New physics effects on the W-boson mass from a doublet extension of the SM Higgs sector

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based on 2204.05269 and 2103.07484

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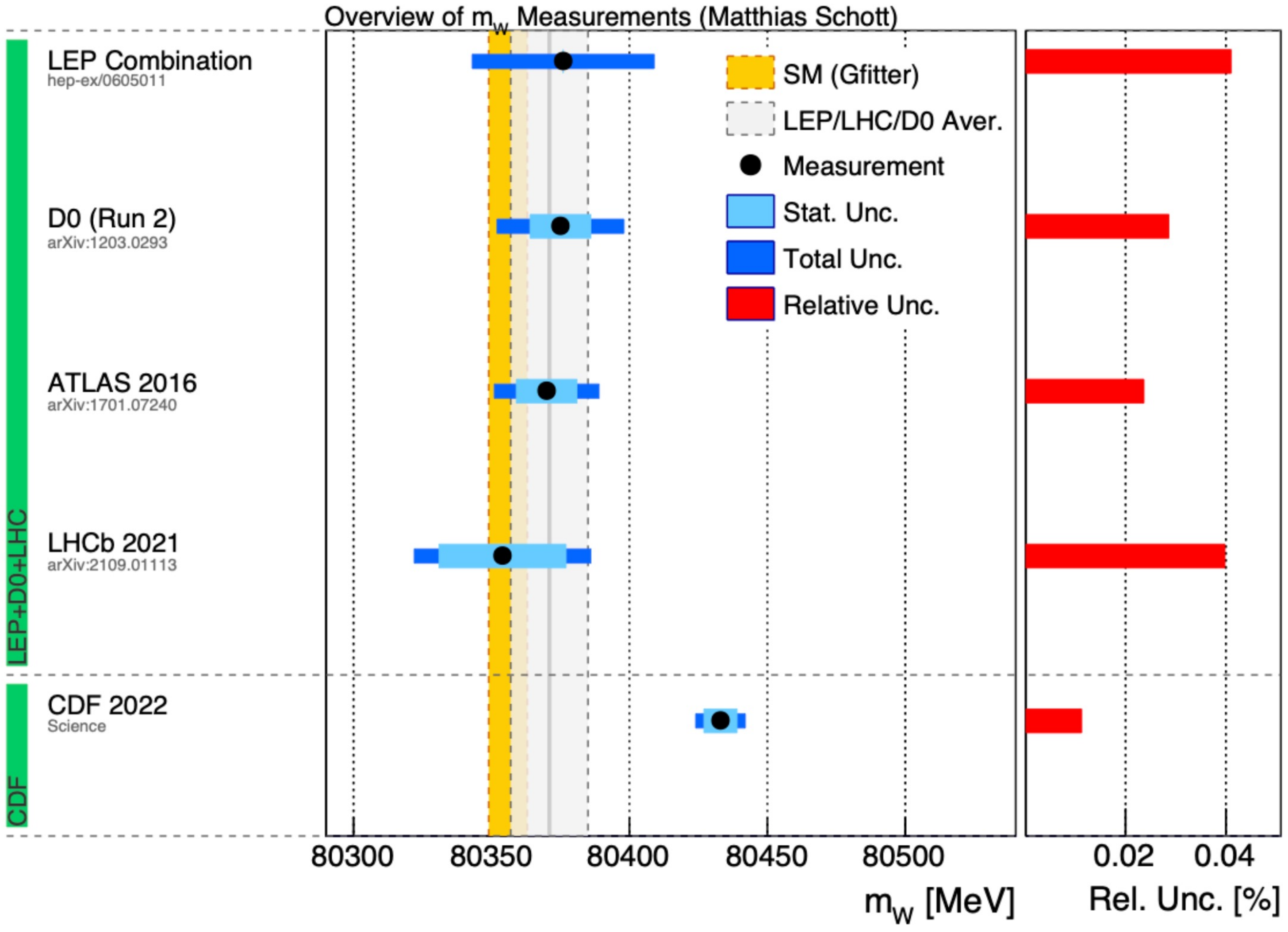
Talk outline

- Introduction
- M_W in the 2HDM
- Implications for LHC searches
- Conclusions

Introduction

M_W measurements



Predicting M_W in the SM

1. Measure Fermi constant G_F via muon decay.

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} F\left(\frac{m_e^2}{m_\mu^2}\right)\left(1+\frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)(1+\Delta q),$$

QED corrections

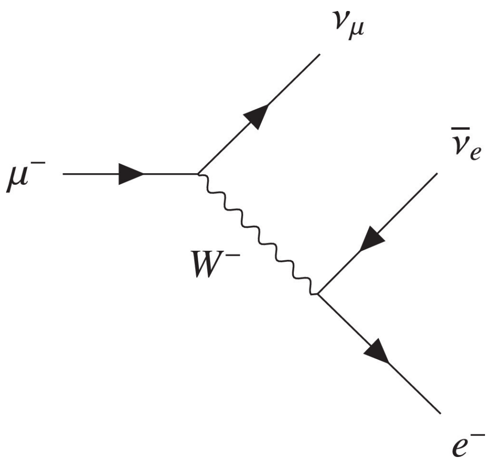
2. Relate M_W to G_F via

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right) = \frac{\pi\alpha_{em}}{\sqrt{2}G_F}(1+\Delta r)\,.$$

Loop corrections

3. Extract M_W^{SM} via iteration.

$M_W^{SM} = 80.357 \pm 6$ GeV



Theoretical calculation/prediction is more precise than experimental determination; no large shifts expected.

New physics in M_W?

How can we shift M_W w.r.t. the SM value? CDF paper has already 82 citations…

- Change relation between M_W and G_F at the **tree level**:
  - Extensions of the SM gauge group: Z', W' models, …;
  - Extensions of the SM Higgs sector: $Y = 0$ triplet, $Y = 3/2$ quadruplet, …;
  - …
- Change relation between M_W and G_F at the **loop level**:
  - Extensions of the SM Higgs sector: 2nd doublet, $Y = 1$ triplet, …;
  - Additional fermions: 4th generation, vector-like fermions, …;
  - Leptoquarks;
  - SUSY;
  - …
- Change relation between **muon lifetime** and G_F:
  - Right-handed neutrinos;
  - …

Focus of this talk: M_W in the 2HDM

M_W in the 2HDM

The 2-Higgs-doublet-model (2HDM)

- Focus first on **2HDM type I** in the alignment limit (similar results expected for other types/models).

$$V_{\rm 2HDM}(\Phi_1,\Phi_2) = m_{11}^2\,\Phi_1^\dagger\Phi_1 + m_{22}^2\,\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right)$$
$$+\frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5\left((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right).$$

- 2 Higgs doublets → 5 physical Higgs bosons: CP-even h, H; CP-odd A; charged $H^\pm$.

SM-like Higgs boson

- Convenient choice of input parameters: $m_h, m_H, m_A, m_{H^\pm}$, $t_\beta = \tan\beta \equiv v_2/v_1$, $M = m_{12}/(s_\beta c_\beta)$.

- Higgs masses are related to λs via: $m_i^2 = M^2 + \sum_j c_{ij}\lambda_j v^2$

M_W in the 2HDM

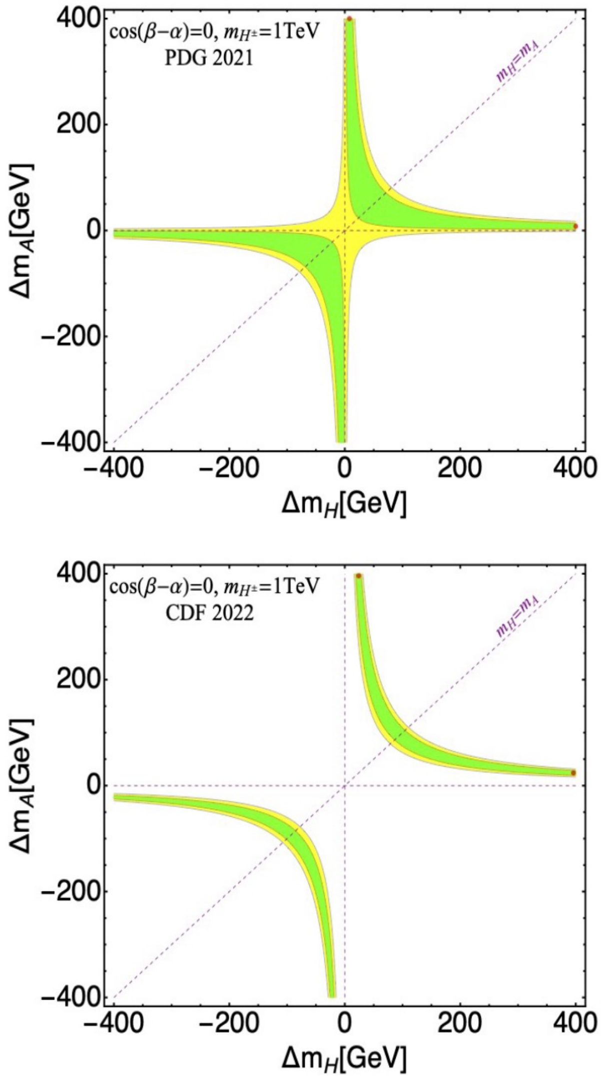
- Non-SM one-loop corrections to muon decay result in

$$\Delta\rho^{(1)}_{\text{non-SM}} = \frac{\alpha}{16\pi^2 s_W^2 M_W^2}\left\{\frac{m_A^2 m_H^2}{m_A^2 - m_H^2}\ln\frac{m_A^2}{m_H^2} - \frac{m_A^2 m_{H^\pm}^2}{m_A^2 - m_{H^\pm}^2}\ln\frac{m_A^2}{m_{H^\pm}^2} - \frac{m_H^2 m_{H^\pm}^2}{m_H^2 - m_{H^\pm}^2}\ln\frac{m_H^2}{m_{H^\pm}^2} + m_{H^\pm}^2\right\},$$

$$\Delta M_W \simeq \frac{1}{2} M_W \frac{c_W^2}{c_W^2 - s_W^2}\Delta\rho\,.$$

- Restoration of custodial symmetry (i.e. $\Delta M_W \simeq 0$) if $m_A = m_{H^\pm}$ or $m_H = m_{H^\pm}$.

