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

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Workshop on Multi-Higgs Models 2022

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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

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

$\Gamma_\alpha, \Delta_\alpha$: 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 $V = V_0 + V_1$

$$V_0 = \mu_i^2 |\Phi^i|^2 + \lambda_i |\Phi^i|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \mu_S{}^2 |S|^2 + \lambda_1' |S|^4$$

$$+\lambda_2' |\Phi_1|^2 |S|^2 + \lambda_3' |\Phi_2|^2 |S|^2 \qquad (i = 1,2)$$ 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.

Also the model is gauge anomaly free[1]

[1]This work was inspired considering local $U(1)'$ symmetry where gauge anomalies are forbidden.

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	$\begin{bmatrix} -3x \\ -3x \\ 21x-6y \end{bmatrix}$	$\begin{bmatrix} x-y \\ -7x+y \\ 21x-6y \end{bmatrix}$	$\frac{1}{3}\begin{bmatrix} -x-2y \\ -17x+2y \\ 39x-12y \end{bmatrix}$
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 1: Allowed charges for the various models. For model νBGL-I and -IIa we have $x_{tL} = -7x + 2y$ and $x_{tR} = -16x + 5y$. Model ν BGL-IIb has $x_{tL} = (-13x + 4y)/3$and $x_{tR} = (-32x + 11y)/3$. In order for the BGL textures to be preserved, we additionally require that$y \neq 4x$.

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}
$U(1)_Y$	1/2	1/2	0	1/6	1/6	1/6	2/3	2/3	2/3	-1/3	-1/3	-1/3
$SU(2)_L$	**2**	**2**	**1**	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(3)_C$	**1**	**1**	**1**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
$U(1)'$	-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}
$U(1)_Y$	-1/2	-1/2	-1/2	-1	-1	-1	0	0	0
$SU(2)_L$	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(3)_C$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)'$	-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.

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

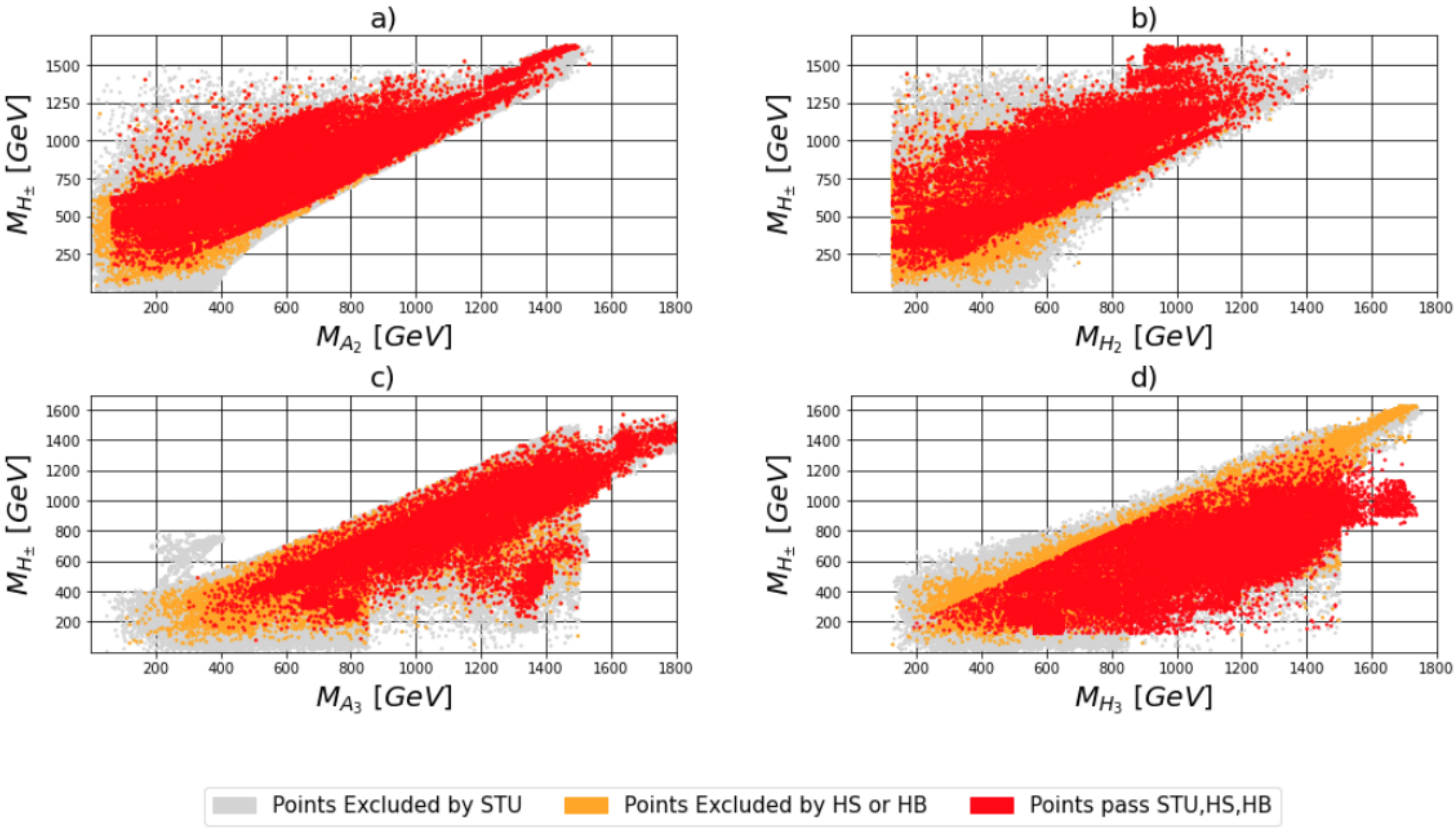
Were we require $\Delta x^2 < 7.815$, which is translated to 95% confidence level (CL) agreement with the electroweak fit.

