$B \to K^\star \mu\mu$ 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

SPP/CEA Saclay, June 12th 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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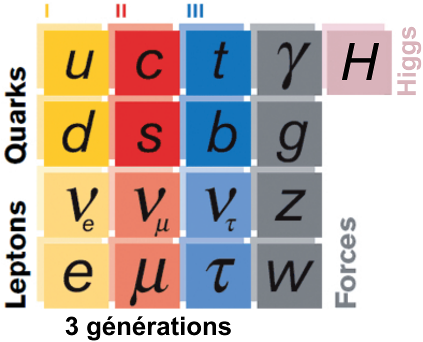
i.e. which degrees of freedom, symmetries, scales ?



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

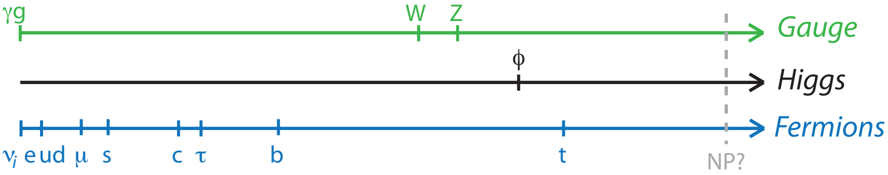
- Highly symmetric (gauge symmetry, flavour symmetry)
- Well-tested experimentally (electroweak precision tests)
- Stable with respect to quantum corrections

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 $\mathrm{SM}_{m_\nu=0}$

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

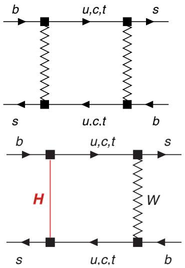
With interesting phenomenological consequences

- 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

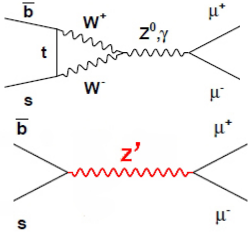
Flavour-Changing Neutral Currents

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

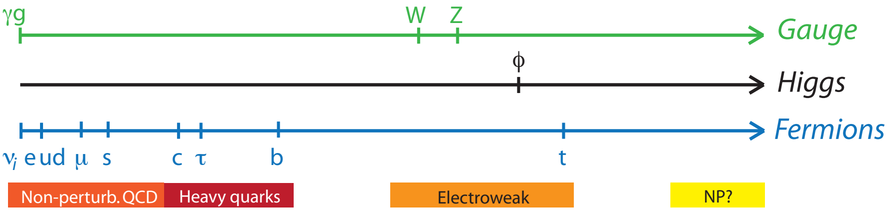


$\Delta F = 1$: $B_s \to \mu\mu$



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)

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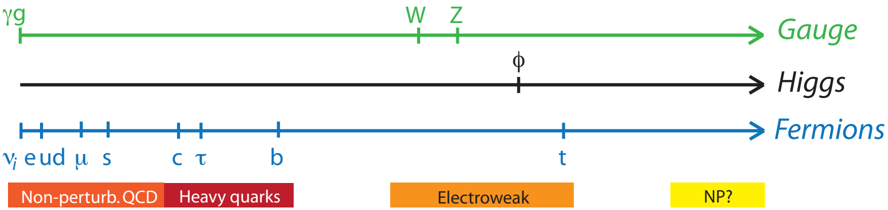

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- Main theo problem from hadronisation of quarks into hadrons: description/parametrisation in terms of QCD quantities

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

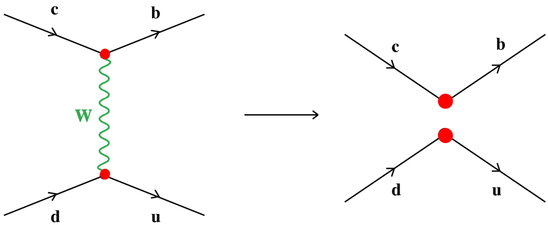
  lattice QCD simulations, effective theories...

Effective approaches

Fermi-like approach: separation of different scales

short distances (numerical coeffs) versus long dist (local operator)

(separation also valid for QCD corrections)



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

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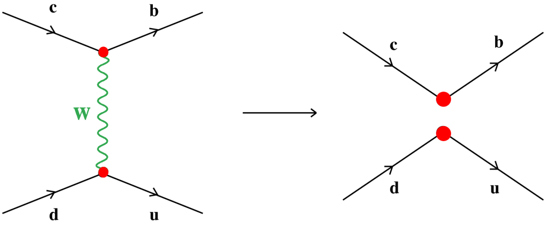


$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c + O(1/M_W^2)$$

Before/below SM, Fermi theory carry info on underlying (EW) physics

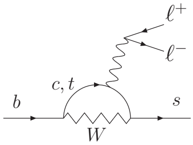
- G_F: scale of underlying physics
- $\mathcal{O}_i$: interaction with left-handed fermions, through charged spin 1
- Obviously not all info (gauge structure, Z^0 ...),

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

Looking for interesting processes

Starting from the SM
(or one of its extensions)

$$\mathcal{H}^{\text{eff}} = CKM \times \mathcal{C}_i \times \mathcal{O}_i$$
$$\langle M|\mathcal{H}^{\text{eff}}|B\rangle = CKM \times \mathcal{C}_i \times \langle M|\mathcal{O}_i|B\rangle$$



