Higgs bosons in non-minimal Models

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On behalf of ATLAS and CMS

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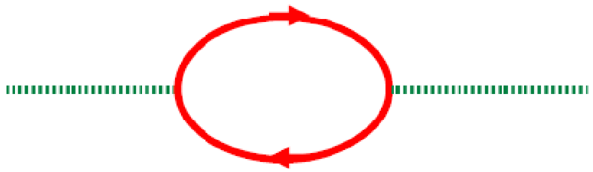
Summary

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



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

$$\delta m_h^2 \propto a_W\Lambda^2$$ from gauge bosons

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

Example: if Λ = 10 TeV the lowest order corrections are:

~ (2 TeV)^2	top loops
~ - (750 GeV)^2	W/Z loops
~ -(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 O(200 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

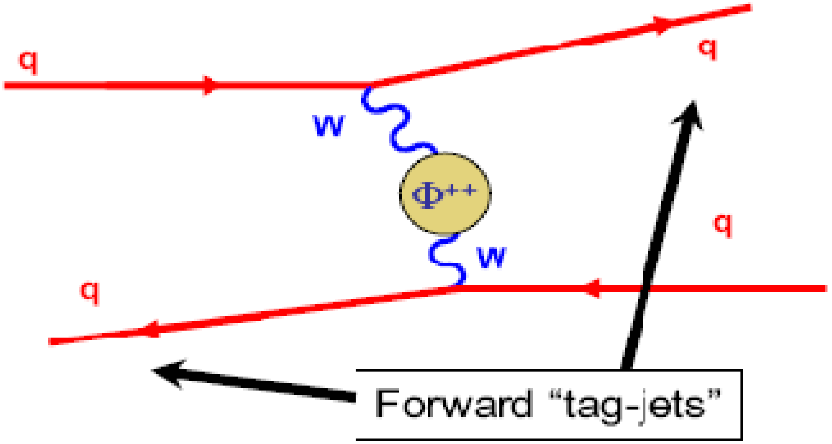
- Two (left and right) Higgs triplets provide a parity conserving Lagrangian

- 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 (~10^{11} GeV)

➡ see-saw mechanism possible
➡ natural explanation of the low, non-zero mass of left-handed neutrinos

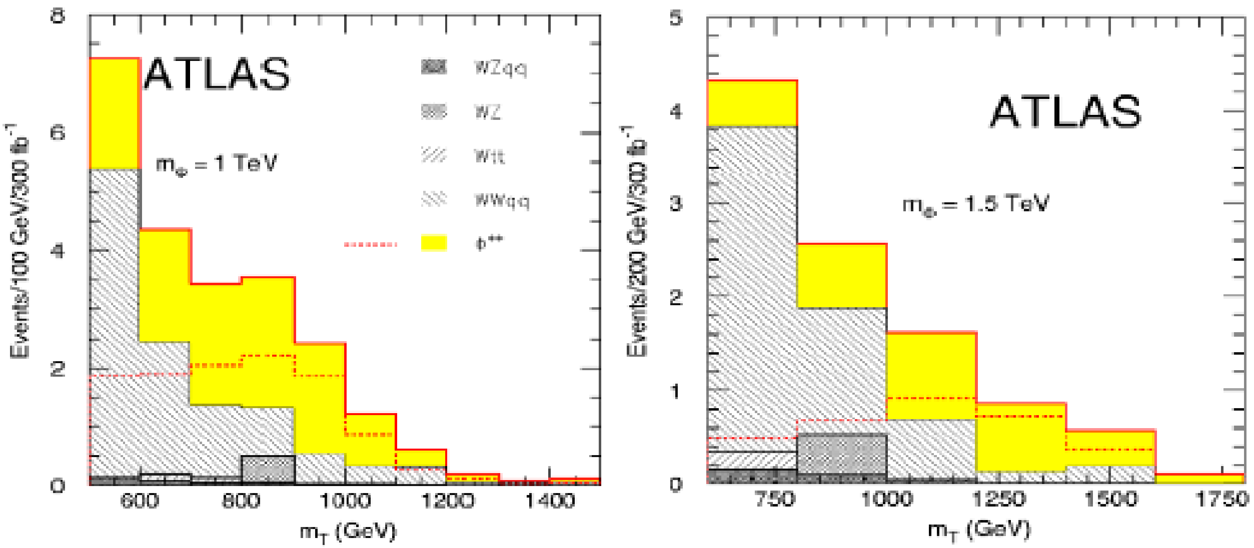


Production: VBF mechanism

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

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

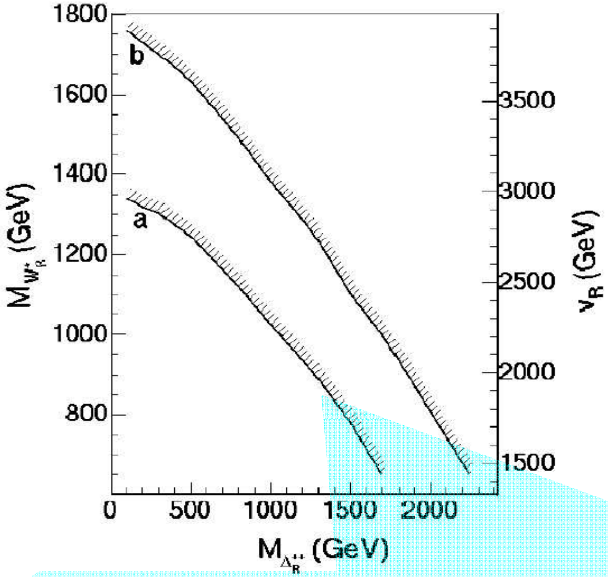
- Two positive leptons with $p_T >$ 150, 20 GeV and $|\eta|<2.5$
- $|p_{T1} - p_{T2}| >$ 200 GeV
- $|\eta_1 - \eta_2| < 2.0$
- $E_T^{miss} >$ 50 GeV
- Two "tag jets", $p_T > 15$, E > 200, 100 GeV, $|\eta_1 - \eta_2| > 5$



