ERC Workshop “EFTfCPFPaEWSB”, November 12, 2014

Status of old & new physics in $b \to s$ transitions

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Tensions in $b \longrightarrow s$ transitions, November 2014

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[16, 19.25]$	0.47 ± 0.05	0.31 ± 0.07	CDF	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	A_{FB}	$[2, 4.3]$	-0.04 ± 0.03	-0.20 ± 0.08	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.79 ± 0.03	0.26 ± 0.19	ATLAS	$+2.7$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[2, 4.3]$	-0.16 ± 0.03	0.12 ± 0.14	LHCb	-2.0
$\bar{B}^- \to \bar{K}^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[4, 6]$	0.50 ± 0.08	0.26 ± 0.10	LHCb	$+1.9$
$\bar{B}^- \to \bar{K}^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[15, 19]$	0.59 ± 0.06	0.40 ± 0.08	LHCb	$+1.8$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.53	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.10	0.37 ± 0.22	CDF	$+2.3$
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[1, 6]$	0.39 ± 0.06	0.23 ± 0.05	LHCb	$+2.0$

$\Rightarrow$ QCD or New Physics or ... ? [Altmannshofer, DS]

Strategy

1. Use state of the art for SM predictions
2. Parametrize remaining uncertainties in a conservative way
3. Compare to all available data. If there are tensions:
   - Investigate which source of theoretical uncertainty could have been underestimated
   - Investigate whether new physics could account for the effect

Outline

1. Theory uncertainties
   - Form factors
   - Hadronic effects
2. SM vs. data
3. NP vs. data
   - Model-independent analysis
   - Violation of lepton flavour universality
   - Implications for $b \to s\nu\bar{\nu}$
4. Conclusions

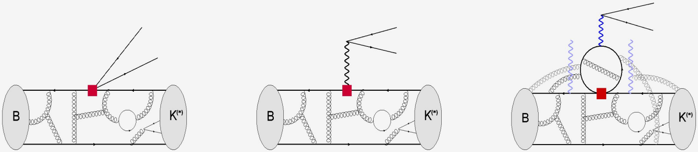
Based on:

W. Altmannshofer, DS [arXiv:1411.SOON]

A. Bharucha, DS, R. Zwicky [arXiv:1411.SOON]

Theory callenges in $B \to K^{(*)}\mu^+\mu^-$

$$\mathcal{L} = \mathcal{L}_{QED+QCD} - \mathcal{C}_7\,[\bar{s}\sigma^{\mu\nu}P_R b]\,F_{\mu\nu} - \mathcal{C}_2\,[\bar{s}\gamma^\nu P_L c]\,[\bar{c}\gamma^\mu P_L b] + \cdots$$



$\mathcal{C}_9$ **contribution:** $\mathcal{A}_9 = \mathcal{C}_9\,\langle K_\lambda^{(*)}|\bar{s}\gamma_\mu P_L b|B\rangle L^\mu = \mathcal{C}_9\,F_\lambda(q^2)$

$\mathcal{C}_7$ **contribution:** $\mathcal{A}_7 = \mathcal{C}_7\,\langle K_\lambda^{(*)}|\bar{s}\sigma_{\mu\nu}P_R b|B\rangle \frac{eq^\mu}{q^2} L^\nu = \mathcal{C}_7\,T_\lambda(q^2)$

$\mathcal{C}_2$ **contribution:** $\mathcal{A}_2 = \mathcal{C}_2 \cdot \frac{e^2}{q^2} L^\mu \int dx^4 e^{iq\cdot x}\langle K_\lambda^{(*)}|T\{j_\mu^{c\bar{c}}(x)\mathcal{O}_2(0)\}|B\rangle$

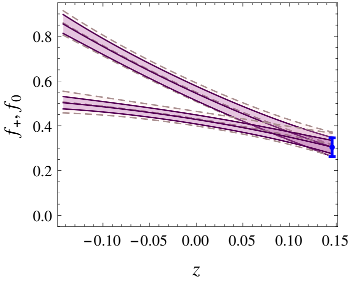
2 main problems:

1. Precise determination of Form Factors (LCSRs, LQCD, . . .)
2. Computation of the hadronic contribution (SCET/QCDF, OPE, . . .)

