The $\mathcal{B}(\bar{B} \to X_s\gamma)$ for an arbitrary charm quark mass

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Based on:

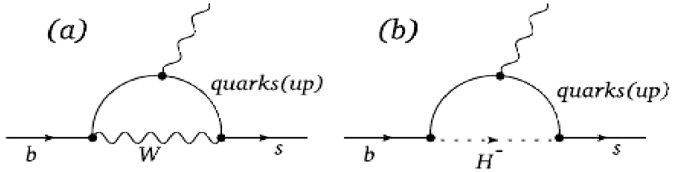
M. Misiak, H. Asatrian, R. Boughezal, M. Czakon, T. Ewerth, A. Ferroglia, P. Fiedler, P. Gambino, C. Greub, U. Haisch, T. Huber, M. Kamiński, G. Ossola, M. Poradziński, A. Rehman, T. Schutzmeier, M. Steinhauser and J. Virto
Phys. Rev. Lett. **114** (2015) 22, 221801 [arXiv:1503.01789].

M. Misiak, A. Rehman and M. Steinhauser, to be published.

- **Introduction: radiative B-decays**
- **Interpolation in the charm quark mass**
- **NNLO ($\mathcal{O}(\alpha_s^2)$) counterterms: no interpolation**
- **Outlook of bare NNLO calculations**
- **Summary**

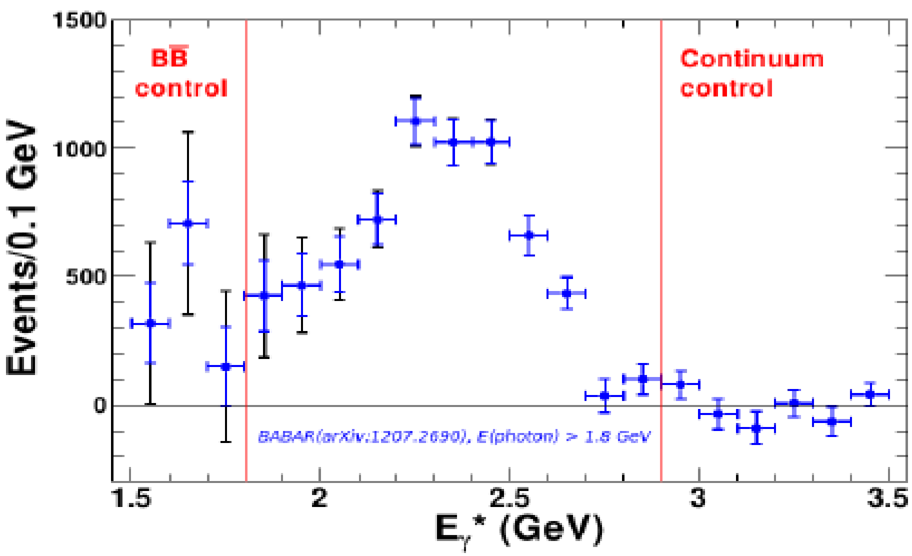
Motivation

FCNC process $\Rightarrow$ **bounds on beyond-SM physics**



Photon energy spectrum in inclusive measurements

BABAR [arXiv:1207.2690] ; $E_\gamma > 1.8$ GeV



Background grows for smaller E_0.

Recent bounds on $\mathbf{M_{H^\pm}}$; [arXiv:1503.01789]

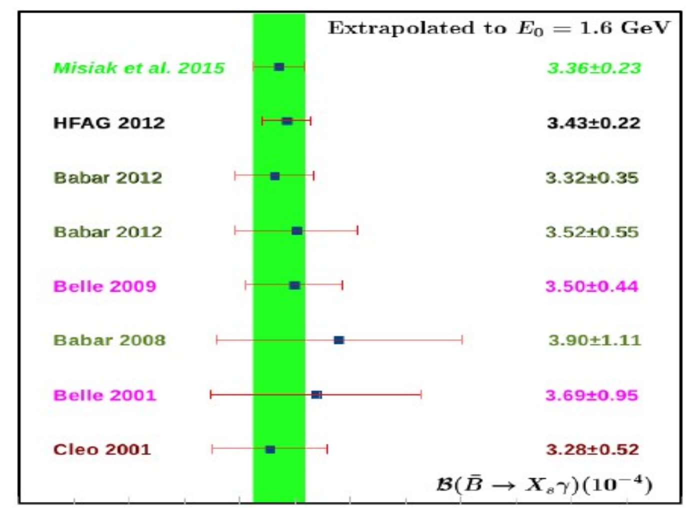
in 2HDM II

$$M_{H^\pm} > 480 \text{ GeV at } 95\% \text{C.L.}$$

$$M_{H^\pm} > 358 \text{ GeV at } 99\% \text{C.L.}$$

Branching fraction; HFAG [arXiv:1412.7515] uncertainty 6.5%

$$\mathcal{B}(\bar{B} \to X_s\gamma)^{Exp}_{E_\gamma > 1.6\text{GeV}} = (3.43 \pm 0.22) \cdot 10^{-4}$$



Belle-II

Better accuracy is expected in 2017.

SM Prediction; [arXiv:1503.01789] uncertainty 7.0%

$$\mathcal{B}(\bar{B} \to X_s\gamma)^{SM}_{E_\gamma > 1.6\text{GeV}} = (3.36 \pm 0.23) \cdot 10^{-4}$$

Interpolation uncertainty is 3%.