Is this compatible with other constraints?

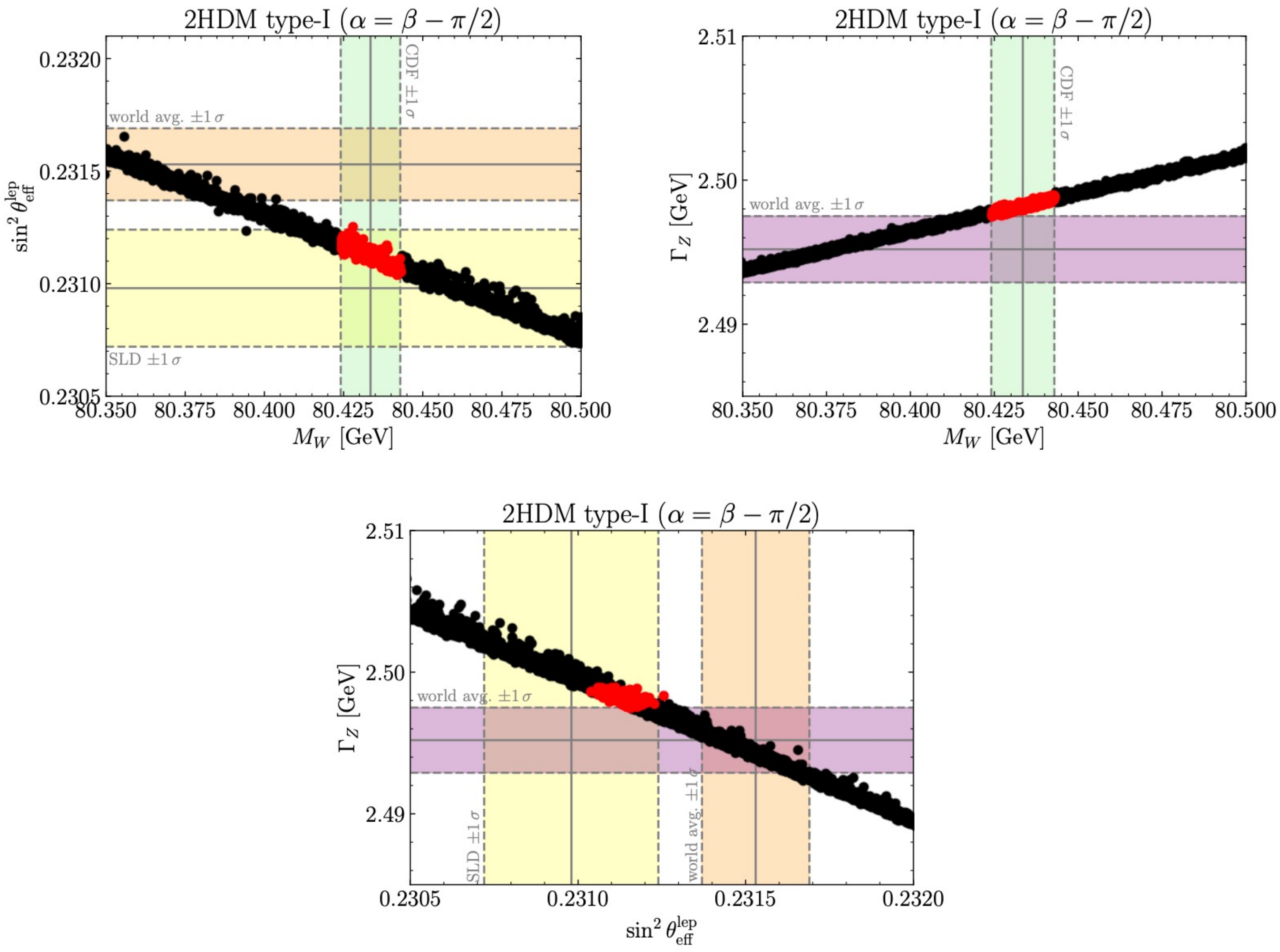


[2204.03796, Lu et al.]

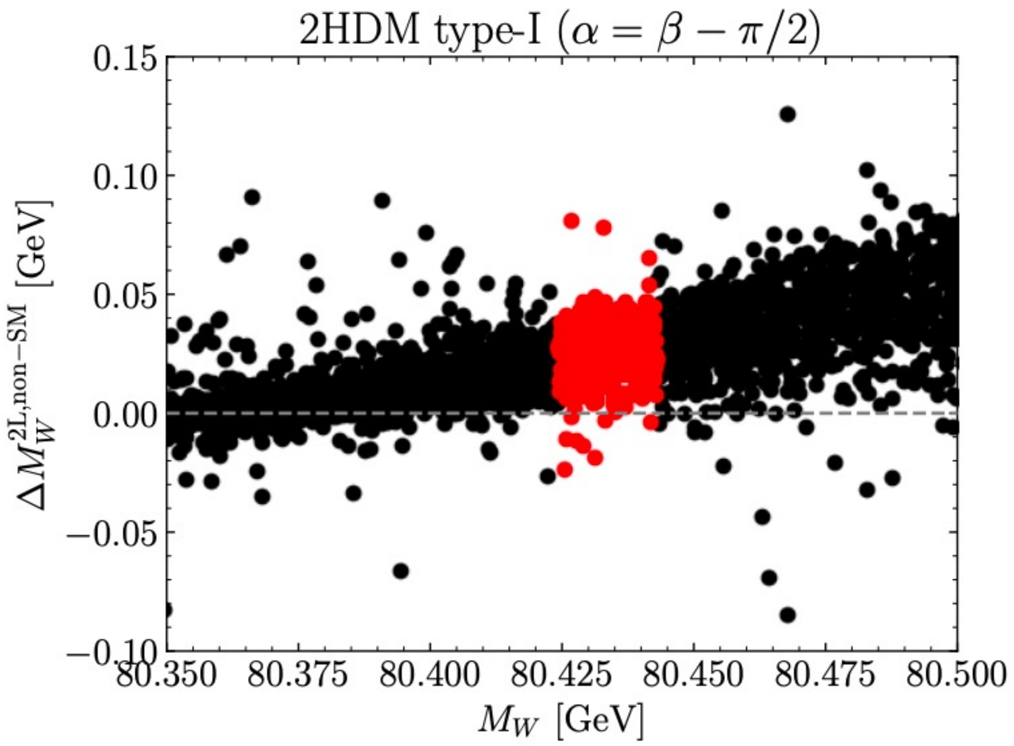
2HDM parameter scan

- We checked for:
  - Vacuum stability and boundedness-from-below.
  - NLO perturbative unitarity.
  - SM-like Higgs measurements via HiggsSignals.
  - Direct searches for BSM scalars via HiggsBounds.
  - b-physics constraints.
- Most constraints checked using ScannerS.
- Loop corrections affecting M_W will also affect other electroweak precision observables.
- Calculate electroweak precision observables — M_W, effective weak mixing angle $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lep}}$, Z decay width — at the 2L level using THDM_EWPOS [Hessenberger,Hollik,1607.04610].

Scan results — EWPOs

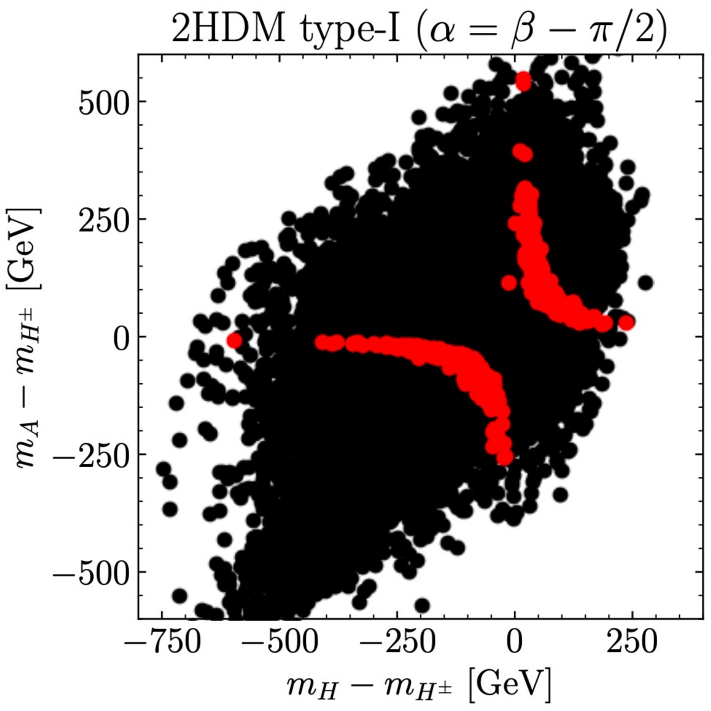


Scan results — 1L vs. 2L



Two-loop non-SM corrections important for precise results.

