All you need is logs

Uli Haisch, MPI Munich, ZPW2025, 7.1.25

During the years, the ZPW …

has developed into a forum to discuss in an informal setting the latest developments on different aspects of particle physics phenomenology. In 2025 we will have a special focus on present and future prospects in precision physics, and a special session dedicated to the evolution of effective field theory methods from low to high energies, in occasion of the 75th birthday of Daniel Wyler.

This talk explores the highlighted aspects & their link to Daniel's & my research

Large logarithms in flavor physics

$$\boxed{Q_2} = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)\,, \qquad \boxed{Q_7} = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$$

current-current operator

electromagnetic dipole operator

[seminal work on b→sγ by Greub, Hurth & Wyler, hep-ph/9603404]

Large logarithms in flavor physics

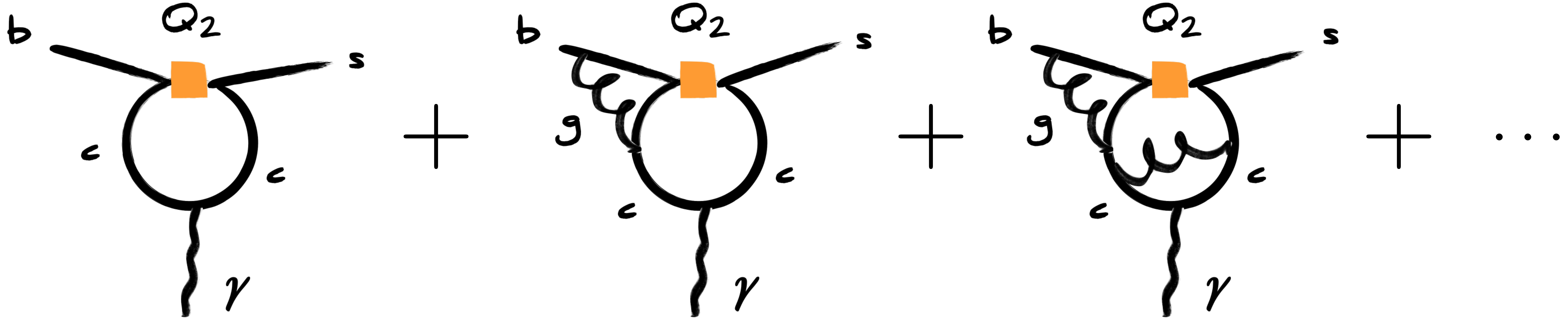
$$\frac{dC_7(\mu)}{d\ln\mu} = \frac{\gamma_{27}}{16\pi^2} C_2(\mu) \qquad \Rightarrow \qquad \frac{C_7(m_b)}{C_2(M_W)} \simeq -\frac{\gamma_{27}}{16\pi^2} \ln\frac{M_W}{m_b}$$

anomalous dimension
encoding mixing $Q_2 \to Q_7$

leading logarithm (LL)
resummed by RGE

Large logarithms in flavor physics

$\gamma_{27} =$



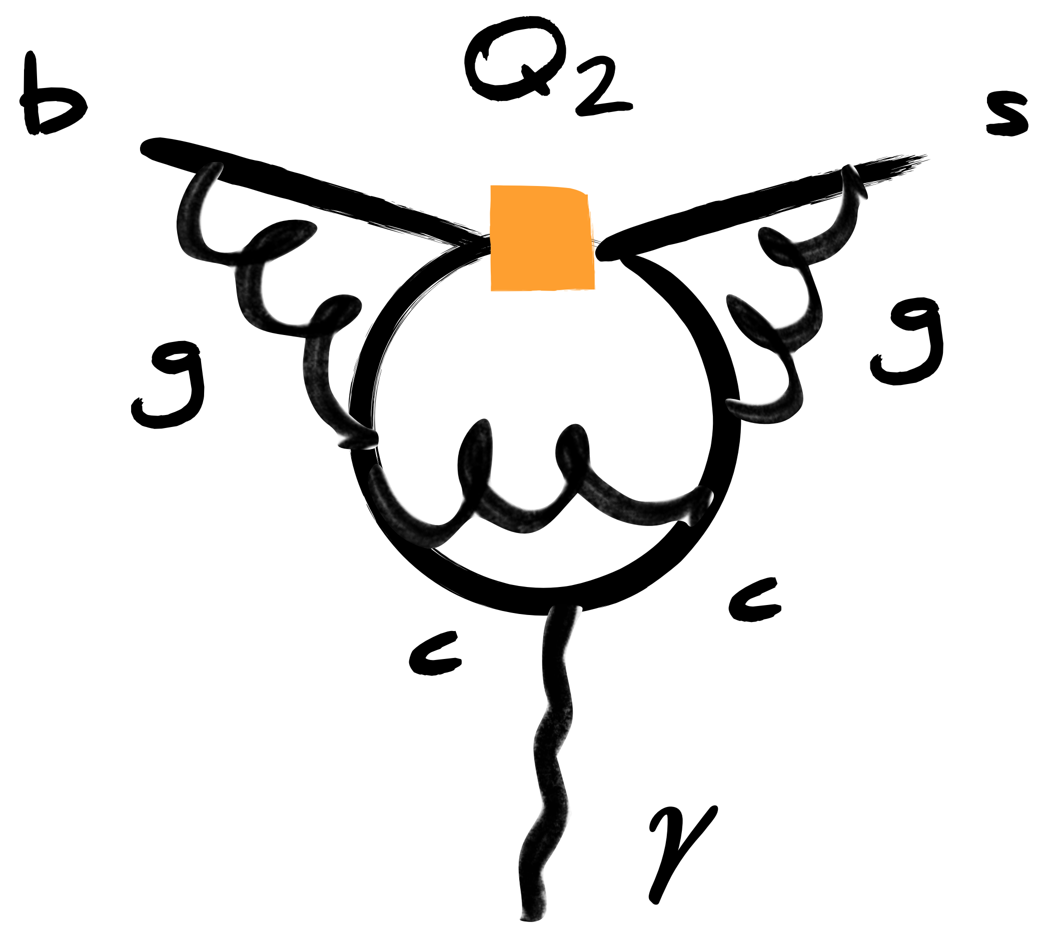
$= \frac{0}{\epsilon}$

LL

NLL

[LL, Ciuchini et al., hep-ph/9307364, hep-ph/9311357; NLL, Chetyrkin, Misiak & Münz, hep-ph/9612313]

NNLL endavor in 2006



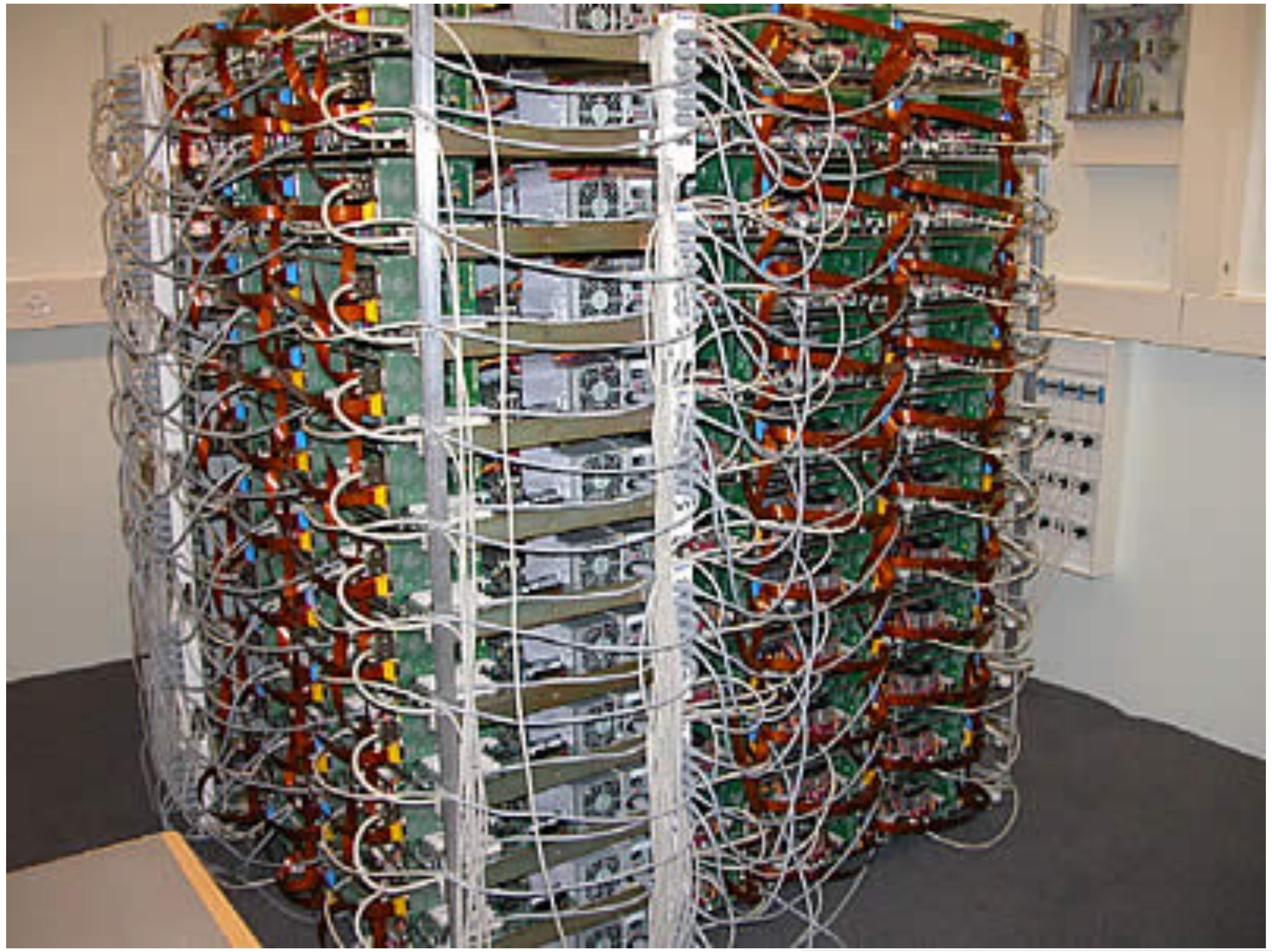
$+$ 21985 diagrams

Calculation of 4-loop anomalous dimensions proved to be a challenge due to large number of diagrams, emergence of numerous "unphysical" operators as ultraviolet subdivergences caused by infrared rearrangement, …

[Czakon, UH & Misiak, arXiv:0612329]

NNLL endavor in 2006

NNLL calculation would not have been possible without (mis)use of zBox1 supercomputer, built in 2002 for cosmological N-body simulations by astrophysics group of University of Zurich



zBox1

Universität Zürich UZH

[Daniel provided funding for zBox4, the great-granddaughter of zBox1]

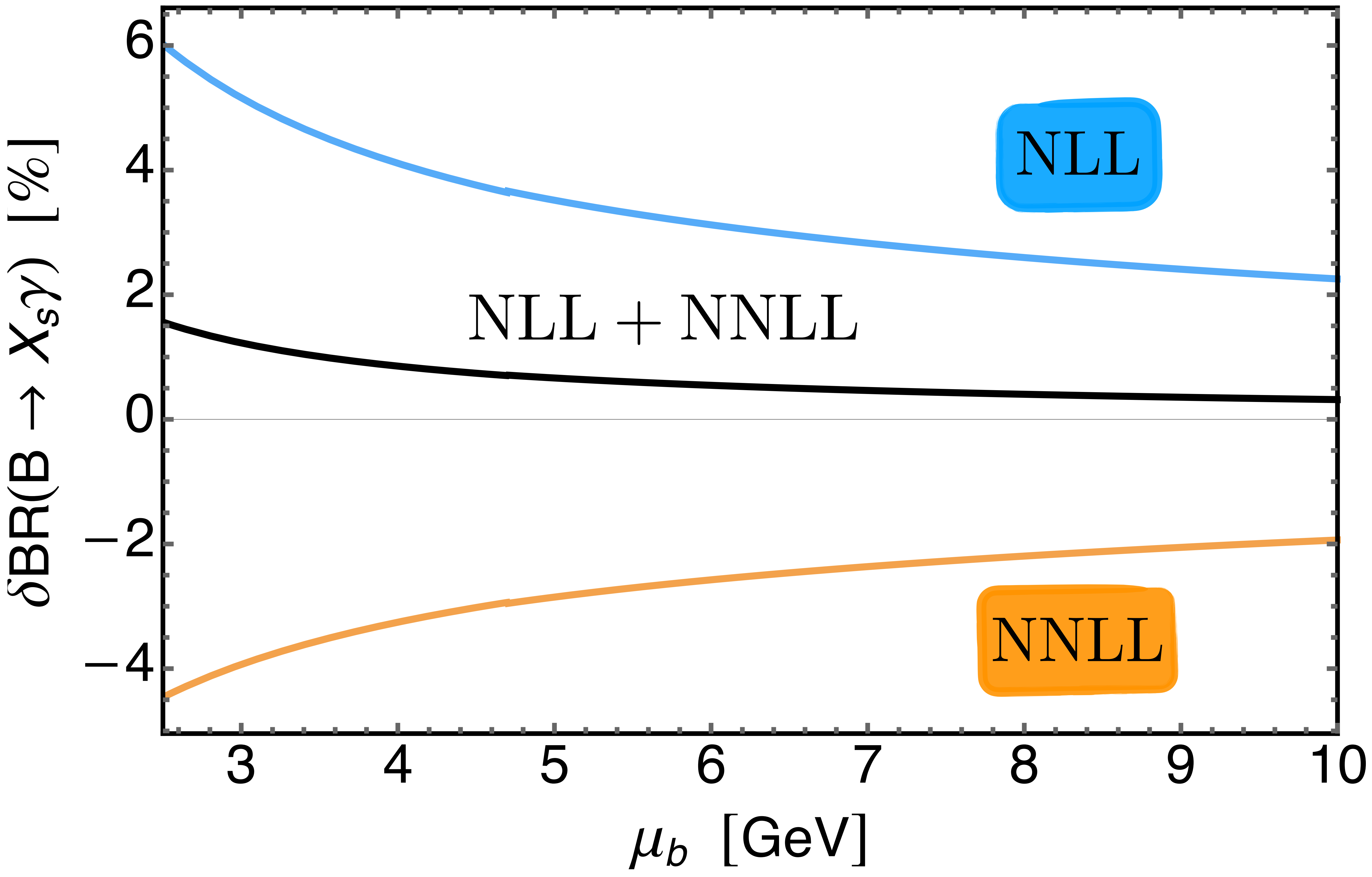
NNLL endavor in 2006

$$
\begin{aligned}
Z_{27} = {} & \frac{\widetilde{\alpha}^2}{\epsilon}\left(\frac{8}{81}+2Q_u\right)+\frac{\widetilde{\alpha}^3}{\epsilon}\left\{\frac{1}{\epsilon}\left[-\frac{4636}{2187}+\frac{80}{729}f-\left(\frac{206}{9}-\frac{16}{9}f\right)Q_u\right]+\frac{6698}{2187}+\frac{64}{2187}f+\left(\frac{128}{27}\right.\right. \\
& \left.\left.-\frac{2}{27}f\right)Q_u\right\}+\frac{\widetilde{\alpha}^4}{\epsilon}\left\{\frac{1}{\epsilon^2}\left[\frac{560390}{19683}-\frac{7400}{2187}f+\frac{208}{2187}f^2+\left(\frac{4379}{18}-\frac{323}{9}f+\frac{4}{3}f^2\right)Q_u+\frac{5}{18}\overline{Q}\right]\right. \\
& +\frac{1}{\epsilon}\left[-\frac{735973}{13122}+\frac{173111}{39366}f+\frac{200}{6561}f^2-\left(\frac{39427}{216}-\frac{613}{27}f+\frac{2}{27}f^2\right)Q_u+\frac{245}{162}\overline{Q}\right]+\frac{3142663}{1417176}+\frac{5068}{2187}\zeta_3 \\
& -\left(\frac{79754}{59049}+\frac{146}{243}\zeta_3\right)f-\frac{140}{6561}f^2+\left[\frac{11699}{36}-\frac{6140}{27}\zeta_3-\left(\frac{17153}{972}+\frac{128}{27}\zeta_3\right)f-\frac{79}{243}f^2\right]Q_u \\
& \left.+\left(-\frac{3695}{648}+\frac{25}{9}\zeta_3\right)\overline{Q}\right\},
\end{aligned}
$$

