Comprehensive study of the light charged Higgs boson in Type-I 2HDM

Jeonghyeon Song, 2021. 11. 17.
With K.Cheung, A.Jueid, C.Lu, S.Lee, J.Kim

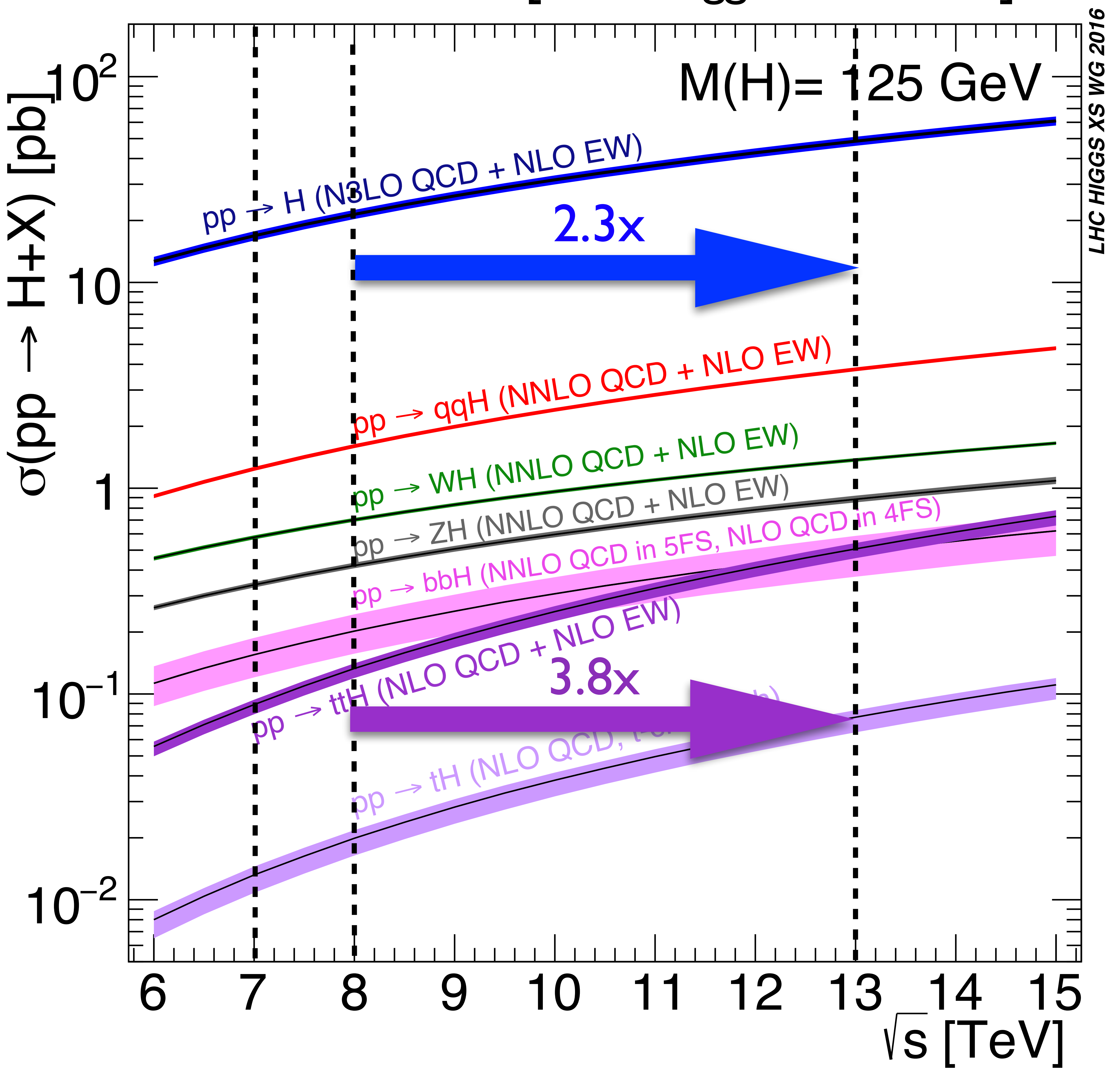
1. **Why do we study H+?**
2. **H+ in 2HDM**
3. **Full scan for a light H+ in Type-I**
4. **Signal-Background Analysis**
5. **Conclusions**

1. Why do we study H+?

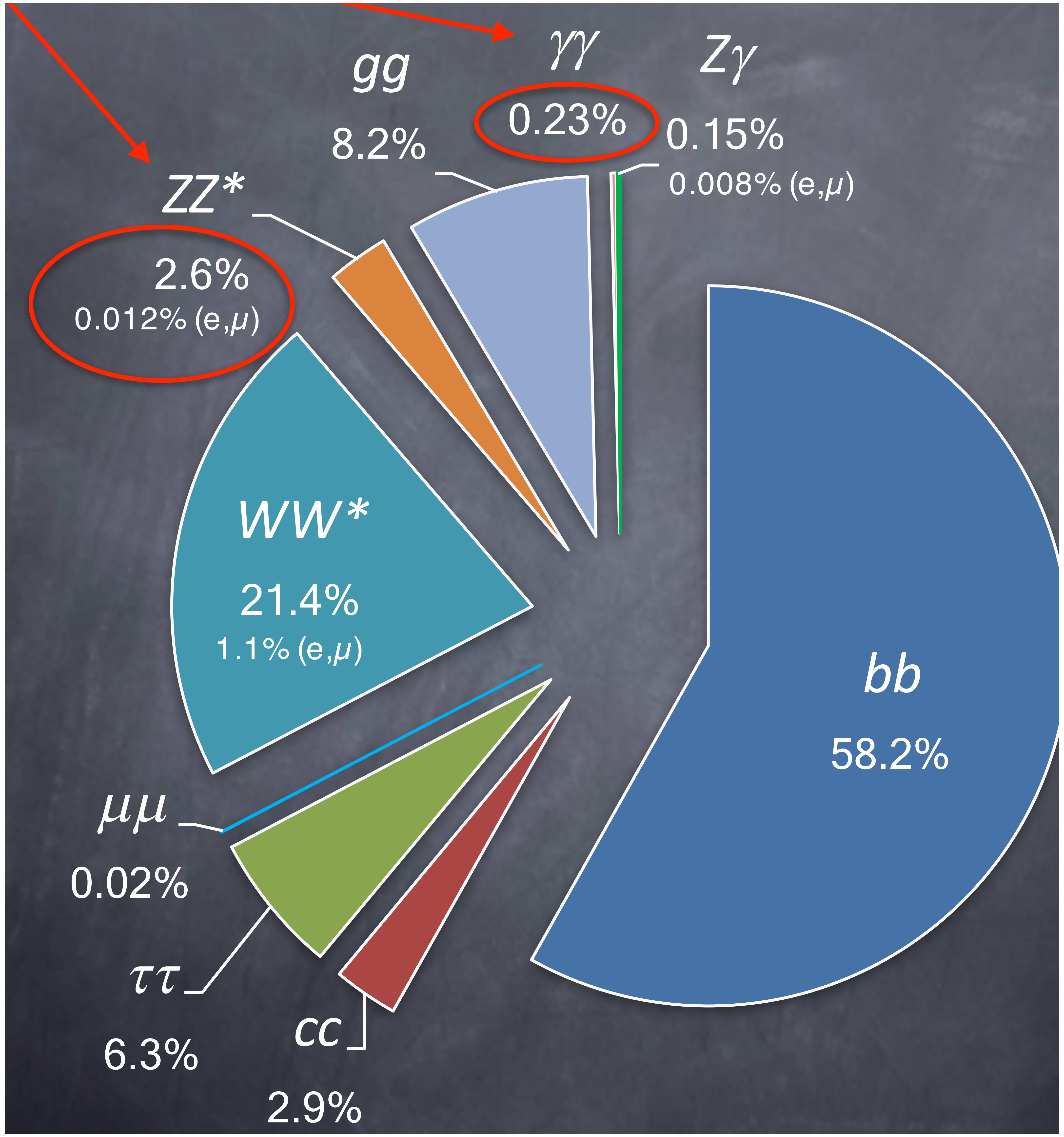
Current status of the Higgs boson measurements at the LHC

Gain from LHC Run-1 to Run-2

[LHC Higgs X-sec WG]



