Global fits to $b \to s\ell\ell$ and violation of lepton-flavour universality

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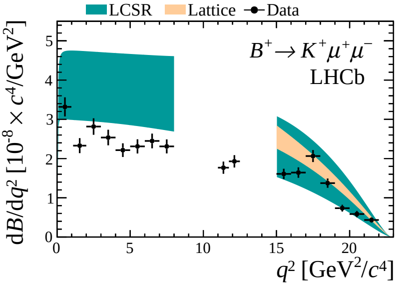
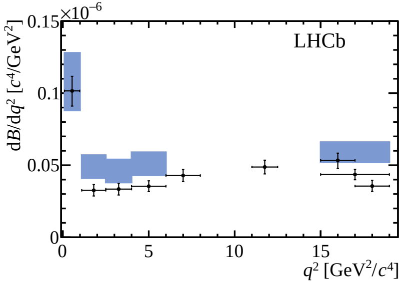
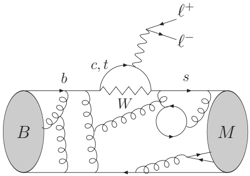
LPT Orsay

Anomalies in $b \to s\ell\ell$

Anomalies in branching ratios

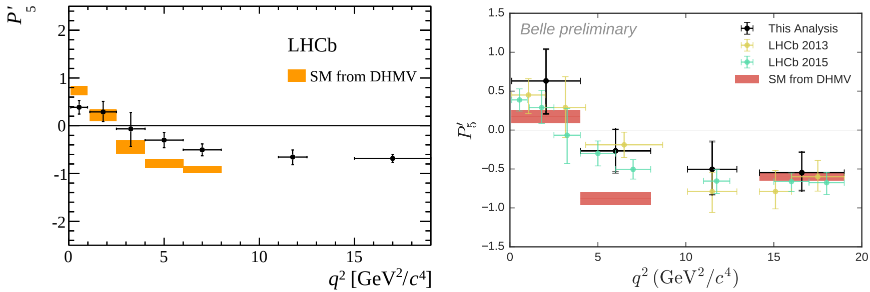






- $Br(B \to K\mu\mu)$ (up), $Br(B \to K^*\mu\mu)$ (down), $Br(B_s \to \phi\mu\mu)$ too low wrt SM
- q^2 invariant mass of $\ell\ell$ pair
- removing bins dominated by J/ψ and ψ' resonances
- large hadronic uncertainties from form factors at
  - Large-meson recoil/low q^2: light-cone sum rules
  - Low-meson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

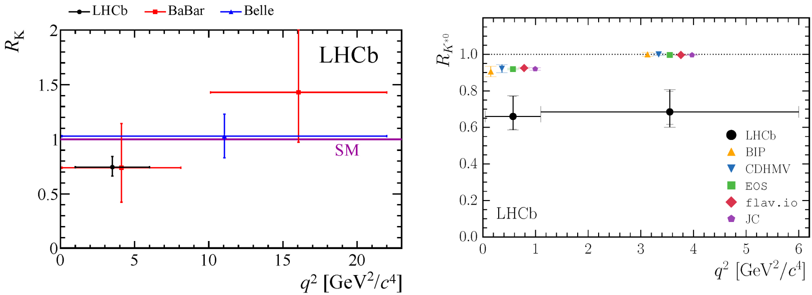
Anomalies in angular observables



- Basis of 6 optimised observables P_i (angular coeffs) with reduced hadronic uncertainties

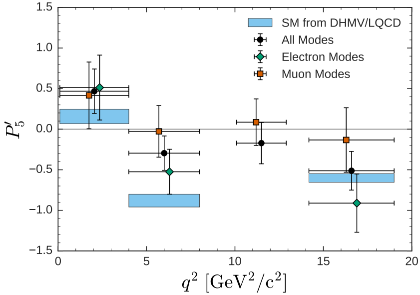
[Matias, Krüger, Becirevic, Schneider, Mescia, Virto, SDG, Ramon, Hurth; Hiller, Bobeth, Van Dyk. . .]

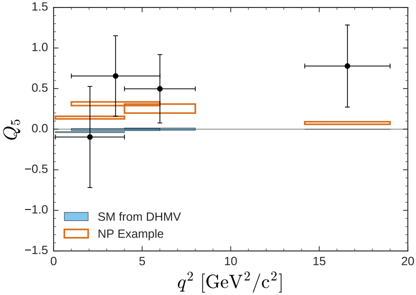
- Measured at LHCb with 1 fb^{-1} (2013) and 3 fb^{-1} (2015)
- Discrepancies for some (but not all) observables, in particular two bins for P'_5 deviating from SM by 2.8 σ and 3.0 σ
- Belle 2016: confirmation, with larger uncertainties
- CMS and ATLAS 2017: large unc., agree only partially with LHCb



- LFU-test ratios $R_K = \frac{Br(B\to K\mu\mu)}{Br(B\to Kee)}$ and $R_{K^*} = \frac{Br(B\to K^*\mu\mu)}{Br(B\to K^*ee)}$ for LHCb
- hadronic uncertainties/effects cancel largely in the SM ($V - A$ interaction only) and for $q^2 \geq 1$ GeV^2 (m_ℓ effects negligible)
- in SM, a single form factor cancel in $R_K = 1$, but several polarisations and form factors in R_{K^*} (small q^2-dep.)
- small effects of QED radiative corrections (1-3 %)
- LHCb: 2.6 σ for $R_{K[1,6]}$, 2.3 and 2.6 σ for $R_{K^*[0.045,1.1]}$ and $R_{K^*[1.1,6]}$

Anomalies in LFU: angular observables





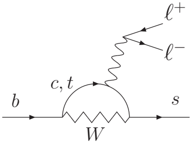
Belle also compared $b \to see$ and $b \to s\mu\mu$ in 2016

- 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 $Q_5 = P_5^{\mu\prime} - P_5^{e\prime}$, deviating from SM
- more data needed to confirm this hint of LFU violation (LFUV)

A global framework for the anomalies

Model-independent approach: $\mathcal{H}_{\rm eff}$

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



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

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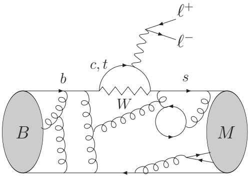

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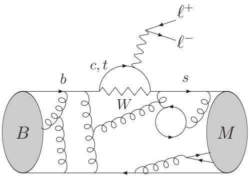

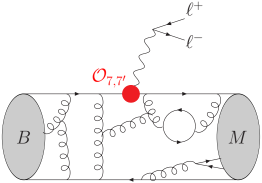

$$\mathcal{H}^{SM}_{b\to s\gamma^{(*)}} \propto \sum V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i$$

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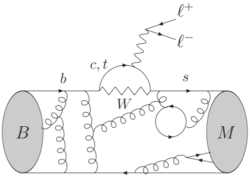
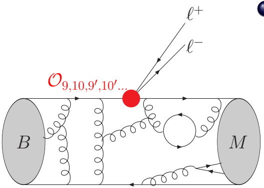
- $\mathcal{O}_7 = \frac{e}{g^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5) F_{\mu\nu}\, b$ [real or soft photon]

Model-independent approach: $\mathcal{H}_{\text{eff}}$





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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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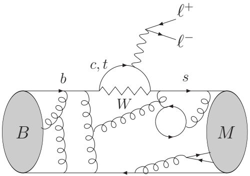

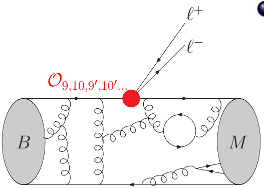

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$$\mathcal{C}_7^{\text{SM}} = -0.29,\ \mathcal{C}_9^{\text{SM}} = 4.1,\ \mathcal{C}_{10}^{\text{SM}} = -4.3$$

A= $\mathcal{C}_i$ (short dist) $\times$ Hadronic qties (long dist)

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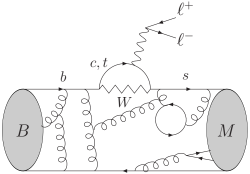

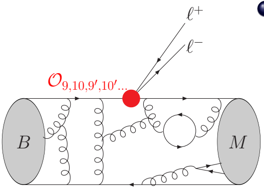

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NP changes short-distance $\mathcal{C}_i$ or add new operators $\mathcal{O}_i$

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

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

175 observables in total (no CP-violating obs) [Capdevila, Crivellin, SDG, 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)
- $B \to K\mu\mu$ (Br in many bins)
- R_K, R_{K^*}, $Q_{4,5}$ (large-recoil 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
- excl large-meson recoil: QCD fact, Soft-collinear effective theory
- excl low-meson recoil: Heavy quark eff th, Quark-hadron duality

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Frequentist analysis

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

1D and 2D fits for NP in $b \to s\mu\mu$ only

- Fits to sets "All" (175 obs)
  or "LFUV" (17 obs: $b \to s\mu\mu$ LFUV, $b \to s\gamma$, $B_s \to \mu\mu$, $B \to X_s\mu\mu$)
- Hypotheses "NP in some $\mathcal{C}_i$ only" to be compared with SM

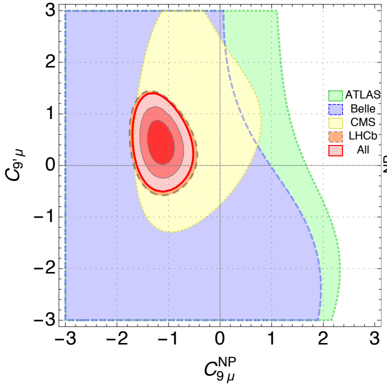
	All				LFUV			
1D Hyp.	Bfp	$1\,\sigma$	Pull$_{\rm SM}$	p-value %	Bfp	$1\,\sigma$	Pull$_{\rm SM}$	p-value %
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.11	$[-1.28, -0.94]$	5.8	68	-1.76	$[-2.36, -1.23]$	3.9	69
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.62	$[-0.75, -0.49]$	5.3	58	-0.66	$[-0.84, -0.48]$	4.1	78
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9\mu}'$	-1.01	$[-1.18, -0.84]$	5.4	61	-1.64	$[-2.13, -1.05]$	3.2	32

	All			LFUV		
2D Hyp.	Best fit	Pull$_{\rm SM}$	p-value %	Best fit	Pull$_{\rm SM}$	p-value %
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}^{\rm NP})$	(-1.01,0.29)	5.7	72	(-1.30,0.36)	3.7	75
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_7')$	(-1.13,0.01)	5.5	69	(-1.85,-0.04)	3.6	66
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{9'\mu})$	(-1.15,0.41)	5.6	71	(-1.99,0.93)	3.7	72
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10'\mu})$	(-1.22,-0.22)	5.7	72	(-2.22,-0.41)	3.9	85

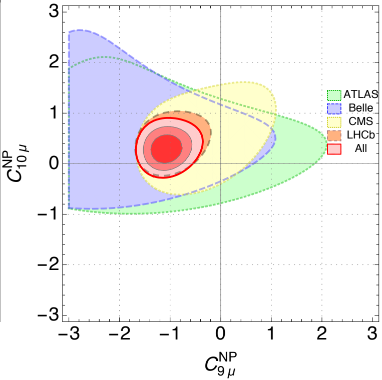
- p-value : $\chi^2_{\rm min}$ considering N_{dof} (SM: All 11.3%, LFUV 4.4%)
  $\Longrightarrow$goodness of fit: does the hypothesis give an overall good fit ?
- Pull$_{\rm SM}$: $\chi^2_{min}(\mathcal{C}_i = 0) - \chi^2_{min}$
  $\Longrightarrow$metrology: how much does the hyp. solve SM deviations ?

