34. 34.1. Lorentz transformations

The energy \( E \) and 3-momentum \( p \) of a particle of mass \( m \) form a 4-vector \( p = (E, \mathbf{p}) \) whose square \( p^2 = E^2 - \mathbf{p}^2 = m^2 \). The velocity of the particle is \( \beta = p/E \). The energy and momentum \((E^*, \mathbf{p}^*)\) viewed from a frame moving with velocity \( \beta_f \) are given by

\[
\left( \frac{E^*}{p^*_f} \right) = \left( \frac{\gamma_f \beta_f}{-\gamma_f \beta_f} \right) \left( \frac{E}{p} \right), \quad p^*_f = p_f.
\]

where \( \gamma_f = (1 - \beta_f^2)^{-1/2} \) and \( p_f, (p_f) \) are the components of \( p \) perpendicular (parallel) to \( \beta_f \). Other 4-vectors, such as the space-time coordinates of events, of course transform in the same way. The scalar product of two 4-momenta

\[
\mathbf{E} \cdot \mathbf{P} = \frac{E_0}{c} \gamma_p \cos \theta
\]

where \( \theta \) is the angle between the particles. In the frame where one particle (of mass \( m_2 \)) is at rest (lab frame),

\[
E_{cm}^2 = \left[ \left( E_1 + E_2 \right)^2 - (p_1 + p_2)^2 \right]^{1/2} = \left[ m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1 \beta_2 \cos \theta) \right]^{1/2},
\]

where \( \beta_1 = p_1/(E_1 + m_2) \) and \( \beta_2 = p_2/(E_2 + m_2) \).

The velocity of the center-of-mass in the lab frame is

\[
\gamma_{cm} = (E_1 + m_2)/E_{cm},
\]

The c.m. momenta of particles 1 and 2 are of magnitude

\[
p_{cm} = p_{ab}/E_{cm},
\]

where \( p_{ab} \equiv p_{1ab} \) and \( p_{2ab} \) are the momenta of particles 1 and 2, respectively.

The state normalization is such that

\[
\langle p' | p \rangle = (2\pi)^3 \delta^3(p - p').
\]

34.2. Center-of-mass energy and momentum

In the collision of two particles of masses \( m_1 \) and \( m_2 \) the total center-of-mass energy can be expressed in the Lorentz-invariant form

\[
E_{cm} = \left[ \left( E_1 + E_2 \right)^2 - (p_1 + p_2)^2 \right]^{1/2},
\]

where \( E_{cm} = E_1 + E_2 \).

The velocity of the center-of-mass in the lab frame is

\[
\beta_{cm} = p_{ab}/(E_1 + m_2),
\]

where \( p_{ab} \equiv p_{1ab} \) and \( p_{2ab} \) are the momenta of particles 1 and 2.

For example, if a 0.80 GeV/c kaon beam is incident on a proton target, the center of mass energy is 1.699 GeV and the center of mass momentum of either particle is 0.442 GeV/c. It is also useful to note that

\[
E_{cm} dE_{cm} = m_2 dE_1/(E_1 + m_2) d\Omega_{lab}.
\]

34.3. Lorentz-invariant amplitudes

The matrix elements for a scattering or decay process are written in terms of an invariant amplitude \( \mathcal{M} \). As an example, the \( S \)-matrix for 2 \( \rightarrow 2 \) scattering is related to \( \mathcal{M} \) by

\[
\langle p' | p_S | p_1p_2 \rangle = i(2\pi)^3 \delta^3(p_1 + p_2 - p'_1 - p'_2)
\]

\[
\times \frac{\mathcal{M}}{(2E_1)^{1/2}(2E_2)^{1/2}(2E_1^{1/2})(2E_2^{1/2})}.\]

The state normalization is such that

\[
\langle p' | p \rangle = (2\pi)^3 \delta^3(p - p').
\]

34.4. Particle decays

The partial decay rate of a particle of mass \( M \) into \( n \) bodies in its rest frame is given in terms of the Lorentz-invariant matrix element \( \mathcal{M} \) by

\[
d\Gamma = \frac{(2\pi)^4}{2M} |\mathcal{M}|^2 d\Phi_n(P; p_1, \ldots, p_n),
\]

where \( d\Phi_n \) is an element of \( n \)-body phase space given by

\[
d\Phi_n(P; p_1, \ldots, p_n) = \delta^4(P - \sum_{i=1}^{n} p_i) \prod_{i=1}^{n} \frac{d^3p_i}{(2\pi)^3 2E_i}.
\]

This phase space can be generated recursively, viz.

\[
d\Phi_n(P; p_1, \ldots, p_n) = d\Phi_1 (q; p_1, \ldots, p_n)
\]

\[
\times d\Phi_{n-1} (P - q; p_1, \ldots, p_n)(2\pi)^3 dq^2,
\]

where \( q^2 = (\sum_{i=1}^{j} E_i)^2 - \sum_{i=1}^{j} p_i^2 \). This form is particularly useful in the case where a particle decays into another particle that subsequently decays.