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

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

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

Results

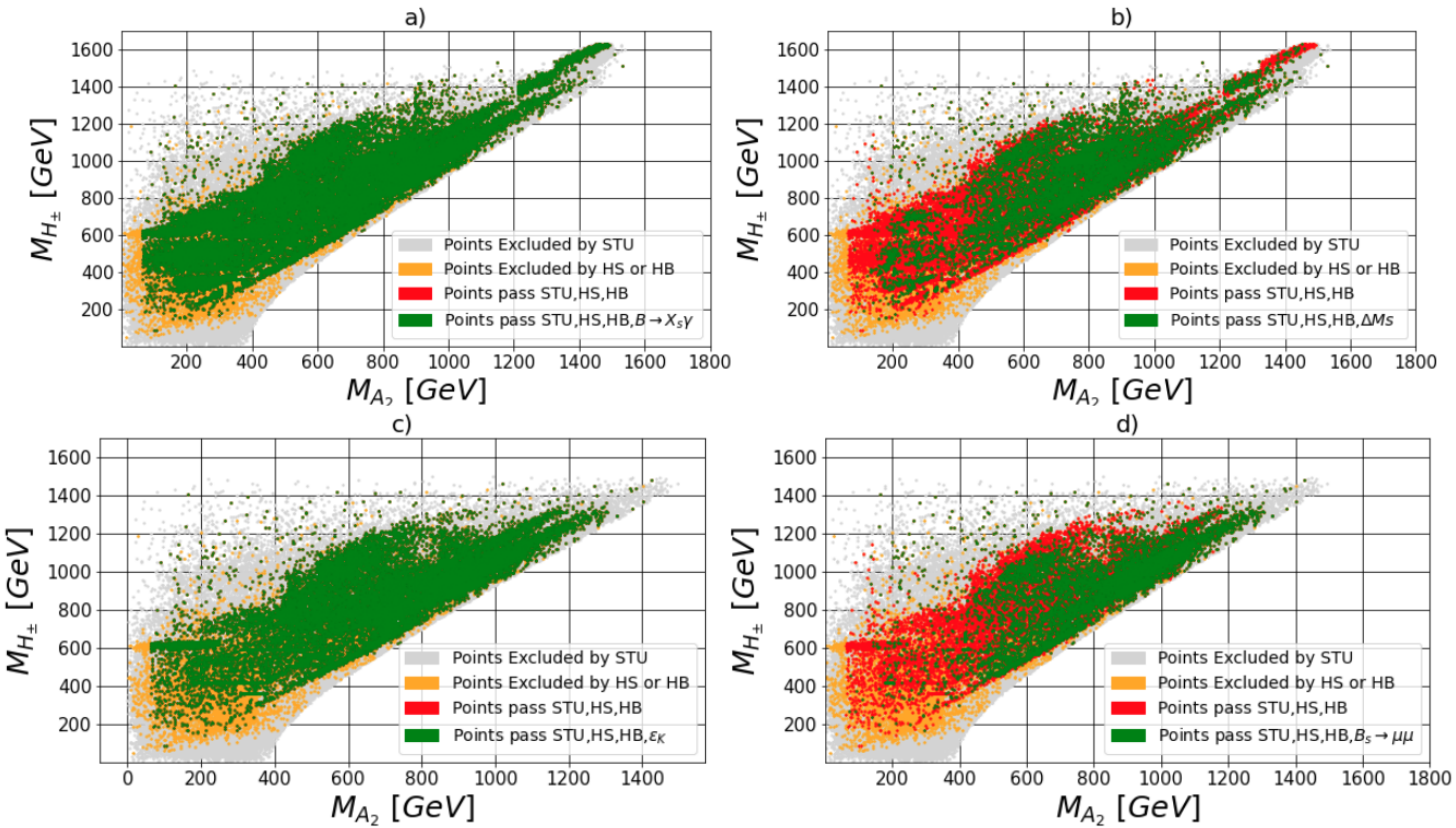


a)
b)
c)
d)
$M_{H^\pm}$ [GeV]
M_{A_2} [GeV]
M_{H_2} [GeV]
M_{A_3} [GeV]
M_{H_3} [GeV]
Points Excluded by STU
Points Excluded by HS or HB
Points pass STU,HS,HB

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

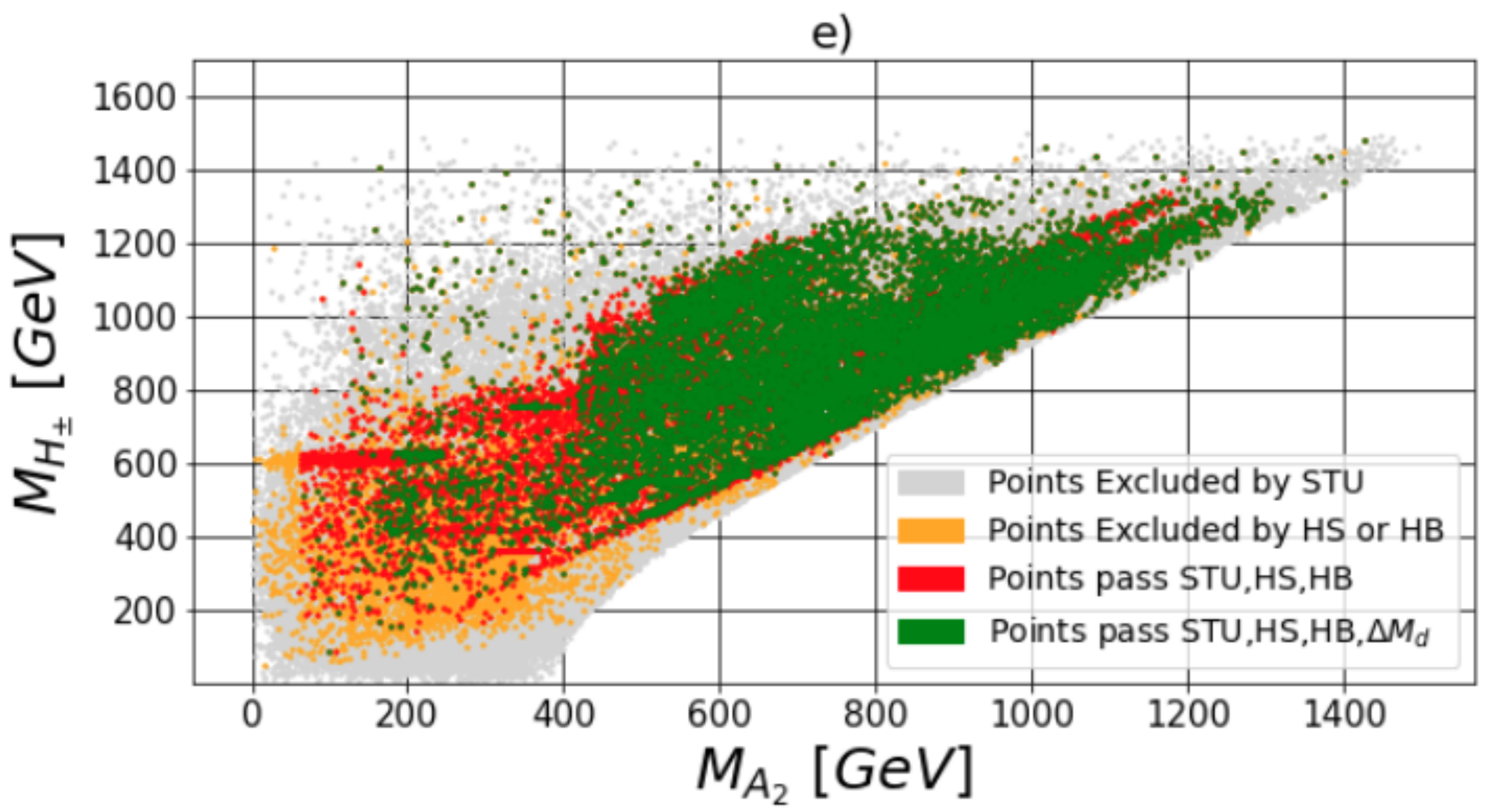
Channel	$\mathcal{O}_{SM}$	σ_{SM}	$\mathcal{O}_{Exp}$	σ_{Exp}	σ
$\mathrm{BR}(\mathrm{B} \to \chi_{\mathrm{s}}\gamma)$	3.29×10^{-4}	1.87×10^{-5}	3.32×10^{-4}	0.16×10^{-4}	0.075
$\mathrm{BR}(\mathrm{B_s} \to \mu\mu)$	3.66×10^{-9}	1.66×10^{-10}	2.80×10^{-9}	0.06×10^{-9}	0.038
ΔM_d (GeV)	3.97×10^{-13}	5.07×10^{-14}	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