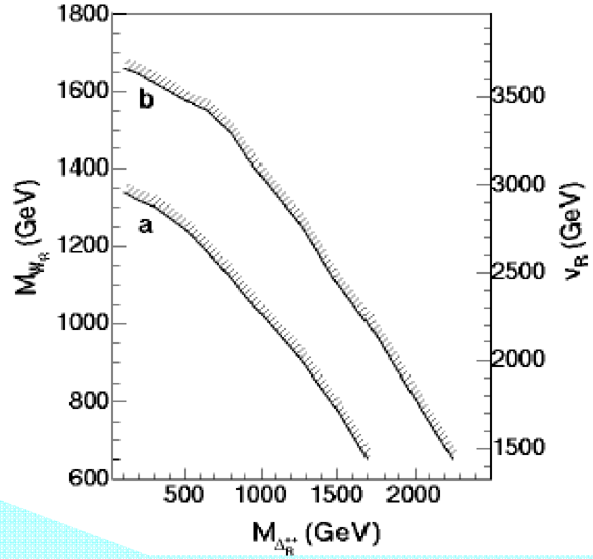
Azuelos et al. , Eur.Phys.J. C39S2 (2005) 13-24

Search for RH doubly charged Higgs (LRSM)

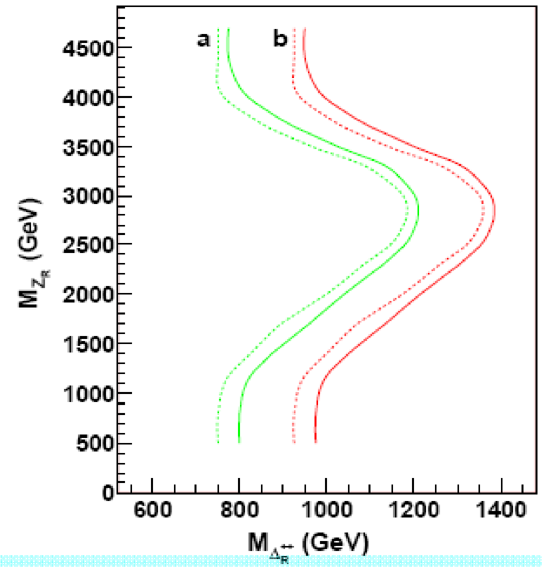
Same-sign di-leptons



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}

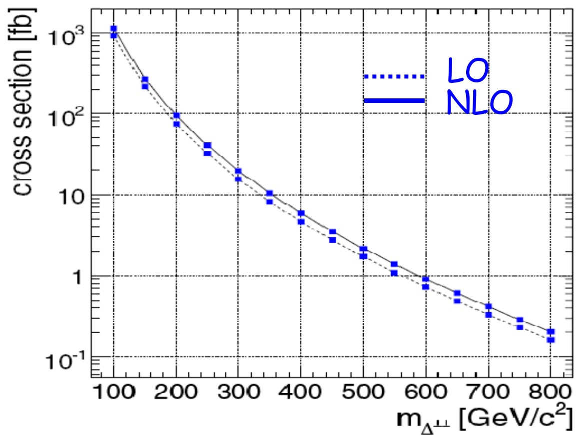
	Δ^{++} 300 GeV	Δ^{++} 800 GeV	$W^+W^+\,qq$	$W\ t\bar{t}$	$WZqq$	$t\bar{t}$	total backg
Isolated leptons	278 (327)	63 (95)	109/12	7.6/0.6	0/0.8	17/0	133/13
Lepton P_T	256 (301)	63 (94)	63/11	5.9/0.5	0/0.8	1.1/0	70/12
$2.4(P_T^{l_1}+P_T^{l_2})-M_{ll}>480$	191(227)	59(85)	10/2.1	1.3/0.3	0	0	12/2.4
Fwd Jet 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

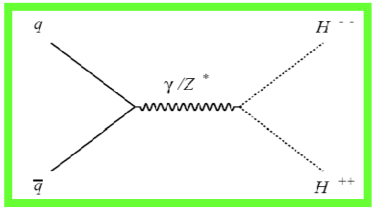
ATLAS

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

Search for pair production of doubly charged Higgs

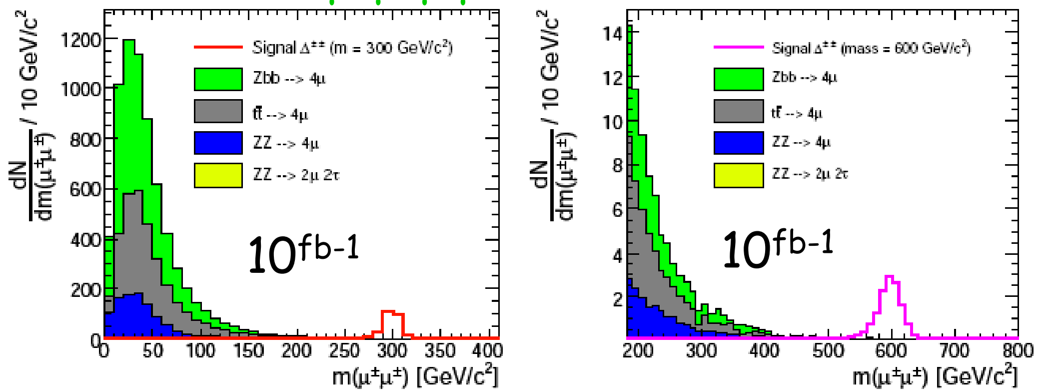
Drell-Yan production of $\Delta^{++}\Delta^{--}$
NLO σ (Spira, Muhlleitner, 2003)



