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Weak and electromagnetic interactions

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One of the recurrent dreams in elementary particle physics is that of a possible fundamental synthesis between electromagnetism and weak interaction. The idea has its origin in the following shared characteristics:

1. Both forces affect equally all forms of matter-leptons as well as hadrons.
2. Both are vector in character.
3. Both (individually) possess universal coupling strengths.

Since universality and vector character are features of a gauge theory those shared characteristics suggest that weak forces just like the electromagnetic forces arise from a gauge principle. There is of course also a profound difference: electromagnetic coupling strength is vastly different from the weak. Quantitatively one may state it thus: if weak forces are assumed to have been mediated by intermediate bosons (W), the boson mass would have to equal from 50 to as large as 137 M_p, in order that the (dimensionless) weak coupling constant $g_w^2/4\pi$ equals $e^2/4\pi$.

I shall approach this synthesis from the point of view of renormalization theory. I had hoped that I would be able to report on weak and electromagnetic interactions throughout physics, but the only piece of work that is complete is that referring to leptonic interactions, so I will present only that today. Ward and I worked with these ideas intermittently (1, 2), particularly the last section on renormalization of Yang-Mills theories. The material I shall present today, incorporating some ideas of Higgs & Kibble, was given in lectures (unpublished) at Imperial College. Subsequently I discovered that an almost identical development had been made by Weinberg (3) who apparently was also unaware of Ward's and my work.

The renormalization point of view has become increasingly more and more important as time has gone on. In fact, if I have heard the reports rightly, the major activity in the U.S.A. last year, at least according to the rumours we heard about it, was the attempt to renormalize the radiative corrections to beta-decay, particularly at Princeton, by Gell-Mann, Goldberger, Kroll, Low and others. I will not say that the problem of renormalization of weak interactions, together with their radiative corrections, has acquired the same

importance now as in 1947 it had for electrodynamics in connection with the Lamb shift, but I think it is a pretty serious problem, which must be treated at a fundamental level.

Today it is not the renormalization to second order that one is speaking about. I have in mind a renormalization program that should apply for the complete theory just as the program applied for electrodynamics itself. From this point of view we shall see that this unification of electromagnetism and weak interactions becomes more and more of a necessity. Further, it places a large number of restraints on the type of theory one can have.

For leptonic weak interactions the basic problem is of course that one is dealing with vector and axial vector interactions of spin half particles. The four-fermion interaction has not the slightest vestige of renormalizability. We thus consider intermediate boson theory and what we wish to do is to formulate the theory such that the photon appears as the neutral intermediate boson. Before I do this I shall briefly review what we know about the renormalization problem of vector mesons. As is well known, the lack of renormalizability of the theory arises from massive vector mesons from the $k_\mu k_\nu/m^2(k^2-m^2)$ term in the propagator.

(*a*) Consider *neutral vector* mesons, where there is hope that currents can be conserved. In this case Feynman's old proof, in which he showed that this $k_\mu k_\nu$ term latches on to the currents J_μ and J_ν at either of the vertices and disappears because of the conservation law, applies. The theory is renormalizable even if the vector meson is massive, as was first shown by Matthews. Thus current conservation must be preserved at all costs as a minimum requirement.

(*b*) Clearly, for an *axial* current the mass of the source Fermi particle (electron or meson), which makes the current non-conserved, will destroy any hope of renormalizability. Therefore the second restriction is that we must not have a fundamental Fermi mass in the theory.

(*c*) If one is dealing with charged vector or axial mesons the currents must include these particles themselves. To construct a conserved current this time we must have a recipe which includes contributions of the vector and axial vector mesons themselves within the current. The only known method for constructing such currents is the Yang-Mills recipe which arises when one is dealing with gauge symmetries associated with non-abelian symmetry groups.

