The future of the WG3 BSM NES.

R. Gerosa, H. Logan, R. Santos,
S. Su, X. Sun

WG3 BSM: Neutral Extended Scalars

LHCHXSWG

8 July 2016

The past

BP1: CP-conserving 2HDM with softly-broken Z2-symmetry. [*Howard Haber, Oscar Stål*]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/HH_OS_2HDM_Benchmarks.pdf

BP2: **:** CP-conserving 2HDM with softly-broken Z2-symmetry. [*Felix Kling, Shufang Su*]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/Exotic_Benchmarks.pdf

BP3: **:** CP-conserving 2HDM with softly-broken Z2-symmetry.[*Glauber Dorsch, Stephan Huber, Ken Mimasu, Jose Miguel No*]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/2HDM_Cosmic_Benchmarks.pdf

BP4: **:** CP-conserving 2HDM with softly-broken Z2-symmetry. [*Robin Aggleton, Daniele Barducci, Alexandre Nikitenko, Stefano Moretti, Claire Shepherd-Themistocleous*]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/2HDM_WG-final.pdf

BP5: Inert 2HDM. [Agnieszka Ilnicka, Maria Krawczyk, Tania Robens]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/IDM_benchmarks.pdf

BP6: Fermiophobic 2HDM. [David Lopez-Val]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/fermiophobic.pdf

BP7 Complex 2HDM benchmarks *[D. Fontes, J.C. Romao, R. Santos and J.P. Silva]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmark-C2HDM.pdf

BP8 Flavour-changing 2HDM benchmarks *[F.J. Botella, G.C. Branco, M. Nebot and M. Rebelo]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmark-FCNC2HDM.pdf

BP9 Real and complex singlet benchmarks *[R. Costa, M. Muhlleitner, M.O.P. Sampaio and R. Santos]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/BenchmarksCxSM_and_RxSM.pdf

BP10 Singlet benchmarks *[T. Robens and T.Stefaniak]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmarks_robens_stefaniak.pdf

BP11 Georgi-Machacek model benchmark *[H. Logan]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/h5plane-benchmark.pdf

Georgi-Machacek model (custodial-symmetric triplet scalars)

Georgi & Machacek 1985; Chanowitz & Golden 1985

- Two custodial singlets $\rightarrow h^0,\ H^0$ $m_h,\ m_H$ $\leftarrow$ very similar
- Custodial triplet $\rightarrow (H_3^+, H_3^0, H_3^-)$ m_3 $\leftarrow$ to 2HDM
- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ m_5 $\leftarrow$ new!

$\rightarrow$ Focus on direct searches for H_5 states

In YR4: [H. Logan and M. Zaro]

- **H5plane** benchmark for direct H_5 searches (200–3000 GeV)

- Tables of VBF $\rightarrow H_5$ cross sections (NNLO QCD, LO EW, onshell H_5) and H_5 decay widths (LO doubly offshell)

Details are in talk by Rui Santos at January 2016 meeting

The present

X (750) from extended scalar sectors?

- **SM + singlet (real or complex)**

Both the Scalar production cross sections and its branching ratio to two photons are similar or smaller than the SM ones.

- **2HDM**

$$\sum_{\Phi} \sigma(gg \to \Phi) \times \mathrm{BR}(\Phi \to \gamma\gamma) \approx 1.5 \times 10^{-2} \cot^2 \beta \ [\mathrm{fb}]$$

"For tanβ =1, we are more than two orders of magnitude away from the diphoton signal and, even for tanβ =1/3, we are still more than one order of magnitude below. Very large additional contributions are thus needed."

Scenarii for interpretations of the LHC diphoton excess: two Higgs doublets and vector-like quarks and leptons

A. Angelescu, A. Djouadi, G. Moreau; PLB756 (2016) 126-132.

X(750) Benchmarking Study in the GM Triplet Model

Georgi-Machacek model (custodial-symmetric triplets):
Can it accommodate the X(750)?

(1) Fabbichesi & Urbano, 1601.02447 → Yes
(2) Chiang & Kuo, 1601.06394 → No

Independent study in progress using GMCALC;
preliminary results support (2).

The future (just a few topics)

Some recent work

- EW corrections to important observables in BSM Higgs sectors

  Example: corrections to Higgs decays in singlet and 2HDM extensions.