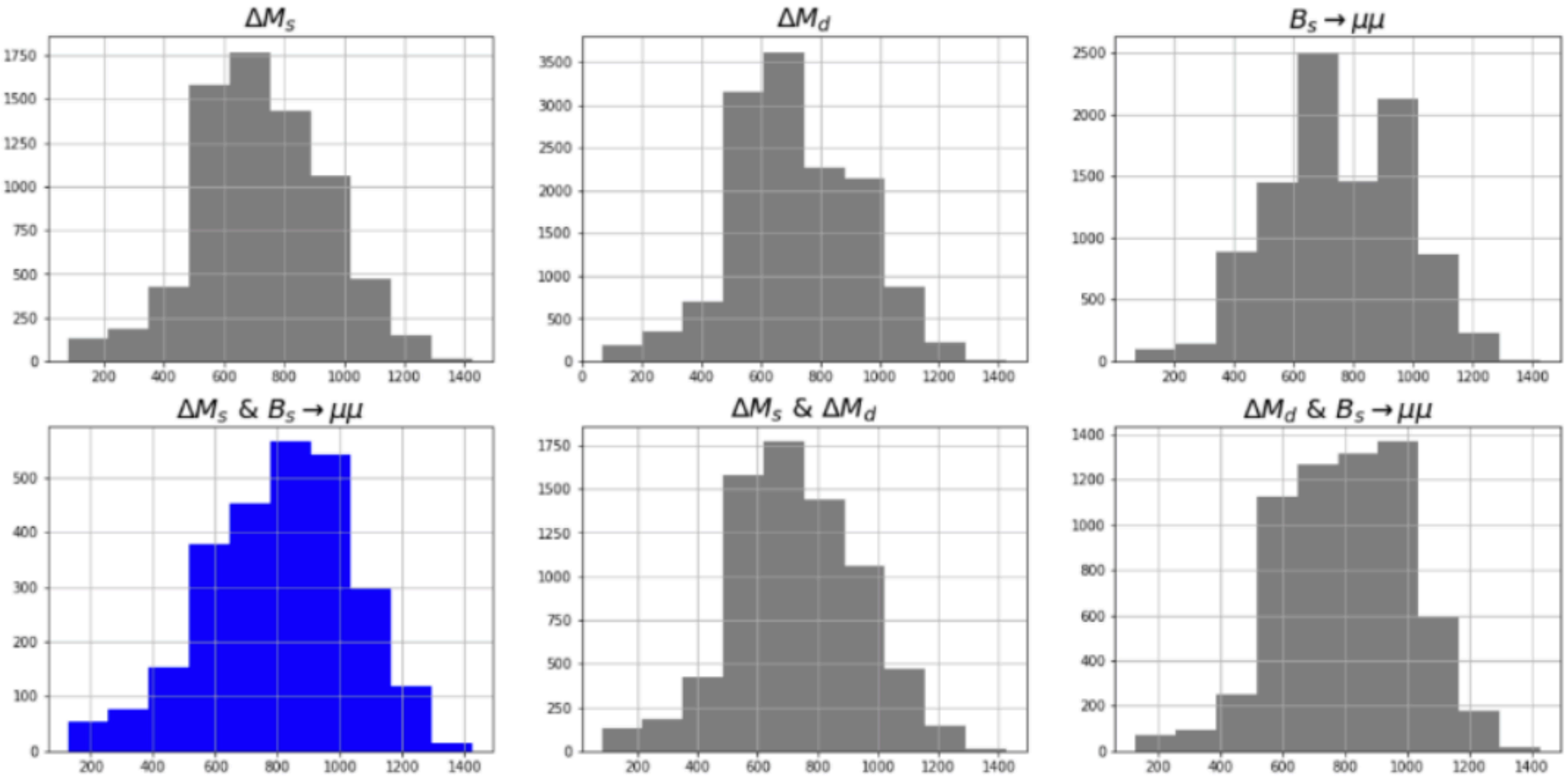
Results



a)
b)
c)
d)
$M_{H_\pm}$ [GeV]
M_{A_2} [GeV]
Points Excluded by STU
Points Excluded by HS or HB
Points pass STU,HS,HB
Points pass STU,HS,HB,$B \to X_s\gamma$
Points pass STU,HS,HB,ΔMs
Points pass STU,HS,HB,ε_K
Points pass STU,HS,HB,$B_s \to \mu\mu$

Results

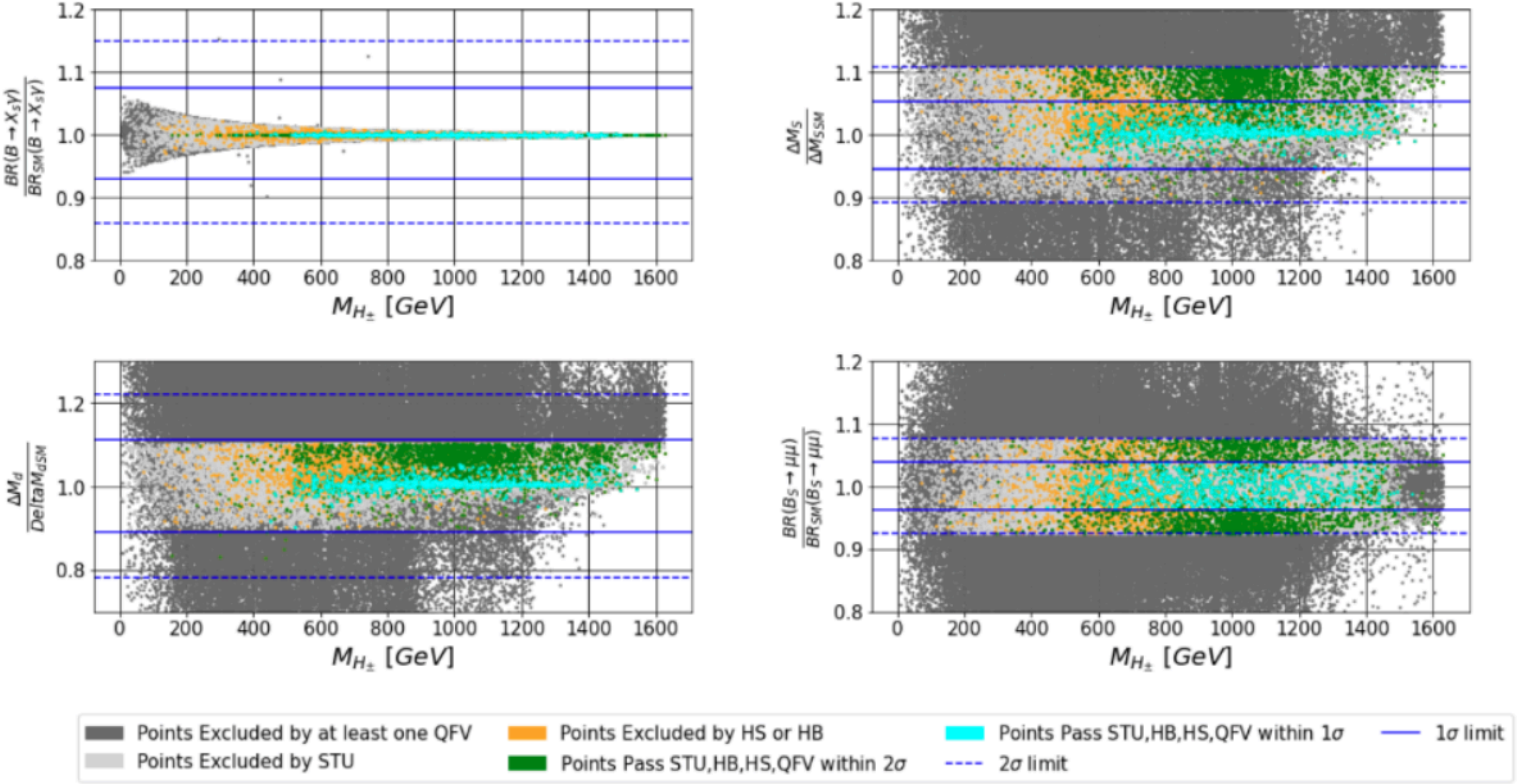




Set of QFV observables	Acceptance ratio
$\mathrm{BR}\,(B \to \chi_s \gamma)$	100.0%
$\mathrm{BR}\,(B_s \to \mu\mu)$	35.0%
ΔM_d (GeV)	48.0%
ΔM_s (GeV)	26.0%
ϵ_K (GeV)	100.0%
$\mathrm{BR}\,(B_s \to \mu\mu)$ & ΔM_s	9.39%
$\mathrm{BR}\,(B_s \to \mu\mu)$ & ΔM_d	22.21%
ΔM_s & ΔM_d	25.57%

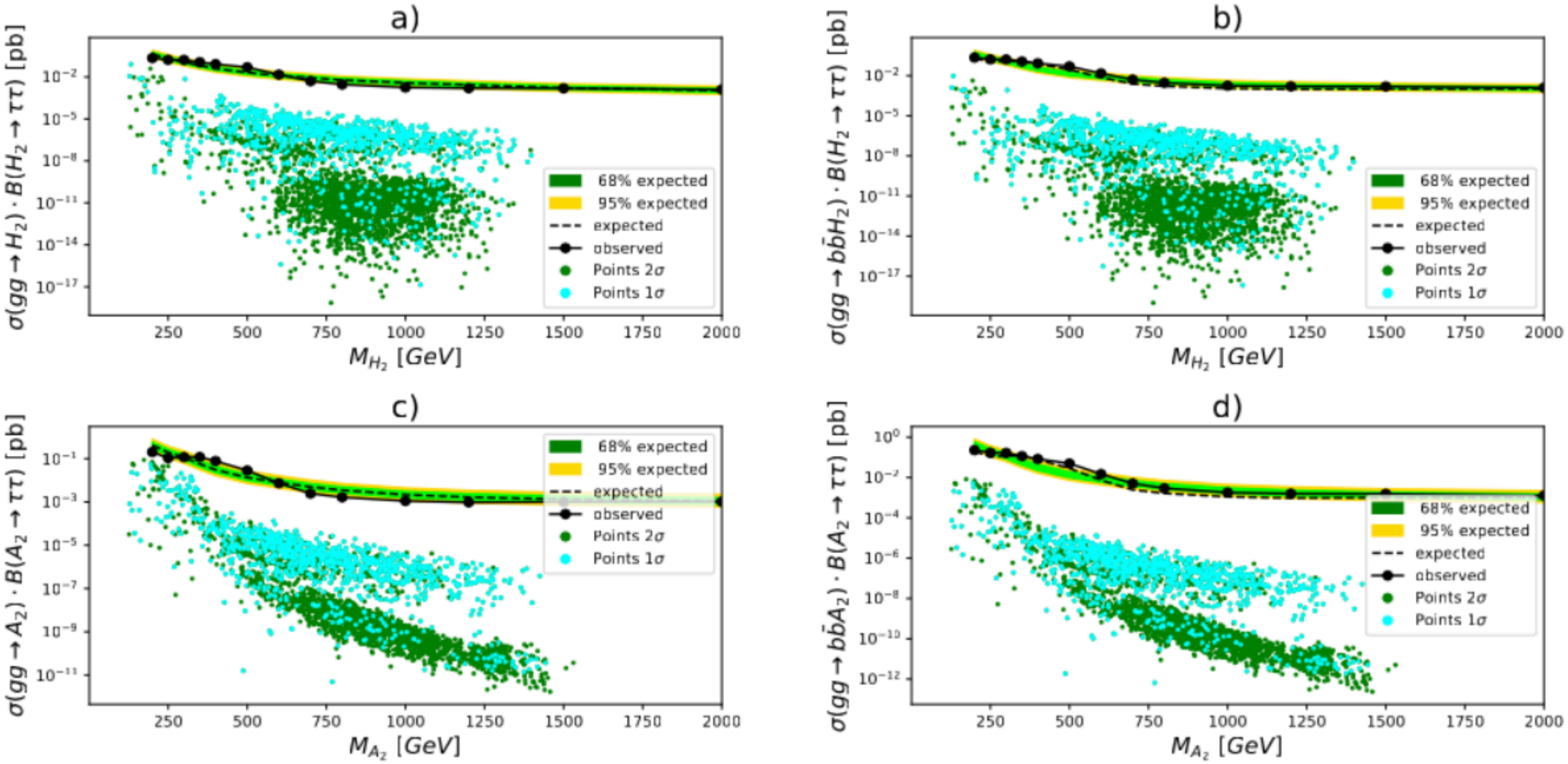
Figure 5: Histograms containing points that survive STU, HS, HB and a given QFV (or pair of) in bins of the A_2 mass. The most restrictive is coloured in *blue*.

