WG3 Extended Scalars* status report

*Formed from the merger of the Charged Higgs and Neutral Extended Scalars subgroups in May 2018

Heather Logan
Carleton University
Ottawa, Canada

LHC HXSWG 15th General Assembly Meeting
2018 December 11
Introduction

There are plenty of models of extended scalar sectors.

No need to search for each one separately – just need to capture the full range of phenomenology so that nothing is missed.

→ Identify prototypical signatures and codify as benchmarks

→ Prioritize based on how common / universal a signature is across models

→ Understand interplay between direct searches and $h_{125}$ coupling measurements to constrain parameter space
Meetings over the past year: (agendas in the backup slides)

- 2018 Mar 13: meeting on signatures for low-mass fermiophobic scalars in Georgi-Machacek model
  - Focus on Drell-Yan production of pairs of $H_5$ states
  - $H_5^0 \rightarrow \gamma\gamma$: diphoton resonance fiducial xsec limits → recast
  - $H_5^\pm \rightarrow W^\pm\gamma$: study in progress
  - $H_5^{\pm\pm} \rightarrow W^\pm W^\pm$: Run-1 theorist-recast: $m_{H_5^{\pm\pm}} \gtrsim 75$ GeV

- 2018 Sep 20: theory report on $H^\pm \rightarrow W^\pm\gamma$ to WG3 meeting
  - UFO file available with $H^\pm W^{\mp\gamma}$ effective vertex (GM model)

- 2018 Oct 24: open meeting for benchmark proposals & discussion
  - 8 talks, many benchmarks; some details in following slides
The simplest extension: SM + real singlet (R$x$SM)

Two physical Higgs bosons $\phi^{0,r}$ (doublet) and $s$ (singlet)

Mass eigenstates: $m_h < m_H$
$h = \cos \alpha \phi^{0,r} - \sin \alpha s$
$H = \sin \alpha \phi^{0,r} + \cos \alpha s$

All couplings are SM times $\cos \alpha$ for $h$, SM times $\sin \alpha$ for $H$.
Only possible new decay channel is $H \rightarrow hh$.

→ Interpretation for SM-like Higgs coupling measurements as a single overall signal-strength modifier $\mu \equiv \cos \alpha$

→ Interpretation for searches for heavy SM-like Higgs boson with overall suppression of all couplings $\mu_H \equiv \sin \alpha$
Combined limits on $|\sin \alpha|$  

$m_W$ still strongest constraint for $m_H \gtrsim 300$ GeV; 
⇒ strong improvement: direct searches (ZZ @ 13 TeV)←

Newest update using Run II results in HiggsSignals: 
Signal strengths strongest constraint up to 800 GeV: $\sin \alpha \leq 0.22$

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WG3 Extended Scalars 2018 Dec 11
Benchmark for scalar resonance $H \rightarrow hh$ ($h = h_{125}$) in RxSM

Production cross section of $H = \sin^2 \alpha \times \sigma_{SM}(M_H)$

| $m_H$ [GeV] | $|\sin \alpha|_{\text{max}}$ | $BR_{\min}^{H \rightarrow hh}$ | $BR_{\max}^{H \rightarrow hh}$ | $m_H$ [GeV] | $|\sin \alpha|_{\text{max}}$ | $BR_{\min}^{H \rightarrow hh}$ | $BR_{\max}^{H \rightarrow hh}$ |
|-------------|----------------|-----------------|----------------|-------------|----------------|----------------|----------------|
| 260         | 0.22           | 0.17            | 0.32           | 470         | 0.22           | 0.23           | 0.29           |
| 270         | 0.22           | 0.22            | 0.37           | 520         | 0.22           | 0.20           | 0.27           |
| 280         | 0.22           | 0.23            | 0.39           | 590         | 0.22           | 0.20           | 0.26           |
| 290         | 0.22           | 0.24            | 0.40           | 670         | 0.22           | 0.20           | 0.26           |
| 310         | 0.22           | 0.25            | 0.40           | 770         | 0.22           | 0.22           | 0.24           |
| 330         | 0.22           | 0.25            | 0.39           | 880         | 0.19           | 0.22           | 0.25           |
| 350         | 0.22           | 0.25            | 0.38           | 920         | 0.18           | 0.22           | 0.25           |
| 370         | 0.22           | 0.24            | 0.36           | 980         | 0.17           | 0.23           | 0.25           |
| 400         | 0.22           | 0.22            | 0.32           | 1000        | 0.16           | 0.23           | 0.25           |

Minimal and maximal branching ratios for $H \rightarrow hh$

Tania Robens, WG3 Extended Scalars subgroup meeting, 2018/10/24

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2018 Dec 11
Model-specific electroweak radiative corrections calculated!

