$$|N\rangle = \alpha^+(\vec{k}_N)\ldots\alpha^+(\vec{k}_2)\,\alpha^+(\vec{k}_1)\,|0\rangle$$

$$\alpha^+(\vec{k}) = a_3^+(\vec{k}) - a_0^+(\vec{k})$$

$$[a_3(\vec{k}') - a_0(\vec{k}'),\ \alpha^+(\vec{k})] = 0$$

$$\boxed{(a_3 - a_0)|\psi\rangle = 0}$$

$$(\qquad)|\psi\rangle = 0$$

$\langle f|$ $\qquad |\psi(+\infty)\rangle = S\,|i\rangle$

$\underline{\langle f|S|i\rangle}$

$$S = \sum_{n=0}^{\infty} S^{(n)} = \sum_{n=0}^{\infty} \frac{(-i)^n}{n!} \int \cdots \int d^4x_1 \cdots d^4x_n \, T\left(\mathcal{H}_I(x_1) \cdots \mathcal{H}_I(x_n)\right)$$

$$\mathcal{H}_I = -e : \bar{\psi}(x) \cancel{A}(x) \psi(x) :$$

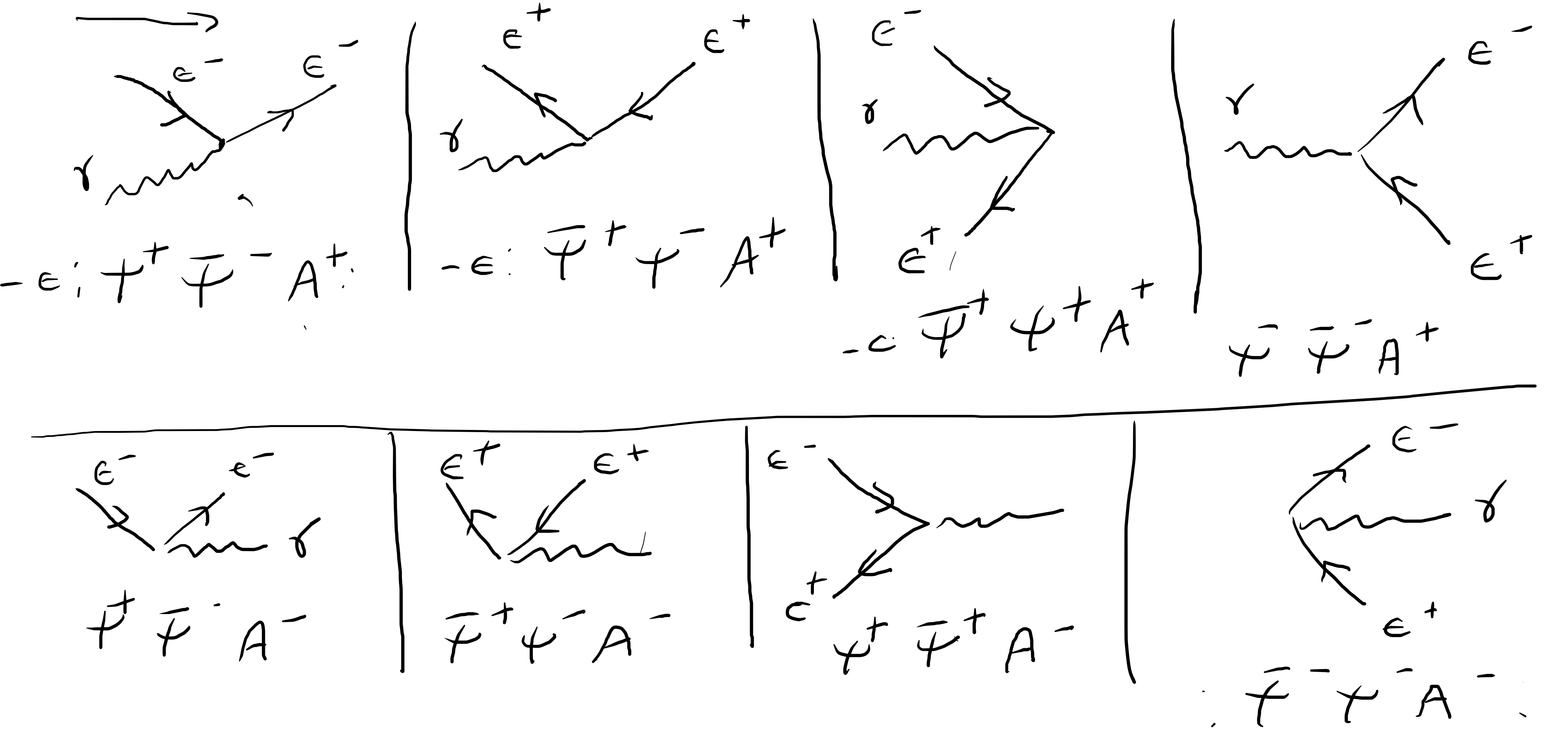
ψ^+, $\bar{\psi}^-$: op dest. e criação resp de e^-

