Rare flavour changing neutral current $b \to s$ decays and the search for New Physics

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Outline

1. Motivation: Flavour-Changing-Neutral-Current B-decays
2. Effective Field Theory:
   EW Interactions (Standard Model) of $\Delta B = 1$ decays
3. Inclusive decays: $\bar{B} \to X_s \gamma$ and $\bar{B} \to X_s l\bar{l}$
4. Exclusive decays: $\bar{B}_s \to l\bar{l}$ and $\bar{B} \to K l\bar{l}$
5. Summary

Flavour-Changing-Neutral-Current (FCNC) B-Decays

B-Meson System (PDG)

$B^+ = (u\bar{b}) \quad B^0 = (d\bar{b}) \quad B_s^0 = (s\bar{b}) \quad B_c^+ = (c\bar{b})$

FCNC Decays

Initial and final state hadrons contain quarks of different flavour but same charge

- down quark sector $\quad s \to d, \quad b \to d, \quad b \to s$
- up quark sector $\quad c \to u, \quad t \to u, \quad t \to c$

In the SM (Standard Model) flavour-changing interactions at tree-level are

$$\mathcal{L}_{udW} \sim V_{\rm CKM}^{ij} (\bar{u}_i \gamma^\mu P_L d_j) W_\mu^+$$

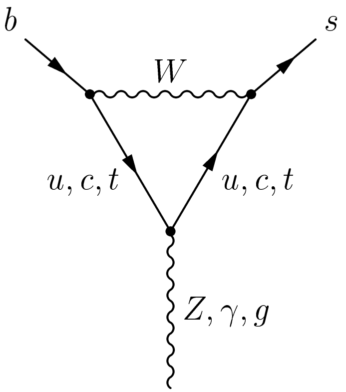
FCNC decays are $\longrightarrow$ ”LOOP suppressed” in the SM!

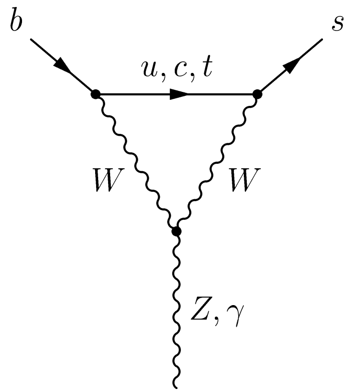
In the limit $V_{\rm CKM} \to \mathbb{1}$ FCNC’s are absent in the SM.

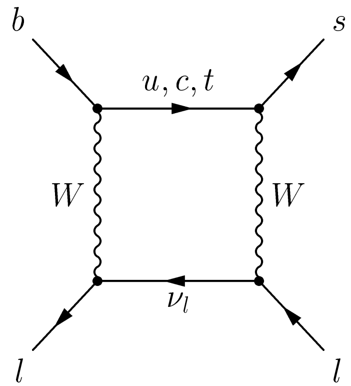
Examples of FCNC B-decays ($b \to s$)

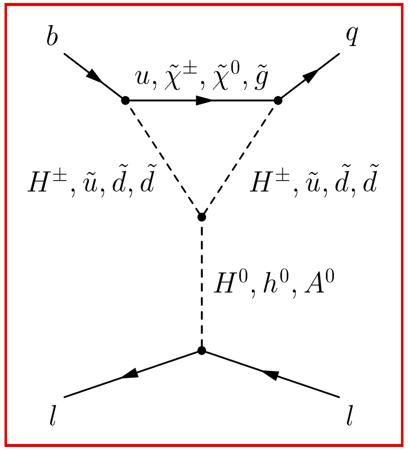
$\bar{B}_s \to \mu\bar{\mu}$	(leptonic)	$\approx 10^{-9}$ (SM pred.)
$\bar{B} \to \{X_s, K^*\} + \gamma, \quad b \to s + gluon$	(radiative)	$\approx 10^{-4}$ (exp.)
$\bar{B} \to \{X_s, K, K^*\} + \nu\bar{\nu}$		$\approx 10^{-6}$ (SM pred.)
$\bar{B} \to \{X_s, K, K^*\} + l\bar{l}$	(semi-leptonic)	$\approx 10^{-6}$ (exp.)
$B_s - \bar{B}_s$	(mixing)	
$\bar{B}_s \to \gamma\gamma, \quad \bar{B}_s \to l\bar{l} + \gamma, \quad (\Lambda_b \to \Lambda + l\bar{l})$		

SM diagrams governing FCNC B-decays









New Physics (NP) diagrams could give comparably large contributions!

Why B decays?

- heavy quark physics = physics of heavy hadrons - theoretically better accessible
- flavour physics - understanding of flavour in the SM and beyond
  = CKM-matrix + quark masses
- CP-violating observables in the B-system
- testing quantum structure of the SM – t quark mass effects at loop level
- constraining parameter spaces of NP scenarios

Where?

- B-factories: Belle at KEK and BaBar at SLAC
- CDF and DØ at Tevatron (B_s-mixing: $\Delta M_s, \Delta\Gamma_s$; $\bar{B}_s \to \mu\bar{\mu}; \ldots$)
- LHCb (and ATLAS, CMS) at CERN

Problem: Disentangling EW and QCD interactions

Multi-scale problem

- B meson (in restframe) $m_b \sim 5$ GeV
- EW interactions (virtual W-exchange) $M_W \sim 80$ GeV
- QCD interactions (hadronic bound state) $\Lambda_{\text{QCD}} \sim 0.5$ GeV

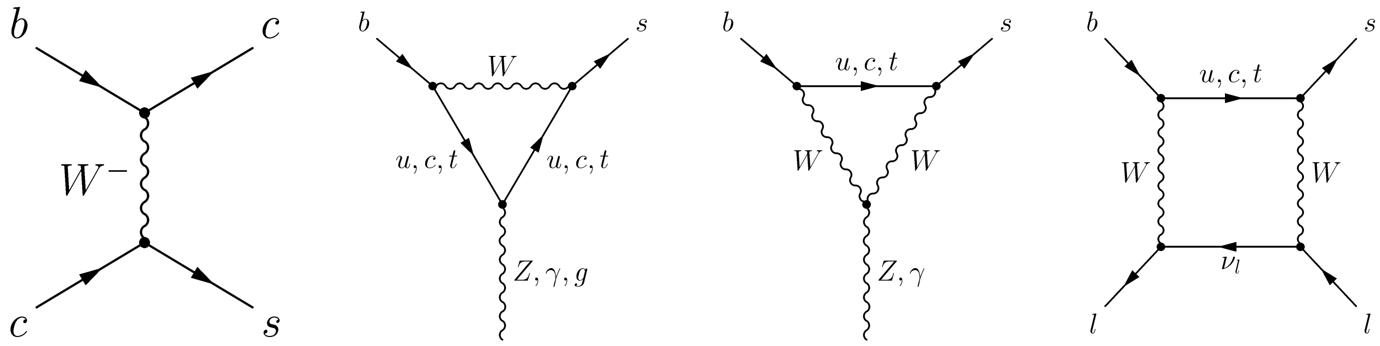
Hierarchy: $\Lambda_{\text{QCD}} \ll m_b \ll M_W$

Construction of effective field theories (EFT) to decouple stepwise short-distance from long-distance interactions

Can be done in perturbation theory (PT) in $\alpha_s(\mu)$ down to energy scales $\mu \gtrsim 1$ GeV

EFT of $\Delta B = 1$ decays

Why EFT's? Problem: Large Log's in PT from QCD and QED radiative corrections for theories with widely separated scales $m \ll M$!



