Phenomenology of a flavoured multiscalar BGL-like model with three generations of massive neutrinos

Speaker: Vasileios Vatellis[1]

Collaborators: P.M. Ferreira, Felipe F. Freitas, João Gonçalves, António P. Morais, Roman Pasechnik and Vasileios Vatellis,

Project link: arXive:2202.13153

[1]Physics Department and Centre for Research and Development in Mathematics and Applications (CIDMA), Department of Mathematics, University of Aveiro, Portugal.

ICHEP 2022 BOLOGNA

universidade de aveiro

FCT Fundação para a Ciência e a Tecnologia

CIDMA CENTRO DE I&D EM MATEMÁTICA E APLICAÇÕES CENTER FOR R&D IN MATHEMATICS AND APPLICATIONS

Gr@v

A generic Next-to-Minimal Two Higgs Doublet Model (NTHDM) with a BGL structure

An SM extension with:

- a flavour non-universal $U(1)'$ global symmetry,
- a second Higgs Doublet Φ_2,
- a scalar singlet S
- three generations of right-handed neutrinos $\nu_R^{1,2,3}$, with a type-I seesaw mechanism

That follow the Branco-Grimus-Lavoura (BGL) quark textures.

Model Introduction

$$-\mathcal{L}_{\text{Yukawa}} = \overline{q_L^0}\Gamma_a\Phi^a d_R^0 + \overline{q_L^0}\Delta_a\tilde{\Phi}^a u_R^0 + \overline{\ell_L^0}\Pi_a\Phi^a e_R^0 + \overline{\ell_L^0}\Sigma_a\tilde{\Phi}^a \nu_R^0$$

$$+\frac{1}{2}\overline{\nu_R^{c\,0}}\left(\mathrm{A} + \mathrm{B}S + \mathrm{C}S^*\right)\nu_R^0 + \mathrm{h.c.},$$

$\Gamma_\alpha, \Delta_\alpha$: Yukawa matrices for the down- and up- quarks,

$\Pi_\alpha, \Sigma_\alpha$: Yukawa matrices for the charged leptons and neutrinos

B, C : Majorana-like Yukawa matrices

A : Majorana mass term

$$\Gamma_1 : \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix}, \Gamma_2 : \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}, \Delta_1 : \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}, \Delta_2 : \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

Note: The choice of textures implies that tree-level FCNCs will appear only in the down quark sector

Model Introduction

BGL was introduced in: G. C. Branco, W. Grimus, and L. Lavoura, Phys. Lett. **B380**, 119 (1996), arXiv:hep-ph/9601383 [hep-ph].

Rotating the Yukawa matrices in the Higgs base:

$$\left(N_u\right)_{ij} = \left(t_\beta \delta_{ij} - \left(t_\beta + t_\beta^{-1}\right) \delta_{ij}\delta_{j3}\right) m_{u_j},$$

$$\left(N_d\right)_{ij} = \left(t_\beta \delta_{ij} - \left(t_\beta + t_\beta^{-1}\right) V_{3i}^{*} V_{3j}\right) m_{d_j},$$

- Only the down-quark sector has non-diagonal terms (FCNCs on the down sector)
- FCNCs suppressed by CKM matrix elements

$t_\beta = \tan\beta = v_1/v_2$, V: Cabibbo–Kobayashi–Maskawa (CKM), flavor changing neutral current (FCNC)

Model Introduction

The potential is defined as $V = V_0 + V_1$

$$V_0 = \mu_i^2 |\Phi^i|^2 + \lambda_i |\Phi^i|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \mu_S{}^2 |S|^2 + \lambda_1' |S|^4$$
$$+\lambda_2' |\Phi_1|^2 |S|^2 + \lambda_3' |\Phi_2|^2 |S|^2 \qquad (i = 1{,}2) \text{ and}$$
$$V_1 = \mu_3^2 \Phi_2^\dagger \Phi_1 + \frac{1}{2}\mu_b^2 S^2 + a_1 \Phi_1^\dagger \Phi_2 S + a_2 \Phi_1^\dagger \Phi_2 S^\dagger + a_3 \Phi_1^\dagger \Phi_2 S^2 + a_4 \Phi_1^\dagger \Phi_2 {S^\dagger}^2 + \mathrm{h.c.}.$$

Given that the singlet S carries a non-trivial $U(1)'$ charge X_S, then, out of the four $a_{1,2,3,4}$ and μ_b terms, only one is allowed in the limit of an exact $U(1)'$. However, both a_1 and a_2, as well as μ_b, can be introduced to softly break the flavour symmetry and are allowed to coexist with either a_3 or a_4.

Model Introduction

Anomaly cancellation

This work was inspired considering local $U(1)'$ symmetry where gauge anomalies are forbidden. With this in mind, and with the purpose of making the considered model consistent with a gauged version (to be studied elsewhere), one must also include a set of restrictions that incorporate the $U(1)'$.

Anomaly cancellation conditions

The set of restrictions for the gauge anomalies of the $\mathrm{U}(1)'$ charges are the following triangle anomalies

$$
\begin{gathered}
\left[\mathrm{U}(1)'\right]^3, \;\; \mathrm{U}(1)'\left[\mathrm{Gravity}\right]^2, \\
\mathrm{U}(1)'\left[\mathrm{U}(1)_{\mathrm{Y}}\right]^2, \;\; \mathrm{U}(1)'\left[\mathrm{SU}(2)_{\mathrm{L}}\right]^2 \\
\mathrm{U}(1)'\left[\mathrm{SU}(3)_{\mathrm{C}}\right]^2, \;\; \left[\mathrm{U}(1)'\right]^2 \mathrm{U}(1)_{\mathrm{Y}} .
\end{gathered}
$$

Anomaly-free conditions

$$-\mathscr{L}_{\mathrm{Yukawa}} = \overline{q_L^0}\Gamma_a\Phi^a d_R^0 + \overline{q_L^0}\Delta_a\tilde{\Phi}^a u_R^0 + \overline{\ell_L^0}\Pi_a\Phi^a e_R^0 + \overline{\ell_L^0}\Sigma_a\tilde{\Phi}^a \nu_R^0 + \frac{1}{2}\overline{\nu_R^{c\,0}}\left(\mathrm{A} + \mathrm{B}S + \mathrm{C}S^*\right)\nu_R^0 + \mathrm{h.c.},$$

Based on the BGL quark structure we have 36 constrains:

$$\begin{aligned}
&X_{q_{1,2}} - X_{d_{1,2,3}} = X_{\Phi_1}, \;\; X_{q_3} - X_{d_{1,2,3}} \neq X_{\Phi_1}, \\
&X_{q_3} - X_{d_{1,2,3}} = X_{\Phi_2}, \;\; X_{q_{1,2}} - X_{d_{1,2,3}} \neq X_{\Phi_2}, \\
&X_{q_{1,2}} - X_{u_{1,2}} = -X_{\Phi_1}, \;\; X_{q_3} - X_{u_{1,2,3}} \neq -X_{\Phi_1}, \\
&X_{q_{1,2}} - X_{u_3} \neq -X_{\Phi_1}, \;\; X_{q_3} - X_{u_3} = -X_{\Phi_2}, \\
&X_{q_{1,2}} - X_{u_{1,2,3}} \neq -X_{\Phi_2}, \;\; X_{q_3} - X_{u_{1,2}} \neq -X_{\Phi_2}.
\end{aligned}$$

Anomaly-free conditions

For the lepton and neutrino

- Three massive charged leptons $\det M_e \neq 0$
- Three generations of massive neutrinos $\det M_\nu \neq 0$;
- A non-zero complex phase in the PMNS matrix $\det[M_e M_e^\dagger] \neq 0$ and $\det[M_\nu M_\nu^\dagger] \neq 0$

There are 11 minimal textures for A, B and C that fulfil this constrains. Also, in the presence of the $U(1)'$ flavour symmetry one must fulfil the transformation laws

$$A_{ij} = e^{i\alpha(X_{\nu_i}+X_{\nu_j})}A_{ij}, \quad B_{ij} = e^{i\alpha(X_{\nu_i}+X_{\nu_j}+X_S)}B_{ij}, \quad C_{ij} = e^{i\alpha(X_{\nu_i}+X_{\nu_j}-X_S)}C_{ij}\,.$$

Last, from the potential V_1 and the terms $a_{1,2,3,4}$ we extra the conditions

$$X_S = \pm\left(X_{\Phi_1} - X_{\Phi_2}\right), \quad X_S = \pm\frac{1}{2}\left(X_{\Phi_1} - X_{\Phi_2}\right),$$

Anomaly-free solution

1. νBGL-I Scenario

$$\Pi_1, \Sigma_1, B = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \Pi_2, \Sigma_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix},$$

$$A = \mathbb{0}, \quad C = \begin{pmatrix} 0 & 0 & \times \\ 0 & 0 & \times \\ \times & \times & 0 \end{pmatrix}.$$

2. νBGL-IIa Scenario

$$\Pi_1, \Sigma_1 = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$\Pi_2 = \begin{pmatrix} 0 & 0 & 0 \\ \times & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad \Sigma_2 = \begin{pmatrix} 0 & \times & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$A = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad B = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix}, \quad C = \mathbb{0}.$$

3. νBGL-IIb Scenario

$$A = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix}, \quad B = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$C = \mathbb{0}.$$

Model Introduction

Charges	νBGL-I	νBGL-IIa	νBGL-IIb
q_L	$\begin{bmatrix} x \\ x \\ x_{tL} \end{bmatrix}$	$--$	$--$
u_R	$\begin{bmatrix} y \\ y \\ x_{tR} \end{bmatrix}$	$--$	$--$
d_R	$\begin{bmatrix} 2x-y \\ 2x-y \\ 2x-y \end{bmatrix}$	$--$	$--$
ℓ_L	$\begin{bmatrix} -3x \\ -3x \\ 21x-6y \end{bmatrix}$	$\begin{bmatrix} x-y \\ -7x+y \\ 21x-6y \end{bmatrix}$	$\frac{1}{3}\begin{bmatrix} -x-2y \\ -17x+2y \\ 39x-12y \end{bmatrix}$

Charges	νBGL-I	νBGL-IIa	νBGL-IIb
e_R	$\begin{bmatrix} -2x-y \\ -2x-y \\ 30x-9y \end{bmatrix}$	$\begin{bmatrix} 2x-2y \\ -6x \\ 30x-9y \end{bmatrix}$	$\frac{1}{3}\begin{bmatrix} 2x-5y \\ -14x-y \\ 58x-19y \end{bmatrix}$
ν_R	$\begin{bmatrix} -4x+y \\ -4x+y \\ 12x-3y \end{bmatrix}$	$\begin{bmatrix} 0 \\ -8x+2y \\ 12x-3y \end{bmatrix}$	$\frac{1}{3}\begin{bmatrix} -4x+y \\ -20x+5y \\ 20x-5y \end{bmatrix}$
Φ	$\begin{bmatrix} -x+y \\ -9x+3y \end{bmatrix}$	$\begin{bmatrix} -x+y \\ -9x+3y \end{bmatrix}$	$\frac{1}{3}\begin{bmatrix} 3(-x+y) \\ -19x+7y \end{bmatrix}$
S	$8x-2y$	$-4x+y$	$\frac{8x-2y}{3}$

TABLE I: Allowed charges for the various models. For model νBGL-I and -IIa we have $x_{tL} = -7x+2y$ and $x_{tR} = -16x+5y$. Model νBGL-IIb has $x_{tL} = (-13x+4y)/3$ and $x_{tR} = (-32x+11y)/3$.

