Vasileios Vatellis

Pre-beer seminar

ID-IS | Intelligent Data-Intensive Systems

Education

Uppsala University

MSc, Physics; Particle Physics

National & Kapodistrian University of Athens

BSc, Physics; Particle Physics

Experience

Student research fellow

Universidade de Aveiro

Jul 2020 - Mar 2023 (2 years 9 months)

Publications

- Phenomenology of a flavored multiscalar Branco-Grimus-Lavoura-like model with three generations of massive neutrinos**,** *Phys.Rev.D 106 (2022) 7, 075017 e-Print: 2202.13153 – Published Feb 26, 2022*
- Collider phenomenology of new neutral scalars in a flavoured multi-Higgs model, *Phys.Rev.D 106 (2022) 7, 075017 e-Print: 2202.13153 [hep-ph] - Published Nov 18, 2022*

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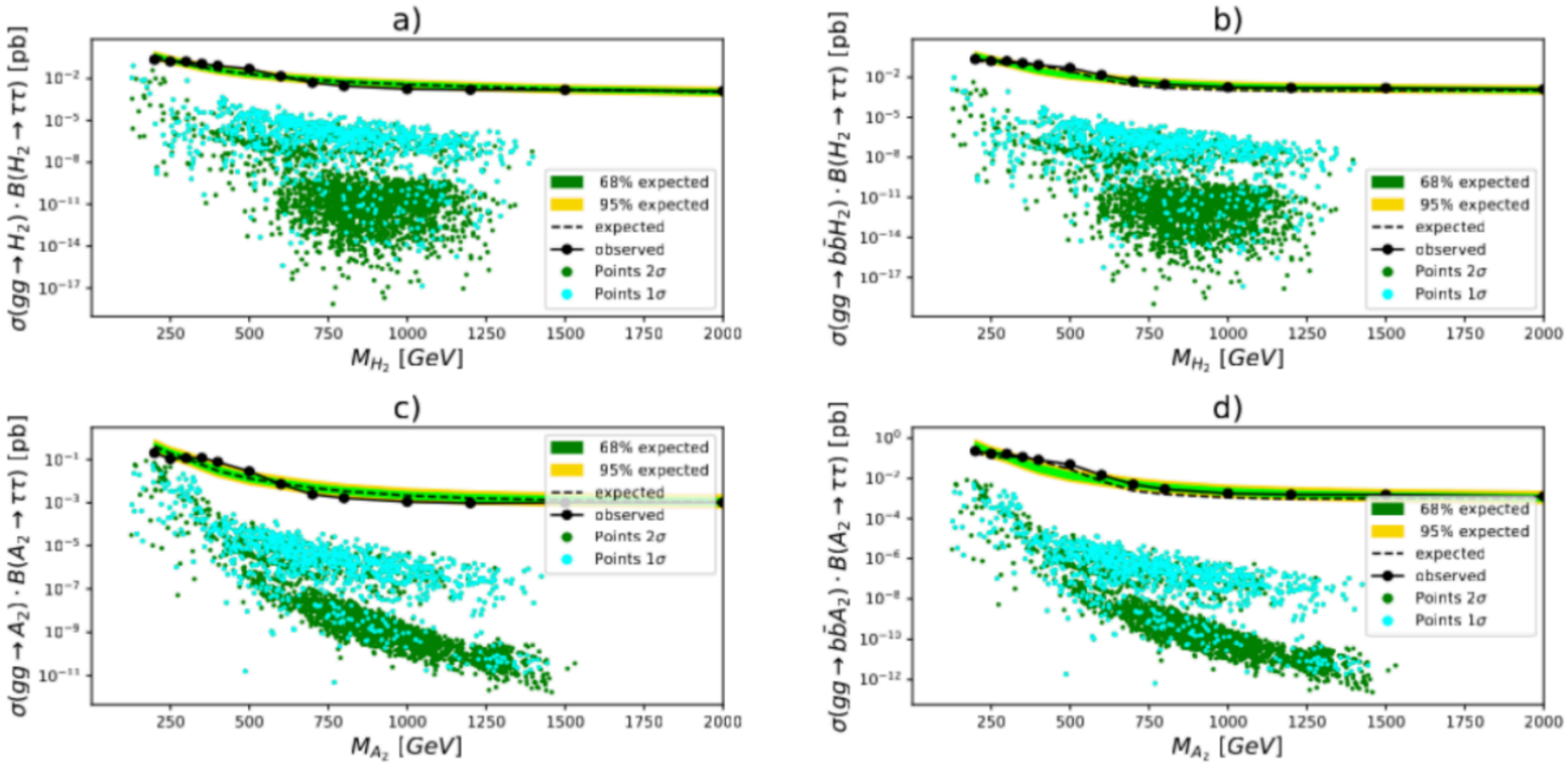
- Take the model to a pipeline of softwares and tailor made codes that calculate interesting information
- Analyse data
- Produce nice plots



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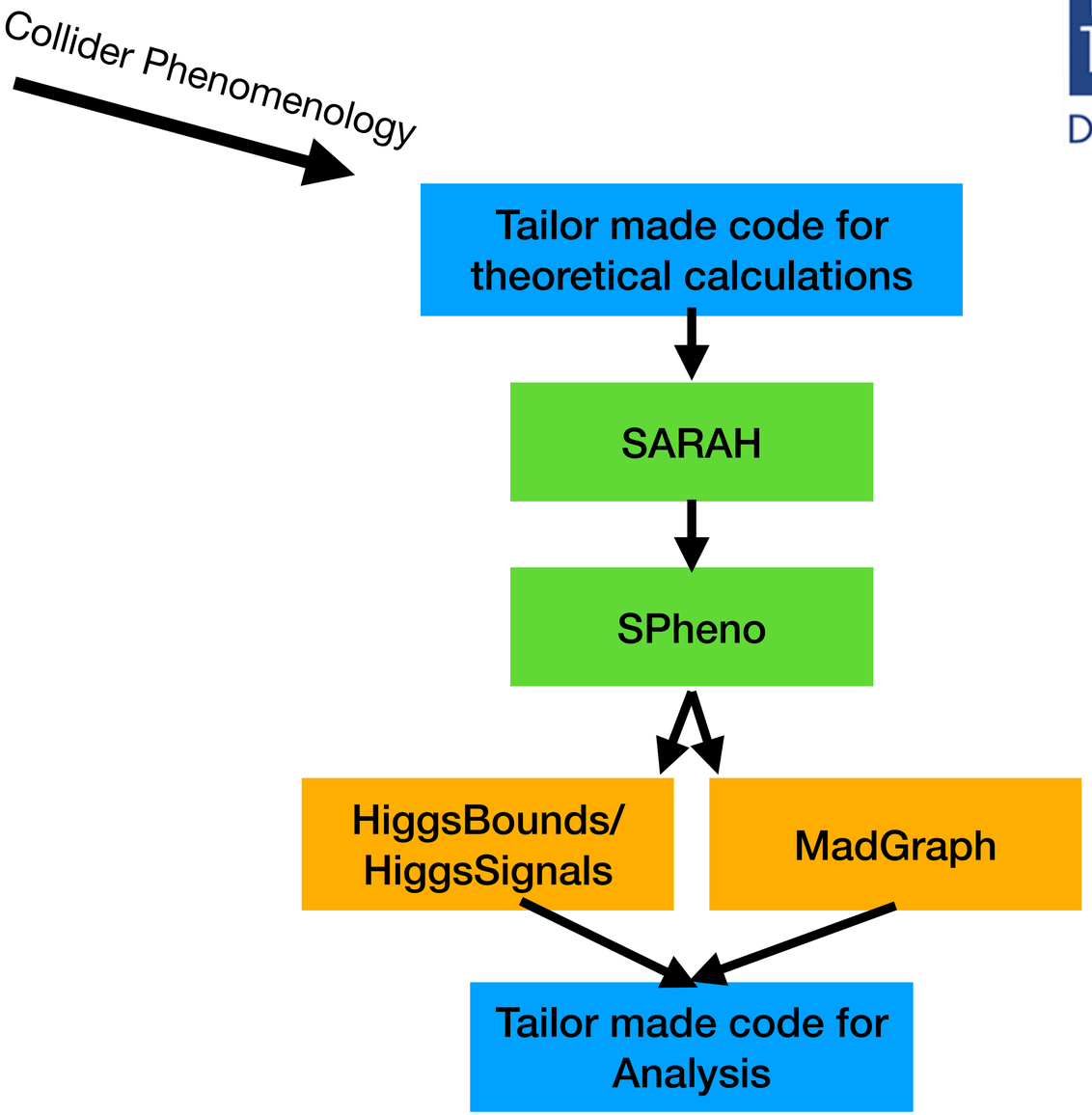

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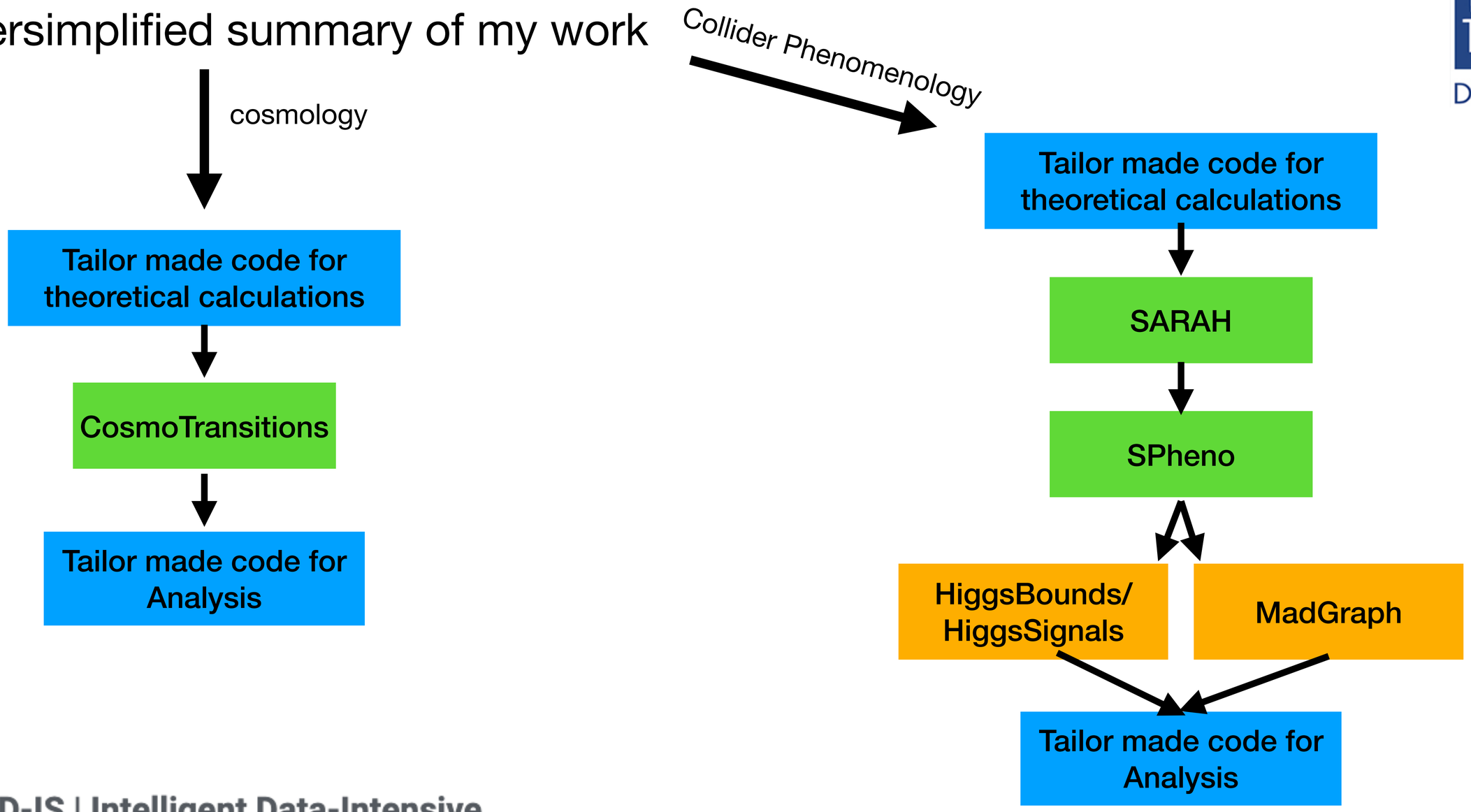

Technical difficulties had to be faced:

- Random scans
- Limited knowledge of the domain in computer intelligence
- Limited computer resources

Phenomenology of a flavoured NTHDM BGL-like model with three massive neutrino generations

