New physics in semileptonic B decays (?)

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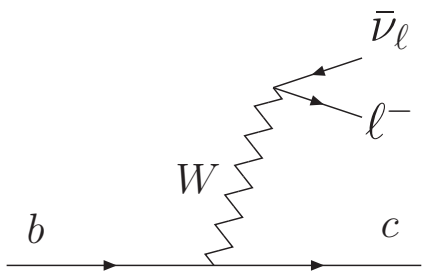
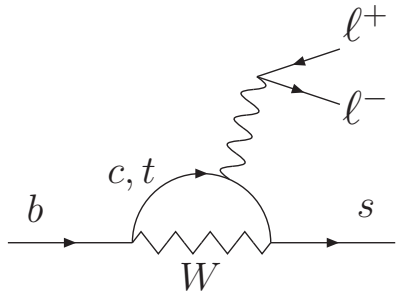
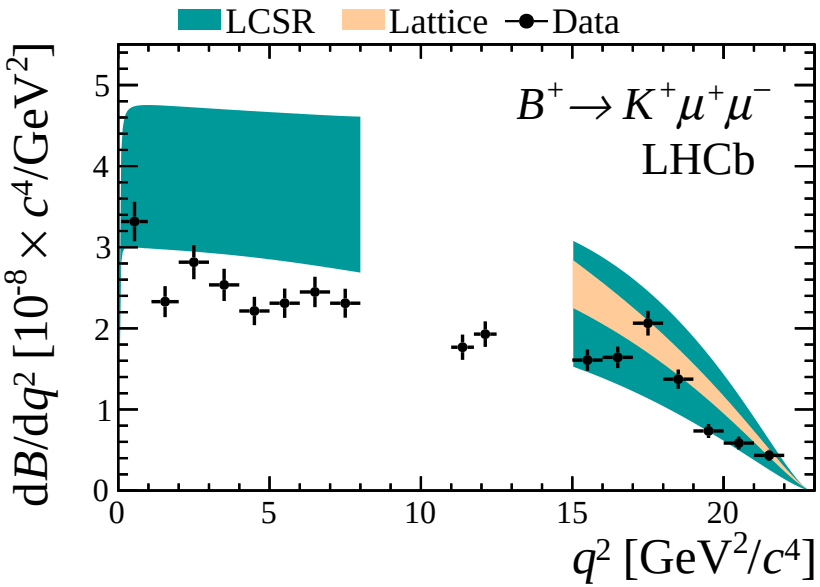
From scattered anomalies to an emerging pattern

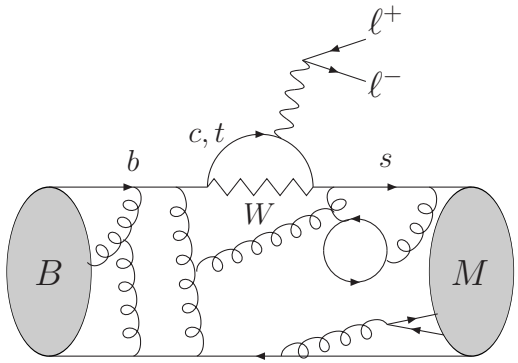
Interesting Flavour-Changing Currents

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

Two transitions exhibiting interesting patterns of deviations from SM

Anomalies in $B \to K\ell\ell$





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

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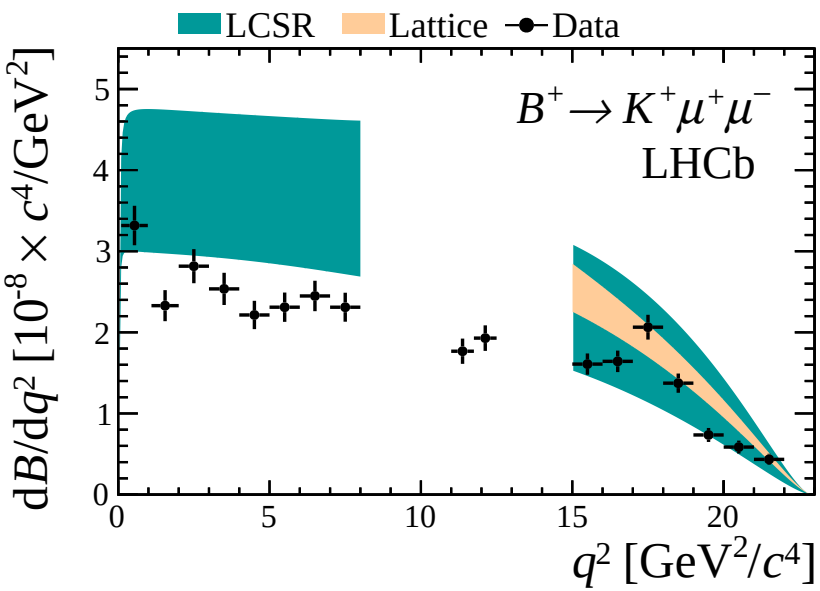
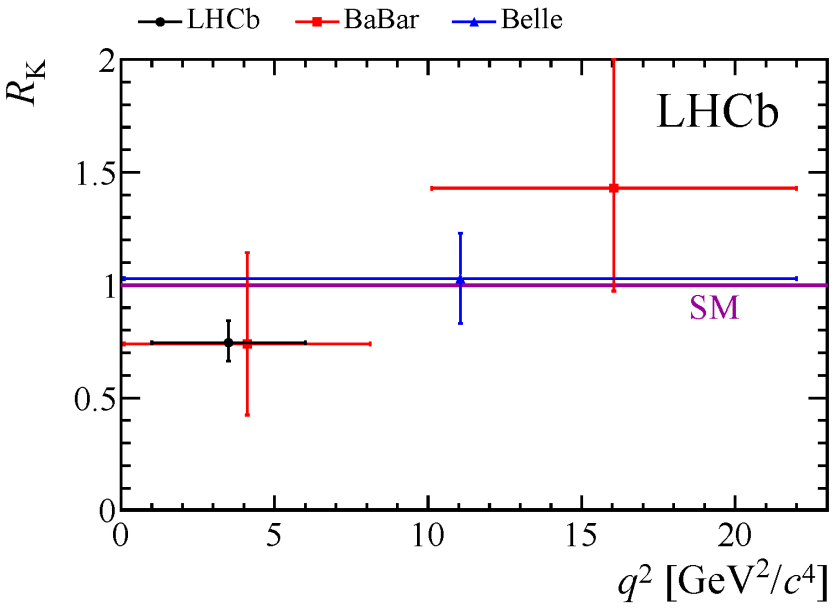
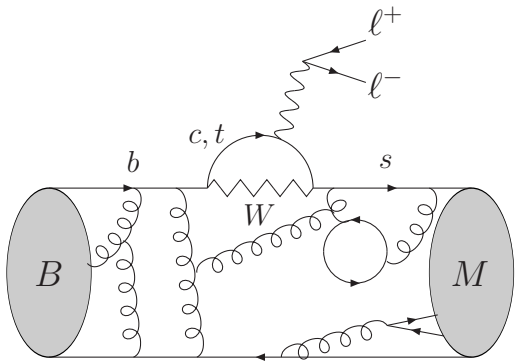
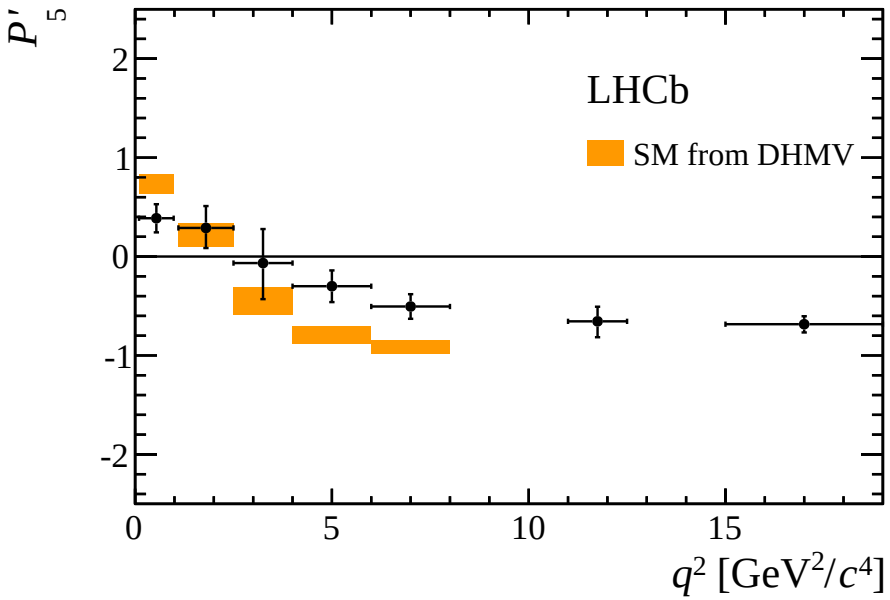






- $Br(B \to K\mu\mu)$ too low compared to SM
- $R_K = \left.\frac{Br(B\to K\mu\mu)}{Br(B\to Kee)}\right|_{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$
- equals to 1 in SM (universality of lepton coupling), 2.6 σ dev
- would require NP coupling differently to μ and e

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



- Optimised observables P_i with reduced hadronic uncertainties

  [Matias, Krüger, Becirevic, Schneider, Mescia, Virto, SDG, Ramon, Hurth; Hiller, Bobeth, Van Dyk. . .]
- Measured at LHCb with 1 fb^{-1} (2013) and 3 fb^{-1} (2015)
- Discrepancies for some (but not all) observables,
  in particular two bins for P'_5 deviating from SM by 2.8 σ and 3.0 σ

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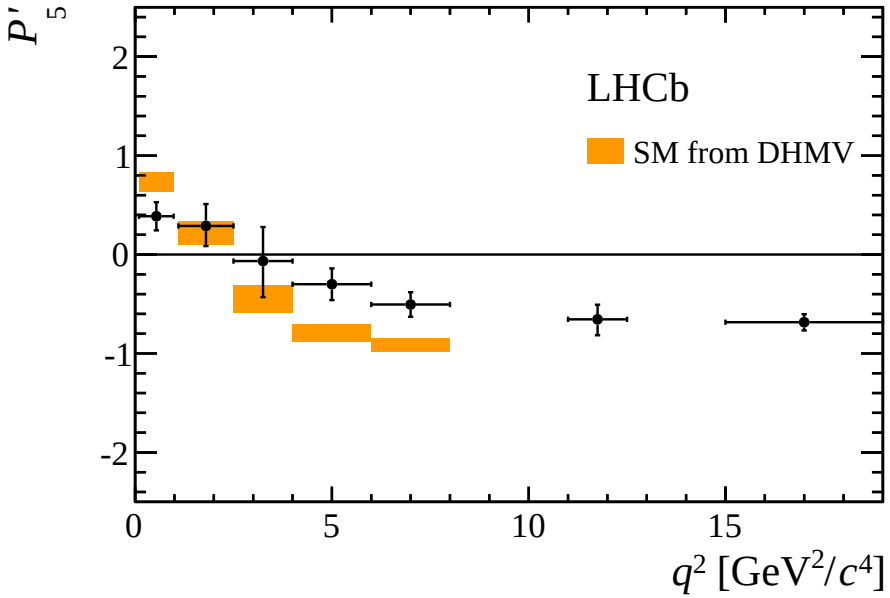

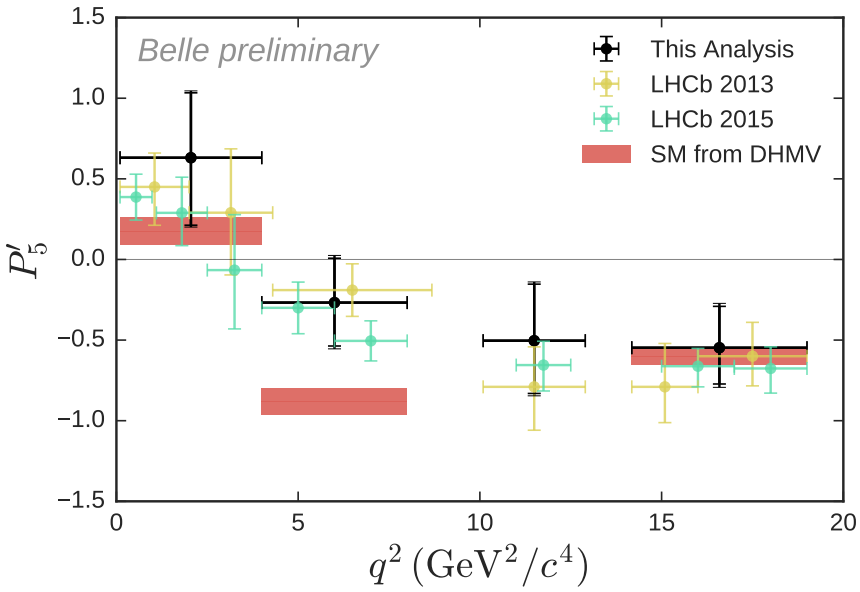

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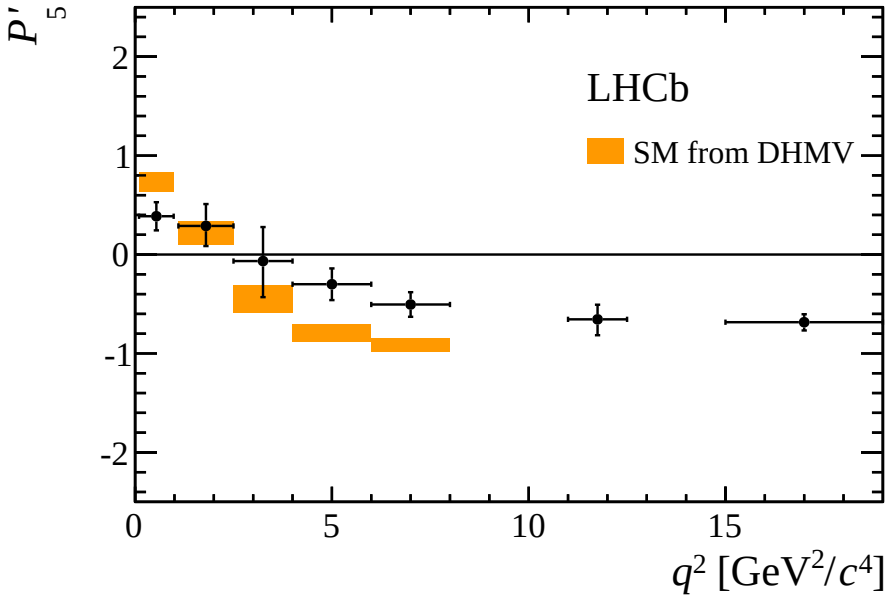

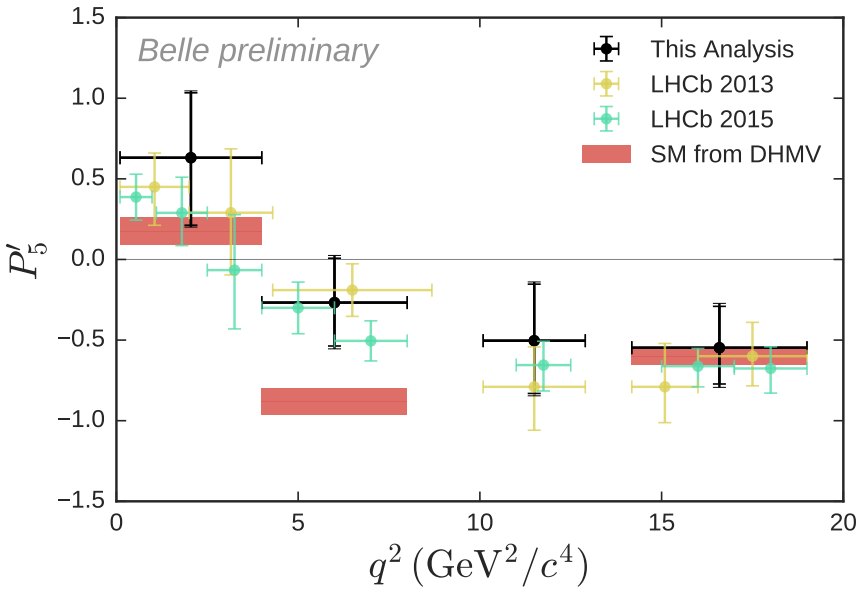

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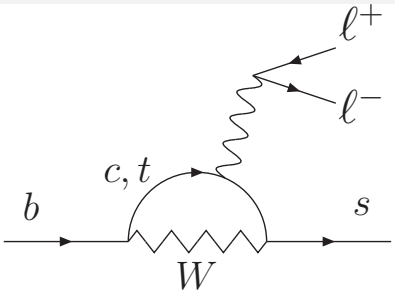
- Discrepancies for some (but not all) observables,
  in particular two bins for P'_5 deviating from SM by 2.8 σ and 3.0 σ
- . . . confirmed by Belle a few months ago
- Also deviations in $BR(B \to K^* \mu\mu)$ and $BR(B_s \to \phi\mu\mu)$ at low recoil