Results



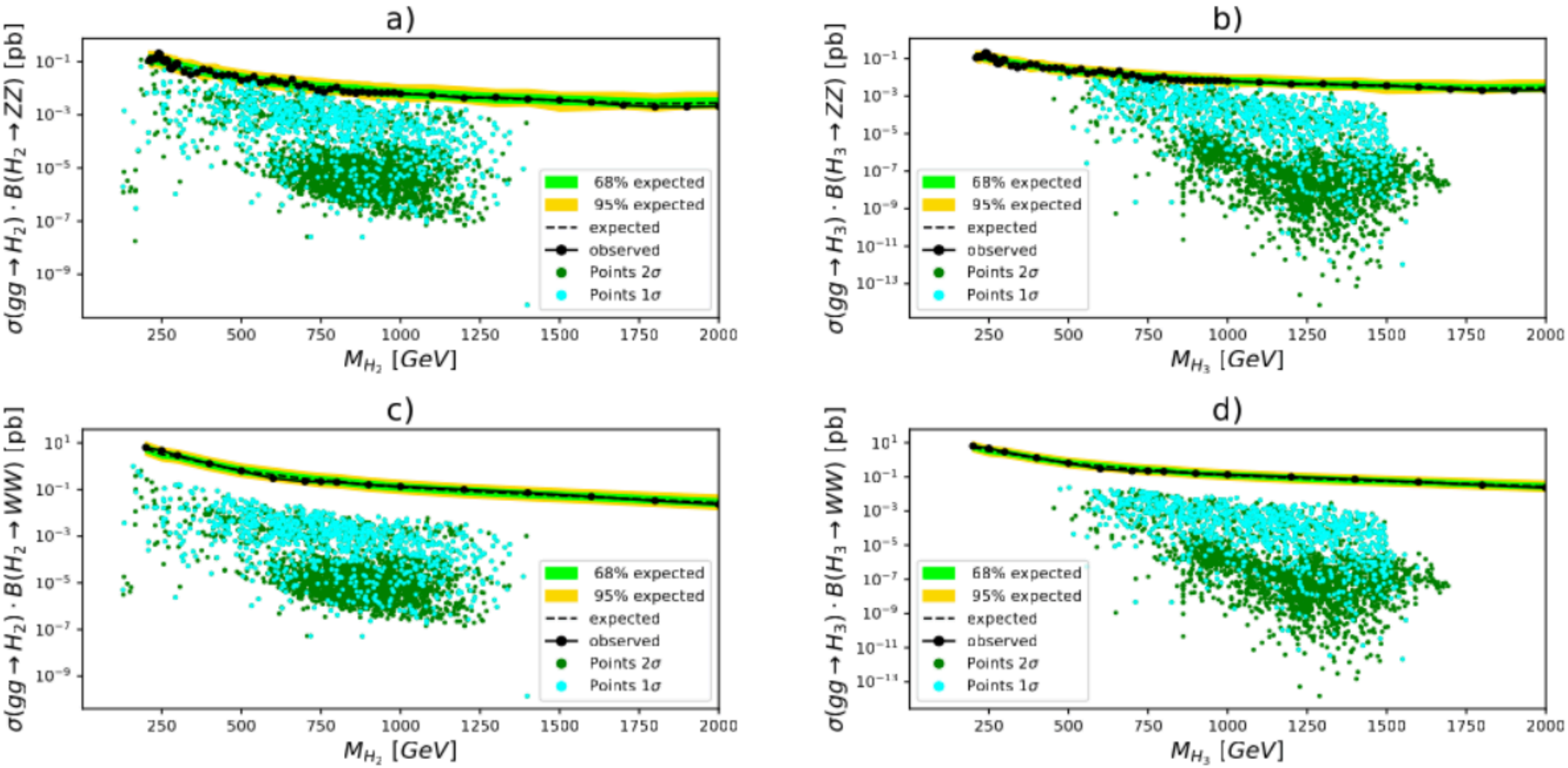
$\frac{BR(B \to X_S \gamma)}{BR_{SM}(B \to X_S \gamma)}$
$\frac{\Delta M_S}{\Delta M_{SSM}}$
$\frac{\Delta M_d}{DeltaM_{dSM}}$
$\frac{BR(B_S \to \mu\mu)}{BR_{SM}(B_S \to \mu\mu)}$
$M_{H_\pm}$ [GeV]
Points Excluded by at least one QFV
Points Excluded by STU
Points Excluded by HS or HB
Points Pass STU,HB,HS,QFV within 2σ
Points Pass STU,HB,HS,QFV within 1σ
2σ limit
1σ limit

Results



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

Results


a)
$\sigma(gg \to H_2) \cdot B(H_2 \to ZZ)$ [pb]
M_{H_2} [GeV]
b)
$\sigma(gg \to H_3) \cdot B(H_3 \to ZZ)$ [pb]
M_{H_3} [GeV]
c)
$\sigma(gg \to H_2) \cdot B(H_2 \to WW)$ [pb]
M_{H_2} [GeV]
d)
$\sigma(gg \to H_3) \cdot B(H_3 \to WW)$ [pb]
M_{H_3} [GeV]
68% expected
95% expected
expected
observed
Points 2σ
Points 1σ
250
500
750
1000
1250
1500
1750
2000

