The forgotten channels: charged Higgs boson decays to a $W^{\pm}$ and a non-SM-like Higgs boson

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in collaboration with

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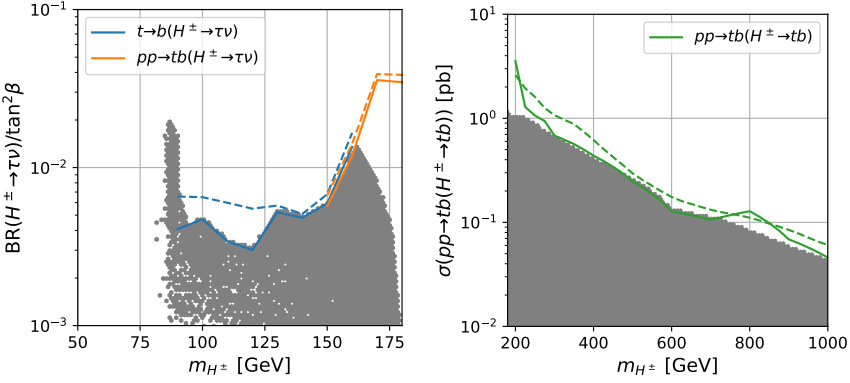
Existing experimental searches for charged Higgs bosons

Production process	Higgs decay	Final state	# of exp. searches
$pp \to H^\pm tb$	$H^\pm \to \tau\nu_\tau$	$tb(\tau\nu_\tau)$	5
$pp \to H^\pm tb$	$H^\pm \to tb$	$tbtb$	4
$pp \to tt, t \to H^\pm b$	$H^\pm \to cb$	$tbcb$	1
$pp \to tt, t \to H^\pm b$	$H^\pm \to cs$	$tbcs$	2
$pp \to H^\pm qq'$ (VBF)	$H^\pm \to W^\pm Z$	$W^\pm Zqq'$	3
$pp \to tt, t \to H^\pm b$	$H^\pm \to W^\pm A$	$W^\pm \mu^+\mu^-$	1
$pp \to H \to H^\pm W^\mp$	$H^\pm \to W^\pm h$	$W^\pm W^\mp bb$	1

$\to$ 12 searches in fermionic channels, 5 searches for bosonic channels (3 of which only appear for triplet-like $H^\pm$).

Are the bosonic charged Higgs decay channels theoretically less motivated?

Current impact of fermionic charged Higgs boson searches



- All points pass theoretical and experimental constraints,
- constraints evaluated using `ScannerS`, `HDecay`, `HiggsBounds`, `HiggsSignals`,
- $H^\pm \to \tau\nu_\tau$ relevant in low mass region,
- $H^\pm \to tb$ hardly constraining in high mass region.

Bosonic charged Higgs boson couplings

- Radiative EW: $H^\pm H^\mp \gamma, H^\pm H^\mp Z$,
- triple Higgs: $H^\pm H^\mp h_i/a_i$,
- mixed EW: $H^\pm W^\mp Z/\gamma$ (only in triplet extensions),
- Higgs EW: $H^\pm W^\mp h_i/a_i$

In the 2HDM, we have (with h_i being the $\mathcal{CP}$-even Higgs bosons)

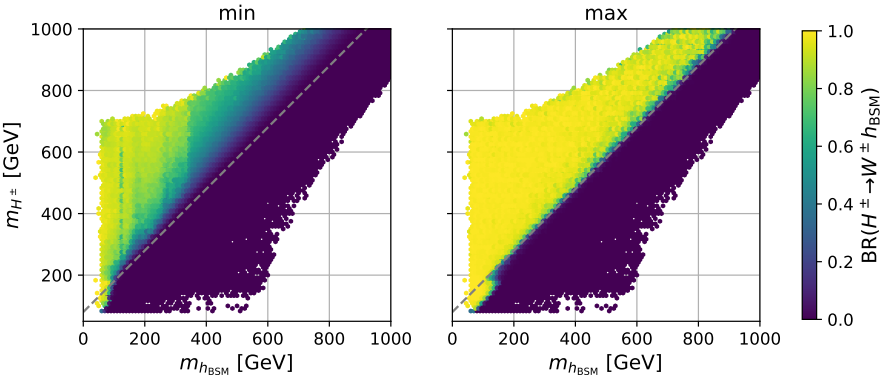
$$g(H^\pm W^\mp h_1) \propto c_{\beta-\alpha}, \quad g(H^\pm W^\mp h_2) \propto s_{\beta-\alpha}, \quad g(H^\pm W^\mp A) = -\frac{g}{2}\,.$$

