PHENOMENOLOGY OF ADDITIONAL SCALAR BOSONS AT THE LHC

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The compatibility of LHC Run 1 data with a heavy scalar of mass around 270 GeV

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Abstract

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The impact of additional scalar bosons at the LHC

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Phenomenological signatures of additional scalar bosons at the LHC

Stefan von Buddenbrock[a,1], Nabarun Chakrabarty[b,2], Alan S. Cornell[c,1], Deepak Kar[d,1], Mukesh Kumar[e,3], Tanumoy Mandal[f,4], Bruce Mellado[g,1], Biswarup Mukhopadhyaya[h,2], Robert G. Reed[i,1] and Xifeng Ruan.[j,1]

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Abstract In this article we study the search strategies for new scalars beyond the Standard Model (SM) Higgs at the Large Hadron Collider (LHC). We consider an effective model by introducing two hypothetical real scalars, H and χ - a dark matter candidate, where the masses of these scalars are $2m_h < m_H < 2m_t$ and $m_\chi \approx m_h/2$ with m_h and m_t being the SM Higgs boson and top quark masses, respectively. A distortion in the transverse momentum distributions of h in the intermediate region of the spectrum through the processes $pp \to H \to h\chi\chi$ could be observed in this model. An additional scalar, S, has been postulated to explain large $H \to h\chi\chi$ branching ratios, assuming $m_h \lesssim m_S \lesssim m_H - m_h$ and $m_S > 2m_\chi$ in detail. Furthermore, a scenario of a two Higgs doublet model (2HDM) is introduced and in this spe-

1 Introduction

The aftermath of the discovery of a Higgs-like scalar [1–6] has been full of activities as intense as the very process of first unravelling its signature at the Large Hadron Collider (LHC). One notices two streams in such activities: (a) experimental efforts to closely examine if details of the behaviour of this scalar reveal any discrepancy with predictions of the Standard Model (SM), and (b) theoretical studies on how any trace of new physics, both model-dependent and independent, can be discerned. The 'new physics' possibilities in this context often stress on the possible presence of additional scalars that may have participate in electroweak symmetry breaking (EWSB). Based on such expec-

WHAT EXPERIMENTAL DATA TELLS US - LHC AT 7, 8 & 13 TEV EXCESSES / ANOMALY / FLUCTUATIONS OR CONSISTENCIES !!

- Differential Higgs boson pT spectra: h -> di-photons (yy) and h -> ZZ* > 4l [arXiv: 1407.4222, 1408.3226, 1508.07819, CMS-PAS-HIG-14-028]

- Di-Higgs boson resonance searches: Limits on H -> hh in different final states with bb~\tau+\tau-, yyWW*, yybb~, bb~bb~ and multi-lepton [arXiv: 1509.04670, 1510.01181, 1410.2751, CMS-PAS-HIG-13-032]

