$b \to s\ell\ell$ 2015 and New Physics

much ado about...something ?

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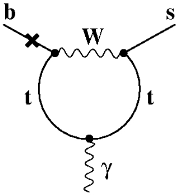
LPT Orsay

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

$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\Delta F=1} \propto \sum_{i=1}^{10} V^*_{ts} V_{tb} C_i Q_i + \dots$$



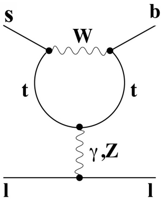
- $Q_7 = \frac{e}{g^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]
- $Q_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma_\mu\ell$ [$b \to s\mu\mu$ via Z/hard γ]
- $Q_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma_\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

NP changes short-distance C_i and/or add new operators Q'_i

- Chirally flipped ($W \to W_R$) $Q_7 \to Q_{7'} \propto \bar{s}\sigma^{\mu\nu}(1-\gamma_5)F_{\mu\nu}\, b$
- (Pseudo)scalar ($W \to H^+$) $Q_9, Q_{10} \to Q_S \propto \bar{s}(1+\gamma_5)b\bar{\ell}\ell, Q_P$
- Tensor operators ($\gamma \to T$) $Q_9 \to Q_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5)b\, \bar{\ell}\sigma_{\mu\nu}\ell$

Aim: disentangle hadronic effects from electroweak and NP effects

Wilson Coefficients and processes



Matching SM at high-energy scale $\mu_0 = m_t$ and evolving down at $\mu_{\rm ref} = 4.8$ GeV

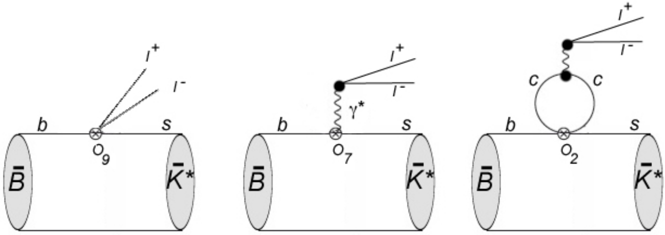
$$C_7^{SM} = -0.29, C_9^{SM} = 4.1, C_{10}^{SM} = -4.3,$$

(formulae known up to NNLO + e.m. corrections)

- $b \to s\gamma$ versus $b \to s\ell\ell$: $C_{7,7'}$ versus other Wilson coefficients
- Inclusive versus exclusive: OPE versus form factor uncertainties

- $B \to X_s\gamma$: strong constraints on $C_7, C_{7'}$ [Misiak, Gambino, Steinhauser. . .]
- $B \to X_s\ell\ell$: only loose constraints [Misiak, Bobeth, Gorbahn, Haisch, Huber, Lunghi. . .]
- $B_s \to \mu\mu$: recent th. and exp. progress [Misiak, Bobeth, Gorbahn. . .]
- $B \to K(^*)\ell\ell$: New LHCb analysis in Moriond 2015 for $B \to K^*$

$B \to K(^*)\mu\mu$: amplitudes with $\mathcal{H}_{eff}$



- $2q, 2\ell$ $[C_{9('),10('),S('),P(')}]$ $\quad A_9 = C_9 \langle M_\lambda | \bar{s}\gamma_\mu P_L b | B \rangle L^\mu \to C_9 F_\lambda(q^2)$
- Electromag $[C_{7(')}]$ $\quad A_7 = C_7 \langle M_\lambda | \bar{s}\sigma_{\mu\nu} P_L b | B \rangle \frac{eq^\mu}{q^2} L^\nu \to C_7 T_\lambda(q^2)$
- 4-quark ops $[C_{1,2\ldots})]$: nonlocal contribution, related to $c\bar{c}$ loops

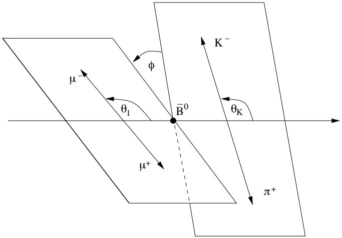
$$A_2 = C_2 \int d^4x e^{iqx} \langle M_\lambda | T[(\bar{s}\gamma^\mu P_L c\ \bar{c}\gamma_\mu P_L b)(0)\ J_\nu^{em,c\bar{c}}(x)] | B \rangle \frac{e^2}{q^2} L^\nu$$

[L^μ lepton current]