Alignment limit

$g^2(H^\pm W^\mp h_{125}) \to 0$, $g^2(H^\pm W^\mp h_{\text{BSM}}) \to \frac{g^2}{4} = g^2(H^\pm W^\mp A)$

$\to$ Charged Higgs boson couplings to a W and a non-SM-like Higgs boson are maximized!

Parameter scan in the 2HDM type I



- All points pass theoretical and experimental constraints,
- similar results for BR($H^\pm \to W^\pm h_{\text{BSM}}$).

$\to$ Searches for bosonically decaying charged Higgs bosons well motivated!

Benchmark scenarios for bosonic charged Higgs searches

Concept

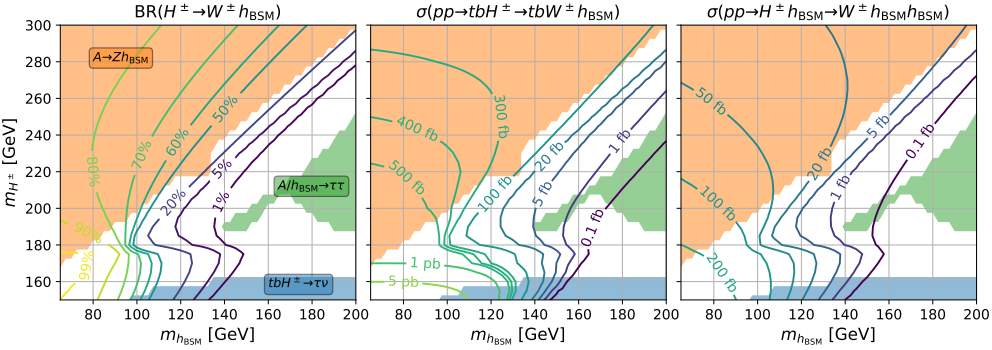
Define $(m_{h_{\text{BSM}}}, m_{H^\pm})$ planes with sizeable unconstrained $H^\pm \to W^\pm h_{\text{BSM}}$ signal.

- Take into account all experimental and theoretical constraints,
- benchmark scenarios cover different mass ranges and different decay modes of h_{BSM}.

All scenarios defined in 2HDM type I (except of cH($Wh^{\text{light}}_{\text{BSM}}$) scenario):

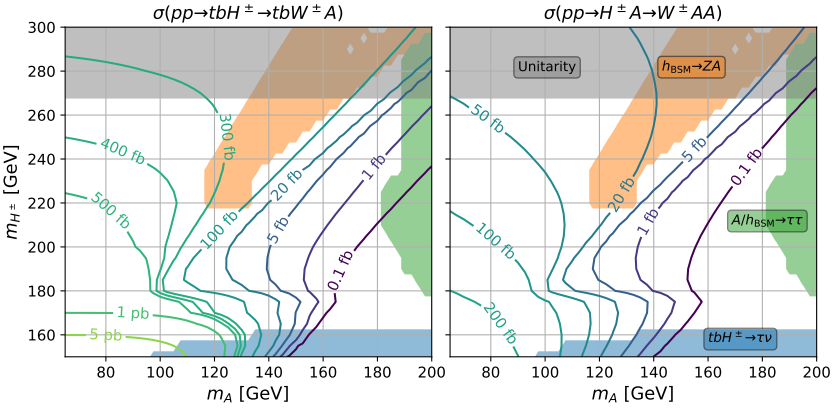
- cH(Wh_{BSM}) scenario $\to$ exact alignment, $m_A = m_{H^\pm}$;
- cH(WA) scenario $\to$ same as cH(Wh_{BSM}) scenario but $h_{\text{BSM}} \leftrightarrow A$;
- cH($Wh^{\text{fphob}}_{\text{BSM}}$) scenario $\to$ approximate alignment, fermiophobic h_{BSM}, $m_A = m_{H^\pm}$;
- cH($Wh^{\text{light}}_{\text{BSM}}$) scenario $\to$ approximate alignment, light h_{BSM}, $m_A = m_{H^\pm}$;
- cH($Wh^{\text{light}}_{\text{BSM}}$) scenario $\to \sim$ cH($Wh^{\text{light}}_{\text{BSM}}$) but in lepton-specific 2HDM, $m_A = m_{H^\pm}$.

