Scope for New Physics in the Higgs Data

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August 12, 2013

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- *Till a reliable measurement of self-coupling is available, how to attempt an answer?*
- *Carefully analyse various other final states which reflect Higgs couplings*

Data are becoming available
on various Higgs channels

$$pp \longrightarrow HX \longrightarrow \gamma\gamma, ZZ^*, WW^*, \tau^+\tau^-, b\bar{b}$$

Also, various production channels:
$gg \longrightarrow HX, q\bar{q} \longrightarrow q^{(')}\bar{q}^{(')}H, q\bar{q} \longrightarrow VH,$
$q\bar{q}(gg) \longrightarrow t\bar{t}H$

Some of these provide useful 'tags'
$(jj, 2\ell, \ell + MET, ...)$

All result from Higgs coupling to particle pairs

Probing the various interactions
$\Rightarrow$ *information on deviation from SM predictions*

Different angles...

Careful examination of uncertainties in SM prediction:

......
I. Stewart, F. J. Tackmann (2011)
A. Denner, S. Heinmeyer, I. Puljak, D. Rebuzi, P. Spira (2011)
F. Richardson, D. Winn (2012)
J. Baglio, A. Djouadi, R. M. Godbole (2012)
A. Djouadi (2012)

- *Examination of the data in view of specific BSM scenarios:*

Different angles...

- *Examination of the data in view of specific BSM scenarios:*
- *Model-independent analysis of data–*
  how much room is there for departure from SM?

A huge mass of studies ....

A. Arbey, M. Battaglia, A. Djouadi (2011, 2012)
D. Alves,P. Fox, N. Weiner (2012)
N. Desai, BM, S. Niyogi (2012)
B. Grzadkowski, J. Gunion (2012)
J. de Sandes, R. Rosenfeld (2012)
H. Kubota, M. Nojiri (2012)
I. Low, J. Lykken, G. Shaughnessy (2012)
J. Gunion, Y. Jiang, S. Kraml (2012)
N. Desai, U. Maitra, BM(2013)
......
J. Ellis, T. You (2012,2013)
P. Giradino et al (2012,2013)
S. Banerjee, S. Mukhopadhyaya, BM (2012, 2013)
A. Azatov, Contino, J. Galloway (2012)
J. Espinosa, C. Grojean, M. Muhlleitner, M. Trott (2012)
T. Plehn, M. Rauch (2012)
T. Corbett, O. Eboli, J. Gonalez-Fraile, M. C. Gonzalez-Garcia (2012)
....

To be covered in the present discussion.....

- *An updated model-independent analysis: including invisible decay and a phase in the $Ht\bar{t}$ effective amplitude S. Banerjee, S. Mukhopadhyaya, BM, JHEP 1210, 062 (2012)*

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- *A study including the sensitivity of additional HVV operators to cuts:*
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- *A study including the sensitivity of additional HVV operators to cuts: S. Banerjee, S. Mukhopadhyaya, BM, in preperation*
- *A cut-based analysis constraining radion-Higgs mixing in the Randall-Sundrum scenario N. Desai, U. Maitra, BM, arXiv:1307.3018*

Case - 1 :

When the Higgs amplitudes are modified by multiplicative factors....

S. Banerjee, S. Mukhopadhyay, BM, (2012, updated 2013)

BSM effects
$\Rightarrow$ Higgs couplings to $\Rightarrow$ $T_3 = +1/2$ and $-1/2$ fermions can have different deviations from SM values

Example: SUSY, 2HD models....

$$\mathcal{A}^{eff}_{H\bar{t}t} = e^{i\delta}\alpha_u \mathcal{A}^{SM}$$
$$\mathcal{A}^{eff}_{H\bar{b}b} = \alpha_d \mathcal{A}^{SM}$$

Modification in SM Yukawa couplings,
$+$
A phase in the top quark effective amplitude
(shows up in the interference between the fermion-and W-loops in $H \longrightarrow \gamma\gamma$)

Modified gauge boson pair couplings...

$$\mathcal{L}_{HWW} = \beta_W \frac{2m_W^2}{v} H W_\mu^+ W^{\mu -}$$
$$\mathcal{L}_{HZZ} = \beta_Z \frac{m_Z^2}{v} H Z_\mu Z^\mu$$

$\beta_W \neq \beta_Z$ **can arise, for example, from gauge invariant effective operators of higher dimension**

