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

Gudrun Hiller
CERN and Munich (ASC/LMU)

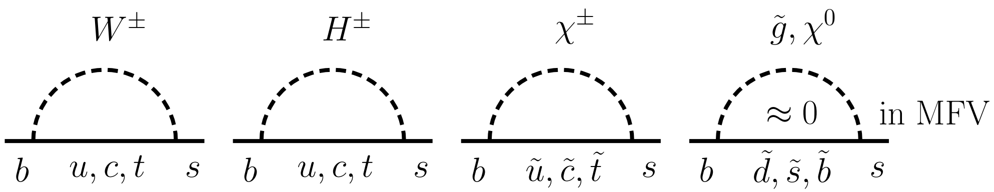
ETH Lausanne, February 7, 2005

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

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

FCNC $b \to s$ transitions

- 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: $B \to K^* \gamma$, $B \to X_s \gamma$, $B \to K \mu^+ \mu^-$, $B \to \Phi K$,...

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 $b \to s\gamma\gamma$ decays

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

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

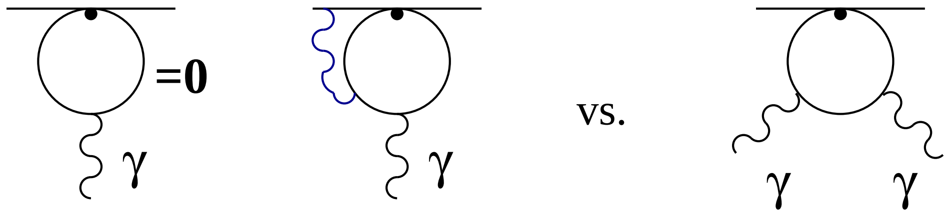
- α_{em} suppression of the rate
- correlation with $b \to s\gamma$ (bremsstrahlung)
- hadronic physics more complicated, non-local matrix element

true, but...

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

- branching ratios of $\mathcal{O}(10^{-8})$ accessible at current (future) $B-$experiments; same order in α_{em} as $b \to s\ell\ell$

- NP in 4-Fermi operators is LO in $s\gamma\gamma$, subleading in $b \to s\gamma$



- $B \to (X_s, K, K^*)\gamma\gamma$ 3-body decay, design interesting (clean and sensitive) observables such as $A_{FB}(B \to K^*\mu^+\mu^-)$

- interesting hadronic physics; non-perturbative functions related to other decay modes: $B \to K^{(*)}$ form factors, λ_B

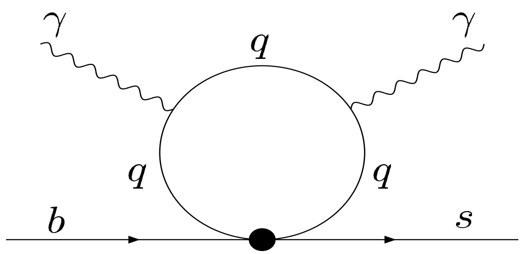
$$\mathcal{H}_{\rm eff}(b \to s\gamma) = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

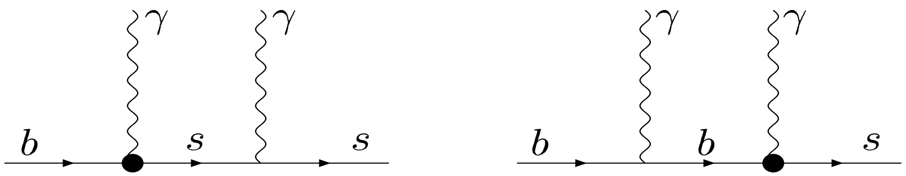
$\mathcal{O}_{1,2} \simeq (\bar{s}\gamma^\mu Lc)(\bar{c}\gamma_\mu Lb)$, em dipole operator $\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \bar{s}\sigma^{\mu\nu} Rb F_{\mu\nu}$

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

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

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





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

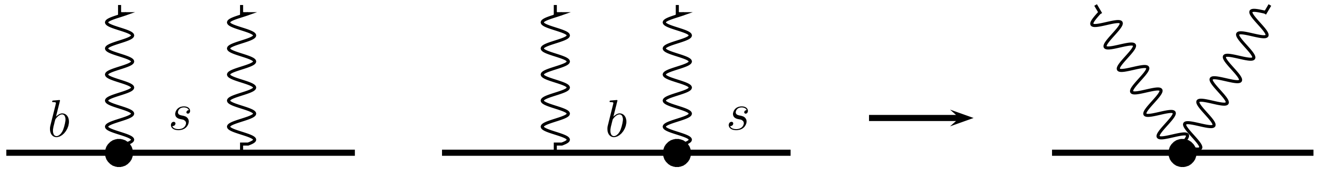
modes	$\mathcal{B}_{SM}$	90 % C.L. bounds	2HDM	RPV
$B_d \to \gamma\gamma$	$3.1^{+6.4+1.0+1.0+1.3}_{-1.6-0.9-0.7-1.0} \cdot 10^{-8}$	$1.7 \cdot 10^{-6}$ BaBar	–	–
$B_s \to \gamma\gamma$	$1.2^{+2.5+0.3+0.3+0.01}_{-0.6-0.3-0.2-0.02} \cdot 10^{-6}$	$1.48 \cdot 10^{-4}$ L3	2	16
$B \to X_s\gamma\gamma$	$(3.7 - 5.1) \cdot 10^{-7}$	–	2-3	5
$B \to K\gamma\gamma$	$(0.5 - 5.6) \cdot 10^{-7}$ A,B	–	–	–
$B \to K^*\gamma\gamma$	few $\cdot 10^{-7}$ C	–	–	–

