

SCALAR PROXY

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1. INTRODUCTION

We will work most with the scalar proxy given by the lagrangian,

$$(1.1) \quad \mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2M^2}\Box\phi\Box\phi - \frac{\kappa}{2}\Box\phi\phi^2$$

The idea here is reintegrate the higher derivative term, in order to obtain a lower derivative term, but in terms of additional fields. This is easily done by,

$$(1.2) \quad \mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \Box\phi\eta + \frac{M^2}{2}\eta^2 - \frac{\kappa}{2}\Box\phi\phi^2$$

The new lagrangian has mixed propagator terms, to diagonalize it is also easy, we just open in terms of $\phi = h - \eta$,

$$(1.3) \quad \mathcal{L} = -\frac{1}{2}\partial_\mu h\partial^\mu h + \partial_\mu h\partial^\mu\eta - \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{\kappa}{2}\Box(h-\eta)(h-\eta)^2 + \eta\Box(h-\eta) + \frac{M^2}{2}\eta^2$$

$$(1.4) \quad \mathcal{L} = -\frac{1}{2}\partial_\mu h\partial^\mu h + \partial_\mu h\partial^\mu\eta - \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{\kappa}{2}\Box(h-\eta)(h-\eta)^2 - \partial_\mu\eta\partial^\mu(h-\eta) + \frac{M^2}{2}\eta^2$$

$$(1.5) \quad \mathcal{L} = -\frac{1}{2}\partial_\mu h\partial^\mu h + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta + \frac{M^2}{2}\eta^2 - \frac{\kappa}{2}\Box(h-\eta)(h-\eta)^2$$

The Feynman rules are easily read as,

- $h \text{-----} h = \frac{1}{i} \frac{1}{p^2}$
- $\eta \text{-----} \eta = -\frac{1}{i} \frac{1}{p^2+M^2}$
- $h_1 \text{-----} \begin{array}{c} \diagup h_2 \\ \diagdown h_3 \end{array} = i\kappa(p_1^2 + p_2^2 + p_3^2)$
- $h_1 \text{-----} \begin{array}{c} \diagup h_2 \\ \diagdown \eta_3 \end{array} = -i\kappa(p_1^2 + p_2^2 + p_3^2)$
- $h_1 \text{-----} \begin{array}{c} \diagup \eta_2 \\ \diagdown \eta_3 \end{array} = i\kappa(p_1^2 + p_2^2 + p_3^2)$
- $\eta_1 \text{-----} \begin{array}{c} \diagup \eta_2 \\ \diagdown \eta_3 \end{array} = -i\kappa(p_1^2 + p_2^2 + p_3^2)$

Which can also be seen directly from the Feynman rules of the ϕ field,

- $\phi \text{-----} \phi = \frac{1}{i} \frac{1}{p^2 + \frac{p^4}{M^2}}$

$$\bullet \quad \phi_1 \text{---} \text{---} \text{---} \begin{array}{c} \nearrow \phi_2 \\ \searrow \phi_3 \end{array} = i\kappa(p_1^2 + p_2^2 + p_3^2) = i\kappa(p_1 + p_2 + p_3)^2 - 2i\kappa(p_1 \cdot p_2 + p_2 \cdot p_3 + p_3 \cdot p_1) = -i\kappa(\langle 12 \rangle [12] + \langle 23 \rangle [23] + \langle 31 \rangle [31])$$

So that the four point amplitude can be computed by,

$$(1.6) \quad \begin{array}{c} \phi_2 \\ \searrow \\ \text{---} \xrightarrow{P} \text{---} \nearrow \phi_3 \\ \swarrow \phi_1 \quad \searrow \phi_4 \end{array} = \frac{1}{i}(-i\kappa)^2 \frac{1}{P^2 + \frac{P^4}{M^2}} (\langle 12 \rangle [12] + \langle 2P \rangle [2P] + \langle P1 \rangle [P1]) (\langle 34 \rangle [34] - \langle 4P \rangle [4P] - \langle P3 \rangle [P3])$$