**Real Singlet model**

$H \rightarrow hh$

NLO Corrections shown to be only a few percent

Bojarski, Chalons, Lopez-Val, Robens, JHEP1602 (2016) 142
Two Higgs Doublet Model (2HDM)

Physical spectrum: $h, H, A, H^\pm$ (assuming CP conservation)
Same as in MSSM, but with two key differences:

1) MSSM has “Type II” Yukawa coupling structure; 2HDM can have any of Type I, II, X (Lepton Specific), or Y (Flipped).

2) MSSM quartic scalar couplings are fixed by $g, g'$; not true in 2HDM: can have much larger mass splittings among $H, A, H^\pm$

Less constrained spectra allow for Higgs-to-Higgs decays:
$A \rightarrow ZH / H \rightarrow ZA$ (also $A \rightarrow Zh_{125}$) $\rightarrow$ ATLAS + CMS
$H^+ \rightarrow W^+ S$ ($S = H, A, h_{125}$) $\rightarrow$ CMS, $S = A(\rightarrow \mu\mu)$
$H \rightarrow AA \rightarrow$ ATLAS, $AA \rightarrow 4\gamma$

$H \rightarrow H^+H^- \rightarrow \tau\nu \rightarrow$ not being done
$H/A \rightarrow W^\pm H^\mp \rightarrow$ not being done
“Standard” high-mass charged Higgs search \( pp \rightarrow tH^- \rightarrow tW^-b\bar{b} \):

In 2HDM can decay via \( H^- \rightarrow W^-A(\rightarrow b\bar{b}) \); large \( H^- \) and \( A \) widths give large interference between signal and background.

A. Arhrib et al., 1712.05018

Study in progress to see how big an issue this is in MSSM:

D. Azevedo, R. Santos, S. Moretti, P. Sharma, R. Benbrik, A. Arhrib & R. Patrick

\( H^+ \) width can be large enough to lead to significant interference

Left to right: hMSSM; \( m_{h^+}^{mod+} \), \( m_{h^+}^{125}(\tilde{\tau}) \)

Color code: \( H^+ \) total width (GeV)

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Benchmark cross-sections

Benchmarks points are chosen where there is a large charged Higgs width and smallest $m_{A}^{0}$:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$h_{\text{MSSM}}$</th>
<th>$m_{h}^{\text{mod}+}$</th>
<th>$m_{h}^{125}(\tilde{\tau})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$ (GeV)</td>
<td>200</td>
<td>200</td>
<td>1000</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>1.01</td>
<td>3.42</td>
<td>3.19</td>
</tr>
<tr>
<td>$m_{H^{\pm}}$ (GeV)</td>
<td>633.91</td>
<td>303.08</td>
<td>628.08</td>
</tr>
<tr>
<td>$\Gamma_{H^{\pm}}$ (GeV)</td>
<td>27.777</td>
<td>0.925</td>
<td>2.677</td>
</tr>
</tbody>
</table>

Production cross-sections:

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>Signal (pb)</th>
<th>Background (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{\text{MSSM}}$</td>
<td>$(3.2402 \pm 0.0014) \times 10^{-2}$</td>
<td>$13.092 \pm 0.004$</td>
</tr>
<tr>
<td>$m_{h}^{\text{mod}+}$</td>
<td>$(8.8502 \pm 0.0033) \times 10^{-2}$</td>
<td>$13.103 \pm 0.004$</td>
</tr>
<tr>
<td>$m_{h}^{125}(\tilde{\tau})$</td>
<td>$(1.6802 \pm 0.0058) \times 10^{-2}$</td>
<td>$13.177 \pm 0.004$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>Signal+Background (pb)</th>
<th>Interference (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{\text{MSSM}}$</td>
<td>$13.143 \pm 0.004$</td>
<td>$0.019 \pm 0.008$</td>
</tr>
<tr>
<td>$m_{h}^{\text{mod}+}$</td>
<td>$13.200 \pm 0.004$</td>
<td>$0.009 \pm 0.008$</td>
</tr>
<tr>
<td>$m_{h}^{125}(\tilde{\tau})$</td>
<td>$13.197 \pm 0.004$</td>
<td>$0.003 \pm 0.008$</td>
</tr>
</tbody>
</table>