Speaker: Vasileios Vatellis*

- Phenomenology of a flavored multiscalar Branco-Grimus-Lavoura-like model with three generations of massive neutrinos**,** *Phys.Rev.D 106 (2022) 7, 075017 e-Print: 2202.13153 – Published Feb 26, 2022*
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Collaborator: P. M. Ferreira, Felipe F. Freitas, João Conçalves, Antonio P. Morais, Roman Pasechnik, and Vasileios Vatellis

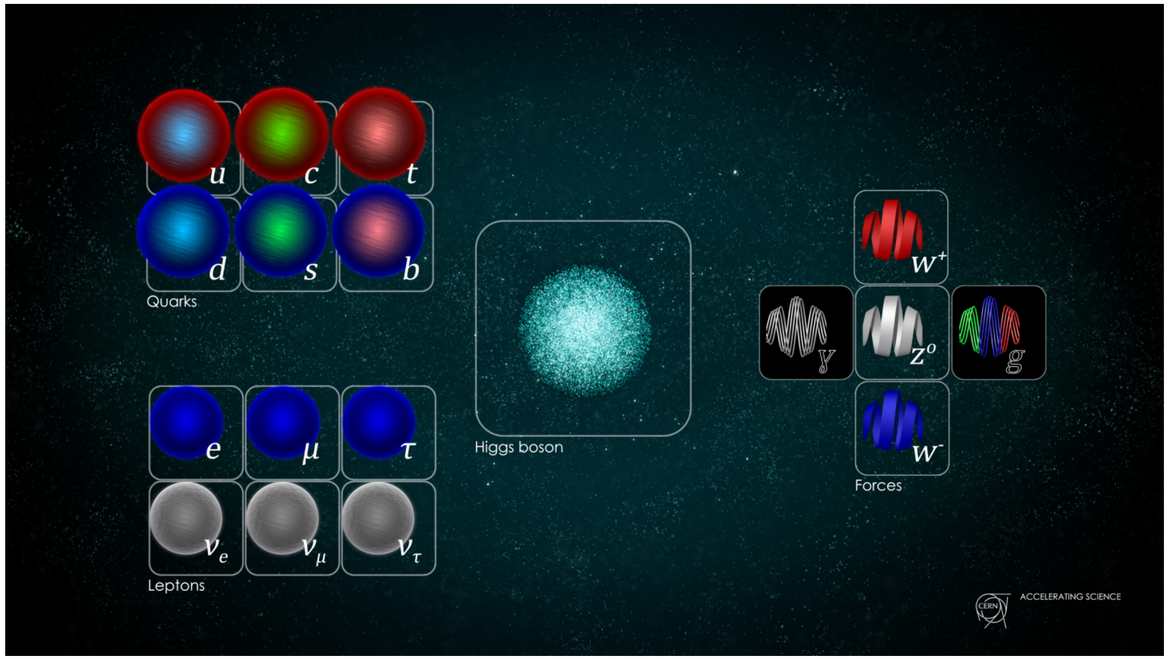
universidade de aveiro

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

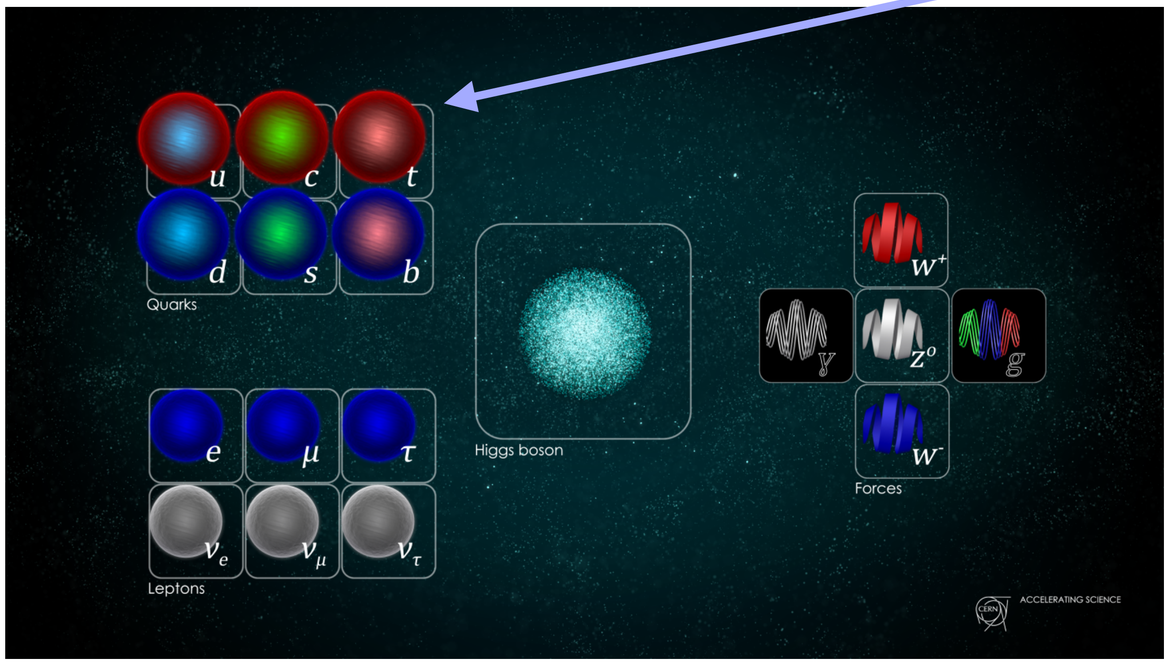
The Standard Model (SM)



The Picture is take from CERN web page [3]

The Standard Model (SM)

Quarks



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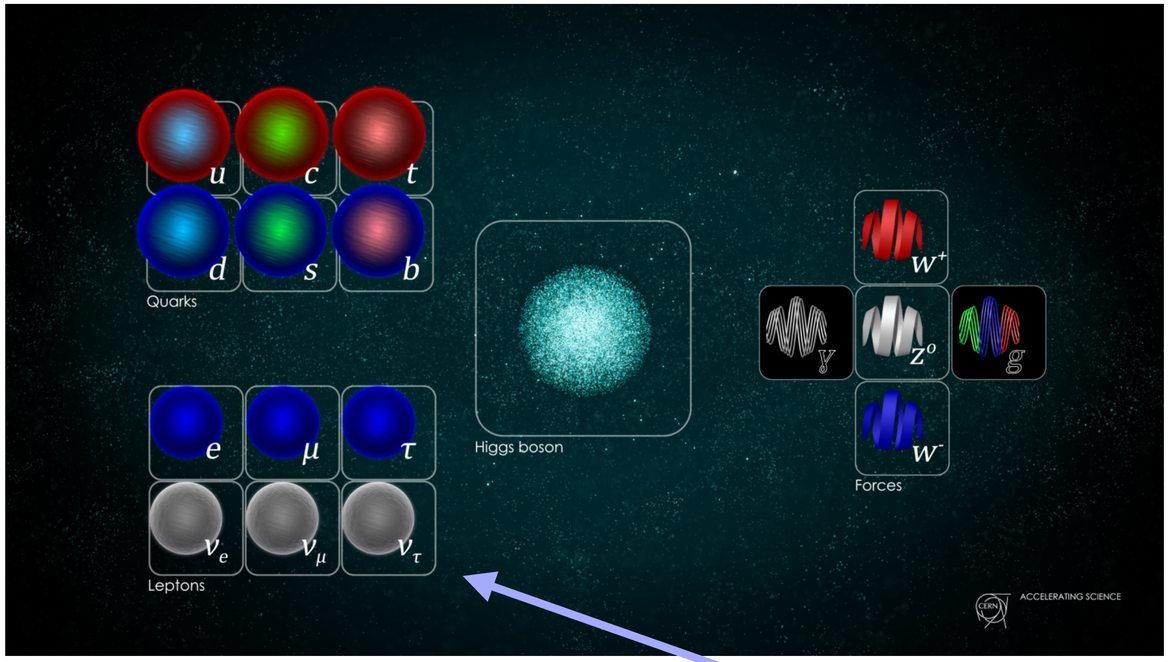
All matter around us is made of elementary particles, the building blocks of matter. These particles occur in two basic types called quarks and leptons. Each group consists of six particles, which are related in pairs, or “generations”. The lightest and most stable particles make up the first generation, whereas the heavier and less-stable particles belong to the second and third generations. All stable matter in the universe is made from particles that belong to the first generation; any heavier particles quickly decay to more stable ones. The six quarks are paired in three generations – the “up quark” and the “down quark” form the first generation, followed by the “charm quark” and “strange quark”, then the “top quark” and “bottom (or beauty) quark”. Quarks also come in three different “colours” and only mix in such ways as to form colourless objects

Source CERN web page [3]

The Standard Model (SM)



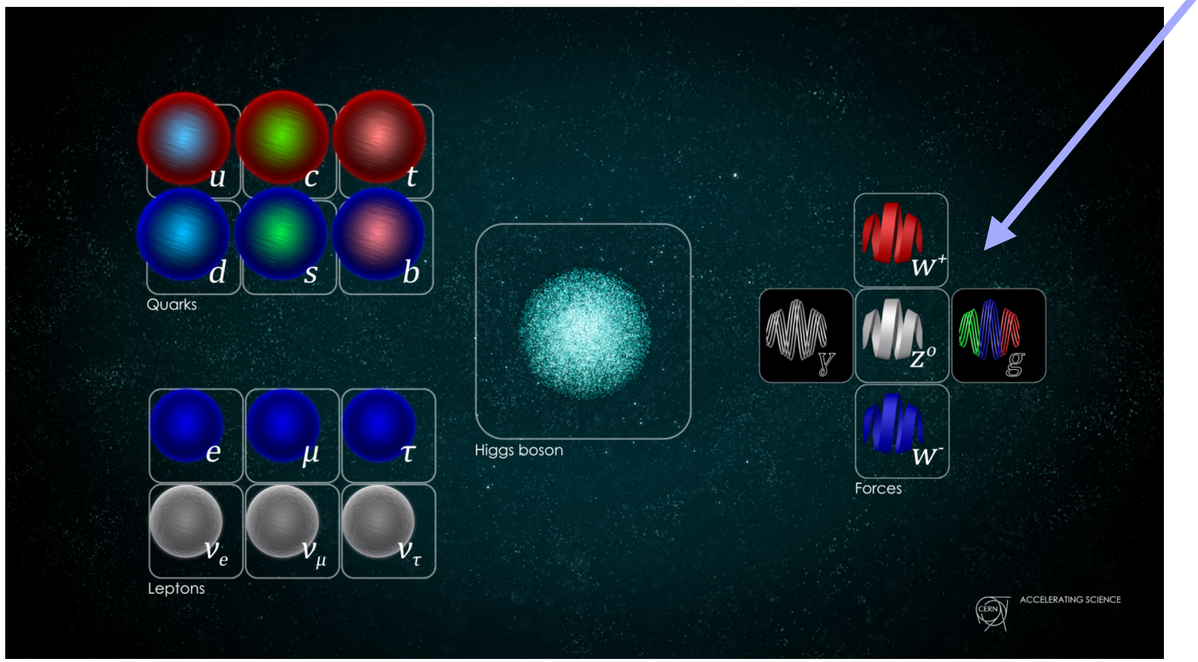
The Picture is take from CERN web page [3]

Leptons

The six leptons are similarly arranged in three generations – the “electron” and the “electron neutrino”, the “muon” and the “muon neutrino”, and the “tau” and the “tau neutrino”. The electron, the muon and the tau all have an electric charge and a sizeable mass, whereas the neutrinos are electrically neutral and have very little mass.