Some favoured scenarios

- $\mathcal{C}_{9\mu}^{NP} \simeq -1$ favoured in all "good" scenarios
- NP in $\mathcal{C}_{9\mu}$ only: p-value=68%, $\text{pull}_{SM} = 5.8\sigma$, $[-1.28, -0.94]$ at 1σ



NP in $\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{9'\mu}^{NP}$



NP in $\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{10\mu}^{NP}$

- $\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}$ good scenario (NP models obeying $SU(2)_L$)
- LHCb dominates the field !

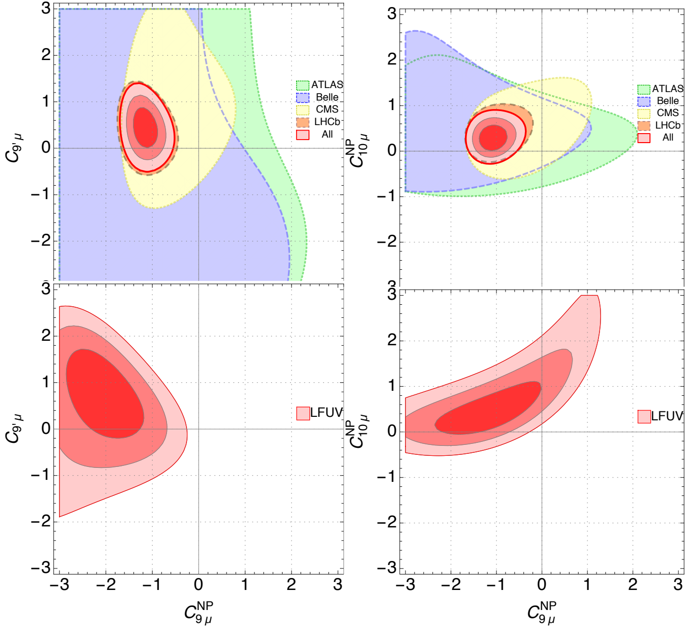
Improving on the main anomalies

- $\mathcal{C}_{9\mu}^{NP} \simeq -1$ favoured in all "good" scenarios
- Not all anomalies "solved", but many are alleviated

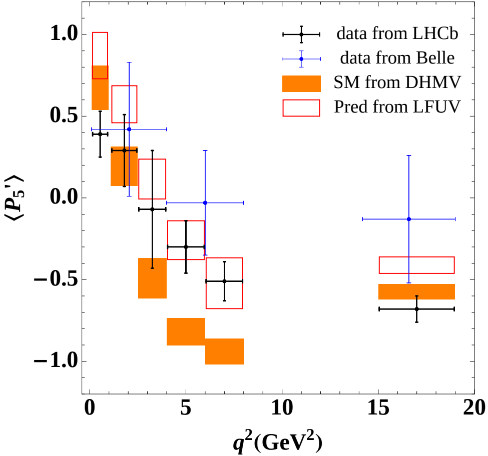
Largest pulls	$\langle P_5' \rangle^{[4,6]}$	$\langle P_5' \rangle^{[6,8]}$	$R_K^{[1,6]}$	$R_{K^*}^{[0.045,1.1]}$
Experiment	-0.30 ± 0.16	-0.51 ± 0.12	$0.745^{+0.097}_{-0.082}$	$0.66^{+0.113}_{-0.074}$
SM pred.	-0.82 ± 0.08	-0.94 ± 0.08	1.00 ± 0.01	0.92 ± 0.02
Pull (σ)	-2.9	-2.9	+2.6	+2.3
Pred. $\mathcal{C}_{9\mu}^{\rm NP} = -1.1$	-0.50 ± 0.11	-0.73 ± 0.12	0.79 ± 0.01	0.90 ± 0.05
Pull (σ)	-1.0	-1.3	+0.4	+1.9

Largest pulls	$R_{K^*}^{[1.1,6]}$	$\mathcal{B}_{B_s\to\phi\mu^+\mu^-}^{[2,5]}$	$\mathcal{B}_{B_s\to\phi\mu^+\mu^-}^{[5,8]}$
Experiment	$0.685^{+0.122}_{-0.083}$	0.77 ± 0.14	0.96 ± 0.15
SM pred.	1.00 ± 0.01	1.55 ± 0.33	1.88 ± 0.39
Pull (σ)	+2.6	+2.2	+2.2
Pred. $\mathcal{C}_{9\mu}^{\rm NP} = -1.1$	0.87 ± 0.08	1.30 ± 0.26	1.51 ± 0.30
Pull (σ)	+1.2	+1.8	+1.6

Consistency between fits to All and LFUV obs

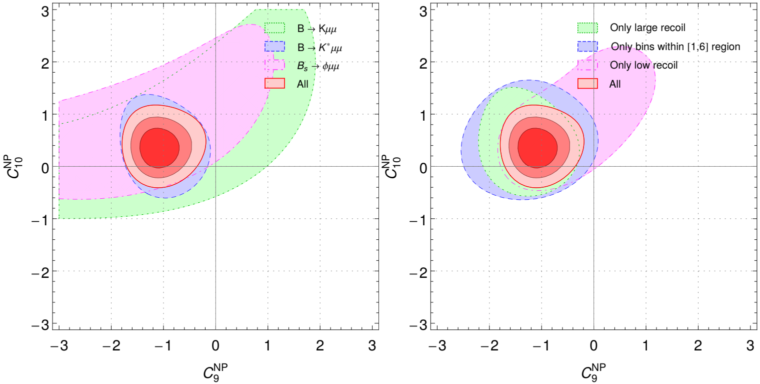


Consistency: P_5' from LFUV obs



- Fit to LFUV obs only to determine $\mathcal{C}_{9\mu}^{NP}$
- ...then predict value of P_5'
- Confirms the very good agreement between fits to LFUV only and the other observables
- Disagreements with Standard Model in $b \to s\ell\ell$ obey a pattern

Consistency: by channels, low versus large recoil



Split by decay channel *Split by q^2 region*

- Analysis prior to R_{K^*}, with only LHCb data [SDG, Hofer, Matias, Virto]
- Different processes, kinematic ranges, theoretical tools (SCET/QCDF vs HQET/OPE, LCSR vs lattice)
- $B \to K^* \mu\mu$ tighter than $B_s \to \phi\mu\mu$, tighter than $B \to K\mu\mu$
- Large and low recoil bins both favour points away from SM

[Horgan et al., Bouchard et al., Altmannshofer and Straub]

$b \to s\mu\mu$: 6D hypothesis

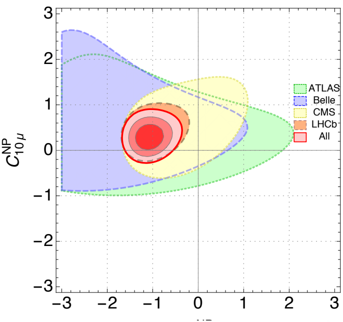
Letting all 6 Wilson coefficients for muons vary (but only real)

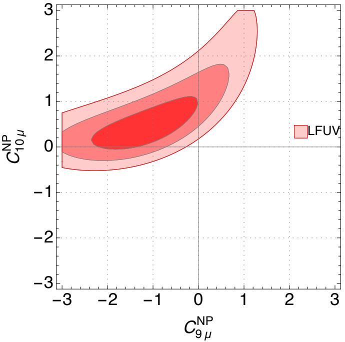
	Best fit	$1\ \sigma$	$2\ \sigma$
$\mathcal{C}_7^{\rm NP}$	+0.03	$[-0.01, +0.05]$	$[-0.03, +0.07]$
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.12	$[-1.34, -0.88]$	$[-1.54, -0.63]$
$\mathcal{C}_{10\mu}^{\rm NP}$	+0.31	$[+0.10, +0.57]$	$[-0.08, +0.84]$
$\mathcal{C}_{7'}$	+0.03	$[+0.00, +0.06]$	$[-0.02, +0.08]$
$\mathcal{C}_{9'\mu}$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

- Pattern: $\mathcal{C}_7^{\rm NP} \gtrsim 0$, $\mathcal{C}_{9\mu}^{\rm NP} < 0$, $\mathcal{C}_{10\mu}^{\rm NP} > 0$, $\mathcal{C}_7' \gtrsim 0$, $\mathcal{C}_{9\mu}' > 0$, $\mathcal{C}_{10\mu}' \gtrsim 0$
- $\mathcal{C}_9$ is consistent with SM only above 3σ
- All others are consistent with zero at 1σ except for $\mathcal{C}_{10}$ at $2\ \sigma$
- $\mathrm{Pull}_{\rm SM}$ for the 6D fit is 5.0σ (used to be $3.6\ \sigma$)

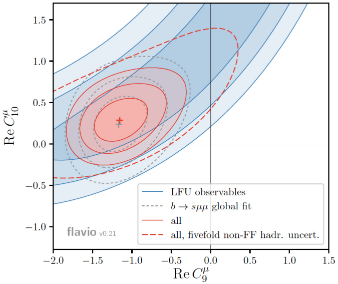
Other recent analyses (smaller sets of data/other approaches) : same patterns, different significances [Altmannshofer, Stangl, Straub; Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli; Geng, Grinstein, Jäger, Camalich, Ren, Shi; Hurth, Mahmoudi, Martinez Santos, Neshatpour. . .]

