Silver Linings from the Flavor Sector: The $B \to K^* \mu\mu$ Anomaly

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Outline

EFTs, Accidental Symmetries and New Physics

Proton Decay — Baryon Number

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{c}{\Lambda^2_{\rm GUT}}[Q^T C\, Q][Q^T C\, L] + \cdots \;\Rightarrow \Lambda_{\rm GUT} \gtrsim 10^{15}{\rm GeV}$$

Neutrino Masses — Lepton Number

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{c}{\Lambda_{\rm M}}[L^T C\, L][H^\dagger H] + \cdots \;\Rightarrow \Lambda_{\rm M} \sim 10^{13-15}{\rm GeV}$$

Baryon Asymmetry / EDMs — CP $\Rightarrow$ Flavor?

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD+QED} + \frac{c\, M_\Psi}{\Lambda^2_{\rm CP}}[\bar\Psi \sigma^{\mu\nu}\gamma_5 \Psi F_{\mu\nu}] + \cdots \;\Rightarrow \Lambda^{\rm NP}_{\rm CP} \sim {\rm TeV??}$$

Effective Operators for Flavor Physics

- Quark Flavor Physics = Precision physics of weak hadron decays
- Weak hadron decays $\longrightarrow$ "Low energy" physics

$$E \sim \Lambda_{QCD}, m_Q \ll M_W$$

Effective lagrangian at the hadronic scale

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} + \mathcal{L}_{\rm QED} + \sum_i \left(\frac{c_i^{\rm SM}}{M_W^2} + \frac{c_i^{\rm NP}}{\Lambda_1^2} + \cdots \right) \mathcal{O}_i^{(6)} + \cdots$$

- Precision = Sensitivity to RG effects and to high values of $\Lambda_{\rm NP}$
- Present frontier: $\Lambda_{\rm NP}^{K-\bar{K}} > 10^{4-5}$ TeV (Tree level, flavor-generic NP)

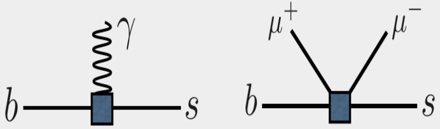
  [Or for example: $M_{\tilde{b}_L} \gtrsim 3$ TeV in Natural SUSY, F. Mescia, JV – 1208.0534]

Radiative and Dileptonic $b \to s$ Operators

Significant progress made recently regarding radiative and dileptonic $b \to s$ operators – Driven by new data on exclusive B decay modes.

Radiative and Dileptonic $b \to s$ Operators

$$\begin{aligned}
\mathcal{O}_{7(\prime)} &= [\bar{s}\sigma^{\mu\nu} P_{R(L)} b] F_{\mu\nu} \\
\mathcal{O}_{9(\prime)} &= [\bar{s}\gamma^{\mu} P_{L(R)} b][\bar{\ell}\gamma_{\mu}\ell] \\
\mathcal{O}_{10(\prime)} &= [\bar{s}\gamma^{\mu} P_{L(R)} b][\bar{\ell}\gamma_{\mu}\gamma_5\ell]
\end{aligned}$$



Effective (sl) Hamiltonian

$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\mathcal{C}_7\mathcal{O}_7 + \mathcal{C}_{7'}\mathcal{O}_{7'} + \mathcal{C}_9\mathcal{O}_9 + \mathcal{C}_{9'}\mathcal{O}_{9'} + \mathcal{C}_{10}\mathcal{O}_{10} + \mathcal{C}_{10'}\mathcal{O}_{10'} \Big]$$

Note: We write $\mathcal{C}_i = \mathcal{C}_i^{\rm SM} + \mathcal{C}_i^{\rm NP}$:

$$\mathcal{C}_{7\rm eff}^{\rm SM} = -0.29, \ \mathcal{C}_9^{\rm SM} = 4.07, \ \mathcal{C}_{10}^{\rm SM} = -4.31, \ \mathcal{C}_{i'}^{\rm SM} \simeq 0$$

Radiative and Dileptonic $b \to s$ Operators

How to Measure Radiative and Dileptonic Operators?

1. Identify decay modes and observables most sensitive to such ops

Decay modes for $b \to s\gamma$ and $b \to s\ell\ell$

$B \to X_s\gamma$	$B \to X_s\ell\ell$	$B_s \to \ell^+\ell^-$
$B \to K^*\gamma$	$B \to K^*\ell\ell$	$B \to K\ell\ell$

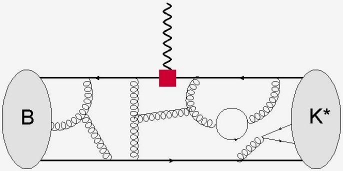
2. Compute the observables in the effective theory
3. Buy a full set of non-perturbative parameters from the Black Market
4. Fit the data, extract CL intervals for the $\mathcal{C}_i(m_b)$.
5. Interpret the results:
   - **5.1** Compute $\mathcal{C}_i^{\rm SM}(m_b)$ to high orders in RG-improved PT.
   - **5.2** Obtain CL intervals for $\mathcal{C}_i^{\rm NP}(m_b) \longrightarrow$ test NP

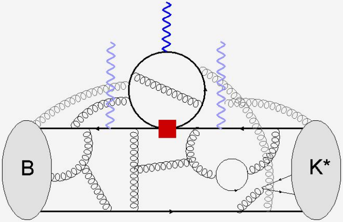
Note: We will fit directly to $\mathcal{C}_i^{\rm NP}(m_b)$

Diversion: Computing amplitudes with Mesons

Example: $B \to K^* \gamma^{(*)}$ $\quad (B \sim \bar{b}s,\ K^* \sim \bar{s}d)$

$$\mathcal{L} = \mathcal{L}_{QED} + \mathcal{L}_{QCD} + \mathcal{C}_7\,[\bar{s}\sigma^{\mu\nu} P_R b]\,F_{\mu\nu} + \mathcal{C}_2\,[\bar{s}\gamma^\nu P_L c]\,[\bar{c}\gamma^\mu P_L b] + \cdots$$





$\mathcal{C}_7$ **contribution:** $\quad \mathcal{A}_7 = \mathcal{C}_7\,\langle K^*_\lambda | \bar{s}\sigma_{\mu\nu} P_R b | B\rangle q^\mu \epsilon^\nu_\lambda = \mathcal{C}_7\, T_\lambda(q^2)$

$\mathcal{C}_2$ **contribution:** $\quad \mathcal{A}_2 = \mathcal{C}_2 \cdot \epsilon^{*\mu}_\lambda \int dx^4 e^{iq\cdot x} \langle K^*_\lambda | T\{ j^{c\bar{c}}_\mu(x) \mathcal{O}_2(0)\} | B\rangle$

Note: There are similar contributions from $\mathcal{O}_8$ and other 4-quark ops.
These operators are contained in what we call $\mathcal{H}^{\rm had}_{\rm eff}$.

