Phenomenology of Multiscalar Models - why not Machine Learning?

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

Gr@v

Overview

- **Introduction to Machine Learning**
- **Physics Model**
- **Machine Learning in our model**
- **An overview of Machine Learning in Physics**

Based on Oxford Languages by Google

The definition of Machine Learning (ML) is: The use and development of computer systems that are able to learn and adapt without following explicit instructions, by using algorithms and statistical models to analyse and draw inferences from patterns in data.

The definition of Deep Learning (DL) is: A type of machine learning based on artificial neural networks in which multiple layers of processing are used to extract progressively higher level features from data.

If you are interested in ML or DL and you don’t know how to start join Kaggle [1]

Kaggle offers a no-setup, customizable, Jupyter Notebooks environment. Access GPUs at no cost to you and a huge repository of community published data & code. (There are also courses for beginners)

The most known example of DL is the discrimination of pictures that have cats & dogs

If you are interested to try it, try the example of Kaggle [2] (Keras Convolutional neural network-CNN)

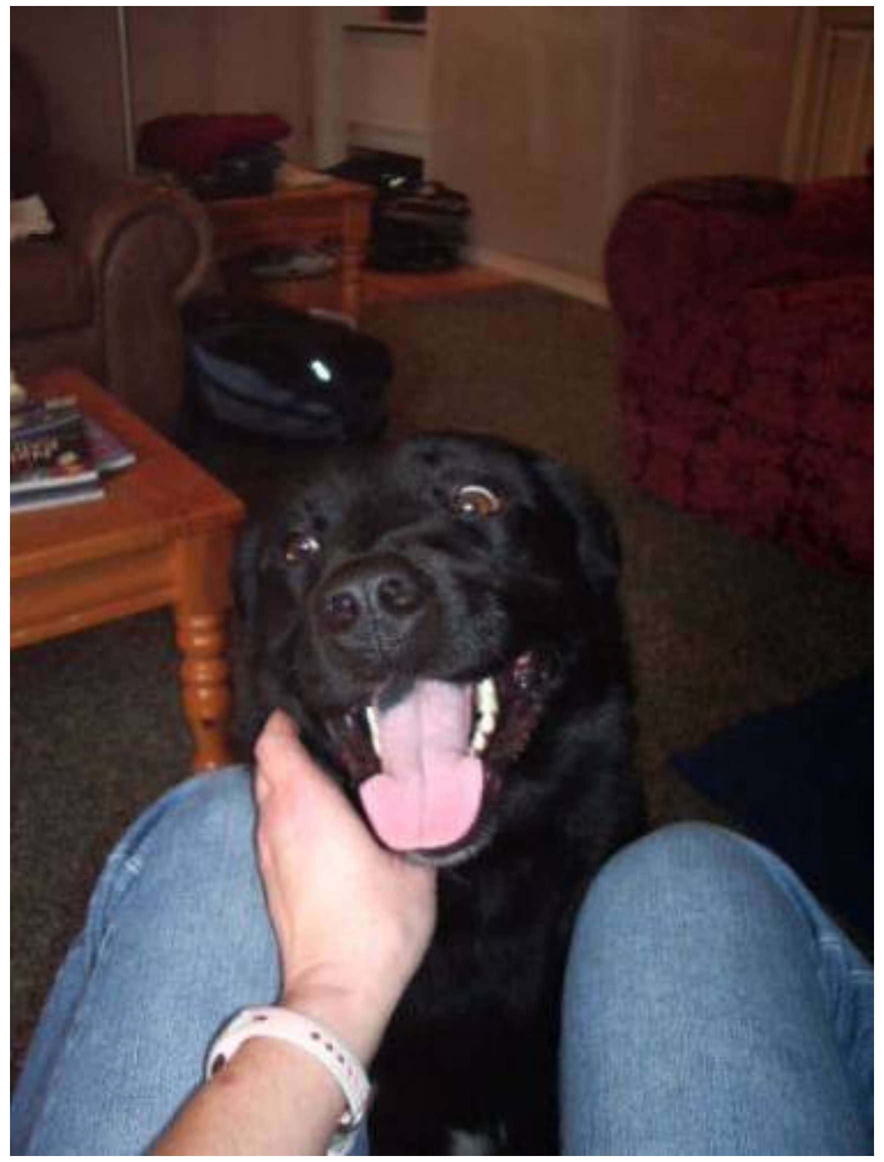
The main idea is that we build a neural network (NN) and we train it with images of cats and dogs. Then we use another set of images that are unknown to the neural network and we measure its success in the discrimination between cats and dogs.

In the example in Kaggle, the NN had an average score of 94.6% Success rate

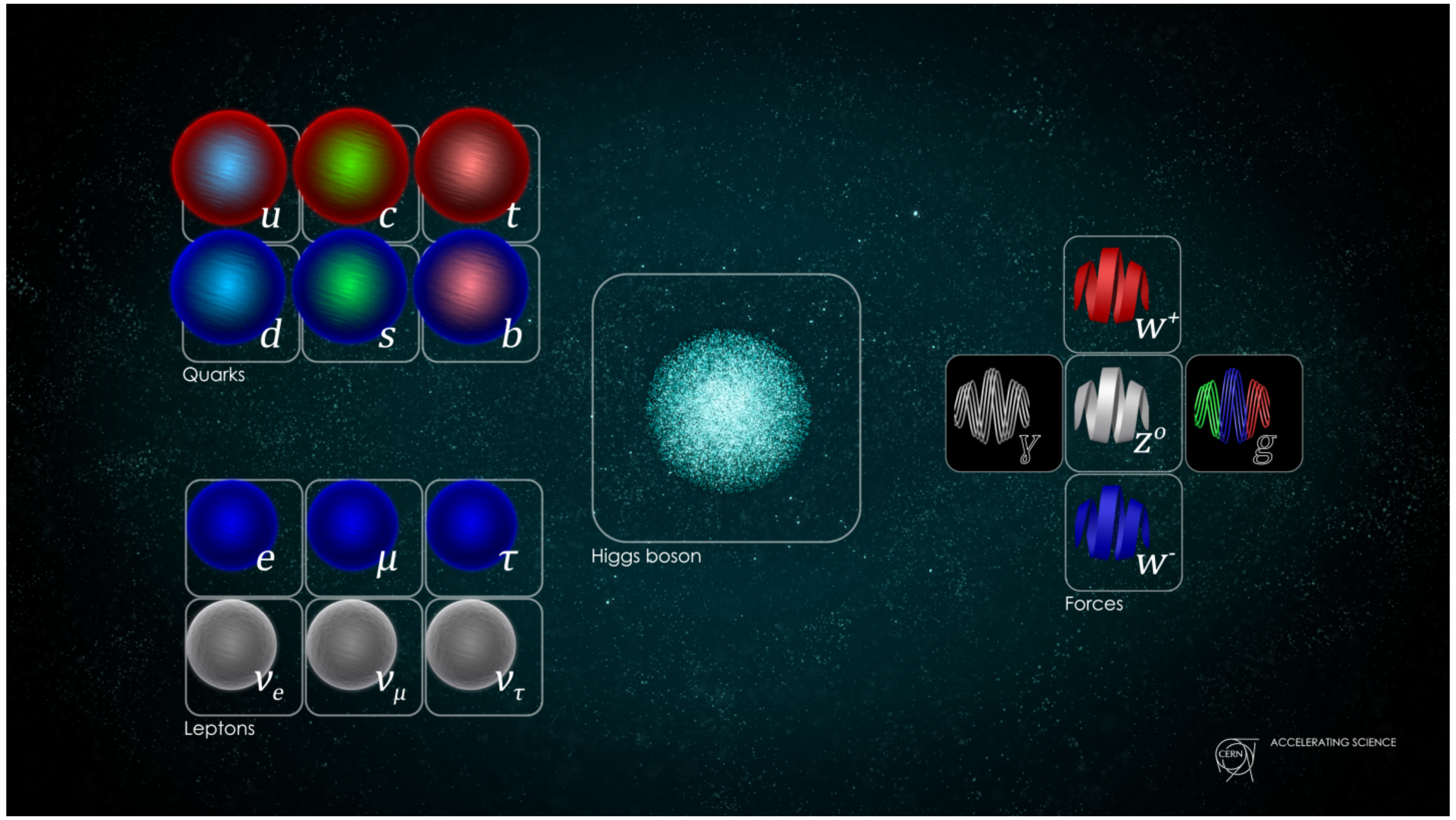
Cat

Dog ?

Dog



The Standard Model (SM)



The Picture is take from CERN web page [3]

Physics Model

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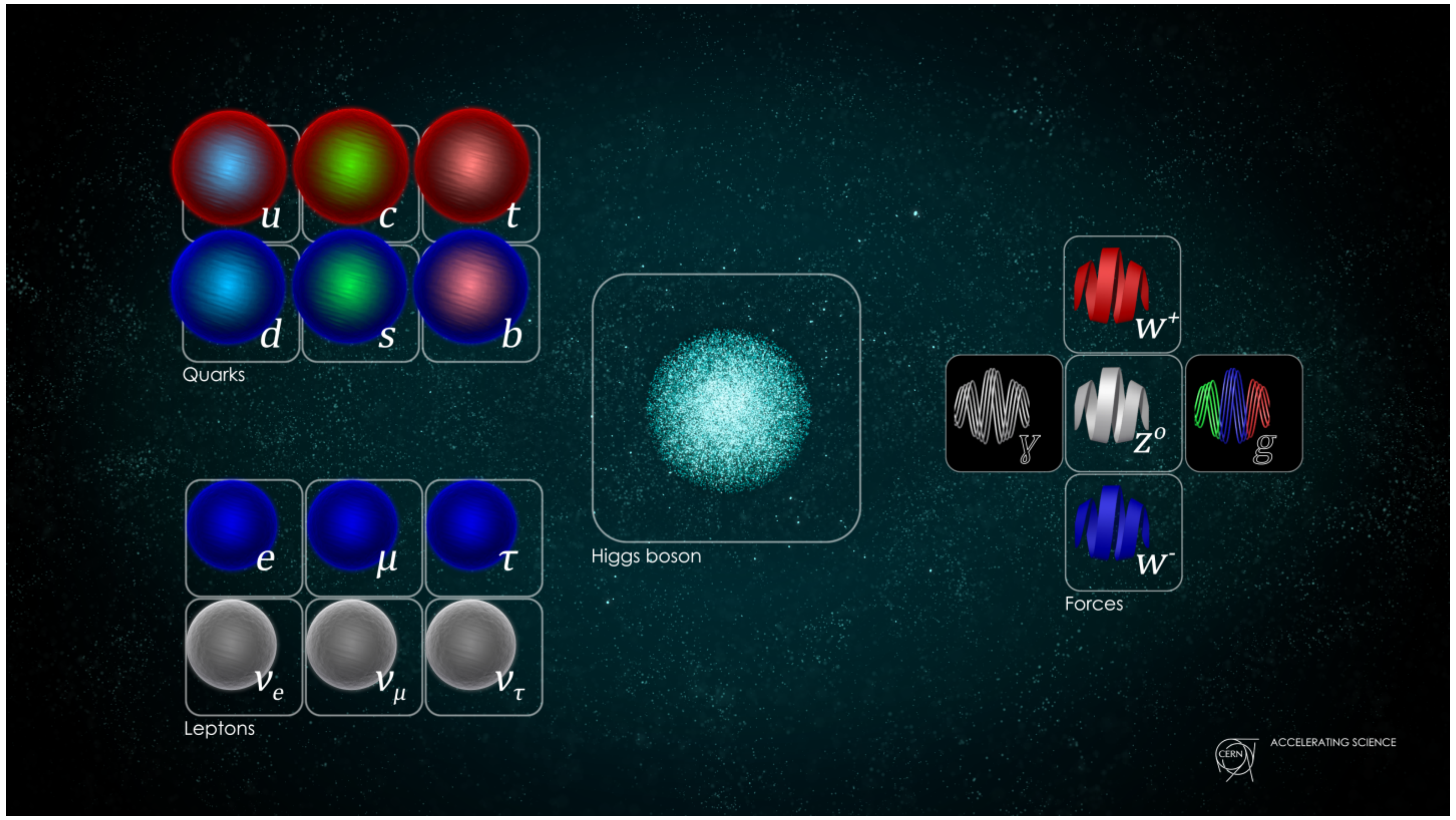

