HPNP2023 — The 6th International Workshop on "Higgs as a Probe of New Physics 2023"
2023. 6.5.

Exotic but efficient channels to probe the fermiophobic Higgs boson in the type-I 2HDM

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JHEP 04 (2023) 083, *Phys.Lett.B* 834 (2022)

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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 $138\,\text{fb}^{-1}$. 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.

Too early to give up!

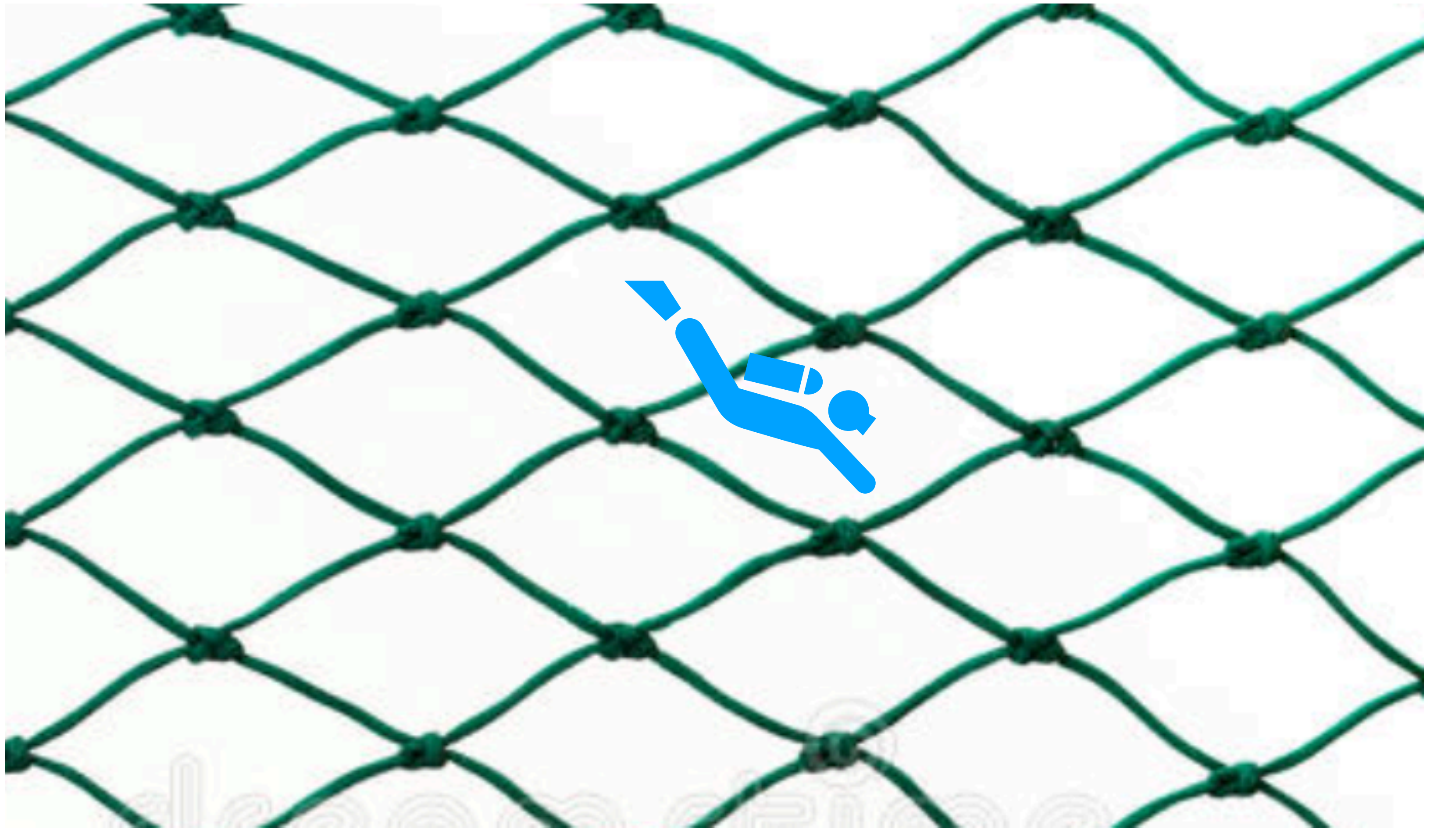
Let’s check every loophole.

What if the NP signal is hidden in the shadow under the lamp?

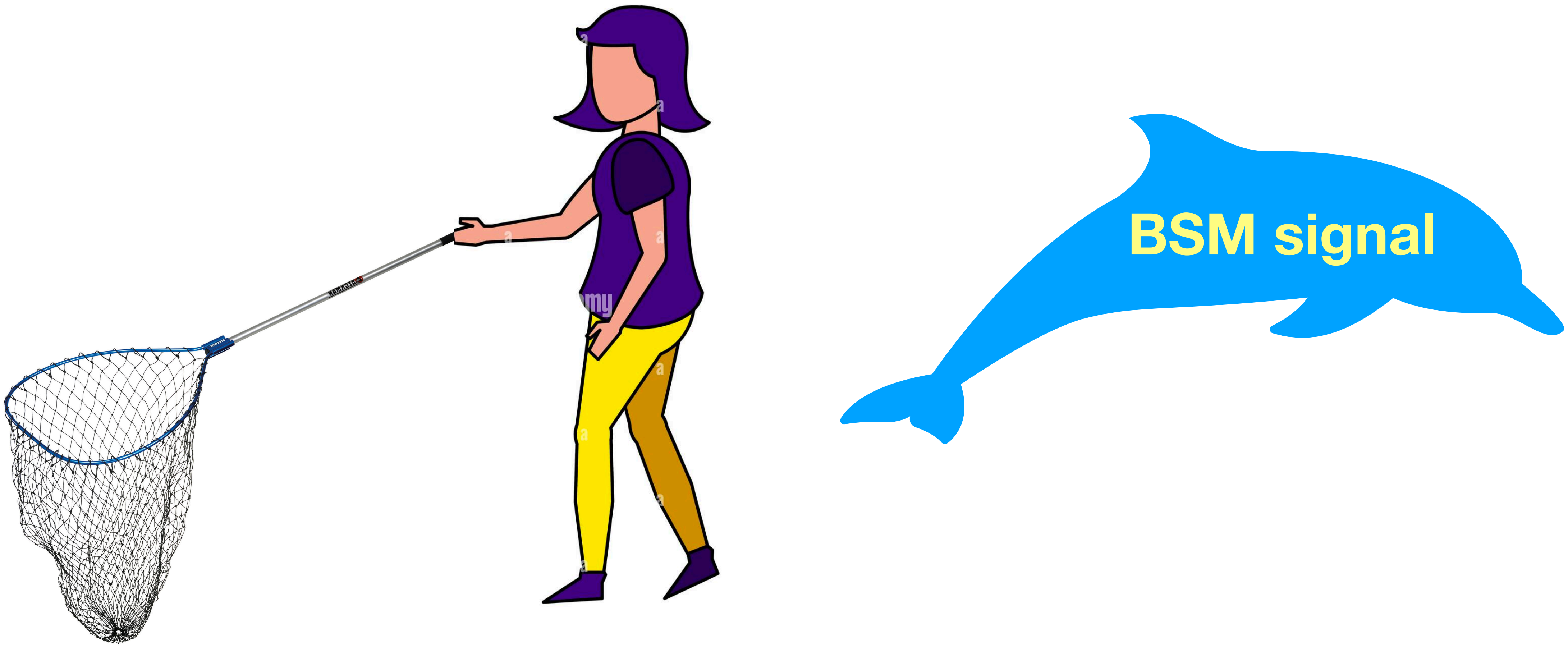
What if the NP signal is hidden in the shadow under the lamp?

Two explanations

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



2. We did not search the right place.



A new particle
which satisfies two conditions:

