

That wasn't so bad, was it?
We will move on to a real
model/theory, namely QED,
but first need to take a (slight)
detour to the Dirac equation

$$E = T + U = \frac{p^2}{2m} + U$$

$$\mathbf{p} \rightarrow -i\nabla, E \rightarrow i\frac{\partial}{dt}$$

$$E\Psi = T\Psi + U\Psi = \frac{p^2}{2m}\Psi + U\Psi$$

$$-\frac{1}{2m}\nabla^2\Psi + U\Psi = i\frac{\partial\Psi}{dt}$$

$$-\frac{1}{2m}\nabla^2\Psi = i\frac{\partial\Psi}{dt} \text{ (for free particle)}$$

Many problems with this! Most noticeably:

1) No discussion of spin

2) Energy is the classical definition

3) Equations are not Lorentz invariant

(second order in position, first order in time!)

Let's build in Lorentz invariance

$$p^2 = p_\mu p^\mu = m^2$$

$$p_\mu \rightarrow i\partial_\mu = i\frac{\partial}{\partial x^\mu}$$

$$i^2 \frac{\partial^2 \Psi}{\partial t^2} - i^2 \frac{\partial^2 \Psi}{\partial x^2} - i^2 \frac{\partial^2 \Psi}{\partial y^2} - i^2 \frac{\partial^2 \Psi}{\partial z^2} = m^2 \Psi$$

$$\nabla^2 \Psi - \frac{\partial^2 \Psi}{\partial t^2} = m^2 \Psi$$

Klein-Gordon equation. One major problem left over - doesn't account for spin!

$$(p^0)^2 - m^2 = 0 = (p^0 + m)(p^0 - m) = (E + m)(E - m) \text{ only for } \mathbf{p} = 0$$

What happens when \mathbf{p} is not 0?

$$p^\mu p_\mu - m^2 = 0 = (\beta^k p_k + m)(\gamma^\lambda p_\lambda - m)$$

Need to find β and γ (each have 4 components, so 8 numbers in total)

$$\beta^k \gamma^\lambda p_k p_\lambda + m(\gamma^\lambda p_\lambda - \beta^k p_k) - m^2 = 0$$

Dirac's crazy idea rewritten a bit

$$\beta^k \gamma^\lambda p_k p_\lambda + m(\gamma^\lambda p_\lambda - \beta^k p_k) - m^2 = 0$$

Why can I rewrite the dummy indices like this? Let's write out all terms to check...

$$\beta^k \gamma^\lambda p_k p_\lambda + m(\gamma^k - \beta^k) p_k - m^2 = 0$$

$$\beta^k \gamma^\lambda p_k p_\lambda + m(\gamma^k - \beta^k) p_k - m^2 = 0 = p^\mu p_\mu - m^2$$

Note that right-hand side has no p_μ terms,
which implies...

$$(\gamma^k - \beta^k) = 0 \rightarrow \gamma^k = \beta^k$$

$$\beta^k \gamma^\lambda p_k p_\lambda = \gamma^k \gamma^\lambda p_k p_\lambda = p^\mu p_\mu$$

Let's write this out

$$\gamma^k \gamma^\lambda p_k p_\lambda = p^\mu p_\mu$$

$$\gamma^k p_k (\gamma^0 p_0 - \gamma^1 p_1 - \gamma^2 p_2 - \gamma^3 p_3) = (p_0)^2 - (p_1)^2 - (p_2)^2 - (p_3)^2$$

$$(\gamma^0 p_0 - \gamma^1 p_1 - \gamma^2 p_2 - \gamma^3 p_3) (\gamma^0 p_0 - \gamma^1 p_1 - \gamma^2 p_2 - \gamma^3 p_3) = (p_0)^2 - (p_1)^2 - (p_2)^2 - (p_3)^2$$

$$\begin{aligned} & p_0^2 (\gamma^0 \gamma^0) + p_1^2 (\gamma^1 \gamma^1) + p_2^2 (\gamma^2 \gamma^2) + p_3^2 (\gamma^3 \gamma^3) + \\ & p_0 (-\gamma^0 \gamma^1 p_1 - \gamma^0 \gamma^2 p_2 - \gamma^0 \gamma^3 p_3) + \\ & p_1 (-\gamma^1 \gamma^0 p_0 + \gamma^1 \gamma^2 p_2 + \gamma^1 \gamma^3 p_3) + \\ & p_2 (-\gamma^2 \gamma^0 p_0 + \gamma^2 \gamma^1 p_1 + \gamma^2 \gamma^3 p_3) + \\ & p_3 (-\gamma^3 \gamma^0 p_0 + \gamma^3 \gamma^1 p_1 + \gamma^3 \gamma^2 p_2) = \\ & (p_0)^2 - (p_1)^2 - (p_2)^2 - (p_3)^2 \end{aligned}$$

Let's rewrite that a bit

$$\begin{aligned}
 & p_0^2(\gamma^0\gamma^0) + p_1^2(\gamma^1\gamma^1) + p_2^2(\gamma^2\gamma^2) + p_3^2(\gamma^3\gamma^3) + \\
 & p_0(-\gamma^0\gamma^1p_1 - \gamma^0\gamma^2p_2 - \gamma^0\gamma^3p_3) + \\
 & p_1(-\gamma^1\gamma^0p_0 + \gamma^1\gamma^2p_2 + \gamma^1\gamma^3p_3) + \\
 & p_2(-\gamma^2\gamma^0p_0 + \gamma^2\gamma^1p_1 + \gamma^2\gamma^3p_3) + \\
 & p_3(-\gamma^3\gamma^0p_0 + \gamma^3\gamma^1p_1 + \gamma^3\gamma^2p_2) = \\
 & (p_0)^2 - (p_1)^2 - (p_2)^2 - (p_3)^2
 \end{aligned}$$

$$\begin{aligned}
 & p_0^2(\gamma^0\gamma^0) + p_1^2(\gamma^1\gamma^1) + p_2^2(\gamma^2\gamma^2) + p_3^2(\gamma^3\gamma^3) + \\
 & p_0p_1(-\gamma^0\gamma^1 - \gamma^1\gamma^0) + \\
 & p_0p_2(-\gamma^0\gamma^2 - \gamma^2\gamma^0) + \\
 & p_0p_3(-\gamma^0\gamma^3 - \gamma^3\gamma^0) + \\
 & p_1p_2(\gamma^1\gamma^2 + \gamma^2\gamma^1) + \\
 & p_1p_3(\gamma^1\gamma^3 + \gamma^3\gamma^1) + \\
 & p_2p_3(\gamma^2\gamma^3 + \gamma^3\gamma^2) = \\
 & (p_0)^2 - (p_1)^2 - (p_2)^2 - (p_3)^2
 \end{aligned}$$

$$(\gamma^0)^2 = 1$$

$$(\gamma^1)^2 = (\gamma^2)^2 = (\gamma^3)^2 = -1$$

$$\gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 0, \mu \neq \nu$$

Does not hold for ordinary numbers, but it works if they are **matrices**

$$(\gamma^0)^2 = 1$$

$$(\gamma^1)^2 = (\gamma^2)^2 = (\gamma^3)^2 = -1$$

$$\gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 0, \mu \neq \nu$$

$$\{\gamma^\mu, \gamma^\nu\} = \gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 2g^{\mu\nu}$$

$$\gamma^0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}$$

$$i = 1, 2, 3$$

$$\gamma^0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}$$
$$i = 1, 2, 3$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Pauli spin matrices



Gamma matrices are really 4x4 matrices, easier to write in this form

$$\gamma^0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$\gamma^y = \begin{pmatrix} 0 & \sigma_y \\ -\sigma_y & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{pmatrix}$$

$$\gamma^\mu p_\mu - m = 0, p_\mu \rightarrow i\partial_\mu$$

$$i\gamma^\mu \partial_\mu \psi - m\psi = 0$$

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$

$$i\gamma^\mu \partial_\mu \psi - m\psi = 0$$

If wave function does not depend on position, then $\mathbf{p} = 0$ (is that clear why?).

Then equation becomes

$$i\gamma^0 \partial_0 \psi - m\psi = 0$$

$$i\gamma^0 \frac{\partial \psi}{\partial t} - m\psi = 0$$

$$i \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \frac{\partial \psi}{\partial t} = m\psi$$

$$i \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \frac{\partial \psi}{\partial t} = m \psi$$

$$i \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} \partial \psi_A / \partial t \\ \partial \psi_B / \partial t \end{pmatrix} = m \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix}$$

Nicely factorizes like this since the gamma matrix is diagonal

$$\psi_A = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}, \psi_B = \begin{pmatrix} \psi_3 \\ \psi_4 \end{pmatrix}$$

Two-component spinors

Electrons

$$\text{Spin up } \psi_1 = e^{-imt} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \text{ Spin down } \psi_2 = e^{-imt} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

Positrons

$$\text{Spin down } \psi_3 = e^{+imt} \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}, \text{ Spin up } \psi_4 = e^{+imt} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

Four solution to zero momentum Dirac equation

$$\partial\psi_A/\partial t = -im\psi_A \rightarrow \psi_A(t) = e^{-imt}\psi_A(0)$$

$$\partial\psi_B/\partial t = im\psi_B \rightarrow \psi_B(t) = e^{+imt}\psi_B(0)$$

Recall that we object was not moving, so energy of $\psi_A = m$, as expected. But energy of $\psi_B = -m$!

ψ_A represents particles such as electrons with mass m and positive energy, ψ_B represents anti-particles such as anti-electrons with mass m and negative energy

Let's try and find generic plane wave solutions

$$\psi(x) = ae^{-ik \cdot x} u(k)$$

$u(k)$ is a bi-spinor

$$i\gamma^\mu \partial_\mu \psi - m\psi = 0$$

Write this way
to be explicit:

Don't forget:

$$\mathbf{k} \cdot \mathbf{r} = k_x r^x + k_y r^y + k_z r^z$$

$$\partial_\mu = \frac{\partial}{\partial x^\mu} \neq \frac{\partial}{\partial x_\mu}$$

$$k \cdot x = k_0 t^t - \mathbf{k} \cdot \mathbf{r}$$

$$\partial_\mu \psi = \frac{\partial}{\partial t} \left[ae^{-i(k_0 t^t - \mathbf{k} \cdot \mathbf{r})} u(k) \right] - \nabla_\mu \left[ae^{-i(k_0 t^t - k_x r^x - k_y r^y - k_z r^z)} u(k) \right]$$

$$\partial_\mu \psi = -ik_0 \psi - ik_x \psi - ik_y \psi - ik_z \psi = -ik_\mu \psi$$

Plugging that in

$$i\gamma^\mu(-ik_\mu\psi) - m\psi = 0$$

$$\gamma^\mu(k_\mu - m)\psi = (\gamma^\mu k_\mu - m) a e^{-ik \cdot x} u(k) = 0$$

$$(\gamma^\mu k_\mu - m) u(k) = 0$$

$$\gamma^\mu k_\mu = \gamma^0 k^0 - \boldsymbol{\gamma} \cdot \mathbf{k} = k^0 \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} - \mathbf{k} \cdot \begin{pmatrix} 0 & \vec{\sigma} \\ -\vec{\sigma} & 0 \end{pmatrix} = \begin{pmatrix} k^0 & -\vec{k} \cdot \vec{\sigma} \\ \vec{k} \cdot \vec{\sigma} & -k^0 \end{pmatrix}$$

So...

$$\begin{pmatrix} k^0 - m & -\vec{k} \cdot \vec{\sigma} \\ \vec{k} \cdot \vec{\sigma} & -k^0 - m \end{pmatrix} \begin{pmatrix} u_A \\ u_B \end{pmatrix} = 0$$

$$\begin{pmatrix} k^0 - m & -\vec{k} \cdot \vec{\sigma} \\ \vec{k} \cdot \vec{\sigma} & -k^0 - m \end{pmatrix} \begin{pmatrix} u_A \\ u_B \end{pmatrix} = 0$$

$$\begin{pmatrix} (k^0 - m)u_A - (\vec{k} \cdot \vec{\sigma})u_B \\ (\vec{k} \cdot \vec{\sigma})u_A - (k^0 + m)u_B \end{pmatrix} = 0$$

$$(k^0 - m)u_A - (\vec{k} \cdot \vec{\sigma})u_B = 0$$

$$(\vec{k} \cdot \vec{\sigma})u_A - (k^0 + m)u_B = 0$$

$$(k^0 - m)u_A - (\vec{k} \cdot \vec{\sigma})u_B = 0 \rightarrow u_A = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 - m} u_B$$

$$(\vec{k} \cdot \vec{\sigma})u_A - (k^0 + m)u_B = 0 \rightarrow u_B = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 + m} u_A$$

$$u_A = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 - m} u_B$$

$$u_B = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 + m} u_A$$

$$u_A = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 - m} \frac{\vec{k} \cdot \vec{\sigma}}{k^0 + m} u_A$$

$$u_A = \frac{(\vec{k} \cdot \vec{\sigma})^2}{(k^0)^2 - m^2} u_A$$

$$\vec{k} \cdot \vec{\sigma} = k_x \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} + k_y \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} + k_z \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad \vec{k} \cdot \vec{\sigma} = \begin{pmatrix} k_z & k_x - ik_y \\ k_x + ik_y & -k_z \end{pmatrix}$$

$$\left(\vec{k} \cdot \vec{\sigma}\right)^2 = \begin{pmatrix} k_z & k_x - ik_y \\ k_x + ik_y & -k_z \end{pmatrix} \begin{pmatrix} k_z & k_x - ik_y \\ k_x + ik_y & -k_z \end{pmatrix}$$

$$\left(\vec{k} \cdot \vec{\sigma}\right)^2 = \begin{pmatrix} k_z^2 + (k_x - ik_y)(k_x + ik_y) & k_z(k_x - ik_y) - k_z(k_x - ik_y) \\ k_z(k_x + ik_y) - k_z(k_x + ik_y) & (k_x + ik_y)(k_x - ik_y) + k_z^2 \end{pmatrix}$$

$$\left(\vec{k} \cdot \vec{\sigma}\right)^2 = \mathbf{k}^2 \mathbf{1}$$

$$u_A = \frac{\vec{k}^2}{(k^0)^2 - m^2} u_A \quad \longrightarrow \quad (k^0)^2 - m^2 = \vec{k}^2$$

$$k^2 = m^2 \rightarrow k^\mu = \pm p^\mu$$

Let's get back to our solutions

$$u_A = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 - m} u_B = \frac{\vec{p} \cdot \vec{\sigma}}{E - m} u_B$$

$$u_B = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 + m} u_A = \frac{\vec{p} \cdot \vec{\sigma}}{E + m} u_A$$

Pick positive solution so we don't divide by zero when $\mathbf{p}=0$

From before:

$$\vec{k} \cdot \vec{\sigma} = \vec{p} \cdot \vec{\sigma} = \begin{pmatrix} k_z & k_x - ik_y \\ k_x + ik_y & -k_z \end{pmatrix} = \begin{pmatrix} p_z & p_x - ip_y \\ p_x + ip_y & -p_z \end{pmatrix}$$

Independent solution 1:

$$u_A = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, u_B = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 + m} u_A = \frac{\vec{p} \cdot \vec{\sigma}}{E + m} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$u_A = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, u_B = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 + m} u_A = \frac{1}{E + m} \begin{pmatrix} p_z \\ p_x + ip_y \end{pmatrix}$$

Let's get back to our solutions

$$u_A = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 - m} u_B = \frac{\vec{p} \cdot \vec{\sigma}}{E - m} u_B$$

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Independent solution 2:

$$u_A = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, u_B = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 + m} u_A = \frac{\vec{p} \cdot \vec{\sigma}}{E + m} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$u_A = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, u_B = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 + m} u_A = \frac{1}{E + m} \begin{pmatrix} p_x - ip_y \\ -p_z \end{pmatrix}$$

Let's get back to our solutions

$$u_A = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 - m} u_B = \frac{\vec{p} \cdot \vec{\sigma}}{E - m} u_B$$

$$u_B = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 + m} u_A = \frac{\vec{p} \cdot \vec{\sigma}}{E + m} u_A$$

Pick negative solution so we don't divide by zero when $\mathbf{p}=0$ (anti-particles)

From before:

$$\vec{k} \cdot \vec{\sigma} = \vec{p} \cdot \vec{\sigma} = \begin{pmatrix} k_z & k_x - ik_y \\ k_x + ik_y & -k_z \end{pmatrix} = \begin{pmatrix} p_z & p_x - ip_y \\ p_x + ip_y & -p_z \end{pmatrix}$$

Independent solution 3:

$$u_B = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, u_A = \frac{\vec{p} \cdot \vec{\sigma}}{E - m} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$u_B = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, u_A = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 - m} u_B = \frac{1}{-E - m} \begin{pmatrix} p_z \\ p_x + ip_y \end{pmatrix}$$

Let's get back to our solutions

$$u_A = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 - m} u_B = \frac{\vec{p} \cdot \vec{\sigma}}{E - m} u_B$$

$$u_B = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 + m} u_A = \frac{\vec{p} \cdot \vec{\sigma}}{E + m} u_A$$

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$$\vec{k} \cdot \vec{\sigma} = \vec{p} \cdot \vec{\sigma} = \begin{pmatrix} k_z & k_x - ik_y \\ k_x + ik_y & -k_z \end{pmatrix} = \begin{pmatrix} p_z & p_x - ip_y \\ p_x + ip_y & -p_z \end{pmatrix}$$

Independent solution 4:

$$u_B = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, u_A = \frac{\vec{p} \cdot \vec{\sigma}}{E - m} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$u_B = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, u_A = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 - m} u_B = \frac{1}{-E - m} \begin{pmatrix} p_x - ip_y \\ -p_z \end{pmatrix}$$

As in Griffiths, we'll follow notation to use u for particles and v for anti-particles

Normalization of our spinors

Unnormalized 1)

$$u_A = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, u_B = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 + m} u_A = \frac{1}{E + m} \begin{pmatrix} p_z \\ p_x + ip_y \end{pmatrix}$$

Unnormalized 2)

$$u_A = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, u_B = \frac{\vec{k} \cdot \vec{\sigma}}{k^0 + m} u_A = \frac{1}{E + m} \begin{pmatrix} p_x - ip_y \\ -p_z \end{pmatrix}$$

$$u(1) = N \begin{pmatrix} 1 \\ 0 \\ (p_z)/(E + m) \\ (p_x + ip_y)/(E + m) \end{pmatrix}$$

$$u^\dagger(1)u(1) = |N|^2 \begin{pmatrix} (1)(0) & \begin{pmatrix} p_z \\ E + m \end{pmatrix} & \begin{pmatrix} p_x - ip_y \\ E + m \end{pmatrix} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ (p_z)/(E + m) \\ (p_x + ip_y)/(E + m) \end{pmatrix}$$

Normalization of our spinors

$$u^\dagger(1)u(1) = |N|^2 \left((1)(0) \left(\frac{p_z}{E+m} \right) \left(\frac{p_x - ip_y}{E+m} \right) \right) \begin{pmatrix} 1 \\ 0 \\ (p_z)/(E+m) \\ (p_x + ip_y)/(E+m) \end{pmatrix}$$

$$u^\dagger(1)u(1) = |N|^2 \left(1 + 0 + \frac{p_z^2}{(E+m)^2} + \frac{p_x^2 + p_y^2}{(E+m)^2} \right)$$

$$u^\dagger(1)u(1) = |N|^2 \left(1 + \frac{\mathbf{p}^2}{(E+m)^2} \right)$$

$$u^\dagger(1)u(1) = |N|^2 \left(\frac{\mathbf{p}^2 + (E+m)^2}{(E+m)^2} \right)$$

$$u^\dagger(1)u(1) = |N|^2 \left(\frac{E^2 - m^2 + E^2 + m^2 + 2Em}{(E+m)^2} \right)$$

$$u^\dagger(1)u(1) = |N|^2 \left(\frac{2E^2 + 2Em}{(E+m)^2} \right)$$

$$u^\dagger(1)u(1) = |N|^2 \frac{2E}{E+m}$$

What do we want the spinor to be normalized to?
 Convenient choice (following Griffiths) is $2E$

$$u^\dagger(1)u(1) = |N|^2 \frac{2E}{E + m} = 2E$$

$$N = \sqrt{E + m}$$

I leave it to you to check that the same normalization holds true for $u(2)$, $v(1)$ and $v(2)$

How do Dirac spinors transform?

