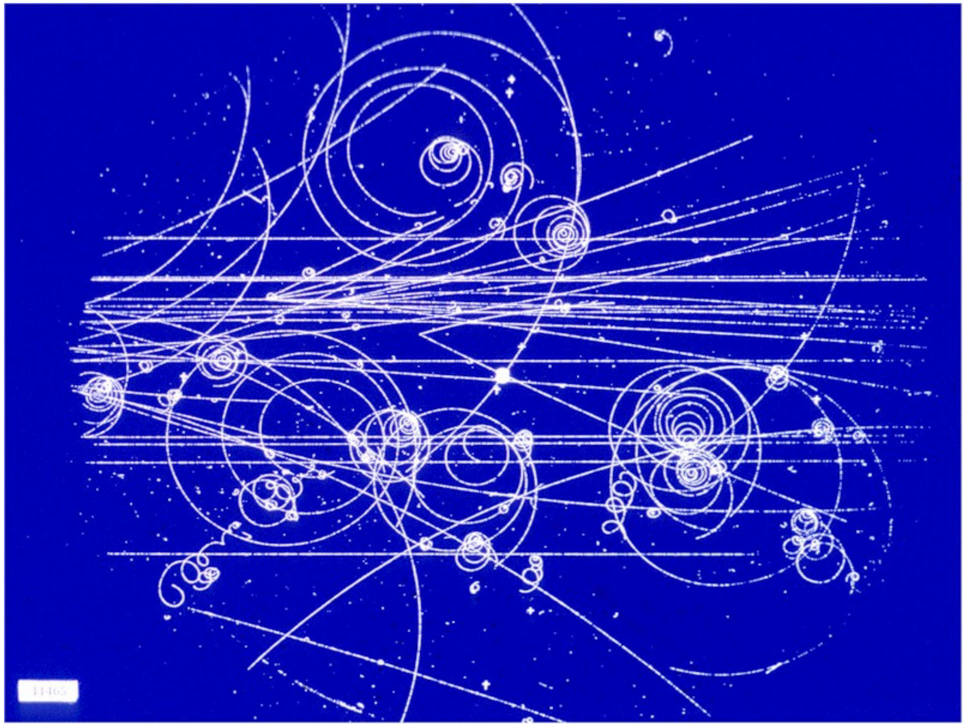
Particle Physics

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



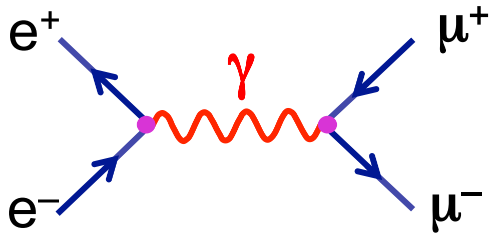
Handout 4 : Electron-Positron Annihilation

QED Calculations

- **How to calculate a cross section using QED (e.g. $e^+e^- \to \mu^+\mu^-$):**

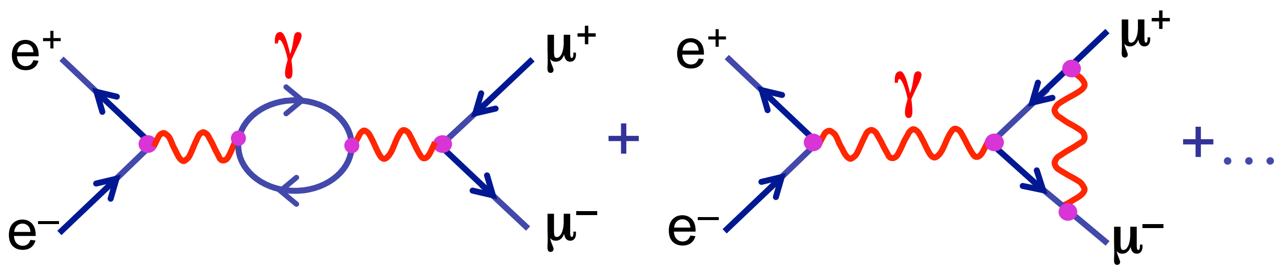
❶ **Draw all possible Feynman Diagrams**

- **For $e^+e^- \to \mu^+\mu^-$ there is just one lowest order diagram**



$$M \propto e^2 \propto \alpha_{em}$$

+ many second order diagrams + …



$$M \propto e^4 \propto \alpha_{em}^2$$

❷ **For each diagram calculate the matrix element using Feynman rules derived in handout 4.**

❸ **Sum the individual matrix elements (i.e. sum the amplitudes)**

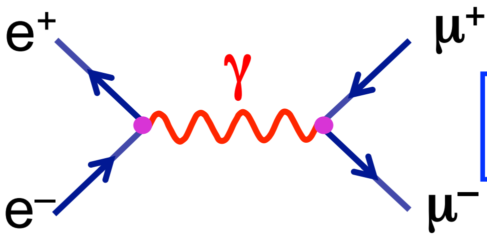
$$M_{fi} = M_1 + M_2 + M_3 + \ldots.$$

- **Note: summing amplitudes therefore different diagrams for the same final state can interfere either positively or negatively!**

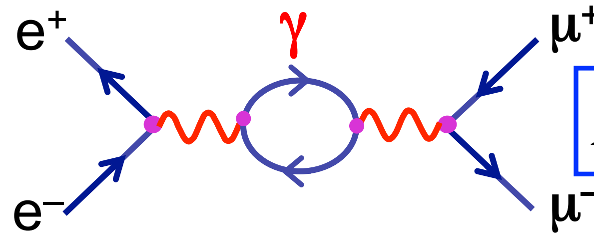
and then square $|M_{fi}|^2 = (M_1 + M_2 + M_3 + \dots)(M_1^* + M_2^* + M_3^* + \dots)$

➡ this gives the full perturbation expansion in α_{em}

- For QED $\alpha_{em} \sim 1/137$ the lowest order diagram dominates and for most purposes it is sufficient to **neglect** higher order diagrams.



$M^2 \propto \alpha_{em}^2$

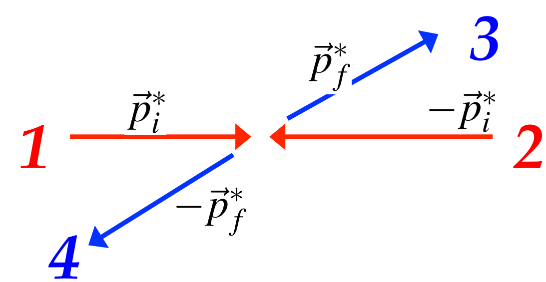


$M^2 \propto \alpha_{em}^4$

❹ Calculate decay rate/cross section using formulae from handout 1.

- e.g. for a decay

$$\Gamma = \frac{p^*}{32\pi^2 m_a^2} \int |M_{fi}|^2 d\Omega$$



(1)

- For scattering in the centre-of-mass frame

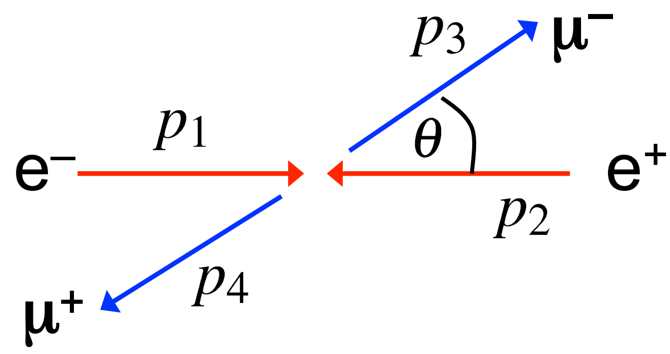
$$\frac{d\sigma}{d\Omega^*} = \frac{1}{64\pi^2 s} \frac{|\vec{p}_f^*|}{|\vec{p}_i^*|} |M_{fi}|^2$$

- For scattering in lab. frame (neglecting mass of scattered particle)

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} \left(\frac{E_3}{ME_1}\right)^2 |M_{fi}|^2$$

Electron Positron Annihilation

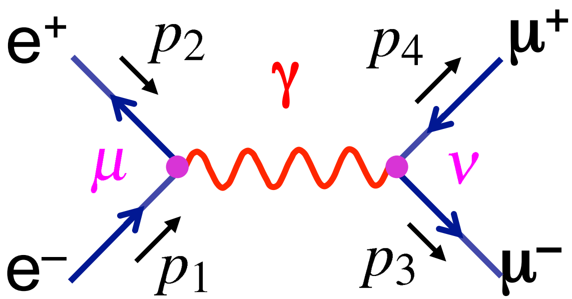
★ **Consider the process:** $e^+e^- \to \mu^+\mu^-$