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

1. Fermiophobic Higgs boson in Type-I 2HDM

2. Viable parameter space with a high cutoff scale

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

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

5. Conclusions

1. Fermiophobic Higgs boson in Type-I 2HDM

- Two Higgs doublet fields

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

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

- Discrete Z_2 symmetry to avoid tree-level FCNC

$$\boxed{\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_1}$$

- SM Higgs boson: a linear combination of 2 CP-even Higgs bosons

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

Two setups in Type-I

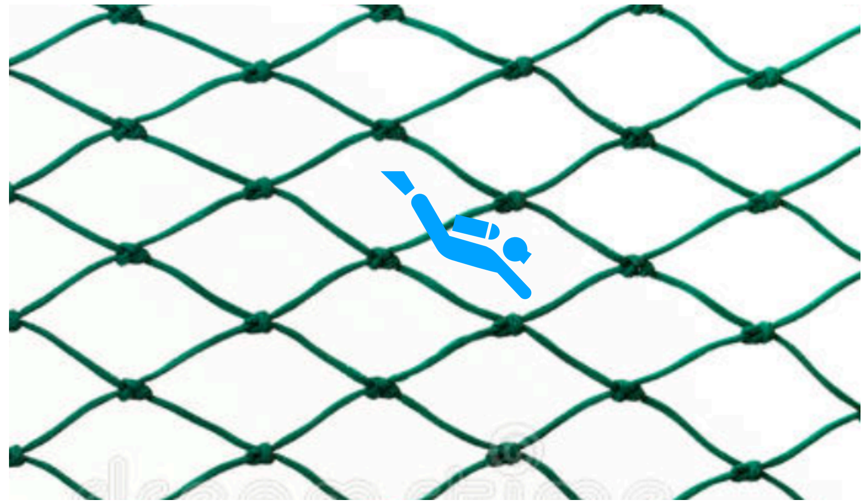
1. Inverted Higgs scenario

2. Fermiophobic light CP-even Higgs boson

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

0

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



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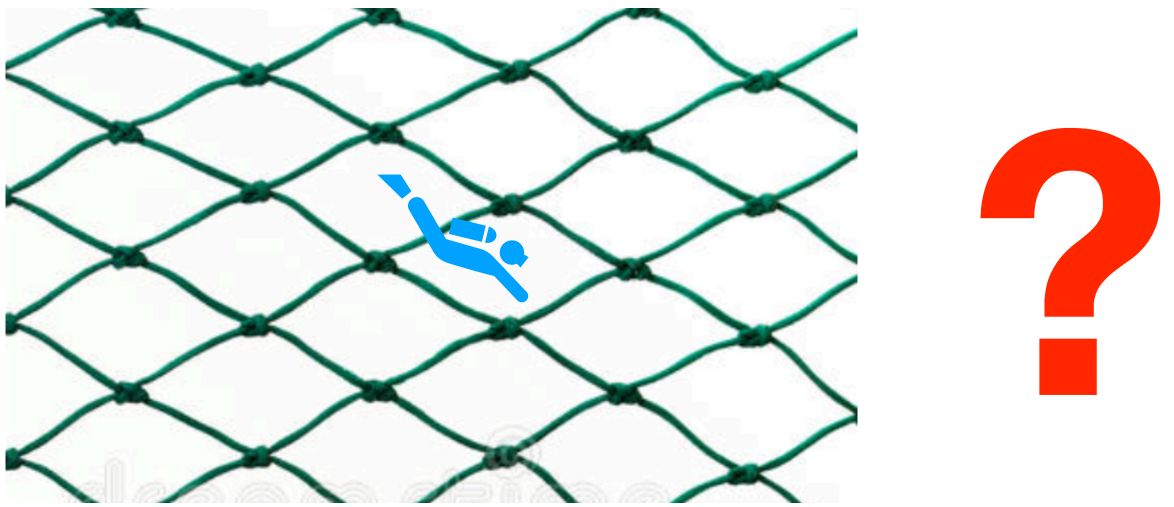
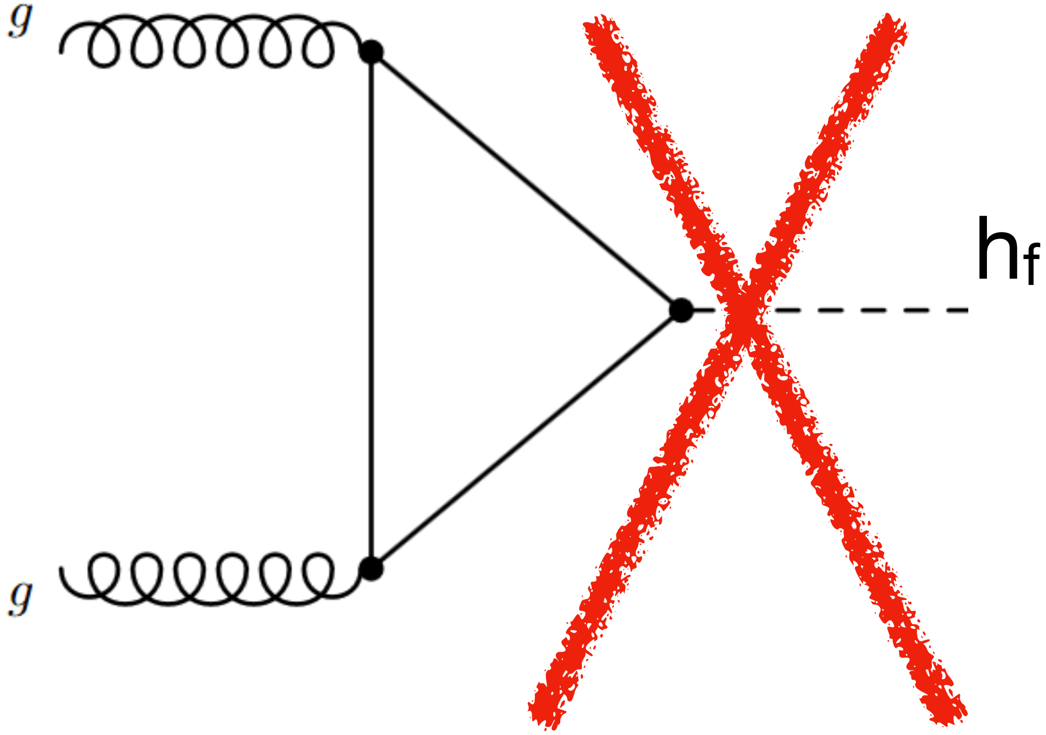
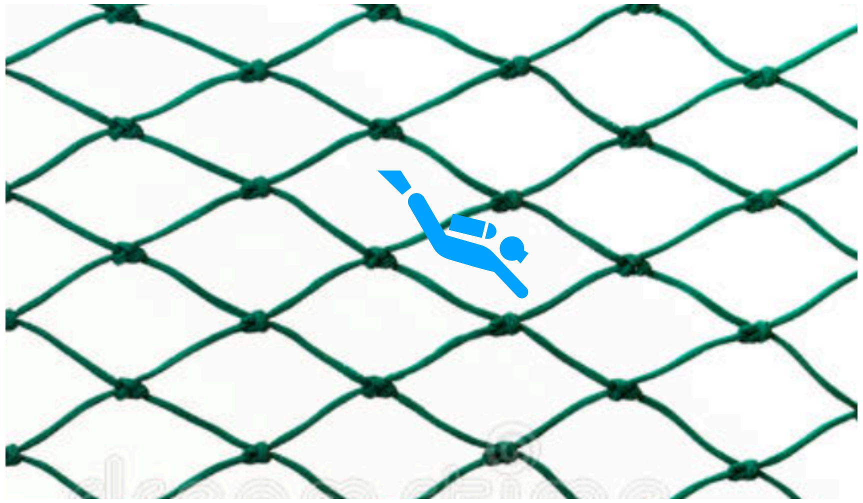




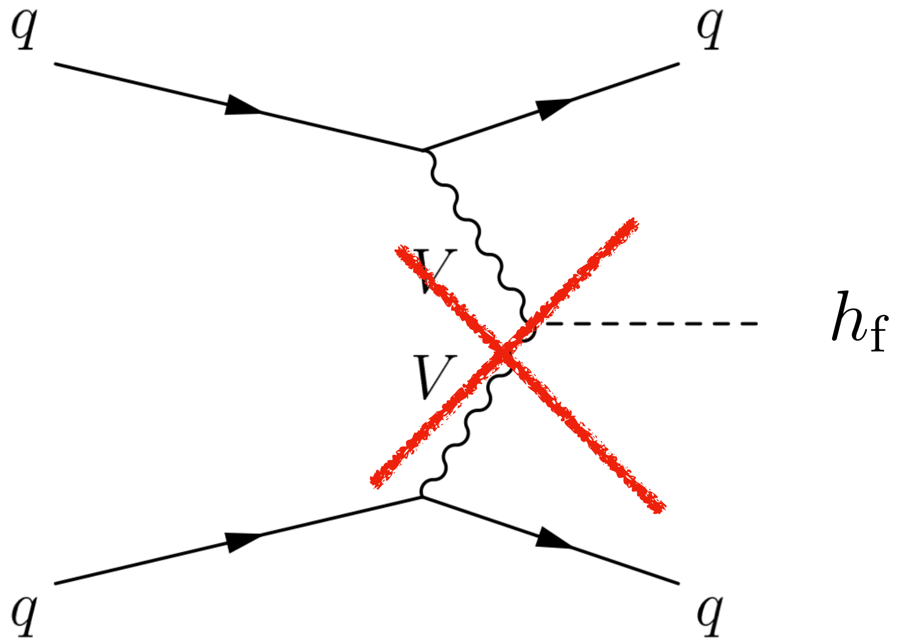
Gluon fusion productions are prohibited!



VBF is also prohibited!