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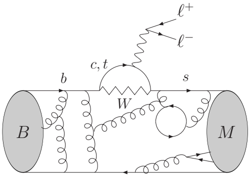

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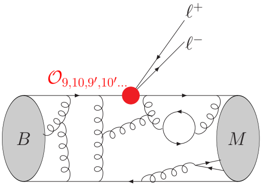

involving hadronic quantities such as form factors
selecting processes for accurate predictions:

- semileptonic decays (form factors, not more complicated objects)
- ratios of branching ratios with different leptons
- ratios of observables with similar dependence on form factors

$\Longrightarrow$observables with limited sensitivity to (ratio of form) factors

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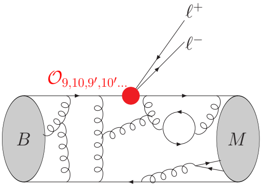

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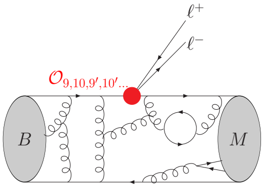
Two possible uses of effective approaches

- fixing $\mathcal{C}_i$, computing SM and comparing with the data
- determining short-distance $\mathcal{C}_i$ from the data and compare with SM

B-meson form factors



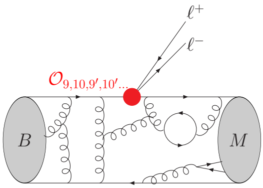
For illustration, take $B \to V$ transitions, described in general by 7 form factors: V (vector), $A_{0,1,2}$ (axial) and $T_{1,2,3}$ (tensor), depending on $q^2 = (p-k)^2$

$$\begin{aligned}
\langle V(k)|\bar{s}\gamma_\mu(1-\gamma_5)|B(\epsilon,p)\rangle &= -i\epsilon_\mu(m_B+m_V)A_1(q^2) + i(p+k)_\mu(\epsilon^*\cdot q)\frac{A_2(q^2)}{m_B+m_V} \\
&\quad + iq_\mu(\epsilon^*\cdot q)\frac{2m_V}{q^2}\tilde{A}_0(q^2) + \epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p^\rho k^\sigma\frac{2V(q^2)}{m_B+m_V} \\
\langle V(k)|\bar{s}\sigma_{\mu\nu}q^\nu(1+\gamma_5)|B(\epsilon,p)\rangle &= i\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p^\rho k^\sigma 2T_1(q^2) + \epsilon^*_\mu(m_B^2-m_V^2)T_2(q^2) \\
&\quad -(p+k)_\mu(\epsilon^*\cdot q)\tilde{T}_3(q^2) + q_\mu(\epsilon^*\cdot q)T_3(q^2)
\end{aligned}$$

with $\tilde{A}_0$ linear combination of $A_{0,1,2}$ and $\tilde{T}_3$ of $T_{2,3}$

Can these form factors be further simplified/factorised using $\Lambda \ll m_B$?

The last step of factorisation



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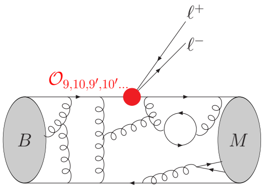

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Large recoil of the meson $(\Lambda \ll E_V \sim m_B)$

- Light-cone sum rules (light V, parton language)
- Soft Collinear Effective Theory [Charles et al., Beneke, Feldmann]
  - in the limit $m_b \to \infty$, two soft form factors $\xi_\perp(q^2)$ and $\xi_{||}(q^2)$
  - corrections: $O(\alpha_s)$ from hard gluons + nonperturbative $O(\Lambda/m_B)$

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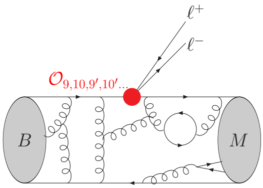

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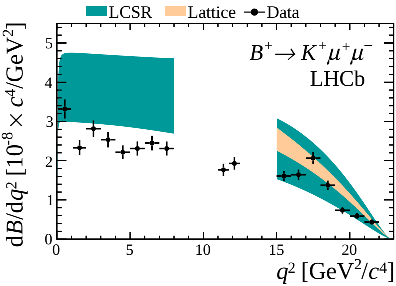
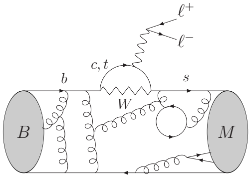
Low recoil of the meson $(E_V \sim \Lambda_{QCD} \ll m_B)$

- Lattice QCD simulations (discretised QCD)
- Heavy Quark Effective Theory [Neubert, Grinstein, Pirjol, Hiller, Bobeth, Van Dyk…]
  - in the limit $m_b \to \infty$, three soft form factors $f_\perp(q^2), f_{||}(q^2), f_0(q^2)$
  - corrections: $O(\alpha_s)$ from hard gluons + nonperturbative $O(\Lambda/m_B)$

Radiative decays as seen by LHCb

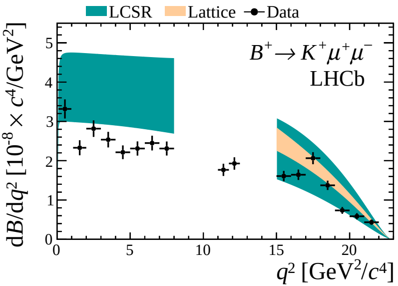
$b \to s\ell^+\ell^-$: $B \to K\ell\ell$