$$(1.7) \quad = \frac{1}{i}(-i\kappa)^2 \frac{1}{P^2 + \frac{P^4}{M^2}} (\langle 12 \rangle [12] - \langle P2 \rangle [2P] - \langle P1 \rangle [1P]) (\langle 34 \rangle [34] + \langle P4 \rangle [4P] + \langle P3 \rangle [3P])$$

$$(1.8) \quad = \frac{1}{i}(-i\kappa)^2 \frac{1}{P^2 + \frac{P^4}{M^2}} (\langle 12 \rangle [12] + \langle P | 1 + 2 | P \rangle) (\langle 34 \rangle [34] - \langle P | 3 + 4 | P \rangle)$$

$$(1.9) \quad = \frac{1}{i}(-i\kappa)^2 \frac{1}{P^2 + \frac{P^4}{M^2}} (\langle 12 \rangle [12] - \langle P | P | P \rangle) (\langle 34 \rangle [34] - \langle P | P | P \rangle)$$

$$(1.10) \quad = \frac{1}{i}(-i\kappa)^2 \frac{1}{P^2 + \frac{P^4}{M^2}} (\langle 12 \rangle [12] - 2P^2) (\langle 34 \rangle [34] - 2P^2)$$

$$(1.11) \quad = -i \frac{(\kappa M)^2}{s(M^2 - s)} (\langle 12 \rangle [12] + 2s) (\langle 34 \rangle [34] + 2s)$$

It's trivial to read the t and u channels from this expression,

$$(1.12) \quad \begin{array}{c} \phi_2 \quad \phi_3 \\ \searrow \quad \swarrow \\ \text{---} \downarrow P \text{---} \\ \swarrow \quad \searrow \\ \phi_1 \quad \phi_4 \end{array} = -i \frac{(\kappa M)^2}{t(M^2 - t)} (\langle 23 \rangle [23] + 2t) (\langle 41 \rangle [41] + 2t)$$

$$(1.13) \quad \begin{array}{c} \phi_2 \quad \phi_4 \\ \searrow \quad \swarrow \\ \text{---} \downarrow P \text{---} \\ \swarrow \quad \searrow \\ \phi_1 \quad \phi_3 \end{array} = -i \frac{(\kappa M)^2}{u(M^2 - u)} (\langle 24 \rangle [24] + 2u) (\langle 31 \rangle [31] + 2u)$$

So that the full 4-point amplitude is,

$$(1.14) \quad \begin{array}{c} \phi_2 \quad \phi_3 \\ \searrow \quad \swarrow \\ \text{---} \text{---} \text{---} \text{---} \\ \swarrow \quad \searrow \\ \phi_1 \quad \phi_4 \end{array} = -i \frac{(\kappa M)^2}{stu(M^2 - s)(M^2 - t)(M^2 - u)} [(\langle 12 \rangle [12] + 2s)(\langle 34 \rangle [34] + 2s)tu(M^2 - t)(M^2 - u) + (\langle 23 \rangle [23] + 2t)(\langle 41 \rangle [41] + 2t) + (\langle 24 \rangle [24] + 2u)(\langle 31 \rangle [31] + 2u)]$$

Let us specialize when 1, 2 are massless and 3, 4 are massive, then,

$$(2.2) \quad i\Pi^{(1)} = -\frac{3}{2}ig^2 \int \frac{d^D\ell}{(2\pi)^D} \frac{1}{i} \frac{1}{\ell^2} \frac{1}{\ell^2 + m^2}$$

$$(2.3) \quad i\Pi^{(1)} = -\frac{3}{2}g^2 \int \frac{d^D\ell}{(2\pi)^D} \frac{1}{\ell^2} \frac{1}{\ell^2 + m^2}$$

$$(2.4) \quad i\Pi^{(1)} = -\frac{3}{2}g^2 \frac{i}{(4\pi)^{\frac{D}{2}} \Gamma(\frac{D}{2})} (m^2)^{\frac{D}{2}-2} \frac{\Gamma(2-\frac{D}{2})\Gamma(\frac{D}{2}-1)}{\Gamma(1)}$$

