

SUSY 07



Higgs bosons in non-minimal Models



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On behalf of ATLAS and CMS



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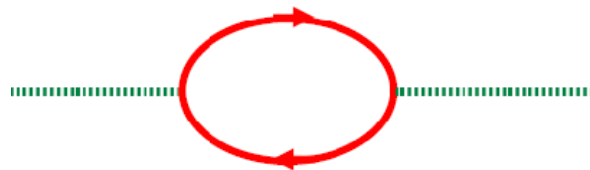
Introduction



Despite its longstanding huge predictive power, the Standard Model is affected by a few flaws. One of them is the famous Hierarchy Problem

Assuming that SM is an effective low-energy theory with an Ultraviolet cut-off Λ

The most important radiative corrections to the Higgs boson mass arise from loops involving top, gauge bosons and the Higgs itself



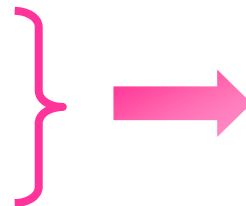
$$\delta m_h^2 = \frac{3}{8\pi^2} \lambda_t^2 \Lambda^2 \quad \text{from top}$$

$$\delta m_h^2 \propto a_w \Lambda^2 \quad \text{from gauge bosons}$$

$$\delta m_h^2 \approx \frac{\lambda}{16\pi^2} \Lambda^2 \quad \text{from higgs}$$

Example: if $\Lambda = 10 \text{ TeV}$ the lowest order corrections are:

$\sim (2 \text{ TeV})^2$	top loops
$\sim - (750 \text{ GeV})^2$	W/Z loops
$\sim -(1.25 m_H)^2$	Higgs loops



Higgs mass would explode unless extremely un-natural fine tuning is applied at all orders so to keep $m_H \sim O(200 \text{ GeV})$

So ... what ?



Aside from just passively accepting that Mother Nature might be so fine-tuned

Try other viable theoretical solutions, e.g.

- ❑ Stabilize the Higgs mass through additional symmetries
 - ❑ Supersymmetry (Plenty of coverage in other talks)
 - ❑ Little Higgs models
 - ❑ LRSM
- ❑ Shift the cut-off to lower energies
 - ❑ Extra Dimensions, e.g. Randall-Sundrum

Littlest Higgs Model



The (SM) Higgs boson remains light thanks to a global symmetry which breaks at the TeV scale

New particles:

$$W_H^\pm, Z_H, \gamma_H : \lesssim 1 \text{ TeV}$$

New heavy gauge bosons $M_{W_H} < 6\text{TeV} \left(\frac{m_h}{200\text{GeV}} \right)^2$

$$T : \lesssim 1 \text{ TeV}$$

Heavy Top quark $M_T < 2\text{TeV} \left(\frac{m_h}{200\text{GeV}} \right)^2$

$$\phi^{\pm\pm}, \phi^\pm, \phi^0 : \lesssim 10 \text{ TeV}$$

Triplet of heavy Higgs bosons

Are required to provide cancellation of the one-loop quadratic divergences to the SM Higgs mass

New Higgses appear: lose mass constraints

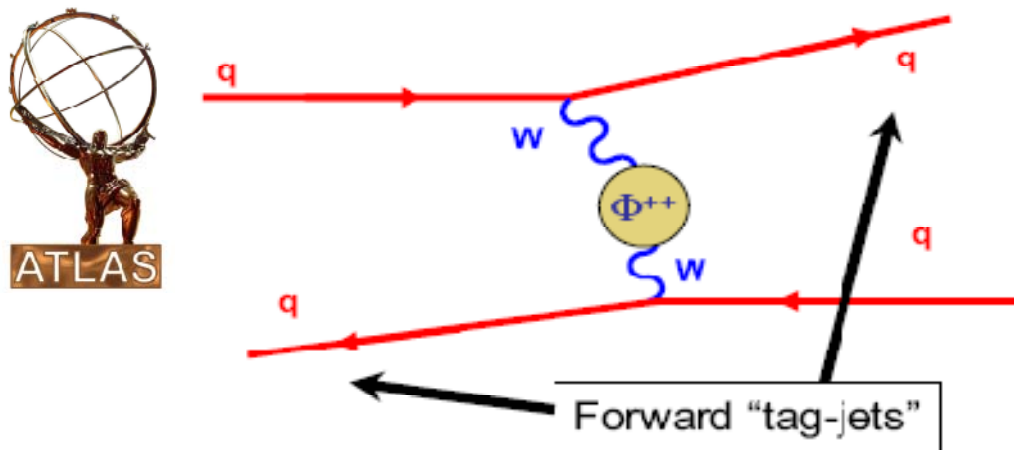
SM Higgs is still there: usual searches

Left Right Symmetric Models



- Two (left and right) Higgs triplets provide a parity conserving Lagrangian
- All fermions are treated symmetrically as LH and RH doublets
- Symmetry based on $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
→ New neutrinos, bosons, Higgses
- Yukawa couplings of the triplet Higgs allow for Majorana mass terms of the RH neutrinos ($\sim 10^{11}$ GeV)
 - ➡ see-saw mechanism possible
 - ➡ natural explanation of the low, non-zero mass of left-handed neutrinos

Search for doubly charged Higgs (Littlest Higgs)

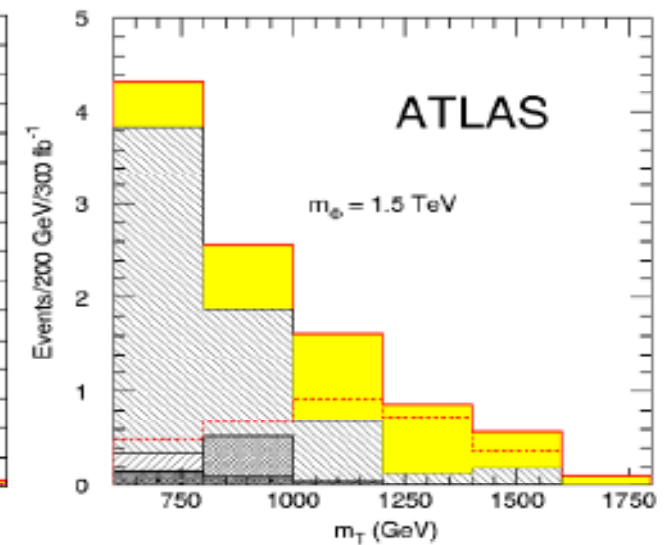
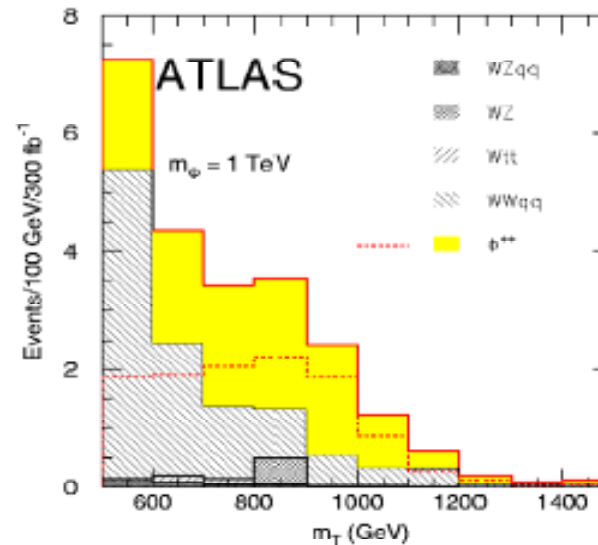