LL NLL NNLL

[Czakon, UH & Misiak, arXiv:0612329]

NNLL endavor in 2006



Large 4-loop anomalous dimensions make NNLL & NLL comparable in size. Cancellation between NLL & NNLL contributions results in total RGE effects of O(1%)

[Czakon, UH & Misiak, arXiv:0612329]

NNLL endavor was important part of

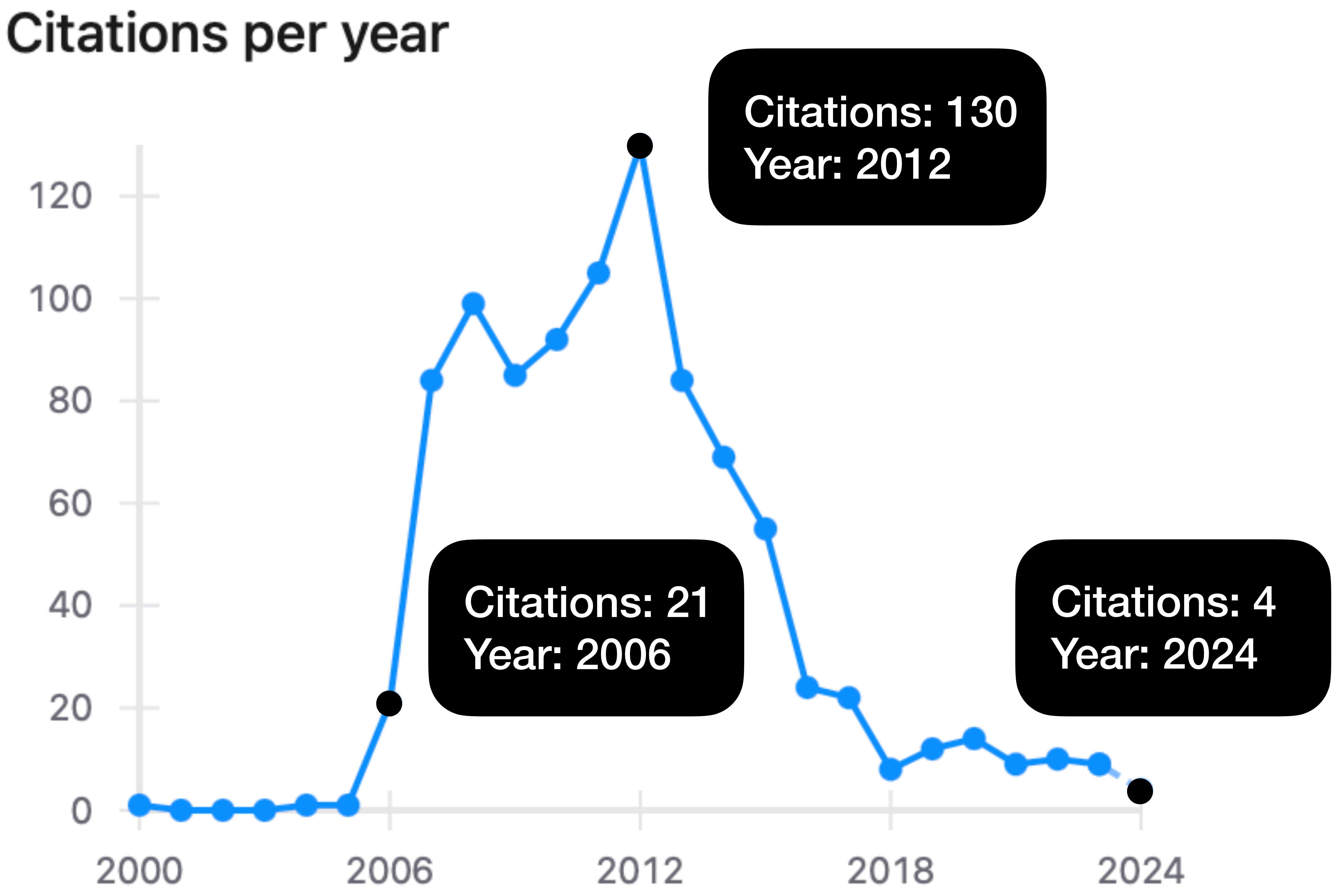
Estimate of $\mathcal{B}(\bar{B} \to X_s\gamma)$ at $\mathcal{O}(\alpha_s^2)$

M. Misiak,[1,2] H. M. Asatrian,[3] K. Bieri,[4] M. Czakon,[5] A. Czarnecki,[6] T. Ewerth,[4] A. Ferroglia,[7] P. Gambino,[8] M. Gorbahn,[9] C. Greub,[4] U. Haisch,[10] A. Hovhannisyan,[3] T. Hurth,[2,11] A. Mitov,[12] V. Poghosyan,[3] M. Ślusarczyk,[6] and M. Steinhauser[9]

Combining our results for various $\mathcal{O}(\alpha_s^2)$ corrections to the weak radiative B-meson decay, we are able to present the first estimate of the branching ratio at the next-to-next-to-leading order in QCD. We find $\mathcal{B}(\bar{B} \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ for $E_\gamma > 1.6$ GeV in the $\bar{B}$-meson rest frame. The four types of uncertainties: nonperturbative (5%), parametric (3%), higher-order (3%) and m_c-interpolation ambiguity (3%) have been added in quadrature to obtain the total error.

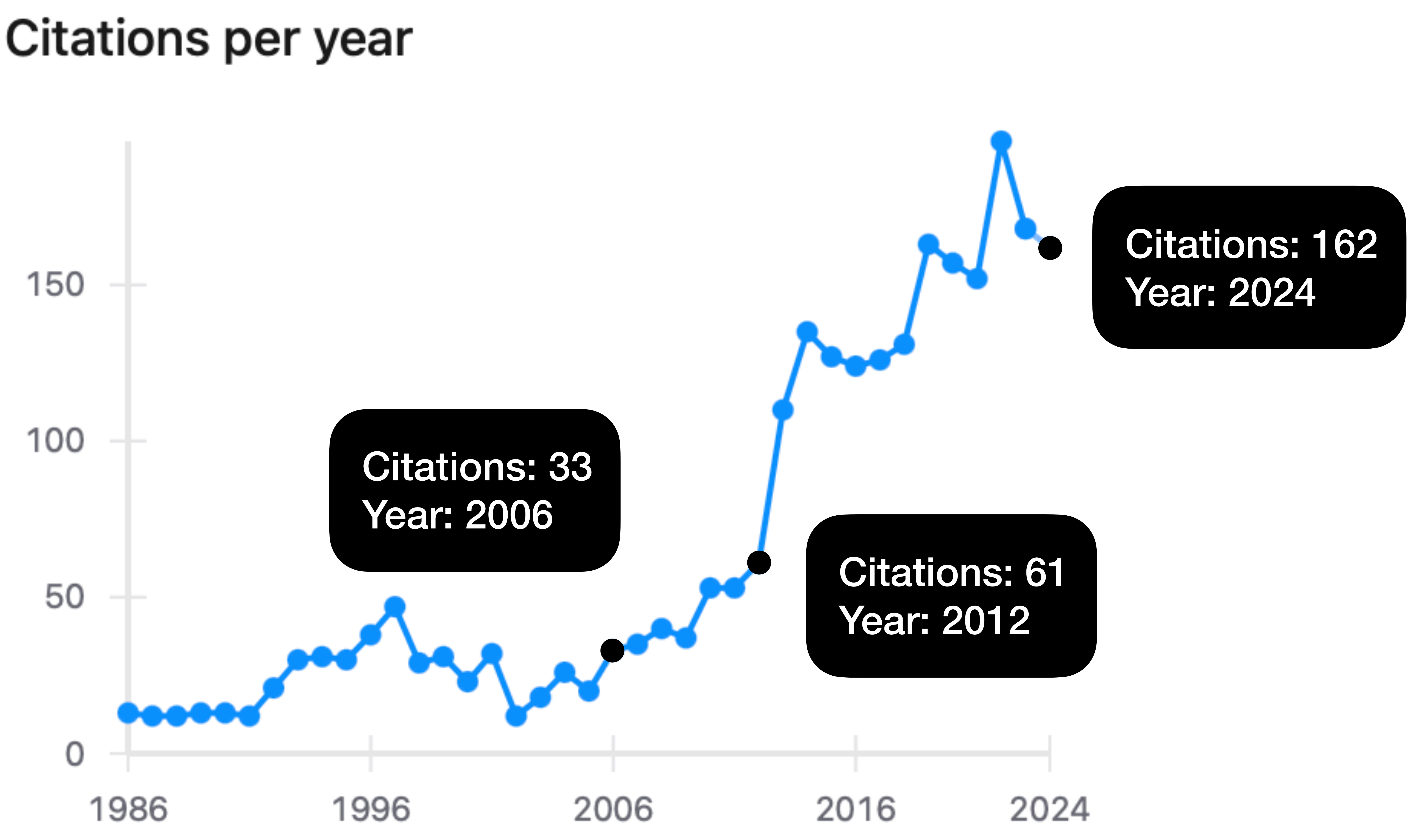
[Misiak et al., arXiv:0609232]

But physics landscape has changed



[Misiak et al., arXiv:0609232]

Today more popular to work on



Who is this sleeping beauty?

EFFECTIVE LAGRANGIAN ANALYSIS OF NEW INTERACTIONS

AND FLAVOUR CONSERVATION

A B S T R A C T

New interactions with a scale Λ larger than the Fermi scale $G_F^{-\frac{1}{2}}$ will manifest themselves at energies below Λ through small deviations from the standard model, which can be described by an effective Lagrangian containing non-renormalizable $SU(3)\times SU(2)\times U(1)$ invariant operators. We construct the first two terms of this Lagrangian in an expansion in powers of $1/\Lambda$ and study systematically possible effects of new interactions such as anomalous magnetic moments, deviations from universality in weak interactions and rare processes. Among the flavour conserving processes the universality of the charged current weak interactions yields the strongest bound on the new interaction scale, $\Lambda > 5$ TeV.

[Buchmüller & Wyler, Nucl. Phys. B 268]

Now with 40, she is called

The Standard Model effective field theory at work

The striking success of the Standard Model in explaining precision data and, at the same time, its lack of explanations for various fundamental phenomena, such as dark matter or the baryon asymmetry of the universe, suggests new physics at an energy scale much larger than the electroweak scale. In the absence of a short-range–long-range conspiracy, the Standard Model can be viewed as the leading term of an effective ‚remnant‘ theory (referred to as the SMEFT) of a more fundamental structure. Over the last years, many aspects of the SMEFT have been investigated and it has become a standard tool to analyze experimental results in an integral way. In this article, after briefly presenting the salient features of the Standard Model, we review the construction of the SMEFT. We discuss the range of its applicability and bounds on its coefficients imposed by general theoretical considerations. Since new-physics models are likely to exhibit exact or approximate accidental global symmetries, especially in the flavor sector, we also discuss their implications for the SMEFT. The main focus of our review is the phenomenological analysis of experimental results. We show explicitly how to use various effective field theories to study the phenomenology of theories beyond the Standard Model. We give a detailed description of the matching procedure and the use of the renormalization group

[Isidori, Wilsch & Wyler, 2303.16922]

LL in SMEFT: a simple example

$$\boxed{Q_{Hq,33}^{(1)}} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_3 \gamma^\mu q_3)\,, \qquad \boxed{Q_{Hq,33}^{(3)}} = (H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{q}_3 \gamma^\mu \sigma^i q_3)$$

$$\mathcal{L}_{\mathrm{LEFT}} \supset -\frac{e}{2 s_w c_w} \left(\boxed{C_{Hq,33}^{(1)}} + \boxed{C_{Hq,33}^{(3)}} \right) \sum_{i,j} V_{ti}^* V_{tj}\, \bar{d}_{L,i} \gamma_\mu d_{L,j} Z^\mu$$

[discussion follows Brod et al., 1408.0792]

LL in SMEFT: a simple example

$$\boxed{C^{(1)}_{Hq,33}(\Lambda)} + \boxed{C^{(3)}_{Hq,33}(\Lambda)} = \boxed{0}$$

absence of tee-level modifications of $d_j \bar{d}_i Z$ couplings at scale Λ

[discussion follows Brod et al., 1408.0792]

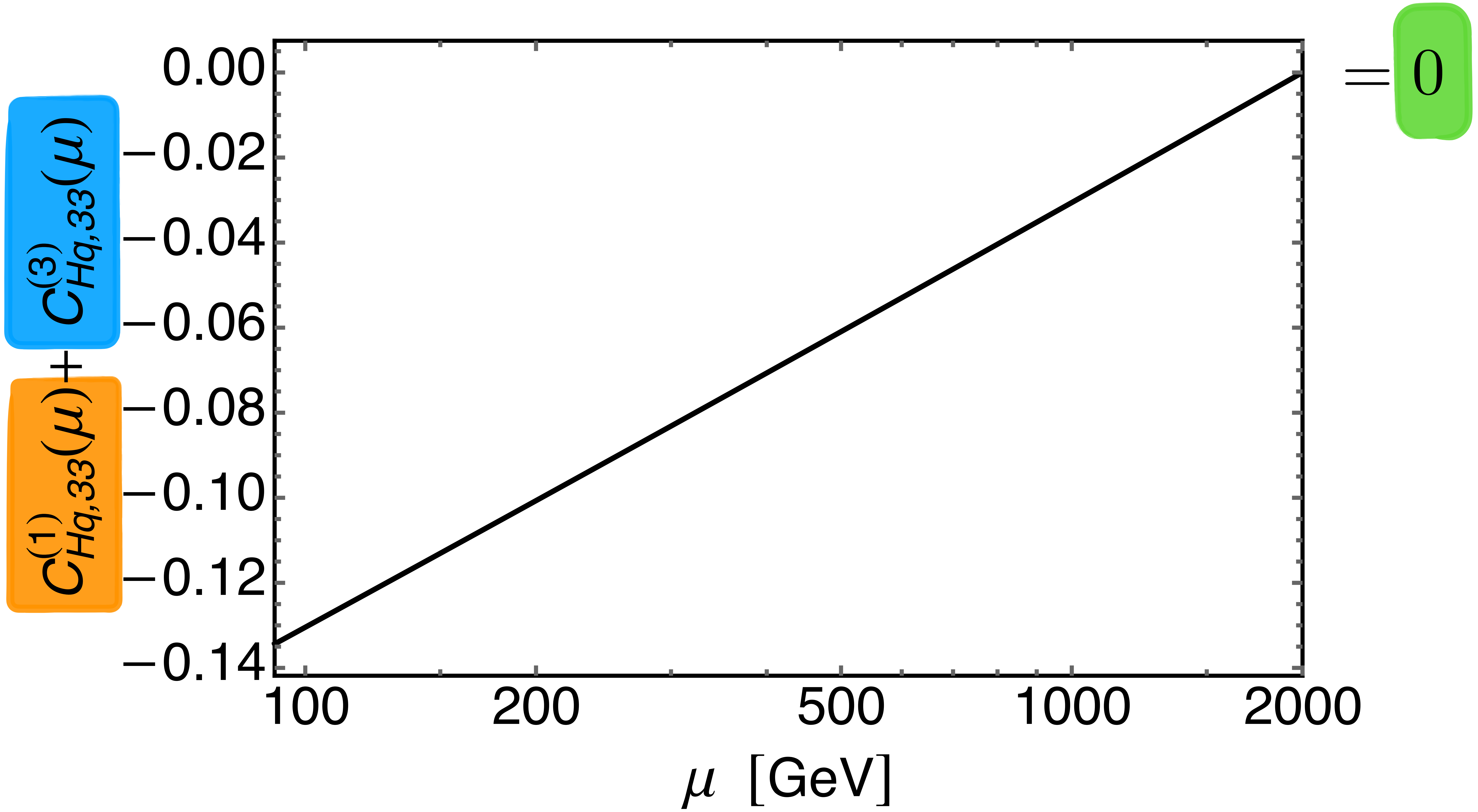
LL in SMEFT: a simple example

$$\frac{dC^{(1)}_{Hq,33}}{d\ln\mu} = \frac{y_t^2}{16\pi^2}\left(10C^{(1)}_{Hq,33} - 9C^{(3)}_{Hq,33}\right) + \dots$$

$$\frac{dC^{(3)}_{Hq,33}}{d\ln\mu} = \frac{y_t^2}{16\pi^2}\left(-3C^{(1)}_{Hq,33} + 8C^{(3)}_{Hq,33}\right) + \dots$$