Where

$$(S + B)^{2} = S^{2} + B^{2} + \text{Interference} \quad (1)$$

$\rightarrow$ Still large errors but interferences seem to be present.

Work in progress.
2HDM with explicit CP violation (C2HDM)

Physical spectrum: $H_1, H_2, H_3, H^\pm$

3 neutral scalars $H_1, H_2, H_3$ are CP admixtures in general
- Motivated by need for new sources of CP violation to explain baryon asymmetry of the universe
- Constrained by null searches for electric dipole moments

New processes not present in Real 2HDM:
- $H \rightarrow SS \rightarrow 4W$ ($S \neq h_{125}$): $\rightarrow$ ATLAS
- $H_3 \rightarrow H_1 H_2$: one of these must be $h_{125}$; motivates $H \rightarrow h_{125} S$
  selection ($m_S \neq 125$ GeV) $\rightarrow$ not being done

Both of these can also happen in CP-conserving 2HDM + real singlet (“N2HDM”), which has 3 CP-even neutral Higgs bosons.

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What do we know about possible CP-violating couplings of $h_{125}$?

CP properties have been tested so far in $hZZ$, $hWW$ couplings
- $h \rightarrow 4\ell$ distributions, production distributions in VBF

CP-even SM $hV_\mu V^\mu$ is tree level / dim-4 operator
CP-odd $hV_\mu\tilde{V}^{\mu\nu}$ is one-loop / dim-6 operator
→ CP-odd coupling in $hVV$ is generically small

Next place to look is the Yukawa couplings. For Type-II Yukawas:

$t$: $Y_{C2HDM}^{TypeII} = \cos \alpha_2 Y_{2HDM}^{TypeII} - i\gamma_5 \sin \alpha_2 \cot \beta$

$b, \tau$: $Y_{C2HDM}^{TypeII} = \cos \alpha_2 Y_{2HDM}^{TypeII} - i\gamma_5 \sin \alpha_2 \tan \beta$

$\alpha_2$ is mixing angle between pseudoscalar and scalars;
$\kappa_V = \cos \alpha_2 \sin(\beta - \alpha)$ so $|\cos \alpha_2|$ must be near 1 already.

But, $\tan \beta$ can be large: look for CP-violating effects in the Yukawas with $\tan \beta$ enhancement!

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Rate measurements constrain CP-even and CP-odd parts of Yukawa couplings to lie in a ring: \( Y = a + ib\gamma_5 \), rate \( \propto |a|^2 + |b|^2 \)

Electric dipole moment measurements (of \( n \), atoms, molecules) constrain the amount of CP violation.

Depends on Yukawa structure!
Large CPV Yukawas excluded in Type I and in Type II when \( h_{125} \) = lightest neutral scalar.

Most interesting scenarios:

Lepton-specific
(Type X)

Can have CP-odd \( h_{\tau\tau} \) and CP-even \( h_{tt}, h_{bb} \)

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Flipped
(Type Y)

Can have CP-odd $h_{bb}$ and CP-even $htt, h\tau\tau$

Type II
with $h_{125} = H_2$

Can have CP-odd $h_{bb}, h\tau\tau$ and CP-even $htt$

Probe using $\tau$ decay distributions! Benchmark points available.

