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Looking for new single heavy leptons in electron-positron collisions

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We discuss the production and decay of possible new heavy leptons in some extensions of the standard model. We present a comparison between models and the recent results from the CERN e^+e^- collider LEP and analyze the most reliable signatures for heavy leptons in the reaction $e^+e^- \to lL$. A clear separation among models and masses can be done using a Monte Carlo reconstruction of the events.

I. INTRODUCTION

The recent results from the CERN e^+e^- collider LEP imply two main conclusions. They show a remarkable agreement with the standard model and no signal of "new physics." In practically all the generalizations of the standard model one has new particles and experiment must decide which one is realized in nature, if any. This is the case for pair production of new leptonic degrees of freedom up to the kinematical limit $M_Z/2$. Another search, for single production, was done in the region of masses between $M_Z/2$ and M_Z. In both cases no new particles were found. In this last case most experimental searches were done in radiative channels of the type $L \to l\gamma$. Limits on couplings were obtained using an effective interaction Lagrangian. We would like to mention that no intensive study has been done for single heavy lepton production in extended gauge models.

If a heavy lepton is experimentally found the main question to be answered is its theoretical origin. In this paper we have compared predictions from different models in order to establish the theoretical source of possible new single heavy leptons produced in e^+e^- collisions. In Sec. II we present the general interactions of the new leptons in three different models: the vector singlet (VSM), the fermion–mirror-fermion (FMF), and the vector doublet (VDM) models. The mixing angle bounds and the decays for new heavy leptons are discussed in Sec. III. In Sec. IV we show our results for the total cross section and a Monte Carlo reconstruction of the most significant distribution of the final-state particles. We have concentrated our attention on new heavy leptons in the mass range between $M_Z/2$ and M_Z. Our main results can be extended to higher energies. Finally in Sec. V we resume our conclusions.

II. MODELS

The general charged and neutral interactions of the new leptons (L^0, L^-) mixed with the usual ones and the standard W and Z can be written as

$$\mathcal{L}_{\rm CC} = \frac{-g}{2\sqrt{2}}[\bar{L}^0\gamma^\mu(a_1 - b_1\gamma^5)e^- + \bar{\nu}\gamma^\mu(a_2 - b_2\gamma^5)L^-]W_\mu \tag{1}$$

and

$$\mathcal{L}_{\rm NC} = \frac{-g}{4\cos\theta_W}\sum_{i,j}[\bar{f}_i\gamma^\mu(v - a\gamma^5)f_j]Z_\mu \,. \tag{2}$$

As examples of the theoretical motivation we have analyzed three models. The models differ in the assignments of the fundamental representations although they have different physical motivations. The VDM has a natural place in the superstring-inspired scenario [1]. A new neutral lepton (L^0) and new charged leptons $(L^\pm)$ are in doublets with right and left helicities. In the FMF model [2] the right-left symmetry is restored through a new right-handed doublet and new left-handed singlets. The VSM [3] is a simple realization of the seesaw mechanism and includes new left- and right-handed L^0, L^- in singlets. Following the notation of Ref. [1] the mixing parameters are given in Table I.

Since we have single heavy lepton production in e^+e^- mediated by the Z^0 we first concentrate our attention to the neutral-current couplings in Table I. The VDM and VSM show a very clear difference: whereas the first one is pure $V+A$, the second one is pure $V-A$. The general FMF model can have arbitrary V, A couplings. A reasonable hypothesis in the right-left-symmetric scenario is to have equal right and left angles [2] with purely axial-vector neutral currents. We have also considered the case $\theta_L = -\theta_R$ which implies pure vector neutral couplings. With these choices we have the four possibilities for neutral couplings: $V-A$, $V+A$, V, and A.

For the new charged currents the difference among models is not so clear. The VSM predicts a pure $V-A$ coupling but the others depend on combinations of the angles. If all angles are equal, the VDM is $V+A$ and the FMF model is axial vector. One can have situations with the same couplings for different models, which make them indistinguishable.

III. MIXING ANGLES AND DECAY MODES

Upper bounds on the mixing angles were obtained from phenomenological analysis [4] and imply $\sin^2\theta_i \approx 0.03-0.05$. In our estimates we have employed $\sin^2\theta_i = 0.01$ and equal angles, except for the phase in the

TABLE I. General mixing angles for the new possible charged and neutral heavy lepton interactions. The columns VDM, FMF, and VSM correspond to the vector doublet, fermion–mirror-fermion, and vector singlet models, respectively.

