THE UNIVERSITY OF CHICAGO

Irreducible Uncertainties in $\bar{B} \to X_s \gamma$

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M. Benzke, S.J. Lee, M. Neubert, GP [arXiv:1003.5012]

S.J. Lee, M. Neubert, GP PRD **75** 114005 (2007)

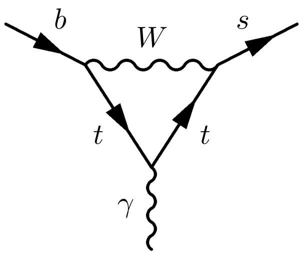
Introduction

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

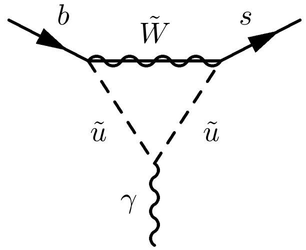
$$\mathcal{H}_{\rm eff} \ni \frac{G_F}{\sqrt{2}} C_{7\gamma} Q_{7\gamma}$$

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

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

  $b \to s\gamma$ can have contribution from new physics e.g. SUSY

  (only one diagram shown):



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

- BSM calculations are becoming advanced e.g.

  Complete NLO SUSY MFV

  SusyBSG package (Degrassi, Gambino, Slavich '07)

- Need to think seriously about errors!

How To Make a Photon?

- Produce it directly...

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

- Or make a gluon or a quark pair

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

and convert them to a photon

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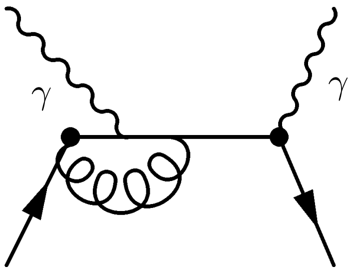
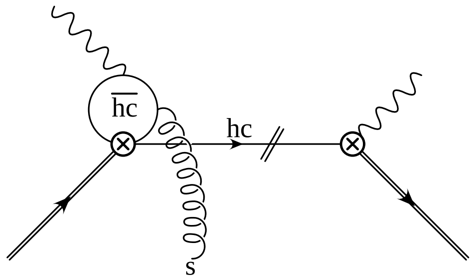
- But it will cost you..

α_s or $1/m_b$





Effective Hamiltonian

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

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

  - 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:

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

Total Rate

- Previous studies of $Q_i - Q_j$ contributions focus on $\Gamma(\bar{B} \to X_s\,\gamma)$

  and mostly on α_s suppressed effects

- Common lore:

  like $\Gamma(\bar{B} \to X_u\,l\,\bar{\nu})$ non perturbative effects arise at $1/m_b^2$

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- Hints that not all is well
  - $Q_{8g} - Q_{8g}$ (Ali, Greub '95; Kapustin, Ligeti, Politzer '95)
  - $Q_1 - Q_{7\gamma}$ (Voloshin '96; Ligeti, Randall, Wise '97; Grant, Morgan, Nussinov, Peccei '97; Buchalla, Isidori, Rey '97)
  - No local OPE for $\Gamma(\bar{B} \to X_s \gamma)$ (Ligeti, Randall, Wise '97)

  But effects were thought to be under control or small ...

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  But effects were thought to be under control or small ...

- **Never** a systematic study!

  In fact uncertainty from $Q_{7\gamma} - Q_{8g}$ was **missed**!

  (Lee, Neubert, GP '06)

  Non perturbative effects in $\Gamma(\bar{B} \to X_s\,\gamma)$ arise at $1/m_b$

- What do we find from a systematic analysis?

