Radions at LHC and LC

Albert De Roeck (CERN)

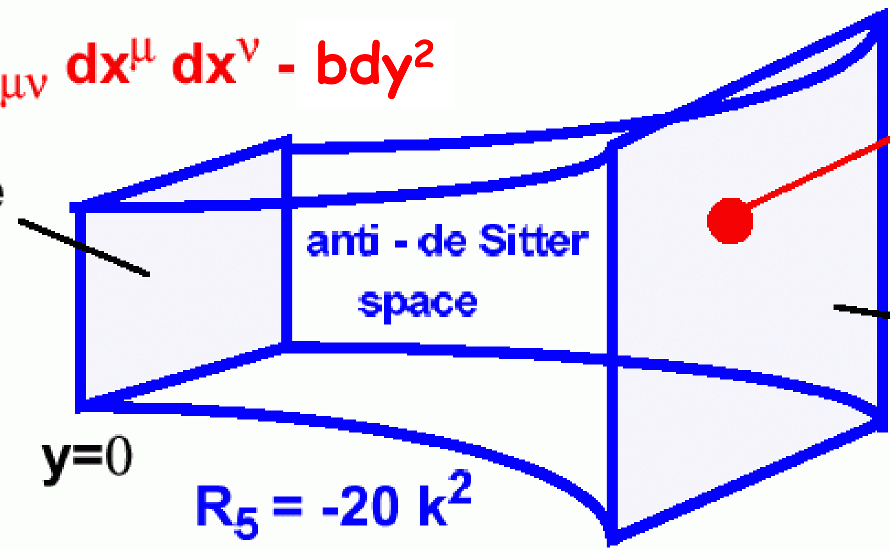
Contents

- Introduction
- Search for radions in $\gamma\gamma$ and ZZ decay channels
- Search for radions in $\phi \rightarrow hh$
- LHC/LC complementarity in Radion/Higgs searches and analysis
- Radions at a photon collider

Curved Space: RS Extra Dimensions

Randall, Sundrum, PRL 83, 3370 (1999)

$ds^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu - bdy^2$



$R_5 = -20\ k^2$

k ~ curvature

$M_{5D}^3 = k\ M_{Planck}^2$

- Gravity strong at y=0 and falls like exp(-ky)
- Gravity scale $\Lambda_\pi = M_{Planck}\exp(-k\pi r_c)$ ~ TeV — no hierarchy
- Graviton resonances $m_n = x_n\, k \exp(-k\pi r_c)$, $J_1(x_n)=0$
- $M_{Planck}/M_{electroweak} \Rightarrow kr_c \sim 11\text{-}12$
- Newton's law $\Rightarrow |R_5| < M_{5D}^2 \Rightarrow$ coupling $c < 0.1$

Radions

Radions (graviscalars) RS models: quantum excitations of the brane separation

Three Fundamental Parameters :

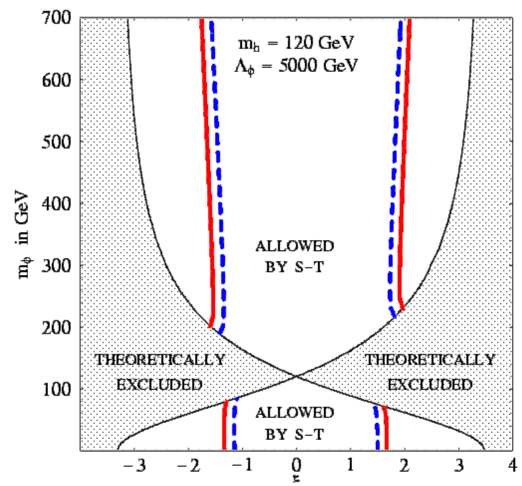
$$m_r \qquad \xi \qquad v/\Lambda$$

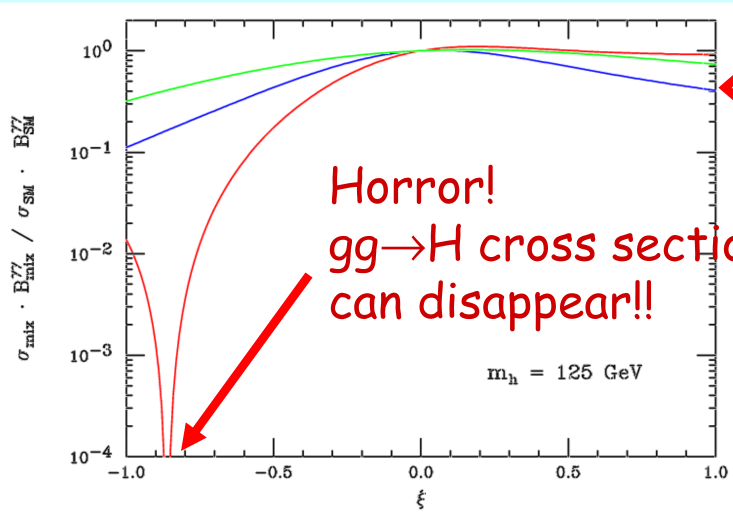
- Radion couplings to Gauge bosons and Fermions similar to SM H
- ϕ mixing to H ξ causes shift in g_{HVV} and g_{Hff} couplings

$$\frac{g'_{HVV}}{g^{SM}_{HVV}} = \frac{g'_{Hff}}{g^{SM}_{Hff}} = f_1(\xi, v/\Lambda, m_\phi) + \frac{v}{\Lambda} f_2(\xi, v/\Lambda, m_\phi)$$

Couplings to $\gamma\gamma$ and gg receive anomalous contributions

EW constraints





Gunion, Toharia & Wells hep-ph/0311219

Radions

Some Useful References

G Giudice, R Rattazzi and J Wells, *Nucl. Phys.* **B 595** (2001), 250 and hep-ph/0002178

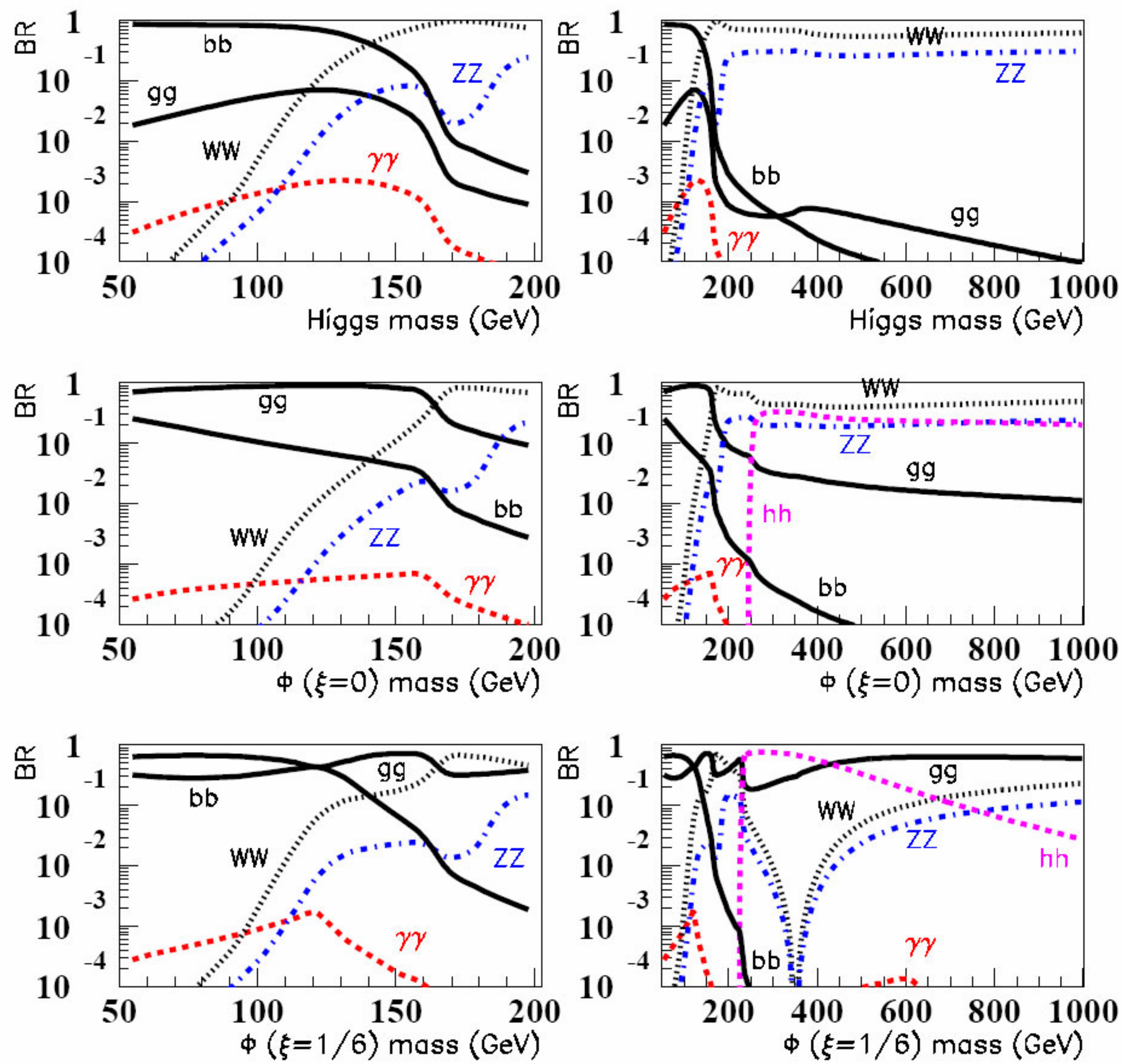
J Hewett and T Rizzo, *Radion Mixing Effects on the Properties of the SM Higgs Boson*, SLAC-PUB-9072 and hep-ph/0112343

J Hewett and T Rizzo, *Shifts in the Properties of the Higgs Boson from Radion Mixing*, SLAC-PUB-9132 and hep-ph/0202155

