Status of $b \to s\ell\ell$ and $b \to s\gamma$ fits

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$b \to s\,\mu^+\mu^-$ anomalies

D. Wang's talk this morning

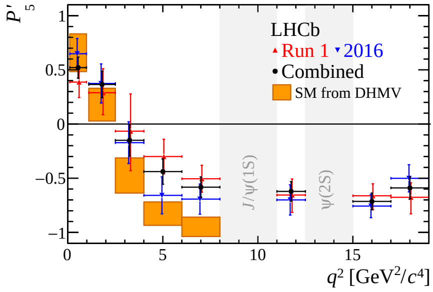
Several LHCb measurements deviate from Standard model (SM) predictions by 2-3σ:

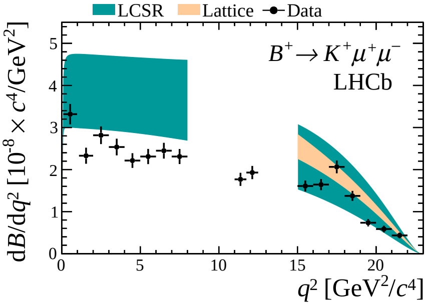
- Branching ratios of $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, and $B_s \to \phi\mu^+\mu^-$.

  LHCb 1403.8044, 1506.08777, 1606.04731

- Angular observable P_5' in $B \to K^*\mu^+\mu^-$ [new, 4.7 fb^{-1}]

  LHCb 2003.04831, ATLAS, CMS, Belle





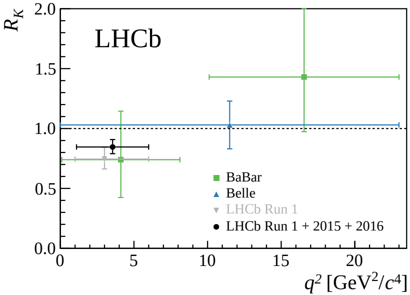
LFU violation in $b \to s\,\ell^+\ell^-$ decays

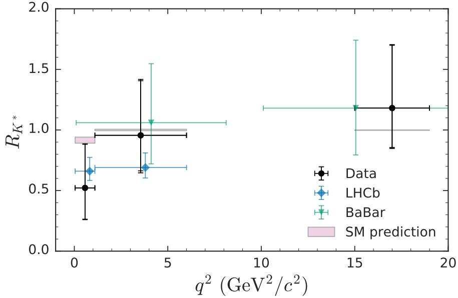
M. Mulder's talk this morning

- Measurements of lepton flavour universality (LFU) ratios $R_K^{[1,6]}$, $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$ show deviations from SM by about 2.5σ each.

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu^+\mu^-)}{BR(B \to K^{(*)}e^+e^-)}$$

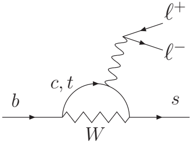
LHCb, 1705.05802, 1903.09252, Belle, 1904.02440, 1908.01848





- $Q_5 = P'_{5\mu} - P'_{5e} \neq 0$ central values but large unc Belle 1612.05014
- $\Lambda_b \to pK\ell\ell$: $R_{pK} < 1$ ($q^2 \in [0.1, 6]$GeV^2,$m_{pK} < 2.6$GeV) LHCb 1912.08139

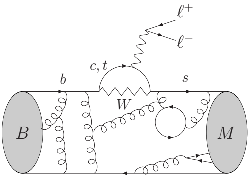
$b \to s\ell\ell$ effective Hamiltonian



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

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

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



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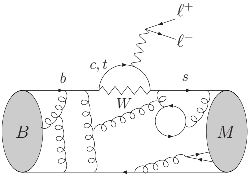

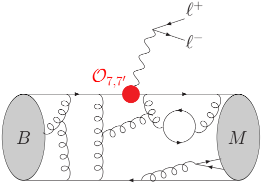

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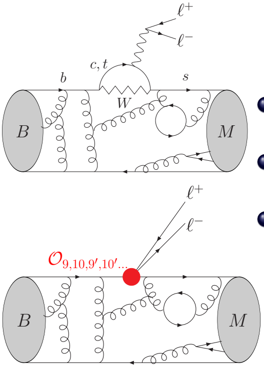
- $\mathcal{O}_7 = \frac{e}{g^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]

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



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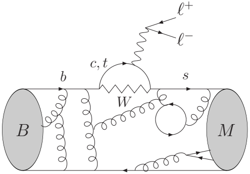
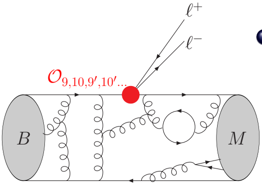
- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

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





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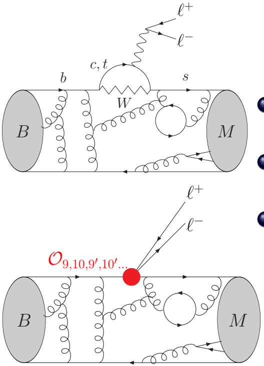
$$\mathcal{C}_7^{\rm SM} = -0.29,\ \mathcal{C}_9^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3$$

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



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

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

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

Two sources of hadronic uncertainties

D. van Dyk's talk, this afternoon

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

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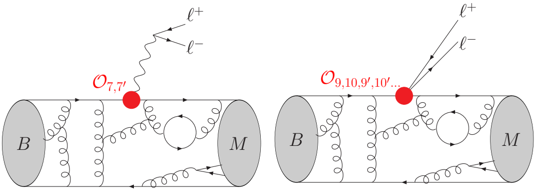

Form factors (local)

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

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

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

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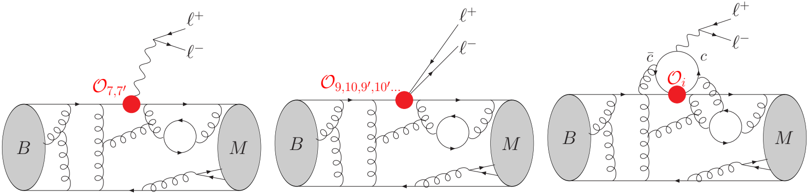

Form factors (local) Charm loop (non-local)

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

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

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

Fits

Once long dist understood, fit data to extract NP in short-dist $\mathcal{C}_i$

- Fits perfomed with 2019 data by [Aebischer et al., 1903.10434, Ciuchini et al., 1903.09632, Datta et al., 1903.10086, Kowalska et al., 1903.10932, Arbey et al., 1904.08399]
- Updated 2020 results in appendix of [Algueró, Capdevila, Crivellin, SDG, Masjuan, Matias, Novoa-Brunet, Virto, 1903.09578], also as Addendum to published version
- Two other 2020 updates available from [Biswas, Nandi, Ray, Kumar Patra, 2004.14687] and [Bhom, Chrzaszcz, Mahmoudi, Prim, Scott, White, 2006.03489]

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Frequentist analysis of [Algueró et al, 1903.09578]

- likelihood from experimental and theoretical uncertainties and correlations in Gaussian approx
- two statistical quantities of interest to assess a NP scenario/hyp
  - p-value of a given hypothesis: $\chi^2_{\rm min}$ considering N_{dof} (in %)
    goodness of fit: does the hypothesis give an overall good fit ? and if not, can we exclude it ?
  - $\text{Pull}_{\rm SM}$: $\chi^2(\mathcal{C}_i = 0) - \chi^2_{min}$ considering N_{dof} (in σ units)
    metrology: how well does the hypothesis solve SM deviations ?

