LNU and LFV in B and D decays

based on works with Stefan de Boer, Martin Schmaltz and Ivo de Medeiros Varzielas arXiv:1408.1627, arXiv:1411.4773, arXiv:1503.01084, arXiv:1510.00311

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Generational structure & mixing is a feature of the SM and many BSM particles. VIRTUES:

i) high sensitivity to BSM in flavor violation;
FCNCs $b \to s\ell\ell, \mu \to e\gamma, ..$
we may discover BSM in flavor physics (even first)

ii) flavorful processes are intrinsically linked to the "flavor puzzle":
masses, i.e., Yukawa matrices in $\mathcal{L}_{SM} = -\bar{Q}Y_u H^C U - \bar{Q}Y_d H D + ...$
do not appear to be random but rather structured - from where?
with a BSM-signal, we may be able to progress here

iii) plenty of modes $s \to d$, $c \to u$, $b \to s, d$, $t \to c, u$, $\mu \to e$, $\tau \to \mu, e$
plus charged ones and $h \to f\bar{f}'$; ongoing & future experiments, too.
we may identify $\mathcal{L}_{BSM}$; complementary to direct searches

Flavor Themes 2015/16+(simplified)

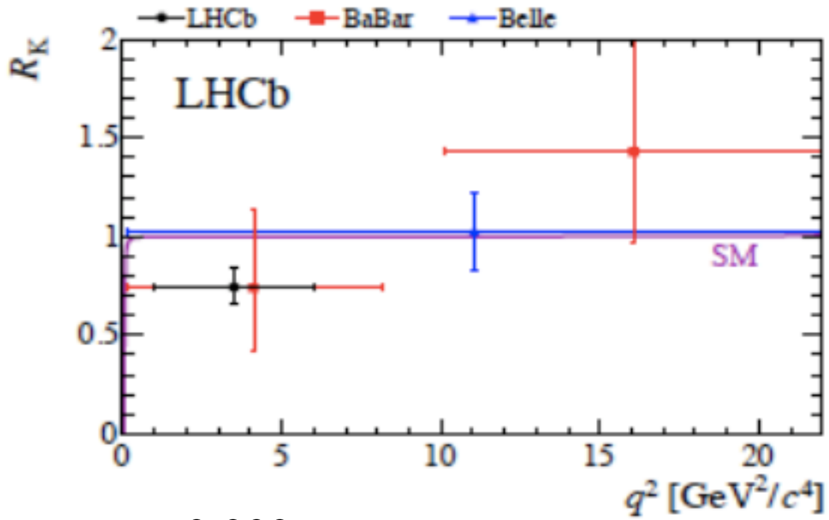
– crosstalk theory(SM/BSM)/pheno/experiment

– new bottom-up New Physics benchmark models $\leftrightarrow$ Z', extra Higgses, leptoquarks

– leptons $\leftrightarrow$ quarks $\leftrightarrow$ hints of lepton-nonuniversality in B-decays R_K, $R_{D^{(*)}}$

$$R_H = \frac{\mathcal{B}(\bar{B}\to\bar{H}\mu\mu)}{\mathcal{B}(\bar{B}\to\bar{H}ee)}, \quad H = K, K^*, X_s, \ldots$$

Lepton-universal models(SM): $R_H = 1+$tiny, GH, Krüger '03



LHCb 2014: $R_K = 0.745 \pm^{0.090}_{0.074} \pm 0.036 < 1$ at 2.6 σ

http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.151601, arXiv:1406.6482 [hep-ex]

physics highlight: http://physics.aps.org/articles/v7/102

apriori too few muons, or too many electrons, or combination thereof.

$B^{\pm} \to K^{\pm} ee$ and $B^{\pm} \to K^{\pm} \mu\mu$ events at LHCb. Full data set, $3 \mathrm{fb}^{-1}$, from 7 and 8 TeV LHC run.

