Direct CP Asymmetry in $\bar{B} \to X_{s,d}\,\gamma$

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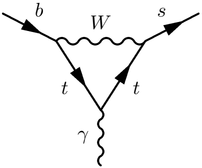
PRL **106**, 141801 (2011) [arXiv:1012.3167 (hep-ph)]

$\bar{B} \to X_s \gamma$ in the SM

- $b \to s\gamma$ is a flavor changing neutral current (FCNC)
  In SM no FCNC at tree level
  Arises as a loop effect:



gives rise to the operator:

$$Q_{7\gamma} = \frac{-e}{8\pi^2} m_b \bar{s} \sigma_{\mu\nu} F^{\mu\nu} (1+\gamma_5) b$$

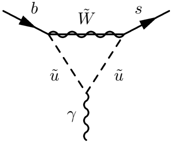
part of the effective Hamiltonian

$$\mathcal{H}_{\rm eff} \ni \frac{G_F}{\sqrt{2}} C_{7\gamma} Q_{7\gamma}$$

Constraints on New Physics: $\bar{B} \to X_s\gamma$

- **$\bar{\mathbf{B}} \to \mathbf{X_s}\gamma$ is an important probe of new physics**

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



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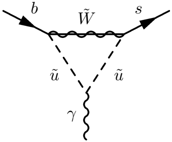

  leads to same operator, modifies $C_{7\gamma}$

- But $Q_{7\gamma}$ is not the whole story...

How To Make a Photon?

- Produce it directly...

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- Or make a gluon or a quark pair

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

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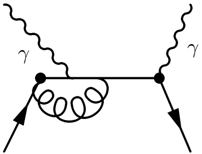
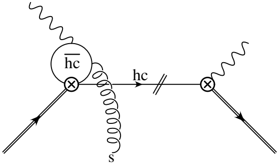
  and convert them to a photon
- But it will cost you..

α_s or $1/m_b$





Effective Hamiltonian

- For $\bar{B} \to X_s \gamma$ need Effective Hamiltonian

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

  - At leading power only $Q_{7\gamma} - Q_{7\gamma}$ contribute
  - At higher orders need other $Q_i - Q_j$ contributions

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  - At leading power only $Q_{7\gamma} - Q_{7\gamma}$ contribute
  - At higher orders need other $Q_i - Q_j$ contributions
  - Most important: $Q_{7\gamma}$, Q_{8g}, and Q_1

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

- Ratio of Wilson coefficients:

$$\begin{array}{ccccc} C_1 & : & C_{7\gamma} & : & C_{8g} \\ & & & & \\ 3 & : & 1 & : & \frac{1}{2} \end{array}$$

CP asymmetry

- Measured [Heavy Flavor Averaging Group, arXiv:1010.1589]

$$\mathcal{A}_{X_s\gamma} = \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)} = -(1.2 \pm 2.8)\%$$

Experiments measure $\mathcal{A}_{X_s\gamma}(E_\gamma \geq E_0)$ where $1.9 \leq E_0 \leq 2.1\,\text{GeV}$

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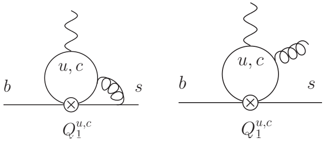
  Experiments measure $\mathcal{A}_{X_s\gamma}(E_\gamma \geq E_0)$ where $1.9 \leq E_0 \leq 2.1\,\mathrm{GeV}$
- Theoretically, thought to be of a perturbative origin, e.g.



  We need
  - "Weak" (CP odd) phase: CKM phase $\propto \lambda^2$, C_i of $\mathcal{H}_{\mathrm{eff}}$ (not in SM)
  - "Strong" (CP even) phase: α_s suppressed