Model Introduction

Chosen Scenario: νBGL-I

$$x = 1\,,\ y = 1/3$$

	Φ_1	Φ_2	S	q_1	q_2	q_3	u_{R_1}	u_{R_2}	u_{R_3}	d_{R_1}	d_{R_2}	d_{R_3}
$\mathrm{U(1)_Y}$	1/2	1/2	0	1/6	1/6	1/6	2/3	2/3	2/3	-1/3	-1/3	-1/3
$\mathrm{SU(2)_L}$	**2**	**2**	**1**	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**
$\mathrm{SU(3)_C}$	**1**	**1**	**1**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
$\mathrm{U(1)'}$	-2/3	-8	22/3	1	1	-19/3	1/3	1/3	-43/3	5/3	5/3	5/3

	ℓ_1	ℓ_2	ℓ_3	e_{R_1}	e_{R_2}	e_{R_3}	ν_{R_1}	ν_{R_2}	ν_{R_3}
$\mathrm{U(1)_Y}$	-1/2	-1/2	-1/2	-1	-1	-1	0	0	0
$\mathrm{SU(2)_L}$	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**
$\mathrm{SU(3)_C}$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$\mathrm{U(1)'}$	-3	-3	19	-7/3	-7/3	27	-11/3	-11/3	11

Restrictions

For the peruse of this analysis we have test our model under

1) STU electroweak precision observables (or oblique parameters),
2) Higgs observables
3) Most relevant Quark Flavour Violation (QFV) observables

1) STU: We use the values for the electroweak fit for the STU parameter from [41], and we use also SPheno to calculate the STU in our model.

$$\begin{aligned} S &= -0.01 \pm 0.10 \\ T &= 0.03 \pm 0.12 \\ U &= 0.02 \pm 0.11 \end{aligned} \, , \qquad \rho_{ij} = \begin{pmatrix} 1 & 0.92 & -0.80 \\ 0.92 & 1 & -0.93 \\ -0.80 & -0.93 & 1 \end{pmatrix}$$

Were we require $\Delta x^2 < 7.815$, which is translated to 95% confidence level (CL) agreement with the electroweak fit.

$$\Delta\chi^2 = \sum_{ij} \left(\Delta\mathcal{O}_i - \Delta\mathcal{O}_i^{(0)} \right) \left[(\sigma^2)^{-1} \right]_{ij} \left(\Delta\mathcal{O}_j - \Delta\mathcal{O}_j^{(0)} \right)$$

[41] P. A. Zyla *et al.* (Particle Data Group), PTEP **2020**, 083C01 (2020).

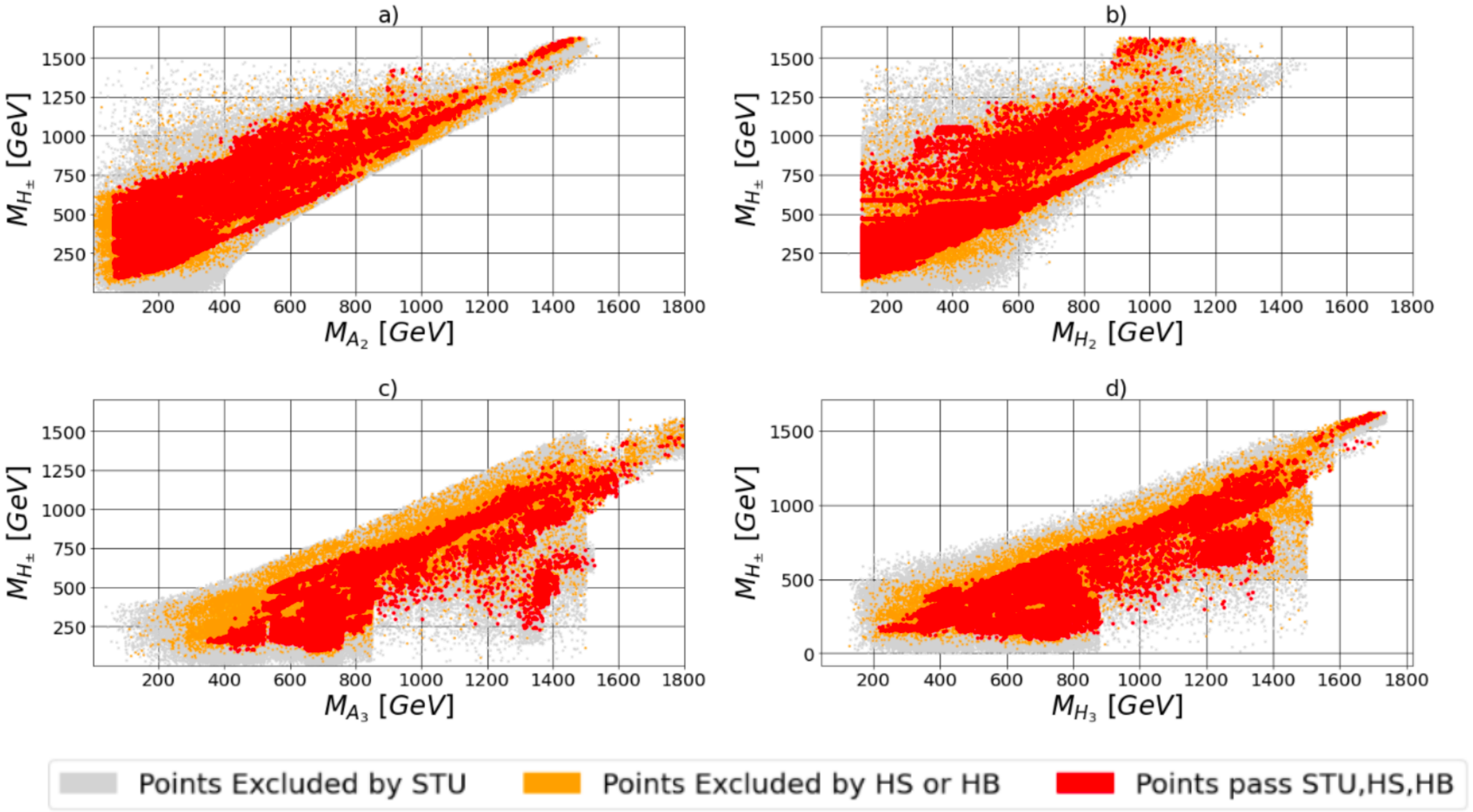
Restrictions

2) <u>Higgs observables:</u> For the Higgs observables we have used SPheno to calculate the values in our model and HiggsBounds/HiggsSignals for the validity of our model

3) For the Quark Flavour Violation (QFV) observables we have only take into consideration the most relevant channels summarised in the table below.

Channel	$\mathcal{O}_{SM}$	σ_{SM}	$\mathcal{O}_{Exp}$	σ_{Exp}	σ
$\mathrm{BR}(\mathrm{B} \to \chi_{\mathrm{s}}\gamma)$	3.29×10^{-4}	1.87×10^{-5}	3.32×10^{-4}	0.16×10^{-4}	0.075
$\mathrm{BR}(\mathrm{B_s} \to \mu\mu)$	3.66×10^{-9}	1.66×10^{-10}	2.80×10^{-9}	0.06×10^{-9}	0.038
ΔM_d (GeV)	3.97×10^{-13}	5.07×10^{-14}	3.33×10^{-13}	0.013×10^{-13}	0.11
ΔM_s (GeV)	1.24×10^{-11}	7.08×10^{-13}	1.17×10^{-11}	0.0014×10^{-11}	0.054
ϵ_K (GeV)	1.81×10^{-3}	2.00×10^{-4}	2.23×10^{-3}	0.011×10^{-3}	0.14

