LHC signatures of unparticles in decays of $Z'$

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Abstract
We investigate the rare radiative decays of extra gauge neutral bosons. In particular, we established the theoretical predictions for the production of unparticle in decays of $Z'$ - bosons. The implementation of our prediction in the analysis at the LHC experiments should be straightforward and lead to more precise determination or limits of unparticle couplings and/or $Z'$ couplings and masses.

1 Introduction

There is an extensive literature (see, e.g., the incomplete set of papers [1] and the references therein) concerning the phenomenology of scale-invariant hidden sector which is realized through the so-called unparticles in the particle physics. The unparticles (or the scale-invariant stuff) introduced by H. Georgi in 2007 [2] with continuous mass distribution, obey the conformal (or scale) invariance.

In 1982, Banks and Zaks [3] investigated the gauge theories containing the non-integer numbers of Dirac fermions where the two-loop $\beta$-function disappeared. In this case, one says about the non-trivial infra-red (IR) fixed point at which the theory possesses the scale-invariant nature, and there is no chance to interpret it in terms of particles with definite masses. The main idea is based on the following statement: at high enough values of energy the theory contains both the fields of the Standard Model (SM) and the fields yielding the sector with the IR point. Both of these sectors interact with each other by means of exchange with the particles (fields) having a large mass scale $M$. At the energies below $M$, the interaction
between the fields has the form $O_{SM} O_{BZ} M^{-a}$, where $O_{SM}$ and $O_{BZ}$ are the operators of the SM fields and the Banks-Zaks (BZ) sector, respectively. The hidden conformal sector may flow to IR fixed point scale at some scale $\Lambda < M$.

In the effective theory with energies $\leq \Lambda$, the interaction above mentioned has the same form but composed by new set of operators $\sim \Lambda^{d_{BZ} - d} O_{SM} O_{U} M^{-a}$, where $d_{BZ}$ and $d$ mean the scale dimensions of the operator $O_{BZ}$ and the new operator $O_{U}$ of the $U$-unparticle, respectively.

The most interesting scale is $\Lambda \sim O(\text{TeV})$, at which the dynamics of unparticles could be seen at CERN Large Hadron Collider (LHC) through the different processes including the decays with the production of $U$-unparticles.

In the papers [2], it has been emphasized that the renormalizable interactions between the SM fields and the fields of yet hidden conformal sector could be realized by means of explore the hidden energy at high energy collisions and/or associated with the registration of non-integer number of invisible particles. In this case the conformal sector described in terms of "unparticles" does not possess those quantum numbers which are known in the SM. For illustration purposes, we quote here the well-known formula for the propagator $\Delta(p, m; d)$ of the scalar unparticle effectively having the non-existing mass $m$ and the momentum $p$ with scale dimension $1 \leq d < 2$:

$$
\Delta(p, m; d) = \int d^4x \, e^{ipx} \langle 0 | T O_{U}(x) O_{U}^{+}(0) | 0 \rangle
$$

$$
= \frac{A_{d}}{2\pi} \int_{m^2}^{\infty} (M^2 - m^2)^{d-2} \frac{i M^2}{p^2 - M^2 + i \epsilon} = \frac{A_{d}}{2 \sin(d\pi)} \frac{i}{(m^2 - p^2 - i \epsilon)^{2-d}}.
$$

This formula with the well-defined normalization constant $A_{d}$ [2] and providing the correct behavior of the unparticle propagation in the limit $m \to 0$, is nothing other but the propagator of the scalar particle if $d$ assumes the canonical meaning $d = 1$.

The investigation of unparticles has two directions of their study: the first one is related to issues which carry the theoretical aspects where the main objects are associated with the interactions of unparticles with the matter fields. One of the most important manifestations of this branch is the coupling between the electroweak symmetry breaking through the conformal symmetry breaking by means of input in the theory the superrenormalizable operator $\Lambda^{2-d} O_{U} H^2$ which ensures the conformal symmetry breaking on the scale $\left(\Lambda^{2-d} v^2\right)^{1/(4-d)}$ for the Higgs field $H$ with its vacuum expectation value (v.e.v.) $v \simeq 246$ GeV (see, e.g., [4,5]). The second direction is related to the phenomenology where the main efforts are concentrated on hunting of the unparticles in different physical processes, in particular, in decays of the particles (scalars, pseudoscalars, gauge bosons, etc.) that might be most actual.
for the modern high energy physics at the machines in operation (Tevatron, LHC) and the future accelerators (e.g., ILC).

It is a common belief the SM is extended at energies well above the weak scale. Depending of the rank of new extended gauge group, e.g., $SO(10)$ or $E_6$ with the symmetry breaking of the latter ones to the symmetry of the SM at the certain scale, the additional neutral gauge bosons $Z'$ can appear, and they are associated with the additional $U'(1)$ - symmetry. These $Z'$s couple primarily to the third generation quarks.