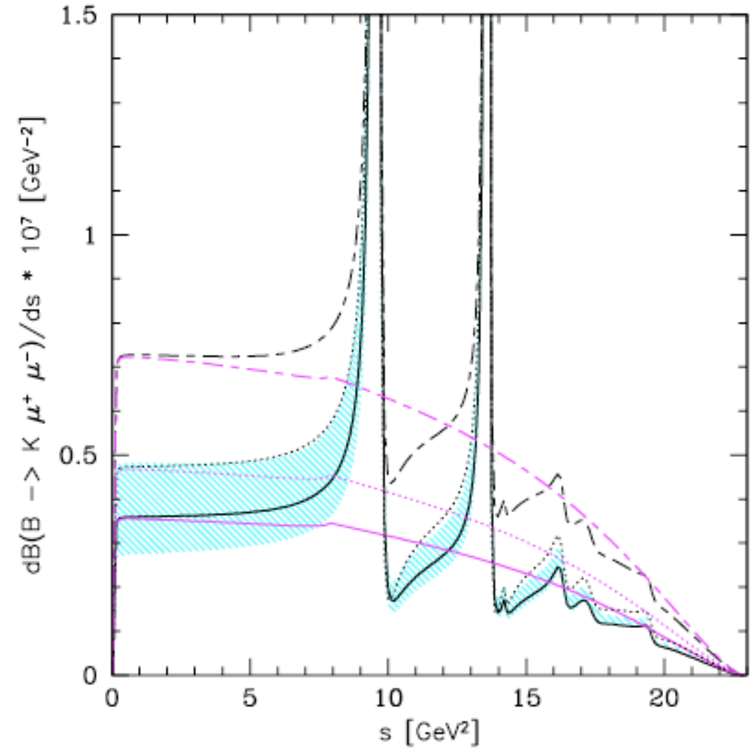


Fig from 9910221, solid: SM, dotted and dot-dashed: BSM scenario

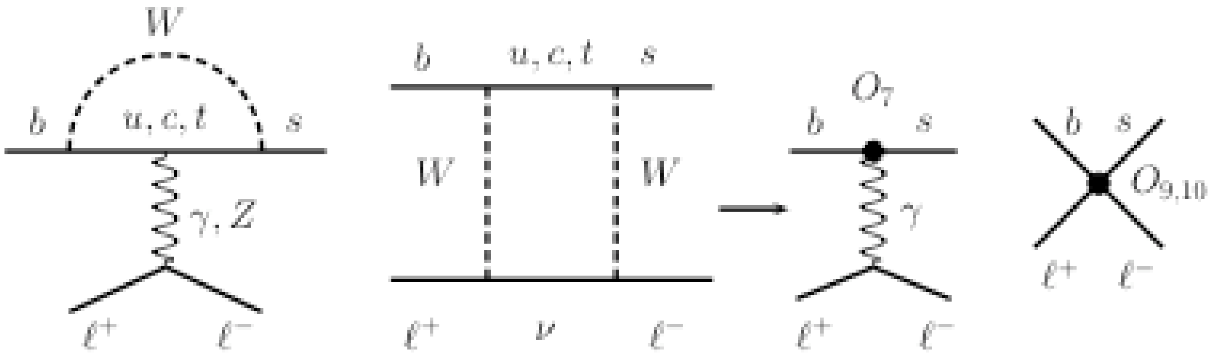
Select low dilepton mass window: $1 \leq q^2 < 6\,\mathrm{GeV}^2$ below J/Ψ.

situation for numerator $\mu\mu$ and denominator ee of R_K separately:

	LHCb[a]	SM[b]
$\mathcal{B}(B \to K\mu\mu)_{[1,6]}$	$(1.21 \pm 0.09 \pm 0.07) \cdot 10^{-7}$	$(1.75^{+0.60}_{-0.29}) \cdot 10^{-7}$
$\mathcal{B}(B \to Kee)_{[1,6]}$	$(1.56^{+0.19+0.06}_{-0.15-0.04}) \cdot 10^{-7}$	same
$R_K\vert_{[1,6]}$	$0.745 \pm^{0.090}_{0.074} \pm 0.036$	$\simeq 1$

[a] 1209.4284 (μ) and 1406.6482 (e) [b] Bobeth, GH, van Dyk ’12, form factors from 1006.4945

Individual branching ratios make presently no case for new physics, although muons are a bit below SM. The ratio R_K is much cleaner.



Construct EFT $\mathcal{H}_{\rm eff} = -4\frac{G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i C_i(\mu)O_i(\mu)$ at dim 6

V,A operators $\mathcal{O}_9 = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \ell]\,, \quad \mathcal{O}_9' = [\bar{s}\gamma_\mu P_R b]\,[\bar{\ell}\gamma^\mu \ell]$

$\mathcal{O}_{10} = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \gamma_5 \ell]\,, \quad \mathcal{O}_{10}' = [\bar{s}\gamma_\mu P_R b]\,[\bar{\ell}\gamma^\mu \gamma_5 \ell]$

S,P operators $\mathcal{O}_S = [\bar{s} P_R b]\,[\bar{\ell}\ell]\,, \quad \mathcal{O}_S' = [\bar{s} P_L b]\,[\bar{\ell}\ell]\,,$ ONLY O_9, O_{10} are SM, all other BSM

$\mathcal{O}_P = [\bar{s} P_R b]\,[\bar{\ell}\gamma_5 \ell]\,, \quad \mathcal{O}_P' = [\bar{s} P_L b]\,[\bar{\ell}\gamma_5 \ell]$

and tensors $\mathcal{O}_T = [\bar{s}\sigma_{\mu\nu} b]\,[\bar{\ell}\sigma^{\mu\nu} \ell]\,, \quad \mathcal{O}_{T5} = [\bar{s}\sigma_{\mu\nu} b]\,[\bar{\ell}\sigma^{\mu\nu}\gamma_5 \ell]$

lepton specific $C_i O_i \to C_i^\ell O_i^\ell$, $\ell = e, \mu, \tau$

Model-independent interpretations with V,A operators: Das et al 1406.

$$0.7 \lesssim \mathrm{Re}[X^e - X^\mu] \lesssim 1.5\,,$$
$$X^\ell = C_9^{\mathrm{NP}\ell} + C_9^{\prime\ell} - (C_{10}^{\mathrm{NP}\ell} + C_{10}^{\prime\ell})$$

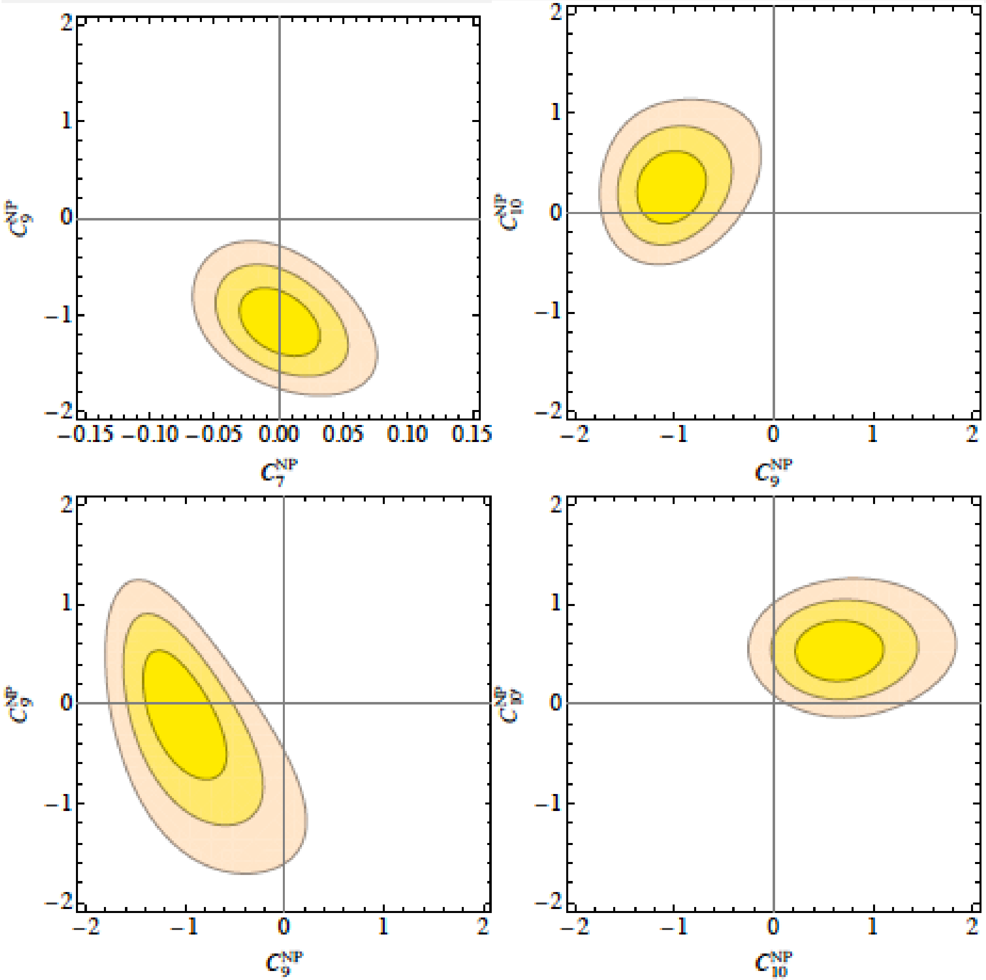
The required NP is sizeable $C_9^{\mathrm{SM}} \simeq -C_{10}^{\mathrm{SM}} \simeq 4.2$.

