

**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 $D = 4 + \delta$ space

Weakness of gravity: Due to large compact spatial dimensions

$$G_N = \frac{G_N^D}{V_{D-4}}$$

Plank masses

$$G_N \sim \frac{1}{M_{\text{pl}}^2}$$

$$G_N^D \sim \frac{1}{M_D^{D-2}}$$

$$M_{\text{pl}} = \frac{1}{\sqrt{8\pi}} M_D (\mathbf{R} M_D)^{\frac{D-4}{2}}$$

$$M_D \simeq 1 \text{ TeV} \quad \Rightarrow \quad R \simeq 10^{\frac{30}{\delta}-17} \text{ cm}$$

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

Gauge invariant spectrum

- Massive Graviton

$$\mathbf{L}_{\text{int}}(\mathbf{x}) \sim \frac{1}{M_{\text{pl}}} \sum_n \mathbf{G}_{\mu\nu}^{(n)}(\mathbf{x}) \mathbf{T}^{\mu\nu}(\mathbf{x})$$

- Massive Gravisclar

$$\mathbf{L}_{\text{int}}(\mathbf{x}) \sim \frac{1}{M_{\text{pl}}} \sum_n \mathbf{S}^{(n)}(\mathbf{x}) \mathbf{T}_{\mu}^{\mu}(\mathbf{x})$$

Masses of KK excitations $M_n^2 \sim \frac{n^2}{R^2}$

Inclusive production of KK Gravitons

- Mass splitting

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

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

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

- For small $\delta \leq 6$:

Large number of accessible KK modes.

$$\sum_{\mathbf{n}} \longrightarrow \int dN$$

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

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

- Inclusive production of KK Gravitons

$$\left(\frac{E}{M_{\text{pl}}} \right)^2 \Rightarrow \left(\frac{E}{M_D} \right)^{2+\delta}$$

Experimental Bounds on M_D

$$e^+e^- \rightarrow \gamma + G$$

G detected as missing energy

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

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

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

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

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

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

From Astrophysics (Low energy modes)

- SuperNova SN1987A collapse

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

- Cosmic γ -Rays

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

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

Virtual KK Gravitons exchange

- The KK Gravitons exchange induces local dim. 8 operators $(T_{\mu\nu}T^{\mu\nu})$:
 $e^-e^+ \rightarrow f\bar{f}$, $e^-e^+ \rightarrow \gamma\gamma$, $W^+W^- \rightarrow W^+W^-$, etc.
- Real part of amplitude $\text{Re}[A]$ is divergent.
Predictivity in terms of M_D is lost.
- Imaginary part $\text{Im}[A]$ is finite (due to branch-cut singularity of real gravitons emission)
- Resonant SM processes can have interference with $\text{Im}[A]$ 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

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

$$\mathcal{S}(s) = \frac{1}{\bar{M}_P^2} \sum_n \frac{1}{s - m_n^2} \quad \sum_n \rightarrow \int$$

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

- Real part is divergent
- Imaginary part is finite

$$\text{Im}[\mathcal{S}(s)] = \frac{A_{\delta-1}}{2} \frac{s^{\frac{\delta-2}{2}}}{M_D^{2+\delta}}$$

Gravitational interference at Z pole

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

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

$$S_f(x) = 1 + x^2 - \Delta_1 (1 - 3x^2) + 2A_e A_f (x + \Delta_2 x^3)$$

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

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

- **New contribution: vanishes** when integrated over the full range of $\cos\theta = (-1, 1)$
- $\delta = 2, M_D = 1 \text{ TeV} \Rightarrow \Delta_{1,2} \simeq \mathcal{O}(10^{-4})$
too tiny for present **EXP.** sensitivity

Virtual KK Gravitons in Higgs production

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

Light Higgs

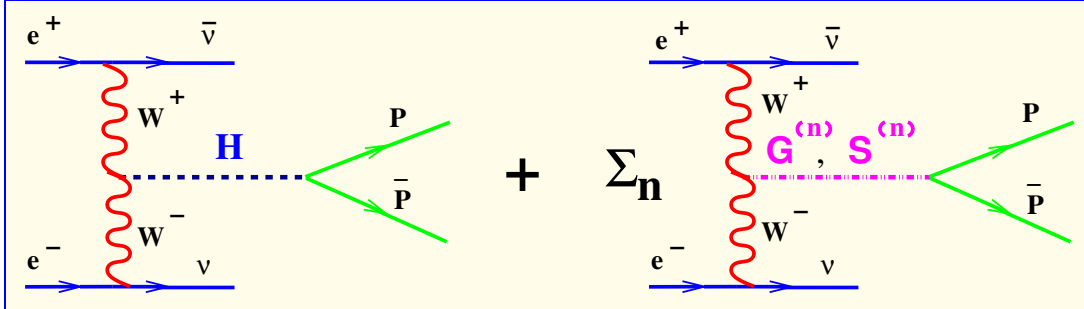
- **Hadron Colliders:** $gg \rightarrow H \rightarrow \gamma\gamma$ (1-loop)²
- Interference with $Im[A(gg \rightarrow G, S \rightarrow \gamma\gamma)]$
- Quite small effect, being coupled to the $Trace[T_\mu^\mu]$

