

LHC/ILC complementarity for Higgs in extra dimensions

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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

DD, B. Grzadkowski, J. Gunion, M. Toharia, Nucl.Phys.B671:243 2003

M. Battaglia, S. De Curtis, A. De Roeck, DD, J. Gunion, Phys.Lett.B568:92 2003

Recent motivation for extra dimensions: the hierarchy problem, or why

$$M_W \ll M_{Pl}$$

New idea: geometry may be responsible for the hierarchy

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

$$\overline{M}_{Pl} = \overline{M}_D^{1+\delta/2} V^{\delta/2}$$

$\overline{M}_D \sim TeV$ fundamental Planck scale, V_δ compactification volume

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

$$\overline{M}_{Pl} = \Lambda \exp(\pi k R)$$

$$\Lambda \sim TeV, kR \sim 11-12$$

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.

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

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

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 ($\sim 10^{10} \text{yr}$).

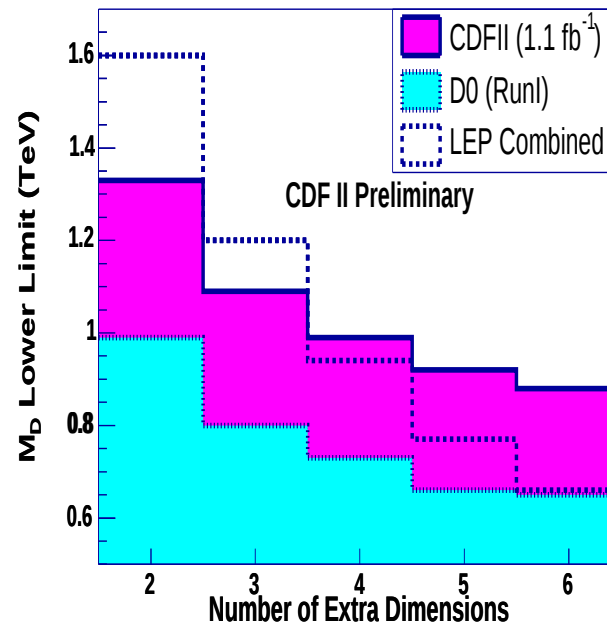
Interactions with SM fields

$$-\frac{1}{\overline{M}_{Pl}} G^{(\vec{n})\mu\nu} T_{\mu\nu} + \frac{1}{\overline{M}_{Pl}} \sqrt{\frac{\delta-1}{3(\delta+2)}} H^{(\vec{n})} T^\mu_\mu$$

95% CL Limits on M_D (TeV) from colliders

Generic signature: a final state with missing $\cancel{E}_T$, due to the KK excitations which are radiated away into the extra dimensions.

Collider bounds: from graviton emission process at LEP2 ($e^+e^- \rightarrow \gamma \cancel{E}_T, e^+e^- \rightarrow Z \cancel{E}_T$) and Tevatron ($p\bar{p} \rightarrow \gamma \cancel{E}_T, p\bar{p} \rightarrow jets \cancel{E}_T$).



$$M_D = (2\pi)^{\frac{\delta}{\delta+2}} \overline{M}_D$$

The presence of an interaction between the Higgs H and the Ricci scalar curvature of the induced 4-dimensional metric g_{ind} ,

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

generates, after the shift $H = (\frac{v+h}{\sqrt{2}}, 0)$, a mixing term (Giudice, Rattazzi and Wells) $(H^{(\vec{n})} = \frac{1}{\sqrt{2}}(s_{\vec{n}} + ia_{\vec{n}}))$

$$\mathcal{L}_{mix} = \epsilon h \sum_{\vec{n} > 0} s_{\vec{n}} \quad (1)$$

with

$$\epsilon = -\frac{2\sqrt{2}}{\overline{M}_{Pl}} \xi v m_h^2 \sqrt{\frac{3(\delta - 1)}{\delta + 2}}.$$

ξ is a dimensionless parameter and $s_{\vec{n}}$ 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 Γ_{inv} calculated by extracting the imaginary part of the mixing contribution to the Higgs self energy (Giudice et al, Wells):

$$\langle hh \rangle = \text{---} + \sum_n \frac{\overset{\varepsilon}{\text{---}} \text{---} \overset{\varepsilon}{\text{---}}}{s_n} + \dots$$

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

$$\mathcal{A}(WW \rightarrow F)(p^2) \sim \frac{g_{WWh}g_{hF}}{p^2 - m_h^2 + im_h\Gamma_h + iG(p^2) + F(p^2) + i\bar{\epsilon}}$$

Writing $F(p^2) = F(m_{h_{eff}}^2) + (p^2 - m_{h_{eff}}^2)F'(m_{h_{eff}}^2) + \dots$,
 where $m_{h_{eff}}^2 - m_h^2 + F(m_{h_{eff}}^2) = 0$,

$$\mathcal{A}(WW \rightarrow F)(p^2) \sim \frac{g_{WWh}g_{hF}}{(p^2 - m_{h_{eff}}^2)[1 + F'(m_{h_{eff}}^2)] + im_{h_{eff}}(\Gamma_h + \Gamma_{inv})}$$

with

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

In conclusion:

$$\sigma(WW \rightarrow h' + \sum_{\vec{n}>0} s_{\vec{n}} \rightarrow F) = \sigma_{SM}(WW \rightarrow h \rightarrow F) \left[\frac{1}{1 + F'(m_{eff}^2)} \right]^2 \times \left[\frac{\Gamma_{h \rightarrow F}^{SM}}{\Gamma_h^{SM} + \Gamma_{inv}} \right]$$

$$\begin{aligned}
G(m_h^2) &\rightarrow -\frac{\epsilon^2}{2} \text{Im} \int dm^2 \rho_\delta(m) \frac{1}{m_h^2 - m^2 + i\bar{\epsilon}} \\
&= -\epsilon^2 \frac{1}{4} \frac{\overline{M}_{Pl}^2}{M_D^{2+\delta}} S_{\delta-1}(-\pi) (m_h^2)^{(\delta-2)/2}
\end{aligned}$$

$$\begin{aligned}
\Gamma_{inv} &\sim (16 \text{ MeV}) 20^{2-\delta} \xi^2 S_{\delta-1} \frac{3(\delta-1)}{\delta+2} \\
&\quad \times \left(\frac{m_h}{150 \text{ GeV}} \right)^{1+\delta} \left(\frac{3 \text{ TeV}}{M_D} \right)^{2+\delta}
\end{aligned}$$

