WG3 - Extended Higgs Sector, theory

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ISEL & CFTC-UL

LHCHXSWG

17th Workshop

10 November 2020

ATLAS: J. Schaarshmidt, L. Zivkovic

CMS: R. Gerosa, J. Steggeman

Theory: H. Logan, S. Su

Outline

- **Requests completed: Large BR($H^{\pm} \to cb$), Large BR($H^{\pm} \to W^{\pm}\gamma$), Extending the search $q\bar{q} \to H^{++}H^{--} \to 4W$ to low masses, Interference in Charged Higgs processes**

- **Brief review of codes for BSM decays**

- **Some new results**

- **The future**

Requests completed

1. Charged Higgs decays to cb can be large in the aligned 2HDM and in 2 versions of the 3HDM, the Flipped and the Democratic.

- A large BR($H^\pm \to cb$) is not expected in 2HDMs with NFC
- BR($H^\pm \to cb$) up to 80% is possible in:

i) 3HDM (flipped and democratic) and ii) Aligned 2HDM

- At present, one search (CMS, 8 TeV, 20 fb^{-1}) for $t \to H^\pm b$, with $H^\pm \to cb$
- BR($t \to H^\pm b$) $\times$ BR($H^\pm \to cb$) $<$ 1% for

90 GeV $< m_{H^\pm} <$ 150 GeV

- No limits in the region 80 GeV $< m_{H^\pm} <$ 89 GeV
- LEP2 only partially covered 80 GeV $< m_{H^\pm} <$ 89 GeV

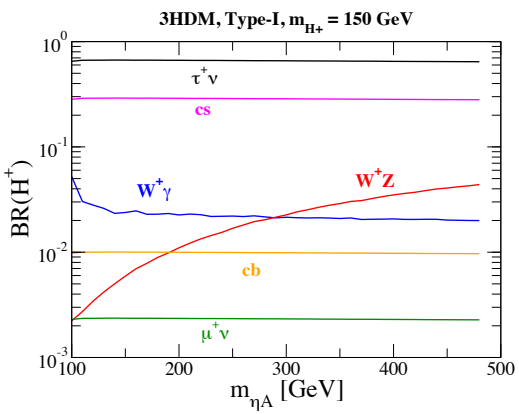
slide from A. Akeroyd

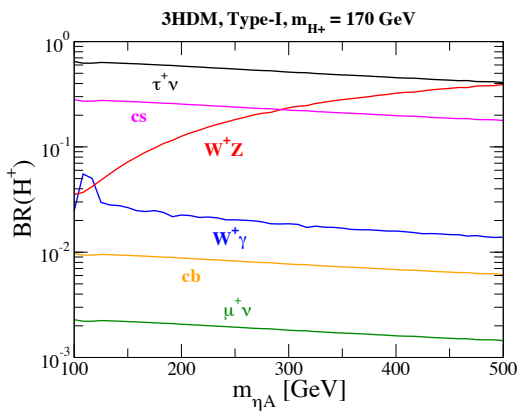
Requests completed

2. BR($H^\pm \to W^\pm\gamma$) can be large in some versions of the 3HDM, GM and 2HDM+VLQ but mainly in mass regions where the channel $H^\pm \to W^\pm Z$ is closed. Very tuned regions of the GM model allow for larger masses.

Arhrib, Benbrik, Chabab, JPG34 (2007) 907

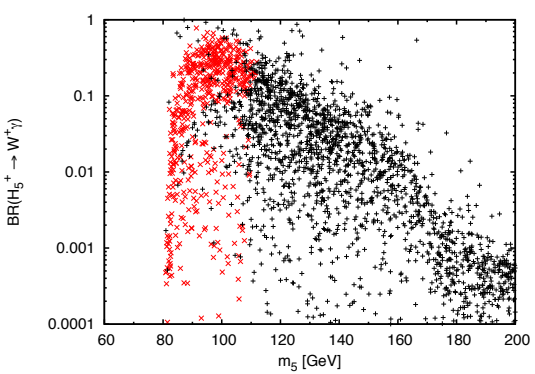
Moretti, Rojas, Yagyu, JHEP 1508 (2015) 116

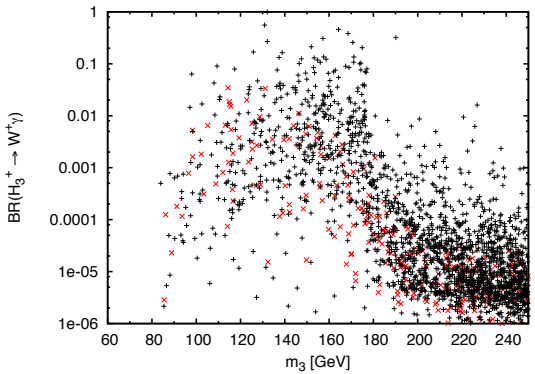


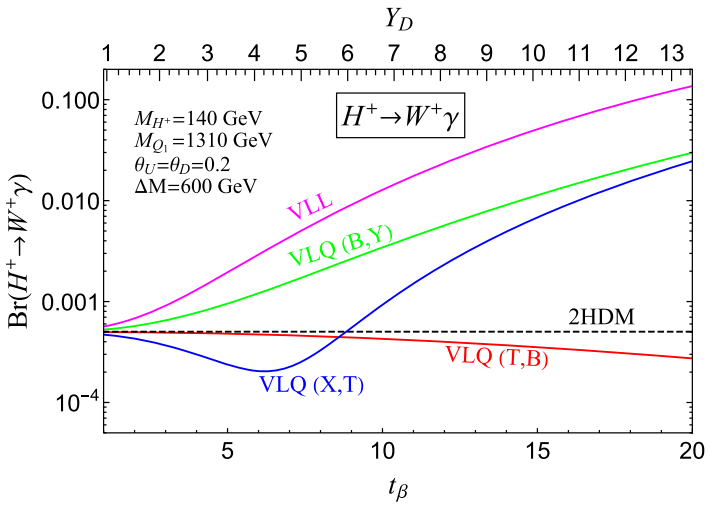


Large parameter space and weakest constraints; extra loops; or more extra loops and less loops.