Experimental inputs

- R_K, R_{K^*} (large- and low-recoil bins)
- $B \to K^* \mu\mu$ (Br and ang obs)
- $B \to K^* ee$ (ang obs)
- $B_s \to \phi\mu\mu$ (Br and ang obs)
- $B^+ \to K^+ \mu\mu$, $B^0 \to K^0 \mu\mu$ (Br and ang obs)
- $B \to X_s\gamma$,$B \to X_s\mu\mu$,$B_s \to \mu\mu$,$B_s \to \phi\gamma$, $B \to K^*\gamma$ (Br)

including LHCb, ATLAS, CMS, Babar and Belle data whenever available, and in particular the latest LHCb update of $B \to K^* \mu\mu$

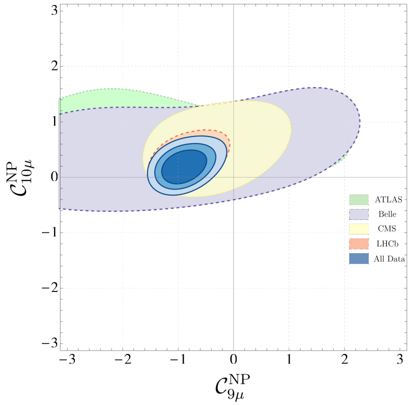
- Some additional obs from some groups ($\Lambda_b \to \Lambda\ell\ell$, $b \to s\gamma$ obs)
- [Algueró et al] and [most groups] No inclusion of additional observables that are not directly related to $b \to s\ell\ell$ and $b \to s\gamma$ (would require extra assumption on NP model)
- [Aebischer et al] correlate theory inputs in $B_s \to \mu\mu$ with $\Delta F = 2$ observables assuming SM there and enhancing $B_s \to \mu\mu$ role

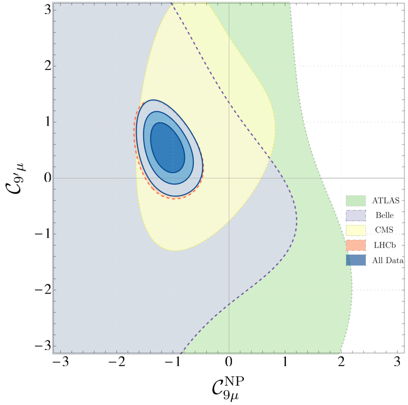
1D Scenarios for $\mathcal{C}_{i\mu}$ (2020)

	All			LFUV		
1D Hyp.	$1\,\sigma$	$\mathrm{Pull}_{\mathrm{SM}}$	p-value	$1\,\sigma$	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	$[-1.19, -0.88]$	6.3	37.5 %	$[-1.25, -0.61]$	3.3	60.7 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}$	$[-0.59, -0.41]$	5.8	25.3 %	$[-0.50, -0.28]$	3.7	75.3 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{9'\mu}$	$[-1.17, -0.87]$	6.2	34.0 %	$[-2.15, -1.05]$	3.1	53.1 %

- LFUV fit: R_K, R_{K^*}, $Q_{4,5}$ $(P'_{i,\mu} - P'_{i,e})$, $B_s \to \mu\mu$, $b \to s\gamma$
- All : all $b \to s\ell\ell$ and $b \to s\gamma$ observables
- $\mathrm{Pull}_{\mathrm{SM}}$ in σ units increased wrt [2019] by 0.6-0.7 σ for fit All
- *p*-value of SM hyp down from 11% to 1.4% (2.5σ) for the fit “All”

2D Scenarios for $\mathcal{C}_{i\mu}$ (2019)





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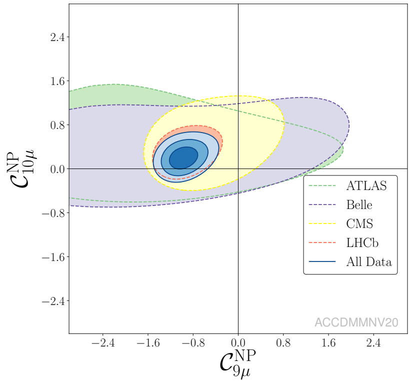
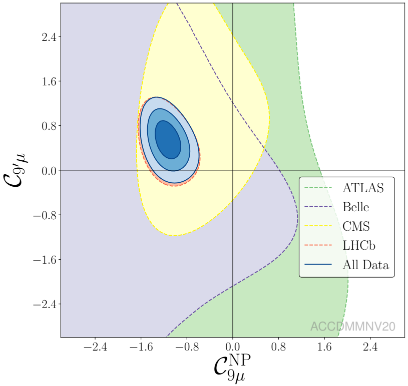




2D and 6D Scenarios for $\mathcal{C}_{i\mu}$ (2020)

	All			LFUV		
2D Hyp.	Best fit	Pull_{SM}	p-value	Best fit	Pull_{SM}	p-value
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}})$	(-0.98,0.19)	6.2	39.8 %	(-0.31,0.44)	3.2	70.0 %
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu})$	(-1.14,0.55)	6.5	47.4 %	(-1.86,1.20)	3.5	81.2 %
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10'\mu})$	(-1.17,-0.33)	6.6	50.3 %	(-1.87,-0.59)	3.7	89.6 %
$(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\text{NP}} = \mathcal{C}_{10'\mu})$	(-1.10,0.28)	6.5	48.9 %	(-1.69,0.29)	3.5	82.4 %
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$	(-1.17,0.23)	6.6	51.1 %	(-2.05,0.50)	3.8	91.9 %

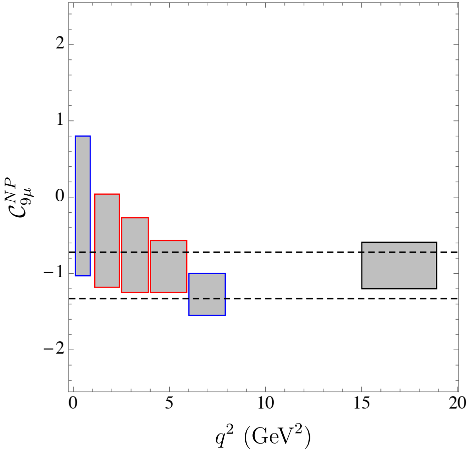
- Right-handed currents appear quite naturally
- Slght decrease of the p-values, increase of the pull_{SM}
- No change in the hierarchy of scenarios compared to 2019

	$\mathcal{C}_7^{\text{NP}}$	$\mathcal{C}_{9\mu}^{\text{NP}}$	$\mathcal{C}_{10\mu}^{\text{NP}}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Bfp	+0.00	-1.13	+0.20	+0.00	+0.49	-0.10
1 σ	$[-0.02, +0.02]$	$[-1.30, -0.96]$	$[+0.05, +0.37]$	$[-0.01, +0.02]$	$[+0.04, +0.95]$	$[-0.33, +0.14]$
2 σ	$[-0.03, +0.04]$	$[-1.46, -0.78]$	$[-0.09, +0.57]$	$[-0.03, +0.04]$	$[-0.39, +1.45]$	$[-0.55, +0.41]$

- Pull_{SM}: 5.1 [2019] $\to$ 5.8σ [2020]
- *p*-value: 81.6% [2019] $\to$ 46.8% [2020]

Consistency of the results over the q^2 range

Sanity check possible for the $C_{9\mu}$ NP hypothesis



- $B \to K^* \mu\mu$ Br + ang obs + $B_s \to \mu\mu$ + $B \to X_s \mu\mu$ + $b \to s\gamma$
- $C_{9\mu}^{\mathrm{NP}}$ fitted independently for each bin
- Good agreement with global fit (2σ dashed band)
- No indication of a q^2 variation: hadronic effects in control
- Low and large recoils: very different systematics

$\Longrightarrow$Similar stability of $\mathcal{C}_{9\mu}$ as a function of q^2 for other NP scenarios

Other works (2019)

[Aebischer et al., 1903.10434], [Alok et al. 1903.09617] [Kowalska et al. 1903.10932] [D'amico et al. 1704.05438 updated] [Ciuchini et al. 1903.09632] with different settings, similar favoured NP scenarios

