Fermion family recurrences in the Dyson-Schwinger formalism

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Abstract. We study the multiple solutions of the truncated propagator Dyson-Schwinger equation for a simple fermion theory with Yukawa coupling to a scalar field. Upon increasing the coupling constant g, other parameters being fixed, more than one non-perturbative solution breaking chiral symmetry becomes possible and we find these numerically. These "recurrences" appear as a mechanism to generate different fermion generations as quanta of the same fundamental field in an interacting field theory, without assuming any composite structure. The number of recurrences or flavors is reduced to a question about the value of the Yukawa coupling, and has no special profound significance in the Standard Model. The resulting mass function can have one or more nodes and the measurement that potentially detects them can be thought of as a collider-based test of the virtual dispersion relation $E = \sqrt{p^2 + M(p^2)^2}$ for the charged lepton member of each family. This requires three independent measurements of the charged lepton's energy, three-momentum and off-shellness. We illustrate how this can be achieved for the (more difficult) case of the tau lepton.

PACS. 12.15.Ff Quark and lepton masses and mixing – 11.30.Rd Chiral symmetries

1 Introduction

Why Nature has laid down exactly three fermion families in the same representation of the Standard Model's gauge groups with universal couplings to the gauge bosons remains to be explained. Many ideas have been presented in the literature and we quote some to exemplify the far-reaching implications of any experimental progress in the first question of what has been called the "Fermion problem".

"Democratic approaches" [1] are in general based on the idea of equal fermion-to-Higgs Yukawa couplings. One then needs mechanisms to generate specific lepton or quark mass patterns, see for example [2]. Let us also recall the classic work of Froggat and Nielsen [3] that introduces the concept of "horizontal flavor" symmetry (nowadays often called Interfamily symmetry) by which the three families are degenerate or quasi-degenerate at some high scale beyond present experimental reach, due to unknown symmetry. At lower energies dynamical (renormalization group) effects amplify any small symmetry breaking term causing the ratios between masses that we see in current accelerators. In essence, the idea is that each of the elementary particle types, for example the charged leptons (e, μ, τ) provide a representation of the posited interfamily symmetry. Since the symmetry is broken at the TeV scale and below, revealing it requires theoretical extrapolation

from current experimental data. The same authors have followed-up with ideas based on Anti-grand unification [4].

An alternative line of research assumes that the known elementary particles are really composite objects of more fundamental "preons" [5]. To date no experiment has revealed composite structure beyond the usual layers of quantum pairs involved in radiative corrections around seemingly point-like sources. One can argue that a new strong interaction binds preons and this might conceivably be revealed in future experimental efforts.

Further, dynamical breaking of chiral symmetry as a genuine quantum effect is well known in strong interaction physics [6,7] and has also been invoked in flavor physics as an alternative to the tree-level Higgs mechanism, for example by Brauner and Hosek [8].

However no one seems to have paid attention to the fact that the Dyson-Schwinger equations do provide one with several solutions depending on the strength of the coupling. In this work we call attention to this point and its potential relevance for the fermion problem. Each of the three fermions corresponds in this hypothesis to a quantum over a different vacuum (but in the covariant formalism one pursues the study of correlation functions, here propagators, and sidesteps the issue of the vacuum wave functional). Far from attempting a complete theory, we will show the general features of the mechanism within a simple model of a fermion field coupled to a scalar boson through a Yukawa coupling.

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From this prospective, different flavored fermions, one corresponding to each family, are quanta of the same field, so the lagrangian can be more economically written. Each fermion is an elementary one-particle excitation on top of a vacuum that is a local minimum of the Hamiltonian. The excitations over the ground-state vacuum provide the lightest fermion family. Finally, at fixed coupling g, the Dyson-Schwinger equation has a finite number of solutions, so a finite number of families arise. The question on why three families becomes only a question of the value of g, the interaction coupling, and may have no special significance.

The equivalent of the propagator Dyson-Schwinger equation in a non-covariant framework is the well studied mass gap equation of potential models of QCD. The equation has been numerically solved for the harmonic oscillator potential [9], [10], the linear potential [11], and the linear plus Coulomb potential [12,13]. Bicudo, Ribeiro and Nefediev have systematically studied the excited solutions of this equation [15]. Our results seem compatible with this prior work.

2 Dyson-Schwinger equation and its numerical solution

We examine a simple Yukawa theory for one fermion field coupled to a real scalar field with Lagrangian density in Euclidean space

$$\mathcal{L} = \bar{\Psi}(i\,\not{p} - m_\Psi)\Psi + g\bar{\Psi}\Psi\phi + \frac{1}{2}\phi(\partial_\mu\partial^\mu - m_\phi^2)\phi \ . \quad (1)$$

The Dyson-Schwinger equation for the fermion propagator in this theory is represented in figure 1 in the rainbow approximation (neglecting the vertex dressing).

To examine generic features of dynamical chiral symmetry breaking we can further ignore the running of the wavefunction renormalization and set $Z(p^2) = 1$, a constant. This leaves one scalar equation for the fermion mass function that reads

$$M(p^2) = m_\Psi Z_2 + \int_0^\infty dq F(q,p)\frac{M(q^2)}{q^2 + M^2(q^2)} \ . \quad (2)$$

In the chiral limit $m_\Psi \to 0$ this equation becomes homogeneous and accepts a chiral-symmetry preserving solution $M = 0$ that continuously deforms into a soft-running mass form when m_Ψ is not zero. But for strong enough kernels F it also admits other solutions that break chiral symmetry.

The kernel in this simple Yukawa theory is

$$F(q,p) = \frac{g^2q^3}{4\pi^3}\int_{-1}^1 \sqrt{1-y^2}dy\frac{1}{(q-p)^2 + m_\phi^2} \quad (3)$$

with y the cosine of the polar angle in Euclidean four-dimensional space from p to q.

To obtain excited solutions for M as function of p^2 we apply an iterative linear method with different initial guesses with or without nodes for $M(p^2)$. This method

proceeds by examining linear deviations of the exact solution

$$M(p^2) = M_0(p^2) + \epsilon(p^2) \quad (4)$$

that yield

$$\epsilon(p^2) - \int_0^\infty dq F(q,p)\epsilon(q^2)\left(\frac{q^2 - M^2(q^2)}{(q^2 + M^2(q^2))^2}\right) \quad (5)$$

$$= m_\Psi Z_2 - M_0(p^2) + \int_0^\infty dq F(q,p)\frac{M_0(q^2)}{q^2 + M_0^2(q^2)} \ .$$

This can in turn be discretized (simply discretizing p) and cast as a linear system

$$A_{ij}\epsilon_j = (RHS)_i \quad (6)$$

and solved with standard numerical linear algebra tools. The kernels require only the calculation of 2-dimensional integrals that are also standard fare in modern computers.

By naive dimensional analysis one sees that the integral needs UV regularization. We accomplish this by a simple cut-off method. Then the parameters should be chosen to run with the cutoff $g(\Lambda)$, $m_\psi(\Lambda)$ to ensure that the mass functions turn largely independent of Λ. In our results we display the dependence of the solution with g at fixed Λ. The boson mass m_ϕ is chosen to be 1 and sets the unit of the theory.

3 Numerical results and discussion

In this section we present the chiral-symmetry breaking conventional and new excited state solutions. By running our computer program incrementing g we meet critical g values g_0, g_1, ...g_n above which there are exactly $n + 1$ solutions, the last with n nodes, that we find numerically. For example the first solution appears for a critical $g_0 \simeq 6.8$ (of course this number runs with the cutoff).

We show in figure 2 the three solutions obtained with $g = 14$, $\Lambda = 200$.

Then in figure 3 we plot the nodeless solution at fixed cutoff incrementing g sequentially to show the dependence of the mass function on the coupling.

Only the nodeless solution has been widely used in past literature for its applications in hadron physics. The others are sometimes rejected [16] on the basis of "wrong" UV asymptotic behavior, arguing that they do not match with conventional mass running in perturbation theory, and artificially imposing a boundary condition that discards all but one solution.

We point out here that this mismatch poses no problem. One should interpret these solutions as the one-particle excitations above different extrema of the Hamiltonian or vacuum replicae. Therefore they cannot all be matched to the same perturbation theory around one particular vacuum.

If one insists on viewing them from the one vacuum that connects smoothly to perturbation theory, then they have to be written down as complicated collective states in terms of the one-particle solutions over this vacuum.
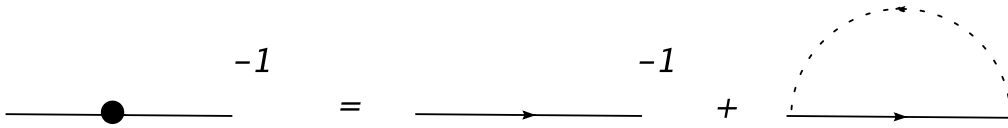
Fig. 1. Dyson-Schwinger equation for the fermion propagator in Yukawa theory, in the rainbow approximation.
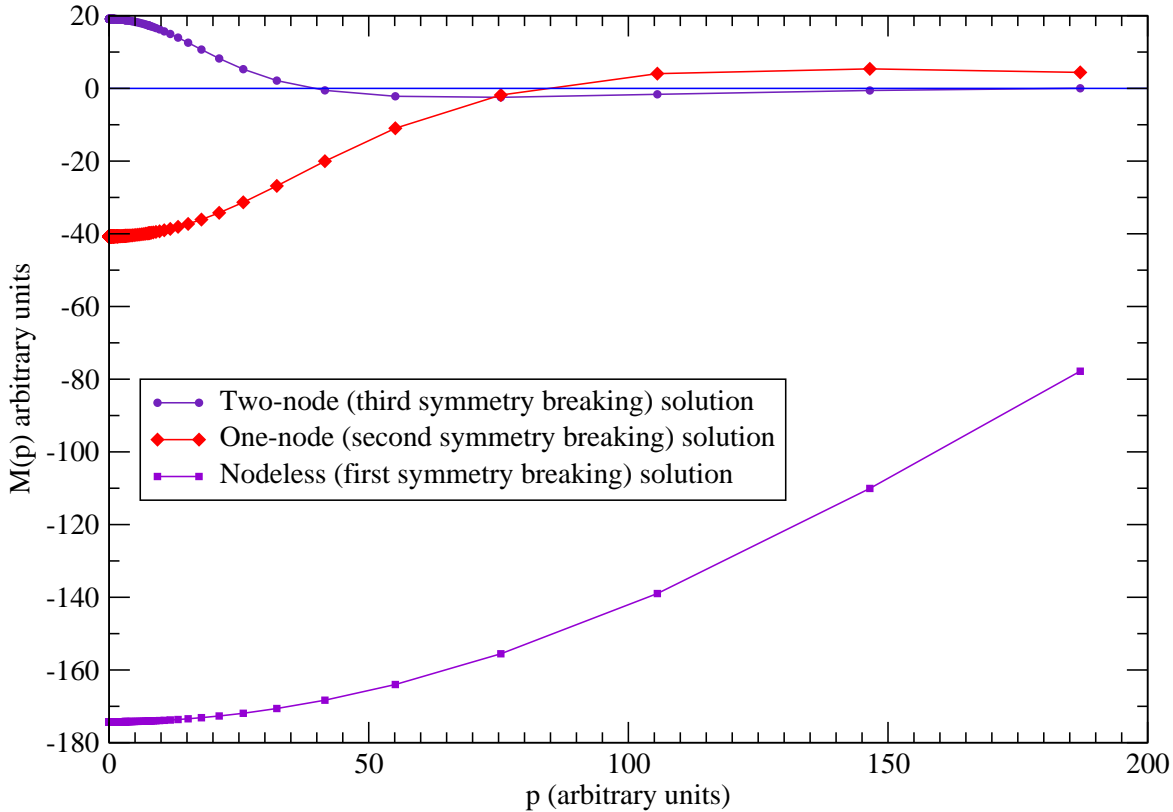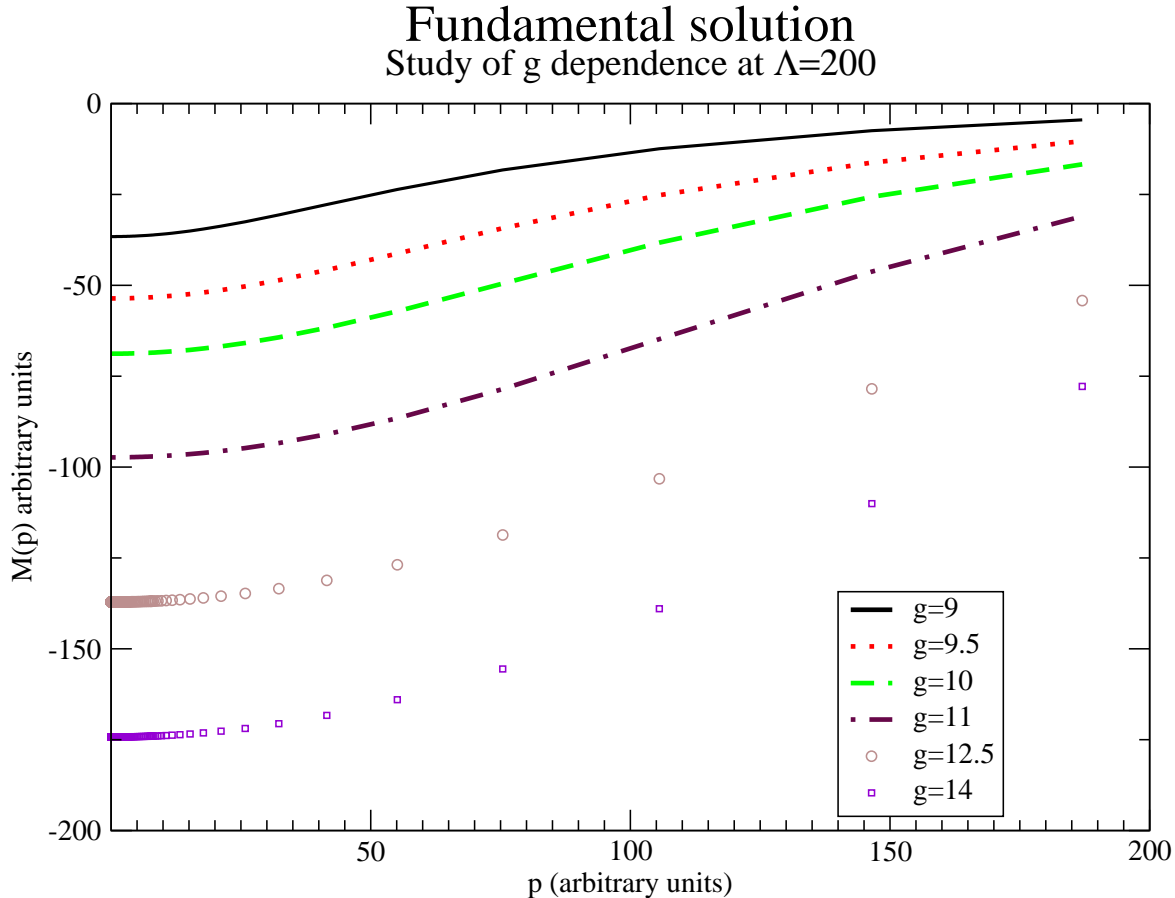