cH(Wh_{BSM}) scenario



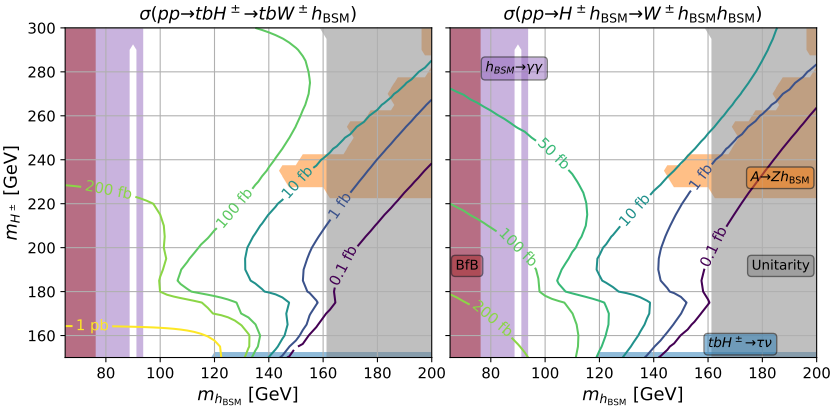
- Complementarity to neutral Higgs boson searches,
- BR($h_{\mathrm{BSM}} \to b\bar{b}$) $\sim$ 80%, BR($h_{\mathrm{BSM}} \to \tau^+\tau^-$) $\sim$ 8%, BR($h_{\mathrm{BSM}} \to \gamma\gamma$) $\sim$ 0.01%.

cH(*WA*) scenario



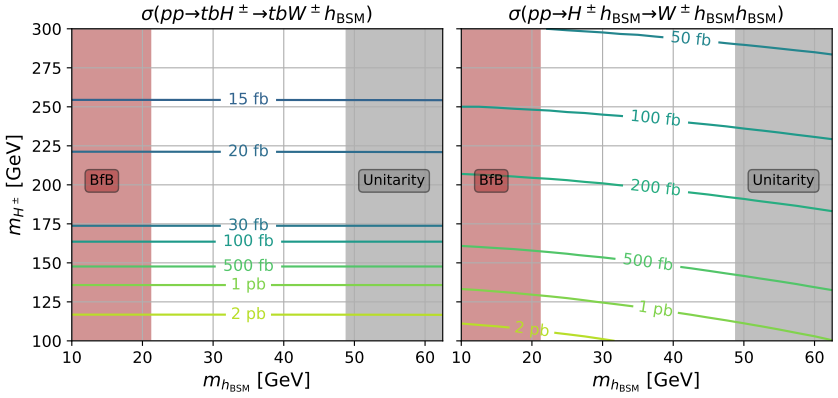
- Weaker constraints from neutral Higgs boson searches,
- slightly enhanced BR($h_{\text{BSM}} \to \gamma\gamma$) $\sim 0.01 - 0.1\%$.

cH($Wh^{\text{fphob}}_{\text{BSM}}$) scenario — fermiophobic h_{BSM}



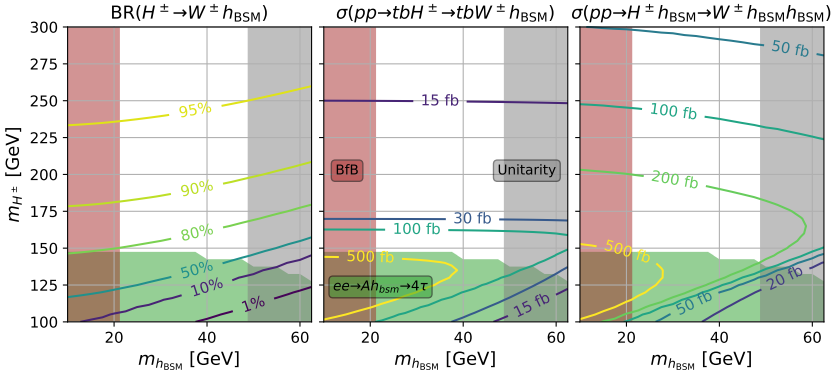
- h_{BSM} only decays to vector bosons ($\gamma\gamma, W^+W^-, ZZ$).

