Machine Learning-Enhanced Feasibility Studies on the Production of New Particles with Preferential Couplings to Third Generation Fermions at the LHC

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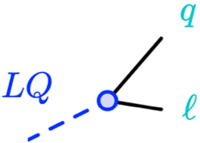
Outline

The vector leptoquark U_1 model

A leptoquark is defined as a particle with a vertex that mix vectors and quarks.

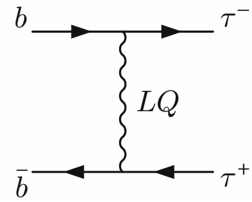


If U_1 is a vector leptoquark that preserves the chirality on the vertex, we expect an interaction term like

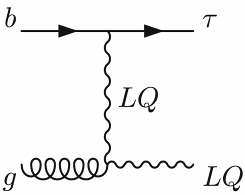
$$\sim \beta_L U_1^{\mu} \bar{q}_L \gamma_\mu \ell_L,$$

and these allows a similar interaction term for the right handed currents

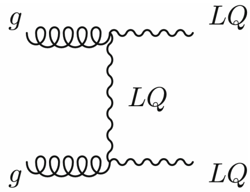
$$\sim \beta_R U_1^{\mu} \bar{d}_R \gamma_\mu e_R.$$



Non-resonant

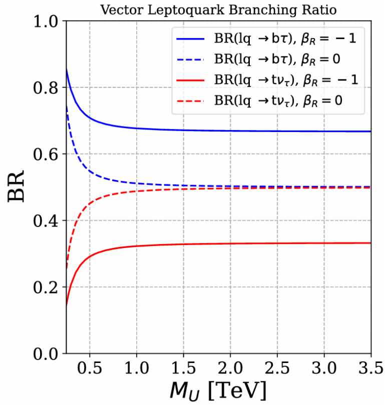


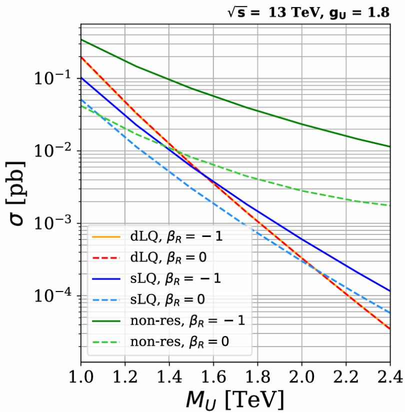
Single LQ



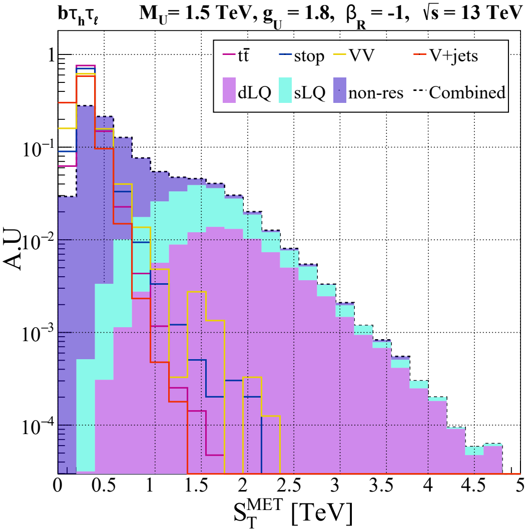
Double LQ

Leptoquark Production at pp Colliders

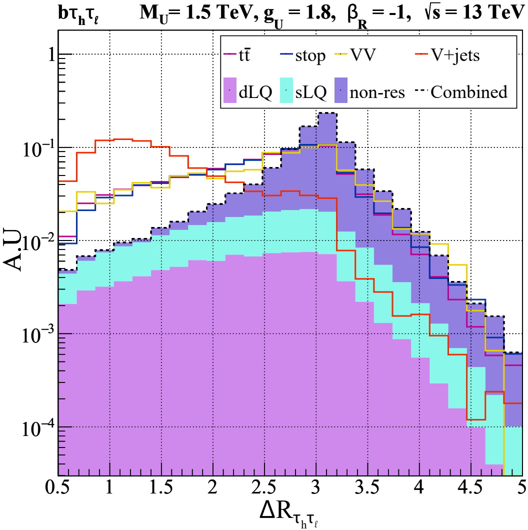




