Theory of FCNC Semileptonic *B* Decays

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Introduction

A few words on the motivation:

- Historically: FCNC processes played an important role in the construction of the Standard Model (SM)
- Currently: FCNC Processes are throught to provide a good window to beyond SM (BSM) physics
- Semileptonic processes such as $b \to s\ell^+\ell^-$ provide many different observables
- $b \to s$ transitions have measurable rates in the SM
- ... and are (to some extend) tractable from the theory side
  - Effective Field Theory approach
  - Hadronic matrix elements, local and non-local
  - Effects from BSM physics

Contents

We focus on $b \to s$ transitions

Effective Field Theory: Weak Effective Theory (WET)

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda_{\text{CKM}} \sum_i C_i O_i$$

Starting point: Effective Hamiltonian

$$O_1 = (\bar{b}_{L,i} \gamma_\mu q_{L,i})(\bar{q}_{L,j} \gamma^\mu s_{L,j}) \ (q = u, c)$$
$$O_2 = (\bar{b}_{L,i} \gamma_\mu q_{L,j})(\bar{q}_{L,j} \gamma^\mu s_{L,i}) \ (q = u, c)$$

$$O_3 = (\bar{b}_{L,i} \gamma_\mu s_{L,i}) \sum_q (\bar{q}_{L,j} \gamma^\mu q_{L,j})$$
$$O_4 = (\bar{b}_{L,i} \gamma_\mu s_{L,j}) \sum_q (\bar{q}_{L,j} \gamma^\mu q_{L,i})$$
$$O_5 = (\bar{b}_{L,i} \gamma_\mu s_{L,i}) \sum_q (\bar{q}_{R,j} \gamma^\mu q_{R,j})$$
$$O_6 = (\bar{b}_{L,i} \gamma_\mu s_{L,j}) \sum_q (\bar{q}_{R,j} \gamma^\mu q_{R,i})$$

$$O_7 = \frac{e}{16\pi^2} m_b (\bar{b}_{R,i} \sigma_{\mu\nu} s_{L,i}) F^{\mu\nu}$$
$$O_8 = \frac{g_s}{16\pi^2} m_b (\bar{b}_{R,i} \sigma^{\mu\nu} T^a s_{L,i}) G^a_{\mu\nu}$$
$$O_7' = \frac{e}{16\pi^2} m_s (\bar{b}_{L,i} \sigma_{\mu\nu} s_{R,i}) F^{\mu\nu}$$
$$O_8' = \frac{g_s}{16\pi^2} m_s (\bar{b}_{L,i} \sigma^{\mu\nu} T^a R_{L,i}) G^a_{\mu\nu}$$

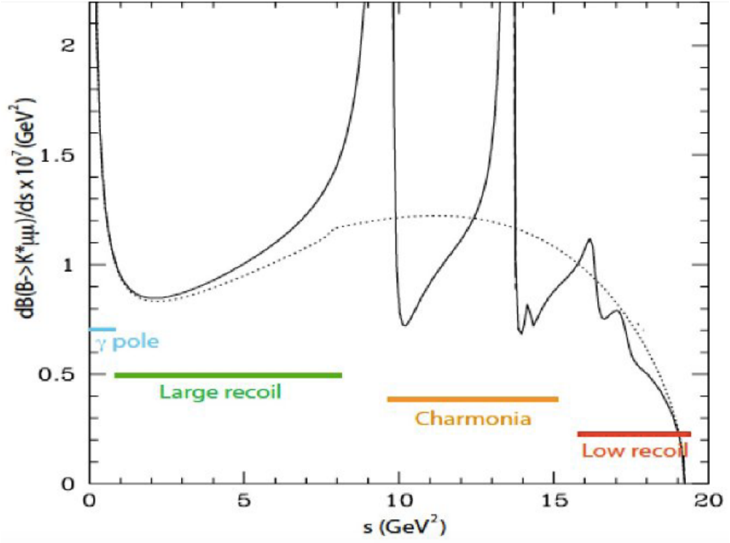
$$O_9 = (\bar{b}_{L,i} \gamma_\mu s_{L,i})(\bar{\ell} \gamma^\mu \ell)$$
$$O_{10} = (\bar{b}_{L,i} \gamma_\mu s_{L,i})(\bar{\ell} \gamma^\mu \gamma_5 \ell)$$

The Wilson Coefficients C_i ...