cH($Wh^{\text{light}}_{\text{BSM}}$) scenario — light h_{BSM}



- Requires fine-tuning of m_{12}^2 and $\tan\beta$ to suppress $h_{125} \to h_{\text{BSM}} h_{\text{BSM}}$ decays,
- $\text{BR}(h_{\text{BSM}} \to b\bar{b}) \sim 80\%$, $\text{BR}(h_{\text{BSM}} \to \gamma\gamma) \sim 10\%$,
- see also talk by Yan Wang.

cH($Wh^{\ell\text{phil}}_{\text{BSM}}$) scenario — light h_{BSM} in the LS 2HDM



- Same as cH($Wh^{\text{light}}_{\text{BSM}}$) scenario but defined in the lepton-specific 2HDM
  $\to$ BR($h_{\text{BSM}} \to \tau\tau$) $\sim$ 100%

Conclusions

- Most existing experimental searches for charged Higgs bosons concentrate on fermionic decays,
- the bosonic $H^\pm \to W^\pm h_{\text{BSM}}/A$ decay has, however, a naturally large branching ratio close to the alignment limit.

$\to$ Proposed five 2HDM benchmark scenarios to motivate future searches for bosonically decaying charged Higgs bosons.

- Sizeable signal cross sections for various production and decay modes,
- large variety of possible decay modes for neutral Higgs bosons.

For every scenario, full XS and branching ratio data available as arXiv ancillary material.

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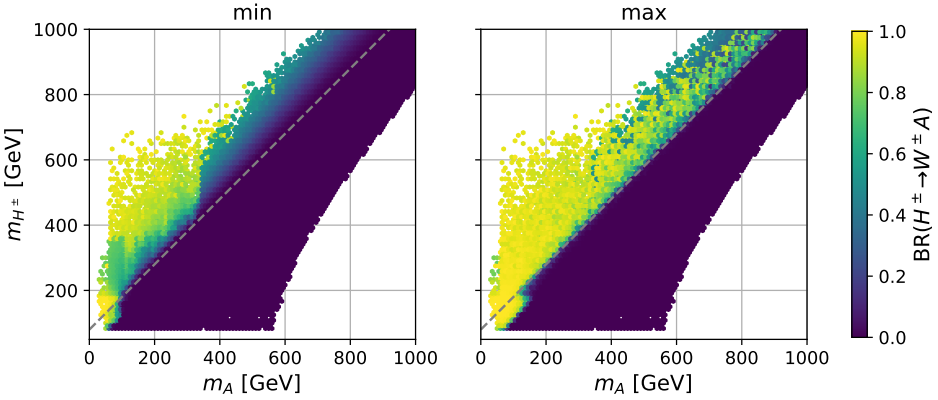
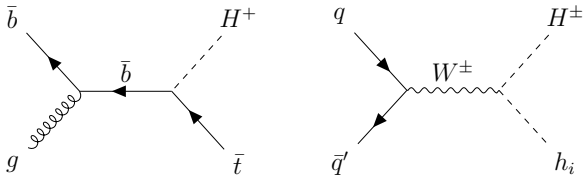
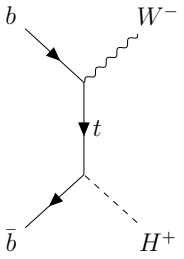
Thanks for your attention!


min
max
1000
800
600
400
200
0
200
400
600
800
1000
$m_{H^\pm}$ [GeV]
m_A [GeV]
m_A [GeV]
1.0
0.8
0.6
0.4
0.2
0.0
BR($H^\pm \to W^\pm A$)

