B-physics anomalies: SM vs NP

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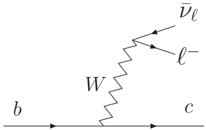
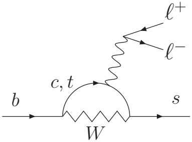
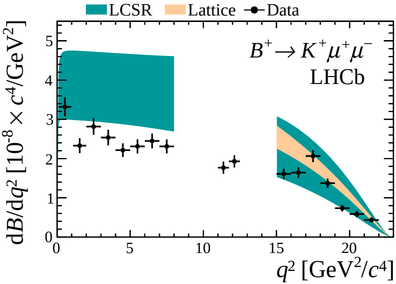
LPT Orsay

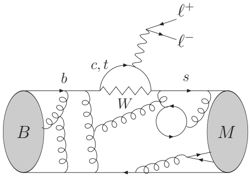
B-physics anomalies

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

Two transitions exhibiting interesting patterns of deviations from SM
hinting at Lepton Flavour Universality Violation
Here, focus on $b \to s\ell\ell$

Anomalies in $B \to K\ell\ell$ (see also talk by S. Reichert)





- q^2 invariant mass of $\ell\ell$ pair
- $Br(B \to K\mu\mu)$ too low compared to SM

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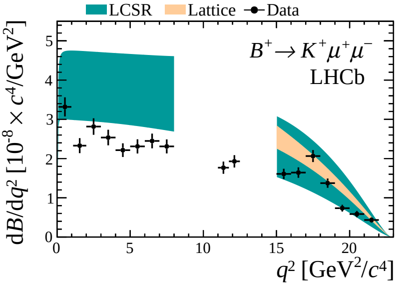
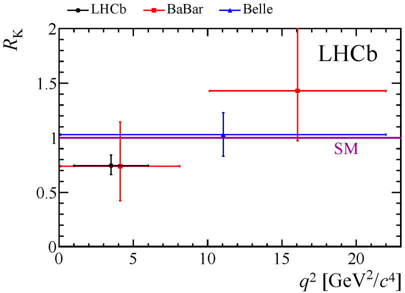
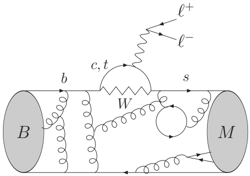
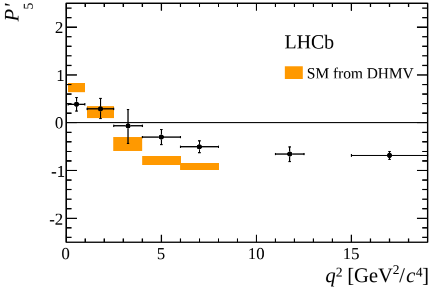






- q^2 invariant mass of $\ell\ell$ pair
- $Br(B \to K\mu\mu)$ too low compared to SM
- $R_K = \left.\frac{Br(B\to K\mu\mu)}{Br(B\to Kee)}\right|_{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$
- equals to 1 in SM (universality of lepton coupling), 2.6 σ dev
- NP coupling $\neq$ to μ and e

Anomalies in $B \to K^* \mu\mu$ (see also talk by K. De Bruyn)



- Optimised observables P_i 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

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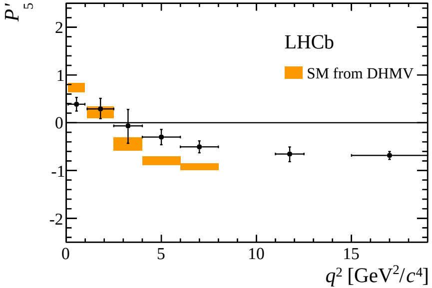

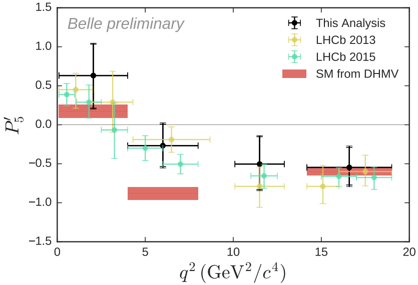

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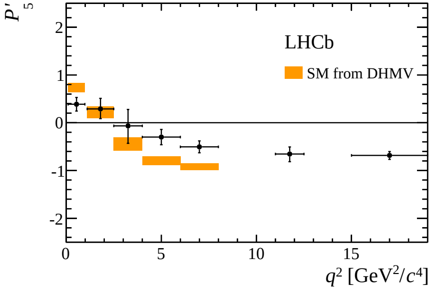

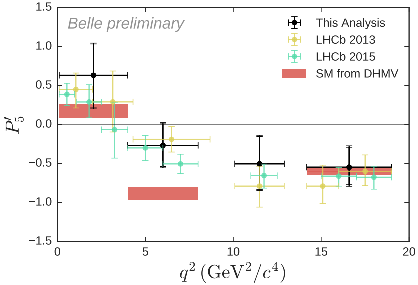

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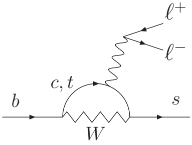
- Discrepancies for some (but not all) observables, in particular two bins for P'_5 deviating from SM by 2.8 σ and 3.0 σ
- ...confirmed by Belle in 2016
- Deviations in $BR(B \to K^*\mu\mu)$ and $BR(B_s \to \phi\mu\mu)$

A global framework

$b \to s\mu\mu$ effective hamiltonian



$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\Delta F=1} \propto \sum V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i + \ldots$$

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

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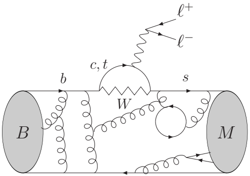

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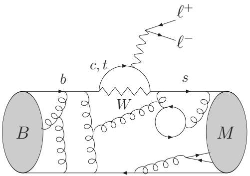

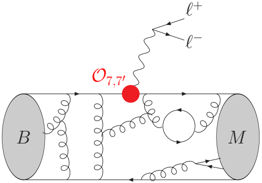

- $\mathcal{O}_7 = \frac{e}{g^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5) F_{\mu\nu} \, b$ [real or soft photon]

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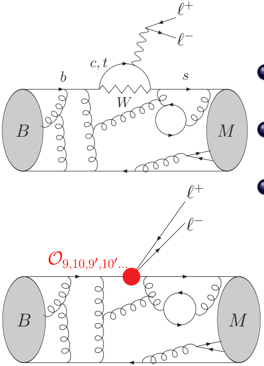

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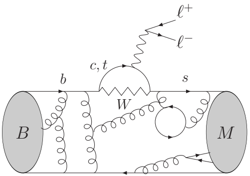
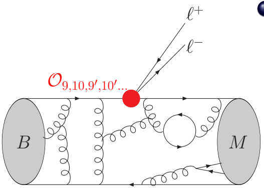
- $\mathcal{O}_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5) b \; \bar{\ell}\gamma^\mu \ell$ [$b \to s\mu\mu$ via Z/hard $\gamma\ldots$]
- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5) b \; \bar{\ell}\gamma^\mu\gamma_5 \ell$ [$b \to s\mu\mu$ via Z]

$b \to s\mu\mu$ effective hamiltonian





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

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

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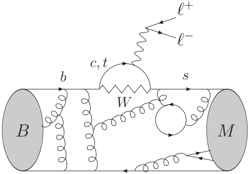

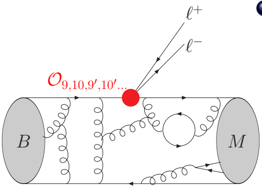

to separate short and long distances ($\mu_b = m_b$)

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NP changes short-distance $\mathcal{C}_i$ for SM or involve additional operators $\mathcal{O}_i$

