# Status of $b \to s\,\gamma$ decay

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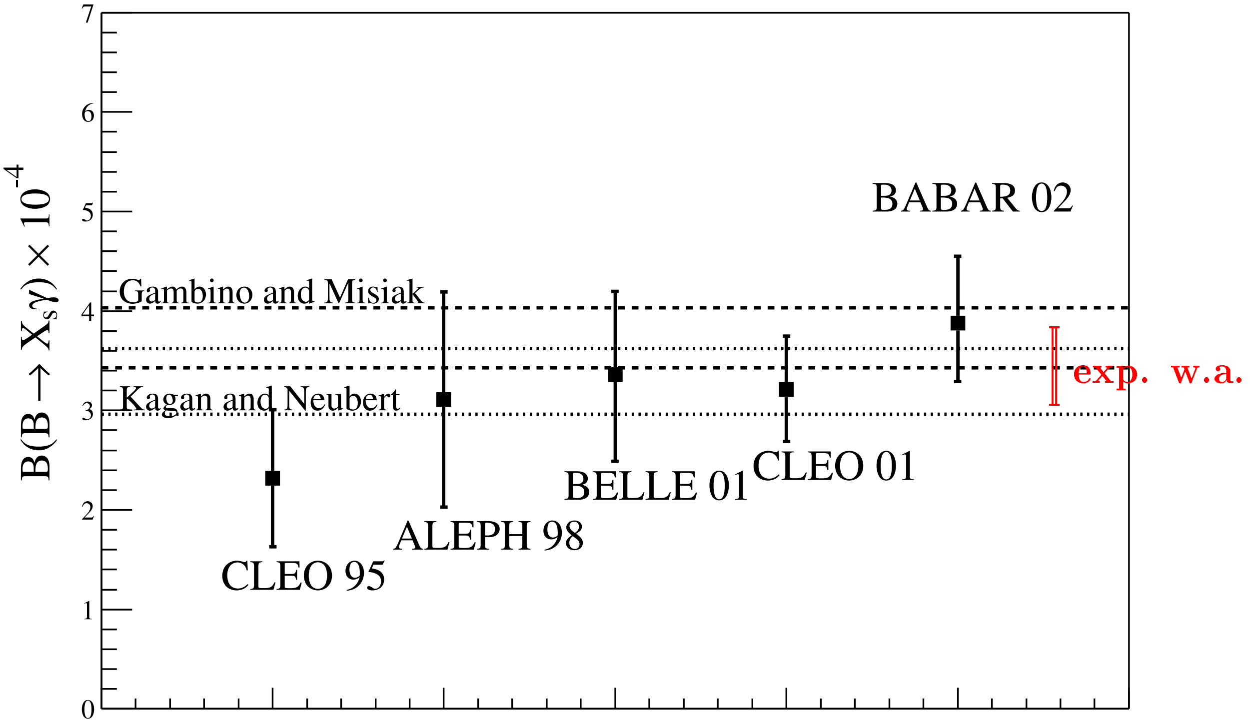
**Starting point:**

$$\Gamma[\bar{B} \to X_s\gamma] \simeq \Gamma[b \to X_s^{\rm parton}\gamma] \equiv \Gamma[b \to s\gamma] + \Gamma[b \to s\gamma g] + \ \ldots$$




# Summary of experimental results and SM predictions (BABAR [hep-ex/0207076])

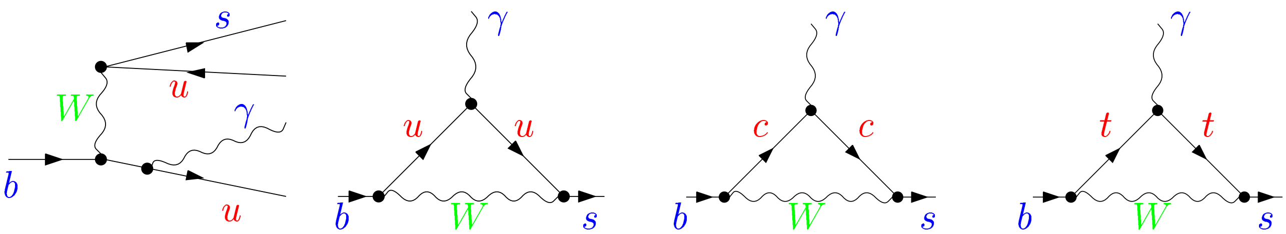
## Experimental weighted average (MM):

$$\mathrm{BR}[\bar{B} \to X_s \gamma]_{\mathrm{exp}} = \left[3.40 \ \underbrace{\binom{+0.42}{-0.37}}_{\sim \pm 12\%}\right] \times 10^{-4}$$

