



An Equivalent Gauge and the Equivalence Theorem

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Received 28 October 2013; received in revised form 20 May 2014; accepted 20 May 2014

Available online 27 May 2014

Editor: Stephan Stieberger

Abstract

I describe a novel covariant formulation of massive gauge theories in which the longitudinal polarization vectors do not grow with the energy. Therefore in the present formalism, differently from the ordinary one, the energy and coupling power-counting is completely transparent at the level of individual Feynman diagrams, with obvious advantages both at the conceptual and practical level.

Since power-counting is transparent, the high-energy limit of the amplitudes involving longitudinal particles is immediately taken, and the Equivalence Theorem is easily demonstrated at all orders in perturbation theory. Since the formalism makes the Equivalence Theorem self-evident, and because it is based on a suitable choice of the gauge, we can call it an “Equivalent Gauge”.

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1. Introduction

Massive gauge theories are so extraordinarily important for the physics of Fundamental Interactions that studying them requires no specific motivation, provided one can make some little progress on such a well-understood subject. However we do have a specific reason to be particularly interested in the high energy regime of these theories, which is now, and for the first time, under direct experimental investigation at the LHC. With the first run of the LHC machine, and even more so with the planned upgrade to 14 TeV, particle physics is entering the age of high

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energy EW processes. In the forthcoming years it will become more and more common to deal with such processes, both from the experiment and from the theory side.

In the high energy regime, where highly boosted EW bosons are involved, the standard formulation of massive gauge theories suffers of a well-known technical limitation, which I aim to overcome in the present paper. This is the fact that the polarization vectors associated with longitudinally polarized vector bosons, of energy E and mass m , display an anomalous high energy behavior, namely they grow like E/m . This growth is problematic because it often does not correspond to a physical effect, in most cases the extra powers of E from the polarization vectors cancel out in the final result, and this frequently happens through a complicated conspiracy among different diagrams. The longitudinal W scattering process, $W_L W_L \rightarrow W_L W_L$ is a famous example of this situation. By naive power-counting, taking into account the energy behavior of vertices and propagators, one would predict at high energy a quartically divergent scattering amplitude, $\mathcal{A} \sim g_W^2 (E/m)^4$, while the actual result is much different. In the absence of a Higgs boson, $\mathcal{A} \sim (E/v)^2$, where $v = 2m/g_W$ is the EWSB scale, while in the SM $\mathcal{A} \sim \lambda$, where λ is the quadrilinear Higgs coupling.¹ Naive power-counting badly fails for this process. Not only it predicts the wrong energy scaling, but also the wrong dependence on the couplings. In spite of originating from gauge vertices, with coupling proportional to g_W , the W_L scattering is not mediated by the gauge force, but by completely different interactions. Indeed the amplitude would remain different from zero also in the limit $g_W \rightarrow 0$. This happens because $m = g_W v/2$, and therefore the E/m factors from the polarization vectors carry negative powers of g_W which cancel positive powers from the Feynman vertices and change the coupling dependence of the final result.²

In summary, the E/m behavior of the polarization vectors invalidates power-counting, and this is a limitation in all problems where a coupling or energy expansion needs to be set up. At the purely theoretical level, the problem shows up when one tries to demonstrate general theorems for high energy EW processes, related for instance to high energy factorization like the Effective W Approximation (EWA) [1]. In that context, the lack of a reliable power-counting makes the theorem virtually impossible to prove in the standard covariant gauges, to the point that some authors [2] were led to question its validity. The EWA is on the contrary rather straightforward to demonstrate in the axial gauge [3,4], where there is no anomalous growth of the polarization vectors and power-counting is manifest. However the axial gauge is not covariant, for the EWA and for similar applications it could instead be useful to formulate a covariant gauge where the polarization vectors are well-behaved, in this way one would combine the advantage of explicit covariance with the one of manifest power-counting. Identifying one gauge with these properties is the purpose of the present paper.

For what concerns phenomenology, the lack of a reliable power-counting in the ordinary covariant gauges is also a problem. It makes difficult to understand the physical origin of a given effect and to estimate its size before performing an explicit calculation. This is a problem already in the SM, but even more so in the context of BSM theories, where plenty of new coupling are typically introduced. A quick estimate of their effects, or deciding whether or not they are relevant in the high-energy limit, is mandatory. Power-counting would also help with explicit calculations, either at the tree-level or including radiative corrections. By power-counting one

¹ A second contribution, of order g_W^2 , is also present in the SM amplitude, the quadrilinear coupling contribution dominates only for heavy Higgs.

² The top quark decay, which is mediated by the Yukawa and not by the gauge force, is probably the most famous textbook example of this phenomenon.

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