W condensation at the LHC?

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Abstract

We discuss the possibility of the generation and subsequent decay of a $W$ and $Z$ condensate in LHC collisions. We point out that a process like $h \rightarrow \gamma\gamma$, which involves a virtual $W$ loop, may have an enhancement if the condensate exists. Even if this is not the case, the $W$ propagator is influenced by the strong, but short lived magnetic field generated in proton-proton collisions. This will influence the di-gamma decay of the Higgs particle.

The major discovery of the Higgs particle [1],[2] gives ample opportunity for analyzing the experimental data in order to see if there are clues for deviations from the Standard Model (SM) [3],[4]. In particular, the preliminary data indicating that the two photon decay of the Higgs boson ($h$) may deviate by a factor 1.5-2 from the SM gives rise to new ideas [3],[4]. At the same time it must be understood why the channels $h \rightarrow ZZ^*$ and $h \rightarrow WW^*$ seem to essentially agree with the SM. It may of course well be that the relatively modest excess in $h \rightarrow \gamma\gamma$ may diminish when all the data are analysed [3], so that in the end the SM works perfectly.

In this note we presents the point of view that we should be sure that when the perturbative SM is used as a calibration of the data, there are no modifications from non-perturbative condensates existing in the SM. For example, the process $h \rightarrow \gamma\gamma$, which is calculated perturbatively [5]-[12], proceeds through loops involving all momenta for the $W$ mesons (or quarks) which are, at least in principle, sensitive to background fields. If vector boson condensation occurs, it means that there are more vectors than dictated by perturbation theory, which is an expansion around $W = Z = 0$.

In subsection 1 we discuss the arguments for a $W$ and $Z$ condensate, and in subsection 2 we present arguments against such a condensate. In 3 we present a brief discussion of the difference between $h \rightarrow \gamma\gamma$ and $h \rightarrow$ vector-vector.

1. Arguments for a $W$ and $Z$ condensate.

Within the SM there may be an “anomalous” behavior relative to perturbation theory in the form of condensation of $W$ and $Z$ mesons. This phenomenon was discussed a long time
ago by Ambjørn and the author [13] as a possibility in high energy collisions. The starting point is that in the proton-proton collision large magnetic fields are generated by quarks with charge $e_q$,

$$
H = \frac{e_q}{4\pi} \frac{\mathbf{v} \times \mathbf{r}}{r^3 \sqrt{1 - v^2}}
$$

(1)

where

$$
r^2 = b^2 + \frac{r_L^2}{1 - v^2}.
$$

(2)

Here $v \sim 1$ and $\mathbf{r}$ is the vector from the simultaneous point of observation to the point charge. Also $b$ is the impact parameter and $r_L$ is the component of $\mathbf{r}$ in the direction of $\mathbf{v}$.

It has been known for a long time that magnetic fields exceeding the limit

$$
H \geq \frac{m_w^2}{e}
$$

(3)

lead to an instability [14] provided the field is homogeneous.

The $H$-field (1) easily exceeds the threshold (3). For example in proton-proton scattering [13]

$$
2H_{\text{crit}} = \frac{m_w}{e} \quad \text{for} \quad \sqrt{s} = 420 \text{ GeV} \quad (e_q = e/3),
$$

$$
= 210 \text{ GeV} \quad (e_q = 2e/3).
$$

(4)

Of course the field (1) is not homogeneous, but it provides an environment with a very large background magnetic field, exceeding the threshold (3) considerably. This is potentially an unstable situation because the electroweak Lagrangian contains a term

$$
-i (e f^\text{external}_{\mu\nu} + g \cos \theta Z_{\mu\nu}) W^*_{\mu} W_{\nu}.
$$

(5)

When the external magnetic field exceeds the threshold value (3) this term becomes tachyonic. For a $H$ field in the third direction the eigenvalues are $\pm eH$ with eigenvector $(W_1, W_2)$. The negative eigenvalue exceeds the mass term $-m_w^2 W^*_{\mu} W_{\mu}$ and causes energy to be transferred from the $H$ field to the $W$'s (and $Z$'s). These fields are expected to increase exponentially with time. An ultimate stabilization is expected from the $W^4$ term in the Lagrangian. For further discussion we refer to [13].

