WG3 Extended Scalars* status report

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

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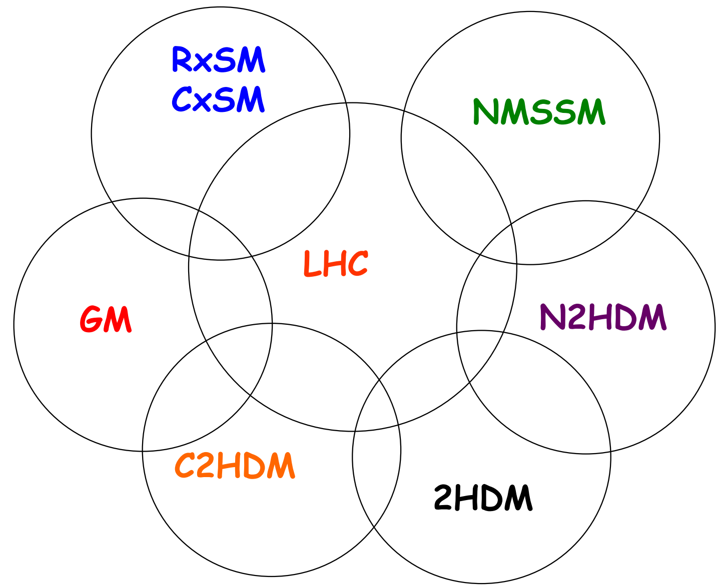
Ottawa, Canada

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
    - $H_5^0 \to \gamma\gamma$: diphoton resonance fiducial xsec limits $\to$ recast
    - $H_5^\pm \to W^\pm\gamma$: study in progress
    - $H_5^{\pm\pm} \to W^\pm W^\pm$: Run-1 theorist-recast: $m_{H_5^{\pm\pm}} \gtrsim 75$ GeV

- 2018 Sep 20: theory report on $H^\pm \to W^\pm\gamma$ 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 (RxSM)

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

Mass eigenstates: $m_h < m_H$

$h = \cos\alpha\,\phi^{0,r} - \sin\alpha\,s \qquad H = \sin\alpha\,\phi^{0,r} + \cos\alpha\,s$

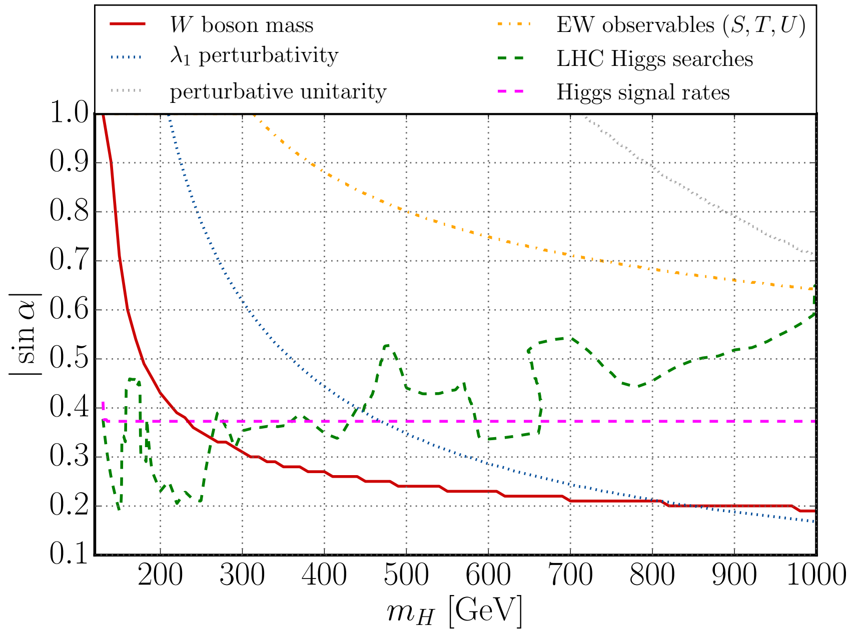
All couplings are SM times $\cos\alpha$ for h, SM times $\sin\alpha$ for H.
Only possible new decay channel is $H \to hh$.

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

$\to$ Interpretation for searches for heavy SM-like Higgs boson with overall suppression of all couplings $\mu_H \equiv \sin\alpha$

Combined limits on $|\sin\alpha|$

(A. Ilnicka, TR, T. Stefaniak, Mod.Phys.Lett. A33 (2018) no.10n11, 1830007)



m_W still strongest constraint for $m_H \gtrsim 300\,\mathrm{GeV}$;

$\Rightarrow$ strong improvement: direct searches (ZZ @ 13 TeV) $\Leftarrow$

Tania Robens Updates WG3 subgroup, 24.10.18

Newest update using Run II results in HiggsSignals:

Signal strengths strongest constraint up to 800 GeV: $\sin\alpha \leq 0.22$

Benchmark for scalar resonance $H \to hh$ ($h = h_{125}$) in RxSM

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

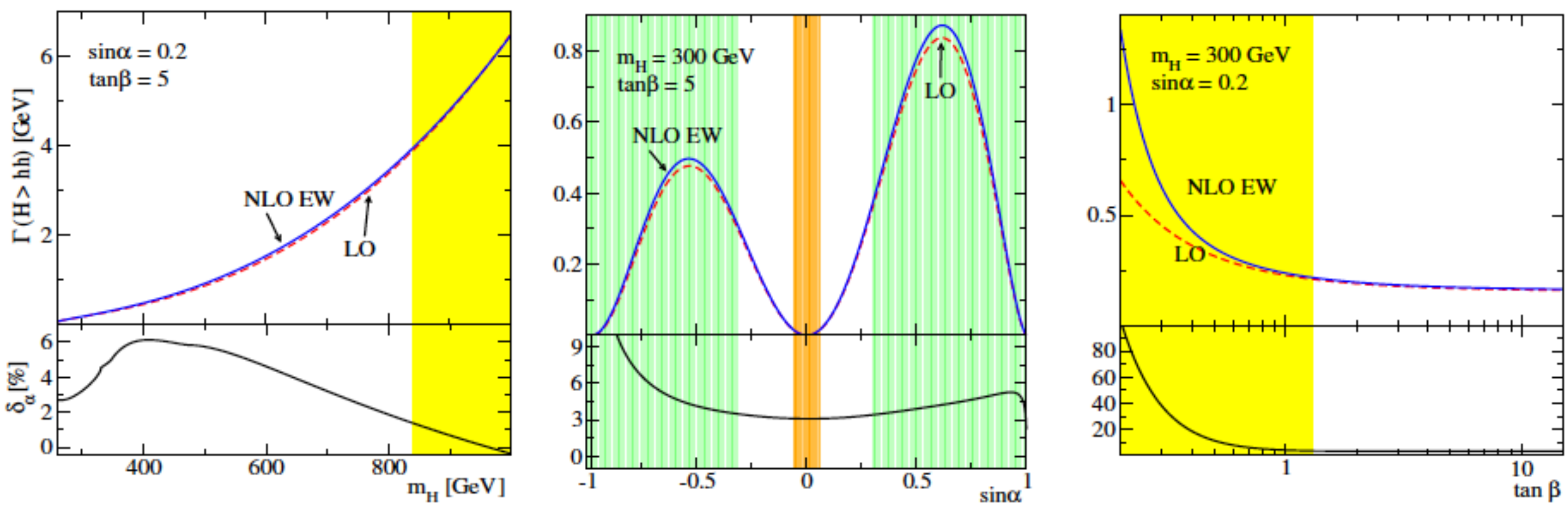
m_H[GeV]	$\lvert\sin\alpha\rvert_{max}$	$BR^{H\to hh}_{min}$	$BR^{H\to hh}_{max}$	m_H[GeV]	$\lvert\sin\alpha\rvert_{max}$	$BR^{H\to hh}_{min}$	$BR^{H\to hh}_{max}$
260	0.22	0.17	0.32	470	0.22	0.23	0.29
270	0.22	0.22	0.37	520	0.22	0.20	0.27
280	0.22	0.23	0.39	590	0.22	0.20	0.26
290	0.22	0.24	0.40	670	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 $H \to h\,h$

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

Model-specific electroweak radiative corrections calculated!