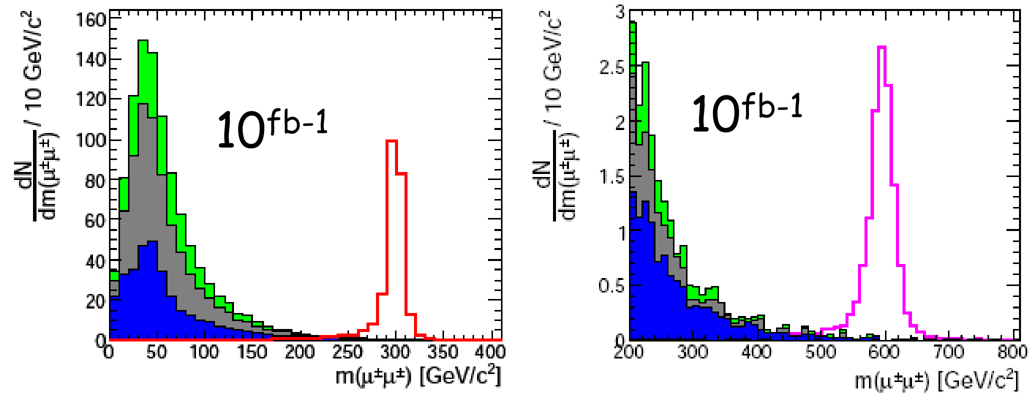


Same-sign lepton final state
SM bkg very small

$\Delta^{++}\Delta^{--} \to \mu^+\mu^+\mu^-\mu^-$ after online selection



$\Delta^{++}\Delta^{--} \to \mu^+\mu^+\mu^-\mu^-$ after offline selection



Δ^{++} decays:

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

were studied

4μ

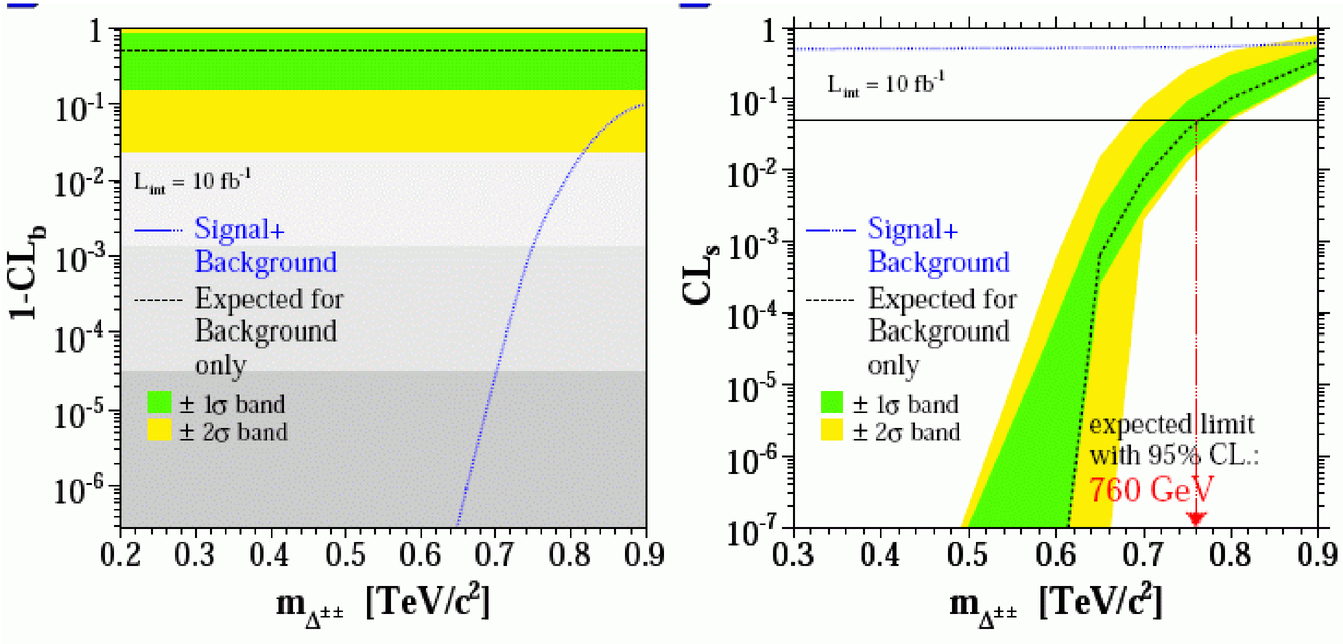
$1\mu3\tau$, $2\mu2\tau$, $3\mu1\tau$

with $\tau \to$ hadrons

Rommerskirchen et al, CMS Note 2006/081

Δ++/-- discovery and exclusion

4μ final state



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

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

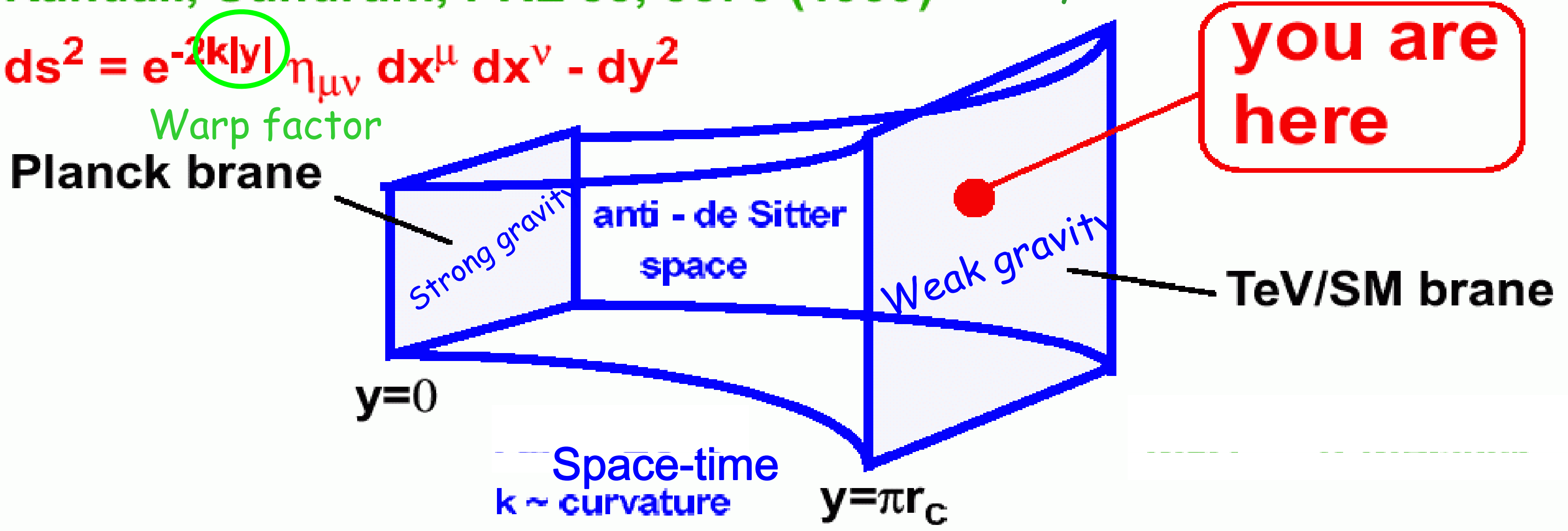
With τ in the final state. No background left !

