

Predictions for $B \rightarrow K\gamma\gamma$ decays

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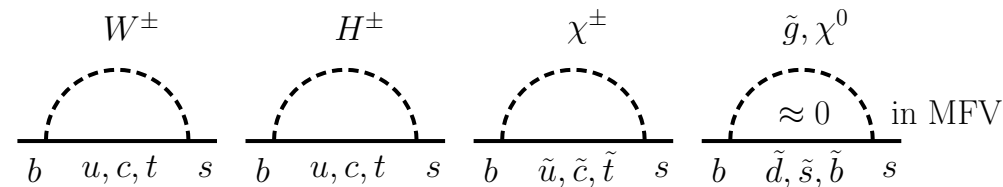
CERN and Munich (ASC/LMU)

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- *Introduction flavor changing neutral currents (FCNCs)*
- *Double radiative b -decays $b \rightarrow (s, d)\gamma\gamma$*
- *$B \rightarrow K\gamma\gamma$ decays **
- *Summary*

** based on works with Salim Safir, hep-ph/0411344, to appear in JHEP*

- probe flavor/CP aspects of the Standard Model (SM), CKM
- sensitivity to New Physics (NP)
- study hadronic physics (“QCD background”)
- rich experimental program: B -factories Belle, BaBar, b -physics at the Tevatron, LHC



examples: $B \rightarrow K^* \gamma$, $B \rightarrow X_s \gamma$, $B \rightarrow K \mu^+ \mu^-$, $B \rightarrow \Phi K, \dots$

to date agreement with SM, some $2 - 3\sigma$ hints, many couplings (CP violation, chirality $V + A$, FCNC couplings to τ 's and ν 's ...) untested

Double radiative $b \rightarrow s\gamma\gamma$ decays

mode	# theory papers
$B_{d,s} \rightarrow \gamma\gamma$	$\mathcal{O}(50)$
$B \rightarrow X_s \gamma\gamma$	$\mathcal{O}(20)$
$B \rightarrow K \gamma\gamma$	3+1
$B \rightarrow K^* \gamma\gamma$	1

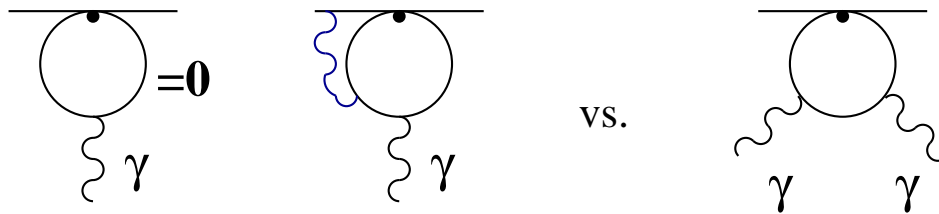
$b \rightarrow s\gamma\gamma$ quite neglected so far w.r.t. $b \rightarrow s\gamma$

- α_{em} suppression of the rate
- correlation with $b \rightarrow s\gamma$ (bremsstrahlung)
- hadronic physics more complicated, non-local matrix element

true, but...

Double radiative $b \rightarrow s\gamma\gamma$ decays

- branching ratios of $\mathcal{O}(10^{-8})$ accessible at current (future) B -experiments; same order in α_{em} as $b \rightarrow s\ell\ell$
- NP in 4-Fermi operators is LO in $s\gamma\gamma$, subleading in $b \rightarrow s\gamma$



- $B \rightarrow (X_s, K, K^*)\gamma\gamma$ 3-body decay, design interesting (clean and sensitive) observables such as $A_{FB}(B \rightarrow K^*\mu^+\mu^-)$
- interesting hadronic physics; non-perturbative functions related to other decay modes: $B \rightarrow K^{(*)}$ form factors, λ_B