Degrande, Hartling, Logan, PRD96 (2017) 075013





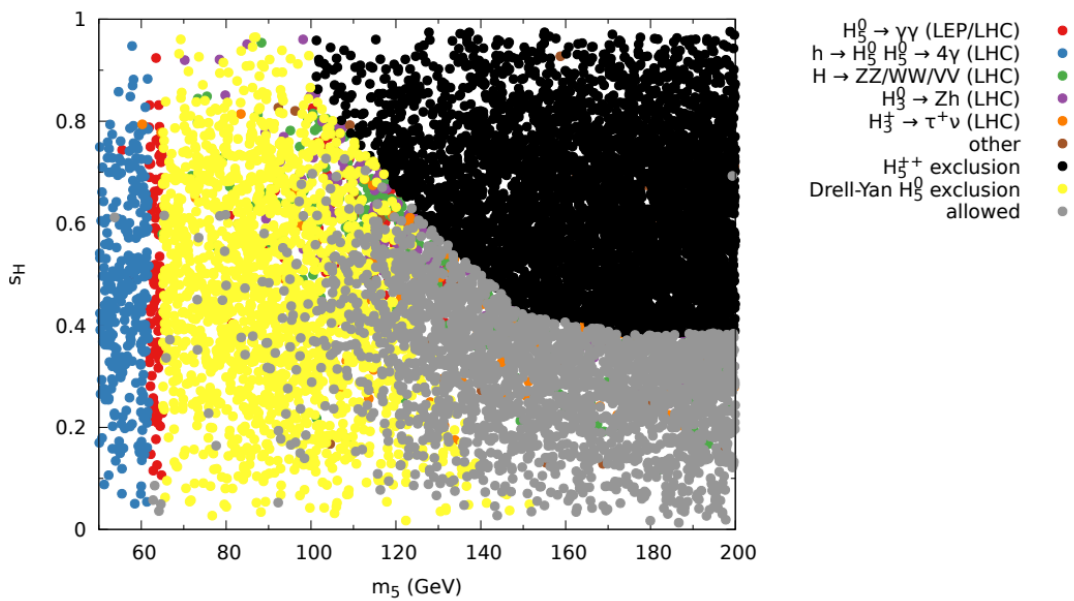


Song, Yoon, PRD100 (2019) 055006

Logan, Wu, JHEP 1811 (2018) 121

Requests completed

3. The search in $q\bar{q} \to H^{++}H^{--} \to 4W$ should be extended to the low charged Higgs mass region.



There is still plenty of parameter space to be explored in the low m5 mass region (updated recently).

Ismail, Logan, Wu, 2003.02272.

FIG. 10. Allowed parameter points (gray, plotted on top) from a general scan of 10,000 points with $m_5 \in [50, 200)$ GeV in the GM model. Points excluded by the ATLAS constraint on VBF $H_5^{\pm\pm}$ decaying to $W^\pm W^\pm$ [12, 32] are shown in black and points excluded by the constraint on Drell-Yan production of H_5^0 decaying to diphotons (see Section IV) are shown in yellow. The rest of the points shown in color are excluded by HiggsBounds 5.2.0 and come from Refs. [1, 2, 34, 37, 38, 40, 42, 43, 45–48, 50–54, 56, 57, 60–62].

If the search for H++ H-- -> 4W excludes the entire region of H5 masses below 200 GeV, the decay to Wgamma becomes uninteresting, because the custodial symmetry forces H5+ and H5++ degenerate.

Requests completed

4. The Interference effects between signal and background can be large if the ratio width to mass is large $pp \to tH^-(+\bar{t}H^+) \to tAW^- \to tW^-\bar{b}b$ (2HDM) or $pp \to \bar{b}tH^-(b\bar{t}H^+) \to \bar{t}t\bar{b}b$ (hMSSM). Increasingly important as analysis move up in mass, CMS (3TeV) and ATLAS (2TeV) - see Lidija talk, next.

- Studies generally model Signal and Background separately.
- The assumption that the Interference is small may not hold for some regions of the parameter space but it can be of the same order as signal, and sometimes negative.
- Interference is large mainly when width to mass ratio is large.

BP	Signal (pb)	Background (pb)	Total (pb)	Interference (pb)
BP1	0.031	10.03	9.96	-0.101
BP2	0.052	9.96	10.02	-0.008
BP3	0.144	10.07	10.18	0.034
BP4	0.469	9.94	10.31	-0.102
BP5	0.742	10.43	10.72	-0.452

TABLE V: Cross sections (in pb) for signal, background, total and interference for the BPs Type II and Flipped.

	$\tan\beta$	$\sin(\beta-\alpha)$	$m_{H^\pm}$ (GeV)	m_A (GeV)	m_{12}^2 (GeV^2)
BP1 (II)	10.25	0.98	509.14	248.27	52287.83
BP2 (II)	16.75	0.99	545.82	268.41	33622.43
BP3 (II)	18.80	0.99	457.71	247.22	16427.97
BP4 (F)	37.21	0.99	469.45	258.03	9800.68
BP5 (F)	44.10	1.00	519.45	288.32	10200.34

TABLE III: Type II and Flipped input parameters for the BPs.

