B-physics anomalies, fluctuations and patterns: a status report

Sébastien Descotes-Genon

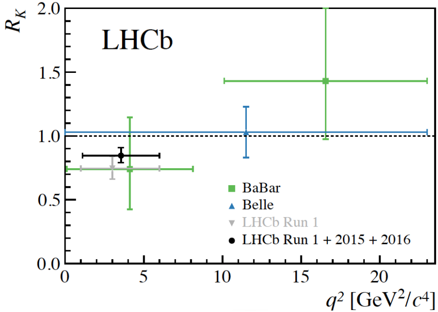
Laboratoire de Physique Théorique
CNRS, Univ. Paris-Sud, Université Paris-Saclay, Orsay, France

ALPS 2019, Obergurgl, 23/4/19

From Moriond to Obergurgl

LFU violation in $b \to s\ell\ell$

Two updates@Moriond on Lepton Flavour Unversality Violation (LFUV)



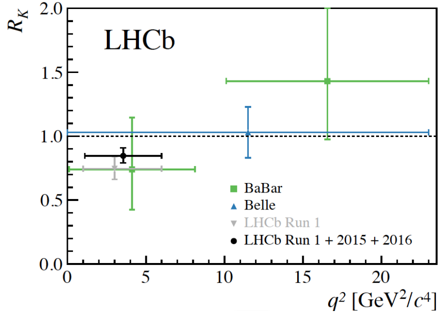
- LHCb update

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

- From 2.6σ to 2.5σ deviation wrt SM

LFU violation in $b \to s\ell\ell$

Two updates@Moriond on Lepton Flavour Unversality Violation (LFUV)

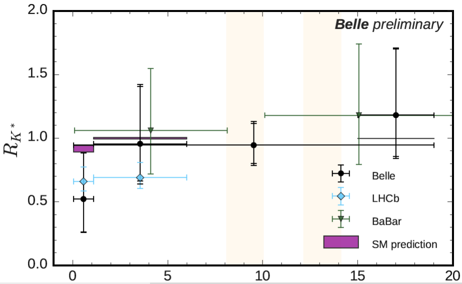


- LHCb update

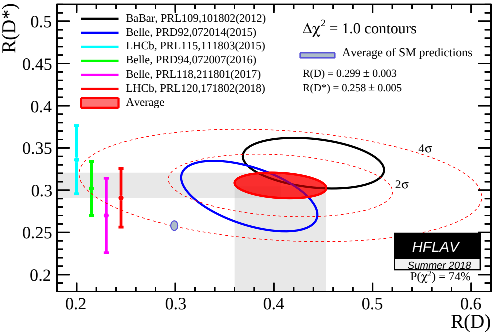
$$R_K^{[1.1,6]} = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}$$
$$= 0.846^{+0.060+0.016}_{-0.054-0.014}$$

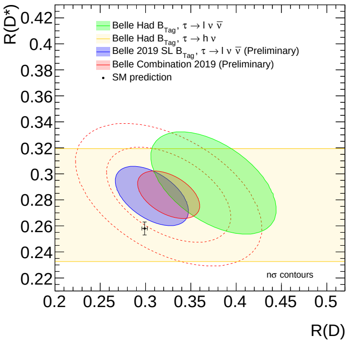
- From 2.6σ to 2.5σ deviation wrt SM

- Belle: $R_{K^*} = \frac{B(B \to K^*\mu\mu)}{B(B \to K^*ee)}$ in 3 bins (large/low-K^* recoil)
- OK with SM, but also LHCb [2.3 (2.6) σ from SM for $R_{K^*}^{[0.045,1.1]}$ ($[1.1,6]$)]



LFU violation in $b \to c\ell\nu$





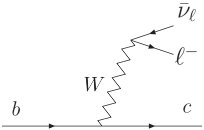
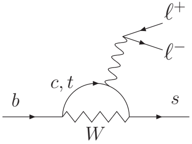
- Belle update @Moriond

  (semileptonic tag for B and leptonic decay for τ)

$$R_D = \frac{Br(B \to D\tau\nu)}{Br(B \to D\ell\nu)} \qquad R_{D^*} = \frac{Br(B \to D^*\tau\nu)}{Br(B \to D^*\ell\nu)}$$

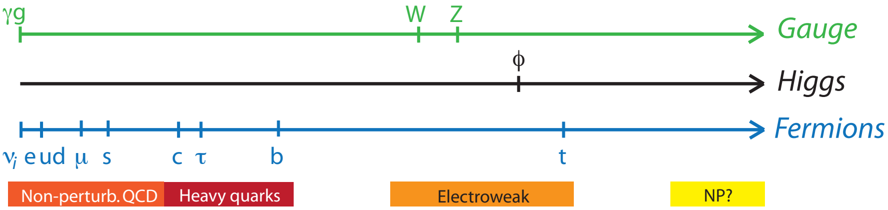
- Closer to SM than earlier determinations by Babar, Belle, LHCb
- World average deviating from SM by $3.8\sigma \to 3.1\sigma$ currently

Two sets of "anomalies"

	$b \to c\ell\bar{\nu}_\ell$	$b \to s\ell^+\ell^-$
		
SM	tree (charged) $(V-A)$	loop (neutral)
Spin 0	$\overline{B} \to D\ell\bar{\nu}_\ell$	$B \to K\ell\ell$
Spin 1	$\overline{B} \to D^*\ell\bar{\nu}_\ell$	$B \to K^*\ell\ell$, $B_s \to \phi\ell\ell$
Observables	Total Br	$d\Gamma/dq^2$ + Angular obs
with	$\ell = \tau, \mu, e$	$\ell = \mu, e$
LFUV tensions	$R_{D^{(*)}} = \dfrac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}\ell\bar{\nu}_\ell)}$	$R_{K^{(*)}} = \dfrac{Br(B \to K^{(*)}\mu\mu)}{Br(B \to K^{(*)}ee)}$
Other tensions		$Br\ (K, K^*, \phi + \mu\mu)$ angular obs (e.g., P_5')

Two transitions exhibiting interesting patterns of deviations from SM with in particular lepton-flavour universality violation (LFUV)

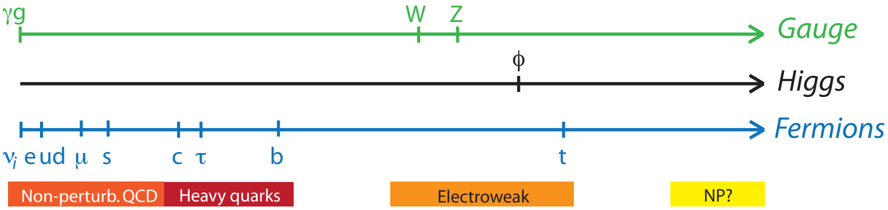
A multi-scale problem



- Several steps to separate/factorise scales

simplified model	$\rightarrow$	SMEFT	$\rightarrow$	Weak EFT	$\rightarrow$	SCET/HQET
BSM	$\rightarrow$	SM+$1/\Lambda_{NP}$	$\rightarrow$	$\mathcal{H}_{eff}$	$\rightarrow$	B-hadron eff. th.
		$(\Lambda_{EW}/\Lambda_{NP})$		(m_b/Λ_{EW})		(Λ_{QCD}/m_b)

A multi-scale problem



- Several steps to separate/factorise scales

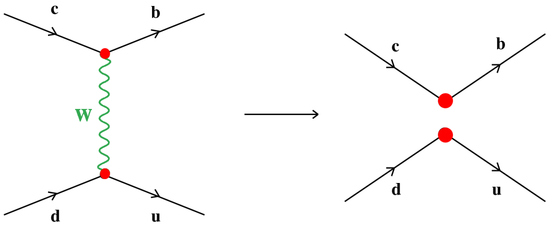
simplified model	$\to$	SMEFT	$\to$	Weak EFT	$\to$	SCET/HQET
BSM	$\to$	SM+$1/\Lambda_{NP}$	$\to$	$\mathcal{H}_{eff}$	$\to$	B-hadron eff. th.
		$(\Lambda_{EW}/\Lambda_{NP})$		(m_b/Λ_{EW})		(Λ_{QCD}/m_b)

- Main theo problem from hadronisation of quarks into hadrons
  description/parametrisation in terms of QCD quantities
  decay constants, form factors, bag parameters...
- Long-distance non-perturbative QCD: source of uncertainties
  lattice QCD simulations, sum rules, effective theories...