[Slide by J. Virto @ CKM 2014]

Form factors: $B \to K$

- Recent lattice computation at high q^2 [Bouchard et al. 1306.2384]
- Excellent agreement with LCSR at low q^2 [Ball and Zwicky hep-ph/0406232] see also [Khodjamirian et al. 1006.4945]
- here: combined fit to lattice + LCSR at $q^2 = 0$



Form factors: $B \longrightarrow K^*$ and $B_s \longrightarrow \phi$

- 7 form factors
- Recent lattice computation [Horgan et al. 1310.3722]
- LCSR calculations: [Ball and Zwicky hep-ph/0412079, Khodjamirian et al. 1006.4945]

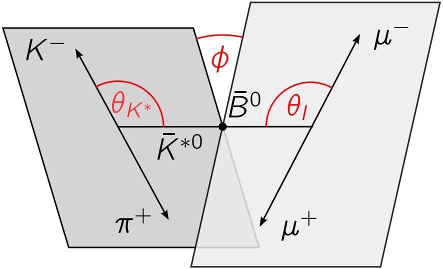
Possible strategy for low q^2

[Jäger and Camalich 1212.2263, Descotes-Genon et al. 1407.8526]

- 7 form factors reduce to 2 “soft” form factors in the heavy quark limit
- Look at observables where “soft” FFs drop out at LO
- Parametrize (factorizable) power corrections as uncertainties

Using the full form factors

In $B \to K^* \mu^+ \mu^-$, not only branching ratios have been measured but also angular observables involving ratios of form factors

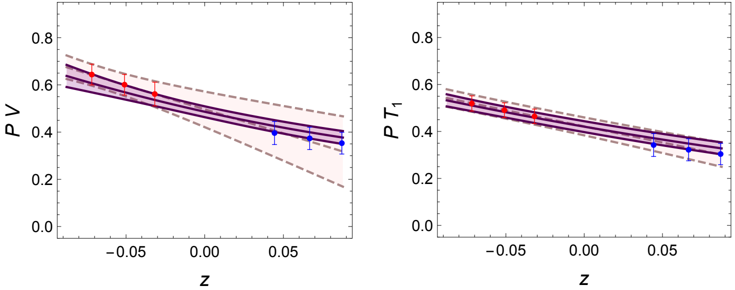


Correlations between form factor uncertainties are crucial!

New results on $B \to K^*$, $B_s \to \phi$ form factors

[A. Bharucha, DS, Roman Zwicky (soon!)]

- Numerical $B \to K^*$ form factors as z expansion with correlated uncertainties (cf. Th. Mannel's talk)
- Combined fit with recent lattice computation



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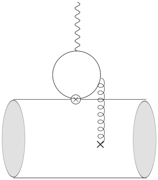
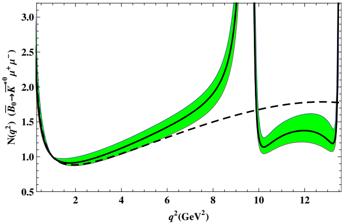
Hadronic uncertainties: low q^2

- Systematic calculation within QCDF [Beneke et al. hep-ph/0106067, Beneke et al. hep-ph/0412400] or SCET [Ali et al. hep-ph/0601034]
- Weak annihilation and chromomagnetic contribution beyond the heavy quark limit calculated within LCSR
  [Dimou et al. 1212.2242, Lyon and Zwicky 1305.4797]
- Soft gluon correction to charm loop calculated within LCSR
  [Khodjamirian et al. 1006.4945, Khodjamirian et al. 1211.0234]





“Naive” parametrization of subleading hadronic effects

In $B \to K\mu^+\mu^-$

$$[C_9^{\text{eff}}(q^2)]^{\text{SM}} \to [C_9^{\text{eff}}(q^2)]^{\text{SM}} \left[1 + a_K e^{i\phi_a} + b_K e^{i\phi_b}(q^2/6\,\text{GeV}^2)\right]$$

In $B \to K^*\mu^+\mu^-$

$$[C_7^{\text{eff}}]^{\text{SM}} \to [C_7^{\text{eff}}]^{\text{SM}} \left[1 + a_\lambda e^{i\phi_a^\lambda} + b_\lambda e^{i\phi_b^\lambda}(q^2/6\,\text{GeV}^2)\right]$$

- Arbitrary strong phases allowed
- Size chosen such that LCSR charm loop effect is well within 1σ
- Expected suppression of $\lambda = +$ amplitude “built in”
  [Jäger and Camalich 1212.2263]

We only use data up to $q^2 = 6\,\text{GeV}^2$!