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

Heavy Higgs

- **e^+e^- Colliders:** $WW \rightarrow H \rightarrow WW$ **Tree!**
- Large interference $Im[A(WW \rightarrow G, S \rightarrow WW)]$
since $T_\mu^\mu \propto M_W^2$
- **$\mu^+\mu^-$ Colliders:** $\mu^+\mu^- \rightarrow H \rightarrow (WW), (\bar{t}t)$

Vector boson fusion in Higgs production



$P = W, Z, t$

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

SM + Interf. with KK Gravitons exchange

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

$(x = \cos\theta)$ $\Delta_0^P =$ Graviscales $\Delta_{2,\lambda}^P =$ 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 $\sqrt{\hat{s}} = m_H$

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

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

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

$$\mathbf{R}_\delta \sim \frac{A_{\delta-1}}{\mathbf{G}_F \mathbf{M}_D^2} \left(\frac{m_H}{\mathbf{M}_D} \right)^\delta \left(\frac{\Gamma_H}{m_H} \right)$$

$W_\lambda W_\lambda \rightarrow H \rightarrow WW$ ($\lambda = L, T$)

$m_H(\text{GeV})$	$\Gamma_H(\text{GeV})$	$\Delta_{2,T}^W$	$\Delta_{2,L}^W$	Δ_0^W
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}

$W_\lambda W_\lambda \rightarrow H \rightarrow t\bar{t}$

$m_H(\text{GeV})$	$\Gamma_H(\text{GeV})$	$\Delta_{2,T}^t$	$\Delta_{2,L}^t$	Δ_0^t
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}

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

- The **Graviton** interference weighted by $(1 - 3 \cos^2 \theta)$ vanishes
- **Graviscalar** interference effects survive
- To pin down **Gravitons** effects \rightarrow **angular cuts, new asymmetries**
- The $e^+e^-(WW) \rightarrow \nu\bar{\nu}P\bar{P}$ cross section

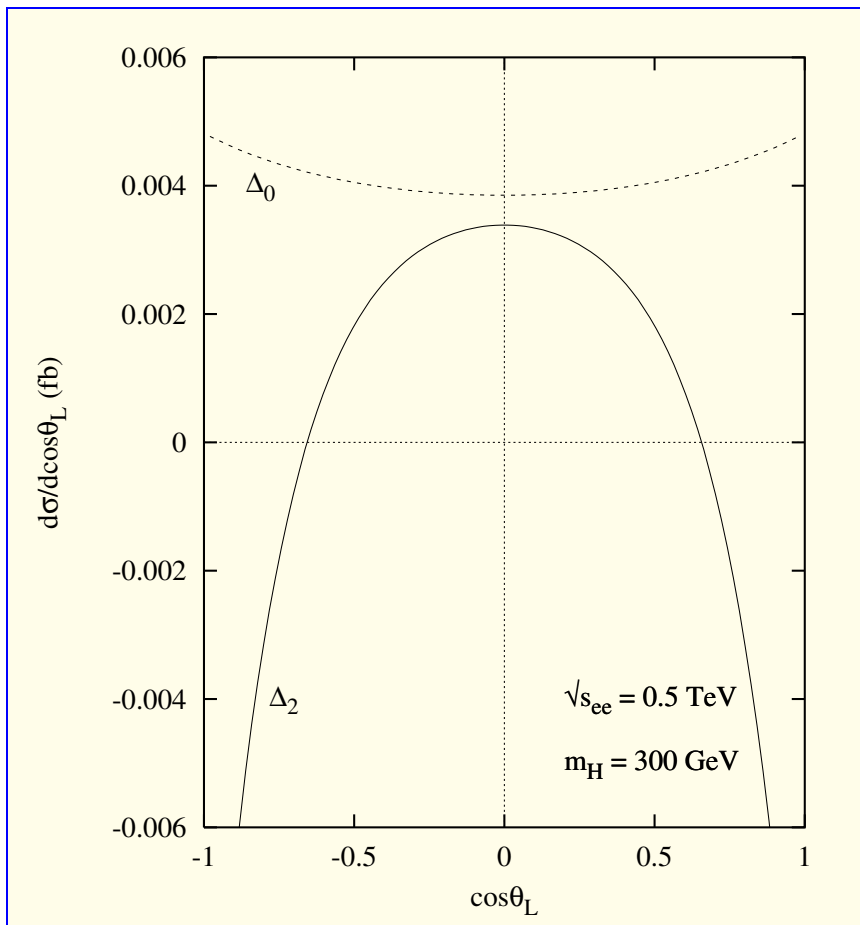
$$\frac{d\sigma_{ee}^P(S)}{d \cos \theta_L} = \sum_{\lambda=L,T} \int dx_1 dx_2 \left\{ P_\lambda^W(x_1) P_\lambda^W(x_2) \frac{d\sigma_\lambda^P(\hat{s})}{d \cos \theta_L} \right\}$$