Inconsistencies → No Gravity in SM

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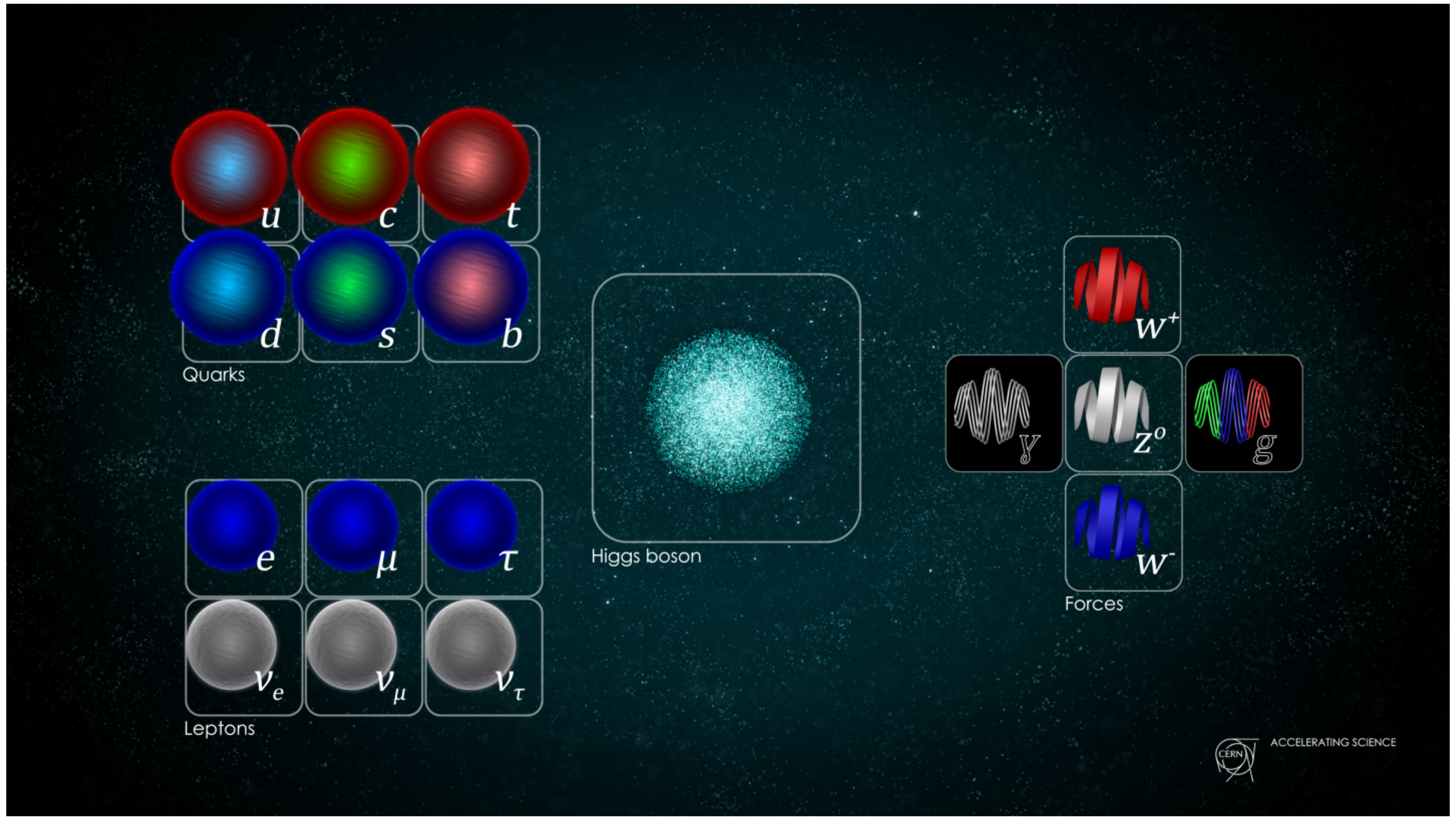

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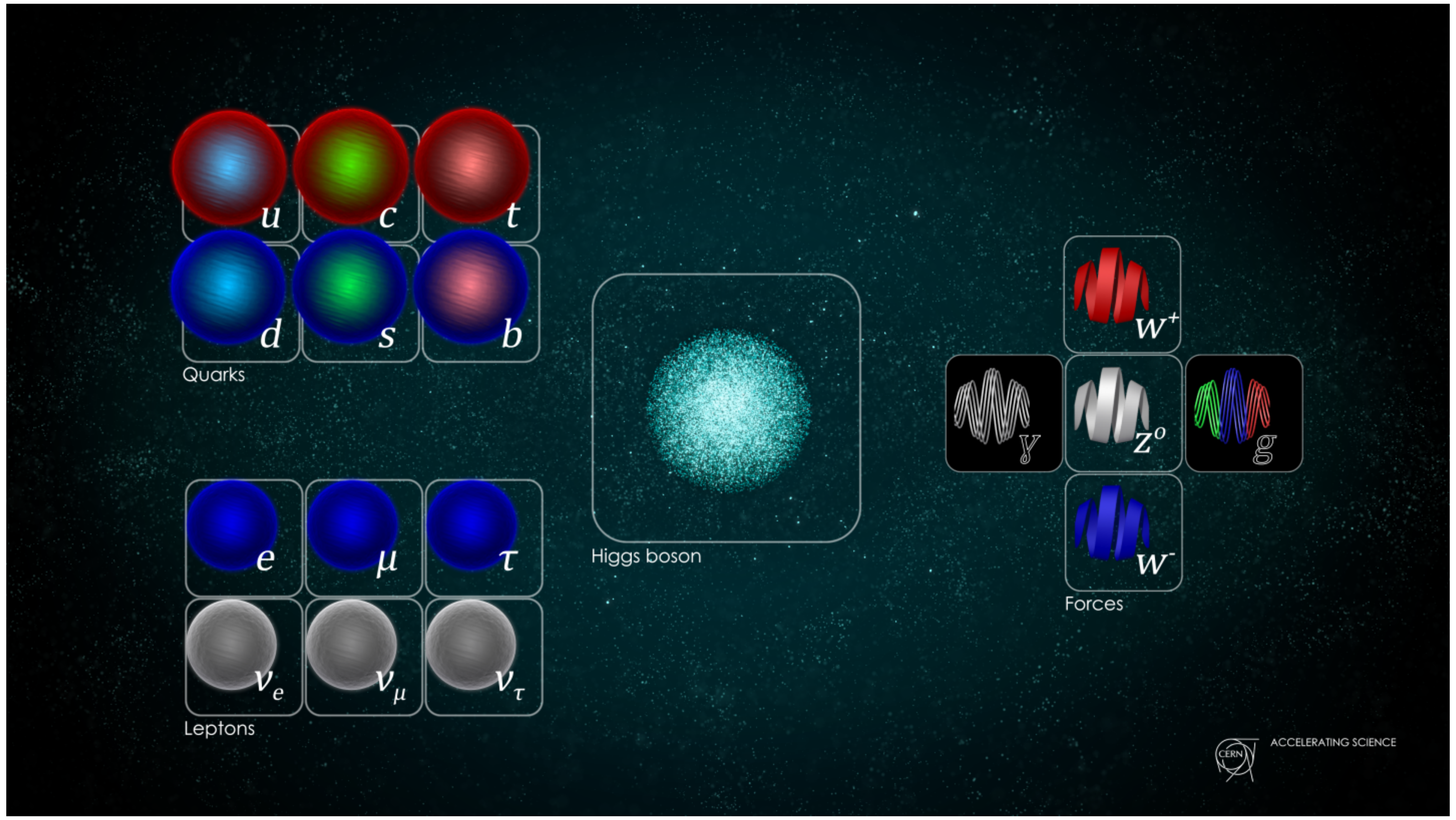

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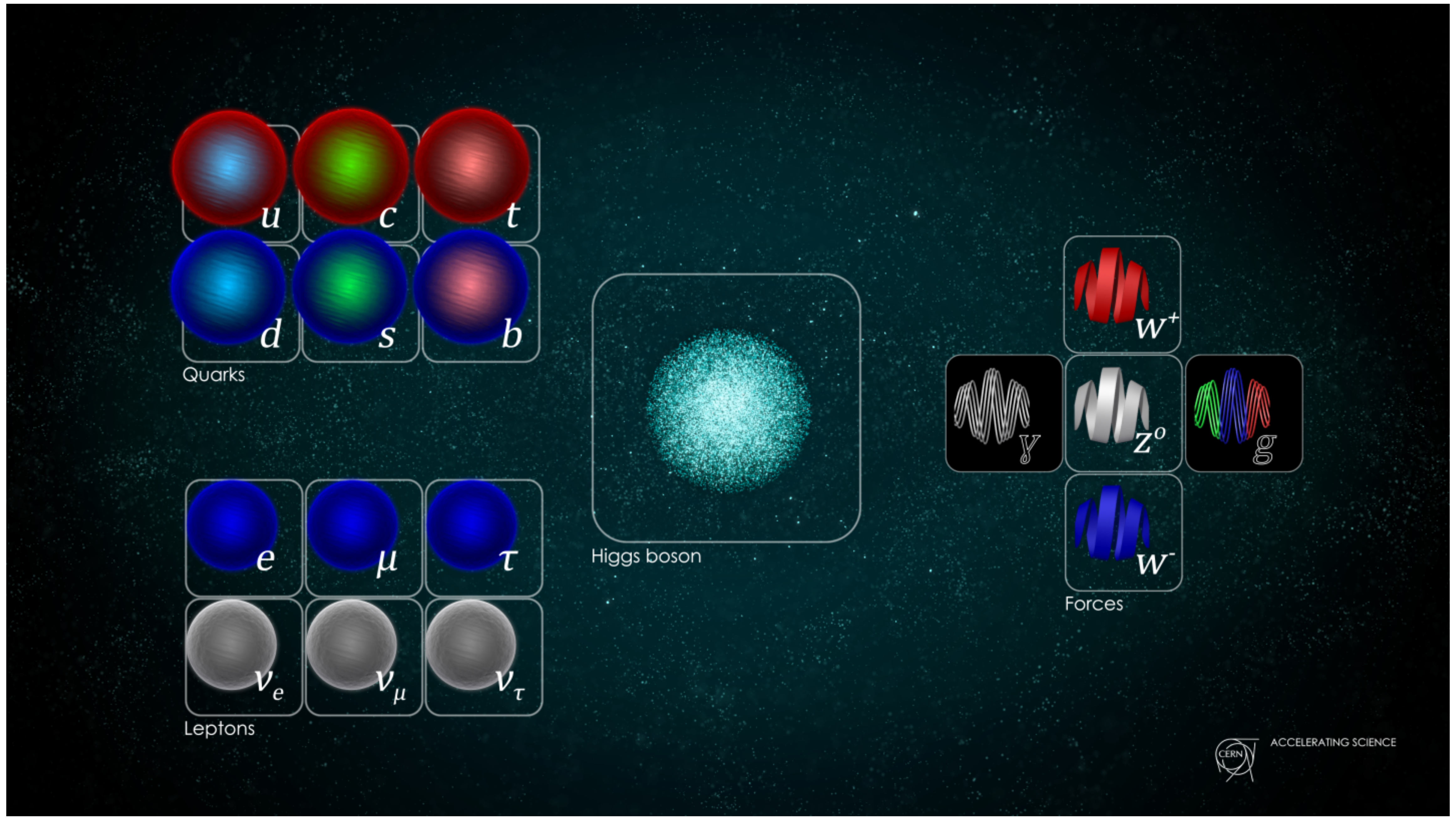

