Large Extra Dimensions Effects in Higgs Production via Vector Boson Fusion

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Summary

- Q-Gravity in Large Extra Dimensions
- Virtual KK-Gravitons exchanges
- Effects in Higgs boson production via Vector Boson Fusion
- Conclusions

Q-Gravity in Large Extradimensions

Arkani-Hamed, Dimopoulos, Dvali ('98)
A new approach to the hierarchy problem

Λ_{EW} is a fundamental scale and M_{pl} is a derived effect

This requires

- **Compact Extra Spatial Dimensions**
- **Confinement of matter on subspaces**

The idea: Matter fields confined in the usual 4 dimensional space, Gravity propagating in $\mathrm{D} = 4 + \delta$ space

Weakness of gravity: Due to large compact spatial dimensions

$$\boxed{\mathrm{G}_{\mathrm{N}} = \frac{\mathrm{G}_{\mathrm{N}}^{\mathrm{D}}}{\mathrm{V}_{\mathrm{D}-4}}}$$

Plank masses

$$\boxed{G_N \sim \frac{1}{M_{\rm pl}^2}} \qquad \boxed{G_N^D \sim \frac{1}{M_D^{D-2}}}$$

$$\boxed{\mathbf{M}_{\rm pl} = \frac{1}{\sqrt{8\pi}}\mathbf{M}_{\mathbf{D}}\,(\mathbf{RM}_{\mathbf{D}})^{\frac{D-4}{2}}}$$

$\mathbf{M}_{\mathbf{D}} \simeq 1$ TeV $\quad \Rightarrow \quad \boxed{R \simeq 10^{\frac{30}{\delta}-17}\ \text{cm}}$

Tests on Newton Law $\Rightarrow \boxed{\delta \geq \mathbf{2}}$

Gauge invariant spectrum

- **Massive Graviton**

$$\boxed{\mathbf{L}_{\mathbf{int}}(\mathbf{x}) \sim \frac{\mathbf{1}}{\mathbf{M}_{\rm pl}}\Sigma_{\mathbf{n}}\,\mathbf{G}_{\mu\nu}^{(\mathbf{n})}(\mathbf{x})\mathbf{T}^{\mu\nu}(\mathbf{x})}$$

- **Massive Graviscalar**

$$\boxed{\mathbf{L}_{\mathbf{int}}(\mathbf{x}) \sim \frac{\mathbf{1}}{\mathbf{M}_{\rm pl}}\Sigma_{\mathbf{n}}\,\mathbf{S}^{(\mathbf{n})}(\mathbf{x})\mathbf{T}^{\mu}_{\mu}(\mathbf{x})}$$

Masses of KK excitations $\boxed{\mathrm{M}_{\mathrm{n}}^2 \sim \frac{n^2}{R^2}}$

Inclusive production of KK Gravitons

- Mass splitting

$$\boxed{\mathbf{\Delta m \simeq \frac{1}{R} = M_D \left(\frac{M_D}{M_{pl}}\right)^{2/\delta}}}$$

$\Delta m = 20\text{KeV} \qquad (\delta = 4)$

$\Delta m = 7\text{MeV} \qquad (\delta = 6)$

- For small $\delta \le 6$:

  Large number of accessible KK modes.

  $\mathbf{\sum_n \longrightarrow \int dN}$

$$dN = A_{\delta-1} \left(\frac{\bar{M}_{Pl}^2}{M_D^{2+\delta}}\right) m_G^{\delta-1} dm_G$$

  $A_{\delta-1}$ area of δ-sphere, m_G graviton mass

- Inclusive production of KK Gravitons

$$\boxed{\mathbf{(E/M_{pl})^2}} \quad \Rightarrow \quad \boxed{\mathbf{(E/M_D)^{2+\delta}}}$$