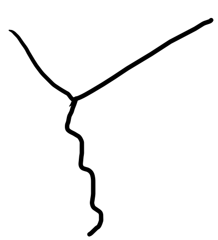
$\bar{\psi}^+$, ψ^- " " " " e^+

A^+, A^- " " " γ

$\mathcal{H}$

$$\mathcal{H}_I = -e : (\bar{\Psi}^+ + \bar{\Psi}^-)(A^+ + A^-)(\Psi^+ + \Psi^-) :$$ 8





8 vértices QED

não é compatível
c/ uma dada
lei de conservação

$$\langle f | S | i \rangle = 0$$

$$\epsilon (\ast) + \epsilon^2 (\ast\ast) = 0$$

$$[\hat{Q}, H] = 0$$

$$[\hat{Q}, S] = 0$$

$$0 = \langle f | [\hat{Q}, S] | i \rangle = \langle f | \hat{Q} S - S \hat{Q} | i \rangle$$

$$= (\lambda_f - \lambda_i) \underbrace{\langle f | S | i \rangle}_{= 0}$$

$\langle f | S^{(1)} | i \rangle_0$, ,

$+ \epsilon^2$

$$\langle f | S^{(n)} | i \rangle = 0$$

$$\underline{\langle f | S^{(1)} | i \rangle = 0} \qquad \underline{e^2 \sim \alpha = \frac{1}{137}}$$

$$\frac{\langle e^- | S^{(1)} | e^- \gamma \rangle}{E}$$

$$E = mc^2$$

$$= mc^2 + \delta$$

$$E_\gamma$$

$$\boxed{S^{(2)} = \frac{(-i)^2}{2!} \int d^4x_1 \int d^4x_2 \, T\left(\mathcal{H}_I(x_1)\, \mathcal{H}_I(x_2) \right)}$$

$$S^{(2)} = \sum_{i=A}^{F} S_i^{(2)}$$

$$S_A^{(2)} = -\frac{e^2}{2!}\int d^4x_1\, d^4x_2 \, :(\bar\psi \not{A} \psi)_{x_1}(\bar\psi \not{A} \psi)_{x_2}:$$

$$S_B^{(2)} = -\frac{e^2}{2!}\int d^4x_1\, d^4x_2 \Big\{ :(\bar\psi \not{A} \underbrace{\psi)_{x_1}(\bar\psi}_{} \not{A} \psi)_{x_2} +$$

$$+ (\underbrace{\bar\psi \not{A} \psi)_{x_1}(\bar\psi \not{A} \psi}_{})_{x_2}: \Big\}$$

$$S_C^{(2)} = -\frac{e^2}{2!}\int d^4x_1\, d^4x_2 :(\bar\psi \underbrace{\not{A} \psi)_{x_1}(\bar\psi \not{A}}_{} \psi)_{x_2}:$$

$$S_P^{(2)} = -\frac{e^2}{2!}\int d^4x_1\, d^4x_2 \Big\{ :(\bar\psi \not{A} \psi)_{x_1} (\bar\psi \not{A} \psi)_{x_2}:$$

$$+ :(\bar\psi \not{A} \psi)_{x_1} (\bar\psi \not{A} \psi)_{x_2}: \Big\}$$

$$S_E^{(2)} = -\frac{e^2}{2!}\int d^4x_1\, d^4x_2 \; :(\bar\psi \not{A} \psi)_{x_1} (\bar\psi \not{A} \psi)_{x_2}:$$

$$S_F^{(2)} = -\frac{e^2}{2!}\int d^4x_1\, d^4x_2 \; :(\bar\psi \not{A} \psi)_{x_1} (\bar\psi \not{A} \psi)_{x_2}:$$

$$\langle f | S_A^{(2)} | i \rangle = 0$$

$$:(\bar{\psi} \not{A} \psi)_{x_1} (\bar{\psi} \not{A} \psi)_{x_2}: \; = \; :(\bar{\psi}_\alpha \gamma^\mu_{\alpha\beta} A_\mu \psi_\beta)_{x_1} \times (\bar{\psi}_\gamma \gamma^\nu_{\gamma\delta} A_\nu \psi_\delta)_{x_2}:$$