Fontes et al, 1711.09419

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Higgs Triplet Model (HTM)

SM Higgs doublet plus 1 complex triplet $X = (\chi^+, \chi^+, \chi^0)$

Motivation: \( y_{\nu}^{ij} L_i X L_j \) coupling gives neutrino masses \( m_\nu \sim y_\nu \langle \chi^0 \rangle \)

\( \langle \chi^0 \rangle \) is very strongly constrained by the \( \rho \) parameter:

\[
\rho \equiv \frac{\text{weak neutral current}}{\text{weak charged current}} = \frac{(g^2 + g'^2)/M^2_Z}{g^2/M^2_W} = \frac{v^2_\phi + a \langle X^0 \rangle^2}{v^2_\phi + b \langle X^0 \rangle^2}
\]

\[
a = 4 \left[ T(T + 1) - Y^2 \right] c \quad Q = T^3 + Y; \text{ SM doublet: } Y = 1/2
\]

\[
b = 8 Y^2
\]

Expt: \( \rho = 1.00039 \pm 0.00019 \) (2018 PDG)

\( \Rightarrow \langle \chi^0 \rangle \lesssim \text{GeV}; \) negligible mixing of \( \chi^0 \) with SM-like Higgs
\( \chi^{\pm\pm} \) decays to \( \ell^{\pm\ell^{\pm}} \) or \( W^{\pm}W^{\pm} \) depending on size of triplet vev

(assumes no \( \chi^{\pm\pm} \rightarrow \chi^{\pm}W^{\pm} \))

Rely on Drell-Yan production of \( \chi^{++}\chi^{--} \) or \( \chi^{\pm\pm}\chi^{\mp} \).

Like-sign dilepton resonance search is very sensitive – exclude \( \chi^{\pm\pm} \) up to \( \sim 800 \) GeV depending on assumptions about \( e/\mu/\tau \) fractions → ATLAS + CMS

Aoki, Kanemura & Yagyu, 1110.4625
$\chi^{\pm\pm} \rightarrow W^\pm W^\pm$ search done for first time in Run 2 ($Ws$ on shell)

![Graph showing observed and expected upper limits for $\chi^{\pm\pm} \rightarrow W^\pm W^\pm$](image)

**ATLAS**

$\sqrt{s}=13$ TeV  36.1 fb$^{-1}$

- Observed 95% CL upper limit
- Expected 95% CL upper limit
- Expected limit ($\pm 2\sigma$)
- Expected limit ($\pm 1\sigma$)
- $H^{\pm\pm}$ theory (NLO QCD)

**Theorist recast of ATLAS Run-1 like-sign dimuon data sets lower bound** $m_{\chi^{\pm\pm}} \gtrsim 84$ GeV  Kanemura, Kikuchi, Yagyu & Yokoya, 1412.7603

**Gap at intermediate masses** $< 200$ GeV: need offshell $Ws$!

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Models with triplets (or larger) contributing to EWSB:

Have to model-build to avoid $\rho \neq 1$. Only two known approaches:

1) Use the septet $(T, Y) = (3, 2)$: $\rho = 1$ by accident!
Doublet $\left(\frac{1}{2}, \frac{1}{2}\right)$ + septet $(3, 2)$: Scalar septet model
   Hisano & Tsumura, 1301.6455; Kanemura, Kikuchi & Yagyu, 1301.7303

2) Use global $SU(2)_L \times SU(2)_R$ imposed on the scalar potential
Global $SU(2)_L \times SU(2)_R \rightarrow$ custodial $SU(2)$ ensures tree-level $\rho = 1$
Doublet + triplets $(1, 0) + (1, 1)$: Georgi-Machacek model
   Georgi & Machacek 1985; Chanowitz & Golden 1985

   Doublet + quartets $\left(\frac{3}{2}, \frac{1}{2}\right) + \left(\frac{3}{2}, \frac{3}{2}\right)$: Generalized Georgi-
   Doublet + quintets $(2, 0) + (2, 1) + (2, 2)$: Machacek models
   Galison 1984; Robinett 1985; HEL 1999; Chang et al 2012; HEL & Rentala 2015

Larger than sextets $\rightarrow$ too many large multiplets, violates perturbativity

All contain doubly-charged Higgs with $H^{\pm \pm} W^\mp W^\mp$ coup. $\propto \langle X^0 \rangle$!
Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs (bi-)doublet + triplets \((1, 0) + (1, 1)\) in a bi-triplet:

\[
\Phi = \begin{pmatrix} \phi^0 \ast & \phi^+ \\ -\phi^+ \ast & \phi^0 \end{pmatrix}, \quad X = \begin{pmatrix} \chi^0 \ast & \xi^+ & \chi^{++} \\ -\chi^{++} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{++} & \chi^0 \end{pmatrix}
\]