1D hyp	Algueró	Aebischer	Alok	Arbey	D'amico	Kowalska
$\mathcal{C}_{9\mu}^{\rm NP}$	5.6σ	5.9σ	6.2σ	5.3σ	6.5σ	4.7σ
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	5.2σ	6.6σ	6.4σ	4.5σ	5.9σ	4.8σ
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}^{\rm NP}$	5.5σ	-	6.4σ	-	-	-

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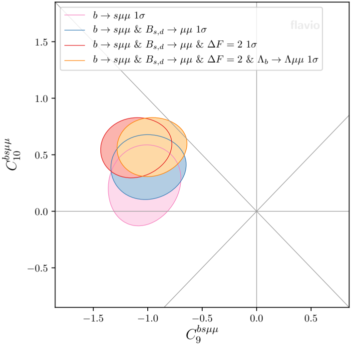
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	5.2σ	6.6σ	6.4σ	4.5σ	5.9σ	4.8σ
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}^{\rm NP}$	5.5σ	-	6.4σ	-	-	-

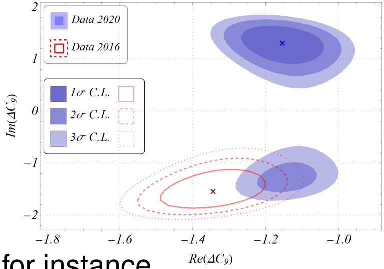
- NP hyps with significant pulls
- Right-handed currents interesting (due to R_K closer to 1)
- $\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$ favoured by [Aebischer et al.] as a combined effect of
  - $BR(B_s \to \mu\mu)$
  - $\Lambda_b \to \Lambda\mu\mu$ inputs
  - $\Delta m_{d,s}$ assuming no NP in $\Delta B = 2$ (not done in other fits)



Other works (2020)

[Biswas, Nandi, Ray, Kumar Patra, 2004.14687]

- Complex Wilson coefficients (NP weak phases)
- Include CP-asymmetries for $B \to K^* \mu\mu$, $B_s \to \phi\mu\mu$
- Favoured scenarios with real and imaginary parts in $\mathcal{C}_{9,9',10}$



- Large imaginary parts are allowed, for instance

$$Re(\mathcal{C}_{9\mu}^{\rm NP}) \to -1.14 \pm 0.11,\ Im(\mathcal{C}_{9\mu}^{\rm NP}) \to -0.22 \pm 0.42$$
$$Re(\mathcal{C}_{9'\mu}) \to 0.40 \pm 0.23,\ Im(\mathcal{C}_{9'\mu}) \to -1.05 \pm 0.38$$

- Results for CP-averaged observables close to real NP scenarios

[Bhom, Chrzaszcz, Mahmoudi, Prim, Scott, White, 2006.03489]

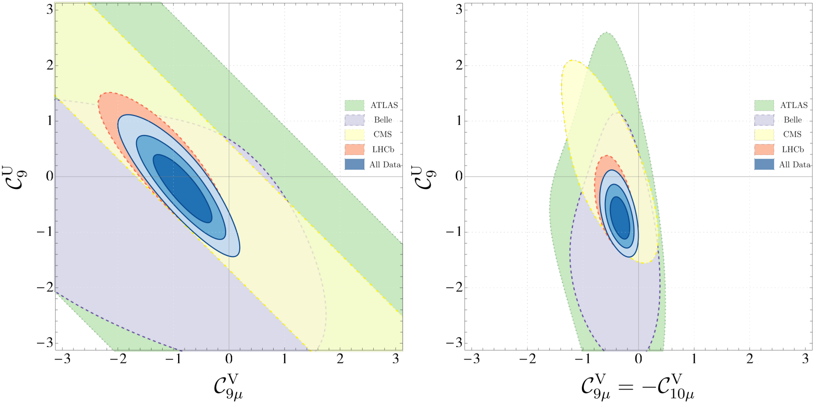
- Gambit framework (frequentist, correlation recomputed pt-by-pt)
- NP real contributions to $\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}$ with pull$_{\rm SM}$=6.0σ
- 1σ CI: $[0.002, 0.028], [-1.19, -0.85], [-0.06, 0.20]$

Scenarios for LFU and LFUV $\mathcal{C}_i$ (2019)

G. Isidori's talk, this morning

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

$\mathcal{C}_{ie} = \mathcal{C}_i^{\mathrm{U}} \qquad \mathcal{C}_{i\mu} = \mathcal{C}_i^{\mathrm{U}} + \mathcal{C}_{i\mu}^{\mathrm{V}}$ (first discussed in [Algueró et al, 1809.08447])

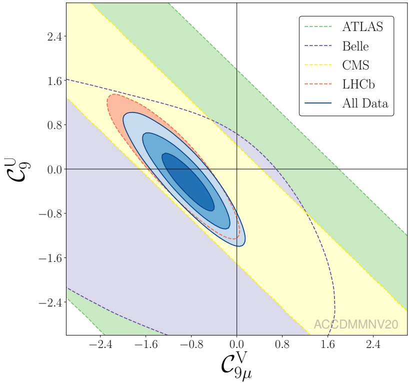


Scenarios for LFU and LFUV $\mathcal{C}_i$ (2020)

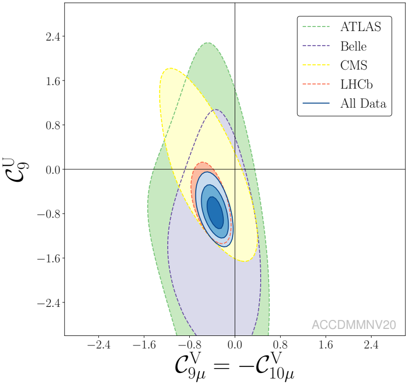
G. Isidori's talk, this morning

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

$\mathcal{C}_{ie} = \mathcal{C}_i^{\rm U} \qquad \mathcal{C}_{i\mu} = \mathcal{C}_i^{\rm U} + \mathcal{C}_{i\mu}^{\rm V}$ (first discussed in [Algueró et al, 1809.08447])

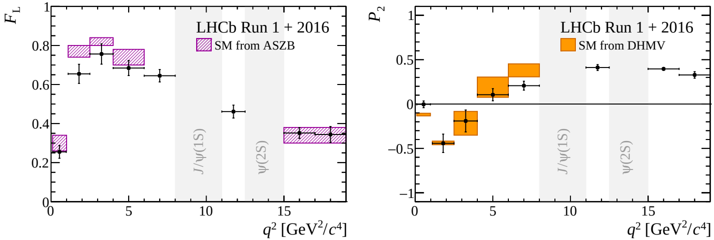


pull$_{\rm SM}$=6.0 σ
p-value =36%



pull$_{\rm SM}$=6.5 σ
p-value=48.4%

Comments on the $B \to K^* \mu\mu$ data



New data from LHCb

- uncertainty reduced by $30 - 50\%$ (in particular $[1.1, 2.5]$ $[2.5, 4]$)
- new average value for F_L in the bin $[2.5, 4]$ more than 4σ below 1, helping the discussion in terms of optimised observables P_i

Excellent consistency

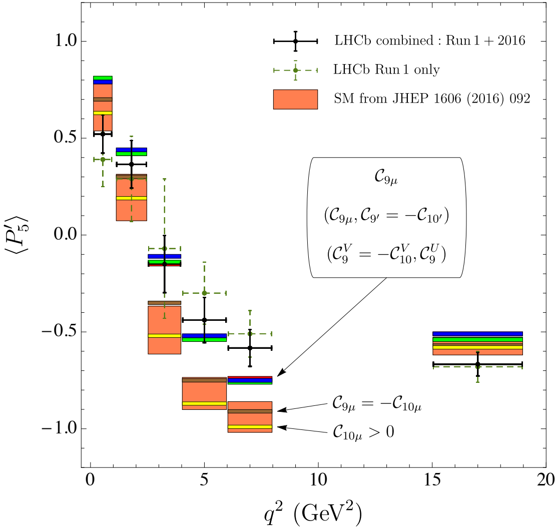
- new tensions wrt SM in $\langle P_3 \rangle_{[1.1,2.5]}$, $\langle P'_6 \rangle_{[6,8]}$ and $\langle P'_8 \rangle_{[1.1,2.5]}$
- enhanced tension for other obs such as $P_{1,2}$
- tension in first bin of P'_5 decreased, agrees more with theory