$S_T^{\mathrm{meT}} = \mathrm{met} + \sum_i |p_T^i|$



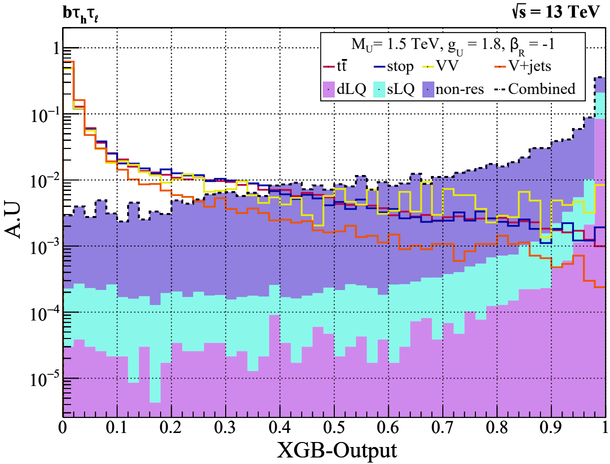
$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$



The optimized observable

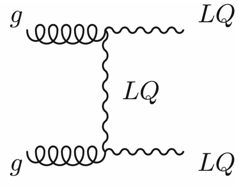
XGB-output

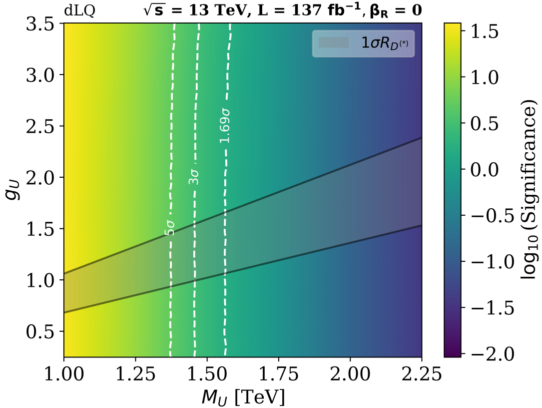
We can evaluate a score for the signal and background events using the discriminator algorithm.



Double Leptoquark Production

The Sensitivity Reach / only left-handed currents

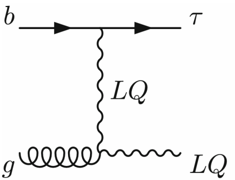


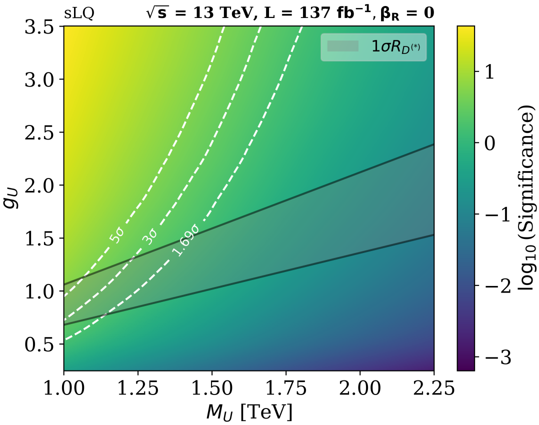


Double leptoquark production is sensitive to the leptoquark mass, its production depends only on the QCD coupling constant and the available energy.

Single leptoquark production

The Sensitivity Reach / only left-handed currents

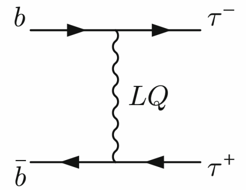


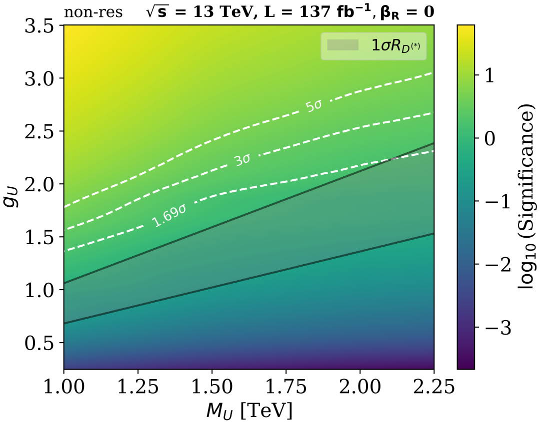


Single leptoquark production is sensitive to both, mass and couplings. It contributes to the regions of high coupling constants at higher masses than double leptoquark production.

