, u}\right) + C_2 \right]$$

$$+ \lambda B_1 m^2 \ln\left(\frac{\Lambda^2}{b_p p^2 + b_m m^2}\right) + \lambda B_2 m^2 - \delta m^2$$

$$p^2 \left[1 + \frac{p^2}{p^2} \left(\frac{p^2}{p^2} \right) \right] \left(\frac{p^2}{p^2} \right)$$

$$\frac{-i(\delta z p^2 - \delta m^2)}{p^2}$$



$$\Delta \Gamma^{(q)} = \lambda^2 \int \frac{d^4 q_E}{(2\pi)^4} \left(\frac{1}{q_E^2 + m^2} \right)^2 + \delta \lambda$$

$$= \lambda^2 \left[C_1 \ln \left(\frac{\Lambda^2}{s, t, u} \right) + C_2 \right] + \delta \lambda$$

$$+ \lambda B_1 m^2 \ln \left(\frac{\Lambda^2}{b_p p^2 + b_m m^2} \right) + \lambda B_2 m^2 - \delta m^2$$