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

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

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

Model-independent estimate for exclusive decays



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

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

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

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 $Q = \{m_b, E_K, Q_{1,2}^{s,b}, \sqrt{q^2}\}$

$$\bar{s} W_7^{\mu\nu} b \epsilon(k_1)^\mu \epsilon(k_2)^\nu \;\to\; -\frac{1}{2}\left\{\left(\frac{1}{(Q_1^s)^2}-\frac{1}{(Q_1^b)^2}\right)\mathcal{Q}_1+\left(\frac{1}{(Q_2^s)^2}-\frac{1}{(Q_2^b)^2}\right)\mathcal{Q}_1' + \frac{m_b E_K}{(Q_1^s)^2 (Q_2^b)^2}\mathcal{Q}_2+\frac{m_b E_K}{(Q_2^s)^2 (Q_1^b)^2}\mathcal{Q}_2'\right\}$$

$\mathcal{Q}_1 = \frac{m_b}{4}\bar{\chi}\sigma_{\mu\nu}\sigma_{\alpha\beta} R h_v F_1^{\alpha\beta} F_2^{\mu\nu}$ $\qquad$ $\mathcal{Q}_2 = -2 i m_b \bar{\chi}\sigma_{\mu\nu} R h_v F_1^{\mu\nu} F_2^{\alpha\beta} v^\alpha n^\beta$

$\mathcal{Q}_3 = \bar{\chi}\gamma^\mu L h_v F_1^{\alpha\beta} D_\alpha \tilde{F}_{2\,\beta\mu}$ (1PI) Adler-Rosenberg tensor

1PR and 1PI same order in $1/Q$! (in $B \to \gamma\gamma$ 1PR dominates)

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

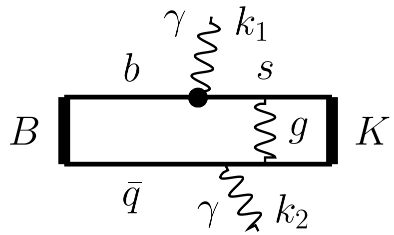
$\langle K(n)|\bar{\chi}\sigma_{\mu\nu} h_v|B(v)\rangle = -2iE_K \zeta(E_K)\,(v_\mu n_\nu - v_\nu n_\mu)$

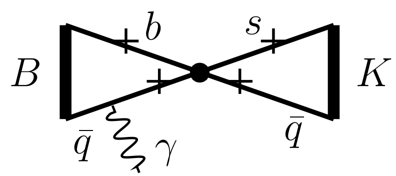
only one form factor $\zeta = f_+$, known from $B \to K\ell\ell$

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

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

- photon radiation off the spectator
  - soft gluons: kinematically forbidden ! $\boldsymbol{p}_s \simeq -\boldsymbol{k}_1$ and $\boldsymbol{p}_{\bar{q}} \simeq -\boldsymbol{k}_2$: K cannot be formed if-as in OPE region-angle between γs is large
  - energetic gluons: α_s-suppressed; in SCET $\bar{\chi} h_v \gamma$-coll. g operator
- weak annihilation in $B^\pm \to K^\pm \gamma\gamma$ thru $\mathcal{O}^u_{1,2} \simeq (\bar{s}\gamma^\mu L u)(\bar{u}\gamma_\mu L b)$ 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 $\mu = m_b$





Resonance contributions

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

$$\mathcal{B}(B \to K\eta_c) \times \mathcal{B}(\eta_c \to \gamma\gamma) \simeq 4 \cdot 10^{-7}$$
$$\mathcal{B}(B \to K\chi_{c0}) \times \mathcal{B}(\chi_{c0} \to \gamma\gamma) \simeq 2 \cdot 10^{-7}$$
$$\mathcal{B}(B \to K\chi_{c2}) \times \mathcal{B}(\chi_{c2} \to \gamma\gamma) < 1 \cdot 10^{-8}$$

