$B \to K^\star \mu\mu$ and other $b \to s\ell\ell$ transitions: a theory status report

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in collaboration with B. Capdevilla, L. Hofer, J. Matias, J. Virto

LAL Orsay, May 19th 2016

LPT Orsay

What's all that fuss about P_5' ?

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Outline

1. A few ideas around flavour physics
2. The observed anomalies in $b \to s\ell\ell$ decays
3. The conclusions of a global analysis
4. Assessing the nature of the anomalies
5. More observables to conclude

A Swiss knife for particle physics

Particle physics

Central question of QFT-based particle physics

$$\mathcal{L} = ?$$

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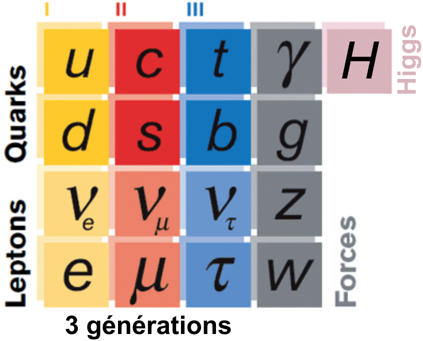
i.e. which degrees of freedom, symmetries, scales ?



SM best answer up to now, but

- neutrino masses
- dark matter
- dark energy
- baryon asymmetry of the universe
- hierarchy problem

$\Longrightarrow$3 generations playing a particular role in the SM

Why flavour ?

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j)$$

Gauge part $\mathcal{L}_{gauge}(A_a, \Psi_j)$

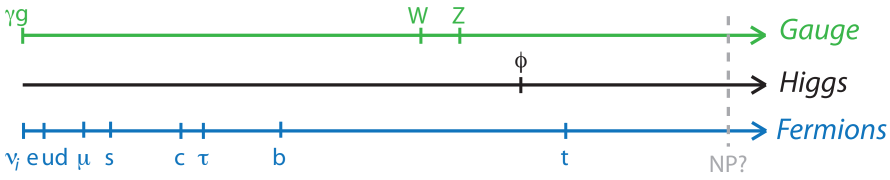
- Highly symmetric (gauge symmetry, flavour symmetry)
- Well-tested experimentally (electroweak precision tests)
- Stable with respect to quantum corrections

Higgs part $\mathcal{L}_{Higgs}(\phi, A_a, \Psi_j)$

- Ad hoc potential
- Dynamics not fully tested
- Not stable w.r.t quantum corrections
- Origin of flavour structure of the Standard Model

Flavour structure: Quark masses and CKM matrix from diagonalisation of Yukawa couplings after EWSB

Flavour parameters and SM



Important, unexplained hierarchy among 10 of 19 params of $SM_{m_\nu=0}$

- Mass (6 params, a lot of small ratios of scales)
- CP violation (4 params, strong hierarchy between generations)

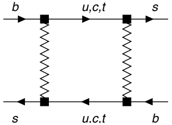
With interesting phenomenological consequences

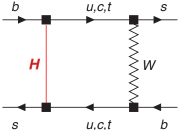
- Hierarchy of CP asymmetries according to generations
- Quantum sensitivity (via loops) to large range of scales
  within the Standard Model and beyond. . .
- GIM suppression of Flavour-Changing Neutral Currents

Flavour-Changing Neutral Currents

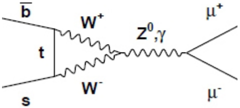
Forbidden in SM at tree level, and suppressed by GIM at one loop
so good place for NP to show up (tree or loops)

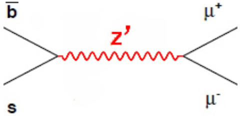
$\Delta F = 2$: B_s mixing





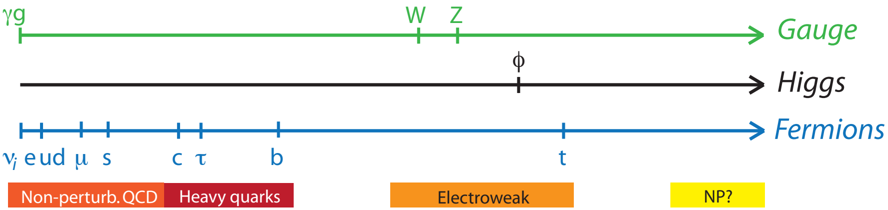
$\Delta F = 1$: $B_s \to \mu\mu$





Experimental and theoretical effort
on interesting FCNC transitions

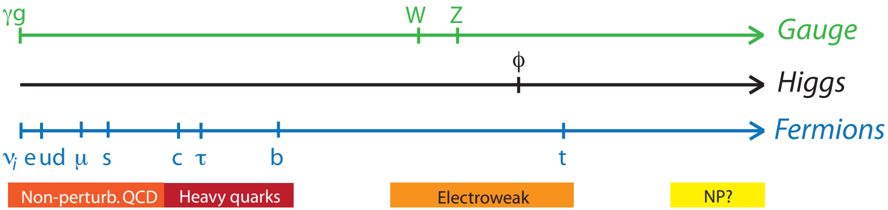
A multi-scale problem



- Tough multi-scale challenge with 3 interactions intertwined
- Several steps to separate/factorise scales

  BSM $\rightarrow$ SM+$1/\Lambda_{NP}$ ($\Lambda_{EW}/\Lambda_{NP}$) $\rightarrow \mathcal{H}_{eff}$ *(m_b/Λ_{EW})* $\rightarrow$ *eff. theories (Λ_{QCD}/m_b)*

A multi-scale problem



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- Main theo problem from hadronisation of quarks into hadrons:

  description/parametrisation in terms of QCD quantities

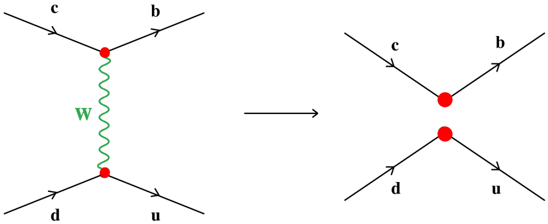
  decay constants, form factors, bag parameters...
- Long-distance non-perturbative QCD: source of uncertainties

  lattice QCD simulations, effective theories...

Effective approaches

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

- Short distances : numerical coefficients
- Long distances : local operator



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

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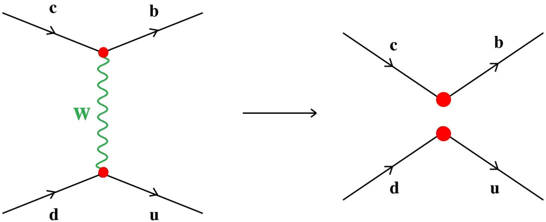


$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c + O(1/M_W^2)$$

Before/below SM, Fermi theory carried info on yesterday's NP (=EW)

- G_F: scale of NP physics
- $\mathcal{O}_i$: interaction with left-handed fermions, through charged spin 1
- Obviously not all info (gauge structure, Z^0 ...),

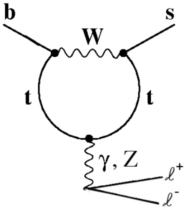
  but a good start if no new particle (= W) already seen

Radiative decays as seen by LHCb

Radiative decays

- $b \to s\gamma$ and $b \to s\ell^+\ell^-$ Flavour-Changing Neutral Currents
- enhanced sensitivity to New Physics effects
- analysed in model-independent approach effective Hamiltonian

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



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

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

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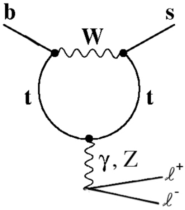

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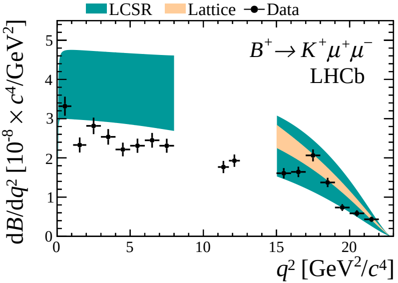
NP changes short-distance $\mathcal{C}_i$ for SM or new long-distance ops $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) — $\mathcal{O}_7 \to \mathcal{O}_{7'} \propto \bar{s}\sigma^{\mu\nu}(1-\gamma_5)F_{\mu\nu}\, b$
- (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 ($\gamma \to T$) — $\mathcal{O}_9 \to \mathcal{O}_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5)b\ \bar\ell\sigma_{\mu\nu}\ell$

Several deviations wrt SM: $B \to K\ell\ell$



- Simple kinematics: only branching ratio (decay probability into this channel) brings information
- $Br(B \to K\mu\mu)$ too low compared to SM

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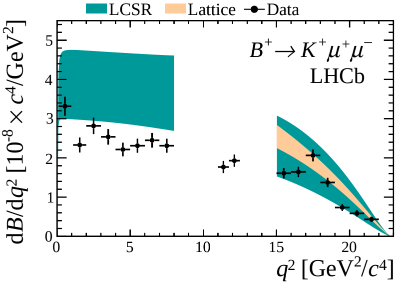

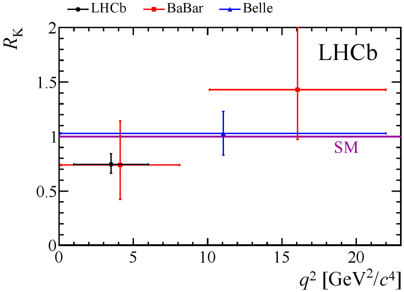

- Simple kinematics: only branching ratio (decay probability into this channel) brings information
- $Br(B \to K\mu\mu)$ too low compared to SM
- $R_K = \left.\frac{Br(B\to K\mu\mu)}{Br(B\to Kee)}\right|_{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$
- equals to 1 in SM (universality of lepton coupling)
- deviation cannot be mimicked by a hadronic effect
- would require NP coupling differently to μ and e