Double radiative $b \rightarrow s\gamma\gamma$ decays, \mathcal{H}_{eff}

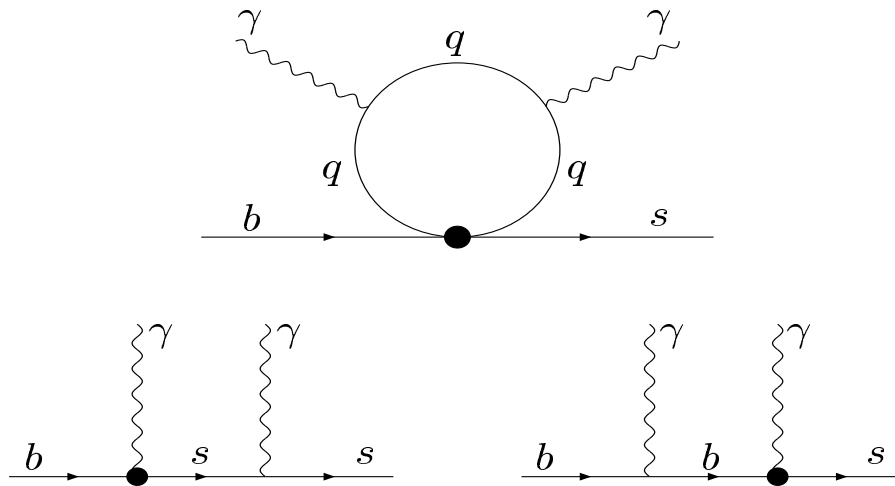
$$\mathcal{H}_{\text{eff}}(b \rightarrow s\gamma) = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) \mathcal{O}_i(\mu)$$

$\mathcal{O}_{1,2} \simeq (\bar{s}\gamma^\mu Lc)(\bar{c}\gamma_\mu Lb)$, em dipole operator $\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \bar{s}\sigma^{\mu\nu} Rb F_{\mu\nu}$

penguins $\sim \bar{s}\Gamma b \sum_q \bar{q}\Gamma' q$, $q = u, d, s, c, b$

$$\mathcal{H}_{\text{eff}}(b \rightarrow s\gamma\gamma) = \mathcal{H}_{\text{eff}}(b \rightarrow s\gamma) + \mathcal{O}((m_b/m_W)^4)$$

No gauge invariant dim 6 operator with 2 photons that cannot be related to the \mathcal{O}_i by equations of motion



Double radiative $b \rightarrow s\gamma\gamma$ decays, status

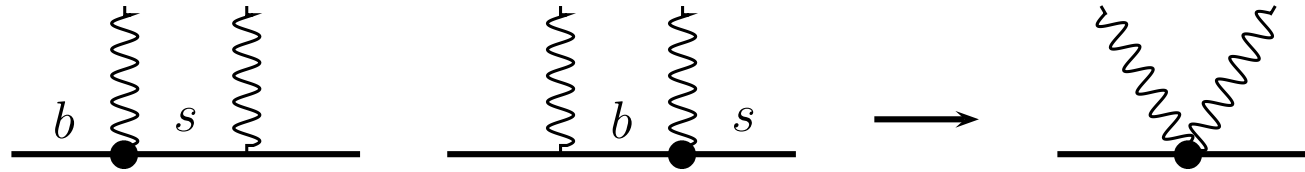
modes	\mathcal{B}_{SM}	90 % C.L. bounds	2HDM	RPV
$B_d \rightarrow \gamma\gamma$	$3.1_{-1.6}^{+6.4+1.0+1.0+1.3} \cdot 10^{-8}$	$1.7 \cdot 10^{-6}$ BaBar	–	–
$B_s \rightarrow \gamma\gamma$	$1.2_{-0.6}^{+2.5+0.3+0.3+0.01} \cdot 10^{-6}$	$1.48 \cdot 10^{-4}$ L3	2	16
$B \rightarrow X_s \gamma\gamma$	$(3.7 - 5.1) \cdot 10^{-7}$	–	2-3	5
$B \rightarrow K \gamma\gamma$	$(0.5 - 5.6) \cdot 10^{-7}$ A,B	–	–	–
$B \rightarrow K^* \gamma\gamma$	few $\cdot 10^{-7}$ C	–	–	–

A: Singer, Zhang '97 **B:** Choudhury et al '03 **C:** Choudhury et al '04

Note $\sum_{H=K,K^*} \mathcal{B}(B \rightarrow H\gamma\gamma) < \mathcal{B}(B \rightarrow X_s\gamma\gamma)$

$B \rightarrow \gamma\gamma$ errors: $\lambda_B, f_B, \mu, \gamma$ Bosch, Buchalla '02

Model-independent estimate for exclusive decays



propagators of 1PR diagrams with \mathcal{O}_7 :

$$(Q_1^s)^2 = (p_s + k_2)^2 = m_b^2 - 2m_b E_1 \quad (Q_1^b)^2 = -[(p_b - k_1)^2 - m_b^2] = 2m_b E_1$$

$$(Q_2^s)^2 = (p_s + k_1)^2 = m_b^2 - 2m_b E_2 \quad (Q_2^b)^2 = -[(p_b - k_2)^2 - m_b^2] = 2m_b E_2$$

choose photon energies $E_{1,2}$ such that all $Q_{1,2}^{s,b}$ large $\sim \mathcal{O}(m_b)$