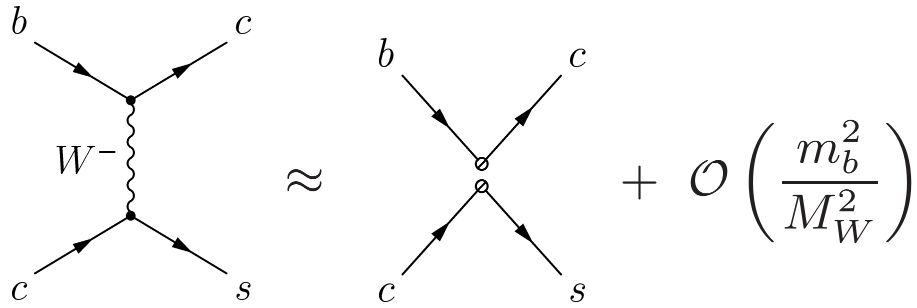
Amplitude: $$\mathcal{A}(b \to s) \sim G_F V_{\rm CKM} \left(\ldots + \alpha_s \ln \frac{m^2}{M^2} + \alpha_s^2 \ln^2 \frac{m^2}{M^2} + \ldots \right)$$

with $\alpha_s(M_Z) \approx 0.12$ and $\ln \frac{m_b^2}{M_W^2} \approx \ln \frac{5^2}{80^2} \approx -5.5$

$\Rightarrow$ PT questionable, actual expansion parameter is: $\left| \alpha_s \ln \frac{m_b^2}{M_W^2} \right| \sim 0.67$

How to construct the EFT?

At scales $\sqrt{s} \sim m_b \sim 5$ GeV $\ll M_W, M_Z, m_t$ EW interaction (analog to Fermi theory of β-decay) is short-distance-like = point-like interaction



"Integrating out" = Decoupling of heavy degrees of freedom (W, Z, t) using

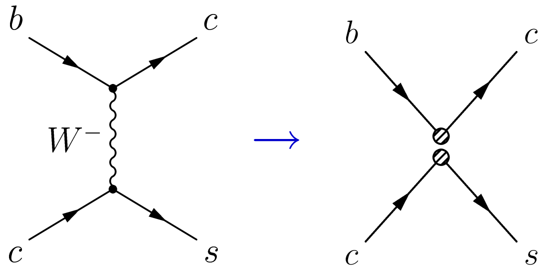
$\Rightarrow$ Operator Product Expansion (OPE)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED}\times\text{QCD}}(u,d,s,c,b,e,\mu,\tau) + \frac{4G_F}{\sqrt{2}} V_{\text{CKM}} \sum_{\text{SM}} C_i \mathcal{O}_i + \sum_{\text{NP}} C_j \mathcal{O}_j$$

C_i ... Wilson coefficients = effective couplings (short-distance)

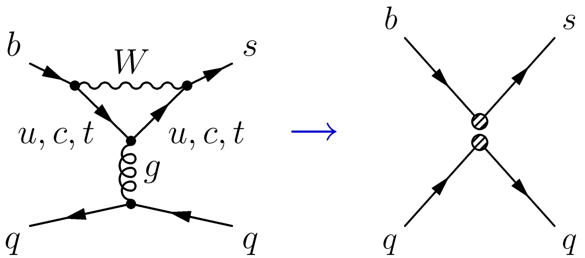
$\mathcal{O}_i$ ... operators (long-distance) describing dynamics of $u, d, s, c, b, e, \mu, \tau \ldots$

Structure of operators of the $\Delta B = 1$ EFT of the SM?



current-current op.

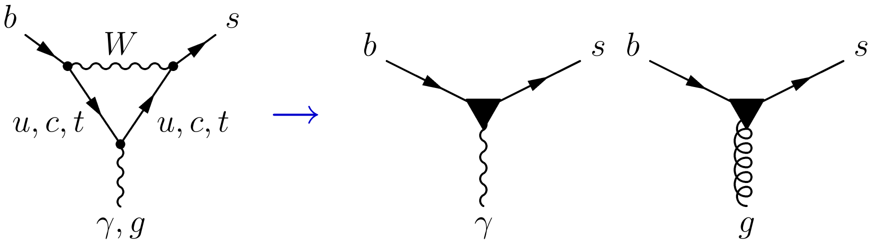
$$\mathcal{O}_{1,2} \sim [\bar{s}\,\gamma_\mu P_L\; c][\bar{c}\,\gamma^\mu P_L\; b]$$



QCD and QED penguin op.

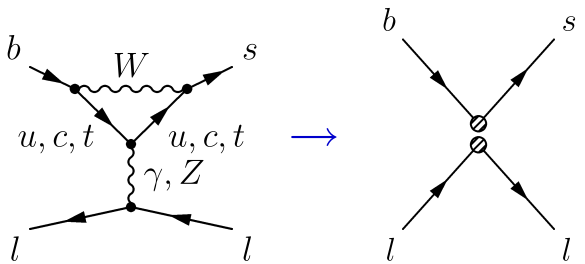
$$\mathcal{O}_{3,4,5,6} \sim [\bar{s}\,\gamma_\mu P_L\; b] \textstyle\sum_q [\bar{q}\,\gamma^\mu P_{L,R}\; q]$$

$$\mathcal{O}^Q_{3,4,5,6} \sim [\bar{s}\,\gamma_\mu P_L\; b] \textstyle\sum_q Q_q [\bar{q}\,\gamma^\mu P_{L,R}\; q]$$



electro- & chromo-magnetic op.

$$\mathcal{O}_{7,8} \sim m_b [\bar{s}\,\sigma_{\mu\nu} P_R\; b] G^{\mu\nu}$$



semi-leptonic op.

$$\mathcal{O}_{9,10} \sim [\bar{s}\,\gamma_\mu P_L\; b] \textstyle\sum_l [\bar{l}\,\gamma^\mu \{\mathbb{1}, \gamma_5\}\; l]$$

Calculation of Wilson coefficients "Matching" in PT $G_F\{\mathbb{1}, \alpha_s, \alpha_s^2, \alpha_e, \alpha_e\alpha_s\}$

$$\boxed{\mathcal{A}^{\text{eff}}(m, C_i, \mu_0) \stackrel{!}{=} \mathcal{A}^{\text{full}}(m, M, \mu_0)}$$

1. μ_0 renormalization scale $\Rightarrow \ln m/M = \ln m/\mu_0 + \ln \mu_0/M$
2. EFT $\stackrel{!}{=}$ Full Theory $\Rightarrow$ same long-distance (m-) dependence
   $\Rightarrow \ln(m/\mu_0)$ cancel and $C = C(M, \mu_0)$ independent of m
3. Convergence of PT if $\mu_0 \approx M \Rightarrow \ln(\mu_0/M) \approx 0 \Rightarrow$ Matching scale μ_0

$$C(\mu_0) = C_s^{(0)} + \frac{\alpha_s}{4\pi} C_s^{(1)} + \frac{\alpha_s^2}{(4\pi)^2} C_s^{(2)} + \frac{\alpha_s^3}{(4\pi)^3} C_s^{(3)} + \frac{\alpha_e}{4\pi} C_e^{(1)} + \frac{\alpha_e \alpha_s}{(4\pi)^2} C_e^{(2)} + \ldots$$

[Buchalla/Buras], [Misiak/Urban], [Bobeth/Misiak/Urban], [Buras/Gambino/Haisch], [Gambino/Haisch]
[Misiak/Steinhauser]