- **Work in C.o.M. frame (this is appropriate for most e^+e^- colliders).**

$$p_1 = (E,0,0,p) \qquad p_2 = (E,0,0,-p)$$
$$p_3 = (E,\vec{p}_f) \qquad p_4 = (E,-\vec{p}_f)$$

- **Only consider the lowest order Feynman diagram:**



♦ **Feynman rules give:**

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

NOTE:
- **Incoming anti-particle** $\overline{v}$
- **Incoming particle** u
- **Adjoint spinor written first**

- **In the C.o.M. frame have**

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\frac{|\vec{p}_f|}{|\vec{p}_i|}|M_{fi}|^2 \qquad \textbf{with} \qquad s = (p_1+p_2)^2 = (E+E)^2 = 4E^2$$

Electron and Muon Currents

- Here $q^2=(p_1+p_2)^2=s$ and matrix element

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

➡ $$M=-\frac{e^2}{s}g_{\mu\nu}[\overline{v}(p_2)\gamma^\mu u(p_1)][\overline{u}(p_3)\gamma^\nu v(p_4)]$$

- In handout 2 introduced the **four-vector** current

$$j^\mu=\overline{\psi}\gamma^\mu\psi$$

which has same form as the two terms in [ ] in the matrix element

- The matrix element can be written in terms of the electron and muon currents

$$(j_e)^\mu=\overline{v}(p_2)\gamma^\mu u(p_1) \quad \text{and} \quad (j_\mu)^\nu=\overline{u}(p_3)\gamma^\nu v(p_4)$$

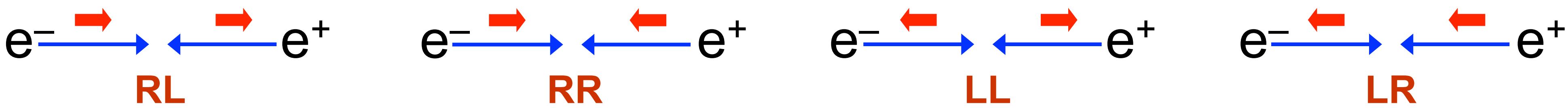
➡ $$M=-\frac{e^2}{s}g_{\mu\nu}(j_e)^\mu(j_\mu)^\nu$$

$$\boxed{M=-\frac{e^2}{s}j_e.j_\mu}$$

- Matrix element is a four-vector scalar product – confirming it is **Lorentz Invariant**

Spin in e^+e^- Annihilation

- In general the electron and positron will not be polarized, i.e. there will be equal numbers of positive and negative helicity states
- There are four possible combinations of spins in the **initial state** !



- Similarly there are four possible helicity combinations in the final state
- In total there are **16** combinations e.g. **RL→RR, RL→RL, ….**
- To account for these states we need to **sum** over **all 16 possible helicity** combinations and then **average** over the number of **initial helicity states**:

$$\langle|M|^2\rangle = \frac{1}{4}\sum_{\text{spins}}|M_i|^2 = \frac{1}{4}\left(|M_{LL\rightarrow LL}|^2 + |M_{LL\rightarrow LR}|^2 + \ldots\right)$$

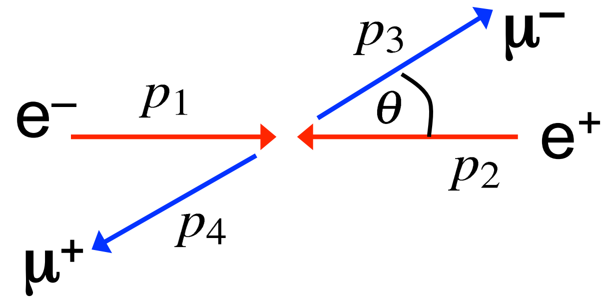
★ i.e. need to evaluate:

$$M = -\frac{e^2}{s}j_e.j_\mu$$

for all 16 helicity combinations !

★ Fortunately, in the limit $E \gg m_\mu$ only 4 helicity combinations give non-zero matrix elements – we will see that this is an important feature of QED/QCD

•In the C.o.M. frame in the limit $E \gg m$



$$p_1 = (E,0,0,E); \quad p_2 = (E,0,0,-E)$$
$$p_3 = (E, E\sin\theta, 0, E\cos\theta);$$
$$p_4 = (E, -\sin\theta, 0, -E\cos\theta)$$

•Left- and right-handed helicity spinors (handout 3) for particles/anti-particles are:

$$u_\uparrow = N\begin{pmatrix} c \\ e^{i\phi}s \\ \frac{|\vec{p}|}{E+m}c \\ \frac{|\vec{p}|}{E+m}e^{i\phi}s \end{pmatrix} \quad u_\downarrow = N\begin{pmatrix} -s \\ e^{i\phi}c \\ \frac{|\vec{p}|}{E+m}s \\ -\frac{|\vec{p}|}{E+m}e^{i\phi}c \end{pmatrix} \quad v_\uparrow = N\begin{pmatrix} \frac{|\vec{p}|}{E+m}s \\ -\frac{|\vec{p}|}{E+m}e^{i\phi}c \\ -s \\ e^{i\phi}c \end{pmatrix} \quad v_\downarrow = N\begin{pmatrix} \frac{|\vec{p}|}{E+m}c \\ \frac{|\vec{p}|}{E+m}e^{i\phi}s \\ c \\ e^{i\phi}s \end{pmatrix}$$

where $s = \sin\frac{\theta}{2}$; $c = \cos\frac{\theta}{2}$ and $N = \sqrt{E+m}$

•In the limit $E \gg m$ these become:

$$u_\uparrow = \sqrt{E}\begin{pmatrix} c \\ se^{i\phi} \\ c \\ se^{i\phi} \end{pmatrix}; \; u_\downarrow = \sqrt{E}\begin{pmatrix} -s \\ ce^{i\phi} \\ s \\ -ce^{i\phi} \end{pmatrix}; \; v_\uparrow = \sqrt{E}\begin{pmatrix} s \\ -ce^{i\phi} \\ -s \\ ce^{i\phi} \end{pmatrix}; \; v_\downarrow = \sqrt{E}\begin{pmatrix} c \\ se^{i\phi} \\ c \\ se^{i\phi} \end{pmatrix}$$

•The initial-state electron can either be in a left- or right-handed helicity state

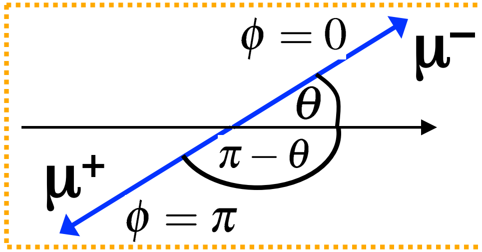
$$u_\uparrow(p_1) = \sqrt{E}\begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}; \; u_\downarrow(p_1) = \sqrt{E}\begin{pmatrix} 0 \\ 1 \\ 0 \\ -1 \end{pmatrix};$$

- For the initial state positron $(\theta = \pi)$ can have either:

$$v_\uparrow(p_2) = \sqrt{E}\begin{pmatrix}1\\0\\-1\\0\end{pmatrix};\ v_\downarrow(p_2) = \sqrt{E}\begin{pmatrix}0\\1\\0\\1\end{pmatrix}$$

- Similarly for the final state μ^- which has polar angle θ and choosing $\phi = 0$

$$u_\uparrow(p_3) = \sqrt{E}\begin{pmatrix}c\\s\\c\\s\end{pmatrix};\ u_\downarrow(p_3) = \sqrt{E}\begin{pmatrix}-s\\c\\s\\-c\end{pmatrix};$$



- And for the final state μ^+ replacing $\theta \rightarrow \pi - \theta;\quad \phi \rightarrow \pi$ obtain

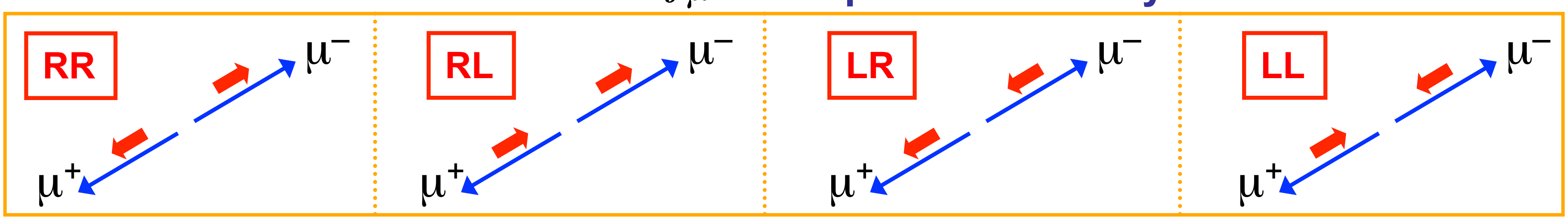
$$v_\uparrow(p_4) = \sqrt{E}\begin{pmatrix}c\\s\\-c\\-s\end{pmatrix};\ v_\downarrow(p_4) = \sqrt{E}\begin{pmatrix}s\\-c\\s\\-c\end{pmatrix};$$

using

$$\sin\left(\tfrac{\pi-\theta}{2}\right) = \cos\tfrac{\theta}{2}$$
$$\cos\left(\tfrac{\pi-\theta}{2}\right) = \sin\tfrac{\theta}{2}$$
$$e^{i\pi} = -1$$