- ... are computed by matching the SM to WET
- ... at the scale $\mu = M_W \sim M_Z \sim m_t$
- ... depend thus on m_t^2 / M_W^2 (some of them)
- ... are known in the SM at least to NLO, including RG improvement.

The EFFTh approach is flexible, i.e it can incorporate also BSM effects!

Problem: How to compute $\langle B | H_{\text{eff}} | K^{(*)} \ell^+ \ell^- \rangle$?


2
1.5
1
0.5
0
0
5
10
15
20
s (GeV^2)
dB(B->K*μμ)/ds x 10^7 (GeV^2)
γ pole
Large recoil
Charmonia
Low recoil

Hadronic matrix elements

Decay Amplitude for $B \to K^{(*)}\ell\ell$ (Schematically):

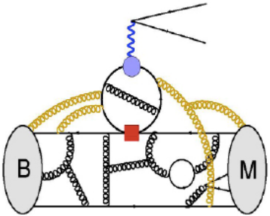
$$\mathcal{A}(B \to K^{(*)}\ell\ell) = \mathcal{N}\left[(C_9 L_V^\mu + C_{10} L_A^\mu)F_\mu - \frac{L_V^\mu}{s}(C_7 F_{T,\mu} + \mathcal{H}_\mu)\right]$$

Hadronic matrix elements are the limiting factors for precise predictions!

- Local matrix elements: Form factors ($M = K, K^*$):

$$\mathcal{F}_\mu^{B\to M}(k,q) \equiv \langle M(k)|\bar{s}\gamma_\mu P_L\, b|\bar{B}(q+k)\rangle \;,$$

$$\mathcal{F}_{T,\mu}^{B\to M}(k,q) \equiv \langle M(k)|\bar{s}\sigma_{\mu\nu}q^\nu P_R\, b|\bar{B}(q+k)\rangle \;,$$



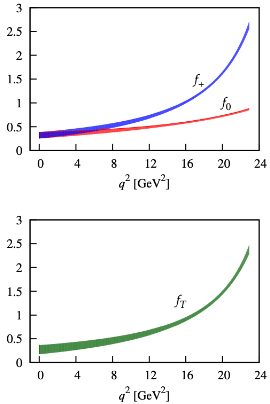
- $$\mathcal{H}_\mu^{B\to M}(k,q) \equiv i\int d^4x\, e^{iq\cdot x}\,\langle M(k)|T\{j_\mu^{\text{em}}(x),(C_1\mathcal{O}_1 + C_2\mathcal{O}_2)(0)\}|\bar{B}(q+k)\rangle$$

Form Factors

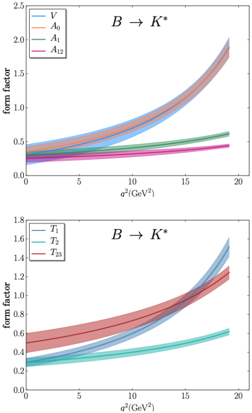
relatively well under control:

- Lattice simulations at high s (i.e. low hadronic recoil)
- Light-cone Sum-rule estimates at $s \sim 0$
- Inter-/Extrapolation using the z expansion

Uncertainty $\sim$ 10%



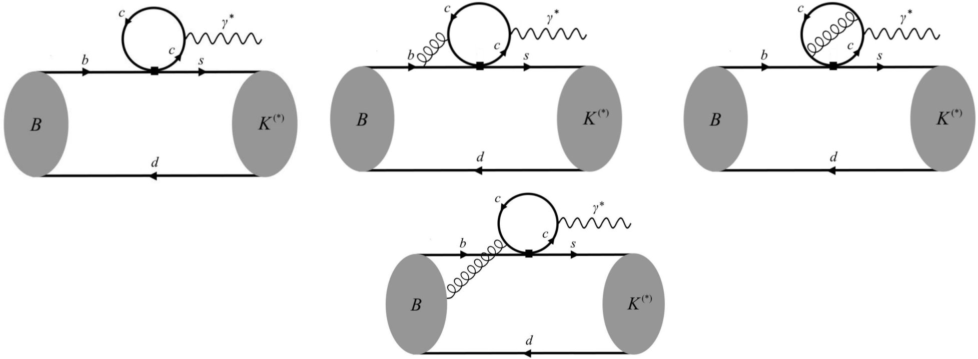
(HPQCD 2013)