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

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

[SDG, Hofer, Matias, Virto]

96 observables in total (LHCb for exclusive, no CP-violating obs)

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

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Various tools

- 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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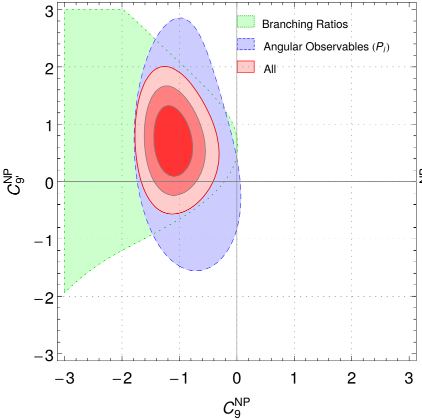
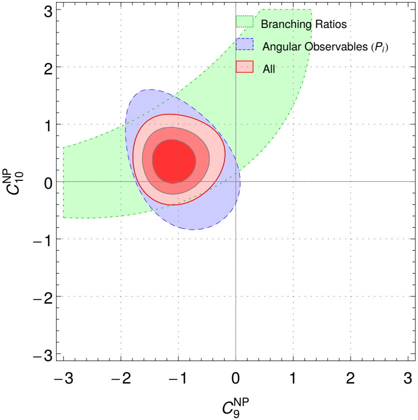
Frequentist analysis

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

Some favoured scenarios



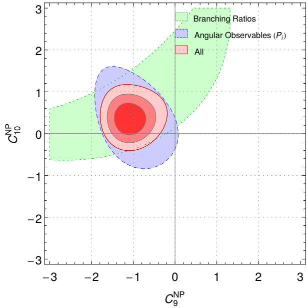
NP in $\mathcal{C}_9^{\rm NP}, \mathcal{C}_{9'}^{\rm NP}$



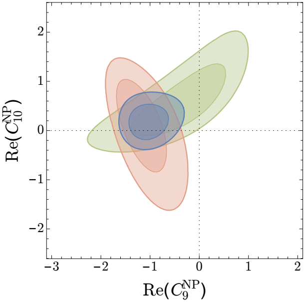
NP in $\mathcal{C}_9^{\rm NP}, \mathcal{C}_{10}^{\rm NP}$

- NP in $\mathcal{C}_9$ only: p-value=48% (11% for SM), $\text{pull}_{SM} = 4.2\sigma$
- BRs and angular obs both favour $\mathcal{C}_9^{NP} \simeq -1$ in all "good" scenarios
- Results in agreement with [Altmanshoffer, Straub] and [Hurth, Mahmoudi, Neshatpour]

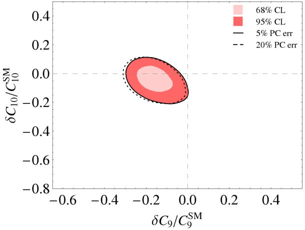
Consistency: Three different analyses



[SDG, Hofer, Matias, Virto]



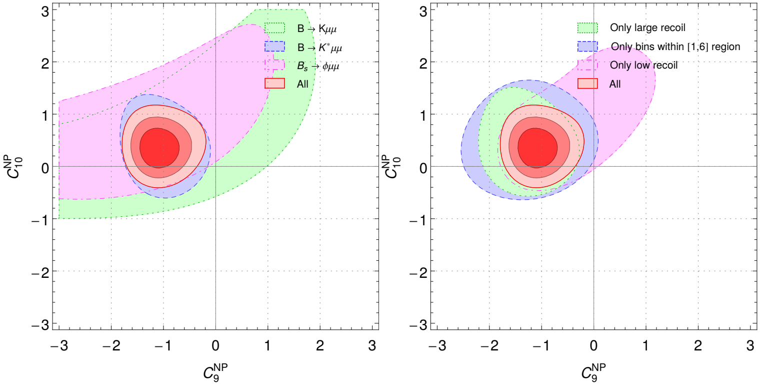
[Altmanshoffer, Straub]



[Hurth, Mahmoudi, Neshatpour]

- Different observables (LHCb only or averages, P_i or J_i)
- Different form factor inputs
- Different treatments of hadronic corrections
- Same pattern of NP scenarios favoured (here, $\mathcal{C}_9^{NP}, \mathcal{C}_{10}^{NP}$)

Consistency: by channels, low versus large recoil



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

- Different processes and different kinematic ranges involving different theoretical tools
- $B \to K^*\mu\mu$ tighter than $B_s \to \phi\mu\mu$, tighter than $B \to K\mu\mu$
- Large recoil driving the discussion, but [1,6] bins already providing bulk of the effect, and low-recoil also in favour of $\mathcal{C}_9^{NP} < 0$

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

Anomalies can be a sign from many things

- unlucky statistical fluctuations

  Collect more data (more runs)
- underestimated syst in the experimental analysis

  Cross-checks from different experiments (LHCb vs Belle)
- underestimated syst in the theoretical computation

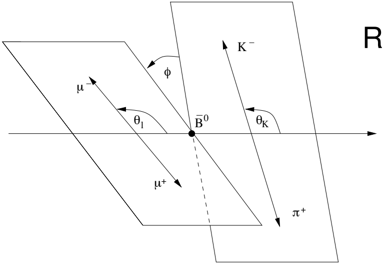
  Check and recheck the hypotheses
- something really new...

  Add more observables, and interpret

Since exclusive decays play an important role in global fits necessary to cross-checks SM computations !

Theoretical uncertainties for $B \to K^*\mu\mu$

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



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 Dyck, Buras, Altmanshoffer, Straub, Bharucha, Zwicky, Gratrex, Hopfer, Becirevic, Sumensari, Zukanovic-Funchal . . .]

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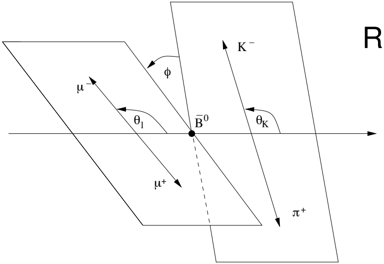

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- Transversity amplitudes in terms of Wilson coefficients and 7 form factors $A_{0,1,2}$, V, $T_{1,2,3}$
- EFT relations between form factors in limit $m_B \to \infty$, either when K^* very soft or very energetic (low/large-recoil)

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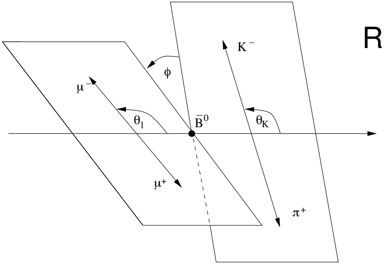

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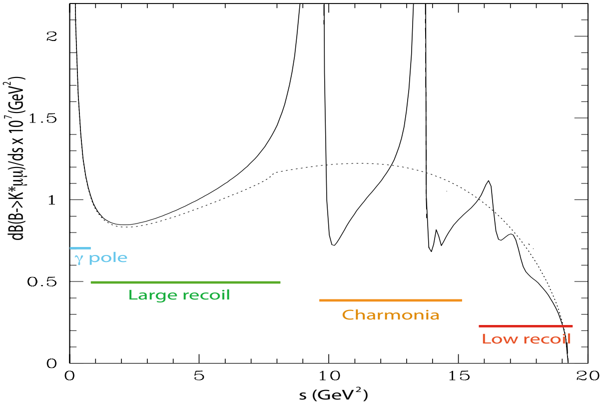
- Build ratios of J_i where form factors cancel in these limits
- Optimised observables P_i with reduced hadronic uncertainties