- Wish to calculate the matrix element $M = -\frac{e^2}{s} j_e . j_\mu$

★ first consider the muon current j_μ for 4 possible helicity combinations



The Muon Current

- Want to evaluate $(j_\mu)^\nu = \overline{u}(p_3)\gamma^\nu v(p_4)$ for all four helicity combinations
- For arbitrary spinors $\psi,\ \phi$ with it is straightforward to show that the components of $\overline{\psi}\gamma^\mu\phi$ are

$$\overline{\psi}\gamma^0\phi = \psi^\dagger\gamma^0\gamma^0\phi = \psi_1^*\phi_1 + \psi_2^*\phi_2 + \psi_3^*\phi_3 + \psi_4^*\phi_4 \quad (3)$$

$$\overline{\psi}\gamma^1\phi = \psi^\dagger\gamma^0\gamma^1\phi = \psi_1^*\phi_4 + \psi_2^*\phi_3 + \psi_3^*\phi_2 + \psi_4^*\phi_1 \quad (4)$$

$$\overline{\psi}\gamma^2\phi = \psi^\dagger\gamma^0\gamma^2\phi = -i(\psi_1^*\phi_4 - \psi_2^*\phi_3 + \psi_3^*\phi_2 - \psi_4^*\phi_1) \quad (5)$$

$$\overline{\psi}\gamma^3\phi = \psi^\dagger\gamma^0\gamma^3\phi = \psi_1^*\phi_3 - \psi_2^*\phi_4 + \psi_3^*\phi_1 - \psi_4^*\phi_2 \quad (6)$$

- Consider the $\mu_R^-\mu_L^+$ combination using $\psi = u_\uparrow \quad \phi = v_\downarrow$

with $v_\downarrow = \sqrt{E}\begin{pmatrix} s \\ -c \\ s \\ -c \end{pmatrix};\ u_\uparrow = \sqrt{E}\begin{pmatrix} c \\ s \\ c \\ s \end{pmatrix};$

$$\overline{u}_\uparrow(p_3)\gamma^0 v_\downarrow(p_4) = E(cs - sc + cs - sc) = 0$$

$$\overline{u}_\uparrow(p_3)\gamma^1 v_\downarrow(p_4) = E(-c^2 + s^2 - c^2 + s^2) = 2E(s^2 - c^2) = -2E\cos\theta$$

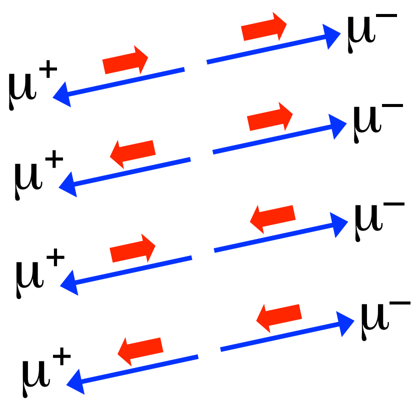
$$\overline{u}_\uparrow(p_3)\gamma^2 v_\downarrow(p_4) = -iE(-c^2 - s^2 - c^2 - s^2) = 2iE$$

$$\overline{u}_\uparrow(p_3)\gamma^3 v_\downarrow(p_4) = E(cs + sc + cs + sc) = 4Esc = 2E\sin\theta$$

- Hence the four-vector muon current for the **RL** combination is

$$\bar{u}_{\uparrow}(p_3)\gamma^{\nu}v_{\downarrow}(p_4) \quad = \quad 2E(0,-\cos\theta,i,\sin\theta)$$

- The results for the 4 helicity combinations (obtained in the same manner) are:



$$\begin{aligned}
\bar{u}_{\uparrow}(p_3)\gamma^{\nu}v_{\downarrow}(p_4) &= 2E(0,-\cos\theta,i,\sin\theta) \\
\bar{u}_{\uparrow}(p_3)\gamma^{\nu}v_{\uparrow}(p_4) &= (0,0,0,0) \\
\bar{u}_{\downarrow}(p_3)\gamma^{\nu}v_{\downarrow}(p_4) &= (0,0,0,0) \\
\bar{u}_{\downarrow}(p_3)\gamma^{\nu}v_{\uparrow}(p_4) &= 2E(0,-\cos\theta,-i,\sin\theta)
\end{aligned}$$

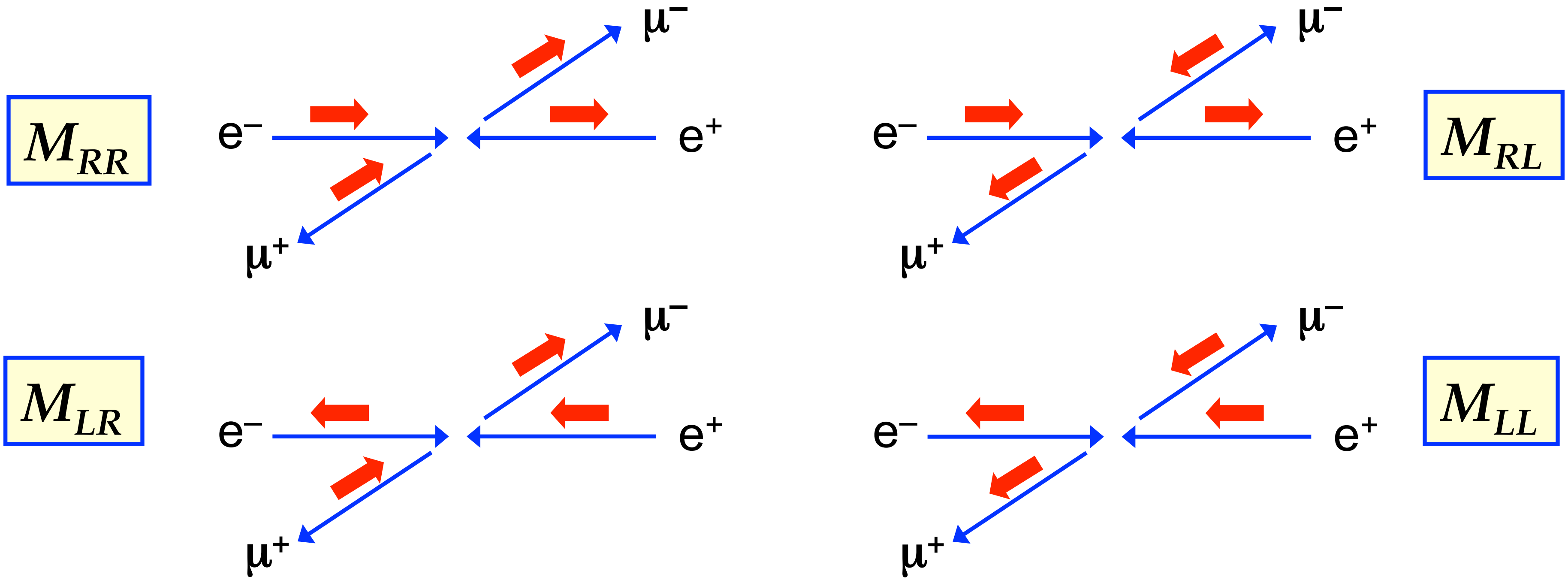
RL
RR
LL
LR

★ **IN THE LIMIT** $E \gg m$ **only two helicity combinations are non-zero !**

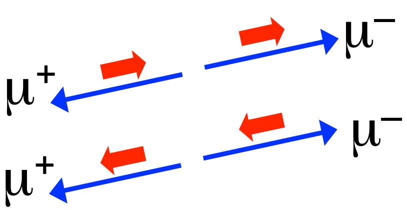
- This is an important feature of QED. It applies equally to QCD.
- In the Weak interaction only one helicity combination contributes.
- The origin of this will be discussed in the last part of this lecture
- But as a consequence of the 16 possible helicity combinations only four given non-zero matrix elements

Electron Positron Annihilation cont.