- Near the Higgs alignment limit:

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



2. Viable parameter space

(1) Theoretical stabilities

— Scalar potential bounded from below

— Perturbative unitarity of scalar-scalar scattering at tree level

— Vacuum stability

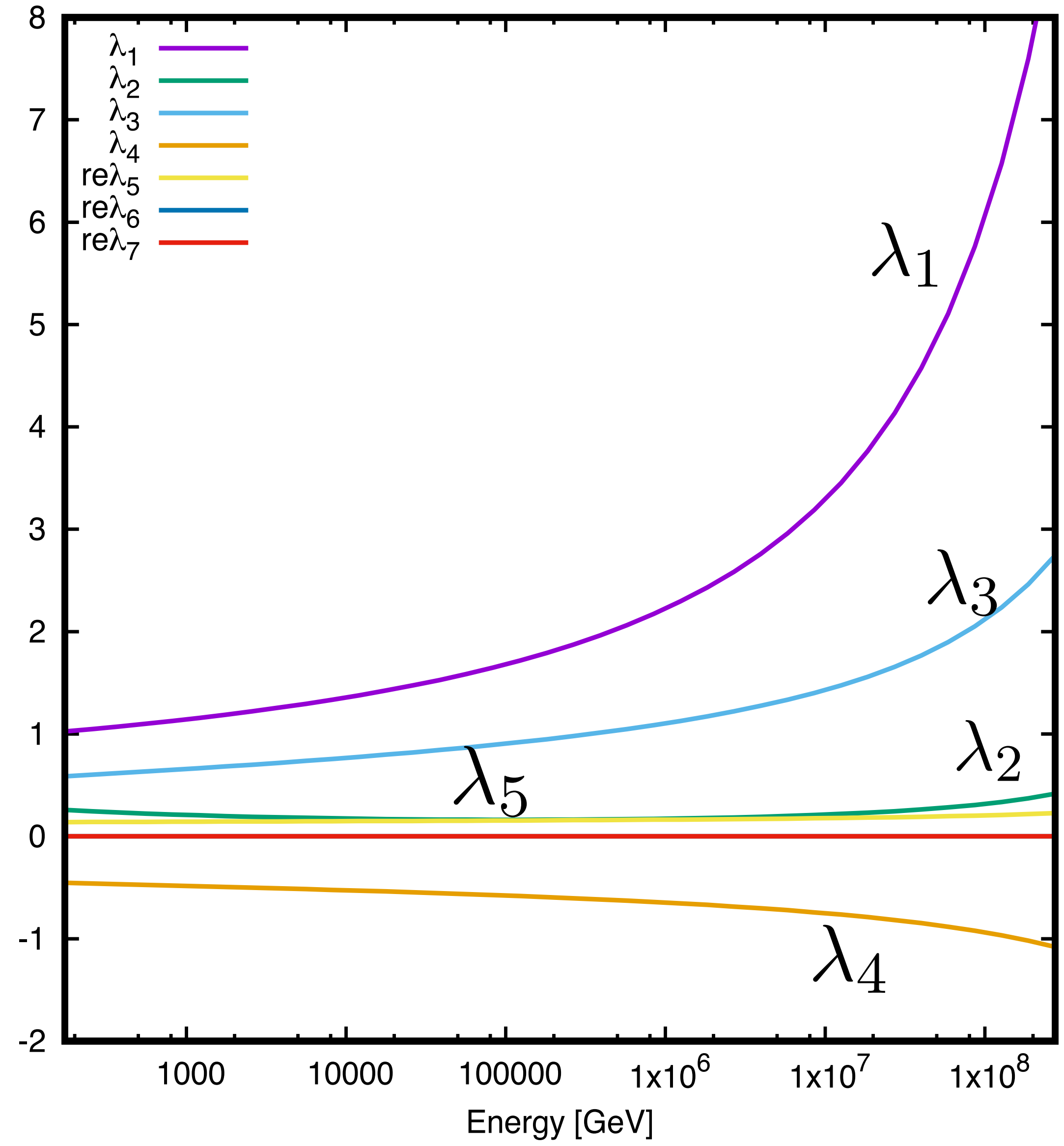
(2) Experimental constraints

— B physics

— Higgs precision data via HiggsSignals

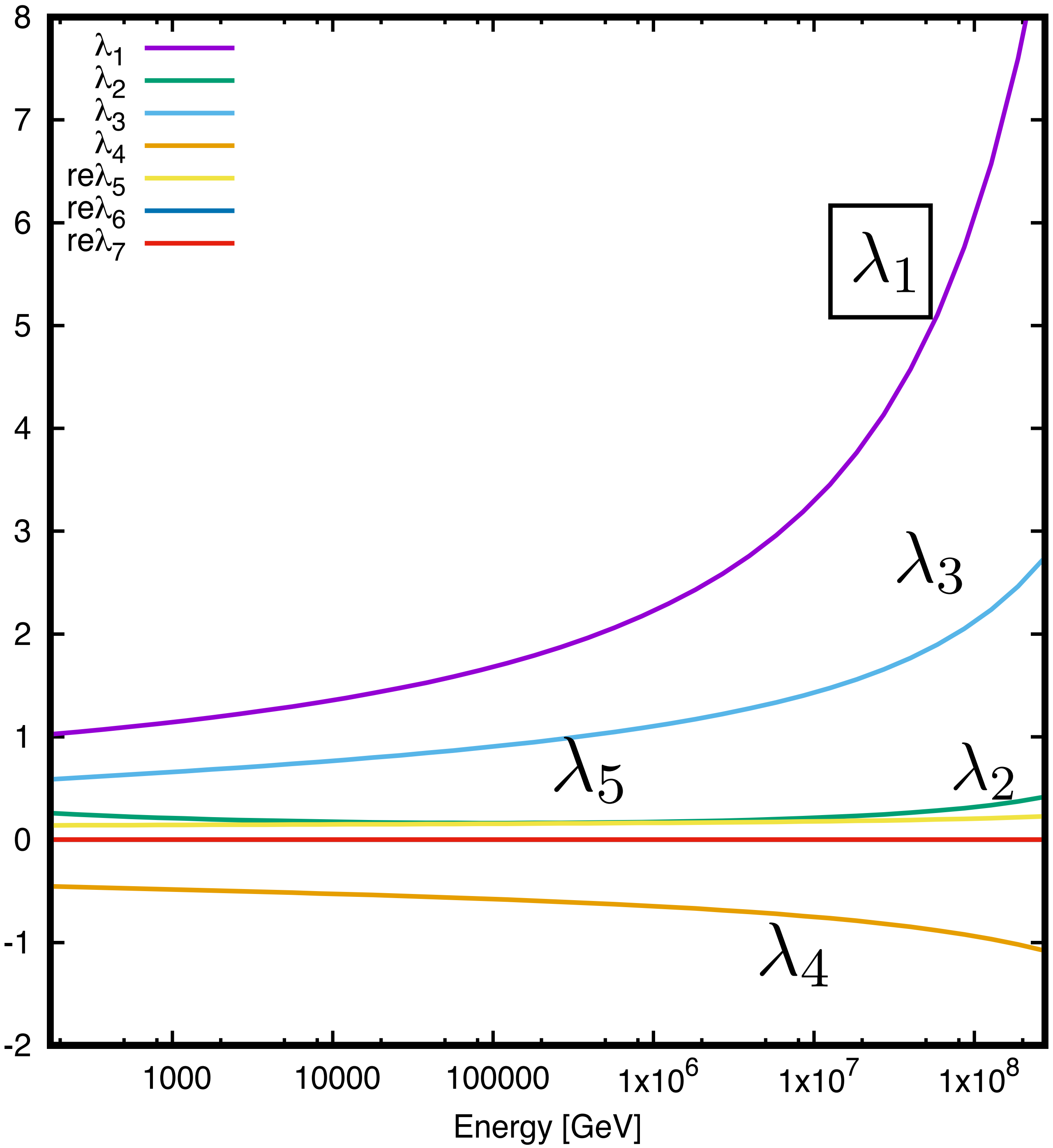
— Direct search bounds at the LEP, Tevatron, and LHC via HiggsBounds

BUT the scalar quartic couplings run fast under RGEs!



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

BP-IS



Theoretical stability is broken at Λ.