Non-perturbative	5%	mostly $\mathcal{O}(\alpha_s \Lambda / m_b)$
Parametric	2%	$\alpha_s(M_Z)(0.75\%), \mathcal{B}^{Exp}_{SL}(1.49\%)$, CKM(0.12%), ...
Charm mass dependence	3%	$\mathcal{Q}_1,\ \mathcal{Q}_2$ matrix elements
Higher order NNNLO	3%	$\mu_b(2.0\text{GeV}), \mu_c(2.0\text{GeV}), \mu_0(160\text{GeV})$

Theoretical framework

Decoupling of W, Z, t, H^0 $\Rightarrow$ effective weak Lagrangian

$$\mathcal{L}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{8} C_i(\mu_b) \mathcal{Q}_i$$

Operators basis: Chetyrkin, Misiak, Münz, 1996

$$\mathcal{Q}_1 = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L)$$
$$\mathcal{Q}_2 = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)$$
$$\mathcal{Q}_7 = \frac{e}{16\pi^2} m_b \, (\bar{s}_L \sigma_{\mu\nu} b_R) \, F^{\mu\nu}$$
$$\mathcal{Q}_8 = \frac{g}{16\pi^2} m_b \, (\bar{s}_L \sigma_{\mu\nu} T^a b_R) \, G^{a\mu\nu}$$
$$\mathcal{Q}_3 = (\bar{s}_L \gamma_\mu b_L) \sum\nolimits_q (\bar{q} \gamma^\mu q)$$
$$\mathcal{Q}_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum\nolimits_q (\bar{q} \gamma^\mu T^a q)$$
$$\mathcal{Q}_5 = (\bar{s}_L \gamma_{\mu 1} \gamma_{\mu 2} \gamma_{\mu 3} b_L) \sum\nolimits_q (\bar{q} \gamma^{\mu 1} \gamma^{\mu 2} \gamma^{\mu 3} q)$$
$$\mathcal{Q}_6 = (\bar{s}_L \gamma_{\mu 1} \gamma_{\mu 2} \gamma_{\mu 3} T^a b_L) \sum\nolimits_q (\bar{q} \gamma^{\mu 1} \gamma^{\mu 2} \gamma^{\mu 3} T^a q)$$

$|C_7| : |C_{1,2}| : |C_8| \simeq 1 : 3 : 1/2$

current-current	photonic dipole	gluonic dipole	penguin
$\mathcal{Q}_{1,2}$	$\mathcal{Q}_7$	$\mathcal{Q}_8$	$\mathcal{Q}_{3,4,5,6}$
$C_{1,2}(m_b) \sim 1$	$C_7(m_b) \sim -0.3$	$C_8(m_b) \sim -0.15$	$C_{3,4,5,6}(m_b) \sim 0.07$

Higher-order EW and/or CKM-suppressed effects ($|V_{ub} V_{us}^* / V_{tb} V_{ts}^*| < 0.02$) bring other operators.

The matrix elements can be effectively evaluated in perturbation theory

$$\Gamma(\bar{B} \to X_s \gamma)_{E_\gamma > E_0} = \Gamma(b \to X_s^p \gamma)_{E_\gamma > E_0} + \begin{pmatrix} \text{Non-perturbative} \\ \sim (\pm 5)\% \\ \text{arXiv} : 1003.5012 \end{pmatrix}$$

$b \in \bar{B} = B^-(b\bar{u})$ or $\bar{B}^0(b\bar{d})$

Provided that E_0 is large ($\sim m_b/2$) but not close to endpoint ($m_b - 2E_0 \gg \Lambda_{QCD}$).
$E_0 \sim m_b/3 \simeq 1.6$ GeV is now conventional.

$$\Gamma(b \to X_s^p \gamma)_{E_\gamma > E_0} = N \sum_{i,j=1}^{8} C_i^{\rm eff}(\mu_b) C_j^{\rm eff}(\mu_b) \widetilde{G}_{ij}(E_0, \mu_b)$$

$$K_{ij} \equiv \widetilde{G}_{ij} / G_u^{\rm semi}$$

$N = \frac{G_F^2 m_b^5}{32\pi^3} \left(\frac{\alpha_{em}}{\pi}\right) |V_{tb} V_{ts}^*|^2$

$\mu_b \sim m_b/2$

$\delta = 1 - 2E_0/m_b$

$z = m_c^2/m_b^2$

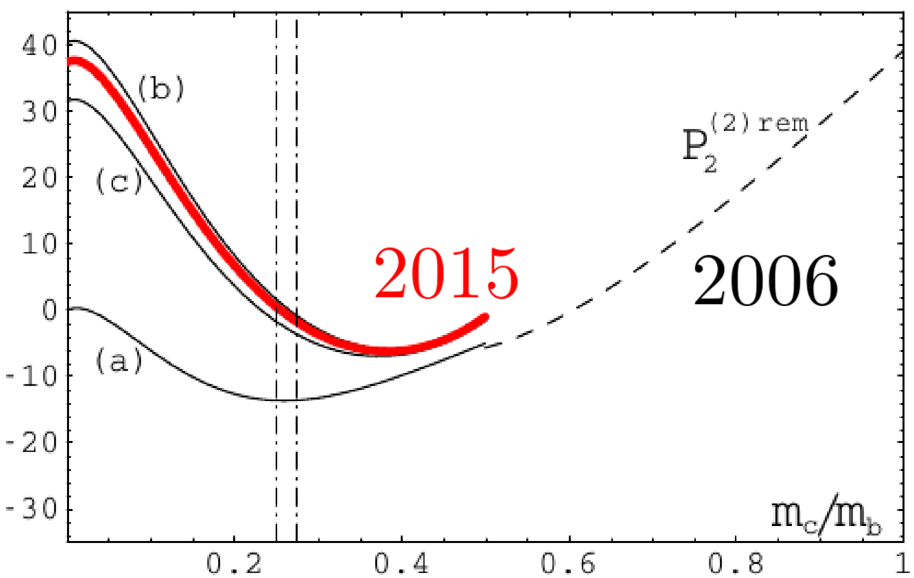
At NNLO $K_{77}^{(2)}$, $K_{17}^{(2)}$, $K_{27}^{(2)}$ depend on z. The central value of $z \simeq 0.056$.

