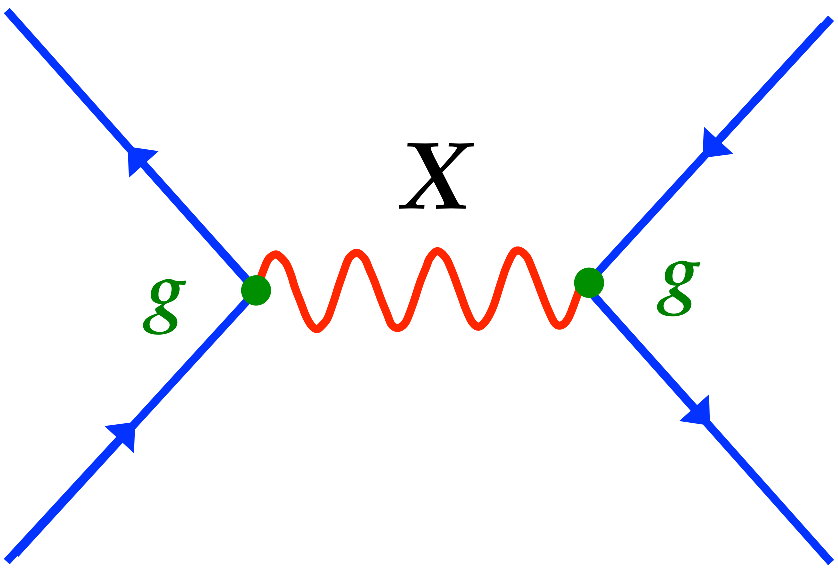
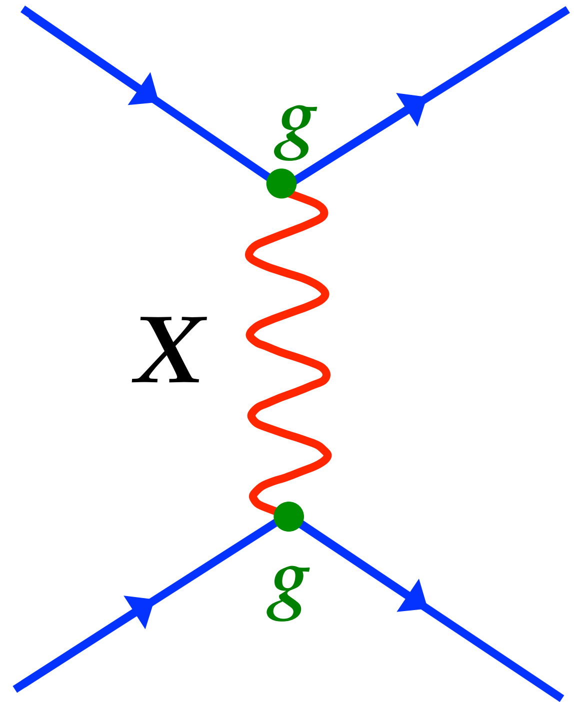
Particle Physics

Handout from Prof. Mark Thomson's lectures
Adapted to UZH by Prof. Canelli and Prof. Serra





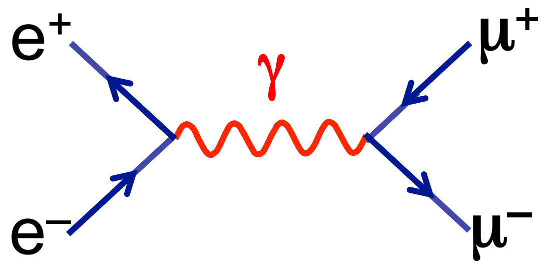
Handout 3 : Interaction by Particle Exchange and QED

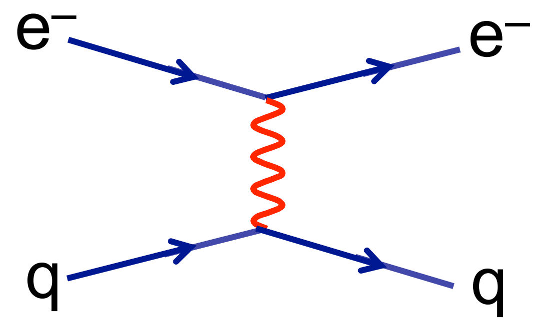
Recap

★ **Working towards a proper calculation of decay and scattering processes**

Initially concentrate on:

- $e^+e^- \rightarrow \mu^+\mu^-$
- $e^- q \rightarrow e^- q$





★ **In Handout 1 covered the relativistic calculation of particle decay rates and cross sections**

$$\sigma \propto \frac{|M|^2}{\text{flux}} \times (\text{phase space})$$

★ **In Handout 2 covered relativistic treatment of spin-half particles**

Dirac Equation

★ **This handout concentrate on the Lorentz Invariant Matrix Element**

- **Interaction by particle exchange**
- **Introduction to Feynman diagrams**
- **The Feynman rules for QED**

