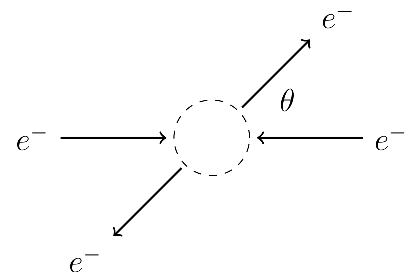
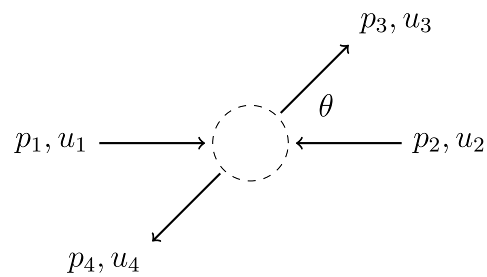
Moller scattering is the result of interactions between electrons. The following diagram shows the geometry of a typical collider experiment that generates Moller scattering data.



Here is the same diagram with momentum and spinor labels.



In center of mass coordinates the momentum vectors are

$$p_1 = \begin{pmatrix} E \\ 0 \\ 0 \\ p \end{pmatrix} \quad p_2 = \begin{pmatrix} E \\ 0 \\ 0 \\ -p \end{pmatrix} \quad p_3 = \begin{pmatrix} E \\ p\sin\theta\cos\phi \\ p\sin\theta\sin\phi \\ p\cos\theta \end{pmatrix} \quad p_4 = \begin{pmatrix} E \\ -p\sin\theta\cos\phi \\ -p\sin\theta\sin\phi \\ -p\cos\theta \end{pmatrix}$$

where $E = \sqrt{p^2 + m^2}$. The spinors are

$$u_{11} = \begin{pmatrix} E+m \\ 0 \\ p \\ 0 \end{pmatrix} \quad u_{21} = \begin{pmatrix} E+m \\ 0 \\ -p \\ 0 \end{pmatrix} \quad u_{31} = \begin{pmatrix} E+m \\ 0 \\ p_{3z} \\ p_{3x} + ip_{3y} \end{pmatrix} \quad u_{41} = \begin{pmatrix} E+m \\ 0 \\ p_{4z} \\ p_{4x} + ip_{4y} \end{pmatrix}$$

$$u_{12} = \begin{pmatrix} 0 \\ E+m \\ 0 \\ -p \end{pmatrix} \quad u_{22} = \begin{pmatrix} 0 \\ E+m \\ 0 \\ p \end{pmatrix} \quad u_{32} = \begin{pmatrix} 0 \\ E+m \\ p_{3x} - ip_{3y} \\ -p_{3z} \end{pmatrix} \quad u_{42} = \begin{pmatrix} 0 \\ E+m \\ p_{4x} - ip_{4y} \\ -p_{4z} \end{pmatrix}$$

The spinors shown above are not individually normalized. Instead, a combined spinor normalization constant $N = (E+m)^4$ will be used.

The following formula computes a probability density $|\mathcal{M}_{abcd}|^2$ for Moller scattering where the subscripts $abcd$ are the spin states of the electrons.

$$|\mathcal{M}_{abcd}|^2 = \frac{e^4}{N} \left| \frac{1}{t}(\bar{u}_{3c}\gamma^\mu u_{1a})(\bar{u}_{4d}\gamma_\mu u_{2b}) - \frac{1}{u}(\bar{u}_{4d}\gamma^\nu u_{1a})(\bar{u}_{3c}\gamma_\nu u_{2b}) \right|^2$$

Symbol e is electron charge. Symbols t and u are Mandelstam variables $t = (p_1 - p_3)^2$ and $u = (p_1 - p_4)^2$.

Let

$$a_1 = (\bar{u}_{3c}\gamma^\mu u_{1a})(\bar{u}_{4d}\gamma_\mu u_{2b}) \qquad a_2 = (\bar{u}_{4d}\gamma^\nu u_{1a})(\bar{u}_{3c}\gamma_\nu u_{2b})$$

Then

$$\begin{aligned}
|\mathcal{M}_{abcd}|^2 &= \frac{e^4}{N}\left|\frac{a_1}{t} - \frac{a_2}{u}\right|^2 \\
&= \frac{e^4}{N}\left(\frac{a_1}{t} - \frac{a_2}{u}\right)\left(\frac{a_1}{t} - \frac{a_2}{u}\right)^* \\
&= \frac{e^4}{N}\left(\frac{a_1 a_1^*}{t^2} - \frac{a_1 a_2^*}{tu} - \frac{a_1^* a_2}{tu} + \frac{a_2 a_2^*}{u^2}\right)
\end{aligned}$$

The expected probability density $\langle|\mathcal{M}|^2\rangle$ is computed by summing $|\mathcal{M}_{abcd}|^2$ over all spin states and dividing by the number of inbound states. There are four inbound states.