Global \(\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R\) → custodial symmetry \(\langle \chi^0 \rangle = \langle \xi^0 \rangle = v_\chi\)

Physical spectrum:

Bi-doublet: \(2 \otimes 2 \rightarrow 1 \oplus 3\)  
Bi-triplet: \(3 \otimes 3 \rightarrow 1 \oplus 3 \oplus 5\)

- Two custodial singlets mix \(\rightarrow h, H\) \(m_h, m_H, \text{angle } \alpha\)
  
  Usually identify \(h = h(125)\)

- Two custodial triplets mix \(\rightarrow (H_3^+, H_3^0, H_3^-)\) \(m_3 + \text{Goldstones}\)
  
  Phenomenology very similar to \(H^\pm, A^0\) in 2HDM Type I, \(\tan \beta \rightarrow \cot \theta_H\)

- Custodial fiveplet \(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--}\) \(m_5\)
  
  Fermiophobic; \(H_5 VV\) couplings \(\propto s_H \equiv \sqrt{8}v_\chi/v_{\mathrm{SM}}\)
  
  \(s_H^2 \equiv \text{exotic fraction of } M_W^2, M_Z^2\)
Explicit LHC searches up to now:

\[
\text{VBF} \to H_{5}^{\pm\pm} \to W^{\pm}W^{\pm} \to \text{CMS} \quad \text{VBF + like-sign dileptons + MET}
\]

\[
\text{VBF} \to H_{5}^{\pm} \to W^{\pm}Z \to \text{ATLAS + CMS} \quad \text{VBF } qg\ell\ell; \text{ VBF } 3\ell+\text{MET}
\]

Cross section \( \propto s_{H}^{2} \equiv \text{fraction of } M_{W}^{2}, M_{Z}^{2} \) due to exotic scalars
Most stringent constraint: \( \text{VBF} \rightarrow H_{5}^{\pm\pm} \rightarrow W^\pm W^\pm \) CMS, arXiv:1709.05822

Also searches for \( \text{VBF} \rightarrow H_{5}^{\pm} \rightarrow W^\pm Z \rightarrow \text{ATLAS} + \text{CMS} \)

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For $H_{5}^{\pm\pm}, H_{5}^{\pm}, H_{5}^{0}$ masses below 200 GeV, constraints are mainly theory-recast:

new "low-$m_{5}$" benchmark in GM model,

Ben Keeshan, WG3 Extended Scalars meeting, 2018-10-24

Recast ATLAS Run1 VBF $\to W^{\pm}W^{\pm}$, 1407.5053

Recast ATLAS Run1 dimuons, 1412.7603, 1502.01275

(Preliminary)

CMS VBF $\to H^{\pm\pm} \to W^{\pm}W^{\pm}$

1709.05822

Allowed

Recast ATLAS Run1 $\gamma\gamma$ resonance, GMCALC 1.5.0 beta

Extending Drell-Yan $H^{\pm\pm} \to W^{\pm}W^{\pm}$ search to masses below 200 GeV (w/ offshell $W$s) could exclude entire low-$m_{5}$ region!

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For \( m_5 \) below threshold for \( H_5 \rightarrow VV \) (\( V = W, Z \)) decays, BRs for loop-induced decays \( H_5^0 \rightarrow \gamma\gamma \), \( H_5^\pm \rightarrow W^\pm \gamma \) become important (remember \( H_5 \) is fermiophobic)

**Sensitivity study for** \( H_5^\pm \rightarrow W^\pm \gamma \) (production by Drell-Yan):

Expected 95\%CL exclusion with 300 fb\(^{-1}\) at 14 TeV LHC

Recast ATLAS Run1 \( \gamma\gamma \) resonance search current exclusion

\( H_5^\pm \rightarrow W^\pm \gamma \) simulation tool now public: UFO model for MG5

If low-\( m_5 \) region in GM model is excluded by \( H^{\pm \pm} \rightarrow W^{\pm}W^{\pm} \), a new theory benchmark to motivate \( H^+ \rightarrow W^+\gamma \) will be needed.

