

# Charged Higgs Online workshop

Monday, 30 August 2021 - Tuesday, 31 August 2021



## Book of Abstracts



# Contents

Discussion . . . . .	1
Charged Higgs-Talk-1 . . . . .	1
Charged Higgs-Talk-2 . . . . .	1
Charged Higgs-Talk-3 . . . . .	1
Charged Higgs-Talk-4 . . . . .	1
Charged Higgs-Talk-5 . . . . .	1
Charged Higgs-Talk-6 . . . . .	1
Session-1 . . . . .	1
Session-2 . . . . .	2
Parallel session-1 . . . . .	2
Parallel session-2 . . . . .	2
B meson processes within a 2HDM-III . . . . .	2
New Discovery Modes for a Light Charged Higgs Boson at the LHC . . . . .	2
The analysis of $W + 4\gamma$ in the 2HDM type-I at the LHC . . . . .	3
CP-violation of charged Higgs in 3HDM CP asymmetries of $\bar{B} \rightarrow X_s/X_d\gamma$ in models with three Higgs doublets and the constraints from the electric dipole moments(EDMs) . . . . .	3
The forgotten charged Higgs decay mode at the LHC. . . . .	4
Phenomenology of Charged Higgs . . . . .	4
Discussion (All) . . . . .	4
CMS overview of singly- and doubly-charged Higgs bosons . . . . .	5
ATLAS overview of singly- and doubly-charged Higgs bosons . . . . .	5
Extended Higgs sector at present and future colliders . . . . .	5
Discussion . . . . .	5
The muon $g-2$ in an Aligned 2-Higgs Doublet Model with Right-Handed Neutrinos . . . . .	5

Indirect Searches for Charged Higgs . . . . .	6
B meson processes whitin a 2HDM-III . . . . .	6
Summary of the talks . . . . .	6
Summary of the brainstorming . . . . .	6
New Discovery Modes for a Light Charged Higgs Boson at the LHC . . . . .	6
The analysis of $W + 4\gamma$ in the 2HDM type-I at the LHC . . . . .	6
B meson processes whitin a 2HDM-III . . . . .	7
The muon $g-2$ in an Aligned 2-Higgs Doublet Model with Right-Handed Neutrinos . . . .	7
CP-violation of charged Higgs in 3HDM CP asymmetries of $\bar{u}d \rightarrow \bar{u}d/\bar{u}u$ in models with three Higgs doublets and the constraints from the electric dipole moments(EDMs) . . .	7
Charged Higgs boson decays with NLO corrections in the NMSSM . . . . .	7
The forgotten charged Higgs decay mode at the LHC . . . . .	7
Searches for $H^+$ to $cb$ in ATLAS . . . . .	8
Searches for $H^+$ to $AW$ in ATLAS . . . . .	8
Overview of searches for doubly-charged Higgs bosons and other exotic Higgs bosons at the LHC . . . . .	8
Overview of searches for exotic Higgs bosons at the LHC . . . . .	8
The muon $g-2$ in an Aligned 2-Higgs Doublet Model with Right-Handed Neutrinos . . . .	8
Discussion (All) . . . . .	8
Charged Higgs boson decays with NLO corrections in the NMSSM . . . . .	9
Announcement . . . . .	9
Session #4: Indirect Searches . . . . .	9
Charged Higgs and flavor . . . . .	9
B meson processes whitin a 2HDM-III . . . . .	9
The muon $g-2$ in an Aligned 2-Higgs Doublet Model with Right-Handed Neutrinos . . . .	9
Charged Higgs boson production via $cb$ -fusion at the Large Hadron Collider . . . . .	10
Charged Higgs boson production via $cb$ -fusion at the Large Hadron Collider . . . . .	10