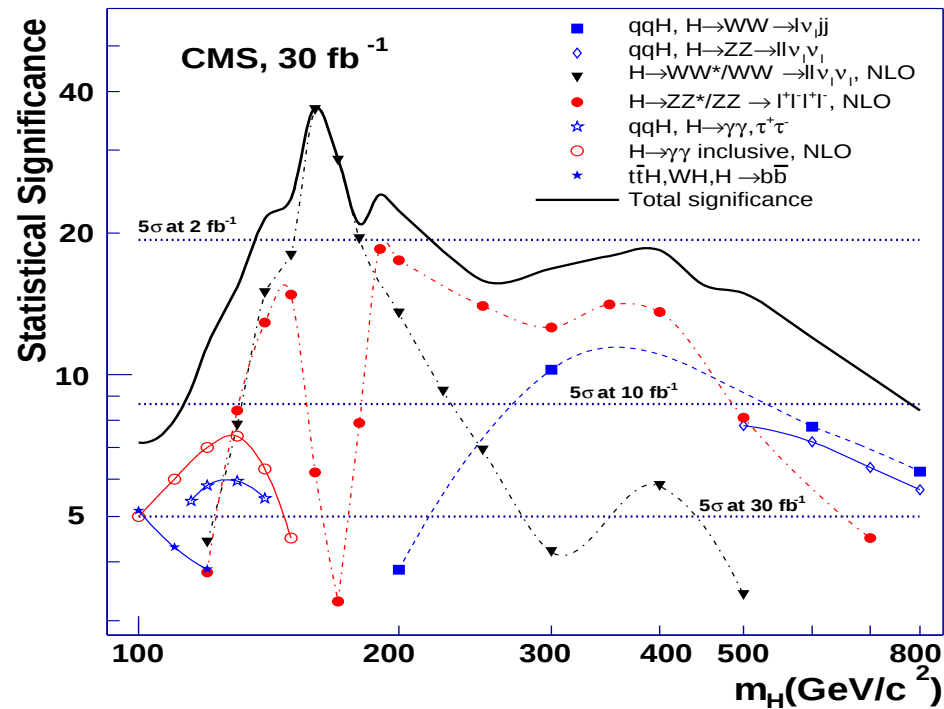
$S_\delta = 2\pi^{\delta/2}/\Gamma(\delta/2)$ denotes the surface of a unit radius sphere in δ dimensions.

- 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 $m_h \ll M_D$.

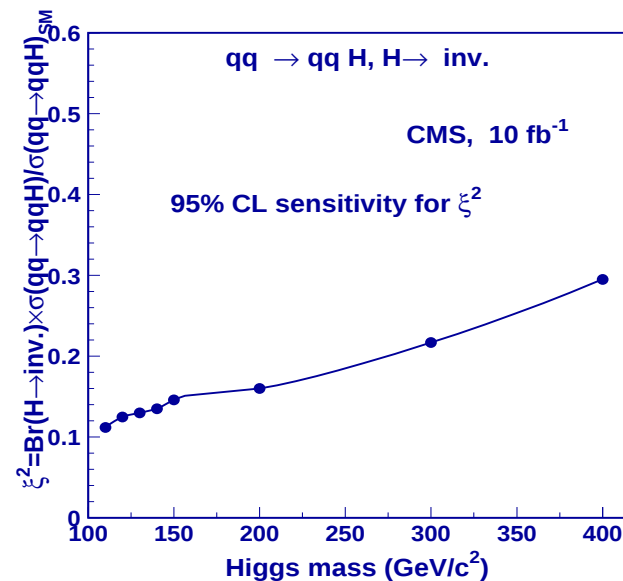
- For a light Higgs the invisible width causes a significant suppression of the LHC rates in the standard visible channels

- 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)

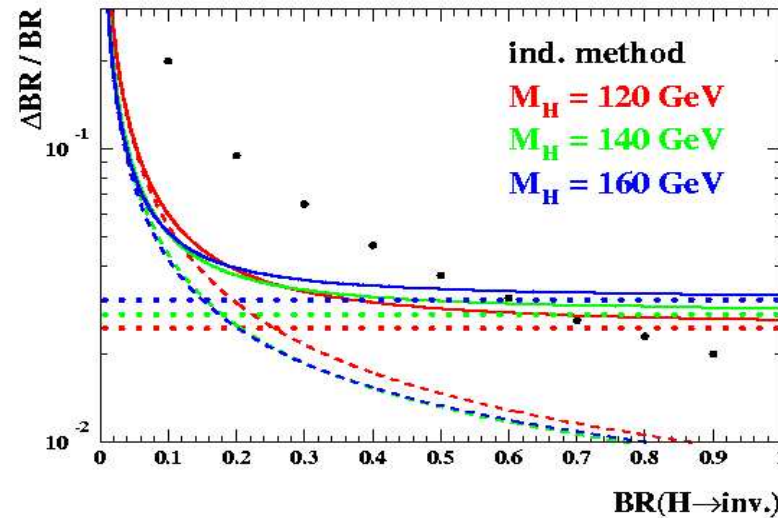
Higgs boson production in $qq \rightarrow qqVV \rightarrow qqh \rightarrow qq \text{ inv.}$
 Signal characterized by two very energetic forward jets well separated in pseudorapidity. With 100 fb^{-1} sensitive at 5σ at $B_{inv} \sim 0.1$.



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

Sensitivity to Γ_{inv} at the ILC

Signal process: $e^+e^- \rightarrow ZH \rightarrow \text{two jets} + \cancel{E}_T$. 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).

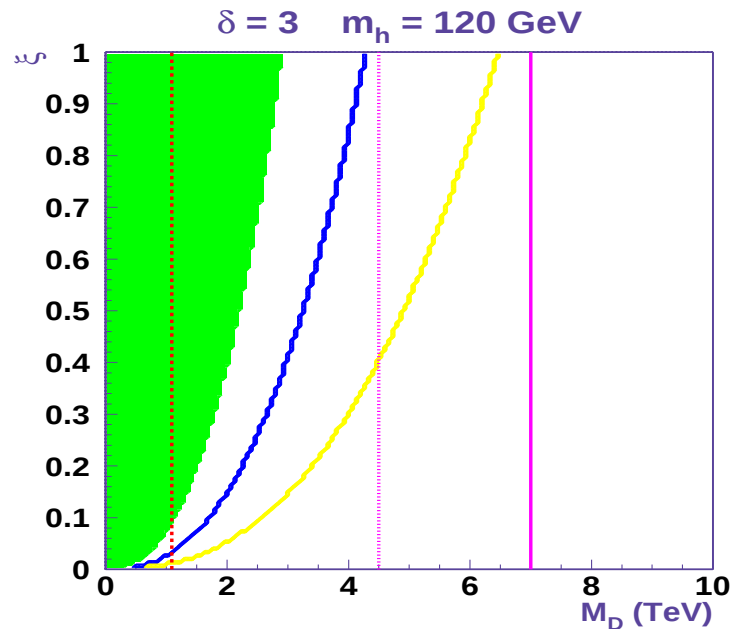
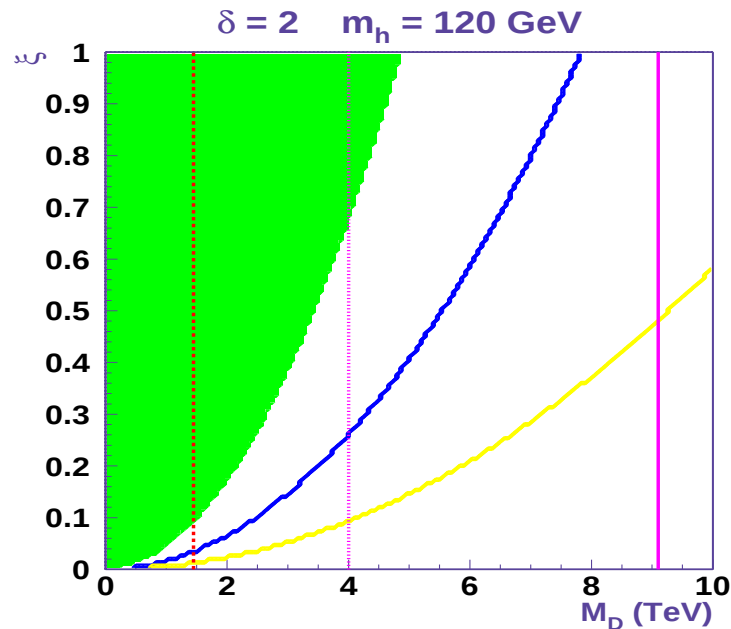


Invisible Higgs discovered down to $B \sim 0.02$.