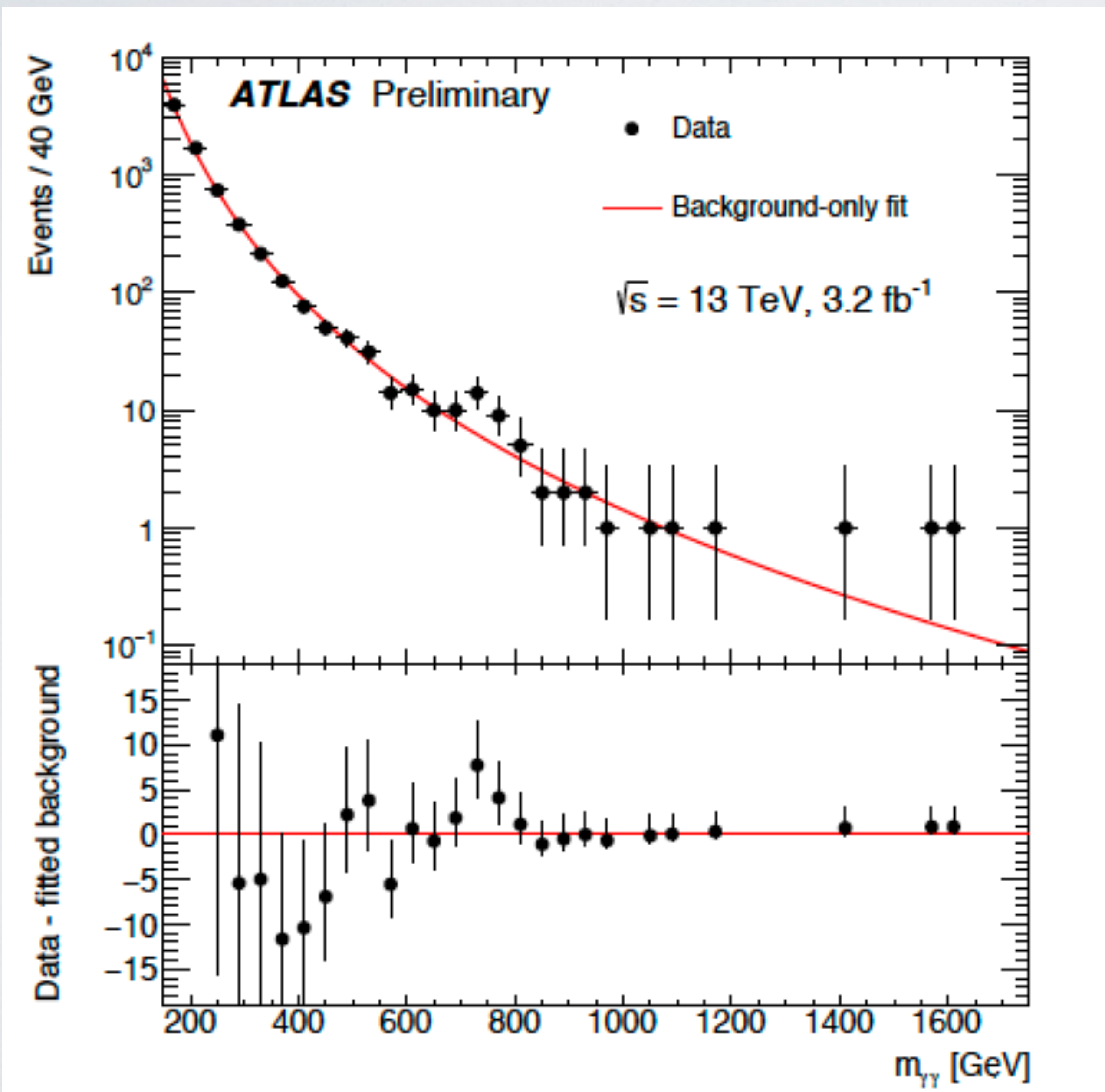
- Top associated Higgs boson production - multi-leptons decay channels including measurements on h -> yy and h -> bb~ decay modes [arXiv: 1409.3122, 1506.05988, 1503.05066, 1408.1682]