★ For $e^+e^- \rightarrow \mu^+\mu^-$ now only have to consider the 4 matrix elements:



•Previously we derived the muon currents for the allowed helicities:



$$\mu_R^-\mu_L^+ \; : \quad \bar{u}_\uparrow(p_3)\gamma^\nu v_\downarrow(p_4) = 2E(0,-\cos\theta,i,\sin\theta)$$
$$\mu_L^-\mu_R^+ \; : \quad \bar{u}_\downarrow(p_3)\gamma^\nu v_\uparrow(p_4) = 2E(0,-\cos\theta,-i,\sin\theta)$$

•Now need to consider the electron current

The Electron Current

- The incoming electron and positron spinors (L and R helicities) are:

$$u_\uparrow = \sqrt{E}\begin{pmatrix}1\\0\\1\\0\end{pmatrix};\ u_\downarrow = \sqrt{E}\begin{pmatrix}0\\1\\0\\-1\end{pmatrix};\qquad v_\uparrow = \sqrt{E}\begin{pmatrix}1\\0\\-1\\0\end{pmatrix};\ v_\downarrow = \sqrt{E}\begin{pmatrix}0\\1\\0\\1\end{pmatrix}$$

- The electron current can either be obtained from equations (3)-(6) as before or it can be obtained directly from the expressions for the muon current.

$$(j_e)^\mu = \overline{v}(p_2)\gamma^\mu u(p_1) \qquad\qquad (j_\mu)^\mu = \overline{u}(p_3)\gamma^\mu v(p_4)$$

- Taking the Hermitian conjugate of the muon current gives

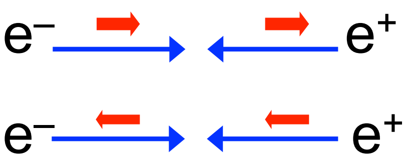
$$\begin{aligned}
[\overline{u}(p_3)\gamma^\mu v(p_4)]^\dagger &= \left[u(p_3)^\dagger\gamma^0\gamma^\mu v(p_4)\right]^\dagger \\
&= v(p_4)^\dagger\gamma^{\mu\dagger}\gamma^{0\dagger}u(p_3) && (AB)^\dagger = B^\dagger A^\dagger \\
&= v(p_4)^\dagger\gamma^{\mu\dagger}\gamma^0 u(p_3) && \gamma^{0\dagger} = \gamma^0 \\
&= v(p_4)^\dagger\gamma^0\gamma^\mu u(p_3) && \gamma^{\mu\dagger}\gamma^0 = \gamma^0\gamma^\mu \\
&= \overline{v}(p_4)\gamma^\mu u(p_3)
\end{aligned}$$

- Taking the complex conjugate of the muon currents for the two non-zero helicity configurations:

$$\bar{v}_\downarrow(p_4)\gamma^\mu u_\uparrow(p_3) \quad = \quad \left[\bar{u}_\uparrow(p_3)\gamma^\nu v_\downarrow(p_4)\right]^* = 2E(0,-\cos\theta,-i,\sin\theta)$$

$$\bar{v}_\uparrow(p_4)\gamma^\mu u_\downarrow(p_3) \quad = \quad \left[\bar{u}_\downarrow(p_3)\gamma^\nu v_\uparrow(p_4)\right]^* = 2E(0,-\cos\theta,i,\sin\theta)$$

To obtain the electron currents we simply need to set $\theta = 0$



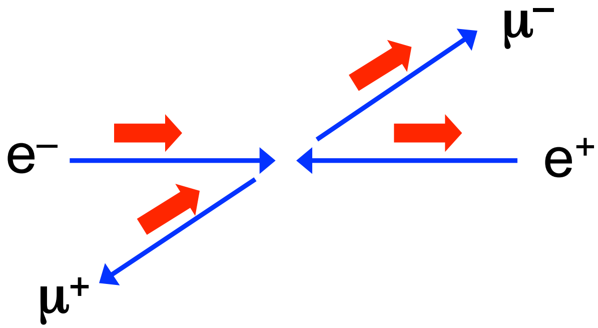
$$e^-_R e^+_L \; : \quad \bar{v}_\downarrow(p_2)\gamma^\nu u_\uparrow(p_1) \quad = \quad 2E(0,-1,-i,0)$$

$$e^-_L e^+_R \; : \quad \bar{v}_\uparrow(p_2)\gamma^\nu u_\downarrow(p_1) \quad = \quad 2E(0,-1,i,0)$$

Matrix Element Calculation

•We can now calculate $M = -\frac{e^2}{s} j_e . j_\mu$ for the four possible helicity combinations.

e.g. the matrix element for $e^-_R e^+_L \rightarrow \mu^-_R \mu^+_L$ which will denote M_{RR}



Here the first subscript refers to the helicity of the e⁻ and the second to the helicity of the μ⁻. Don't need to specify other helicities due to "helicity conservation", only certain chiral combinations are non-zero.

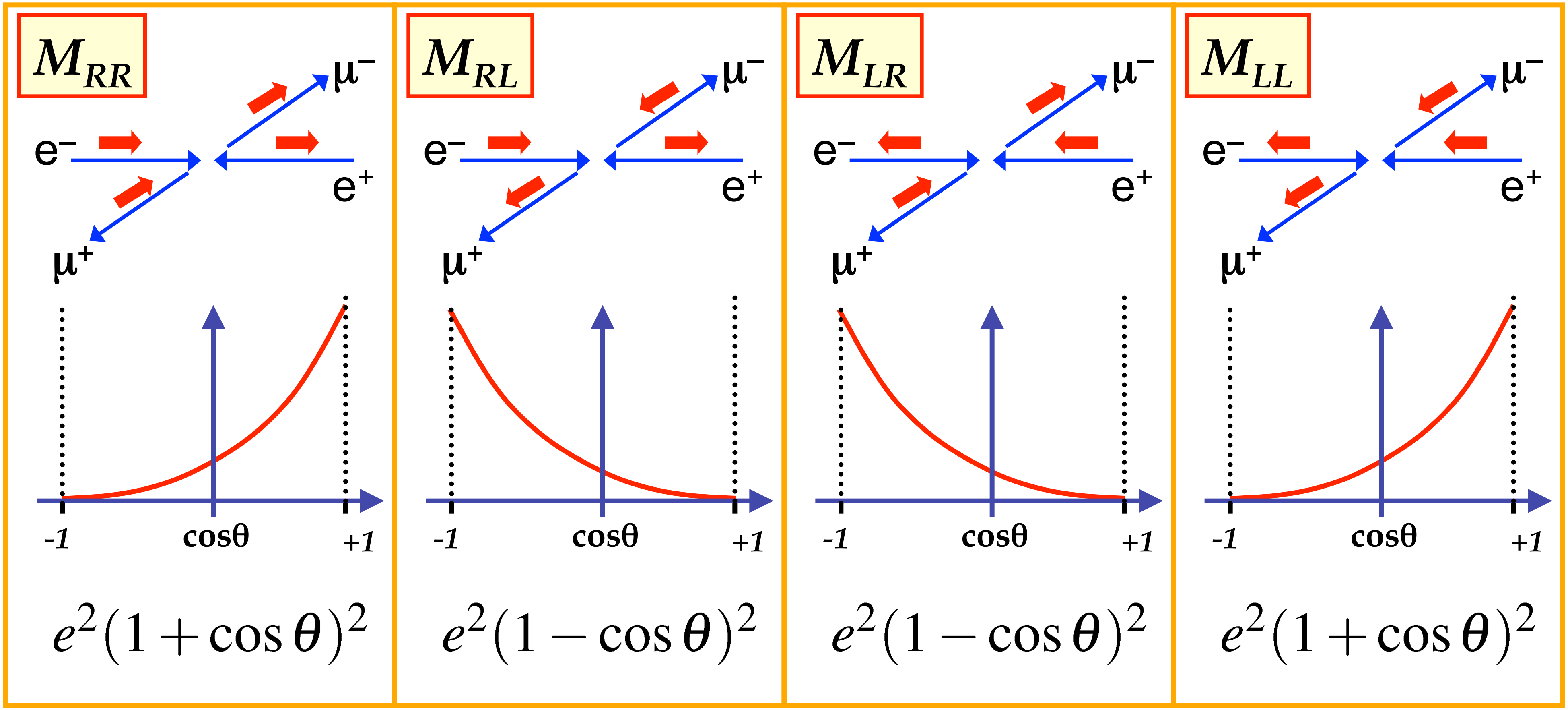
★Using: $e^-_R e^+_L$: $(j_e)^\mu = \overline{v}_\downarrow(p_2)\gamma^\mu u_\uparrow(p_1) = 2E(0,-1,-i,0)$

$\mu^-_R \mu^+_L$: $(j_\mu)^\nu = \overline{u}_\uparrow(p_3)\gamma^\nu v_\downarrow(p_4) = 2E(0,-\cos\theta,i,\sin\theta)$

gives
$$
\begin{aligned}
M_{RR} &= -\frac{e^2}{s}[2E(0,-1,-i,0)].[2E(0,-\cos\theta,i,\sin\theta)] \\
&= -e^2(1+\cos\theta) \\
&= -4\pi\alpha(1+\cos\theta)
\end{aligned}
$$
where $\alpha = e^2/4\pi \approx 1/137$