EW precision constraints less severe, if there are more than one higher-dim. operators

Modified gluon-gluon and photon-photon couplings...

$$\mathcal{L}_{gg}^{eff} = -x_g f(\alpha_u) \frac{\alpha_s}{12\pi v} H G^a_{\mu\nu} G^{a\mu\nu}$$

$$\mathcal{L}_{\gamma\gamma}^{eff} = -x_\gamma g(\alpha_u, \alpha_d, \beta_W, \delta) \frac{\alpha_{em}}{8\pi v} H F_{\mu\nu} F^{\mu\nu}$$

f, g: **Effects of modified fermion and gauge boson couplings**

x_g, x_γ: **Effects of additional states participating in loops**

Invisible width...

Possible effect of the Higgs serving as light dark matter portal

ϵ **= Invisible branching ratio**

$$\Gamma_{inv} = \frac{\epsilon}{1-\epsilon} \sum \Gamma_{vis}$$

All coupling modifications affect ϵ

Task: to find the best fit in $\alpha_u, \alpha_d, \beta_W, \beta_Z, x_g, x_\gamma, \delta, \Gamma_{inv}$ via χ^2-minimization

Locate the 95% C.L. spreads of individual parameters about the minimum in χ^2

Input data used: Best fit values for $\hat{\mu} = \sigma_{obs}/\sigma_{SM}$ with the corresponding errors, for

$\gamma\gamma, ZZ^* \to 4\ell, WW^* \to \ell\nu\ell\nu, \tau\tau, b\bar{b}$ from CMS and ATLAS (both 7 and 8 TeV) and

$WW^*, b\bar{b}, \gamma\gamma$ from Tevatron

No additional operators $\Rightarrow$ cut efficiencies unaffected (more on this later)

To minimize
$\chi^2 = \sum_i \frac{(\mu_i - \hat{\mu}_i)^2}{\sigma_i^2}$
where $\mu_i = \sigma / \sigma_{SM}$ **in the** i**th channel**
For combining input data,

$$\frac{1}{\bar{\sigma}^2} = \sum_i \frac{1}{\sigma_i^2}$$

$$\frac{\bar{\hat{\mu}}}{\bar{\sigma}^2} = \sum_i \frac{\hat{\mu}_i}{\sigma_i^2}$$

$$\mu_i = R_i^{prod} \times R_i^{decay} / R^{width}$$

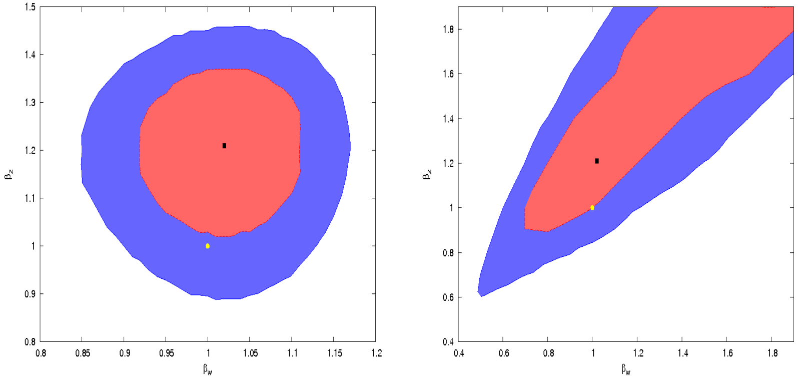
R **= modification due to BSM effects**
All R**'s and** μ**'s are determined by the free parameters**

Best fit values...

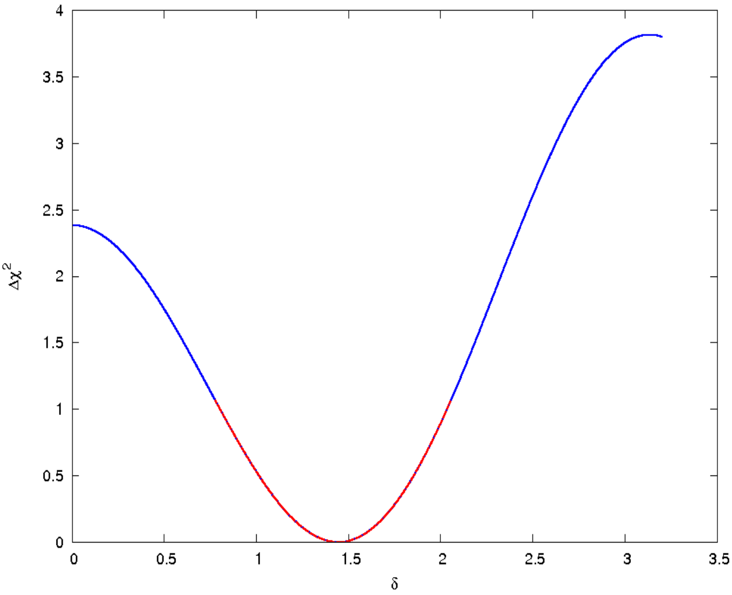
Case	α_u	α_d	β_w	β_z	δ	x_g	x_γ	ϵ
Case A	0.93	1.15	1.02	1.21	0.0*	1.05	1.18	0.06
Case B	0.76	1.19	1.12	1.12	1.44	1.24	0.89	0.02