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*WG3 Extended Scalars*  

*2018 Dec 11*
Several recent “low-mass” results rely on Drell-Yan production of pairs of new scalars.

Request to provide Drell-Yan xsec tables (in progress, NLO QCD)

- GM model $pp \rightarrow H_5^{++} H_5^{--}$, $H_5^{\pm\pm} H_5^{\mp\mp}$, $H_5^+ H_5^-$, $H_5^\pm H_5^0$

- HTM $pp \rightarrow \chi^{++} \chi^{--}$, $\chi^{\pm\pm} \chi^{\mp\mp}$ etc.

- 2HDM

Simple relations between cross sections in different models due to gauge quantum numbers of scalars.
GM model benchmark for $H \to hh$: full parameter scan (Prelim)
Summary: “wish list” of missing search channels

\( H_3 \to H_1 H_2 \), where all three Higgs bosons have different masses. \( h_{125} \) could be any of these three. (our #1 priority for a new search)

\( H^{\pm\pm} \to W^{\pm} W^{\pm} \): extend search to masses below 200 GeV (off-shell \( W \)s). Production via Drell-Yan in pairs or with \( H^{{\mp}} \).

\( H \to H^+ H^- \to \tau \nu \tau \nu \) \((H \neq h_{125})\)

\( H \to W^+ H^- \) \((H \neq h_{125})\)

\( H^+ \to W^+ \gamma \): search for fermiophobic charged Higgs including at low mass (below 200 GeV); production via Drell-Yan.

\( H_{125} \to \tau \tau \) CP measurement from \( \tau \) polarization kinematic distributions [this belongs to SM Higgs Characterization]
the end
BACKUP SLIDES
WG3: Extended Scalars meeting

Tuesday 13 Mar 2018, 14:00 → 16:00  Europe/Zurich

Vidyo only (CERN)

There are minutes attached to this event. Show them.

14:00 → 14:05  Introduction

Speakers: Heather Logan (Carleton University), Dr Raffaele Angelo Gercsa (Univ. of California San Diego (US)), Rui Santos (IST), Shufang Su (University of Arizona), Xiangyang Ju (University of Wisconsin Madison (US)), Xiaohu Sun (University of Alberta (CA))

14:05 → 14:25  Drell-Yan H5^0 --> gamma gamma

Speaker: Roberto Vega-Morales

14:25 → 14:45  H5^+ --> W^+ gamma theory

Speaker: Yongcheng Wu

14:45 → 15:05  H5^+ --> W^+ gamma experiment

Speakers: Brigitte Vachon, Kays Haddad, Kays Haddad (McGill University (CA))

15:05 → 15:25  Drell-Yan H5^+++ --> W^+ W^- --> like-sign leptons

Speaker: Heather Logan (Carleton University)

15:25 → 15:35  Discussion
WG3 Fall Meeting: Recap of Recent Progress

Description: In this meeting we will hear talks summarizing recent experimental results and theoretical progress. The goal is to gather feedback from within the WG3 community on recent results and to begin to plan the work for the next few months in preparation for the LHC-HXSWG General Meeting in December.

Contact: dsperka@cern.ch

16:00 → 16:30  Experimental Results and Progress: ATLAS
Speaker: Adam Bailey (Univ. of Valencia and CSIC (ES))

16:30 → 17:00  Experimental Results and Progress: CMS
Speaker: Dr Raffaele Angelo Gerosa (Univ. of California San Diego (US))

17:00 → 17:30  Searching for the W-gamma decay of a charged scalar in Georgi-Machacek Model
Speaker: Dr Yongcheng Wu (Carleton University)

17:30 → 18:00  MSSM benchmark scenarios for Run 2 and beyond
Speaker: Stefan Rainer Liebler (KIT - Karlsruhe Institute of Technology (DE))
WG3: Benchmark Discussion

**Wednesday 24 Oct 2018, 17:00 → 20:00**

**Europe/Zurich**

**304-1-007 (CERN)**

**17:00 → 17:05** *Introduction*
Speaker: Bai Shaojun (BES and PDPC SL)

**17:05 → 17:15** *Benchmark Points for Type-II 2HDMs with a light h*
Speaker: William Klemm

**17:15 → 17:25** *Benchmark Point with low-mass CP-odd Higgs A with strong couplings to leptons and top quarks*
Speaker: Dominik Stoeckinger

