Impact of new results on global fits

Sébastien Descotes-Genon

arXiv:1903.09578 in collaboration with M.Algueró, B.Capdevila, A.Crivellin, P.Masjuan, J.Matias, J.Virto

Laboratoire de Physique Théorique
CNRS, Univ. Paris-Sud, Université Paris-Saclay, Orsay, France

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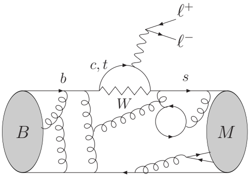
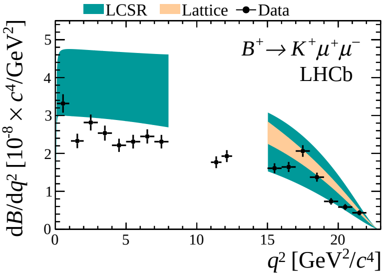
IPPP Durham, 3/4/19

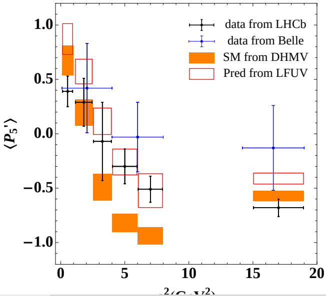
LPT Orsay

$b \to s\ell\ell$ as a powerful probe of SM and NP



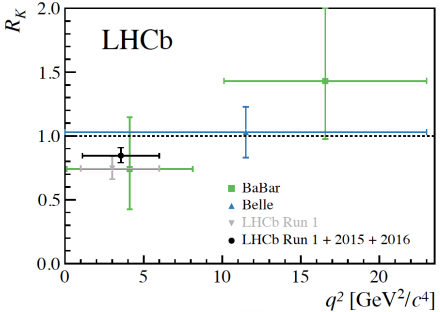
- FCNC, suppressed in SM, potential high sensitivity to NP contributions
- deviations observed w.r.t. SM
  - BR for $B \to K\mu\mu$, $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$ (require knowledge of hadronic uncertainties)
  - Angular distr of $B \to K^*\mu\mu$ with optimised obs (eg P_5'), where part of hadronic uncertainties cancel
  - Hints of lepton flavour universality violation: $b \to see$ vs $b \to s\mu\mu$

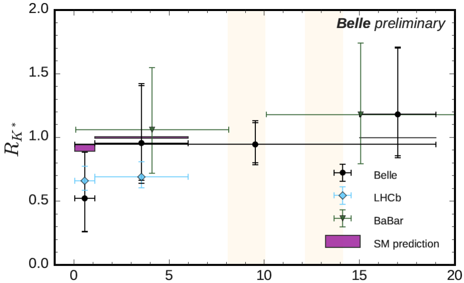




[LHCb, Belle, ATLAS, CMS]

Recent news from Moriond





- LHCb update

$$R_K^{[1.1,6]} = \frac{Br(B\to K\mu\mu)}{Br(B\to Kee)} = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

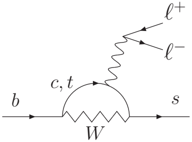
- From 2.6σ to 2.5σ deviation wrt SM

- Belle update for

$$R_{K^*} = \frac{B(B\to K^*\mu\mu)}{B(B\to K^*ee)}$$

- three bins, including low-K^* recoil
- agree with SM, but also LHCb [2.3 (2.6) σ from SM for $R_{K^*}^{[0.045,1.1]}$ ([1.1,6])]

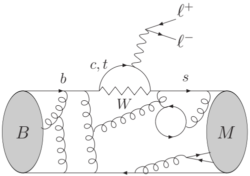
$b \to s\ell\ell$ effective Hamiltonian



$$\mathcal{H}(b \to s\gamma(^*)) \propto G_F V_{ts}^* V_{tb} \sum_i \mathcal{C}_i \mathcal{O}_i$$

to separate short and long distances ($\mu_b = m_b$)

$b \to s\ell\ell$ effective Hamiltonian



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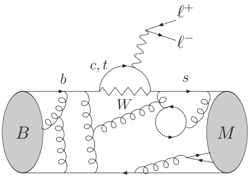

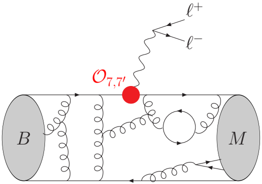

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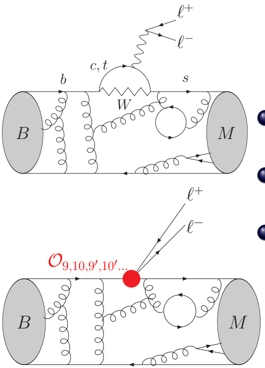

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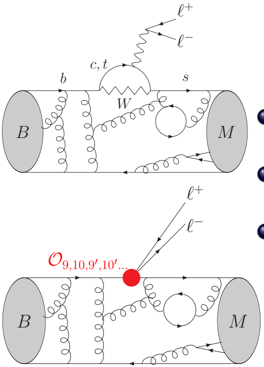
- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

$b \to s\ell\ell$ effective Hamiltonian



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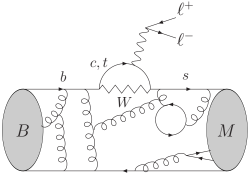
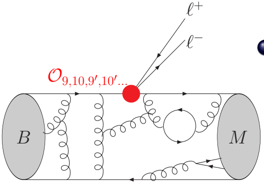
$$\mathcal{C}_7^{\rm SM} = -0.29, \; \mathcal{C}_9^{\rm SM} = 4.1, \; \mathcal{C}_{10}^{\rm SM} = -4.3$$

$b \to s\ell\ell$ effective Hamiltonian





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$$\mathcal{C}_7^{\rm SM} = -0.29,\ \mathcal{C}_9^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3$$

NP changes short-distance $\mathcal{C}_i$ or add new operators $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) $\quad \mathcal{O}_7 \to \mathcal{O}_{7'} \propto \bar{s}\sigma^{\mu\nu}(1-\gamma_5)F_{\mu\nu}\, b$
- (Pseudo)scalar ($W \to H^+$) $\quad \mathcal{O}_9, \mathcal{O}_{10} \to \mathcal{O}_S \propto \bar{s}(1+\gamma_5)b\bar{\ell}\ell, \mathcal{O}_P$
- Tensor operators ($\gamma \to T$) $\quad \mathcal{O}_9 \to \mathcal{O}_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5)b\, \bar{\ell}\sigma_{\mu\nu}\ell$

Global analysis of $b \to s\ell\ell$ anomalies

178 observables in total [Alguero, Capdevila, Crivellin, SDG, Masjuan, Matias, Virto]

- $B \to K^*\mu\mu$ (Br, $P_{1,2}, P'_{4,5,6,8}, F_L$ in large- and low-recoil bins)
- $B \to K^*ee$ ($P_{1,2,3}, P'_{4,5}, F_L$ in large- and low-recoil bins)
- $B_s \to \phi\mu\mu$ (Br, $P_1, P'_{4,6}, F_L$ in large- and low-recoil bins)
- $B^+ \to K^+\mu\mu$, $B^0 \to K^0\mu\mu$ (Br in several bins)
- $B \to X_s\gamma$,$B \to X_s\mu\mu$,$B_s \to \mu\mu$,$B_s \to \phi\gamma$(Br),$B \to K^*\gamma$(Br, A_I, $S_{K^*\gamma}$)
- R_K, R_{K^*} (update with both large- and low-recoil bins)

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Various computational approaches

- inclusive: OPE
- large recoil: QCD fact, Soft-collinear effective theory, sum rules
- low recoil: Heavy quark eff th, Quark-hadron duality, lattice

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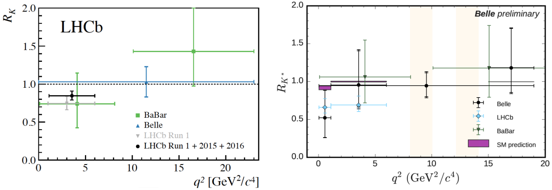
Frequentist analysis

- $\mathcal{C}_i(\mu_{ref}) = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$, with $\mathcal{C}_i^{NP}$ assumed to be real (no CPV)
- Experimental correlation matrices provided
- Theoretical inputs (form factors. . .) with correlation matrix computed treating all theo errors as Gaussian random variables

Other analyses from [Aebischer et al, 1903.10434, Alok et al. 1903.09617, Ciuchini et al 1903.09632, D'Amico et al 1704.05438]

