Neutral Pion-like Resonances at Photon Colliders

Outline

- What so unique about $\gamma\gamma$ collisions in probing new physics
- Highlights from large extra dimensions and Randall-Sundrum scenarios
- Techni-Pions of TC model
What so unique of $\gamma\gamma$ Collisions

- The SM $\gamma\gamma \rightarrow \gamma\gamma$ amplitude only goes through box diagrams, so highly suppressed.
- Any new physics that involves tree-level exchanges would be easily seen over the SM background.
- In particular, those with anomaly-type couplings to $\gamma\gamma$.
- Examples are low-scale gravity, the radion of RS model, techni-pions, ...
Low-scale gravity (ADD model)

Branes separated by

\[ \frac{1}{\mu_c} = R \]

Gravity only

Our World 3+1 dim.

Some hidden brane

The size of the extra dimensions can be as large as \( R \lesssim 1 \) mm.

\[ \mu_c \equiv R^{-1} \gtrsim 10^{-4} \text{ eV} \ll M_{EW} \]

\[ M_{P1}^2 \sim M_D^{n+2} R^n \quad (\text{Gauss}) \]
Light-by-light Scattering

ADD

\( G_{\mu\nu} \)

SM

\( t, W \)

\( G_{\mu\nu} \)
\( \gamma \gamma \rightarrow \gamma \gamma \)

(a) \( \sqrt{s_{\gamma \gamma}} \) (GeV)

- \( M_{\gamma}=4 \text{TeV}, n=2,4,6 \)
- \( M_{\gamma}=6 \text{TeV}, n=2,4,6 \)
- SM

(b) \( |\cos \theta_{\gamma}| \) (\( r \))

- \( M_{\gamma}=4 \text{ TeV}, n=2 \)
- SM

\( |\cos \theta_{\gamma}| \) < \( \cos(30^\circ) \)

\( \sqrt{s} = 0.5 \text{ TeV} \)

\( \sigma \) (pb)

\( d\sigma/d|\cos \theta_{\gamma}| \) (pb)
Randall Sundrum Model: Radion

The RS model has a 4D massless scalar, radion, about the background metric

\[ ds^2 = e^{-2k\phi T(x)} g_{\mu\nu}(x) dx^\mu dx^\nu - T^2(x)d\phi^2 \]

\(T(x)\) is the modulus field describing the distance between the two branes. A stabilization mechanism (GW) using a bulk scalar field to generate a potential.

The radion acquires a \(O(0.1 - 1\text{TeV})\) mass with a coupling strength \(1/\text{TeV}\).

**Interactions of the Radion:**

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

The radion coupling to a pair of gluons (photons) has a contribution from the trace anomaly.

\[ T^\mu_\mu (SM)_{\text{anom}} = \sum_a \frac{\beta_a(g_a)}{2g_a} F^\mu_\nu F^{\nu_\mu}_a. \]

where \( \beta_{\text{QCD}}/2g_s = -\left(\frac{\alpha_s}{8\pi}\right)b_{\text{QCD}} \) and \( b_{\text{QCD}} = 11 - 2n_f/3 \)

\[ \left( p_1 \cdot p_2 \cdot g_{\mu\nu} \right) \text{B} \left( p_1 \cdot p_2 \right) \]

where

\[ \text{B} = b_2 + b_Y - (2 + 3y_W + 3y_W(2 - y_W)f(y_W)) + \frac{8}{3} y_t (1 + (1 - y_t)f(y_t)), \]

\[ y_i = 4m_i^2/2p_1 \cdot p_2. \]
Higgs-Radion Mixing

Gauge and Poincare invariance do not forbid the mixing between the gravity scalar and the Higgs boson:

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

where \( R(g_{\text{vis}}) \) is the Ricci scalar on the visible brane.

* A nonzero \( \xi \) will induce some triple couplings

\[ h - \phi - \phi, \quad h_{\mu\nu}^{(n)} - h - \phi, \quad \phi - \phi - \phi, \quad h_{\mu\nu}^{(n)} - \phi - \phi \]
The corresponding analogs at $e^+ e^-$ and hadronic machines:

$$e^+ e^- \rightarrow G_{\mu \nu}^{(n)} \rightarrow h\phi; \quad pp \rightarrow G_{\mu \nu}^{(n)} \rightarrow h\phi$$

have been performed (Cheung, Kim, Song PRD03, PRD04)
Neutral Techni-Pions

Because of the anomaly type coupling (like $\pi^0$-$\gamma$-$\gamma$), we can use $\gamma\gamma$ collision to probe neutral-pion-like resonances.

Technicolor Straw Man model (TCSM, Lane 99):

- techni-isospin is a good symmetry
- the lightest techni-mesons are constructed solely from the lightest techni-fermion doublet $\langle T_U, T_D \rangle$. They form isotriplet, isosinglet:

  pseudoscalar: $\pi^0_T, \pi_T^\prime$, vector: $\rho_T^0, \omega_T^0$
Consider two models of technicolor

Rescaled QCD model:
- A simple rescaling by the $v/f_{\pi 0}$. $\pi_T^0$ couples to $\gamma\gamma$, $\gamma Z$, $ZZ$ only.