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Baryon Asymmetry

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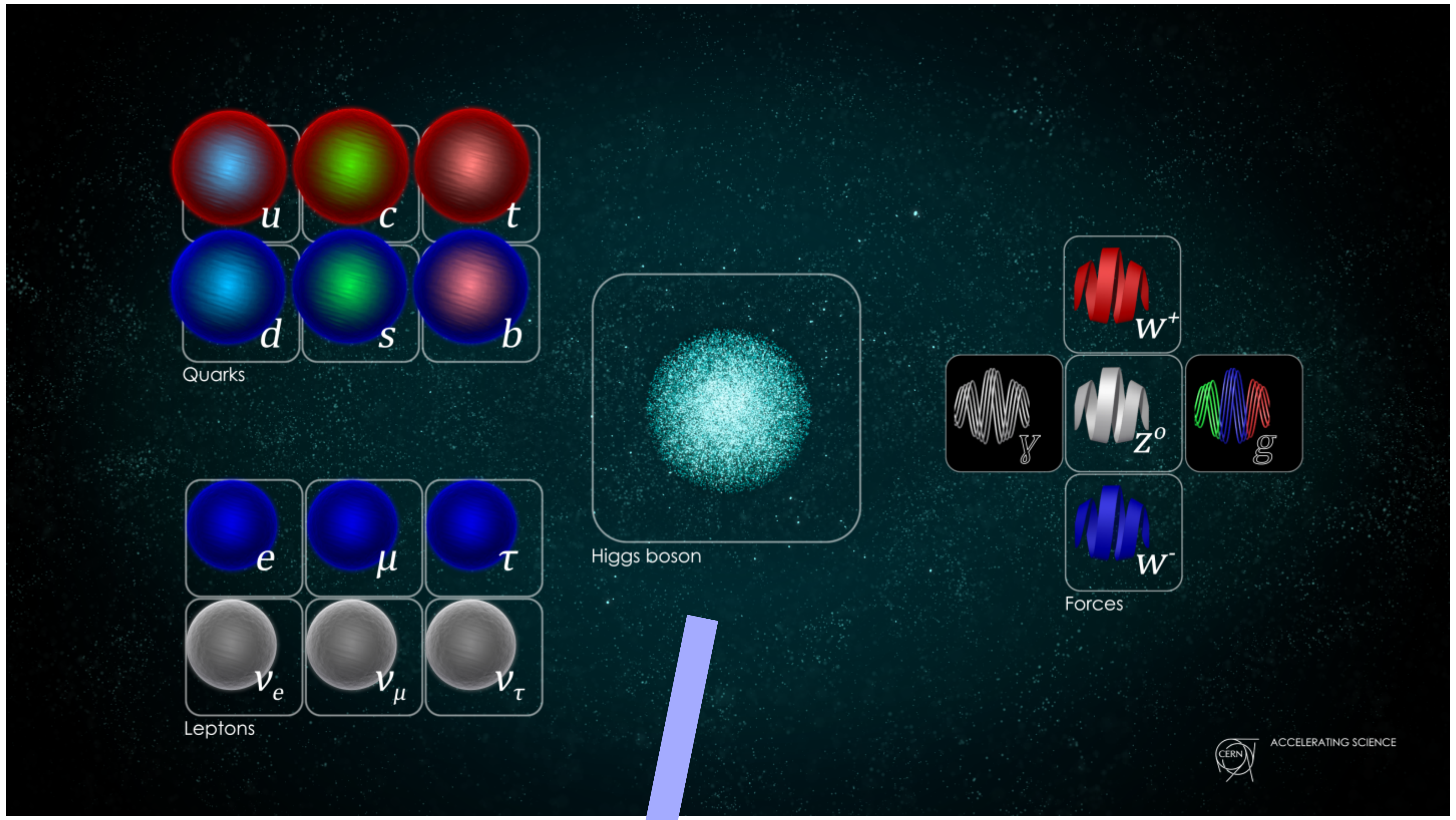

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Baryon Asymmetry

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

H_2 A $H^{\pm}$

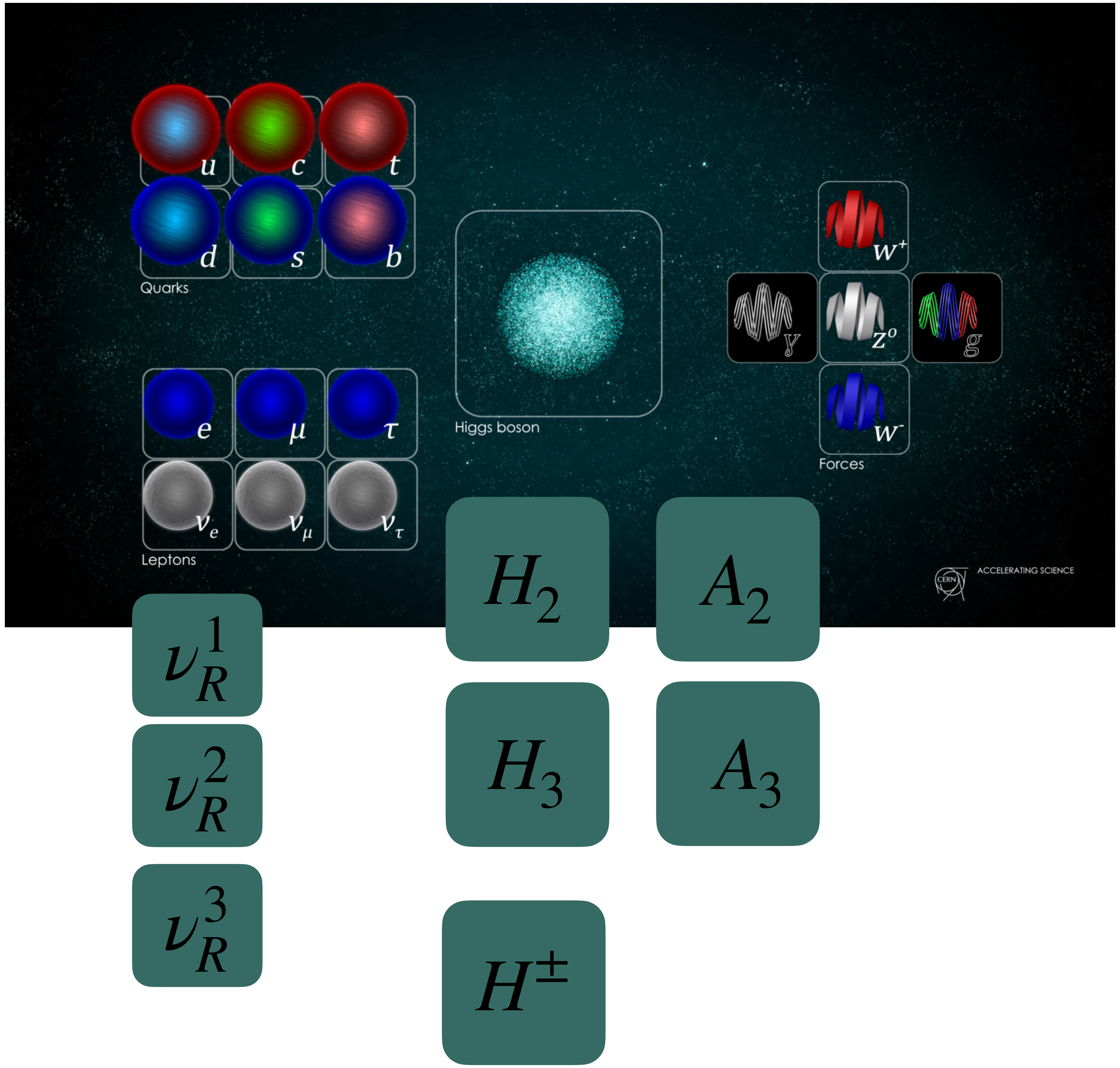
A generic Next-to-Minimal Two Higgs Doublet Model (NTHDM) with a BGL structure [4]

An Standard Model (SM) extension with:

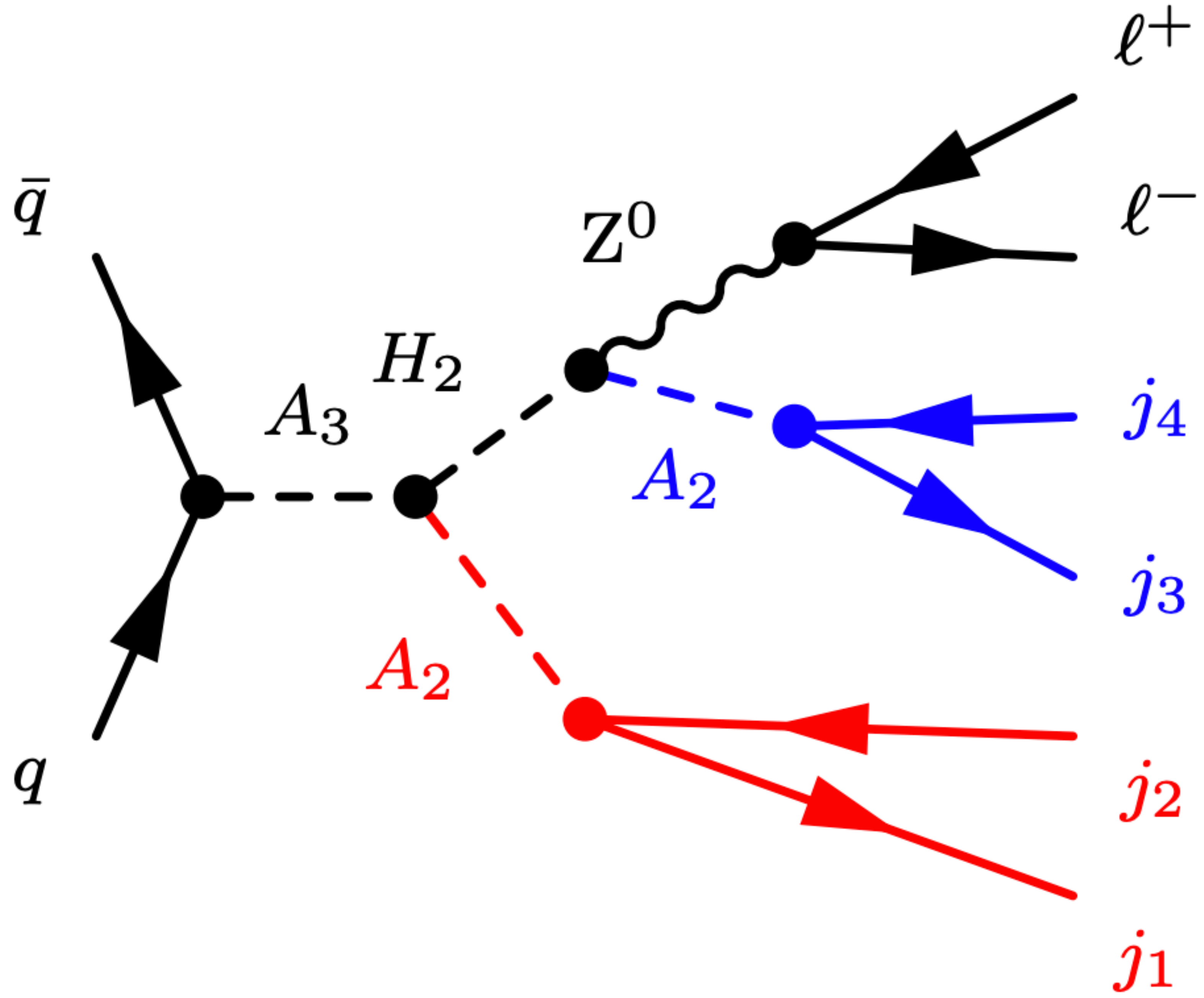
- a flavour non-universal $U(1)'$ global symmetry,
- a second Higgs Doublet Φ_2,
- a scalar singlet S
- three generations of right-handed neutrinos $\nu_R^{1,2,3}$, with a type-I seesaw mechanism

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

Physics Model



Interesting topology



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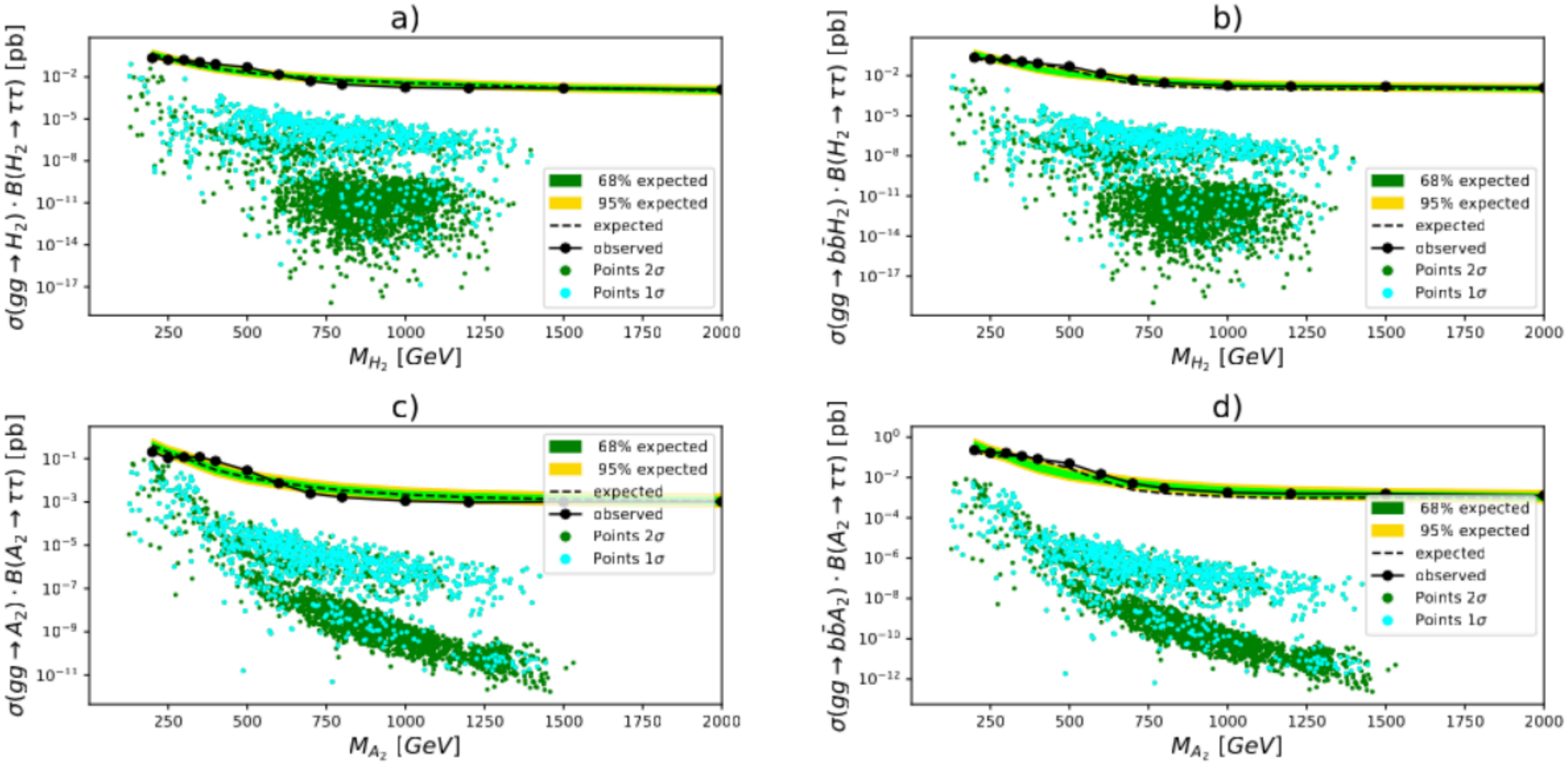

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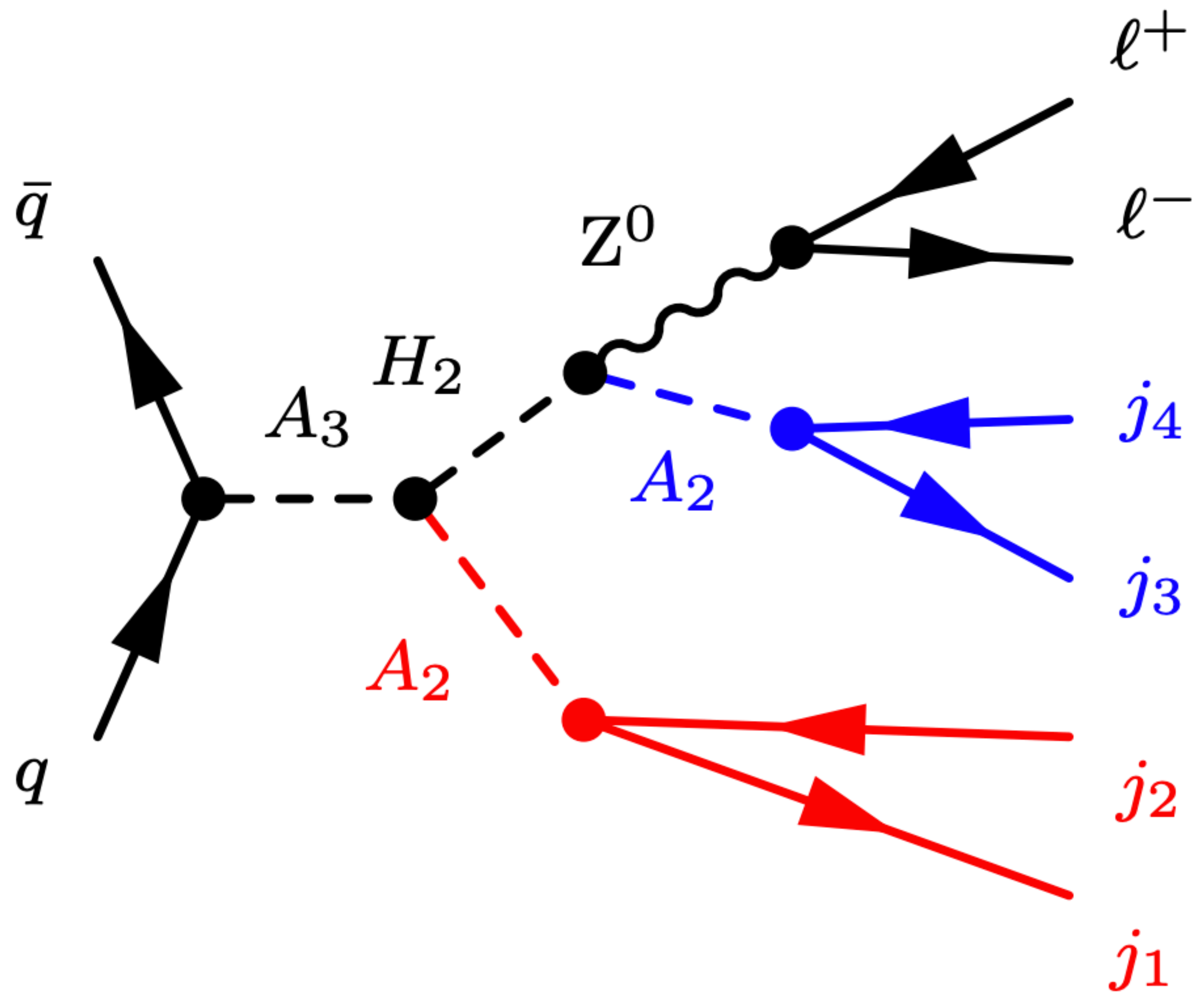


- Mass information can be use to match pairs of jets to original scalars fields
- $\Delta M = M(j_1, j_2) - M(j_3, j_4) < \varepsilon$
  - **Signal:** small ε
  - **Background** Arbitrary ε
- Loop over all possible combinations of jets and select the pairs with smallest ε