System moving in x direction

$$\psi \rightarrow \psi' = S\psi$$

$$S = a_+ + a_- \gamma^0 \gamma^1 = \begin{pmatrix} a_+ & 0 & 0 & 0 \\ 0 & a_+ & 0 & 0 \\ 0 & 0 & a_+ & 0 \\ 0 & 0 & 0 & a_+ \end{pmatrix} + a_- \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} 0 & \sigma_x \\ -\sigma_x & 0 \end{pmatrix}$$

$$S = a_+ + a_- \gamma^0 \gamma^1 = \begin{pmatrix} a_+ & 0 & 0 & 0 \\ 0 & a_+ & 0 & 0 \\ 0 & 0 & a_+ & 0 \\ 0 & 0 & 0 & a_+ \end{pmatrix} + a_- \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix}$$

$$S = a_+ + a_- \gamma^0 \gamma^1 = \begin{pmatrix} a_+ & 0 & 0 & 0 \\ 0 & a_+ & 0 & 0 \\ 0 & 0 & a_+ & 0 \\ 0 & 0 & 0 & a_+ \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 & a_- \\ 0 & 0 & a_- & 0 \\ 0 & a_- & 0 & 0 \\ a_- & 0 & 0 & 0 \end{pmatrix}$$

$$a_{\pm} = \pm \sqrt{\frac{1}{2}(\gamma \pm 1)}$$

$$\gamma = (1 - v^2)^{-1/2}$$

$$S = a_+ + a_- \gamma^0 \gamma^1 = \begin{pmatrix} a_+ & 0 & 0 & a_- \\ 0 & a_+ & a_- & 0 \\ 0 & a_- & a_+ & 0 \\ a_- & 0 & 0 & a_+ \end{pmatrix}$$

Why is that? (Problem 7.11)

$$i\gamma^\mu \partial_\mu \psi - m\psi = 0$$

$$i\gamma^\mu \partial'_\mu \psi' - m\psi' = 0 \quad \partial'_\mu = \frac{\partial}{\partial x^{\mu'}} = \frac{\partial x^\nu}{\partial x^{\mu'}} \frac{\partial}{\partial x^\nu} = \frac{\partial x^\nu}{\partial x^{\mu'}} \partial_\nu$$

$$\psi' = S\psi$$

$$i\gamma^\mu \frac{\partial x^\nu}{\partial x^{\mu'}} \partial_\nu (S\psi) - m(S\psi) = 0$$

$$S^{-1} \left[i\gamma^\mu \frac{\partial x^\nu}{\partial x^{\mu'}} \partial_\nu (S\psi) - m(S\psi) \right] = 0$$

$$S^{-1} \left[i\gamma^\mu \frac{\partial x^\nu}{\partial x^{\mu'}} \partial_\nu (S\psi) - m(S\psi) \right] = 0 = i\gamma^\nu \partial_\nu \psi - m\psi$$

$$S^{-1} \gamma^\mu \frac{\partial x^\nu}{\partial x^{\mu'}} S = \gamma^\nu$$

$$S^{-1} \gamma^\mu S \frac{\partial x^\nu}{\partial x^{\mu'}} = \gamma^\nu$$

$$\frac{\partial x^0}{\partial x^{0'}} = \gamma$$

$$S^{-1} \gamma^\mu S \frac{\partial x^\nu}{\partial x^{\mu'}} = \gamma^\nu$$

$$\frac{\partial x^0}{\partial x^{1'}} = \gamma v$$

Others are zero (these just come from the transformation laws)

$$\frac{\partial x^1}{\partial x^{0'}} = \gamma v$$

$$\frac{\partial x^1}{\partial x^{1'}} = \gamma$$

$$\gamma^0 = S^{-1} \gamma^0 S \frac{\partial x^0}{\partial x^{0'}} + S^{-1} \gamma^1 S \frac{\partial x^0}{\partial x^{1'}} + S^{-1} \gamma^2 S \frac{\partial x^0}{\partial x^{2'}} + S^{-1} \gamma^3 S \frac{\partial x^0}{\partial x^{3'}}$$

$$\gamma^1 = S^{-1} \gamma^0 S \frac{\partial x^1}{\partial x^{0'}} + S^{-1} \gamma^1 S \frac{\partial x^1}{\partial x^{1'}} + S^{-1} \gamma^2 S \frac{\partial x^1}{\partial x^{2'}} + S^{-1} \gamma^3 S \frac{\partial x^1}{\partial x^{3'}}$$

$$\frac{\partial x^2}{\partial x^{2'}} = 1$$

$$\gamma^2 = S^{-1} \gamma^0 S \frac{\partial x^2}{\partial x^{0'}} + S^{-1} \gamma^1 S \frac{\partial x^2}{\partial x^{1'}} + S^{-1} \gamma^2 S \frac{\partial x^2}{\partial x^{2'}} + S^{-1} \gamma^3 S \frac{\partial x^2}{\partial x^{3'}}$$

$$\frac{\partial x^3}{\partial x^{3'}} = 1$$

$$\gamma^3 = S^{-1} \gamma^0 S \frac{\partial x^3}{\partial x^{0'}} + S^{-1} \gamma^1 S \frac{\partial x^3}{\partial x^{1'}} + S^{-1} \gamma^2 S \frac{\partial x^3}{\partial x^{2'}} + S^{-1} \gamma^3 S \frac{\partial x^3}{\partial x^{3'}}$$

Those partial derivatives

$$\frac{\partial x^0}{\partial x^{0'}} = \gamma$$

$$\frac{\partial x^0}{\partial x^{1'}} = \gamma v$$

$$\frac{\partial x^1}{\partial x^{0'}} = \gamma v$$

$$\frac{\partial x^1}{\partial x^{1'}} = \gamma$$

$$\frac{\partial x^2}{\partial x^{2'}} = 1$$

$$\frac{\partial x^3}{\partial x^{3'}} = 1$$

$$\gamma^0 = S^{-1} \gamma^0 S \gamma + S^{-1} \gamma^1 S \gamma v$$

$$\gamma^1 = S^{-1} \gamma^0 S \gamma v + S^{-1} \gamma^1 S \gamma$$

$$\gamma^2 = S^{-1} \gamma^2 S$$

$$\gamma^3 = S^{-1} \gamma^3 S$$

Now multiply by S

$$S \gamma^0 = \gamma^0 S \gamma + \gamma^1 S \gamma v$$

$$S \gamma^1 = \gamma^0 S \gamma v + \gamma^1 S \gamma$$

$$S \gamma^2 = \gamma^2 S$$

$$S \gamma^3 = \gamma^3 S$$

Does our solution satisfy these?

$$S\gamma^0 = \gamma^0 S\gamma + \gamma^1 S\gamma^v$$

$$S\gamma^1 = \gamma^0 S\gamma^v + \gamma^1 S\gamma$$

$$S\gamma^2 = \gamma^2 S$$

$$S\gamma^3 = \gamma^3 S$$

Useful relation: we've seen it, please remember !):

$$\gamma^\mu \gamma^\nu = -\gamma^\nu \gamma^\mu, \mu \neq \nu$$

Ensures that last two equations hold (see why?)

$$S = a_+ + a_- \gamma^0 \gamma^1 = \begin{pmatrix} a_+ & 0 & 0 & 0 \\ 0 & a_+ & 0 & 0 \\ 0 & 0 & a_+ & 0 \\ 0 & 0 & 0 & a_+ \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 & a_- \\ 0 & 0 & a_- & 0 \\ 0 & a_- & 0 & 0 \\ a_- & 0 & 0 & 0 \end{pmatrix}$$

$$S = a_+ + a_- \gamma^0 \gamma^1 = \begin{pmatrix} a_+ & 0 & 0 & a_- \\ 0 & a_+ & a_- & 0 \\ 0 & a_- & a_+ & 0 \\ a_- & 0 & 0 & a_+ \end{pmatrix}$$

First equation

$$S\gamma^0 = \gamma^0 S\gamma + \gamma^1 S\gamma v$$

$$(a_+ + a_-\gamma^0\gamma^1)\gamma^0 = \gamma^0(a_+ + a_-\gamma^0\gamma^1)\gamma + \gamma^1(a_+ + a_-\gamma^0\gamma^1)\gamma v$$

Another useful relation:

$$\gamma^\mu \gamma^\mu = 1, \mu = 0$$

$$\gamma^\mu \gamma^\mu = -1, \mu \neq 0$$

$$a_+\gamma^0 + a_-\gamma^0\gamma^1\gamma^0 = \gamma^0 a_+\gamma + \gamma^0 a_-\gamma^0\gamma^1\gamma + \gamma^1 a_+\gamma v + \gamma^1 a_-\gamma^0\gamma^1\gamma v$$

$$a_+\gamma^0 - a_-\gamma^0\gamma^0\gamma^1 = a_+\gamma\gamma^0 + a_-\gamma\gamma^0\gamma^0\gamma^1 + a_+\gamma v\gamma^1 - a_-\gamma v\gamma^1\gamma^1\gamma^0$$

$$a_+\gamma^0 - a_-\gamma^1 = a_+\gamma\gamma^0 + a_-\gamma\gamma^1 + a_+\gamma v\gamma^1 + a_-\gamma v\gamma^0$$

$$a_+\gamma^0 - a_-\gamma^1 = (a_+\gamma + a_-\gamma v)\gamma^0 + (a_-\gamma + a_+\gamma v)\gamma^1$$

$$a_+ \gamma^0 - a_- \gamma^1 = (a_+ \gamma + a_- \gamma v) \gamma^0 + (a_- \gamma + a_+ \gamma v) \gamma^1$$

$$\gamma = (1 - v^2)^{-1/2} \rightarrow (\gamma)^2 = \frac{1}{1 - v^2}$$

$$1 - v^2 = \frac{1}{(\gamma)^2}$$

$$v^2 = 1 - \frac{1}{(\gamma)^2} = \frac{(\gamma)^2 - 1}{(\gamma)^2}$$

$$v = \frac{\sqrt{(\gamma + 1)(\gamma - 1)}}{\gamma}$$

$$a_+ \gamma^0 - a_- \gamma^1 = (a_+ \gamma + a_- \gamma v) \gamma^0 + (a_- \gamma + a_+ \gamma v) \gamma^1$$

$$a_+ \gamma + a_- \gamma v = \gamma \sqrt{\frac{1}{2}(\gamma + 1)} - \gamma \sqrt{\frac{1}{2}(\gamma - 1)} \frac{\sqrt{(\gamma + 1)(\gamma - 1)}}{\gamma}$$

$$a_+ \gamma + a_- \gamma v = \gamma \sqrt{\frac{1}{2}(\gamma + 1)} - \sqrt{\frac{1}{2}(\gamma - 1)} \sqrt{(\gamma + 1)(\gamma - 1)}$$

$$a_+ \gamma + a_- \gamma v = \gamma \sqrt{\frac{1}{2}(\gamma + 1)} - (\gamma - 1) \sqrt{\frac{1}{2}(\gamma + 1)}$$

$$a_+ \gamma + a_- \gamma v = \sqrt{\frac{1}{2}(\gamma + 1)} (\gamma - \gamma + 1)$$

$$a_+ \gamma + a_- \gamma v = \sqrt{\frac{1}{2}(\gamma + 1)} = a_+$$



Now the second part

$$a_+ \gamma^0 - a_- \gamma^1 = (a_+ \gamma + a_- \gamma v) \gamma^0 + (a_- \gamma + a_+ \gamma v) \gamma^1$$

$$a_- \gamma + a_+ \gamma v = -\gamma \sqrt{\frac{1}{2}(\gamma - 1)} + \gamma \sqrt{\frac{1}{2}(\gamma + 1)} \frac{\sqrt{(\gamma + 1)(\gamma - 1)}}{\gamma}$$

$$a_- \gamma + a_+ \gamma v = -\gamma \sqrt{\frac{1}{2}(\gamma - 1)} + \sqrt{\frac{1}{2}(\gamma + 1)} \sqrt{(\gamma + 1)(\gamma - 1)}$$

$$a_- \gamma + a_+ \gamma v = -\gamma \sqrt{\frac{1}{2}(\gamma - 1)} + (\gamma + 1) \sqrt{\frac{1}{2}(\gamma - 1)}$$

$$a_- \gamma + a_+ \gamma v = \sqrt{\frac{1}{2}(\gamma - 1)} (-\gamma + \gamma + 1)$$

$$a_- \gamma + a_+ \gamma v = \sqrt{\frac{1}{2}(\gamma - 1)} = -a_- \quad \checkmark$$

Second equation

$$S\gamma^0 = \gamma^0 S\gamma + \gamma^1 S\gamma v$$

$$S\gamma^1 = \gamma^0 S\gamma v + \gamma^1 S\gamma$$

$$S = a_+ + a_- \gamma^0 \gamma^1$$

$$S\gamma^2 = \gamma^2 S$$

$$S\gamma^3 = \gamma^3 S$$

$$S\gamma^1 = \gamma^0 S\gamma v + \gamma^1 S\gamma$$

$$(a_+ + a_- \gamma^0 \gamma^1) \gamma^1 = \gamma v \gamma^0 (a_+ + a_- \gamma^0 \gamma^1) + \gamma \gamma^1 (a_+ + a_- \gamma^0 \gamma^1)$$

$$a_+ \gamma^1 - a_- \gamma^0 = \gamma v a_+ \gamma^0 + \gamma v a_- \gamma^1 + \gamma a_+ \gamma^1 + \gamma a_- \gamma^0$$

$$a_+ \gamma^1 - a_- \gamma^0 = \gamma^0 (\gamma v a_+ + \gamma a_-) + \gamma^1 (a_- \gamma v + a_+ \gamma)$$

These are the exact conditions we already just worked out!

Phew! Is this an invariant?

$$\psi^\dagger \psi = (\psi_1^* \psi_2^* \psi_3^* \psi_4^*) \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix} = |\psi_1|^2 + |\psi_2|^2 + |\psi_3|^2 + |\psi_4|^2$$

NO!

$$(\psi^\dagger \psi)' = (\psi'^\dagger \psi') = (S\psi)^\dagger S\psi = \psi^\dagger S^\dagger S\psi \neq (\psi^\dagger \psi)$$

Let's check this:

But define: $\bar{\psi} = \psi^\dagger \gamma^0 = ((\psi_1^*) (\psi_2^*) (-\psi_3^*) (-\psi_4^*))$

$$S^\dagger \gamma^0 S = \gamma^0 \quad \text{Part of your homework}$$

$$(\bar{\psi}\psi)' = (\psi^\dagger \gamma^0 \psi)' = (\psi'^\dagger) \gamma^0 \psi'$$

$$(\bar{\psi}\psi)' = (S\psi)^\dagger \gamma^0 S\psi = \psi^\dagger S^\dagger \gamma^0 S\psi = \psi^\dagger \gamma^0 \psi = (\bar{\psi}\psi) \quad \checkmark$$

What about parity transformation?

Our
earlier
friend:

$$S^{-1} \gamma^\mu S \frac{\partial x^\nu}{\partial x^{\mu'}} = \gamma^\nu$$

$$S = \gamma^0$$

$$x' = -x; y' = -y; z' = -z$$

$$t = t$$

$$\frac{\partial x^0}{\partial x^{0'}} = 1$$

$$\frac{\partial x^1}{\partial x^{1'}} = -1$$

$$\frac{\partial x^2}{\partial x^{2'}} = -1$$

$$\frac{\partial x^3}{\partial x^{3'}} = -1$$

$$S^{-1} \gamma^0 S = \gamma^0 \rightarrow \gamma^0 S = S \gamma^0$$

$$-S^{-1} \gamma^1 S = \gamma^1 \rightarrow \gamma^1 S = -S \gamma^1$$

$$-S^{-1} \gamma^2 S = \gamma^2 \rightarrow \gamma^2 S = -S \gamma^2$$

$$-S^{-1} \gamma^3 S = \gamma^3 \rightarrow \gamma^3 S = -S \gamma^3$$

Do we see why?

All other partial derivatives are zero

$$\psi \rightarrow \gamma^0 \psi$$

$$(\bar{\psi}\psi)' = (\psi^\dagger \gamma^0 \psi)' = (\psi^\dagger)' \gamma^0 \psi' = (\gamma^0 \psi)^\dagger \gamma^0 \gamma^0 \psi$$

$$(\bar{\psi}\psi)' = \psi^\dagger \gamma^{0\dagger} \gamma^0 \gamma^0 \psi = (\psi^\dagger \gamma^0 \psi) = (\bar{\psi}\psi)$$

So it transforms like a scalar

Can we make a pseudoscalar?

$$(\bar{\psi}\gamma^5\psi)' = (\psi^\dagger\gamma^0\gamma^5\psi)' = \psi'^\dagger\gamma^{0'}\gamma^{5'}\psi'$$

Define: $\bar{\psi}\gamma^5\psi$

$$\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3$$

$$(\bar{\psi}\gamma^5\psi)' = \psi^\dagger\gamma^{0\dagger}\gamma^0\gamma^5\gamma^0\psi$$

$$(\bar{\psi}\gamma^5\psi)' = \psi^\dagger\gamma^5\gamma^0\psi$$

$$\gamma^5\gamma^0 = i\gamma^0\gamma^1\gamma^2\gamma^3\gamma^0 = -i\gamma^0\gamma^1\gamma^2\gamma^0\gamma^3 = +i\gamma^0\gamma^1\gamma^0\gamma^2\gamma^3$$

$$\gamma^5\gamma^0 = -i\gamma^0\gamma^0\gamma^1\gamma^2\gamma^3 = -\gamma^0\gamma^5$$

$$(\bar{\psi}\gamma^5\psi)' = -\psi^\dagger\gamma^0\gamma^5\psi = -(\bar{\psi}\gamma^5\psi)$$

Pseudoscalar

$$\bar{\psi}\gamma^5\psi$$

Vector $\bar{\psi}\gamma^\mu\psi$

Pseudovector $\bar{\psi}\gamma^\mu\gamma^5\psi$

OK, let's get to QED. A useful table from Griffiths

Electrons

$$\psi(x) = ae^{-(i/\hbar)p \cdot x} u^{(s)}(p)$$

Positrons

$$\psi(x) = ae^{(i/\hbar)p \cdot x} v^{(s)}(p) \quad (7.94)$$

where $s = 1, 2$ for the two spin states. The spinors $u^{(s)}$ and $v^{(s)}$ satisfy the momentum space Dirac equation(s):

$$(\gamma^\mu p_\mu - mc)u = 0 \quad (\gamma^\mu p_\mu + mc)v = 0 \quad (7.95)$$

their adjoints, $\bar{u} = u^\dagger \gamma^0$, $\bar{v} = v^\dagger \gamma^0$, satisfy

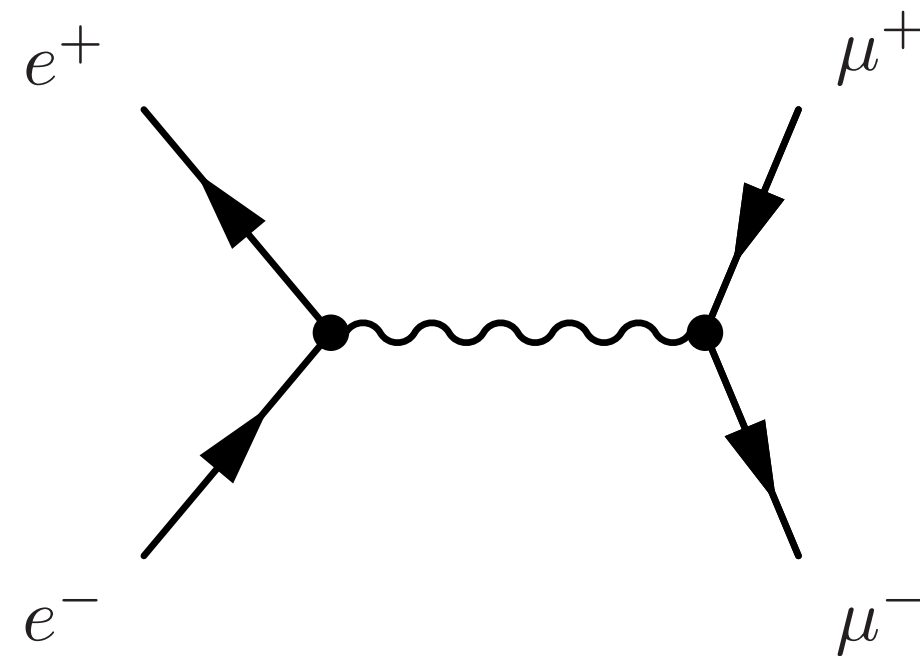
$$\bar{u}(\gamma^\mu p_\mu - mc) = 0 \quad \bar{v}(\gamma^\mu p_\mu + mc) = 0 \quad (7.96)$$

They are orthogonal,

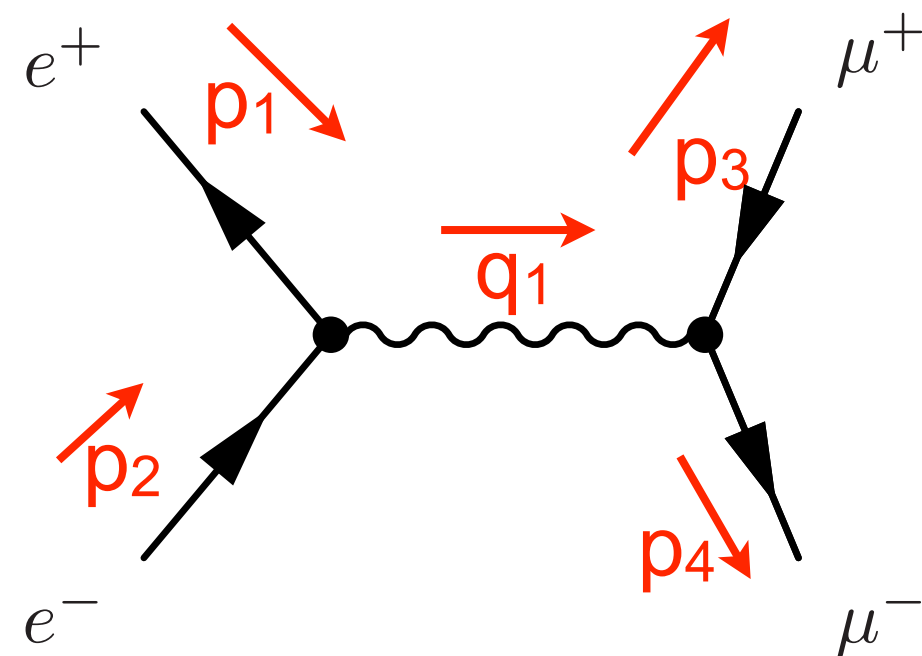
$$\bar{u}^{(1)} u^{(2)} = 0 \quad \bar{v}^{(1)} v^{(2)} = 0 \quad (7.97)$$

normalized,

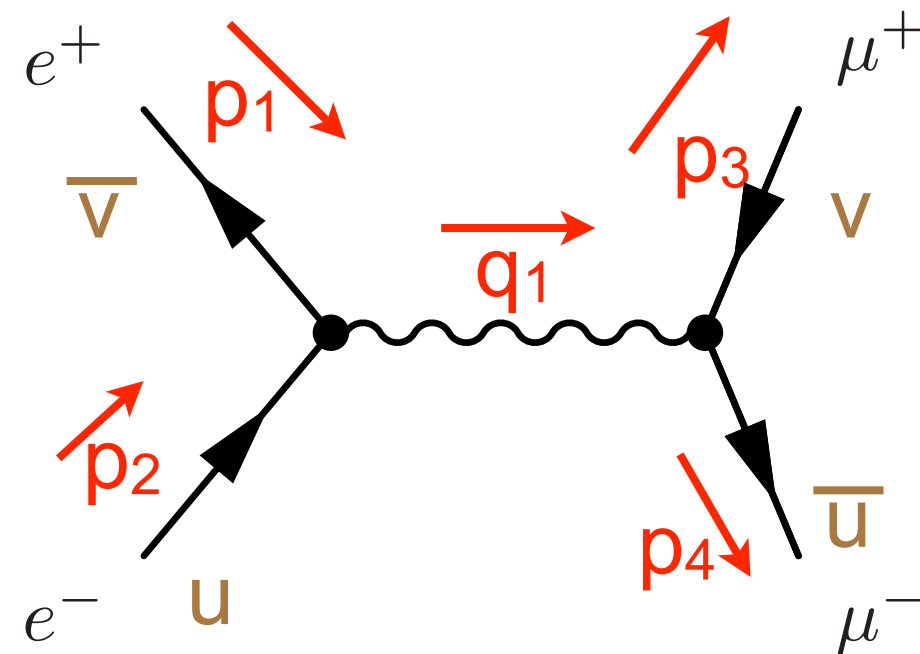
$$\bar{u}u = 2mc \quad \bar{v}v = -2mc \quad (7.98)$$