Hadronic uncertainties: high q^2

- Violation of quark/hadron duality: observables cannot be predicted "locally" as functions of q^2
- In q^2-integrated observables (sufficiently above the narrow $c\bar{c}$ resonances), effects of duality violation expected to be small [Beylich et al. 1101.5118]

- We only use data in large bins above $q^2 = 15\,\text{GeV}^2$
- parametrization of subleading effects:

$$[C_9^{\text{eff}}(q^2)]^{\text{SM}} \to [C_9^{\text{eff}}(q^2)]^{\text{SM}} \left[1 + c_\lambda e^{i\phi_c^\lambda}\right]$$

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Global fit

- Angular observables in $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$
- (Differential) branching ratios of
  - $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$
  - $B^- \to K^{*-}\mu^+\mu^-$
  - $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$
  - $B^- \to K^-\mu^+\mu^-$
  - $B_s \to \phi\mu^+\mu^-$
  - $B_s \to \mu^+\mu^-$
  - $\bar{B}^0 \to \bar{K}^{*0}\gamma$
  - $B^- \to K^{*-}\gamma$
  - $B \to X_s\gamma$
  - $B \to X_s\mu^+\mu^-$

Fit methodology

We construct a χ^2 containg **78** measurements of 62 different observables by 6 different experiments

$$\chi^2(\vec{C}^{\text{NP}}) = \left[\vec{O}_{\text{exp}} - \vec{O}_{\text{th}}(\vec{C}^{\text{NP}})\right]^T \left[C_{\text{exp}} + C_{\text{th}}\right]^{-1} \left[\vec{O}_{\text{exp}} - \vec{O}_{\text{th}}(\vec{C}^{\text{NP}})\right].$$

- Full dependence on Wilson coefficients contained in $\vec{O}_{\text{th}}$
- NP dependence neglected but all correlations retained in C_{th}
- Theory correlations have an important impact

Fit result in the SM

- $\chi^2_{\text{SM}} = 97.2$ for 78 measurements (p value 6.9%)

Including also $b \to se^+e^-$ processes:

- $\chi^2_{\text{SM}} = 106.1$ for 81 measurements (p value 3.6%)

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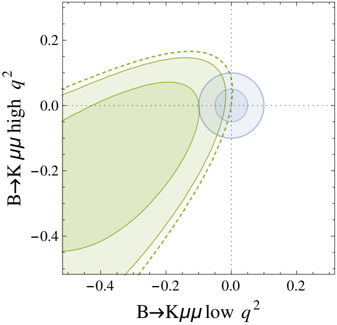
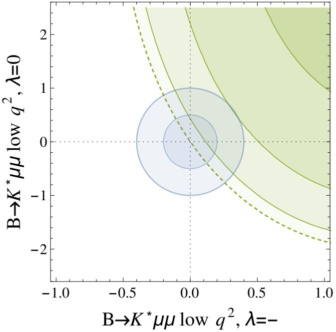
Underestimated hadronic effects?

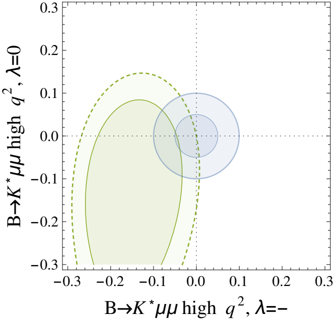
- Plot the change in χ^2_{SM} under variation of the central values of the *a*, *b*, *c* parameters parametrizing subleading hadronic effects
- Green dashed: χ^2 unchanged
- Green solid: χ^2 reduced by 1, 4.
- Blue: our nominal uncertainties



$\Rightarrow$ χ^2 can be reduced by $\sim$4 in the presence of large hadronic effects in $B \to K\mu^+\mu^-$ at low q^2

Underestimated hadronic effects in $B \to K^*\mu^+\mu^-$?