Several deviations wrt SM: branching ratios

$10^7 \times BR(B^0 \to K^0 \mu^+\mu^-)$	SM	LHCb	Pull
[0.1, 2]	0.62 ± 0.19	0.23 ± 0.11	+1.8
[2, 4]	0.65 ± 0.21	0.37 ± 0.11	+1.2
[4, 6]	0.64 ± 0.22	0.35 ± 0.10	+1.2
[6, 8]	0.63 ± 0.23	0.54 ± 0.12	+0.4
[15, 19]	0.91 ± 0.12	0.67 ± 0.12	+1.4

$10^7 \times BR(B^0 \to K^{*0} \mu^+\mu^-)$	SM	LHCb	Pull
[0.1, 2]	1.30 ± 1.00	1.14 ± 0.18	+0.2
[2, 4.3]	0.85 ± 0.59	0.69 ± 0.12	+0.3
[4.3, 8.68]	2.62 ± 4.92	2.15 ± 0.31	+0.1
[16, 19]	1.66 ± 0.15	1.23 ± 0.20	+1.7

$10^7 \times BR(B^+ \to K^{*+} \mu^+\mu^-)$	SM	LHCb	Pull
[0.1, 2]	1.35 ± 1.05	1.12 ± 0.27	+0.2
[2, 4]	0.80 ± 0.55	1.12 ± 0.32	−0.5
[4, 6]	0.95 ± 0.70	0.50 ± 0.20	+0.6
[6, 8]	1.17 ± 0.92	0.66 ± 0.22	+0.5
[15, 19]	2.59 ± 0.25	1.60 ± 0.32	+2.5

$10^7 \times BR(B_s \to \phi \mu^+\mu^-)$	SM	LHCb	Pull
[0.1, 2.]	1.81 ± 0.36	1.11 ± 0.16	+1.8
[2., 5.]	1.88 ± 0.32	0.77 ± 0.14	+3.2
[5., 8.]	2.25 ± 0.41	0.96 ± 0.15	+2.9
[15, 18.8]	2.20 ± 0.17	1.62 ± 0.20	+2.2

Interesting pattern of deviations

- Different exclusive modes
- Different type of observables (angular versus BR)

Several deviations wrt SM: $B \to K^* \mu\mu$

- $B \to K^* \mu\mu$: rich kinematics, providing many observables
- Optimised observables P_i with reduced hadronic uncertainties

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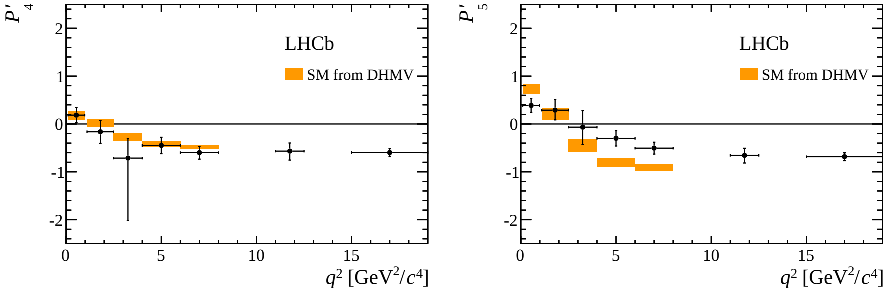
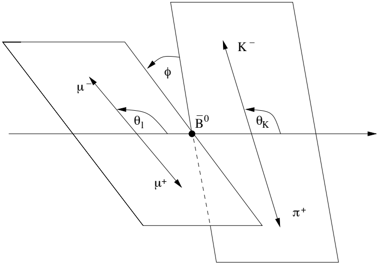


- Measured at LHCb with 1 fb^{-1} (2013) and 3 fb^{-1} (2015)
- Discrepancies for some (but not all) observables
- Two bins for P'_5 deviating from SM by 2.9 σ each
- Deviation for P_2 at 1 fb^{-1} but hidden by stat fluct of F_L at 3 fb^{-1}

$B \to K^*\ell\ell$: angular analysis



- Three angles $\theta_\ell, \theta_K, \phi$
- q^2 dilepton invariant mass

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi} = \sum_i f_i(\theta_K, \phi, \theta_l) \times J_i$$

12 angular coeffs J_i, interferences of 2 between 8 transversity ampl.

- $\perp, ||, 0, t$ polarisation of (real) K^* and (virtual) $V^* = \gamma^*, Z^*$
- L, R chirality of $\mu^+\mu^-$ pair [Zwicky, Gratrex, Hopfer, Becirevic, Sumensari, Zukanovic-Funchal]

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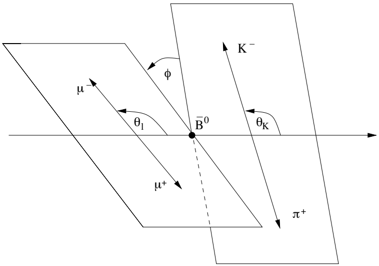

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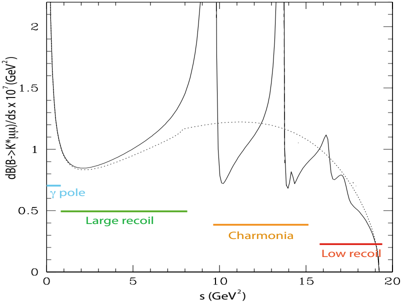
Transversity ampl. $A_{\perp,L/R}$, $A_{||,L/R}$, $A_{0,L/R}$, A_t + scalar A_s depend on

- q^2 (lepton pair invariant mass)
- Short-dist $C_7, C_9, C_{10}, \ldots$
- Long-dist $B \to K^*$ form factors $A_{0,1,2}$, V, $T_{1,2,3}$ from $\langle K^*|Q_i|B\rangle$

Four different regions



- Very large K^*-recoil ($4m_\ell^2 < q^2 < 1$ GeV^2): γ almost real

  C_7/q^2 divergence and light resonances

- Large K^*-recoil ($q^2 < 9$ GeV^2): energetic K^* ($E_{K^*} \gg \Lambda_{QCD}$)

  Form factors from light-cone sum rules LCSR

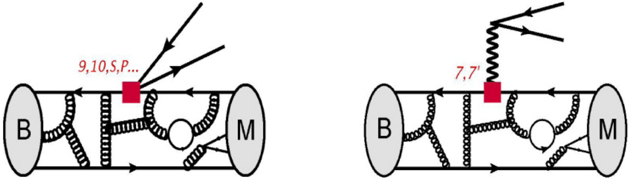
  Large Energy Eff Th, QCD factorisation, Soft-Collinear Eff Th

- 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^* $E_{K^*} \simeq \Lambda_{QCD}$

  Form factors lattice QCD; Operator Product Exp, Heavy Quark Eff. Th.

Form factors

7 independent form factors $A_{0,1,2}$, V $(O_{9,10})$ and $T_{1,2,3}$ (O_7)



In the limits of low and large K^* recoil, separation of scales Λ and m_B

- Large-recoil limit ($\sqrt{q^2} \sim \Lambda_{QCD} \ll m_B$) [LEET/SCET, QCDF]
  - two soft form factors $\xi_\perp(q^2)$ and $\xi_{||}(q^2)$
  - $O(\alpha_s)$ corr. from hard gluons [computable], $O(\Lambda/m_B)$ [nonpert]

[Charles et al., Beneke and Feldmann]

- Low-recoil limit ($E_{K^*} \sim \Lambda_{QCD} \ll m_B$) [OPE, HQET]
  - three soft form factors $f_\perp(q^2)$, $f_{||}(q^2)$, $f_0(q^2)$
  - $O(\alpha_s)$ corr. from hard gluons [computable] and $O(\Lambda/m_B)$ [nonpert]

[Grinstein and Pirjol, Hiller, Bobeth, Van Dyk. . .]

Optimised observables

= Obs. where soft form factors cancel at LO in Λ/m_b and α_s

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- For instance, transversity asymmetry [Krüger, Matias; Becirevic, Schneider]

$$P_1 = A_T^{(2)} = \frac{J_3}{2J_{2s}} = \frac{|A_\perp|^2_{L+R} - |A_{||}|^2_{L+R}}{|A_\perp|^2_{L+R} + |A_{||}|^2_{L+R}},$$

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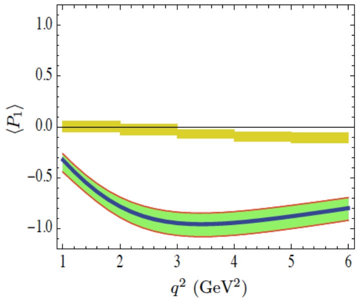

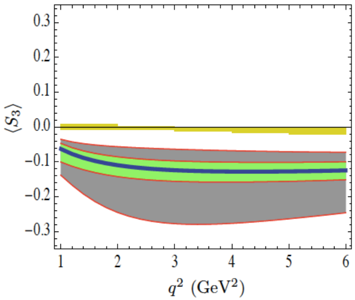

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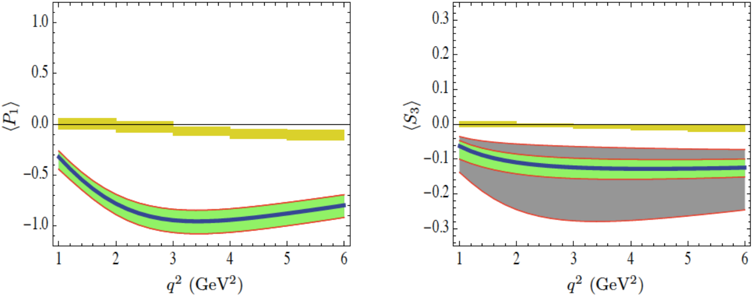
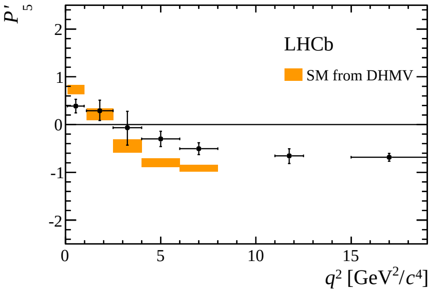


- 6 optimised observables at large recoil (P_1, P_2, P_3, P_4', P_5', P_6')
  + 2 form-factor dependent obs. (Γ, A_{FB}, F_L...)
  exhausting information in (partially redundant) angular coeffs J_i

[Matias, Krüger, Mescia, SDG, Virto, Hiller, Bobeth, Dyck, Buras, Altmanshoffer, Straub...]