	$\Gamma(A)$	$\Gamma(H^\pm)$	BR$(A \to b\bar{b})$	BR$(H^+ \to b\bar{t})$	BR$(H^+ \to W^+A)$
BP1 (II)	0.47	72.85	0.83	0.01	0.29
BP2 (II)	1.29	91.97	0.86	0.02	0.29
BP3 (II)	1.50	34.83	0.87	0.05	0.17
BP4 (F)	5.45	50.45	0.99	0.13	0.16
BP5 (F)	10.46	85.45	1.00	0.18	0.26

TABLE IV: Partial widths (in GeV) and BRs in Type II and Flipped for the BPs.

TABLE IX. Cut flow of the cross sections for signal (BP5 in the 2HDM flipped) and irreducible background at the 14 TeV LHC. Conjugate processes are included here.

	σ [fb]			
Cuts	Signal	Background	Total	Interference
C0: No Cuts	740	10 430	10 720	−450
C1: Only one lepton	115.0	1 116.2	1 151.2	−80.1
C2: At least five light jets	91.9	680.8	703.5	−69.2
C3: Cut on $H_T > 500$ GeV	70.8	173.8	173.6	−71.1

Each event in the analysis is assumed to be a tH^- event decaying to W^+W^-jjj and one hadronic and one leptonic W. Thus, each single event is considered to have at least one lepton, five jets, and missing transverse energy.

Arhrib, Benbrik, Moretti, RS, Sharma, PRD97 (2018) no.7, 075037

Arhrib, Azevedo, Benbrik, Harouiz, Moretti, Patrick, RS, JHEP 10 (2020) 209.

CODES

GMCALC
A calculator for the Georgi-Machacek model

Description:

The Georgi-Machacek model adds scalar triplets to the Standard Model Higgs sector in such a way as to preserve custodial SU(2) symmetry in the scalar potential. This allows the triplets to have a non-negligible vacuum expectation value while satisfying constraints from the rho parameter. Depending on the parameters, the 125 GeV neutral Higgs particle can have couplings to WW and ZZ larger than in the Standard Model due to mixing with the triplets. The model also contains singly- and doubly-charged Higgs particles that couple to vector boson pairs at tree level (WZ and like-sign WW, respectively).

GMCALC is a FORTRAN program that, given a set of input parameters, calculates the particle spectrum and tree-level couplings, checks theoretical and indirect constraints on the model, and computes the branching ratios and total widths of the scalars. It also generates a param_card.dat file for MadGraph5 (LO, NLO, and an EFT version) to be used with the corresponding FeynRules model implementations.

The full functionality of GMCALC v1.3.0 and higher requires an installation of the LoopTools package. There is an option to compile GMCALC v1.3.0 and higher without LoopTools; if this is done then the loop-induced decay widths of H_5^0 to Z gamma and H_3^+, H_5^+ to W^+ gamma will be set to zero.

Authors:

- Celine Degrande, Katy Hartling, Kunal Kumar, Heather E. Logan, Andrea D. Peterson, Mark B. Reimer, and Yongcheng Wu (v1.4.x)
- Celine Degrande, Katy Hartling, Kunal Kumar, Heather E. Logan, and Andrea D. Peterson (v1.3.x)
- Katy Hartling, Kunal Kumar, Heather E. Logan, and Andrea D. Peterson (v1.2.x)
- Katy Hartling, Kunal Kumar, and Heather E. Logan (v1.0.x, 1.1.x)

Downloads:

- GMCALC v1.4.1 (.tar.gz, includes manual and changes log)
- Manual (pdf)
- Log of changes (txt)

If you use this program to write a paper, please cite:

- K. Hartling, K. Kunal, and H. E. Logan, "GMCALC: a calculator for the Georgi-Machacek model," arXiv:1412.7387 [hep-ph] [InSPIRE record].

The physics that went into this code is described in more detail in the following references:

- K. Hartling, K. Kunal, and H. E. Logan, "The decoupling limit in the Georgi-Machacek model," Phys. Rev. D 90, 015007 (2014) [arXiv:1404.2640 [hep-ph]] [InSPIRE record].
- K. Hartling, K. Kunal, and H. E. Logan, "Indirect constraints on the Georgi-Machacek model and implications for Higgs couplings," Phys. Rev. D 91, 015013 (2015) [arXiv:1410.5538 [hep-ph]] [InSPIRE record].
- C. Degrande, K. Hartling, and H. E. Logan, "Scalar decays to gamma gamma, Z gamma, and W gamma in the Georgi-Machacek model," Phys. Rev. D 96, 075013 (2017) [arXiv:1708.08753 [hep-ph]] [InSPIRE record].

Requests and bug reports:

Contact Heather Logan at logan@physics.carleton.ca.

http://people.physics.carleton.ca/~logan/gmcalc/

HDECAY and its variations

- **Based on implementation of new models in HDECAY (includes SM, MSSM and 2HDM)**

- **Stand-alone codes with inclusion of relevant QCD corrections and off-shell decays. EW corrections turned off.**

Djouadi, Kalinowski, Spira, CPC 108 (1998) 56.
Djouadi, Kalinowski, Mühlleitner, Spira, CPC 238 (2019) 214.

sHDECAY (http://www.itp.kit.edu/~maggie/sHDECAY/)

- Real singlet + SM in symmetric (dark) phase, RxSM-dark: 1 Higgs + 1 Dark
- Real singlet + SM in broken phase, RxSM-broken: 1 mixing Higgs
- Complex singlet + SM in symmetric phase, CxSM-dark: 2 mixing Higgs + 1 Dark
- Complex singlet + SM in broken phase, CxSM-broken: 3 mixing Higgs

Costa, Mühlleitner, Sampaio, RS, JHEP 06 (2016) 034.