R_K and R_{K^*}: hadronic unc and $\mathcal{C}_{9,9',10,10'}$



- R_K: $Br(B \to K\ell\ell)$ involves one amplitude depending on
  - three $B \to K$ form factors (one suppressed by m_ℓ^2/q^2, one by $\mathcal{C}_7$)
  - $\mathcal{C}_9 + \mathcal{C}_{9'}$ and $\mathcal{C}_{10} + \mathcal{C}_{10'}$

$\Longrightarrow$form factors cancel so that R_K very accurate for all q^2 and $\mathcal{C}_i$

- R_{K^*}: $Br(B \to K^*\ell\ell)$ involve several helicity ampl depending on
  - 7 $B \to K^*$ form factors (one suppressed by m_ℓ^2/q^2)
  - depending on helicity amplitude: $\mathcal{C}_9 \pm \mathcal{C}_{9'}$ and $\mathcal{C}_{10} \pm \mathcal{C}_{10'}$

$\Longrightarrow$Cancellation of form factors in SM due to $V - A$ suppression of helicity amplitudes, but less efficient with NP (larger uncertainties)

Some favoured 1D hypotheses

- *p*-value : $\chi^2_{\rm min}$ considering N_{dof}
  $\Longrightarrow$goodness of fit: does the hypothesis give an overall good fit ?
- Pull$_{\rm SM}$: $\chi^2(\mathcal{C}_i = 0) - \chi^2_{min}$ considering N_{dof}
  $\Longrightarrow$metrology: how much does the hyp. solve SM deviations ?

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- All: fit to 178 obs

2017		Best fit	1 σ CL	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	$L_q \otimes V_\ell$	-1.11	$[-1.28, -0.94]$	5.8	68 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	$L_q \otimes L_\ell$	-0.62	$[-0.75, -0.49]$	5.3	58 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}$	$A_q \otimes V_\ell$	-1.01	$[-1.18, -0.84]$	5.4	61 %

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- All: fit to 178 obs (SM p-value 8%)

2019		Best fit	1 σ CL	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	$L_q \otimes V_\ell$	-1.02	$[-1.18, -0.85]$	5.8	65 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	$L_q \otimes L_\ell$	-0.49	$[-0.59, -0.40]$	5.4	55 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}$	$A_q \otimes V_\ell$	-1.02	$[-1.18, -0.85]$	5.7	61 %
$\mathcal{C}_{10\mu}^{\rm NP}$	$L_q \otimes A_\ell$	0.55	$[0.41, 0.70]$	4.0	29 %

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- LFUV: 20 obs (LFUV,$b \to s\gamma$,$B_s \to \mu\mu$,$B \to X_s\mu\mu$)

2017		Best fit	1 σ CL	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	$L_q \otimes V_\ell$	-1.76	$[-2.36, -1.23]$	3.9	69 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	$L_q \otimes L_\ell$	-0.66	$[-0.84, -0.48]$	4.1	78.0 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}$	$A_q \otimes V_\ell$	-1.65	$[-2.13, -1.05]$	3.2	32 %

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$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}$	$A_q \otimes V_\ell$	-1.02	$[-1.18, -0.85]$	5.7	61 %
$\mathcal{C}_{10\mu}^{\rm NP}$	$L_q \otimes A_\ell$	0.55	$[0.41, 0.70]$	4.0	29 %

- LFUV: 20 obs (LFUV,$b \to s\gamma$,$B_s \to \mu\mu$,$B \to X_s\mu\mu$) (SM p-val 5%)

2019		Best fit	1 σ CL	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	$L_q \otimes V_\ell$	-1.02	$[-1.38, -0.69]$	3.5	51 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	$L_q \otimes L_\ell$	-0.44	$[-0.55, -0.32]$	4.0	74 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}$	$A_q \otimes V_\ell$	-1.66	$[-2.15, -1.05]$	3.1	35 %
$\mathcal{C}_{10\mu}^{\rm NP}$	$L_q \otimes A_\ell$	0.69	$[0.50, 0.89]$	3.9	72 %

Some favoured 2D hypotheses

2017	All			LFUV		
2D Hyp.	Best fit	Pull_{SM}	p-value	Best fit	Pull_{SM}	p-value
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}})$	(-1.01,0.29)	5.7	72 %	(-1.30,0.36)	3.7	75 %
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_7')$	(-1.13,0.01)	5.5	69 %	(-1.85,-0.04)	3.6	66 %
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu})$	(-1.15,0.41)	5.6	71 %	(-1.99,0.93)	3.7	72 %
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10'\mu})$	(-1.22,-0.22)	5.7	72 %	(-2.22,-0.41)	3.9	85 %
Hyp. 1	(-1.16,0.38)	5.7	73 %	(-1.68,0.60)	3.8	78 %
Hyp. 2	(-1.15, 0.01)	5.0	57 %	(-2.16,0.41)	3.0	37 %
Hyp. 3	(-0.67,-0.10)	5.0	57 %	(0.61,2.48)	3.7	73 %
Hyp. 4	(-0.70,0.28)	5.0	57 %	(-0.74,0.43)	3.7	72 %

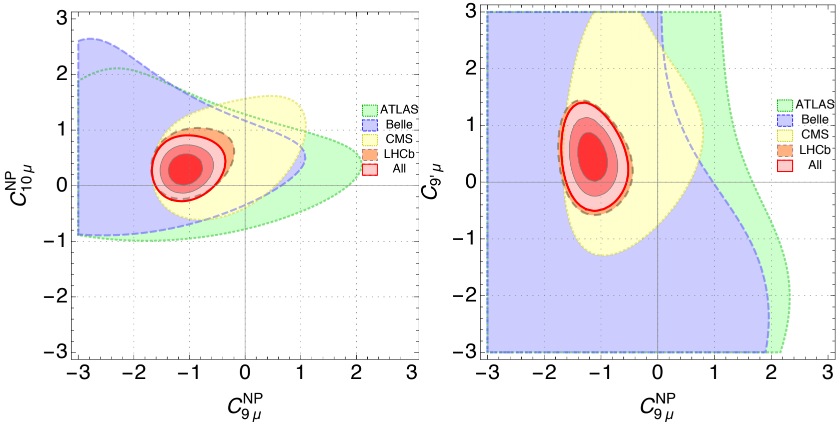
- Hyp. 1: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\text{NP}} = \mathcal{C}_{10'\mu})$ $\quad A_q \otimes V_\ell, V_q \otimes A_\ell$
- Hyp. 2: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\text{NP}} = -\mathcal{C}_{10'\mu})$ $\quad A_q \otimes V_\ell, A_q \otimes A_\ell$
- Hyp. 3: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = \mathcal{C}_{10'\mu})$ $\quad L_q \otimes L_\ell, R_q \otimes R_\ell$
- Hyp. 4: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$ $\quad L_q \otimes L_\ell, R_q \otimes L_\ell$

Some favoured 2D hypotheses

2019	All			LFUV		
2D Hyp.	Best fit	$\mathrm{Pull}_{\mathrm{SM}}$	p-value	Best fit	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{10\mu}^{\mathrm{NP}})$	(-0.95,0.20)	5.7	70 %	(-0.30,0.52)	3.6	75 %
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{7}')$	(-1.03,0.02)	5.6	68 %	(-1.03,-0.04)	3.1	54 %
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{9'\mu})$	(-1.13,0.54)	5.9	74 %	(-1.88,1.14)	3.6	76 %
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{10'\mu})$	(-1.17,-0.34)	6.1	78 %	(-2.07,-0.63)	4.0	93 %
Hyp. 1	(-1.09,0.28)	6.0	76 %	(-1.69,0.32)	3.6	77 %
Hyp. 2	(-1.00,0.09)	5.4	64 %	(-2.00,0.26)	3.3	61 %
Hyp. 3	(-0.50,0.08)	5.1	56 %	(-0.43,-0.09)	3.6	74 %
Hyp. 4	(-0.52,0.11)	5.2	59 %	(-0.50,0.15)	3.7	82 %
Hyp. 5	(-1.17,0.24)	6.1	78 %	(-2.20,0.52)	4.1	94 %