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

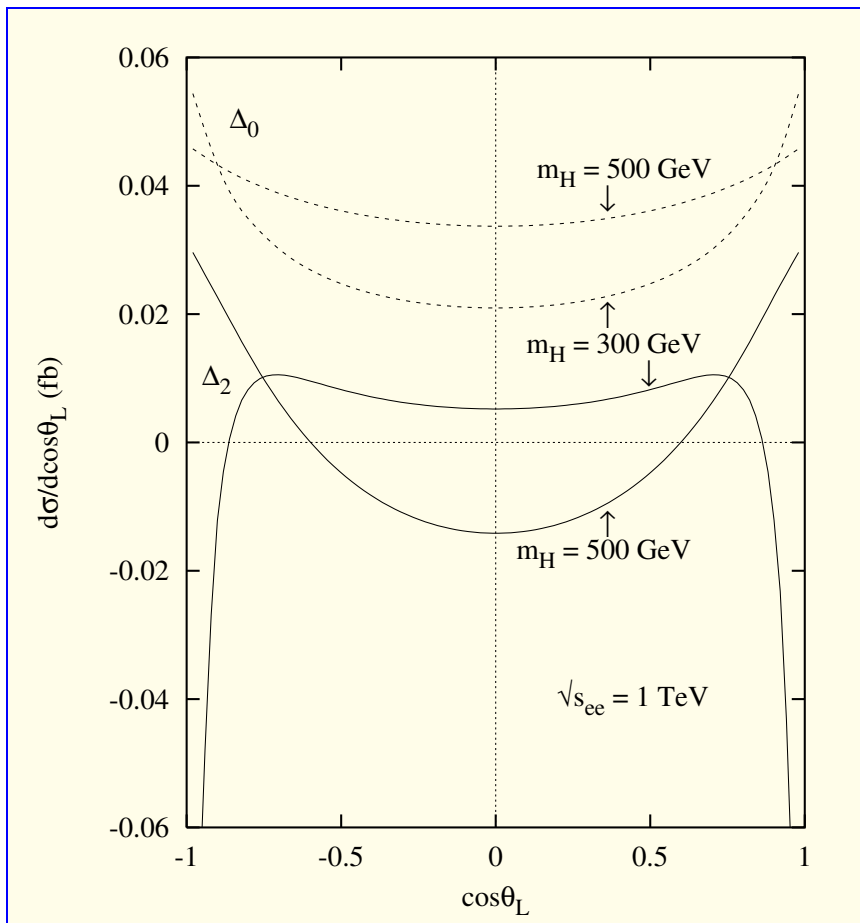
$P_\lambda^W(x) = W$ fluxes

- Approx. of Breit-Wigner with delta-Dirac

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



$\sqrt{S} = 500 \text{ GeV}$



$\sqrt{S} = 1 \text{ TeV}$

Optimized angular cuts are applied to enhance KK gravitons effect

$$|\cos \theta_L| < \epsilon$$

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

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

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

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

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

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

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

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



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

Conclusions

- In **ADD** scenario, we analyzed Higgs production via **Vector Boson fusion** in $e^+e^-(WW) \rightarrow \nu\bar{\nu}P\bar{P}$ 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 M_D
- Near SM **resonant regions**, interference of SM amplitude with **Im[A]** dominates with respect to interference with **Re[A]**
- For **$m_H = 500 - 800$ GeV**, Gravit. interference effects ($\delta = 2$, $M_D = 1\text{TeV}$) are **$\mathcal{O}(\%)$** on the total SM cross section.
- We also analyzed the same effect at muon collider, via $\mu^+\mu^- \rightarrow H \rightarrow P\bar{P}$. Gravitational effects are quite large. For $P = t$ and $m_H = 800$ GeV, SM deviations can reach **$\simeq 10\%$** effect