HDECAY and its variations

N2HDECAY (CP-conserving) (http://www.itp.kit.edu/~maggie/N2HDECAY/) and (https://gitlab.com/jonaswittbrodt/N2HDECAY)

- 2HDM + real singlet in broken phase (dark) phase, 3 CP-even, 1 CP-odd, 1 Charged scalar
- 2HDM + real singlet in unbroken phase (singlet DM), 2 CP-even, 1 CP-odd, 1 Charged, 1DM
- 2HDM + real singlet in unbroken phase (IDM+singlet), 2 CP-even + IDM

Mühlleitner, Sampaio, RS, Wittbrodtm JHEP 1703 (2017) 094.

Engeln, Mühlleitner, Wittbrodt CPC 234 (2019), 256.

C2HDECAY (http://www.itp.kit.edu/~maggie/C2HDM/)

- CP-violating 2HDM: 3 CP-mixed scalars, 1 charged Higgs pair

Mühlleitner, Romão, RS, Silva, Wittbrodt, JHEP 180206 (2018) 073.

More decays

2HDECAY (CP-conserving) EW corrections to 2HDM scalar decays in different gauge independent renormalisation schemes (https://github.com/marcel-krause/2HDECAY)

Krause, Mühlleitner, Spira, CPC 246 (2020) 106852.

Altenkamp, Dittmaier, Rzehak, JHEP 09 (2017) 134.

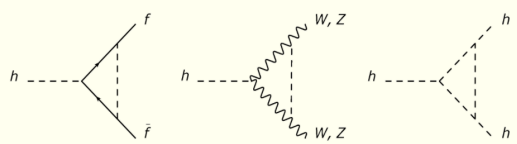
Denner, Dittmaier, Lang, JHEP 11 (2018) 104.

ewN2HDECAY (CP-conserving) EW corrections in the broken N2HDM in different gauge independent renormalisation schemes (https://github.com/marcel-krause/ewN2HDECAY)

Krause, Mühlleitner, 1904.02103.

anyHDECAY (Wittbrodt) Modern C++17 library that wraps the non-supersymmetric HDECAY variants (https://gitlab.com/jonaswittbrodt/anyhdecay)

H-COUP



(http://www-het.phys.sci.osaka-u.ac.jp/~hcoup/)

NEW!! H-COUP version 2.3 was released (30 Apr. 2020)

H-COUP version 2 (1 Sep. 2019) is a calculation tool composed of a set of Fortran codes to compute the Higgs boson decay rates and the branching ratios with radiative corrections (NNLO for QCD and NLO for EW) in various non-minimal Higgs models, such as the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model. H-COUP ver. 2 contains all the functions in H-COUP ver. 1.

Authors:
Shinya Kanemura, Mariko Kikuchi, Kentarou Mawatari, Kodai Sakurai and Kei Yagyu

The manual for H-COUP version 2 can be taken on arXiv:1910.12769 [hep-ph].

2HDMC

2HDMC is a general-purpose calculator for the two-Higgs doublet model. It allows parametrization of the Higgs potential in many different ways, convenient specification of generic Yukawa sectors, the evaluation of decay widths (including higher-order QCD corrections), theoretical constraints and much more.

2HDMC material

- Latest version
- Physics and Manual

  2HDMC - Two-Higgs-Doublet Model Calculator
  D. Eriksson, J. Rathsman, O. Stål
  Comput.Phys.Commun.181:189-205 (2010);
  Comput.Phys.Commun.181:833-834 (2010)
  [arXiv:0902.0851]

Recommendations for evaluation of Higgs production cross sections and branching ratios at the LHC in the 2HDM
R. Harlander, M. Mühlleitner, J. Rathsman, M. Spira, O. Stål
[arXiv:1312.5571]

Release history

1.8.0	2020-02-10	Included new interface for HiggsBounds/HiggsSignals. [Thanks to J. Wittbrodt]. Added get_yukawas_type() and modified write_LesHouches() to work with HB/HS [Thanks to J. Wittbrodt]. Updated code to C++11 [Thanks to J. Wittbrodt]. Corrected sorting in hhh and hhhh couplings. Corrected so that massive corrections for hqq are only applied for equal masses. Clean-up of obsolete features.

ScannerS

ScannerS alows general scalar potential with automatic:

- Analysis of tree level local minimum/stability
- Detection of tree level scalar spectrum and mixing
- Tree level unitarity test

Interfaces to:

- HDECAY, sHDECAY, N2HDECAY, C2HDECAY
- HiggsBounds/Signals (collider bounds/measurements)
- micrOMEGAS (dark matter observables)
- SusHi (+ internal numerical tables for gluon fusion)
- SuperIso (flavour physics observables)

User/model defined functions to:

- Check boundedness from below
- Check global stability
- Implement phenomenological analysis for each point