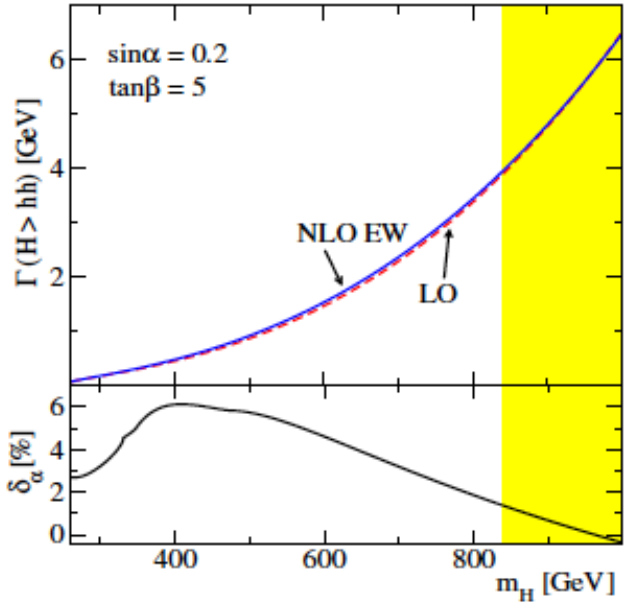
- Make a stronger case for specific searches

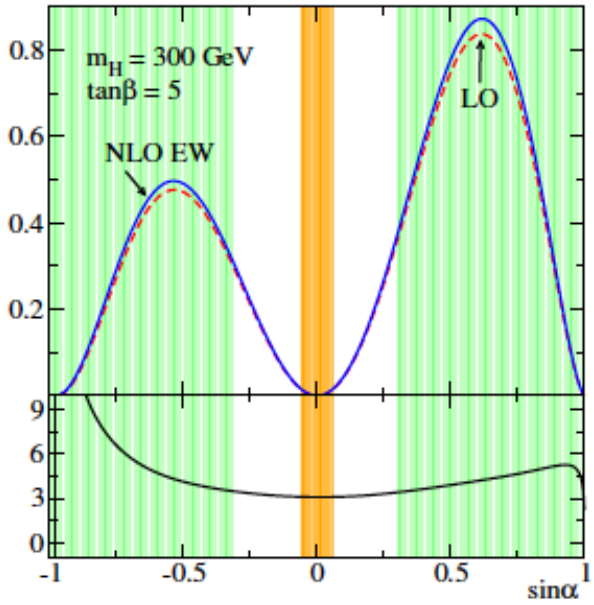
  Example: $H_i \to H_j H_k \qquad j \neq k$

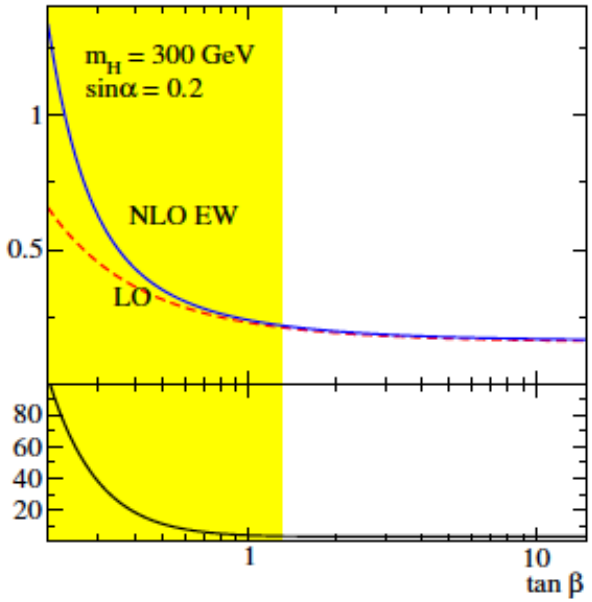
- Discuss other extensions like 3HDM (with symmetries), N2HDM, etc, if they lead to phenomenological differences.

Real Singlet model

Heavy to light Higgs boson decays at NLO in the Singlet Extension of the SM
F. Bojarski, G. Chalons, D. Lopez-Val, T. Robens; JHEP 1602 (2016) 147