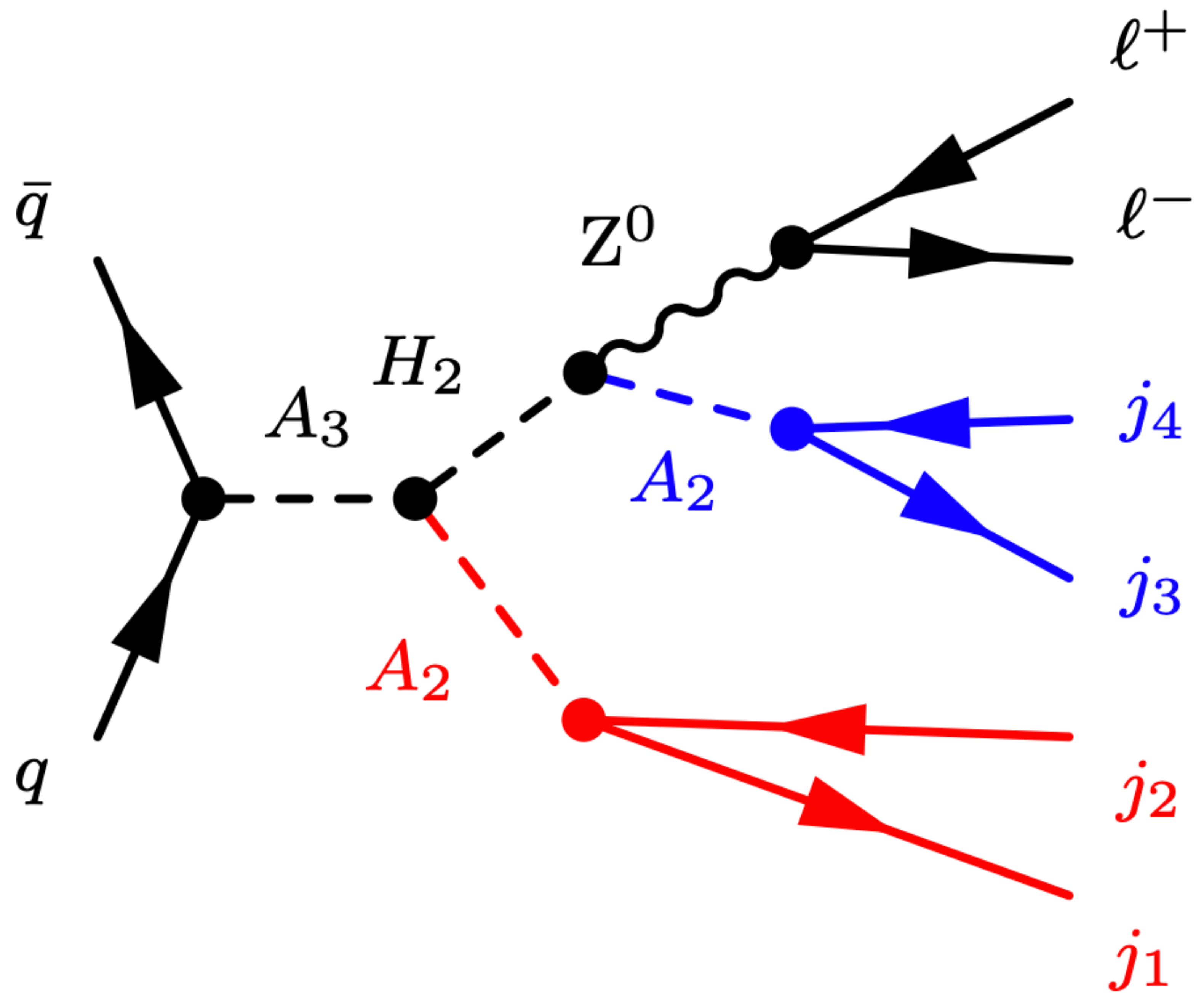
Results

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	160.21	4.99×10^{-3}	0.007354	8.01×10^{-4}	$BR(W^+W^*) = 0.881$
	BP2	347.99	6.65×10^{-7}	3.25×10^{-8}	3.67×10^{-9}	$BR(H_1H_1) = 0.611$
	BP3	129.26	0.0127	3.59×10^{-4}	4.3×10^{-5}	$BR(W^+W^*) = 0.377$
	BP4	132.27	0.0357	0.0830	0.00967	$BR(b\bar{b}) = 0.590$
	BP5	668.49	6.14×10^{-6}	7.42×10^{-8}	1.01×10^{-8}	$BR(A_2Z^0) = 0.75$
A_2	BP1	194.99	0.0336	0.0546	0.00532	$BR(b\bar{b}) = 0.553$
	BP2	173.55	0.0264	0.0874	0.008249	$BR(b\bar{b}) = 0.432$
	BP3	1077.21	2.65×10^{-5}	1.0×10^{-6}	1.62×10^{-7}	$BR(t\bar{t}) = 0.711$
	BP4	937.61	3.49×10^{-5}	6.36×10^{-9}	8.66×10^{-10}	$BR(t\bar{t}) = 0.918$
	BP5	126.74	2.48×10^{-3}	3.2×10^{-5}	3.0×10^{-6}	$BR(c\bar{c}) = 0.922$

ϕ	ID	Mass (GeV)	$BR(\phi \to W^+W^-)$	$BR(\phi \to Z^0Z^0)$	$\sigma(gg \to \phi \to W^+W^-)$ (pb)	$\sigma(gg \to \phi \to Z^0Z^0)$ (pb)	Maximum BR
H_2	BP1	160.21	0.881	0.0210	1.0032	0.00054	$BR(W^+W^*) = 0.881$
	BP2	347.99	0.129	0.0589	0.00722	0.003319	$BR(H_1H_1) = 0.611$
	BP3	129.26	0.377	0.0449	3.0×10^{-6}	1.0×10^{-6}	$BR(W^+W^*) = 0.377$
	BP4	132.27	0.239	0.0299	0.00366	0.001426	$BR(b\bar{b}) = 0.590$
	BP5	668.49	0.416	0.203	0.00506	0.00244	$BR(A_2Z^0) = 0.75$
H_3	BP1	929.20	0.124	0.0616	0.00341	0.00167	$BR(H_1H_1) = 0.456$
	BP2	823.89	0.0922	0.0455	1.36×10^{-4}	6.7×10^{-5}	$BR(A_2A_2) = 0.228$
	BP3	1093.01	0.166	0.0824	0.002964	0.001468	$BR(H_1H_2) = 0.531$
	BP4	1156.49	0.0598	0.0297	0.000192	9.4×10^{-5}	$BR(t\bar{t}) = 0.617$
	BP5	754.64	0.0517	0.0254	8.4×10^{-4}	4.1×10^{-4}	$BR(t\bar{t}) = 0.591$

The next two slides concerning a follow up work that we expect to be uploaded to arxive very soon, and has already been presented by João Gonçalves in FLASY2022 & ICHEP.

The next two slides are a summary of João talks.



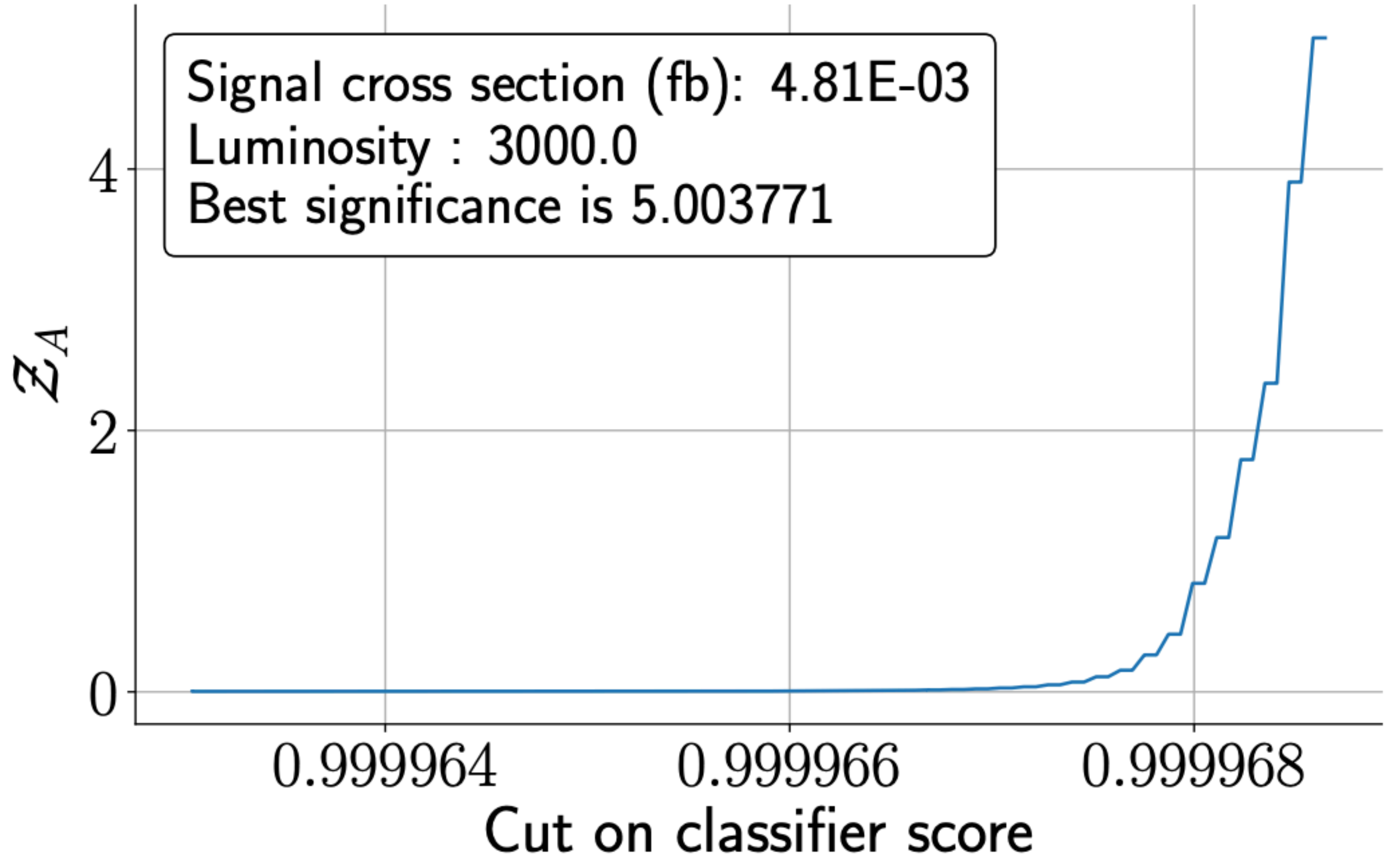
- Mass information can be use to match pairs of jets to original scalars fields
- $\Delta M = M(j_1, j_2) - M(j_3, j_4) < \varepsilon$
  - **Signal:** small ε
  - **Background** Arbitrary ε
- Loop over all possible combinations of jets and select the pairs with smallest ε