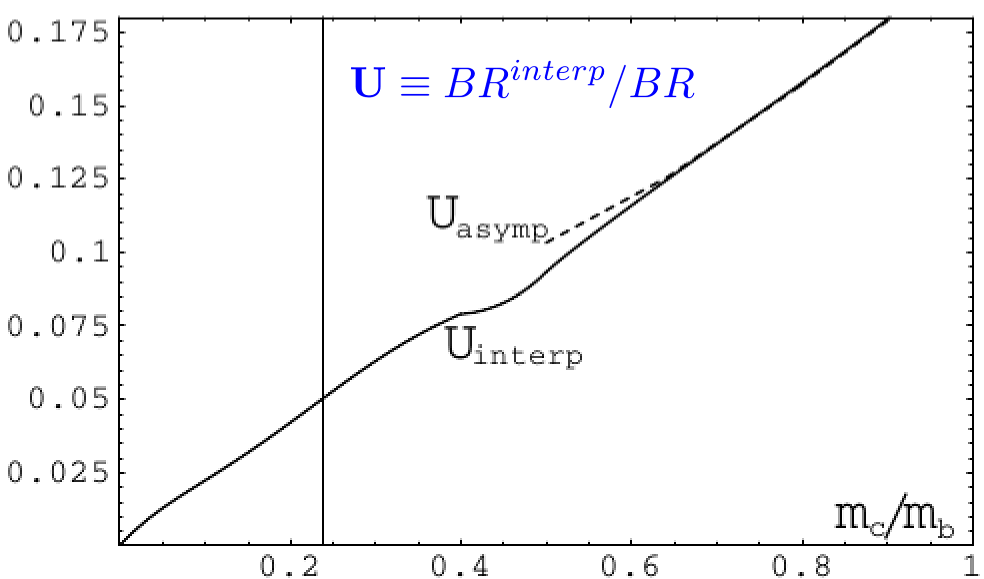
Interpolation in the charm quark mass

$$C_i(\mu_b) = \sum_{n=0} \left(\frac{\alpha_s(\mu_b)}{4\pi}\right)^n C_i^{(n)}(\mu_b) \quad \textbf{and} \quad K_{ij} = \sum_{n=0} \left(\frac{\alpha_s(\mu_b)}{4\pi}\right)^n K_{ij}^{(n)}$$

$$\sum_{i,j=1}^{8} C_i^{(0)}(\mu_b) C_j^{(0)}(\mu_b) K_{ij}^{(2)}(E_0,\mu_b) \equiv P_2^{(2)} = \underbrace{P_2^{(2)\beta_0}}_{\text{BLM}} + \underbrace{P_2^{(2)\text{rem}}}_{\text{Non-BLM}}$$

- **BLM with arbitrary charm quark mass** — K. Bieri, C. Greub, M. Steinhauser, 2003; Z. Ligeti, M. Luke, A. Manohar, M. Wise, 1999
- **Non-BLM by interpolation in m_c** assuming BLM at $m_c = 0$ — M. Steinhauser, M. Misiak, 2006
- **Non-BLM by interpolation in m_c** with explicit calculation at $m_c = 0$ — M. Czakon, P. Fiedler, T. Huber, M. Misiak, T. Schutzmeier, M. Steinhauser; 2015

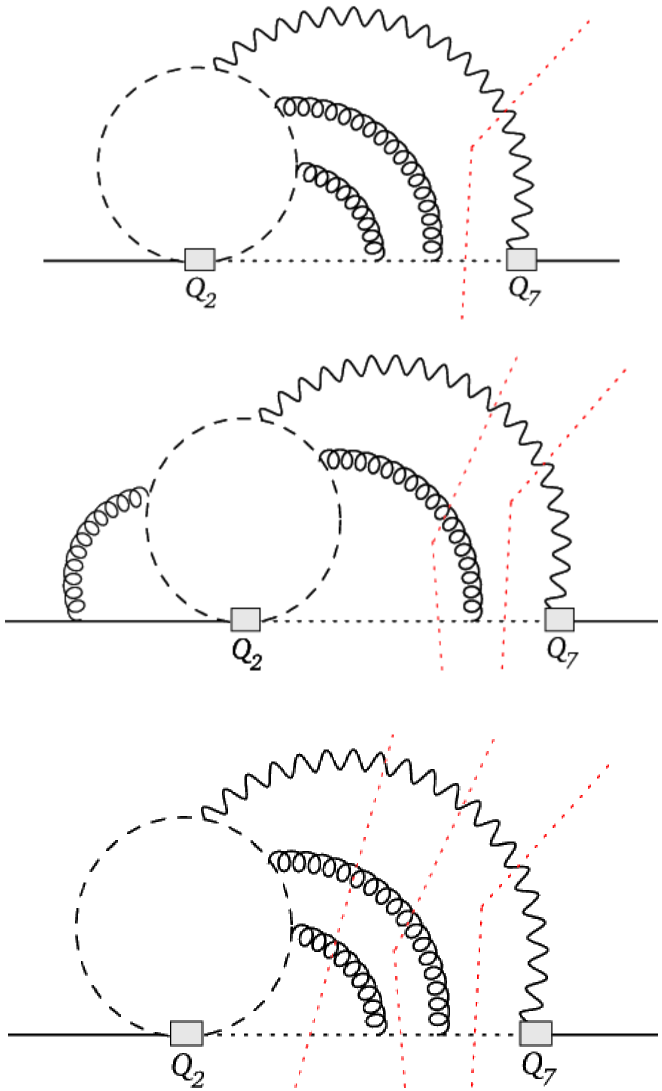




Interpolation uncertainty estimate remains unchanged w.r.t. 2006 ($\pm 3\%$)