(Horgan, Liu, Meinel, Wingate, 2013)

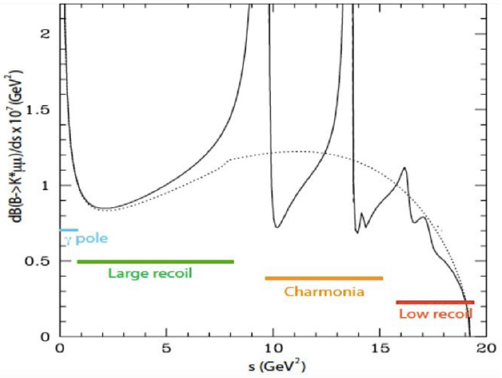
Non-Local contributions

Related to charm loops



Options for the charm loop:

- Local Expansion for $s \ll m_c^2$
  Expansion parameter s/m_c^2
  Valid in the pole region
  (Buchalla, Isidori, Rey 1997, Voloshin 1996)
- Light-Cone expansion for $4m_c^2 - s \ll \Lambda_{\mathrm{QCD}}^2$
  Expansion parameter $\Lambda_{\mathrm{QCD}}/\sqrt{4m_c^2 - s}$
  Valid for $0 \leq s \leq 4m_c^2$
- Narrow Resonances: Approximate by
  $B \to (J/\psi, \psi')K^{(*)} \to \ell^+\ell^- K^{(*)}$
  Valid for $4m_c^2 \leq s \leq M_{\psi'}^2$
- Above $s \leq M_{\psi'}^2$: difficult! (Grinstein, Pirjol, 2004)



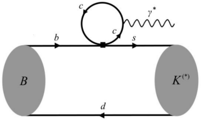
This is still the largest source of uncertainties!

Interesting region for hunting anomalies: $0 \leq s \leq 4m_c^2$
Decompose the non-local matrix element into helicity components

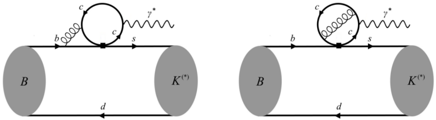
$$\mathcal{H}_\mu^{B\to K} = S_\mu^P \mathcal{H}_0^{B\to K} \quad \text{and} \quad \mathcal{H}_\mu^{B\to K^*} \sum_\lambda S_\mu^\lambda \mathcal{H}_0^{B\to K^*}, \quad \lambda = \perp, ||, 0$$

$$\mathcal{H}_\lambda(q^2) = C_\lambda(q^2)\mathcal{F}_\lambda(q^2) + \tilde{C}_\lambda(q^2)\mathcal{V}_\lambda(q^2) + \cdots$$

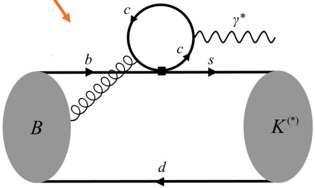
leading power (LO in α_s)



+ hard gluons (α_s) corrections



soft gluon correction
non-perturbative
$\Longrightarrow$ not α_s suppressed



Light Cone OPE for $\mathcal{V}_\lambda$:

$$\langle 0|\bar{d}(x)G_{\alpha\beta}(uy)h_v(0)|B(v)\rangle$$
$$= \frac{f_B m_B}{4}\mathrm{Tr}\left\{\gamma_5 P_+\left[(v_\alpha\gamma_\beta - v_\beta\gamma_\alpha)(\boldsymbol{\Psi_A}-\boldsymbol{\Psi_V}) - i\sigma_{\alpha\beta}\boldsymbol{\Psi_V} - (y_\alpha v_\beta - y_\beta v_\alpha)\frac{\boldsymbol{X_A}}{v\cdot y} + (y_\alpha\gamma_\beta - y_\beta\gamma_\alpha)\frac{\boldsymbol{Y_A}}{v\cdot y}\right]\right\}(\boldsymbol{x},\boldsymbol{uy})$$