Renormalization Group Equation (RGE)

$$\left(\mu \frac{d}{d\mu} \mathbb{1} - \hat{\gamma}^T \right) \vec{C}(\mu) = 0$$

Anomalous Dimension Matrix (ADM)

$$\gamma = \frac{\alpha_s}{4\pi} \gamma_s^{(0)} + \frac{\alpha_s^2}{(4\pi)^2} \gamma_s^{(1)} + \frac{\alpha_s^3}{(4\pi)^3} \gamma_s^{(2)} + \frac{\alpha_s^4}{(4\pi)^4} \gamma_s^{(3)} + \frac{\alpha_e}{4\pi} \gamma_e^{(1)} + \frac{\alpha_e \alpha_s}{(4\pi)^2} \gamma_e^{(2)}$$

"Running" to long-dist. scale μ_b

$$\vec{C}(\mu_b \approx m) = \hat{U}(\mu_b, \mu_0, \alpha_s, \alpha_e, \hat{\gamma}) \vec{C}(\mu_0 \approx M)$$

Resummation of large logarithms to all orders n

QCD: LO $\longrightarrow$ $\alpha_s^n \ln^n(\mu_b/\mu_0)$,

NLO $\longrightarrow$ $\alpha_s^n \ln^{n-1}(\mu_b/\mu_0)$,

N^2LO $\longrightarrow$ $\alpha_s^n \ln^{n-2}(\mu_b/\mu_0)$,

N^3LO $\longrightarrow$ $\alpha_s^n \ln^{n-3}(\mu_b/\mu_0)$

QED: LO $\longrightarrow$ $\alpha_e \ln(\mu_b/\mu_0)\, \alpha_s^{n-1} \ln^n(\mu_b/\mu_0)$

NLO $\longrightarrow$ $\alpha_e \ln(\mu_b/\mu_0)\, \alpha_s^{n-1} \ln^{n-1}(\mu_b/\mu_0)$

QCD: [Chetyrkin/Misiak/Münz], [Gambino/Gorbahn/Haisch], [Gorbahn/Haisch], [Gorbahn/Haisch/Misiak], [Czackon/Haisch/Misiak]

QED: [Baranowski/Misiak], [Bobeth/Gambino/Gorbahn/Haisch], [Huber/Lunghi/Misiak/Wyler]

Summary of EFT

- Matching + Running $\Rightarrow$ $\boxed{\mathcal{L}_{\text{eff}}^{\text{NNLO}}(\mu_b) + \mathcal{O}\left(\frac{m_b^2}{M_W^2}\right)}$

- factorization of short-distance interactions (of heavy degrees of freedom $\sim \mu_0$) into effective couplings (= Wilson coefficients)
  $\Rightarrow \mathcal{L}_{\text{eff}}^{\text{NNLO}}(\mu_b) \sim \sum_i C_i(\mu_0, \mu_b)\mathcal{O}_i(\mu_b)$

- long distance interactions (light degrees of freedom $\sim \mu_b$) described by effective vertices (= operators) $\mathcal{O}_i$

- $C_i(\mu_0, \mu_b)$ Wilson coefficients calculable in PT $\Rightarrow$ ”RGE-improved”

- NP included by additional matching calculation into $C_i(\mu_0, \mu_b)$

Ready to calculate observables using EFT $\Rightarrow$ Problem: hadronic matrix elements: non-perturbative hadronic input

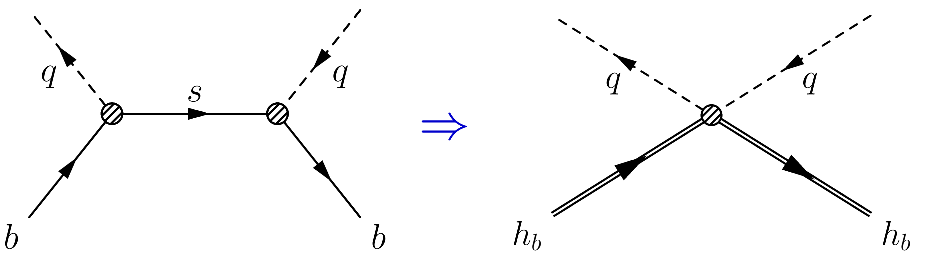
Inclusive Decays $\bar{B} \to X_s + \{\gamma, l\bar{l}\}$ - Heavy Quark Expansion

$$d\Gamma = \frac{1}{2M_B} \sum_{X_s} d[PS](2\pi)^4 \delta^{(4)}(p_B - p_{X_s} - q) \langle B|(i\mathcal{L}_{\text{eff}})^\dagger|X_s\gamma\rangle\langle\gamma X_s|i\mathcal{L}_{\text{eff}}|B\rangle$$

$\Downarrow$ optical theorem $\to$ absorptive part of $B \to B$

$$d\Gamma \sim \frac{1}{2M_B} d[PS](2\pi)^4 \delta^{(4)}(p_B - p_{X_s} - q)\ \text{Im}\langle B|\hat{T}\{\mathcal{L}^\dagger_{\text{eff}}\mathcal{L}_{\text{eff}}\}|B\rangle$$

local OPE because $m_b \gg \Lambda_{\text{QCD}}$



$$+\ \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right)$$

z_i = Wilson coefficients at scale $\mu \sim m_b$

$$\Rightarrow \hat{T}\{\mathcal{L}^\dagger_{\text{eff}}\mathcal{L}_{\text{eff}}\} \sim z_1(\bar{b}b) + \frac{z_2}{m_b^2}(\bar{b}g_s\sigma\cdot Gb) + \sum \frac{z_{qi}}{m_b^3}(\bar{b}\Gamma_i q)(\bar{q}\Gamma_i b) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right)$$

$$\langle B|\hat{T}\{\mathcal{L}_{\rm eff}^{\dagger}\mathcal{L}_{\rm eff}\}|B\rangle = \langle B|\bar{b}b|B\rangle + \frac{1}{2m_b^2}\langle B|\bar{b}(iD)^2 b|B\rangle + \frac{1}{4m_b^2}\langle B|\bar{b}(g_s\sigma\cdot G)b|B\rangle + \dots$$

$$= 2M_B\left[1+\frac{1}{2m_b^2}(\lambda_1+3\lambda_2)\right]+\mathcal{O}\left[\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^3\right]$$

hadronic matrix elements (ME): $\lambda_1 = (-0.3 \pm 0.1)\ \mathrm{GeV}^2, \quad \lambda_2 = 0.12\ \mathrm{GeV}^2$

$$d\Gamma \sim \text{parton result} + \mathcal{O}\left[\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^2\right]$$

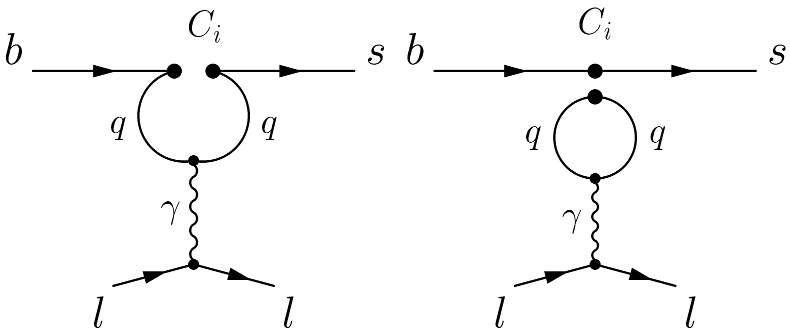
$\Rightarrow \Lambda_{\rm QCD}/m_b$ corrections known up to 3rd order [Chay/Georgi/Grinstein], [Falk/Luke/Savage], [Ali/Hiller], [Buchalla/Isidori], [Bauer/Burrell]