Experimental Bounds on M_D

$\boxed{e^+e^- \to \gamma + G}$ G detected as missing energy

- **LEP200**, with $\mathcal{L} = 4 \times 500$ fb^{-1}

  $\boxed{\delta = 2 \qquad M_D > 1.3 \text{ TeV}}$

- e^+e^- **colliders** ($\sqrt{s}$=1 TeV), with $\mathcal{L}$=200 fb^{-1}

  $\boxed{\delta = 2 \qquad M_D > 4.1 \text{ TeV}}$

- **LHC at CERN**, with $\mathcal{L} = 100$ fb^{-1}

  $\boxed{\delta = 2 \qquad M_D > 8.5 \text{ TeV}}$ $(\sigma_{\text{Signal}} > 5\sqrt{\sigma_B \mathcal{L}}/\mathcal{L})$

From Astrophysics (Low energy modes)

- **SuperNova SN1987A collapse**

  $\boxed{M_D > 30 \text{ TeV } (\delta = 2)}$

- **Cosmic γ-Rays**

  $G \to \gamma\gamma \qquad \tau \simeq 3 \times 10^9 \text{yrs} \left(\frac{100\text{MeV}}{m_G}\right)^3$

  $\boxed{M_D > 110 \text{ TeV } (\delta = 2)}$

Virtual KK Gravitons exchange

- The KK Gravitons exchange induces local dim. 8 operators $(T_{\mu\nu}T^{\mu\nu})$:
  $e^-e^+ \to f\bar{f}$, $e^-e^+ \to \gamma\gamma$, $W^+W^- \to W^+W^-$, etc.

- Real part of amplitude $\mathbf{Re}[\mathbf{A}]$ is divergent.
  Predictivity in terms of M_D is lost.

- Imaginary part $\mathbf{Im}[\mathbf{A}]$ is finite (due to branch-cut singularity of real gravitons emission)

- Resonant SM processes can have interference with $\mathbf{Im}[\mathbf{A}]$ of the graviton exchange
  Finite result predicted in terms of M_D.

- Virtual Graviton exchanges at the Z-pole in large Extra Dimensions
  A. Datta, E.G, and B. Mele, PLB 552 (2003) 237

Scattering amplitude (s-channel)

$$\mathcal{A} = \frac{1}{\bar{M}_P^2} \sum_n \left\{ T_{\mu\nu} \frac{P^{\mu\nu\alpha\beta}}{s - m_{G_n}^2} T_{\alpha\beta} + \frac{1}{3} \left(\frac{\delta - 1}{\delta + 2} \right) \frac{T_\mu^\mu T_\nu^\nu}{s - m_{S_n}^2} \right\}$$

Graviton projector (unitary gauge)

$$P^{\mu\nu\alpha\beta} = \frac{1}{2} \left(\eta^{\mu\alpha}\eta^{\nu\beta} + \eta^{\mu\beta}\eta^{\nu\alpha} \right) - \frac{1}{3}\eta^{\mu\nu}\eta^{\alpha\beta} + \dots$$

$T_{\mu\nu}$ does not depend on n $\rightarrow$ Factorization

$$\boxed{\mathcal{A} = \mathcal{S}(\mathbf{s}) \left(\mathbf{T}_{\mu\nu}\mathbf{T}^{\mu\nu} - \frac{1}{\delta + 2} \left(\mathbf{T}_\mu^\mu \right)^2 \right)}$$

$$\boxed{\mathcal{S}(\mathbf{s}) = \frac{1}{\bar{\mathbf{M}}_\mathbf{P}^2} \sum\nolimits_\mathbf{n} \frac{1}{\mathbf{s} - \mathbf{m}_\mathbf{n}^2}} \qquad \sum\nolimits_n \rightarrow \int$$

$$\mathcal{S}(\mathbf{s}) = \frac{1}{M_D^{2+\delta}} \int \mathbf{d}^\delta \mathbf{q}_\mathbf{T} \frac{1}{\mathbf{s} - \mathbf{q}_\mathbf{T}^2} = \frac{\pi^{\frac{\delta}{2}}}{M_D^4} \mathbf{\Gamma}(\mathbf{1} - \frac{\delta}{2}) \left(-\frac{s}{M_D^2} \right)^{\frac{\delta}{2} - \mathbf{1}}$$