Two main tasks for the theorists

- Determine the form factors F_λ, T_λ using nonperturbative methods
- Assess the contribution from 4-quark operators, i.e., $c\bar{c}$ loops in A_2

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



- θ_l: angle of emission between $K^{\star 0}$ and μ^- in di-lepton rest frame
- θ_{K^*}: angle of emission between $K^{\star 0}$ and K^- in di-meson rest frame.
- ϕ: angle between the two planes
- q^2: dilepton invariant mass square

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \sum_i f_i(\theta_{K^*}, \phi, \theta_l) \times I_i$$

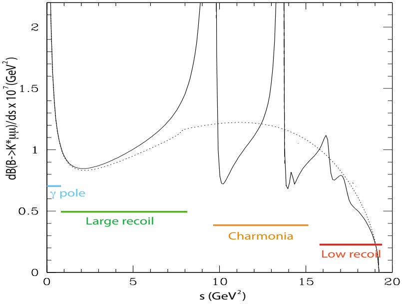
with 12 angular coeffs I_i, interferences between 8 transversity ampl.

- $\perp, ||, 0, t$ polarisation of (real) K^* and (virtual) $V^* = \gamma^*, Z^*$
- L, R chirality of $\mu^+\mu^-$ pair

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

- Wilson coefficients $C_7, C_9, C_{10}, C_S, C_P$ (and flipped chiralities)
- $B \to K^*$ form factors $A_{0,1,2}$, V, $T_{1,2,3}$ from $\langle K^*|Q_i|B\rangle$
- terms describing $c\bar{c}$ contribution

Four kinematic regions



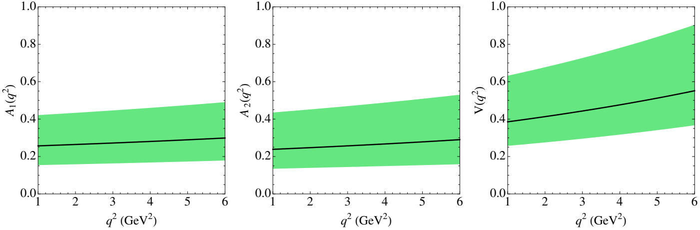
- Very large K^*-recoil ($4m_\ell^2 < q^2 < 1$ GeV^2): γ almost real (C_7/q^2 divergence and light resonances)
- Large K^*-recoil ($q^2 < 9$ GeV^2): energetic K^* ($E_{K^*} \gg \Lambda_{QCD}$: form factors via light-cone sum rules LCSR)

- 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)

EFT approaches at low and large-K^* recoils : expansion in

- Λ/m_b (separating soft and hard dynamics)
- α_S (for dynamics of hard gluons)

$B \to K^*$ form factors



[Khodjamirian et al.]

In the limits of low and large K^* recoil, separation of scales Λ and m_B in the 7 form factors for

- 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 ($E_{K^*} \sim \Lambda_{QCD} \ll m_B$) [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]

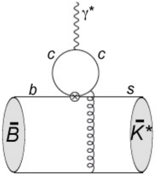
[Grinstein and Pirjol, Hiller, Bobeth, Van Dyk...]

From form factors to amplitudes

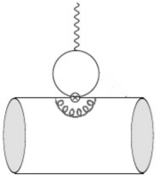
Large recoil: NLO QCD factorisation

[Beneke, Feldmann, Seidel]

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



in FFs (factor)



- $V, A_i, T_i = \xi_{||,\perp}$ + factorisable $O(\alpha_s, \Lambda/m_b)$
- $A_{0,||,\perp} = C_i \times \xi_{||,\perp}$ + factorisable $O(\alpha_s, \Lambda/m_b)$ + nonfactorisable $O(\alpha_s, \Lambda/m_b)$

- Two approaches to get correlations among form factors
  - Extract soft form factors + factorisable power corrections from fit to full form factors [Matias, Virto, Hofer, Mescia, SDG...]
  - Replace soft form factors + factorisable power corrections by full form factors with correlations [Buras, Ball, Bharucha, Altmanshoffer, Straub...]