Consistency with analysis of (Altmannshofer, Stangl, Straub)





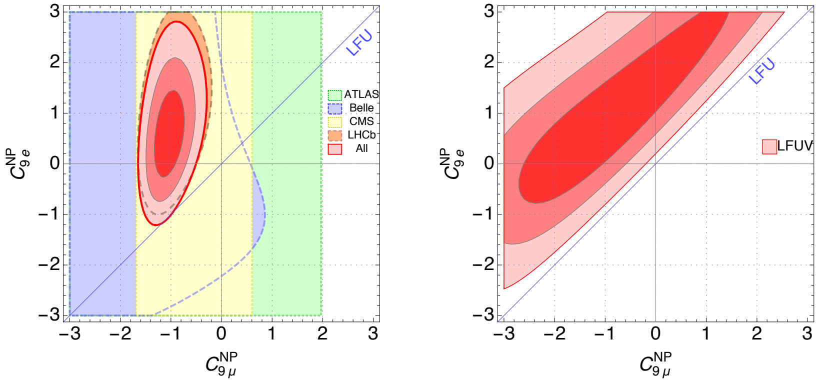
[Capdevila, Crivellin, SDG, Matias, Virto]



[Altmannshofer, Stangl, Straub]

- Different angular obs.
- Different form factor inputs
- Different hadronic corrections
- Same NP scenarios favoured (higher significances for [Altmannshofer, Stangl, Straub])

NP in both $b \to s\mu\mu$ and $b \to see$



NP in $\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{9e}^{NP}$

- Up to now, only NP in $b \to s\mu\mu$, what about $b \to see$?
- Need for contribution for $\mathcal{C}_{9\mu}$ (angular obs, Br) but not for $\mathcal{C}_{9e}$
- But not forbidden either: for instance, $\mathcal{C}_{9\mu} = -3\mathcal{C}_{9e}$ very good ($U(1)$ models for neutrino mixing [Bhatia, Chakraborty, Dighe])

Cross-checking theoretical uncertainties

$\mathcal{C}_9^{\text{NP}} = \mathcal{C}_9^{\text{New Physics}}$ or $\mathcal{C}_9^{\text{Non Perturbative}}$?

SM alternative to explain these deviations/anomalies ?

- hadronic effects ($B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$ at low and large recoils)
- statistical fluctuation and/or pb with e/μ (R_K, R_{K^*})
- bad luck (short-distance scenarios can accomodate all discrepancies very well by chance)

$\Longrightarrow$Lack the consistency of the short-distance explanation

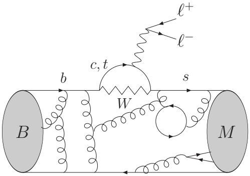
But it remains essential to

- Understand better the sources of hadronic uncertainties SM
- Add more observables to confirm/distinguish the patterns

$B \to K^*\ell\ell$ decays play an important role in global fits and thus in these discussions !

Two sources of hadronic uncertainties

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



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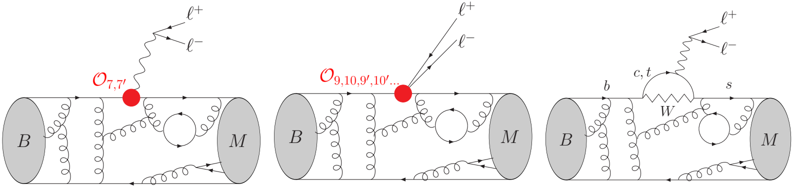

Form factors (local)

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

$$\begin{aligned} A_\mu &= -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle V_\lambda | \bar{s}\sigma_{\mu\nu} P_R b | B\rangle + \mathcal{C}_9 \langle V_\lambda | \bar{s}\gamma_\mu P_L b | B\rangle \\ B_\mu &= \mathcal{C}_{10} \langle V_\lambda | \bar{s}\gamma_\mu P_L b | B\rangle \qquad \lambda: \ K^* \text{ helicity} \end{aligned}$$

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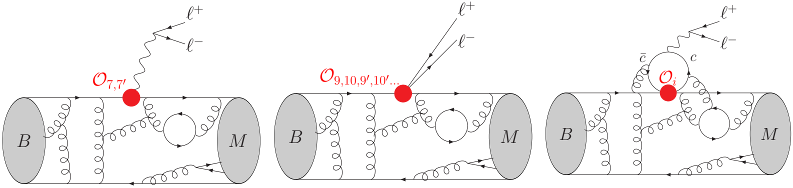

Form factors (local) Charm loop (non-local)

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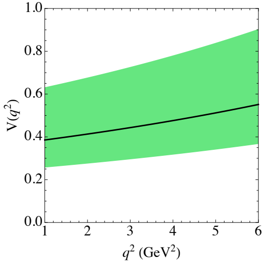
- Non-local contributions (charm loops): hadronic contribs.

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

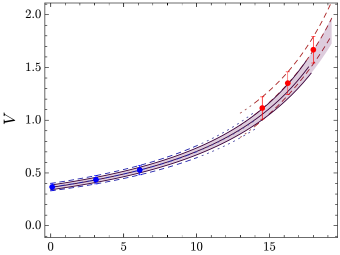
Form factors

- low K^* recoil: lattice, with correlations [Horgan, Liu, Meinel, Wingate]
- large K^* recoil: B-meson Light-Cone Sum Rule,
  large error bars and no correlations [Khodjamirian, Mannel, Pivovarov, Wang]
- all: fit K^*-meson LCSR + lattice, small errors bars, correlations

[Bharucha, Straub, Zwicky]



KMPW (LCSR, low q^2)



BSZ (fit LCSR + lattice)

Form factors

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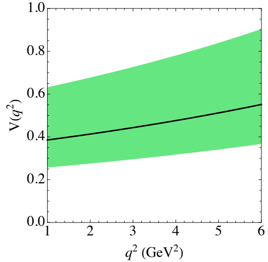

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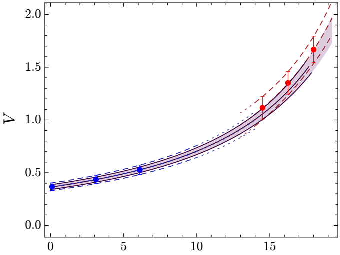
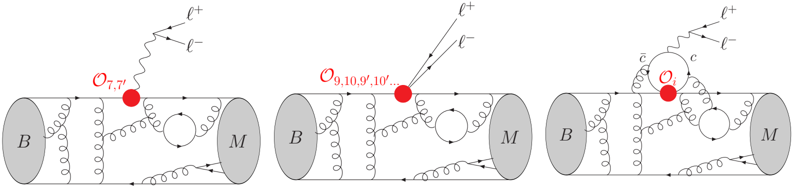


BSZ (fit LCSR + lattice)

Reduce uncertainties and restore correlations among 7 form factors using EFT correlations arising in $m_b \to \infty$, e.g., at large K^* recoil

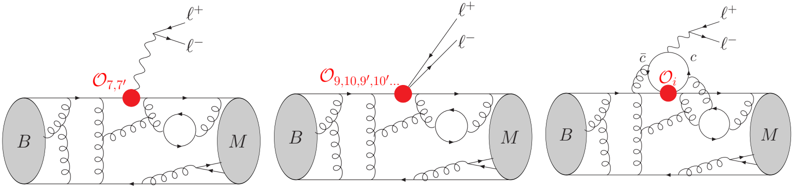
$$\xi_\perp = \frac{m_B}{m_B + m_{K^*}} V = \frac{m_B + m_{K^*}}{2E_{K^*}} A_1 = T_1 = \frac{m_B}{2E_{K^*}} T_2 \qquad + O(\alpha_s, \Lambda/m_b) \text{ corr}$$

Form factors and power corrections



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

Form factors and power corrections

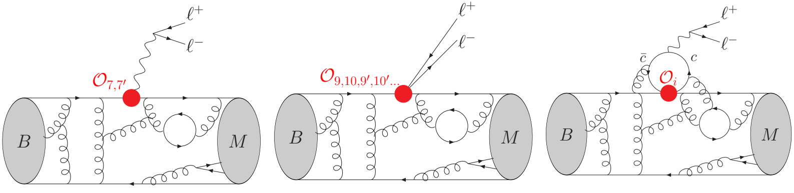


Form factors (local) Charm loop (non-local)

Uncertainties in form factors ?

- form factor inputs + correlations from EFT with limit $m_b \to \infty$ but $O(\Lambda/m_b)$ power corrections to this limit
- Power corrs with large impact on optimised obs. ? [Camalich, Jäger]

Form factors and power corrections



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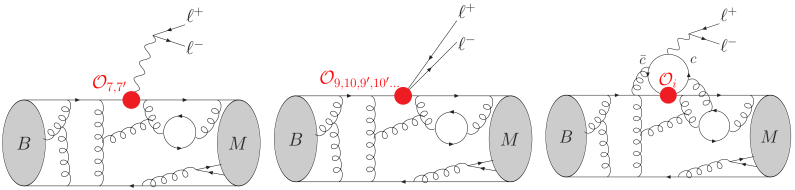
- No, but accurate predictions require [Matias, Virto, Hofer, Capdevilla, SDG]
  - appropriate def of soft form factors $\xi_{\perp,||}$ in $m_b \to \infty$ limit (scheme)
  - correlations from EFT (heavy-quark sym.) among form factors
  - power corrs varied in agreement with form factor inputs

Form factors and power corrections



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

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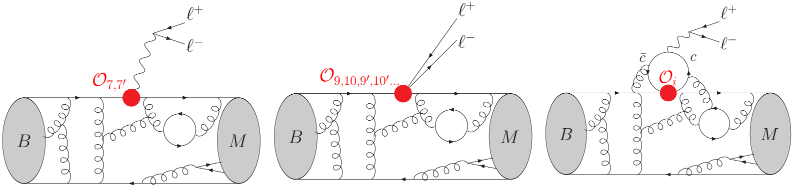
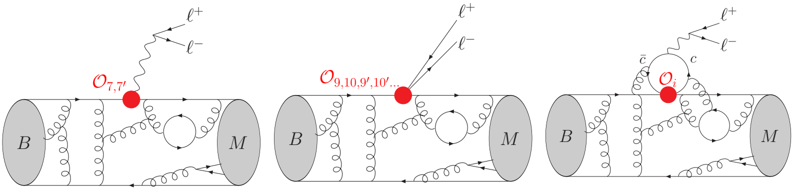
  - correlations from EFT (heavy-quark sym.) among form factors
  - power corrs varied in agreement with form factor inputs
- [Camalich, Jäger] artefacts from ill-advised scheme/variation for pcs

Charm-loop contribution



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

Charm-loop contribution



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

Uncertainties from charm loops ? [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

- Effect well-known (loop process, charmonium resonances)
- Yields q^2- and hadron-dependent contrib with $\mathcal{O}_{7,9}$-like structures
  - Contribution $\Delta\mathcal{C}_9^{BK^{(*)}}$ from LCSR computation [Khodjamirian, Mannel et al.]
  - Global fits use this result as order of magn, or $O(\Lambda/m_b)$ estimates

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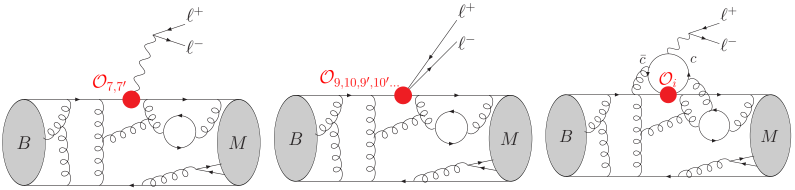