- Real and Complex Scalar Singlet Extensions:
  R. Costa, M. Mühlleitner, M.O.P. Sampaio, R. Santos, JHEP 1606 (2016) 034 + see YR4
  R. Coimbra, M.O.P. Sampaio, R. Santos, EPJ C73 (2013) 2428
  R. Costa, A. Morais, M.O.P. Sampaio, R. Santos, Phys.Rev. D92 (2015) 2, 025024
  - **RxSM-dark**: 1 Higgs + 1 Dark ($\mathbb{Z}_2$)
  - **RxSM-broken**: 2 Higgs mixing ($\mathbb{Z}_2$ spont.broken)
  - **CxSM-dark**: 2 Higgs mixing + 1 Dark
  - **CxSM-broken**: 3 Higgs mixing

  New: Input files allow *Scan* or *Check* point mode.
  see → *How to run scalar singlet extensions in ScannerS* (`indico.cern.ch/event/640710`)
- Scalar Doublet Extensions
  - **2HDM**: *Scan* or *Check* point modes available.
    P.M. Ferreira, R. Guedes, M.O.P. Sampaio, R. Santos, JHEP 12 (2014) 067
  - **N2HDM-broken**: 2HDM + Real singlet $\mathbb{Z}_2$ spont. broken. *Scan* mode (*Check* mode available soon . . .)
    M.M. Mühlleitner M.O.P. Sampaio, R. Santos, J. Wittbrodt, JHEP 1703 (2017) 094
  - **N2HDM-dark**: 2HDM + Real singlet $\mathbb{Z}_2$ (under dev.)
  - **C2HDM**: .
    M.M. Mühlleitner M.O.P. Sampaio, R. Santos, J. Wittbrodt, arXiv:1703.07750

Coimbra, Sampaio, RS, EPJ C73 (2013) 2428.

Recent developments: improvement of performance; simplified installation with automatic dependency management

(https://jonaswittbrodt.gitlab.io/ScannerS/)

Mühlleitner, Sampaio, RS, Wittbrodt, 2007.02985.

HPAIR

HPAIR (SPIRA) SM and MSSM, $gg, qq \to hh, HH, AA, hH, hA, HA$ (http://tiger.web.psi.ch/hpair/)

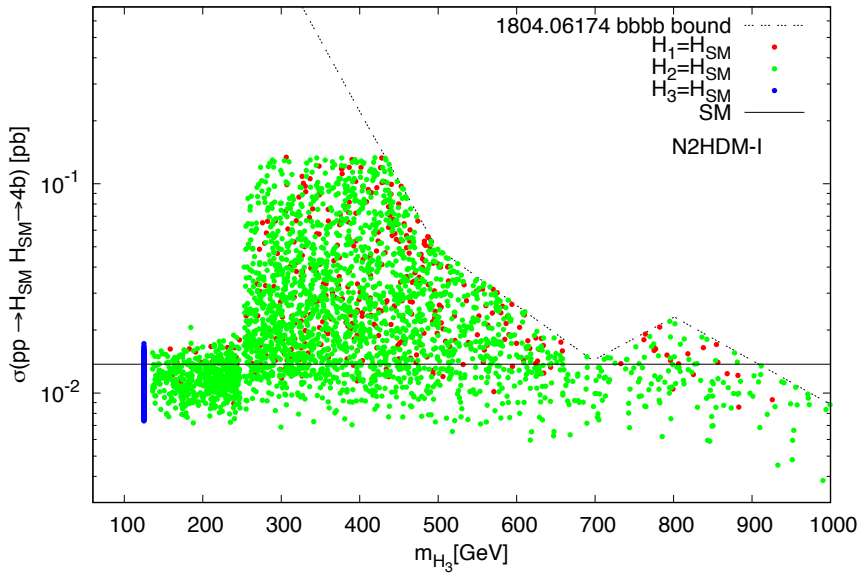
NMSSM version (private)

Baglio, Dao, Gröber, Mühlleitner, Rzehak, EPJ Web Conf. 49 (2013) 12001.

C2HDM version (private)

Gröber, Mühlleitner, Spira, NPB925 (2017) 1.

2HDM and N2HDM versions (private) Mühlleitner



See Maggie's talk tomorrow at 14.20

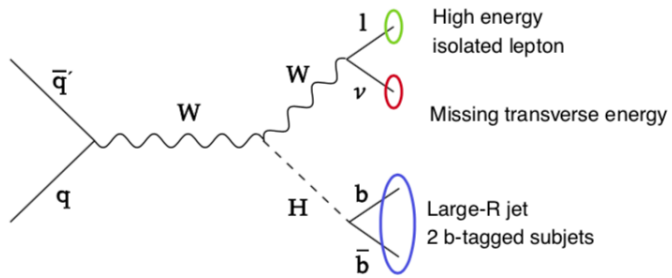
Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, Mühlleitner, RS, work in progress.

CP numbers of the discovered Higgs (WWh and ZZh)

Term coming from a CPV operator.
Contribution from the SM at 2-loop

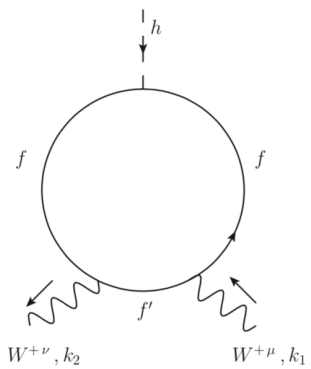
$$\mathcal{M}(hW^+W^-) \sim a_1^{W^+W^-} m_W^2 \epsilon^*_{W^+} \epsilon^*_{W^-} + a_3^{W^+W^-} f^*_{\mu\nu} \tilde{f}^{*-\mu\nu}$$

