Some Physics Beyond the SM at $\gamma\gamma$ collisions

LCWS 2004

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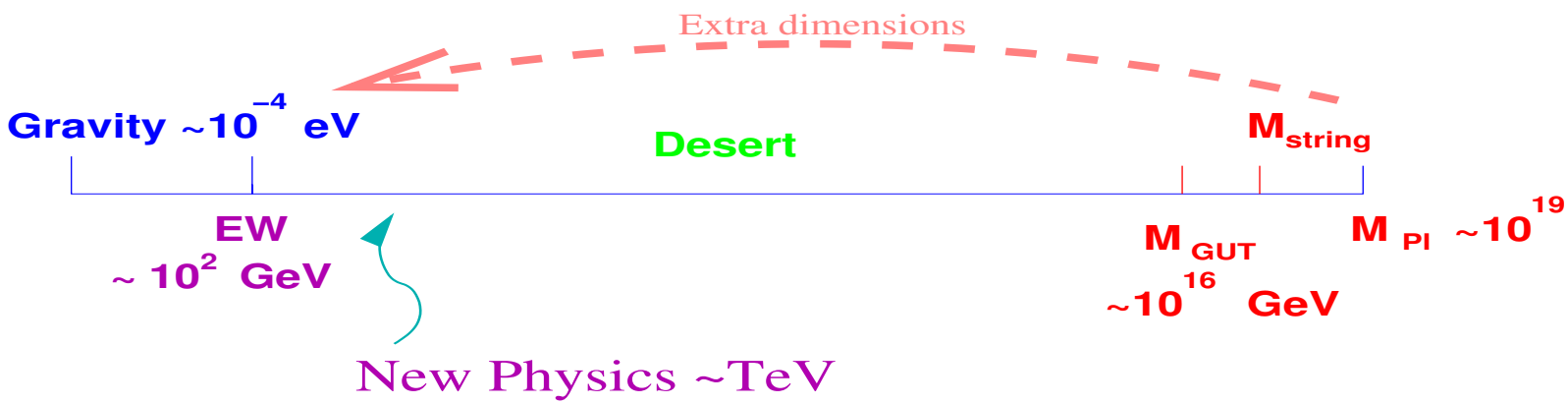
Outline

- Large Extra Dimensions (ADD model)
- Randall-Sundrum Model, and radion
- Universal extra dimension
- Techni-Pions

Motivation for Beyond the SM

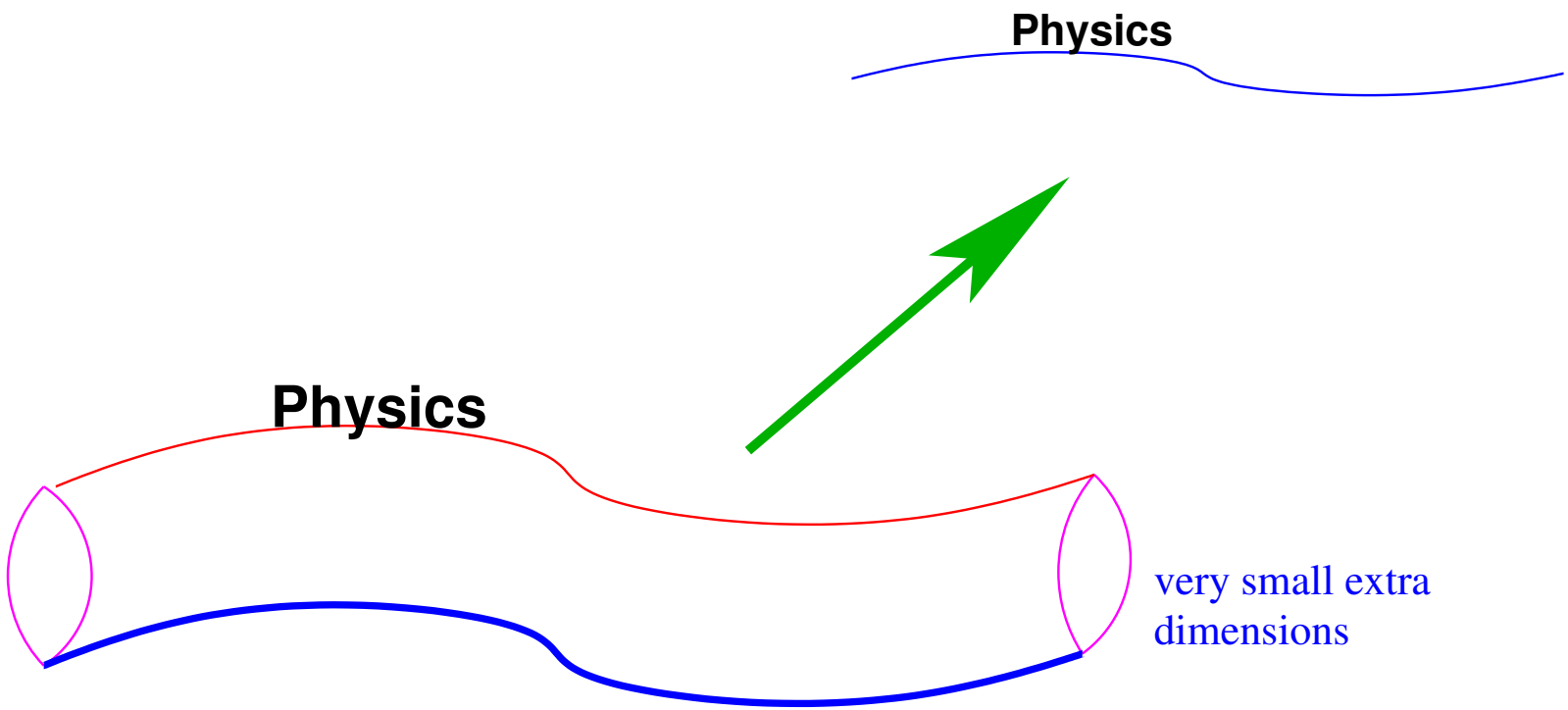
- Large Hierarchy: $M_{\text{Planck}} \gg M_W$.
  New physics needed to stabilize the hierarchy, e.g., Supersymmetry.
  Recent developments in string theories and extra dimensions transform the hierarchy into geometry stabilization.
- Other observational hints: dark matter, dark energy, inflation, ν mass, ...

