Radiative B-meson decays within general two-Higgs-doublet models

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Implications of LHCb measurements and future prospects, Geneva   4 Nov. 2015

Outline

Introduction

Theoretical framework for radiative B-meson decays

Two-Higgs-doublet models with MFV hypothesis

Charged-Higgs effects on radiative B-meson decays

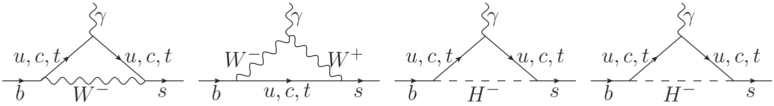
Conclusion and outlook

Why interested in radiative B-meson decays?

- Within the SM, absent at tree level, occur only at loop level, therefore loop-suppressed FCNCs in the SM;

- Some NP contributions not necessarily suppressed compared to the SM, therefore these processes provide a very sensitive indirect probe of physics beyond the SM;

- Theoretically well-understood and experimentally studied extensively at BaBar, Belle, and LHCb;



The one-loop diagrams contributing to $b \to s\gamma$ within the SM and 2HDM.

Current status of radiative B-meson decays

- On the exp. side: both Brs and even CP- and isospin-asymmetries measured for several $b \to s(d)\gamma$ decays, mainly from BaBar, Belle, but now also from LHCb; [*HFAG, 1412.7515.*]

- On the theo. side: $\mathrm{Br}(B \to X_{s,d}\gamma)$ calculated with a very high precision ($\sim 7\%$), while exclusive $B \to V\gamma$ plagued by large non-pert. QCD effects; [*Misiak etal, 1503.01789; Hurth, Nakao, 1005.1224.*]

- Focus on: exclusive $B \to V\gamma$ decays, like $B \to K^*\gamma$, $B \to \rho\gamma$ and $B_s \to \phi\gamma$, within the QCDF approach; Other methods like light-cone sum rules, perturbative QCD, and $\cdots$;

  [*Beneke, Feldmann and Seidel, hep-ph/0106067, hep-ph/0412400.*]

  [*Bosch and Buchalla, hep-ph/0106081, hep-ph/0408231.*]

- Features of exclusive $B \to V\gamma$ decays: while theoretically more difficult, the exp. measurements much easier; beyond Br, more interesting observables like the CP- and isospin-asymmetries;

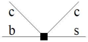
Theoretical framework for radiative B decays

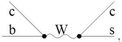
- Radiative B decays are governed by the interplay between weak and strong interactions; multi-scale involved, large logarithms $\log^m(\mu_b/\mu_W)$ appear and have to be resumed;

- Weak effective Hamiltonian $\mathcal{H}_{\rm eff}$: obtained by integrating out the heavy d.o.f. like m_W, m_t, $m_{H^\pm}$, $\cdots$; OPE & RG-improved perturbative theory; [*Buchalla, Buras, Lautenbacher, hep-ph/9512380.*]

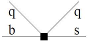
$$\mathcal{H}_{\rm eff} = -\frac{G_F}{\sqrt{2}}\left[\lambda_t^{(D)}\sum_{i=1}^{8} C_i Q_i + \lambda_u^{(D)}\sum_{i=1}^{2} C_i\left(Q_i^c - Q_i^u\right)\right]$$

taken from Misiak talk.

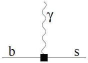
$Q_{1,2}$ = 

$= (\bar{s}\Gamma_i c)(\bar{c}\Gamma_i' b)$, from 

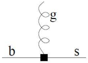
$|C_i(m_b)| \sim 1$

$Q_{3,4,5,6}$ = 

$= (\bar{s}\Gamma_i b)\sum_q(\bar{q}\Gamma_i' q)$, $|C_i(m_b)| < 0.07$

Q_7 = 

$= \frac{e m_b}{16\pi^2}\,\bar{s}_L\sigma^{\mu\nu}b_R F_{\mu\nu}$, $C_7(m_b) \simeq -0.3$

Q_8 = 

$= \frac{g m_b}{16\pi^2}\,\bar{s}_L\sigma^{\mu\nu}T^a b_R G^a_{\mu\nu}$, $C_8(m_b) \simeq -0.15$