Similarly

$$|M_{RR}|^2 = |M_{LL}|^2 = (4\pi\alpha)^2(1+\cos\theta)^2$$
$$|M_{RL}|^2 = |M_{LR}|^2 = (4\pi\alpha)^2(1-\cos\theta)^2$$



- **Assuming that the incoming electrons and positrons are unpolarized, all 4 possible initial helicity states are equally likely.**

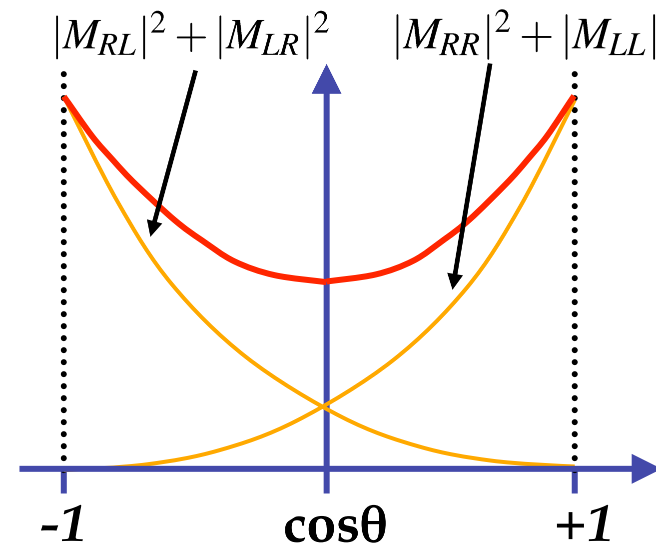
Differential Cross Section

- The cross section is obtained by averaging over the initial spin states and summing over the final spin states:

$$\frac{d\sigma}{d\Omega} = \frac{1}{4} \times \frac{1}{64\pi^2 s}\left(|M_{RR}|^2 + |M_{RL}|^2 + |M_{LR}|^2 + |M_{LL}^2|\right)$$

$$= \frac{(4\pi\alpha)^2}{256\pi^2 s}\left(2(1+\cos\theta)^2 + 2(1-\cos\theta)^2\right)$$

$$\Rightarrow \quad \boxed{\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}(1+\cos^2\theta)}$$

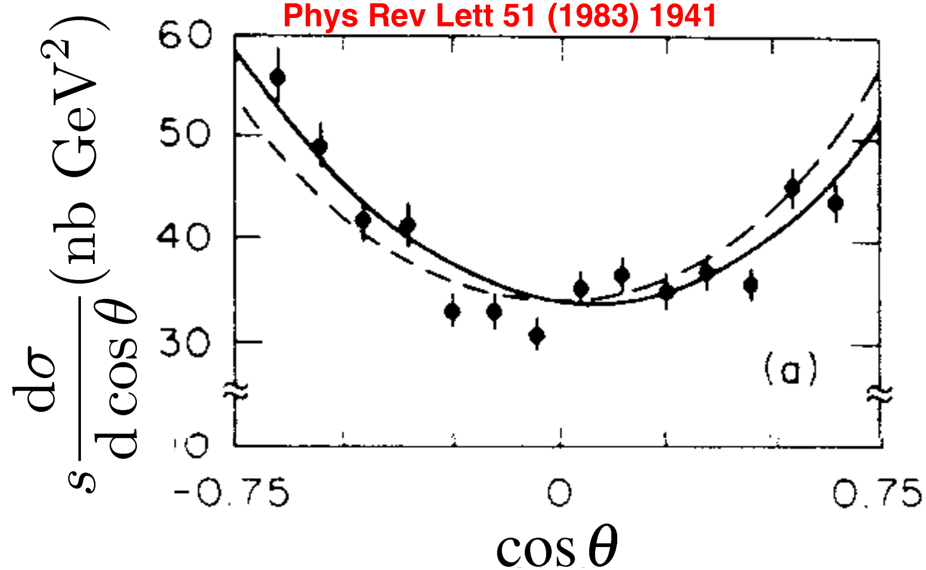


Example:

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

$\sqrt{s} = 29$ GeV

Mark II Expt., M.E.Levi et al., Phys Rev Lett 51 (1983) 1941



- - - - - pure QED, $O(\alpha^3)$

——— QED plus Z contribution

Angular distribution becomes slightly asymmetric in higher order QED or when Z contribution is included

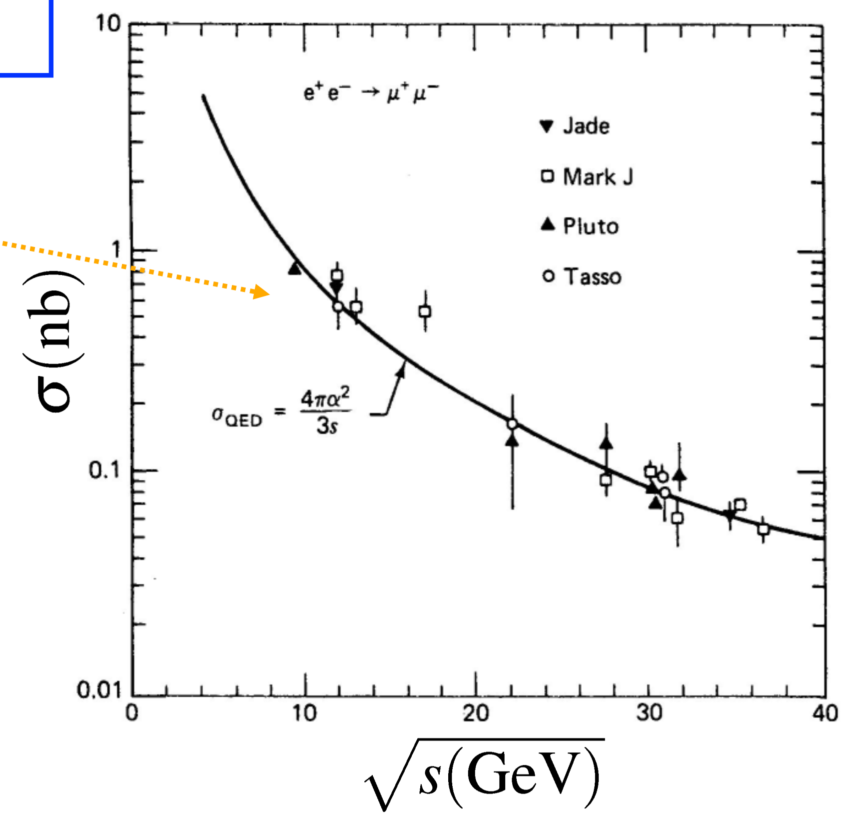
- The total cross section is obtained by integrating over θ, ϕ using

$$\int (1+\cos^2\theta)\mathrm{d}\Omega = 2\pi \int_{-1}^{+1} (1+\cos^2\theta)\,\mathrm{d}\cos\theta = \frac{16\pi}{3}$$

giving the **QED** total cross-section for the process $e^+e^- \to \mu^+\mu^-$

$$\sigma = \frac{4\pi\alpha^2}{3s}$$

★ Lowest order cross section calculation provides a good description of the data **!**



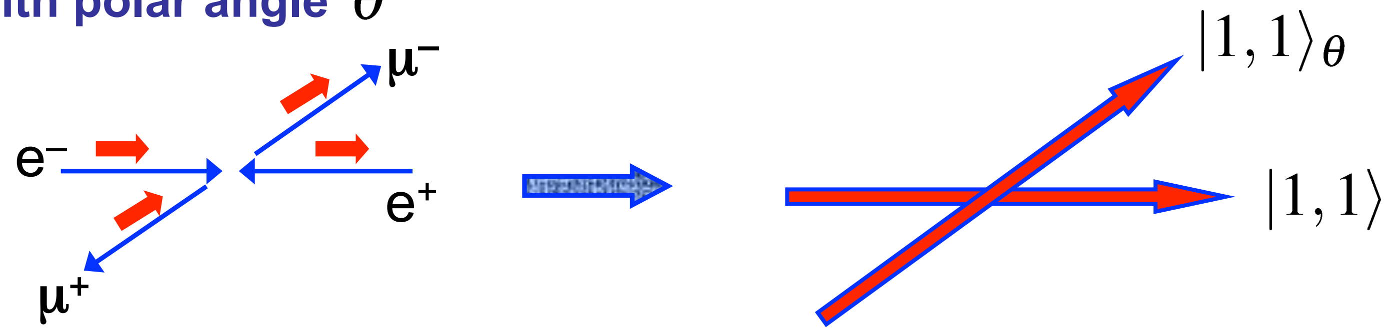
This is an impressive result. From first principles we have arrived at an expression for the electron-positron annihilation cross section which is good to **1%**

