Probing Ultraheavy Quanta with Photon-Photon or Gluon-Gluon Scattering

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The existence of ultraheavy quanta too heavy to produce directly may be probed by means of the rising cross sections they would induce in scattering at the TeV energy scale of photon or gluon pairs to weak boson pairs, for instance $\gamma\gamma \to ZZ$ or $gg \to ZZ$.

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We do not know if there are even heavier matter fields than the still undiscovered top quark. Heavier quanta with mass generated by electroweak symmetry breaking are possible if they satisfy the weak-isospin degeneracy constraint [1] imposed by the measured value of the ρ parameter, $\rho \equiv (M_W/M_Z \cos\theta_W)^2 \simeq 1$, and the constraint from the radiative parameter [2] S. Such ultraheavy quanta could be additional quark-lepton families, techniquarks, or could occur in totally unexpected forms. The purpose of this paper is to show that the existence of ultraheavy quanta with mass generated by $SU(2)_L \times U(1)_Y$ symmetry breaking can be probed in the scattering of photon or gluon pairs into longitudinally polarized W or Z boson pairs at energies large compared to M_W but small compared to the production threshold of the ultraheavy particles. As explained below the electric- or color-charge weighted "count" obtained in this way is similar to but more generally accessible than information obtainable from on-mass-shell Higgs boson processes such as $H \to \gamma\gamma$ [3] or $Z \to H\gamma$ [4].

To illustrate the mechanism I will focus in this paper on Higgs boson models and on the process $\gamma\gamma \to ZZ$ that vanishes in tree approximation. Using the backscattered laser technique [5] at TeV e^+e^- colliders, it may be possible to create $\gamma\gamma$ collisions of energy and luminosity comparable to that of the parent e^+e^- collider [6]. Similar information can be obtained from gluon-gluon scattering, $gg \to ZZ$ or WW, that can be studied at the Superconducting Super Collider (SSC) or CERN Large Hadron Collider (LHC), to be discussed elsewhere [7]. The presentation here is only illustrative of the order of magnitude of the background for $\gamma\gamma \to ZZ$ because an important contribution from W boson loops has not been computed.

Corrections to the high-energy scattering signals and also to the on-shell Higgs boson decay amplitudes may arise from strong Yukawa interactions of the ultraheavy quanta. If with further study those corrections are found to be large the signals quoted here would only serve as guides to the order of magnitude. As such they would indicate the existence of ultraheavy quanta but could not be interpreted as to the charges and numbers of quanta.

In the following sections I will describe the asymptotic signal, the backgrounds, and the strategy for experimental detection. A concluding section describes some related issues including the present limits on ultraheavy quanta, applicability to technicolor and supersymmetric quanta, a puzzle involving the equivalence theorem, the question of strong corrections and their relationship to the trace anomaly, and comparison of the high-energy scattering signals to the on-shell Higgs boson amplitudes.

The asymptotic signal.— Consider the minimal one-Higgs-boson model [8] for simplicity. Suppose X is an ultraheavy particle of spin $J_X = 0$ or $\frac{1}{2}$ and that its mass is generated by the Higgs boson, $m_X = y_X \langle H \rangle_0$, where y_X is the HXX (Yukawa) coupling constant. Assume the hierarchy

$$m_X^2 \gg s \gg m_H^2, M_Z^2 , \tag{1}$$

where $\sqrt{s}$ is the $\gamma\gamma$ center-of-mass energy. (The condition $s \gg m_H^2$ is not essential; if it is replaced by $s \gtrsim m_H^2$ the signal is increased by $s^2/[(s-m_H^2)^2 + m_H^2\Gamma_H^2]$.) The X particle contributes to $\gamma\gamma \to ZZ$ scattering by means of the triangle and box diagrams shown in Fig. 1, including two topological variants of the box diagram not shown. The standard-model background arises from analogous diagrams with quark, lepton, and W boson loops, including in the latter case additional diagrams with four-point $\gamma\gamma WW$ and $WWZZ$ vertices.

In the limit of inequality (1) the contribution of the X particle to the box diagrams is negligible, $O(s/M_X^2)$ relative to the leading contribution. The X contribution to the triangle amplitude, Fig. 1(a), is significant in two respects: It does not decouple and for longitudinally polarized Z bosons it increases linearly with s in the domain

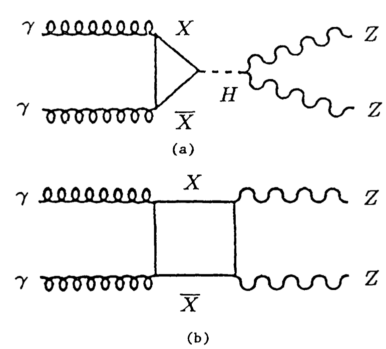

FIG. 1. Feynman diagrams for $\gamma\gamma \to ZZ$.

of inequality (1). These properties were noted by Glover and van der Bij in their study of $gg \to ZZ$ scattering [9].

