B-physics anomalies: a status report

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LPT Orsay

Lepton Flavour Universality Violation in B decays

Lepton Flavour Universality Violation

A powerful test of the SM

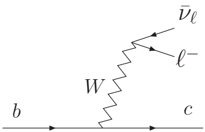
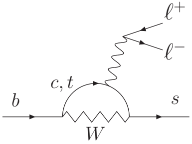
- all leptons with the same couplings in SM
- tested to a high accuracy in many different settings

  W, Z decays, decays of light mesons...

Generating a lot of interest

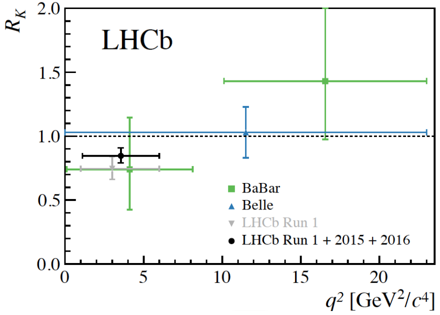
- since 2014, quiet a lot of activity in B-meson decays
- from Babar, Belle, LHCb, and soon Belle II
- with a few updates in 2019

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 + P_{τ,D^*}	$d\Gamma/dq^2$ + 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)

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



- LHCb update

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

- Belle at low and large K^* recoils, 1 ± 0.2, but 20% isospin asymmetry
- From 2.6 to 2.5σ wrt SM

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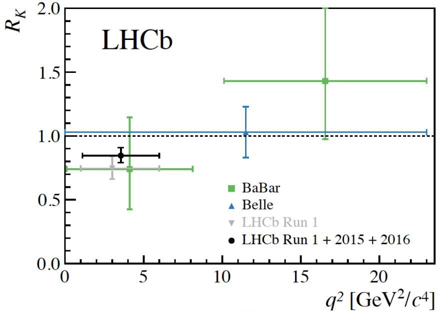

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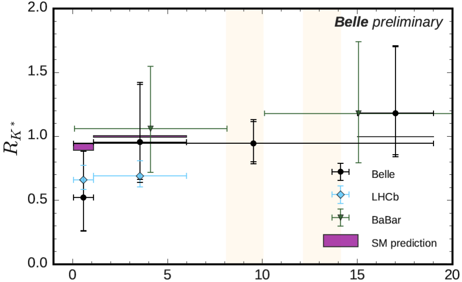
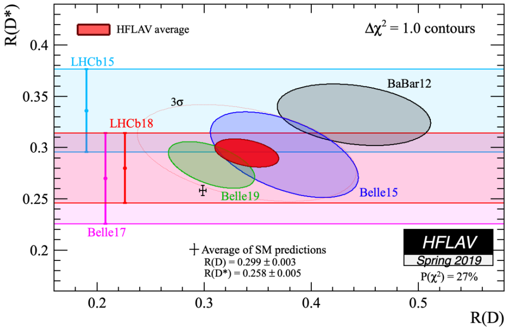
- Belle: $R_{K^*} = \frac{B(B \to K^*\mu\mu)}{B(B \to K^*ee)}$ in 3 bins (large/low-K^* recoil)
- OK with SM, but also LHCb [2.3 (2.6) σ from SM for $R_{K^*}^{[0.045,1.1]}$ ([1.1,6])]



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



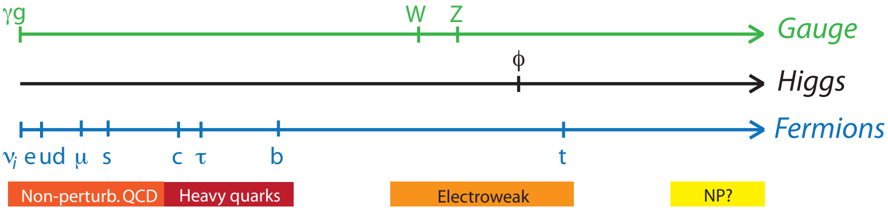
- Belle update @Moriond19

  (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

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)

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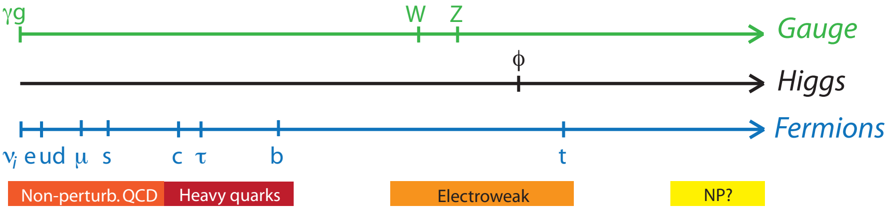

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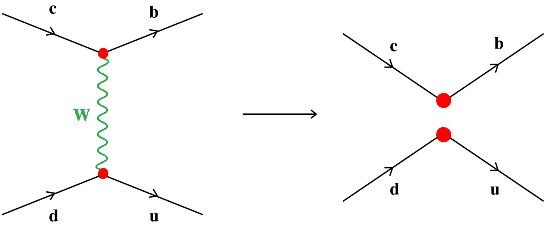
		$(\Lambda_{EW}/\Lambda_{NP})$		(m_b/Λ_{EW})		(Λ_{QCD}/m_b)

- Big 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



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

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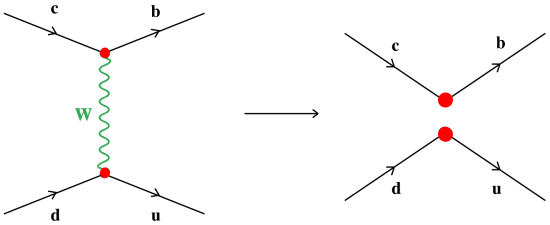


$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c + O(1/M_W^2)$$

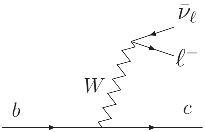
Fermi theory carries some info on the underlying theory

- 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 $\mu = m_b$



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

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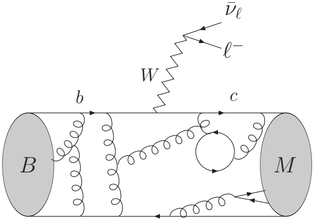

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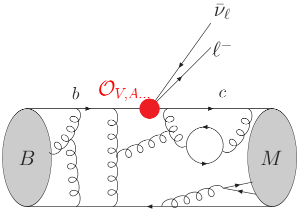

involving hadronic quantities such as form factors

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

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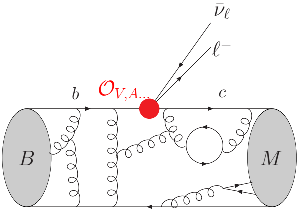

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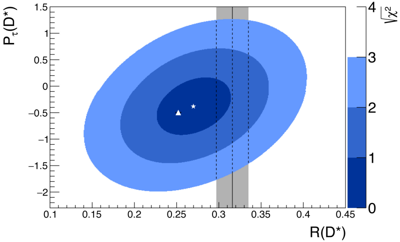
Two possible uses of effective approaches