Solve earlier tensions of the fit discussed in [Algueró et al, 1902.04900]

Consistency of scenarios with $B \to K^* \mu\mu$ data

- Increase of significance for some scenarios (up to 0.8 σ), but same hierarchies

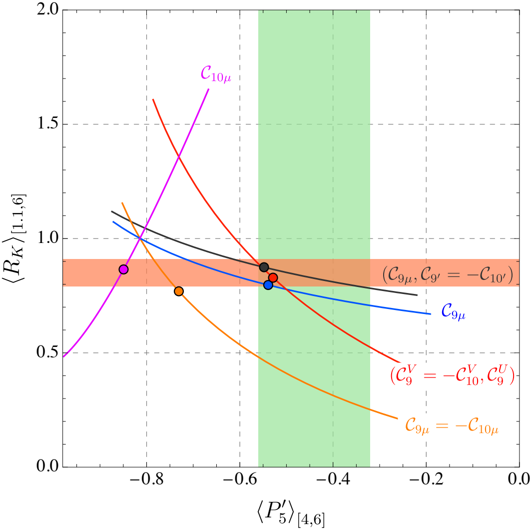
Consistency of scenarios with $B \to K^* \mu\mu$ data



- Increase of significance for some scenarios (up to 0.8 σ), but same hierarchies
- Reduction of the internal tensions of the fit
  - for P_5'

for some of the scenarios

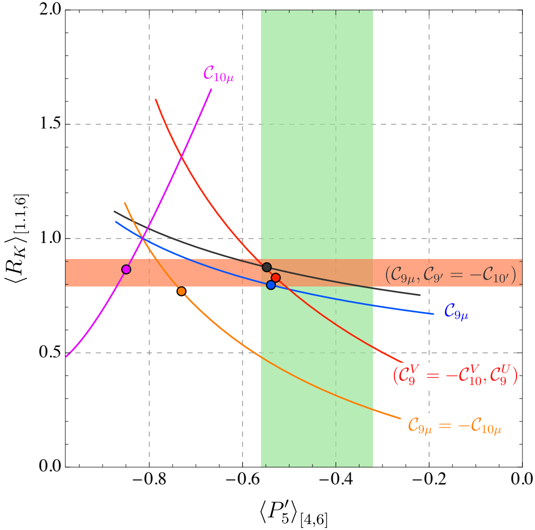
Consistency of scenarios with $B \to K^*\mu\mu$ data



- Increase of significance for some scenarios (up to 0.8 σ), but same hierarchies
- Reduction of the internal tensions of the fit
  - for P_5'
  - between P_5' and R_K

  for some of the scenarios

Consistency of scenarios with $B \to K^*\mu\mu$ data

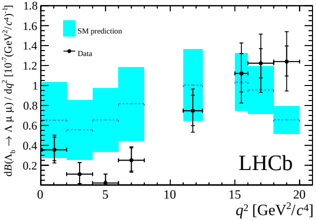


- Increase of significance for some scenarios (up to 0.8 σ), but same hierarchies
- Reduction of the internal tensions of the fit
  - for P_5'
  - between P_5' and R_K

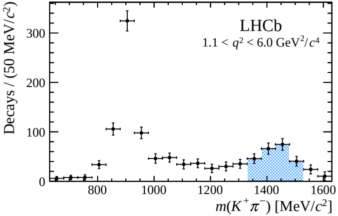
  for some of the scenarios
- p-value of SM decreased to 1.4%

Disentangling scenarios: more modes

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



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

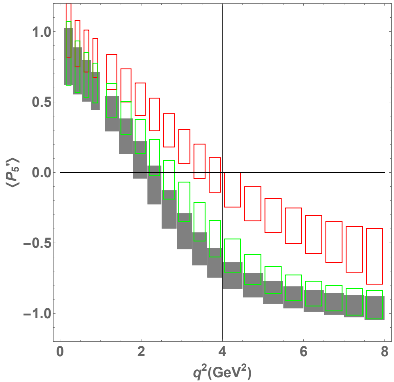


Different info and systematics in angular distributions known for

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

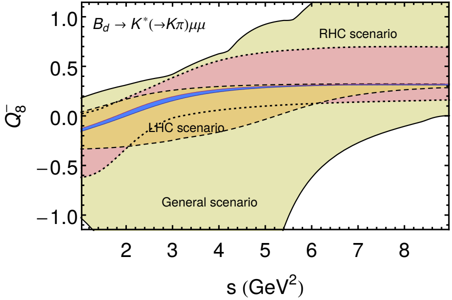
- Form factors poorly known [Detmold, Lin, Meinel, Wingate, Rendon; SDG, Khodjamirian, Virto]
- Large recoil: factorisation, $c\bar{c}$ contributions
- Low recoil: estimate of quark-hadron duality violation

Disentangling scenarios: more observables



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 1502.05509]

and $B_d \to K_S\ell\ell$

[SDG, Novoa Brunet, Vos, in prep]

Conclusions

New $B \to K^* \mu\mu$ data confirm the solidity of $b \to s\ell\ell$ landscape

- Increased consistency between $B \to K^* \mu\mu$ data and the rest of the global fit, in particular between R_K and P_5'
- Increase in the pull_{SM} of the favoured scenarios, no change in hierarchy of scenarios
- Significant decrease of the p-value of the SM
- Right-handed currents in several favoured scenarios

More from LHCb ? Belle II and CMS data ?

Better theory estimates ? NP models ?

Thanks for your attention !

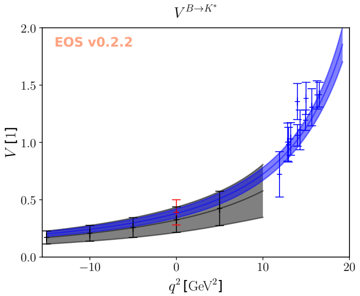
Backup slides

Hadronic uncertainties: form factors

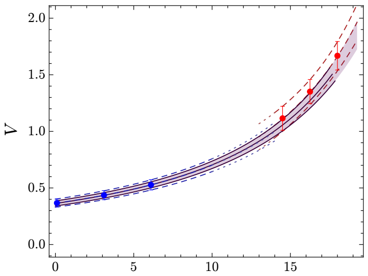
3 form factors for K, 7 form factors for K^* and ϕ

- 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



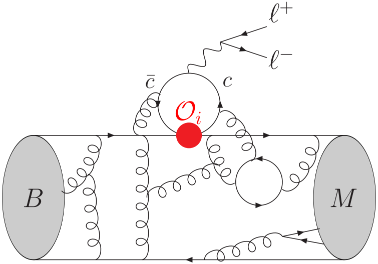
Light-meson LCSR + lattice

- correlations among the form factors needed from
  - direct determination and/or combined fit to low and large recoils
  - EFT with $m_b \to \infty$ + $O(\alpha_s)$ + $O(1/m_b)$

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

Hadronic uncertainties: charm loops

- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_{9\ell}$
- depends on q^2, lepton univ.
- quark-hadron duality approx at large q^2 (syst of few %)



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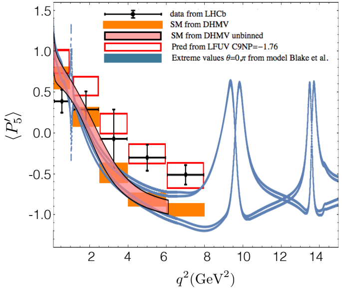