Theoretical framework for radiative B decays

- Weak effective Hamiltonian: $\mathcal{H}_{\rm eff}^{(t)} = C_1\, Q_1^c + C_2\, Q_2^c + \sum_{i=3}^{8} C_i\, Q_i$

- Wilson coefficients C_i: calculable perturbatively for a given model, and now the NNLO program for the SM complete;

  - ▷ 2-loop/3-loop matching calculations at the initial scale μ_W;

    [*Bobeth, Misiak and Urban, hep-ph/9910220.*]

    [*Misiak and Steinhauser, hep-ph/0401041.*]

  - ▷ 3-loop/4-loop anomalous dimension matrices for RG running;

    [*Gorbahn and Haisch, hep-ph/0411071.*]

    [*Gorbahn, Haisch and Misiak, hep-ph/0504194.*]

    [*Czakon, Haisch and Misiak, hep-ph/0612329.*]

- Matrix elements of O_i: differ between inclusive and exclusive processes; currently the most difficult and uncertain part;

Theoretical framework for radiative B decays

- For inclusive $B \to X_{s,d}\gamma$: quark-hadron duality and HME to derive a well-defined decay rates in powers of Λ_{QCD}/m_b;

$$\Gamma(B \to X_s\gamma) = \Gamma(b \to X_s^{\text{parton}}\gamma) + \Delta^{\text{nonpert.}}$$

- Exp. averages: [*HFAG, 1412.7515; Trabelsi, talk at EPS-HEP 2015.*]

$$\text{Br}(B \to X_s\gamma)\,|_{E_0>1.6 \text{ GeV}} = (3.41 \pm 0.15 \pm 0.04) \times 10^{-4}$$

$$\text{Br}(B \to X_d\gamma)\,|_{E_0>1.6 \text{ GeV}} = (1.41 \pm 0.57) \times 10^{-5}$$

- Theo. predictions: [*Misiak etal, 1503.01789; Gambino, talk at KEK-FF workshop 2015.*]

$$\text{Br}(B \to X_s\gamma)\,|_{E_0>1.6 \text{ GeV}} = (3.36 \pm 0.23) \times 10^{-4}$$

$$\text{Br}(B \to X_d\gamma)\,|_{E_0>1.6 \text{ GeV}} = (1.73^{+0.12}_{-0.22}) \times 10^{-5}$$

- Good agreement between exp. data and theo. predictions, and therefore strong constraints on various NP expected.

Theoretical framework for radiative B decays

- For exclusive $B \to V\gamma$: how to calculating precisely $\langle V\gamma|\mathcal{Q}_i|\bar{B}\rangle$;
- QCDF/SCET method: the basis of the up-to-date predictions of exclusive decays; [*Beneke, Feldmann and Seidel, hep-ph/0106067, hep-ph/0412400; Bosch and Buchalla, hep-ph/0106081, hep-ph/0408231.*]

$$\langle V\gamma|\mathcal{H}_{\rm eff}^{(i)}|\bar{B}\rangle \propto \mathcal{T}_{\perp}^{(i)}(0)\left\{\epsilon^{\mu\nu\rho\sigma}\,\eta_{\mu}^{*}\,\varepsilon_{\nu}^{*}\,p_{\rho}p'_{\sigma}-i\left[(\eta^{*}\cdot\varepsilon^{*})\,(p'\cdot q)-(\eta^{*}\cdot p')\,(\varepsilon^{*}\cdot q)\right]\right\}$$

- $\mathcal{T}_{\perp}^{(i)}(0)$: encode all the dynamical information, and satisfy the following factorization formula;

$$\mathcal{T}_{\perp}^{(i)}(0) = T_1(0)\,C_{\perp}^{(i)} + \frac{\pi^2}{N_c}\frac{f_B f_V^{\perp}}{m_B}\sum_{\pm}\int\frac{d\omega}{\omega}\Phi_{B,\pm}(\omega)\int_0^1 du\,\phi_{\perp}(u)\,T_{\perp,\pm}^{(i)}(u,\omega)$$