Effective approaches

Fermi-like approach (for decoupling th): separation of different scales

Short dist/Wilson coefficients and Long dist/local operator

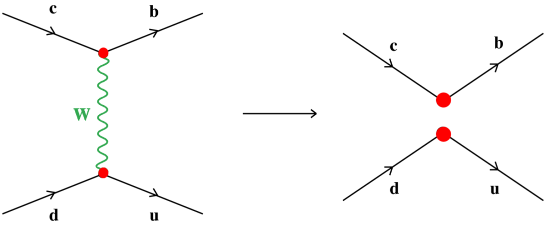


$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \frac{m_W^2}{m_W^2 - p_W^2} \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c$$

Effective approaches

Fermi-like approach (for decoupling th): separation of different scales

Short dist/Wilson coefficients and Long dist/local operator



$$V_{ud}V_{cb}^*\,\frac{G_F}{\sqrt{2}}\;\bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c+O(1/M_W^2)$$

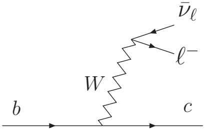
Fermi theory carries some info on the underlying theory

- G_F: scale of underlying physics
- $\mathcal{O}_i$: interaction with left-handed fermions, through charged spin 1
- Losing some info (gauge structure, Z^0 ...)
- But a good start to build models if no particle (=W) already seen

Effective Hamiltonian for B decays

From the SM (or an extension)

down to $\mu = m_b$



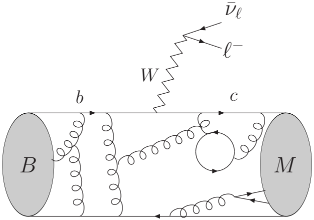
$$\mathcal{H}^{\text{eff}} = CKM \times \mathcal{C}_i \times \mathcal{O}_i$$

$$\langle M|\mathcal{H}^{\text{eff}}|B\rangle = CKM \times \mathcal{C}_i \times \langle M|\mathcal{O}_i|B\rangle$$

Effective Hamiltonian for B decays

From the SM (or an extension)
down to $\mu = m_b$

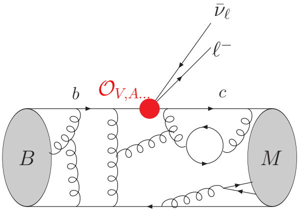
$$\mathcal{H}^{\rm eff} = CKM \times \mathcal{C}_i \times \mathcal{O}_i$$
$$\langle M|\mathcal{H}^{\rm eff}|B\rangle = CKM \times \mathcal{C}_i \times \langle M|\mathcal{O}_i|B\rangle$$



Effective Hamiltonian for B decays

From the SM (or an extension)
down to $\mu = m_b$

$$\mathcal{H}^{\rm eff} = CKM \times \mathcal{C}_i \times \mathcal{O}_i$$
$$\langle M|\mathcal{H}^{\rm eff}|B\rangle = CKM \times \mathcal{C}_i \times \langle M|\mathcal{O}_i|B\rangle$$



involving hadronic quantities such as form factors
selecting processes for accurate predictions:

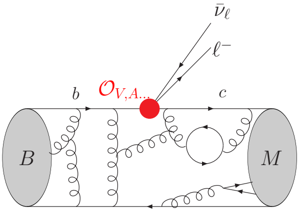
- semileptonic decays (form factors, not more complicated objects)
- ratios of BRs with different leptons (same SM coupling)
- ratios of observables with similar dependence on form factors

$\Longrightarrow$observables with limited sensitivity to (ratio of form) factors

Effective Hamiltonian for B decays

From the SM (or an extension)
down to $\mu = m_b$

$$\mathcal{H}^{\rm eff} = CKM \times \mathcal{C}_i \times \mathcal{O}_i$$
$$\langle M|\mathcal{H}^{\rm eff}|B\rangle = CKM \times \mathcal{C}_i \times \langle M|\mathcal{O}_i|B\rangle$$



involving hadronic quantities such as form factors

selecting processes for accurate predictions:

- semileptonic decays (form factors, not more complicated objects)
- ratios of BRs with different leptons (same SM coupling)
- ratios of observables with similar dependence on form factors

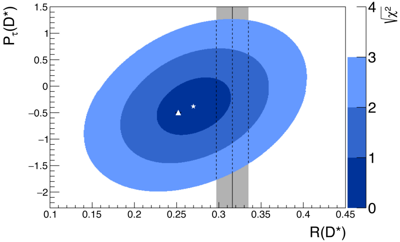
$\Longrightarrow$observables with limited sensitivity to (ratio of form) factors

Two possible uses of effective approaches

- fix $\mathcal{C}_i$, compute SM and compare with the data
- determine $\mathcal{C}_i$ from the data, remove SM part, identify type of NP

A fluid situation for $b \to c\ell\bar{\nu}_\ell$

In addition to R_D, R_{D^*}



τ polarisation in $B \to D^*\tau\nu$

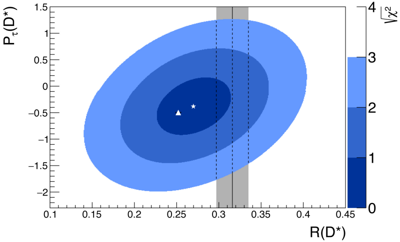
- Belle with $\tau \to X\nu$, $X = \rho$ (or π)

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}[1 + \alpha_X P_\tau \cos\theta_\tau]$$

θ_τ angle $(\vec{p}_X, -\vec{p}_{\tau\nu})$

- Large stat unc, SM compatible, $P_\tau > 0.5$ excluded at 90% CL

In addition to R_D, R_{D^*}



τ polarisation in $B \to D^*\tau\nu$

- Belle with $\tau \to X\nu$, $X = \rho$ (or π)

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}[1 + \alpha_X P_\tau \cos\theta_\tau]$$

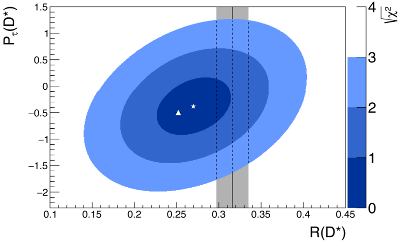
θ_τ angle $(\vec{p}_X, -\vec{p}_{\tau\nu})$

- Large stat unc, SM compatible, $P_\tau > 0.5$ excluded at 90% CL

D^* polarisation in $B \to D^*\tau\nu$

- Angular analysis: $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3}{4}\left[2F_L\cos^2\theta_{D^*} + (1-F_L)\sin^2\theta_{D^*}\right]$
- Belle: $F_L = 0.60 \pm 0.08 \pm 0.04$, agree with SM at 1.7 σ

In addition to R_D, R_{D^*}



τ polarisation in $B \to D^* \tau \nu$

- Belle with $\tau \to X\nu$, $X = \rho$ (or π)

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta} = \frac{1}{2} [1 + \alpha_X P_\tau \cos\theta_\tau]$$

θ_τ angle $(\vec{p}_X, -\vec{p}_{\tau\nu})$

- Large stat unc, SM compatible, $P_\tau > 0.5$ excluded at 90% CL

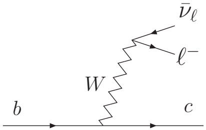
D^* polarisation in $B \to D^* \tau \nu$

- Angular analysis: $\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta} = \frac{3}{4} \left[2F_L \cos^2\theta_{D^*} + (1 - F_L) \sin^2\theta_{D^*} \right]$
- Belle: $F_L = 0.60 \pm 0.08 \pm 0.04$, agree with SM at 1.7 σ

$R_{J/\psi}$ $(B_c \to J/\psi \ell \bar{\nu}_\ell)$

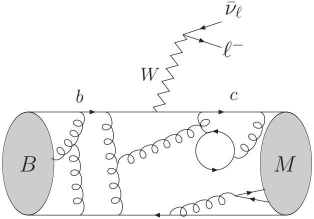
- LHCb: $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ $\qquad \frac{R_D}{R_{D;SM}} \simeq \frac{R_{D^*}}{R_{D^*;SM}} \simeq \frac{R_{J/\psi}}{R_{J/\psi;SM}}$
- Form factors based on models with uncertainties difficult to assess

$b \to c\ell\bar{\nu}_\ell$ effective Hamiltonian



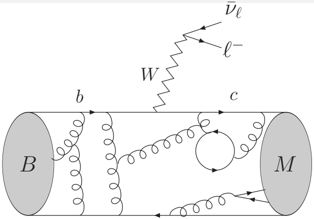
$$\mathcal{H}^{\mathrm{eff}}(b \to c\ell\nu) \propto G_F V_{cb} \sum \mathcal{C}_i \mathcal{O}_i$$

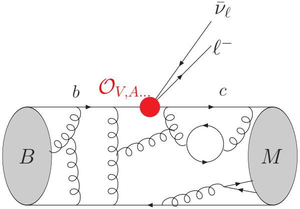
$b \to c\ell\bar{\nu}_\ell$ effective Hamiltonian



$$\mathcal{H}^{\rm eff}(b \to c\ell\nu) \propto G_F V_{cb} \sum \mathcal{C}_i \mathcal{O}_i$$

$b \to c\ell\bar{\nu}_\ell$ effective Hamiltonian

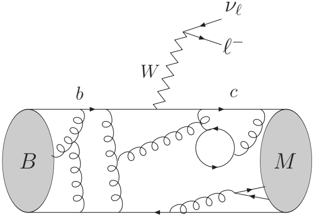


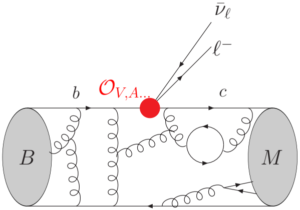


$$\mathcal{H}^{\rm eff}(b \to c\ell\nu) \propto G_F V_{cb} \sum \mathcal{C}_i \mathcal{O}_i$$