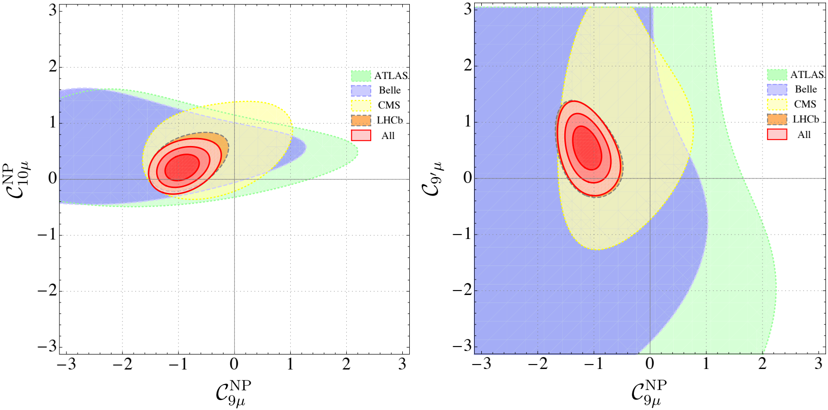
- Hyp. 1: $(\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\mathrm{NP}} = \mathcal{C}_{10'\mu})$ — $A_q \otimes V_\ell, V_q \otimes A_\ell$
- Hyp. 2: $(\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\mathrm{NP}} = -\mathcal{C}_{10'\mu})$ — $A_q \otimes V_\ell, A_q \otimes A_\ell$
- Hyp. 3: $(\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}, \mathcal{C}_{9'\mu} = \mathcal{C}_{10'\mu})$ — $L_q \otimes L_\ell, R_q \otimes R_\ell$
- Hyp. 4: $(\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$ — $L_q \otimes L_\ell, R_q \otimes L_\ell$
- Hyp. 5: $(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$ — $L_q \otimes V_\ell, R_q \otimes L_\ell$

Contributions of data subsets



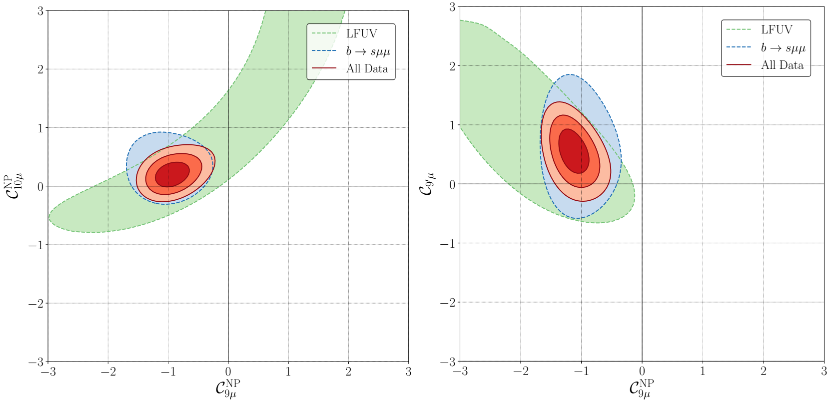
- $(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{10\mu}^{NP})$ and $(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{9'\mu})$ in 2017

Contributions of data subsets



- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}^{\rm NP})$ and $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{9'\mu})$ in 2017 and in 2019

Contributions of data subsets



- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}^{\rm NP})$ and $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{9'\mu})$ in 2017 and in 2019
- Separating 3 σ regions for $b \to s\mu\mu$ and purely LFUV
  - LFUV favours $\mathcal{C}_{10\mu}^{\rm NP} > 0$ and $\mathcal{C}_{9'\mu}^{\rm NP} > 0$
  - $b \to s\mu\mu$ essentially in favour of $\mathcal{C}_{9\mu} < 0$

Impact of the new data

1D hypotheses

- Hierarchy of hypotheses unchanged
- "All": $\mathcal{C}_9^{\rm NP}$ only and $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}$ favoured wrt $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$
- "LFUV": $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$ preferred wrt $\mathcal{C}_9^{\rm NP}$ and $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}$

2D hypotheses

- Good scenarios with $\mathcal{C}_{9\mu}$ and ($\mathcal{C}_{9'\mu}$ or $\mathcal{C}_{10\mu}$ or $\mathcal{C}_{10'\mu}$)
- Scenarios with small right-handed current $(\mathcal{C}_{9\mu}, \mathcal{C}_{10'\mu})$ or $(\mathcal{C}_{9\mu}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$ accommodate better the new situation
- at the same level as $(\mathcal{C}_{9\mu}, \mathcal{C}_{10\mu})$ or even better

No dramatic shift compared to our earlier analyses
(in particular, $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}$ among favoured scenarios)

LFUV but also LFU NP ?

R_K and R_{K^*} support LFUV NP, but there could also be a LFU piece

$$\mathcal{C}_{ie} = \mathcal{C}_i^{\rm U} \qquad \mathcal{C}_{i\mu} = \mathcal{C}_i^{\rm U} + \mathcal{C}_{i\mu}^{\rm V}$$

with interesting reshuffling between LF**U** and LFU**V** contributions

[Algueró, Capdevila, SDG, Masjuan, Matias]

2017		Best-fit point	1 σ	$\text{Pull}_{\rm SM}$	p-value
Sc. 5	$\mathcal{C}_{9\mu}^{\rm V}$	-0.16	$[-0.94, +0.46]$	5.8	78 %
	$\mathcal{C}_{10\mu}^{\rm V}$	$+1.00$	$[+0.18, +1.59]$		
	$\mathcal{C}_9^{\rm U} = \mathcal{C}_{10}^{\rm U}$	-0.87	$[-1.43, -0.14]$		
Sc. 6	$\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$	-0.64	$[-0.77, -0.51]$	6.0	79 %
	$\mathcal{C}_9^{\rm U} = \mathcal{C}_{10}^{\rm U}$	-0.44	$[-0.58, -0.29]$		
Sc. 7	$\mathcal{C}_{9\mu}^{\rm V}$	-1.57	$[-2.14, -1.06]$	5.7	72 %
	$\mathcal{C}_9^{\rm U}$	$+0.56$	$[+0.01, +1.15]$		
Sc. 8	$\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$	-0.42	$[-0.57, -0.27]$	5.8	74 %
	$\mathcal{C}_9^{\rm U}$	-0.67	$[-0.90, -0.42]$		

LFUV but also LFU NP ?

R_K and R_{K^*} support LFUV NP, but there could also be a LFU piece

$$\mathcal{C}_{ie} = \mathcal{C}_i^{\mathrm{U}} \qquad \mathcal{C}_{i\mu} = \mathcal{C}_i^{\mathrm{U}} + \mathcal{C}_{i\mu}^{\mathrm{V}}$$

with interesting reshuffling between LF**U** and LFU**V** contributions

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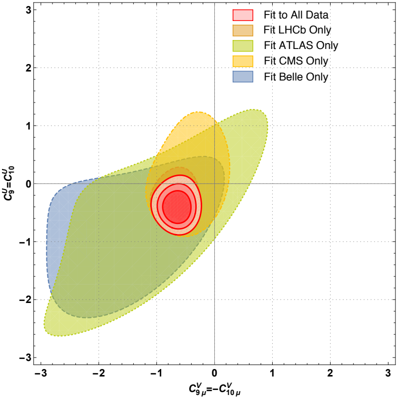
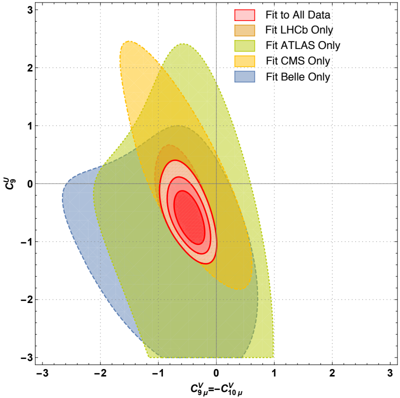
2019		Best-fit point	1 σ	Pull$_{\mathrm{SM}}$	p-value
Sc. 5	$\mathcal{C}_{9\mu}^{\mathrm{V}}$	-0.34	$[-0.93, +0.19]$	5.5	72 %
	$\mathcal{C}_{10\mu}^{\mathrm{V}}$	$+0.69$	$[+0.21, +1.12]$		
	$\mathcal{C}_9^{\mathrm{U}} = \mathcal{C}_{10}^{\mathrm{U}}$	-0.50	$[-0.92, +0.02]$		
Sc. 6	$\mathcal{C}_{9\mu}^{\mathrm{V}} = -\mathcal{C}_{10\mu}^{\mathrm{V}}$	-0.52	$[-0.64, -0.41]$	5.8	71 %
	$\mathcal{C}_9^{\mathrm{U}} = \mathcal{C}_{10}^{\mathrm{U}}$	-0.37	$[-0.52, -0.22]$		
Sc. 7	$\mathcal{C}_{9\mu}^{\mathrm{V}}$	-0.91	$[-1.25, -0.58]$	5.5	65 %
	$\mathcal{C}_9^{\mathrm{U}}$	-0.08	$[-0.46, +0.31]$		
Sc. 8	$\mathcal{C}_{9\mu}^{\mathrm{V}} = -\mathcal{C}_{10\mu}^{\mathrm{V}}$	-0.33	$[-0.45, -0.22]$	5.9	74 %
	$\mathcal{C}_9^{\mathrm{U}}$	-0.72	$[-0.93, -0.47]$		