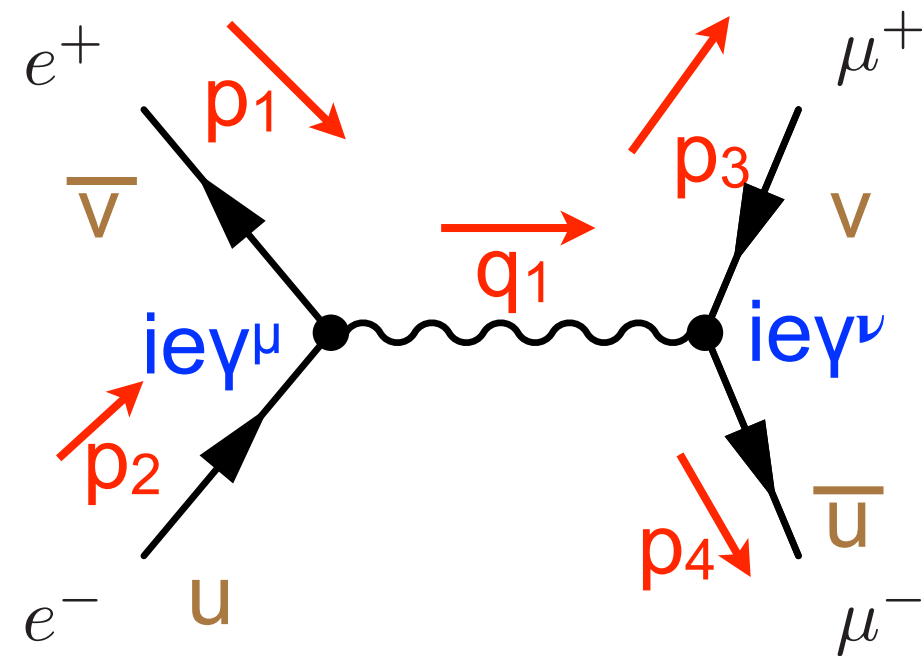
Here we have one of the diagrams contributing to electron-positron scattering into muon+antimuon pairs



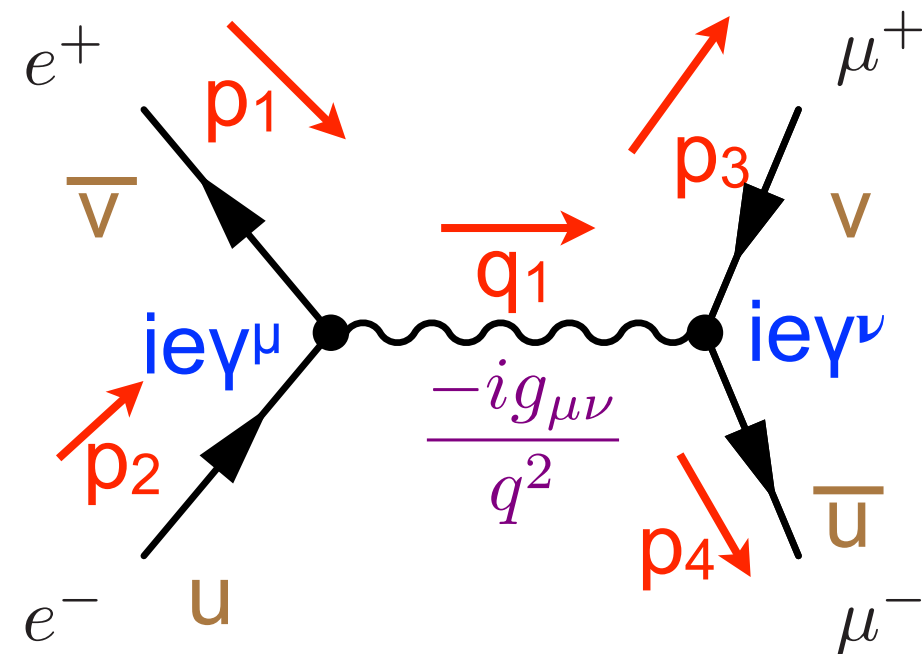
Label all incoming and outgoing lines with p_1, p_2, \dots, p_n
Internal lines can go either way
Use arrows to keep track of what is going in and out (of course we have arrows on the anti-particles, but that is different)



Incoming (outgoing) electrons/muons get a factor of $u(\bar{u})$, outgoing (incoming) anti-electrons/anti-muons get a factor of $\bar{v}(\bar{\nu})$. Incoming (outgoing) photons get a factor of $\epsilon_\mu (\epsilon_\mu^*)$



Add factors of $ie\gamma^\mu$ at each vertex

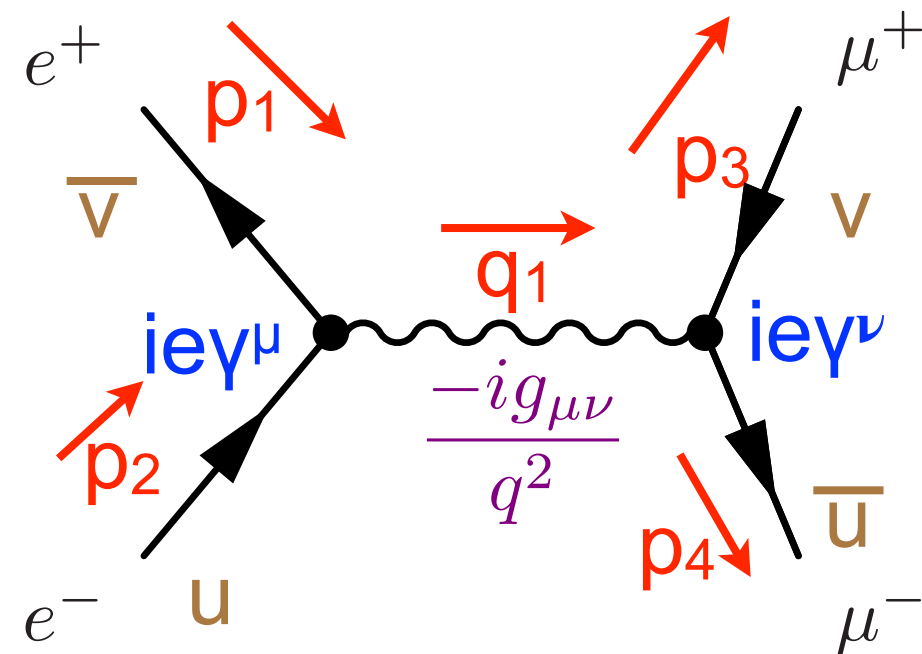


For each internal photon line add a factor for the propagator

$$\frac{i(\gamma^\mu q_\mu + m)}{q^2 - m^2}$$

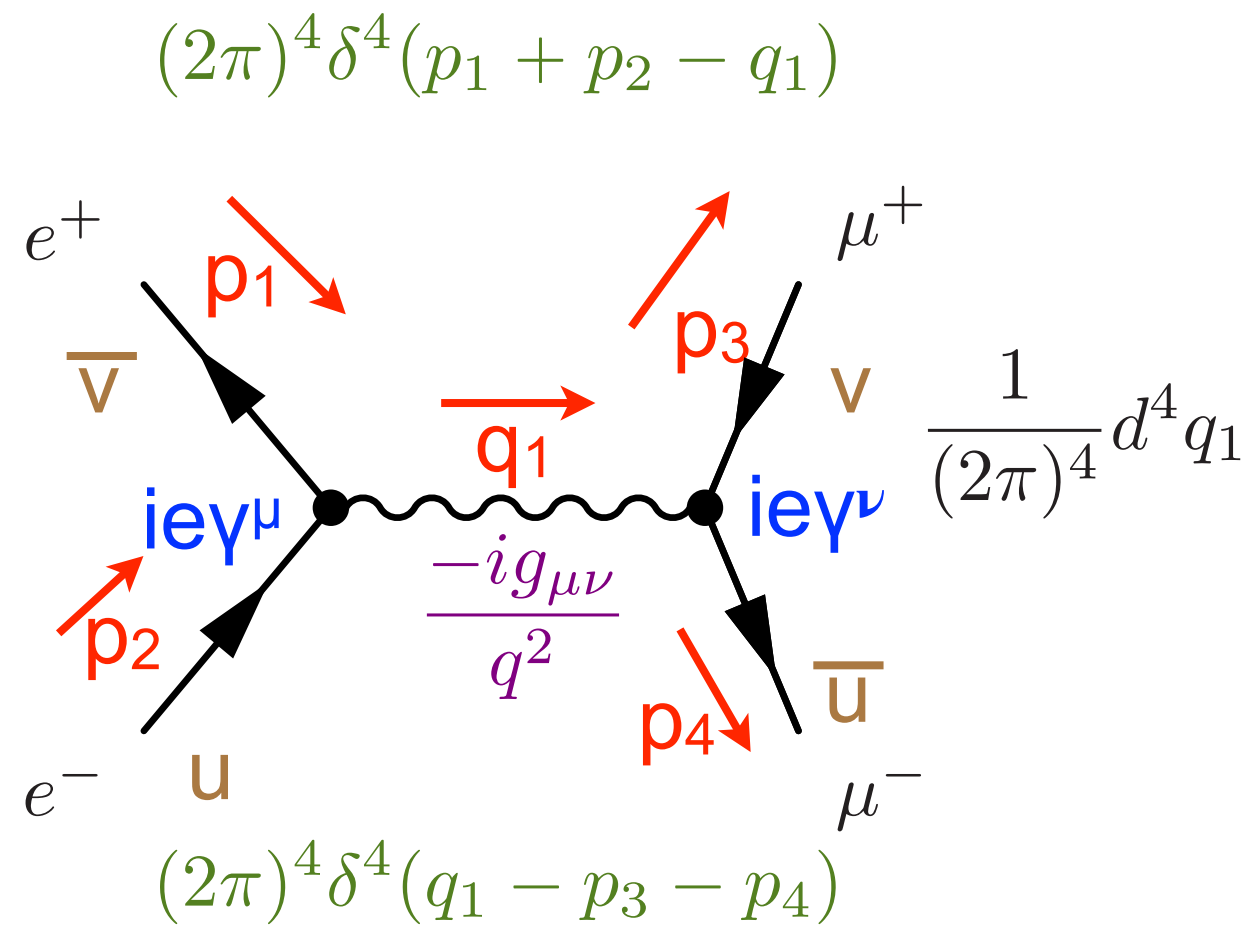
for internal electrons/positrons

$$(2\pi)^4 \delta^4(p_1 + p_2 - q_1)$$

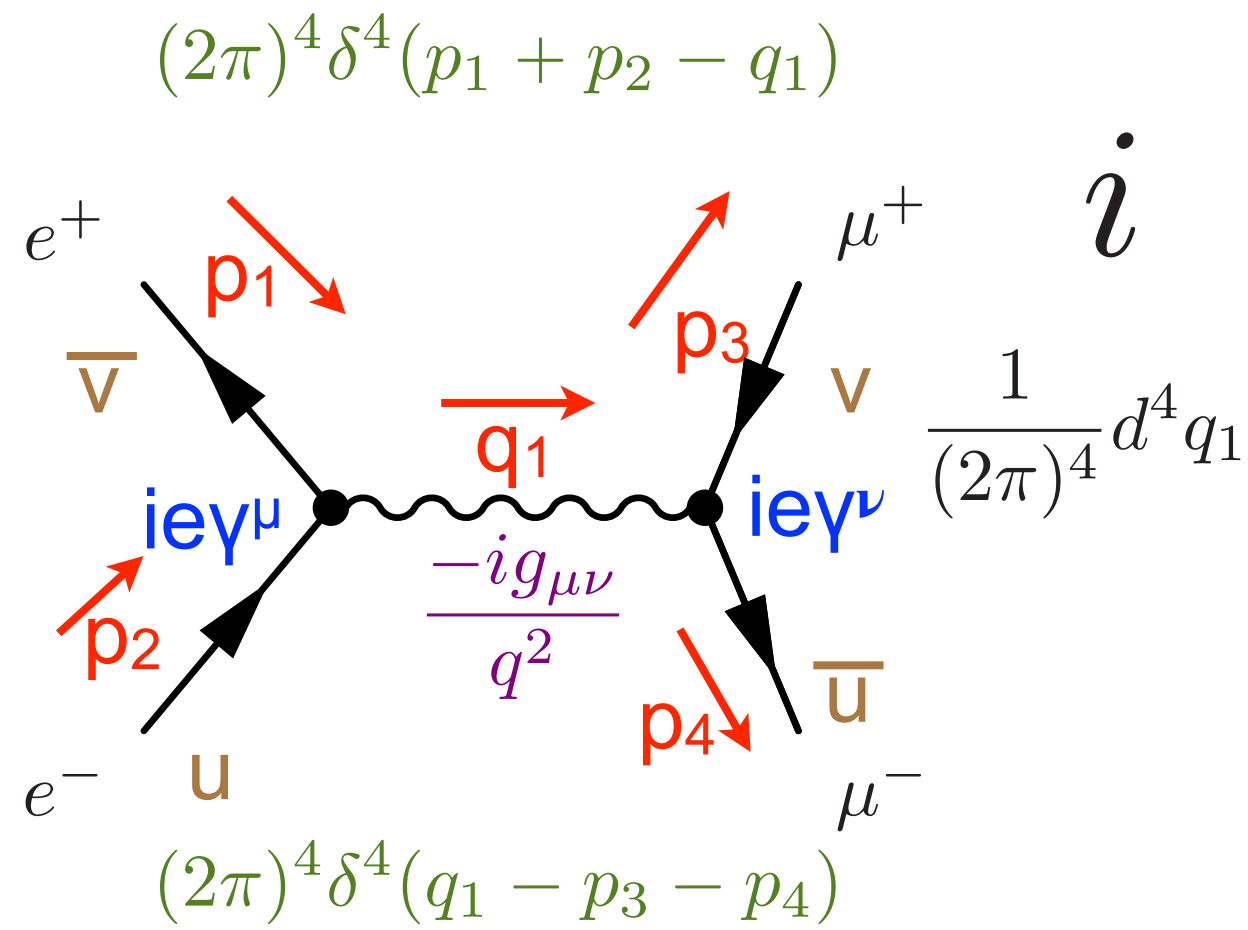


$$(2\pi)^4 \delta^4(q_1 - p_3 - p_4)$$

Impose conservation of energy and momentum at each vertex with 4d Dirac Delta function (with appropriate 2pi normalization)

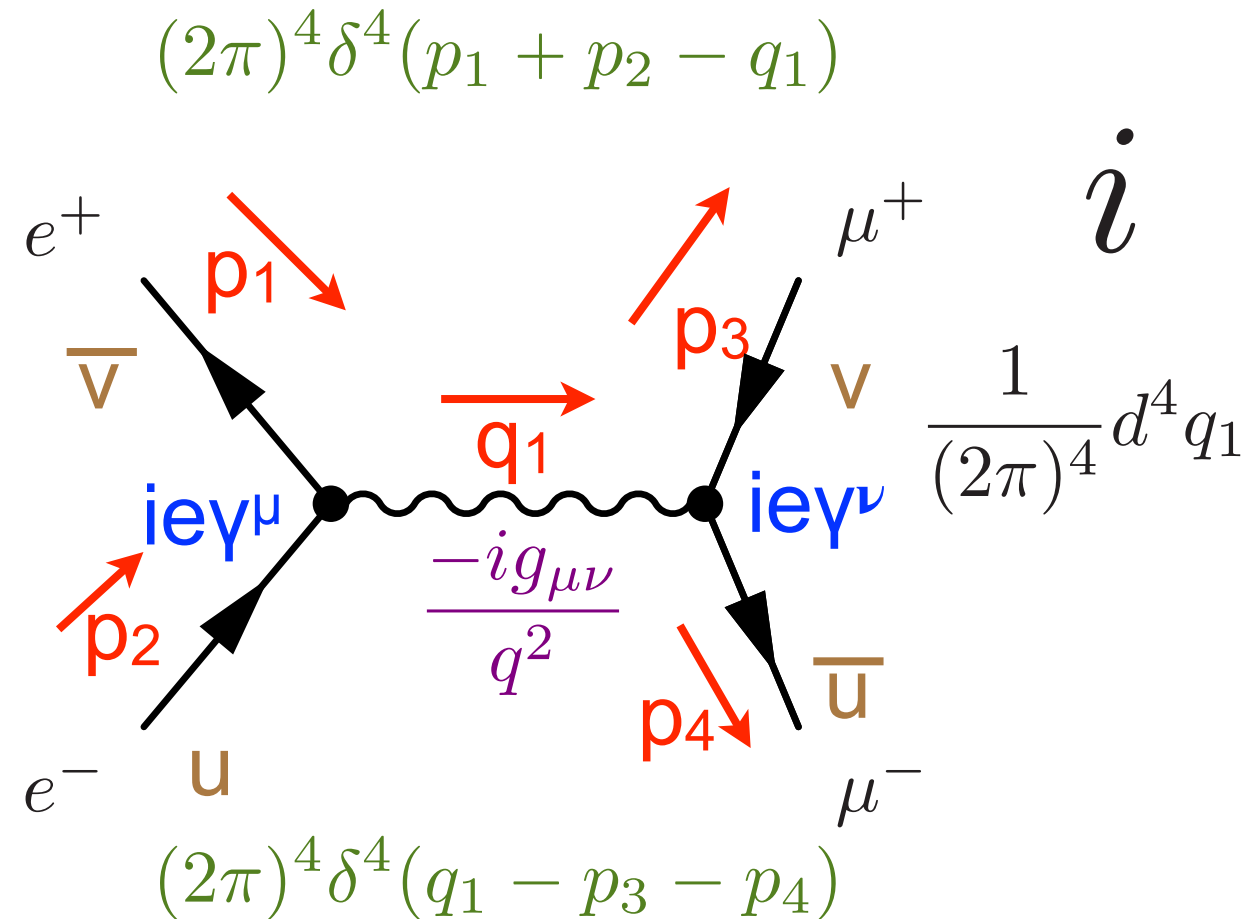


Integrate over 4-momentum of internal lines with appropriate 2π normalization factor



Cancel remaining delta function and add a factor of i , and you have the matrix element

Feynman rules for QED (8)

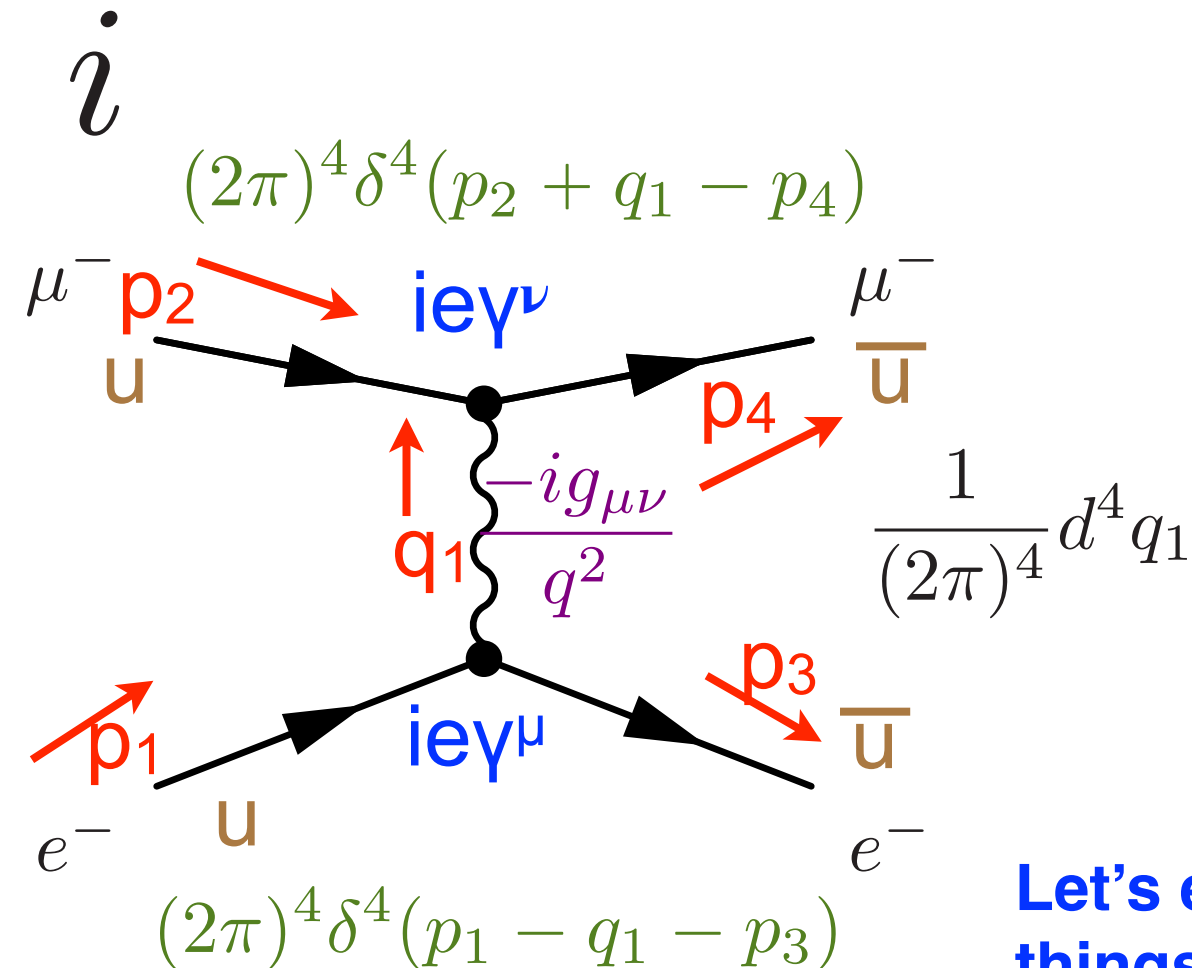


Add minus sign between diagrams differing only in exchange of two incoming or two outgoing fermions, or incoming fermion and outgoing anti-fermion (or vice versa)

We'll call the E&M coupling "e" and not g_e so as not to get confused (Griffiths has "g"s all over the place!)