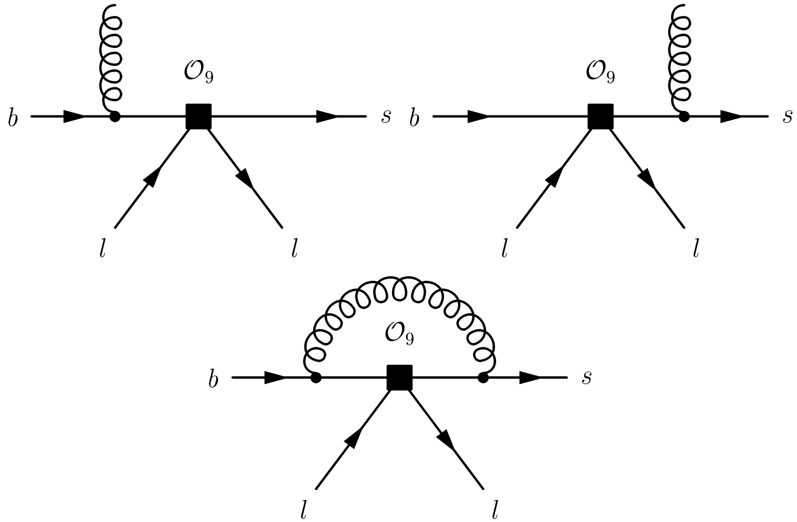
$\Rightarrow$ similar power corrections $\Lambda_{\rm QCD}/m_c$ are known up to 2nd order [Buchalla/Isidori/Rey]

ME at parton level $b \to s\gamma$ and $b \to s l\bar{l}$ (virtual + real corrections)

• QCD: $(1 + \frac{\alpha_s}{4\pi} M_s^{(1)} + \frac{\alpha_s^2}{(4\pi)^2} M_s^{(2)} + \frac{\alpha_s^3}{(4\pi)^3} M_s^{(3)}) < \mathcal{O} >_{\rm tree}$

[Asatrian/Asatrian/Greub/Walker], [Ghinculov/Isidori/Hurth/Yao], [Bieri/Greub/Steinhauser], [Misiak/Steinhauser]





• QED: $(1 + \frac{\alpha_e}{4\pi} M_e^{(1)}) < \mathcal{O} >_{\rm tree}$

including collinear logarithms: $\ln(m_l/m_b)$

[Huber/Lunghi/Misiak/Wyler], [Huber/Hurth/Lunghi]

$\bar{B} \to X_s\gamma$

SM prediction at NNLO

[Misiak et al. arXiv:hep-ph/0609232]

$$\mathcal{B}[\bar{B} \to X_s\gamma]_{\rm SM} = (3.15 \pm 0.23) \times 10^{-4} \quad \text{for} \quad E_\gamma > 1.6 \text{ GeV}$$

uncertainties added in quadrature

- 5% non-perturbative
- 3% parametric
- 3% higher order (perturbative)
- 3% m_c-interpolation ambiguity (3-loop ME of 4-quark operators)

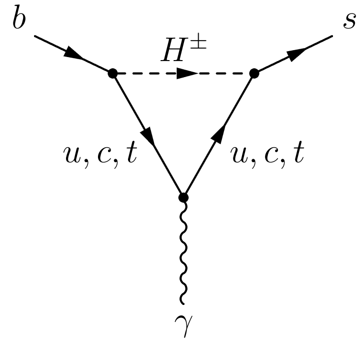
Experimental result

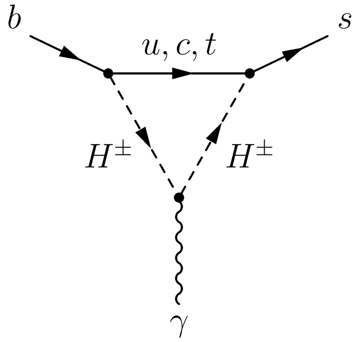
$$\mathcal{B}[\bar{B} \to X_s\gamma]_{\rm exp} = (3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4} \quad \text{for} \quad E_\gamma > 1.6 \text{ GeV}$$

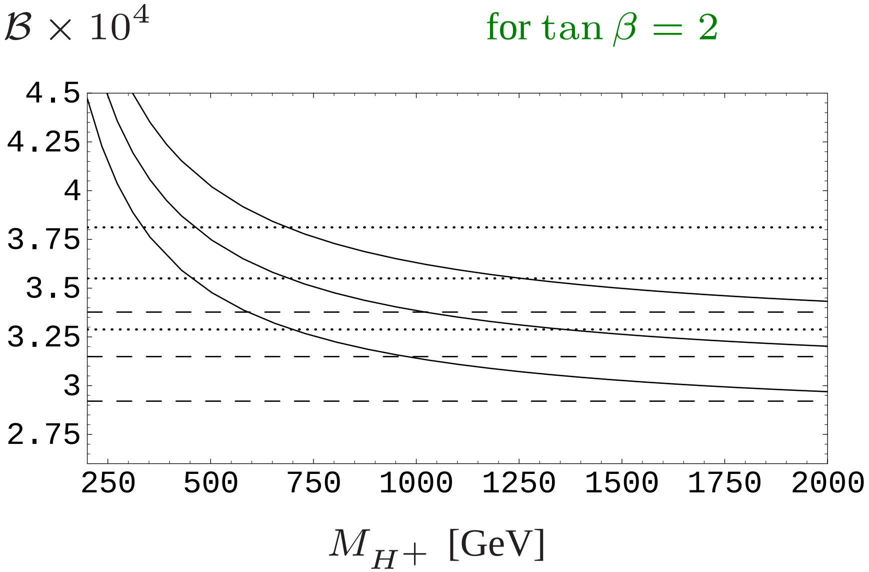
NP example:

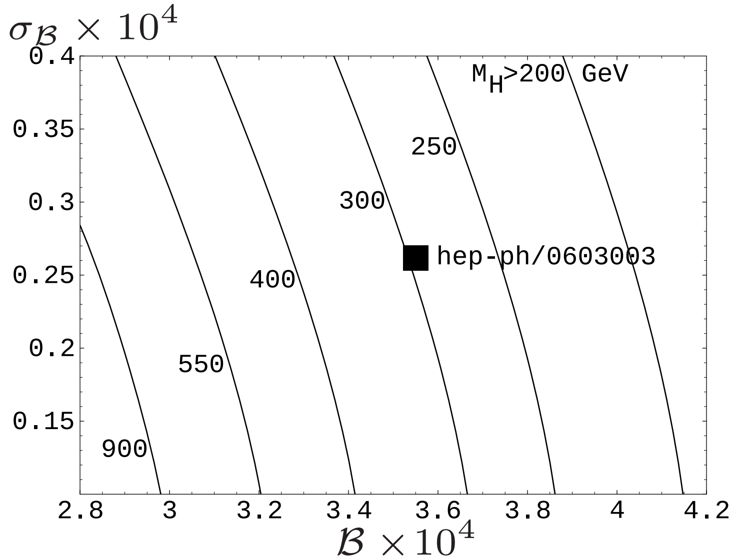
2-Higgs Doublet Model (2HDM)

new parameters: $M_{H+}, \tan\beta$









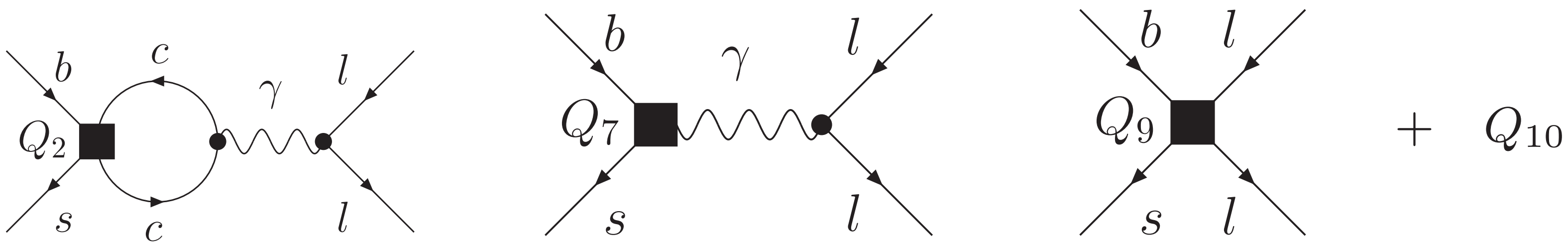
dashed = SM prediction, dotted = experimental result