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



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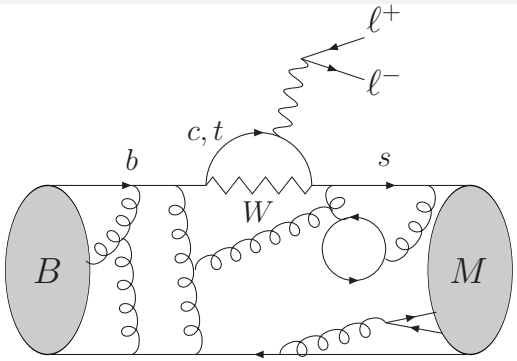

$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\Delta F=1} \propto \sum V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i + \dots$$

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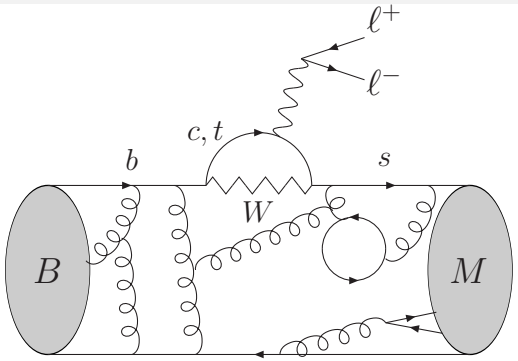

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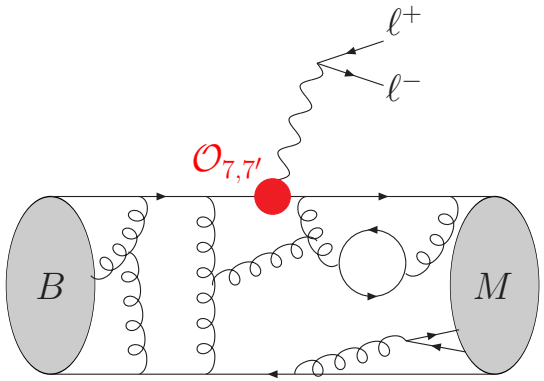
- $\mathcal{O}_7 = \frac{e}{g^2} m_b \, \bar{s} \sigma^{\mu\nu} (1+\gamma_5) F_{\mu\nu} \, b$ [real or soft photon]



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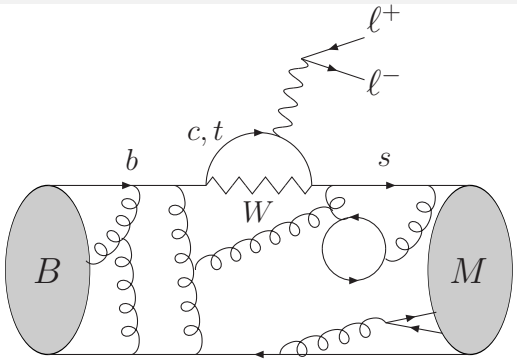

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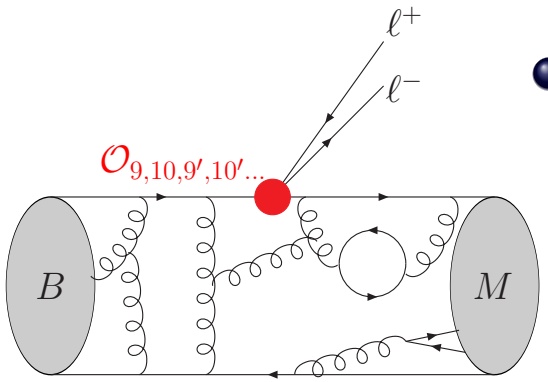
- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s} \gamma_\mu (1-\gamma_5) b \, \bar{\ell} \gamma^\mu \gamma_5 \ell$ [$b \to s\mu\mu$ via Z]



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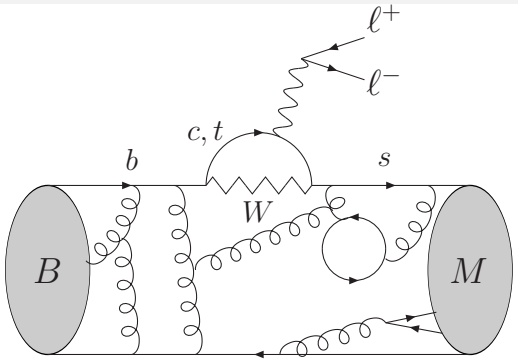

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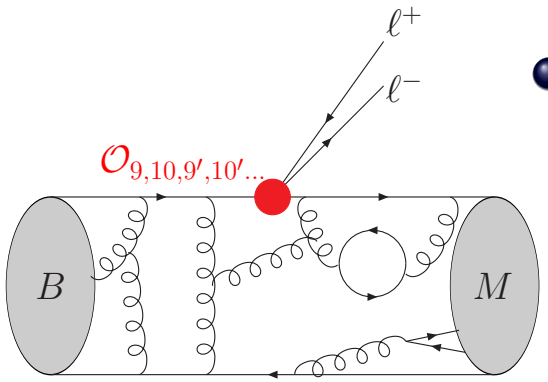

$\mathcal{C}_7^{\rm SM} = -0.29$, $\mathcal{C}_9^{\rm SM} = 4.1$, $\mathcal{C}_{10}^{\rm SM} = -4.3$ @ $\mu_b = m_b$

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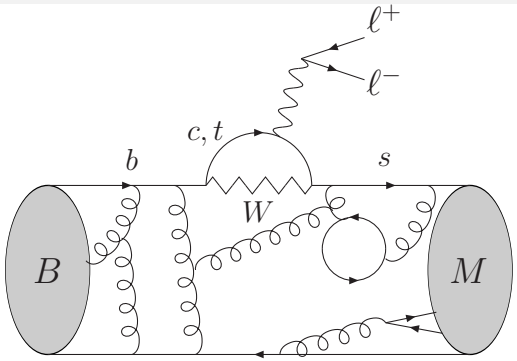

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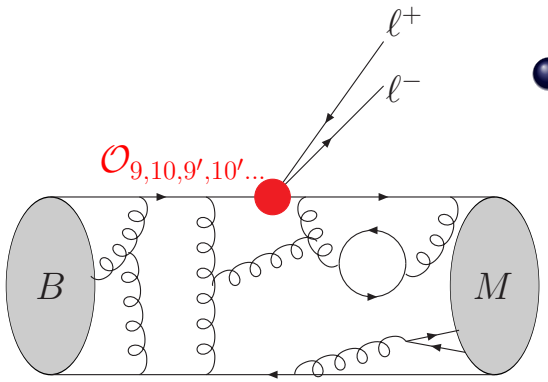

$$\mathcal{C}_7^{\rm SM} = -0.29, \; \mathcal{C}_9^{\rm SM} = 4.1, \; \mathcal{C}_{10}^{\rm SM} = -4.3 \; @ \; \mu_b = m_b$$

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

Pattern of operators $\leftrightarrow$ type of NP at work

Global analysis of $b \to s\ell\ell$ anomalies (SDG, L. Hofer, J. Matias, J. Virto)

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

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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)
- $B \to X_s \gamma$, $B \to X_s \mu\mu$, $B_s \to \mu\mu$
- $B \to K^* \gamma$ (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
- Exp. correls. provided ($B \to K(^*)$) and/or error propag. ($B_s \to \phi$)
- Th. correlation matrix treating all th errors as Gaussian

$b \to s\mu\mu$: 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 ?)
- contribution to $\mathcal{C}_9$ always favoured

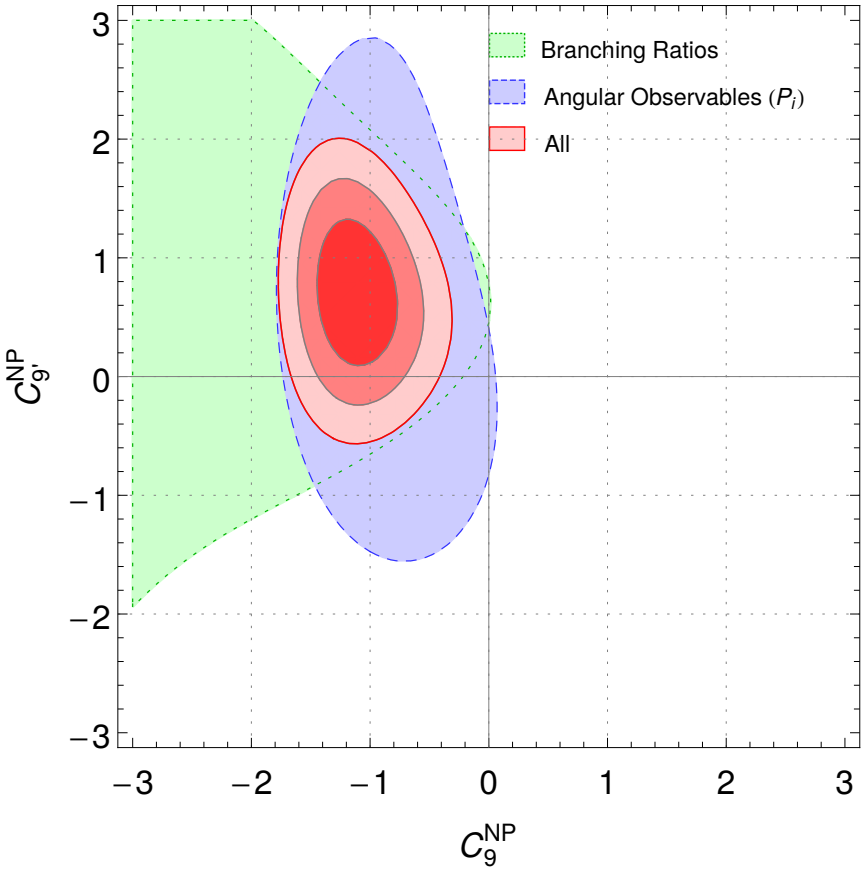
Coefficient	Best Fit Point	3σ	$\text{Pull}_{\rm SM}$	p-value (%)
SM	–	–	–	16.0
$\mathcal{C}_7^{\rm NP}$	−0.02	$[-0.07, 0.03]$	1.2	17.0
$\mathcal{C}_9^{\rm NP}$	−1.09	$[-1.67, -0.39]$	4.5	63.0
$\mathcal{C}_{10}^{\rm NP}$	0.56	$[-0.12, 1.36]$	2.5	25.0
$\mathcal{C}_9^{\rm NP} = \mathcal{C}_{10}^{\rm NP}$	−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

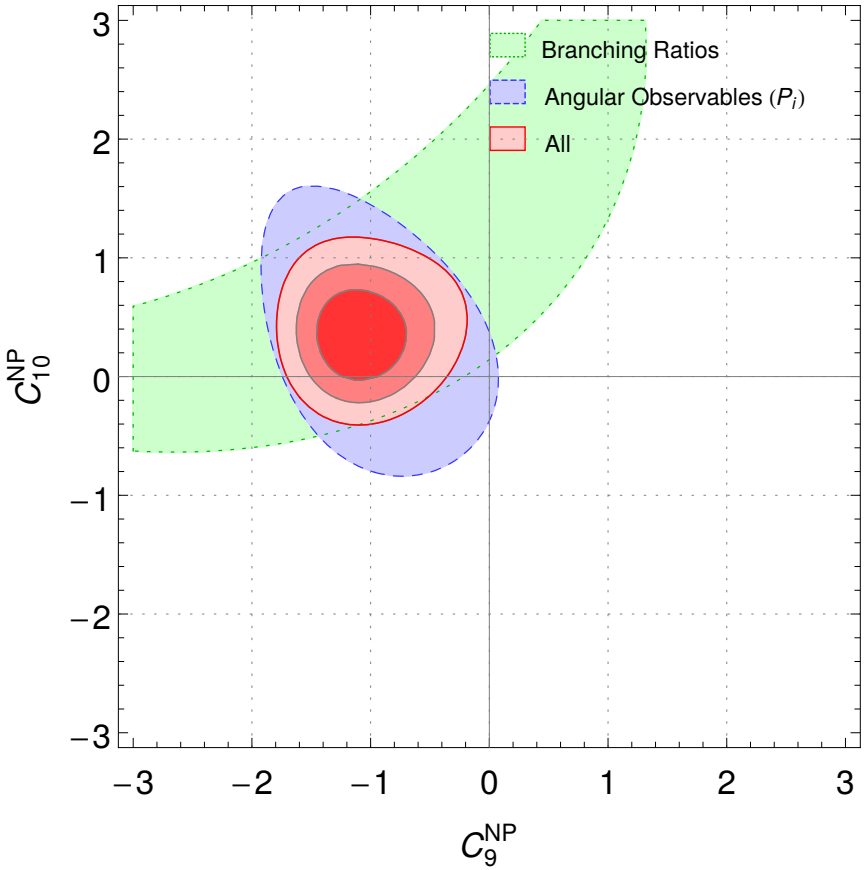
- Pull for the SM point in each scenario from $\chi^2_{\rm min} - \chi^2(\mathcal{C}_i = \mathcal{C}_j = 0)$
- *p*-value from $\chi^2_{\rm min}$ and N_{dof}
- several favoured scenarios, all with $\mathcal{C}_9^{\rm NP}$, hard to distinguish

Coefficient	Best Fit Point	$\text{Pull}_{\rm SM}$	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



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



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

- p-value=71% (goodness of fit), pull$_{SM} = 4.5\sigma$ (metrology)
- BRs and angular obs both favour $\mathcal{C}_9^{NP} \simeq -1$ in all "good" scenarios
- results in agreement with [Altmanshoffer, Straub] and [Hurth, Mahmoudi, Neshatpour]

$$C_9^{\text{NP}} \ldots$$

$$C_9^{\text{New Physics}} \text{ or } C_9^{\text{Non Perturbative}}$$

?

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

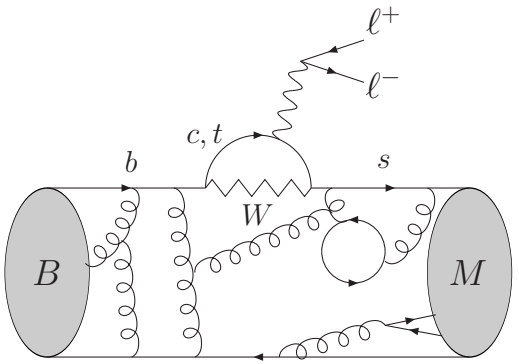
- something really new. . .