Factorization at Subleading Power

and

Irreducible Uncertainties

in

$\bar{B} \to X_s\gamma$ Decay

M. Benzke, S.J. Lee, M. Neubert, GP [arXiv:1003.5012]

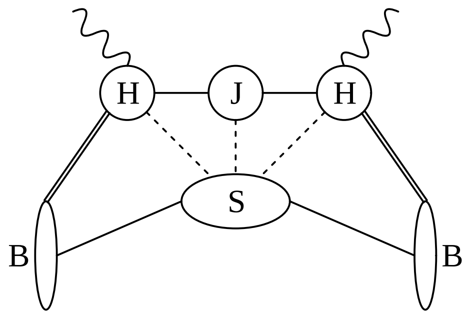
New Factorization Formula: Schematically

At the endpoint region: $m_b - 2E_\gamma \sim \Lambda_{\rm QCD}$

- Considering only $Q_{7\gamma} - Q_{7\gamma}$: factorization formula for $d\Gamma/dE_\gamma$

  (Korchemsky, Sterman '94; Bauer, Pirjol, Stewart '01)

$H \cdot J \otimes S$



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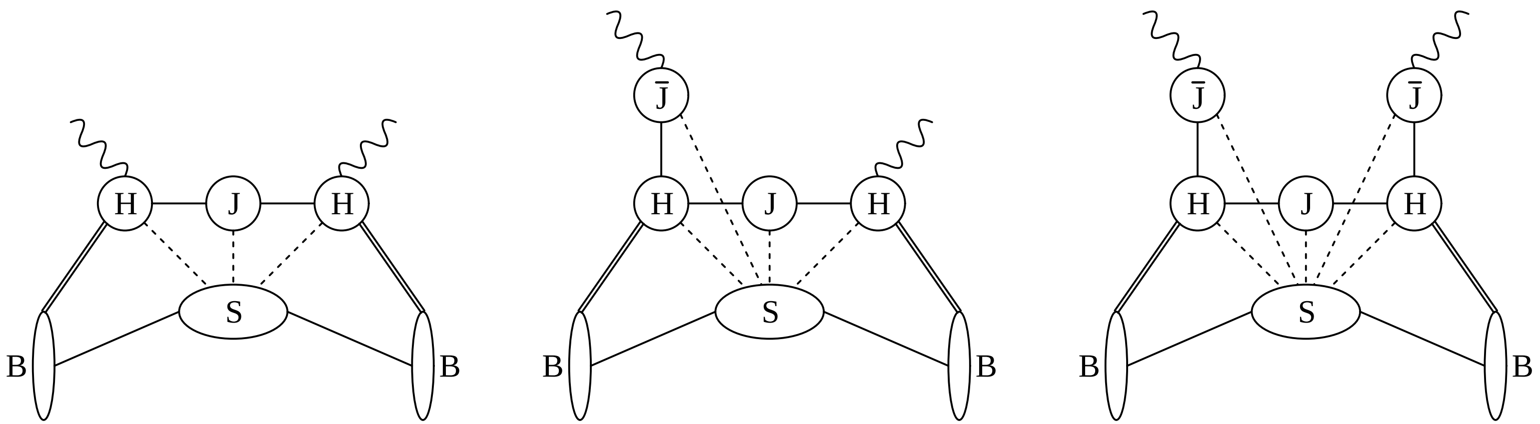
- Considering only $Q_{7\gamma} - Q_{7\gamma}$: factorization formula for $d\Gamma/dE_\gamma$

  (Korchemsky, Sterman '94; Bauer, Pirjol, Stewart '01)