CP asymmetry

- The perturbative prediction

  [Kagan, Neubert PRD **58**, 094012 (1998); Asatryan, Asatrian, Yeghiyan, Savvidy Int. J. Mod. Phys. A **16**, 3805 (2001)]

$$\mathcal{A}^{\rm dir}_{X_s\gamma}(E_0) = \alpha_s \left\{ \frac{40}{81}\,{\rm Im}\,\frac{C_1}{C_{7\gamma}} - \frac{8z}{9}\left[v(z)+b(z,\delta)\right]{\rm Im}\left[(1+\epsilon_s)\,\frac{C_1}{C_{7\gamma}}\right] \right.$$

$$\left. - \frac{4}{9}\,{\rm Im}\,\frac{C_{8g}}{C_{7\gamma}} + \frac{8z}{27}\,b(z,\delta)\,\frac{{\rm Im}[(1+\epsilon_s)\,C_1\,C_{8g}^*]}{|C_{7\gamma}|^2} + \frac{16z}{27}\,\tilde{b}(z,\delta)\left|\frac{C_1}{C_{7\gamma}}\right|^2 {\rm Im}\,\epsilon_s \right\}$$

where $\delta = (m_b - 2E_0)/m_b$, $z = (m_c/m_b)^2$

and $\epsilon_s = (V_{ub}V_{us}^*)/(V_{tb}V_{ts}^*) \approx \lambda^2(i\bar{\eta} - \bar{\rho})$

CP asymmetry

- Taking $m_c^2 = \mathcal{O}(m_b \Lambda_{\rm QCD})$, expand $z, \delta = \mathcal{O}(\Lambda_{\rm QCD}/m_b)$

$$\mathcal{A}_{X_s\gamma}^{\rm dir} = \alpha_s \left\{ \quad \frac{40}{81}\,{\rm Im}\frac{C_1}{C_{7\gamma}} - \frac{4}{9}\,{\rm Im}\frac{C_{8g}}{C_{7\gamma}} \right.$$
$$\left. - \frac{40\Lambda_c}{9m_b}\,{\rm Im}\left[\left(1+\epsilon_s\right)\frac{C_1}{C_{7\gamma}}\right] + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}^2}{m_b^2}\right)\right\}$$

where $\Lambda_c(m_c, m_b) \approx 0.38\,\text{GeV}$

- In the SM triple suppression:
α_s, ${\rm Im}(\epsilon_s) \sim \lambda^2$, and $(m_c/m_b)^2 \sim \Lambda_{\rm QCD}/m_b$

CP asymmetry in the Standard Model

- In SM asymmetry around 0.5%
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  $\mathcal{A}^{\rm SM}_{X_s\gamma} = (0.44\,^{+0.15}_{-0.10} \pm 0.03\,^{+0.19}_{-0.09})\%$
  errors: m_c/m_b, CKM parameters, and scale

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CP asymmetry in Future B factories

- SM asymmetry around 0.5%
- Measured, $\mathcal{A}_{X_s\gamma} = -(1.2 \pm 2.8)\%$, room for new physics
- One of the goals of the super B factories:
  - Super B in Italy
  - Belle 2 in Japan

CP asymmetry in Future B factories

Conceptual Design Report
arXiv:0709.0451

Table 2-2. *The expected precision of some of the most important measurements that can be performed at SuperB. For comparison we put the reach of the B Factories at 2 ab^{-1}. Numbers quoted as percentages are relative precisions. Measurements marked (†) will be systematics limited, and those marked (∗) will be theoretically limited, with 75 ab^{-1}. Note that in many of these cases, there exist data driven methods of reducing the errors. See the text for further discussion of each measurement.*

Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$A_{CP}(b \to s\gamma)$	0.012 (†)	0.004 (†)

CP asymmetry in Future B factories

Technical Design Report
arXiv:1011.0352

Observable	Belle 2006 (~0.5 ab^{-1})	SuperKEKB (5 ab^{-1})	SuperKEKB (50 ab^{-1})	†LHCb (2 fb^{-1})	†LHCb (10 fb^{-1})
$A_{CP}(B \to X_s \gamma)$	0.058	0.01	0.005	-	-

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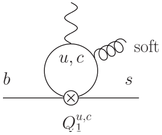

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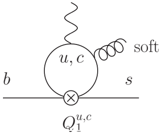

- Give non-perturbative $\mathcal{O}(\Lambda_{\rm QCD}/m_b)$ corrections to $\Gamma(\bar{B} \to X_s \gamma)$
  Unlike $\Gamma(\bar{B} \to X_{c,u} l \bar{\nu})$, where non-perturbative $= \mathcal{O}(\Lambda^2_{\rm QCD}/m_b^2)$
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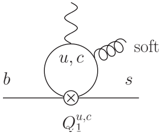

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  Currently **largest irreducible** error of $\sim 5\%$ on $\Gamma(\bar{B} \to X_s\gamma)$
- Calculated from a systematic study using
  Soft Collinear Effective Theory (SCET)

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$\Rightarrow$ Potentially big effect!