The search for $Z'$ at the Tevatron and at the LHC have a significant contribution in the investigation of new physics. The LHC will observe $Z'$ - boson in mass region up to a few TeV. Using the mass from the LHC, we can test the cross-section to obtain all of the $Z'$ -couplings. The probability of appearance of $Z'$ - like objects, in particular, in the Drell-Yan channel, is discussed extensively in the literature (see, e.g., [6] and the references therein). If such the objects are light enough this would serve as the direct message for occurrence of new physics with a certain confirmation at the LHC even at relatively low integral luminosity [7,8].

Once such the particles ($Z'$, ...) are discovered and their masses, widths, spin are defined, it is needed to study how these new sector bosons are coupled to different SM fields, that will allow to check the theoretical models dealing with new physics effects. There is the hope the LHC experiments allow to clarify the nature of a definite combination set of coupling constants of new particles with the SM fermions by means of model-independent way. These combinations can be measured with high precision in CERN’s CMS [7] and ATLAS [8] experiments at high integral luminosity $\geq 100 \, fb^{-1}$. The modern bounds on the $Z'$ mass, $m_{Z'} > 650 - 900 \, GeV$ depending on the model scheme, are already known from experiments CDF [9] and D0 [10] at the Tevatron (two-lepton channel). If $Z'$s are coupled to leptons, they can provide clean and spectacular signals at colliders.

The experimental channels of multi-gauge boson production ensure the unique possibility to investigate the anomalous triple effects of interaction between the bosons. We point out the study of non-abelian gauge structure of the SM, and, in addition, the search for new types of interaction which, as expected, can be evident at the energies above the electroweak scale. The triple couplings of neutral gauge bosons, e.g., $ZZ'\gamma$, $ZZZ'$ etc. can be studied in pair production at the hadron (lepton) colliders: $pp, pp(e^+e^-) \rightarrow Z' \rightarrow Z\gamma, ZZ,...$

Unparticle production at the LHC will be a signal that the scale where conformal invariance becomes important to particle physics is as low as a few TeV. At this scale, the unparticle stuff sector is strongly coupled. This requires that, somehow, a series of new reactions that involve unparticle stuff in an essential way turn on between
Tevatron and TeV energies. It will be important to understand this transition as precisely as possible. This can be done through the LHC study of $pp \rightarrow \gamma + U$ and the identification of the effects from $Z'$ resonances in $pp \rightarrow \text{fermion} + \text{antifermion}$.

In this paper, we study the production of unparticle $U$ in the decays of $Z'$ with emission of a monophoton. In this circumstance, we have a hidden sector whose main couplings to matter fields are through the gauge fields. Such a hidden sector can have distinct signatures at colliders. Before going to the concrete model, we have to make the following retreat. First of all, we go to the extension of the Landau-Yang theorem [11, 12] for the decay of a vector particle into two vector states. Within this theorem, the decay of particle with spin-1 into two photons is forbidden (because both outgoing particles are massless). The direct interaction between $Z'$-boson and a vector massive particle, e.g., $Z$ or $U$ - vector unparticle, accompanied by a photon, does not exist. To the lowest order of the coupling constant $g$, the contribution given by $g^3$ in the decay $Z' \rightarrow \gamma U$ is provided mainly by heavy quarks in the loop. What is the origin of this claim? First, it is worth to remember the known calculation of the anomaly triangle diagram $ZZ\gamma$ [13], where the anomaly contribution result contains two parts, one of which has no the dependence of the mass $m_f$ of (intermediate) charged fermions in the loop, while the second part is proportional to $m_f^2$. An anomaly term disappears in the case if all the fermions from the same generation are taking into account or the masses of the fermions of each of generation are equal to each other. The reason explaining the above mentioned noted is the equality to zero of the sum $\Sigma f N_f^f g_V^f g_A^f Q_f$, where $g_V^f (g_A^f)$ is the vector (axial-vector) coupling constant of massive gauge bosons to fermions, $Q_f$ is the fermion charge, $N_f^f = 3(1)$ for quarks (leptons). The anomaly contribution for the decay $Z' \rightarrow \gamma U$ does not disappear due to heavy quarks, and the amplitude of this decay is induced by the anomaly effect. The contribution from light quarks with the mass $m_q$ is suppressed as $m_q^2/m_Z^2 \sim 10^{-8} - 10^{-6}$, where $m_Z$ is the mass of $Z'$-boson. Despite the decay $Z' \rightarrow \gamma U$ is the rare, there is a special attention to the sensitivity of the latter to both the top-quark and the quarks of fourth generation.

Since the photon has the only vector nature of interaction with the SM fields, the possible types of interaction $Z'-U-\gamma$ would be either $V-A-V$ or $A-V-V$, where $V(A)$ means the vector (axial-vector) interaction.