$\Rightarrow$ χ^2 can be reduced by $\sim$9 in the presence of simultaneous huge hadronic effects in the $-$ and 0 helicity amplitudes in $B^* \to K\mu^+\mu^-$ at low q^2

Outline

Model-independent new physics analysis

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$

$$O_7 = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu} \qquad O_7' = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu}$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad O_9' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$$

$$O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \qquad O_{10}' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

Lessons from the SMEFT

- Tensor operators $(\bar{s}\sigma^{\mu\nu} P_{L,R} b)(\bar{\ell}\sigma^{\mu\nu} P_{L,R} \ell)$ and scalar $(\bar{s} P_{L,R} b)(\ell P_{L,R} \ell)$ “secretly dim. 8”
- $(\bar{s} P_{L,R} b)(\ell P_{R,L} \ell)$ strongly constrained by $B_s \to \mu^+\mu^-$

More lessons from the SMEFT

Pattern of effects frequently encountered in NP models:

- ***Z* penguins**

$$i(\bar{q}_L\gamma_\mu q_L)H^\dagger D^\mu H \qquad\qquad i(\bar{d}_R\gamma_\mu d_R)H^\dagger D^\mu H$$

$$\Rightarrow C_9^{\text{NP}} = 0.08\, C_{10}^{\text{NP}} \qquad\qquad \Rightarrow C_9' = 0.08\, C_{10}'$$

& always lepton flavour universal!

- **semi-leptonic operators (e.g. Z' models)**

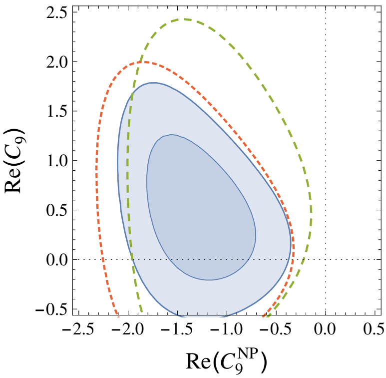
$$(\bar{q}_L\gamma_\mu q_L)(\bar{l}_L\gamma^\mu l_L) \quad (\bar{q}_L\gamma_\mu q_L)(\bar{l}_R\gamma^\mu l_R) \quad (\bar{q}_R\gamma_\mu q_R)(\bar{l}_L\gamma^\mu l_L) \quad (\bar{q}_R\gamma_\mu q_R)(\bar{l}_R\gamma^\mu l_R)$$

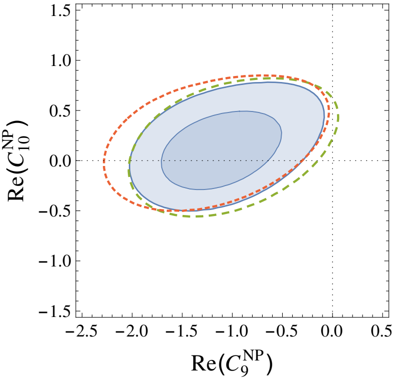
$$C_9^{\text{NP}} = -C_{10}^{\text{NP}} \quad C_9^{\text{NP}} = +C_{10}^{\text{NP}} \quad C_9' = -C_{10}' \quad C_9' = +C_{10}'$$

Best-fit values for NP in individual Wilson coefficients

Coeff.	best fit	1σ	2σ	$\chi^2_{\text{b.f.}} - \chi^2_{\text{SM}}$
C_7^{NP}	-0.04	$[-0.07, -0.01]$	$[-0.10, 0.02]$	1.8
C_7'	-0.05	$[-0.14, 0.03]$	$[-0.22, 0.11]$	0.4
C_9^{NP}	-1.19	$[-1.54, -0.82]$	$[-1.88, -0.45]$	**10.7**
C_9'	0.11	$[-0.18, 0.39]$	$[-0.46, 0.67]$	0.1
C_{10}^{NP}	0.49	$[0.23, 0.75]$	$[-0.01, 1.04]$	3.9
C_{10}'	-0.12	$[-0.34, 0.09]$	$[-0.56, 0.30]$	0.3
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.07	$[-0.32, 0.21]$	$[-0.56, 0.51]$	0.1
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.46	$[-0.64, -0.29]$	$[-0.84, -0.12]$	**7.7**
$C_9' = C_{10}'$	-0.12	$[-0.42, 0.17]$	$[-0.73, 0.45]$	0.2
$C_9' = -C_{10}'$	0.07	$[-0.06, 0.20]$	$[-0.19, 0.34]$	0.3