Spin Considerations $(E \gg m)$

★ The angular dependence of the QED electron-positron matrix elements can be understood in terms of angular momentum

- Because of the allowed helicity states, the electron and positron interact in a spin state with $S_z = \pm 1$, i.e. in a total spin 1 state aligned along the z axis: $|1,+1\rangle$ or $|1,-1\rangle$
- Similarly the muon and anti-muon are produced in a total spin 1 state aligned along an axis with polar angle θ

e.g. M_{RR}



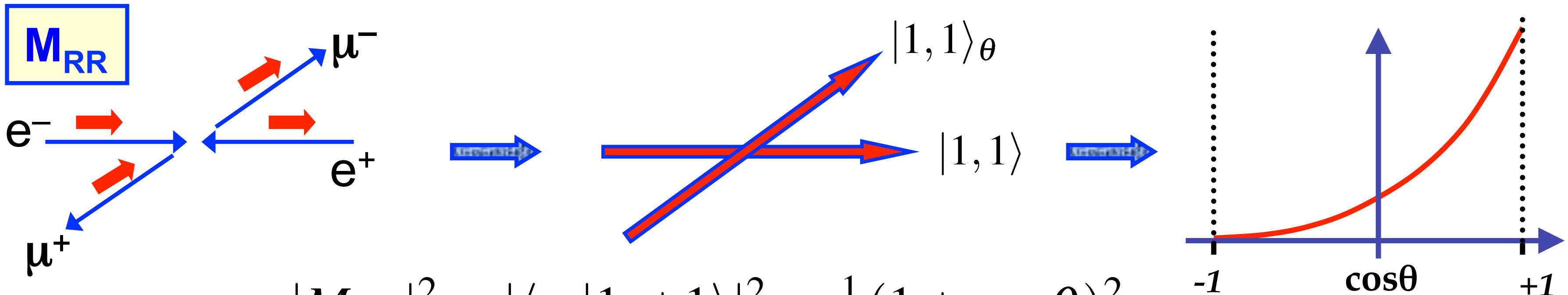
- Hence $M_{RR} \propto \langle\psi|1,1\rangle$ where ψ corresponds to the spin state, $|1,1\rangle_\theta$, of the muon pair.
- To evaluate this need to express $|1,1\rangle_\theta$ in terms of eigenstates of S_z
- In the appendix (and also in IB QM) it is shown that:

$$|1,1\rangle_\theta = \tfrac{1}{2}(1-\cos\theta)|1,-1\rangle + \tfrac{1}{\sqrt{2}}\sin\theta|1,0\rangle + \tfrac{1}{2}(1+\cos\theta)|1,+1\rangle$$

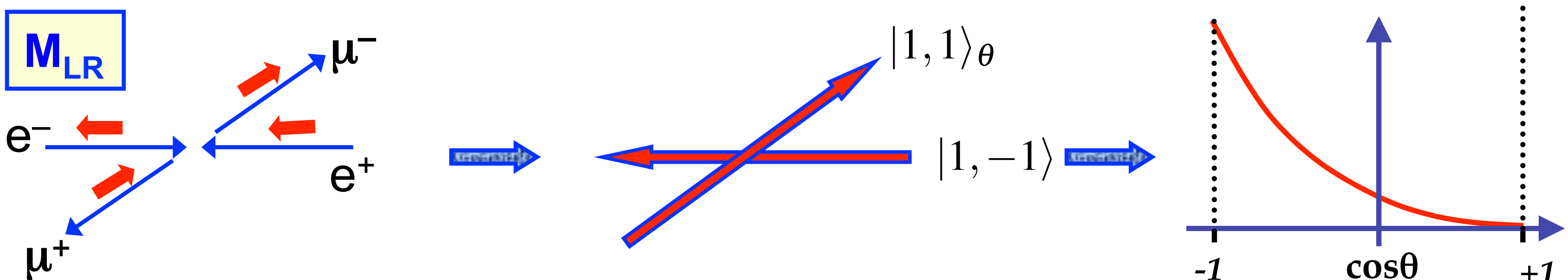
- Using the wave-function for a spin 1 state along an axis at angle θ

$$\psi = |1,1\rangle_\theta = \tfrac{1}{2}(1-\cos\theta)|1,-1\rangle + \tfrac{1}{\sqrt{2}}\sin\theta|1,0\rangle + \tfrac{1}{2}(1+\cos\theta)|1,+1\rangle$$

can immediately understand the angular dependence



$$|M_{RR}|^2 \propto |\langle\psi|1,+1\rangle|^2 = \tfrac{1}{4}(1+\cos\theta)^2$$

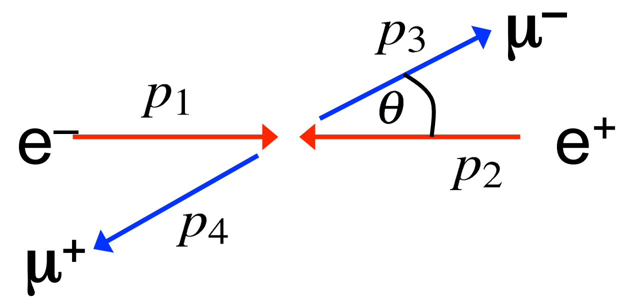


$$|M_{LR}|^2 \propto |\langle\psi|1,-1\rangle|^2 = \tfrac{1}{4}(1-\cos\theta)^2$$

Lorentz Invariant form of Matrix Element

- Before concluding this discussion, note that the spin-averaged Matrix Element derived above is written in terms of the muon angle in the C.o.M. frame.

$$\begin{aligned}\langle|M_{fi}|^2\rangle &= \frac{1}{4}\times(|M_{RR}|^2+|M_{RL}|^2+|M_{LR}|^2+|M_{LL}^2|)\\ &= \frac{1}{4}e^4(2(1+\cos\theta)^2+2(1-\cos\theta)^2)\\ &= e^4(1+\cos^2\theta)\end{aligned}$$



- The matrix element is **Lorentz Invariant** (scalar product of 4-vector currents) and it is desirable to write it in a frame-independent form, i.e. express in terms of Lorentz Invariant 4-vector scalar products

- In the C.o.M. $\quad p_1=(E,0,0,E) \quad p_2=(E,0,0,-E)$

$$p_3=(E,E\sin\theta,0,E\cos\theta) \qquad p_4=(E,-E\sin\theta,0,-E\cos\theta)$$

giving: $\quad p_1.p_2=2E^2; \quad p_1.p_3=E^2(1-\cos\theta); \quad p_1.p_4=E^2(1+\cos\theta)$

- Hence we can write

$$\langle|M_{fi}|^2\rangle = 2e^4\frac{(p_1.p_3)^2+(p_1.p_4)^2}{(p_1.p_2)^2} \qquad \equiv 2e^4\left(\frac{t^2+u^2}{s^2}\right)$$

★Valid in any frame !

CHIRALITY

- The helicity eigenstates for a particle/anti-particle for $E \gg m$ are:

$$u_\uparrow = \sqrt{E}\begin{pmatrix} c \\ se^{i\phi} \\ c \\ se^{i\phi} \end{pmatrix};\ u_\downarrow = \sqrt{E}\begin{pmatrix} -s \\ ce^{i\phi} \\ s \\ -ce^{i\phi} \end{pmatrix};\ v_\uparrow = \sqrt{E}\begin{pmatrix} s \\ -ce^{i\phi} \\ -s \\ ce^{i\phi} \end{pmatrix};\ v_\downarrow = \sqrt{E}\begin{pmatrix} c \\ se^{i\phi} \\ c \\ se^{i\phi} \end{pmatrix}$$

where $s = \sin\frac{\theta}{2}; \quad c = \cos\frac{\theta}{2}$

- Define the matrix

$$\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

- <u>In the limit</u> $E \gg m$ the helicity states are also eigenstates of γ^5

$$\gamma^5 u_\uparrow = +u_\uparrow;\ \gamma^5 u_\downarrow = -u_\downarrow;\ \gamma^5 v_\uparrow = -v_\uparrow;\ \gamma^5 v_\downarrow = +v_\downarrow$$

★ <u>In general</u>, define the eigenstates of γ^5 as LEFT and RIGHT HANDED <u>CHIRAL</u> states $u_R;\quad u_L;\quad v_R;\quad v_L$

i.e. $\gamma^5 u_R = +u_R;\ \gamma^5 u_L = -u_L;\ \gamma^5 v_R = -v_R;\ \gamma^5 v_L = +v_L$

- In the LIMIT $E \gg m$ (and ONLY IN THIS LIMIT):

$$u_R \equiv u_\uparrow;\quad u_L \equiv u_\downarrow;\quad v_R \equiv v_\uparrow;\quad v_L \equiv v_\downarrow$$

★This is a subtle but important point: in general the **HELICITY** and **CHIRAL** eigenstates **are not the same**. It is **only** in the **ultra-relativistic limit** that the chiral eigenstates correspond to the helicity eigenstates.