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

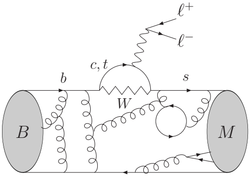
Low and large K^* recoils for $B \to K^*\mu\mu$



- 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, HQET

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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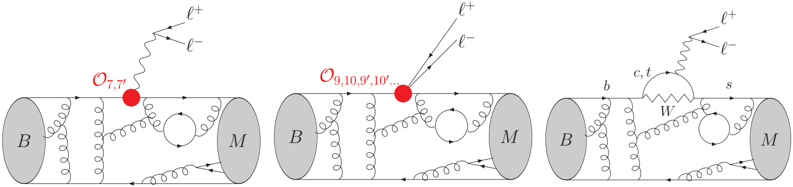

Form factors (local)

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

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

$$B_\mu = \mathcal{C}_{10} \langle V_\lambda | \bar{s} \gamma_\mu P_L b | B \rangle \qquad \lambda : \ K^* \text{ helicity}$$

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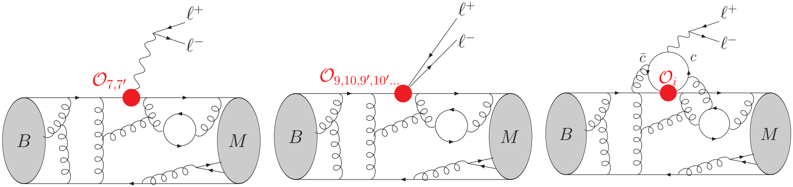

Form factors (local) Charm loop (non-local)

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$$B_\mu = \mathcal{C}_{10} \langle V_\lambda | \bar{s}\gamma_\mu P_L b | B \rangle \qquad \lambda: \ K^* \text{ helicity}$$

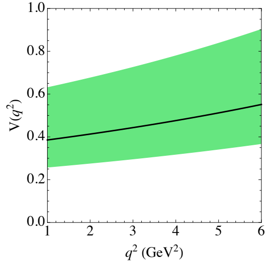
- Non-local contributions (charm loops): hadronic contribs.

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

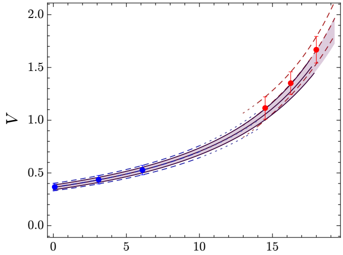
Form factors

- 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)

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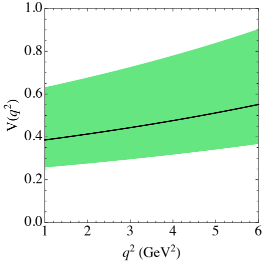

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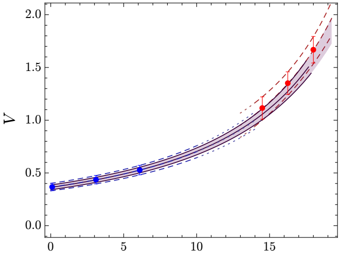
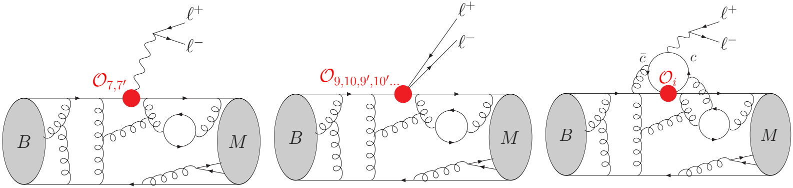


BSZ (fit LCSR + lattice)

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

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

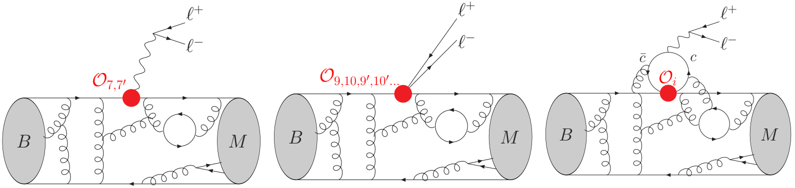
Form factors and power corrections



Form factors (local)

Charm loop (non-local)

Form factors and power corrections



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

Uncertainties in form factors ? [Camalich, Jäger;Matias,Virto,Hofer,Capdevilla,SDG]

- EFT with limit $m_b \to \infty$ useful to correlate form factors
  but $O(\Lambda/m_b)$ power corrections to this limit
- Power corrs with large impact on optimised observables ?

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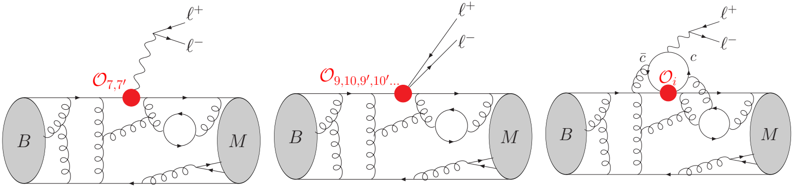

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  - appropriate def of soft form factors $\xi_{\perp,||}$ in $m_b \to \infty$ limit (scheme)
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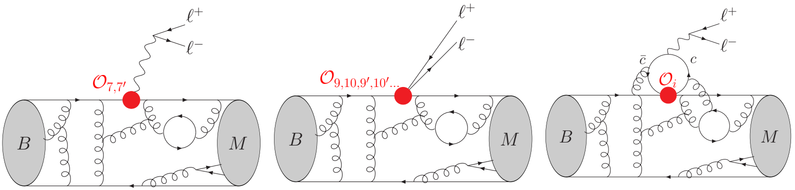

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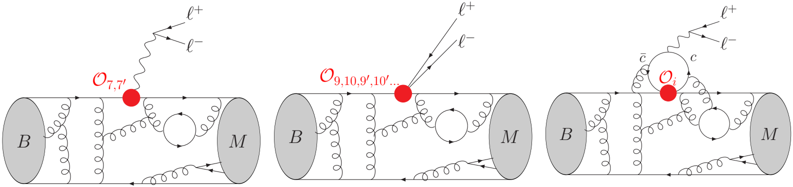
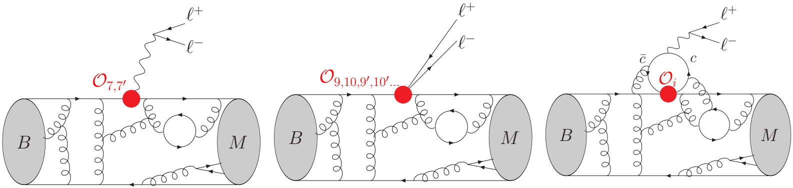
  - power corrections varied in agreement with info on form factors
- [Camalich, Jäger] artefacts from ill-advised scheme/variation for pcs

Charm-loop contribution



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

Charm-loop contribution

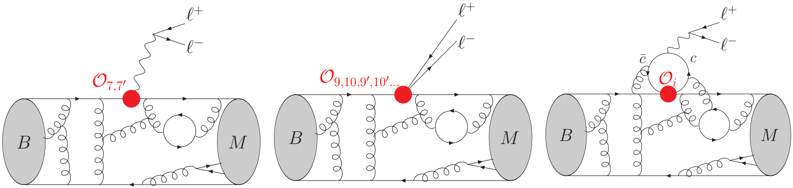


Form factors (local) Charm loop (non-local)

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 et al.]
  - Global fits use this result as order of magn, or $O(\Lambda/m_b)$ estimates