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

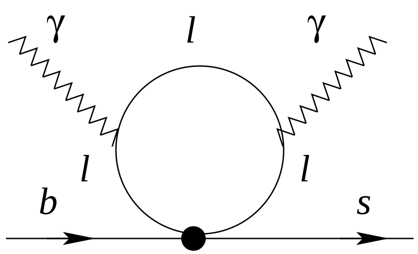
q^2 not large enough to expand charm loop function $\kappa_c(q^2, m_c^2) = \kappa_c(q^2, 0)$ $+\mathcal{O}(m_c^2/q^2) \simeq 1/2$ for model-independent estimate Grinstein,Pirjol ‘04; Breit-Wigner parametrization

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

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

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 $B \to K\pi$

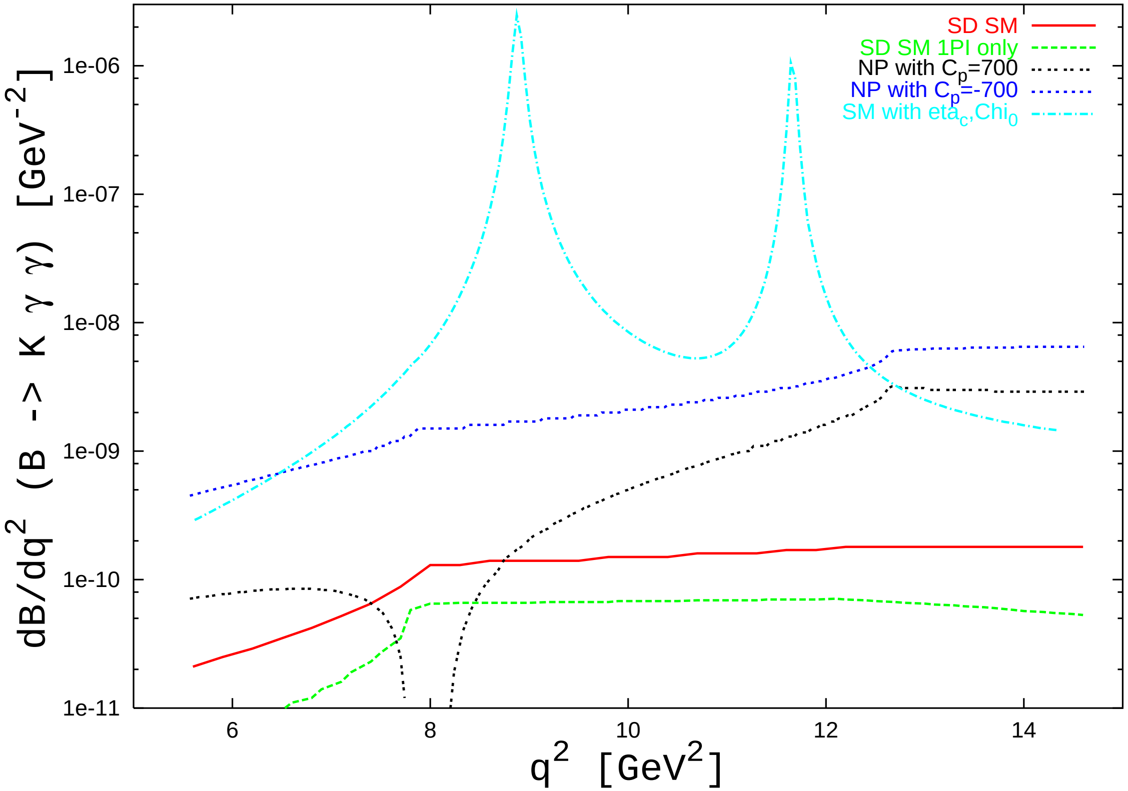
$$\mathcal{O}^\ell_{S(P)} = \frac{\alpha_{em}}{4\pi}\bar{s}Rb\bar{\ell}(\gamma_5)\ell \qquad \ell = e, \mu, \tau$$



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

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

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



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

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

Summary

- double radiative $B \to (X_s, K^{(*)})\gamma\gamma$ decays are interesting modes
  - reasonable experimental signature
  - in some NP scenarios $b \to s\gamma\gamma$ is complementary to $b \to s\gamma$
  - exclusive $B \to K^{(*)}\gamma\gamma$ 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) $B \to K$ form factor; di-photon modes way more complex than $B \to K^*\gamma$
- branching ratios small in SM
  $\mathcal{B}(B \to K\gamma\gamma) \sim \left[\frac{|\kappa_c Q_u^2 C_2|^2}{|C_9|^2+|C_{10}|^2} \text{or} \frac{|C_7|^2}{|C_9|^2+|C_{10}|^2}\right] \times \mathcal{B}(B \to K\ell^+\ell^-) \simeq \mathcal{O}(10^{-9})$
- 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: $\mathcal{B}(B \to K^* \gamma\gamma)^{OPE\,1PI}_{SM} =$ few $\cdot\, 10^{-9}$