**1**

**Discussion**

**2**

**Charged Higgs-Talk-1**

**3**

**Charged Higgs-Talk-2**

**4**

**Charged Higgs-Talk-3**

**5**

**Charged Higgs-Talk-4**

**6**

**Charged Higgs-Talk-5**

**7**

**Charged Higgs-Talk-6**

**8**

**Session-1**

9

**Session-2**

10

**Parallel session-1****Corresponding Authors:** farida.fassi@cern.ch, apetrov@physics.wayne.edu

11

**Parallel session-2****Corresponding Authors:** mchabab@ucam.ac.ma, eva.halkiadakis@cern.ch

12

**B meson processes whitin a 2HDM-III****Author:** Melina Gomez Bock<sup>1</sup>**Co-authors:** Lao Tse López Lozano ; Octavio E. Hernandez Alvarez<sup>1</sup> *Universidad de las Américas Puebla***Corresponding Authors:** melina.gomez@udlap.mx, lao\_lopez@uaeh.edu.mx

In the SM the conservation of discrete symmetry of quark flavors is a key issue for the model, only through charged EW interactions flavor changing is permitted. Nevertheless, the current data of experiments have showed some B semileptonic decays non-universality for lepton families. This difference can not be accomplished by electroweak SM processes, since they are exactly the same for the three families. We explore the contributions of charged Higgs bosons to some B meson processes, in the context of an extended model, one extra scalar doublet, where both of the two Higgs doublets couple with both type of fermions, the 2HDM type III. We analyze these processes in order to establish the viability of the Type-III of the THDM contrasting with the experimental data of the B meson phenomenology.

13

**New Discovery Modes for a Light Charged Higgs Boson at the LHC****Author:** Mohamed Krab<sup>None</sup>**Co-authors:** Abdesslam Arhrib ; Rachid Benbrik ; Stefano Moretti ; Bouzid Manaut ; Yan Wang ; Qi-Shu Yan

**Corresponding Author:** med.krab@gmail.com

At the Large Hadron Collider (LHC), both the ATLAS and CMS Collaborations have been searching for light charged Higgs bosons via top (anti)quark production and decays channels, like  $pp \rightarrow t\bar{t}$  with one top (anti)quark decaying into a charged Higgs boson and a  $b$  (anti)quark, when the decay is kinematically open. In this talk, we propose new searches at the LHC involving light charged Higgs bosons via their pair production channels like  $pp \rightarrow H^\pm h/A$  and  $pp \rightarrow H^+ H^-$  in the 2-Higgs Doublet Model (2HDM) Type-I and -X scenarios. We demonstrate that for a light charged Higgs boson state, at the LHC, such di-Higgs production and their bosonic decays, such as  $H^\pm \rightarrow W^\pm h$  and/or  $H^\pm \rightarrow W^\pm A$ , can give rise to signatures with event rates much larger than those emerging from  $pp \rightarrow t\bar{t} \rightarrow t\bar{b}H^- + \text{c.c.}$ . We specifically study  $h/A \rightarrow b\bar{b}$  and  $\tau^+\tau^-$  decays. We, therefore, claim that the discussed combination of new production and decay modes can result in an alternative discovery channel for charged Higgs bosons lighter than the top (anti)quark at the LHC within the above two 2HDM Types. This talk is based on arXiv:2106.13656.

14

## The analysis of $W + 4\gamma$ in the 2HDM type-I at the LHC

**Authors:** Abdesslam Arhrib<sup>1</sup>; Qi-Shu Yan<sup>2</sup>; Stefano Moretti<sup>3</sup>; Yan Wang<sup>4</sup>; B. Manaut<sup>None</sup>; Rachid Benbrik<sup>5</sup>; mohamed krab<sup>None</sup>

<sup>1</sup> *U*

<sup>2</sup> *University of Chinese Academy of Sciences*

<sup>3</sup> *Science and Technology Facilities Council STFC (GB)*

<sup>4</sup> *Deutsches Elektronen-Synchrotron (DESY), Institute of High Ener*

<sup>5</sup> *Cadi Ayyad University*

**Corresponding Authors:** yanqishu@ucas.ac.cn, yan.wang@desy.de, r.benbrik@uca.ac.ma, mohamed.krab@usms.ac.ma, b.manaut@usms.ma, stefano.moretti@cern.ch, arhrib@gmail.com

This talk is based on arXiv:2107.01451.