- In the SM
  - $\mathcal{O}_{V_L} = (\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell)$ [W exchange]
  - $\mathcal{C}_{V_L} = 1$ and universal for all three leptons
- Hadronic uncertainties all summarised in form factors defined from $\langle M|\mathcal{O}_i|B\rangle$

$b \to c\ell\bar{\nu}_\ell$ effective Hamiltonian



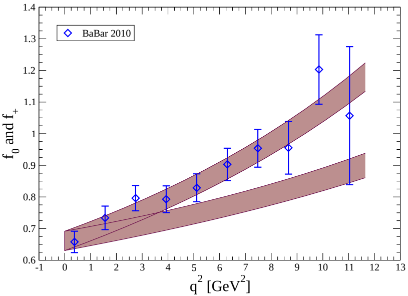


$$\mathcal{H}^{\text{eff}}(b \to c\ell\nu) \propto G_F V_{cb} \sum \mathcal{C}_i \mathcal{O}_i$$

- In the SM
  - $\mathcal{O}_{V_L} = (\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell)$ [W exchange]
  - $\mathcal{C}_{V_L} = 1$ and universal for all three leptons
- Hadronic uncertainties all summarised in form factors defined from $\langle M|\mathcal{O}_i|B\rangle$
- NP changes short-distance $\mathcal{C}_i$ for SM or new long-distance ops $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) $\qquad \mathcal{O}_{V_L} \to \mathcal{O}_{V_R} \propto (\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu_\ell)$
- (Pseudo)scalar ($W \to H^+$) $\qquad \mathcal{O}_{V_L} \to \mathcal{O}_{S_L} \propto (\bar{c} P_L b)(\bar{\ell} P_L \nu_\ell), \mathcal{O}_{S_R}$
- Tensor operators ($W \to T$) $\qquad \mathcal{O}_{V_L} \to \mathcal{O}_{T_L} \propto (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu_\ell)$

Differential decay rates

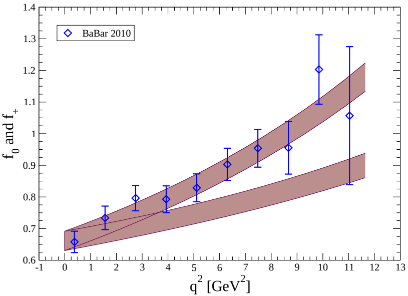


$B \to D\ell\bar{\nu}_\ell$

- Involves in SM 2 form factors $f_+(q^2)$ (vector), $f_0(q^2)$ (scalar)
- NP extension requires one more form factor f_T (tensor)
- From lattice QCD, extrapolated over whole kinematic range

[HPQCD collaboration]

Differential decay rates



$B \to D\ell\bar{\nu}_\ell$

- Involves in SM 2 form factors $f_+(q^2)$ (vector), $f_0(q^2)$ (scalar)
- NP extension requires one more form factor f_T (tensor)
- From lattice QCD, extrapolated over whole kinematic range

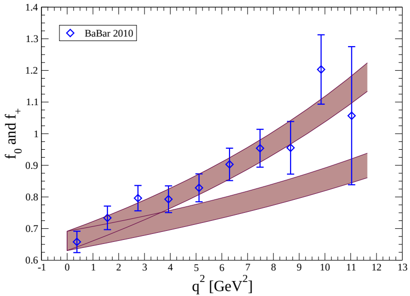
[HPQCD collaboration]

$B \to D^*\ell\nu$

[Fajfer, Kamenik, Nisandzic]

- Amplitudes H_λ for $B \to D^*(\to D\pi)\ell\bar{\nu}_\ell$ with λ helicity of $V^* \to \ell\bar{\nu}_\ell$
- Form factors $V, A_{0.1,2}$ (vector, axial) in SM + $T_{1,2,3}$ (tensor) with NP

Differential decay rates



$B \to D\ell\bar{\nu}_\ell$

- Involves in SM 2 form factors $f_+(q^2)$ (vector), $f_0(q^2)$ (scalar)
- NP extension requires one more form factor f_T (tensor)
- From lattice QCD, extrapolated over whole kinematic range

[HPQCD collaboration]

$B \to D^*\ell\nu$

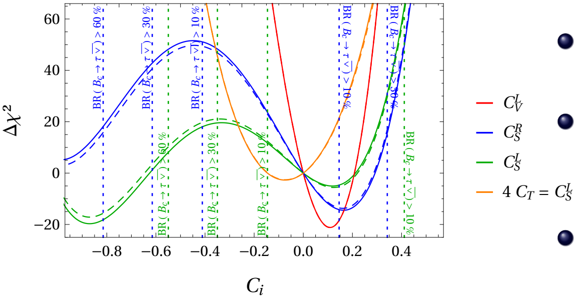
[Fajfer, Kamenik, Nisandzic]

- Amplitudes H_λ for $B \to D^*(\to D\pi)\ell\bar{\nu}_\ell$ with λ helicity of $V^* \to \ell\bar{\nu}_\ell$
- Form factors V, $A_{0,1,2}$ (vector, axial) in SM + $T_{1,2,3}$ (tensor) with NP
- No complete lattice determination, need other approaches
  - HQET: Form factors related in the limit $m_b, m_c \to \infty$, estimation of $O(\Lambda/m)$ corr debated, but no impact on R_{D^*}

    [Bigi, Gambino, Schacht; Bernlochner, Papucci, Ligeti, Robinson]
  - Fit to Belle differential decay rate $B \to D^*\ell\bar{\nu}_\ell$ $(\ell = e, \mu)$ assuming no NP for light leptons

Global fits for $b \to c\ell\bar{\nu}_\ell$

[Bhattacharyaa,Nandi,Patra;Alok,Kumar,Kumar,Kumbhakar,Uma Sankar;Kumar,London,Watanabe;Freytsis,Ligeti,Ruderman; Greljo, Camalich, Ruiz-Alvarez. . .



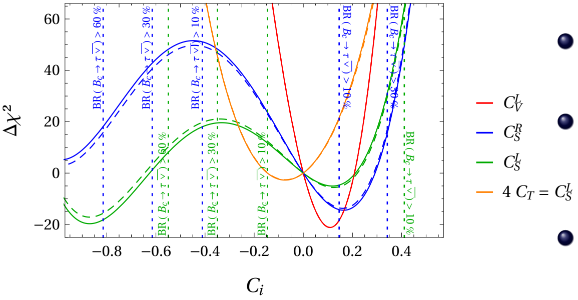
[Blanke,Crivellin,de Boer,Moscati,Nierste, Nišandžić, Kitahara]

- Fits to R_D, R_{D^*}, $P_\tau(D^*)$, $F_L(D^*)$, sometimes $R_{J/\psi}$
- Often NP only in $\ell = \tau$, with real Wilson coeffs (no CP violation)
- Fit to one or two NP couplings at a time

Global fits for $b \to c\ell\bar{\nu}_\ell$

[Bhattacharyaa,Nandi,Patra;Alok,Kumar,Kumar,Kumbhakar,Uma Sankar;Kumar,London,Watanabe;Freytsis,Ligeti,Ruderman;

Greljo, Camalich, Ruiz-Alvarez. . .

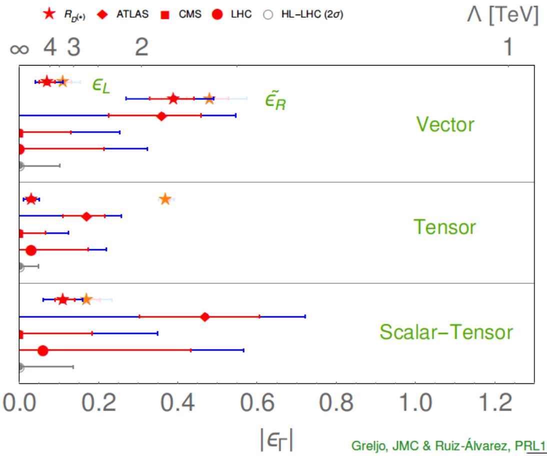


[Blanke,Crivellin,de Boer,Moscati,Nierste, Nišandžić, Kitahara]

- Fits to R_D, R_{D^*}, $P_\tau(D^*)$, $F_L(D^*)$, sometimes $R_{J/\psi}$
- Often NP only in $\ell = \tau$, with real Wilson coeffs (no CP violation)
- Fit to one or two NP couplings at a time

- Right-handed and (pseudo)scalar couplings disfavoured by B_c width (bound on $B_c \to \tau\nu$) and shape of $d\Gamma(B \to D^*\tau\nu)/dq^2$
- Tensor disfavoured by F_L, but often together with scalar in models
- Most simple explanation: NP in $\mathcal{C}_{V_L\tau}$ [change of G_F for $b \to c\tau\bar{\nu}_\tau$]

Global fits for $b \to c\ell\bar{\nu}_\ell$

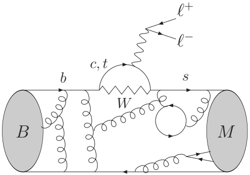


Greljo, JMC & Ruiz-Álvarez, PRL122, 131803 (updated)

- LHC constraints from $pp \to \tau\nu X$ [Greljo, Camalich, Ruiz-Álvarez]
- Various explanations in terms of single mediators, but leptoquarks preferred over W' or charged Higgs