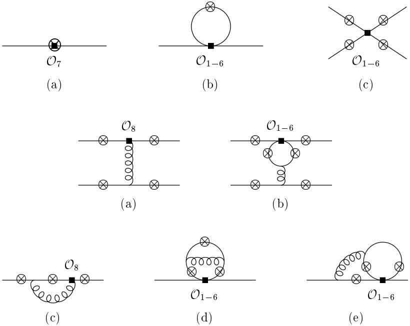
- 1st term: from vertex correction; 2nd term: spectator correction;
- $T_1(0)$, f_B, $f_V^{\perp}$, $\Phi_{B,\pm}(\omega)$ and $\phi_{\perp}(u)$: tensor form factor, decay constants, LCDAs; process-independent non-perp. quantities;

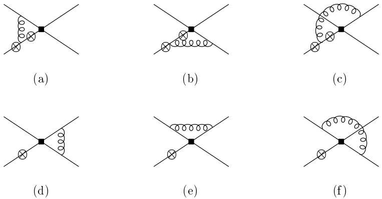
Theoretical framework for radiative B decays

- $C_{\perp}^{(i)}$ and $T_{\perp,\pm}^{(i)}(u,\omega)$: the hard-scattering kernels, and calculable perturbatively; [*Beneke, Feldmann and Seidel, hep-ph/0106067, hep-ph/0412400; Bosch and Buchalla, hep-ph/0106081, hep-ph/0408231.*]

$$C_{\perp}^{(i)} \;=\; C_{\perp}^{(0,i)} + \frac{\alpha_s C_F}{4\pi}\, C_{\perp}^{(1,i)} + \ldots$$

$$T_{\perp,\pm}^{(i)}(u,\omega) \;=\; T_{\perp,\pm}^{(0,i)}(u,\omega) + \frac{\alpha_s C_F}{4\pi}\, T_{\perp,\pm}^{(1,i)}(u,\omega) + \ldots$$





Theoretical framework for radiative B decays

- Decay rates for $B \to V\gamma$: [*Beneke, Feldmann, Seidel, hep-ph/0106067, hep-ph/0412400; Bosch and Buchalla, hep-ph/0106081, hep-ph/0408231.*]

$$\Gamma(\bar{B} \to V\gamma) = \frac{G_F^2}{8\pi^3} m_B^3 S \left(1 - \frac{m_V^2}{m_B^2}\right)^3 \frac{\alpha_{\rm em}}{4\pi}\, m_b^2 \left|\lambda_t^{(D)} \mathcal{T}_\perp^t(0) + \lambda_u^{(D)} \mathcal{T}_\perp^u(0)\right|^2$$

- Some interesting physical observables besides Brs in $B \to V\gamma$:
  - the direct CP asymmetry:

$$A_{CP}(B \to V\gamma) = \frac{\Gamma(\overline{B} \to V\gamma) - \Gamma(B \to \overline{V}\gamma)}{\Gamma(\overline{B} \to V\gamma) + \Gamma(B \to \overline{V}\gamma)}$$

  - the isospin asymmetries: Kagan and Neubert, hep-ph/0110078

$$\Delta(K^*\gamma) = \frac{\bar{\Gamma}(B^0 \to K^{*0}\gamma) - \bar{\Gamma}(B^+ \to K^{*+}\gamma)}{\bar{\Gamma}(B^0 \to K^{*0}\gamma) + \bar{\Gamma}(B^+ \to K^{*+}\gamma)}$$