Fig. 2. We plot together the three solutions to the Dyson-Schwinger equation for a fermion-scalar Yukawa coupling $g = 14$, cutoff $\Lambda = 200$, and the scale set by the scalar mass being fixed to $m_\phi = 1$. Note the equation for M in the chiral limit (zero current fermion mass) cannot distinguish M from $-M$ so the global sign of any one solution in this graph is irrelevant and for display purposes only. In particular all M(0) can be taken as positive.

In the particular case of the Yukawa theory, the angular integral in eq. 3 can be performed analytically [14], but we prefer keeping a two-dimensional integral thinking of future work with more complicated model Lagrangians.

In agreement with the findings of [15], we see that the higher excited vacua in this covariant Euclidean formulation present zeroes in the mass function. A version of the Sturm-Liouville theorem must be at work (this is not surprising since the Hamiltonian is hermitian).

Also note that the values of $M(0)$ generated in this covariant Yukawa theory show quite some hierarchy. In figure 2 one can see that they are well-spaced. Therefore

this field-theory mechanism might conceivably be at work in the fermion flavor problem. However $M(0)$ seems to be larger for the nodeless solution than for the excited ones (this puzzling property also appears in the equal-time approach of [15], and the extent of its model dependence needs to be further investigated). To confirm this point, we choose a different set of parameters and implementation of the computer code. With $m_\phi = 100$, a cutoff $\Lambda = 10^4$ implemented as a Gaussian fall-off of the integration measure (as opposed to terminating the grid), and $g = 50$, with a small bare fermion mass $m_\psi = 5 \cdot 10^{-4}$, one obtains the three solutions depicted in figure 4. This graph

Fig. 3. Nodeless solution for increasing values of the coupling constant ($m_\phi = 1$ and $\Lambda = 200$ are held fixed). Note how $M(0)$ grows steadily with g (the sign of M is irrelevant).

confirms that the nodeless solution is higher in mass, and that it is possible to generate sizeable mass hierarchies between the solutions. We use this run to also illustrate the dependence of M_2 with the cutoff, displayed in figure 5. As can be seen, the excited solution does not decrease monotonically as $g \to 0$, it rather seems to become a singular solution at the critical coupling. This technicality is however probably irrelevant for physical applications.

In hadron physics the strength of the interaction being fixed by extensive phenomenology, there would be no freedom to vary g. In the physically relevant cases studied in [15], excited solutions exist at physical values of the coupling. In [17] Ribeiro and Nefediev have further extended their original results to include bound states (mesons) constructed with the replicated quasiparticles. In particular there are Goldstone bosons over the replicated vacuum, that are of course not massless pions but would appear as excited pion states (separated from the ground state pion by the mass gap between the two vacua). Whether any conventional mesons accept a more convenient description

as replicated mesons instead of excited mesons over the standard vacuum remains an open question.

Working in Euclidean space as we do provides fastly convergent integrals. This technicality may be avoided by employing a Lehmann representation [18] that allows a direct solution in Minkowski space with similar results.

4 Experimental signature

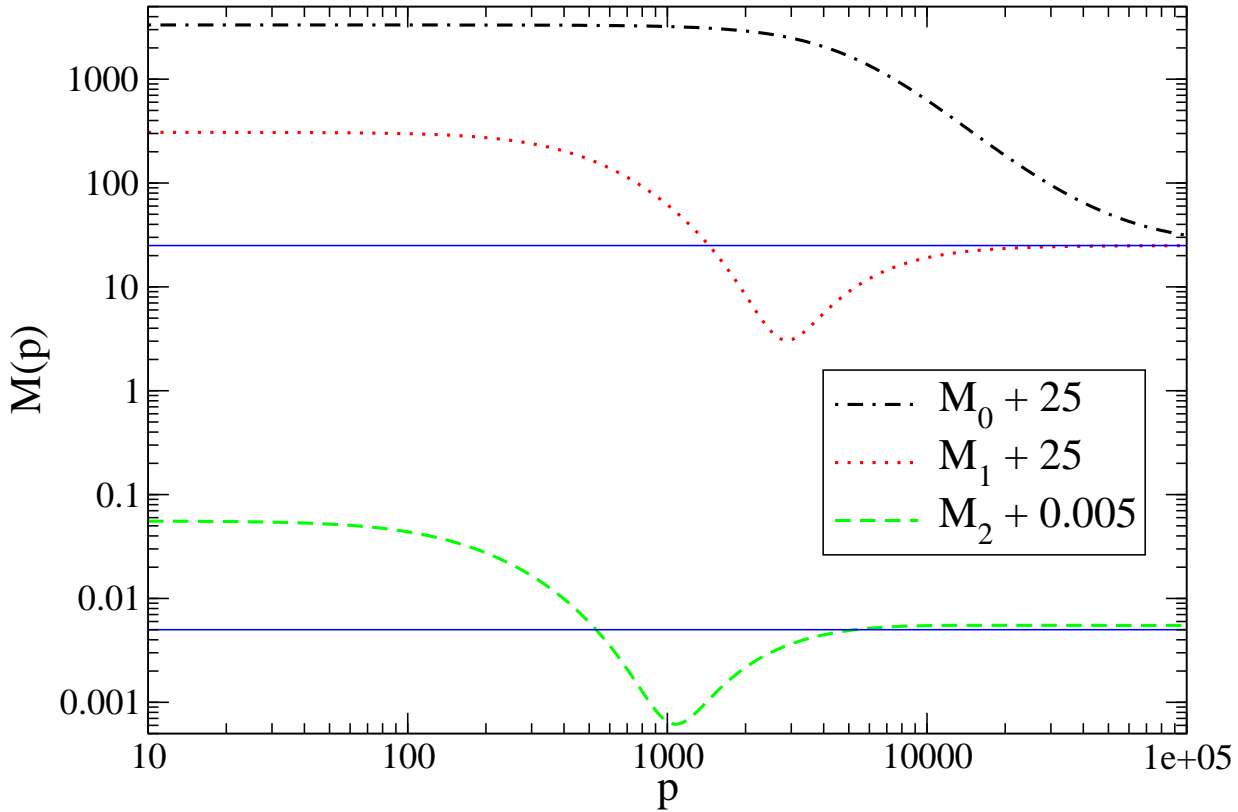In a free field theory, a field quantum of mass m satisfies the equation

$$E = \sqrt{\mathbf{p}^2 + m^2} \qquad (7)$$

that causes a pole in the free propagator

$$S = \frac{i}{p^2 - m^2} \ . \qquad (8)$$

In an interacting field theory this pole will be shifted due to renormalization from its bare to its physical position. The dependence on the renormalization scale can

Multiple gap functions solving the same DSE
(shifted for clarity)

Fig. 4. Three solutions to the gap equation in Yukawa theory obtained with $m_\phi = 100$, $\Lambda = 10^4$, $m_\psi = 5 \cdot 10^{-4}$, $g = 50$, confirming that the nodeless solution is higher in mass, and that a sizeable hierarchy of masses is possible. To represent them in a log-log plot, M_1 and M_2 being negative in part of their domain, the solutions have been shifted by a constant amount to positive values.

be traded by a dependence on the particle Euclidean 4-momentum so that

$$S = \frac{iZ(p^2)}{p^2 - M(p^2)^2} \qquad (9)$$

yielding the transcendental equation for the pole position

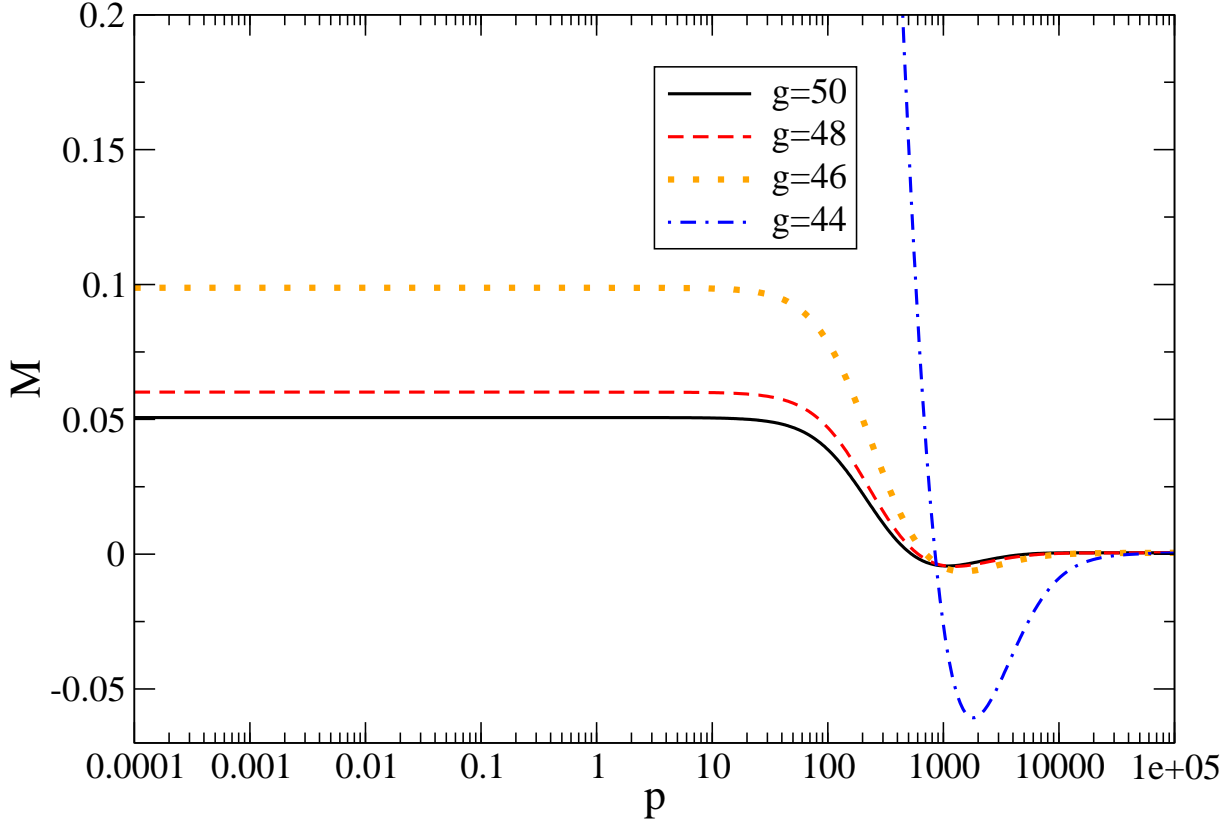$$E = \sqrt{\mathbf{p}^2 + M(E^2 - \mathbf{p}^2)^2} \; . \qquad (10)$$

Another way of visualizing the function $M(p^2)$ of the interacting theory is to trade p^2 by the space-like part $\mathbf{p}^2$ as argument of M, generating therefore a non-trivial dispersion relation for virtual particles, and the zeroes of the mass function M appear as points where $E = |\mathbf{p}|$ that would otherwise only be reached asymptotically at large $\mathbf{p}$ (see figure 7). Tests for a non-trivial (real particle) dispersion relation have been proposed and some carried out in the search for violations of Lorentz invariance [19]. However these are very indirect and usually performed at low

energy, so an accelerator-based test of the (virtual particle) dispersion relation by separately measuring E, $\mathbf{p}$ and the off-shellness is preferable. In our case, real particles still provide representations of the Poincaré group and have constant, physical mass. However virtual particles off their mass shell will display the running mass function and this can be captured by analyzing the amplitudes of physical processes in perturbation theory.

