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New discovery channels for the fermiophobic Higgs in type-I 2HDM with high cutoff scales

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w/ J. Kim, S. Lee, P. Sanyal, D. Wang
[2202.05467]

Longing for **BSM**, but

The same sentence repeated in the experimental papers at the LHC

Search for new physics in the τ lepton plus missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration

Abstract

A search for physics beyond the standard model (SM) in the final state with a hadronically decaying tau lepton and a neutrino is presented. This analysis is based on data recorded by the CMS experiment from proton-proton collisions at a center-of-mass energy of 13 TeV at the LHC, corresponding to a total integrated luminosity of 138 fb^{-1}. The transverse mass spectrum is analyzed for the presence of new physics. No significant deviation from the SM prediction is observed. Limits are set on the production cross section of a W' boson decaying into a tau lepton and a neutrino.

Spirit of invincibility!

Let’s check every loophole.

What if we may miss the signal?

It is dark under the lamp.

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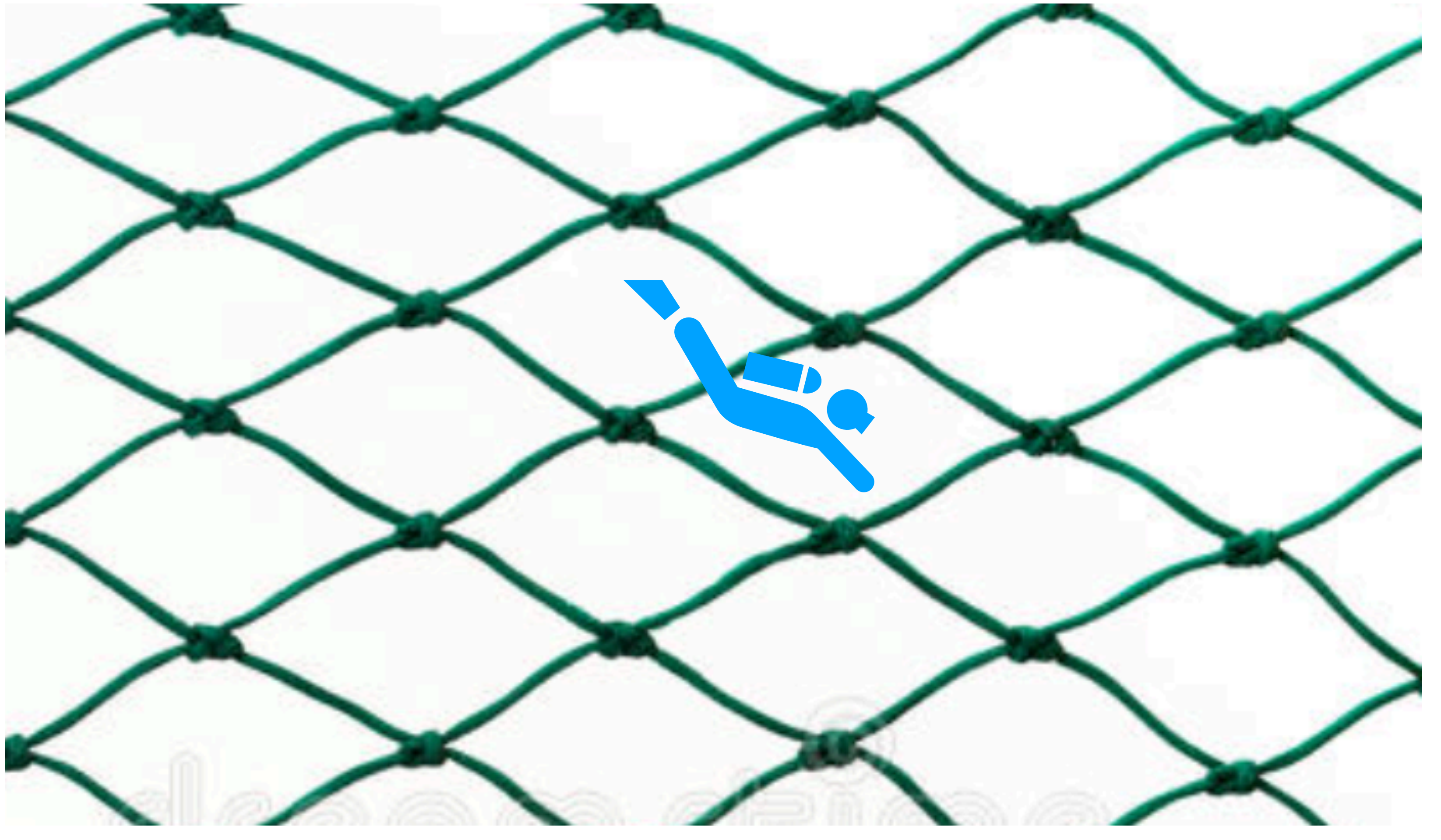
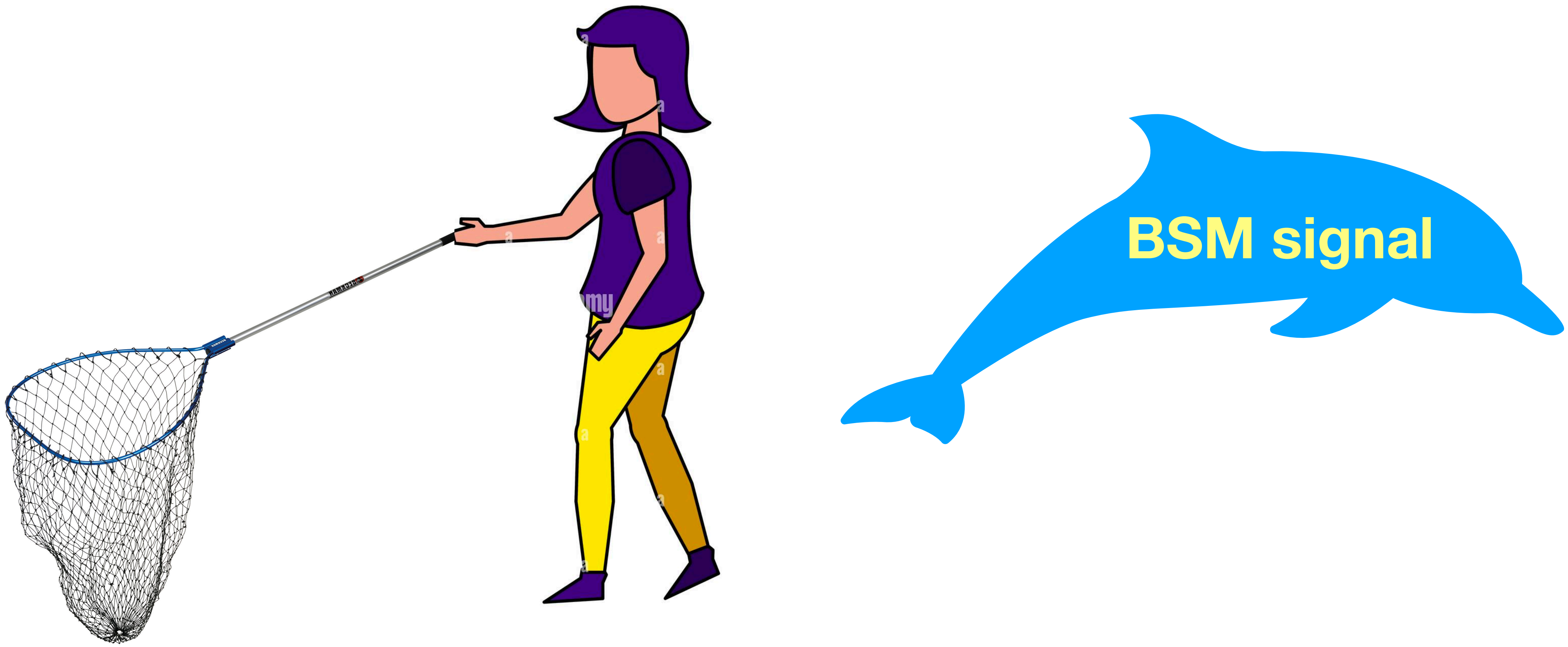
It is dark under the lamp.

Two explanations

1. The new particle is generically elusive at the LHC.



2. We did not search the right place.



A well-motivated BSM model
which satisfy two cases:

Fermiophobic Higgs boson
in type-I 2HDM
with a high cutoff scale

1. Fermiophobic Higgs boson in Type-I 2HDM
2. RGE
3. Big impacts on the fermiophobic type-I from the high cutoff scale
4. Characteristics of the parameters with high cutoff scale
5. Golden channel 1: $\tau^{\pm}\nu\gamma\gamma$
6. Golden channel 2: $\ell^{\pm}\ell^{\pm}\gamma\gamma$ + X
7. Conclusions

1. Fermiophobic Higgs boson in Type-I 2HDM

- Basic theory setup

$$\Phi_i = \begin{pmatrix} w_i^+ \\ \dfrac{v_i + h_i + i\eta_i}{\sqrt{2}} \end{pmatrix}, \quad i = 1, 2,$$

where $v = \sqrt{v_1^2 + v_2^2} = 246$ GeV.

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- Discrete Z_2 symmetry to avoid tree-level FCNC

$$\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_1$$

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$$\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_1$$

- Scalar potential with CP-invariance

Soft braking of Z2

$$\begin{aligned} V_\Phi = \; & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{H.c.}) \\ & + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \frac{1}{2}\lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + \text{H.c.} \right], \end{aligned}$$

- Four types

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	+	−	−	−	−	+
Type II	+	−	−	+	+	+
Type X	+	−	−	−	+	+
Type Y	+	−	−	+	−	+

$$-\mathcal{L}_{\rm Yukawa} = Y_{u2}\,\overline{Q}_L\,\tilde{\Phi}_2\,u_R + Y_{d2}\,\overline{Q}_L\,\Phi_2\,d_R + Y_{\ell 1}\,\overline{L}_L\,\Phi_1\,e_R + \text{h.c.}$$

- Four types

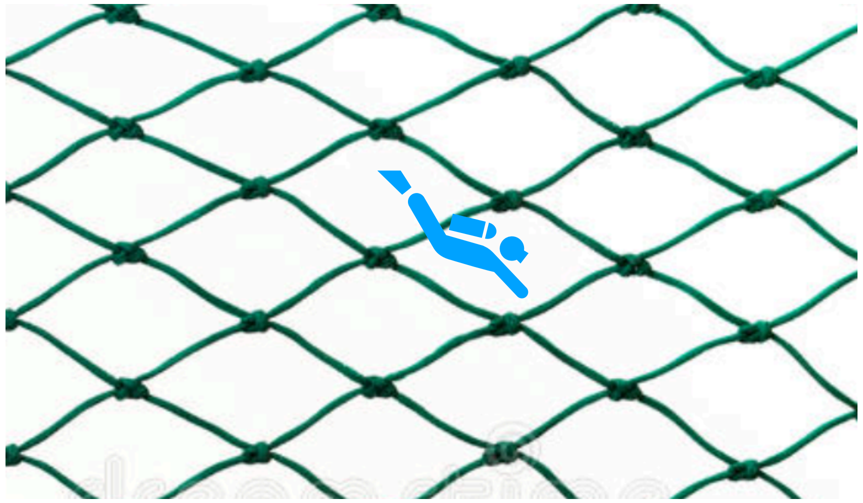
	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	+	−	−	−	−	+
Type II	+	−	−	+	+	+
Type X	+	−	−	−	+	+
Type Y	+	−	−	+	−	+

fermiophobic type-I: $M_H = 125$ GeV, $\alpha = \pi/2$.

$$\xi_f^h = \frac{c_\alpha}{s_\beta}, \quad \kappa_f^H = \frac{s_\alpha}{s_\beta}, \quad \xi_t^A = -\xi_b^A = -\xi_\tau^A = \frac{1}{t_\beta}.$$

0

Lighter h_f becomes fermiophobic!