Production: **VBF mechanism**

$$\phi^{++} \rightarrow W^+W^+ \rightarrow \ell^+\ell^+\nu\nu$$

Sensitivity up to 2 TeV
Requires VEV large enough
in conflict with bounds from
electro-weak fits

- Two positive leptons with $p_T > 150, 20$ GeV and $|\eta| < 2.5$
- $|p_{T1} - p_{T2}| > 200$ GeV
- $|\eta_1 - \eta_2| < 2.0$
- $E_{T,miss} > 50$ GeV
- Two "tag jets", $p_T > 15$, $E > 200, 100$ GeV, $|\eta_1 - \eta_2| > 5$

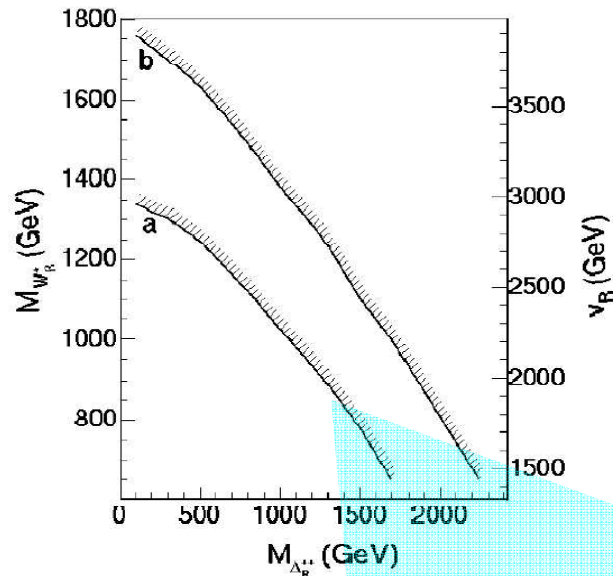


Azuelos et al. , Eur.Phys.J. C39S2 (2005) 13-24

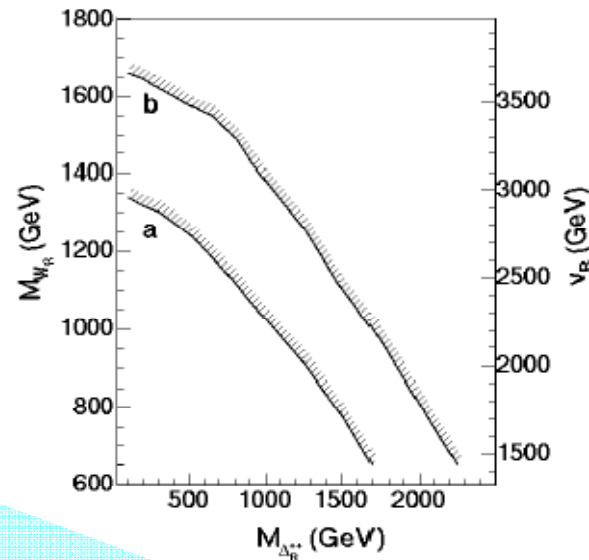
Search for RH doubly charged Higgs (LRSM)



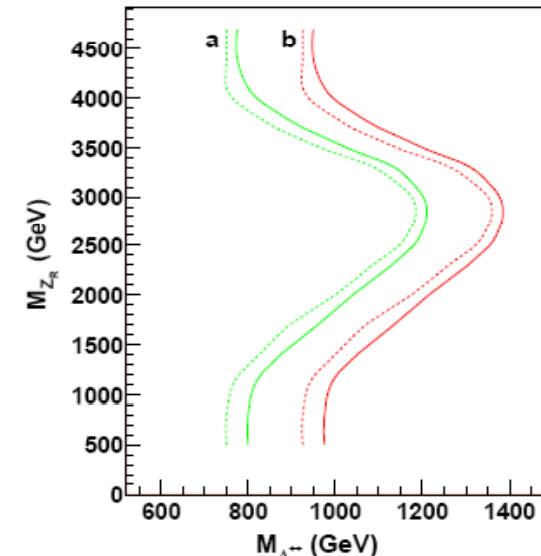
Same-sign di-leptons



Di-leptons from τ pairs



Doubly-charged RH Higgs pair production via new ZR



Discovery reach (>10 events, low background, after selection) for a) 100 fb^{-1} and b) 300 fb^{-1}



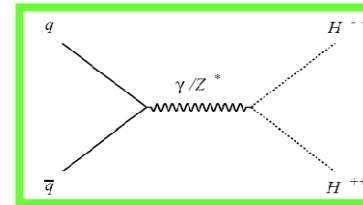
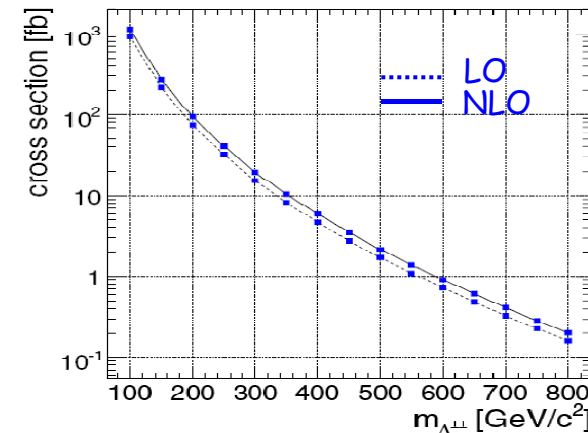
	Δ^{++} 300 GeV	Δ^{++} 800 GeV	$W^+W^+ qq$	$W t\bar{t}$	$WZqq$	$t\bar{t}$	total backg
Isolated leptons	278 (327)	63 (95)	109/12	7.6/0.6	0/0.8	17/0	133/13
Lepton P_T	256 (301)	63 (94)	63/11	5.9/0.5	0/0.8	1.1/0	70/12
$2.4(P_T^{l1} + P_T^{l2}) - M_{ll} > 480$	191(227)	59(85)	10/2.1	1.3/0.3	0	0	12/2.4
Fwd Jet tagging	156(186)	56(74)	6.0/1.3	0.1/0	0	0	6/1.3
ptmiss	154(181)	56(68)	3.0/0.3	0/0	0	0	3.1/0.3

Azuelos et al., J. Phys. G: Nucl. Part. Phys. 32 (2006) 73-91

Search for pair production of doubly charged Higgs



Drell-Yan production of $\Delta^{++}\Delta^{--}$
NLO σ (Spira, Muhlleitner, 2003)