$$(2.5) \quad i\Pi^{(1)} = -\frac{3}{2}ig^2 \frac{(m^2)^{-\epsilon} \Gamma(\epsilon) \Gamma(1-\epsilon)}{(4\pi)^{2-\epsilon} \Gamma(2-\epsilon)}$$

$$(2.6) \quad i\Pi^{(2)} = \frac{1}{2}(ig)^2 \int \frac{d^D\ell}{(2\pi)^D} \frac{1}{i^2} \frac{1}{\ell^2(\ell+p)^2} \frac{(m^2 + \ell^2 + p^2 + (\ell+p)^2)^2}{\ell^2 + m^2} \frac{1}{(\ell+p)^2 + m^2}$$

For the mass renormalization we can take $p = 0$,

$$(2.7) \quad i\Pi^{(2)} = \frac{1}{2}g^2 \int \frac{d^D\ell}{(2\pi)^D} \frac{(m^2 + 2\ell^2)^2}{\ell^4(\ell^2 + m^2)^2}$$

Let's compute the four point amplitude for this theory,

$$(2.8) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \quad \nearrow \quad \searrow \\ \quad \text{---} P \text{---} \\ \quad \nwarrow \quad \swarrow \\ \phi_1 \quad \quad \phi_4 \end{array} = (ig)^2 \frac{(p_1^2 + p_2^2 + (p_1 + p_2)^2 + m^2)(p_3^2 + p_4^2 + (p_3 + p_4)^2 + m^2)}{i(p_1 + p_2)^2((p_1 + p_2)^2 + m^2)}$$

First let's consider all legs massless,

$$(2.9) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \quad \nearrow \quad \searrow \\ \quad \text{---} P \text{---} \\ \quad \nwarrow \quad \swarrow \\ \phi_1 \quad \quad \phi_4 \end{array} = ig^2 \frac{(-s + m^2)(-s + m^2)}{(-s)(-s + m^2)} = -ig^2 \frac{(-s + m^2)}{s}$$

So,

$$(2.10) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \quad \nearrow \quad \searrow \\ \quad \text{---} \text{---} \\ \quad \nwarrow \quad \swarrow \\ \phi_1 \quad \quad \phi_4 \end{array} = -ig^2 \frac{(-s + m^2)}{s} - ig^2 \frac{(-t + m^2)}{t} - ig^2 \frac{(-u + m^2)}{u} - 3ig^2$$

$$(2.11) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \quad \nearrow \quad \searrow \\ \quad \text{---} \text{---} \\ \quad \nwarrow \quad \swarrow \\ \phi_1 \quad \quad \phi_4 \end{array} = -ig^2 \frac{(-s + m^2)}{s} - ig^2 \frac{(-t + m^2)}{t} - ig^2 \frac{(-u + m^2)}{u} - ig^2 \frac{s}{s} - ig^2 \frac{t}{t} - ig^2 \frac{u}{u}$$

$$(2.12) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \quad \nearrow \quad \searrow \\ \quad \text{---} \text{---} \\ \quad \nwarrow \quad \swarrow \\ \phi_1 \quad \quad \phi_4 \end{array} = -ig^2 m^2 \left(\frac{1}{s} + \frac{1}{t} + \frac{1}{u} \right) = ig^2 m^2 \left(\frac{1}{\langle 12 \rangle [12]} + \frac{1}{\langle 14 \rangle [14]} + \frac{1}{\langle 13 \rangle [13]} \right)$$

Para uma perna massiva, ϕ_4 ,

$$(2.13) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \quad \searrow \quad \nearrow \\ \quad \text{---} P \text{---} \\ \quad \nearrow \quad \searrow \\ \phi_1 \quad \quad \phi_4 \end{array} = (ig)^2 \frac{(-s+m^2)(-s)}{i(-s)(-s+m^2)} = ig^2$$