Sample diagrams for bare and counterterm NNLO contributions

$G_{27,17}$
$m_c \neq 0$



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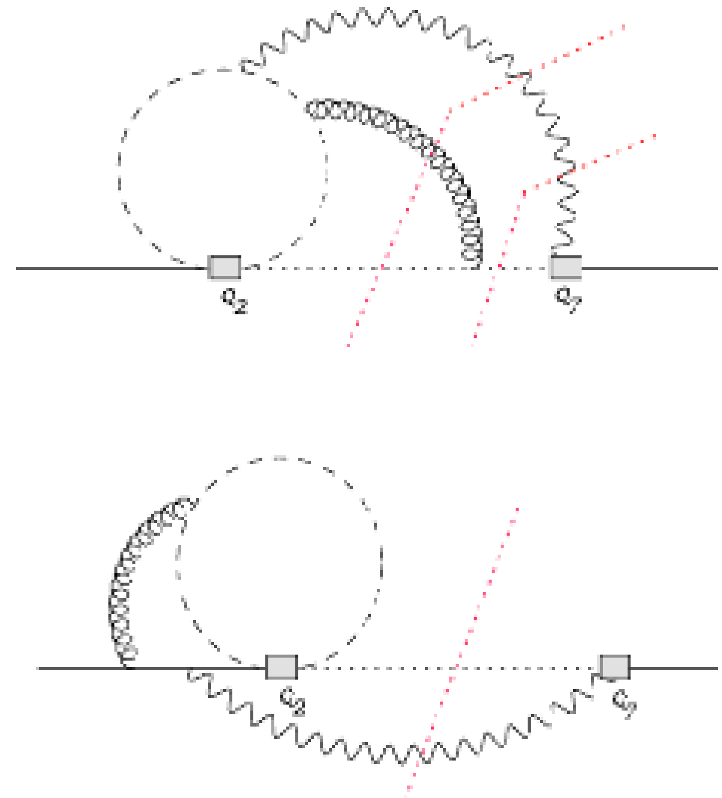
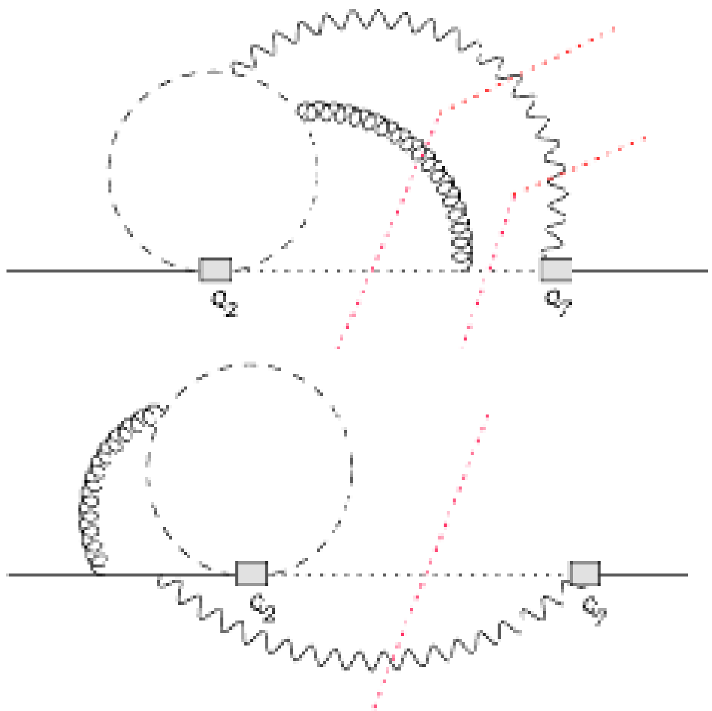


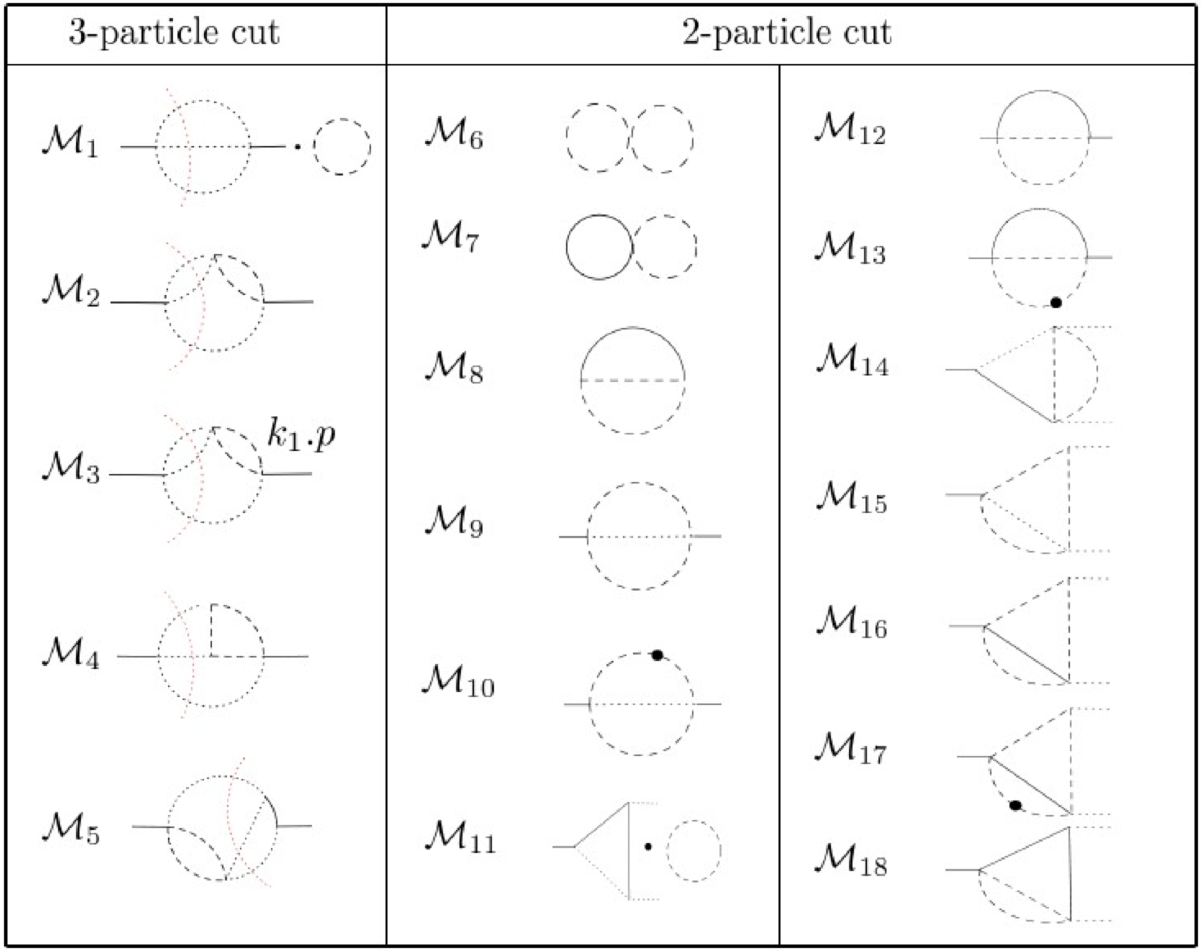
$+ \;\cdots\cdots$

$s\gamma, s\gamma g, s\gamma gg, s\gamma q\bar{q}$

Calculational method

Such contributions are obtained from three-loop propagators with unitarity cuts.