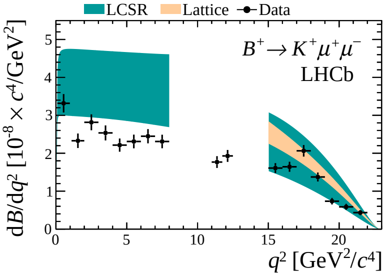
A stable situation for $b \to s\ell\ell$

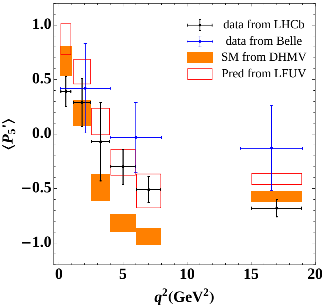
In addition to R_K, R_{K^*}



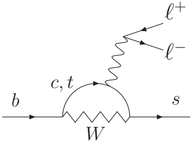
- Many observables for $B \to K\mu\mu$, $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$
- 2-3σ deviations observed w.r.t. SM
  - BR for $B \to K\mu\mu$, $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$ (require knowledge of hadronic uncertainties)
  - Angular distr of $B \to K^*\mu\mu$ with optimised obs (eg P_5'), where part of hadronic uncertainties cancel
  - Hints of lepton flavour universality violation: $b \to see$ vs $b \to s\mu\mu$

[LHCb, Belle, ATLAS, CMS]





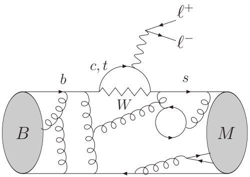
$b \to s\ell\ell$ effective Hamiltonian



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

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

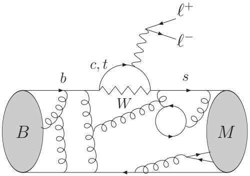
$b \to s\ell\ell$ effective Hamiltonian

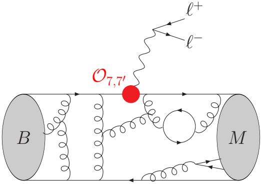


$$\mathcal{H}(b \to s\gamma(^*)) \propto G_F V_{ts}^* V_{tb} \sim \mathcal{C}_i \mathcal{O}_i$$

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

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



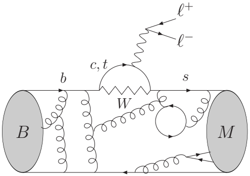


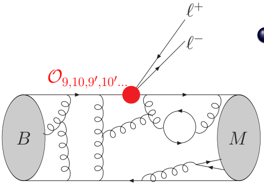
$$\mathcal{H}(b \to s\gamma(^*)) \propto G_F V_{ts}^* V_{tb} \sim \mathcal{C}_i \mathcal{O}_i$$

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

- $\mathcal{O}_7 = \frac{e}{g^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]

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



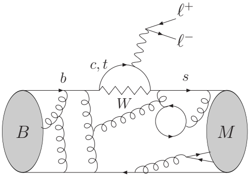


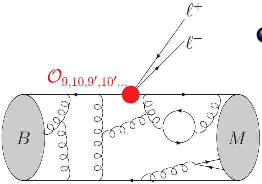
$$\mathcal{H}(b \to s\gamma(^*)) \propto G_F V_{ts}^* V_{tb} \sim \mathcal{C}_i \mathcal{O}_i$$

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

- $\mathcal{O}_7 = \frac{e}{g^2} m_b\, \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]
- $\mathcal{O}_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\ell$ [$b \to s\mu\mu$ via Z/hard $\gamma\ldots$]
- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

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





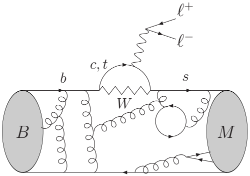
$$\mathcal{H}(b \to s\gamma(^*)) \propto G_F V_{ts}^* V_{tb} \sim \mathcal{C}_i \mathcal{O}_i$$

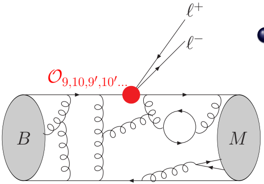
to separate short and long distances ($\mu_b = m_b$)

- $\mathcal{O}_7 = \frac{e}{g^2} m_b\, \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]
- $\mathcal{O}_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\ell$ [$b \to s\mu\mu$ via Z/hard $\gamma\ldots$]
- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

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

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





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

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

- $\mathcal{O}_7 = \frac{e}{g^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]
- $\mathcal{O}_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\ell$ [$b \to s\mu\mu$ via Z/hard $\gamma\ldots$]
- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

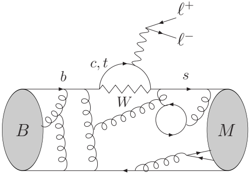
$$\mathcal{C}_7^{\rm SM} = -0.29,\ \mathcal{C}_9^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3$$

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 ($\gamma \to T$) $\quad \mathcal{O}_9 \to \mathcal{O}_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5)b\ \bar{\ell}\sigma_{\mu\nu}\ell$

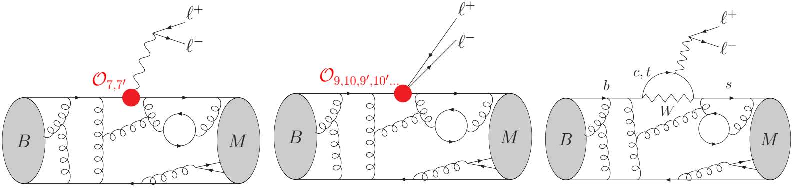
Two sources of hadronic uncertainties

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



Two sources of hadronic uncertainties

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



Form factors (local)

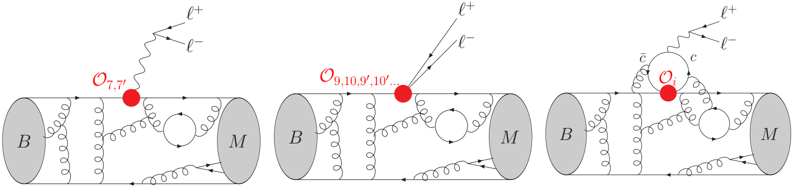
- Local contributions (more terms if NP in non-SM $\mathcal{C}_i$): form factors

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

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

Two sources of hadronic uncertainties

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



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

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

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

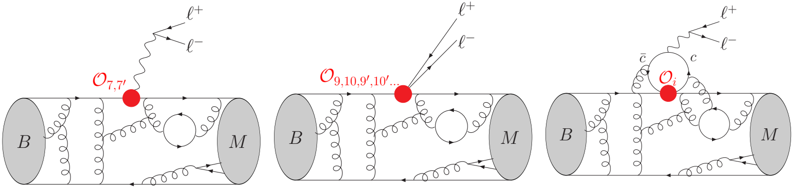
$$B_\mu = \mathcal{C}_{10} \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

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

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

Two sources of hadronic uncertainties

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



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

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

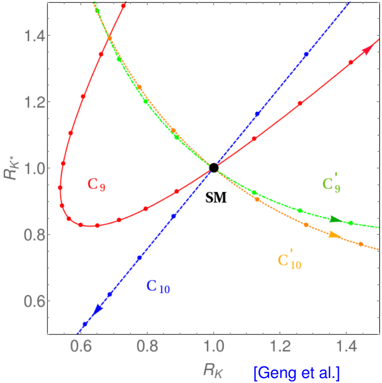
$$A_\mu = -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle M|\bar{s}\sigma_{\mu\nu} P_R b|B\rangle + \mathcal{C}_9 \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$
$$B_\mu = \mathcal{C}_{10} \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

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

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

- Overal agreement about both contributions, using various tools

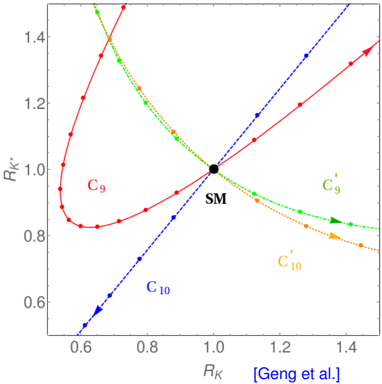
R_K and R_{K^*} in EFT



- R_K: $Br(B \to K\ell\ell)$ involves one amplitude depending on
  - 3 $B \to K$ form factors (one suppr by m_ℓ^2/q^2, one by $\mathcal{C}_7$)
  - charmonium contributions (process-dependent but LFU)
  - $\mathcal{C}_9 + \mathcal{C}_{9'}$ and $\mathcal{C}_{10} + \mathcal{C}_{10'}$

$\Longrightarrow$hadronic contrib cancel for R_K, very accurate for all q^2 and $\mathcal{C}_i$

R_K and R_{K^*} in EFT



[Geng et al.]

