Unparticle Phenomenology – A Mini Review

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Abstract. We review some collider phenomenology of unparticle physics, including real emissions and virtual exchanges of unparticle. Existing experimental constraints from collider physics as well as astrophysics are briefly discussed.

Keywords: Unparticle, LHC, ILC
PACS: 12.38.Qk, 12.60.-i, 12.90.+b, 13.40.Em, 14.80.-j

INTRODUCTION

The notion of unparticle introduced by Georgi [1] was based on the hypothesis that there could be an exact scale invariant hidden sector resisted at a high energy scale. A prototype model of such sector is given by the Banks-Zaks theory [2] which flows to an infrared fixed point at a lower energy scale \( \Lambda_U \) through dimensional transmutation. Below \( \Lambda_U \), unparticle physics emerges and manifest itself as interpolating fields \( O \) of various scaling dimensions and Lorentz structures.

One of the interesting feature of unparticle operator is that it has a continuous spectral density \( \rho(P^2) \) as a consequence of scale invariance [1]

\[
\rho(P^2) = A_{d_U} \theta(P^0) \theta(P^2)(P^2)^{d_U-2}
\]  
(1)

where \( d_U \) is the scaling dimension of the unparticle operator with 4-momentum \( P \) and \( A_{d_U} \) is a free normalization factor. Due to their similar kinematical exponent, Georgi [1] chose \( A_{d_U} \) to be the prefactor of \( d_U \) massless particle phase space

\[
dLIPS_{d_U} = A_{d_U} \left( (p_1 + p_2 + \cdots + p_{d_U})^2 \right)^{d_U-2}
\]  
(2)

where \( p_i^2 = 0 \) \((i = 1, \ldots, d_U)\). Thus

\[
A_{d_U} = \frac{16 \pi^{d_U/2}}{(2\pi)^{d_U} \Gamma(d_U - 1) \Gamma(2d_U)}
\]  
(3)

As \( d_U \) approaches 1, Eq.(1) reduces to the familiar one massless particle phase space. This suggests unparticle behaves like a collection of \( d_U \) massless particles. Since \( d_U \) can be non-integral, one can now speak of fractional particle. This metaphor draws immediate attention of many physicists worldwide as well as the general public [1].

Soon after the introduction of unparticle, its propagator was deduced by using unitarity cuts [3] and the spectral decomposition formula [4]. For a scalar unparticle, its Feynman propagator is given by

\[
\Delta_F(P) = \frac{A_{d_U}}{2 \sin \left( d_U \pi \right)} \frac{1}{(-P^2 - i0^+)^{d_U - 2}} .
\]  
(4)

The presence of an extra CP-conserving phase factor \( \exp (-i d_U \pi) \) in (4) for non-integral \( d_U \) and time-like \( P^2 > 0 \) was pointed out in [3,4] and the intricate interference effects in phenomenology were also first studied there. Analogous formulas can also be written down for the spin 1 [3,4] and spin 2 [5] unparticle operators, while the fermionic spin 1/2 case was given in [6].

Unparticle operators can interact with the Standard Model (SM) fields via exchange of some heavy particles of mass \( M \). Integrating out such heavy fields induces a series of effective operators describing how unparticle interact with SM fields at low energy [1]. Some examples of these operators are [1,4]

- Spin 0:
  \[
  \lambda_0 \frac{1}{\Lambda_U^{d_U-1}} \bar{f} O f , \quad \lambda_0'' \frac{1}{\Lambda_U^{d_U-1}} \bar{f} i \gamma^5 f O ,
  \]
- Spin 1:
  \[
  \lambda_1 \frac{1}{\Lambda_U^{d_U-1}} \bar{T} \gamma \mu O \mu , \quad \lambda_1' \frac{1}{\Lambda_U^{d_U-1}} \bar{T} \gamma \mu \gamma_5 O \mu ,
  \]
- Spin 2:
  \[
  - \frac{1}{4} \lambda_2 \frac{1}{\Lambda_U^{d_U-1}} \bar{\psi} \left( \gamma \mu D_\nu + \gamma_\nu D_\mu \right) \psi O_{\mu\nu} ,
  \]

1. One can even find an entry of unparticle in the Wikipedia database.
and so on. Here $O, O^\mu$ and $O^{\mu\nu}$ denote the spin 0, 1 and 2 unparticle operators respectively with $d_U$ its corresponding scaling dimension. The $\lambda$-coefficients in front of these operators are effective couplings that depend on the short distance physics among the heavy exchange particles with the hidden sector and the SM sector. Thus they are free parameters and a priori of order unity. Besides the above operators, more complete lists of gauge invariant operators have been written down in [7]. Antisymmetric rank 2 tensor unparticle operator was discussed in [8].

The hypothesis of scale invariance of unparticle physics can be extended further to become conformal. The implication to unparticle physics of unitarity constraints on the scaling dimensions deduced from general conformal field theories was emphasized in [10]. The unparticle propagators for this general case have been worked out in [11]. Other theoretical aspects of unparticle were reviewed by Rajaraman [12].