Tensors and S,P muon operators are excluded as sole sources of R_K; S,P electronic operators allowed at 2 σ and require cancellations, testable with $\bar{B} \to \bar{K}ee$ angular distributions.

$X^e \simeq 0$ and $X^\mu \simeq C_9^{\mu NP} \simeq -1$ is consistent with global fit to existing $b \to s$ data!

Descotes-Genon et al

Global fits: 2D hypotheses



Hyp.	Best-fit pt	Pull
(C_7^{NP}, C_9^{NP})	(0.0, -1.1)	4.2
(C_9^{NP}, C_{10}^{NP})	(-1.1, 0.2)	4.2
$(C_9^{NP}, C_{9'})$	(-1.0, -0.1)	4.2
$(C_{10}^{NP}, C_{10'})$	(0.5, 0.6)	3.4

$\rightarrow$ Main effect from C_9

Explanations ?

- Z' boson
- Leptoquarks
- Composite models
- Difficult with susy (?)

[Almannshoffer, Straub, Haisch, Gauld, Peczak, Buras, De Fazio, Girrbach, Hiller, Schmaltz, Varzielas, Crivellin. . .]

S. Descotes-Genon (LPT-Orsay) | $b \to s\ell\ell$ 2015 & NP | 12/06/15 18

$b \to s$ fits: lepton flavor structure

Why are muons different from electrons?

Splitting electrons from muons:

Z'- $U(1)_{\tau-\mu}$ (BSM in $b \to s\mu\mu$, not in $b \to see$).

Altmannshofer, Crivellin, Fuentes, Vicente, .. et al

Links with $h \to \tau\mu$ with extras Higgses Crivellin et al, Heeck et al

new particle exchanged at tree level, including leptoquarks, MSSM with R-Parity violation amended with Froggatt-Nielsen flavor symmetry (both $\mu\mu$ and/or ee possible) Fajfer, Schmaltz, Gripaios, Varzielas, .. et al

This naturally provides a link for LFV decays Guadagnoli, Kane, Varzielas which however is not strict Alonso et al, Fuentes et al

pl see original refs for complete list of contributions to this effort

Leptoquark model $\mathcal{L} = -\lambda_{d\ell}\, \varphi\, (\bar{d} P_L \ell)$ with scalar leptoquark $\varphi(3,2)_{1/6}$ with mass M; includes R-parity violating MSSM)

$\mathcal{H}_{\text{eff}} = -\frac{|\lambda_{d\ell}|^2}{M^2} (\bar{d} P_L \ell)\, (\bar{\ell} P_R d) = \frac{|\lambda_{d\ell}|^2}{2M^2} [\bar{d}\gamma^\mu P_R d]\, [\bar{\ell}\gamma_\mu P_L \ell]$
from tree level φ exchange and fierzing.

In terms of the usual Wilson coefficients:

$$C_{10}^{\prime e} = -C_9^{\prime e} = \frac{\lambda_{se}\lambda_{be}^*}{V_{tb}V_{ts}^*} \frac{\pi}{\alpha_e} \frac{\sqrt{2}}{4M^2 G_F} = -\frac{\lambda_{se}\lambda_{be}^*}{2M^2} (24\text{TeV})^2$$

R_K-data implies $\lambda_{se}\lambda_{be}^*/M^2 \simeq 1/(24\text{TeV})^2$

Viable parameters of the (scalar) leptoquarks read

$$1\,\text{TeV} \lesssim M \lesssim 48\,\text{TeV}$$
$$2 \cdot 10^{-3} \lesssim |\lambda_{se}\lambda_{be}^*| \lesssim 4$$

The upper limit on M arises from correlation with B_s mixing, which constrains $(\lambda_{se}\lambda_{be}^*)^2/M^2$.

– $SU(2)$ implies corresponding effects in $b \to s\nu\nu$ (only electron-neutrinos affected, signal diluted over 3 species).
$\mathcal{B}(B \to K\nu\nu)$ reduced by 5 %, $\mathcal{B}(B \to K^*\nu\nu)$ enhanced by 5 %, F_L enhanced by 2 % w.r.t SM.

– Further correlation with $b \to s\gamma$, and direct searches.

– Decay modes of φ-dublet: $\varphi^{2/3} \to b\, e^+ \,, \quad \varphi^{-1/3} \to b\, \nu$

$$\mathcal{L} = -\lambda_{b\mu}\,\varphi^*\,q_3\ell_2 - \lambda_{s\mu}\,\varphi^*\,q_2\ell_2, \qquad\qquad \varphi(3,3)_{-1/3}$$

$$\mathcal{H}_{\rm eff} = -\frac{\lambda^*_{s\mu}\lambda_{b\mu}}{M^2}\left(\tfrac{1}{4}[\bar{q}_2\tau^a\gamma^\mu P_L q_3]\,[\bar{\ell}_2\tau^a\gamma_\mu P_L\ell_2] + \tfrac{3}{4}[\bar{q}_2\gamma^\mu P_L q_3]\,[\bar{\ell}_2\gamma_\mu P_L\ell_2]\right)$$

gives $C_9^{\rm NP\mu} = -C_{10}^{\rm NP\mu} = \frac{\pi}{\alpha_e}\frac{\lambda^*_{s\mu}\lambda_{b\mu}}{V_{tb}V^*_{ts}}\frac{\sqrt{2}}{2M^2G_F} \simeq -0.5$ and similar mass range as other model.