Focus on P'_5

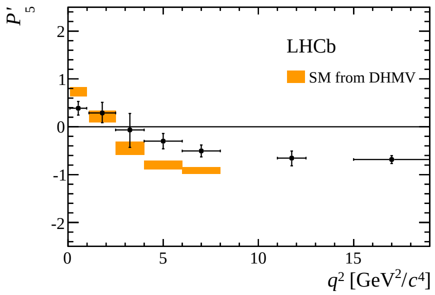


$A^{\ell\ell}_{K^*}$ $\begin{matrix}\text{chirality}\\ \text{transversity}\end{matrix}$ interfering in J_i

$$P'_5 = \frac{J_5}{2\sqrt{-J_{2c}J_{2s}}} = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_{||}|^2)}}$$

[SDG, Matias, Ramon, Virto]

Focus on P'_5



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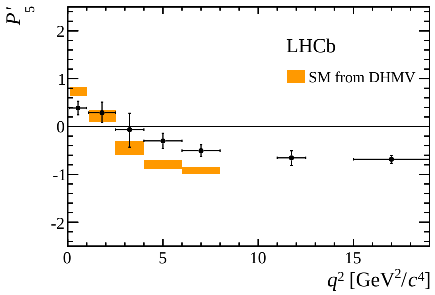
[SDG, Matias, Ramon, Virto]

In large recoil limit with no right-handed current

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

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

Focus on P_5'



$A_{K^*}^{\ell\ell}$ chirality transversity interfering in J_i

$$P_5' = \frac{J_5}{2\sqrt{-J_{2c}J_{2s}}} = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_{||}|^2)}}$$

[SDG, Matias, Ramon, Virto]

In large recoil limit with no right-handed current

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

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

- In SM, $\mathcal{C}_9 \simeq -\mathcal{C}_{10} > 0$ 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

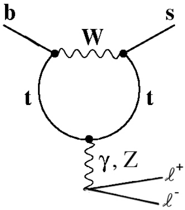
A more global viewpoint

Why a global analysis

Global analysis needed

- eff Hamiltonian adapted for a global model-independent analysis
- identify universal short-distance contributions
- cross-checks to confirm estimates of hadronic uncertainties

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



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

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

Global analysis of $b \to s\ell\ell$ 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)
- $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B_s \to \mu\mu$
- $B \to K^*\gamma$ (A_I and $S_{K^*\gamma}$)

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Frequentist analysis

- $C_i(\mu_{ref}) = C_i^{SM} + C_i^{NP}$, with C_i^{NP} assumed to be real
- Use optimised observables (P_i) whenever possible
- Experimental correlation matrix
  - provided experimentally ($B \to K(^*)$)
  - obtained by error propagation from J_i ($B_s \to \phi$)
- Theoretical correlation matrix treating all theo errors (form factors. . .) as Gaussian random variables
- Various hypotheses "NP in some $\mathcal{C}_i$ only" to be compared with SM

$b \to s\mu\mu$: 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 ?)

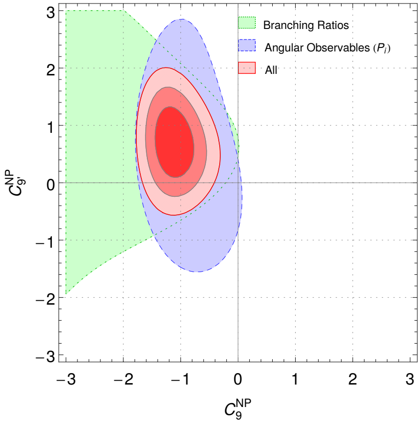
Coefficient	Best Fit Point	3σ	$\mathrm{Pull}_{\mathrm{SM}}$	p-value (%)
SM	–	–	–	16.0
$\mathcal{C}_7^{\mathrm{NP}}$	-0.02	$[-0.07, 0.03]$	1.2	17.0
$\mathcal{C}_9^{\mathrm{NP}}$	-1.09	$[-1.67, -0.39]$	4.5	63.0
$\mathcal{C}_{10}^{\mathrm{NP}}$	0.56	$[-0.12, 1.36]$	2.5	25.0
$\mathcal{C}_9^{\mathrm{NP}} = \mathcal{C}_{10}^{\mathrm{NP}}$	-0.22	$[-0.74, 0.50]$	1.1	16.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{10}^{\mathrm{NP}}$	-0.68	$[-1.22, -0.18]$	4.2	56.0
$\mathcal{C}_{9'}^{\mathrm{NP}} = \mathcal{C}_{10'}^{\mathrm{NP}}$	-0.07	$[-0.86, 0.68]$	0.3	14.0
$\mathcal{C}_{9'}^{\mathrm{NP}} = -\mathcal{C}_{10'}^{\mathrm{NP}}$	0.19	$[-0.17, 0.55]$	1.6	18.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{9'}^{\mathrm{NP}}$	-1.06	$[-1.60, -0.40]$	4.8	72.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{10}^{\mathrm{NP}} = -\mathcal{C}_{9'}^{\mathrm{NP}} = -\mathcal{C}_{10'}^{\mathrm{NP}}$	-0.69	$[-1.37, -0.16]$	4.1	53.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{10}^{\mathrm{NP}} = \mathcal{C}_{9'}^{\mathrm{NP}} = -\mathcal{C}_{10'}^{\mathrm{NP}}$	-0.19	$[-0.55, 0.15]$	1.7	19.0

$b \to s\mu\mu$: 2D hypotheses

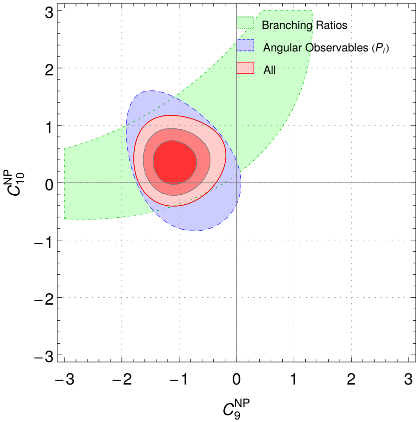
- Pull for the SM point in each scenario from $\chi^2_{\rm min} - \chi^2(\mathcal{C}_i = \mathcal{C}_j = 0)$
- p-value from $\chi^2_{\rm min}$ and N_{dof}
- several favoured scenarios, all with $\mathcal{C}_9^{\rm NP}$, hard to single out one

Coefficient	Best Fit Point	$\mathrm{Pull_{SM}}$	p-value (%)
SM	–	–	16.0
$(\mathcal{C}_7^{\rm NP}, \mathcal{C}_9^{\rm NP})$	$(-0.00, -1.07)$	4.1	61.0
$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{10}^{\rm NP})$	$(-1.08, 0.33)$	4.3	67.0
$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{7'}^{\rm NP})$	$(-1.09, 0.02)$	4.2	63.0
$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{9'}^{\rm NP})$	$(-1.12, 0.77)$	4.5	72.0
$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{10'}^{\rm NP})$	$(-1.17, -0.35)$	4.5	71.0
$(\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}, \mathcal{C}_{10}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP})$	$(-1.15, 0.34)$	4.7	75.0
$(\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}, \mathcal{C}_{10}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP})$	$(-1.06, 0.06)$	4.4	70.0
$(\mathcal{C}_9^{\rm NP} = \mathcal{C}_{9'}^{\rm NP}, \mathcal{C}_{10}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP})$	$(-0.64, -0.21)$	3.9	55.0
$(\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}, \mathcal{C}_{9'}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP})$	$(-0.72, 0.29)$	3.8	53.0

Some favoured scenarios (1)

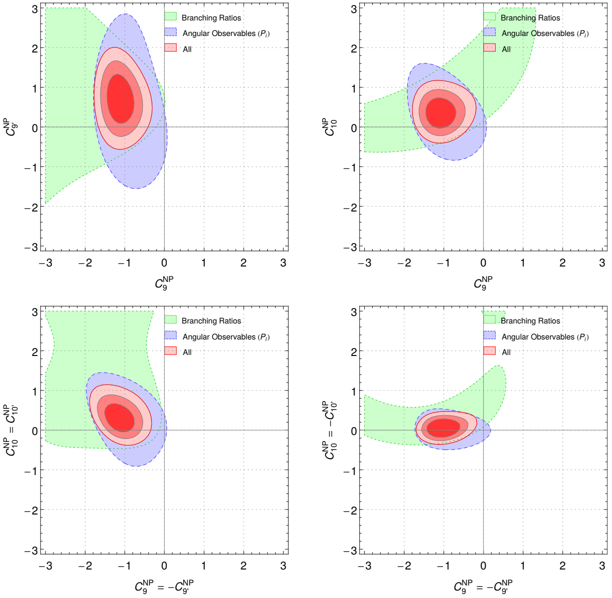


$\mathcal{C}_9^{NP}, \mathcal{C}_{9'}^{NP}$



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

Some favoured scenarios (2)



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

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

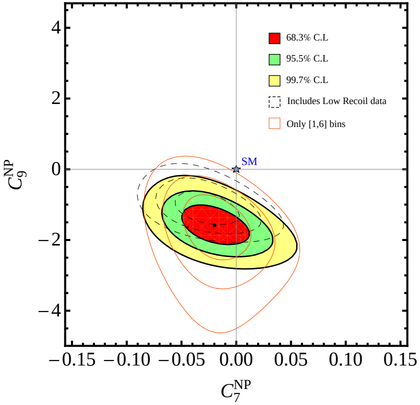
Letting all 6 Wilson coefficients vary (but only real)

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

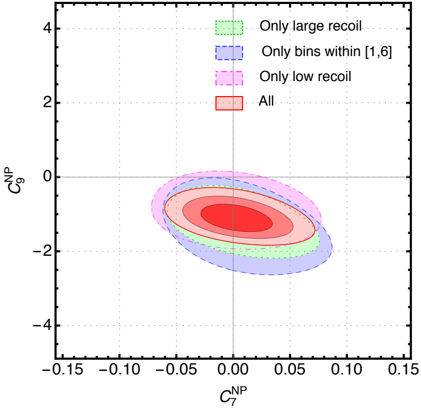
- $\mathcal{C}_9$ is consistent with SM only above 3σ
- All others are consistent with zero at 1σ except for $\mathcal{C}_{9'}$ at 2 σ
- Pull_{SM} for the 6D fit is 3.6σ

From 2013 to 2016

Many improvements from experiment and theory, but…



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



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

A few recent analyses

	[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 $B \to K^*\mu\mu$ 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	[-1.29,-0.87]	[-1.54,-0.53]	[-0.27,-0.13]
pull$_{SM}$	4.5 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

$$\mathcal{C}_9^{\text{NP}}\ldots$$

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

?