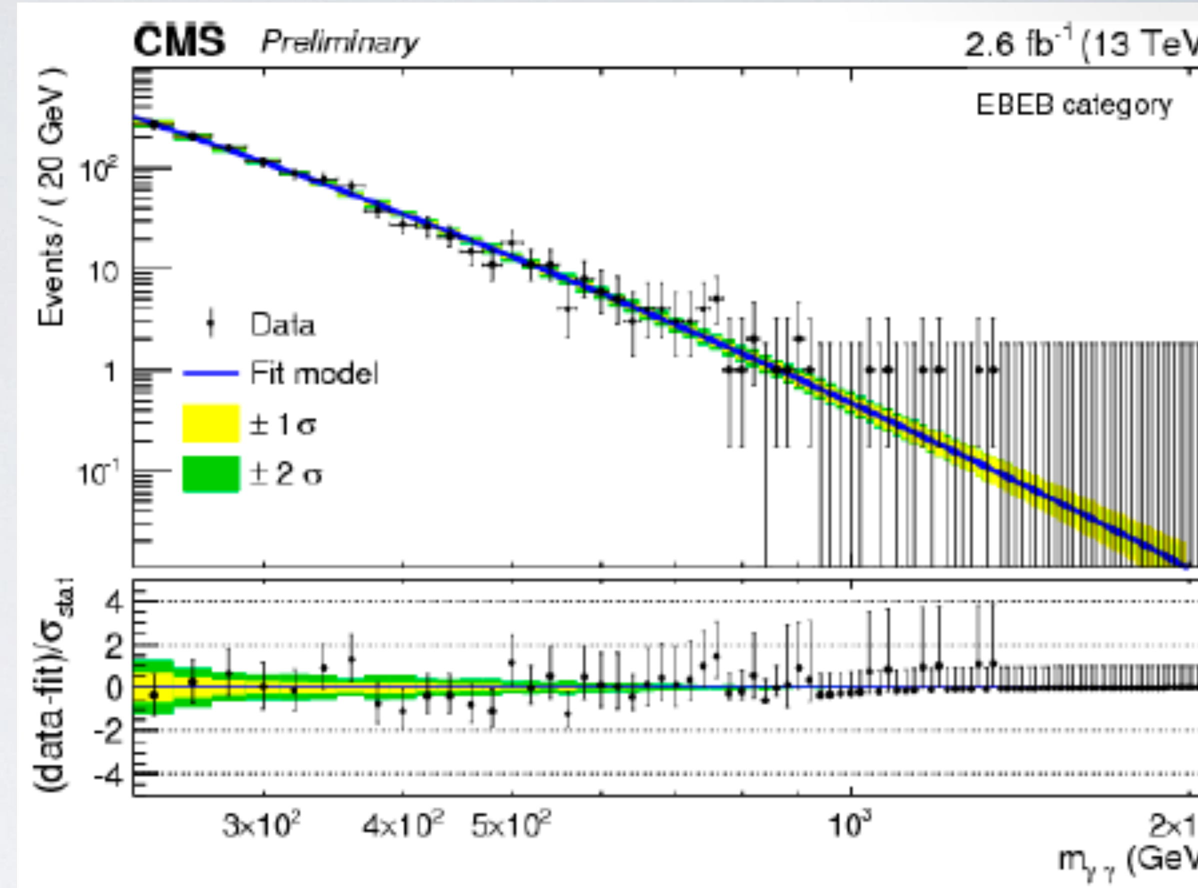
- Limits on H -> WW and ZZ decays [arXiv: 1509.00389, 1507.05930, 1504.00936]

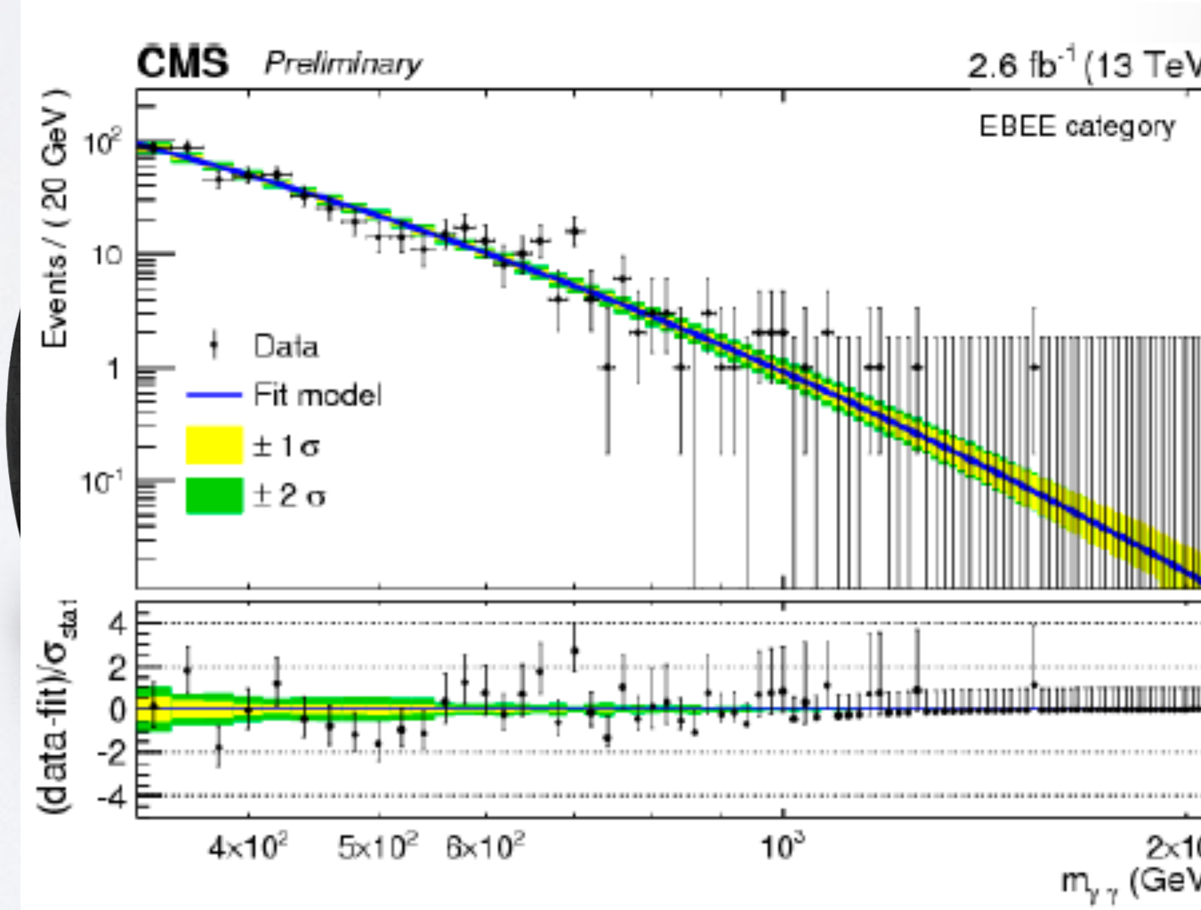
- Same flavour opposite-sign leptons, jets + missing energy (MET) : Z+j+MET [arXiv: 1503.03290, 1502.06031, ATLAS-CONF-2015-082, CMS-PAS-SUS-15-011]