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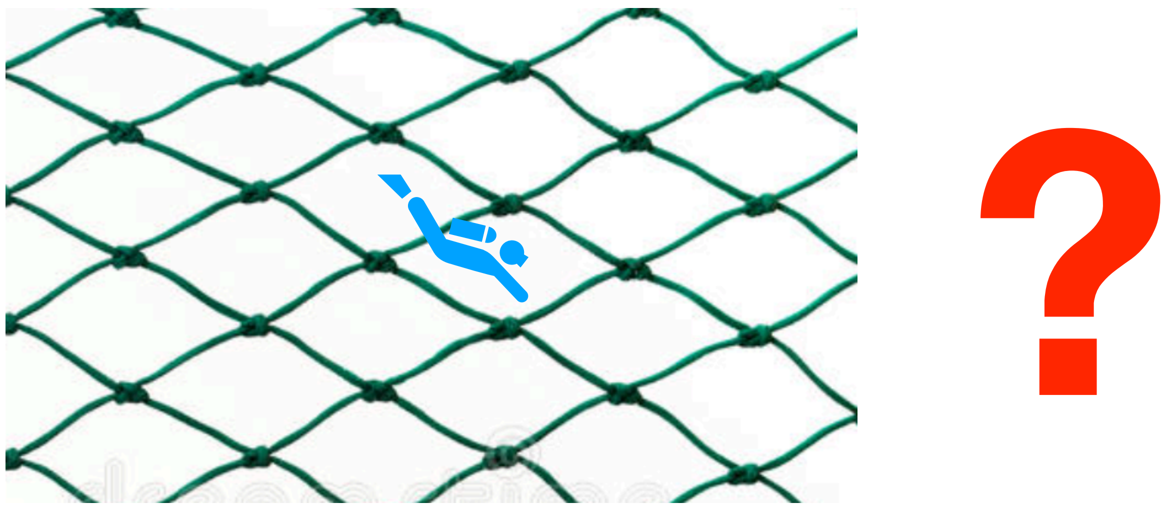
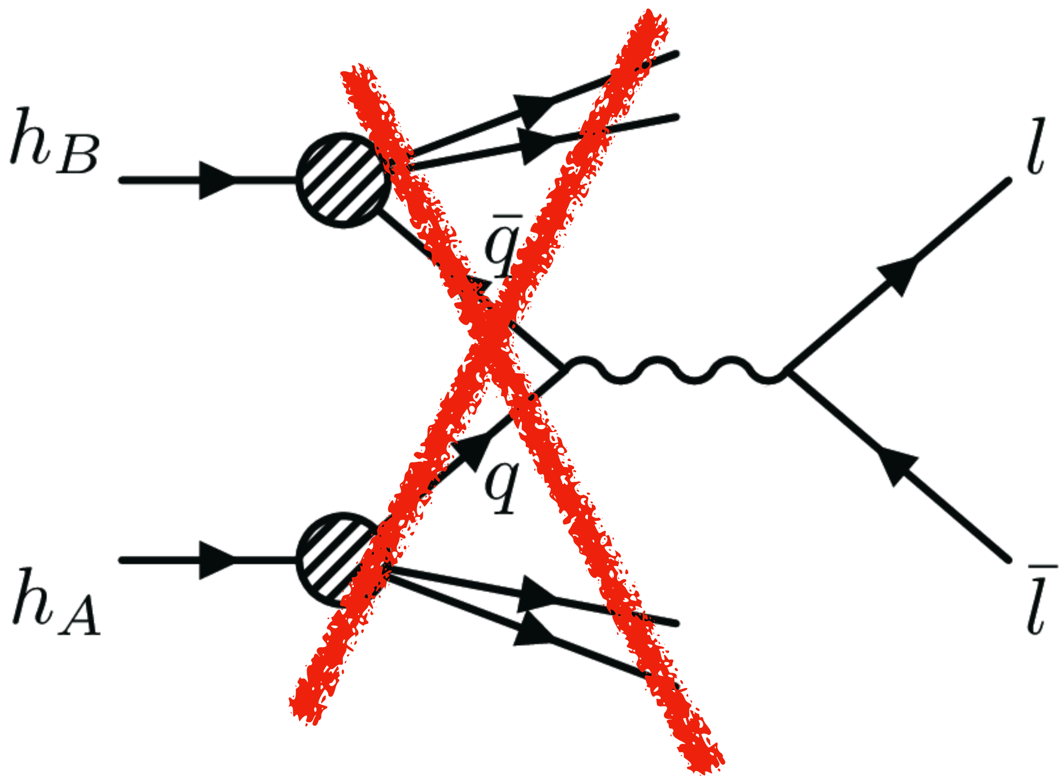
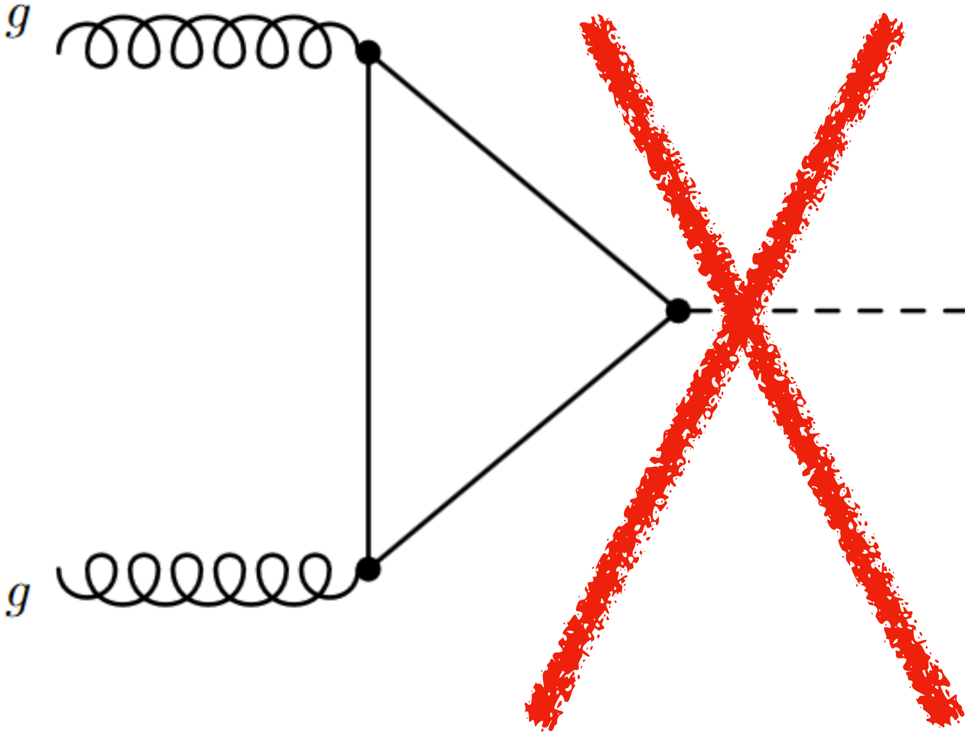


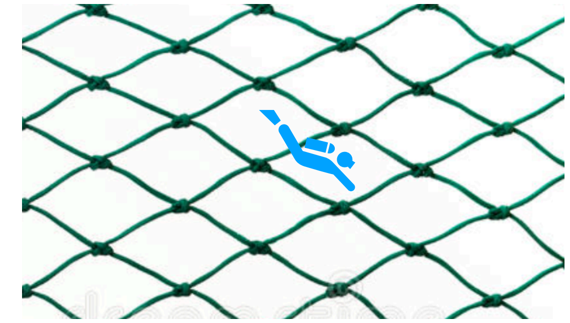




Normal productions are prohibited!

- SM Higgs boson

$$h_{\rm SM} = s_{\beta-\alpha} h + c_{\beta-\alpha} H.$$



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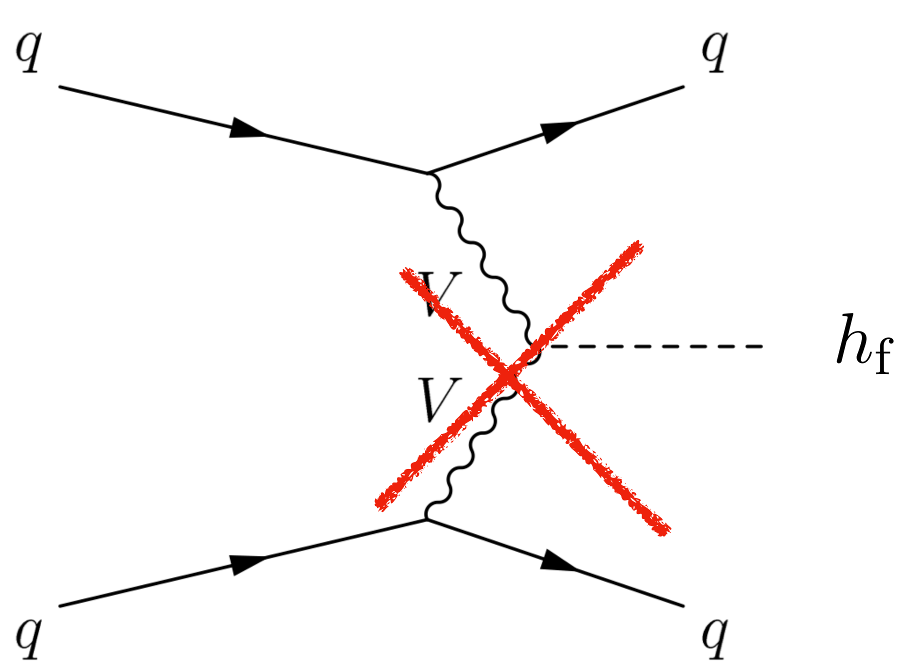
- Near the Higgs alignment limit:

$$c_{\beta-\alpha} \simeq 1 \Longrightarrow g_{h_{\rm f}-V-V} \simeq 0$$



2. RGE

❀ Does this model satisfy the theoretical stabilities?

❏ Yes. We obtain the viable parameters.

❀ But that's true at the WE scale. The couplings run!

- Running of gauge couplings

$$16\pi^2\beta_{g_3} = -7g_3^3,$$

$$16\pi^2\beta_{g_2} = \left(-\frac{10}{3} + \frac{n_d}{6}\right) g_2^3 = -3g_2^3,$$

$$16\pi^2\beta_{g_1} = \left(\frac{20}{3} + \frac{n_d}{6}\right) = 7g_1^3,$$

2 in the 2HDM

- Running of Yukawa couplings has two contributions.

$$\boxed{\beta_Y = \beta_Y^g + \beta_Y^Y}$$

$$16\pi^2\beta^g_{Y_t} = -\left(\frac{17}{12}g_1^2 + \frac{9}{4}g_2^2 + 8g_3^2\right)Y_t, \qquad 16\pi^2\beta^Y_{Y_t} = \left(\frac{3}{2}Y_b^2 + \frac{9}{2}Y_t^2\right)Y_t$$

$$16\pi^2\beta^g_{Y_\tau} = -\left(\frac{15}{4}g_1^2 + \frac{9}{4}g_2^2\right)Y_\tau, \qquad 16\pi^2\beta^Y_{Y_\tau} = \frac{5}{2}Y_\tau^3$$

- Running of quartic couplings from bosonic contributions and fermonic contributions

