Theory of inclusive and exclusive radiative B decays

Gil Paz

Department of Physics and Astronomy, Wayne State University

Comment

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

  Radiative and Electroweak Penguin B Decays chapter
  Authors: T. Feldmann, U. Haisch, M. Misiak, GP, E. Kou, R. Zwicky

  This influenced this talk

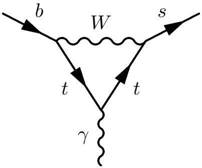
Outline

- The Big picture
- Inclusive $\bar{B} \to X_q\gamma$
- Exclusive $b \to q\gamma$
- Conclusions

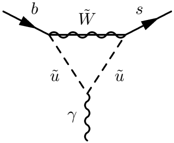
The Big picture

Motivation

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



- $b \to s\gamma$ 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

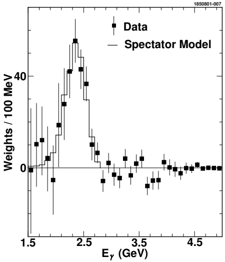
Motivation

- Radiative B decays are... theoretically interesting

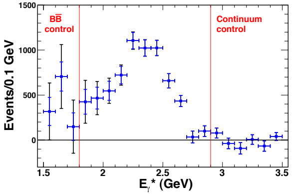
- Test of basic QFT tools
  - Factorization theorems
  - Operator product expansion

- Window to non-perturbative physics, e.g.

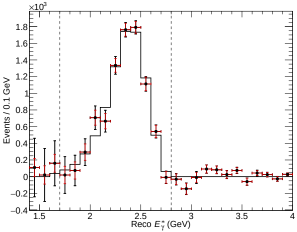
CLEO (2001)



BaBar (2012)



Belle (2016)



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

Motivation

- Radiative B decays have... large impact
- CLEO top cited papers: #1 ($\bar{B} \to X_s\gamma$ '95), #2 (CLEO-II detector)
  #3 ($\bar{B} \to K^*\gamma$ '93), #4 ($\bar{B} \to X_s\gamma$ '01)
- Belle top cited papers: #4 ($\bar{B} \to X_s\gamma$ '01)
- BaBar top cited papers: #21 ($\bar{B} \to X_s\ell^+\ell^-$ '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

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

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

$$\begin{aligned} Q_{7\gamma} &= \frac{-e}{8\pi^2} m_b \bar{s}\sigma_{\mu\nu}(1+\gamma_5)F^{\mu\nu} b \\ Q_{8g} &= \frac{-g_s}{8\pi^2} m_b \bar{s}\sigma_{\mu\nu}(1+\gamma_5)G^{\mu\nu} b \\ Q_1^q &= (\bar{q}b)_{V-A}(\bar{s}q)_{V-A} \quad (q = u, c) \end{aligned}$$

  - C_i known at NNLO

- Non-perturbative effects arise at $\Lambda_{\rm QCD}/m_b$

Inclusive $\bar{B} \to X_q \gamma$

$\bar{B} \to X_q\gamma$

- Theoretical predictions
  - $\text{Br}(\bar{B} \to X_s\gamma) = (3.36 \pm 0.23) \times 10^{-4}$
  - $\text{Br}(\bar{B} \to X_d\gamma) = (1.73^{+0.12}_{-0.22}) \times 10^{-5}$

  [Misiak *et al.*, PRL **114**, 221801 (2015)]

- Experimental values
  - $\text{Br}(\bar{B} \to X_s\gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$

    [Heavy Flavor Averaging Group, arXiv:1412.7515 [hep-ex]]
  - $\text{Br}(\bar{B} \to X_d\gamma) = (1.41 \pm 0.57) \times 10^{-5}$

    [BaBar PRD **82**, 051101 (2010);

    Misiak *et al.*, PRL **114**, 221801 (2015)]

    Extrapolated to $E_\gamma > 1.6$ GeV

$\Gamma(\bar{B} \to X_s\gamma)$: Perturbative

- At leading power in $\Lambda_{\rm QCD}/m_b$
  $\Gamma(\bar{B} \to X_s\gamma) = \Gamma(b \to s\gamma)$

- Since $\Gamma \propto |\mathcal{H}_{\rm eff}|^2$, 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)

$\Gamma(\bar{B} \to X_s\gamma)$: 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)]

$\Gamma(\bar{B} \to X_s\gamma)$: Non-perturbative

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

- Other operators are more complicated
  lead to resolved photon contributions, e.g.

- $Q_{8g} \Rightarrow b \to sg \to s\bar{q}q\gamma$
- $Q_1 \Rightarrow b \to s\bar{c}c \to sg\gamma$

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

$\Gamma(\bar{B} \to X_s\gamma)$: Non-perturbative

- At Λ_{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 $\langle O_{k,n} \rangle \Rightarrow$ improve $Q_1 - Q_{7\gamma}$
- Isospin asymmetry between B^+ and $\bar{B}^0 \Rightarrow$ improve $Q_{7\gamma} - Q_{8g}$

Data driven!

$\Gamma(\bar{B} \to X_s\gamma)$: CP asymmetry

- Resolved photon contributions affect CP asymmetry
  Change $\sim 0.5\%$ from perturbative effects to $[-0.6\%, 2.8\%]$
  [Benzke, Lee, Neubert GP, PRL **106**, 141801 (2011);
  GP CKM 2012 talk]

- New physics test: isospin difference of CP asymmetries: ΔA_{CP}
  [Benzke, Lee, Neubert GP, PRL **106**, 141801 (2011);
  GP CKM 2012 talk]

- BaBar measurement $\Delta A_{CP} = +(5.0 \pm 3.9 \pm 1.5)\%$
  Also constrain Im $C_{8g}/C_{7\gamma}$:

$$-1.64 \leq \mathrm{Im}\, C_{8g}/C_{7\gamma} \leq 6.52, \quad 90\%\mathrm{CL}$$

  [BaBar PRD **90**, 092001 (2014)]

$\Gamma(\bar{B} \to X_s\gamma)$: 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 $E_\gamma \sim 1.9$ GeV to $E_\gamma > 1.6$ GeV
  The issue of extrapolation should be revisited

- Both can benefit from detailed E_γ *cut effects*

Exclusive $\bar{b} \to q\gamma$

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- 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

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

- SM prediction

$$R^{\text{SM}}_{K^*\gamma/\phi\gamma} = 0.78 \pm 0.18$$

[Lyon, Zwicky, PRD **88** 094004 (2013) updated in B2TiP report]

- LHCb measurement

$$R^{\text{exp}}_{K^*\gamma/\phi\gamma} = 1.23 \pm 0.12$$

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

Isospin asymmetries

- SM prediction

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

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

- Experimental measurement

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

[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 $B \to V\gamma$
- Photon helicity sensitive to right handed new physics
- LHCb observed up-down asymmetry proportional to the photon polarization in $B^{\pm} \to K^{\pm}\pi^{\mp}\pi^{\pm}\gamma$
  [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 $b \to s\gamma$ 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!