**Dotted lines $\leftrightarrow$ S.M. prediction A.D. 1998**
**Dashed lines $\leftrightarrow$ S.M. prediction A.D. 2001**
**Central values of the two predictions differ mainly due to different renormalization schemes used for $m_c$ in the NLO 2-loop corrections.**

**Present w.a. $\Rightarrow$ $M_{H^\pm} > 300$ GeV in 2HDM (II)**

## Electroweak transitions mediating $\bar{B} \to X_s \gamma$:



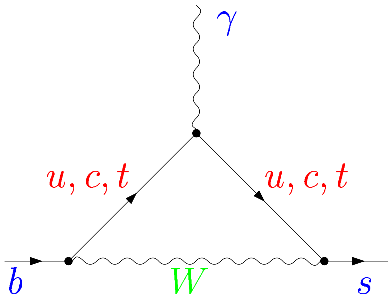

$$\left|\frac{V_{ub}V_{us}}{V_{cb}}\right| \simeq \left|\frac{V_{ub}V_{us}}{V_{ts}}\right| \simeq 2\%$$

$\sim +200\%$ $\sim -100\%$

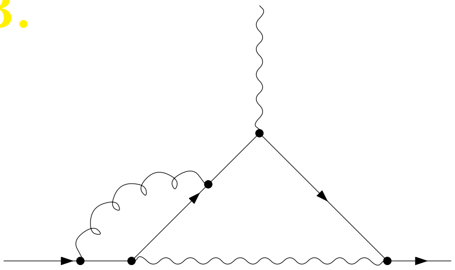
**In the amplitude, after including LO QCD effects.**

## Examples of Feynman diagrams contributing to $b \to s\gamma$ at various orders in the renormalization-group-improved perturbation theory:

**A.**



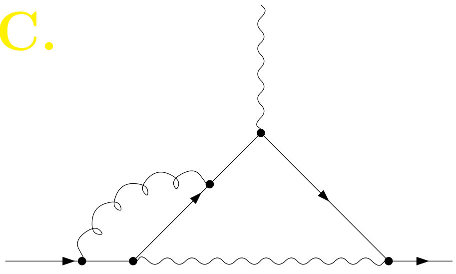

**B.**



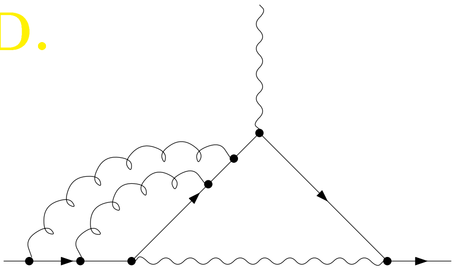
$\alpha_s \ln \frac{M_W^2}{m_b^2}$**: $\sim$ +65% in amplitude**