$$\beta_\lambda = \beta_\lambda^b + \beta_\lambda^Y$$

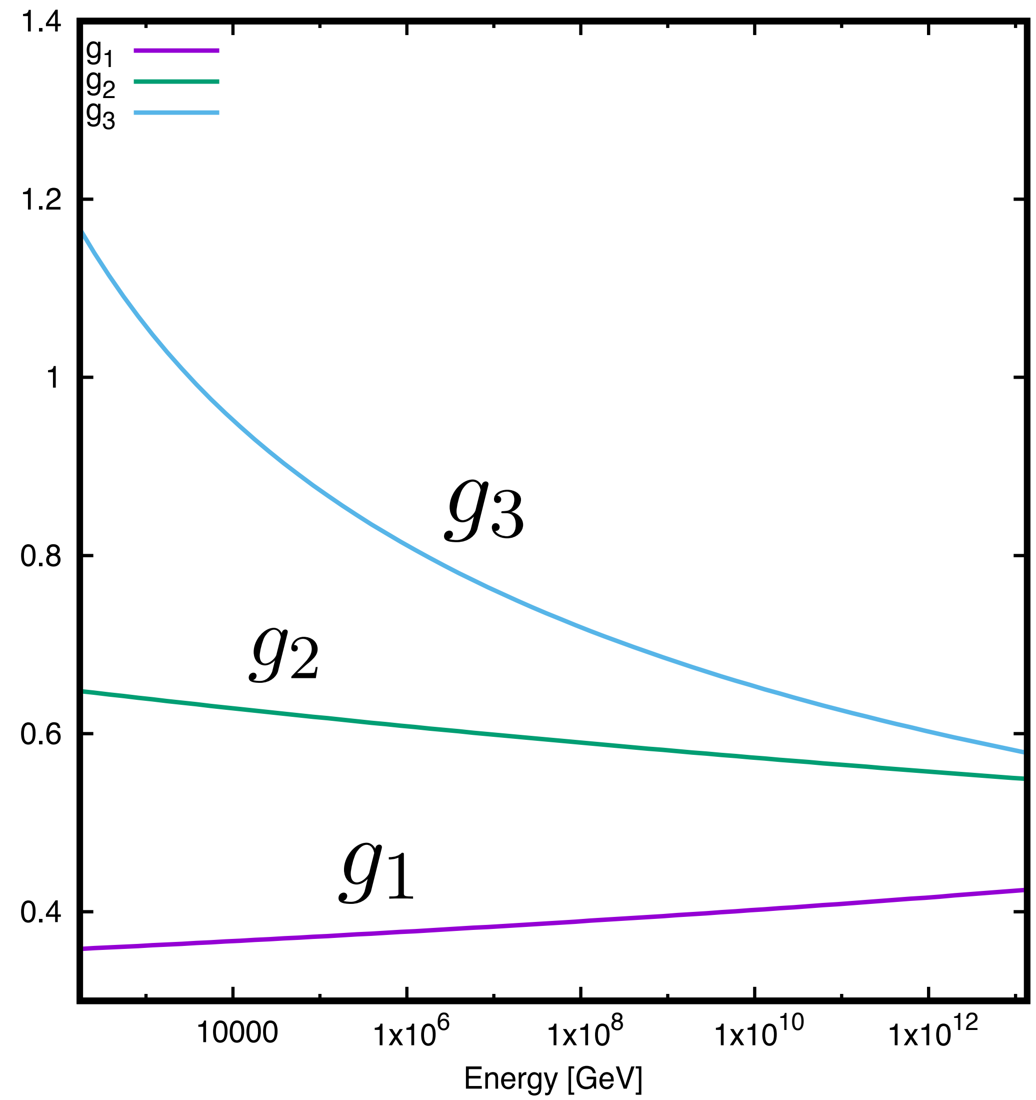
- In type-X, for example,

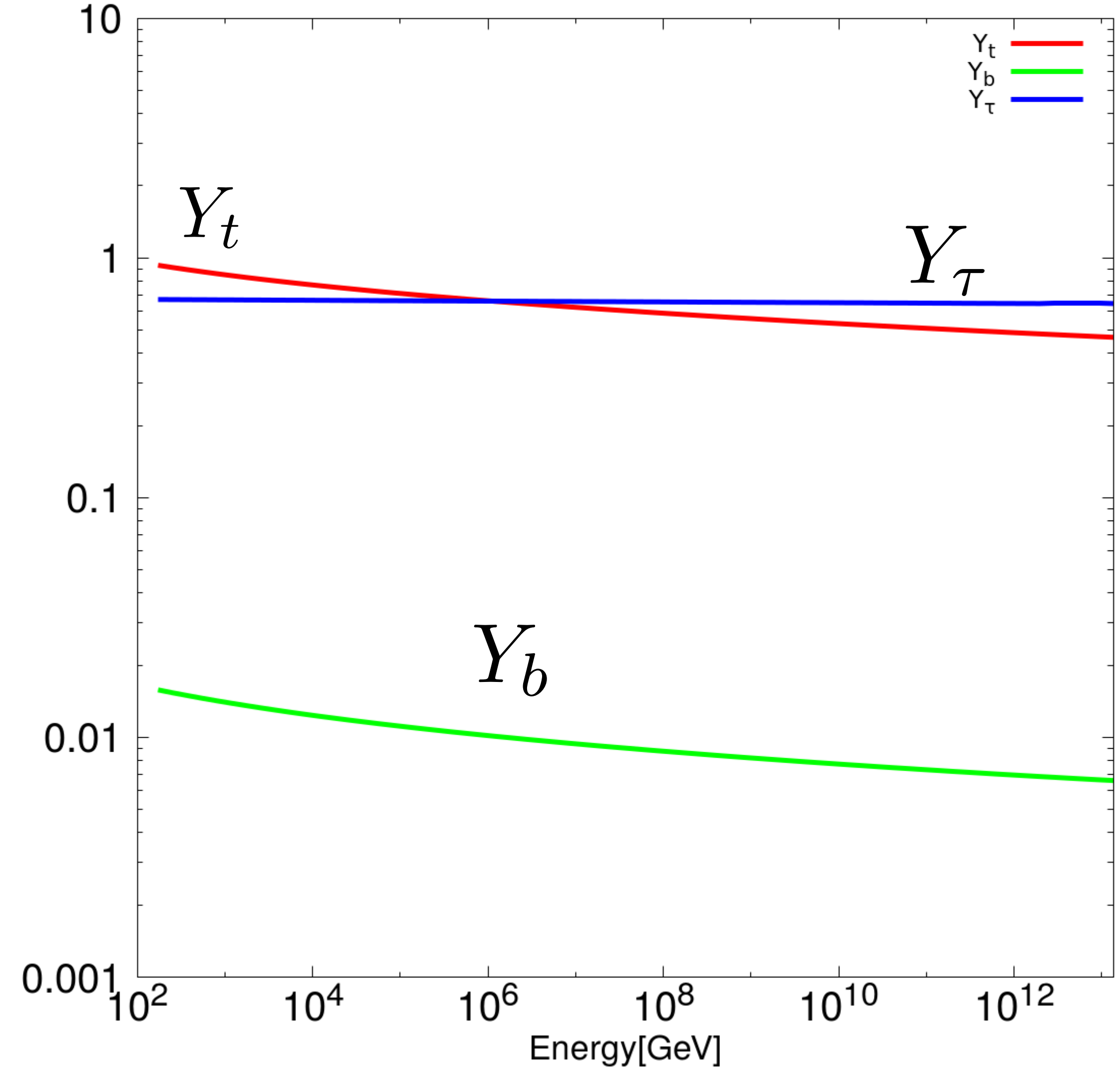
$$\begin{aligned}
16\pi^2 \beta_{\lambda_1}^b =& \frac{3}{4} g_1^4 + \frac{3}{2} g_1^2 g_2^2 + \frac{9}{4} g_2^4 \\
& - 3 g_1^2 \lambda_1 - 9 g_2^2 \lambda_1 + 12 \lambda_1^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 2\lambda_5^2, \\
16\pi^2 \beta_{\lambda_1}^Y =& - 4 Y_\tau^4 + 4 Y_\tau^2 \lambda_1.
\end{aligned}$$

BP-IS

M_H in GeV	93.6073
M_A in GeV	15.7859
$M_{H^\pm}$ in GeV	135.00
λ_1	1.0251
λ_2	0.25767
λ_3	0.58636
λ_4	-0.45412
λ_5	0.138905
m_{12}^2 in GeV^2	393.28757
$\tan\beta$	22.0
$\sin(\beta-\alpha)$	0.00601127
$y_h^\ell \times \sin(\beta-\alpha)$	1.13220955

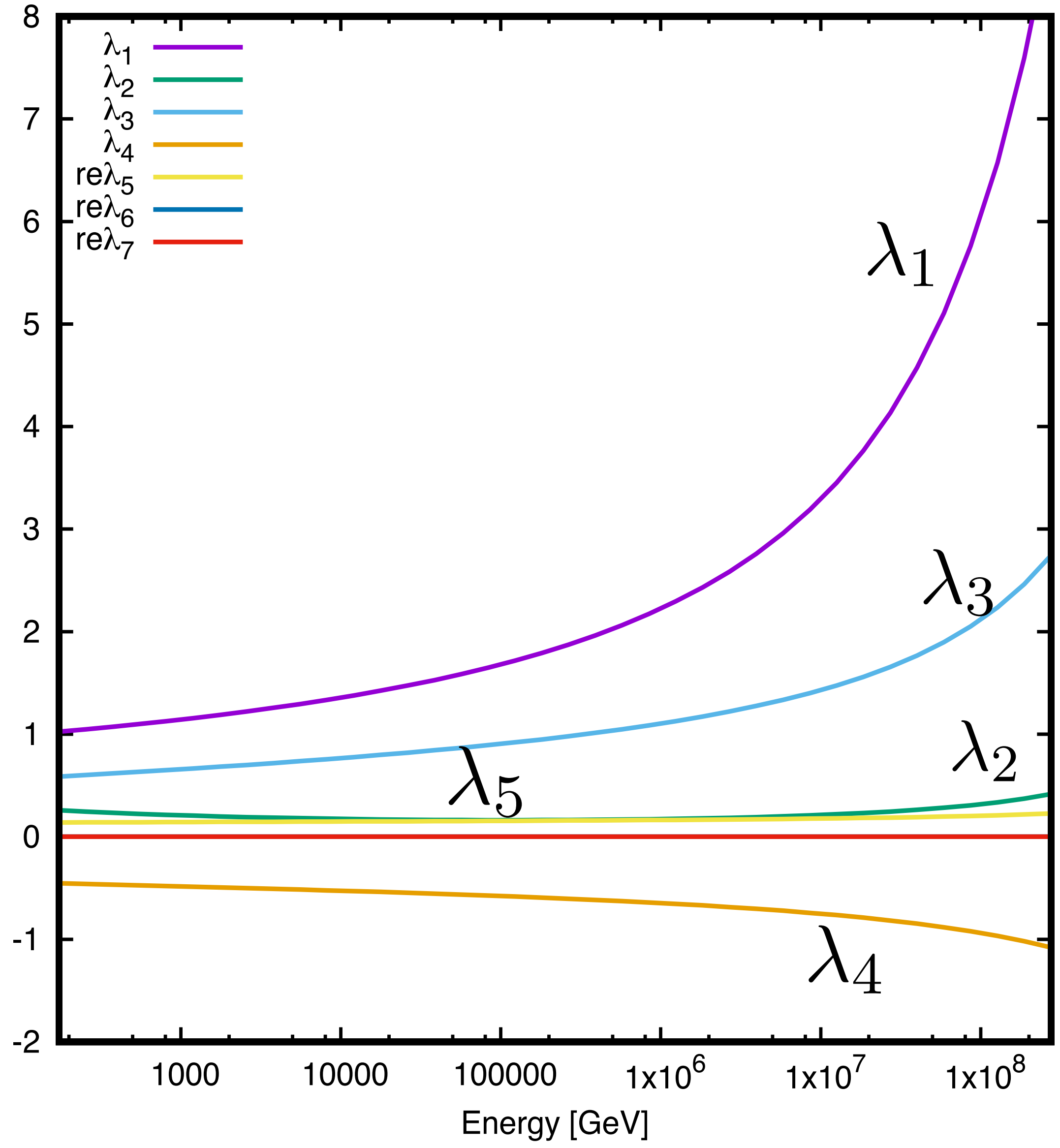
BP-IS





- No dramatic changes

BP-IS



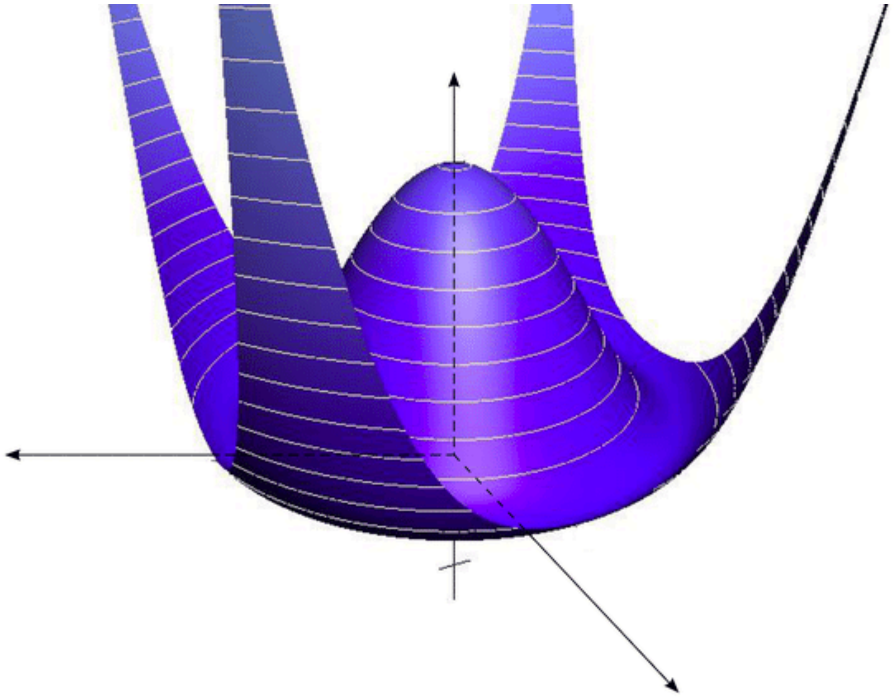
- Quartic couplings can be very large at high energy scale.

- Why is the large quartic coupling a problem?
- It can threaten the theoretical stabilities.

Theoretical stabilities

- Scalar potential bounded from below:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2},$$
$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}.$$



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2. Perturbative unitarity of scalar-scalar scattering at tree level

$$\begin{aligned}
a_\pm &= \frac{3}{2}(\lambda_1+\lambda_2) \pm \sqrt{\frac{9}{4}(\lambda_1-\lambda_2)^2 + (2\lambda_3+\lambda_4)^2}, \\
b_\pm &= \frac{1}{2}\left(\lambda_1+\lambda_2 \pm \sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_4^2}\right), \\
c_\pm &= \frac{1}{2}\left(\lambda_1+\lambda_2 \pm \sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_5^2}\right), \\
f_+ &= \lambda_3 + 2\lambda_4 + 3\lambda_5, \quad f_- = \lambda_3 + \lambda_5, \quad f_1 = f_2 = \lambda_3 + \lambda_4, \\
e_1 &= \lambda_3 + 2\lambda_4 - 3\lambda_5, \quad e_2 = \lambda_3 - \lambda_5, \quad p_1 = \lambda_3 - \lambda_4.
\end{aligned}$$

$$< 8\pi$$

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\end{aligned}$$

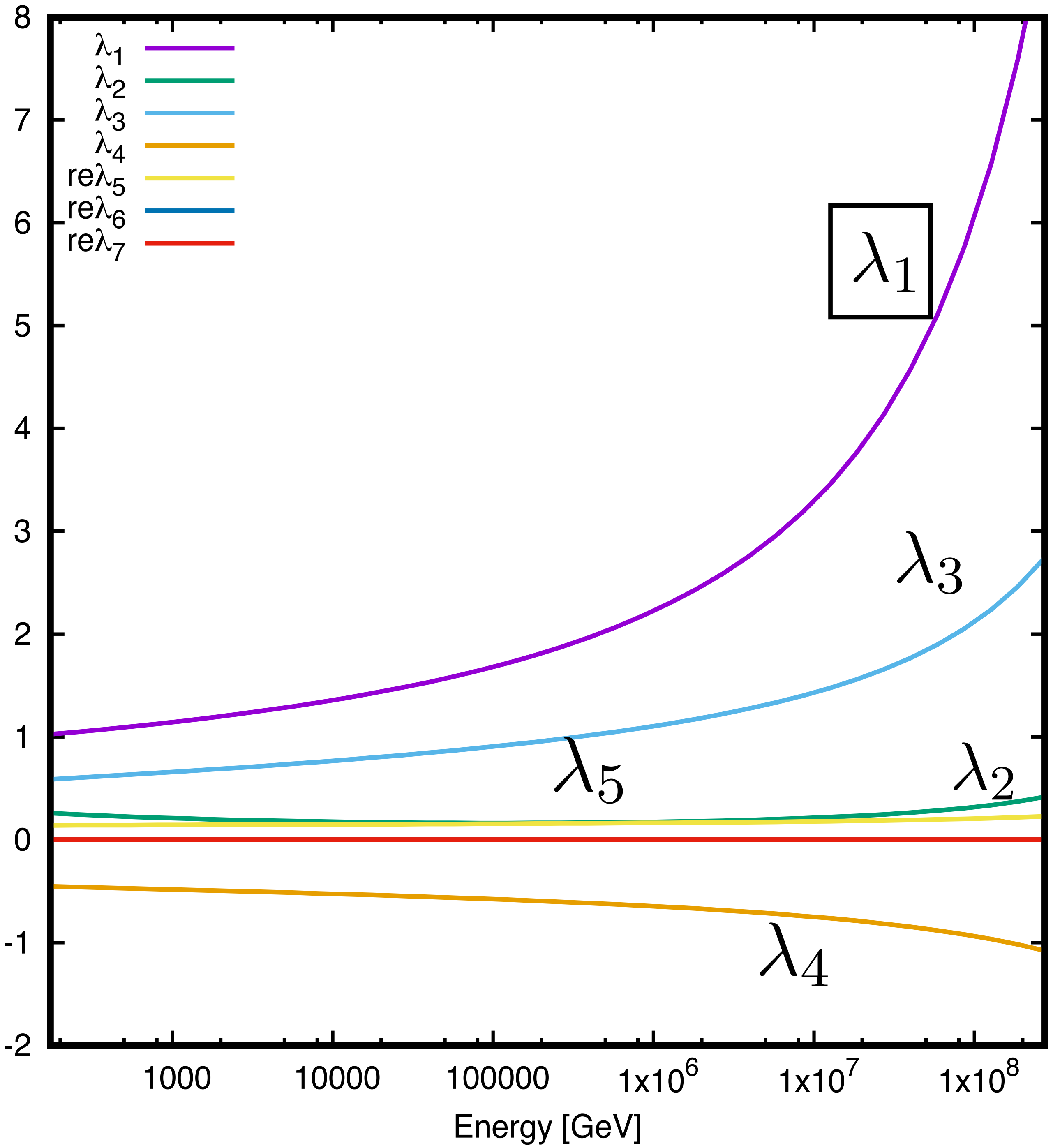
$$< 8\pi$$

3. Vacuum stability

$$D = m_{12}^2 \left(m_{11}^2 - k^2 m_{22}^2\right)\left(t_\beta - k\right) > 0,$$

$$k = (\lambda_1/\lambda_2)^{1/4}$$

BP-IS



Theoretical stability is broken at Λ.