⬇

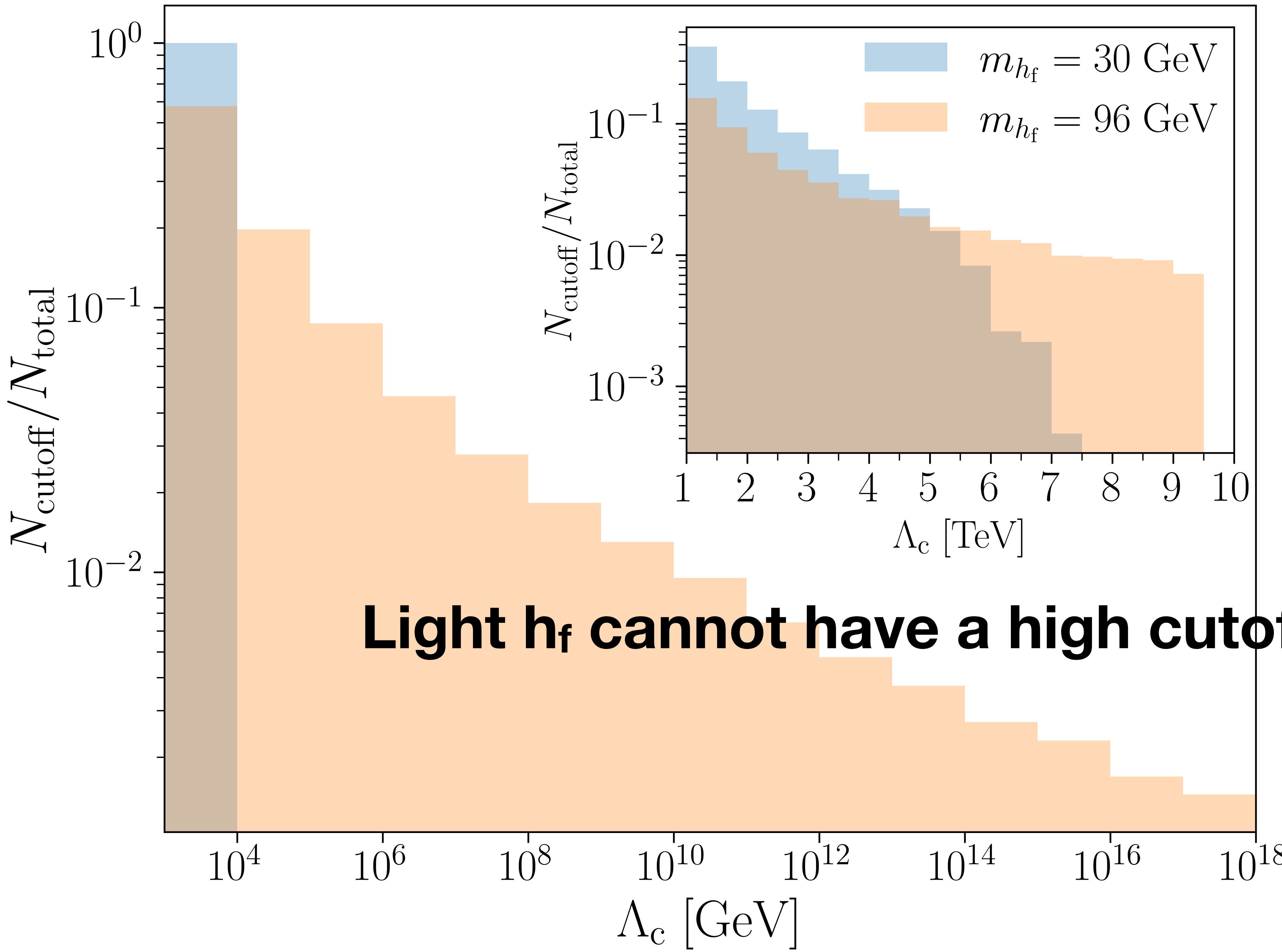
NP is not valid at Λ.

⬇

Λ is the cutoff scale of NP.

2. Viable parameter space with a high cutoff scale

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

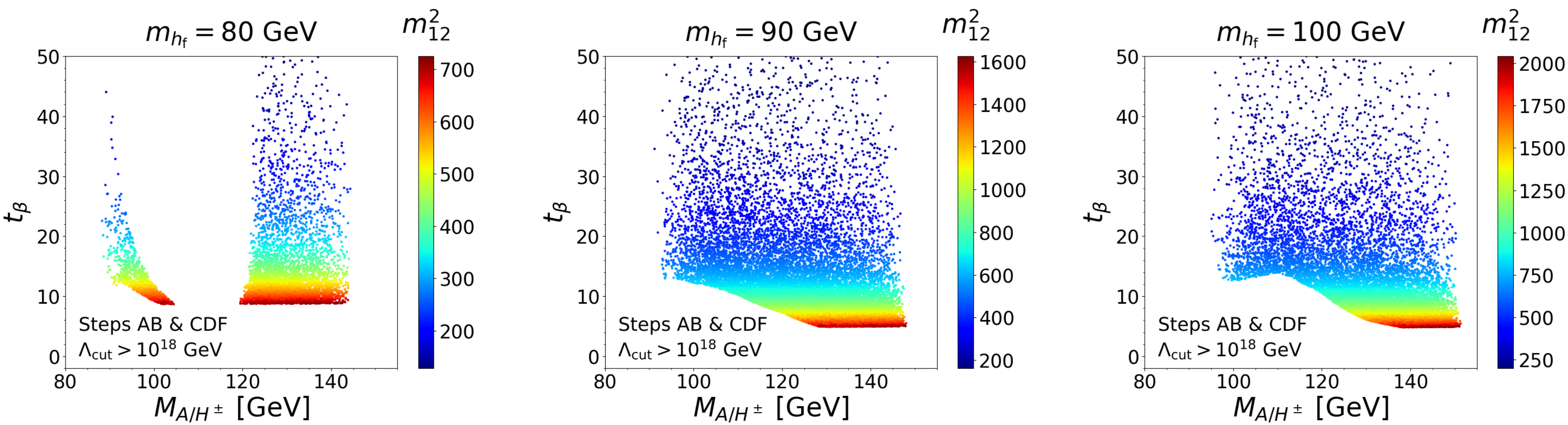


Light h_f cannot have a high cutoff scale!

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

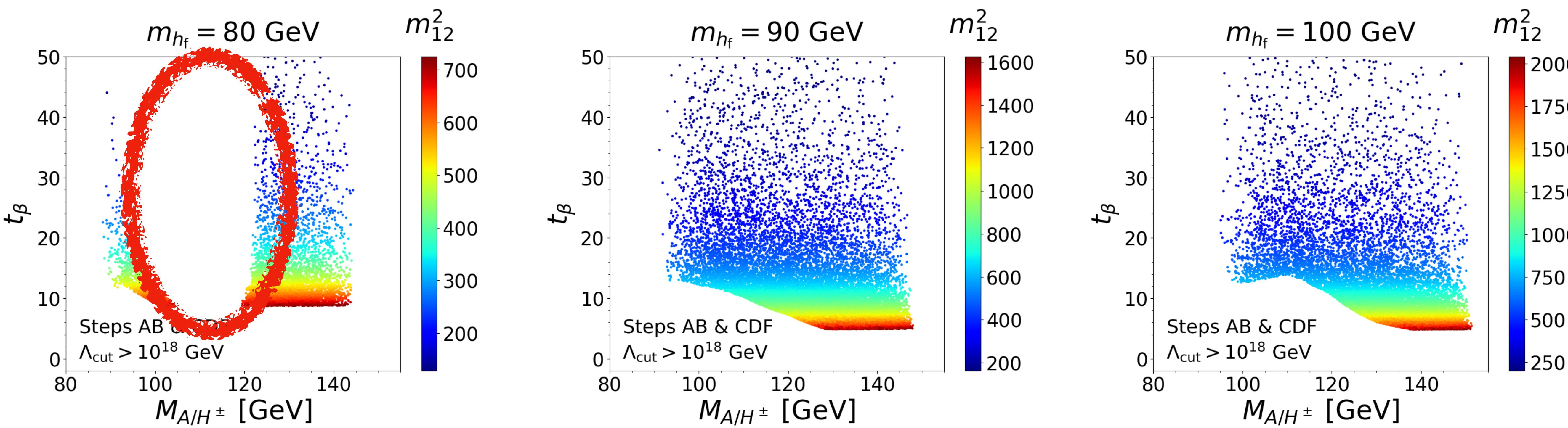
$$m_{h_\mathrm{f}} = 80,\ 90,\ 100\ \mathrm{GeV}.$$

Viable parameter points with Λ>10[18] GeV



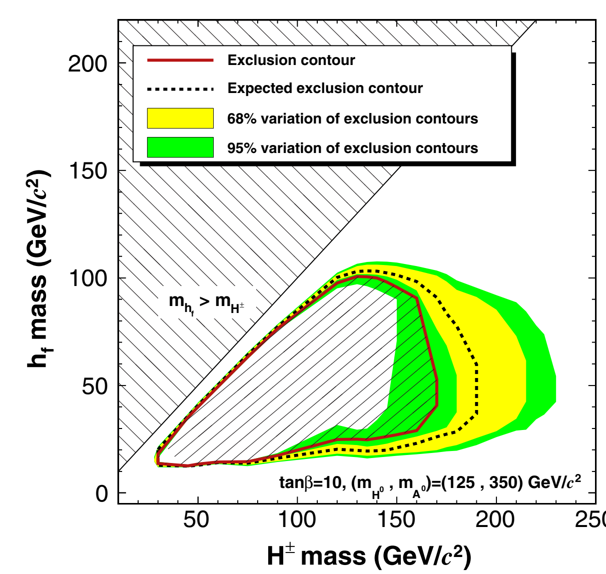
Viable parameter points with $\Lambda > 10^{18}$ GeV