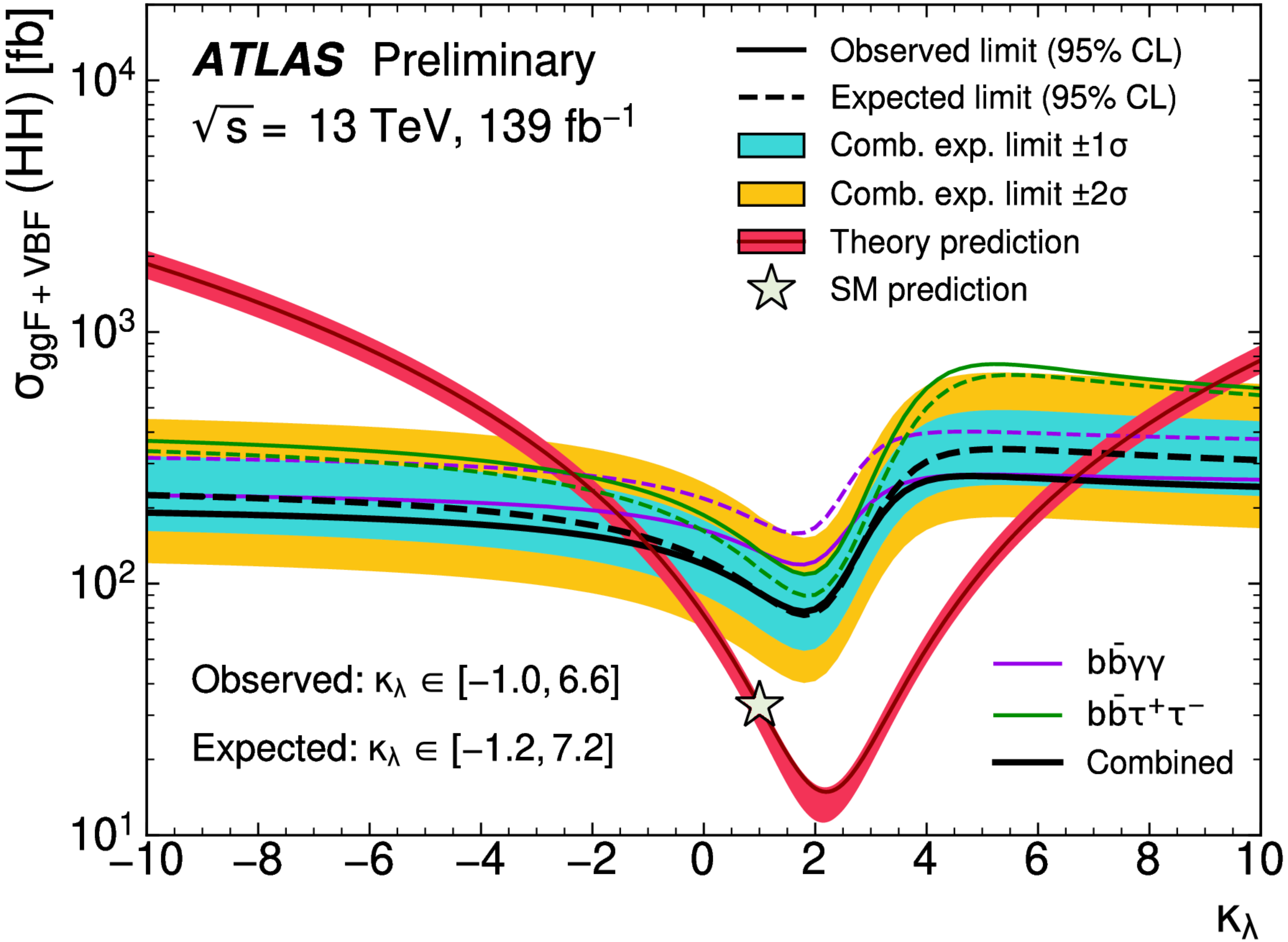
Higgs decays in the SM



ALL SM-like

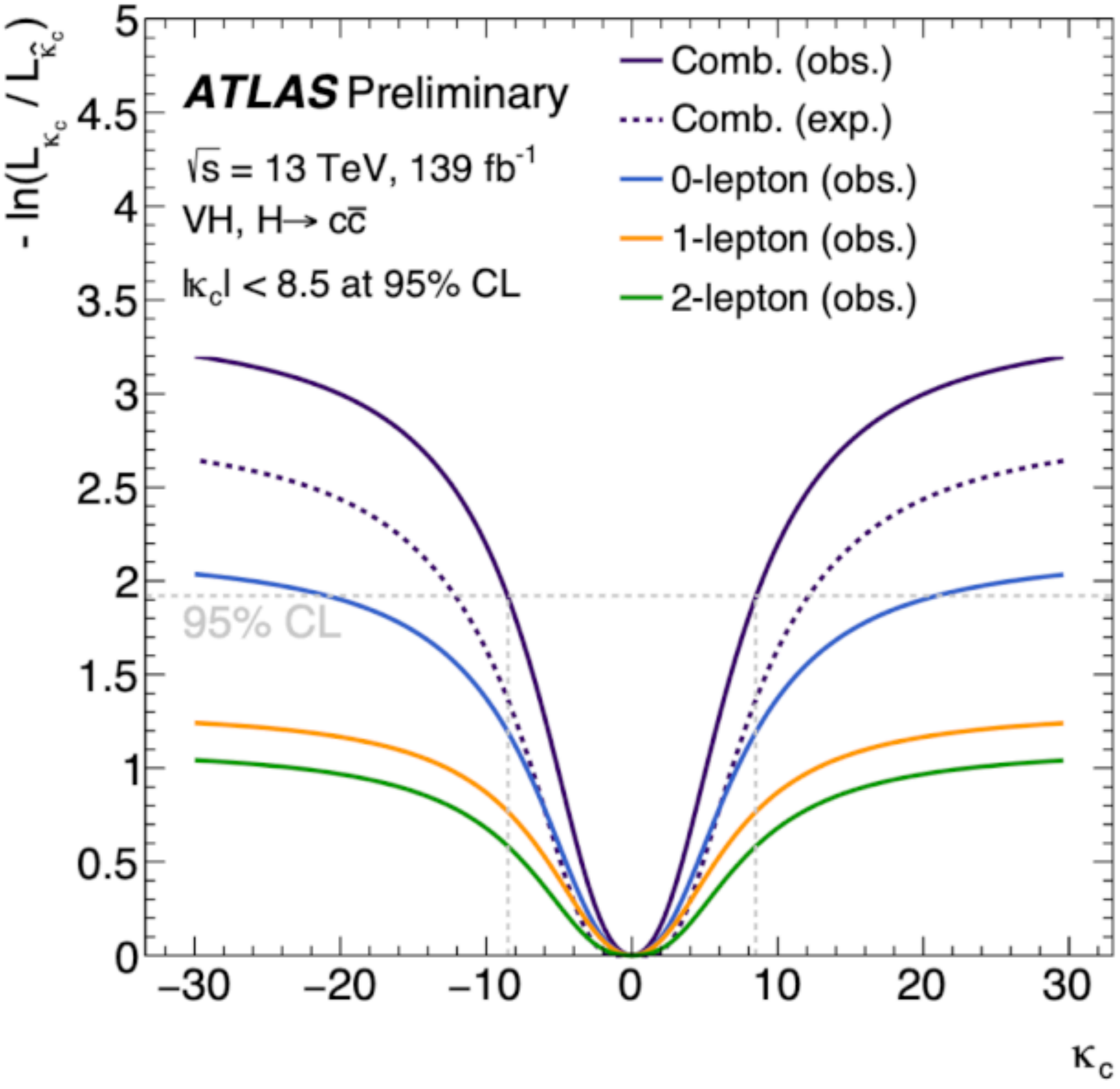
LHC began to measure challenging modes for the Higgs decays.

1. Why?



ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Observed limit (95% CL)
Expected limit (95% CL)
Comb. exp. limit ±1σ
Comb. exp. limit ±2σ
Theory prediction
SM prediction
Observed: $\kappa_\lambda \in [-1.0, 6.6]$
Expected: $\kappa_\lambda \in [-1.2, 7.2]$
$b\bar{b}\gamma\gamma$
$b\bar{b}\tau^+\tau^-$
Combined
$\sigma_{ggF+VBF}$ (HH) [fb]
κ_λ
10^4
10^3
10^2
10^1
−10
−8
−6
−4
−2
0
2
4
6
8
10

1. Why?



ATLAS Preliminary
√s = 13 TeV, 139 fb-1
VH, H→ cc̄
|κc| < 8.5 at 95% CL
Comb. (obs.)
Comb. (exp.)
0-lepton (obs.)
1-lepton (obs.)
2-lepton (obs.)
95% CL
- ln(Lκc / Lκ̂c)
κc

Unanswered Questions

A. Dark matter

B. Baryogenesis & Strong EW phase transition

C. Neutrino mass

D. Flavor physics

E. Stability of the Higgs vacuum

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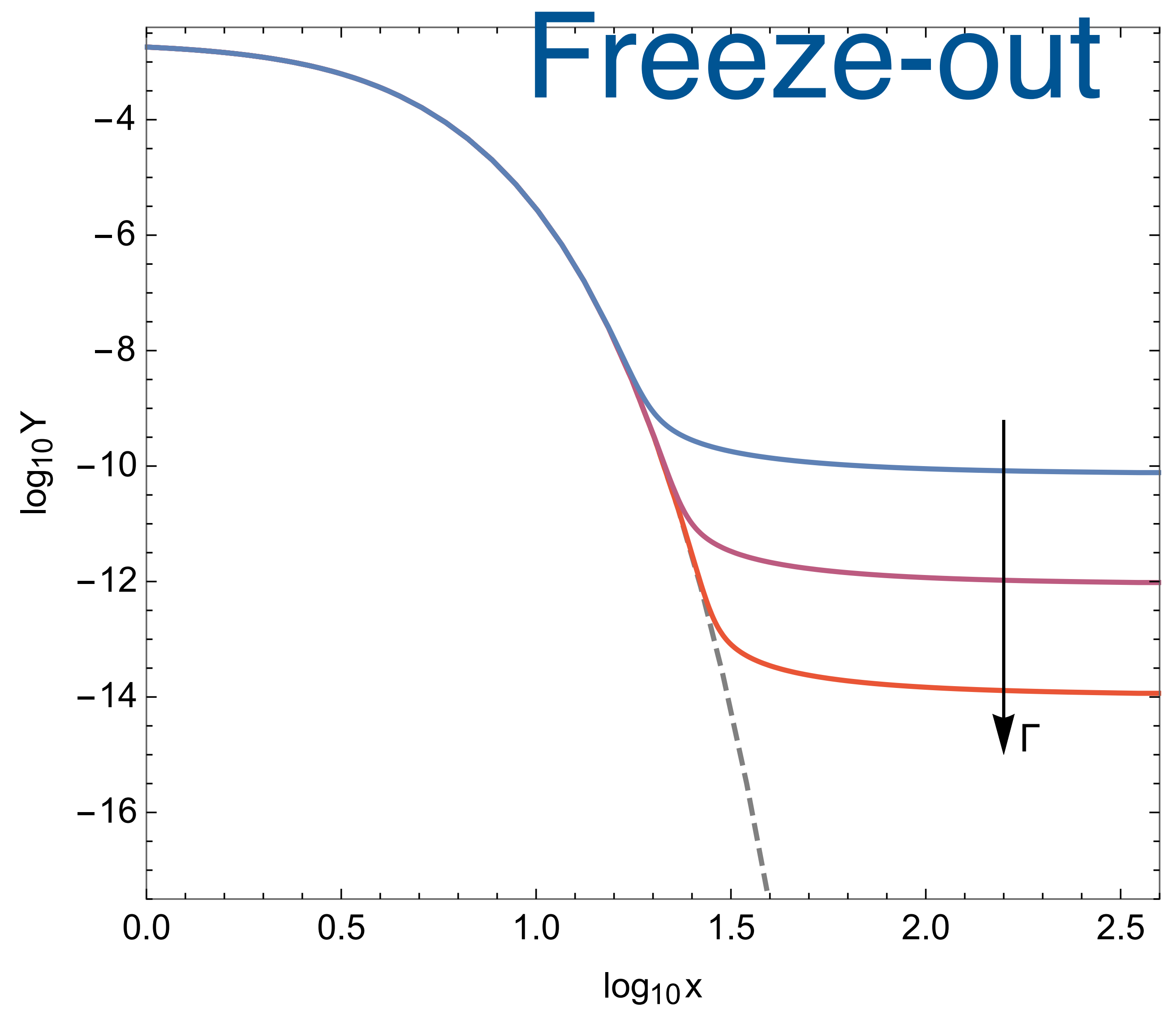
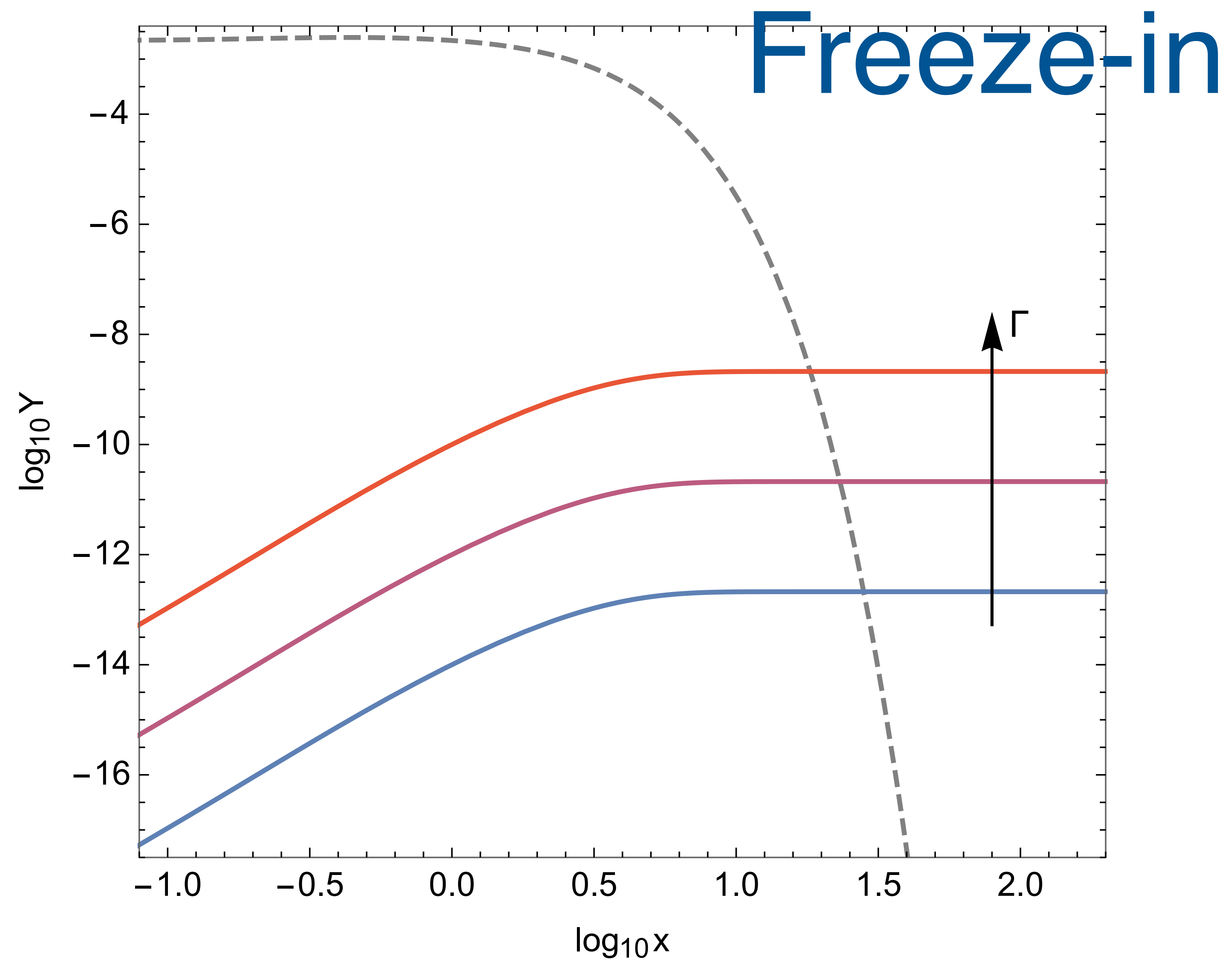
A New Higgs sector can solve all.

Freeze-in genesis of Dark matter: Feebly Interacting Massive Particles

- DM interacts with the SM so weakly that it cannot come into equilibrium
  ⇒ Feebly interaction
  ⇒ g below 10^(-7)

- The population of χ is initially zero, but can be produced by the decays of the heat bath particles





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Simplest FIMP: Higgs portal

Baryogengesis $\Leftarrow$ strong EW phase transition

- Explaining the origin of the cosmic matter-antimatter asymmetry
- Very probably, it is connected with EWSB
- 2 key ingredients that the SM cannot offer:
  - First-order strong EW phase transition
  - adequate sources of CP-violation
- 125 GeV Higgs mass $\Rightarrow$ Second-order EWPT

Neutrino mass generation

- Various NP modes to explain the neutrino masses and mixing angles

Parameter	best-fit
Δm^2_{21} [10^{-5} eV ^{2}]	7.37
$\Delta m^2_{31(23)}$ [10^{-3} eV ^{2}]	2.56 (2.54)
$\sin^2\theta_{12}$	0.297
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216
δ/π	1.38 (1.31)

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How to discriminate the models?