- R_K: $Br(B \to K\ell\ell)$ involves one amplitude depending on
  - 3 $B \to K$ form factors (one suppr by m_ℓ^2/q^2, one by $\mathcal{C}_7$)
  - charmonium contributions (process-dependent but LFU)
  - $\mathcal{C}_9 + \mathcal{C}_{9'}$ and $\mathcal{C}_{10} + \mathcal{C}_{10'}$

  $\Longrightarrow$hadronic contrib cancel for 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)
  - charmonium contributions (process-dependent but LFU)
  - depending on helicity amplitude: $\mathcal{C}_9 \pm \mathcal{C}_{9'}$ and $\mathcal{C}_{10} \pm \mathcal{C}_{10'}$

  $\Longrightarrow$hadronic contrib cancel for R_{K^*} in SM because right-handed helicities suppressed but less efficient with NP (slightly larger unc)

Global fits for $b \to s\ell\ell$

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)

Global fits for $b \to s\ell\ell$

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)

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

Global fits for $b \to s\ell\ell$

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)

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

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)
- Most of the discussion on

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

Other analyses from [Aebischer et al, 1903.10434, Alok et al. 1903.09617, Ciuchini et al 1903.09632, Arbey et al 1904.08399]

NP in $b \to s\mu\mu$: 1D

- p-value : $\chi^2_{\rm min}$ considering N_{dof} (in %)
  $\Longrightarrow$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} (in σ units)
  $\Longrightarrow$metrology: how much does the hyp. solve SM deviations ?

NP in $b \to s\mu\mu$: 1D

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

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

NP in $b \to s\mu\mu$: 1D

- p-value : $\chi^2_{\rm min}$ considering N_{dof} (in %)
  $\Longrightarrow$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} (in σ units)
  $\Longrightarrow$metrology: how much does the hyp. solve SM deviations ?

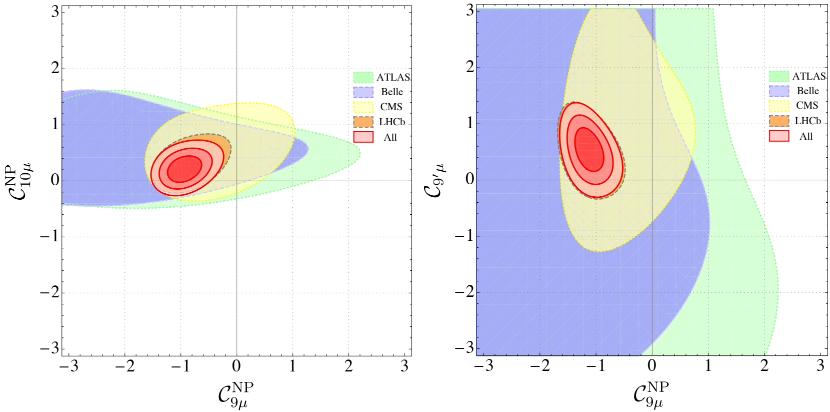
- Subset: 20 obs (LFUV,$b \to s\gamma$,$B_s \to \mu\mu$,$B \to X_s\mu\mu$) (SM p-val 5%)

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 %

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

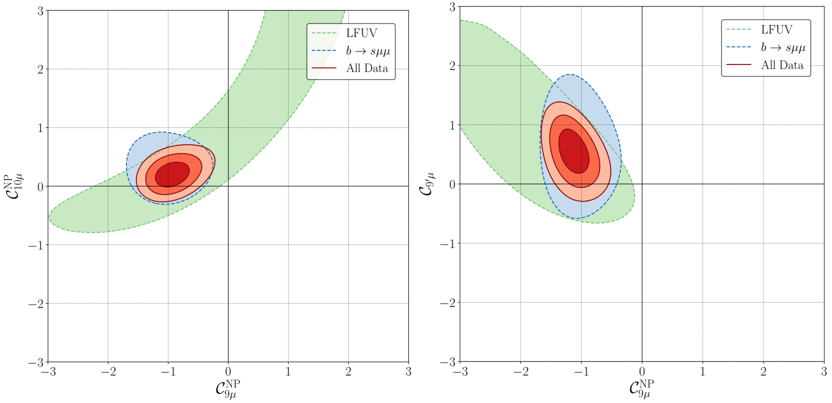
2019		Best fit	1 σ CL	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	$L_q \otimes V_\ell$	-1.02	$[-1.18, -0.85]$	5.8	65 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	$L_q \otimes L_\ell$	-0.49	$[-0.59, -0.40]$	5.4	55 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}$	$A_q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

NP in $b \to s\mu\mu$: 2D



- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}^{\rm NP})$: 5.6$\sigma$ (2017) $\to$ 5.9σ (2019) (left-handed, SM-like)
- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{9'\mu})$: 5.7$\sigma$ (2017) $\to$ 6.1σ (2019) (right-handed currents)

NP in $b \to s\mu\mu$: 2D



- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}^{\rm NP})$: 5.6$\sigma$ (2017) $\to$ 5.9σ (2019) (left-handed, SM-like)
- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{9'\mu})$: 5.7$\sigma$ (2017) $\to$ 6.1σ (2019) (right-handed currents)
- 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 $\mathcal{C}_{9\mu} < 0$

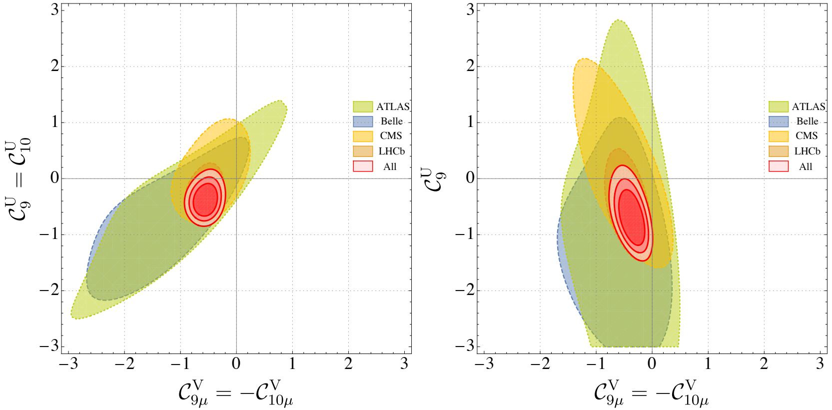
LFUV but also LFU NP ?

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

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

[Algueró, Capdevila, SDG, Masjuan, Matias]

Favoured scenarios (SM pulls 5.8-5.9σ) with LF**U** and LFU**V** contribs



LFUV-NP $L_q \otimes L_\ell$, LFU-NP $L_q \otimes R_\ell$ LFUV-NP $L_q \otimes L_\ell$, LFU-NP $L_q \otimes V_\ell$

Connecting the anomalies

A first EFT connection

Connect the two anomalies within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$$ with higher-dim ops involving only SM fields

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

A first EFT connection

Connect the two anomalies within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$$ with higher-dim ops involving only SM fields

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

- Two operators with left-handed doublets (*ijkl* generation indices)

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

A first EFT connection

Connect the two anomalies within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

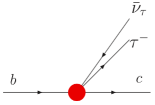
$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$ with higher-dim ops involving only SM fields

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

- Two operators with left-handed doublets (*ijkl* generation indices)

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

- FCCC part of $\mathcal{O}^{(3)}_{2333}$ can describe $R_{D^{(*)}}$ (rescaling of G_F)



A first EFT connection

Connect the two anomalies within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

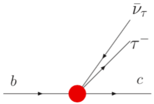
$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$ with higher-dim ops involving only SM fields

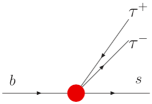
[Grzadkowski, Iskrzynski, Misiak, Rosiek ; Alonso, Grinstein, Camalich]

- Two operators with left-handed doublets (*ijkl* generation indices)

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

- FCCC part of $\mathcal{O}^{(3)}_{2333}$ can describe $R_{D(*)}$ (rescaling of G_F)
- FCNC part of $\mathcal{O}^{(1,3)}_{2333}$ with $C^{(1)}_{2333} = C^{(3)}_{2333}$ [Capdevila, Crivellin, SDG, Hofer, Matias]
  - Large NP contribution $b \to s\tau\tau$ through $\mathcal{C}^{\rm V}_{9\tau} = -\mathcal{C}^{\rm V}_{10\tau}$
  - Avoids bounds from $B \to K(^*)\nu\nu$, Z decays, direct production in $\tau\tau$





A first EFT connection

Connect the two anomalies within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

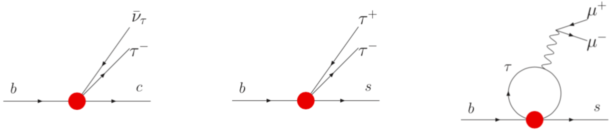
$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$ with higher-dim ops involving only SM fields

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

- Two operators with left-handed doublets (*ijkl* generation indices)

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

- FCCC part of $\mathcal{O}^{(3)}_{2333}$ can describe $R_{D^{(*)}}$ (rescaling of G_F)
- FCNC part of $\mathcal{O}^{(1,3)}_{2333}$ with $C^{(1)}_{2333} = C^{(3)}_{2333}$ [Capdevila, Crivellin, SDG, Hofer, Matias]
  - Large NP contribution $b \to s\tau\tau$ through $\mathcal{C}^{\rm V}_{9\tau} = -\mathcal{C}^{\rm V}_{10\tau}$
  - Avoids bounds from $B \to K(^*)\nu\nu$, Z decays, direct production in $\tau\tau$
  - Through radiative effects, (small) NP contribution to $\mathcal{C}^{\rm U}_9$