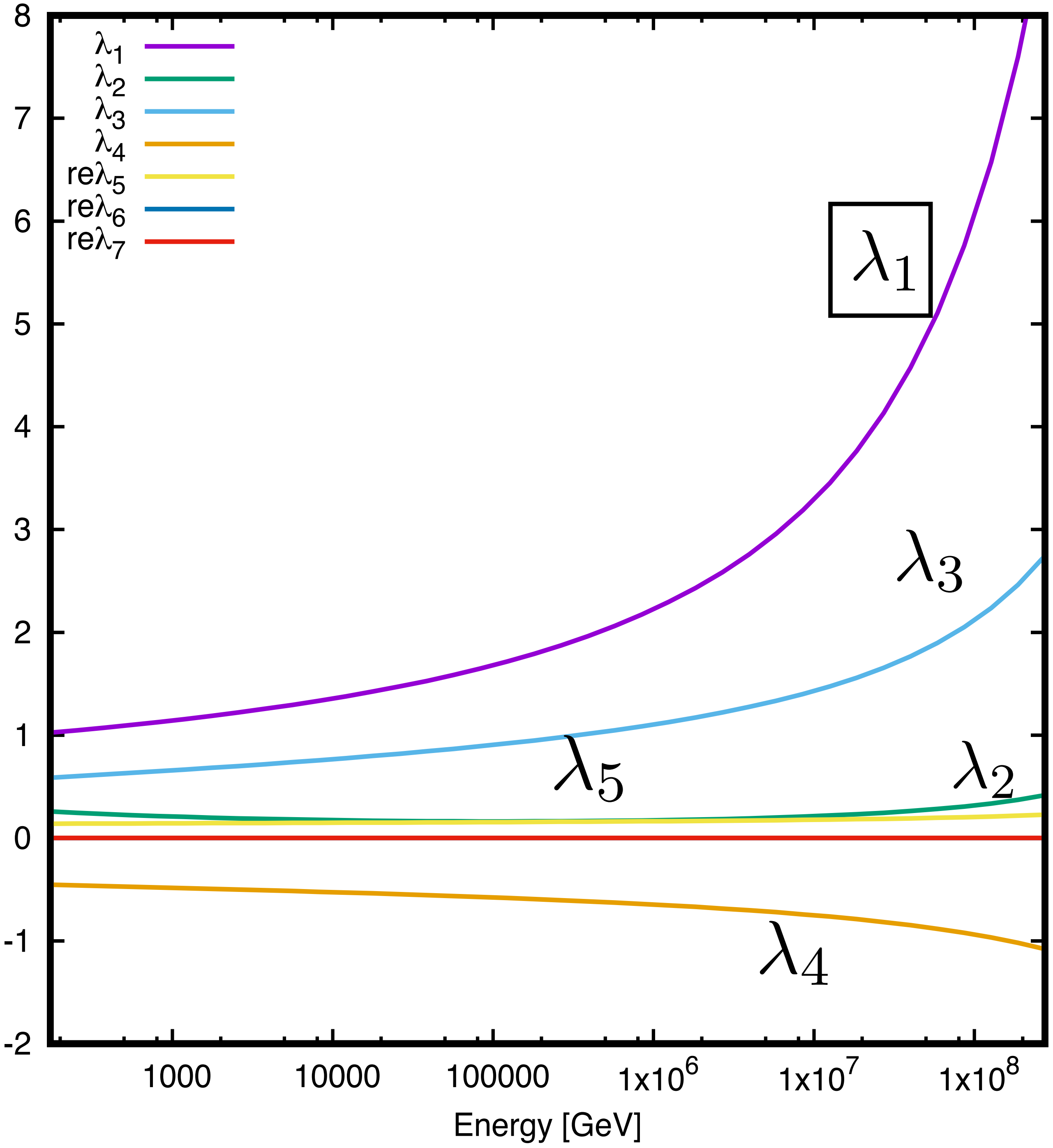
⬇

NP is not valid at Λ.

⬇

Λ is the cutoff scale of NP.

BP-IS



If Λ is the Planck scale, the model is well motivated.

- RGE analysis to calculate the cutoff scale

1. Run each parameter point to the next high energy scale via the RGEs.
2. Check three conditions—unitarity, perturbativity, and vacuum stability.
3. If any condition is broken at a particular energy scale, we stop the evolution and record the energy scale as the cutoff scale.

$$g_s, \quad g, \quad g', \quad \lambda_{1,\cdots,5}, \quad \xi_f^{h,H,A}, \quad m_{ij}^2, \quad v_i, \quad (i=1,2).$$

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3. Big impacts on the fermiophobic type-I from the high cutoff scale

Kim, Lee, Sanyal, Song [2207.05104]
PLB 2022

- Scanning

For $m_{h_\mathrm{f}} \;=\; 20,\;\; 30,\;\; 40,\;\; 60,\;\; 96\ \mathrm{GeV},$

$$M_{A/H^\pm} \in [80,\ 900]\ \ \mathrm{GeV},$$
$$t_\beta \in [1,\ 100]\,, \qquad\quad m_{12}^2 \in [0, 15000]\ \ \mathrm{GeV}^2.$$

- Scanning steps

Step A Theoretical requirements and the low energy data

1. Higgs potential being bounded from below;
2. Perturbative unitarity of the scattering amplitudes;
3. Perturbativity of the quartic couplings;
4. Vacuum stability;
5. FCNC observables.

Step B High energy collider data

1. Higgs precision data via HiggsSignals;
2. direct searches at high energy collider via HiggsBounds.

- Model survives at the EW scale, except for m_{hf}=60 GeV.

	Survival probabilities				
m_{h_f} [GeV]	20	30	40	60	96
Step-B(2)	1.10%	0.27%	0.13 %	0.026 %	25.7%
Step-B(3)	0.207%	0.048%	0.011%	0.000%	25.7%

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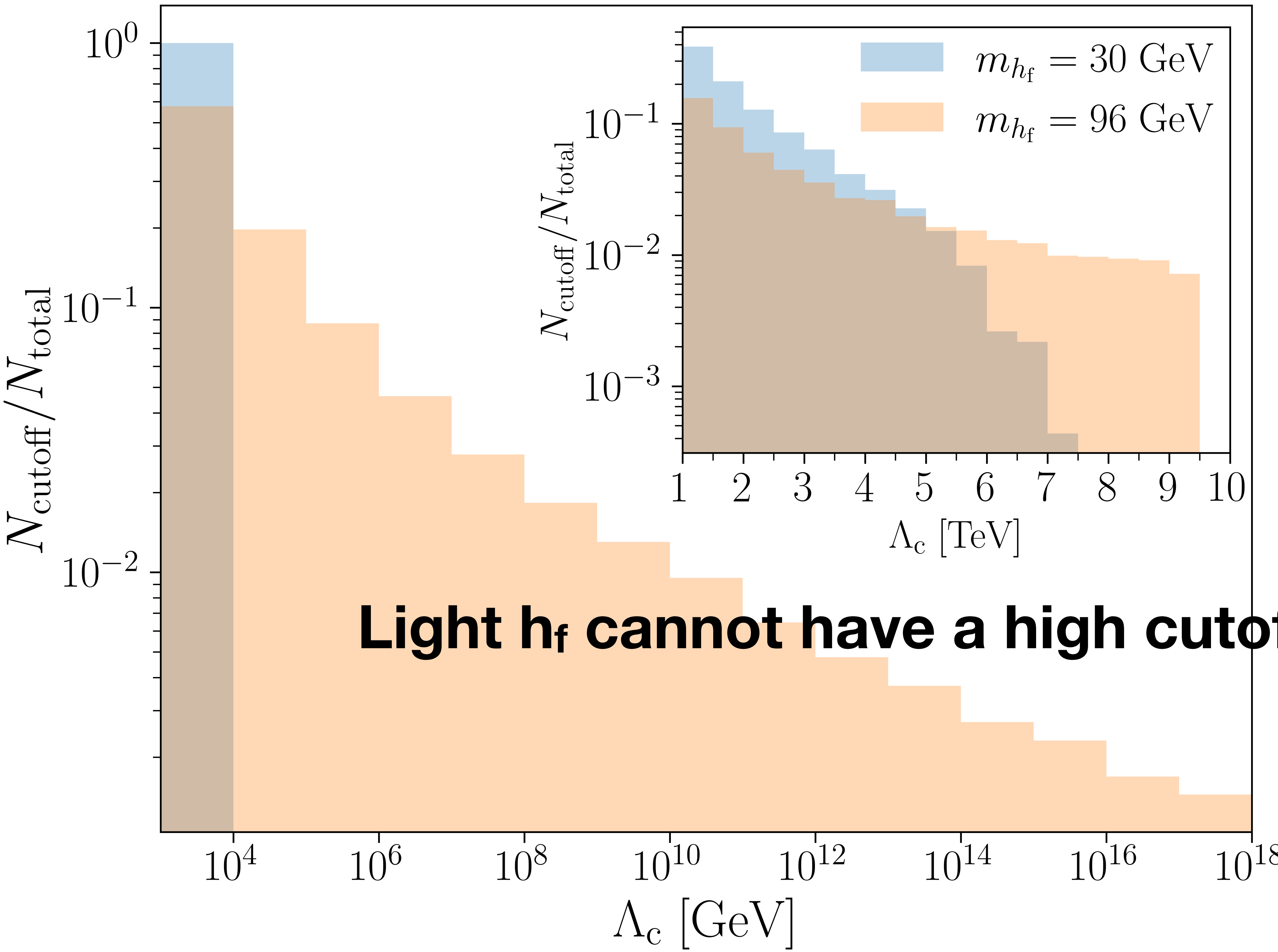
- Different high-energy scale behaviors, according to m_{hf}



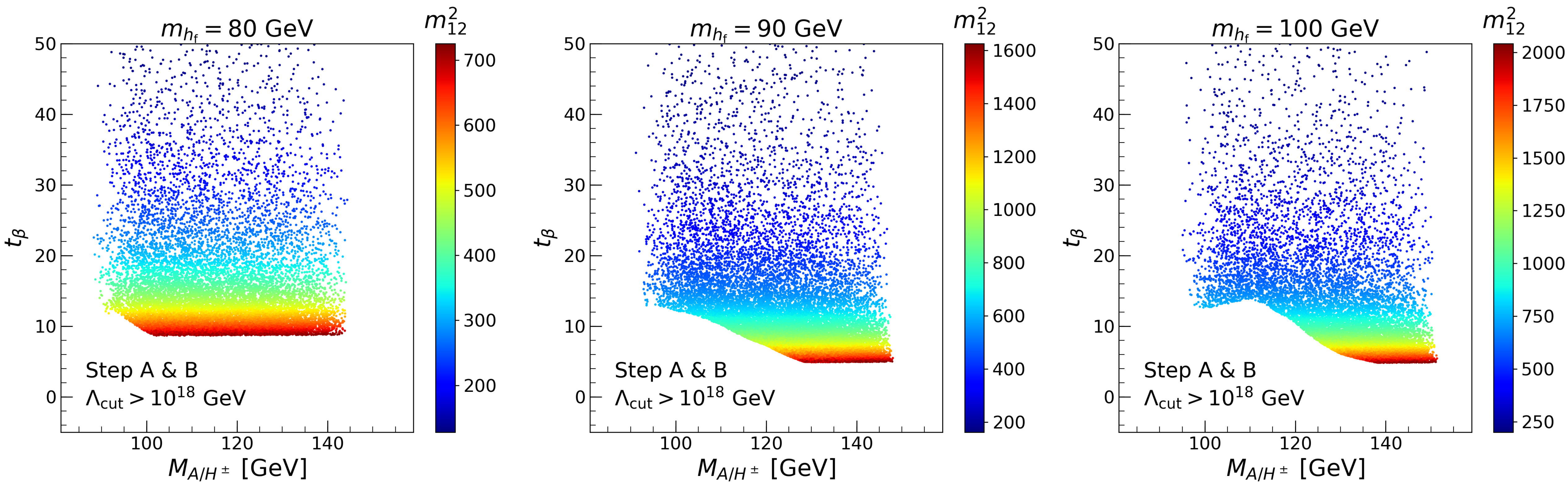
Light h_f cannot have a high cutoff scale!