The anomaly triple gauge bosons contributions play an essential role in estimation of the decay $Z' \rightarrow Z\gamma$ normalized to two-lepton decay or the decays with the production of quark-antiquark pairs (e.g., the ratio $\Gamma(Z' \rightarrow Z\gamma)/\Gamma(Z' \rightarrow e^+e^-) \sim 10^{-6}$ has been obtained in $E_6$ - model [14]). Based on the extended $SU(2)_R \times SU(2)_L \times U(1)$ model in [15], the following estimations have been done: $\Gamma(Z' \rightarrow Z\gamma)/\Gamma(Z' \rightarrow ll) \sim 10^{-5}(\mu^+\mu^-), \sim 10^{-4} - 10^{-3}(\tau^+\tau^-), \Gamma(Z' \rightarrow Z\gamma)/\Gamma(Z' \rightarrow ll) \sim 10^{-5}(\mu^+\mu^-), \sim 10^{-4} - 10^{-3}(\tau^+\tau^-), \Gamma(Z' \rightarrow Z\gamma)/\Gamma(Z' \rightarrow ll) \sim 10^{-5}(\mu^+\mu^-), \sim 10^{-4} - 10^{-3}(\tau^+\tau^-)$.
\(q\bar{q}) \sim 10^{-6} (q : b, top)\) with the account of the fourth generation quarks. Note, that the papers on the \(U\) - unparticle production in radiative decays \(H \rightarrow \gamma U\) and \(Z \rightarrow \gamma U\) are published in [16] and [17], respectively.

The main reason of the study in this work is related to the fact that the \(Z'\) couples to quarks both with a vector and axial-vector coupling, and it follows that in radiative decays one can reach all spin-parity final states. This suggest, then, that it might be possible to use these mean to reach the unparticles, in particular, to estimate the contribution from the \(Z'\) in its rare radiative decays to \(U\) - unparticle and to take into account the possible contributions from up - and down - quarks of the fourth generation with the masses \(> 258 - 268\) GeV (see, e.g., the data by CDF [18] and the references in [19]). Note, the fourth generation quarks lead to new dimensionless effective constants \(\lambda_1, \bar{\lambda}_1, c_v, a_v\) in the interactions of the form

\[
\lambda_1 \frac{c_v}{\Lambda^{d-1}} q \bar{q} \gamma_{\mu} q O^\mu_U, \quad \bar{\lambda}_1 \frac{a_v}{\Lambda^{d-1}} \bar{q} \gamma_{\mu} \gamma_5 q O^\mu_U,
\]

where \(O^\mu_U\) being the operator of the unparticle (spin-1) on the scale \(\Lambda\) with dimension \(d\).

In Sec. 2, we will present the model. Section 3 focuses on the calculations of the photon energy spectrum, the branching ratio of the decay \(Z' \rightarrow \gamma U\) and the cross section of the process \(pp \rightarrow Z' \rightarrow \gamma U\). In Sec. 4, we give the experimental constraints for \(U\)-unparticle observable. Our conclusions are presented in Sec. 5.

## 2 Model

Let us consider the following interaction Lagrangian density

\[
-L = g_{Z'} \sum_{q} \bar{q}(v'_q \gamma^\mu - a'_q \gamma^\mu \gamma_5) q Z'_{\mu} + \frac{1}{\Lambda^{d-1}} \sum_{q} \bar{q}(\lambda_1 c_v \gamma^\mu - \bar{\lambda}_1 a_v \gamma^\mu \gamma_5) q O^\mu_U, \tag{2}
\]

where \(g_{Z'} = (\sqrt{5b/3} s_W g_Z)\) is the gauge constant of \(U'(1)\) group (the coupling constant of \(Z'\) with a quark \(q\)) with the group factor \(\sqrt{5/3}, b \sim O(1), g_Z = g/c_W; s_W(c_W) = \sin \theta_W(\cos \theta_W), \theta_W\) is the angle of weak interactions (often called as Weinberg angle); \(v'_q\) and \(a'_q\) are generalized vector and the axial-vector \(U'(1)\) -charges, respectively, which are \(Z'\)-pattern model-dependent, for example, in the frame of \(E_8 \times E_8, E_6, \ldots\) groups. These latter charges are dependent on both (joint) gauge group and the Higgs representation which is responsible for the breaking of initial gauge group to the SM one; \(\lambda_1, \bar{\lambda}_1\) are defined in [II]. Actually, the second term in
is identical to the first one up to the $d$-dimensional factor $\Lambda^{1-d}$. In the model, we assume $O_{\mu U}$ is a non-primary operator derived by $O_{\mu U}(x) \sim \partial_{\mu}S(x)$ through the pseudo-Goldstone field of conformal symmetry $S(x)$ - pseudo-dilaton mode. The scalar field $S(x)$ serves as a conformal compensator with continuous mass. Because the conformal sector is strongly coupled, the mode $S(x)$ may be one of new states accessible at high energies. $O_{\mu U}$ has both the vector and the axial-vector couplings to quarks in the loop.

It is known that both $Z$ and $Z'$ are not the mass eigenstates. There is the $Z$-$Z'$ mixing (with mixing angle $\varphi$) which leads to rotation of the neutral sector to the physical states $Z_1$ and $Z_2$ with the masses $m_1$ and $m_2$, respectively:

$$\tan^2\varphi = \frac{m_2^2 - m_1^2}{m_2^2 - m_Z^2}.$$ 

Within its small absolute value [15], the angle $\varphi$ does not play an essential role in the calculations. It turns out, one can identify $Z$ and $Z'$ with the physical neutral states. Actually, $m_1 \simeq m_Z << m_2 \simeq m_{Z'}$.