Structure of the Decay Amplitude

"Semileptonic" contribution $\longrightarrow$ New Physics

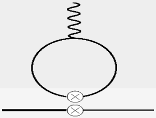
$$\langle K^*\ell\ell|\mathcal{O}_{9^{(\prime)},10^{(\prime)}}|B\rangle = \langle \ell^+\ell^-|\bar{\ell}\gamma_\mu(\gamma_5)\ell|0\rangle\langle K^*|\bar{s}\gamma^\mu P_{L,R}b|B\rangle \sim F_{i,\lambda}^{B\to K^*}(q^2)$$

$$\langle K^*\ell\ell|T\{j_{em}^\ell\mathcal{O}_{7^{(\prime)}}\}|B\rangle = \langle \ell^+\ell^-|\bar{\ell}\gamma_\mu\ell|0\rangle\frac{q_\nu}{q^2}\langle K^*|\bar{s}\sigma^{\mu\nu}P_{R,L}b|B\rangle \sim T_{i,\lambda}^{B\to K^*}(q^2)$$

$$\mathcal{A}^{\rm sl} = \sum_i f_i(\mathcal{C}_{7^{(\prime)}},\mathcal{C}_{9^{(\prime)}},\mathcal{C}_{10^{(\prime)}}) \times (\text{Form Factor})_i$$

"Hadronic" contribution $\longrightarrow$ QCD $[\mathcal{C}_{1,2},\mathcal{C}_8,\mathcal{C}_{3,4,5,6}]$

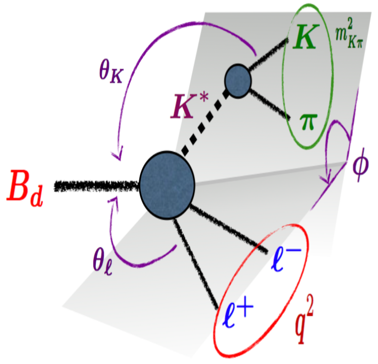
$$\mathcal{A}^{\rm had} = i\frac{e^2}{q^2}\langle \ell^+\ell^-|\bar{\ell}\gamma_\mu\ell|0\rangle\int d^4x e^{iq\cdot x}\langle K^*|T\{j_{em}^\mu(x)\mathcal{H}_{\rm eff}^{\rm had}(0)\}|B\rangle$$



2 main problems:

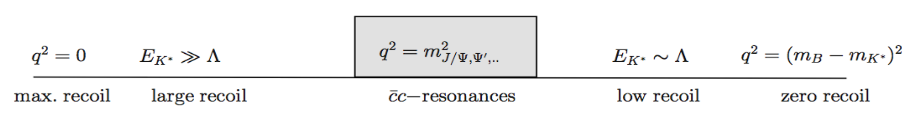
1. Precise determination of Form Factors (LCSRs, LQCD, . . .)
2. Computation of the hadronic contribution (SCET/QCDF, OPE, . . .)

Kinematics and angular distribution



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi} \times$$

$$\Big[J_{1s} \sin^2\theta_K + J_{1c}\cos^2\theta_K + J_{2s}\sin^2\theta_K \cos 2\theta_l$$
$$+ J_{2c}\cos^2\theta_K \cos 2\theta_l + J_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi$$
$$+ J_4 \sin 2\theta_K \sin 2\theta_l \cos\phi + J_5 \sin 2\theta_K \sin\theta_l \cos\phi$$
$$+ J_{6s}\sin^2\theta_K \cos\theta_l + J_{6c}\cos^2\theta_K \cos\theta_l$$
$$+ J_7 \sin 2\theta_K \sin\theta_l \sin\phi + J_8 \sin 2\theta_K \sin 2\theta_l \sin\phi$$
$$+ J_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi \Big]$$



Optimized Observables

Several Form Factor ratios can be predicted:

- At large recoil $\longrightarrow$ SCET — Charles et.al. hep-ph/9812358, Beneke, Feldmann, hep-ph/0008255
- At low recoil $\longrightarrow$ HQET — Grinstein, Pirjol, hep-ph/0404250

Example — SCET relation at large recoil

$$\frac{\epsilon_-^{*\mu} q^\nu \langle K_-^* | \bar{s}\sigma_{\mu\nu} P_R b | B\rangle}{i m_B \langle K_-^* | \bar{s} \not\epsilon_-^{*} P_L b | B\rangle} = 1 + \mathcal{O}(\alpha_s, \Lambda/m_b)$$

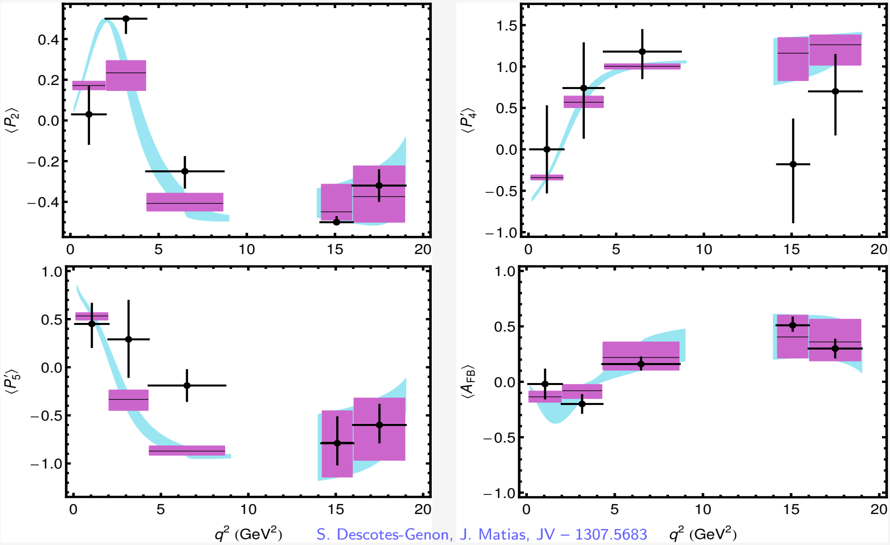
This allows to build observables with **reduced dependence on FFs**.