$$\begin{aligned}
\langle|\mathcal{M}|^2\rangle &= \frac{1}{4}\sum_{a=1}^2\sum_{b=1}^2\sum_{c=1}^2\sum_{d=1}^2 |\mathcal{M}_{abcd}|^2 \\
&= \frac{e^4}{4N}\sum_{a=1}^2\sum_{b=1}^2\sum_{c=1}^2\sum_{d=1}^2\left(\frac{a_1 a_1^*}{t^2} - \frac{a_1 a_2^*}{tu} - \frac{a_1^* a_2}{tu} + \frac{a_2 a_2^*}{u^2}\right)
\end{aligned}$$

Use the Casimir trick to replace sums over spins with matrix products.

$$\begin{aligned}
f_{11} &= \frac{1}{N}\sum_{abcd} a_1 a_1^* = \operatorname{Tr}\left((\not{p}_3 + m)\gamma^\mu(\not{p}_1 + m)\gamma^\nu\right)\operatorname{Tr}\left((\not{p}_4 + m)\gamma_\mu(\not{p}_2 + m)\gamma_\nu\right) \\
f_{12} &= \frac{1}{N}\sum_{abcd} a_1 a_2^* = \operatorname{Tr}\left((\not{p}_3 + m)\gamma^\mu(\not{p}_1 + m)\gamma^\nu(\not{p}_4 + m)\gamma_\mu(\not{p}_2 + m)\gamma_\nu\right) \\
f_{22} &= \frac{1}{N}\sum_{abcd} a_2 a_2^* = \operatorname{Tr}\left((\not{p}_4 + m)\gamma^\mu(\not{p}_1 + m)\gamma^\nu\right)\operatorname{Tr}\left((\not{p}_3 + m)\gamma_\mu(\not{p}_2 + m)\gamma_\nu\right)
\end{aligned}$$

Hence

$$\langle|\mathcal{M}|^2\rangle = \frac{e^4}{4}\left(\frac{f_{11}}{t^2} - \frac{f_{12}}{tu} - \frac{f_{12}^*}{tu} + \frac{f_{22}}{u^2}\right)$$

Run "moller-scattering-1.txt" to verify the Casimir trick.

The following momentum formulas are equivalent to the Casimir trick. (Recall that $a \cdot b = a^\mu g_{\mu\nu} b^\nu$)

$$\begin{aligned}
f_{11} &= 32(p_1\cdot p_2)(p_3\cdot p_4) + 32(p_1\cdot p_4)(p_2\cdot p_3) - 32m^2(p_1\cdot p_3) - 32m^2(p_2\cdot p_4) + 64m^4 \\
f_{12} &= -32(p_1\cdot p_2)(p_3\cdot p_4) + 16m^2(p_1\cdot p_2) + 16m^2(p_1\cdot p_3) + 16m^2(p_1\cdot p_4) \\
&\qquad + 16m^2(p_2\cdot p_3) + 16m^2(p_2\cdot p_4) + 16m^2(p_3\cdot p_4) - 32m^4 \\
f_{22} &= 32(p_1\cdot p_2)(p_3\cdot p_4) + 32(p_1\cdot p_3)(p_2\cdot p_4) - 32m^2(p_1\cdot p_4) - 32m^2(p_2\cdot p_3) + 64m^4
\end{aligned}$$

In Mandelstam variables $s = (p_1 + p_2)^2$, $t = (p_1 - p_3)^2$, and $u = (p_1 - p_4)^2$ the formulas are

$$\begin{aligned}
f_{11} &= 8s^2 + 8u^2 - 64sm^2 - 64um^2 + 192m^4 \\
f_{12} &= -8s^2 + 64sm^2 - 96m^4 \\
f_{22} &= 8s^2 + 8t^2 - 64sm^2 - 64tm^2 + 192m^4
\end{aligned}$$

High energy approximation

When $E \gg m$ a useful approximation is to set $m = 0$ and obtain

$$\begin{aligned} f_{11} &= 8s^2 + 8u^2 \\ f_{12} &= -8s^2 \\ f_{22} &= 8s^2 + 8t^2 \end{aligned}$$

For $m = 0$ the Mandelstam variables are

$$\begin{aligned} s &= 4E^2 \\ t &= -2E^2(1 - \cos\theta) \\ u &= -2E^2(1 + \cos\theta) \end{aligned}$$