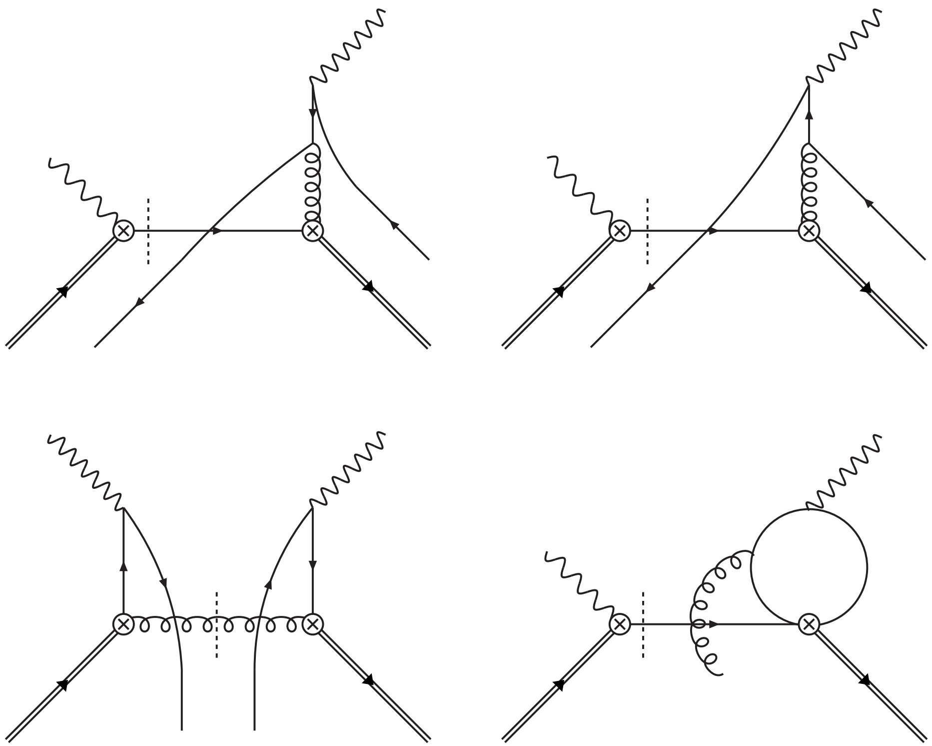
- Considering also other operators $\Rightarrow$ **new** factorization formula for $d\Gamma/dE_\gamma$ (Benzke, Lee, Neubert, GP '10)

$H \cdot J \otimes S$ $\qquad$ $H \cdot J \otimes S \otimes \bar{J}$ $\qquad$ $H \cdot J \otimes S \otimes \bar{J} \otimes \bar{J}$



- No analog for semileptonic decays
- New "resolved photon" contributions $\Rightarrow$ $1/m_b$ corrections to $\Gamma(\bar{B} \to X_s\,\gamma)$
- What are they?

Resolved Photon Contributions



Top line:	$Q_{7\gamma} - Q_{8g}$
Bottom left:	$Q_{8g} - Q_{8g}$
Bottom right:	$Q_1 - Q_{7\gamma}$

- $Q_1 - Q_{8g}$ and $Q_1 - Q_1$ give a $1/m_b^2$ effect

Resolved Photon Contributions

- Non perturbative effects arise from "Resolved Photon Contributions"

  They have the form

$$\Delta\Gamma \sim \quad \bar{J} \quad \otimes \quad h$$

$$\begin{array}{ccc} \bar{J} & & h \\ \uparrow & & \uparrow \\ \text{Calc. in PT} & & \text{Non pert.} \end{array}$$

- The non perturbative functions h_{ij} are

$$h_{88}(\omega_1, \omega_2) \quad \text{F.T. of} \quad \langle \bar{B}|\bar{b}(0)\cdots s(un)\bar{s}(r\bar{n})\cdots b(0)|\bar{B}\rangle$$

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

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

The Integrated Rate

- For a photon energy cut $E_\gamma > E_0$ define

$$\mathcal{F}_E(\Delta) = \frac{\Gamma(E_0) - \Gamma(E_0)|_{\rm OPE}}{\Gamma(E_0)|_{\rm OPE}},$$

where $\Delta = m_b - 2E_0$ and $\Gamma(E_0)|_{\rm OPE}$ is the older calculation