[Misiak et al. arXiv:hep-ph/0609232]

$M_H^+ > 295(230)$ GeV at $95(99)\%$ C.L. in the 2HDM

$\bar{B} \to X_s l\bar{l}$

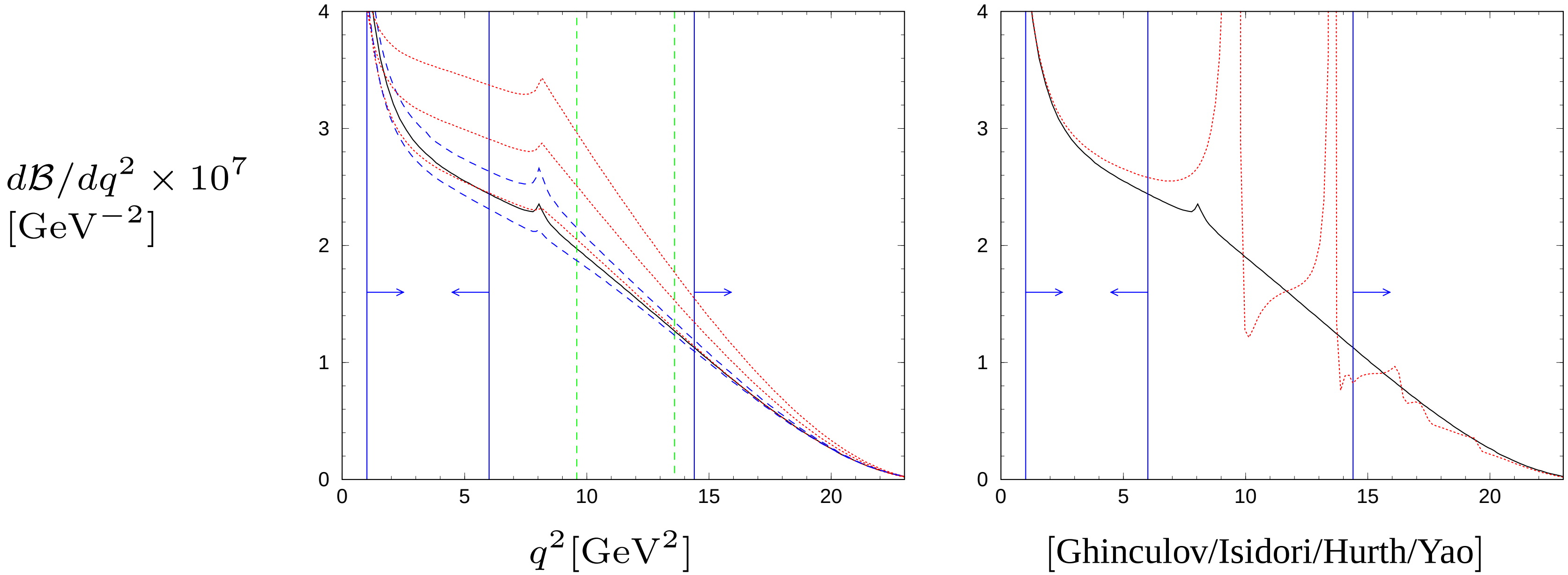
SM prediction at NNLO



$$\frac{d\Gamma[\bar{B} \to X_s l\bar{l}]}{d\hat{s}} = \frac{G_F^2 m_{b,\text{pole}}^5 \left|V_{ts}^* V_{tb}\right|^2}{48\pi^3} \left(\frac{\alpha_e}{4\pi}\right)^2 (1-\hat{s})^2 \left\{ \left(4 + \frac{8}{\hat{s}}\right) \left|\widetilde{C}_7^{\text{eff}}(\hat{s})\right|^2 \right.$$

$$\left. + (1+2\hat{s}) \left(\left|\widetilde{C}_9^{\text{eff}}(\hat{s})\right|^2 + \left|\widetilde{C}_{10}^{\text{eff}}(\hat{s})\right|^2 \right) + 12\,\text{Re}\left(\widetilde{C}_7^{\text{eff}}(\hat{s})\widetilde{C}_9^{\text{eff}}(\hat{s})^*\right) + \frac{d\Gamma^{\text{Brems}}}{d\hat{s}} \right\}$$

$q^2 \equiv (p_{l^-} + p_{l^+})^2 \ldots$ invariant mass of the $l^+ l^-$-pair $\qquad \hat{s} \equiv q^2/m_b^2$



[Ghinculov/Isidori/Hurth/Yao]

NNLO QCD corrections

- change of the $\mathcal{B}/dq^2$ by -20% (-25%) in low-q^2 (high-q^2) region
- $\mu_{0,b}$ uncertainties from $\pm 20\%$ ($\pm 15\%$) to $\pm 6\%$ ($\pm 3\%$) in low-q^2 (high-q^2) region

NLO QED corrections

- inclusion of NLO QED corrections $\longrightarrow$ reduction of uncertainty of $\pm 8\%$ due to choice of $\alpha_e(m_b) \sim 1/133$ or $\alpha_e(M_W) \sim 1/128$ at LO in QED ($\mathcal{B}(\bar{B} \to X_s l\bar{l}) \sim \alpha_e^2$)
- collinear logs: enhancement of $\mathcal{B}(\bar{B} \to X_s \mu\bar{\mu})$ by $+2\%$ and $\mathcal{B}(\bar{B} \to X_s e\bar{e})$ by $+5\%$

low: $q^2 \in [1,6]$ GeV^2	high: $q^2 > 14.4$ GeV^2
$\mathcal{B}(\bar{B} \to X_s e\bar{e}) = (1.64 \pm 0.11) \times 10^{-6}$ $\mathcal{B}(\bar{B} \to X_s \mu\bar{\mu}) = (1.59 \pm 0.11) \times 10^{-6}$	$\mathcal{B}(\bar{B} \to X_s e\bar{e}) = (0.21 \pm 0.07) \times 10^{-6}$ $\mathcal{B}(\bar{B} \to X_s \mu\bar{\mu}) = (0.24 \pm 0.07) \times 10^{-6}$