  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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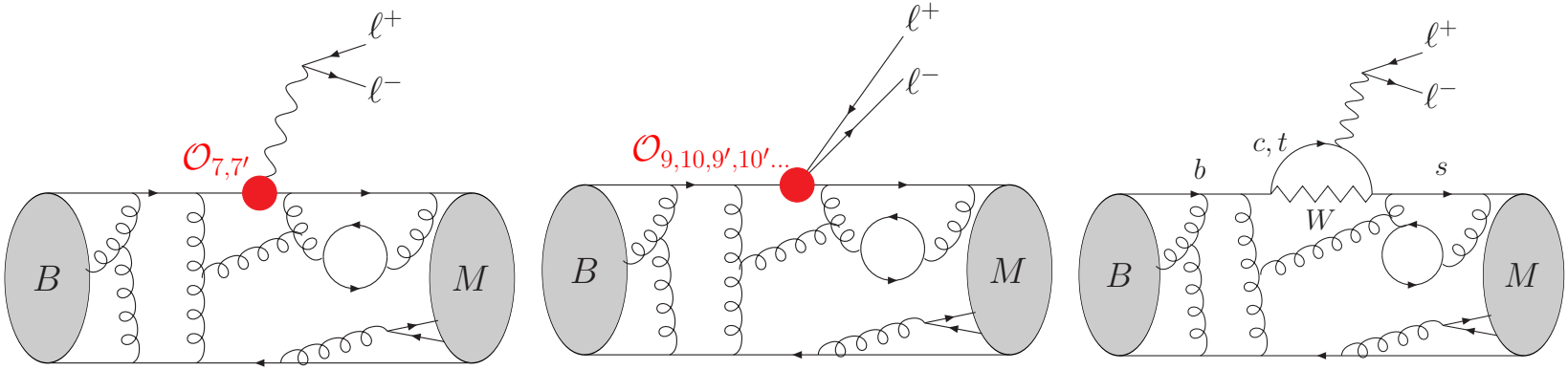

Form factors (local)

- 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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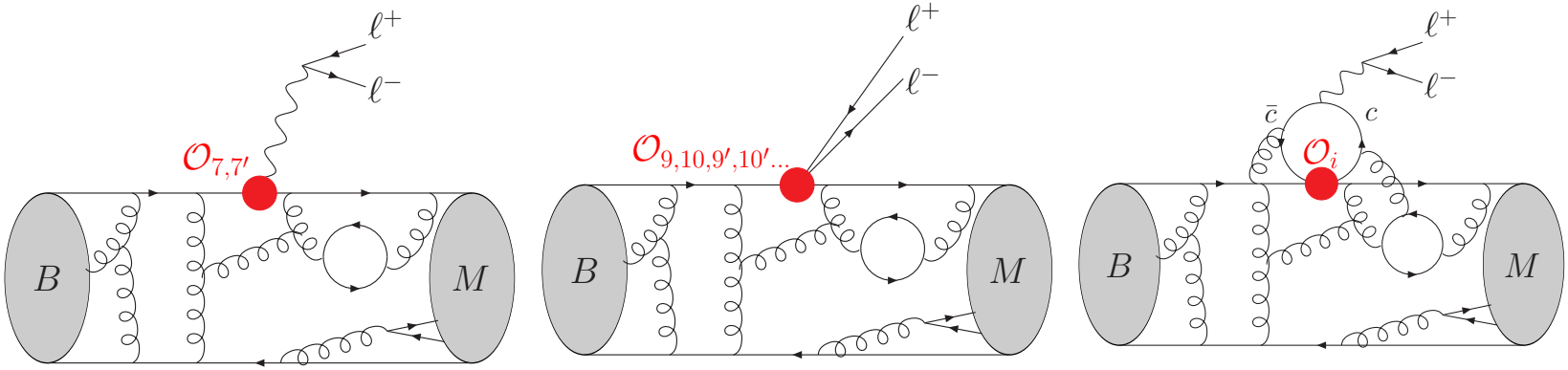

Form factors (local) Charm loop (non-local)

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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.

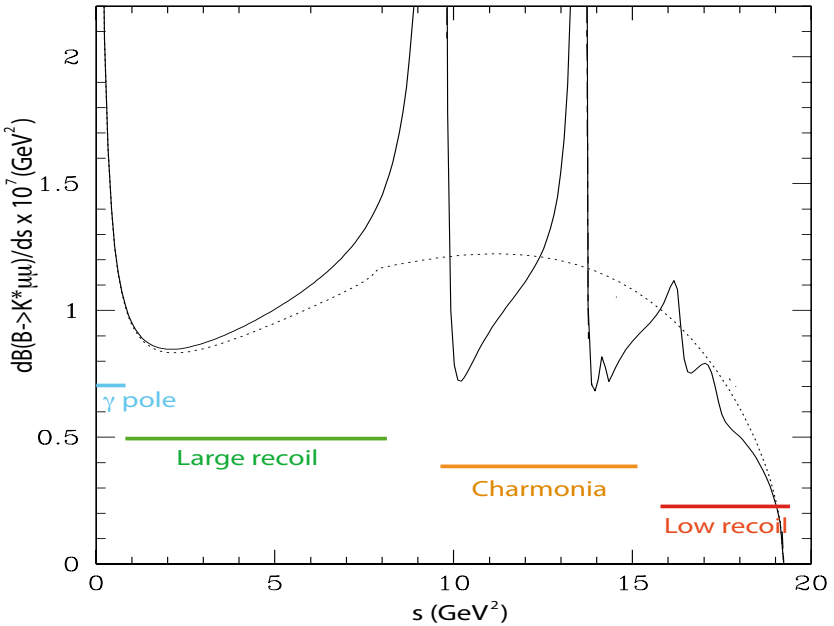
T_μ contributes like $\mathcal{O}_{7,9}$, but depends on q^2 and external states

Different approaches for three global fits

	[SDG, Hofer Matias, Virto]	[Straub & Altmannshofer]	[Hurth, Mahmoudi, Neshatpour]
Statistical approach	Frequentist $\Delta\chi^2$	Frequentist $\Delta\chi^2$	Frequentist $\Delta\chi^2$ & χ^2
Data $B \to K^* \mu\mu$ 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
$c\bar{c}$ loop	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

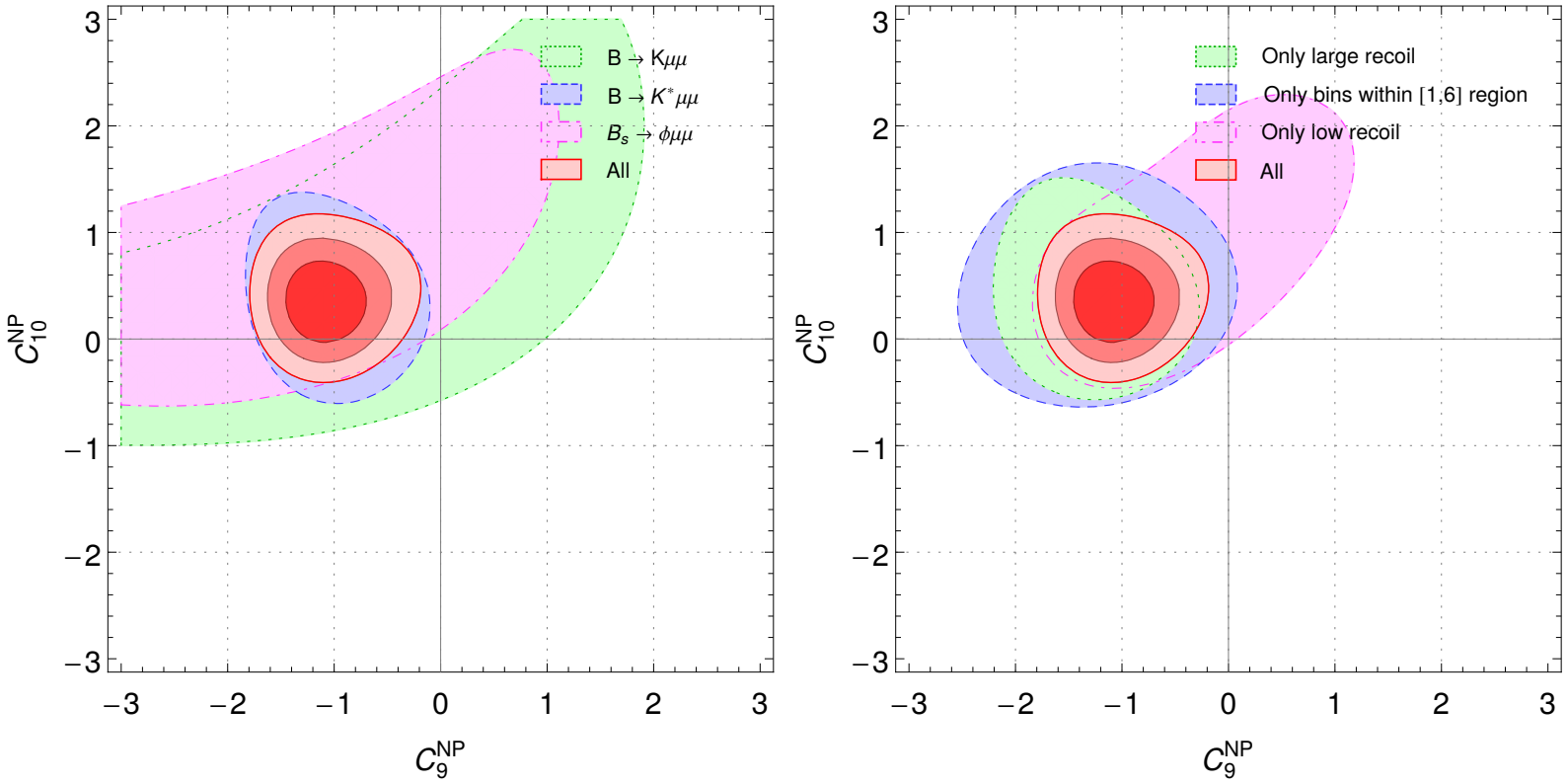
Four different regions



- 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)
- 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)

$\Longrightarrow$ different theoretical approaches/inputs for low and large recoils

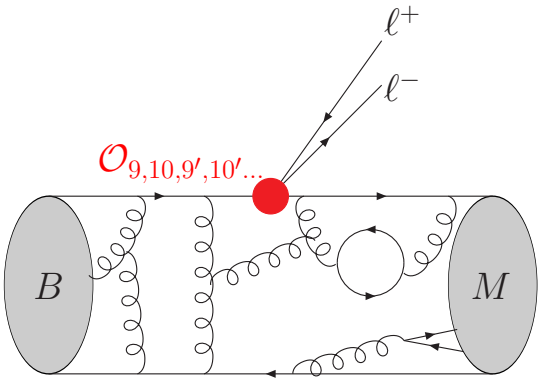
Cross-checks: Low and large recoils



- $B \to K^* \mu\mu$ 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 $\mathcal{C}_9^{\rm NP} < 0$

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

Form factors and EFT



7 form factors: V (vector), $A_{0,1,2}$ (axial) and $T_{1,2,3}$ (tensor)
but possible to split soft $O(\Lambda)$ and hard $O(m_b)$ physics via EFT

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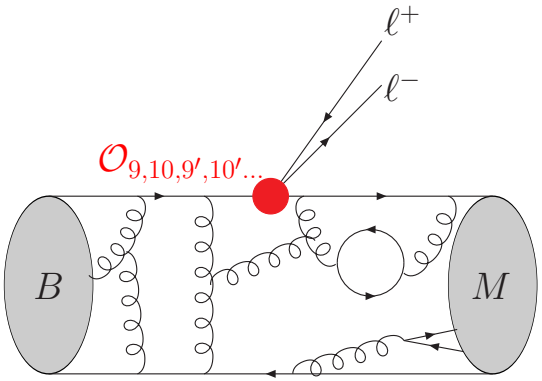

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Large recoil of the meson $(\Lambda \ll E_V \sim m_B)$

- 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 $\xi_{||}(q^2)$
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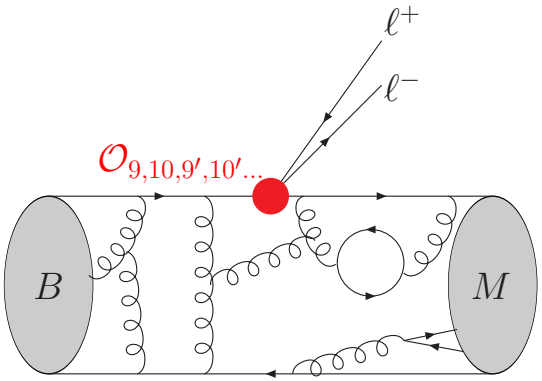

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- Amplitudes computed in QCD factorisation

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 $O(\Lambda/m_B)$
- Amplitudes computed using Operator Product Expansion

Correlating 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]

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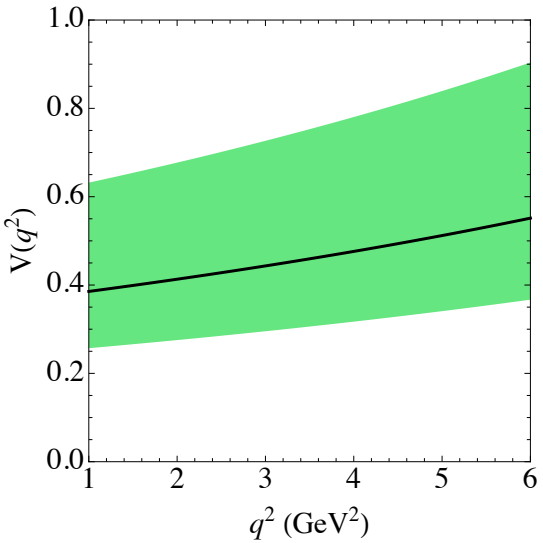
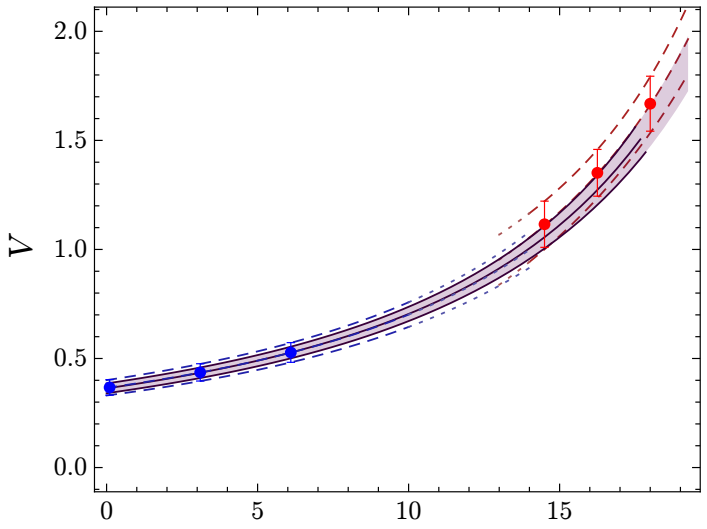


KMPW (LCSR, low q^2)



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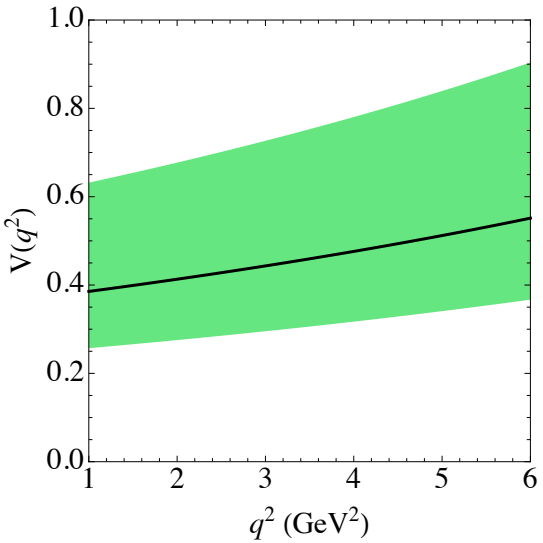

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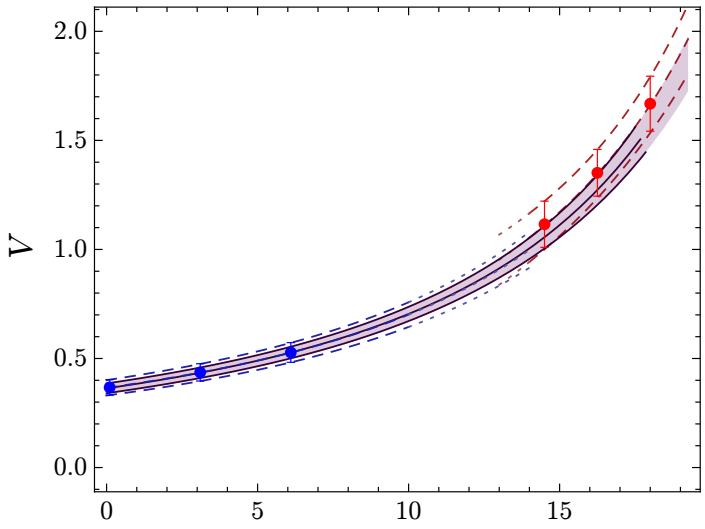

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Reduce uncertainties thanks to correls among ffs from $m_b \to \infty$, e.g.