- Assuming $\Delta \gg \Lambda_{\rm QCD}$

$$\mathcal{F}_E(\Delta) = \frac{C_1(\mu)}{C_{7\gamma}(\mu)} \frac{\Lambda_{17}(m_c^2/m_b,\mu)}{m_b} + \frac{C_{8g}(\mu)}{C_{7\gamma}(\mu)} 4\pi\alpha_s(\mu) \frac{\Lambda_{78}^{\rm spec}(\mu)}{m_b}$$
$$+ \left(\frac{C_{8g}(\mu)}{C_{7\gamma}(\mu)}\right)^2 \left[4\pi\alpha_s(\mu)\frac{\Lambda_{88}(\Delta,\mu)}{m_b} - \frac{C_F\alpha_s(\mu)}{9\pi}\frac{\Delta}{m_b}\ln\frac{\Delta}{m_s}\right] + \dots,$$

where **model independently**,

$$\Lambda_{17}\Big(\frac{m_c^2}{m_b},\mu\Big) = e_c \,{\rm Re}\int_{-\infty}^{\infty}\frac{d\omega_1}{\omega_1}\left[1 - F\left(\frac{m_c^2 - i\varepsilon}{m_b\,\omega_1}\right) + \frac{m_b\,\omega_1}{12m_c^2}\right] h_{17}(\omega_1,\mu)\,,$$

$$\Lambda_{78}^{\rm spec}(\mu) = {\rm Re}\int_{-\infty}^{\infty}\frac{d\omega_1}{\omega_1 + i\varepsilon}\int_{-\infty}^{\infty}\frac{d\omega_2}{\omega_2 - i\varepsilon}\, {h_{78}}^{(5)}(\omega_1,\omega_2,\mu)\,,$$

$$\Lambda_{88}(\Delta,\mu) = e_s^2\left[\int_{-\infty}^{\Lambda_{\rm UV}}\frac{d\omega_1}{\omega_1 + i\varepsilon}\int_{-\infty}^{\Lambda_{\rm UV}}\frac{d\omega_2}{\omega_2 - i\varepsilon}\, 2{h_{88}}^{\rm cut}(\Delta,\omega_1,\omega_2,\mu)\right.$$
$$\left. - \frac{C_F}{8\pi^2}\,\Delta\left(\ln\frac{\Lambda_{\rm UV}}{\Delta} - 1\right)\right].$$

The Integrated Rate

- We need to estimate three parameters:

$$\Lambda_{17}\Big(\frac{m_c^2}{m_b},\mu\Big) = e_c \,\mathrm{Re}\int_{-\infty}^{\infty}\frac{d\omega_1}{\omega_1}\left[1-F\left(\frac{m_c^2-i\varepsilon}{m_b\,\omega_1}\right)+\frac{m_b\,\omega_1}{12m_c^2}\right]h_{17}(\omega_1,\mu)\,,$$

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$$\Lambda_{88}(\Delta,\mu) = e_s^2\left[\int_{-\infty}^{\Lambda_{\mathrm{UV}}}\frac{d\omega_1}{\omega_1+i\varepsilon}\int_{-\infty}^{\Lambda_{\mathrm{UV}}}\frac{d\omega_2}{\omega_2-i\varepsilon}\,2h_{88}{}^{\mathrm{cut}}(\Delta,\omega_1,\omega_2,\mu) -\frac{C_F}{8\pi^2}\,\Delta\left(\ln\frac{\Lambda_{\mathrm{UV}}}{\Delta}-1\right)\right].$$

- Naively, if $\Lambda_{ij}\sim\Lambda_{\mathrm{QCD}}\sim 0.5$ GeV

  Effect on the rate can be up to 30%

- Fortunately, it is possible to constrain Λ_{17} and $\Lambda_{78}^{\mathrm{spec}}$

  We now discuss each of the three parameters

Λ_{17}

- We need to estimate

$$\Lambda_{17}\Big(\frac{m_c^2}{m_b},\mu\Big) = e_c\,\mathrm{Re}\int_{-\infty}^{\infty}\frac{d\omega_1}{\omega_1}\left[1 - F\Big(\frac{m_c^2 - i\varepsilon}{m_b\,\omega_1}\Big) + \frac{m_b\,\omega_1}{12m_c^2}\right]h_{17}(\omega_1,\mu)$$

- Recall

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

where intuitively ω_1 is the soft gluon momentum

- $h_{17}(\omega_1)$
  - An even function of ω_1
  - Its normalization is $2\lambda_2 \approx 0.24\,\mathrm{GeV}^2$