	Mixing parameters		
Parameters	VDM	FMF	VSM
$a_{1(e,L^0)}$	$\sin(\theta_L^\nu-\theta_L^e)-\cos(\theta_R^\nu)\sin(\theta_R^e)$	$\cos(\theta_L^e)\sin(\theta_L^\nu)-\sin(\theta_R^e)\cos(\theta_R^\nu)$	$\sin(\theta_L^\nu)\cos(\theta_L^e)$
$b_{1(e,L^0)}$	$\sin(\theta_L^\nu-\theta_L^e)+\cos(\theta_R^\nu)\sin(\theta_R^e)$	$\cos(\theta_L^e)\sin(\theta_L^\nu)+\sin(\theta_R^e)\cos(\theta_R^\nu)$	$\sin(\theta_L^\nu)\cos(\theta_L^e)$
$a_{2(\nu,L^-)}$	$-\sin(\theta_L^\nu-\theta_L^e)-\sin(\theta_R^\nu)\cos(\theta_R^e)$	$\sin(\theta_L^e)\cos(\theta_L^\nu)-\cos(\theta_R^e)\sin(\theta_R^\nu)$	$\cos(\theta_L^\nu)\sin(\theta_L^e)$
$b_{2(\nu,L^-)}$	$-\sin(\theta_L^\nu-\theta_L^e)+\sin(\theta_R^\nu)\cos(\theta_R^e)$	$\sin(\theta_L^e)\cos(\theta_L^\nu)+\cos(\theta_R^e)\sin(\theta_R^\nu)$	$\cos(\theta_L^\nu)\sin(\theta_L^e)$
$v_{(e,L^+)}$	$\sin(\theta_R^e)\cos(\theta_R^e)$	$\sin(\theta_L^e)\cos(\theta_L^e)-\sin(\theta_R^e)\cos(\theta_R^e)$	$\sin(\theta_L^e)\cos(\theta_L^e)$
$a_{(e,L^+)}$	$-\sin(\theta_R^e)\cos(\theta_R^e)$	$\sin(\theta_L^e)\cos(\theta_L^e)+\sin(\theta_R^e)\cos(\theta_R^e)$	$\sin(\theta_L^e)\cos(\theta_L^e)$
$v_{(\nu,L^0)}$	$\sin(\theta_R^\nu)\cos(\theta_R^\nu)$	$\sin(\theta_L^\nu)\cos(\theta_L^\nu)-\sin(\theta_R^\nu)\cos(\theta_R^\nu)$	$\sin(\theta_L^\nu)\cos(\theta_L^\nu)$
$a_{(\nu,L^0)}$	$-\sin(\theta_R^\nu)\cos(\theta_R^\nu)$	$\sin(\theta_L^\nu)\cos(\theta_L^\nu)+\sin(\theta_R^\nu)\cos(\theta_R^\nu)$	$\sin(\theta_L^\nu)\cos(\theta_L^\nu)$

FMF model. So, our results are not upper bounds and can be easily scaled.

For the models we have considered one can compute [5] the main disintegration modes for heavy leptons into light observable particles. The result is shown in Table II. Transitions of the type $L^0 \leftrightarrow L^-$ are possible but can be strongly suppressed by phase space and have not been considered here. There is no significant model dependence on the branching ratios.

The LEP detectors [6] have done a search in the radiative channels and set bounds on effective couplings. For the models we have considered these channels are possible via one-loop diagrams and are suppressed. We compute $\Gamma(L \longrightarrow l\gamma)/\Gamma(L \longrightarrow \nu l \bar{\nu}_l)$ as in the Marciano-Sanda [7] calculation. We have considered the neutral and the charged heavy lepton mass of the same order and that charged-current exchange dominates. Details are given in Appendix A. We find $3\alpha/\pi, 2\alpha/\pi$, and $2\alpha/\pi$ for the FMF, VDM, and VSM models, respectively. For the L3 luminosities [8] of 3.3 pb^{-1} less than one event of type $L \longrightarrow l\gamma$ is expected.