Interaction by Particle Exchange

- Calculate transition rates from **Fermi's Golden Rule**

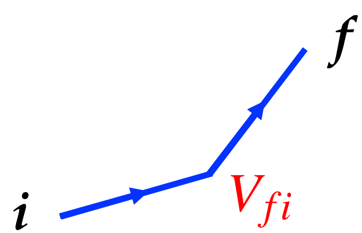
$$\Gamma_{fi} = 2\pi |T_{fi}|^2 \rho(E_f)$$

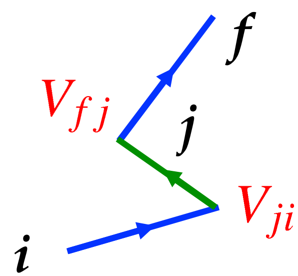
where T_{fi} is perturbation expansion for the Transition Matrix Element

$$T_{fi} = \langle f|V|i\rangle + \sum_{j\neq i} \frac{\langle f|V|j\rangle\langle j|V|i\rangle}{E_i - E_j} + \ldots$$

- For particle scattering, the first two terms in the perturbation series can be viewed as:

"scattering in a potential"

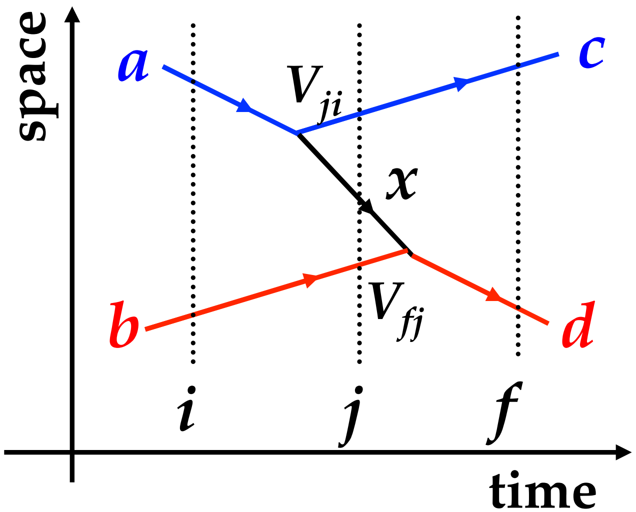




"scattering via an intermediate state"

- **"Classical picture"** – particles act as sources for fields which give rise a potential in which other particles scatter – **"action at a distance"**
- **"Quantum Field Theory picture"** – forces arise due to the exchange of virtual particles. No action at a distance + **forces** between particles now **due to particles**

- Consider the particle interaction $a+b \rightarrow c+d$ which occurs via an intermediate state corresponding to the exchange of particle x
- One possible space-time picture of this process is:



Initial state i : $a+b$
Final state f : $c+d$
Intermediate state j : $c+b+x$

- This **time-ordered** diagram corresponds to a "emitting" x and then b absorbing x

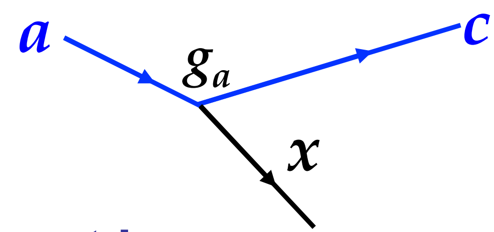
- The corresponding term in the perturbation expansion is:

$$T_{fi} = \frac{\langle f|V|j\rangle\langle j|V|i\rangle}{E_i - E_j}$$

$$T_{fi}^{ab} = \frac{\langle d|V|x+b\rangle\langle c+x|V|a\rangle}{(E_a+E_b)-(E_c+E_x+E_b)}$$

- T_{fi}^{ab} refers to the time-ordering where a emits x before b absorbs it

- Need an expression for $\langle c+x|V|a\rangle$ in non-invariant matrix element T_{fi}



- Ultimately aiming to obtain Lorentz Invariant ME
- Recall T_{fi} is related to the invariant matrix element by

$$T_{fi} = \prod_k (2E_k)^{-1/2} M_{fi}$$

where k runs over all particles in the matrix element

- Here we have

$$\langle c+x|V|a\rangle = \frac{M_{(a\to c+x)}}{(2E_a 2E_c 2E_x)^{1/2}}$$

$M_{(a\to c+x)}$ is the "Lorentz Invariant" matrix element for $a \to c + x$

★ The simplest Lorentz Invariant quantity is a scalar, in this case

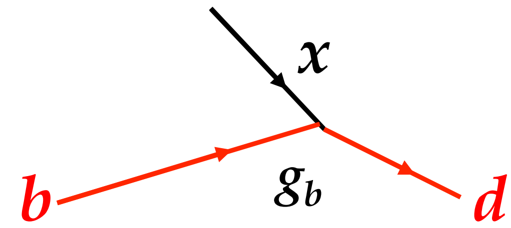
$$\langle c+x|V|a\rangle = \frac{g_a}{(2E_a 2E_c 2E_x)^{1/2}}$$

g_a is a measure of the strength of the interaction $a \to c + x$

Note : the matrix element is only LI in the sense that it is defined in terms of LI wave-function normalisations and that the form of the coupling is LI

Note : in this "illustrative" example g is not dimensionless.