$\Longrightarrow$ size of LFU-NP quite dependent on structure of LFUV-NP

Two 2D favoured scenarios with LFU and LFUV NP



Scenario 6 (2018)



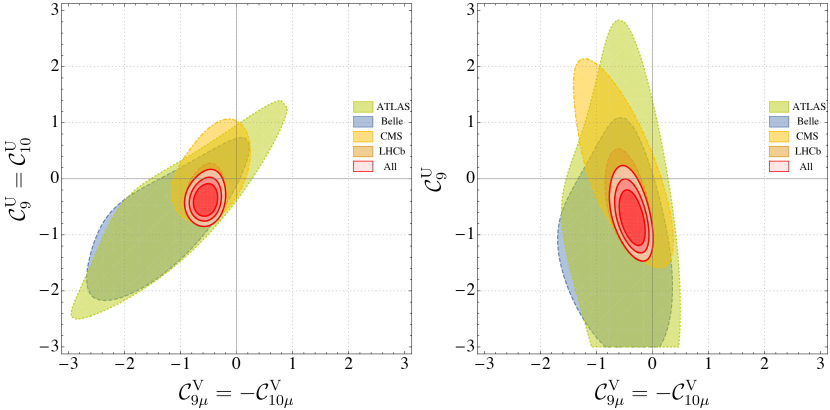
Scenario 8 (2018)

Mild preference for same scenarios as in [Algueró, Capdevila, SDG, Masjuan, Matias]

- scenario 6: LFUV-NP $L_q \otimes L_\ell$ and LFU-NP $L_q \otimes R_\ell$
- scenario 8: LFUV-NP $L_q \otimes L_\ell$ and LFU-NP $L_q \otimes V_\ell$

No dramatic shift compared to our earlier analyses

Two 2D favoured scenarios with LFU and LFUV NP



Scenario 6 (2019) Scenario 8 (2019)

Mild preference for same scenarios as in [Algueró, Capdevila, SDG, Masjuan, Matias]

- scenario 6: LFUV-NP $L_q \otimes L_\ell$ and LFU-NP $L_q \otimes R_\ell$
- scenario 8: LFUV-NP $L_q \otimes L_\ell$ and LFU-NP $L_q \otimes V_\ell$

No dramatic shift compared to our earlier analyses

An EFT illustration

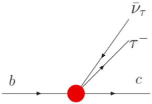
Models to connect & explain $b \to s\ell\ell$ & $b \to c\ell\nu$ [A. Crivellin's and I. Nišandžić talks]
but we may get less model-dep connection in SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

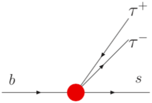
[Grzadkowski, Iskrzynski, Misiak, Rosiek ; Alonso, Grinstein, Camalich]

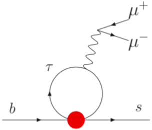
- Two operators with left-handed doublets [Capdevila, Crivellin, SDG, Hofer, Matias]

$$\mathcal{O}^{(1)}_{ijkl} = [\bar{Q}_i \gamma_\mu Q_j][\bar{L}_k \gamma^\mu L_l] \qquad \mathcal{O}^{(3)}_{ijkl} = [\bar{Q}_i \gamma_\mu \vec{\sigma} Q_j][\bar{L}_k \gamma^\mu \vec{\sigma} L_l]$$

- FCCC part of $\mathcal{O}^{(1,3)}_{2333}$ can describe $R_{D^{(*)}}$ with $C^{(1)}_{2333} = C^{(3)}_{2333}$
  - Simple rescaling of G_F for $b \to c\tau\nu$
- FCNC part of $\mathcal{O}^{(1,3)}_{2333}$
  - Contribute to $b \to s\tau\tau$ with opposite contributions to $\mathcal{C}^{\rm V}_{9\tau} = -\mathcal{C}^{\rm V}_{10\tau}$
  - Avoids bounds from $B \to K(^*)\nu\nu$, Z decays, direct production in $\tau\tau$
  - Through radiative effects, (small) NP contribution to $\mathcal{C}^{\rm U}_9$







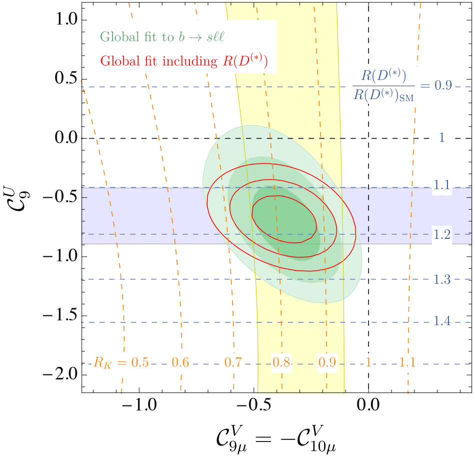
An EFT illustration

Scenario 8 studied before

- $\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$ from small $\mathcal{O}_{2322}$ [$b \to s\mu\mu$]
- $\mathcal{C}_{9}^{\rm U}$ from radiative corr from large $\mathcal{O}_{2333}$ [$b \to c\tau\nu$ and $b \to s\mu\mu$]

Generic flavour structure and NP at the scale Λ yields

$$\mathcal{C}_9^{\rm U} \approx 7.5\left(1-\sqrt{\frac{R_{D^{(*)}}}{R_{D^{(*)};\rm SM}}}\right) \times \left(1+\frac{\log(\Lambda^2/(1{\rm TeV}^2))}{10.5}\right)$$



$\Longrightarrow$Agreement with Belle updated (R_D, R_{D^*}) for $\Lambda = 1 - 10$ TeV

[G. Cartio's talk@Moriond EW]

More models/scenarios with LFU + LFUV NP

Vector-like quark(s) [Bobeth, Buras, Celis, Jung]

- SM $\otimes$ $U(1)_{L_\mu - L_\tau}$ broken by scalars ($SU(2)_L$ singlets or doublets)
- SM quarks Yuakwa-coupled to vector-like quark coupling to Z'
- Z' exchange ($\mathcal{C}^{\mathrm{V}}_{9(')\mu}$) + corrections to Z vertex ($\mathcal{C}^{\mathrm{U}}_{10(')}$)

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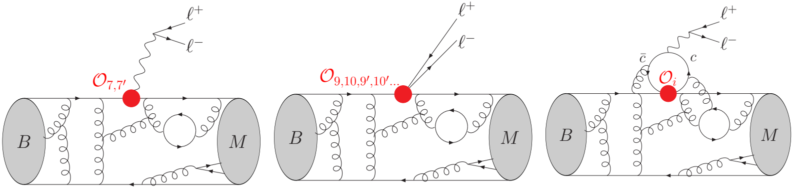
- Z' exchange ($\mathcal{C}^{\rm V}_{9(')\mu}$) + corrections to Z vertex ($\mathcal{C}^{\rm U}_{10(')}$)

2019		Best-fit point	1 σ	Pull$_{\rm SM}$	p-value
Sc. 9	$\mathcal{C}^{\rm V}_{9\mu} = -\mathcal{C}^{\rm V}_{10\mu}$	-0.63	$[-0.79, -0.47]$	5.3	73 %
	$\mathcal{C}^{\rm U}_{10}$	-0.39	$[-0.65, -0.13]$		
Sc. 10	$\mathcal{C}^{\rm V}_{9\mu}$	-0.99	$[-1.17, -0.80]$	5.7	69.7 %
	$\mathcal{C}^{\rm U}_{10}$	$+0.29$	$[0.10, 0.48]$		
Sc. 11	$\mathcal{C}^{\rm V}_{9\mu}$	-1.07	$[-1.25, -0.88]$	5.9	73.9 %
	$\mathcal{C}^{\rm U}_{10'}$	-0.31	$[-0.48, -0.13]$		
Sc. 12	$\mathcal{C}^{\rm V}_{9'\mu}$	-0.05	$[-0.23, 0.14]$	1.7	13.1 %
	$\mathcal{C}^{\rm U}_{10}$	$+0.43$	$[0.22, 0.65]$		
Sc. 13	$\mathcal{C}^{\rm V}_{9\mu}$	-1.12	$[-1.29, -0.94]$	5.6	78.7 %
	$\mathcal{C}^{\rm V}_{9'\mu}$	$+0.48$	$[0.19, 0.85]$		
	$\mathcal{C}^{\rm U}_{10}$	$+0.26$	$[0.01, 0.50]$		
	$\mathcal{C}^{\rm U}_{10'}$	-0.05	$[-0.28, 0.18]$		

So many scenarios, so many models, how to separate all them ?