The nondecoupling property of the scalar-vector-vector triangle diagram was first observed in connection with the trace anomaly of scale invariance [10], which is in fact relevant to the present application, especially as concerns the question of higher-order corrections discussed below. Under the conditions of inequality (1) the X contribution can be evaluated using the low-energy theorem for the dilaton-photon-photon vertex derived in Ref. [9] from the trace anomaly, with the Higgs boson standing in for the dilaton. The leading result is, for longitudinally polarized Z bosons, Z_L, and photons of equal helicity, $\lambda_1 = \lambda_2$,

$$\mathcal{M}(\gamma\gamma \to Z_L Z_L)_X = \frac{\alpha R_X}{3\pi} \frac{s}{v^2} \delta_{\lambda_1 \lambda_2}, \qquad (2)$$

where $v = (\sqrt{2} G_F)^{-1/2} = 246$ GeV and R_X is the quantity familiar from e^+e^- annihilation, $R_X = \sum_{J_X = 1/2} Q_X^2 + \frac{1}{4} \sum_{J_X = 0} Q_X^2$. The accounting of energy factors is as follows: a factor s from the $F_{\mu\nu}F^{\mu\nu}$ structure of the trace anomaly (required by gauge invariance), a factor $1/s$ from the H propagator, and a factor s from the HZ_LZ_L vertex. Equation (2) exhibits "pseudo bad high-energy behavior"—the growth in s only occurs below $\bar{X}X$ threshold. Above the $\bar{X}X$ threshold instead of a factor s the triangle contributes a constant factor proportional to m_X^2, resulting in a well-behaved $\gamma\gamma \to ZZ$ amplitude at asymptotically large energies.

If Eq. (2) were the dominant contribution, the cross section in the domain of inequality (1) would be

$$\sigma(\gamma\gamma \to ZZ)_X = \left(\frac{\alpha R_X}{24\pi^{3/2}} \right)^2 \frac{s}{v^4}. \qquad (3)$$

For instance if X were a fourth ultraheavy quark-lepton family with $R_X = \frac{8}{3}$, Eq. (2) would become $\sigma_X = (2.57 \text{ fb}) \times [s\ (\text{TeV}^2)]$. That cross section, with a cut on the scattering angle, $|\cos\theta_Z| < 0.9$, is plotted as the solid line in Fig. 2.

Background.—The irreducible standard-model background to $\gamma\gamma \to ZZ$ arises from the contribution of the three known quark-lepton families to the loop amplitudes indicated in Fig. 1 plus the contribution of W boson loop diagrams. The W loops have not been computed and will require a serious effort. They will not change the energy dependence of the background cross section, which falls like $1/s$ in the domain of inequality (1), nor are they likely to differ in order of magnitude from the contribution of the three quark-lepton families. I have computed the three-family contribution by adapting the code of Glover and van de Bij [9] for $gg \to ZZ$ scattering. The resulting cross section with $m_H = 100$ GeV, $m_t = 150$ GeV, and $|\cos\theta_Z| < 0.9$ is shown as the dashed line in Fig. 2. It falls below the solid line representing the signal of an ultraheavy family at $E_{\gamma\gamma} \simeq 550$ GeV and is smaller than that signal by 1 order of magnitude at 1 TeV and by nearly 2 orders of magnitude at 1.5 TeV.

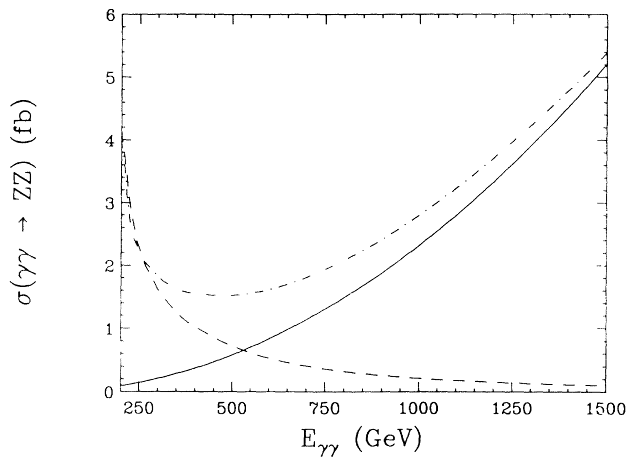

FIG. 2. Cross section for $\gamma\gamma \to ZZ$ with $|\cos\theta| < 0.9$. The solid line is the signal for one ultraheavy fermion family from Eq. (3), the dashed line is the contribution to the background from the three known families, and the dash-dotted line coherently sums the three-family background with the contribution of a fourth family weighing 2 TeV computed from the complete matrix element.