Real Singlet model



$H \to hh$

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:
$A \to ZH$ / $H \to ZA$ (also $A \to Zh_{125}$) $\to$ ATLAS + CMS
$H^+ \to W^+S$ ($S = H, A, h_{125}$) $\to$ CMS, $S = A(\to \mu\mu)$
$H \to AA$ $\to$ ATLAS, $AA \to 4\gamma$

$H \to H^+H^- \to \tau\nu$ $\to$ not being done
$H/A \to W^\pm H^\mp$ $\to$ not being done

"Standard" high-mass charged Higgs search $pp \to tH^- \to tW^- b\bar{b}$:

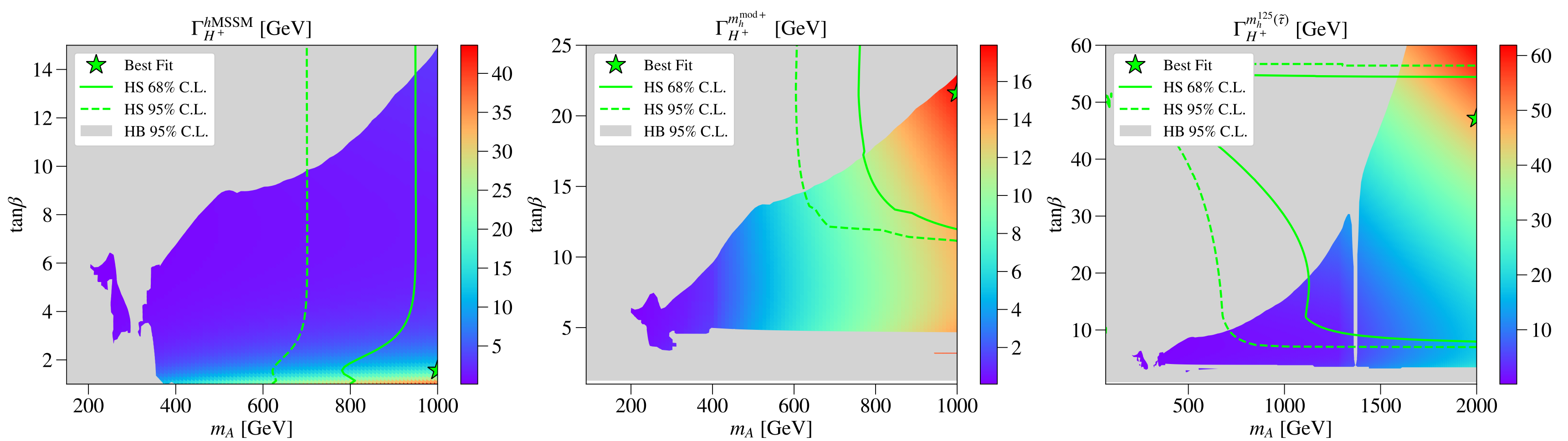
In 2HDM can decay via $H^- \to W^- A(\to b\bar{b})$; large H^- and A widths give large interference between signal and background.

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)

Benchmark cross-sections

→ Benchmarks points are chosen where there is a large charged Higgs width and smallest m_A^0:

Parameters	**hMSSM**	$\mathbf{m_h^{mod+}}$	$\mathbf{m_h^{125}}(\tilde{\tau})$
μ (GeV)	200	200	1000
$\tan\beta$	1.01	3.42	3.19
m_{H^+} (GeV)	633.91	303.08	628.08
Γ_{H^+} (GeV)	27.777	0.925	2.677

Production cross-sections:

Benchmark	Signal (pb)	Background (pb)
hMSSM	$(3.2402 \pm 0.0014) \times 10^{-2}$	13.092 ± 0.004
m_h^{mod+}	$(8.8502 \pm 0.0033) \times 10^{-2}$	13.103 ± 0.004
$m_h^{125}(\tilde{\tau})$	$(1.6802 \pm 0.0058) \times 10^{-2}$	13.177 ± 0.004

Benchmark	Signal+Background (pb)	**Interference** (pb)
hMSSM	13.143 ± 0.004	0.019 ± 0.008
m_h^{mod+}	13.200 ± 0.004	0.009 ± 0.008
$m_h^{125}(\tilde{\tau})$	13.197 ± 0.004	0.003 ± 0.008

Where

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

→ 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:
- $H \to SS \to 4W$ ($S \neq h_{125}$): $\to$ ATLAS
- $H_3 \to H_1 H_2$: one of these must be h_{125}; motivates $H \to h_{125} S$ selection ($m_S \neq 125$ GeV) $\to$ not being done

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

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

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

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

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

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

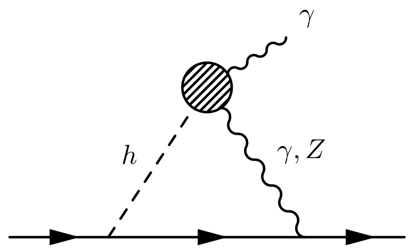
$b,\ \tau$: $\quad Y^{TypeII}_{\text{C2HDM}} = \cos\alpha_2 Y^{TypeII}_{\text{2HDM}} - i\gamma_5 \sin\alpha_2 \tan\beta$

α_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!

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!

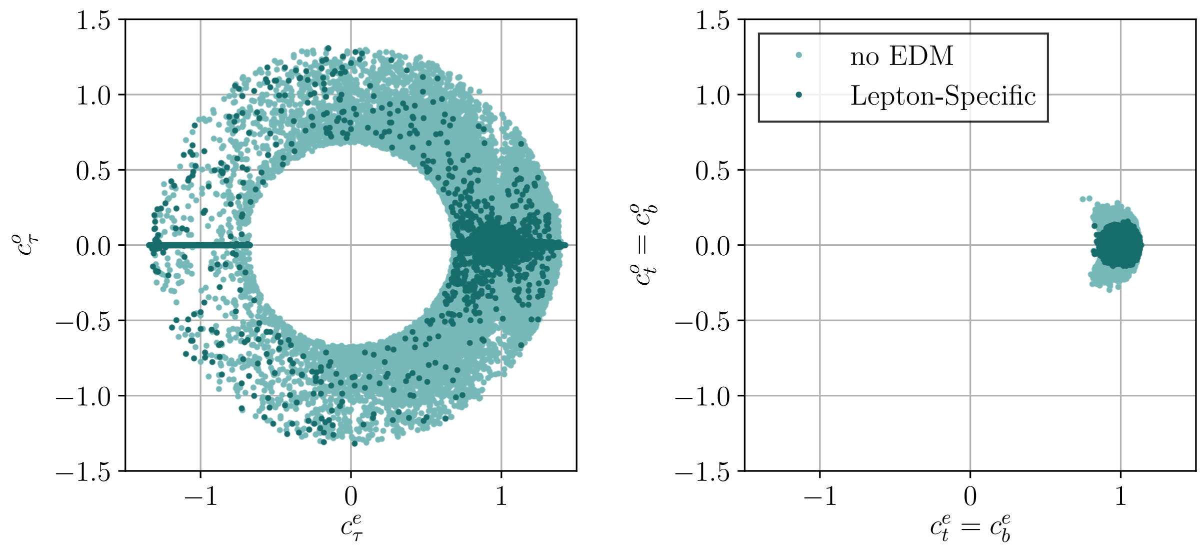
Large CPV Yukawas excluded in Type I and in Type II when h_{125} = lightest neutral scalar.