We consider the model [20,21] containing the $Z\chi^{-}$ boson on the scale $O(1 \text{ TeV})$ in the frame of the symmetry based on the $E_6$ effective gauge group. The group $U(1)_{\chi}$ arises in the following consequence of the symmetry breaking of the parent group $E_6$: $E_6 \rightarrow SO(10) \times U(1)_{\psi} \rightarrow SU(5) \times U(1)_{\chi} \times U(1)_{\psi}$. We suppose that $SO(10)$ breaks to $SU(5) \times U(1)_{\chi}$ at the same scale where $SU(5)$ breaks to the SM group $SU(3)_c \times SU(2)_L \times U(1)_Y$ with respective coupling constants $g_s$, $g$, $g'$. The coupling constant of $U(1)_{\chi}$ has the form $g_{\chi} = \sqrt{5/3} e/c_W$.

The amplitude of the decay $Z' \rightarrow U\gamma$, where the coupling $Z'U\gamma$ is supposed to be extended by the intermediate loop containing the quarks $q$, has the form:

$$A_m(z_u, z_q) = \frac{e^2}{c_W} \sqrt{\frac{5}{3}} \sum_q e_q \left( \lambda_1 c_v a'_q + \bar{\lambda}_1 a_v v'_q \right) I(z_u, z_q)$$

with $z_u = P_U^2/m_{Z'}^2$, $z_q = m_q^2/m_{Z'}^2$, for the momentum $P_U$ of $U$ - unparticle and the quarks $q$ (in the loop) with the mass $m_q$. We deal with the following expression for $I(z_u, z_q)$:

$$I = \frac{1}{1 - z_u} \left\{ \frac{1}{2} + \frac{z_q}{1 - z_u} \left[ F(z_q) - F\left(\frac{z_q}{z_u}\right) \right] - \frac{1}{2(1 - z_u)} \left[ G(z_q) - G\left(\frac{z_q}{z_u}\right) \right] \right\}$$

adopted for the decay $Z' \rightarrow U\gamma$ taking into account the results obtained in [14] and [17]. For heavy quarks, $m_q > 0.5 m_{Z'}$, the functions $F(x)$ and $G(x)$ in (4) have the
following forms [14]:

\[
F(x) = -2 \left( \sin^{-1} \sqrt{\frac{1}{4x}} \right)^2, \quad G(x) = 2\sqrt{4x-1} \sin^{-1} \left( \sqrt{\frac{1}{4x}} \right),
\]

while for light quarks \((m_q < 0.5 m_{Z'})\), one has to use the formulas:

\[
F(x) = \frac{1}{2} \left( \ln \frac{y^+}{y^-} \right)^2 + i\pi \ln \frac{y^+}{y^-} - \frac{\pi^2}{2}, \quad G(x) = \sqrt{1 - 4x} \left( \ln \frac{y^+}{y^-} + i\pi \right),
\]

where \(y^\pm = 1 \pm \sqrt{1 - 4x}\). To get (6), we have used the complex continuation applied to (5): \(\sin^{-1} \sqrt{\frac{1}{4x}} \rightarrow i(\text{arccosh} \sqrt{\frac{1}{4x}} + i\pi/2) = i(\ln y^+/y^- + i\pi/2)\) and \(\sqrt{4x-1} \rightarrow -i\sqrt{1 - 4x}\). The variable \(z_u\) is related to the energy \(E_\gamma\) of the photon as \(z_u = 1 - 2 E_\gamma/m_{Z'}\). In the frame of the \(Z_\chi\) - model, we choose \(v'_{up} = 0, a'_{up} = \sqrt{6} s_W/3, v'_{down} = 2 \sqrt{6} s_W/3, a'_{down} = -\sqrt{6} s_W/3\) for up - and down - quarks. Actually, the account of the only light quarks leads to the zeroth result for the amplitude (3). The contribution \(\sim \lambda_1 a_v v'_{q}\) is nonzero for the only \(b\) - quarks and down - quarks of fourth generation. We emphasize that the nonvanishing result for the amplitude \(Z' \rightarrow U\gamma\) is the reflection of the anomaly contribution due to the presence of heavy quarks.

### 3 Photon energy spectrum, branching ratio and cross section

In the decay \(Z' \rightarrow U\gamma\), the unparticle can not be identified with the definite invariant mass. \(U\)- unparticles stuff possesses by continuous mass spectrum, and can not be in the rest frame (there is the similarity to the massless particles). Since the unparticles are stable (and do not decay), the experimental signal of their identification could be looking via the hidden (missing) energy and/or the measurement of the momentum distributions in the case when the \(U\)- unparticle is produced in \(Z' \rightarrow \gamma U\) or \(Z' \rightarrow f \bar{f} U\).