- Real part is divergent
- **Imaginary part is finite**

$$\boxed{\mathbf{Im}[\mathcal{S}(\mathbf{s})] = \frac{A_{\delta-1}}{2} \frac{\mathbf{s}^{\frac{\delta-2}{2}}}{\mathbf{M}_\mathbf{D}^{2+\delta}}}$$

Gravitational interference at Z pole

A. Datta, E.G, and B. Mele, PLB 552 (2003) 237

$$\frac{d\sigma_f}{d\cos\theta} = \frac{9\pi}{2M_Z^2}\frac{\Gamma_{e^+e^-}\Gamma_{f\bar{f}}}{\Gamma_Z^2} S_f(\cos\theta)$$

$$\boxed{\mathbf{S_f(x) = 1 + x^2 - \Delta_1\left(1 - 3x^2\right) + 2A_eA_f\left(x + \Delta_2 x^3\right)}}$$

$$\Delta_1 = R_\delta \frac{A_e A_f}{g_V^e g_V^f}, \qquad \Delta_2 = \frac{R_\delta}{g_A^e g_A^f},$$

$$R_\delta = \frac{\pi S_{\delta-1}}{32\sqrt{2} G_F M_Z^2}\left(\frac{\Gamma_Z}{M_Z}\right)\left(\frac{M_Z}{M_D}\right)^{2+\delta}$$

- **New contribution:** **vanishes** when integrated over the full range of $\cos\theta = (-1, 1)$

- $\delta = 2$, $M_D = 1$ **TeV** $\Rightarrow \Delta_{1,2} \simeq \mathcal{O}(10^{-4})$ **too tiny for present EXP. sensititvity**

Virtual KK Gravitons in Higgs production

A. Datta, E.G, and B.Mele, hep-ph/0303259

Light Higgs

- **Hadron Colliders**: $\boxed{gg \to H \to \gamma\gamma}$ **(1-loop)^2**

- Interference with $\boxed{Im[A(\ gg \to G, S \to \gamma\gamma\ )]}$

- Quite small effect, being coupled to the Trace$[T^\mu_\mu]$

  For massless final states $\boxed{T^\mu_\mu \propto \mathcal{O}(\alpha_S, \alpha_e)}$ gravitational anomalies.

Heavy Higgs

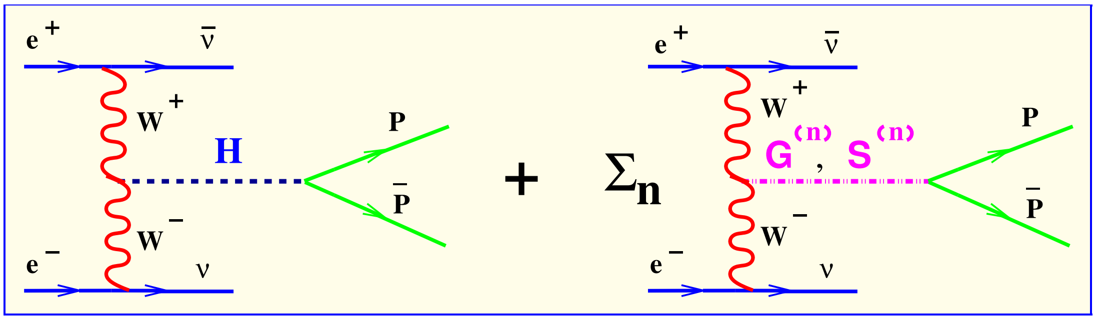
- e^+e^- **Colliders**: $\boxed{WW \to H \to WW}$ **Tree!**

- Large interference $\boxed{Im[A(WW \to G, S \to WW)]}$

  since $T^\mu_\mu \propto M_W^2$

- $\mu^+\mu^-$ **Colliders**: $\boxed{\mu^+\mu^- \to H \to (WW),\ (\bar{t}t)}$

Vector boson fusion in Higgs production



$P = W, Z, t$

$\boxed{\mathbf{WW \to H \to P\bar{P}}} + \sum_n \boxed{\mathbf{WW \to G^{(n)}, S^{(n)} \to P\bar{P}}}$

