Invisible Higgs in the ADD model at LHC

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- **Review of the ADD model**
- **Invisible Higgs**
- **Conclusions**

Based on

Battaglia, DD, Gunion, Wells hep-ph/0402062

Battaglia, DD, Gunion, Wells in preparation

ADD model: a model with large ED

(Arkani-Hamed, Dimopoulos, Dvali, Antoniadis)

A geometrical reformulation of the hierarchy problem, combining braneworld and Kaluza Klein ideas: gravity in $D = 4 + \delta$ dimensions, SM particles localized on a 3 dimensional brane.

$$\overline{M}_P^2 = M_D^{\delta+2} R^\delta \sim (\mathrm{TeV})^{\delta+2} R^\delta$$

R is the radius of the compactified space, a δ-torus.
$\overline{M}_P$ ($\overline{M}_P = (8\pi G_N)^{-1/2}$) is not fundamental, $\overline{M}_P$ large because R is large.
Fenomenological implications:
light KK states (KK gravitons and graviscalars)

$$m_{\vec{n}}^2 = \vec{n}^2 R^2 \quad \vec{n} = (n_1, \ldots, n_\delta)$$

$$\Delta m_{\vec{n}} \sim 10^{-3}\mathrm{eV} - 10\,\mathrm{MeV}, \;\; \delta = 2 - 6$$

and very long lived ($\sim 10^{10}$yr).
Interactions with SM fields

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

95% CL Limits on M_D (TeV) from colliders

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

Collider bounds: from graviton emission process at LEP 2 ($e^+e^- \to \gamma \not{E}_T$, $e^+e^- \to Z \not{E}_T$) and Tevatron ($p\bar{p} \to \gamma \not{E}_T$, $p\bar{p} \to jets \not{E}_T$).

δ	2	3	4	5	6
LEP 2/Tevatron (Giudice, Strumia)	1.45	1.09	0.87	0.72	0.65

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

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

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

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

with

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

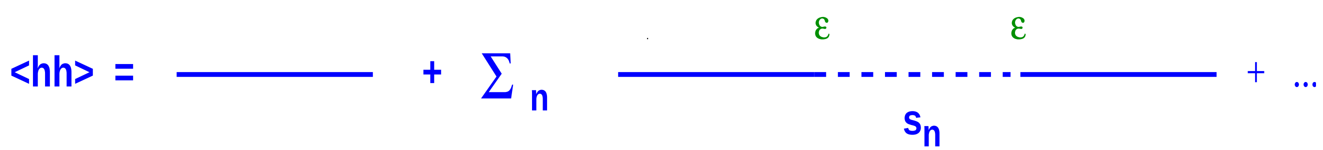
ξ is a dimensionless parameter and $s_{\vec{n}}$ is a graviscalar KK excitation.

Invisible Higgs width

The mixing requires diagonalization to the physical eigenstates h' and $s'_{\vec{n}}$: the $s'_{\vec{n}}$ are nearly continuous and so those near in mass to the h' act coherently together with the h'.

This mixing generates an oscillation of the Higgs itself into the closest KK graviscalar levels which are invisible since they are weakly interacting and mainly reside in the extra dimensions.

The mixing invisible width $\Gamma_{h \to graviscalar}$ calculated by extracting the imaginary part of the mixing contribution to the Higgs self energy. **(Giudice et al, Wells)**



In an equivalent way: first the mixing term can be eliminated with the transformation to the new fields h' and $s'_{\vec{n}}$

Then in computing a process such as $WW \to h' + \sum_{\vec{m}>0} s'_{\vec{m}} \to F$, the full coherent sum over physical states must be performed. The result at the amplitude level is

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

where

$$F(p^2) \equiv -\epsilon^2 \mathrm{Re} \left[\sum_{\vec{m}>0} \frac{1}{p^2 - m_{\vec{m}}^2 + i\bar{\epsilon}} \right]$$

and

$$G(p^2) \equiv -\epsilon^2 \mathrm{Im} \left[\sum_{\vec{m}>0} \frac{1}{p^2 - m_{\vec{m}}^2 + i\bar{\epsilon}} \right]$$

Writing $F(p^2) = F({m_h}_{eff}^2) + (p^2 - {m_h}_{eff}^2) F'({m_h}_{eff}^2) + \ldots$, where ${m_h}_{eff}^2 - m_h^2 + F({m_h}_{eff}^2) = 0$, we obtain the structure

$$\mathcal{A}(WW \to F)(p^2) \sim \frac{g_{WWh} g_{hF}}{(p^2 - {m_h}_{eff}^2)[1 + F'({m_h}_{eff}^2)] + i m_h (\Gamma_h + \Gamma_{inv})}$$

with

$$m_h \Gamma_{inv} = G(p^2)|_{{m_h}_{eff}^2} = Im\Sigma(p^2)|_{{m_h}_{eff}^2}$$

In conclusion:

$$\sigma(WW \to h' + \sum_{\vec{n}>0} s_{\vec{n}} \to F) = \sigma_{SM}(WW \to h \to F)\left[\frac{1}{1+F'(m^2_{eff})}\right]^2 \times \left[\frac{\Gamma^{SM}_{h\to F}}{\Gamma^{SM}_{h} + \Gamma_{h_{eff}\to graviscalar}}\right]$$

$$G({m_h}^2) \to -\epsilon^2 Im\frac{1}{2}\int dm^2 \rho_\delta(m)\frac{1}{{m_h}^2 - m^2 + i\bar{\epsilon}}$$

$$= -\epsilon^2\frac{1}{4}\frac{\overline{M}_P^2}{M_D^{2+\delta}} S_{\delta-1}(-\pi)({m_h}^2)^{(\delta-2)/2}$$

$$\Gamma_{h_{eff}\to graviscalar} \sim (16\,MeV)20^{2-\delta}\xi^2 S_{\delta-1}\frac{3(\delta-1)}{\delta+2} \times \left(\frac{m_h}{150\,GeV}\right)^{1+\delta}\left(\frac{3\,TeV}{M_D}\right)^{2+\delta}$$

S_δ denotes the surface of a unit radius sphere in δ dimensions.