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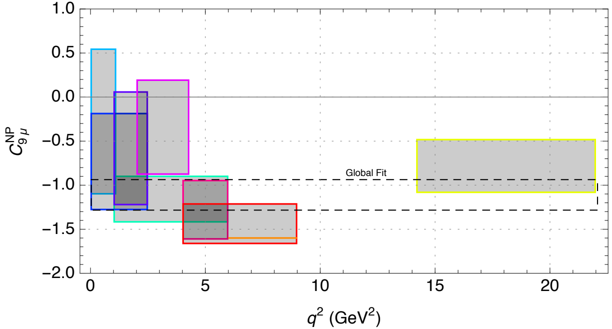
  - Contribution $\Delta\mathcal{C}_9^{BK^{(*)}}$ from LCSR computation [Khodjamirian, Mannel et al.]
  - Global fits use this result as order of magn, or $O(\Lambda/m_b)$ estimates
- Bayesian extraction from $B \to K^*\mu\mu$ performed by [Ciuchini et al.]
  - q^2 dependence in agreement with $\Delta\mathcal{C}_9^{BK^{(*)}}$ + constant $\mathcal{C}_9^{\mathrm{NP}}$
  - no need for extra q^2-dep. contribution (no missed hadronic contrib)
  - actually not contradicting results of global fits, though less precise

[Matias, Virto, Hofer, Capdevilla, SDG; Hurth, Mahmoudi, Neshatpour]

Cross-check: q^2-dependence of $\mathcal{C}_9$



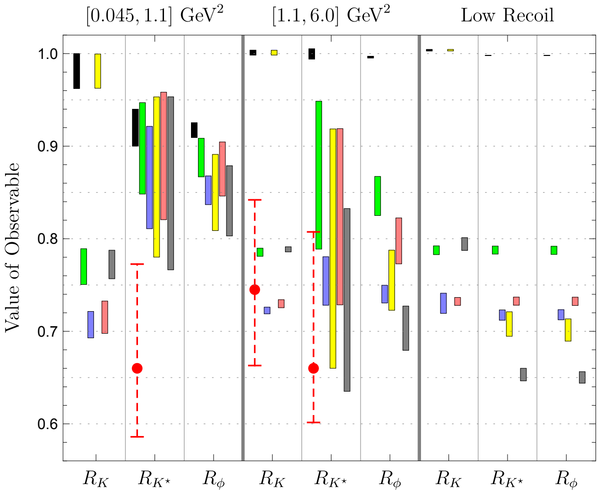
[Capdevila, Crivellin, Matias, Virto, SDG]

- Fit to $\mathcal{C}_9^{NP}$ from individual bins of $b \to s\mu\mu$ data (NP only in $\mathcal{C}_{9\mu}$)
  - NP in $\mathcal{C}_9$ from short distances, q^2-independent
  - Hadronic physics in $\mathcal{C}_9$ related to $c\bar{c}$ dynamics, (likely) q^2-dependent
- No indication of additional q^2-dependence missed by the fit
- Can be checked for other NP scenarios
- In agreement with other analyses [Altmanshoffer, Straub]
- Further estimates from LHCb data-driven analyses (D. Van Dyk's talk)

Looking for more observables

LFUV in branching ratios

[Capdevila, Crivellin, SDG, Matias, Virto]



- Black: SM
- Green: $\mathcal{C}_{9\mu}^{NP} = -1.1$
- Blue: $\mathcal{C}_{9\mu}^{NP} = \mathcal{C}_{10\mu}^{NP} = -0.61$
- Yellow: $\mathcal{C}_{9\mu}^{NP} = \mathcal{C}_{9'\mu}^{NP} = -1.01$
- Orange: $\mathcal{C}_{9\mu}^{NP} = -3\mathcal{C}_{9e}^{NP} = -1.06$
- Gray: Best fit point for 6 dim fit

R_{K^*} with conservative [Khodjamirian et al] but R_ϕ computed with [Bharucha et al]

LFUV in angular observables: Q_i, B_i, M

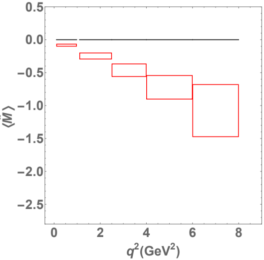
[Capdevilla, Matias, Virto, SDG]

Expecting measurements of BR and angular coefficients for $B \to K^* ee$

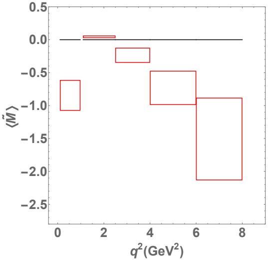
- null SM tests (up to m_ℓ effects): $Q_i = P_i^\mu - P_i^e$, $\quad B_i = \frac{J_i^\mu}{J_i^e} - 1$
- angular coeffs J_5 and J_{6s} with only a linear dependence on $\mathcal{C}_9$

$$M = (J_5^\mu - J_5^e)(J_{6s}^\mu - J_{6s}^e)/(J_{6s}^\mu J_5^e - J_{6s}^e J_5^\mu)$$

  - cancellation of hadronic contribs in $\mathcal{C}_9$ if NP in $\mathcal{C}_{9\mu}$ only
  - different sensitivity to NP scenarios compared to $R_{K^{(*)}}$

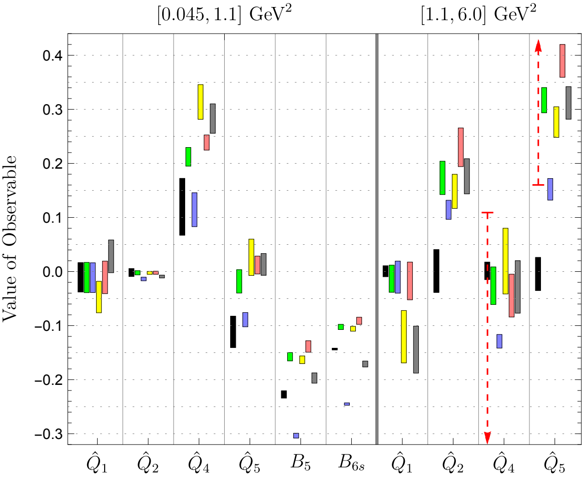


$\mathcal{C}_{9\mu}^{\rm NP} = -1.1, \mathcal{C}_{ie}^{\rm NP} = 0$



$\mathcal{C}_{9\mu}^{\rm NP} = \mathcal{C}_{10\mu}^{\rm NP} = -0.65, \mathcal{C}_{ie}^{\rm NP} = 0$

LFUV in angular observables: Q_i, B_i



[Capdevila, Crivellin, SDG, Matias, Virto]

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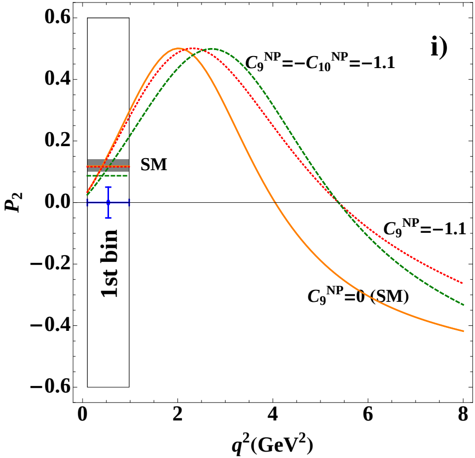
- Gray: Best fit point for 6 dim fit

- Precise measurement of Q_5 in [1,6] can discard $\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}$
- Other obs. useful to separate various scenarios

Additional observables: P_1 and P_2 at very low q^2

At very low q^2, $\mathcal{C}_9$ kinematically suppressed in P_1 and P_2
$\Longrightarrow$way of probing other Wilson coefficients



Probes of other Wilson coefficients

- $P_1 \leftrightarrow \mathcal{C}_{7(')}$ (not competitive with $B \to X_s\gamma$)
- $P_2 \leftrightarrow \mathcal{C}_7\mathcal{C}_{10}, \mathcal{C}_{7'}\mathcal{C}_{10'}$ (interesting for $\mathcal{C}_{10(')}$)

[Becirevic, Schneider, Capdevila, Hofer, Matias, SDG]

Outlook

B physics anomalies

- $b \to s\ell^+\ell^-$ with many obs., more or less sensitive to hadronic unc.
- Interesting deviations from SM expectations
- Indications of violation of lepton flavour universality
- Global fit supports large $\mathcal{C}_{9\mu}^{NP}$ with very good consistency (Br vs angular vs R, channels, recoil regions, LFUV and All obs. . .)
- Does not seem to favour hadronic explanations (power corrections for form factors, charm loop contributions)

Where to go ?

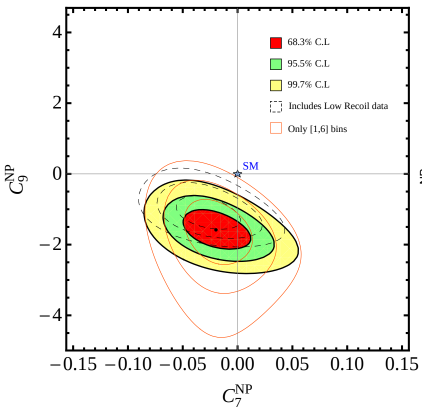
- Other LFU violating observables: R_ϕ, Q_i. . .
- Charm loops (estimates, data-driven info on resonances, new obs)
- More determinations of form factors to control uncertainties
- More accurate constraints on other Wilson coefficients ($\mathcal{C}_{9'}, \mathcal{C}_{10}$)
- Model building to connect with other anomalies (like $b \to c\ell\nu_\ell$)

A lot of (interesting) work on the way !

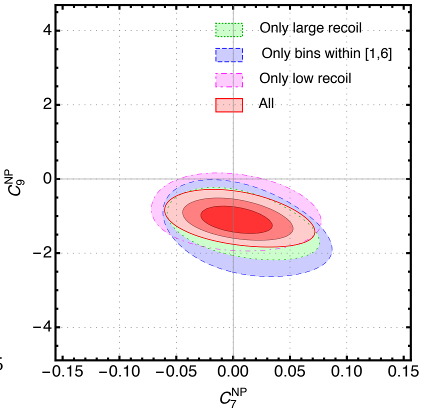
Thank you for your attention !

From 2013 to 2016

Many improvements from experiment and theory, but...