D Dominici *et al.*, *Higgs Boson Interactions within the Randal Sundrum Model*, hep-ph/0206197

D Dominici *et al.*, *The Scalar Sector of the Randall-Sundrum Model*, hep-ph/0206192

Branching Ratios of Radion and Higgs

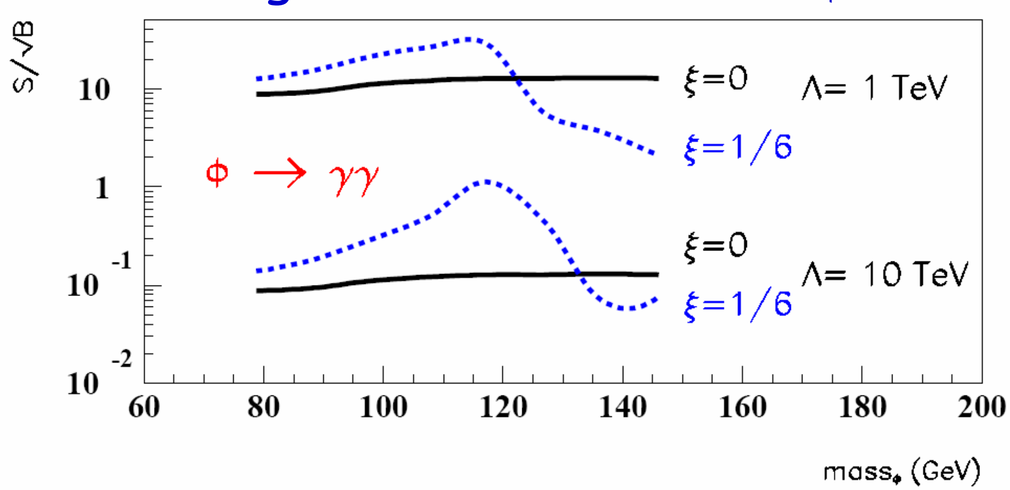


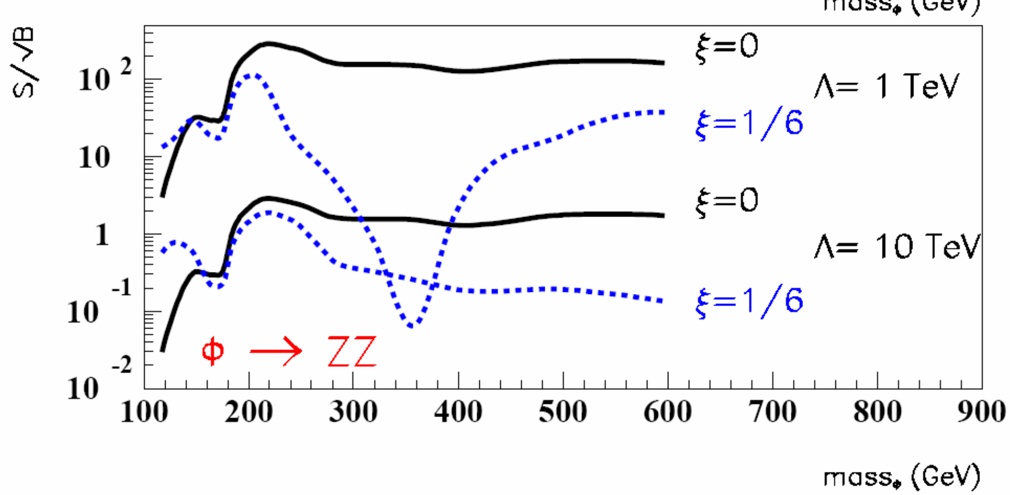
RADIONS

Radion searches at LHC

G. Azuelos et al, Eur. Phys. J. C4 16 2002

Significance to observe ϕ





Channels:
- $\phi \to \gamma\gamma$
- $\phi \to ZZ^{(*)} \to$ 4 leptons

Re-interprete the ATLAS Higgs signal significance

$$\frac{S/\sqrt{B}(\phi;\gamma\gamma,ZZ)}{S/\sqrt{B}(h;\gamma\gamma,ZZ)} = \frac{\Gamma_{\phi\to gg} BR(\phi\to\gamma\gamma,ZZ)}{\Gamma_{h\to gg} BR(h\to\gamma\gamma,ZZ)}\sqrt{\frac{\sigma_h^{\gamma\gamma,ZZ}}{\sigma_\phi^{\gamma\gamma,ZZ}}}$$

100 fb^{-1}

$\gamma\gamma \to S/\sqrt{B}$ = 10 (0.1) for Λ_ϕ =1 (10) TeV
$ZZ \to S/\sqrt{B}$ = 100 (1) for Λ_ϕ =1 (10) TeV

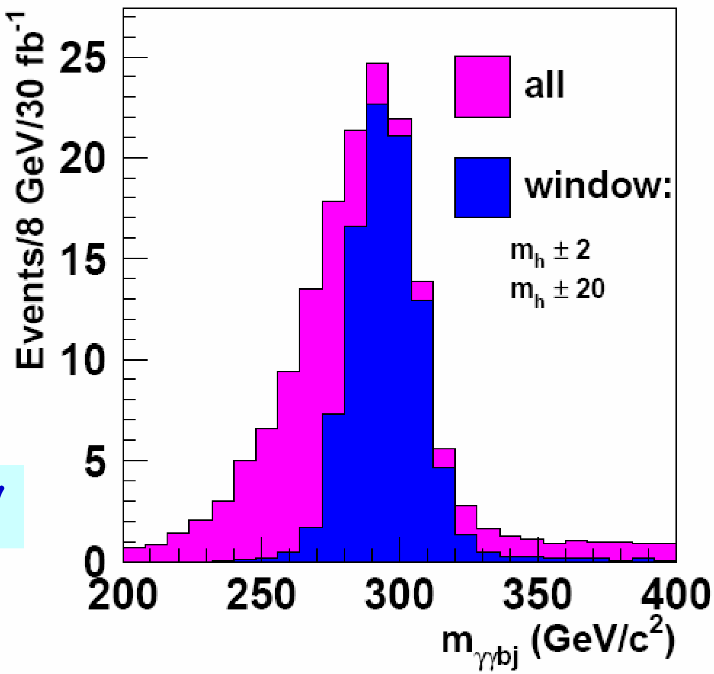
Radion searches at the LHC

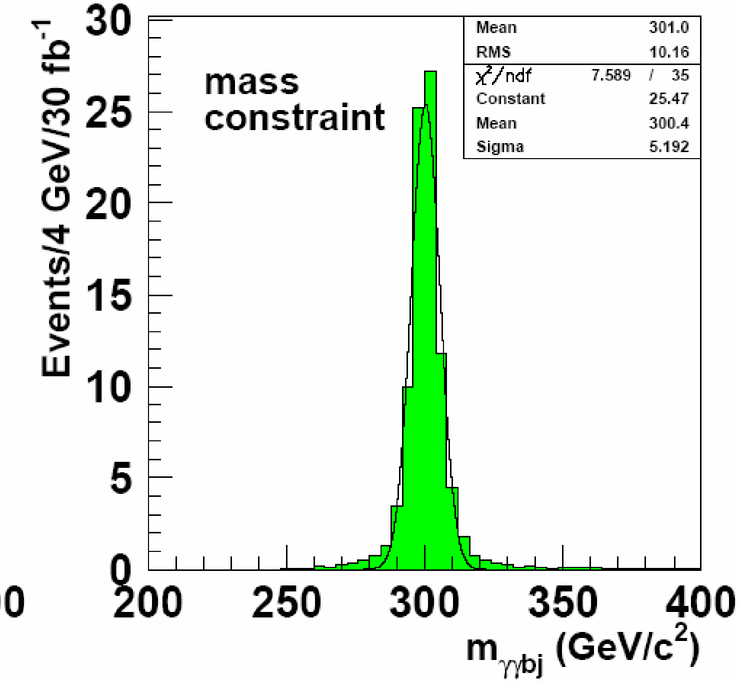
ATLAS fast simulation

$\phi \rightarrow hh \rightarrow \gamma\gamma bb$

30 fb^{-1}

M_h=125 GeV





	$m_\phi = 300$ GeV	$m_\phi = 600$ GeV
$\xi = 0, \Lambda_\phi = 1$ TeV	84.5	7.0
$\xi = 0, \Lambda_\phi = 10$ TeV	0.9	0.1
$\xi = 1/6, \Lambda_\phi = 1$ TeV	150.9	5.3
$\xi = 1/6, \Lambda_\phi = 10$ TeV	1.2	0.1
background	$1.42\ 10^{-4}$	0

Pythia→

events for 30 fb^{-1}

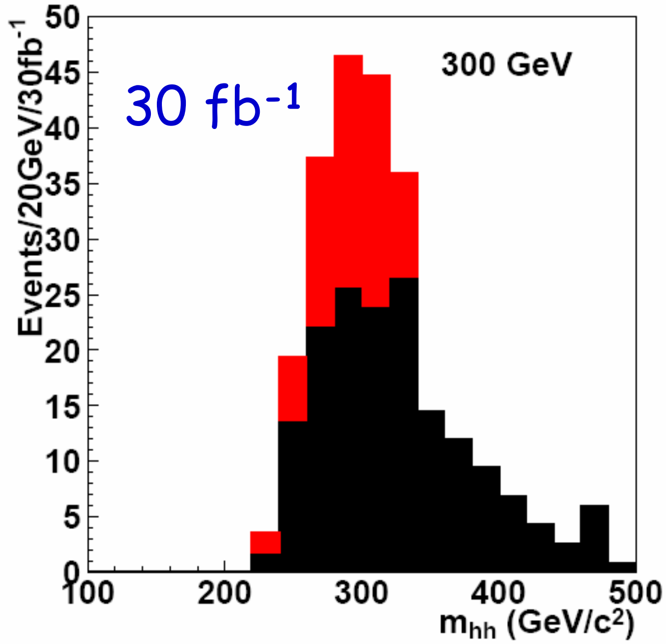
	$m_\phi = 300$ GeV	$m_\phi = 600$ GeV
$\xi = 0, \Lambda_\phi = 1$ TeV	4	(43)
$\xi = 0, \Lambda_\phi = 10$ TeV	(333)	N/A
$\xi = 1/6, \Lambda_\phi = 1$ TeV	2	(57)
$\xi = 1/6, \Lambda_\phi = 10$ TeV	(250)	N/A