Charm-loop contribution



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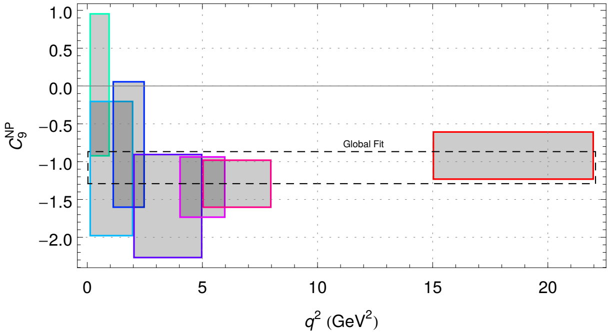
  - Global fits use this result as order of magn, or $O(\Lambda/m_b)$ estimates
- Bayesian extraction from $B \to K^* \mu\mu$ performed by [Ciuchini et al.]
  - q^2 dependence in agreement with $\Delta\mathcal{C}_9^{BK^{(*)}}$ + constant $\mathcal{C}_9^{\rm NP}$
  - no need for extra q^2-dep. contribution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

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

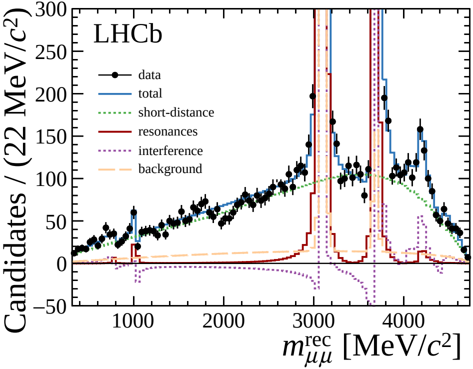
Cross-check: q^2-dependence of $\mathcal{C}_9$

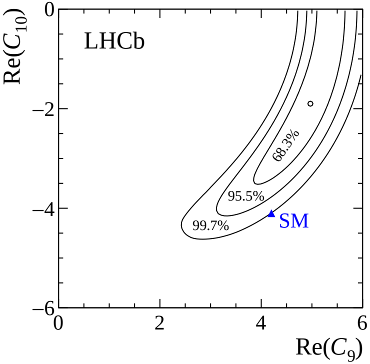


[Matias,Virto,Hofer,SDG]

- Fit to $\mathcal{C}_9^{NP}$ from individual bins of $b \to s\mu\mu$ data (NP only in $\mathcal{C}_9$)
  - 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 similar findings in [Altmanshoffer, Straub]

Resonances from $B \to K\ell\ell$ data (see also talk by K. De Bruyn)





- $\mathcal{C}_9^{\rm eff} = \mathcal{C}_9^{SD}$+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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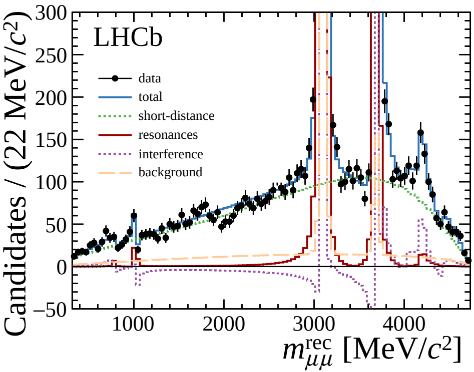

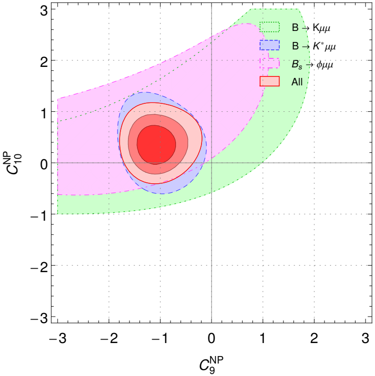

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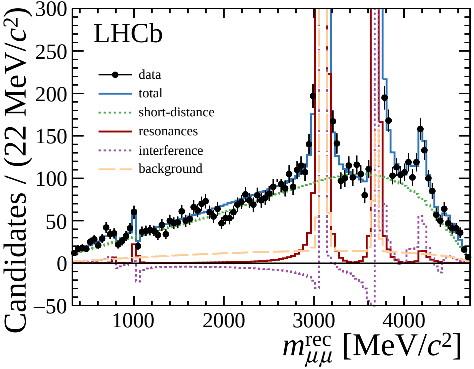

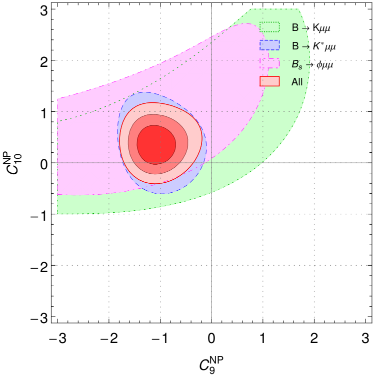

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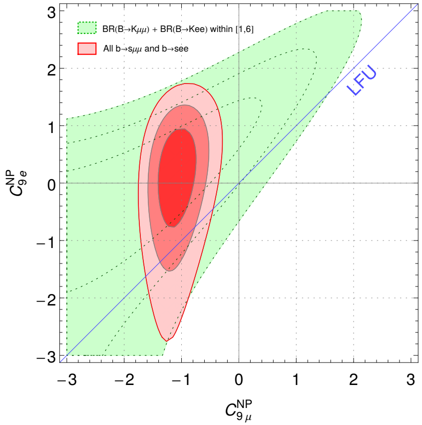
- similar data-driven estimate of resonance contrib for $B \to K^*$?

Exploring
Lepton-Flavour Non-Universality

Lepton-flavour (non) universality



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

- Adding LHCb $BR(B \to Kee)$ and large-recoil obs for $B \to K^* ee$
- Favours violation of LFU, compatible with no NP in $b \to see$
- For favoured scenarios with NP in $b \to s\mu\mu$ only, SM pull increases by $\sim 0.5\sigma$ (e.g., 4.7 σ for $\mathcal{C}_{9\mu}^{NP}$ only)
- If NP violating LFU, new clean observables by comparing $b \to see$ and $b \to s\mu\mu$!

Additional observables: R's

LHCb: already R_K, expecting other LFUV studies [see also talk by S. Reichert]
in particular expecting R_{K^*} at low and large K^* recoils

	$R_K[1,6]$	$R_{K^*}[0.045,1.1]$	$R_{K^*}[1.1,6]$	$R_\phi[1.1,6]$
SM	1.00 ± 0.01	0.92 ± 0.02	1.00 ± 0.01	1.00 ± 0.01
$\mathcal{C}_{9\mu}^{\rm NP} = -1.1$	0.79 ± 0.01	0.90 ± 0.05	0.87 ± 0.08	0.84 ± 0.02
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}^{\rm NP} = -1.07$	1.00 ± 0.01	0.87 ± 0.10	0.78 ± 0.14	0.74 ± 0.03
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP} = -0.65$	0.67 ± 0.01	0.87 ± 0.07	0.74 ± 0.03	0.69 ± 0.01
$\left.\begin{array}{c}\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}^{\rm NP} = -1.18 \\ \mathcal{C}_{10\mu}^{\rm NP} = \mathcal{C}_{10'\mu}^{\rm NP} = 0.38\end{array}\right\}$	0.88 ± 0.01	0.87 ± 0.10	0.75 ± 0.12	0.71 ± 0.03

- $R_M = BR(B \to Mee)/BR(B \to M\mu\mu)$ clean probes of NP [Hiller, Schmalz]
- Radiative QED corrections only a few percent, already included at the experimental level [Bordone, Isidori, Pattori]
- Predicted assuming NP only in $b \to s\mu\mu$
- $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$ yields very low values of R's, other intermediate