[discussion follows Brod et al., 1408.0792]

LL in SMEFT: a simple example



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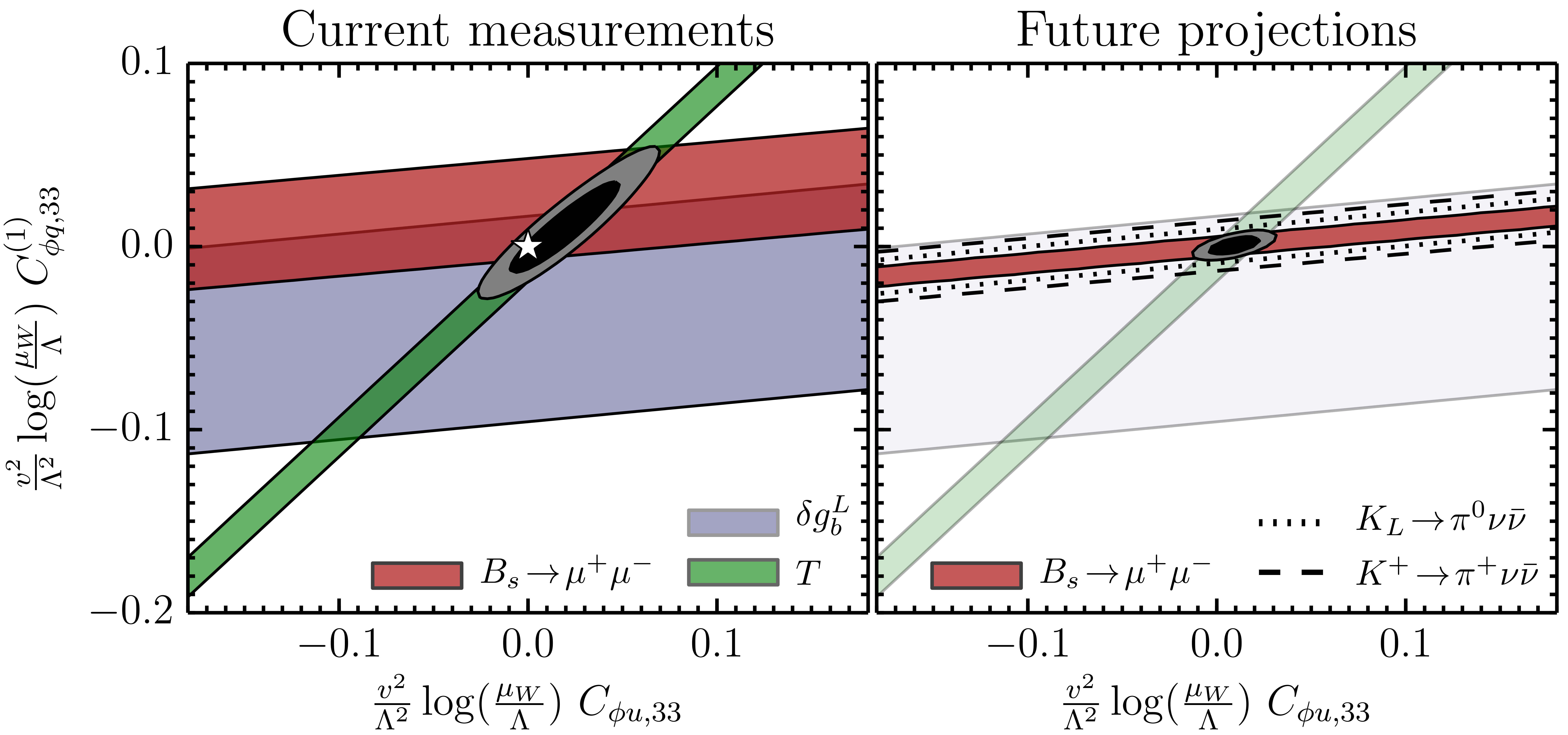
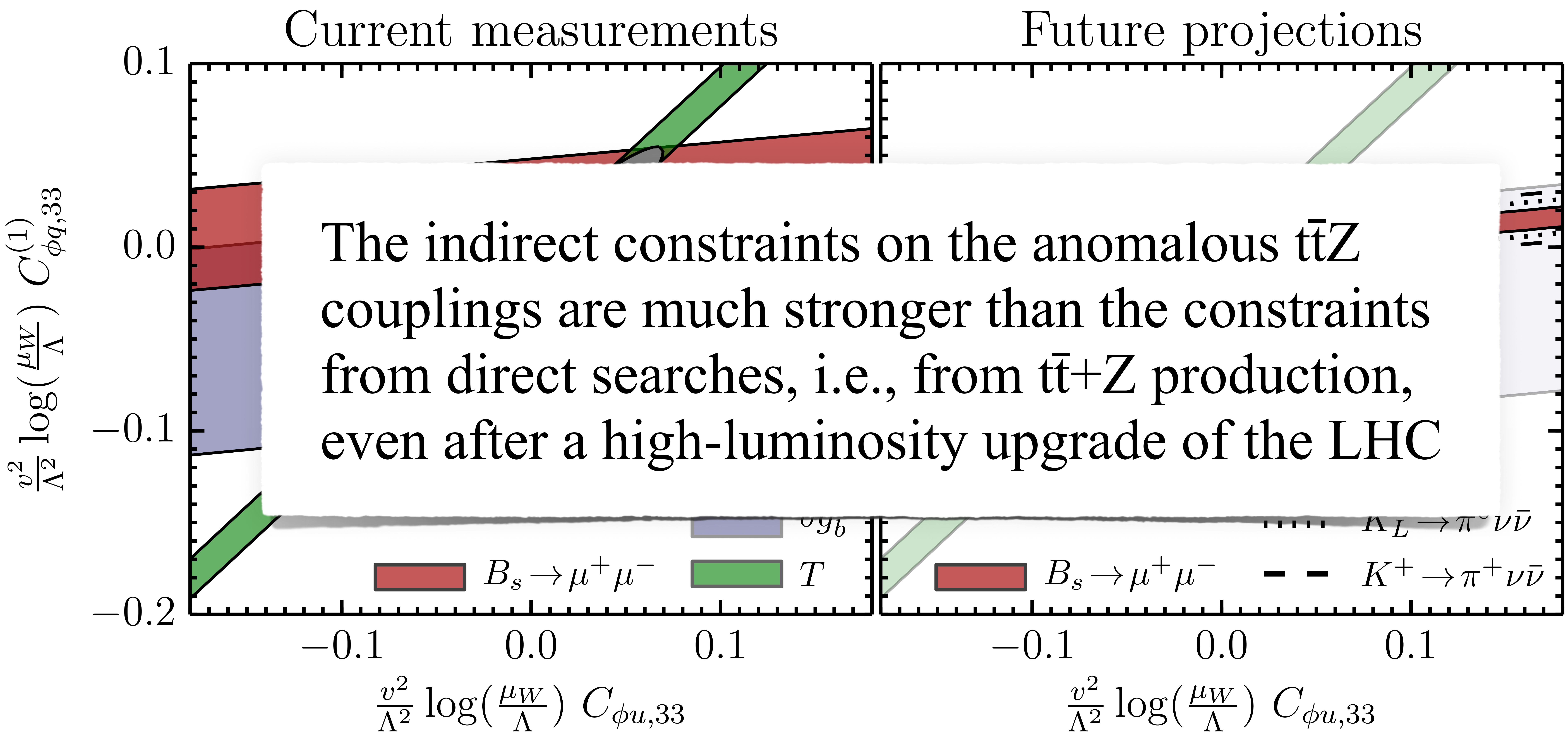
LL in SMEFT: a simple example



[Brod et al., 1408.0792]

LL in SMEFT: a simple example



The indirect constraints on the anomalous $t\bar{t}Z$ couplings are much stronger than the constraints from direct searches, i.e., from $t\bar{t}$+Z production, even after a high-luminosity upgrade of the LHC

[Brod et al., 1408.0792]

System of three operators Q_i, Q_m & Q_j

$$\frac{C_j(\mu)}{C_i(\mu_0)} \simeq -\frac{\boxed{\gamma_{ji}}}{16\pi^2} \boxed{\ln\left(\frac{\mu_0}{\mu}\right)} + \frac{\boxed{\gamma_{jm}\gamma_{mi}}}{512\pi^4} \boxed{\ln^2\left(\frac{\mu_0}{\mu}\right)}$$

mixing $Q_i \to Q_j$

mixing $Q_i \to Q_m \to Q_j$

[discussion follows Buras & Jung, 1804.05852]

System of three operators Q_i, Q_m & Q_j

$$\frac{C_j(\mu)}{C_i(\mu_0)} \simeq \boxed{-\frac{\gamma_{ji}}{16\pi^2}\ln\left(\frac{\mu_0}{\mu}\right)} + \boxed{\frac{\gamma_{jm}\gamma_{mi}}{512\pi^4}\ln^2\left(\frac{\mu_0}{\mu}\right)}$$

1-loop LL effect

2-loop LL effect

[discussion follows Buras & Jung, 1804.05852]

System of three operators Q_i, Q_m & Q_j

The 2-loop LL effects can be derived from the known 1-loop anomalous dimensions. The 2-loop anomalous dimensions solely generate NLL corrections

[discussion follows Buras & Jung, 1804.05852]

Examples of 2-loop LL effects

$$C_{H\Box}(\mu) \propto \frac{y_t^4}{(4\pi)^4}\, C_{tt}^{(1)}(\mu_0)\, \ln^2\left(\frac{\mu_0}{\mu}\right)\,,$$

$$C_{HG}(\mu) \propto \frac{g_s^3 y_t^2}{(4\pi)^4}\, C_G(\mu_0)\, \ln^2\left(\frac{\mu_0}{\mu}\right)\,,$$

$$C_{HW}(\mu) \propto \frac{g^2 y_b y_t}{(4\pi)^4}\, C_{qtqb}^{(1)}(\mu_0)\, \ln^2\left(\frac{\mu_0}{\mu}\right)\,, \ldots$$

[UH, unpublished]

2-loop LL effects in gg→h

$$\delta\kappa_g \simeq \frac{12\pi^2}{\alpha_s}\frac{\gamma_{HG,tG}\,\gamma_{tG,G}}{512\pi^4}\frac{v^2}{\Lambda^2}C_G(\Lambda)\ln^2\left(\frac{\Lambda}{m_h}\right)$$

$$\simeq -\frac{27 g_s y_t^2}{8\pi}\frac{v^2}{\Lambda^2}C_G(\Lambda)\ln^2\left(\frac{\Lambda}{m_h}\right) \simeq -0.09\,C_G$$

[UH, unpublished]

2-loop LL effects in gg→h

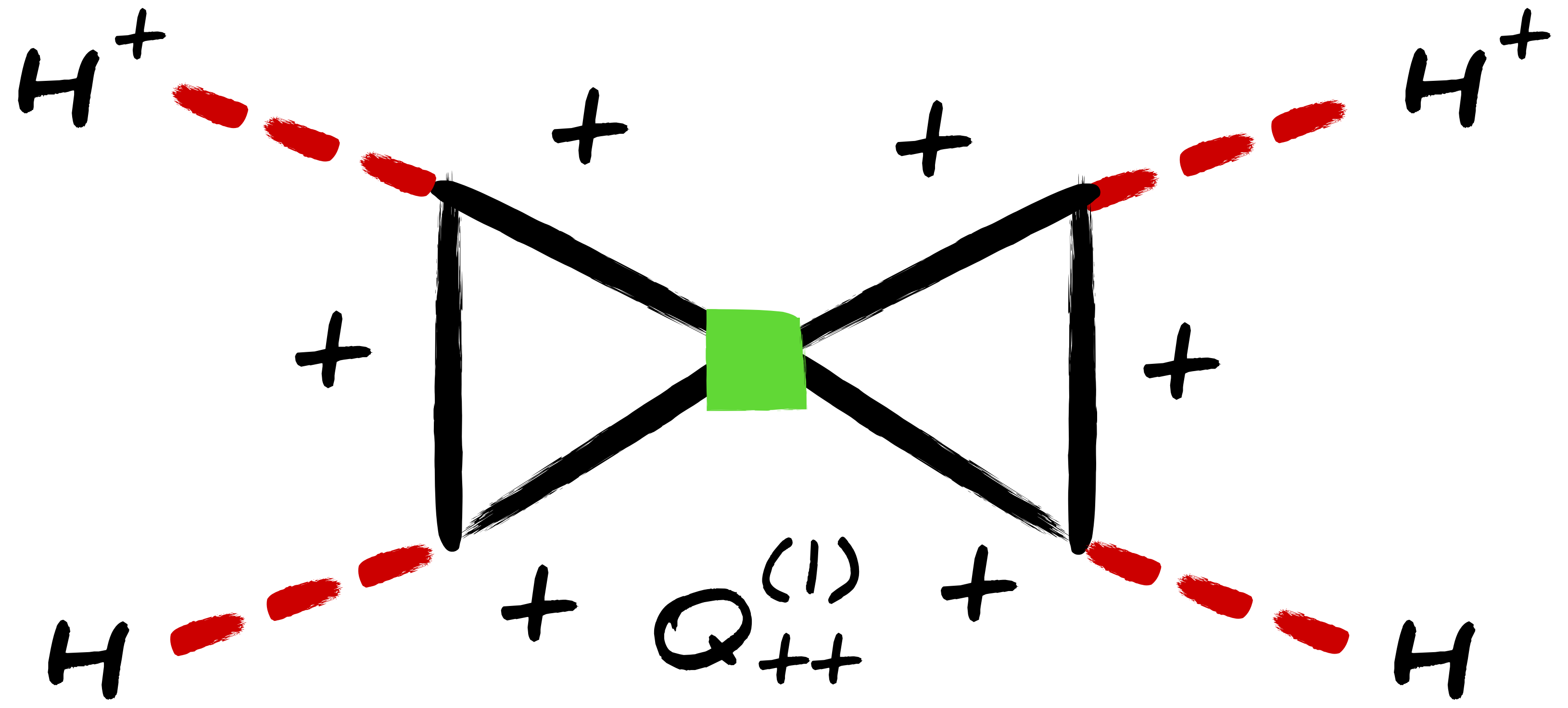
$\delta\kappa_g$

A 10% measurement of the signal strength in gluon-gluon-fusion Higgs production enables setting an indirect bound on the triple gluon operator, which is as good or better than direct limits obtained from di-jet or top-pair production

C_G

[UH, unpublished]

How big are 2-loop NLL effects?