In this work, we analyze a light charged Higgs boson in the 2-Higgs Doublet Model (2HDM) Type-I, when its mass satisfies the condition  $M_{H^\pm} < M_t + M_b$  and the parameter space is consistent with theoretical requirements of self-consistency as well as the latest experimental constraints from Large Hadron Collider (LHC) and other data. Over such a parameter space, wherein the Standard Model (SM)-like state discovered at the LHC in 2012 is the heaviest CP-even state of the 2HDM, it is found that the decay modes of the charged Higgs boson are dominated by  $H^\pm \rightarrow W^{\pm(*)}h$ .

Furthermore, the light neutral Higgs boson  $h$  dominantly decays into two photons. Under these conditions, we find that the production and decay process  $pp \rightarrow H^\pm h \rightarrow W^{\pm(*)}hh \rightarrow \ell\nu_\ell + 4\gamma$  ( $\ell = e, \mu$ ) is essentially background free. However, since the  $W^{\pm(*)}$  could be largely off-shell and the  $h$  state is very light, so that both the lepton coming from the former and the photons coming from the latter could be rather soft, we perform here a full Monte Carlo (MC) analysis at the detector level demonstrating that such a  $W^\pm + 4\gamma$  signal is very promising, as it would be yielding significant excesses at the LHC with an integrated luminosity of  $L = 300 \text{ fb}^{-1}$  at both  $\sqrt{s} = 13$  and 14 TeV.

16

## CP-violation of charged Higgs in 3HDM CP asymmetries of $\bar{B} \rightarrow X_s/X_d\gamma$ in models with three Higgs doublets and the constraints from the electric dipole moments(EDMs)

**Authors:** Andrew Akeroyd<sup>1</sup>; Stefano Moretti<sup>2</sup>; Tetsuo Shindou<sup>3</sup>; Muyuan Song<sup>1</sup>; Heather Logan<sup>4</sup>; Diana Rojas-Ciofalo<sup>5</sup>

<sup>1</sup> *University of Southampton*

<sup>2</sup> *University of Southampton*

<sup>3</sup> *Kogakuin University*

<sup>4</sup> *Carleton University*

<sup>5</sup> *National Centre for Nuclear Research, Warsaw*

**Corresponding Authors:** shindou@cc.kogakuin.ac.uk, diana.rojas-ciofalo@ncbj.gov.pl, logan@physics.carleton.ca, ms32g13@soton.ac.uk, a.g.akeroyd@soton.ac.uk

This talk contains two research papers, arXiv: 2009.05779 [hep-ph] and 2012.08846 [hep-ph]. We investigated the general two  $Z_2$  symmetry three-Higgs-doublet model (3HDM) with two experiment constraints,  $\bar{B} \rightarrow X_s \gamma$  and electric dipole moment (EDM) when CP-violation appear in charged Higgs sector.

Direct CP asymmetries ( $calA_{CP}$ ) in the inclusive decays of  $\bar{B} \rightarrow X_s \gamma$  and  $\bar{B} \rightarrow X_{s+d} \gamma$  of the order of 1% will be probed at the BELLE II experiment. In this work, three such asymmetries are studied in the context of a 3HDM, and it is shown that all three  $calA_{CP}$  can be as large as the current experimental limits. Of particular interest is  $calA_{CP}$  for  $\bar{B} \rightarrow X_{s+d} \gamma$ , which is predicted to be effectively zero in the Standard Model (SM). A measurement of 2.5% or more for this observable with the full BELLE II data would give  $5\sigma$  evidence for physics beyond the SM. We display parameter space in the 3HDM for which such a clear signal is possible. Furthermore, We demonstrate a new type of cancellation of contributions to the electron and neutron EDMs that occurs in 3HDM. The cancellation becomes exact when the two physical charged Higgs bosons in the model are degenerate in mass.