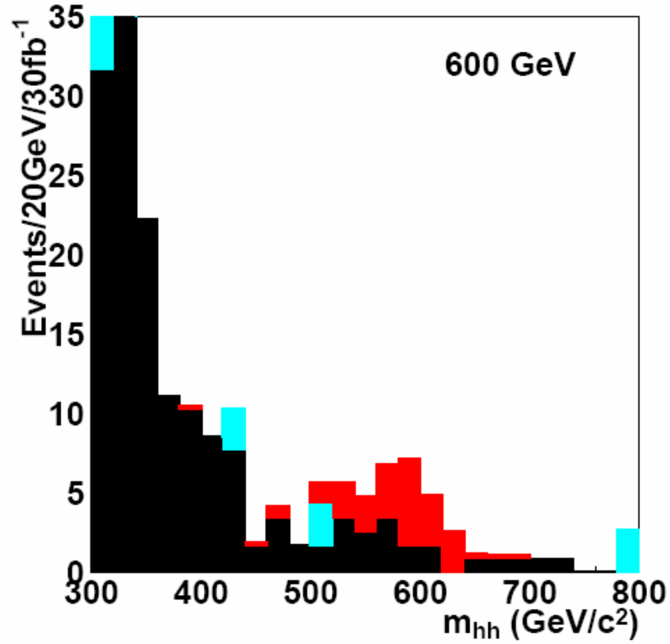
Min. integrated lumi (fb^{-1}) for 10 evts

Radion searches at the LHC

$\phi \to hh \to \tau\tau bb$

M_h=125 GeV





	m_ϕ=300 GeV	m_ϕ=600 GeV
Signal	57	17.1
$t\bar{t}$	98	10
Z + jets	13	0
W + jets	0	0
$S/\sqrt{B}$	5.4	5.4

events for 30 fb^{-1}

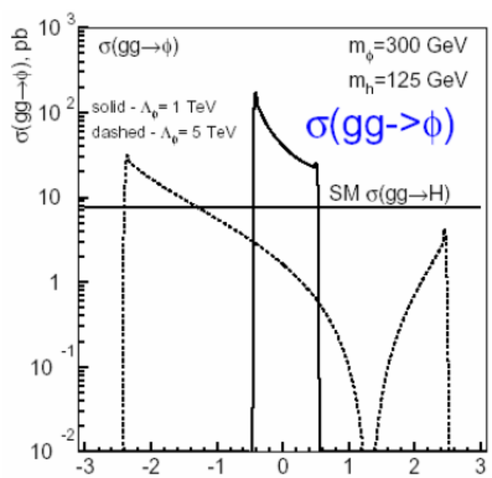
For m_ϕ= 300 (600) GeV and ξ=0
$\phi \to hh \to \gamma\gamma bb$:
$\Rightarrow$ Reach in Λ_ϕ =2.2 (0.6) TeV
$\phi \to hh \to \tau\tau bb$:
$\Rightarrow$ Reach in Λ_ϕ ~ 1 TeV

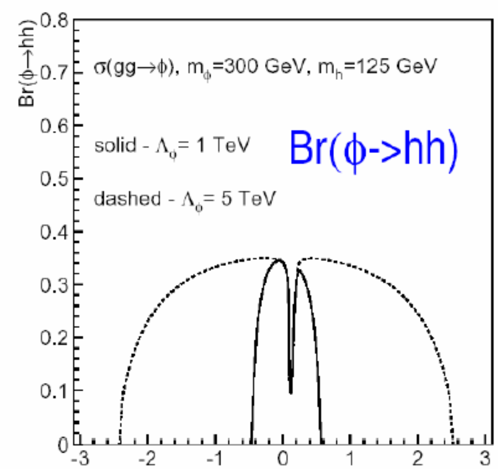
Radions at the LHC

Derwhist, Dominici, Gennai, Fano, Nikitenko

CMS: Full simulation for the signal/fast simulation for the background
Fix M_ϕ =300 GeV M_h=125 GeV $\Rightarrow$ scan the (ξ,Λ_ϕ) plane

$$\sigma(gg \to \phi) = \sigma_{SM}(gg \to h) \frac{\Gamma(\phi) \cdot BR(\phi \to gg)}{\Gamma_{SM}(h) \cdot BR_{SM}(h \to gg)}$$

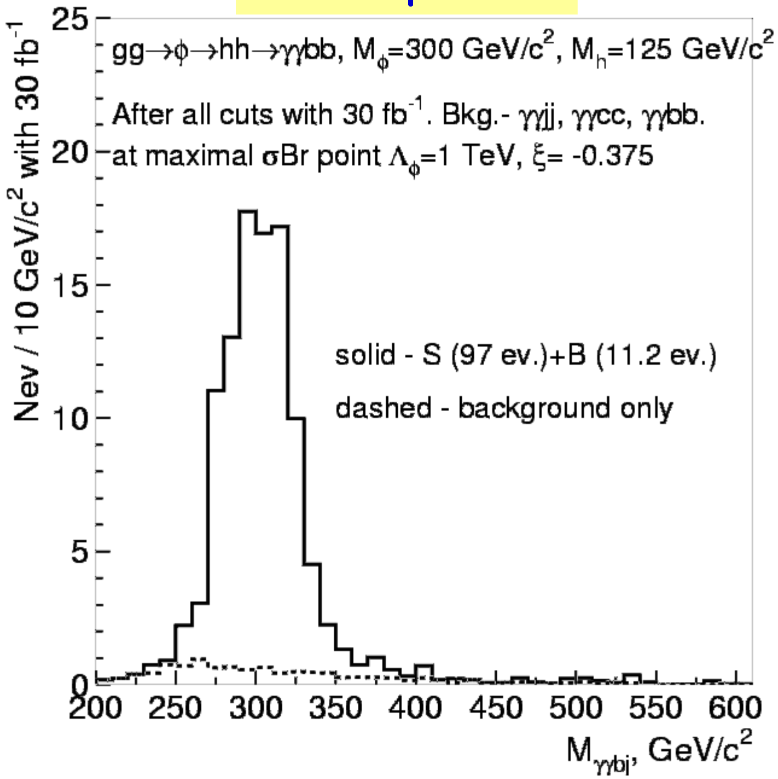




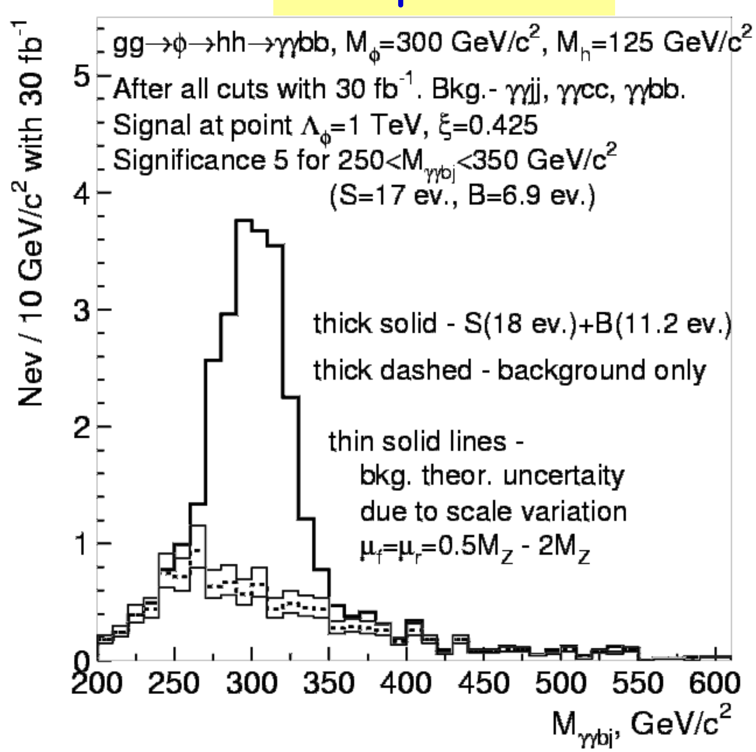
Contribution to the Les Houches 2003 proceedings
CMS note in preparation

$gg \to \phi \to \gamma\gamma$ bb

$gg \to \phi \to \gamma\gamma$ bj
"best point"



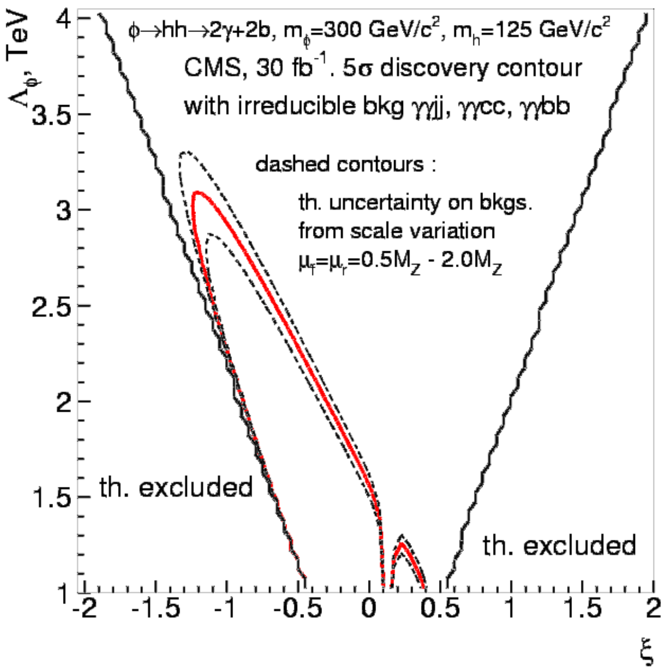
$gg \to \phi \to \gamma\gamma$ bj
"5σ point"