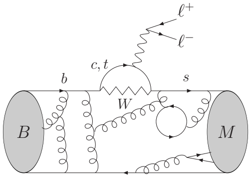


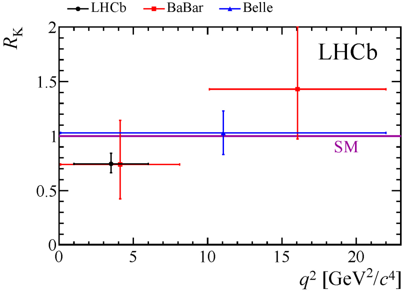


- $Br(B \to K\mu\mu)$ too low compared to SM

$b \to s\ell^+\ell^-$: $B \to K\ell\ell$

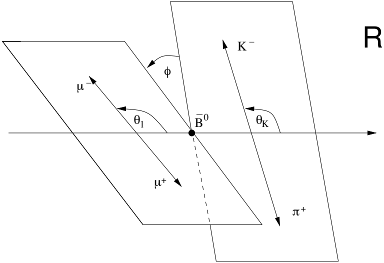






- $Br(B \to K\mu\mu)$ too low compared to SM
- $R_K = \left.\frac{Br(B\to K\mu\mu)}{Br(B\to Kee)}\right|_{[1,6]} =$ $0.745^{+0.090}_{-0.074} \pm 0.036$
- equals to 1 in SM (universality of lepton coupling), 2.6 σ dev
- would require NP coupling differently to μ and e

$b \to s\ell^+\ell^-$: $B \to K^*(\to K\pi)\mu\mu$ (1)



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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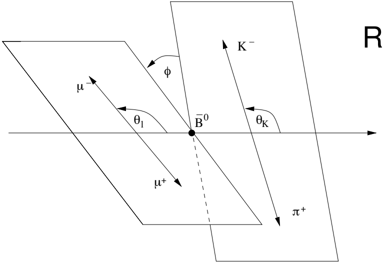

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- Transversity amplitudes in terms of 7 form factors $A_{0,1,2}$, V, $T_{1,2,3}$
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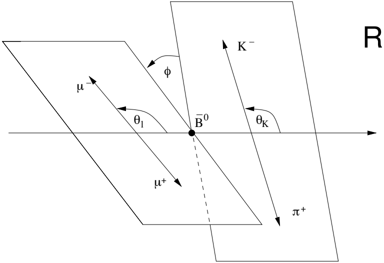

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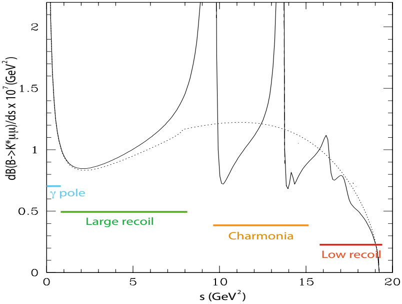
- Relations between form factors in limit $m_B \to \infty$,
  either when K^* very soft or very energetic (low/large-recoil)
- Build ratios of J_i where form factors cancel in these limits
  (corrections by hard gluons $O(\alpha_s)$, power corrs $O(\Lambda/m_B)$)
- Optimised observables P_i with reduced hadronic uncertainties

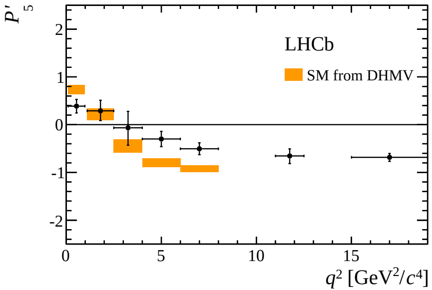
[Matias, Krüger, Becirevic, Schneider, Mescia, Virto, SDG, Ramon, Hurth; Hiller, Bobeth, Van Dyk]

$b \to s\ell^+\ell^-$: $B \to K^*\mu\mu$ (2)



- 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^* ($E_{K^*} \gg \Lambda_{QCD}$)
  LCSR, SCET, QCD factorisation
- 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, Operator Product Expansion

$b \to s\ell^+\ell^-$: $B \to K^*\mu\mu$ (3)



- Optimised observables P_i with reduced hadronic uncertainties at large recoil [Matias, Mescia, Virto, SDG, Ramon, Hurth, Hofer]
- 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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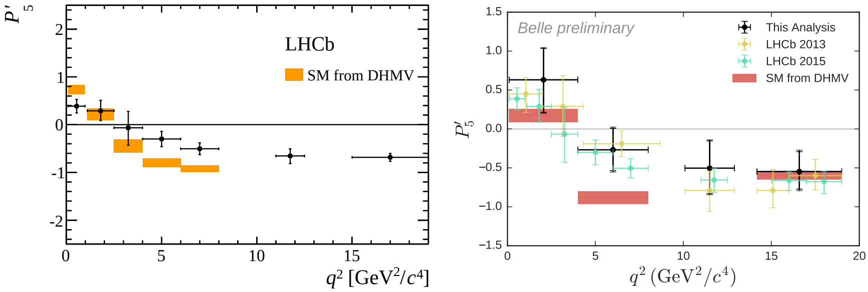

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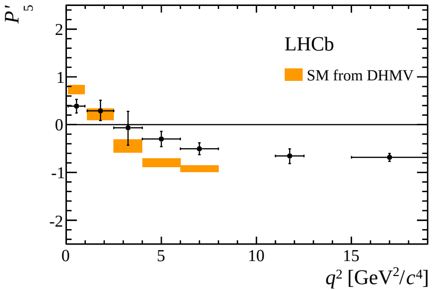