Similarly $\langle d|V|x+b\rangle = \frac{g_b}{(2E_b 2E_d 2E_x)^{1/2}}$



Giving $T_{fi}^{ab} = \frac{\langle d|V|x+b\rangle\langle c+x|V|a\rangle}{(E_a+E_b)-(E_c+E_x+E_b)}$

$$= \frac{1}{2E_x}\cdot\frac{1}{(2E_a 2E_b 2E_c 2E_d)^{1/2}}\cdot\frac{g_a g_b}{(E_a-E_c-E_x)}$$

★The "Lorentz Invariant" matrix element for the **entire** process is

$$M_{fi}^{ab} = (2E_a 2E_b 2E_c 2E_d)^{1/2} T_{fi}^{ab}$$

$$= \frac{1}{2E_x}\cdot\frac{g_a g_b}{(E_a-E_c-E_x)}$$

Note:

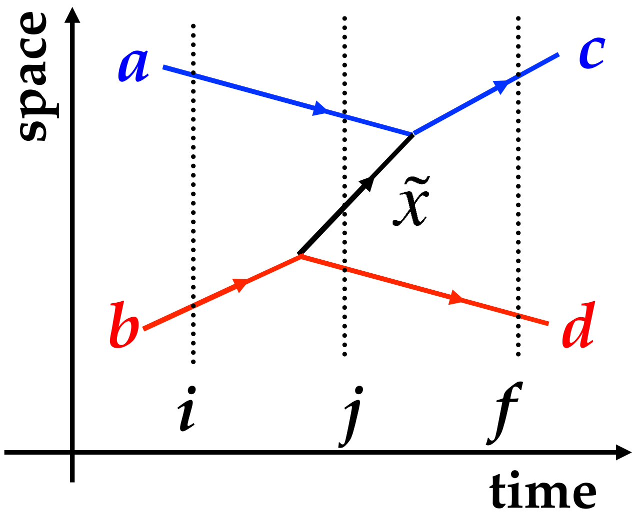
- M_{fi}^{ab} refers to the time-ordering where a emits x before b absorbs it

Momentum is conserved at each interaction vertex but not energy

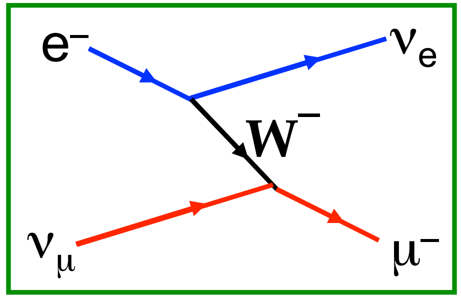
$E_j \neq E_i$

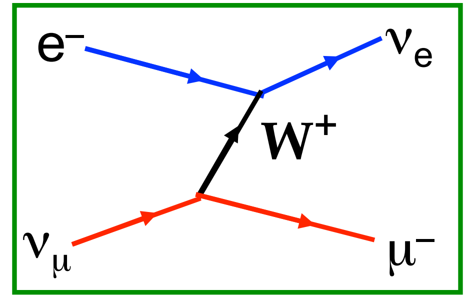
- Particle x is "on-mass shell" i.e. $E_x^2 = \vec{p}_x^{\,2} + m^2$

★ But need to consider also the other time ordering for the process



- This **time-ordered** diagram corresponds to b "emitting" $\tilde{x}$ and then a absorbing $\tilde{x}$
- $\tilde{x}$ is the anti-particle of x e.g.