Term in the SM at tree-level
but also in models with CP-violation



$$\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}} \in [-0.81, 0.31]$$

Present experimental bound
from ATLAS and CMS



complex 2-Higgs doublet model

$$c_{\rm CPV}^{\rm C2HDM} \simeq 6.6 \times 10^{-4} \sim \mathcal{O}(10^{-3})$$

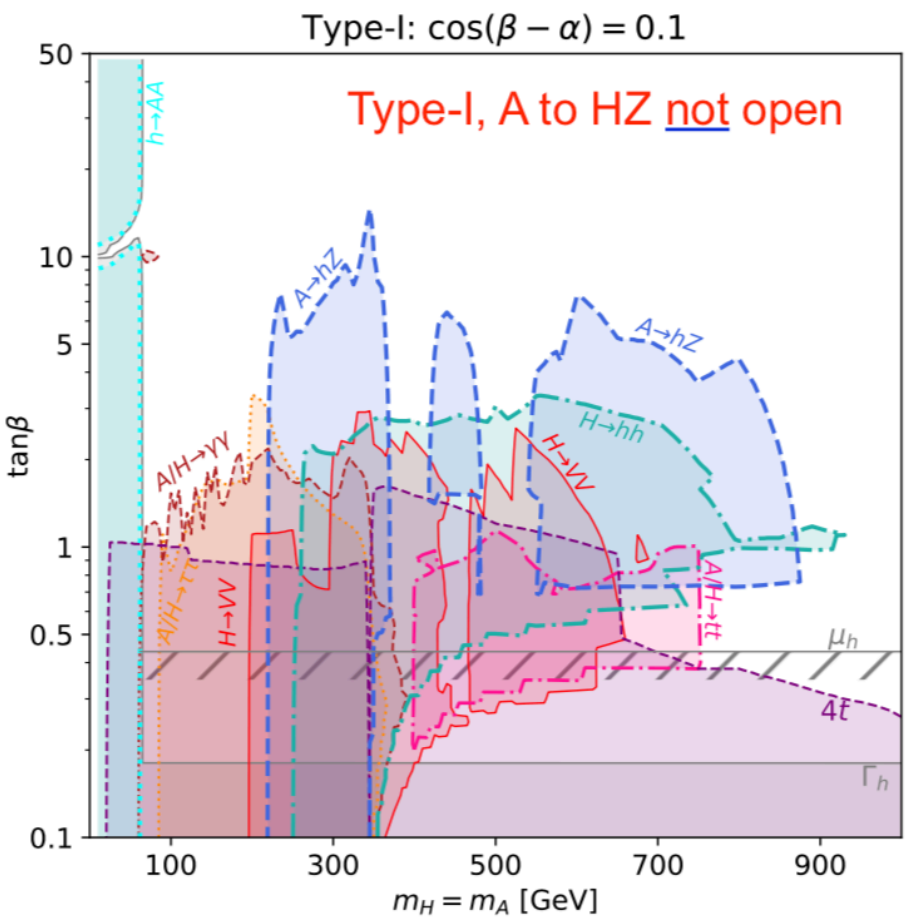
$$c_{\rm CPV} = 2\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}}$$

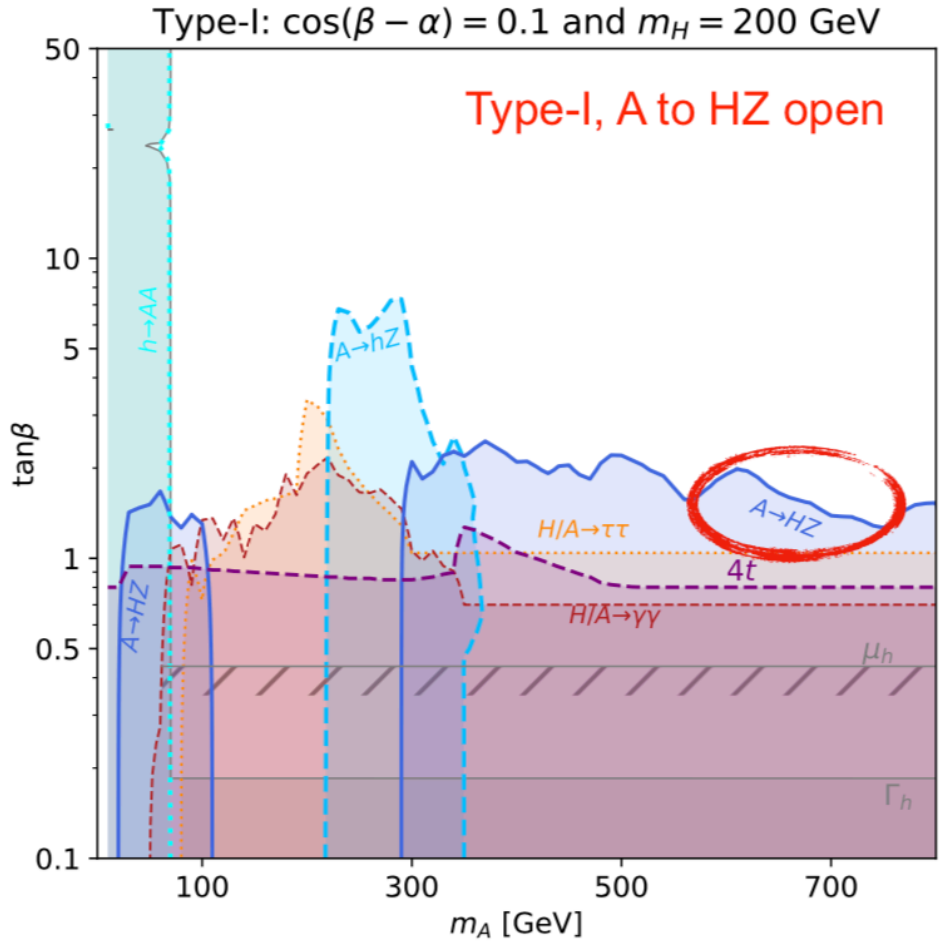
$$c_{\rm CPV}^{\rm C2HDM} = \frac{N_c g^2}{32\pi^2}|V_{tb}|^2 \left[\frac{c_t^o m_t^2}{m_W^2} \mathcal{I}_1\left(\frac{m_t^2}{m_W^2}, \frac{m_b^2}{m_W^2}\right) + \frac{c_b^o m_b^2}{m_W^2} \mathcal{I}_1\left(\frac{m_b^2}{m_W^2}, \frac{m_t^2}{m_W^2}\right) \right]$$