34.4.1. Survival probability: If a particle of mass \( M \) has mean proper lifetime \( \tau \) (= \( 1/\Gamma \)) and has momentum \((E, \mathbf{p})\), then the probability that it lives for a time \( t_0 \) or greater before decaying is given by

\[
P(t_0) = e^{-\Gamma t_0/\Gamma} = e^{-Mt_0/\Gamma},
\]

and the probability that it travels a distance \( x_0 \) or greater is

\[
P(x_0) = e^{-Mx_0/\Gamma}.\]
Defining \( p_{ij} = p_i + p_j \) and \( m_{ij}^2 = p_{ij}^2 \), then \( m_{12}^2 + m_{23}^2 + m_{13}^2 = M^2 + m_1^2 + m_2^2 + m_3^2 \) and \( m_{ij}^2 = (p - p_3)^2 = M^2 + m_3^2 - 2M E_3 \), where \( E_3 \) is the energy of particle 3 in the rest frame of \( M \). In that frame, the momenta of the three decay particles lie in a plane. The relative orientation of these three momenta is fixed if their energies are known. The momenta can therefore be specified in space by giving three Euler angles \((\alpha, \beta, \gamma)\) that specify the orientation of the final system relative to the initial particle \([1]\).

Then

\[
d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{16M^2} |\mathbf{\mathcal{M}}|^2 \, df_{E_1} \, df_{E_2} \, df (\cos \beta) \, d\gamma.
\] (34.18)

Alternatively

\[
d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{16M^2} |\mathbf{\mathcal{M}}|^2 \left| \mathbf{p}_{1}^* \right| \left| \mathbf{p}_{3} \right| \, df_{m_{12}} \, df_{\Omega_{12}} \, df_{\Omega_{13}},
\] (34.19)

where \( \left| \mathbf{p}_{1}^* \right| \), \( \Omega_{12} \), and \( \Omega_{13} \) is the momentum of particle 1 in the rest frame of 1 and 2, and \( \Omega_{13} \) is the angle of particle 3 in the rest frame of the decaying particle. \( \left| \mathbf{p}_{1}^* \right| \) and \( \left| \mathbf{p}_{3} \right| \) are given by

\[
\left| \mathbf{p}_{1}^* \right| = \left[ \left( m_{12}^2 - (m_1 + m_2)^2 \right) \left( m_1^2 - (m_1 - m_2)^2 \right) \right]^{1/2},
\] (34.20a)

and

\[
\left| \mathbf{p}_{3} \right| = \left[ \left( M^2 - (m_1 + m_2)^2 \right) \left( M^2 - (m_1 - m_2)^2 \right) \right]^{1/2}. \] (34.20b)

However, \( \Omega_{12} \) is not the angle of particle 3 in the rest frame of 1 and 2, but \( \Omega_{12} \) is the angle of particle 3 in the rest frame of the decaying particle.\[\text{[Compare with Eq. (34.16).]}\]

If the decaying particle is a scalar or we average over its spin states, then the integration over the angles in Eq. (34.18) gives

\[
d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{8M^2} \left| \mathbf{\mathcal{M}} \right|^2 \, df_{E_1} \, df_{E_2}
\]

\[
= \frac{1}{(2\pi)^3} \frac{1}{32M^4} \left| \mathbf{\mathcal{M}} \right|^2 \, df_{m_{12}} \, df_{\Omega_{12}} \, df_{\Omega_{13}}.
\] (34.21)

This is the standard form for the Dalitz plot.