$\Delta^{++}\Delta^{--} \rightarrow \mu^+\mu^+\mu^-\mu^-$ before selections

Same-sign lepton final state
SM bkg very small

Δ^{++} decays:

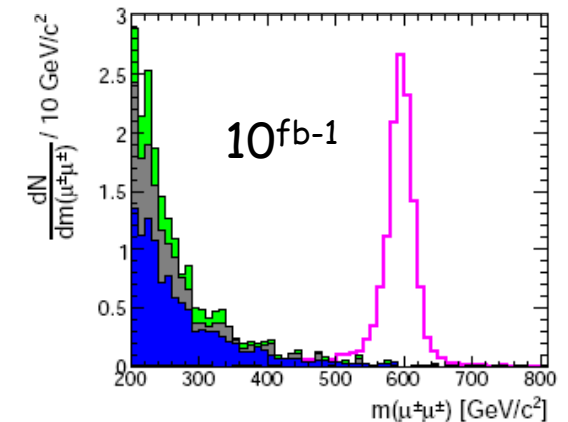
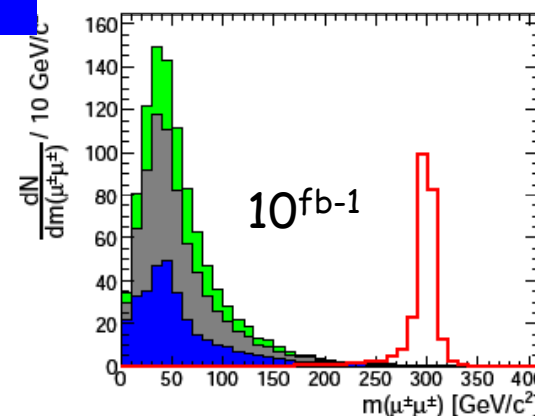
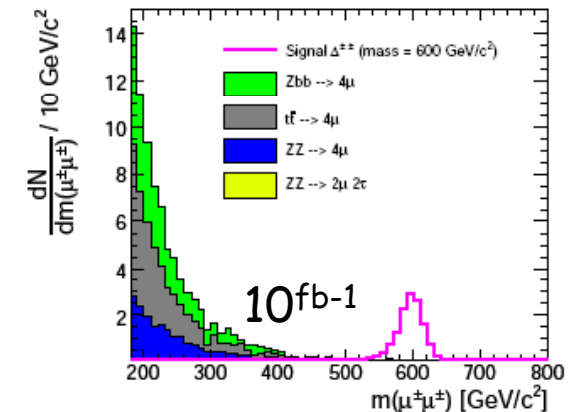
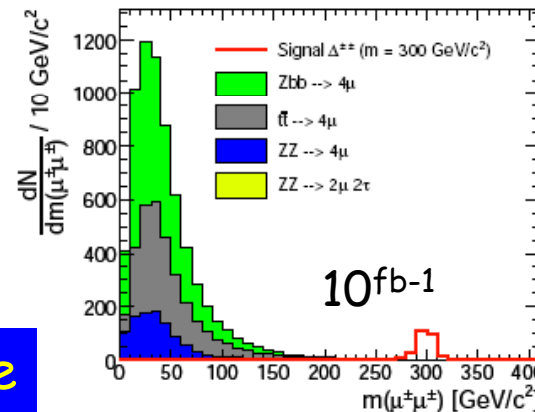
$\mu^+\mu^+, \mu^+\tau^+, \tau^+\tau^+$

were studied

4μ

$1\mu 3\tau, 2\mu 2\tau, 3\mu 1\tau$

with $\tau \rightarrow \text{hadrons}$

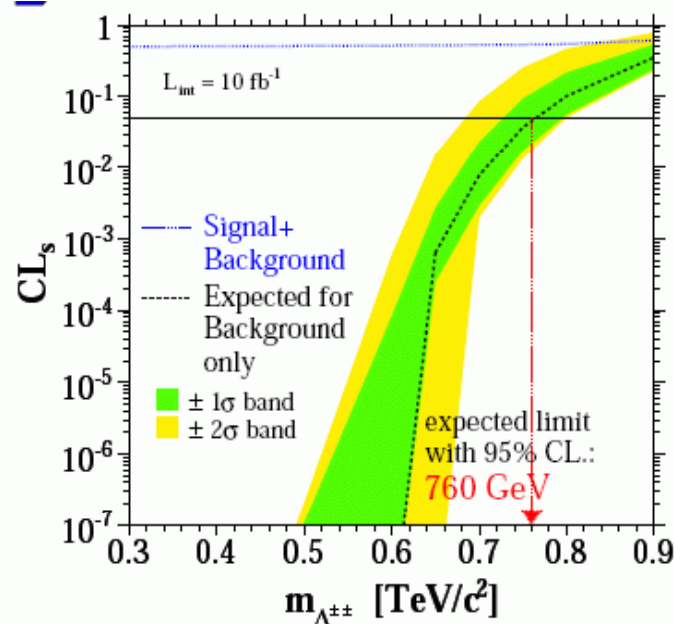
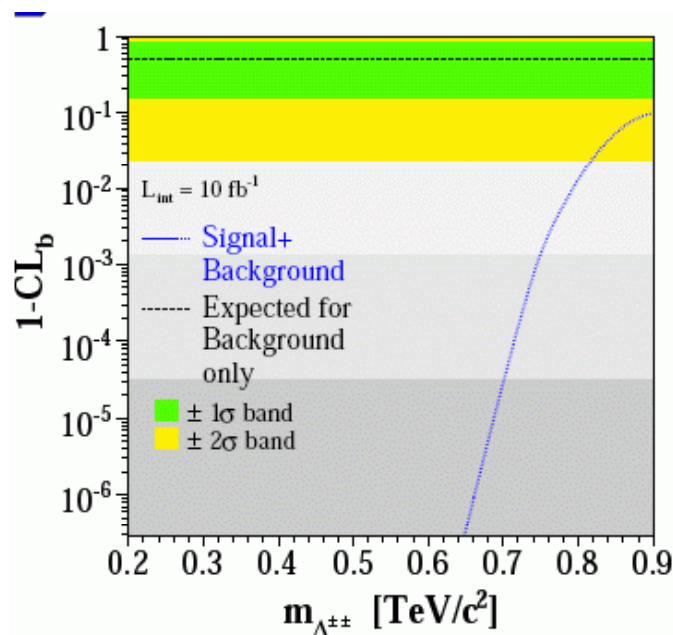


Rommerskirchen et al, CMS Note 2006/081

$\Delta^{++}/--$ discovery and exclusion



4 μ final
state



$$\text{Exclusion Limit} = (760^{+0.5}_{-2}(\text{bkg}) \pm 10(\text{signal}) \pm 4(\text{lumi})) \text{ GeV}/c^2$$

$$\text{Discovery Limit} = (650^{+0.4}_{-0.3}(\text{bkg}) +^{+3}_{-0.4}(\text{signal}) \pm 0.2(\text{lumi})) \text{ GeV}/c^2$$

With τ in the final state. No background left !