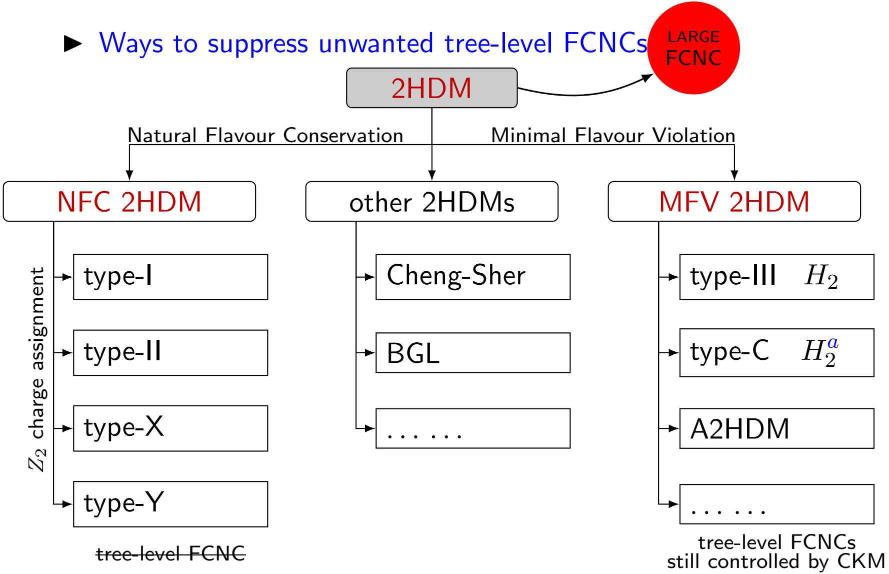
$$\Delta(\rho\gamma) = \frac{\bar{\Gamma}(B^+ \to \rho^+\gamma)}{2\bar{\Gamma}(B^0 \to \rho^0\gamma)} - 1$$

Overview of the 2HDM

- A scalar particle with $126\ \mathrm{GeV}$ discovered at the LHC: Is it just the SM Higgs? or are there more scalars? [ATLAS, 1207.7214; CMS, 1207.7235.]
- 2HDM: one of the simplest extensions on the SM Higgs sector; [Branco, Ferreira, Lavoura, Rebelo, Sher and Silva, 1106.0034; Gunion, Haber, Kane and Dawson, Front.Phys.**80**, 1 (2000).]
  - ✓ duplicate a complex $SU(2)_L$ Higgs doublet with the same hypercharge $Y = \frac{1}{2}$ as the SM one;
  - ✓ featured by five physical Higgs states, especially a charged Higgs boson;
  - ✓ very rich and viable phenomenologies in collider, low-energy flavour physics, and $\cdots$;
- In a generic 2HDM: existing tree-level FCNCs $\Rightarrow$ to satisfy the stringent exp. constraints, should find a way to avoid them!

Overview of the 2HDM

- Ways to suppress unwanted tree-level FCNCs



- For details on various versions of 2HDMs: [Branco, Ferreira, Lavoura, Rebelo, Sher, Silva, 1106.0034; Buras, Carlucci, Gori, Isidori, 1005.5310.]

2HDMs with MFV

- "Higgs basis": only one doublet Φ_1 gets a nonzero vev and behaves the same as the SM one; [Davidson, Haber, hep-ph/0504050.]

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + S_1 + iG^0\right) \end{bmatrix}, \qquad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(S_2 + iS_3\right) \end{bmatrix}$$

- Most general Yukawa interactions of the scalars with the quarks: [Degrassi and Slavich, 1002.1071; Manohar and Wise, hep-ph/0606172.]

$$-\mathcal{L}_Y = \bar{q}_L^0 \tilde{\Phi}_1 Y^U u_R^0 + \bar{q}_L^0 \Phi_1 Y^D d_R^0 + \bar{q}_L^0 \tilde{\Phi}_2^{(a)} T_R^{(a)} \bar{Y}^U u_R^0 + \bar{q}_L^0 \Phi_2^{(a)} T_R^{(a)} \bar{Y}^D d_R^0$$

- MFV hypothesis: all FC interactions controlled by CKM matrix, achieved by requiring that $\bar{Y}^{U,D}$ be composed of pairs of $Y^{U,D}$;

$$\bar{Y}^U = A_u^*(1 + \epsilon_u^* Y^U Y^{U\dagger} + \ldots)Y^U, \quad \bar{Y}^D = A_d(1 + \epsilon_d Y^U Y^{U\dagger} + \ldots)Y^D$$

- $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ representation of Φ_2: either $(\mathbf{1}, \mathbf{2})_{1/2}$ colour-singlet (Type-III) or $(\mathbf{8}, \mathbf{2})_{1/2}$ colour-octet (Type-C).