Electron-muon scattering example

$$i \int [\bar{u}^{(s_3)}(p_3)(ie\gamma^\mu)u^{(s_1)}(p_1)] \frac{-ig_{\mu\nu}}{q^2} [\bar{u}^{(s_4)}(p_4)(ie\gamma^\nu)u^{(s_2)}(p_2)] (2\pi)^4 \delta^4(p_1 - q_1 - p_3) (2\pi)^4 \delta^4(p_2 + q_1 - p_4) \frac{d^4 q_1}{(2\pi)^4}$$



Let's examine the order of things. What order matters? What order doesn't matter?

Electron-muon scattering example

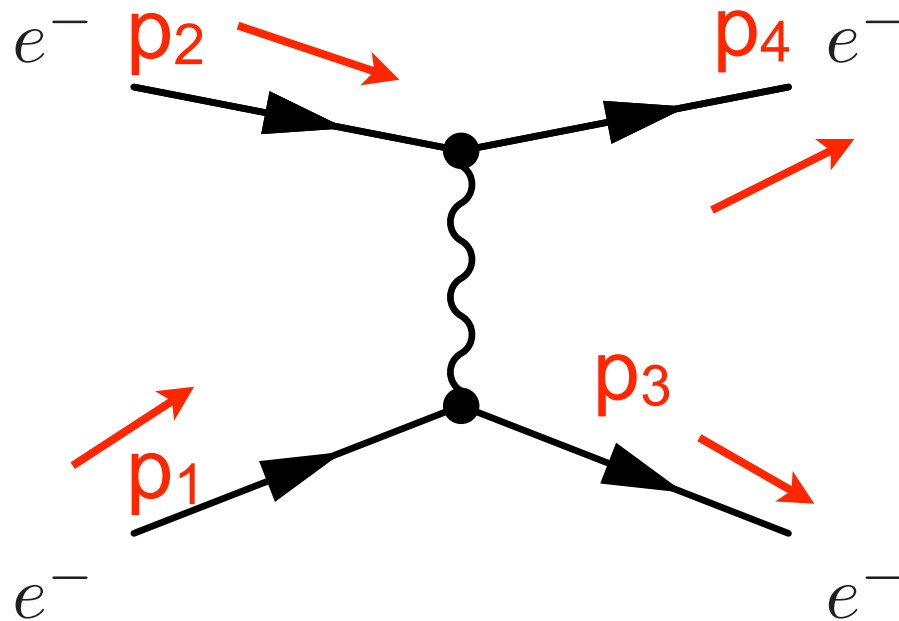
$$i \int [\bar{u}^{(s3)}(p3)(ie\gamma^\mu)u^{(s1)}(p1)] \frac{-ig_{\mu\nu}}{q^2} [\bar{u}^{(s4)}(p4)(ie\gamma^\nu)u^{(s2)}(p2)] (2\pi)^4 \delta^4(p1 - q1 - p3) (2\pi)^4 \delta^4(p2 + q1 - p4) \frac{d^4q1}{(2\pi)^4}$$

Matrix element (let's check why together) =

$$\mathcal{M} = -\frac{e^2}{(p_1 - p_3)^2} [\bar{u}^{(s3)}(p3)\gamma^\mu u^{(s1)}(p1)] [\bar{u}^{(s4)}(p4)\gamma_\mu u^{(s2)}(p2)]$$

Doesn't look very insightful or useful, but this is a number that you can calculate given some initial-state and final-state kinematics

Electron-Electron scattering



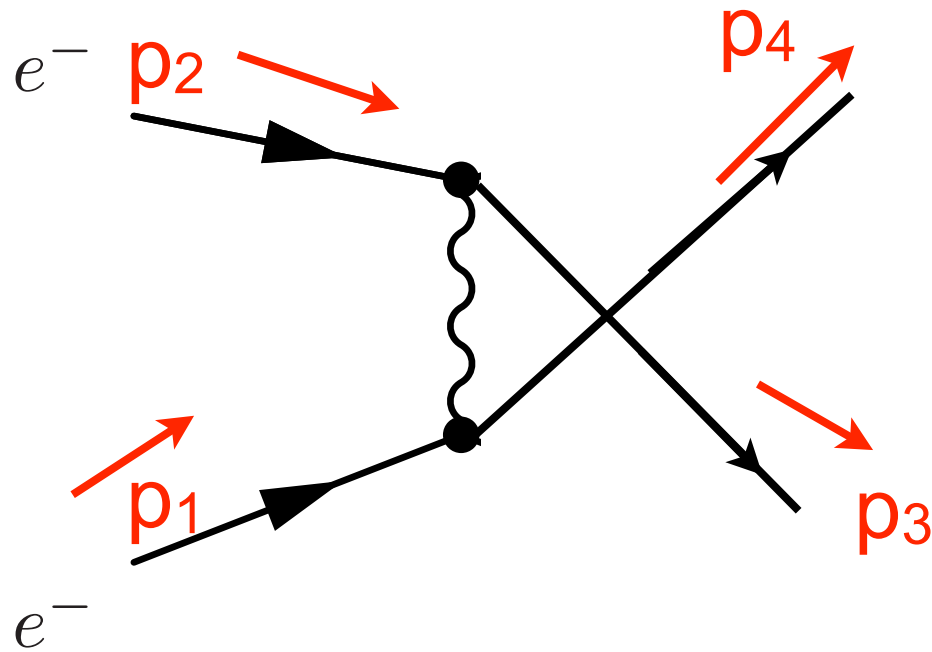
Matrix element
(let's check together) =

$$\mathcal{M} = -\frac{e^2}{(p_1 - p_3)^2} [\bar{u}^{(s3)}(p3)\gamma^\mu u^{(s1)}(p1)][\bar{u}^{(s4)}(p4)\gamma_\mu u^{(s2)}(p2)]$$

$$-\frac{e^2}{(p_1 - p_3)^2} [\bar{u}(3)\gamma^\mu u(1)][\bar{u}(4)\gamma_\mu u(2)]$$

Slightly simpler notation

Electron-Electron scattering, second diagram



Twisted/crossed diagram! Rule 8 says they get a relative minus sign

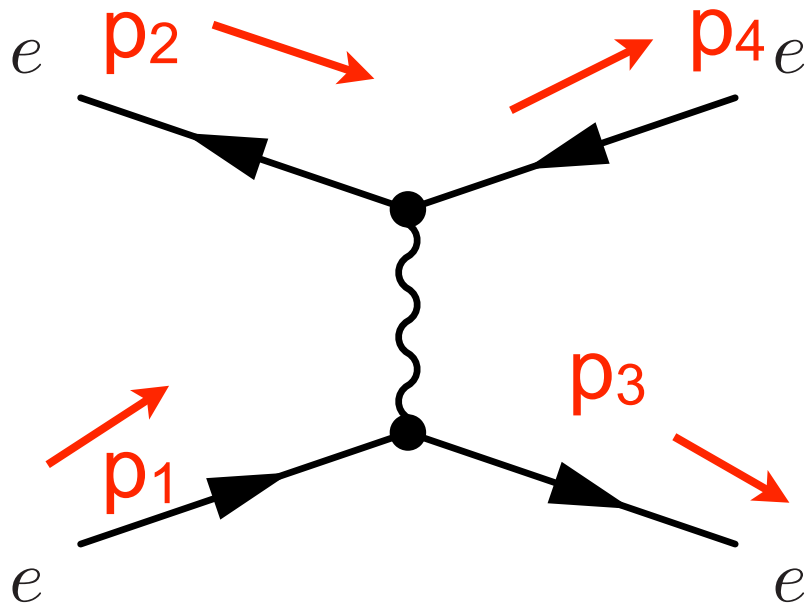
Total matrix element =

$$-\frac{e^2}{(p_1 - p_3)^2} [\bar{u}(3)\gamma^\mu u(1)][\bar{u}(4)\gamma_\mu u(2)] +$$

$$\frac{e^2}{(p_1 - p_4)^2} [\bar{u}(4)\gamma^\mu u(1)][\bar{u}(3)\gamma_\mu u(2)] +$$

Slightly simpler notation

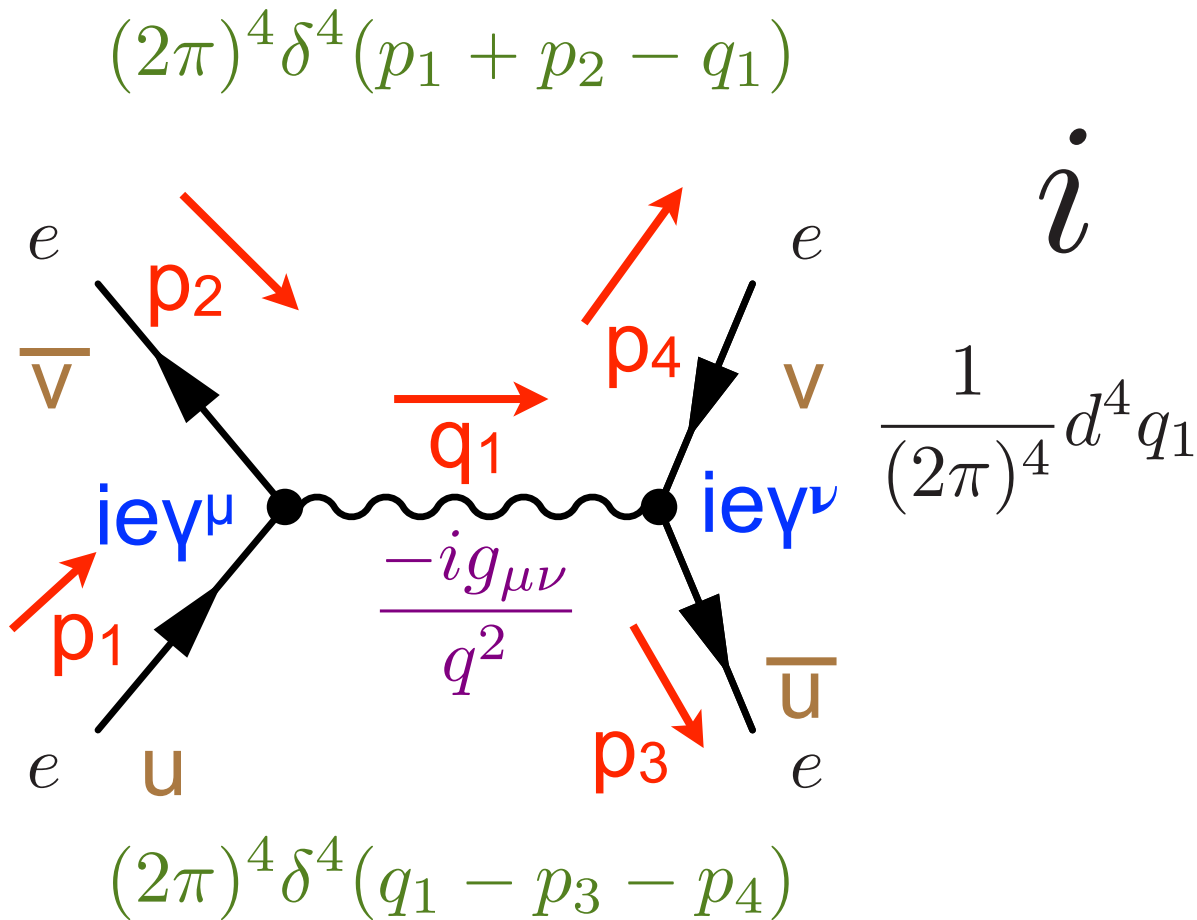
Electron-Positron scattering, first diagram



Note that we must **follow fermion lines backwards** to get the matrix algebra right

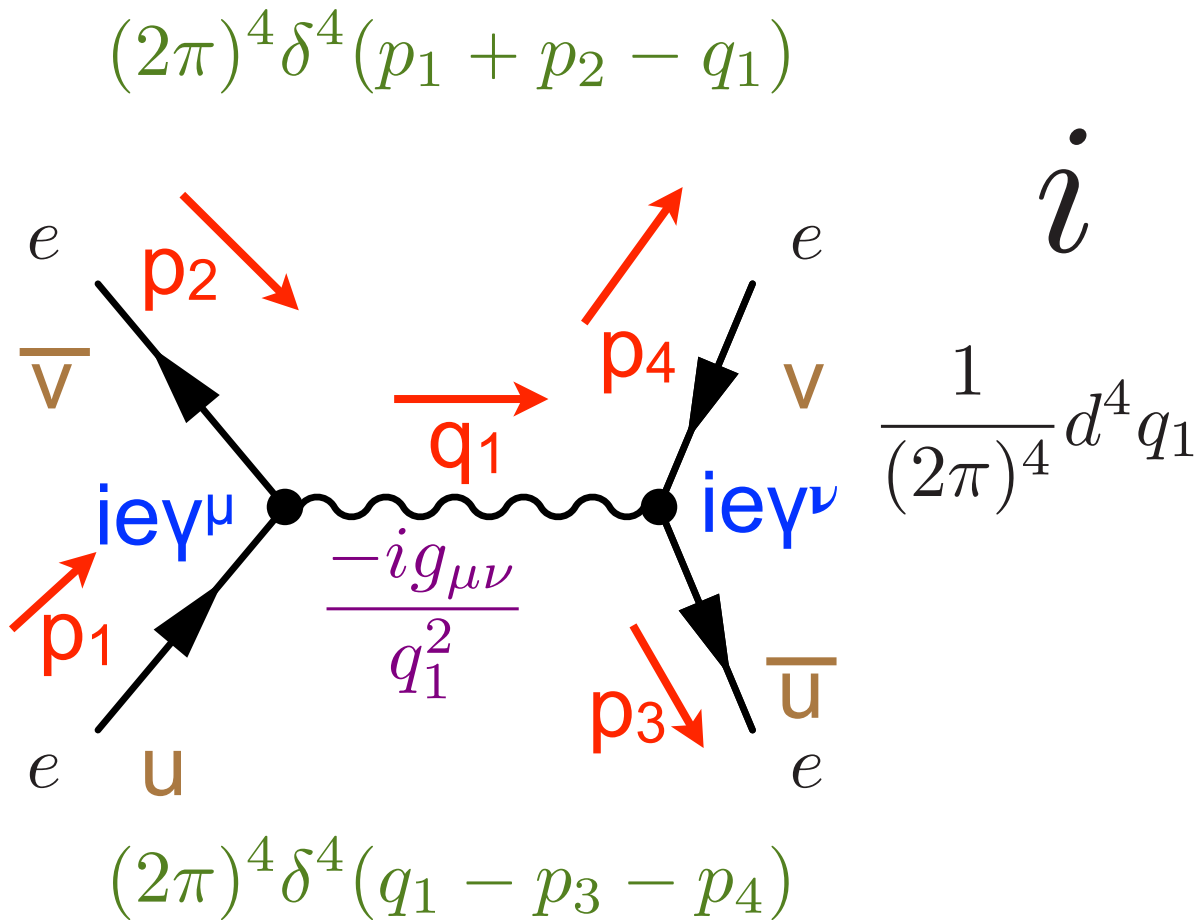
$$-\frac{e^2}{(p_1 - p_3)^2} [\bar{u}(3)\gamma^\mu u(1)][\bar{v}(2)\gamma_\mu v(4)]$$

Electron-Positron scattering, second diagram



Similar to when we wrote down the rules

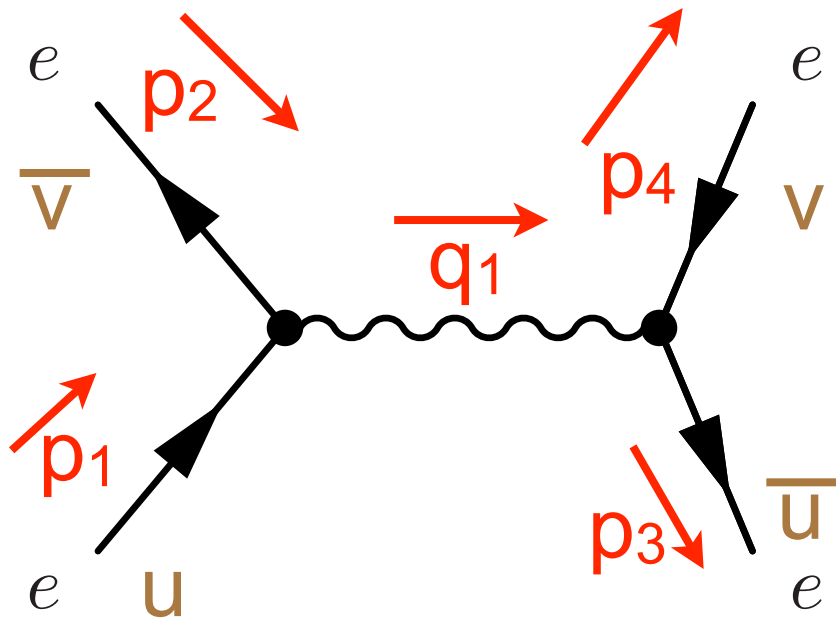
Electron-Positron scattering, second diagram



$$i \int [\bar{u}(3)(ie\gamma^\mu)v(4)] \frac{-ig_{\mu\nu}}{q_1^2} [\bar{v}(2)(ie\gamma^\nu)u(1)] (2\pi)^4 \delta^4(p_1 + p_2 - q_1) (2\pi)^4 \delta^4(q_1 - p_3 - p_4) \frac{d^4 q_1}{(2\pi)^4}$$

Electron-Positron scattering, second diagram

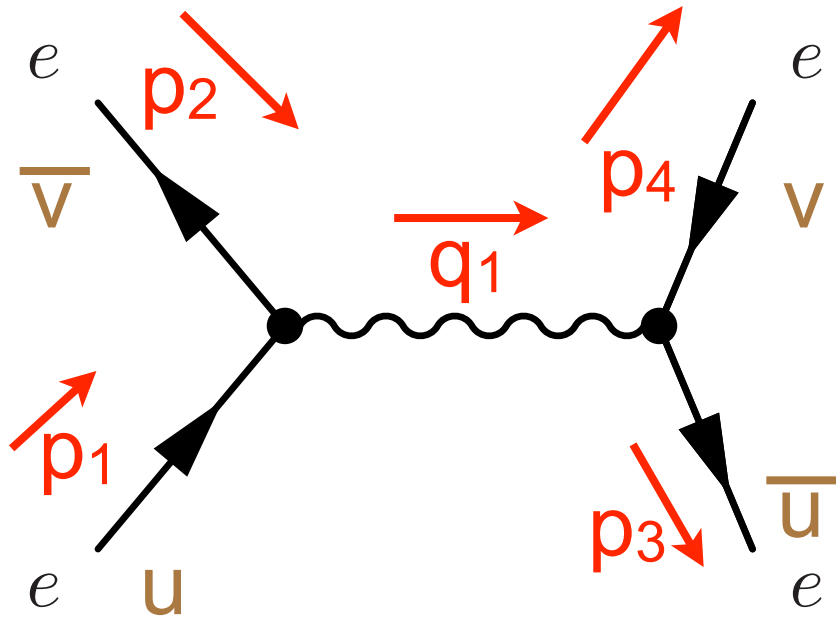
$$i \int [\bar{u}(3)(ie\gamma^\mu)v(4)] \frac{-ig_{\mu\nu}}{q_1^2} [\bar{v}(2)(ie\gamma^\nu)u(1)] (2\pi)^4 \delta^4(p_1 + p_2 - q_1) (2\pi)^4 \delta^4(q_1 - p_3 - p_4) \frac{d^4 q_1}{(2\pi)^4}$$



$$-(2\pi)^4 e^2 \int [\bar{u}(3)(\gamma^\mu)v(4)] \frac{g_{\mu\nu}}{q_1^2} [\bar{v}(2)(\gamma^\nu)u(1)] \delta^4(p_1 + p_2 - q_1) \delta^4(q_1 - p_3 - p_4) d^4 q_1$$