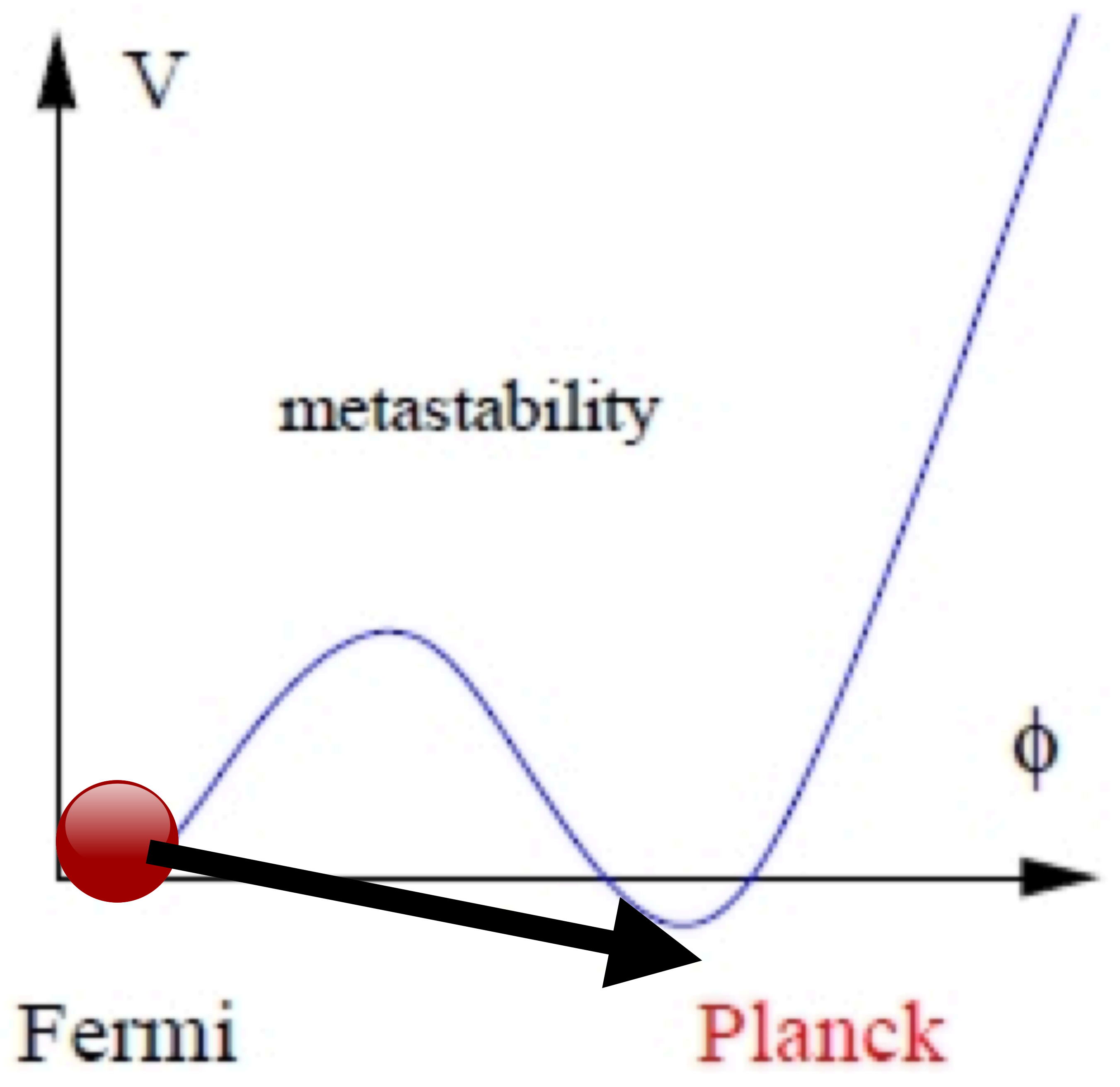
Lepton Flavor Violation

Flavor puzzles

- How to explain the structure (smallness and hierarchy) in the charged fermion masses and the CKM mixing angles?
- Why no structure (no hierarchy, degeneracy, or smallness) in the neutrino-related flavor parameters?
- Measure new flavor parameters beyond CKM, especially in the Higgs sector

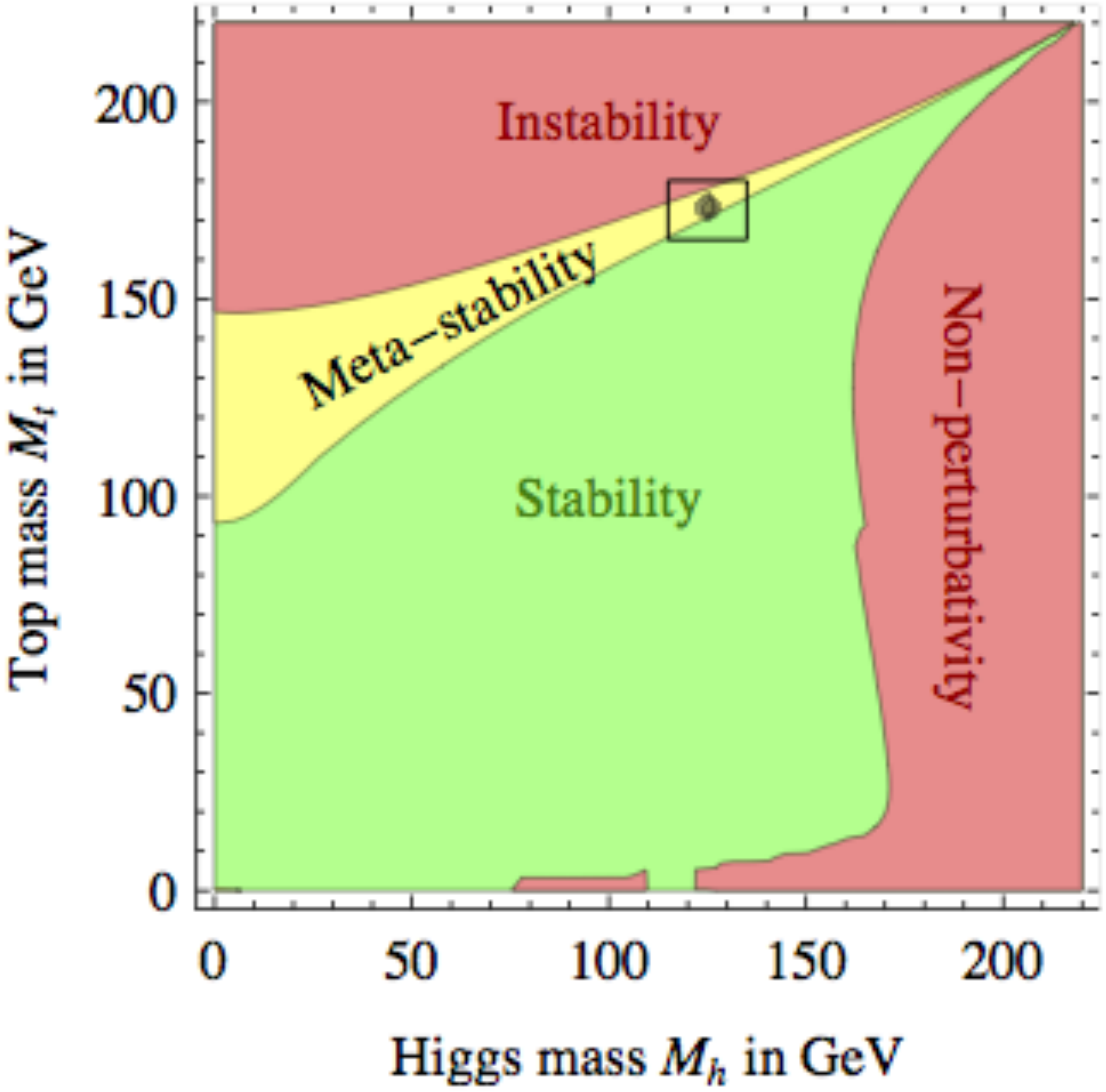
Stability of the Higgs vaccum

- The Higgs potential determines whether the Universe is in a true vacuum, or a false vacuum.
- If it is metastable, we shall meet the most quick, clean, and efficient extinction.
- In the SM, the measurements of the Higgs boson mass seem to indicate the vacuum is metastable.



Lifetime > Universe age

1. Why? Stabiliy



New Higgs Sector

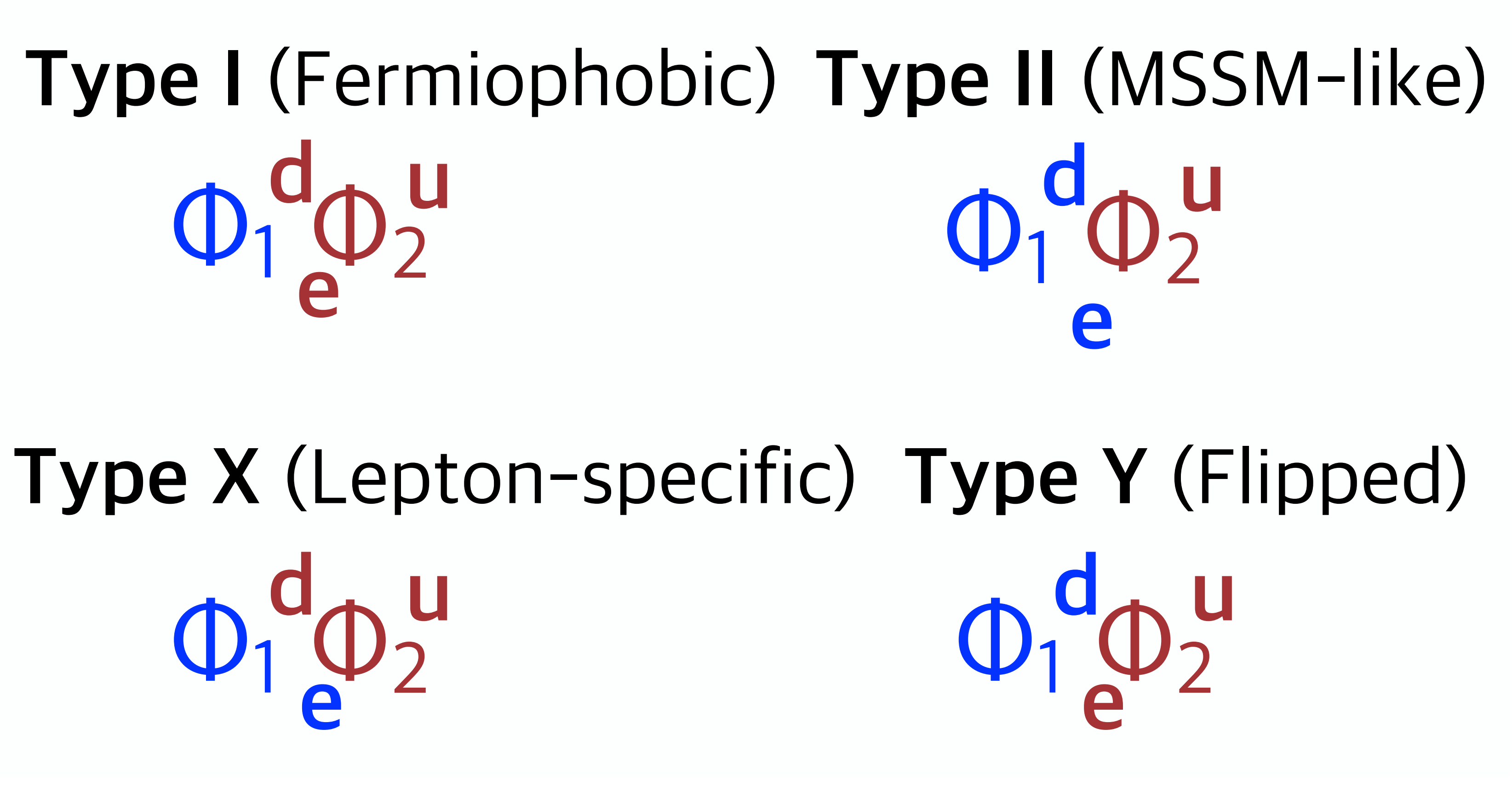
Clean signal?

Charged Higgs boson

1. Why?

Two kinds of NP for charged Higgs

- Doublet models
  - 5 scalars



- Triplet models
  Georgi-Machacek Model
  - add one real and one complex SU(2) triplet
  - H+ phenomenology different from the doublet models
  - H+WZ couplings at tree level
  - Double-charged Higgs bosons H++

2. H^+ in 2HDM

Two Higgs doublets

$$\Phi_1 \text{ and } \Phi_2$$

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ \dfrac{v_a + \rho_a + i\eta_a}{\sqrt{2}} \end{pmatrix}, \quad a = 1, 2.$$

2. H+ in 2HDM

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

$$v^2 \equiv v_1^2 + v_2^2 = (246 \text{ GeV})^2, \qquad \frac{v_2}{v_1} = \tan\beta.$$

Mixing angle!

