General Extensions of the Standard Model

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General extensions

- The Standard Model has to be extended
- The experimental evidence does not tell us which model is correct

- We would like to have a model independent approach
- Not just a parametrization but a QFT that extends the SM in a general and systematic way:

   1. Effective field theory with the fields and symmetries of the SM
   2. Addition of new particles that couple to the SM ones

Effective field theory approach

- Add new gauge invariant operators to the Standard Model lagrangian
- Decoupling scenario
- They will be non-renormalizable (dim. > 4)
- They are organized according to their dimension

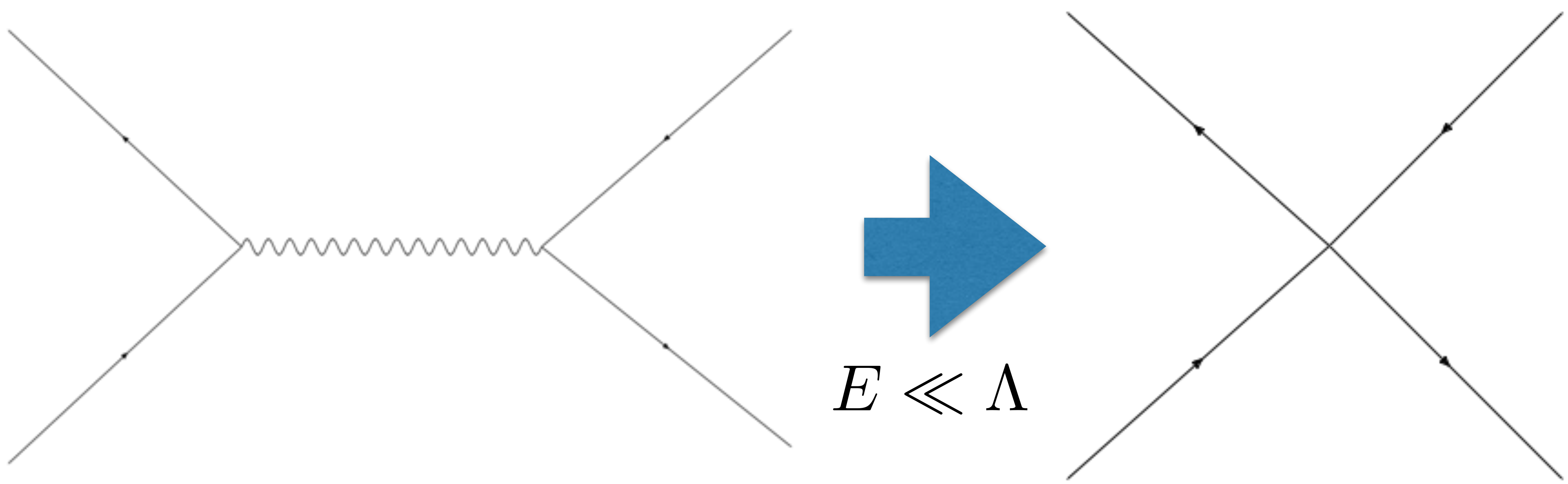
$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{\alpha}{\Lambda^{n-4}} \mathcal{O}^{(n)}$$

In a process with energy E the contribution from an operator of dimension n is $\sim (E/\Lambda)^{n-4}$

Disadvantage of EFT extensions

Range of validity: energies lower than the cutoff

It does not take into account production of new particles



$E \ll \Lambda$

New particles

Study the ones that couple linearly to SM:
- Leading contribution to SM interactions
- Decays determined these terms
- Simple production

SM fields

SM symmetries

Renormalizability

Operators formed by SM fields and one new field: $\mathcal{O} = \phi\mathcal{O}_{SM}$

All possible representations of new fields coupling linearly to SM

Example: vector-like quarks

- Fourth generation is excluded by experiments
- Vector-like fermions have mass terms:

$$\mathcal{L}_{mass} = M\left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L\right)$$