**$\sim$ +175% in BR**

**C.**



**D.**

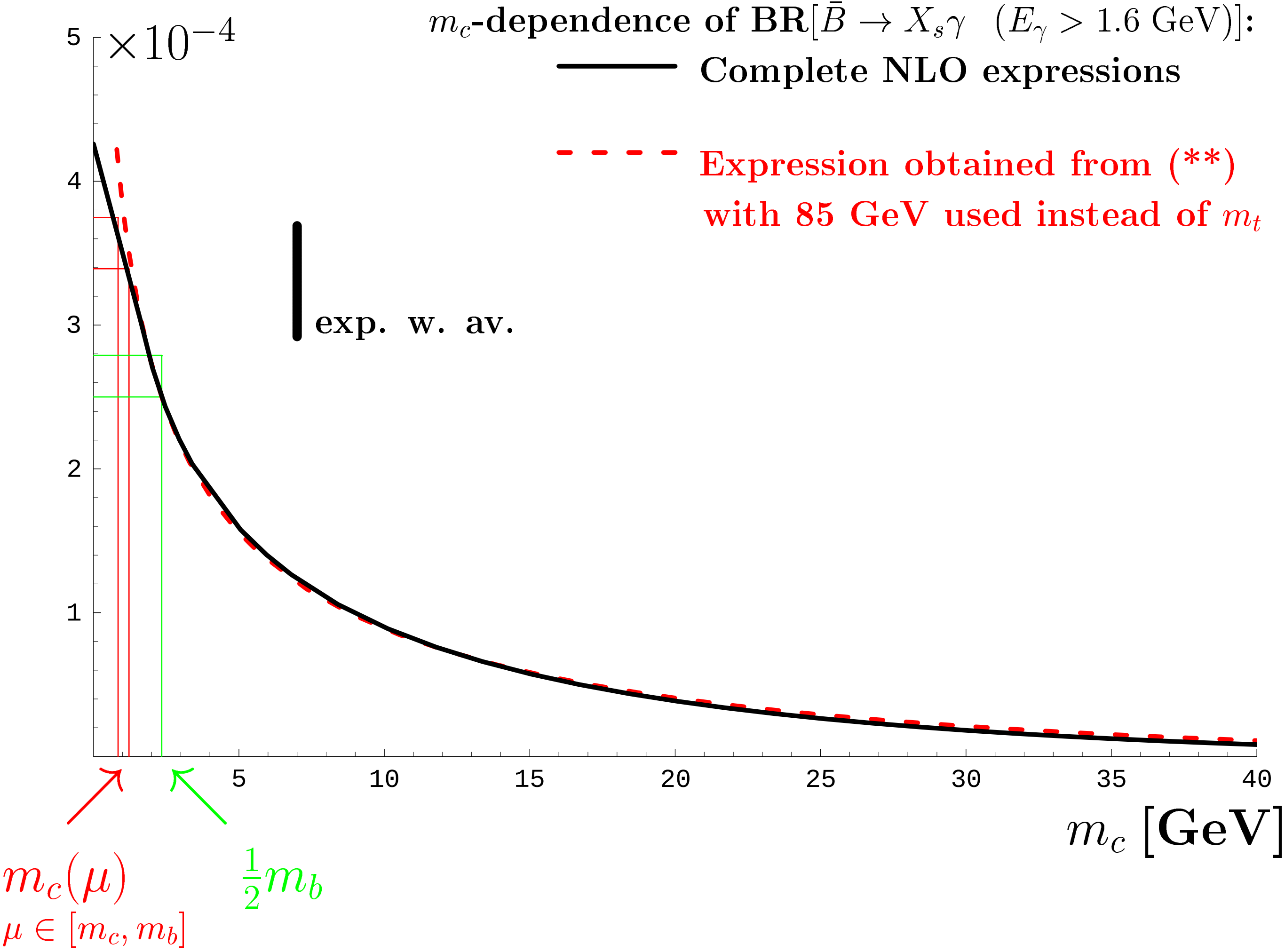


$\underbrace{\text{non} - \text{logarithmic} \qquad\qquad \text{logarithmic}}_{\sim +20\% \text{ in BR}}$

**If the quark masses satisfied the inequalities $m_b \ll m_c, m_t \ll M_W$, the leading contribution to $\mathrm{BR}[\bar{B} \to X_s \gamma]$ would be proportional to $\alpha_s^2$:**

$$\frac{\mathrm{BR}[\bar{B} \to X_s \gamma]}{\mathrm{BR}[\bar{B} \to X_c e \bar{\nu}]} \simeq \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 \frac{6 \alpha_{\mathrm{em}}}{\pi \mathbf{C}} \left[ \frac{\alpha_{\mathbf{s}}(\mathbf{m_b})}{\pi} \, \frac{104}{81} \ln \frac{m_c}{m_t} \right]^2 \qquad (**)$$

$C =$ **(semileptonic phase-space factor)**



**The effective Lagrangian:**

$$\mathcal{L} = \mathcal{L}_{QCD\times QED}(u,d,s,c,b) + \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{8} C_i(\mu) O_i$$

$$O_i = \begin{cases} (\bar{s}\Gamma_i c)(\bar{c}\Gamma_i' b), & i = 1,2, & |C_i(m_b)| \sim 1 \\ (\bar{s}\Gamma_i b)\mathbf{\Sigma}_q(\bar{q}\Gamma_i' q), & i = 3,4,5,6, & |C_i(m_b)| < 0.07 \\ \frac{e m_b}{16\pi^2} \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu}, & i = 7, & C_7(m_b) \sim -0.3 \\ \frac{g m_b}{16\pi^2} \bar{s}_L \sigma^{\mu\nu} T^a b_R G^a_{\mu\nu}, & i = 8, & C_8(m_b) \sim -0.15 \end{cases}$$

## Three steps of the calculation:

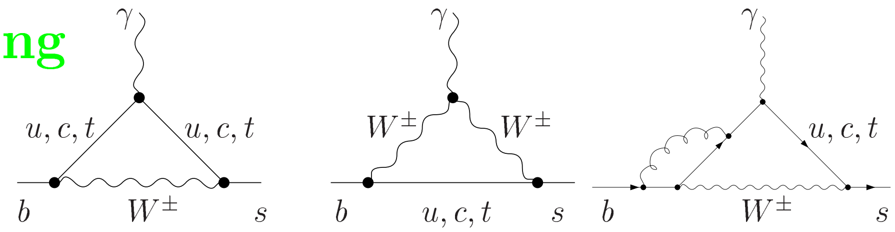
**Matching:** **Evaluating $C_i(\mu_0)$ at $\mu_0 \sim M_W$ by requiring equality of the SM and eff. theory Green functions.**