According to Table II the channels $L^+ \longrightarrow \bar{\nu}_e + \text{hadrons}$ and $L^+ \longrightarrow e^+ + \text{hadrons}$ offer a more reliable opportunity for experimental detections. If one adds these disintegration modes, one can have almost 70% of the produced L^+ events with an associated primary electron. This is almost three orders of magnitude greater than the $L \longrightarrow l\gamma$ events. Since we have an observable light primary charged lepton this channel can be fully reconstructed. As a consequence it will give us much more information on model details as shown in Sec. IV.

TABLE II. Branching ratios (in percentage) for the new possible charged and neutral heavy lepton decays.

Branching ratios	
Channel	(%)
$L^- \longrightarrow \nu_e + \text{hadrons}$	49.2
$L^- \longrightarrow e^- + \text{hadrons}$	16.3
$L^- \longrightarrow \nu_e(e^-\bar{\nu}_e), \nu_e(\mu^-\bar{\nu}_\mu), \nu_e(\tau^-\bar{\nu}_\tau)$	8.3
$L^- \longrightarrow e^-(\nu_e\bar{\nu}_e), e^-(\nu_\mu\bar{\nu}_\mu), e^-(\nu_\tau\bar{\nu}_\tau)$	2.1
$L^- \longrightarrow e^-(e^+e^-), e^-(\mu^+\mu^-), e^-(\tau^+\tau^-)$	1.0
$L^- \longrightarrow e^-\gamma$	0.1
$L^0 \longrightarrow e^- + \text{hadrons}$	49.6
$L^0 \longrightarrow \nu_e + \text{hadrons}$	16.3
$L^0 \longrightarrow e^-(\nu_e e^+), e^-(\nu_\mu \mu^+), e^-(\nu_\tau \tau^+)$	8.3
$L^0 \longrightarrow \nu_e(\nu_e\bar{\nu}_e), \nu_e(\nu_\mu\bar{\nu}_\mu), \nu_e(\nu_\tau\bar{\nu}_\tau)$	2.1
$L^0 \longrightarrow \nu_e(e^-e^+), \nu_e(\mu^-\mu^+), \nu_e(\tau^-\tau^+)$	1.0
$L^0 \longrightarrow \nu\gamma$	0.1

IV. RESULTS

The total cross section for single heavy lepton production (charged or neutral) is given in Fig. 1, for $\sin^2\theta_i = 0.01$. In all estimates we take $\sin^2\theta_W = 0.219$ and

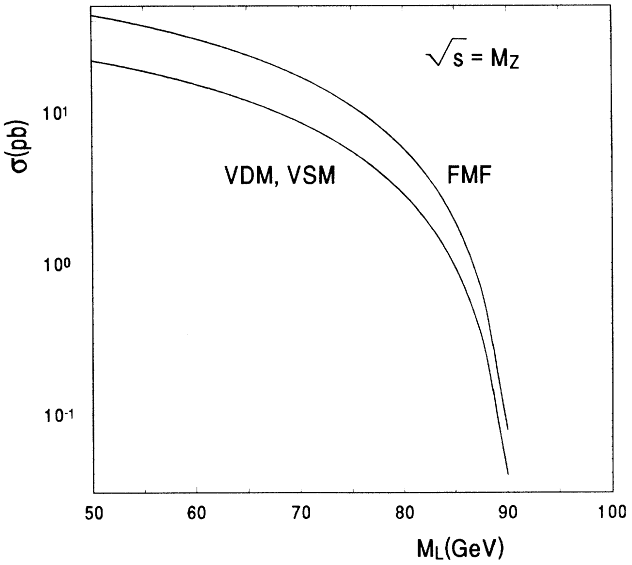

FIG. 1. Total cross section for the heavy lepton production at $\sqrt{s} = M_Z$. The neutral and charged cases give the same value. All mixing angles are taken $\sin^2\theta_i = 0.01$.