Decay modes of φ-triplet:

$$\begin{aligned} \varphi^{2/3} &\to t\,\nu \\ \varphi^{-1/3} &\to b\,\nu\,,\ t\,\mu^- \\ \varphi^{-4/3} &\to b\,\mu^- \end{aligned}$$

Leptoquark triplet or doublet? That is, more generally,

C (V-A-quark currents) versus
C' (V+A quark currents)?

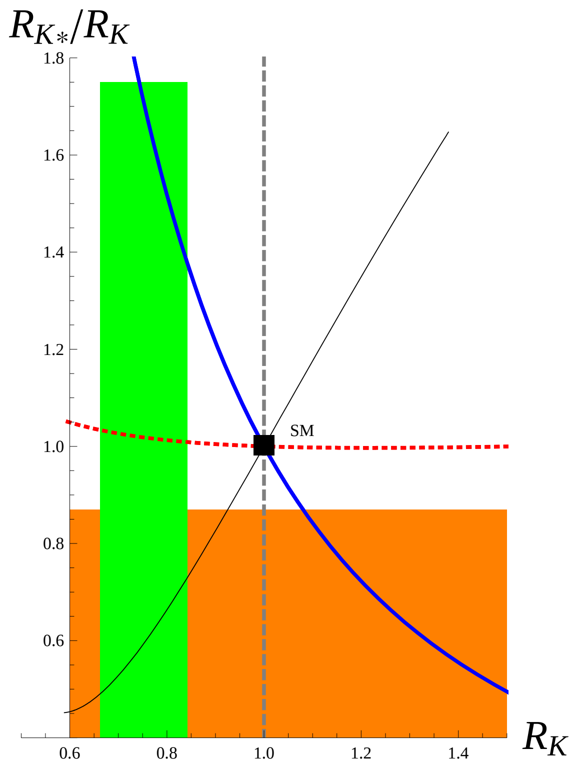
By parity and lorentz invariance, C, C' enter decay amplitudes $B \to K\ell\ell$ etc as

$$
\begin{aligned}
C + C' : &\quad K, K^*_\perp, \ldots \\
C - C' : &\quad K_0(1430), K^*_{0,\|}, \ldots
\end{aligned}
$$

so different ratios R_K, R_{K^*} etc are complementary, double ratios R_{K^*}/R_K are cleanly probing right-handed currents!

predictions: $R_K = R_\eta$, $R_{K^*} = R_\Phi$ plus correlations among R_H.

Distinguish R_K explanations



Green band: R_K 1 sigma LHCb. Curves: different BSM scenarios. red dashed: pure C_{LL}. Black solid: $C_{LL} = -2C_{RL}$. Blue: C_{RL}. Orange band is prediction for R_{K^*} (not significantly measurend) based on R_K and $B \to X_s \ell\ell$: $R_{X_s}^{\mathrm{Belle}'09} = 0.42 \pm 0.25\,, \quad R_{X_s}^{\mathrm{BaBar}'13} = 0.58 \pm 0.19$.

Diagnosing quark and lepton flavor

Given the breakdown of lepton-universality, chances are that generically there is lepton flavor violation, too arXiv:1411.0565.

Explaining R_K with muons and electrons requires theory of flavor. Thats an opportunity– given a signal– to access origin of flavor arXiv:1503.01084

Leptoquark coupling matrix: $\lambda_{ql} \equiv \begin{pmatrix} \lambda_{q_1 e} & \lambda_{q_1 \mu} & \lambda_{q_1 \tau} \\ \lambda_{q_2 e} & \lambda_{q_2 \mu} & \lambda_{q_2 \tau} \\ \lambda_{q_3 e} & \lambda_{q_3 \mu} & \lambda_{q_3 \tau} \end{pmatrix}$

$\rightarrow$ Size of BSM effects depends on flavor!

Use $U(1)$-flavor-symmetry for quarks (rows) and non-abelian one e.g. A_4 for leptons (columns) and assume Higgs to be uncharged. Predicts generically hierarchies for quarks and ”zeros” and ”ones” for leptons. Explicit realizations include

$$\lambda_{ql} \sim \begin{pmatrix} \rho_d \kappa & \rho_d & \rho_d \\ \rho \kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix}, \quad \begin{pmatrix} 0 & * & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix}, \quad \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix}, \ldots$$

LQs make interesting link between quark (hierarchy) and lepton (anarchy? non-abelian discrete?) flavor 1503.01084.

predictions:

$$\mathcal{B}(B \to K\mu^\pm e^\mp) \simeq 3 \cdot 10^{-8}\,\kappa^2 \left(\frac{1 - R_K}{0.23}\right)^2 , \quad (1)$$

$$\mathcal{B}(B \to K e^\pm \tau^\mp) \simeq 2 \cdot 10^{-8}\,\kappa^2 \left(\frac{1 - R_K}{0.23}\right)^2 , \quad (2)$$

$$\mathcal{B}(B \to K\mu^\pm \tau^\mp) \simeq 2 \cdot 10^{-8} \left(\frac{1 - R_K}{0.23}\right)^2 , \quad (3)$$

and

$$\mathcal{B}(\mu \to e\gamma) \simeq 2 \cdot 10^{-12} \, \frac{\kappa^2}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \quad (4)$$

$$\mathcal{B}(\tau \to e\gamma) \simeq 4 \cdot 10^{-14} \, \frac{\kappa^2}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \quad (5)$$

$$\mathcal{B}(\tau \to \mu\gamma) \simeq 3 \cdot 10^{-14} \, \frac{1}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \quad (6)$$

$$\mathcal{B}(\tau \to \mu\eta) \simeq 4 \cdot 10^{-11} \, \rho^2 \left(\frac{1 - R_K}{0.23} \right)^2 . \quad (7)$$

asymmetric branching ratios:

$$\frac{\mathcal{B}(B_s \to \ell^+ \ell'^-)}{\mathcal{B}(B_s \to \ell^- \ell'^+)} \simeq \frac{m_\ell^2}{m_{\ell'}^2} \,. \quad \text{Left-handed leptons only} \tag{8}$$