Recent proposal: working at $\sqrt{s} = 230$ GeV for $L=50 \text{ fb}^{-1}$

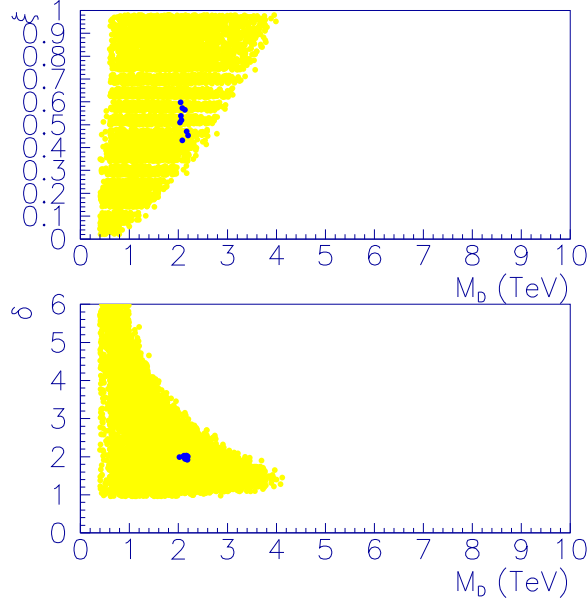
(Richard, Bambade).

The **green regions**: the Higgs signal at the LHC $< 5 \sigma$ for 100 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 5σ by the analysis of jets/ γ 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 $L = 500 \text{ fb}^{-1}$.

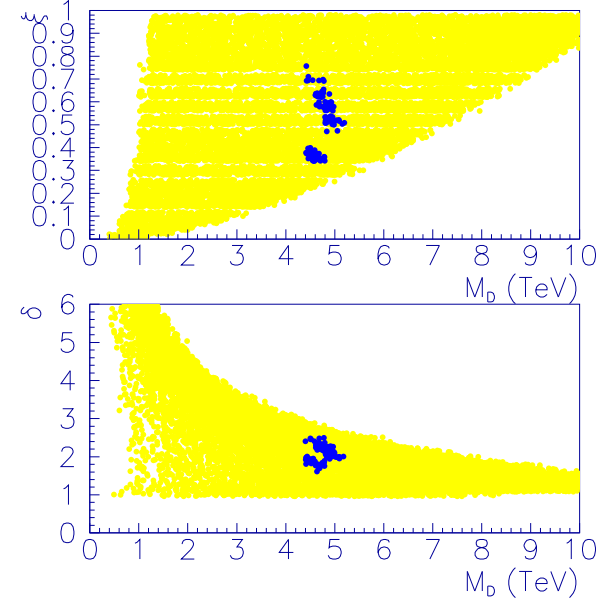


Determining ADD parameters from LHC and ILC data

$\delta = 2, M_H = 120 \text{ GeV}, M_D = 2 \text{ TeV}, \xi = .5$



$\delta = 2, M_H = 120 \text{ GeV}, M_D = 5 \text{ TeV}, \xi = .5$



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 $\sqrt{s} = 350 \text{ GeV}$.

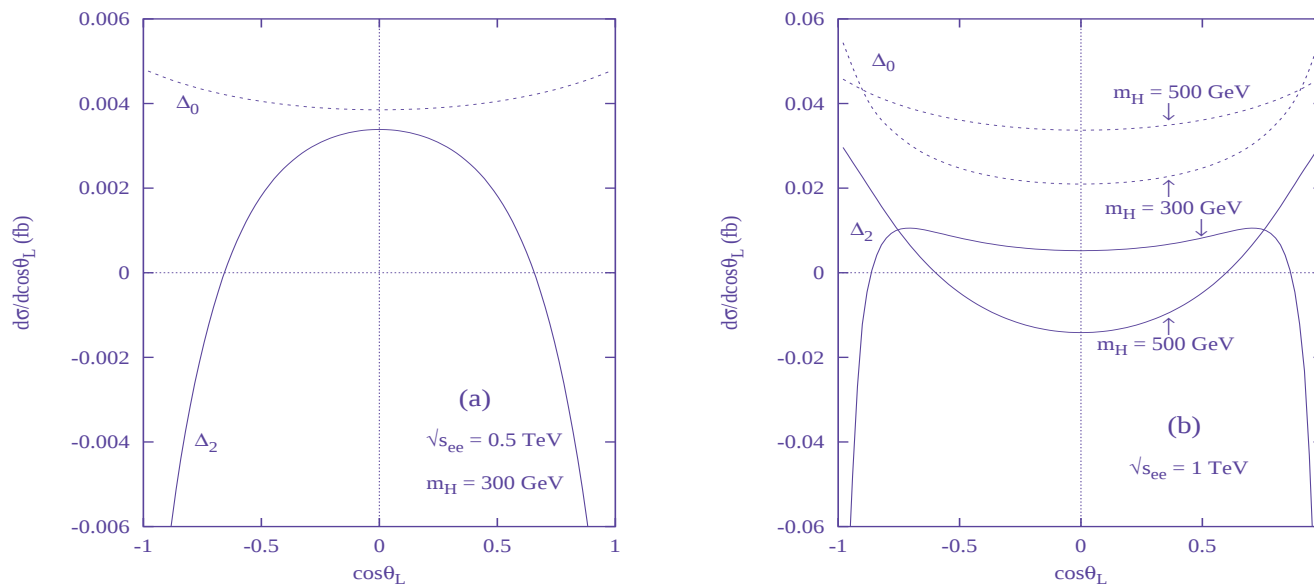
ILC $\gamma + \cancel{E}_T$ signal at two different energies: at $\sqrt{s} = 500 \text{ GeV}$ and $\sqrt{s} = 1000 \text{ GeV}$ of respectively, 1000 fb^{-1} and 2000 fb^{-1} , respectively,

$P_{e^-} = 0.80, P_{e^+} = 0.60, E_\gamma < 0.625 E_{beam}$. 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, Δ_2 , and graviscalar, Δ_0 , interference with resonant Higgs, present also when $\xi = 0$. $e^+e^-(WW) \rightarrow \nu\bar{\nu}P\bar{P}$, $P = W, Z, t$
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 $t\bar{t}$. 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 $\sigma(y) = kb_0|y|$. 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 $\Lambda_\phi = \sqrt{6} \overline{M}_{Pl} \Omega_0$, $\Omega_0 \equiv e^{-kb_0/2}$ is the warp factor.