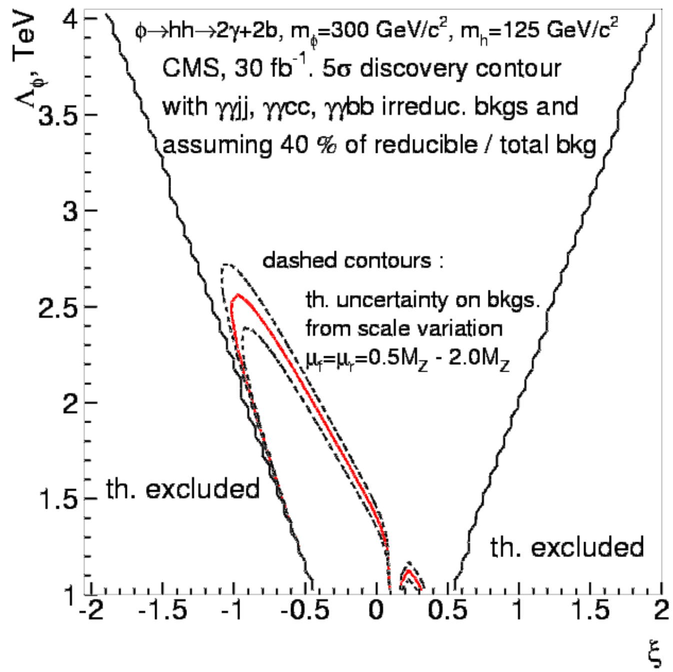
- 2 isolated photons (E_T> 40,25) GeV, 2 jets with E_T> 30 GeV and at least one b-tag, combinations compatible with Higgs mass → 3.7% eff.
- Irreducible background simulated with LO-ME MCs (CompHep,MadGraph)!

$gg \rightarrow \phi \rightarrow \gamma\gamma$ bb

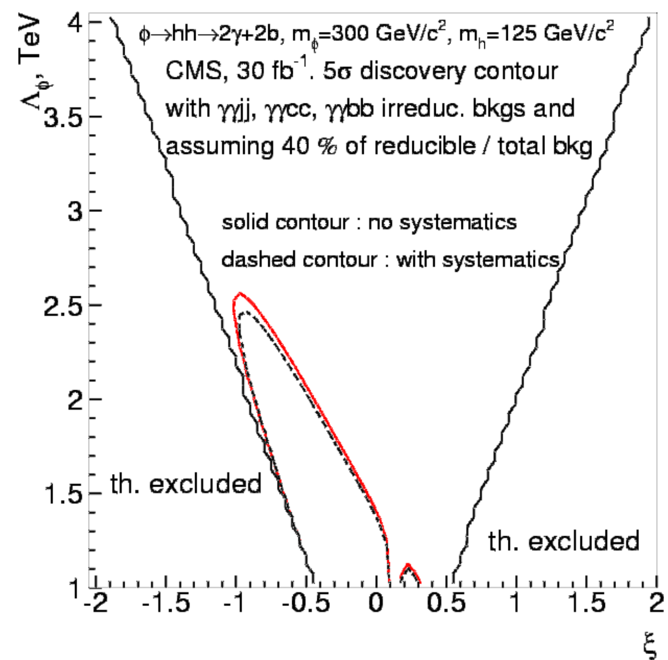
5σ discovery contours for 30 fb^{-1}



Only irreduc. bckg



Full background
(scaled reducable bckg).

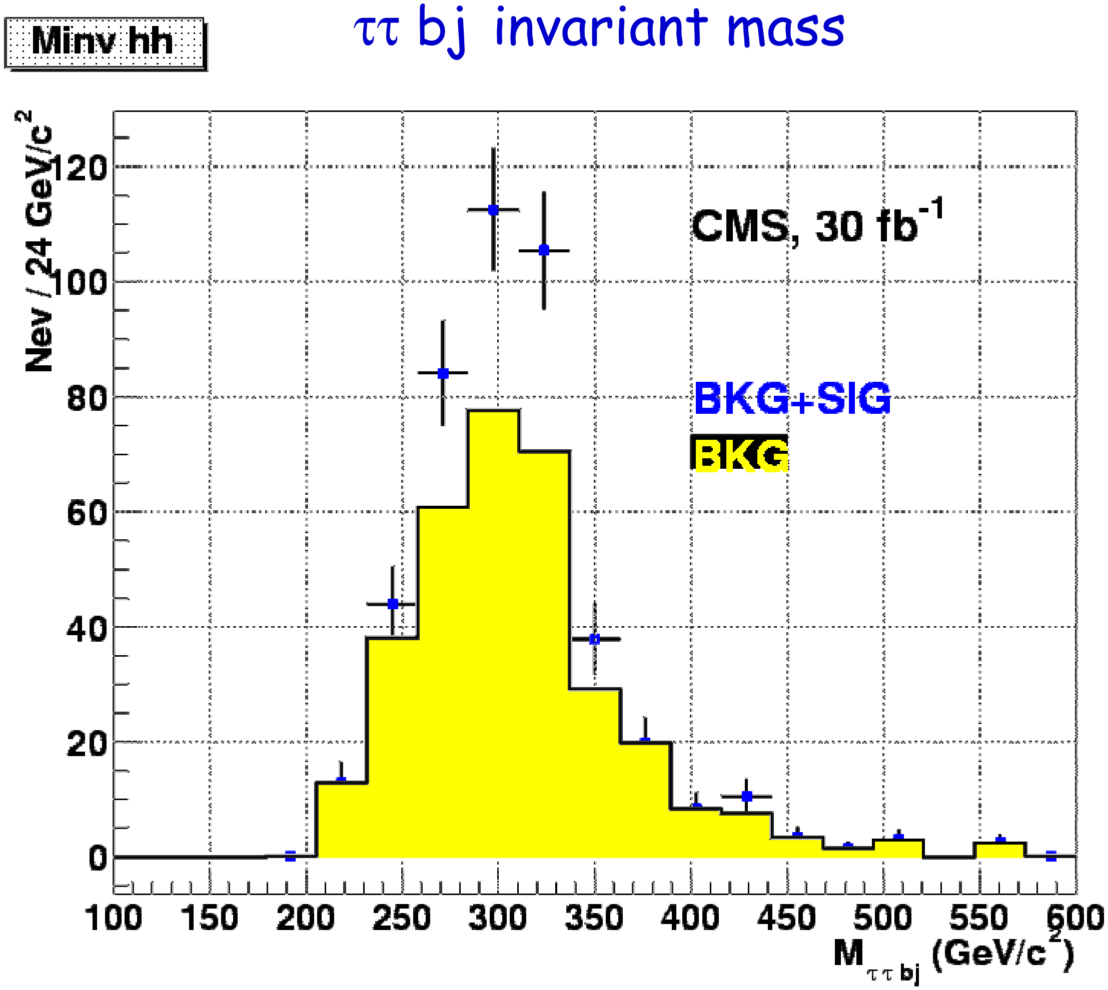


Background+effect
of systematic errors

Reach in Λ_ϕ up to 2.5 TeV

$gg \rightarrow \phi \rightarrow \tau\tau$ bb

$\tau\tau$ bj invariant mass



NLO cross sections for signal and background
$\sigma \bullet$BR maximal for Λ= 1 TeV
ξ = -0.35$\rightarrow$ 0.96 pb

A hadronic and leptonic tau, 2 jets with E_T> 30 GeV and at least one b-tag,

backgrounds

$t\bar{t} \rightarrow Wb + W\bar{b} \rightarrow l + \nu + jets + b\bar{b}$

$t\bar{t} \rightarrow Wb + W\bar{b} \rightarrow l + \nu + \tau - jet + b\bar{b}$

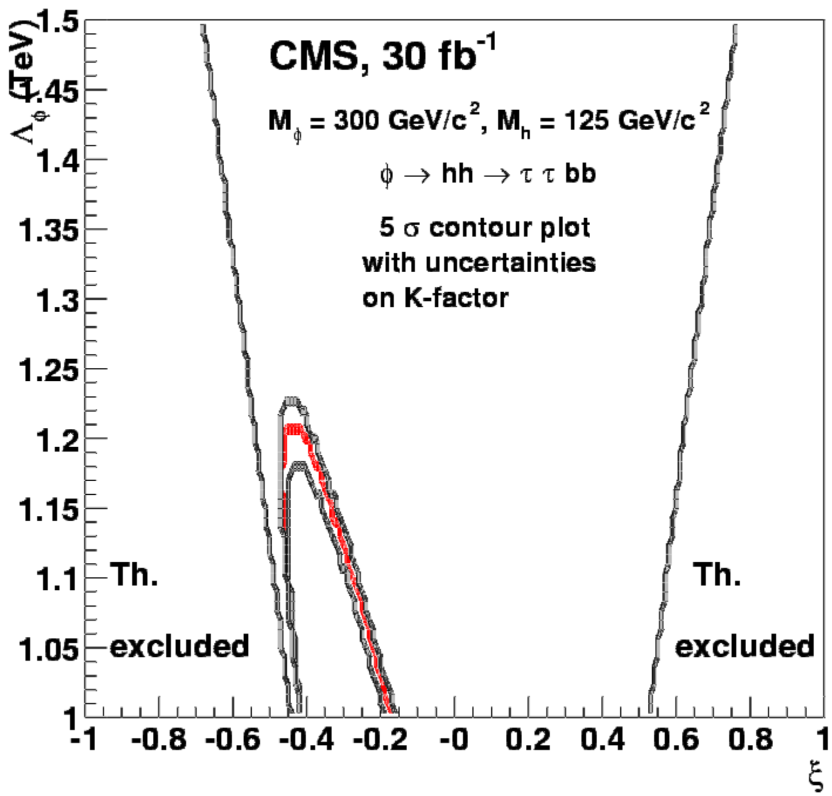
$Zb\bar{b} \rightarrow \tau\tau + b\bar{b}$