CDF 4γ

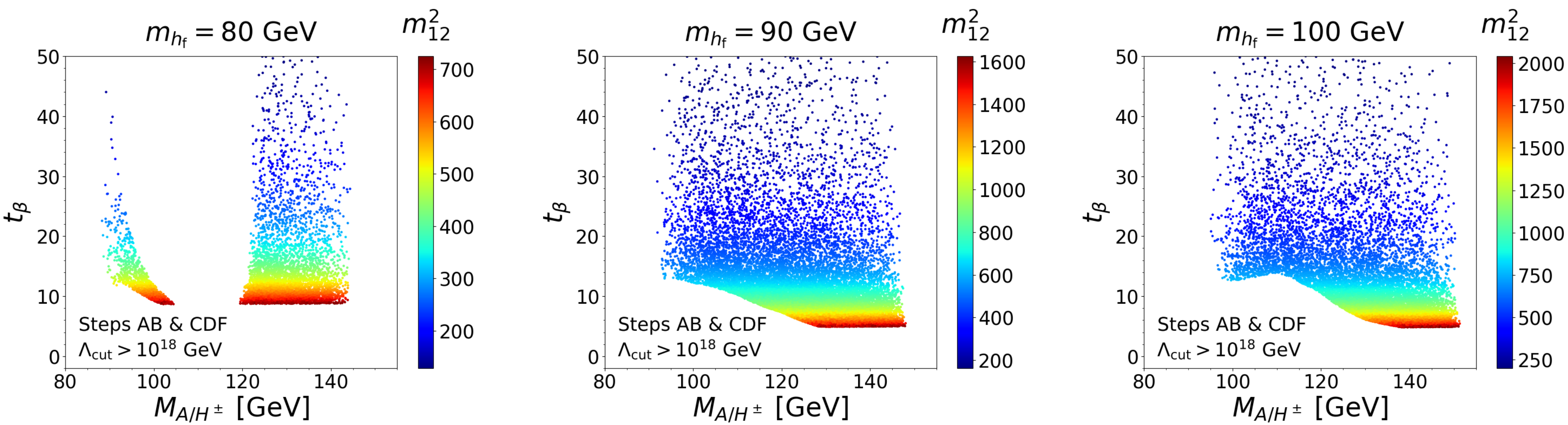


PHYSICAL REVIEW D **93,** 112010 (2016)

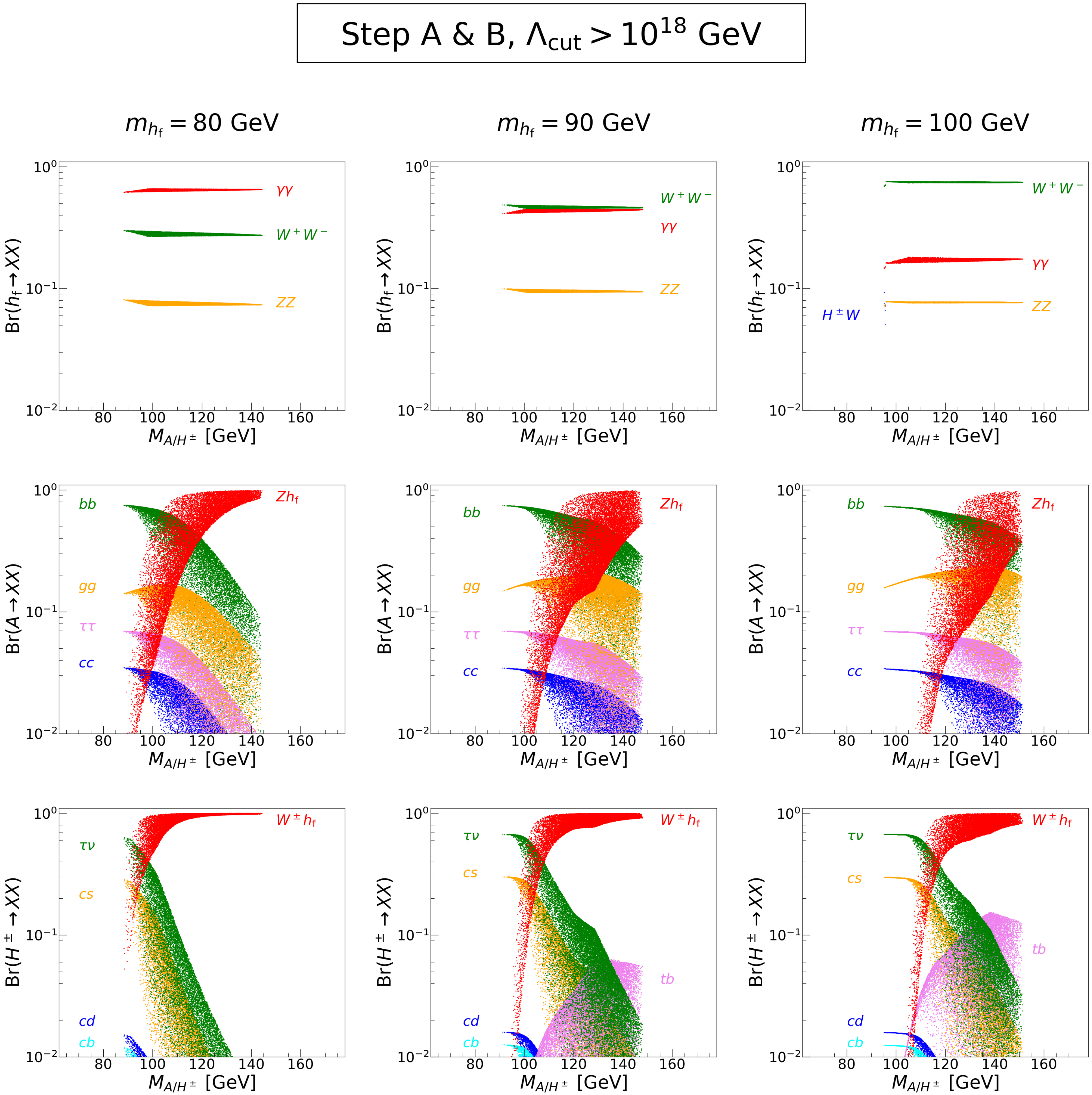
Search for a low-mass neutral Higgs boson with suppressed couplings to fermions using events with multiphoton final states

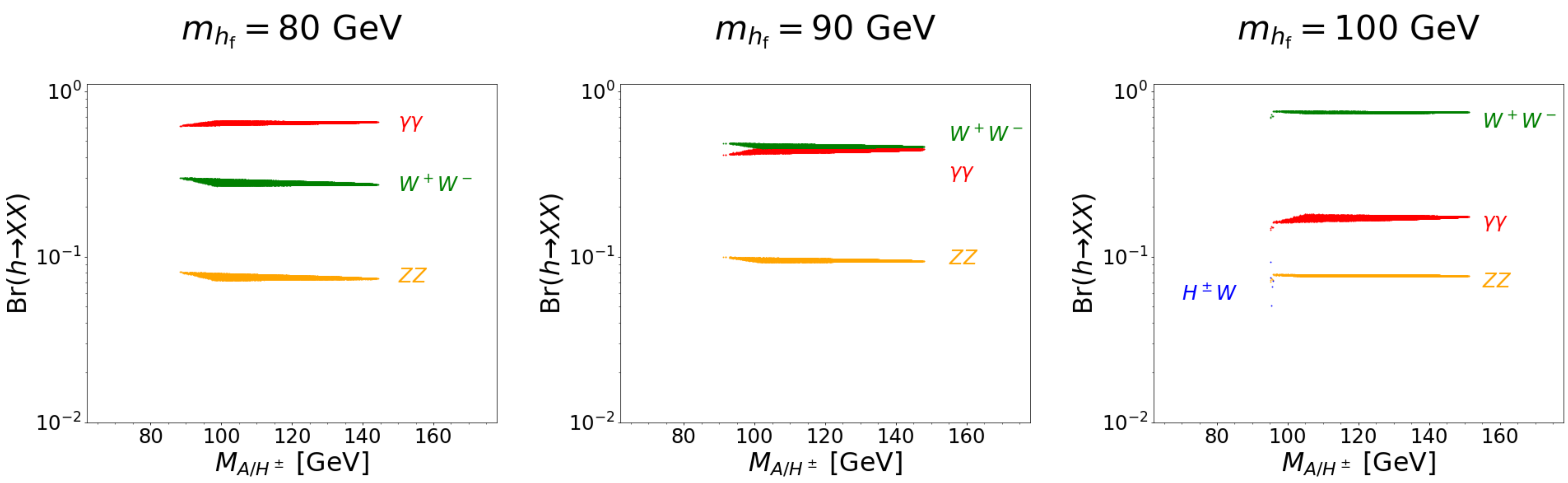


Viable parameter points with Λ>10[18] GeV



- **Charge Higgs boson and A masses below about 145 GeV.**
- **tanβ > 5 are allowed.**
- **$m_{12}{}^2$ is small.**


Step A & B, $\Lambda_{\rm cut} > 10^{18}$ 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
Zh_f
gg
$\tau\tau$
cc
$\mathrm{Br}(H^\pm \to XX)$
$W^\pm h_f$
$\tau\nu$
cs
tb
cd
cb
10^0
10^{-1}
10^{-2}
80
100
120
140
160
$M_{A/H^\pm}$ [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