Extra Dimensions

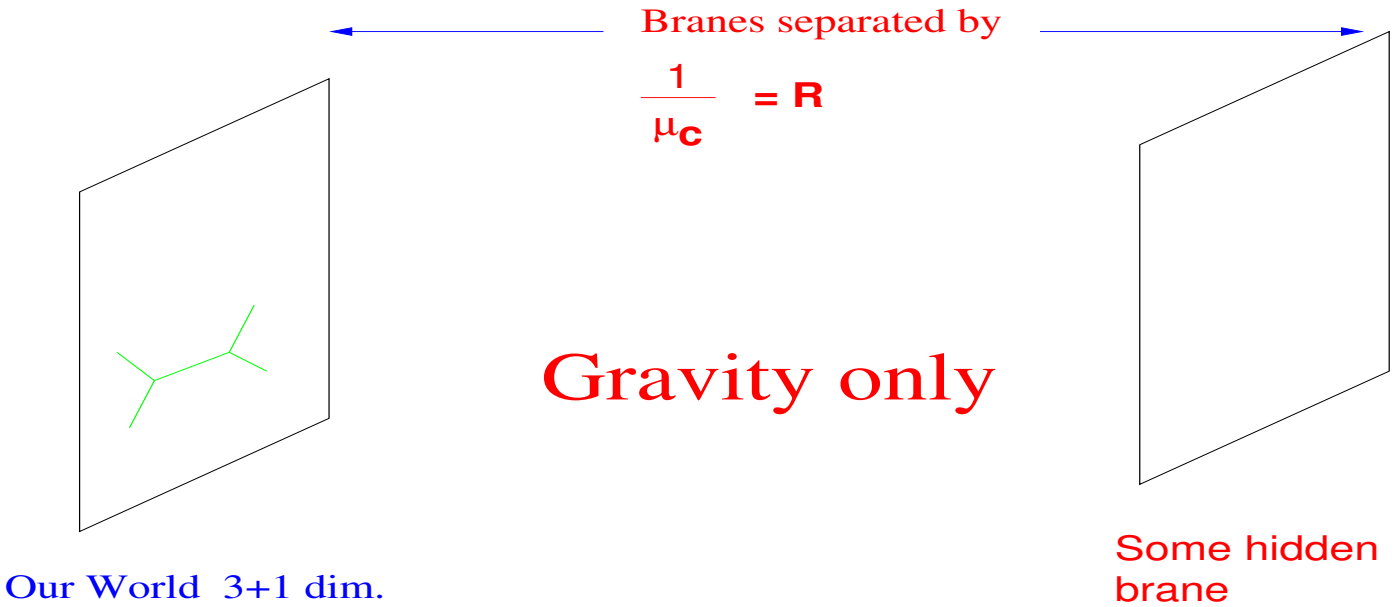


- Huge difference between $M_{\rm EW}$ and $M_{\rm Pl}$.
- New physics at $\sim$ TeV, e.g. SUSY.
- New ideas using extra dimensions can bring $M_{\rm Pl}$ down to TeV.