**Mixing:** **Deriving the eff. theory RGE and evolving $C_i(\mu)$ from $\mu_0$ to $\mu_b \sim m_b$.**

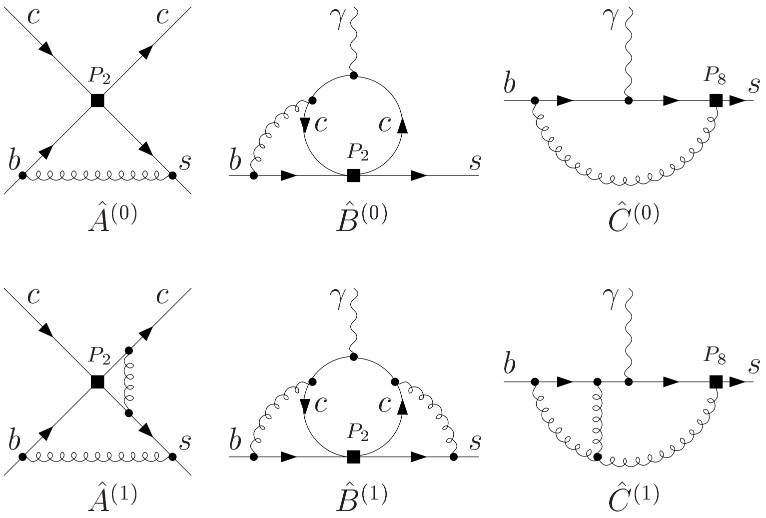
**Matrix elements:** **Evaluating the on-shell amplitudes at $\mu_b \sim m_b$.**

# Examples of diagrams that have been calculated at LO and NLO:

## Matching



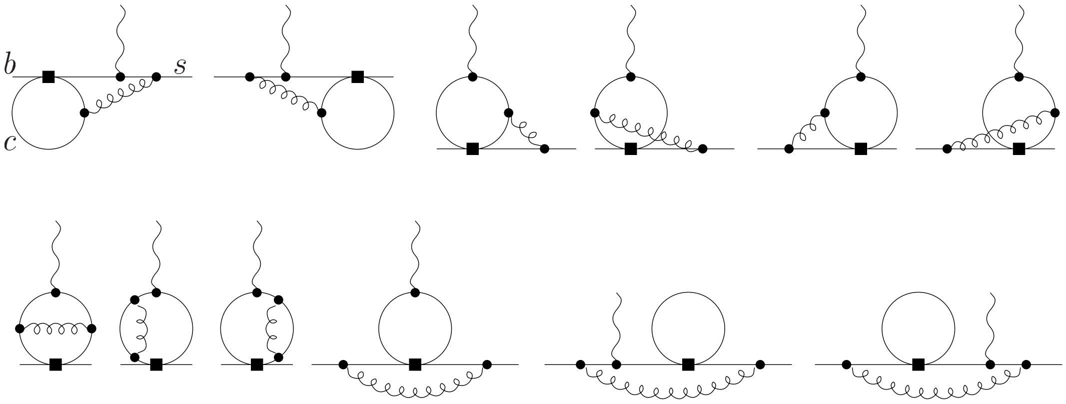

## Mixing




$(LO)$

$(NLO)$

## Matrix elements:




# At NNLO – one gluon more in each case.

**Three methods have been used for calculating 2-loop matrix elements with charm-quark loops:**

1. **Mellin-Barnes transform of Feynman-parameter integrals $\Rightarrow$ Expansion in $m_c/m_b$**
   [Greub, Hurth, Wyler, 1996]

2. **Asymptotic expansions $\Rightarrow$ Expansion in $m_c/m_b$**
   [Buras, Czarnecki, Misiak, Urban, 2001]

3. **"Brute force" $\Rightarrow$ No expansion in $m_c/m_b$**
   [Buras, Czarnecki, Misiak, Urban, 2002]
   **Goal: Diagrams which $b$-quark loops**
   **$\Rightarrow$ Formally complete NLO calculation**

**The $b \to s\gamma$ amplitude becomes dependent on $m_c$ only at the NLO, via 2-loop diagrams.**
**The question whether we should use:**