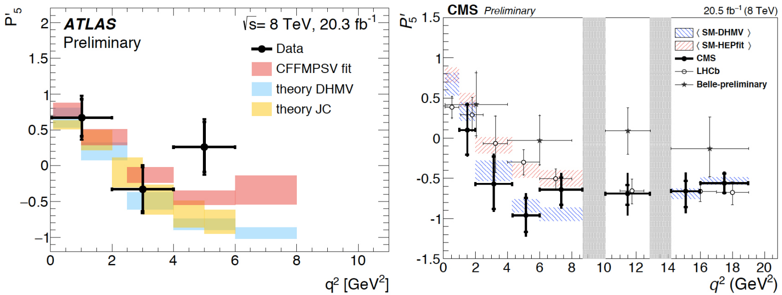


[SDG, J. Matias, Virto] (2013)



[SDG, L. Hofer J. Matias, Virto] (2016)

Anomalies in angular obs: CMS and ATLAS



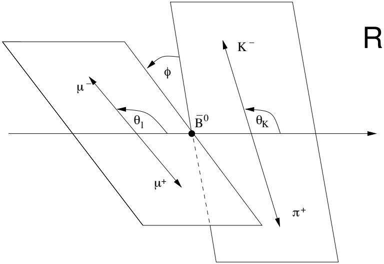
- ATLAS and CMS in 2017, but with larger uncertainties
- ATLAS: full basis, deviation in P_5' (OK with LHCb) and P_4' (not OK)
- CMS: only P_1 and P_5' using input on F_L from earlier analyses (not clear why) leading to lower P_5' than others
- There is more to $B \to K^*\mu\mu$ than just P_5'
  - P_2 also interesting deviations in LHCb 1 fb^{-1} data in [2,4] bin (but not seen at 3 fb^{-1} due to too large F_L leading to large uncert.)
  - useful that other optimised observables in agreement with SM

A few recent global fits (before R_{K^*})

	[SDG, Hofer Matias, Virto]	[Straub, Stangl & Altmannshofer]	[Hurth, Mahmoudi, Neshatpour]
Statistical approach	Frequentist $\Delta\chi^2$	Frequentist $\Delta\chi^2$	Frequentist $\Delta\chi^2$ & χ^2
Data $B \to K^*\mu\mu$ data	LHCb P_i, Max likelihood	Averages S_i, Max likelihood	LHCb S_i, Max l.& moments
Form factors	B-meson LCSR [Khodjamirian et al.] + lattice QCD	[Bharucha, Straub, Zwicky] fit light-meson LCSR + lattice QCD	[Bharucha, Straub, Zwicky]
Theo approach	soft and full ff	full ff	soft and full ff
$c\bar{c}$ large recoil	magnitude from [Khodjamirian et al.]	polynomial param	polynomial param
$\mathcal{C}_9^\mu$ 1D 1σ	[-1.22,-0.79]	[-1.54,-0.53]	[-0.27,-0.13]
pull$_{SM}$	4.2 σ	3.7 σ	4.2σ
"good scenarios"	see before	$\mathcal{C}_9^{NP}, \mathcal{C}_9^{NP} = -\mathcal{C}_{10}^{NP}$ $(\mathcal{C}_9^{NP}, \mathcal{C}_{9'}^{NP}), (\mathcal{C}_9, \mathcal{C}_{10}^{NP})$	$(\mathcal{C}_9^{NP}, \mathcal{C}_{9'}^{NP}), (\mathcal{C}_9^{NP}, \mathcal{C}_{10}^{NP})$

$\Longrightarrow$Good overall agreement for the results of the three fits

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

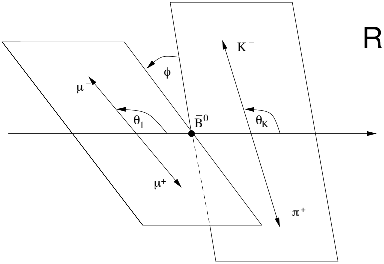


Rich kinematics

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

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

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



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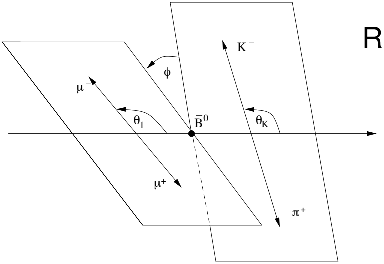
- Transversity amplitudes (K^* polarisation, $\ell\ell$ chirality) in terms of Wilson coefficients and 7 form factors $A_{0,1,2}$, V, $T_{1,2,3}$
- EFT relations between form factors in limit $m_B \to \infty$, either when K^* very soft or very energetic (low/large-recoil)

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



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  with $q^2 = (p_{\ell^+} + p_{\ell^-})^2$
- interferences between 8 transversity amplitudes for $B \to K^*(\to K\pi)V^*(\to \ell\ell)$

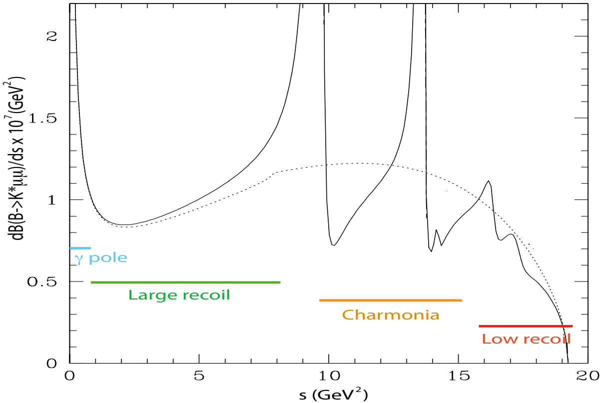
[Ali, Hiller, Matias, Krüger, Mescia, SDG, Virto, Hofer, Bobeth, van Dyk, Buras, Altmanshoffer, Straub, Bharucha, Zwicky, Gratrex, Hopfer, Becirevic, Sumensari, Zukanovic-Funchal ...]

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

- Build ratios of J_i where form factors cancel in these limits
- Optimised observables P_i with reduced hadronic uncertainties

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

Low and large K^* recoils for $B \to K^*\mu\mu$

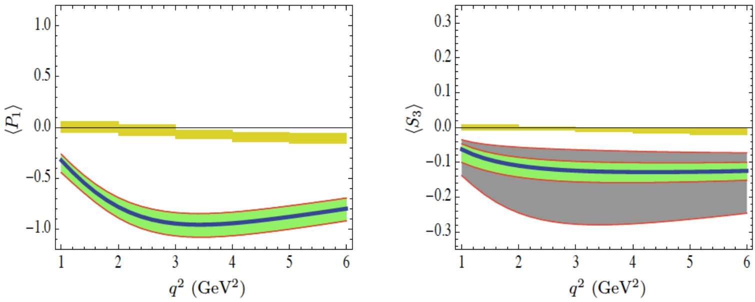


- Very large K^*-recoil ($4m_\ell^2 < q^2 < 1$ GeV^2) γ almost real
- Large K^*-recoil ($q^2 < 9$ GeV^2) energetic K^* ($E_{K^*} \gg \Lambda_{QCD}$)

  Light-Cone Sum Rules, QCD factorisation, SCET
- 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, OPE, HQET

Sensitivity of observables to form factors



- P_i designed to have limited sensitivity to form factors
- S_i CP-averaged version of J_i

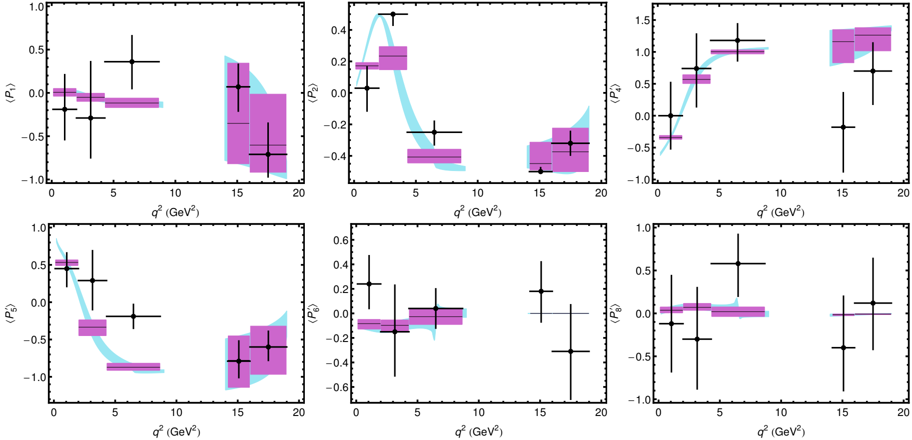
$$P_1 = \frac{2S_3}{1-F_L} \qquad F_L = \frac{J_{1c}+\bar{J}_{1c}}{\Gamma+\bar{\Gamma}} \qquad S_3 = \frac{J_3+\bar{J}_3}{\Gamma+\bar{\Gamma}}$$

Illustration for arbitrary NP point for two sets of LCSR form factors:

green [Ball, Zwicky] versus gray [Khodjamirian et al.]

more or less easy to discriminate against yellow (SM prediction)

SM predictions and LHCb results at 1 fb^{-1}

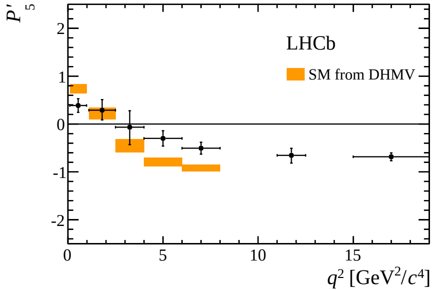


Meaning of the discrepancy in P_2 and P'_5 ? [SDG, Matias, Virto]

- P_2 same zero as A_{FB}, related to C_9/C_7
- $P_{5'} \to -1$ as q^2 grows due to $A^R_{\perp,||} \ll A^L_{\perp,||}$ for $C_9^{SM} \simeq -C_{10}^{SM}$
- A negative shift in C_7 and C_9 can move them in the right direction

Focus on P_5'

[SDG, J. Matias, M. Ramon, J. Virto]



$B \to K^* \mu\mu$ with $A^{\ell\ell}_{\text{transversity}}$ chirality

$$P_5' = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2+|A_{||}|^2)}}$$

LHCb measurements (crosses) significantly away from SM (boxes) in the large-recoil region

In large recoil limit with no right-handed current, with $\xi_{\perp,||}$ ffs

$$A^L_{\perp,||} \propto \pm\left[\mathcal{C}_9 - \mathcal{C}_{10} + 2\frac{m_b}{s}\mathcal{C}_7\right]\xi_\perp(s) \qquad A^R_{\perp,||} \propto \pm\left[\mathcal{C}_9 + \mathcal{C}_{10} + 2\frac{m_b}{s}\mathcal{C}_7\right]\xi_\perp(s)$$

$$A^L_0 \propto -\left[\mathcal{C}_9 - \mathcal{C}_{10} + 2\frac{m_b}{m_B}\mathcal{C}_7\right]\xi_{||}(s) \qquad A^R_0 \propto -\left[\mathcal{C}_9 + \mathcal{C}_{10} + 2\frac{m_b}{m_B}\mathcal{C}_7\right]\xi_{||}(s)$$

- In SM, $\mathcal{C}_9 \simeq -\mathcal{C}_{10}$ leading to $|A^R_{\perp,||}| \ll |A^L_{\perp,||}|$
- If $\mathcal{C}_9^{\mathrm{NP}} < 0$, $|A^R_{0,||,\perp}|$ increases, $|A^L_{0,||,\perp}|$ decreases, $|P_5'|$ gets lower
- For P_4', sum with $A_{0,||}$, so not sensitive to $\mathcal{C}_9$ in the same way