★Chirality is an import concept in the structure of QED, and any interaction of the form $\bar{u}\gamma^{\nu}u$

- In general, the eigenstates of the chirality operator are:

$$\gamma^5 u_R = +u_R; \;\; \gamma^5 u_L = -u_L; \;\; \gamma^5 v_R = -v_R; \;\; \gamma^5 v_L = +v_L$$

- Define the **projection operators**:

$$P_R = \tfrac{1}{2}(1+\gamma^5); \qquad P_L = \tfrac{1}{2}(1-\gamma^5)$$

- The projection operators, project out the chiral eigenstates

$$P_R u_R = u_R; \quad P_R u_L = 0; \quad P_L u_R = 0; \quad P_L u_L = u_L$$
$$P_R v_R = 0; \quad P_R v_L = v_L; \quad P_L v_R = v_R; \quad P_L v_L = 0$$

- Note P_R projects out **right-handed particle states** and **left-handed anti-particle states**

- We can then write any spinor in terms of it left and right-handed chiral components:

$$\psi = \psi_R + \psi_L = \tfrac{1}{2}(1+\gamma^5)\psi + \tfrac{1}{2}(1-\gamma^5)\psi$$

Chirality in QED

- In QED the basic interaction between a fermion and photon is:

$$ie\overline{\psi}\gamma^{\mu}\phi$$

- Can decompose the spinors in terms of Left and Right-handed chiral components:

$$\begin{aligned} ie\overline{\psi}\gamma^{\mu}\phi &= ie(\overline{\psi}_L+\overline{\psi}_R)\gamma^{\mu}(\phi_R+\phi_L) \\ &= ie(\overline{\psi}_R\gamma^{\mu}\phi_R+\overline{\psi}_R\gamma^{\mu}\phi_L+\overline{\psi}_L\gamma^{\mu}\phi_R+\overline{\psi}_L\gamma^{\mu}\phi_L) \end{aligned}$$

- Using the properties of γ^5 (Q8 on examples sheet)

$$(\gamma^5)^2=1; \quad \gamma^{5\dagger}=\gamma^5; \quad \gamma^5\gamma^{\mu}=-\gamma^{\mu}\gamma^5$$

it is straightforward to show (Q9 on examples sheet)

$$\overline{\psi}_R\gamma^{\mu}\phi_L=0; \quad \overline{\psi}_L\gamma^{\mu}\phi_R=0$$

★ Hence only certain combinations of chiral eigenstates contribute to the interaction. This statement is **ALWAYS** true.

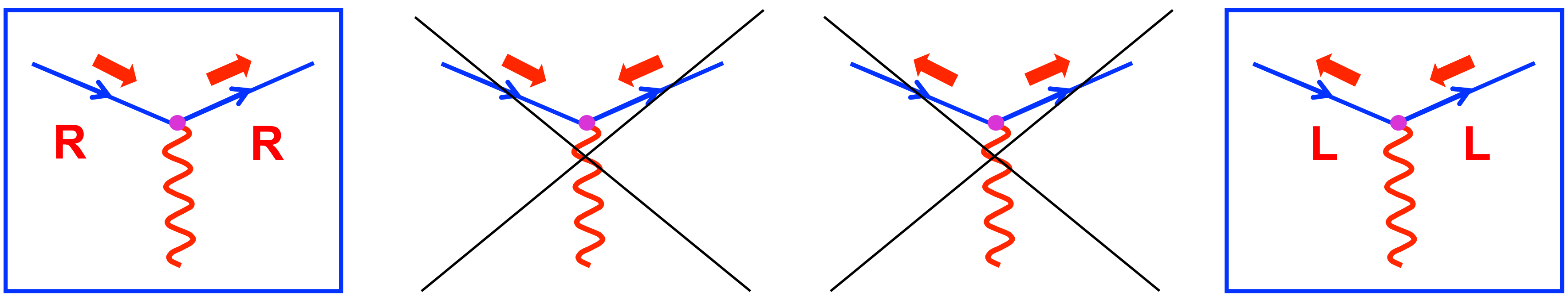
- For $E \gg m$, the chiral and helicity eigenstates are equivalent. This implies that for $E \gg m$ only certain helicity combinations contribute to the QED vertex ! This is why previously we found that for two of the four helicity combinations for the muon current were zero

Allowed QED Helicity Combinations

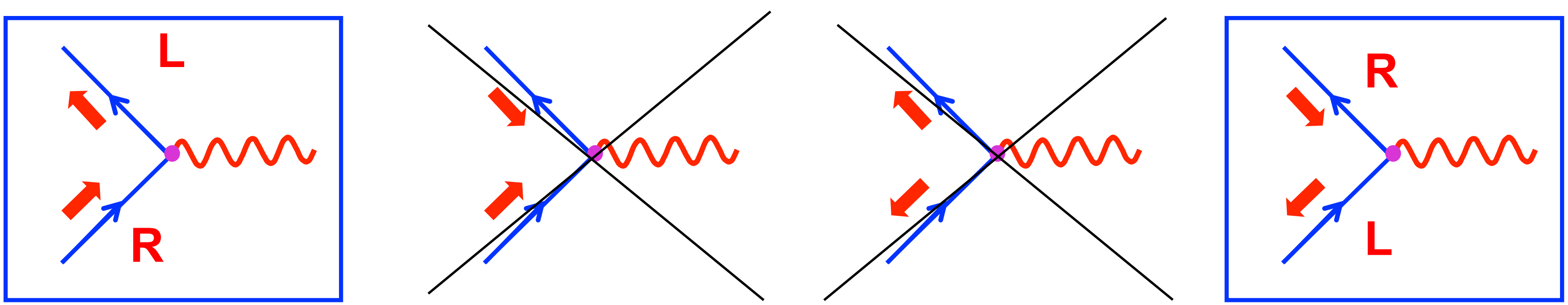
- In the ultra-relativistic limit the helicity eigenstates ≡ chiral eigenstates
- In this limit, the only non-zero **helicity** combinations in QED are:

Scattering:

"Helicity conservation"



Annihilation:



Summary

★ In the centre-of-mass frame the $e^+e^- \rightarrow \mu^+\mu^-$ differential cross-section is

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}(1+\cos^2\theta)$$

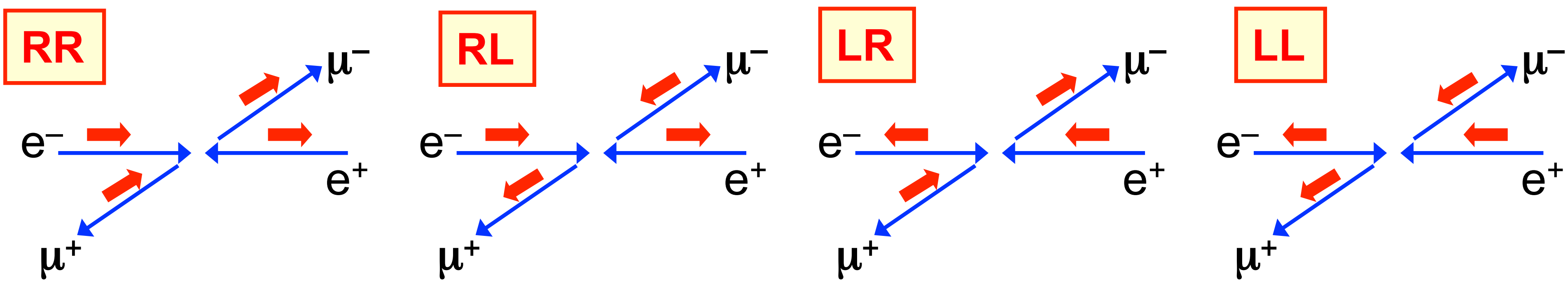
NOTE: neglected masses of the muons, i.e. assumed $E \gg m_\mu$

★ In QED only certain combinations of **LEFT-** and **RIGHT-HANDED CHIRAL** states give non-zero matrix elements

★ CHIRAL states defined by chiral projection operators

$$P_R = \tfrac{1}{2}(1+\gamma^5); \qquad P_L = \tfrac{1}{2}(1-\gamma^5)$$

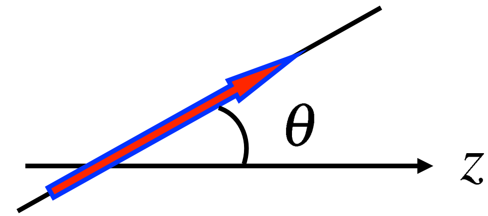
★ In limit $E \gg m$ the chiral eigenstates correspond to the HELICITY eigenstates and only certain HELICITY combinations give non-zero matrix elements