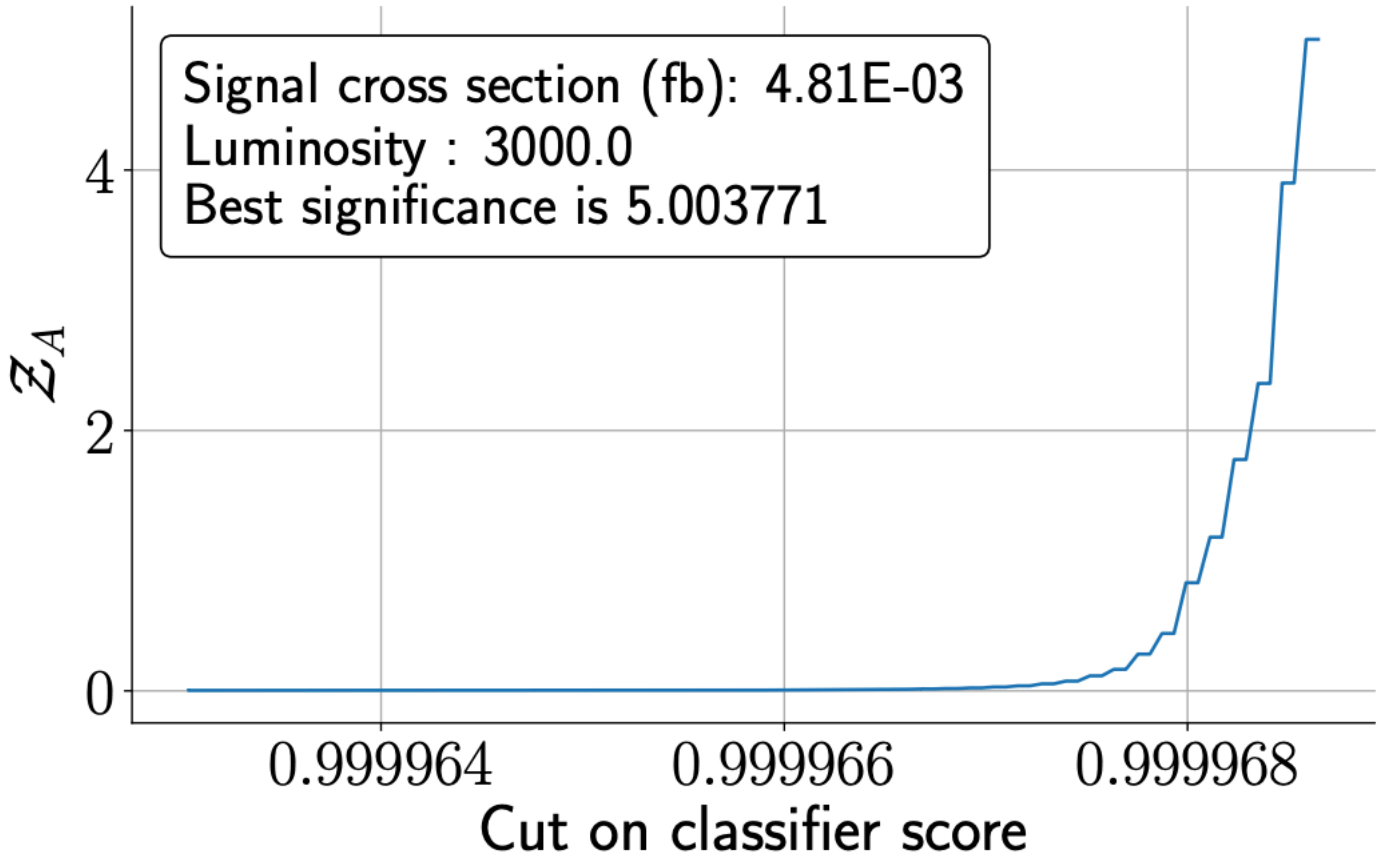
Match jets to H_2 scalar: $min(|M(j_n, j_m) - M(Z^0) - M(H_2)|)$

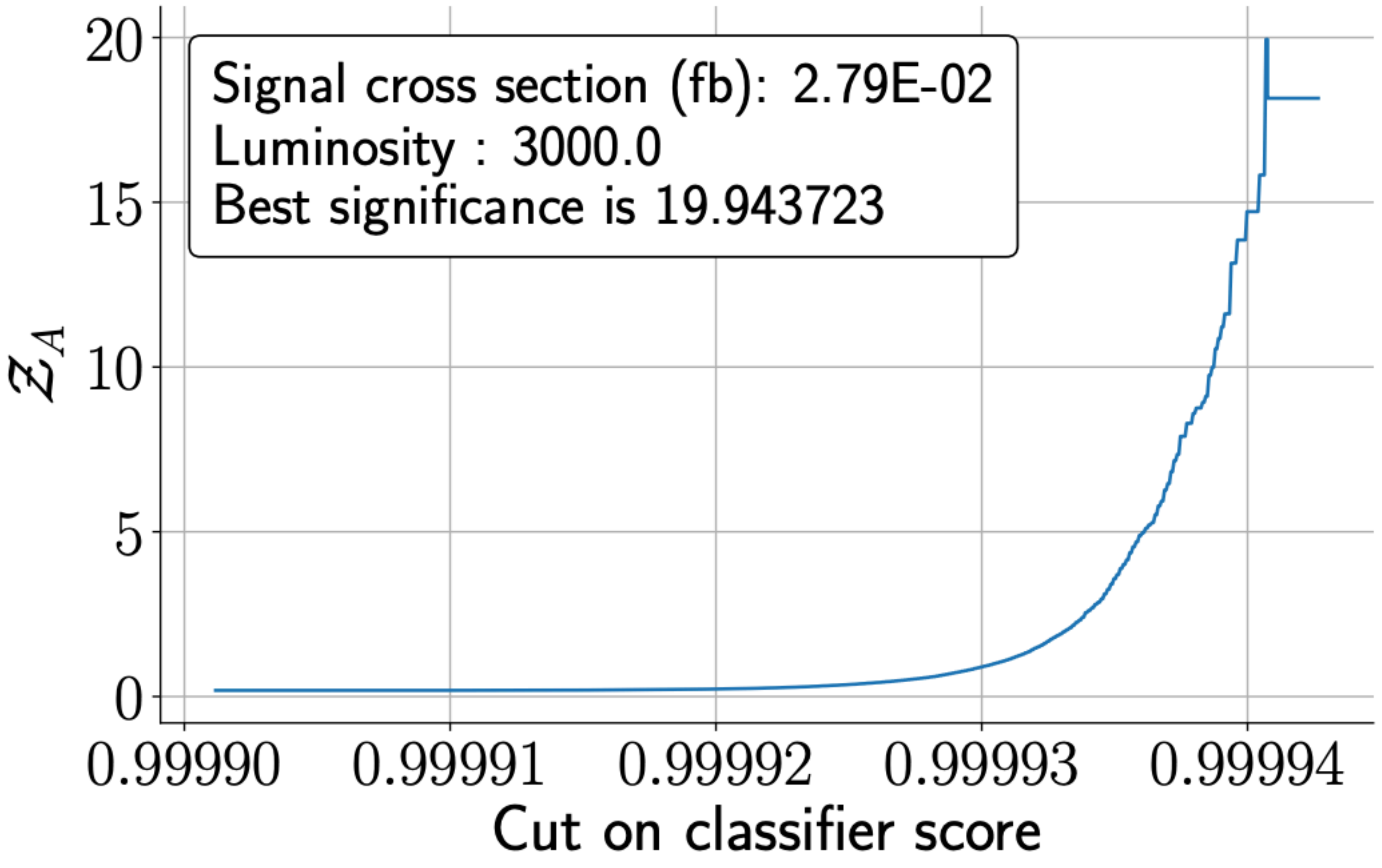
If the minimum is for pair (j_3, j_4), then this is matched to the blue leg and the pair (j_1, j_2) is matched to the red leg.

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

Machine Learning in our model

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





$M(j) > 10$ GeV and $\Delta M < 35$ 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.

What can ML do in Particle Physics?

The use of neural networks for discrimination of images is very efficient, as we so in the example of Cats vs Dogs.

Also, neural networks are very good in the separation of signal and background.

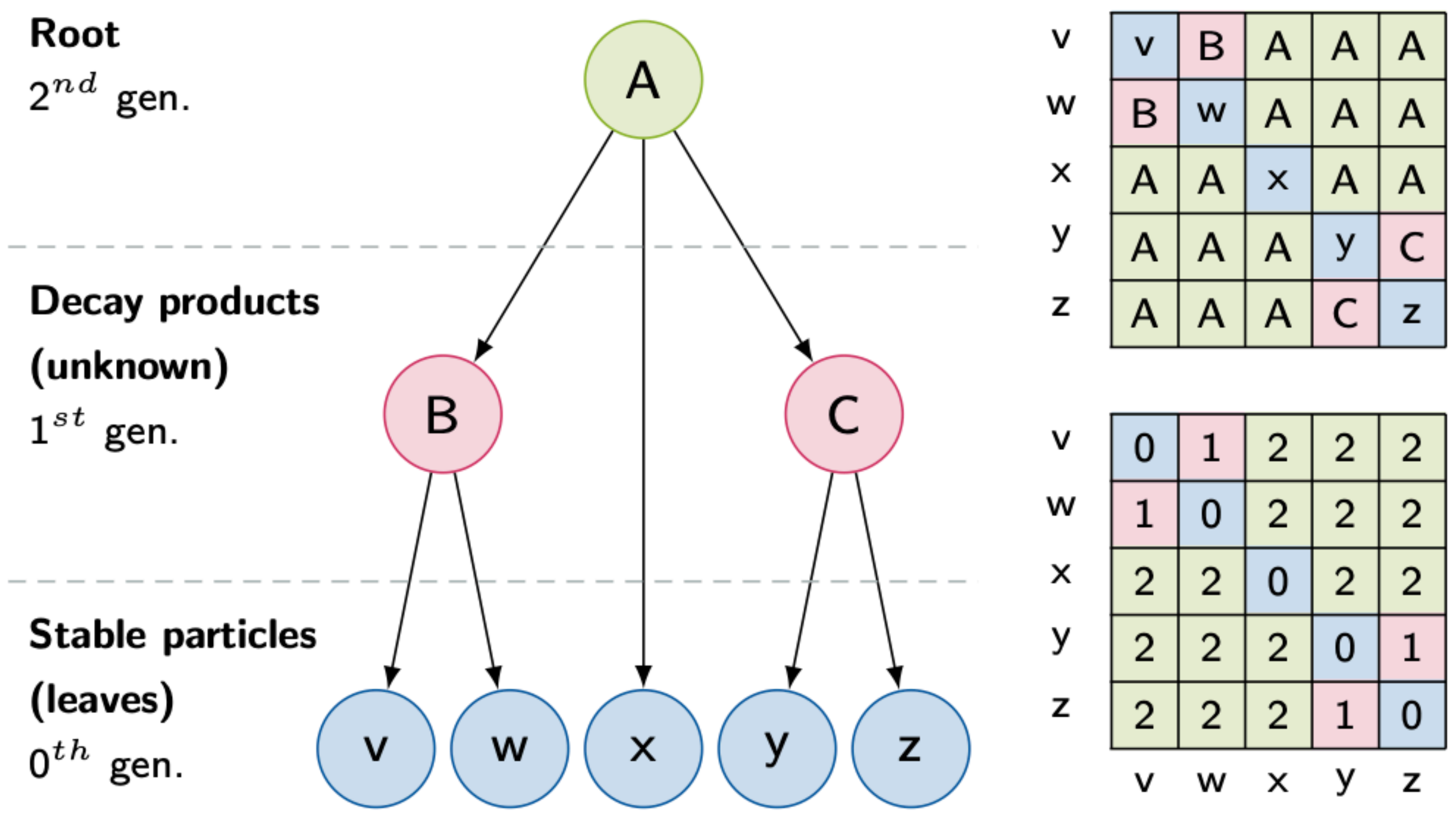
Except of our work, another example is : Phenomenology at the Large Hadron Collider with Deep Learning: the case of vector-like quarks decaying to light jets [5], and many other where we use NN to separate signal from background.