Most interesting scenarios:

Fontes et al, 1711.09419

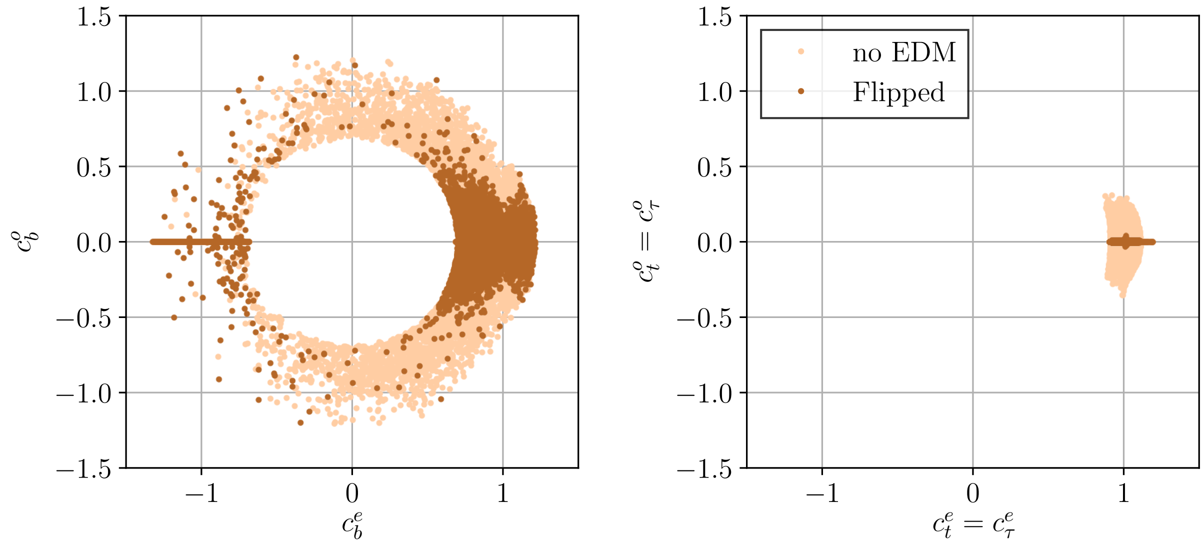
Lepton-specific (Type X)

Can have CP-odd $h\tau\tau$ and CP-even htt, hbb



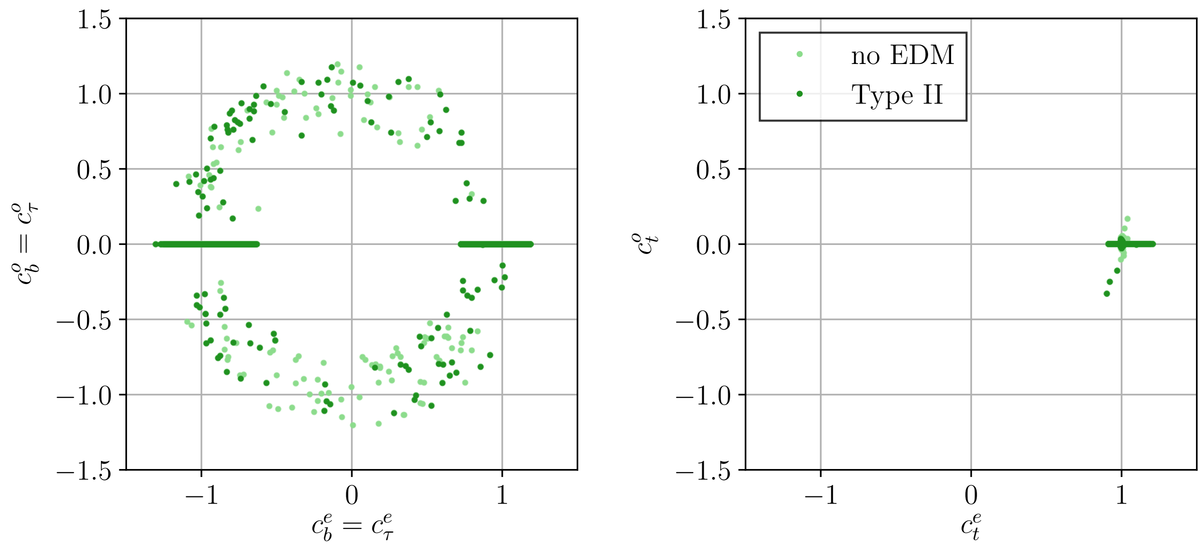
Flipped
(Type Y)

Can have CP-odd hbb and CP-even htt, $h\tau\tau$



Type II
with $h_{125} = H_2$

Can have CP-odd hbb, $h\tau\tau$ and CP-even htt



Probe using τ decay distributions! Benchmark points available.

Fontes et al, 1711.09419

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 ρ parameter:

$$\rho \equiv \frac{\text{weak neutral current}}{\text{weak charged current}} = \frac{(g^2 + g'^2)/M_Z^2}{g^2/M_W^2} = \frac{v_\phi^2 + a\langle X^0 \rangle^2}{v_\phi^2 + b\langle X^0 \rangle^2}$$

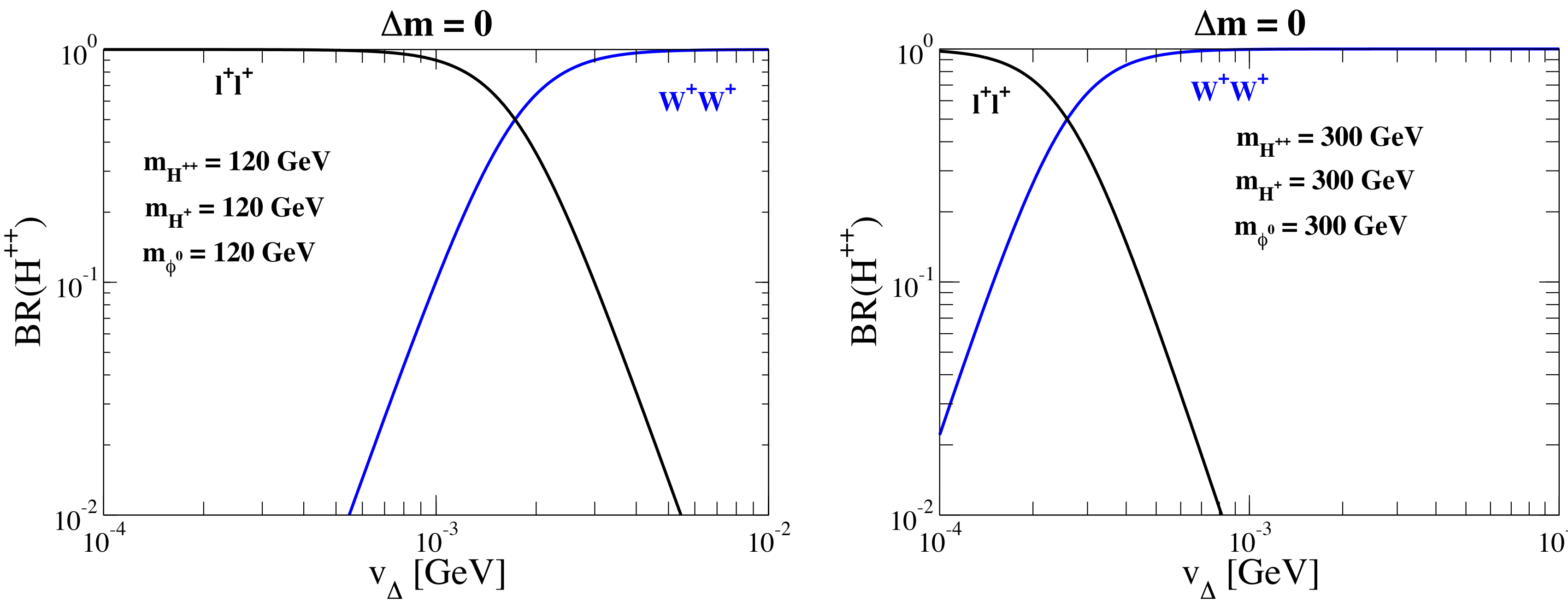
$$\begin{aligned} a &= 4\left[T(T+1) - Y^2\right] c \\ b &= 8Y^2 \end{aligned}$$