Why we do not see extra dimensions



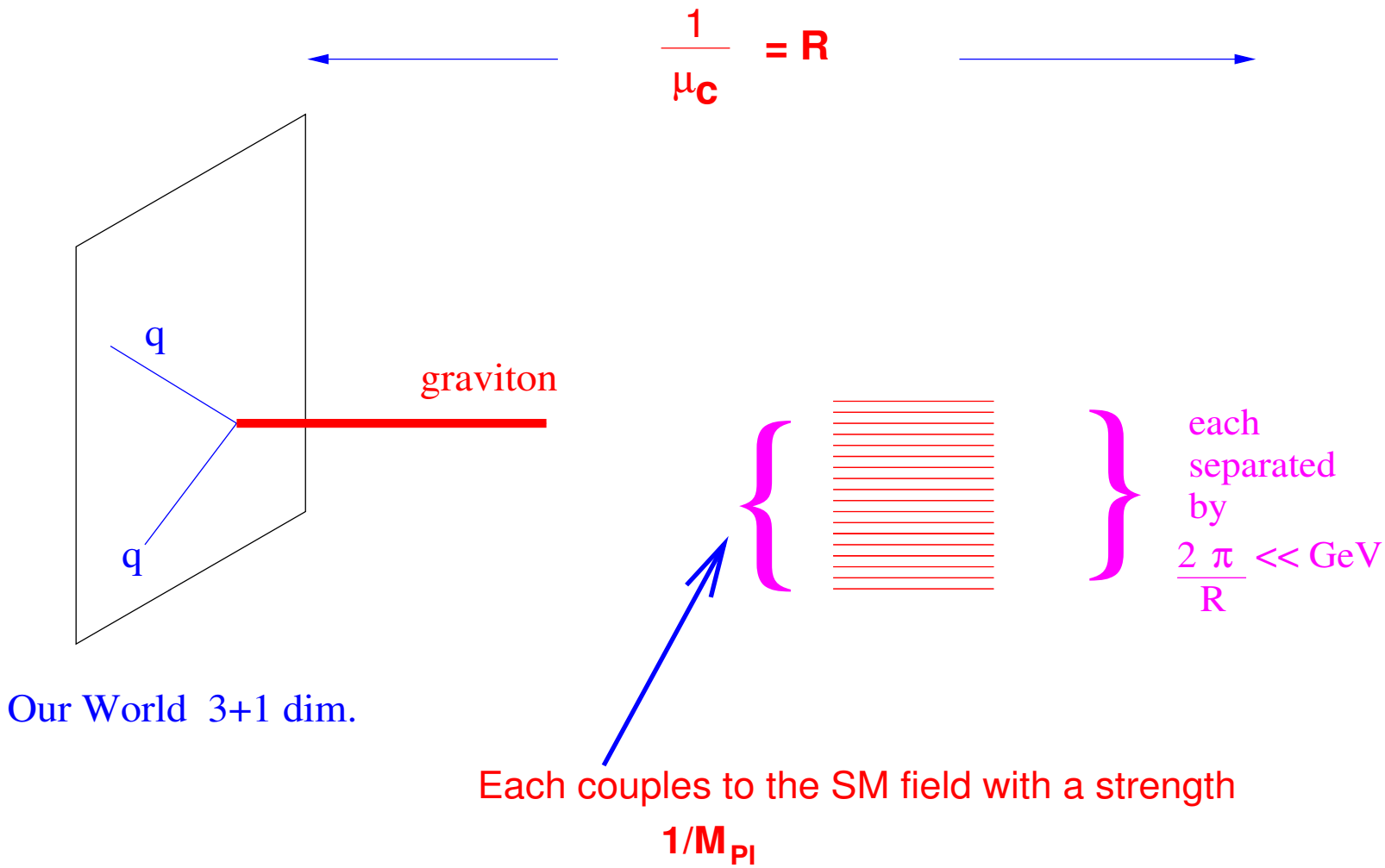
ADD model



Proposed by Arkani et al. the size of the extra dimensions can be as large as $R \lesssim 1$ mm.

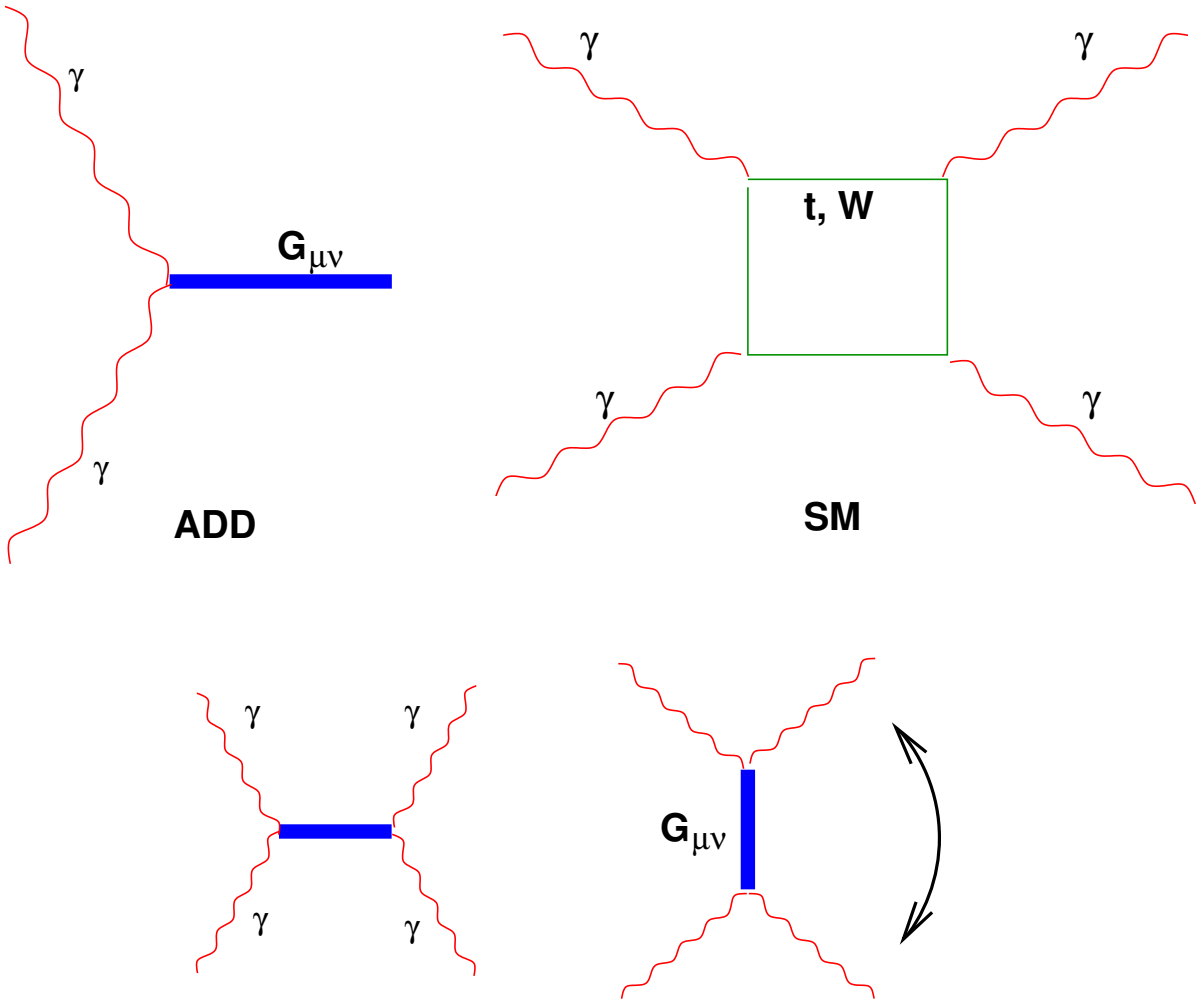
$$\mu_c \equiv R^{-1} \gtrsim 10^{-4}\ \mathrm{eV} \ll M_{\mathrm{EW}}$$

$$M_{\mathrm{Pl}}^2 \sim M_D^{n+2}\ R^n \qquad \text{(Gauss)}$$



- Effectively, interaction $\sim \frac{1}{M_D} = (1\text{TeV})^{-1}$.

Light-by-light Scattering



Light-by-light Scattering

Via s-, t-, u-channel graviton exchanges:

$$\overline{\sum}|\mathcal{M}|^2 = \frac{\kappa^4}{8}\,|D(s)|^2\,(s^4+t^4+u^4)\,,$$

where

$$\kappa = \sqrt{16\pi G_N}, \qquad D(s) = \sum_k \frac{i}{s - m_k^2 + i\epsilon}$$