$$= \langle 0 | \bar{\psi}_\alpha(x_1) \psi_\delta(x_2) | 0 \rangle \, : \gamma^\mu_{\alpha\beta} A_\mu(x_1) \psi_\beta(x_1) \, \underline{\bar{\psi}_\gamma(x_2) \gamma^\nu_{\gamma\delta}} A_\nu(x_2) :$$

$$= - \langle 0 | \psi_\delta(x_2) \bar{\psi}_\alpha(x_1) | 0 \rangle (-1) \, : \bar{\psi}_\gamma(x_2) \gamma^\nu_{\gamma\delta} A_\nu(x_2) \, \gamma^\mu_{\alpha\beta} A_\mu(x_1) \psi_\beta(x_1) :$$

$$= \; : \underline{\bar{\psi}_\gamma(x_2) \gamma^\nu_{\gamma\delta} A_\nu(x_2)} \, \psi_\delta(x_2) \bar{\psi}_\alpha(x_1) \, \underline{\gamma^\mu_{\alpha\beta} A_\mu(x_1) \psi_\beta(x_1)} :$$

$$S_B^{(2)} = -e^2 \int d^4x_1\, d^4x_2 \; :(\bar{\psi} \cancel{A} \psi)_{x_1} (\bar{\psi} \cancel{A} \psi)_{x_2}:$$

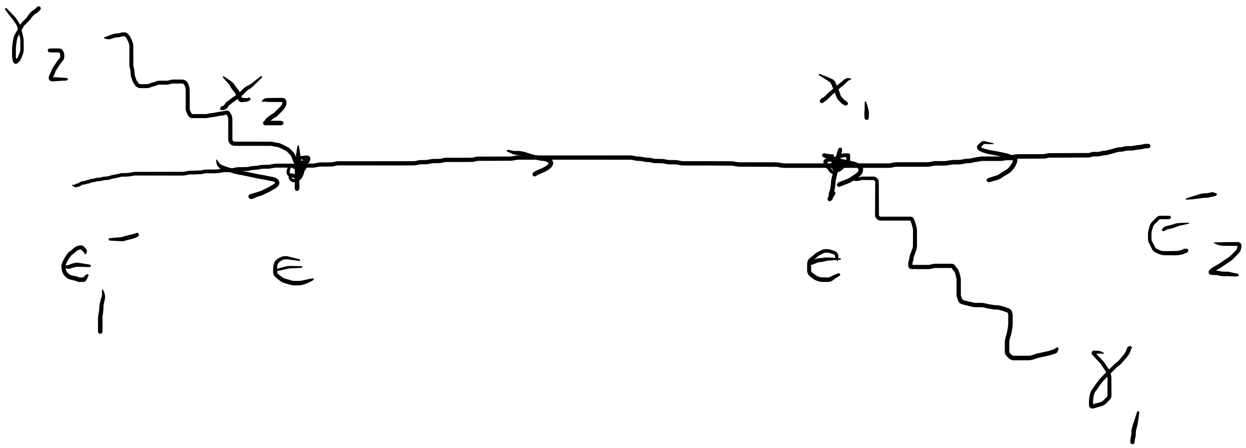
Espalhamento Compton (1923) (1950)

$$\gamma + e^- \longrightarrow \gamma + e^-$$

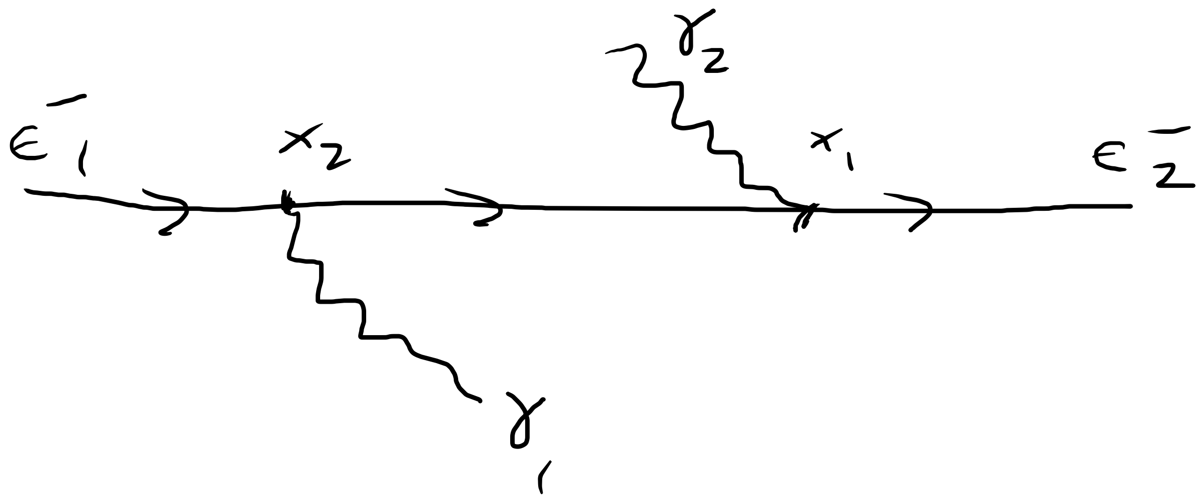
$$S^{(2)}(\gamma + e^- \to \gamma + e^-) = \underline{S_a + S_b}$$