Source CERN web page [3]

The Standard Model (SM)



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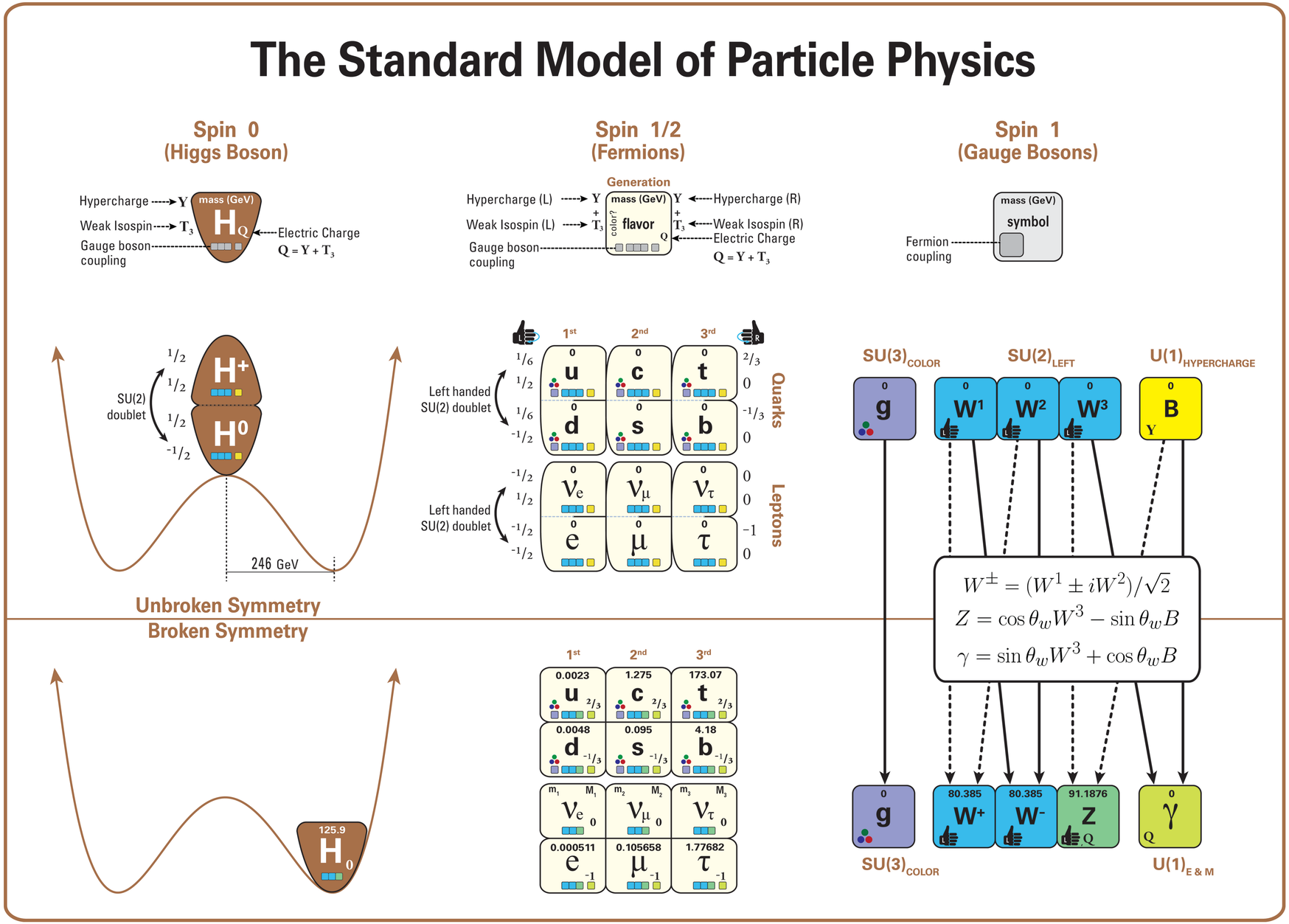
Forces and carrier particles

There are four fundamental forces at work in the universe: the strong force, the weak force, the electromagnetic force, and the gravitational force. They work over different ranges and have different strengths. Gravity is the weakest but it has an infinite range. The electromagnetic force also has infinite range but it is many times stronger than gravity. The weak and strong forces are effective only over a very short range and dominate only at the level of subatomic particles. The weak force is weaker than the strong force and the electromagnetic force, but it is still much stronger than gravity. The strong force, as the name suggests, is the strongest of all four fundamental interactions.

Three of the fundamental forces result from the exchange of force-carrier particles, which belong to a broader group called “bosons”. Particles of matter transfer discrete amounts of energy by exchanging bosons with each other. Each fundamental force has its own corresponding boson – the strong force is carried by the “gluon”, the electromagnetic force is carried by the “photon”, and the “W and Z bosons” are responsible for the weak force.

Source CERN web page [3]

Introduction



The Standard model symmetry groups

SU(3)×SU(2)×U(1).

electroweak

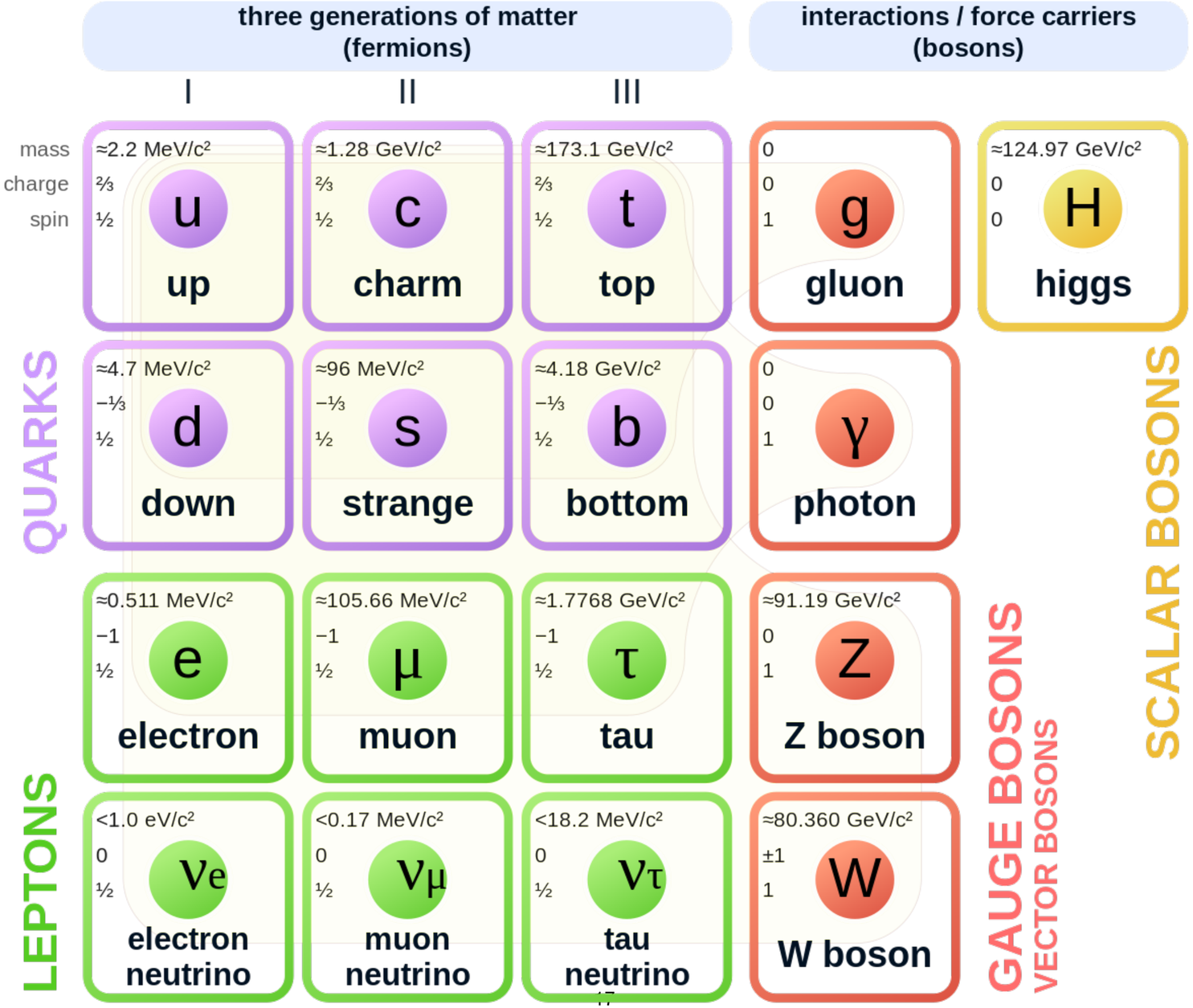
Strong Force

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Source: Cabibbo–Kobayashi–Maskawa matrix. (2023, September 12). In Wikipedia. https://en.wikipedia.org/wiki/Cabibbo%E2%80%93Kobayashi%E2%80%93Maskawa_matrix

Source: *Mathematical formulation of the Standard Model. (2023, September 14). In Wikipedia. https://en.wikipedia.org/wiki/Mathematical_formulation_of_the_Standard_Model*

Introduction



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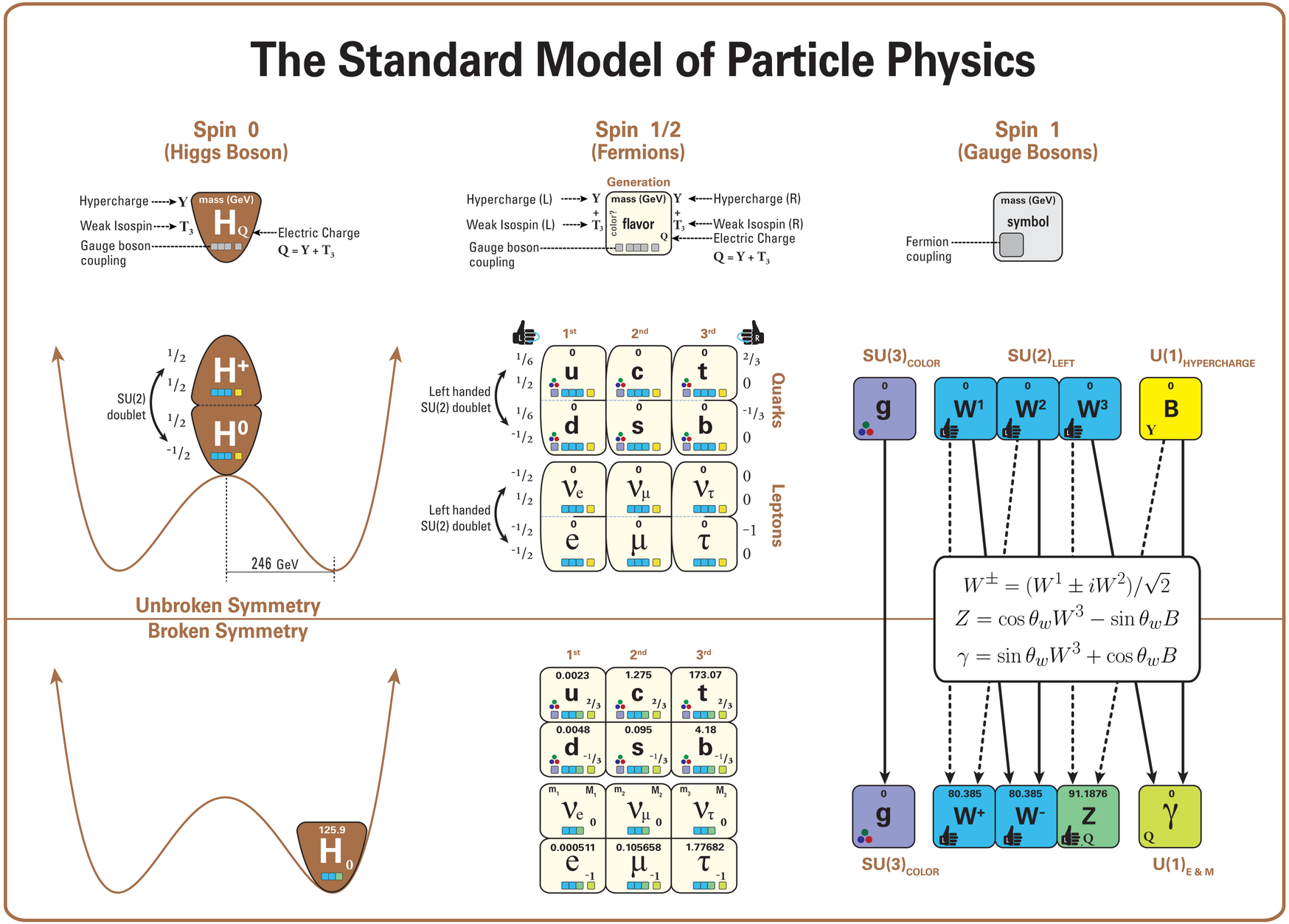