So,

$$(2.14) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \quad \searrow \quad \nearrow \\ \quad \text{---} \text{---} \\ \quad \nearrow \quad \searrow \\ \phi_1 \quad \quad \phi_4 \end{array} = ig^2 + ig^2 + ig^2 - 3ig^2 = 0$$

Para duas pernas massivas, $\phi_{3,4}$,

$$(2.15) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \quad \searrow \quad \nearrow \\ \quad \text{---} P \text{---} \\ \quad \nearrow \quad \searrow \\ \phi_1 \quad \quad \phi_4 \end{array} = (ig)^2 \frac{(-s+m^2)(-s-m^2)}{i(-s)(-s+m^2)} = ig^2 \frac{s+m^2}{s}$$

$$(2.16) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \quad \searrow \quad \nearrow \\ \quad \text{---} \\ \quad \downarrow P \\ \phi_1 \quad \quad \phi_4 \end{array} = (ig)^2 \frac{(-t)(-t)}{i(-t)(-t+m^2)} = -ig^2 \frac{t}{-t+m^2}$$

$$(2.17) \quad \begin{array}{c} \phi_2 \quad \quad \phi_4 \\ \quad \searrow \quad \nearrow \\ \quad \text{---} \\ \quad \downarrow P \\ \phi_1 \quad \quad \phi_3 \end{array} = -ig^2 \frac{u}{-u+m^2}$$

So,

$$(2.18) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \quad \searrow \quad \nearrow \\ \quad \text{---} \text{---} \\ \quad \nearrow \quad \searrow \\ \phi_1 \quad \quad \phi_4 \end{array} = ig^2 \frac{s+m^2}{s} - ig^2 \frac{t}{-t+m^2} - ig^2 \frac{u}{-u+m^2} - 3ig^2$$

$$(2.19) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \quad \searrow \quad \nearrow \\ \quad \text{---} \text{---} \\ \quad \nearrow \quad \searrow \\ \phi_1 \quad \quad \phi_4 \end{array} = ig^2 \frac{s+m^2}{s} - ig^2 \frac{t}{-t+m^2} - ig^2 \frac{u}{-u+m^2} - ig^2 \frac{s}{s} - ig^2 \frac{-t+m^2}{-t+m^2} - ig^2 \frac{-u+m^2}{-u+m^2}$$

$$(2.20) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \quad \searrow \quad \nearrow \\ \quad \text{---} \text{---} \\ \quad \nearrow \quad \searrow \\ \phi_1 \quad \quad \phi_4 \end{array} = -ig^2 m^2 \left(-\frac{1}{s} + \frac{1}{-t+m^2} + \frac{1}{-u+m^2} \right) = -ig^2 m^2 \left(\frac{1}{\langle 12 \rangle [12]} + \frac{1}{\langle 14 \rangle [14]} + \frac{1}{\langle 13 \rangle [13]} \right)$$

Para uma perna sem massa ϕ_1 ,

$$(2.21) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \diagdown \quad \diagup \\ \text{---} P \text{---} \\ \diagup \quad \diagdown \\ \phi_1 \quad \quad \phi_4 \end{array} = (ig)^2 \frac{(-s)(-s-m^2)}{i(-s)(-s+m^2)} = -ig^2 \frac{s+m^2}{-s+m^2}$$

$$(2.22) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \diagdown \quad \diagup \\ \text{---} P \text{---} \\ \diagup \quad \diagdown \\ \phi_1 \quad \quad \phi_4 \end{array} = (ig)^2 \frac{(-t)(-t-m^2)}{i(-t)(-t+m^2)} = -ig^2 \frac{t+m^2}{-t+m^2}$$

$$(2.23) \quad \begin{array}{c} \phi_2 \quad \quad \phi_4 \\ \diagdown \quad \diagup \\ \text{---} P \text{---} \\ \diagup \quad \diagdown \\ \phi_1 \quad \quad \phi_3 \end{array} = (ig)^2 \frac{(-u)(-u-m^2)}{i(-u)(-u+m^2)} = -ig^2 \frac{u+m^2}{-u+m^2}$$