Results

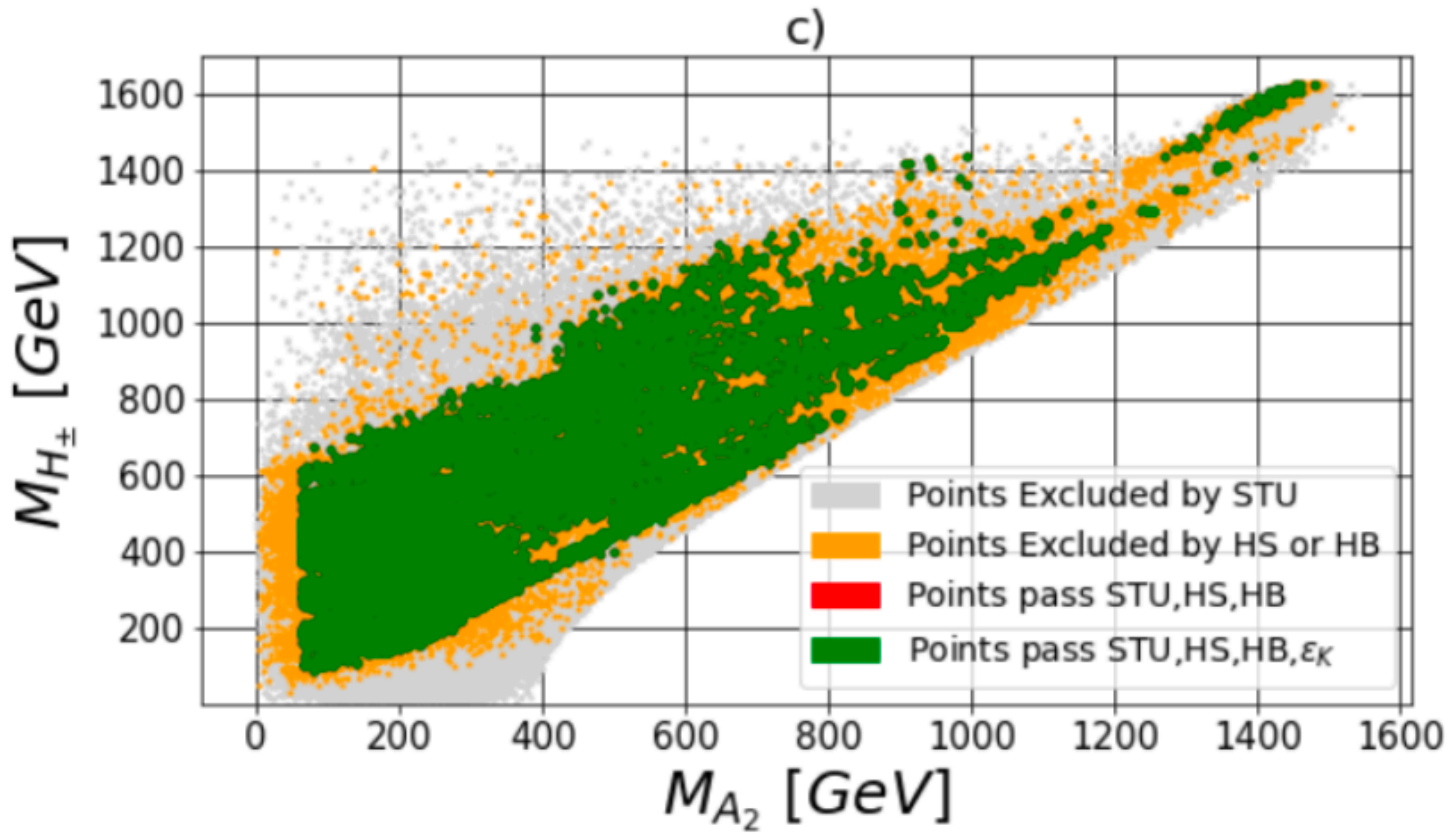


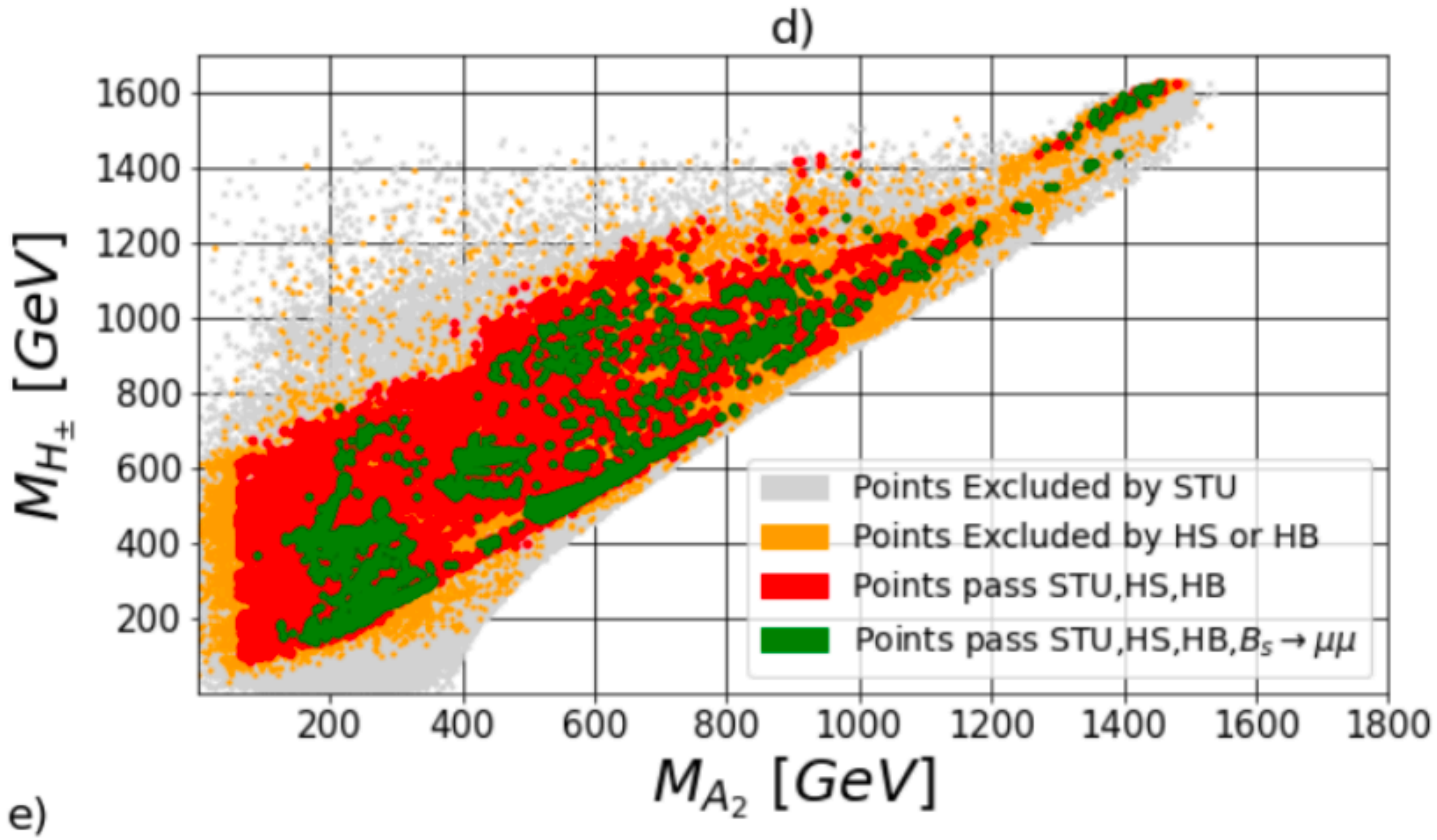
a)
b)
c)
d)
$M_{H_\pm}$ [GeV]
M_{A_2} [GeV]
M_{H_2} [GeV]
M_{A_3} [GeV]
M_{H_3} [GeV]
Points Excluded by STU
Points Excluded by HS or HB
Points pass STU,HS,HB

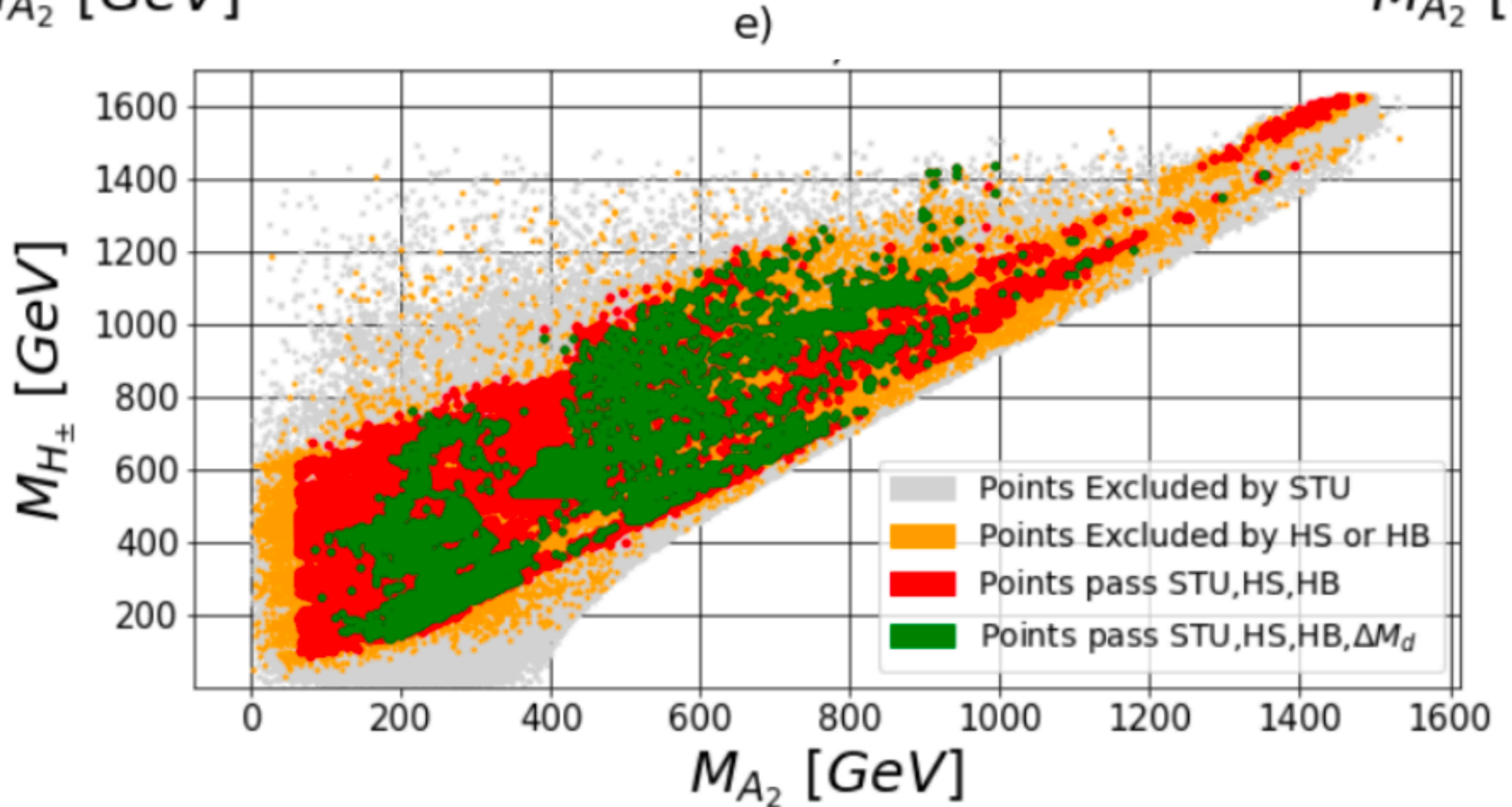
Results

Mass of the charged Higgs versus the mass of the lightest pseudoscalar A_2. Grey points are excluded by STU observables, orange points are excluded by HS or HB while still passing STU, and red points pass STU, HS and HB constraints. In green, we showcase the points that pass a given QFV observable, namely, we have a) $B \to \chi_S\gamma$, b) ΔM_s