- 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

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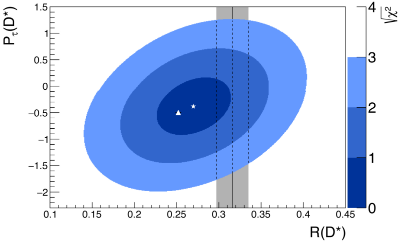

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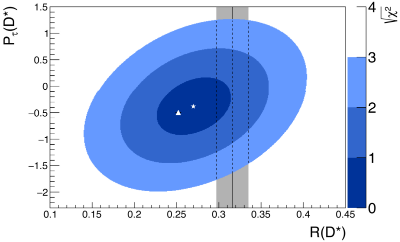
D^* polarisation in $B \to D^*\tau\nu$

- 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^*}



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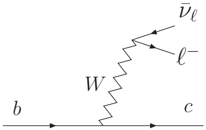
$R_{J/\psi}$ ($B_c \to J/\psi \ell \bar{\nu}_\ell$)

- 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



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

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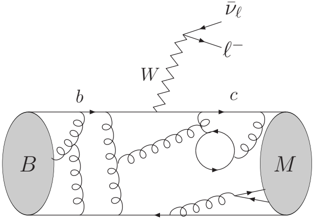

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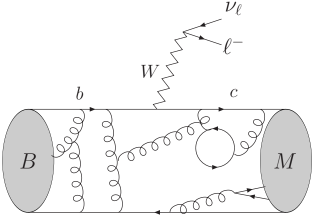

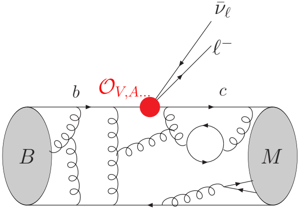

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- In the SM
  - $\mathcal{O}_{V_L} = (\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell)$ [W exchange]
  - $\mathcal{C}_{V_L} = 1$ and universal for all three leptons
- Hadronic uncertainties all summarised in form factors defined from $\langle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

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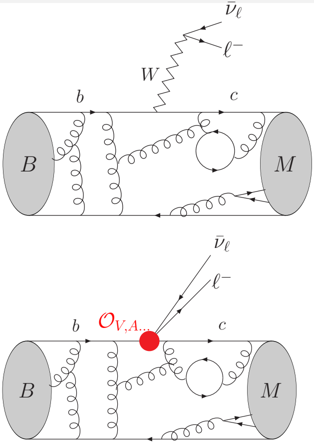

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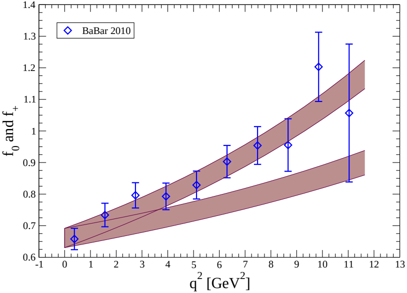
- Hadronic uncertainties all summarised in form factors defined from $\langle M|\mathcal{O}_i|B\rangle$
- NP changes short-distance $\mathcal{C}_i$ for SM or new long-distance ops $\mathcal{O}_i$

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

Differential decay rates

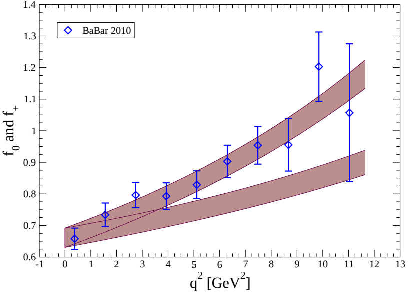


$B \to D\ell\bar{\nu}_\ell$

- 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



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

[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

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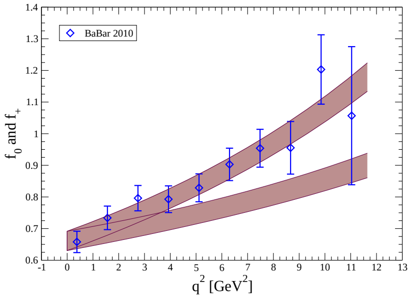

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- Form factors $V, A_{0,1,2}$ (vector, axial) in SM + $T_{1,2,3}$ (tensor) with NP
- No complete lattice determination, need other approaches
  - HQET: Form factors related in the limit $m_b, m_c \to \infty$, estimation of $O(\Lambda/m)$ corr debated, 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;

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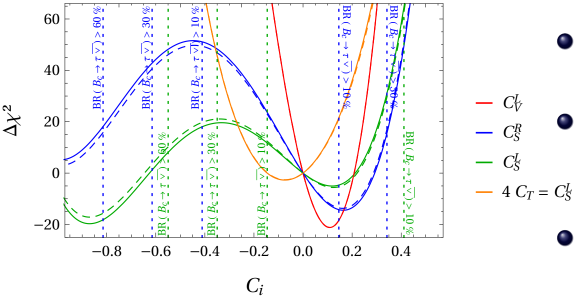

- Fits to R_D, R_{D^*}, $P_\tau(D^*)$, $F_L(D^*)$, sometimes $R_{J/\psi}$
- Often NP only in $\ell = \tau$, with real Wilson coeffs (no CP violation)
- Fit to one or two NP couplings at a time

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

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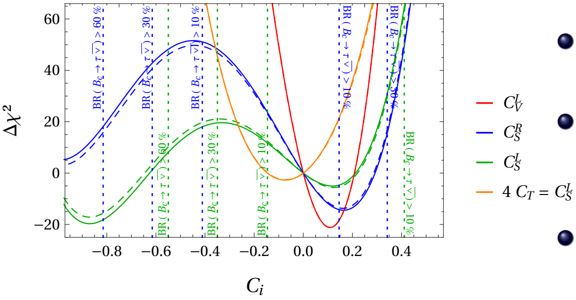

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- Right-handed and (pseudo)scalar couplings disfavoured by B_c width (bound on $B_c \to \tau\nu$) mainly [shape of $d\Gamma(B \to D^*\tau\nu)/dq^2$]
- Tensor disfavoured by F_L, but often together with scalar in models
- Most simple explanation: NP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