- H± production in association with top (t) and bottom (b)-quarks and decays to tb, considering mH± > mt, excess observed in wide mass range (200-600 GeV) using multi-jet final states with one electron or muon [arXiv: 1512.03704]

RECENT DI-PHOTON EXCESS ~750 GEV RESONANCE IN RUN 2 ATLAS AND CMS 13 TEV RESULTS



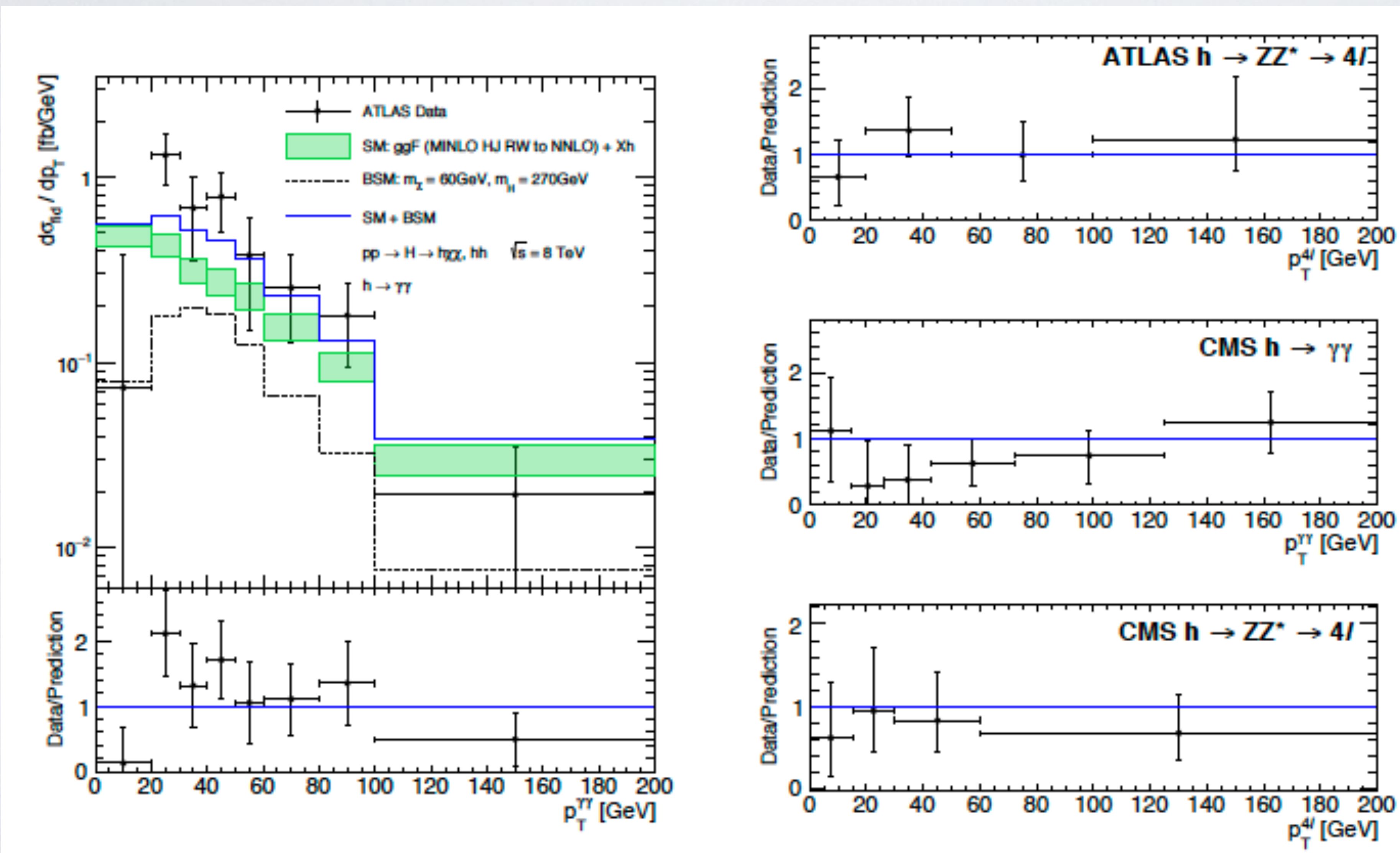




PHENOMENOLOGY : EXPLAIN EXPERIMENTAL DATA !

The compatibility of LHC Run 1 data with a heavy scalar of mass around 270 GeV

Stefan von Buddenbrock,[1,*] Nabarun Chakrabarty,[2,†] Alan S. Cornell,[3,‡] Deepak Kar,[1,§] Mukesh Kumar,[3,¶] Tanumoy Mandal,[2,**] Bruce Mellado,[1,††] Biswarup Mukhopadhyaya,[2,‡‡] and Robert G. Reed[1,§§]

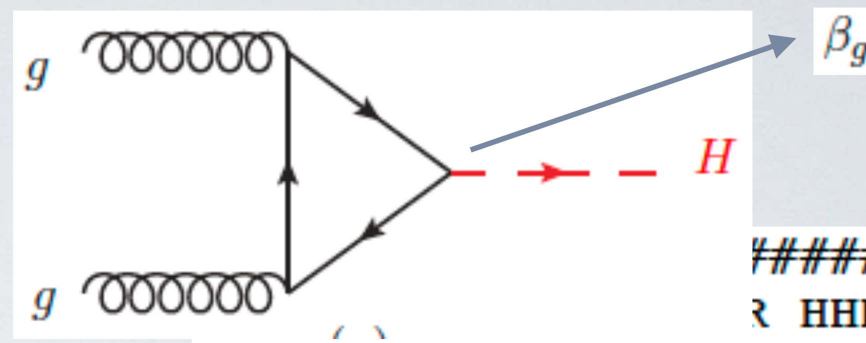


Result
Differential Higgs boson p_T spectra
Di-Higgs boson resonance searches
Top associated Higgs boson production
$H \to VV$ decays

[arXiv: 1506.00612]