Optimized observables at large recoil — Matias, Mescia, Ramon, JV – 1202.4266; Descotes-Genon, Matias, Ramon, JV – 1207.2753

$$P_1 = \frac{J_3}{2J_2} \qquad P_2 = \frac{J_{6s}}{8J_{2s}} \qquad P_4' = \frac{J_4}{\sqrt{-J_{2s}J_{2c}}}$$

$$P_5' = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}} \qquad P_6' = \frac{-J_7}{2\sqrt{-J_{2s}J_{2c}}} \qquad P_8' = \frac{-J_8}{\sqrt{-J_{2s}J_{2c}}}$$

Theory vs. Experiment (LHCb: April'13 + July'13)



S. Descotes-Genon, J. Matias, JV – 1307.5683

Fitting the data: Set of data and pulls

Observable	Experiment	SM prediction	Pull
$\langle P_1\rangle_{[0.1,2]}$	$-0.19^{+0.40}_{-0.35}$	$0.007^{+0.043}_{-0.044}$	-0.5
$\langle P_1\rangle_{[2,4.3]}$	$-0.29^{+0.65}_{-0.46}$	$-0.051^{+0.046}_{-0.046}$	-0.4
$\langle P_1\rangle_{[4.3,8.68]}$	$0.36^{+0.30}_{-0.31}$	$-0.117^{+0.056}_{-0.052}$	$+1.5$
$\langle P_1\rangle_{[1,6]}$	$0.15^{+0.39}_{-0.41}$	$-0.055^{+0.041}_{-0.043}$	$+0.5$
$\langle P_2\rangle_{[0.1,2]}$	$0.03^{+0.14}_{-0.15}$	$0.172^{+0.020}_{-0.021}$	-1.0
$\langle P_2\rangle_{[2,4.3]}$	$0.50^{+0.00}_{-0.07}$	$0.234^{+0.060}_{-0.086}$	$+2.9$
$\langle P_2\rangle_{[4.3,8.68]}$	$-0.25^{+0.07}_{-0.08}$	$-0.407^{+0.049}_{-0.037}$	$+1.7$
$\langle P_2\rangle_{[1,6]}$	$0.33^{+0.11}_{-0.12}$	$0.084^{+0.060}_{-0.078}$	$+1.8$
$\langle P_4'\rangle_{[0.1,2]}$	$0.00^{+0.52}_{-0.52}$	$-0.342^{+0.031}_{-0.026}$	$+0.7$
$\langle P_4'\rangle_{[2,4.3]}$	$0.74^{+0.54}_{-0.60}$	$0.569^{+0.073}_{-0.063}$	$+0.3$
$\langle P_4'\rangle_{[4.3,8.68]}$	$1.18^{+0.26}_{-0.32}$	$1.003^{+0.028}_{-0.032}$	$+0.6$
$\langle P_4'\rangle_{[1,6]}$	$0.58^{+0.32}_{-0.36}$	$0.555^{+0.067}_{-0.058}$	$+0.1$
$\langle P_5'\rangle_{[0.1,2]}$	$0.45^{+0.21}_{-0.24}$	$0.533^{+0.033}_{-0.041}$	-0.4
$\langle P_5'\rangle_{[2,4.3]}$	$0.29^{+0.40}_{-0.39}$	$-0.334^{+0.097}_{-0.113}$	$+1.6$
$\langle P_5'\rangle_{[4.3,8.68]}$	$-0.19^{+0.16}_{-0.16}$	$-0.872^{+0.053}_{-0.041}$	$+4.0$
$\langle P_5'\rangle_{[1,6]}$	$0.21^{+0.20}_{-0.21}$	$-0.349^{+0.088}_{-0.100}$	$+2.5$
$\langle P_6'\rangle_{[0.1,2]}$	$0.24^{+0.23}_{-0.20}$	$-0.084^{+0.034}_{-0.044}$	$+1.6$
$\langle P_6'\rangle_{[2,4.3]}$	$-0.15^{+0.38}_{-0.36}$	$-0.098^{+0.043}_{-0.056}$	-0.1
$\langle P_6'\rangle_{[4.3,8.68]}$	$0.04^{+0.16}_{-0.16}$	$-0.027^{+0.060}_{-0.063}$	$+0.4$
$\langle P_6'\rangle_{[1,6]}$	$0.18^{+0.21}_{-0.21}$	$-0.089^{+0.042}_{-0.052}$	$+1.3$
$\langle P_8'\rangle_{[0.1,2]}$	$-0.12^{+0.56}_{-0.56}$	$0.037^{+0.037}_{-0.030}$	-0.3
$\langle P_8'\rangle_{[2,4.3]}$	$-0.30^{+0.60}_{-0.58}$	$0.070^{+0.045}_{-0.034}$	-0.6
$\langle P_8'\rangle_{[4.3,8.68]}$	$0.58^{+0.34}_{-0.38}$	$0.020^{+0.054}_{-0.055}$	$+1.5$
$\langle P_8'\rangle_{[1,6]}$	$0.46^{+0.36}_{-0.38}$	$0.063^{+0.042}_{-0.033}$	$+1.0$
$\langle A_{\rm FB}\rangle_{[0.1,2]}$	$-0.02^{+0.13}_{-0.13}$	$-0.136^{+0.051}_{-0.048}$	$+0.8$
$\langle A_{\rm FB}\rangle_{[2,4.3]}$	$-0.20^{+0.08}_{-0.08}$	$-0.081^{+0.055}_{-0.069}$	-1.1
$\langle A_{\rm FB}\rangle_{[4.3,8.68]}$	$0.16^{+0.06}_{-0.05}$	$0.220^{+0.138}_{-0.113}$	-0.5
$\langle A_{\rm FB}\rangle_{[1,6]}$	$-0.17^{+0.06}_{-0.06}$	$-0.035^{+0.037}_{-0.034}$	-2.0