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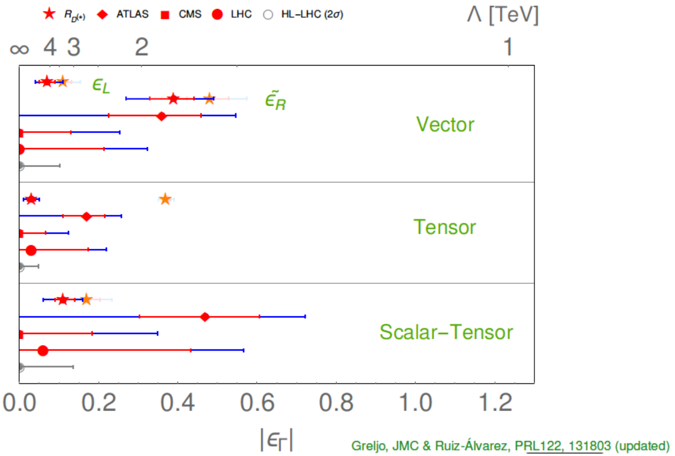
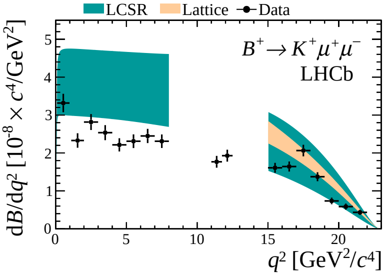
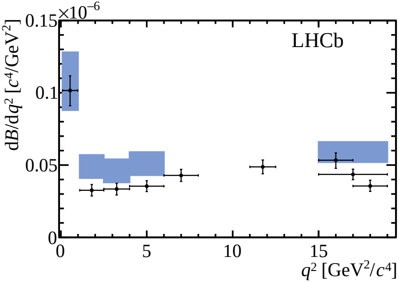


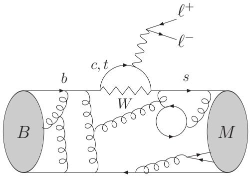
- LHC constraints from $pp \to \tau\nu X$ [Greljo, Camalich, Ruiz-Álvarez]
- Various explanations in terms of single mediators, but leptoquarks preferred over W' or charged Higgs

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

In addition to R_K, R_{K^*}: branching ratios

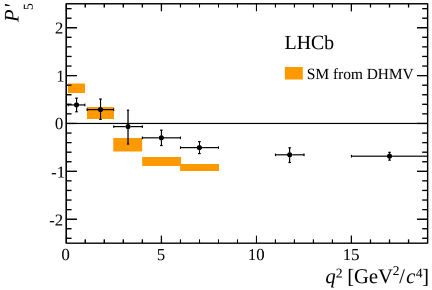


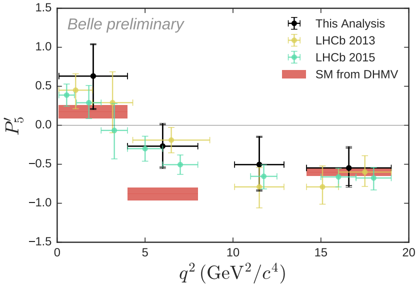




- $Br(B \to K\mu\mu)$ (up), $Br(B \to K^*\mu\mu)$ (down), $Br(B_s \to \phi\mu\mu)$ too low wrt SM
- q^2 invariant mass of $\ell\ell$ pair
- remove bins with J/ψ or ψ' $[B \to K(^*) + \psi(\to \ell\ell)]$
- large hadronic uncertainties from form factors at
  - Large-meson recoil/low q^2: light-cone sum rules
  - Low-meson recoil/large q^2: lattice QCD

In addition to R_K, R_{K^*}: angular observables



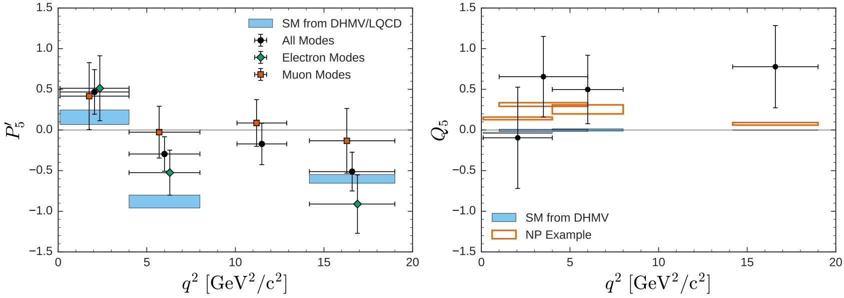


- Basis of 6 optimised observables P_i (angular coeffs) for $B \to K^*\mu\mu$ and $B_s \to \phi\mu\mu$ with reduced hadronic uncertainties

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

- Measured at LHCb with 1 fb^{-1} (2013) and 3 fb^{-1} (2015)
- Discrepancies for some (but not all) observables, in particular two bins for P_5' deviating from SM by 2.8 σ and 3.0 σ
- Belle 2016: confirmation, with larger uncertainties
- CMS and ATLAS 2017: large unc., agree only partially with LHCb

In addition to R_K, R_{K^*}: LFU in angular observables



Belle also compared $B \to K^* \mu\mu$ and $B \to K^* ee$ in 2016

- different systematics from LHCb
- 2.6 σ deviation for $\langle P_5' \rangle^{\mu}_{[4,8]}$ versus 1.3 σ deviation for $\langle P_5' \rangle^{e}_{[4,8]}$
- same indication by looking at LFU-violating observable $Q_5 = P_5^{\mu\prime} - P_5^{e\prime}$, deviating from SM, not in a significant way (yet ?)

Understanding the $B \to K^* \mu^+ \mu^-$ Anomaly

Sébastien Descotes-Genon[a], Joaquim Matias[b] and Javier Virto[b]

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[b] *Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona*

We present a global analysis of the $B \to K^*(\to K\pi)\mu^+\mu^-$ decay using the recent LHCb measurements of the primary observables $P_{1,2}$ and $P'_{4,5,6,8}$. Some of them exhibit large deviations with respect to the SM predictions. We explain the observed pattern of deviations through a large New Physics contribution to the Wilson coefficient of the semileptonic operator $\mathcal{O}_9$. This contribution has an opposite sign to the SM one, i.e., reduces the size of this coefficient significantly. A good description of data is achieved by allowing for New Physics contributions to the Wilson coefficients $\mathcal{C}_7$ and $\mathcal{C}_9$ only. We find a $4.5\,\sigma$ deviation with respect to the SM prediction, combining the large-recoil $B \to K^*(\to K\pi)\mu^+\mu^-$ observables with other radiative processes. Once low-recoil observables are included the significance gets reduced to $3.9\,\sigma$. We have tested different sources of systematics, none of them modifying our conclusions significantly. Finally, we propose additional ways of measuring the primary observables through new foldings.