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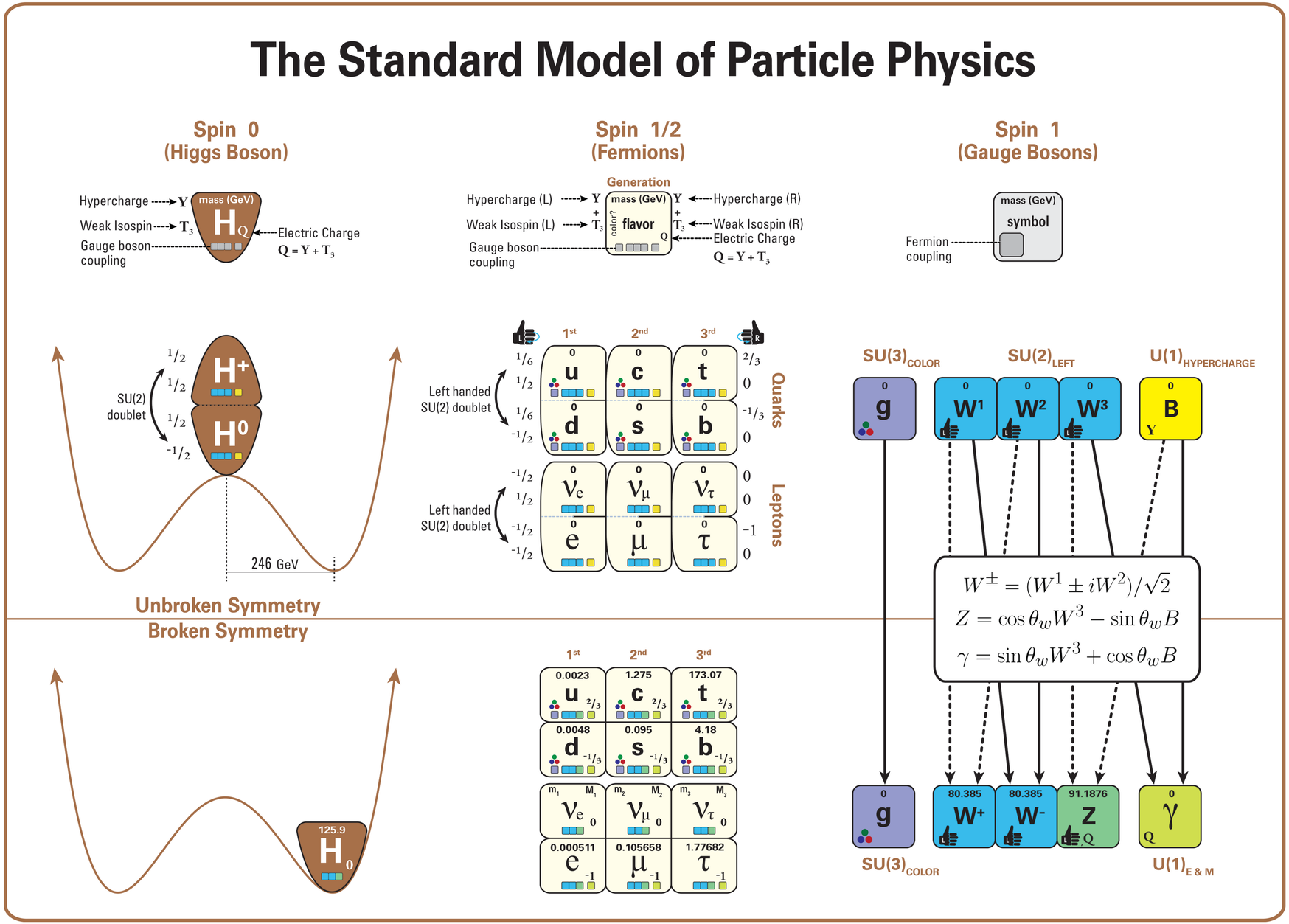

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$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Source: Pontecorvo–Maki–Nakagawa–Sakata matrix. (2023, March 31). In Wikipedia. https://en.wikipedia.org/wiki/Pontecorvo%E2%80%93Maki%E2%80%93Nakagawa%E2%80%93Sakata_matrix

SU(3)×SU(2)×U(1)×?

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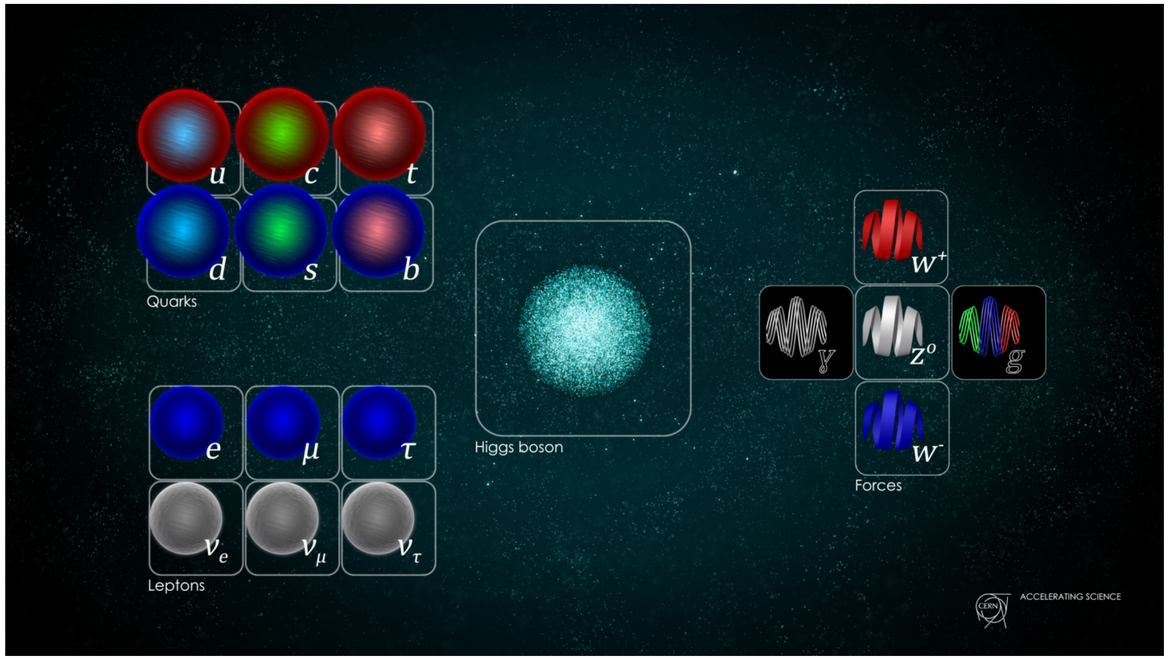
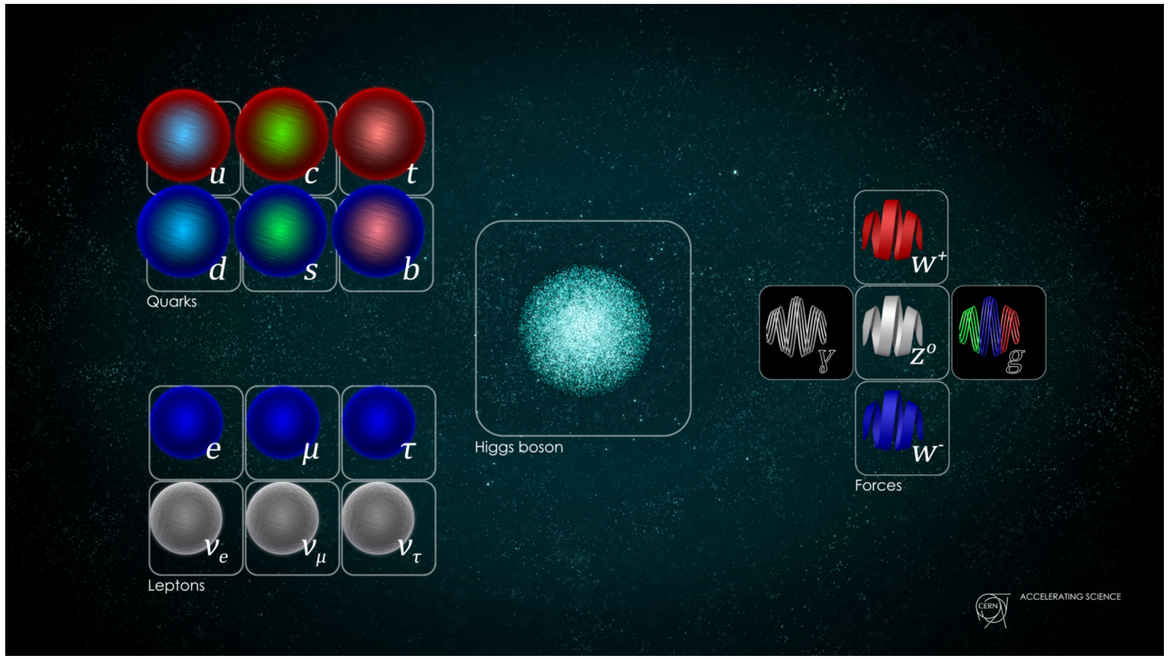


Inconsistencies → No Gravity in SM

The Standard Model (SM)



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No Gravity in SM

No Dark Matter in SM

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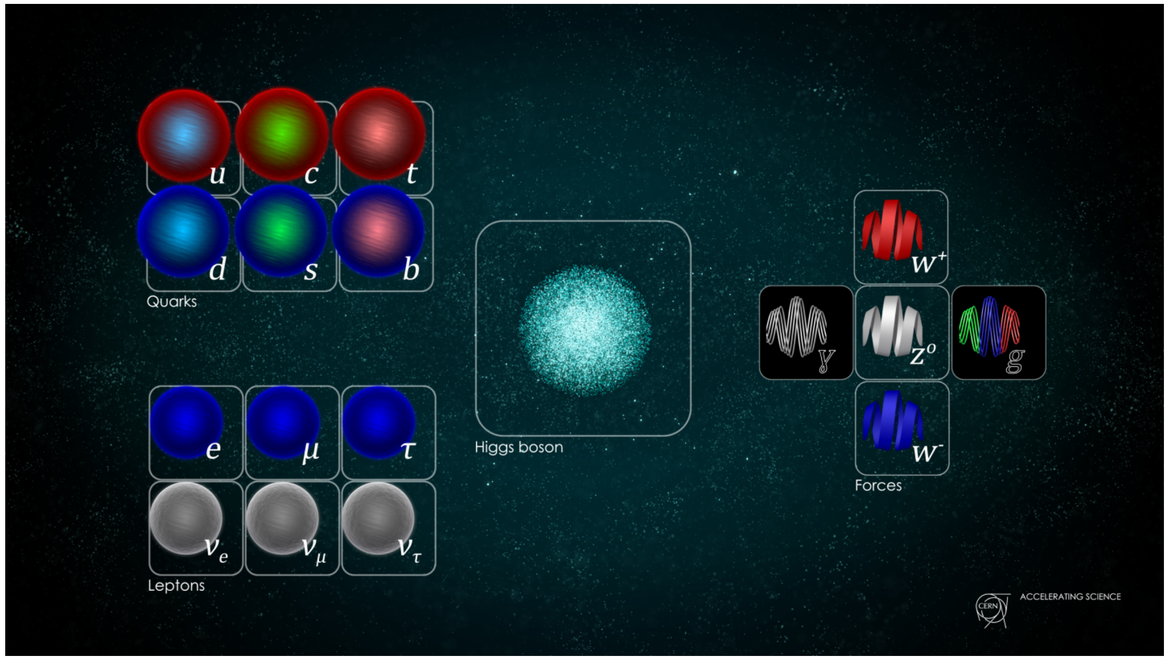

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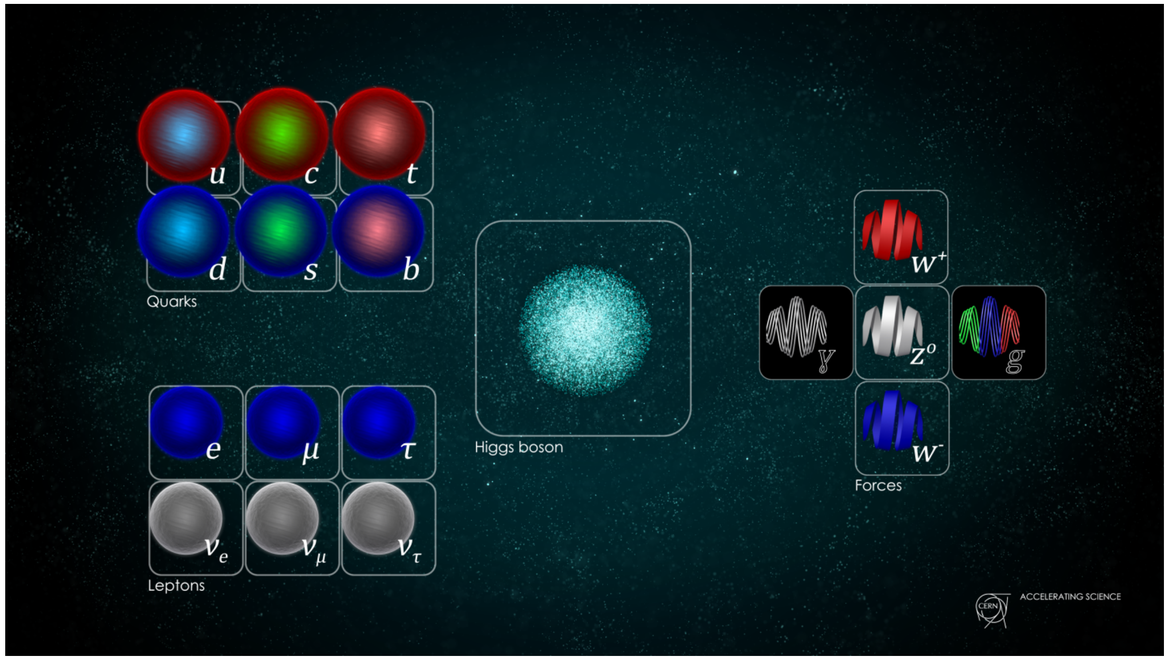
No Gravity in SM