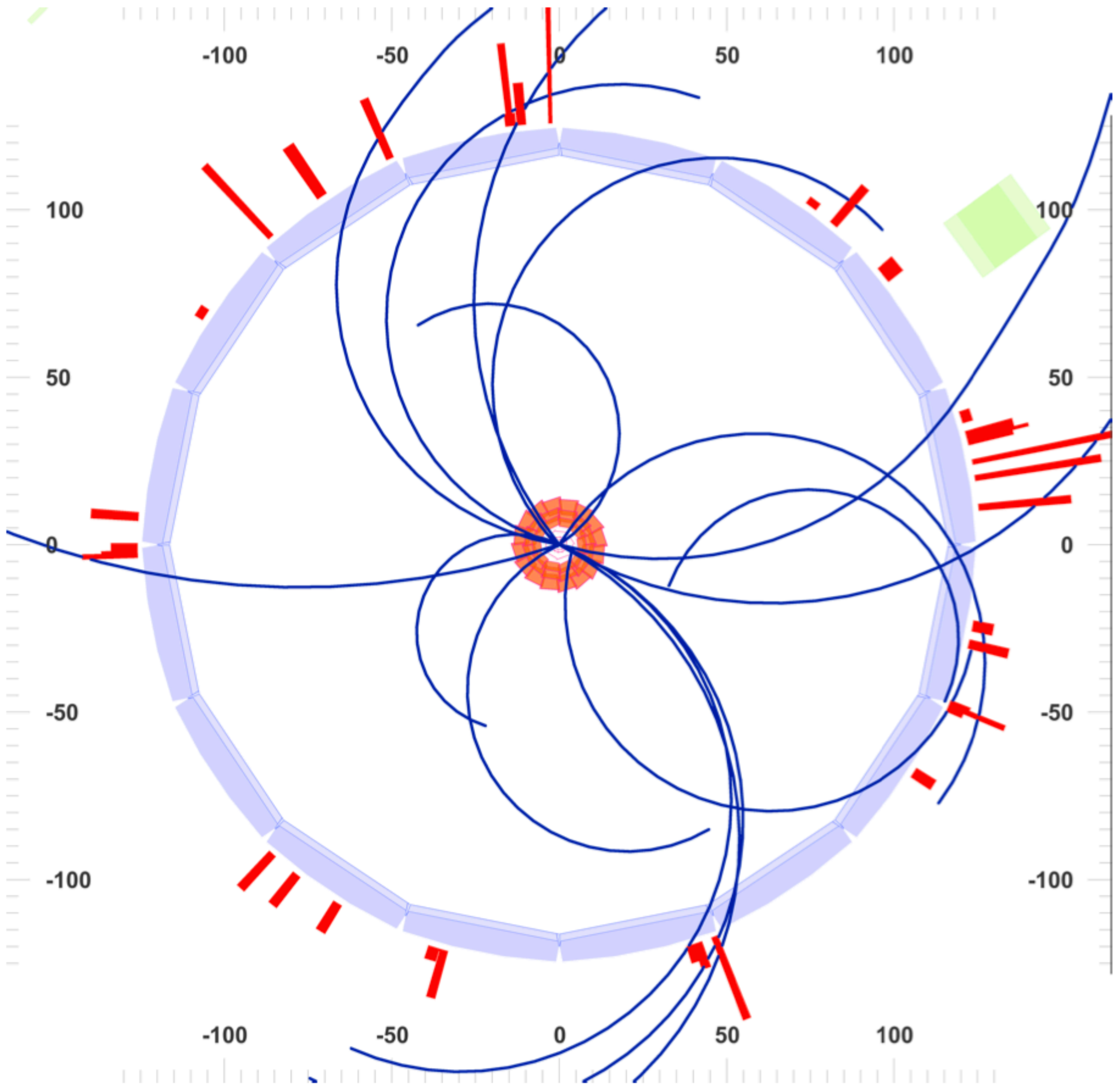
But is ML only good to do discrimination between signal and background?

Overview of Machine Learning in Physics

In the resent work (Published 14 September 2022): Learning tree structures from leaves for particle decay reconstruction [6]

Their results show that when selecting an appropriate Graph Neural Network (GNN), in this case the Neural Relational Inference (NRI) encoder, the network is able to correctly predict the lowest common ancestor generations (LCAG) matrix for 92.5% of decay trees up to 6 leaves

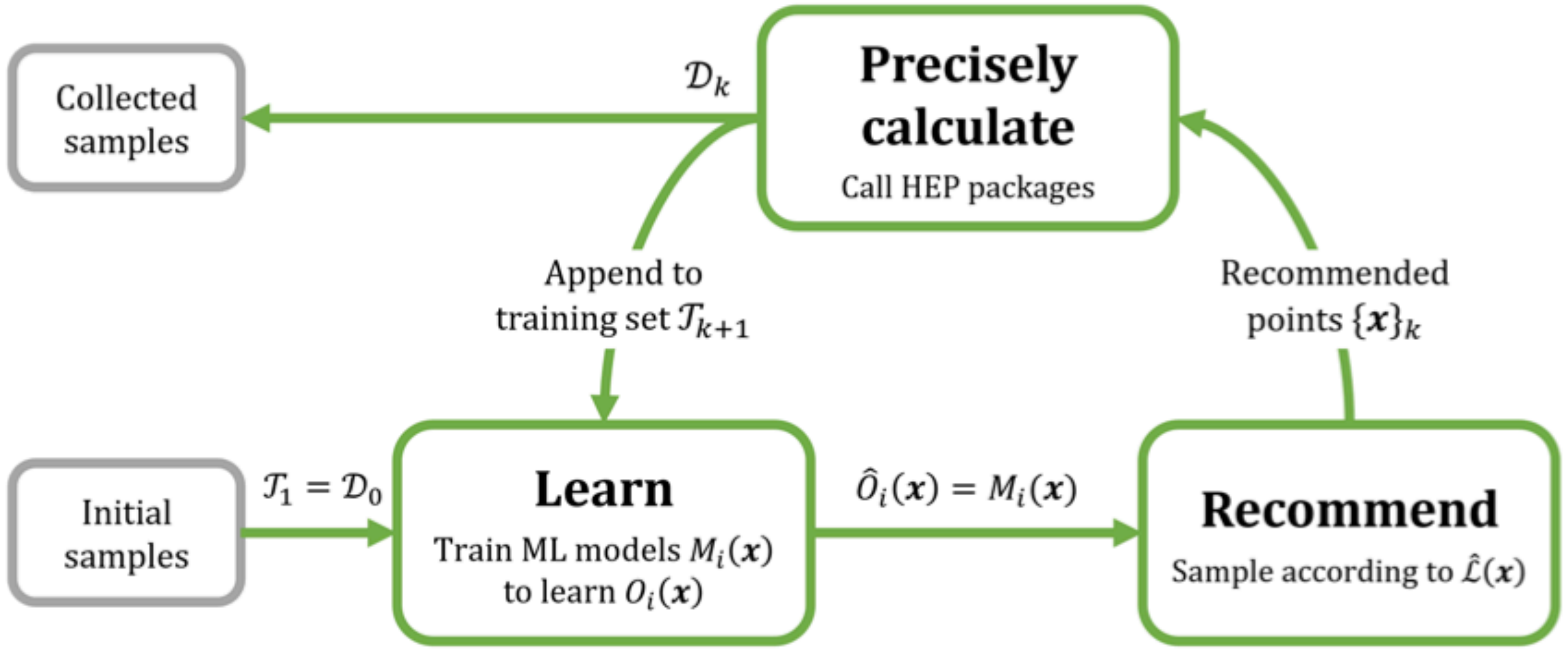




Overview of Machine Learning in Physics

An other interesting use of ML this time for theoretical particle physics is explored in: Exploring Supersymmetry with machine learning [7]

They propose a self-exploration method, named Machine Learning Scan (MLS), to achieve an efficient test of models.



The MLS works iteratively. First, train machine learning models using the already collected samples as training data. Then, sample the important regions according to the reconstructed likelihood. Next, calculate observables of the recommended points using HEP packages, and append these samples to the training set to improve the machine learning models in the next iteration. The procedure repeats until sufficient target samples are collected.

Conclusion

ML can be a powerful tool and used for different approaches (theoretical physics, experimental physics, phenomenology)

It can be time and sources efficient.

Currently, ML is rising and we are trying to explore new ways that we can use that powerful tool.

Thank you very much!

Backup slides

Physics Model

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

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

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

Physics Model

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)

Physics Model

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.

Physics Model

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

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

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

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 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$y \neq 4x$.

Physics Model

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

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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

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) <u>STU</u>: 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.

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

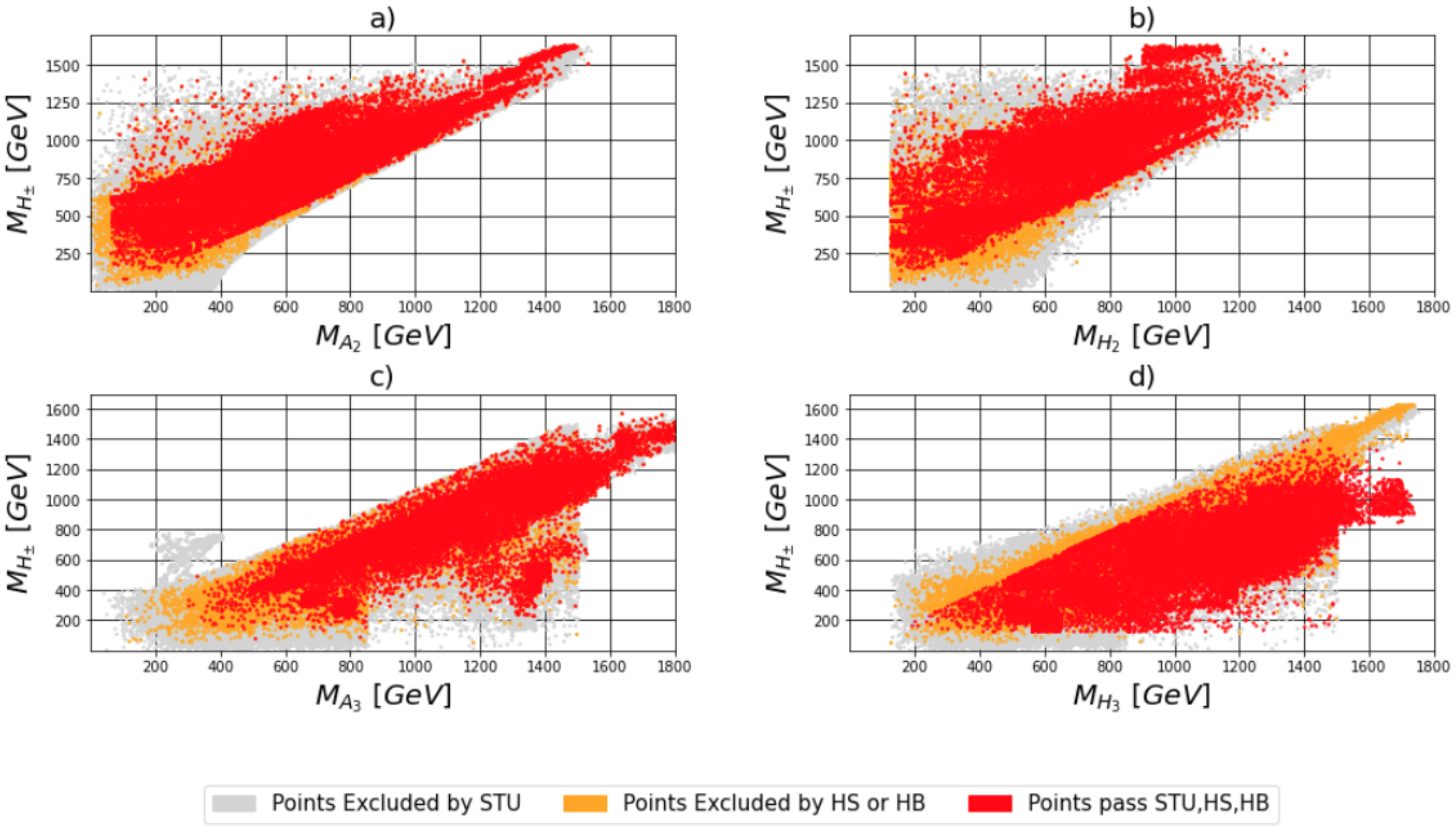
Were we require $\Delta x^2 < 7.815$, which is translated to 95% confidence level (CL) agreement with the electroweak fit.