QCD or BSM ?

Anomalies can be a sign from many things

- unlucky statistical fluctuations
- underestimated syst in the experimental analysis
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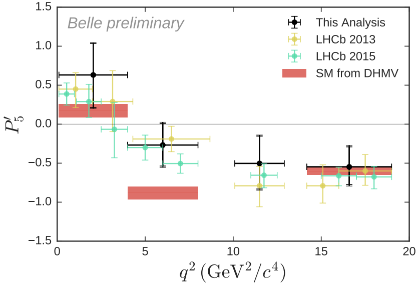

- Belle news: not a stat fluctuation/exp pb in P_5'

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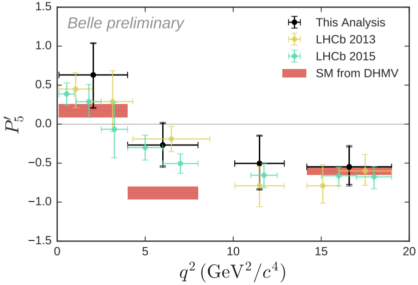
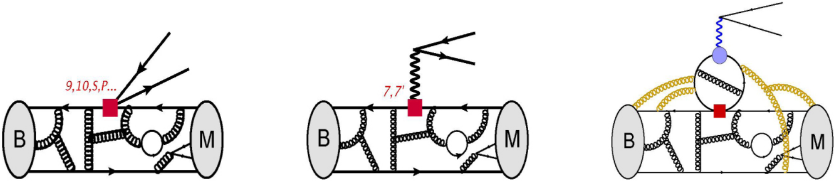


- Belle news: not a stat fluctuation/exp pb in P_5'
- Cross-checks for theory (deviations from exclusive)
  - Framework used for computations
  - Hadronic inputs: form factors, charm contribution
  - Additional observables

Amplitudes for exclusive decays

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



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

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

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

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

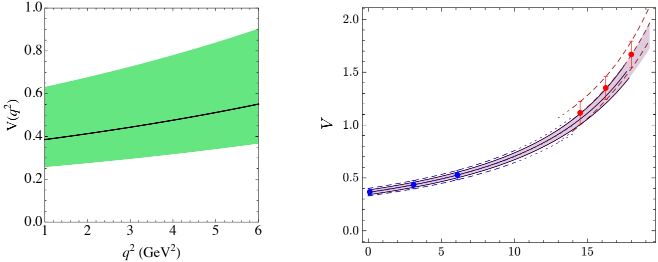
$$T_\mu = -\frac{16 i \pi^2}{q^2} \sum_{i=1\ldots6,8} \mathcal{C}_i \int d^4x\, e^{iqx} \langle V_\lambda | T[J_\mu^{em}(x) \mathcal{O}_i(0)] | B\rangle$$

same structure as $\mathcal{O}_9$, but depends on q^2 and external states

Form factors

- low recoil: lattice, with correlations [Horgan, Liu, Meinel, Wingate]
- large recoil: B-meson LCSR, large error bars and no correlations

  [Khodjamirian, Mannel, Pivovarov, Wang]
- all: fit light-meson LCSR + lattice, small errors bars and correlations [to be updated] [Bharucha, Straub, Zwicky]



KMPW (LCSR, low q^2) BSZ (fit LCSR + lattice)

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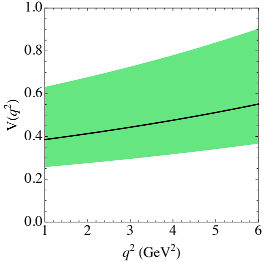

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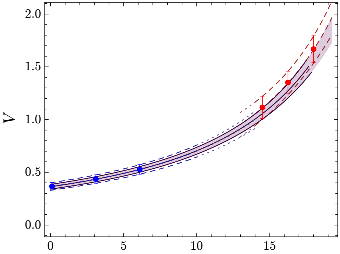

BSZ (fit LCSR + lattice)

Dominant correls among ffs from large-recoil, heavy quark limit

$$\xi_\perp = \frac{m_B}{m_B + m_{K*}} V = \frac{m_B + m_{K*}}{2E_{K*}} A_1 = T_1 = \frac{m_B}{2E_{K*}} T_2$$

$$\xi_{||} = \frac{m_{K*}}{E_{K*}} A_0 = \frac{m_B + m_{K*}}{2E_{K*}} - \frac{m_B - m_{K*}}{m_B} A_2 = \frac{m_B}{2E_{K*}} T_2 - T_3$$

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 $\Delta V^\Lambda = O(\Lambda/m_B)$
  - Extract soft form factors + (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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  - $B \to V\ell\ell$ from soft form factors + hard gluons + power corrections
- 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)

Correlating form factors

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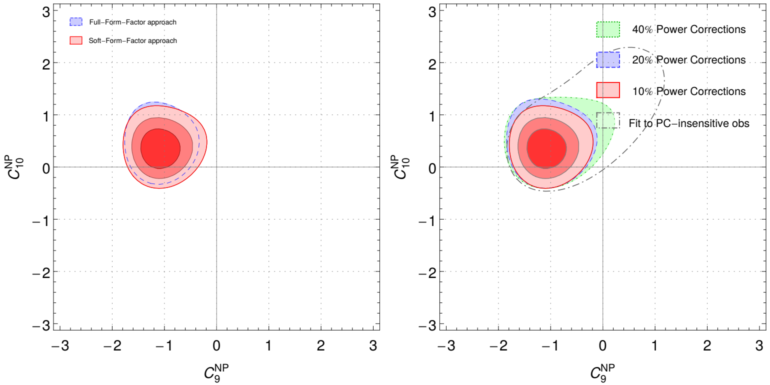
Choice of observables

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

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

Controversies: Form factors and power corrs (1)

Large (uncontrolled) effect of factorisable power corrs ? [Camalich, Jäger]

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

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1. Particular choice of scheme to define $\xi_{||,\perp}$

$$\xi_\perp^{(1)} = \frac{m_B}{m_B + m_K^*} V \quad \xi_{||}^{(1)} = \frac{m_B + m_K^*}{2E} A_1 - \frac{m_B - m_{K^*}}{m_B} A_2 \qquad \xi_\perp^{(2)} = T_1 \quad \xi_{||}^{(2)} = \frac{m_K^*}{E} A_0$$

   - Irrelevant if all correlations known and kept among form factors
   - Important if relevant form factors V, A_1, A_2 reconstructed from $\xi_{\perp,||}$ + (estimated) power corrections, adding further uncertainties

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   - Irrelevant if all correlations known and kept among form factors
   - Important if relevant form factors V, A_1, A_2 reconstructed from $\xi_{\perp,||}$ + (estimated) power corrections, adding further uncertainties
2. Choice of form factors
   - Spread of central values (LCSR, Dyson-Schwinger. . .) ignoring uncertainties, and input from $B \to K^*\gamma$: $\xi_\perp(0) = 0.31 \pm 0.04$
   - One determination with large uncert. (KMPW): $\xi_\perp(0) = 0.31^{+0.20}_{-0.10}$

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Large (uncontrolled) effect of factorisable power corrs ? [Camalich, Jäger]

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

1. Particular choice of scheme to define $\xi_{||,\perp}$

$$\xi_\perp^{(1)} = \frac{m_B}{m_B + m_K^*} V \quad \xi_{||}^{(1)} = \frac{m_B + m_K^*}{2E} A_1 - \frac{m_B - m_{K^*}}{m_B} A_2 \qquad \xi_\perp^{(2)} = T_1 \quad \xi_{||}^{(2)} = \frac{m_K^*}{E} A_0$$

   - Irrelevant if all correlations known and kept among form factors
   - Important if relevant form factors V, A_1, A_2 reconstructed from $\xi_{\perp,||}$ + (estimated) power corrections, adding further uncertainties

2. Choice of form factors
   - Spread of central values (LCSR, Dyson-Schwinger...) ignoring uncertainties, and input from $B \to K^*\gamma$: $\xi_\perp(0) = 0.31 \pm 0.04$
   - One determination with large uncert. (KMPW): $\xi_\perp(0) = 0.31^{+0.20}_{-0.10}$

3. Estimate of power corrections
   - 10% of full form factors
   - central values = 0 or set to recover central values of full form factors

Controversies: Form factors and power corrs (2)

Large (uncontrolled) effect of factorisable power corrs ? [Camalich, Jäger]

1. Scheme to define $\xi_{||,\perp}$
   potential overestimation of impact power corrections
2. Choice of form factors
   potential underestimation of soft form factor uncertainties
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   potential disagreement with current form factor estimates

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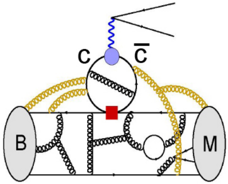
Form factors	Approach	ξ scheme	$P_5'[4,6]$	$F_L[0.1, 0.98]$
KMPW	Soft ff	1	± 0.08	± 0.25
BSZ	Full ff	None	± 0.07	± 0.06
CJ	Soft ff	2	± 0.35	± 0.18

Hadronic uncertainties should cancel more efficiently in P_5' than F_L...