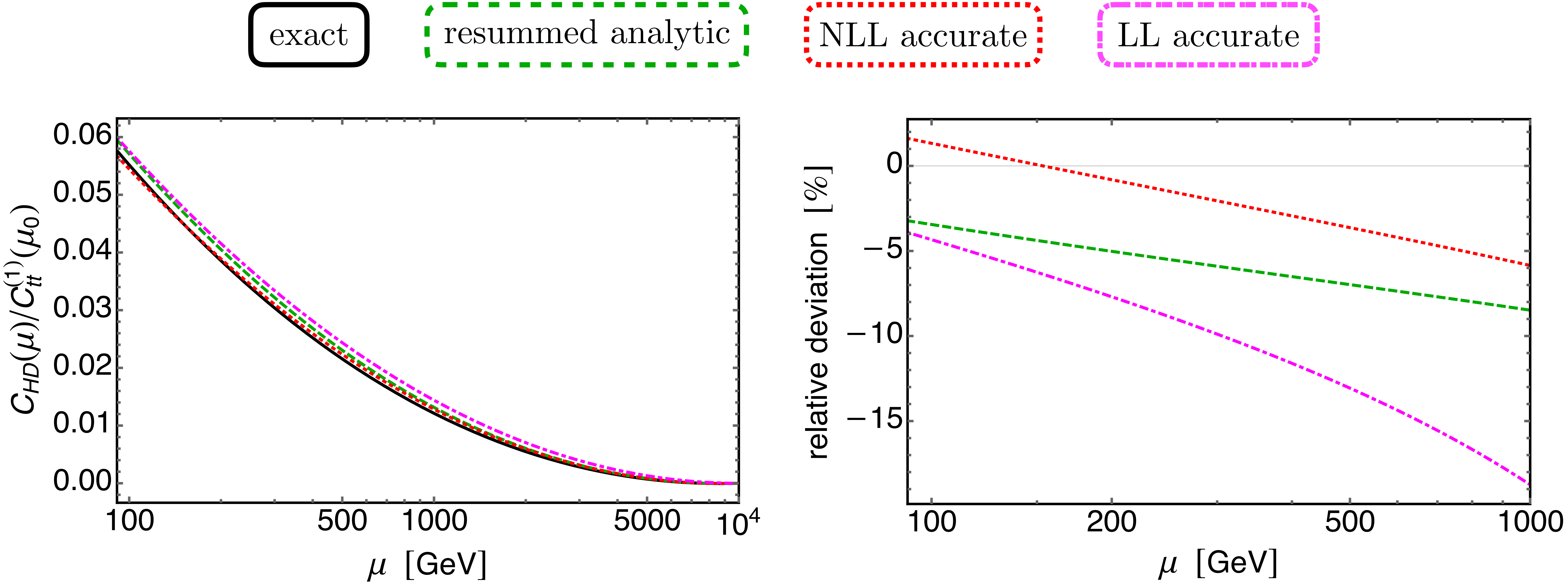


$$\Rightarrow \quad Q_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D^\mu H)$$

$$\boxed{\gamma_{HD,qq}^{(1)}}(\mu) = \frac{3y_t^4}{2\pi^2}\,, \quad \boxed{\gamma_{HD,qq}^{(3)}}(\mu) = \frac{9y_t^4}{2\pi^2}\,, \quad \boxed{\gamma_{HD,tt}^{(1)}}(\mu) = \frac{3y_t^4}{\pi^2}$$

[based on UH & Schnell, 2410.13304; unpublished]

How big are 2-loop NLL effects?



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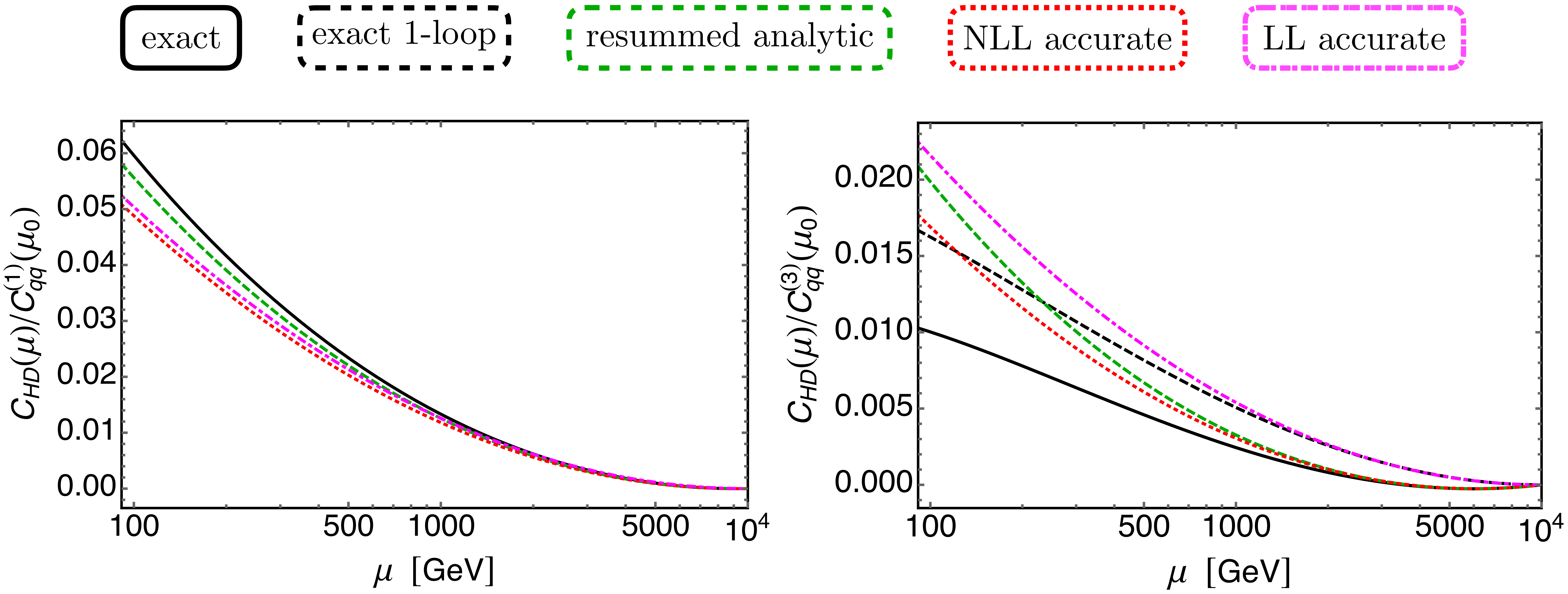

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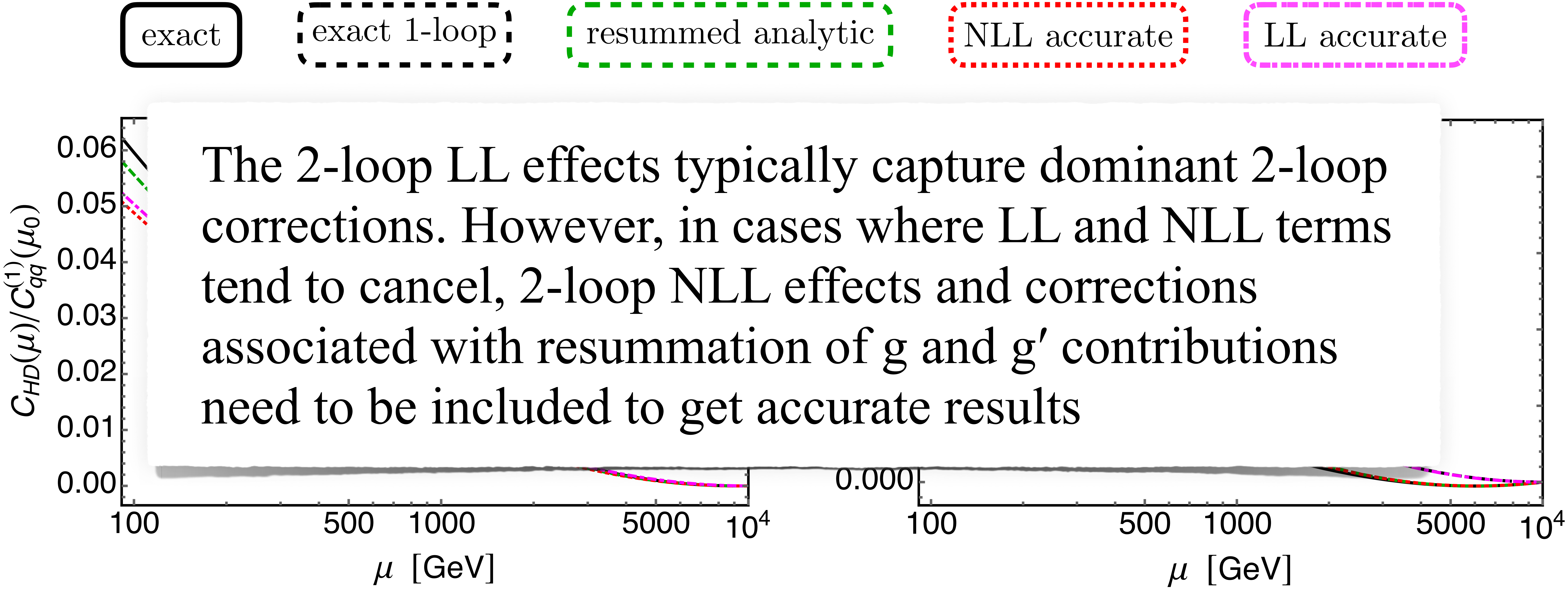
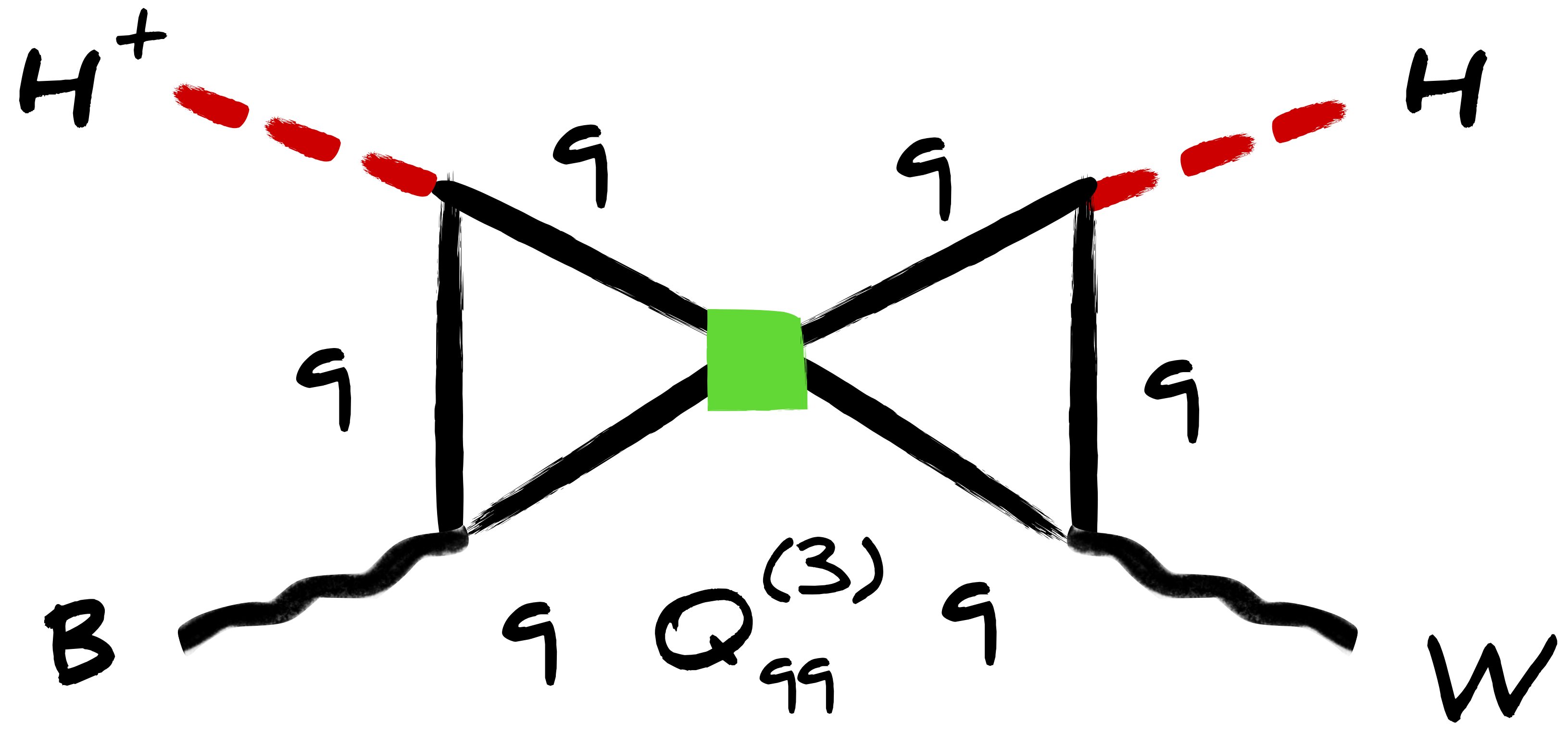
How big are 2-loop NLL effects?



The 2-loop LL effects typically capture dominant 2-loop corrections. However, in cases where LL and NLL terms tend to cancel, 2-loop NLL effects and corrections associated with resummation of g and g′ contributions need to be included to get accurate results

[based on UH & Schnell, 2410.13304; unpublished]

An example with only 2-loop NLLs

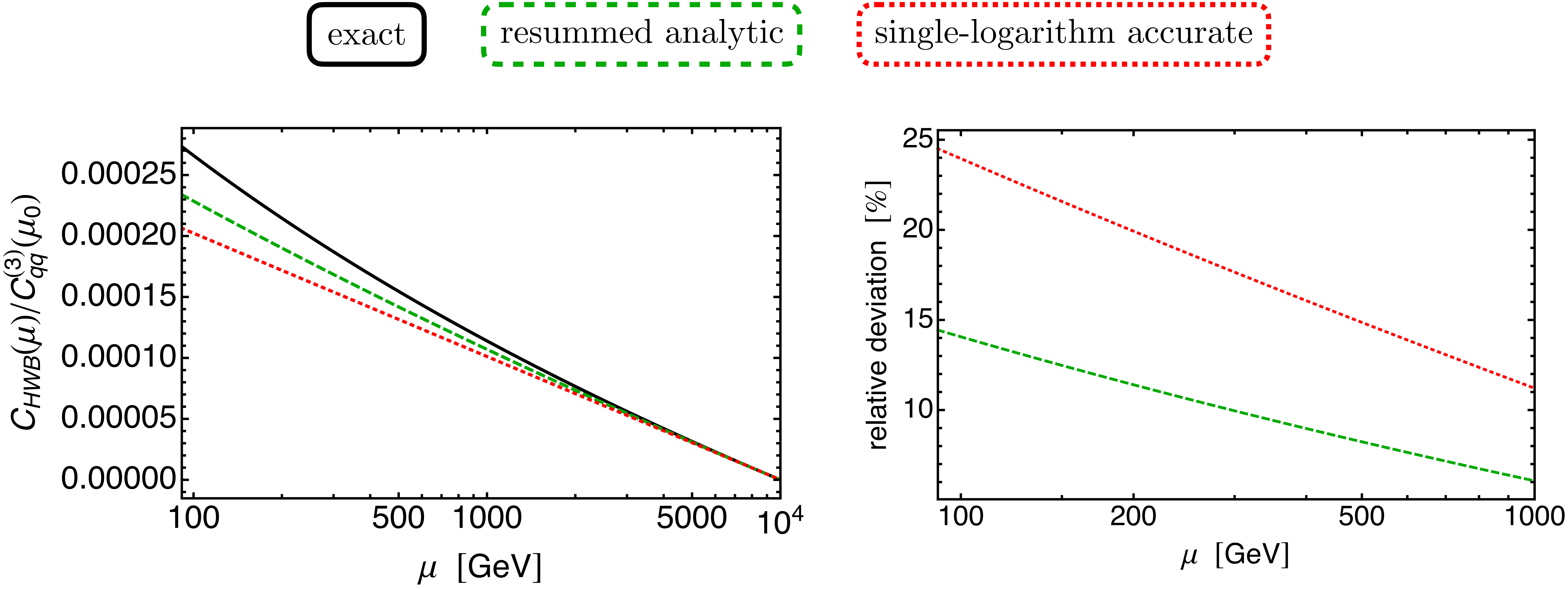


$$\Rightarrow \quad Q_{HWB} = (H^\dagger \sigma^i H) W^i_{\mu\nu} B^{\mu\nu}$$

$$\boxed{\gamma_{HWB,\,qq}^{(3)}}(\mu) = -\frac{g g' y_t^2}{2\pi^2}$$

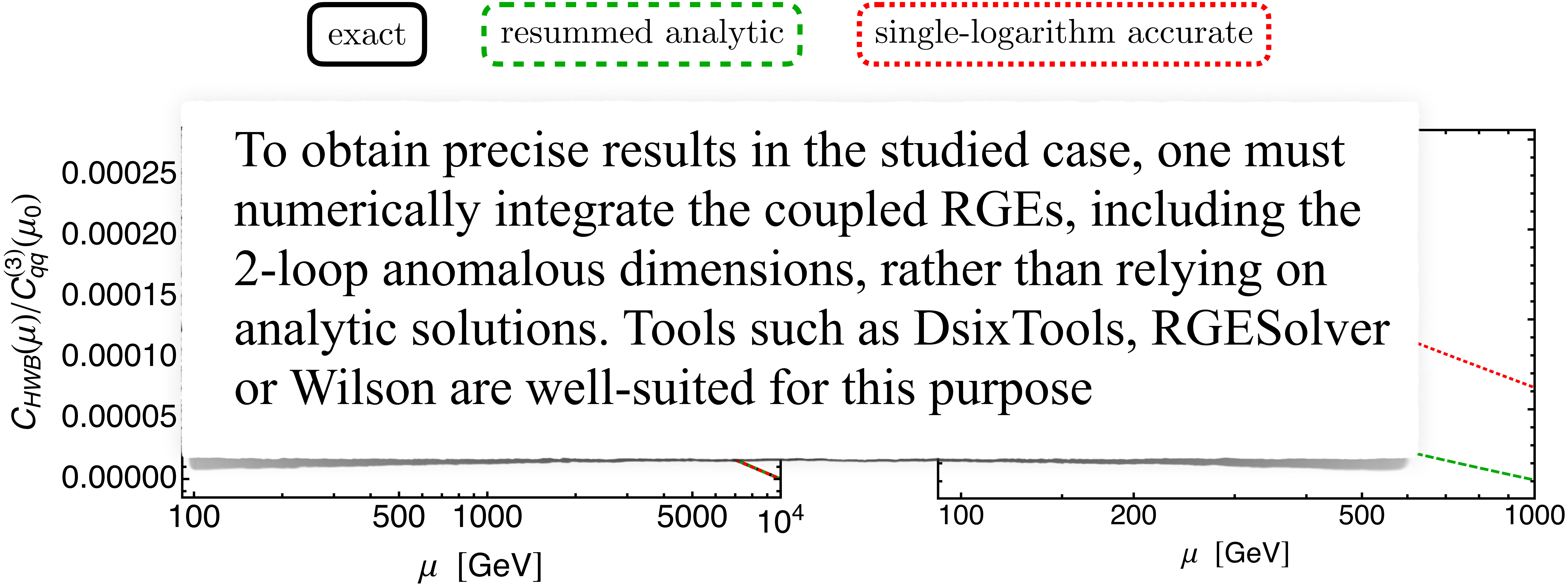
[based on UH & Schnell, 2410.13304; unpublished]

