LHC/ILC complementarity for Higgs in extra dimensions

Daniele Dominici
Florence University

13-9-2007
ILC Physics in Florence

- Higgs phenomenology in ADD model
- Higgs and radion phenomenology in RS model
- Conclusions

Based on
M. Battaglia, DD, J. Gunion, in preparation
M. Battaglia, DD, J. Gunion, J. Wells, LCWS 2005 and hep-ph/0402062
Recent motivation for extra dimensions: the hierarchy problem, or why

\[ M_W << M_{Pl} \]

New idea: geometry may be responsible for the hierarchy

- Large volume of \( \delta \) extra dimensions (Arkani-Hamed, Dimopoulos, Dvali, Antoniadis)

\[ M_{Pl} = M_D^{1+\delta/2} V^{\delta/2} \]

\( M_D \sim TeV \) fundamental Planck scale, \( V_\delta \) compactification volume

- Strong curvature of the extra dimension (Randall, Sundrum)

\[ M_{Pl} = \Lambda \exp (\pi kR) \]

\( \Lambda \sim TeV, \ kR \sim 11-12 \)

Both can modify the Higgs phenomenology.
Higgs phenomenology in ADD model
(Arkani-Hamed, Dimopoulos, Dvali, Antoniadis)

Gravity in $D = 4 + \delta$ dimensions, SM particles localized on a 3 dimensional brane.

$$S = \frac{M_D^{2+\delta}}{2} \int d^D x \sqrt{|g|} R + \int d^4 x \sqrt{-g_{\text{ind}}} \mathcal{L}_{\text{SM}}$$

$$g_{AB} = \eta_{AB} + \frac{2}{M_D^{1+\delta/2}} h_{AB}, \quad h_{AB} = \sum_{\vec{n}} \frac{1}{\sqrt{V_\delta}} h^{(\vec{n})}_{AB}(x) e^{-i \sum_{j=1}^{\delta} n_j y_j}$$

Light KK states (KK gravitons and graviscalars)

$$m_{\vec{n}} = \frac{|\vec{n}|}{R}, \quad \Delta m_{\vec{n}} \sim 10^{-3} \text{eV} - 10 \text{MeV}, \quad \delta = 2 - 6$$

and very long lived ($\sim 10^{10} \text{yr}$).

Interactions with SM fields

$$- \frac{1}{M_{Pl}} G^{(\vec{n})}_{\mu\nu} T_{\mu\nu} + \frac{1}{M_{Pl}} \sqrt{\frac{\delta - 1}{3(\delta + 2)}} H^{(\vec{n})} T_{\mu}$$
95% CL Limits on $M_D$ (TeV) from colliders

Generic signature: a final state with missing $\not{E}_T$, due to the KK excitations which are radiated away into the extra dimensions.

Collider bounds: from graviton emission process at LEP2 ($e^+e^- \rightarrow \gamma \not{E}_T, e^+e^- \rightarrow Z \not{E}_T$) and Tevatron ($p\bar{p} \rightarrow \gamma \not{E}_T, p\bar{p} \rightarrow jets \not{E}_T$).

$$M_D = (2\pi)^{\frac{\delta}{\delta+2}} M_D$$
The presence of an interaction between the Higgs $H$ and the Ricci scalar curvature of the induced 4-dimensional metric $g_{\text{ind}}$,

$$S_{\xi} = -\xi \int d^4x \sqrt{g_{\text{ind}}} R(g_{\text{ind}}) H^\dagger H$$

generates, after the shift $H = (\frac{v+h}{\sqrt{2}}, 0)$, a mixing term (Giudice, Rattazzi and Wells) 

$$H^{(\bar{n})} = \frac{1}{\sqrt{2}} (s_{\bar{n}} + ia_{\bar{n}})$$

$$\mathcal{L}_{\text{mix}} = \epsilon h \sum_{\bar{n}>0} s_{\bar{n}}$$

(1)

with

$$\epsilon = -\frac{2\sqrt{2}}{M_{Pl}} \xi v m^2_h \sqrt{\frac{3(\delta - 1)}{\delta + 2}}.$$

$\xi$ is a dimensionless parameter and $s_{\bar{n}}$ is a graviscalar KK excitation.
Invisible Higgs width