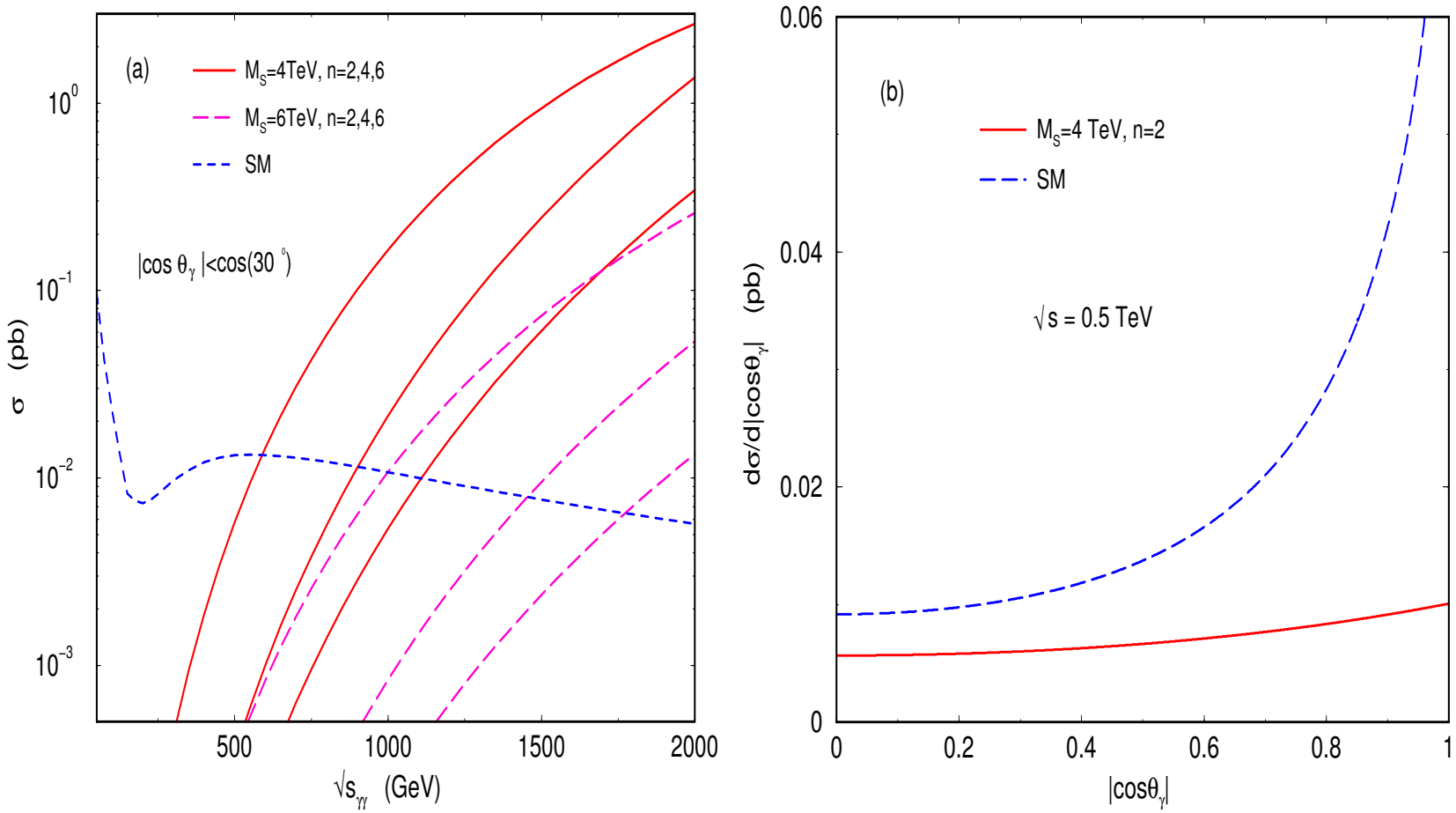
The angular distribution is

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

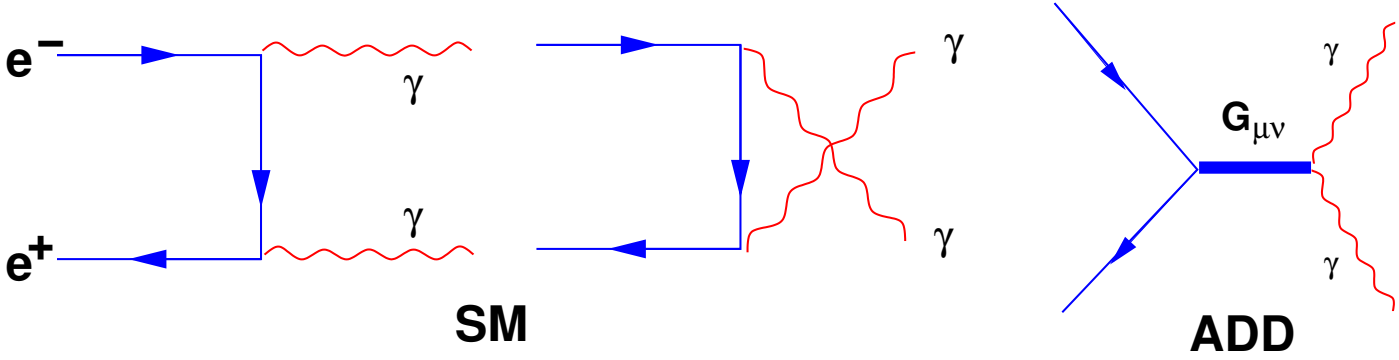
where

$$\mathcal{F} = \begin{cases} \log(M_S^2/s) & \text{for } n=2 \\ 2/(n-2) & \text{for } n>2 \end{cases}$$