An example with only 2-loop NLLs



[based on UH & Schnell, 2410.13304; unpublished]

An example with only 2-loop NLLs



To obtain precise results in the studied case, one must numerically integrate the coupled RGEs, including the 2-loop anomalous dimensions, rather than relying on analytic solutions. Tools such as DsixTools, RGESolver or Wilson are well-suited for this purpose

[based on UH & Schnell, 2410.13304; unpublished]

New 2-loop anomalous dimensions @ work

$$T \simeq -\frac{3y_t^4}{8\pi^4\alpha}\,\frac{v^2}{\Lambda^2}\,C_{tt}^{(1)}(\Lambda)\left[\ln^2\left(\frac{\Lambda}{M_Z}\right) - \frac{1}{4}\ln\left(\frac{\Lambda}{M_Z}\right)\right]$$

$$T \in [-0.23, 0.25] \quad \Rightarrow \quad \frac{C_{tt}^{(1)}}{\Lambda^2} \in \frac{[-2.04, 1.87]}{\mathrm{TeV}^2}$$

[based on UH & Schnell, 2410.13304; unpublished]

New 2-loop anomalous dimensions @ work

$$S \simeq \frac{y_t^2}{2\pi^3}\frac{v^2}{\Lambda^2} C_{qq}^{(3)}(\Lambda) \ln\left(\frac{\Lambda}{M_Z}\right)$$

$$S \in [-0.24, 0.16] \quad \Rightarrow \quad \frac{C_{qq}^{(3)}}{\Lambda^2} \in \frac{[-63.2, 95.5]}{\mathrm{TeV}^2}$$

[based on UH & Schnell, 2410.13304; unpublished]

New 2-loop anomalous dimensions @ work

Indirect 2-loop constraints on Wilson coefficients from EW precision measurements can match or even surpass the sensitivity of direct tree-level probes (such as 4-top production in the examples shown) only if the indirect probe receives a LL correction at the 2-loop level

[based on UH & Schnell, 2410.13304; unpublished]

What was Daniel doing around 2005?

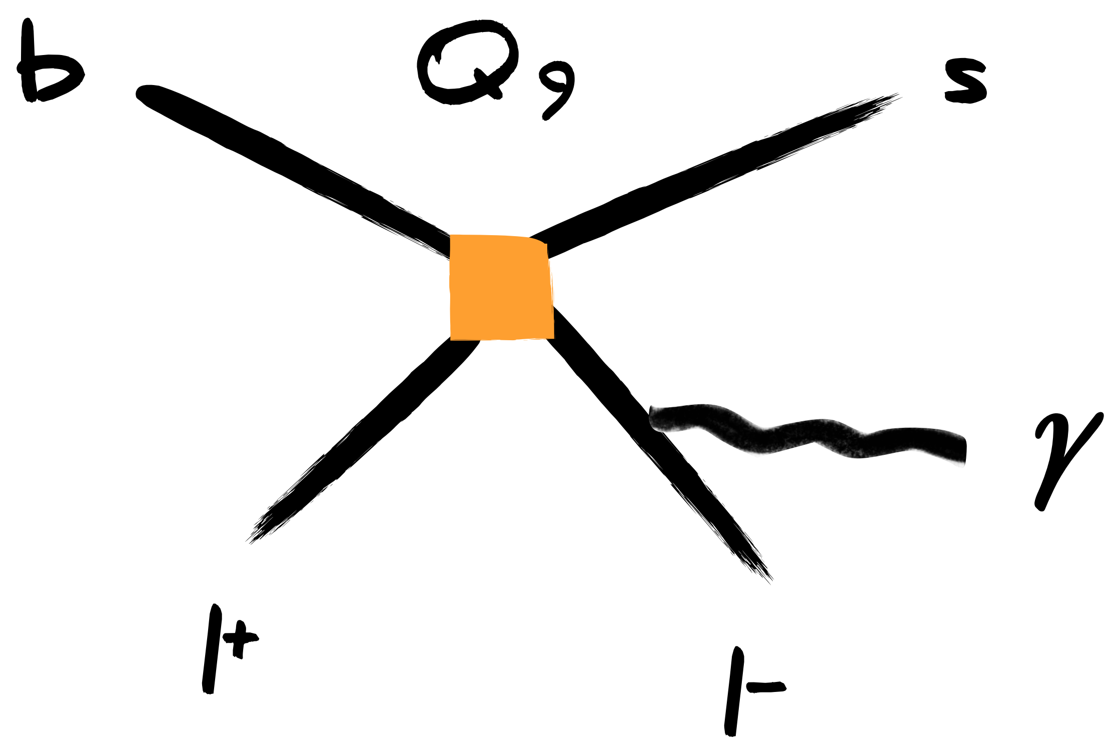
Electromagnetic Logarithms in $\bar{B} \to X_s \ell^+ \ell^-$

Abstract

The $\bar{B} \to X_s \ell^+ \ell^-$ decay rate is known at the next-to-next-to-leading order in QCD. It is proportional to $\alpha_{em}(\mu)^2$ and has a $\pm 4\%$ scale uncertainty before including the $\mathcal{O}\left(\alpha_{em} \ln(M_W^2/m_b^2)\right)$ electromagnetic corrections. We evaluate these corrections and confirm the earlier findings of Bobeth *et al.*. Furthermore, we complete the calculation of logarithmically enhanced electromagnetic effects by including also QED corrections to the matrix elements of four-fermion operators. Such corrections contain a collinear logarithm $\ln(m_b^2/m_\ell^2)$ that survives integration over the low dilepton invariant mass region $1\ \mathrm{GeV}^2 < m_{\ell\ell}^2 < 6\ \mathrm{GeV}^2$ and enhances the integrated decay rate in this domain. For the low-$m_{\ell\ell}^2$ integrated branching ratio in the muonic case, we find $\mathcal{B}(B \to X_s \mu^+ \mu^-) = (1.59 \pm 0.11) \times 10^{-6}$, where the error includes the parametric and perturbative uncertainties only. For $\mathcal{B}(B \to X_s e^+ e^-)$, in the current BaBar and Belle setups, the logarithm of the lepton mass gets replaced by angular cut parameters and the integrated branching ratio for the electrons is expected to be close to that for the muons.

[Huber, Lunghi, Misiak & Wyler, hep-ph/0512066]

Origin of QED logarithms



$$\Rightarrow \quad \frac{\alpha}{\pi} \ln\left(\frac{m_b^2}{m_l^2}\right) \simeq \begin{cases} 4.2\%\,, & l = e \\ 1.7\%\,, & l = \mu \\ 0.4\%\,, & l = \tau \end{cases}$$

Hard collinear emissions of photons result in flavor-dependent logarithms.

Understanding of effects crucial for precision measurements of $R_{K^{(*)}}$, V_{cb}, …

[see e.g. Bordone, Isidori & Pattori, 1605.07633; Cornella, König & Neubert, 2212.14430 for studies of QED effects in B physics]

Lepton energy spectrum in b→clν

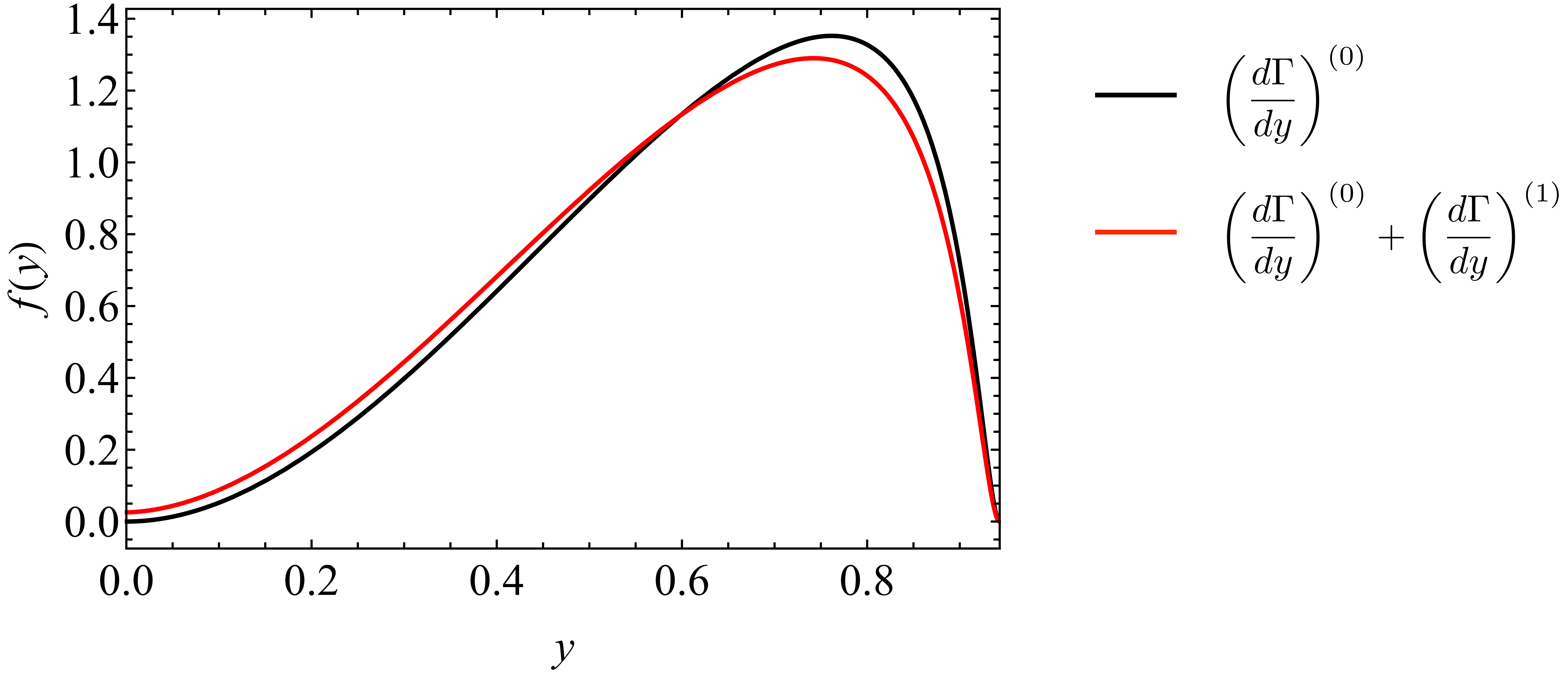
$$y = \frac{2E_l}{m_b}\,, \qquad \rho = \frac{m_c^2}{m_b^2}\,, \qquad P_{ll}^{(0)}(z) = \left[\frac{1+z^2}{1-z}\right]_+$$

$$\left(\frac{d\Gamma}{dy}\right)^{(1)} = \frac{\alpha}{2\pi}\left[\ln\left(\frac{m_b^2}{m_l^2}\right) - 1\right]\int_y^{1-\rho}\frac{dx}{x}\,P_{ll}^{(0)}\left(\frac{y}{x}\right)\left(\frac{d\Gamma}{dx}\right)^{(0)}$$

LL corrections to spectrum obtained from tree-level result through convolution with leading-order lepton-lepton splitting function

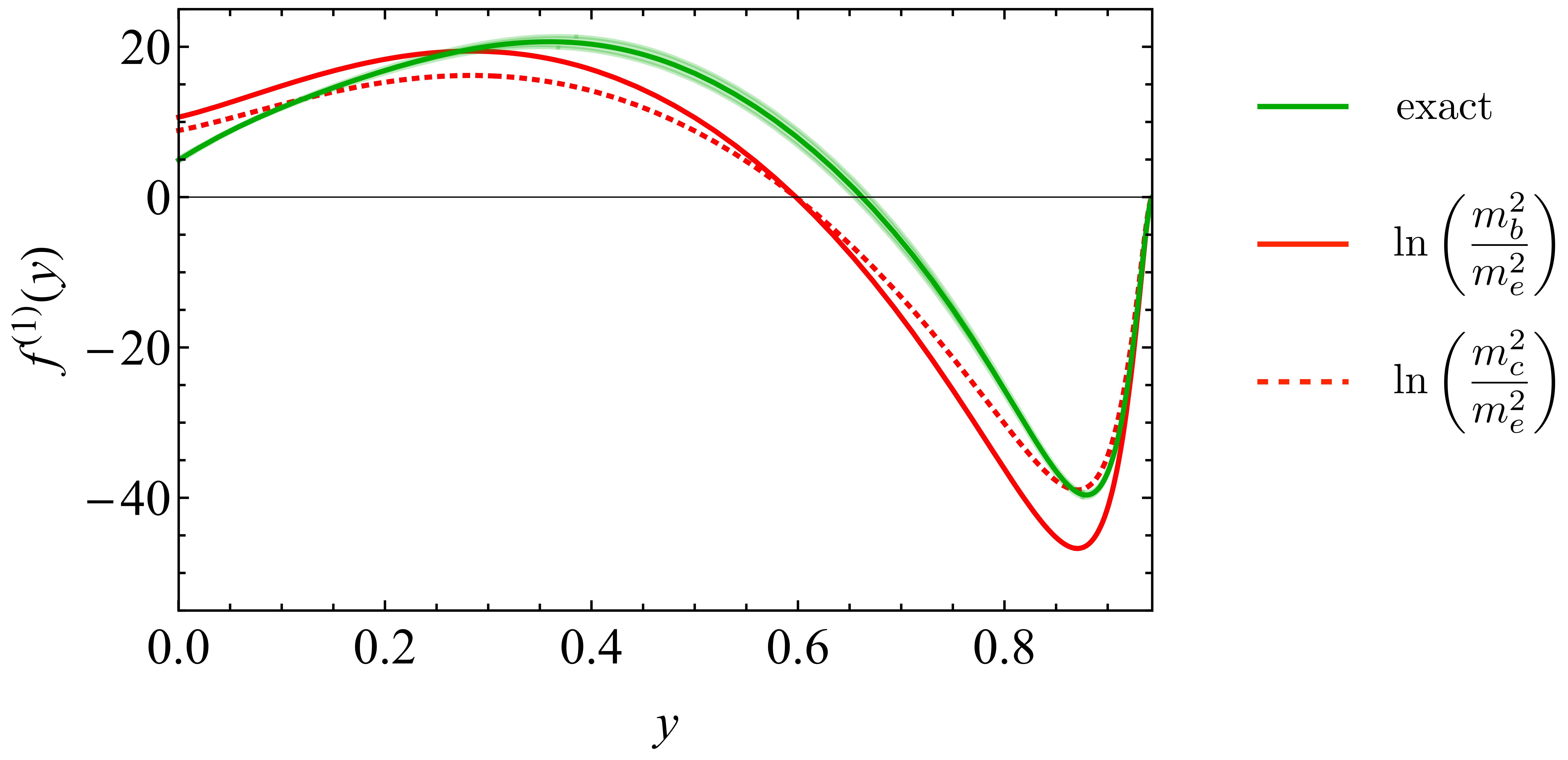
[see e.g. Arbuzov et al., hep-ph/0202102, hep-ph/0205172, hep-ph/0206036 for structure function approach]