34.4.3.1. Dalitz plot: For a given value of \( m_{12}^2 \), the range of \( m_{23}^2 \) is determined by its values when \( p_2 \) is parallel or antiparallel to \( p_3 \).

\[
\langle m_{23}^2 \rangle_{\text{max}} = (E_2^* + E_3^*)^2 - \left( \sqrt{E_2^* - m_2^2} - \sqrt{E_3^* - m_3^2} \right)^2,
\] (34.22a)

\[
\langle m_{23}^2 \rangle_{\text{min}} = (E_2^* + E_3^*)^2 - \left( \sqrt{E_2^* - m_2^2} + \sqrt{E_3^* - m_3^2} \right)^2.
\] (34.22b)

Here \( E_2^* = (m_{12}^2 - m_1^2 + m_2^2)/2m_{12} \) and \( E_3^* = (M^2 - m_1^2 - m_2^2)/2m_{12} \) are the energies of particles 2 and 3 in the \( m_{12} \) rest frame. The scatter plot in \( m_{12}^2 \) and \( m_{23}^2 \) is called a Dalitz plot. If \( \left| \mathbf{\mathcal{M}} \right|^2 \) is constant, the allowed region of the plot will be uniformly populated with events [see Eq. (34.21)]. A nonuniformity in the plot gives immediate information on \( \left| \mathbf{\mathcal{M}} \right|^2 \). For example, in the case of \( D \to K^* \pi \), bands appear when \( m(K\pi) = m(K^{*}(892)) \), reflecting the appearance of the decay chain \( D \to K^{*}(892) \pi \to K^* \).

34.4.4. Kinematic limits: In a three-body decay the maximum of \( \left| \mathbf{p}_{1}^* \right| \) (given by Eq. (34.20)), is achieved when \( m_{12} = m_1 + m_2 \), i.e., particles 1 and 2 have the same vector velocity in the rest frame of the decaying particle. If, in addition, \( m_3 > m_1, m_2 \), then \( \left| \mathbf{p}_{1}^* \right|_{\text{max}} > \left| \mathbf{p}_{3} \right|_{\text{max}}, \left| \mathbf{p}_{2} \right|_{\text{max}}. \)

Figure 34.3: Dalitz plot for a three-body final state. In this example, the state is \( \pi^{0} K^{0} p \) at 3 GeV. Four-momentum conservation restricts events to the shaded region.

34.4.5. Multibody decays: The above results may be generalized to final states containing any number of particles by combining some of the particles into “effective particles” and treating the final states as 2 or 3 “effective particle” states. Thus, if \( p_{ijk} = p_i + p_j + p_k + \ldots \),

\[
m_{ijk} = \sqrt{p_{ijk}^2},
\] (34.23)

\( m_{ijk} \) may be used in place of \( e.g., m_{12} \) in the relations in Sec. 34.4.3 or 34.4.3.1 above.

Figure 34.4: Definitions of variables for production of an \( n \)-body final state.

34.5. Cross sections

The differential cross section is given by

\[
\frac{d\sigma}{d\Omega_{12}} = \frac{(2\pi)^5}{4} \left| \mathbf{\mathcal{M}} \right|^2 \left( p_1 \cdot p_2 \right)^2 - m_1^2 m_2^2
\times \left( \Phi_{1} + \Phi_{2} + \Phi_{3} + \ldots + \Phi_{n+2} \right).
\] (34.24)

[See Eq. (34.11).] In the rest frame of the \( m_{2\text{lab}} \),

\[
\left( p_1 \cdot p_2 \right)^2 - m_1^2 m_2^2 = m_{2\text{lab}} p_{1\text{lab}} \to \sqrt{m_{2\text{lab}}^2 - m_1^2 m_2^2} = m_{2\text{lab}} \to \sqrt{m_{2\text{lab}}^2 - m_1^2 m_2^2} = p_{1\text{lab}} \sqrt{s}.
\] (34.25a)

while in the center-of-mass frame

\[
\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2} = p_{1\text{cm}} \sqrt{s}.
\] (34.25b)

34.5.1. Two-body reactions:

Figure 34.5: Definitions of variables for a two-body final state.
Two particles of momenta $p_1$ and $p_2$ and masses $m_1$ and $m_2$ scatter to particles of momenta $p_3$ and $p_4$ and masses $m_3$ and $m_4$; the Lorentz-invariant Mandelstam variables are defined by

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

(34.26)

(34.27)

(34.28)

and they satisfy

$$s + t + u = m_1^2 + m_2^2 + m_3^2 + m_4^2.$$  

(34.29)

The two-body cross section may be written as

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s} \frac{1}{|p_{cm}|^2} |\mathcal{M}|^2.$$  

(34.30)