Additional observables: Q_i, B_i, M

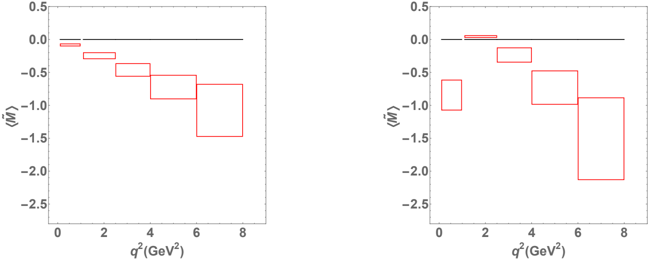
[Capdevilla, Matias, Virto, SDG]

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 $\mathcal{C}_9$

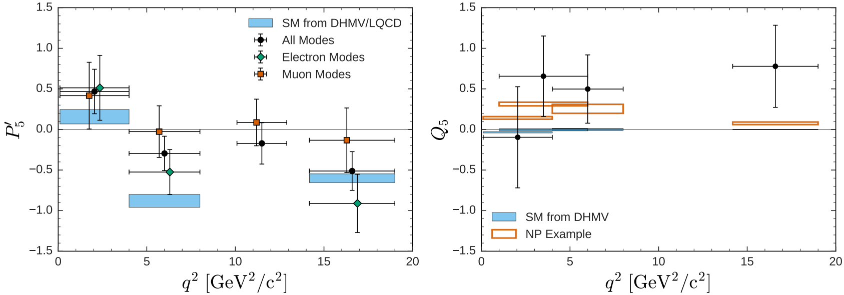
$$M = (J_5^\mu - J_5^e)(J_{6s}^\mu - J_{6s}^e)/(J_{6s}^\mu J_5^e - J_{6s}^e J_5^\mu)$$

  - 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*}



$\mathcal{C}_{9\mu}^{\rm NP} = -1.1, \mathcal{C}_{ie}^{\rm NP} = 0$ $\qquad$ $\mathcal{C}_{9\mu}^{\rm NP} = \mathcal{C}_{10\mu}^{\rm NP} = -0.65, \mathcal{C}_{ie}^{\rm NP} = 0$

A first hint from Belle ?

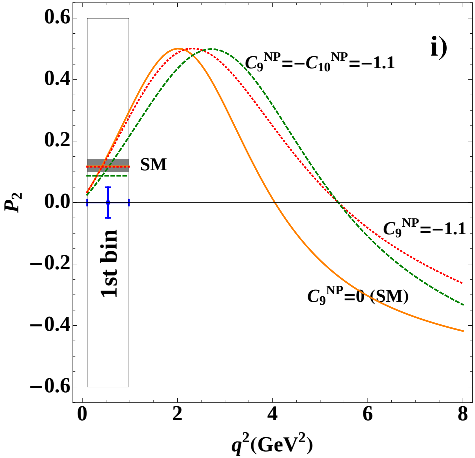


Belle has compared $b \to see$ and $b \to s\mu\mu$ in 2016

- different systematics from LHCb
- 2.6 σ deviation for $\langle P'_5 \rangle^{\mu}_{[4,8]}$ versus 1.3 σ deviation for $\langle P'_5 \rangle^{e}_{[4,8]}$
- Q_5 hinting at the same direction of NP in $\mathcal{C}^{\rm NP}_{9\mu} \simeq -1.1$ (in red)
- more data needed to determine if hint to be taken seriously

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, Capdevilla, Hofer, Matias, SDG]

NP interpretations (see also talks by A. Crivellin and A. Greljo)

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 (R_K)
- bad luck ($\mathcal{C}_9$ can accomodate all discrepancies by chance)

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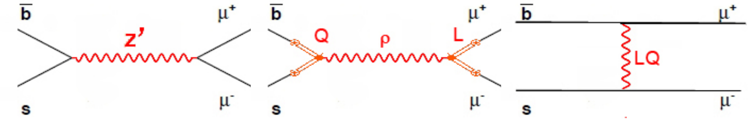


NP models with new scale around TeV

- Z' boson
- Partial compositeness
- Leptoquarks
- NP in $b \to c\bar{c}s$
- but susy (MSSM) not favoured . . .

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

Outlook

B physics anomalies

- $b \to s\ell^+\ell^-$ with many obs., more or less sensitive to hadronic unc.
- Interesting deviations from SM expectations
- Hints of violation of lepton flavour universality
- Global fit to $b \to s\ell^+\ell^-$ supporting large deviation for $\mathcal{C}_9$ in $b \to s\mu\mu$
- Does not seem to favour hadronic explanations (power corrections for form factors, charm loop contributions)

Where to go ?

- Other LFU violating observables: R_{K^*}, Q_i...
- Charm-loop for $b \to s\mu\mu$ (estimates, data-driven info on interferences, clean observables)
- More determinations of form factors to control uncertainties
- Model building to connect with other anomalies (like $b \to c\ell\nu_\ell$)

A lot of (interesting) work on the way !

A few recent global fits

	[SDG, Hofer Matias, Virto]	[Straub & Altmannshofer]	[Hurth, Mahmoudi, Neshatpour]
Statistical approach	Frequentist $\Delta\chi^2$	Frequentist $\Delta\chi^2$	Frequentist $\Delta\chi^2$ & χ^2
Data	LHCb	Averages	LHCb
$B \to K^*\mu\mu$ data	P_i, Max likelihood	S_i, Max likelihood	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	$\mathcal{C}_9^{\rm NP}, \mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$ $(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{9'}^{\rm NP}), (\mathcal{C}_9, \mathcal{C}_{10}^{\rm NP})$	$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{9'}^{\rm NP}), (\mathcal{C}_9^{\rm NP}, \mathcal{C}_{10}^{\rm NP})$

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

$b \to s\mu\mu$: 1D hypotheses

- SM pull: $\chi^2(\mathcal{C}_i = 0) - \chi^2_{\min}$ (metrology, how far best fit from SM ?)
- p-value: $\chi^2_{\min}$ and N_{dof} (goodness of fit, how good is best fit ?)

Coefficient	1σ	3σ	$\mathrm{Pull}_{\mathrm{SM}}$	p-value (%)
SM	–	–	–	11.0
$\mathcal{C}_7^{\mathrm{NP}}$	$[-0.04, 0.00]$	$[-0.07, 0.04]$	1.0	12.0
$\mathcal{C}_9^{\mathrm{NP}}$	$[-1.22, -0.79]$	$[-1.60, -0.31]$	4.2	48.0
$\mathcal{C}_{10}^{\mathrm{NP}}$	$[0.29, 0.75]$	$[-0.14, 1.26]$	2.3	19.0
$\mathcal{C}_{7'}^{\mathrm{NP}}$	$[-0.01, 0.04]$	$[-0.06, 0.09]$	0.6	11.0
$\mathcal{C}_{9'}^{\mathrm{NP}}$	$[0.09, 0.66]$	$[-0.46, 1.25]$	1.3	13.0
$\mathcal{C}_{10'}^{\mathrm{NP}}$	$[-0.38, -0.01]$	$[-0.77, 0.37]$	1.0	12.0
$\mathcal{C}_9^{\mathrm{NP}} = \mathcal{C}_{10}^{\mathrm{NP}}$	$[-0.36, 0.03]$	$[-0.69, 0.57]$	0.9	12.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{10}^{\mathrm{NP}}$	$[-0.79, -0.44]$	$[-1.15, -0.13]$	3.9	41.0
$\mathcal{C}_{9'}^{\mathrm{NP}} = \mathcal{C}_{10'}^{\mathrm{NP}}$	$[-0.31, 0.21]$	$[-0.84, 0.70]$	0.2	11.0
$\mathcal{C}_{9'}^{\mathrm{NP}} = -\mathcal{C}_{10'}^{\mathrm{NP}}$	$[0.03, 0.27]$	$[-0.21, 0.52]$	1.2	13.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{9'}^{\mathrm{NP}}$	$[-1.18, -0.76]$	$[-1.53, -0.30]$	4.3	51.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{10}^{\mathrm{NP}} = -\mathcal{C}_{9'}^{\mathrm{NP}} = -\mathcal{C}_{10'}^{\mathrm{NP}}$	$[-0.45, -0.45]$	$[-0.12, -0.12]$	3.8	40.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{10}^{\mathrm{NP}} = \mathcal{C}_{9'}^{\mathrm{NP}} = -\mathcal{C}_{10'}^{\mathrm{NP}}$	$[-0.34, -0.10]$	$[-0.58, 0.13]$	1.9	16.0

