Large Extra Dimensions Effects in Higgs Production via Vector Boson Fusion

Emidio Gabrielli
(Helsinki Institute of Physics)

PLANCK 03
From the Planck Scale to the Electroweak Scale
May 26-31 2003
CSIC, Madrid, (Spain)

Work made in collaboration with

Anindya Datta (HIP)
Barbara Mele (INFN, Univ. of Roma 1)

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

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

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

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

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

Gauge invariant spectrum

- **Massive Graviton**

$$\mathbf{L_{int}(x)} \sim \frac{\mathbf{1}}{\mathbf{M_{\rm pl}}} \sum\nolimits_{\mathbf{n}} \mathbf{G}_{\mu\nu}^{\mathbf{(n)}}\mathbf{(x)} \mathbf{T}^{\mu\nu}\mathbf{(x)}$$

- **Massive Graviscalar**

$$\mathbf{L_{int}(x)} \sim \frac{\mathbf{1}}{\mathbf{M_{\rm pl}}} \sum\nolimits_{\mathbf{n}} \mathbf{S^{(n)}(x)} \mathbf{T}_{\mu}^{\mu}\mathbf{(x)}$$

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

Inclusive production of KK Gravitons

- Mass splitting

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

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

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

- For small $\delta \lesssim 6$:

  Large number of accessible KK modes.

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

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

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

- Inclusive production of KK Gravitons

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

Experimental Bounds on M_D

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

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

  $\delta = 2 \quad M_D > 1.3$ **TeV**

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

  $\delta = 2 \quad M_D > 4.1$ **TeV**

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

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

From Astrophysics   (Low energy modes)

- **SuperNova SN1987A collapse**

  $M_D > 30$ **TeV** $(\delta = 2)$

- **Cosmic γ-Rays**

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

  $M_D > 110$ **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 $\mathbf{Re[A]}$ is divergent.
  Predictivity in terms of M_D is lost.

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

- Resonant SM processes can have interference with $\mathbf{Im[A]}$ 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)

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

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

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

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

$\sum_n \rightarrow \int$

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

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

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

Gravitational interference at Z pole

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

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

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

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

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

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

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

Virtual KK Gravitons in Higgs production

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

Light Higgs

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

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

- Quite small effect, being coupled to the Trace[T^μ_μ]

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

Heavy Higgs

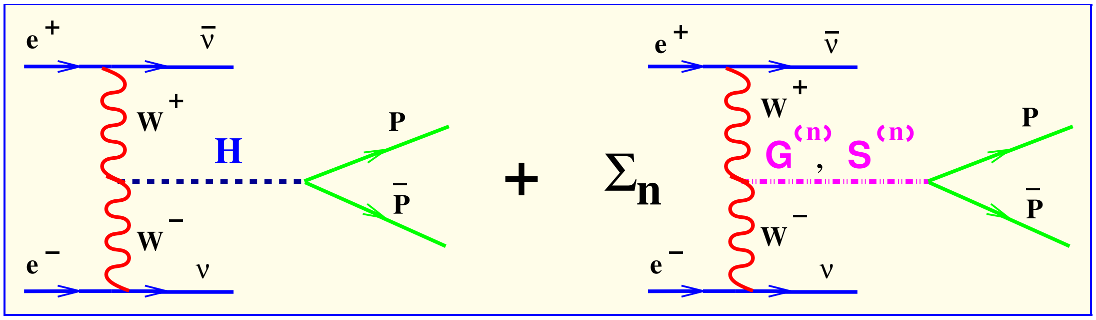
- $\mathrm{e}^+\mathrm{e}^-$ **Colliders**: $WW \to H \to WW$ **Tree!**

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

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

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

Vector boson fusion in Higgs production



$P = W, Z, t$

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

SM + Interf. with KK Gravitons exchange

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

$(x = \cos\theta)$ 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 $\sqrt{\hat{s}} = m_H$

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

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

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

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

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

$m_H(GeV)$	$\Gamma_H(GeV)$	$\Delta^W_{2,T}$	$\Delta^W_{2,L}$	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