- For a light Higgs boson both the wave function renormalization and the mass renormalization effects are small.
- A simple estimate of the quantity $F'(m^2_{h\,eff})$, appearing in the wave function renormalization, suggests that it is of order $\xi^2 \frac{m_h^4}{\Lambda^4}$, where $\Lambda \sim M_D$, therefore quite small for the $m_h \ll M_D$.
- Increasing δ, $\Gamma(h \rightarrow graviscalar)$ decreases: the density of states in which the Higgs can oscillate decreases.

Invisible width from direct two graviscalar decay

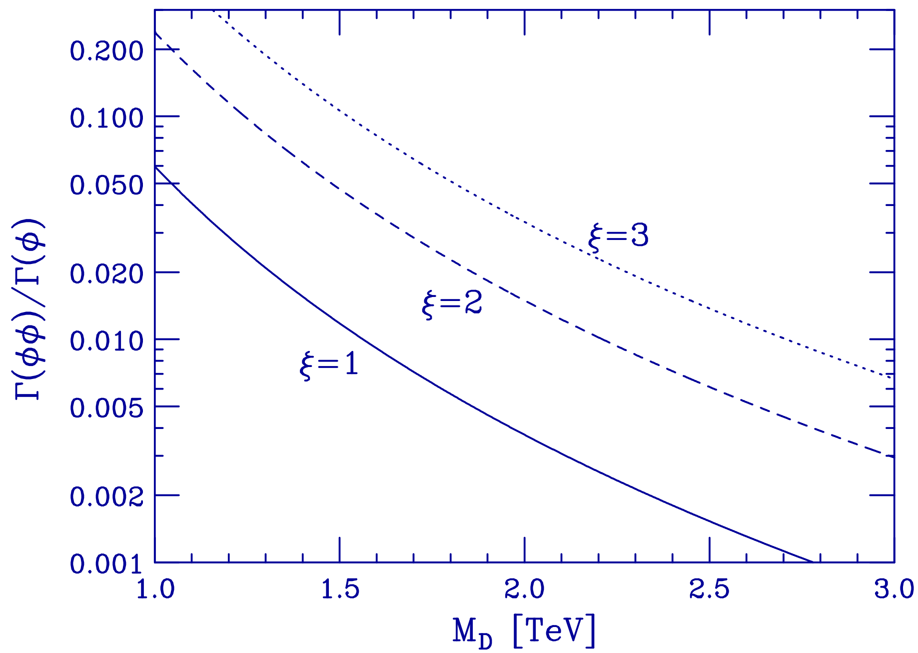
In addition to the Higgs invisible decay due to the oscillation in graviscalar by mixing, one expects also a contribution to the invisible width from the H decays into two graviscalars. Several sources of the cubic interactions. We have

$$\Gamma(h' \to graviscalar\ pairs) = \frac{18}{\pi}\frac{m_h^{3+2\delta}v^2}{M_D^{4+2\delta}}\xi^4\left(\frac{\delta-1}{\delta+2}\right)^2\left[\frac{\pi^{\delta/2}}{\Gamma(\delta/2)}\right]^2 I\,,$$

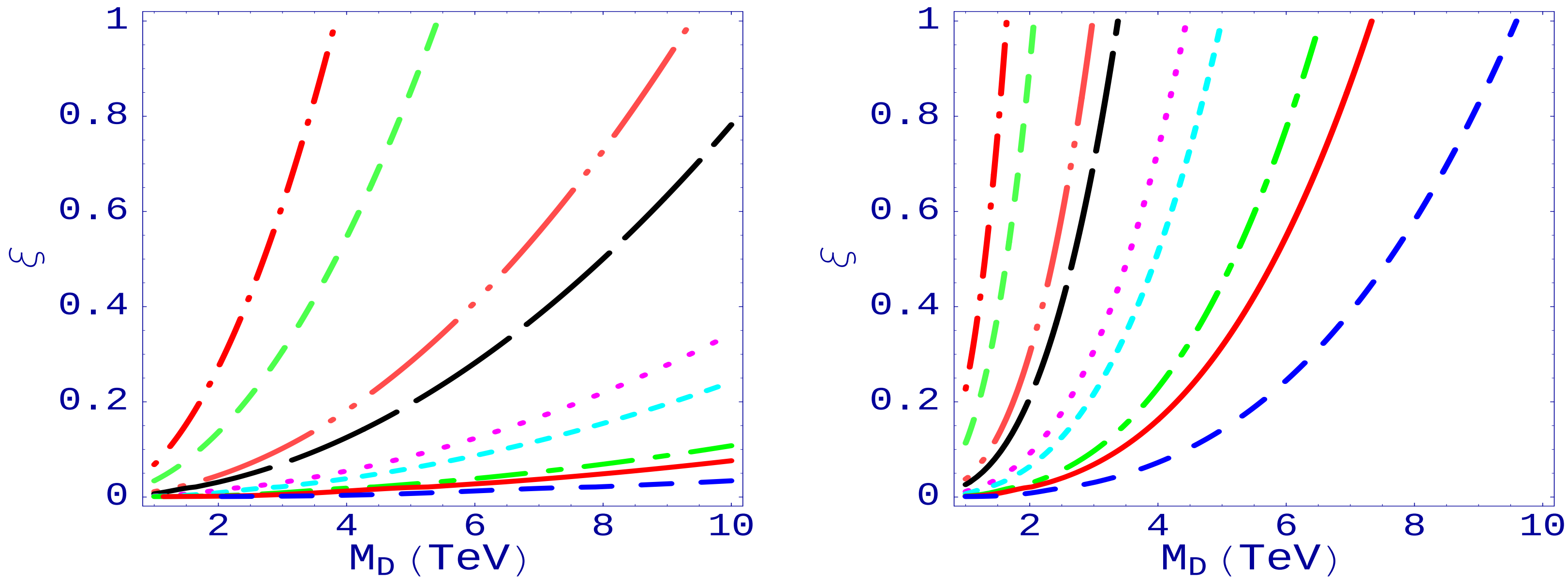
where I is an integral coming from the sum over all the possible kinematically allowed $h' \to s_k s_l$ decays. The integral I decreases rapidly as δ increases. The ratio of the two widths is given by:

$$\frac{\Gamma(h' \to graviscalar\ pairs)}{\Gamma(h' \to graviscalar)} = \frac{3(\delta-1)}{2\pi^2(\delta+2)}\xi^2\left(\frac{m_h}{M_D}\right)^{2+\delta}\frac{\pi^{\delta/2}}{\Gamma(\delta/2)}I\,.$$

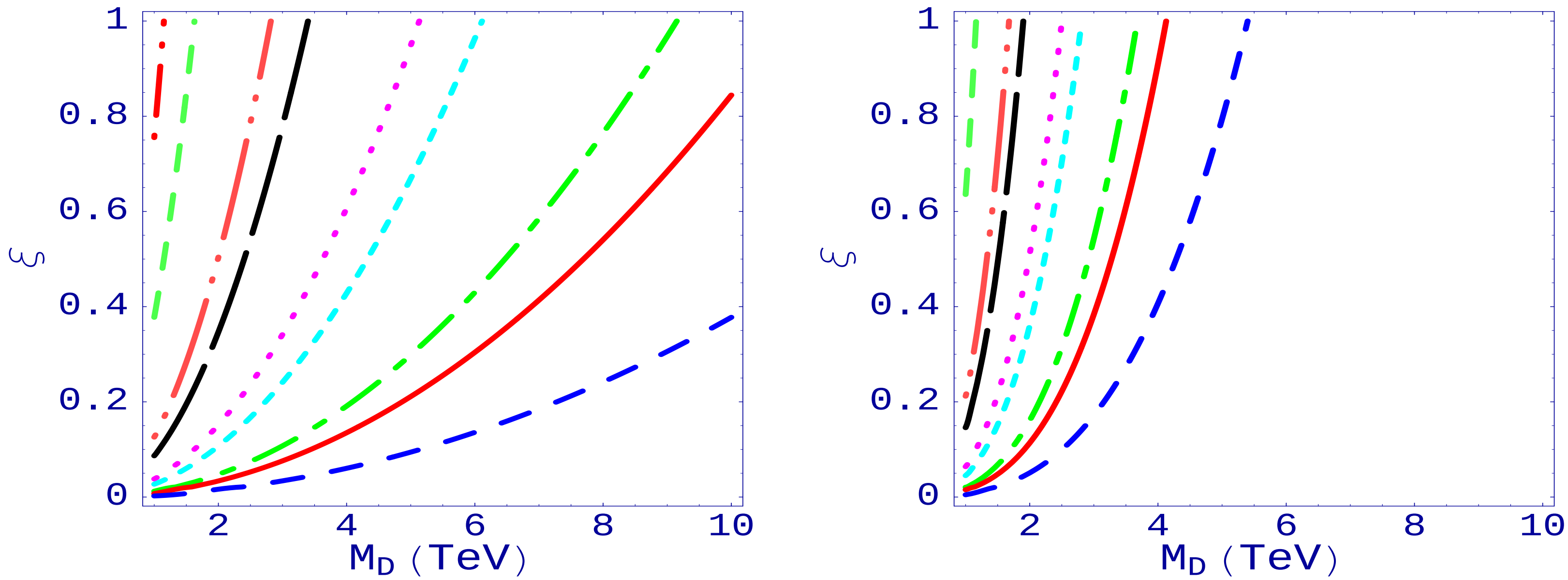
The ratio of the two-graviscalars decay width to the one-graviscalar decay width for a 1 TeV Higgs boson. ($\xi = 1$ solid, $\xi = 2$ dashed, $\xi = 3$ dotted), $\delta = 2$.



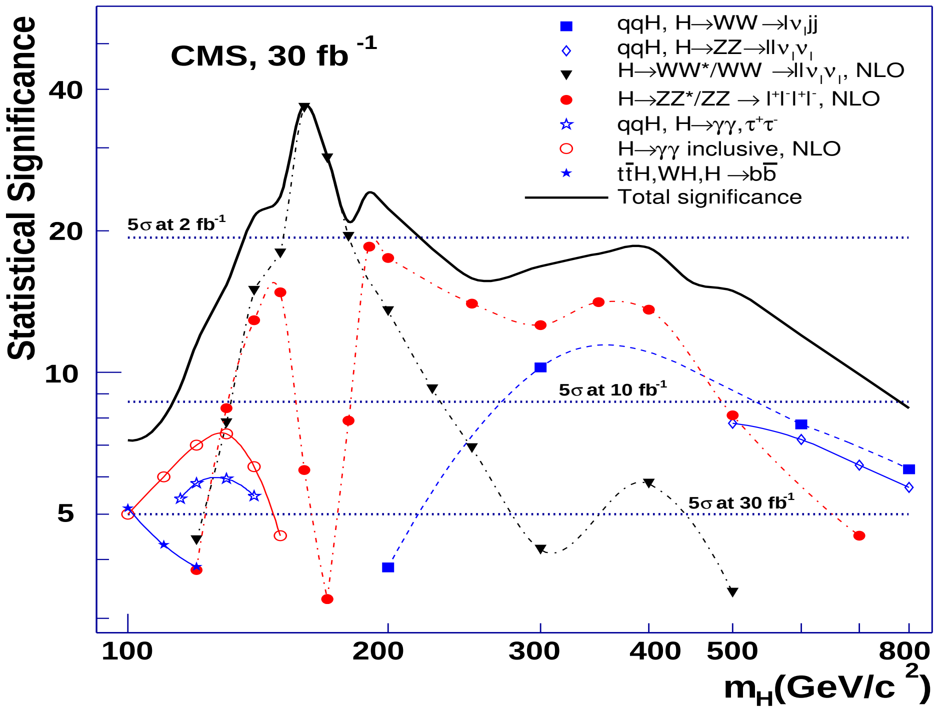
Contours of fixed $BR(h' \to graviscalar)$ in the M_D(TeV) – ξ parameter space for $m_h = 120$ GeV $\delta = 2$ (left) and $\delta = 4$ (right). In order of increasing ξ values, the width contours correspond to: 0.0001 (large blue dashes), 0.0005 (solid red line), 0.001 (green long dash – short dash line), 0.005 (short cyan dashes), $.01$ (purple dots), $.05$ (long black dashes), 0.1 (chartreuse long dashes with double dots), and 0.5 (green dashes), and 0.85 (red long dash, short dot line at high ξ and low M_D)