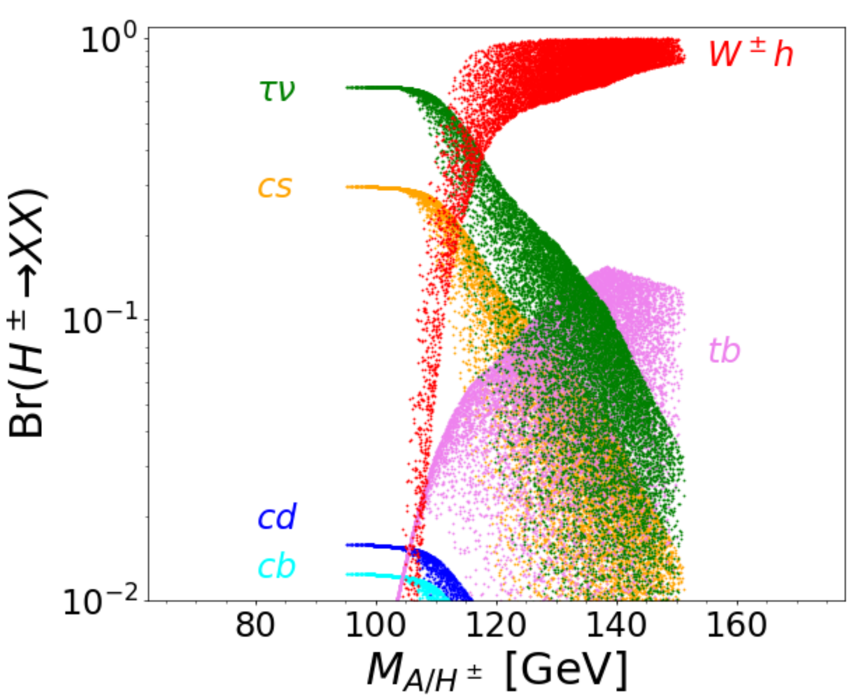
Production \ Final	$\gamma\gamma b\bar{b}$	$\gamma\gamma\ell^+\ell^-/\gamma\gamma\nu\bar{\nu}$ $\gamma\gamma qq$	$4\gamma\nu\bar{\nu}$ $4\gamma qq$	$\gamma\gamma X$	$4\gamma X$
$e^+e^- \to h_f A$	DELPHI				
$e^+e^- \to h_f A$ $\to h_f h_f Z$			DELPHI		
$e^+e^- \to h_f Z$ (✗)		DELPHI			
$p\bar{p} \to h_f H^\pm$ $\to h_f h_f W^{(*)}$					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 a pair of fermiophobic Higgs bosons$_f$ can have another efficient mode, $\gamma\gamma WW$.**

$$
\begin{aligned}
m_{h_\mathrm{f}} = 80\ \mathrm{GeV}: &\quad \mathcal{B}(h_\mathrm{f} \to \gamma\gamma)\mathcal{B}(h_\mathrm{f} \to WW^*) \simeq 18\%, \quad \mathcal{B}(h_\mathrm{f} \to \gamma\gamma)^2 \simeq 36\%, \\
m_{h_\mathrm{f}} = 90\ \mathrm{GeV}: &\quad \mathcal{B}(h_\mathrm{f} \to \gamma\gamma)\mathcal{B}(h_\mathrm{f} \to WW^*) \simeq 20\%, \quad \mathcal{B}(h_\mathrm{f} \to \gamma\gamma)^2 \simeq 20\%, \\
m_{h_\mathrm{f}} = 100\ \mathrm{GeV}: &\quad \mathcal{B}(h_\mathrm{f} \to \gamma\gamma)\mathcal{B}(h_\mathrm{f} \to WW^*) \simeq 15\%, \quad \mathcal{B}(h_\mathrm{f} \to \gamma\gamma)^2 \simeq 4\%.
\end{aligned}
$$

- **A light charged Higgs boson dominantly decays into $\tau\nu$**



- Existing searches for the fermiophobic Higgs boson

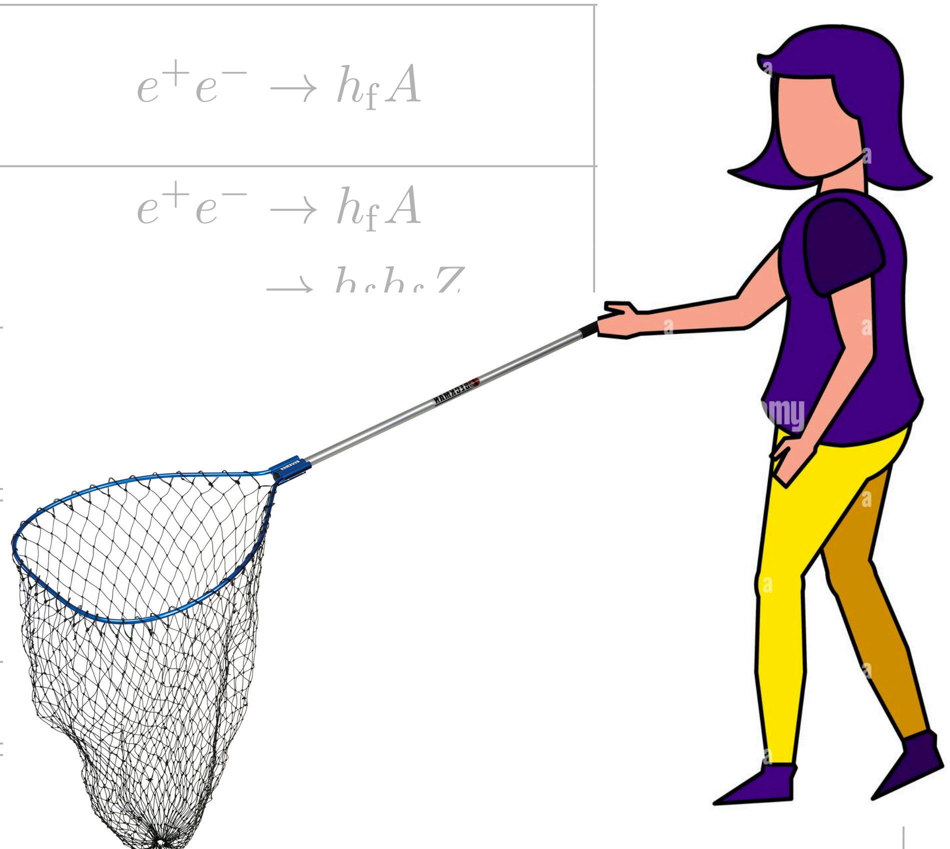
Production \ Final	$\gamma\gamma b\bar{b}$	$\gamma\gamma\ell^+\ell^-/\gamma\gamma\nu\bar{\nu}$ $\gamma\gamma qq$	$4\gamma\nu\bar{\nu}$ $4\gamma qq$	$\gamma\gamma X$	$4\gamma X$
$e^+e^- \to h_f A$	DELPHI				
$e^+e^- \to h_f A$ $\to h_f h_f Z$			DELPHI		
$e^+e^- \to h_f Z$ (✗)		DELPHI			
$p\bar{p} \to h_f H^\pm$ $\to h_f h_f W^{(*)}$					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	

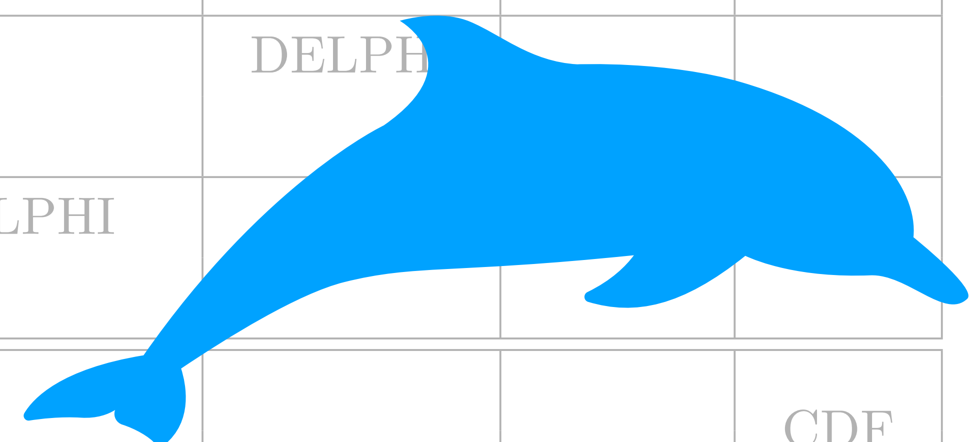
$H^\pm \to h_f W^{\pm *}$

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

- Existing searches for the fermiophobic Higgs boson

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





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

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 $M_{A/H^\pm}$
	$H^\pm \to \tau\nu$	$H^\pm \to h_f W^*$
	$A \to bb$	$A \to h_f Z^*$

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

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

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

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

$h_f h_f W^\pm$

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

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

$$h_f h_f W^\pm \to \gamma\gamma W^+ W^- W^\pm$$

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

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

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

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

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For the basic selection

- We select events with at least one $\tau_{\rm h}$-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	$jj\gamma$	$j\gamma\gamma$	$W^{\pm}\gamma\gamma$	$Z\gamma\gamma$
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$$P_{j\to\gamma} = 5 \times 10^{-4}$$

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

We can tame the background!