Appendix : Spin 1 Rotation Matrices

•Consider the spin-1 state with spin +1 along the axis defined by unit vector

$$\vec{n} = (\sin\theta, 0, \cos\theta)$$



•Spin state is an eigenstate of $\vec{n}.\vec{S}$ with eigenvalue +1

$$(\vec{n}.\vec{S})|\psi\rangle = +1|\psi\rangle \quad \text{(A1)}$$

•Express in terms of linear combination of spin 1 states which are eigenstates of S_z

$$|\psi\rangle = \alpha|1,1\rangle + \beta|1,0\rangle + \gamma|1,-1\rangle$$

with
$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

• (A1) becomes

$$(\sin\theta S_x + \cos\theta S_z)(\alpha|1,1\rangle + \beta|1,0\rangle + \gamma|1,-1\rangle) = \alpha|1,1\rangle + \beta|1,0\rangle\gamma|1,-1\rangle \quad \text{(A2)}$$

•Write S_x in terms of ladder operators $S_x = \frac{1}{2}(S_+ + S_-)$

where
$$S_+|1,1\rangle = 0 \qquad S_+|1,0\rangle = \sqrt{2}|1,1\rangle \qquad S_+|1,-1\rangle = \sqrt{2}|1,0\rangle$$
$$S_-|1,1\rangle = \sqrt{2}|1,0\rangle \qquad S_-|1,0\rangle = \sqrt{2}|1,-1\rangle \qquad S_-|1,-1\rangle = 0$$

- from which we find

$$S_x|1,1\rangle = \tfrac{1}{\sqrt{2}}|1,0\rangle$$
$$S_x|1,0\rangle = \tfrac{1}{\sqrt{2}}(|1,1\rangle + |1,-1\rangle)$$
$$S_x|1,-1\rangle = \tfrac{1}{\sqrt{2}}|1,0\rangle$$

- (A2) becomes

$$\sin\theta\left[\frac{\alpha}{\sqrt{2}}|1,0\rangle + \frac{\beta}{\sqrt{2}}|1,-1\rangle + \frac{\beta}{\sqrt{2}}|1,1\rangle + \frac{\gamma}{\sqrt{2}}|1,0\rangle\right] +$$
$$\alpha\cos\theta|1,1\rangle - \gamma\cos\theta|1,-1\rangle = \alpha|1,1\rangle + \beta|1,0\rangle\gamma|1,-1\rangle$$

- which gives

$$\left.\begin{aligned} \beta\frac{\sin\theta}{\sqrt{2}} + \alpha\cos\theta &= \alpha \\ (\alpha+\gamma)\frac{\sin\theta}{\sqrt{2}} &= \beta \\ \beta\frac{\sin\theta}{\sqrt{2}} - \gamma\cos\theta &= \gamma \end{aligned}\right\}$$

- using $\alpha^2+\beta^2+\gamma^2 = 1$ the above equations yield

$$\alpha = \tfrac{1}{\sqrt{2}}(1+\cos\theta) \qquad \beta = \tfrac{1}{\sqrt{2}}\sin\theta \qquad \gamma = \tfrac{1}{\sqrt{2}}(1-\cos\theta)$$

- hence

$$\psi = \tfrac{1}{2}(1-\cos\theta)|1,-1\rangle + \tfrac{1}{\sqrt{2}}\sin\theta|1,0\rangle + \tfrac{1}{2}(1+\cos\theta)|1,+1\rangle$$

•The coefficients α, β, γ are examples of what are known as quantum mechanical **rotation matrices**. The express how angular momentum eigenstate in a particular direction is expressed in terms of the eigenstates defined in a different direction

$$d^j_{m',m}(\theta)$$

•For spin-1 $(j=1)$ we have just shown that

$$d^1_{1,1}(\theta) = \tfrac{1}{2}(1+\cos\theta) \qquad d^1_{0,1}(\theta) = \frac{1}{\sqrt{2}}\sin\theta \qquad d^1_{-1,1}(\theta) = \tfrac{1}{2}(1-\cos\theta)$$

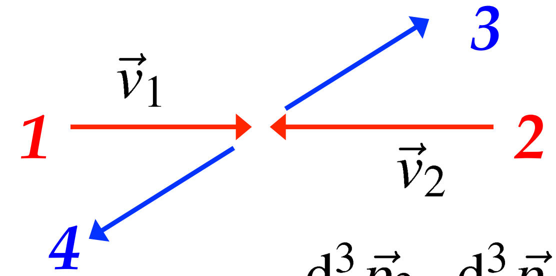
•For spin-1/2 it is straightforward to show

$$d^{\frac{1}{2}}_{\frac{1}{2},\frac{1}{2}}(\theta) = \cos\frac{\theta}{2} \qquad d^{\frac{1}{2}}_{-\frac{1}{2},\frac{1}{2}}(\theta) = \sin\frac{\theta}{2}$$

Backup Slides

Xsection CM

$$\color{red}{1} + \color{red}{2} \rightarrow \color{blue}{3} + \color{blue}{4}$$



- **Start from Fermi's Golden Rule:**

$$\Gamma_{fi} = (2\pi)^4 \int |T_{fi}|^2 \delta(E_1 + E_2 - E_3 - E_4)\delta^3(\vec{p}_1 + \vec{p}_2 - \vec{p}_3 - \vec{p}_4)\frac{\mathrm{d}^3\vec{p}_3}{(2\pi)^3}\frac{\mathrm{d}^3\vec{p}_4}{(2\pi)^3}$$

where T_{fi} is the transition matrix for a normalisation of 1/unit volume

- **Now**

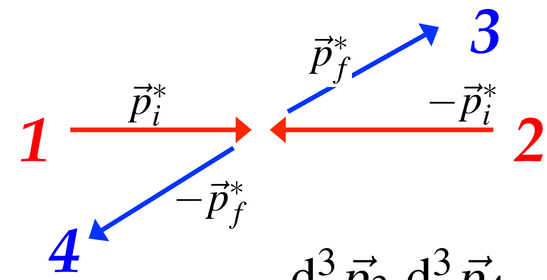
$$\begin{aligned}\text{Rate/Volume} &= (\text{flux of 1}) \times (\text{number density of 2}) \times \sigma \\ &= n_1(v_1 + v_2) \times n_2 \times \sigma\end{aligned}$$

- **For 1 target particle per unit volume** $\text{Rate} = (v_1 + v_2)\sigma$

$$\sigma = \frac{\Gamma_{fi}}{(v_1 + v_2)}$$

$$\sigma = \frac{(2\pi)^4}{v_1 + v_2} \int |T_{fi}|^2 \delta(E_1 + E_2 - E_3 - E_4)\delta^3(\vec{p}_1 + \vec{p}_2 - \vec{p}_3 - \vec{p}_4)\frac{\mathrm{d}^3\vec{p}_3}{(2\pi)^3}\frac{\mathrm{d}^3\vec{p}_4}{(2\pi)^3}$$

the parts are not Lorentz Invariant



$$M_{fi} = (2E_1\,2E_2\,2E_3\,2E_4)^{1/2}T_{fi}$$

$$\sigma = \frac{(2\pi)^{-2}}{2E_1 2E_2(v_1+v_2)}\int |M_{fi}|^2\delta(E_1+E_2-E_3-E_4)\delta^3(\vec{p}_1+\vec{p}_2-\vec{p}_3-\vec{p}_4)\frac{\mathrm{d}^3\vec{p}_3}{2E_3}\frac{\mathrm{d}^3\vec{p}_4}{2E_4}$$

$$F = 2E_1 2E_2(v_1+v_1) = 4\left[(p_1^\mu p_{2\mu})^2 - m_1^2 m_2^2\right]^{1/2}$$

- **Centre-of-Mass Frame**

$$\vec{p}_1+\vec{p}_2 = 0 \quad \text{and} \quad E_1+E_2=\sqrt{s}$$

$$\begin{aligned} F &= 4E_1E_2(v_1+v_2) \\ &= 4E_1E_2(|\vec{p}^*|/E_1+|\vec{p}^*|/E_2) \\ &= 4|\vec{p}^*|(E_1+E_2) \\ &= 4|\vec{p}^*|\sqrt{s} \end{aligned}$$

$$\sigma = \frac{(2\pi)^{-2}}{4|\vec{p}_i^*|\sqrt{s}}\int |M_{fi}|^2\delta(\sqrt{s}-E_3-E_4)\delta^3(\vec{p}_3+\vec{p}_4)\frac{\mathrm{d}^3\vec{p}_3}{2E_3}\frac{\mathrm{d}^3\vec{p}_4}{2E_4}$$

$$\sigma = \frac{1}{64\pi^2 s}\frac{|\vec{p}_f^*|}{|\vec{p}_i^*|}\int |M_{fi}|^2 \mathrm{d}\Omega^*$$