Contours of fixed $BR(h' \to graviscalar)$ in the M_D(TeV) – ξ parameter space for $m_h = 237$ GeV $\delta = 2$ (left) and $\delta = 4$ (right). In order of increasing ξ values, the width contours correspond to: 0.0001 (large blue dashes), 0.0005 (solid red line), 0.001 (green long dash – short dash line), 0.005 (short cyan dashes), $.01$ (purple dots), $.05$ (long black dashes), 0.1 (chartreuse long dashes with double dots), and 0.5 (green dashes), and 0.85 (red long dash, short dot line at high ξ and low M_D)



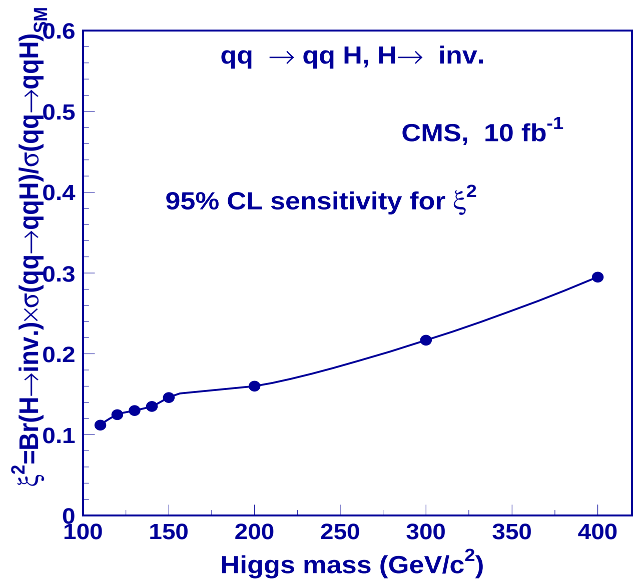
- For a light Higgs boson the invisible width causes a significant suppression of the LHC rates in the standard visible channels
- There are regions where the invisible Higgs could be the first measured effect from extra dimensions
- For visible channels we have used the CMS statistical significance



Sensitivity to Γ_{inv} at LHC

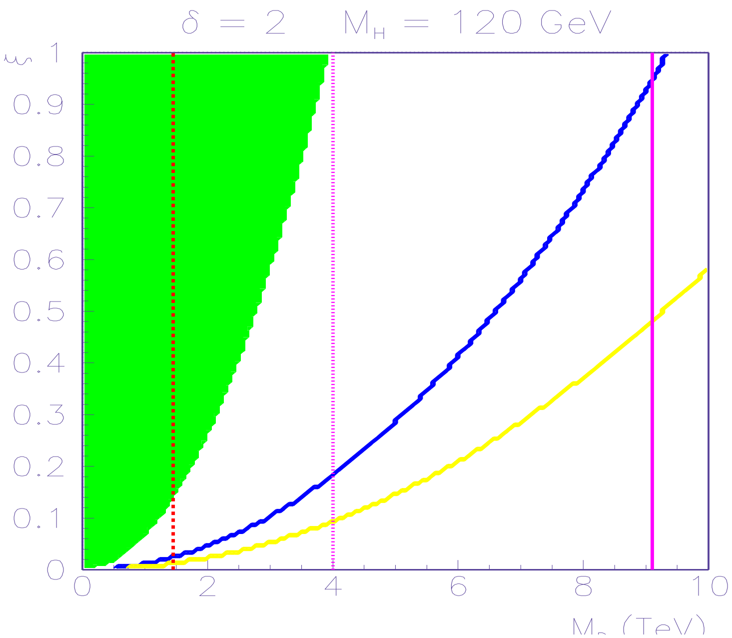
(Fusion channel: Eboli and Zeppenfeld, Di Girolamo et al, Abdullin et al, CMS note)