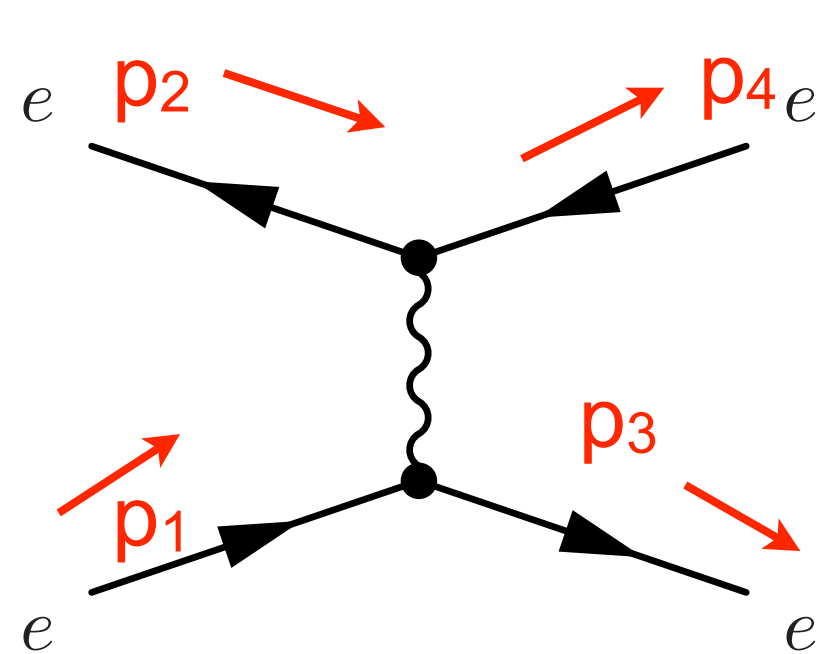
Electron-Positron scattering, second diagram

$$-(2\pi)^4 e^2 \int [\bar{u}(3)(\gamma^\mu)v(4)] \frac{g_{\mu\nu}}{q_1^2} [\bar{v}(2)(\gamma^\nu u(1))] \delta^4(p_1 + p_2 - q_1) \delta^4(q_1 - p_3 - p_4) d^4 q_1$$

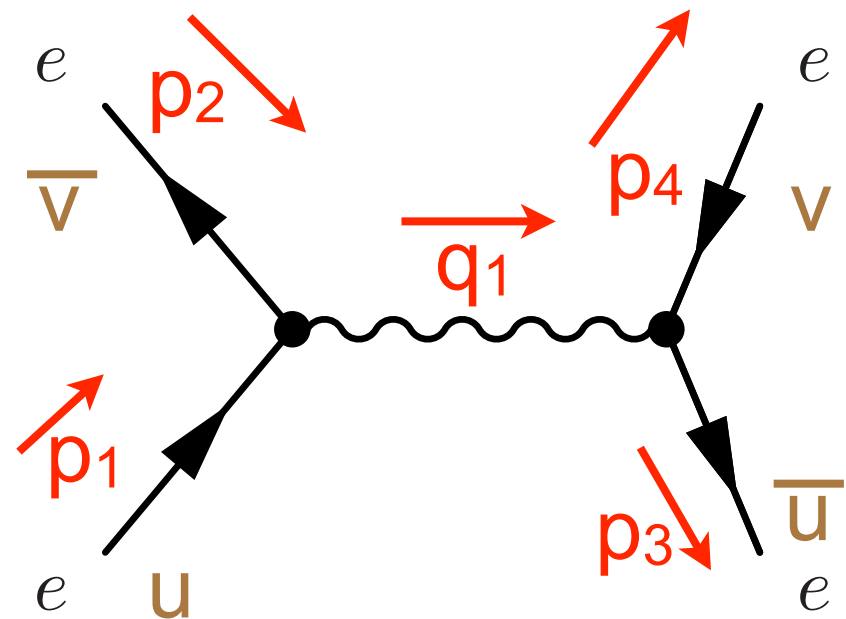


~~$$-\frac{(2\pi)^4 e^2}{(p_1 + p_2)^2} \int [\bar{u}(3)(\gamma^\mu)v(4)] g_{\mu\nu} [\bar{v}(2)(\gamma^\nu u(1))] \delta^4(q_1 - p_3 - p_4)$$~~

Electron-Positron scattering, both diagrams



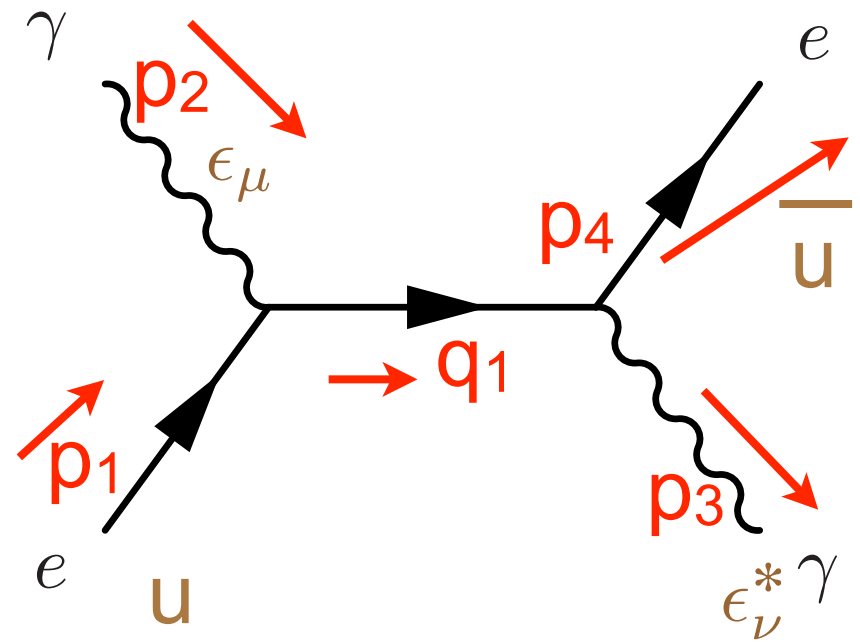
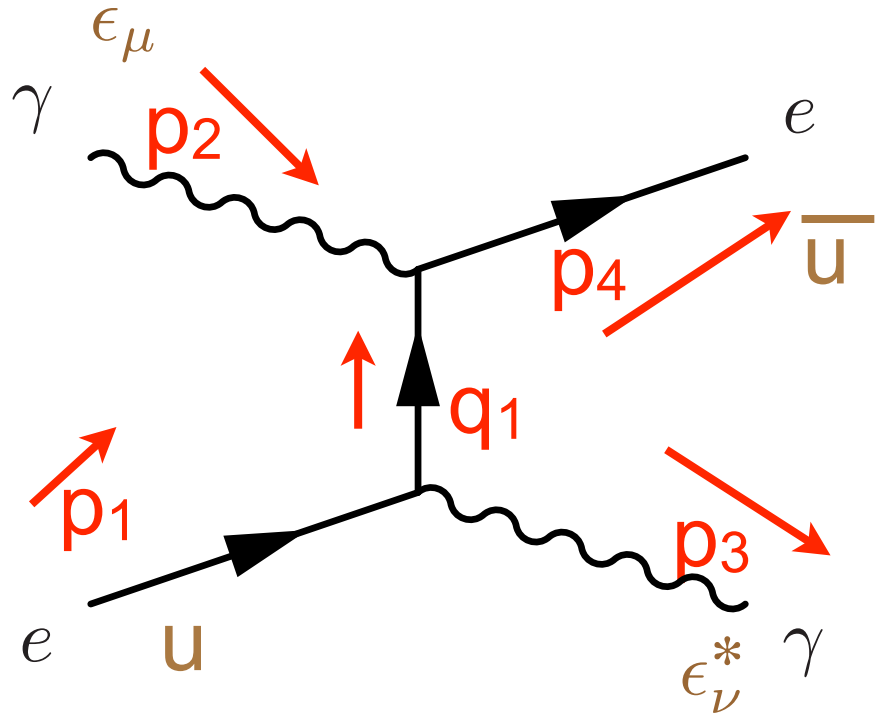
$$-\frac{e^2}{(p_1 - p_3)^2} [\bar{u}(3)\gamma^\mu u(1)][\bar{v}(2)\gamma_\mu v(4)]$$



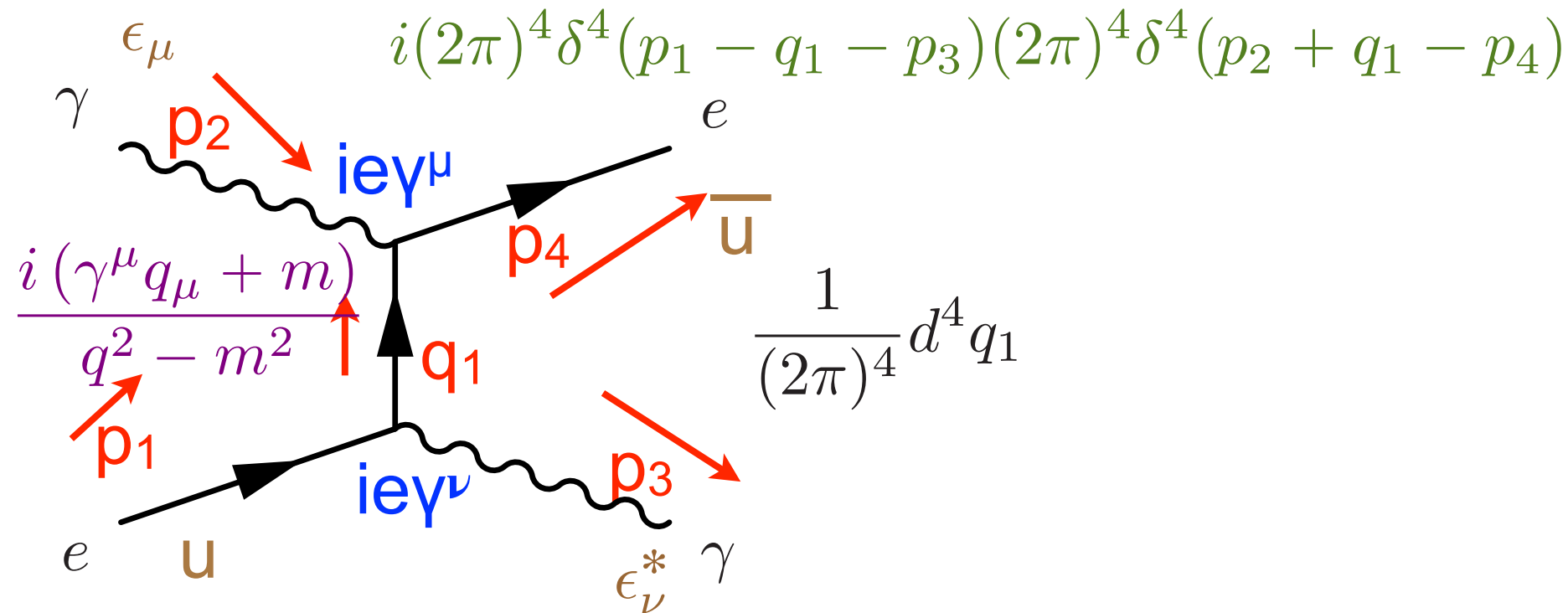
$$-\frac{e^2}{(p_1 + p_2)^2} [\bar{u}(3)(\gamma^\mu)v(4)][\bar{v}(2)\gamma_\mu u(1)]$$

If we swap p_2 (incoming positron) and p_3 (outgoing electron) in first diagram, we get the second diagram! Need relative minus sign

$$-\frac{e^2}{(p_1 - p_3)^2} [\bar{u}(3)\gamma^\mu u(1)][\bar{v}(2)\gamma_\mu v(4)] +$$
$$+\frac{e^2}{(p_1 + p_2)^2} [\bar{u}(3)(\gamma^\mu)v(4)][\bar{v}(2)\gamma_\mu u(1)]$$



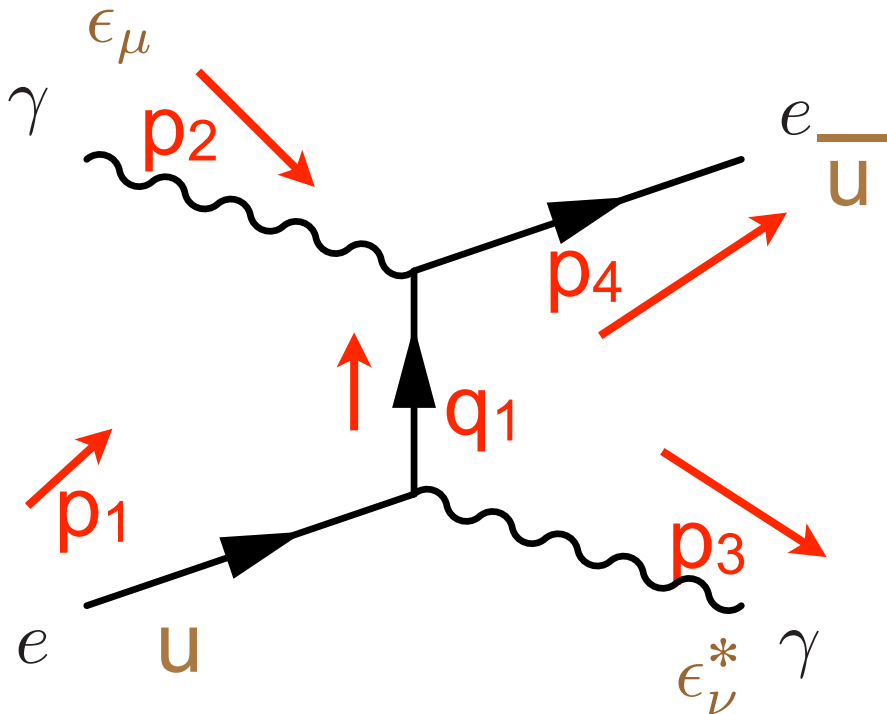
Let's start with first diagram



$$\int i(2\pi)^4 \delta^4(p_1 - q_1 - p_3) (2\pi)^4 \delta^4(p_2 + q_1 - p_4) \epsilon_\mu(2) \bar{u}(4) (ie\gamma^\mu) \frac{i(\gamma^\lambda q_\lambda + m)}{q^2 - m^2} (ie\gamma^\nu) u(1) \epsilon_\nu^*(3) \frac{d^4 q_1}{(2\pi)^4}$$

Let's start with first diagram

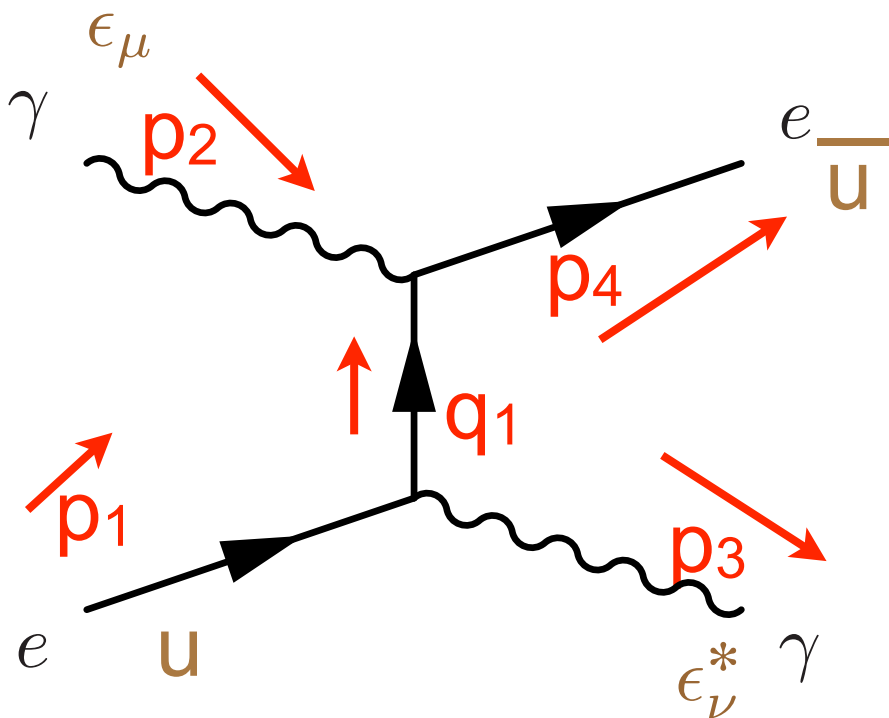
$$\int i(2\pi)^4 \delta^4(p_1 - q_1 - p_3) (2\pi)^4 \delta^4(p_2 + q_1 - p_4) \epsilon_\mu(2) \bar{u}(4) (ie\gamma^\mu) \frac{i(\gamma^\lambda q_\lambda + m)}{q^2 - m^2} (ie\gamma^\nu) u(1) \epsilon_\nu^*(3) \frac{d^4 q_1}{(2\pi)^4}$$



$$(2\pi)^4 e^2 \int \delta^4(p_1 - q_1 - p_3) \delta^4(p_2 + q_1 - p_4) \epsilon_\mu(2) \bar{u}(4) (\gamma^\mu) \frac{(\gamma^\lambda q_\lambda + m)}{q^2 - m^2} (\gamma^\nu) u(1) \epsilon_\nu^*(3) d^4 q_1$$

$$= \frac{(\gamma^\lambda (p_1 - p_3)_\lambda + m)}{(p_1 - p_3)^2 - m^2} e^2 \cancel{(2\pi)^4 \delta^4(p_2 + q_1 - p_4) \epsilon_\mu(2) v(4) \bar{u}(4) (\gamma^\mu) (\gamma^\nu) u(1) \epsilon_\nu^*(3)}$$

So first diagram matrix element is



$$e^2 \frac{(\gamma^\lambda (p_1 - p_3)_\lambda + m)}{(p_1 - p_3)^2 - m^2} \epsilon_\mu(2) \bar{u}(4) (\gamma^\mu) (\gamma^\nu) u(1) \epsilon_\nu^*(3)$$

“Slash” notation is very useful:

$$\not{x} = x^\mu \gamma_\mu$$

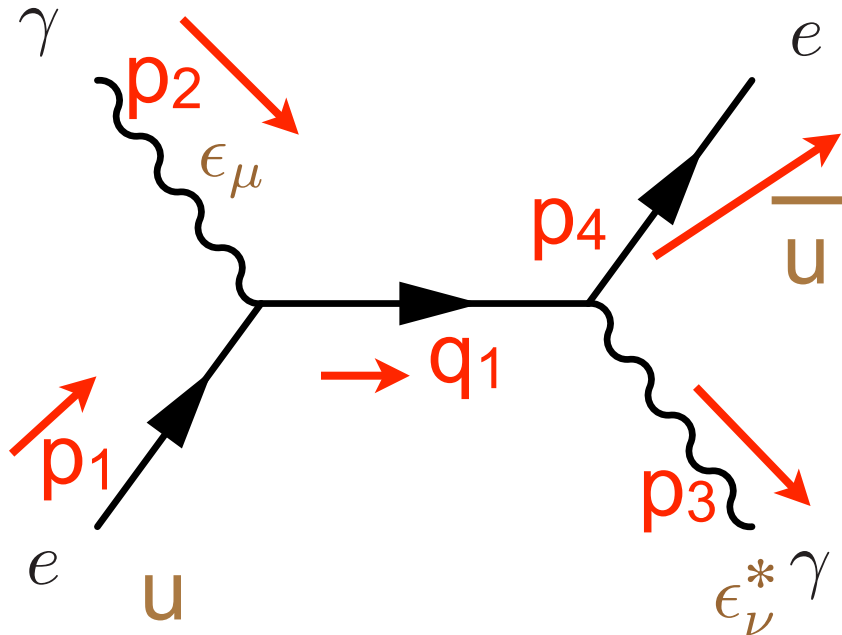
$$e^2 \frac{(\gamma^\lambda (p_1 - p_3)_\lambda + m)}{(p_1 - p_3)^2 - m^2} \epsilon_\mu(2) \bar{u}(4) (\gamma^\mu) (\gamma^\nu) u(1) \epsilon_\nu^*(3)$$

$$e^2 \frac{(p_1 - p_3 + m)}{(p_1 - p_3)^2 - m^2} \epsilon_\mu(2) \bar{u}(4) (\gamma^\mu) (\gamma^\nu) u(1) \epsilon_\nu^*(3)$$

$$e^2 \frac{(p_1 - p_3 + m)}{(p_1 - p_3)^2 - m^2} \not{\epsilon}(2) \bar{u}(4) u(1) \not{\epsilon}^*(3)$$

Now the second diagram

$$i(2\pi)^4 \delta^4(p_1 + p_2 - q_1) (2\pi)^4 \delta^4(q_1 - p_3 - p_4)$$



$$\int i(2\pi)^4 \delta^4(p_1 + p_2 - q_1) (2\pi)^4 \delta^4(q_1 - p_3 - p_4) \epsilon_\mu(2) \bar{u}(4) (ie\gamma^\mu) \frac{i(\gamma^\lambda q_\lambda + m)}{q^2 - m^2} (ie\gamma^\nu) u(1) \epsilon_\nu^*(3) \frac{d^4 q_1}{(2\pi)^4}$$

Can proceed in same way, and total matrix element is sum of the two

Potentially want to calculate processes with given initial and final state spins and polarizations, but more often than not we don't specify either: **average over initial state configurations and sum over final state configurations**

$$\mathcal{M} = -\frac{e^2}{(p_1 - p_3)^2} [\bar{u}^{(s3)}(p3)\gamma^\mu u^{(s1)}(p1)][\bar{u}^{(s4)}(p4)\gamma_\mu u^{(s2)}(p2)]$$

$$|\mathcal{M}|^2 = \frac{e^4}{(p_1 - p_3)^4} [\bar{u}^{(s3)}(p3)\gamma^\mu u^{(s1)}(p1)][\bar{u}^{(s4)}(p4)(\gamma_\mu u^{(s2)}(p2)][\bar{u}^{(s3)}(p3)\gamma^\nu u^{(s1)}(p1)]^* [\bar{u}^{(s4)}(p4)(\gamma_\nu u^{(s2)}(p2)]^*$$

So how to calculate (for example): ???

$$[\bar{u}^{(s3)}(p3)\gamma^\mu u^{(s1)}(p1)][\bar{u}^{(s3)}(p3)\gamma^\nu u^{(s1)}(p1)]^*$$

Or more generally

$$G = [\bar{u}(a)\Gamma_1 u(b)][\bar{u}(a)\Gamma_2 u(b)]^*$$

$$G = [\bar{u}(a)\Gamma_1 u(b)][\bar{u}(a)\Gamma_2 u(b)]^*$$

Reminder that $\bar{a} = a^\dagger \gamma^0$

For 1dx1d
matrix, dagger
and star are
the same

$$G = [\bar{u}(a)\Gamma_1 u(b)][\bar{u}(a)\Gamma_2 u(b)]^*$$

$$G = [u(a)^\dagger \gamma^0 \Gamma_1 u(b)][u(a)^\dagger \gamma^0 \Gamma_2 u(b)]^\dagger$$

$$G = [u(a)^\dagger \gamma^0 \Gamma_1 u(b)][u(b)^\dagger \Gamma_2^\dagger \gamma^{0\dagger} u(a)]$$

$$G = [u(a)^\dagger \gamma^0 \Gamma_1 u(b)][u(b)^\dagger \Gamma_2^\dagger \gamma^0 u(a)] \quad \leftarrow \gamma^{0\dagger} = \gamma^0$$

Continuing with G

$$G = [u(a)^\dagger \gamma^0 \Gamma_1 u(b)] [u(b)^\dagger \Gamma_2^\dagger \gamma^0 u(a)]$$

$$G = [u(a)^\dagger \gamma^0 \Gamma_1 u(b)] [u(b)^\dagger \gamma^0 \gamma^0 \Gamma_2^\dagger \gamma^0 u(a)]$$

$$G = [u(a)^\dagger \gamma^0 \Gamma_1 u(b)] [\bar{u}(b) \bar{\Gamma}_2 u(a)]$$

$$G = [\bar{u}(a) \Gamma_1 u(b)] [\bar{u}(b) \bar{\Gamma}_2 u(a)]$$

WHY?!

$$\bar{\Gamma}_2 = \gamma^0 \Gamma_2^\dagger \gamma^0 \quad \text{For a matrix}$$

$$\bar{a} = a^\dagger \gamma^0 \quad \text{For a spinor}$$

$$\bar{\Gamma} a = (\Gamma a)^\dagger \gamma^0 = a^\dagger \Gamma^\dagger \gamma^0$$

$$\bar{\Gamma} a = a^\dagger \gamma^0 \gamma^0 \Gamma^\dagger \gamma^0$$

$$\bar{\Gamma} a = (a^\dagger \gamma^0) (\gamma^0 \Gamma^\dagger \gamma^0) = \bar{a} \bar{\Gamma}$$

CAREFUL - New definitions!