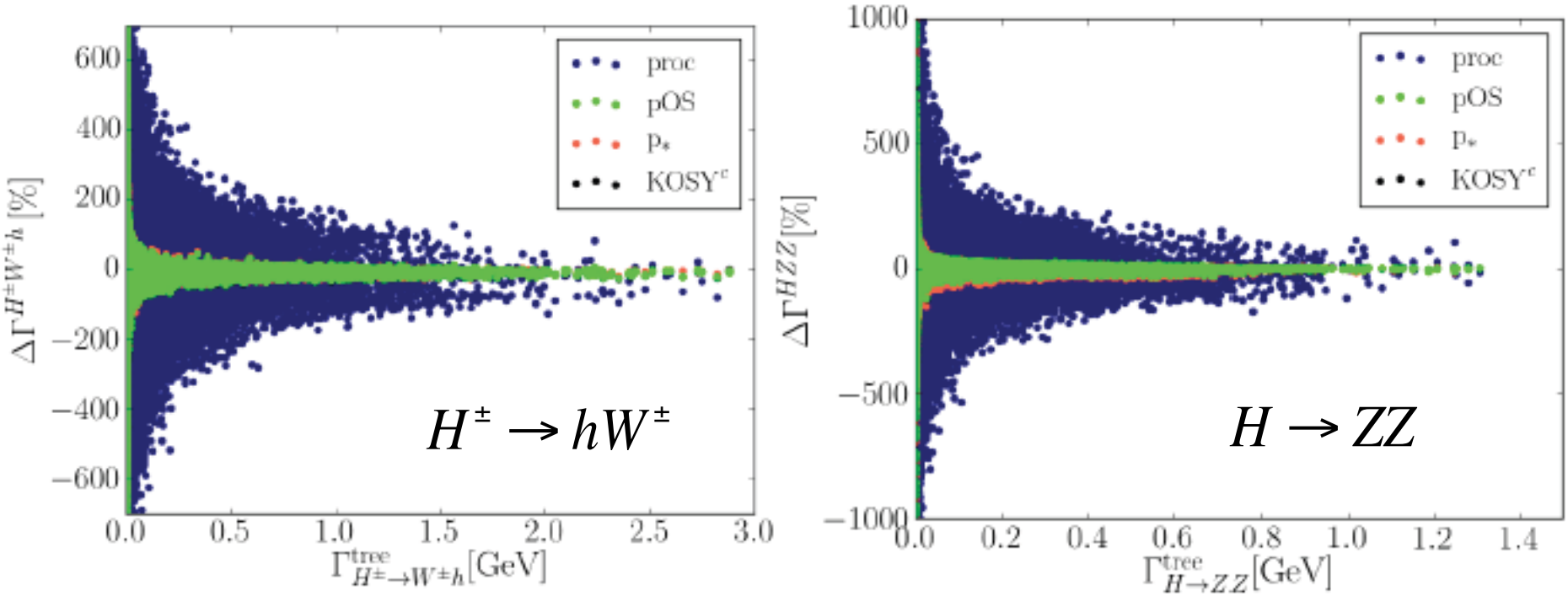


$H \to hh$

NLO Corrections shown
to be only a few percent

2HDM

Gauge-independent Renormalization of the 2-Higgs-Doublet Model,
M. Krause, R. Lorenz, M. Mühlleitner, R. Santos, H. Ziesche; 1605.04853 [hep-ph].



Several renormalization schemes are compared. Pinched on-shell and p* schemes shown to lead to gauge independent and stable results.