- Renormalizability and gauge invariance then gives 7 possibilities for vector-like quarks:

$$T \sim \mathbf{1}_{2/3} \quad B \sim \mathbf{1}_{-1/3} \quad \begin{pmatrix} X \\ T \end{pmatrix} \sim \mathbf{2}_{7/6} \quad \begin{pmatrix} T \\ B \end{pmatrix} \sim \mathbf{2}_{1/6}$$

$$\begin{pmatrix} X \\ T \\ B \end{pmatrix} \sim \mathbf{3}_{2/3} \quad \begin{pmatrix} T \\ B \\ Y \end{pmatrix} \sim \mathbf{3}_{-1/3} \quad \begin{pmatrix} B \\ Y \end{pmatrix} \sim \mathbf{2}_{-5/6}$$

Example: vector-like quarks

- T and B mix with the SM quarks with the same quantum numbers: {u,c,t} and {d,s,b}

- Experiments on the light generations tell us that the mixing is small with them. The coupling with the heavy generation can be bigger

- We can write the most general lagrangian for these fields and study the phenomenology:

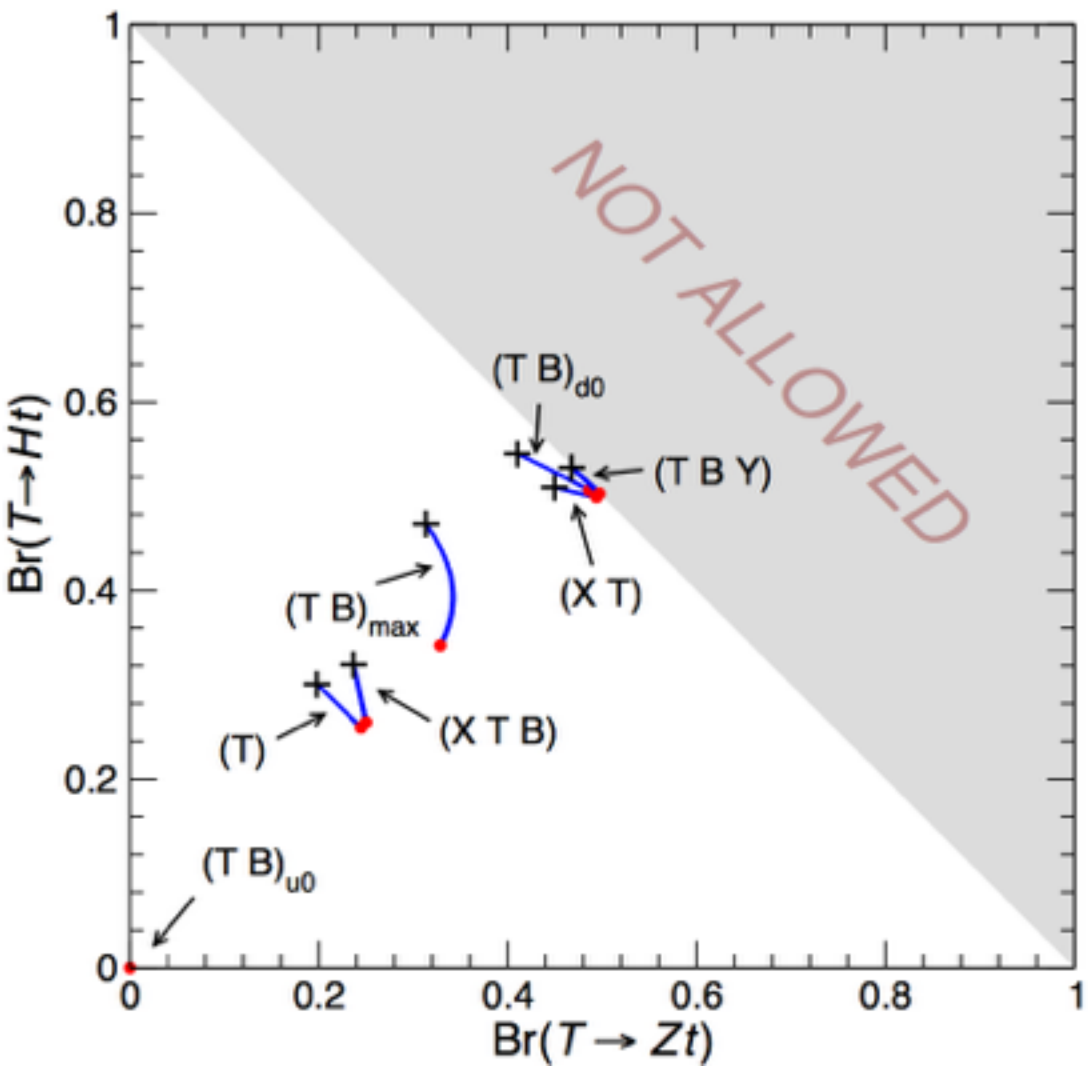
    1. Production: There is always double production from a gluon. Single production due to mixing.