(*d*) Now what about the renormalizability of Yang-Mills theories? Around 1962 the following was proved. Take $U(3)$ symmetry; then out of the, say, nine currents of $U(3)$, three of these, J_0, J_3 and J_8, will allow the corresponding $k_\mu k_\nu/m^2$ terms in the propagator to be transformed away. But, for the remaining currents the corresponding meson propagator must contain these terms and they cannot cancel *even though the currents are conserved.* Thus Yang-Mills

theory with *non-zero meson mass is not renormalizable even if the currents are fully conserved.*

Therefore the only hope for vector mesons is (1) a Yang-Mills theory but also (2) that mesons should be massless. *To state it more generally, it is not current conservation that is the criterion of renormalizability, but gauge invariance.* The mass of the vector meson is not gauge invariant even though it does not interfere with current conservation. Nothing that will destroy the gauge invariance is allowed. Thus the only hope for achieving a renormalizable theory involving vector currents is that the mass of the meson should come through a spontaneous symmetry breaking. Further, since the second source of lack of (axial) gauge invariance is going to be the Fermi mass term, what would be ideal is if the Fermi mass term could also come from spontaneous symmetry breaking and preferably the *same* symmetry breaking. The Fermi mass coming from symmetry breaking was an idea started by Nambu, and has been worked on particularly by Johnson, Baker and Willey in electrodynamics. One adds the mass term in the free part of the Hamiltonian, sets up an interaction representation, computes the self-mass and sets it equal to the physical mass. This gives a self-consistent equation. For the meson case the propagator has no $k_\mu k_\nu/m^2$ terms but just $\delta_{\mu\nu}/(k^2-m^2)$ and the theory from the outset is renormalizable. (See for more details ref. 2.)

A second proposal and a related one is not to do this rather brutal addition and subtraction of mass terms but to work more gently. This is the method of letting the vector mesons interact with a set of scalar particles and to let them acquire physical masses by assuming self-consistently that these scalar particles possess non-zero expectation values. Consider, for example, the charged mesons ϕ and ϕ^* interacting with a neutral vector meson. Compute self-consistently from the theory an expectation value $\langle\phi_0\rangle$ for the ϕ field. The term $e^2\phi^*\phi A_\mu^2$ in the Lagrangian now appears to have a piece $e^2(\phi_0)^2 A_\mu^2$ which acts like the vector meson mass.

Now all this is beautiful, but there was the suspected difficulty with this theory which held people back for a long time. This was the fear of Goldstone mesons. What one feared was that whenever you have such a theory Goldstone boson sits like a snake in the grass ready to strike. According to Goldstone's theorem a number of massless particles must arise in any such theory. To see these massless objects it is simplest to take the same example as before of charged scalar meson; set

$$\phi = \varrho e^{i\theta}, \quad \phi^* = \varrho e^{-i\theta} \tag{1}$$

The Lagrangian equals

$$\mathcal{L} = \partial_\mu\phi^*\partial_\mu\phi + m^2\phi^*\phi = (\partial_\mu\varrho)^2 + \varrho^2(\partial_\mu\theta)^2 + m^2\varrho^2 \tag{2}$$

It clearly has a massless field θ. It is this field θ which for spontaneous symmetry-breaking theories appears as the Goldstone boson.

A big advance in resolving this difficulty has recently been made but I do not think that many people are aware of it. This is due to Higgs and, following him, Kibble who have shown that, true, there may be massless scalar mesons when you have done the spontaneous symmetry breaking. *But if you have a gauge theory* such objects can be transformed away as gauges and they have no coupling to the physical particles. To see this let us go back to the same example. Consider the Lagrangian

$$\mathcal{L} = (\partial_\mu - ieA_\mu)\phi^*(\partial_\mu + ieA_\mu)\phi + F_{\mu\nu}F_{\mu\nu} + m^2\phi^*\phi \tag{3}$$

Now write

$$(\partial_\mu + ieA_\mu)\phi = e^{i\theta}(\partial_\mu \varrho + ieA'_\mu \varrho) \tag{4}$$

where $A'_\mu = A_\mu + \partial_\mu\theta$. Clearly the term $\partial_\mu\theta$ appears in such a way where it can be transformed away through the gauge invariance, and no trace of the θ field is left. Also, if we assume that the expectation value of ϱ could be non-zero, i.e. $\varrho = \langle\varrho_0\rangle + \varrho'$ where ϱ' is the quantized part of ϱ, then the term $e^2\varrho^2A_\mu^2$ now has a piece $e^2(\varrho_0)^2A_\mu^2$, i.e. the vector meson acquires a mass term in this particular gauge specified by $\langle\varrho_0\rangle$.