18

## The forgotten charged Higgs decay mode at the LHC.

**Author:** Rachid Benbrik<sup>1</sup>

<sup>1</sup> *Cadi Ayyad University*

**Corresponding Author:** r.benbrik@uca.ac.ma

In this talk, I will carry out a new (standard) decay mode of charged Higgs decays in the 2-Higgs Doublet Model (2HDM) type-3 and type-1 at the Large Hadron Collider (LHC). Starting from the most recent experimental results (SM-like Higgs boson signal strengths and search limits for new Higgs boson states obtained at Run-1 and -2 of the LHC and previous colliders), from (both direct and indirect) searches for Supersymmetric particles as well as from flavor observable and upon enforcing theoretical constraints (vacuum stability, perturbativity, unitarity). I will present and discuss standard inverted hierarchy situation where light CP-even Higgs fixed at 96GeV, together with light charged Higgs below than top mass can be realized only in type-3. New signatures and benchmarks are suggested.

Session #1 / 19

## Phenomenology of Charged Higgs

**Corresponding Author:** michael.spira@psi.ch

Session #1 / 20



## Discussion (All)

Session #2 (20' talk + 5' questions) / 21

### CMS overview of singly- and doubly-charged Higgs bosons

Corresponding Author: marina.kolosova@cern.ch

Session #2 (20' talk + 5' questions) / 22

### ATLAS overview of singly- and doubly-charged Higgs bosons

Corresponding Author: lironbarak83@gmail.com

Session #3 / 23

### Extended Higgs sector at present and future colliders

Corresponding Author: haber@scipp.ucsc.edu

Session #3 / 24

## Discussion

25

### The muon $g-2$ in an Aligned 2-Higgs Doublet Model with Right-Handed Neutrinos

Authors: Luigi Delle Rose<sup>1</sup>; Shaaban Khalil Ibrahim<sup>2</sup>; Stefano Moretti<sup>3</sup>

<sup>1</sup> *University of Florence*

<sup>2</sup> *ENHEP Egyptian Network of High Energy Physics (EG)*

<sup>3</sup> *University of Southampton*

Corresponding Authors: luigi.dellerose@fi.infn.it, shaaban.khalil@cern.ch

We explain anomalies currently present in various data samples used for the measurement of the anomalous magnetic moment of electron ( $a_e$ ) and muon ( $a_\mu$ ) in terms of an Aligned 2-Higgs Doublet Model with right-handed neutrinos. The explanation is driven by one and two-loop topologies wherein a very light CP-odd neutral Higgs state ( $A$ ) contributes significantly to  $a_\mu$  but negligibly to  $a_e$ , so as to revert the sign of the new physics corrections in the former case with respect to the latter, wherein the dominant contribution is due to a charged Higgs boson ( $H^\pm$ ) and heavy neutrinos with mass at the electroweak scale. For the region of parameter space of our new physics model which

explains the aforementioned anomalies we also predict an almost background-free smoking-gun signature of it, consisting of  $H^\pm A$  production followed by Higgs boson decays yielding multi- $\tau$  final states, which can be pursued at the Large Hadron Collider.

**Session #4: Indirect Searches / 26**

## **Indirect Searches for Charged Higgs**

**Corresponding Author:** sgori@perimeterinstitute.ca

(25' talk + 5' questions)