$Q = T^3 + Y$; SM doublet: $Y = 1/2$

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

$\Rightarrow \langle \chi^0 \rangle \lesssim$ GeV; negligible mixing of χ^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

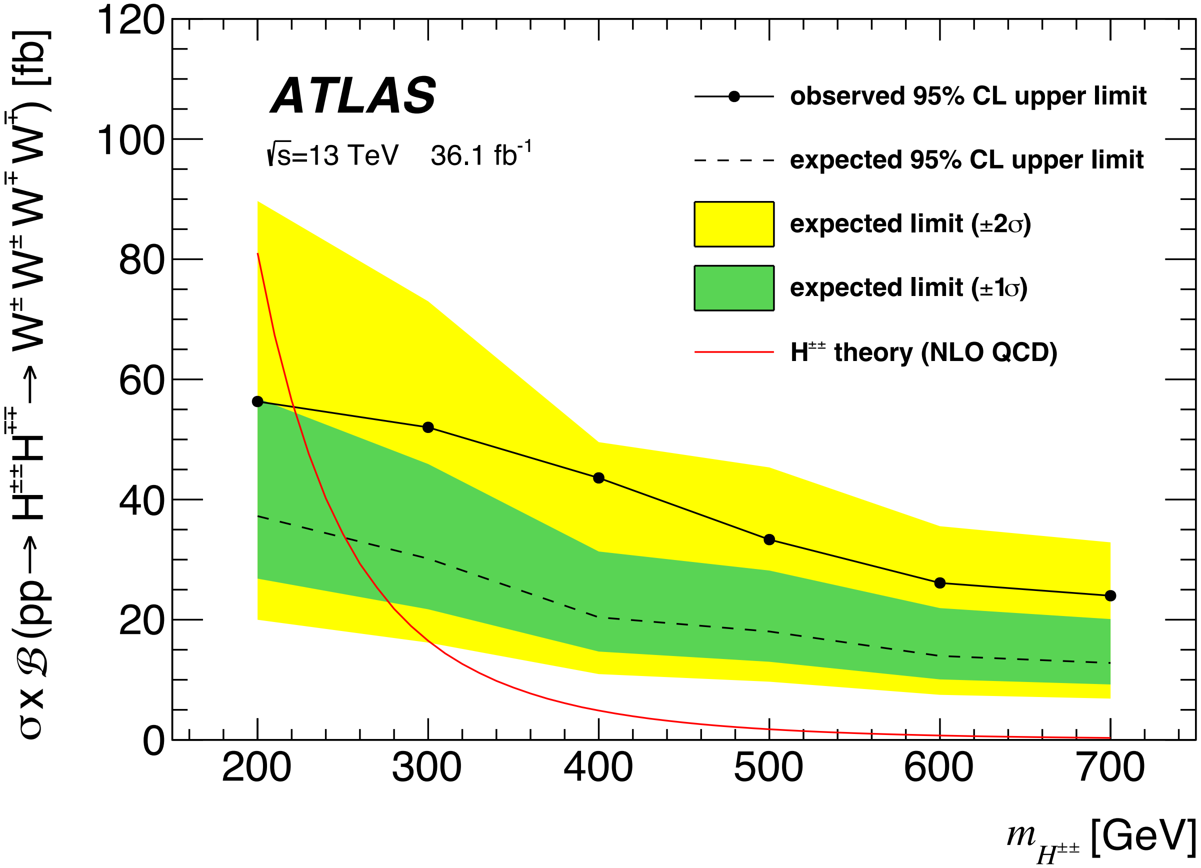


(assumes no $\chi^{\pm\pm} \to \chi^\pm W^\pm$) Aoki, Kanemura & Yagyu, 1110.4625

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

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

$\chi^{\pm\pm} \to W^{\pm}W^{\pm}$ search done for first time in Run 2 (Ws on shell)



ATLAS, arXiv:1808.01899

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

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

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 $\left(\frac{3}{2}, \frac{1}{2}\right) + \left(\frac{3}{2}, \frac{3}{2}\right)$:
Doublet + quintets $(2, 0) + (2, 1) + (2, 2)$:
Doublet + sextets $\left(\frac{5}{2}, \frac{1}{2}\right) + \left(\frac{5}{2}, \frac{3}{2}\right) + \left(\frac{5}{2}, \frac{5}{2}\right)$:
Generalized Georgi-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:

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

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

Physical spectrum:

Bi-doublet: $2 \otimes 2 \to 1 \oplus 3$

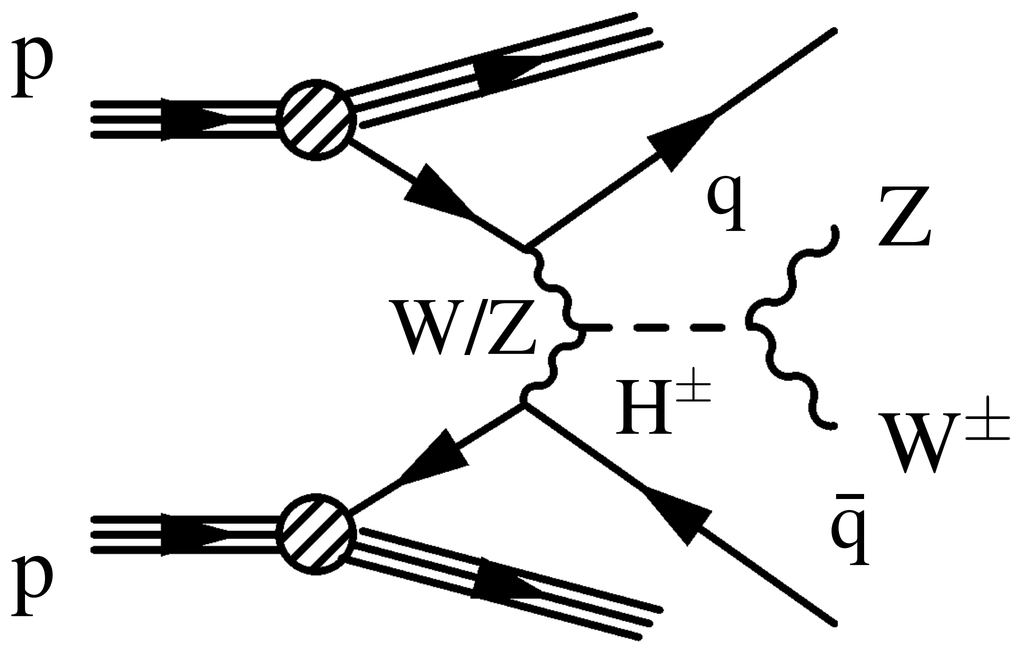
Bi-triplet: $3 \otimes 3 \to 1 \oplus 3 \oplus 5$

- Two custodial singlets mix $\to h$, H m_h, m_H, angle α
  Usually identify $h = h(125)$
- Two custodial triplets mix $\to (H_3^+, H_3^0, H_3^-)$ m_3 + Goldstones
  Phenomenology very similar to $H^\pm, A^0$ in 2HDM Type I, $\tan\beta \to \cot\theta_H$
- Custodial fiveplet $(H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--})$ m_5
  Fermiophobic; H_5VV couplings $\propto s_H \equiv \sqrt{8} v_\chi / v_{SM}$
  $s_H^2 \equiv$ exotic fraction of M_W^2, M_Z^2

Explicit LHC searches up to now:

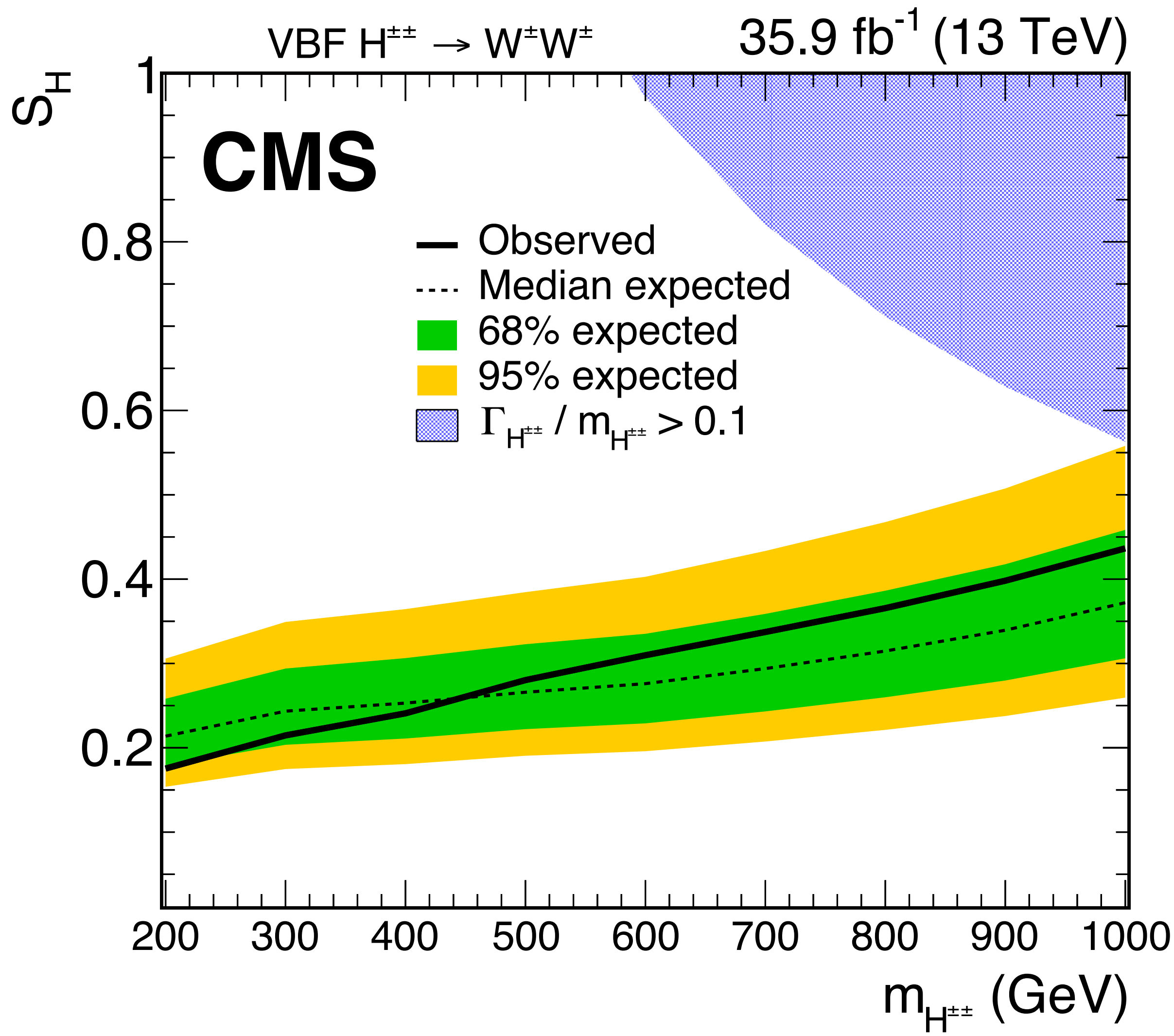
VBF $\to H_5^{\pm\pm} \to W^\pm W^\pm \to$ CMS   VBF + like-sign dileptons + MET

VBF $\to H_5^{\pm} \to W^\pm Z \to$ ATLAS + CMS   VBF $qq\ell\ell$; VBF 3ℓ+MET



Cross section $\propto s_H^2 \equiv$ fraction of M_W^2, M_Z^2 due to exotic scalars

Most stringent constraint: VBF $\to H_5^{\pm\pm} \to W^\pm W^\pm$ CMS, arXiv:1709.05822