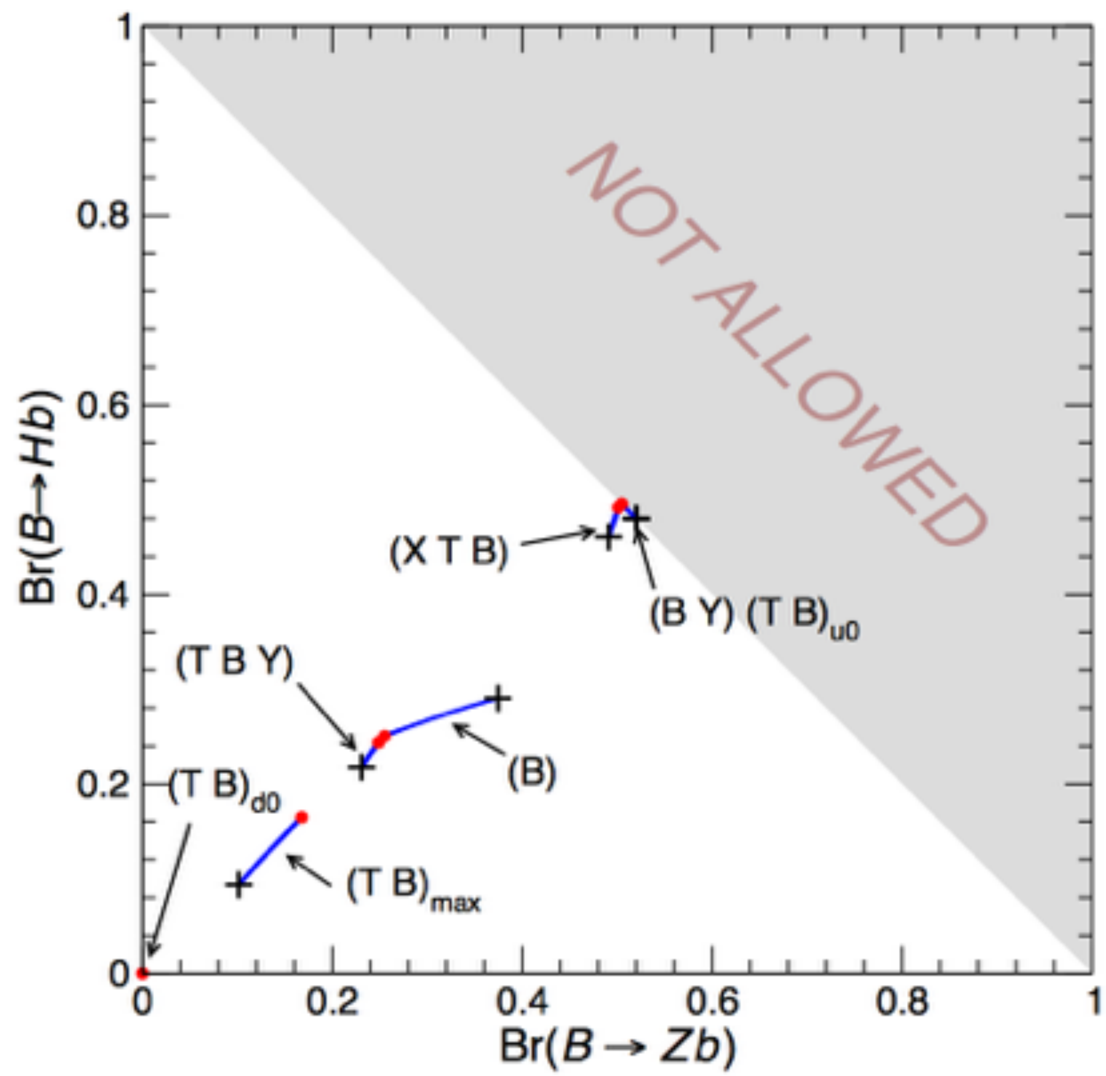
    2. Decays: Branching ratios depend basically on quantum numbers.