- Using an exponential or a Gaussian as a model for $h_{17}(\omega_1)$

$$h_{17}(\omega_1,\mu) = \frac{\lambda_2}{\sigma}\,e^{-\frac{|\omega_1|}{\sigma}} \quad \text{or} \quad h_{17}(\omega_1,\mu) = \frac{2\lambda_2}{\sqrt{2\pi}\sigma}\,e^{-\frac{\omega_1^2}{2\sigma^2}}$$

- Varying σ
  - $(\Lambda_{17}^{\mathrm{exp}})_{\max} = -4.6\,\mathrm{MeV}$ (for $\sigma = 0.51\,\mathrm{GeV}$)
  - $(\Lambda_{17}^{\mathrm{Gauss}})_{\max} = -8.1\,\mathrm{MeV}$ (for $\sigma = 0.77\,\mathrm{GeV}$)

- Not a conservative bound!

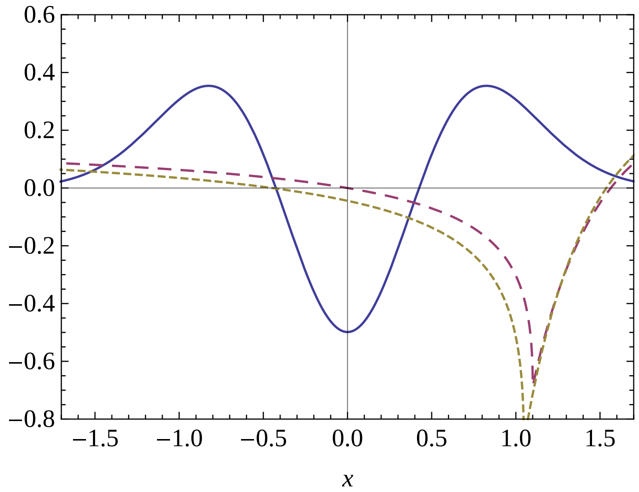
Λ_{17}

- We need to estimate

$$\Lambda_{17}\left(\frac{m_c^2}{m_b},\mu\right) = e_c\,\mathrm{Re}\int_{-\infty}^{\infty}\frac{d\omega_1}{\omega_1}\left[1 - F\left(\frac{m_c^2 - i\varepsilon}{m_b\,\omega_1}\right) + \frac{m_b\,\omega_1}{12m_c^2}\right] h_{17}(\omega_1,\mu)$$

- $h_{17}(\omega_1)$ doesn't have to be positive, e.g.

$$h_{17}(\omega_1,\mu) = \frac{2\lambda_2}{\sqrt{2\pi}\sigma}\,\frac{\omega_1^2 - \Lambda^2}{\sigma^2 - \Lambda^2}\,e^{-\frac{\omega_1^2}{2\sigma^2}}$$



- Blue line: $\sigma = 0.5\,\mathrm{GeV}$ and $\Lambda = 0.425\,\mathrm{GeV} \Rightarrow \Lambda_{17} = -42\,\mathrm{MeV}$
- Another choice: $\sigma = 0.5\,\mathrm{GeV}$ and $\Lambda = 0.575\,\mathrm{GeV} \Rightarrow \Lambda_{17} = 27\,\mathrm{MeV}$.
- Final range: $-60\,\mathrm{MeV} < \Lambda_{17} < 25\,\mathrm{MeV}$

Λ_{78}

- We need to estimate

$$\Lambda_{78}^{\text{spec}}(\mu) = \text{Re}\int_{-\infty}^{\infty} \frac{d\omega_1}{\omega_1 + i\varepsilon} \int_{-\infty}^{\infty} \frac{d\omega_2}{\omega_2 - i\varepsilon}\, {h_{78}}^{(5)}(\omega_1,\omega_2,\mu)$$