This mixing generates an oscillation of the Higgs itself into the closest KK graviscalar levels which are invisible. The mixing invisible width $\Gamma_{inv}$ calculated by extracting the imaginary part of the mixing contribution to the Higgs self energy (Giudice et al, Wells):

$$<hh> = \sum_n \frac{\epsilon}{s_n} \epsilon + ...$$

In an equivalent way: first the mixing term can be eliminated with the transformation to the new fields $h'$ and $s'_n$ and in computing a process such as $WW \to h' + \sum_{\bar{m}>0} s'_{\bar{m}} \to F$, consider the full coherent sum:

$$A(WW \to F)(p^2) \sim \frac{g_{WWh}g_{hF}}{p^2 - m_h^2 + im_h\Gamma_h + iG(p^2) + F(p^2) + i\bar{\epsilon}}$$
Writing \( F(p^2) = F(m_{heff}^2) + (p^2 - m_{heff}^2)F'(m_{heff}^2) + \ldots, \)

where \( m_{heff}^2 - m_h^2 + F(m_{heff}^2) = 0, \)

\[
A(WW \rightarrow F)(p^2) \sim \frac{g_{WW h} g_{h F}}{(p^2 - m_{heff}^2)[1 + F'(m_{heff}^2)]} + i m_{heff}(\Gamma_h + \Gamma_{inv})
\]

with

\[
m_{heff}\Gamma_{inv} = G(p^2)|_{m_{heff}^2} = -\epsilon^2 \text{Im} \left[ \sum_{\vec{m}>0} \frac{1}{p^2 - m_{\vec{m}}^2 + i\epsilon} \right] m_{heff}^2
\]

In conclusion:

\[
\sigma(WW \rightarrow h' + \sum_{\vec{n}>0} s_{\vec{n}} \rightarrow F) = \sigma_{SM}(WW \rightarrow h \rightarrow F)
\]

\[
= \left[ \frac{1}{1 + F'(m_{eff}^2)} \right]^2 \times \left[ \frac{\Gamma_{SM}^{h \rightarrow F}}{\Gamma_{SM}^{h} + \Gamma_{inv}} \right]
\]
\[ G(m_h^2) \to -\frac{\epsilon^2}{2} \text{Im} \int dm^2 \rho_\delta(m) \frac{1}{m_h^2 - m^2 + i\epsilon} \]
\[
= -\epsilon^2 \frac{1}{4} \frac{M_{pl}^2}{M_D^{2+\delta}} S_{\delta-1}(-\pi) (m_h^2)^{(\delta-2)/2}
\]

\[
\Gamma_{inv} \sim (16 \text{ MeV}) 20^{2-\delta} \xi^2 S_{\delta-1} \frac{3(\delta - 1)}{\delta + 2}
\times \left( \frac{m_h}{150 \text{ GeV}} \right)^{1+\delta} \left( \frac{3 \text{ TeV}}{M_D} \right)^{2+\delta}
\]

\( S_{\delta} = 2\pi^{\delta/2}/\Gamma(\delta/2) \) denotes the surface of a unit radius sphere in \( \delta \) dimensions.

- For a light Higgs both the wave function renormalization and the mass renormalization effects are small:
  \( F'(m_{h_{eff}}^2) \sim \xi^2 \frac{m_h^4}{\Lambda^4} \), where \( \Lambda \sim M_D \), therefore quite small for the \( m_h \ll M_D \).

- For a light Higgs the invisible width causes a significant suppression of the LHC rates in the standard visible channels.
In the following analysis: for visible channels we have used the CMS statistical significance.
For invisible Higgs (Fusion channel: Eboli and Zeppenfeld, Di Girolamo et al, Abdullin et al, CMS note)

Higgs boson production in $qq \rightarrow qqVV \rightarrow qqh \rightarrow qq \text{ inv.}$

Signal characterized by two very energetic forward jets well separated in pseudorapidity. With 100 fb$^{-1}$ sensitive at 5$\sigma$ at $B_{\text{inv}} \sim 0.1$.

ZH channel (Dilepton + missing $P_T$) (Godbole, Guchait, Mazumdar, Moretti and Roy, Davoudiasl, Han and Logan) : $B_{\text{inv}} \sim 0.42(0.70)$ probed at 5$\sigma$ level for $m_H = 120(160)$ GeV with 100 fb$^{-1}$. 
Sensitivity to $\Gamma_{\text{inv}}$ at the ILC

Signal process: $e^+e^- \rightarrow ZH \rightarrow$ two jets+$E_T$. Relative accuracy of the measurement of the invisible branching as a function of the branching ratio, for $m_H = 120, 140, 160$ GeV at $\sqrt{s} = 350$ GeV for 500 fb$^{-1}$ (Schumacher).