Results







c) ϵ_K
d) $B_S \to \mu\mu$
e) ΔM_d

Results

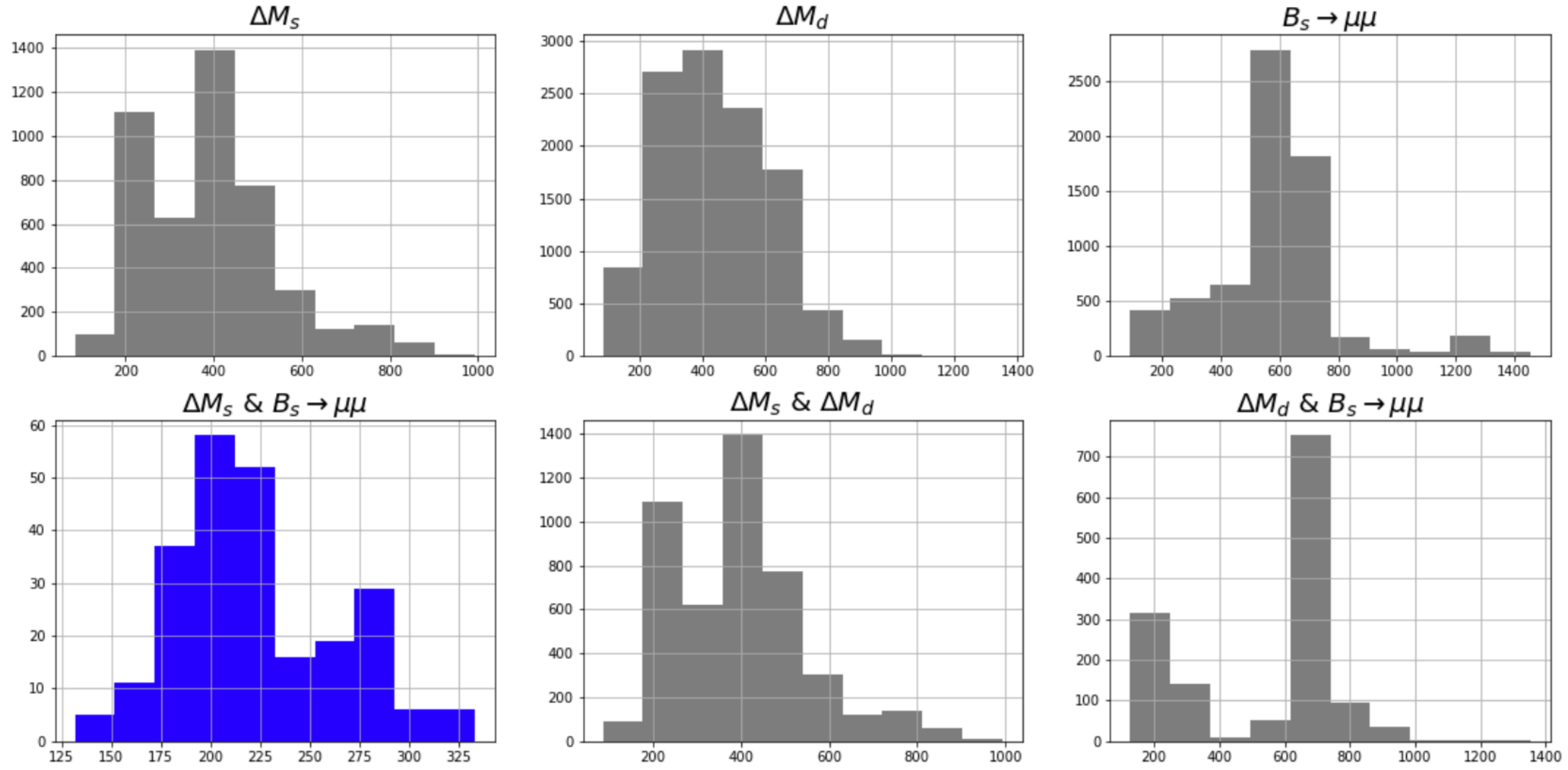
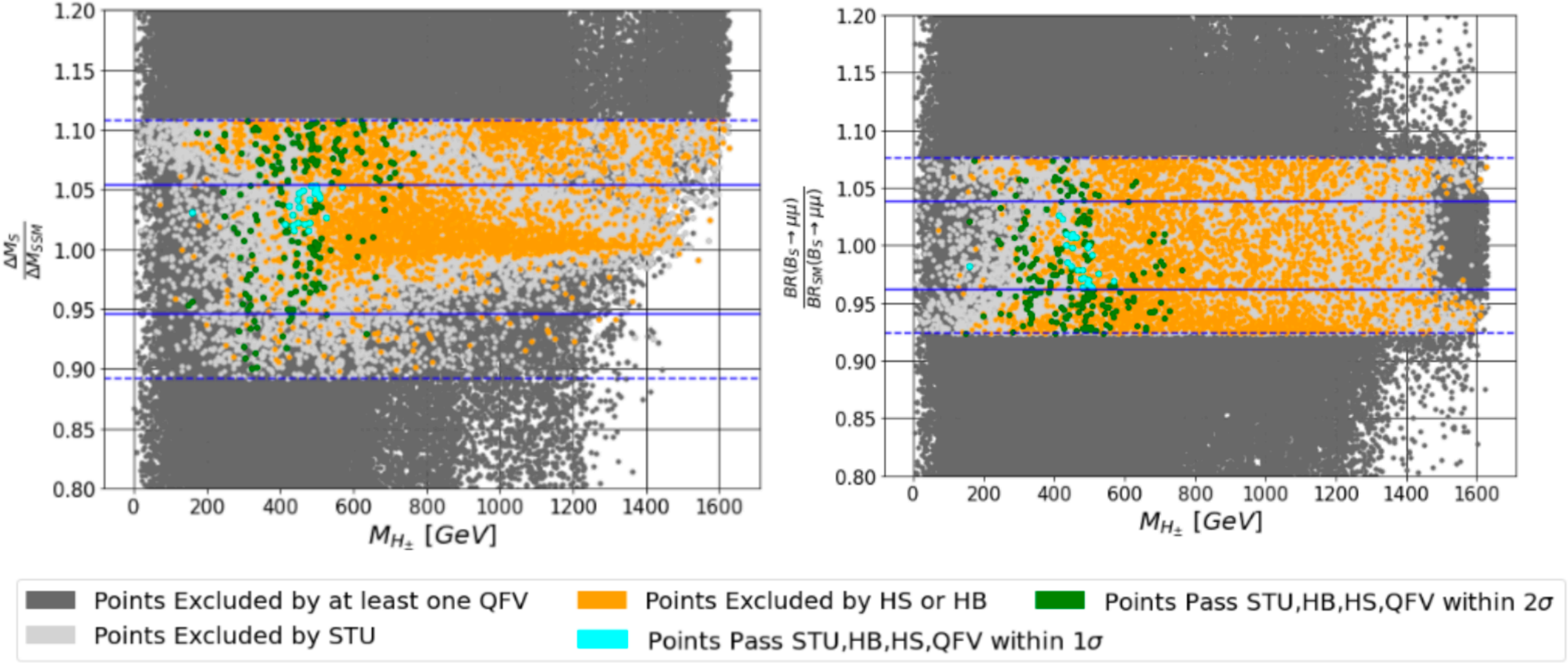


FIG. 5: Histograms containing points that survive STU, HS, HB and a given QFV (or pair of) in bins of the A_2 mass. The most restrictive is coloured in blue.

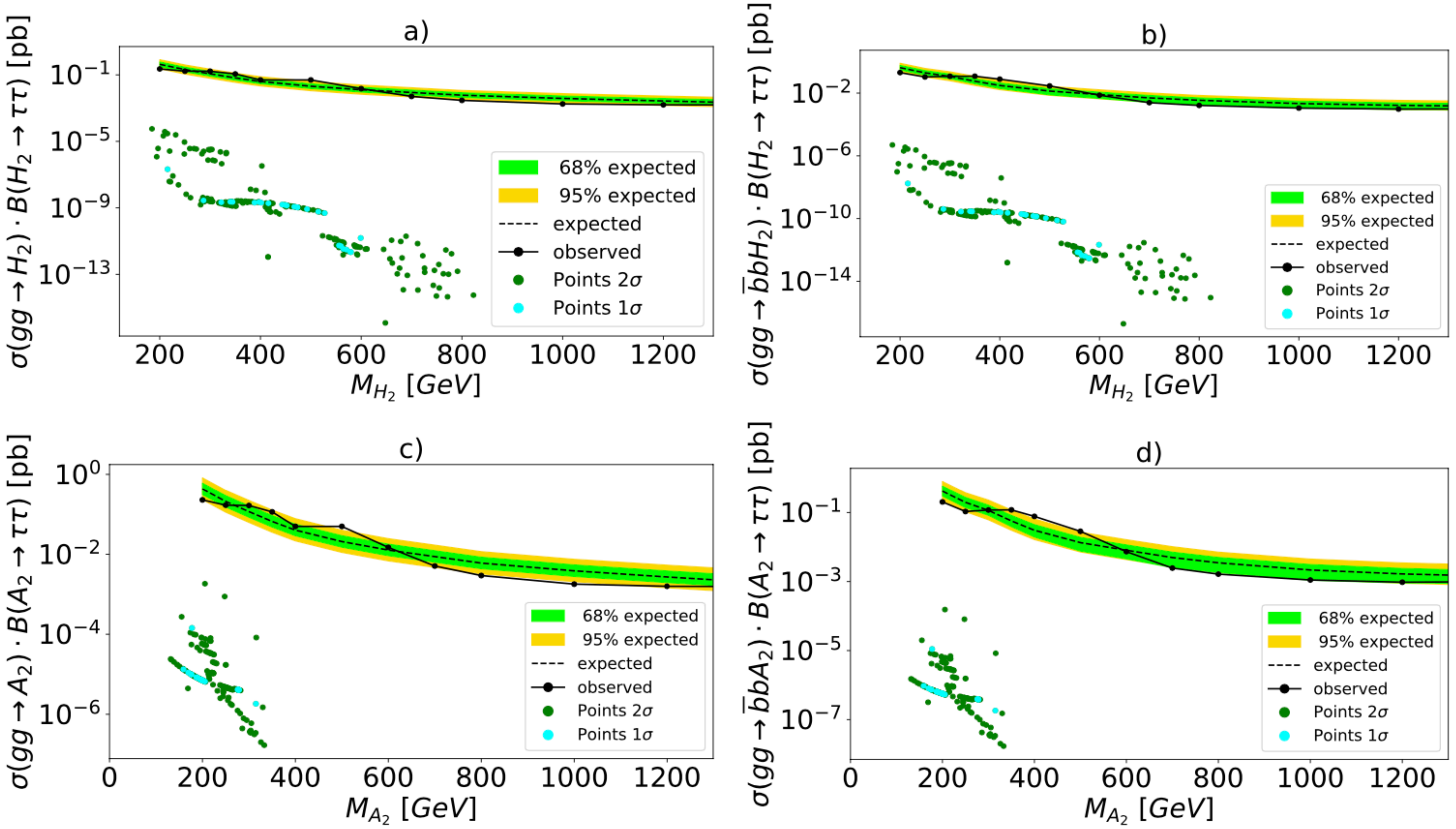
Set of QFV observables	Acceptance ratio
$\mathrm{BR}\,(B \to \chi_s \gamma)$	100.0%
$\mathrm{BR}\,(B_s \to \mu\mu)$	13.0%
ΔM_d (GeV)	21.0%
ΔM_s (GeV)	9.0%
ϵ_K (GeV)	100.0%
$\mathrm{BR}\,(B_s \to \mu\mu)$ & ΔM_s	0.457%
$\mathrm{BR}\,(B_s \to \mu\mu)$ & ΔM_d	2.69%
ΔM_s & ΔM_d	8.788%