Charm-loop effects: resonances

- Low recoil: quark-hadron duality
  - OPE: quark level = hadron level, if average over "enough" resonances
  - Model estimate yield a few % for $BR(B \to K\mu\mu)$ [Beylich, Buchalla, Feldmann]



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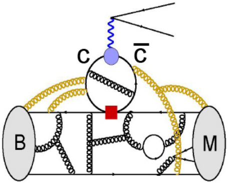

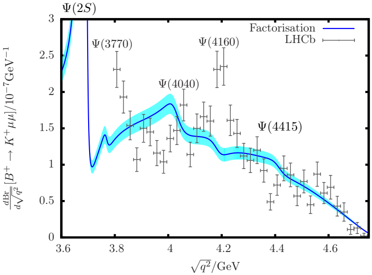

- $B \to K\ell\ell$ resonance spectrum challenging (not recovered from $\sigma(e^+e^- \to hadrons)$ and naive factorisation) [Lyon, Zwicky]
- We take OPE and NLO QCD corrections + complex correction of 10% for each transversity amplitude

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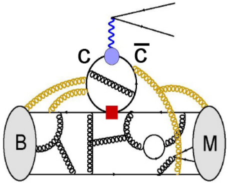

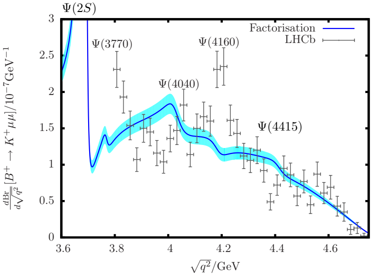

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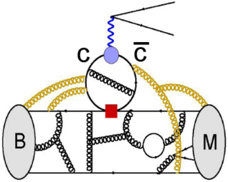
- We take OPE and NLO QCD corrections + complex correction of 10% for each transversity amplitude

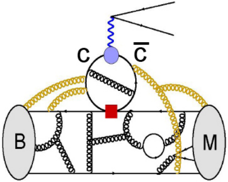
- Large recoil: smoother q^2 behaviour
  - $q^2 \leq$ 7-8 GeV^2 to limit the impact of J/ψ tail
  - Need to include effects of $c\bar{c}$ loop (resonance tail + nonresonant)

Charm-loop effects: large recoil



- Short-distance (hard gluons)
  - $\mathcal{C}_9 \to \mathcal{C}_9 + \delta\mathcal{C}_{9,\mathrm{SD}}^{BK(*)}(q^2)$
  - higher-order short distances via QCD fact

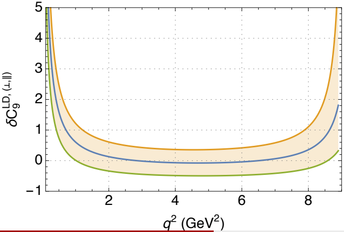
Charm-loop effects: large recoil

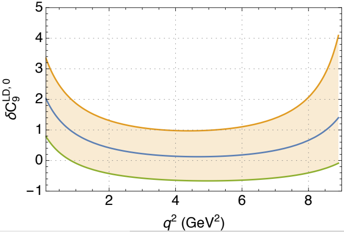


- Short-distance (hard gluons)
  - $\mathcal{C}_9 \to \mathcal{C}_9 + \delta\mathcal{C}_{9,\rm SD}^{BK^{(*)}}(q^2)$
  - higher-order short distances via QCD fact
- Long-distance (soft gluons)
  - $\Delta\mathcal{C}_9^{BK^{(*)},i} > 0$ ($i = 0, ||, \perp$) using LCSR at $q^2 \simeq 0$, extrapoled with dispersion relation reincluding J/ψ (but many unknown parameters)

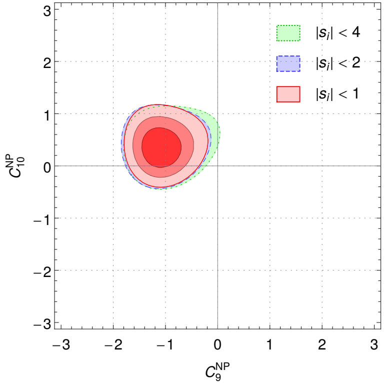
    [Khodjamirian, Mannel, Pivovarov, Wang]
  - We split $\Delta\mathcal{C}_9^{BK^*,i}\Big|_{KMPW} = \delta\mathcal{C}_{9,\rm SD}^{BK^{(*)},i} + \delta\mathcal{C}_{9,\rm LD}^{BK^{(*)},i}$

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





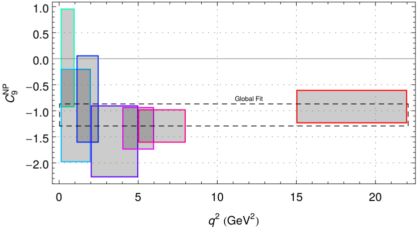
Cross-checks: Charm-loop dependence



- 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 $BR(B \to K\mu\mu)$

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



- $\mathcal{C}_9^{NP}$ bin by bin assuming NP in $\mathcal{C}_9^{NP}$, $\mathcal{C}_9^{NP} = -\mathcal{C}_{9'}^{NP}$ or $\mathcal{C}_9^{NP} = -\mathcal{C}_{10}^{NP}$

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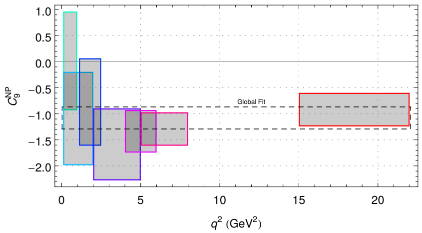

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- Up: Assuming shift in $\mathcal{C}_9$ only tests need for hadronic contrib:
  - NP in $\mathcal{C}_9$ from short distances, q^2-independent
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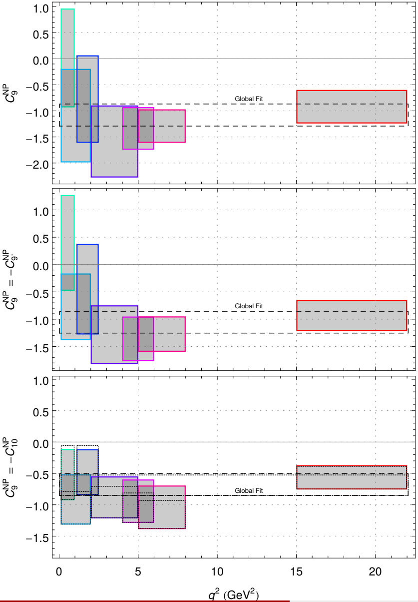

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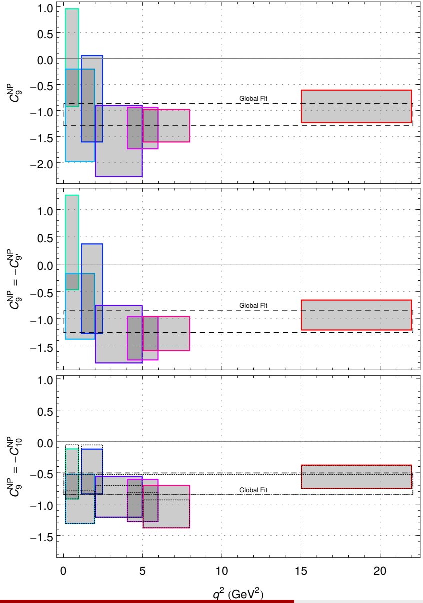

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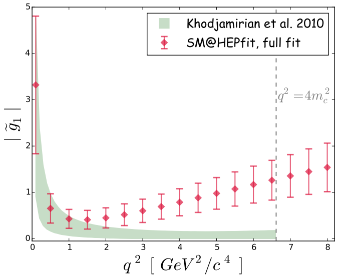
- Mid, down: correlated shift in $\mathcal{C}_9$ and other $\mathcal{C}_i$ (never q^2-depend: are NP scenarios consistent ?)
- No indication of q^2-dependent contribution

Controversies: charm-loop contribution

$c\bar{c}$ contributions to helicity ampl g_i as q^2-polynomial, extracting params from Bayesian to data "fit" [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]



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

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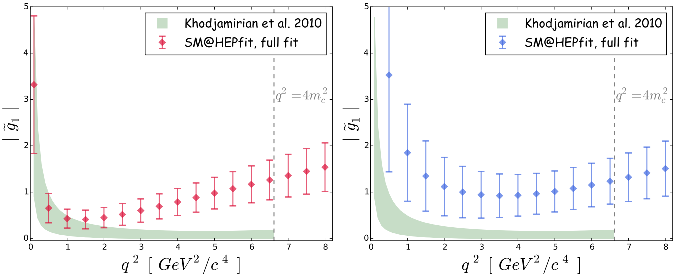

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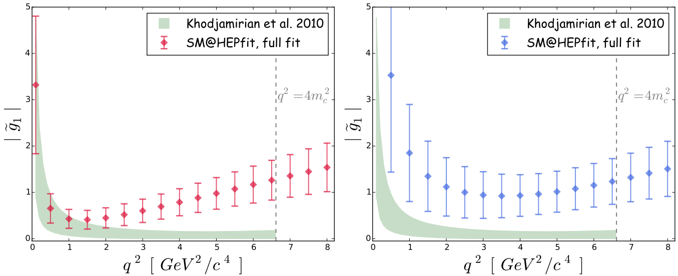

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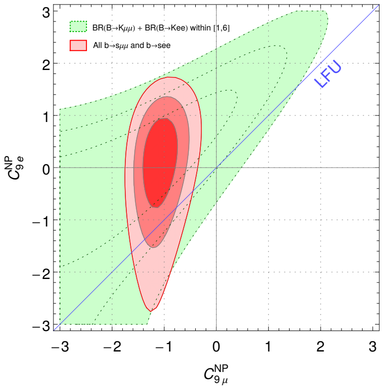
- no explanation for R_K or deviations in low-recoil BRs
- data on $B \to K^* \mu\mu$ to fix q^2-polynomial before any prediction