Non-resonant Production

The Sensitivity Reach / only left-handed currents

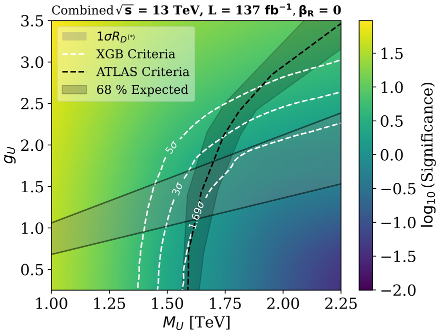


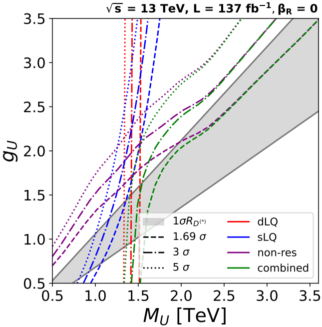


Non-resonant production is highly dependent on the couplings, so it dominates the regions of high coupling constants at all masses.

Combined Sensitivity Reach

The Sensitivity Reach / only left-handed currents

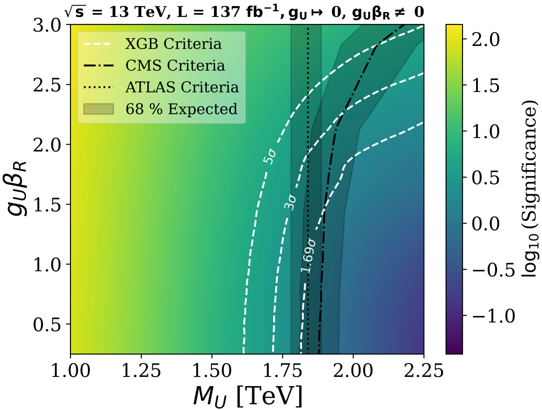




The sensitivity of all signal production processes combined compares our expected exclusion region with the latest one from the ATLAS Collaboration [ArXiv:2305.15962], but we suggest better sensitivity for high coupling constants.

Combined Sensitivity Reach

The Sensitivity Reach / only right-handed currents



The case $BR(lq \to b\tau) = 1$ corresponds to the only right-handed currents coupling. The sensitivity compared with the latest one from the CMS [2308.07826] and ATLAS Collaborations [2303.01294], again we suggest better sensitivity for high coupling constants.

The need of a Z' boson in gauge U_1 models

If U_1 has a gauge origin, we could rewrite the interaction term in the covariant derivative as

$$\psi_L^{\text{SM}} = \begin{pmatrix} q_{Lr} \\ q_{Lg} \\ q_{Lb} \\ \ell_L \end{pmatrix} \implies \mathcal{L}_{\text{int}} \sim U^{\mu}_{1\alpha} \bar{\psi}_L^{\text{SM}} \gamma_\mu T_+^\alpha \psi_L^{\text{SM}} + \text{h.c.}, \quad T_+^\alpha = \begin{pmatrix} 0 & 0 & 0 & \delta_{r\alpha} \\ 0 & 0 & 0 & \delta_{g\alpha} \\ 0 & 0 & 0 & \delta_{b\alpha} \\ 0 & 0 & 0 & 0 \end{pmatrix},$$

we have six generators $T_\pm^\alpha$ with closure relation and projecting into a color singlet operator:

$$\sum_\alpha \left[T_+^\alpha, T_-^\alpha\right] = 3T_{B-L} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -3 \end{pmatrix}.$$

So, the gauge group with this leptoquark must include a $U(1)_{B-L}$ symmetry (The right-handed currents also have a similar interaction term).