Power corrections

- Factorisable power corrections (form factors)
  - Parametrize power corrections to form factors (at large recoil):

$$F(q^2) = F^{\rm soft}(\xi_{\perp,\|}(q^2)) + \Delta F^{\alpha_s}(q^2) + a_F + b_F \frac{q^2}{m_B^2} + \ldots$$

  - Fit $a_F, b_F, \ldots$ to the full form factor F (taken e.g. from LCSR)
    - Respect correlations among $a_{F_i}, b_{F_i}, \ldots$ and kinematic relations
    - Choose appropriate definition of $\xi_{||,\perp}$ from form factors (scheme) or take into account correlations among form factors
  - Vary power corrections as 10% of the total form factor around the central values obtained for $a_F, b_F \ldots$

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- Nonfactorisable power corrections (extra part from amplitudes)
  - Extract from $\langle K^*\gamma^*|H_{eff}|B\rangle$ the part not associated to form factors
  - Multiply each of them with a complex q^2-dependent factor

$$\mathcal{T}_i^{\rm had} \to (1 + r_i(q^2))\mathcal{T}_i^{\rm had}, \quad r_i(s) = r_i^a e^{i\phi_i^a} + r_i^b e^{i\phi_i^b}(s/m_B^2) + r_i^c e^{i\phi_i^c}(s/m_B^2)^2.$$

  - Vary $r_i^{a,b,c} = 0 \pm 0.1$ and phase $\phi_i^{a,b,c}$ free for $i = 0, \perp, ||$

Correlating form factors

Implement correlations among form factors

- Soft form factor approach [Matias, Virto, Hofer, Mescia, SDG...]
  - Decompose, e.g., $V = \frac{m_B+m_{K^*}}{m_B}\xi_\perp + \Delta V^{\alpha_s} + \Delta V^\Lambda$
    with hard gluons ΔV^{α_s}, power corrections $\Delta V^\Lambda = O(\Lambda/m_B)$
  - Define soft form factors by setting some $\Delta = 0$
  - (Factorisable) power corrs. from fit to full form factors, embedding correlations from large-recoil
  - $B \to V\ell\ell$ from soft form factors + hard gluons + power corrections

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- Full form factor approach [Buras, Ball, Bharucha, Altmannshofer, Straub...]
  - Full form factors with correlations
  - $B \to V\ell\ell$ from correlated full form factors
    + hard gluons & power corrs. not from form factors (nonfactorisable)

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Choice of observables

- optimised observables P_i with limited sensitivity to form factors
- averaged angular coefficients S_i with larger sensitivity

Very large power corrections ? (1)

- Scheme: choice of definition for the two soft form factors (all equivalent for $m_B \to \infty$)

$$\{\xi_\perp, \xi_{||}\} = \{V, \alpha A_1 + \beta A_2\}, \{T_1, A_0\}, \ldots$$

- Power corrections for the other form factors from dimensional estimates or fit to available determinations (LCSR)

$$F(q^2) = F^{\rm soft}(\xi_{\perp,||}(q^2)) + \Delta F^{\alpha_s}(q^2) + a_F + b_F \frac{q^2}{m_B^2} + \ldots$$

- For some schemes, large(r) uncertainties found for some optimised observables [Camalich, Jäger]

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- For some schemes, large(r) uncertainties found for some optimised observables [Camalich, Jäger]

Observables are scheme independent, but
procedure to compute them can be either scheme dependent or not

a) Include all correlations among uncertainties for power corr
   more accurate, but hinges on detail of ff determination
b) Assign 10% uncorrelated uncertainties for power corrs a_F, b_F
   depends on scheme (setting $a_F = b_F = 0$ for two form factors)

Very large power corrections ? (2)

Model independent $\longleftrightarrow$ Full LCSR information

$\boxed{1}$

- $\Delta F^{\rm PC} = F \times \mathcal{O}(\Lambda/m_B) \sim F \times 10\%$
- correlations from large-recoil sym. $\to \xi_{\perp,\parallel}, \Delta F^{\rm PC}$ uncorr.

$\boxed{2}$

- $\Delta F^{\rm PC}$ from fit to LCSR
- correlations from large-recoil sym. $\to \xi_{\perp,\parallel}, \Delta F^{\rm PC}$ uncorr.

$\boxed{3}$

- $\Delta F^{\rm PC}$from fit to LCSR
- correlations from LCSR $\to \xi_{\perp,\parallel}, \Delta F^{\rm PC}$ corr.

Very large power corrections ? (2)

Model independent ⟵⟶ Full LCSR information

1
- ★ $\Delta F^{\rm PC} = F \times \mathcal{O}(\Lambda/m_B) \sim F \times 10\%$
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2
- ★ $\Delta F^{\rm PC}$ from fit to LCSR
- ★ correlations from large-recoil sym. $\to \xi_{\perp,\parallel}, \Delta F^{\rm PC}$ uncorr.

3
- ★ $\Delta F^{\rm PC}$from fit to LCSR
- ★ correlations from LCSR $\to \xi_{\perp,\parallel}, \Delta F^{\rm PC}$ corr.

$P_5'[4.0, 6.0]$	scheme 1	scheme 2
1	-0.72 ± 0.05	-0.72 ± 0.12
2	-0.72 ± 0.03	-0.72 ± 0.03
3	-0.72 ± 0.03	-0.72 ± 0.03
full BSZ	-0.72 ± 0.03	

errors only from pc with BSZ form factors

[Capdevilla,SDG, Hofer, Matias]

- [Bharucha, Straub, Zwicky] as example (correl provided)
- scheme indep. restored if $\Delta F^{\rm PC}$ from fit to LCSR, with expected magnitude
- sensitivity to scheme can be understood analytically
- no uncontrolled large power corrections for $P_{5'}$

Scheme dependence of observables

Using the connection between full and soft form factors at large recoil, keeping power corrections

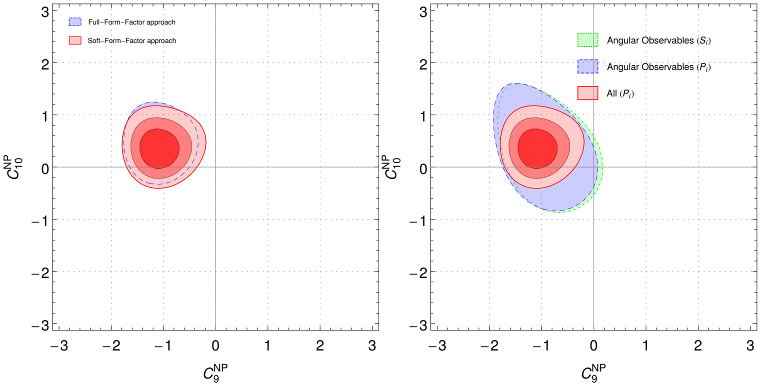
$$P_5'(6\,\mathrm{GeV}^2) = P_5'|_\infty(6\,\mathrm{GeV}^2)\left(1 + 0.18\,\frac{2a_{V_-} - 2a_{T_-}}{\xi_\perp} - 0.73\,\frac{2a_{V_+}}{\xi_\perp} + 0.02\,\frac{2a_{V_0} - 2a_{T_0}}{\tilde{\xi}_\parallel}\right.$$
$$\left. + \text{nonlocal terms}\right) + O\left(\frac{m_{K^*}}{m_B}, \frac{\Lambda^2}{m_B^2}, \frac{q^2}{m_B^2}\right).$$

$$P_1(6\,\mathrm{GeV}^2) = -1.21\,\frac{2a_{V_+}}{\xi_\perp} + 0.05\,\frac{2b_{T_+}}{\xi_\perp} + \text{nonlocal terms} + O\left(\frac{m_{K^*}}{m_B}, \frac{\Lambda^2}{m_B^2}, \frac{q^2}{m_B^2}\right),$$

- scheme dependence of P_5' not fully taken into account in [Camalich,Jäger]
- allows one to understand the scheme dependence of P_i
- P_5' and P_1 with reduced unc. if $\xi_\perp$ defined from V ($a_{V_+} = 0$)

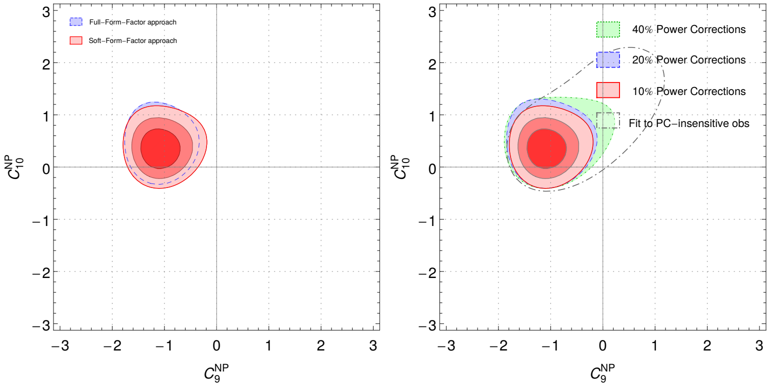
Cross-checks: F. factors

(SDG, Hofer, Matias, Virto)



- Soft form factor approach ([Khodjamirian et al.] ff + EFT correls) vs full ff ([Altmannshofer, Straub] with [Bharucha et al.] ff with correls and small errors)
- Similar results using either optimised or angular coeffs (if correlations of form factors included through EFT)

Cross-checks: F. factors & power corrs (SDG, Hofer, Matias, Virto)



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- Similar results using either optimised or angular coeffs (if correlations of form factors included through EFT)
- Increasing power corrections weakens role of large recoil, but low recoil enough to pull fit away from the SM

Charm-loop effects: large recoil

- Short-distance (hard gluons)
  - $\mathcal{C}_9 \to \mathcal{C}_9 + Y(q^2) = \mathcal{C}_9 + \delta\mathcal{C}_{9,\mathrm{SD}}^{BK^{(*)}}(q^2)$, dependence on m_c
  - higher-order short-distance QCD via QCDF/HQET

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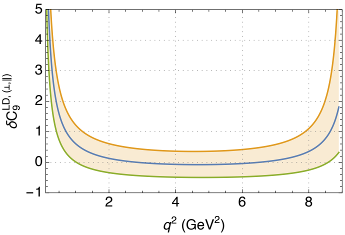
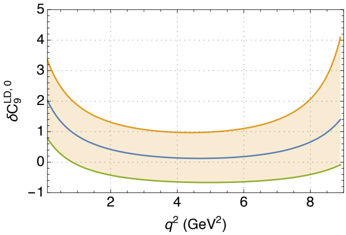
  - higher-order short-distance QCD via QCDF/HQET
- Long-distance (soft gluons)
  - $\Delta\mathcal{C}_9^{BK^{(*)},i} > 0$ ($i = 0, ||, \perp$) using LCSR [Khodjamirian, Mannel, Pivovarov, Wang]
  - Computed for $q^2 < 0$ and small, then extrapolated through dispersion relation reincluding J/ψ (but many unknown parameters)
  - For us, order of magnitude: $\Delta\mathcal{C}_9^{BK^*}\big|_{KMPW} = \delta\mathcal{C}_{9,\mathrm{SD}}^{BK^{(*)}} + \delta\mathcal{C}_{9,\mathrm{LD}}^{BK^{(*)}}$