Five physical Higgs bosons

$$h^0, H^0, A^0, H^{\pm}$$

Two Higgs doublets

$$\Phi_1 \text{ and } \Phi_2$$

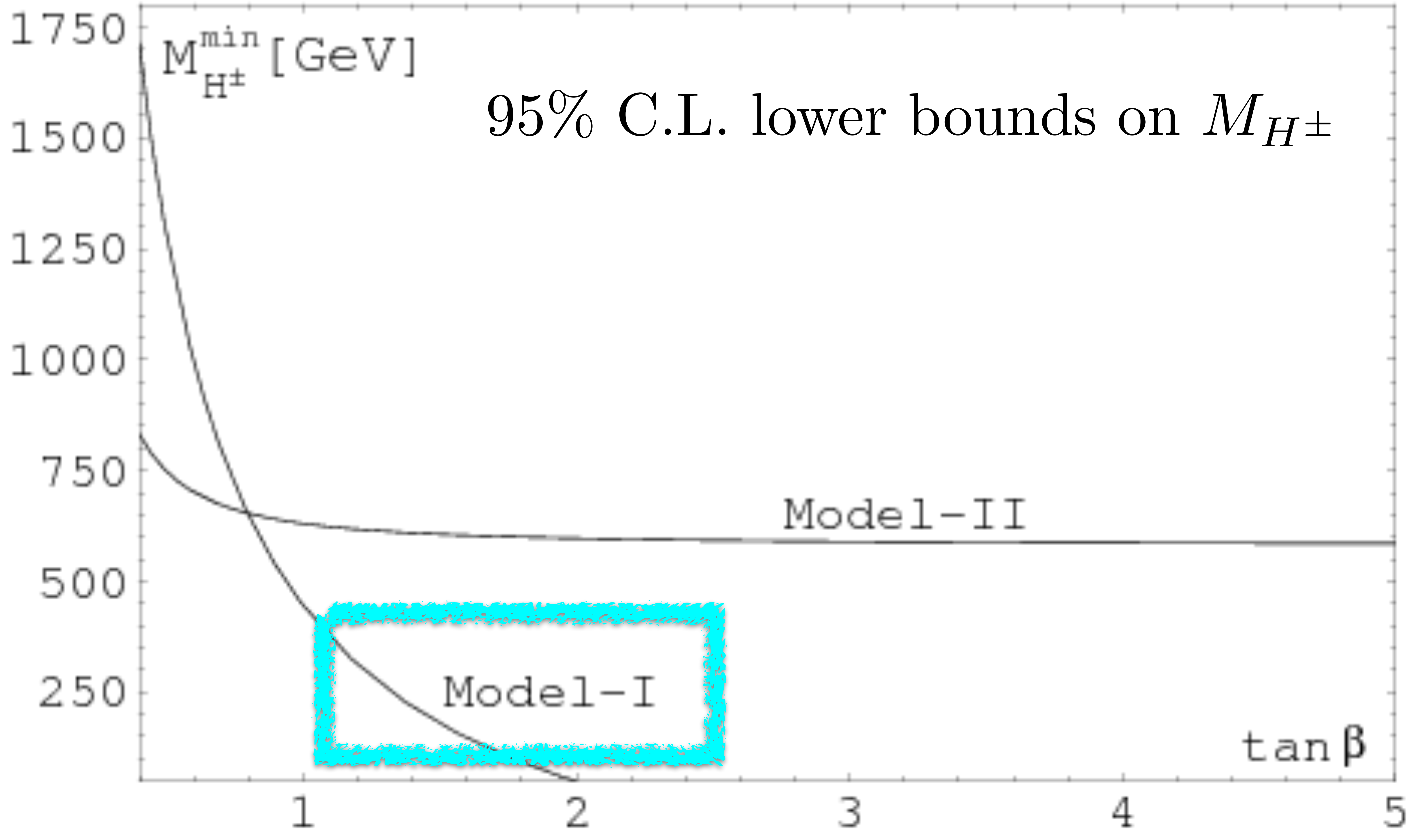
In order to suppress FCNC at tree level, we impose Z2 symmetry

$$\Phi_1 \to \Phi_1 \quad \text{and} \quad \Phi_2 \to -\Phi_2$$

Four types according to the charge assignment under Z2 symmetry

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

FCNC constraint



Misiak et al, Eur.Phys.J. C77 (2017) no.3, 201

Special limit: Higgs Alignment

$$H^{\rm SM} = s_{\beta-\alpha} h^0 + c_{\beta-\alpha} H^0$$

For $h^0 = h_{125}$

$$s_{\beta-\alpha} = 1$$

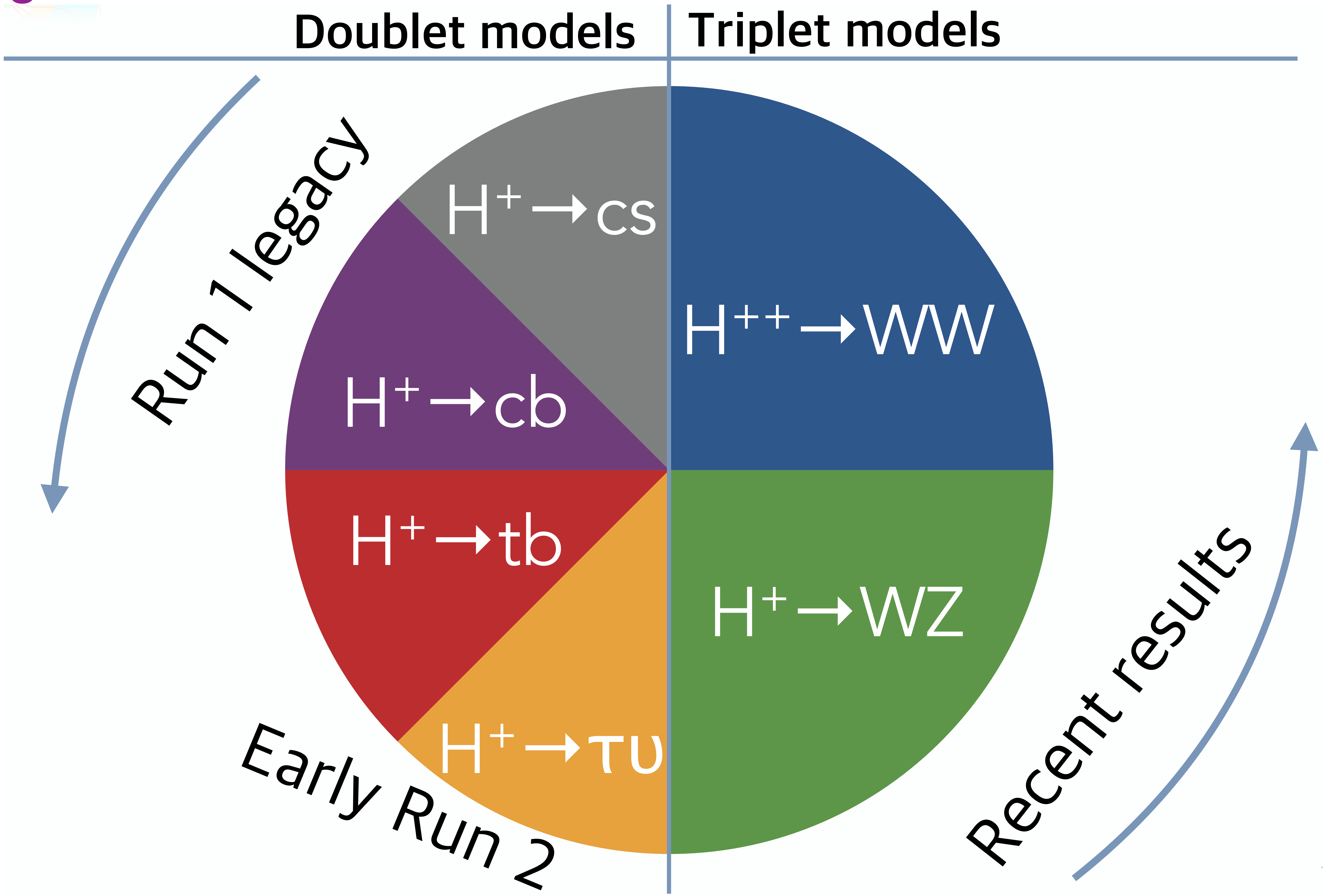
$$\sin(\beta-\alpha) \ : \ g_{hW^+W^-}, \quad g_{hZZ}, \quad g_{ZAH}, \quad g_{W^\pm H^\mp H},$$

$$\cos(\beta-\alpha) \ : \ g_{HW^+W^-}, \quad g_{HZZ}, \quad g_{ZAh}, \quad g_{W^\pm H^\mp h}, \quad g_{Hhh}.$$

ZERO!

3. Full scan for a light H+ in Type-I

3. Type-I for light H+



3. Type-I for light H+

Production \ Decay	$[\tau^\pm \nu]$	$[cb]$	$[cs]$	$[W^\pm \varphi^0/A]$	$[W^\pm h_{SM}/A]$
$t \to H^\pm b$	Type-I Type-X			IS Type-I N2HDM	Type-I [?]
	ATLAS CMS	ATLAS	ATLAS CMS		
$W^{\pm *} \to H^\pm \varphi^0$				IS Type-I	
$W^{\pm *} \to H^\pm A$	Type-X			IS Type-I,X	
$pp \to H^+ H^-$				IS Type-I,X	
$qb \to q' b H^\pm$	MSSM				
$cs/cb \to H^\pm$	Type-III				
$W^{\pm *} W^{\pm *} \to H^\pm H^\pm$	$\mathcal{B}_{\tau\nu} = 1$			Type-I,X	

If the charged Higgs boson is light in Type-I,

how can we cover all the viable parameter space?

3. Type-I for light H+

$$\boxed{\text{We fix } M_{H^\pm} = 110\ \text{GeV}}$$

(i) Theoretical stabilities

(ii) Electroweak precision data

(iii) $b \to s\gamma$ **constraints**

(iv) Higgs precision data

(v) Direct searches at the LEP, Tevatron, and LHC

3. Type-I for light H+

We fix $M_{H^\pm} = 110$ GeV

(i) Theoretical stabilities

Only 0.2% survived!