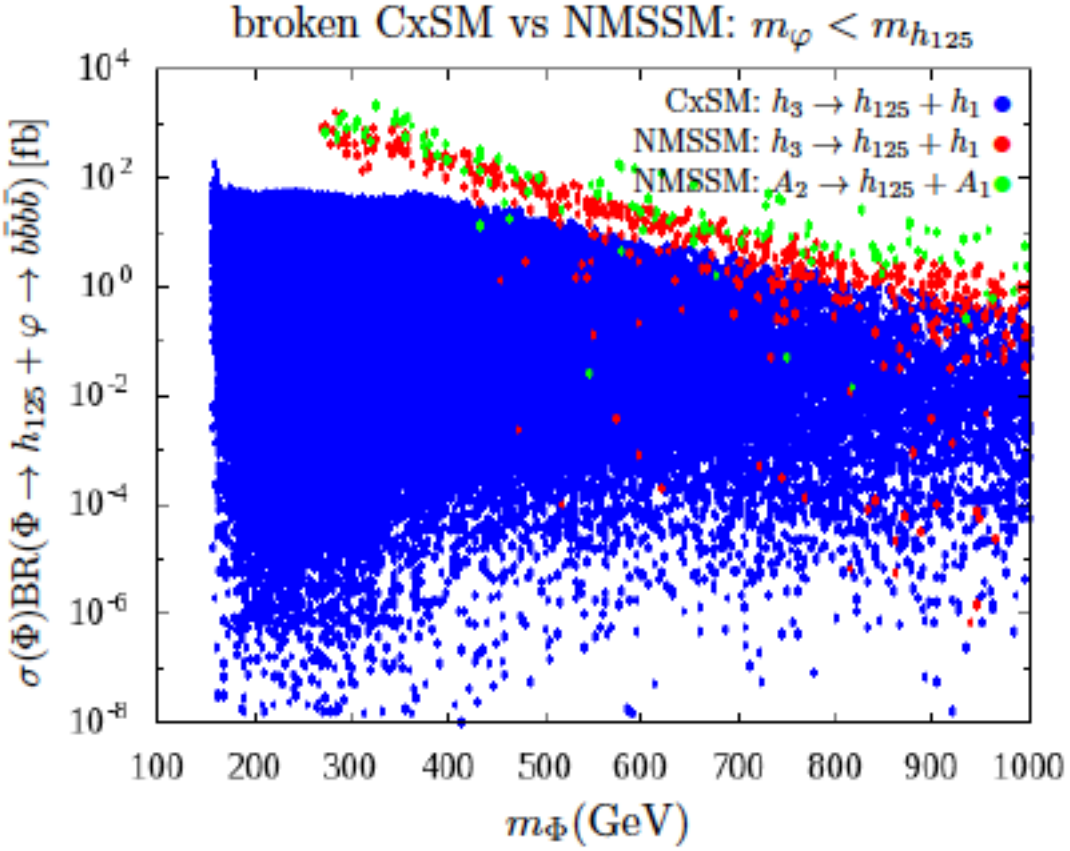
Corrections can be large in some regions of the parameter space.

The decay $H_i \to H_j H_k \qquad j \neq k$

To distinguish between models

Singlet Extensions of the Standard Model at LHC Run 2: Benchmarks and Comparison with the NMSSM

R. Costa, M. Mühlleitner, M.O.P. Sampaio, R. Santos; JHEP 1606 (2016) 034.



A comparison between the NMSSM and the broken Complex Singlet extension of the SM for final states with two scalars with different masses.

The models can be distinguished in some regions of the parameter space.

The decay $H_i \to H_j H_k \quad j \neq k$

Hint for CP violation? **Combinations of three decays**

$h_1 \to ZZ \quad \Leftarrow \quad \mathrm{CP}(h_1) = 1$

$h_3 \to h_2 h_1 \quad \Rightarrow \quad \mathrm{CP}(h_3) = \mathrm{CP}(h_2)\ \mathrm{CP}(h_1) = \mathrm{CP}(h_2)$

Already observed

Decay	CP eigenstates	Model
$h_3 \to h_2 Z \quad \mathrm{CP}(h_3) = -\mathrm{CP}(h_2)$	None	C2HDM, other CPV extensions
$h_{2(3)} \to h_1 Z \quad \mathrm{CP}(h_{2(3)}) = -1$	2 CP-odd; None	C2HDM, NMSSM,3HDM...
$h_2 \to ZZ \quad \mathrm{CP}(h_2) = 1$	3 CP-even; None	C2HDM, cxSM, NMSSM,3HDM...