4. Characteristics of the parameters with high cutoff scale

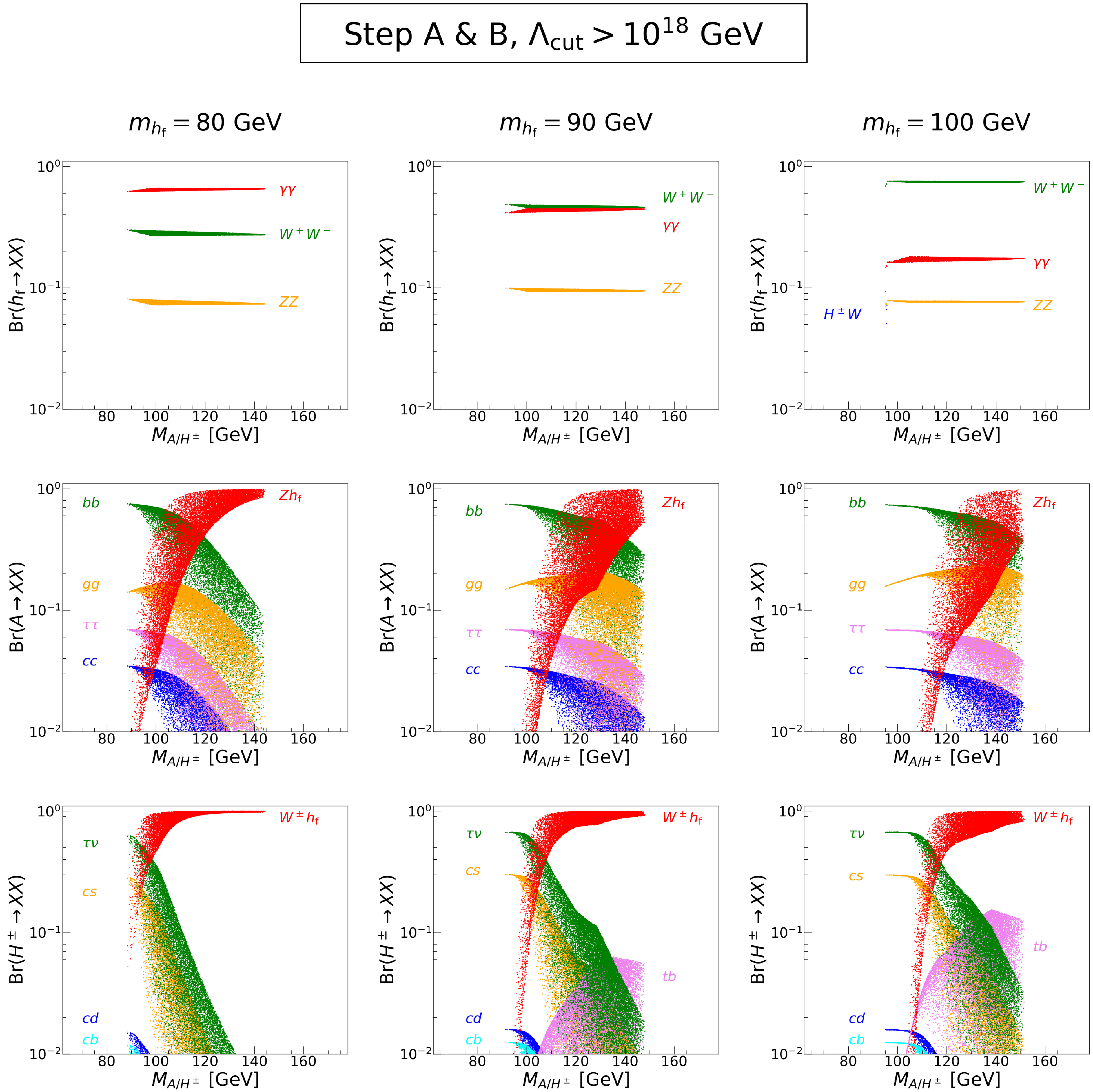
Let's focus on the fermiophobic Higgs boson which can accommodate high $\mathbf{\Lambda}$.

$$m_{h_{\rm f}} = 80,\ 90,\ 100\ {\rm GeV}.$$

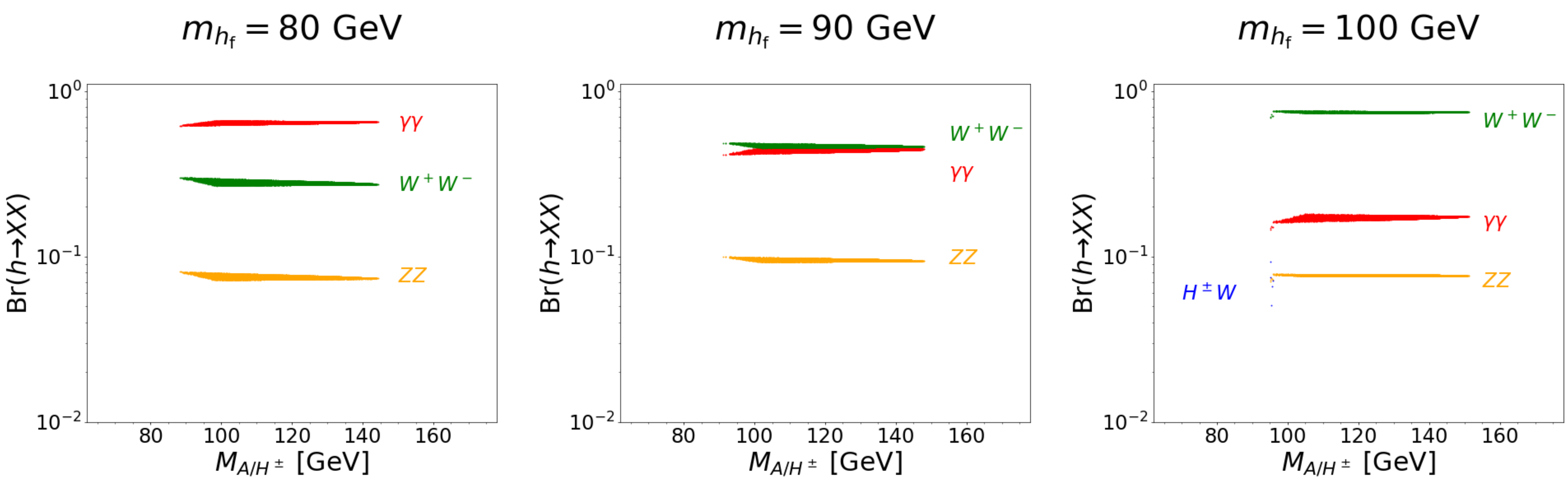
Viable parameter points with $\Lambda > 10^{18}$ GeV



- Light masses for the other BSM Higgs bosons
- tan β > 6
- m_{12}^2 is small.



Step A & B, $\Lambda_{cut} > 10^{18}$ GeV
$m_{h_f} = 80$ GeV
$m_{h_f} = 90$ GeV
$m_{h_f} = 100$ GeV
$\mathrm{Br}(h_f \to XX)$
$\gamma\gamma$
W^+W^-
ZZ
$H^\pm W$
$\mathrm{Br}(A \to XX)$
bb
gg
$\tau\tau$
cc
Zh_f
$\mathrm{Br}(H^\pm \to XX)$
$W^\pm h_f$
$\tau\nu$
cs
cd
cb
tb
$M_{A/H^\pm}$ [GeV]



- **h_f decays into a photon pair, but not dominantly.**
- **WW (3-body and 4-body) is also sizable.**

- Existing searches for the fermiophobic Higgs boson

Production \ Final	$\gamma\gamma b\bar{b}$	$\gamma\gamma\ell^+\ell^-/\gamma\gamma\nu\bar{\nu}$ $\gamma\gamma qq$	$4\gamma\nu\bar{\nu}$ $4\gamma qq$	$\gamma\gamma X$	$4\gamma X$
$e^+e^- \to h_f A$	DELPHI				
$e^+e^- \to h_f A$ $\to h_f h_f Z$			DELPHI		
$e^+e^- \to h_f Z$ (✗)		DELPHI			
$p\bar{p} \to h_f H^\pm$ $\to h_f h_f W^{(*)}$					CDF
$pp \to h_{SM} \to h_f h_f$					CMS
$pp/p\bar{p} \to h_f V/h_f jj$ (✗)				CDF D0 CMS ATLAS	

- All rely on $h_f \to \gamma\gamma$ or $h_f h_f \to \gamma\gamma\,\gamma\gamma$

- **Single h_f decay mode: a photon pair.**
- **BUT h_f h_f can have another efficient mode, γγWW.**

$$m_{h_\mathrm{f}} = 80 \text{ GeV}: \qquad \mathrm{Br}(h_\mathrm{f} h_\mathrm{f} \to \gamma\gamma WW) \simeq 36\%, \qquad \mathrm{Br}(h_\mathrm{f} \to \gamma\gamma)^2 \simeq 35\%,$$

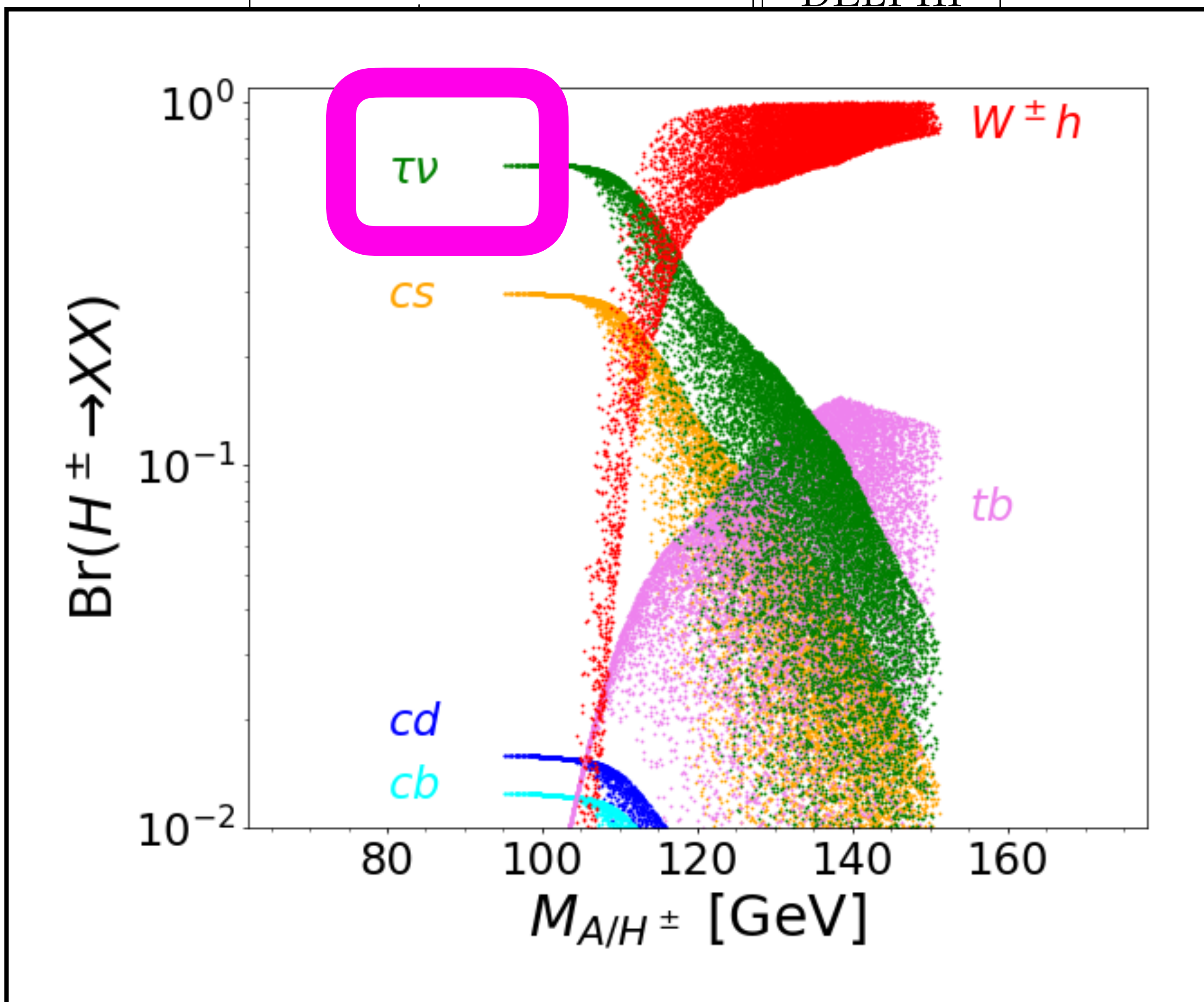
$$m_{h_\mathrm{f}} = 90 \text{ GeV}: \qquad \mathrm{Br}(h_\mathrm{f} h_\mathrm{f} \to \gamma\gamma WW) \simeq 40\%, \qquad \mathrm{Br}(h_\mathrm{f} \to \gamma\gamma)^2 \simeq 20\%,$$

$$m_{h_\mathrm{f}} = 100 \text{ GeV}: \qquad \mathrm{Br}(h_\mathrm{f} h_\mathrm{f} \to \gamma\gamma WW) \simeq 30\%, \qquad \mathrm{Br}(h_\mathrm{f} \to \gamma\gamma)^2 \simeq 4\%,$$

- Existing searches for the fermiophobic Higgs boson

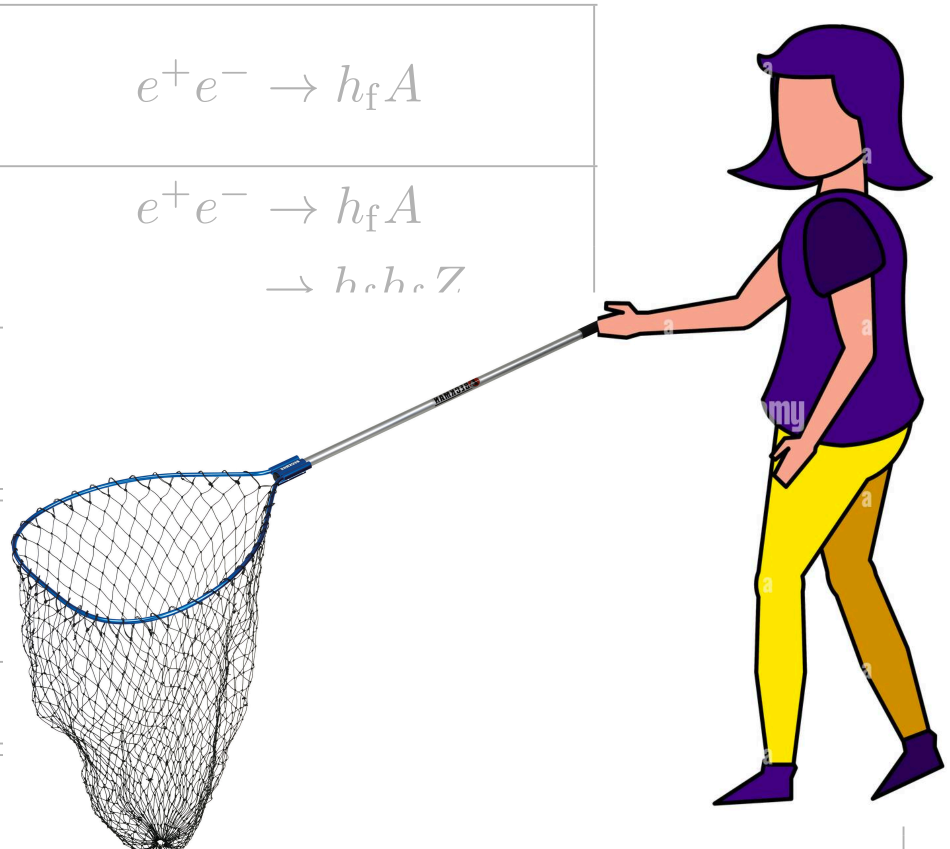
Production \ Final	$\gamma\gamma b\bar{b}$	$\gamma\gamma\ell^+\ell^-/\gamma\gamma\nu\bar{\nu}$ $\gamma\gamma qq$	$4\gamma\nu\bar{\nu}$ $4\gamma qq$	$\gamma\gamma X$	$4\gamma X$
	DELPHI				
			DELPHI		
		I			
					CDF
					CMS
				CDF D0 CMS ATLAS	