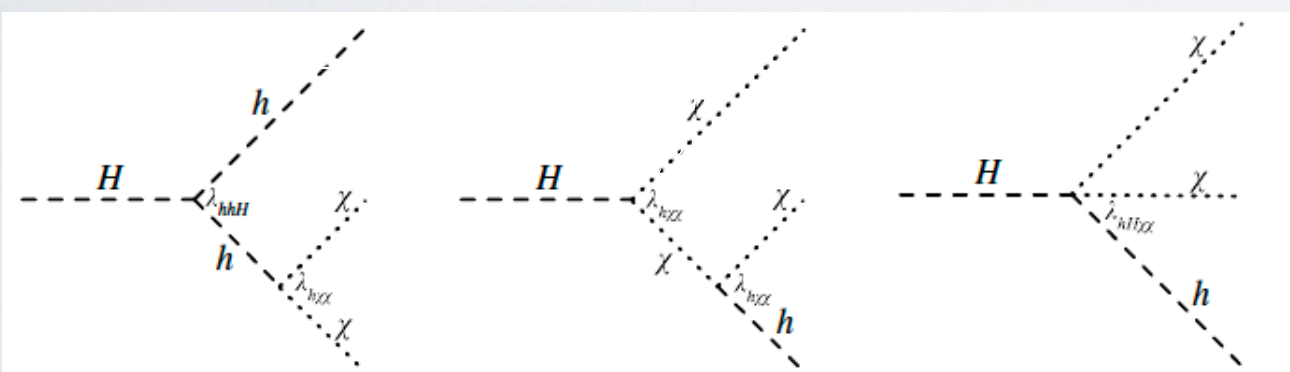
Higgs-Portal

Effective theory approach: introducing a heavy scalar H and a scalar dark matter candidate X



$$\mathcal{V}_H = -\frac{1}{4}\,\beta_g \kappa^{\rm SM}_{hgg}\, G_{\mu\nu}G^{\mu\nu} H + \beta_V \kappa^{\rm SM}_{hVV}\, V_\mu V^\mu H,$$
$$\mathcal{V}_{\rm Y} = -\frac{1}{\sqrt{2}}\left[y_{ttH}\bar{t}tH + y_{bbH}\bar{b}bH\right],$$
$$\mathcal{V}_{\rm T} = -\frac{1}{2}\,v\left[\lambda_{Hhh}Hhh + \lambda_{h\chi\chi}h\chi\chi + \lambda_{H\chi\chi}H\chi\chi\right],$$
$$\mathcal{V}_{\rm Q} = -\frac{1}{2}\lambda_{Hh\chi\chi}Hh\chi\chi - \frac{1}{4}\lambda_{HHhh}HHhh - \frac{1}{4}\lambda_{hh\chi\chi}hh\chi\chi - \frac{1}{4}\lambda_{HH\chi\chi}HH\chi\chi,$$