Resolved Photon Contributions

$$\mathcal{A}_{X_s\gamma} \sim \underset{\substack{\uparrow \\ \text{Calc. in PT}}}{\bar{J}} \otimes \underset{\substack{\uparrow \\ \text{Non pert.}}}{h}$$

- The non perturbative functions h_{ij} are

$$h_{17}(\omega_1) \quad \text{F.T. of} \quad \langle \bar{B}|\bar{b}(0)\cdots G(s\bar{n})\cdots b(0)|\bar{B}\rangle$$

$$h_{78}^{(1)}(\omega_1,\omega_2) \quad \text{F.T. of} \quad \langle \bar{B}|\bar{b}(0)\cdots b(0)\sum_q e_q\,\bar{q}(r\bar{n})\cdots q(s\bar{n})|\bar{B}\rangle$$

Cannot be extracted from data, must be modeled

Resolved Photon Contributions

- How can a dimension 5 and 6 operators

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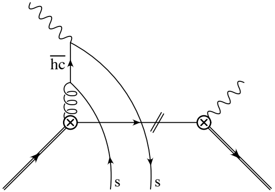

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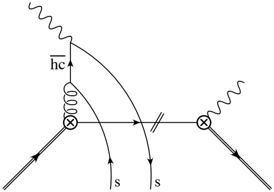

$$\frac{\not{p}}{p^2} = \frac{n\cdot p\frac{\not{\bar{n}}}{2} + \bar{n}\cdot p\frac{\not{n}}{2}}{\bar{n}\cdot p\, n\cdot p} \approx \frac{1}{\bar{n}\cdot p}\frac{\not{\bar{n}}}{2} \approx \frac{1}{\Lambda_{\rm QCD}}$$

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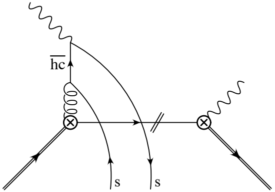

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- Soft functions are convoluted with jet functions $\bar{J}$ which enhance their contribution

Strong Phase

- For a non-zero asymmetry we need
  - "Weak" (CP odd) phase: CKM phase $\propto \lambda^2$, C_i of $\mathcal{H}_{\rm eff}$ (not in SM)
  - "Strong" (CP even) phase: What is it?

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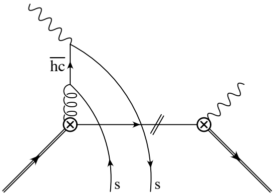
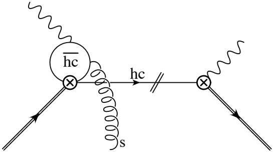
- Resolved photon contributions

$Q_{7\gamma} - Q_{8g}$



$Q_1 - Q_{7\gamma}$



- h_{ij} are real due to PT and heavy quark symmetry

  J are complex: arise from uncut propagators and loops

Resolved Photon contributions to CP asymmetry

- At lowest order in α_s and $\mathcal{O}(\Lambda_{QCD}/m_b)$

$$\mathcal{A}^{\rm res}_{X_s\gamma} = \frac{\pi}{m_b}\left\{ {\rm Im}\left[(1+\epsilon_s)\,\frac{C_1}{C_{7\gamma}}\right]\tilde{\Lambda}^c_{17} - {\rm Im}\left[\epsilon_s\,\frac{C_1}{C_{7\gamma}}\right]\tilde{\Lambda}^u_{17} + {\rm Im}\,\frac{C_{8g}}{C_{7\gamma}}\,4\pi\alpha_s\,\tilde{\Lambda}^{\bar{B}}_{78}\right\},$$

with

$$\tilde{\Lambda}^u_{17} = \frac{2}{3}\,h_{17}(0)$$

$$\tilde{\Lambda}^c_{17} = \frac{2}{3}\int_{4m_c^2/m_b}^{\infty}\frac{d\omega_1}{\omega_1}\,f\left(\frac{m_c^2}{m_b\,\omega_1}\right)h_{17}(\omega_1)$$

$$\tilde{\Lambda}^{\bar{B}}_{78} = 2\int_{-\infty}^{\infty}\frac{d\omega_1}{\omega_1}\left[h^{(1)}_{78}(\omega_1,\omega_1) - h^{(1)}_{78}(\omega_1,0)\right]$$

where

$$f(x) = 2x\ln\frac{1+\sqrt{1-4x}}{1-\sqrt{1-4x}}$$

- Model h_{ij} as in
  [Benzke, Lee, Neubert, GP JHEP **1008** 099 (2010)]