- The **Lorentz invariant matrix element** for this time ordering is:

$$M_{fi}^{ba} = \frac{1}{2E_x} \cdot \frac{g_a g_b}{(E_b - E_d - E_x)}$$

★ In QM need to sum over matrix elements corresponding to same final state:

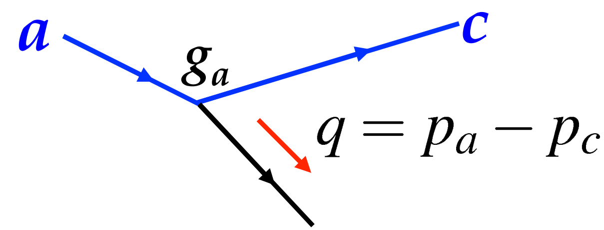
$$\begin{aligned} M_{fi} &= M_{fi}^{ab} + M_{fi}^{ba} \\ &= \frac{g_a g_b}{2E_x} \cdot \left(\frac{1}{E_a - E_c - E_x} + \frac{1}{E_b - E_d - E_x} \right) \\ &= \frac{g_a g_b}{2E_x} \cdot \left(\frac{1}{E_a - E_c - E_x} - \frac{1}{E_a - E_c + E_x} \right) \end{aligned}$$

Energy conservation: $(E_a + E_b = E_c + E_d)$

•Which gives
$$M_{fi} = \frac{g_a g_b}{2E_x} \cdot \frac{2E_x}{(E_a - E_c)^2 - E_x^2}$$
$$= \frac{g_a g_b}{(E_a - E_c)^2 - E_x^2}$$

•From 1st time ordering $E_x^2 = \vec{p}_x^{\,2} + m_x^2 = (\vec{p}_a - \vec{p}_c)^2 + m_x^2$

giving
$$M_{fi} = \frac{g_a g_b}{(E_a - E_c)^2 - (\vec{p}_a - \vec{p}_c)^2 - m_x^2}$$
$$= \frac{g_a g_b}{(p_a - p_c)^2 - m_x^2}$$



(end of non-examinable section)

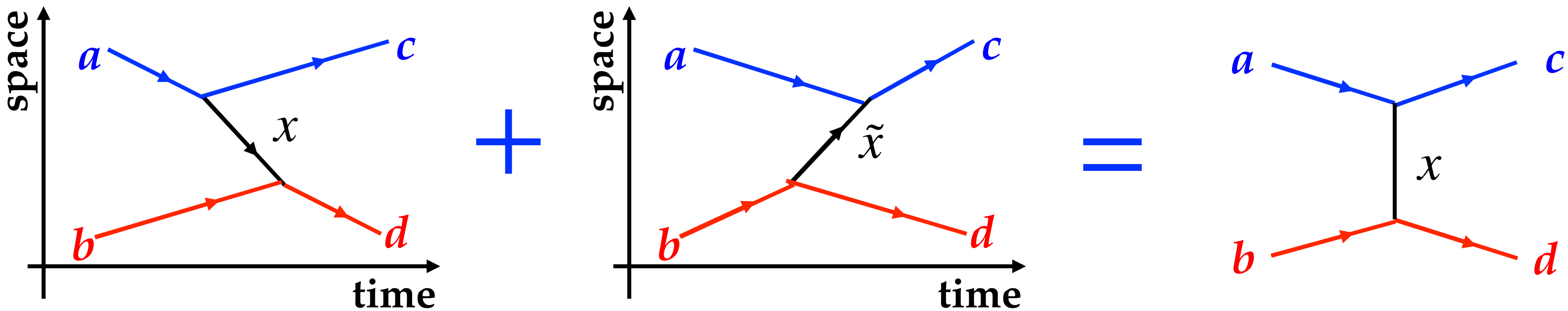
$$\Rightarrow \quad \boxed{M_{fi} = \frac{g_a g_b}{q^2 - m_x^2}}$$

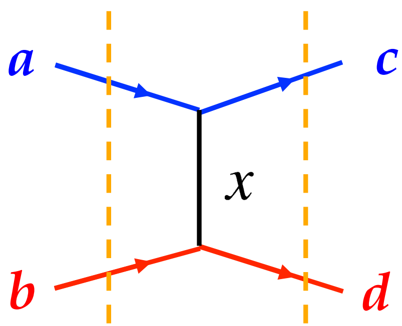
- After summing over all possible time orderings, M_{fi} is (as anticipated) Lorentz invariant. This is a remarkable result – the sum over all time orderings gives a frame independent matrix element.

•Exactly the same result would have been obtained by considering the annihilation process

Feynman Diagrams

- The sum over all possible time-orderings is represented by a **FEYNMAN diagram**





In a Feynman diagram:

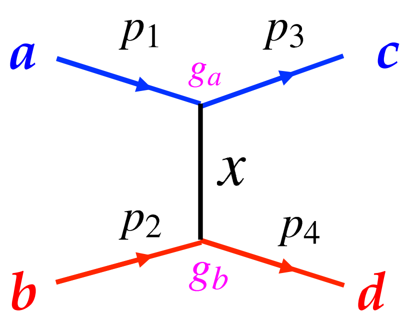
- the LHS represents the initial state
- the RHS is the final state
- everything in between is "how the interaction happened"

- It is important to remember that **energy and momentum** are conserved at each interaction vertex in the diagram.