Invisible Higgs discovered down to $B \sim 0.02$.
Recent proposal: working at $\sqrt{s} = 230$ GeV for L=50 fb$^{-1}$ (Richard, Bambade).
The green regions: the Higgs signal at the LHC $< 5 \sigma$ for $100 \text{ fb}^{-1}$. The regions above the blue line are where the LHC invisible Higgs signal in the $WW$-fusion channel $> 5 \sigma$. The purple line shows the upper limit on $M_D$ which can be probed at the $5 \sigma$ by the analysis of jets/$\gamma$ with missing energy at the LHC. The red dashed line 95% CL lower limit from Tevatron and LEP/LEP2 limits. The regions above the yellow line are the parts where the ILC invisible Higgs signal $> 5 \sigma$ assuming $\sqrt{s} = 350 \text{ GeV}$ and $L = 500 \text{ fb}^{-1}$.
Determining ADD parameters from LHC and ILC data

The yellow regions are the 95% CL regions using only $\Delta \chi^2(LHC)$. Blue regions or points are the 95% CL regions using $\Delta \chi^2(LHC + ILC)$.

LHC: visible and invisible Higgs signal assuming SM production rate for 100 $fb^{-1}$.

ILC: visible ($WW^*$, $b\bar{b}$) and the invisible branching ratio at $\sqrt{s} = 350$ GeV.

ILC $\gamma + p_T$ signal at two different energies: at $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1000$ GeV of respectively, 1000 $fb^{-1}$ and 2000 $fb^{-1}$, respectively, $P_{e^-} = 0.80$, $P_{e^+} = 0.60$, $E_\gamma < 0.625$ $E_{beam}$. Polarization extremely effective in reducing $e^+ e^- \rightarrow \gamma \nu \bar{\nu}$ background.
KK graviton and graviscalar interference with Higgs

(Datta, Gabrielli, Mele)

Virtual KK graviton, $\Delta_2$, and graviscalar, $\Delta_0$, interference with resonant Higgs, present also when $\xi = 0$. $e^+e^-(WW) \to \nu\overline{\nu}P\overline{P}$, $P = W, Z, t$

Relevant only for heavy Higgs, low $M_D$ and $\delta = 2$. $\Delta_0 \sim 2\%$ for $m_H = 800$ GeV.

The KK graviscalar (dashed), and the KK graviton contribution (continuous) to the total interference with the SM amplitude in the angular distribution at $\sqrt{s} = 500$ and 1000 GeV. Largest effect in $t\overline{t}$. With suitable cuts grav/SM $O(\%)$ for $m_H = 800$ GeV.
Higgs and radion phenomenology in RS model

Usual 2-brane RS 5D warped space scenario

\[ ds^2 = e^{-2\sigma(y)} \eta_{\mu\nu} dx^\mu dx^\nu - b_0^2 dy^2 \]

where \( \sigma(y) = k b_0 |y| \). Gravitational fluctuations around the above background metric:

\[ \eta_{\mu\nu} \rightarrow \eta_{\mu\nu} + \epsilon h_{\mu\nu}(x, y) \quad b_0 \rightarrow b_0 + b(x) . \]

The canonically normalized radion field \( \phi_0(x) \) is defined by:

\[ \phi_0(x) = \Lambda_\phi e^{-kb(x)/2} \]

with \( \Lambda_\phi = \sqrt{6} \, M_{Pl} \Omega_0 \), \( \Omega_0 \equiv e^{-kb_0/2} \) is the warp factor.