No Dark Matter in SM

Neutrino oscillations

Introduction

The Standard Model (SM)



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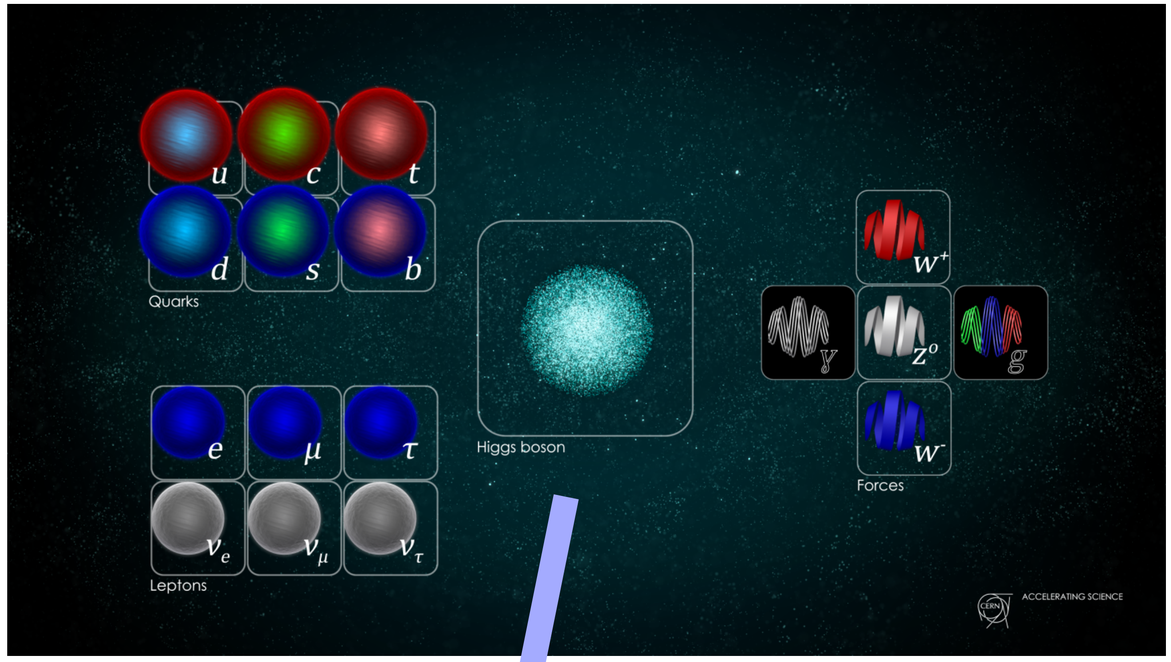
Neutrino oscillations

Baryon Asymmetry

The Standard Model (SM)



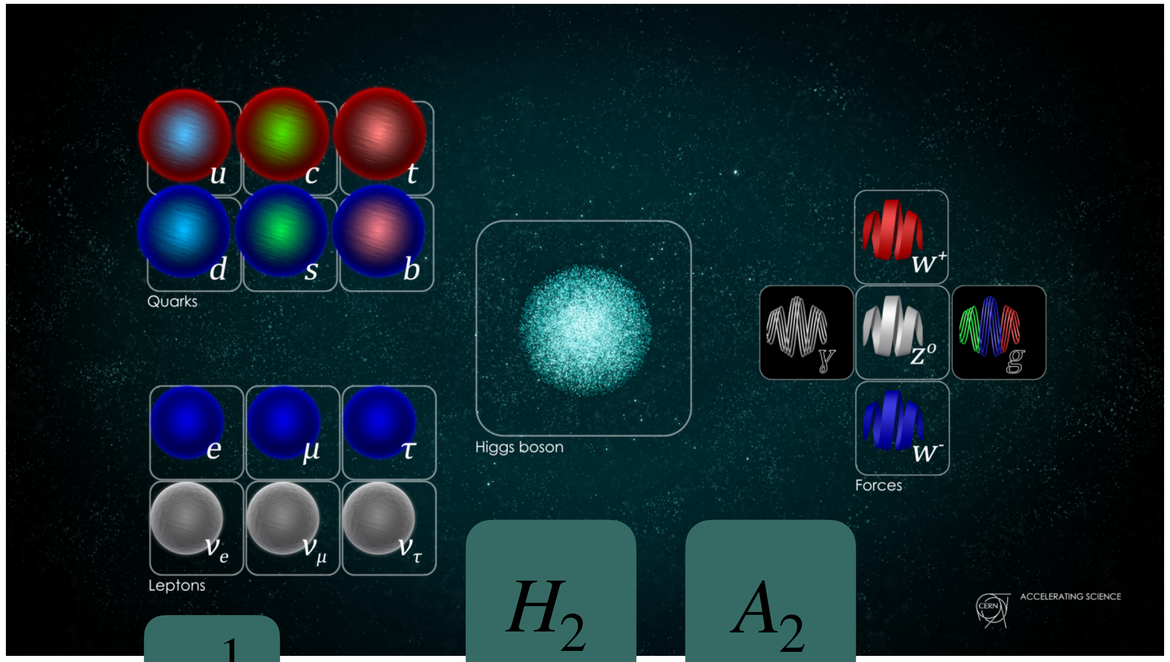
Inconsistencies →

- No Gravity in SM
- No Dark Matter in SM
- Neutrino oscillations
- Baryon Asymmetry

We extend the SM and we introduce new scalar particles (Multiscalar models)

H_2 A $H^\pm$

Introduction



ν_R^1

ν_R^2

ν_R^3

H_2

H_3

$H^\pm$

A_2

A_3

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

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

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

$\Gamma_\alpha, \Delta_\alpha$: 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

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.

Also the model is gauge anomaly free[1]

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

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:

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

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 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 νBGL-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}
$\mathrm{U(1)_Y}$	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

Model Introduction

Parameter space:

Parameter	$\alpha_2, \alpha_3, \gamma_1$	$\tan\beta$	δ	a_3, a_4
range	$[-\pi, \pi]$	$[0.5, 30]$	$[\frac{\pi}{2} - 1, \frac{\pi}{2} + 1]$	0

Parameter	M_{A_2}, $M_{H^\pm}$	M_{A_3}	M_{H_2}, M_{H_3}	a_2
range [GeV]	$[0.5, 1600]$	$[30, 2000]$	$[126, 1800]$	$[-1, 1]$

the chosen scanning ranges for δ are centered around π/2 where sin δ = 1. While α_2 must be small, we let it range between –π and π in order to let cosα_2 capture both positive and negative values. Furthermore, the somewhat large ranges set for both δ and α_2 were deliberately picked in order to ensure that the allowed off-alignment

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.

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

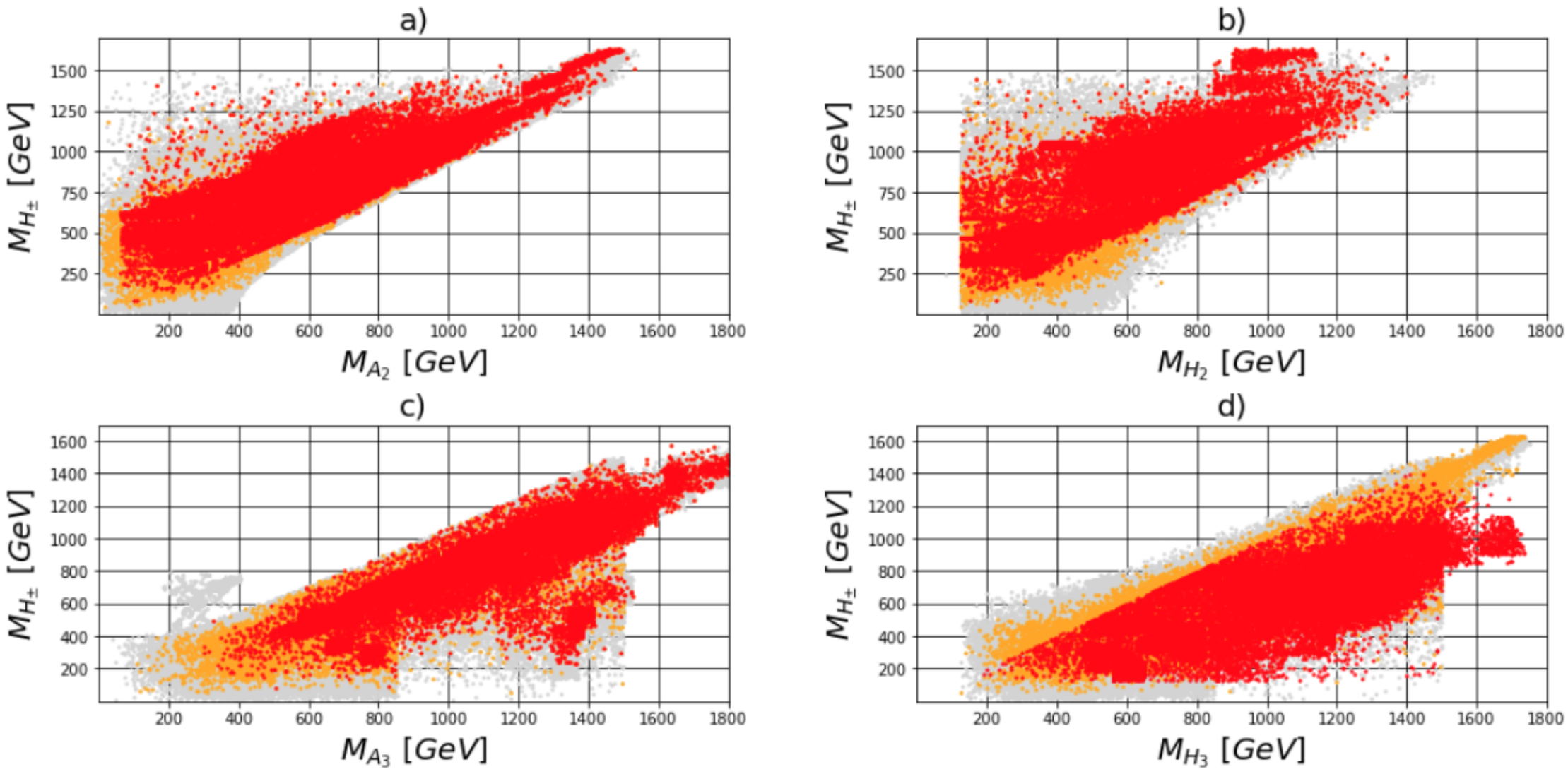
Were we require $\Delta x^2 < 7.815$, which is translated to 95% confidence level (CL) agreement with the electroweak fit.

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

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

Restrictions

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
$\mathrm{BR}(\mathrm{B} \to \chi_s \gamma)$	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