(Khodjamirian, M, Pivovarov, Wang 2010)

$$= \frac{f_B m_B}{4}\mathrm{Tr}\left\{\gamma_5 P_+\left[(v_\alpha\gamma_\beta - v_\beta\gamma_\alpha)(\boldsymbol{\Psi_A}-\boldsymbol{\Psi_V}) - i\sigma_{\alpha\beta}\boldsymbol{\Psi_V} - (y_\alpha v_\beta - y_\beta v_\alpha)\frac{\boldsymbol{X_A}}{v\cdot y} + (y_\alpha\gamma_\beta - y_\beta\gamma_\alpha)\frac{\boldsymbol{W}+\boldsymbol{Y_A}}{v\cdot y}\right.\right.$$
$$\left.\left. - i\epsilon_{\alpha\beta\sigma\rho}y^\sigma v^\rho\gamma_5\frac{\boldsymbol{\tilde{X}_A}}{v\cdot y} + i\epsilon_{\alpha\beta\sigma\rho}y^\sigma\gamma^\rho\gamma_5\frac{\boldsymbol{\tilde{Y}_A}}{v\cdot y} - (y_\alpha v_\beta - y_\beta v_\alpha)y_\sigma\gamma^\sigma\frac{\boldsymbol{W}}{(v\cdot y)^2} + (y_\alpha\gamma_\beta - y_\beta\gamma_\alpha)y_\sigma\gamma^\sigma\frac{\boldsymbol{Z}}{(v\cdot y)^2}\right]\right\}(\boldsymbol{x},\boldsymbol{uy})$$

(Gubernari, van Dyk, Virto 2020)

Additional contributions up to twist 4

Transition	$\tilde{\mathcal{V}}(q^2 = 1\,\mathrm{GeV}^2)$	This work	Ref. [11]
$B \to K$	$\tilde{\mathcal{A}}$	$(+4.9 \pm 2.8) \cdot 10^{-7}$	$(-1.3^{+1.0}_{-0.7}) \cdot 10^{-4}$
	$\tilde{\mathcal{V}}_1$	$(-4.4 \pm 3.6) \cdot 10^{-7}\,\mathrm{GeV}$	$(-1.5^{+1.5}_{-2.5}) \cdot 10^{-4}\,\mathrm{GeV}$
$B \to K^*$	$\tilde{\mathcal{V}}_2$	$(+3.3 \pm 2.0) \cdot 10^{-7}\,\mathrm{GeV}$	$(+7.3^{+14}_{-7.9}) \cdot 10^{-5}\,\mathrm{GeV}$
	$\tilde{\mathcal{V}}_3$	$(+1.1 \pm 1.0) \cdot 10^{-6}\,\mathrm{GeV}$	$(+2.4^{+5.6}_{-2.7}) \cdot 10^{-4}\,\mathrm{GeV}$

This work = Gubernari, van Dyk, Virto 2020, Model for the functions: Braun, Ji Manashov, 2017

Ref[11] = Khodjamirian, M, Pivovarov, Wang 2010, simple exponential model

Factor more than 100! ... Why?

- Cancellations between the various contributions, which was not present in KMPW2010, may be model dependent?
- More recent calculations of the normalization constants of the $\bar{q}Gh_v$ LCDA

$$\lambda_E^2 \sim \langle 0|g_s\bar{q}\gamma_0(\vec{\gamma}\cdot\vec{E})\gamma_5 h_v|B(v)\rangle$$
$$\lambda_H^2 \sim \langle 0|g_s\bar{q}(\vec{\sigma}\cdot\vec{B})\gamma_5 h_v|B(v)\rangle$$

	Neubert Grozin 96	Nishikawa/Tanaka 14	Rahimi Wald 20
λ_E^2 (GeV^2)	0.11 ± 0.06	0.03 ± 0.02	0.01 ± 0.01
λ_H^2 (GeV^2)	0.18 ± 0.07	0.06 ± 0.03	0.11 ± 0.02

$(\lambda_E^2 = \lambda_E^2(\mu = 1\,GeV),\ \lambda_H^2 = \lambda_H^2(\mu = 1\,GeV))$

- Estimates are based on different! QCD sum rules

Lepton (Flavour) Universality Violation (LFUV)