A mixing among the radion and the Higgs \( \hat{H} \) is induced by

(Giudice, Rattazzi, Wells)

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

KK mode expansion in the extra dimension

\[ h_{\mu\nu}(x, y) = \sum_n h_{\mu\nu}^n(x) \frac{\chi_n(y)}{\sqrt{b_0}} \]

KK Graviton couplings:

\[ -\frac{1}{M_{Pl}} h^0_{\mu\nu} T^{\mu\nu} - \frac{1}{\hat{\Lambda}_W} \sum_{n=1}^{\infty} h^n_{\mu\nu} T^{\mu\nu} \]

where

\[ \hat{\Lambda}_W \sim \sqrt{2M_{Pl}\Omega_0} \sim \text{TeV}, \]
Our choice of parameters:

\[
\begin{array}{cccc}
\xi & \Lambda_\phi & m_h & m_\phi \\
\end{array}
\]

Additional parameter for fixing the phenomenology of KK excitations of the gravitons \( h_{\mu \nu}^n \),

\[
m_1 = x_1 \frac{k \Lambda_\phi}{M_{Pl} \sqrt{6}}
\]

\( m_1 \) is the mass of the first KK graviton excitation. \( x_1 \sim 3.83 \) is the first zero of the Bessel function \( J_1 \).

\[\blacklozenge\] Radion-Higgs couplings to gauge bosons and fermions

\[
\overline{g}_{ZZh} = \frac{g m_Z}{c_W} (d + \gamma b), \quad \overline{g}_{ZZ\phi} = \frac{g m_Z}{c_W} (c + \gamma a),
\]

WW couplings: \( \frac{g m_Z}{c_W} \rightarrow m_W \)

\[
\overline{g}_{f\bar{f}h} = -\frac{g m_f}{2 m_W} (d + \gamma b), \quad \overline{g}_{f\bar{f}\phi} = -\frac{g m_f}{2 m_W} (c + \gamma a);
\]

\[\gamma \equiv v/\Lambda_\phi.\]
Run II analysis searches for high mass di-photon states

For example, $k/M_{Pl} = 0.1$, $m_1 > 850$ GeV implying $\Lambda_\phi > 5.4$ TeV. Including $e^+e^-$ graviton decay, $m_1 > 889$ GeV (D0 $m_1 > 865$).
Allowed regions for $\Lambda_{\phi} = 5$ TeV and $m_h = 120$ GeV. The light yellow portion is eliminated by LEP/LEP2 constraints on $g_{ZZs}^2$ (untagged hadronic events) or on $g_{ZZs}^2 BR(s \rightarrow b\bar{b})$, with $s = h$ or $s = \phi$ (OPAL, LEPHIGGS wg).

For $m_h = 112$ GeV, almost all excluded. For $\Lambda_{\phi} = 1$ TeV light radion much more constrained.
The branching ratios for $h$ (left) and $\phi$ (right) for $m_h = 120$ GeV and $m_\phi = 200$ GeV, $\Lambda_\phi = 5$ TeV.
The branching ratios for $\phi$ decays to $b\bar{b}$, $gg$, for $m_h = 120$ GeV and $\Lambda_\phi = 5$ TeV as functions of $\xi$ for $m_\phi = 20$ GeV.
Prospects for $h$ discovery at LHC

The ratio of the rates for $gg \rightarrow h \rightarrow \gamma\gamma$ and $WW \rightarrow h \rightarrow \tau^+\tau^-$ to the corresponding rates for the SM Higgs boson for $m_h = 120$ GeV and $\Lambda_\phi = 5$ TeV as functions of $\xi$ for $m_\phi = 20$, 55 and 200 GeV.
Complementarity at LHC

Regions of $gg \to h$ with $h \to \gamma\gamma$, $h \to ZZ^* \to 4 \ell$, $h\bar{t}t(h \to \bar{b}b)$ and $gg \to \phi \to ZZ^* \to 4 \ell$ detectability at LHC for one expt and 30 fb$^{-1}$. The cyan regions: Higgs signal significance $< 5\sigma$. The blue curves: $gg \to \phi \to ZZ^{(*)} \to 4 \ell$ signal exceeds $5\sigma$. For $m_h=120$ GeV and $\Lambda_\phi = 5$ TeV.
The red curves: the regions where the ILC measurements of the $h$ couplings to $b\bar{b}$ and $W^+W^-$ would provide a $> 2.5 \, \sigma$ evidence for the radion mixing effect. For $m_h=120$ GeV and $\Lambda_\phi = 5$ TeV.
Prospects for $\phi$ discovery at ILC, in $e^+e^- \rightarrow \nu \bar{\nu}\phi \rightarrow \text{miss} + gg$ (Datta, Huitu)