**Session #4: Indirect Searches / 27**

## **B meson processes within a 2HDM-III**

**Corresponding Author:** melina.gomez@udlap.mx

**Session #5 / 28**

## **Summary of the talks**

**Corresponding Author:** ketevi.adikle.assamagan@cern.ch

**Session #5 / 29**

## **Summary of the brainstorming**

**Corresponding Author:** kamal.benslama@gmail.com

**Parallel session-2 (15' talk + 2' questions) / 30**

## **New Discovery Modes for a Light Charged Higgs Boson at the LHC**

**Corresponding Author:** mohamed.krab@usms.ac.ma

**Parallel session-2 (15' talk + 2' questions) / 31**

## **The analysis of $W + 4\gamma$ in the 2HDM type-I at the LHC**

**Corresponding Author:** yan.wang@desy.de

Parallel session-2 (15' talk + 2' questions) / 32

## B meson processes within a 2HDM-III

Corresponding Author: melina.gomez@udlap.mx

Parallel session-2 (15' talk + 2' questions) / 33

## The muon $g-2$ in an Aligned 2-Higgs Doublet Model with Right-Handed Neutrinos

Corresponding Author: luigi.dellerose@fi.infn.it

Parallel session-2 (15' talk + 2' questions) / 34

## CP-violation of charged Higgs in 3HDM CP asymmetries of $\mu \rightarrow e \gamma$ in models with three Higgs doublets and the constraints from the electric dipole moments (EDMs)

Corresponding Author: ms32g13@soton.ac.uk

35

## Charged Higgs boson decays with NLO corrections in the NMSSM

Authors: Thi Nhung Dao<sup>1</sup>; Milada Margarete Muehleitner<sup>None</sup>; Shruti Patel<sup>2</sup>; Kodai Sakurai<sup>3</sup>

<sup>1</sup> ICISE

<sup>2</sup> Karlsruhe institute of Technology

<sup>3</sup> Tohoku University

Corresponding Authors: dtnhung2008@gmail.com, kodai.sakurai.e3@tohoku.ac.jp, milada.muehleitner@kit.edu

Indirect searches for new particles become increasingly important since no direct sign of new particles has been observed so far.

Accurate theoretical predictions are inevitable in order to be able to indirectly find new physics and also to identify the underlying model in case of discovery.

In this study, we calculated the full one-loop corrections to the decay widths of charged Higgs boson decays

in the framework of the Next-to-Minimal Supersymmetric Model (NMSSM) with CP violation.

In this talk, we discuss the impact of the NLO corrections on the charged Higgs branching ratios in a wide range of the parameter space that is compatible with the experimental constraints.

Parallel session-1 (15' talk + 2' questions) / 36

## The forgotten charged Higgs decay mode at the LHC

**Corresponding Author:** r.benbrik@uca.ac.ma

**Parallel session-1 (15' talk + 2' questions) / 37**

## **Searches for $H^+$ to $cb$ in ATLAS**

**Corresponding Author:** chen.peng@cern.ch

**Parallel session-1 (15' talk + 2' questions) / 38**

## **Searches for $H^+$ to $AW$ in ATLAS**

**Corresponding Author:** waleed.syed.ahmed@cern.ch

39

## **Overview of searches for doubly-charged Higgs bosons and other exotic Higgs bosons at the LHC**

**Author:** Jana Schaarschmidt<sup>1</sup>

<sup>1</sup> *University of Washington (US)*

**Corresponding Author:** jana.schaarschmidt@cern.ch

Many extensions of the Standard Model introduce additional Higgs-like bosons as well as exotic decays of the 125 GeV Higgs boson. The current status of searches by ATLAS and CMS for doubly-charged Higgs bosons, additional neutral Higgs bosons and non-SM decays of the 125 GeV scalar particle, based on the LHC Run 2 dataset, are presented.