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

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

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

Results

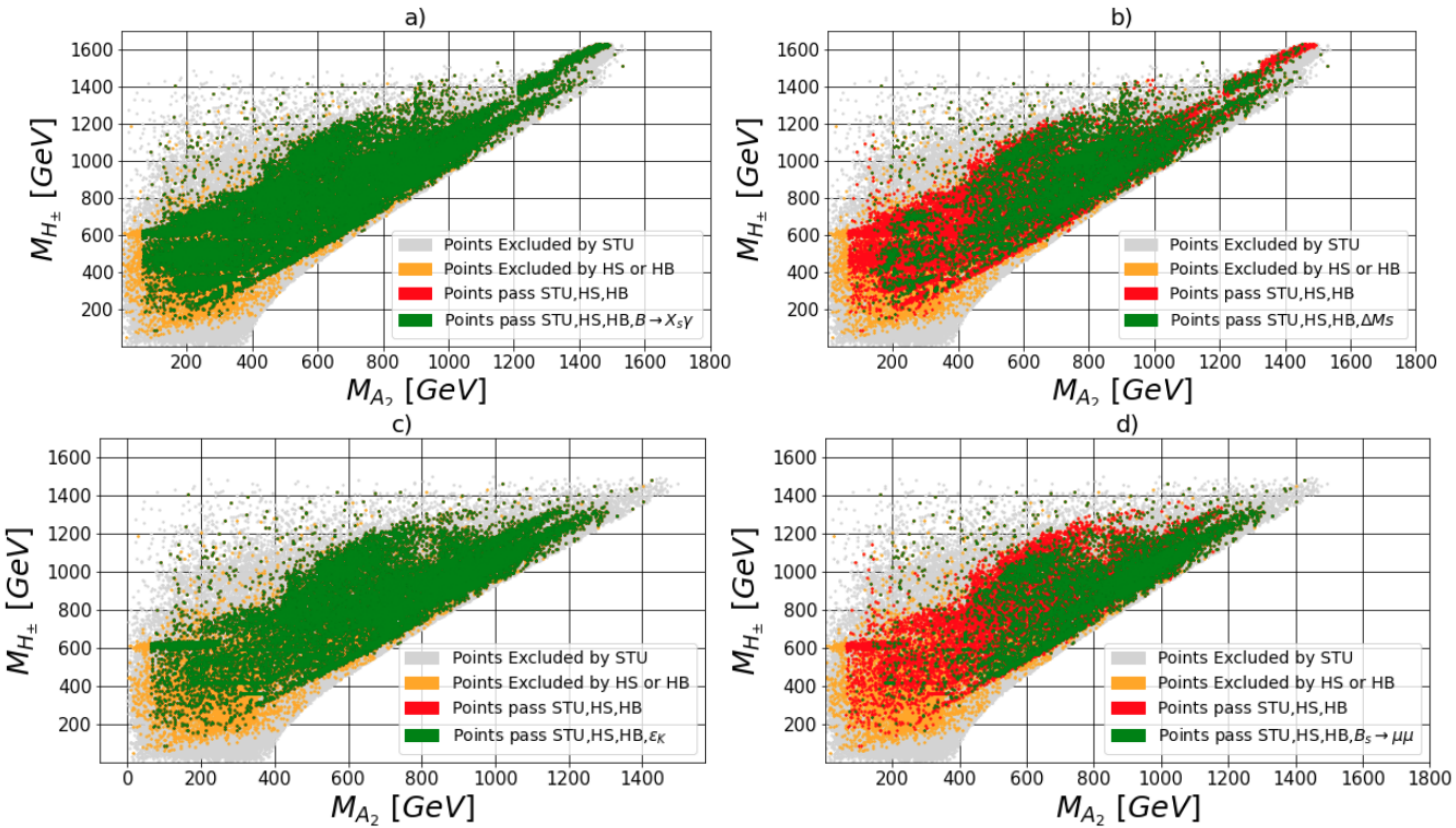


a)
b)
c)
d)
$M_{H^\pm}$ [GeV]
M_{A_2} [GeV]
M_{H_2} [GeV]
M_{A_3} [GeV]
M_{H_3} [GeV]
Points Excluded by STU
Points Excluded by HS or HB
Points pass STU,HS,HB

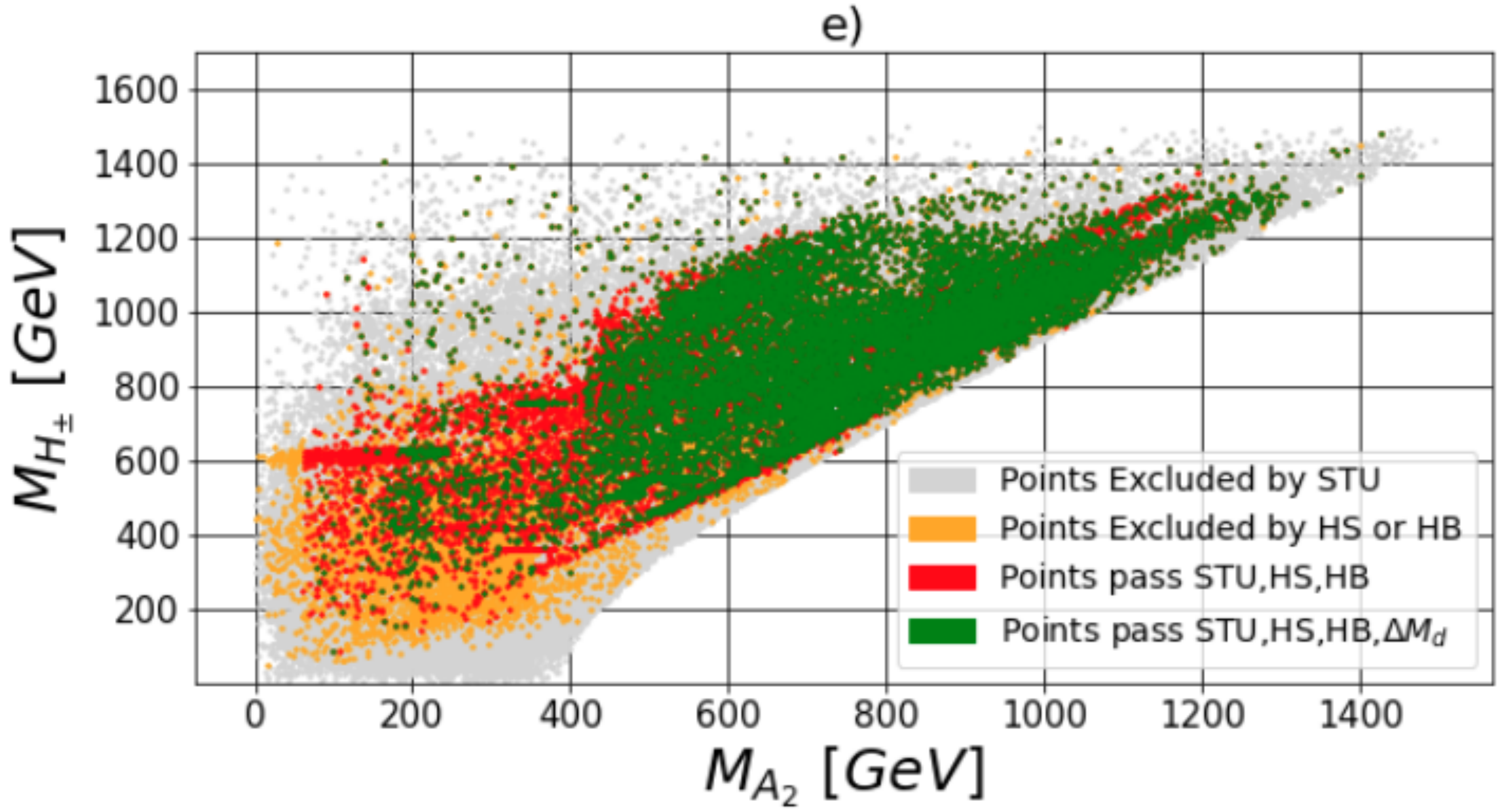
3) For the Quark Flavour Violation (QFV) observables we have only take into consideration the most relevant channels summarised in the table below.