2HDMs with MFV

- Charged-Higgs interaction with quarks: in the mass-eigenstate basis; [Li, Yang, Yuan, 1311.2786; Degrassi and Slavich, 1002.1071.]

$$\mathcal{L}_{H^+} = \frac{g}{\sqrt{2}m_W} \bar{u}_i T_R^{(a)} (A_u^i m_{u_i} P_L - A_d^i m_{d_j} P_R) V_{ij} d_j H_{(a)}^+ + \text{h.c.}$$

$$A_{u,d}^i = A_{u,d}\left(1 + \epsilon_{u,d}\frac{m_t^2}{v^2}\delta_{i3}\right), \quad A_{u,d}^t = A_{u,d}\left(1 + \epsilon_{u,d}\frac{m_t^2}{v^2}\right)$$

- Type-III: T_R is the identity matrix in colour space;

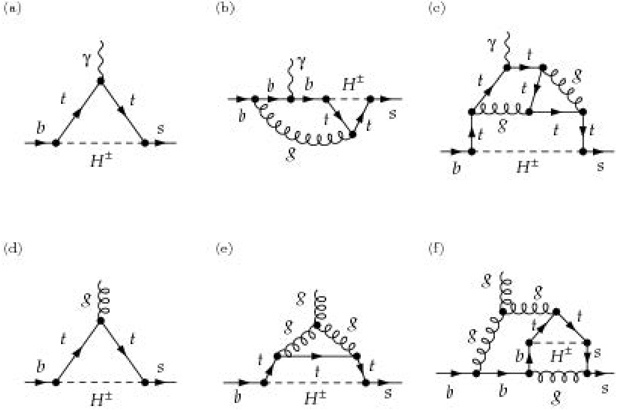
- Type-C: $T_R^a = T_F^a$ $(a = 1, \cdots, 8)$ is $SU(3)_C$ generator acts on quark fields; featured by three colour-octet particles;

- A2HDM: Yukawa matrices aligned in flavour space, and similar to Type-III; [Pich and Tuzón, 0908.1554; Jung, Pich and Tuzón, 1006.0470.]

- Very rich and interesting pheno. in: collider physics, low-energy flavour physics, and $\cdots$;

Charged-Higgs effects on radiative B-meson decays

- Radiative B decays affected by $H^{\pm}$-mediated photon penguin diagrams, contribute at the same level as the $W^{\pm}$-mediated ones; [Hermann, Misiak, Steinhauser, 1208.2788.]



- With the approx. $m_s = 0$, no new operator basis compared to the SM, and only $C^{\text{eff}}_{4,7,8}(\mu_W)$ non-zero at μ_W; [Hermann, Misiak, Steinhauser, 1208.2788; Degrassi and Slavich, 1002.1071.]

Charged-Higgs effects on radiative B-meson decays

- At μ_b, only $C_{7,8}^{\rm eff}(\mu_b)$ show significant deviations from the SM predictions; with $m_{H^\pm} = 200\,{\rm GeV}$ and $\mu_b = 2.5\,{\rm GeV}$,

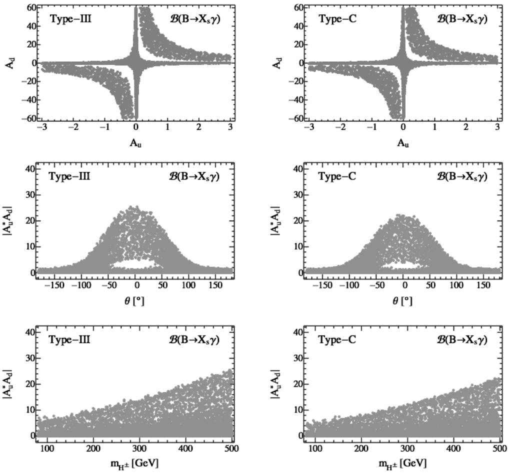
$$C_7^{\rm eff}(\mu_b)/C_{7,\rm SM}^{\rm eff}(\mu_b) = \begin{cases} 1 - 0.28 A_u^* A_d + 0.045|A_u|^2 & \text{for type-III} \\ 1 - 0.27 A_u^* A_d + 0.044|A_u|^2 & \text{for type-C} \end{cases}$$