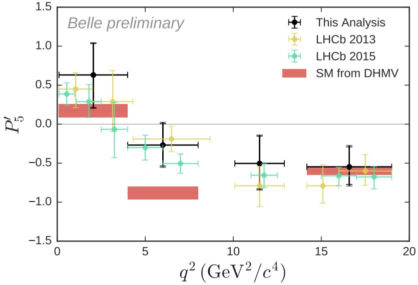

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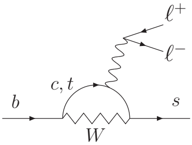
- Also deviations in $BR(B \to K^*\mu\mu)$ and $BR(B_s \to \phi\mu\mu)$ at low recoil

A more global viewpoint

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



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

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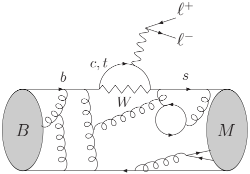

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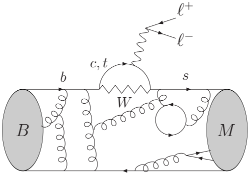

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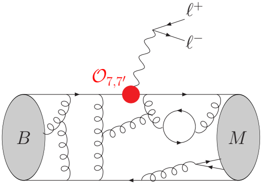

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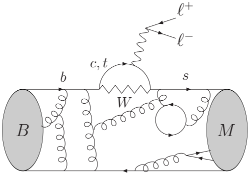

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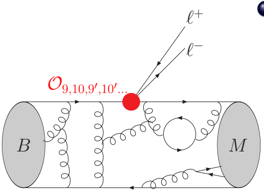
- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5) b\; \bar{\ell}\gamma^\mu\gamma_5 \ell$ [$b \to s\mu\mu$ via Z]



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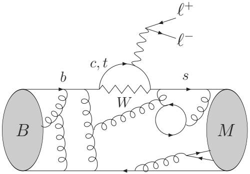

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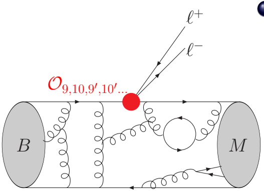

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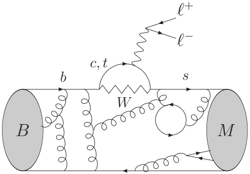

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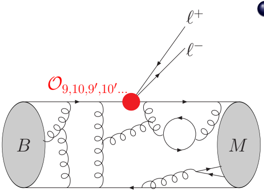

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NP changes short-distance $\mathcal{C}_i$ for SM or new long-distance ops $\mathcal{O}_i$

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

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

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

[SDG, Hofer, Matias, Virto]

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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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Frequentist analysis

- $\mathcal{C}_i(\mu_{ref}) = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$, with $\mathcal{C}_i^{NP}$ assumed to be real
- Experimental correlation matrix provided
- 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: $\chi^2(\mathcal{C}_i = 0) - \chi^2_{\rm min}$ (metrology, how far best fit from SM ?)
- p-value: $\chi^2_{\rm min}$ and N_{dof} (goodness of fit, how good is best fit ?)

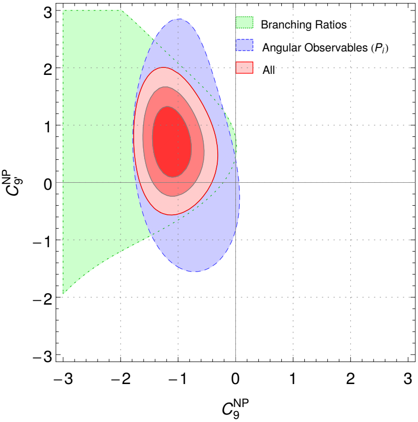
Coefficient	Best Fit Point	3σ	$\text{Pull}_{\rm SM}$	p-value (%)
SM	–	–	–	16.0
$\mathcal{C}_7^{\rm NP}$	-0.02	$[-0.07, 0.03]$	1.2	17.0
$\mathcal{C}_9^{\rm NP}$	-1.09	$[-1.67, -0.39]$	4.5	63.0
$\mathcal{C}_{10}^{\rm NP}$	0.56	$[-0.12, 1.36]$	2.5	25.0
$\mathcal{C}_9^{\rm NP} = \mathcal{C}_{10}^{\rm NP}$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

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

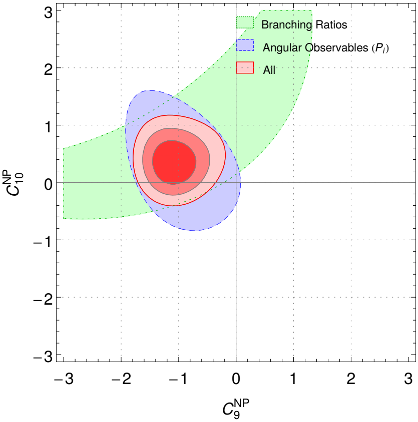
- Pull for the SM point in each scenario from $\chi^2_{\rm min} - \chi^2(\mathcal{C}_i = \mathcal{C}_j = 0)$
- p-value from $\chi^2_{\rm min}$ and N_{dof}
- several favoured scenarios, all with $\mathcal{C}_9^{\rm NP}$, hard to single out one

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)