Results



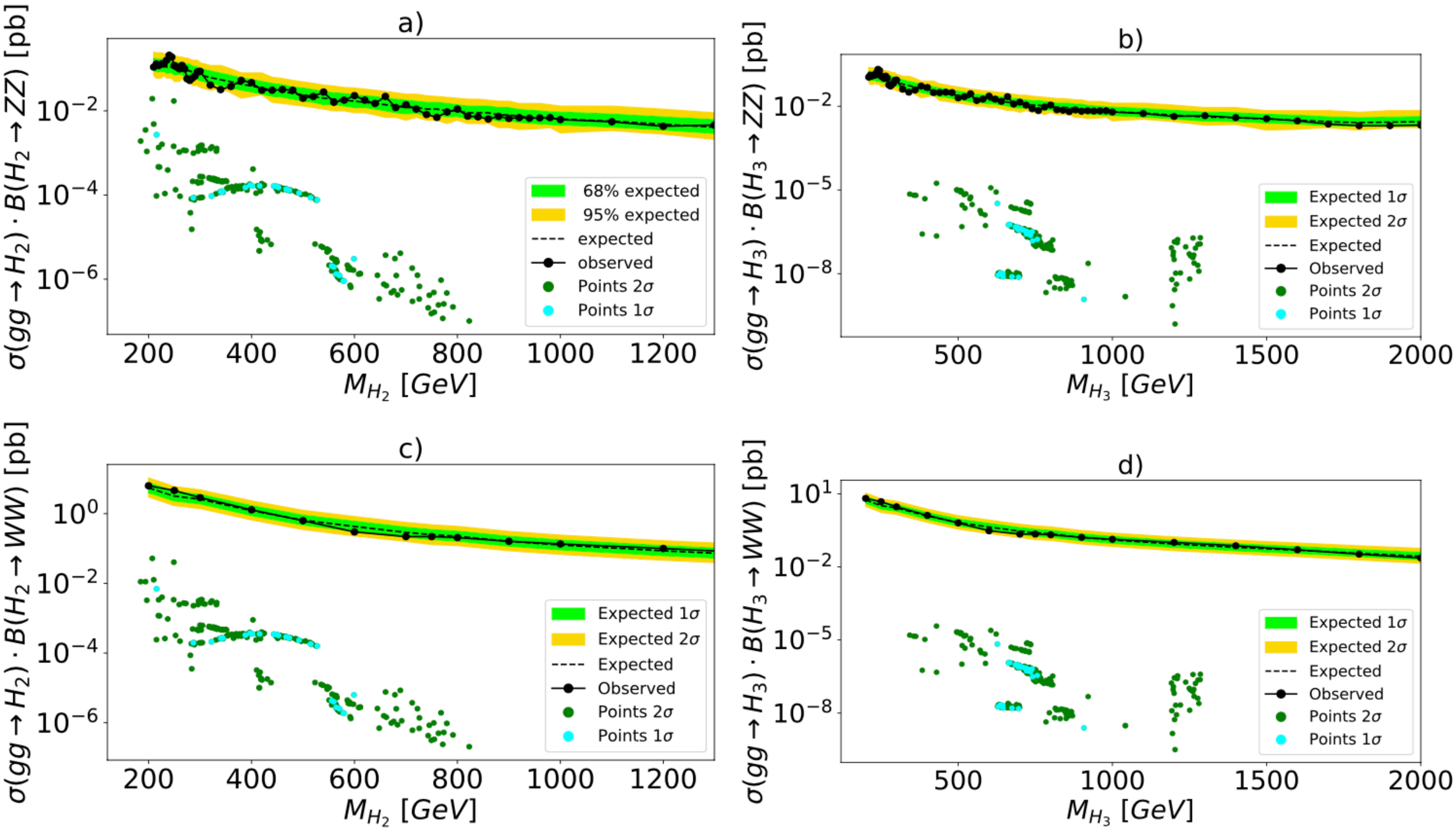
$\frac{\Delta M_S}{\Delta M_{SSM}}$
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0
200
400
600
800
1000
1200
1400
1600
$M_{H_\pm}$ [GeV]
$\frac{BR(B_S \to \mu\mu)}{BR_{SM}(B_S \to \mu\mu)}$
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0
200
400
600
800
1000
1200
1400
1600
$M_{H_\pm}$ [GeV]
Points Excluded by at least one QFV
Points Excluded by STU
Points Excluded by HS or HB
Points Pass STU,HB,HS,QFV within 1σ
Points Pass STU,HB,HS,QFV within 2σ

Results



a)
b)
c)
d)
68% expected
95% expected
expected
observed
Points 2σ
Points 1σ
$\sigma(gg \to H_2) \cdot B(H_2 \to \tau\tau)$ [pb]
$\sigma(gg \to \overline{b}bH_2) \cdot B(H_2 \to \tau\tau)$ [pb]
$\sigma(gg \to A_2) \cdot B(A_2 \to \tau\tau)$ [pb]
$\sigma(gg \to \overline{b}bA_2) \cdot B(A_2 \to \tau\tau)$ [pb]
M_{H_2} [GeV]
M_{A_2} [GeV]

Results


a)
$\sigma(gg \to H_2) \cdot B(H_2 \to ZZ)$ [pb]
M_{H_2} [GeV]
68% expected
95% expected
expected
observed
Points 2σ
Points 1σ
b)
$\sigma(gg \to H_3) \cdot B(H_3 \to ZZ)$ [pb]
M_{H_3} [GeV]
Expected 1σ
Expected 2σ
Expected
Observed
Points 2σ
Points 1σ
c)
$\sigma(gg \to H_2) \cdot B(H_2 \to WW)$ [pb]
M_{H_2} [GeV]
Expected 1σ
Expected 2σ
Expected
Observed
Points 2σ
Points 1σ
d)
$\sigma(gg \to H_3) \cdot B(H_3 \to WW)$ [pb]
M_{H_3} [GeV]
Expected 1σ
Expected 2σ
Expected
Observed
Points 2σ
Points 1σ

Results

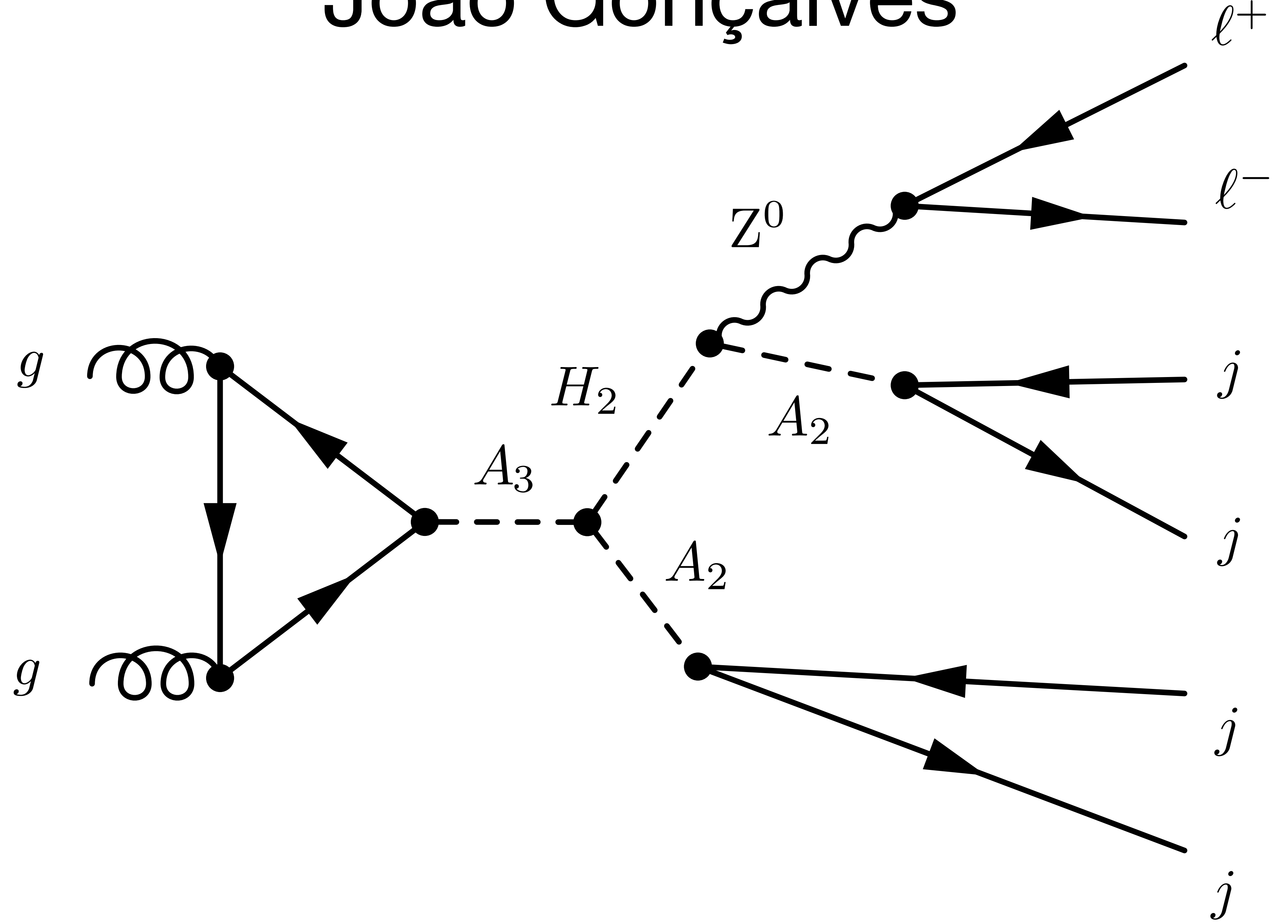
ϕ	ID	Mass (GeV)	$\mathrm{BR}(\phi \to \tau^+\tau^-)$	$\sigma(gg \to \phi) \cdot \mathrm{BR}$ (pb)	$\sigma(gg \to b\bar{b}\phi) \cdot \mathrm{BR}$ (pb)	Maximum BR
H_2	BP1	249.13	1.14×10^{-4}	9.0×10^{-6}	9.04×10^{-7}	$\mathrm{BR(W^+W^-)} = 0.563$
	BP2	207.21	1.84×10^{-4}	2.2×10^{-5}	2.02×10^{-6}	$\mathrm{BR(W^+W^-)} = 0.477$
	BP3	194.05	2.6×10^{-5}	1.0×10^{-6}	9.6×10^{-8}	$\mathrm{BR}(c\bar{c}) = 0.642$
	BP4	184.64	3.4×10^{-4}	5.7×10^{-5}	4.93×10^{-6}	$\mathrm{BR}(c\bar{c}) = 0.886$
	BP5	388.25	4.34×10^{-7}	2.06×10^{-9}	2.47×10^{-10}	$\mathrm{BR}(A_2\mathrm{Z}^0) = 0.34$
A_2	BP1	247.83	0.0013	8.7×10^{-4}	8.1×10^{-5}	$\mathrm{BR}(c\bar{c}) = 0.606$
	BP2	205.40	0.002	0.0018	1.5×10^{-4}	$\mathrm{BR}(c\bar{c}) = 0.929$
	BP3	155.23	3.6×10^{-4}	2.7×10^{-4}	2.0×10^{-5}	$\mathrm{BR}(c\bar{c}) = 0.967$
	BP4	176.24	1.6×10^{-4}	5.5×10^{-6}	4.0×10^{-6}	$\mathrm{BR}(c\bar{c}) = 0.971$
	BP5	186.77	7.8×10^{-5}	8.0×10^{-6}	6.5×10^{-7}	$\mathrm{BR}(c\bar{c}) = 0.886$