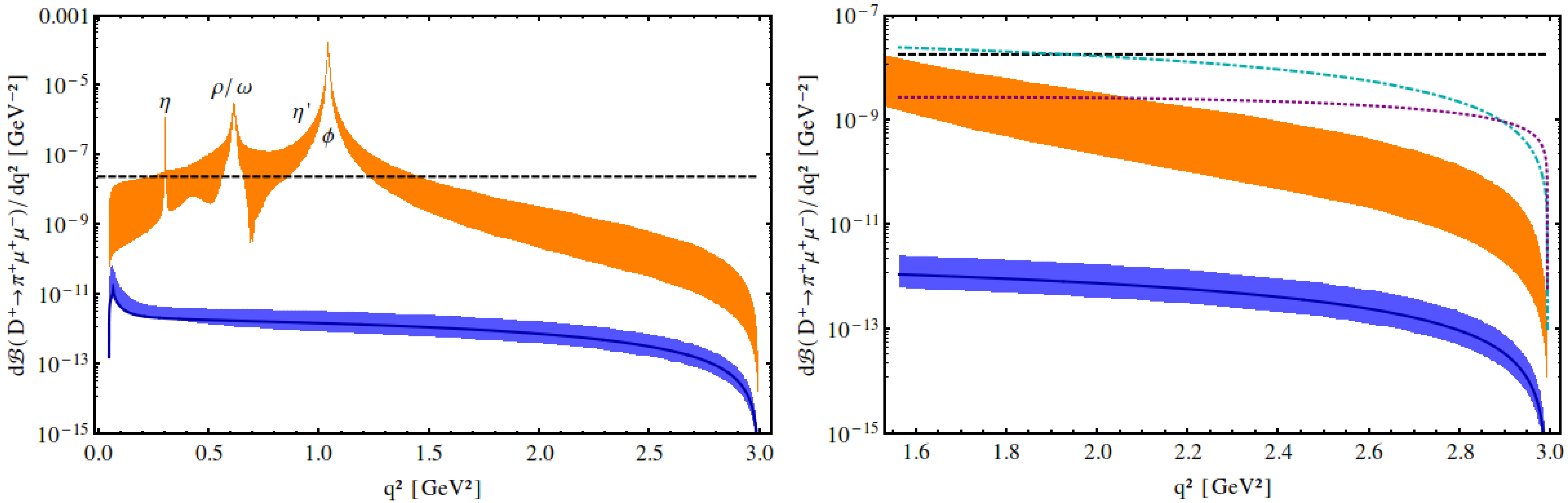
$$\frac{\mathcal{B}(B_s \to \mu^+ e^-)}{\mathcal{B}(B_s \to \mu^+ \mu^-)_{\rm SM}} \simeq 0.01\, \kappa^2 \cdot \left(\frac{1 - R_K}{0.23}\right)^2 , \tag{9}$$

$$\frac{\mathcal{B}(B_s \to \tau^+ e^-)}{\mathcal{B}(B_s \to \mu^+ \mu^-)_{\rm SM}} \simeq 4\, \kappa^2 \cdot \left(\frac{1 - R_K}{0.23}\right)^2 , \tag{10}$$

$$\frac{\mathcal{B}(B_s \to \tau^+ \mu^-)}{\mathcal{B}(B_s \to \mu^+ \mu^-)_{\rm SM}} \simeq 4 \cdot \left(\frac{1 - R_K}{0.23}\right)^2 , \tag{11}$$

Impact on $c \to u\ell\ell$?

Resonance contributions vs BSM



BSM windows in $D \to \pi l^+ l^-$ branching ratios at high and very low q^2 only; BSM Wilson coefficients need to be very large, ~ 1.

$|C_9^R(q^2 = 1.5\,\text{GeV}^2)| \simeq 0.8$ versus $|C_9^{nr\,\text{SM}}(q^2 \gtrsim 1\,\text{GeV}^2)| \lesssim 5 \cdot 10^{-4}$.

To observe BSM in rare charm either i) BSM is very large (plot to the right) or ii) contributes to SM null tests (LFV, LNU, CP, angular distr.)

Flavor patterns of leptoquark coupling matrix λ (rows=quark flavor, columns=lepton flavor):

$$\lambda_{ql} \sim \begin{pmatrix} \rho_d\kappa & \rho_d & \rho_d \\ \rho\kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix}, \quad \begin{pmatrix} 0 & * & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix}, \quad \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix}, \ldots$$

LQs make interesting link between quark (hierarchy) and lepton (anarchy? non-abelian discrete?) flavor 1503.01084.

	$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$	$\mathcal{B}(D^0 \to \mu^+\mu^-)$	$\mathcal{B}(D^+ \to \pi^+ e^\pm \mu^\mp)$	$\mathcal{B}(D^0 \to \mu^\pm e^\mp)$	$\mathcal{B}(D^+ \to \pi^+ \nu\bar{\nu})$
i)	SM-like	SM-like	$\lesssim 2 \cdot 10^{-13}$	$\lesssim 7 \cdot 10^{-15}$	$\lesssim 3 \cdot 10^{-13}$
ii.1)	$\lesssim 7 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$\lesssim 3 \cdot 10^{-9}$	0	0	$\lesssim 8 \cdot 10^{-8}$
ii.2)	SM-like	$\lesssim 4 \cdot 10^{-13}$	0	0	$\lesssim 4 \cdot 10^{-12}$
iii.1)	SM-like	SM-like	$\lesssim 2 \cdot 10^{-6}$	$\lesssim 4 \cdot 10^{-8}$	$\lesssim 2 \cdot 10^{-6}$
iii.2)	SM-like	SM-like	$\lesssim 8 \cdot 10^{-15}$	$\lesssim 2 \cdot 10^{-16}$	$\lesssim 9 \cdot 10^{-15}$

Table 1: Branching fractions for the full q^2-region (high q^2-region) for different classes of leptoquark couplings. Summation of neutrino flavors is understood. ”SM-like” denotes a branching ratio which is dominated by resonances or is of similar size as the resonance-induced one. All $c \to u e^+ e^-$ branching ratios are ”SM-like” in the models considered. Note that in the SM $\mathcal{B}(D^0 \to \mu\mu) \sim 10^{-13}$.

LHCb: arXiv:1512.00322 [hep-ex] $\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 1.3 \cdot 10^{-8}$ at 90 % CL

i): hierarchy, ii) muons only iii) skewed, 1) no kaon bounds 2) kaon bounds apply for $SU(2)_L$-dublets $Q = (c, s)$

– Great prospects to test the SM and look for BSM physics in semileptonic rare decays.