The four-body $B \to K^*(\to K\pi)\mu^+\mu^-$ decay and its plethora of different observables [1–15] is becoming one of the key players not only in our search for New Physics (NP) in the flavour sector but also to guide us in the construction of viable new models, which explains the remarkable experimental effort devoted to its precise measurement [16–20]. In the effective Hamiltonian approach used to analyse radiative decays at low energies, one of the most prominent virtues of this decay is the capacity to unveil NP contributions inside the short-distance Wilson coefficients, denoted $\mathcal{C}_i = \mathcal{C}_i^{\rm SM} + \mathcal{C}_i^{\rm NP}$, not only for the Standard Model (SM) electromagnetic and dileptonic operators

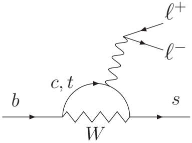
$$\mathcal{O}_7 \;=\; e/(16\pi^2)\, m_b(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad (1)$$

$$\mathcal{O}_9 \;=\; e^2/(16\pi^2)\,(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\ell), \qquad (2)$$

towards a scenario consistent with the SM, but with small deviations in $A_{\rm FB}$ (in both the q^2 bin [2-4.3] GeV^2 and the position of the zero). The next generation of measurements included a theoretically-controlled version of $A_{\rm FB}$ called $A_T^{(\rm re)}$ [6] or P_2 [7], and P_1, which are both less sensitive to hadronic effects and able to magnify deviations due to NP. Finally, LHCb has issued very recent results [20] completing the basis of P_i and P'_i primary observables [7, 15, 21]. These observables, with little sensitivity to hadronic uncertainties at low q^2, have unveiled a set of tensions with respect to the SM that have to be understood from the theoretical point of view. This paper aims at providing such a consistent picture, where the Wilson coefficient $\mathcal{C}_9$ plays an essential role.

In Sec. 1 we discuss the experimental evidence, i.e., the pattern of deviations observed at LHCb. In Sec. 2, we

$b \to s\ell\ell$ 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 ($\mu_b = m_b$)

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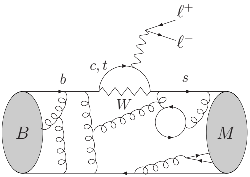

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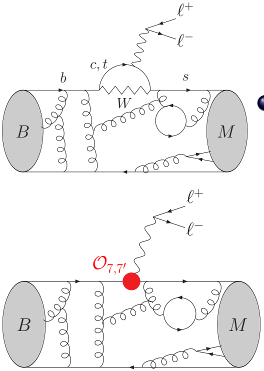

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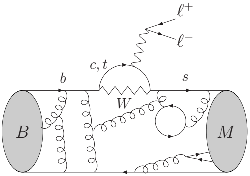

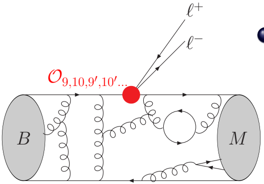

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- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

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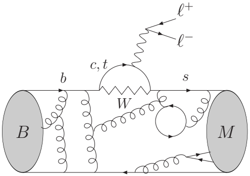

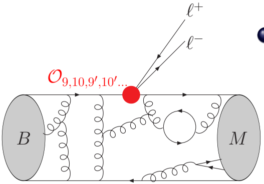

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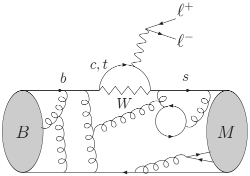
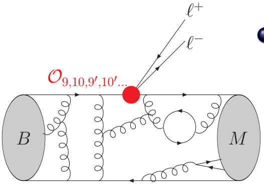
$$\mathcal{C}_7^{\rm SM} = -0.29, \; \mathcal{C}_9^{\rm SM} = 4.1, \; \mathcal{C}_{10}^{\rm SM} = -4.3$$

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





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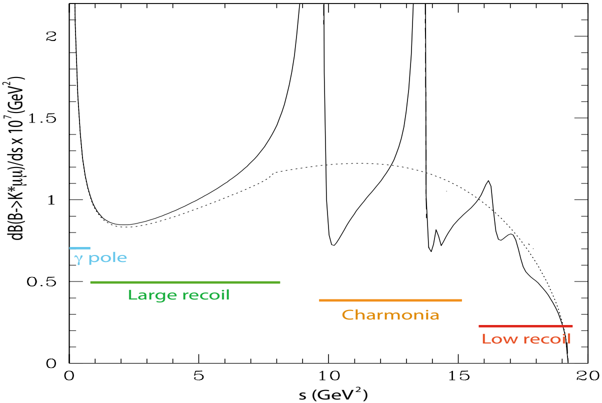
NP changes short-distance $\mathcal{C}_i$ or add new operators $\mathcal{O}_i$

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

Various tools for exclusive decays ($B \to K^* \mu\mu$)



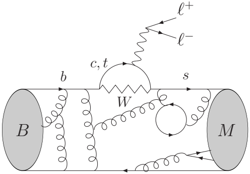
- Very large K^*-recoil ($4m_\ell^2 < q^2 < 1$ GeV^2) γ almost real
- Large K^*-recoil ($q^2 < 9$ GeV^2) energetic K^* ($E_{K^*} \gg \Lambda_{QCD}$)

  LCSR, SCET, QCD factorisation
- Charmonium region ($q^2 = m^2_{\psi,\psi'\ldots}$ 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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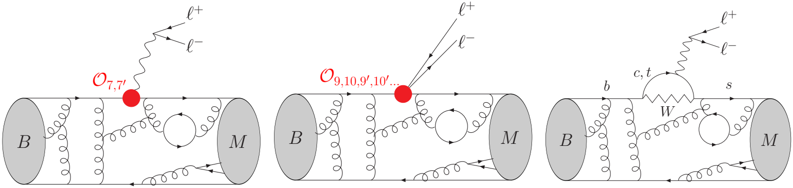

Form factors (local)

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

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

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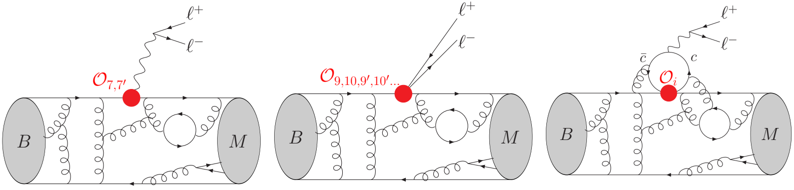

Form factors (local) Charm loop (non-local)

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

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

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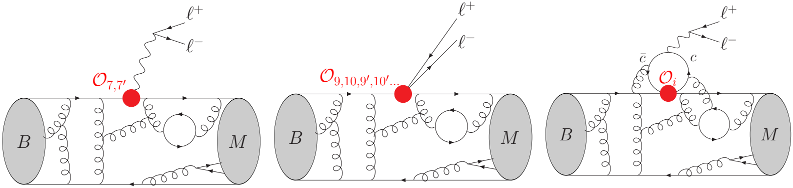

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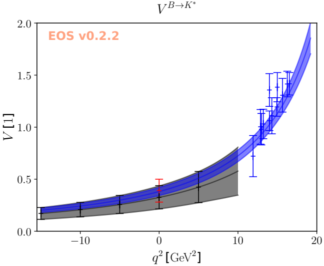
- Overal agreement about both contributions, using various tools

Hadronic uncertainties: form factors

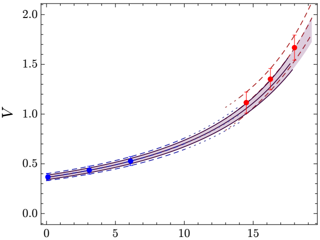
3 form factors for K, 7 form factors for K^* and ϕ

- low recoil: lattice QCD [Horgan, Liu, Meinel, Wingate; HPQCD collab]
- large recoil: Light-Cone Sum Rules (B-meson or light-meson DAs)

[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, known or recovered from HQET/SCET, (used to define optimised angular observables)

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

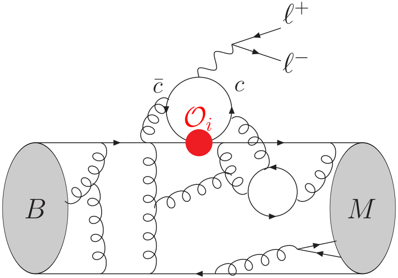
- impact of narrow-width limit and excited resonances : up to 10% ?