Reduction to master integrals

FIRE [arXiv:1408.2372v2]
Reduze [arXiv:1201.4330v1]

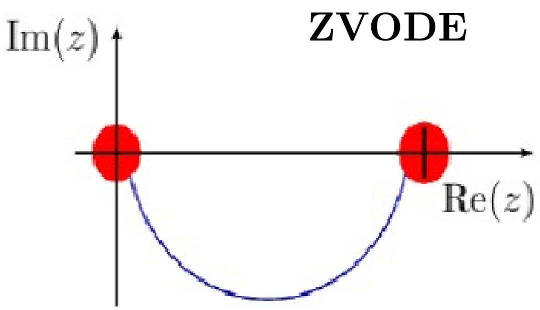
Reverse unitarity

$$\int \frac{\mathrm{d}^D k}{(2\pi)^{D-1}} \theta(k^0)\delta(k^2 - m^2)$$

$$\frac{i}{k^2 - m^2 - i0} - \frac{i}{k^2 - m^2 + i0}$$

$$\frac{\mathrm{d}}{\mathrm{d}z}\mathcal{M}_n(z,\epsilon) = \sum_m R_{nm}(z,\epsilon)\mathcal{M}_m(z,\epsilon)$$

ZVODE



Boundary conditions at large z

MB method, MB.m, M. Czakon
Asymptotic expansions, exp, M. Steinhauser

NNLO Counterterms: no interpolation

$\frac{G_{27,17}}{m_c \neq 0}$

Renormalization

$$\widetilde{\alpha}_s \widetilde{G}_{27}^{(1)} + \widetilde{\alpha}_s^2 \widetilde{G}_{27}^{(2)} = Z_b^{OS} Z_m^{OS} \bar{Z}_{77} \Big\{ \widetilde{\alpha}_s^2 s^{3\varepsilon} \widetilde{G}_{27}^{(2)\text{bare}} + (Z_m^{OS} - 1) s^{\varepsilon} \left[\bar{Z}_{24} \hat{G}_{47}^{(0)m} + \widetilde{\alpha}_s s^{\varepsilon} \hat{G}_{27}^{(1)m} \right]$$
$$+ \widetilde{\alpha}_s (Z_G^{OS} - 1) s^{2\varepsilon} \hat{G}_{27}^{(1)3P} + \bar{Z}_{27} Z_m^{OS} \left[\hat{G}_{77}^{(0)} + \widetilde{\alpha}_s s^{\varepsilon} \hat{G}_{77}^{(1)\text{bare}} \right]$$
$$+ \widetilde{\alpha}_s \bar{Z}_{28} s^{\varepsilon} \hat{G}_{78}^{(1)\text{bare}} + \sum_{j=1,\ldots,6,11,12} \bar{Z}_{2j} s^{\varepsilon} \left[\hat{G}_{j7}^{(0)} + \widetilde{\alpha}_s s^{\varepsilon} Z_g^2 \hat{G}_{j7}^{(1)\text{bare}} \right] \Big\}$$
$$+ 2\widetilde{\alpha}_s \left(\frac{\mu_b^2}{\mu_c^2} \right)^{\varepsilon} s^{2\varepsilon} (\bar{Z}_m - 1)\, z \frac{d}{dz} \widetilde{G}_{27}^{(1)\text{bare}} + \mathcal{O}(\widetilde{\alpha}_s^3)$$

$$Q_{11} = (\bar{s}_L \gamma_{\mu 1} \gamma_{\mu 2} \gamma_{\mu 3} T^a c_L)(\bar{c}_L \gamma^{\mu 1} \gamma^{\mu 2} \gamma^{\mu 3} T^a b_L) - 16 Q_1$$
$$Q_{12} = (\bar{s}_L \gamma_{\mu 1} \gamma_{\mu 2} \gamma_{\mu 3} c_L)(\bar{c}_L \gamma^{\mu 1} \gamma^{\mu 2} \gamma^{\mu 3} b_L) - 16 Q_2$$

The $\hat{G}_{ij}$'s correspond to $\widetilde{G}_{ij}$'s once we replace C^{eff}'s with C's.

$$\hat{G}_{27}^{(1)} = \hat{G}_{27}^{(1)2P} + \hat{G}_{27}^{(1)3P}$$

$$\widetilde{\alpha}_s = \alpha_s / 4\pi = g_s^2 / 16\pi^2$$

$$s = \frac{4\pi \mu_b^2}{m_b^2} e^{\gamma}$$

$\hat{G}_{j7}^{(0)}$ vanish for $j = 1, 2, 11, 12$

Now, $m_c = 0$ counterterms are known to all order in ϵ except $\hat{G}_{47}^{(1)}$, [AR, PhD thesis].

$$\hat{G}_{27}^{(1)3P}(z) = g_0(z) + \epsilon\, g_1(z) + \mathcal{O}(\epsilon^2) \qquad \hat{G}_{27}^{(1)2P}(z) = -\frac{92}{81\epsilon} + f_0(z) + \epsilon\, f_1(z) + \mathcal{O}(\epsilon^2)$$

$$\hat{G}_{7(12)}^{(1)3P}(z) = 0 - \epsilon\, (20\, g_0(z)) + \mathcal{O}(\epsilon^2) \qquad \hat{G}_{7(12)}^{(1)2P}(z) = \frac{2096}{81} + \epsilon\, e_1(z) + \mathcal{O}(\epsilon^2)$$

$$\hat{G}_{27}^{(1)m,3P}(z) = j_0(z) + \epsilon\, j_1(z) + \mathcal{O}(\epsilon^2) \qquad \hat{G}_{27}^{(1)m,2P}(z) = -\frac{1}{3\epsilon^2} + \frac{1}{\epsilon} r_{-1}(z) + r_0(z) + \epsilon\, r_1(z) + \mathcal{O}(\epsilon^2)$$