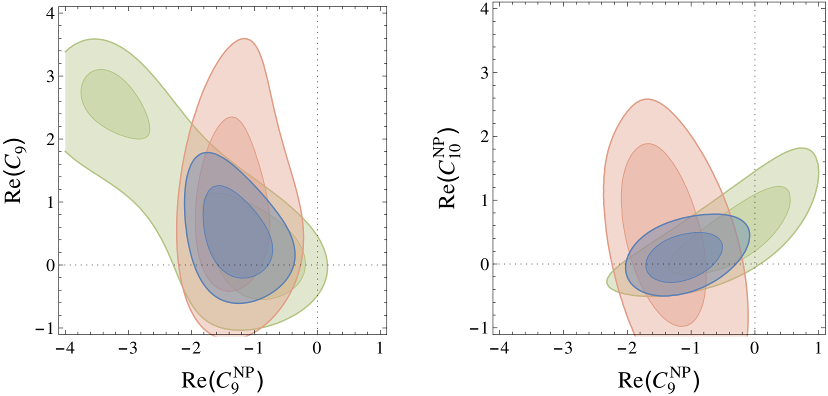
Allowed regions for 2 (real) Wilson coefficients





- Green: 2σ when doubling form factor uncertainties
- Red: 2σ when doubling non-form factor hadronic uncertainties

Angular observables vs. branching ratios

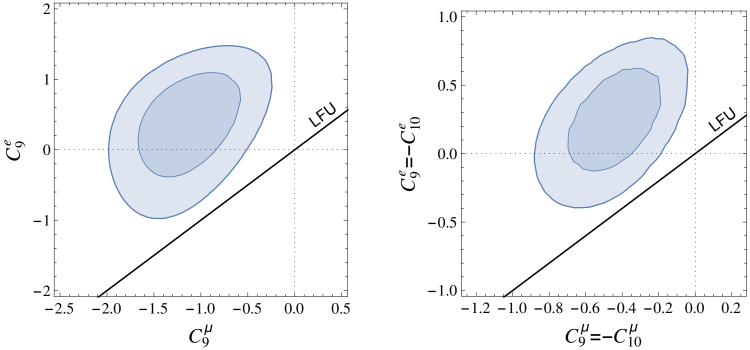


- Green: all branching ratios
- Red: $B \to K^* \mu^+ \mu^-$ angular observables only

Violation of lepton flavour universality?

$$R_K = \frac{\text{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\text{BR}(B \to Ke^+e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036\,, \quad R_K^{\text{SM}} \simeq 1.00$$

Global fit of $b \to s\mu\mu$ and $b \to see$ (cf. [Ghosh et al. 1408.4097, Hurth et al. 1410.4545])



Future tests of LFU

Spectacular deviations in $B \to K^* \mu^+ \mu^-$ vs $B \to K^* e^+ e^-$ angular observables and others can distinguish between different scenarios!

Observable	Ratio of muon vs. electron mode			
	$C_9^{\text{NP}} = -1.5$	-1.5	-0.7	-1.3
	$C_9' = 0$	0.8	0	0
	$C_{10}^{\text{NP}} = 0$	0	0.7	0.3
$10^7 \ \frac{dBR}{dq^2}(\bar{B}^0 \to \bar{K}^{*0} \ell^+ \ell^-)_{[1,6]}$	0.83	0.77	0.79	0.81
$10^7 \ \frac{dBR}{dq^2}(\bar{B}^0 \to \bar{K}^{*0} \ell^+ \ell^-)_{[15,22]}$	0.76	**0.69**	0.76	0.75
$A_{\text{FB}}(\bar{B}^0 \to \bar{K}^{*0} \ell^+ \ell^-)_{[4,6]}$	**0.18**	**0.10**	0.75	**0.27**
$S_5(\bar{B}^0 \to \bar{K}^{*0} \ell^+ \ell^-)_{[4,6]}$	**0.66**	**0.66**	0.93	0.71
$10^8 \ \frac{dBR}{dq^2}(B^+ \to K^+ \ell^+ \ell^-)_{[1,6]}$	0.75	0.82	0.77	0.74
$10^8 \ \frac{dBR}{dq^2}(B^+ \to K^+ \ell^+ \ell^-)_{[15,19]}$	0.75	0.83	0.77	0.75