Disentangling scenarios: more precision



- Reduce hadronic uncertainties on form factors
  - low recoil: lattice [Horgan, Liu, Meinel, Wingate; HPQCD collab]
  - large recoil: B-meson LCSR [Khodjamirian, Mannel, Pivovarov, Wang]
  - all: fit of light-meson LCSR + lattice [Bharucha, Straub, Zwicky]
  - all: fit of B-meson LCSR + lattice [Gubernari, Kokulu, van Dyk]

  $\Longrightarrow$only one (BSZ) computation for $B_s \to \phi$ form factors for now ?

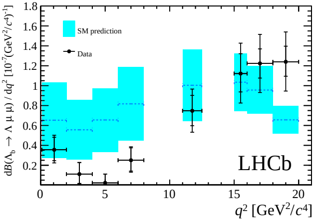
- Reduce hadronic uncertainties on $c\bar{c}$ contributions
  - Many different estimates at large recoil (all in agreement)

    $\Longrightarrow$check normalisation through light-meson LCSR at $q^2 \leq 0$?
  - Low-recoil involves estimate of quark-hadron duality violation

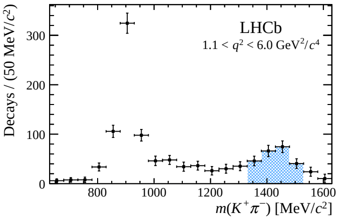
    $\Longrightarrow$based on Shifman's model applied to $BR(B \to K\ell\ell)$, can we do any better ? [Beylich, Buchalla, Feldmann]

Disentangling scenarios: more modes

$d\Gamma(\Lambda_b \to \Lambda(\to N\pi)\ell^+\ell^-)/dq^2$



$B \to K\pi\mu\mu$ around $K^*(1430)$

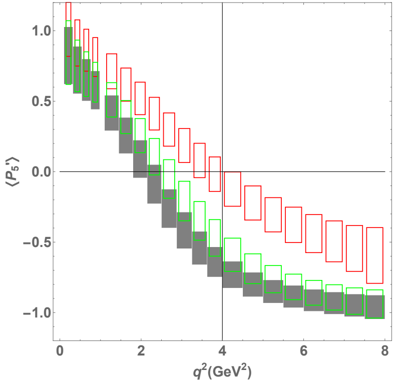


Different info and systematics in angular distributions known for

- $\Lambda_b \to \Lambda(\to N\pi)\ell^+\ell^-$ [Böer, Feldmann, van Dyk; Detmold, Meinel; Diganta; Blake, Kreps]
- $\Lambda_b \to \Lambda(1520)(\to NK)\ell^+\ell^-$ [SDG, Novoa Brunet]
- $B \to K^{*J}(\to K\pi)\ell^+\ell^-$ [Lu, Wang; Gratrex, Hopfer, Zwicky; Dey; Das, Kindra, Kumar, Mahajan]

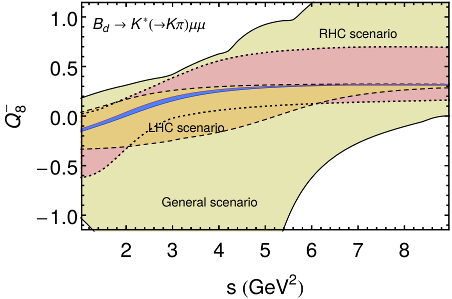
- Form factors not so well known [Detmold, Lin, Meinel, Wingate, Rendon]
- Large recoil
  - Status of factorisation for not-so-light mesons ? baryons ?
  - Could be tackled with form factors + analytic repr. of $c\bar{c}$ contribution but normalisation of $c\bar{c}$ at $q^2 \leq 0$ [LCSR] [Bobeth, Chrzaszcz, van Dyk, Virto]
- Low recoil: estimate of quark-hadron duality violation ?

Disentangling scenarios: more observables (1)



Smaller bins to probe q^2 dependence better

(green $\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$, red $\mathcal{C}_{9\mu}^{\rm NP}$)



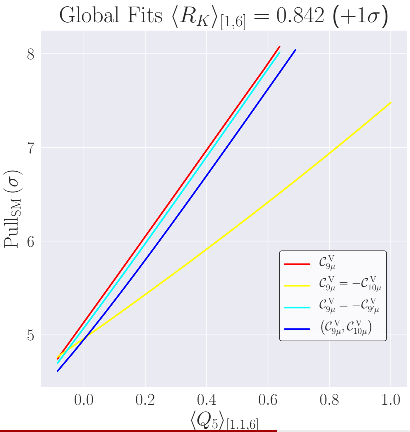
Time-dependent observables in $B_d \to K^*(\to K_S\pi^0)\ell^+\ell^-$ and $B_s \to \phi(\to K^+K^-)\ell^+\ell^-$

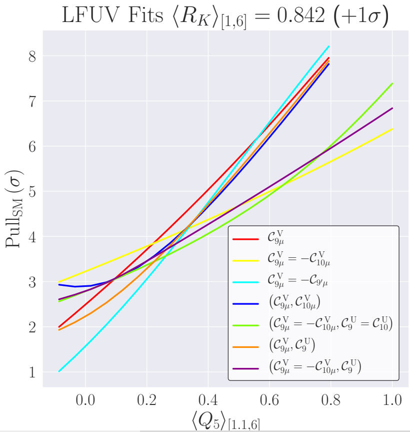
[SDG, Virto]

Disentangling scenarios: more observables (2)

- other LFUV quantities: R_ϕ, $R^{T,L}_{K,\phi}$, $Q_i = P_i^\mu - P_i^e$
- $Q_5 = P_5^{\mu\prime} - P_5^{e\prime}$ interesting observable to disentangle
  - $\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}$ from others NP scenarios in $b \to s\mu\mu$
  - classes of scenarios allowing for LFU contributions

[Alguero, Capdevila, SDG, Masjuan, Matias]





Outlook (1)

Anomalies/deviations/tensions in $b \to s\ell\ell$

- $b \to s\mu\mu$ branching ratios and angular observables
- R_{K^*}: LFUV for $B \to K(^*)\mu\mu$ vs $B \to K(^*)ee$
- Recent updates from LHCb and Belle for R_K R_{K^*}

How to understand these deviations ?

- Effective Hamiltonian: separation of scale
- All NP encoded in Wilson coefficients to be fit to the data
- Large set of observables from $b \to s\mu\mu$, $b \to see$, $b \to s\gamma$
- Still need to focus on specific scenarios for Wilson coefficients

Ongoing activity from several groups

- Assess hadronic uncertainties
- Update experimental inputs
- Interpret the data in terms of SM and NP scenarios
- With various statistical approaches, theoretical prejudices…

Update from 1903.09578 [Algueró, Capdevila, Crivellin, SDG, Masjuan, Matias, Virto]
including R_K and R_{K*} new results (low and large recoil)

Outlook (2)

Very similar structure as in 2017 for 1D NP in $b \to s\mu\mu$

- Fit to All: preference for $\mathcal{C}_{9\mu}^{\rm NP}$ only and $\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}^{\rm NP}$ compared to $\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$, but reduced difference of pulls
- Fit to LFUV: inverted preference with increased difference of pulls

A few changes compared to 2017 for 2D NP in $b \to s\mu\mu$

- Scenarios with right-handed currents $(\mathcal{C}_{9\mu}, \mathcal{C}_{10'\mu})$ or $(C_{9\mu}, C_{9'\mu} = -C_{10'\mu})$ accomodate quite well the situation
- Scenario $\mathcal{C}_{9\mu}, \mathcal{C}_{10\mu}$ good, with slightly lower SM pull

Scenarios with both LFU and LFUV NP

- Favours LFUV-NP $L_q \otimes L_\ell$ and LFU-NP either $L_q \otimes R_\ell$ or $L_q \otimes V_\ell$
- Latter naturally implemented in EFT, with connection between $b \to s\mu\mu$ and $b \to c\tau\nu$ via radiative effects
- Good overall description of current data, improved with new $R_{D^{(*)}}$

Still many competing scenarios improving wrt SM
More observables needed soon to disentangle them !