$$(2.24)$$

So,

$$(2.25) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \diagdown \quad \diagup \\ \text{---} \text{---} \\ \diagup \quad \diagdown \\ \phi_1 \quad \quad \phi_4 \end{array} = -ig^2 \frac{s+m^2}{-s+m^2} - ig^2 \frac{t+m^2}{-t+m^2} - ig^2 \frac{u+m^2}{-u+m^2} - 3ig^2$$

$$(2.26) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \diagdown \quad \diagup \\ \text{---} \text{---} \\ \diagup \quad \diagdown \\ \phi_1 \quad \quad \phi_4 \end{array} = -ig^2 \frac{s+m^2}{-s+m^2} - ig^2 \frac{t+m^2}{-t+m^2} - ig^2 \frac{u+m^2}{-u+m^2} - ig^2 \frac{-s+m^2}{-s+m^2} - ig^2 \frac{-t+m^2}{-t+m^2} - ig^2 \frac{-u+m^2}{-u+m^2}$$

$$(2.27) \quad \begin{array}{c} \phi_2 \quad \quad \phi_3 \\ \diagdown \quad \diagup \\ \text{---} \text{---} \\ \diagup \quad \diagdown \\ \phi_1 \quad \quad \phi_4 \end{array} = -ig^2 m^2 \left(\frac{1}{-s+m^2} + \frac{1}{-t+m^2} + \frac{1}{-u+m^2} \right) = -ig^2 m^2 \left(\frac{1}{\langle 12 \rangle [12]} + \frac{1}{\langle 14 \rangle [14]} + \frac{1}{\langle 13 \rangle [13]} \right)$$

Cut comparison, only massless legs

$$(2.28) \quad \begin{array}{c} \quad \quad \quad \text{---} \text{---} \\ \quad \quad \quad \diagdown \quad \diagup \\ \quad \quad \quad \text{---} \text{---} \\ \quad \quad \quad \diagup \quad \diagdown \\ \quad \quad \quad \text{---} \text{---} \\ \quad \quad \quad \diagdown \quad \diagup \\ \quad \quad \quad \text{---} \text{---} \\ \quad \quad \quad \diagup \quad \diagdown \\ \quad \quad \quad \text{---} \text{---} \end{array} = \frac{ig^2 m^2 (igm^2)^2}{(im^2)^3} \left(\frac{1}{\langle 12 \rangle [12]} - \frac{1}{\langle 1l \rangle [1l]} - \frac{1}{\langle 2l \rangle [2l]} \right)$$

to solve for the cuts, $l^2 = (l+3+4)^2 = (l+4)^2 = 0$,

$$(2.29) \quad l^2 = 0 \Rightarrow l = -|l\rangle[l]$$

$$(2.30) \quad 0 = (l+4)^2 = \langle l4 \rangle [l4] = 0 \Rightarrow |l\rangle = |4\rangle$$

$$(2.31) \quad 0 = (l+3+4)^2 = \langle lP_{34} \rangle [lP_{34}] + (3+4)^2 = \langle l|3+4\rangle [l] + \langle 34 \rangle [34] = \langle l|3+4\rangle [l] + \langle 34 \rangle [34]$$

$$(2.32) \quad \langle 43 \rangle [34] = -\langle l3 \rangle [34] \Rightarrow |l\rangle = -|4\rangle + z|3\rangle$$

$$(2.33) \quad l = -(-|4\rangle + z|3\rangle)[4|$$

The cuts are solved by this. Hence,

$$\begin{aligned} &= g^4 \left(\frac{1}{\langle 12 \rangle [12]} - \frac{1}{\langle 1l \rangle [1l]} - \frac{1}{\langle 2l \rangle [2l]} \right) \\ &= g^4 \left(\frac{1}{\langle 12 \rangle [12]} - \frac{1}{(-\langle 14 \rangle + z\langle 13 \rangle)[14]} - \frac{1}{(-\langle 24 \rangle + z\langle 23 \rangle)[24]} \right) \end{aligned}$$