We were looking at: $G = [\bar{u}(a) \Gamma_1 u(b)] [\bar{u}(a) \Gamma_2 u(b)]^*$

$$[\bar{u}^{(s3)}(p3) \gamma^\mu u^{(s1)}(p1)] [\bar{u}^{(s3)}(p3) \gamma^\nu u^{(s1)}(p1)]^*$$

So now we have G

We were looking at:

$$[\bar{u}^{(s3)}(p3)\gamma^\mu u^{(s1)}(p1)][\bar{u}^{(s3)}(p3)\gamma^\nu u^{(s1)}(p1)]^*$$

And defined $G = [\bar{u}(a)\Gamma_1 u(b)][\bar{u}(a)\Gamma_2 u(b)]^*$

And found that $G = [\bar{u}(a)\Gamma_1 u(b)][\bar{u}(b)\bar{\Gamma}_2 u(a)]$

We are interested in summing over spins $s1$ and $s3$ since we are not isolating any particular spin

$$G = \bar{u}(a)\Gamma_1 \sum_{b-spin} [u(b)\bar{u}(b)] \bar{\Gamma}_2 u(a)$$

Now we have a new problem (it is progress, I promise). Need to find

$$\sum_{b-spin} [u(b)\bar{u}(b)]$$

Aside: The completeness relation

$$\sum_{b\text{-spin}} [u(b)\bar{u}(b)]$$

Reminder of our two solutions for u (not v),
appropriately normalized

$$u(1) = \begin{pmatrix} \sqrt{E+m} \\ 0 \\ \frac{p_z}{\sqrt{E+m}} \\ \frac{p_x + ip_y}{\sqrt{E+m}} \end{pmatrix} \quad u(2) = \begin{pmatrix} 0 \\ \sqrt{E+m} \\ \frac{p_x - ip_y}{\sqrt{E+m}} \\ \frac{-p_z}{\sqrt{E+m}} \end{pmatrix}$$

$$\sum_{b\text{-spin}} [u(b)\bar{u}(b)] = u(1)\bar{u}(1) + u(2)\bar{u}(2)$$

The completeness relation

$$\sum_{b\text{-spin}} [u(b)\bar{u}(b)] = u(1)\bar{u}(1) + u(2)\bar{u}(2)$$

$$\bar{u} = u^\dagger \gamma^0 =$$

$$u^\dagger \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Minus signs

But also
extra -1 on
every i

Minus
signs

$$\begin{pmatrix} \sqrt{E+m} \\ 0 \\ \frac{p_z}{\sqrt{E+m}} \\ \frac{p_x + ip_y}{\sqrt{E+m}} \end{pmatrix} \begin{pmatrix} \sqrt{E+m} & 0 & \frac{-p_z}{\sqrt{E+m}} & \frac{-p_x + ip_y}{\sqrt{E+m}} \end{pmatrix} + \begin{pmatrix} 0 \\ \sqrt{E+m} \\ \frac{p_x - ip_y}{\sqrt{E+m}} \\ \frac{-p_z}{\sqrt{E+m}} \end{pmatrix} \begin{pmatrix} 0 & \sqrt{E+m} & \frac{-p_x - ip_y}{\sqrt{E+m}} & \frac{p_z}{\sqrt{E+m}} \end{pmatrix}$$

$$\begin{pmatrix} E+m & 0 & -p_z & -p_x + ip_y \\ 0 & 0 & 0 & 0 \\ p_z & 0 & \frac{-p_z^2}{E+m} & \frac{-p_x p_z + ip_y p_z}{E+m} \\ p_x + ip_y & 0 & \frac{-p_x p_z - ip_y p_z}{E+m} & \frac{-p_x^2 - p_y^2}{E+m} \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & E+m & -p_x - ip_y & p_z \\ 0 & p_x - ip_y & \frac{-p_x^2 - p_y^2}{E+m} & \frac{p_x p_z - ip_y p_z}{E+m} \\ 0 & -p_z & \frac{p_x p_z + ip_y p_z}{E+m} & \frac{-p_z^2}{E+m} \end{pmatrix}$$

The completeness relation

$$\sum_{b\text{-spin}} [u(b)\bar{u}(b)] = u(1)\bar{u}(1) + u(2)\bar{u}(2)$$

$$\begin{pmatrix} E+m & 0 & -p_z & -p_x + ip_y \\ 0 & 0 & 0 & 0 \\ p_z & 0 & \frac{-p_z^2}{E+m} & \frac{-p_x p_z + ip_y p_z}{E+m} \\ p_x + ip_y & 0 & \frac{-p_x p_z - ip_y p_z}{E+m} & \frac{-p_x^2 - p_y^2}{E+m} \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & E+m & -p_x - ip_y & p_z \\ 0 & p_x - ip_y & \frac{-p_x^2 - p_y^2}{E+m} & \frac{p_x p_z - ip_y p_z}{E+m} \\ 0 & -p_z & \frac{p_x p_z + ip_y p_z}{E+m} & \frac{-p_z^2}{E+m} \end{pmatrix}$$

$$=$$

$$\begin{pmatrix} E+m & 0 & -p_z & -p_x + ip_y \\ 0 & E+m & -p_x - ip_y & p_z \\ p_z & p_x - ip_y & \frac{-p_x^2 - p_y^2 - p_z^2}{E+m} & 0 \\ p_x + ip_y & -p_z & 0 & \frac{-p_x^2 - p_y^2 - p_z^2}{E+m} \end{pmatrix}$$

The completeness relation

$$\sum_{b\text{-spin}} [u(b)\bar{u}(b)] = u(1)\bar{u}(1) + u(2)\bar{u}(2)$$

$$\left(\begin{array}{cccc} E + m & 0 & -p_z & -p_x + ip_y \\ 0 & E + m & -p_x - ip_y & p_z \\ p_z & p_x - ip_y & \frac{-p_x^2 - p_y^2 - p_z^2}{E+m} & 0 \\ p_x + ip_y & -p_z & 0 & \frac{-p_x^2 - p_y^2 - p_z^2}{E+m} \end{array} \right)$$

$$\left(\begin{array}{cccc} E + m & 0 & -p_z & -p_x + ip_y \\ 0 & E + m & -p_x - ip_y & p_z \\ p_z & p_x - ip_y & \frac{-\mathbf{p}^2}{E+m} & 0 \\ p_x + ip_y & -p_z & 0 & \frac{-\mathbf{p}^2}{E+m} \end{array} \right)$$

The completeness relation

$$\sum_{b\text{-spin}} [u(b)\bar{u}(b)] = u(1)\bar{u}(1) + u(2)\bar{u}(2)$$

$$\begin{pmatrix} E+m & 0 & -p_z & -p_x + ip_y \\ 0 & E+m & -p_x - ip_y & p_z \\ p_z & p_x - ip_y & \frac{-\mathbf{p}^2}{E+m} & 0 \\ p_x + ip_y & -p_z & 0 & \frac{-\mathbf{p}^2}{E+m} \end{pmatrix}$$

$$\frac{-\mathbf{p}^2}{E+m} = \frac{m^2 - E^2}{E+m} = \frac{(m-E)(m+E)}{E+m} = m - E$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\mathbf{p} \cdot \boldsymbol{\sigma} = \begin{pmatrix} p_z & p_x - ip_y \\ p_x + ip_y & -p_z \end{pmatrix}$$

The completeness relation

$$\sum_{b\text{-spin}} [u(b)\bar{u}(b)] = u(1)\bar{u}(1) + u(2)\bar{u}(2)$$

$$\begin{pmatrix} E+m & 0 & -p_z & -p_x + ip_y \\ 0 & E+m & -p_x - ip_y & p_z \\ p_z & p_x - ip_y & \frac{-\mathbf{p}^2}{E+m} & 0 \\ p_x + ip_y & -p_z & 0 & \frac{-\mathbf{p}^2}{E+m} \end{pmatrix} =$$

$$\begin{pmatrix} m+E & 0 & -\mathbf{p} \cdot \boldsymbol{\sigma} & \\ 0 & m+E & & \\ \mathbf{p} \cdot \boldsymbol{\sigma} & & m-E & 0 \\ & & 0 & m-E \end{pmatrix} =$$

$$m + \gamma^0 E - \mathbf{p} \cdot \begin{pmatrix} 0 & \boldsymbol{\sigma} \\ -\boldsymbol{\sigma} & 0 \end{pmatrix} = \gamma^\mu p_\mu + m$$

$$\sum_{b\text{-spin}} [u(b)\bar{u}(b)] = u(1)\bar{u}(1) + u(2)\bar{u}(2) = \gamma^\mu p_\mu + m$$

Phew! Will not prove but (you can...)

$$\sum_{b\text{-spin}} [v(b)\bar{v}(b)] = v(1)\bar{v}(1) + v(2)\bar{v}(2) = \gamma^\mu p_\mu - m$$

$$G = \bar{u}(a)\Gamma_1 \sum_{b\text{-spin}} [u(b)\bar{u}(b)] \bar{\Gamma}_2 u(a) = \bar{u}(a)\Gamma_1 [\gamma^\mu p_\mu^b + m_b] \bar{\Gamma}_2 u(a)$$


$$G = \bar{u}(a)\Gamma_1 (\not{p}_b + m_b) \bar{\Gamma}_2 u(a)$$

$$G = \bar{u}(a)\Gamma_1(\not{p}_b + m_b)\bar{\Gamma}_2 u(a)$$

Now let's sum over a spins

$$\sum_{a,b \text{ spins}} G = \sum_{sa=1,2} \bar{u}(sa)\Gamma_1(\not{p}_b + m_b)\bar{\Gamma}_2 u(sa)$$

Scalar quantity we're calculating (sum of 4 numbers)



1x4 matrix



4x4 matrix



4x1 matrix (spinor)



Continuing on with G

$$\sum_{a,b \text{ spins}} G = \sum_{sa=1,2} \bar{u}(sa) \Gamma_1(\not{p}_b + m_b) \bar{\Gamma}_2 u(sa)$$

$$\sum_{a,b \text{ spins}} G = \sum_{sa=1,2} \sum_{i,j=1}^4 \bar{u}(sa)_i \left[\Gamma_1(\not{p}_b + m_b) \bar{\Gamma}_2 \right]_{ij} u(sa)_j$$

$$\sum_{a,b \text{ spins}} G = \sum_{i,j=1}^4 \left[\Gamma_1(\not{p}_b + m_b) \bar{\Gamma}_2 \right]_{ij} \sum_{sa=1,2} u(sa)_j \bar{u}(sa)_i$$

$$\sum_{a,b \text{ spins}} G = \sum_{i,j=1}^4 \left[\Gamma_1(\not{p}_b + m_b) \bar{\Gamma}_2 \right]_{ij} (\not{p}_a + m_a)_{ji} = \text{Trace}[\Gamma_1(\not{p}_b + m_b) \bar{\Gamma}_2 (\not{p}_a + m_a)]$$

$$\sum_{spins} [\bar{u}(a)\Gamma_1 u(b)][\bar{u}(a)\Gamma_2 u(b)]^* = \text{Trace}[\Gamma_1(\not{p}_b + m_b)\bar{\Gamma}_2(\not{p}_a + m_a)]$$

If u is replaced by v , the mass gets a minus sign (as we saw before)

Did this really gain us anything except for a headache?!?!

$$|\mathcal{M}|^2 = \frac{e^4}{(p_1 - p_3)^4} [\bar{u}^{(s3)}(p3)\gamma^\mu u^{(s1)}(p1)][\bar{u}^{(s4)}(p4)\gamma_\mu u^{(s2)}(p2)][\bar{u}^{(s3)}(p3)\gamma^\nu u^{(s1)}(p1)]^* [\bar{u}^{(s4)}(p4)\gamma_\nu u^{(s2)}(p2)]^*$$

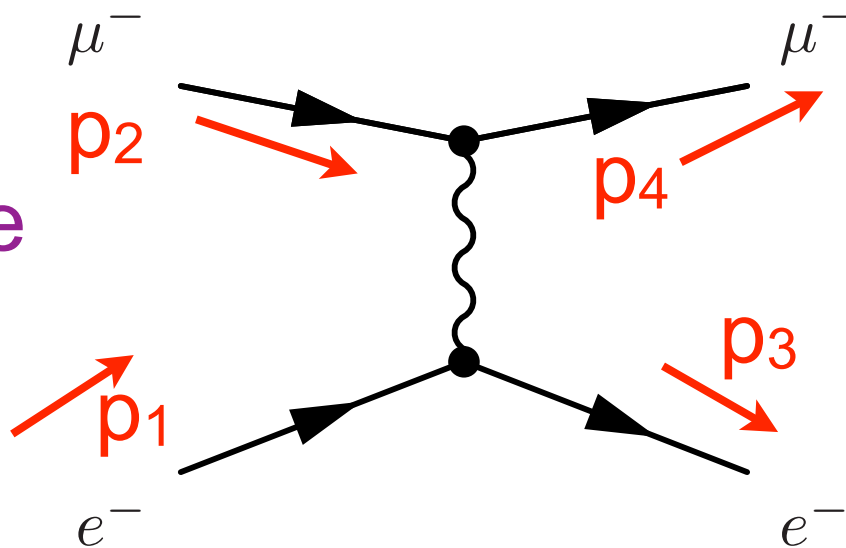
Electron-muon scattering

$$\sum_{\text{spins}} [\bar{u}(a)\Gamma_1 u(b)][\bar{u}(a)\Gamma_2 u(b)]^* = \text{Trace}[\Gamma_1(\not{p}_b + m_b)\bar{\Gamma}_2(\not{p}_a + m_a)]$$

$$|\mathcal{M}|^2 = \frac{e^4}{(p_1 - p_3)^4} [\bar{u}^{(s_3)}(p_3)\gamma^\mu u^{(s_1)}(p_1)][\bar{u}^{(s_4)}(p_4)\gamma_\mu u^{(s_2)}(p_2)][\bar{u}^{(s_3)}(p_3)\gamma^\nu u^{(s_1)}(p_1)]^* [\bar{u}^{(s_4)}(p_4)\gamma_\nu u^{(s_2)}(p_2)]^*$$

$$|\mathcal{M}|^2 = \frac{e^4}{4(p_1 - p_3)^4} \text{Trace}[\gamma^\mu(\not{p}_1 + m_1)\bar{\gamma}^\nu(\not{p}_3 + m_3)] \text{Trace}[\gamma_\mu(\not{p}_2 + m_2)\bar{\gamma}_\nu(\not{p}_4 + m_4)]$$

1/4
to average
over
initial
spins



$$m_1 = m_3 = m_e$$

$$m_2 = m_4 = m_\mu$$

One missing piece

$$\bar{\gamma}^\mu = \gamma^0 \gamma^{\mu\dagger} \gamma^0$$

$$\bar{\gamma}^0 = \gamma^0 \gamma^{0\dagger} \gamma^0 = \gamma^0 \gamma^0 \gamma^0 = \gamma^0$$

$$\bar{\gamma}^\mu = \gamma^\mu$$

$$\bar{\gamma}^i = \gamma^0 \gamma^{i\dagger} \gamma^0 = \gamma^0 \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}^\dagger \gamma^0$$

$$\bar{\gamma}^i = \gamma^0 \gamma^{i\dagger} \gamma^0 = \gamma^0 \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}^\dagger \gamma^0$$

$$\bar{\gamma}^i = \gamma^0 \begin{pmatrix} 0 & -\sigma^{i\dagger} \\ \sigma^{i\dagger} & 0 \end{pmatrix} \gamma^0$$

Obvious?

$$\bar{\gamma}^i = \gamma^0 \begin{pmatrix} 0 & -\sigma^i \\ \sigma^i & 0 \end{pmatrix} \gamma^0 = -\gamma^0 \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix} \gamma^0 = -\gamma^0 \gamma^i \gamma^0$$

$$\bar{\gamma}^i = -(-\gamma^i \gamma^0) \gamma^0 = \gamma^i$$

Electron-muon scattering

$$|\mathcal{M}|^2 = \frac{e^4}{4(p_1 - p_3)^4} \text{Trace}[\gamma^\mu (\not{p}_1 + m_1) \bar{\gamma}^\nu (\not{p}_3 + m_3)] \text{Trace}[\gamma_\mu (\not{p}_2 + m_2) \bar{\gamma}_\nu (\not{p}_4 + m_4)]$$

$$|\mathcal{M}|^2 = \frac{e^4}{4(p_1 - p_3)^4} \text{Trace}[\gamma^\mu (\not{p}_1 + m_1) \gamma^\nu (\not{p}_3 + m_3)] \text{Trace}[\gamma_\mu (\not{p}_2 + m_2) \gamma_\nu (\not{p}_4 + m_4)]$$

Griffiths has a number of “Trace theorems” in Chapter 7.7. Please look at them (don’t want to spend time deriving them all, but we’ll go over a couple)

Trace theorems from Griffiths

$$\text{Tr}(A + B) = \text{Tr}(A) + \text{Tr}(B)$$

$$\text{Tr}(\alpha A) = \alpha \text{Tr}(A)$$

$$\text{Tr}(AB) = \text{Tr}(BA)$$

$$g_{\mu\nu} g^{\mu\nu} = 4$$

$$\gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 2g^{\mu\nu}$$

$$\not{a}\not{b} + \not{b}\not{a} = 2a \cdot b$$

$$\gamma_\mu \gamma^\mu = 4$$

$$\gamma_\mu \gamma^\mu \gamma^\nu = -2\gamma^\nu$$

$$\gamma_\mu \not{a} \gamma^\mu = -2\not{a}$$

$$\gamma_\mu \gamma^\nu \gamma^\lambda \gamma^\mu = 4g^{\nu\lambda}$$

$$\gamma_\mu \not{a}\not{b} \gamma^\mu = 4(a \cdot b)$$

$$\gamma_\mu \gamma^\nu \gamma^\lambda \gamma^\sigma \gamma^\mu = -2\gamma^\sigma \gamma^\lambda \gamma^\nu$$

$$\gamma_\mu \not{a}\not{b}\not{c} = -2\not{c}\not{b}\not{a}$$

$$\text{Tr}(\gamma^\mu \gamma^\nu \gamma^\lambda) = 0$$

$$\text{Tr}(\gamma^\mu \gamma^\nu) = 4g^{\mu\nu}$$

$$\text{Tr}(\not{a}\not{b}) = 4(a \cdot b)$$

$$\text{Tr}(\gamma^\mu \gamma^\nu \gamma^\lambda \gamma^\sigma) = 4(g^{\mu\nu} g^{\lambda\sigma} - g^{\mu\lambda} g^{\nu\sigma} + g^{\mu\sigma} g^{\nu\lambda})$$

$$\text{Tr}(\not{a}\not{b}\not{c}\not{d}) = 4(a \cdot bc \cdot d - a \cdot cb \cdot d + a \cdot db \cdot c)$$

Phew

Some trace theorem proofs

$$\text{Tr}(A) = \sum_i A_{ii}$$

$$\text{Tr}(A + B) = \sum (A + B)_{ii} = \sum A_{ii} + \sum B_{ii} = \text{Tr}A + \text{Tr}B$$

$$\text{Tr}(\alpha A) = \sum (\alpha A)_{ii} = \sum (\alpha A_{ii}) = \alpha \text{Tr}(A)$$

$$\text{Tr}(AB) = \sum (AB)_{ii} = \sum_i \sum_j (A_{ij} B_{ji}) = \sum_i \sum_j B_{ji} A_{ij} = \sum_j (BA)_{jj} = \text{Tr}(BA)$$

$$\text{Tr}(ABC) = \sum (ABC)_{ii} = \sum_i \sum_j \sum_k (A_{ij} B_{jk} C_{ki}) = \sum_i \sum_j \sum_k C_{ki} A_{ij} B_{jk} = \sum_j \sum_k (CA)_{kj} B_{jk} = \text{Tr}(CAB)$$

Tr(ABC) = Tr(CAB) = Tr(BCA) but this is not the same as Tr(BAC)