**Session #3 / 40**

## **Overview of searches for exotic Higgs bosons at the LHC**

**Corresponding Author:** jana.schaarschmidt@cern.ch

**Session #4: Indirect Searches / 41**

## **The muon $g-2$ in an Aligned 2-Higgs Doublet Model with Right-Handed Neutrinos**

**Corresponding Author:** l.delle-rose@soton.ac.uk

**Session #4: Indirect Searches / 42**

**Discussion (All)**

**Parallel session-1 (15' talk + 2' questions) / 43**

**Charged Higgs boson decays with NLO corrections in the NMSSM**

**Corresponding Author:** kodai.sakurai.e3@tohoku.ac.jp

**Session #5 / 44**

**Announcement**

**Corresponding Authors:** farida.fassi@cern.ch, ketevi.adikle.assamagan@cern.ch, kamal.benslama@gmail.com

45

**Session #4: Indirect Searches**

**Corresponding Author:** hassan.jawahery@cern.ch

**Session #4: Other Charged Higgs Searches / 46**

**Charged Higgs and flavor**

**Corresponding Author:** goris@uchicago.edu

**Session #4: Other Charged Higgs Searches / 47**

**B meson processes whitin a 2HDM-III**

**Corresponding Author:** melina.gomez@udlap.mx

**Session #4: Other Charged Higgs Searches / 48**

**The muon  $g-2$  in an Aligned 2-Higgs Doublet Model with Right-Handed Neutrinos**

**Corresponding Author:** l.delle-rose@soton.ac.uk

## Charged Higgs boson production via $cb$ -fusion at the Large Hadron Collider

**Authors:** Carlos Honorato<sup>1</sup>; Sebastian Rosado Navarro<sup>None</sup>; Jaime Hernández-Sánchez<sup>2</sup>; Stefano Moretti<sup>3</sup>

<sup>1</sup> BUAP

<sup>2</sup> Benemérita Universidad Autónoma de Puebla

<sup>3</sup> University of Southampton

**Corresponding Authors:** carlos.g.honorato@correo.buap.mx, sebastian.rosado@protonmail.com, jaime.hernandez@correo.buap.mx

We analyze the production of a light charged Higgs boson at the Large Hadron Collider (LHC) via the quark-fusion mechanism  $cb^- \rightarrow H^-$  considering the decay channel  $H^- \rightarrow \tau\nu^- \tau$  in the final state. We study this process in the framework of the two-Higgs-doublet model type III (2HDM-III) which assumes a four-zero texture in the Yukawa matrices and a general Higgs potential, wherein the two Higgs doublets coupling to both up and down fermions do generate flavor-changing neutral currents, yet the latter can be controlled by the texture when flavor physics constraints are considered. We consider the parameter space of the model where this signal is enhanced and in agreement with both theoretical constraints and experimental data. In particular, we exploit the setup with lepton-specific-like Yukawa couplings and assess the LHC sensitivity to such  $H^\pm$  signals against the dominant irreducible and reducible backgrounds. We show that in our model  $BR(H^\pm \rightarrow cb) \sim 0.1 - 0.2$  and  $BR(H^\pm \rightarrow \tau\nu) \sim 0.7 - 0.9$  so that, under these conditions the prospects for  $H^\pm$  detection in the 2HDM-III in the aforementioned production and decay channels are excellent assuming standard collider energy and luminosity conditions.

We analyze the production of a light charged Higgs boson at Large Hadron Collider (LHC), via the quark-fusion  $c\bar{b} + h.c. \rightarrow H^-$ , considering the decay channel  $H^- \rightarrow \tau\bar{\nu}_\tau$  in the final state. We study this process in the framework of the 2-Higgs Doublet Model Type III (2HDM-III) which assumes a four-zero texture in the Yukawa matrices and a general Higgs potential, wherein the two Higgs doublets coupling to both up and down fermions do generate flavor-changing neutral currents, yet the latter can be controlled by the texture when flavor physics constraints are considered. We consider the parameter space of the model where this signal is enhanced and in agreement with both theoretical constraints and experimental data. In particular, we exploit the setup with lepton-specific-like Yukawa couplings and assess the LHC sensitivity to such  $H^\pm$  signals against a variety of both reducible and irreducible backgrounds. We show that under this scheme  $BR(H^\pm \rightarrow cb) \sim 0.1 - 0.2$  and  $BR(H^\pm \rightarrow \tau\nu) \sim 0.7 - 0.9$  so that, under these conditions the prospects for  $H^\pm$  detection in the 2HDM-III in the aforementioned production and decay channels are excellent assuming standard collider energy and luminosity conditions.

**Parallel session-2 (15' talk + 2' questions) / 50**

## Charged Higgs boson production via $cb$ -fusion at the Large Hadron Collider

**Corresponding Author:** sebastian.rosado.navarro@cern.ch