Observable	Experiment	SM prediction	Pull
$\langle P_1\rangle_{[14.18,16]}$	$0.07^{+0.26}_{-0.28}$	$-0.352^{+0.697}_{-0.468}$	$+0.6$
$\langle P_1\rangle_{[16,19]}$	$-0.71^{+0.36}_{-0.26}$	$-0.603^{+0.589}_{-0.315}$	-0.2
$\langle P_2\rangle_{[14.18,16]}$	$-0.50^{+0.03}_{-0.00}$	$-0.449^{+0.136}_{-0.041}$	-1.1
$\langle P_2\rangle_{[16,19]}$	$-0.32^{+0.08}_{-0.08}$	$-0.374^{+0.151}_{-0.126}$	$+0.3$
$\langle P_4'\rangle_{[14.18,16]}$	$-0.18^{+0.54}_{-0.70}$	$1.161^{+0.190}_{-0.332}$	-2.1
$\langle P_4'\rangle_{[16,19]}$	$0.70^{+0.44}_{-0.52}$	$1.263^{+0.119}_{-0.248}$	-1.1
$\langle P_5'\rangle_{[14.18,16]}$	$-0.79^{+0.27}_{-0.22}$	$-0.779^{+0.328}_{-0.363}$	$+0.0$
$\langle P_5'\rangle_{[16,19]}$	$-0.60^{+0.21}_{-0.18}$	$-0.601^{+0.282}_{-0.367}$	$+0.0$
$\langle P_6'\rangle_{[14.18,16]}$	$0.18^{+0.24}_{-0.25}$	$0.000^{+0.000}_{-0.000}$	$+0.7$
$\langle P_6'\rangle_{[16,19]}$	$-0.31^{+0.38}_{-0.39}$	$0.000^{+0.000}_{-0.000}$	-0.8
$\langle P_8'\rangle_{[14.18,16]}$	$-0.40^{+0.60}_{-0.50}$	$-0.015^{+0.009}_{-0.013}$	-0.6
$\langle P_8'\rangle_{[16,19]}$	$0.12^{+0.52}_{-0.54}$	$-0.008^{+0.005}_{-0.007}$	$+0.2$
$\langle A_{\rm FB}\rangle_{[14.18,16]}$	$0.51^{+0.07}_{-0.05}$	$0.404^{+0.199}_{-0.191}$	$+0.5$
$\langle A_{\rm FB}\rangle_{[16,19]}$	$0.30^{+0.08}_{-0.08}$	$0.360^{+0.205}_{-0.172}$	-0.3
$10^4\,\mathcal{B}_{B\to X_s\gamma}$	3.43 ± 0.22	3.15 ± 0.23	$+0.9$
$10^6\,\mathcal{B}_{B\to X_s\mu^+\mu^-}$	1.60 ± 0.50	1.59 ± 0.11	$+0.0$
$10^9\,\mathcal{B}_{B_s\to\mu^+\mu^-}$	2.9 ± 0.8	3.56 ± 0.18	-0.8
$A_I(B\to K^*\gamma)$	0.052 ± 0.026	0.041 ± 0.025	$+0.3$
$S_{K^*\gamma}$	-0.16 ± 0.22	-0.03 ± 0.01	-0.6

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Fitting the data: Patterns

Simplified Linearized expressions:

$$\delta\langle P_2\rangle_{[0.1,2]} \simeq +0.37\,\mathcal{C}_7^{\rm NP} \qquad -0.03\,\mathcal{C}_{10}^{\rm NP} \quad \ominus$$

$$\delta\langle P_2\rangle_{[2,4.3]} \simeq -2.48\,\mathcal{C}_7^{\rm NP} \quad -0.17\,\mathcal{C}_9^{\rm NP} \quad +0.03\,\mathcal{C}_{10}^{\rm NP} \quad \oplus$$

$$\delta\langle P_2\rangle_{[4.3,8.68]} \simeq -0.71\,\mathcal{C}_7^{\rm NP} \quad -0.09\,\mathcal{C}_9^{\rm NP} \quad -0.04\,\mathcal{C}_{10}^{\rm NP} \quad \oplus$$

$$\delta\langle P_4'\rangle_{[0.1,2]} \simeq +0.59\,\mathcal{C}_7^{\rm NP} \quad -0.08\,\mathcal{C}_9^{\rm NP} \quad -0.13\,\mathcal{C}_{10}^{\rm NP} \quad \oplus$$

$$\delta\langle P_4'\rangle_{[2,4.3]} \simeq +2.45\,\mathcal{C}_7^{\rm NP} \quad +0.06\,\mathcal{C}_9^{\rm NP} \quad -0.14\,\mathcal{C}_{10}^{\rm NP} \quad \oplus$$

$$\delta\langle P_4'\rangle_{[4.3,8.68]} \simeq +0.33\,\mathcal{C}_7^{\rm NP} \quad +0.01\,\mathcal{C}_9^{\rm NP} \quad \oplus$$

$$\delta\langle P_5'\rangle_{[0.1,2]} \simeq -0.91\,\mathcal{C}_7^{\rm NP} \quad -0.12\,\mathcal{C}_9^{\rm NP} \quad -0.03\,\mathcal{C}_{10}^{\rm NP} \quad \ominus$$

$$\delta\langle P_5'\rangle_{[2,4.3]} \simeq -3.04\,\mathcal{C}_7^{\rm NP} \quad -0.29\,\mathcal{C}_9^{\rm NP} \quad -0.03\,\mathcal{C}_{10}^{\rm NP} \quad \oplus$$

$$\delta\langle P_5'\rangle_{[4.3,8.68]} \simeq -0.52\,\mathcal{C}_7^{\rm NP} \quad -0.08\,\mathcal{C}_9^{\rm NP} \quad -0.03\,\mathcal{C}_{10}^{\rm NP} \quad \oplus$$

Fitting the data: Results

Strategy:

We fit to **47** observables by means of a frequentist χ^2 approach.