$$S_a = -e^2 \underbrace{\int d^4x_1\, d^4x_2 \; : \bar{\psi}^{-}(x_1) \gamma^\mu \, i S_F(x_1 - x_2) \gamma^\nu \psi^{+}(x_2)} A^-_\mu(x_1) A^+_\nu(x_2)$$

$$S_b = -e^2 \qquad \qquad \| \qquad \qquad A^-_\nu(x_2) A^+_\mu(x_1):$$



$\equiv \quad S_a$

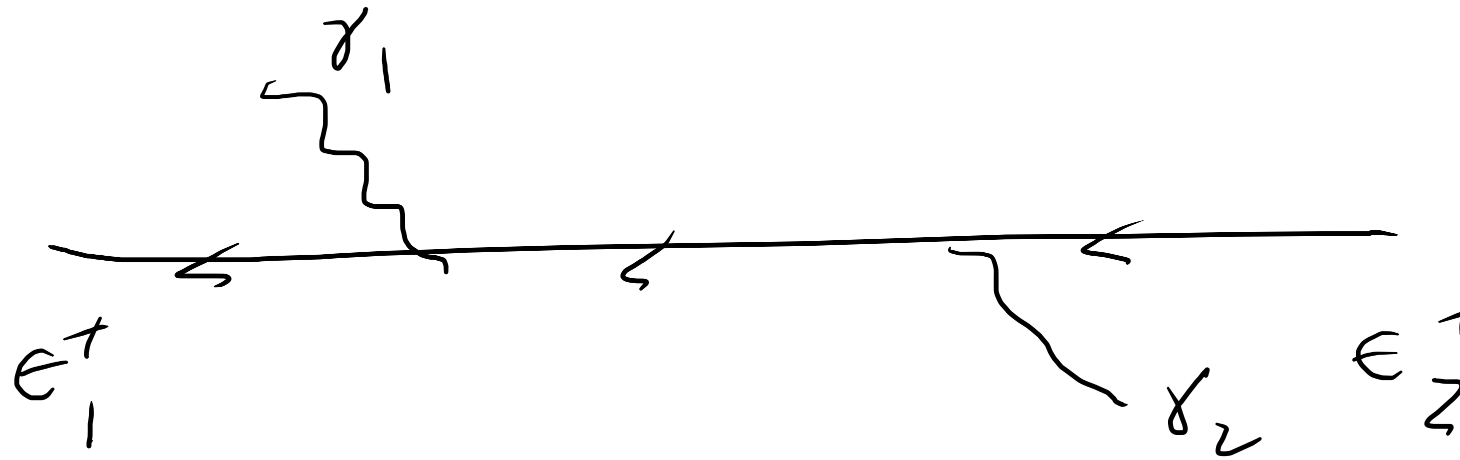


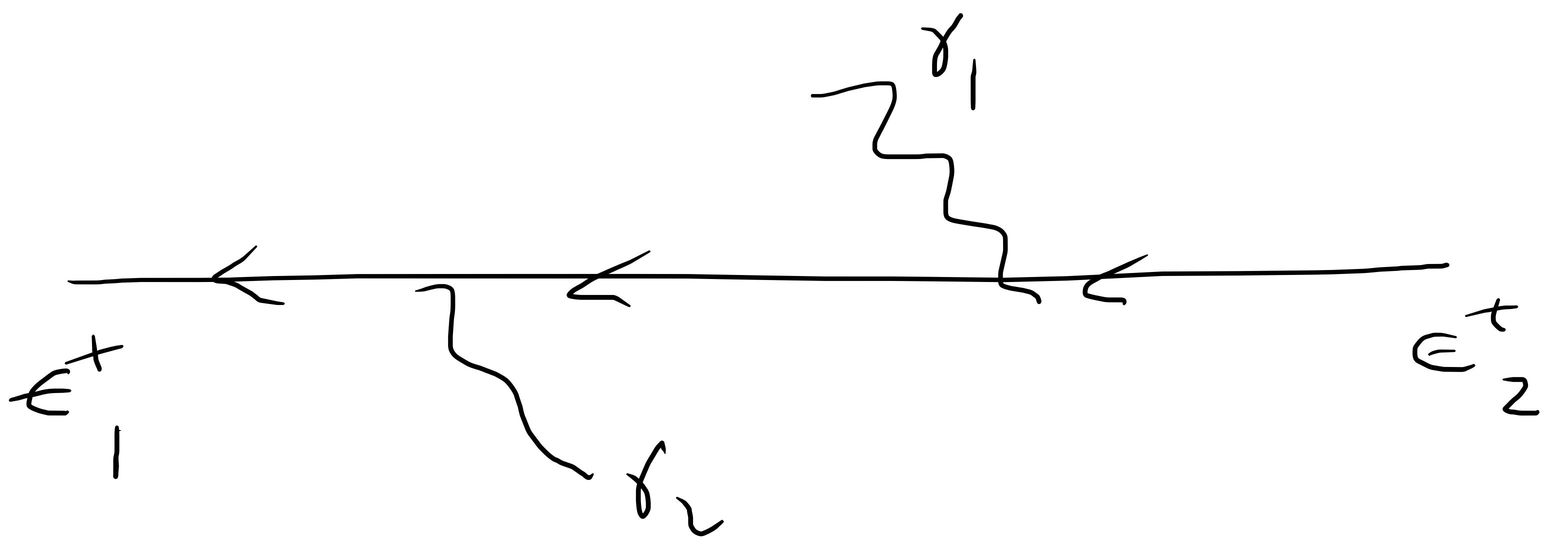
$\equiv \quad S_b$

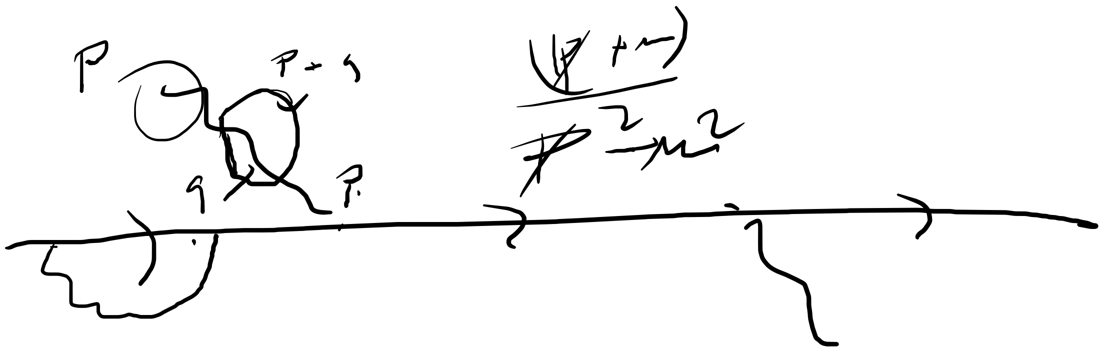
$$\langle e^-\gamma | e^-\gamma \rangle = S_a + S_b$$

$$|\langle \quad \rangle|^2 = |S_a|^2 + |S_b|^2 + \underline{S_a S_b^* + S_a^* S_b}$$