Bonus track

Finding patterns of NP

Effective Hamiltonian approach

- Separation of scales, all NP info to be determined in $\mathcal{C}_i$
- Global fit useful tool to identify consistent patterns that alleviate the deviations (otherwise fluctuations !)
- SM LFU: $\mathcal{C}_{ie}^{\rm SM} = \mathcal{C}_{i\mu}^{\rm SM}$, but not always true for NP contribution $\mathcal{C}_{i\ell}^{\rm NP}$

Finding patterns of NP

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NP in which Wilson coefficients ?

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NP in which Wilson coefficients ?

- Hints of LFUV and deviations in $b \to s\mu\mu$ but not in $b \to see$
  $\Longrightarrow$Focus first on NP in $b \to s\mu\mu$

Finding patterns of NP

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  $\Longrightarrow$Focus first on NP in $b \to s\mu\mu$
- No indication of CPV in the data
  $\Longrightarrow$NP contributions generally taken as real (no weak phase)

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  $\Longrightarrow$Focus first on NP in $b \to s\mu\mu$
- No indication of CPV in the data
  $\Longrightarrow$NP contributions generally taken as real (no weak phase)
- $Br(B \to X_s\gamma)$ in very good agreement with SM and LFUV hints
  $\Longrightarrow$Disregard first LFU contributions from $\mathcal{C}_7^{\rm NP}$ and $\mathcal{C}_{7'}^{\rm NP}$

Finding patterns of NP

Effective Hamiltonian approach

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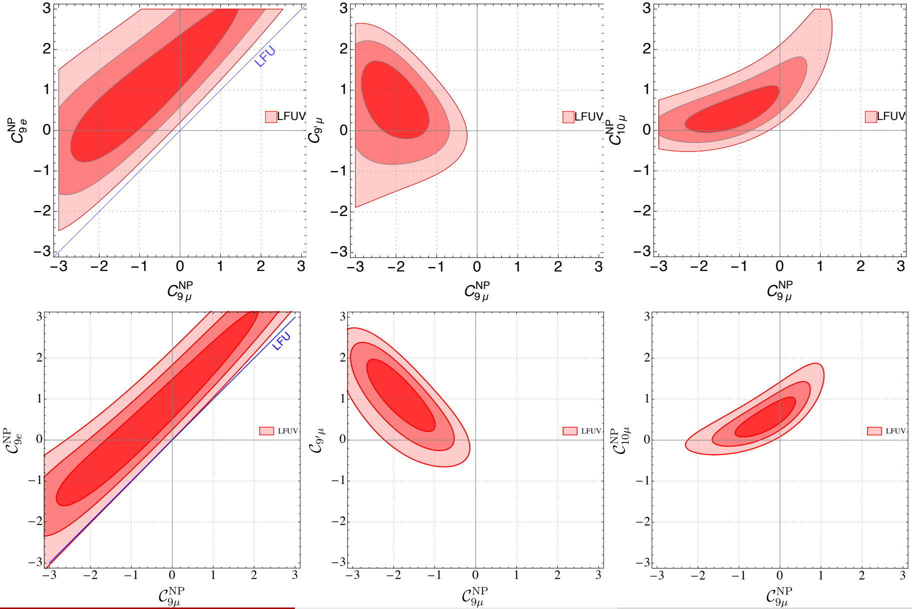
  $\Longrightarrow$Focus first on NP in $b \to s\mu\mu$
- No indication of CPV in the data
  $\Longrightarrow$NP contributions generally taken as real (no weak phase)
- $Br(B \to X_s\gamma)$ in very good agreement with SM and LFUV hints
  $\Longrightarrow$Disregard first LFU contributions from $\mathcal{C}_7^{\rm NP}$ and $\mathcal{C}_{7'}^{\rm NP}$
- No indication for large scalar/pseudoscalar contributions
  $\Longrightarrow$Focus first on vector and axial contributions

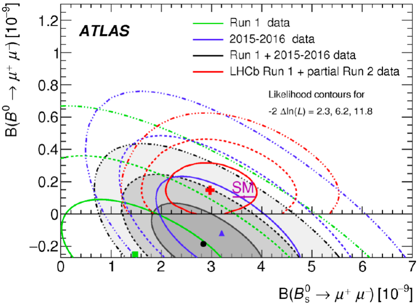
$$\mathcal{O}_9 \sim L_q \otimes V_\ell \quad \mathcal{O}_{10} \sim L_q \otimes A_\ell \quad \mathcal{O}_{9'} \sim R_q \otimes V_\ell \quad \mathcal{O}_{10'} \sim R_q \otimes A_\ell$$

[Ciuchini, Coutinho, Fedele, Franco, Mishima, Paul, Silvestrini, Valli; Straub, Altmannshoffer; Hurth, Mahmoudi, Neshatpour...]

LFUV fits in 2017 (top) and 2019 (bottom)



$B_s \to \mu\mu$



- Recent results increasing a bit the discrepancy between SM and (a tad too low) exp average ($\sim 1.8\sigma$)
  - ATLAS 2018 $Br(B_s \to \mu\mu) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$
  - LHCb 2017 $Br(B_s \to \mu\mu) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$
  - CMS 2013 $Br(B_s \to \mu\mu) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$
- $B(B_s \to \mu\mu)$ depending on
  - $\mathcal{C}_{10} - \mathcal{C}_{10'}$ and one decay constant f_{B_s} at LO
  - higher orders (EW, QCD) computed accurately in SM [Bobeth et al.]

Other interesting scenarios

2017	$\mathcal{C}_7^{\rm NP}$	$\mathcal{C}_{9\mu}^{\rm NP}$	$\mathcal{C}_{10\mu}^{\rm NP}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Bfp	+0.03	-1.12	+0.31	+0.03	+0.38	+0.02
1 σ	$[-0.01, +0.05]$	$[-1.34, -0.88]$	$[+0.10, +0.57]$	$[+0.00, +0.06]$	$[-0.17, +1.04]$	$[-0.28, +0.36]$
2 σ	$[-0.03, +0.07]$	$[-1.54, -0.63]$	$[-0.08, +0.84]$	$[-0.02, +0.08]$	$[-0.59, +1.58]$	$[-0.54, +0.68]$

- 6D scenario (SM + chirally flipped in $b \to s\mu\mu$) in 2017

Other interesting scenarios

2019	$\mathcal{C}_7^{\rm NP}$	$\mathcal{C}_{9\mu}^{\rm NP}$	$\mathcal{C}_{10\mu}^{\rm NP}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Bfp	+0.02	-1.13	+0.21	+0.02	+0.39	-0.12
1 σ	$[-0.01, +0.05]$	$[-1.28, -0.91]$	$[+0.04, +0.42]$	$[+0.00, +0.04]$	$[-0.09, +0.96]$	$[-0.40, +0.17]$
2 σ	$[-0.03, +0.06]$	$[-1.48, -0.71]$	$[-0.12, +0.61]$	$[-0.02, +0.06]$	$[-0.56, +1.14]$	$[-0.57, +0.34]$

- 6D scenario (SM + chirally flipped in $b \to s\mu\mu$) in 2017 and 2019
  - $\mathcal{C}_{9\mu}^{\rm NP} < 0$ needed, $\mathcal{C}_{9'\mu}^{\rm NP} > 0$, $\mathcal{C}_{10\mu}^{\rm NP} > 0$, $\mathcal{C}_{10'\mu}^{\rm NP} < 0$ favoured
  - SM pull 5.3 σ (5.0 σ in 2017)

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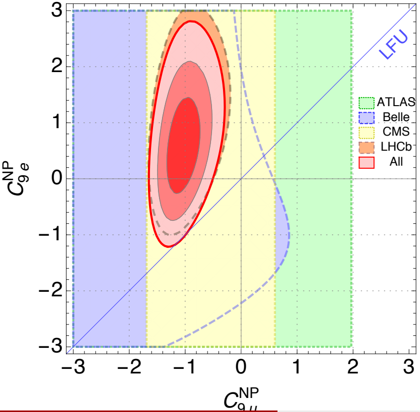

- NP in $(\mathcal{C}_{9\mu}, \mathcal{C}_{9e})$ in 2017

Other interesting scenarios

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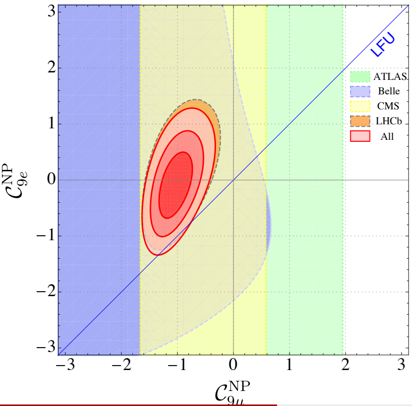