- The factor $1/(q^2 - m_x^2)$ is the propagator; it arises naturally from the above discussion of interaction by particle exchange

★ **The matrix element:** $M_{fi} = \dfrac{g_a g_b}{q^2 - m_x^2}$ **depends on:**

- **The fundamental strength of the interaction at the two vertices** g_a, g_b
- **The four-momentum,** q **, carried by the (virtual) particle which is determined from energy/momentum conservation at the vertices. Note** q^2 **can be either positive or negative.**

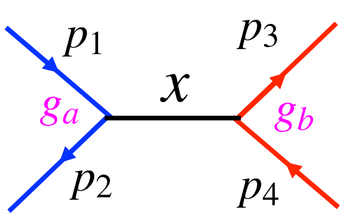


Here $q = p_1 - p_3 = p_4 - p_2 = t$ **"t-channel"**

For elastic scattering: $p_1 = (E, \vec{p}_1); \quad p_3 = (E, \vec{p}_3)$

$$q^2 = (E-E)^2 - (\vec{p}_1 - \vec{p}_3)^2$$

$q^2 < 0$ **termed "space-like"**



Here $q = p_1 + p_2 = p_3 + p_4 = s$ **"s-channel"**

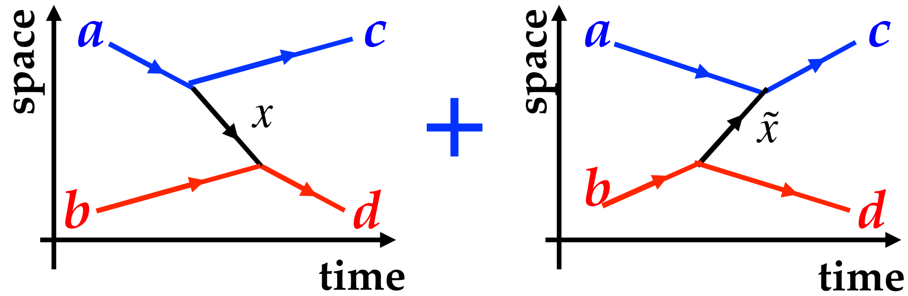
In CoM: $p_1 = (E, \vec{p}); \quad p_2 = (E, -\vec{p})$

$$q^2 = (E+E)^2 - (\vec{p} - \vec{p})^2 = 4E^2$$

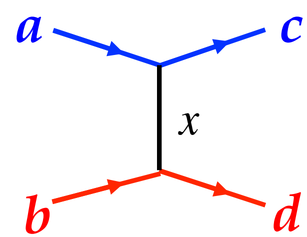
$q^2 > 0$ **termed "time-like"**

Virtual Particles

"Time-ordered QM"



Feynman diagram



$$M_{fi} = \frac{g_a g_b}{q^2 - m_x^2}$$

- Momentum conserved at vertices
- Energy **not** conserved at vertices
- Exchanged particle **"on mass shell"**

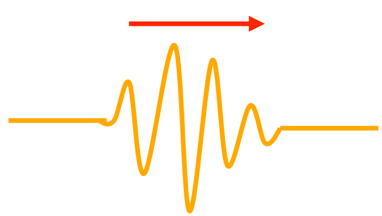
$$E_x^2 - |\vec{p}_x|^2 = m_x^2$$

- Momentum **AND** energy conserved at interaction vertices
- Exchanged particle **"off mass shell"**

$$E_x^2 - |\vec{p}_x|^2 = q^2 \neq m_x^2$$

VIRTUAL PARTICLE

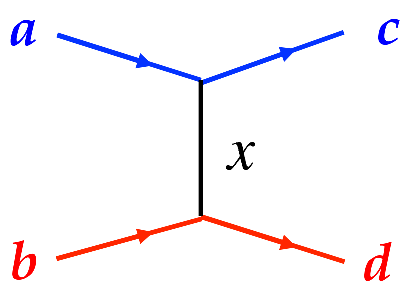
- Can think of observable "on mass shell" particles as propagating waves and unobservable virtual particles as normal modes between the source particles:



Aside: V(r) from Particle Exchange

★ Can view the scattering of an electron by a proton at rest in two ways:

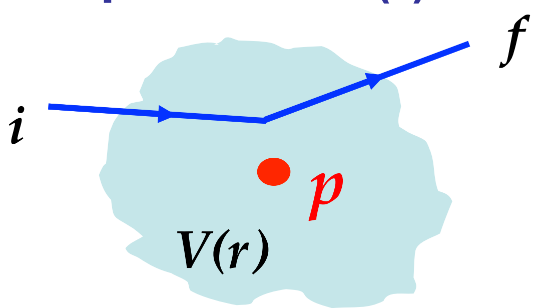
- Interaction by particle exchange in 2nd order perturbation theory.



$$M_{fi} = \frac{g_a g_b}{q^2 - m_x^2}$$

- Could also evaluate the same process in first order perturbation theory treating proton as a fixed source of a field which gives rise to a potential V(r)

$$M = \langle \psi_f | V(r) | \psi_i \rangle$$



Obtain same expression for M_{fi} using

$$V(r) = g_a g_b \frac{e^{-mr}}{r}$$

YUKAWA potential

★ In this way can relate potential and forces to the particle exchange picture

★ However, scattering from a fixed potential $V(r)$ is not a relativistic invariant view

Quantum Electrodynamics (QED)

★ Now consider the interaction of an electron and tau lepton by the exchange of a photon. Although the general ideas we applied previously still hold, we now have to account for the spin of the electron/tau-lepton and also the spin (polarization) of the virtual photon.