SM + Interf. with KK Gravitons exchange

$$\boxed{\frac{d\sigma_\lambda^P}{d\cos\theta} = \frac{\bar{\sigma}_\lambda^P}{2}\left\{1 + \Delta_0^P + \Delta_{2,\lambda}^P\,(1 - 3\cos^2\theta)\right\}}$$

$(x = \cos\theta)$ Δ_0^P = Graviscalars $\Delta_{2,\lambda}^P$ = Gravitons

$\lambda = T, L$ are the W polarizations

- **SM cross section**

$$\bar{\sigma}_\lambda^P = \frac{1}{16\pi\hat{s}}\,\frac{g^4 m_W^4 \xi_P}{(\hat{s} - m_H^2)^2 + m_H^2\Gamma_H^2}\sqrt{\frac{\hat{s} - 4m_P^2}{\hat{s} - 4m_W^2}}\,\rho_\lambda^P\left(\frac{\hat{s}}{m_W^2}\right)$$

At Higgs mass peak $\sqrt{\hat{s}} = m_H$

$$\mathbf{\Delta_0^P = R_\delta \, c_P \left(\frac{\delta - 1}{\delta + 2}\right)}$$

$$\mathbf{\Delta_{2,\lambda}^P = R_\delta \, f_\lambda^P \left(\frac{m_H^2}{m_W^2}\right)}$$

$c_W = \frac{4}{3} \qquad c_Z = \frac{2}{3} \qquad c_t = \frac{4}{3}$

$$\mathbf{R_\delta \sim \frac{A_{\delta-1}}{G_F M_D^2} \left(\frac{m_H}{M_D}\right)^\delta \left(\frac{\Gamma_H}{m_H}\right)}$$

$\mathbf{W_\lambda W_\lambda \to H \to WW} \qquad (\lambda = L, T)$

$m_H(GeV)$	$\Gamma_H(GeV)$	$\Delta^W_{2,T}$	$\Delta^W_{2,L}$	Δ^W_0
300	8.5	6.7×10^{-4}	-5.1×10^{-4}	2.6×10^{-4}
500	67.5	7.7×10^{-3}	-4.4×10^{-3}	3.3×10^{-3}
800	308.7	5.2×10^{-2}	-2.7×10^{-2}	2.4×10^{-2}

$\mathbf{W_\lambda W_\lambda \to H \to t\bar{t}}$

$m_H(GeV)$	$\Gamma_H(GeV)$	$\Delta^t_{2,T}$	$\Delta^t_{2,L}$	Δ^t_0
400	28.8	-4.5×10^{-3}	2.7×10^{-3}	1.1×10^{-3}
500	67.5	-1.3×10^{-2}	7.8×10^{-3}	3.3×10^{-3}
800	308.7	-9.7×10^{-2}	5.0×10^{-2}	2.4×10^{-2}