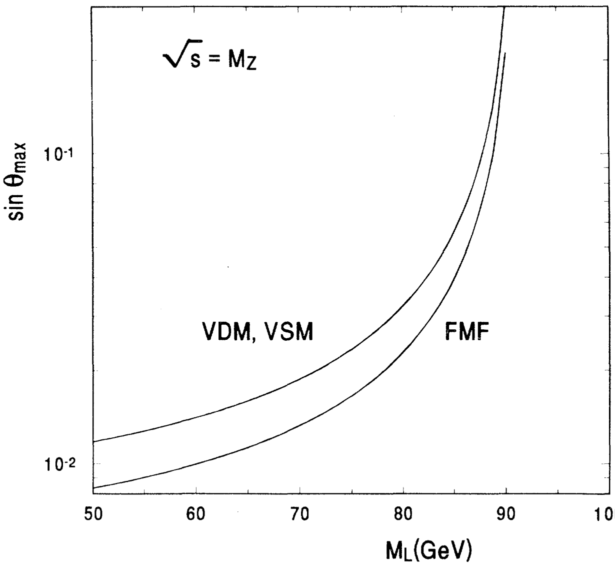

FIG. 2. Upper bounds on the neutral current mixing angle for $Z(\bar{\nu}L^0)$ coupling taken from the L3 experiment.

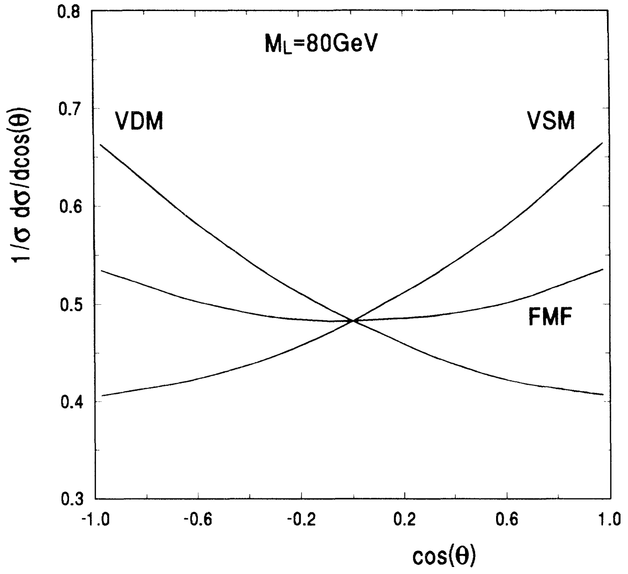

FIG. 4. Same as Fig. 3 but for $M_L = 80$ GeV.

$M_Z = 91.1$ GeV. These curves can be easily obtained from the angular distribution given in Appendix B. Values for the other choices of mixing angles are obtained by simple scaling. The recent heavy neutrino search done by the L3 Collaboration [8] can be converted in upper bounds for the neutral mixing as shown in Fig. 2.

The angular distribution of the primary electron produced with L^+ allows a clear separation among models as depicted in Figs. 3 and 4. This model-dependent distribution is a very interesting effect. In other reactions such as electron-proton collisions it is difficult to make experimental distinctions between models [5]. The symmetrical FMF behavior is a consequence of the pure axial-vector or vector coupling of this model. The $V + A$ contribution of the VDM gives a more peaked distribution for $\cos\theta \approx -1$. For the vector-singlet model [3] with a $V - A$ neutral interaction, the angular distributions of

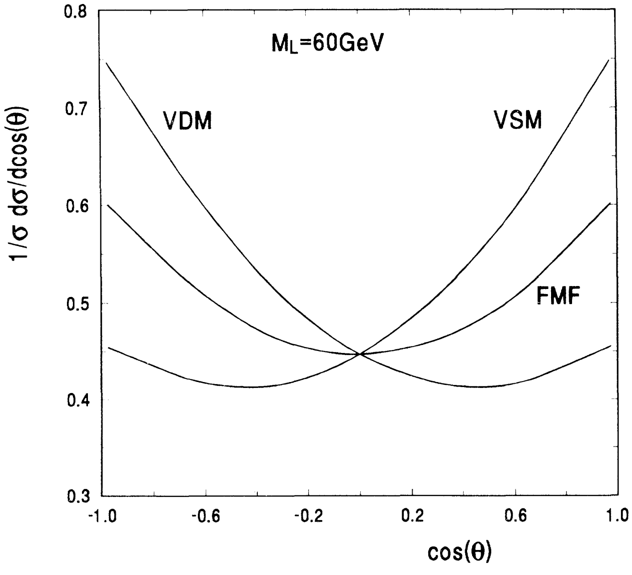

FIG. 3. Angular distributions of the primary electron with respect to the incident electron direction for the decay $L^+ \longrightarrow e^+ +$hadrons for $M_L = 60$ GeV at $\sqrt{s} = M_Z$.