$m_{\Delta^{\pm\pm}}$ (GeV)	200	300	400	500
N_{ev} expected at 10 fb^{-1}	26	10	4	2
$\sigma_{\text{NLO}} \pm \text{stat} \pm \text{syst}$ (fb)	$93.9^{+19.3}_{-17.5} \pm 12.2$	$19.6^{+6.6}_{-5.6} \pm 2.5$	$5.9^{+3.4}_{-2.5} \pm 0.8$	$2.2^{+1.9}_{-1.3} \pm 0.3$
Luminosity for 95% CL exclusion, fb^{-1}	1.3	3.0	7.7	16.8

Curved Space: Extra Dimensions

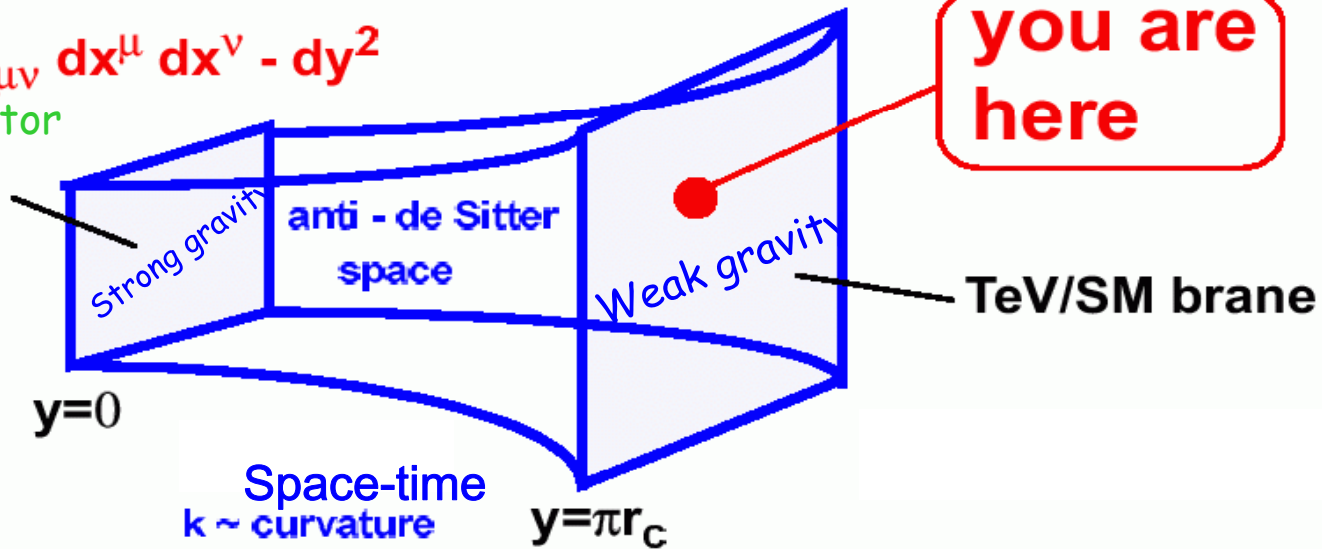


Randall, Sundrum, PRL 83, 3370 (1999) Only one extra dimension

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

Warp factor

Planck brane



Two four dimensional (Minkowskian) branes, bounding a five dimensional bulk between them

Gravity scale: $\Lambda_\pi = M_{\text{Pl}} e^{-kr_c\pi}$, r_c = compactification radius

The hierarchy between Planck and EW scale is removed by the exponential warp factor if $kr_c \sim 12 \rightarrow r_c \sim 10^{-32} \text{ m} \rightarrow$ no deviations from Newton's law

Radions



Radion, ϕ , scalar field representing the fluctuation of the distance between the two branes

Introduced in the model to stabilize the size of extra dimension ($kr_c \sim 12$)

Goldberger and Wise, PRL 83 (1999) 4922

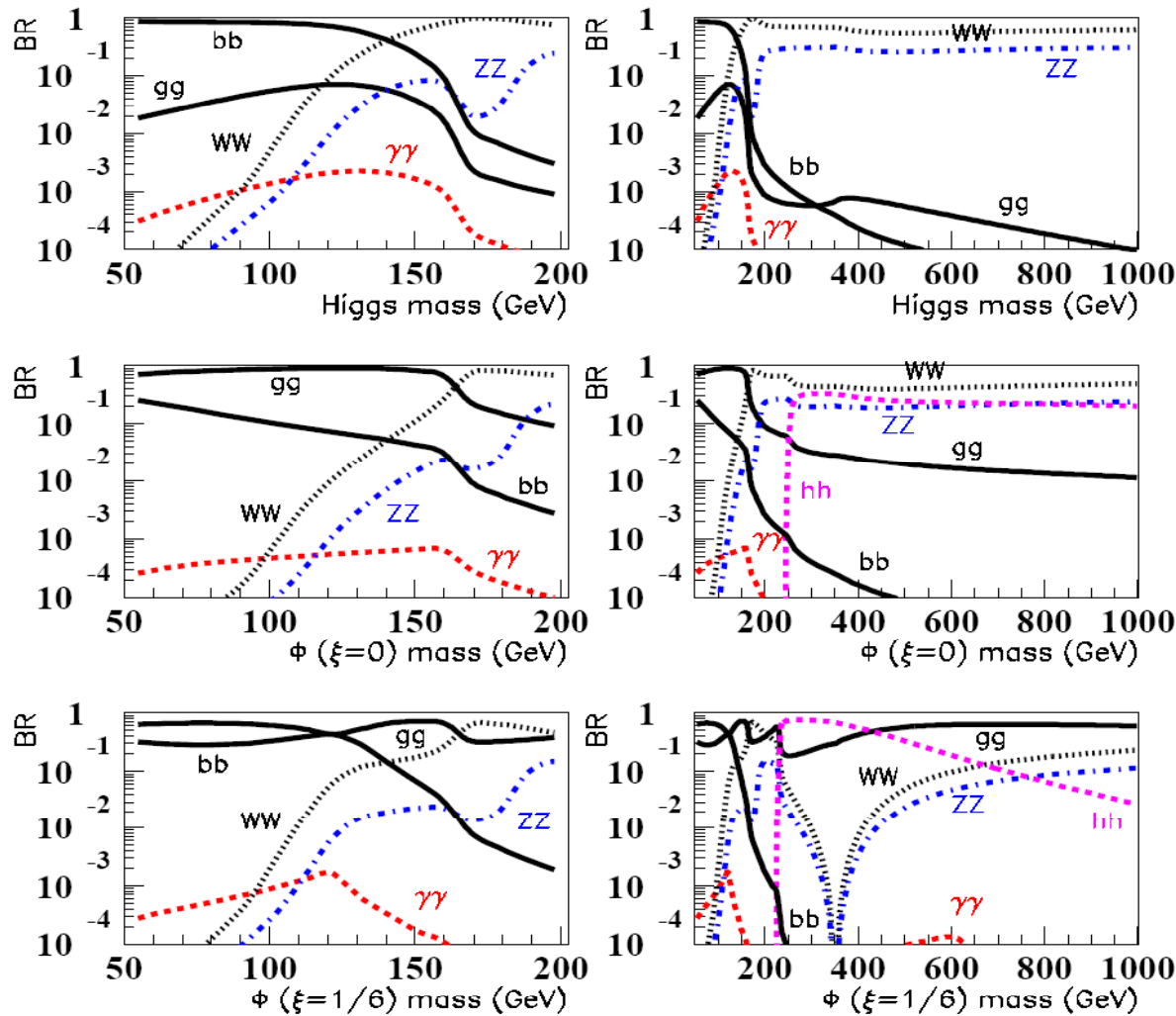
Very important phenomenological side: without any fine tuning of parameters $\Lambda_\phi \sim 1 \text{ TeV}$ and $m_\phi < \text{TeV}$