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

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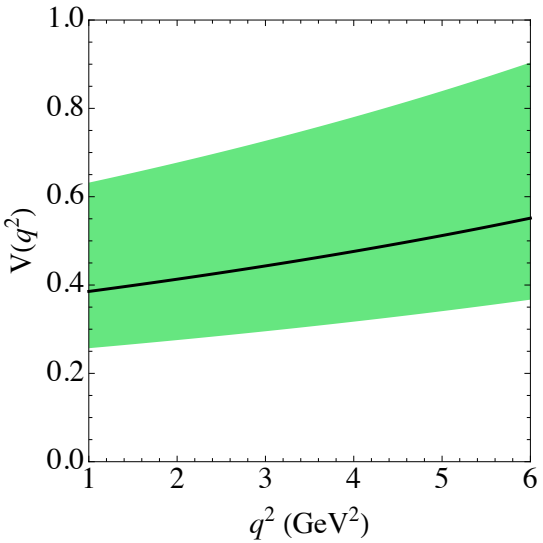

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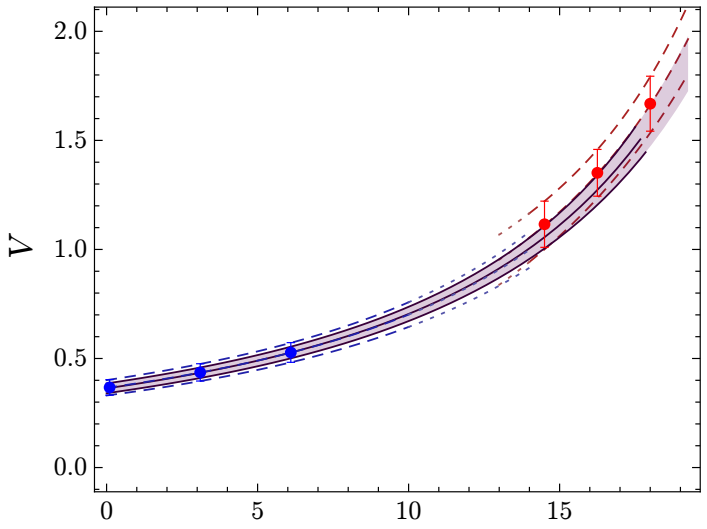

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$+O(\alpha_s)$ and
$O(\Lambda/m_b)$ corrections

Controversies: Form factors and power corrs (1)

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

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

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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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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] [Capdevila, SDG, Hofer, Matias]

1. Scheme to define $\xi_{||,\perp}$
   potential overestimation of impact of power corrections
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   potential underestimation of soft form factor uncertainties
3. Estimate of power corrections
   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 unc. should cancel less efficiently in F_L (not optimised) than P_5' (optimised: soft form factors cancel at LO)

More on scheme dependence in back-up slides

Charm-loop effects : resonances

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

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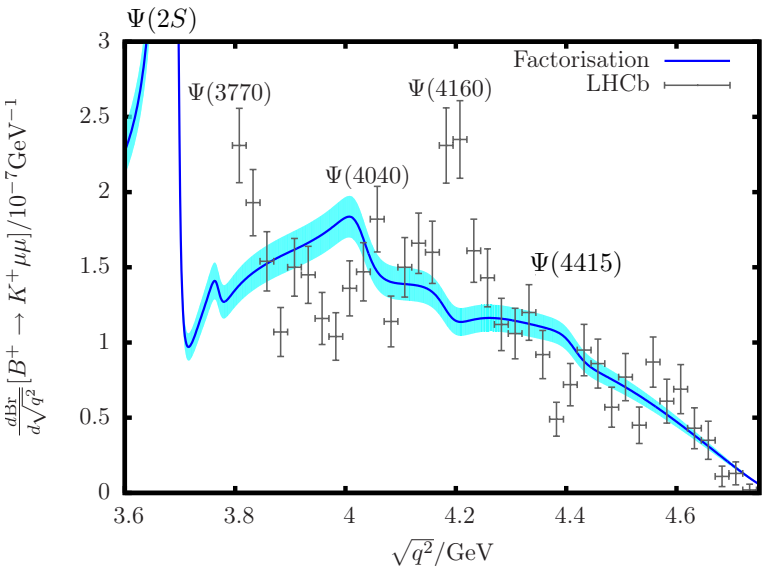

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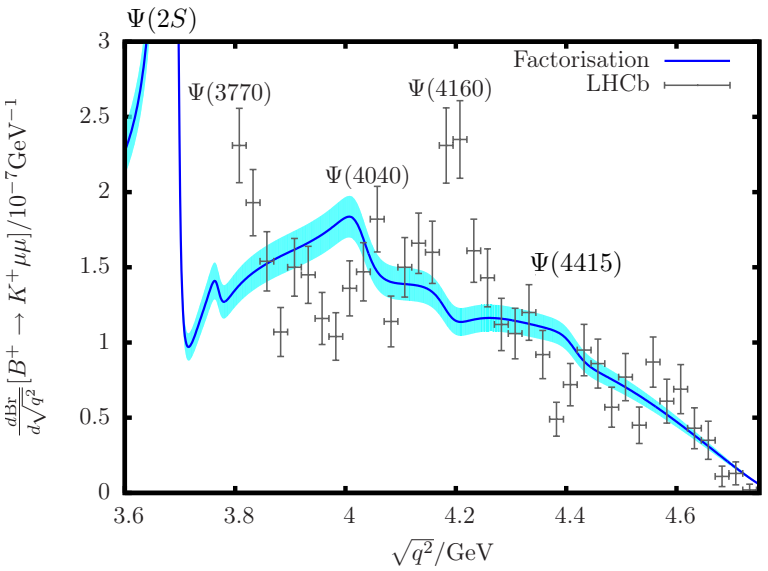

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- Large recoil
  - $q^2 \leq$ 7-8 GeV^2 to limit the impact of J/ψ tail
  - Still need to include the effect of $c\bar{c}$ loop (tail of resonances + nonresonant)

Charm-loop effects: large recoil

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

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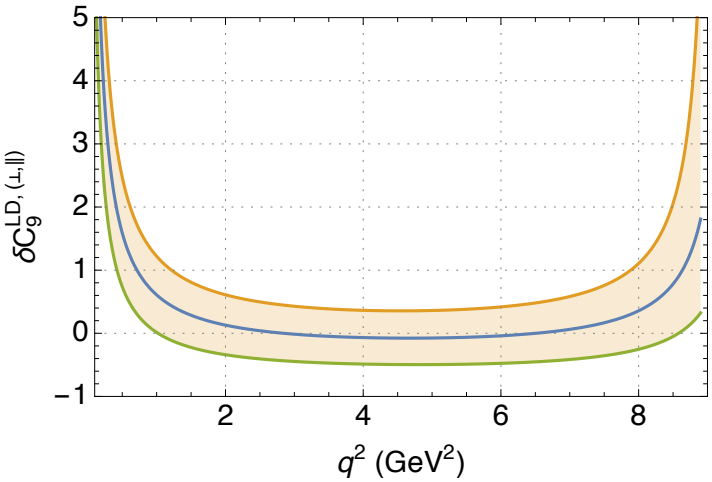
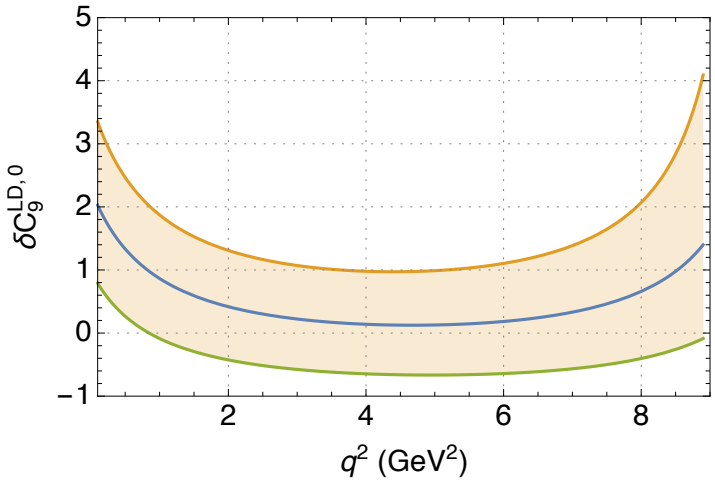
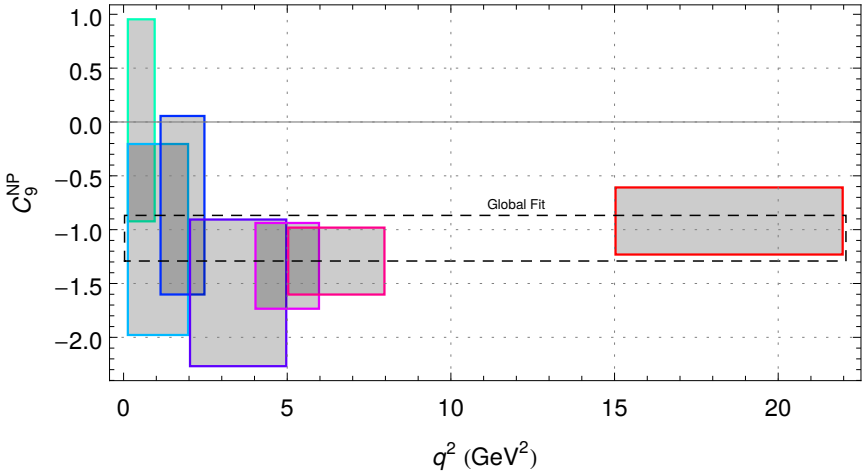
  - higher-order short-distance QCD via QCDF/HQET
- Long-distance (soft gluons)
  - $\Delta\mathcal{C}_9^{BK^{(*)},i} > 0$ $(i = 0, ||, \perp)$ using LCSR [Khodjamirian, Mannel, Pivovarov, Wang]
  - Computed for $q^2 < 0$ and small, then extrapolated through dispersion relation reincluding J/ψ (but many unknown parameters)
  - For us, order of magnitude: $\Delta\mathcal{C}_9^{BK^*}\big|_{KMPW} = \delta\mathcal{C}_{9,\mathrm{SD}}^{BK^{(*)}} + \delta\mathcal{C}_{9,\mathrm{LD}}^{BK^{(*)}}$
    taking $\Delta\mathcal{C}_9^{BK^*,i} = \delta\mathcal{C}_{9,\mathrm{SD}}^{BK^{(*)},i} + s_i\, \delta\mathcal{C}_{9,\mathrm{LD}}^{BK^{(*)},i}$ with $s_i = 0 \pm 1$





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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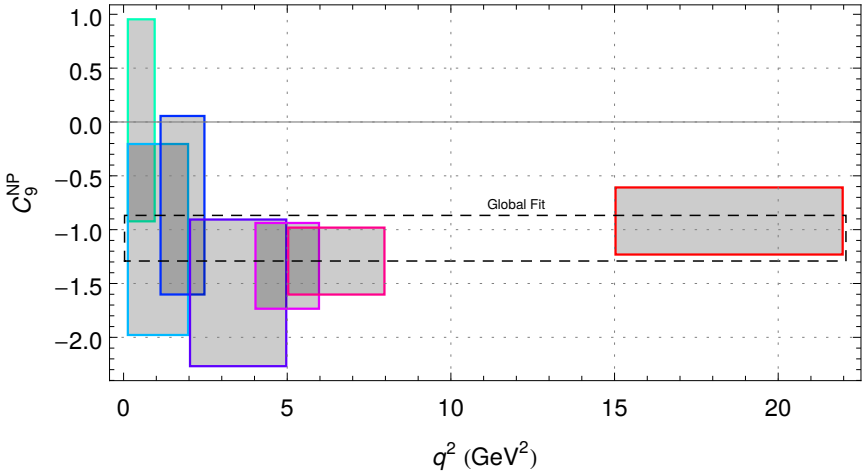

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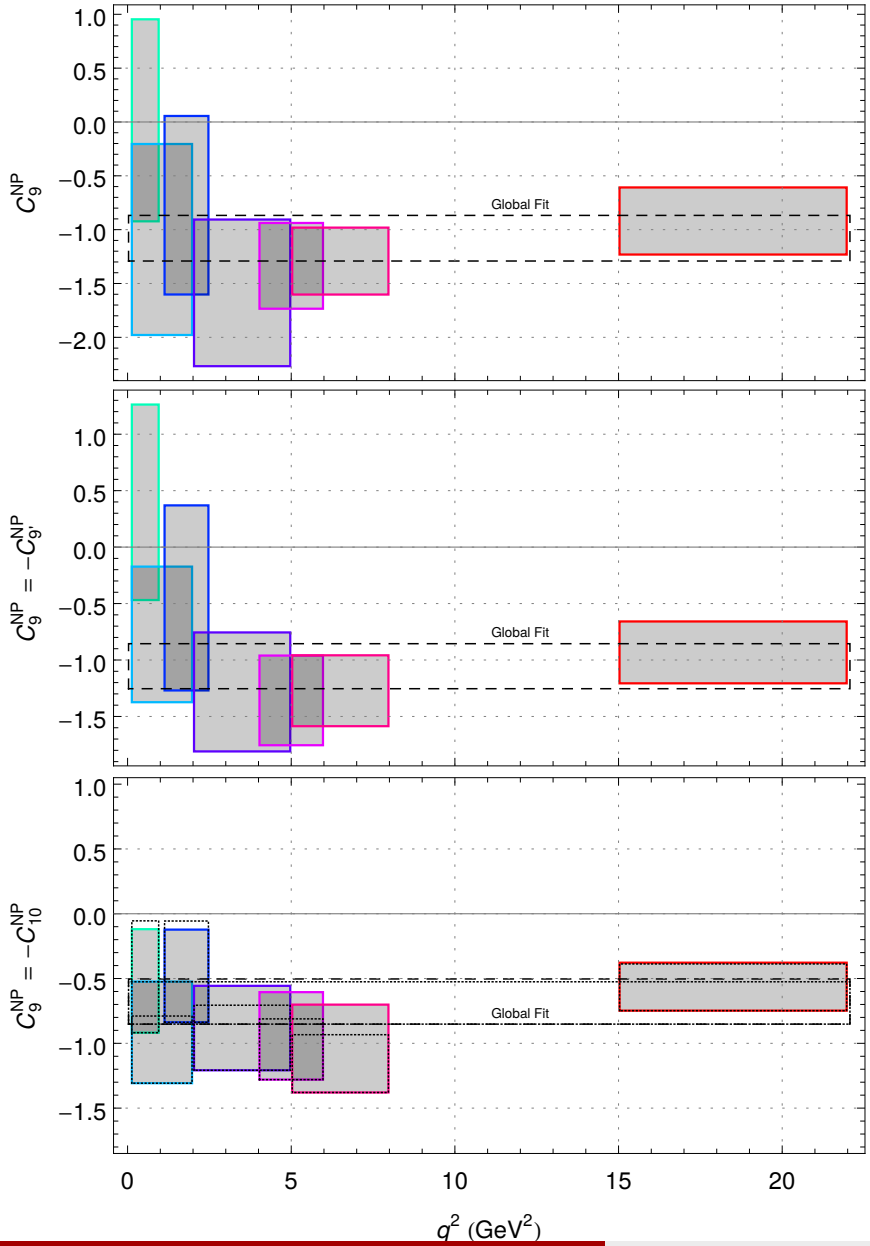
- Up: Assuming shift in $\mathcal{C}_9$ only tests need for hadronic contrib:
  - NP in $\mathcal{C}_9$ from short distances, q^2-independent
  - Hadronic physics in $\mathcal{C}_9$ is related to $c\bar{c}$ dynamics, (likely) q^2-dependent