[Khodjamirian, SDG, 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



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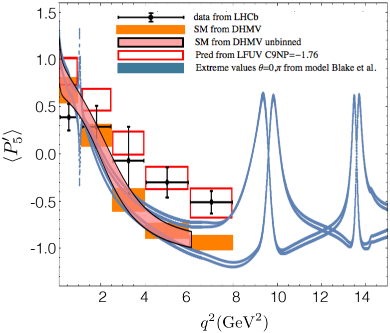

Several theo/pheno approaches agree

- LCSR estimates [Khodjamirian, Mannel, Pivovarov, Wang; Gubenari, Van Dyk]
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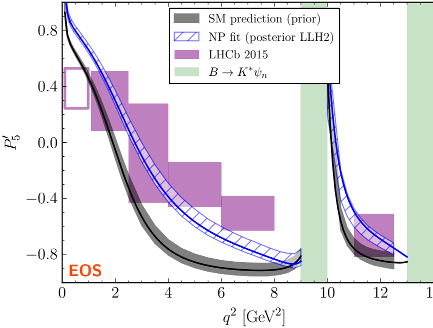

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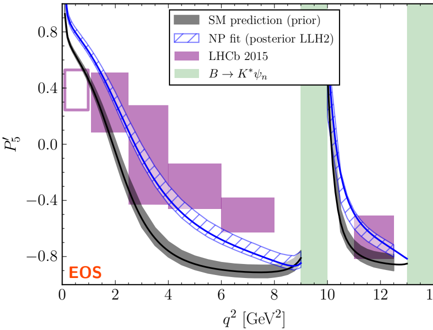

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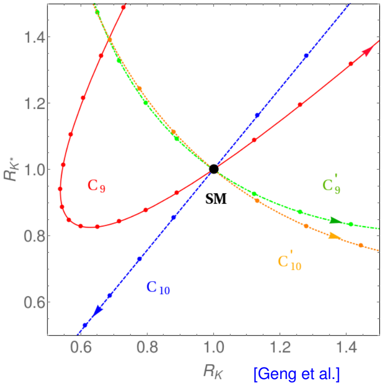
No sign of missing large (hadronic) q^2-dependent contrib to $b \to s\mu\mu$

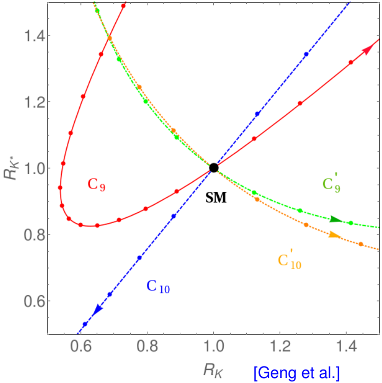
R_K and R_{K^*} in EFT



- 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.]

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$\Longrightarrow$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 $b \to s\ell\ell$

180 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, $S_{K^*\gamma}$)
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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)
- 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 ?

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- Subset: 22 obs (LFUV,$b \to s\gamma$,$B_s \to \mu\mu$,$B \to X_s\mu\mu$) (SM p-val 8%)

2019		Best fit	1 σ CL	Pull$_{\rm SM}$	p-value
$\mathcal{C}^{\rm NP}_{9\mu}$	$L_q \otimes V_\ell$	-0.89	$[-1.23, -0.59]$	3.3	52 %
$\mathcal{C}^{\rm NP}_{9\mu} = -\mathcal{C}^{\rm NP}_{10\mu}$	$L_q \otimes L_\ell$	-0.46	$[-0.53, -0.29]$	4.0	74 %
$\mathcal{C}^{\rm NP}_{9\mu} = -\mathcal{C}_{9'\mu}$	$A_q \otimes V_\ell$	-1.61	$[-2.13, -0.96]$	3.0	42 %

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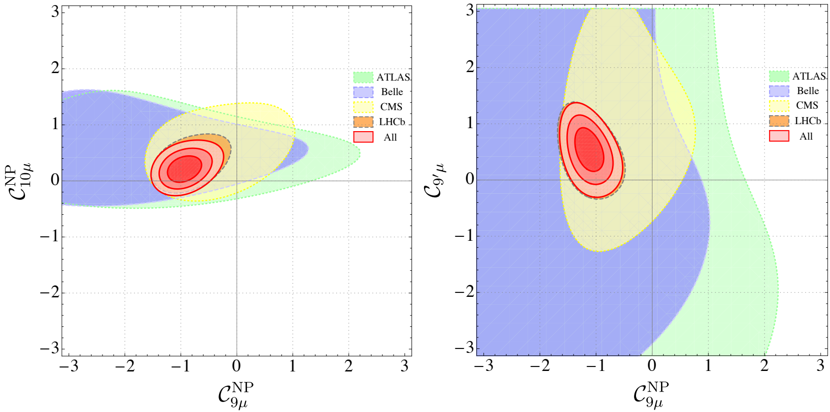
- All: fit to 180 obs (SM p-value 11%)

2019		Best fit	1 σ CL	Pull_{SM}	p-value
$\mathcal{C}_{9\mu}^{\text{NP}}$	$L_q \otimes V_\ell$	-0.98	$[-1.15, -0.81]$	5.6	65 %
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	$L_q \otimes L_\ell$	-0.46	$[-0.56, -0.37]$	5.2	56 %
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}$	$A_q \otimes V_\ell$	-0.99	$[-1.15, -0.82]$	5.5	63 %

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



- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}^{\rm NP})$: 5.6σ (2017) $\to$ 5.4σ (2019) (left-handed, SM-like)
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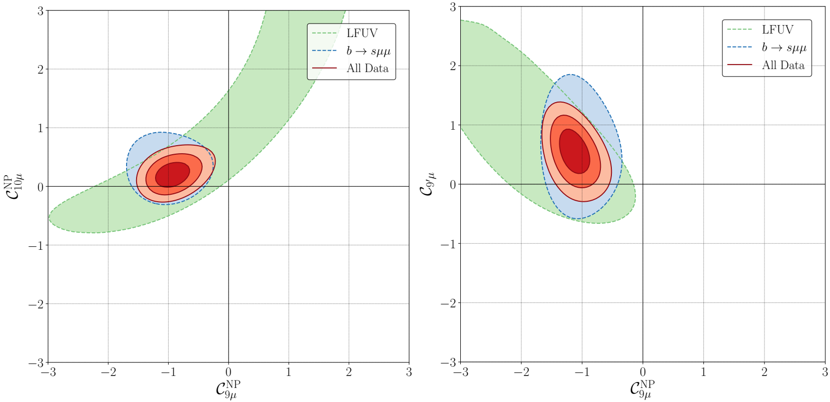