Electron energy spectrum in b→ceν



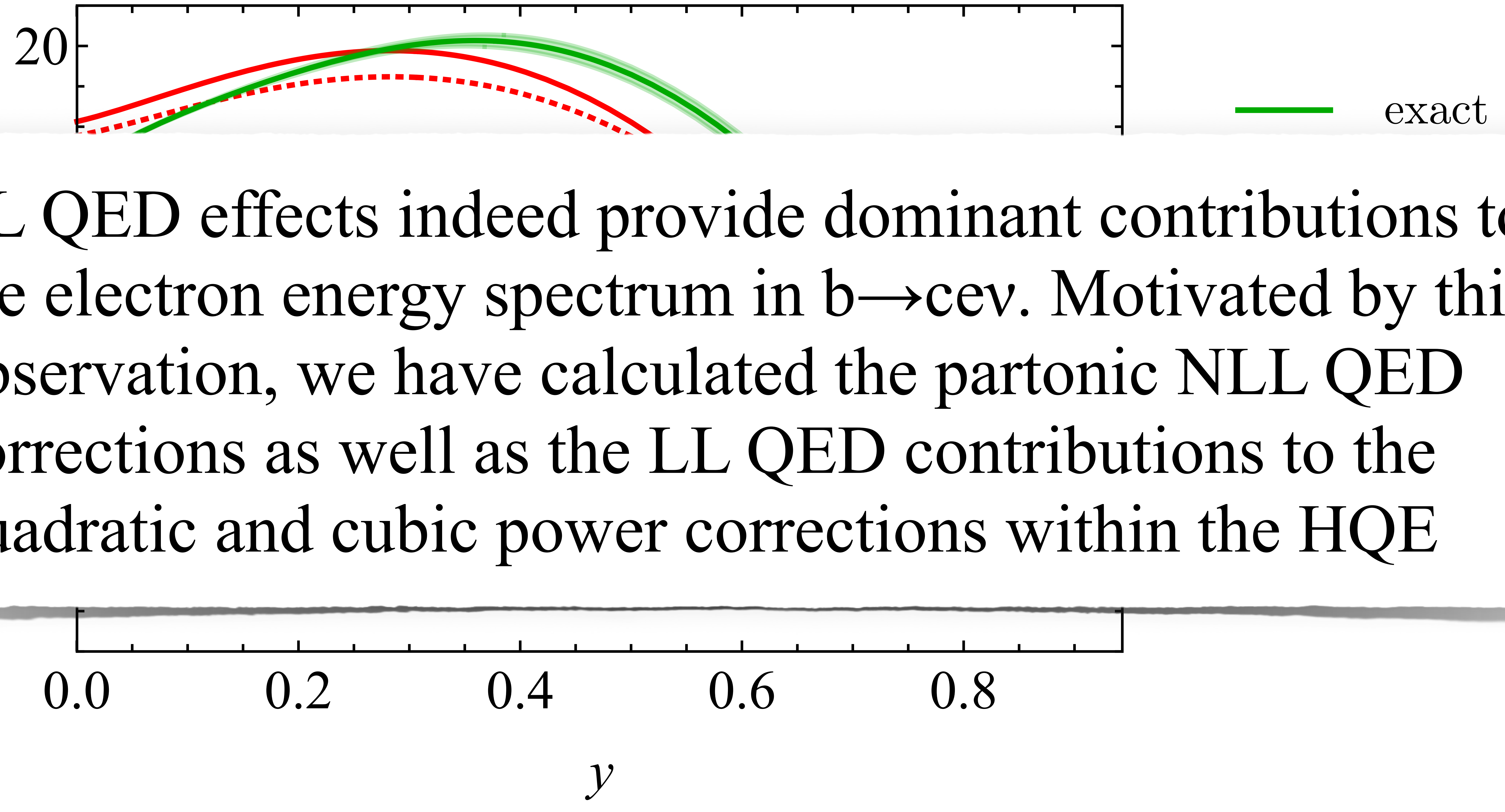
[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

Electron energy spectrum in b→ceν



[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

Electron energy spectrum in b→ceν



LL QED effects indeed provide dominant contributions to the electron energy spectrum in b→ceν. Motivated by this observation, we have calculated the partonic NLL QED corrections as well as the LL QED contributions to the quadratic and cubic power corrections within the HQE

[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

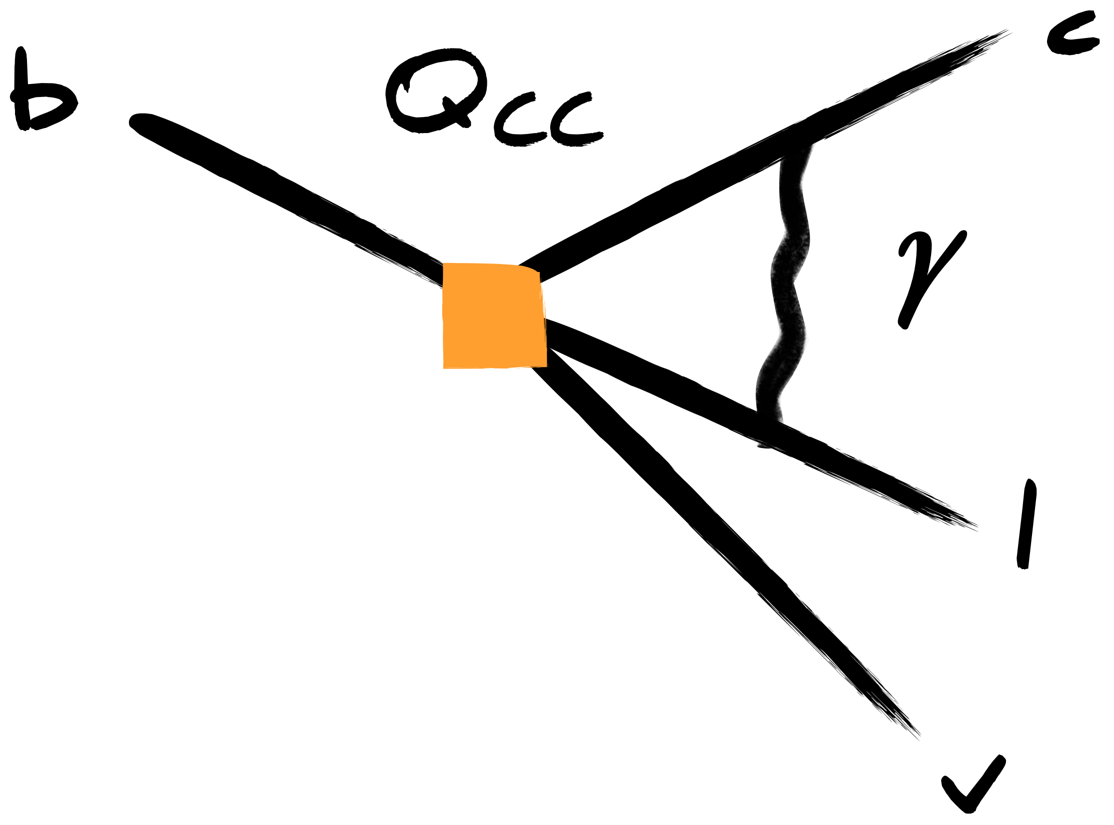
QED effects in total decay width of b→clν

$$\int_0^1 dz\, \boxed{P_{ll}^{(0)}(z)} = 0 \qquad \Rightarrow \qquad \int_0^{1-\rho} dy\, \boxed{\left(\frac{d\Gamma}{dy}\right)^{(1)}} = 0$$

In total decay width of b→clν, LL QED corrections are not present as required by Kinoshita-Lee-Nauenberg theorem — true also for power-suppressed OPE contributions. What are dominant corrections to total decay width?

[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

QED effects in total decay width of b→clν



$$\Rightarrow \qquad \frac{2\pi\alpha}{3} \simeq 1.6\%$$

π²-enhanced QED effects, i.e. so-called Coulomb corrections, arise from soft virtual photon exchange from configurations close to charm threshold

[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

QED effects in total decay width of b→clv

$$\frac{\Gamma}{\Gamma^{(0)}} = 1 + \frac{\alpha}{\pi}\left[\boxed{\ln\left(\frac{M_Z^2}{m_b^2}\right)} - \frac{11}{6} + \boxed{5.516(14)}\right]$$

short-distance EW LL

pure photonic corrections

[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

QED effects in total decay width of b→clv

$$\frac{\Gamma}{\Gamma^{(0)}} = 1 + \frac{\alpha}{\pi}\left[\ln\left(\frac{M_Z^2}{m_b^2}\right) - \frac{11}{6} + 5.516(14)\right]$$

$$= 1 + 1.43\% - 0.44\% + 1.32\% = 1 + 2.31\%$$

π^2-enhanced terms give 1.57%

[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

QED effects in total decay width of b→clν

$$\frac{\Gamma}{\cdots} = 1 + \frac{\alpha}{\cdots}\left[\ln\left(\frac{M_Z^2}{\cdots}\right) - \frac{11}{\cdots} + 5.516(14)\right]$$

The QED corrections to the total decay width of b→clν amount to 2.3%. They are dominated by the short-distance EW LL contributions, derived by Sirlin in his seminal 1982 paper, and by π^2-enhanced threshold corrections

π^2-enhanced terms give 1.57%

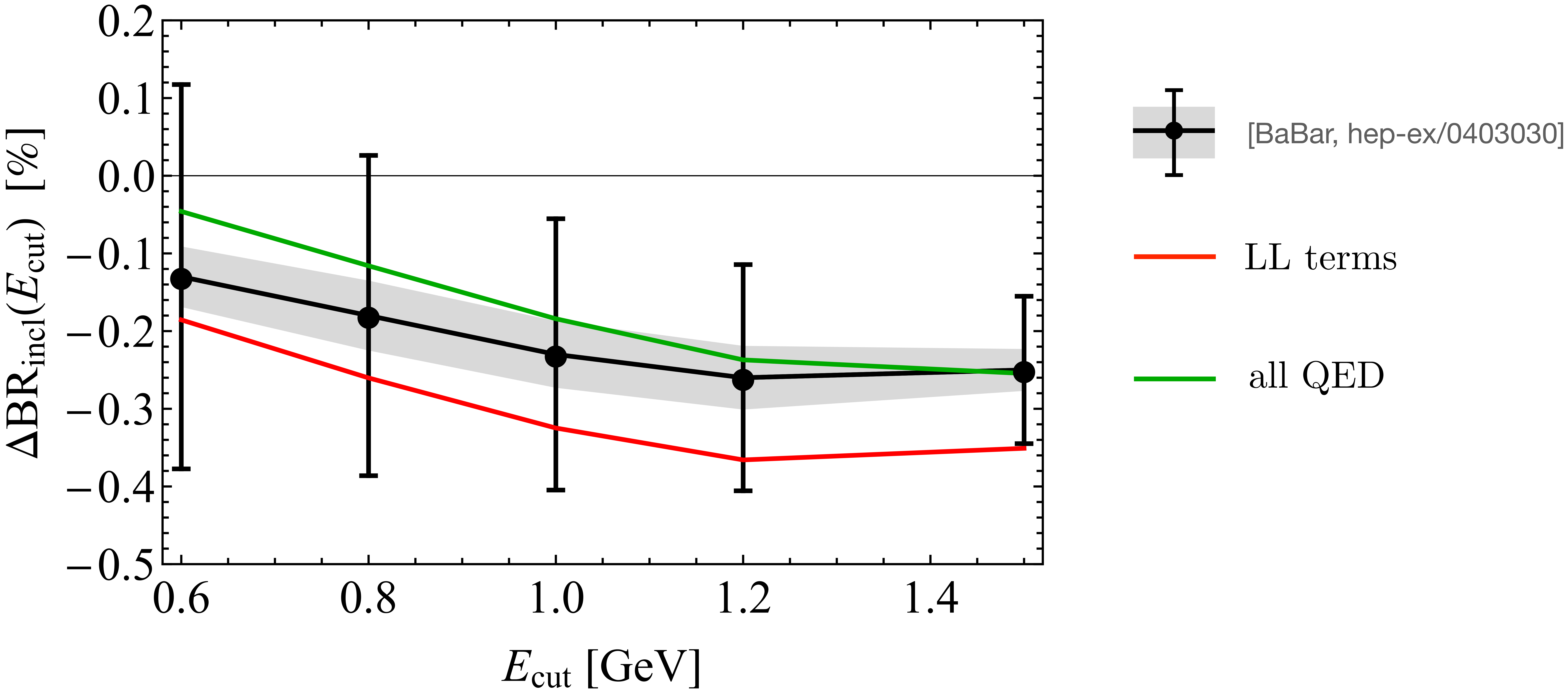
[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

Comparison to experiment

In BaBar & Belle, photon radiation is removed in analyses of $b \to c e \nu$ spectra. Subtraction is performed using PHOTOS, which includes soft & collinear radiation from final-state charged leptons & hadrons with logarithmic accuracy. It lacks interference between initial- & final-state photons, hard & structure-dependent radiative effects as well as virtual effects, like π^2-enhanced terms. How good are these approximations?