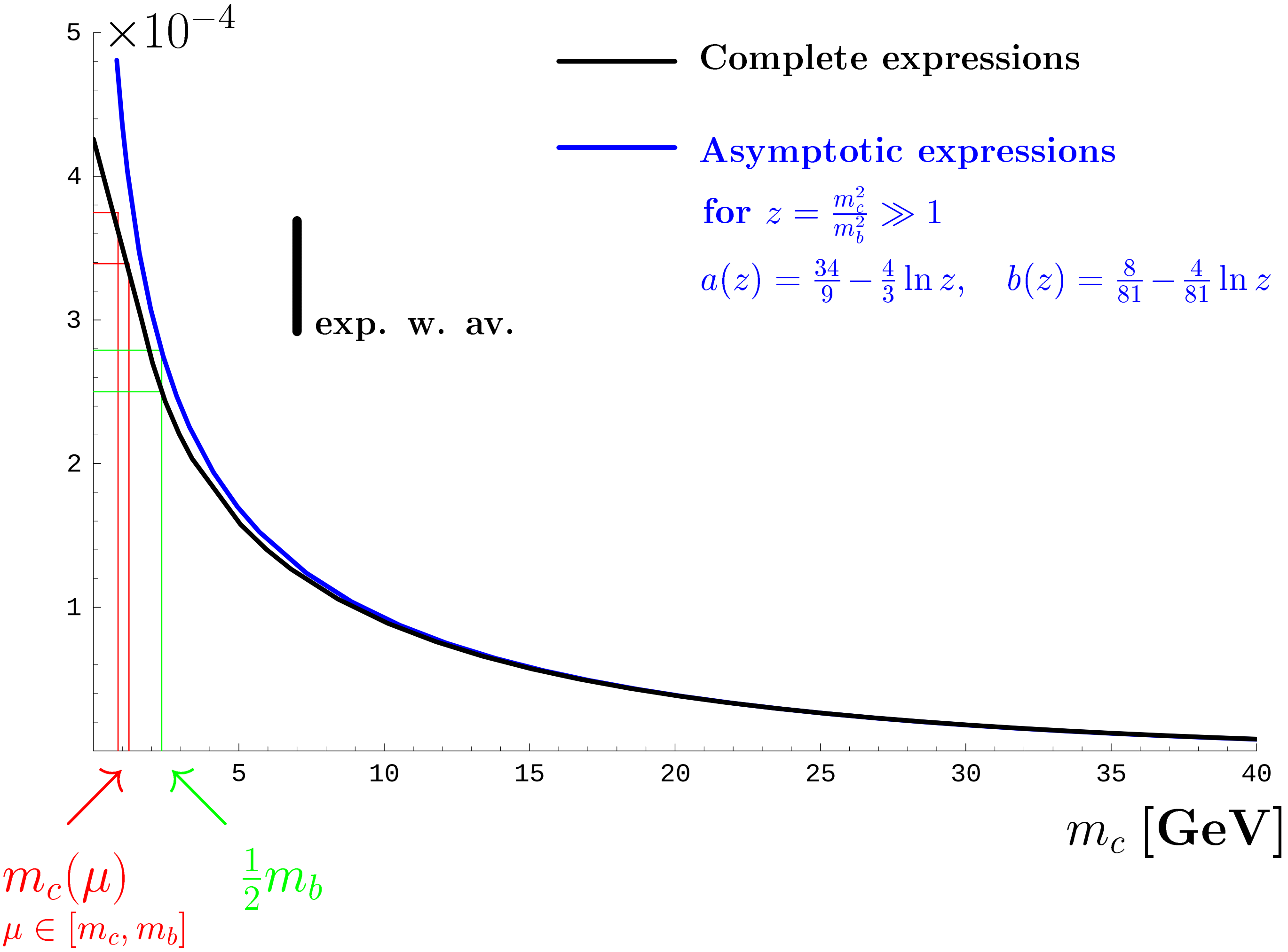
$$\frac{m_c^{\rm pole}}{m_b^{\rm pole}} = 0.29 \pm 0.02 \qquad \textbf{or} \qquad \frac{m_c^{\overline{\rm MS}}(\mu)}{m_b^{\rm pole}} = \underset{\mu \in [m_c, m_b]}{0.22 \pm 0.04}$$

**can, in principle, be asked only at NNLO. However, changing $m_c/m_b$ from 0.29 to 0.22 enhances BR$[\bar{B} \to X_s\gamma]$ by 10% ! Accuracy $\searrow$**

**Way out: NNLO calculation**

# Charm mass dependence of

# $\mathbf{BR}[\bar{B} \to X_s \gamma \quad (E_\gamma > 1.6 \text{ GeV})]$




$\Rightarrow$ **Hint for NNLO: large $m_c$ expansion + extrapolation.**

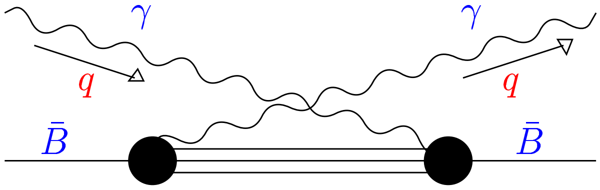
$\Rightarrow$ **Indication that the dominant charm mass-dependence might be of short-distance origin. If so, the associated non-perturbative effects would be under control.**