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]
0
200
400
600
800
1000
1200
1400
1600
1800
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%

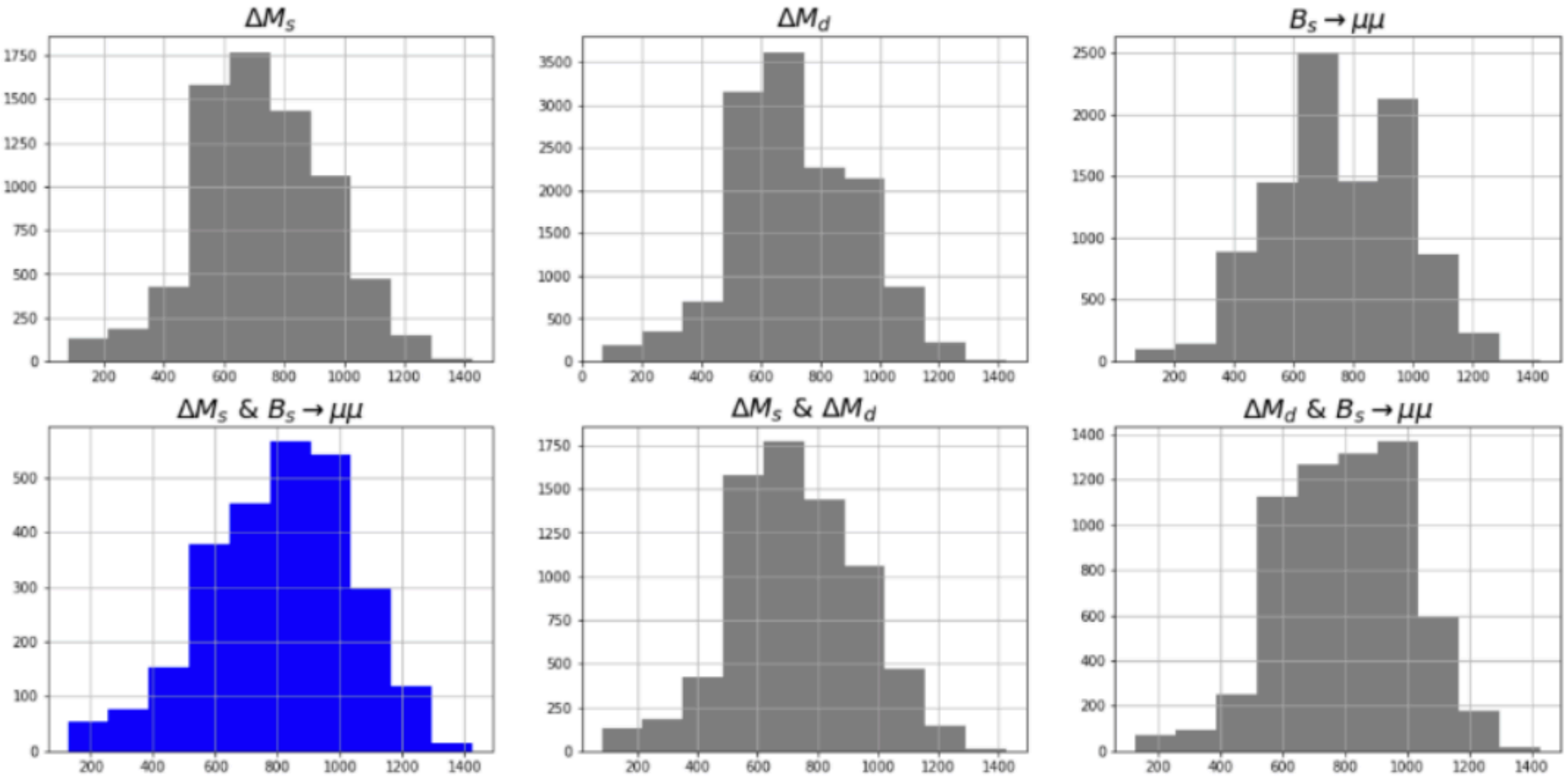
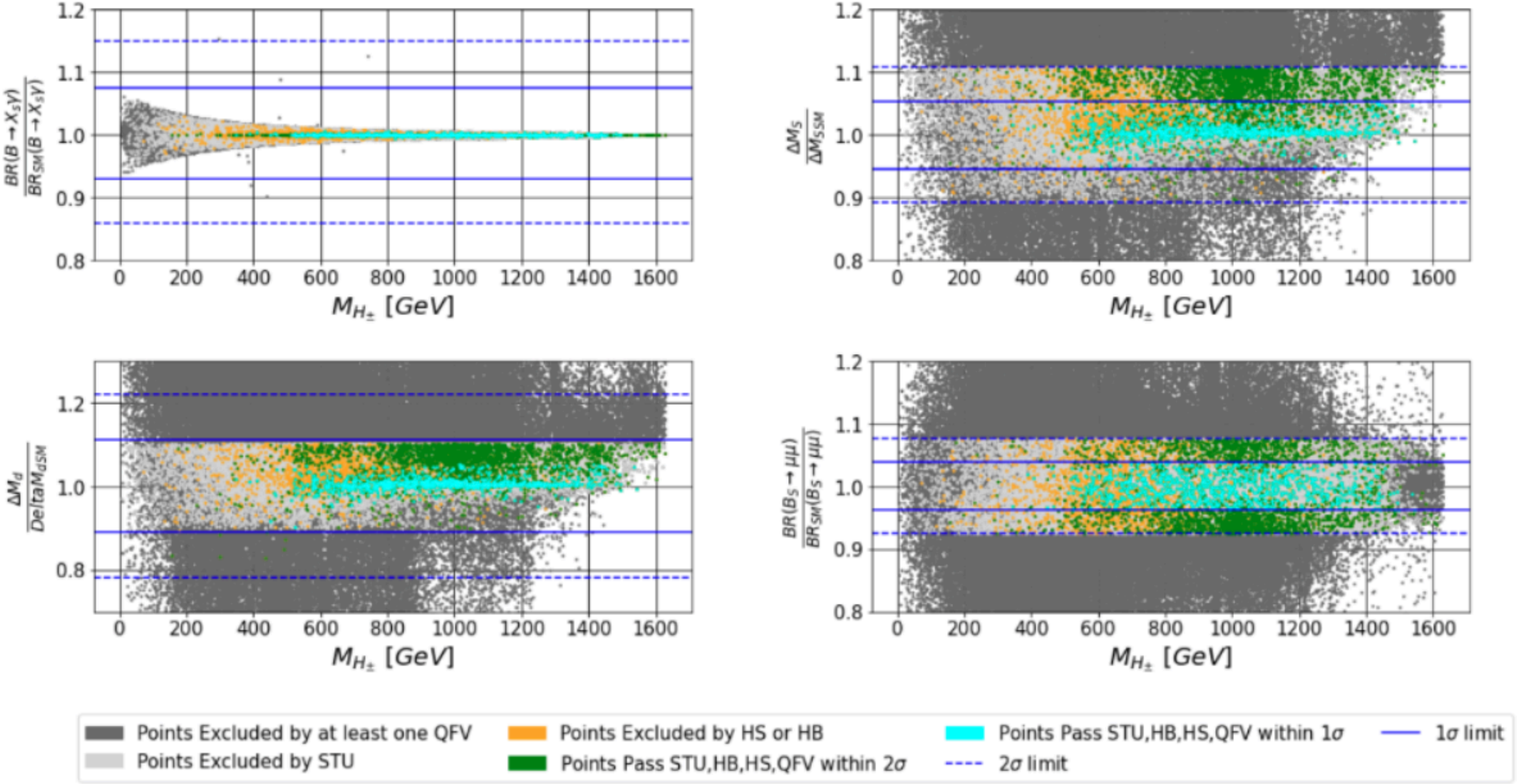


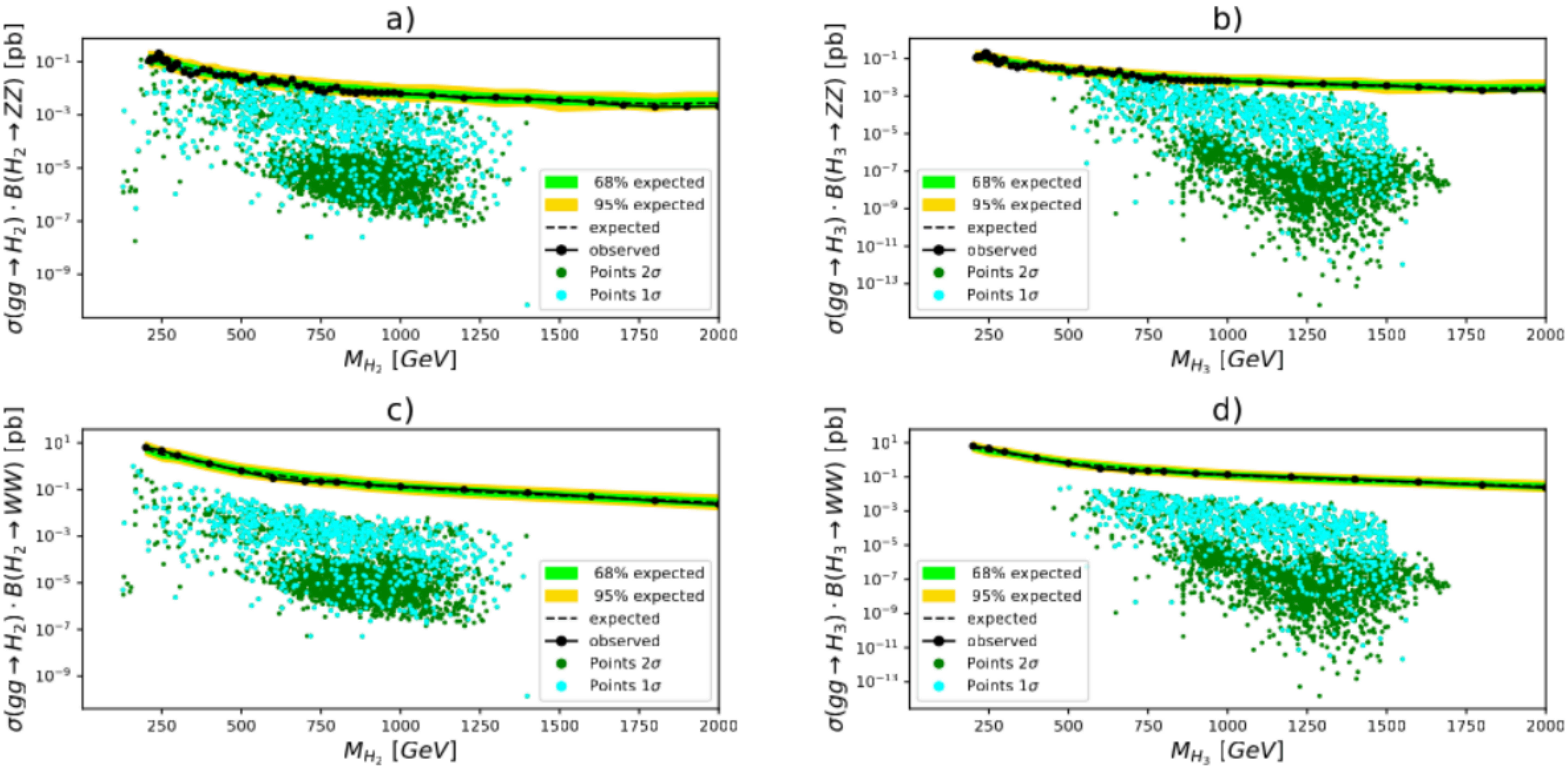
Figure 5: Histograms containing points that survive STU, HS, HB and a given QFV (or pair of) in bins of the A_2 mass. The most restrictive is coloured in *blue*.

Results



1.2
1.1
1.0
0.9
0.8
0
200
400
600
800
1000
1200
1400
1600
$M_{H_\pm}$ [GeV]
$\frac{BR(B \to X_S \gamma)}{BR_{SM}(B \to X_S \gamma)}$
$\frac{\Delta M_S}{\Delta M_{SSM}}$
$\frac{\Delta M_d}{DeltaM_{dSM}}$
$\frac{BR(B_S \to \mu\mu)}{BR_{SM}(B_S \to \mu\mu)}$
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)
$\sigma(gg \to H_2) \cdot B(H_2 \to ZZ)$ [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
250
500
750
1000
1250
1500
1750
2000