Several approaches agree at low-q^2

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

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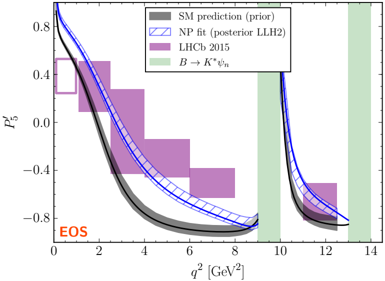

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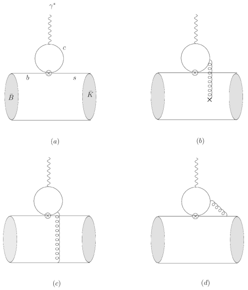
- fit of sum of resonances to the data [Blake, Egede, Owen, Pomery, Petridis]
- fit of q^2-parametrisation to the data

  [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli; Capdevila, SDG, Hofer, Matias]

- dispersive representation + $J/\psi, \psi(2S)$ data [Bobeth, Chrzaszcz, van Dyk, Virto]

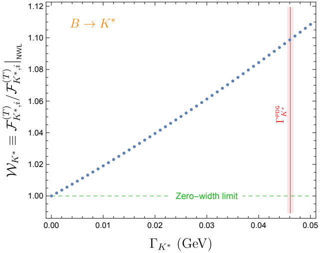
Pending questions on $c\bar{c}$ contributions



- Estimate of soft-gluon $c\bar{c}$ contribution from Light-Cone Sum Rules
  - Several $c\bar{c}$ contributions, with hard and soft gluons (hard to estimate)
  - Soft-gluon correction from LCSR smaller than thought ? [Gubernari, Van Dyk]
  - Impact on contribution to be worked out (not used at face value in fits)

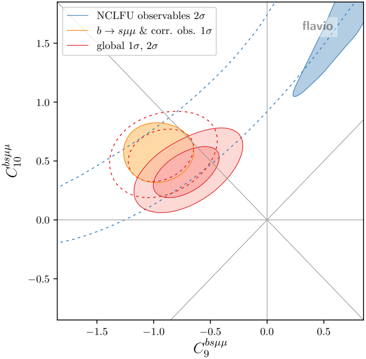
- Narrow-width approx for form factors
  - Not problem for K or ϕ, but for K^* ?
  - Lattice QCD : other collaborations ?
  - K^*-meson LCSR: not able to catch the effect (need to use $K\pi$ DAs)
  - B-meson LCSR: universal 10% effect, increasing SM discrepancy

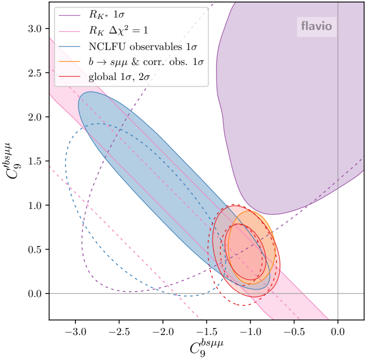
[Khodjamirian, SDG, Virto]



(Aebischer et al., 1903.10434)

- Obs: same + $\Lambda_b \to \Lambda\mu\mu$ [BR,A_{FB}]
- Stat approach: Frequentist, flavio code
- Form factors: global fit to K^*-meson LCSR + lattice
- LD charm: q^2-polynomial with 10% from amplitude

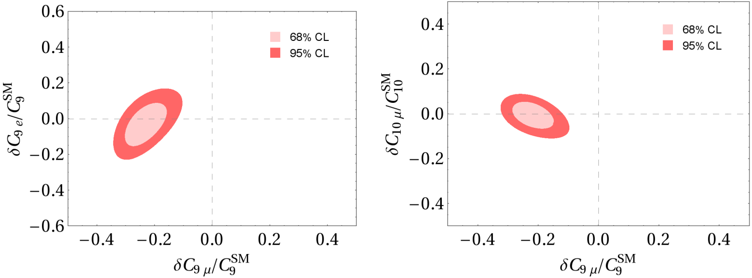




- Higher pulls: 6.3σ and 6.0σ (p-value: 22% for $b \to s\mu\mu$ obs only)
- 1D hyps: preference for $\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$ with tensions among obs.

(Arbey et al., 1904.08399)

- Obs: similar to Algueró et al
- Stat approach: Frequentist, SuperIso code
- Form factors: global fit to K^*-meson LCSR + lattice
- LD charm: q^2-polynomial with 10% size of QCD fact



- decreased tension between $R_{K^{(*)}}$ and others concerning $\mathcal{C}_{10\mu}^{\rm NP}$
- 1D hyps: preference for $\mathcal{C}_{9\mu}^{\rm NP}$
- No need for NP in electrons (in agreement with other groups)

Scenarios for LFU and LFUV $\mathcal{C}_i$ (2020)

Scenario		Best-fit point	1 σ	2 σ	Pull_{SM}	p-value
Sc. 5	$\mathcal{C}_{9\mu}^{\text{V}}$	-0.54	$[-1.06, -0.06]$	$[-1.68, +0.39]$	6.0	39.4 %
	$\mathcal{C}_{10\mu}^{\text{V}}$	$+0.58$	$[+0.13, +0.97]$	$[-0.48, +1.33]$		
	$\mathcal{C}_{9}^{\text{U}} = \mathcal{C}_{10}^{\text{U}}$	-0.43	$[-0.85, +0.05]$	$[-1.23, +0.67]$		
Sc. 6	$\mathcal{C}_{9\mu}^{\text{V}} = -\mathcal{C}_{10\mu}^{\text{V}}$	-0.56	$[-0.65, -0.47]$	$[-0.75, -0.38]$	6.2	41.4 %
	$\mathcal{C}_{9}^{\text{U}} = \mathcal{C}_{10}^{\text{U}}$	-0.41	$[-0.53, -0.29]$	$[-0.64, -0.16]$		
Sc. 7	$\mathcal{C}_{9\mu}^{\text{V}}$	-0.84	$[-1.15, -0.54]$	$[-1.48, -0.26]$	6.0	36.5 %
	$\mathcal{C}_{9}^{\text{U}}$	-0.25	$[-0.59, +0.10]$	$[-0.92, +0.47]$		
Sc. 8	$\mathcal{C}_{9\mu}^{\text{V}} = -\mathcal{C}_{10\mu}^{\text{V}}$	-0.34	$[-0.44, -0.25]$	$[-0.54, -0.16]$	6.5	48.4 %
	$\mathcal{C}_{9}^{\text{U}}$	-0.80	$[-0.98, -0.60]$	$[-1.16, -0.39]$		
Sc. 9	$\mathcal{C}_{9\mu}^{\text{V}} = -\mathcal{C}_{10\mu}^{\text{V}}$	-0.66	$[-0.79, -0.52]$	$[-0.93, -0.40]$	5.7	28.4 %
	$\mathcal{C}_{10}^{\text{U}}$	-0.40	$[-0.63, -0.17]$	$[-0.86, +0.07]$		
Sc. 10	$\mathcal{C}_{9\mu}^{\text{V}}$	-1.03	$[-1.18, -0.87]$	$[-1.33, -0.71]$	6.2	41.5 %
	$\mathcal{C}_{10}^{\text{U}}$	$+0.28$	$[+0.12, +0.45]$	$[-0.04, +0.62]$		
Sc. 11	$\mathcal{C}_{9\mu}^{\text{V}}$	-1.11	$[-1.26, -0.95]$	$[-1.40, -0.78]$	6.3	43.9 %
	$\mathcal{C}_{10'}^{\text{U}}$	-0.29	$[-0.44, -0.15]$	$[-0.58, -0.01]$		
Sc. 12	$\mathcal{C}_{9'\mu}^{\text{V}}$	-0.06	$[-0.21, +0.10]$	$[-0.37, +0.26]$	2.1	2.2 %
	$\mathcal{C}_{10}^{\text{U}}$	$+0.44$	$[+0.26, +0.62]$	$[+0.09, +0.81]$		
Sc. 13	$\mathcal{C}_{9\mu}^{\text{V}}$	-1.16	$[-1.31, -1.00]$	$[-1.46, -0.83]$	6.2	49.2 %
	$\mathcal{C}_{9'\mu}^{\text{V}}$	$+0.56$	$[+0.27, +0.83]$	$[-0.02, +1.10]$		
	$\mathcal{C}_{10}^{\text{U}}$	$+0.28$	$[+0.08, +0.49]$	$[-0.11, +0.70]$		
	$\mathcal{C}_{10'}^{\text{U}}$	$+0.01$	$[-0.19, +0.22]$	$[-0.40, +0.42]$		