reference point: $E_{1,2,K} \sim m_b/3$ “Mercedes Benz”, also $q^2 = m_b^2/3$ hard

integrate out $\mathcal{O}(m_b)$ scales: match onto SCET Stewart etal, Beneke etal

$$\bar{s}\Gamma b \rightarrow \sum_i c_i(\mu) \bar{\chi}\Gamma_i h_v$$

h_v heavy, χ collinear quark with light-like $n = p_K/E_K$

(leading order) OPE in $Q = \{m_b, E_K, Q_{1,2}^{s,b}, \sqrt{q^2}\}$

$$\bar{s}W_7^{\mu\nu} b\epsilon(k_1)^\mu \epsilon(k_2)^\nu \rightarrow -\frac{1}{2} \left\{ \left(\frac{1}{(Q_1^s)^2} - \frac{1}{(Q_1^b)^2} \right) Q_1 + \left(\frac{1}{(Q_2^s)^2} - \frac{1}{(Q_2^b)^2} \right) Q_1' + \frac{m_b E_K}{(Q_1^s)^2 (Q_2^b)^2} Q_2 + \frac{m_b E_K}{(Q_2^s)^2 (Q_1^b)^2} Q_2' \right\}$$

$$Q_1 = \frac{m_b}{4} \bar{\chi} \sigma_{\mu\nu} \sigma_{\alpha\beta} R h_\nu F_1^{\alpha\beta} F_2^{\mu\nu} \quad Q_2 = -2im_b \bar{\chi} \sigma_{\mu\nu} R h_\nu F_1^{\mu\nu} F_2^{\alpha\beta} v^\alpha n^\beta$$

$$Q_3 = \bar{\chi} \gamma^\mu L h_\nu F_1^{\alpha\beta} D_\alpha \tilde{F}_{2\beta\mu} \text{ (1PI) Adler-Rosenberg tensor}$$

1PR and 1PI same order in 1/Q ! (in B → γγ 1PR dominates)

$$\langle K(n) | \bar{\chi} h_\nu | B(v) \rangle = 2E_K \zeta(E_K) \quad \langle K(n) | \bar{\chi} \gamma_\mu h_\nu | B(v) \rangle = 2E_K \zeta(E_K) n_\mu$$

$$\langle K(n) | \bar{\chi} \sigma_{\mu\nu} h_\nu | B(v) \rangle = -2iE_K \zeta(E_K) (v_\mu n_\nu - v_\nu n_\mu)$$

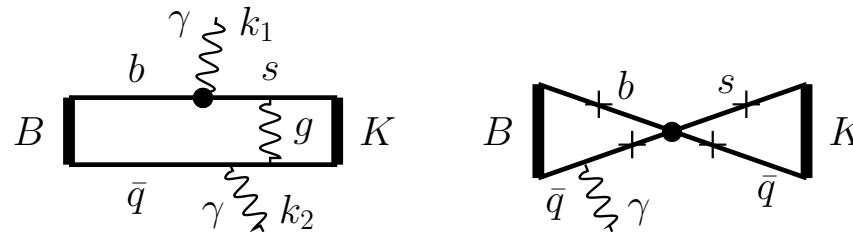
only one form factor $\zeta = f_+$, known from B → Kℓℓ

$$\begin{aligned} \frac{d\Gamma}{dE_2 dE_1} = & \frac{\alpha_{em}^2 G_F^2 |V_{tb} V_{ts}^*|^2}{256 m_B \pi^5} |\zeta(E_K)|^2 \left\{ m_b^2 Q_d^2 |C_7|^2 \frac{(m_B - 2(E_1 + E_2))^2}{E_1^2 E_2^2} \right. \\ & \times \left(24 E_1^2 E_2^2 - 4 m_B E_1 E_2 (E_1 + E_2) + m_B^2 (E_1^2 + E_2^2) \right) \\ & + 32 m_b Q_d Q_u^2 \operatorname{Re}(C_7 \kappa_c^*) (C_1 N_C + C_2) m_B (m_B - E_1 - E_2) (m_B - 2(E_1 + E_2)) \\ & \left. + 32 Q_u^4 |\kappa_c|^2 (C_1 N_C + C_2)^2 m_B^2 (m_B - E_1 - E_2)^2 \right\} \end{aligned}$$

- $K\gamma\gamma$ vanishes for $q^2 \simeq -m_B^2 + 2m_B(E_1 + E_2) \rightarrow 0$ like $B \rightarrow K\gamma$
- phase space integration is IR finite (as opposed to $B \rightarrow X_s \gamma\gamma$, which needs cancellation with virtual em corrections)
- valid for fast K and $Q_{1,2}^{s,b}$ and di-photon mass hard