Low recoil: OPE + HQET

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

- $A_{0,||,\perp} = C_i \times f_{0,||,\perp} + O(\alpha_s)$ corrections + $O(\Lambda/m_b)$ corrections
- $f_{0,||,\perp} \propto CL(A_1, A_2), A_1, V + O(\Lambda/m_b)$ corrections

[or use directly lattice results for the form factors]

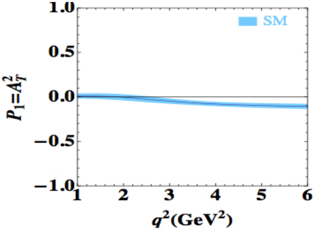
Form-factor "independent" observables

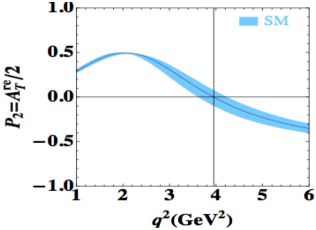
= Observable where (soft) form factors cancel at LO in EFT

- Zero of forward-back. asym. $A_{FB}(s_0) = 0$: $C_9^{\rm eff}(s_0) + 2\frac{m_b M_B}{s_0} C_7^{\rm eff} = 0$
- Transversity asymmetries

[Krüger, Matias; Becirevic, Schneider]

$$P_1 = A_T^{(2)} = \frac{I_3}{2 I_{2s}} = \frac{|A_\perp|^2 - |A_{||}|^2}{|A_\perp|^2 + |A_{||}|^2}, \quad P_2 = \frac{A_T^{re}}{2} = \frac{I_{6s}}{8 I_{2s}} = \frac{Re[A_\perp^{L*} A_{||}^L - A_\perp^R A_{||}^{R*}]}{|A_\perp|^2 + |A_{||}|^2}$$

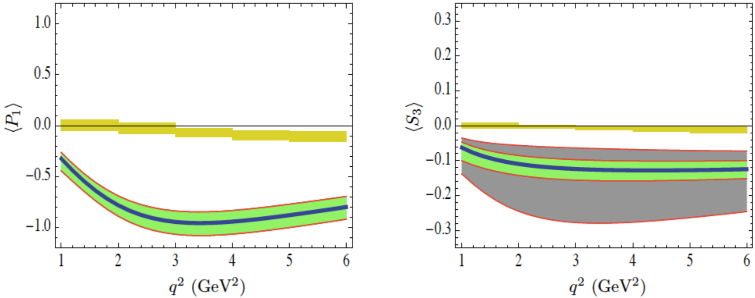




- 6 form-factor indep. observ. at large recoil $P_1, P_2, P_3, P'_4, P'_5, P'_6$
  + 2 form-factor dependent obs. (Γ, A_{FB}, $F_L \ldots$) $[A_{FB} = -3/2 P_2 (1 - F_L)]$
  exhausting information in (partially redundant) angular coeffs I_i

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

Sensitivity to form factors



- P_i designed to have limited sensitivity to form factors
- S_i CP-averaged version of angular coefficient I_i

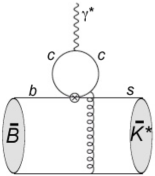
$$P_1 = \frac{2S_3}{1-F_L} \qquad F_L = \frac{I_{1c}+\bar{I}_{1c}}{\Gamma+\bar{\Gamma}} \qquad S_3 = \frac{I_3+\bar{I}_3}{\Gamma+\bar{\Gamma}}$$

different sensivity to form factors inputs for given NP scenario (form factors from LCSR: green [Ball, Zwicky] vs gray [Khodjamirian et al.])

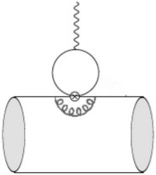
- P_1 apt to discriminate NP (green/gray) vs SM case (yellow)

Power corrections

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



in FFs (factor)



Observables with limited sensitivity to soft form factors

$\Longrightarrow$important role played by $O(\Lambda/m_b)$ power corrections !

Power corrections to form factors

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

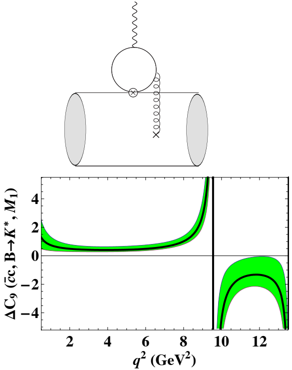
- Set $\xi_{||,\perp}$ identifying them with two form factors
- Central value $a_F, b_F, \ldots$: fit to the full form factor F
- Error on $a_F, b_F, \ldots$: 10% of the full form factor F

Remaining power corrections to amplitudes

- multiply part not associated to form factors $\mathcal{T}_i^{\rm had}$ with a complex q^2-dependent factor (10% magnitude) $\mathcal{T}_i^{\rm had} \to (1 + r_i(q^2))\mathcal{T}_i^{\rm had}$
- since contributions from rescattering may yield arbitrary phases