Best fit table for Case A ($\beta_w \neq \beta_z$ and $\delta = 0$) and Case B ($\beta_w = \beta_z$ and $\delta \neq 0$). $*$ in Case A $\Rightarrow$ δ not varied.

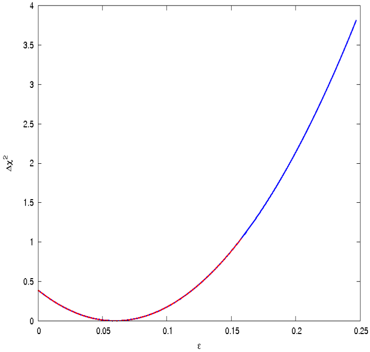
95% C.L. contours–case B (left: non-marginalised, right:marginalised)

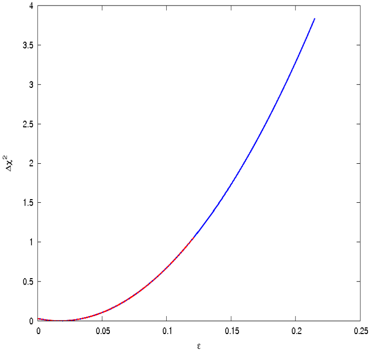


Case B: δ at 2σ...



Invisible BR at 2σ (left: Case A, right: Case B)...





Case - 2 :
Going beyond multiplicative modifications in HVV couplings....

Where cuts can affect the new operators differently

S. Banerjee, S. Mukhopadhyay, BM (2013)

Gauge invariant higher-dim. HVV operators....

- $\frac{f_{\Phi,1}}{\Lambda^2}(D_\mu\phi)^\dagger\phi\phi^\dagger(D^\mu\phi)$
- $\frac{f_{BW}}{\Lambda^2}\phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\phi$
- $\frac{f_{DW}}{\Lambda^2}Tr\left(\left[D_\mu,\hat{W}_{\nu\rho}\right]\left[D^\mu,\hat{W}^{\nu\rho}\right]\right)$
- $\frac{f_{DB}}{\Lambda^2}\frac{g'^2}{2}(\partial_\mu B_{\nu\rho})(\partial^\mu B^{\nu\rho})$
- $\frac{f_{\Phi,2}}{\Lambda^2}\frac{1}{2}\partial^\mu(\phi^\dagger\phi)\partial_\mu(\phi^\dagger\phi)$
- $\frac{f_{\Phi,3}}{\Lambda^2}\frac{1}{3}(\phi^\dagger\phi)^3$
- $\frac{f_{WWW}}{\Lambda^2}Tr[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_\rho^\mu]$
- $\frac{f_{WW}}{\Lambda^2}\Phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$
- $\frac{f_{BB}}{\Lambda^2}\Phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$
- $\frac{f_W}{\Lambda^2}(D_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\Phi)$
- $\frac{f_B}{\Lambda^2}(D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\Phi)$

f_{WW}, f_{BB}: Relatively less constrained by EWPT/TGV

Studies of Higgs data with higher-dim operators.......

....

....