Hints for LFU violation in $b \to c\,\ell\,\nu$ decays

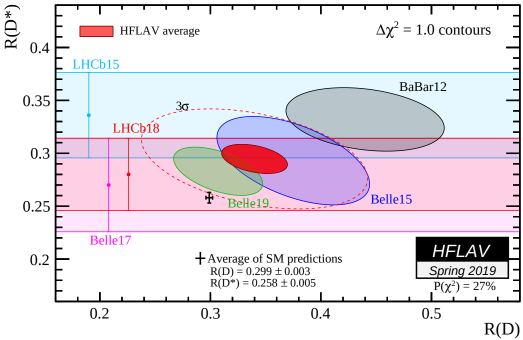
Measurements of LFU ratios R_D and R_{D^*} by BaBar, Belle, and LHCb show combined deviation from SM by about 3σ.

BaBar, 1205.5442, 1303.0571, LHCb, 1506.08614, 1708.08856

Belle, 1507.03233, 1607.07923, 1612.00529, 1904.08794

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

$$\ell \in \{e, \mu\}$$



HFLAV, hflav.web.cern.ch

Connection with charged currents: SMEFT

Connect $b \to s\ell\ell$ and $b \to c\ell\nu$ 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 ops. with left-handed doublets

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

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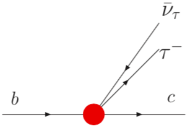
- FCCC part of $\mathcal{O}^{(3)}_{2333}$ describe $R_{D^{(*)}}$ (rescale G_F for $b \to c\tau\nu$)



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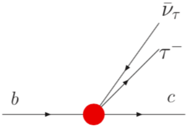
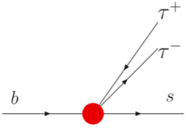
- FCNC part of $\mathcal{O}^{(1,3)}_{2333}$ with $C^{(1)}_{2333} = C^{(3)}_{2333}$ [Capdevila et al, 1712.01919]
  - Large NP contribution $b \to s\tau\tau$ through $\mathcal{C}^{\rm V}_{9\tau} = -\mathcal{C}^{\rm V}_{10\tau}$
  - Avoids bounds from $B \to K^{(*)}\nu\nu$, Z decays, direct production in $\tau\tau$





Connection with charged currents: SMEFT

Connect $b \to s\ell\ell$ and $b \to c\ell\nu$ within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

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

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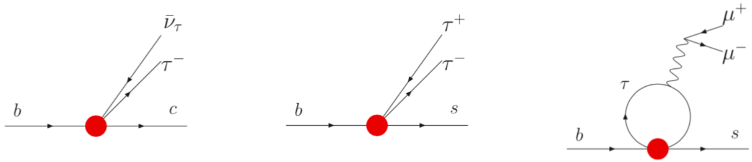
  - Avoids bounds from $B \to K^{(*)}\nu\nu$, Z decays, direct production in $\tau\tau$
  - Through radiative effects, (small) NP contribution to $\mathcal{C}^{\mathrm{U}}_9$



Connection with charged currents: *B* anomalies

Scenario 8:

- $\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$ from small $\mathcal{O}_{2322}$ [$b \to s\mu\mu$]
- $\mathcal{C}_{9}^{\rm U}$ from rad corr to large $\mathcal{O}_{2333}$ [$b \to c\tau\nu$, $b \to s\mu\mu$]
- No contrib from $\mathcal{O}_{3333}$ [EWPO, direct LHC searches in $\tau^+\tau^-$]

Generic flavour struct, NP scale Λ

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

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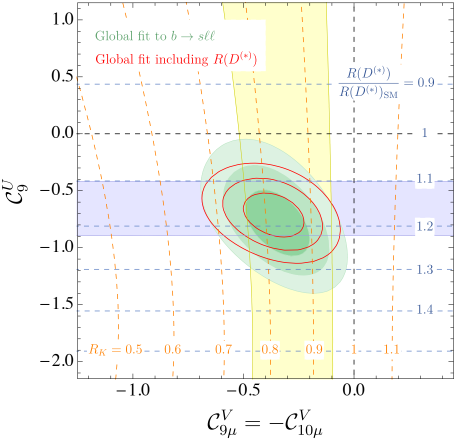
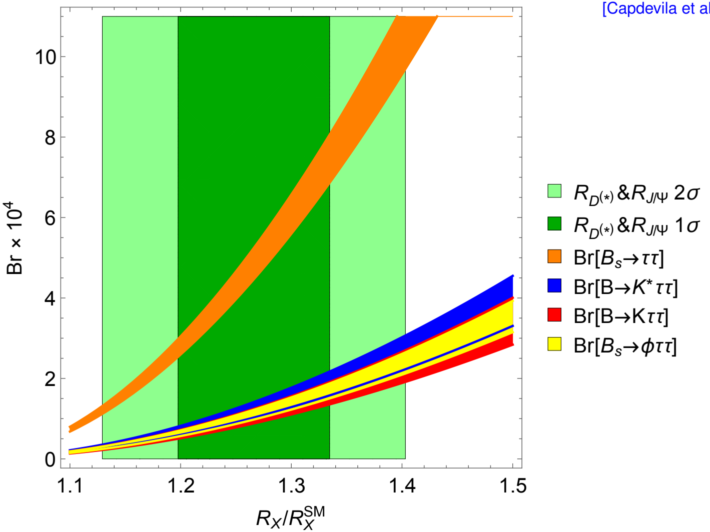


- Agreement with (R_D, R_{D^*}) for $\Lambda = 1 - 10$ TeV
- Scenario 8 has $\text{Pull}_{\rm SM}$ of 7.4 σ once R_{D^*} included
- Huge enhancement of $b \to s\tau\tau$ modes $O(10^{-4})$

[Capdevila et al, 1712.01919]

Connection with charged currents: $b \to s\tau\tau$

[Capdevila et al, 1712.01919]



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

Hints of NP in neutral currents with neutrinos

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- Connection between FCNC with charged and neutral leptons

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- SM: $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})_{\rm SM} = (9.6 \pm 0.9) \times 10^{-6}$
  and $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM} = (5.6 \pm 0.5) \times 10^{-6}$
- Belle: 90%CL bounds of a few 10^{-5}
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$K \to \pi\nu\bar\nu$

- SM: $\mathcal{B}(K^+ \to \pi^+\nu\bar\nu)_{\rm SM} = (9.31 \pm 0.76) \times 10^{-11}$
  and $\mathcal{B}(K_L \to \pi^0\nu\bar\nu)_{\rm SM} = (3.74 \pm 0.72) \times 10^{-11}$
- NA62: $\mathcal{B}(K^+ \to \pi^+\nu\bar\nu)_{\rm exp} < 2.24 \times 10^{-10}$ (aims $O(10\%)$ SM acc)
- KOTO: $\mathcal{B}(K_L \to \pi^0\nu\bar\nu)_{\rm exp} = 2.1^{+2.0(+4.1)}_{-1.1(-1.7)} \times 10^{-9}$ (!)
- [Grossman,Nir] bound $\mathcal{B}(K_L \to \pi^0\nu\bar\nu) \le 4.3\,\mathcal{B}(K^+ \to \pi^+\nu\bar\nu)$ not OK
  possible escape: light flavour-violating NP [Ziegler, Zupan, Zwicky 2005.00451]