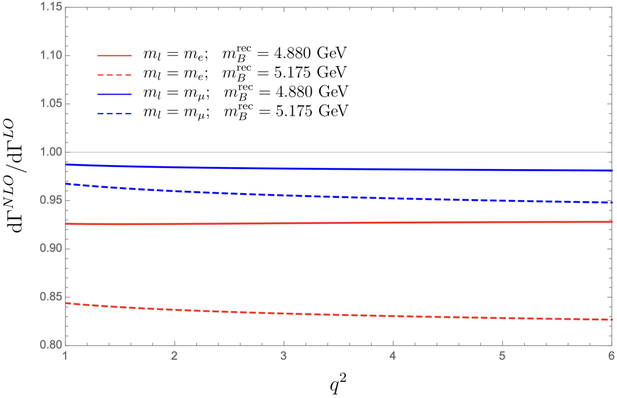
In the SM:

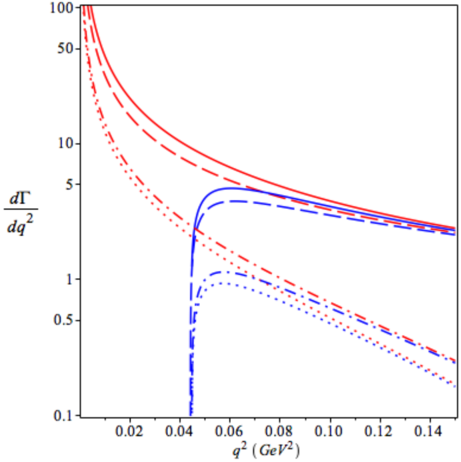
- LFUV originates exclusively form the different lepton masses!
- For e and μ the power like corrections are (too) small
- QED Corrections from soft and collienar photons depend on m_ℓ
- These induce contributions of the form

$$\frac{\alpha}{\pi} \ln \left(\frac{\Delta^2}{m_\ell^2} \right)$$

- Their size depends on the experimental cut Δ
- Controllable!

For $B \to K^* \ell\ell$:





(Bordone, Isodori, Pattori, 1605.07633)

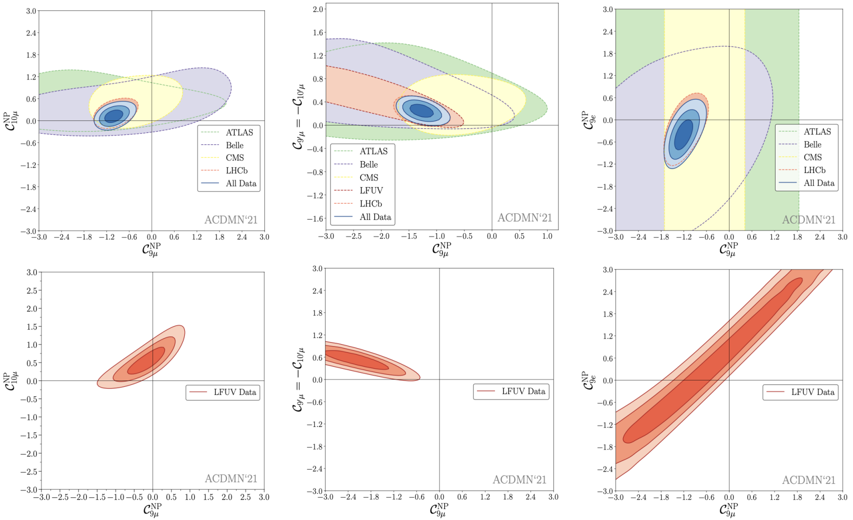
Beyond the Standard Model

Current Highlight: “*B*-Anomalies”

- Partial rates
- Angular Distributions
- Lepton Universality

The EffTh approach is very versatile:

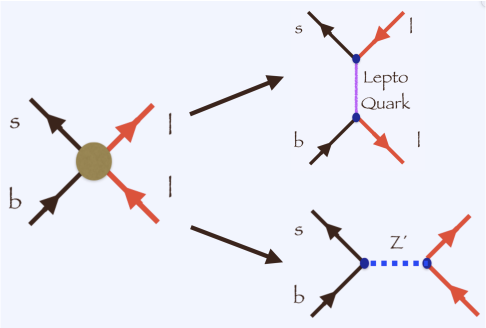
- Modification of Wilson coefficients relative to the SM values
- Additional Operators nor present in the SM
  e.g. Operators with right-handed currents, usually marked with a prime
- ... but it cannot tell you much about the details of BSM physics