Charged Higgs production

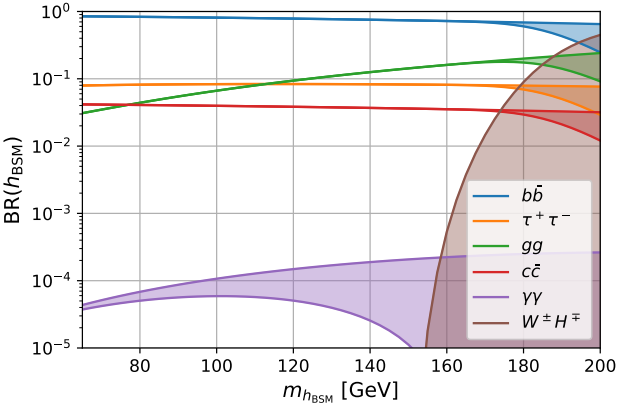


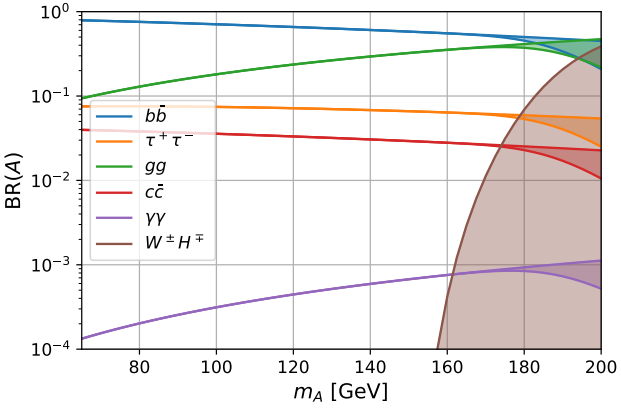


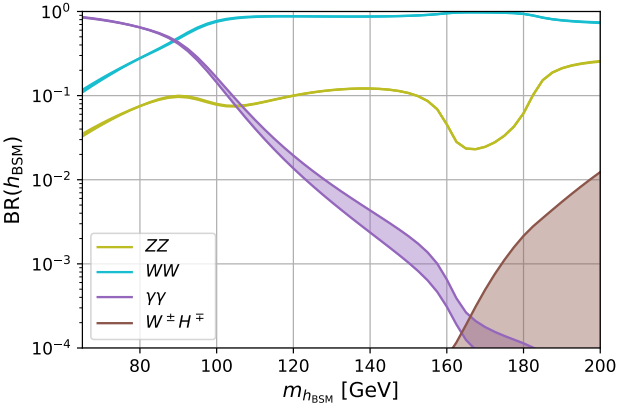
- $H^\pm tb$ production, $\propto 1/\tan^2\beta$,
- $H^\pm h_i$, $H^\pm A$ production, maximized in alignment limit,
- $H^\pm W^\mp$ production, $\propto 1/\tan^2\beta$.

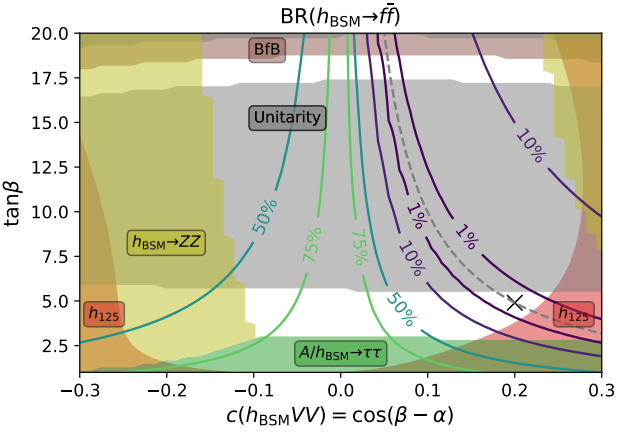
	$m_{h_{125}}$ [GeV]	$m_{H^\pm}$ [GeV]	$m_{h_{\text{BSM}}}$ [GeV]	m_A [GeV]	$c(h_{\text{BSM}}VV)$	$\tan\beta$	m_{12}^2 [GeV^2]
cH(Wh_{BSM})	125.09	150–300	65–200	$m_{H^\pm}$	0	3	500
cH(WA)			$m_{H^\pm}$	65–200			5000
cH($Wh_{\text{BSM}}^{\text{fphob}}$)	125.09	150–300	65–200	$m_{H^\pm}$	0.2	~ 4.9	1200
cH($Wh_{\text{BSM}}^{\text{light}}$)		100–300	10–62.5	$m_{H^\pm}$	-0.062	16.6	~ 25
cH($Wh_{\text{BSM}}^{\ell\text{phil}}$)	same as cH($Wh_{\text{BSM}}^{\text{light}}$) but in the lepton-specific 2HDM						