The situation is more complicated than indicated by the simple minded considerations above. The magnetic field is time dependent, and the whole set up should be investigated numerically. We mention that for the pure Yang-Mills Lagrangian there has recently been numerical calculations [15] which shows that a large magnetic field in one color direction is unstable, and energy is transferred to other degrees of freedom which grow exponentially in time as $\exp(t \sqrt{gH})$. This is valid for magnetic fields coherent over a distance scale which is large compared to the Larmor scale $1/\sqrt{gH}$. It would of course be desirable if numerical calculations with a realistic proton-proton field could be carried out in the electroweak case for the background field (1).

It should be mentioned that if the background field is large enough then in the static case ultimately the broken symmetry is restored [16], [17], [18], because the $W$ and $Z$ condensates
become so large that the Higgs breaking disappears. Whether this can happen in the time dependent case is not known, but it is an interesting possibility, especially in view of the fact that the field (1) can be large enough for small impact parameters $b$ to induce a transition to the unbroken phase.

2. Arguments against a $W$ and $Z$ condensate

Soon after the appearance of ref. [13] a paper was published with the conclusion that the proposed process of $W$-boson condensation in high-energy $p-p$ collisions does not work [19]. With the protons moving in the $z$ direction the magnetic field was assumed to have an infinite extension in the $x-y$ plane, corresponding to a field

$$H = \frac{e}{b} \delta(r_L) \mathbf{e}_x,$$

(6)

where $b$ is the impact parameter. It is argued that the neglect of the fall-off of the field (1) in the transverse direction is acceptable if the impact parameter is much larger than the size of the Landau orbits in the magnetic field. The final result of the calculations in [19] violates this condition, and hence the negative conclusion follows.

In [19] the time dependence of the condensation has not been taken into consideration, although this is obviously needed in a fully realistic treatment of the problem. Another possible criticism of the critique in [19] is that the delta-function (6) is perhaps too structureless. The inverse impact parameter enters as a factor in front of the delta function, but one also has an implicit $b$ dependence in $\delta(0) \propto \gamma/b$.

3. Consequences of a condensate: $h \rightarrow \gamma\gamma$

Bearing in mind that the existence of a $W$ and $Z$ condensate may only be marginally possible, we now end this note by some remarks on how to see a condensate should it exist in spite of the complaints in [19].

The possible existence of a condensate means that $W'$s and $Z'$s are extracted from the vacuum. The real vacuum then consists of non-trivial fields, in contrast to the perturbative vacuum which is an expansion around $W = Z = 0$. Thus the condensate means that there should be vector fields which do not exist perturbatively. This is true in the infrared, since the instability occurs only when the relevant momenta are below $\sqrt{eH} > m_W$.

The increase in the number of vector particles due to the condensate thus only happens if infrared momenta are involved. The inovlvement of a range of (virtual) momenta happens in the process $h \rightarrow \gamma\gamma$ which proceeds through a loop [5]-[12], thus integrating over all loop momenta, including the infrared crucial for condensation. The $W-$propagators involved in the loop should be propagators calculated in the background of the strong magnetic field. Thus, in the indirect decay of the Higgs particle to two photons the condensate can have its full impact, provided of course that it exists.

For the direct processes $h \rightarrow W^*W$ and $h \rightarrow Z^*Z$ the situation is not so clear, since the momenta of the vectors decaying from the Higgs particle are totally fixed by the kinematics, in contrast to the di-photon decay where the momentum is a loop variable. In the direct decay there are no vector propagators, so the condensate will not have a direct effect, even if it exists.
In conclusion we see that if there is a $W$ and $Z$-condensate there is a difference between the process $h \rightarrow \gamma\gamma$, where the $W$'s can be extracted non-perturbatively through condensation, and the direct vector decay, where no $W$ propagators are involved. The important question is of course whether the condensate does exist. However, it should be emphasized that even if there is not enough time for condensation to occur, the $W$-propagator is influenced by the large magnetic field (1). The calculations of the di-gamma decay [5]-[12] are based on the perturbative $W$ propagator, which is thus not entirely realistic, which may explain possible experimental deviations in the decay $h \rightarrow \gamma\gamma$ from the calculations.

The most likely place where to find the effects discussed above is in heavy ion collisions. In any case it is most likely that numerical studies are needed to settle the question of the magnitude of the magnetic effect.

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