- NP in $(\mathcal{C}_{9\mu}, \mathcal{C}_{9e})$ in 2019
  - Less need for NP in $b \to see$
  - Though some room available (not many obs)
  - SM pull=5.5 σ, p-value=65% (unchanged wrt 2017)

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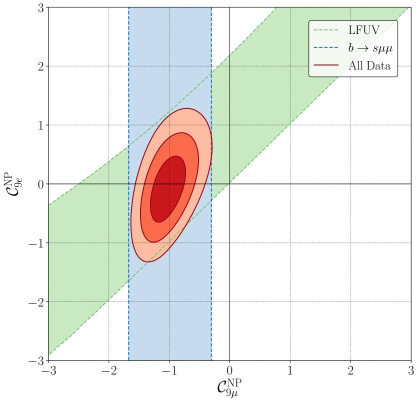

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arXiv.org > hep-ph > arXiv:1903.09617

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High Energy Physics – Phenomenology

Continuing search for new physics in $b \to s\mu\mu$ decays: two operators at a time

Ashutosh Kumar Alok, Amol Dighe, Shireen Gangal, Dinesh Kumar

(Submitted on 22 Mar 2019)

The anomalies in the measurements of observables involving $b \to s\mu\mu$ decays, namely R_K, R_{K^*}, P_5', and B_s^ϕ, may be addressed by adding lepton-universality-violating new physics contributions to the effective operators $\mathcal{O}_9, \mathcal{O}_{10}, \mathcal{O}_9', \mathcal{O}_{10}'$. We analyze all the scenarios where the new physics contributes to a pair of these operators at a time. We perform a global fit to all relevant data in the $b \to s$ sector to estimate the corresponding new Wilson coefficients, $C_9^{\rm NP}, C_{10}^{\rm NP}, C_9', C_{10}'$. In the light of the new data on R_K and R_{K^*} presented in Moriond 2019, we find that the scenarios with new physics contributions to the ($C_9^{\rm NP}$, C_9') or ($C_9^{\rm NP}$, C_{10}') pair remain the most favored ones. On the other hand, though the competing scenario ($C_9^{\rm NP}$, $C_{10}^{\rm NP}$) remains attractive, its advantage above the SM reduces significantly due to the tension that emerges between the R_K and R_{K^*} measurements with the new data. The movement of the R_K measurement towards unity would also result in the re-emergence of the one-parameter scenario $C_9^{\rm NP} = -C_9'$.

arXiv:1903.09632

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High Energy Physics – Phenomenology

New Physics in $b \to s\ell^+\ell^-$ confronts new data on Lepton Universality

Marco Ciuchini, António M. Coutinho, Marco Fedele, Enrico Franco, Ayan Paul, Luca Silvestrini, Mauro Valli

(Submitted on 22 Mar 2019)

In light of the very recent updates on the R_K and R_{K^*} measurements from the LHCb and Belle collaborations, we systematically explore here imprints of New Physics in $b \to s\ell^+\ell^-$ transitions using the language of effective field theories. We focus on effects that violate Lepton Flavour Universality both in the Weak Effective Theory and in the Standard Model Effective Field Theory. In the Weak Effective Theory we find a preference for scenarios with the simultaneous presence of two operators, a left-handed quark current with vector muon coupling and a right-handed quark current with axial muon coupling, irrespective of the treatment of hadronic uncertainties. In the Standard Model Effective Field Theory we select different scenarios according to the treatment of hadronic effects: while an aggressive estimate of hadronic uncertainties points to the simultaneous presence of two operators, one with left-handed quark and muon couplings and one with left-handed quark and right-handed muon couplings, a more conservative treatment of hadronic matrix elements leaves room for a broader set of scenarios, including the one involving only the purely left-handed operator with muon coupling.

arXiv:1903.10434

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High Energy Physics – Phenomenology

B-decay discrepancies after Moriond 2019

Jason Aebischer, Wolfgang Altmannshofer, Diego Guadagnoli, Meril Reboud, Peter Stangl, David M. Straub

(Submitted on 25 Mar 2019)

Following the updated measurement of the lepton flavour universality (LFU) ratio R_K in B -> Kll decays by LHCb, as well as a number of further measurements, e.g. R_K* by Belle and B_s -> mu mu by ATLAS, we analyse the global status of new physics in b -> s transitions in the weak effective theory at the b-quark scale, in the Standard Model effective theory at the electroweak scale, and in simplified models of new physics. We find that the data continues to strongly prefer a solution with new physics in semi-leptonic Wilson coefficients. A purely muonic contribution to the combination C_9 = -C_10, well suited to UV-complete interpretations, is now favoured with respect to a muonic contribution to C_9 only. An even better fit is obtained by allowing an additional LFU shift in C_9. Such a shift can be renormalization-group induced from four-fermion operators above the electroweak scale, in particular from semi-tauonic operators, able to account for the potential discrepancies in b -> c transitions. This scenario is naturally realized in the simplified U_1 leptoquark model. We also analyse simplified models where a LFU effect in b -> sll is induced radiatively from four-quark operators and show that such a setup is on the brink of exclusion by LHC di-jet resonance searches.

arXiv.org > hep-ph > arXiv:1704.05438

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High Energy Physics – Phenomenology

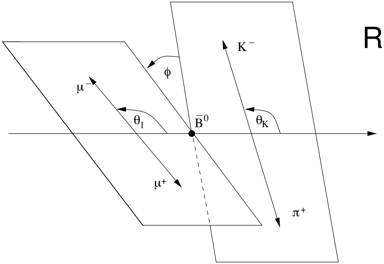
Flavour anomalies after the R_{K^*} measurement

Guido D'Amico, Marco Nardecchia, Paolo Panci, Francesco Sannino, Alessandro Strumia, Riccardo Torre, Alfredo Urbano

(Submitted on 18 Apr 2017 (v1), last revised 25 Mar 2019 (this version, v4))

The LHCb measurement of the μ/e ratio R_{K^*} indicates a deficit with respect to the Standard Model prediction, supporting earlier hints of lepton universality violation observed in the R_K ratio. We show that the R_K and R_{K^*} ratios alone constrain the chiralities of the states contributing to these anomalies, and we find deviations from the Standard Model at the 4σ level. This conclusion is further corroborated by hints in the theoretically challenging $b \to s\mu^+\mu^-$ distributions. Theoretical interpretations in terms of Z', lepto-quarks, loop mediators, and composite dynamics are discussed. We highlight their distinctive features in terms of chiralities and flavour structure relevant for the observed anomalies.

$B \to K^*(\to K\pi)\mu\mu$ (1)



Rich kinematics

- differential decay rate in terms of 12 angular coeffs $J_i(q^2)$ with $q^2 = (p_{\ell^+} + p_{\ell^-})^2$
- interferences between 8 transversity amplitudes for $B \to K^*(\to K\pi)V^*(\to \ell\ell)$

[Ali, Hiller, Matias, Krüger, Mescia, SDG, Virto, Hofer, Bobeth, van Dyck, Buras, Altmanshoffer, Straub, Bharucha, Zwicky, Gratrex, Hopfer, Becirevic, Sumensari, Zukanovic-Funchal . . .]

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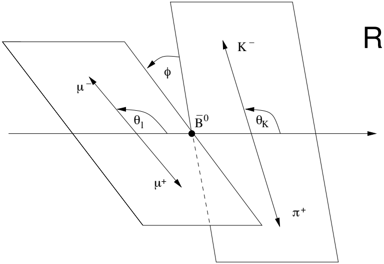

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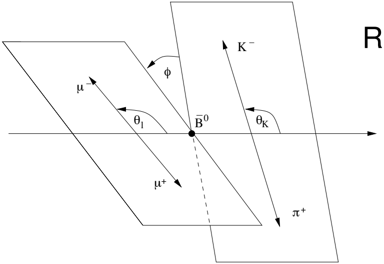
- Transversity amplitudes in terms of 7 form factors $A_{0,1,2}$, V, $T_{1,2,3}$
- Relations between form factors in limit $m_B \to \infty$, either when K^* very soft or very energetic (low/large-recoil)

$B \to K^*(\to K\pi)\mu\mu$ (1)