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



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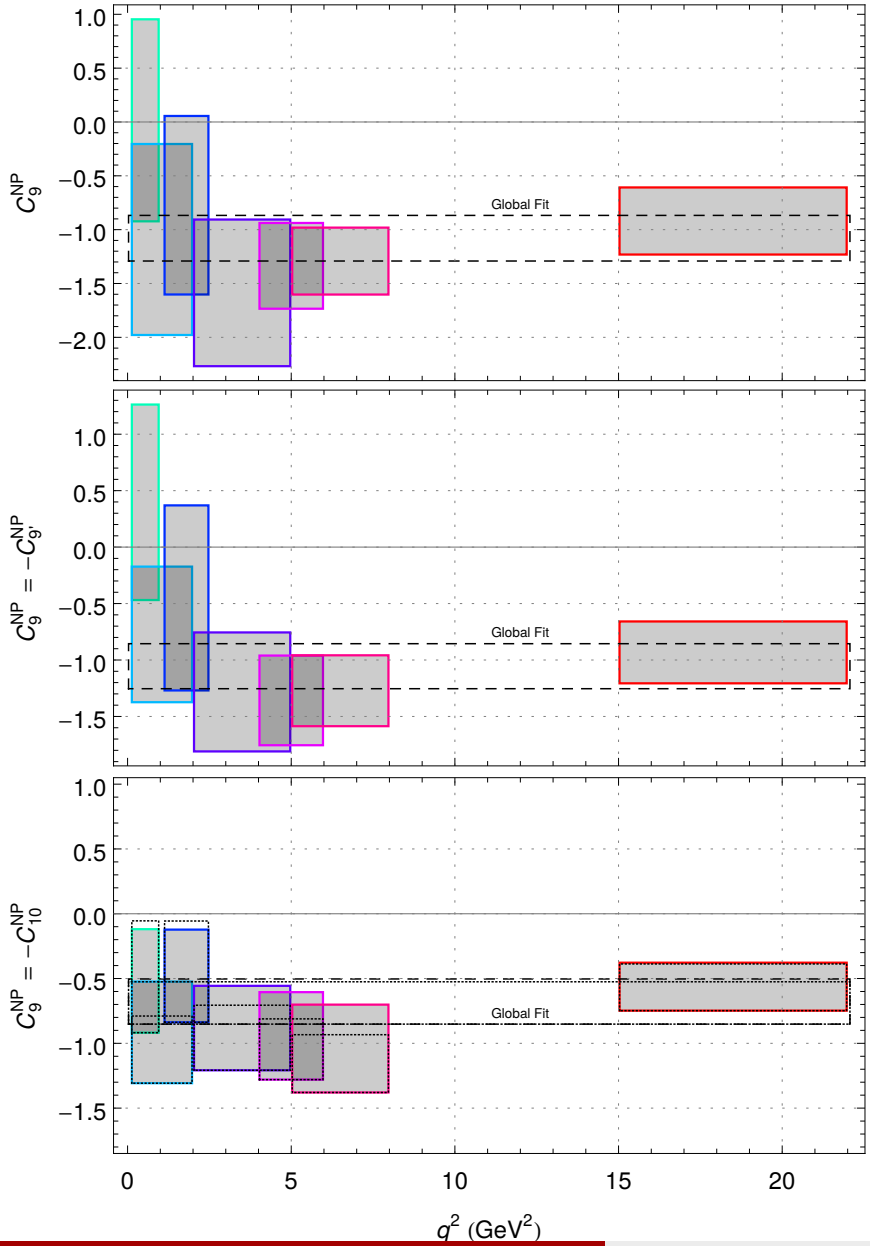

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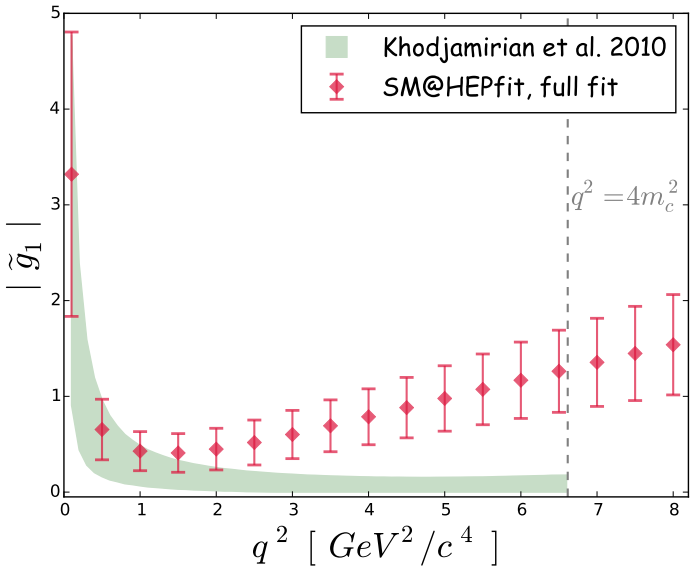
- Mid, down: correlated shift in $\mathcal{C}_9$ and other $\mathcal{C}_i$ (never q^2-depend: are NP scenarios consistent ?)
- No indication of q^2-dependent contribution

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]



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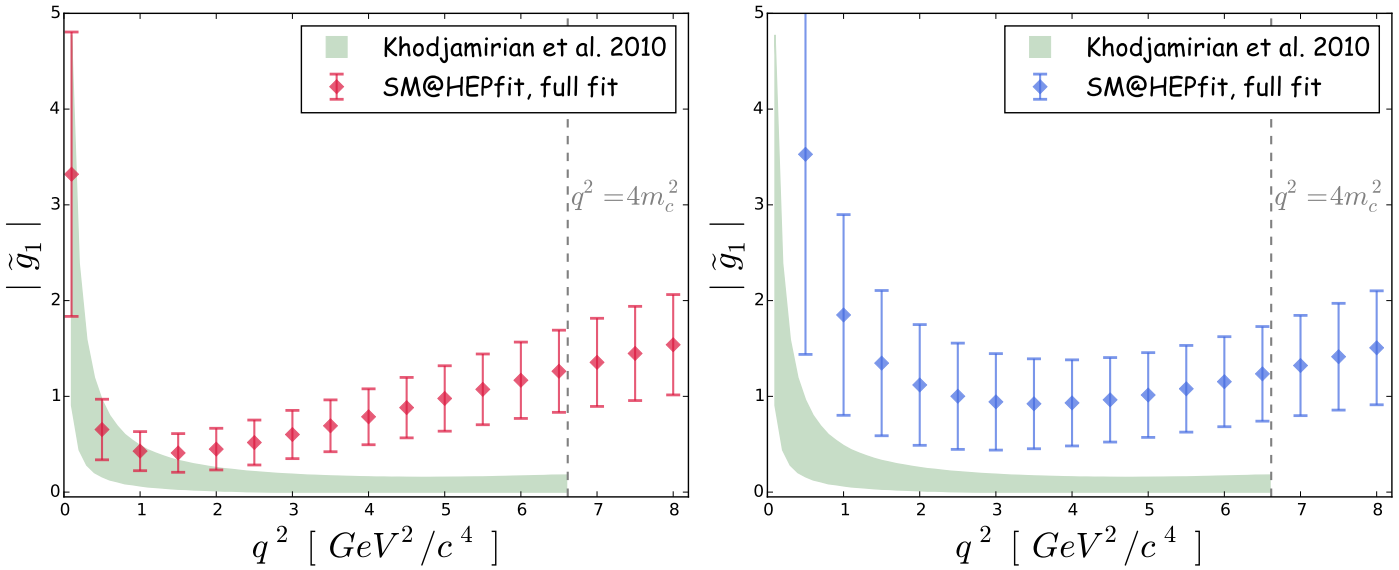

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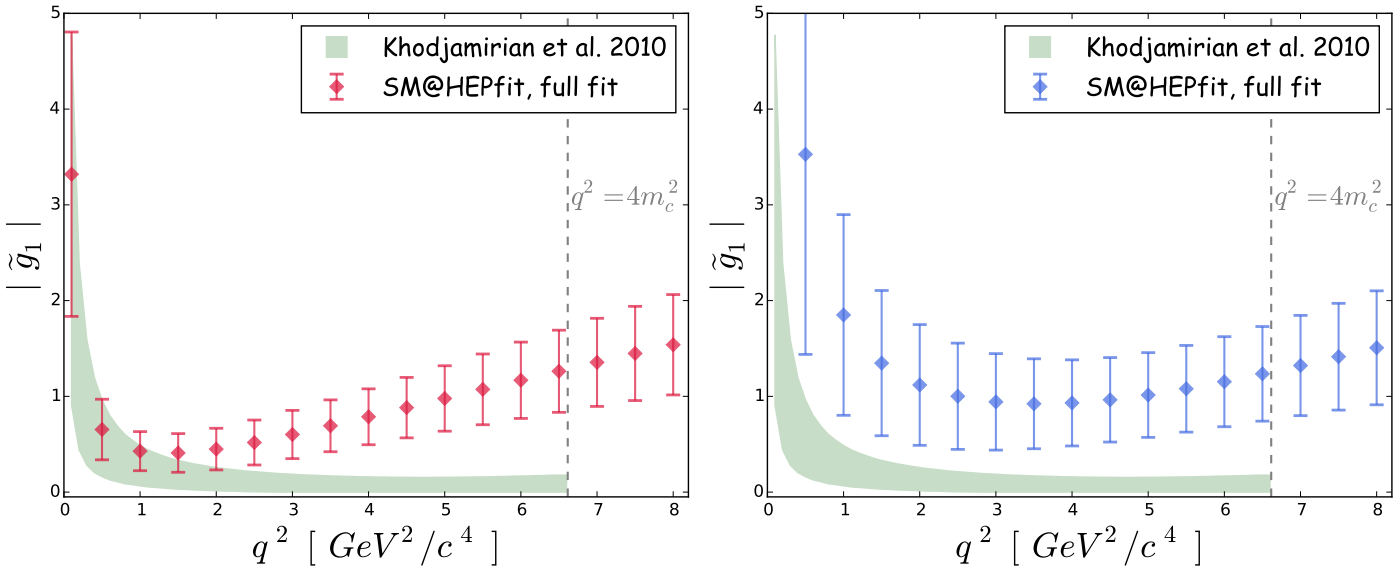

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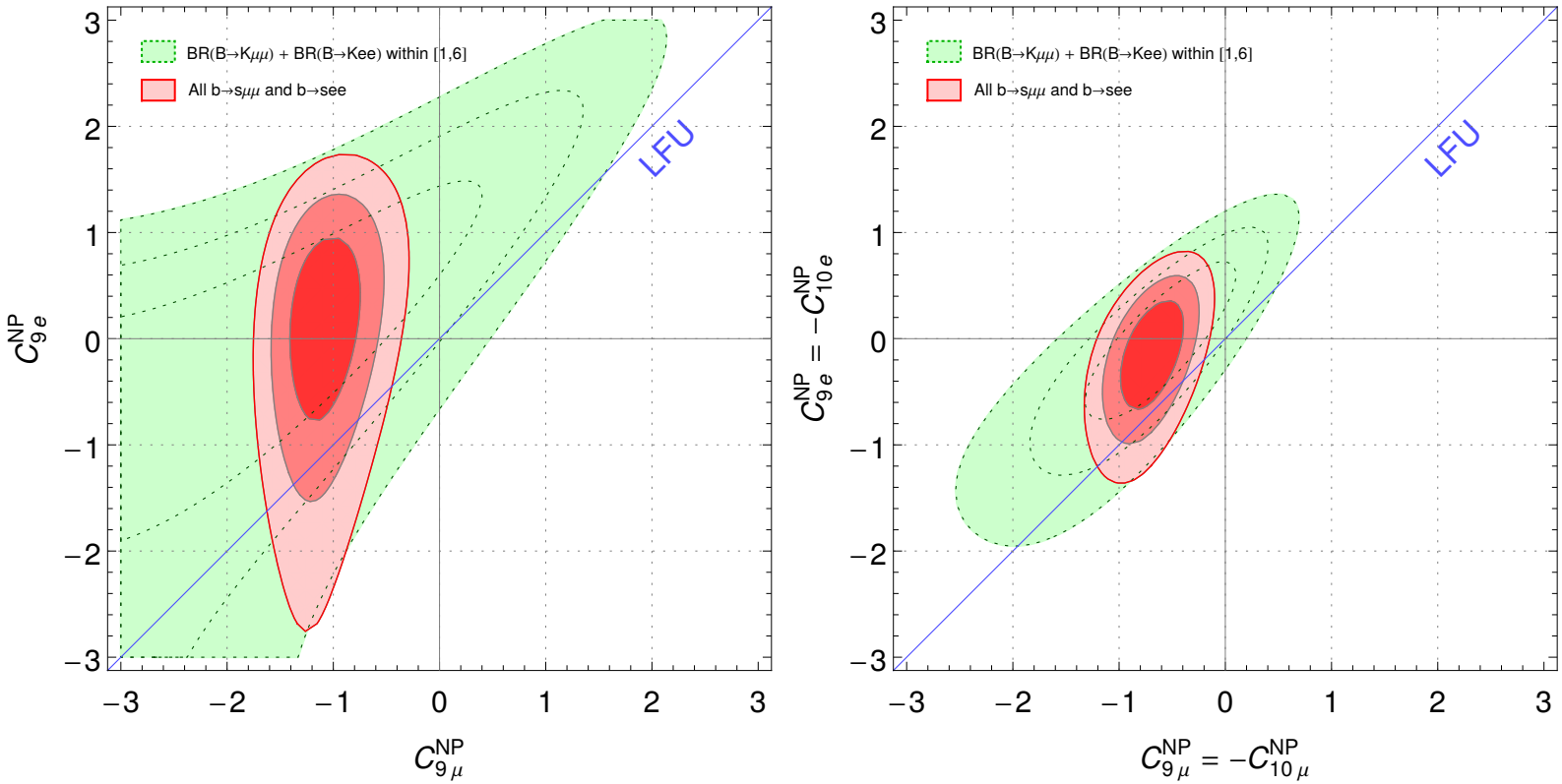
- no explanation for R_K or low-recoil BRs
- data on $B \to K^* \mu\mu$ to fix q^2-polynomial before any prediction

Looking for more inputs

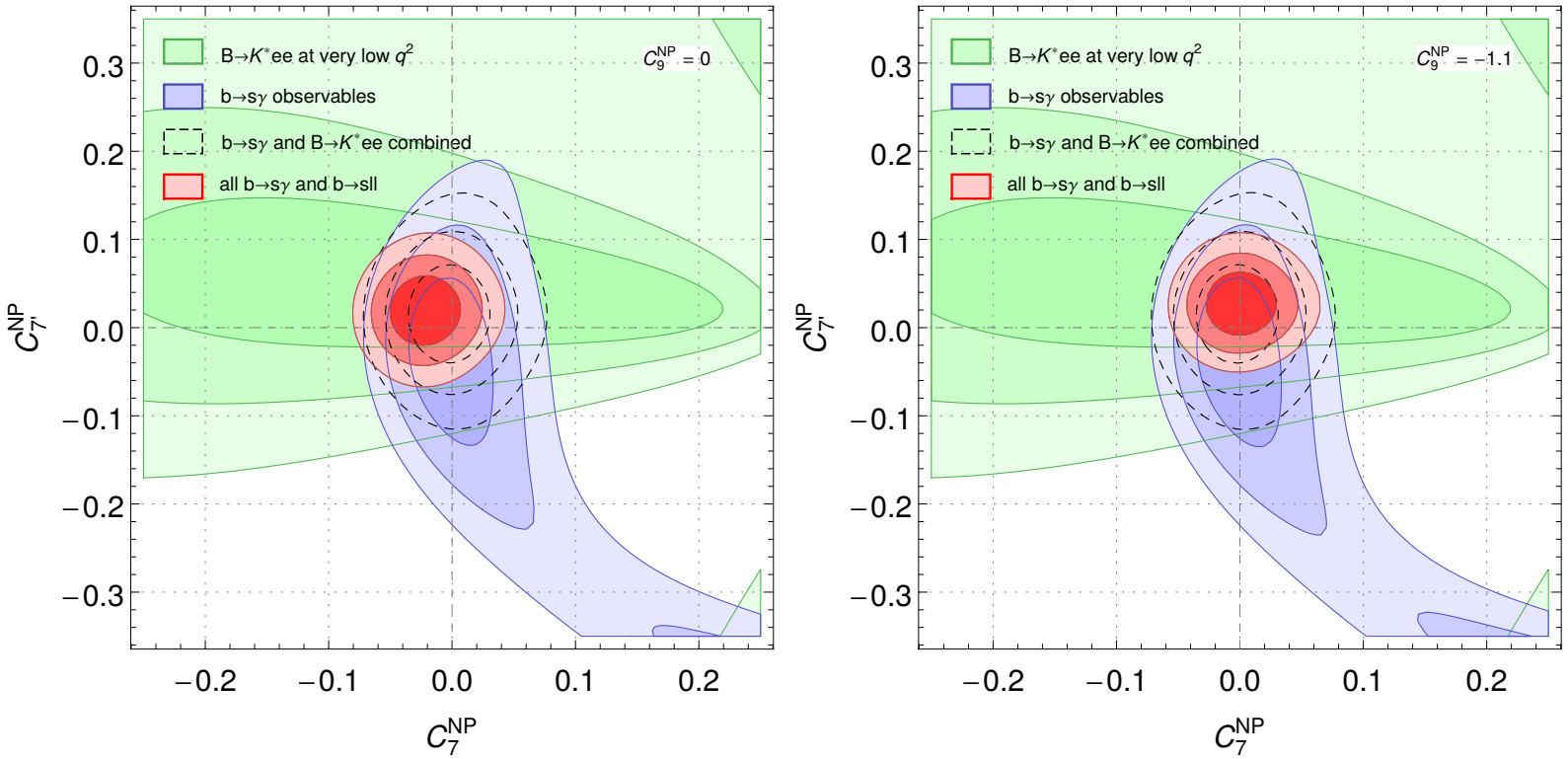
Adding electrons to the game

- Include LHCb $BR(B \to Kee)$ and large-recoil obs for $B \to K^* ee$
- For several favoured scenarios, SM pull increases by $\sim 0.5\sigma$



- Investigate scenarios with $\mathcal{C}_{9e}^{\rm NP} \neq \mathcal{C}_{9\mu}^{\rm NP}$
- 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 $\mathcal{C}_9^{\rm NP} = -1.1$ (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
$\mathcal{C}_9^{\rm NP}$	$+$					
	$-$	✓	✓	✓	✓	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, ff)
  - 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 (for $B \to K^* \mu\mu$, $B_s \to \phi\mu\mu$)
- statistical fluctuation (for R_K)
- bad luck ($\mathcal{C}_9$ can accomodate all discrepancies by chance)

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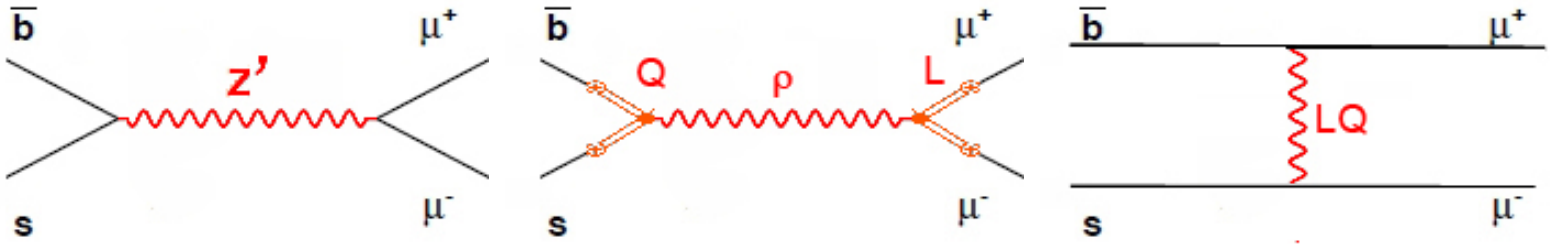
NP models quite successful with new scale around TeV

- 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...