Example: vector-like quarks

$\mathrm{Br}\,(T \to Ht) + \mathrm{Br}\,(T \to Zt) + \mathrm{Br}\,\left(T \to W^{+}b\right) = 1$

$\mathrm{Br}\,(B \to Hb) + \mathrm{Br}\,(B \to Zb) + \mathrm{Br}\,\left(B \to W^{-}t\right) = 1$





• $m_Q = 2\,\mathrm{TeV}$ + $m_Q = m_{Q,min}$

More general: EFT with new particles

- Contribution of non-renormalizable operator of dimension n>4: $\sim (E/\Lambda)^{n-4}$
- Importance decreases with dimension (reduce to a finite number of operators by imposing a maximum dimension)
- Corrections to particles that couple through renormalizable operators too
- Leading contributions when considering particles that only have non-renormalizable interactions

All new quarks coupling linearly to SM through operators of arbitrary dimension

Obtain every representation of a new quark Q that couples to the SM like $\bar{Q}\mathcal{O}_{SM}$

All representations of combinations of SM fields that are color triplets

Representations of dimension D under SU(2) and hypercharge Y under U(1)

$\mathbf{D}_Y$ with $Y \in \begin{cases} \mathbb{Z} + 2/3 & \text{if } \mathbf{D} \in 2\mathbb{N}+1 \\ \mathbb{Z} + 1/6 & \text{if } \mathbf{D} \in 2\mathbb{N} \end{cases}$

Example: heavy quarks with dimension 5 interactions

Heavy quarks multiplets:

$$X \sim \mathbf{1}_{5/3} \qquad T \sim \mathbf{1}_{2/3} \qquad B \sim \mathbf{1}_{-1/3} \qquad Y \sim \mathbf{1}_{-4/3}$$

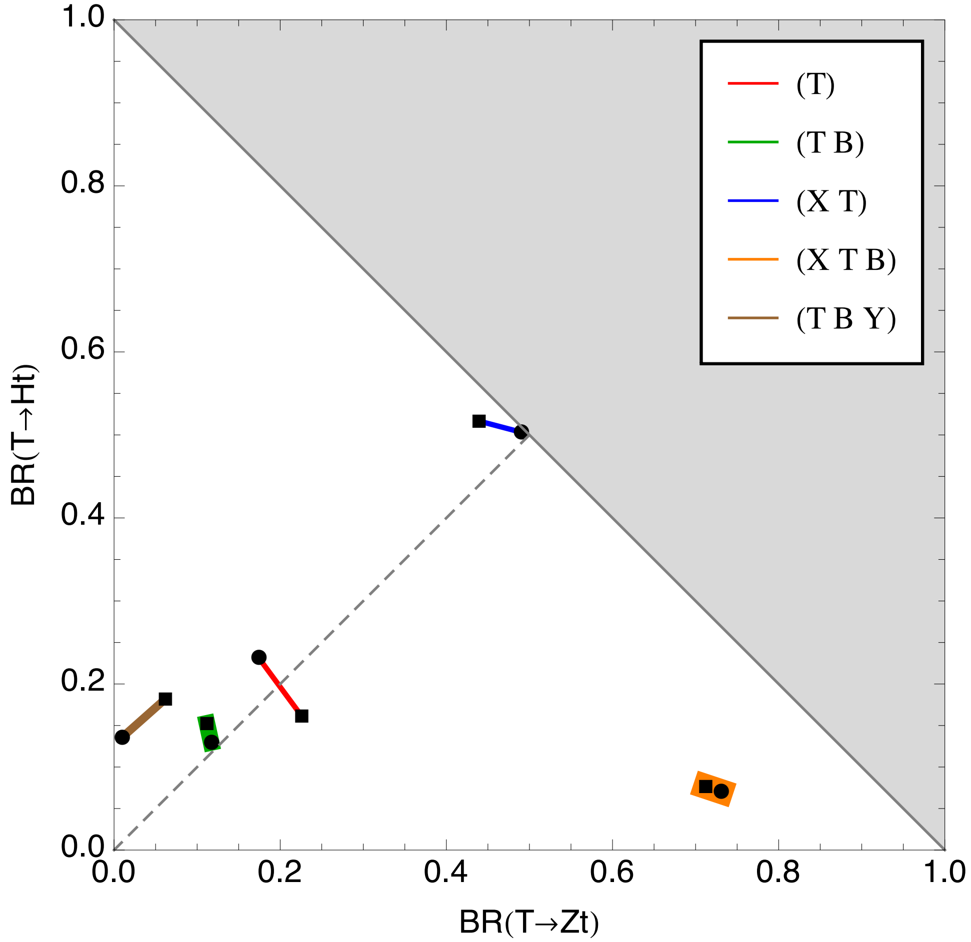
$$\begin{pmatrix} X \\ T \end{pmatrix} \sim \mathbf{2}_{7/6} \quad \begin{pmatrix} T \\ B \end{pmatrix} \sim \mathbf{2}_{1/6} \quad \begin{pmatrix} B \\ Y \end{pmatrix} \sim \mathbf{2}_{-5/6}$$