Scan results — mass hierarchies



- CDF M_W measurement favors

$$m_H, m_A < m_{H^\pm}, \qquad m_{H^\pm} < m_H, m_A$$

- CDF M_W measurement disfavors

$$m_{H,A} < m_{H^\pm} < m_{A,H}, \qquad m_H \sim m_A \sim m_{H^\pm}$$

How can we test this scenario at the LHC?

m_H [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$ –	M^2 [GeV^2]	M_W [GeV] (non-SM@1L)	M_W [GeV] (non-SM@2L)	$\sin^2\theta_{\rm eff}^{\rm lep}$ –	Γ_Z [GeV]
853.813	928.352	809.047	1.206	444.166×10^3	80.4001	80.4337	0.23113	2.4981
351.962	751.498	762.911	1.255	55.451×10^3	80.3990	80.4339	0.23109	2.4979

Implications for LHC searches

Bosonic Higgs couplings

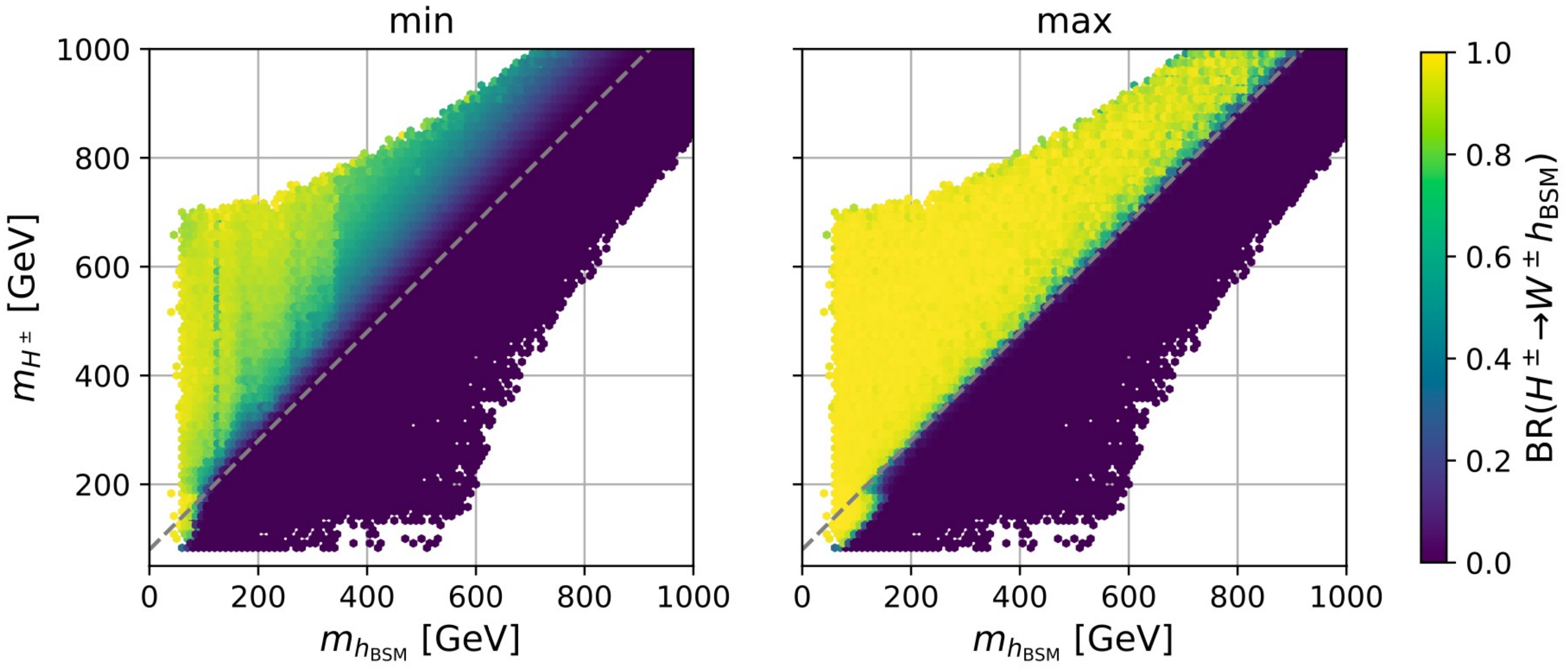
- Fermionic decays modes of BSM Higgs bosons comparably well explored.
- But also bosonic decay modes are important (α: mixing angle between CP-even Higgs bosons):

$$g(ZAh) \propto c_{\beta-\alpha}, \quad g(ZAH) \propto s_{\beta-\alpha}$$

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

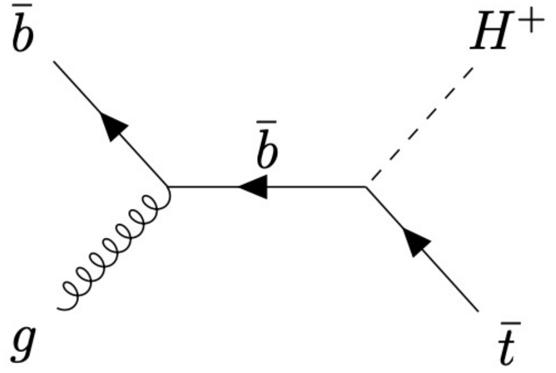
- In the alignment limit both the ZAH, $H^\pm W^\mp H$, and $H^\pm W^\mp A$ couplings are maximized.
- Mass hierarchies favored by CDF M_W measurement allow for $H^\pm \to W^\pm A/H$ or $A/H \to W^\pm H^\mp$ decays.
- Focus here on $H^\pm \to W^\pm A/H$ decays.

Bosonic Higgs couplings

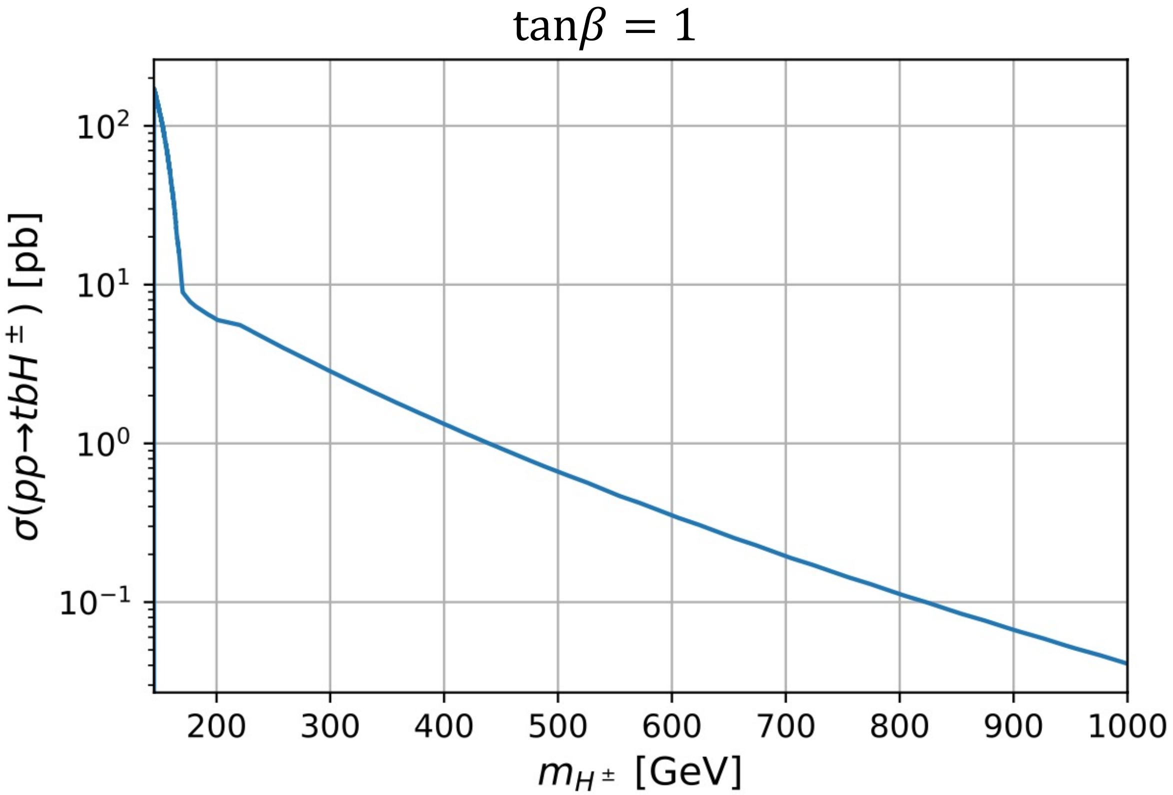


➡ Very large $\mathrm{BR}(H^\pm \to W^\pm A/H)$ expected if decay kinematically allowed.