Experimental information

Integrated $d\mathcal{B}[\bar{B} \to X_s l\bar{l}]/dq^2 \times 10^{-6}$

$q^2 \in [q^2_{min}, q^2_{max}]$	Belle	BaBar	Average
$[(2m_\mu)^2, (m_b - m_s)^2]$	$4.1 \pm 0.8 \pm 0.9$	$5.6 \pm 1.5 \pm 1.3$	4.5 ± 1.0
low: $[1,6]$ GeV^2	$1.49 \pm 0.50^{+0.41}_{-0.32}$	$1.8 \pm 0.7 \pm 0.5$	1.6 ± 0.5
high: > 14.4 GeV^2	$0.42 \pm 0.12^{+0.06}_{-0.07}$	$0.5 \pm 0.25^{+0.08}_{-0.07}$	0.44 ± 0.12

expected final accuracy at B-factories $\sim 15\%$

Cuts in experimental analysis

- q^2 ...: $(2m_\mu)^2 < q^2$ and "around charm-resonances" (theory)
- M_{X_s} ...: $M_{X_s} < 2$ GeV [Belle] and $M_{X_s} < 1.8$ GeV [BaBar]
  $\Rightarrow$ to suppress backgrounds - for example $b \to c(\to se^+\nu)e^-\bar{\nu}$
  $\Rightarrow$ extrapolation beyond cut with Fermi-Motion model [Ali/Hiller]

Forward-backward asymmetry

$$\frac{dA[\bar{B} \to X_s l\bar{l}]}{dq^2} = \left[\int_{-1}^{0} - \int_{0}^{1}\right] d\cos\theta_l \, \frac{d^2\Gamma}{dq^2\, d\cos\theta_l} \Bigg/ \frac{d\Gamma}{dq^2}$$

$\theta_l = \sphericalangle(p_B, p_{l+})$ in dilepton c.m.s.

position of zero:

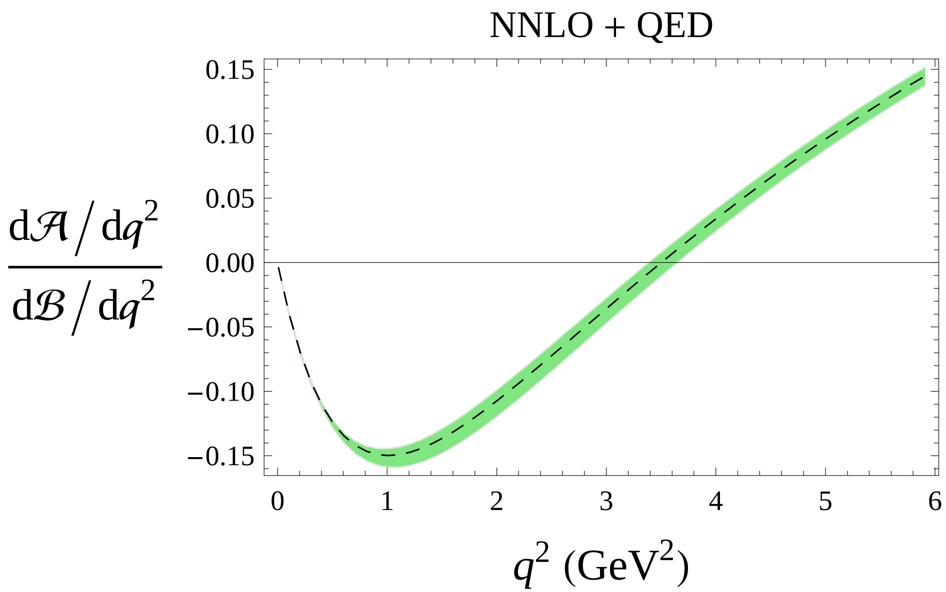
- $\bar{B} \to X_s \mu\bar{\mu}$:

  $q_0^2 = 3.50 \pm 0.12\ \mathrm{GeV}^2$

- $\bar{B} \to X_s e\bar{e}$:

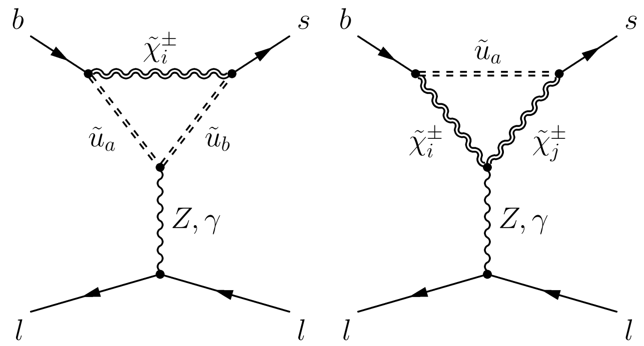
  $q_0^2 = 3.38 \pm 0.11\ \mathrm{GeV}^2$

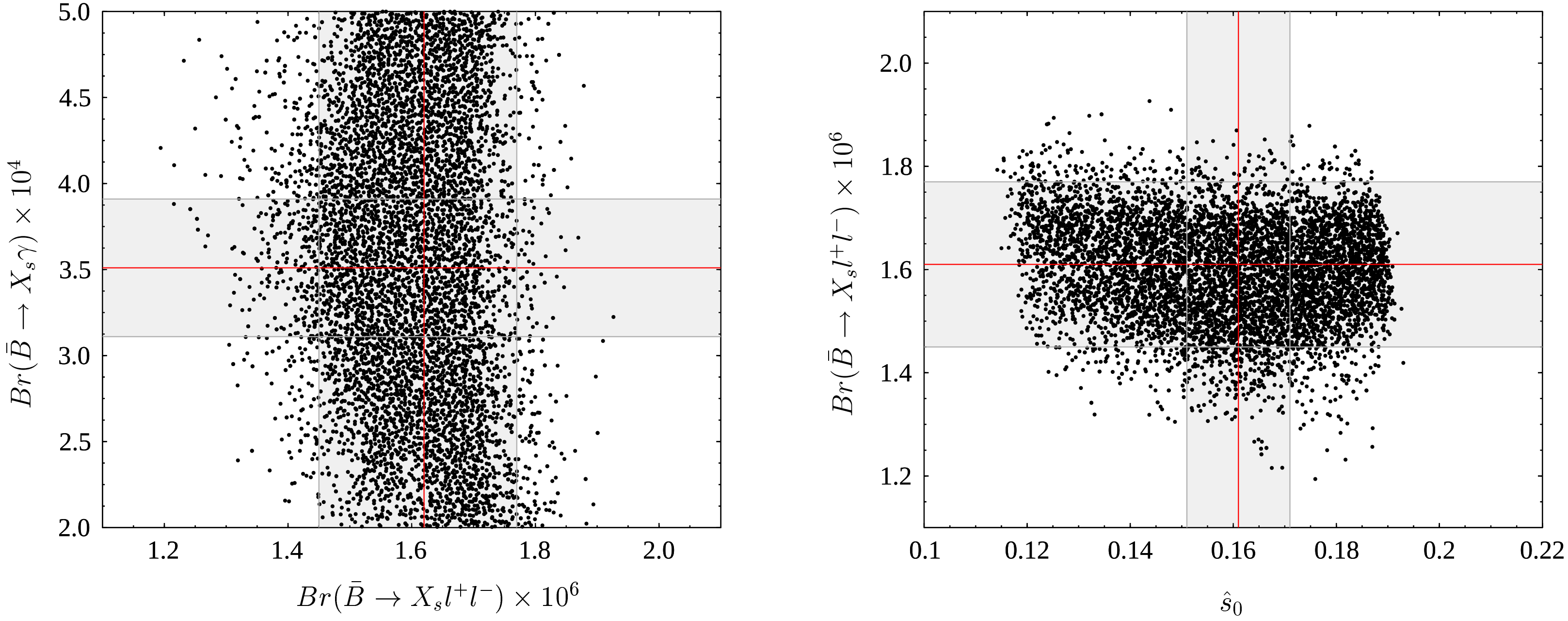
[Huber/Hurth/Lunghi]



No experimental results yet.