Some trace theorem proofs

$$\begin{aligned}
 g_{\mu\nu}g^{\mu\nu} = & g_{00}g^{00} + \cancel{g_{01}g^{01}} + \cancel{g_{02}g^{02}} + \cancel{g_{03}g^{03}} + \\
 & \cancel{g_{10}g^{10}} + g_{11}g^{11} + \cancel{g_{12}g^{12}} + \cancel{g_{13}g^{13}} + \\
 & \cancel{g_{20}g^{20}} + \cancel{g_{21}g^{21}} + g_{22}g^{22} + \cancel{g_{23}g^{23}} + \\
 & \cancel{g_{30}g^{30}} + \cancel{g_{31}g^{31}} + \cancel{g_{32}g^{32}} + g_{33}g^{33}
 \end{aligned}$$

$$g_{\mu\nu}g^{\mu\nu} = g_{00}g^{00} + g_{11}g^{11} + g_{22}g^{22} + g_{33}g^{33} = (1)(1) + (-1)(-1) + (-1)(-1) + (-1)(-1) = 4$$

Some trace theorem proofs

$$a\cancel{b} + \cancel{b}a = (a_\mu \gamma^\mu)(b_\nu \gamma^\nu) + (b_\nu \gamma^\nu)(a_\mu \gamma^\mu)$$

$$a\cancel{b} + \cancel{b}a = (a_\mu b_\nu)(\gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu)$$

$$a\cancel{b} + \cancel{b}a = (a_\mu b_\nu)(2g^{\mu\nu}) = 2a_\mu b^\mu = 2a \cdot b$$

$$\gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 2g^{\mu\nu}$$

$$g_{\mu\nu} (\gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu) = g_{\mu\nu} (2g^{\mu\nu})$$

$$\gamma_\nu \gamma^\nu + \gamma_\nu \gamma^\nu = 2\gamma_\nu \gamma^\nu = 2g_{\mu\nu} g^{\mu\nu}$$

$$\gamma_\nu \gamma^\nu = g_{\mu\nu} g^{\mu\nu}$$

$$\gamma_\nu \gamma^\nu = 4$$

$$\gamma_\mu \gamma^\nu \gamma^\mu = \gamma_\mu (2g^{\mu\nu} - \gamma^\mu \gamma^\nu)$$

$$\gamma_\mu \gamma^\nu \gamma^\mu = 2\gamma_\mu g^{\mu\nu} - \gamma_\mu \gamma^\mu \gamma^\nu$$

$$\gamma_\mu \gamma^\nu \gamma^\mu = 2\gamma^\nu - 4\gamma^\nu$$

$$\gamma_\mu \gamma^\nu \gamma^\mu = -2\gamma^\nu$$

Some trace theorem proofs

$$\text{Tr}(\gamma^\mu \gamma^\nu \gamma^\sigma) = \text{Tr}(\gamma^\mu \gamma^\nu \gamma^\sigma \gamma^5 \gamma^5)$$

$$\text{Tr}(\gamma^\mu \gamma^\nu \gamma^\sigma) = (-1)^1 \text{Tr}(\gamma^\mu \gamma^\nu \gamma^5 \gamma^\sigma \gamma^5)$$

$$\text{Tr}(\gamma^\mu \gamma^\nu \gamma^\sigma) = (-1)^2 \text{Tr}(\gamma^\mu \gamma^5 \gamma^\nu \gamma^\sigma \gamma^5)$$

$$\text{Tr}(\gamma^\mu \gamma^\nu \gamma^\sigma) = (-1)^3 \text{Tr}(\gamma^5 \gamma^\mu \gamma^\nu \gamma^\sigma \gamma^5)$$

$$\text{Tr}(AB) = \text{Tr}(BA) \rightarrow \text{Tr}(\gamma^\mu \gamma^\nu \gamma^\sigma) = (-1)^3 \text{Tr}(\gamma^5 \gamma^\mu \gamma^\nu \gamma^\sigma \gamma^5) = (-1)^3 \text{Tr}(\gamma^\mu \gamma^\nu \gamma^\sigma \gamma^5 \gamma^5)$$

$$\text{Tr}(\gamma^\mu \gamma^\nu \gamma^\sigma) = (-1)^3 \text{Tr}(\gamma^\mu \gamma^\nu \gamma^\sigma \gamma^5 \gamma^5) \rightarrow \text{Tr}(\gamma^\mu \gamma^\nu \gamma^\sigma) = 0$$



True for any odd number of
gamma matrices

Some trace theorem proofs

$$\text{Tr}(1) = \text{Tr} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = 1 + 1 + 1 + 1 = 4$$

$$\text{Tr}(\gamma^\mu \gamma^\nu) = \text{Tr}(\gamma^\nu \gamma^\mu) \rightarrow \text{Tr}(\gamma^\mu \gamma^\nu) = \frac{1}{2} [\text{Tr}(\gamma^\mu \gamma^\nu) + \text{Tr}(\gamma^\nu \gamma^\mu)] = \frac{1}{2} \text{Tr}(\gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu)$$

$$\text{Tr}(\gamma^\mu \gamma^\nu) = \frac{1}{2} \text{Tr}(2g^{\mu\nu}) = g^{\mu\nu} \text{Tr}(1) = 4g^{\mu\nu}$$

$$\text{Tr}(\gamma^5) = \text{Tr} \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} = 0$$

Phew. Again. Are we ready to calculate some matrix elements again? (It's been awhile since we've calculated any, and for sure been a long detour)

Back to Electron-muon scattering

$$|\mathcal{M}|^2 = \frac{e^4}{4(p_1 - p_3)^4} \text{Trace}[\gamma^\mu (\not{p}_1 + m_1) \gamma^\nu (\not{p}_3 + m_3)] \text{Trace}[\gamma_\mu (\not{p}_2 + m_2) \gamma_\nu (\not{p}_4 + m_4)]$$

$$\text{Tr}[\gamma^\mu (\not{p}_1 + m_1) \gamma^\nu (\not{p}_3 + m_3)] =$$

$$\text{Tr}[\gamma^\mu \not{p}_1 \gamma^\nu \not{p}_3] + \text{Tr}[\gamma^\mu m_1 \gamma^\nu \not{p}_3] + \text{Tr}[\gamma^\mu \not{p}_1 \gamma^\nu m_3] + \text{Tr}[\gamma^\mu m_1 \gamma^\nu m_3] =$$

$$\text{Tr}[\gamma^\mu \gamma^\sigma p_{1,\sigma} \gamma^\nu \gamma^\lambda p_{3,\lambda}] + \text{Tr}[\gamma^\mu m_1 \gamma^\nu \gamma^\lambda p_{3,\lambda}] + \text{Tr}[\gamma^\mu \gamma^\sigma p_{1,\sigma} \gamma^\nu m_3] + \text{Tr}[\gamma^\mu m_1 \gamma^\nu m_3]$$



$$\text{Tr}(\gamma^\mu \gamma^\nu \gamma^\lambda) = 0$$

Electron-muon scattering

$$|\mathcal{M}|^2 = \frac{e^4}{4(p_1 - p_3)^4} \text{Trace}[\gamma^\mu (\not{p}_1 + m_1) \gamma^\nu (\not{p}_3 + m_3)] \text{Trace}[\gamma_\mu (\not{p}_2 + m_2) \gamma_\nu (\not{p}_4 + m_4)]$$

$$\begin{aligned} \text{Tr}[\gamma^\mu (\not{p}_1 + m_1) \gamma^\nu (\not{p}_3 + m_3)] = \\ \text{Tr}[\gamma^\mu \gamma^\sigma p_{1,\sigma} \gamma^\nu \gamma^\lambda p_{3,\lambda}] + \text{Tr}[\gamma^\mu m_1 \gamma^\nu m_3] \end{aligned}$$

$$\text{Tr}(\gamma^\mu \gamma^\nu) = 4g^{\mu\nu}$$

$$\text{Tr}(\gamma^\mu \gamma^\nu \gamma^\lambda \gamma^\sigma) = 4(g^{\mu\nu} g^{\lambda\sigma} - g^{\mu\lambda} g^{\nu\sigma} + g^{\mu\sigma} g^{\nu\lambda})$$

$$\begin{aligned} \text{Tr}[\gamma^\mu (\not{p}_1 + m_1) \gamma^\nu (\not{p}_3 + m_3)] = \\ \text{Tr}[\gamma^\mu \gamma^\sigma p_{1,\sigma} \gamma^\nu \gamma^\lambda p_{3,\lambda}] + \text{Tr}[\gamma^\mu m_1 \gamma^\nu m_3] = \\ 4p_{1,\sigma} p_{3,\lambda} [g^{\mu\sigma} g^{\nu\lambda} - g^{\mu\nu} g^{\sigma\lambda} + g^{\mu\lambda} g^{\sigma\nu}] + 4m_1 m_3 g^{\mu\nu} \end{aligned}$$

Electron-muon scattering

$$|\mathcal{M}|^2 = \frac{e^4}{4(p_1 - p_3)^4} \text{Trace}[\gamma^\mu (\not{p}_1 + m_1) \gamma^\nu (\not{p}_3 + m_3)] \text{Trace}[\gamma_\mu (\not{p}_2 + m_2) \gamma_\nu (\not{p}_4 + m_4)]$$

Careful of
 μ index vs muon object!

$$m_1 = m_3 = m_e$$

$$m_2 = m_4 = m_\mu$$

$$\begin{aligned} \text{Tr}[\gamma^\mu (\not{p}_1 + m_1) \gamma^\nu (\not{p}_3 + m_3)] &= \\ 4p_{1,\sigma} p_{3,\lambda} [g^{\mu\sigma} g^{\nu\lambda} - g^{\mu\nu} g^{\sigma\lambda} + g^{\mu\lambda} g^{\sigma\nu}] + 4m_1 m_3 g^{\mu\nu} &= \\ 4[p_1^\mu p_3^\nu - g^{\mu\nu} p_1 \cdot p_3 + p_1^\nu p_3^\mu + m_1 m_3 g^{\mu\nu}] &= \\ 4[p_1^\mu p_3^\nu + p_1^\nu p_3^\mu + g^{\mu\nu} (m_e^2 - p_1 \cdot p_3)] & \end{aligned}$$

Electron-muon scattering

$$|\mathcal{M}|^2 = \frac{e^4}{4(p_1 - p_3)^4} \text{Trace}[\gamma^\mu(\not{p}_1 + m_1)\gamma^\nu(\not{p}_3 + m_3)] \text{Trace}[\gamma_\mu(\not{p}_2 + m_2)\gamma_\nu(\not{p}_4 + m_4)]$$

$$\begin{aligned} \text{Tr}[\gamma^\mu(\not{p}_1 + m_1)\gamma^\nu(\not{p}_3 + m_3)] &= \\ 4[p_1^\mu p_3^\nu + p_1^\nu p_3^\mu + g^{\mu\nu}(m_e^2 - p_1 \cdot p_3)] & \quad \mathbf{m_1 = m_3 = m_e} \\ & \quad \mathbf{m_2 = m_4 = m_\mu} \end{aligned}$$

$$\begin{aligned} \text{Tr}[\gamma_\mu(\not{p}_2 + m_2)\gamma_\nu(\not{p}_4 + m_4)] &= \\ 4[p_{2\mu} p_{4\nu} + p_{2\nu} p_{4\mu} + g_{\mu\nu}(m_\mu^2 - p_2 \cdot p_4)] & \end{aligned}$$

$$\begin{aligned} |\mathcal{M}|^2 &= \frac{e^4}{4(p_1 - p_3)^4} \text{Tr}[\gamma^\mu(\not{p}_1 + m_1)\gamma^\nu(\not{p}_3 + m_3)] \text{Tr}[\gamma_\mu(\not{p}_2 + m_2)\gamma_\nu(\not{p}_4 + m_4)] = \\ & \frac{e^4}{4(p_1 - p_3)^4} 4[p_1^\mu p_3^\nu + p_1^\nu p_3^\mu + g^{\mu\nu}(m_e^2 - p_1 \cdot p_3)] \times \\ & 4[p_{2\mu} p_{4\nu} + p_{2\nu} p_{4\mu} + g_{\mu\nu}(m_\mu^2 - p_2 \cdot p_4)] \end{aligned}$$

Electron-muon scattering

$$|\mathcal{M}|^2 = \frac{4e^4}{(p_1 - p_3)^4} [p_1^\mu p_3^\nu + p_1^\nu p_3^\mu + g^{\mu\nu}(m_e^2 - p_1 \cdot p_3)] \times [p_{2\mu} p_{4\nu} + p_{2\nu} p_{4\mu} + g_{\mu\nu}(m_\mu^2 - p_2 \cdot p_4)]$$

$$|\mathcal{M}|^2 = \frac{4e^4}{(p_1 - p_3)^4} [(p_1 \cdot p_2)(p_3 \cdot p_4) + (p_1 \cdot p_4)(p_2 \cdot p_3) + m_\mu^2(p_1 \cdot p_3) - (p_1 \cdot p_3)(p_2 \cdot p_4) + (p_1 \cdot p_4)(p_2 \cdot p_3) + (p_1 \cdot p_2)(p_3 \cdot p_4) + m_\mu^2(p_1 \cdot p_3) - (p_1 \cdot p_3)(p_2 \cdot p_4) + m_e^2(p_2 \cdot p_4) - (p_2 \cdot p_4)(p_1 \cdot p_3) + m_e^2(p_2 \cdot p_4) - (p_2 \cdot p_4)(p_1 \cdot p_3) + 4(m_e^2 - (p_1 \cdot p_3))(m_\mu^2 - (p_2 \cdot p_4))]$$

$$|\mathcal{M}|^2 = \frac{4e^4}{(p_1 - p_3)^4} (2(p_1 \cdot p_2)(p_3 \cdot p_4) + 2(p_1 \cdot p_4)(p_2 \cdot p_3) - 2m_\mu^2(p_1 \cdot p_3) - 2m_e^2(p_2 \cdot p_4) + 4m_e^2 m_\mu^2)$$

$$|\mathcal{M}|^2 = \frac{8e^4}{(p_1 - p_3)^4} ((p_1 \cdot p_2)(p_3 \cdot p_4) + (p_1 \cdot p_4)(p_2 \cdot p_3) - m_\mu^2(p_1 \cdot p_3) - m_e^2(p_2 \cdot p_4) + 2m_e^2 m_\mu^2)$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} \frac{|M|^2}{(E_1 + E_2)^2} \frac{|\mathbf{p}_f|^2}{|\mathbf{p}_i|^2}$$

What if muon is stationary and we neglect its recoil? (Even better - protons are heavier than muons, have same $|q|$, and don't decay!)

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} \frac{|M|^2}{(E_1 + E_2)^2} \frac{|\mathbf{p}_f|^2}{|\mathbf{p}_i|^2}$$

When electron scatters off of a proton (we're assuming we're not so energetic that the electron sees the quarks!), the proton doesn't budge. It's an elastic collision and $|\mathbf{p}_f| = |\mathbf{p}_i|$.

$$E_1 + E_2 = E_1 + m_p = m_p$$

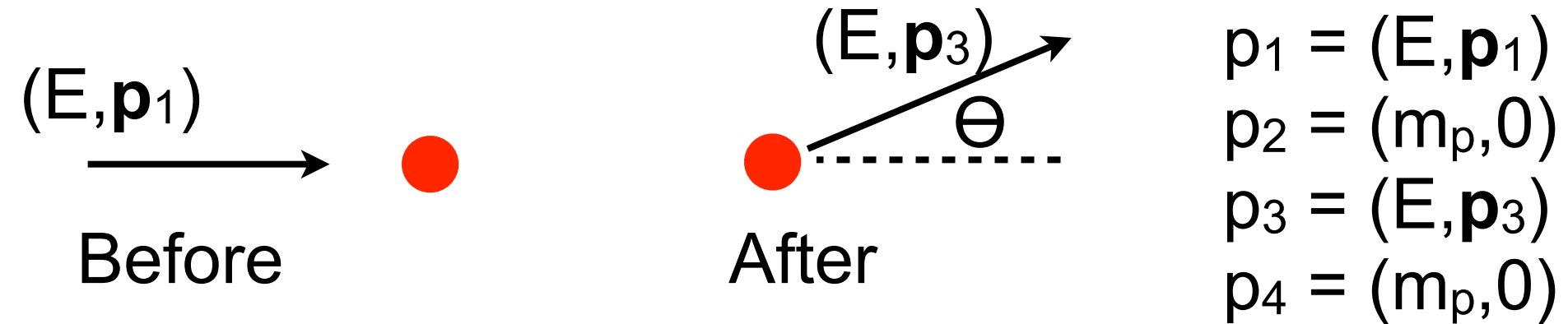
$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} \frac{|M|^2}{m_p^2}$$



$$\begin{aligned}
 p_1 &= (E, \mathbf{p}_1) \\
 p_2 &= (m_p, 0) \\
 p_3 &= (E, \mathbf{p}_3) \\
 p_4 &= (m_p, 0)
 \end{aligned}$$

$$|\mathbf{p}_1| = |\mathbf{p}_3|$$

Electron-proton scattering



$$\mathbf{p}_1 \cdot \mathbf{p}_3 = p^2 \cos \theta$$

$$(p_1 - p_3)^2 = (E - E)^2 - (\mathbf{p}_1 - \mathbf{p}_3)^2 = -\mathbf{p}_1^2 - \mathbf{p}_3^2 + 2\mathbf{p}_1 \cdot \mathbf{p}_3$$

$$(p_1 - p_3)^2 = -2\mathbf{p}^2 + 2\mathbf{p}^2 \cos \theta = -2\mathbf{p}^2(1 - \cos \theta)$$

$$|\mathcal{M}|^2 = \frac{8e^4}{(p_1 - p_3)^4} ((p_1 \cdot p_2)(p_3 \cdot p_4) + (p_1 \cdot p_4)(p_2 \cdot p_3) - m_p^2(p_1 \cdot p_3) - m_e^2(p_2 \cdot p_4) + 2m_e^2 m_p^2)$$

$$p_1 \cdot p_2 = p_3 \cdot p_4 = p_1 \cdot p_4 = p_2 \cdot p_3 = Em_p$$

$$p_1 \cdot p_3 = E^2 - \mathbf{p}_1 \cdot \mathbf{p}_3 = E^2 - p^2 \cos \theta$$

$$p_2 \cdot p_4 = m_p^2$$

Electron-proton scattering

$$|\mathcal{M}|^2 = \frac{8e^4}{(p_1 - p_3)^4} ((p_1 \cdot p_2)(p_3 \cdot p_4) + (p_1 \cdot p_4)(p_2 \cdot p_3) - m_p^2(p_1 \cdot p_3) - m_e^2(p_2 \cdot p_4) + 2m_e^2m_p^2)$$

$$p_1 \cdot p_2 = p_3 \cdot p_4 = p_1 \cdot p_4 = p_2 \cdot p_3 = Em_p$$

$$p_1 \cdot p_3 = E^2 - \mathbf{p}_1 \cdot \mathbf{p}_3 = E^2 - \mathbf{p}^2 \cos \theta$$

$$(p_1 - p_3)^2 = -2\mathbf{p}^2(1 - \cos \theta) \quad p_2 \cdot p_4 = m_p^2$$

$$|\mathcal{M}|^2 = \frac{8e^4}{4\mathbf{p}^4(1 - \cos \theta)^2} (E^2m_p^2 + E^2m_p^2 - m_p^2(E^2 - \mathbf{p}^2 \cos \theta) - m_e^2m_p^2 + 2m_e^2m_p^2)$$

$$|\mathcal{M}|^2 = \frac{2e^4m_p^2}{\mathbf{p}^4(1 - \cos \theta)^2} (E^2 + \mathbf{p}^2 \cos \theta + m_e^2)$$

$$E^2 = \mathbf{p}^2 + m_e^2$$

$$|\mathcal{M}|^2 = \frac{2e^4m_p^2}{\mathbf{p}^4(1 - \cos \theta)^2} (\mathbf{p}^2(1 + \cos \theta) + 2m_e^2)$$

Electron-proton scattering

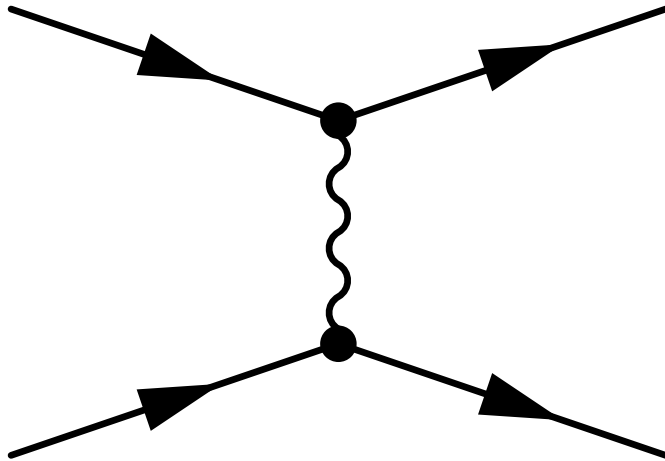
$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} \frac{|M|^2}{m_p^2}$$

$$\frac{d\sigma}{d\Omega} = \frac{e^4}{32\pi^2 \mathbf{p}^4 (1 - \cos \theta)^2} (\mathbf{p}^2 (1 + \cos \theta) + 2m_e^2)$$

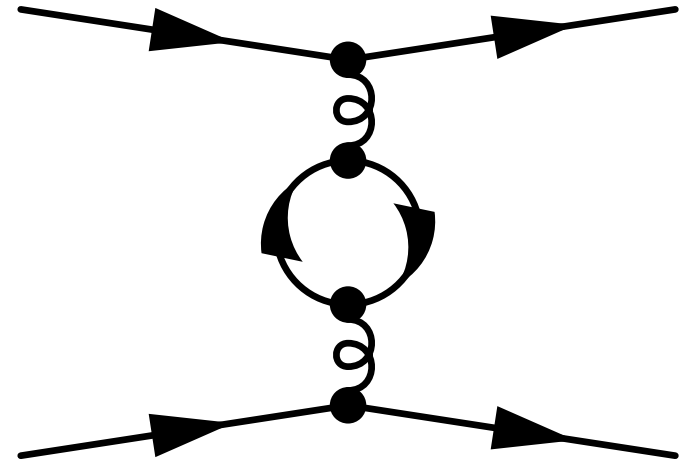
If electron is not relativistic, $m_e \gg \mathbf{p}^2$ and $\mathbf{p}^4 = (m_e v)^4$

$$\frac{d\sigma}{d\Omega} = \frac{e^4}{32\pi^2 m_e^4 v^4 (1 - \cos \theta)^2} (2m_e^2)$$