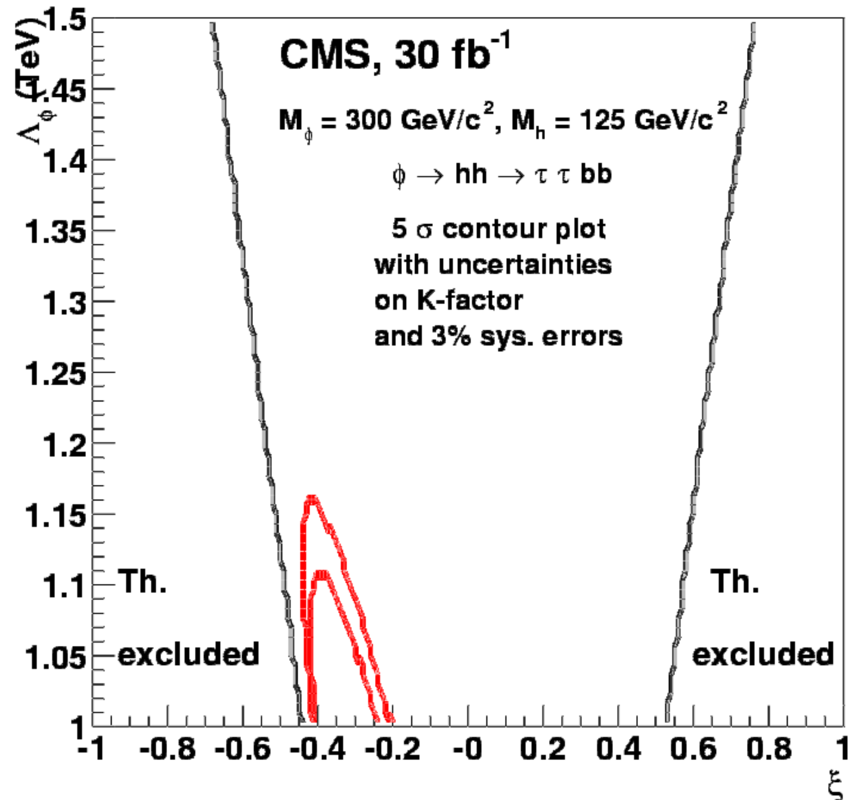
$Z + jets \rightarrow \tau\tau + jets$

$W + jets \rightarrow l + \nu + jets$

$gg \rightarrow \phi \rightarrow \tau\tau$ bb

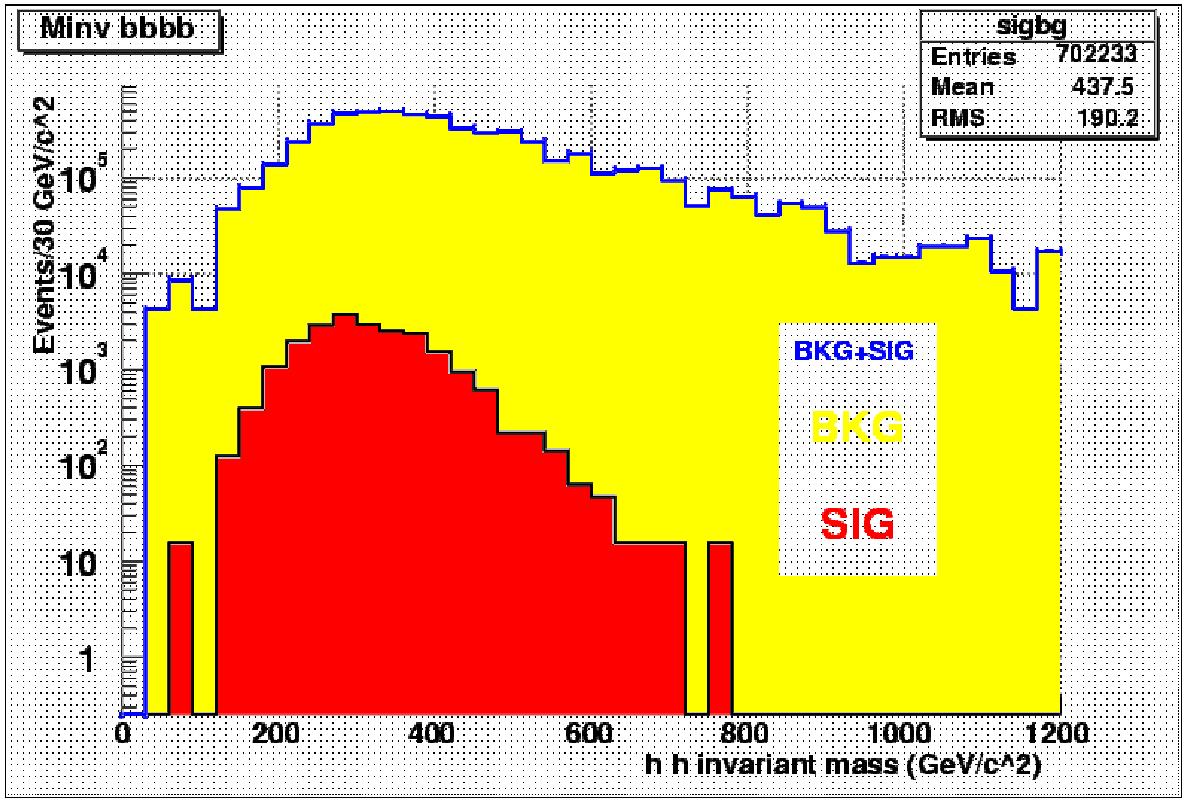
5σ discovery contours for 30 fb^{-1}





Discovery range more limited: Reach in Λ_ϕ up to 1.1-1.2 TeV

$gg \to \phi \to bb\ bb$



bbjj invariant mass: background much larger than signal.
In order to confirm a signal in this channel the background needs to be known to 0.1% (e.g via extrapolation from non-signal region)

Radions at the LHC & LC

M. Battaglia et al hep-ph/0304245

Radion-Higgs mixing

- Check where the Higgs discovery at LHC gets more difficult/impossible
- Can one observe $gg \to \phi \to ZZ^*$ in those regions ?
- Perspectives for identifying the nature of the observed scalar at a LHC & LC

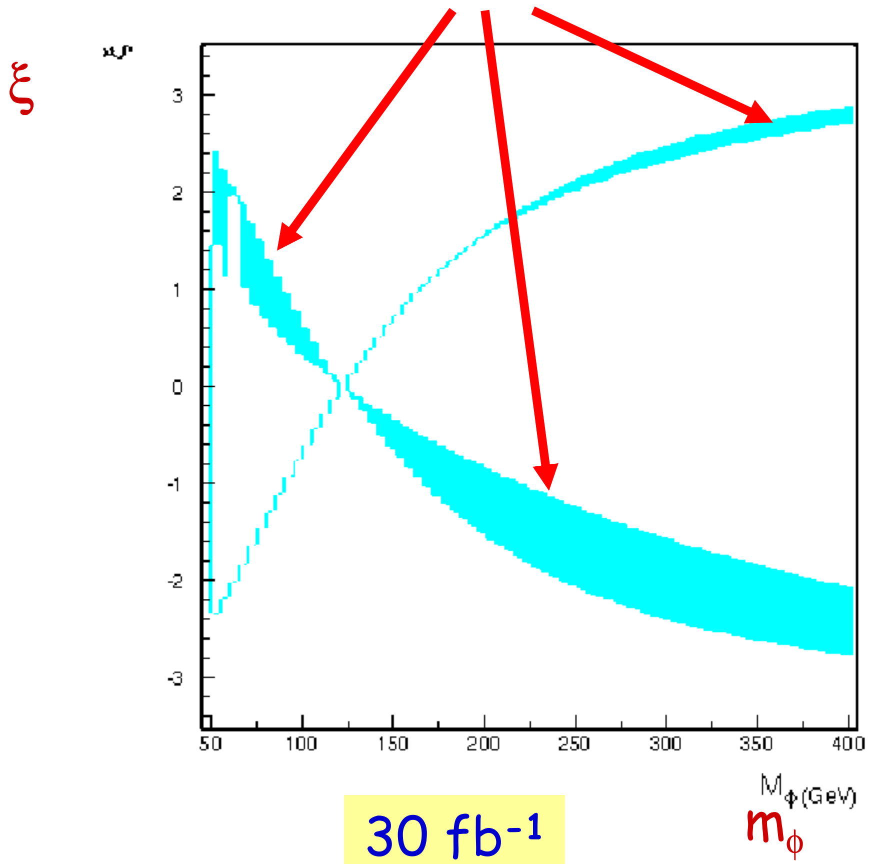
Tool used:
HDECAY, introducing relevant terms for radions (J. Gunion/D. Dominici)

Radion $\phi \to ZZ^* \to$ 4leptons $50\ \text{GeV} < M_\phi < 400\ \text{GeV}$
Take experimental bounds (Tevatron/LEP) into account

