Theory of inclusive and exclusive radiative B decays

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Recently I contributed to
Belle II Theory interface Platform (B2TiP) report

Radiative and Electroweak Penguin B Decays chapter

This influenced this talk
Outline

- The Big picture

- Inclusive $\bar{B} \rightarrow X_q\gamma$

- Exclusive $b \rightarrow q\gamma$

- Conclusions
The Big picture
Motivation

- Radiative B decays are... an important probe of New Physics
  - $b \rightarrow s\gamma$ is a flavor changing neutral current (FCNC)
    - In SM no FCNC at tree level, arises as a loop effect:

- $b \rightarrow s\gamma$ can have contribution from new physics e.g. SUSY
  (only one diagram shown):

- Radiative B decays constrain many models of new physics
Motivation

- Radiative B decays are... theoretically clean

- Since $5 \text{GeV} \sim m_b \gg \Lambda_{\text{QCD}} \sim 0.5 \text{GeV}$

  Observables expanded as a power series in $\Lambda_{\text{QCD}}/m_b \sim 0.1$

- $\Gamma_{77}(\bar{B} \to X_q \gamma)$ known to $\Lambda_{\text{QCD}}^5/m_b^5$

- Allows to control non-perturbative effects
Motivation

- Radiative $B$ decays are... theoretically interesting
- Test of basic QFT tools
  - Factorization theorems
  - Operator product expansion
- Window to non-perturbative physics, e.g.


- At leading twist the photon spectrum is the $B$-meson pdf
Motivation

- Radiative B decays have... large impact

- CLEO top cited papers: #1 ($\bar{B} \rightarrow X_s \gamma$ '95), #2 (CLEO-II detector) #3 ($\bar{B} \rightarrow K^{*}\gamma$ '93), #4 ($\bar{B} \rightarrow X_s \gamma$ '01)

- Belle top cited papers: #4 ($\bar{B} \rightarrow X_s \gamma$ '01)

- BaBar top cited papers: #21 ($\bar{B} \rightarrow X_s \ell^+\ell^-$ '04)

- Theoretical predictions: hundreds of citations
Themes

- Interplay of perturbative (short distance) and non-perturbative (long distance) physics

- Asymmetries:
  - Isospin asymmetries ($\bar{B} \to X_s\gamma$, $\bar{B} \to K^*\gamma$, $\bar{B} \to \rho\gamma$)
  - CP asymmetries ($\bar{B} \to X_s\gamma$, $\bar{B} \to K^*\gamma$, $\bar{B} \to \rho\gamma$)
  and even

- Isospin difference of CP asymmetries

[Benzke, Lee, Neubert GP, PRL 106, 141801 (2011);
BaBar PRD 90, 092001 (2014)]
Perturbative and Non-perturbative

The perturbative physics is described by the effective Hamiltonian

\[ \mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left( C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3,\ldots,10} C_i Q_i + C_{7\gamma} Q_{7\gamma} + C_{8g} Q_{8g} \right) \]

- Most important: \( Q_{7\gamma}, Q_{8g}, \) and \( Q_1 \)

\[
\begin{align*}
Q_{7\gamma} & = \frac{-e}{8\pi^2} m_b \bar{s}s \sigma_{\mu\nu}(1 + \gamma_5) F^{\mu\nu} b \\
Q_{8g} & = \frac{-g_s}{8\pi^2} m_b \bar{s}s \sigma_{\mu\nu}(1 + \gamma_5) G^{\mu\nu} b \\
Q_1^q & = (\bar{q} b)_{VA} (\bar{s} q)_{VA} (q = u, c)
\end{align*}
\]

- \( C_i \) known at NNLO

Non-perturbative effects arise at \( \Lambda_{\text{QCD}} / m_b \)
Inclusive $\bar{B} \to X_q \gamma$
$\bar{B} \rightarrow X_q\gamma$

- **Theoretical predictions**
  - $\text{Br}(\bar{B} \rightarrow X_s\gamma) = (3.36 \pm 0.23) \times 10^{-4}$
  - $\text{Br}(\bar{B} \rightarrow X_d\gamma) = (1.73^{+0.12}_{-0.22}) \times 10^{-5}$
  
      [Misiak et al., PRL 114, 221801 (2015)]

- **Experimental values**
  - $\text{Br}(\bar{B} \rightarrow X_s\gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$
    