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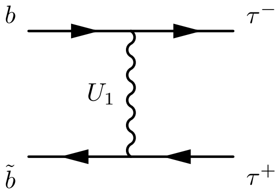
The interaction terms for the Z' boson have the form

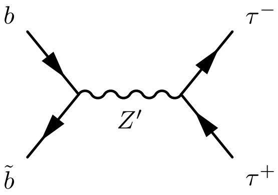
$$\begin{aligned} \mathcal{L}_{\rm int} &\sim Z'_\mu \left(\bar{\psi}_L^{\rm SM} \gamma^\mu (3T_{B-L}) \psi_L^{\rm SM}\right) \\ &\sim Z'_\mu \left(\bar{q}_L \gamma^\mu q_L - 3\bar{\ell}_L \gamma^\mu \ell_L\right). \end{aligned}$$

Interference with a Z' vector boson

Non-Resonant Production (leptoquarks)



Resonant Production (neutral bosons)



so

$$\mathcal{M}_{U_1} \sim \frac{1}{t - m_{U_1}^2 + i m_{U_1}\Gamma_{U_1}}, \qquad (1)$$

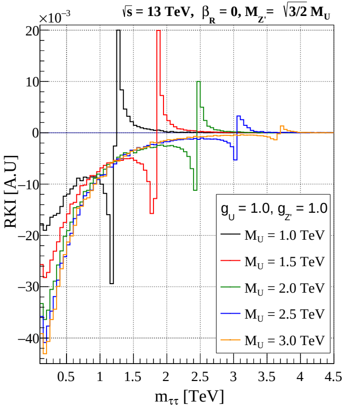
$$\mathcal{M}_{Z'} \sim \frac{1}{s - m_{Z'}^2 + i m_{Z'}\Gamma_{Z'}}, \qquad (2)$$

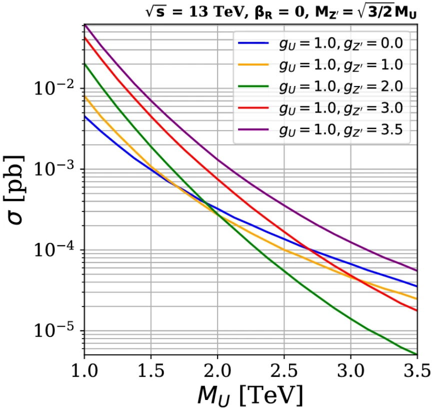
the interference has the form

$$\frac{\mathrm{d}}{\mathrm{d}m}\left[\sigma_{LQ+Z'} - \left(\sigma_{LQ} + \sigma_{Z'}\right)\right] \sim \frac{g_{z'}g_U}{s}\frac{m_{LQ}m_{Z'}\Gamma_{LQ}\Gamma_{Z'} - (t - m_{LQ}^2)(s - m_{Z'}^2)}{\left[(t - m_{LQ}^2)^2 + m_{LQ}^2\Gamma_{LQ}^2\right]\left[(s - m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2\right]}.$$

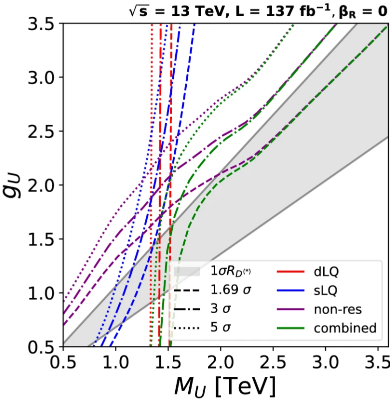
Similary for Polarized final states.