$\gamma\gamma \to \gamma\gamma$

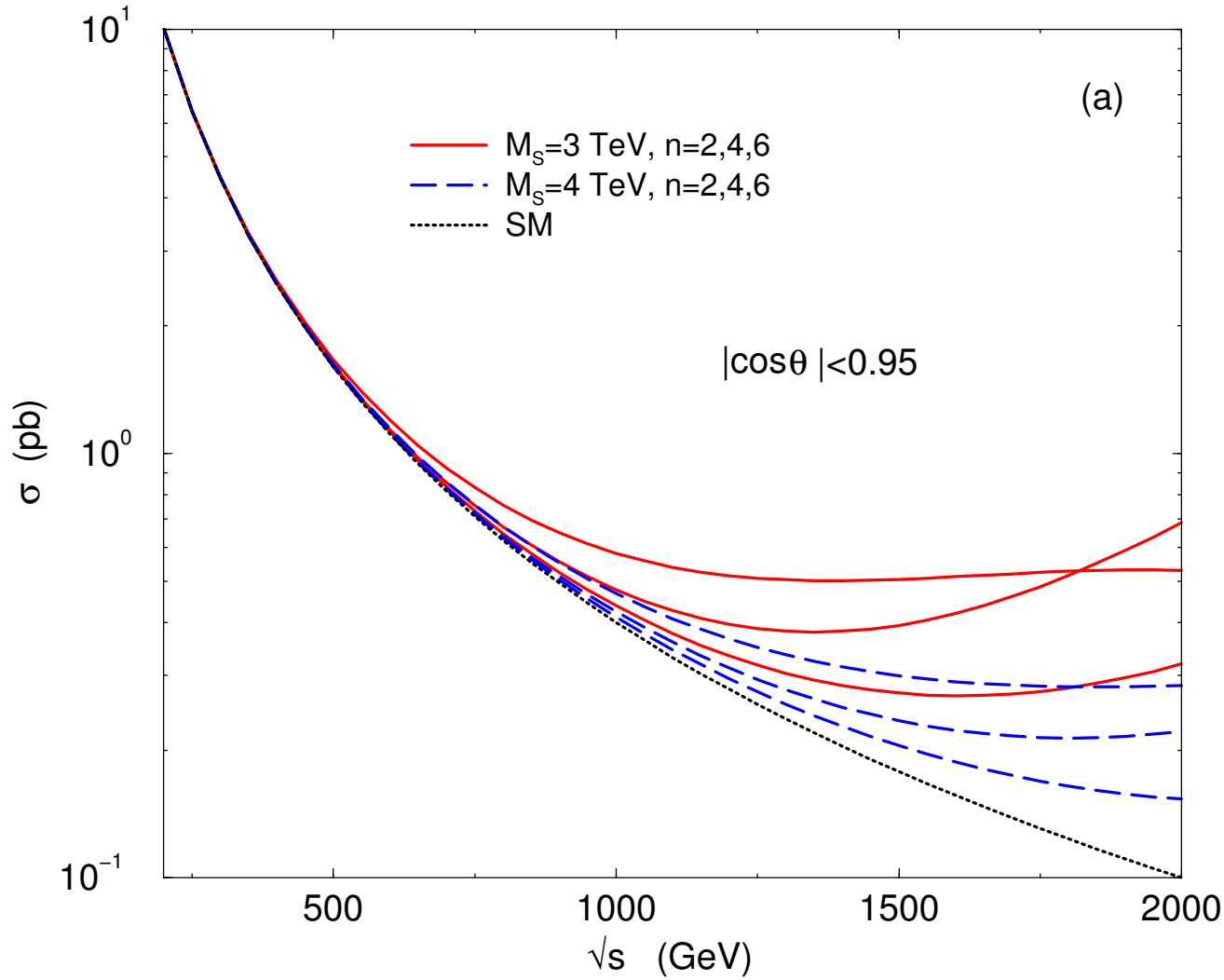


Compare with $e^+e^- \to \gamma\gamma$

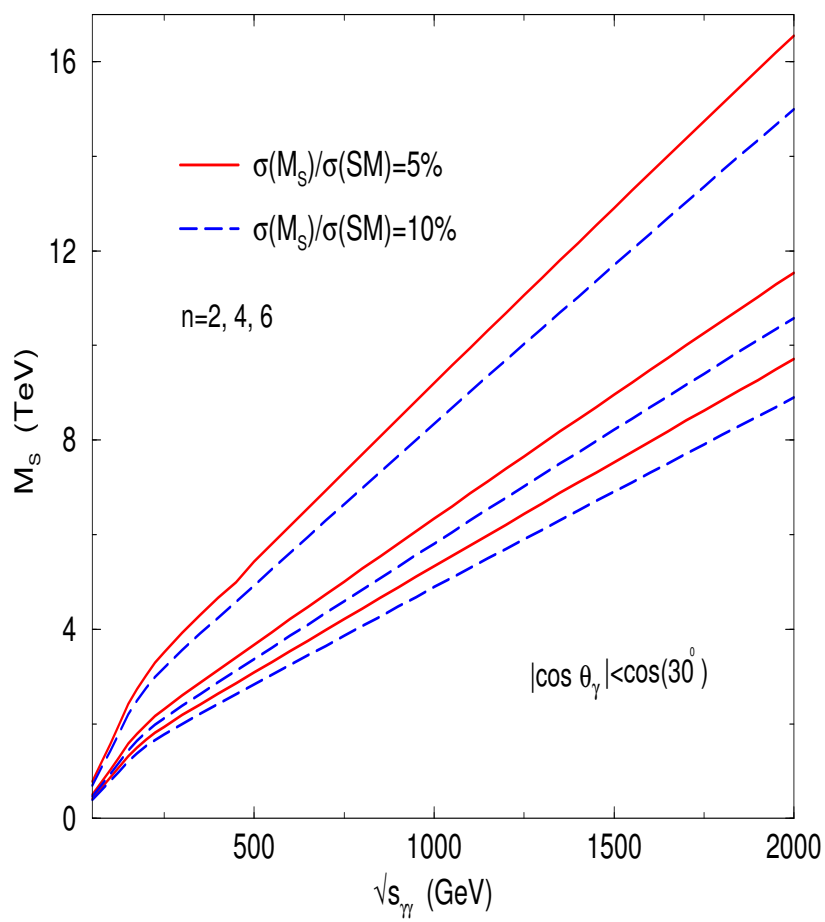


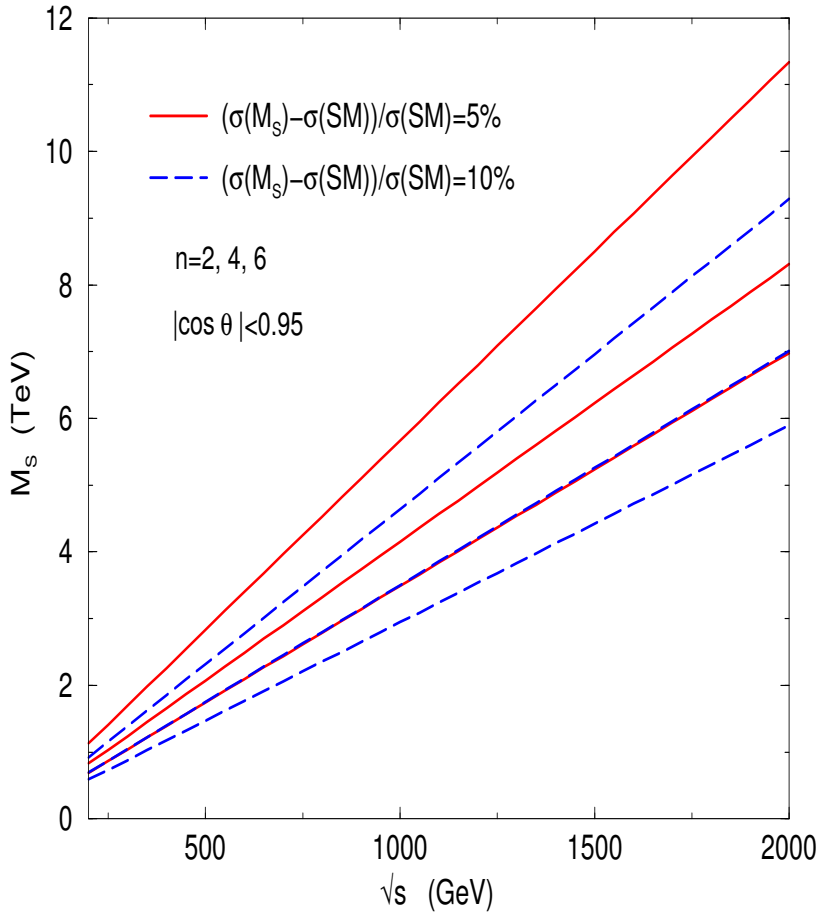
$$\frac{d\sigma(e^+e^- \to \gamma\gamma)}{dz} = \frac{2\pi}{s}\left(\alpha^2 \frac{1+z^2}{1-z^2} + \frac{\alpha}{4}\frac{s^2}{M_S^4}\mathcal{F}\left(1+z^2\right) + \frac{1}{64}\frac{s^4}{M_S^8}\mathcal{F}^2\left(1-z^4\right)\right)$$

Compare with $e^+e^- \to \gamma\gamma$

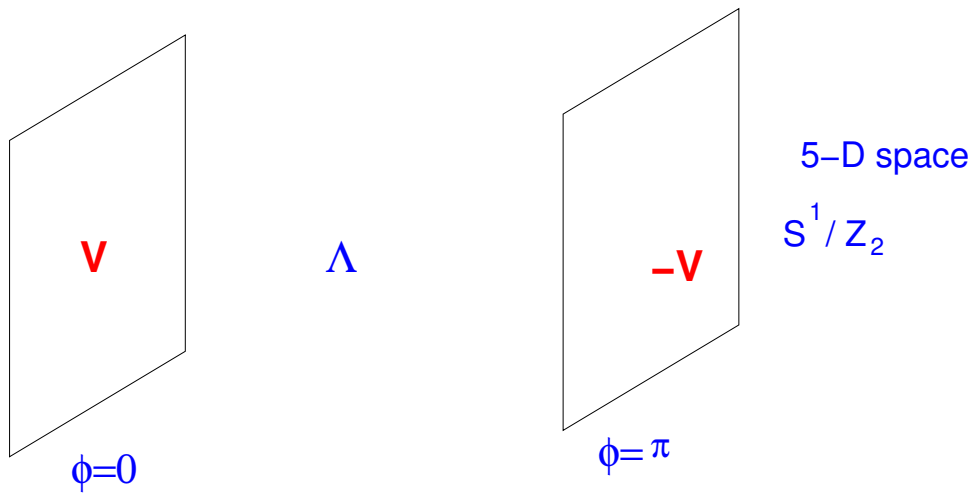


Compare with $e^+e^- \to \gamma\gamma$





Randall Sundrum Model



With a nonfactorizable metric

$$ds^2 = e^{-2kr_c|\phi|}\,\eta_{\mu\nu}dx^\mu\,dx^\nu - r_c^2 d\phi^2$$

$\overline{M_5}$ is the 5D fundamental Planck scale, k: curvature of the AdS space.

$$\overline{M_{\rm Pl}}^2 = \overline{M_5}/k$$

The scale $\Lambda_\pi \equiv \overline{M_{\rm Pl}}\,e^{-kr_c\pi}$ describes the scale of physical processes on the TeV brane.

The weak scale can be generated from the Planck scale for kr_c around 12.

RS Gravitons

can be obtained by fluctuation of the metric $G_{\mu\nu}$.

After compactification, the KK of the graviton has the spectrum

$$m_n = x_n \, k \, e^{-2r_c\pi} = x_n \, \Lambda_\pi \frac{k}{\overline{M}_{\rm Pl}}$$

The interactions are given by

$$\mathcal{L} = -\frac{1}{\overline{M}_{\rm Pl}} T^{\mu\nu} h^{(0)}_{\mu\nu} - \frac{1}{\Lambda_\pi} T^{\mu\nu}(x) \sum_{n=1}^{\infty} h^{(n)}_{\mu\nu}(x)$$

The 0th mode decouples, but others have a coupling strength of 1/TeV.

- Signatures indicate discrete unevenly spaced resonances.
- Laser back scattering provides a continuous spectrum, good for seeing multiple RS graviton resonances.
- Again, the background is loop suppressed.

RS Radion

The RS model also 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 $O(0.1 - 1TeV)$ mass with a coupling strength 1/TeV.