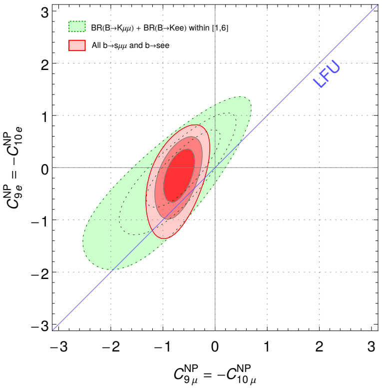
Looking for more inputs

Lepton-flavour (non) universality

- Include LHCb $BR(B \to Kee)$ and large-recoil obs for $B \to K^* ee$
- For several favoured scenarios, SM pull increases by $\sim 0.5\sigma$
  (but not $\mathcal{C}_9^{NP} = -\mathcal{C}_{9'}^{NP}$ which does not explain R_K)



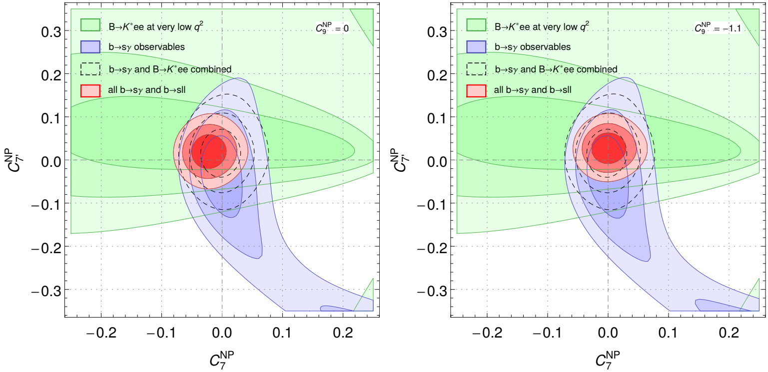
$\mathcal{C}_{9e}^{NP}, \mathcal{C}_{9\mu}^{NP}$



$\mathcal{C}_{9e}^{NP} = -\mathcal{C}_{10e}^{NP}, \mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}$

- Favours violation of LFU, compatible with no NP in $b \to see$

$\mathcal{C}_7, \mathcal{C}_{7'}$ from very low q^2 data



- $b \to s\gamma$ (blue) and $B \to K^* ee$ (green) at very low q^2 (near photon pole) sensitive to $\mathcal{C}_7$ and $\mathcal{C}_{7'}$ only
- fit in good agreement with global fit result
- results independent of $\mathcal{C}_9$: SM (left) or $\mathcal{C}_9^{NP} = -1.1$ (right)

Anomaly patterns

		R_K	$\langle P_5' \rangle_{[4,6],[6,8]}$	$BR(B_s \to \phi\mu\mu)$	low recoil BR	Best fit now
$\mathcal{C}_9^{\text{NP}}$	$+$					
	$-$	✓	✓	✓	✓	X
$\mathcal{C}_{10}^{\text{NP}}$	$+$	✓		✓	✓	X
	$-$		✓			
$\mathcal{C}_{9'}^{\text{NP}}$	$+$			✓	✓	X
	$-$	✓	✓			
$\mathcal{C}_{10'}^{\text{NP}}$	$+$	✓	✓			
	$-$			✓	✓	X

- $\mathcal{C}_9^{\text{NP}} < 0$ consistent with all anomalies
- no consistent and global alternative from long-dist dynamics
  - R_K (stat fluct, exp issues with e vs μ)
  - P_5' ($c\bar{c}$ contrib, power corrections)
  - $BR(B_s \to \phi\mu\mu)$ ($c\bar{c}$ contrib, form factors)
  - low-recoil $BR(B \to M\mu\mu)$ (lattice, duality violation)
- lower sensitivity to other $\mathcal{C}_i$ (cannot be mimicked by long distances), with $\mathcal{C}_{10}$ most promising but no consistent picture yet

NP interpretations

SM explanations seem contrived

- 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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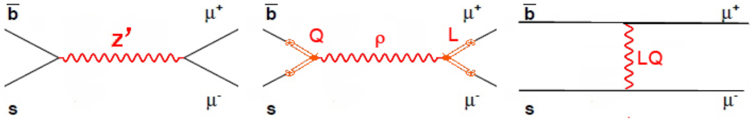
NP models with new scale around TeV

often trying to connect with $B \to D(^*)\ell\nu$ anomalies

- Z' boson (larger gauge group, e..g, $SU_C(3) \otimes SU_L(3) \otimes U_Y(1)$)
- Partial compositeness (mixing between known and extra fermions transforming under $SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U_Y(1)$)
- Leptoquarks (coupling to a quark and a lepton, like $(3, 2, 1/6)$)
- MSSM susy definitely not favoured ...



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

Additional observables: R's

	$R_K[1,6]$	$R_{K^*}[1.1,6]$		$R_\phi[1.1,6]$
SM	1.00 ± 0.01	1.00 ± 0.01	$[1.00 \pm 0.01]$	1.00 ± 0.01
$\mathcal{C}_9^{\rm NP} = -1.11$	0.79 ± 0.01	0.87 ± 0.08	$[0.84 \pm 0.02]$	0.84 ± 0.02
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP} = -1.09$	1.00 ± 0.01	0.79 ± 0.14	$[0.74 \pm 0.04]$	0.74 ± 0.03
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP} = -0.69$	0.67 ± 0.01	0.71 ± 0.03	$[0.69 \pm 0.01]$	0.69 ± 0.01
$\mathcal{C}_9^{\rm NP} = -1.15, \mathcal{C}_{9'}^{\rm NP} = 0.77$	0.91 ± 0.01	0.80 ± 0.12	$[0.76 \pm 0.03]$	0.76 ± 0.03
$\mathcal{C}_9^{\rm NP} = -1.16, \mathcal{C}_{10}^{\rm NP} = 0.35$	0.71 ± 0.01	0.78 ± 0.07	$[0.75 \pm 0.02]$	0.76 ± 0.01
$\mathcal{C}_9^{\rm NP} = -1.23, \mathcal{C}_{10'}^{\rm NP} = -0.38$	0.87 ± 0.01	0.79 ± 0.11	$[0.75 \pm 0.02]$	0.76 ± 0.02
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP} = -1.14$, $\mathcal{C}_{10}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP} = 0.04$	1.00 ± 0.01	0.78 ± 0.13	$[0.74 \pm 0.04]$	0.74 ± 0.03
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP} = -1.17$, $\mathcal{C}_{10}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP} = 0.26$	0.88 ± 0.01	0.76 ± 0.12	$[0.71 \pm 0.04]$	0.71 ± 0.03

- $R_M = BR(B \to Mee)/BR(B \to M\mu\mu)$ clean probes of NP [Hiller, Schmalz]
- 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
- [Bharucha, Straub, Zwicky] ff in brackets compared to our default set

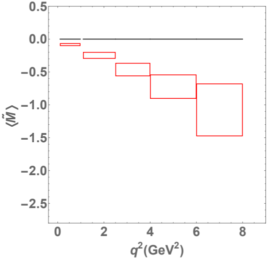
Additional observables: Q_i, B_i, M

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

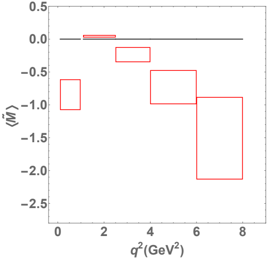
- Null SM tests (up to m_ℓ effects): $Q_i = P_i^\mu - P_i^e$, $\quad B_i = \frac{J_i^\mu}{J_i^e} - 1$
- J_5 and J_{6s} with only a linear dependence on $\mathcal{C}_9$

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

  - cancellation of hadronic contribs in $\mathcal{C}_9$ in some NP scenarios
  - different sensitivity to NP scenarios compared to R_{K*}

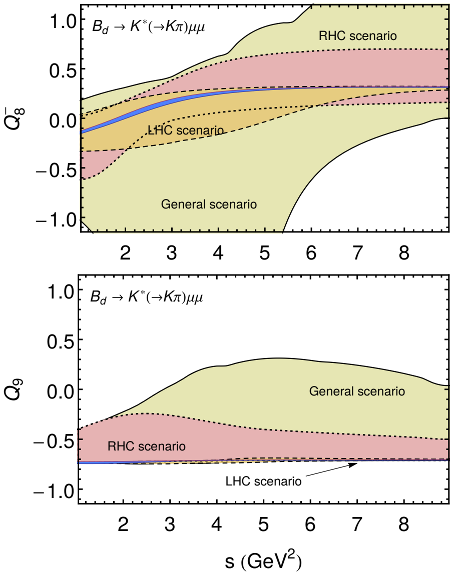


$\mathcal{C}_{9\mu}^{\rm NP} = -1.1, \mathcal{C}_{ie}^{\rm NP} = 0$



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

Additional obs: time dependence in $B \to V\ell\ell$



- time-dependence in $B_d \to K^*(\to K_s\pi^0)\ell\ell$ or $B_s \to \phi(\to K^+K^-)\ell\ell$
- interference of transversity ampl. with mixing phase
- lifts part of the degeneracy in the angular coefficients
- two new optimised observables Q_8^- and Q_9 with potential to disentangle various scenarios, but require flavour tagging

[SDG, Virto]

Outlook

$b \to s\ell\ell$

- Many observables, more or less sensitive to hadronic unc.
- Confirmation of LHCb results for $B \to K^*\mu\mu$, supporting $\mathcal{C}_9^{\rm NP} < 0$ with large significance and room for NP in other Wilson coeffs
- Several discrepancies in $b \to s\mu\mu$ require more global viewpoint
- Global fit does not seem to favour hadronic explanations

Where to go ?

- Improve measurements of q^2-dependence to check status of $\mathcal{C}_i^{\rm NP}$
- Confirm R_K with other LFU violating observables
- Better estimate soft-gluon contributions and duality violation
- Provide lattice form factors over larger range (large recoil ?)
- Look for new observables : CP-violation, time-dependence, involving τ, LFUV and LFV observables…

A lot of (interesting) work on the way !