Contributions beyond the OPE

- photon radiation off the spectator
 - soft gluons: kinematically forbidden ! $\mathbf{p}_s \simeq -\mathbf{k}_1$ and $\mathbf{p}_{\bar{q}} \simeq -\mathbf{k}_2$:
 K cannot be formed if-as in OPE region-angle between γ s is large
 - energetic gluons: α_s -suppressed; in SCET $\bar{\chi}h_v\gamma$ -coll. g operator
- weak annihilation in $B^\pm \rightarrow K^\pm\gamma\gamma$ thru $\mathcal{O}_{1,2}^u \simeq (\bar{s}\gamma^\mu Lu)(\bar{u}\gamma_\mu Lb)$ CKM suppressed $\sim V_{ub}V_{us}^*/(V_{tb}V_{ts}^*)$ but leading power $\frac{f_B f_K}{m_B \Lambda_{QCD} f_+} \propto \mathcal{O}(1)$
 $\mathcal{A}^{WA}/\mathcal{A}^{FF} \sim \lambda^2 C_2/C_7 \sim \mathcal{O}(10\%)$; $C_7 = -0.3$, $C_2 \simeq 1$ at $\mu = m_b$



$B \rightarrow K(c\bar{c}) \rightarrow K\gamma\gamma$ background –similar to $b \rightarrow s(c\bar{c}) \rightarrow s\ell^+\ell^-$

$$\mathcal{B}(B \rightarrow K\eta_c) \times \mathcal{B}(\eta_c \rightarrow \gamma\gamma) \simeq 4 \cdot 10^{-7}$$

$$\mathcal{B}(B \rightarrow K\chi_{c0}) \times \mathcal{B}(\chi_{c0} \rightarrow \gamma\gamma) \simeq 2 \cdot 10^{-7}$$

$$\mathcal{B}(B \rightarrow K\chi_{c2}) \times \mathcal{B}(\chi_{c2} \rightarrow \gamma\gamma) < 1 \cdot 10^{-8}$$

factorization forbidden modes into $\chi_{c0,c2}$ sizable !

q^2 not large enough to expand charm loop function $\kappa_c(q^2, m_c^2) = \kappa_c(q^2, 0) + \mathcal{O}(m_c^2/q^2) \simeq 1/2$ for model-independent estimate [Grinstein, Pirjol '04](#);

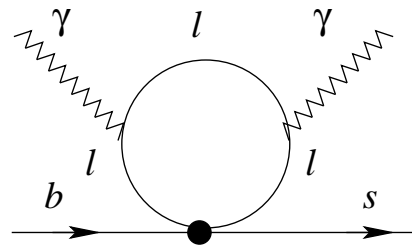
Breit-Wigner parametrization

contributions via $B \rightarrow (K^* \rightarrow K\gamma)\gamma$ with $E_\gamma \simeq m_B/2$ and $B \rightarrow K\eta^{(\prime)} \rightarrow K\gamma\gamma$ with $q^2 \simeq m_{\eta^{(\prime)}}^2$ outside OPE region

NP in C_7 tightly constrained by $\mathcal{B}(B \rightarrow X_s\gamma)$

QCD penguins $\sim \bar{s}\gamma_\mu b \sum_q \bar{q}\gamma^\mu q$ small coefficients $C_{SM}^{QCD}/C_2 \sim 10^{-2}$, significant enhancements in conflict with hadronic 2-bodies $B \rightarrow K\pi$