The corresponding dispersion relations are plotted in figures 6 and 7.

Lacking a real theory there are two possibilities we cannot discern at present. Either all three families of fermions arise as solutions spontaneously breaking chiral symmetry, in which case two of them should already have a zero in their mass function, or the first generation reflects the trivial solution only slightly modifying the bare mass, and the second and third generation solutions with dynamically broken chiral symmetry, in which case only one of

Dependence of M_2 with the coupling g

Fig. 5. Dependence of M_2 with the coupling constant at fixed $m_\phi = 100$, $\Lambda = 10^4$, $m_\psi = 5 \cdot 10^{-4}$. Upon comparing with figure 3 we see that the qualitative behavior when the solution approaches the critical coupling and is about to cease existing, here $g = 43$, is quite different for the ground and excited solutions.
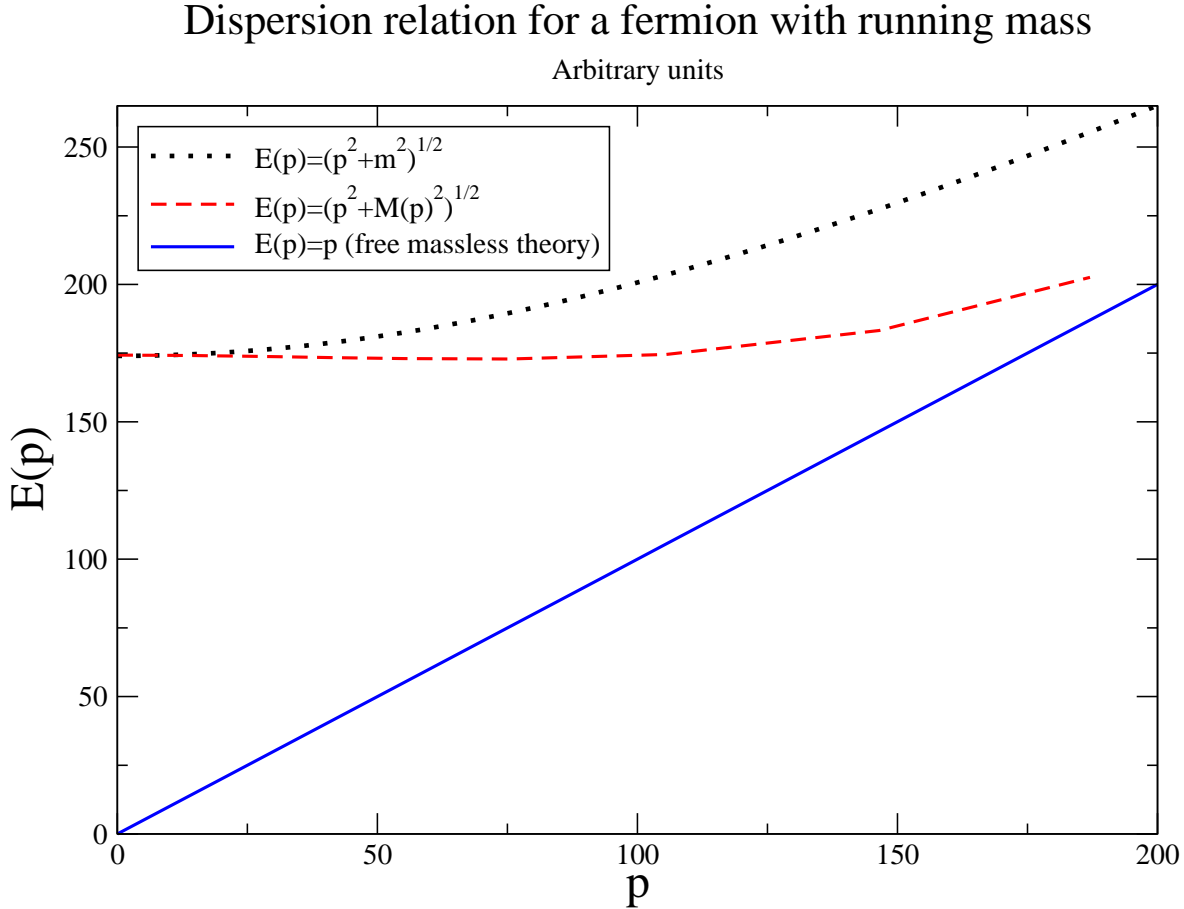
them would present a node. In either case a zero is present in the mass function of one of the fermions.

An interesting experiment is therefore a measurement of $\boldsymbol{p}$, E and the off-shellness $\Delta^2 = p^2 - M^2(p^2)$ of a τ, at various momenta $\boldsymbol{p}$. The B factories have accumulated large τ samples [23] that are under analysis and can be employed for this purpose.

The process one may investigate is depicted in Fig. 10 in the appendix below. An electron-positron pair collides and annihilates into a $\tau^{-*}\tau^+$ pair, where the τ^{-*} is off its mass shell. Its four-momentum can be infered from the center-of-momentum energy of the incoming e^-e^+ pair and by reconstructing the energy and momentum of the on-shell τ^+ from its decay products, as detailed shortly. Finally, one needs the off-shellness, but this can be obtained from the number of counts with given E, $|\boldsymbol{p}|$. This is obvious since the cross section for a specific process where the off-shell τ^- decays into for example $l^-\bar{\nu}_l\nu_\tau$, depends on the off-shellness Δ^2 of the τ^- (see also App. A).

Let us now detail the possible analysis:

1. In the center of mass frame of an e^-e^+ collision one can identify two back-to-back hadron jets, tagging the flavor by demanding that one of them kinematically reconstructs an on-shell τ. This is rendered difficult by the undetected neutrino, that we assume to be the only unreconstructed track on the left side of the event.
2. Complete reconstruction of the energy and momentum on the left side of the event (see Fig. 8) is possible with a vertex detector (giving the direction of motion of the on-shell τ). The total energy is taken from collider calibration, and matched to the energy of the visible tracks. Balancing energy provides the energy of the missing neutrino, and automatically the momentum of the left side, that can be tested against the hypothesis of a physical τ being produced.
3. Next one examines the right side of the reaction, where the secondary and primary vertex seem to coincide (as appropriate for a virtual, off-shell τ decaying rapidly).

Dispersion relation for a fermion with running mass

Arbitrary units

Fig. 6. The virtual particle dispersion relation at fixed cutoff scale for the nodeless $M(p^2)$ solution. Note that the interacting theory falls below the usual Yukawa dispersion relation because the mass function drops with p. This is not very different from standard perturbative running with p except the effect is much larger in the case of dynamical chiral symmetry breaking.

The total three-momentum is known a priori. One balances momentum to obtain the momentum taken by the undetected ν_τ, and obtains the total energy. Now, it is not necessarily true that $E^2 - \mathbf{p}^2 = m_\tau^2$.

4. The number of counts with given E, $\mathbf{p}$ on the right side is normalized to a cross section in terms of the off-shellness $\sigma(\Delta^2)$ and used to obtain M from the value of the intermediate propagator in perturbation theory.

An alternative possibility is to carry out the measurement on the expected O(20-30) τ events at the OPERA experiment [21] in Gran Sasso National Laboratory. Given the momentum of the neutrinos from the CNGS beam one can attempt full kinematical reconstruction of $(E, \mathbf{p})$. However here the difficulty resides in the off-shellness since a small value will be forced for the identification of the τ.

The experimental test for the muon and the electron is even simpler, for example through Compton and reverse Compton scattering where the fermion is off-shell in the intermediate state. For quarks one needs to take into account that they always appear in bound states, and therefore the mass function is always under an integral sign and reconstruction from experimental data difficult. However a particularly simple case is
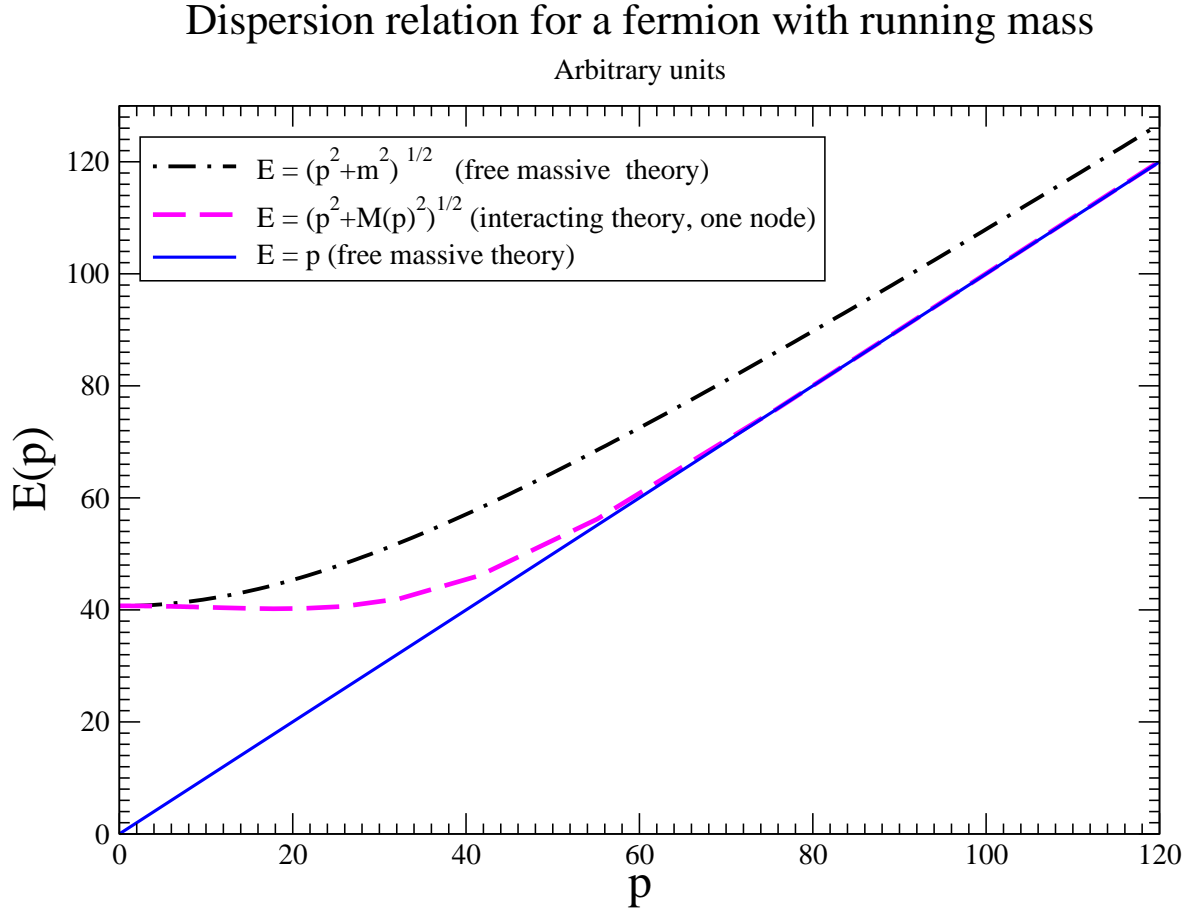
$$e^- e^+ \to \gamma^* \to s\bar{s}$$

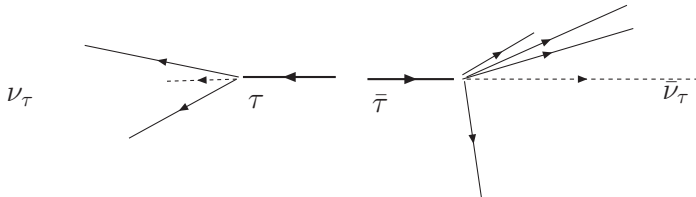where the strangeness be completely tagged by counting all hyperons in both jets.