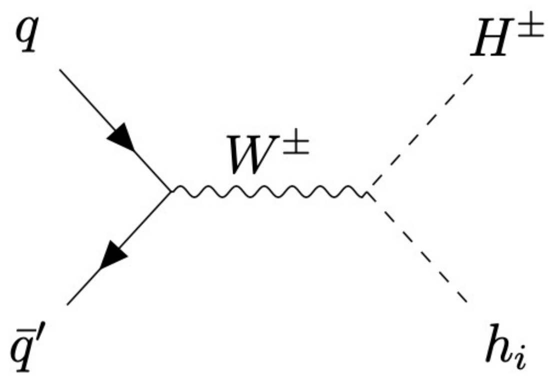
$H^{\pm}$ production at the LHC — $pp \to H^{\pm}tb$



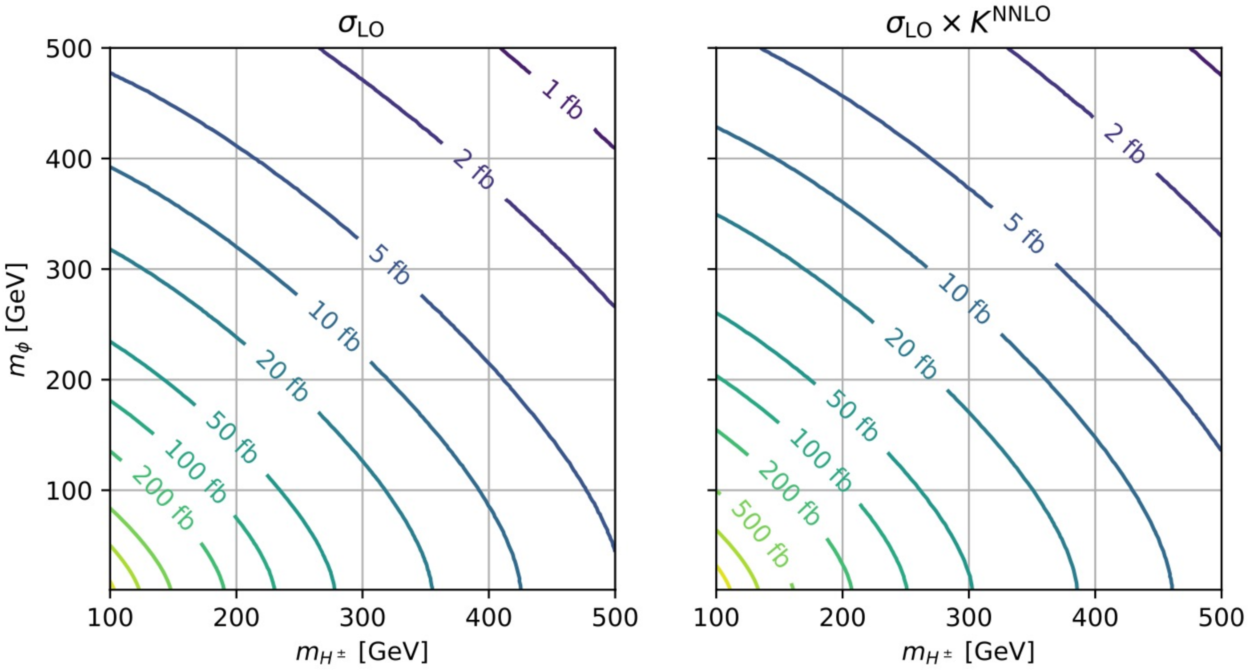
Suppressed by $\propto 1/\tan^2\beta$.



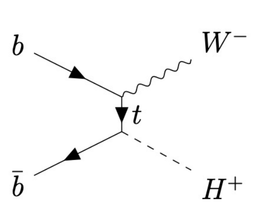
$H^{\pm}$ production at the LHC — $pp \to H^{\pm}H/A$



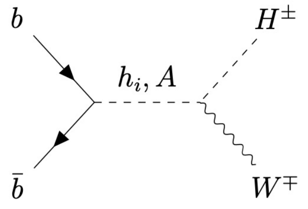
Not suppressed by $\tan\beta$.



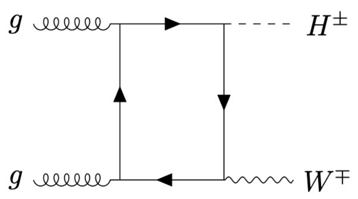
$H^{\pm}$ production at the LHC — $pp \to H^{\pm}W^{\mp}$

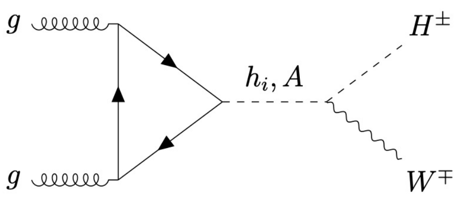


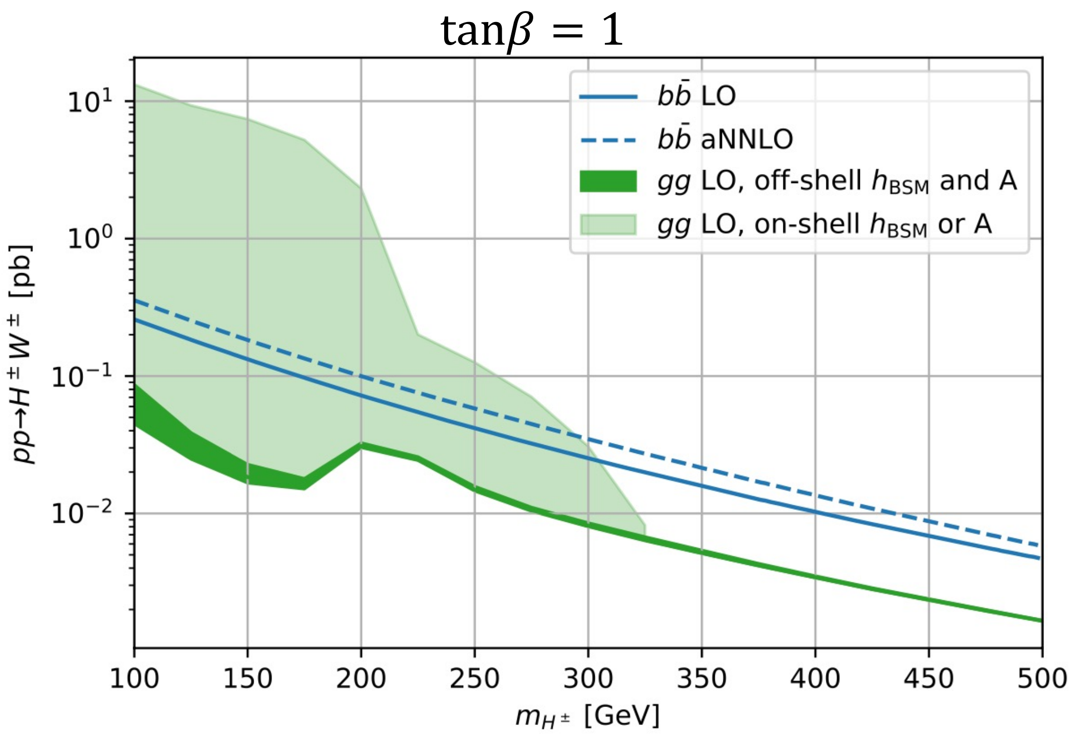
(a) $b\bar{b}$ initiated (non-resonant)



(b) $b\bar{b}$ initiated (resonant)







Dependence tanβ varies between subchannels.

Existing charged Higgs boson searches

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
$pp \to tt, t \to H^{\pm}b$	$H^{\pm} \to W^{\pm}A$	$tbW^{\pm}\mu^{+}\mu^{-}$	2
$pp \to H \to H^{\pm}W^{\mp}$	$H^{\pm} \to W^{\pm}h$	$W^{\pm}W^{\mp}bb$	1

Do these existing searches (as well as other constraint) still allow for large $H^{\pm} \to W^{\pm}H/A$ signals?