The differential distribution of the decay width \(\Gamma(Z' \rightarrow U\gamma)\) over the variable \(z_u\) looks like (see also [17]):

\[
\frac{d\Gamma}{dz_u} = \frac{1}{2 m_{Z'}} \sum |M|^2 \frac{A_d}{16 \pi^2} \left( m_{Z'}^2 \right)^{d-1} z_u^{d-2} (1 - z_u),
\]

where

\[
\sum |M|^2 = \frac{1}{6 \pi^4} z_u (1 - z_u)^2 (1 + z_u) |Am(z_u, z_q)|^2 m_{Z'}^2,
\]
and
\[
A_d = \frac{16 \pi^{5/2}}{(2\pi)^2d} \frac{\Gamma(d + 1/2)}{\Gamma(d - 1)\Gamma(2d)}
\]

One of the requirements applied to the amplitude in (8) is that it disappears in case of "massless" unparticle (Landau-Yang theorem), and when \(z_u = 1\).

Some bound regimes in (7) may be both useful and instructive for further investigation. For this, we consider the quark-loop couplings in the amplitude (3) as the sum of the contributions given by light quarks \(q\) and heavy ones \(Q\) (the contribution from the quarks of 4-th generation is also possible):

\[
\sum_q e_q (\lambda_1 c_v a'_q + \bar{\lambda}_1 a_v v'_q) I(z_u, z_q) + \sum_Q e_Q (\lambda_1 c_v a'_Q + \bar{\lambda}_1 a_v v'_Q) I(z_u, z_Q).
\]

For light quarks, \(z_q << 1\), there are no \(q\) - mass dependence in the one-loop function \(I(z_u, z_q)\) in the limit \(m_q \to 0\)

\[
I(z_u, z_q) \simeq \frac{1}{2(1-z_u)} \left[ 1 - 4 \frac{z_q}{z_u} \left( \frac{10}{3} + i\pi \right) \right].
\]

On the other hand, if the quarks inside the loop become heavy enough, \(z_Q > 1\), we estimate the following function \(I(z_u, z_Q)\)

\[
I(z_u, z_Q) \simeq \frac{1}{24 z_Q} \left[ 1 + \left( \frac{2}{7} \right)^2 \frac{1+z_u}{1-z_u} \right] - \frac{1}{576 z_Q^2} \frac{1+z_u+z_Q^2}{1-z_u},
\]

which is very small in the limit \(z_Q >> 1\).

For the unparticle spectrum at low rates of \(z_u\), the only heavy quarks \(Q\) with the masses \(m_Q > 0.5m_Z\) are responsible for the production of \(U\)-unparticles and the distribution \(d\Gamma/dz_u\) has the form

\[
\lim_{z_u \to 0} \frac{d\Gamma}{dz_u} \simeq \frac{5A_d}{(2\pi)^6} \left( \frac{e^2}{c_W} \right)^2 \left( \frac{z_u}{\Lambda^2} \right)^{d-1} \left( m_Z^2 \right)^{d-1/2} \sum_Q e_Q (\lambda_1 c_v a'_Q + \bar{\lambda}_1 a_v v'_Q) I(z_Q)^2,
\]

where \(I(z_Q) = 0.5[1 - G(z_Q)] + z_Q \cdot F(z_Q)\) for \(z_Q > 1/4\) and \(d \neq 1\). In this case, the photon energy \(E_\gamma = m_Z(1 - m_{z_u})/2\) in the limit \(z_u \to 0\) gets its finite value. The limit \(z_u \to 1\) is trivial and we do not consider this.

Within the fact of the combination \(\lambda_1 c_v a'_q + \bar{\lambda}_1 a_v v'_q\) in (3) with the effective constants of unparticles \(\lambda_1 c_v\) and \(\bar{\lambda}_1 a_v\), the decay amplitude of \(Z' \to \gamma U\) does not disappear when the summation on all the quarks degree of freedom is performed.
In Table 1, the monophoton energy distribution $E_\gamma^{-1}d\Gamma/dz_u$ is tabulated for a range of photon energy $E_\gamma = 0 - 450$ GeV and various choices of $d$. For simplicity, we use the $E_\gamma$-model assuming the flavor blind universality $\lambda_1 c_v = \bar{\lambda}_1 a_v = 1$ for all three generation quarks, $\Lambda$ and $m_{Z'}$ are set to be 1 TeV each.

**Table 1.** Energy distribution $E_\gamma^{-1}d\Gamma/dz_u \times 10^8$ for $E_\gamma = 0 - 450$ GeV, depending on $d = 1.1 - 1.9$; $\lambda_1 c_v = \bar{\lambda}_1 a_v = 1$, $\Lambda = 1$ TeV, $m_{Z'} = 1$ TeV.

| $E_\gamma$, GeV | 0   | 50  | 100 | 200  | 300  | 400  | 450  |
|------------------|-----|-----|-----|------|------|------|------|
| $d = 1.1$        | 5.70| 5.41| 5.10| 4.40 | 3.74 | 2.90 | 2.53 |
| $d = 1.3$        | 7.10| 6.64| 6.03| 4.92 | 3.83 | 2.76 | 1.92 |
| $d = 1.5$        | 4.42| 4.05| 3.50| 2.70 | 1.92 | 1.25 | 0.74 |
| $d = 1.7$        | 2.24| 1.90| 1.73| 1.23 | 0.80 | 0.40 | 0.24 |
| $d = 1.9$        | 0.80| 0.70| 0.64| 0.40 | 0.30 | 0.11 | 0.06 |

The sensitivity of the scale dimension $d$ to the energy distribution is evident, and $E_\gamma^{-1}d\Gamma/dz_u$ decreases with the photon energy $E_\gamma$.