$$C_8^{\rm eff}(\mu_b)/C_{8,\rm SM}^{\rm eff}(\mu_b) = \begin{cases} 1 - 0.49 A_u^* A_d + 0.058|A_u|^2 & \text{for type-III} \\ 1 + 0.42 A_u^* A_d - 0.090|A_u|^2 & \text{for type-C} \end{cases}$$

- $C_7^{\rm eff}(\mu_b)$: quite similar for both type-III and type-C, therefore they are almost indistinguishable if based on Brs only;

- $C_8^{\rm eff}(\mu_b)$: while similar magnitudes but with opposite signs, therefore we may use observables like the CP- and isospin-asymmetries to distinguish between the cases.

Constraints from CP-averaged branching ratios



Parameters within:

$|A_u| \in [0, 3]$

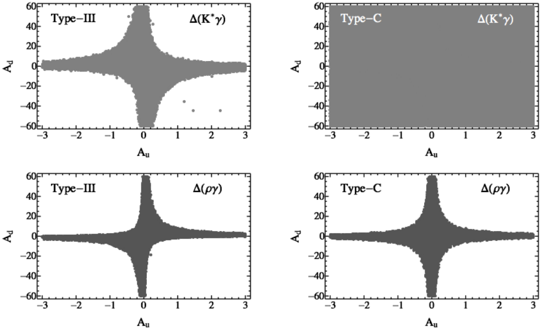
$|A_u^* A_d| \in [0, 60]$

$\theta \in [-180^\circ, 180^\circ]$

$m_{H^\pm} \in [80, 500]\,\mathrm{GeV}$

- Since $\mathrm{Br} \propto |C_7^{\mathrm{eff}}(\mu_b)|^2$ to LO, almost indistinguishable for type-III and type-C;
- Allowed regions: small & cons. close to the axes, large & dest. flipping $C_7^{\mathrm{eff}}(\mu_b)$;
- Regions with simult. large A_u and A_d but with opposite signs already excluded.

Constraints from isospin asymmetries

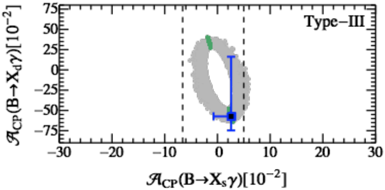


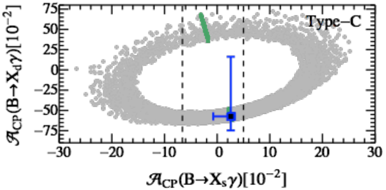
Three sources for $\Delta(V\gamma)$: [Lyon and Zwicky, 1305.4797.]

- weak anni. mediated by Q_i;
- quark-loop s.p. through Q_i;
- s.p. through Q_8;

- Since $\Delta(V\gamma) \propto 1/C_7^{\rm eff}(\mu_b)$ while $\mathrm{Br} \propto |C_7^{\rm eff}(\mu_b)|^2$, complementary provided, especially excluding already the large same-sign solutions allowed by Brs;
- For $\Delta(K^*\gamma)$, quite different between type-III and type-C because $C_8^{\rm eff}(\mu_b)$ have similar magnitudes but opposite signs;
- For $\Delta(\rho\gamma)$, since $\lambda_u^{(d)} \sim \lambda_t^{(d)}$, different dependence on θ from $\Delta(K^*\gamma)$;
- Combined constraints from $\mathcal{B}(B \to X_s\gamma)$, $\Delta(\rho\gamma)$ and $\Delta(K^*\gamma)$ more stringent.