Observables included in the analysis

$$BR(B \to X_s\gamma), \quad BR(B \to X_s\mu^+\mu^-)_{Low\ q^2}$$

$$BR(B_s \to \mu^+\mu^-), \quad A_I(B \to K^*\gamma), \quad S(B \to K^*\gamma)$$

$$B \to K^*\mu^+\mu^- : \ \langle P_1\rangle, \langle P_2\rangle, \langle P_4'\rangle, \langle P_5'\rangle, \langle P_6'\rangle, \langle P_8'\rangle, \langle A_{\rm FB}\rangle$$

in several different bins (see later)

Observables *not* included in the analysis

$$B \to K\mu^+\mu^-, \quad B_s \to \phi\mu^+\mu^-, \quad B \to X_s\mu^+\mu^- \text{ @ } Large\ q^2, \ \ldots$$

not considered for different reasons (see also ‘future directions’)

Fitting the data: Results

Strategy:

We fit to **47** observables by means of a frequentist χ^2 approach.

1. General analysis of constraints:
   All $\mathcal{C}_i$ are treated as independent free parameters.
2. Statistical scrutiny of all posible scenarios (several $\mathcal{C}_i$ to zero).
3. A favourable scenario: ($\mathcal{C}_7^{\rm NP}$- $\mathcal{C}_9^{\rm NP}$)
4. We consider 3 different sets of $B \to K^* \mu\mu$ observables:
   - 3 large-recoil + 2 low recoil bins.
   - 3 large-recoil bins only.
   - A wide large-recoil bin: [1-6] GeV.

Fitting the data: Results

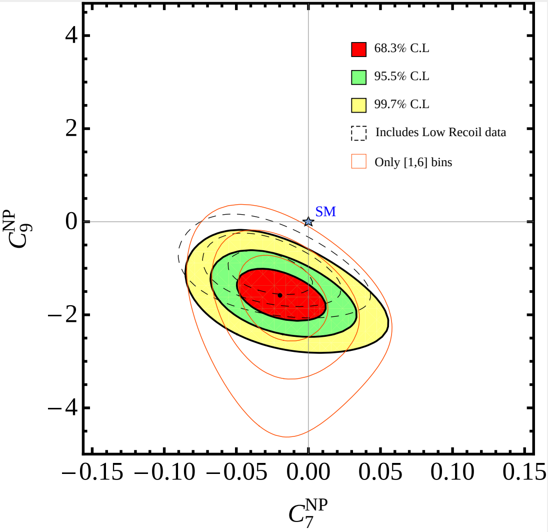
General Fit

Coefficient	$1\,\sigma$	$2\,\sigma$	$3\,\sigma$
$\mathcal{C}_7^{\rm NP}$	$[-0.05, -0.01]$	$[-0.06, 0.01]$	$[-0.08, 0.03]$
$\mathcal{C}_9^{\rm NP}$	$[-1.6, -0.9]$	$[-1.8, -0.6]$	$[-2.1, -0.2]$
$\mathcal{C}_{10}^{\rm NP}$	$[-0.4, 1.0]$	$[-1.2, 2.0]$	$[-2.0, 3.0]$
$\mathcal{C}_{7'}^{\rm NP}$	$[-0.04, 0.02]$	$[-0.09, 0.06]$	$[-0.14, 0.10]$
$\mathcal{C}_{9'}^{\rm NP}$	$[-0.2, 0.8]$	$[-0.8, 1.4]$	$[-1.2, 1.8]$
$\mathcal{C}_{10'}^{\rm NP}$	$[-0.4, 0.4]$	$[-1.0, 0.8]$	$[-1.4, 1.2]$

- Negative values for $(\mathcal{C}_7^{\rm NP}, \mathcal{C}_9^{\rm NP})$ favoured at $> (1\sigma, \mathbf{3}\sigma)$.
- Large-recoil only $\longrightarrow$ effect enhanced ($\mathcal{C}_9^{\rm NP} \sim -1.6$).
- Only [1-6] bin: Same pattern, less significance.

Fitting the data: Results

$\mathcal{C}_7^{\rm NP}$- $\mathcal{C}_9^{\rm NP}$ Scenario



- At 68.5% CL:

  $\mathcal{C}_7^{\rm NP} \in [-0.035, 0.000]$

  $\mathcal{C}_9^{\rm NP} \in [-1.9, -1.3]$

- Pulls for SM Hyp.:

  Large-recoil: **4.5σ**

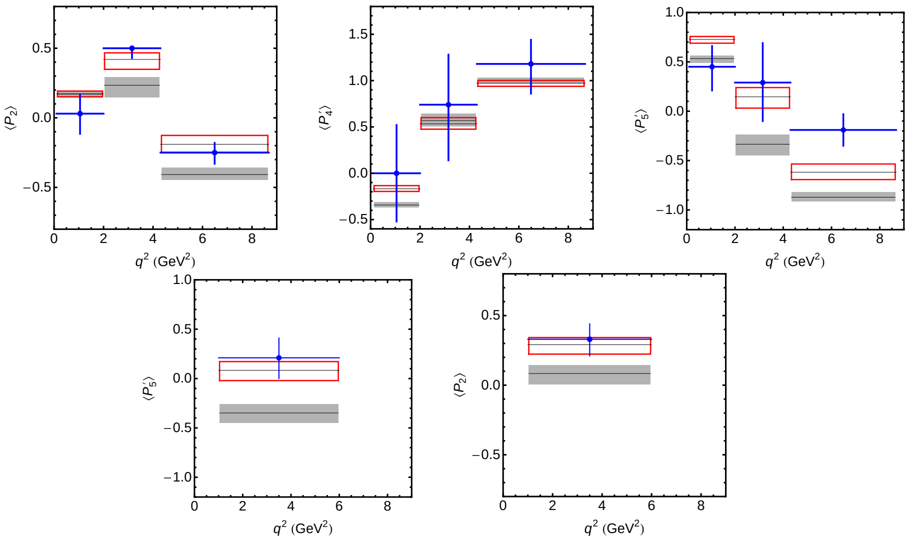
  Large + Low-recoil: **3.9σ**

  Only [1-6] GeV bin: **3.2σ**

- The overall quality of the fit is very good.