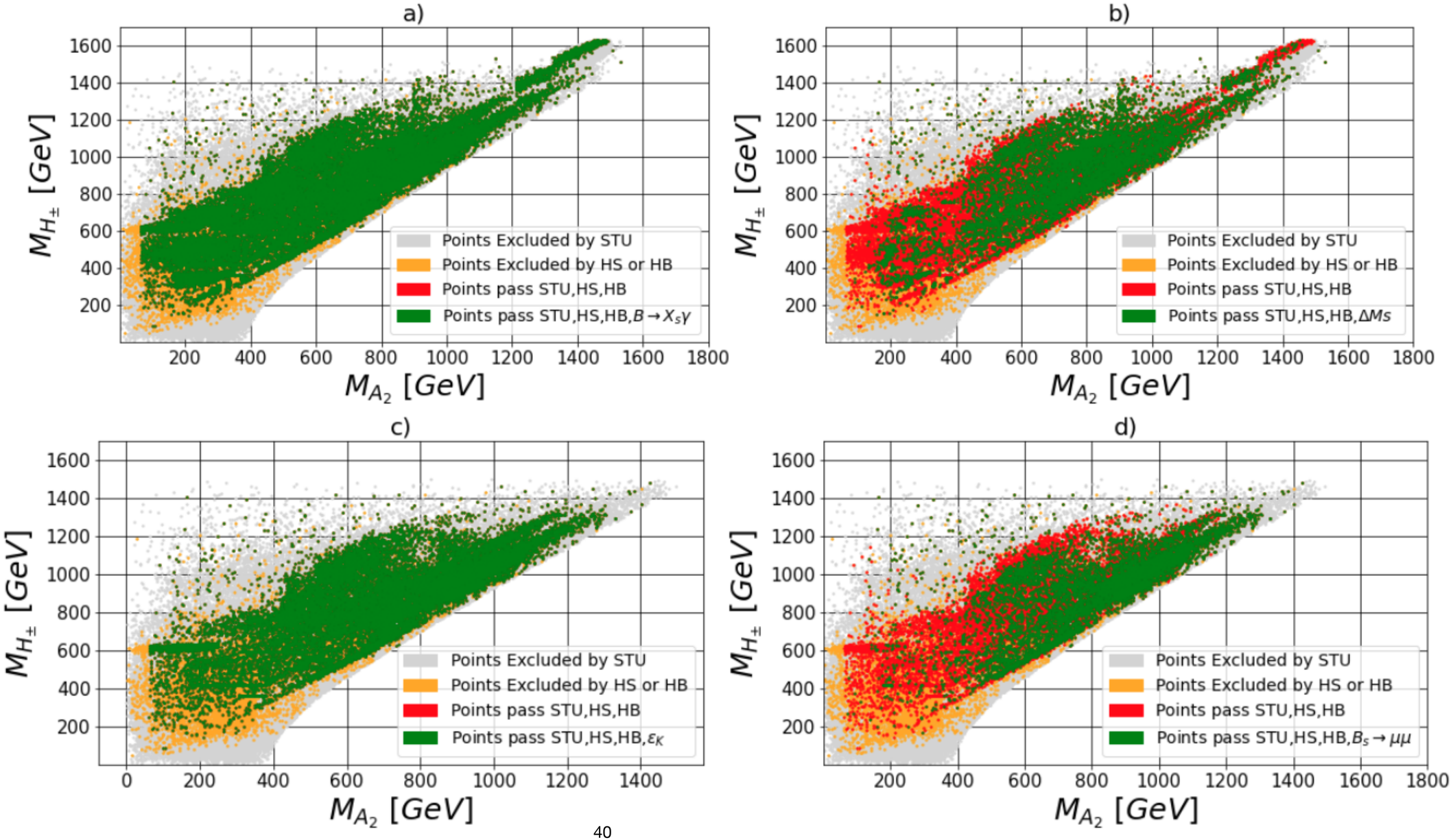
A) $B \to X_S\gamma$

B) ΔM_S

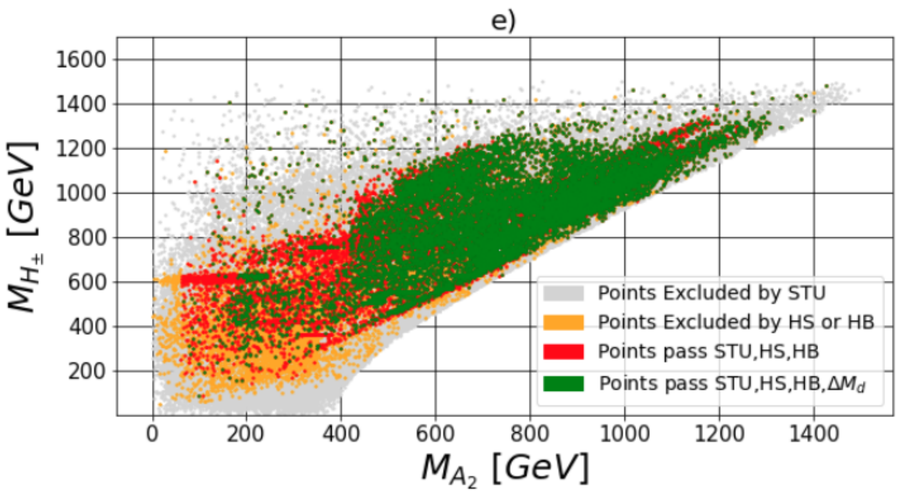
C) ε_K

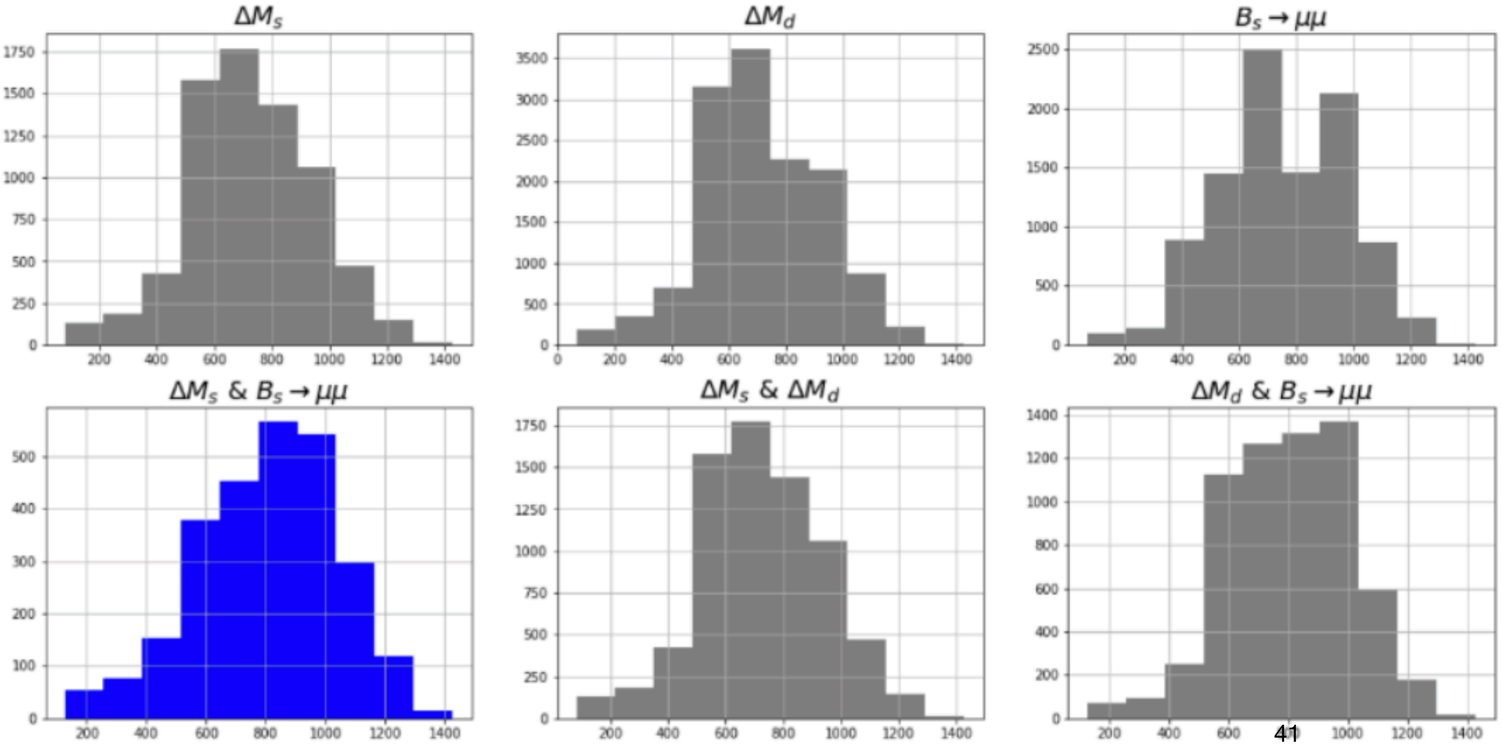
D) $B_S \to \mu\mu$

E) ΔM_d



Results

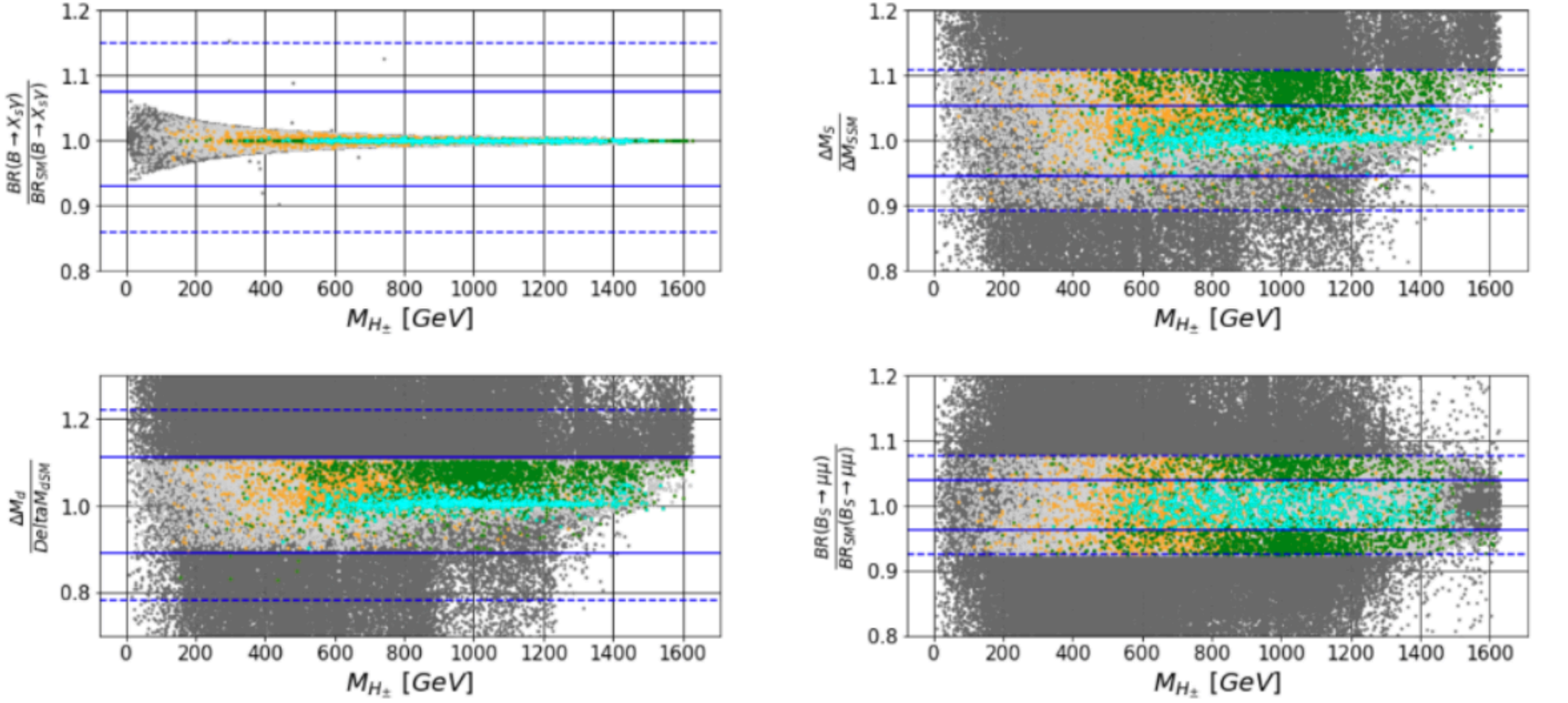




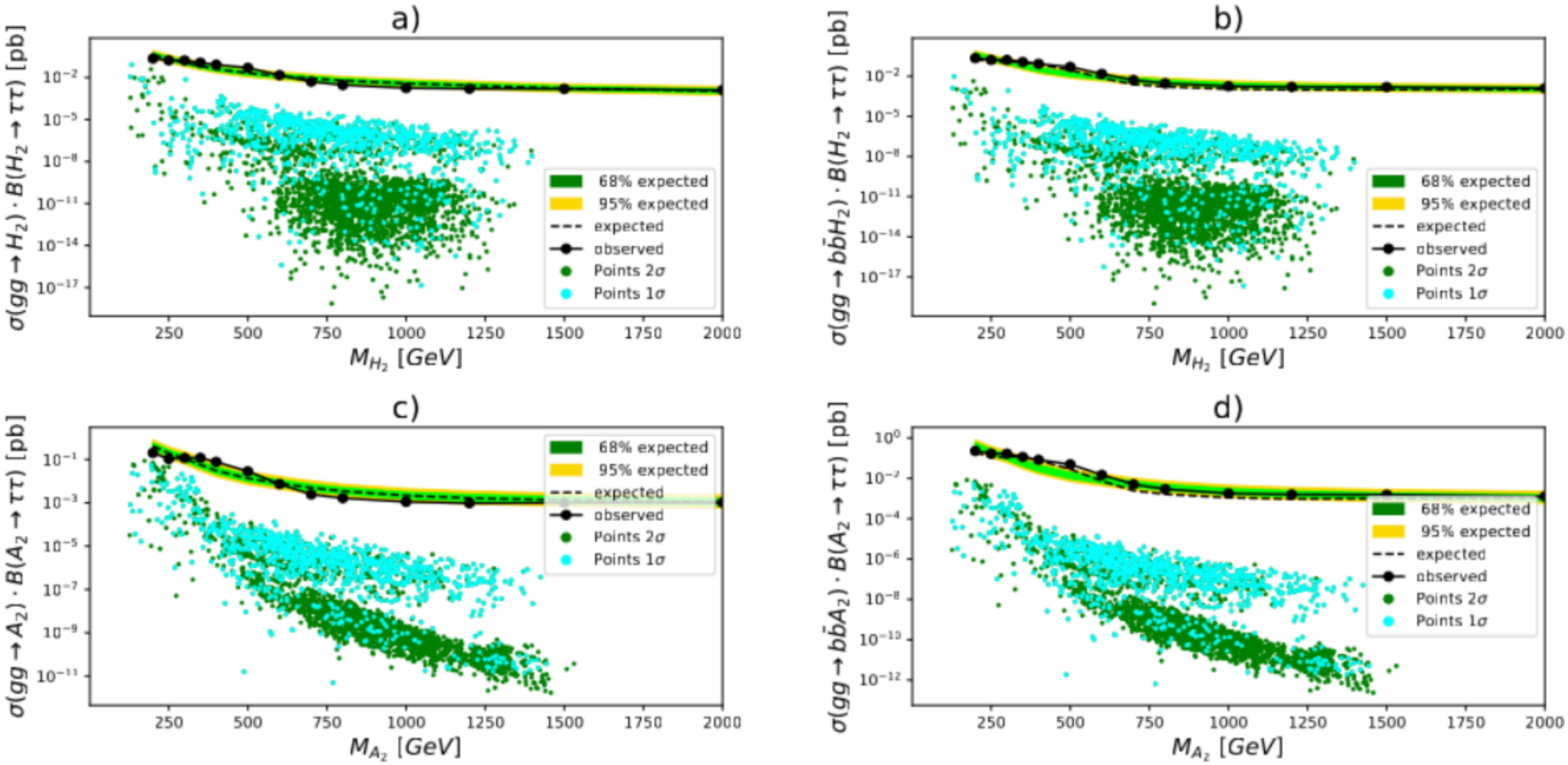
Set of QFV observables	Acceptance ratio
$\mathrm{BR}\,(B \to \chi_s \gamma)$	100.0%
$\mathrm{BR}\,(B_s \to \mu\mu)$	35.0%
ΔM_d (GeV)	48.0%
ΔM_s (GeV)	26.0%
ϵ_K (GeV)	100.0%
$\mathrm{BR}\,(B_s \to \mu\mu)$ & ΔM_s	9.39%
$\mathrm{BR}\,(B_s \to \mu\mu)$ & ΔM_d	22.21%
ΔM_s & ΔM_d	25.57%

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*.

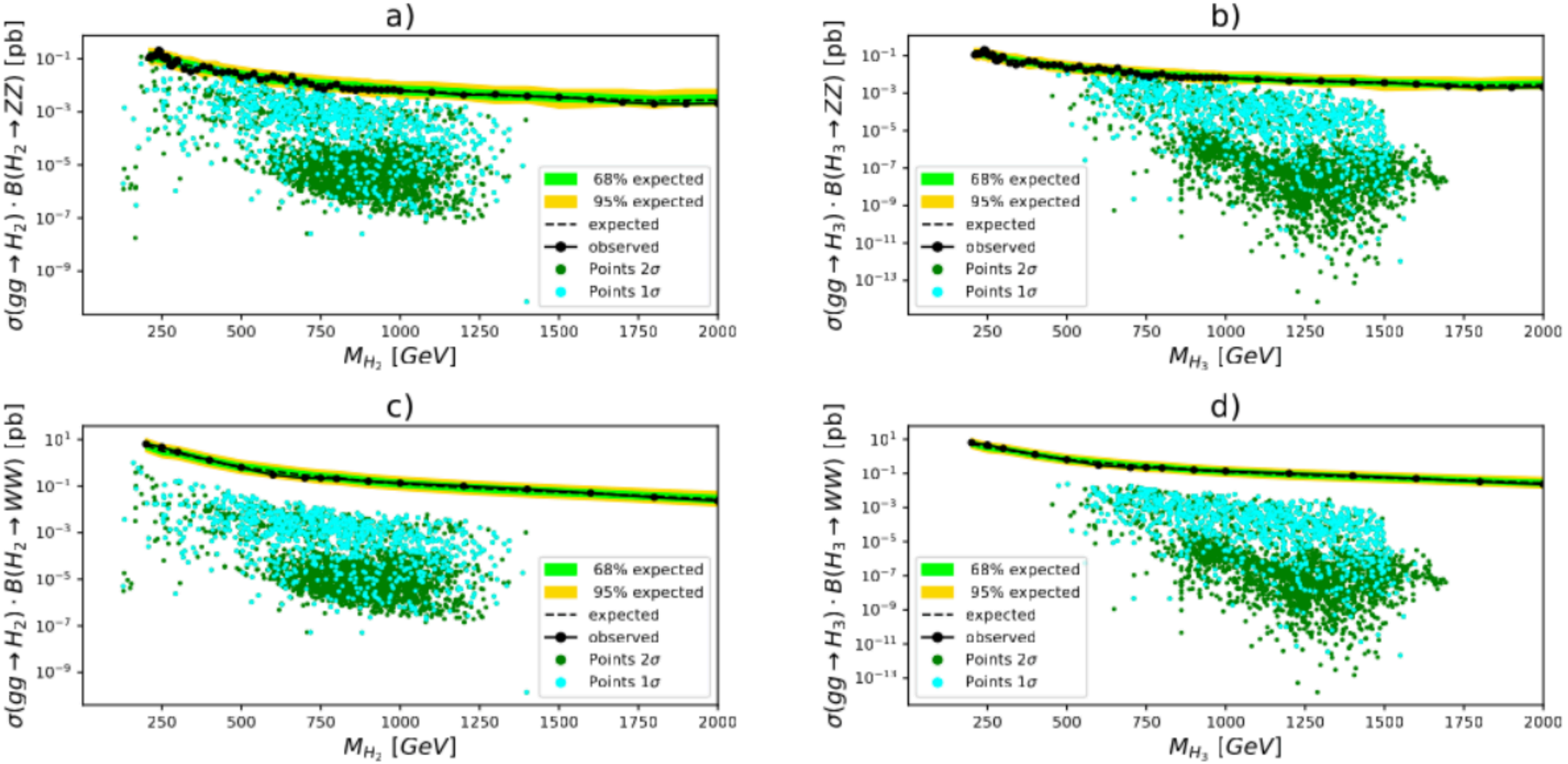
Results


$\frac{BR(B \to X_s\gamma)}{BR_{SM}(B \to X_s\gamma)}$
$\frac{\Delta M_S}{\Delta M_{S\,SM}}$
$\frac{\Delta M_d}{\Delta M_{d\,SM}}$
$\frac{BR(B_S \to \mu\mu)}{BR_{SM}(B_S \to \mu\mu)}$
$M_{H_\pm}$ [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)
b)
c)
d)
$\sigma(gg \to H_2) \cdot B(H_2 \to \tau\tau)$ [pb]
$\sigma(gg \to b\bar{b}H_2) \cdot B(H_2 \to \tau\tau)$ [pb]
$\sigma(gg \to A_2) \cdot B(A_2 \to \tau\tau)$ [pb]
$\sigma(gg \to b\bar{b}A_2) \cdot B(A_2 \to \tau\tau)$ [pb]
M_{H_2} [GeV]
M_{A_2} [GeV]