What has happened? We started with the two fields ϱ and θ. One of the fields, ϱ, I can use for spontaneous symmetry breaking. The other field was massless. The symmetry breaking gave mass to the vector meson and the massless objects got transformed away. So you have the best of all possible worlds in this theory. Since the mass term has come in gently through symmetry breaking, our claim is that the theory is renormalizable. It clearly is in the original formulation with ϕ, ϕ^* fields.

Let us now make use of this in the case of weak and electromagnetic interactions. I will try to get a Yang–Mills theory of weak and electromagnetic interactions combined because that is the only way of keeping currents conserved. Since there is a mass of the fermion, the Yang–Mills theory will want to be broken spontaneously. If the same symmetry breaking can be arranged to give masses to the charged intermediate bosons which mediate weak current but not to the neutral meson representing the electromagnetic field we would have removed the major objection to the unification of weak and electromagnetic fields of having in one multiplet massive and massless objects.

The application of the Yang-Mills ideas to weak and electromagnetic interaction has been carried through by Gatto, Ne'eman, Ward, Salam and recently Weinberg. I will write it in an $SU(3)$ notation and I hope that this will prove to be more than a notational nicety. What you do is that you have a four-

component neutrino, a negative electron and positive muon, and define the lepton triplet

$$L = \begin{pmatrix} \nu \\ e^- \\ \mu^+ \end{pmatrix} \tag{5}$$

Consider *I*-spin and *V*-spin subgroups of $SU(3)$ where I define the scalars in *I*-space and *V*-space as

$$I_0 = T^8, \quad V_0 = \frac{\sqrt{3}}{2} T^3 - \tfrac{1}{2} T^8 \tag{6}$$

The lepton charge equals

$$Q_l = \begin{pmatrix} 0 & & \\ & -1 & \\ & & 1 \end{pmatrix} \tag{7}$$

Notice that the hadronic charge in the same notation is

$$Q_h = T^3 + \frac{i}{\sqrt{3}} T^8 = \begin{pmatrix} \tfrac{2}{3} & & \\ & -\tfrac{1}{3} & \\ & & -\tfrac{1}{3} \end{pmatrix} \tag{8}$$

so that Q_h and Q_l are "orthogonal" combinations in T^3, T^8 space. Define right and left particles, conventionally,

$$\psi_{L, R} = \tfrac{1}{2}(1 \pm \gamma_5) \psi \tag{9}$$

and note that

$$I_{3L} - V_{3R} = \tfrac{1}{4}(Q_l + 3\gamma_5 Q_h)$$
$$I_{0L} - V_{0R} = \tfrac{1}{2}(Q_l - \gamma_5 Q_h). \tag{10}$$

Now the weak interaction can be written as

$$\mathcal{L}_{\text{weak}} = [(\bar{e}^- \nu)_L + (\bar{\nu}\mu^+)_R] W^- + \text{h.c.} = (I_{L1} + V_{R1}) W_1 + (I_{L2} - V_{R2}) W_2 \tag{11}$$

where the intermediate bosons are W^+ and W^-. Note that the anti-neutrino right come in with muon and neutrino left with the electron so that all four components of the neutrino field are used up. This is a minor merit of the formulation. If one has a theory of symmetries it is undesirable to have to work with two-component neutrinos and four-component electrons and muons, because in some conceptual limit you would like to transform them into each other.

To complete the Yang-Mills gauge group we must introduce the third component of the vector W, adding on the term $(I_{3L} - V_{3R})\,W_3$ to the Lagrangian. Ideally one would have liked this to be nothing but the electromagnetic field. Unfortunately the $I_{3L} - V_{3R}$ term contains the $\gamma_5 Q_h$ piece which has nothing to do with electromagnetism. One must therefore introduce in this theory an additional neutral vector meson W_0 and add in a term

$$\mathcal{L}_{\text{neutral}} = (I_{3L} - V_{3R})\,W_3 - \sqrt{3}\,\tan\theta(I_{0L} - V_{0R})\,W_0 \tag{12}$$

to the Lagrangian (11). The factor $\sqrt{3}\,\tan\theta$ gives an arbitrary scale factor between the two neutral currents. In terms of the quantities

$$A^0 = W_0 \cos\theta + W_3 \sin\theta$$
$$X^0 = -W_0 \sin\theta + W_3 \cos\theta \tag{13}$$

one can write the neutral currents as

$$(\cos\theta\, Q_X X^0 + \sin\theta\, Q_l A^0) \tag{14}$$

where

$$Q_X = \tfrac{1}{4} \sec^2\theta(3Q_h \gamma_5 + (2\cos\theta - 1)\,Q_l) \tag{15}$$

Identify A^0 with the Maxwell field. In addition one has to buy—as about the minimum price for this unification—another field X^0 which is neutral and has the current Q_X. Note that the current Q_X is diagonal in all the particles and does not transform electrons to muons.