Benchmark scenarios for bosonic charged Higgs searches

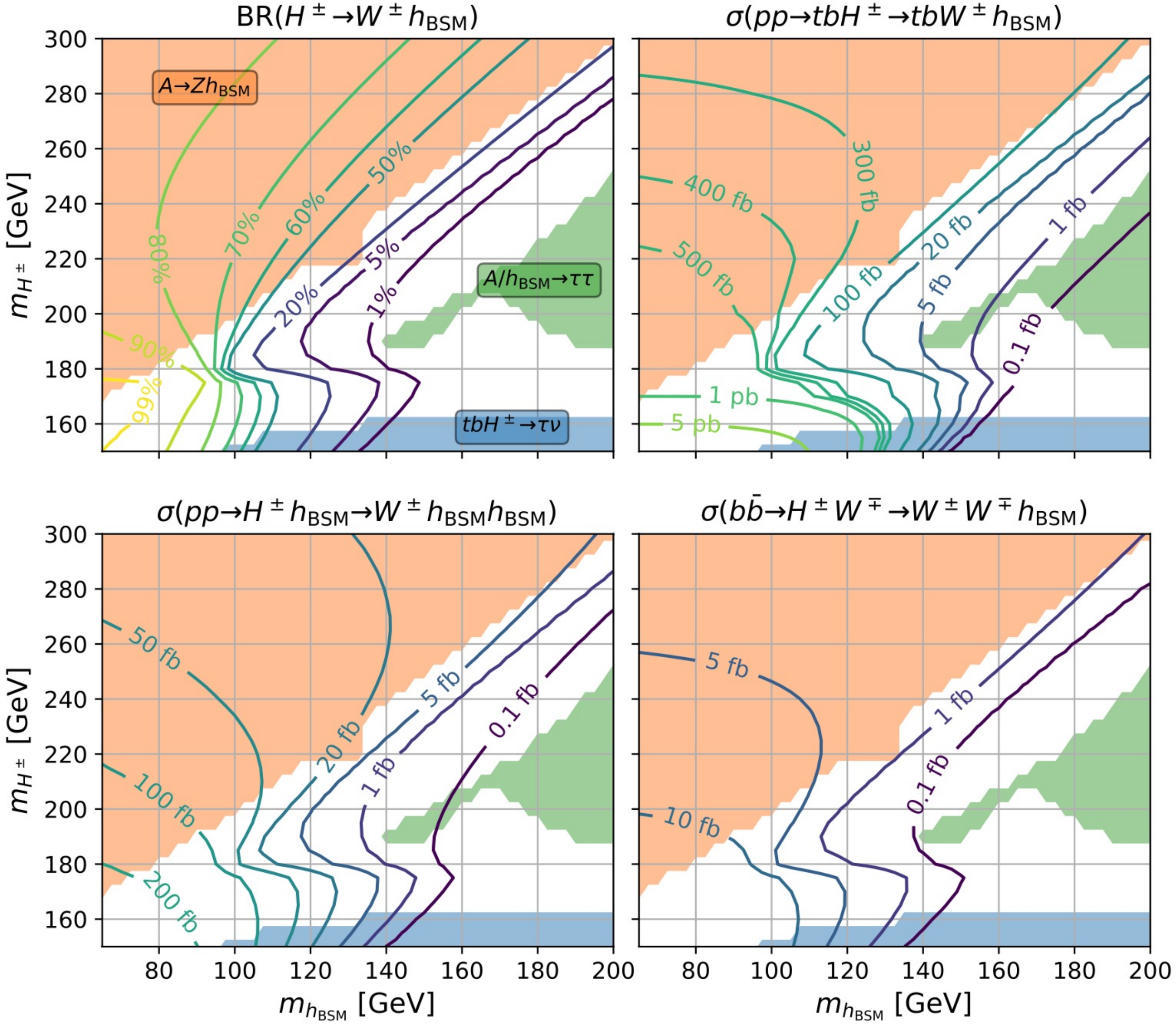
Concept: define $(m_{H,A}, m_{H^\pm})$ planes with sizeable unconstrained $H^\pm \to W^\pm H/A$ signal.

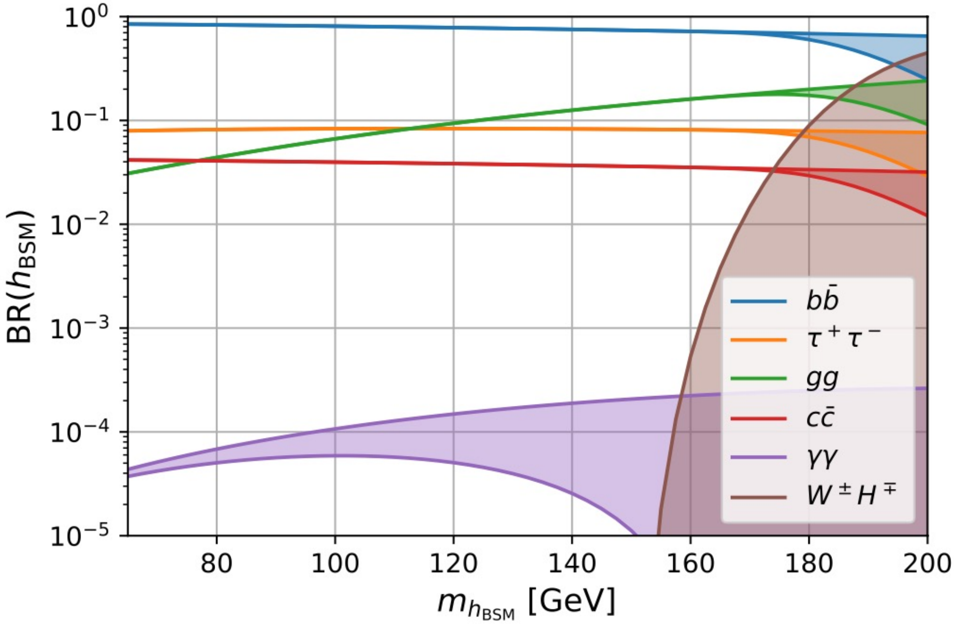
- Take into account all experimental and theoretical constraints.
- Benchmark scenarios cover different mass ranges and different decay modes of H/A.

Benchmark scenarios:

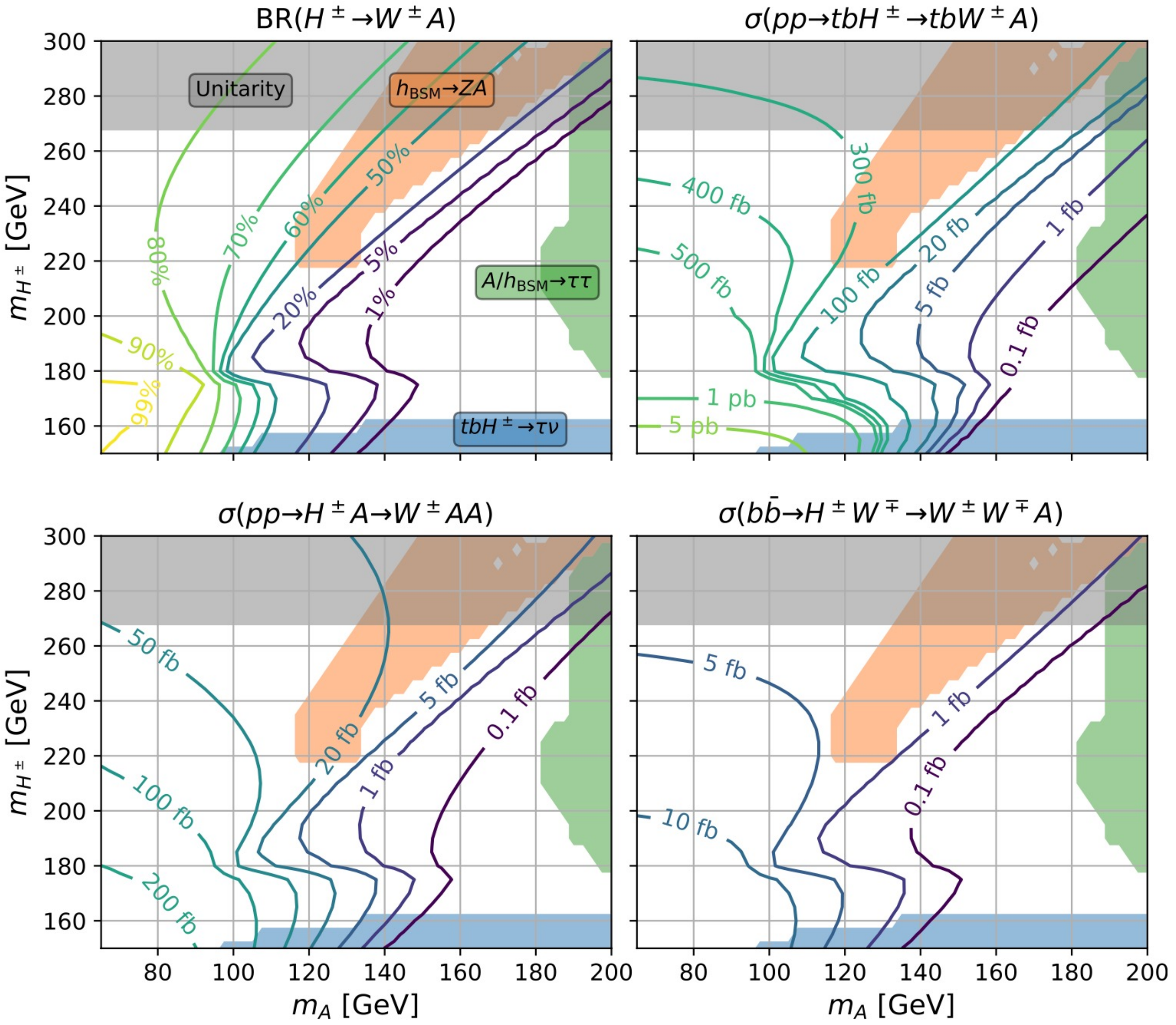
- $\mathrm{cH}(Wh_{\mathrm{BSM}})$ scenario → exact alignment, $m_A = m_{H^\pm}$, type I.
- $\mathrm{cH}(WA)$ scenario → same as $\mathrm{cH}(Wh_{\mathrm{BSM}})$ scenario, but $h_{\mathrm{BSM}} \leftrightarrow A$.
- $\mathrm{cH}\left(Wh_{\mathrm{BSM}}^{\mathrm{fphob}}\right)$ scenario → approximate alignment, fermiophobic $h_{\mathrm{BSM}}, m_A = m_{H^\pm}$, type I.
- $\mathrm{cH}\left(Wh_{\mathrm{BSM}}^{\mathrm{light}}\right)$ scenario → approximate alignment, light BSM Higgs, $m_A = m_{H^\pm}$, type I.
- $\mathrm{cH}\left(Wh_{\mathrm{BSM}}^{l\mathrm{phil}}\right)$ scenario → same as $\mathrm{cH}\left(Wh_{\mathrm{BSM}}^{\mathrm{light}}\right)$ scenario but in lepton-specific 2HDM.