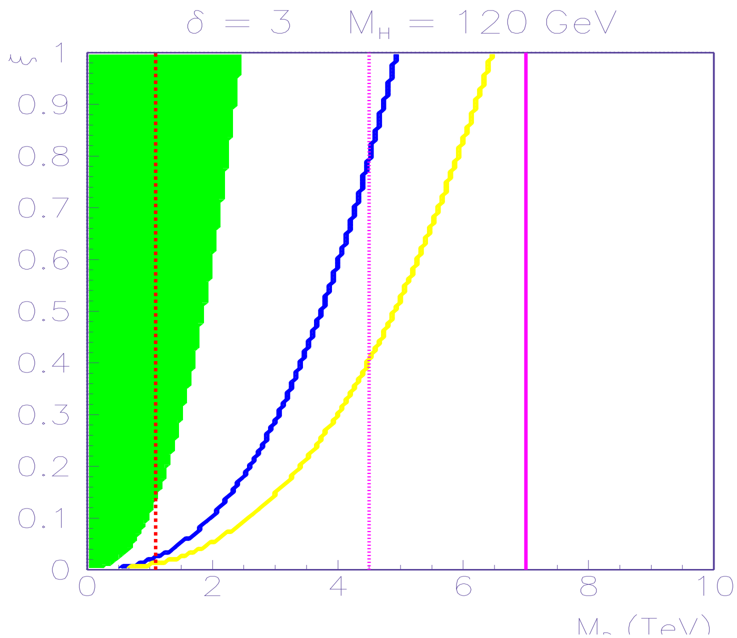
Higgs boson production in $qq \to qqVV \to qqh$ and subsequent h invisible decay. Signal characterized by two very energetic forward jets well separated in pseudorapidity. With $B_{inv} = 1$ and 10 (100) fb^{-1} it is possible discover Higgs up to 480 (770) GeV .



ZH channel (Dilepton +missing $\not\!\!E_T$) (Godbole, Guchait, Mazumdar, Moretti and Roy) : $B_{inv} \sim 0.42(0.70)$ probed at 5σ level for $m_H = 120(160)$ GeV with 100 fb^{-1}.

The green regions: the Higgs standard signal at the LHC $< 5\ \sigma$ for 100 fb^{-1}. The regions above the blue line are the parts where the LHC invisible Higgs signal in the WW-fusion channel $> 5\ \sigma$. The purple line at the largest M_D value shows the upper limit on M_D which can be probed at the $5\ \sigma$ by the analysis of jets/γ with missing energy at the LHC. The red dashed line at the lowest M_D value is the 95% CL lower limit from Tevatron and LEP/LEP2 limits. The regions above the yellow line are the parts of the parameter space where the LC invisible Higgs signal will exceed $5\ \sigma$ assuming $\sqrt{s} = 350$ GeV and $L = 500$ fb^{-1} (We made use of the (Schumacher) analysis on invisible H in $e^+e^- \rightarrow 2jets + \not{E}_T$).