Let us not worry about muon mass for the moment and concentrate on the electron. We shall now introduce one common source of breaking the symmetry introduced above which will give (a) mass to the electron (b) mass for W^+, W^- and for X^0 (but not to A^0). To bring out the structure of this term let us rewrite the symmetry introduced above in a more familiar language, define a lepton hypercharge and write

$$\tfrac{1}{2}Y = -\sqrt{3}\,T^8 \tag{16}$$

All that I described above in the $SU(3)$ notation can be re-expressed in the following way: we make a doublet out of the electron-left and neutrino-left with hypercharge -1 and let the electron-right correspond to $I=0$ with $Y=-2$. This can be indicated in this way

	I_3	Y	$Q = I_3 + \tfrac{1}{2}Y$
ν_L^0	$\tfrac{1}{2}$	-1	0
e_L^-	$-\tfrac{1}{2}$	-1	-1
e_R^-	0	-2	-1

To bring out the analogy with hadron physics, it would be as if we were dealing with Ξ and Ω^-.

Write

$$\mathcal{L}_m = m\bar{e}_R e_L + \text{h.c.} \overset{\text{analogy}}{=} f\bar{\Omega}^-(\langle\mathcal{K}\rangle\tau_2\Xi) + \text{h.c.}; \quad \mathcal{K} = \begin{pmatrix} \bar{K}^0 \\ K \end{pmatrix} \tag{17}$$

Since I would now want to get this mass term as an expectation value of some scalar entity, I have written it in a suggestive form in analogy with a sort of $\Delta I = \frac{1}{2}$ rule for *I*-spin breaking. To do this I have exhibited an analogous interaction of Ω^- and Ξ particles. The idea is that we introduce into the theory an object which transforms like the $\bar{K}$-meson in *leptonic I-space* and that this object—or rather the K_{01} component of it—possesses a non-zero expectation value, $f\langle K_{01}\rangle m$. The $\bar{K}$-meson thus introduced must itself have a gauge interaction plus a mass term (plus a four-field interaction to allow it to acquire a non-zero expectation value). Thus its Lagrangian is

$$\mathcal{L} = (\partial_\mu - ieW_\mu)\mathcal{K}^+(\partial_\mu + ieW_\mu)\mathcal{K} + m^2\mathcal{K}^+\mathcal{K} + \lambda(\mathcal{K}^+\mathcal{K})^2 \tag{18}$$

If one does a very simple-minded calculation the expectation value of K^0 comes out of the magnitude

$$\langle K_{01}\rangle \approx m^2/2\lambda \tag{19}$$

where m is the mass of the K-particle. We now use the Higgs ansatz and go into a special gauge where all objects except K_{01} are transformed away. Higgs would tell us that of the four real fields contained in $\mathcal{K}$, K_{01} to which we have hopefully assigned the spontaneously introduced non-zero expectation value, will survive in the Lagrangian while K_{02}, K^+ and K^- can be transformed away. What is further remarkable is that this will give mass terms proportional to $e^2\langle K_{01}\rangle^2$ to the charged intermediate bosons W^+, W^- and to X^0 but not A^0. The simplest way to see this is to remark that the vector meson field corresponding to the symmetry which survives (electric charge conservation) started with zero mass and will end up in the special gauge with zero mass. There is only one symmetry which we are preserving in the whole business and that is the symmetry corresponding to the electromagnetic field. We had no mass for this field to start with and no mass when we finish. The other three are the symmetries we break; the corresponding vector fields acquire masses which are $e^2\langle K_{01}\rangle^2$. The whole thing has therefore worked out in a unified and beautiful manner; a renormalizable theory of massive vector mesons, in which electromagnetism is built in as part of the theory and the Lagrangian is perfectly symmetrical. Only when one goes to a special gauge, where

$$\mathcal{K} = e^{i(\mathbf{I}\cdot\boldsymbol{\theta}+\frac{1}{2}Y\theta_3)} \begin{pmatrix} \varrho \\ 0 \end{pmatrix} \tag{20}$$

and where $\langle\varrho\rangle = K_{01}$, only in this gauge does the Lagrangian look ugly.