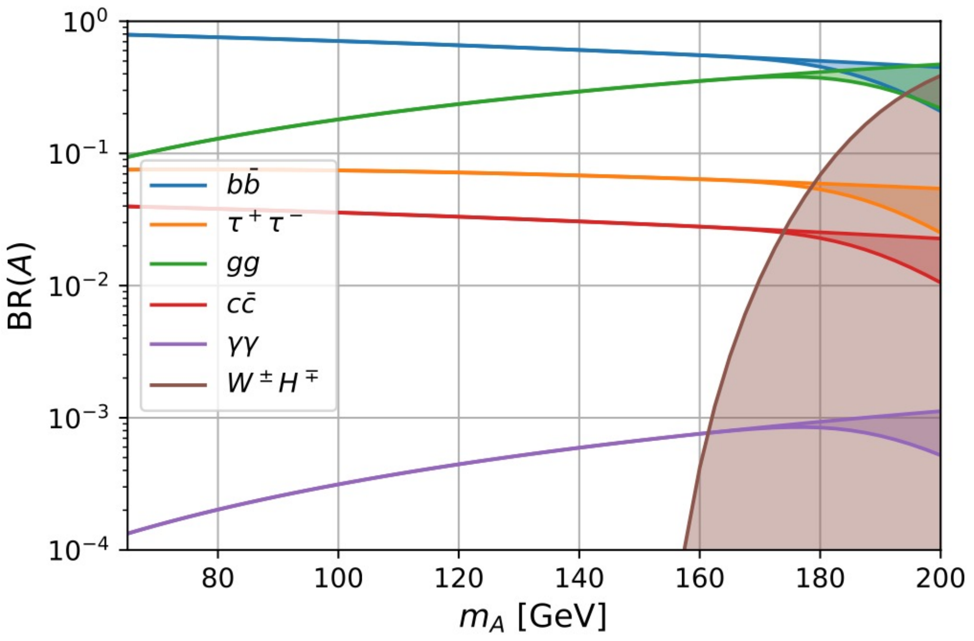
cH($W h_{\mathrm{BSM}}$) scenario





cH(WA) scenario





Conclusions

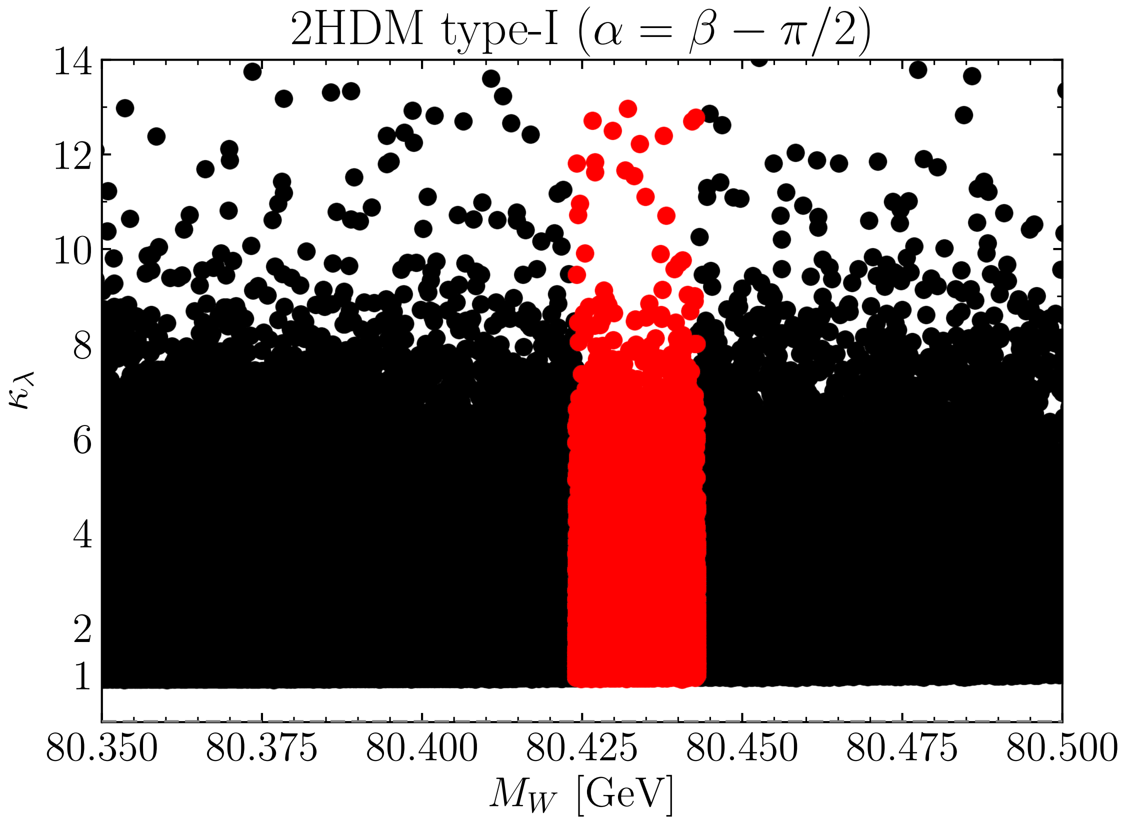
Conclusions

- Many BSM models can accommodate M_W measurement by CDF.
- Should check for every model that this is still consistent with other constraints.
- We showed that the 2HDM can explain the CDF M_W measurement while still satisfying other constraints.
- CDF M_W measurements favours large mass splitting between neutral and charged Higgs bosons.
- The 2HDM explanation of the CDF M_W measurement could be probed by LHC searches for $H^{\pm} \rightarrow W^{\pm}H/A$ or $H/A \rightarrow H^{\pm}W^{\mp}$.

Thanks for your attention!

Appendix

M_W in the 2HDM – correlation with κ_λ?