The $U$-unparticle could behave as a very broad vector boson since its mass could be distributed over a large energy spectrum. The production cross-section into each energy bin could be much smaller than in the case where a SM vector boson has that particular mass. This may be the reason why we have not yet seen the $U$-unparticle trace in the experiment.

In the appropriate approximation when the relation between the total decay width $\Gamma_{Z'}$ and $m_{Z'}$ is small, the contribution to the cross section of the process $pp \rightarrow Z' \rightarrow \gamma U$ can be separated into $Z'$ production cross section $\sigma(pp \rightarrow Z')$ and the relevant branching fraction of the $Z'$-boson: $\sigma(pp \rightarrow Z' \rightarrow \gamma U) = \sigma(pp \rightarrow Z') \cdot B(Z' \rightarrow \gamma U)$. The $Z'$ state can be directly produced at a hadron collider via the $\bar{q}q \rightarrow Z'$ subprocesses, for which the cross section in the case of infinitely narrow $Z'$ is given by

$$\sigma(\bar{q}q \rightarrow Z') = k_{QCD} \frac{4\pi^2}{3} \frac{\Gamma(Z' \rightarrow \bar{q}q)}{m_{Z'}} \delta(s - m_{Z'}^2),$$

where $k_{QCD} \simeq 1.3$ represents the enhancement from higher order QCD processes. Conservation of the energy-momentum implies that the invariant mass of $Z'$ is equal to the parton center-of-mass energy $\sqrt{\hat{s}}$, where $\hat{s} = x_1 x_2 s$ depends of the fractions, $x_1$ and $x_2$, of those momenta carried by partons that initiate the process $\bar{q}q \rightarrow Z'$.

The decay width $\Gamma(Z' \rightarrow \bar{q}q)$ is

$$\Gamma(Z' \rightarrow \bar{q}q) = \frac{G_F m_{Z'}^5}{6\pi \sqrt{2}} N_c m_{Z'} \sqrt{1 - 4 z_q} \left[ (v_q')^2 (1 + 2 z_q) + (a_q')^2 (1 - 4 z_q) \right],$$

where
where $G_F$ is the Fermi coupling constant. In the narrow width approximation, the cross section (10) reduces to $\left( z_q \ll 1 \right)$

$$
\sigma(\bar{q}q \to Z') \simeq k_{QCD} \frac{2a}{3} G_F \frac{1}{\sqrt{2}} \left( \frac{m_Z}{m_{Z'}} \right)^2 \left[ \left( v'_q \right)^2 + \left( a'_q \right)^2 \right] \left( \frac{s}{m_{Z'}^2 - 1} \right)^2 + a^2.
$$

(11)

where $a = \Gamma_{Z'}/m_{Z'}$.

For quarks obeying the condition $0 \leq z_q \leq 1/4$ the branching ratio for $Z' \to \gamma U$ decay, $B(Z' \to \gamma U) = \Gamma(Z' \to \gamma U)/\Gamma_{Z'}$, does not disappear even at $z_q = 0$

$$
B(Z' \to \gamma U) = \frac{5 A_d}{a c_W^2} \left( \frac{\alpha}{2 \pi} \right)^2 \left( \frac{m_{Z'}^2}{\Lambda^2} \right)^{d-1} \sum_q e_q \left( \lambda_1 c_v a'_q + \bar{\lambda}_1 a_v v'_q \right)^2 \left[ \frac{1}{2d(d+2)} - \frac{20}{3} \frac{\Gamma \left( \frac{d+1}{2} \right)}{d+1} \frac{\Gamma \left( \frac{d+1}{2} \right) z_q} \right].
$$

(12)

In Table 2, $B(Z' \to \gamma U)$ is tabulated with the assumption of $\lambda_1 c_v = \bar{\lambda}_1 a_v = 1$ for all three generation quarks, $\Lambda$ is set to be 1 TeV, the range of $d$ is chosen as $1.1 - 1.9$ for the definite spectrum of $m_{Z'} = 0.5; 0.7; 0.9; 1.1; 2.0; 3.0$ TeV. The total decay width $\Gamma_{Z'}$ of $Z'$-boson is chosen in the framework of the Sequential SM ($Z_{SSM}'$) , where the ratio $\Gamma_{Z'}/m_{Z'}$ has the maximal value $a = 0.03$ among the Grand Unification Theories (GUT) inspired $Z'$ models (as a review, see, for example, the paper by P. Langacker in [6]).