Correlation between direct CP asymmetries





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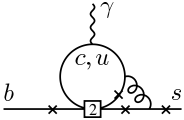
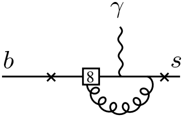
- 

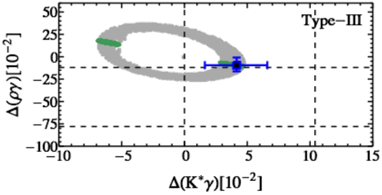


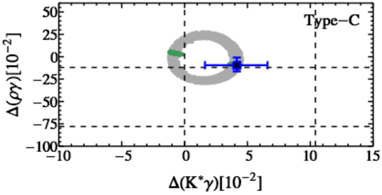
$$\mathrm{Im}[(1+\epsilon_s)C_7^*] = -\mathrm{Im}C_7 + \mathcal{O}(\lambda^2)$$
$$\mathrm{Im}[(1+\epsilon_d)C_7^*] = -\mathrm{Re}C_7 \cdot \eta$$

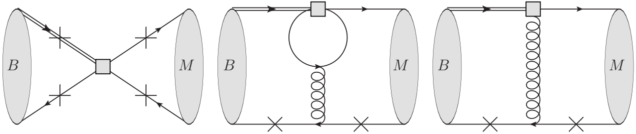
- $$A_{\rm CP}^{b\to s\gamma} = \frac{\alpha_s(m_b)}{|C_7|^2}\left\{ \frac{40}{81}\,\mathrm{Im}[C_2 C_7^*] - \frac{8z}{9}\left[v(z) + b(z,\delta)\right]\mathrm{Im}[(1+\epsilon_s)C_2 C_7^*] - \frac{4}{9}\,\mathrm{Im}[C_8 C_7^*] + \frac{8z}{27}\,b(z,\delta)\,\mathrm{Im}[(1+\epsilon_s)C_2 C_8^*] \right\},$$

$$\epsilon_q = \frac{V_{uq}^* V_{ub}}{V_{tq}^* V_{tb}}$$

Correlations between the isospin asymmetries





▶ 

- weak annihilation mediated by four-quark operators;
- quark-loop spectator scattering through four-quark operators;
- spectator scattering through chromo-magnetic operator $\mathcal{O}_8$;

Conclusion and outlook

- Radiative B-meson decays nontrivial test of the CKM (used to determine $|V_{td}/V_{ts}|$), sensitive probes of physics beyond the SM;
- Inclusive branching ratios $\mathcal{B}(B \to X_{s,d}\gamma)$ usually used, due to the comparable precision achieved by both theo. and exp.;
- Exclusive $B \to V\gamma$ decays provides more interesting observables, like CP and isospin asymmetries $\Delta(\rho\gamma)$ and $\Delta(K^*\gamma)$;
- MFV 2HDMs very rich and interesting phenomenologies in flavour physics, especially due to the charged-Higgs;
- Time-dependent CP asymmetry in $B_s \to \phi\gamma$ also interesting, RH current? [Muheim, Xie and Zwicky, 0802.0876.]

Points to be discussed:

Soni, Kagan, Zwicky, Ligeti,...

- Do the 2HDM keep the chiral structure of the SM? Are we sensitive to any angular observable?

  If assuming $m_{s,d} = 0$, no new operators compared to the SM; $\mathcal{S}(B \to P^0 V^0 \gamma)$ like $\mathcal{S}(B \to K_S \phi \gamma)$ need the angular distribution infor.;

- Is there any constraint inside 2HDM for b-baryon radiative decays?

  b-baryon radiative decays access to the helicity structure of the SD operators, complementary to mesonic counterpart;

- Are the direct CP and isospin asymmetries the most sensitive observables for exclusive B decays? Are there other observables?

  Time-dependent CP asymmetries also very sensitive to RH currents, like in $B_s \to \phi\gamma$;

- Which are the observables with larger correlations that we should measure at LHCb?

  $\Delta\mathcal{A}_{X_s\gamma} = A_{X_s^-\gamma} - A_{X_s^0\gamma} \approx 4\pi^2 \alpha_s \bar{\Lambda}_{78} \mathrm{Im}\frac{C_{8g}}{C_{7\gamma}}$; [Benzke, Lee, Neubert and Paz, 1012.3167.]