– Whether new Physics can be seen depends on flavor, and vice versa; links between K, D, B-physics and LFV can provide new insights into flavor.

– Current anomalies in the flavor sector have triggered new types of bottom-up model-building (Z', leptoquarks, ..), that deserves attention in direct searches.

BACK-UP

$c \to u$ amplitudes are strongly GIM-suppressed:

$\mathcal{A}_{c\to u} \simeq \sin\Theta_C[f(m_s^2/m_W^2) - f(m_d^2/m_W^2)] + O(\sin^5\Theta_C)$

Resulting (non-resonant) SM branching ratios are $10^{-12} - 10^{-13}$:

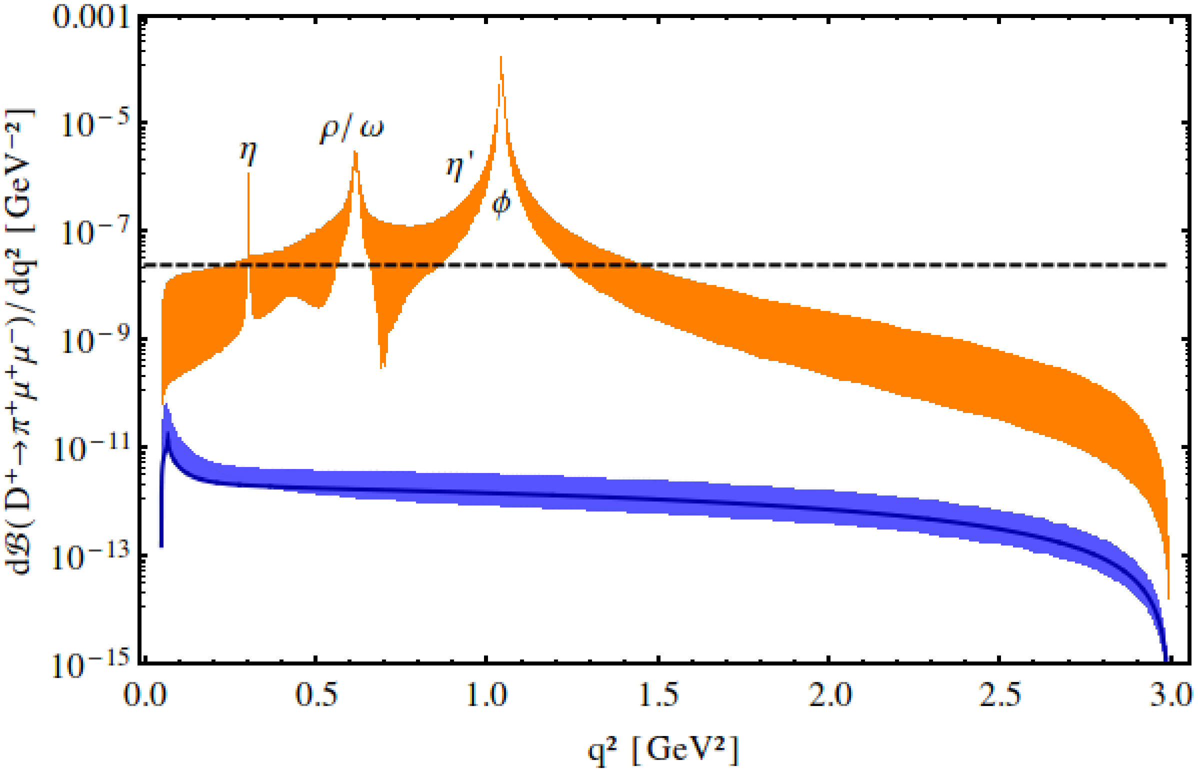
q^2-bin	$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)^{\rm SM}_{\rm nr}$	90% CL limit LHCb'13
full q^2:	$3.7 \cdot 10^{-12}\,(\pm1, \pm3, ^{+16}_{-15}, \pm1, ^{+4}_{-1}, ^{+158}_{-1}, ^{+16}_{-12})$	$7.3 \cdot 10^{-8}$
low q^2:	$7.4 \cdot 10^{-13}\,(\pm1, \pm4, ^{+23}_{-21}, ^{+10}_{-11}, ^{+11}_{-1}, ^{+238}_{-23}, ^{+6}_{-5})$	$2.0 \cdot 10^{-8}$
high q^2:	$7.5 \cdot 10^{-13}\,(\pm1, \pm6, ^{+15}_{-14}, \pm6, ^{+2}_{-1}, ^{+136}_{-45}, ^{+27}_{-20})$	$2.6 \cdot 10^{-8}$

Table 2: Non-negligible uncertainties correspond to (normalization, m_c, m_s, μ_W, μ_b, μ_c, f_+), respectively, given in percent arXiv:1510.00311

Largest uncertainty: μ_c-scale dependence $m_c/\sqrt{2} < \mu_c \leq \sqrt{2}m_c$.

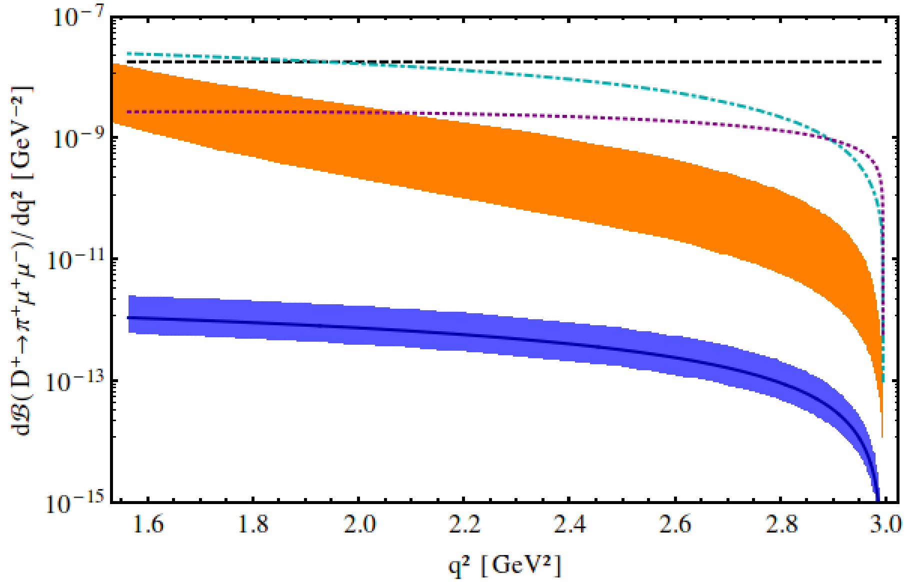
$D \to \pi M \to \pi l^+ l^-$, with $M = \eta^{(\prime)}, \rho, \omega, \Phi$

Model with Breit-Wigners, branching ratio data and relative phases:



solid blue: SM with μ_c-uncertainty, dashed 90% CL upper limit, gray: resonance contribution

Model-independent constraints on BSM



$c \to u\mu\mu$: $|C^{(\prime)}_{V,A}| \lesssim 1$ (illustrated above), $|C_{T,T5}| \lesssim 1$, $|C^{(\prime)}_{S,P}| \lesssim 0.1$.