In principle the same analysis carried out here could also be undertaken for Majorana particles but this is out of our scope in this preliminary work.

5 Conclusions

We have called attention to an interesting feature of field theory, namely the possibility of having several solutions of the one-particle Dyson-Schwinger equations for a broad

Dispersion relation for a fermion with running mass

Arbitrary units

Fig. 7. The virtual dispersion relation at fixed renormalization scale for the solution with two nodes (we find similar result for one node). As the running mass actually has a zero, the dispersive curve touches the massless limit that would otherwise be reached only asymptotically.

Fig. 8. In center of mass frame production where $\mathbf{p}_\tau + \mathbf{p}_{\bar{\tau}} = \mathbf{0}$ one can fully reconstruct the decay of both τ leptons if only the neutrinos escape undetected. The analysis steps are described in the text.

class of theories. The excited solutions appear upon increasing the coupling constant sufficiently, breaking chiral symmetry.

The spectrum of states on top of each of the vacua is called "replica" or "recurrence" and provides a mechanism that might be interesting for the theory of flavor. The number of recurrences arises from no special symmetry, since non-linear equations can perfectly have a finite number of solutions (again depending on the value of the coupling, this can be chosen to be three).

These solutions have been shown in the past in a Hamiltonian framework [15] and we have minimally extended the results of these authors to show that the covariant formulation allows similar phenomena. The excited solutions have mass functions that present zeroes and this reflects in the virtual dispersion relation (feature of an interacting field theory that should not be confused with breaking of Lorentz invariance).

Whether these solutions will be relevant to the fermion family problem can be tested at B factories employing their large τ samples directly produced.

At this point it is a meaningless exercise to attempt to obtain the fermion masses in this scheme. Three data points $M_i(0)$ should be used to fit three parameters, the current fermion mass (that we have here set to zero), the boson mass, and g at a given cutoff, so the current predictive power is null. However we find this field theory mechanism still worth attention given the ease with which fermion coupling universality can be incorporated by having three recurrences of the same field.

Testing the off-shell dispersion relation should allow to immediately discard the scenario so we believe we have presented a valid physical hypothesis. Of course, the success of radiative corrections in the standard model make one wish for a measurement at the highest possible energy, maybe at a future linear collider.

A τ-pair production in e^+e^- collisions

A.1 On-shell cross section

We look at the $e^+e^- \to \tau^+\tau^-$ process depicted in Fig. 9, where all ingoing and outgoing particles are on their mass shell. Using the conventions of Ref. [22], the amplitude for the depicted process is

$$-i\mathcal{M} = \overline{u}_{\eta^-}^{\tau^-}(p^-)\ (-ie\gamma^\nu)\ v_{\eta^+}^{\tau^+}(p^+)\ \left(\frac{-ig_{\mu\nu}}{Q^2}\right)$$
$$\times\ \overline{v}_{\xi^+}^{e^+}(k^+)\ (ie\gamma^\mu)\ u_{\xi^-}^{e^-}(k^-)\,. \quad (11)$$

For the unpolarized cross section, one needs the squared amplitude averaged over initial and summed over final spins

$$\overline{\sum}|\mathcal{M}|^2 = \frac{1}{4}\frac{e^4}{s^2}\sum_{\text{all spins}} \overline{u}_{\eta^-}^{\tau^-}(p^-)\,\gamma_{\mu_{\eta^-\eta^+}}\,v_{\eta^+}^{\tau^+}(p^+)$$
$$\times\ \overline{v}_{\xi^+}^{e^+}(k^+)\,\gamma^\mu{}_{\xi^+\xi^-}\,u_{\xi^-}^{e^-}(k^-)\,\overline{u}_{\xi'^-}^{e^-}(k^-)\,\gamma^\nu{}_{\xi'^-\xi'^+}\,v_{\xi'^+}^{e^+}(k^+)$$
$$\times\ \overline{v}_{\eta'^+}^{\tau^+}(p^+)\,\gamma_{\nu_{\eta'^+\eta'^-}}\,u_{\eta'^-}^{\tau^-}(p^-)\,, \quad (12)$$

where the spinor indices are explicitly shown. For e^+e^- annihilation, one has $Q^2 = s$. One can now rearrange the factors in Eq. (12). Making use of the relations

$$u_\xi^l(p)\overline{u}_{\xi'}^l(p) = (\not{p} + m_l)_{\xi\xi'}\,, \quad (13a)$$

$$v_\xi^l(p)\overline{v}_{\xi'}^l(p) = (\not{p} - m_l)_{\xi\xi'}\,, \quad (13b)$$

one can write Eq. (12) as a product of traces

$$\overline{\sum}|\mathcal{M}|^2 = \frac{1}{4}\frac{e^4}{s^2}\,\text{Tr}\left[(\not{k}^- + m_e)\,\gamma^\nu\,(\not{k}^+ - m_e)\,\gamma^\mu\right]$$
$$\times\,\text{Tr}\left[(\not{p}^- + m_\tau)\,\gamma_\mu\,(\not{p}^+ - m_\tau)\,\gamma_\nu\right]\,. \quad (14)$$

Neglecting the electron mass, this results in

$$\overline{\sum}|\mathcal{M}|^2 = \frac{8e^4}{s^2}\left(k^-\cdot p^-\,k^+\cdot p^+ + k^-\cdot p^+\,k^+\cdot p^-\right.$$
$$\left. + m_\tau^2\,k^-\cdot k^+\right)\,. \quad (15)$$

This can be written in terms of Mandelstam variables

$$s = (k^- - k^+)^2 = (p^+ - p^-)^2 = Q^2\,, \quad (16a)$$
$$t = (k^- - p^-)^2 = (p^+ - k^+)^2\,, \quad (16b)$$
$$u = (k^- - p^+)^2 = (p^- - k^+)^2\,, \quad (16c)$$

as

$$\overline{\sum}|\mathcal{M}|^2 = \frac{2e^4}{s^2}\left(t^2 + u^2 + 4m_\tau^2 s - 2m_\tau^4\right)\,, \quad (17)$$

where at high energies, the mass terms become negligible. In the center-of-momentum (com) frame, the amplitude is

$$\overline{\sum}|\mathcal{M}|^2 = \frac{e^4}{s^2}\left[s^2\left(1 + \cos^2(\theta_\tau)\right)\right.$$
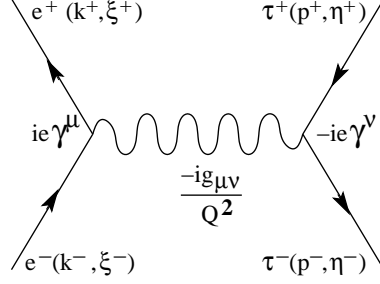$$\left. + 4m_\tau^2 s\left(1 - \cos^2(\theta_\tau)\right)\right]\,, \quad (18)$$

with θ_τ the com-angle between incoming electron e^- and outgoing τ^-.

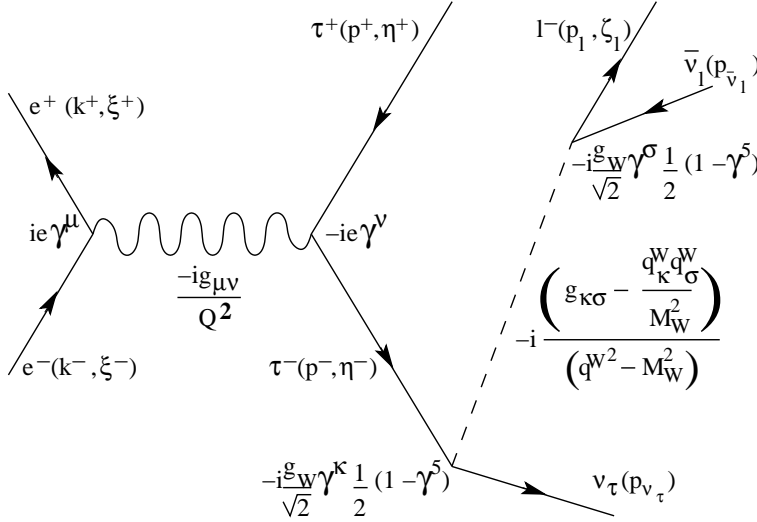The differential cross section in the com-frame is then given by

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right|_{\text{com}} = \frac{\alpha^2}{4s^2}\sqrt{1 - \frac{4m_\tau^2}{s}}$$
$$\times\left[s\left(1 + \cos^2(\theta_\tau)\right) + 4m_\tau^2\sin^2(\theta_\tau)\right]\,, \quad (19)$$

with $\alpha = e^2/4\pi$. The total cross section is

$$\sigma_{\text{tot.}}^{\text{com}} = \frac{4\pi\alpha^2}{3s}\sqrt{1 - \frac{4m_\tau^2}{s}}\left(1 + \frac{2m_\tau^2}{s}\right)\,. \quad (20)$$

Fig. 9. On-shell τ-pair production in e^+e^- collisions. The particles' momenta and spins are indicated, as well as the conventions for the photon propagator and the vertices.

Fig. 10. Half off-shell τ-pair production in e^+e^- collisions. The particles' momenta and spins are indicated, as well as the conventions for the boson propagators and the vertices.

A.2 Half off-shell cross section

In this part of the Appendix, we look at the $e^-e^+ \rightarrow \tau^-\tau^+$ process, where one of the τ-particles is off its mass shell and decays into a lighter lepton l (electron or muon). We discuss the case for an off-shell τ^-. The case for an off-shell τ^+ is clearly completely analogous. The process is displayed in Fig. 10.

The off-shellness of one of the τ's changes the kinematics. The total energy in the reaction is unevenly divided: $E_{\tau^+} \neq E_{\tau^-} \neq W_{\text{com}}/2$, where $W_{\text{com}} = \sqrt{s}$ is the total energy in the com-frame. The amplitude for the process depicted in Fig. 10 is

$$
-i\mathcal{M} = \overline{u}^{l^-}_{\zeta_l}(p_l)\left(-i\frac{g_W}{\sqrt{2}}\gamma^\sigma\frac{1}{2}\left(1-\gamma^5\right)\right)v^{\bar{\nu}_l}(p_{\bar{\nu}_l})
$$

$$
\times (-i)\frac{\left(g_{\kappa\sigma} - \frac{q^W_\kappa q^W_\sigma}{M^2_W}\right)}{\left(q^{W2} - M^2_W\right)}\overline{u}^{\nu_\tau}(p_{\nu_\tau})\left(-i\frac{g_W}{\sqrt{2}}\gamma^\sigma\frac{1}{2}\left(1-\gamma^5\right)\right)
$$

$$
\times \frac{i}{(\not{p}^- - M_{\tau^-})}(-ie\gamma^\nu)\,v^{\tau^+}_{\eta^+}(p^+)\left(\frac{-ig_{\mu\nu}}{q^2}\right)
$$

$$
\times \overline{v}^{e^+}_{\xi^+}(k^+)\,(ie\gamma^\mu)\,u^{e^-}_{\xi^-}(k^-). \quad (21)
$$

The propagator of the off-shell τ^- will give rise to a dependence of the amplitude on the *off-shellness* $\Delta^2 = E^2_{\tau^-} - \boldsymbol{p}^2_\tau - M^2_{\tau^-}$.

In the limit of infinite mass of the W-boson and vanishing electron mass, the unpolarized squared amplitude for the process depicted in Fig. 10 is [24]

$$
\overline{\sum}|\mathcal{M}|^2 = \frac{2^{12}\,\pi^4\,\alpha^2_{\text{QED}}\,\alpha^2_{\text{weak}}}{M^4_W\,\Delta^4\,q^4}\,p_{\nu_\tau}\cdot p_l
$$

$$
\times\Big[\,p_{\bar{\nu}_l}\cdot p^-\left(m_\tau\,M_{\tau^-}\,k^+\cdot k^- + k^+\cdot p^+\,k^-\cdot p^- + k^+\cdot p^-\,k^-\cdot p^+\right)
$$

$$
-\frac{\Delta^2}{2}\left(k^+\cdot p_{\bar{\nu}_l}\,k^-\cdot p^+ + k^+\cdot p^+\,k^-\cdot p_{\bar{\nu}_l}\right)\Big]. \quad (22)
$$

The (differential) cross section for this process is proportional to the above squared amplitude, integrated over the threemomenta of the outgoing τ-neutrino and lepton-antineutrino. This is a standard computation that can be incorporated in the computerr code if needed, yet it is clear that the resulting cross section will depend on the off-shellness Δ^2 and the virtual τ mass-energy dispersion relation. In particular, at large off-shellness, the cross section behaves as $1/\Delta^2$ and the constant multiplying this parametric behavior can be fit to data.