$m_{\Delta}^{\pm\pm}$ (GeV)	200	300	400	500
N_{ev} expected at 10 fb^{-1}	26	10	4	2
σ_{NLO} ± stat ± 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



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

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

The hierarchy between Planck and EW scale is removed by the exponential warp factor if $kr_c \sim 12$ → $r_c \sim 10^{-32}$ m → 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

Free parameters of 5D Randall-Sundrum model:

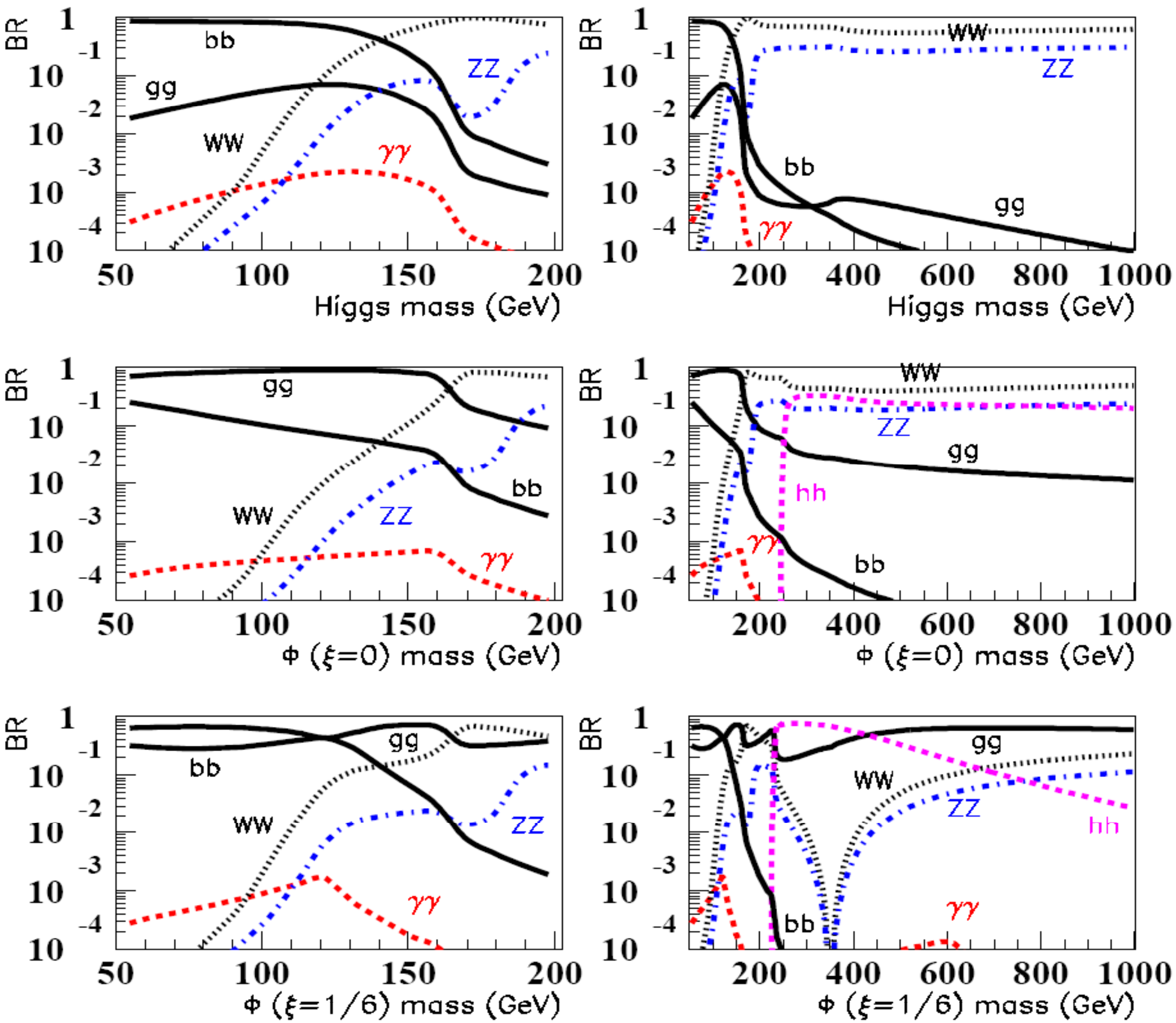
m_ϕ, m_h, Λ_ϕ (ϕ vev), ξ (ϕ-h mixing)