Table 2. Branching ratio $B(Z' \to \gamma U) \times 10^7$ for $\lambda_1 c_v = \bar{\lambda}_1 a_v = 1$, $\Lambda = 1$ TeV depending on $d = 1.1 - 1.9$ and $m_{Z'} = 0.5; 0.7; 0.9; 1.1; 2.0; 3.0$ TeV with $\Gamma_{Z'}$ given by the $Z_{SSM}'$-model ($a = 0.03$)

| $m_{Z'},$ TeV | 0.5 | 0.7 | 0.9 | 1.1 | 2.0 | 3.0 |
|---------------|-----|-----|-----|-----|-----|-----|
| $d = 1.1$     | 2.39 | 2.56 | 2.69 | 2.80 | 3.16 | 3.42 |
| $d = 1.3$     | 1.78 | 2.18 | 2.54 | 2.88 | 4.11 | 5.23 |
| $d = 1.5$     | 0.68 | 0.95 | 1.22 | 1.50 | 2.72 | 4.08 |
| $d = 1.7$     | 0.21 | 0.34 | 0.49 | 0.65 | 1.50 | 2.64 |
| $d = 1.9$     | 0.053 | 0.093 | 0.15 | 0.21 | 0.63 | 1.31 |

We find the smooth increasing of $B(Z' \to \gamma U)$ with $m_{Z'}$ and its decreasing with the dimension $d$. 


In Table 3, the cross section $\sigma(\bar{q}q \to Z' \to \gamma U)$ is tabulated in the case of up-quarks annihilation, where $x_1 \sim x_2 \sim \sqrt{x_{\text{min}}}$, $x_{\text{min}} = m_{Z'}^2/s$; the range of $d$ is chosen as $= 1.1 - 1.9$ for $m_{Z'} = 0.5; 0.7; 0.9; 1.1; 2.0; 3.0 \text{ TeV}$; $a = 0.03$.

**Table 3.** Cross section $\sigma(\bar{q}q \to Z' \to \gamma U) \times 10^2, \text{ fb}$ with the assumption of up-quarks annihilation, where $d = 1.1 - 1.9$, $m_{Z'} = 0.5; 0.7; 0.9; 1.1; 2.0; 3.0 \text{ TeV}$; $a = 0.03$.

| $m_{Z'}, \text{TeV}$ | 0.5 | 0.7 | 0.9 | 1.1 | 2.0 | 3.0 |
|---------------------|-----|-----|-----|-----|-----|-----|
| $d = 1.1$           | 11.20 | 5.90 | 4.00 | 2.70 | 0.92 | 0.44 |
| $d = 1.3$           | 8.37  | 5.01 | 3.81 | 2.80 | 1.19 | 0.70 |
| $d = 1.5$           | 3.20  | 2.19 | 1.83 | 1.45 | 0.79 | 0.53 |
| $d = 1.7$           | 0.99  | 0.78 | 0.74 | 0.63 | 0.44 | 0.34 |
| $d = 1.9$           | 0.25  | 0.21 | 0.21 | 0.20 | 0.18 | 0.18 |

For 100 $fb^{-1}$ luminosity at the LHC, we find for a 0.9 TeV $Z'$ and with up-type quarks annihilation, a small number of events, corresponding to 4 signal events at $d = 1.1$, while at $d = 1.9$ this number does not exceed the single one. In the case of down-type quarks, the events estimation is five times more which is more optimistically to be observed at the LHC.

It is known that for the pole mass, e.g., $m_{Z'} = 1 \text{ TeV}$, the invariant di-lepton mass resolutions for Drell-Yan processes $pp \to \ell \ell$ for both ATLAS [8] and CMS [7] detectors are about 2% for $e^+e^-$, and twice more in the case of $\mu^+\mu^-$ final pairs. It means that for GUT inspired $Z'$, LHC will be at the threshold or even not be able to measure the $\ell\ell$ pair production via the $Z'$ boson decay. On the other hand, within the aim to explore the $U$-unparticles, the parent particle, $Z'$, can also be in the state containing the continuously distributed mass. Such a $Z'$ - boson looks like, e.g., the $E_6$ $Z'$ with some nonzero internal decay $\Gamma^{\text{int}}_{Z'}$ width determined by the spectral function $\rho(t)$ in the following approximate equality [22]:

$$\int_0^\infty \frac{\rho(t) \, dt}{p^2 - t - i\epsilon} \simeq \frac{1}{p^2 - m_{Z'}^2 + i m_{Z'} \Gamma^{\text{int}}_{Z'}}.$$

where

$$\rho(t) = \frac{m_{Z'} \Gamma^{\text{int}}_{Z'}}{\pi (t - m_{Z'}^2)^2 + (\Gamma^{\text{int}}_{Z'})^2 m_{Z'}^2}.$$

The relatively large ratio $\Gamma^{\text{int}}_{Z'}/m_{Z'}$ is bigger than the $\ell\ell$ invariant mass resolution, and, then, the discovery of broad heavy vector resonance will clarify the internal structure of $Z'$.  

