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Rare B decays with invisible Higgs bosons

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Plan

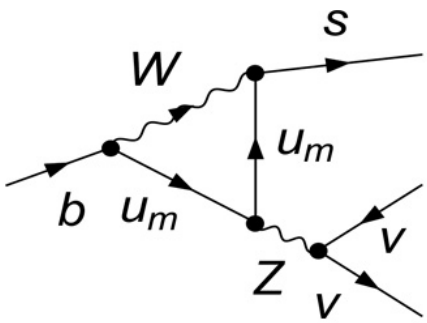
1. Motivation
2. Calculation
   - Extended Lagrangian of the Standard Model
   - Evaluation of the Higgs Penguin
3. Conclusions

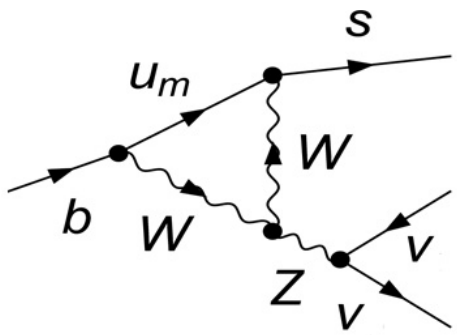
Motivation

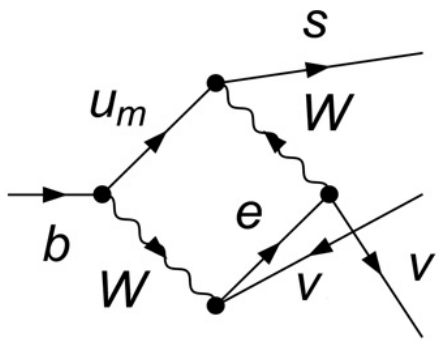
- Searching of invisible decays. The upper bound is provided by Belle Collaboration [O. Lutz et al.(Belle), 2013]

$$\mathcal{BR}(B^+ \to K^{*+}\nu\bar{\nu}) < 4.0 \times 10^{-5},$$
$$\mathcal{BR}(B^0 \to K^{*0}\nu\bar{\nu}) < 5.5 \times 10^{-5}.$$

- The Standard Model predicts the branches ratio of order 10^{-6} [W.Altmannshofer, A.J.Buras, D.M.Straub, M.Wick, 2009] .
- The Standard Model Feynman graphs are







Motivation

- Tiny branching ratio makes invisible decays very sensitive to new physics.
- There are many scenarios which contribute to the $B \to K+$ invisible, we want to concentrate on the Higgs portal with scalar mediator.

The Model

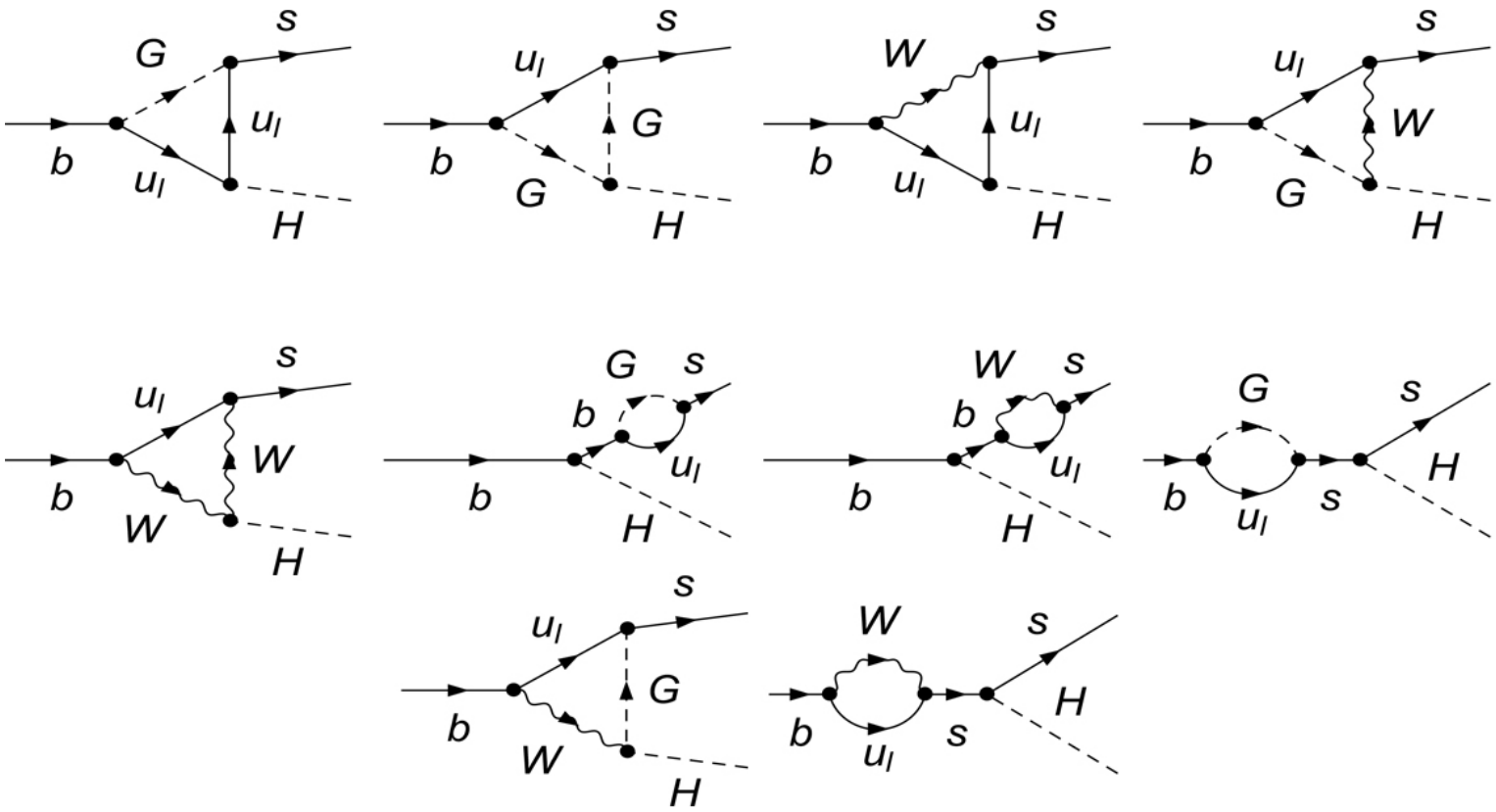
- The general Lagrangian of the model has the form