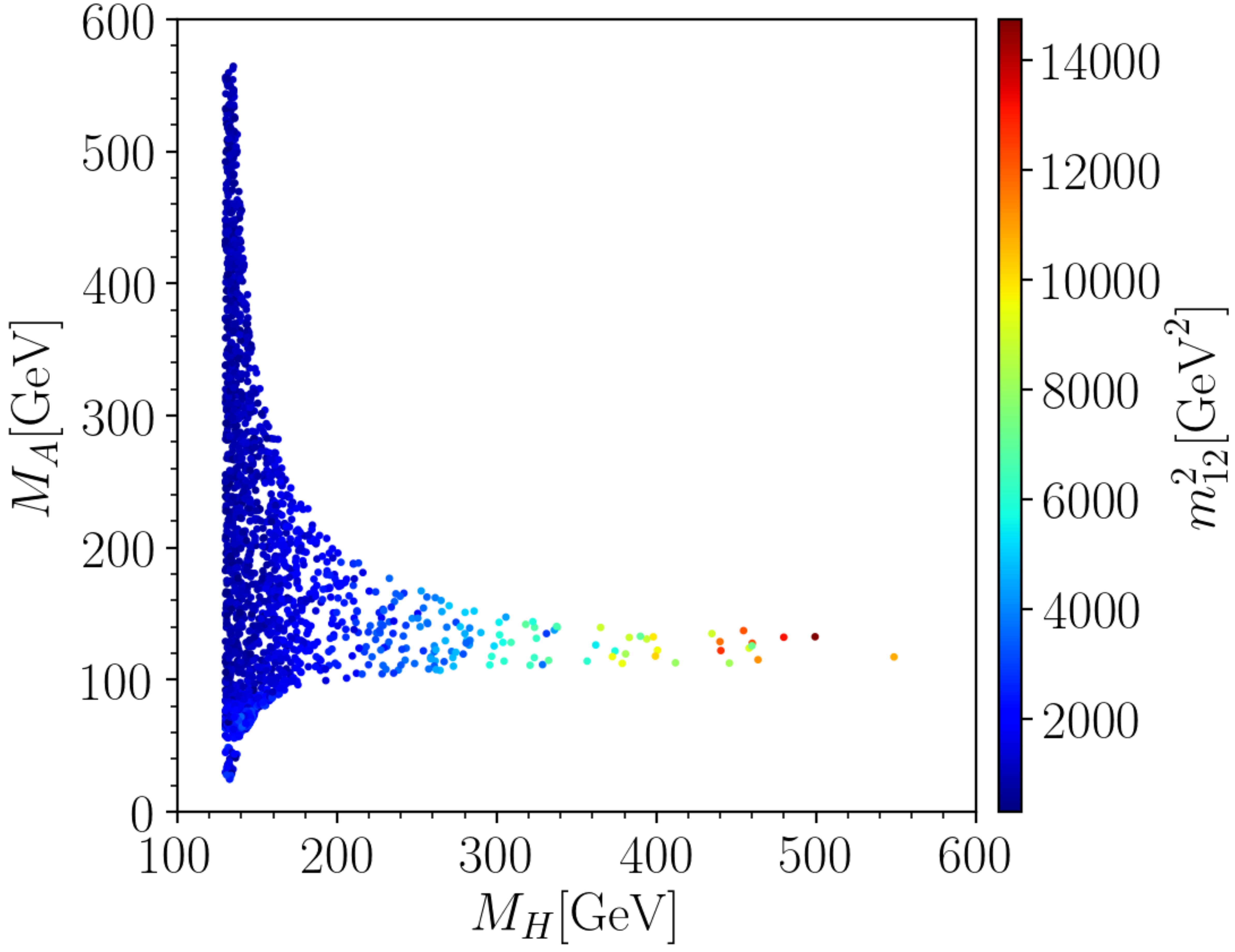
(ii) Electroweak precision data

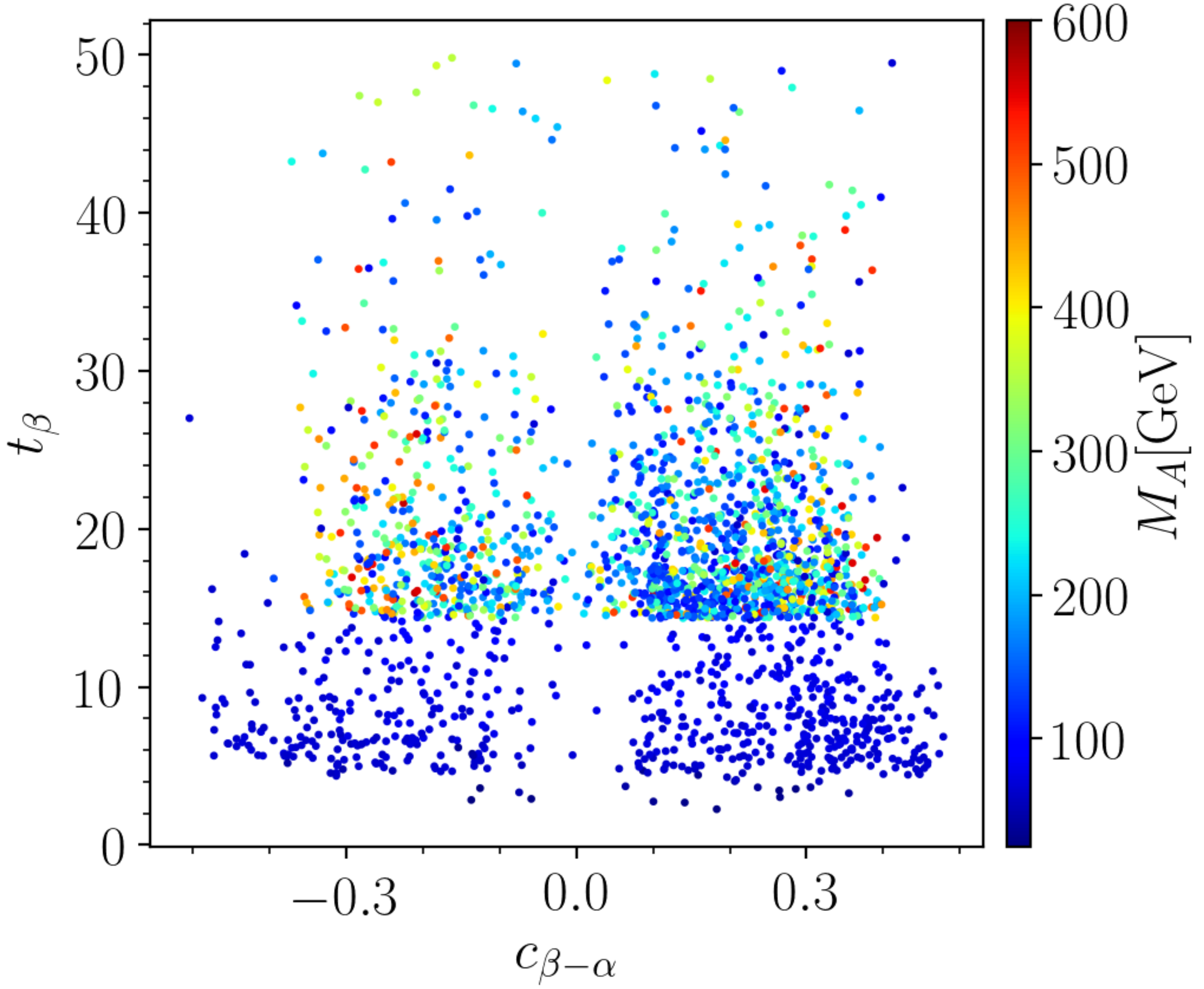
(iii) $b \to s\gamma$ constraints

(iv) Higgs precision data

(v) Direct searches at the LEP, Tevatron, and LHC

3. Type-I for light H+

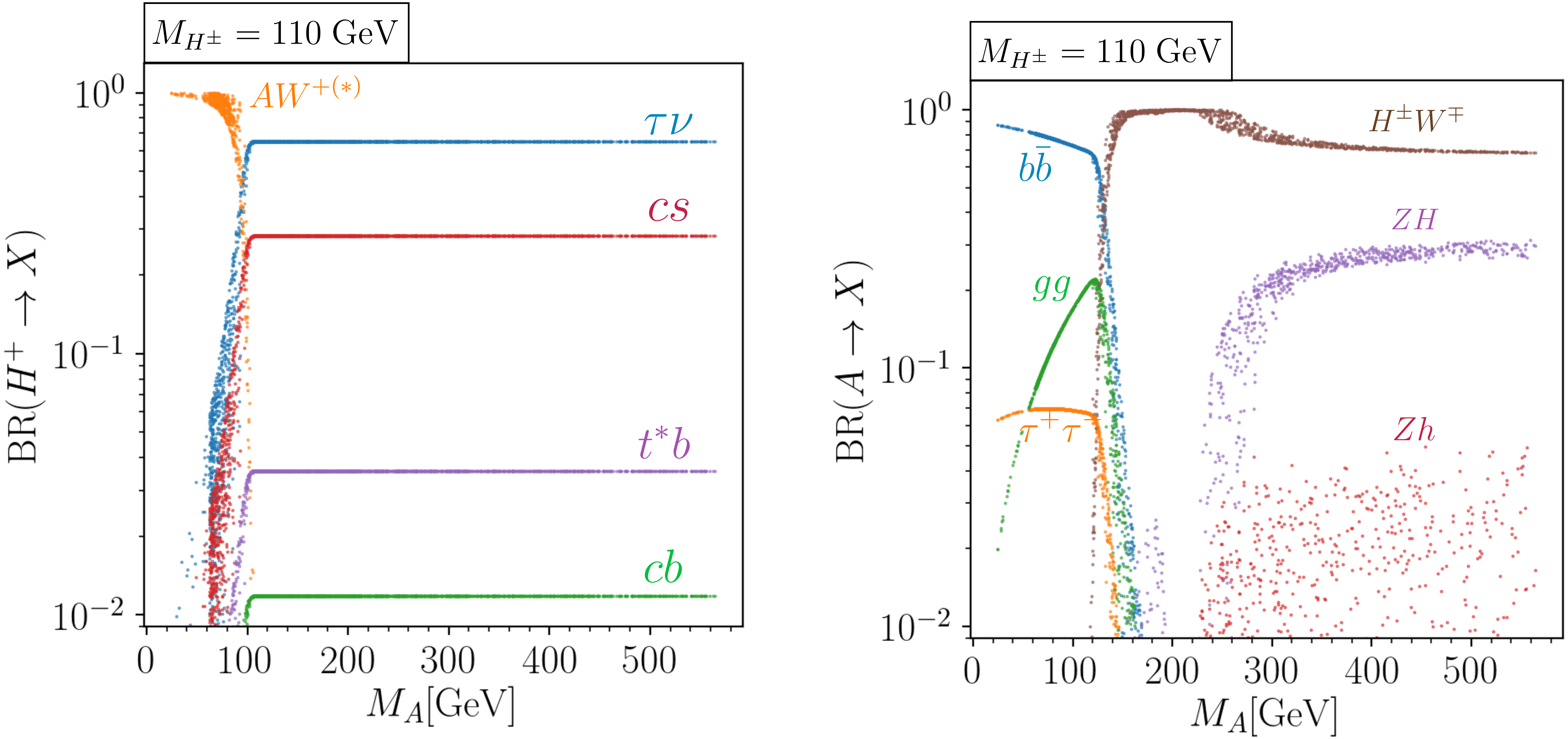




3. Type-I for light H+

Key parameter: MA

3. Type-I for light H+



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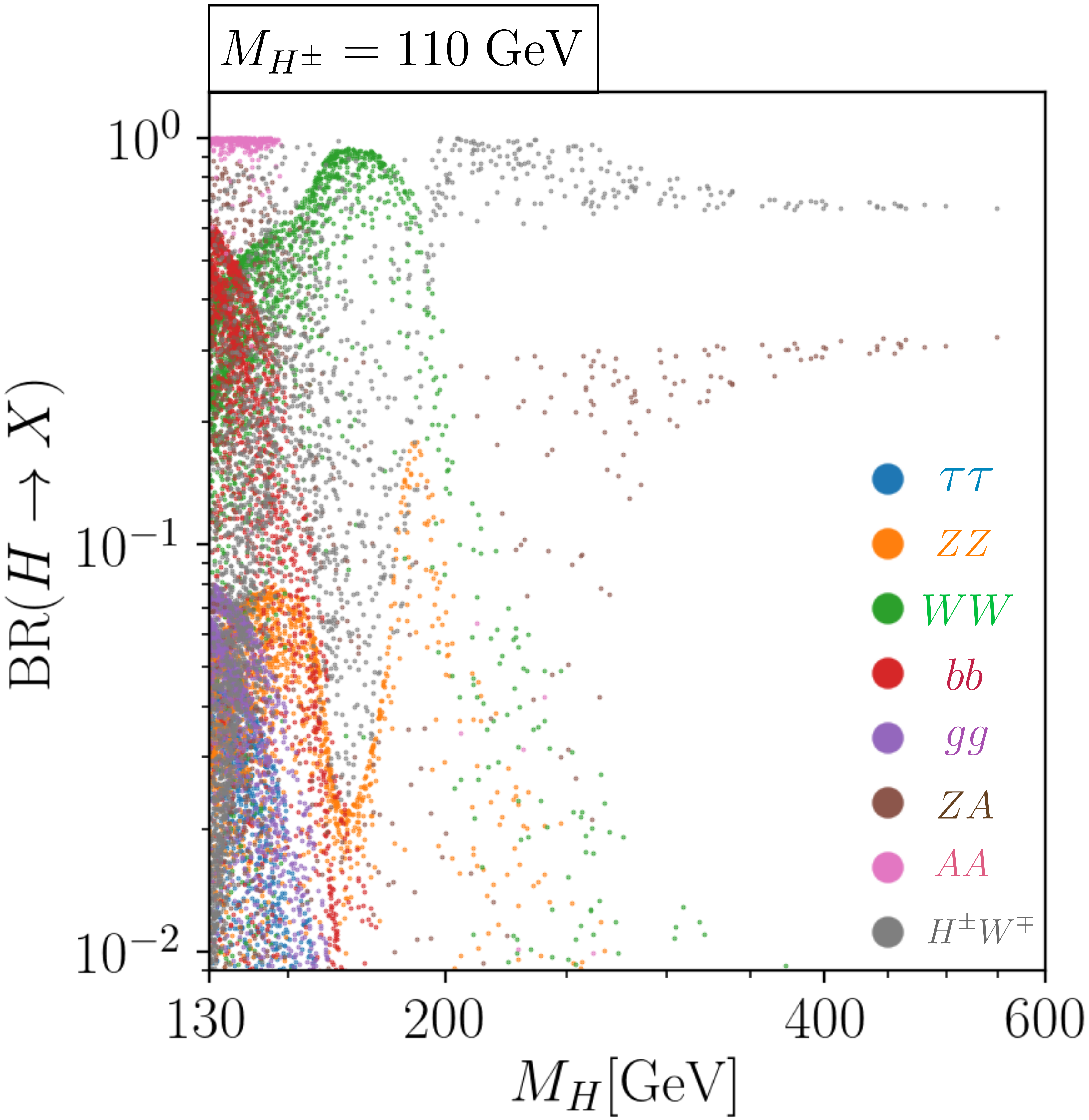
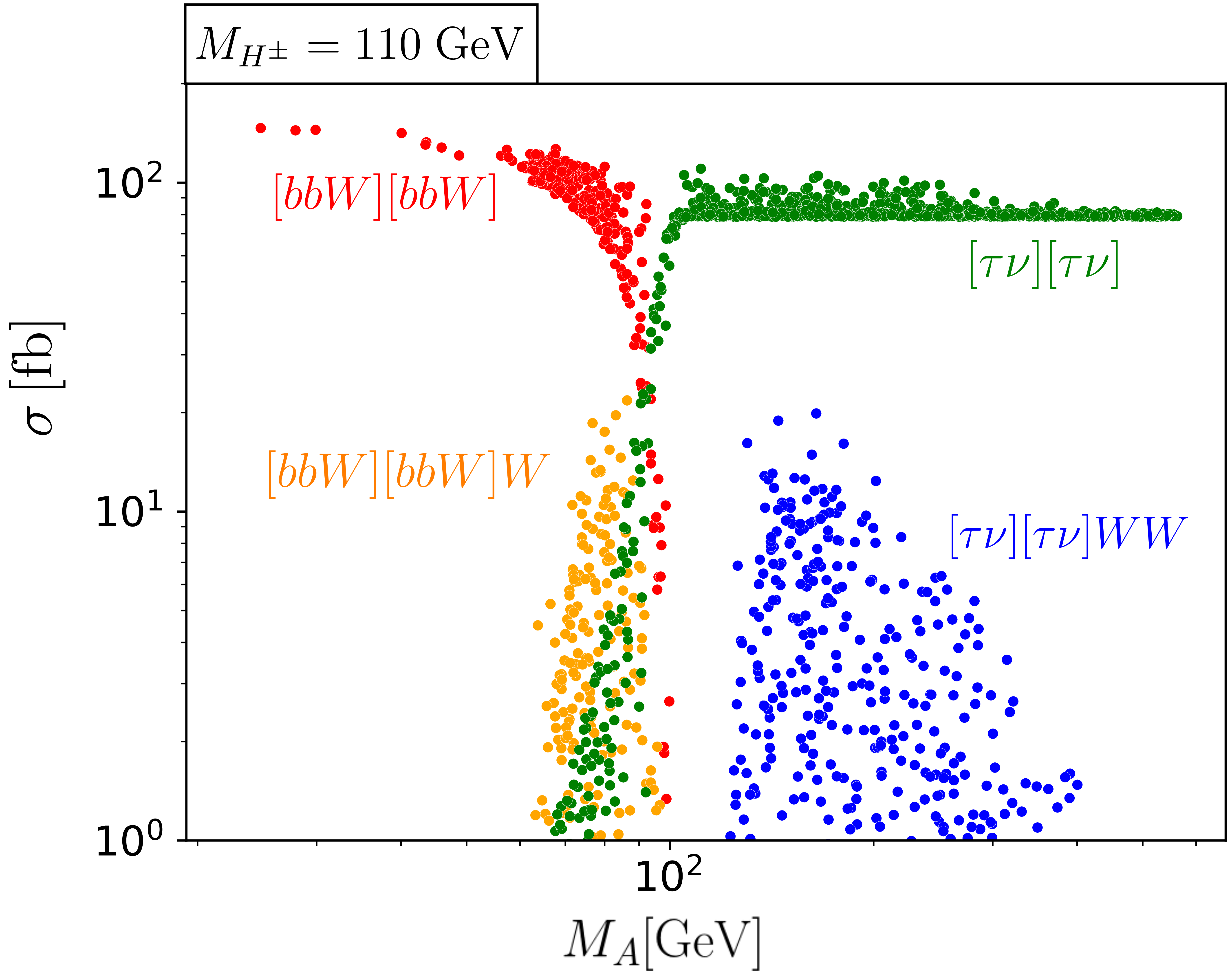