(Non-examinable)

• The basic interaction between a photon and a charged particle can be introduced by making the minimal substitution (part II electrodynamics)

$$\vec{p} \rightarrow \vec{p} - q\vec{A}; \quad E \rightarrow E - q\phi$$

(here $q =$ charge)

In QM:

$$\vec{p} = -i\vec{\nabla}; \quad E = i\partial/\partial t$$

Therefore make substitution: $i\partial_\mu \rightarrow i\partial_\mu - qA_\mu$

where $A_\mu = (\phi, -\vec{A}); \quad \partial_\mu = (\partial/\partial t, +\vec{\nabla})$

• The Dirac equation:

$$\gamma^\mu \partial_\mu \psi + im\psi = 0 \quad \Rightarrow \quad \gamma^\mu \partial_\mu \psi + iq\gamma^\mu A_\mu \psi + im\psi = 0$$

$$(\times i) \quad \Rightarrow \quad i\gamma^0 \frac{\partial \psi}{\partial t} + i\vec{\gamma}.\vec{\nabla}\psi - q\gamma^\mu A_\mu \psi - m\psi = 0$$

$$i\gamma^0\frac{\partial\psi}{\partial t} = \gamma^0\hat{H}\psi \quad = \quad m\psi - i\vec{\gamma}.\vec{\nabla}\psi + q\gamma^\mu A_\mu\psi$$

$$\times\gamma^0: \qquad \hat{H}\psi \quad = \quad \underbrace{(\gamma^0 m - i\gamma^0\vec{\gamma}.\vec{\nabla})}_{\text{Combined rest mass + K.E.}}\psi + \underbrace{q\gamma^0\gamma^\mu A_\mu}_{\text{Potential energy}}\psi$$

Combined rest mass + K.E.

Potential energy

- We can identify the potential energy of a charged spin-half particle in an electromagnetic field as:

$$\boxed{\hat{V}_D = q\gamma^0\gamma^\mu A_\mu}$$

(note the A_0 term is just: $q\gamma^0\gamma^0 A_0 = q\phi$)

- The final complication is that we have to account for the photon polarization states.

$$A_\mu = \varepsilon_\mu^{(\lambda)} e^{i(\vec{p}.\vec{r} - Et)}$$

e.g. for a real photon propagating in the z direction we have two orthogonal transverse polarization states

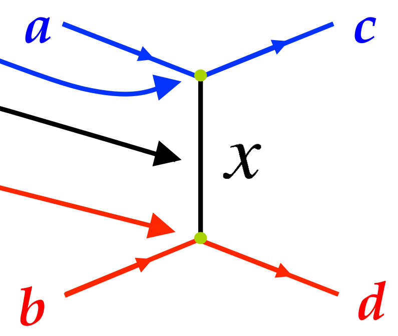
$$\varepsilon^{(1)} = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} \qquad \varepsilon^{(2)} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

Could equally have chosen circularly polarized states

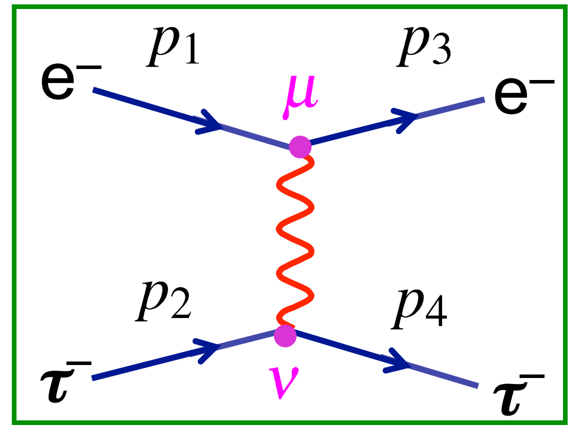
•Previously with the example of a simple spin-less interaction we had:

$$M = \langle \psi_c | V | \psi_a \rangle \frac{1}{q^2 - m_x^2} \langle \psi_d | V | \psi_b \rangle$$

$\langle \psi_c | V | \psi_a \rangle = g_a$, $\langle \psi_d | V | \psi_b \rangle = g_b$