# Non-perturbative effects in $\bar{B} \to X_s \gamma$

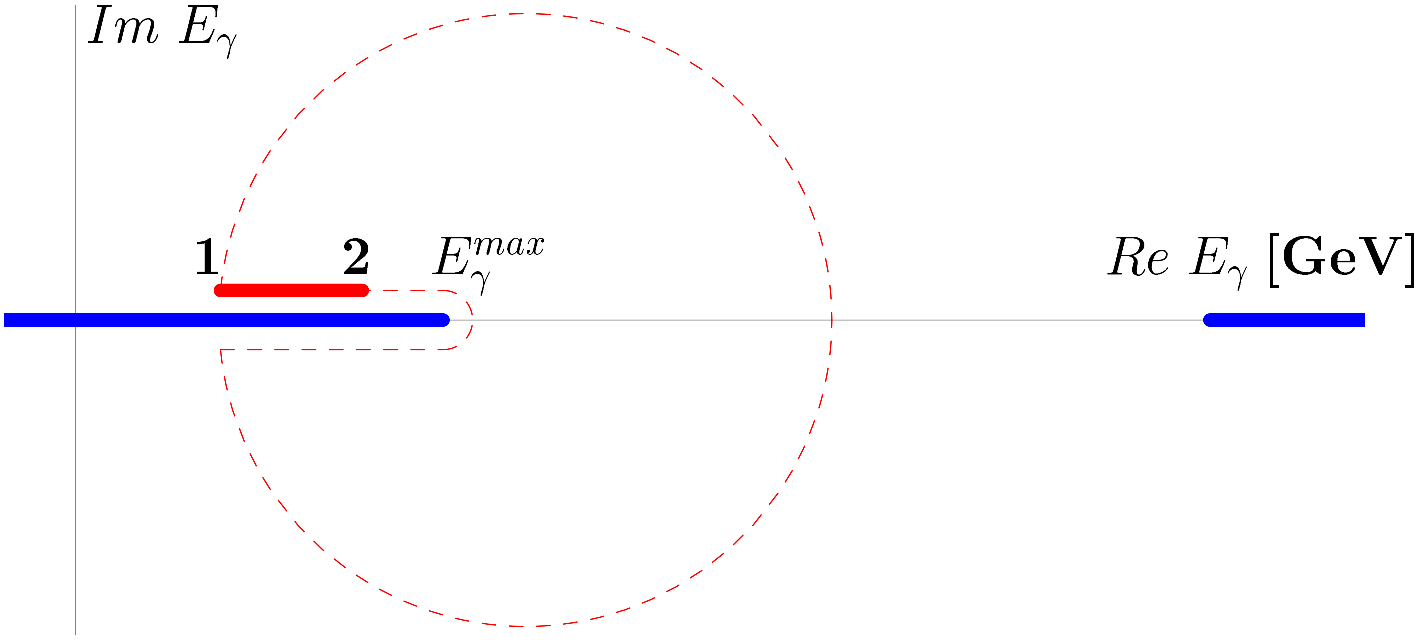
**We need to sum the matrix elements of the effective Hamiltonian:**

$$\Sigma_{X_s} \left| C_7 \langle X_s \gamma | O_7 | \bar{B} \rangle + C_2 \langle X_s \gamma | O_2 | \bar{B} \rangle + \ldots \right|^2$$

**The "77" term in the above sum can be related via optical theorem to the imaginary part of the elastic forward scattering amplitude:**

$Im\{$  $\} \equiv Im\ A$


**In this amplitude, we can perform OPE when the photons are soft enough, i.e. when** $|m_B - 2E_\gamma| \gg \Lambda_{QCD}$.




$$\int_{1\ \mathrm{GeV}}^{E_\gamma^{max}} dE_\gamma\ E_\gamma^n\ Im\ A(E_\gamma) \sim \oint_{\mathrm{big\ circle}} dE_\gamma\ E_\gamma^n\ A(E_\gamma)$$

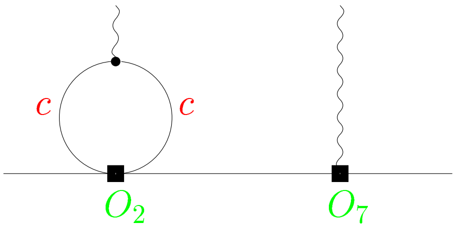
## HQET gives us a double expansion:

$$\Sigma_{X_s} \mathrm{BR}[\bar{B} \to X_s \gamma]_{E_\gamma > 1 \ \mathrm{GeV}} = \left[ a_{00} + a_{02} \left( \frac{\Lambda}{m_B} \right)^2 + \ldots \right] + \frac{\alpha_s(m_b)}{\pi} \left[ a_{10} + a_{12} \left( \frac{\Lambda}{m_B} \right)^2 + \ldots \right] + \mathcal{O}\left[ \left( \frac{\alpha_s(m_b)}{\pi} \right)^2 \right]$$

+ [ Contributions other than the "77" term].