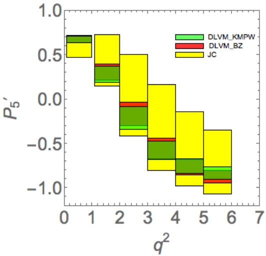
Charm-loop effects

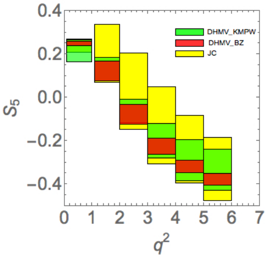
- Charmonium resonances
  - Large recoil: $q^2 \leq$ 7-8 GeV^2 to avoid J/ψ tail
  - Low recoil: quark-hadron duality OK at a few percent if wide bin
- Short-distance non-resonant (hard gluons) [Beylich, Buchalla, Feldmann]
  - LO included $C_9 \to C_9 + Y(q^2)$, dependence on m_c
  - higher-order short-distance QCD via QCDF/HQET



- Long-dist. non-resonant (soft gluons)
  - At large recoil (partly included already in power corrections)
  - Global $\Delta C_9^{BK^{(*)}}$ using LCSR : for $B \to K^*$, partial computation yields $\Delta C_9^{BK^*} > 0$ [Khodjamirian, Mannel, Pivovarov Wang]
  - Perform the separation $\Delta C_9^{BK^*} = \delta C_{9,\mathrm{pert}}^{BK^{(*)}} + \delta C_{9,\mathrm{non\ pert}}^{BK^{(*)}}$ and compute uncertainty by varying nonperturbative part $\pm\delta C_{9,\mathrm{non\ pert}}^{BK^{(*)}}$

Resulting uncertainties for SM predictions: P_5' vs S_5





P_5' and S_5 computed with

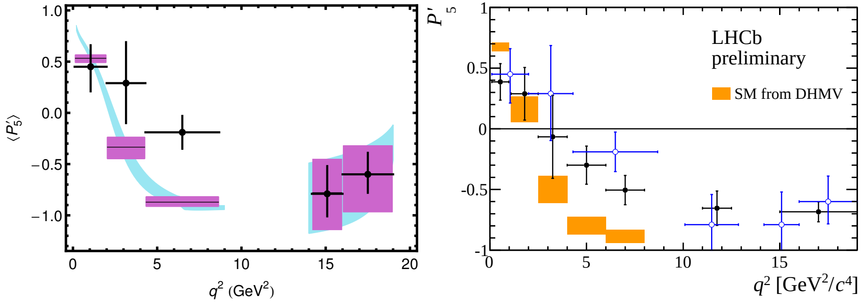
- [Khodjamirian et al.] form factors (green)
- [Ball and Zwicky] ffs (red)
- [Jäger and Camalich] approach (yellow)

- 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

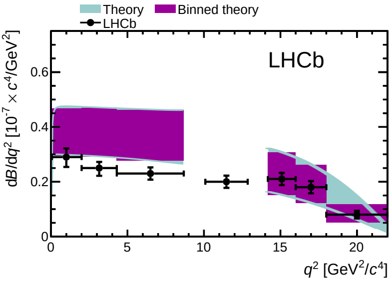
- Non optimal scheme to determine soft form factors
- No use of information from form factors to set power corrections $\Longrightarrow$range in the absence of info on form factors (enhancing errors)

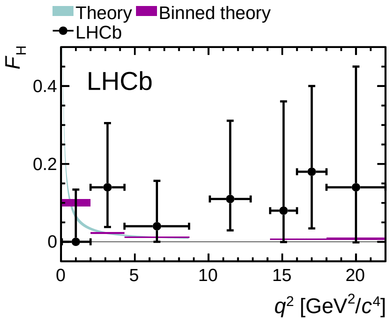
P'_5 in 2013 and 2015



- Definition: $P'_5 = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_{||}|^2)}}$
- Improved consistency of the 2015 data
- 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)