Match jets to H_2 scalar: $min(|M(j_n, j_m) - M(Z^0) - M(H_2)|)$

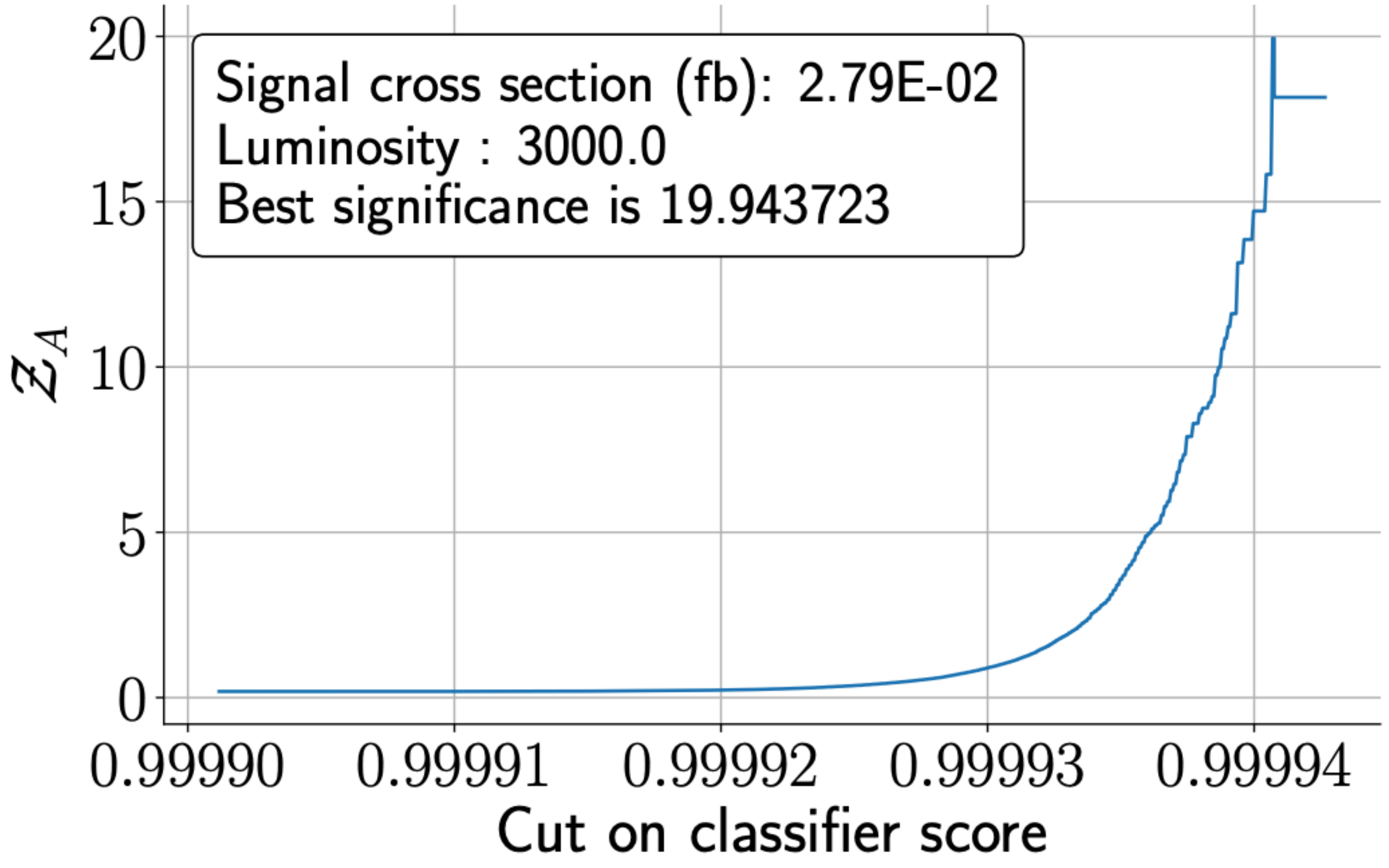
If the minimum is for pair (j_3, j_4), then this is matched to the blue leg and the pair (j_1, j_2) is matched to the red leg.

Since ε is expected to be arbitrary, the matching procedure can help reduce backgrounds for small values of ε.

$$M(j) > 10 \text{ GeV and } \Delta M < 35 \text{ GeV}$$



(a) $M_{A_2} = 215 \text{ GeV}/M_{H_2} = 400 \text{ GeV}$



(b) $M_{A_2} = 300 \text{ GeV}/M_{H_2} = 600 \text{ GeV}$

Relaxed constraints on jet mass distributions increases the significance. Particularly helpful for lower mass scalar fields. Still, **high cuts** on data for optimal results.

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 νBGL-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 90.6% 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

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

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

Anomaly-free conditions

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

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

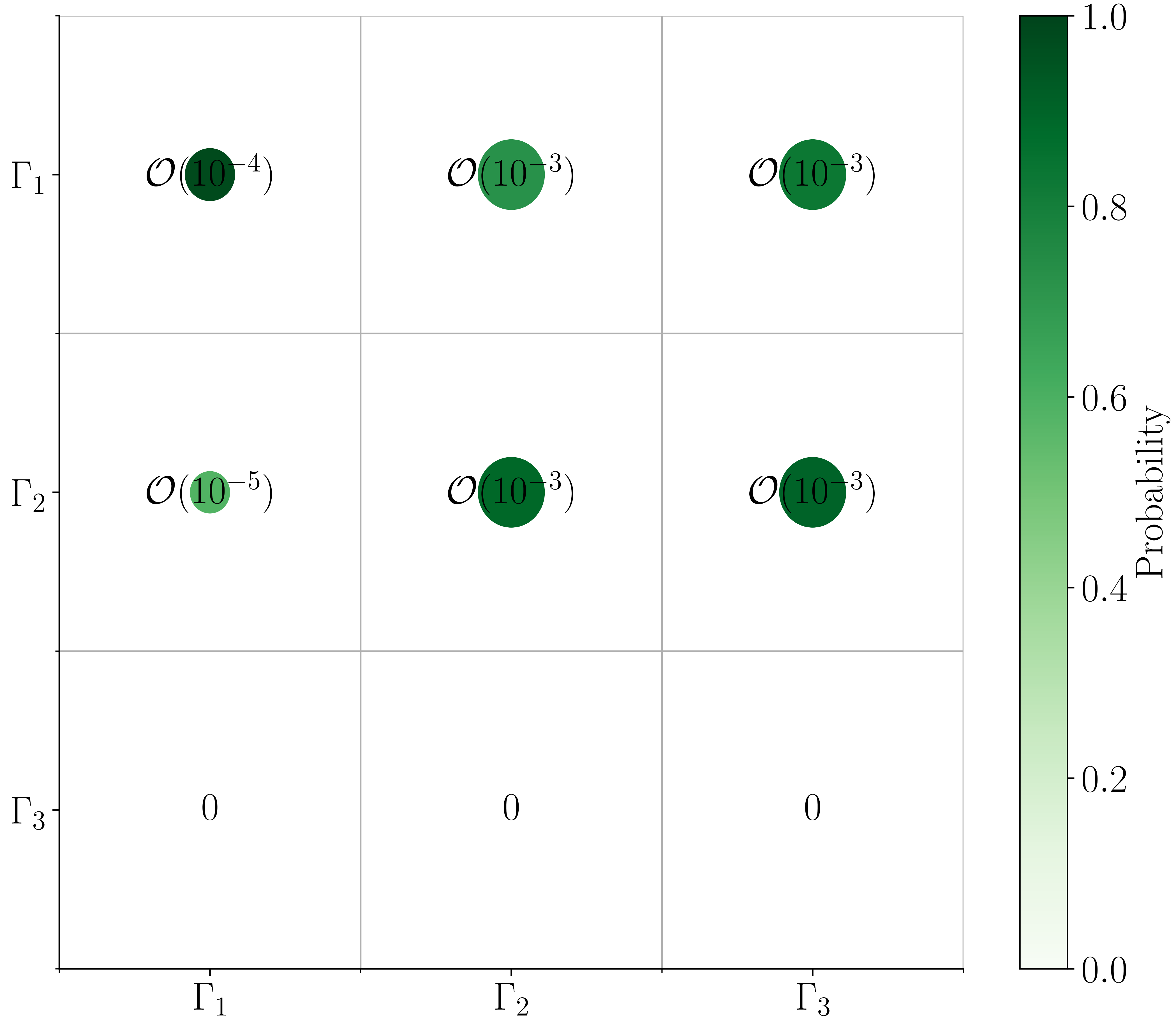
$$A_{ij} = e^{i\alpha(X_{\nu_i}+X_{\nu_j})}A_{ij}, \quad B_{ij} = e^{i\alpha(X_{\nu_i}+X_{\nu_j}+X_S)}B_{ij}, \quad C_{ij} = e^{i\alpha(X_{\nu_i}+X_{\nu_j}-X_S)}C_{ij}\,.$$