Radion

couples to gauge bosons and fermions similarly to SM Higgs
mixes with the Higgs

Free parameters of 5D Randall-Sundrum model:
 $m_\phi, m_h, \Lambda_\phi (\phi \text{ vev}), \xi (\phi\text{-}h \text{ mixing})$

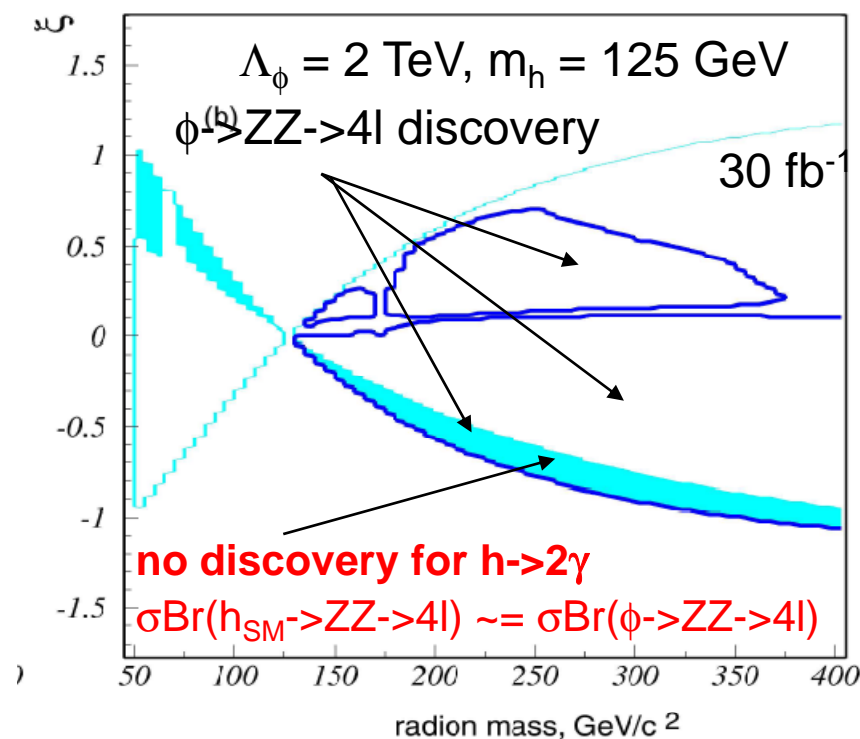
Branching Ratios of Radion and Higgs



Tri-linear terms in the
Higgs radion sector
open $\phi \rightarrow hh$

e.g. $BR(\phi \rightarrow hh) \sim 20-30\%$
for $m_h = 120 \text{ GeV}$
 $m_\phi \sim 250-350 \text{ GeV}$
 $\Lambda_\phi = 5 \text{ TeV}$

Higgs in radion decays



Channels:

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

2 high- P_T isolated photons + 2 b-jets

Di-photon trigger

Low backgrounds from:

$\gamma\gamma bb$ (irred.), $\gamma\gamma bj$, $\gamma\gamma jj$, $\gamma\gamma cc$, $\gamma\gamma cc$

$\phi \rightarrow hh \rightarrow \tau\tau bb$

1 isolated lepton + 2 b-jet + 1 τ -jet

Backgrounds:

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

$\phi \rightarrow hh \rightarrow bbbb$

Largest signal rate but

HUGE multi-jet background

Hopeless

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



Analysis assumes h already been discovered

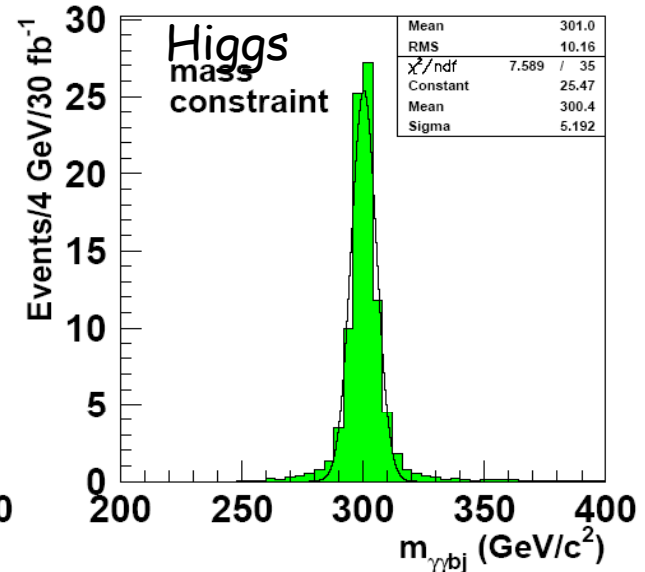
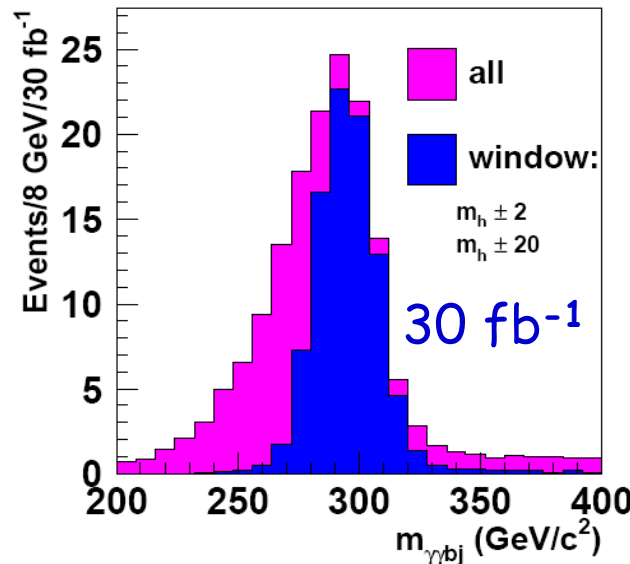
Fast detector simulation

PYTHIA for signal/bkg

$m_h = 125 \text{ GeV}$

$m_\phi = 300 \text{ GeV}$

$\Lambda_\phi = 1 \text{ TeV}$



Event Selection:

- ❑ Two isolated photons with $P_T > 20 \text{ GeV}$, $|\eta| < 2.4$
- ❑ Two jets of $E_T > 15 \text{ GeV}$, $|\eta| < 2.5$, at least one b-tagged jet
- ❑ $m_{\gamma\gamma} = m_h \pm 2 \text{ GeV}$, $m_{bj} = m_h \pm 20 \text{ GeV}$, $m_{\gamma bj}$ mass cuts

For $m_\phi = 300 \text{ (600) GeV}$ and $\xi=0$

\Rightarrow Reach in $\Lambda_\phi = 2.2 \text{ (0.6) TeV}$

Azuelos et al. , EPJDirect C, 4, (2002) 16

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

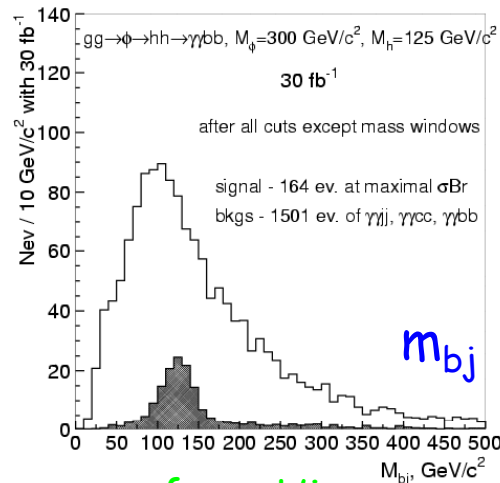
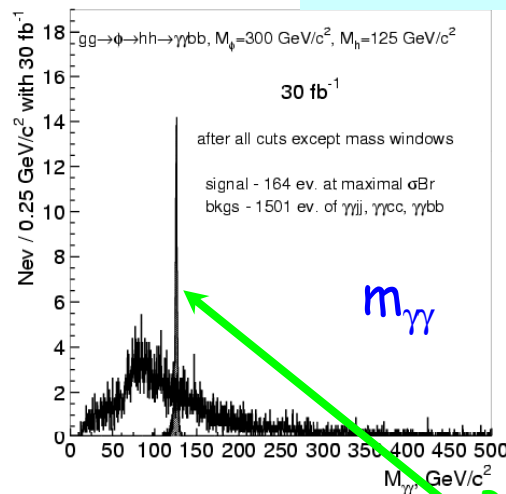


Full simulation for the signal (corrected Pythia)
Fast simulation for the background
MadGraph for $\gamma\gamma jj$, $\gamma\gamma bb$, $\gamma\gamma cc$, CompHep for Zbb
Fix $M_\phi = 300 \text{ GeV}$ $M_h = 125 \text{ GeV} \Rightarrow$ scan the (ξ, Λ_ϕ) plane
Designed to discover Higgs + Radion

Event Selection:

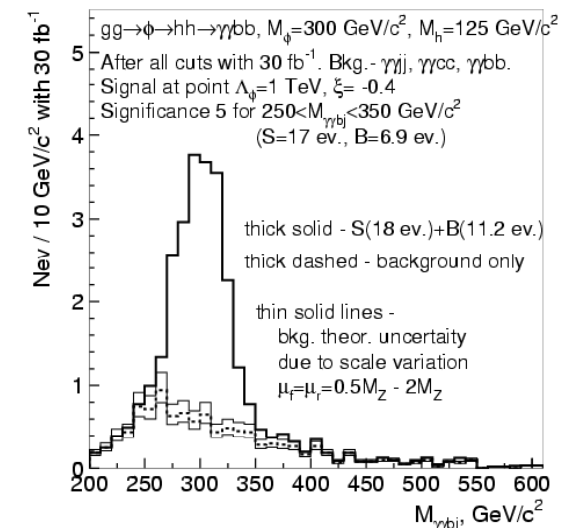
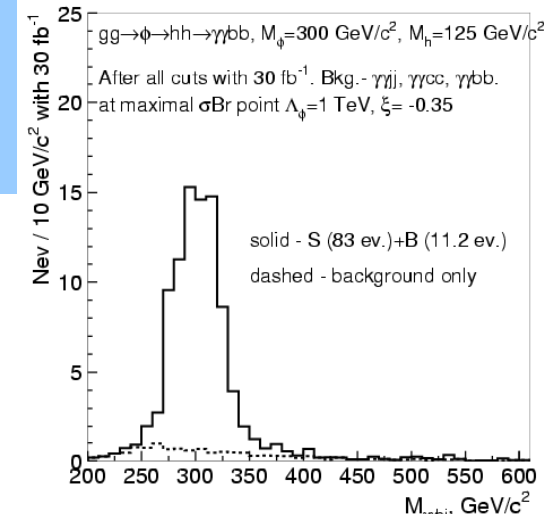
- ❑ Two isolated photons with $P_{T1} > 40 \text{ GeV}$, $P_{T2} > 25$, $|\eta| < 2.4$
- ❑ Two jets of $E_T > 15 \text{ GeV}$, $|\eta| < 2.5$, at least one b-tagged jet
- ❑ $m_{\gamma\gamma}$ m_{bj} $m_{\gamma bj}$ mass cuts
- ❑ 3.7% efficiency

Selected γbj sample



Presence of one Higgs

at maximal signal σBr point in Λ_ϕ - ξ plane



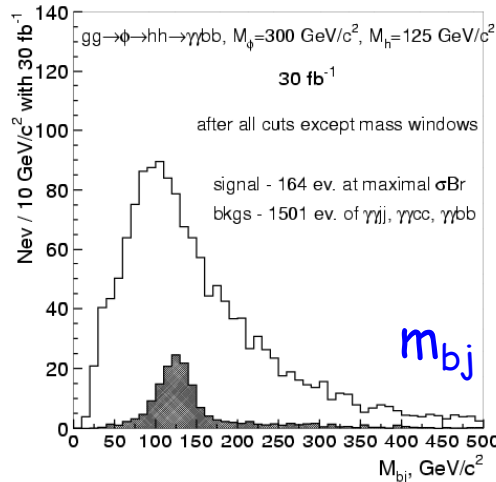
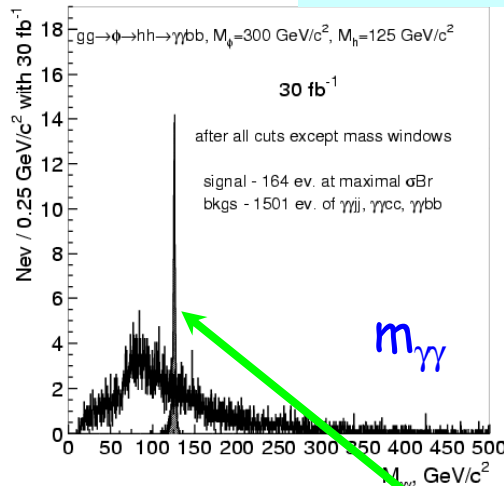
$\phi \rightarrow hh \rightarrow \gamma\gamma bb$