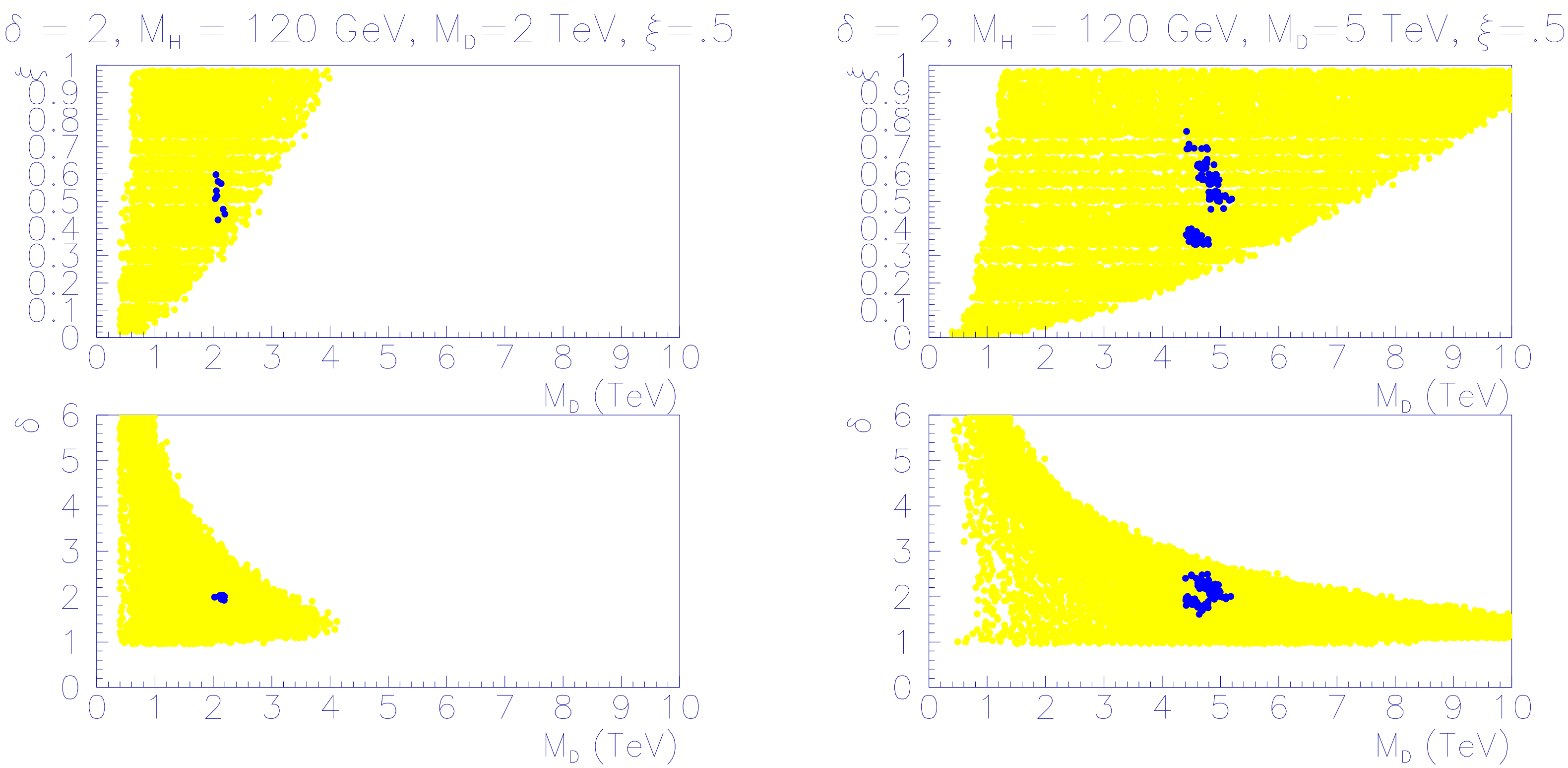




Determining ADD parameters from LHC and LC data

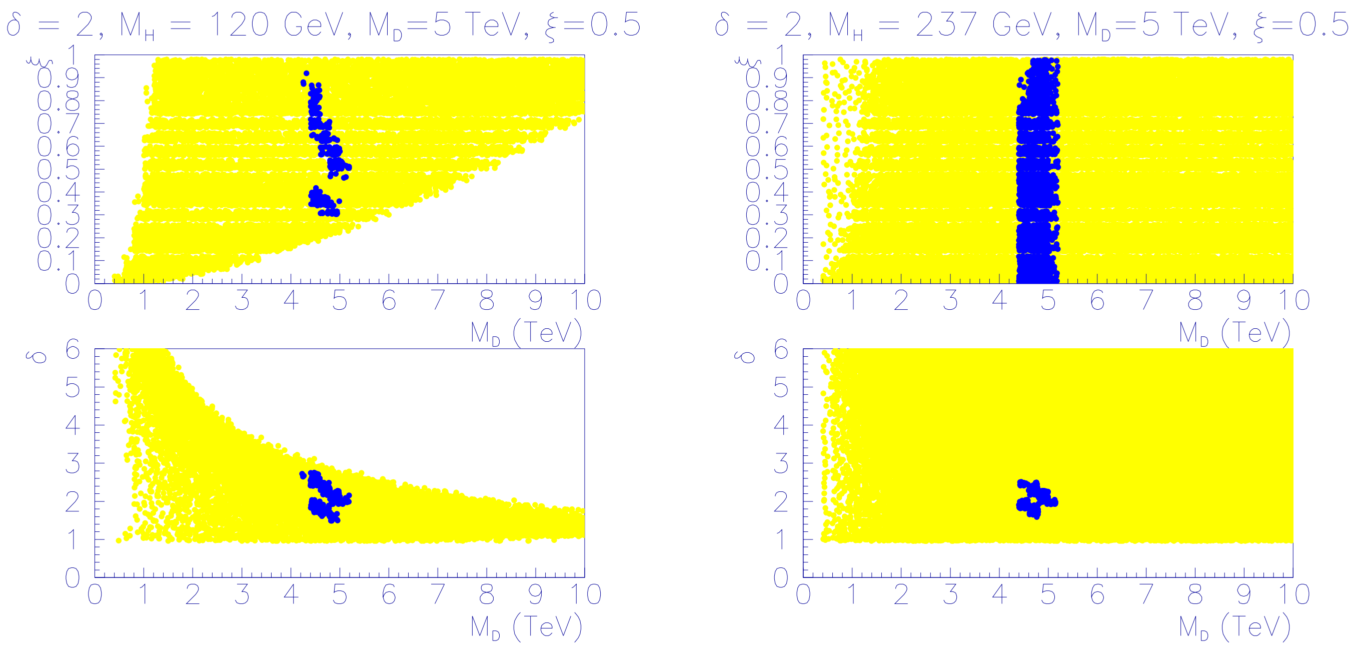
- For LHC we employed the visible and invisible Higgs signal assuming SM production rate for 30 fb^{-1} and 100 fb^{-1}.
- For LC we have used measurements of the visible (WW^*, $b\bar{b}$) and the invisible branching ratio at $\sqrt{s} = 350$ GeV.
- For LC we have also used the measurements of $\gamma + \not{E}_T$ signal at two different energies: the ratio of the two cross sections gives a strong constraint on δ. We have considered measurements performed at $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1000$ GeV of either 500 fb^{-1} and 1000 fb^{-1}, respectively, or 1000 fb^{-1} and 2000 fb^{-1}, respectively.

Determining ADD parameters from LHC and LC data



The larger (yellow) regions are the 95% CL regions using only $\Delta\chi^2(LHC)$. The smaller (blue) regions or points are the 95% CL regions using $\Delta\chi^2(LHC + LC)$.