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

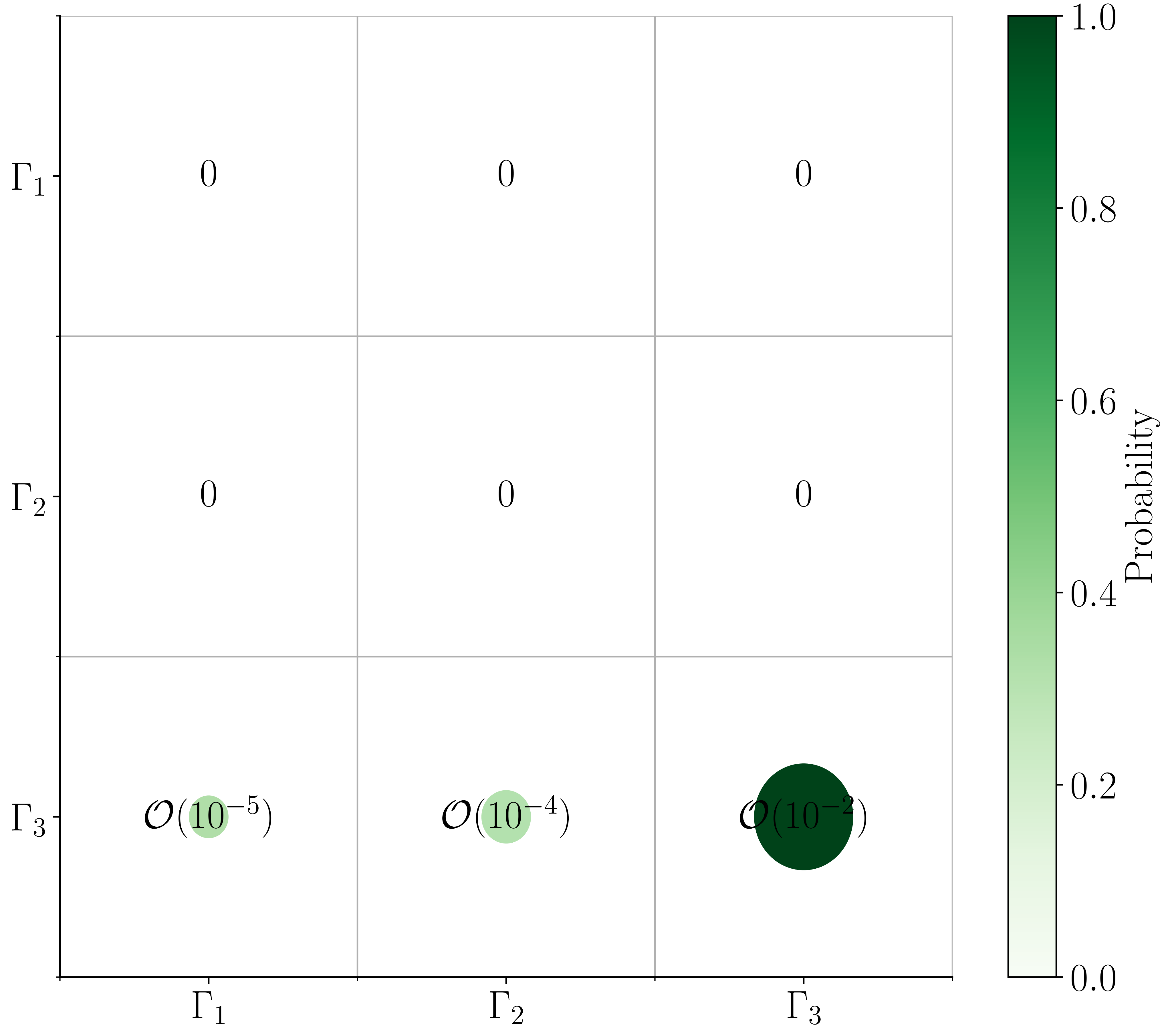
$$X_S = \pm\left(X_{\Phi_1} - X_{\Phi_2}\right), \quad X_S = \pm\frac{1}{2}\left(X_{\Phi_1} - X_{\Phi_2}\right),$$