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

Radion

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

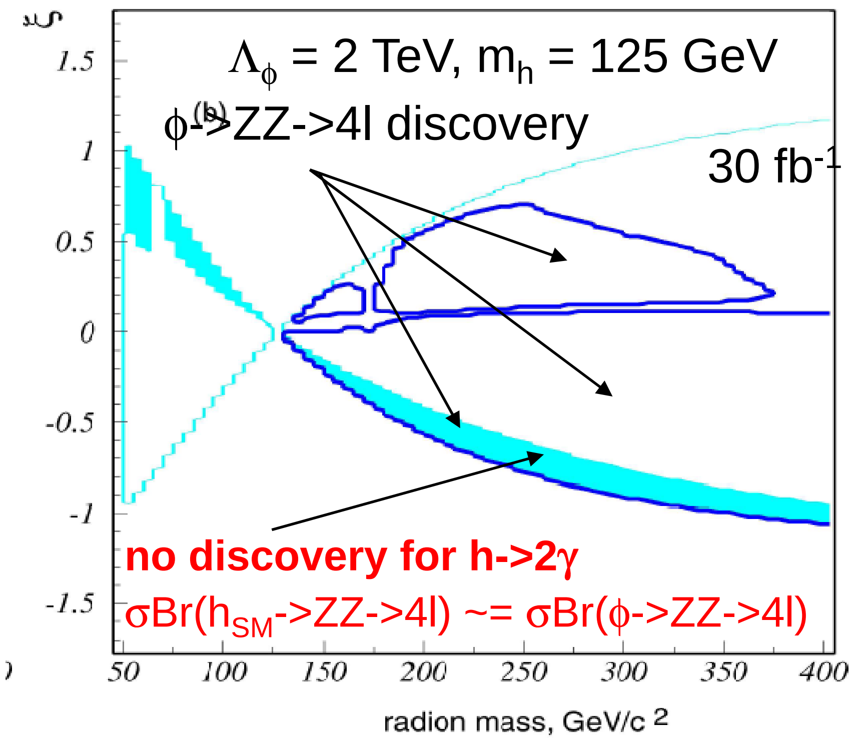
Branching Ratios of Radion and Higgs



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

e.g. BR($\phi \to hh$) ~ 20-30%
for m_h = 120 GeV
m_ϕ ~ 250-350 GeV
Λ_ϕ = 5 TeV

Higgs in radion decays



Channels:

$\phi \to hh \to \gamma\gamma bb$

2 high-P_T isolated photons + 2 b-jets
Di-photon trigger
Low backgrounds from:
$\gamma\gamma bb$ (irred.), $\gamma\gamma bj$, $\gamma\gamma jj$, $\gamma\gamma cj$, $\gamma\gamma cc$

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

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

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

$\phi \to hh \to bbbb$

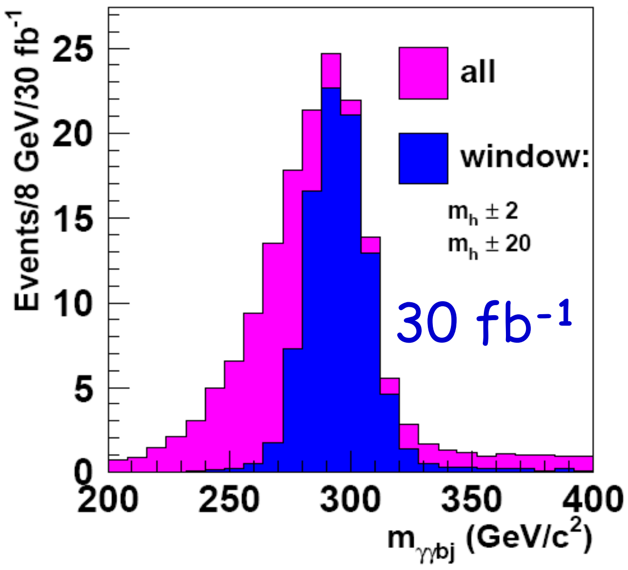
Largest signal rate but
HUGE multi-jet background
Hopeless

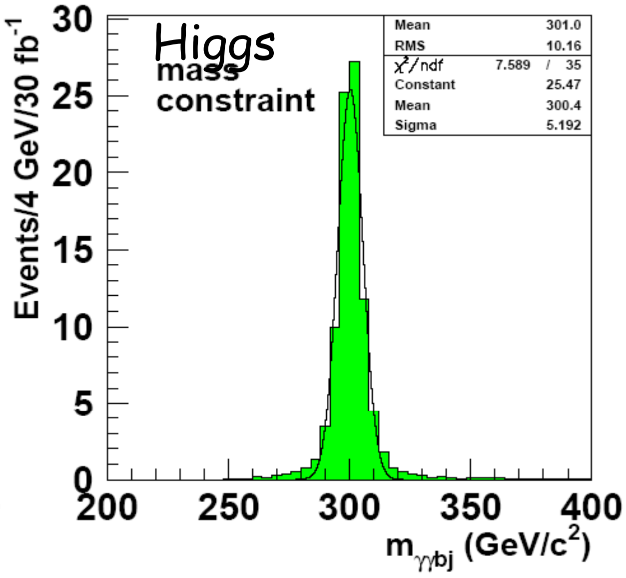
$\phi \rightarrow hh \rightarrow \gamma\gamma bb$

Analysis assumes h already been discovered

Fast detector simulation

PYTHIA for signal/bkg
m_h=125 GeV
m_ϕ=300GeV
Λ_ϕ = 1 TeV





Event Selection:

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

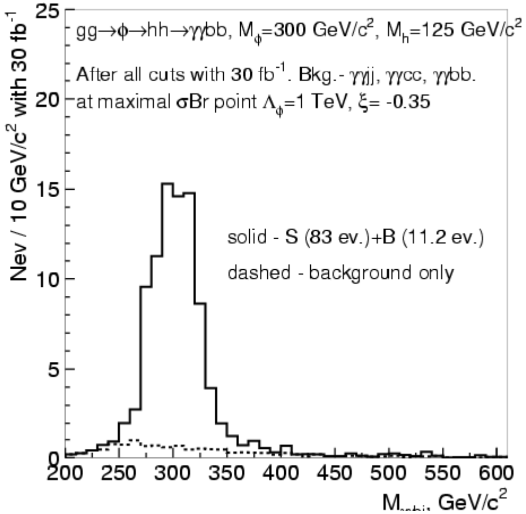
For m_ϕ= 300 (600) GeV and ξ=0
$\Rightarrow$ Reach in Λ_ϕ =2.2 (0.6) TeV