Then look at $m_{\gamma b j}$ for those events with
 $m_{\gamma\gamma} = \gamma\gamma$ observed peak ± 4 GeV
 $m_{bj} = \gamma\gamma$ observed peak ± 30 GeV
 Radion is found from the excess of events

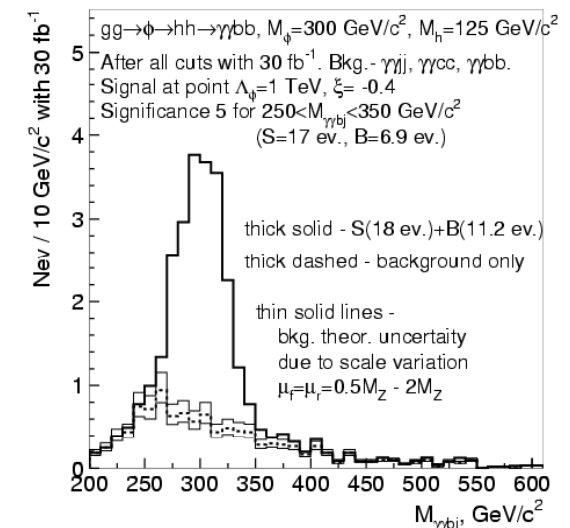
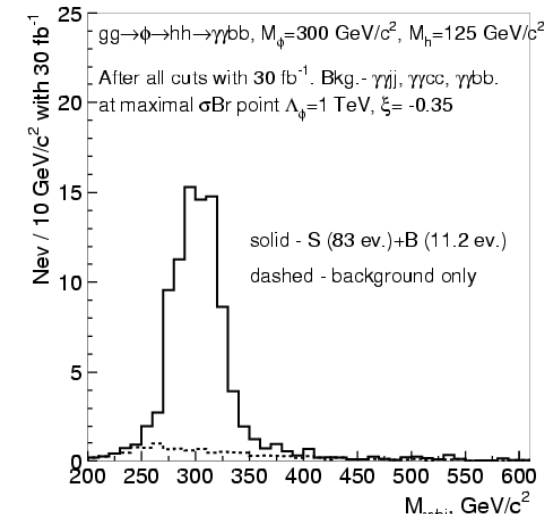
D. Dominici et al. CMS Note 2005/007

Selected $\gamma b j$ sample



Presence of one Higgs

at maximal signal σBr point in
 $\Lambda\phi$ - ξ plane



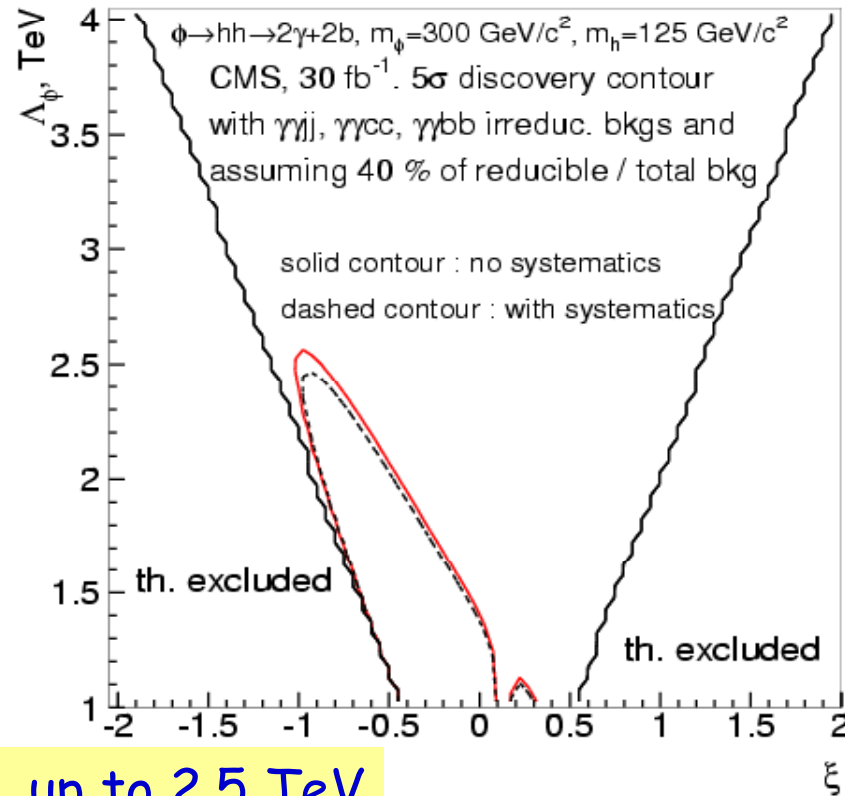
$$\phi \rightarrow hh \rightarrow \gamma\gamma bb$$



Scan in (Λ_ϕ, ξ) plane for $m_\phi = 300 \text{ GeV}/c^2$, $m_h = 125 \text{ GeV}/c^2$

5σ discovery contours for 30 fb^{-1}

Effects due to Background + systematic errors are included

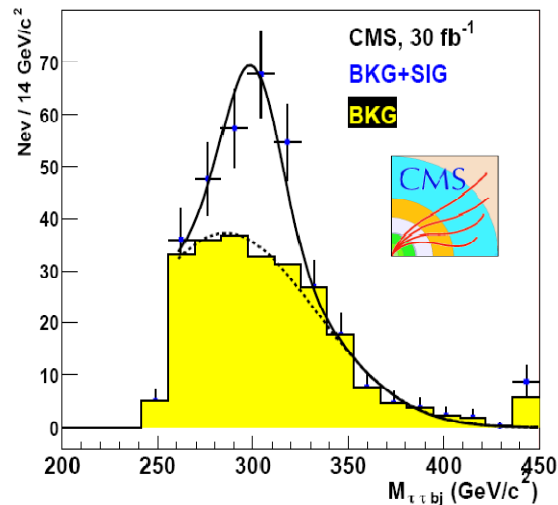
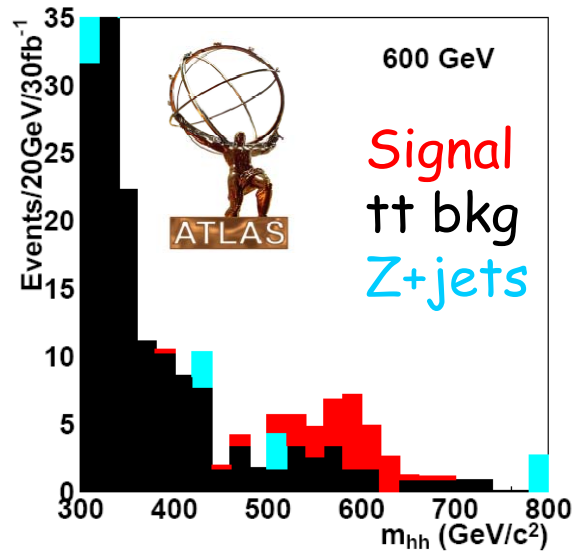
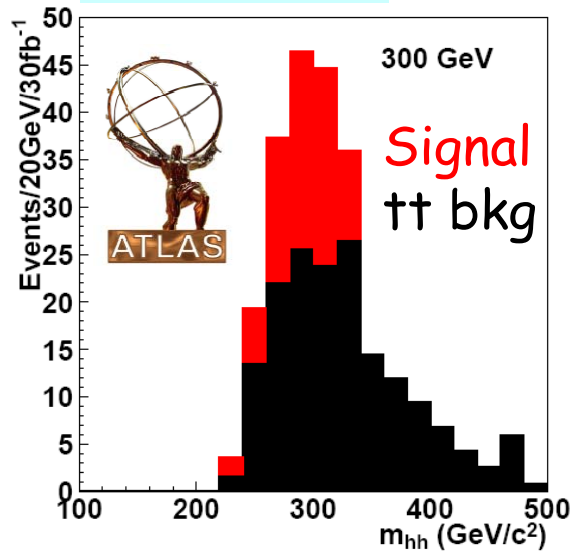