Table: Parameter choices in the five benchmark scenarios for the $H^\pm \to W^\pm\phi$ ($\phi = h_{\text{BSM}}, A$) decay the 2HDM. All scenarios except cH($Wh_{\text{BSM}}^{\ell\text{phil}}$) are defined in the type I 2HDM.

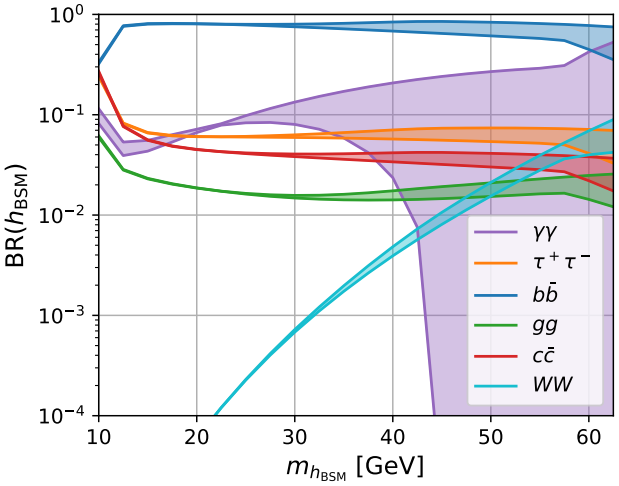

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
BR(h_{BSM})
80
100
120
140
160
180
200
$m_{h_{\text{BSM}}}$ [GeV]
$b\bar{b}$
$\tau^+\tau^-$
gg
$c\bar{c}$
$\gamma\gamma$
$W^\pm H^\mp$

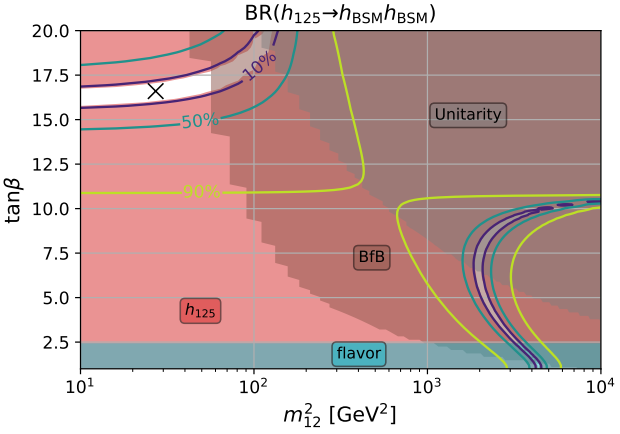

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
BR(A)
$b\bar{b}$
$\tau^+\tau^-$
gg
$c\bar{c}$
$\gamma\gamma$
$W^\pm H^\mp$
80
100
120
140
160
180
200
m_A [GeV]


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
BR(h_{BSM})
80
100
120
140
160
180
200
$m_{h_{\mathrm{BSM}}}$ [GeV]
ZZ
WW
$\gamma\gamma$
$W^{\pm}H^{\mp}$



$$\tan\beta = \frac{\sqrt{1-c(h_{\mathrm{BSM}}VV)^2}}{c(h_{\mathrm{BSM}}VV)} \tag{1}$$


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
BR(h_{BSM})
10
20
30
40
50
60
$m_{h_{\mathrm{BSM}}}$ [GeV]
$\gamma\gamma$
$\tau^+\tau^-$
$b\bar{b}$
gg
$c\bar{c}$
WW



$$g_{h_1 h_1 h_2} = 0 : m_{12}^2 = \frac{(m_{h_2}^2 + 2m_{h_1}^2) c_\alpha s_\alpha}{3\frac{c_\alpha s_\alpha}{c_\beta s_\beta} - 1} \tag{2}$$