Number of signal (+ for $\xi \neq 0$ and dashed line is for $\xi = 0$), SM Higgs (dotted line) and background (solid histogram) events as a function of the invariant mass of the jets. The upper histogram the actual number of background events. The lower histogram the 5$\sigma$ fluctuation of background. Points (representing the signal from Higgs and radion) above the lower histogram can be explored at 5$\sigma$. $\Lambda_\phi = 1$ TeV, $m_H = 150$ GeV.
ILC sensitivity to the graviton-Higgs-radion coupling

(Cheung, Kim, Song)

The dotted regions are for
\[ \sigma_{\text{tot}}(e^+e^- \rightarrow h_{\mu\nu}^n \rightarrow h\phi \rightarrow b\bar{b}b\bar{b}) > 0.03 \text{ fb.} \]
\[ m_h = 120 \text{ GeV, } \Lambda_{\phi} = 5 \text{ TeV.} \]
Radion phenomenology in RS model with bulk fermions and gauge bosons (Csáki, Hubisz, Lee)

\[ R_{\gamma\gamma}^S = \frac{S(\phi)}{S(h_{SM})} \] with \( \Lambda_{\phi} = 2 \) TeV for various combinations of brane kinetic terms for the photon and the gluon. Dashed is RS model.

In some region more likely to find a radion!

13-9-2007
ILC Physics in Florence

Daniele Dominici
Florence University
Higgs phenomenology in RS model with bulk fermions and
gauge bosons (Djouadi, Moreau)

Effect of new quark $b'$ the $SU(2)_R$ partner of the heavy top
quark doublet in $gg \rightarrow H$

Ratio $\mathcal{R} = \frac{\sigma_H^{RS}}{\sigma_H^{SM}}$ for fixed value $c_b = 0.6$. The filled regions correspond from
white to darkest grey to, respectively, the intervals $\mathcal{R} \in [1, 0.75]$, $[0.75, 0.25]$, $[0.25, 0.1]$ and $\mathcal{R} \leq 0.1$ (left), $\mathcal{R} \in [1, 1.2]$, $[1.2, 2]$, $[2, 4]$ and $\mathcal{R} > 4$ (right).
Conclusions

Higgs phenomenology can be modified in extra dimension models ADD

- For a light Higgs boson the process $pp \rightarrow W^*W^* + X \rightarrow Higgs, graviscalars + X \rightarrow invisible + X$ will be observable at the $5\,\sigma$ level at the LHC for a large portion of the Higgs-graviscalar mixing ($\xi$) and $D$-dimensional Planck mass ($M_D$) parameter space where channels relying on visible Higgs decays fail to achieve a $5\,\sigma$ signal.

- However LHC will not be able to determine $M_D$, $\xi$ and $\delta$.

- Measurements of $\Delta BR(H)/BR(H)$ for the visible and the invisible channels and $\gamma + \not{E}_T$ at the $e^+e^-$ ILC combined with LHC determine with good accuracy $M_D$, $\xi$ and $\delta$ as long as not both $\delta$ and $M_D$ are large.
RS

- LHC detection of the $h$ in $gg \rightarrow h \rightarrow \gamma\gamma$ not guaranteed. LHC detection of the $\phi$ in $gg \rightarrow \phi \rightarrow \gamma\gamma$ likely to be difficult unless $\Lambda_\phi \sim 1$-2 TeV and gauge bosons in the bulk.

- However, for almost the entire region of the parameter space where the Higgs signal significance at LHC $\leq 5 \sigma$, the $gg \rightarrow \phi \rightarrow Z^0 Z^{0(*)} \rightarrow 4\ell$ process can be observed.

- A $e^+ e^-$ linear collider would complement the LHC both for the Higgs observability and for the detection of the radion mixing effects, through the precision measurements of the individual Higgs particle couplings.

- Other interesting channels for LHC/ILC:
  - $pp, e^+ e^- \rightarrow h_{\mu\nu} \rightarrow h\phi$
  - $e^+ e^- \rightarrow \nu\bar{\nu}\phi \rightarrow miss + gg$
  - $\phi \rightarrow hh \rightarrow bb\gamma\gamma, 4b's, bb\tau\tau$; for $m_\phi = 300$ GeV, LHC sensitive to $\Lambda_\phi \leq 3$ TeV.
If at LHC an intermediate mass scalar observed its non SM-like nature can in some cases be detected through measurements of rates.

One particularly interesting complication for $\xi \neq 0$ is the presence of the non-standard decay channel $h \rightarrow \phi\phi \rightarrow bbgg, 4b's$. 