E. Masso and V. Sanz (2013),

A. Falkowski, F. Riva, A. Urbano(2013),

T. Corbett et al. (2013),

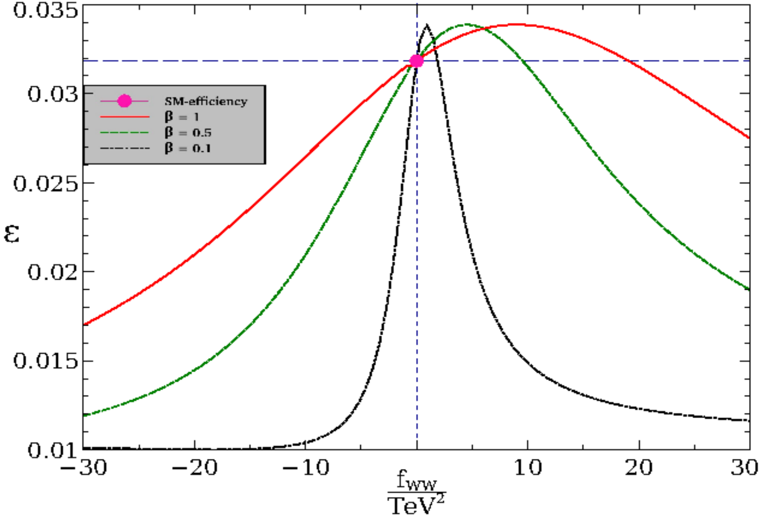
B. Dumont, S. Fichet, G. v. Gersdorff

......

- *Some angular distributions etc. studied, but no clear demonstration of how cuts affect different operators*
- *The f's and $\beta_{W(Z)}$ mostly not varied simultaneously*
- *A detailed study attempted....*
  S. Banerjee, S. Mukhopadhyay, BM

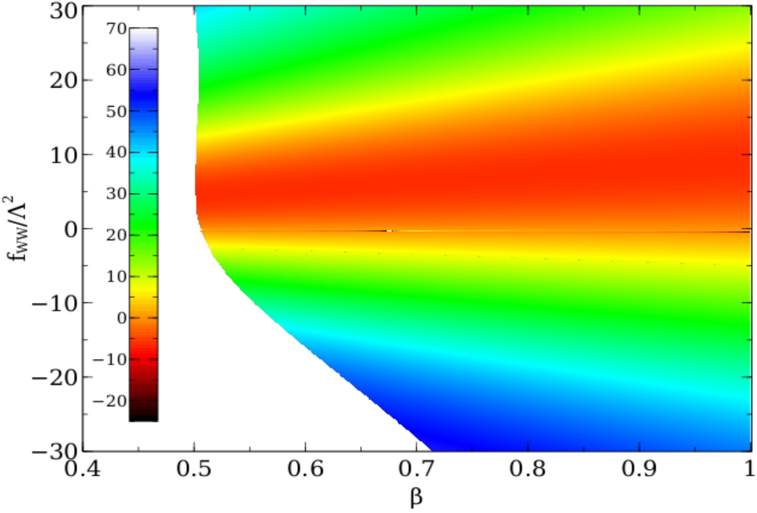
Cut efficiency against f_{WW}/Λ^2 (TeV^{-2})

$pp \longrightarrow H + 2j \rightarrow \ell\nu\ell\nu jj$: (Red/Green/Black: $\beta = 1.0/0.5/0.1$)



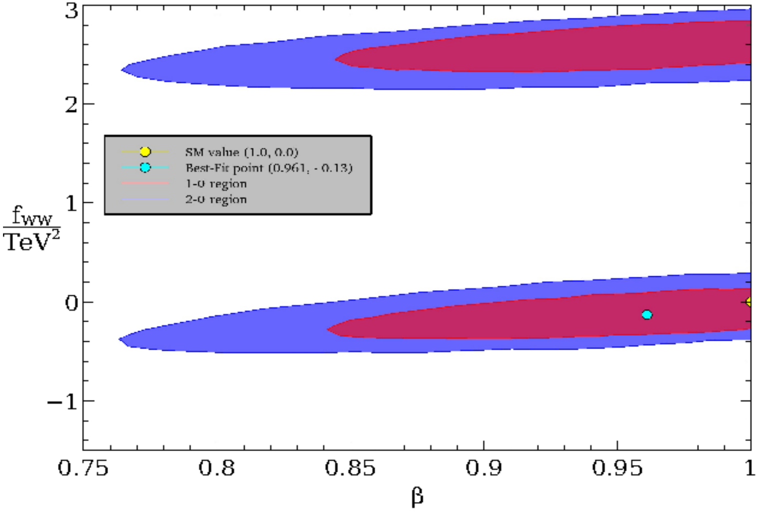
Colour-codes for $(Eff_{SM} - Eff)/Eff_{SM}$