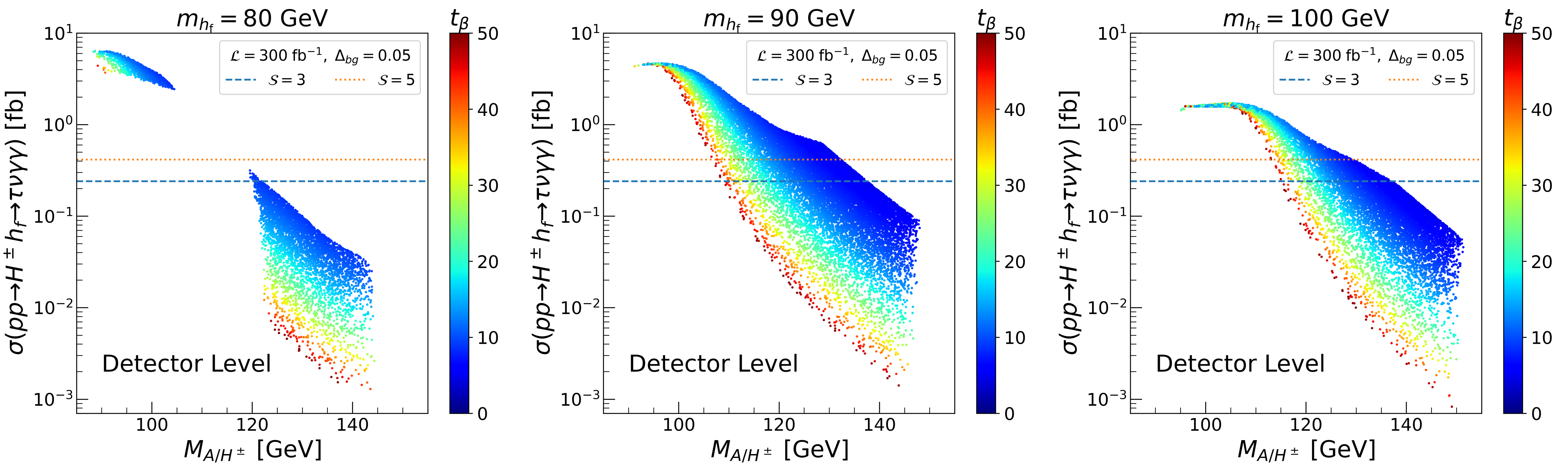
Significance with 300/fb

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

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

Very promising!

Other viable parameter points?



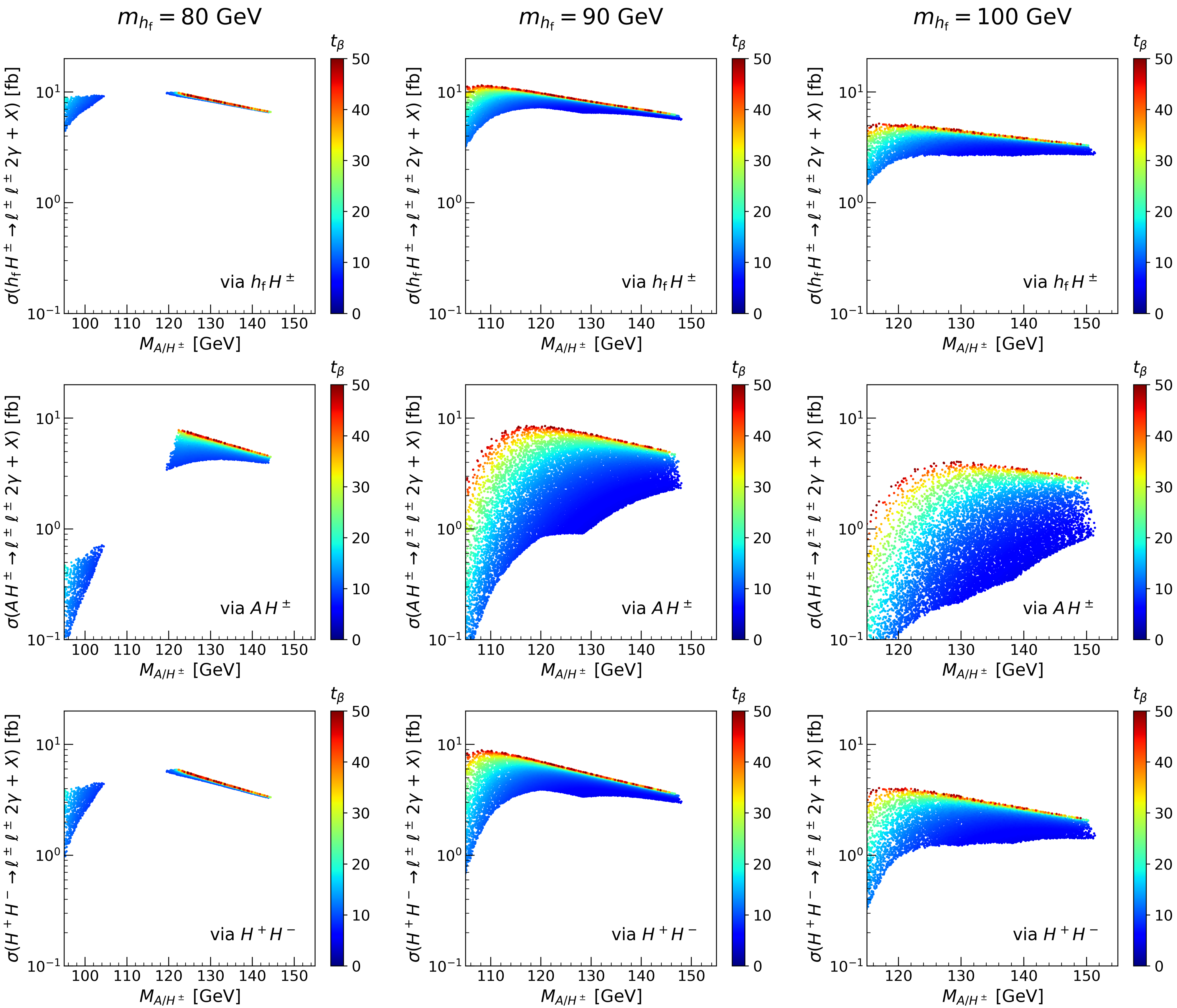
- Most of the parameters with light $M_{H\pm}$ can enjoy the significance larger than 5 with 300/fb.
- The larger tanβ, the smaller σ.

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

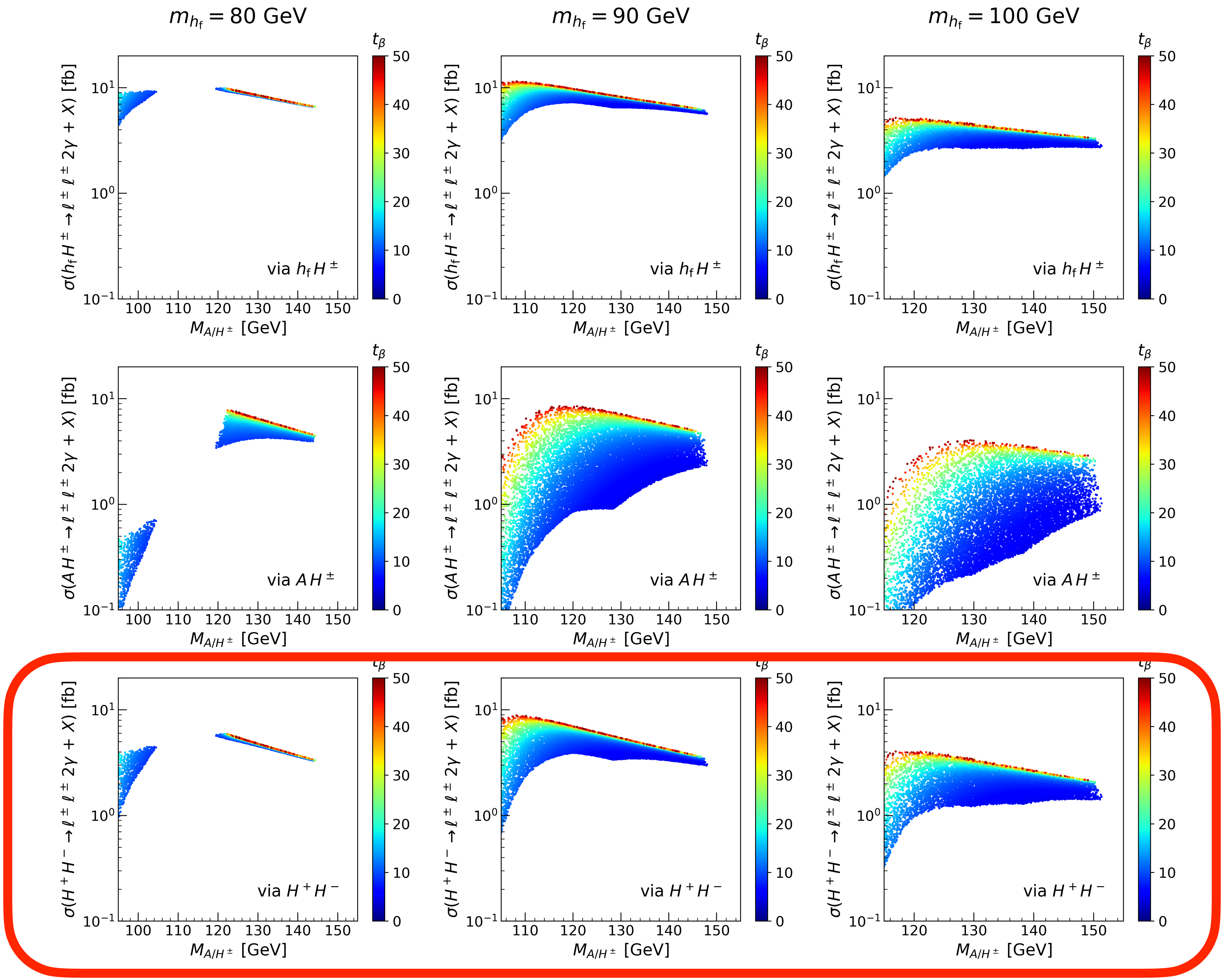
Initial production	Final states	
$q\bar{q}' \to W^* \to H^\pm h_f$	$[2\gamma]\tau^\pm\nu$ ✓	$[\ell^\pm\ell^\pm\gamma\gamma\not{E}_T]X$ ✓
$q\bar{q}' \to W^* \to AH^\pm$	$b\bar{b}\tau^\pm\nu$	$[\ell^\pm\ell^\pm\gamma\gamma\not{E}_T]X$ ✓
$q\bar{q} \to \gamma^*/Z^* \to H^+H^-$	$\tau^\pm\nu\tau^\pm\nu$	$[\ell^\pm\ell^\pm\gamma\gamma\not{E}_T]X$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