where $\beta_g = y_{ttH}/y_{tth}$

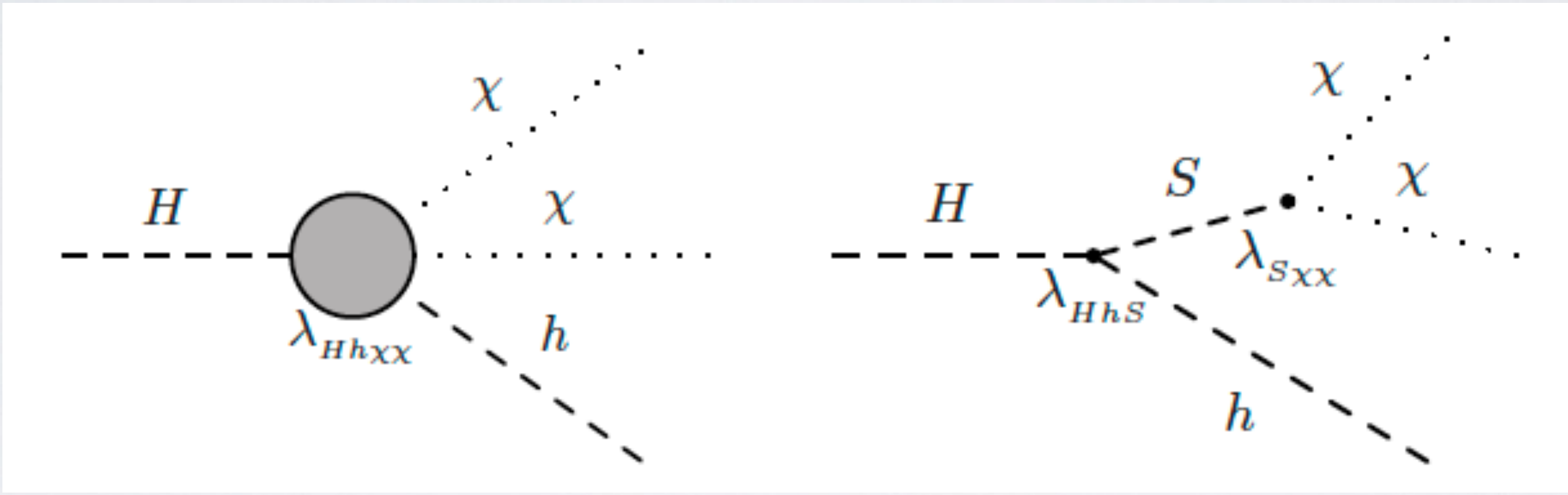


Best Fit results: mH = 272+12-9 GeV

```
####################
R HHDMINPUTS
###################################
Block hhdminputs
    1 0.000000e+00 # lHHRR
    2 0.000000e+00 # lRRXX
    3 0.000000e+00 # lHHXX
    4 1.136900e+00 # lHRXX
    5 0.007287e+00 # lHHR
    6 0.000600e+00 # lHXX
    7 0.000000e+00 # lRXX
    8 1.000000e+00 # btg
    9 0.004405e+00 # btW
   10 0.000000e+00 # btZ
   11 1.000000e+00 # btb
   12 1.000000e+00 # kpg
   13 1.000000e+00 # kpV
   14 1.000000e+00 # KfacH
   15 1.000000e+00 # KfacR

###################################
## INFORMATION FOR MASS
###################################
Block mass
    5 4.700000e+00 # MB
    6 1.720000e+02 # MT
   15 1.777000e+00 # MTA
   23 9.118760e+01 # MZ
   25 1.250000e+02 # MH
  601 6.000000e+01 # MX
  602 270.00 # MR
```

Explaining large branching $H \to h\chi\chi$
by Introducing 'S' - a real singlet scalar.



arXiV: 1603.01208,1606.01674

In result: particle spectrum will be h, H, χ and S
with other SM fermions, bosons.

The Two Higgs Doublet Model:

A minimal extension to the SM

CP even real bosons h, H

CP odd boson A

Charged Higgs boson $H^{\pm}$

$$
\begin{aligned}
\mathcal{V}(\Phi_1,\Phi_2) = {} & m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) + \frac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2 \\
& + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left|\Phi_1^\dagger\Phi_2\right|^2 + \frac{1}{2}\lambda_5\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \text{h.c.}\right] \\
& + \left[\left[\lambda_6\left(\Phi_1^\dagger\Phi_1\right) + \lambda_7\left(\Phi_2^\dagger\Phi_2\right)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right].
\end{aligned}
$$

Generalised

$$
\begin{aligned}
\mathcal{V}(\Phi_1,\Phi_2,\chi) = {} & \mathcal{V}(\Phi_1,\Phi_2) + \frac{1}{2}m_\chi^2\chi^2 + \frac{\lambda_{\chi 1}}{2}\Phi_1^\dagger\Phi_1\chi^2 + \frac{\lambda_{\chi 2}}{2}\Phi_2^\dagger\Phi_2\chi^2 \\
& + \frac{\lambda_{\chi 3}}{4}(\Phi_1^\dagger\Phi_2 + \text{h.c})\chi^2 + \frac{\lambda_{\chi 4}}{8}\chi^4.
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{V}(\Phi_1,\Phi_2,S) = {} & \mathcal{V}(\Phi_1,\Phi_2) + \frac{1}{2}m_{S_0}^2S^2 + \frac{\lambda_{S_1}}{2}\Phi_1^\dagger\Phi_1S^2 + \frac{\lambda_{S_2}}{2}\Phi_2^\dagger\Phi_2S^2 \\
& + \frac{\lambda_{S_3}}{4}(\Phi_1^\dagger\Phi_2 + \text{h.c})S^2 + \frac{\lambda_{S_4}}{4!}S^4 \\
& + \mu_1\Phi_1^\dagger\Phi_1S + \mu_2\Phi_2^\dagger\Phi_2S + \mu_3\left[\Phi_1^\dagger\Phi_2 + \text{h.c}\right]S + \mu_SS^3.
\end{aligned}
$$

Mass-Matrix, mixing, diagonalisation

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix}$$

which satisfy

$$R\mathcal{M}^2 R^{\mathrm{T}} = \mathcal{M}^2_{\mathrm{diag}} = \mathrm{diag}(M_1^2, M_2^2, M_3^2).$$

In our case

$$\begin{pmatrix} \rho_1 \\ \rho_2 \\ \varphi \end{pmatrix} \simeq \begin{pmatrix} -\sin\alpha & \cos\alpha & \delta_{13} \\ \cos\alpha & \sin\alpha & \delta_{23} \\ \delta_{31} & \delta_{32} & 1 \end{pmatrix} \begin{pmatrix} h \\ H \\ S \end{pmatrix}$$