- Recall

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

- Method I: Fierz and use VIA

$$h_{78}(\omega_1,\omega_2)\big|_{\text{VIA}} = -e_{\text{spec}}\,\frac{f_B^2\, M_B}{8}\left(1-\frac{1}{N_c^2}\right)\phi_+^B(-\omega_1)\,\phi_+^B(-\omega_2)$$

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

- Λ_{78} depends on LCDA’s inverse moment λ_B

$$\Lambda_{78}^{\text{spec}}\big|_{\text{VIA}} = -e_{\text{spec}}\left(1-\frac{1}{N_c^2}\right)\frac{f_B^2\, M_B}{8\lambda_B^2(\mu)} \in e_{\text{spec}}\,[-386\,\text{MeV}, -35\,\text{MeV}]$$

$e_{\text{spec}}= \dfrac{1}{3}$ for $\bar{B}^0$, $\quad -\dfrac{2}{3}$ for B^-

Λ_{78}

- We need to estimate

$$\Lambda_{78}^{\rm spec}(\mu) = \text{Re}\int_{-\infty}^{\infty} \frac{d\omega_1}{\omega_1 + i\varepsilon} \int_{-\infty}^{\infty} \frac{d\omega_2}{\omega_2 - i\varepsilon}\, {h_{78}}^{(5)}(\omega_1, \omega_2, \mu)$$

- Recall

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

- Method II: **Assume** $SU(3)$ flavor symmetry

$\Rightarrow$ $\Lambda_{78}^{\rm spec}$ is determined by isospin asymmetry (Misiak '09)

$$\Delta_{0-} = \frac{\Gamma(\bar{B}^0 \to X_s\gamma) - \Gamma(B^- \to X_s\gamma)}{\Gamma(\bar{B}^0 \to X_s\gamma) + \Gamma(B^- \to X_s\gamma)}$$

measured by BaBar to be $\Delta_{0-} = (-1.3 \pm 5.9)\%$

- Including 30% $SU(3)$ flavor breaking gives

$$\Lambda_{78}^{\rm spec} \approx -4.5\,\text{GeV}\,(e_{\rm spec} \pm 0.05)\,\Delta_{0-}$$

Λ_{88}

- We need to estimate

$$\Lambda_{88}(\Delta,\mu) = e_s^2\left[\int_{-\infty}^{\Lambda_{\rm UV}}\frac{d\omega_1}{\omega_1+i\varepsilon}\int_{-\infty}^{\Lambda_{\rm UV}}\frac{d\omega_2}{\omega_2-i\varepsilon}\,2h_{88}{}^{\rm cut}(\Delta,\omega_1,\omega_2,\mu) - \frac{C_F}{8\pi^2}\,\Delta\left(\ln\frac{\Lambda_{\rm UV}}{\Delta}-1\right)\right]$$

- Recall

$$h_{88}(\omega_1,\omega_2) \quad \text{F.T. of} \quad \langle\bar B|\bar b(0)\cdots s(un)\bar s(r\bar n)\cdots b(0)|\bar B\rangle$$

- We model $\Lambda_{88}(\Delta,\mu)$ by

$$\Lambda_{88}(\Delta,\mu)\approx e_s^2\,\Lambda(\mu)\,, \qquad \Lambda(\mu)>0\,,$$

with $0<\Lambda(\mu)<1\,\text{GeV}$

Total Uncertainty

$$\mathcal{F}_E(\Delta) = \frac{C_1(\mu)}{C_{7\gamma}(\mu)} \frac{\Lambda_{17}(m_c^2/m_b,\mu)}{m_b} + \frac{C_{8g}(\mu)}{C_{7\gamma}(\mu)} 4\pi\alpha_s(\mu) \frac{\Lambda_{78}^{\rm spec}(\mu)}{m_b}$$
$$+ \left(\frac{C_{8g}(\mu)}{C_{7\gamma}(\mu)}\right)^2 \left[4\pi\alpha_s(\mu) \frac{\Lambda_{88}(\Delta,\mu)}{m_b} - \frac{C_F\alpha_s(\mu)}{9\pi} \frac{\Delta}{m_b} \ln\frac{\Delta}{m_s}\right] + \dots ,$$