3. Type-I for light H+

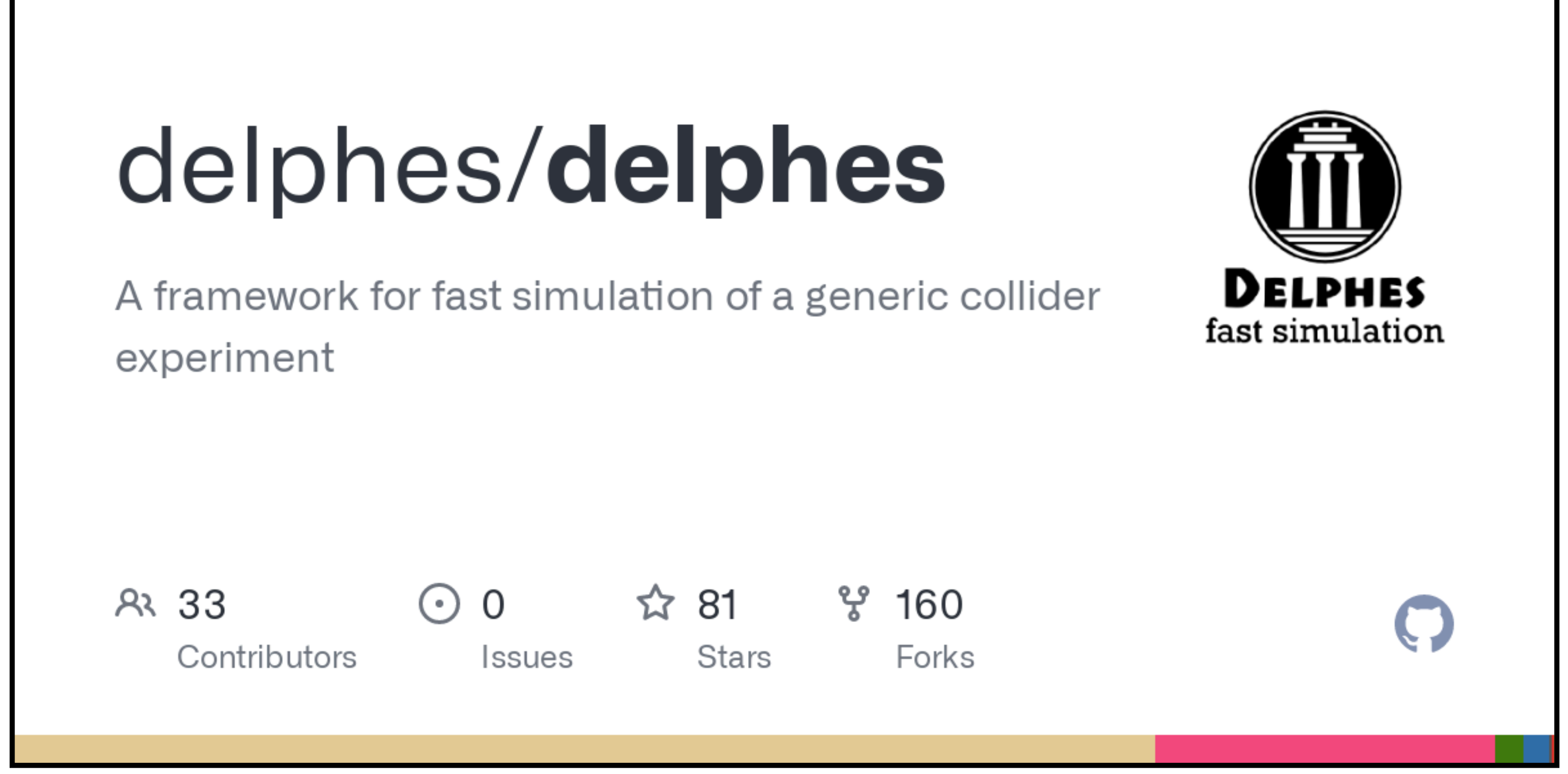
	light A case	heavy A case
Target decay modes	$H^\pm \to AW^\pm$	$H^\pm \to \tau\nu$
	$A \to b\bar{b}$	$A \to H^\pm W^{\mp(*)}$
	$H \to H^\pm W^\mp$	
Initial production	Final states	
$gg \to h/H/A \to H^\pm W^\mp$	$[b\bar{b}W^\pm]W^\mp$	$[\tau\nu]W^\pm$
$q\bar{q}' \to W^* \to H^\pm h$	$[b\bar{b}W^\pm]\,h$	$[\tau\nu]h$
$gg \to H \to AZ$	$[b\bar{b}W^\pm]W^\mp Z$	$[\tau\nu]W^\pm Z$
$gg \to HZ,\ q\bar{q} \to Z^* \to HZ$	$[b\bar{b}W^\pm]W^\mp Z$	$[\tau\nu]W^\pm Z$
$q\bar{q}' \to W^* \to H^\pm A$	$[b\bar{b}W^\pm]b\bar{b}$	$[\tau\nu][\tau\nu]W^\pm$
$q\bar{q}' \to W^* \to H^\pm H$	$[b\bar{b}W^\pm][b\bar{b}W^\pm]W^\mp$ ✓	$[\tau\nu][\tau\nu]W^\pm$
$pp \to H^+H^-$	$[b\bar{b}W^\pm][b\bar{b}W^\mp]$ ✓	$[\tau\nu][\tau\nu]$ ✓
$q\bar{q} \to Z^* \to HA$	$[b\bar{b}W^\pm]b\bar{b}W^\mp$	$[\tau\nu][\tau\nu]W^\pm W^\pm$ ✓
$gg \to HH$	$[b\bar{b}W^\pm][b\bar{b}W^\pm]W^\mp W^\mp$	$[\tau\nu][\tau\nu]W^\pm W^\pm$ ✓
$gg \to AA$	$b\bar{b}b\bar{b}$	$[\tau\nu][\tau\nu]W^\pm W^\pm$ ✓

3. Type-I for light H+



4. Signal-Background Analysis

4. Signal-Background



$$\tau - \text{tagging}$$

$$P_{\tau\to\tau} = 0.85, \quad P_{j\to\tau} = 0.02, \quad \text{in the one-prong } \tau \text{ decays;}$$

$$P_{\tau\to\tau} = 0.65, \quad P_{j,b\to\tau} = 0.01, \quad \text{in the three-prong } \tau \text{ decays.}$$

$$b - \text{tagging}$$

$$P_{b\to b} = 70\%, \quad P_{c\to b} = 10\%, \quad P_{j\to b} = 0.2\%.$$

$$\mathcal{S} = \left[2(N_s + N_b) \log\left(\frac{(N_s + N_b)(N_b + \delta_b^2)}{N_b^2 + (N_s + N_b)\delta_b^2} \right) - \frac{2N_b^2}{\delta_b^2} \log\left(1 + \frac{\delta_b^2 N_s}{N_b(N_b + \delta_b^2)} \right) \right]^{1/2},$$

4. Signal-Background

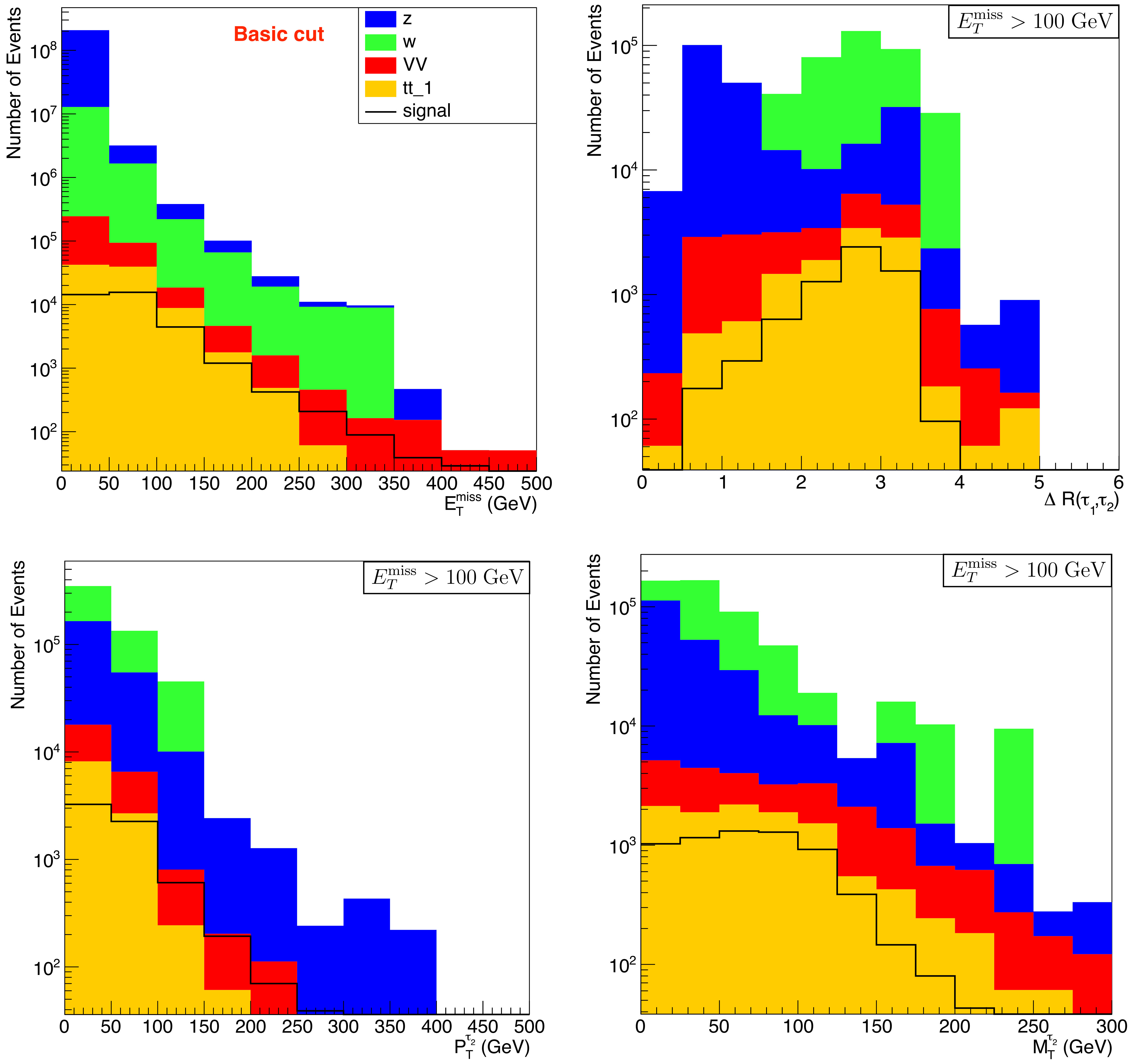
A. $[\tau\nu][\tau\nu]$

Background

- $pp \to W$+jets
- $pp \to Z/\gamma$+jets
- $t\bar{t}$+jets;
- VV'+jets including WW+jets, WZ+jets, and ZZ+jets.
- tW+jets.