68% expected
95% expected
expected
observed
Points 2σ
Points 1σ

Results


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

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

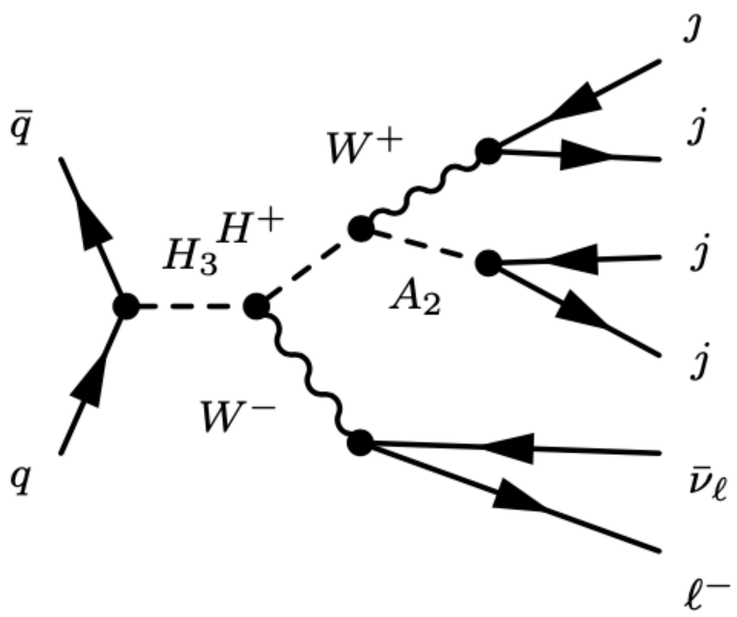
ϕ	ID	Mass (GeV)	BR($\phi \to W^+W^-$)	BR($\phi \to Z^0Z^0$)	$\sigma(gg \to \phi \to W^+W^-)$ (pb)	$\sigma(gg \to \phi \to Z^0Z^0)$ (pb)	Maximum BR
H_2	BP1	160.21	0.881	0.0210	1.0032	0.00054	BR(W^+W^*) = 0.881
	BP2	347.99	0.129	0.0589	0.00722	0.003319	BR(H_1H_1) = 0.611
	BP3	129.26	0.377	0.0449	3.0×10^{-6}	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

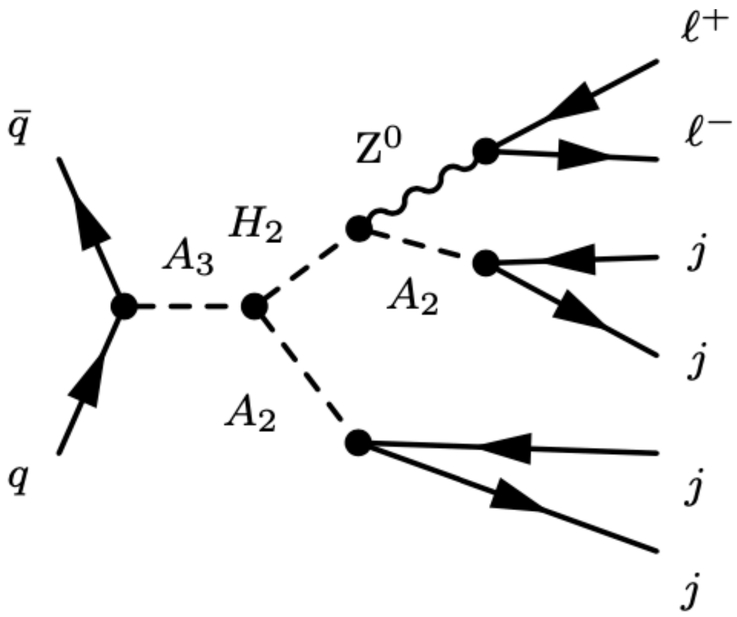
Collider Phenomenology

The next part of my presentation follows João's Gonçalves presentation in FLASY2022 & ICHEP for our project *Collider phenomenology of new neutral scalars in a flavoured multi-Higgs model,* *Phys.Rev.D 106 (2022) 7, 075017 e-Print: 2202.13153 [hep-ph] - Published Nov 18, 2022*

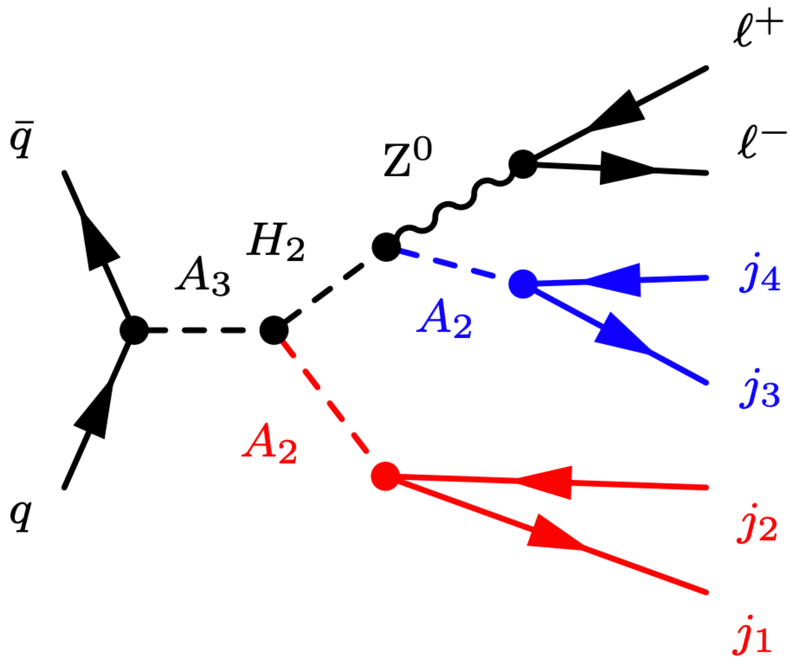
In general (with some exceptions!), most searches focus on BSM Higgs decays to heavy SM states

However, our model contains more complex final states, involving various BSM scalars in the same topology.