INDIRECT INTERFERENCE EFFECTS

The complex nature of the unparticle propagator [4] for non-integral $d_U$ and time-like $P^2$ can give rise to intricate interference patterns among the amplitudes of the unparticle and SM fields exchange in various elementary processes that are relevant in linear as well as hadronic colliders. Georgi [3] showed that the interference effects depend sensitively on the scaling dimension in the total cross section as well as in the forward-backward asymmetry of the process $e^- e^+ \rightarrow \mu^- \mu^+$. These effects are most easily palpable around the $Z$ pole. Similar effects were demonstrated for the Drell-Yan process at the Tevatron in [4]. More detailed studies of these two processes and some other related ones were presented in [5]. Similar analysis of these complicated interference patterns due to spin 0 and spin 2 unparticle exchange at the Large Hadron Collider (LHC) were given in [13] for the Drell-Yan process and in [14] for the diphoton production. Analogous processes were also studied in [5] for a future International Linear Collider (ILC).

In Fig. 1 typical example of the sensitive dependence on the scaling dimension of a spin 1 and spin 2 unparticle operator in the intricate interference patterns is shown for the angular distribution of $e^- e^+ \rightarrow \mu^- \mu^+$ at the LEP2 energy and at the ILC energy of $\sqrt{s} = 0.5$ TeV respectively.

One of the most transparent effects of unparticle phase factor $\exp(-i d_U \pi)$ can be observed in the lepton-pair invariant mass spectrum near the $Z$ pole in Drell-Yan production. In Fig. 2, we depict the fractional difference from the SM prediction in units of $\Delta \sigma^2 (\text{with small } \lambda_1)$ while keeping $\Lambda_U = 1$ TeV of the Drell-Yan distribution as a function of the invariant mass of the lepton pair for various $d_U$. Interesting interference patterns around the $Z$ pole are easily discerned.

Three different groups [15] have also studied these interference effects for the process $\gamma\gamma \rightarrow \gamma\gamma$ at a photon collider.

The static limits of unparticle propagators of various spins can also give rise to new long range forces that are severely constrained by low energy experiments.
Coupling of these types of new forces to the energy-momentum stress tensor \( \Lambda U \), the baryon number current \( \rho U \), and the spin-spin interactions among electrons \( \rho U \) as well as the solar and reactor neutrinos \( \nu U \) have been studied in the literature.

**DIRECT PRODUCTION OF UNPARTICLE STUFF**

Unparticle operator \( O \) with a continuous spectral distribution given by Eq. (1) implies the stuff it creates from the vacuum will have an indefinite dispersion relation given by \( P^2 = (P^0)^2 - P^2 \geq 0 \) with \( P^0 \geq 0 \). This stuff was coined as unparticle [1] since this is quite peculiar from the particle point of view that we so get used to. We will denote this unparticle stuff generically by \( U \). Signatures for detection of unparticle stuff are the missing energy and momentum carried away by the unparticle [1].

Search strategies for unparticle stuff are therefore similar to the search of Kaluza-Klein modes in the large extra dimension models. Even in a 2 body decay of \( 1 \to 2 + U \), the kinematics of the particle 2 is no longer fixed due to the indefinite dispersion relation of \( U \).

Many processes have been studied for real emission of unparticle stuff. These include \( t \to b U \) [1], \( Z \to f f U \) [4, 5], Higgs \( \to \gamma U \) [21], \( Z \to \gamma U \) [22, 23], \( e^- e^+ \to (\gamma Z)/U \) [4, 5, 7], quarkonia \( \to \gamma U \) [23] etc. Similar to the indirect interference effects, sensitive dependence on the scaling dimensions of the unparticle operators can be observed in the missing energy/momentum distributions for these processes. Production of multi-unparticle in the final state was considered in [24].

Production of monojet plus unparticle was also studied in details at the LHC [4, 5]. It was shown that the strong dependence on the scaling dimensions of the matrix elements at the parton level is completely washed out at the hadron collider due to parton smearing effects. However, it has been demonstrated in [25] that the monojet shape is still useful to distinguish the unparticle signals from large extra dimension models and the SM monojet background.

The mono-photon recoil mass distributions of \( e^- e^+ \to \gamma U \) for spin 1 (left panel) and spin 2 (right panel) unparticle \( U \) are plotted in Fig. 3 for various choices of \( d_U \) at the center-of-mass energy \( \sqrt{s} = 1 \text{ TeV} \). The SM background from \( e^- e^+ \to \gamma Z \to \gamma \nu \bar{\nu} \) is also displayed for comparison. The peculiar feature of unparticle effects due to the non-integral values of \( d_U \) is easily seen in these recoil mass distributions. This is in sharp contrast with the case in the hadronic machines.