$e^+e^-(WW) \to \nu\bar{\nu}P\bar{P}$

- The Graviton interference weighted by $(1 - 3\cos^2\theta)$ vanishes

- Graviscalar interference effects survive

- To pin down Gravitons effects $\to$ angular cuts, new asymmetries

- The $e^+e^-(WW) \to \nu\bar{\nu}P\bar{P}$ cross section

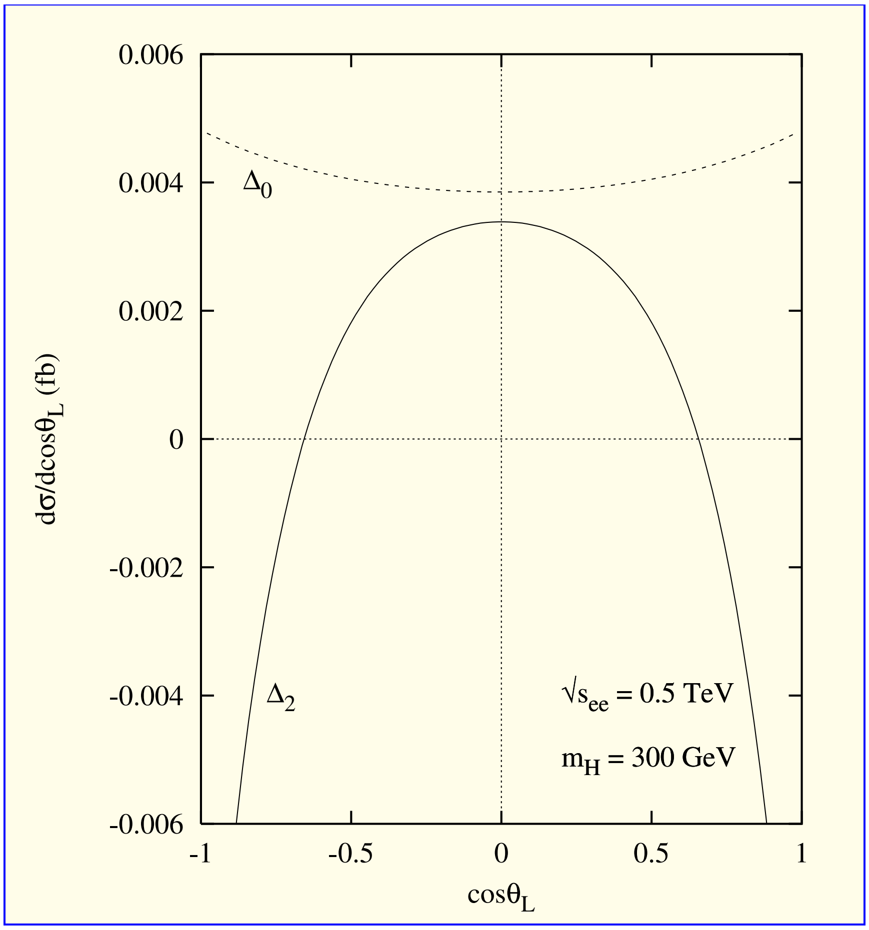
$$\frac{d\sigma^P_{ee}(S)}{d\cos\theta_L} = \Sigma_{\lambda=L,T} \int dx_1\, dx_2 \left\{ P^W_\lambda(x_1)\, P^W_\lambda(x_2)\, \frac{d\sigma^P_\lambda(\hat{s})}{d\cos\theta_L} \right\}$$