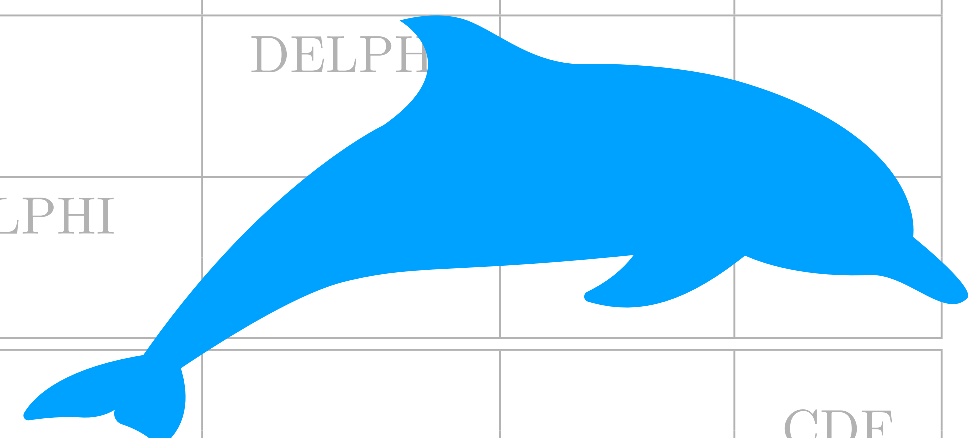
$H^{\pm} \to h_f W^{\pm *}$



- Existing searches for the fermiophobic Higgs boson

Production \ Final	$\gamma\gamma b\bar{b}$	$\gamma\gamma\ell^+\ell^- / \gamma\gamma\nu\bar{\nu}$ $\gamma\gamma qq$	$4\gamma\nu\bar{\nu}$ $4\gamma qq$	$\gamma\gamma X$	$4\gamma X$
$e^+e^- \to h_f A$					
$e^+e^- \to h_f A$ $\to h_f h_f Z$			DELPH		
		DELPHI			
					CDF
					CMS
$p\bar{p}/pp \to h_f V / h_f jj$ (X)				CDF D0 CMS ATLAS	

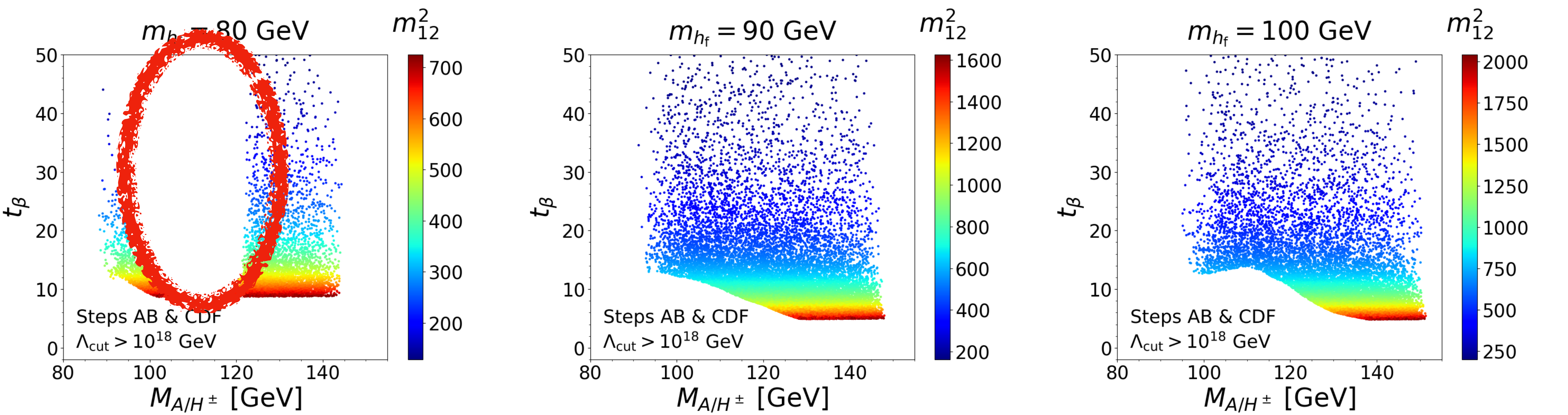




Viable parameter points with Λ>10^{18} GeV

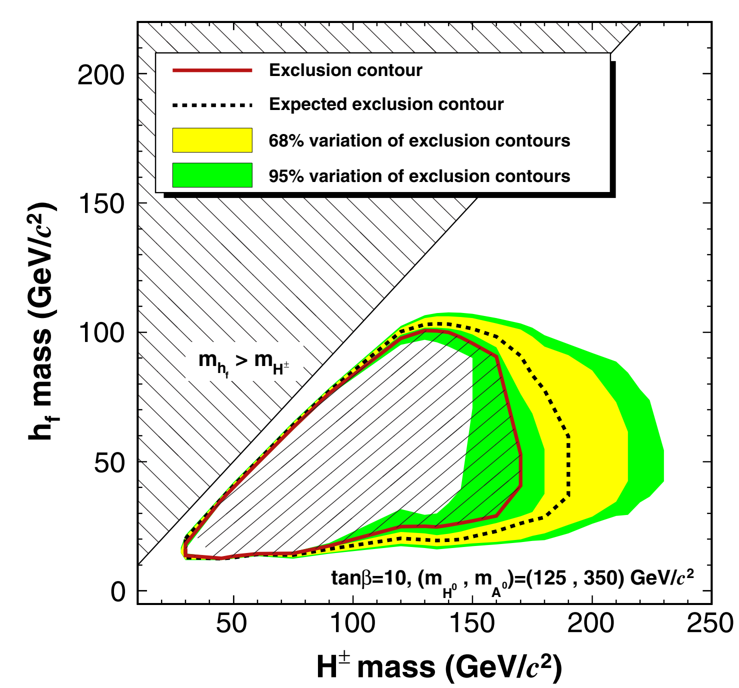
CDF 4γ

mhf=70 GeV is excluded



PHYSICAL REVIEW D **93,** 112010 (2016)

Search for a low-mass neutral Higgs boson with suppressed couplings to fermions using events with multiphoton final states



Brainstorming of all the possible final states, which depend on $M_{H^\pm}$

Target decay modes	$h_f \to 2\gamma, \quad h_f h_f \to 2\gamma W W^*$	
	Light $M_{A/H^\pm}$	Heavy $M_{A/H^\pm}$
	$H^\pm \to \tau\nu$	$H^\pm \to h_f W^*$
	$A \to bb$	$A \to h_f Z^*$

Initial production	Final states	
$q\bar{q}' \to W^* \to h_f H^\pm$	$[2\gamma]\tau\nu$ ✓	$[2\gamma\ell^\pm\ell^\pm \not{E}_T]X$ ✓
$q\bar{q}' \to W^* \to AH^\pm$	$b\bar{b}\tau\nu$	$[2\gamma\ell^\pm\ell^\pm \not{E}_T]X$ ✓
$q\bar{q} \to \gamma^*/Z^* \to H^+H^-$	$\tau\nu\tau\nu$	$[2\gamma\ell^\pm\ell^\pm \not{E}_T]X$ ✓

Brainstorming of all the possible final states, which depend on $M_{H^\pm}$

Target decay modes	$h_f \to 2\gamma, \quad h_f h_f \to 2\gamma W W^*$	
	Light $M_{A/H^\pm}$	Heavy $M_{A/H^\pm}$
	$H^\pm \to \tau\nu$	$H^\pm \to h_f W^*$
	$A \to bb$	$A \to h_f Z^*$

Initial production	Final states	
$q\bar{q}' \to W^* \to h_f H^\pm$	$[2\gamma]\tau\nu$ ✓	$[2\gamma\ell^\pm\ell^\pm \not{E}_T]X$ ✓
$q\bar{q}' \to W^* \to A H^\pm$	$b\bar{b}\tau\nu$	$[2\gamma\ell^\pm\ell^\pm \not{E}_T]X$ ✓
$q\bar{q} \to \gamma^*/Z^* \to H^+H^-$	$\tau\nu\tau\nu$	$[2\gamma\ell^\pm\ell^\pm \not{E}_T]X$ ✓

Brainstorming of all the possible final states, which depend on $M_{H^\pm}$

Target decay modes	$h_\mathrm{f} \to 2\gamma, \quad h_\mathrm{f} h_\mathrm{f} \to 2\gamma W W^*$	
	Light $M_{A/H^\pm}$	Heavy $M_{A/H^\pm}$
	$H^\pm \to \tau\nu$	$H^\pm \to h_\mathrm{f} W^*$
	$A \to bb$	$A \to h_\mathrm{f} Z^*$
Initial production	**Final states**	
$q\bar{q}' \to W^* \to h_\mathrm{f} H^\pm$	$[2\gamma]\tau\nu$ ✓	$[2\gamma\ell^\pm\ell^\pm \not{E}_T]X$ ✓
$q\bar{q}' \to W^* \to A H^\pm$	$b\bar{b}\tau\nu$	$[2\gamma\ell^\pm\ell^\pm \not{E}_T]X$ ✓
$q\bar{q} \to \gamma^*/Z^* \to H^+ H^-$	$\tau\nu\tau\nu$	$[2\gamma\ell^\pm\ell^\pm \not{E}_T]X$ ✓

$W^+W^-W^\pm$

Brainstorming of all the possible final states, which depend on $M_{H^\pm}$

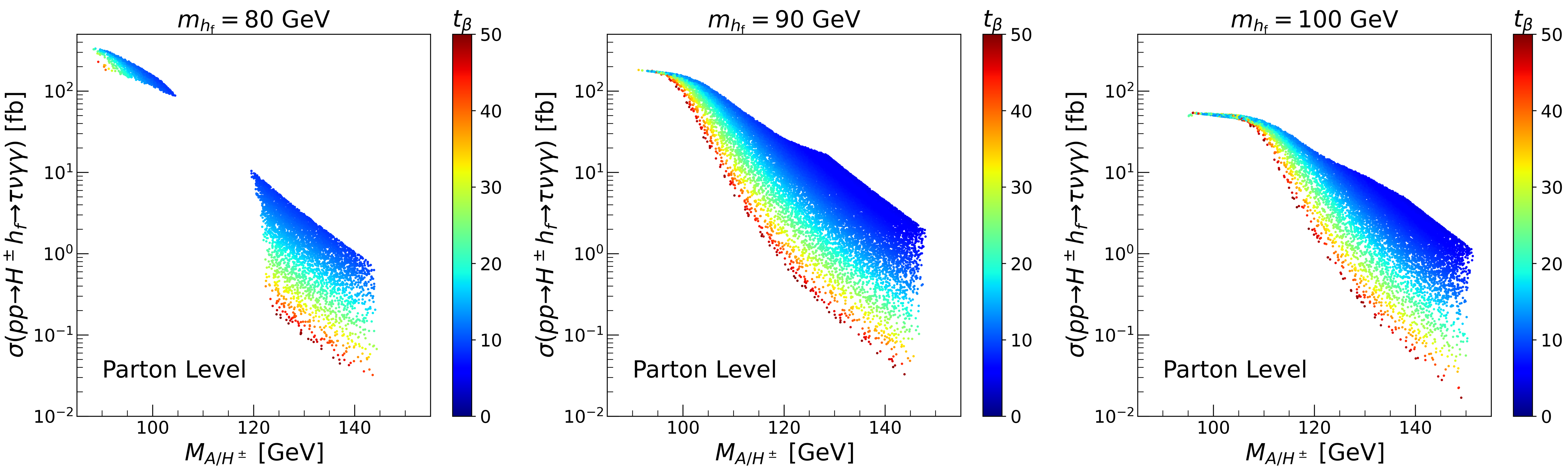
Target decay modes	$h_\mathrm{f} \to 2\gamma, \quad h_\mathrm{f} h_\mathrm{f} \to 2\gamma W W^*$	
	Light $M_{A/H^\pm}$	Heavy $M_{A/H^\pm}$
	$H^\pm \to \tau\nu$	$H^\pm \to h_\mathrm{f} W^*$
	$A \to bb$	$A \to h_\mathrm{f} Z^*$

Initial production	Final states	
$q\bar{q}' \to W^* \to h_\mathrm{f} H^\pm$	$[2\gamma]\tau\nu$ ✓	$[2\gamma\ell^\pm\ell^\pm \not{E}_T]X$ ✓
$q\bar{q}' \to W^* \to AH^\pm$	$b\bar{b}\tau\nu$	$[2\gamma\ell^\pm\ell^\pm \not{E}_T]X$ ✓
$q\bar{q} \to \gamma^*/Z^* \to H^+H^-$	$\tau\nu\tau\nu$	$[2\gamma\ell^\pm\ell^\pm \not{E}_T]X$ ✓

$W^+W^-W^\pm$

5. The first golden channel: $\tau^{\pm}\nu\gamma\gamma$

Parton-level cross sections



- The larger tanβ, the smaller σ.
- The larger MH±, the smaller σ.
- The signal rate is sizable, above 100 fb.