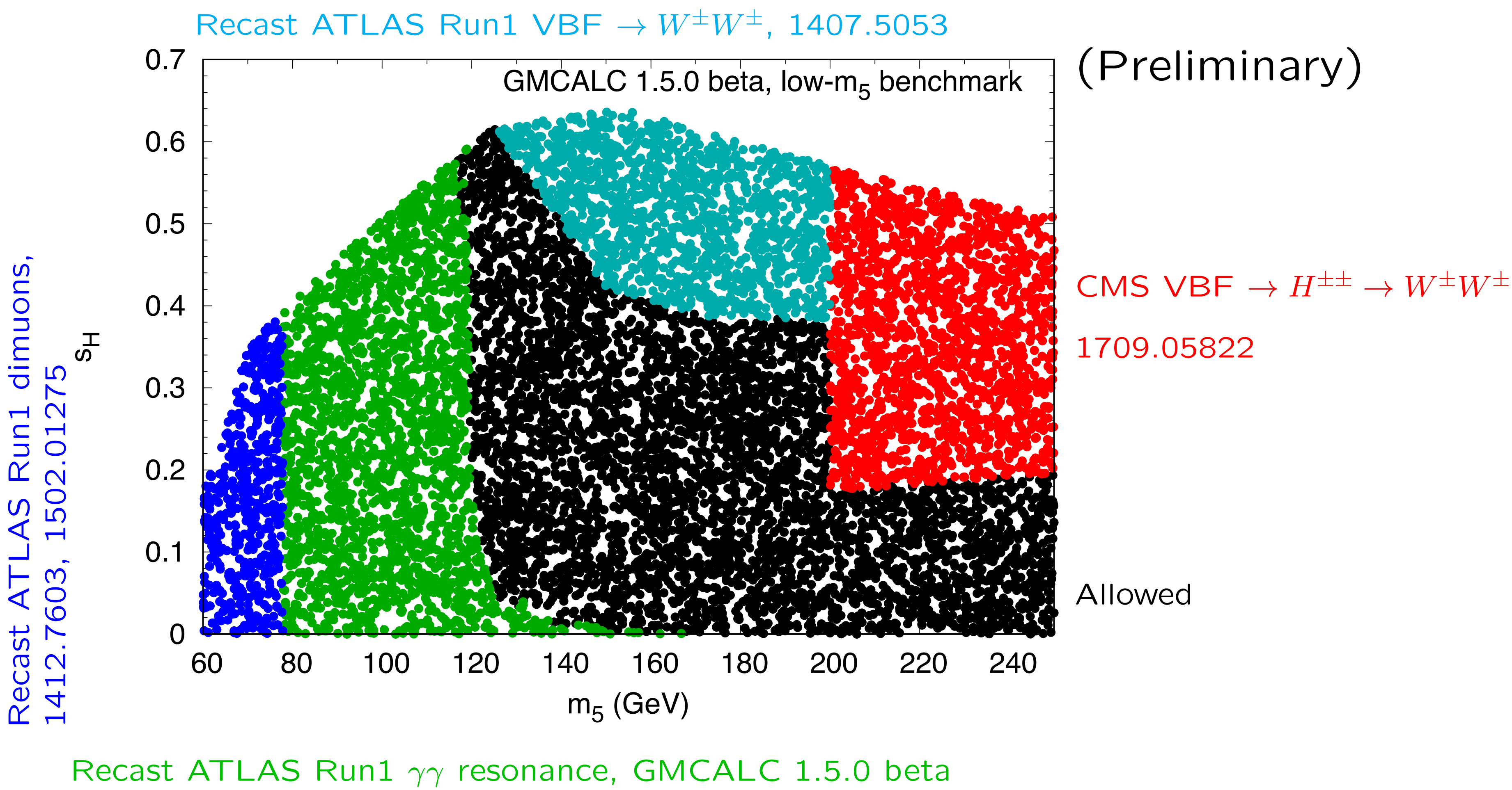


$m_{H^{++}} \geq 200$ GeV

Also searches for VBF $\to H_5^\pm \to W^\pm Z$ → ATLAS + CMS

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

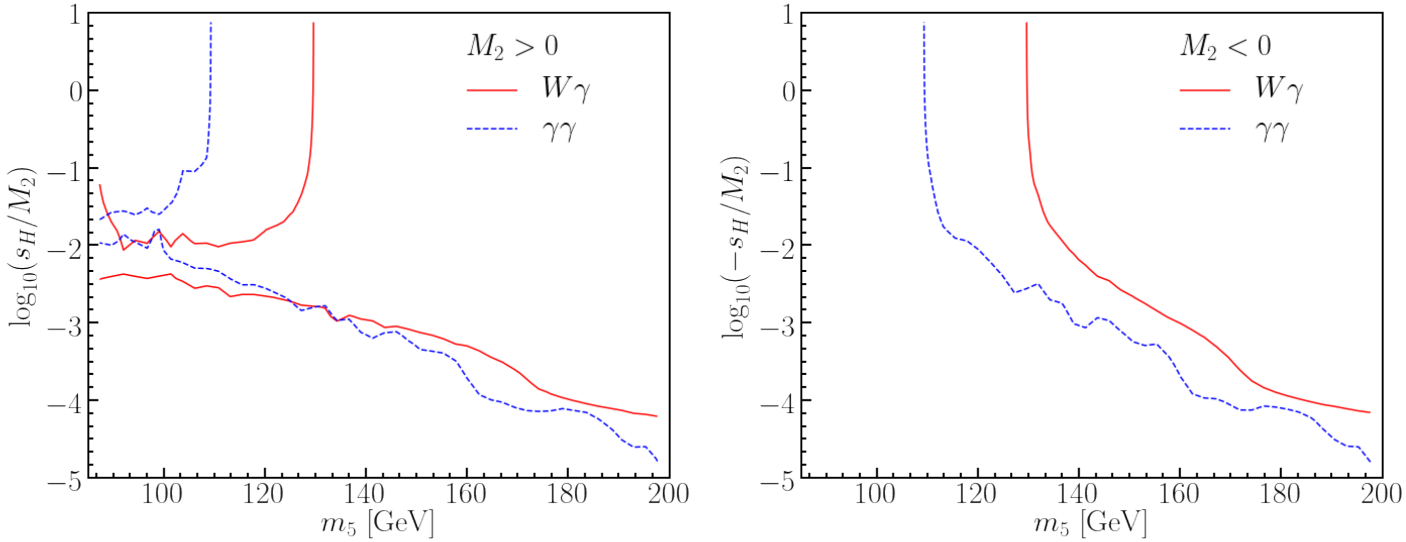


Extending Drell-Yan $H^{\pm\pm} \to W^\pm W^\pm$ search to masses below 200 GeV (w/ offshell Ws) could exclude entire low-m_5 region!

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

Logan & Wu, 1809.09127

Sensitivity study for $H_5^\pm \to W^\pm\gamma$ (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

$H_5^\pm \to W^\pm\gamma$ simulation tool now public: UFO model for MG5

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

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)

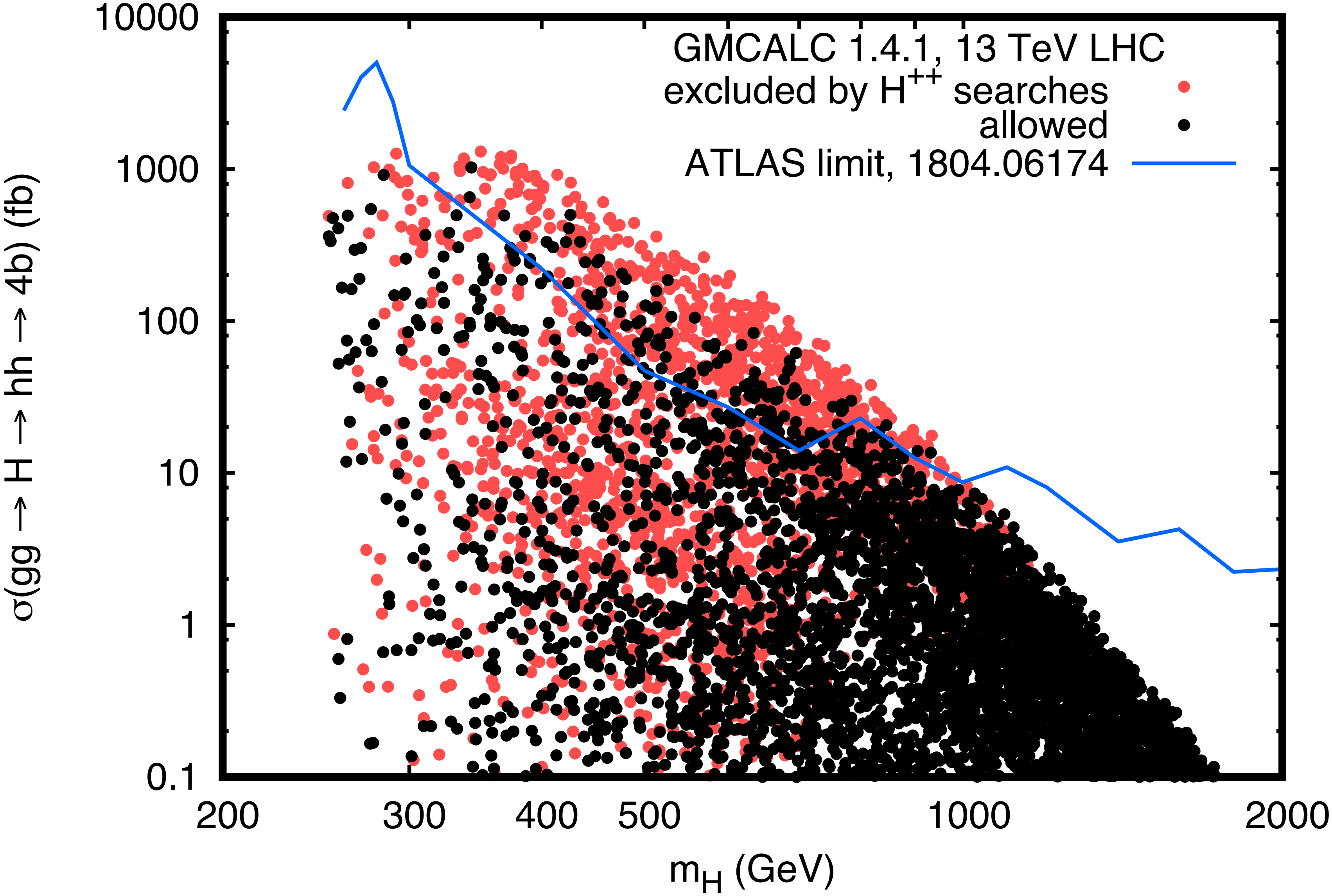
- GM model $pp \to H_5^{++} H_5^{--}$, $H_5^{\pm\pm} H_5^{\mp}$, $H_5^{+} H_5^{-}$, $H_5^{\pm} H_5^{0}$

- HTM $pp \to \chi^{++}\chi^{--}$, $\chi^{\pm\pm}\chi^{\mp}$ 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 Ws). 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 τ 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)

Videoconference Rooms WG3__Extended_Scalars_meeting Join

There are minutes attached to this event. Show them.

14:00 → 14:05 **Introduction** 5m

Speakers: Heather Logan (Carleton University), Dr Raffaele Angelo Gerosa (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** 20m

Speaker: Roberto Vega-Morales

ExtendedHiggsMee...

14:25 → 14:45 **H5+ --> W+ gamma theory** 20m

Speaker: Yongcheng Wu

H5WGAinGM_ycwu...

14:45 → 15:05 **H5+ --> W+ gamma experiment** 20m

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

Charged Higgs Grou...