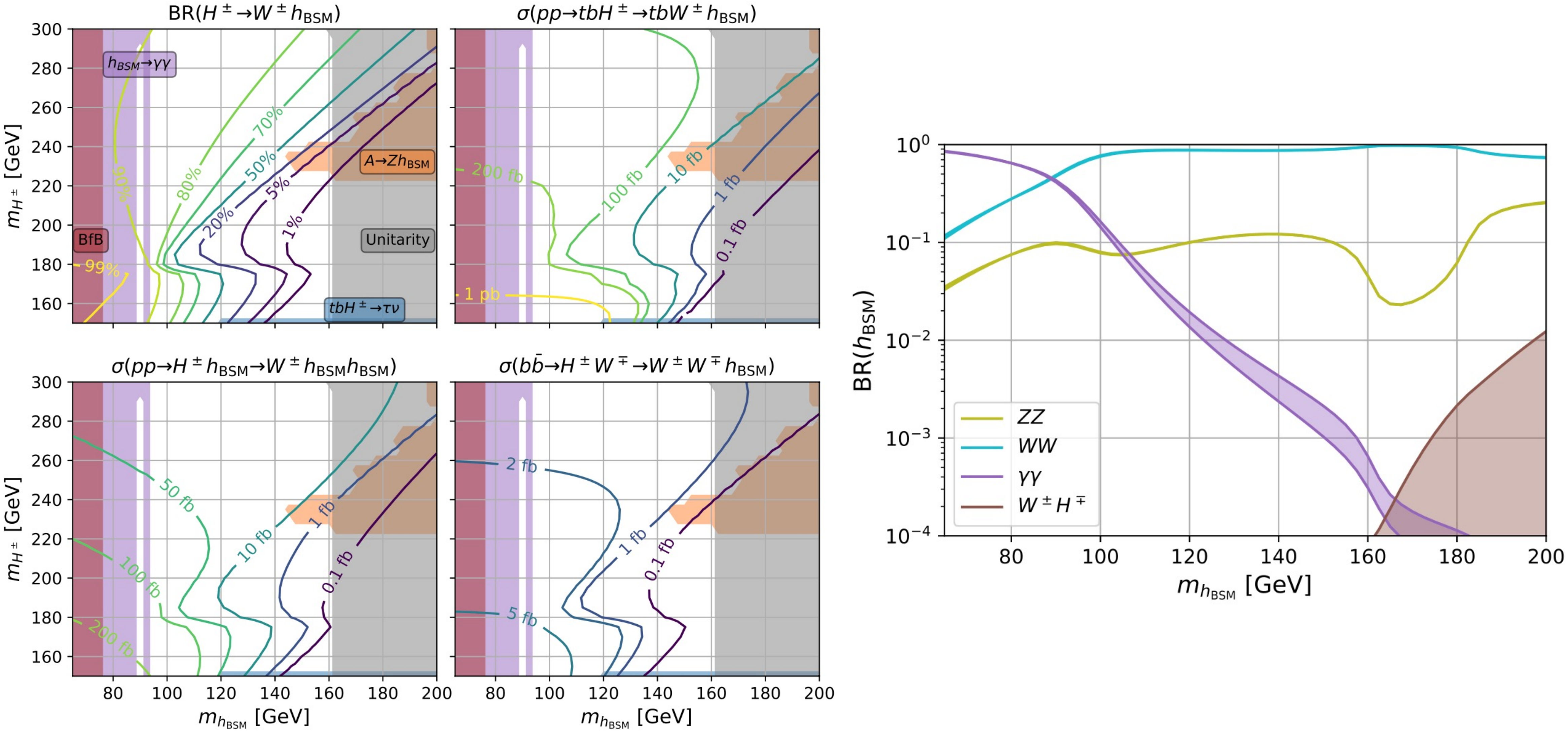
2HDM types

Type	u_R	d_R	l_R	λ_{uu}	λ_{dd}	λ_{ll}
I	$+$	$+$	$+$	$\cot\beta$	$\cot\beta$	$\cot\beta$
II	$+$	$-$	$-$	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Flipped	$+$	$-$	$+$	$\cot\beta$	$-\tan\beta$	$\cot\beta$
Lepton-specific	$+$	$+$	$-$	$\cot\beta$	$\cot\beta$	$-\tan\beta$

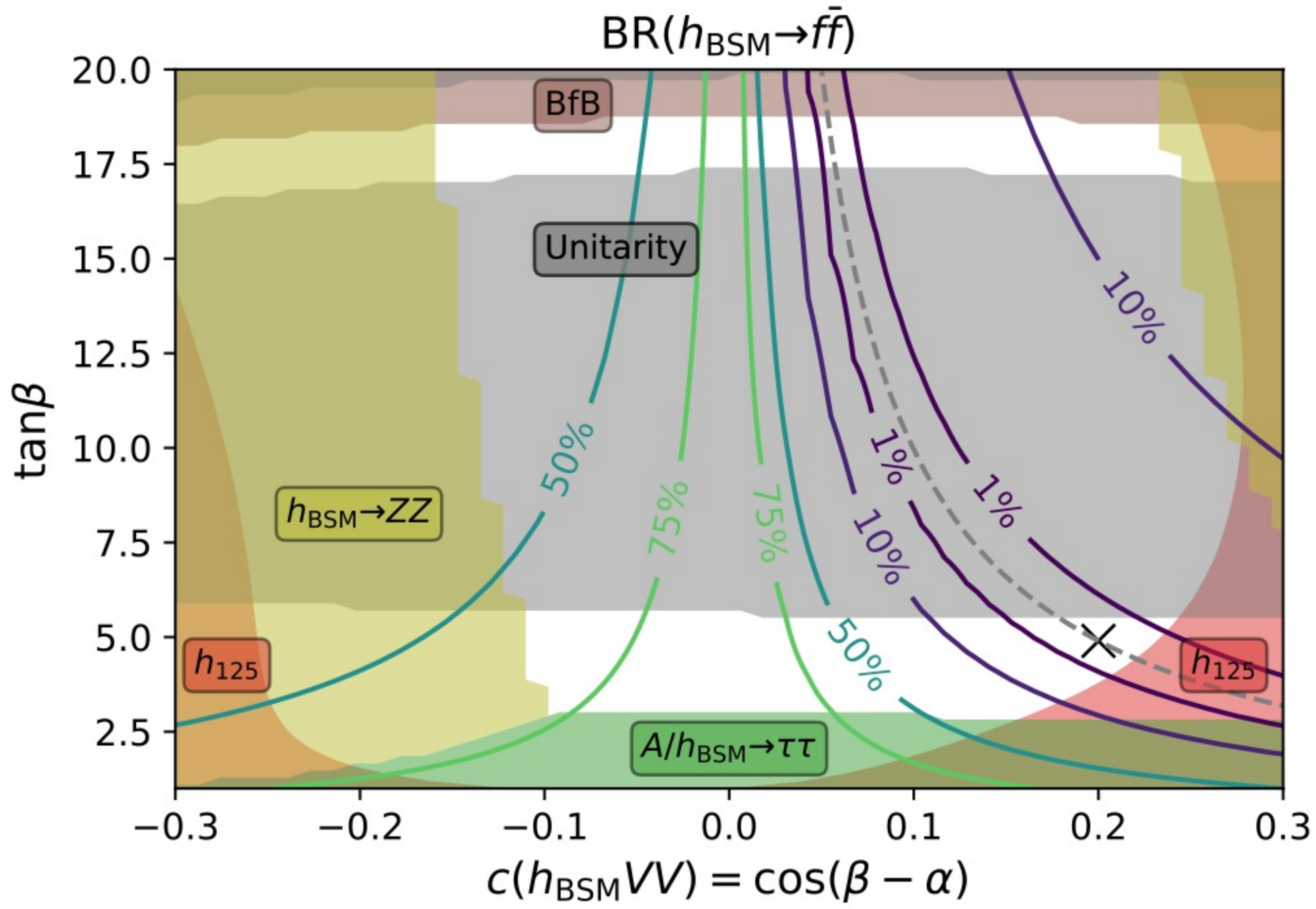
Benchmark scenarios

	$m_{h_{125}}$ [GeV]	$m_{H^\pm}$ [GeV]	$m_{h_{\rm BSM}}$ [GeV]	m_A [GeV]	$c(h_{\rm BSM}VV)$	$\tan\beta$	m_{12}^2 [GeV^2]
cH($Wh_{\rm BSM}$)	125.09	150–300	65–200	$m_{H^\pm}$	0	3	500
cH(WA)	125.09	150–300	$m_{H^\pm}$	65–200	0	3	5000
cH($Wh_{\rm BSM}^{\rm fphob}$)	125.09	150–300	65–200	$m_{H^\pm}$	0.2	Eq. (26)	1200
cH($Wh_{\rm BSM}^{\rm light}$)	125.09	100–300	10–62.5	$m_{H^\pm}$	-0.062	16.6	Eq. (33)
cH($Wh_{\rm BSM}^{\ell\rm phil}$)		same as cH($Wh_{\rm BSM}^{\rm light}$) but in the lepton-specific 2HDM					

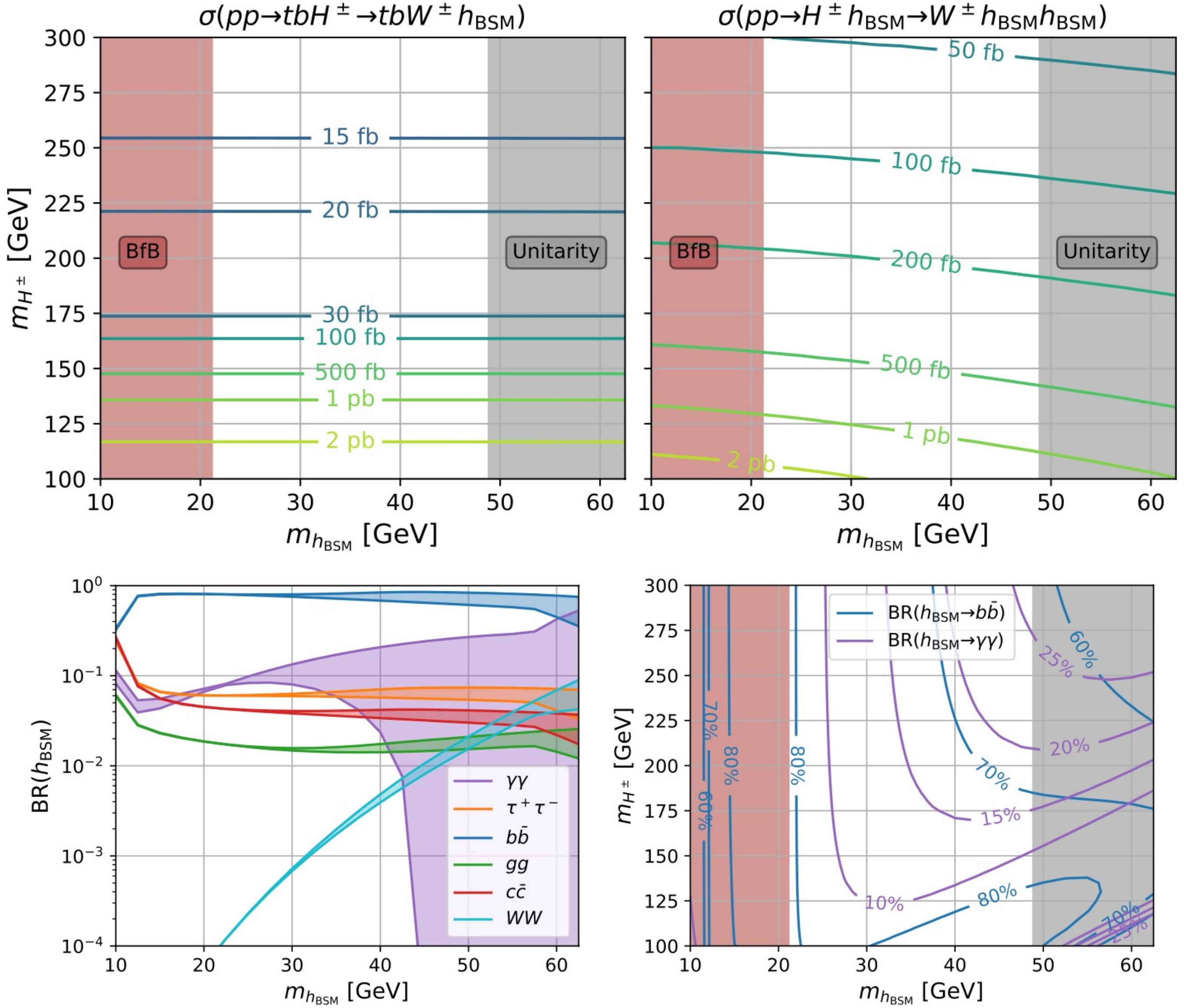
cH $\left(W h_{\mathrm{BSM}}^{\mathrm{fphob}}\right)$ scenario