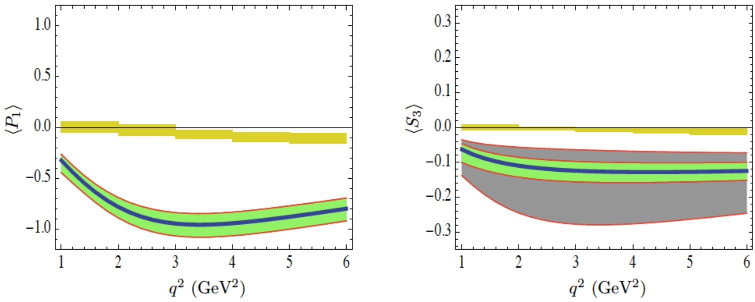
$b \to s\mu\mu$: 6D hypothesis

Letting all 6 Wilson coefficients vary (but only real)

Coefficient	1σ	2σ	3σ	Preference
$\mathcal{C}_7^{\rm NP}$	$[-0.02, 0.03]$	$[-0.04, 0.04]$	$[-0.05, 0.08]$	no pref
$\mathcal{C}_9^{\rm NP}$	$[-1.4, -1.0]$	$[-1.7, -0.7]$	$[-2.2, -0.4]$	negative
$\mathcal{C}_{10}^{\rm NP}$	$[-0.0, 0.9]$	$[-0.3, 1.3]$	$[-0.5, 2.0]$	positive
$\mathcal{C}_{7'}^{\rm NP}$	$[-0.02, 0.03]$	$[-0.04, 0.06]$	$[-0.06, 0.07]$	no pref
$\mathcal{C}_{9'}^{\rm NP}$	$[0.3, 1.8]$	$[-0.5, 2.7]$	$[-1.3, 3.7]$	positive
$\mathcal{C}_{10'}^{\rm NP}$	$[-0.3, 0.9]$	$[-0.7, 1.3]$	$[-1.0, 1.6]$	no pref

- $\mathcal{C}_9$ is consistent with SM only above 3σ
- All others are consistent with zero at 1σ except for $\mathcal{C}_{9'}$ at $2\ \sigma$
- $\text{Pull}_{\rm SM}$ for the 6D fit is 3.6σ

Sensitivity of observables to form factors



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

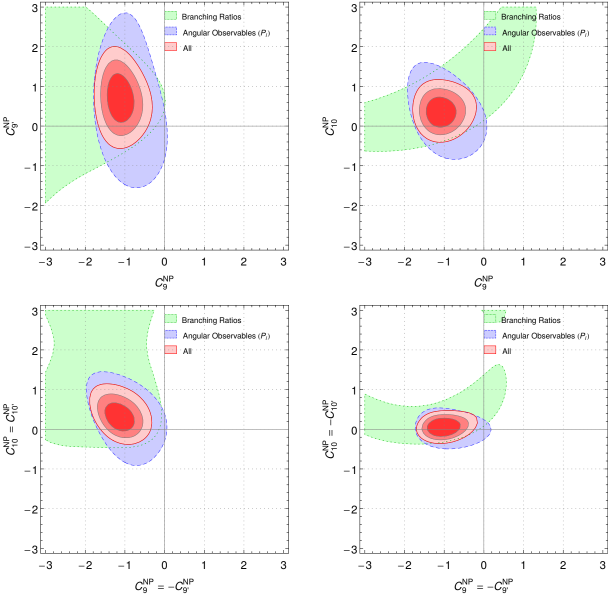
$$P_1 = \frac{2S_3}{1-F_L} \qquad F_L = \frac{J_{1c}+\bar{J}_{1c}}{\Gamma+\bar{\Gamma}} \qquad S_3 = \frac{J_3+\bar{J}_3}{\Gamma+\bar{\Gamma}}$$

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)

Some favoured scenarios



From the fit

- $\mathcal{C}_9^{NP}, \mathcal{C}_{9'}^{NP}$
- $\mathcal{C}_9^{NP}, \mathcal{C}_{10}^{NP}$
- $\mathcal{C}_9^{NP} = -\mathcal{C}_{9'}^{NP}$, $\mathcal{C}_{10}^{NP} = \mathcal{C}_{10'}^{NP}$
- $\mathcal{C}_9^{NP} = -\mathcal{C}_{9'}^{NP}$, $\mathcal{C}_{10}^{NP} = -\mathcal{C}_{10'}^{NP}$

For model builders $\mathcal{C}_9^{NP} = -\mathcal{C}_{10}^{NP}$ natural if $SU_L(2)$ symmetry used for all fermions

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)

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

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

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

a) Include all correlations among errors 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 ⟷ Full LCSR information

1

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

2

- ★ ΔF^{PC} from fit to LCSR
- ★ correlations from large-recoil sym.
  $\rightarrow \xi_{\perp,\|}, \Delta F^{\mathrm{PC}}$ uncorr.

3

- ★ $\Delta F^{\mathrm{PC}}$from fit to LCSR
- ★ correlations from LCSR
  $\rightarrow \xi_{\perp,\|}, \Delta F^{\mathrm{PC}}$ corr.

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$\boxed{1}$

★ $\Delta F^{\rm PC} = F \times \mathcal{O}(\Lambda/m_B)$
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$\boxed{2}$

★ $\Delta F^{\rm PC}$ 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.

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

errors only from pc with BSZ form factors

[Matias,Hofer,Capdevilla,SDG]

- [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

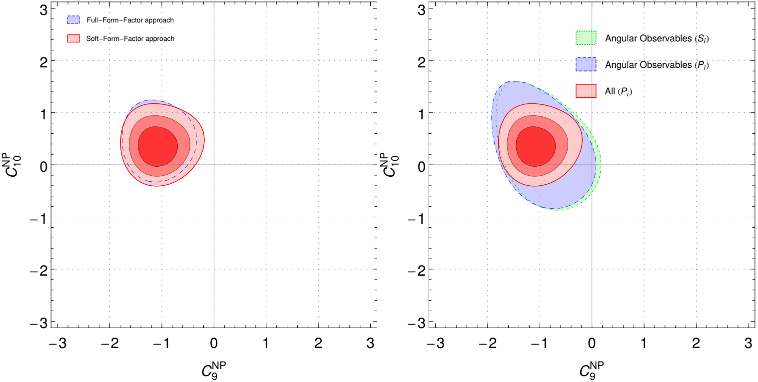
Using the connection between full and soft form factors at large recoil, keeping power corrections