In the center-of-mass frame

$$t = (E_{1cm} - E_{3cm})^2 - (p_{1cm} - p_{3cm})^2 - 4p_{1cm}p_{3cm}\sin^2(\theta_{cm}/2)$$
$$= t_0 - 4p_{1cm}p_{3cm}\sin^2(\theta_{cm}/2),$$  

(34.31)

where $\theta_{cm}$ is the angle between particle 1 and 3. The limiting values $t_0$ ($\theta_{cm} = 0$) and $t_1$ ($\theta_{cm} = \pi$) for $2 \to 2$ scattering are

$$t_0(t_1) = \left(\frac{m_1^2 - m_3^2 - m_2^2 + m_4^2}{2\sqrt{s}}\right)^2 - (p_{1cm} \mp p_{3cm})^2.$$  

(34.32)

In the literature the notation $t_{\text{min}}$ ($t_{\text{max}}$) for $t_0$ ($t_1$) is sometimes used, which should be discouraged since $t_0 > t_1$. The center-of-mass energies and momenta of the incoming particles are

$$E_{1cm} = \frac{s + m_3^2 - m_1^2}{2\sqrt{s}}, \quad E_{2cm} = \frac{s + m_2^2 - m_3^2}{2\sqrt{s}}.$$  

(34.33)

For $E_{3cm}$ and $E_{4cm}$, change $m_1$ to $m_3$ and $m_2$ to $m_4$. Then

$$p_{cm} = \frac{\sqrt{E_{cm}^2 - m_1^2}}{s}$$

and $p_{cm} = \frac{p_{lab}m_2}{\sqrt{s}}$.

(34.34)

Here the subscript $lab$ refers to the frame where particle 2 is at rest. [For other relations see Eqs. (34.2)–(34.4).]

34.5.2. **Inclusive reactions.** Choose some direction (usually the beam direction) for the $z$-axis; then the energy and momentum of a particle can be written as

$$E = m_T \cosh y, \quad p_x = p_y = p_z = m_T \sinh y,$$  

(34.35)

where $m_T$ is the transverse mass

$$m_T^2 = m^2 + p_T^2 + y^2,$$  

(34.36)

and the rapidity $y$ is defined by

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z}\right) = \ln \left(\frac{E + p_z}{m_T}\right).$$  

(34.37)

Under a boost in the $z$-direction to a frame with velocity $\beta$, $y \to y - \tanh^{-1} \beta$. Hence the shape of the rapidity distribution $dN/dy$ is invariant. The invariant cross section may also be rewritten

$$d\sigma = \frac{d\sigma}{dy dp_2 dp_T} \rightarrow \frac{d\sigma}{\pi dy dp_T^2}.$$  

(34.38)

The second form is obtained using the identity $dy dp_2 = 1/E$, and the third form represents the average over $\phi$.

Feynman’s $x$ variable is given by

$$x = \frac{p_T}{p_T \text{max}} \approx \frac{E + p_z}{(E + p_T \text{max})} (p_T \ll |p_z|).$$  

(34.39)

In the c.m. frame,

$$x \approx \frac{2p_{cm}}{\sqrt{s}} = \frac{2m_T \sinh y_{cm}}{\sqrt{s}}$$

and

$$y_{cm} = \ln (\sqrt{s}/m).$$  

(34.40)

(34.41)

For $p \gg m$, the rapidity $y$ for $p_{cm}$ and $\theta \gg 1/\gamma$, and in any case can be measured when the mass and momentum of the particle is unknown. From the definition one can obtain the identities

$$\sinh y = \cot \theta, \quad \cosh y = 1/\sin \theta, \quad \tanh y = \cos \theta.$$  

(34.42)

(34.43)

34.5.3. **Partial waves.** The amplitude in the center of mass for elastic scattering of spinless particles may be expanded in Legendre polynomials

$$f(k, \theta) = \frac{1}{k} \sum_{l}(2l + 1)\alpha_l P_l(\cos \theta),$$  

(34.44)

where $k$ is the c.m. momentum, $\theta$ is the c.m. scattering angle, $\alpha_l = (\eta \epsilon^{2k-1} - 1)/2i$, $0 \leq \eta \epsilon \leq 1$, and $\delta_l$ is the phase shift of the $l$th partial wave. For purely elastic scattering, $\eta = 1$. The differential cross section is

$$\frac{d\sigma}{d\Omega} = |f(k, \theta)|^2.$$  

(34.45)

The optical theorem states that

$$\sigma_{tot} = \frac{4\pi}{k} \text{Im} f(k, 0),$$  

(34.46)

and the cross section in the $l$th partial wave is therefore bounded:

$$\sigma_l = \frac{4\pi}{k^2} (2l + 1)\alpha_l^2 \leq \frac{4\pi(2l + 1)}{k^2}.$$  

(34.47)

The evolution with energy of a partial-wave amplitude $\alpha_l$ can be displayed as a trajectory in an Argand plot, as shown in Fig. 34.6.