ϕ	ID	Mass (GeV)	$\mathrm{BR}(\phi \to W^+W^-)$	$\mathrm{BR}(\phi \to \mathrm{Z}^0\mathrm{Z}^0)$	$\sigma(gg \to \phi \to W^+W^-)$ (pb)	$\sigma(gg \to \phi \to \mathrm{Z}^0\mathrm{Z}^0)$ (pb)	Maximum BR
H_2	BP1	249.13	0.553	0.234	0.04	0.017	$\mathrm{BR(W^+W^-)} = 0.563$
	BP2	207.21	0.477	0.181	0.051	0.019	$\mathrm{BR(W^+W^-)} = 0.477$
	BP3	194.05	0.257	0.082	0.011	0.003	$\mathrm{BR}(c\bar{c}) = 0.642$
	BP4	184.64	0.071	0.012	0.011	0.002	$\mathrm{BR}(c\bar{c}) = 0.886$
	BP5	388.25	0.075	0.035	3.2×10^{-4}	1.5×10^{-4}	$\mathrm{BR}(A_2\mathrm{Z}^0) = 0.34$
H_3	BP1	605.79	0.045	2.1×10^{-3}	2.5×10^{-5}	1.19×10^{-5}	$\mathrm{BR}(A_2A_2) = 0.201$
	BP2	623.08	0.0037	1.8×10^{-3}	1.7×10^{-5}	8.43×10^{-6}	$\mathrm{BR}(A_2A_2) = 0.221$
	BP3	588.45	0.0007	3.5×10^{-4}	1.0×10^{-6}	5.28×10^{-7}	$\mathrm{BR}(A_2A_2) = 0.221$
	BP4	522.07	0.0014	6.9×10^{-4}	5.0×10^{-6}	2.22×10^{-6}	$\mathrm{BR}(A_2A_2) = 0.415$
	BP5	728.92	4.7×10^{-4}	2.3×10^{-4}	5.7×10^{-7}	2.8×10^{-7}	$\mathrm{BR}(A_2\mathrm{Z}^0) = 0.296$

Results

ϕ	ID	Mass (GeV)	BR($\phi \to \tau^+\tau^-$)	$\sigma(gg \to \phi)\cdot$BR (pb)	$\sigma(gg \to b\bar{b}\phi)\cdot$BR (pb)	Maximum BR
H_2	BP1	249.13	1.14×10^{-4}	9.0×10^{-6}	9.04×10^{-7}	BR(W^+W^-) = 0.563
	BP2	207				W^-) = 0.477
	BP3	194				$c\bar{c}$) = 0.642
	BP4	184				$c\bar{c}$) = 0.886
	BP5	388				$_2Z^0$) = 0.34
A_2	BP1	247				$c\bar{c}$) = 0.606
	BP2	205				$c\bar{c}$) = 0.929
	BP3	155				$c\bar{c}$) = 0.967
	BP4	176				$c\bar{c}$) = 0.971
	BP5	186				$c\bar{c}$) = 0.886

João Gonçalves



ϕ	ID	Mass (GeV)	BR(ϕ			(pb)	Maximum BR
H_2	BP1	249.13					BR(W^+W^-) = 0.563
	BP2	207.21					BR(W^+W^-) = 0.477
	BP3	194.05					BR($c\bar{c}$) = 0.642
	BP4	184.64					BR($c\bar{c}$) = 0.886
	BP5	388.25					BR(A_2Z^0) = 0.34
H_3	BP1	605.79	0.045	2.1×10^{-3}	2.5×10^{-5}	1.19×10^{-5}	BR(A_2A_2) = 0.201
	BP2	623.08	0.0037	1.8×10^{-3}	1.7×10^{-5}	8.43×10^{-6}	BR(A_2A_2) = 0.221
	BP3	588.45	0.0007	3.5×10^{-4}	1.0×10^{-6}	5.28×10^{-7}	BR(A_2A_2) = 0.221
	BP4	522.07	0.0014	6.9×10^{-4}	5.0×10^{-6}	2.22×10^{-6}	BR(A_2A_2) = 0.415
	BP5	728.92	4.7×10^{-4}	2.3×10^{-4}	5.7×10^{-7}	2.8×10^{-7}	BR(A_2Z^0) = 0.296

Conclusion

An anomaly-free implementations of a NTHDM-BGL model with three generations of right-handed neutrinos

Constrained by: 1) STU, 2) Higgs, 3) flavour observables

We have successfully assessed the viability of the low mass region and found that even for a number of scenarios with new scalars around the EW scale, the vBGL-I model remains unconstrained

The majority of the excluded scenarios came from ΔM_S and BR$(B_S \to \mu\mu)$ QFV observables, which have eliminated approximately 99.5% of the sampled points.

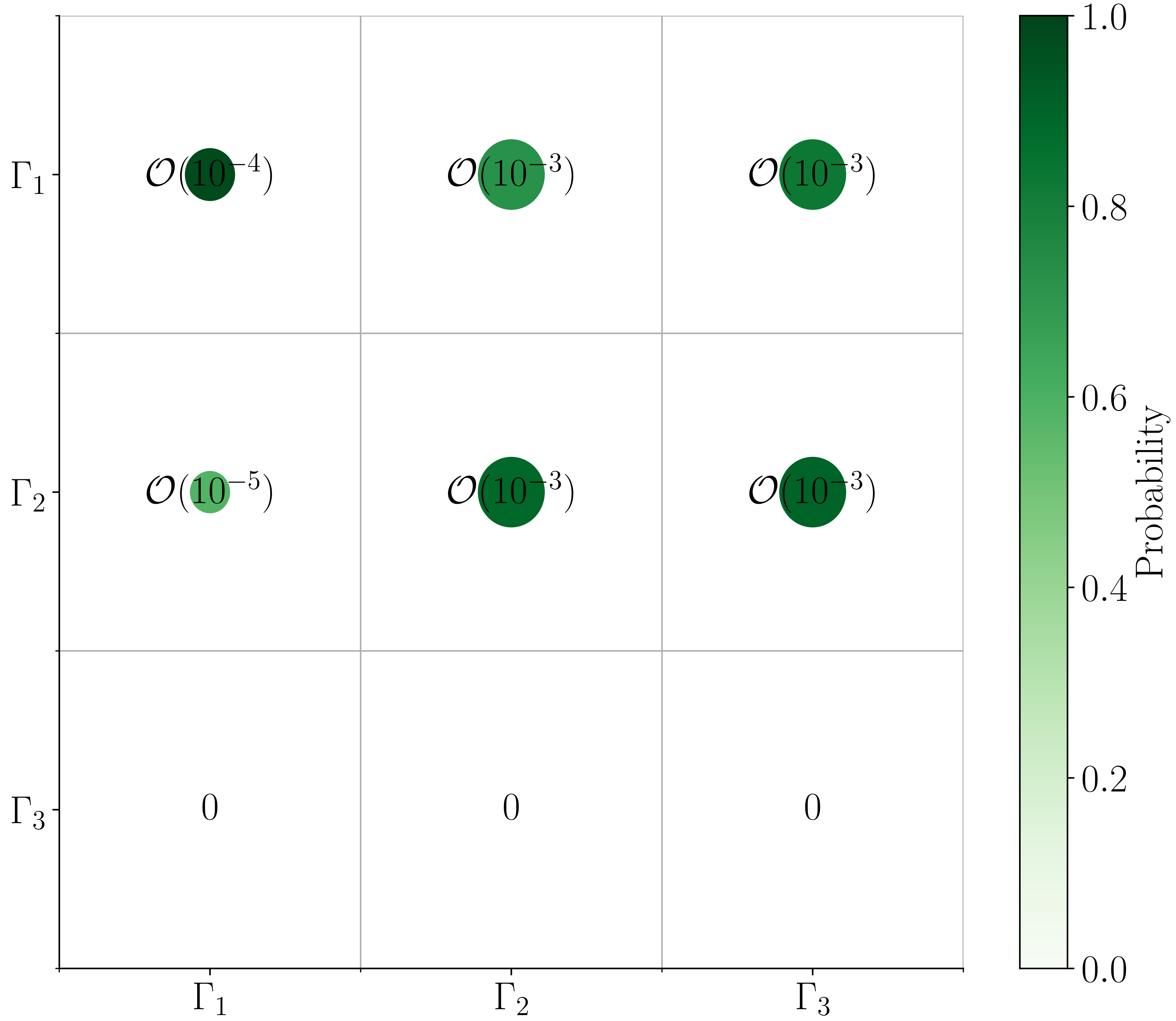
All points are consistent with existing LHC constrains for

$$gg \to H_2 \to \tau\tau,\ gg \to A_2 \to \tau\tau,\ gg \to b\bar{b}\ H_2 \cdot H_2 \to \tau\tau,\ gg \to b\bar{b}\ A_2 \cdot A_2 \to \tau\tau$$
$$gg \to H_2 \to ZZ,\ gg \to H_2 \to WW,\ gg \to H_3 \to ZZ,\ gg \to H_3 \to WW$$

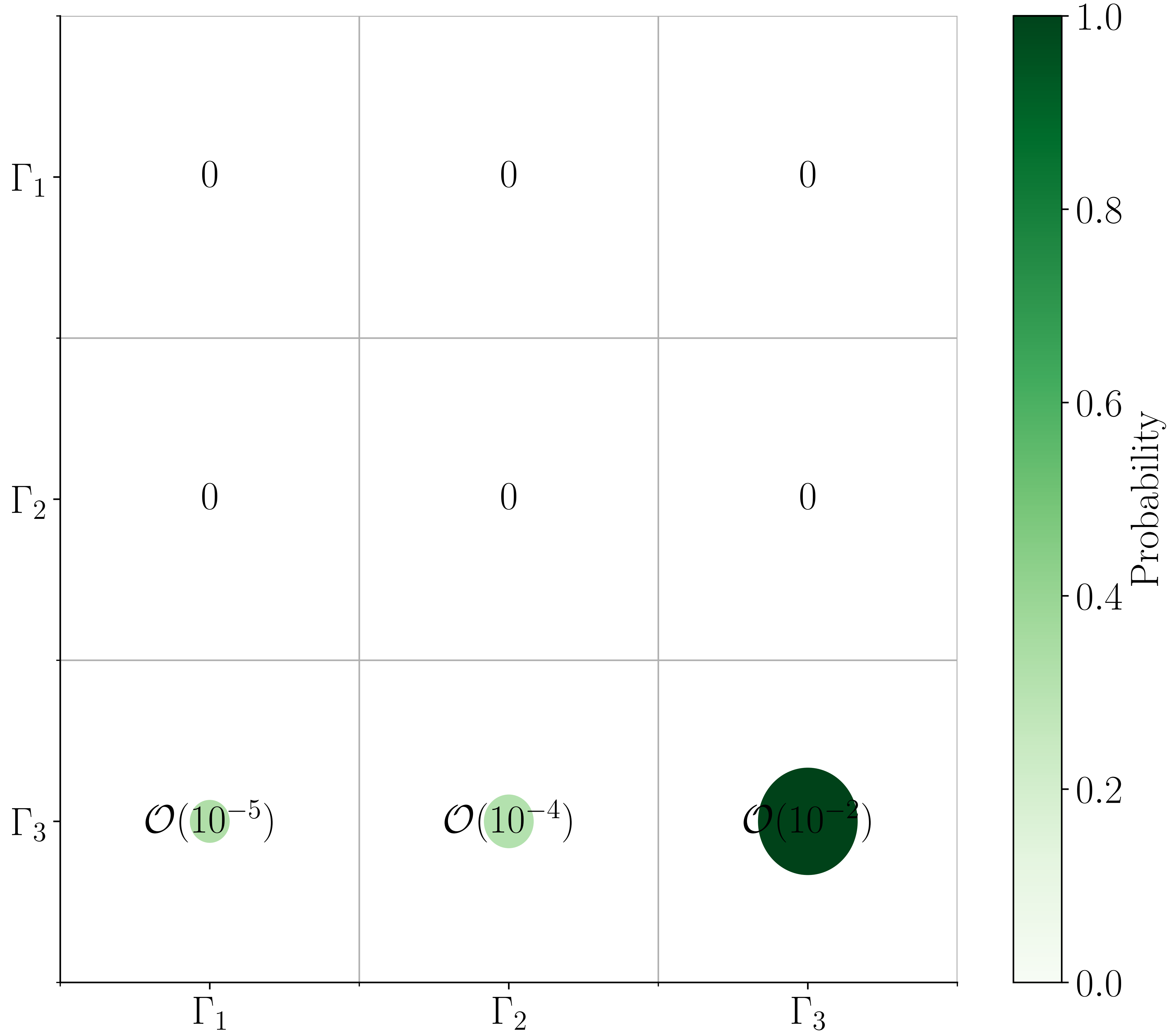
Thank you very much!