      [Heavy Flavor Averaging Group, arXiv:1412.7515 [hep-ex]]
  - $\text{Br}(\bar{B} \rightarrow X_d\gamma) = (1.41 \pm 0.57) \times 10^{-5}$
    
      [BaBar PRD 82, 051101 (2010); Misiak et al., PRL 114, 221801 (2015)]

  Extrapolated to $E_\gamma > 1.6$ GeV
\[ \Gamma(\bar{B} \rightarrow X_s \gamma) : \text{Perturbative} \]

- At leading power in \( \Lambda_{QCD}/m_b \)
  \[ \Gamma(\bar{B} \rightarrow X_s \gamma) = \Gamma(b \rightarrow s\gamma) \]

- Since \( \Gamma \propto |\mathcal{H}_{\text{eff}}|^2 \), need pairs of operators
  - \( Q_7 \gamma - Q_7 \gamma \) known at NNLO
  - \( Q_8 \gamma - Q_8 \gamma \) known at NNLO
  - \( Q_{1,2} - Q_7 \gamma \) known at NNLO for two \( m_c \) limits

- Interpolation in \( m_c \) leads to \( \pm 3\% \) perturbative uncertainty

- Future improvement requires calculation at physical \( m_c \) (challenging)
$\Gamma(\bar{B} \rightarrow X_S \gamma) : \text{Non-perturbative}$

- $Q_{7\gamma} - Q_{7\gamma}$ obeys local OPE

$$\Gamma_{77} = \sum_{n=0}^{\infty} \frac{1}{m_b^n} \sum_k c_{k,n} \langle O_{k,n} \rangle$$

- $c_{k,n}$ are Wilson coefficients: perturbative
- $\langle O_{k,n} \rangle$ are matrix elements of HQET operators: non-perturbative

- Current status
  - $n = 0$ free quark
  - $n = 1$ vanishes
  - $c_{k,2}$ known at $\mathcal{O}(\alpha_s)$
    [Ewerth, Gambino, Nandi, NPB 830 278 (2010)]
  - $c_{k,\{3,4,5\}}$ known at $\mathcal{O}(\alpha_s^0)$, but $\langle O_{k,n} \rangle$ not well known
    [Gambino, Healey, Turczyk PLB 763, 60 (2016)]
\[ \Gamma(\bar{B} \to X_s \gamma) : \text{Non-perturbative} \]

- \( Q_7 \to Q_7 \) obeys local OPE

- Other operators are more complicated
  lead to resolved photon contributions, e.g.
  - \( Q_8 \to b \to s g \to s\bar{q}q\gamma \)
  - \( Q_1 \to b \to s\bar{c}c \to s g\gamma \)

[Benzke, Lee, Neubert GP, JHEP 08 099 (2010); GP CKM 2010 talk]

- For rate \( \Gamma \sim \bar{J} \otimes h \)
  - \( \bar{J} \) perturbative
  - \( h \) non-perturbative: modeled or extract from (future) data

- At \( \Lambda_{QCD}/m_b \) contribution from
  \( Q_1 - Q_7 \), \( Q_7 \to Q_8 \), \( Q_8 \to Q_8 \)
  Total uncertainty 5% (largest)
\[ \Gamma(\bar{B} \rightarrow X_s \gamma) : \text{Non-perturbative} \]

- At \( \Lambda_{QCD}/m_b \) contribution from
  \[ Q_1 - Q_{7\gamma}, Q_{7\gamma} - Q_{8g}, Q_{8g} - Q_{8g} \]
  Total uncertainty 5\% (largest)

- Improvements:
  - Knowledge of \( \langle O_{k,n} \rangle \) ⇒ improve \( Q_1 - Q_{7\gamma} \)
  - Isospin asymmetry between \( B^+ \) and \( \bar{B}^0 \) ⇒ improve \( Q_{7\gamma} - Q_{8g} \)

Data driven!
\[ \Gamma(\bar{B} \rightarrow X_s \gamma) : \text{CP asymmetry} \]

- Resolved photon contributions affect CP asymmetry
  Change \(\sim 0.5\%\) from perturbative effects to \([-0.6\%, 2.8\%]\)

- New physics test: isospin difference of CP asymmetries: \(\Delta A_{CP}\)