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 - \mu_S^2 S^2 - \frac{1}{2}(\alpha S^2 + \alpha_1 S)(H^\dagger H) - \frac{1}{4}\lambda_S S^4 \\ &+ \mathcal{L}[S - DM] + \mathcal{L}[DM]\end{aligned}$$

- Here Higgs boson is the SM Higgs, for scalar particle we can consider 2 scenarios with *vev* and without.
- *vev* of scalar particle provide to the domain wall problem.

Evaluation of the Higgs Penguin

- The Higgs penguin in Feynman diagrams



Evaluation of the Higgs Penguin

This diagrams we easily evaluated:

- all external momenta we kept arbitrary,
- all masses except of m_b, M_W, M_H, m_t are equal 0,
- for simplification we use expansion in Higgs momentum square up to 0 order, and in mass of b-quark up to first order,
- the calculation was performed in Feynman, unitary and R_ξ gauges.

The amplitudes are generated with Mathematica package FeynArts [T. Hahn, 2001] and they are evaluated with FeynCalc [V. Shtabovenko, R. Mertig, A. Denner, 2016] and FeynHelpers [V. Shtabovenko, 2017]

- If we naively expand also in mass of Higgs which appears in the G-G-H vertex, we will reproduce the result Willey and Yu [Willey and Yu, (PRD 26 vol 11, 1982)]

$$\mathcal{M} = 3\frac{g'^3 m_b V_{tb} V_{ts}^{\star}(\bar{s}P_L b)}{128\pi^2 M_W}x,$$

where $x = \frac{m_t}{M_W}$.

Evaluation of the Higgs Penguin

- Willey and Yu formula widely present in the literature, but it was calculated for $m_h << M_W$.
- Expansion in momentum square, but keeping Yukava coupling as it is generate a bit different result

$$\begin{aligned}\mathcal{M} &= \frac{g'^3 m_b V_{tb} V_{ts}^{\star} (\bar{s} P_L b)}{256\pi^2 M_W (x-1)^3} \left(2m_H^2 (x^3 + 2x^2)\log(x)\right. \\ &- \left. m_H^2 (x^2 - 1) + 6M_W^2 x (x-1)^3\right).\end{aligned}$$

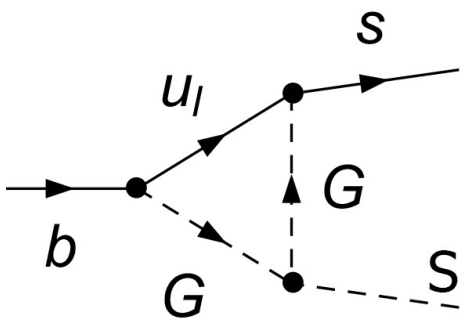
- All additional contribution came from the diagram which contain G-G-H vertex.

Evaluation of the Higgs Penguin

- If we calculate Higgs Penguin with R_ξ we will see gauge dependence explicit.

$$\begin{aligned}\mathcal{M} &= \frac{g'^3 m_b V_{tb} V_{ts}^\star (\bar{s} P_L b)}{256\pi^2 M_W (x-\xi_W)^3}\left(2m_H^2 x^2 \log(x)(x-2\xi_W)\right.\\ &- m_H^2 \xi_W \log(\xi_W)(\xi_W^2 - 3x\xi_W + x^2)\\ &+ \left. m_H^2(\xi_W^2 + x\xi_W) - 6M_W^2(2x^2\xi_W - x\xi_W^2 - x^3)\right).\end{aligned}$$

- Gauge dependence is cancelled by including the diagram with Goldstone bosons - New scalar particle vertices :



Conclusions

- For studying flavour DM we need precise understand loop calculation.
- Future Belle II searches $b \to s+$ missing energy will probe generic DM scenarious with scalar mediator which are mixed with SM Higgs boson.