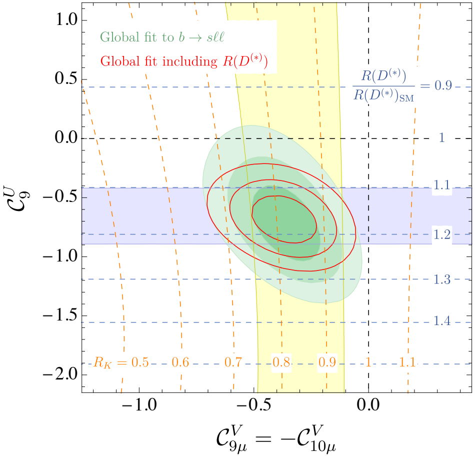
A first EFT connection

Scenario LFU + LFUV NP

- $\mathcal{C}^{\rm V}_{9\mu} = -\mathcal{C}^{\rm V}_{10\mu}$ from small $\mathcal{O}_{2322}$ [$b \to s\mu\mu$]
- $\mathcal{C}^{\rm U}_{9}$ 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

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



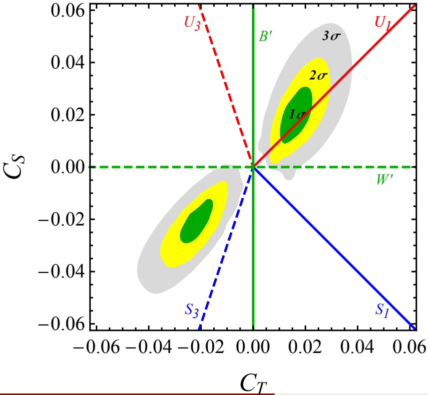
$\Longrightarrow$Agreement with Belle updated (R_D, R_{D^*}) for $\Lambda = 1 - 10$ TeV

Connecting through flavour symmetries

- $U_q(2) \otimes U_\ell(2)$ flavour symmetry
  - Large(ish) NP in $b \to c\tau\nu$ compared to SM tree contribution
  - Small NP in $b \to s\mu\mu$ compared to SM loop contribution
  - $U(2)$ protects first two generations from large NP contributions

Connecting through flavour symmetries

- $U_q(2) \otimes U_\ell(2)$ flavour symmetry
  - Large(ish) NP in $b \to c\tau\nu$ compared to SM tree contribution
  - Small NP in $b \to s\mu\mu$ compared to SM loop contribution
  - $U(2)$ protects first two generations from large NP contributions
- Restrictive (but reasonable) assumptions yield same flavour structure for 2 ops, with 3 couplings λ^q_{sb}, $\lambda^\ell_{\tau\mu}$, $\lambda^\ell_{\mu\mu}$ to be fitted

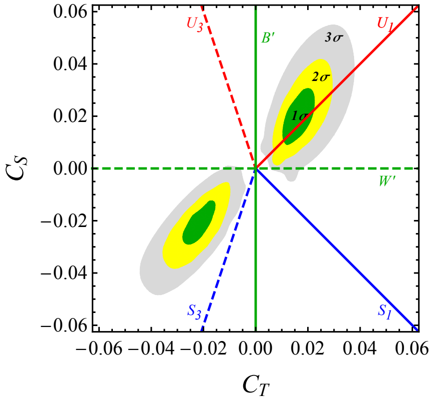


[Butazzo, Greljo, Isidroi, Marzocca]

$$\lambda^q_{ij}\lambda^\ell_{ab}\Big[C_S(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^a_L\gamma^\mu L^b_L) + C_T(\bar{Q}^i_L\gamma_\mu\sigma^\alpha Q^j_L)(\bar{L}^a_L\gamma^\mu\sigma^\alpha L^b_L)\Big]$$

$$Q^i_L = \begin{pmatrix} V^*_{ji} u^j_L \\ d^i_L \end{pmatrix} \qquad L^a_L = \begin{pmatrix} \nu^a_L \\ \ell^a_L \end{pmatrix}$$

Resulting single-mediator models

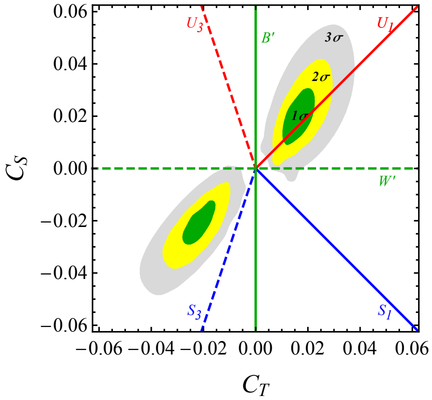


[Butazzo, Greljo, Isidroi, Marzocca]

- Several possible mediators
- Disfavours colourless vectors (W', Z', green) and coloured scalars (S_1, S_3 leptoquarks, blue)
- Favours U_1 vector leptoquark $(3, 1, 2/3)$
- Same conclusions taking a general structure of the couplings [Kumar, London, Watanabe]

Resulting single-mediator models

[Butazzo, Greljo, Isidroi, Marzocca]



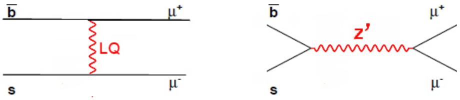
- Several possible mediators
- Disfavours colourless vectors (W', Z', green) and coloured scalars (S_1, S_3 leptoquarks, blue)
- Favours U_1 vector leptoquark $(3, 1, 2/3)$
- Same conclusions taking a general structure of the couplings [Kumar, London, Watanabe]

U_1 leptoquark

- Passes LHC constraints on direct production ($pp \to \tau X, \tau\tau X$)
- Could also accomodate (small) right-handed couplings
- Requires additional particles for UV completion (at least a Z')

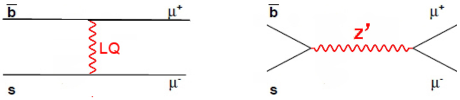
[Barbieri, isidori, Pattori, Sen; Di Luzio, Greljo, Nardecchia. . .]

Other simplified models



- Two scalar leptoquarks $S_1(\bar{3}, 1, 1/3)$ and $S_3(\bar{3}, 3, 1/3)$, purely left-handed currents [Crivellin, Muller, Ota; Buttazzo et al; Marzocca]
- Two scalar leptoquarks $R_2(3, 2, 7/6)$ and $S_3(\bar{3}, 3, 1/3)$, generating both left- and right-handed currents, easily embedded in GUT [Becirevic, Fajfer, Faroughy, Košnik, Sumensary]
- But no succesful models with heavy Higgses or W', Z' only

Other simplified models



- Two scalar leptoquarks $S_1(\bar{3}, 1, 1/3)$ and $S_3(\bar{3}, 3, 1/3)$, purely left-handed currents [Crivellin, Muller, Ota; Buttazzo et al; Marzocca]
- Two scalar leptoquarks $R_2(3, 2, 7/6)$ and $S_3(\bar{3}, 3, 1/3)$, generating both left- and right-handed currents, easily embedded in GUT [Becirevic, Fajfer, Faroughy, Košnik, Sumensary]
- But no succesful models with heavy Higgses or W', Z' only

Many constraints to accommodate

- flavour (CKM, 1st and 2nd generation, $B_s\bar{B}_s$ mixing, $B \to K(^*)\nu\bar{\nu}$)
- bounds on LFV processes $B \to K(^*)e\mu, e\tau, \mu\tau$; $B_s \to e\mu$; $\mu \to e\gamma$
- LEP electroweak constraints
- LHC direct production $pp \to \tau\tau X$, $b\bar{b}X$, $t\bar{t}X$
  - simple or double leptoquark production of leptoquarks
  - other particles (like Z' or coloured excited boson G')

Outlook

Outlook

Intriguing set of deviations in $b \to s\ell\ell$ and $b \to c\ell\nu$

- several different discrepancies with SM, some hinting at LFUV
- EFT fits show favoured patterns of NP deviations, either in SM operators or with right-handed currents
- Simplified models able to reproduce data for both sets, with leptoquarks, possibly with friends (Z', W', vector-like fermions. . .)

How to progress from there ?