Like all suggestions in physics this one too has some associated difficulties. The first difficulty of course is "what shall we do with this expectation value?" We would like the mass of the vector meson

$$m_V^2 = e^2 \langle K_{01} \rangle^2 \tag{21}$$

to be larger than 50 BeV or so to get the weak interaction constant to equal the electromagnetism. If we want the coupling constant e to be the electromagnetic coupling constant, then $\langle K_{01} \rangle$ must be of the order of 500–1000 BeV. We can, of course, arrange for such a large value of $\langle K_{01} \rangle$ by making the mass m in front of the term $\mathcal{K}^+ \mathcal{K}$ large. But this is really shifting the problem of a large mass for the intermediate boson to a (still) larger mass for the scalar K-meson.

This is not so pleasant. There may be another way out. Suppose we were using similar ideas for the baryon case, with something like a fundamental quark field which we assume to be very massive. If such a quark mass were also to arise from spontaneous symmetry breaking, the scalar object similar to what we called the K-meson above, coupling to such quarks, would need to possess an enormous value for its vacuum expectation value. Such a scalar object would couple with the intermediate bosons just like the K-particle above and give them mass. It may be more pleasant to find the source of large vector boson mass thus through its association with baryons rather than leptons. The point is that since weak bosons couple both to leptons *and* baryons, their large mass may come from the baryon side rather than leptons since all contributions of the type $\langle K_{01} \rangle^2$ which determine both the baryon masses and boson masses come additively in the latter.

All I am trying to say is that you must have a complete theory. And one must not be allowed to break symmetries in the fundamental Lagrangian ad hoc if vector meson renormalizability is to be preserved. I feel that this is a line worth pursuing just because it is so restrictive.

Now some remarks on the construction of a similar theory for hadrons. This Ward and myself tried very hard to do in 1964 but we failed. The main source of the failure was always the Cabibbo angle. One does not want the neutral current introduced into the theory to be strangeness changing. In every theory with a non-zero Cabibbo angle this will inevitably happen.

One line we tried was to use the same combination of I_L and V_R for the hadrons with two types of intermediate bosons

$$[I_L \cos \theta + V_R \sin \theta] W_1 + [-I_L \sin \theta + V_R \cos \theta] W_2 \tag{22}$$

as far as hadrons are concerned. Let only W_1-particles interact with the leptons and require that the charge values on leptons and hadrons given by the appropriate neutral current be Q_l and Q_h,

$$Q_l = T^3 - \sqrt{3}\, T^8, \quad Q_h = T^3 + \frac{1}{\sqrt{3}}\, T^8 \tag{23}$$

This gives a unique value for $\theta = 15°$ which, it so happens, is the right numerical value for Cabibbo suppression of leptonic decays of hadrons. It is easy to check that there are no neutral strangeness-changing currents. I am not presenting this as the solution for the hadron problem, firstly because in such a theory we would get a $V + A$ charged strangeness-changing quark weak current; secondly, to get any non-leptonic strangeness-changing decays at all we shall need to use a further spontaneous symmetry breaking which must employ something like a non-zero expectation value for the physical K_0-particles ($\langle K_{01} \rangle \neq 0$) in addition to the intermediate boson theory above. The hadron problem is still unsolved.

References

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Discussion

Pais

Suppose you have by some mechanism or other a range for the effective mass of the charged W. Suppose I calculate some leptonic process, in which more than a single W-meson goes across between leptons. Is it not seriously divergent?

Salam

My claim is that in the theory I discussed there is no $k_\mu k_\nu$ term in the propagator.

Pais

In that case I want to ask a second question namely the following one. You have auxiliary scalar fields. I thought what you said is the following. The purpose of this field is by some self-consistency condition to generate the mass. At the same time you have no Goldstone particles. Suppose I have now re-transformed the theory into this form. In what way does that theory now present itself to me in a different fashion from a theory in which I had an ordinary mass from the very beginning?

Salam

Formally none. Except that this mass does not have the same origin. All your troubles are now computing this mass.