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Fermion family recurrences in the Dyson-Schwinger formalism

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Abstract. We study the multiple solutions of the truncated propagator Dyson-Schwinger equation for a simple fermion theory with Yukawa coupling to a scalar field. Upon increasing the coupling constant g, other parameters being fixed, more than one non-perturbative solution breaking chiral symmetry becomes possible and we find these numerically. These "recurrences" appear as a mechanism to generate different fermion generations as quanta of the same fundamental field in an interacting field theory, without assuming any composite structure. The number of recurrences or flavors is reduced to a question about the value of the Yukawa coupling, and has no special profound significance in the Standard Model. The resulting mass function can have one or more nodes and the measurement that potentially detects them can be thought of as a collider-based test of the virtual dispersion relation $E = \sqrt{p^2 + M(p^2)^2}$ for the charged lepton member of each family. This requires three independent measurements of the charged lepton's energy, three-momentum and off-shellness. We illustrate how this can be achieved for the (more difficult) case of the tau lepton.

PACS. 12.15.Ff Quark and lepton masses and mixing – 11.30.Rd Chiral symmetries

1 Introduction

Why Nature has laid down exactly three fermion families in the same representation of the Standard Model's gauge groups with universal couplings to the gauge bosons remains to be explained. Many ideas have been presented in the literature and we quote some to exemplify the far-reaching implications of any experimental progress in the first question of what has been called the "Fermion problem".

"Democratic approaches" [1] are in general based on the idea of equal fermion-to-Higgs Yukawa couplings. One then needs mechanisms to generate specific lepton or quark mass patterns, see for example [2]. Let us also recall the classic work of Froggat and Nielsen [3] that introduces the concept of "horizontal flavor" symmetry (nowadays often called Interfamily symmetry) by which the three families are degenerate or quasi-degenerate at some high scale beyond present experimental reach, due to unknown symmetry. At lower energies dynamical (renormalization group) effects amplify any small symmetry breaking term causing the ratios between masses that we see in current accelerators. In essence, the idea is that each of the elementary particle types, for example the charged leptons (e, μ, τ) provide a representation of the posited interfamily symmetry. Since the symmetry is broken at the TeV scale and below, revealing it requires theoretical extrapolation

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from current experimental data. The same authors have followed-up with ideas based on Anti-grand unification [4].

An alternative line of research assumes that the known elementary particles are really composite objects of more fundamental "preons" [5]. To date no experiment has revealed composite structure beyond the usual layers of quantum pairs involved in radiative corrections around seemingly point-like sources. One can argue that a new strong interaction binds preons and this might conceivably be revealed in future experimental efforts.

Further, dynamical breaking of chiral symmetry as a genuine quantum effect is well known in strong interaction physics [6,7] and has also been invoked in flavor physics as an alternative to the tree-level Higgs mechanism, for example by Brauner and Hosek [8].

However no one seems to have paid attention to the fact that the Dyson-Schwinger equations do provide one with several solutions depending on the strength of the coupling. In this work we call attention to this point and its potential relevance for the fermion problem. Each of the three fermions corresponds in this hypothesis to a quantum over a different vacuum (but in the covariant formalism one pursues the study of correlation functions, here propagators, and sidesteps the issue of the vacuum wave functional). Far from attempting a complete theory, we will show the general features of the mechanism within a simple model of a fermion field coupled to a scalar boson through a Yukawa coupling.

From this prospective, different flavored fermions, one corresponding to each family, are quanta of the same field, so the lagrangian can be more economically written. Each fermion is an elementary one-particle excitation on top of a vacuum that is a local minimum of the Hamiltonian. The excitations over the ground-state vacuum provide the lightest fermion family. Finally, at fixed coupling g, the Dyson-Schwinger equation has a finite number of solutions, so a finite number of families arise. The question on why three families becomes only a question of the value of g, the interaction coupling, and may have no special significance.

The equivalent of the propagator Dyson-Schwinger equation in a non-covariant framework is the well studied mass gap equation of potential models of QCD. The equation has been numerically solved for the harmonic oscillator potential [9], [10], the linear potential [11], and the linear plus Coulomb potential [12,13]. Bicudo, Ribeiro and Nefediev have systematically studied the excited solutions of this equation [15]. Our results seem compatible with this prior work.

2 Dyson-Schwinger equation and its numerical solution

We examine a simple Yukawa theory for one fermion field coupled to a real scalar field with Lagrangian density in Euclidean space

$$\mathcal{L} = \bar{\Psi}(i\,\not{p} - m_\Psi)\Psi + g\bar{\Psi}\Psi\phi + \frac{1}{2}\phi(\partial_\mu\partial^\mu - m_\phi^2)\phi \ . \quad (1)$$

The Dyson-Schwinger equation for the fermion propagator in this theory is represented in figure 1 in the rainbow approximation (neglecting the vertex dressing).

To examine generic features of dynamical chiral symmetry breaking we can further ignore the running of the wavefunction renormalization and set $Z(p^2) = 1$, a constant. This leaves one scalar equation for the fermion mass function that reads

$$M(p^2) = m_\Psi Z_2 + \int_0^\infty dq F(q,p)\frac{M(q^2)}{q^2 + M^2(q^2)} \ . \quad (2)$$

In the chiral limit $m_\Psi \to 0$ this equation becomes homogeneous and accepts a chiral-symmetry preserving solution $M = 0$ that continuously deforms into a soft-running mass form when m_Ψ is not zero. But for strong enough kernels F it also admits other solutions that break chiral symmetry.

The kernel in this simple Yukawa theory is

$$F(q,p) = \frac{g^2 q^3}{4\pi^3}\int_{-1}^1 \sqrt{1-y^2}dy\frac{1}{(q-p)^2 + m_\phi^2} \quad (3)$$

with y the cosine of the polar angle in Euclidean four-dimensional space from p to q.

To obtain excited solutions for M as function of p^2 we apply an iterative linear method with different initial guesses with or without nodes for $M(p^2)$. This method proceeds by examining linear deviations of the exact solution

$$M(p^2) = M_0(p^2) + \epsilon(p^2) \quad (4)$$

that yield

$$\epsilon(p^2) - \int_0^\infty dq F(q,p)\epsilon(q^2)\left(\frac{q^2 - M^2(q^2)}{(q^2 + M^2(q^2))^2}\right) \quad (5)$$

$$= m_\Psi Z_2 - M_0(p^2) + \int_0^\infty dq F(q,p)\frac{M_0(q^2)}{q^2 + M_0^2(q^2)} \ .$$

This can in turn be discretized (simply discretizing p) and cast as a linear system

$$A_{ij}\epsilon_j = (RHS)_i \quad (6)$$

and solved with standard numerical linear algebra tools. The kernels require only the calculation of 2-dimensional integrals that are also standard fare in modern computers.

By naive dimensional analysis one sees that the integral needs UV regularization. We accomplish this by a simple cut-off method. Then the parameters should be chosen to run with the cutoff $g(\Lambda)$, $m_\psi(\Lambda)$ to ensure that the mass functions turn largely independent of Λ. In our results we display the dependence of the solution with g at fixed Λ. The boson mass m_ϕ is chosen to be 1 and sets the unit of the theory.

3 Numerical results and discussion

In this section we present the chiral-symmetry breaking conventional and new excited state solutions. By running our computer program incrementing g we meet critical g values g_0, g_1, ...g_n above which there are exactly $n + 1$ solutions, the last with n nodes, that we find numerically. For example the first solution appears for a critical $g_0 \simeq 6.8$ (of course this number runs with the cutoff).

We show in figure 2 the three solutions obtained with $g = 14$, $\Lambda = 200$.

Then in figure 3 we plot the nodeless solution at fixed cutoff incrementing g sequentially to show the dependence of the mass function on the coupling.

Only the nodeless solution has been widely used in past literature for its applications in hadron physics. The others are sometimes rejected [16] on the basis of "wrong" UV asymptotic behavior, arguing that they do not match with conventional mass running in perturbation theory, and artificially imposing a boundary condition that discards all but one solution.

We point out here that this mismatch poses no problem. One should interpret these solutions as the one-particle excitations above different extrema of the Hamiltonian or vacuum replicae. Therefore they cannot all be matched to the same perturbation theory around one particular vacuum.

If one insists on viewing them from the one vacuum that connects smoothly to perturbation theory, then they have to be written down as complicated collective states in terms of the one-particle solutions over this vacuum.
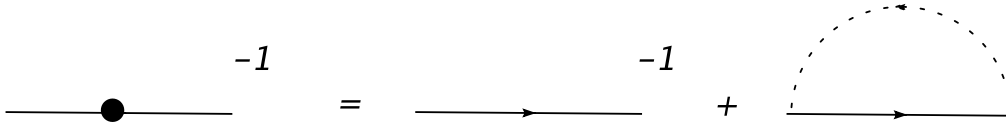
Fig. 1. Dyson-Schwinger equation for the fermion propagator in Yukawa theory, in the rainbow approximation.
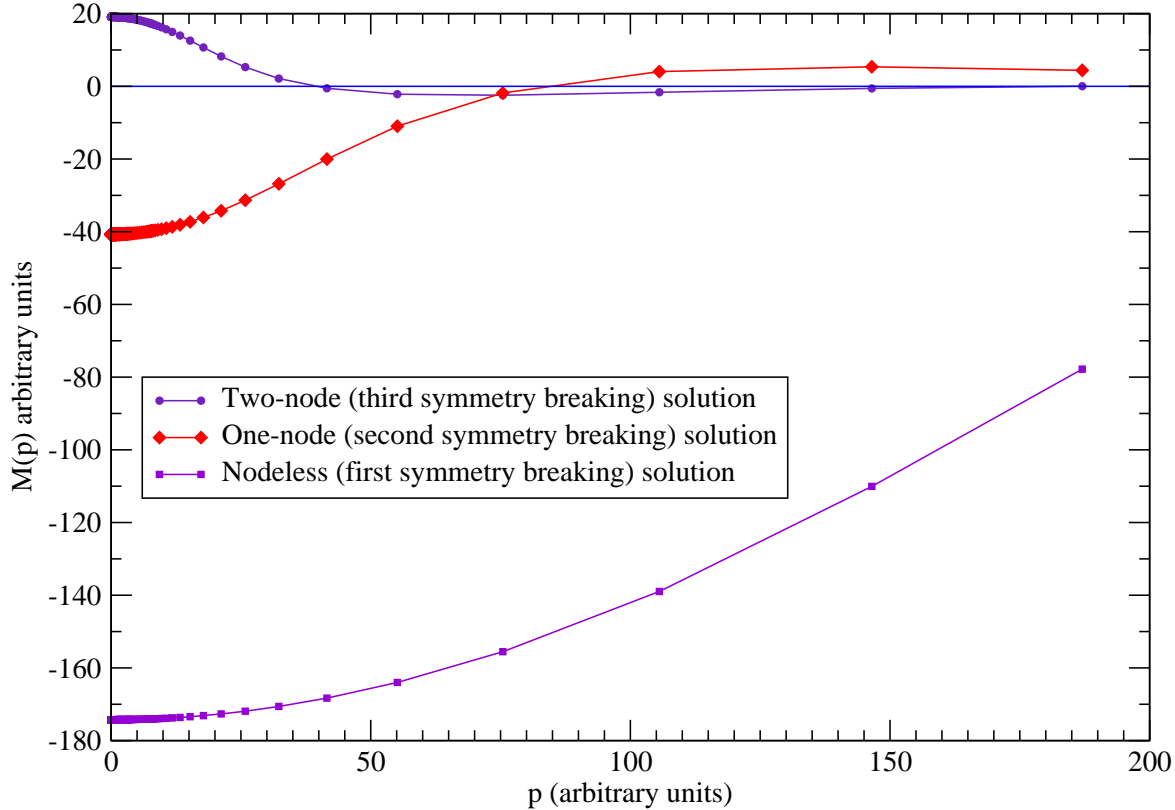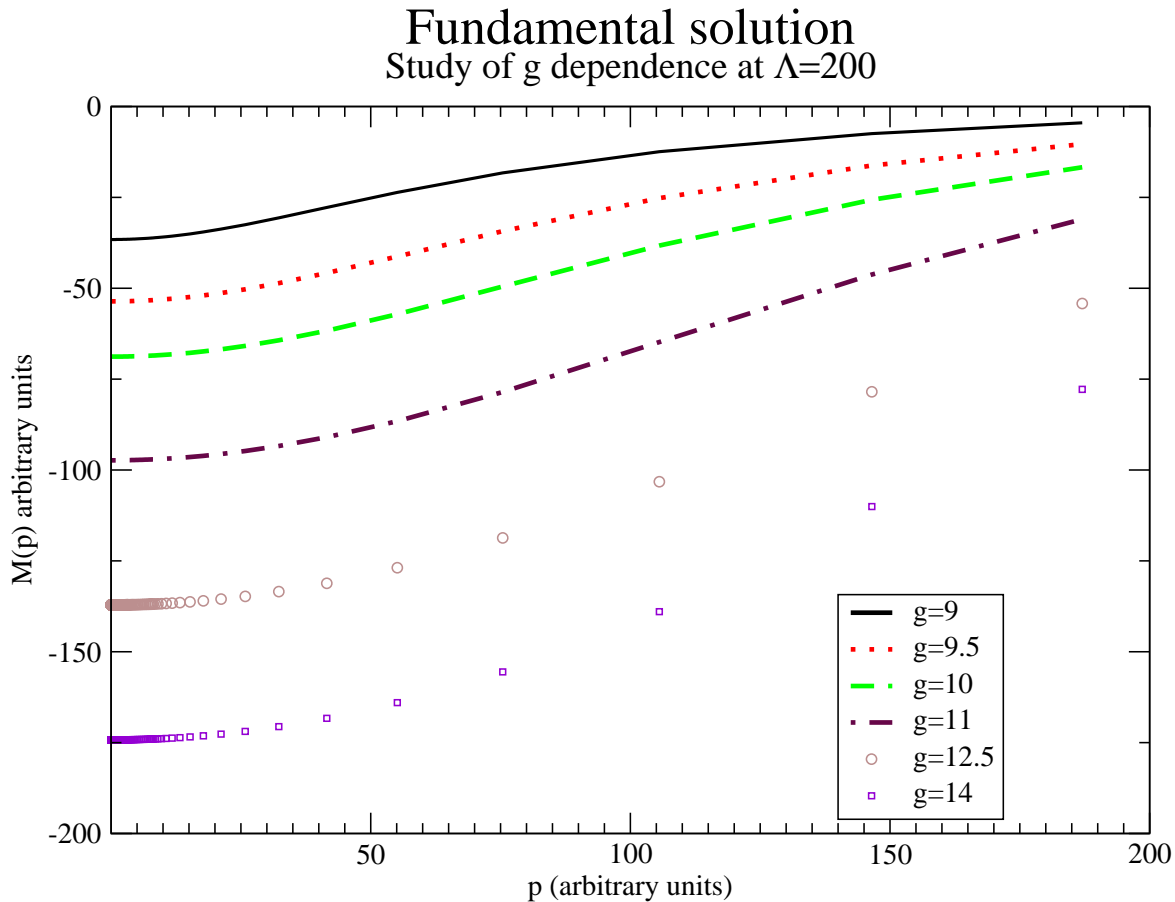