4. Signal-Background

A. $[\tau\nu][\tau\nu]$



4. Signal-Background

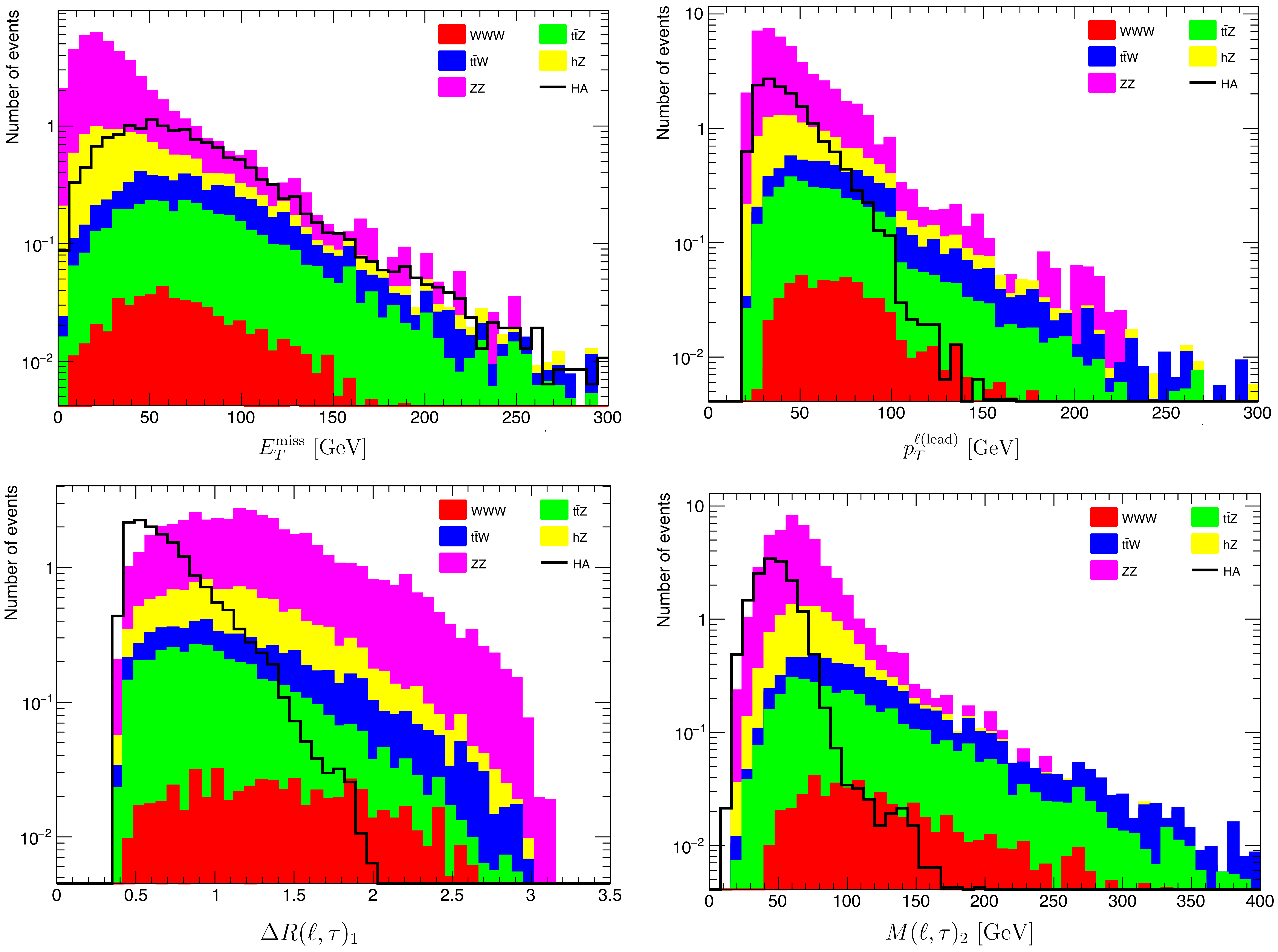
A. $[\tau\nu][\tau\nu]$

$[\tau\nu][\tau\nu]$						
Cut	Wjj	Zjj	$t\bar{t}jj$	$VV'jj$	N_b	N_s
Initial	6.2×10^{11}	4.39×10^{10}	1.33×10^{9}	4.41×10^{8}	6.65×10^{11}	1.04×10^{6}
Basic cuts	1.45×10^{7}	1.96×10^{8}	92929	271570	2.11×10^{8}	36413
$E_T^{\text{miss}} > 100$ GeV	298782	208799	11158	14478	533217	6448
$\lvert\Delta\phi(\tau_1, \tau_2)\rvert > 2.4$	202117	36374	5914	5503	249908	3926
$\Delta R\tau_1, \tau_2 < 3$	114240	8328	2926	2500	127994	2328
$M_{\tau_1\tau_2} > 300$ GeV	0	1054	182	183	1419	465
$p_T^{\tau_2} > 100$ GeV	0	737	121	121	979	347
$M_T^{\tau_2} > 50$ GeV	0	0	121	101	222	284

Significance = 19.06, 10.2(10% uncertainty)

4. Signal-Background

B. $[\tau\nu][\tau\nu]WW$



$\mathbf{B.}\quad [\tau\nu][\tau\nu]WW$

Background

- $pp \to t\bar{t} + W^+ \to b\ell^+\nu\bar{b}\tau^-\nu + \ell^+\nu$
- $pp \to W^-W^+W^+ \to \tau_{\rm h}^-\nu\ell^+\nu\ell^+\nu$
- $pp \to ZZ \to \tau_{\ell^+}^+\tau_{\rm h}^-\tau_{\ell^+}^+\tau_{\rm h}^-$
- $pp \to t\bar{t} + Z \to b\ell^+\nu\bar{b}\tau^-\nu + \tau_{\ell^+}^+\tau^-.$
- $pp \to h_{\rm SM} + Z \to \tau_{\ell^+}^+\tau_{\rm h}^- + \tau_{\ell^+}^+\tau_{\rm h}^-.$

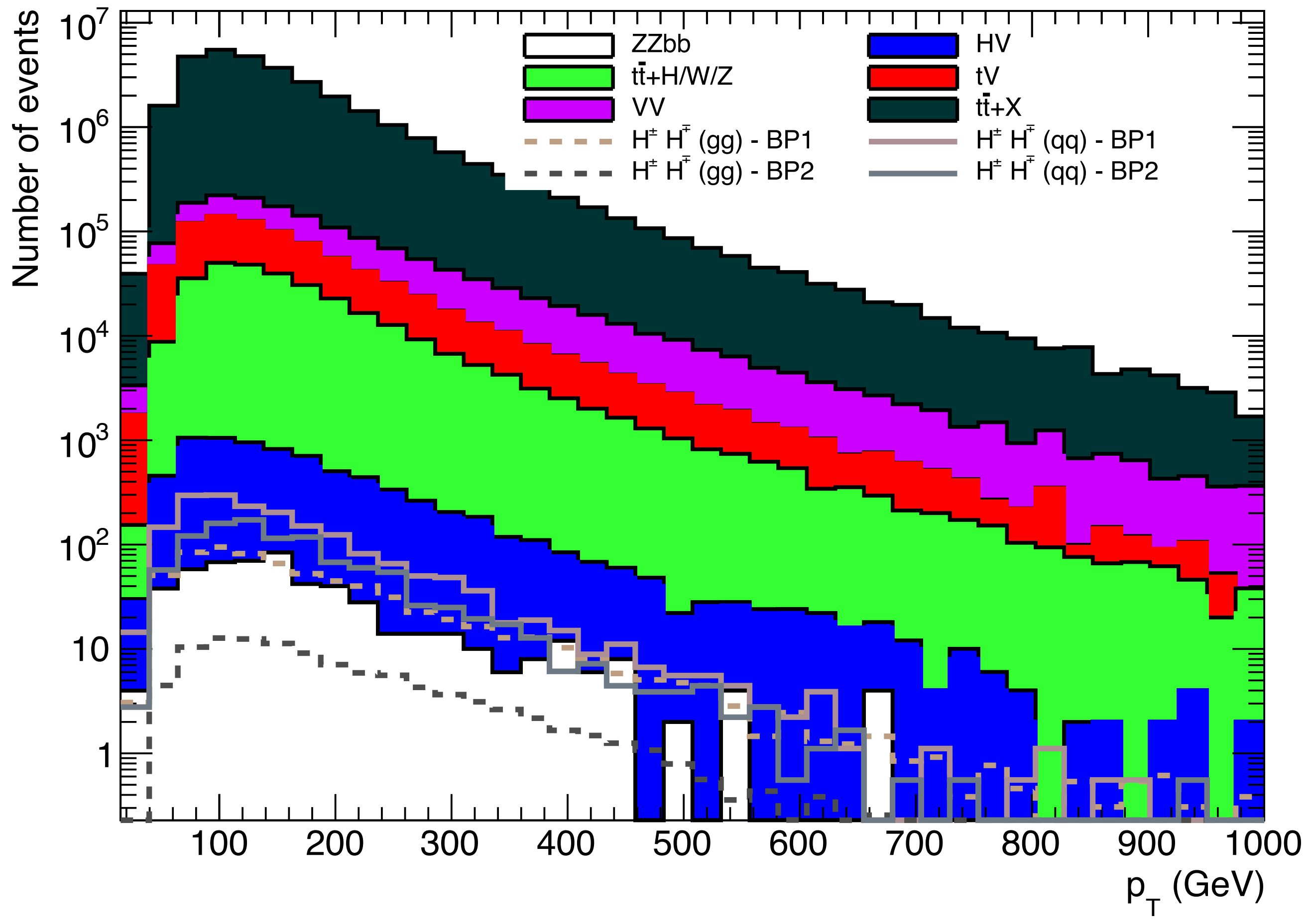
B. $[\tau\nu][\tau\nu]WW$

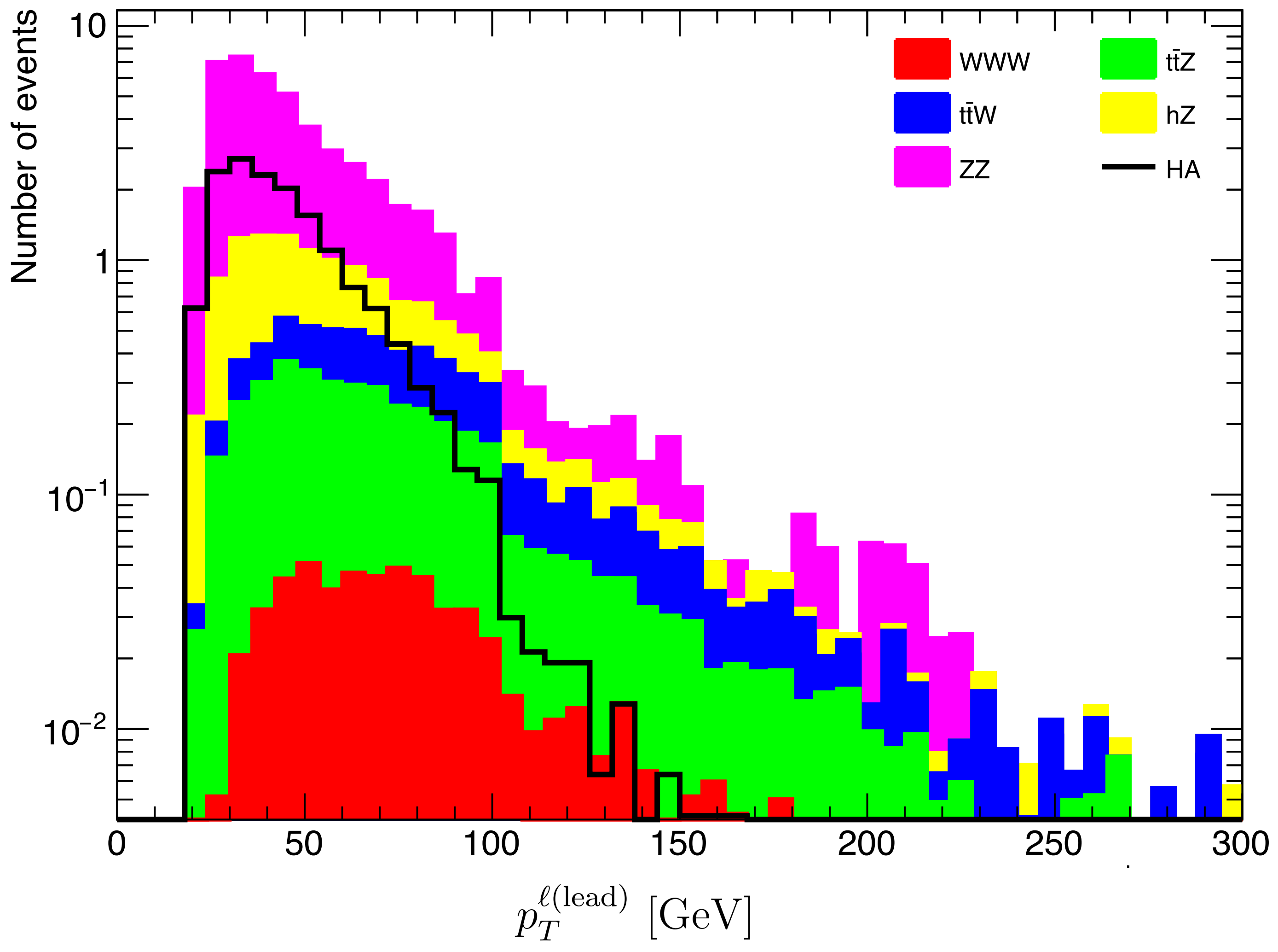
$[\tau\nu][\tau\nu]\ell^{\pm}\nu\ell^{\pm}\nu$							
Cut	$t\bar{t}W$	WWW	ZZ	$t\bar{t}Z$	$h_{\rm SM}Z$	N_b	N_s
Initial	4560	1290	16567	1825	1407	25649	426
Basic cuts	15.14	0.63	35.37	17.04	6.42	74.6	15.6
b-jet veto	2.7	0.62	34.97	3.42	6.35	48.06	15.43
$E_T^{\rm miss} > 45$ GeV	2.07	0.47	7.47	2.64	2.09	14.74	10.73
$p_T^{\ell({\rm lead})} < 70$ GeV	0.94	0.19	5.33	1.53	1.43	9.42	9.59
$p_T^{\tau({\rm lead})} > 40$ GeV	0.77	0.15	4.36	1.25	1.29	7.82	9.09
$0.4 < \Delta R(\ell,\tau)_1 < 0.8$	0.17	0.03	1.49	0.38	0.37	2.44	6.56
$M(\ell,\tau)_1 < 60$ GeV	0.16	0.03	1.31	0.35	0.35	2.2	6.43
$0.4 < \Delta R(\ell,\tau)_2 < 3.0$	0.1	0.01	1.24	0.28	0.35	1.98	6.36
$M(\ell,\tau)_2 < 70$ GeV	0.04	0	1.04	0.14	0.24	1.46	6.04