$\tilde{\Lambda}_{78}^{\bar{B}}$

- We need to estimate

$$\tilde{\Lambda}_{78}^{\bar{B}} = 2\int_{-\infty}^{\infty} \frac{d\omega_1}{\omega_1} \left[h_{78}^{(1)}(\omega_1, \omega_1) - h_{78}^{(1)}(\omega_1, 0) \right]$$

- Recall

$$h_{78}^{(1)}(\omega_1, \omega_2) \quad \text{F.T. of} \quad \langle \bar{B}|\bar{b}(0)\cdots b(0)\sum_q e_q\, \bar{q}(r\bar{n})\cdots q(s\bar{n})|\bar{B}\rangle$$

$\tilde{\Lambda}_{78}^{\bar{B}}$

- We need to estimate

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- Fierz and use VIA

$$\tilde{\Lambda}_{78}^{\bar{B}}\Big|_{\rm VIA} = e_{\rm spec}\, \frac{2f_B^2\, M_B}{9} \int_0^{\infty} d\omega_1\, \frac{\left[\phi_+^B(\omega_1,\mu)\right]^2}{\omega_1}$$

where $\phi_+^B(\omega_1)$ is B-meson LCDA ("wave function")

- Using [Lee, Neubert PRD **72**, 094028 (2005)] to constrain the integral

$$\tilde{\Lambda}_{78}^{\bar{B}}\Big|_{\rm VIA} \in e_{\rm spec}[17\,\text{MeV},\ 190\,\text{MeV}]$$

$\tilde{\Lambda}_{17}^{c}$ and $\tilde{\Lambda}_{17}^{u}$

- We need to estimate

$$\tilde{\Lambda}_{17}^{c} = \frac{2}{3}\int_{4m_c^2/m_b}^{\infty} \frac{d\omega_1}{\omega_1}\, f\left(\frac{m_c^2}{m_b\,\omega_1}\right) h_{17}(\omega_1)$$

- $h_{17}(\omega_1)$ has support over hadronic range

  The convolution starts at $4m_c^2/m_b \approx 1$ GeV

  $\Rightarrow$ small overlap

$$-9\,\text{MeV} < \tilde{\Lambda}_{17}^{c} < +11\,\text{MeV}$$

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$$\tilde{\Lambda}_{17}^{u} = \frac{2}{3}\, h_{17}(0)$$

  We find

$$-330\,\text{MeV} < \tilde{\Lambda}_{17}^{u} < +525\,\text{MeV}$$

  Asymmetric range since $h_{17}(\omega_1)$ normalization is $2\lambda_2 \approx 0.24\,\mathrm{GeV}^2$

  Same result as naive dimensional analysis

Correct CP asymmetry in the SM

- Including both direct and resolved contributions using $\mu = 2\,\text{GeV}$ for the factorization scale

$$\mathcal{A}_{X_s\gamma}^{\rm SM} \approx \pi \left|\frac{C_1}{C_{7\gamma}}\right| \text{Im}\,\epsilon_s \left(\frac{\tilde{\Lambda}_{17}^u - \tilde{\Lambda}_{17}^c}{m_b} + \frac{40\alpha_s}{9\pi}\,\frac{\Lambda_c}{m_b}\right)$$
$$= \left(1.15 \times \frac{\tilde{\Lambda}_{17}^u - \tilde{\Lambda}_{17}^c}{300\,\text{MeV}} + 0.71\right)\%\,.$$

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$$= \left(1.15 \times \frac{\tilde{\Lambda}^u_{17} - \tilde{\Lambda}^c_{17}}{300\,\text{MeV}} + 0.71\right)\%\,.$$

- CP asymmetry dominated by non-perturbative effects!