Backup slides

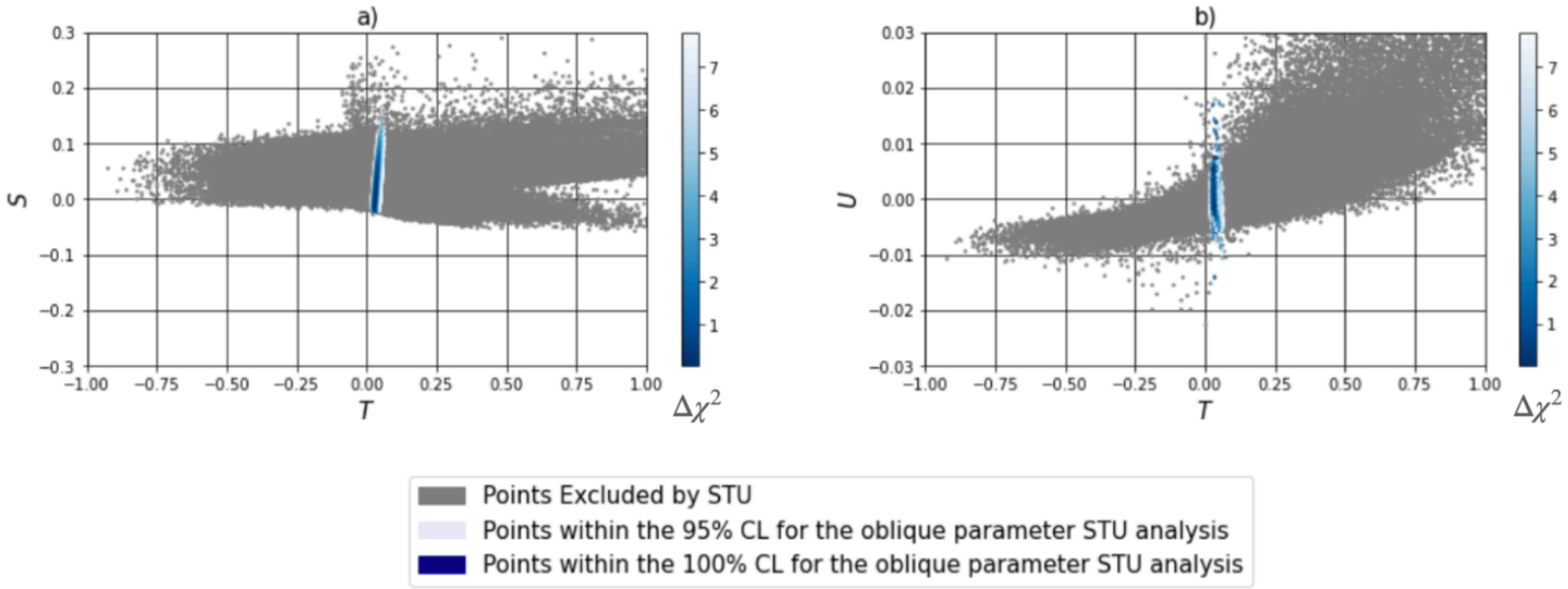
Values of Γ_1 matrix



Values of Γ_2 matrix

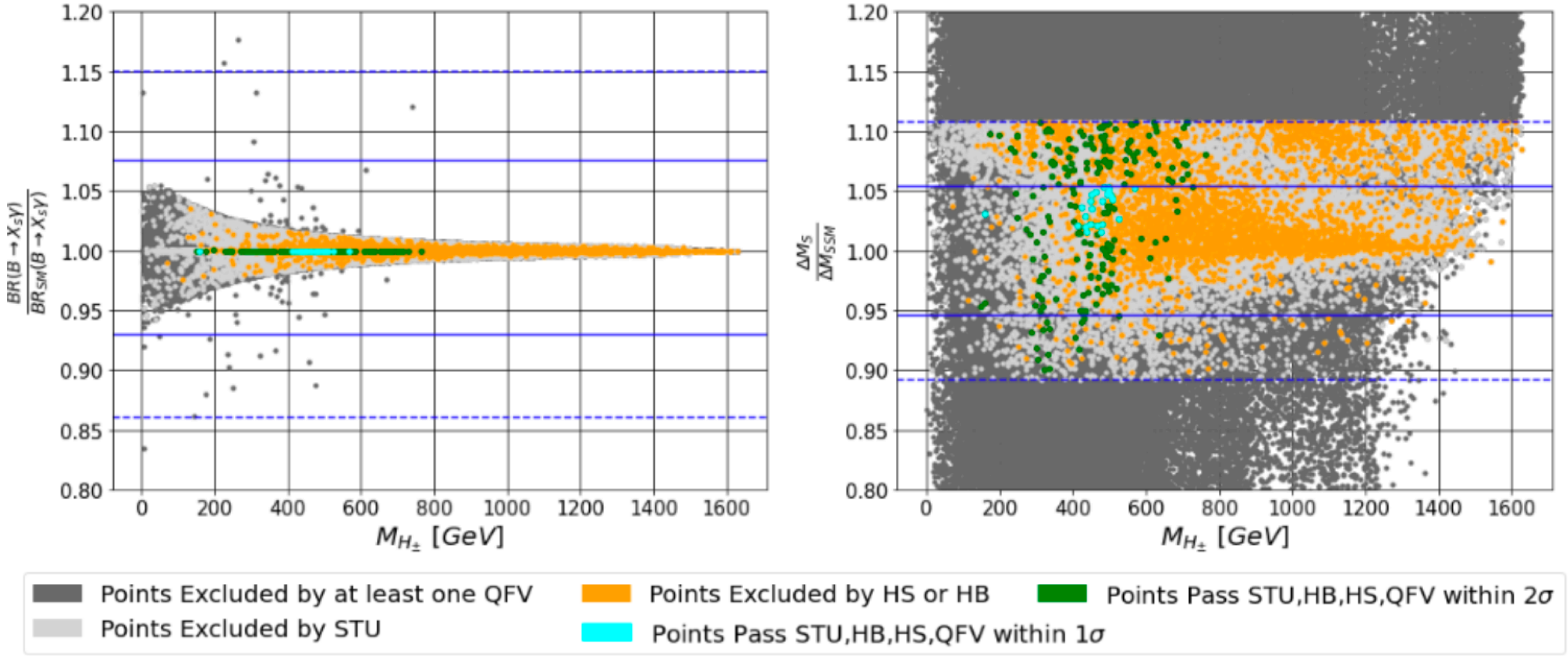


Results



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
$\frac{BR(B \to X_s\gamma)}{BR_{SM}(B \to X_s\gamma)}$
$M_{H_\pm}$ [GeV]
$\frac{\Delta M_S}{\Delta M_{SSM}}$
$M_{H_\pm}$ [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

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

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

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

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

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

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

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:

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

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

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

[….]

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

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

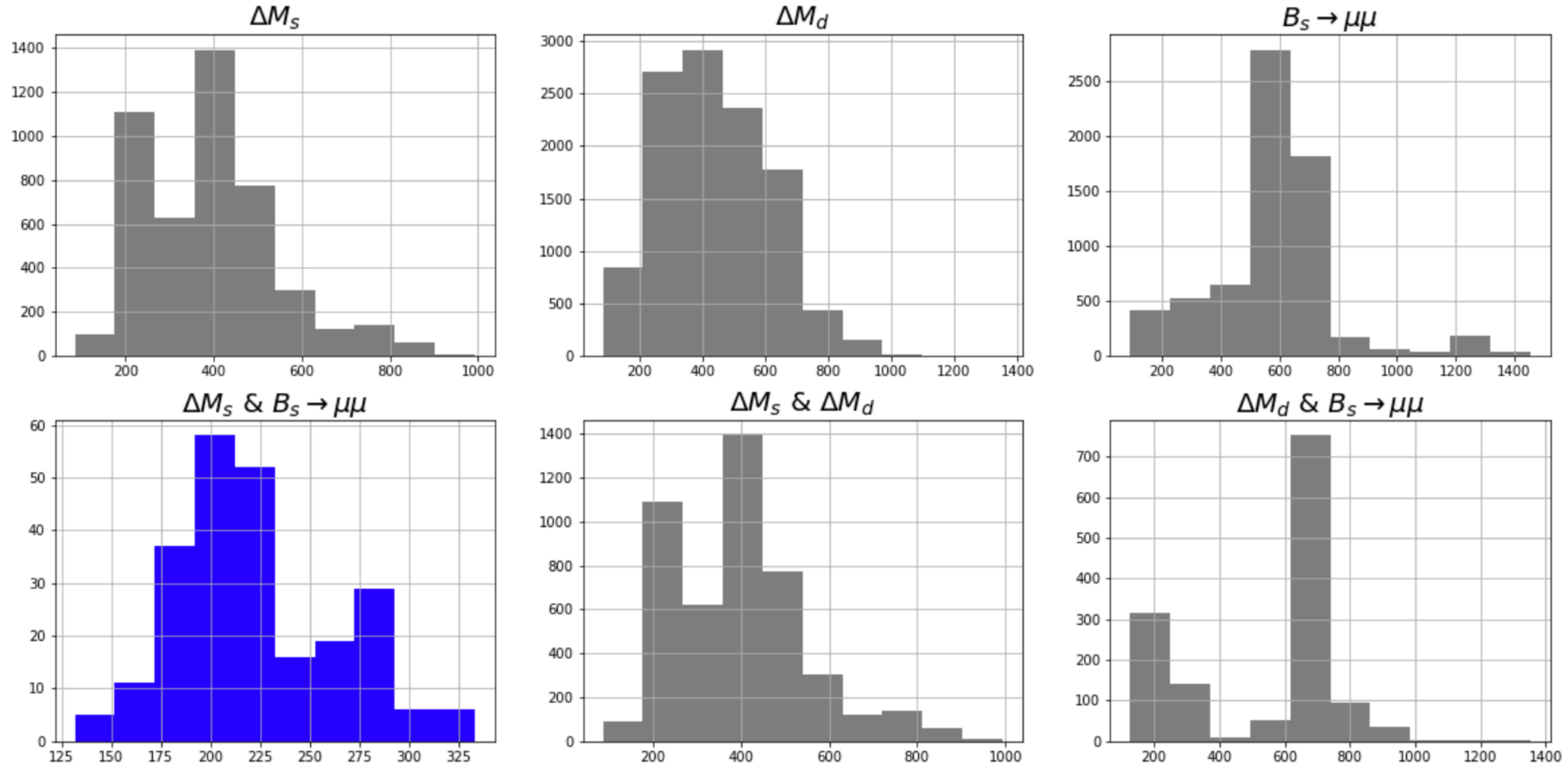
Whose off-diagonal elements are responsible for inducing tree-level FCNC interactions. One of the features of the BGL model is that those matrices can be re-expresses in terms of quark masses, CKM mixing elements and β angle

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

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

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

Results



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%

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.