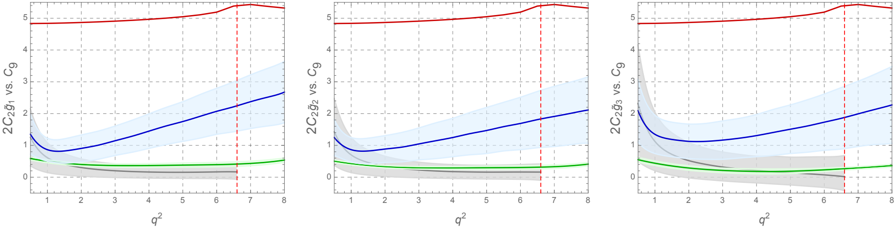
    taking $\Delta\mathcal{C}_9^{BK^*,i} = \delta\mathcal{C}_{9,\mathrm{SD}}^{BK^{(*)},i} + s_i\, \delta\mathcal{C}_{9,\mathrm{LD}}^{BK^{(*)},i}$ with $s_i = 0 \pm 1$





Charm-loop fit to $B \to K^* \ell\ell$ (1)

- $c\bar{c}$ contributions to 3 K^* helicity amplitudes $g_{1,2,3}$ as q^2-polynomial
- params from Bayesian fit to data [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]



In units of $\mathcal{C}_9$: Short-Dist, QCDF, fit, KMPW $\Delta\mathcal{C}_9^{BK^*}$

- constrained fit: imposing SM + $\Delta\mathcal{C}_9^{BK^*}$ [Khodjamirian et al.] at $q^2 < 1$ GeV^2 yields q^2-dependent $c\bar{c}$ contribution, with "large" coefs for q^4

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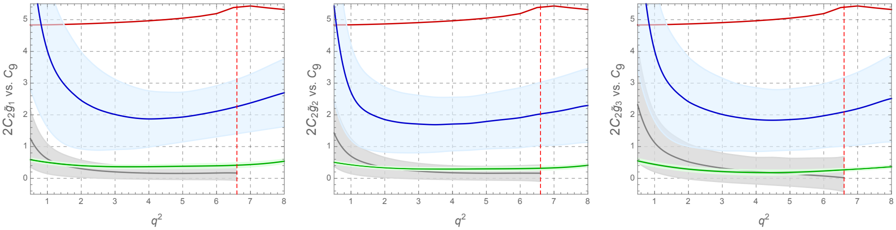

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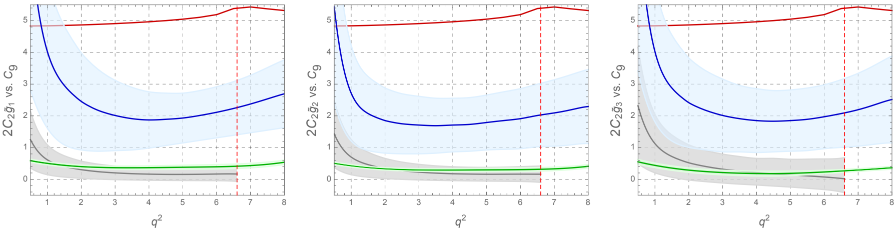

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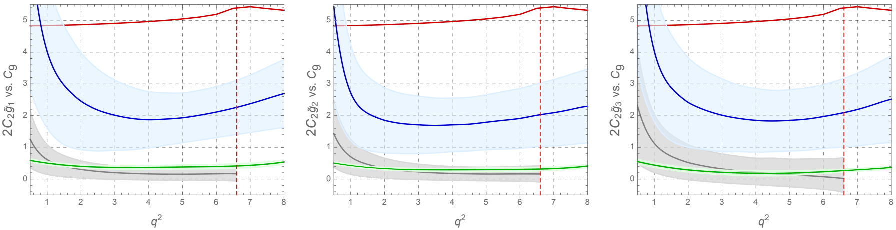

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- constrained fit forced at low q^2, compensation skewing high q^2
- no dynamical hadronic explanation for enhancement at high q^2

Charm-loop fit to $B \to K^*\ell\ell$ (2)

Problem related to q^4 contribution ? [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

- strong q^2 dependence due to hadronic, not NP ?
- not clear: q^4 dependence already from $\mathcal{C}_i \times FF(q^2)$

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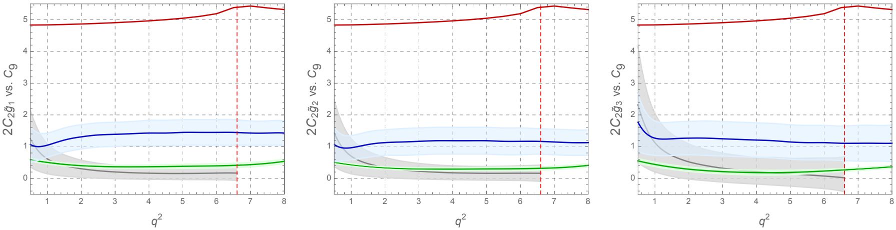

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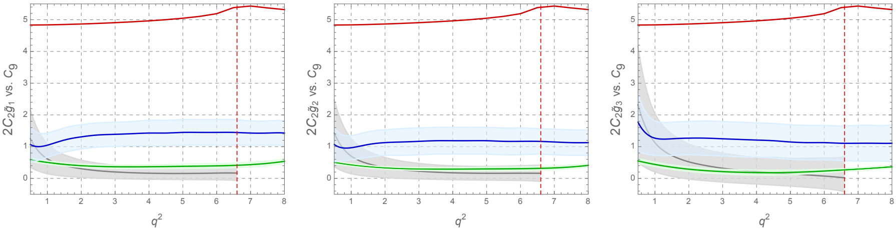

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[Capdevila, Hofer, Matias, SDG; Hurth, Mahmoudi, Neshatpour]

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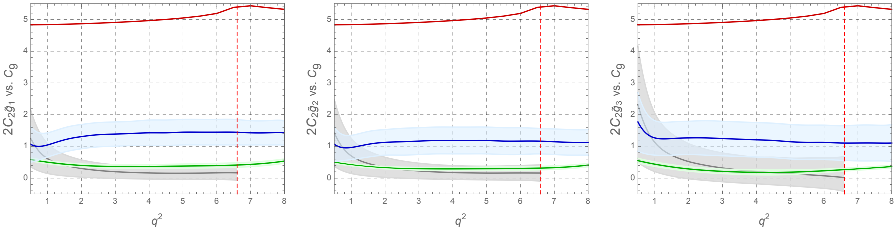

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- if $c\bar{c}$, why same constant $\mathcal{C}_9^{\rm NP}$ for all mesons and helicities, which explanation for $R_{K^{(*)}}$, what causes deviations in low-recoil BRs ?

Charm-loop fit to $B \to K^*\ell\ell$ (3) (Capdevila, Hofer, Matias, SDG)

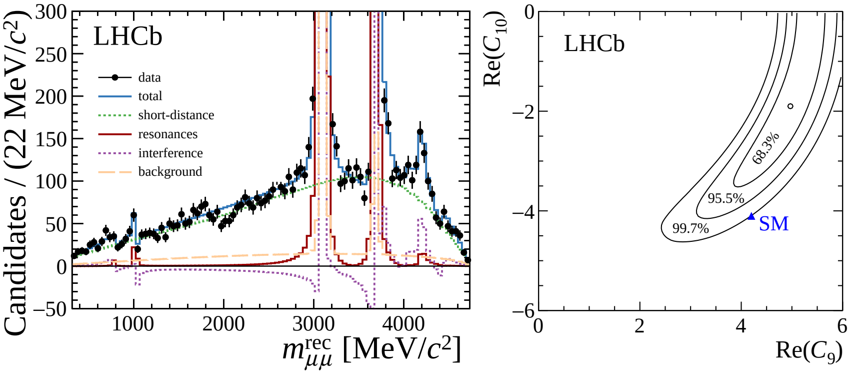
$$\begin{aligned}
A^0_{L,R} &= A^0_{L,R}(s_i=0) + \frac{N}{q^2}\left(h_0^{(0)} + \frac{q^2}{1\ \mathrm{GeV}^2}h_0^{(1)} + \frac{q^4}{1\ \mathrm{GeV}^4}h_0^{(2)}\right),\\
A^{\|}_{L,R} &= A^{\|}_{L,R}(s_i=0)\\
&\quad + \frac{N}{\sqrt{2}q^2}\left[(h_+^{(0)} + h_-^{(0)}) + \frac{q^2}{1\ \mathrm{GeV}^2}(h_+^{(1)} + h_-^{(1)}) + \frac{q^4}{1\ \mathrm{GeV}^4}(h_+^{(2)} + h_-^{(2)})\right],\\
A^{\perp}_{L,R} &= A^{\perp}_{L,R}(s_i=0)\\
&\quad + \frac{N}{\sqrt{2}q^2}\left[(h_+^{(0)} - h_-^{(0)}) + \frac{q^2}{1\ \mathrm{GeV}^2}(h_+^{(1)} - h_-^{(1)}) + \frac{q^4}{1\ \mathrm{GeV}^4}(h_+^{(2)} - h_-^{(2)})\right],
\end{aligned}$$

- $s_i = 0$ means no contrib from long-distance $c\bar{c}$
- n order of the polynomial added, coeffs fit in frequentist framework
- testing nested hyp: pull from $\chi^{2(n-1)}_{\min} - \chi^{2(n)}_{\min}$ $(\chi^{2(-1)}_{\min} = \mathrm{SM})$

n	0		1		2		3	
$B \to K^*\mu\mu$, $C_9^{\mu,\mathrm{NP}} = 0$	2.88	(0.8 σ)	17.90	(3.5 σ)	0.08	(0.0 σ)	0.34	(0.1 σ)
$B \to K^*\mu\mu$, $C_9^{\mu,\mathrm{NP}} = -1.1$	4.79	(1.3 σ)	9.73	(2.3 σ)	0.20	(0.0 σ)	0.39	(0.1 σ)
$b \to s\ell\ell$, $C_9^{\mu,\mathrm{NP}} = 0$	1.55	(0.4 σ)	21.40	(3.9 σ)	0.61	(0.1 σ)		

No need for high-order polyn or strong q^2-dep impossible with short distance contrib, contrary to claims by [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

