\[ \mathcal{M}_f = (\text{ie})^2 \frac{4mc}{m_{\mu}} \frac{\delta^{S_3S_4} \delta^{S_3S_5}}{\sqrt{(\vec{p}_1 - \vec{p}_3)^2}} \]

**Non-relativistic**

\[ \mathcal{M}_f = \frac{4mcm_{\mu}}{m_{\mu}} \delta^{S_3S_4} \delta^{S_3S_5} \left( \gamma^\mu \gamma^0 \right) \]

\[ V = \frac{e^2}{r} \]

\[ \mathcal{M}_f = (\text{ie})^2 \frac{4mc}{m_{\mu}} \frac{\delta^{S_3S_4} \delta^{S_3S_5}}{\sqrt{(\vec{p}_1 - \vec{p}_3)^2}} \]

\[ \mathcal{M}_f = (\text{ie})^2 \frac{4mc}{m_{\mu}} \frac{\delta^{S_3S_4} \delta^{S_3S_5}}{\sqrt{(\vec{p}_1 - \vec{p}_3)^2}} \]

\[ \mathcal{M}_f = (\text{ie})^2 \frac{4mc}{m_{\mu}} \frac{\delta^{S_3S_4} \delta^{S_3S_5}}{\sqrt{(\vec{p}_1 - \vec{p}_3)^2}} \]
Ultra-relativistic.

\[ R \ \epsilon_1 \to \infty \quad (s \to \infty) \]

\[ U_{\mu_1}^s = \begin{pmatrix} e^{i \beta \sigma \lambda_2} & 0 \\ 0 & e^{i \beta \sigma \lambda_2} \end{pmatrix} \begin{pmatrix} \xi^{(s)} \\ \xi^{(s')} \end{pmatrix} \sqrt{2m} \]

\[ e^{i \beta \sigma \lambda_2} = \cosh \beta \sigma \lambda_2 + \sinh \beta \sigma \lambda_2 \beta \cdot \sigma \approx \frac{1}{2} e^{\beta \sigma \lambda_2} (1 + \beta \cdot \sigma) \quad \beta \to \infty \]

\[ U_{\mu_1}^{-s} = e^{-i \beta \sigma \lambda_2} = \cosh \beta \sigma \lambda_2 - \sinh \beta \sigma \lambda_2 \beta \cdot \sigma \approx \frac{1}{2} e^{\beta \sigma \lambda_2} (1 - \beta \cdot \sigma) \]

\[ U_{\mu_1}^s \approx \frac{1}{2} e^{\beta \sigma \lambda_2} \begin{pmatrix} 1 + \beta \cdot \sigma & 0 \\ 0 & 1 - \beta \cdot \sigma \end{pmatrix} \begin{pmatrix} \xi^{(s)} \\ \xi^{(s')} \end{pmatrix} \]

Take \( (\beta \cdot \sigma) \xi^{(s)} = 1 \), \( (\beta \cdot \sigma) \xi^{(s')} = -1 \)

\[ U_{\mu_1}^{(s)} \approx \begin{pmatrix} e^{i \beta \sigma \lambda_2} & 0 \\ 0 & e^{-i \beta \sigma \lambda_2} \end{pmatrix} \begin{pmatrix} 0 \\ \xi \end{pmatrix} \]

\[ U_{\mu_1}^{(s')} \approx e^{i \beta \sigma \lambda_2} \begin{pmatrix} 0 \\ \xi \end{pmatrix} \]

Up and down in dir. of mom.

Rel.:

\[ \begin{pmatrix} e^{i \beta \sigma \lambda_2} & 0 \\ 0 & e^{-i \beta \sigma \lambda_2} \end{pmatrix} \]

\[ -s^2 \gamma^\mu U_{\mu_1}^s U_{\mu_1}^{(s')} = 2m \begin{pmatrix} \xi^{(s)} & 0 \\ \xi^{(s')} & \xi^{(s')} \end{pmatrix} \begin{pmatrix} \sigma^\mu & 0 \\ 0 & \sigma^\mu \end{pmatrix} \begin{pmatrix} \xi^{(s)} \\ \xi^{(s')} \end{pmatrix} = 2m \xi^{(s)} \sigma^\mu \xi^{(s')} \]

But \( 2m \xi^{(s')} \begin{pmatrix} \xi^{(s)} \\ \xi^{(s')} \end{pmatrix} = 0 \)
at high energies, helicity is conserved (or polarization)
at low $\alpha$, spin $\approx \alpha$.