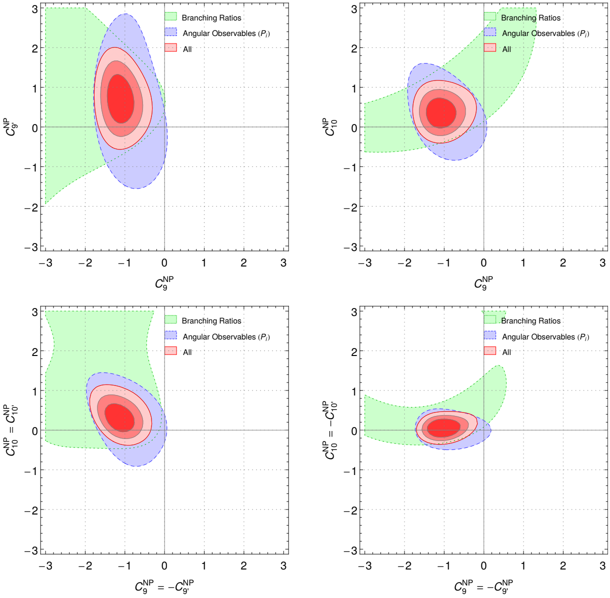
$\mathcal{C}_9^{NP}, \mathcal{C}_{9'}^{NP}$



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

- 1,2,3 σ regions
- Separately BRs and angular observables (+ $b \to s\gamma$ and inclusive)

Some favoured scenarios (2)

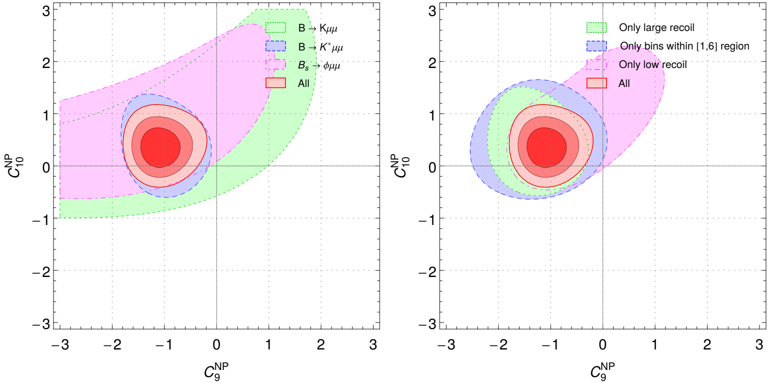


From the fit

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

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

Cross-checks: Processes, low vs large recoil



- 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]

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

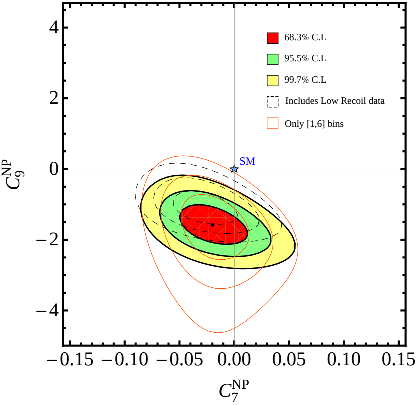
Letting all 6 Wilson coefficients vary (but only real)

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

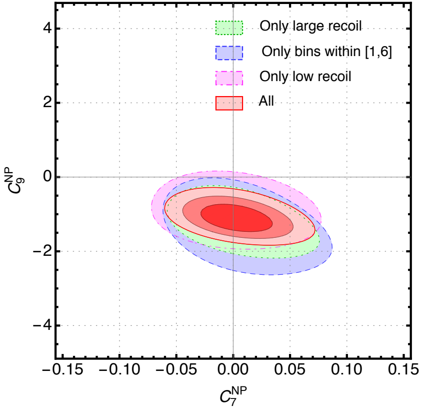
- $\mathcal{C}_9$ is consistent with SM only above 3σ
- All others are consistent with zero at 1σ except for $\mathcal{C}_{9'}$ at 2 σ
- Pull_{SM} for the 6D fit is 3.6σ

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

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

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

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

?

QCD or BSM ?

Anomalies can be a sign from many things

- unlucky statistical fluctuations

  Take more data

- underestimated syst in the experimental analysis

  Cross-checks from other experiments (Belle for P_i)

- underestimated syst in the theoretical computation

  Check and recheck the hypotheses

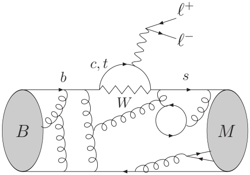
- something really new...

  Add more observables, and interpret

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

Amplitudes for exclusive decays

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



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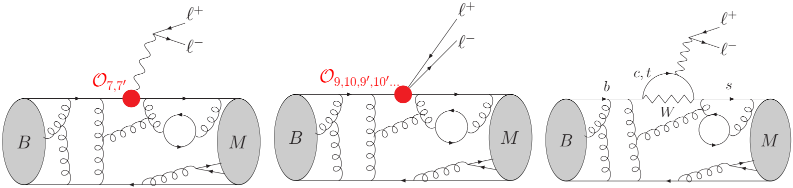

Form factors (local)

- 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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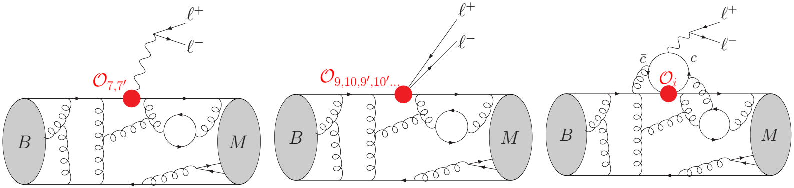