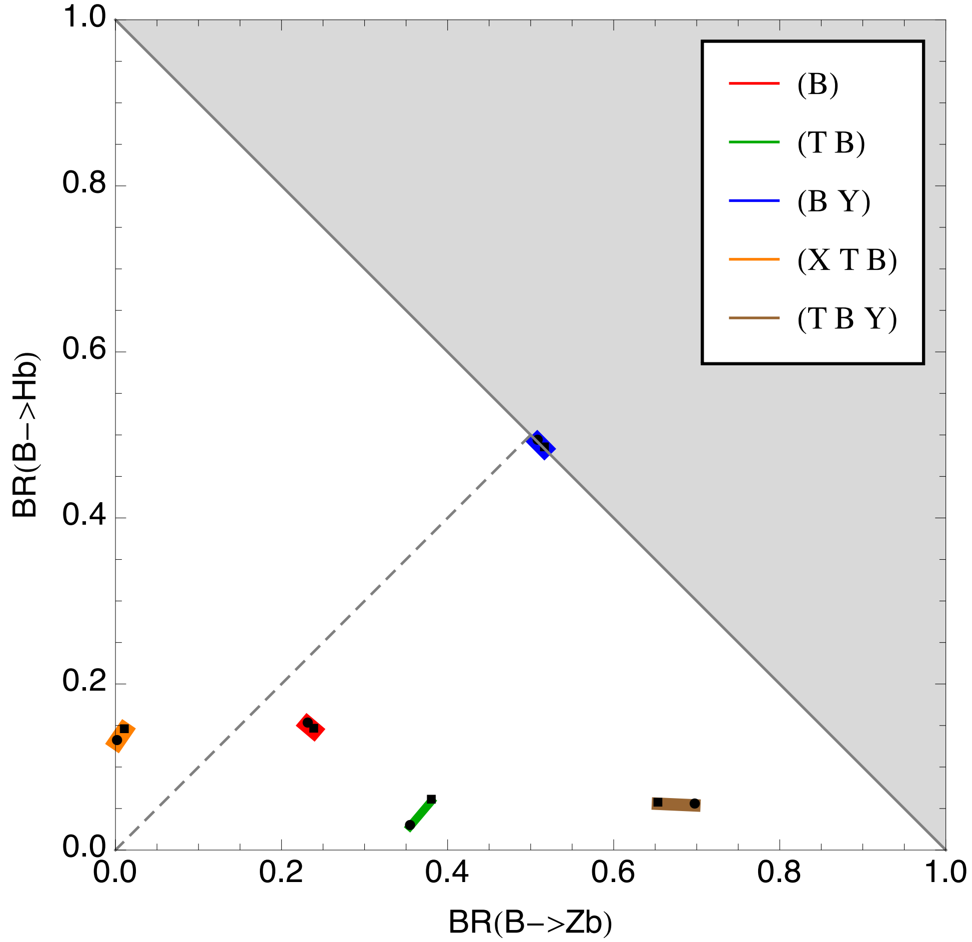
$$\begin{pmatrix} X' \\ X \\ T \end{pmatrix} \sim \mathbf{3}_{5/3} \quad \begin{pmatrix} X \\ T \\ B \end{pmatrix} \sim \mathbf{3}_{2/3} \quad \begin{pmatrix} T \\ B \\ Y \end{pmatrix} \sim \mathbf{3}_{-1/3} \quad \begin{pmatrix} B \\ Y \\ Y' \end{pmatrix} \sim \mathbf{3}_{5/3}$$