It follows that

$$t^2u^2 = 16E^8 \sin^4\theta$$

The corresponding expected probability density is

$$\begin{aligned} \langle|\mathcal{M}|^2\rangle &= \frac{e^4}{4}\left(\frac{f_{11}}{t^2} - \frac{f_{12}}{tu} - \frac{f_{12}^*}{tu} + \frac{f_{22}}{u^2}\right) \\ &= \frac{e^4}{4t^2u^2}\left(u^2 f_{11} - tuf_{12} - tuf_{12}^* + t^2 f_{22}\right) \\ &= \frac{e^4}{4t^2u^2}\left(u^2\left(8s^2 + 8u^2\right) + 16s^2tu + t^2\left(8s^2 + 8t^2\right)\right) \\ &= \frac{e^4}{64E^8\sin^4\theta}\left(256E^8\cos^4\theta + 1536E^8\cos^2\theta + 2304E^8\right) \\ &= \frac{4e^4}{\sin^4\theta}\left(\cos^4\theta + 6\cos^2\theta + 9\right) \\ &= 4e^4\frac{\left(\cos^2\theta + 3\right)^2}{\sin^4\theta} \end{aligned}$$

Run “moller-scattering-2.txt” to verify.

Cross section

The differential cross section is

$$\frac{d\sigma}{d\Omega} = \frac{\langle|\mathcal{M}|^2\rangle}{64\pi^2 s} = \frac{e^4}{64\pi^2E^2}\frac{\left(\cos^2\theta + 3\right)^2}{\sin^4\theta}$$

Substituting $e^4 = 16\pi^2\alpha^2$ yields

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2}\frac{\left(\cos^2\theta + 3\right)^2}{\sin^4\theta}$$

We can integrate $d\sigma$ to obtain a cumulative distribution function. Recall that

$$d\Omega = \sin\theta\, d\theta\, d\phi$$

Hence

$$d\sigma = \frac{\alpha^2}{4E^2}\frac{\left(\cos^2\theta + 3\right)^2}{\sin^4\theta}\sin\theta\, d\theta\, d\phi$$

Let $I(\theta)$ be the following integral of $d\sigma$.

$$\begin{aligned}
I(\theta) &= \left(\frac{4E^2}{\alpha^2}\right)\frac{1}{2\pi}\int_0^{2\pi}\int d\sigma \\
&= \int \frac{\left(\cos^2\theta + 3\right)^2}{\sin^4\theta}\sin\theta\,d\theta \\
&= -\cos\theta - \frac{8\cos\theta}{\sin^2\theta}, \qquad a \le \theta \le \pi - a
\end{aligned}$$

Angular support is limited to an arbitrary $a > 0$ because $I(0)$ and $I(\pi)$ are undefined.

Let C be the normalization constant

$$C = I(\pi - a) - I(a)$$

Then the cumulative distribution function $F(\theta)$ is

$$F(\theta) = \frac{I(\theta) - I(a)}{C}, \qquad a \le \theta \le \pi - a$$

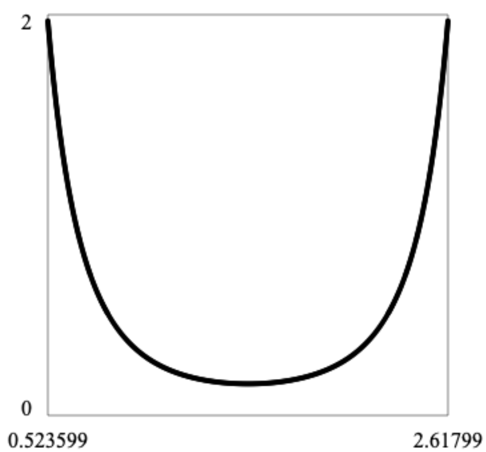
The probability of observing scattering events in the interval θ_1 to θ_2 can now be computed.

$$P(\theta_1 \le \theta \le \theta_2) = F(\theta_2) - F(\theta_1)$$

Probability density function $f(\theta)$ is the derivative of $F(\theta)$.

$$f(\theta) = \frac{dF(\theta)}{d\theta} = \frac{1}{C}\frac{\left(\cos^2\theta + 3\right)^2}{\sin^4\theta}\sin\theta$$

Run "moller-scattering-3.txt" to draw a graph of $f(\theta)$ for $a = \pi/6 = 30°$.



The following table shows the probability distribution for 30° bins ($a = \pi/6 = 30°$).

θ_1	θ_2	$P(\theta_1 \le \theta \le \theta_2)$
0°	30°	–
30°	60°	0.40
60°	90°	0.10
90°	120°	0.10
120°	150°	0.40
150°	180°	–

Notes on Eigenmath scripts

In component notation, the trace operators of the Casimir trick become sums over a repeated index, in this case α.