A mixing among the radion and the Higgs $\widehat{H}$ is induced by
(Giudice, Rattazzi, Wells)

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

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:

$$-\frac{1}{\overline{M}_{Pl}} h_{\mu\nu}^0 T^{\mu\nu} - \frac{1}{\hat{\Lambda}_W} \sum_{n=1}^{\infty} h_{\mu\nu}^n T^{\mu\nu}$$

where

$$\hat{\Lambda}_W \sim \sqrt{2\overline{M}_{Pl}\Omega_0} \sim \text{TeV},$$

Our choice of parameters:

$$\xi \quad \Lambda_\phi \quad m_h \quad m_\phi$$

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

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

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 .

❖ Radion-Higgs couplings to gauge bosons and fermions

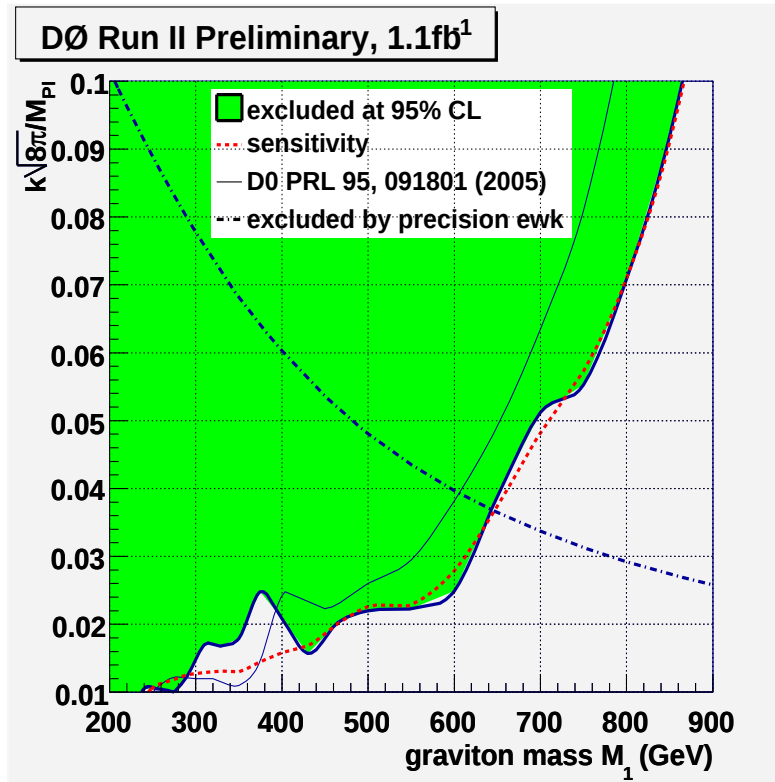
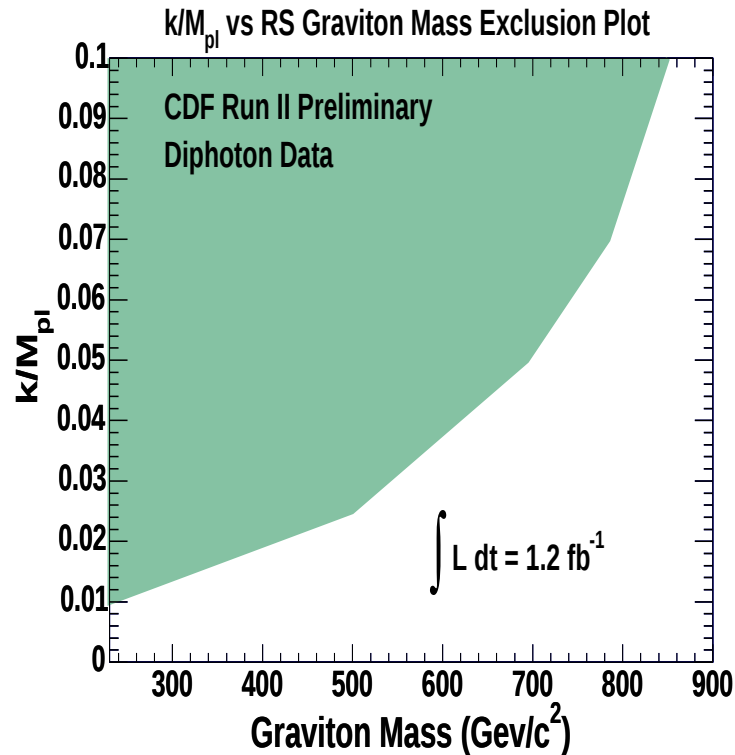
$$\bar{g}_{ZZh} = \frac{g m_Z}{c_W} (d + \gamma b), \quad \bar{g}_{ZZ\phi} = \frac{g m_Z}{c_W} (c + \gamma a),$$