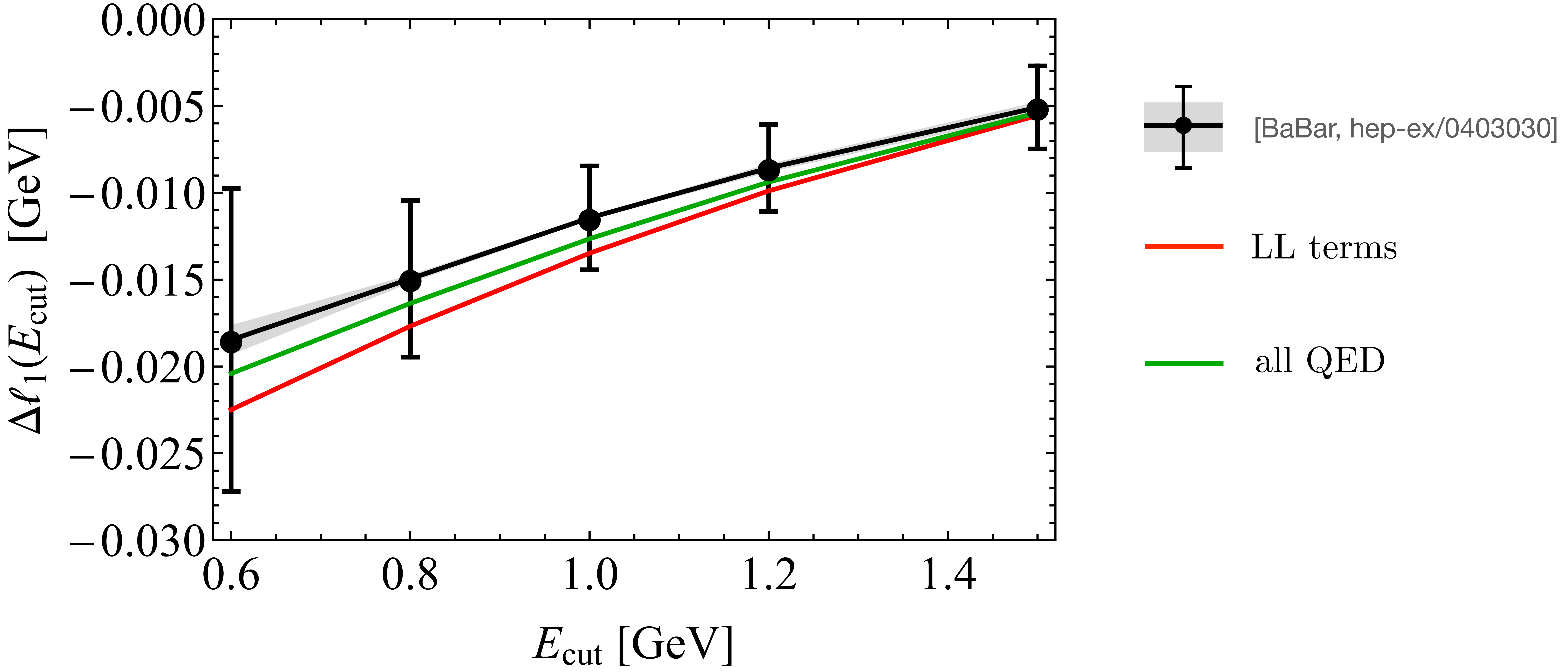
[see e.g. Barberio & Was, Comput. Phys. Commun. 79 for details on PHOTOS]

Comparison to experiment



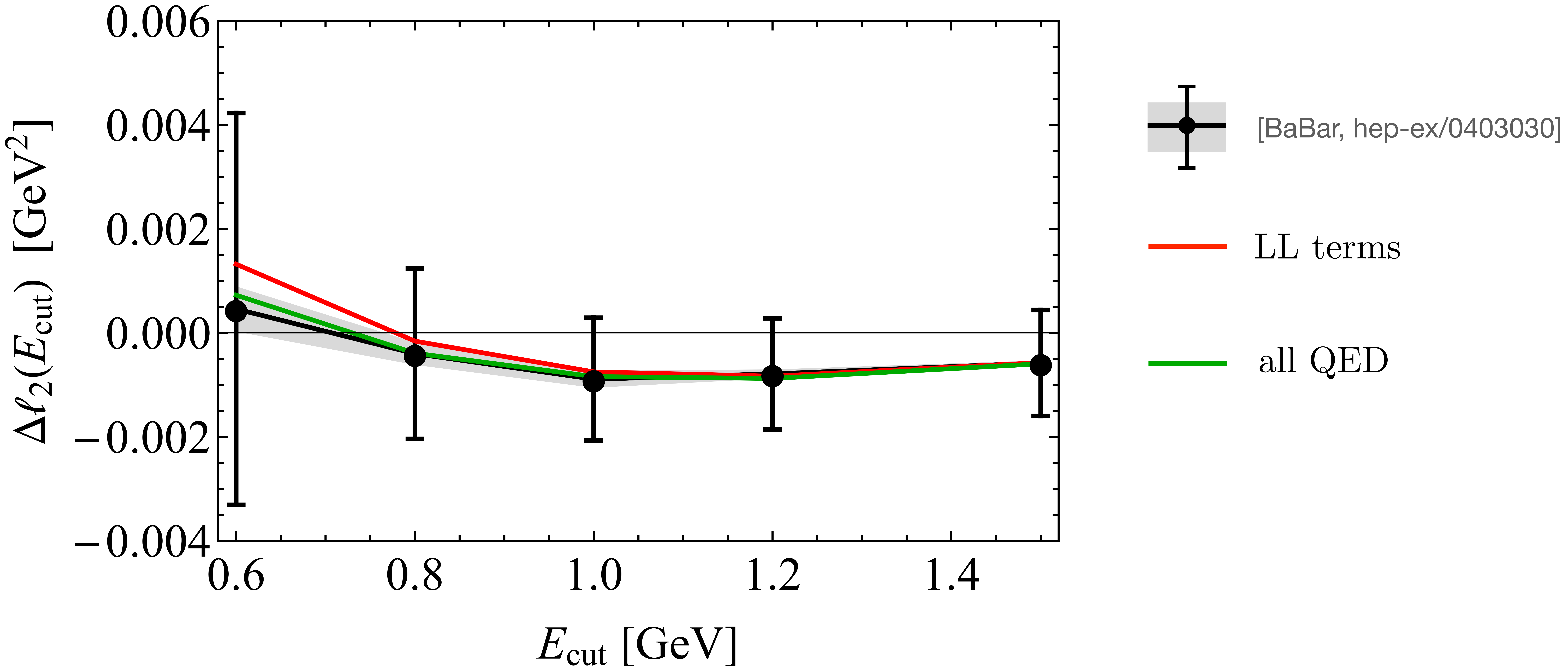
[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

Comparison to experiment



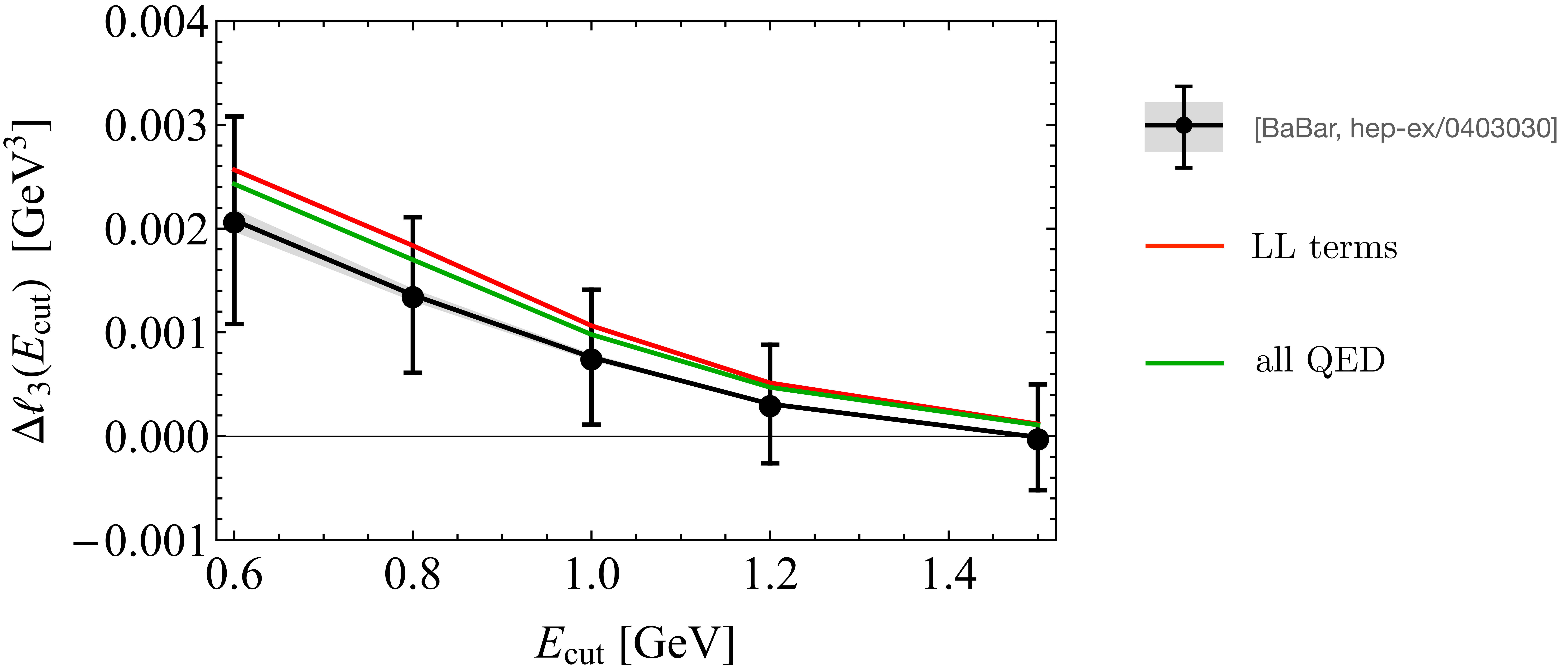
[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

Comparison to experiment



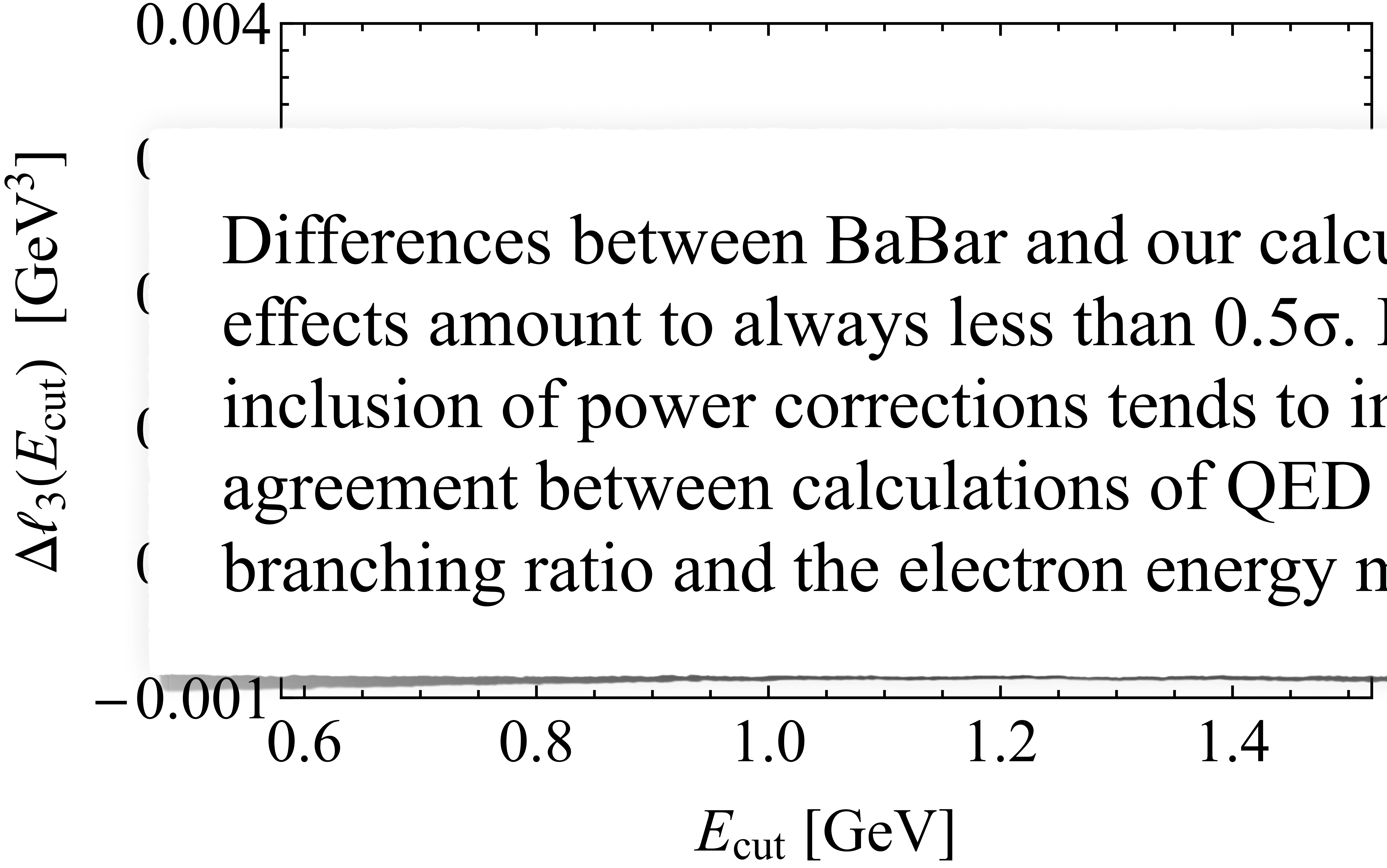
[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

Comparison to experiment



[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

Comparison to experiment



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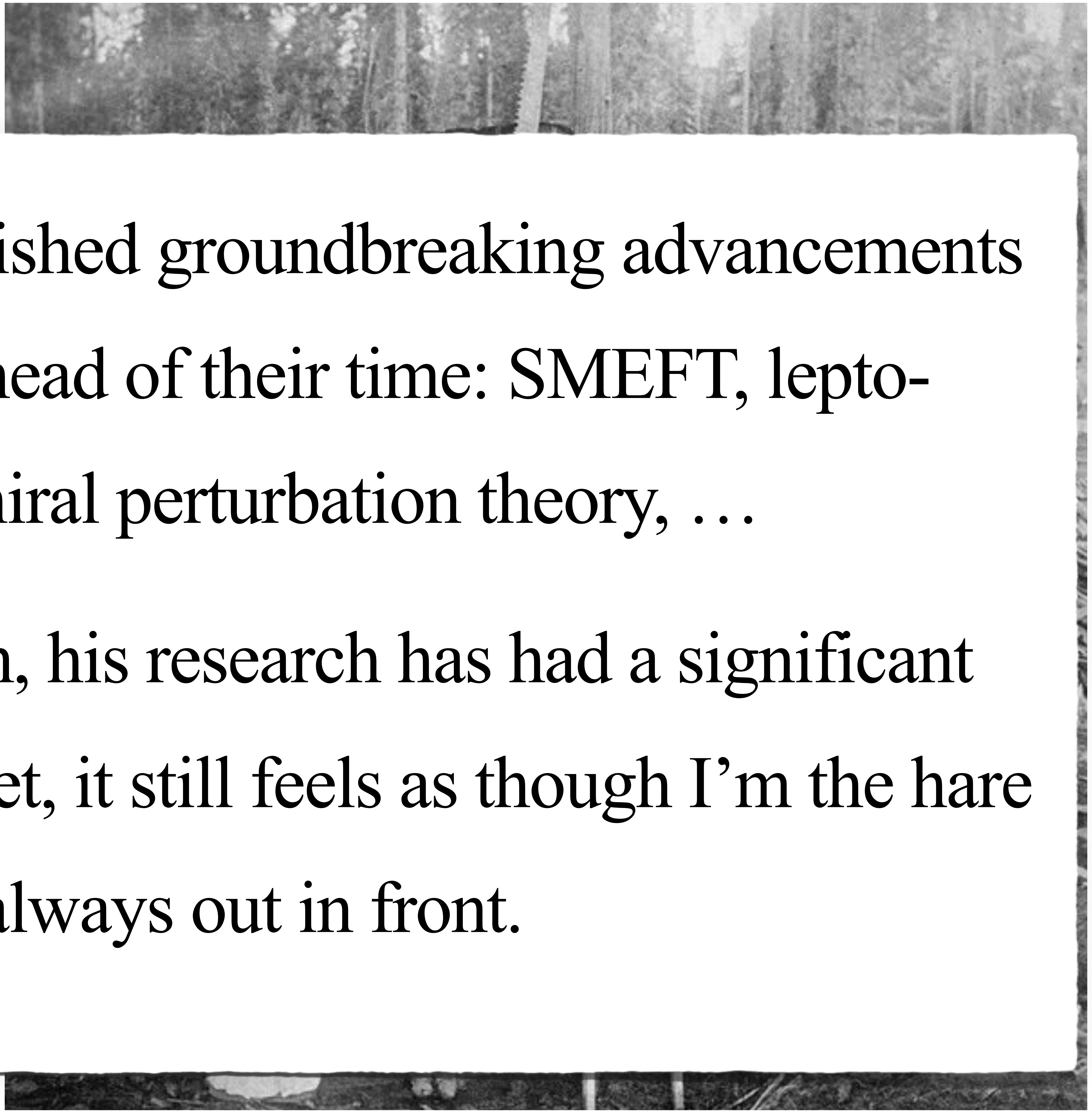
Differences between BaBar and our calculation of QED effects amount to always less than 0.5σ. Interestingly, the inclusion of power corrections tends to improve the agreement between calculations of QED effects in the branching ratio and the electron energy moments