The actual cross section in the presence of ultraheavy quanta will include interference of the ultraheavy and standard-model loop diagrams. The cross section from the full amplitude for $m_X = 2$ TeV including interference with the three light families is shown as the dot-dashed line in Fig. 2. It has the expected behavior, approaching the standard-model cross section at low energy where the ultraheavy contribution is small while approaching the incoherent approximation, Eq. (3), at high energy where the ultraheavy contribution dominates. The precise relationship (including interference effects) between the signal and background depends on the uncalculated W loop contribution but the energy dependences of signal, growing like s, and background, falling like $1/s$, are generally valid and the signal is still likely to dominate at an energy near 1 TeV.

Detection.—The actual $\gamma\gamma$ luminosity distribution is a function of $E_{\gamma\gamma}$ that also depends on the laser and electron energies [6]. The integrated $\gamma\gamma$ luminosity for energies of order the initial e^+e^- energy, say $\gtrsim \frac{2}{3} E_{e^+e^-}$, is of the order of (and can be as much as twice as big as) the luminosity of the parent e^+e^- collider. To estimate the signal and background yields I will assume a 100-fb^{-1} sample of monochromatic $\gamma\gamma$ collisions at $E_{\gamma\gamma} = 1$ TeV. This is conservative relative to the parameters discussed for TeV colliders such as the proposed Japan Linear Collider (JLC) III [11] that call for e^+e^- integrated luminosity of 130 fb^{-1} at energy $(s_{e^+e^-})^{1/2} = 1.5$ TeV. Since the background is falling and the signal is rising between 1 and 1.5 TeV, the actual signal and signal to background at a 1.5-TeV collider will be more favorable than the simple estimate based on monochromatic $\gamma\gamma$ collisions at $E_{\gamma\gamma} = 1$ TeV. Taking the signal cross section from Eq. (3), i.e., the solid line in Fig. 2, we find 2.3 pb or 230 events in our hypothetical data sample. The (three-family) background is 0.21 pb or 21 events, an order of magnitude smaller than the signal.

It is commonly believed that W and Z boson pairs can be detected decaying to quark jets at e^+e^- colliders, in contrast to hadron colliders where at least one if not both bosons of a weak gauge boson pair must be detected decaying to electrons or muons with accompanying loss of rate. However, the enormous cross section for W boson pair production, $\sigma(\gamma\gamma \to WW) \simeq 90$ pb [12], creates an overwhelming background to the $\gamma\gamma \to ZZ \to$ 4-jet signal. While much of this cross section disappears along the beam direction at high energy, even with $|\cos\theta_W| < 0.9$ at $\sqrt{s} = 1$ TeV there would be of order 10^6 WW events in a 100-fb^{-1} data sample [13], dwarfing the corresponding 230-event signal.

To eliminate the WW background it is necessary to "tag" at least one of the Z bosons. The most certain strategy is to detect one Z decaying to a pair of charged leptons while the second decays to any charged lepton or quark pair (excluding $\bar{\tau}\tau\bar{\tau}\tau$ events that may be difficult to reconstruct). The net branching ratio is 0.15, corresponding to 35 signal events and 3 background events. Probably also viable is the larger class of events in which one Z decays to neutrinos while the second decays to a charged lepton or quark pair. The experimental signature of large missing transverse energy recoiling against an observed Z boson with high transverse momentum is probably cleanly recognizable. This sample would add $\simeq 0.30$ of branching ratio to the previous 0.15. Our 100-fb^{-1} $\gamma\gamma$ data sample would then yield about 100 signal events and 10 background events.