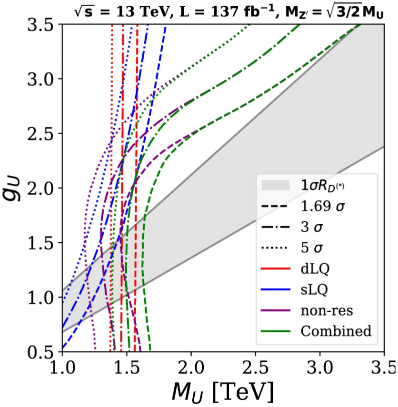
Interference with a Z' vector boson





Effects on the Sensitivity reach





Where the SM charges for the leptoquark, in the $Y = 2(Q - T_3)$ convention, are

	$\bar{q}_L$	ℓ_L^j	$\bar{q}_L \gamma_\mu \ell_L$	U_1^μ
$U(1)$	$-1/3$	-1	$-4/3$	$+4/3$
SU(2)	$\bar{\mathbf{2}}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
SU(3)	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{3}$

Then, the leptoquark $U_1 \sim (\mathbf{3}_C, \mathbf{1}_I, 4/3_Y)$.

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The full Lagrangian for the vector leptoquark is

$$\mathcal{L}_U = -\frac{1}{2} U_{\mu\nu}^\dagger U^{\mu\nu} + M_U^2 U_\mu^\dagger U^\mu - i g_s U_\mu^\dagger T^a U_\nu G_a^{\mu\nu} - \frac{2i}{3} g' U_\mu^\dagger U_\nu B^{\mu\nu}$$
$$+ \frac{g_U}{\sqrt{2}} \left[U_1^\mu \left(\beta_L^{ij} \bar{q}_L^i \gamma_\mu e_L^j + \beta_R^{ij} \bar{d}_R^i \gamma_\mu e_R^j \right) + \text{ h.c. } \right]$$

where $U_{\mu\nu} = \mathcal{D}_\mu U_\nu - \mathcal{D}_\nu U_\mu$, $\mathcal{D}_\mu = \partial_\mu - i g_s G_\mu^a T^a - i \frac{2}{3} g_Y B_\mu$, and the couplings β_L and β_R are complex 3×3 matrices in flavor space.

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where $U_{\mu\nu} = \mathcal{D}_\mu U_\nu - \mathcal{D}_\nu U_\mu$, $\mathcal{D}_\mu = \partial_\mu - ig_s G_\mu^a T^a - i\frac{2}{3}g_Y B_\mu$, and the couplings β_L and β_R are complex 3×3 matrices in flavor space.

Constraints from $\Delta F = 2$ and lepton flavor violation impose a hierarchy with dominant third generation couplings:

$$\left|\beta_L^{11}\right|, \left|\beta_L^{12}\right|, \left|\beta_L^{21}\right|, \left|\beta_L^{22}\right|, \left|\beta_L^{31}\right| \ll \left|\beta_L^{13}\right| \ll \left|\beta_L^{23}\right|, \left|\beta_L^{32}\right| \ll \left|\beta_R^{33}\right|, \left|\beta_L^{33}\right| = \mathcal{O}(1), \quad (3)$$

where β_R is diagonal.

Two body scattering

CM-Frame

Consider the process

$$A(\vec{p}_1) + B(\vec{p}_2) \longrightarrow C(\vec{p}_3) + D(\vec{p}_4), \tag{4}$$

From the Golden Rule, the cross section is given by

$$\sigma = \frac{n!(2\pi)^4}{4\sqrt{(\vec{p}_1 \cdot \vec{p}_2)^2 - (m_1 m_2)^2}} \int |\mathcal{M}|^2 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) \frac{d^3\vec{p}_3}{(2\pi)^3 2E_3} \frac{d^3\vec{p}_4}{(2\pi)^3 2E_4}. \tag{5}$$

But, in the CM frame, $\vec{p}_1 + \vec{p}_2 = 0$, where

$$\sqrt{(\vec{p}_1 \cdot \vec{p}_2)^2 - (m_1 m_2)^2} = E_1 E_2 |\vec{p}_1|, \tag{6}$$

$$\delta^{(4)}(p_1 + p_2 - p_3 - p_4) = \delta\left(E_1 + E_2 - E_3 - E_4\right) \delta^{(3)}(\vec{p}_3 + \vec{p}_4). \tag{7}$$