- BaBar measurement \(\Delta A_{CP} = +(5.0 \pm 3.9 \pm 1.5)\%\)
  Also constrain \(\text{Im } C_{8g}/C_{7\gamma}:\)
  \[-1.64 \leq \text{Im } C_{8g}/C_{7\gamma} \leq 6.52, \ 90\%\text{CL}\]
  [BaBar PRD 90, 092001 (2014)]
\[ \Gamma(\bar{B} \to X_s \gamma) : \text{Photon spectrum} \]

- Resolved photon effects for spectrum not known numerically relevant for HQET parameters and \( |V_{cb}| \) and \( |V_{ub}| \)

- Comparison between theory and experiment relays on extrapolation from measured \( E_\gamma \sim 1.9 \text{ GeV} \) to \( E_\gamma > 1.6 \text{ GeV} \)
  The issue of extrapolation should be revisited

- Both can benefit from detailed \( E_\gamma \) cut effects
Exclusive $\bar{b} \rightarrow q\gamma$
Exclusive $\bar{b} \to q\gamma$

- Decays such as
  - $b \to s\gamma : B_{(q,s)} \to (K^*, \phi)\gamma$
  - $b \to d\gamma : B_{(q,s)} \to (\rho/\omega, \bar{K}^*)\gamma$

- Combination of Short Distance (SD) effects from $Q_7\gamma$
  (still requires $B \to V$ form factors)
  and Long Distance (LD) effects from other operators

- Look at ratios and asymmetries to reduce hadronic uncertainties
Ratios

- \( \text{Br}(B \rightarrow K^*\gamma)/\text{Br}(B_s \rightarrow \phi\gamma) \)

- **SM prediction**

  \[ R_{K^*\gamma/\phi\gamma}^{SM} = 0.78 \pm 0.18 \]


- **LHCb measurement**

  \[ R_{K^*\gamma/\phi\gamma}^{\text{exp}} = 1.23 \pm 0.12 \]

  [LHCb PRD 85 112013 (2012); LHCb NPB 867 1 (2013)]
Isospin asymmetries

- **SM prediction**

\[
\bar{a}_I^{\text{SM}}(K^*\gamma) = (4.9 \pm 2.6)\%
\]
\[
\bar{a}_I^{\text{SM}}(\rho\gamma) = (5.2 \pm 2.8)\%
\]

[Lyon, Zwicky, PRD 88 094004 (2013)]

- **Experimental measurement**

\[
\bar{a}_I^{\text{exp}}(K^*\gamma) = (5.2 \pm 2.6)\%
\]
\[
\bar{a}_I^{\text{exp}}(\rho\gamma) = (30^{+16}_{-13})\%
\]

[Heavy Flavor Averaging Group, arXiv:1207.1158 [hep-ex]]
CP asymmetries

- Time dependent CP asymmetries

- SD only

\[ S^{\text{SM, SD}}_{K^*(K_s\pi^0)\gamma} = -2 \frac{m_s}{m_b} \sin 2\phi_1 \]

\[ S^{\text{SM, SD}}_{\rho^0(\pi^+\pi^-)\gamma} = 0 \]

- Including LD effects

\[ S^{\text{SM}}_{K^*(K_s\pi^0)\gamma} = -(2.3 \pm 1.6)\% \]

\[ S^{\text{SM}}_{\rho^0(\pi^+\pi^-)\gamma} = (0.2 \pm 1.6)\% \]

[ Ball, Zwicky PLB 642 478 (2006); Ball, Jones, Zwicky PRD 75 054004 (2007)]
Photon Helicity

- Photon can have two helicities in $B \rightarrow V\gamma$
- Photon helicity sensitive to right handed new physics
- LHCb observed up-down asymmetry proportional to the photon polarization in $B^{\pm} \rightarrow K^{\pm}\pi^{\mp}\pi^{\pm}\gamma$
  
  [LHCb, PRL 112, 161801 (2014)]

- “.. the values for the up-down asymmetry, may be used, if theoretical predictions become available, to determine for the first time a value for the photon polarization, and thus constrain the effects of physics beyond the SM in the $b \rightarrow s\gamma$ sector”
  
  [LHCb, PRL 112, 161801 (2014)]

- See also Kou’s talk at CKM 2014
Conclusions
Conclusions

- Other radiative decays: $B \to \gamma\gamma$, $B \to X_q\gamma\gamma$

- Radiative B decays have rich structure
  Show intricate interplay of perturbative and non-perturbative physics

- The theory is mature, but there is still room for improvements

- LHCb and soon Belle II will motivate further theoretical work

- Thank you!