- Smaller uncertainties thanks to increased statistics
- More observables (angular obs, LFUV, Λ_b. . .)
- Better understanding of exp issues with different leptons (e, μ, τ)
- Hadronic unc (form factors, charmonium) more accurate (lattice ?)
- Better exploitation of LHC constraints on direct production

Eagerly awaiting updates from LHC experiments and start of Belle II

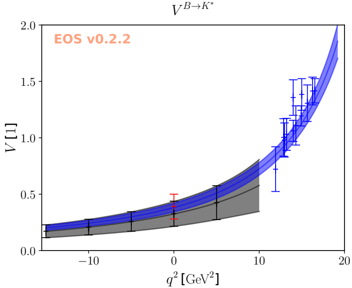
Back-up

Hadronic uncertainties: form factors

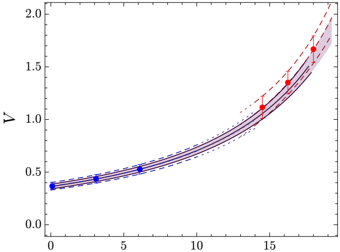
3 form factors for K, 7 form factors for K^* and ϕ

- low recoil: lattice QCD [Horgan, Liu, Meinel, Wingate; HPQCD collab]
- large recoil: Light-Cone Sum Rules with different settings/inputs (B-meson or light-meson distribution amplitude)

[Khodjamirian, Mannel, Pivovarov, Wang; Bharucha, Straub, Zwicky; Gubernari, Kokulu, van Dyk]



B-meson LCSR + lattice



Light-meson LCSR + lattice

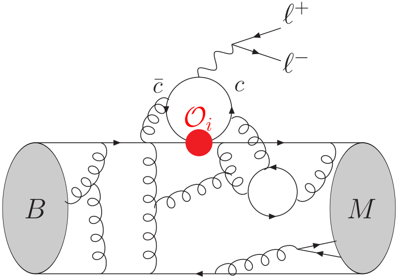
- correlations among the form factors needed, either known or recovered from HQET/SCET, shown to yield consistent results

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

Hadronic uncertainties: charm loops

Charm loops

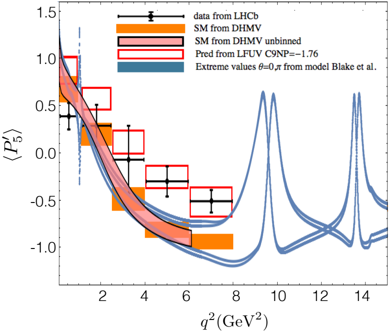
- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_{9\ell}$
- should depend on q^2, but lepton universal



Hadronic uncertainties: charm loops

Charm loops

- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_{9\ell}$
- should depend on q^2, but lepton universal



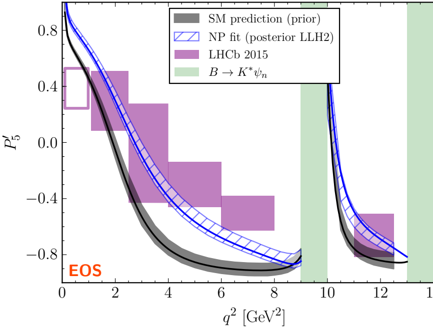
Several theo/pheno approaches agree

- 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]

Hadronic uncertainties: charm loops

Charm loops

- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_{9\ell}$
- should depend on q^2, but lepton universal



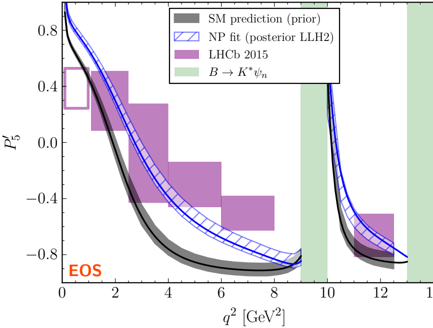
Several theo/pheno approaches agree

- 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]
- 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 $\mathcal{C}_{9\ell}$
- should depend on q^2, but lepton universal



Several theo/pheno approaches agree

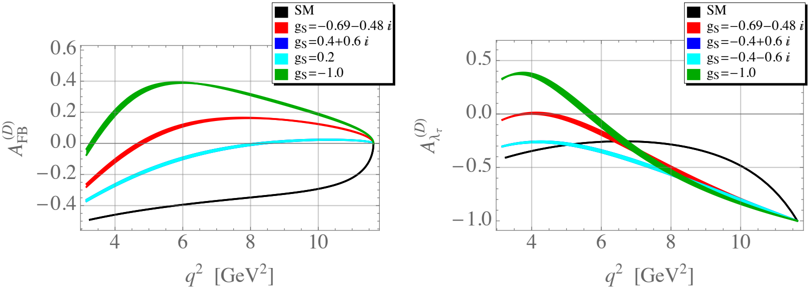
- LCSR estimate [Khodjamirian, Mannel, Pivovarov, Wang]
- order of magnitude estimate for the fits (LCSR or Λ/m_b), check with bin-by-bin fits [Crivellin, Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]
- fit of sum of resonances to the data [Blake, Egede, Owen, Pomery, Petridis]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

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

$b \to c\ell\bar{\nu}_\ell$: more observables on the way

3 observables for $B \to D\ell\nu$

- differential decay rate $d\Gamma/dq^2$
- forward-backward asymmetry
- lepton-polarisation asymmetry

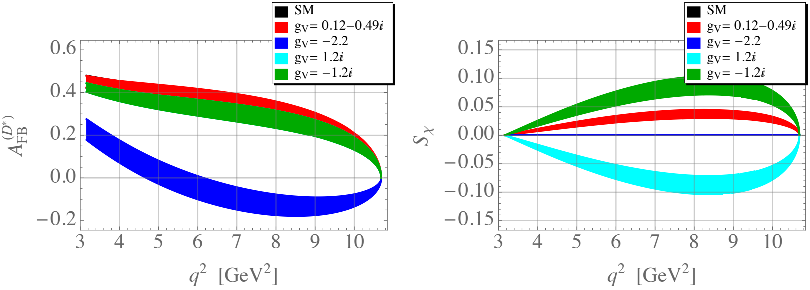


[Fajfer, Kamenik, Nisandzic, Becirevic, Tayduganov. . .]

$b \to c\ell\bar{\nu}_\ell$: more observables on the way

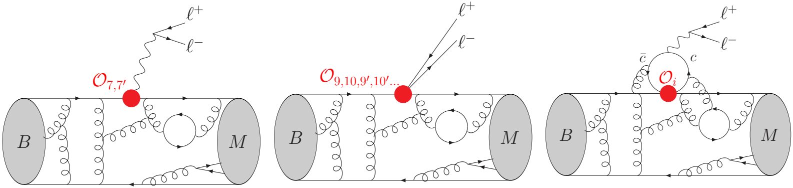
11 observables for $B \to D^*(\to D\pi)\ell\nu$

- differential decay rate $d\Gamma/dq^2$
- forward-backward asymmetry
- lepton-polarisation asymmetry
- partial decay rate according to D^* polar $(d\Gamma_L/dq^2)/(d\Gamma_T/dq^2)$
- angular observables (asymmetries with respect to two angles)



[Fajfer, Kamenik, Nisandzic, Becirevic, Tayduganov. . .]

Disentangling scenarios: more precision

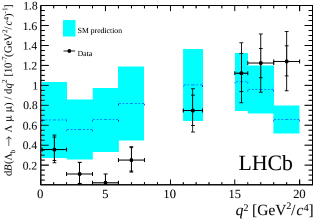


- Reduce hadronic uncertainties on form factors
  - low recoil: lattice [Horgan, Liu, Meinel, Wingate; HPQCD collab]
  - large recoil: B-meson LCSR [Khodjamirian, Mannel, Pivovarov, Wang]
  - all: fit of light-meson LCSR + lattice [Bharucha, Straub, Zwicky]
  - all: fit of B-meson LCSR + lattice [Gubernari,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

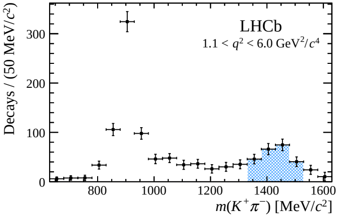
  $\Longrightarrow$only one (BSZ) computation for $B_s \to \phi$ form factors for now ?
- Reduce hadronic uncertainties on $c\bar{c}$ contributions
  - Many different estimates at large recoil (all in agreement)
    $\Longrightarrow$check normalisation through light-meson LCSR at $q^2 \leq 0$?
  - Low-recoil 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 $K^*(1430)$

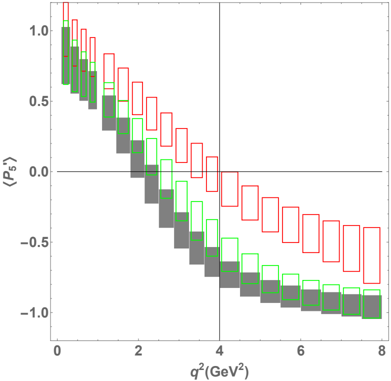


Different info and systematics in angular distributions known for

- $\Lambda_b \to \Lambda(\to N\pi)\ell^+\ell^-$ [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]

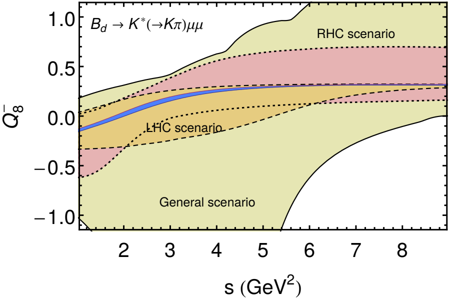
- Form factors not so well known [Detmold, Lin, Meinel, Wingate, Rendon]
- Large recoil
  - Status of factorisation for not-so-light mesons ? baryons ?
  - Could be tackled with form factors + analytic repr. of $c\bar{c}$ contribution but normalisation of $c\bar{c}$ at $q^2 \leq 0$ [LCSR] [Bobeth, Chrzaszcz, 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 $\mathcal{C}_{9\mu}^{\rm NP}$)