Form factors (local) Charm loop (non-local)

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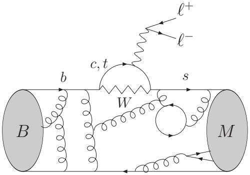
$$B_\mu = \mathcal{C}_{10}\langle V_\lambda|\bar{s}\gamma_\mu P_L b|B\rangle \qquad \lambda: K^* \text{ helicity}$$

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

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

Controversies: form factors and power corrs



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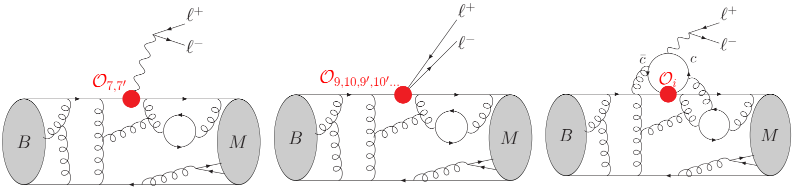

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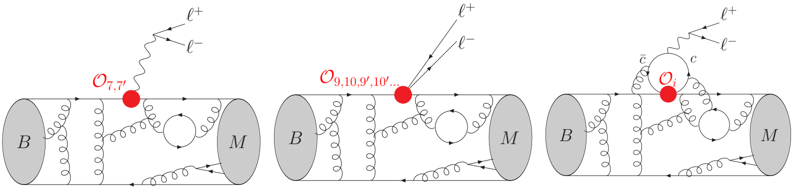
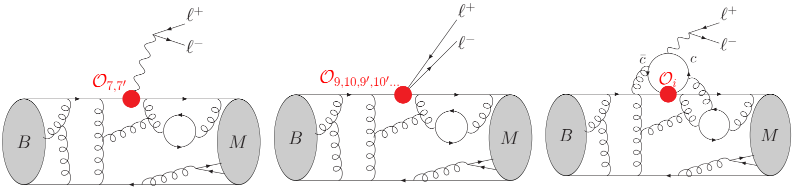


Form factors (local) Charm loop (non-local)

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

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

Controversies: form factors and power corrs



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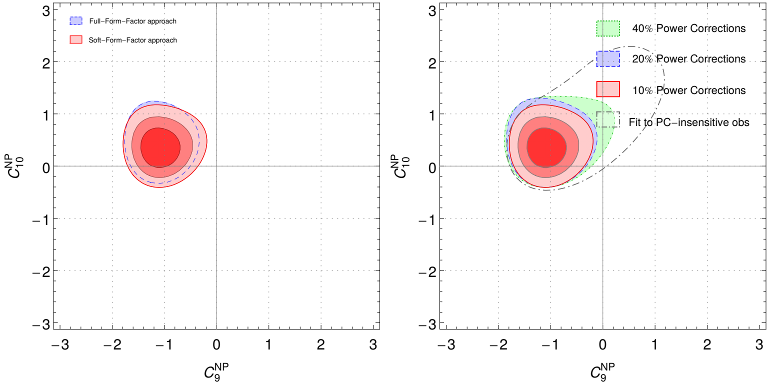
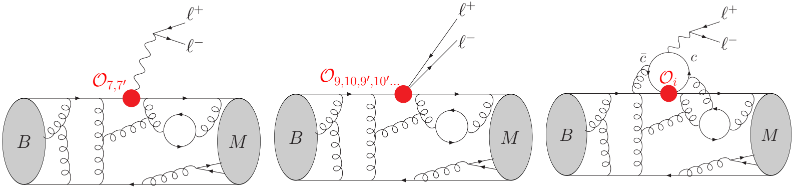
- EFT with limit $m_b \to \infty$ useful to correlate form factors with $O(\Lambda/m_b)$ power corrections to this limit
- Corrections with large impact on optimised observables ?
- No, but accurate predictions require
  - appropriate definition of form factors in $m_b \to \infty$ limit
  - power corrections varied in agreement with info on form factors
  - proper propagation of correlations induced among form factors

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)
- Increasing size of power corrections weakens role of large recoil, but low recoil enough to pull fit away from the SM

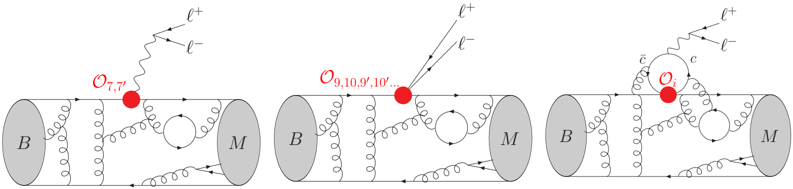
Controversies: charm loops



Form factors (local)

Charm loop (non-local)

Controversies: charm loops



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

Uncertainties from charm loops

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

- Effect well-known (loop process, charmonium resonances)
- Yields q^2- and hadron-dependent contrib with $\mathcal{O}_{7,9}$-like structures
  - order of magnitude from [Khodjamirian et al.] used in [SDG, Hofer, Matias, Virto]
  - other global fits use q^2-dependent param. with $O(\Lambda/m_b)$ estimates