$$\gamma + e^+ \to \gamma + e^+$$

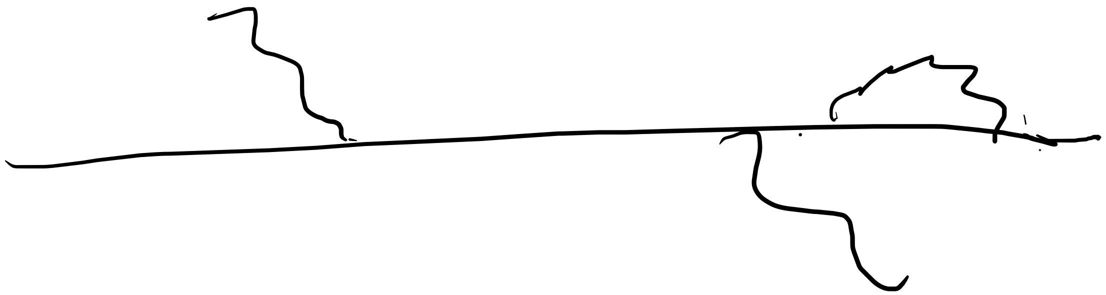






α

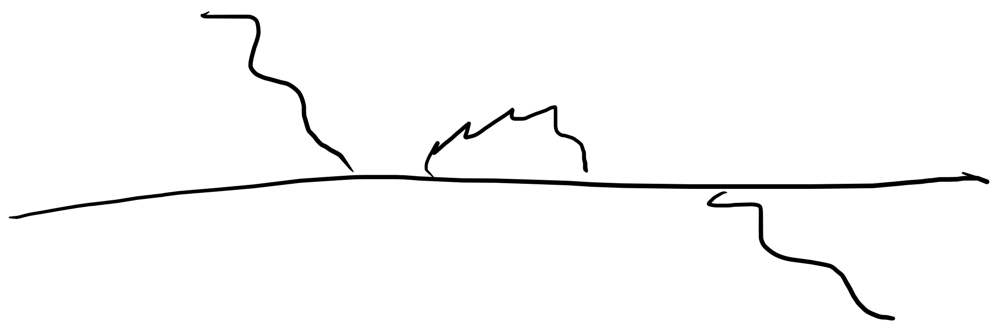
$e^4 \sim \alpha^2$



$\alpha = \frac{e^2}{4\pi\hbar c}$

α

$= \frac{1}{137}$



α

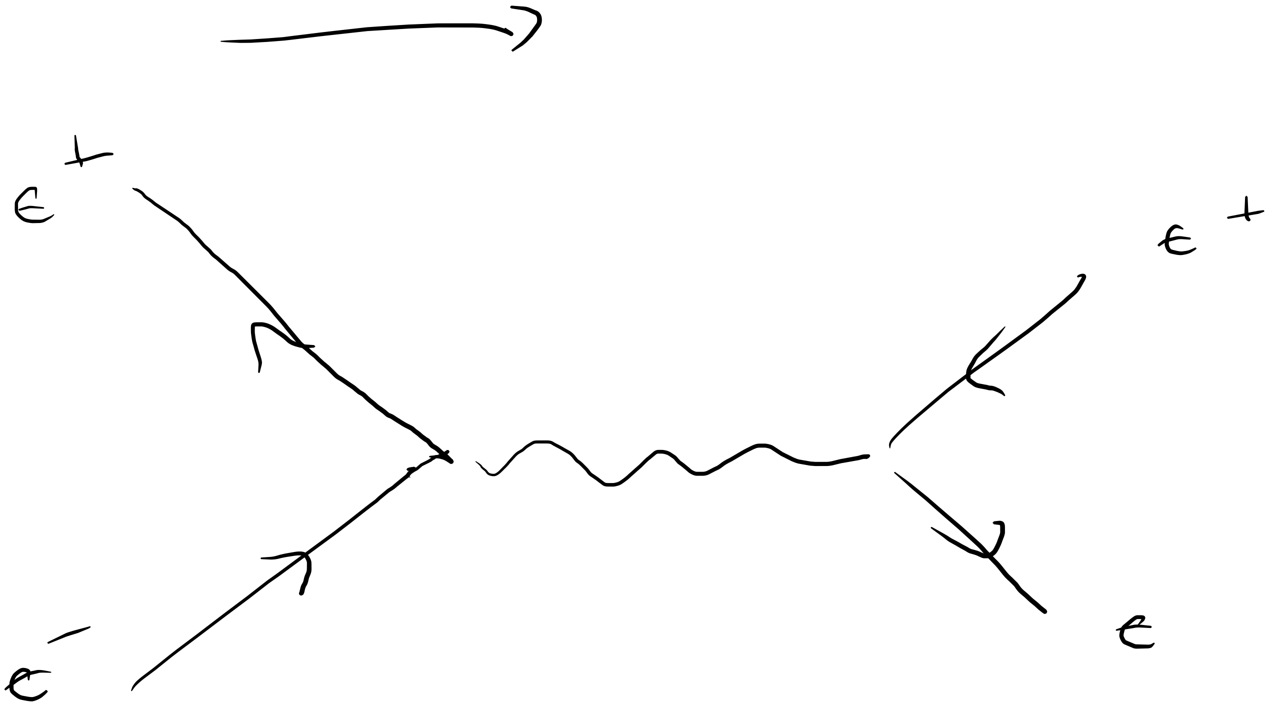
$$\langle e\gamma | e\gamma \rangle = 1 + \alpha(S_a + S_b) + \alpha^2(\ \ )$$