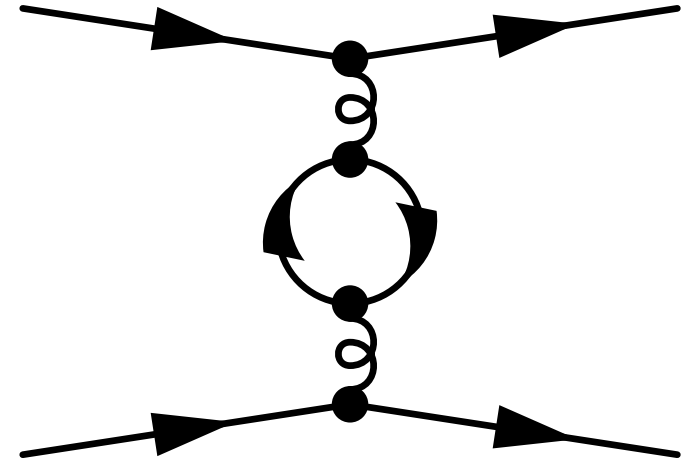
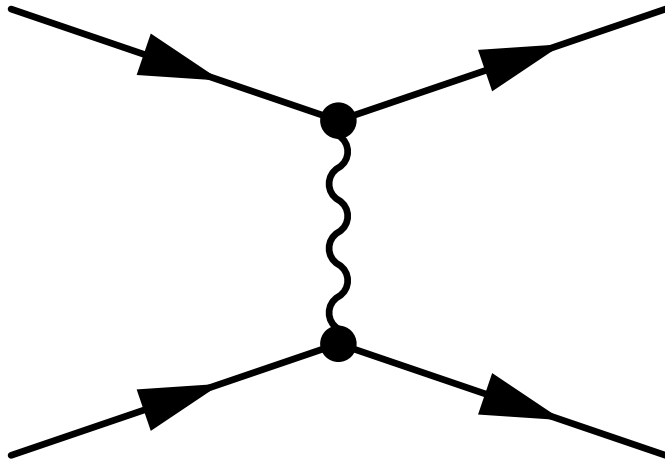
$$\frac{d\sigma}{d\Omega} = \frac{e^4}{16\pi^2 m_e^2 v^4 (1 - \cos \theta)^2}$$



Leading order
electron-muon
scattering



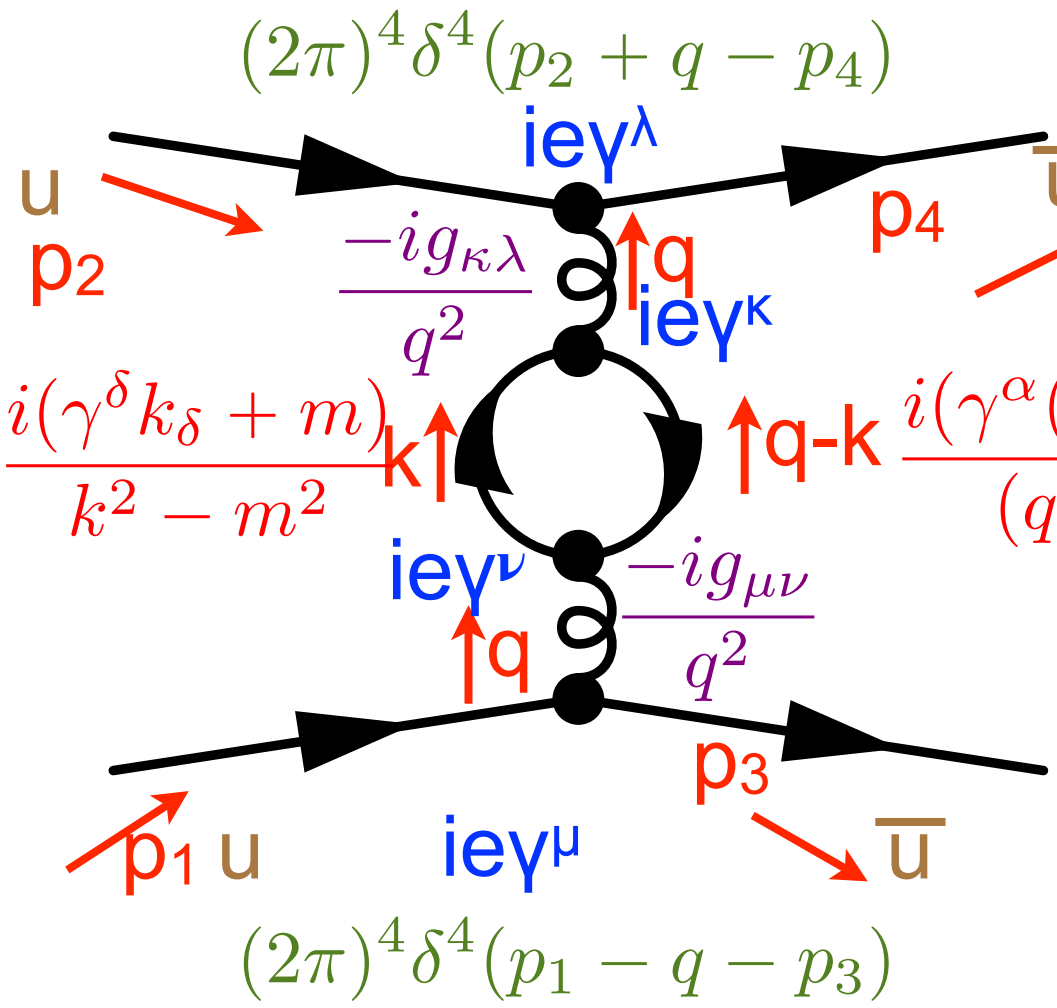
Vacuum
polarization
diagram modifying
effective charge of
electron



Difference is modifying the photon propagator term. Naively, this leads to infinities! But we have tricks to deal with them

Let's see if we can calculate it

Cheated a bit here and already applied some delta functions!



i

$$\frac{1}{(2\pi)^4} d^4 q \frac{1}{(2\pi)^4} d^4 k$$

$$i \int [\bar{u}(3)(ie\gamma^\mu)u(1)] \frac{-ig_{\mu\nu}}{q^2}$$

$$ie\gamma^\nu \frac{i(\gamma^\delta k_\delta) + m}{k^2 - m^2} \frac{i(\gamma^\alpha (q_\alpha - k_\alpha) + m)}{(q - k)^2 - m^2} ie\gamma^\kappa \frac{-ig_{\kappa\lambda}}{q^2}$$

$$[\bar{u}(4)(ie\gamma^\lambda)u(2)]$$

$$(2\pi)^4 \delta^4(p_1 - q_1 - p_3) (2\pi)^4 \delta^4(p_2 + q - p_4) \frac{d^4 q}{(2\pi)^4} \frac{d^4 k}{(2\pi)^4}$$

Some cleanup

$$\begin{aligned}
& i \int [\bar{u}(3)(ie\gamma^\mu)u(1)] \frac{-ig_{\mu\nu}}{q^2} \\
& ie\gamma^\nu \frac{i(\gamma^\delta k_\delta) + m}{k^2 - m^2} \frac{i(\gamma^\alpha(q_\alpha - k_\alpha) + m)}{(q - k)^2 - m^2} ie\gamma^\kappa \frac{-ig_{\kappa\lambda}}{q^2} \\
& [\bar{u}(4)(ie\gamma^\lambda)u(2)] \\
& (2\pi)^4 \delta^4(p_1 - q_1 - p_3) (2\pi)^4 \delta^4(p_2 + q - p_4) \frac{d^4q}{(2\pi)^4} \frac{d^4k}{(2\pi)^4}
\end{aligned}$$

$$\begin{aligned}
& ie^4 \int [\bar{u}(3)(\gamma^\mu)u(1)] \frac{g_{\mu\nu}}{q^2} \\
& \gamma^\nu \frac{(\gamma^\delta k_\delta) + m}{k^2 - m^2} \frac{(\gamma^\alpha(q_\alpha - k_\alpha) + m)}{(q - k)^2 - m^2} \gamma^\kappa \frac{g_{\kappa\lambda}}{q^2} \\
& [\bar{u}(4)(\gamma^\lambda)u(2)] \\
& (2\pi)^4 \delta^4(p_1 - q_1 - p_3) (2\pi)^4 \delta^4(p_2 + q - p_4) \frac{d^4q}{(2\pi)^4} \frac{d^4k}{(2\pi)^4}
\end{aligned}$$

$$\begin{aligned}
& ie^4 \int [\bar{u}(3)(\gamma^\mu)u(1)] \frac{g_{\mu\nu}}{q^2} \\
& \gamma^\nu \frac{(\gamma^\delta k_\delta) + m}{k^2 - m^2} \frac{(\gamma^\alpha (q_\alpha - k_\alpha) + m)}{(q - k)^2 - m^2} \gamma^\kappa \frac{g_{\kappa\lambda}}{q^2} \\
& [\bar{u}(4)(\gamma^\lambda)u(2)] \\
& (2\pi)^4 \delta^4(p_1 - q_1 - p_3) (2\pi)^4 \delta^4(p_2 + q - p_4) \frac{d^4 q}{(2\pi)^4} \frac{d^4 k}{(2\pi)^4}
\end{aligned}$$

$$\begin{aligned}
& ie^4 \int [\bar{u}(3)(\gamma_\nu)u(1)] \\
& \frac{\gamma^\nu}{q^2} \frac{(\not{k} + m)}{k^2 - m^2} \frac{(\not{q} - \not{k} + m)}{(q - k)^2 - m^2} \frac{\gamma_\lambda}{q^2} \\
& [\bar{u}(4)(\gamma^\lambda)u(2)] \\
& (2\pi)^4 \delta^4(p_1 - q - p_3) (2\pi)^4 \delta^4(p_2 + q - p_4) \frac{d^4 q}{(2\pi)^4} \frac{d^4 k}{(2\pi)^4}
\end{aligned}$$

$$ie^4 \int [\bar{u}(3)(\gamma_\nu)u(1)]$$

$$\frac{\gamma^\nu}{q^2} \frac{(\not{k} + m)}{k^2 - m^2} \frac{(\not{q} - \not{k} + m)}{(q - k)^2 - m^2} \frac{\gamma_\lambda}{q^2}$$

$$[\bar{u}(4)(\gamma^\lambda)u(2)]$$

$$(2\pi)^4 \delta^4(p_1 - q - p_3) (2\pi)^4 \delta^4(p_2 + q - p_4) \frac{d^4 q}{(2\pi)^4} \frac{d^4 k}{(2\pi)^4}$$

$$ie^4 \int [\bar{u}(3)(\gamma_\nu)u(1)]$$

$$\frac{\gamma^\nu}{(p_1 - p_3)^2} \frac{(\not{k} + m)}{k^2 - m^2} \frac{(\not{p}_1 - \not{p}_3 - \not{k} + m)}{(p_1 - p_3 - k)^2 - m^2} \frac{\gamma_\lambda}{(p_1 - p_3)^2} \frac{d^4 k}{(2\pi)^4}$$

$$[\bar{u}(4)(\gamma^\lambda)u(2)]$$

$$(2\pi)^4 \delta^4(p_2 + p_1 - p_3 - p_4)$$

$$ie^4 \int [\bar{u}(3)(\gamma_\nu)u(1)]$$

$$\frac{\gamma^\nu}{(p_1 - p_3)^2} \frac{(\not{k} + m)}{k^2 - m^2} \frac{(p_1 - p_3 - \not{k} + m)}{(p_1 - p_3 - k)^2 - m^2} \frac{\gamma_\lambda}{(p_1 - p_3)^2} \frac{d^4 k}{(2\pi)^4}$$

$$[\bar{u}(4)(\gamma^\lambda)u(2)]$$

$$(2\pi)^4 \delta^4(p_2 + p_1 - p_3 - p_4)$$

$$ie^4 \int [\bar{u}(3)(\gamma_\nu)u(1)]$$

$$\frac{\gamma^\nu}{(p_1 - p_3)^2} \frac{(\not{k}) + m}{k^2 - m^2} \frac{(p_1 - p_3 - \not{k}) + m}{(p_1 - p_3 - k)^2 - m^2} \frac{\gamma_\lambda}{(p_1 - p_3)^2} \frac{d^4 k}{(2\pi)^4}$$

$$[\bar{u}(4)(\gamma^\lambda)u(2)]$$
~~$$(2\pi)^4 \delta^4(p_2 + p_1 - p_3 - p_4)$$~~

Cancel

$$\mathcal{M} = ie^4 [\bar{u}(3)(\gamma_\mu)u(1)] I^{\mu\nu} [\bar{u}(4)(\gamma_\nu)u(2)]$$

$$I^{\mu\nu} = \int \frac{\gamma^\mu}{(p_1 - p_3)^2} \frac{\not{k} + m}{k^2 - m^2} \frac{\not{p}_1 - \not{p}_3 - \not{k} + m}{(p_1 - p_3 - k)^2 - m^2} \frac{\gamma^\nu}{(p_1 - p_3)^2} \frac{d^4 k}{(2\pi)^4}$$

If we compare this new matrix element to the leading order one, we see that it is a modification to the photon propagator! Note that it depends on $(p_1 - p_3)$, or q , as we might expect.

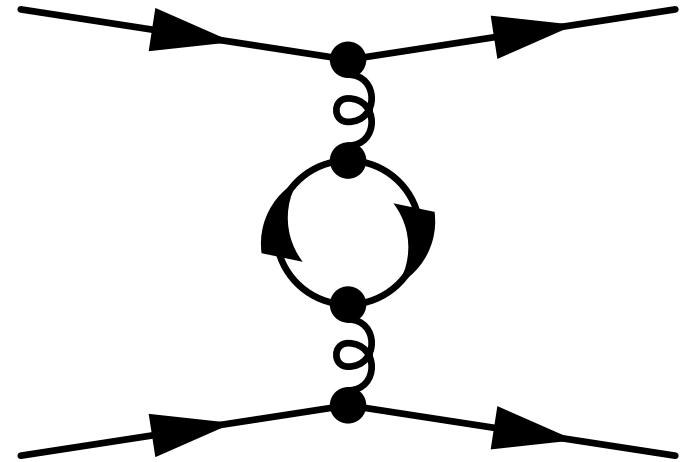
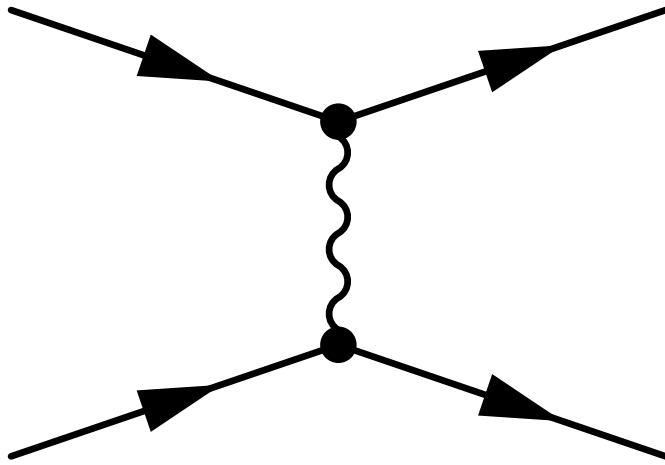
Why?

$$I^{\mu\nu} = \int \frac{\gamma^\mu}{(p_1 - p_3)^2} \frac{\not{k} + m}{k^2 - m^2} \frac{p_1 - p_3 - \not{k} + m}{(p_1 - p_3 - k)^2 - m^2} \frac{\gamma^\nu}{q^2} \frac{d^4 k}{(2\pi)^4}$$

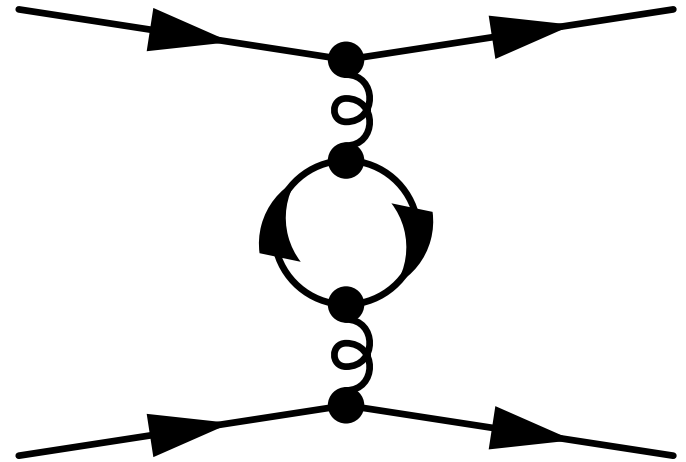
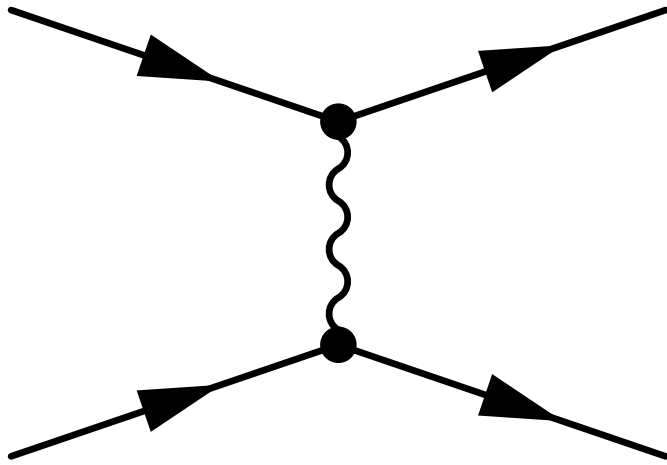
$$I \propto \int \frac{k^2}{k^4} d^4 k$$

$$I \propto \int \frac{k^2}{k^4} k^3 dk$$

$$I \rightarrow \infty \text{ for } k \rightarrow \infty$$

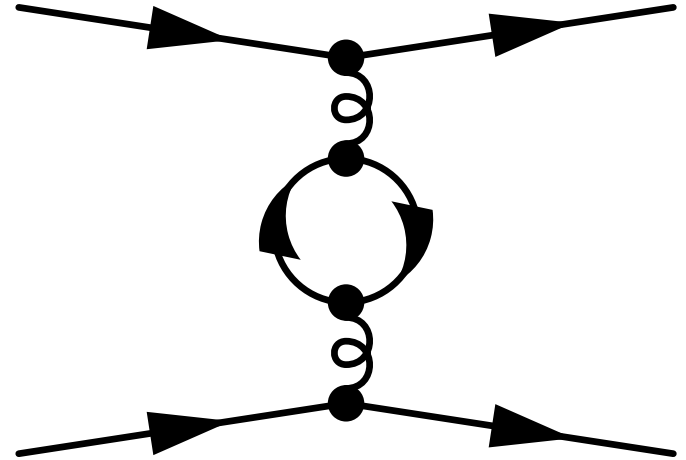
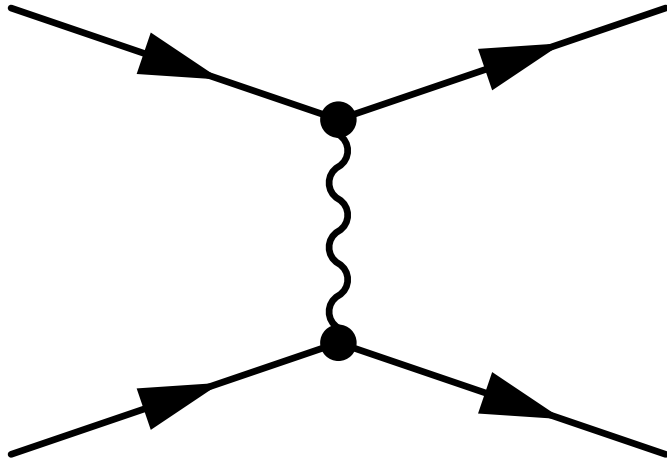


“Infinity” can be removed if we include it in the definition of electron charge, ie the renormalized electron charge. That seems odd, but is OK - the renormalized charge (these diagrams, plus others up to infinite order) are really what we measure in the lab, not the bare value of e !



When we renormalize the electric charge there is a leftover term that is finite, but depends on q^2 . This is as before the running of the coupling constant. One way to think of this - the larger q^2 the closer the particles can get, which changes the effective electromagnetic screening. A small but measurable effect!

Of course, those were two terms... there are an infinite number!



$$\alpha(q^2) = \frac{\alpha(0)}{1 - \frac{\alpha(0)}{3\pi} \ln(q^2/m^2)}$$

It's OK to
cry
sometimes



This onion won't
make me cry



You will never
understand
renormalization



Some homework for you

7.6,7.13,7.18,7.48,7.49 (use your answer to 6.8 for part e)
due 1 week from today

Also, send me:

- 1) An outline of your presentation (can just be in an email, but it should be a complete outline). Looking for roughly one item per slide, and remember that a good rule of thumb is one slide per minute (remember, it's a 20 minute presentation)
- 2) At least two references that you are going to use for material and/or background information and/or reading to prepare for your talk, **NOT** including the ones that are the main paper you are presenting. Also tell me what you are using them for. A good starting point is some references or links from that paper, however you can also use textbooks or other papers. Wikipedia doesn't count :)

7.6,7.13,7.18,7.48,7.49 (use your answer to 6.8 for part e) due 1 week from today

Also, before class that day, send me at least two references that you are going to use for material and/or background information and/or reading to prepare for your talk, **NOT** including the ones that are the main paper you are presenting. Also tell me what you are using them for. A good starting point is some references or links from that paper, however :)