$$t_0(t_1) = \left[\frac{m_1^2 - m_3^2 - m_2^2 + m_4^2}{2\sqrt{s}}\right]^2$$
$$-\left\{\left[\left(\frac{s + m_1^2 - m_2^2}{2\sqrt{s}}\right)^2 - m_1^2\right]^{1/2}\right.$$
$$\left.\mp\left[\left(\frac{s + m_3^2 - m_4^2}{2\sqrt{s}}\right)^2 - m_3^2\right]^{1/2}\right\}^2 . \tag{23.34}$$

Note that t_1 is always negative. In the literature the notation $t_{\rm min}$ ($t_{\rm max}$) for t_0 (t_1) is sometimes used. This usage should be discouraged since $t_0 > t_1$. The center-of-mass energies and momenta of the incoming particles are

$$E_{\rm cm} = \frac{s + m_1^2 - m_2^2}{2\sqrt{s}} , \tag{23.35}$$

$$p_{\rm cm} = \frac{\left[\left(s - (m_1 + m_2)^2\right)\left(s - (m_1 - m_2)^2\right)\right]^{1/2}}{2\sqrt{s}}$$
$$= \frac{p_{1\,\rm lab} m_2}{\sqrt{s}} , \tag{23.36}$$

Here the subscript lab refers to the frame where particle 2 is at rest. [For other relations see Eqs. (23.2)–(23.4).]

23.5.2. *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

$$E = m_T \cosh y \ , \ p_x \ , \ p_y \ , \ p_z = m_T \sinh y \ , \tag{23.37}$$

where m_T is the transverse mass

$$m_T^2 = m^2 + p_x^2 + p_y^2 , \tag{23.38}$$

and the rapidity y is defined by

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$
$$= \ln\left(\frac{E + p_z}{m_T}\right) = \tanh^{-1}\left(\frac{p_z}{E}\right) . \tag{23.39}$$

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

$$E\frac{d^3\sigma}{d^3p} = \frac{d^3\sigma}{d\phi\, dy\, p_T dp_T} \Longrightarrow \frac{d^2\sigma}{\pi\, dy\, d(p_T^2)} . \tag{23.40}$$