Fig. 2. We plot together the three solutions to the Dyson-Schwinger equation for a fermion-scalar Yukawa coupling $g = 14$, cutoff $\Lambda = 200$, and the scale set by the scalar mass being fixed to $m_\phi = 1$. Note the equation for M in the chiral limit (zero current fermion mass) cannot distinguish M from $-M$ so the global sign of any one solution in this graph is irrelevant and for display purposes only. In particular all M(0) can be taken as positive.

In the particular case of the Yukawa theory, the angular integral in eq. 3 can be performed analytically [14], but we prefer keeping a two-dimensional integral thinking of future work with more complicated model Lagrangians.

In agreement with the findings of [15], we see that the higher excited vacua in this covariant Euclidean formulation present zeroes in the mass function. A version of the Sturm-Liouville theorem must be at work (this is not surprising since the Hamiltonian is hermitian).

Also note that the values of $M(0)$ generated in this covariant Yukawa theory show quite some hierarchy. In figure 2 one can see that they are well-spaced. Therefore

this field-theory mechanism might conceivably be at work in the fermion flavor problem. However $M(0)$ seems to be larger for the nodeless solution than for the excited ones (this puzzling property also appears in the equal-time approach of [15], and the extent of its model dependence needs to be further investigated). To confirm this point, we choose a different set of parameters and implementation of the computer code. With $m_\phi = 100$, a cutoff $\Lambda = 10^4$ implemented as a Gaussian fall-off of the integration measure (as opposed to terminating the grid), and $g = 50$, with a small bare fermion mass $m_\psi = 5 \cdot 10^{-4}$, one obtains the three solutions depicted in figure 4. This graph

Fundamental solution
Study of g dependence at Λ=200

Fig. 3. Nodeless solution for increasing values of the coupling constant ($m_\phi = 1$ and $\Lambda = 200$ are held fixed). Note how $M(0)$ grows steadily with g (the sign of M is irrelevant).

confirms that the nodeless solution is higher in mass, and that it is possible to generate sizeable mass hierarchies between the solutions. We use this run to also illustrate the dependence of M_2 with the cutoff, displayed in figure 5. As can be seen, the excited solution does not decrease monotonically as $g \to 0$, it rather seems to become a singular solution at the critical coupling. This technicality is however probably irrelevant for physical applications.

In hadron physics the strength of the interaction being fixed by extensive phenomenology, there would be no freedom to vary g. In the physically relevant cases studied in [15], excited solutions exist at physical values of the coupling. In [17] Ribeiro and Nefediev have further extended their original results to include bound states (mesons) constructed with the replicated quasiparticles. In particular there are Goldstone bosons over the replicated vacuum, that are of course not massless pions but would appear as excited pion states (separated from the ground state pion by the mass gap between the two vacua). Whether any conventional mesons accept a more convenient description

as replicated mesons instead of excited mesons over the standard vacuum remains an open question.

Working in Euclidean space as we do provides fastly convergent integrals. This technicality may be avoided by employing a Lehmann representation [18] that allows a direct solution in Minkowski space with similar results.

4 Experimental signature

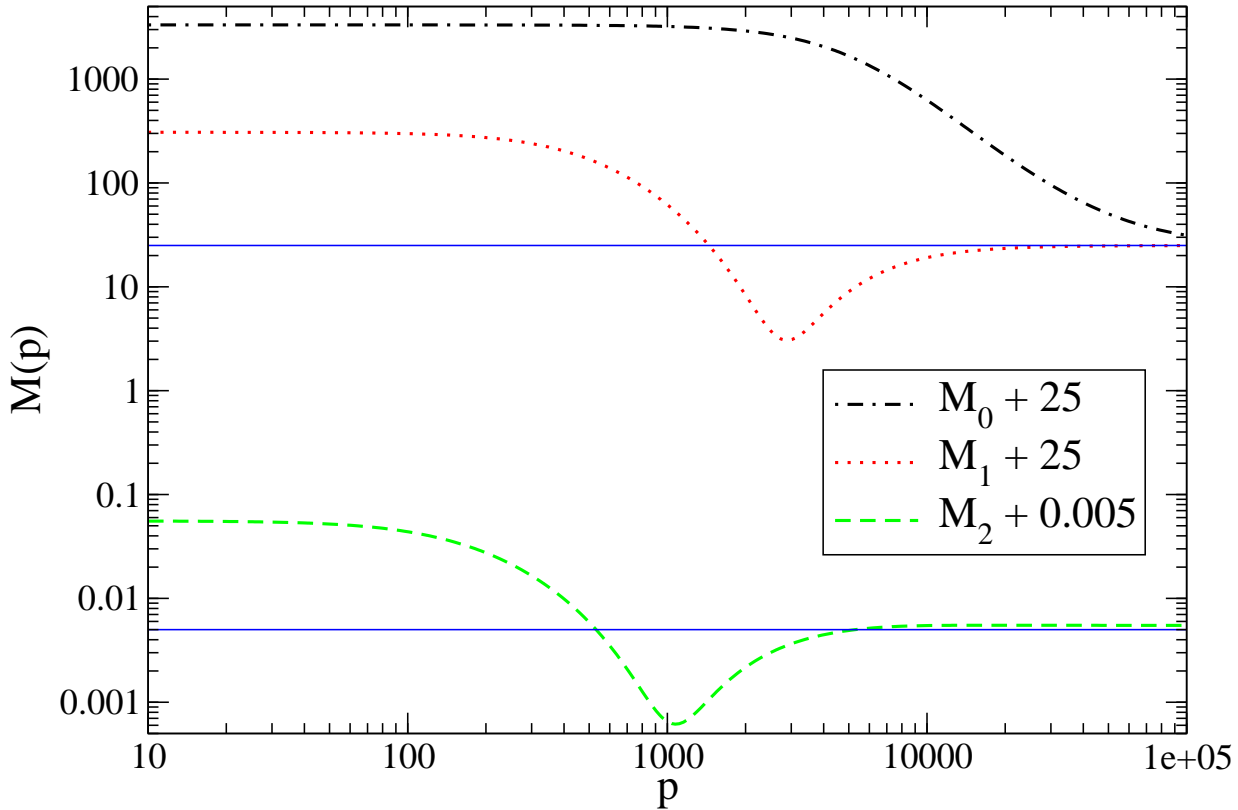In a free field theory, a field quantum of mass m satisfies the equation

$$E = \sqrt{\mathbf{p}^2 + m^2} \qquad (7)$$

that causes a pole in the free propagator

$$S = \frac{i}{p^2 - m^2} \ . \qquad (8)$$

In an interacting field theory this pole will be shifted due to renormalization from its bare to its physical position. The dependence on the renormalization scale can

Multiple gap functions solving the same DSE
(shifted for clarity)

Fig. 4. Three solutions to the gap equation in Yukawa theory obtained with $m_\phi = 100$, $\Lambda = 10^4$, $m_\psi = 5 \cdot 10^{-4}$, $g = 50$, confirming that the nodeless solution is higher in mass, and that a sizeable hierarchy of masses is possible. To represent them in a log-log plot, M_1 and M_2 being negative in part of their domain, the solutions have been shifted by a constant amount to positive values.

be traded by a dependence on the particle Euclidean 4-momentum so that

$$S = \frac{iZ(p^2)}{p^2 - M(p^2)^2} \quad (9)$$

yielding the transcendental equation for the pole position

$$E = \sqrt{\mathbf{p}^2 + M(E^2 - \mathbf{p}^2)^2} \ . \quad (10)$$

Another way of visualizing the function $M(p^2)$ of the interacting theory is to trade p^2 by the space-like part $\mathbf{p}^2$ as argument of M, generating therefore a non-trivial dispersion relation for virtual particles, and the zeroes of the mass function M appear as points where $E = |\mathbf{p}|$ that would otherwise only be reached asymptotically at large $\mathbf{p}$ (see figure 7). Tests for a non-trivial (real particle) dispersion relation have been proposed and some carried out in the search for violations of Lorentz invariance [19]. However these are very indirect and usually performed at low
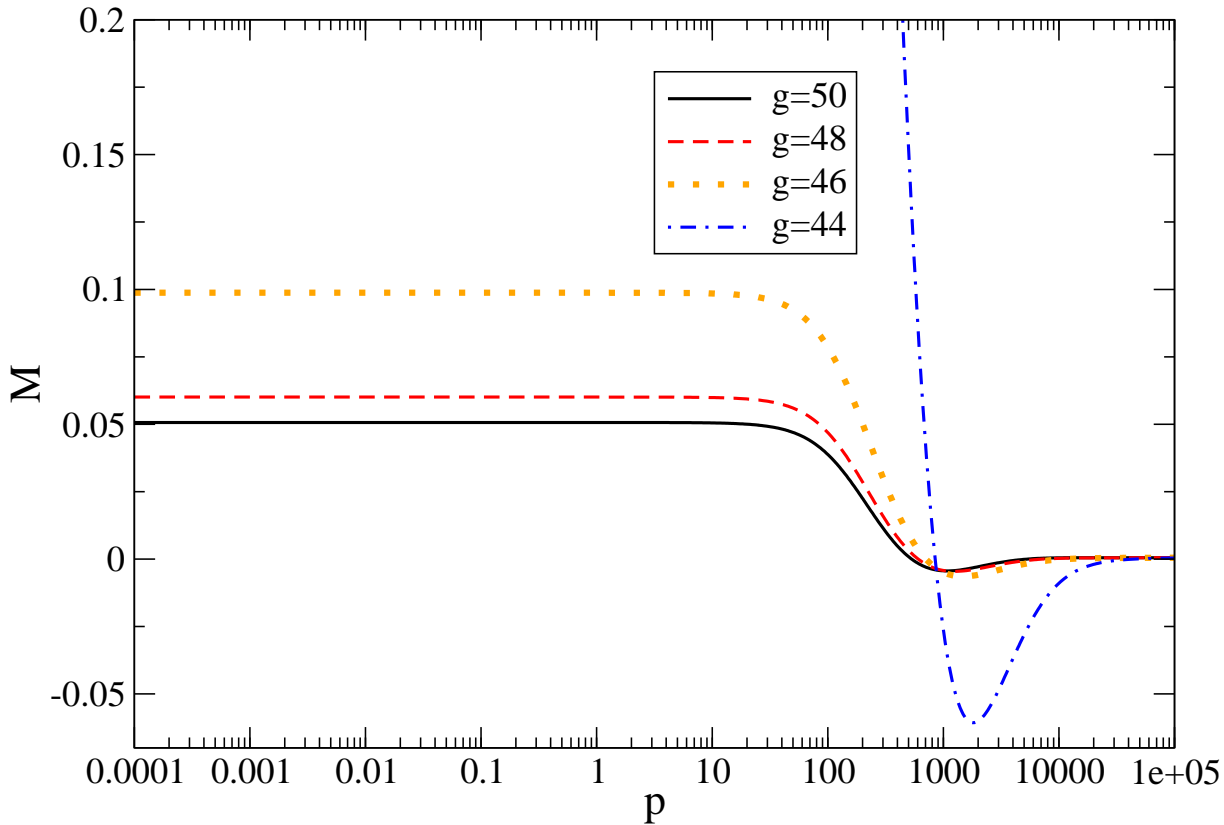
energy, so an accelerator-based test of the (virtual particle) dispersion relation by separately measuring E, $\mathbf{p}$ and the off-shellness is preferable. In our case, real particles still provide representations of the Poincaré group and have constant, physical mass. However virtual particles off their mass shell will display the running mass function and this can be captured by analyzing the amplitudes of physical processes in perturbation theory.