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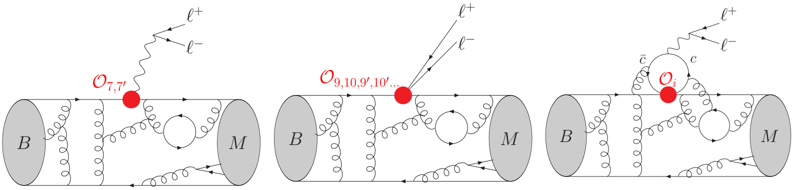

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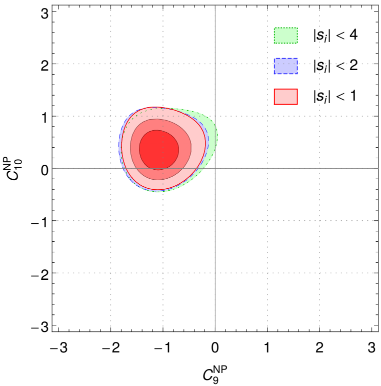
  - other global fits use q^2-dependent param. with $O(\Lambda/m_b)$ estimates
- Bayesian extraction from data performed by [Ciuchini et al.]
  - q^2-dependence present (as expected), apparently signficant
  - actually not contradicting results of global fits, though less precise

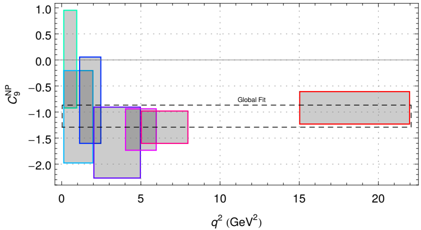
Cross-checks: charm loops (1)



- Estimates of charm loops from [Khodjamirian, Mannel, Pivovarov, Wang] $\Delta\mathcal{C}_9^{BK(*),i}$ for each $B \to K^*\mu\mu$ transversity
- Use it as an order of magnitude $\Delta\mathcal{C}_9^{BK(*),i} = \delta\mathcal{C}_{9,\mathrm{pert}}^{BK(*),i} + s_i\delta\mathcal{C}_{9,\mathrm{non\ pert}}^{BK(*),i}$ ($s_i = 1$ corresponds to [Khodjamirian, Mannel, Pivovarov, Wang])
- Ditto for $B_s \to \phi$, with all 6 s_i independent, and very small for $B \to K\mu\mu$, $c\bar{c}$

- 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: charm loops (2)



- $\mathcal{C}_9^{NP}$ 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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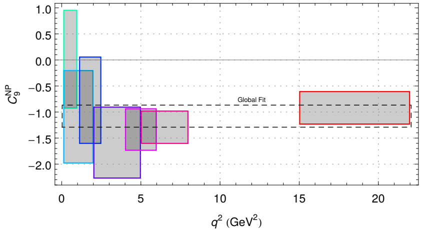

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  - NP in $\mathcal{C}_9$ from short distances, q^2-independent
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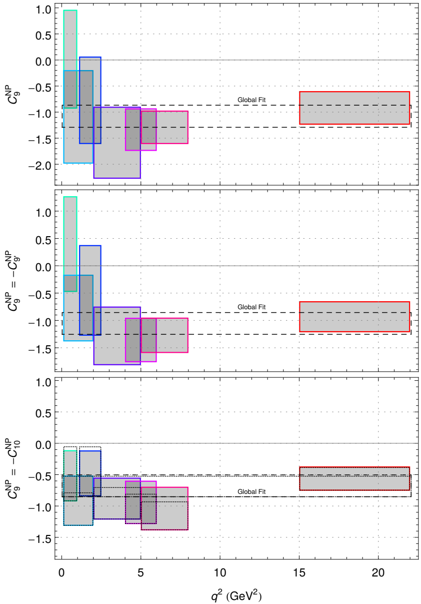

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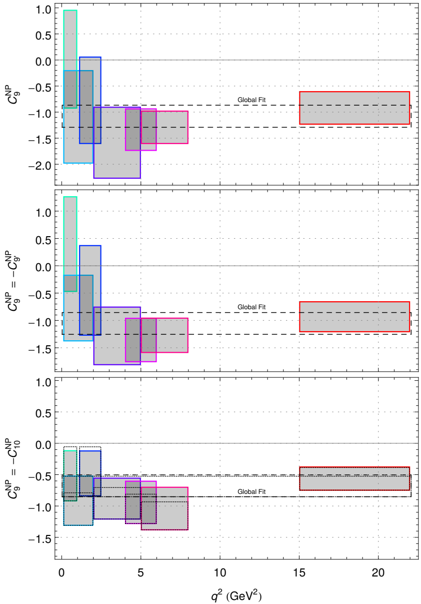

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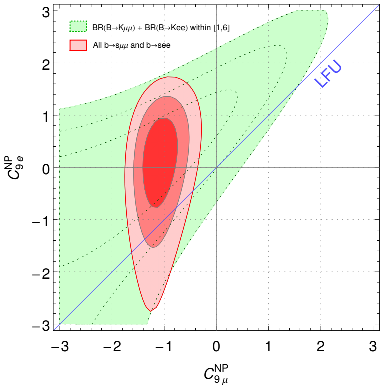
- Mid, down: correlated shift in $\mathcal{C}_9$ and other $\mathcal{C}_i$ (never q^2-depend: are NP scenarios consistent ?)
- No indication of q^2-dependent contribution