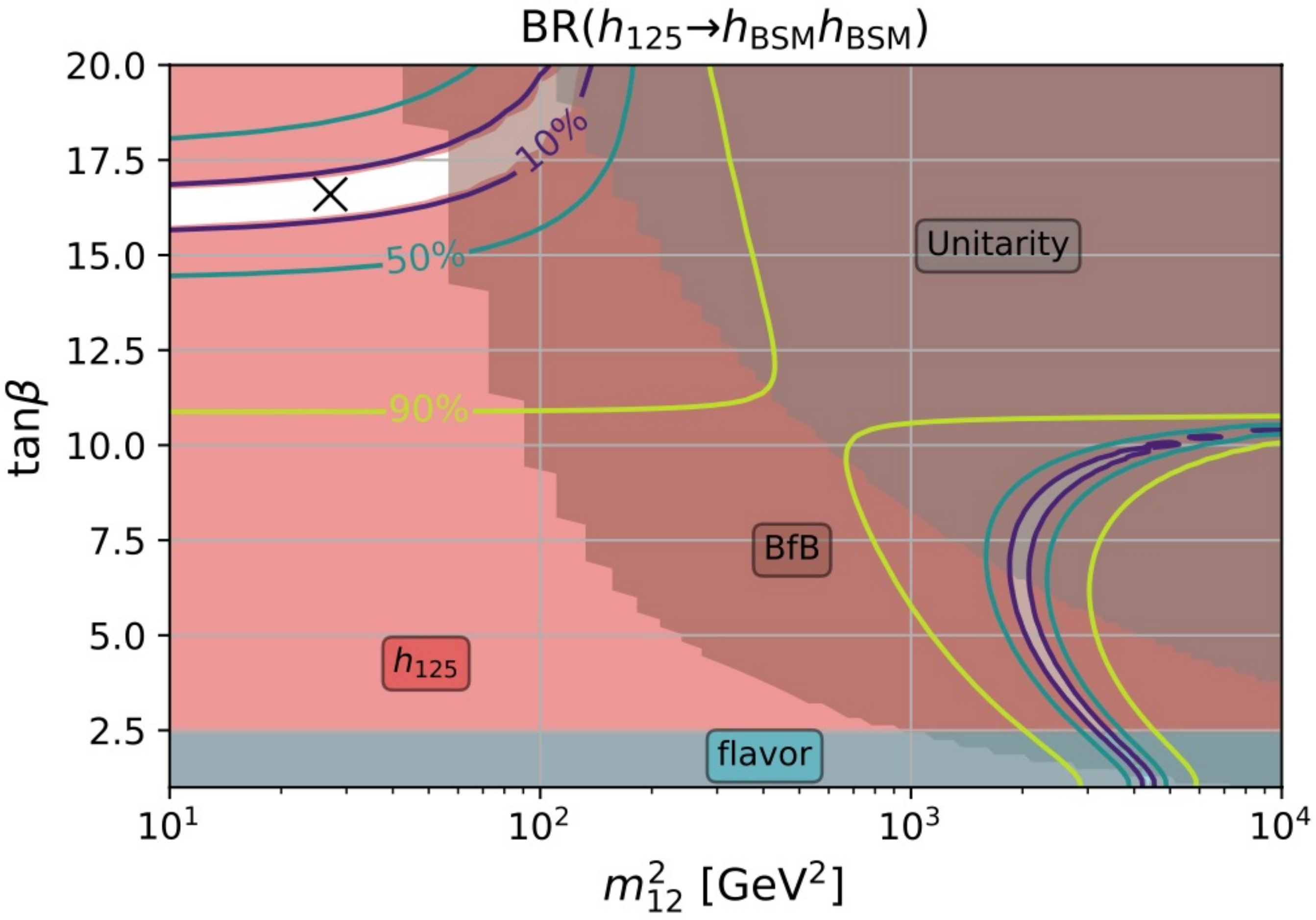
cH $\left(Wh_{\text{BSM}}^{\text{fphob}}\right)$ scenario — tuning



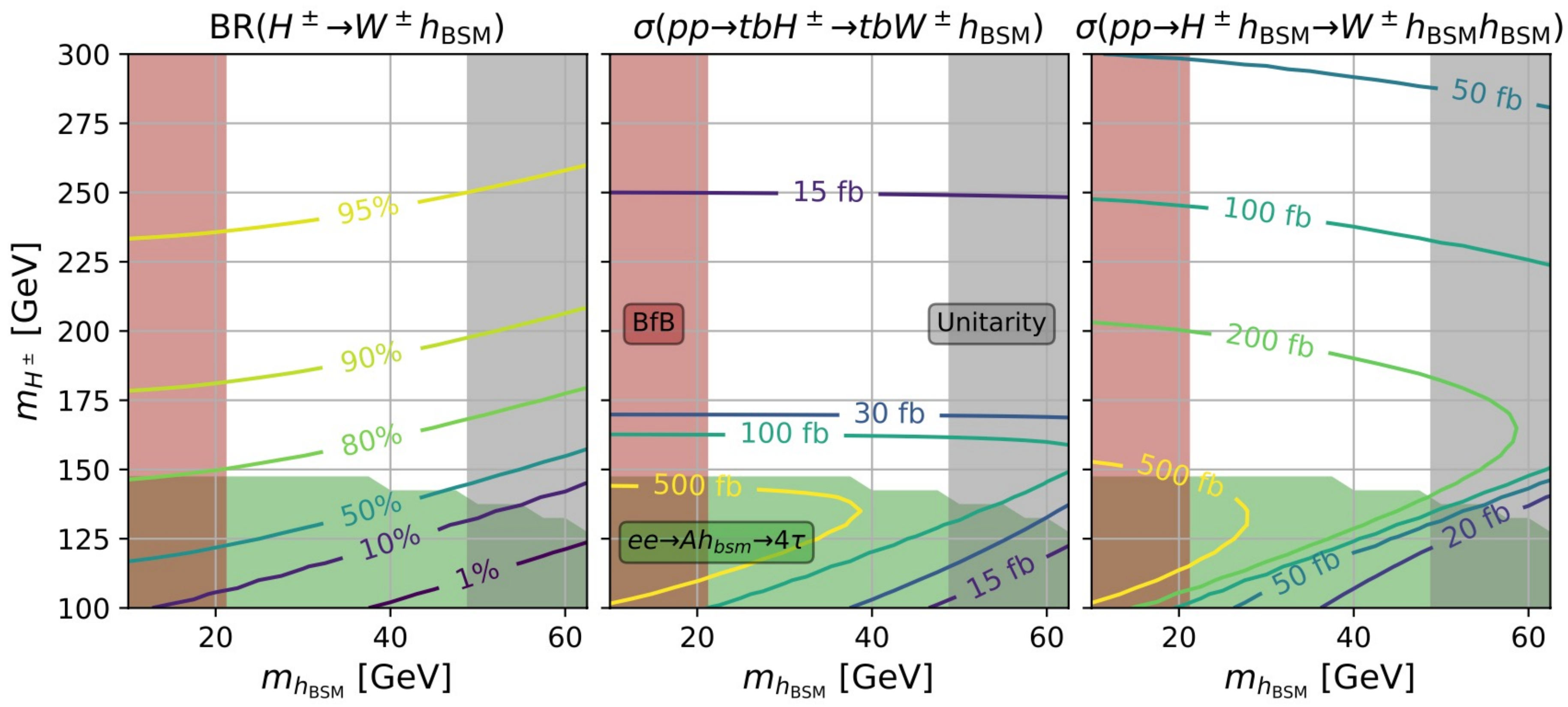
cH $\left(W h_{\text{BSM}}^{\text{light}}\right)$ scenario



$\mathrm{cH}\left(W h_{\mathrm{BSM}}^{\mathrm{light}}\right)$ scenario— tuning



cH $\left(W h_{\mathrm{BSM}}^{l\mathrm{phil}}\right)$ scenario



$\mathrm{BR}(h_{BSM} \to \tau^+\tau^-) \simeq 1$