Charm loop from resonances in $B \to K\ell\ell$ data



- $\mathcal{C}_9^{\rm eff} = \mathcal{C}_9^{SD}$+sum of resonant Breit-Wigner (ω, ρ^0, ϕ, charmonia)
- LHCb data driven fit to couplings and phases, as well as $\mathcal{C}_9, \mathcal{C}_{10}$
- 4 equivalent sols, with tiny contrib from resonances below J/ψ

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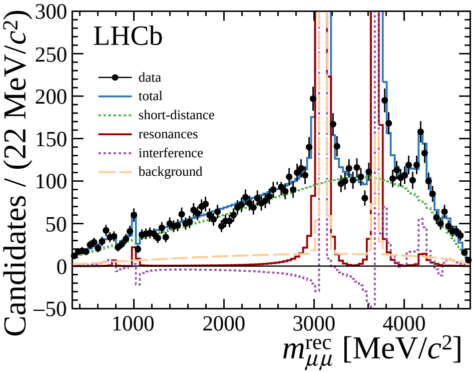

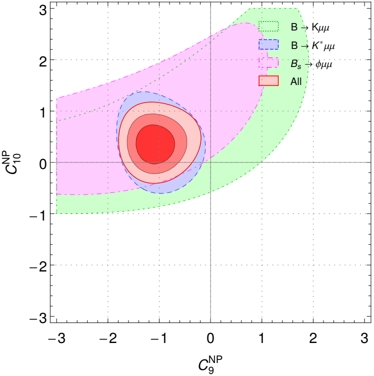

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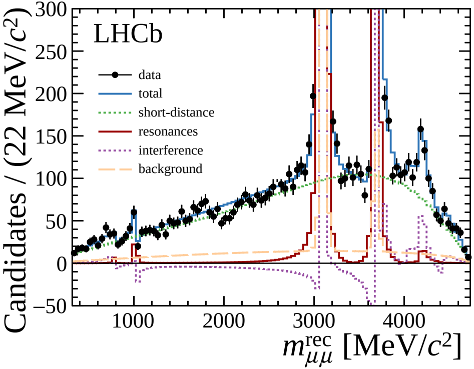

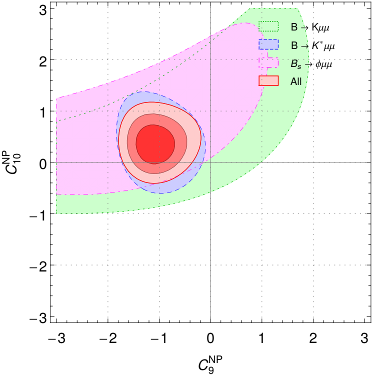

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- extension to $B \to K^*\ell\ell$ from [Blake et al.], agrees with $c\bar{c}$ models for fits

Data-driven charm loop contribution (1)

[Bobeth, Chrzaszcz, Van Dyk, Virto]

Rather than fitting unphysical polynomial with arbitray coefficients

- Known analytic structure of charm loop contribution
  - Analytical up to poles and a cut starting $q^2 = 4M_D^2$
  - Inherit all singularities from form factors (M_{B_s} pole for instance)
- Appropriate parametrisation valid up to $D\bar{D}$ cut
  - z-expansion (better conv below cut, mapped into disc $|z| \leq 1$)
  - Poles for J/ψ and ψ' + good asymptotic behaviour

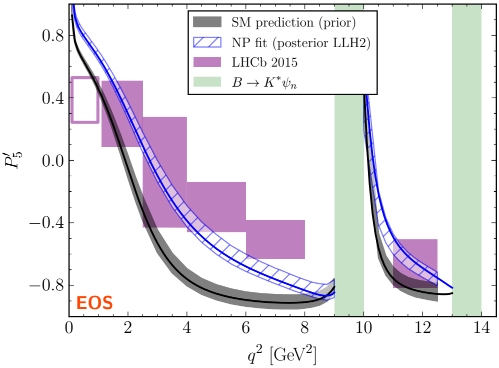
$$\eta_\alpha^* \mathcal{H}^{\alpha\mu} = i \int d^4x\, e^{iq\cdot x} \langle \bar{K}^*(k,\eta)| T\{j^\mu_{\rm em}(x), \mathcal{C}_2\mathcal{O}_2(y)\}|\bar{B}(p)\rangle$$

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}, \quad t_+ = 4M_D^2, \quad t_0 = t_+ - \sqrt{t_+(t_+ - M^2_{\psi(2S)})}$$

$$\mathcal{H}_\lambda(z) = \frac{1 - z\, z^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z\, z^*_{\psi(2S)}}{z - z_{\psi(2S)}} \Big[\sum_{k=0}^{K\leq 2} \alpha_k^{(\lambda)} z^k \Big] \mathcal{F}_\lambda(z)$$

Data-driven charm loop contribution (2)

[Bobeth, Chrzaszcz, Van Dyk, Virto]



- Exploit info to determine the coefficients
  - Experimental info: discarded LHCb bins to fix J/ψ ans ψ' residues
  - Theoretical info: LCSR for $q^2 \leq 0$ (most accurate)

- Compute the observables
  - $c\bar{c}$ contribution in agreement with earlier estimates
  - P_5' for SM in disagreement with LHCb data
  - Agreement if $\mathcal{C}_9^{NP} \simeq -1.1$
  - Access to intermediate region between J/ψ and ψ'
  - Extension possible to other $b \to s\ell\ell$ modes

Charm-loop effects : resonances (1)

- Low recoil: quark-hadron duality
  - Average "enough" resonances to equate quark and hadron levels
  - Model estimate yield a few % for $BR(B \to K\mu\mu)$ [Beylich, Buchalla, Feldmann]

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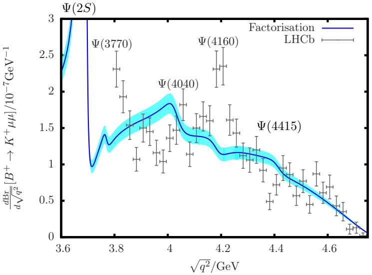

- Probably (?) effect of similar size for $B \to K^*\mu\mu$ (BR and angular obs.)
- OPE corrections + NLO QCD corrections + complex correction of 10% for each transversity amplitude
- Difficulties to explain $B \to K\ell\ell$ low-recoil spectrum using $\sigma(e^+e^- \to hadrons)$ and naive factorisation [Lyon, Zwicky]

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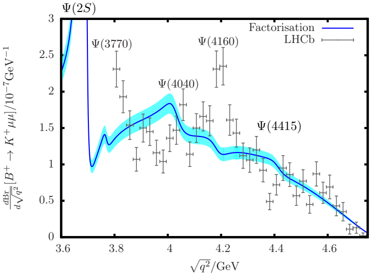

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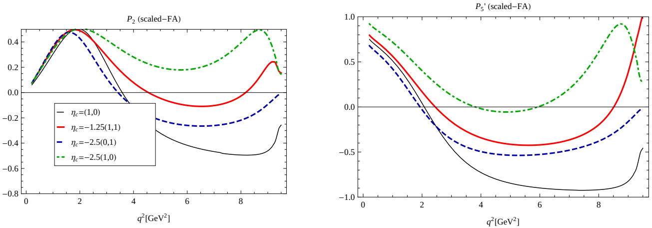
- Large recoil
  - $q^2 \leq$ 7-8 GeV^2 to limit the impact of J/ψ tail
  - Still need to include the effect of $c\bar{c}$ loop (tail of resonances + nonresonant)
  - LHCb on $B \to K\mu\mu$: resonance tails have very limited impact

Charm-loop effects : resonances (2)

On the basis of a model for $c\bar{c}$ resonances for low-recoil $B \to K\mu\mu$ [Zwicky and Lyon] proposed very large $c\bar{c}$ contrib for large-recoil $B \to K^*\mu\mu$

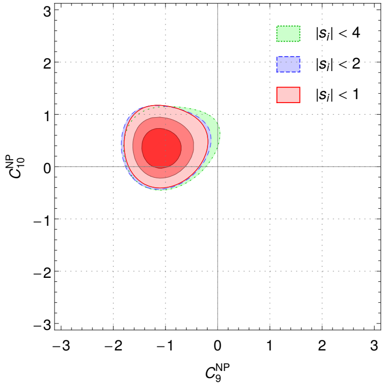
$$\mathcal{C}_9^{\rm eff} = \mathcal{C}_9^{SM} + \mathcal{C}_9^{\rm NP} + \eta h(q^2) \text{ and } \mathcal{C}_{9'} = \mathcal{C}_{9'}^{NP} + \eta' h(q^2)$$

where $\eta + \eta' = -2.5$ where conventional expectations are $\eta = 1, \eta' = 0$



- P_2 and P'_5 could have more zeroes for $4 \le q^2 \le 9$ GeV^2
- $P'_{5[6,8]}$ would be above or equal to $P'_{5[4,6]}$, whereas global effects (like $\mathcal{C}_9^{\rm NP}$) predicts $P'_{5[6,8]} < P'_{5[4,6]}$ in agreement with experiment
- Not in agreement with LHCb findings for $B \to K\ell\ell$
- R_K and R_{K^*} unexplained since it would affect identically $\ell = e, \mu$

Cross-checks: Charm-loop dependence



- For each $B \to K^*\mu\mu$ transversity $\Delta\mathcal{C}_9^{BK^{(*)},i} = \delta\mathcal{C}_{9,\mathrm{pert}}^{BK^{(*)},i} + s_i\delta\mathcal{C}_{9,\mathrm{non\ pert}}^{BK^{(*)},i}$
- Ditto for $B_s \to \phi$, with all 6 s_i independent
- For $B \to K\mu\mu$, $c\bar{c}$ estimated as very small
- Increasing the range allowed for s_i makes low-recoil and $B \to K\mu\mu$ dominate more and more

- Does not alter the pull, and does not explain LFUV

NP interpretations

No consistent global alternative from SM/long-dist. for $b \to s\ell\ell$

- hadronic effects ($B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$ at low and large recoils)
- statistical fluctuation and/or pb with e/μ (R_K, R_{K^*})
- bad luck (short-distance scenarios can accomodate all discrepancies very well by chance)

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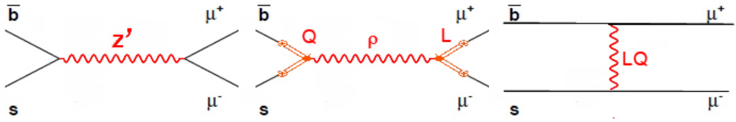

NP models with new scale around TeV

- Z' boson and leptoquarks are favourite
- Partial compositeness and NP in $b \to c\bar{c}s$ also investigated
- but susy (MSSM) not favoured (hard to generate large $\mathcal{C}_{9\mu}$-like contribution without having flavour problems in other places)

[Buras, De Fazio, Girrbach, Blanke, Altmannshofer, Straub, Crivellin, D'Ambrosio, Becirevic, Sumensari, Isidori, Greljo, Jäger, Lenz. . .]