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

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

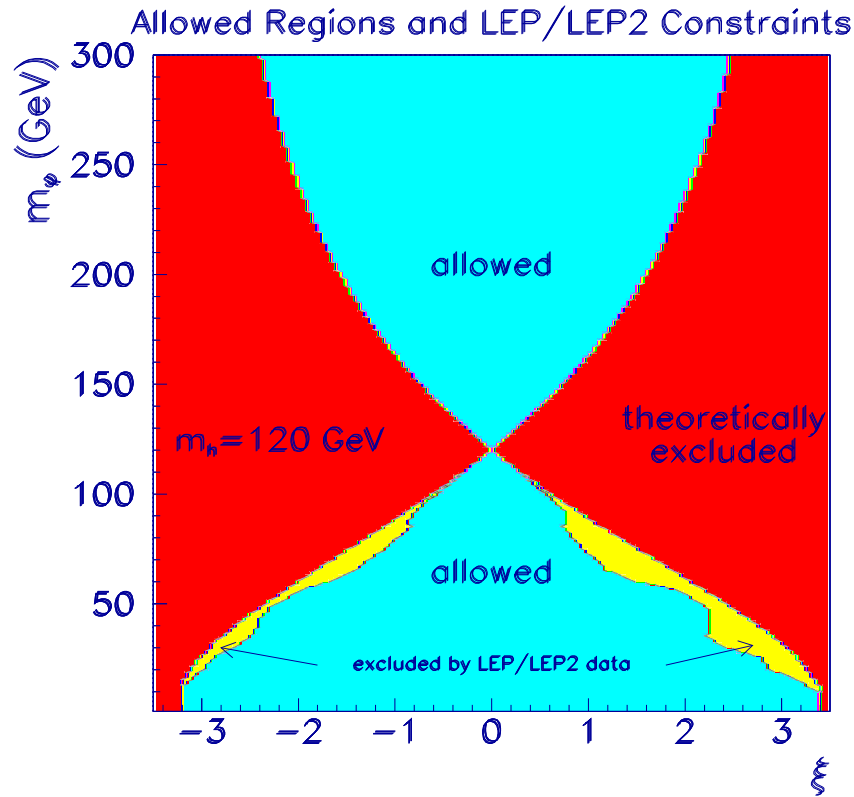
$$\gamma \equiv v/\Lambda_\phi.$$

Run II analysis searches for high mass di-photon states



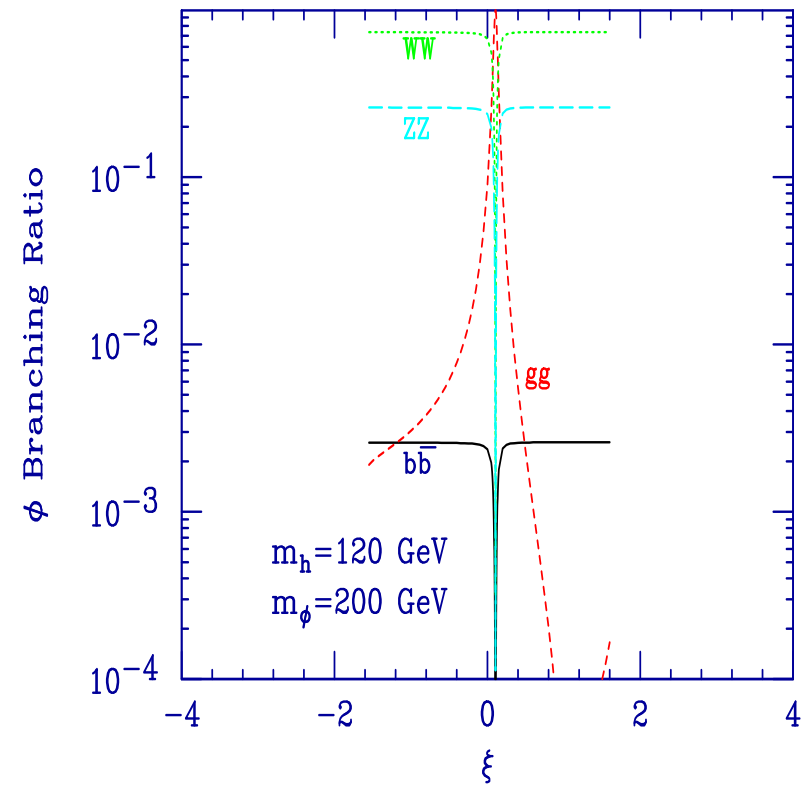
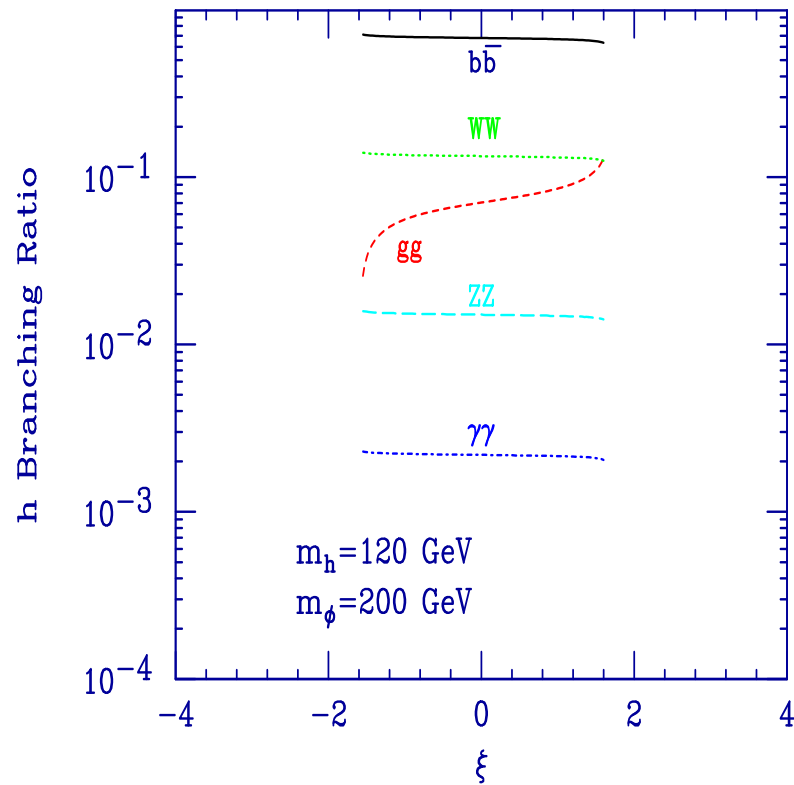
For example, $k/\bar{M}_{Pl} = 0.1$, $m_1 > 850 \text{ GeV}$ implying $\Lambda_\phi > 5.4 \text{ TeV}$. Including e^+e^- graviton decay, $m_1 > 889 \text{ GeV}$ (D0 $m_1 > 865$).

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).

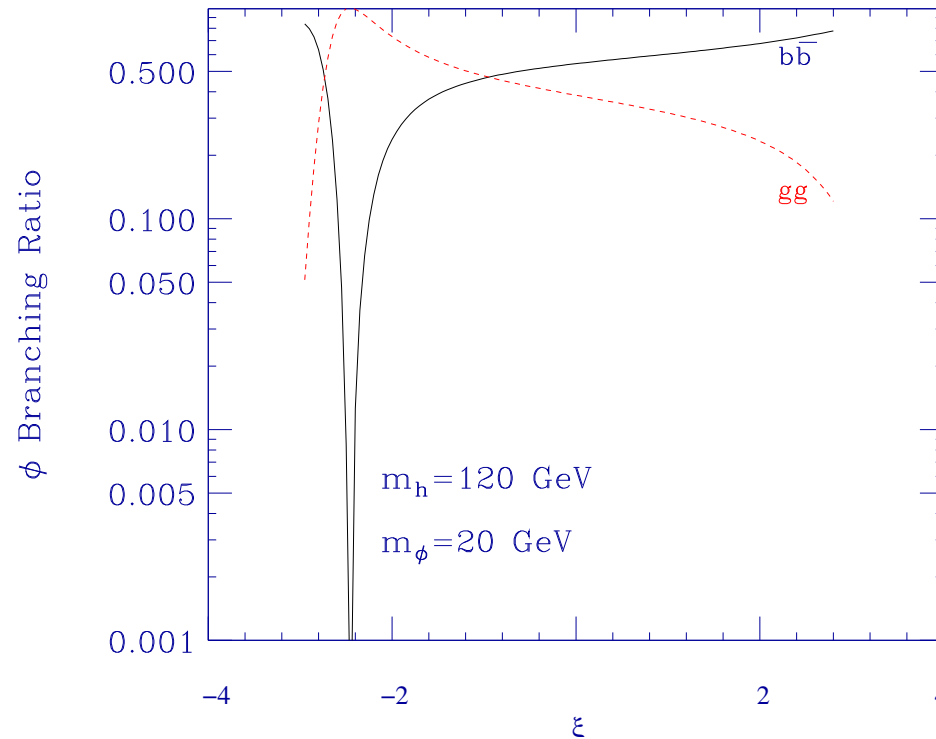


For $m_h = 112$ GeV, almost all excluded. For $\Lambda_\phi = 1$ TeV light radion much more constrained.