Results: 3-body

for $\delta = 1$

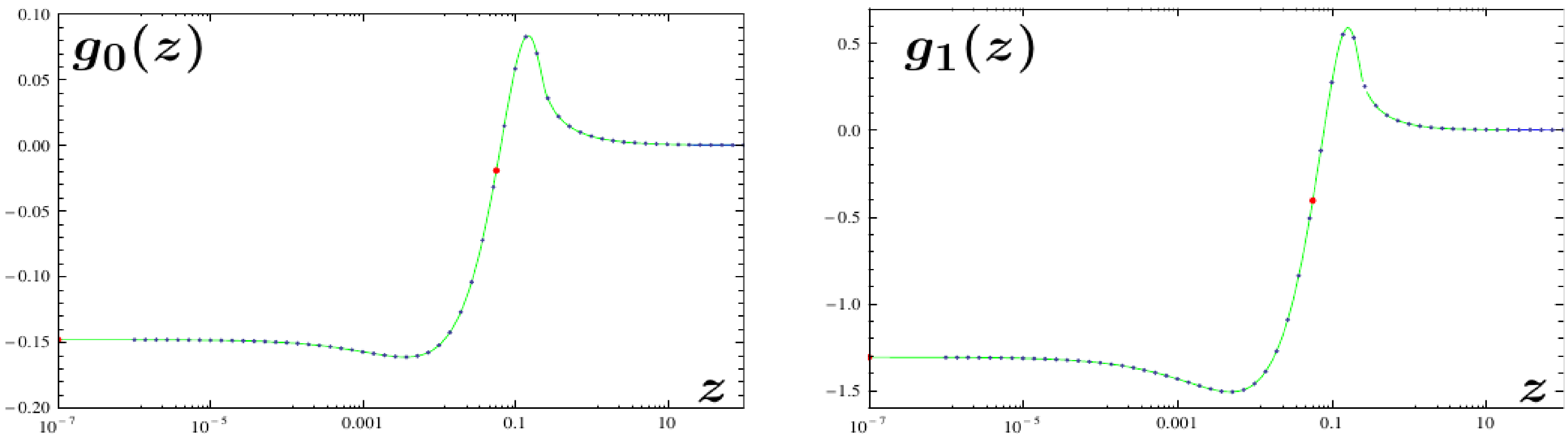
$$\hat{G}_{27}^{(1)3P}(z) = g_0(z) + \epsilon\, g_1(z) + \mathcal{O}(\epsilon^2)$$

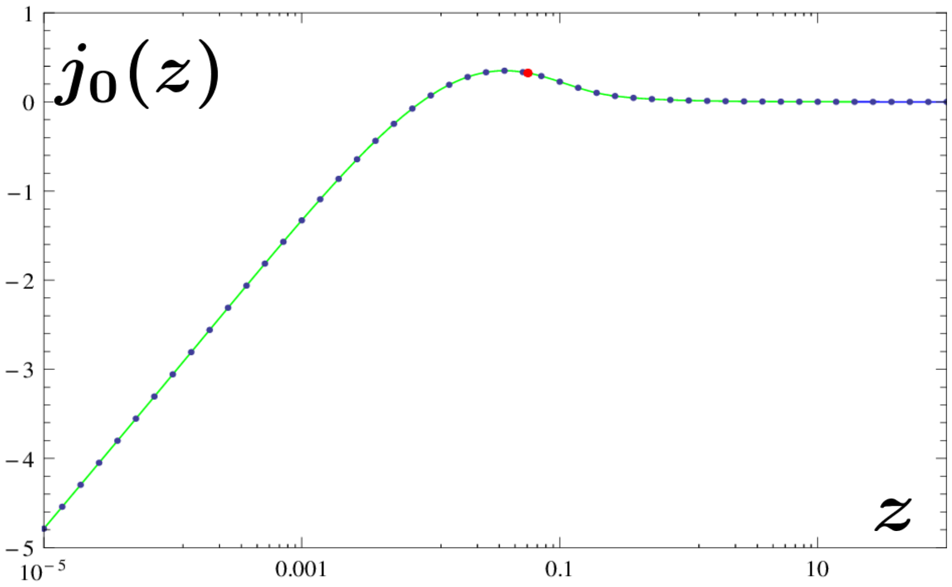
$$\hat{G}_{7(12)}^{(1)3P}(z) = 0 - \epsilon\,(20\, g_0(z)) + \mathcal{O}(\epsilon^2)$$

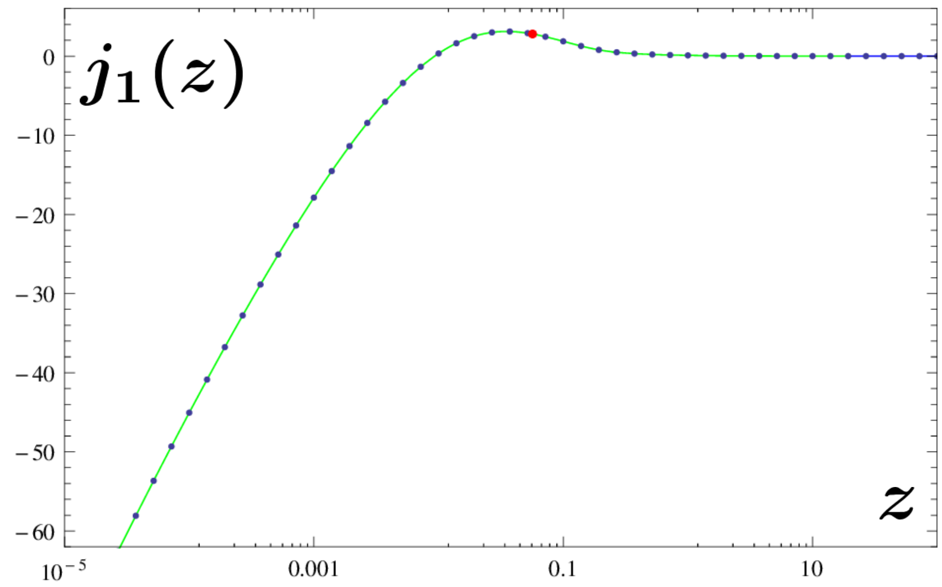
$$\hat{G}_{27}^{(1)m,3P}(z) = j_0(z) + \epsilon\, j_1(z) + \mathcal{O}(\epsilon^2)$$

$$g_0(z) = \begin{cases} -\frac{4}{27} - \frac{14}{9}z + \frac{8}{3}z^2 + \frac{8}{3}z(1-2z)\, s\, L + \frac{16}{9}z(6z^2-4z+1)\left(\frac{\pi^2}{4} - L^2\right), & \text{for } z \le \frac{1}{4}, \\ -\frac{4}{27} - \frac{14}{9}z + \frac{8}{3}z^2 + \frac{8}{3}z(1-2z)\, t\, A + \frac{16}{9}z(6z^2-4z+1)\, A^2, & \text{for } z > \frac{1}{4}, \end{cases}$$

where $s = \sqrt{1-4z}$, $L = \ln(1+s) - \frac{1}{2}\ln 4z$, $t = \sqrt{4z-1}$, and $A = \arctan(1/t)$.