11
4 U- observable and experimental constraints

In some sense, the unparticle sector carries the SM features in terms of operators. It means that the hidden sector could be strongly constrained by existing experimental data. One of the important and practical implications for unparticle phenomenon in the framework of experimental constraints is the analysis of the operator form (already mentioned schematically in the Introduction):

\[ \text{const} \frac{\Lambda^{d_{BZ} - d}}{M^{d_{BZ} - 2}} |H|^2 O_U \]  \hspace{1cm} (13)

containing the Higgs field \( H \) in the IR with dimension \( d \) towards the breaking of the conformal invariance. Within the Higgs v.e.v. requirement, the theory becomes nonconformal below the scale

\[ \tilde{\Lambda} = \left( \frac{\Lambda^{d_{BZ} - d}}{M^{d_{BZ} - 2}} v^2 \right)^{\frac{1}{4 - d}} < \Lambda, \]

where \( U \)-unparticle sector becomes as known particle one. For practical (experimental) consistency we require \( \tilde{\Lambda} < \sqrt{s} \). It implies that unparticle physics phenomena can be seen at high energy experiment with the energies

\[ s > \left( \frac{\Lambda^{d_{BZ} - d}}{M^{d_{BZ} - 2}} v^2 \right)^{\frac{2}{4 - d}} \]

even when \( d \to d_{BZ} \). Note, that any observable involving operators \( O_{SM} \) and \( O_U \) in (13) will be given by the operator

\[ \hat{o} = \left( \frac{\Lambda^{d_{BZ} - d}}{M^{d_{BZ} + n - 4}} \right)^2 s^{d + n - 4}, \]

where \( n \) is the dimension of the SM operator. Then, the observation of the unparticle sector is bounded by the minimal energy

\[ s > \hat{o}^{\frac{1}{n}} M^2 \left( \frac{v}{M} \right)^{\frac{4}{n}}. \]  \hspace{1cm} (14)

No both \( d \)- and \( d_{BZ} \) - dimensions we have in the lower bound (14). The main model parameter is the mass \( M \) of heavy messenger. If the experimental deviation from the SM is detected at the level of the order \( \hat{o} \sim 1\% \) at \( n = 4 \), the lower bound on \( \sqrt{s} \) would be from 0.9 TeV to 2.8 TeV for \( M \)'s running from 10 TeV to 100 TeV, respectively. Thus, both the Tevatron and the LHC are the ideal colliders where the unparticle physics can be tested well.
5 Conclusions

In conclusion, we have studied the decay of extra neutral gauge boson $Z'$ into vector $U$-unparticle and a single photon. Both vector and axial-vector couplings to quarks (including the heavy quarks of the 4th generation) play a significant role. A nontrivial scale invariance sector of dimension $d$ may give rise to peculiar missing energy distributions in $Z' \rightarrow \gamma U$ that can be treated at the LHC. The energy distribution for $pp \rightarrow Z' \rightarrow \gamma U$ can discriminate $d$. The branching ratio $B(Z' \rightarrow \gamma U)$ is small and at best of the order of $10^{-7}$ for small scale dimension $d = 1.1$. For larger $d$, the branching ratio is at least smaller by one order of the magnitude. For $100 \text{ fb}^{-1}$ luminosity at the LHC, we find the required production range for $\gamma U$ is around $4 - 20$ signal events at $d = 1.1$ for a 0.9 TeV $Z'$, while for larger values of $d$ the events number decreases sharply.

Unless the LHC can collect a very large sample of $Z'$, detection of $U$-unparticles through $Z' \rightarrow \gamma U$ would be quite challenging. At the LHC or even at the ILC, we expect the beam energies which can be run at the $Z'$-pole, and with a large number of $Z'$'s the branching ratio $B(Z' \rightarrow \gamma U)$ as low as $10^{-8} - 10^{-7}$ can be tested.

For the case when $Z'$-boson has continuously distributed mass, the branching ratio has an additional suppression factor due to nonzero $\Gamma_{Z'}^{\text{int}}$. The experimental estimation of $B(Z' \rightarrow \gamma U)$ will provide us with the quantity of $\Gamma_{Z'}^{\text{int}}$.

The implementation of our prediction in the LHC analyses should be straightforward and lead to more precise determination or limits of unparticles couplings and/or $Z'$ couplings and masses. We have shown numerical results for $Z'$-bosons associated with the $Z_{\chi}$ - model. The calculations are easily applicable to other extended gauge models, e.g., Little Higgs scenario models, Left-Right Symmetry Model, Sequential SM.

We have ignored issues of efficiencies and backgrounds; these must of course be included in a data analyses.

The new phenomena like the $Z'$-bosons with the mass $\sim O(1 \text{ TeV})$ could be discovered at the LHC in 2011 run, optimistically, at $100 \text{ fb}^{-1}$ and $\sqrt{s} \sim 8-10$ TeV. When physics (beyond the SM) of the $Z'$-bosons becomes a reality, it will be much clearer to the physics community what the unparticle stuff is for and why it is needed to be incorporated in new physics. If the model of new couplings between $Z'$ and $U$-unparticles that we are discussing in this paper is correct, the first signs of that new physics will be discovered at the LHC.
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