The branching ratios for h (left) and ϕ (right) for $m_h = 120$ GeV and $m_\phi = 200$ GeV, $\Lambda_\phi = 5$ TeV.

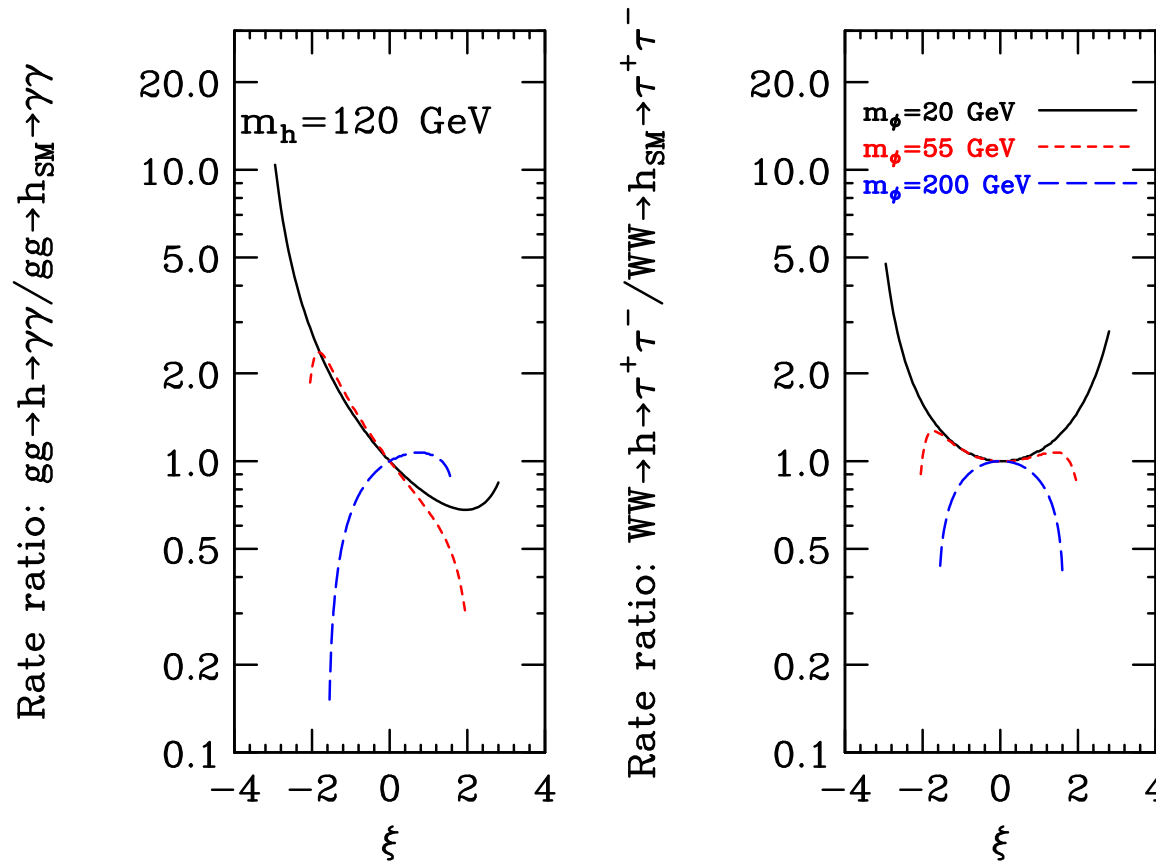


The branching ratios for ϕ decays to $b\bar{b}$, gg , for $m_h = 120$ GeV and $\Lambda_\phi = 5$ TeV as functions of ξ for $m_\phi = 20$ GeV

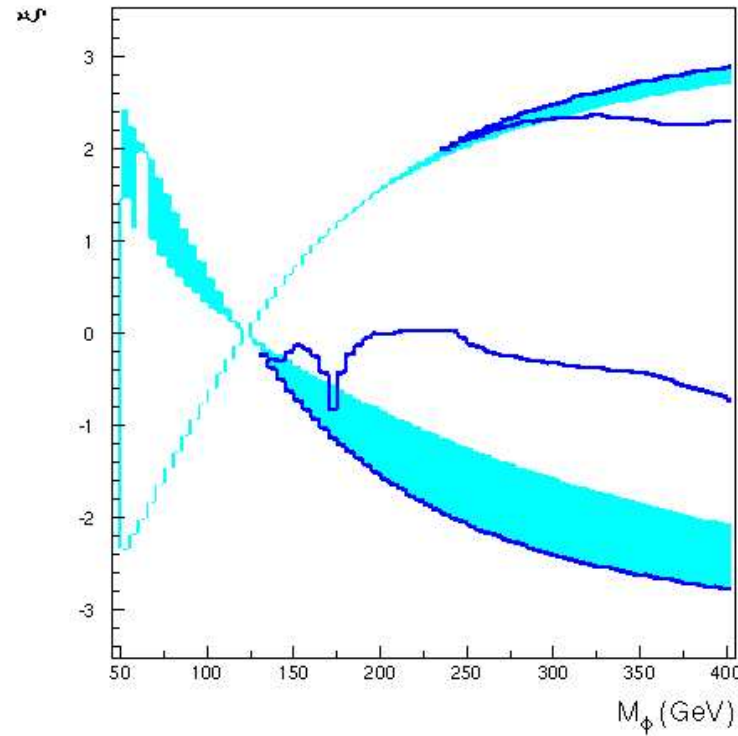


Prospects for h discovery at LHC

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 ξ for $m_\phi = 20, 55$ and 200 GeV.