...Neubert, Bauer, Mahmoudi, Boucenna, Celis, Fuentes-Martin, Vicente, Virto...]

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

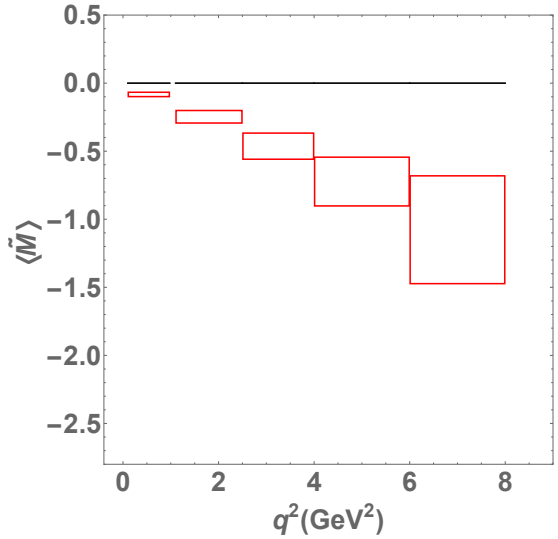
[Capdevilla, Matias, Virto, SDG]

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

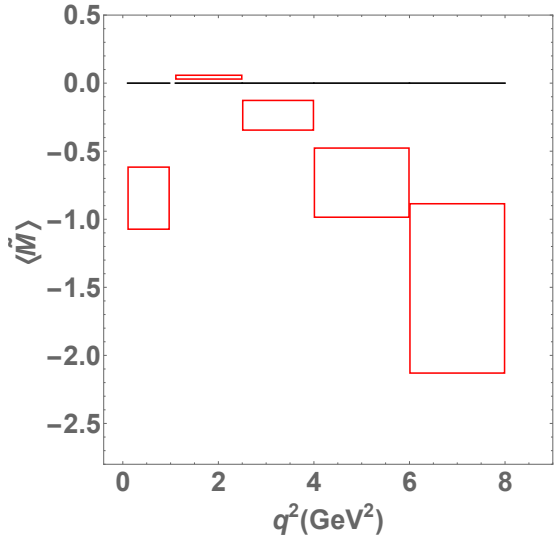
- Null SM tests (up to m_ℓ effects): $Q_i = P_i^\mu - P_i^e$, $\quad B_i = \frac{J_i^\mu}{J_i^e} - 1$
- angular coeffs J_5 and J_{6s} with only a linear dependence on $\mathcal{C}_9$

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

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

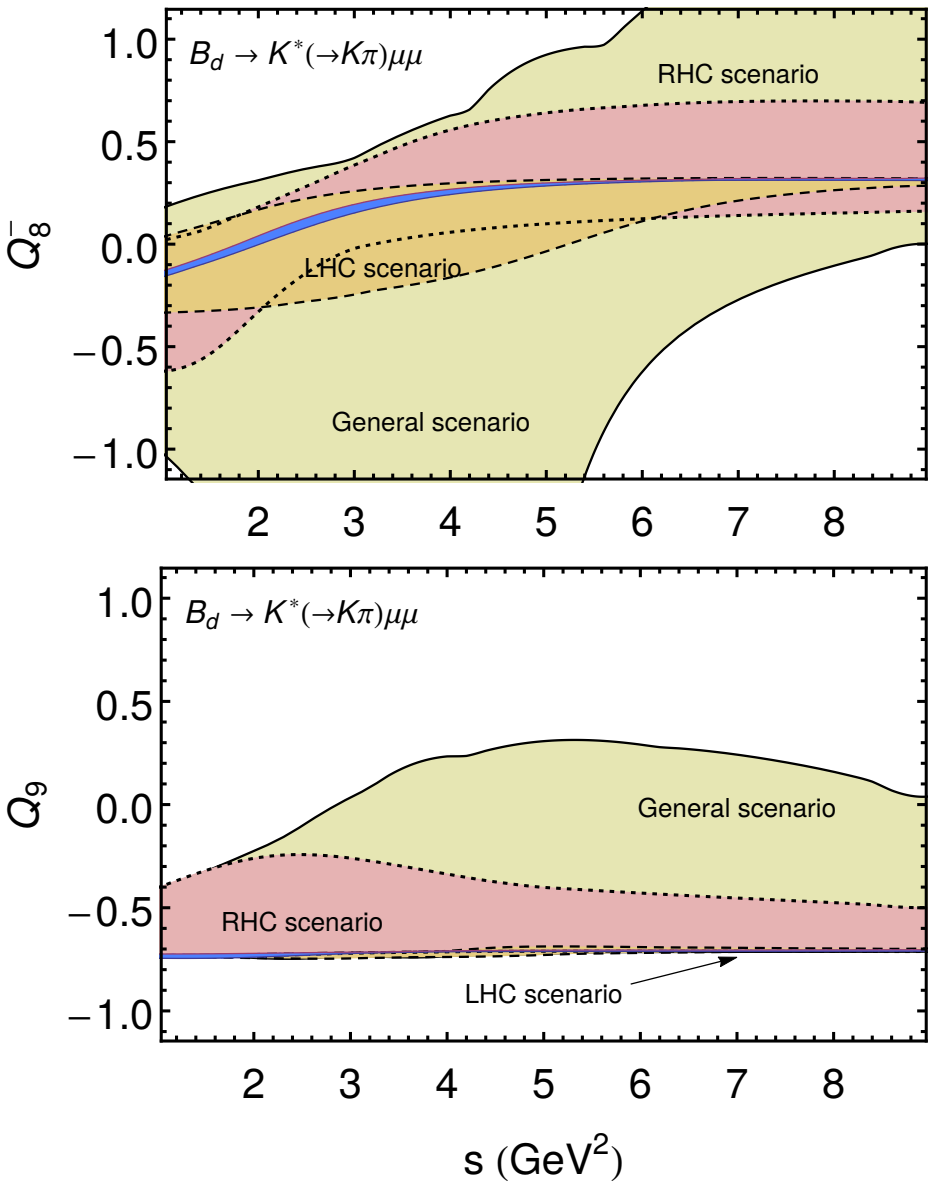


$$\mathcal{C}_{9\mu}^{\rm NP} = -1.1, \mathcal{C}_{ie}^{\rm NP} = 0$$



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

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, J. 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 observables comparing modes with $\ell = e$ and $\ell = \mu$ with finer binning
- 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

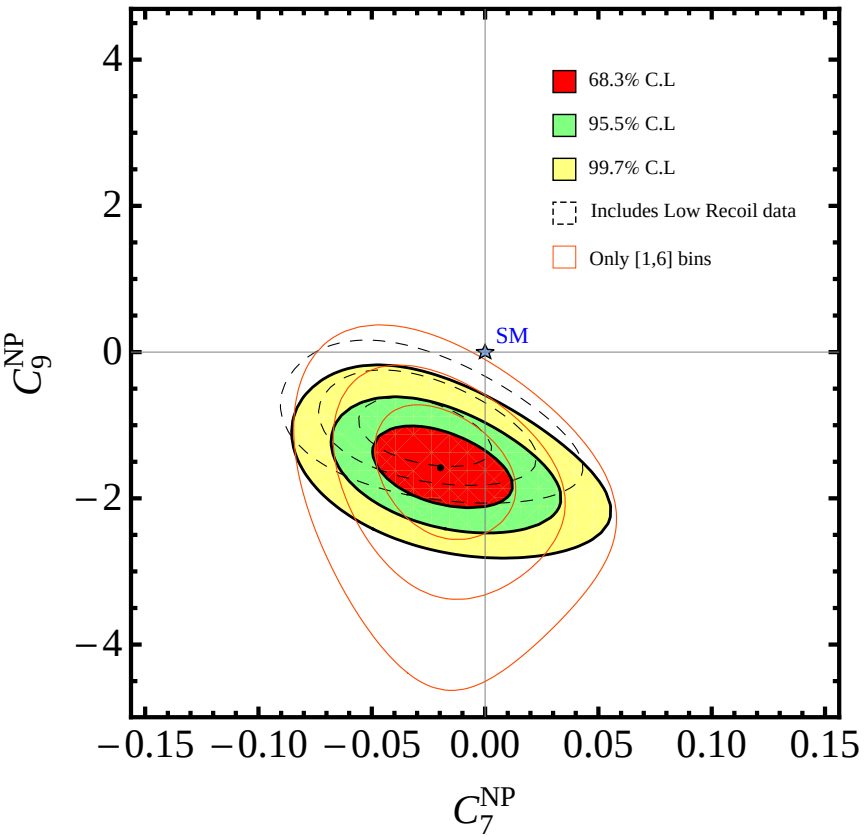
Flavor Physics and New Physics Searches

26-30 September 2016, Fréjus, France

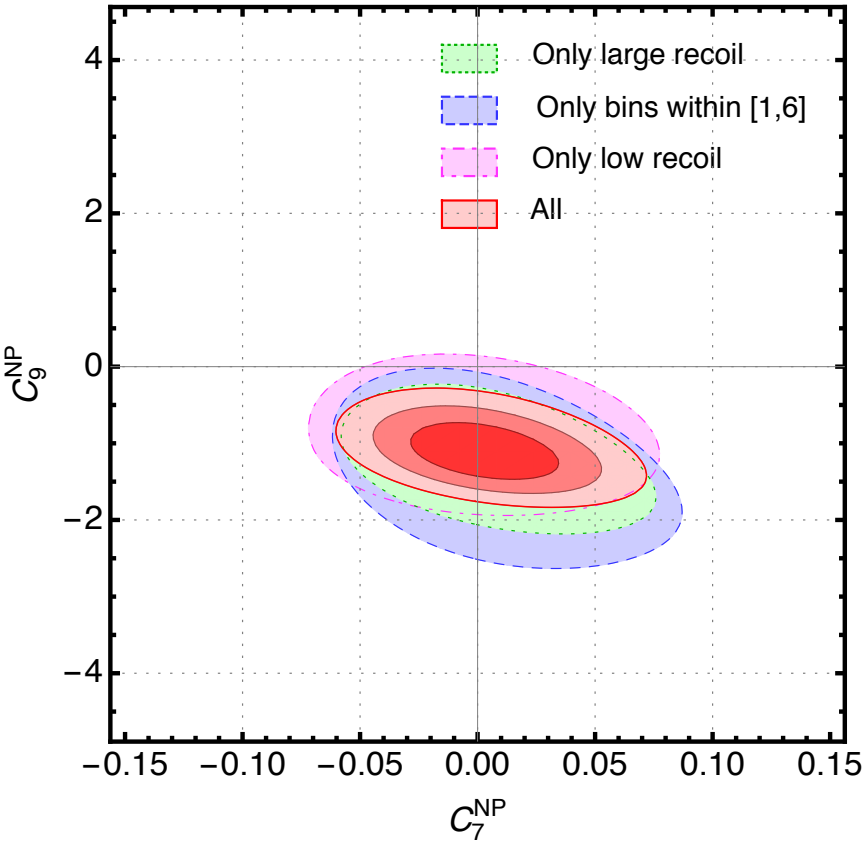
Information and Registration on http://indico.in2p3.fr/e/FlavorNewPhys

From 2013 to 2016

Many improvements from experiment and theory, but. . .



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



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

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

Fit	$\mathcal{C}_{9\ \rm Bestfit}^{\rm NP}$	1σ	$\rm Pull_{SM}$	$N_{\rm dof}$	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

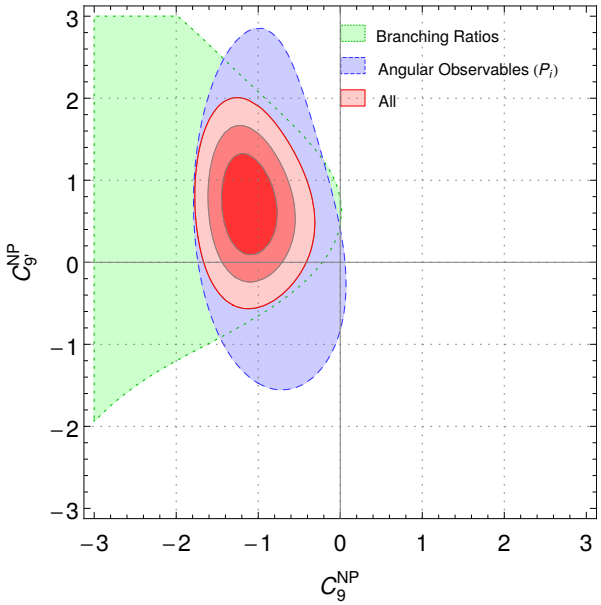
$b \to s\mu\mu$: 6D hypothesis

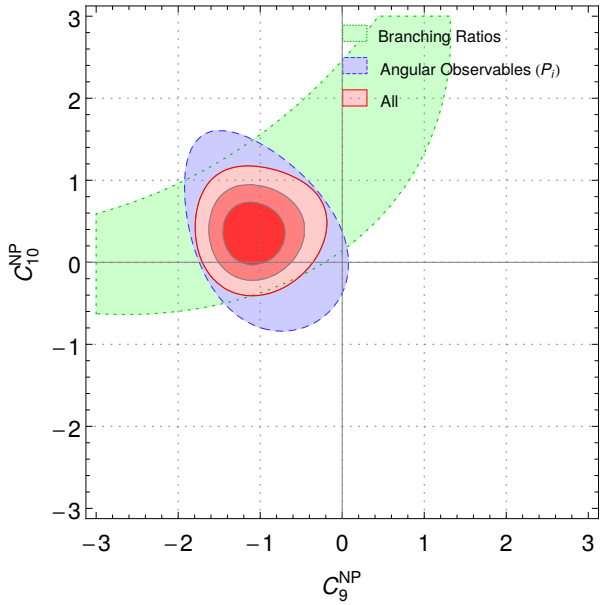
Letting all 6 Wilson coefficients vary (but only real)

