Some Physics Beyond the Standard Model at Gamma Gamma Colliders

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In this talk, I describe a few interesting physics beyond the standard model that are quite unique for $\gamma\gamma$ collisions, including large extra dimension model (ADD), warped extra dimension model (Randall-Sundrum) model, universal extra dimension model, as well as techni-pions of technicolor models.

I. INTRODUCTION

There are strong reasons to believe that the standard model (SM) is only an effective theory below 1 TeV. Theoretically, it has some shortcomings. (i) The SM has too many parameters, (ii) it is not a real unification of all forces, and (iii) the gauge hierarchy problem. There are other observations indicating that the SM is not satisfactory. The most striking evidence is the definite though small neutrino masses. Most of us also believe that there should be dark matter and even dark energy. It is clear that the SM cannot provide these components of the universe. In addition, the SM cannot fulfill all the requirements to give a sufficiently large enough baryon asymmetry of the universe. All these problems lead us to believe that there should be new physics beyond the SM, which should come in TeV scale.

The hierarchy problem has motivated many new physics. In recent years, a number of models in extra dimensions have been proposed. They provide an alternative view of the hierarchy problem into geometric stabilization of the extra dimensions.

Collider experiments of the next generation will definitely search for signs of various extra dimension models. In this talk, I describe a few interesting physics that are quite unique for $\gamma\gamma$ colliders, including large extra dimension model (ADD), warped extra dimension model (Randall-Sundrum), universal extra dimension model, as well as techni-pions of technicolor models.

II. ADD MODEL

It was proposed by Arkani, Dimopoulos, and Dvali [1] that the size $R$ of the extra dimensions that only gravity can propagate can be as large as mm. Suppose the fundamental Planck scale of the model is $M_D$, the observed Planck scale $M_{Pl}$ becomes a derived quantity: $M_{Pl}^2 \sim M_D^{n+2} R^n$. If $R$ is extremely large, as large as a mm, the fundamental Planck scale $M_D$ can be as low as TeV, which removes the gauge hierarchy problem. In this model, the SM particles and fields are confined to a brane while only gravity is allowed to propagate in the extra dimensions. Thus, the only probe of extra dimensions is through graviton interactions. The graviton in the extra dimensions is equivalent to a tower of Kaluza-Klein (KK) states in 4D point of view. The separation between each state is of order $1/R$, which is very small of order of $O(10^{-4})$ eV. This means that in the energy scale of current high energy experiments, the mass spectrum of the KK tower is effectively continuous. Though each of the KK states interacts with a strength of $1/M_{Pl}$, however, when all the KK states are summed up, the interaction has a strength of $1/M_D \sim 1/O(\text{TeV})$.

Below $M_D$ the SM particles can scatter into a graviton, which either (i) goes into extra dimensions and does not come back to the brane, which then gives rise to missing energy and momentum in experiments, or (ii) comes back to the SM brane and decay back into SM particles, the scattering amplitude of which then interferes with the normal SM amplitude. Therefore, experimentally we can search for two types of signatures, the missing energy or the interference effects.

One unique process to search for virtual graviton effect is the light-by-light scattering [2]. The SM amplitude has to go through a box diagram while the graviton-induced amplitude is at tree-level: see Fig. 1(a). In contrast, diphoton production at $pp$ or $e^+e^-$ collisions has tree-level SM contributions. With graviton exchanges the differential cross

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section is given by

\[ \frac{d\sigma(\gamma\gamma \rightarrow \gamma\gamma)}{d|\cos \theta|} = \frac{\pi s^3}{M_S^2} \mathcal{F}^2 \left[ 1 + \frac{1}{8} (1 + 6 \cos^2 \theta + \cos^4 \theta) \right], \]

where \( \mathcal{F} = \log(M_S^2/s) \) or \( 2/(n - 2) \) for \( n = 2 \) or \( n > 2 \). The cross sections for \( \gamma\gamma \rightarrow \gamma\gamma \) for graviton signals and SM background vs \( \sqrt{s_{\gamma\gamma}} \) are shown in Fig. 1(b). It is clear that the signal can easily go above the SM background when \( \sqrt{s_{\gamma\gamma}} \sim 0.5 \text{ TeV} \) for \( M_S \approx 4 \text{ TeV} \). We can also compare the sensitivity reach of \( \gamma\gamma \rightarrow \gamma\gamma \) with \( e^- e^+ \rightarrow \gamma\gamma \), as shown in Fig. 2. The latter has tree-level SM contributions. The \( \gamma\gamma \rightarrow \gamma\gamma \) scattering can probe \( M_S \) upto 16 TeV \( (n = 2) \) for \( \sqrt{s_{\gamma\gamma}} = 2 \text{ TeV} \) compared with about 11 TeV \( (n = 2) \) by \( e^- e^+ \rightarrow \gamma\gamma \).