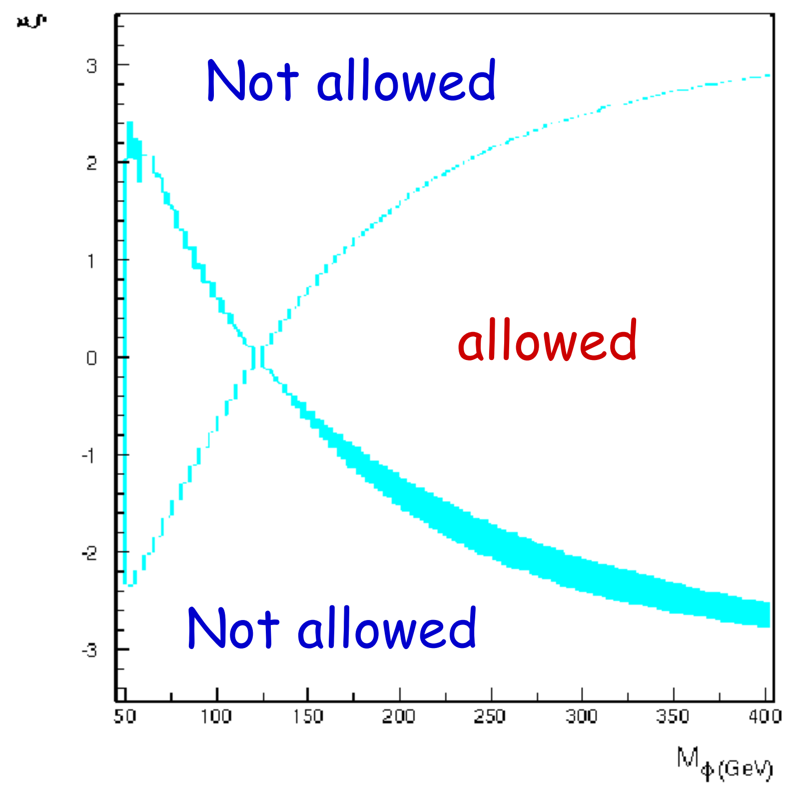
Higgs $H \to ZZ^* \to$ 4leptons
$H \to \gamma\gamma$
$ttH \to ttbb$
low Higgs mass range 120-140 GeV

Higgs/Radion detectability

Region where 30 fb^{-1} is not sufficient to detect the Higgs in the studied decays channels. Other decays need to be looked into (qqH prod. or $H \rightarrow \phi\phi$)



30 fb^{-1}



100 fb^{-1}

m_h=120 GeV, Λ_ϕ= 5 TeV

Higgs/Radion detectability

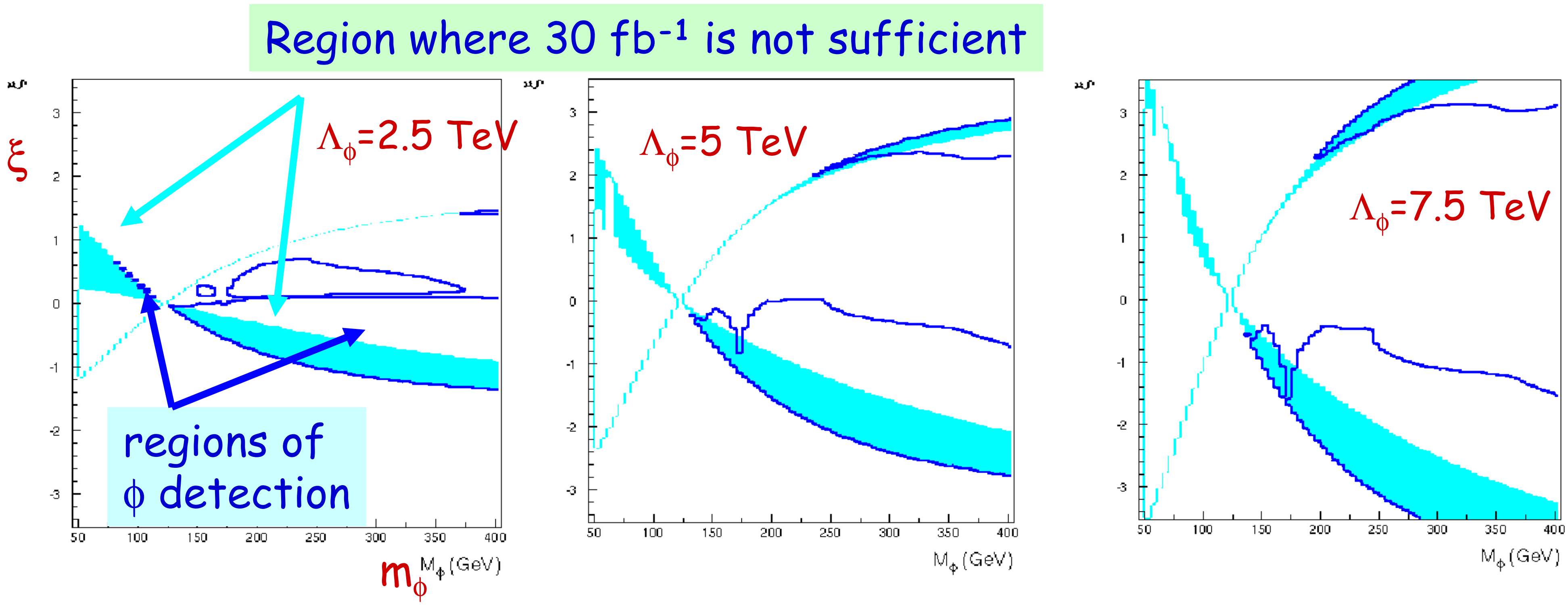
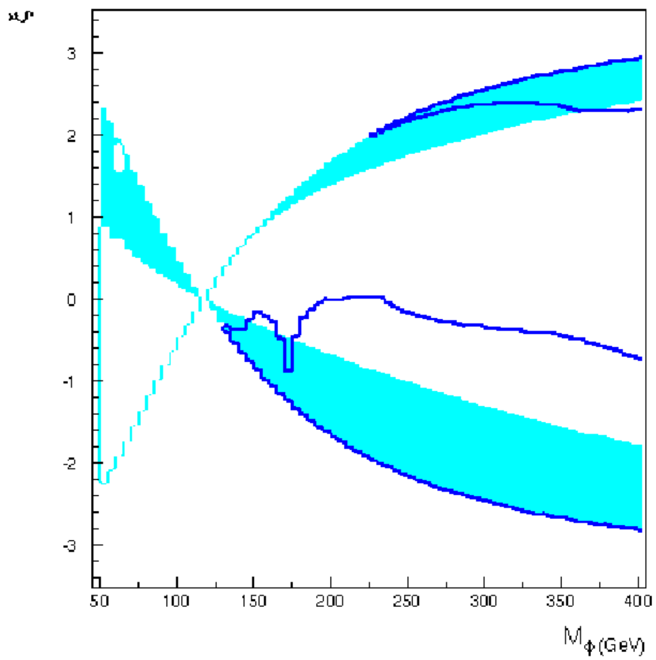


Fig. 3. Regions in (M_ϕ, ξ) parameter space of h detectability (including $gg \to h \to \gamma\gamma$ and other modes) and of $gg \to \phi \to Z^0 Z^{0(*)} \to 4\ell$ detectability at the LHC for one experiment and 30 fb^{-1}. The outermost, hourglass shaped contours define the theoretically allowed region. The light grey regions show the part of the parameter space where the net h signal significance falls below 5σ. The thick grey curves indicate the regions where the significance of the $gg \to \phi \to Z^0 Z^{0(*)} \to 4\ell$ signal exceeds 5σ. Results are presented for $M_h = 120$ GeV and $\Lambda_\phi =$ 2.5 TeV (a), 5.0 TeV (b) and 7.5 TeV (c).

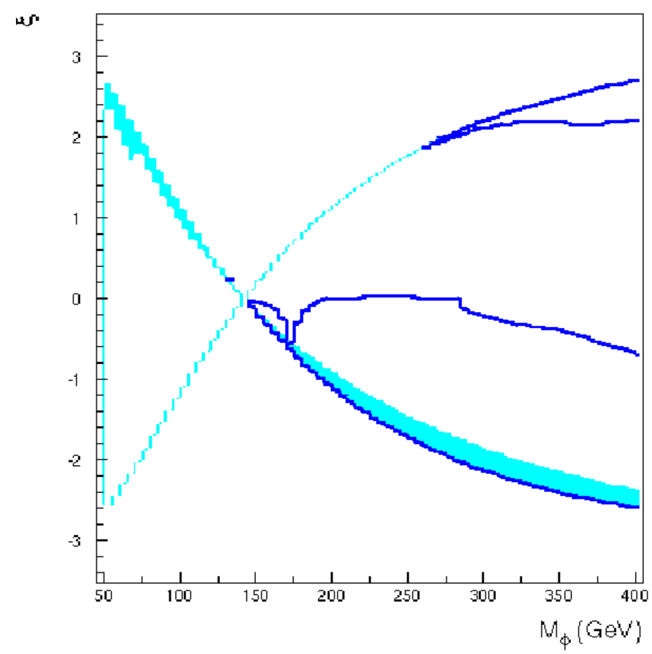
LHC will essentially always see a scalar with 30 fb-1

Higgs/Radion detectability

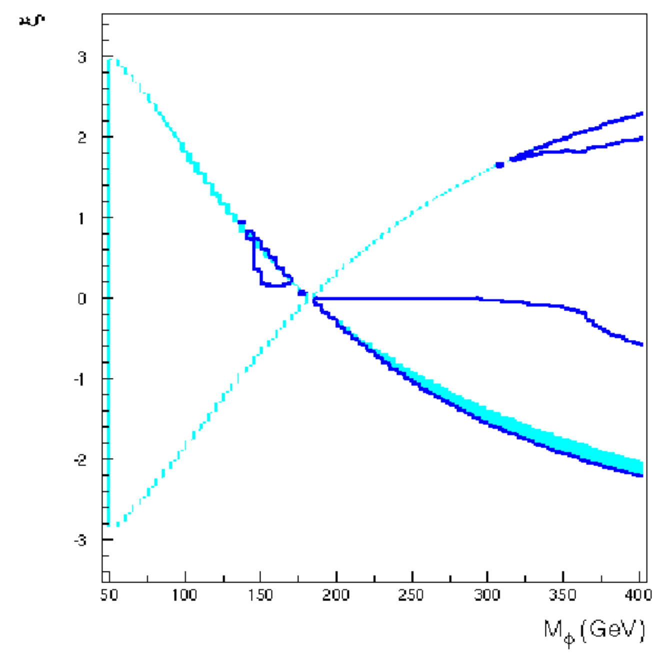
Λ_ϕ=5 TeV



M_h= 115 GeV



M_h= 140 GeV



M_h= 180 GeV

⇒Becomes better for heavier Higgs
other decay modes can be used (e.g. $\phi \rightarrow HH$ for high mass)

LC should always see the light Higgs & ϕ in almost entire region

Higgs or Radion?