International Workshop on

Flavor Physics and New Physics Searches

26-30 September 2016, Fréjus, France

Information and Registration on http://indico.in2p3.fr/e/FlavorNewPhys

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Various tests with $\mathcal{C}_9^{\rm NP}$ 1D hypothesis

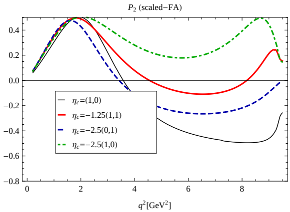
Fit	$\mathcal{C}_{9\ \rm Bestfit}^{\rm NP}$	1σ	$\mathrm{Pull}_{\rm SM}$	$N_{\rm dof}$	p-val (%)
All $b \to s\mu\mu$ in SM	–	–	–	96	16.0
All $b \to s\mu\mu$	-1.09	$[-1.29, -0.87]$	4.5	95	63.0
All $b \to s\ell\ell$, $\ell = e, \mu$	-1.11	$[-1.31, -0.90]$	4.9	101	74.0
All $b \to s\mu\mu$ excluding [6,8]	-0.99	$[-1.23, -0.75]$	3.8	77	37.0
Only $b \to s\mu\mu$ BRs	-1.58	$[-2.22, -1.07]$	3.7	31	43.0
Only $b \to s\mu\mu$ P_i's	-1.01	$[-1.25, -1.25]$	3.1	68	75.0
Only $b \to s\mu\mu$ S_i's	-0.95	$[-1.19, -1.19]$	2.9	68	96.0
Only $B \to K\mu\mu$	-0.85	$[-1.67, -0.20]$	1.4	18	20.0
Only $B \to K^*\mu\mu$	-1.05	$[-1.27, -0.80]$	3.7	61	74.0
Only $B_s \to \phi\mu\mu$	-1.98	$[-2.84, -1.29]$	3.5	24	94.0
Only $b \to s\mu\mu$ at large recoil	-1.30	$[-1.57, -1.02]$	4.0	78	61.0
Only $b \to s\mu\mu$ at low recoil	-0.93	$[-1.23, -0.61]$	2.8	21	75.0
Only $b \to s\mu\mu$ within [1,6]	-1.30	$[-1.66, -0.93]$	3.4	43	73.0
Only $BR(B \to K\ell\ell)_{[1,6]}$, $\ell = e, \mu$	-1.55	$[-2.73, -0.81]$	2.4	10	76.0
All $b \to s\mu\mu$, 40% PCs	-1.08	$[-1.32, -0.82]$	3.8	95	73.0
All $b \to s\mu\mu$, charm$\times$4	-1.06	$[-1.29, -0.82]$	4.0	95	81.0
Only $b \to s\mu\mu$ within [0.1,6]	-1.21	$[-1.57, -0.84]$	3.1	60	30.0
Only $b \to s\mu\mu$ within [0.1,0.98]	0.08	$[-0.92, 0.95]$	0.1	13	33.0

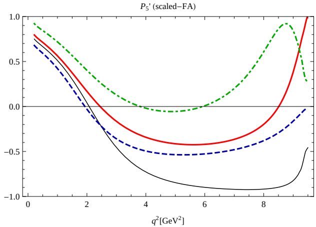
Very large $c\bar{c}$ contributions ?

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 $B \to K^*\mu\mu$

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

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





- P_2 and P_5' could have more zeroes for $4 \leq q^2 \leq 9$ GeV^2
- $P'_{5[6,8]}$ would be above or equal to $P'_{5[4,6]}$, whereas global effects (like $\mathcal{C}_9^{\text{NP}}$) predicts $P'_{5[6,8]} < P'_{5[4,6]}$ in agreement with experiment
- R_K unexplained since it would affect identically $\ell = e, \mu$

Very large power corrections ? (1)

- Scheme: choice of definition for the two soft form factors

$$\{\xi_\perp, \xi_{||}\} = \{V, a_1 A_1 + a_2 A_2\}, \{T_1, A_0\}, \ldots$$

- Power corrections for the other form factors from dimensional estimates or fit to other 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 observables [Martin-Camalich, Jäger]

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

- Option 1: Include all correlations among error power corrections
- Option 2: Assign 10% uncorrelated uncertainties for pc
- 1 hinges on detail of ff determination, 2 depends on scheme ($a_i = b_i = 0$ for different form factors in each scheme)

Very large power corrections ? (2)

Model independent ⟵⟶ Full LCSR information

1

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

2

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

3

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

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

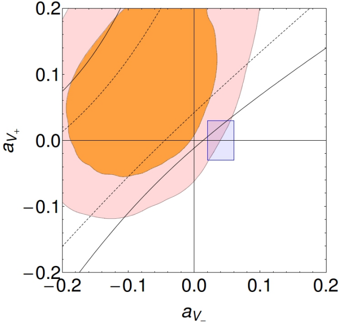
$P_5'[4.0, 6.0]$	scheme 1	scheme 2
1	-0.72 ± 0.05	-0.72 ± 0.12
2	-0.72 ± 0.03	-0.72 ± 0.03
3	-0.72 ± 0.03	-0.72 ± 0.03
full BSZ	-0.72 ± 0.03	

- using [Bharucha, Straub, Zwicky] (correlations provided)
- 2 schemes defining $\xi_{||,\perp}$
- expected magnitude for pc
- scheme indep. restored if $\Delta F^{\rm PC}$ from LCSR
- ff in 1 at odds with LCSR

Very large power corrections ? (3)

[Martin-Camalich, Jäger]

- Different scheme to define soft ff, but no correlations among ff included (leading to scheme-dependent results)
- Various ff "estimates" (LCSR, QCDSR, Schwinger-Dyson) to get a (very) broad estimate for the soft form factors $F^\infty(s)$



- Pc: $|a_F| \leq 0.03$, $|b_F| \leq 0.10$ in $F(s) = F^\infty(s) + a_F + b_F q^2/m_B^2$
- Fit to uncorrelated $B \to K^* \mu\mu$ obs. keeping a_F, b_F in fixed ranges (Rfit)
- Good fits if pc a_{V_+,V_-} varied in [-0.2,0.2], showing that 0 and 0.2 are both acceptable values (?)

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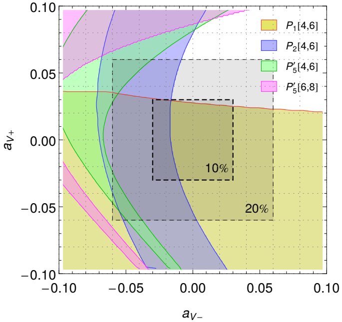

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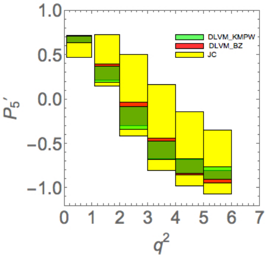
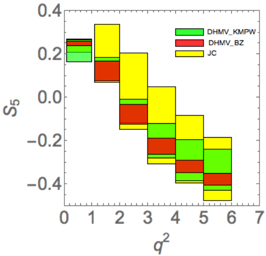
[SDG, Hofer, Matias, Virto]

- a_F can be tuned to get agreement SM pred/data for one given obs.
- but cannot be extended to several observables due to correlations

Uncertainties for SM predictions: P_5' vs S_5





P_5' and S_5 computed with

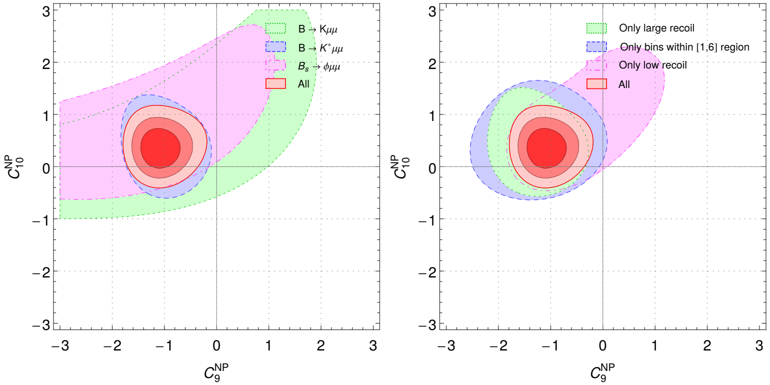
- [Khodjamirian et al.] form factors (green)
- [Ball and Zwicky] ffs (red)
- [Jäger and Camalich] approach (yellow)

- P_5': Agreement and same errors for [Khodjamirian et al.] and [Ball and Zwicky]
- S_5: Different uncertainties for [Khodjamirian et al.] and [Ball and Zwicky] inputs, due to increased sensitivity of S_5 to form factor inputs
- Agreement within errors between our results for [Ball and Zwicky] and the updated analysis of [Bharucha, Straub, Zwicky]

[Jäger and Camalich] approach

- Non optimal scheme use to determine soft form factors
- Large spread for form factor inputs but small errors on soft ffs $\Longrightarrow$ overestimation of power corrections

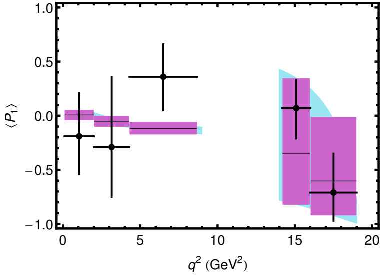
Cross-checks: Processes, low vs large recoil

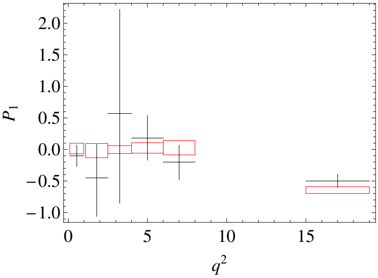


- 3 σ constraints, always including $b \to s\gamma$ and inclusive
- $B \to K^*\mu\mu$ tighter than $B_s \to \phi\mu\mu$, tighter than $B \to K\mu\mu$
- Large recoil driving the discussion, but [1,6] bins already providing bulk of the effect, and low-recoil also in favour of $\mathcal{C}_9^{NP} < 0$