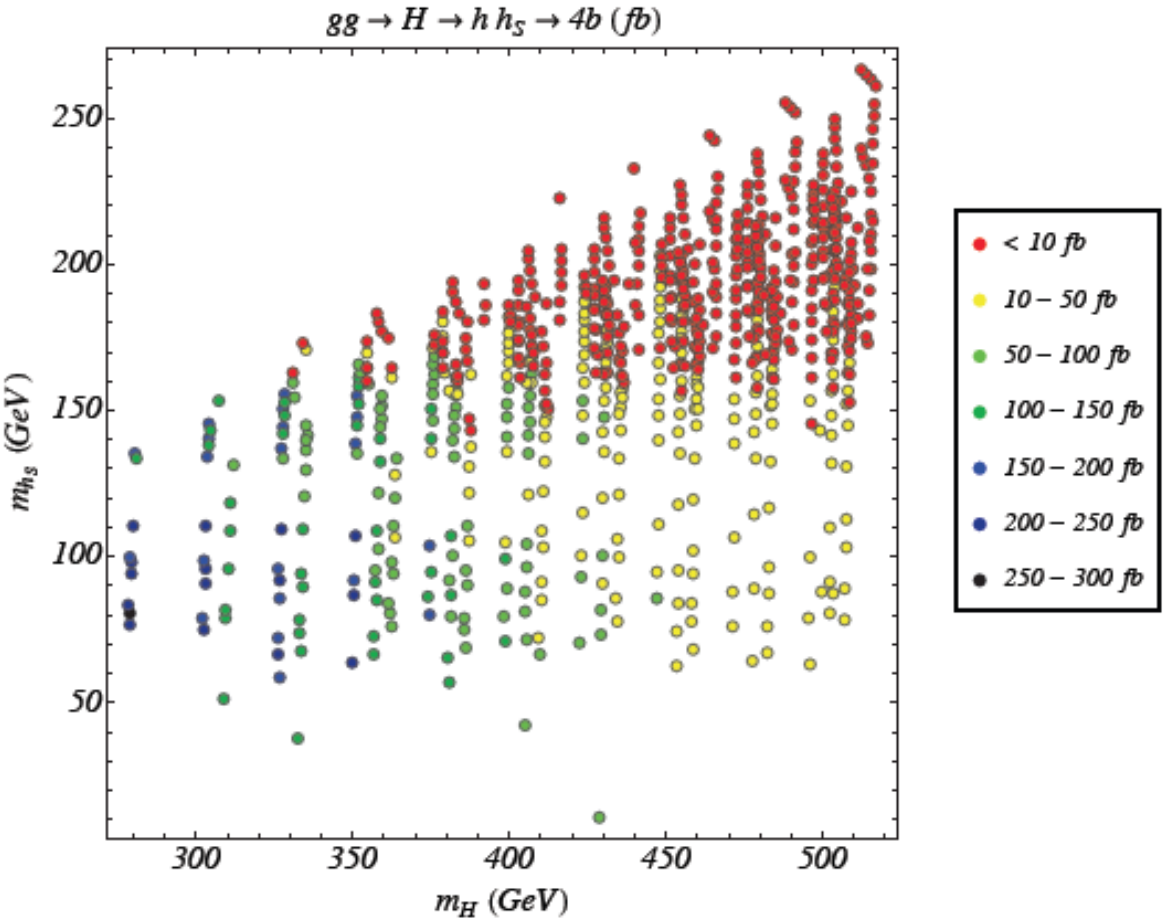
C2HDM - D. Fontes, J.C. Romão, R. Santos, J.P. Silva; PRD92 (2015) 5, 055014.

NMSSM - S.F. King, M. Mühlleitner, R. Nevzorov, K. Walz; NPB901 (2015) 526-555.

The decay $H_i \to H_j H_k \qquad j \neq k$

Large rates in the aligned NMSSM

Alignment limit of the NMSSM Higgs sector
M. Carena, H.E. Haber, I. Low, N.R. Shah, C.E. M. Wagner; PRD93 (2016) 3, 035013.

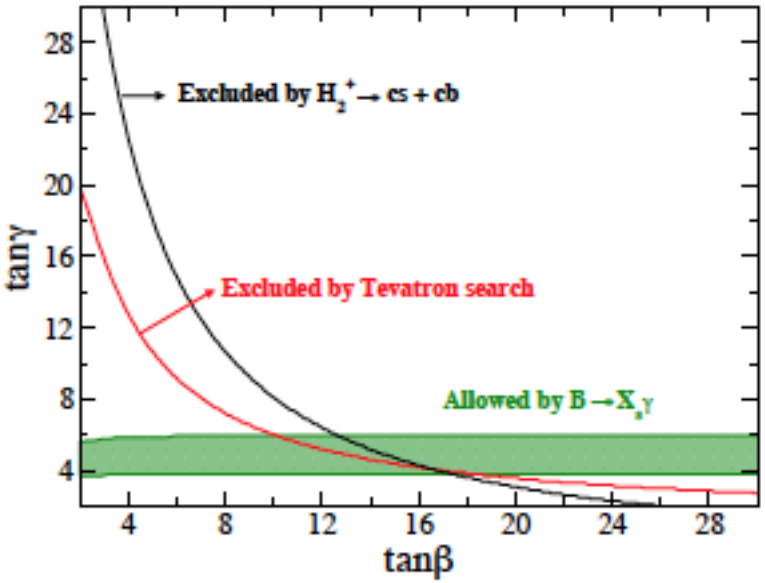


In the alignment limit of the NMSSM Higgs decays to two other scalars with the same mass are supressed.

Other extensions

Charged Higgs in 3HDM

Prospects for charged Higgs searches at the LHC
A.G. Akeroyd eal; 1607.01320.