[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

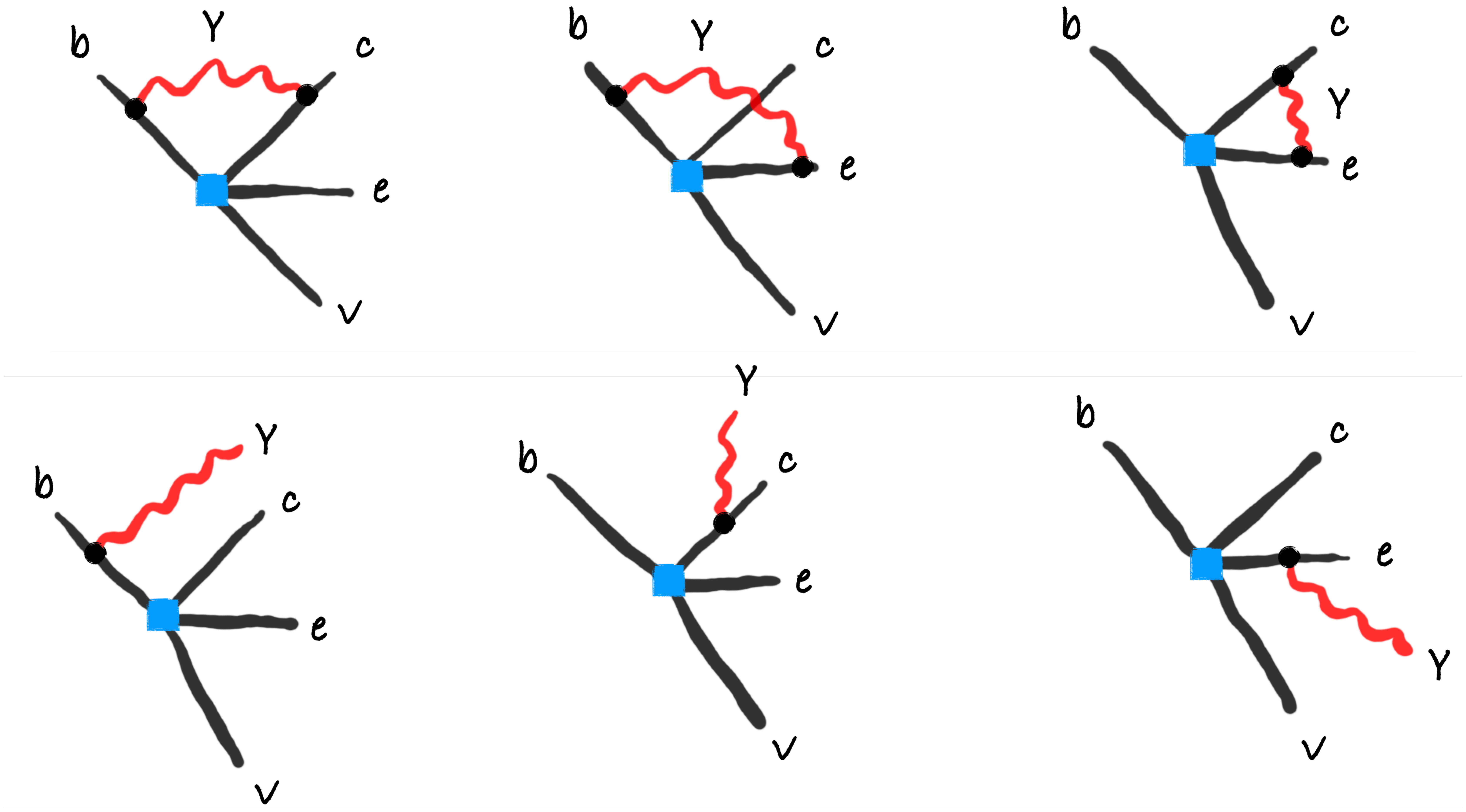
Conclusions



- Daniel has envisioned and accomplished groundbreaking advancements in theoretical particle physics, far ahead of their time: SMEFT, lepto-quarks, neutrinos, flavor physics, chiral perturbation theory, …
- While I never collaborated with him, his research has had a significant indirect impact on my own work. Yet, it still feels as though I'm the hare chasing the hedgehog — Daniel is always out in front.

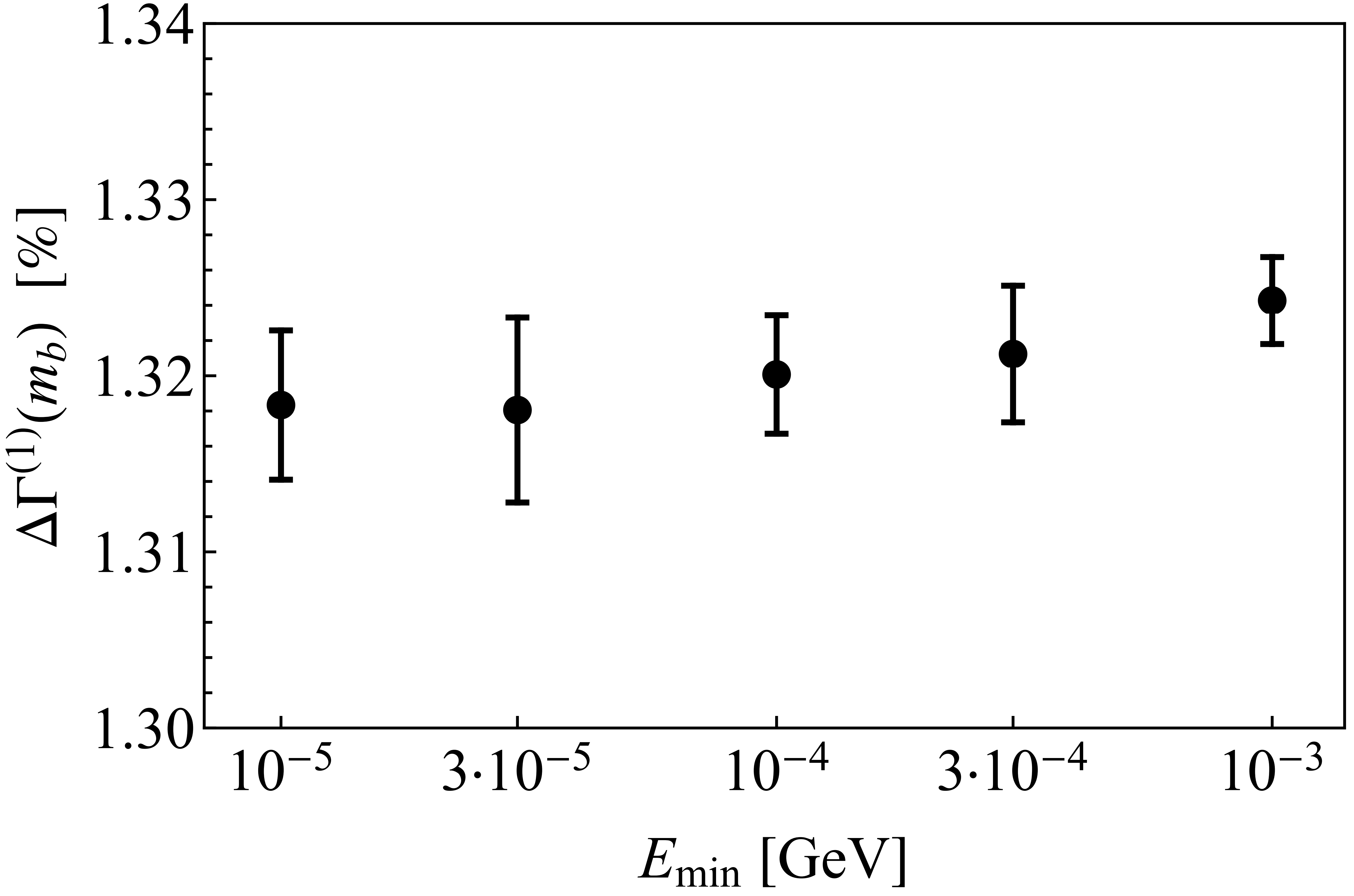
Backup

Exact 1-loop QED effects in b→cev



[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

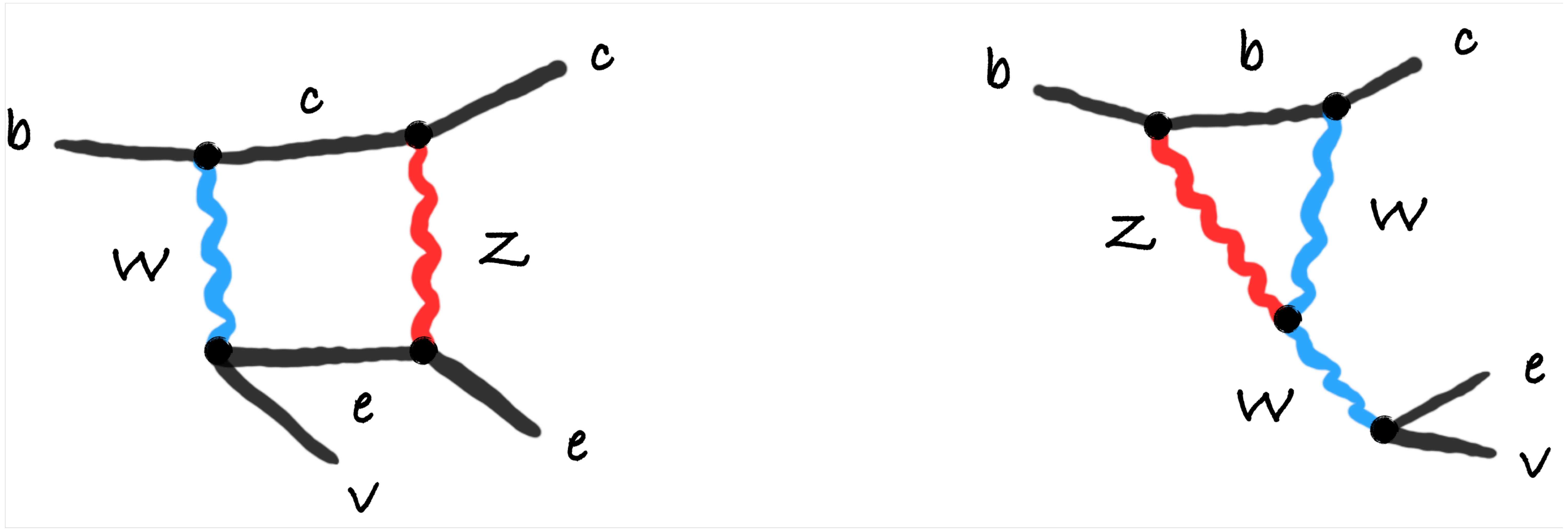
Exact 1-loop QED effects in b→ceν



Weak dependence of QED effects on E_{min} parameter used for phase-space slicing

[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

Short-distance EW corrections



$$C_{\mathrm{CC}}(\mu) = 1 + \frac{\alpha(\mu)}{4\pi} \begin{cases} \left[2\ln\left(\frac{M_Z^2}{\mu^2}\right) - \frac{11}{3}\right], & \text{semi-leptonic} \\ \left[\frac{4}{3}\ln\left(\frac{M_Z^2}{\mu^2}\right) - \frac{22}{9}\right], & \text{non-leptonic} \end{cases}$$

[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

Observables in b→cev

$$R^*(E_{\rm cut}) = \frac{\displaystyle\int_{E_{\rm cut}}^{E_{\rm max}} dE_e\, \frac{d\Gamma}{dE_e}}{\displaystyle\int_{m_e}^{E_{\rm max}} dE_e\, \frac{d\Gamma}{dE_e}}\,, \qquad \langle E_e^n\rangle_{E_e>E_{\rm cut}} = \frac{\displaystyle\int_{E_{\rm cut}}^{E_{\rm max}} dE_e\, E_e^n\, \frac{d\Gamma}{dE_e}}{\displaystyle\int_{E_{\rm cut}}^{E_{\rm max}} dE_e\, \frac{d\Gamma}{dE_e}}$$

$$\ell_1(E_{\rm cut}) = \langle E_e\rangle_{E_e>E_{\rm cut}}\,, \qquad \ell_n(E_{\rm cut}) = \Big\langle \big(E - \langle E_e\rangle\big)^n \Big\rangle_{E_e>E_{\rm cut}}$$

Comparison to BaBar

$E_{\rm cut}$	$\delta{\rm BR}_{\rm incl}^{\rm BaBar}$	$\delta{\rm BR}_{\rm incl}^{\rm LL}$	$\delta{\rm BR}_{\rm incl}^{\rm NLL}$	$\delta{\rm BR}_{\rm incl}^{\alpha}$	$\delta{\rm BR}_{\rm incl}^{1/m_b^2}$	$\delta{\rm BR}_{\rm incl}$	σ
0.6	-1.26%	-1.92%	-1.95%	-0.54%	-0.50%	-0.45%	$+0.34$
0.8	-1.87%	-2.88%	-2.91%	-1.36%	-1.29%	-1.22%	$+0.30$
1.0	-2.66%	-4.03%	-4.04%	-2.38%	-2.26%	-2.15%	$+0.25$
1.2	-3.56%	-5.43%	-5.41%	-3.65%	-3.43%	-3.27%	$+0.14$
1.5	-5.22%	-8.41%	-8.26%	-6.37%	-5.73%	-5.39%	-0.09

[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

Comparison to BaBar

E_{cut}	$\delta\ell_1^{\mathrm{BaBar}}$	$\delta\ell_1^{\mathrm{LL}}$	$\delta\ell_1^{\mathrm{NLL}}$	$\delta\ell_1^{\alpha}$	$\delta\ell_1^{1/m_b^2}$	$\delta\ell_1$	σ
0.6	-1.29%	-1.60%	-1.58%	-1.48%	-1.45%	-1.42%	-0.22
0.8	-1.01%	-1.22%	-1.20%	-1.16%	-1.13%	-1.10%	-0.31
1.0	-0.74%	-0.89%	-0.88%	-0.87%	-0.84%	-0.82%	-0.40
1.2	-0.53%	-0.63%	-0.62%	-0.62%	-0.59%	-0.58%	-0.32
1.5	-0.29%	-0.33%	-0.32%	-0.34%	-0.31%	-0.30%	-0.13

[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

Comparison to BaBar

E_{cut}	$\delta\ell_2^{\text{BaBar}}$	$\delta\ell_2^{\text{LL}}$	$\delta\ell_2^{\text{NLL}}$	$\delta\ell_2^{\alpha}$	$\delta\ell_2^{1/m_b^2}$	$\delta\ell_2$	σ
0.6	$+0.31\%$	$+1.65\%$	$+1.43\%$	$+0.91\%$	$+0.48\%$	$+0.50\%$	$+0.07$
0.8	-0.34%	$+0.50\%$	$+0.34\%$	$+0.04\%$	-0.40%	-0.33%	$+0.01$
1.0	-1.00%	-0.27%	-0.38%	-0.60%	-1.08%	-0.95%	$+0.04$
1.2	-1.27%	-0.78%	-0.85%	-1.05%	-1.60%	-1.42%	-0.08
1.5	-1.91%	-1.15%	-1.18%	-1.40%	-2.24%	-1.93%	-0.01

[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

Comparison to BaBar

E_{cut}	$\delta\ell_3^{\text{BaBar}}$	$\delta\ell_3^{\text{LL}}$	$\delta\ell_3^{\text{NLL}}$	$\delta\ell_3^{\alpha}$	$\delta\ell_3^{1/m_b^2}$	$\delta\ell_3$	σ
0.6	-17.3%	-22.1%	-23.1%	-22.7%	-22.6%	-22.5%	$+0.35$
0.8	-42.8%	-68.9%	-69.2%	-66.7%	-62.9%	-62.9%	$+0.45$
1.0	$+63.9\%$	$+67.3\%$	$+66.3\%$	$+63.9\%$	$+56.2\%$	$+57.6\%$	$+0.34$
1.2	$+11.7\%$	$+18.1\%$	$+17.6\%$	$+17.1\%$	$+13.3\%$	$+14.7\%$	$+0.28$
1.5	-0.47%	$+5.92\%$	$+5.69\%$	$+5.61\%$	$+2.10\%$	$+4.69\%$	$+0.23$

[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849]

QED corrections in $|V_{cb}|$ extraction

Correction δBR_{incl} @ lowest E_{cut} value leads to largest shift of -0.4% in $|V_{cb}|$. QED corrections to moments of electron energy spectrum instead amount to an effect of +0.2%. Applying our new results for the QED corrections to electron energy spectrum & its moments to the BaBar data, therefore gives a total modification of around -0.2% in $|V_{cb}|$ compared to an inclusive determination without QED effects

[Bigi, Bordone, Gambino, UH & Piccione, 2309.02849; Finauri & Gambino, 2310.20324]