- At LHC mostly ratios of couplings are determined
- Radions: same fermions/WW,ZZ coupling ratio as for SM Higgs
- Couplings to $\gamma\gamma$ and gg receive anomalous contributions $\rightarrow$e.g. $g_{h\gamma\gamma}/g_{hWW}$

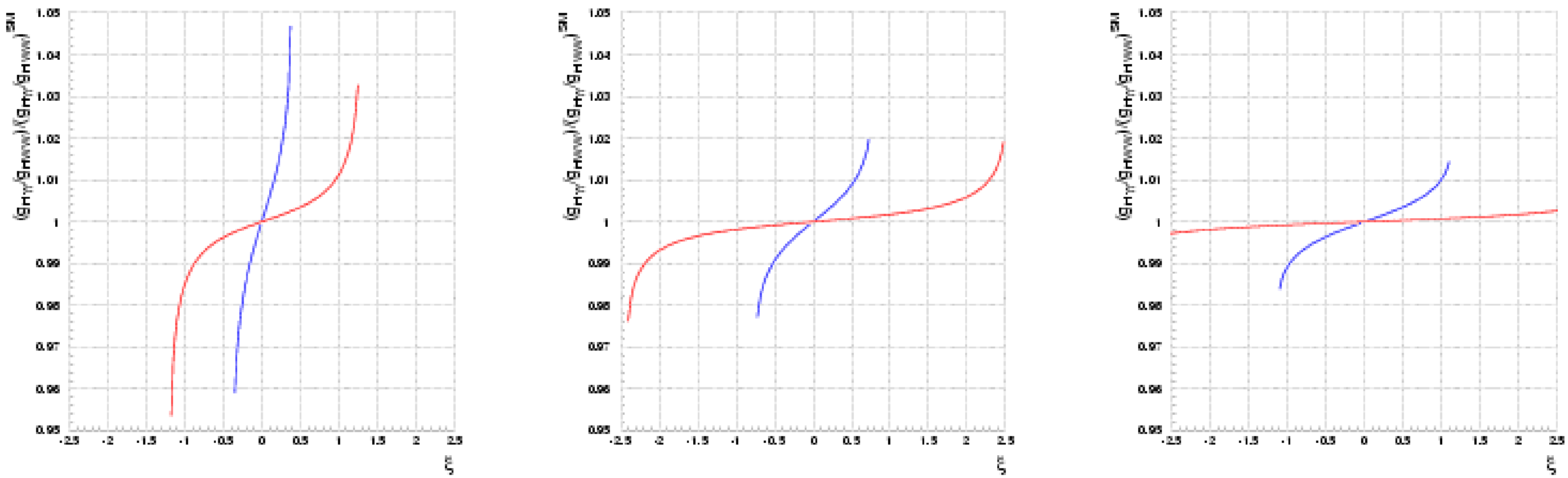


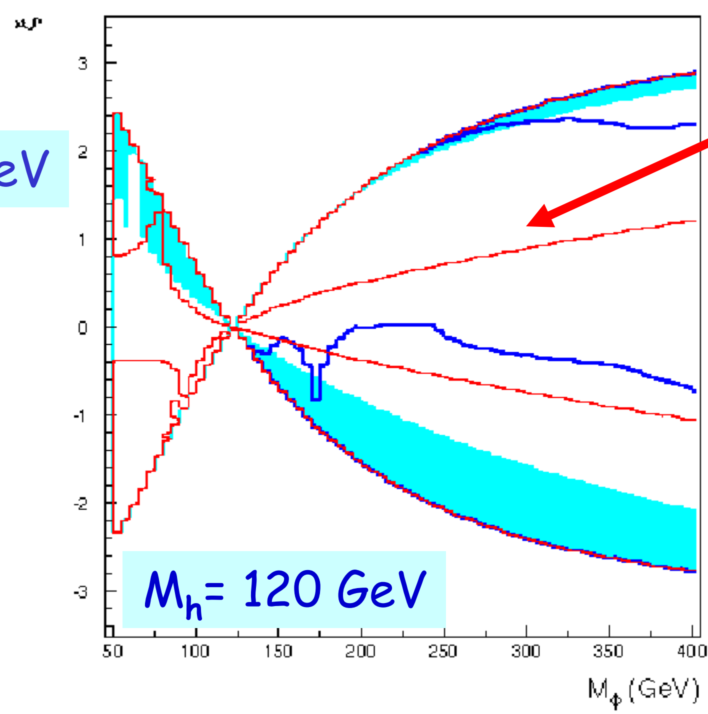
Figure 4: *Ratio of couplings* $g^{effective}_{H\gamma\gamma}/g_{HWW}$ *normalised to the SM prediction as function of* ξ. *Results are obtained for* M_H=120 GeV *and* Λ= 2.5 TeV (*left*), 5.0 TeV (*center*) *and* 7.5 TeV (*right*). *The darker (blue) curves refer to* M_ϕ = 150 GeV *and the lighter (red) to* M_ϕ = 300 GeV.

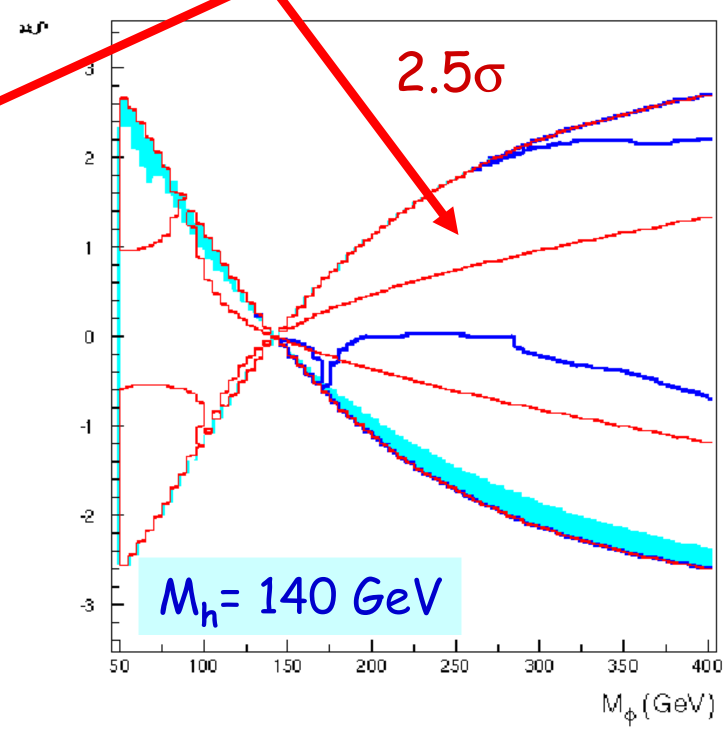
Effects are ~1-5%: Difficult to establish at LHC
Some absolute rates go down up to factor 2 for mϕ> 2mh and $\xi \neq 0$

Linear Collider

- LC will detect a higgs through the entire ($M\phi,\xi$) plane studied here using $e^+e^- \to Zh$
- Nature (h or ϕ) can be determined at LC since it measures absolute coupling strenghts with a few % accuracy: e.g. using couplings to bb and WW