Connection with neutrino currents: SMEFT

[SDG, Fajfer, Kamenik, Novoa-Brunet, 2005.03734]

EFT including right-handed quarks (not leptons)

$$\mathcal{L}_{\rm eff.} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\Big[C_T\left(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L\right)\left(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L\right) + C_S\left(\bar{Q}^i_L\gamma_\mu Q^j_L\right)\left(\bar{L}^\alpha_L\gamma^\mu L^\beta_L\right) + C'_{RL}\left(\bar{d}^i_R\gamma_\mu d^j_R\right)\left(\bar{L}^\alpha_L\gamma^\mu L^\beta_L\right) + C'_{LR}\left(\bar{Q}^i_L\gamma_\mu Q^j_L\right)\left(\bar{\ell}^\alpha_R\gamma^\mu \ell^\beta_R\right) + C'_{RR}\left(\bar{d}^i_R\gamma_\mu d^j_R\right)\left(\bar{\ell}^\alpha_R\gamma^\mu \ell^\beta_R\right)\Big]$$

with flavour structure based on $U(2)$ flavour symmetry [Buttazzo et al 1706.07808] and General Minimal Flavour Violation [Kagan, Volansky, Zupan 0903.1794]

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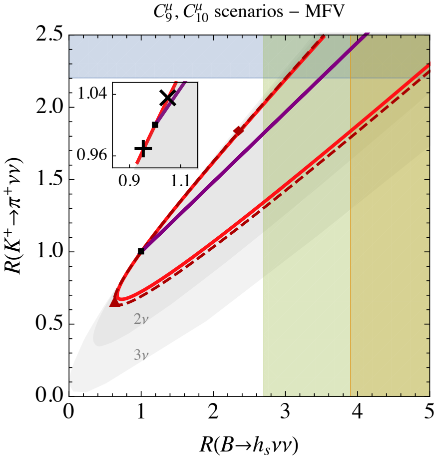
- $b \to s\ell\ell$: $C_T + C_S$ and (depending on NP scenario) C'_{LR}, C'_{RL}, C'_{LR}
- $b \to s\nu\nu$ and $s \to d\nu\nu$: $C_T - C_S$ and C'_{RL}
- Modulated by lepton couplings to 3 generations (sum over $\nu_{e,\mu,\tau}$)
- Right-handed currents suppressed in GMFV but kept to discuss possible breaking, in connection with $b \to s\ell\ell$ NP scenarios

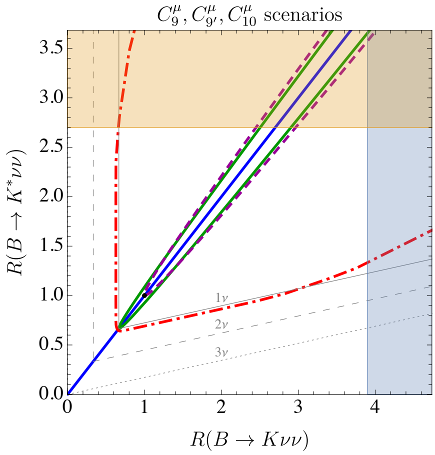
In the case of Linear Minimal Flavour Violation



$$R(i \to f) \equiv \frac{\mathcal{B}(i\to f)}{\mathcal{B}(i\to f)_{\rm SM}}$$

- No right-handed currents
- Dark (light) grey: Arbitrary ν_μ and ν_τ only (all three neutrino flavours)
- Red : NP only in muons ($C_S = 0$: $\times$, $C_T = 0$: $+$)
- Purple: Opposite NP effects in muons and taus
- Brown: Hierarchical NP effects according to the generation, proportional to m_ℓ ($C_S = 0$: $\Diamond$, $C_T = 0$: $\triangle$)

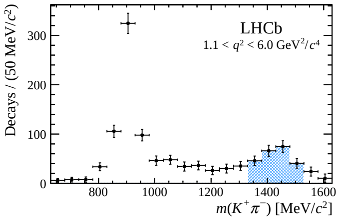
In the presence of right-handed currents



$$R(i \to f) \equiv \frac{\mathcal{B}(i\to f)}{\mathcal{B}(i\to f)_{\rm SM}}$$

- $s \to d$ not easily correlated to $b \to s$
- Blue: (G)MFV case
- $1\ \sigma$ region allowed by $b \to s\mu\mu$ transitions
  - Green: NP only in muons
  - Purple: Opposite NP effects in muons and taus
  - Red: Hierarchical NP effects according to the generation, proportional to m_ℓ
- Grey: no information on $b \to s\mu\mu$ and significant NP couplings to 1, 2, 3 ν

$B \to K_J^*(\to K\pi)\ell\ell$ at high $K\pi$ mass



Several resonances at higher $K\pi$ mass and sometimes higher spin

- $K^*(1410), K_0^*(1430), K_2^*(1430)$
- $K^*(1680), K_3^*(1780), K_4^*(2045)$

LHCb measurements around 1430 MeV

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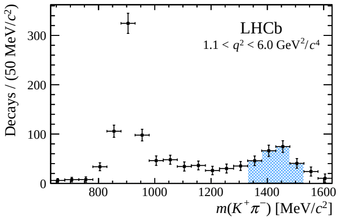

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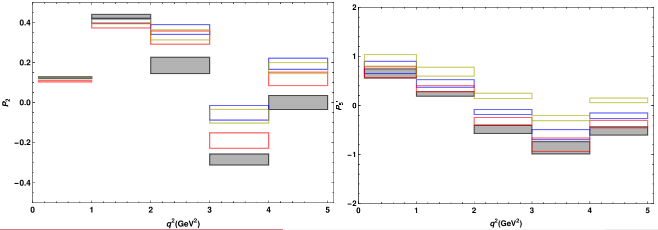
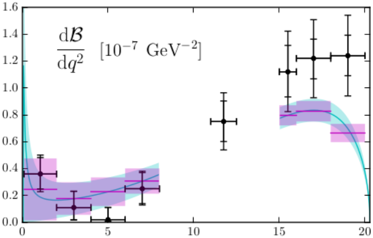
LHCb measurements around 1430 MeV

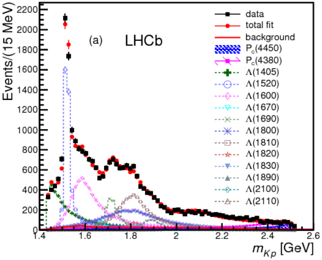
- Form factors: general, in HQET, in SCET, but few inputs
- $c\bar{c}$ loops: quark-had dual (low recoil), LCSR (large recoil, not yet)
- $B \to K_J\mu\mu$ (BR, F_L, A_{FB}) analysed in [Lü, Wang;Dey]
- $B \to K_2^*\mu\mu$ considered in more detail in [Das, Kindra, Kumar, Mahajan]



- quite similar to $B \to K^*\mu\mu$ if no tensor op
- identification of optim. obs. at large recoil

$\Lambda_b \to \Lambda(^*)\ell\ell$ decays

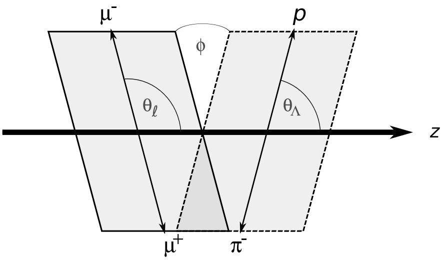




$\Lambda(1115)$	$\Lambda^*(1520)$
$J^P = 1/2^+$	$J^P = 3/2^-$
decays weakly into $p\pi$	decays strongly into pK
BR and low-recoil angular obs measured by LHCb	not measured by LHCb
	peak well seen at $q^2 = m^2_{J/\psi}$