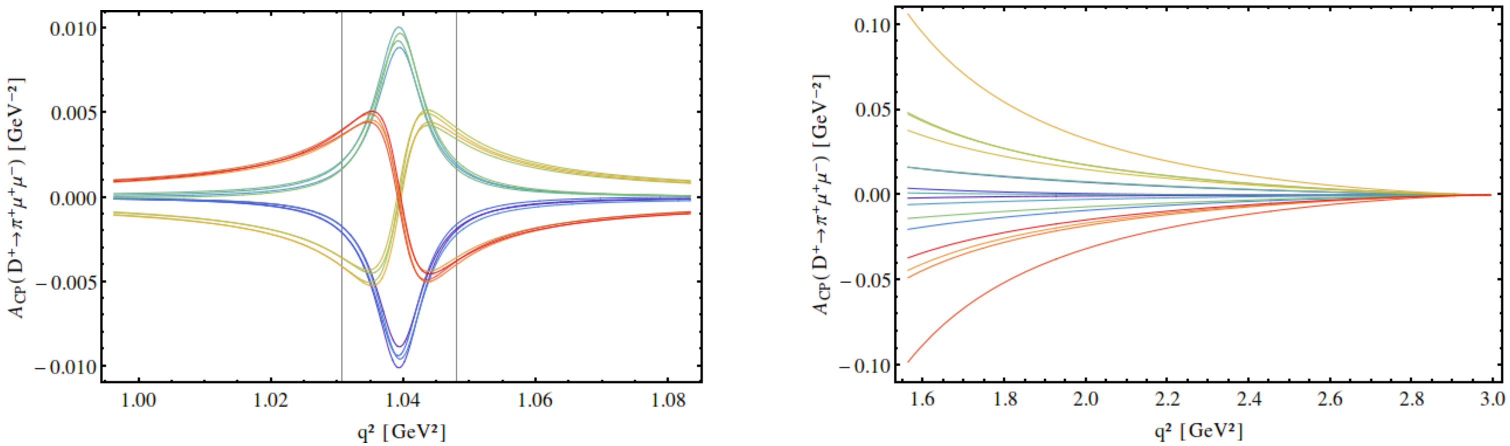
BSM weak loop $\Lambda_{NP} \gtrsim O(5)$ TeV, BSM tree level $\Lambda_{NP} \gtrsim$ weak scale.

$c \to uee$: constraints are weaker (data) by a (2-4) $\times$ muon bounds.

$c \to ue\mu$: weaker by (6-7) $\times$ muon bounds.

Probing even small couplings: A_{CP}

GIM-suppression can be eased by the resonances, which are less $SU(3)_F$-symmetric than the nr- contributions. also "resonance-catalyzed CP", Fajfer et al '13



Large uncertainties, however, large BSM signals possible ($|A_{CP}^{\rm SM}| \lesssim few 10^{-3}$) even independent of strong phases around Φ.

Opportunity to probe SM-like lorentz-structure $C_{V,A}$ even in presence of $SU(2)$-link to K-physics – links between charm and b-physics

Θ: angle between negatively charged lepton and D in dilepton cms

$$\frac{d\Gamma(D\to\pi l^+l^-)}{d\cos\Theta} = \frac{3}{4}(1-F_H)(1-\cos^2\Theta) + A_{FB}\cos\Theta + F_H/2$$ Bobeth et al '07

SM: $A_{FB}, F_H \simeq 0$ by lorentz-structure and small lepton masses. Both require S,P- and or tensor operators.

Model-independently, striking BSM signals possible (high q^2):

$|A_{\rm FB}(D^+ \to \pi^+\mu^+\mu^-)| \lesssim 0.6$, $|A_{\rm FB}(D^+ \to \pi^+ e^+ e^-)| \lesssim 0.8$ and $F_H(D^+ \to \pi^+ l^+ l^-) \lesssim 2$ for $l = e, \mu$.

LFV-rates and dineutrino modes which vanish in SM can be just around the corner (model-independently).

Lets use the chiral basis:

$$\mathcal{O}^{\ell}_{LL} \equiv (\mathcal{O}^{\ell}_{9} - \mathcal{O}^{\ell}_{10})/2\,, \quad \mathcal{O}^{\ell}_{LR} \equiv (\mathcal{O}^{\ell}_{9} + \mathcal{O}^{\ell}_{10})/2\,,$$
$$\mathcal{O}^{\ell}_{RL} \equiv (\mathcal{O}'^{\ell}_{9} - \mathcal{O}'^{\ell}_{10})/2\,, \quad \mathcal{O}^{\ell}_{RR} \equiv (\mathcal{O}'^{\ell}_{9} + \mathcal{O}'^{\ell}_{10})/2\,.$$

R_K sensitive to left-handed leptons:

$$C^{\ell}_{LL} = C^{\ell}_{9} - C^{\ell}_{10}\,, \quad C^{\ell}_{RL} = C'^{\ell}_{9} - C'^{\ell}_{10}\,.$$

right-handed leptons: $C^{\ell}_{LR} = C^{\ell}_{9} + C^{\ell}_{10}$, $C^{\ell}_{RR} = C'^{\ell}_{9} + C'^{\ell}_{10}$

This suggests to use in global fits invariant-constraints such as
$C^{\mathrm{NP}\ell}_{9} = -C^{\mathrm{NP}\ell}_{10}\,, \quad C^{\mathrm{NP}\prime\ell}_{9} = -C^{\mathrm{NP}\prime\ell}_{10}$.