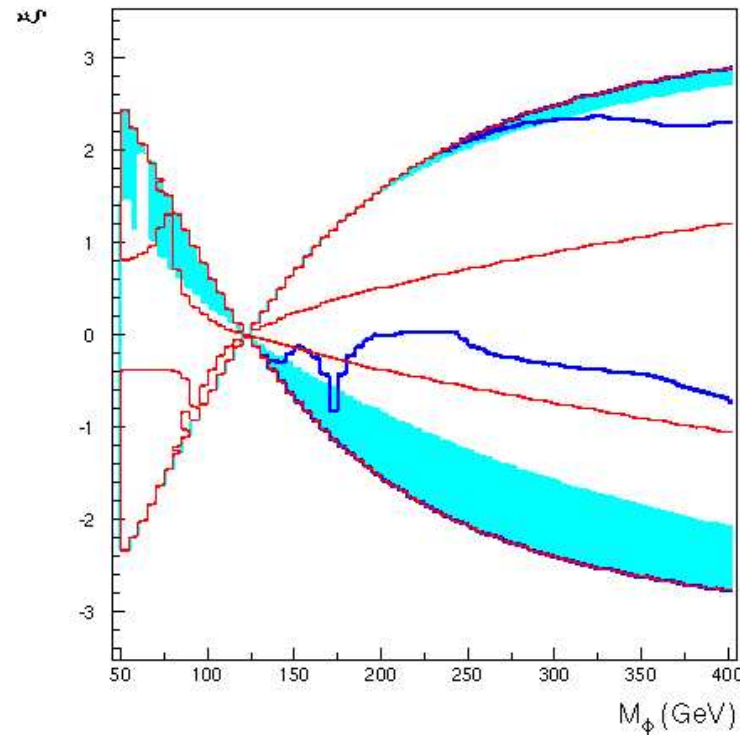


Complementarity at LHC



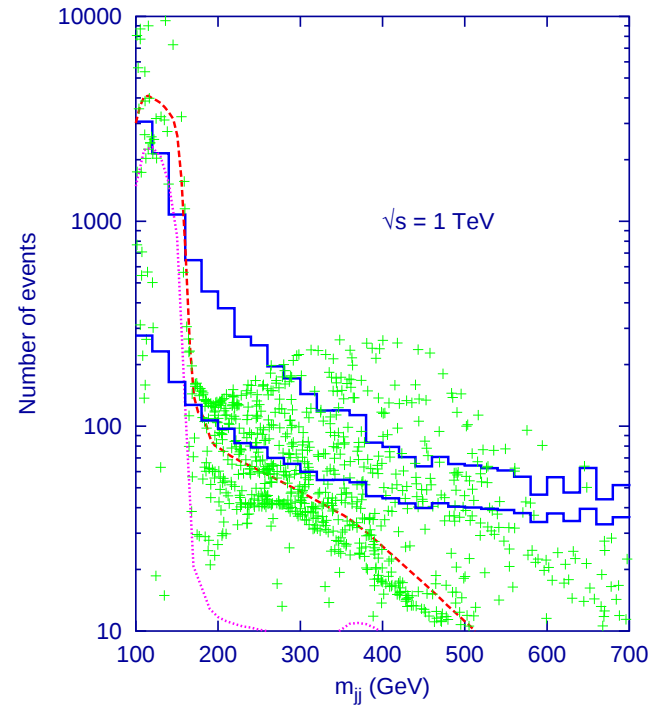
Regions of $gg \rightarrow h$ with $h \rightarrow \gamma\gamma$, $h \rightarrow ZZ^* \rightarrow 4\ell$, $h\bar{t}t(h \rightarrow \bar{b}b)$ and $gg \rightarrow \phi \rightarrow ZZ^* \rightarrow 4\ell$ detectability at LHC for one expt and 30 fb^{-1} . The cyan regions: Higgs signal significance $< 5\sigma$. The blue curves: $gg \rightarrow \phi \rightarrow ZZ^{(*)} \rightarrow 4\ell$ signal exceeds 5σ . For $m_h=120 \text{ GeV}$ and $\Lambda_\phi = 5 \text{ TeV}$.

Complementarity LHC/ILC



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 ϕ discovery at ILC, in $e^+e^- \rightarrow \nu\bar{\nu}\phi \rightarrow miss + gg$ (Datta, Huitu)



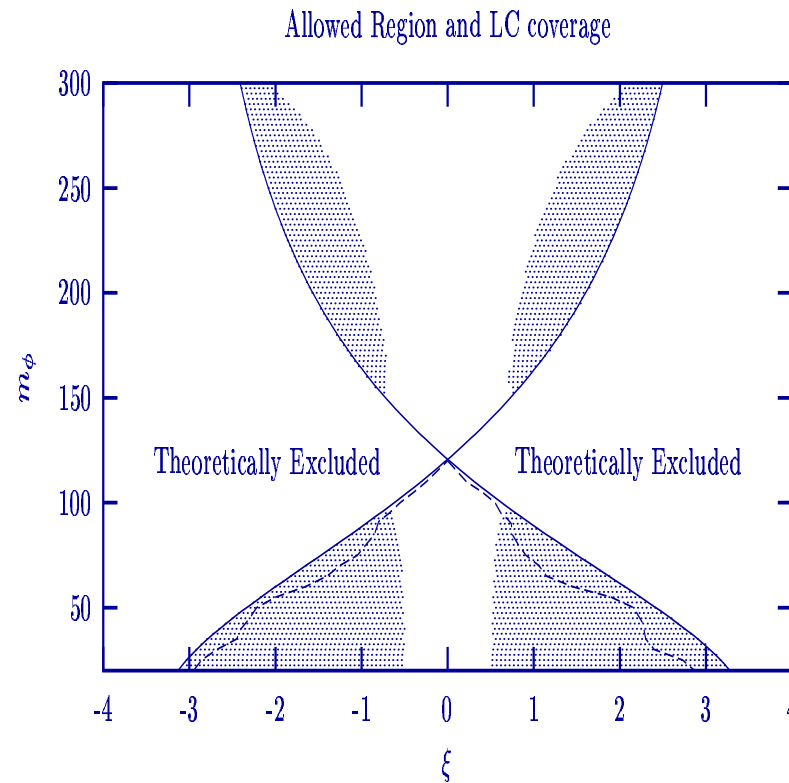
Number of signal (+ for $\xi \neq 0$ and dashed line is for $\xi = 0$), SM Higgs (dotted line) and background (solid histogram) events as a function of the invariant mass of the jets. The upper histogram the actual number of background events. The lower histogram the 5σ fluctuation of background. Points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