Reach in Λ_ϕ up to 2.5 TeV

$\phi \rightarrow hh \rightarrow \tau\tau bb$

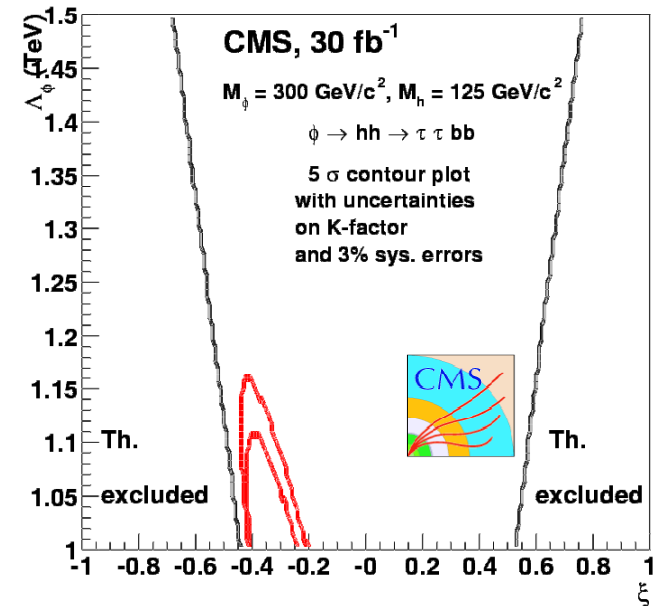


$M_h = 125 \text{ GeV}$

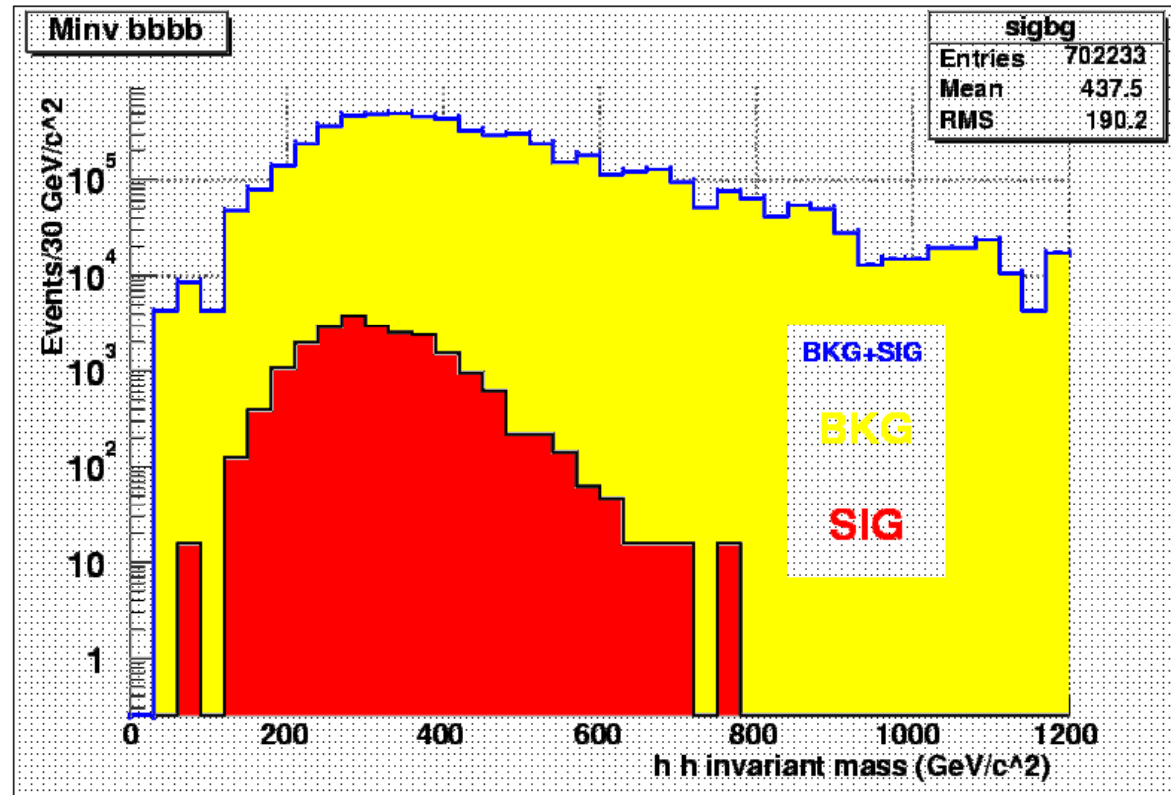


Reach in $\Lambda_\phi \sim 1 \text{ TeV}$

5 σ discovery contours



$$\phi \rightarrow hh \rightarrow bbbb$$



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)

Summary



Non-minimal models (Randall-Sundrum extra dim, Little Higgs) have become popular, aside from Supersymmetry, as alternative solutions to the Hierarchy Problem in the SM

First studies have been performed by both ATLAS and CMS oriented to discovering the new particles/testing the models

Radions (RS): Overall a reach in Λ_ϕ up to 2.5 TeV should be possible
CMS attempts a simultaneous discovery of the SM-like Higgs and the radion (RS) in the $\phi \rightarrow hh \rightarrow \gamma\gamma bb$ channel

Littlest Higgs:

Search of new heavy doubly charged Higgs bosons investigated both in VBF and Drell-Yan production

Sensitivity at large masses ($> \sim 1\text{TeV}$) seems to be rather poor
however discovery can be achieved up to $\sim 650\text{ GeV}$ or exclusion up to $\sim 750\text{ GeV}$

Summary



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Left-Right Symmetric Model

The existence of RH doubly charged Higgs can be probed in the purely leptonic channel up to $\sim 1.7\text{TeV}$ (100 fb^{-1})

Whatever it is waiting for us round the corner it will be fun !