$B \to K\mu\mu$

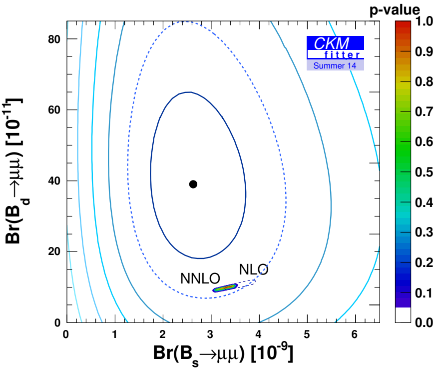




- Simpler kinematics: only one angle and 3 observables: *Br*, F_H, A_{FB} [Hiller, Bobeth, Piranishvili]
- Only *Br* brings information (other observables are small, both exp. and th.)
- 3 form factors, down to 1 soft form factor at large recoil
- Contribution from soft gluons negligible compared to hadronic uncertainties
- Discrepancy with SM at low q^2 (Br involves $C_9 + C_{9'}$)

$B_s \to \mu\mu$

- Sensitive to $C_{10} - C_{10'}$, $C_S - C_{S'}$, $C_P - C_{P'}$



- LHCb+CMS: $\langle Br(B_s \to \mu\mu)\rangle = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$
- Theoretical progress
  - Inclusion of B_s mixing in time-integrated rate from LHCb and CMS: $\langle Br(B_s \to \mu\mu)\rangle \simeq 1.1 Br_{t=0}$
  - NLO QCD + LO EW $\to$ NNLO QCD + NLO EW

[Fleischer et al., Bobeth et al.]

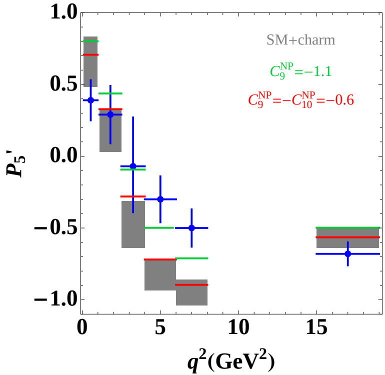
- $Br(B_s \to \mu\mu)$ in very good agreement with SM
- Correlation in SM (and in MFV)

$$Br(B_d \to \mu\mu)_{t=0}/Br(B_s \to \mu\mu)_{t=0} = 0.0298^{+0.0008}_{-0.0010}$$

Global fits: 1D hypotheses

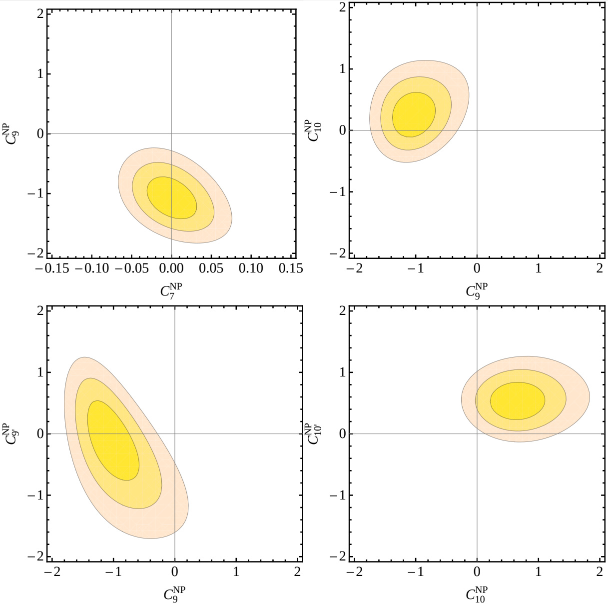
- χ^2 frequentist analysis to determine $C_i(\mu_{ref}) = C_i^{SM} + C_i^{NP}$
- $B \to K^*\mu\mu$ ($P_{1,2}$, $P'_{4,5,6,8}$, F_L: 5 large-recoil + 1 low-recoil bins), $B^+ \to K^+\mu\mu$, $B^0 \to K^0\mu\mu$, $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B_s \to \mu\mu$ (Br), $B \to K^*\gamma$ (A_I and $S_{K^*\gamma}$) [Moriond 15, no correlations]

Hypothesis	Best fit	Pull
$C_9^{\rm NP}$	-1.1	4.6
$C_{10}^{\rm NP}$	0.62	2.4
C'_9	-1.0	3.4
C'_{10}	0.61	3.3
$C_9^{\rm NP} = -C_{10}^{\rm NP}$	-0.62	4.0
$C_9^{\rm NP} = C_{10}^{\rm NP}$	-0.37	1.7
$C_{9'} = C_{10'}$	0.32	1.3
$C_9^{\rm NP} = C_{9'}$	-0.67	4.3
$C_{9'} = -C_{10'}$	-0.42	3.6



$C_9^{NP} < 0$ preferred, but alternatives with $C_9^{\rm NP} = -C_{10}^{\rm NP}$ and $C_9^{\rm NP} = C_{9'}$

Global fits: 2D hypotheses



Hyp.	Best-fit pt	Pull
(C_7^{NP}, C_9^{NP})	(0.0, -1.1)	4.2
(C_9^{NP}, C_{10}^{NP})	(-1.1, 0.2)	4.2
$(C_9^{NP}, C_{9'})$	(-1.0, -0.1)	4.2
$(C_{10}^{NP}, C_{10'})$	(0.5, 0.6)	3.4

$\rightarrow$ Main effect from C_9

Explanations ?