**Figure 34.6:** Argand plot showing a partial-wave amplitude $\alpha_l$ as a function of energy. The amplitude leaves the unitary circle where inelasticity sets in ($\eta<1$).

The usual Lorentz-invariant matrix element $\mathcal{M}$ (see Sec. 34.3 above) for the elastic process is related to $f(k, \theta)$ by

$$\mathcal{M} = -8\pi \sqrt{s} f(k, \theta),$$  

(34.48)

so

$$\sigma_{tot} = \frac{1}{2p_{lab}m_2} \text{Im} \mathcal{M}(t = 0),$$  

(34.49)

where $s$ and $t$ are the center-of-mass energy squared and momentum transfer squared, respectively (see Sec. 34.4.1).
34.5.3.1. **Resonances:** The Breit-Wigner (nonrelativistic) form for an elastic amplitude $a_{\ell}$ with a resonance at c.m. energy $E_R$, elastic width $\Gamma_{el}$, and total width $\Gamma_{tot}$ is

$$a_{\ell} = \frac{\Gamma_{el}/2}{E_R - E - i\frac{\Gamma_{tot}}{2}}. \tag{34.50}$$

where $E$ is the c.m. energy. As shown in Fig. 34.7, in the absence of background the elastic amplitude traces a counterclockwise circle with center $ix_{el}/2$ and radius $x_{el}/2$, where the elasticity $x_{el} = \Gamma_{el}/\Gamma_{tot}$. The amplitude has a pole at $E = E_R - i\frac{\Gamma_{tot}}{2}$.

The spin-averaged Breit-Wigner cross section for a spin-$J$ resonance produced in the collision of particles of spin $S_1$ and $S_2$ is

$$\sigma_{BW}(E) = \frac{(2J + 1)}{(2S_1 + 1)(2S_2 + 1)} \frac{\pi}{k^2} \frac{B_{in}B_{out}\Gamma_{tot}^2}{(E - E_R)^2 + \Gamma_{tot}^2/4}. \tag{34.51}$$

where $k$ is the c.m. momentum, $E$ is the c.m. energy, and $B_{in}$ and $B_{out}$ are the branching fractions of the resonance into the entrance and exit channels. The $2S + 1$ factors are the multiplicities of the incident spin states, and are replaced by 2 for photons. This expression is valid only for an isolated state. If the width is not small, $\Gamma_{tot}$ cannot be treated as a constant independent of $E$. There are many other forms for $\sigma_{BW}$, all of which are equivalent to the one given here in the narrow-width case. Some of these forms may be more appropriate if the resonance is broad.

The relativistic Breit-Wigner form corresponding to Eq. (34.50) is:

$$a_{\ell} = \frac{-m\Gamma_{el}}{s - m^2 + i\frac{\Gamma_{tot}}{2}}. \tag{34.52}$$

A better form incorporates the known kinematic dependences, replacing $m\Gamma_{tot}$ by $\sqrt{s}\Gamma_{tot}(s)$, where $\Gamma_{tot}(s)$ is the width the resonance particle would have if its mass were $\sqrt{s}$, and correspondingly $m\Gamma_{el}$ by $\sqrt{s}\Gamma_{el}(s)$ where $\Gamma_{el}(s)$ is the partial width in the incident channel for a mass $\sqrt{s}$.

$$a_{\ell} = \frac{-\sqrt{s}\Gamma_{el}(s)}{s - m^2 + i\sqrt{s}\Gamma_{tot}(s)} \tag{34.53}$$

For the $Z$ boson, all the decays are to particles whose masses are small enough to be ignored, so on dimensional grounds $\Gamma_{tot}(s) = \sqrt{s}\Gamma_0/m_Z$, where $\Gamma_0$ defines the width of the $Z$, and $\Gamma_{el}(s)/\Gamma_{tot}(s)$ is constant. A full treatment of the line shape requires consideration of dynamics, not just kinematics. For the $Z$ this is done by calculating the radiative corrections in the Standard Model.

**References:**