Signal-to-Background analysis at the detector level

Final state of $\tau^\pm \nu\gamma\gamma$

$$
\begin{aligned}
\text{BP-}\tau 1: \quad & m_{h_\mathrm{f}} = 80 \text{ GeV}, & M_{A/H^\pm} &= 95.8 \text{ GeV}, \\
& m_{12}^2 = 501.1 \text{ GeV}^2, & t_\beta &= 12.5, \\
\text{BP-}\tau 2: \quad & m_{h_\mathrm{f}} = 90 \text{ GeV}, & M_{A/H^\pm} &= 100.3 \text{ GeV}, \\
& m_{12}^2 = 318.4 \text{ GeV}^2, & t_\beta &= 25.4, \\
\text{BP-}\tau 3: \quad & m_{h_\mathrm{f}} = 100 \text{ GeV}, & M_{A/H^\pm} &= 106.9 \text{ GeV}, \\
& m_{12}^2 = 274.3 \text{ GeV}^2, & t_\beta &= 36.4.
\end{aligned}
$$

Cross sections in units of fb for $\tau^{\pm}\nu\gamma\gamma$							
	BP-τ1	BP-τ2	BP-τ3	$jj\gamma$	$j\gamma\gamma$	$W^{\pm}\gamma\gamma$	$Z\gamma\gamma$
parton-level with MG	197.2	122.1	43.5	7.73×10^7	1.08×10^5	140.3	184.7
Basic Selection	21.84	14.87	5.89	1.25×10^3	45.25	0.761	0.954
$p_T^{\gamma_1} > 70$ GeV $p_T^{\gamma_2} > 40$ GeV	9.31	7.08	3.11	144.62	28.73	0.205	0.186
$m_{\gamma_1\gamma_2} \in [62.5, 125]$ GeV	9.20	6.98	3.08	21.94	4.35	0.023	0.032
$\not{E}_T > 70$ GeV	6.49	4.89	2.16	2.51	0.052	0.007	0.003
veto jets	4.36	3.18	1.43	0.98	0.011	0.004	0.002

Cross sections in units of fb for $\tau^{\pm}\nu\gamma\gamma$							
	BP-τ1	BP-τ2	BP-τ3	$jj\gamma$	$j\gamma\gamma$	$W^{\pm}\gamma\gamma$	$Z\gamma\gamma$
parton-level with `MG`	197.2	122.1	43.5	7.73×10^7	1.08×10^5	140.3	184.7
Basic Selection	21.84	14.87	5.89	1.25×10^3	45.25	0.761	0.954
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veto jets	4.36	3.18	1.43	0.98	0.011	0.004	0.002

For the basic selection

- We select events with at least one τ_h-jet and two leading photons with $p_T > 20$ GeV, $|\eta| < 2.5$, and the angular separation of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.4$.
- We require the missing transverse energy $\not{E}_T > 20$ GeV.

Cross sections in units of fb for $\tau^{\pm}\nu\gamma\gamma$							
	BP-τ1	BP-τ2	BP-τ3	$jj\gamma$	$j\gamma\gamma$	$W^{\pm}\gamma\gamma$	$Z\gamma\gamma$
parton-level with MG	197.2	122.1	43.5	7.73×10^7	1.08×10^5	140.3	184.7
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veto jets	4.36	3.18	1.43	0.98	0.011	0.004	0.002

$$P_{j\to\gamma} = 5 \times 10^{-4}$$

- Huge backgrounds from jj**γ**.
- QCD jets can be mistagged as photons or tau.
- The contribution from radiation photons is sizable.

Cross sections in units of fb for $\tau^{\pm}\nu\gamma\gamma$							
	BP-τ1	BP-τ2	BP-τ3	$jj\gamma$	$j\gamma\gamma$	$W^{\pm}\gamma\gamma$	$Z\gamma\gamma$
parton-level with MG	197.2	122.1	43.5	7.73×10^7	1.08×10^5	140.3	184.7
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$p_T^{\gamma_1} > 70$ GeV $p_T^{\gamma_2} > 40$ GeV	9.31	7.08	3.11	144.62	28.73	0.205	0.186
$m_{\gamma_1\gamma_2} \in [62.5, 125]$ GeV	9.20	6.98	3.08	21.94	4.35	0.023	0.032
$\not{E}_T > 70$ GeV	6.49	4.89	2.16	2.51	0.052	0.007	0.003
veto jets	4.36	3.18	1.43	0.98	0.011	0.004	0.002

Veto jets with $p_T > 20$ GeV and $|\eta| < 2.5$

We can tame the background!

Significance with 300/fb

$$\Delta_{\rm bg} = 0: \qquad \mathcal{S}_{\rm BP-\tau 1} = 52.8, \qquad \mathcal{S}_{\rm BP-\tau 2} = 41.0, \qquad \mathcal{S}_{\rm BP-\tau 3} = 20.9,$$

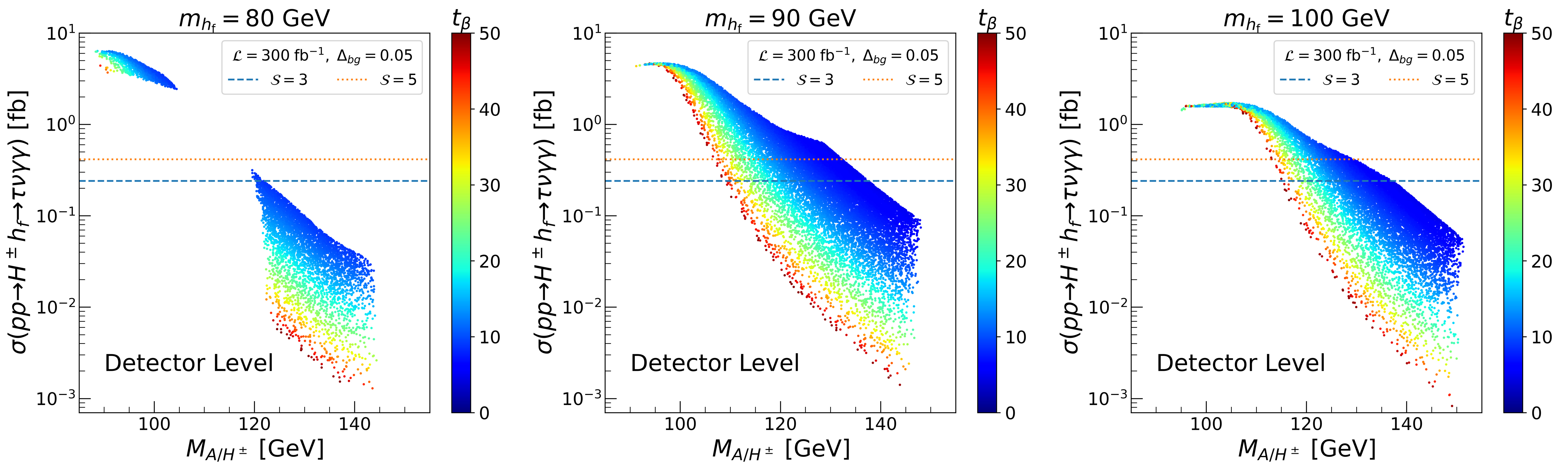
$$\Delta_{\rm bg} = 5\%: \qquad \mathcal{S}_{\rm BP-\tau 1} = 34.2, \qquad \mathcal{S}_{\rm BP-\tau 2} = 27.3, \qquad \mathcal{S}_{\rm BP-\tau 3} = 14.7.$$

Very promising!

- ❀ Isn’t it cherry-picking? The fancy results are for the BPs.

- ❑ OOps

- ❀ What about the other parameters?

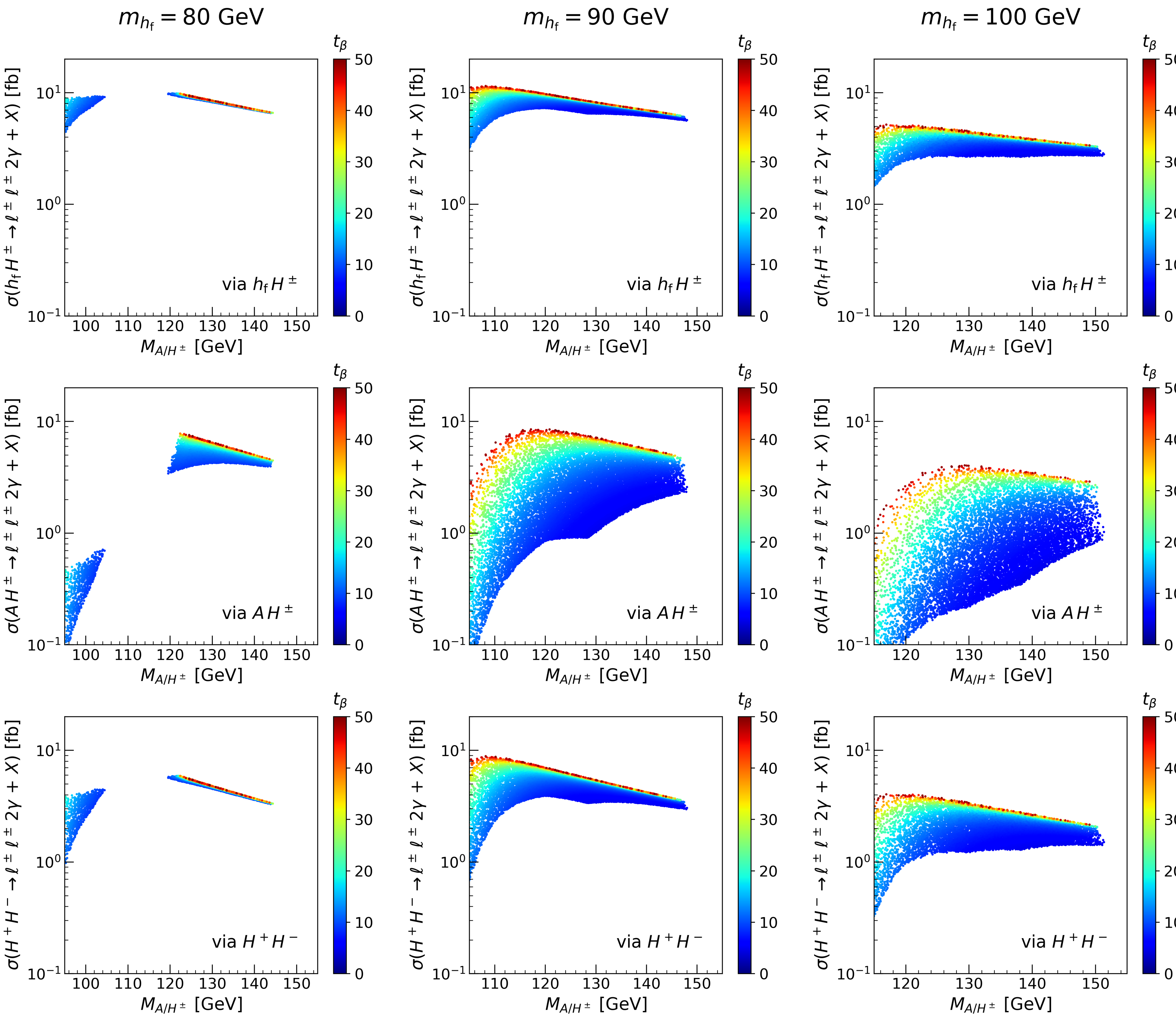


- Most of the parameters with light $M_{H\pm}$ can enjoy the significance larger than 5 with 300/fb.
- The larger tanβ, the smaller σ.

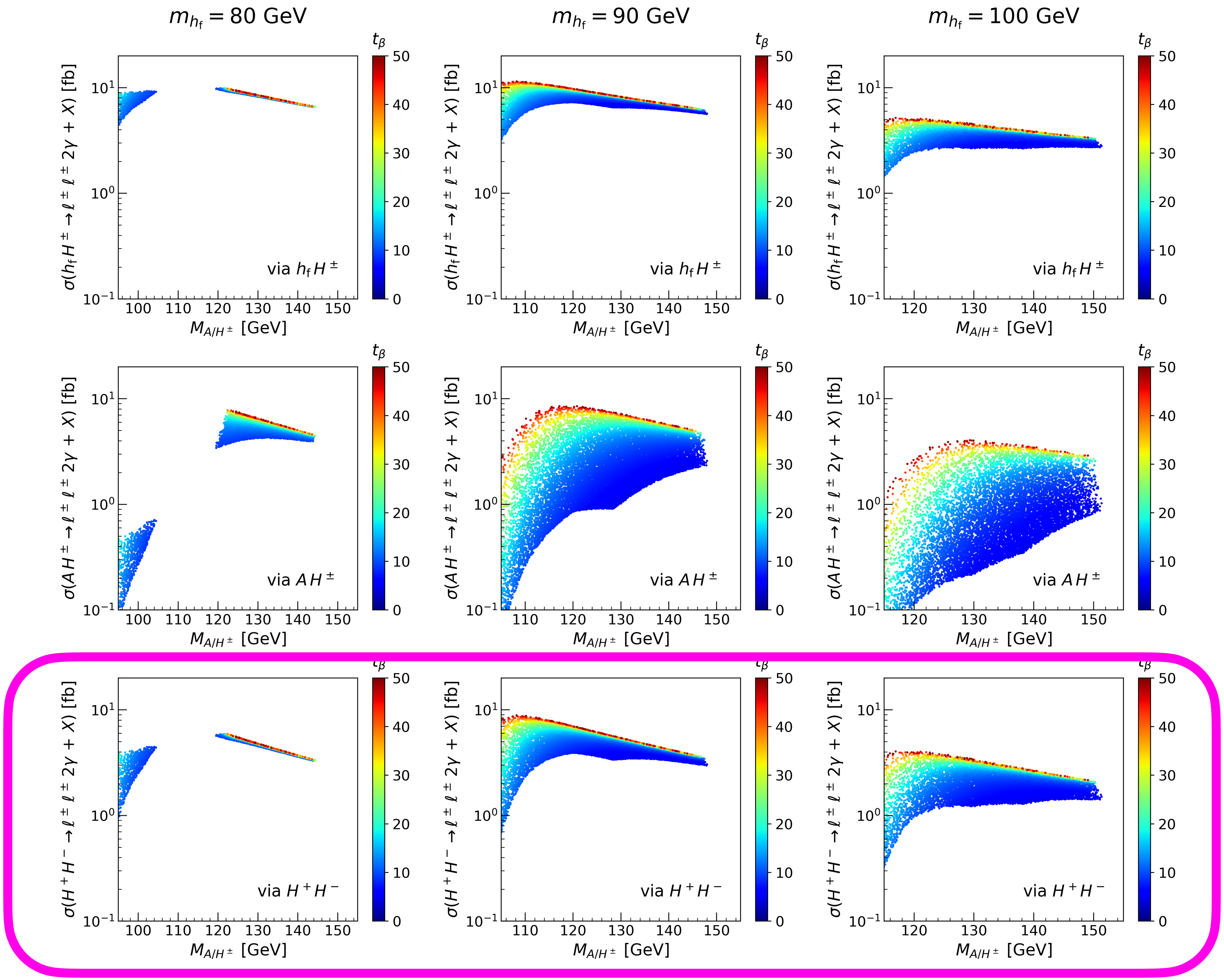
6. The second golden mode: $\ell^{\pm}\ell^{\pm}\gamma\gamma$ + X