Huang, Morais, RS, 2009.09228.

2HDM Neutral Scalars @ LHC

Kling, Su, Su, 2004.04172.

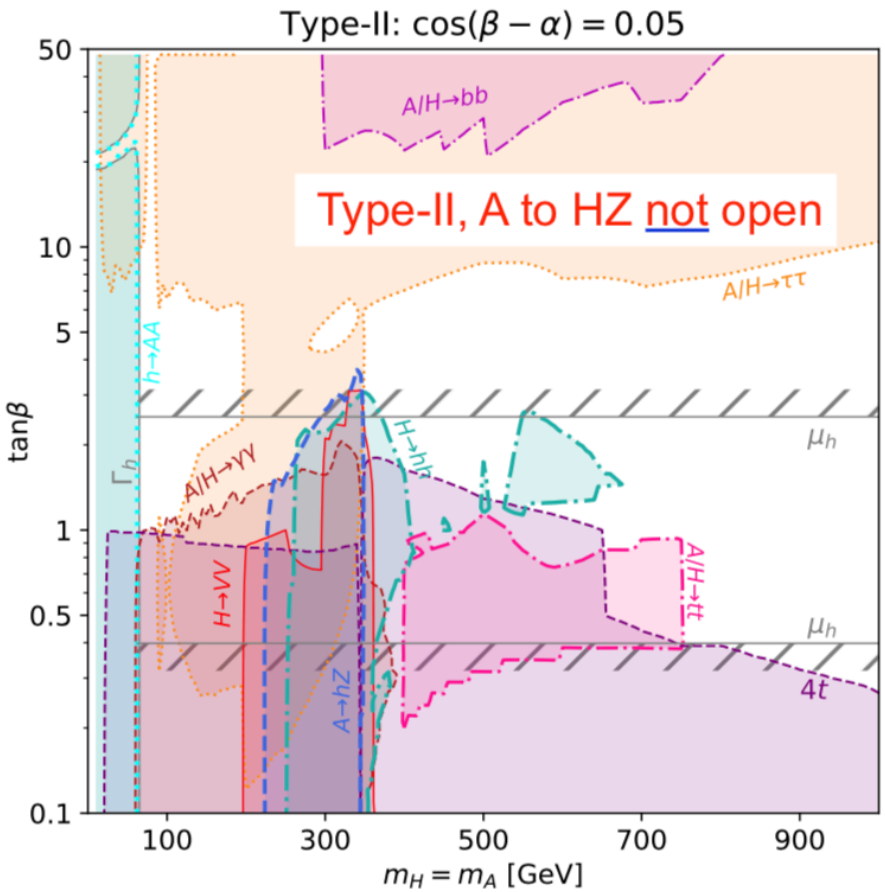


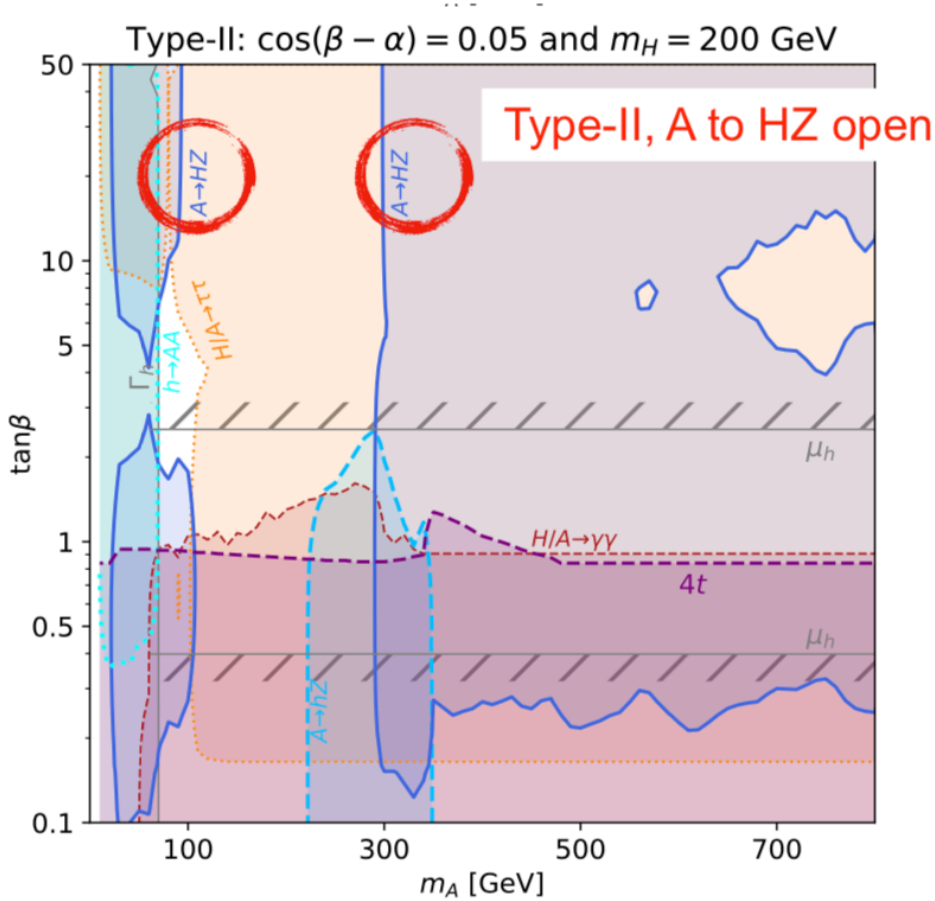


comparison of degenerate mass mA = mH (no A to HZ) case — left plot, and A to HZ open case — right plot. Large TB region is still allowed given the suppression of all Yukawa couplings at large TB. resent experimental bound from atlas and cms

2HDM Neutral Scalars @ LHC

Kling, Su, Su, 2004.04172.

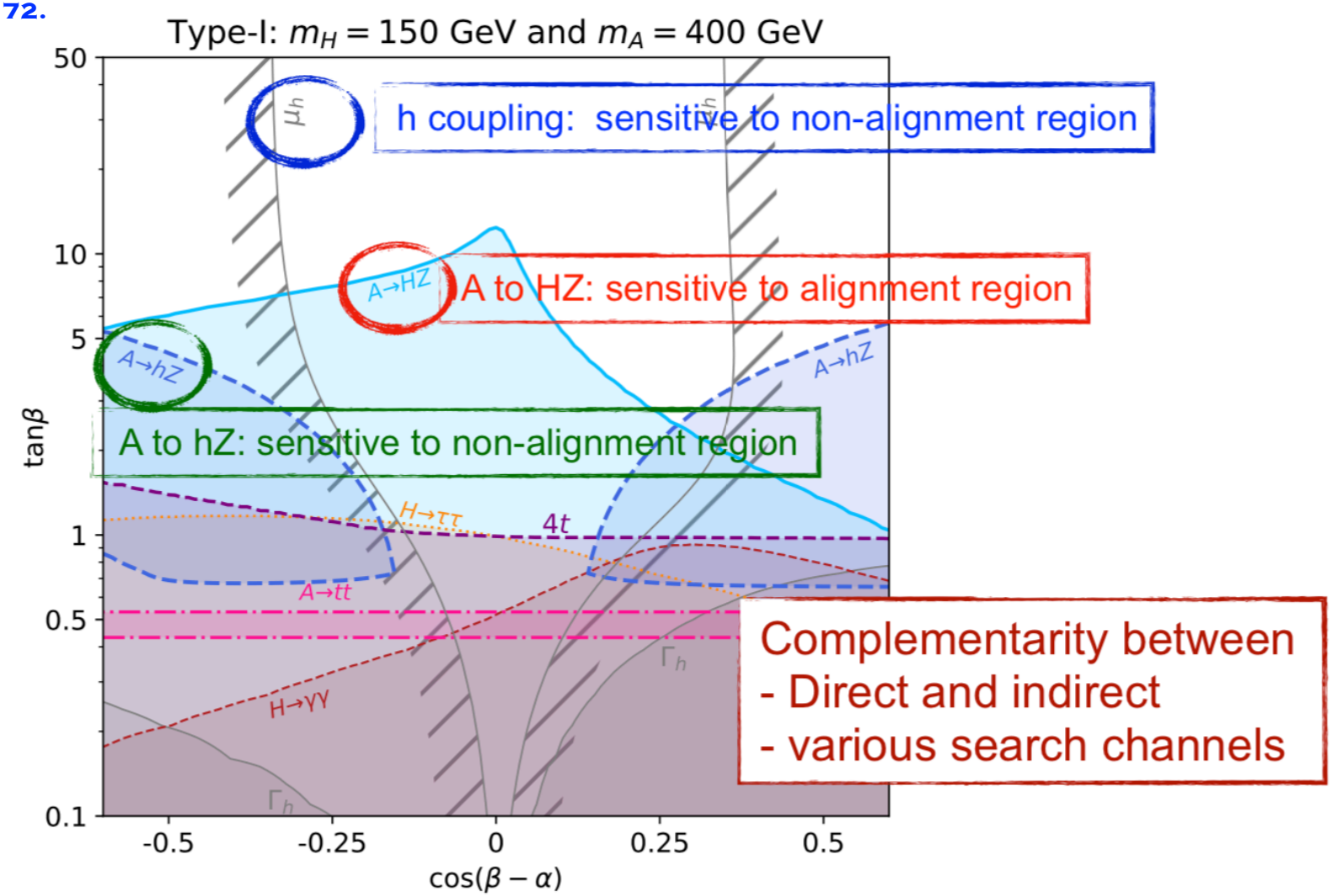




Type II - Exclusion is much stronger

2HDM Neutral Scalars @ LHC

Kling, Su, Su, 2004.04172.



complementarity between direct/indirect (Higgs coupling), and various direct search channels. In Type II for the same choice of parameters the whole region is excluded.

The Future

Meeting in the beginning of February 2021 - Tools for extended scalars - production and decays of the scalars in the models

Call in the end of November 2020

Meeting in the beginning of April 2021 - new call for benchmarks and look at interferences in more detail

Call in the middle of February 2021

Thank you!