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- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{9'\mu})$: 5.7$\sigma$ (2017) $\to$ 5.7σ (2019) (right-handed currents)
- Separating 3 σ regions for $b \to s\mu\mu$ and purely LFUV
  - LFUV favours $\mathcal{C}_{10\mu}^{\rm NP} > 0$ and $\mathcal{C}_{9'\mu}^{\rm NP} > 0$
  - $b \to s\mu\mu$ essentially in favour of $\mathcal{C}_{9\mu} < 0$

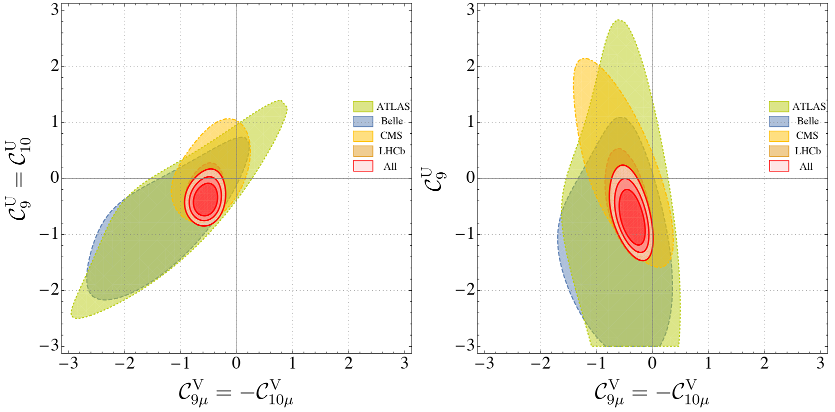
LFUV but also LFU NP ?

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 5.6-5.7σ) 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]

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

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

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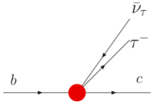
- FCCC part of $\mathcal{O}^{(3)}_{2333}$ can describe $R_{D^{(*)}}$ (rescaling of G_F)



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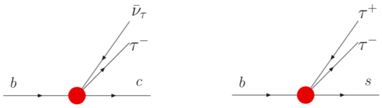
  - Large NP contribution $b \to s\tau\tau$ through $\mathcal{C}^{\mathrm{V}}_{9\tau} = -\mathcal{C}^{\mathrm{V}}_{10\tau}$
  - Avoids bounds from $B \to K(^*)\nu\nu$, Z decays, direct production in $\tau\tau$



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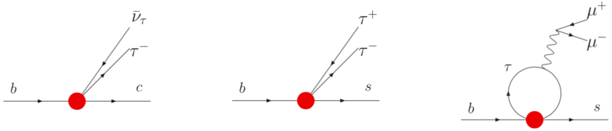
  - Through radiative effects, (small) NP contribution to $\mathcal{C}^{\rm U}_9$



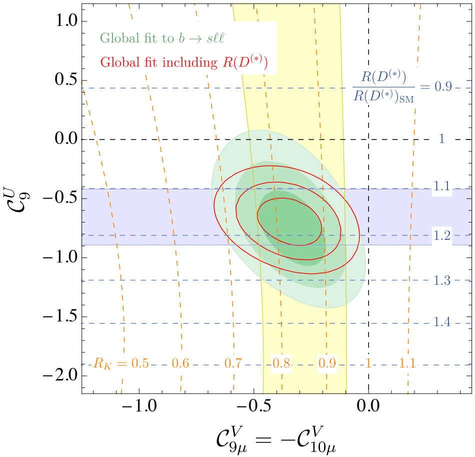
A first EFT connection: anomaly constraints

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 $b \to s\mu\mu]$

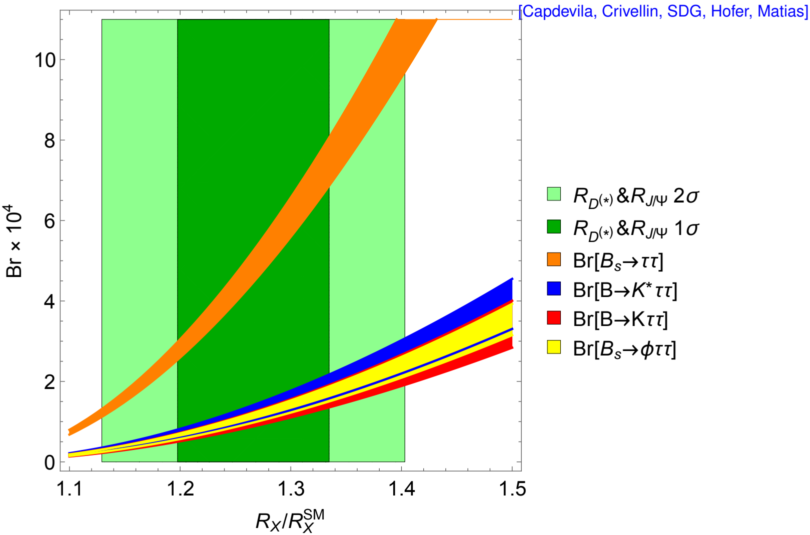
Generic flavour structure and NP at the scale Λ yields

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



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

A first EFT connection: enhancement of $b \to s\tau\tau$



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

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

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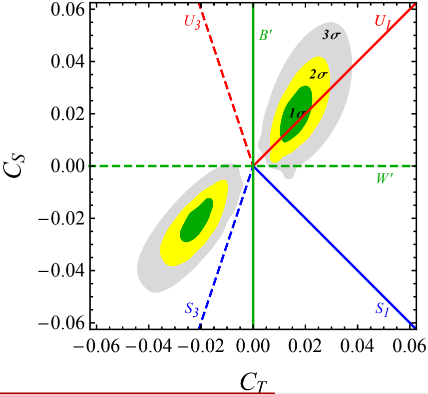
  - $U(2)$ protects first two generations from large NP contributions
- Restrictive (but reasonable) assumptions yield same flavour structure for 2 ops, with 3 couplings λ^q_{sb}, $\lambda^\ell_{\tau\mu}$, $\lambda^\ell_{\mu\mu}$ to be fitted

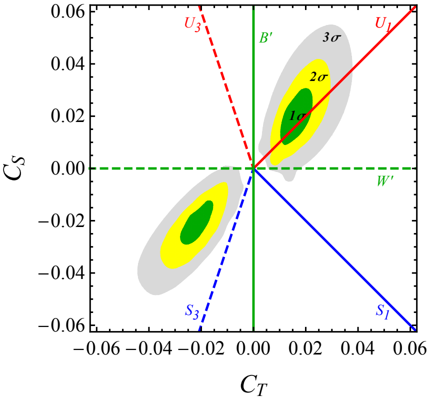


[Butazzo, Greljo, Isidori, Marzocca]