★In QED we could again go through the procedure of summing the time-orderings using Dirac spinors and the expression for $\hat{V}_D$. If we were to do this, remembering to sum over all photon polarizations, we would obtain:



$$M = \left[u_e^\dagger(p_3) q_e \gamma^0 \gamma^\mu u_e(p_1)\right] \sum_\lambda \frac{\varepsilon_\mu^\lambda (\varepsilon_\nu^\lambda)^*}{q^2} \left[u_\tau^\dagger(p_4) q_\tau \gamma^0 \gamma^\nu u_\tau(p_2)\right]$$

Interaction of e^- with photon

Massless photon propagator summing over polarizations

Interaction of τ^- with photon

•All the physics of **QED** is in the above expression !

•The sum over the polarizations of the **VIRTUAL** photon has to include longitudinal and scalar contributions, i.e. 4 polarisation states

$$\varepsilon^{(0)} = \begin{pmatrix}1\\0\\0\\0\end{pmatrix} \quad \varepsilon^{(1)} = \begin{pmatrix}0\\1\\0\\0\end{pmatrix} \quad \varepsilon^{(2)} = \begin{pmatrix}0\\0\\1\\0\end{pmatrix} \quad \varepsilon^{(3)} = \begin{pmatrix}0\\0\\0\\1\end{pmatrix}$$

and gives:

$$\sum_\lambda \varepsilon^\lambda_\mu (\varepsilon^\lambda_\nu)^* = -g_{\mu\nu}$$

This is not obvious – for the moment just take it on trust

and the invariant matrix element becomes:

(end of non-examinable section)

$$M = [u_e^\dagger(p_3) q_e \gamma^0 \gamma^\mu u_e(p_1)] \frac{-g_{\mu\nu}}{q^2} [u_\tau^\dagger(p_4) q_\tau \gamma^0 \gamma^\nu u_\tau(p_2)]$$

•Using the definition of the adjoint spinor $\overline{\psi} = \psi^\dagger \gamma^0$

$$M = [\overline{u}_e(p_3) q_e \gamma^\mu u_e(p_1)] \frac{-g_{\mu\nu}}{q^2} [\overline{u}_\tau(p_4) q_\tau \gamma^\nu u_\tau(p_2)]$$

★ This is a remarkably simple expression ! It is shown in Appendix V of Handout 2 that $\overline{u}_1 \gamma^\mu u_2$ transforms as a four vector. Writing

$$j_e^\mu = \overline{u}_e(p_3) \gamma^\mu u_e(p_1) \qquad j_\tau^\nu = \overline{u}_\tau(p_4) \gamma^\nu u_\tau(p_2)$$

$$M = -q_e q_\tau \frac{j_e \cdot j_\tau}{q^2}$$

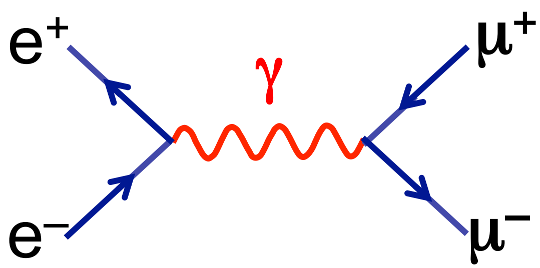
showing that M is **Lorentz Invariant**

Feynman Rules for QED

- It should be remembered that the expression

$$M = [\overline{u}_e(p_3) q_e \gamma^\mu u_e(p_1)] \frac{-g_{\mu\nu}}{q^2} [\overline{u}_\tau(p_4) q_\tau \gamma^\nu u_\tau(p_2)]$$

hides a lot of complexity. We have summed over all possible **time-orderings** and summed over all **polarization states** of the virtual photon. If we are then presented with a new Feynman diagram we don't want to go through the full calculation again. Fortunately this isn't necessary – can just write down matrix element using a set of simple rules



Basic Feynman Rules:

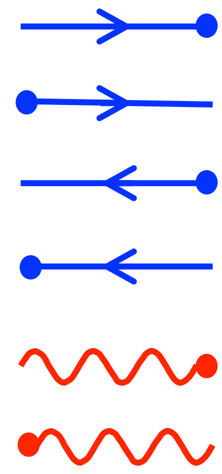
- Propagator factor for each internal line (i.e. each internal virtual particle)
- Dirac Spinor for each external line (i.e. each real incoming or outgoing particle)
- Vertex factor for each vertex

Basic Rules for QED

- **External Lines**

spin 1/2:
- incoming particle $u(p)$
- outgoing particle $\overline{u}(p)$
- incoming antiparticle $\overline{v}(p)$
- outgoing antiparticle $v(p)$