Sudarshan

I would like to pursue this point a little further. Suppose, after the theory has reached its final stage, one attempts to write down rules for computing diagrams. Would I then simply substitute the $g_{\mu\nu}/(k^2 - m^2)$ propagator?

Salam

Let us have it clear. There are two distinct formulations of the theory; the fields in the two formulations are being transformed one into the other by a non-linear (gauge) transformation. One is the perfect theory which contains all of the scalar particles; the gauge is preserved, etc. In that version of the formulation there is no $k_\mu k_\nu$ term and there are no divergences. If you ask me for a dictionary to the conventional theory obtained by transforming to the new set of fields where not all the scalar particles are present I haven't got this dictionary worked out yet. I conjecture that this will be a very simple dictionary but I have not evolved it yet.

Pais

So you have not proved that the $k_\mu k_\nu$ term can be dropped?

Salam

It can clearly be dropped in the symmetrical version of the theory. I believe this will also happen in the normal theory because I know there are no divergences; and also I know the two theories are equivalent so far as the final results are concerned.

Sudarshan

But in that case if I look at the propagator then the effective propagator for this particular particle does it not have a scalar negative norm particle because of the $g_{\mu\nu}$?

Salam

No. It cannot have negative norms because the symmetrical version of the theory does not have them. A local transformation of fields cannot introduce negative norms if there are none before.

Stech

I have some difficulty in understanding such a high mass for the intermediate boson. If one wants to calculate, in a very rough way, an absolute rate for non-leptonic decays as Glashow, Weinberg and Schnitzer did some time ago or when one wants to compare the electromagnetic mass differences with non-leptonic matrix elements of the current–current type one sees that a high mass for the intermediate particle is not likely. There are several arguments against a high value of a mass (Λ) representing the structure of weak interaction. My

own one is based on a comparison of electromagnetic mass differences with one-particle matrix elements of the weak interaction describing non-leptonic decay processes.

One has for an example:

$$\int \frac{d^4q}{-q^2} \int d^4x \, e^{iqx} \langle n \, | \, T(V^\mu_{1-i2}(x) V^8_\mu(0)) | p \rangle = \frac{\sqrt{3} \, m_p(m_n - m_p)}{e^2/4\pi}$$

and

$$\int \frac{d^4q}{-q^2 + \Lambda^2 m_p^2} \frac{\Lambda^2}{m_p^2} \int d^4x \Big\langle n \, | \, T(V^\mu_{1-i2}(x) V^{4-i5}_\mu(0) + A^\mu_{1+i2}(x) A^{4-i5}_\mu(0)) \, | \, \Lambda^0 + \frac{1}{\sqrt{3}} \Sigma^0 \Big\rangle$$

$$= \frac{(2\pi)^4 \Big\langle n \, | \, \mathcal{H}_{\text{weak}} \, | \, \Lambda^0 + \frac{1}{\sqrt{3}} \Sigma^0 \Big\rangle}{\sin \theta \, \cos \theta \, G m_p^2 / \sqrt{2}}$$

A comparison of the two integrals can be made using the assumption that the high momentum transfer region (Björken limit) decisively determines the (dominant) octet parts of the two interactions. Defining a factor x by $x = \langle n | VV + AA | \Lambda^0 + (1/\sqrt{3})\Sigma^0 \rangle / 2\sqrt{2} \langle n | VV | p \rangle$ one gets from the known numerical values of the right hand sides of the above equations (using octet parts only) $|x| \approx 0.16 \, m_p^2/\Lambda^2$. By this relation high values of Λ are excluded even if a sizeable suppression of the weak interaction matrix element (in breaking $SU(3) \times SU(3)$) occurs. This conclusion is, of course, not valid if the high momentum transfer region is unimportant for the value of the integrals. In this case $|x| \approx 0.16 \overline{(1/q^2)} m_p^2$ i.e. rather low values of q^2 determine the integrals. The Björken limit would be irrelevant and could not be held responsible for the octet dominance observed in both interactions.

Salam (remark added after discussion)
The two integrals can be compared only if one neglects Λ^2 in the denominator $1/(-q^2 + \Lambda^2)$. Clearly for $\Lambda^2 \approx (50 \, m_p)^2$ this is questionable. So the argument based on neglecting Λ^2 in the denominator to prove that Λ^2 is small is somewhat circular.