Dots: solutions to the differential equations and/or the exact $z \to 0$ limit.

Boundary condition for the numerical DE's is at $z = 20$.

At $z = 1/4$ we have the charm production threshold, and the DE's have a singular point there.

Agreement with numerical solution of differential equations over wide range of z.

Blue curves: large-z asymptotic expansions above $z = 20$.

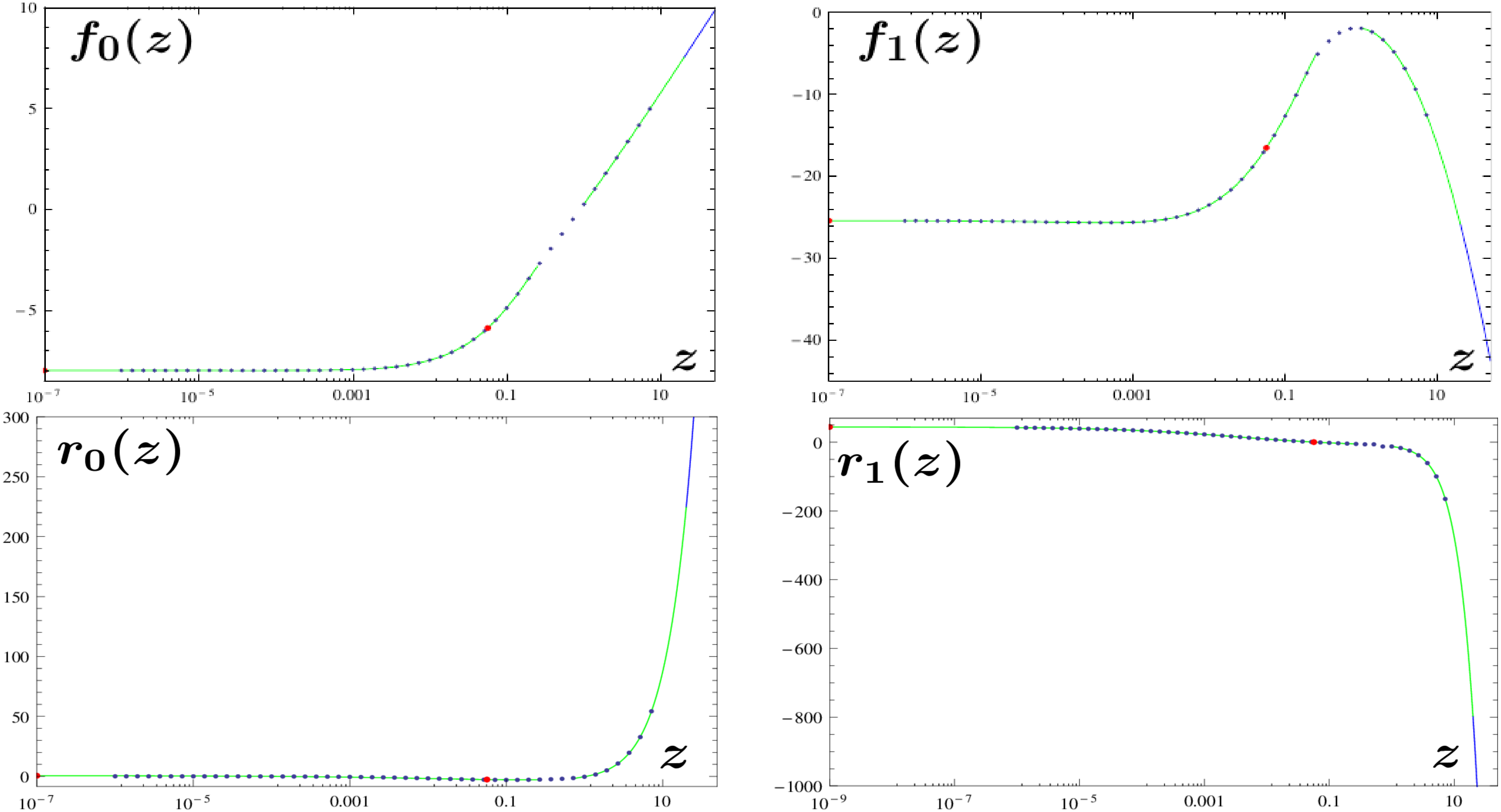
Red dots: Exact $z = 0$ results and numerical results from the DE's at the physical z.

Green curves: known asymptotic expansions either at large z or at small z.

This provides a test of our DE algorithm that is aimed at to be used in bare NNLO calculation where no analytic expansion at small z is going to be available.