Interactions of the Radion:

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

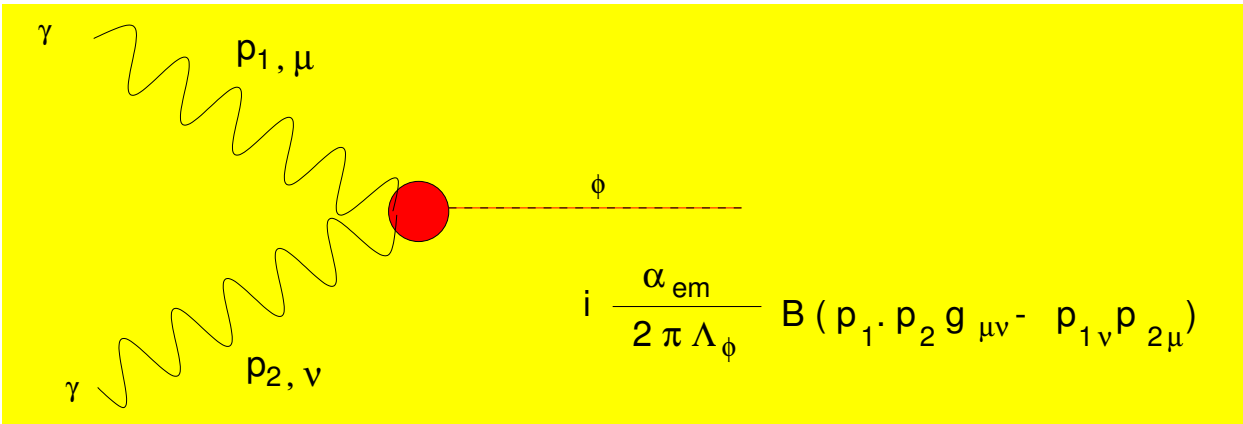
where $\Lambda_\phi = \langle\phi\rangle$ is of order TeV.

RS Radion

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

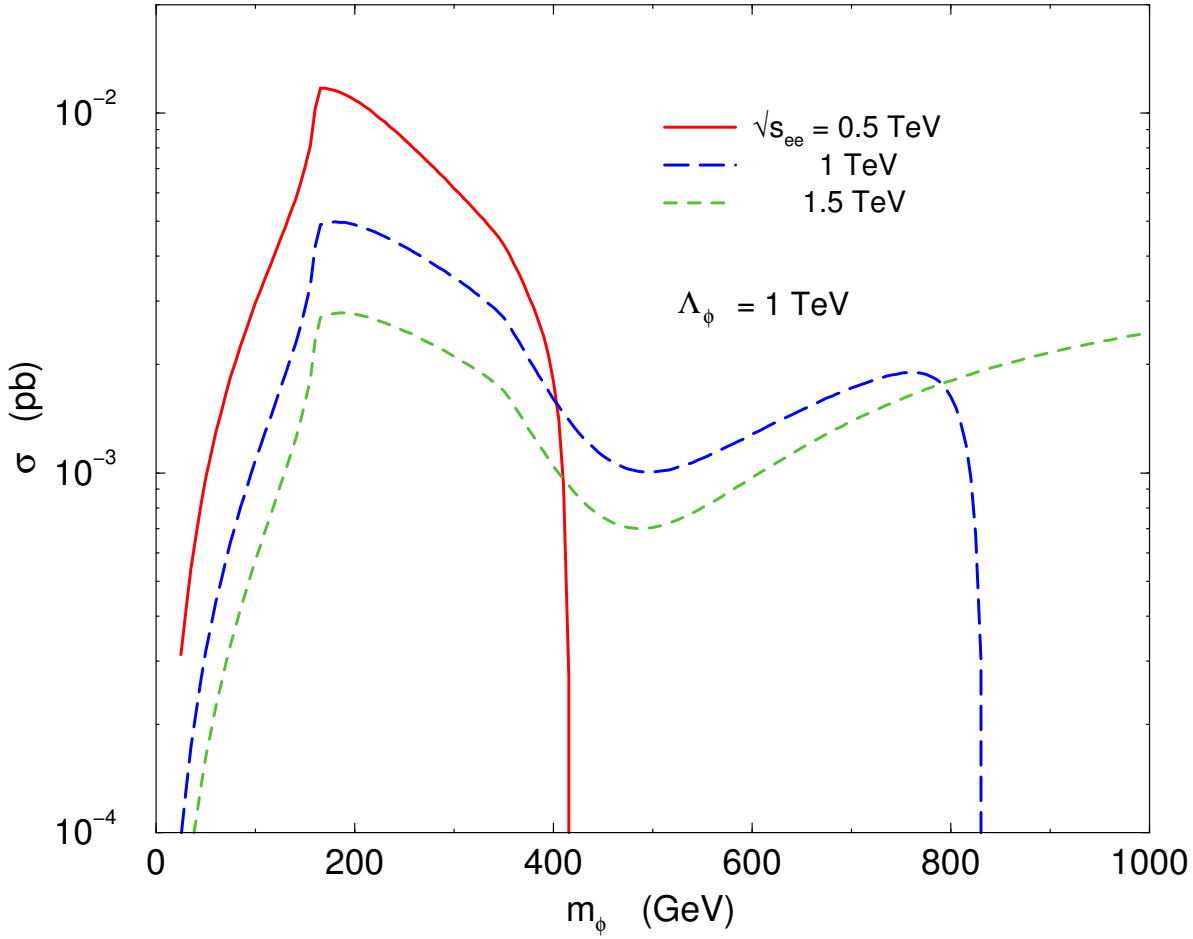
$$T^{\mu}_{\mu}(\mathrm{SM})^{\mathrm{anom}} = \sum_{a} \frac{\beta_a(g_a)}{2g_a} F^a_{\mu\nu} F^{a\mu\nu} \ .$$

where $\beta_{\mathrm{QCD}}/2g_s = -(\alpha_s/8\pi) b_{\mathrm{QCD}}$ and $b_{\mathrm{QCD}} = 11 - 2n_f/3$



where
$B = b_2 + b_Y - (2 + 3y_W + 3y_W(2 - y_W) f(y_W)) + \frac{8}{3} y_t (1 + (1 - y_t) f(y_t)), \ y_i = 4m_i^2/2p_1 \cdot p_2.$