Λ_ϕ=5 TeV

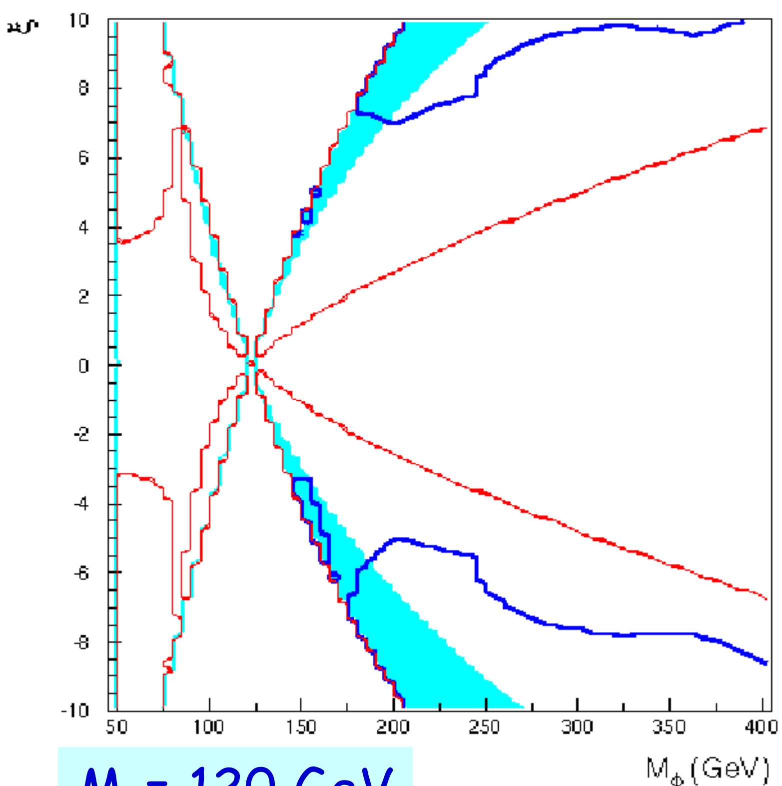




If mixing is strong enough the LC can easily distinguish

Linear Collider

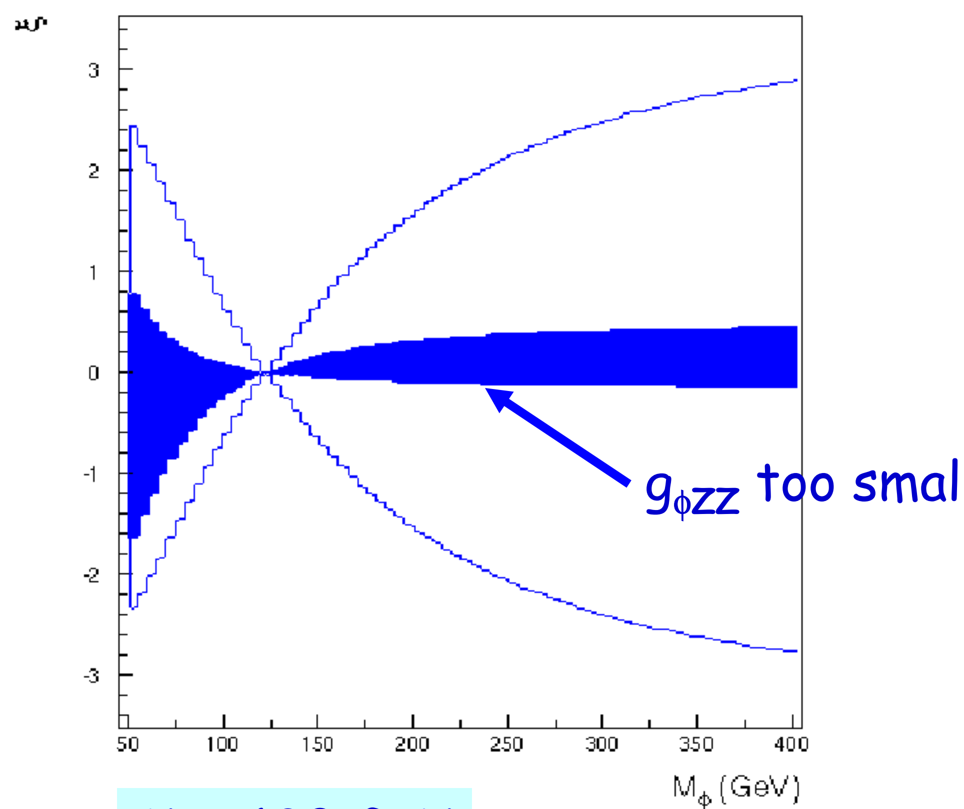
Higgs Detection



M_h= 120 GeV

Λ_ϕ=30 TeV

Radion Detection $\phi \to ZZ \to 4l$

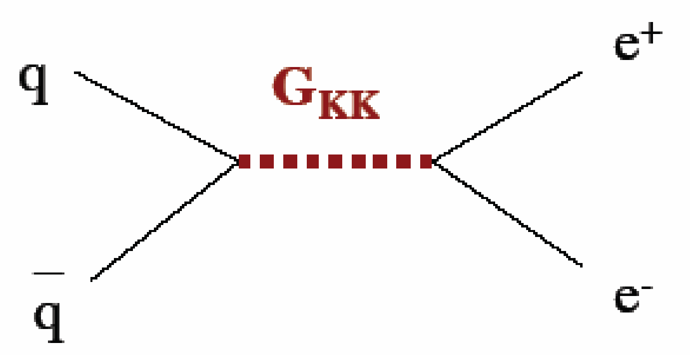


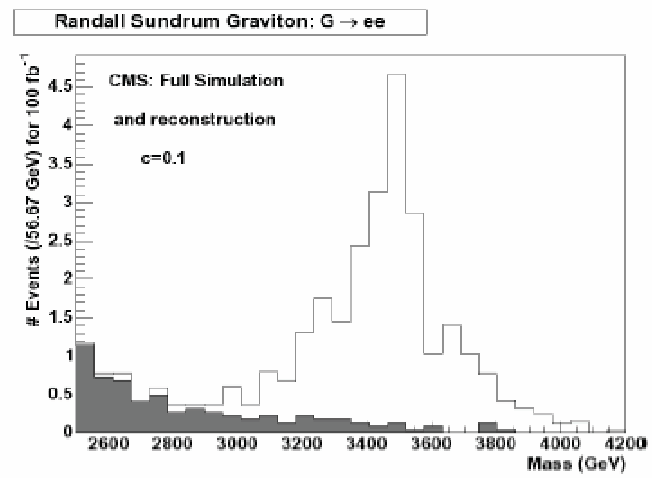
M_h= 120 GeV

Λ_ϕ=5 TeV

RS signals

⇒ Signature of RS: KK graviton excitations
LHC reach ~ O(4TeV)





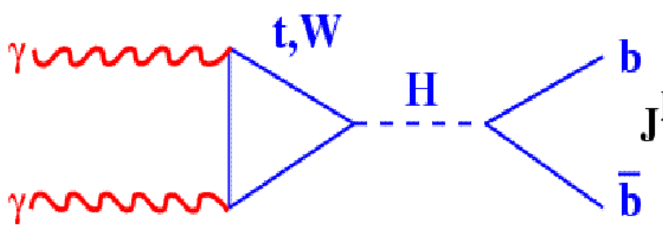
Relation between $\Lambda\phi$ and KK resonance parameters

$$m_1 = x_1 \frac{m_0}{M_{Pl}} \frac{\Lambda_\phi}{\sqrt{6}}.$$

$$x_1 \sim 3.8$$

M_1 = the mass of the first KK excitation
M_0/M_{PL} curvature, related to the width of the resonance
For c=0.1 the LHC will be sensitive to Λ_ϕ = 30 TeV

Photon collider



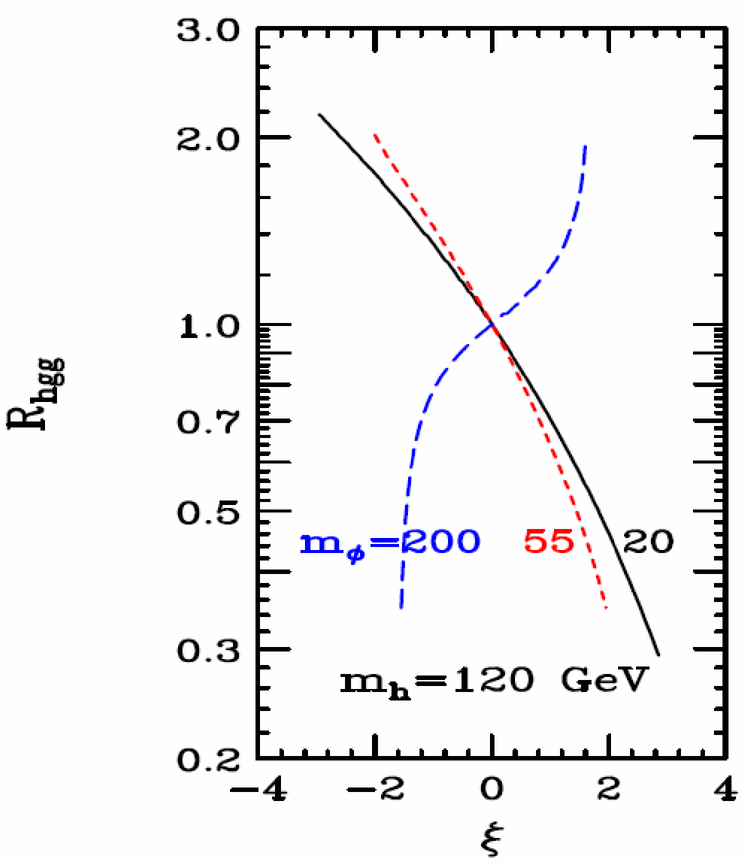
Landau-Yang

$J^{PC}=0^{-+},0^{++},2^{++}$

PC→ $\Gamma(h\to\gamma\gamma)\Gamma(h\to b\bar{b})/\Gamma^h_{tot}$

LHC→ $\Gamma(h\to gg)\Gamma(h\to\gamma\gamma)/\Gamma^h_{tot}$

$$R_{hgg}\equiv\left[\frac{\Gamma(h\to gg)}{\Gamma(h\to b\bar{b})}\right]\left[\frac{\Gamma(h\to gg)}{\Gamma(h\to b\bar{b})}\right]^{-1}_{SM}$$



Directly probes the presence of the anomalous hgg coupling

Study: uses LHC+ CLICHÉ ⇒ 10% precision on R_{hgg}

D. Asner et al. hep-ph/0308103

Summary

- Detectability of Radions in classical channels such as $\phi \to \gamma\gamma$ and $\phi \to ZZ$ for low Λ_ϕ
- $\phi \to hh$ studied in $\gamma\gamma bb$, $\tau\tau bb$ and bbbb decay modes
  - Sensitivity up to 2.5 TeV in Λ_ϕ
- Study of the LC/LHC complementarity for Higgs/Radion discovery and identification
  - In the phase space studied LHC should essentially always find a scalar particle

Couplings at a LC

Light Higgs Profile at LC

	M_H (GeV)	$\delta(X)/X$ LC-500-LC-3000 $0.5ab^{-1}$-$5ab^{-1}$
M_H	120-180	(3-5) $\times 10^{-4}$
Γ_{tot}	120-140	0.04-0.06
g_{HWW}	120-160	0.01-0.03
g_{HZZ}	120-160	0.01-0.02
g_{Htt}	120-140	0.02-0.06
g_{Hbb}	120-160	0.01-0.03
g_{Hcc}	120-140	0.03-0.10
$g_{H\tau\tau}$	120-140	0.03-0.05
$g_{H\mu\mu}$	120-140	0.15 - 0.04-0.06
CP test	120	0.03
g_{HHH}	120	0.20 - 0.07