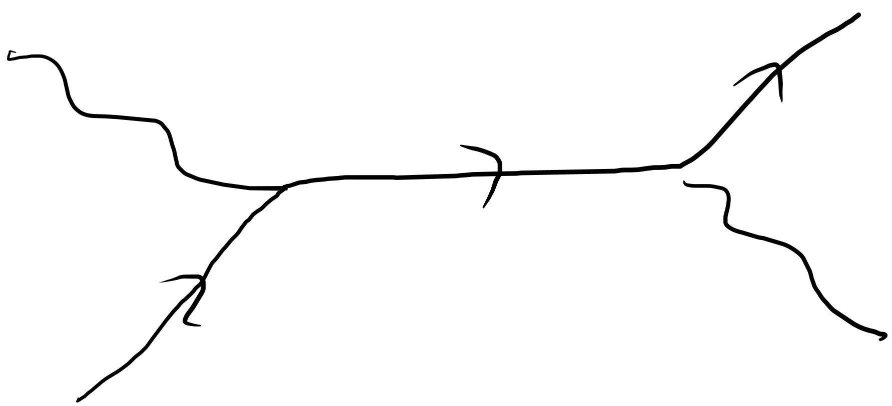
$$\langle t | \, S \, | k \rangle$$

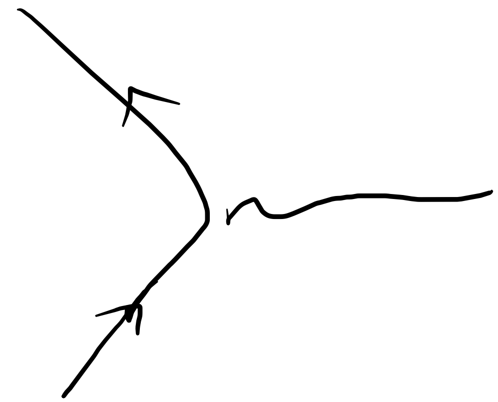
$$a \, c \,) \; c^{\dagger} a^{\dagger} | 0 \rangle$$