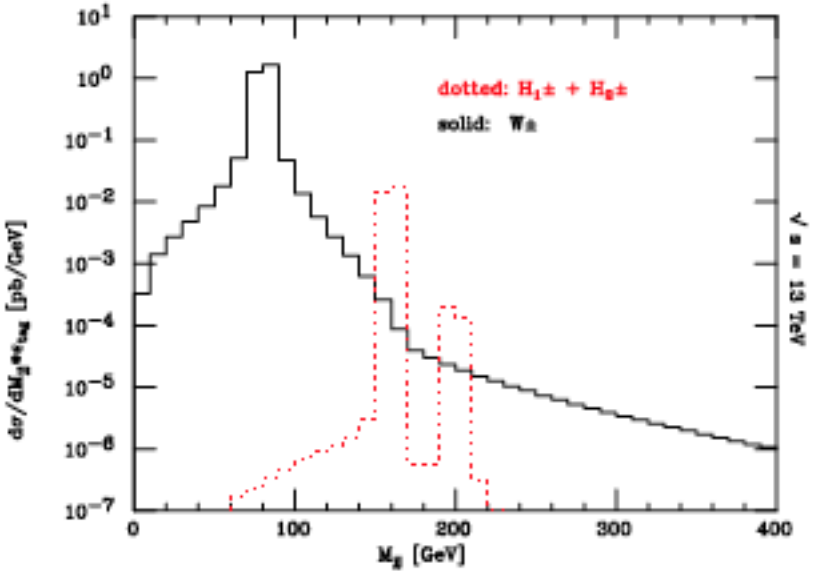


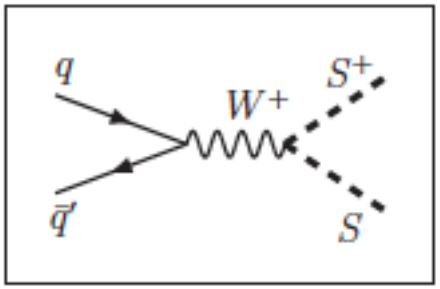
Figure 26: Left: Allowed parameter space for the 3HDM (Model Y) with $M_{H_1^\pm} = 83$ GeV, $M_{H_2^\pm} = 160$ GeV and the mixing angle $\theta_C = -\pi/4$. Only the green shaded region is allowed by the $B \to X_s\gamma$ constraint. Right: Di-jet invariant mass distributions for signal (red) and background (black) for a particular benchmark point (3HDM, Model Y) at the 13 TeV LHC.

A. G. Akeroyd, S. Moretti, K. Yagyu, and E. Yildirim; 1605.05881.

Other extensions

Dark Charged Higgs in Several models

Prospects for charged Higgs searches at the LHC
A.G. Akeroyd eal; 1607.01320.



The S+ decays to an (invisible) S, plus a virtual W+, giving a two-jet or a lepton-neutrino final state. The signal would thus be jets or/and isolated charged lepton (from the W) plus missing transverse energy. If instead the heavier neutral state A is produced together with the S+, some of its decays would lead to two-lepton and three-lepton final states.

In the case of an Inert 2HDM the best search channel is in the hadronic decay of the W, leading to two merging jets plus missing transverse energy.

In some SO(10) scenarios the S+ decays inside the tracker of an LHC experiment. The experimental signature of those points is that the charged track of S+ breaks into a charged lepton track and missing energy.

X. Miao, S. Su, and B. Thomas, PRD82, 035009 (2010).

P. Osland, A. Pukhov, G. Pruna, and M. Purmohammadi, JHEP 1304, 040 (2013).

Exotic Decays of (BSM) Higgses

New channels open up for non-SM Higgs decay

neutral Higgs	HH type ✓	$h_{SM} \rightarrow AA$, $H \rightarrow h_{SM}\, h_{SM}$, $H \rightarrow AA$,
	H^+H^- type	$H/A \rightarrow H^+H^-$
	$WH^\pm$ type	$H/A \rightarrow WH^\pm$
	ZH type ✓	$H \rightarrow ZA$, $A \rightarrow ZH, Zh$
charge Higgs	WH type	$tH^\pm$ production $H^\pm \rightarrow WH, WA$

- detailed exp study of H^+H^-, $WH^\pm$, WH type decay
- cascade exotic decays
- other BSM Higgs extensions (beyond 2HDM) and possible other exotic decay modes (e.g., $H^\pm \rightarrow WZ$)

The end