There is no OPE for the latter term. However, operators containing no charm quark are suppressed by their small Wilson coefficients. As far as the operators containing the charm quark are concerned, we know that their contribution at the leading order in $\alpha_s$ can be expressed as a power series:

$$\langle \bar{B} |$$

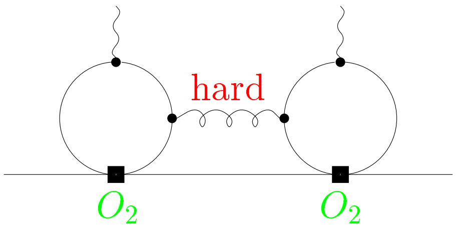



$$| \bar{B} \rangle = \frac{\Lambda^2}{m_c^2} \sum_{n=0}^{\infty} b_n \left( \frac{m_b \Lambda}{m_c^2} \right)^n,$$

which can be truncated to the leading $n = 0$ term, because the coefficients $b_n$ decrease fast with $n$. The calculable $n = 0$ term makes $\mathrm{BR}[\bar{B} \to X_s \gamma]$ increase by around 3%.

At $\mathcal{O}(\alpha_s)$, one encounters matrix elements like:

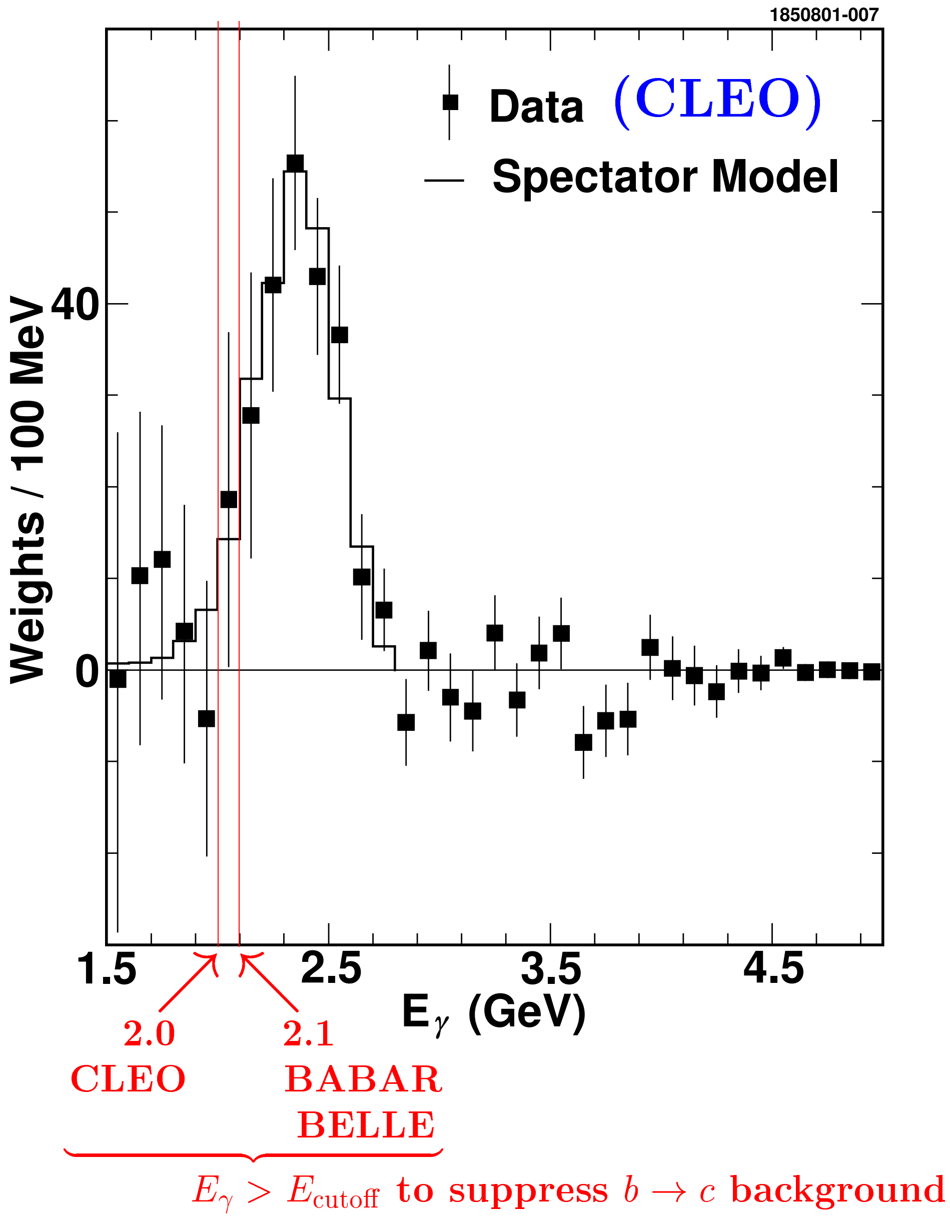
$$\langle \bar{B} |$$




$$| \bar{B} \rangle.$$

Perturbative contributions to such matrix elements are usually small, so it is enough to rely on quark-hadron duality and use the perturbative NLO expressions only. However, the intermediate $\psi$ and $\psi'$ contributions ($\bar{B} \to \psi^{(\prime)} X$ followed by radiative $\psi^{(\prime)}$ decay) must be subtracted on the experimental side.