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

$\phi \to hh \to \gamma\gamma bb$

at maximal signal σBr point in Λ_ϕ-ξ plane

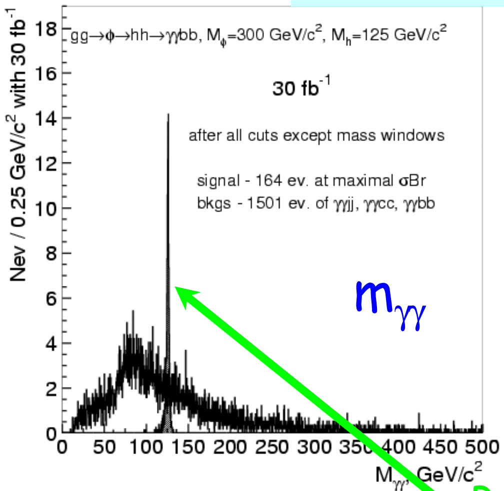
Full simulation for the signal (corrected Pythia)
Fast simulation for the background
MadGraph for $\gamma\gamma jj$, $\gamma\gamma bb$, $\gamma\gamma cc$, CompHep for Zbb
Fix M_ϕ =300 GeV M_h=125 GeV $\Rightarrow$ scan the (ξ,Λ_ϕ) plane
Designed to discover Higgs + Radion

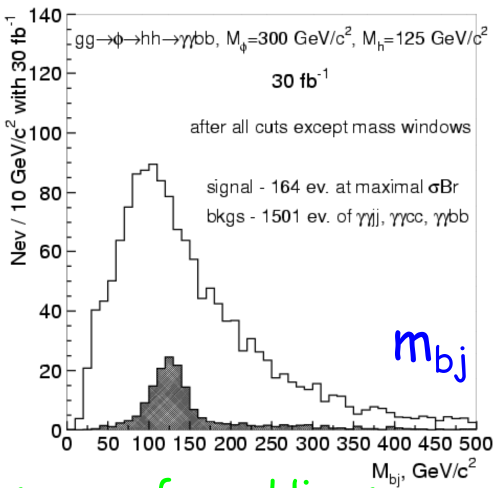


Event Selection:

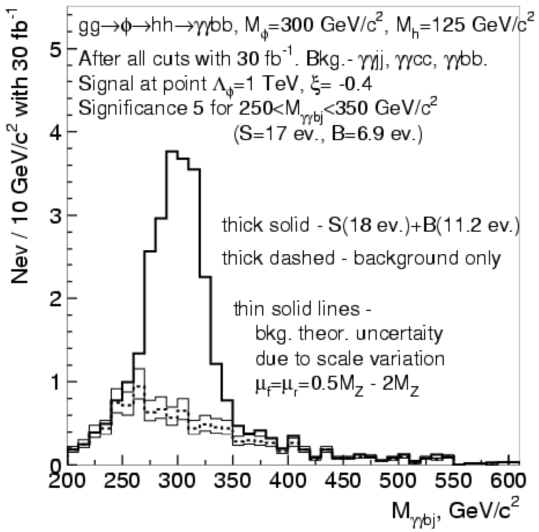
- Two isolated photons with $P_{T1} > 40$ GeV, $P_{T2} > 25$, $|\eta|<2.4$
- Two jets of $E_T > 15$ GeV, $|\eta| < 2.5$, at least one b-tagged jet
- $m_{\gamma\gamma}$ m_{bj} $m_{\gamma\gamma bj}$ mass cuts
- 3.7% efficiency