- Using the above values for Λ_{17} and Λ_{88}

$$\mathcal{F}_E\big|_{17} \in [-1.7, +4.0]\,\% ,$$
$$\mathcal{F}_E\big|_{88} \in [-0.3, +1.9]\,\% .$$

- While for Λ_{78} we have

$$\mathcal{F}_E\big|_{78}^{\rm VIA} \in [-2.8, -0.3]\,\% \quad \text{or} \quad \mathcal{F}_E\big|_{78}^{\rm exp} \in [-4.4, +5.6]\,\% \quad (95\%\ \text{CL})$$

- "Scanning" over the ranges we have

$$-4.8\% < \mathcal{F}_E(\Delta) < +5.6\% \quad (\text{VIA for } \Lambda_{78}^{\rm spec})$$

or

$$-6.4\% < \mathcal{F}_E(\Delta) < +11.5\% \quad (\Lambda_{78}^{\rm spec} \text{ from } \Delta_{0-})$$

- Even if the error on Δ_{0-} was zero

$$-4.0\% < \mathcal{F}_E(\Delta) < +4.8\% \quad (\text{ideal case})\,.$$

$\Gamma(\bar{B} \to X_s\gamma)$ in SM

- Experiment
  - Experimental value of $\text{Br}(\bar{B} \to X_s\gamma)$:
    Extrapolated from measured $E_\gamma \sim 1.9$ GeV to $E_\gamma > 1.6$ GeV
    (HFAG Average '08)
    $\text{Br}(\bar{B} \to X_s\gamma, E_\gamma > 1.6 \text{ GeV }) = (3.52 \pm 0.25) \cdot 10^{-4}$ (error 7%)
- Theory NNLO:
  - OPE: Assume 1.6 GeV is in the OPE region
    (Misiak et. al. '06)
    $\text{Br}(\bar{B} \to X_s\gamma, E_\gamma > 1.6 \text{ GeV }) = (3.15 \pm 0.23) \cdot 10^{-4}$ (error 7%)
  - MSOPE: 1.6 GeV is still in MSOPE region
    (Becher, Neubert '06)
    $\text{Br}(\bar{B} \to X_s\gamma, E_\gamma > 1.6 \text{ GeV }) = (2.98 \pm 0.26) \cdot 10^{-4}$ (error 9%)
- Largest error "non perturbative": estimated **5%**

  based on $Q_{7\gamma} - Q_{8g}$ (Lee, Neubert, GP '06) times 1.5
- Improved numerical estimate based on all $1/m_b$ contributions

  (Benzke, Lee, Neubert, GP '10): **5%**

Conclusions and Outlook

Conclusions and Outlook

- New factorization formula for photon spectrum in endpoint region

$$d\Gamma(\bar{B} \to X_s \gamma) = \overbrace{\sum_{n=0}^{\infty} \frac{1}{m_b^n} \sum_i H_i^{(n)} J_i^{(n)} \otimes S_i^{(n)}}^{\text{known}}$$

$$+ \underbrace{\sum_{n=1}^{\infty} \frac{1}{m_b^n} \left[\sum_i H_i^{(n)} J_i^{(n)} \otimes S_i^{(n)} \otimes \bar{J}_i^{(n)} + \sum_i H_i^{(n)} J_i^{(n)} \otimes S_i^{(n)} \otimes \bar{J}_i^{(n)} \otimes \bar{J}_i^{(n)} \right]}_{\text{new}}$$

- New "resolved photon" contributions $\Rightarrow$ $1/m_b$ corrections to $\Gamma(\bar{B} \to X_s \gamma)$
- From a systematic study we find

  An irreducible error of $\sim 5\%$ on $\Gamma(\bar{B} \to X_s \gamma)$
- This non perturbative error is the largest

$\Rightarrow$ no prospect for an improvement on the theoretical prediction

- Future directions:
  - New contributions to CP asymmetry in $\bar{B} \to X_s \gamma$
  - Effect on the spectrum and the extraction of the HQET parameters