Three production channels

Parton level cross sections at the 14 TeV LHC



All three channels have compatible σ.



Not considered in the literature.

Signal-to-background analysis at the detector level

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

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

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

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

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

$m_{12}^2 = 203.5$ 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	$W^\pm Z j$	$Z \ell^+ \ell^- j$	$W^\pm Z \gamma j$
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
$\lvert\eta\rvert < 2.5,\ \Delta R > 0.$[illegible]	0.735	0.354	0.227	0.070	0.027	0.021

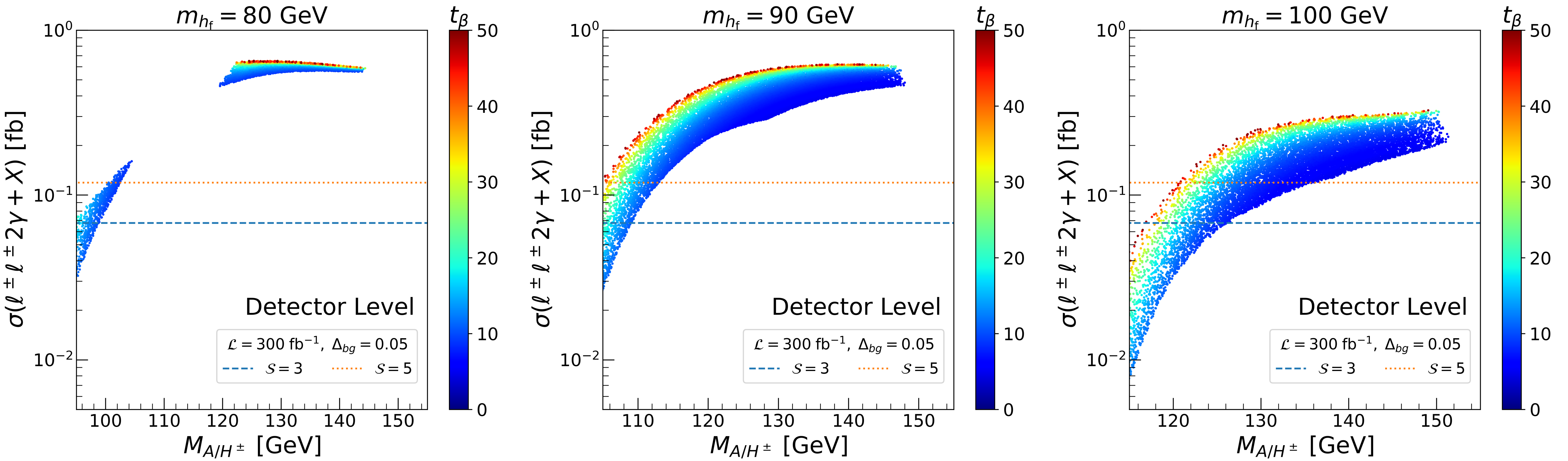
Almost background-free environment with the basic selection

Signal significances with 300/fb

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

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

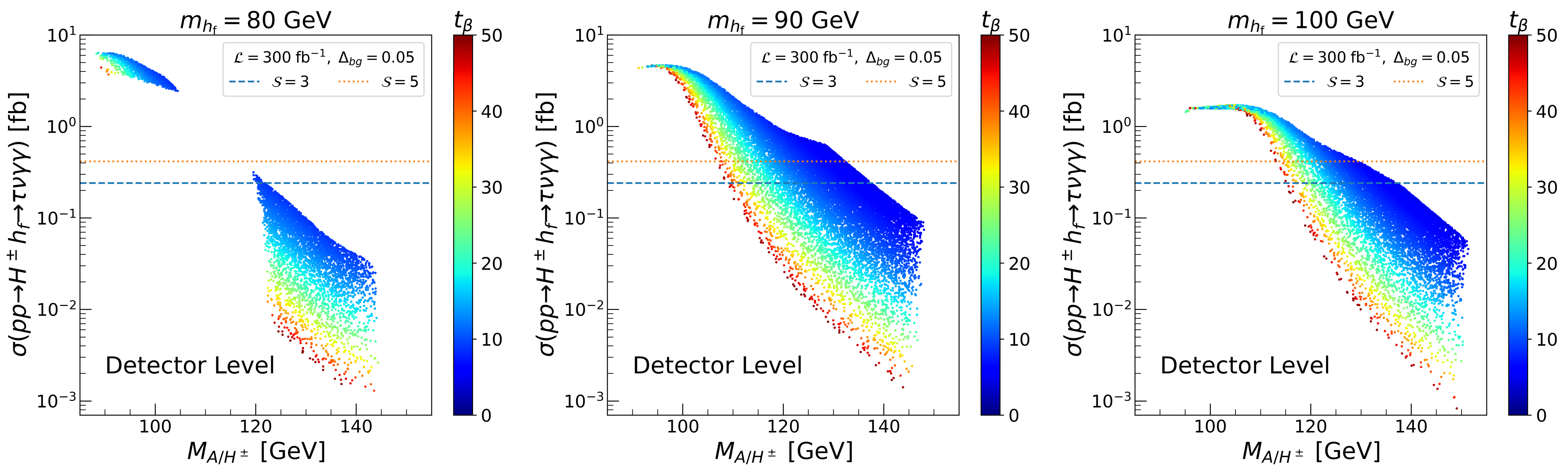
Again very promising!!!



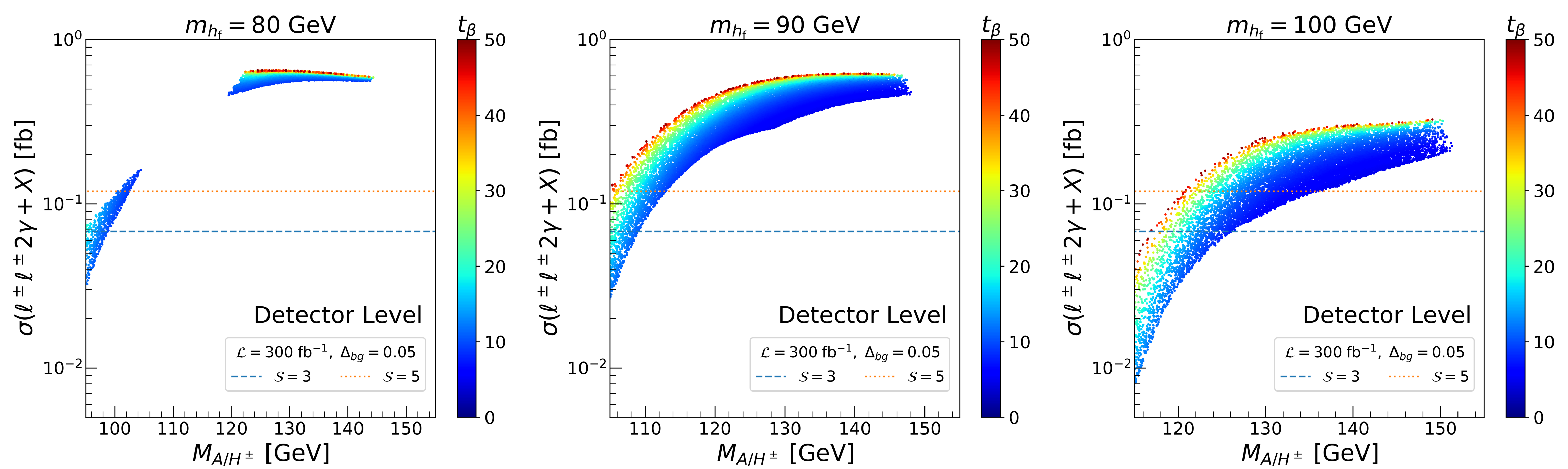
Most parameters with heavy $M_{H\pm}$ can be probed.

Two channels are complementary!

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



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



5. 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. .