**17:25 → 17:35** *Charged Higgs boson benchmarks from top quark polarization*
Speaker: Adil Juma

**17:35 → 17:45** *IDM benchmarks for the LHC at 13 and 27 TeV*
Speaker: Tanris Roberts

**17:45 → 17:55** *Updated constraints for the Real Higgs Singlet Extension of the Standard Model*
Speaker: Tanris Roberts

**17:55 → 18:05** *Interference effects in Hs production at the LHC*
Speaker: Dusko Azevedo

**18:05 → 18:15** *A benchmark for LHC searches for H5±, H5±, and H5  in the Georgi-Machacek model including masses below 200 GeV*
Speaker: Ben Keeshan

**18:15 → 18:25** *Benchmark scenarios in the C2HDM*
Speaker: Jonas Wittbrodt

**18:25 → 18:45** *Discussion*
$H \rightarrow hh$ cross section constrained so far: ATLAS, arXiv:1804.06174

**ATLAS**

$s=13$ TeV, 27.5-36.1 fb$^{-1}$

- Observed 95% CL limit
- Expected 95% CL limit

$\sigma(pp\rightarrow$ Scalar$\rightarrow$ HH$\rightarrow$ b$\bar{b}$b$\bar{b}$) [fb] vs. m(Scalar) [TeV]

Scalor $\rightarrow$ HH $\rightarrow$ b$\bar{b}$b$\bar{b}$
Georgi-Machacek model  

Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs (bi-)doublet + triplets $(1, 0) + (1, 1)$ in a bi-triplet:

$$
\Phi = \begin{pmatrix}
\phi^0* & \phi^+ \\
-\phi^{++} & \phi^0
\end{pmatrix} \quad X = \begin{pmatrix}
\chi^0* & \xi^+ & \chi^{++} \\
-\chi^{++} & \xi^0 & \chi^+ \\
\chi^{+++} & -\xi^{++} & \chi^0
\end{pmatrix}
$$

Global SU(2)$_L \times$ SU(2)$_R \rightarrow$ custodial symmetry $\langle \chi^0 \rangle = \langle \xi^0 \rangle \equiv v_X$

Most general scalar potential invariant under SU(2)$_L \times$ SU(2)$_R$:

$$
V(\Phi, X) = \frac{\mu_2^2}{2} \text{Tr}(\Phi^\dagger \Phi) + \frac{\mu_3^2}{2} \text{Tr}(X^\dagger X) + \lambda_1 [\text{Tr}(\Phi^\dagger \Phi)]^2
$$

$$
+ \lambda_2 \text{Tr}(\Phi^\dagger \Phi) \text{Tr}(X^\dagger X) + \lambda_3 \text{Tr}(X^\dagger XX^\dagger X)
$$

$$
+ \lambda_4 [\text{Tr}(X^\dagger X)]^2 - \lambda_5 \text{Tr}(\Phi^\dagger \tau^a \Phi \tau^b) \text{Tr}(X^\dagger t^a X t^b)
$$

$$
- M_1 \text{Tr}(\Phi^\dagger \tau^a \Phi \tau^b) (UXU^\dagger)_{ab} - M_2 \text{Tr}(X^\dagger t^a X t^b) (UXU^\dagger)_{ab}
$$

9 parameters, 2 fixed by $G_F$ and $m_h \rightarrow$ 7 free parameters.  

Aoki & Kanemura, 0712.4053  
Chiang & Yagyu, 1211.2658; Chiang, Kuo & Yagyu, 1307.7526  
Hartling, Kumar & HEL, 1404.2640
$H^{++} \rightarrow W^+W^+$: Below the $WW$ threshold, same-flavour leptons can come from either of the $W$s, leading to an interference term. Need full $H^{++} \rightarrow 4f$ branching ratios simulation.

Kanemura, Kikuchi, Yagyu & Yokoya, 1407.6547
Set limit $m_{H^{++}} \gtrsim 76$ GeV in GM model.