2.7 Automation of the leading order calculations for $e^+e^- \to$ hadrons

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After some modifications, `carlomat` [1, 2], a program for automatic computation of the leading order (LO) cross sections of multiparticle reactions, that was originally dedicated mainly to description of the processes of production and decay of heavy particles such as top quarks, the Higgs boson, or electroweak gauge bosons, can be used to obtain predictions for $e^+e^- \to$ hadrons in the framework of effective models. At low energies, the hadronic final states consist mostly of pions, kaons, or nucleons which can be accompanied by one or more photons, or light fermion pairs such as e^+e^-, or $\mu^+\mu^-$. Some effective models which can be useful in this context, including the scalar electrodynamics (sQED) and the Wtb interaction with operators of dimension up to 5, were already implemented in version 2 of the program [2].

The effective Lagrangian of the Wtb interaction has the following form [3]:

$$L_{Wtb} = \frac{g}{\sqrt{2}} V_{tb} \left[W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{1}{m_W} \partial_\nu W_\mu^- \bar{b}\, \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t \right] + \text{h.c.}, \quad (3)$$

where the couplings f_i^L, f_i^R, $i = 1, 2$, can be complex in general. The electromagnetic (EM) interaction of spin 1/2 nucleons has a similar form:

$$L_{\gamma NN} = e A_\mu \bar{N}(p') \left[\gamma^\mu F_1(Q^2) + \frac{i}{2m_N} \sigma^{\mu\nu} q_\nu F_2(Q^2) \right] N(p). \quad (4)$$

The form factors $F_1(Q^2)$ and $F_2(Q^2)$, where $Q^2 = -(p - p')^2$, were adopted from `PHOKARA` [4], thus making possible Monte Carlo (MC) simulations of processes involving the EM interaction of nucleons.

At low energies, $\pi^\pm$ can be treated as point like particles and their EM interaction can be effectively described in the framework of sQED [5] the interaction vertices examples of which are shown in Fig. 5.

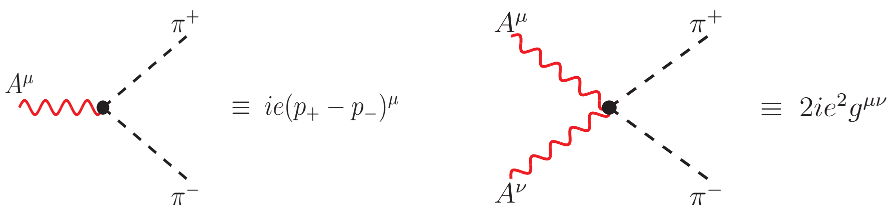

Figure 5: Vertices of sQED

Another step toward better description of $e^+e^- \to$ hadrons at low energies is the inclusion of the Feynman rules of the Resonance Chiral Perturbation Theory (RChPT). The interaction vertices and particle mixing terms of RChPT that can be relevant in this context were provided by Fred Jegerlehner [6]. Some examples of them are shown in Figs. 6 and 7. The implementation of the triple and quartic interaction vertices was more or less straightforward, as it just required writing a few new subroutines for computation of the helicity amplitudes involving the Lorentz tensors that are different from those of the sQED vertices. The couplings $f_{\gamma PP}$, $f_{\rho^0 PP}$, $g_{\gamma\rho^0\pi\pi}$, $g_{\pi\gamma\gamma}$, $g_{\pi^0\gamma\rho^0}$ and $g_{\gamma\pi\pi\pi}$ are currently set either to 1 or e. However, implementation of the particle mixing is more challenging, because it must be added at the stage, where the topologies of diagrams which, in `carlomat`, contain only triple and quartic vertices, are confronted with the Feynman rules. This required substantial changes in the code generating part of the program.

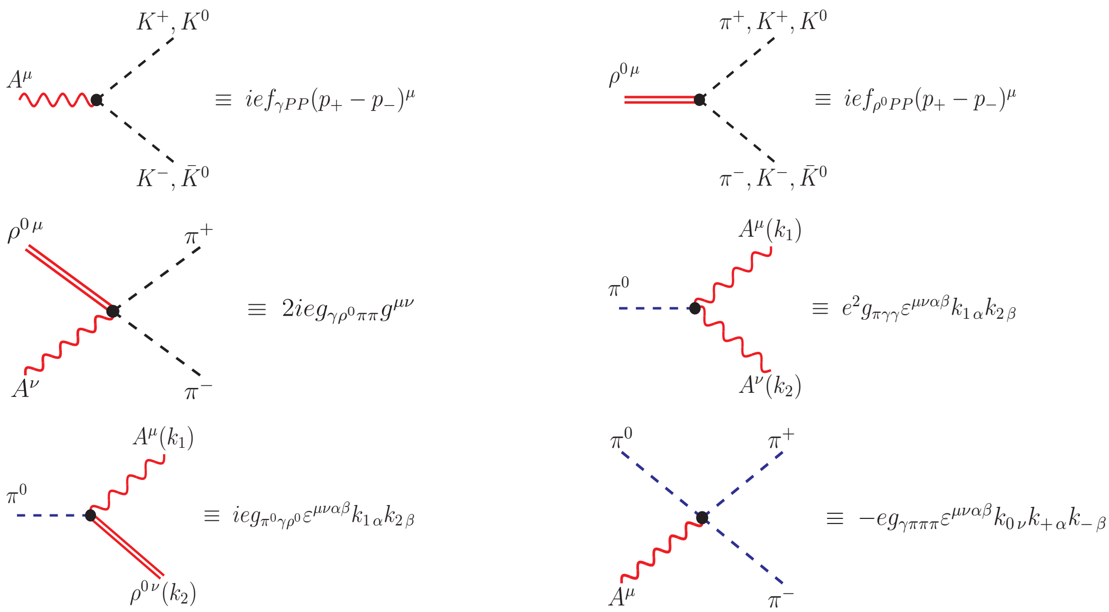

Figure 6: Examples of triple and quartic vertices of RChPT.

Figure 7: Examples of the particle mixing.

To illustrate how the program works, consider the process $e^+e^- \to \pi^+\pi^-\pi^+\pi^-\gamma$. Taking into account the Feynman rules of the standard model and the rules of Figs. 5, 6 and 7, `carlomat` generates the $U(1)$ gauge invariant matrix element, which receives contributions from 903 LO Feynman diagrams, together with a dedicated multichannel phase space integration routine in just a few seconds. A computation of the total cross section, including any number of differential distributions, which is performed as the next step, takes several dozen seconds or several minutes time, dependent on the desired precision of the MC integration.

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