Determining ADD parameters from LHC and LC data

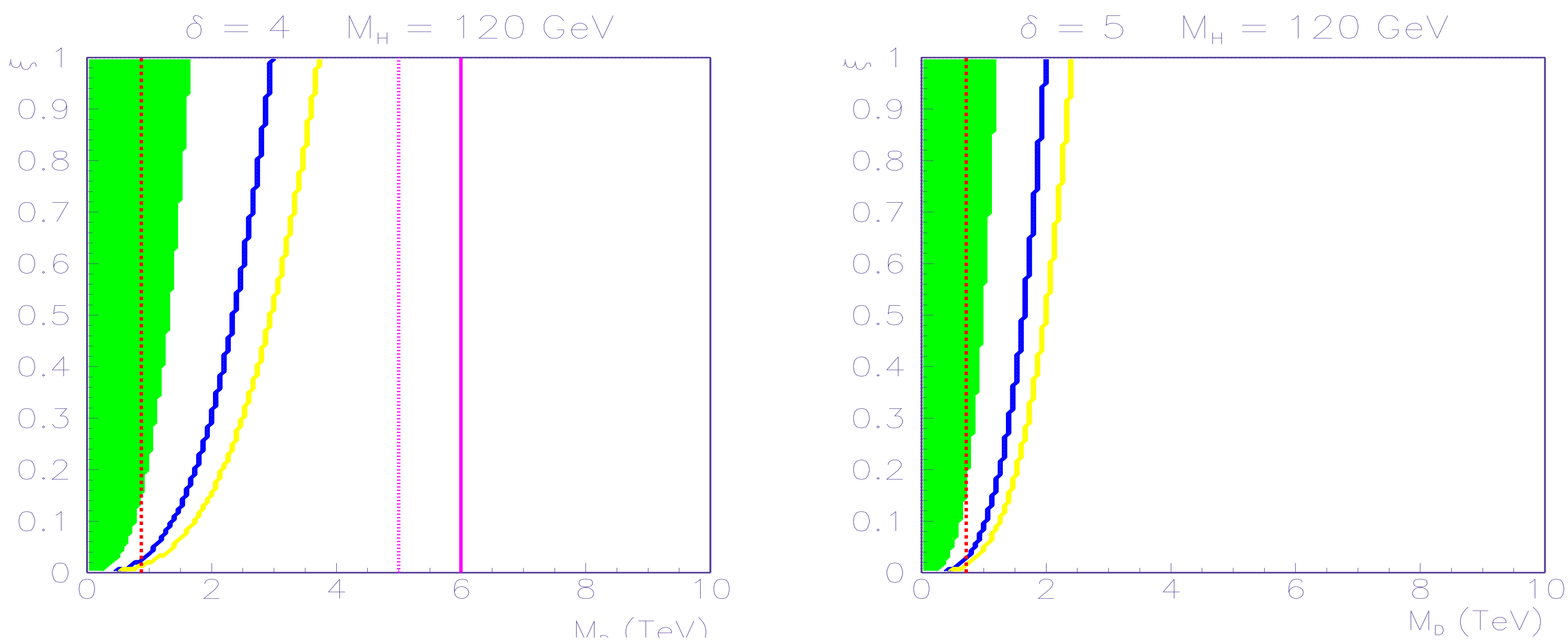


The larger (yellow) regions are the 95% CL regions using only $\Delta\chi^2(LHC)$. The smaller (blue) regions or points are the 95% CL regions using $\Delta\chi^2(LHC + LC)$.
Left: $m_H = 120$ GeV, lower integrated luminosities, $L = 30$ fb^{-1} at the LHC and $L = 500$ fb^{-1} and $L = 1000$ fb^{-1} at $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1000$ GeV at the LC.
Right: $m_H = 237$ GeV, higher integrated luminosities.

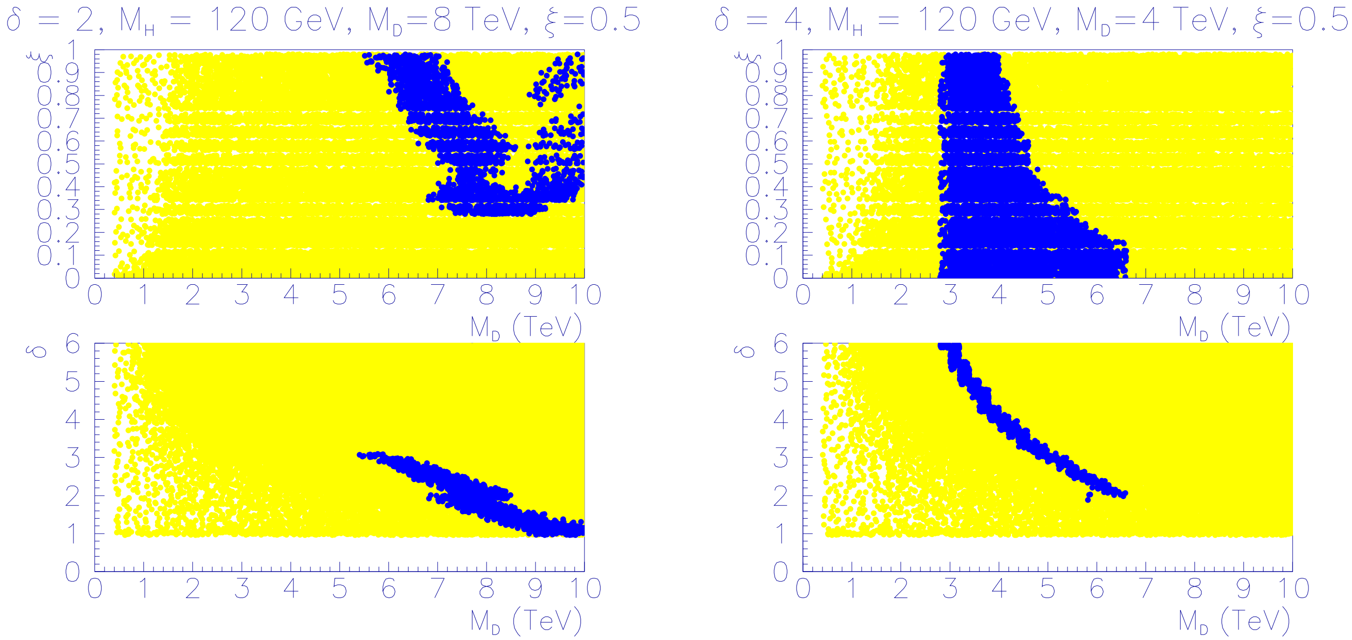
Conclusions

- **For a light Higgs boson the process $pp \to W^*W^* + X \to Higgs, graviscalars + X \to invisible + X$ will be observable at the $5\ \sigma$ level at the LHC for the 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 $5\ \sigma$ signal.**
- **However LHC will not be able to determine M_D, ξ and δ with any real precision.**
- **Measurements of $\Delta BR(H)/BR(H)$ for the visible and the invisible channels and $\gamma + \not{E}_T$ at the e^+e^- LC combined with LHC determine with good accuracy M_D, ξ and δ as long as not both δ and M_D are large.**

The green regions: the Higgs standard signal at the LHC $< 5\ \sigma$ for 100 fb^{-1}. The regions above the blue line are the parts where the LHC invisible Higgs signal in the WW-fusion channel $> 5\ \sigma$. The purple line at the largest M_D value shows the upper limit on M_D which can be probed at the $5\ \sigma$ by the analysis of jets/γ with missing energy at the LHC. The red dashed line at the lowest M_D value is the 95% CL lower limit from Tevatron and LEP/LEP2 limits. The regions above the yellow line are the parts of the parameter space where the LC invisible Higgs signal will exceed $5\ \sigma$ assuming $\sqrt{s} = 350$ GeV and $L = 500$ fb^{-1}.