$$
\begin{aligned}
f_{11} &= \left((\not p_3 + m)^\alpha{}_\beta \gamma^{\mu\beta}{}_\rho (\not p_1 + m)^\rho{}_\sigma \gamma^{\nu\sigma}{}_\alpha\right)\left((\not p_4 + m)^\alpha{}_\beta \gamma_\mu{}^\beta{}_\rho (\not p_2 + m)^\rho{}_\sigma \gamma_\nu{}^\sigma{}_\alpha\right) \\
f_{12} &= (\not p_3 + m)^\alpha{}_\beta \gamma^{\mu\beta}{}_\rho (\not p_1 + m)^\rho{}_\sigma \gamma^{\nu\sigma}{}_\tau (\not p_4 + m)^\tau{}_\delta \gamma_\mu{}^\delta{}_\eta (\not p_2 + m)^\eta{}_\xi \gamma_\nu{}^\xi{}_\alpha \\
f_{22} &= \left((\not p_4 + m)^\alpha{}_\beta \gamma^{\mu\beta}{}_\rho (\not p_1 + m)^\rho{}_\sigma \gamma^{\nu\sigma}{}_\alpha\right)\left((\not p_3 + m)^\alpha{}_\beta \gamma_\mu{}^\beta{}_\rho (\not p_2 + m)^\rho{}_\sigma \gamma_\nu{}^\sigma{}_\alpha\right)
\end{aligned}
$$

To convert the above formulas to Eigenmath code, the γ tensors need to be transposed so that repeated indices are adjacent to each other. Also, multiply γ^μ by the metric tensor to lower the index.

$\gamma^{\beta\mu}{}_\rho \quad \rightarrow$ `gammaT = transpose(gamma)`

$\gamma^\beta{}_{\mu\rho} \quad \rightarrow$ `gammaL = transpose(dot(gmunu,gamma))`

Define the following 4×4 matrices.

$(\not p_1 + m) \quad \rightarrow$ `X1 = pslash1 + m I`

$(\not p_2 + m) \quad \rightarrow$ `X2 = pslash2 + m I`

$(\not p_3 + m) \quad \rightarrow$ `X3 = pslash3 + m I`

$(\not p_4 + m) \quad \rightarrow$ `X4 = pslash4 + m I`

Then for f_{11} we have the following Eigenmath code. The contract function sums over α.

$(\not p_3 + m)^\alpha{}_\beta \gamma^{\mu\beta}{}_\rho (\not p_1 + m)^\rho{}_\sigma \gamma^{\nu\sigma}{}_\alpha \quad \rightarrow$ `T1 = contract(dot(X3,gammaT,X1,gammaT),1,4)`

$(\not p_4 + m)^\alpha{}_\beta \gamma_\mu{}^\beta{}_\rho (\not p_2 + m)^\rho{}_\sigma \gamma_\nu{}^\sigma{}_\alpha \quad \rightarrow$ `T2 = contract(dot(X4,gammaL,X2,gammaL),1,4)`

Next, multiply then sum over repeated indices. The dot function sums over ν then the contract function sums over μ. The transpose makes the ν indices adjacent as required by the dot function.

$f_{11} = \operatorname{Tr}(\cdots\gamma^\mu\cdots\gamma^\nu)\operatorname{Tr}(\cdots\gamma_\mu\cdots\gamma_\nu) \quad \rightarrow$ `contract(dot(T1,transpose(T2)))`

Follow suit for f_{22}.

$(\not p_4 + m)^\alpha{}_\beta \gamma^{\mu\beta}{}_\rho (\not p_1 + m)^\rho{}_\sigma \gamma^{\nu\sigma}{}_\alpha \quad \rightarrow$ `T1 = contract(dot(X4,gammaT,X1,gammaT),1,4)`

$(\not p_3 + m)^\alpha{}_\beta \gamma_\mu{}^\beta{}_\rho (\not p_2 + m)^\rho{}_\sigma \gamma_\nu{}^\sigma{}_\alpha \quad \rightarrow$ `T2 = contract(dot(X3,gammaL,X2,gammaL),1,4)`

Then

$f_{22} = \operatorname{Tr}(\cdots\gamma^\mu\cdots\gamma^\nu)\operatorname{Tr}(\cdots\gamma_\mu\cdots\gamma_\nu) \quad \rightarrow$ `contract(dot(T1,transpose(T2)))`

The calculation of f_{12} begins with

$(\not p_3 + m)^\alpha{}_\beta \gamma^{\mu\beta}{}_\rho (\not p_1 + m)^\rho{}_\sigma \gamma^{\nu\sigma}{}_\tau (\not p_4 + m)^\tau{}_\delta \gamma_\mu{}^\delta{}_\eta (\not p_2 + m)^\eta{}_\xi \gamma_\nu{}^\xi{}_\alpha$

$\rightarrow$ `T = contract(dot(X3,gammaT,X1,gammaT,X4,gammaL,X2,gammaL),1,6)`

Then sum over repeated indices μ and ν.

$f_{12} = \operatorname{Tr}(\cdots\gamma^\mu\cdots\gamma^\nu\cdots\gamma_\mu\cdots\gamma_\nu) \quad \rightarrow$ `contract(contract(T,1,3))`