The corresponding dispersion relations are plotted in figures 6 and 7.

Lacking a real theory there are two possibilities we cannot discern at present. Either all three families of fermions arise as solutions spontaneously breaking chiral symmetry, in which case two of them should already have a zero in their mass function, or the first generation reflects the trivial solution only slightly modifying the bare mass, and the second and third generation solutions with dynamically broken chiral symmetry, in which case only one of

Dependence of M$_2$ with the coupling g

Fig. 5. Dependence of M_2 with the coupling constant at fixed $m_\phi = 100$, $\Lambda = 10^4$, $m_\psi = 5 \cdot 10^{-4}$. Upon comparing with figure 3 we see that the qualitative behavior when the solution approaches the critical coupling and is about to cease existing, here $g = 43$, is quite different for the ground and excited solutions.
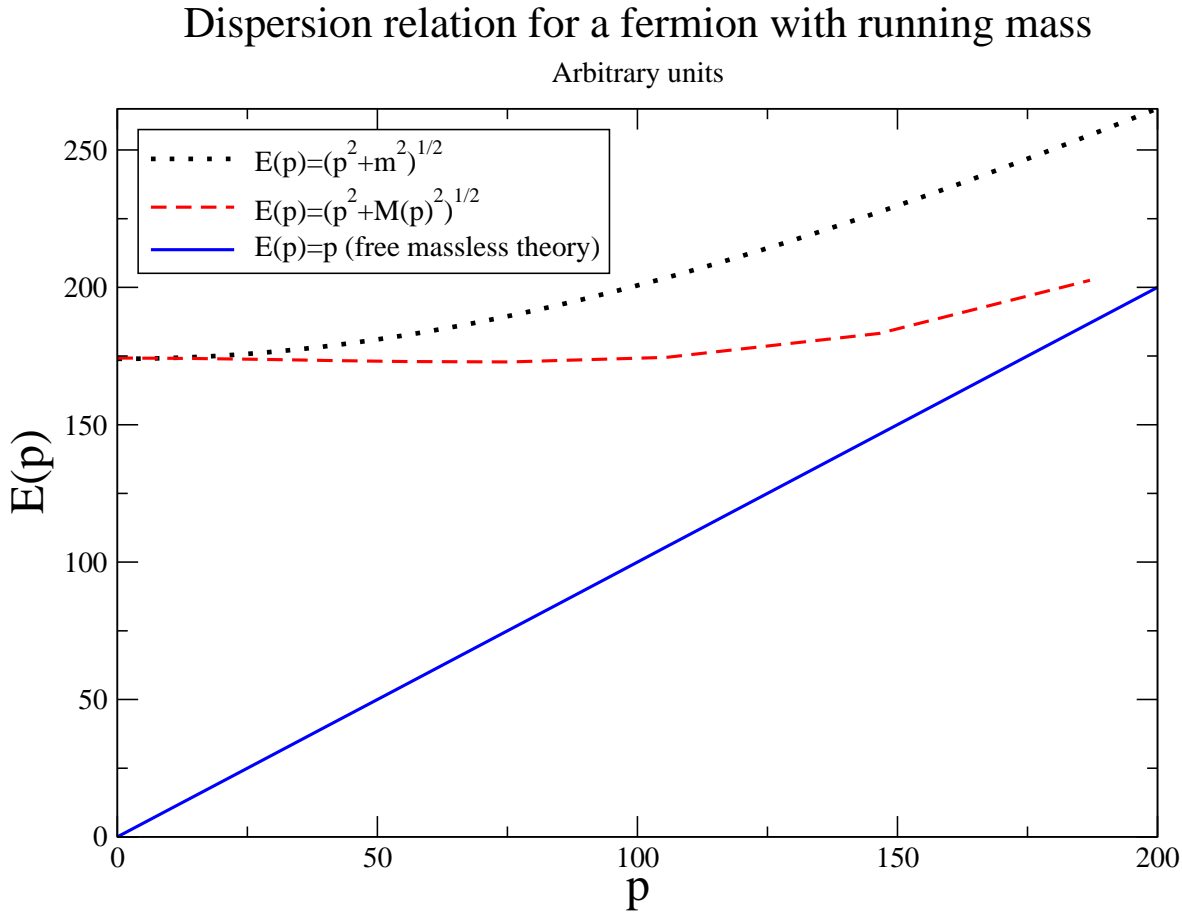
them would present a node. In either case a zero is present in the mass function of one of the fermions.

An interesting experiment is therefore a measurement of p, E and the off-shellness $\Delta^2 = p^2 - M^2(p^2)$ of a τ, at various momenta p. The B factories have accumulated large τ samples [23] that are under analysis and can be employed for this purpose.

The process one may investigate is depicted in Fig. 10 in the appendix below. An electron-positron pair collides and annihilates into a $\tau^{-*}\tau^+$ pair, where the τ^{-*} is off its mass shell. Its four-momentum can be infered from the center-of-momentum energy of the incoming e^-e^+ pair and by reconstructing the energy and momentum of the on-shell τ^+ from its decay products, as detailed shortly. Finally, one needs the off-shellness, but this can be obtained from the number of counts with given E, $|\mathbf{p}|$. This is obvious since the cross section for a specific process where the off-shell τ^- decays into for example $l^- \bar{\nu}_l \nu_\tau$, depends on the off-shellness Δ^2 of the τ^- (see also App. A).

Let us now detail the possible analysis:

1. In the center of mass frame of an e^-e^+ collision one can identify two back-to-back hadron jets, tagging the flavor by demanding that one of them kinematically reconstructs an on-shell τ. This is rendered difficult by the undetected neutrino, that we assume to be the only unreconstructed track on the left side of the event.

2. Complete reconstruction of the energy and momentum on the left side of the event (see Fig. 8) is possible with a vertex detector (giving the direction of motion of the on-shell τ). The total energy is taken from collider calibration, and matched to the energy of the visible tracks. Balancing energy provides the energy of the missing neutrino, and automatically the momentum of the left side, that can be tested against the hypothesis of a physical τ being produced.

3. Next one examines the right side of the reaction, where the secondary and primary vertex seem to coincide (as appropriate for a virtual, off-shell τ decaying rapidly).

Dispersion relation for a fermion with running mass

Fig. 6. The virtual particle dispersion relation at fixed cutoff scale for the nodeless $M(p^2)$ solution. Note that the interacting theory falls below the usual Yukawa dispersion relation because the mass function drops with p. This is not very different from standard perturbative running with p except the effect is much larger in the case of dynamical chiral symmetry breaking.

The total three-momentum is known a priori. One balances momentum to obtain the momentum taken by the undetected ν_τ, and obtains the total energy. Now, it is not necessarily true that $E^2 - \mathbf{p}^2 = m_\tau^2$.

4. The number of counts with given E, $\mathbf{p}$ on the right side is normalized to a cross section in terms of the off-shellness $\sigma(\Delta^2)$ and used to obtain M from the value of the intermediate propagator in perturbation theory.

An alternative possibility is to carry out the measurement on the expected O(20-30) τ events at the OPERA experiment [21] in Gran Sasso National Laboratory. Given the momentum of the neutrinos from the CNGS beam one can attempt full kinematical reconstruction of $(E, \mathbf{p})$. However here the difficulty resides in the off-shellness since a small value will be forced for the identification of the τ.

The experimental test for the muon and the electron is even simpler, for example through Compton and reverse Compton scattering where the fermion is off-shell in the intermediate state. For quarks one needs to take into account that they always appear in bound states, and therefore the mass function is always under an integral sign and reconstruction from experimental data difficult. However a particularly simple case is
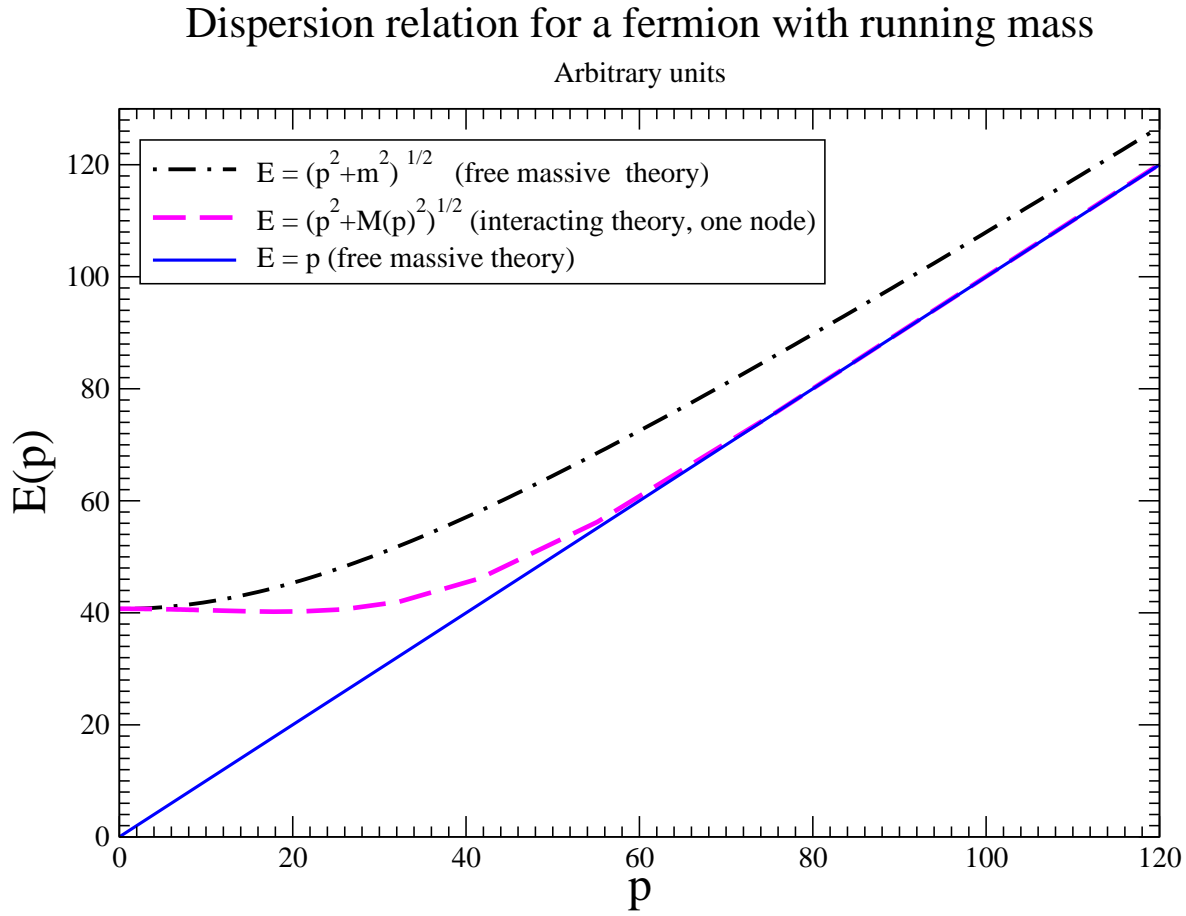
$$e^- e^+ \to \gamma^* \to s\bar{s}$$

where the strangeness be completely tagged by counting all hyperons in both jets.
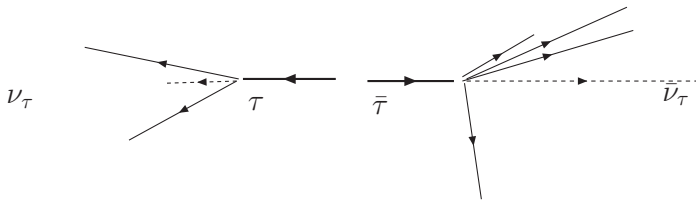
In principle the same analysis carried out here could also be undertaken for Majorana particles but this is out of our scope in this preliminary work.