Selected $\gamma\gamma bj$ sample





Presence of one Higgs

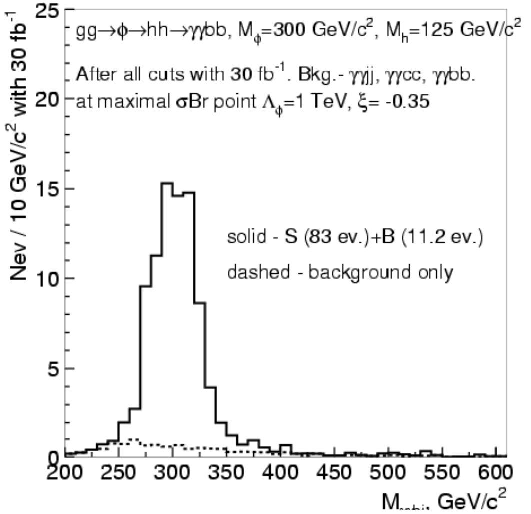


$\phi \to hh \to \gamma\gamma bb$

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

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

D. Dominici et al. CMS Note 2005/007



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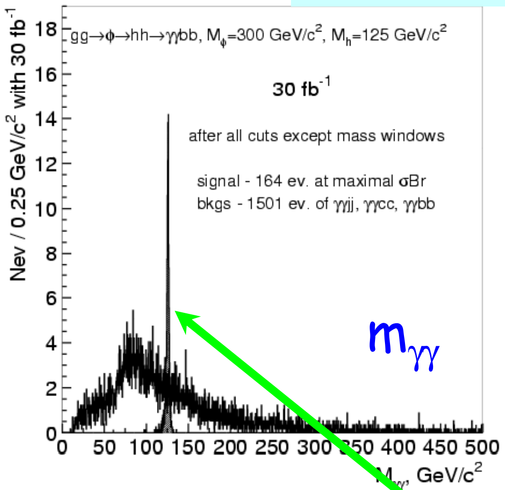
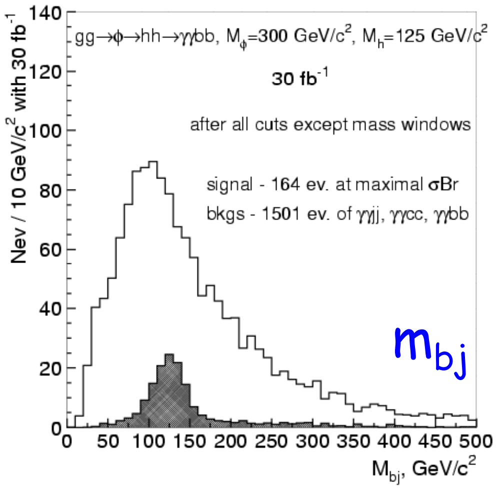
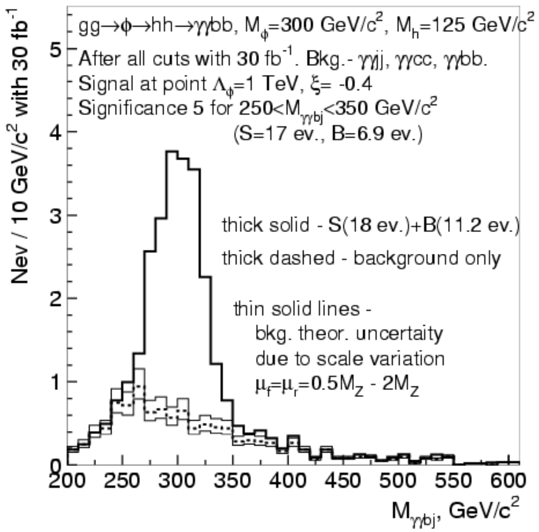






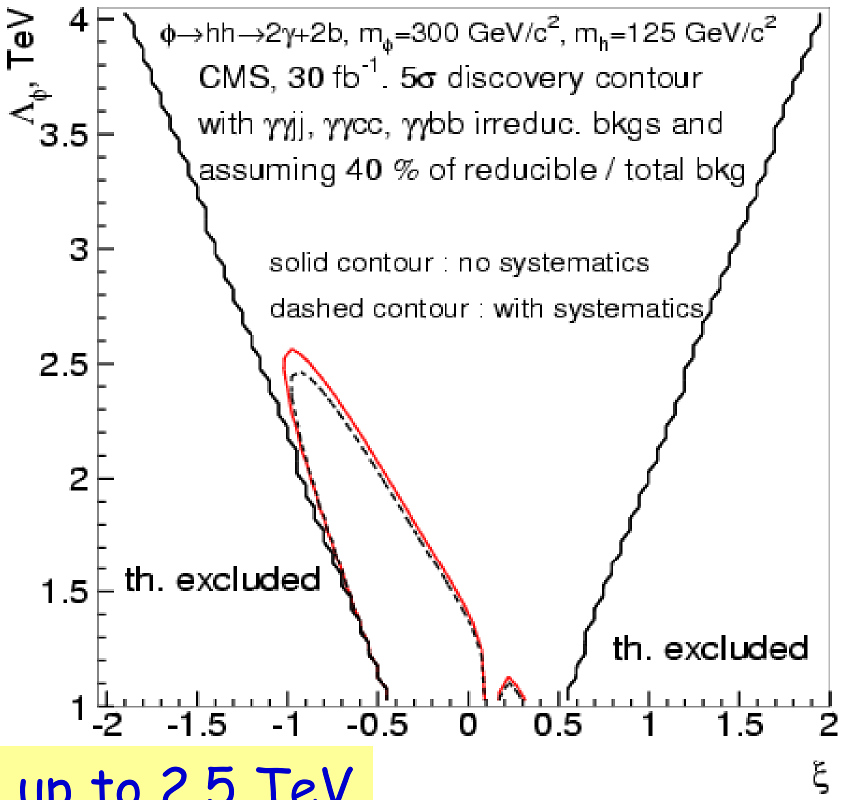
Presence of one Higgs

$\phi \to hh \to \gamma\gamma bb$

Scan in (Λ_ϕ, ξ) plane for m_ϕ=300 GeV/c^2, m_h=125 GeV/c^2

5σ discovery contours for 30 fb^{-1}

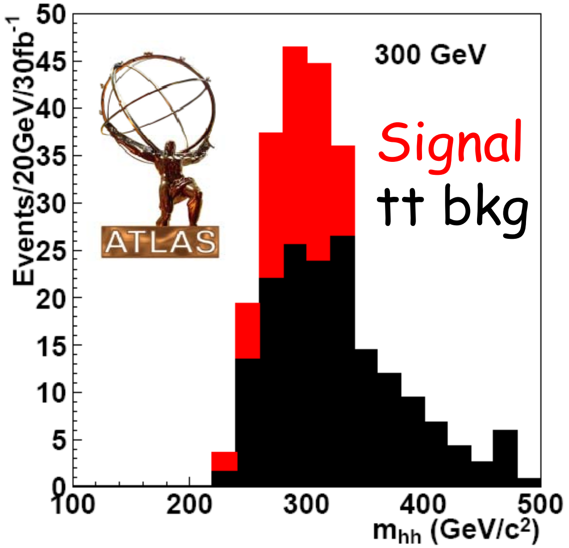
Effects due to Background + systematic errors are included