(Alguero et al., 2104.08921)

Observations from the fit of the Wilson coefficients: (Alguero et al., 2104.08921)

- Viable possibility: Right handed contributions O_9' and O_{10}' for muons
- LFU violation with $C_{9,\mu} = -C_{10,\mu}$ requires also LF-universal NP contributions
- Move on to simplified models:



- ... and eventually also to a UV complete theory

Summary: The Landscape of Anomalies

"New" Anomalies:

- Branching ratios of $b \to s\,\mu\mu$ processes
- Angular distributions in $b \to s\,\mu\mu$ processes
- Ratios of $b \to s\,ee$ versus $b \to s\,\mu\mu$
- Ratios of exclusive $b \to c\tau\bar{\nu}$ versus $b \to c\ell\bar{\nu}$

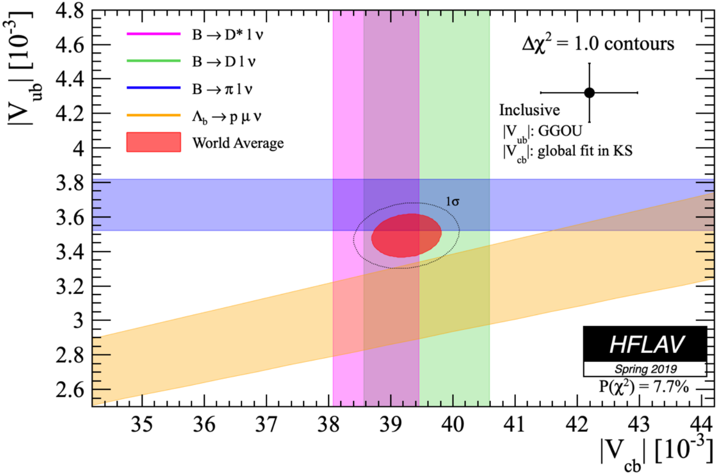
"Old" Anomalies:

- CP Violation: $\Delta a_{\rm CP}$ in Charm and Kaon ϵ'/ϵ
- Exclusive versus inclusive V_{xb}
- Anomalous magnetic moment of the muon

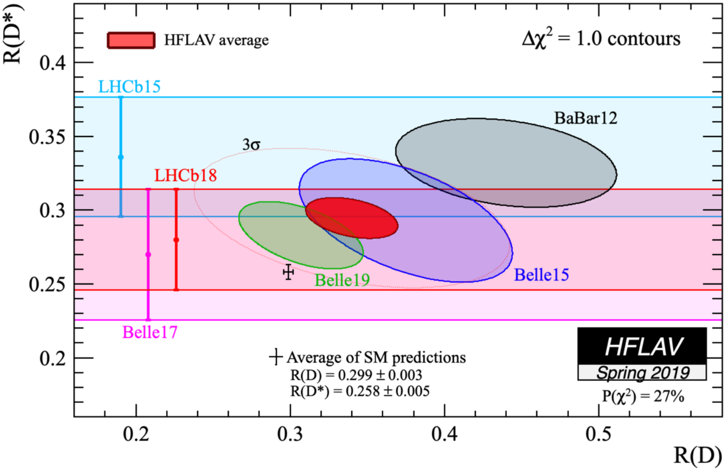
"Brandnew" Anomaly

- Branching ratios of $B_{(s)} \to D_{(s)}\{\pi, K\}$ (Huber et al., 2007.10338)

Charged Current Semileptonics I: V_{xb}



Charged Current Semileptonics II: $B \to D^{(*)}\tau\nu$



- Some interesting anomalies are seen in flavour physics
- They seem to be pretty stable, in particular the $b \to s\ell\ell$ anomalies
- They seem to hint at NP modifications of some specific Wilson coefficients
- Maybe history repeats and flavour gives us decisive hints on BSM physics
- We need a still better control of hadronic effects!