$$-0.6\% < \mathcal{A}^{\rm SM}_{X_s\gamma} < 2.8\%$$

Only value below -2% could be interpreted as sign of new physics

Correct CP asymmetry Beyond the SM

$$
\begin{aligned}
\frac{\mathcal{A}_{X_s\gamma}}{\pi} \approx & \left[\left(\frac{40}{81}-\frac{40}{9}\,\frac{\Lambda_c}{m_b}\right)\frac{\alpha_s}{\pi}+\frac{\tilde{\Lambda}_{17}^c}{m_b}\right] \mathrm{Im}\,\frac{C_1}{C_{7\gamma}} \\
& -\left(\frac{4\alpha_s}{9\pi}-4\pi\alpha_s\, e_{\rm spec}\,\frac{\tilde{\Lambda}_{78}}{m_b}\right) \mathrm{Im}\,\frac{C_{8g}}{C_{7\gamma}} \\
& -\left(\frac{\tilde{\Lambda}_{17}^u-\tilde{\Lambda}_{17}^c}{m_b}+\frac{40}{9}\,\frac{\Lambda_c}{m_b}\,\frac{\alpha_s}{\pi}\right) \mathrm{Im}\left(\epsilon_s\,\frac{C_1}{C_{7\gamma}}\right)
\end{aligned}
$$

- **New** test of physics beyond the SM

$$
\mathcal{A}_{X_s^-\gamma}-\mathcal{A}_{X_s^0\gamma} \approx 4\pi^2\alpha_s\,\frac{\tilde{\Lambda}_{78}}{m_b}\,\mathrm{Im}\,\frac{C_{8g}}{C_{7\gamma}} \approx 12\% \times \frac{\tilde{\Lambda}_{78}}{100\,\mathrm{MeV}}\,\mathrm{Im}\,\frac{C_{8g}}{C_{7\gamma}}
$$

Should be looked at by experiments!

Comments on $\bar{B} \to X_d\gamma$

- $\bar{B} \to X_d\gamma$ analogous to $\bar{B} \to X_s\gamma$:
  replace ϵ_s by $\epsilon_d = (V_{ub}V_{ud}^*)/(V_{tb}V_{td}^*) = (\bar{\rho} - i\bar{\eta})/(1 - \bar{\rho} + i\bar{\eta})$
- CP asymmetry for $\bar{B} \to X_d\gamma$ in SM
  enhanced by $\mathrm{Im}(\epsilon_d)/\mathrm{Im}(\epsilon_s) \approx -22$
- Including resolved photon contributions

$$-62\% < \mathcal{A}_{X_d\gamma}^{\mathrm{SM}} < 14\%$$

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- Untagged CP asymmetry for $\bar{B} \to X_{s+d}\,\gamma$ vanishes in SM
  up to tiny U-spin breaking corrections
  [Soares NPB **367**, 575 (1991); Kagan, Neubert PRD **58**, 094012 (1998);Hurth, Mannel PLB **511**, 196 (2001)]
  Even after including resolved photon effects

Summary: Direct CP Asymmetry in $\bar{B} \to X_{s,d}\,\gamma$

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- Direct CP asymmetry in $\bar{B} \to X_{s,d}\,\gamma$ is a probe of new physics its precise measurement is one of the goals of future B factories

- How well can we calculate $\mathcal{A}_{X_s\gamma}$? Worse than we thought...

- Resolved photon contributions, which are non perturbative, are the **dominant** effect in the SM
  [Benzke, Lee, Neubert, GP PRL **106**, 141801 (2011)]

$$-0.6\% < \mathcal{A}_{X_s\gamma}^{\mathrm{SM}} < 2.8\%$$

  compared to $\mathcal{A}_{X_s\gamma}^{\mathrm{SM}} \approx 0.5\%$ from perturbative effects alone

- **New** test of physics beyond the SM

$$\mathcal{A}_{X_s^-\gamma} - \mathcal{A}_{X_s^0\gamma} \approx 4\pi^2\alpha_s\,\frac{\tilde{\Lambda}_{78}}{m_b}\,\mathrm{Im}\,\frac{C_{8g}}{C_{7\gamma}} \approx 12\% \times \frac{\tilde{\Lambda}_{78}}{100\,\mathrm{MeV}}\,\mathrm{Im}\,\frac{C_{8g}}{C_{7\gamma}}$$