**EXISTING CONSTRAINTS**

The scaling dimensions of unparticle operators and the effective couplings \( \lambda \) that parameterize our ignorance of the underlying unparticle physics can be constrained by existing collider experiments [5] as well as observations from astrophysics and cosmology [26, 27, 28, 29, 30].

Two constraints from different experiments are shown in Fig. 4. In the left panel, the mono-photon plus missing energy production cross section measured at LEP2 [31] was used to constrain \( d_U \) and \( \Lambda_U \). The limits are shown in Table 1. In the right panel, constraints for \( d_U \) and the effective vector coupling \( \lambda_1 \) can also be inferred from the muon anomalous magnetic moment. For the contribution from an antisymmetric rank 2 unparticle operator to the muon anomalous magnetic moment, see [8].

Assuming unparticle physics can extrapolate all the way down to the hot stars’ interiors, emitting of such unparticle stuff can lead to star coolings. Observation of the cooling rates can thus place upper limits on the unknown parameters in the hidden sector of unparticle physics. The cooling mechanisms may include many competing processes like (1) un-Compton scattering \( \gamma e \to e U \); (2)...

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3 Recall that the wave-particle duality, a basic ingredient of quantum theory, is captured mathematically by a definite dispersion relation.
We conclude with some remarks.

- Scale invariance is expected not to be an exact symmetry at low energy. Indeed coupling of a scalar unparticle operator with the SM Higgs field can break scale invariance once the Higgs field develops its vacuum expectation value \( V \). To model the symmetry breaking effects, a finite mass gap \( \mu \) was inserted in the unparticle spectral density by hand \( \mu V \). The unparticle propagator needs to be modified accordingly and it can lead to unresonance behavior discussed in \( \mu \). When the probing energy and the mass gap \( \mu \) are proximate, more careful treatment is necessary in order to avoid the blow up of the amplitudes. Inclusion of the proper self-energy \( \mu \) and the decay width of unparticle \( \mu \) in its propagator have been suggested in the literature.

- Besides the topics we reviewed briefly above, the roles of unparticle in flavour physics \( \mu \), top quark physics \( \mu \), Higgs physics \( \mu \), electroweak symmetry breaking \( \mu \), unitarity in longitudinal \( \mu \) scatterings \( \mu \), supersymmetry \( \mu \), dark matter \( \mu \), gauge unification \( \mu \), hidden valley models \( \mu \), deconstruction via AdS/CFT \( \mu \) or Padé approximants \( \mu \), walking technicolor \( \mu \), baryon number violating nucleon decay \( \mu \), uncosmology \( \mu \), conformal energy and charge correlations \( \mu \) etc have also been explored in the literature. This list is really a tall order for unparticle physics given the fact that its inception was solely based on curiosity. Thus, we refer the readers to these references for details and apologize to those authors whose works we do not mention here due to page limitation.

- In less than two years, numerous unparticle phenomenological studies have been performed despite the physical meanings of many aspects of the unparticle are not yet clear. How does dimensional transmutation occur that leads to the unparticle phenomena? Is unparticle stable? What is the partition function of a system of unparticle? How does one couple gauge field to unparticle? etc. These are interesting theoretical questions awaiting for answers.

- Finally, we note that phenomenology of unparticle has been regarded as a little bit premature \( \mu \). We will let our readers to make their own judgements.

Figure 3. Comparison of recoil mass distributions of \( e^- e^+ \to \gamma U \) with the SM background \( e^- e^+ \to \gamma \nu \bar{\nu} \) for different values of scaling dimension \( d_U = 1.001, 1.2, 1.5, 2 \) and 3 at the center-of-mass energy \( \sqrt{s} = 1 \) TeV. Left and right panels are for spin 1 and spin 2 unparticle respectively. See \( \mu \) for details.

un-bremssstrahlung \( e e \to eeU \), \( eN \to eNU \) and \( NN \to NNU \) where \( N \) denotes a nucleus, (3) photon-photon annihilation \( \gamma\gamma \to U \), (4) electron-positron annihilation \( e^- e^+ \to U \) and (5) plasmon decay \( \gamma \to \gamma U \), etc. The calculation of the energy loss rate for each of these processes is similar to the axion case.

As an example, we show in Fig. 5 the energy loss rate at the Sun and red giant from the emission of spin 1 unparticle in the un-Compton scattering versus the effective coupling \( \lambda \) for various values of \( d_U \) \( \mu \). From these plots one can see that more stringent constraints on the hidden sector of unparticle physics can be deduced from astrophysics than from colliders. More detailed analysis of astrophysical constraints for the unparticle physics can be found in \( \mu \). Interesting constraints can be deduced from the null observation of any new long range force, and they were discussed in \( \mu \). For constraints deduced from recent solar and reactor neutrinos data, see \( \mu \).
ACKNOWLEDGMENTS

This work was supported in part by the NSC under grant No. NSC 96-2628-M-007-002-MY3, the NCTS of Taiwan as well as U.S. DOE under grant No. DE-FG02-84ER40173.

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