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

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

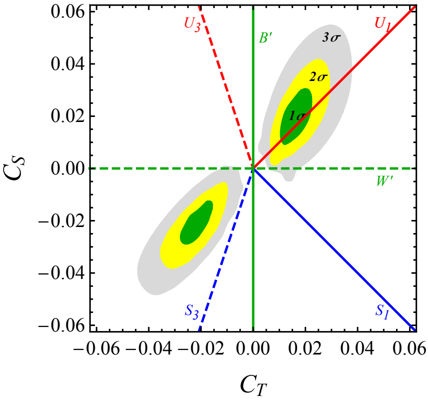
Resulting single-mediator models



[Butazzo, Greljo, Isidori, 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



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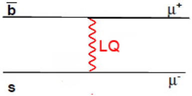
U_1 leptoquark

- 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

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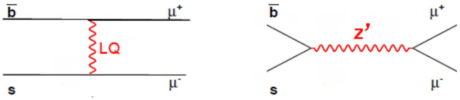

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Many constraints to accommodate
- flavour (CKM, 1st and 2nd generation, $B_s\bar{B}_s$ mixing, $B \to K(^*)\nu\bar{\nu}$)
- bounds on LFV processes $B \to K(^*)e\mu, e\tau, \mu\tau$; $B_s \to e\mu$; $\mu \to e\gamma$
- LEP electroweak constraints
- 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

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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 uncertainties (form factors, charmonium) determined more accurately (sum rules, lattice)
- Better exploitation of LHC constraints on direct production

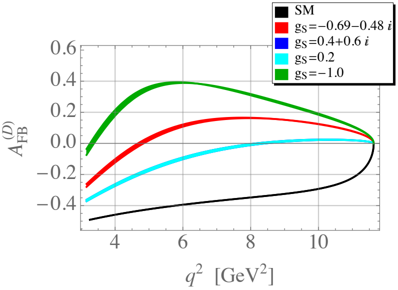
Eagerly awaiting updates from LHC experiments and start of Belle II

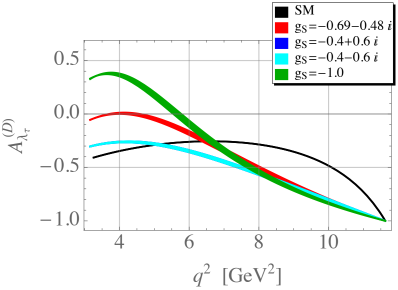
Back-up

$b \to c\ell\bar{\nu}_\ell$: 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



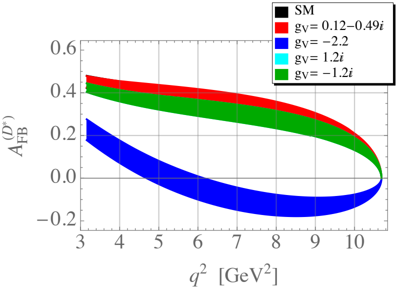


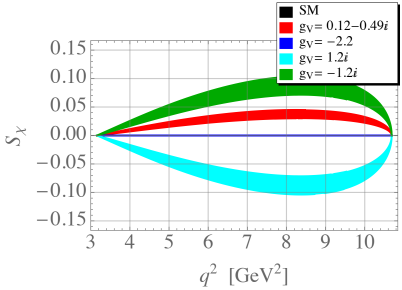
[Fajfer, Kamenik, Nisandzic, Becirevic, Tayduganov. . .]

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

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

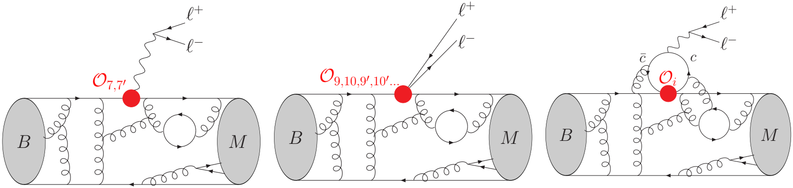
- differential decay rate $d\Gamma/dq^2$
- forward-backward asymmetry
- lepton-polarisation asymmetry
- partial decay rate according to D^* polar $(d\Gamma_L/dq^2)/(d\Gamma_T/dq^2)$
- angular observables (asymmetries with respect to two angles)





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

Disentangling scenarios: more precision

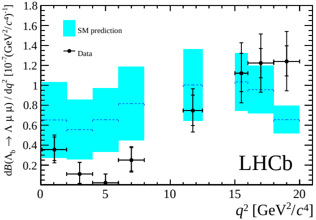


- Reduce hadronic uncertainties on form factors
  - low recoil: lattice [Horgan, Liu, Meinel, Wingate; HPQCD collab]
  - large recoil: B-meson LCSR [Khodjamirian, Mannel, Pivovarov, Wang]
  - all: fit of light-meson LCSR + lattice [Bharucha, Straub, Zwicky]
  - all: fit of B-meson LCSR + lattice [Gubernari,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

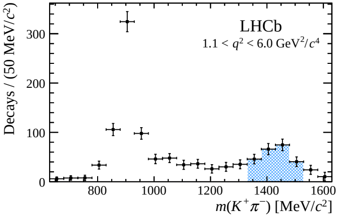
  $\Longrightarrow$only one (BSZ) computation for $B_s \to \phi$ form factors for now ?
- Reduce hadronic uncertainties on $c\bar{c}$ contributions
  - Many different estimates at large recoil (all in agreement)
    $\Longrightarrow$check normalisation through light-meson LCSR at $q^2 \leq 0$?
  - Low-recoil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

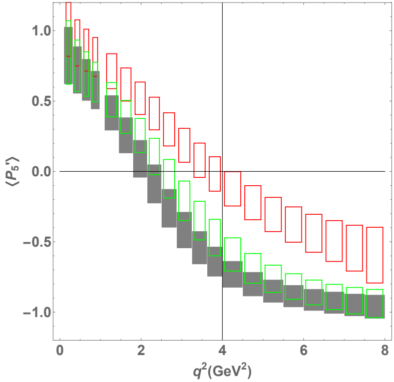


Different info and systematics in angular distributions known for

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

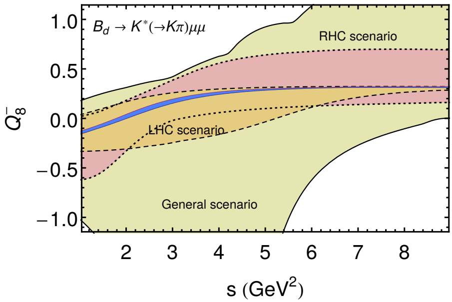
- Form factors not so well known [Detmold, Lin, Meinel, Wingate, Rendon]
- Large recoil
  - Status of factorisation for not-so-light mesons ? baryons ?
  - Could be tackled with form factors + analytic repr. of $c\bar{c}$ contribution but normalisation of $c\bar{c}$ at $q^2 \leq 0$ [LCSR] [Bobeth, Chrzaszcz,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