NP example:
Minimal Supersymmetric SM (MSSM)





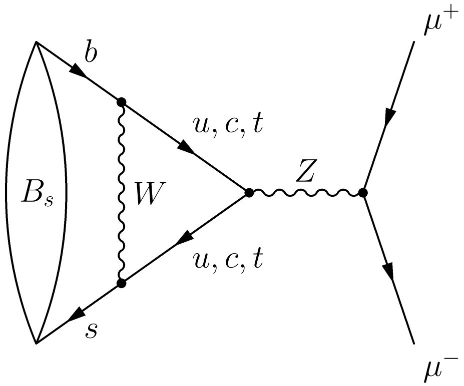
low-q^2 $\mathcal{B}[\bar{B} \to X_s l\bar{l}]$ for Minimal Flavour Violating (MFV) MSSM scenario [Bobeth/Buras/Ewerth]

Exclusive Decays – $\bar{B}_s \to \mu\bar{\mu}$

The SM prediction

$$\mathcal{B}(\bar{B}_s \to \mu\bar{\mu})_{\rm SM} \sim |V_{tb}V_{ts}^*|^2 \; f_{B_s}^2 \; \frac{m_\mu^2}{M_B^2} \; |C_{10}|^2$$

"Helicity suppression"



main uncertainties from decay constant

$f_{B_s} = (240 \pm 30)$ MeV (lattice)

$$\langle 0|\bar{s}\gamma^\mu\gamma_5 b|\bar{B}_s(p_B)\rangle = i p_B^\mu f_{B_s}$$

SM prediction $\quad \mathcal{B}(\bar{B}_s \to \mu\bar{\mu})_{\rm SM} = (3.86 \pm 0.15) \times 10^{-9}$

Experimental information

[CDF + DØ, 2007] $\quad \mathcal{B}(\bar{B}_s \to \mu\bar{\mu})_{\rm exp} < 8.0 \times 10^{-8}$ (90% C.L.)

[CDF + DØ, HEP 2007] $\quad \mathcal{B}(\bar{B}_s \to \mu\bar{\mu})_{\rm exp} < 5.8 \times 10^{-8}$ (95% C.L.)

Experimental prospects at LHC for $\bar{B}_s \longrightarrow \mu\bar{\mu}$ for SM rate

- LHCb: 5 σ discovery of SM prediction with 10 fb^{-1} (5 years) $\approx$ 100 events
- Atlas/CMS: 5 σ discovery of SM prediction after 5 years ($\gtrsim$ 130 fb^{-1})

NP example: New operators

Additional dim 6 operators to $\bar{B}_s \longrightarrow l\bar{l}$

$$\mathcal{O}_{10} = (\bar{s}\gamma^{\mu} P_L b)(\bar{l}\gamma_{\mu}\gamma_5 l), \qquad \mathcal{O}_S^l = (\bar{s}P_R b)(\bar{l}l), \qquad \mathcal{O}_P^l = (\bar{s}P_R b)(\bar{l}\gamma_5 l),$$

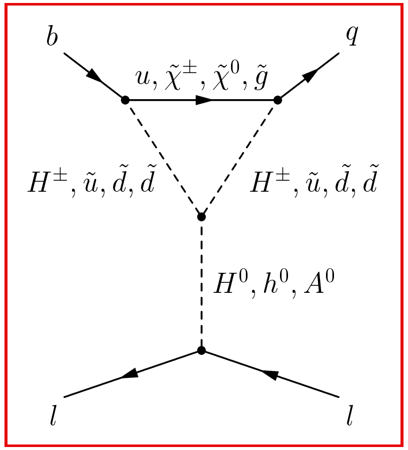
$$\mathcal{O}_S^{l\prime} = (\bar{s}P_L b)(\bar{l}l), \qquad \mathcal{O}_P^{l\prime} = (\bar{s}P_L b)(\bar{l}\gamma_5 l)$$

For example in the MSSM ”neutral Higgs penguin”

SM: suppressed $\quad C_{S,P}^l \sim \dfrac{m_b m_l}{M_W^2}$

MSSM: enhanced $C_{S,P}^l \sim \dfrac{m_b m_l \tan^3\beta}{M_{A^0}^2}$

for high $\tan\beta \gtrsim 40$



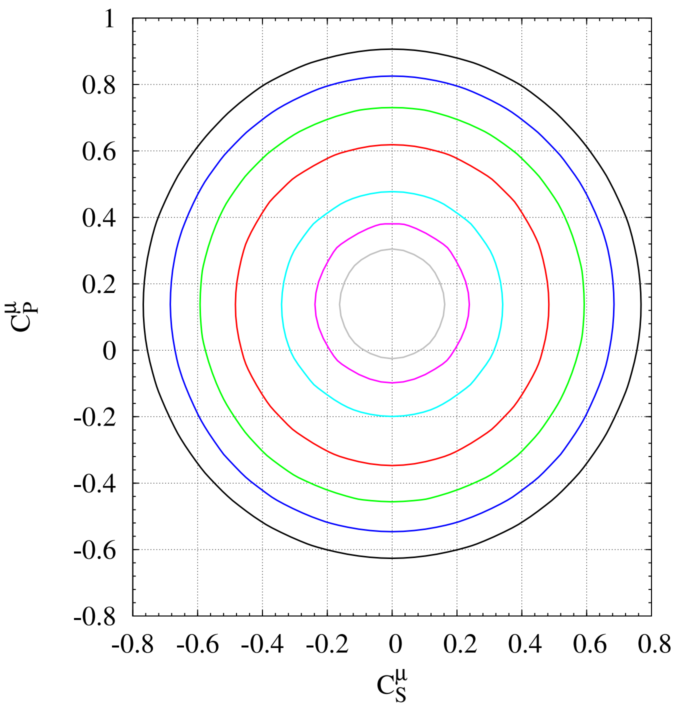
$$\mathcal{B}(\bar{B}_s \to l\bar{l}) = \frac{G_F^2 \alpha_e^2 M_{B_s}^5 f_{B_s}^2 \tau_{B_s}}{64\pi^3} |V_{tb}V_{ts}^*|^2 \sqrt{1 - \frac{4m_l^2}{M_{B_s}^2}}$$

$$\times \left\{ \left(1 - \frac{4m_l^2}{M_{B_s}^2}\right) \left| \frac{C_S^l - C_S^{l\prime}}{m_b + m_s} \right|^2 + \left| \frac{C_P^l - C_P^{l\prime}}{m_b + m_s} + \frac{2m_l}{M_{B_s}^2} C_{10} \right|^2 \right\}$$

In some NP scenarios $C_{S,P}^{l\prime} \sim \frac{m_s}{m_b} C_{S,P}^l$

”Model-independent” analysis of NP in $\{C_S^\mu, C_P^\mu\}$

contours enclose values of
$\mathcal{B}(\bar{B}_s \to \mu\bar{\mu}) < \{0.5, 1, 2, 4, 6, 8, 10\} \times 10^{-8}$
starting with the innermost



Exclusive Decays – $\bar{B} \to K l \bar{l}$

Observables   Normalized angular decay rate of $\bar{B} \to K l \bar{l}$ for $l = \{e, \mu\}$

$$\frac{1}{\Gamma_l[\bar{B} \to K l \bar{l}]} \frac{d\Gamma_l[\bar{B} \to K l \bar{l}]}{d\cos\theta} = \frac{3}{4}(1 - F_H^l)(1 - \cos^2\theta) + \frac{1}{2} F_H^l + A_{\rm FB}^l \cos\theta$$

integrated $q^2 \in [q^2_{\rm min}, q^2_{\rm max}]$ and

$$R_K = \int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \, \frac{d\Gamma[\bar{B} \to K \mu \bar{\mu}]}{dq^2} \Big/ \int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \, \frac{d\Gamma[\bar{B} \to K e \bar{e}]}{dq^2}$$