15:05 → 15:25 **Drell-Yan H5^++ --> W+ W+ --> like-sign leptons** 20m

Speaker: Heather Logan (Carleton University)

H5pp-to-leptons.pdf

15:25 → 15:35 **Discussion** 10m

WG3 Fall Meeting: Recap of Recent Progress

Thursday 20 Sep 2018, 16:00 → 18:00 Europe/Zurich

31-S-028 (CERN)

David Sperka (Boston University (US)), Liron Barak (Tel Aviv University), Pietro Slavich (LPTHE Paris), Stefania Gori (UC Santa Cruz)

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.

Videoconference Rooms WG3_subgroup_meeting Join

Contact dsperka@cern.ch

16:00 → 16:30 **Experimental Results and Progress: ATLAS** ¶ 30m

Speaker: Adam Bailey (Univ. of Valencia and CSIC (ES))

ATLAS_HBSM_LHC...

16:30 → 17:00 **Experimental Results and Progress: CMS** 30m

Speaker: Dr Raffaele Angelo Gerosa (Univ. of California San Diego (US))

Raffaele_20_09_20...

17:00 → 17:30 **Searching for the W-gamma decay of a charged scalar in Georgi-Machacek Model** 30m

Speaker: Dr Yongcheng Wu (Carleton University)

H5WGA_WG3_0920...

17:30 → 18:00 **MSSM benchmark scenarios for Run 2 and beyond** 30m

Speaker: Stefan Rainer Liebler (KIT - Karlsruhe Institute of Technology (DE))

WG3_1809_Liebler....

WG3: Benchmark Discussion

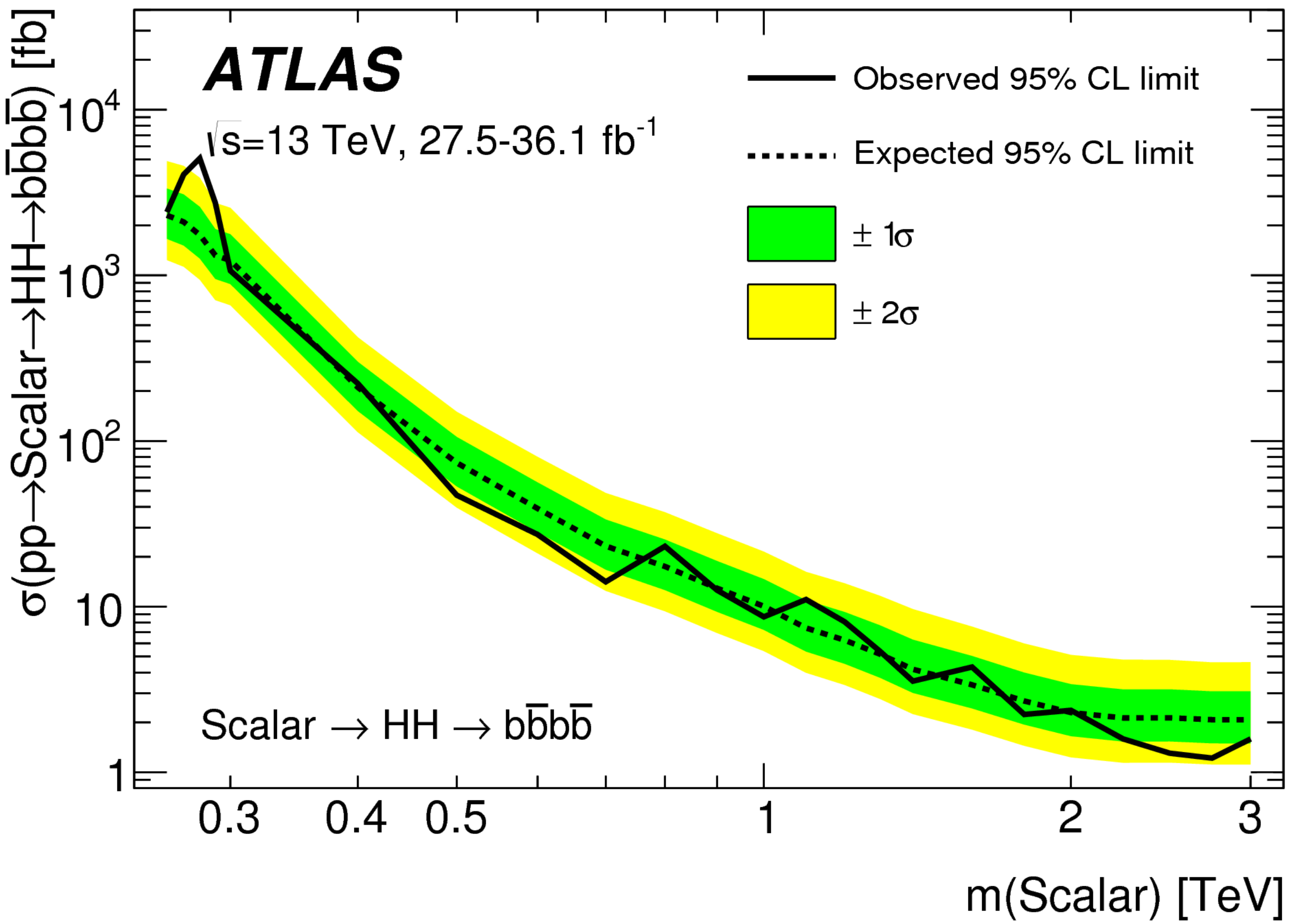
Wednesday 24 Oct 2018, 17:00 → 20:00 Europe/Zurich

304-1-007 (CERN)

Videoconference Rooms: WG3__Benchmark_Discussion — Join

17:00 → 17:05	**Introduction**	Speaker: Rui Santos (ISEL and CFTC-UL)	5m
17:05 → 17:15	**Benchmark Points for Type-I 2HDMs with a light h**	Speaker: William Klemm HXSWG_1018_Klem...	10m
17:15 → 17:25	**Benchmark Point with low-mass CP-odd Higgs A with strong couplings to leptons and top quarks**	Speaker: Dominik Stoeckinger 2018OctoberBMPoi... Paul's master thesis	10m
17:25 → 17:35	**Charged Higgs boson benchmarks from top quark polarization**	Speaker: Adil Jueid LHCHXSWG_AdilJu...	10m
17:35 → 17:45	**IDM benchmarks for the LHC at 13 and 27 TeV**	Speaker: Tania Robens idm_robens.pdf	10m
17:45 → 17:55	**Updated constraints for the Real Higgs Singlet Extension of the Standard Model**	Speaker: Tania Robens singlet_robens.pdf	10m
17:55 → 18:05	**Interference effects in H± production at the LHC**	Speaker: Duarte Azevedo main_v5.pdf	10m
18:05 → 18:15	**A benchmark for LHC searches for H5±±, H5±, and H05 in the Georgi-Machacek model including masses below 200 GeV**	Speaker: Ben Keeshan BenKeeshanHXSW...	10m
18:15 → 18:25	**Benchmark scenarios in the C2HDM**	Speaker: Jonas Wittbrodt benchmarks.pdf	10m
18:25 → 18:45	**Discussion**		20m