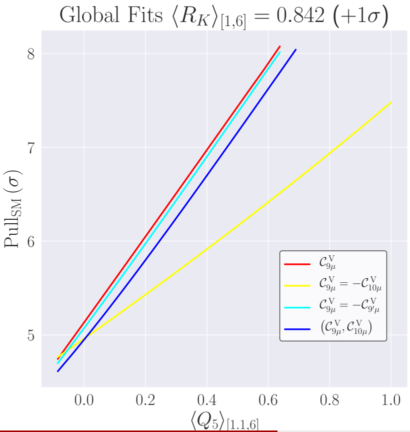
Time-dependent observables in $B_d \to K^*(\to K_S\pi^0)\ell^+\ell^-$ and $B_s \to \phi(\to K^+K^-)\ell^+\ell^-$

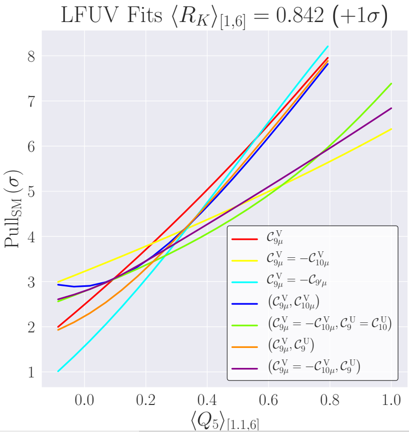
[SDG, Virto]

Disentangling scenarios: more observables (2)

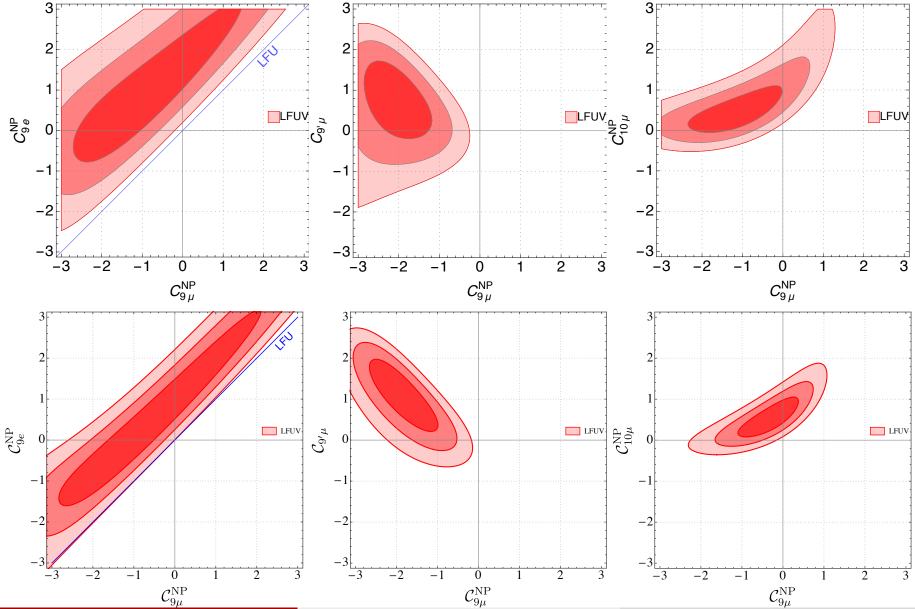
- other LFUV quantities: R_ϕ, $R^{T,L}_{K,\phi}$, $Q_i = P_i^\mu - P_i^e$
- $Q_5 = P_5^{\mu\prime} - P_5^{e\prime}$ interesting observable to disentangle
  - $\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}$ from others NP scenarios in $b \to s\mu\mu$
  - classes of scenarios allowing for LFU contributions

[Alguero, Capdevila, SDG, Masjuan, Matias]

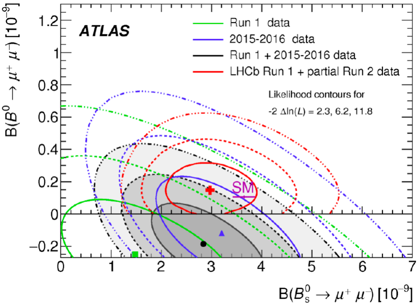




LFUV subset fits in 2017 (top) and 2019 (bottom)



$B_s \to \mu\mu$



- 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	+0.01	-1.10	+0.15	+0.02	+0.36	-0.16
1 σ	$[-0.01, +0.05]$	$[-1.28, -0.90]$	$[-0.00, +0.36]$	$[-0.00, +0.05]$	$[-0.14, +0.87]$	$[-0.39, +0.13]$
2 σ	$[-0.03, +0.06]$	$[-1.44, -0.68]$	$[-0.12, +0.56]$	$[-0.02, +0.06]$	$[-0.49, +1.23]$	$[-0.58, +0.33]$

- 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 5.1 σ (5.0 σ in 2017)

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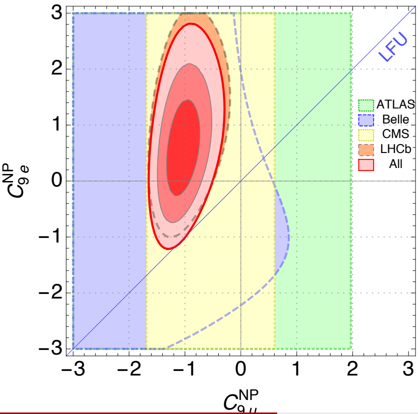

- NP in $(\mathcal{C}_{9\mu}, \mathcal{C}_{9e})$ in 2017

Other interesting scenarios

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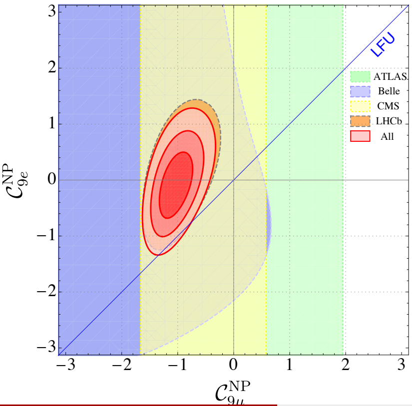

- NP in $(\mathcal{C}_{9\mu}, \mathcal{C}_{9e})$ in 2019
  - Less need for NP in $b \to see$
  - Though some room available (not many obs)
  - SM pull=5.3 σ, p-value=62% (slight decrease wrt 2017)

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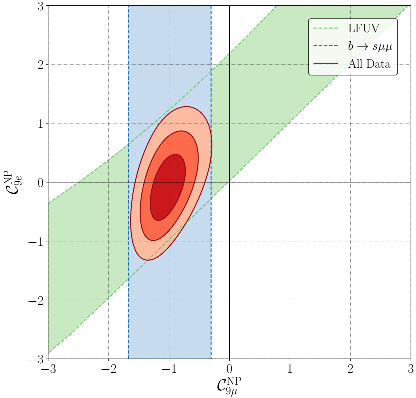

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