ILC sensitivity to the graviton-Higgs-radion coupling

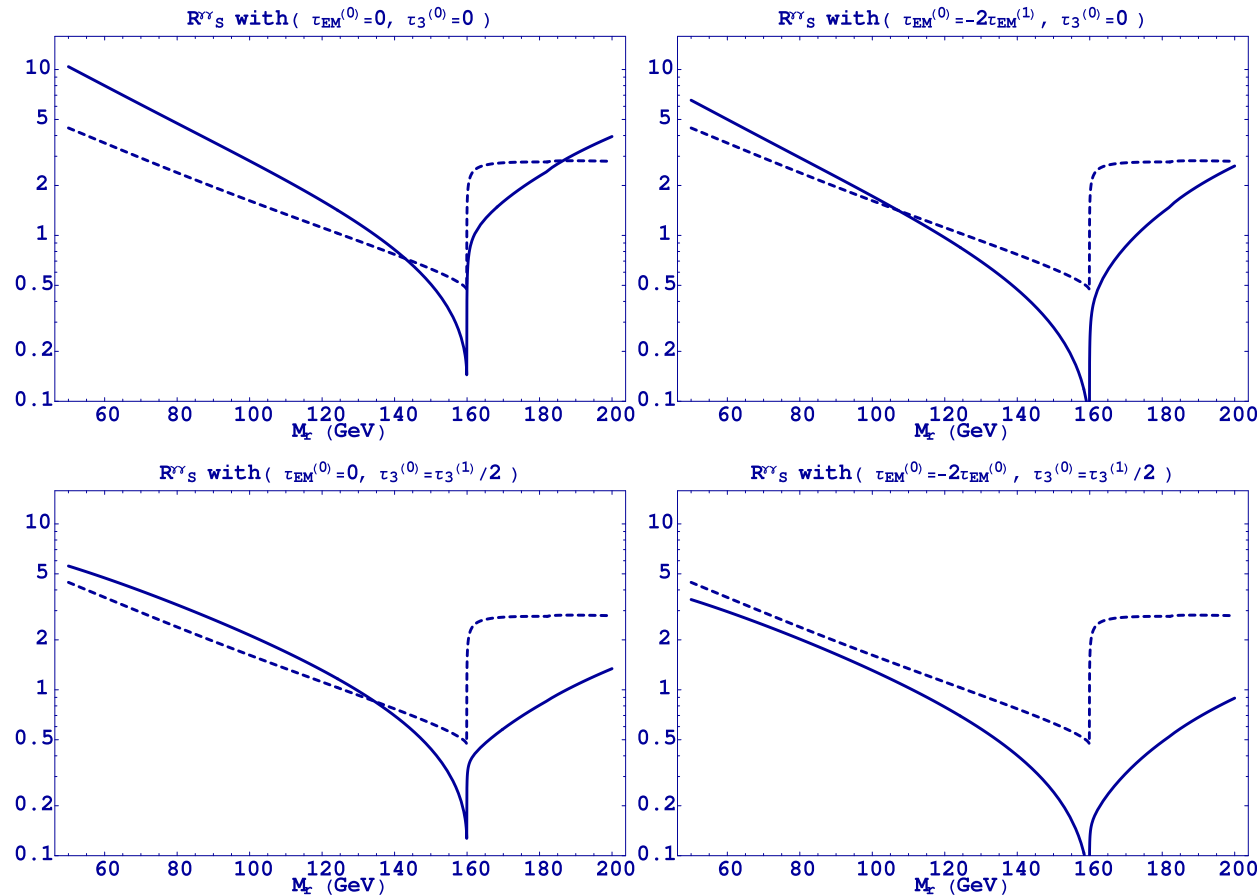
(Cheung, Kim, Song)

The dotted regions are for

$\sigma_{tot}(e^+e^- \rightarrow h_{\mu\nu}^n \rightarrow h\phi \rightarrow b\bar{b}b\bar{b}) > 0.03 \text{ fb. } m_h = 120 \text{ GeV,}$
 $\Lambda_\phi = 5 \text{ TeV.}$



Radion phenomenology in RS model with bulk fermions and gauge bosons (Csáki, Hubisz, Lee)

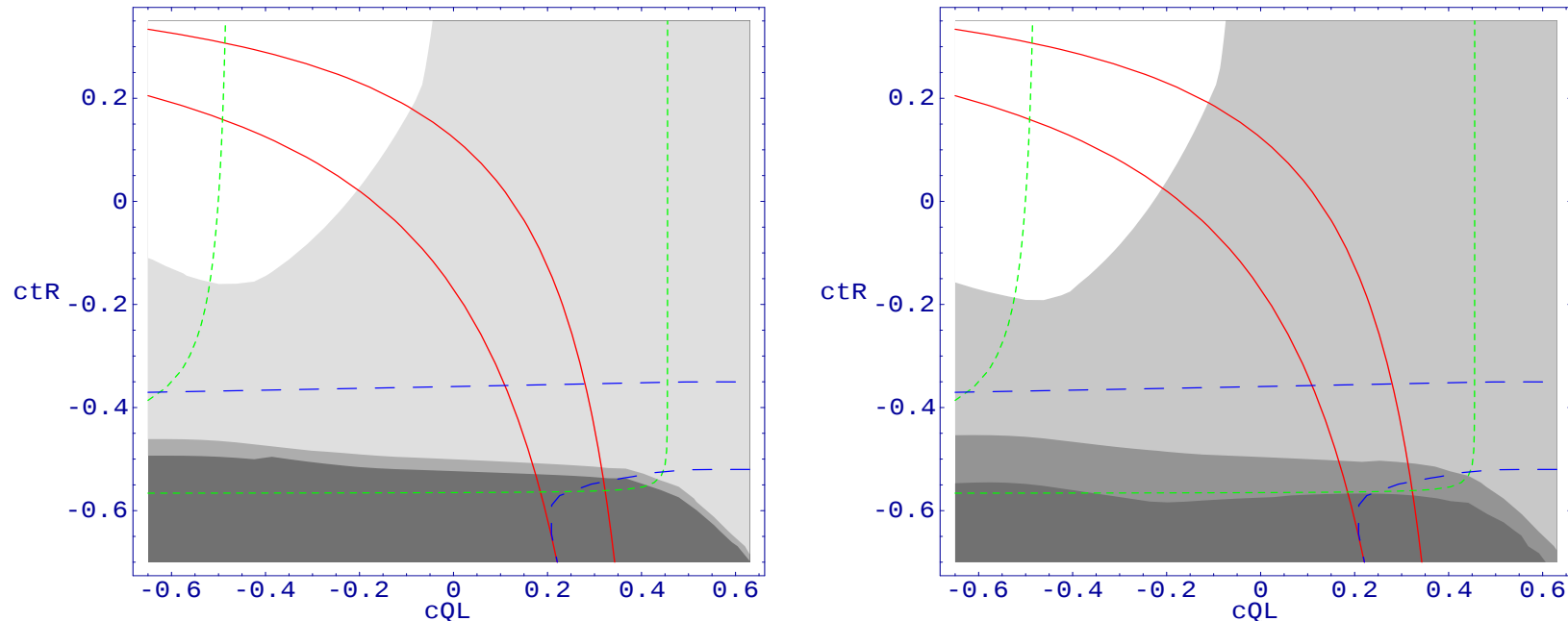


Ratio $R_S^{\gamma\gamma} = S(\phi)/S(h_{SM})$ with $\Lambda_\phi = 2$ TeV for various combinations of brane kinetic terms for the photon and the gluon. Dashed is RS model.

In some region more likely to find a radion!

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 $\mathcal{R} = \sigma_H^{RS} / \sigma_H^{SM}$ 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 5σ level at the LHC for a large portion of the Higgs-graviscalar mixing (ξ) and D -dimensional Planck mass (M_D) parameter space where channels relying on visible Higgs decays fail to achieve a 5σ signal.
- However LHC will not be able to determine M_D , ξ and δ
- Measurements of $\Delta BR(H)/BR(H)$ for the visible and the invisible channels and $\gamma + \cancel{E}_T$ at the e^+e^- ILC combined with LHC determine with good accuracy M_D , ξ and δ as long as not both δ and M_D are large.

RS

- LHC detection of the h in $gg \rightarrow h \rightarrow \gamma\gamma$ not guaranteed. LHC detection of the ϕ in $gg \rightarrow \phi \rightarrow \gamma\gamma$ likely to be difficult unless $\Lambda_\phi \sim 1\text{-}2$ 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:
 $pp, e^+e^- \rightarrow h_{\mu\nu}^n \rightarrow h\phi$
 $e^+e^- \rightarrow \nu\bar{\nu}\phi \rightarrow \text{miss} + gg$
 $\phi \rightarrow hh \rightarrow bb\gamma\gamma, 4b's, bb\tau\tau$; 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 $h \rightarrow \phi\phi \rightarrow bbgg, 4b's$.