Low-scale technicolor model:
- It is a multi-scale technicolor models. Quark and lepton masses are generated by broken extended technicolor gauge interactions in the walking technicolor model.
- There are two types of techni-fermions. One set condense at high scale set by $v = 246$ GeV. One set condense at low scale set by $f_{\pi T} = v/\sqrt{N_D}$.
- Techni-pions will couple to normal quarks and leptons through Yukawa-type couplings.
  $$\pi_T^0 \rightarrow b\bar{b}, t\bar{t}$$
- $\pi_T^0$ couples to $\gamma\gamma$, $\gamma Z$, $ZZ$, $gg$, $b\bar{b}$. 
The Anomaly Vertex

The anomaly coupling to $\pi_T^0 - G_1 - G_2$:

$$
\mathcal{M} = N_{TC} A_{G_1 G_2} \frac{g_1 g_2}{2 \pi^2 f} \epsilon_\nu \epsilon_\lambda \epsilon^\lambda \epsilon^\nu \epsilon^{\lambda \alpha \beta} P_1 \alpha P_2 \beta ,
$$

with

$$
A_{G_1 G_2} = Tr[T^a (\{T_1, T_2\}_L + \{T_1, T_2\}_R)]
$$

$T_i$’s are the generators with the gauge boson $G_i$, and $T^a$ is the axial current associated with the techni-pion

$$
J^{\mu 5a} = \bar{\psi} \gamma^\mu \gamma^5 T^a \psi
$$
\[ A_{\gamma \gamma} = \text{Tr}(T^a Q^2) \quad \text{with} \quad Q = \begin{pmatrix} Q_u & 0 \\ 0 & Q_d \end{pmatrix}, \]

<table>
<thead>
<tr>
<th></th>
<th>(Q_u)</th>
<th>(Q_d)</th>
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<tbody>
<tr>
<td>rescaled</td>
<td>(2/3)</td>
<td>(-1/3)</td>
</tr>
<tr>
<td>low-scale</td>
<td>(4/3)</td>
<td>(1/3)</td>
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\[ \hat{\sigma}(\gamma\gamma \rightarrow \pi_T^0) = \frac{\pi m_{\pi_T}}{64} \left( N_{TC} A_{\gamma\gamma} \frac{e^2}{\pi^2 f_{\pi_T}} \right)^2 \delta^{(0)}(\sqrt{s} - m_{\pi_T}) \]

Fold with photon luminosity function:

\[ \sigma(\gamma\gamma \rightarrow \pi_T^0) = \frac{m_{\pi_T}^2}{2^6 s \pi^3} \left( \frac{N_{TC} A_{\gamma\gamma} e^2}{f_{\pi_T}} \right)^2 \int_{x_{min}}^{x_{max}} \frac{1}{x} F_{\gamma/e}(x) F_{\gamma/e}(\frac{m_{\pi_T}^2}{sx}) dx \]

where

\[ F_{\gamma/e}(x_i) = \frac{1}{D(\xi)} \left[ 1 - x_i + \frac{1}{1 - x_i} - \frac{4x_i}{\xi(1 - x_i)} + \frac{4x_i^2}{\xi^2(1 - x_i)^2} \right] \]
\( \pi_T^0 \) Decay

**Rescaled model:**

\[
\Gamma_{total} = \frac{1}{2^4 \pi m_{\pi T}} \left[ \frac{c^2 m_{\pi T}^4}{2^2} + \frac{c_1^2 (m_{\pi T}^2 - m_Z^2)^3}{(m_{\pi T}^2 + m_Z^2)} + c_2^2 (m_{\pi T}^2 - 4m_Z^2)^2 \right]
\]

\[
B(\pi_T^0 \rightarrow \gamma \gamma) = \frac{\Gamma_{\gamma \gamma}}{\Gamma_{total}}
\]

**Low-scale model:**

Additional contribution to the total width

\[
\Gamma(\pi_T^0 \rightarrow b\bar{b})_{low-scale} = \frac{1}{16\pi f_{\pi T}^2} N_b P_b C_{1b}^2 (m_b + m_b)^2
\]
$\pi^0_T$ Decay: $B(\pi^0_T \to \gamma\gamma)$

**Rescaled model**

**low-scale model**
\( \gamma\gamma \rightarrow \pi^0_T \rightarrow \gamma\gamma \) production

- \( \sqrt{s_{ee}} = 0.5 \) TeV
- \( \sqrt{s_{ee}} = 1 \) TeV
- \( \sqrt{s_{ee}} = 1.5 \) TeV
- \( \sqrt{s_{ee}} = 2 \) TeV
Summary

- Light-by-light scattering and $\gamma \gamma \rightarrow ZZ$ proceed via box diagrams in the SM.
- $\gamma \gamma \rightarrow \gamma \gamma$ is sensitive to the new physics that involves either tree-level couplings or anomaly-type couplings.
- Low scale gravity, RS radion are interesting examples.
- Neutral techni-pions of many technicolor models have anomalous couplings with photons. Photon colliders are unique in probing these kind of resonances.