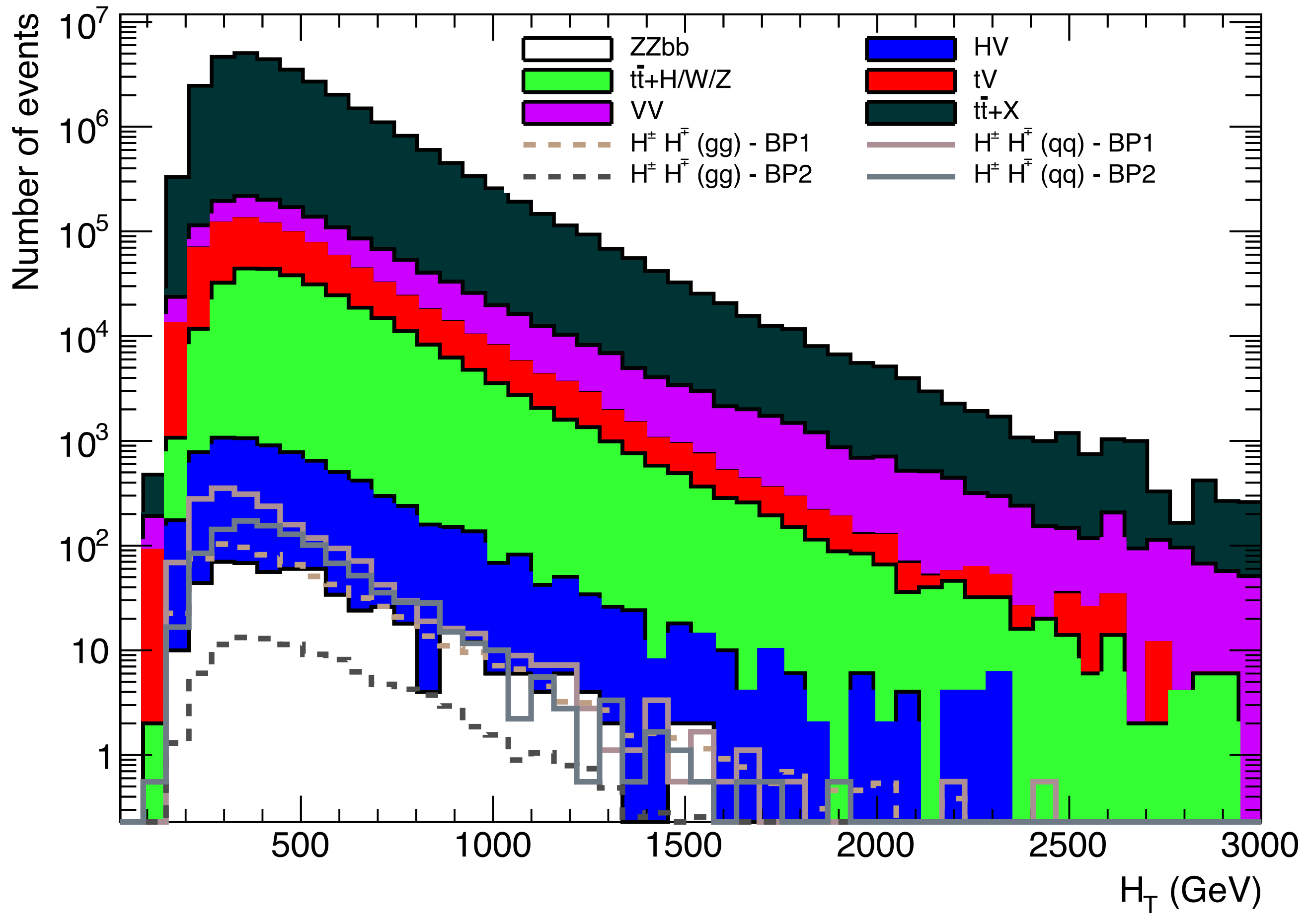
Significance = 3.53, 3.48(10% uncertainty)

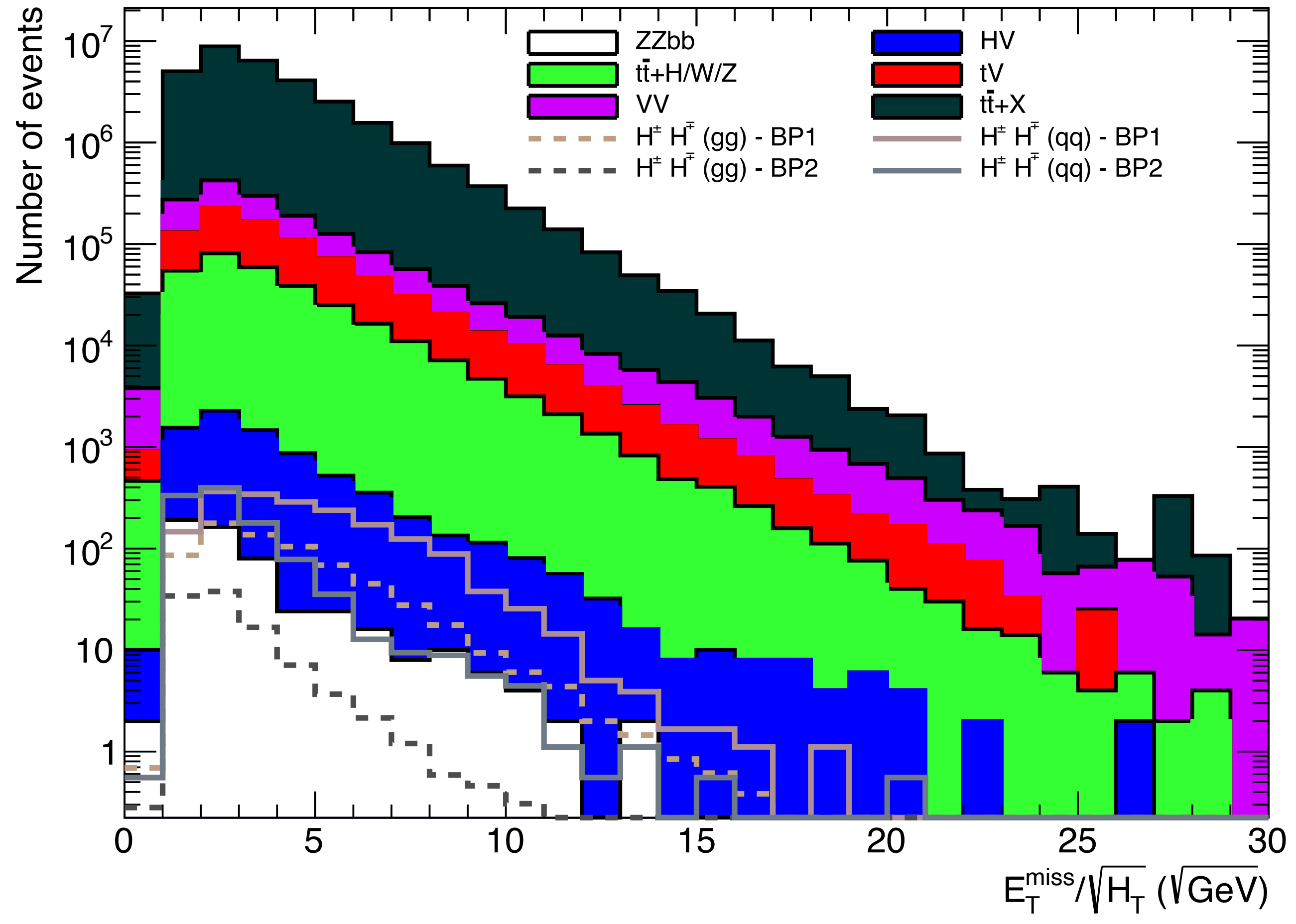
4. Signal-Background

C. $[bbW][bbW]$









4. Signal-Background

C. $[bbW][bbW]$

$[b\bar{b}W][b\bar{b}W]$						
Cut	HV	$tV + t\bar{t}H/V$	$VV + ZZbb$	$t\bar{t}$ + jets	Signal	N_s/N_b
Initial events	6.09×10^6	97.4×10^6	440.9×10^6	1.34×10^9	6.33×10^5	3.34×10^{-4}
One lepton	7.19×10^5	21.2×10^6	71.3×10^6	283.9×10^6	1.20×10^5	3.18×10^{-4}
τ_h veto	6.56×10^5	19.7×10^6	68.5×10^6	259.46×10^6	1.10×10^5	3.18×10^{-4}
$E_T^{\rm miss} > 30$ GeV	4.27×10^5	15.1×10^6	46.42×10^6	206.42×10^6	8.01×10^4	2.98×10^{-4}
$N_{\rm jets} \geq 4, N_b \geq 2$	1.06×10^4	1.0×10^6	1.52×10^5	55.56×10^6	1.06×10^4	1.87×10^{-4}
$M_T^W < 150$ GeV	1.04×10^4	9.65×10^5	1.45×10^5	54.11×10^6	1.03×10^4	1.86×10^{-4}
$M_{bb} < 100$ GeV	5.86×10^3	4.59×10^5	1.13×10^5	20.29×10^6	7.21×10^3	3.45×10^{-4}
$p_T^\ell < 350$ GeV	5.85×10^3	4.59×10^5	1.13×10^5	20.28×10^6	7.21×10^3	3.46×10^{-4}
$p_T^{\rm jet} < p_T^{\rm max}$	5.81×10^3	4.56×10^5	1.10×10^5	20.18×10^6	7.11×10^3	3.42×10^{-4}
$E_T^{\rm miss} < 0.7H_T$	5.72×10^3	4.49×10^5	1.09×10^5	20.00×10^6	7.06×10^3	3.43×10^{-4}
$H_T^W < 0.9H_T$	5.39×10^3	4.33×10^5	1.06×10^5	19.61×10^6	6.92×10^3	3.43×10^{-4}
$E_T^{\rm miss} < 0.4M_{\rm eff}$	5.39×10^3	4.33×10^5	1.06×10^5	19.61×10^6	6.92×10^3	3.43×10^{-4}
$H_T^W < 0.5M_{\rm eff}$	5.39×10^3	4.33×10^5	1.06×10^5	19.61×10^6	6.92×10^3	3.43×10^{-4}
Top veto	5.11×10^3	4.14×10^5	1.00×10^5	18.67×10^6	6.78×10^3	3.54×10^{-4}
$\lvert M_{bbjj} - 110\rvert < 10$ GeV	2.20×10^2	1.45×10^4	2.49×10^3	6.08×10^5	3.90×10^2	6.24×10^{-4}
$H_T < 400$ GeV	1.92×10^2	1.21×10^4	1.84×10^3	5.18×10^5	3.08×10^2	5.78×10^{-4}
$N_b = 2$	1.60×10^2	1.08×10^4	1.68×10^3	4.40×10^5	2.36×10^2	5.21×10^{-4}
$N_b = 3$	3.2×10^1	1.16×10^3	1.54×10^2	7.12×10^4	5.73×10^1	7.90×10^{-4}
$N_b = 4$	0	1.40×10^2	0	6.08×10^3	1.42×10^1	2.28×10^{-3}

Significance = 0.2 ~0.4

Conclusions

- A light $H^{\pm}$ is an interesting NP signal at the LHC.
- In Type-I 2HDM, imposing the light $M_{H^{\pm}}$ restricts the model significantly.
- The smoking-gun signals cover most of the parameter space:
  - $pp \to H^+H^- \to [\tau\nu][\tau\nu]$
  - $pp \to HA/HH/AA \to H^-W^+H^-W^+ + c.c$
  - $pp \to H^+H^- \to AW^+AA^- \to bbbb\ell\nu qq'$