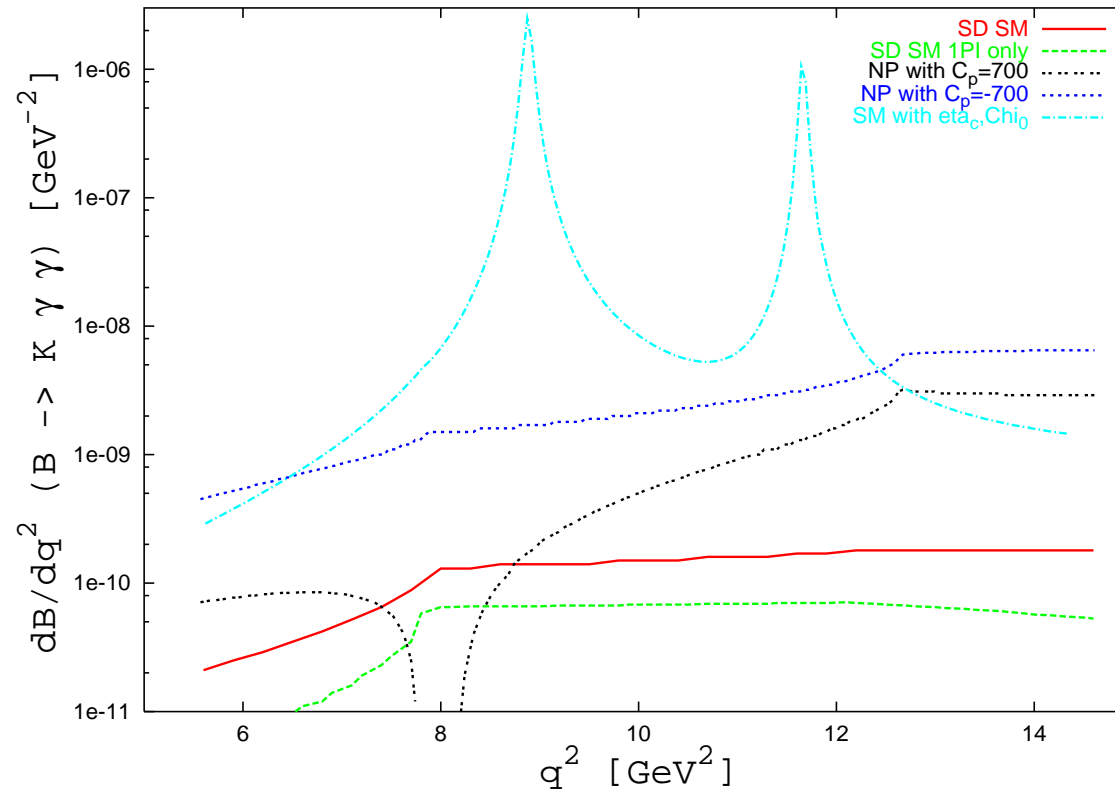
$$\mathcal{O}_{S(P)}^\ell = \frac{\alpha_{em}}{4\pi} \bar{s} R b \bar{\ell} (\gamma_5) \ell \quad \ell = e, \mu, \tau$$



$b \rightarrow s\tau^+\tau^-$ couplings essentially unconstrained $\mathcal{B}(B_s \rightarrow \tau^+\tau^-) < 5\%$

model-independently $|C_{S(P)}^\tau| \lesssim 700$ non- ℓ -universal; $C_{S(P)}^{\tau SM} \simeq m_b m_\tau / m_W^2$

$B \rightarrow K \gamma \gamma$ di-photon spectrum



$\mathcal{B}(B \rightarrow K \gamma \gamma)_{SM}^{OPE} = 1 \cdot 10^{-9}$ with 20,50 % uncertainty from FF, μ

$\mathcal{B}(B \rightarrow K \gamma \gamma)_{SM}^{OPE 1PI} = 0.5 \cdot 10^{-9}$; $\mathcal{B}(B \rightarrow K \gamma \gamma)_{NP_T}^{OPE} \simeq (1 - 2) \cdot 10^{-8}$

- double radiative $B \rightarrow (X_s, K^{(*)})\gamma\gamma$ decays are interesting modes
 - reasonable experimental signature
 - in some NP scenarios $b \rightarrow s\gamma\gamma$ is **complementary** to $b \rightarrow s\gamma$
 - exclusive $B \rightarrow K^{(*)}\gamma\gamma$ decays can be systematically studied in some region of phase space with HQET/SCET: at lowest order in $1/m_b$ only non-perturbative object is the (known) $B \rightarrow K$ form factor; di-photon modes way more complex than $B \rightarrow K^*\gamma$
- branching ratios small in SM
$$\mathcal{B}(B \rightarrow K\gamma\gamma) \sim \left[\frac{|\kappa_c Q_u^2 C_2|^2}{|C_9|^2 + |C_{10}|^2} \text{ or } \frac{|C_7|^2}{|C_9|^2 + |C_{10}|^2} \right] \times \mathcal{B}(B \rightarrow K\ell^+\ell^-) \simeq \mathcal{O}(10^{-9})$$
- factor 10^{-2} smaller than in previous publications (to be revised)

- in SM, charmonium resonances dominate short-distance amplitude in OPE region, i.e. both photons hard, but not maximally $E_{1,2} < m_b/2$
- NP in scalar/pseudoscalar FCNC coupling to taus can enhance the branching ratios by 1 order of magnitude, outside the η_c, χ_{c0} peaks
- similar conclusions for K^* mode: $\mathcal{B}(B \rightarrow K^* \gamma \gamma)_{SM}^{OPE 1PI} = \text{few} \cdot 10^{-9}$