Fitting the data: Results

$\mathcal{C}_7^{\rm NP}$- $\mathcal{C}_9^{\rm NP}$ **Scenario:** Best-Fit point vs SM



Summary / Remarks

- A global fit to $b \to s\gamma$, $b \to s\mu\mu$ observables including the latest data on $B \to K^*\mu\mu$ angular observables show a significant tension w.r.t the SM, pointing (mostly) to a large NP contribution to $\mathcal{C}_9$.

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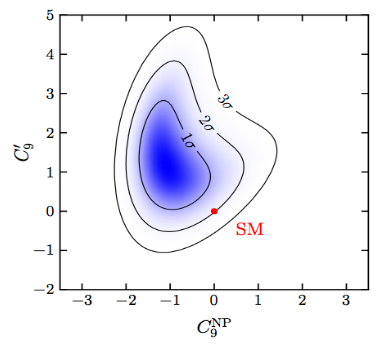
- This has been later confirmed by other groups

  (Altmannshofer,Straub / Bobeth,Beaujean,van Dyk / Horgan,Liu,Meinel,Wingate)



Horgan et al. 1310.3887

COMPLETELY INDEPENDENT ANALYSIS

Recent calculation of FFs in unquenched lattice QCD and fit to **branching ratios** & A.Obs. of

$B \to K^*\mu\mu$ and $B_s \to \phi\mu\mu$

at **low recoil**.

Summary / Remarks

- A global fit to $b \to s\gamma$, $b \to s\mu\mu$ observables including the latest data on $B \to K^*\mu\mu$ angular observables show a significant tension w.r.t the SM, pointing (mostly) to a large NP contribution to $\mathcal{C}_9$.

  S. Descotes-Genon, J. Matias, JV – 1307.5683

- This has been later confirmed by other groups

  (Altmannshofer,Straub / Bobeth,Beaujean,van Dyk / Horgan,Liu,Meinel,Wingate)

- New experimental analyses with the full 3 fb^{-1} of data will clarify a bit more the situation. Also new experimental initiatives:
  - Fit for the q^2-dependent amplitudes within some ansatz.
  - Fit directly for the WCs.
  - Improve on the binning.

- Still a lot to do from the theory side:
  - FFs, hadronic contributions, PCs, resonance tails, etc.
  - New modes & observables.
  - Implications on NP models...

Challenges and Future Directions

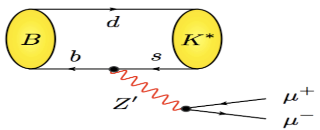
1. Theory correlations $\longrightarrow$ Form Factors and its ratios, etc.
2. Increase the set of observables used ($B_s \to \phi\ell\ell$, $\Lambda_b \to \Lambda_s\ell\ell$, more on $B \to X_s\ell\ell$...)
3. Form factors: ratios in Helicity basis, LCSRs within SCET,...
4. Charm loop: 2-gluon corrections, amplitude dependence of $\Delta\mathcal{C}_9^{\rm eff}$, ...
5. **Power corrections:** Difficult!! Characterize the structure of power suppressed contributions within SCET, model subleading non-perturbative quantities and genuine non-factorizable contributions. Relate to non-leptonic modes. Long term project.
6. Test for similar effects in other channels (e.g. $B \to K\nu\bar{\nu}$) –[Belle II]
7. CP violation, e^+e^- / $\tau^+\tau^-$ modes, polarization observables, ...

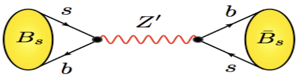
Epilogue: NP scale?

$$\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \mathcal{C}_9 = \frac{c}{\Lambda^2}$$

For $\mathcal{C}_9 \sim 1$ the NP scale Λ would be:

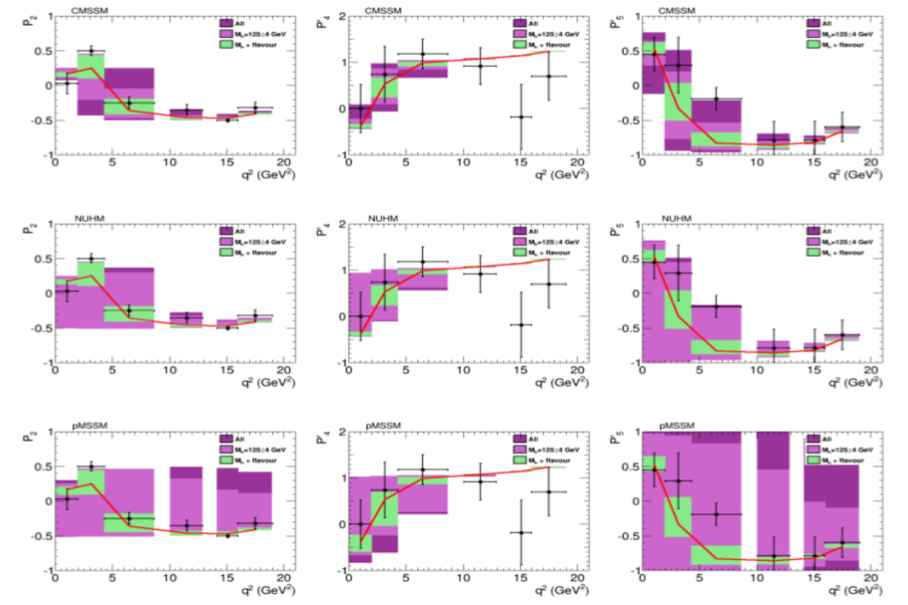
- Tree-level flavor-generic NP, with $g \sim 1$ $(c \sim 1)$: $\Lambda \sim 38\,\mathrm{TeV}$
- Tree-level flavor-CKMish NP, with $g \sim 1$ $(c \sim V_{tb}V_{ts}^*)$: $\Lambda \sim 8\,\mathrm{TeV}$
- Tree-level flavor-generic NP, with $g \sim 0.1$ $(c \sim 0.01)$: $\Lambda \sim 3.8\,\mathrm{TeV}$
- Loop-level flavor-generic NP, with $g \sim 1$ $(c \sim \frac{1}{(4\pi)^2})$: $\Lambda \sim 3\,\mathrm{TeV}$
- Loop-level flavor-CKMish NP, with $g \sim 1$ $(c \sim \frac{V_{tb}V_{ts}^*}{(4\pi)^2})$: $\Lambda \sim 600\,\mathrm{GeV}$