- Z' boson
- Leptoquarks
- Composite models
- Difficult with susy (?)

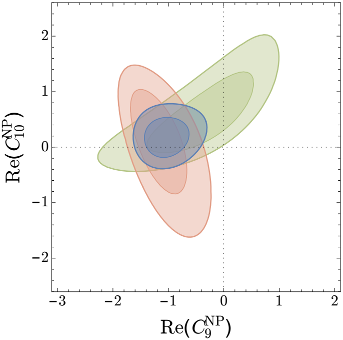
[Almannshoffer, Straub, Haisch, Gauld, Peczak, Buras, De Fazio, Girrbach, Hiller, Schmaltz, Varzielas, Crivellin. . .]

Global fits: to be continued

Work in progress to add [SDG, Hofer, Matias, Virto, in preparation]

- Experimental and theoretical correlations (reduce significance)
- Complex phases in soft-gluon contributions (reduce significance)
- Electronic modes and $B_s \to \phi\mu\mu$ (increase significance)
- New form factors [Bharucha, Straub, Zwicky] (increase significance)

General pattern and preferred hypotheses unchanged !



Similar analysis by [Almannshoffer and Straub]

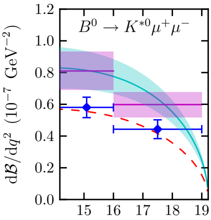
- Full form factors with correlations (rather than soft form factors)
- Different form factors, power corrections, $c\bar{c}$ contributions
- Similar preferred hyp: C_9^{NP} (3.7 σ) or $C_9^{NP} = -C_{10}^{NP}$ (3.2 σ)
- C_9^{NP} can be q^2-independent (NP ?)

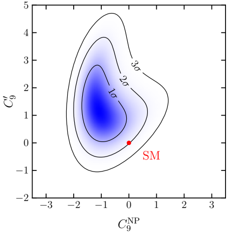
Other interesting results

- $R_K = \left.\frac{Br(B\to K\mu\mu)}{Br(B\to Kee)}\right|_{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$
  - cannot be mimicked by a hadronic effect
  - OK with $C_9^{\mu,NP} \simeq -1$, or $C_9^{\mu,NP} = -C_{10}^{\mu,NP} \simeq -0.5$ $[C_{9,10}^{e,NP} \simeq 0]$

[Hiller, Schmalz]

- Lattice: $B \to K^*\ell\ell$ and $B_s \to \phi\ell\ell$ form factors [Horgan et al.]





- SM preds for BRs higher than exp (blue, pink: SM, dashed: $C_9^{NP} = -C_{9'}^{NP} = -1.1$)
- Frequentist analysis with only low recoil $B_q \to V\ell\ell$ favours $C_9^{NP} < 0$ (and $C_{9'}$ mildly negative)

- Maybe more: LHCb finds $\Lambda_b \to \Lambda\mu\mu$ with too low branching ratio at large recoil. . .

Outlook

$b \to s\ell\ell$ transitions

- Very interesting playing ground for FCNC studies
- Many observables, more or less sensitive to hadronic unc.
- Confirmation of LHCb results for $B \to K^*\mu\mu$, supporting $C_9^{NP} < 0$ with large significance, and room for NP in other Wilson coeffs
- And a lot theoretical discussions on accuracy of computations and/or interpretation in terms of NP

How to improve ?

- Check the size of hadronic effects by comparing different exclusive modes: $B \to K^*\mu\mu, B \to K\mu\mu, B_s \to \phi\mu\mu, \Lambda_b \to \Lambda\mu\mu \ldots$
- Improve the measurement of q^2-dependence of the observables
- Confirm R_K by comparing modes with $\ell = e$ and $\ell = \mu$
- Sharpen the estimate of soft-gluon contribs and power corrections
- Provide lattice form factors over whole kinematic range with corr.

A lot of (interesting) work on the way !