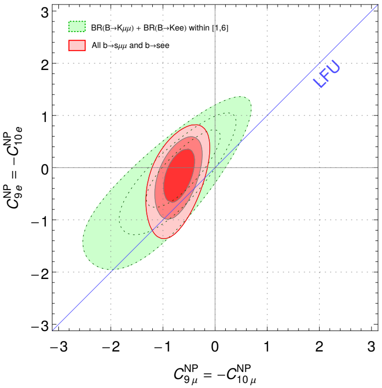
Looking for more inputs

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 $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}$ which does not explain R_K)



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



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

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

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
$\mathcal{C}_9^{\rm NP}$	$+$					
	$-$	✓	✓	✓	✓	X
$\mathcal{C}_{10}^{\rm NP}$	$+$	✓		✓	✓	X
	$-$		✓			
$\mathcal{C}_{9'}^{\rm NP}$	$+$			✓	✓	X
	$-$	✓	✓			
$\mathcal{C}_{10'}^{\rm NP}$	$+$	✓	✓			
	$-$			✓	✓	X

- $\mathcal{C}_9^{\rm NP} < 0$ 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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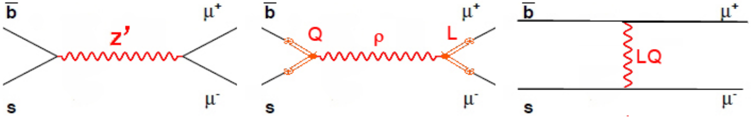
NP models with new scale around TeV

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
$\mathcal{C}_9^{NP} = -1.11$	0.79 ± 0.01	0.87 ± 0.08	$[0.84 \pm 0.02]$	0.84 ± 0.02
$\mathcal{C}_9^{NP} = -\mathcal{C}_{9'}^{NP} = -1.09$	1.00 ± 0.01	0.79 ± 0.14	$[0.74 \pm 0.04]$	0.74 ± 0.03
$\mathcal{C}_9^{NP} = -\mathcal{C}_{10}^{NP} = -0.69$	0.67 ± 0.01	0.71 ± 0.03	$[0.69 \pm 0.01]$	0.69 ± 0.01
$\mathcal{C}_9^{NP} = -1.15, \mathcal{C}_{9'}^{NP} = 0.77$	0.91 ± 0.01	0.80 ± 0.12	$[0.76 \pm 0.03]$	0.76 ± 0.03
$\mathcal{C}_9^{NP} = -1.16, \mathcal{C}_{10}^{NP} = 0.35$	0.71 ± 0.01	0.78 ± 0.07	$[0.75 \pm 0.02]$	0.76 ± 0.01
$\mathcal{C}_9^{NP} = -1.23, \mathcal{C}_{10'}^{NP} = -0.38$	0.87 ± 0.01	0.79 ± 0.11	$[0.75 \pm 0.02]$	0.76 ± 0.02
$\mathcal{C}_9^{NP} = -\mathcal{C}_{9'}^{NP} = -1.14$, $\mathcal{C}_{10}^{NP} = -\mathcal{C}_{10'}^{NP} = 0.04$	1.00 ± 0.01	0.78 ± 0.13	$[0.74 \pm 0.04]$	0.74 ± 0.03
$\mathcal{C}_9^{NP} = -\mathcal{C}_{9'}^{NP} = -1.17$, $\mathcal{C}_{10}^{NP} = \mathcal{C}_{10'}^{NP} = 0.26$	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 $b \to s\mu\mu$
- $\mathcal{C}_9^{NP} = -\mathcal{C}_{10}^{NP}$ 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

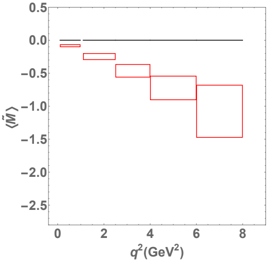
[Capdevilla, Matias, Virto, SDG]

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

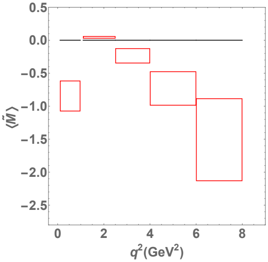
- Null SM tests (up to m_ℓ effects): $Q_i = P_i^\mu - P_i^e$, $\quad B_i = \frac{J_i^\mu}{J_i^e} - 1$
- J_5 and J_{6s} with only a linear dependence on $\mathcal{C}_9$

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

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

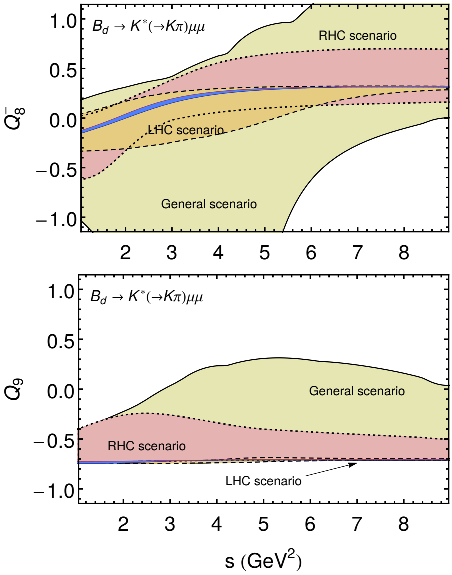


$\mathcal{C}_{9\mu}^{\rm NP} = -1.1, \mathcal{C}_{ie}^{\rm NP} = 0$



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

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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