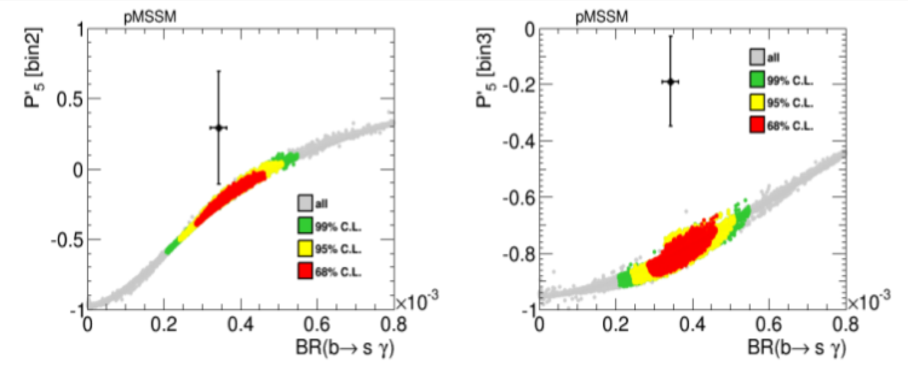
Epilogue: MSSM

F. Mahmoudi, S. Neshatpour, JV, 1401.2145



Epilogue: MSSM

F. Mahmoudi, S. Neshatpour, JV, 1401.2145



P_5' is extremely difficult to reproduce in the MSSM, because:

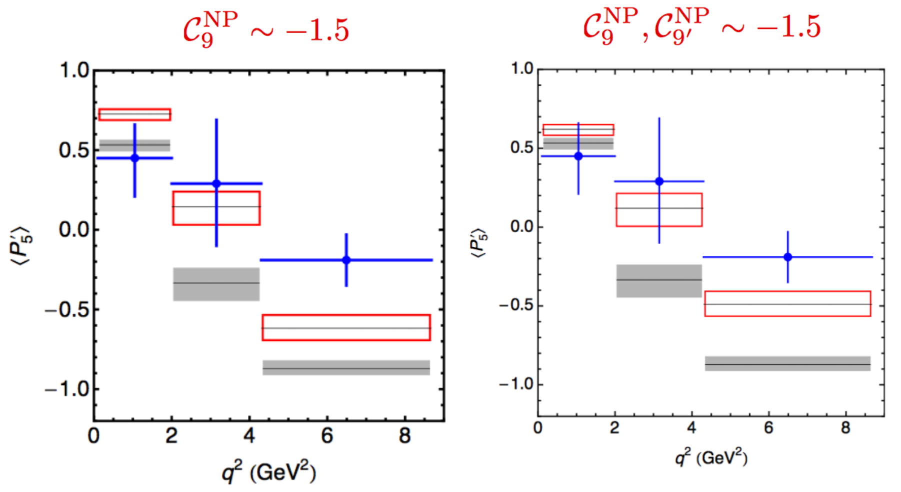
- Large values of $\mathcal{C}_9$ are correlated to large values of other coefficients.
- Large values of $\mathcal{C}_7$ can do it, but are excluded by $B \to X_s\gamma$.

References

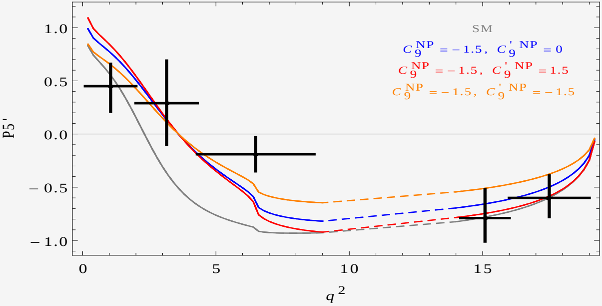
- The LHCb papers on the $B \to K^*\mu\mu$ angular analysis:
  LHCb collaboration, 1304.6325[hep-ex], 1308.1707[hep-ex]
- Statement and analysis of the "$B \to K^*\mu\mu$ Anomaly":
  Descotes-Genon, Matias, JV, 1307.5683[hep-ph]
- Definition of the *Optimised observables* and SM predictions:
  Matias, Mescia, Ramon, JV, 1202.4266[hep-ph]
  Descotes-Genon, Matias, Ramon, JV, 1207.2753[hep-ph]
  Descotes-Genon, Hurth, Matias, JV, 1303.5794[hep-ph]
- Further papers addressing the Anomaly:
  Altmannshofer, Straub, 1308.1501[hep-ph]
  Buras, Girrbach, 1309.2466[hep-ph]
  Beaujean, Bobeth, van Dyk, 1310.2478[hep-ph]
  Gauld, Goertz, Haisch, 1308.1959[hep-ph], 1310.1082[hep-ph]
  Horgan, Liu, Meinel, Wingate, 1310.3887[hep-ph]
  Datta, Duraisamy, Gosh, 1310.1937[hep-ph]
  Mahmoudi, Neshatpour, JV, 1401.2145[hep-ph]
- Form factors and charm-loop effects:
  Khodjamirian, Mannel, Pivovarov, Wang, 1006.4945[hep-ph]
  Horgan, Liu, Meinel, Wingate, 1310.3722[hep-lat]
- The theory of $B \to K^*\ell\ell$ at large and low recoil:
  Beneke, Feldmann, Seidel, 0106067[hep-ph], 0412400[hep-ph]
  Beylich, Buchalla, Feldmann, 1101.5118[hep-ph]
  Grinstein, Pirjol, 0404250[hep-ph]