Now for internal massive lines,

$$(2.34) \quad \begin{array}{c} \text{Diagram: A triangle with three shaded circular vertices. The top vertex has an incoming dashed line from the top-left labeled $l+3+4$ and an outgoing dashed line to the top-right labeled $l+4$. The bottom-left vertex has an incoming dashed line from the bottom-left labeled l and an outgoing dashed line to the bottom-right labeled l. The bottom-right vertex has an incoming dashed line from the bottom-right labeled l and an outgoing dashed line to the top-right labeled $l+4$. The top and bottom edges are dashed, while the left and right edges are solid.} \end{array} = \frac{-ig^2 m^2 (-igm^2)^2}{(-im^2)^3} \left(\frac{1}{\langle 12 \rangle [12]} - \frac{1}{\langle 1l \rangle [1l]} - \frac{1}{\langle 2l \rangle [2l]} \right)$$

With the cuts being, $l^2 = (l+3+4)^2 = (l+4)^2 = -m^2$,

$$(2.35) \quad 0 = (l+4)^2 - l^2 = 2l \cdot p_4$$

$$(2.36) \quad 0 = (l+4+3)^2 - l^2 = 2l \cdot (4+3) + (4+3)^2 = 2l \cdot p_3 + (4+3)^2$$

As ansatz, $l = |4\rangle[4| + \alpha|4\rangle[3| + \beta|3\rangle[4|$ satisfy both conditions above. The remaining condition is,

$$(2.37) \quad l^2 = -m^2$$

$$(2.38) \quad -\alpha\beta[43]\langle 43 \rangle = -m^2 \Rightarrow \alpha = \frac{m^2}{\beta\langle 34 \rangle[34]}$$

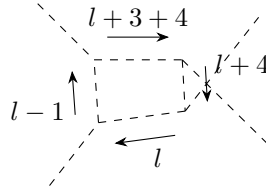
Setting now $-\beta = z$,

$$(2.39) \quad l = |4\rangle[4| - \frac{m^2}{z\langle 34 \rangle[34]} |4\rangle[3| - z|3\rangle[4|$$

The value of the diagram is,

$$\begin{aligned} &= g^4 \left(\frac{1}{\langle 12 \rangle [12]} + \frac{1}{\langle 1l \rangle [1l]} + \frac{1}{\langle 2l \rangle [2l]} \right) \\ &= g^4 \left(\frac{1}{\langle 12 \rangle [12]} + \frac{1}{-\langle 1l \rangle [1l]} + \frac{1}{-\langle 2l \rangle [2l]} \right) \\ &= g^4 \left(\frac{1}{\langle 12 \rangle [12]} - \frac{1}{\langle 14 \rangle [41] - \frac{m^2}{z\langle 34 \rangle[34]} \langle 14 \rangle [31] - z\langle 13 \rangle [41]} - \frac{1}{\langle 2l \rangle [2l]} \right) \end{aligned}$$

The explicit cut loop amplitude is,



Triple cut has no improvement, what about a double cut,

$$(2.40) \quad \begin{array}{c} \text{Diagram: A circular loop with two shaded circular vertices. The top arc is dashed and labeled $\ell+3+4$. The bottom arc is dashed and labeled ℓ. Four external dashed lines are attached to the vertices: p_1 and p_2 to the left vertex, and p_3 and p_4 to the right vertex. The left and right edges are solid, while the top and bottom edges are dashed.} \end{array} = \frac{(ig^2 m^2)^2}{(im^2)^2} \left(\frac{1}{\langle 12 \rangle [12]} - \frac{1}{\langle 1l \rangle [1l]} - \frac{1}{\langle 2l \rangle [2l]} \right) \left(\frac{1}{\langle 34 \rangle [34]} + \frac{1}{\langle 3l \rangle [3l]} + \frac{1}{\langle 4l \rangle [4l]} \right)$$