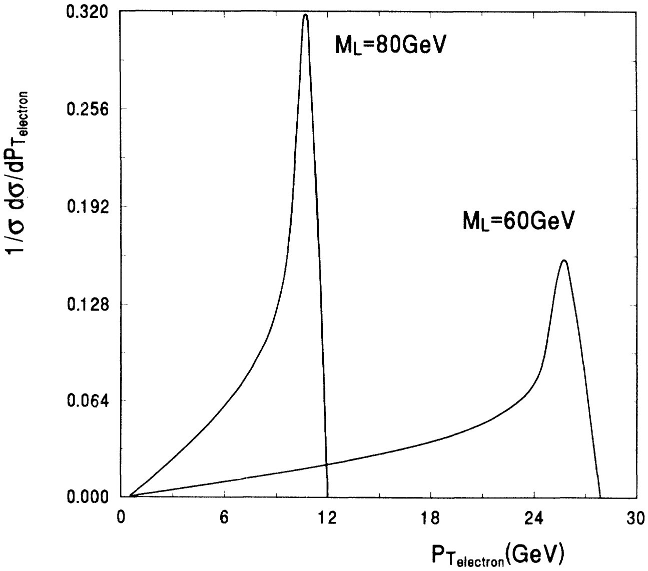

FIG. 5. The primary electron transverse-momentum distribution for $M_L = 60$, 80 GeV.

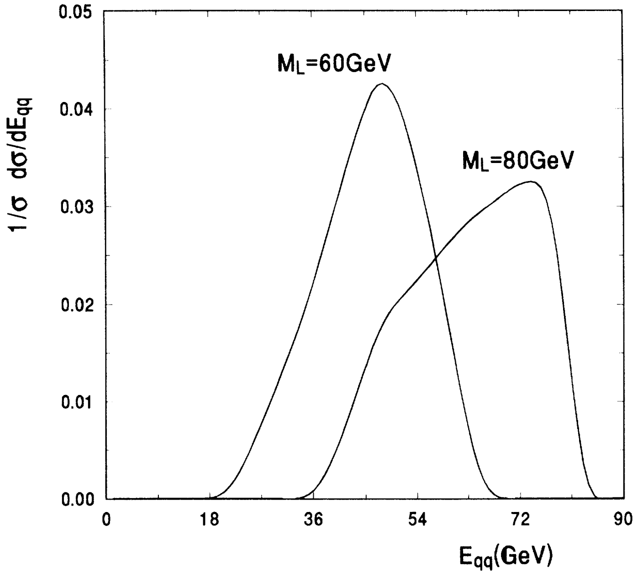

FIG. 6. Hadronic energy distributions for the decay $L^+ \longrightarrow e^+ + \text{hadrons}$.

the Figs. 3 and 4 are symmetrical to the VDM case and then peaked towards $\cos\theta \approx +1$.

The primary electron associated with L^+ production has a sharp energy distribution given by the kinematical constraint $E_e = (s - M_L^2)/2\sqrt{s}$. From this electron energy one can fix the L mass independently of any model. The primary electron transverse-momentum distribution is sensitive to the L^+ mass, as shown in Fig. 5. The hadrons coming from L^+ decays have an energy distribution shown in Fig. 6. These last two figures show a clear M_L dependence but we found no model difference.

V. CONCLUSIONS

From our analysis one can conclude that the three fermion decays of the possible heavy charged leptons are sensitive to phenomena beyond the standard model. The event rate is more significant than the radiative decay channel. The primary electron angular distributions can differentiate models and its energy distributions can determine the heavy lepton mass. If the experimental search finds no signal of these events one can establish new strong bounds on the mixing angles of the considered models.