# $\bar{B} \to X_s \gamma$ photon spectrum




**Extrapolation from the experimental cutoff to lower energies $\Rightarrow$ model-dependence.**

**CLEO:** $\sim \pm 5\%$, **BABAR:** $\sim \pm 9\%$, **BELLE:** $\sim \pm 15\%$

**The measured spectrum is used for extraction of $\bar{\Lambda}$ and $\lambda_1$ parameters of HQET $\Rightarrow$ determination of $V_{ub}$.**

## SM prediction:

$$BR[\bar{B} \to X_s\gamma]^{\text{subtr. } \psi}_{E_\gamma > E_0} = \begin{cases} (3.57 \pm 0.30) \times 10^{-4}, & E_0 = 1.6 \text{ GeV} \\ 3.70 \times 10^{-4}, & E_0 = \frac{1}{20} m_b \end{cases}$$

**The dominant uncertainty ($\sim \pm 6\%$) originates from $m_c$-dependence.**

## Experimental results (for $E_0 = \frac{1}{20} m_b$):

**BABAR** [hep-ex/0207076] **(59.6 M$B\bar{B}$)**

$$\text{BR}[\bar{B}_d \to X_s\gamma] = \left[3.88 \pm 0.36_{\text{stat}} \pm 0.37_{\text{sys}} \left({}^{+0.43}_{-0.23}\right)_{\text{theory}}\right] \times 10^{-4}$$

**CLEO** [PRL 87 (2001) 251807, hep-ex/0108032] **(9.70 M$B\bar{B}$)**

$$\text{BR}[\bar{B}_d \to X_s\gamma] = \left[3.21 \pm 0.43_{\text{stat}} \pm 0.27_{\text{sys}} \left({}^{+0.18}_{-0.10}\right)_{\text{theory}}\right] \times 10^{-4}$$

**BELLE** [PLB 511 (2001) 151, hep-ex/0103042] **(6.07 M$B\bar{B}$)**

$$\text{BR}[\bar{B}_d \to X_s\gamma] = \left[3.36 \pm 0.53_{\text{stat}} \pm 0.42_{\text{sys}} \left({}^{+0.50}_{-0.54}\right)_{\text{theory}}\right] \times 10^{-4}$$

**ALEPH** [PLB 429 (1998) 169] **(4.06 M$Z$)**

$$\text{BR}[b \to s\gamma] = (3.11 \pm 0.80_{\text{stat}} \pm 0.72_{\text{sys}}) \times 10^{-4}$$

**Weighted average:**

$$\text{BR}[\bar{B} \to X_s\gamma \;\; (E_\gamma > \frac{1}{20} m_b)]_{\text{exp}} = \left[3.40 \;\; \left({}^{+0.42}_{-0.37}\right)\right] \times 10^{-4}$$

**After rescaling back to 1.6 GeV, one obtains**

$$\text{BR}[\bar{B} \to X_s\gamma \;\; (E_\gamma > 1.6 \text{ GeV})]_{\text{exp}} = \left[3.28 \;\; \left({}^{+0.41}_{-0.36}\right)\right] \times 10^{-4}$$

## Summary:

**1.**

$$BR[\bar{B} \to X_s\gamma]_{E_\gamma > E_0} = \begin{cases} (3.57 \pm 0.30) \times 10^{-4}, & E_0 = 1.6 \text{ GeV} \\ 3.70 \times 10^{-4}, & E_0 = \frac{1}{20} m_b \end{cases}$$

$$\mathrm{BR}[\bar{B} \to X_s\gamma]_{\mathrm{exp}} = \left[3.40 \;\; \left({}^{+0.42}_{-0.37}\right)\right] \times 10^{-4}$$

$\Rightarrow$ **Theory and experiment agree within** $1\sigma$

**2. The above agreement provides stringent constraints on new physics.**

**3. The dominant theoretical uncertainty is of perturbative origin. It is due to the renormalization-scheme dependence of $m_c$ in two-loop contributions to the decay amplitude. Calculating the NNLO corrections would remove this problem and, in consequence, reduce the theoretical uncertainty by almost a factor of 2. The main challenge at the NNLO are UV-finite parts of 3-loop massive vertex integrals with non-vanishing external momenta.**

**4. The numerical behaviour of $\mathrm{BR}[\bar{B} \to X_s\gamma]$ as a function of $m_c$ suggests that the dominant charm mass dependence originates from distances much smaller than $\Lambda_{\mathrm{QCD}}$. In such a case, the associated non-perturbative effects would be under control.**