- Form factors: lattice (low recoil) or LCSR (large recoil, not yet)
- $c\bar{c}$ loops: quark-hadron dual (low rec) or LCSR (large rec, not yet)

$\Lambda_b \to \Lambda(\to p\pi)\ell^+\ell^-$



$$\frac{d^4\Gamma(\Lambda_b \to \Lambda(\to p\pi)\ell^+\ell^-)}{dq^2 d\cos\theta_\ell d\cos\theta_\Lambda d\phi} = \frac{3}{8\pi} K(q^2, \theta_\ell, \theta_\Lambda, \phi)$$

$$\begin{aligned} K = & \left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right) \\ & + \left(K_{2ss}\sin^2\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2c}\cos\theta_\ell\right)\cos\theta_\Lambda \\ & + \left(K_{3sc}\sin\theta_\ell\cos\theta_\ell + K_{3s}\sin\theta_\ell\right)\sin\theta_\Lambda\sin\phi \\ & + \left(K_{4sc}\sin\theta_\ell\cos\theta_\ell + K_{4s}\sin\theta_\ell\right)\sin\theta_\Lambda\cos\phi\,. \end{aligned}$$

[Böer, Feldmann, van Dyk; Das]

- 10 form factors from lattice QCD [Detmold et al]
- 8 helicity amplitudes
- 10 angular coefficients
- Weak decay of $\Lambda \to p\pi$, parametrised by asymmetry $\alpha \sim 0.7$
- Polarized Λ_b case in [Blake, Kreps]

$$K_{1cc} = \frac{1}{2}\left[|A^R_{\perp 1}|^2 + |A^R_{||1}|^2 + (R \leftrightarrow L)\right],$$

$$K_{2cc} = +\alpha \mathrm{Re}(A^R_{\perp 1} A^{*R}_{||1}) + (R \leftrightarrow L),$$

$$\ldots$$

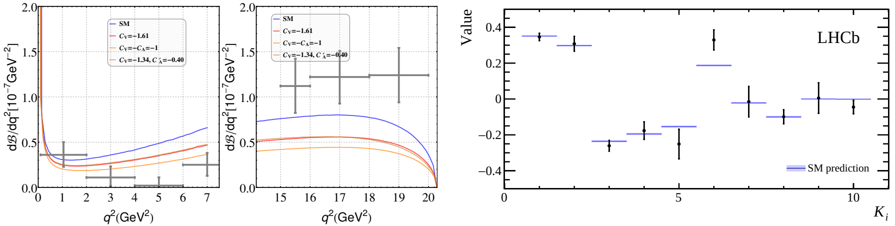
$\Lambda_b \to \Lambda(\to p\pi)\ell^+\ell^-$ angular observables

Large recoil (SCET) [Böer, Feldmann, van Dyk; Das]

- all form factors are equal or vanish
- any ratio of K is optimised

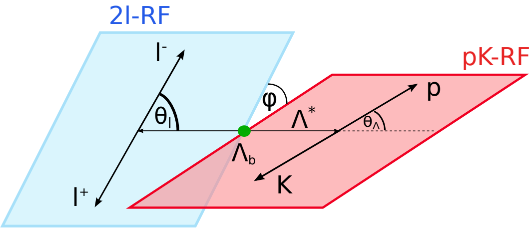
Low recoil (HQET)

- form factors linear combination of 2 form factors ξ_1 and ξ_2
- one optimised observable $X_1 \equiv K_{1c}/K_{2cc}$
- angular moments available from LHCb
  - largest discrepancy for K_{2c}, 2.6 σ from SM (too large, not physical)
  - for the moment, limited sensitivity to favoured NP scenarios



$\Lambda_b \to \Lambda^*(\to Kp)\ell^+\ell^-$

[SDG, Novoa Brunet; Das, Das]



$$\frac{d^4\Gamma(\Lambda_b \to \Lambda^*(\to Kp)\ell^+\ell^-)}{dq^2 d\cos\theta_\ell d\cos\theta_\Lambda d\phi} = \frac{3}{8\pi} L(q^2, \theta_\ell, \theta_\Lambda, \phi)$$

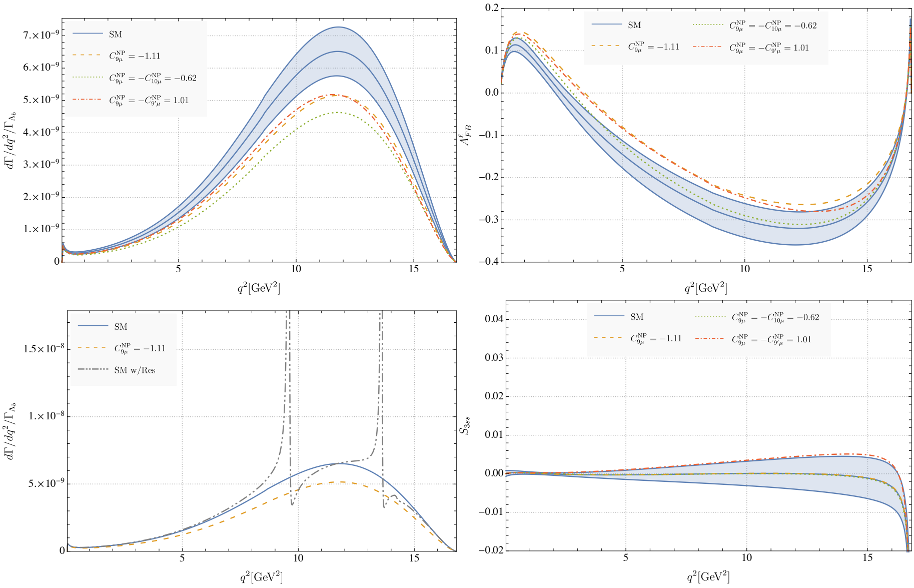
$$\begin{aligned} L = {} & \cos^2\theta_\Lambda \left(L_{1c}\cos\theta_\ell + L_{1cc}\cos^2\theta_\ell + L_{1ss}\sin^2\theta_\ell\right) \\ & + \sin^2\theta_\Lambda \left(L_{2c}\cos\theta_\ell + L_{2cc}\cos^2\theta_\ell + L_{2ss}\sin^2\theta_\ell\right) \\ & + \sin^2\theta_\Lambda \left(L_{3ss}\sin^2\theta_\ell\cos^2\phi + L_{4ss}\sin^2\theta_\ell\sin\phi\cos\phi\right) \\ & + \sin\theta_\Lambda\cos\theta_\Lambda\cos\phi(L_{5s}\sin\theta_\ell + L_{5sc}\sin\theta_\ell\cos\theta_\ell) \\ & + \sin\theta_\Lambda\cos\theta_\Lambda\sin\phi(L_{6s}\sin\theta_\ell + L_{6sc}\sin\theta_\ell\cos\theta_\ell) \end{aligned}$$

- 14 form factors (prelim lattice results [Meinel et al])
- 12 helicity amplitudes
- 12 angular coefficients
- SCET: single form factor, any ratio of L optimised
- HQET: two form factors, no non-trivial optim. obs.
- relationships among L's in both limits

$$L_{1c} \propto \left(\mathrm{Re}(A^L_{\perp 1} A^{L*}_{\parallel 1}) - (L \leftrightarrow R)\right),$$

$$L_{3ss} \propto \left(\mathrm{Re}(B^L_{\parallel 1} A^{L*}_{\parallel 1}) - \mathrm{Re}(B^L_{\perp 1} A^{L*}_{\perp 1}) + (L \leftrightarrow R)\right),$$

$\Lambda_b \to \Lambda^*(\to Kp)\ell^+\ell^-$ angular observables



q^2 [GeV^2] q^2 [GeV^2]