Outline

Correlating $b \to s\ell\ell$ and $b \to s\nu\bar{\nu}$

Dimension-6 SM gauge invariant operators

$$Q_{Hq}^{(1)} = i(\bar{q}_L\gamma_\mu q_L)H^\dagger D^\mu H \qquad Q_{ql}^{(1)} = (\bar{q}_L\gamma_\mu q_L)(\bar{l}_L\gamma^\mu l_L)$$

$$Q_{Hq}^{(3)} = i(\bar{q}_L\gamma_\mu \tau^a q_L)H^\dagger D^\mu \tau_a H \qquad Q_{ql}^{(3)} = (\bar{q}_L\gamma_\mu \tau^a q_L)(\bar{l}_L\gamma^\mu \tau_a l_L)$$

$$Q_{Hd} = i(\bar{d}_R\gamma_\mu d_R)H^\dagger D^\mu H \qquad Q_{dl} = (\bar{d}_R\gamma_\mu d_R)(\bar{l}_L\gamma^\mu l_L)$$

Match onto

$$O_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$O_{L,R} = (\bar{s}\gamma_\mu P_{L(R)} b_{L,R})(\bar{\nu}_L\gamma^\mu \nu_L)$$

$b \to s\ell\ell$ vs. $b \to s\nu\bar{\nu}$ Wilson coefficients

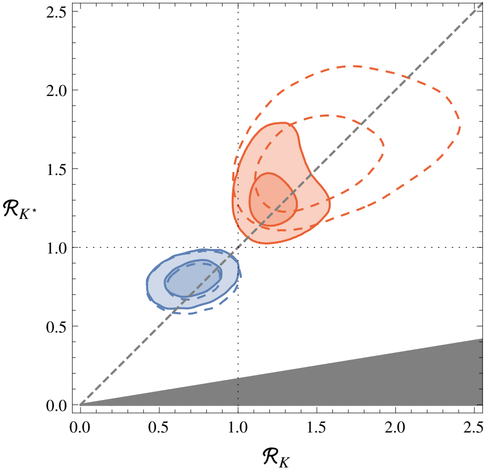
$$
\begin{aligned}
C_L^{\text{NP}} &= \widetilde{c}_{ql}^{(1)} + \widetilde{c}_Z \\
C_R &= \widetilde{c}_{dl} + \widetilde{c}'_Z \\
C_9^{\text{NP}} &= \widetilde{c}_{qe} + \widetilde{c}_{ql}^{(1)} \\
C'_9 &= \widetilde{c}_{de} + \widetilde{c}_{dl} \\
C_{10}^{\text{NP}} &= \widetilde{c}_{qe} - \widetilde{c}_{ql}^{(1)} + \widetilde{c}_Z \\
C'_{10} &= \widetilde{c}_{de} - \widetilde{c}_{dl} + \widetilde{c}'_Z
\end{aligned}
$$

2 scenarios:

- Z penguins: NP in $\widetilde{c}_Z^{(\prime)}$ only
- Z': NP in "4-fermion operators" as generated by exchange of a SM-singlet Z'

(ignoring $\widetilde{c}_{ql}^{(3)}$ and $(1 - 4s_w^2) \approx 0.08$)

Allowed ranges for $B \to K^{(*)}\nu\bar{\nu}$ in Z, Z' scenarios



solid: real Wilson coeff.; dashed: complex

- Global fit to all $b \to s\mu^+\mu^-$ data
- Current data favour suppression in Z scenario and enhancement in Z' scenario

[Buras et al. 1409.4557]

Conclusions & Outlook

- There are several $\sim 2\sigma$ tensions in $b \to s$ transitions
- They could be explained by hadronic effects that are unexpectedly large (we have quantified it)
- They could be due to new physics in C_9 (and possibly C_9', C_{10})
- The hint for lepton flavour non-universality fits well into the picture

Things to look forward to:

- $B \to K^* \mu^+ \mu^-$ update by LHCb with 3/fb
- Angular analysis of $B \to K^* e^+ e^-$: spectacular effects if R_K is due to NP
- $b \to s \nu \bar{\nu}$ at Belle-II