Using 2σ signal strength in $pp \longrightarrow H + 2j \rightarrow \ell\nu\ell\nu jj$ (ATLAS):



Global fit: 2σ region

Best fit: $\beta = 0.96, f_{WW} = -0.13$



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- *In general, the efficiencies can differ considerably on including additional operators, for channels such as* WW^*
- *If we confine ourselves to* 2σ *contours around the global best fits, the cut sensitivities for these operators rarely differ by more than 5%*
- *Some distributions can still make a difference....*

Case - 3 :

A specific scenario: an extra dimension with warped geometry

Constraining radion-Higgs mixing in a Randall-Sundrum model

N. Desai, U. Maitra, BM (2013)

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  Warped 5D geometry with an extra compact spacelike dimension:

  $ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2$

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  [Orbifold fixed points with branes at $\phi = 0$ and $\phi = \pi$]
- *Stabilization of r_c via the Goldberger-Wise mechanism*

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- *One of them (say,* m_H*) is at 125 GeV*
  Free parameters: m_R, Λ_ϕ, ξ

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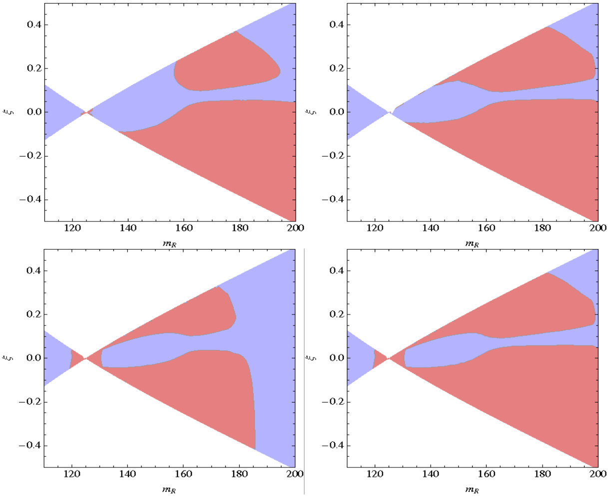
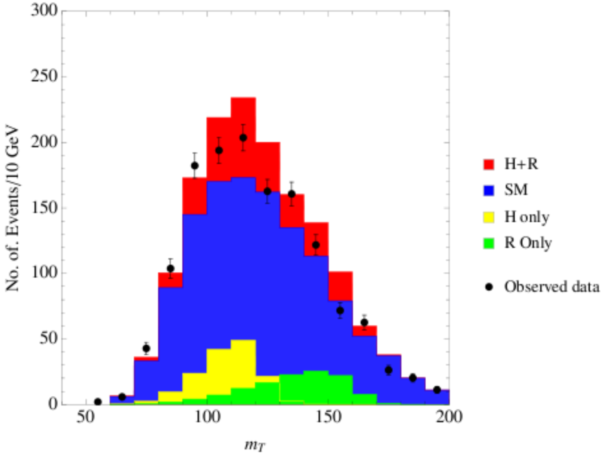
- *Global fits and 2σ regions obtained*

Exclusion modification on inclusion of cuts and interference....



Red: excluded; Light blue: allowed; White: theoretically disallowed

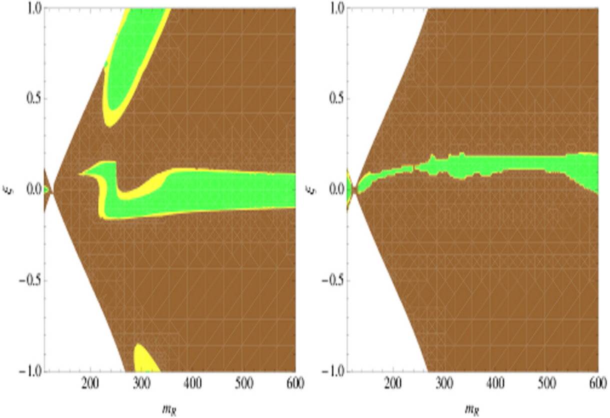
2ℓ + MET M_T distributions....



$\Lambda_\phi = 3$ TeV

An additional scalar ($M_R = 164$ GeV, $\xi = .065$) not ruled out

Best fit regions....



Left: m_R exclusions not used; Right: m_R exclusions used
Green: 68% C.L.; Yellow: 95% C.L.; $\Lambda_\phi = 3$ TeV

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- *The data allow contributions from another scalar, e.g. the radion in the RS model.*