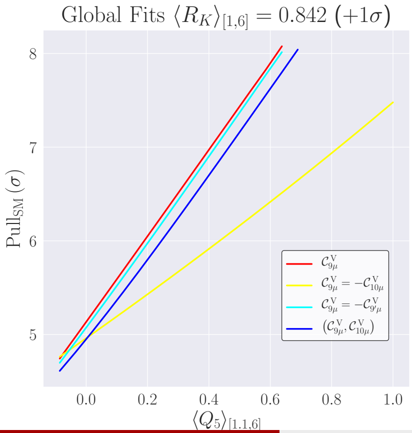
Time-dependent observables in $B_d \to K^*(\to K_S\pi^0)\ell^+\ell^-$ and $B_s \to \phi(\to K^+K^-)\ell^+\ell^-$

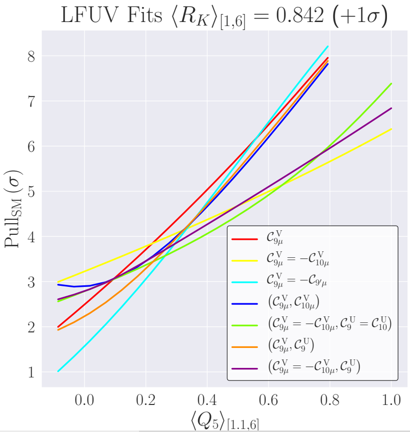
[SDG, Virto]

Disentangling scenarios: more observables (2)

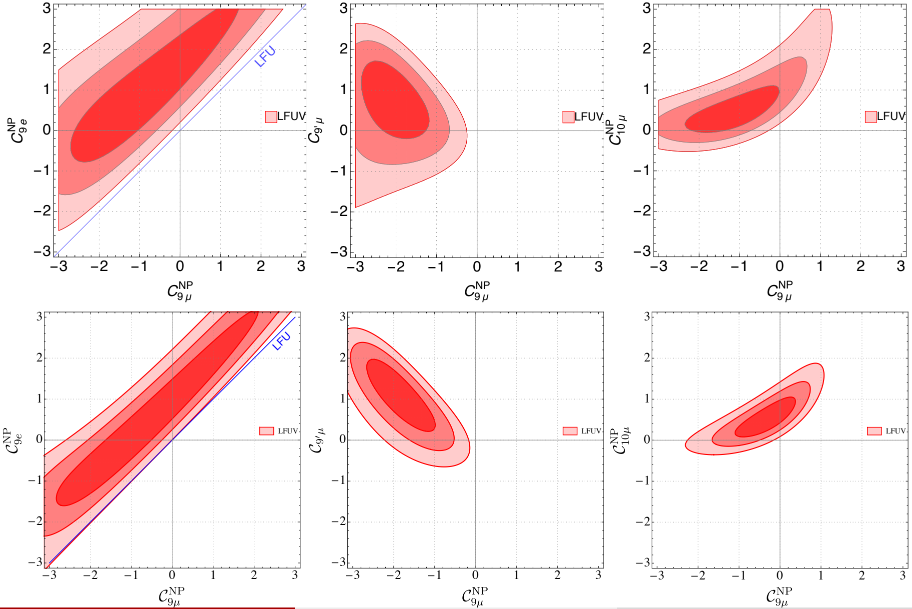
- other LFUV quantities: R_ϕ, $R^{T,L}_{K,\phi}$, $Q_i = P_i^\mu - P_i^e$
- $Q_5 = P_5^{\mu\prime} - P_5^{e\prime}$ interesting observable to disentangle
  - $\mathcal{C}^{NP}_{9\mu} = -\mathcal{C}^{NP}_{10\mu}$ from others NP scenarios in $b \to s\mu\mu$
  - classes of scenarios allowing for LFU contributions

[Alguero, Capdevila, SDG, Masjuan, Matias]

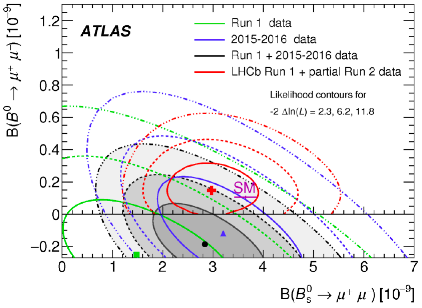




LFUV subset fits in 2017 (top) and 2019 (bottom)



$B_s \to \mu\mu$



- 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

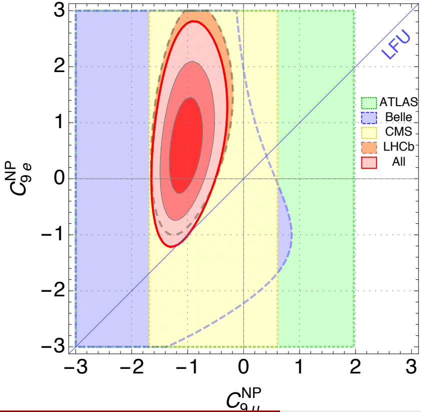
2019	$\mathcal{C}_7^{\rm NP}$	$\mathcal{C}_{9\mu}^{\rm NP}$	$\mathcal{C}_{10\mu}^{\rm NP}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Bfp	+0.02	-1.13	+0.21	+0.02	+0.39	-0.12
1 σ	$[-0.01, +0.05]$	$[-1.28, -0.91]$	$[+0.04, +0.42]$	$[+0.00, +0.04]$	$[-0.09, +0.96]$	$[-0.40, +0.17]$
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)

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)

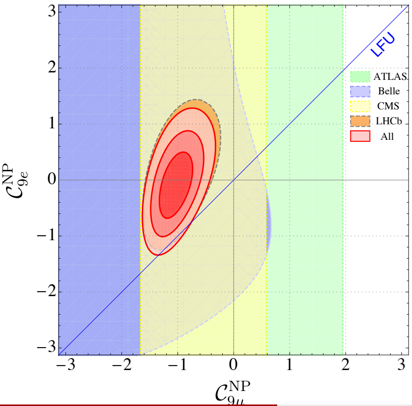


- NP in $(\mathcal{C}_{9\mu}, \mathcal{C}_{9e})$ in 2017

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)

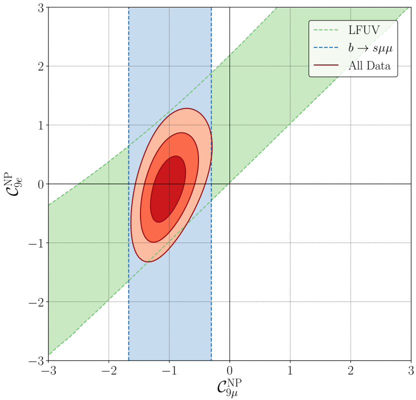


- NP in $(\mathcal{C}_{9\mu}, \mathcal{C}_{9e})$ in 2019
  - Less need for NP in $b \to see$
  - Though some room available (not many obs)
  - SM pull=5.5 σ, p-value=65% (unchanged wrt 2017)

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	$[-0.03, +0.06]$	$[-1.48, -0.71]$	$[-0.12, +0.61]$	$[-0.02, +0.06]$	$[-0.56, +1.14]$	$[-0.57, +0.34]$

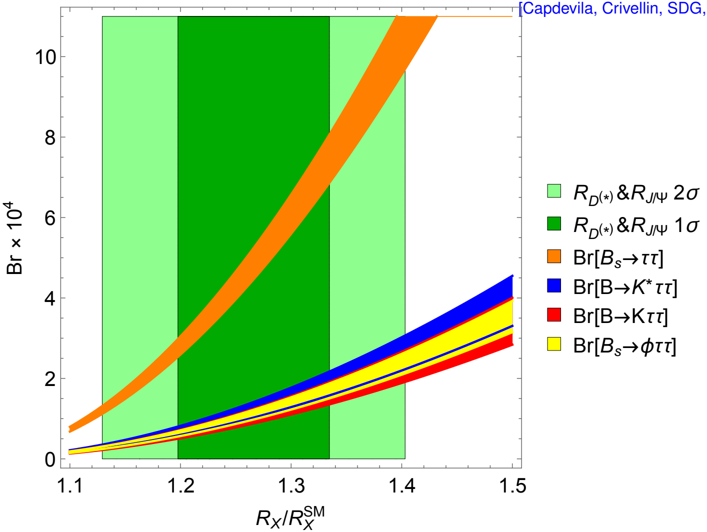
- 6D scenario (SM + chirally flipped in $b \to s\mu\mu$) in 2017 and 2019
  - $\mathcal{C}_{9\mu}^{\rm NP} < 0$ needed, $\mathcal{C}_{9'\mu}^{\rm NP} > 0$, $\mathcal{C}_{10\mu}^{\rm NP} > 0$, $\mathcal{C}_{10'\mu}^{\rm NP} < 0$ favoured
  - SM pull 5.3 σ (5.0 σ in 2017)



- 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)

Enhancement of $b \to s\tau\tau$ for $O^{(1,3)}_{2333}$

[Capdevila, Crivellin, SDG, Hofer, Matias]



$$\mathrm{Br}\left(B_s \to \tau^+\tau^-\right)_{\mathrm{LHCb}} \leq 6.8\times 10^{-3}\,, \quad \mathrm{Br}\left(B \to K\tau^+\tau^-\right)_{\mathrm{Babar}} \leq 2.25\times 10^{-3}\,.$$