Results: 2-body

$$f_0(z) = -\frac{1942}{243} + 2\,\mathcal{R}e\left[a(z) + b(z)\right] \qquad e_1(z) = \frac{39112}{243} - 8\,\mathcal{R}e\left[5\,a(z) + b(z)\right]$$

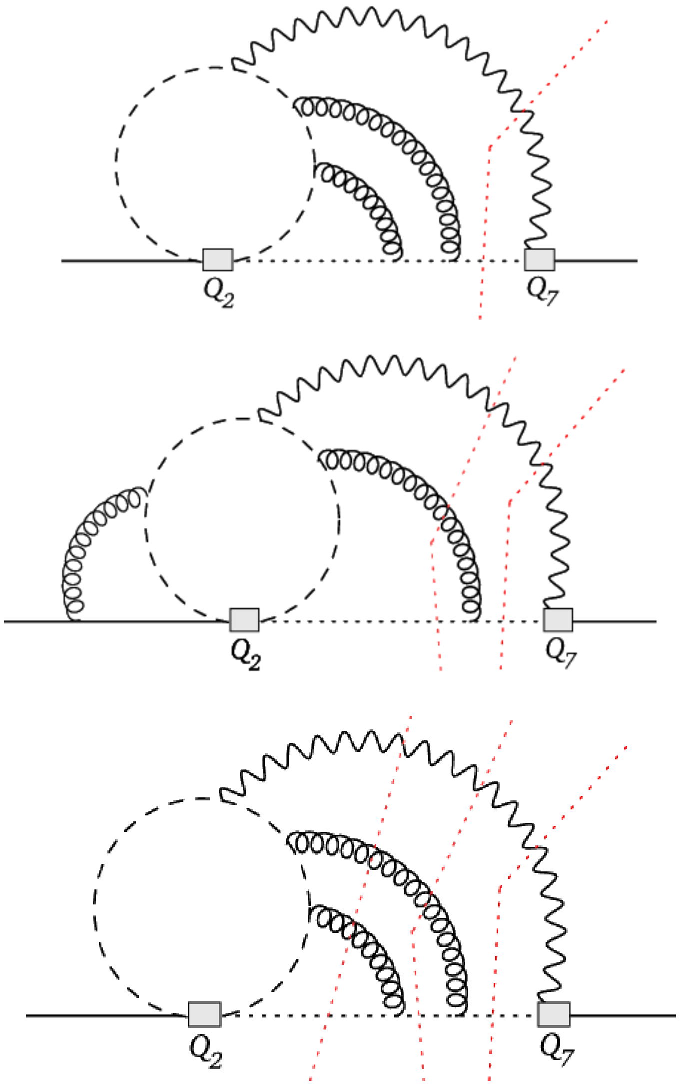


This provides a test of our DE algorithm that is aimed at to be used in bare NNLO calculation where no analytic expansion at small z is going to be available.

Outlook of bare NNLO Contribution

$K^{(2)\mathrm{bare}}_{17,27}(z)$

in progress



$+ \;\cdots\cdots$

$s\gamma, s\gamma g, s\gamma gg, s\gamma q\bar{q}$

Required same techniques as used/mentioned above.

but much more complex.

BCs using automatized asymptotic expansions at $m_c \gg m_b$.

Higher order terms using power-log ansatz

$$I_i(w,\epsilon) = \sum_{n,m,k} c_{inmk}\epsilon^n w^m \mathrm{Log}^k(w) \qquad w = 1/z$$

2-body

number of scalar integrals $\sim 20,000$

number of masters ~ 500

Summary

- The $\bar{B} \to X_s\gamma$ process constrains extensions of the SM in a strong manner. At present, its observed branching ratio agrees with the SM at better than 1σ.

- However, $K_{17}^{(2)}, K_{27}^{(2)}$ are currently included with the help of interpolation in the charm quark mass. This causes about $\pm 3\%$ uncertainty.

- Completing the calculation of $K_{17}^{(2)}, K_{27}^{(2)}$ for arbitrary $z = m_c^2/m_b^2$ to remove $\pm 3\%$ uncertainty is necessary.

- A calculation of the counterterm contribution to $K_{17}^{(2)}(z), K_{27}^{(2)}(z)$ has been presented. Such contributions are obtained by evaluating three-loop propagator diagrams with unitarity cuts.

Backup

Branching ratio; PDG, 2014 $\boldsymbol{\mathcal{B}(\bar{B} \to X_s\gamma)^{Exp}_{E_\gamma>1.6\mathrm{GeV}} = (3.40 \pm 0.21) \cdot 10^{-4}}$

CP-averaged decay rate: $\Gamma_0 = \dfrac{\Gamma(\bar{B}^0 \to X_s\gamma) + \Gamma(B^0 \to X_{\bar{s}}\gamma)}{2}, \qquad \Gamma_\pm = \dfrac{\Gamma(B^- \to X_s\gamma) + \Gamma(B^+ \to X_{\bar{s}}\gamma)}{2};$

Isospin-averaged decay rate: $\Gamma = (\Gamma_0 + \Gamma_\pm)/2$

Isospin asymmetry: $\Delta_{0\pm} = (\Gamma_0 - \Gamma_\pm)/(\Gamma_0 + \Gamma_\pm).$

CP- and isospin-averaged branching ratio: $\mathcal{B}(\bar{B} \to X_s\gamma) = \tau_{B^0}\Gamma \left(\dfrac{1 + r_f r_\tau}{1 + r_f} + \Delta_{0\pm} \dfrac{1 - r_f r_\tau}{1 + r_f} \right)$

$$r_f = f^{+-}/f^{00} = 1.059 \pm 0.027 \quad r_\tau = \tau_{B^+}/\tau_{B^0} = 1.076 \pm 0.004$$

A breakdown of parametric uncertainties in the SM prediction

$\mathcal{B}(\bar{B} \to X_c e\bar{\nu})$	1.50%	m_b^{kin}	0.27%
$\alpha_s(M_Z)$	0.75%	$m_c(\mu_c)$	0.57%
$m_{t,\mathrm{pole}}$	0.19%	m_b/m_q	0.37%
$\lambda = s_{12}$	0.02%	μ_G^2	0.69%
$A = s_{23}/s_{12}^2$	0.01%	μ_π^2	0.03%
$\bar{\rho}$	0.12%	ρ_D^3	0.74%
$\bar{\eta}$	0.01%	ρ_{LS}^3	0.05%

Uncertainties due to the higher-order $\mathcal{O}(\alpha_s^3)$ corrections

$$\frac{\alpha_s(\mu_b)}{\pi} \simeq 0.093, \qquad \left(\frac{\alpha_s(\mu_b)}{\pi}\right)^2 \simeq 0.0087, \qquad \left(\frac{\alpha_s(\mu_b)}{\pi}\right)^3 \simeq 0.00081$$

$$r_{-1}(z) = -1 - \frac{4\pi^2}{81} - 2z + \mathcal{O}(z^8).$$