$\hat{s} = x_1 x_2 S$, $\quad \theta_L = P$ scattering angle in Lab. frame

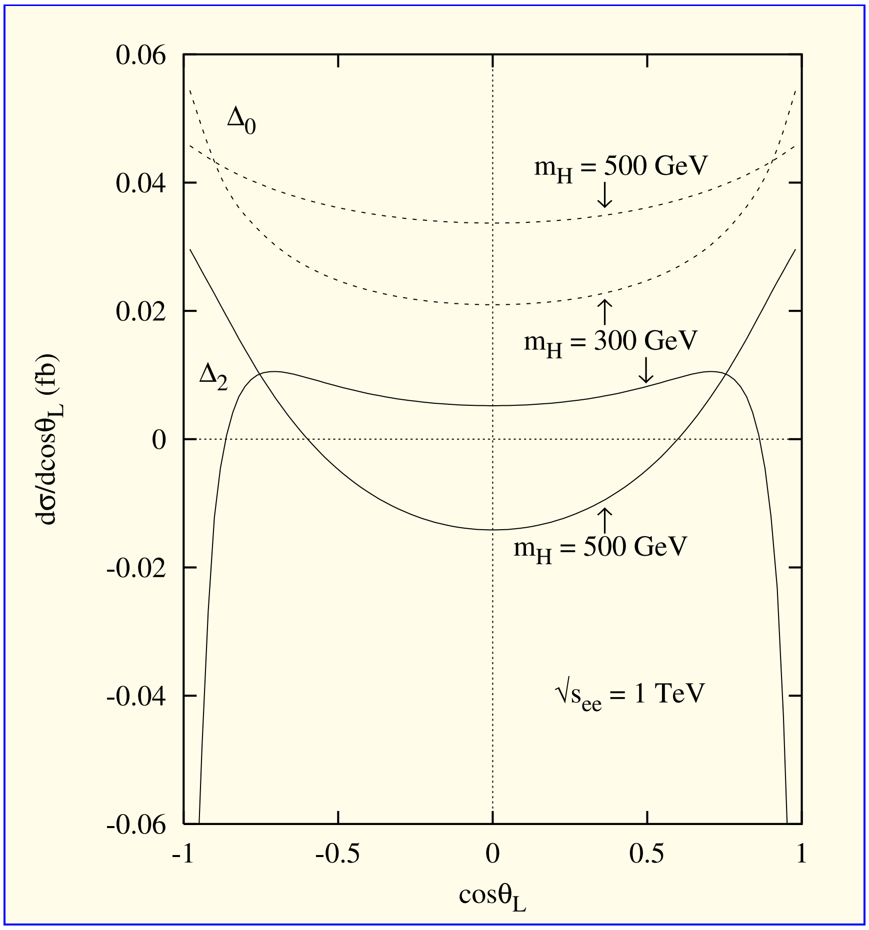
$P^W_\lambda(x) =$ W fluxes

- Approx. of Breight-Wigner with delta-Dirac

$$\frac{1}{(\hat{s} - m_H^2)^2 + m_H^2 \Gamma_H^2} \longrightarrow \frac{\pi}{m_H \Gamma_H}\, \delta(\hat{s} - m_H^2)$$



$\sqrt{S} = 500$ GeV



$\sqrt{S} = 1$ TeV

Optimized angular cuts are applied to enhance KK gravitons effect

$|\cos\theta_L| < \epsilon$

$$\sigma_{\mathbf{ee}}^{\mathbf{P},\epsilon} = \bar{\sigma}_{\mathbf{ee}}^{\mathbf{P},\epsilon} \left(1 + \mathbf{\Delta_0^P} + \alpha_{\mathbf{L}}^{\epsilon}\ \mathbf{\Delta_{2,L}^P} + \alpha_{\mathbf{T}}^{\epsilon}\ \mathbf{\Delta_{2,T}^P}\right)$$

$\bar{\sigma}_{ee}^{P,\epsilon}$ = SM contribution with angular cuts

$\sqrt{S} = 500$ GeV $m_H = 300$ GeV $\epsilon \simeq 0.66$

$\alpha_T \simeq 0.36$ $\alpha_L \simeq 0.16$

$\sqrt{S} = 1$ TeV $m_H = 500$ GeV $\epsilon \simeq 0.60$

$\alpha_T \simeq 0.13$ $\alpha_L \simeq 0.43$

- $\alpha_{L,T}^{\epsilon}$ do NOT depend on the final state

- Largest Grav. Effect is in $H \to \bar{t}t$

$$\Downarrow$$

- $m_H = 500$ GeV Grav-Interf/SM $\simeq 0.5$ %
- $m_H = 800$ GeV Grav-Interf/SM $\simeq \mathcal{O}(\%)$

Conclusions

- In ADD scenario, we analyzed Higgs production via **Vector Boson fusion** in $e^+e^-(WW) \to \nu\bar{\nu}P\bar{P}$ where $P = W, Z, t$

- The **Re[A]** of Amplitude mediated by KK Graviton exchanges is **divergent**, while **Im[A]** (s-channel) is **finite** and predictable in terms of $\mathrm{M_D}$

- Near SM resonant regions, interference of SM amplitude with **Im[A]** dominates with respect to interference with **Re[A]**

- For $\mathbf{m_H = 500 - 800}$ **GeV**, Gravit. interference effects ($\delta = 2$, $M_D = 1$TeV) are $\mathcal{O}(\%)$ on the total SM cross section.

- We also analyzed the same effect at muon collider, via $\mu^+\mu^- \to H \to P\bar{P}$. Gravitational effects are quite large. For $P = t$ and $m_H = 800$ GeV, SM deviations can reach $\simeq 10\%$ effect