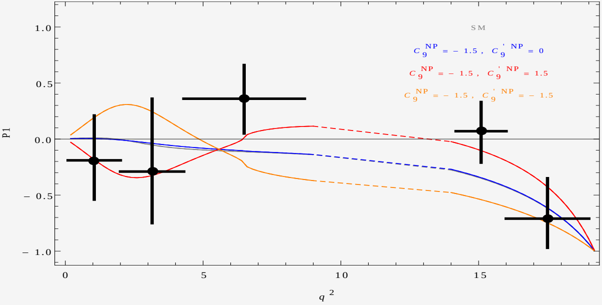
Backup Slides

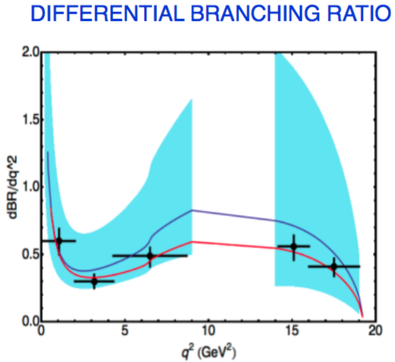
$\mathcal{C}_9$ - $\mathcal{C}_9'$ Scenario



$\mathcal{C}_9$ - $\mathcal{C}_9'$ Scenario

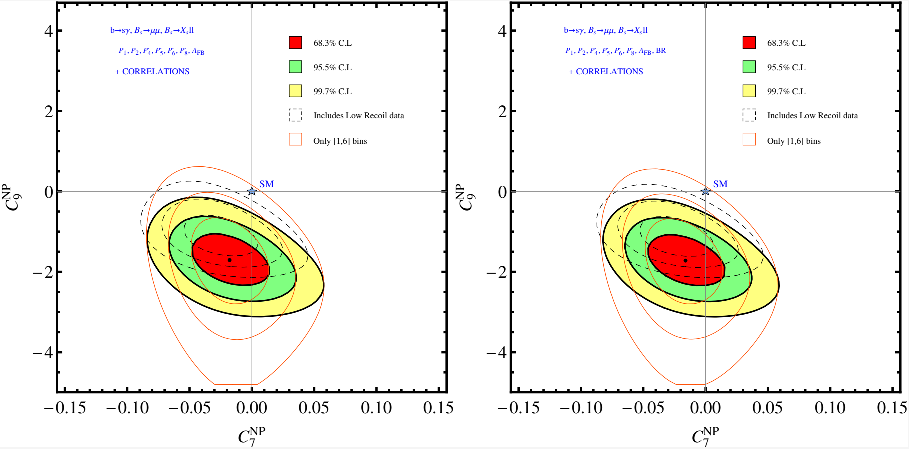




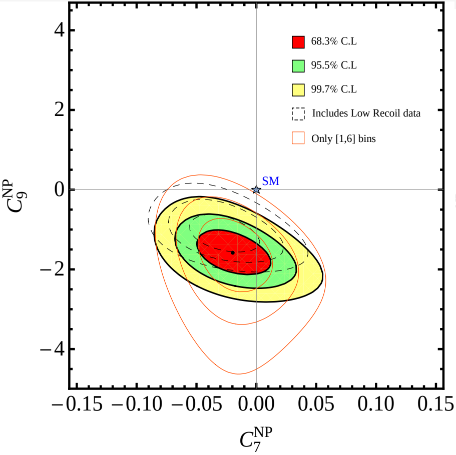


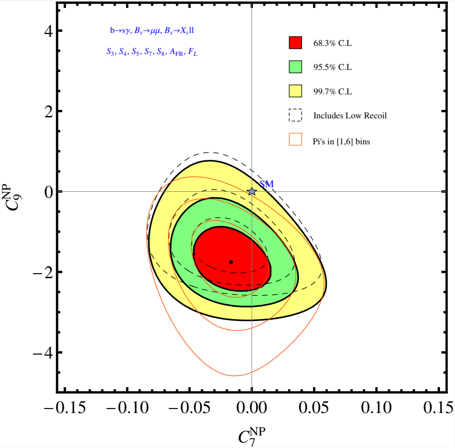
where the blue curve is SM and the red curve corresponds to $C_9^{NP} = -1.5$. Interestingly the central value it goes in the right direction, but given the error bars all is consistent with data.

Experimental correlations & Branching Ratio

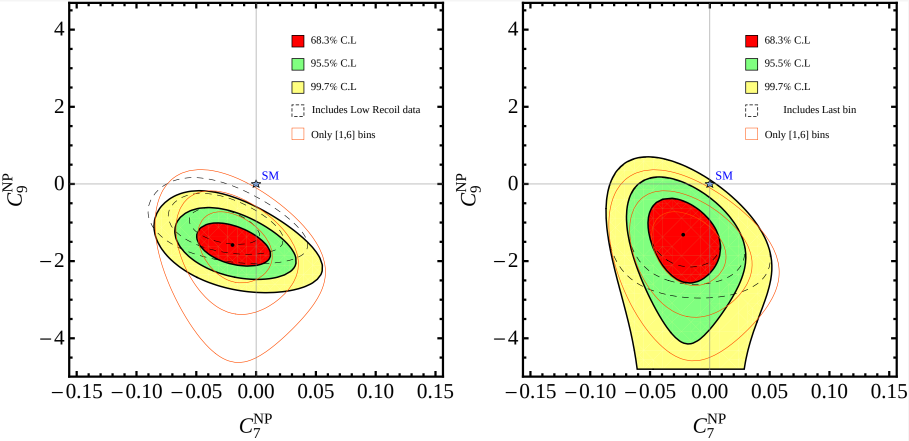


Fit to Form-Factor-dependent observables S_i





Excluding the [4.3,8.68] bin



$B^+ \to K^+\mu^+\mu^-$ Branching Ratio (Preliminary)