Backup slides

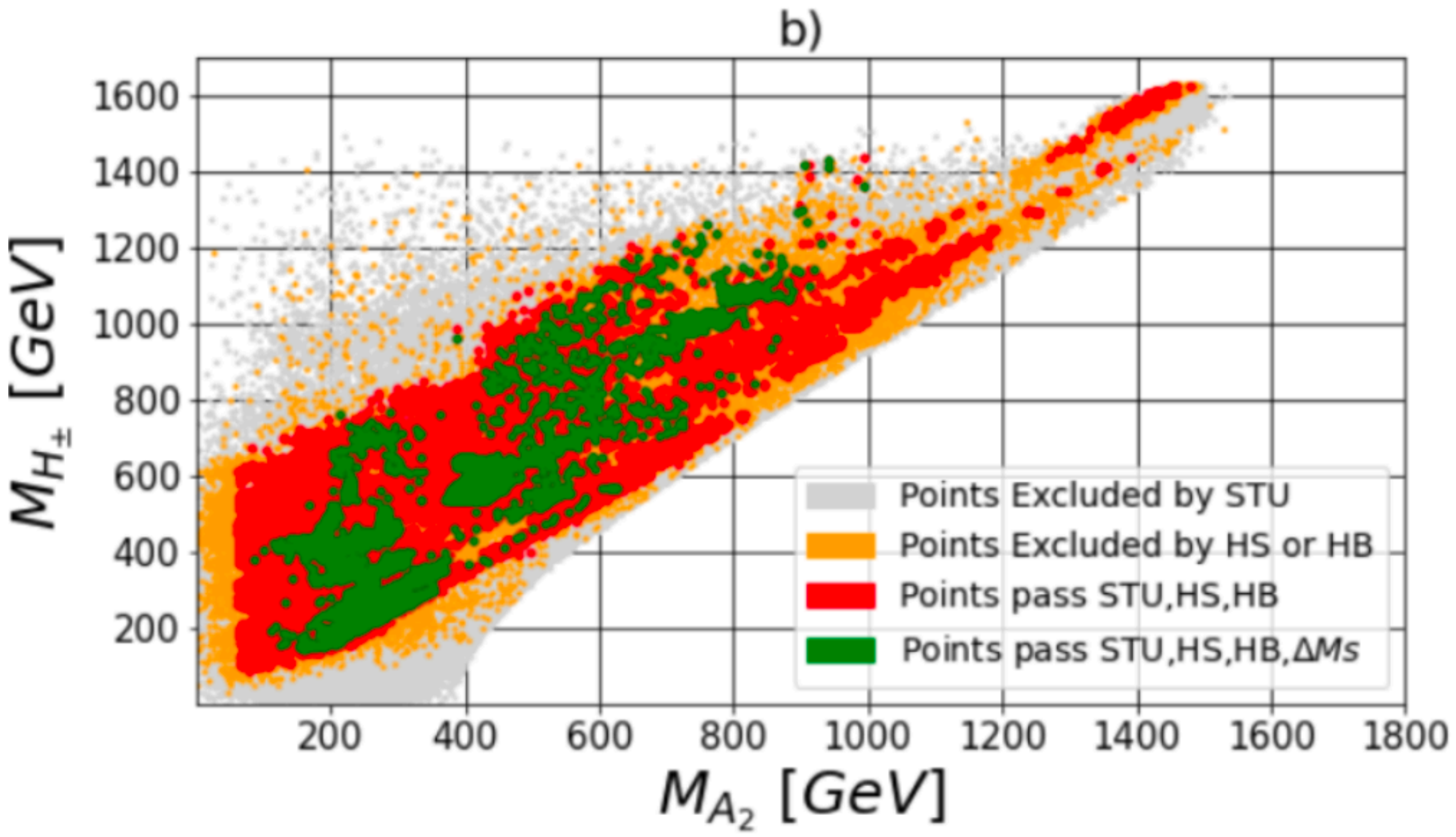
Values of Γ_1 matrix

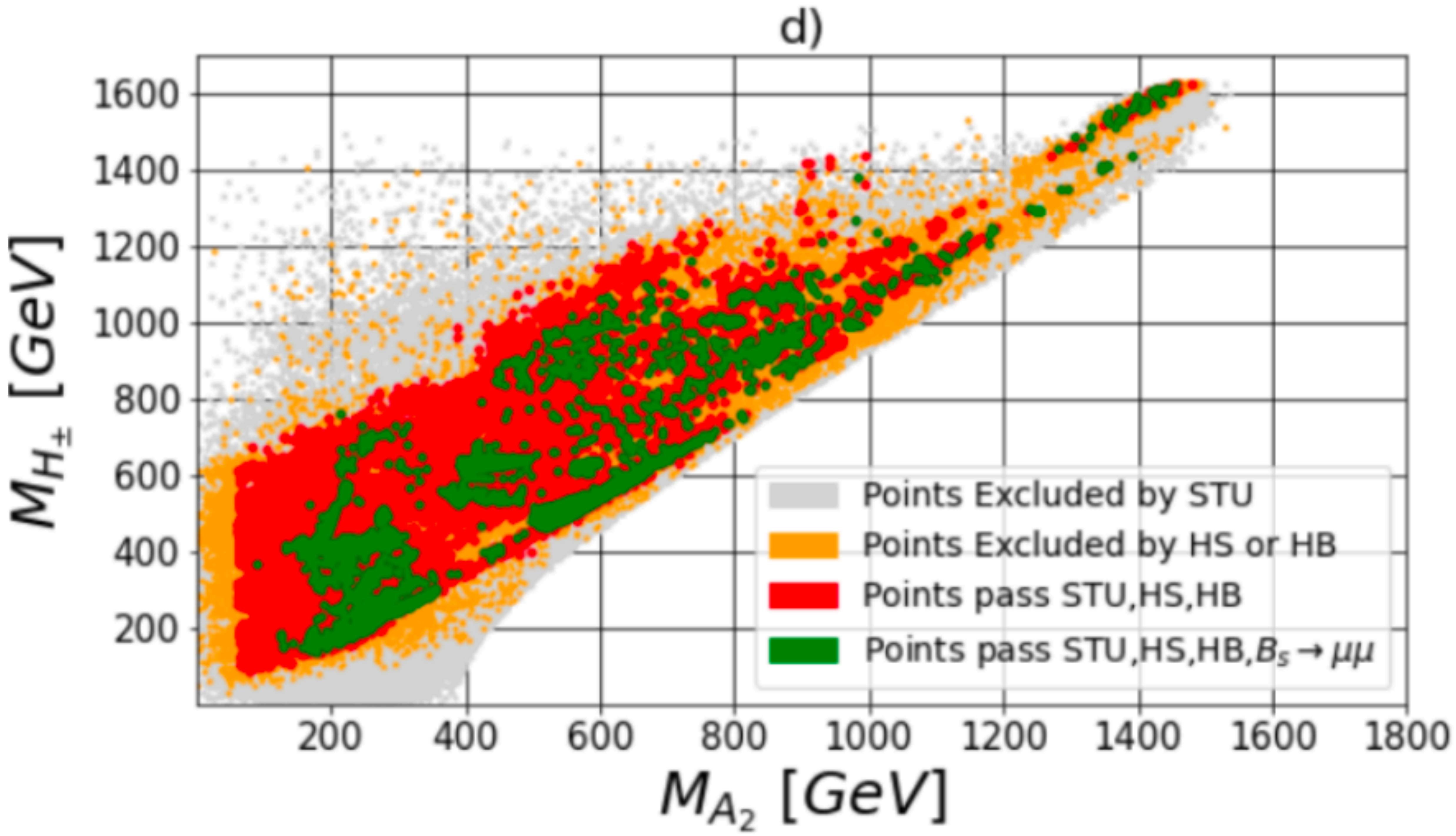


Values of Γ_2 matrix

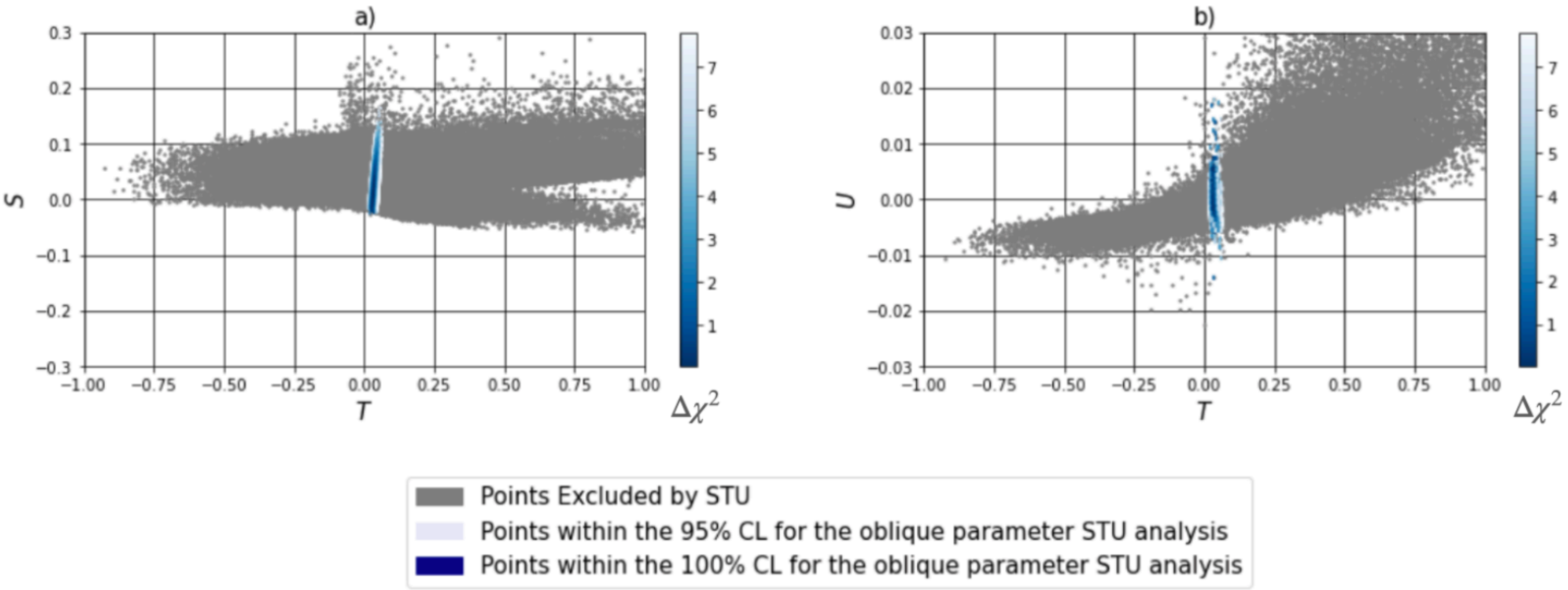


Backup slides



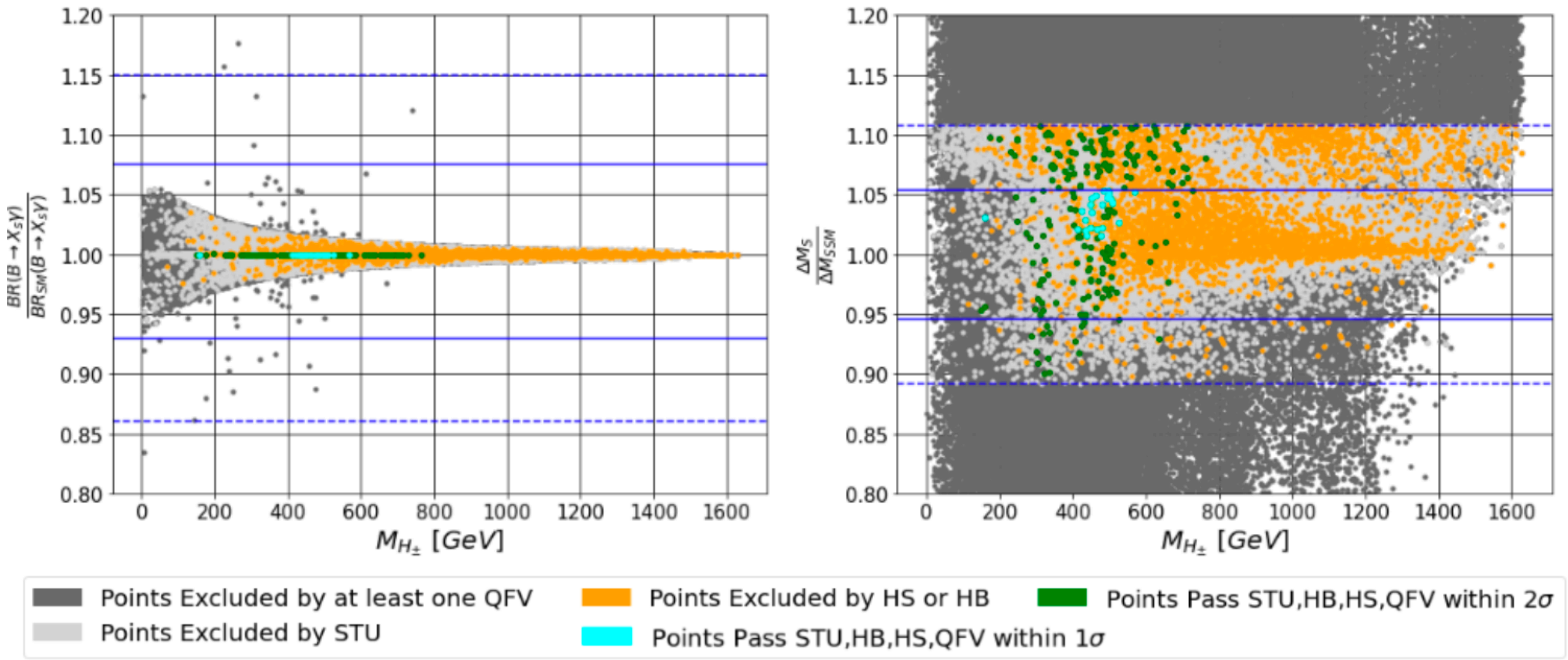


Results



Electroweak precision observables for all simulated points. The colored points are those who pass the STU analysis with a confidence level (CL) of at least 95%. Grey points are excluded by precision EW fit data.

Results



1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0
200
400
600
800
1000
1200
1400
1600
$\frac{BR(B \to X_s \gamma)}{BR_{SM}(B \to X_s \gamma)}$
$\frac{\Delta M_S}{\Delta M_{SSM}}$
$M_{H_\pm}$ [GeV]
Points Excluded by at least one QFV
Points Excluded by STU
Points Excluded by HS or HB
Points Pass STU,HB,HS,QFV within 1σ
Points Pass STU,HB,HS,QFV within 2σ

Anomaly cancellation conditions

$$A_{\mathrm{U(1)'U(1)'U(1)'}} \equiv \sum_{i=1}^{3}\left(6X_{q_i}^3 + 2X_{l_i}^3 - 3X_{u_i}^3 - 3X_{d_i}^3 - X_{e_i}^3 - X_{\nu_i}^3\right) = 0$$

$$A_{\mathrm{ggU(1)'}} \equiv \sum_{i=1}^{3}\left(6X_{q_i} + 2X_{l_i} - 3X_{u_i} - 3X_{d_i} - X_{e_i} - X_{\nu_i}\right) = 0\,,$$

$$A_{\mathrm{U(1)_Y U(1)_Y U(1)'}} \equiv \sum_{i=1}^{3}\left(X_{q_i} + 3X_{l_i} - 8X_{u_i} - 2X_{d_i} - 6X_{e_i}\right) = 0,$$

$$A_{\mathrm{U(1)_Y U(1)'U(1)'}} \equiv \sum_{i=1}^{3}\left(X_{q_i}^2 - X_{l_i}^2 - 2X_{u_i}^2 + X_{d_i}^2 + X_{e_i}^2\right) = 0,$$

$$A_{\mathrm{SU(2)_L SU(2)_L U(1)'}} \equiv \sum_{i=1}^{3}\left(3X_{q_i} + X_{l_i}\right) = 0,$$

$$A_{\mathrm{SU(3)_C SU(3)_C U(1)'}} \equiv \sum_{i=1}^{3}\left(2X_{q_i} - X_{u_i} - X_{d_i}\right) = 0\,,$$

Model Introduction

The model has a type-I seesaw mechanism, were the neutrino Lagrangian can be written as:

$$-\mathscr{L}_\nu^{\text{mass}} = \frac{1}{2}\overline{n_L^0}\mathscr{M}n_L^{0,c} + \text{h.c.}\,,$$

Where

$$\mathscr{M} \equiv \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

Neutrino tree level masses:

$$m_D \equiv \frac{1}{\sqrt{2}}\left(v_1\Sigma_1 + v_2\Sigma_2\right)\ ,\ M_R \equiv \mathrm{A} + \frac{v_S}{\sqrt{2}}(\mathrm{B}+\mathrm{C})$$

Parameter space:

Parameter	$\alpha_2,\alpha_3,\gamma_1$	$\tan\beta$	δ	a_3
range	$[-\pi,\pi]$	$[0.5,30]$	$[\frac{\pi}{2}-1,\frac{\pi}{2}+1]$	$[-1,1]$

Parameter	$M_{A_2},\ M_{H^\pm}$	M_{A_3}	M_{H_2},M_{H_3}	a_1,a_2
range [GeV]	$[0.5,1600]$	$[30,2000]$	$[126,1.800]$	$[-1,1]$

Field expansion:
$$\Phi_a \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi_a^+ \\ v_a\, e^{i\varphi_a} + R_a + iI_a \end{pmatrix}, \; S \equiv \frac{1}{\sqrt{2}} \left(v_S\, e^{i\varphi_S} + \rho + i\eta \right)$$

Tree level masses:

$$M_u^0 \equiv \frac{1}{\sqrt{2}} \left(v_1 \Delta_1 + v_2 \Delta_2 \right),$$

$$M_d^0 = \frac{1}{\sqrt{2}} \left(v_1 \Gamma_1 + v_2 \Gamma_2 \right),$$

$$M_e^0 = \frac{1}{\sqrt{2}} \left(v_1 \Pi_1 + v_2 \Pi_2 \right).$$

Rotation to the mass basis

$$D_f = U_{f\mathrm{L}}^\dagger M_f^0\, U_{f\mathrm{R}},$$

[….]

Model Introduction

One can right the tree level mass matrices in the Higgs basis:

$$N_u^0 = \frac{1}{\sqrt{2}}\left(v_2\Delta_1 - v_1\Delta_2\right) \qquad N_d^0 = \frac{1}{\sqrt{2}}\left(v_2\Gamma_1 - v_1\Gamma_2\right),$$

Whose off-diagonal elements are responsible for inducing tree-level FCNC interactions. One of the features of the BGL model is that those matrices can be re-expresses in terms of quark masses, CKM mixing elements and β angle

$$\left(N_u\right)_{ij} = \left(t_\beta\delta_{ij} - \left(t_\beta + t_\beta^{-1}\right)\delta_{ij}\delta_{j3}\right)m_{u_j},$$

$$\left(N_d\right)_{ij} = \left(t_\beta\delta_{ij} - \left(t_\beta + t_\beta^{-1}\right)V_{3i}^*V_{3j}\right)m_{d_j},$$

$$t_\beta = \tan\beta = v_1/v_2$$

Conclusion

For the points that have survived all constraints we have confronted our results with existing direct searches at the LHC. We have found that new CP-even scalars are largely favouring final states with a pair of W bosons for masses not far from the EW scale. However, as their mass grows, the decay channel $H_2 \to A_2 Z^0$ becomes dominant, thus a preferable option for further searches at the LHC run-III or HL phases. Last but not least, while our results confirm that the di-tau channel is well suited for pseudoscalar searches, their decay branching ratios to a pair of charm quarks is in general largely dominant.

Model Introduction

The model also contains a type-I seesaw mechanism

$$n_L^0 \equiv \begin{pmatrix} \nu_L^0 \\ \nu_R^c \end{pmatrix},$$

$$-\mathscr{L}_\nu^{\text{mass}} = \frac{1}{2}\overline{n_L^0}\mathscr{M} n_L^{0,c} + \text{h.c.}\,,$$

$$m_D \equiv \frac{1}{\sqrt{2}}\left(v_1\Sigma_1 + v_2\Sigma_2\right),$$

$$\mathscr{M} \equiv \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

$$M_R \equiv \mathrm{A} + \frac{v_S}{\sqrt{2}}\left(\mathrm{B} + \mathrm{C}\right)\ ,$$

$$-\mathscr{L}_\nu^{\text{eff}} \equiv \frac{1}{2}\overline{\nu_L^0} m_\nu \nu_L^{0,c} + \text{h.c.}, with m_\nu \equiv -m_D M_R^{-1} m_D^T\,.$$

Backup slides