$H \to hh$ cross section constrained so far: ATLAS, arXiv:1804.06174



Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

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

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

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

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

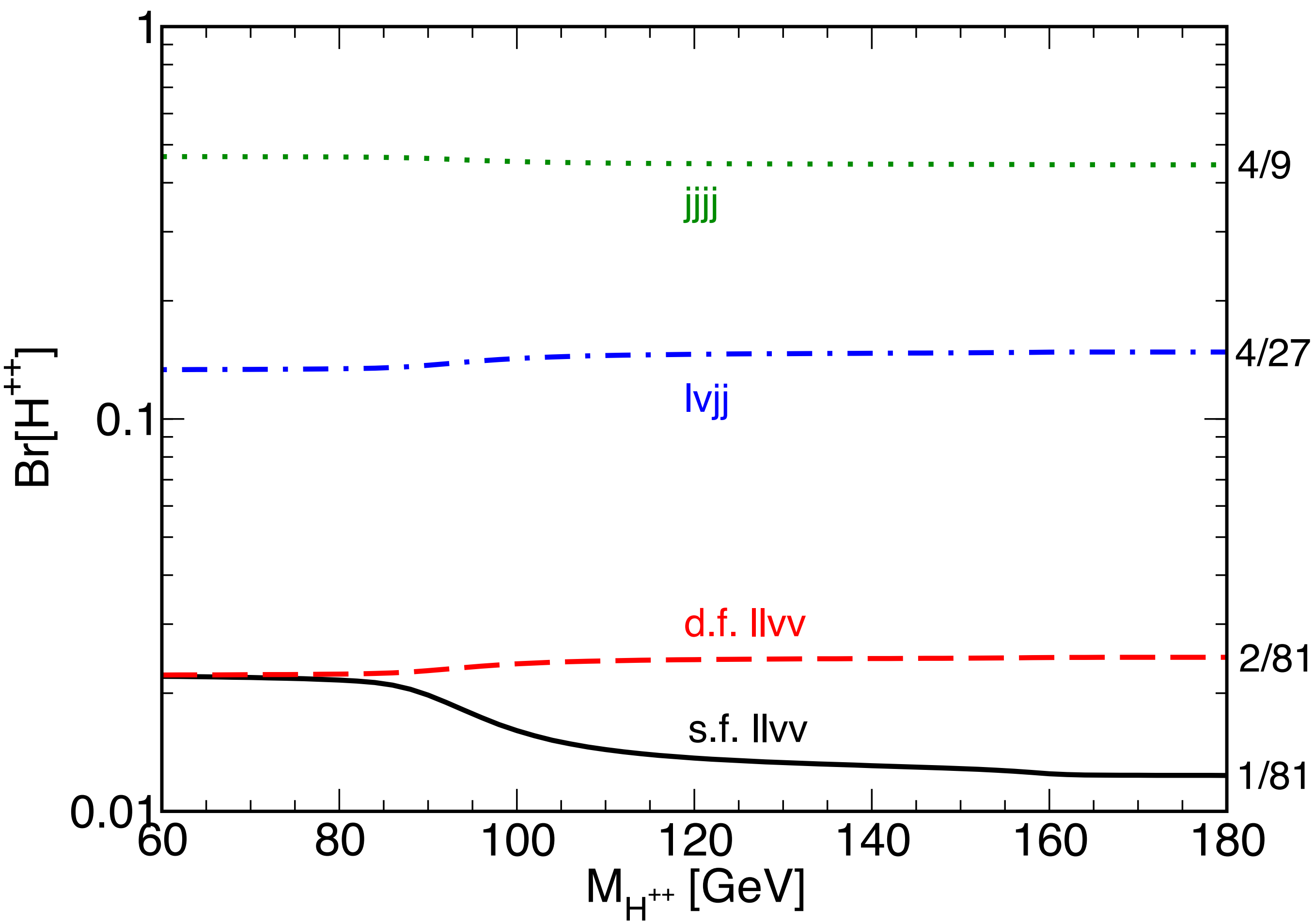
$$\begin{aligned} V(\Phi, X) \;=\; & \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 \\ & +\lambda_2 \mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X) + \lambda_3 \mathrm{Tr}(X^\dagger X X^\dagger X) \\ & +\lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5 \mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)\mathrm{Tr}(X^\dagger t^a X t^b) \\ & -M_1 \mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)(UXU^\dagger)_{ab} - M_2 \mathrm{Tr}(X^\dagger t^a X t^b)(UXU^\dagger)_{ab} \end{aligned}$$

9 parameters, 2 fixed by G_F and m_h $\to$ 7 free parameters. Aoki & Kanemura, 0712.4053

Chiang & Yagyu, 1211.2658; Chiang, Kuo & Yagyu, 1307.7526

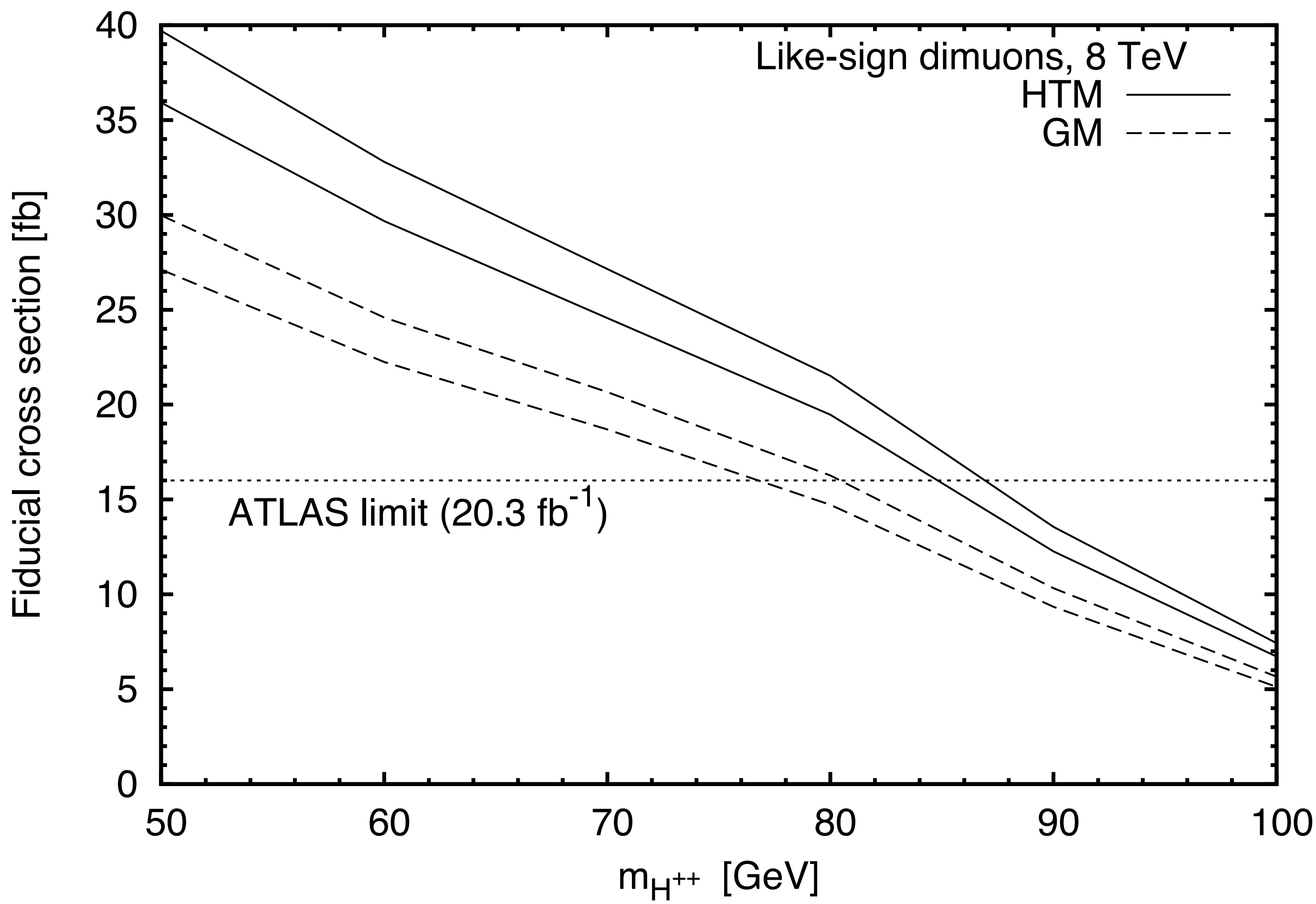
Hartling, Kumar & HEL, 1404.2640

$H^{++} \to W^+W^+$: Below the WW threshold, same-flavour leptons can come from either of the Ws, leading to an interference term. Need full $H^{++} \to 4f$ branching ratios simulation.



Kanemura, Kikuchi, Yagyu & Yokoya, 1407.6547

HEL & Rentala, "All the generalized Georgi-Machacek models," 1502.01275



Set limit $m_{H^{++}} \gtrsim 76$ GeV in GM model.