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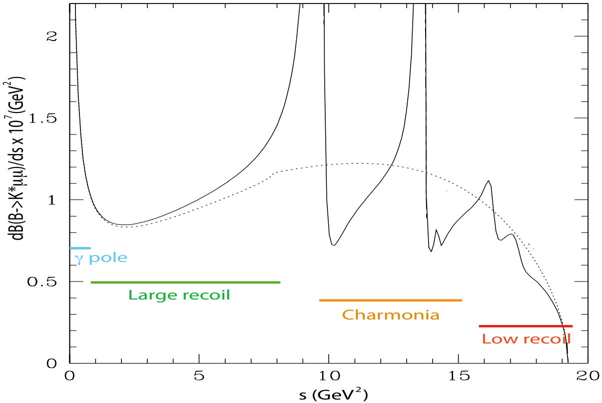
- Transversity amplitudes in terms of 7 form factors $A_{0,1,2}$, V, $T_{1,2,3}$
- Relations between form factors in limit $m_B \to \infty$,
  either when K^* very soft or very energetic (low/large-recoil)
- Build ratios of J_i where form factors cancel in these limits
  (corrections by hard gluons $O(\alpha_s)$, power corrs $O(\Lambda/m_B)$)
- Optimised observables P_i with reduced hadronic uncertainties

[Matias, Krüger, Becirevic, Schneider, Mescia, Virto, SDG, Ramon, Hurth; Hiller, Bobeth, van Dyk]

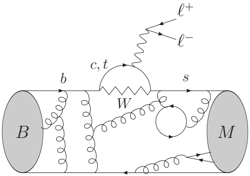
$B \to K^* \mu\mu$ (2)



- Very large K^*-recoil ($4m_\ell^2 < q^2 < 1$ GeV^2) γ almost real
- Large K^*-recoil ($q^2 < 9$ GeV^2) energetic K^* ($E_{K^*} \gg \Lambda_{QCD}$)
  LCSR, SCET, QCD factorisation
- Charmonium region ($q^2 = m^2_{\psi,\psi'...}$ between 9 and 14 GeV^2)
- Low K^*-recoil ($q^2 > 14$ GeV^2) soft K^* ($E_{K^*} \simeq \Lambda_{QCD}$)
  Lattice QCD, HQET, Operator Product Expansion

Two sources of hadronic uncertainties

$$A(B \to M\ell\ell) = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [(A_\mu + T_\mu) \bar{u}_\ell \gamma^\mu v_\ell + B_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell]$$



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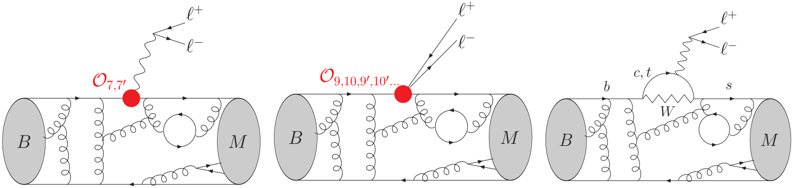

Form factors (local)

- Local contributions (more terms if NP in non-SM $\mathcal{C}_i$): form factors

$$A_\mu = -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle M|\bar{s}\sigma_{\mu\nu} P_R b|B\rangle + \mathcal{C}_9 \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

$$B_\mu = \mathcal{C}_{10} \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

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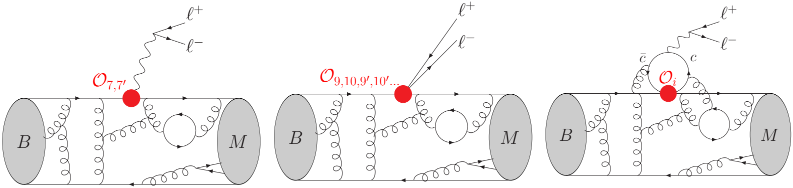

Form factors (local) Charm loop (non-local)

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$$B_\mu = \mathcal{C}_{10}\langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

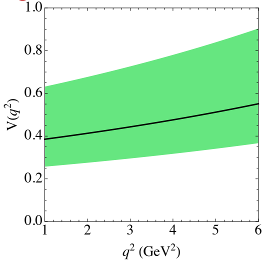
- Non-local contributions (charm loops): hadronic contribs.

T_μ contributes like $\mathcal{O}_{7,9}$, but depends on q^2 and external states

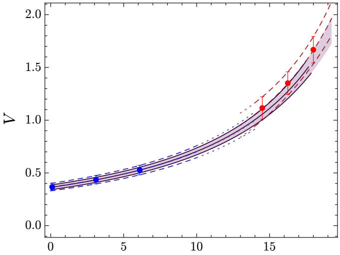
Hadronic uncertainties: form factors

3 form factors for K, 7 form factors for K^* and ϕ

- low recoil: lattice, with correlations [Horgan, Liu, Meinel, Wingate; HPQCD collab]
- large recoil: B-meson Light-Cone Sum Rule,
  large error bars and no correlations [Khodjamirian, Mannel, Pivovarov, Wang]
- all:fit light-meson LCSR + lattice, small errs, correls [Bharucha, Straub, Zwicky]



KMPW (LCSR, low q^2)



BSZ (fit LCSR + lattice)

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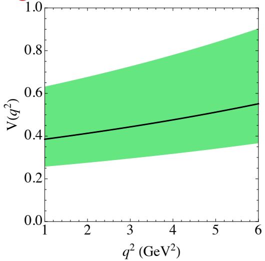

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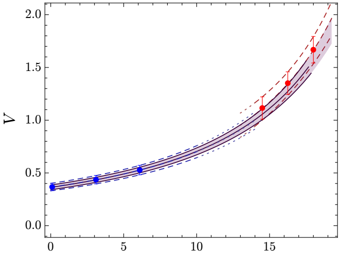


BSZ (fit LCSR + lattice)

- former controversies about EFT to obtain/restore correlations for form factors discussed and all approaches in good agreement

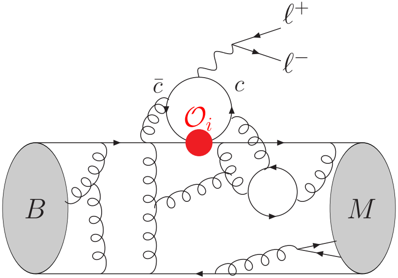
[Jäger, Camalich; Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]

- alternative LCSR determination for $B_s \to \phi\mu\mu$? (only BSZ)

Hadronic uncertainties: charm loops

Charm loops

- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_{9\ell}$
- expected to depend on q^2
- ...but lepton universal (little effect on R_K, even with NP)



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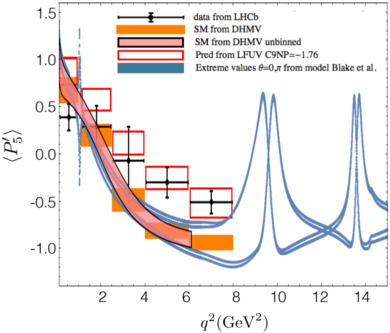

Several theo/pheno approaches

- LCSR estimate [Khodjamirian, Mannel, Pivovarov, Wang]
- order of magnitude estimate for the fits (LCSR or Λ/m_b), check with bin-by-bin fits [Crivellin, Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]
- fit of sum of resonances to the data [Blake, Egede, Owen, Pomery, Petridis]

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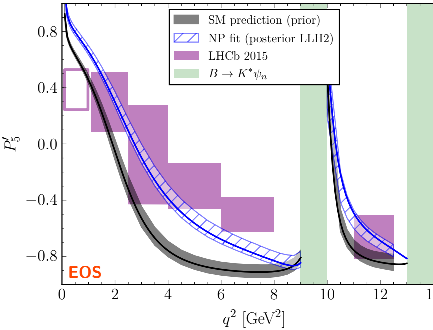

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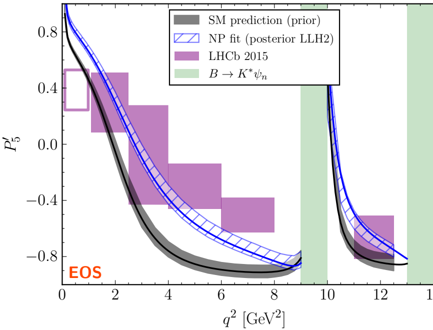
- order of magnitude estimate for the fits (LCSR or Λ/m_b), check with bin-by-bin fits [Crivellin, Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]
- fit of sum of resonances to the data [Blake, Egede, Owen, Pomery, Petridis]
- fit of q^2-parametrisation to the data [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli; Capdevila, SDG, Hofer, Matias]
- dispersive representation + $J/\psi, \psi(2S)$ data [Bobeth, Chrzaszcz, van Dyk, Virto]

Hadronic uncertainties: charm loops

Charm loops

- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_{9\ell}$
- expected to depend on q^2
- ...but lepton universal (little effect on R_K, even with NP)



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No sign of missing large (hadronic) q^2-dependent contrib to $b \to s\mu\mu$