Initial production	Final states	
$q\bar{q}' \to W^* \to H^\pm h_\mathrm{f}$	$[2\gamma]\tau^\pm\nu$ ✓	$[\ell^\pm\ell^\pm\gamma\gamma \not{E}_T]X$ ✓
$q\bar{q}' \to W^* \to AH^\pm$	$b\bar{b}\tau^\pm\nu$	$[\ell^\pm\ell^\pm\gamma\gamma \not{E}_T]X$ ✓
$q\bar{q} \to \gamma^*/Z^* \to H^+H^-$	$\tau^\pm\nu\tau^\pm\nu$	$[\ell^\pm\ell^\pm\gamma\gamma \not{E}_T]X$ ✓

Three channels

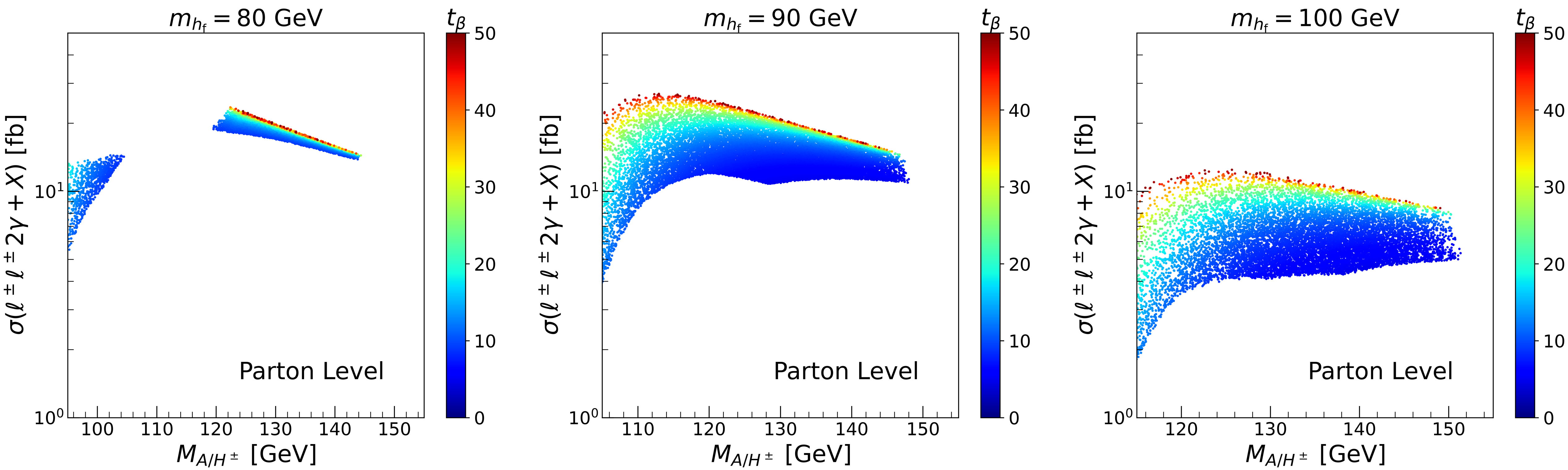


All three channels have compatible σ.



Not considered in the literature.

Inclusive cross sections



- The larger tanβ, the larger σ.
- The signal rate is sizable, above 10 fb.

Signal-to-background analysis at the detector level

BP-SS1: $m_{h_\mathrm{f}} = 80$ GeV, $M_{A/H^\pm} = 122.4$ GeV,

$m_{12}^2 = 166.5\ \mathrm{GeV}^2$, $t_\beta = 38.4$,

BP-SS2: $m_{h_\mathrm{f}} = 90$ GeV, $M_{A/H^\pm} = 112.9$ GeV,

$m_{12}^2 = 166.1\ \mathrm{GeV}^2$, $t_\beta = 48.7$,

BP-SS3: $m_{h_\mathrm{f}} = 100$ GeV, $M_{A/H^\pm} = 125.7$ GeV,

$m_{12}^2 = 203.5\ \mathrm{GeV}^2$, $t_\beta = 49.1$.

Cross sections in units of fb for $\ell^\pm\ell^\pm\gamma\gamma\not{E}_T X$						
	BP-SS1	BP-SS2	BP-SS3	$W^\pm Zj$	$Z\ell^+\ell^-j$	$W^\pm Z\gamma j$
parton-level with MG	23.50	26.95	12.45	1.25×10^3	170.43	7.80
Selecting $\ell^\pm\ell^\pm\gamma\gamma$	9.57	9.53	7.50	115.75	22.10	1.03
$p_T > 20$ GeV, $\not{E}_T > 20$ GeV	1.50	0.77	0.43	0.164	0.046	0.04
$\|\eta\| < 2.5,\ \Delta R > 0.4$	0.735	0.354	0.227	0.070	0.027	0.021

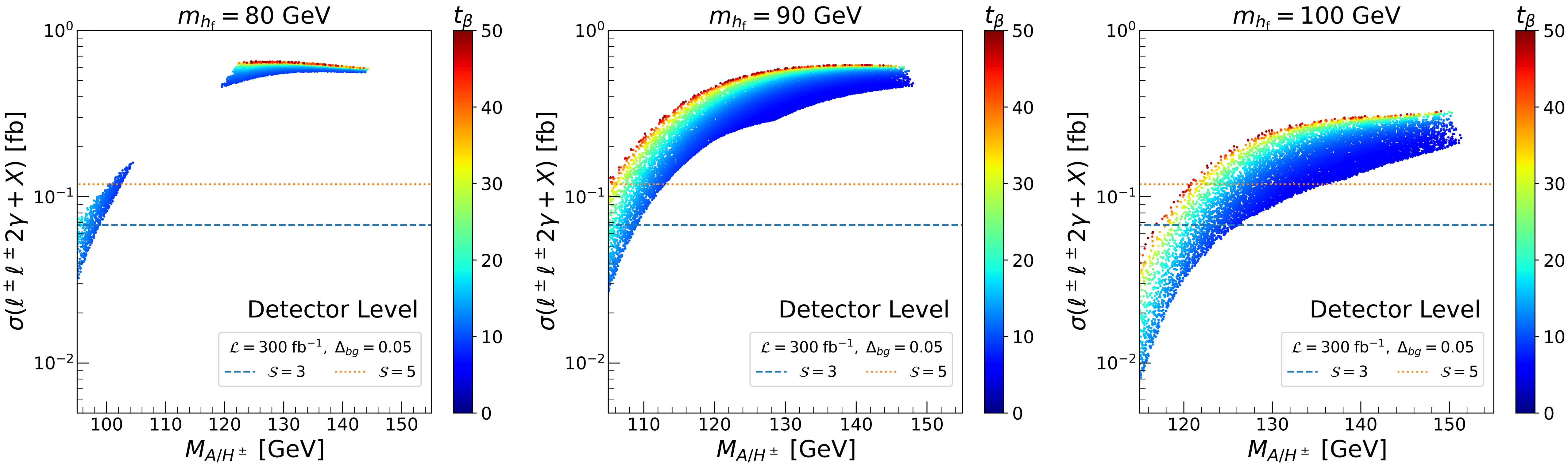
Almost background-free environment with the basic selection

Signal significances with 300/fb

$$\Delta_{\rm bg} = 0: \qquad \mathcal{S}_{\rm BP-SS1} = 23.9, \qquad \mathcal{S}_{\rm BP-SS2} = 13.4, \qquad \mathcal{S}_{\rm BP-SS3} = 9.3,$$

$$\Delta_{\rm bg} = 5\%: \qquad \mathcal{S}_{\rm BP-SS1} = 21.8, \qquad \mathcal{S}_{\rm BP-SS2} = 12.5, \qquad \mathcal{S}_{\rm BP-SS3} = 8.7.$$

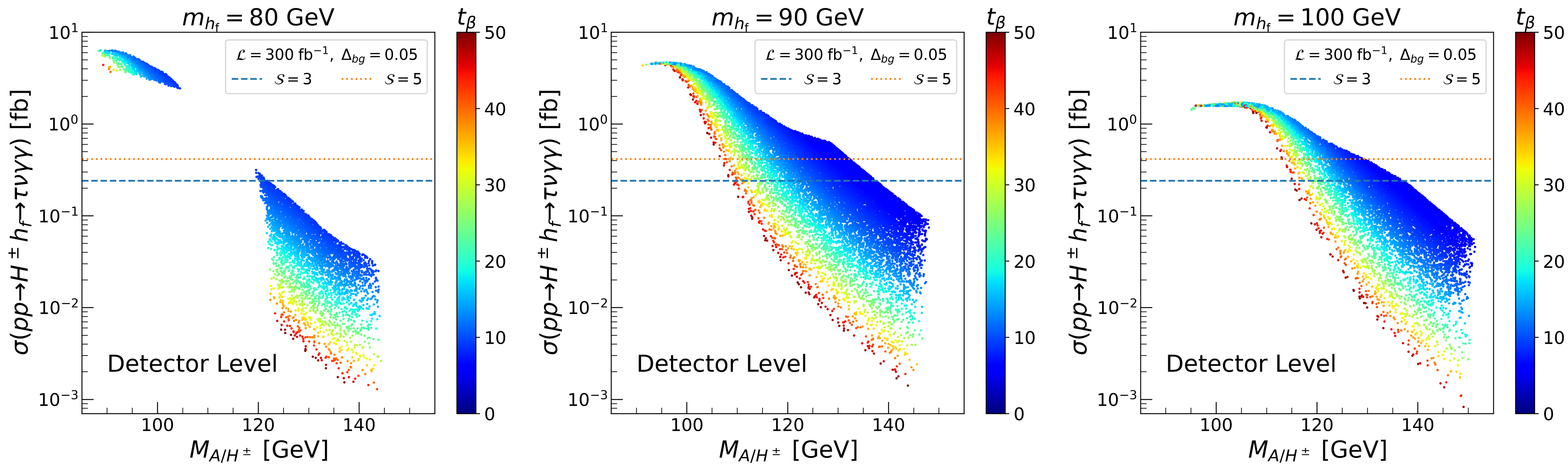
Again very promising!!!



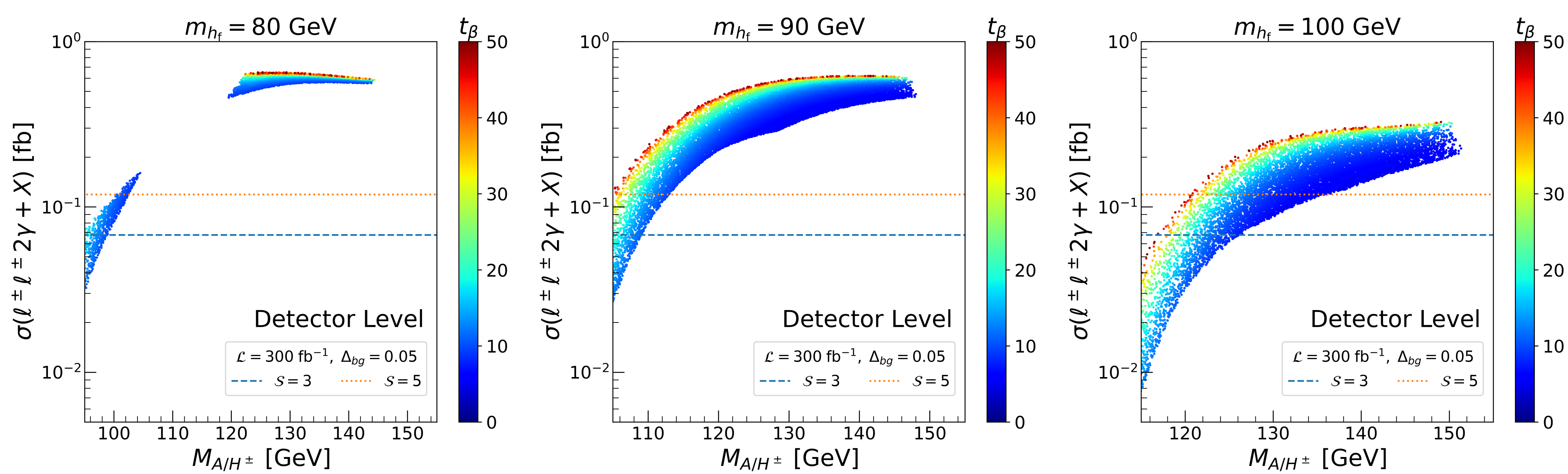
Most parameters with heavy MH± can be probed.

Total complementary between two channels

$\tau^{\pm}\nu\gamma\gamma$



$\ell^{\pm}\ell^{\pm}\gamma\gamma$ + X



7. Conclusions

- The light fermiophobic Higgs boson model in type-I can retain the cutoff scale all the way up to the Planck scale.
- High cutoff scale requires m_{hf} above 80 GeV and $M_A/M_{H^\pm}$ below 142 GeV.
- Two discovery channels, $\tau^\pm\nu\gamma\gamma$ and $\ell^\pm\ell^\pm\gamma\gamma$ + X, can discover the fermiophobic Higgs boson well with 300/fb. .