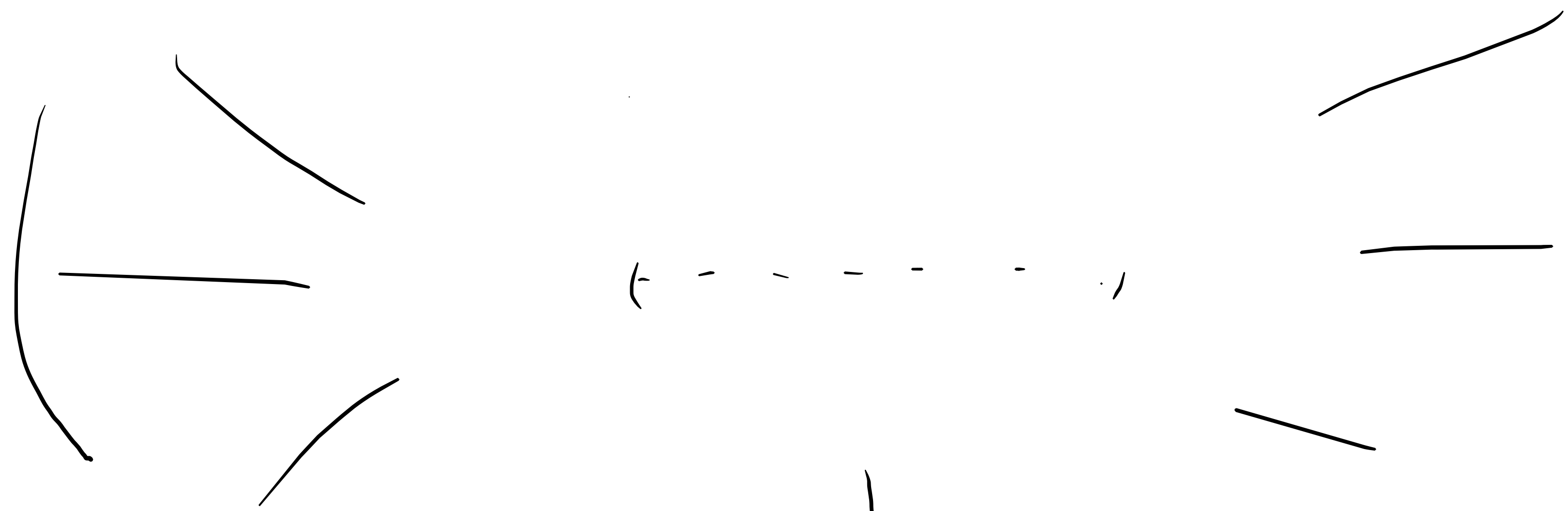
$$\epsilon \gamma$$

$$\delta(k - k')$$


e^+
e^-
e^+
e



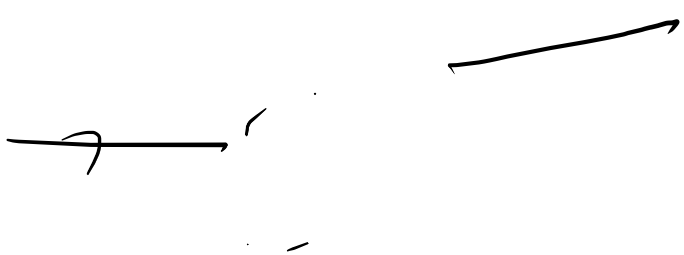


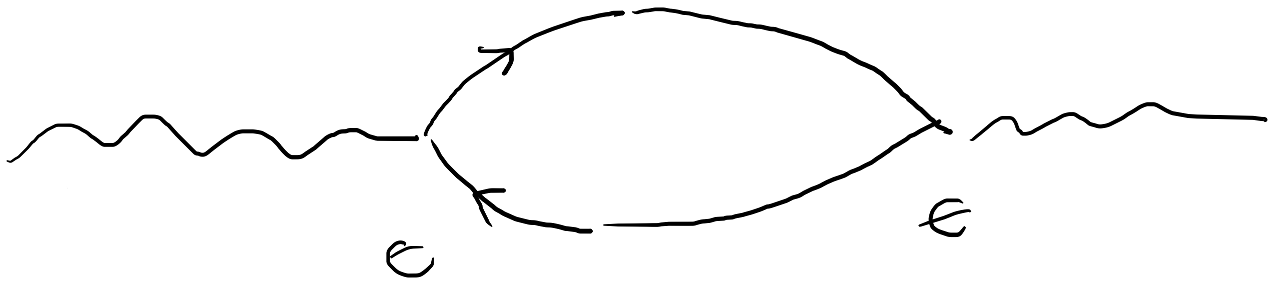


$$\frac{1}{p^2-m^2}$$

125 GeV

TeV





$\propto$

$e^2 = \alpha$

α_B

$\to \frac{1}{128}$ 100 GeV $\alpha = \frac{1}{137}$

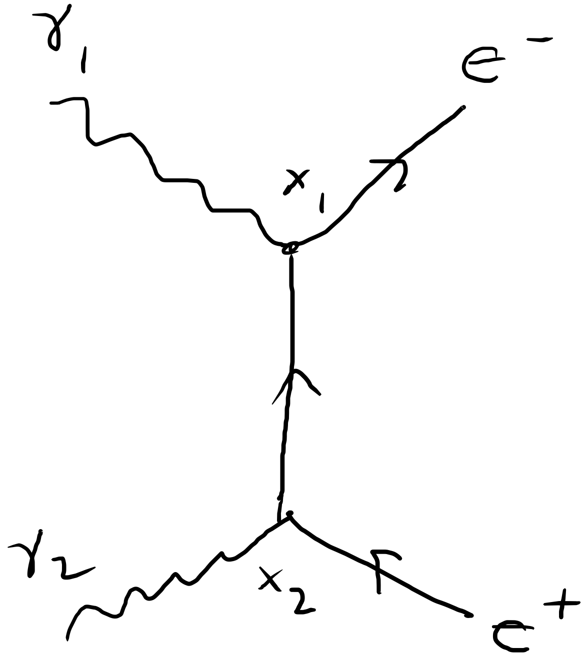
$$\mathcal{L}_{QED} \longrightarrow e\,\underline{(\bar{\psi}\gamma^{\mu}A_{\mu}\psi)} + \frac{1}{e^{2}}F_{\mu\nu}^{2}$$

$$\mathcal{L}_{GR} \longrightarrow \mathcal{L}(R) + \ldots$$

Creación de pares e^+e^-

$$\gamma + \gamma \longrightarrow e^+ + e^-$$

$$S^{(2)}(\gamma\gamma \to e^+e^-) = -e^2 \int d^4x_1\, d^4x_2 \; : \bar{\Psi}^-(x_1)\, \gamma^\mu\, S_F(x_1 - x_2)\, \gamma^\nu\, \Psi^-(x_2) \times \underline{A^+_\mu(x_1)}\, A^+_\nu(x_2)$$



$\gamma + e^- \to \gamma + e^-$