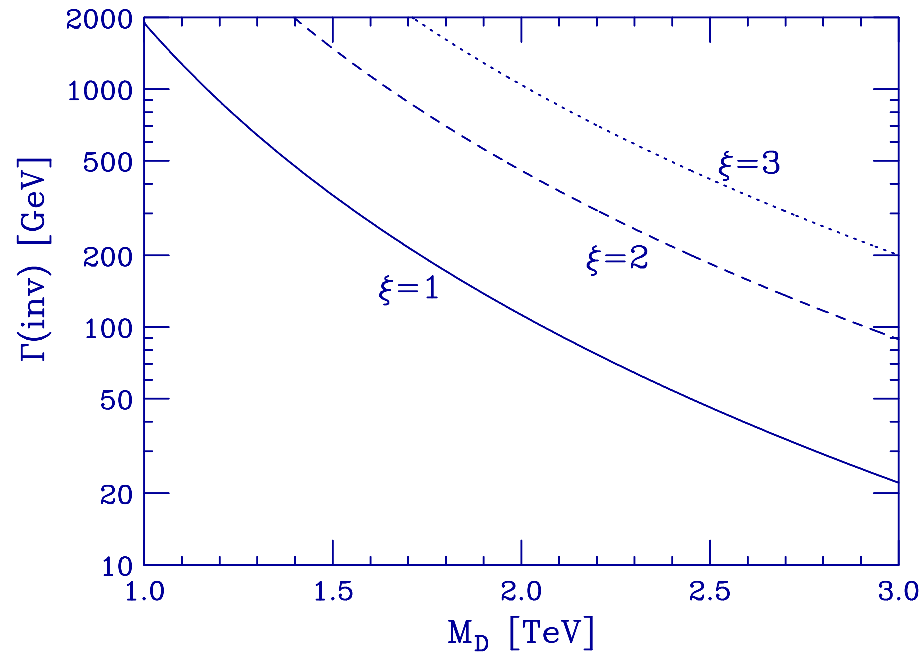


Determining ADD parameters from LHC and LC data



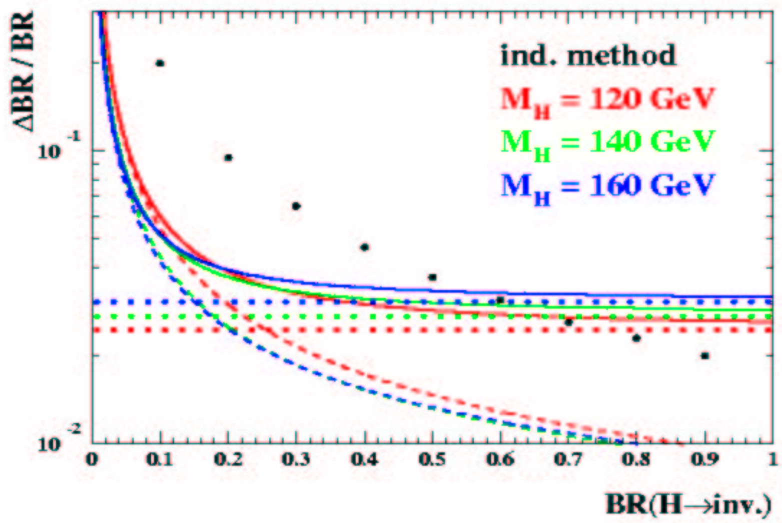
The larger (yellow) regions are the 95% CL regions using only $\Delta\chi^2(LHC)$. The smaller (blue) regions or points are the 95% CL regions using $\Delta\chi^2(LHC + LC)$

The total invisible width of a 1 TeV Higgs boson into one and two graviscalars as a function of M_D for various values of ξ ($\xi = 1$ solid, $\xi = 2$ dashed, $\xi = 3$ dotted), $\delta = 2$.



Sensitivity to ADD Γ_{inv} at the LC

Relative accuracy of the measurement of the invisible branching as a function of the branching ratio, for $m_H = 120,\ 140,\ 160$ GeV for 500 fb^{-1} at $\sqrt{s}$ =350 GeV. (Schumacher).



Signal process: $e^+e^- \to ZH \to twojets\not{E}_T$. Invisible Higgs discovered down to $B \sim 0.02$ for masses 120-160 GeV.

Sensitivity to H_{inv} at the Tevatron

(Martin and Wells). $p\bar{p} \to ZH \to l^+l^- + \not{E}_T$ channel, assuming $BR(H \to inv) = 100\%$:

m_H [GeV]	95% Exclusion Luminosity [fb^{-1}]	3σ Observation Luminosity [fb^{-1}]	5σ Discovery Luminosity [fb^{-1}]
90	3.1	7.3	20
100	5.0	11.6	32
110	7.5	17.5	49
120	10.9	26	71
130	15.7	37	103
140	23	53	146
150	32	74	206

Luminosity required to make a 95% confidence level exclusion, 3σ observation, and 5σ discovery of an invisibly decaying Higgs boson in the $ZH \to l^+l^- + \not{E}_T$ channel.