Randall Sundrum Radion



Higgs-Radion Mixing

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

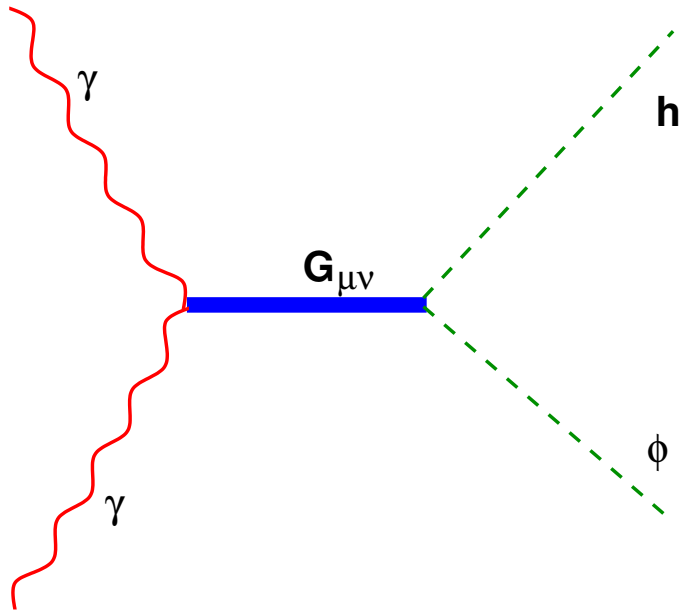
$$S_\xi = \xi \int d^4x \sqrt{g_{\rm vis}} R(g_{\rm vis}) \hat{H}^\dagger \hat{H} \ ,$$

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

$\star$ A nonzero ξ will induce some triple couplings

$$h\text{-}\phi\text{-}\phi, \quad h^{(n)}_{\mu\nu}\text{-}h\text{-}\phi, \quad \phi\text{-}\phi\text{-}\phi, \quad h^{(n)}_{\mu\nu}\text{-}\phi\text{-}\phi$$

$$\gamma\gamma \to G_{\mu\nu}^{(n)} \to h\phi$$



The corresponding analogs at e^+e^- and hadronic machines:

$$e^+e^- \to G_{\mu\nu}^{(n)} \to h\phi, \qquad pp \to G_{\mu\nu}^{(n)} \to h\phi$$

have been performed (Cheung, Kim, Song 03, 03)

Universal Extra Dimensions

All SM particles are free to move in the extra dimensions. Translational invariance

$\Rightarrow$ Conservation of KK numbers (momentum)

Boundary breaks the momentum conservation down to a Z_2 parity,

Conservation of KK parity

Radiation corrections and the boundary terms lift the mass degeneracy of KK states.

B^1, the first KK state of the hypercharge gauge boson, is the lightest KK particle

Appelquist, Cheng, Dobrescu

Phenomenology at $\gamma\gamma$ Collisions

Production of KK quarks and KK leptons.

$$\gamma\gamma \to q^{(1)}\bar{q}^{(1)}, \quad \ell^{+(1)}\ell^{-(1)}$$

Each $q^{(1)}$ decays into jets and $\gamma^{(1)}$,

$$\Rightarrow \text{jets} + \not{E}_T$$

Each $\ell^{(1)}$ decays into lepton plus $\gamma^{(1)}$,

$$\Rightarrow \text{multi-leptons} + \not{E}_T$$

Techni-Pion π_T

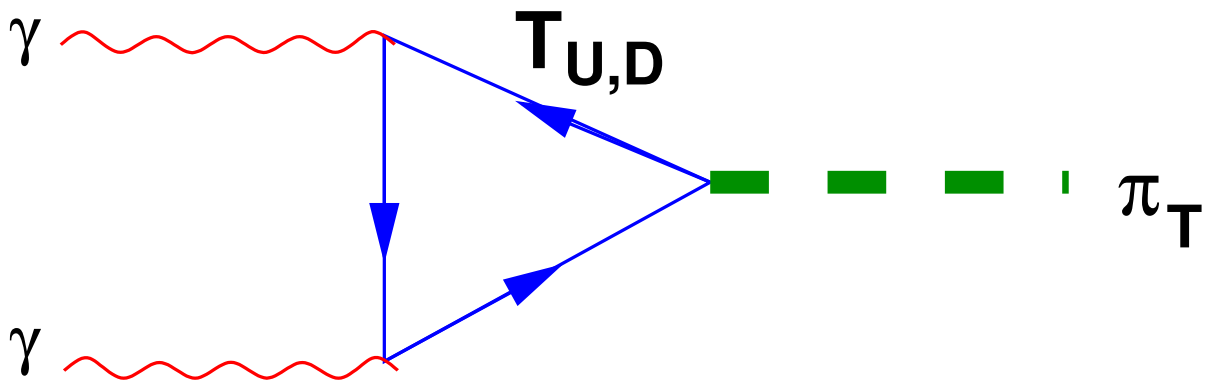
Because of the anomaly type coupling (like $\pi - \gamma - \gamma$), we can use $\gamma\gamma$ collision to probe the QCD pion-like resonances.

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 (T_U, T_D). They form isotriplet, isosinglet:

pseudoscalar: $\pi_T^{0,\pm}$, $\pi_T^{\prime 0}$, vector: $\rho_T^{0,\pm}$, ω_T^0

$\gamma\gamma \to \pi_T$



$$\Gamma = N_{TC}\mathcal{V}_{\gamma\gamma\pi}\frac{e^2}{8\pi^2 F_T}\,\epsilon^{\mu\nu\lambda\rho}\epsilon^*_{1\mu}\epsilon^*_{2\nu}p_{1\lambda}p_{2\rho}$$

where

$$\mathcal{V}_{\gamma\gamma\pi} = 2\,\mathrm{Tr}[T^a Q^2]$$

The integrated cross section is

$$\sigma = \int \frac{dx}{x}\, f_{\gamma/e}(x) f_{\gamma/e}(m^2_{\pi_T}/sx)\, N^2_{TC} V^2_{\gamma\gamma\pi}\frac{\alpha^2}{32\pi F_T^2}\,\frac{m^2_{\pi_T}}{s} \sim O(1\mathrm{fb})$$

Summary

- Light-by-light scattering and $\gamma\gamma \to ZZ$ proceed via box diagrams in the SM.
- Large extra dimenions: continuous spectrum of graviton exchanges.
- Randall Sundrum model, discrete unevenly spaced graviton resonances.
- RS radion has an anomalous coupling to photons, giving rise to large production.
- $\gamma\gamma \to G^{(n)}_{\mu\nu} \to h\phi$ can test for the Higgs-radion mixing.
- Universal extra dimenion model: KK states of quarks and leptons give rise to multijet or multi-lepton plus missing energies.
- Technicolor models: anomaly-type coupling of techni-pion to photons.