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

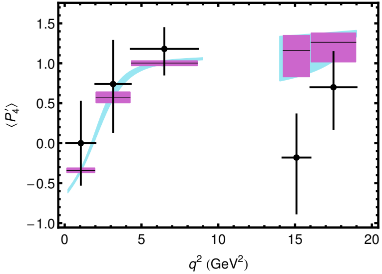
P_1 in 2013 and 2015

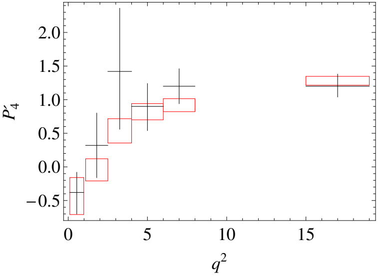




- Definition: $P_1 = A_T^{(2)} = \dfrac{|A_\perp|^2 - |A_{||}|^2}{|A_\perp|^2 + |A_{||}|^2}$
- In the absence of right-handed current, $|A_\perp| \simeq |A_{||}|$
- $P_1 \neq 0$ tests right-handed currents

P'_4 in 2013 and 2015



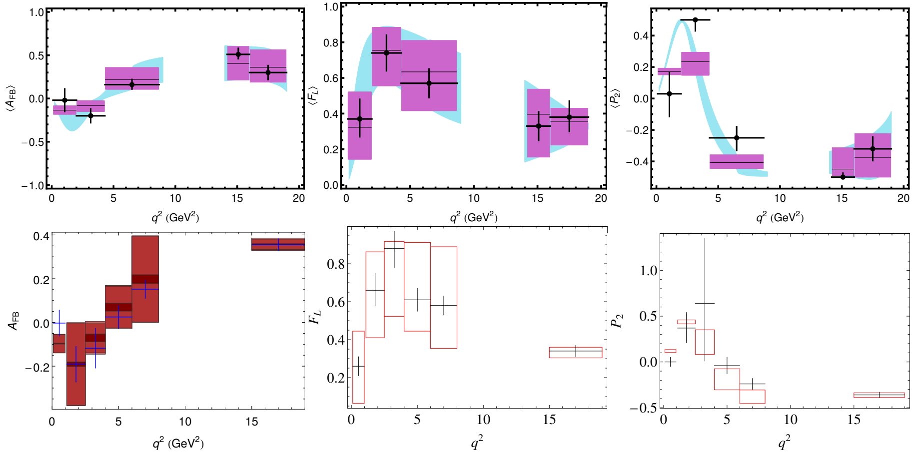


- Definition: $P'_4 = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_{||}^{L*} + A_0^R A_{||}^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_{||}|^2)}}$
- Consistency check of the data due to the bound

$$P_5'^2 - 1 \leq P_1 \leq 1 - P_4'^2$$

relevant for [4,6], [6,8] and low recoil

A_{FB}, F_L, P_2 in 2013 and 2015



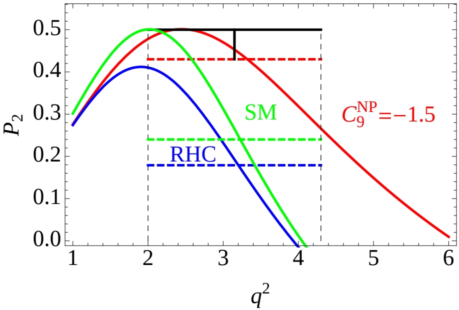
- Definition: $P_2 = \frac{\mathrm{Re}(A_{||}^L A_{\perp}^{L*} - A_{||}^R A_{\perp}^{R*})}{|A_\perp|^2 + |A_{||}|^2}$ (or A_T^{Re} in [Becirevic, Schneider])
- In 2015, upward fluctuation of F_L affects $\langle P_2 \rangle_{[2.5,4]}$ $[A_{FB} = -3/2 P_2(1 - F_L)]$

Role of P_2

Different pieces of information from P_2

(form-factor independent version of A_{FB})

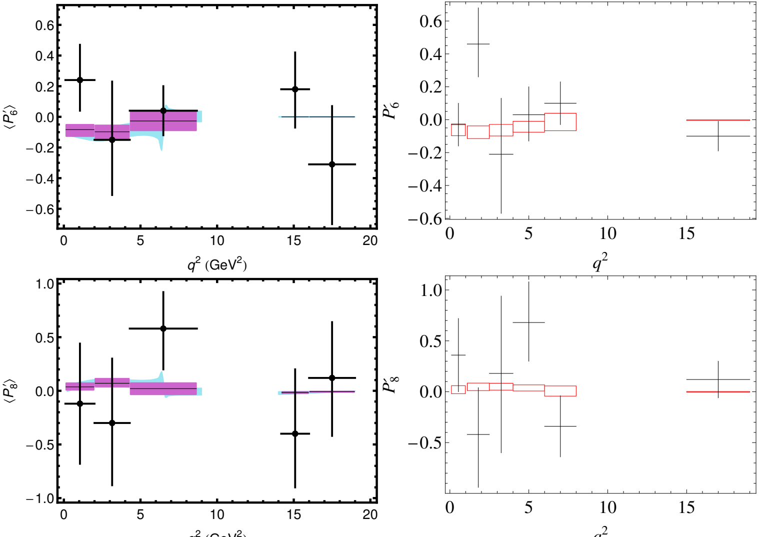
- Position of zero: $q^2_{0,LO} = -\frac{2m_b M_B C_7^{\rm eff}}{C_9^{\rm eff}(q_0^2)}$ (if no right-handed currents)



- Position of maximum: $q^2_{1,LO} = -\frac{2m_b M_B C_7^{\rm eff}}{{\rm Re}\,C_9^{\rm eff}(q_1^2) - C_{10}}$ (if no right-handed currents and $C_9^{\rm eff}$ nearly real)
- Value of the maximum: $P_2^{max} = 1/2$ unless right-handed currents, could be determined with finer binning

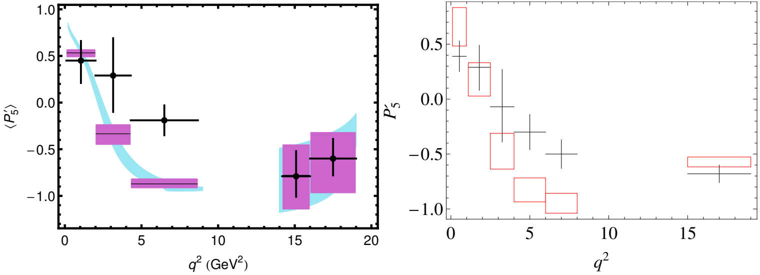
$\rightarrow q^2_{0,SM} \simeq 4$ GeV^2 and $q_1^{2,SM} \simeq 2$ GeV^2

P'_6, P'_8 in 2013 and 2015



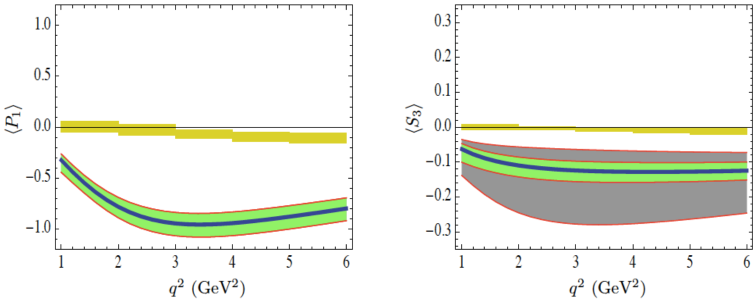
- Sensitive to new weak phases (imaginary parts of interf)
- Globally compatible with SM, with local fluctuations

P'_5 in 2013 and 2015



- Definition: $P'_5 = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_{||}|^2)}}$
- In SM, $C_9 \simeq -C_{10}$ leading to $A^R_{\perp,||,0} \ll A^L_{\perp,||,0}$, P'_5 saturates at -1 when $C_{9,10}$ dominates (i.e. $q^2 > 5$ GeV^2)
- Improved consistency of the 2015 data
  - $P_4'^2(q_0^2) + P_5'^2(q_0^2) \simeq 1$ if no RHC
  - $P'_5 \leq 2P_2/P'_4$ if no new weak phase or scalars

Sensitivity to form factors



- P_i designed to have limited sensitivity to form factors
- S_i CP-averaged version of J_i (A_i for CP-asym)

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

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)

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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  - Vary power corrections as 10% of the total form factor around the central values obtained for $a_F, b_F \ldots$

- 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 $i = 0, \perp, ||$

$1/m_B$ expansion for $B \to K^* \ell\ell$

7 independent form factors, but separation of scales $\Lambda_{(QCD)}$ and m_B in

- Large-recoil limit ($\sqrt{q^2} \sim \Lambda \ll m_B$) [LEET/SCET, QCDF]
    - two soft form factors $\xi_\perp(q^2)$ and $\xi_{||}(q^2)$
    - $O(\alpha_s)$ corr. from hard gluons [computable], $O(\Lambda/m_B)$ [power corrections or pc, nonpert] [Charles et al., Beneke and Feldmann]
- Low-recoil limit ($E_{K^*} \sim \Lambda \ll m_B$) [HQET]
    - three soft form factors $f_\perp(q^2), f_{||}(q^2), f_0(q^2)$
    - $O(\alpha_s)$ corr. from hard gluons [computable] + $O(\Lambda/m_B)$ [pc, nonpert]

[Grinstein and Pirjol, Hiller, Bobeth, Van Dyk. . .]

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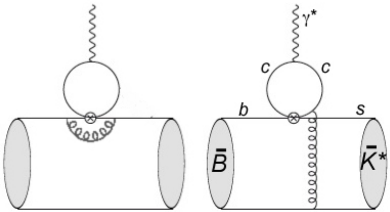
[Grinstein and Pirjol, Hiller, Bobeth, Van Dyk. . .]

from ff (factor.) *in $A_{\perp,||,0}$ (non-factor.)*



Similar separation in amplitudes using $1/m_B$ expansion

- Factorisable contributions (reexpression of form factors)
- Nonfactorisable contributions (specific to amplitudes)