SM predictions   integrated for low $q^2 \in [1, 7]$ GeV^2 [Bobeth/Hiller/Piranishvili]

$$F_H^\mu = 0.0221 \pm 0.0003, \qquad F_H^e \approx 0, \qquad A_{\rm FB}^l \approx 0, \qquad R_K = 1.0003 \pm 0.0001$$

- Observables defined as ratios $\Rightarrow$ Hadronic uncertainties cancel!!!
- $F_H^l \sim m_l^2$ ”(Quasi-) Nulltest” of the SM
- R_K sensitive to non-universal lepton flavour interactions beyond SM

Experimental information [BaBar]

$F_H^l = 0.81^{+0.58}_{-0.61} \pm 0.46$ (lepton-flavour averaged and $q^2 > 0.04$ GeV^2)
$(R_K - 1) = 0.24 \pm 0.31$ ($q^2 > 0.04$ GeV^2)

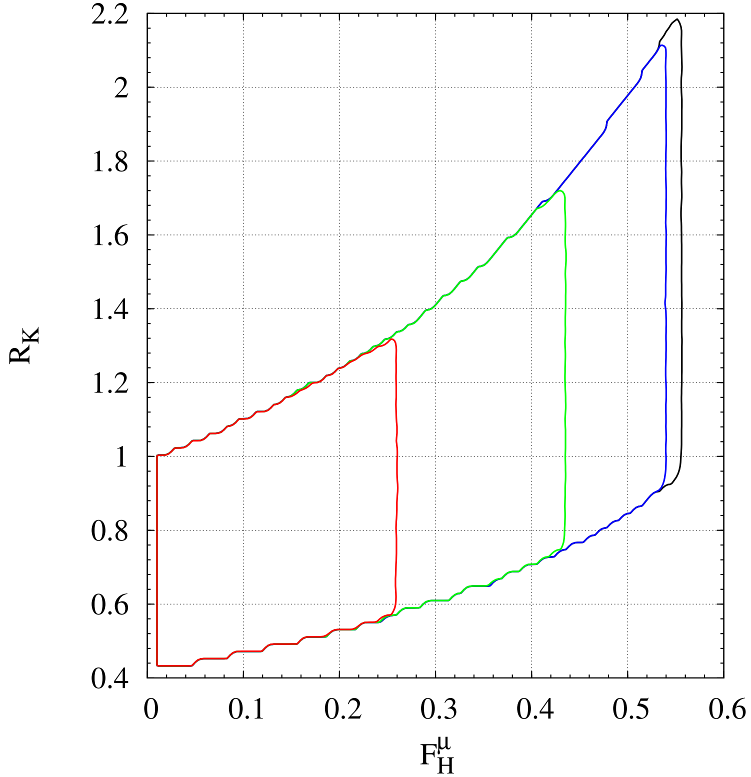
Model-independent NP analysis of F_H^l and R_K

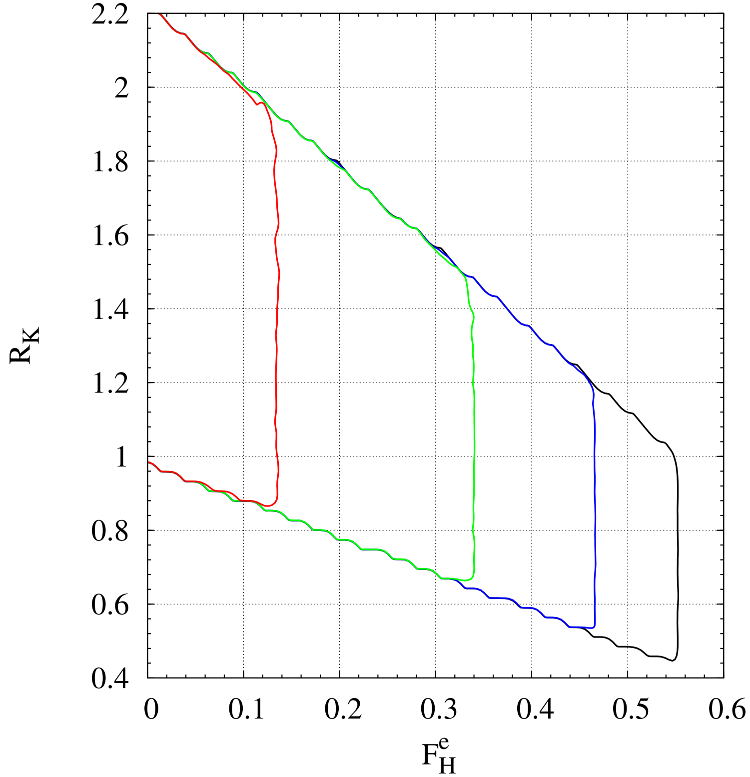
including non-SM operators to $\bar{B} \to K l \bar{l}$ for $l = \{e, \mu\}$

$$\mathcal{O}_S^{l(\prime)} = (\bar{s} P_{R,L} b)(\bar{l} l), \qquad \mathcal{O}_P^{l(\prime)} = (\bar{s} P_{R,L} b)(\bar{l} \gamma_5 l), \qquad \Rightarrow \; C_{S,P}^{e(\prime)}, \; C_{S,P}^{\mu(\prime)}$$

and using constraints at 90% C.L. from

- $\mathcal{B}(\bar{B}_s \to e\bar{e}) < 5.4 \times 10^{-5}$
- $\mathcal{B}(\bar{B}_s \to \mu\bar{\mu}) < 8.0 \times 10^{-8}$
- $\mathcal{B}(\bar{B} \to X_s e\bar{e}) = (4.7 \pm 1.3) \times 10^{-6}$ integrated for $q^2 > 0.04$ GeV^2
- $\mathcal{B}(\bar{B} \to X_s \mu\bar{\mu}) = (4.3 \pm 1.2) \times 10^{-6}$ integrated for $q^2 > 0.04$ GeV^2





Contours of $\mathcal{B}(\bar{B} \to X_s \mu\bar{\mu})_{[1,6]} < \{1.75, 2.0, 2.17\} \times 10^{-6}$ (left),

$\mathcal{B}(\bar{B} \to X_s e\bar{e})_{[1,6]} < \{1.75, 2.0, 2.25, 2.35\} \times 10^{-6}$ (right)

Summary

Standard Model

- Nowadays EFT of $\Delta B = 1$ decays includes: NNLO QCD and NLO QED
- Inclusive decays $\Rightarrow$ HQE $\Rightarrow$ uncertainties of predictions$\lesssim 10\%$
- Exclusive decays $\Rightarrow$ non-perturbative uncert., but also precise observables
- Currently all SM predictions are in ballpark of experimental results

Testing the SM and searching New Physics

- ”Indirect search” – testing NP at quantuum level
- ”Model-dependent” and ”Model-INdependent” analysis are available
- FCNC B-decays provide ”(Quasi-) Nulltests” of the SM
- FCNC B-decays can place serious constraints on NP parameter spaces $(\bar{B} \to X_s\gamma, \bar{B}_s \to \mu\bar{\mu}, \ldots)$
- Complementary search for NP to ”direct searches” at colliders