III. RANDALL-SUNDRUM MODEL

The Randall-Sundrum (RS) model \[3\] beautifully explains the gauge hierarchy with a moderate number through the exponential. The most distinct feature of the RS model is the unevenly spaced KK spectrum for the gravitons \[4\]. Phenomenology associated with the modulus field (known as the radion) \[5\], describing the fluctuation in the separation of the two branes, is another interesting feature of the RS model. The interactions of the radion with SM...
FIG. 3: Radion production vs radion mass.

particles are given by

\[ \mathcal{L}_{\text{int}} = \frac{\phi}{\Lambda_\phi} T^\mu_\mu (\text{SM}), \]

where \( \Lambda_\phi = \langle \phi \rangle \) is of order of TeV and \( T^\mu_\mu (\text{SM}) \) is the trace of the energy-momentum tensor. It is clear that the interactions are very similar to those of the SM Higgs boson with the replacement of the VEV by \( \langle \phi \rangle \). However, the radion has anomalous couplings to gluons and photons from the trace anomaly:

\[ T^\mu_\mu (\text{SM})^{\text{anom}} = \sum_a \frac{\beta_a(g_a)}{2g_a} F_{\mu\nu}^a T^{a\mu\nu}, \]

where \( \beta_a \) are the beta functions for the gauge groups. Because of the anomalous coupling of the radion to photons, photon fusion would be an important production channel for the radion in \( \gamma\gamma \) collisions. In Fig. 3, we show the production cross section of the radion at photon colliders [6].

Another interesting feature of the radion is the possibility of mixing between the radion and the Higgs boson [7]. This is the consequence of a mixing term in the action

\[ S_\xi = \xi \int d^4 x \sqrt{g_{\text{vis}}} R(g_{\text{vis}}) \hat{H}^\dagger \hat{H}, \]

where \( R(g_{\text{vis}}) \) is the Ricci scalar on the visible brane. A nonzero \( \xi \) will induce some special triple vertices [8]:

\[ h - \phi - \phi, \ h_{(n)}^{\mu\nu} - h - \phi, \ \phi - \phi - \phi, \ h_{(n)}^{\mu\nu} - \phi - \phi. \]

One can then use

\[ \gamma\gamma \rightarrow G_{\mu\nu}^{(n)} \rightarrow h\phi \]

to probe the radion-Higgs mixing. Similar studies [9] have been performed for pp and \( e^+e^- \) colliders.

IV. UNIVERSAL EXTRA DIMENSIONS

In this scenario, all SM particles are free to move in all dimensions, dubbed universal extra dimensions [10]. Consider the case with only one extra dimension. The momentum conservation in the fifth dimension, after compactification, becomes conservation in KK numbers. There may be some boundary terms arising from the fixed points that break the conservation of KK numbers into a \( \mathbb{Z}_2 \) parity, called KK parity. Odd parities are assigned to the KK states with an odd KK number. SM particles have even KK parity. The lightest KK state is often the first KK state of the hypercharge gauge boson \( \gamma^{(1)} \). The consequence of the KK parity is that this \( \gamma^{(1)} \) becomes stable and gives missing energy signal. Collider phenomenology is mainly the pair production of KK quarks and KK leptons:

\[ \gamma\gamma \rightarrow q_{(1)} q_{(1)}^*, \ \ell^{(1)}\ell^{-(1)}. \]

Each KK quark decays into a light quark and \( \gamma^{(1)} \) while each KK lepton decays into a lepton and \( \gamma^{(1)} \). Therefore, in the final state there are multi-jets or multi-leptons plus missing energy.
Because of the anomaly-type coupling, such as in QCD $\pi^0\gamma\gamma$, we can use $\gamma\gamma$ collisions to probe for any QCD-like $\pi^0$ resonances. Such resonances are often predicted in some strongly-interacting models, e.g., technicolor models \cite{11}. We use the Technicolor Straw Man model \cite{11} as illustration. The lightest techni-mesons are constructed solely from the lightest techni-fermion doublet ($T_U, T_D$), from which isorotplet $\rho_T^{0,\pm}$ and isosinglet $\omega_T^0, \pi_T^0$ can be formed. In particular, the neutral $\pi_T^0$ and $\pi_T'^0$ have an anomaly coupling, shown in Fig. 4:

$$\Gamma = N_{TC} V_{\gamma\gamma\pi} \frac{e^2}{8\pi^2 F_T} \epsilon_{\mu\nu\lambda\rho}\epsilon_{1\nu}^*\epsilon_{2\nu}^* p_{1\lambda} p_{2\rho}.$$ 

Preliminary calculation shows that the cross section is \cite{12}

$$\sigma = \int \frac{dx}{x} f_{\gamma/e}(x) f_{\gamma/e}(m_{\pi_T}^2/sx) N_{TC}^2 V_{\gamma\gamma\pi}^2 \frac{\alpha^2}{32\pi^2 F_T^2} \frac{m_{\pi_T}^2}{s} \sim O(1{\text{fb}}).$$

With the SM background coming only from box diagrams, this signal has a good chance to be observed.

In summary, I have described some interesting new physics that are quite unique to photon colliders. There are of course many other interesting physics that can be performed. For some reviews please refer to Refs. \cite{13}.

Acknowledgments

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