Discussion.—Ultraheavy quanta with mass generated by electroweak symmetry breaking evade the strongest constraint from precision measurements (from the ρ parameter) if they come in nearly degenerate $SU(2)_L$ multiplets [1]. The remaining constraint, from the parameter S [2], is not yet very restrictive. Recent fits find that S is appreciably more negative than expected in the standard model [14]. The discrepancy would be increased by an additional ultraheavy family, but by an amount that is small ($\sim$15%–20%) relative to the initial discrepancy. If the discrepancy is removed by new data in better agreement with the standard model or if it is explained by new physics (e.g., a Z' boson as suggested by Langacker [14]), there would be little remaining sensitivity to ultraheavy families unless the precision of the data were greatly improved. In Langacker's fit with no other new physics, just one ultraheavy family is allowed at 95% confidence [14]. Peskin and Takeuchi [14] furthermore observe that a constrained fit requiring $S > 0$ results in a much weaker 95%-confidence limit, $S < 0.93$, allowing as many as four ultraheavy families (each contributing $+0.21$).

Since techniquark effective masses are generated by the $SU(2)_L$ breaking condensate, they would also contribute to the scattering signals. However, instead of the Higgs boson pole there is a multiparticle $J = 0$ technihadron state (dual to $\bar{q}_{TC}q_{TC}$) that at a 1–2-TeV collider would not fall in the domain of inequality (1). Equations (2) and (3) would only be a rough guide to the order of magnitude of the signal. Ultraheavy supersymmetric quanta would not contribute significantly to the extent that their masses are not dominantly due to $SU(2)_L$ breaking but to $SU(2)_L$-singlet supersymmetry breaking.

The derivation of Eq. (2) suggests an interesting theoretical puzzle. The equivalence theorem [15] asserts that $\mathcal{M}(\gamma\gamma \to Z_L Z_L) \simeq \mathcal{M}(\gamma\gamma \to zz)$ for $s \gg M_Z^2$ where z is the unphysical Goldstone boson which becomes the longitudinal Z boson by the Higgs mechanism. Since the Hzz vertex is proportional to m_H^2/v rather than s/v, Fig. 1(a) does not give an amplitude linear in s as in Eq. (2). The resolution is that Eq. (2) now arises from the box graphs, Fig. 1(b) and topological variants, that do not decouple because the XXz vertices contribute a factor m_X^2 to the amplitude. We can verify that the zz box graphs reproduce Eq. (2) for $s \ll m_X^2$ without explicit computation [16].

Nonperturbative arguments have been given that the leading-order (canonical) electromagnetic trace anomaly [10] is not corrected by higher-order QCD interactions [17]. The signals of Eqs. (2) and (3) should therefore be similarly unaffected by QCD or any other asymptotically free interactions (e.g., technicolor). In Higgs boson models there may, however, be large corrections from the strong HXX Yukawa interactions, in which case the predictions presented here are only indicative of the order of magnitude of the signal. The question merits further study.

The information extracted from high-energy $\gamma\gamma \to ZZ$ scattering is also available in principle from the on-shell amplitudes $H \to \gamma\gamma$ [2] or $Z \to H\gamma$ [4], but high-energy scattering has significant advantages. $H \to \gamma\gamma$ could be measured directly in $\gamma\gamma$ collisions at $E_{\gamma\gamma} = m_H$ in one of two mass regions in which the (three-family) standard-model signal would be observable above the background: for $70 < m_H < 150$ GeV in $H \to \bar{b}b$ and $200 < m_H < 250$ GeV in $H \to ZZ$ [18]. But the contribution of a fourth family would interfere destructively, decreasing the signal by an order of magnitude [e.g., by $\sim(\frac{15}{47})^2$ for $m_H < 2M_W$] and probably causing it to be lost in the background [13]. No comparable effect occurs in high-energy $\gamma\gamma \to ZZ$ scattering because the X loop amplitude dominates the W and light fermion loop amplitudes by a power of s.

High-energy scattering has another advantage in models with multiple Higgs bosons: The simple equations (2) and (3) remain valid at high energy, $s \gg m_{H_i}^2$, but to extract the same information from $\Gamma(H_i \to \gamma\gamma)$ would require detailed knowledge of the Higgs sector mixing and couplings.

To summarize, $\gamma\gamma \to ZZ$ scattering can be used to probe ultraheavy charged quanta which obtain their mass from $SU(2)_L$ symmetry breaking and are too heavy to produce directly. The results complement what can be learned from precision measurements and from Z and Higgs boson radiative decays. The signal from an ultraheavy fourth family of quarks and leptons would be observable using the backscattered laser technique at a 1.5-TeV e^+e^- collider with e^+e^- luminosity of order 10^{34} cm^{-1}sec^{-1}. Complete evaluation of the background requires computation of the W loop amplitudes. The analogous application of $gg \to ZZ$ scattering at the SSC and LHC is also under study [7].

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