Thus

$$\sigma = \left(\frac{1}{8\pi}\right)^2 \frac{n!}{(E_1 E_2)|\vec{p}_1|} \int |\mathcal{M}|^2 \frac{\delta\left(E_1 + E_2 - \sqrt{\vec{\mathbf{p}}_3^2 + m_3^2} - \sqrt{\vec{\mathbf{p}}_3^2 + m_4^2}\right)}{\sqrt{\vec{\mathbf{p}}_3^2 + m_3^2}\sqrt{\vec{\mathbf{p}}_3^2 + m_4^2}} \mathrm{d}\vec{\mathbf{p}}_3 \tag{8}$$

Integrating over the radial part $|\vec{\mathbf{p}}_3|$, we get

$$\sigma = \left(\frac{1}{8\pi}\right)^2 \frac{n!|\vec{p}_3|}{(E_1+E_2)^2|\vec{p}_1|} \int |\mathcal{M}|^2 \mathrm{d}\Omega, \tag{9}$$

with

$$|\vec{p}_3| = \frac{1}{2}\frac{\sqrt{((E_1+E_2)^2 - m_3^2 - m_4^2)^2 - 4m_3^2 m_4^2}}{E_1+E_2}, \tag{10}$$

the outgoing momentum in the CM frame.

We prefer work with differential cross section as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{64\pi^2}\frac{n!}{(E_1+E_2)^2}\frac{|\vec{p}_3|}{|\vec{p}_1|}|\mathcal{M}|^2. \tag{11}$$

Defining $\sqrt{s} = E_1 + E_2$, we have

$$|\vec{p}_3| = \frac{1}{2}\frac{\sqrt{(s - m_3^2 - m_4^2)^2 - 4m_3^2 m_4^2}}{\sqrt{s}}, \quad |\vec{p}_1| = \frac{1}{2}\frac{\sqrt{(s - m_1^2 - m_2^2)^2 - 4m_1^2 m_2^2}}{\sqrt{s}}. \tag{12}$$

so the differential cross section is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{64\pi^2}\frac{n!}{s}\sqrt{\frac{(s-(m_3+m_4)^2)(s-(m_3-m_4)^2)}{(s-(m_1+m_2)^2)(s-(m_1-m_2)^2)}}|\mathcal{M}|^2. \tag{13}$$

Note that at this point, we don't need to know the explicit form of the matrix element $\mathcal{M}$, so it is a generic result.

Writting t in terms of s and θ

In general, there are three Lorentz-invariant useful kinematical variables to describe the scattering process, known as Mandelstam variables:

$$\hat{s} = (p_1 + p_2)^2 = (p_3 + p_4)^2 = m_1^2 + m_2^2 + 2p_1^\mu p_{2\mu} = m_3^2 + m_4^2 + 2p_3^\mu p_{4\mu}, \tag{14}$$

$$\hat{t} = (p_1 - p_3)^2 = (p_2 - p_4)^2 = m_1^2 + m_3^2 - 2p_1^\mu p_{3\mu} = m_2^2 + m_4^2 - 2p_2^\mu p_{4\mu}, \tag{15}$$

$$\hat{u} = (p_1 - p_4)^2 = (p_2 - p_3)^2 = m_1^2 + m_4^2 - 2p_1^\mu p_{4\mu} = m_2^2 + m_3^2 - 2p_2^\mu p_{3\mu}. \tag{16}$$

In the CM-frame, $\hat{s} = s = (E_1 + E_2)^2$. If, $m_3 = m_4$ and $m_1 = m_2$ with $E_1 = E_2 = E_3 = E_4 = E$, we have

$$t = -\left(\vec{\mathbf{p}}_1 - \vec{\mathbf{p}}_3\right)^2 = -\vec{\mathbf{p}}_1^2 - \vec{\mathbf{p}}_3^2 + 2\vec{\mathbf{p}}_1\vec{\mathbf{p}}_3 \tag{17}$$

where $\vec{\mathbf{p}}_1^2 = E^2 - m_1^2$ and $\vec{\mathbf{p}}_3^2 = E^2 - m_3^2$.

So, in terms of s, t could be written as

$$t = -2s + (m_1^2 + m_3^2) + 2\sqrt{(s/4 - m_1^2)(s/4 - m_3^2)}\cos\theta, \tag{18}$$

with θ the scattering angle in the CM-frame.