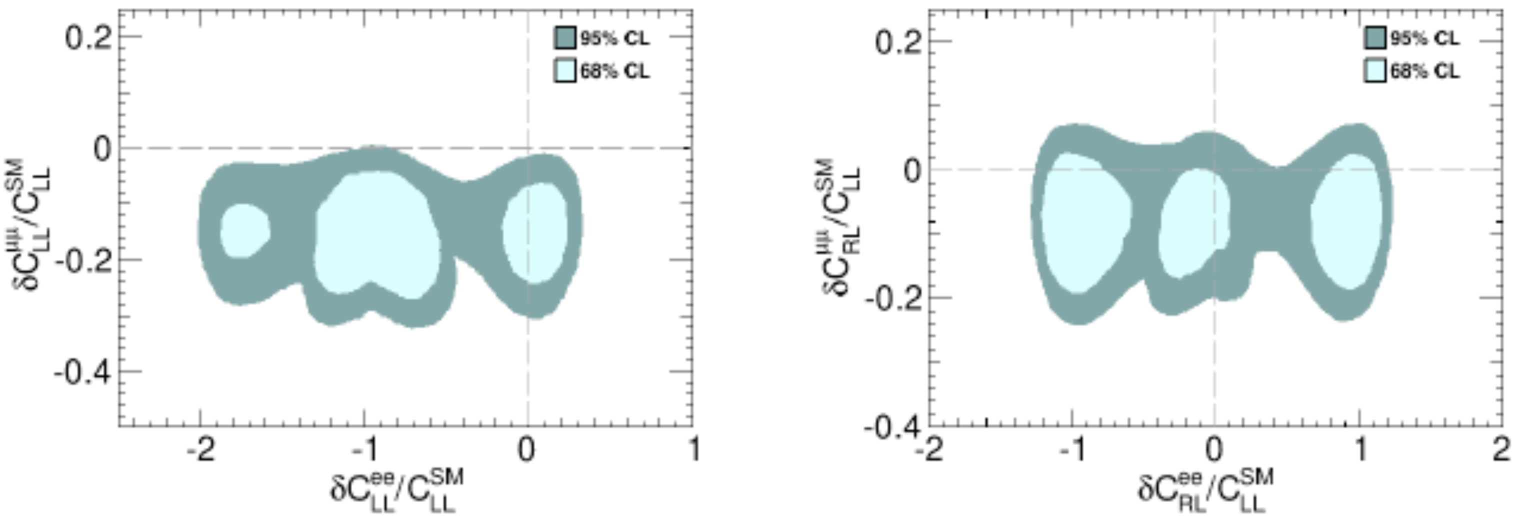


Fig from 1410.4545 – global fit including R_K

– Bounds stronger for $\mu\mu$ (y-axis) than for ee (x-axis).

– Both left-handed quarks C_{LL} (left-handed plot) and right-handed quarks C_{RL} (right-handed plot) can be sizable.

R_K -interpretations – $SU(2)_L$ muons -$B_s \to \mu\mu$

If we assume new physics in muons alone employ $\mathcal{B}(\bar{B}_s \to \mu\mu)$

$$\frac{\mathcal{B}(\bar{B}_s \to \mu\mu)^{\rm exp}}{\mathcal{B}(\bar{B}_s \to \mu\mu)^{\rm SM}} = 0.79 \pm 0.20 \quad \text{is suppressed currently} .$$

$$\begin{aligned} 0.0 &\lesssim \mathrm{Re}[C^\mu_{LR} + C^\mu_{RL} - C^\mu_{LL} - C^\mu_{RR}] \lesssim 1.9 \,, \quad (\mathcal{B}(B_s \to \mu\mu)) \\ 0.7 &\lesssim -\mathrm{Re}[C^\mu_{LL} + C^\mu_{RL}] \lesssim 1.5 \,. \qquad (R_K) \end{aligned}$$

This isolates C^μ_{LL} as the only single operator (particle) interpretation of R_K. Note: this is V-A. Iff $\mathcal{B}(\bar{B}_s \to \mu\mu)$ would be enhanced this would isolate $C^\mu_{RL} \simeq -1$, V+A! $b \to see$ way less constrained.

Of course charm FCNCs are of interest by themselves, however, the recent anomalies in semileptonic B-decays add to the physics case of charm decays into leptons.

Improved (N)NLO calculation in SM: S de Boer et al, to appear, DO-TH 15-11

2-step matching:

$$\mathcal{L}_{\text{eff}}^{\text{weak}}|_{m_W \geq \mu > m_b} = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s,b} V_{cq}^* V_{uq} \left(\tilde{C}_1(\mu) P_1^{(q)}(\mu) + \tilde{C}_2(\mu) P_2^{(q)}(\mu) \right) , \tag{12}$$

$$\mathcal{L}_{\text{eff}}^{\text{weak}}|_{m_b > \mu \geq m_c} = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s} V_{cq}^* V_{uq} \left(\tilde{C}_1(\mu) P_1^{(q)}(\mu) + \tilde{C}_2(\mu) P_2^{(q)}(\mu) - \sum_{i=3}^{10} \tilde{C}_i(\mu) P_i(\mu) \right) . \tag{13}$$

$P_{1,2}^{(q)}$: tree-level W-induced. $P_{3..10}$: penguins

	$j=1$	$j=2$	$j=7$	$j=8$	$j=9$	$j=10$
$\tilde{C}_j^{(0)}$	-1.0275	1.0925	0	0	-0.0030	0
$(\alpha_s/(4\pi))\,\tilde{C}_j^{(1)}$	0.3214	-0.0549	0.0035	-0.0020	0.0004	0
$(\alpha_s/(4\pi))^2\,\tilde{C}_j^{(2)}$	0.0787	-0.0035	0.0002	-0.0001	-0.0048	0
$\tilde{C}_j$	-0.6274	1.0341	0.0037	-0.0021	-0.0074	0

Table 3: The ith order contributions $(\alpha_s/(4\pi))^i\,\tilde{C}_j^{(i)}$, $i = 0, 1, 2$ to the SM Wilson coefficients, at $\mu = m_c$. The last row gives their sum, $\tilde{C}_j(m_c)$. For $j = 3, 4, 5, 6$ see 1510.00311.