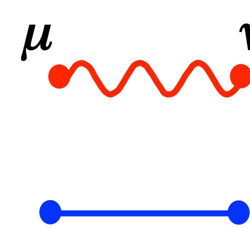
spin 1:
- incoming photon $\varepsilon^{\mu}(p)$
- outgoing photon $\varepsilon^{\mu}(p)^*$



- **Internal Lines (propagators)**

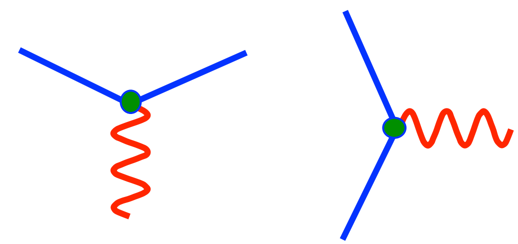
spin 1 photon $-\dfrac{ig_{\mu\nu}}{q^2}$

spin 1/2 fermion $\dfrac{i(\gamma^{\mu}q_{\mu}+m)}{q^2-m^2}$



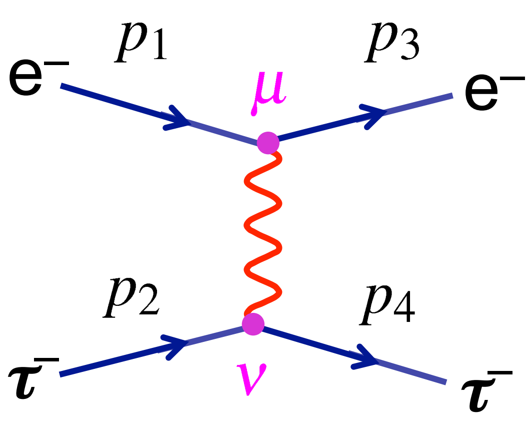
- **Vertex Factors**

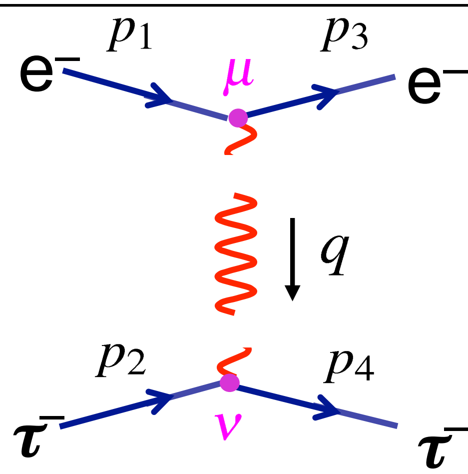
spin 1/2 fermion (charge -|e|) $ie\gamma^{\mu}$



- **Matrix Element** $-iM$ = product of all factors

e.g.





$$\overline{u}_e(p_3)[ie\gamma^\mu]u_e(p_1)$$

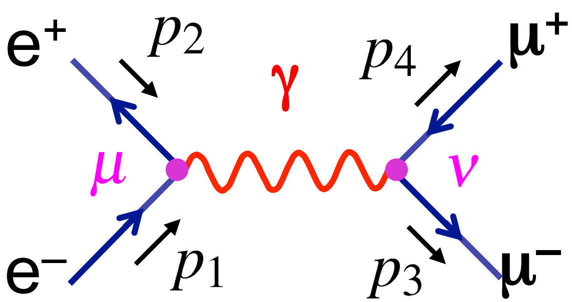
$$\frac{-ig_{\mu\nu}}{q^2}$$

$$\overline{u}_\tau(p_4)[ie\gamma^\nu]u_\tau(p_2)$$

$$-iM = [\overline{u}_e(p_3)ie\gamma^\mu u_e(p_1)]\frac{-ig_{\mu\nu}}{q^2}[\overline{u}_\tau(p_4)ie\gamma^\nu u_\tau(p_2)]$$

- **Which is the same expression as we obtained previously**

e.g.



$$-iM = [\overline{v}(p_2)ie\gamma^\mu u(p_1)]\frac{-ig_{\mu\nu}}{q^2}[\overline{u}(p_3)ie\gamma^\nu v(p_4)]$$

Note:
- **At each vertex the adjoint spinor is written first**
- **Each vertex has a different index**
- **The $g_{\mu\nu}$ of the propagator connects the indices at the vertices**

Summary

★ Interaction by particle exchange naturally gives rise to **Lorentz Invariant Matrix Element** of the form

$$M_{fi} = \frac{g_a g_b}{q^2 - m_x^2}$$

★ Derived the basic interaction in **QED** taking into account the spins of the fermions and polarization of the virtual photons:

$$-iM = [\overline{u}(p_3) ie\gamma^\mu u(p_1)] \frac{-ig_{\mu\nu}}{q^2} [\overline{u}(p_4) ie\gamma^\nu u(p_2)]$$

★ **We now have all the elements to perform proper calculations in QED !**