5 Conclusions

We have called attention to an interesting feature of field theory, namely the possibility of having several solutions of the one-particle Dyson-Schwinger equations for a broad

Dispersion relation for a fermion with running mass

Arbitrary units

Fig. 7. The virtual dispersion relation at fixed renormalization scale for the solution with two nodes (we find similar result for one node). As the running mass actually has a zero, the dispersive curve touches the massless limit that would otherwise be reached only asymptotically.

Fig. 8. In center of mass frame production where $\mathbf{p}_\tau + \mathbf{p}_{\bar\tau} = \mathbf{0}$ one can fully reconstruct the decay of both τ leptons if only the neutrinos escape undetected. The analysis steps are described in the text.

class of theories. The excited solutions appear upon increasing the coupling constant sufficiently, breaking chiral symmetry.

The spectrum of states on top of each of the vacua is called "replica" or "recurrence" and provides a mechanism that might be interesting for the theory of flavor. The number of recurrences arises from no special symmetry, since non-linear equations can perfectly have a finite number of solutions (again depending on the value of the coupling, this can be chosen to be three).

These solutions have been shown in the past in a Hamiltonian framework [15] and we have minimally extended the results of these authors to show that the covariant formulation allows similar phenomena. The excited solutions have mass functions that present zeroes and this reflects in the virtual dispersion relation (feature of an interacting field theory that should not be confused with breaking of Lorentz invariance).

Whether these solutions will be relevant to the fermion family problem can be tested at B factories employing their large τ samples directly produced.

At this point it is a meaningless exercise to attempt to obtain the fermion masses in this scheme. Three data points $M_i(0)$ should be used to fit three parameters, the current fermion mass (that we have here set to zero), the boson mass, and g at a given cutoff, so the current predictive power is null. However we find this field theory mechanism still worth attention given the ease with which fermion coupling universality can be incorporated by having three recurrences of the same field.

Testing the off-shell dispersion relation should allow to immediately discard the scenario so we believe we have presented a valid physical hypothesis. Of course, the success of radiative corrections in the standard model make one wish for a measurement at the highest possible energy, maybe at a future linear collider.

A τ-pair production in e^+e^- collisions

A.1 On-shell cross section

We look at the $e^+e^- \to \tau^+\tau^-$ process depicted in Fig. 9, where all ingoing and outgoing particles are on their mass shell. Using the conventions of Ref. [22], the amplitude for the depicted process is

$$-i\mathcal{M} = \overline{u}_{\eta^-}^{\tau^-}(p^-) \ (-ie\gamma^\nu) \ v_{\eta^+}^{\tau^+}(p^+) \ \left(\frac{-ig_{\mu\nu}}{Q^2}\right)$$
$$\times \ \overline{v}_{\xi^+}^{e^+}(k^+) \ (ie\gamma^\mu) \ u_{\xi^-}^{e^-}(k^-) \ . \quad (11)$$

For the unpolarized cross section, one needs the squared amplitude averaged over initial and summed over final spins

$$\overline{\sum}|\mathcal{M}|^2 = \frac{1}{4}\frac{e^4}{s^2} \sum_{\text{all spins}} \overline{u}_{\eta^-}^{\tau^-}(p^-)\,\gamma_{\mu_{\eta^-\eta^+}}\,v_{\eta^+}^{\tau^+}(p^+)$$
$$\times \ \overline{v}_{\xi^+}^{e^+}(k^+)\,\gamma^\mu{}_{\xi^+\xi^-}\,u_{\xi^-}^{e^-}(k^-)\,\overline{u}_{\xi'^-}^{e^-}(k^-)\,\gamma^\nu{}_{\xi'^-\xi'^+}\,v_{\xi'^+}^{e^+}(k^+)$$
$$\times \ \overline{v}_{\eta'^+}^{\tau^+}(p^+)\,\gamma_{\nu_{\eta'^+\eta'^-}}\,u_{\eta'^-}^{\tau^-}(p^-)\ , \quad (12)$$

where the spinor indices are explicitly shown. For e^+e^- annihilation, one has $Q^2 = s$. One can now rearrange the factors in Eq. (12). Making use of the relations

$$u_\xi^l(p)\overline{u}_{\xi'}^l(p) = (\not{p} + m_l)_{\xi\xi'}\ , \quad (13a)$$
$$v_\xi^l(p)\overline{v}_{\xi'}^l(p) = (\not{p} - m_l)_{\xi\xi'}\ , \quad (13b)$$

one can write Eq. (12) as a product of traces

$$\overline{\sum}|\mathcal{M}|^2 = \frac{1}{4}\frac{e^4}{s^2}\operatorname{Tr}\left[(\not{k}^- + m_e)\,\gamma^\nu\,(\not{k}^+ - m_e)\,\gamma^\mu\right]$$
$$\times \operatorname{Tr}\left[(\not{p}^- + m_\tau)\,\gamma_\mu\,(\not{p}^+ - m_\tau)\,\gamma_\nu\right]\ . \quad (14)$$

Neglecting the electron mass, this results in

$$\overline{\sum}|\mathcal{M}|^2 = \frac{8e^4}{s^2}\left(k^-\cdot p^-\,k^+\cdot p^+ + k^-\cdot p^+\,k^+\cdot p^- + m_\tau^2\,k^-\cdot k^+\right)\ . \quad (15)$$

This can be written in terms of Mandelstam variables

$$s = (k^- - k^+)^2 = (p^+ - p^-)^2 = Q^2\ , \quad (16a)$$
$$t = (k^- - p^-)^2 = (p^+ - k^+)^2\ , \quad (16b)$$
$$u = (k^- - p^+)^2 = (p^- - k^+)^2\ , \quad (16c)$$

as

$$\overline{\sum}|\mathcal{M}|^2 = \frac{2e^4}{s^2}\left(t^2 + u^2 + 4\,m_\tau^2\,s - 2\,m_\tau^4\right)\ , \quad (17)$$

where at high energies, the mass terms become negligible. In the center-of-momentum (com) frame, the amplitude is

$$\overline{\sum}|\mathcal{M}|^2 = \frac{e^4}{s^2}\left[s^2\left(1 + \cos^2(\theta_\tau)\right) + 4\,m_\tau^2\,s\left(1 - \cos^2(\theta_\tau)\right)\right]\ , \quad (18)$$
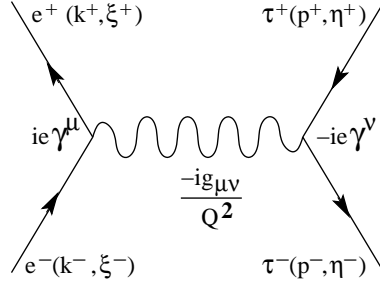
with θ_τ the com-angle between incoming electron e^- and outgoing τ^-.

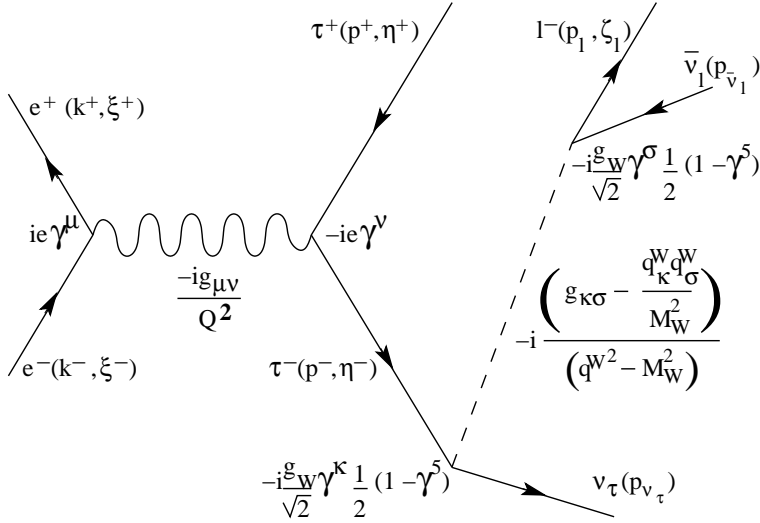The differential cross section in the com-frame is then given by

$$\frac{d\sigma}{d\Omega}\bigg|_{\text{com}} = \frac{\alpha^2}{4s^2}\sqrt{1 - \frac{4m_\tau^2}{s}}$$
$$\times \left[s\left(1 + \cos^2(\theta_\tau)\right) + 4m_\tau^2\sin^2(\theta_\tau)\right]\ , \quad (19)$$

with $\alpha = e^2/4\pi$. The total cross section is

$$\sigma_{\text{tot.}}^{\text{com}} = \frac{4\pi\alpha^2}{3s}\sqrt{1 - \frac{4m_\tau^2}{s}}\left(1 + \frac{2m_\tau^2}{s}\right)\ . \quad (20)$$

Fig. 9. On-shell τ-pair production in e^+e^- collisions. The particles' momenta and spins are indicated, as well as the conventions for the photon propagator and the vertices.

Fig. 10. Half off-shell τ-pair production in e^+e^- collisions. The particles' momenta and spins are indicated, as well as the conventions for the boson propagators and the vertices.

A.2 Half off-shell cross section

In this part of the Appendix, we look at the $e^-e^+ \to \tau^-\tau^+$ process, where one of the τ-particles is off its mass shell and decays into a lighter lepton l (electron or muon). We discuss the case for an off-shell τ^-. The case for an off-shell τ^+ is clearly completely analogous. The process is displayed in Fig. 10.

The off-shellness of one of the τ's changes the kinematics. The total energy in the reaction is unevenly divided: $E_{\tau^+} \neq E_{\tau^-} \neq W_{\rm com}/2$, where $W_{\rm com} = \sqrt{s}$ is the total energy in the com-frame. The amplitude for the process depicted in Fig. 10 is

$$- i\mathcal{M} = \overline{u}_{\zeta_l}^{l^-}(p_l) \left(-i\frac{g_W}{\sqrt{2}} \gamma^\sigma \frac{1}{2}\left(1-\gamma^5\right)\right) v^{\bar\nu_l}(p_{\bar\nu_l})$$

$$\times (-i) \frac{\left(g_{\kappa\sigma} - \frac{q_\kappa^W q_\sigma^W}{M_W^2}\right)}{\left(q^{W\,2} - M_W^2\right)} \overline{u}^{\nu_\tau}(p_{\nu_\tau}) \left(-i\frac{g_W}{\sqrt{2}} \gamma^\sigma \frac{1}{2}\left(1-\gamma^5\right)\right)$$

$$\times \frac{i}{(\not{p}^- - M_{\tau^-})} (-ie\gamma^\nu)\ v_{\eta^+}^{\tau^+}(p^+) \left(\frac{-ig_{\mu\nu}}{q^2}\right)$$

$$\times \overline{v}_{\xi^+}^{e^+}(k^+)\ (ie\gamma^\mu)\ u_{\xi^-}^{e^-}(k^-). \quad (21)$$

The propagator of the off-shell τ^- will give rise to a dependence of the amplitude on the *off-shellness* $\Delta^2 = E_{\tau^-}^2 - \boldsymbol{p}_\tau^2 - M_{\tau^-}^2$.

In the limit of infinite mass of the W-boson and vanishing electron mass, the unpolarized squared amplitude for the process depicted in Fig. 10 is [24]

$$\overline{\sum}|\mathcal{M}|^2 = \frac{2^{12}\ \pi^4\ \alpha_{\rm QED}^2\ \alpha_{\rm weak}^2}{M_W^4\ \Delta^4\ q^4}\ p_{\nu_\tau} \cdot p_l$$

$$\times \Big[p_{\bar\nu_l} \cdot p^- \left(m_\tau\ M_{\tau^-}\ k^+ \cdot k^- + k^+ \cdot p^+\ k^- \cdot p^- + k^+ \cdot p^-\ k^- \cdot p^+\right)$$

$$- \frac{\Delta^2}{2} \left(k^+ \cdot p_{\bar\nu_l}\ k^- \cdot p^+ + k^+ \cdot p^+\ k^- \cdot p_{\bar\nu_l}\right)\Big]. \quad (22)$$

The (differential) cross section for this process is proportional to the above squared amplitude, integrated over the threemomenta of the outgoing τ-neutrino and lepton-antineutrino. This is not a simple task, yet it is clear that the resulting cross section will depend on the off-shellness Δ^2 and the virtual τ mass-energy dispersion relation.

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