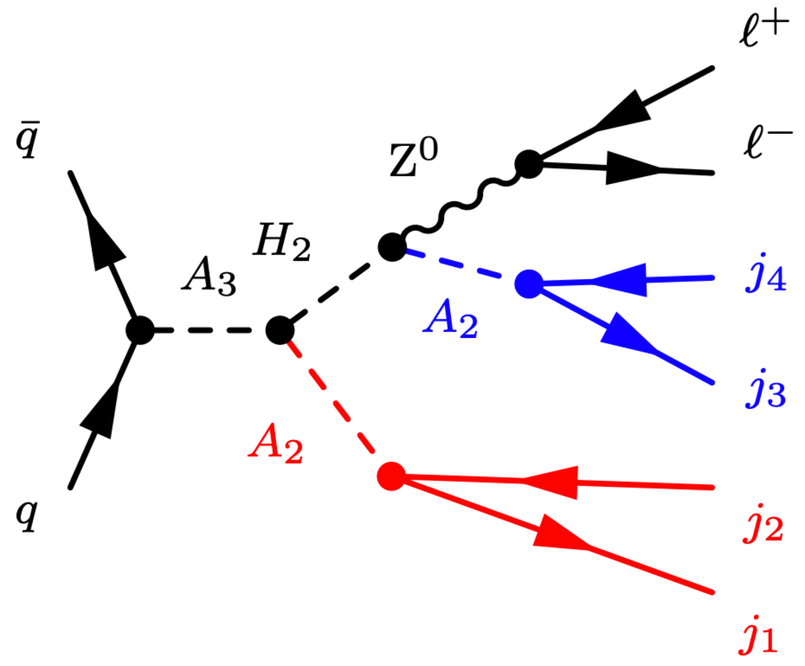
Collider Phenomenology



- Two leptons (μ or e)
- At least four jets from 1st/2nd generation quarks (originate from A_2)
- Two pairs of jets with identical mass

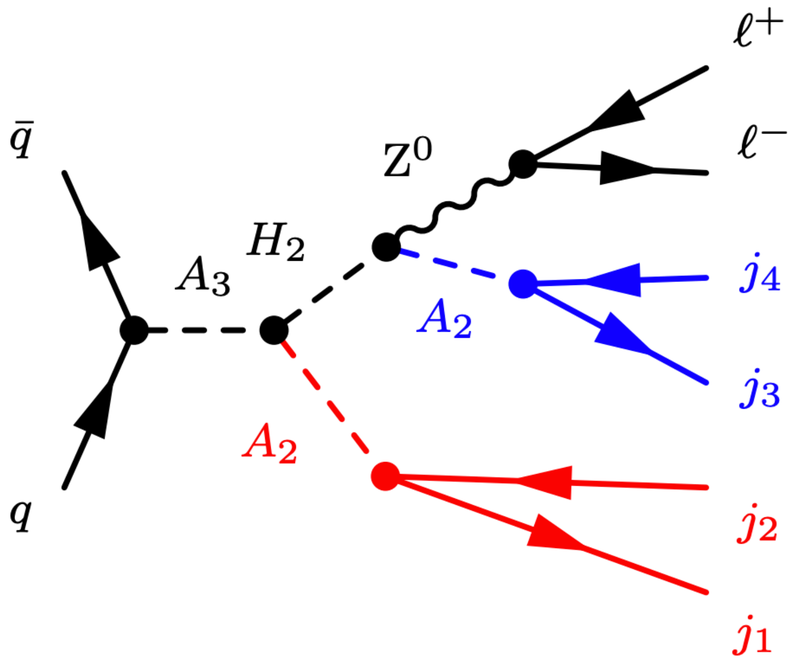
Potentially observable at run-III or at the HL phase of the LHC. Two pseudoscalars and one CP-even scalar running as internal propagators, all on-shell such that

Collider Phenomenology



- Dominant backgrounds: $t\bar{t}$ and Z +jets;
- Sub-leading but relevant: Single top, $t\bar{t}$ + V , Diboson;

Leading-order cross-sections with MadGraph with MLM jet matching. Hadronization in Pythia8 and fast detector simulation of the ATLAS detector with Delphes. ROOT for analysis of distributions.



- 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

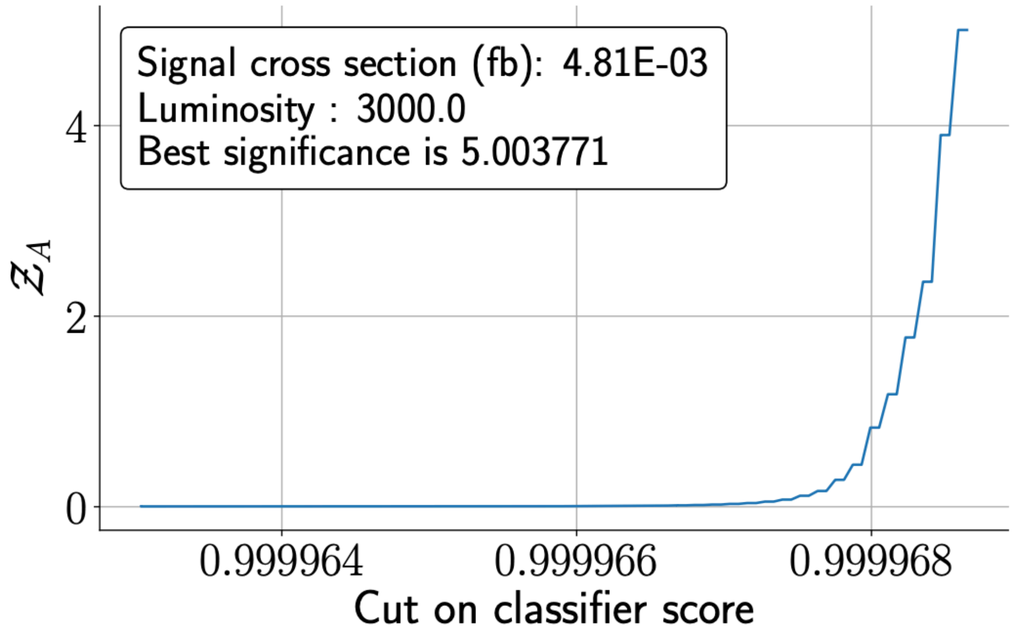
Match jets to H_2 scalar: $min(\,|\,M(j_n, j_m) - M(Z^0) - M(H_2)\,|\,)$

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.

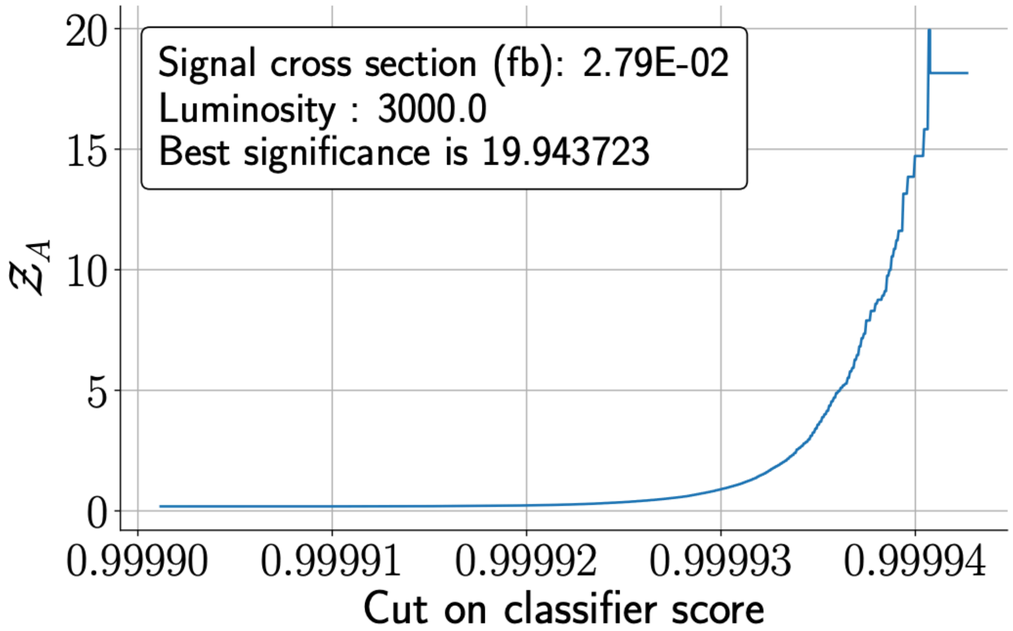
Since ε is expected to be arbitrary, the matching procedure can help reduce backgrounds for small values of ε.

Neural networks to separate signal and background and compute statistical significance following methods of [Adam Elwood and Dirk Krücker arXiv:1806.00322]

$M(j) > 15$ GeV and $\Delta M < 25$ GeV



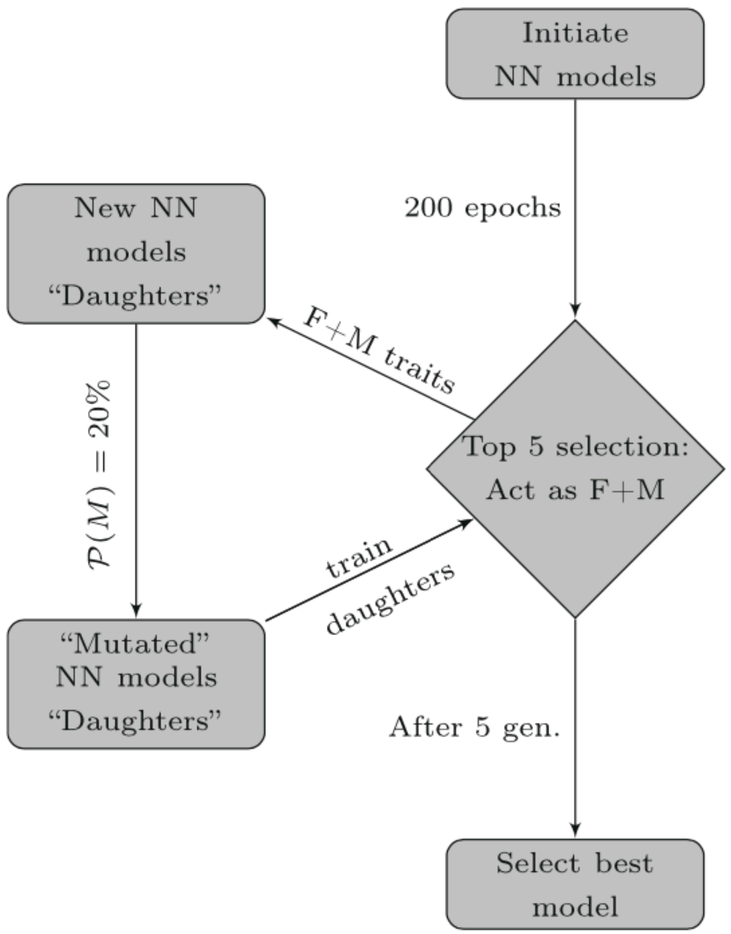
$M_{A2} = 215$ GeV/M_{H_2}= 400 GeV



$M_{A2} = 300$ GeV/M_{H_2}= 600 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.

The algorithm begins by first generating an arbitrary number of neural networks, whose architecture is determined by randomly pooling a list of predefined hyperparameters (number of layers, activation functions, regularisers, etc.). We then train each individual network over the data for a given number of epochs. From the trained networks, we pick the top five best performing ones. From these, we create Father–Mother pairs, where we combine 50% of the Father's traits (that is, its hyperparameters) and 50% of the Mother traits to construct new neural architectures, which we label as Daughters, first introduced in "Phenomenology of vector-like leptons with Deep Learning at the Large"



Conclusion

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

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 90.6% of the sampled points.

All points are consistent with existing LHC constrains for

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

We employing neural networks and shown that these type of topologies can be probed at the high-luminosity phase of the LHC.

Thank you very much!

Technical difficulties had to be faced:

- Random scans
- Limited knowledge of the domain in computer intelligence
- Limited computer resources

We have an input vector $X = [x_1, x_2, \ldots, x_n]$, where x_i are independent and their relation is not trivial

the main problem that arise is the randomly generated values that have a statistical acceptance rate of ~10%

Any ideas for more efficient scanning ?

Could we use regression models or other AI algorithms to by pass the pipelines?