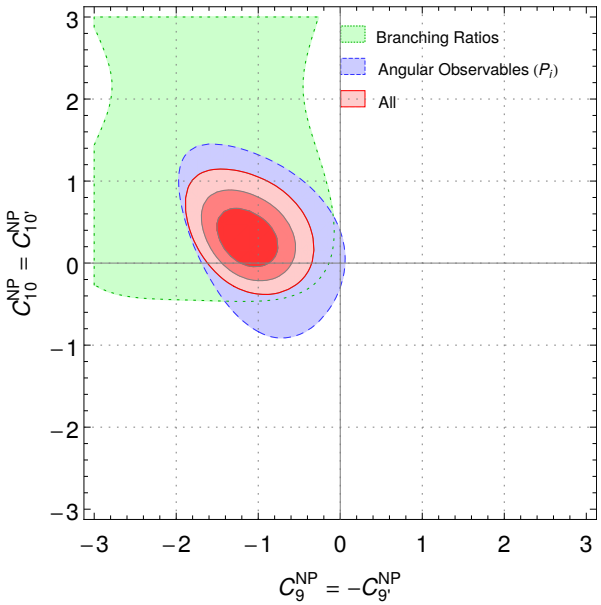
Coefficient	1σ	2σ	3σ	Preference
$\mathcal{C}_7^{\rm NP}$	$[-0.02, 0.03]$	$[-0.04, 0.04]$	$[-0.05, 0.08]$	no pref
$\mathcal{C}_9^{\rm NP}$	$[-1.4, -1.0]$	$[-1.7, -0.7]$	$[-2.2, -0.4]$	negative
$\mathcal{C}_{10}^{\rm NP}$	$[-0.0, 0.9]$	$[-0.3, 1.3]$	$[-0.5, 2.0]$	positive
$\mathcal{C}_{7'}^{\rm NP}$	$[-0.02,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

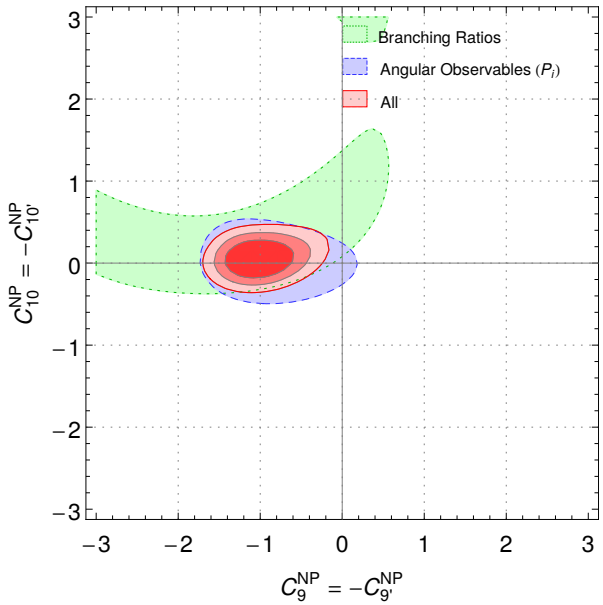
- $\mathcal{C}_9$ is consistent with SM only above 3σ
- All others are consistent with zero at 1σ except for $\mathcal{C}_{9'}$ at 2 σ
- $\text{Pull}_{\rm SM}$ for the 6D fit is 3.6σ

Some favoured scenarios







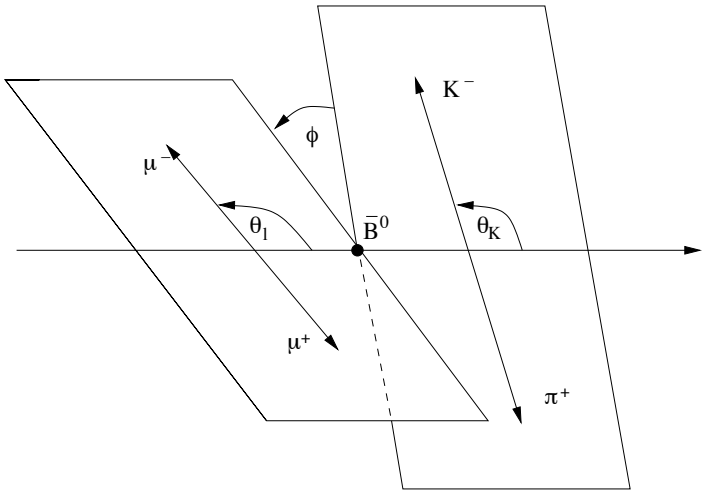


From the fit

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

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

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

leading to $A_{\perp,L/R}$, $A_{||,L/R}$, $A_{0,L/R}$, A_t + scalar A_s

Issues settled about the dictionnary between LHCb and our kinematics (change only for angular observables sensitive to NP phases)

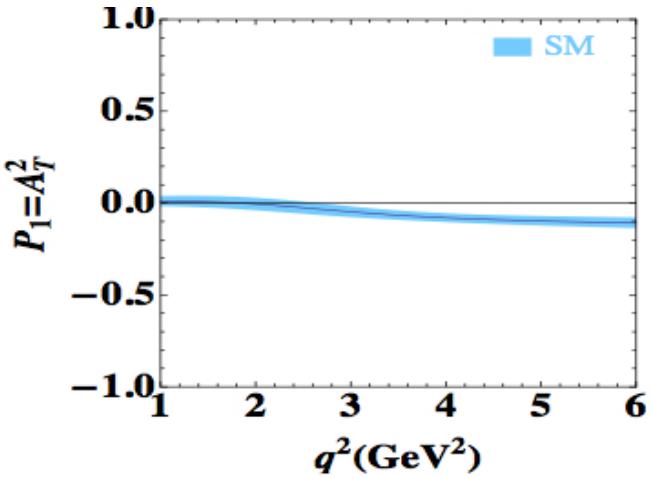
[Grantrex, Hopfer, Zwicky; Becirevic, Sumensari, Zukanovic-Funchal]

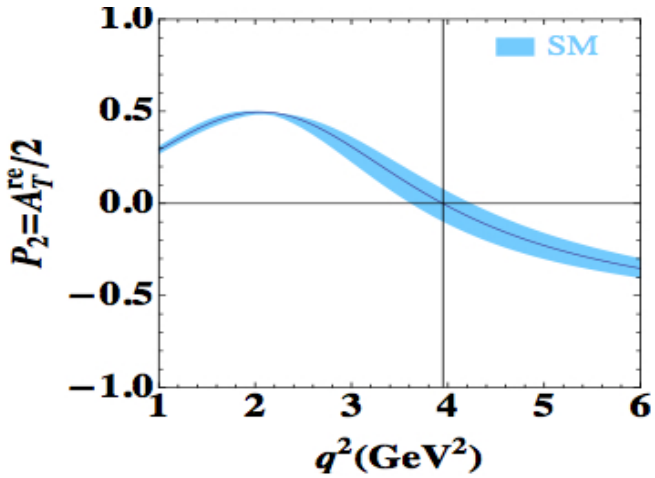
Optimised observables

= Observables where soft form factors cancel at LO in EFT

- Zero of forward-back. asym. $A_{FB}(s_0) = 0$: $\mathcal{C}_9^{\rm eff}(s_0) + 2\frac{m_b M_B}{s_0}\mathcal{C}_7^{\rm eff} = 0$
- Transversity asymmetries [Krüger, Matias; Becirevic, Schneider]

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



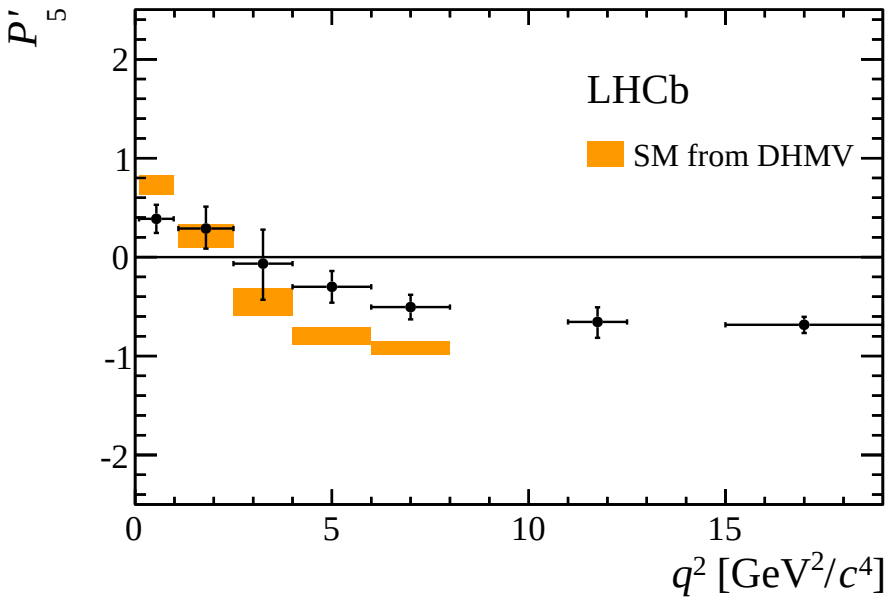


- 6 optimised obs. at large recoil ($P_1, P_2, P_3, P_4', P_5', P_6'$)
  + 2 other (non-optimised) obs. (Γ, A_{FB}, $F_L \ldots$)
  exhausting information in (partially redundant) angular coeffs I_i

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

Focus on P_5'

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



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

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

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

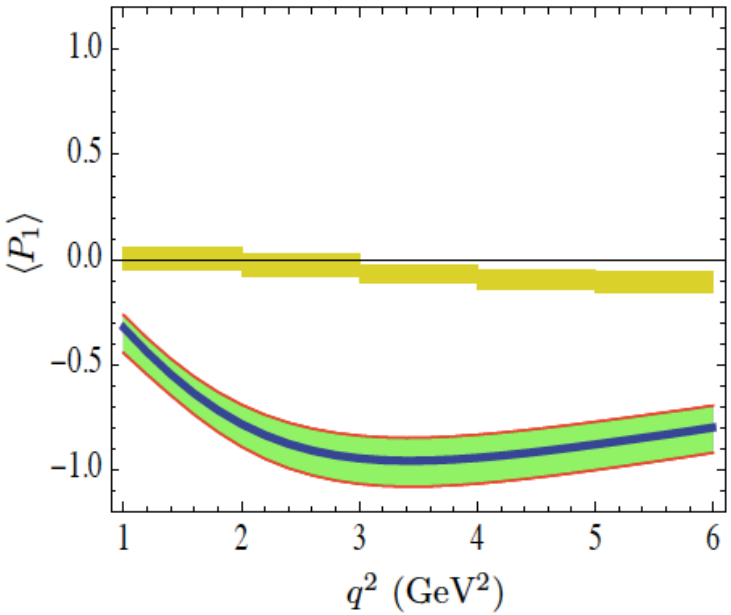
In large recoil limit with no right-handed current, with $\xi_{\perp,||}$ ffs

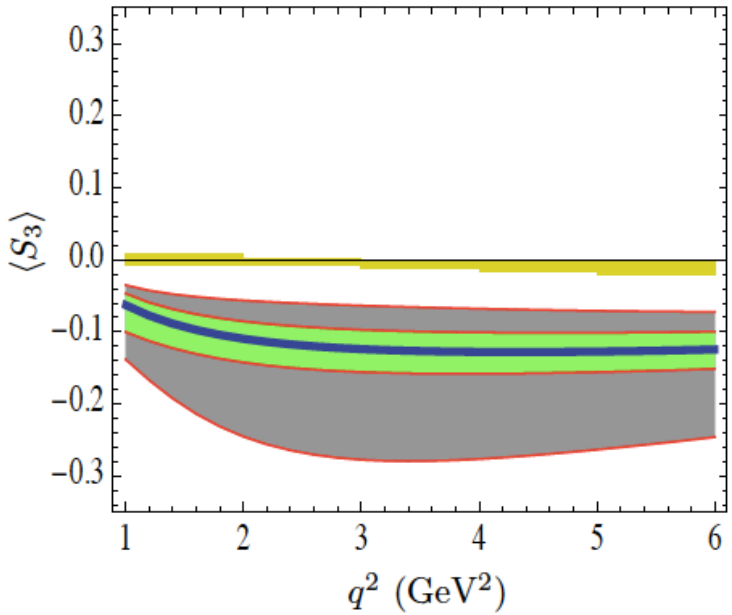
$$A^L_{\perp,||} \propto \pm\left[\mathcal{C}_9 - \mathcal{C}_{10} + 2\frac{m_b}{s}\mathcal{C}_7\right]\xi_\perp(s) \qquad A^R_{\perp,||} \propto \pm\left[\mathcal{C}_9 + \mathcal{C}_{10} + 2\frac{m_b}{s}\mathcal{C}_7\right]\xi_\perp(s)$$

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

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

Sensitivity to form factors





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

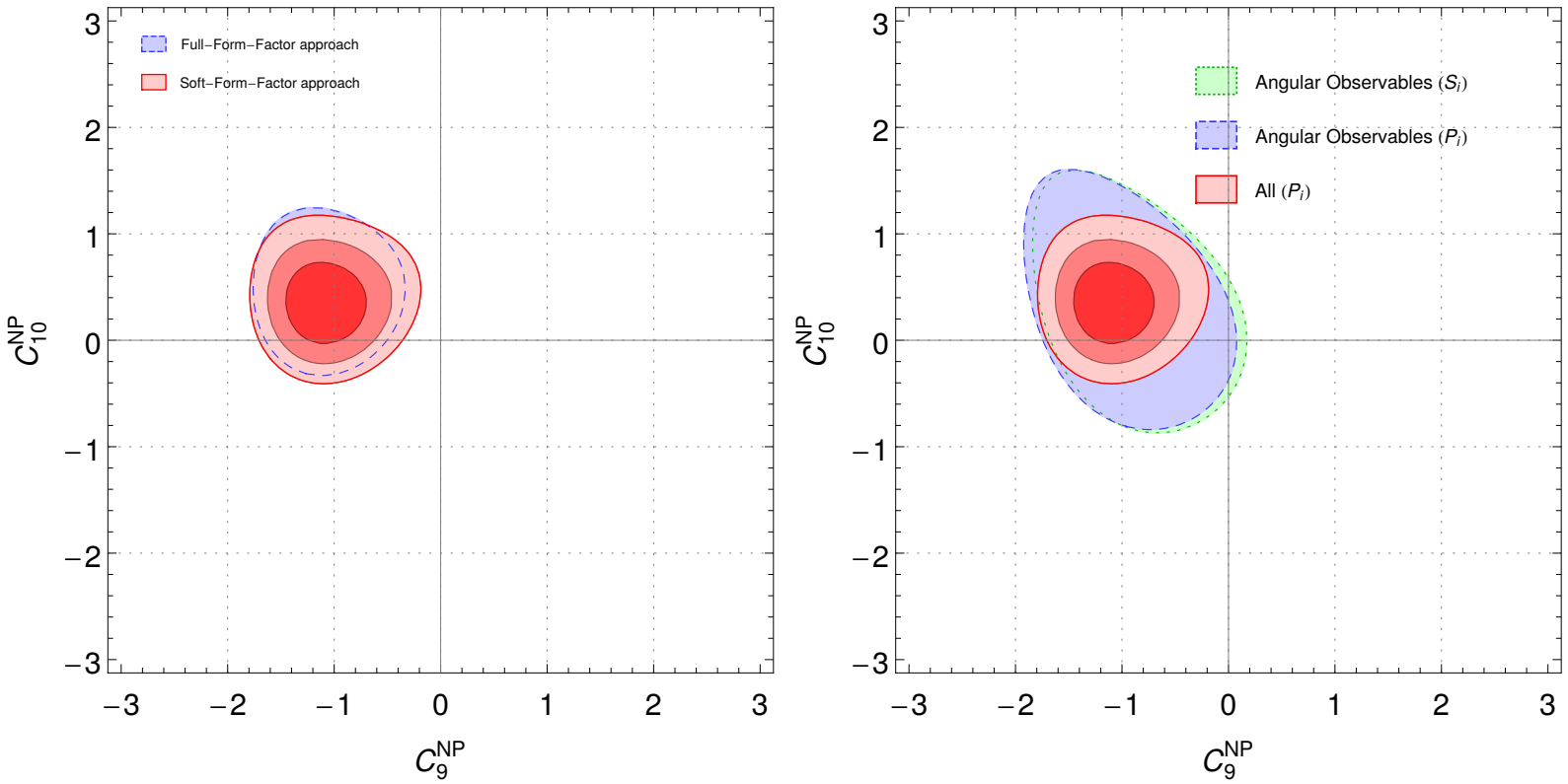
$$P_1 = \frac{2S_3}{1-F_L} \qquad F_L = \frac{I_{1c}+\bar{I}_{1c}}{\Gamma+\bar{\Gamma}} \qquad S_3 = \frac{I_3+\bar{I}_3}{\Gamma+\bar{\Gamma}}$$