ACKNOWLEDGMENTS

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APPENDIX A

The general decay $L \longrightarrow l\gamma$ can occur via one-loop diagrams with both W and Z^0 exchange. The dominant term comes from the charged-current Lagrangian

$$\mathcal{L}_{\rm CC} = \frac{-g}{2\sqrt{2}}[\bar{\nu}\gamma^\mu(a_0 - b_0\gamma^5)e^- + \bar{L}^0\gamma^\mu(a_1 - b_1\gamma^5)e^- + \bar{\nu}\gamma^\mu(a_2 - b_2\gamma^5)L^- + \bar{L}^0\gamma^\mu(a_3 - b_3\gamma^5)L^-] \times W_\mu + \text{H.c.} \tag{A1}$$

The decay rate for $L^- \longrightarrow l^-\gamma$ is

$$\Gamma = \frac{\alpha g^4 M_L^3}{512\pi^4 M_W^4}(A^2 + B^2) , \tag{A2}$$

where the leading term contribution gives

$$\begin{aligned} A &= \frac{-5M_{L^-}}{24}(a_0a_2 + b_0b_2 + a_1a_3 + b_1b_3) + \tfrac{1}{2}M_{L^0}(a_1a_3 - b_1b_3) , \\ B &= \frac{-5M_{L^-}}{24}(a_2b_0 + a_0b_2 + a_1b_3 + a_3b_1) + \tfrac{1}{2}M_{L^0}(a_3b_1 - a_1b_3) . \end{aligned} \tag{A3}$$

If we take all angles to be equal, then we have a $V + A$ coupling for the VDM, a pure axial-vector term for FMF model, and $V - A$ for the VSM. All cases imply the same order of magnitude for $\Gamma(L \longrightarrow e\gamma)$. For all models $a_0 \approx b_0 \approx a_3 \approx b_3 \approx 1$.

APPENDIX B

We give here the expression for the production of usual fermion l and excited (anti)fermion L from e^+e^- collisions including Z and/or $W^\pm$ contributions.

For the coupling of fermions f and f' with a vector boson V, we write the general interaction term:

$$\mathcal{L}_{ff'} = -\bar{f}\gamma_\mu(v_{ff'} - a_{ff'}\gamma^5)f'V^\mu . \tag{B1}$$

The cross section for the process $e^+e^- \longrightarrow \bar{L}l$ is

$$\frac{d\sigma}{d\Omega} = \frac{s}{128\pi^s}(1-\chi^2)(1-\chi^4)\left\{[2A(1+\alpha\cos^2\theta) + 2B(1+\alpha)\cos\theta]\Delta(s)\Delta^*(s) + \left[4(C-D)\left[\frac{1}{1+\chi^2}\right] + (C+D)[1+(1+\alpha)\cos\theta + \alpha\cos^2\theta]\right]\Delta(t)\Delta^*(t) + \{E[1+(1+\alpha)\cos\theta + \alpha\cos^2\theta]2\,\mathrm{Re}[\Delta(s)\Delta^*(t)]\}\right\} , \tag{B2}$$

where θ is the angle between the incoming and the outgoing electrons. This expression is calculated under the assumptions $m_e = m_l = 0$ and the definitions

$$\chi = \frac{M_L}{\sqrt{s}}, \quad t = -\frac{s}{2}(1-\chi^2)(1-\cos\theta), \quad \alpha = \frac{1-\chi^2}{1+\chi^2} ,$$

and

$$A = (v_{ee}^2 + a_{ee}^2)(v_{lL}^2 + a_{lL}^2) , \tag{B3}$$

$$B = 4 v_{ee} a_{ee} v_{lL} a_{lL} , \tag{B4}$$

$$C = (v_{el}^2 + a_{el}^2)(v_{eL}^2 + a_{eL}^2) , \tag{B5}$$

$$D = 4 v_{el} a_{el} v_{eL} a_{eL} , \tag{B6}$$

$$E = (v_{lL} v_{el} + a_{lL} a_{el})(v_{ee} v_{eL} + a_{ee} a_{eL}) + (v_{lL} a_{el} + a_{lL} v_{el})(v_{ee} a_{eL} + a_{ee} v_{eL}) . \tag{B7}$$

In the channel s only Z contributes, then

$$\Delta(s) = \frac{1}{s - M_Z^2 - i\Gamma_Z M_Z} . \tag{B8}$$

On the other hand, in the channel t we can have Z contribution, as in L^+e^- production, or $W^\pm$ contribution, as in $L^0\nu$ production. Then we write

$$\Delta(t) = \frac{1}{t - M_V^2} , \tag{B9}$$

with $V = Z$ or W, according to the case.

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