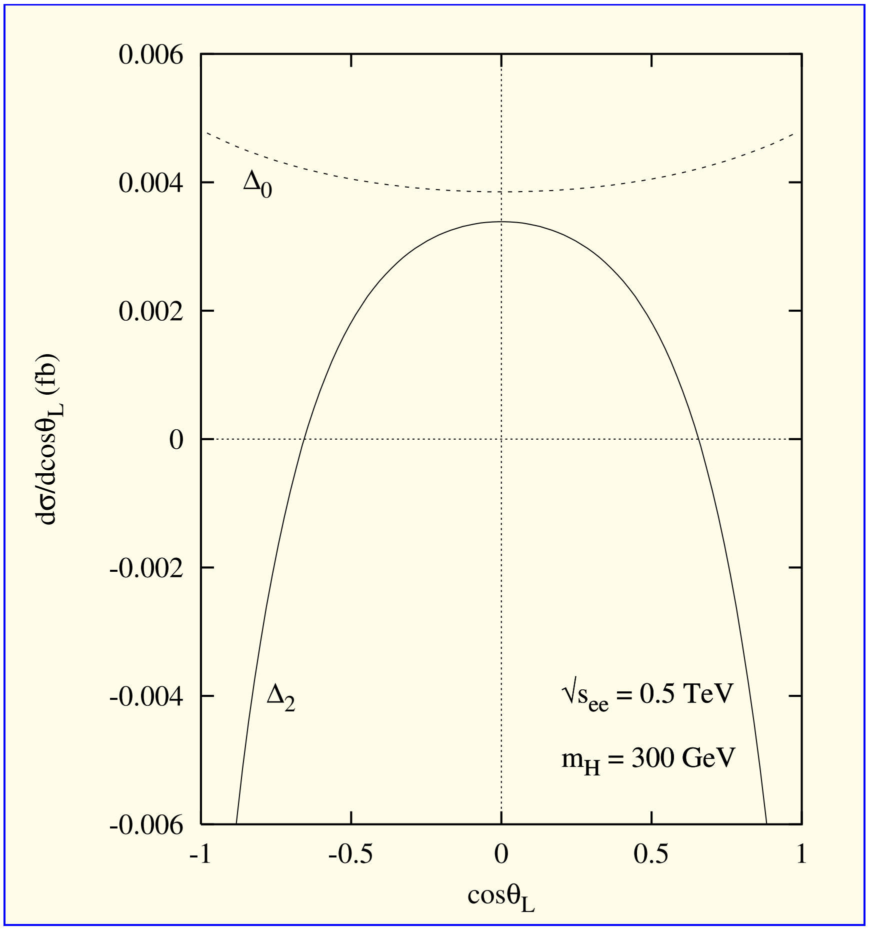
$$\frac{d\sigma^P_{ee}(S)}{d\cos\theta_L} = \Sigma_{\lambda=L,T} \int dx_1\, dx_2 \left\{ P^W_\lambda(x_1)\, P^W_\lambda(x_2)\, \frac{d\sigma^P_\lambda(\hat{s})}{d\cos\theta_L} \right\}$$

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

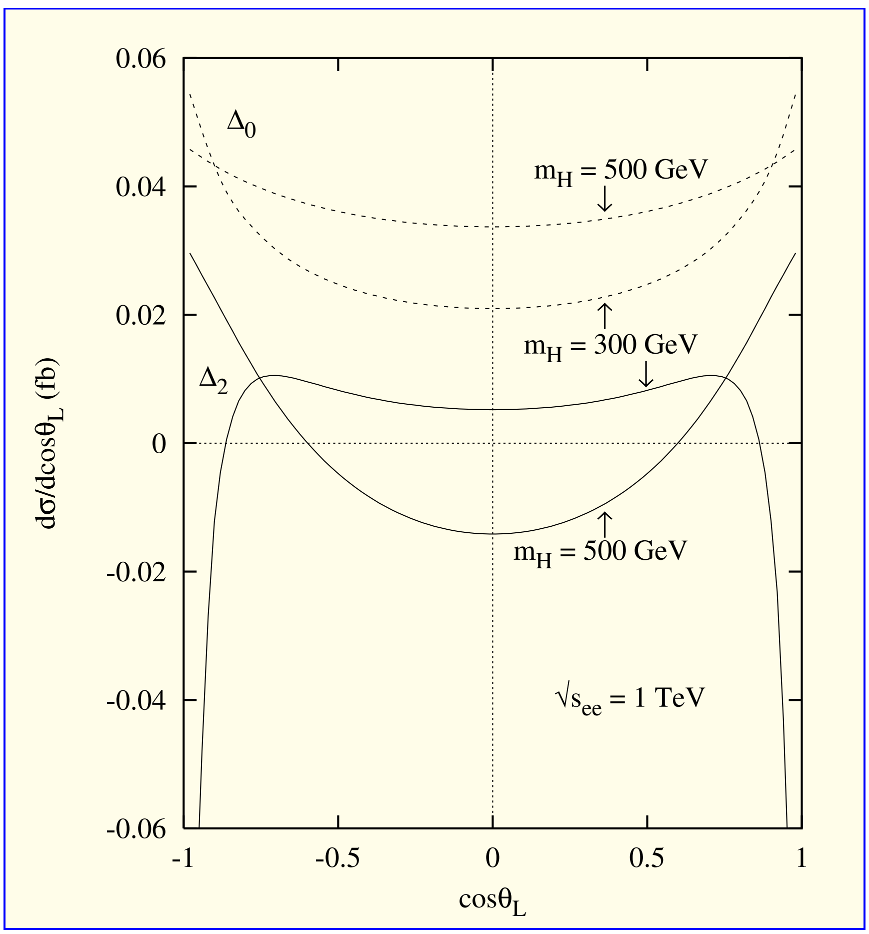
$P^W_\lambda(x)$ = W fluxes

- 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 $\mathbf{M_D}$
- 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 = 1TeV) 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