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

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

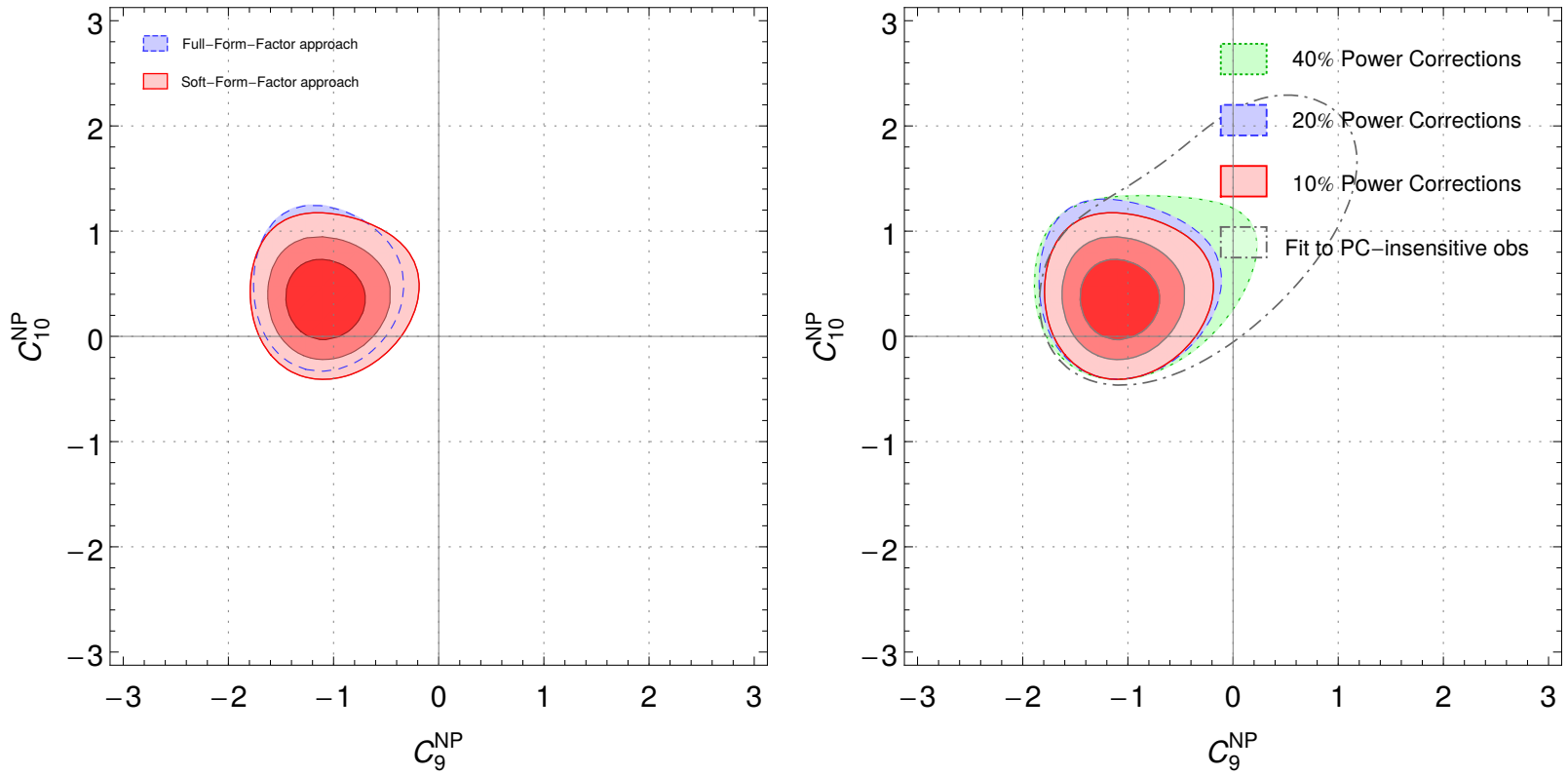
more or less easy to discriminate against yellow (SM prediction)

Cross-checks: Form factors



- Soft form factor approach ([Khodjamirian et al.] ff + EFT correlations, P_i) vs full form factor approach ([Altmannshofer, Straub] with ([Bharucha et al.] ff with small errors and correls + correlations and/or S_i)

Cross-checks: Form factors and power corrs



- Soft form factor approach ([Khodjamirian et al.] ff + EFT correlations, P_i) vs full form factor approach ([Altmannshofer, Straub] with ([Bharucha et al.] ff with small errors and correls + correlations and/or S_i)
- Increasing power corrections weakens role of large recoil, but low recoil enough to pull fit away from the SM

Power corrections

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

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

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

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

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

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

Correlating form factors

Implement correlations among form factors

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

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

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Choice of observables

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

Very large power corrections ? (1)

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

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

- 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 optimised observables [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)

★ $\Delta F^{\rm PC} = F \times \mathcal{O}(\Lambda/m_B)$
$\sim F \times 10\%$

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

★ $\Delta F^{\rm PC}$ from LCSR

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Very large power corrections ? (2)

Model independent ⟵ ⟶ Full LCSR information

1

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3

★ $\Delta F^{\rm PC}$ from LCSR

★ 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	

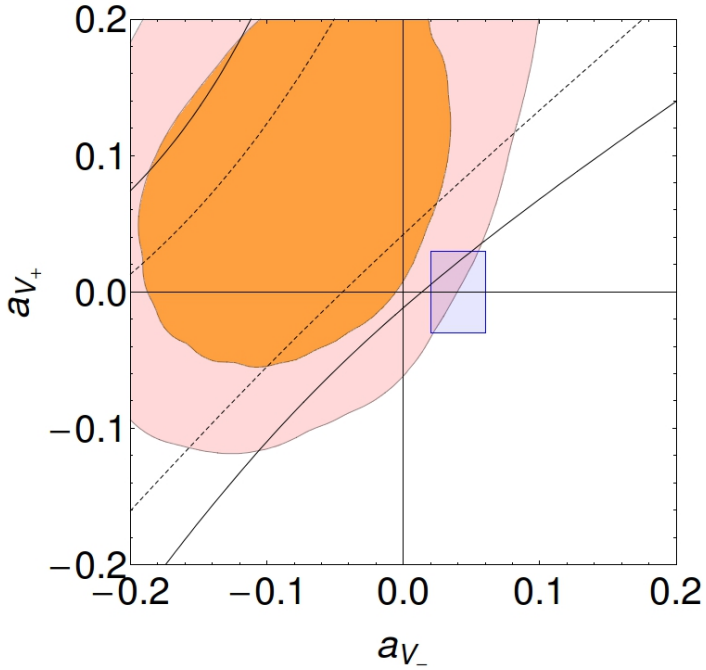
errors only from pc

- 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)

[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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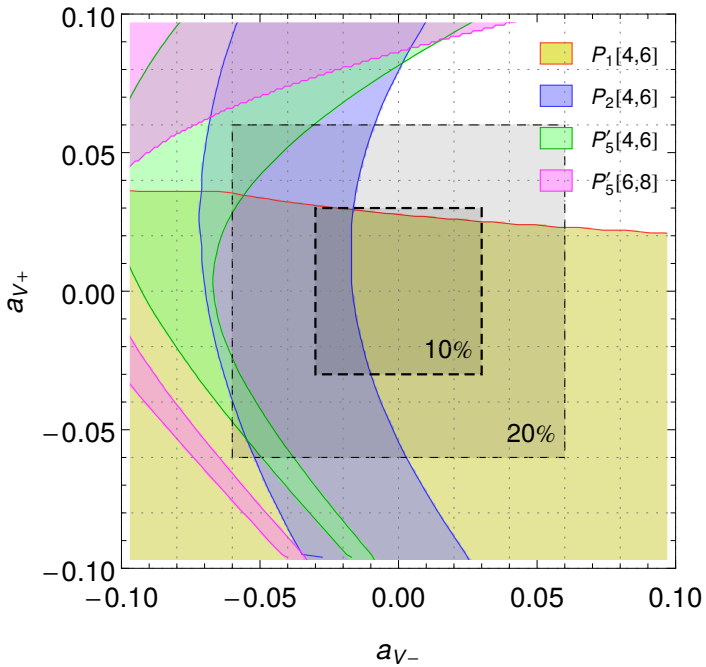

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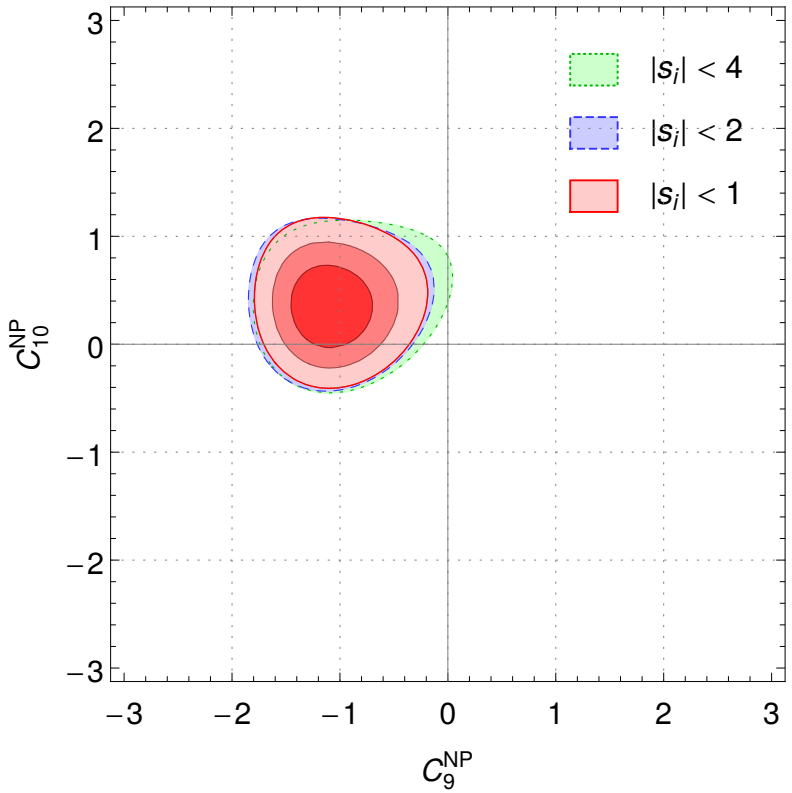
[SDG, L. Hofer, J. Matias, J. Virto]

- 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

Cross-checks: Charm-loop dependence



- For each $B \to K^* \mu\mu$ transversity $\Delta\mathcal{C}_9^{BK^{(*)},i} = \delta\mathcal{C}_{9,\text{pert}}^{BK^{(*)},i} + s_i \delta\mathcal{C}_{9,\text{non pert}}^{BK^{(*)},i}$
- 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

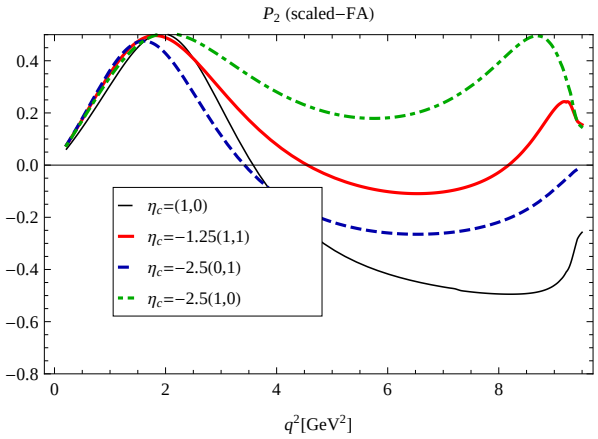
- Does not alter the pull, and would not explain a difference between $BR(B \to Kee)$ and $BR(B \to K\mu\mu)$

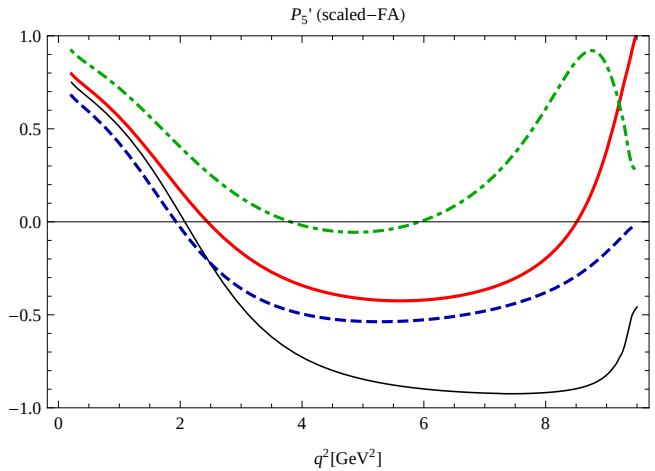
Very large $c\bar{c}$ contributions ?

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

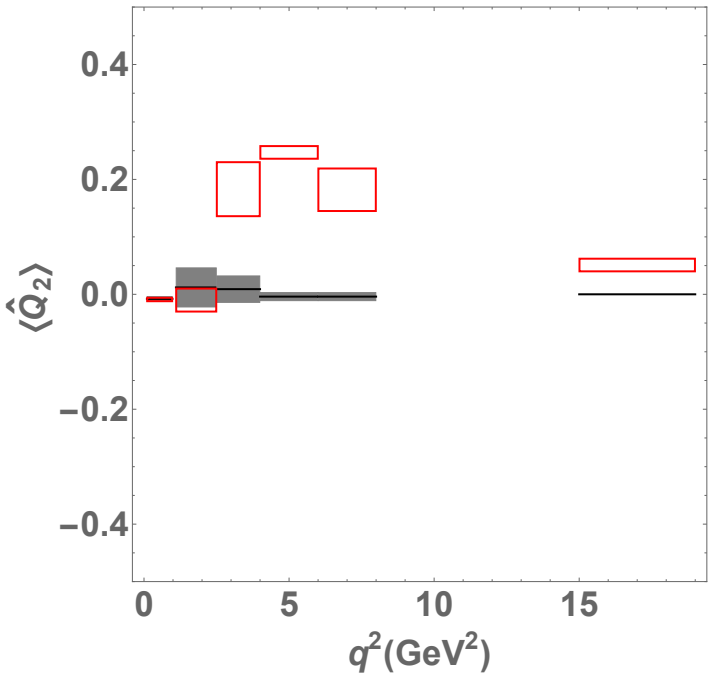
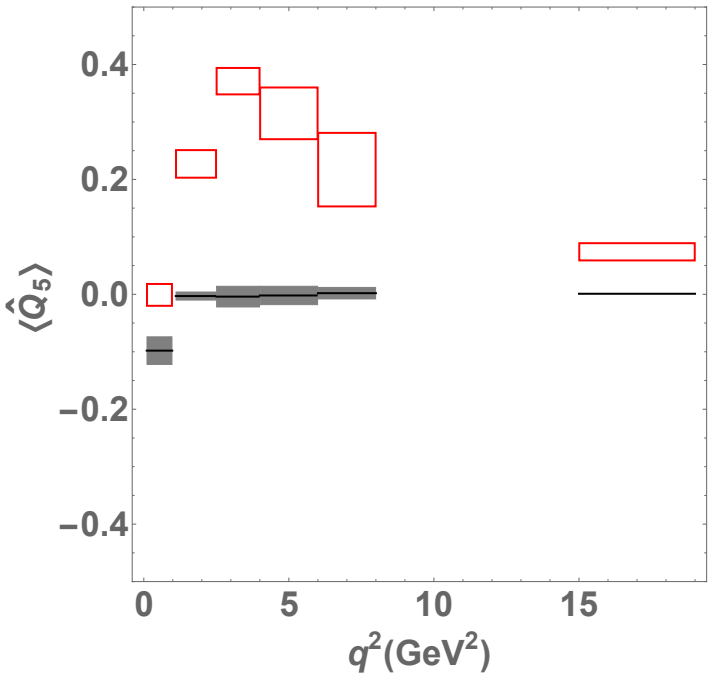
$$\mathcal{C}_9^{\rm eff} = \mathcal{C}_9^{SM} + \mathcal{C}_9^{\rm NP} + \eta h(q^2) \text{ and } \mathcal{C}_{9'} = \mathcal{C}_{9'}^{NP} + \eta' h(q^2)$$

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





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

Null tests of the SM

- Null SM tests (up to m_ℓ effects): $Q_i = P_i^\mu - P_i^e$
- Benefit from little dependence on form factors from P_i
- Powerful to identify LFU-violating NP (e.g., NP in $\mathcal{C}_{9,\mu}$ only)