The masses of the physical states h and H are

$$m^2_{h,H} = \frac{1}{2}\Big[M^2_{11} + M^2_{22} \mp \sqrt{(M^2_{11} - M^2_{22})^2 + 4\,(M^2_{12})^2}\Big],$$

while the mass of S is

$$m^2_S \simeq m^2_0 + \delta_{13}M^2_{13} + \delta_{23}M^2_{23}.$$

For phenomenology, we considered

(a) Light Higgs: $m_h = 125$ GeV (assuming as the SM Higgs),
(b) Heavy Higgs: $2m_h < m_H < 2m_t$,
(c) CP-odd Higgs: $m_A > (m_H + m_V)$, where $(V = W^{\pm}, Z)$,
(d) Charged Higgs: $(m_H + m_V) < m_{H^{\pm}} < m_A$,
(e) Additional scalars χ, S: $m_\chi < m_h/2$ and $m_h \lesssim m_S \lesssim (m_H - m_h)$.

S. No.	Scalars	Decay modes
D.1	h	$b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, $s\bar{s}$, $c\bar{c}$, gg, $\gamma\gamma$, $Z\gamma$, W^+W^-, ZZ
D.2	H	D.1, hh, SS, Sh
D.3	A	D.1, $t\bar{t}$, Zh, ZH, ZS, $W^{\pm}H^{\mp}$
D.4	$H^{\pm}$	$W^{\pm}h$, $W^{\pm}H$, $W^{\pm}S$
D.5	S	D.1, $\chi\chi$

Production modes

(a) $gg \to h,\ H,\ A,\ S,$
(b) $pp \to tH^-(\bar{t}H^+),\ tH^-\bar{b} + \bar{t}H^+b,\ H^+H^-,\ H^\pm W^\pm.$

A List of Searches:

Scalar	Production mode	Search channels
H	$gg \to H, Hjj$ (ggF and VBF)	Direct SM decays as in Table 1 $\to SS/Sh \to 4W \to 4\ell$ + MET $\to hh \to \gamma\gamma b\bar{b},\ b\bar{b}\tau\tau,\ 4b,\ \gamma\gamma WW$ etc. $\to Sh$ where $S \to \chi\chi \implies \gamma\gamma,\ b\bar{b},\ 4\ell$ + MET
	$pp \to Z(W^\pm)H\ (H \to SS/Sh)$	$\to 6(5)l$ + MET $\to 4(3)l + 2j$ + MET $\to 2(1)l + 4j$ + MET
	$pp \to t\bar{t}H, (t+\bar{t})H\ (H \to SS/Sh)$	$\to 2W + 2Z$ + MET and b-jets $\to 6W \to$ 3 same sign leptons + jets and MET
$H^\pm$	$pp \to tH^\pm\ (H^\pm \to W^\pm H)$	$\to 6W \to$ 3 same sign leptons + jets and MET
	$pp \to tbH^\pm\ (H^\pm \to W^\pm H)$	Same as above with extra b-jet
	$pp \to H^\pm H^\mp\ (H^\pm \to HW^\pm)$	$\to 6W \to$ 3 same sign leptons + jets and MET
	$pp \to H^\pm W^\pm\ (H^\pm \to HW^\pm)$	$\to 6W \to$ 3 same sign leptons + jets and MET
A	$gg \to A$ (ggF)	$\to t\bar{t}$ $\to \gamma\gamma$
	$gg \to A \to ZH\ (H \to SS/Sh)$	Same as $pp \to ZH$ above, but with resonance structure over final state objects
	$gg \to A \to W^\pm H^\mp (H^\mp \to W^\mp H)$	$6W$ signature with resonance structure over final state objects

Constrain from Run I LHC data on 2HDM-Type I (II) :

$$\cos(\beta - \alpha) \lesssim 0.5(0.2), m_H \lesssim 380(\approx 380), \tan\beta \lesssim 2(\mathrm{all})$$

These constraints have been made by considering the decay channels

$$A/H/h \to \tau\tau, H \to WW/ZZ, A \to ZH(ll\tau\tau)$$

CMS PAS HIG-16-007

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On-going works:

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- Charged dark matter
- RGE calculations with these new states
- RUN -II LHC ….

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Thank you very much!