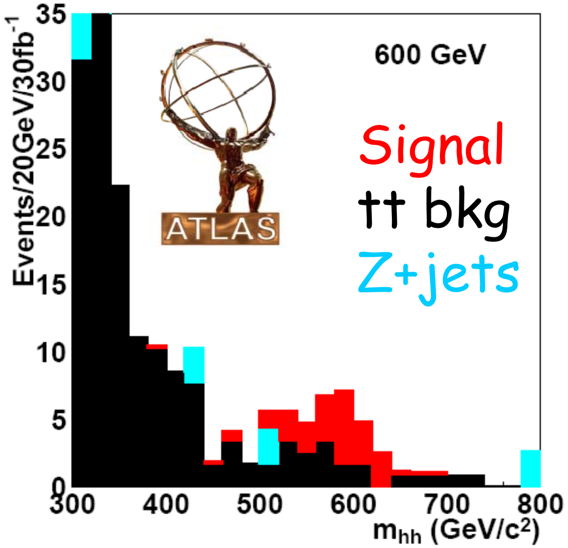


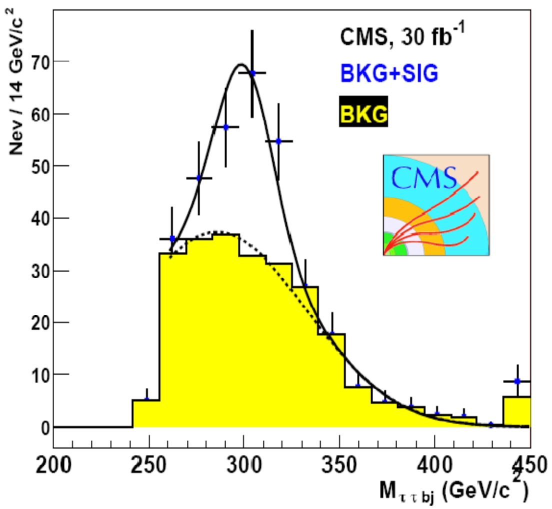
Reach in Λ_ϕ up to 2.5 TeV

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

M_h=125 GeV

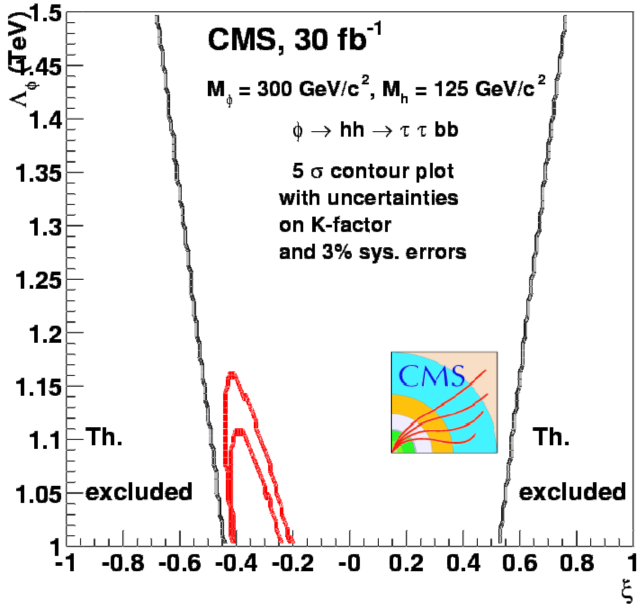




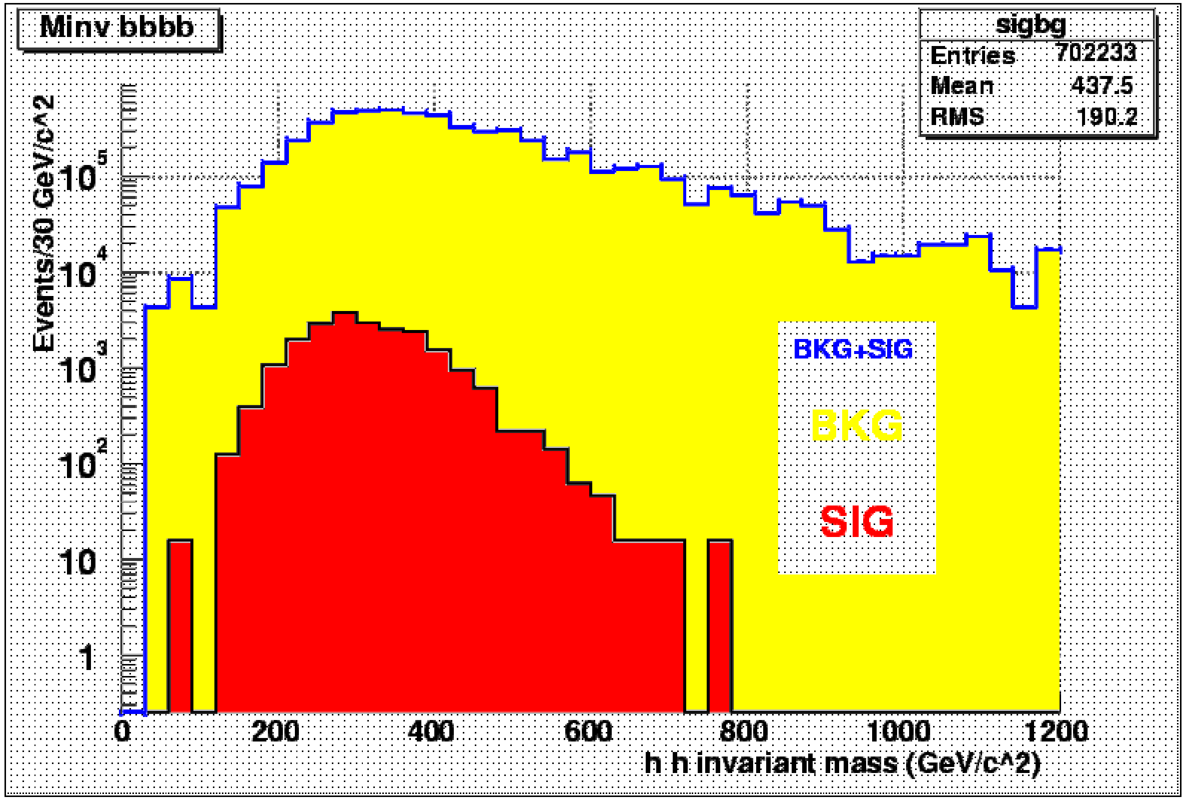


Reach in Λ_ϕ ~ 1 TeV

5σ 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 (>~ 1TeV) seems to be rather poor however discovery can be achieved up to ~650 GeV or exclusion up to ~750 GeV

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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 ~ 1.7TeV (100 fb^{-1})

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