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

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

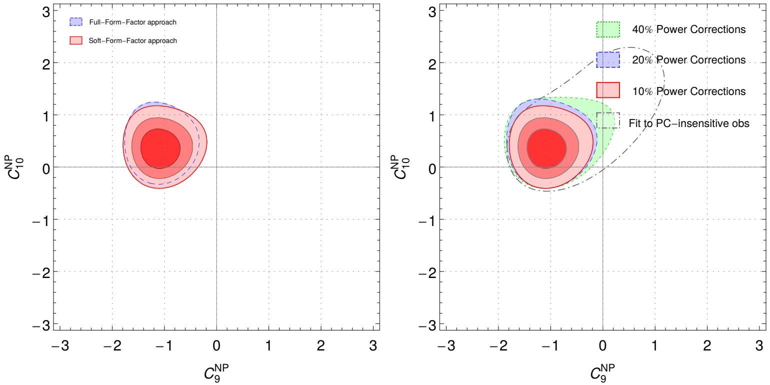
- scheme dependence of P_5' not fully taken into account in [Camalich,Jäger]
- allows to understand the scheme dependence of P_i
- P_5' and P_1 with reduced unc. if $\xi_\perp$ defined from V ($a_{V_+} = 0$)

Cross-checks: Form factors



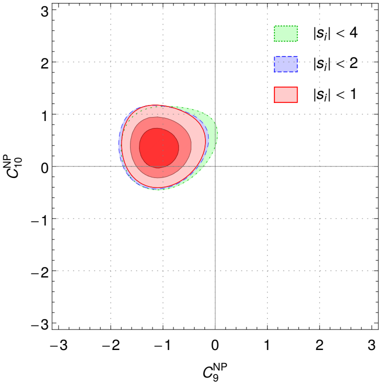
- Soft form factor approach ([Khodjamirian et al.] ff + EFT correls) vs full ff ([Altmannshofer, Straub] with [Bharucha et al.] ff with correls and small errors)
- Similar results using either P_i or S_i (if correlations of form factors taken into account through soft ff approach)

Cross-checks: Form factors and power corrs



- 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 P_i or S_i (if correlations of form factors taken into account through soft ff approach)
- Increasing power corrections weakens role of large recoil, but low recoil enough to pull fit away from the SM

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 a difference between $BR(B \to Kee)$ and $BR(B \to K\mu\mu)$

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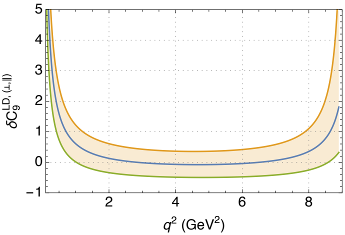
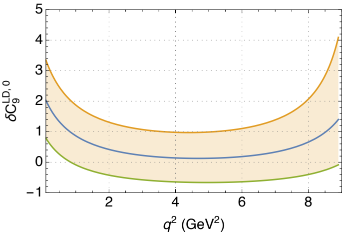
  - higher-order short-distance QCD via QCDF/HQET
- Long-distance (soft gluons)
  - $\Delta\mathcal{C}_9^{BK^{(*)},i} > 0$ $(i = 0, ||, \perp)$ using LCSR [Khodjamirian, Mannel, Pivovarov, Wang]
  - Computed for $q^2 < 0$ and small, then extrapolated through dispersion relation reincluding J/ψ (but many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

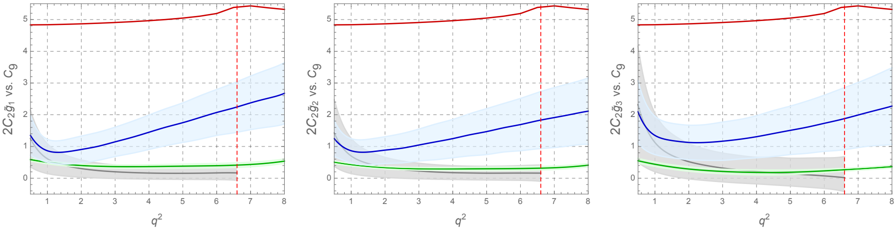
    taking $\Delta\mathcal{C}_9^{BK^*,i} = \delta\mathcal{C}_{9,\mathrm{SD}}^{BK^{(*)},i} + s_i\,\delta\mathcal{C}_{9,\mathrm{LD}}^{BK^{(*)},i}$ with $s_i = 0 \pm 1$





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

- $c\bar{c}$ contributions to 3 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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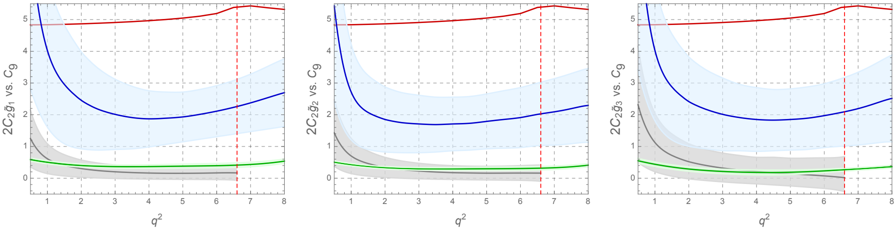

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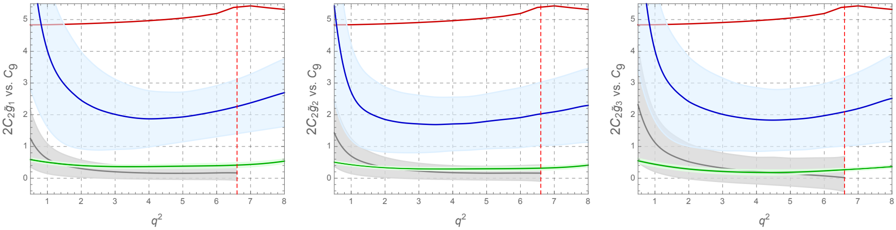

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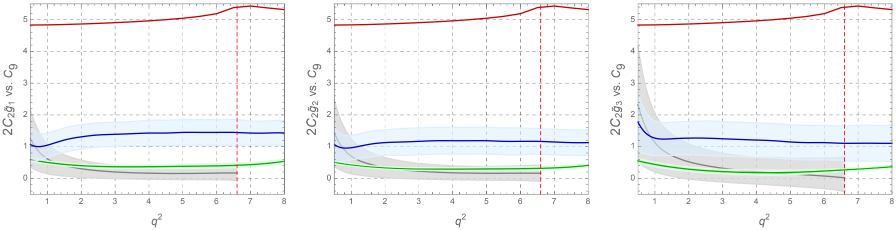
- constrained fit forced at low q^2, compensation skewing high q^2

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

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

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



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

- Bayesian fit without q^4 need same $\mathcal{C}_9^{\rm NP}$ in all three helicities
- Frequentist fits indicates no improvement by adding q^4 term, and adding $\mathcal{C}_9$ better pull than 12 independent coefficients

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

- 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 ?

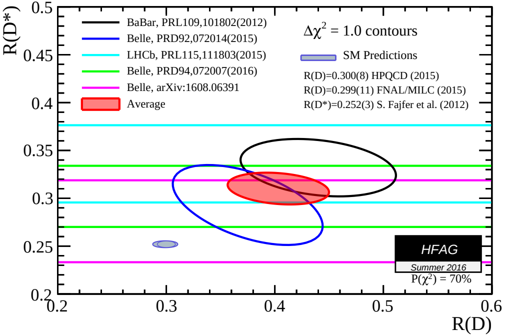
Adding furher coefficients

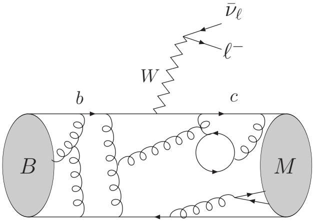
$$
\begin{aligned}
A^0_{L,R} &= A^0_{L,R}(s_i=0) + \frac{N}{q^2}\left(h_0^{(0)} + \frac{q^2}{1\ \mathrm{GeV}^2} h_0^{(1)} + \frac{q^4}{1\ \mathrm{GeV}^4} h_0^{(2)}\right), \\
A^{\parallel}_{L,R} &= A^{\parallel}_{L,R}(s_i=0) \\
&\quad + \frac{N}{\sqrt{2}q^2}\left[(h_+^{(0)} + h_-^{(0)}) + \frac{q^2}{1\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