$$\begin{pmatrix} X' \\ X \\ T \\ B \end{pmatrix} \sim \mathbf{4}_{7/6} \quad \begin{pmatrix} X \\ T \\ B \\ Y \end{pmatrix} \sim \mathbf{4}_{1/6} \quad \begin{pmatrix} T \\ B \\ Y \\ Y' \end{pmatrix} \sim \mathbf{4}_{-5/6}$$

Example: heavy quarks with dimension 5 interactions

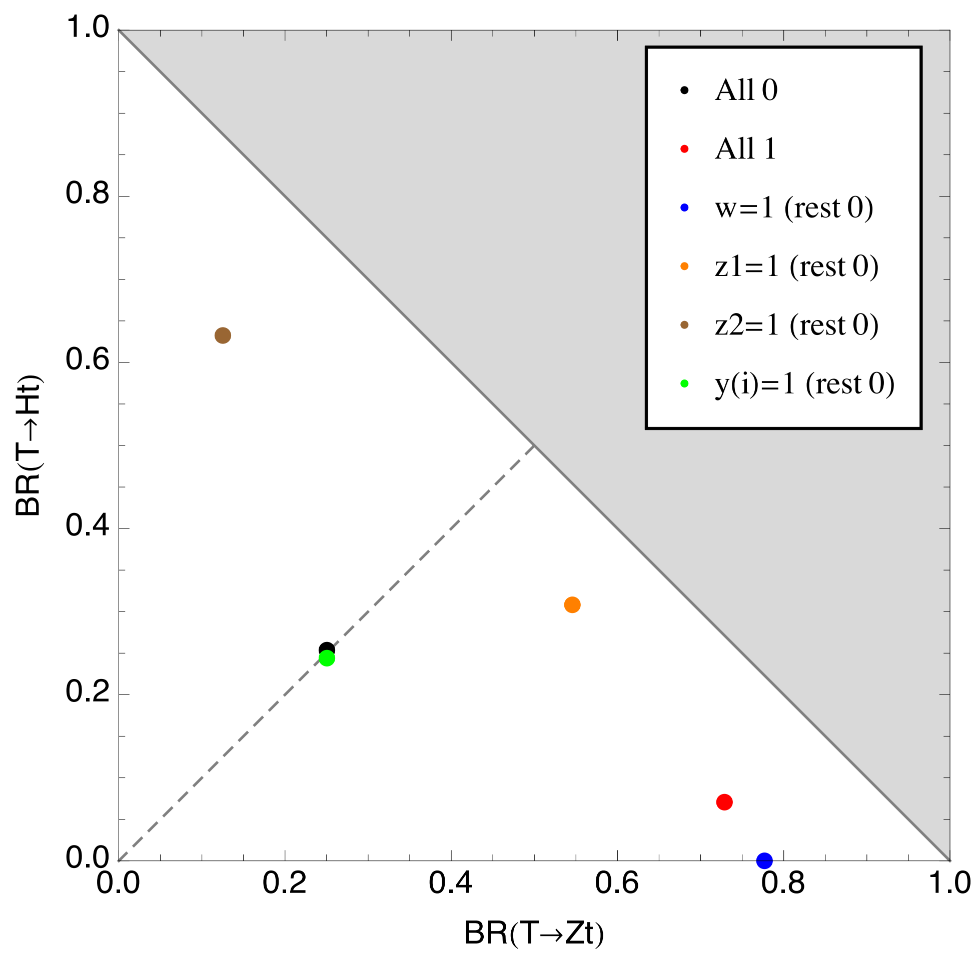
Corrections to branching ratios for some of the renormalizable multiplets are big:

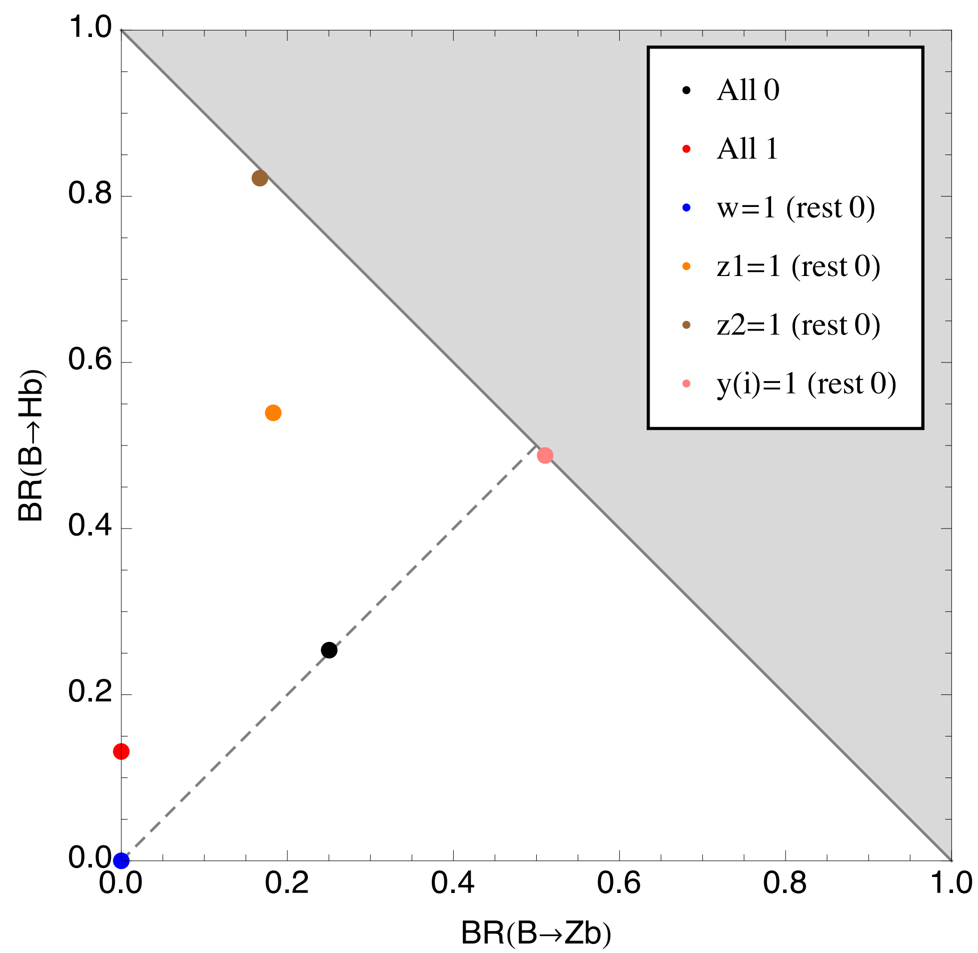




Example: heavy quarks with dimension 5 interactions

For the new multiplets, only non-renormalizable ops contribute. For example, for (X’ X T B):





Conclusions

- Program: using general extensions of the SM to parametrize any new physics effects

- The addition of new particles approach has the advantage of taking into account <u>production</u> and a <u>larger range of validity</u>

- Renormalizability and gauge invariance constrain the <u>possible representations of new particles</u>. Example: 7 reps for vector-like quarks

- The renormalizability constrain can be relaxed to get an <u>EFT with new particles</u>. Example: all possible reps of VLQ that couple to SM through operators of any dimension