- $s_i = 0$ means no estimate from long-distance $c\bar{c}$ estimate
- n order of the polynomial added
- Nested hypotheses: Pull from $\chi^{2(n-1)}_{\min} - \chi^{2(n)}_{\min}$ $(\chi^{2(-1)}_{\min}$ = 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)		

$b \to c\ell\bar{\nu}_\ell$: R_D and R_{D^*}





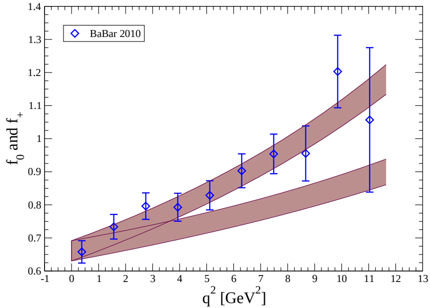
$$R_{D(*)} = \frac{Br(B \to D(^*)\tau\nu)}{Br(B \to D(^*)\ell\bar{\nu}_\ell)}$$

- different identification techniques of the τ for LHCb and B-factories
- $R(D)$ and $R(D^*)$ exceed SM predictions by 2.2 σ and 3.4 σ
- p-value=8.3×10^{-5}, difference with SM preds at 3.9σ level
- consistent with 15% enhancement for $b \to c\tau\bar{\nu}_\tau$

What is the basis for these predictions ?

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

$$\frac{d\Gamma(B \to D\ell\bar{\nu}_\ell)}{dq^2} \propto |V_{cb}|^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 |\vec{p}|^2$$
$$\left[\left(1 - \frac{m_\ell^2}{2q^2}\right)^2 M_B^2 |\vec{p}|^2 f_+^2(q^2) + \frac{3m_\ell^2}{8q^2}(M_B^2 + M_D^2)^2 f_0^2(q^2)\right]$$



- $\vec{p}$ D-momentum in B-frame, $q^2 = (p_B - p_D)^2$ lepton invariant mass
- Two form factors $f_+(q^2)$ (vector) and $f_0(q^2)$ (scalar)
  NP extension requires one more form factor f_T (tensor)
- From lattice QCD, extrapolated over whole kinematic range

[HPQCD, Fermilab/MILC collaboration]

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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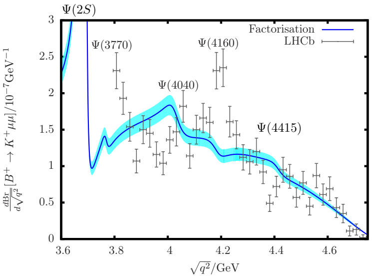

- Probably (?) effect of similar size for $B \to K^*\mu\mu$ (BR and angular obs.)
- OPE corrections + NLO QCD corrections + complex correction of 10% for each transversity amplitude
- Difficulties to explain $B \to K\ell\ell$ low-recoil spectrum using $\sigma(e^+e^- \to hadrons)$ and naive factorisation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

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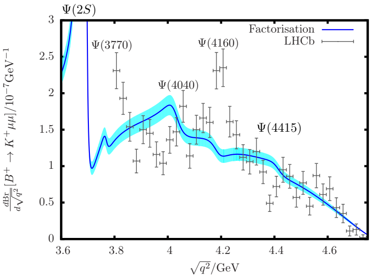

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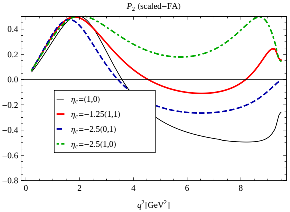
- Large recoil
  - $q^2 \leq$ 7-8 GeV^2 to limit the impact of J/ψ tail
  - Still need to include the effect of $c\bar{c}$ loop (tail of resonances + nonresonant)

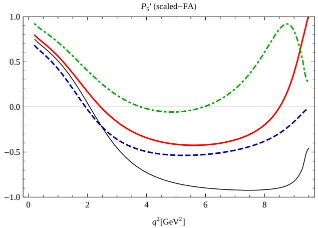
Charm-loop effects : resonances (2)

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 unexplained since it would affect identically $\ell = e, \mu$

$B \to D^*\ell\bar{\nu}_\ell$ branching ratio

$$\frac{d\Gamma(B \to D^*\ell\bar{\nu}_\ell)}{dq^2} \propto |V_{cb}|^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 |\vec{q}|q^2$$
$$\left[\left(1 + \frac{m_\ell^2}{2q^2}\right)^2 (|H_+|^2 + |H_-|^2 + |H_0|^2) + \frac{3m_\ell^2}{2q^2}|H_t|^2\right]$$

- H_λ describing $B \to D^*(\to D\pi)\ell\bar{\nu}_\ell$ with D^* helicity
- Interferences in principle accessible via angular analyses (but ν !)
- Four form factors $V, A_{0.1,2}$ (vector and axial)
  NP extension requires 3 more form factors $T_{1,2,3}$ (tensor)

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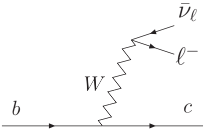
- No complete lattice determination, need other approaches !
  - HQET: Form factors related in the limit $m_b \to \infty$,
    providing ratios of form factors up to $O(\Lambda/m_B)$ corrections
  - Normalisation from Belle on $B \to D^*\ell\bar{\nu}_\ell$ ($\ell = e, \mu$)
    assuming no NP for light leptons

[Fajfer, Kamenik, Nisandzic]

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



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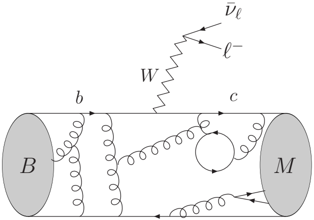

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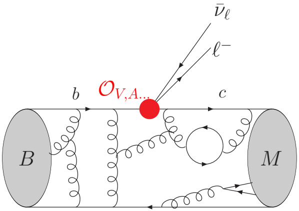

$\mathcal{H}^{\text{eff}}$ to determine short-distance couplings and look for NP model-independently

$$\mathcal{H}^{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \sum_{\ell=e,\mu,\tau} (\bar{\ell}\gamma^\mu P_L \nu_\ell)$$
$$\times[\bar{c}\gamma^\mu P_L b + g_{SL} i\partial^\mu(\bar{c}P_L b) + g_{SR} i\partial^\mu(\bar{c}P_R b)]$$

[with $P_{L,R} = (1 \mp \gamma_5)/2$]

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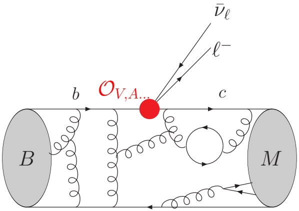

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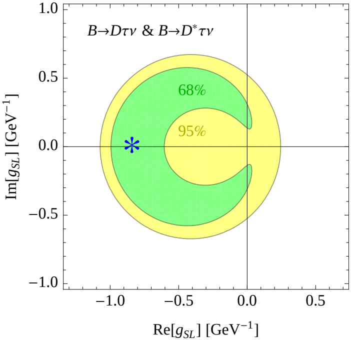

- Fit to R_D and R_{D^*} leading to viable explanation with scalar ops
- However only few observables measured (neutrino in final state)
- Improving on $B \to D^*$ form factors ?

[Fajfer, Kamenik, Nisandzic, Becirevic, Tayduganov, Pokorski, Crivellin, Freytsis, Ligeti, Ruderman. . .]